My name is Teppei

- 2002 B. Sc., Tokyo Institute of Technology (Japan)
- 2008 Ph. D, Indiana University (USA), MiniBooNE and SciBooNE (Fermilab)
- 2009-2013, Postdoc at MIT (USA), MicroBooNE (Fermilab)
- 2013-2019, Lecturer (assistant professor) at Queen Mary University of London (UK)
- 2019- , Reader (associate professor) at King's College London (UK)

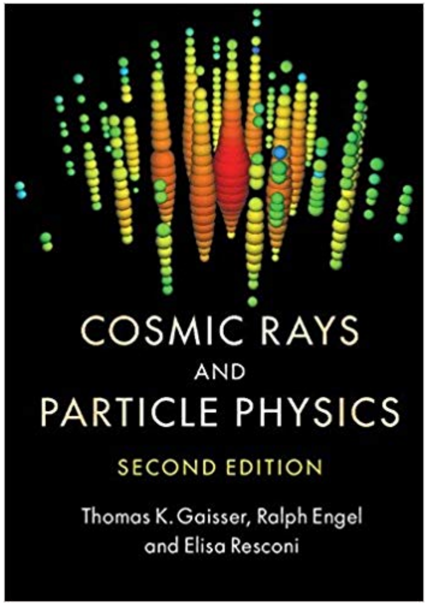
Current focus: T2K, Hyper-Kamiokande, IceCube, NuSTEC, and phenomenology
Current interest: neutrino interaction physics, new physics search with neutrinos

@teppeikatori (twitter, Instagram)

"Institute of Physics Astroparticle Physics"
News on astrophysics in UK
https://www.facebook.com/IOPAPP

"NuSTEC News"
News on neutrino cross-section physics
https://www.facebook.com/nuxsec

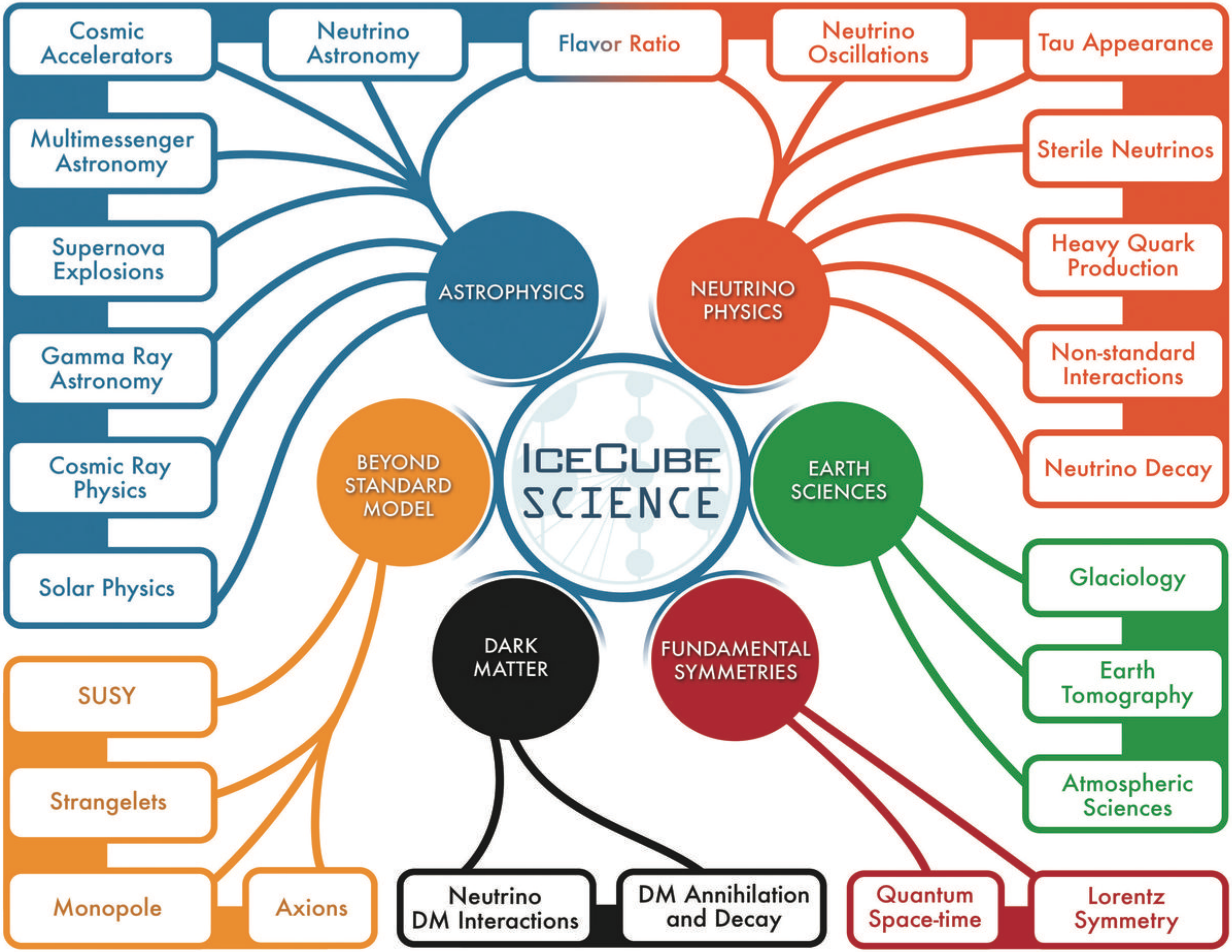
MicroBooNE PMT test stand
(photo by Reidar Hahn, Fermilab)



Cosmic Rays and Particle Physics, 2nd edition
(Cambridge university press, ISBN: 9780521016469)
Thomas K. Gaisser, University of Delaware
Ralph Engel, Karlsruhe Institute of Technology, Germany
Elisa Resconi, Technische Universität München

Slides from conference series

- Neutrino series
https://www.mpi-hd.mpg.de/nu2018/
- TeVPA series (TeV Particle Astrophysics)
https://indico.desy.de/indico/event/18204/page/5
- ICRC series (International Cosmic Ray Conference)
http://www.icrc2017.org/index.php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Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Multimessenger Astronomy
Supernova Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
NEUTRINO PHYSICS
Neutrino Oscillations
Tau Appearance
Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
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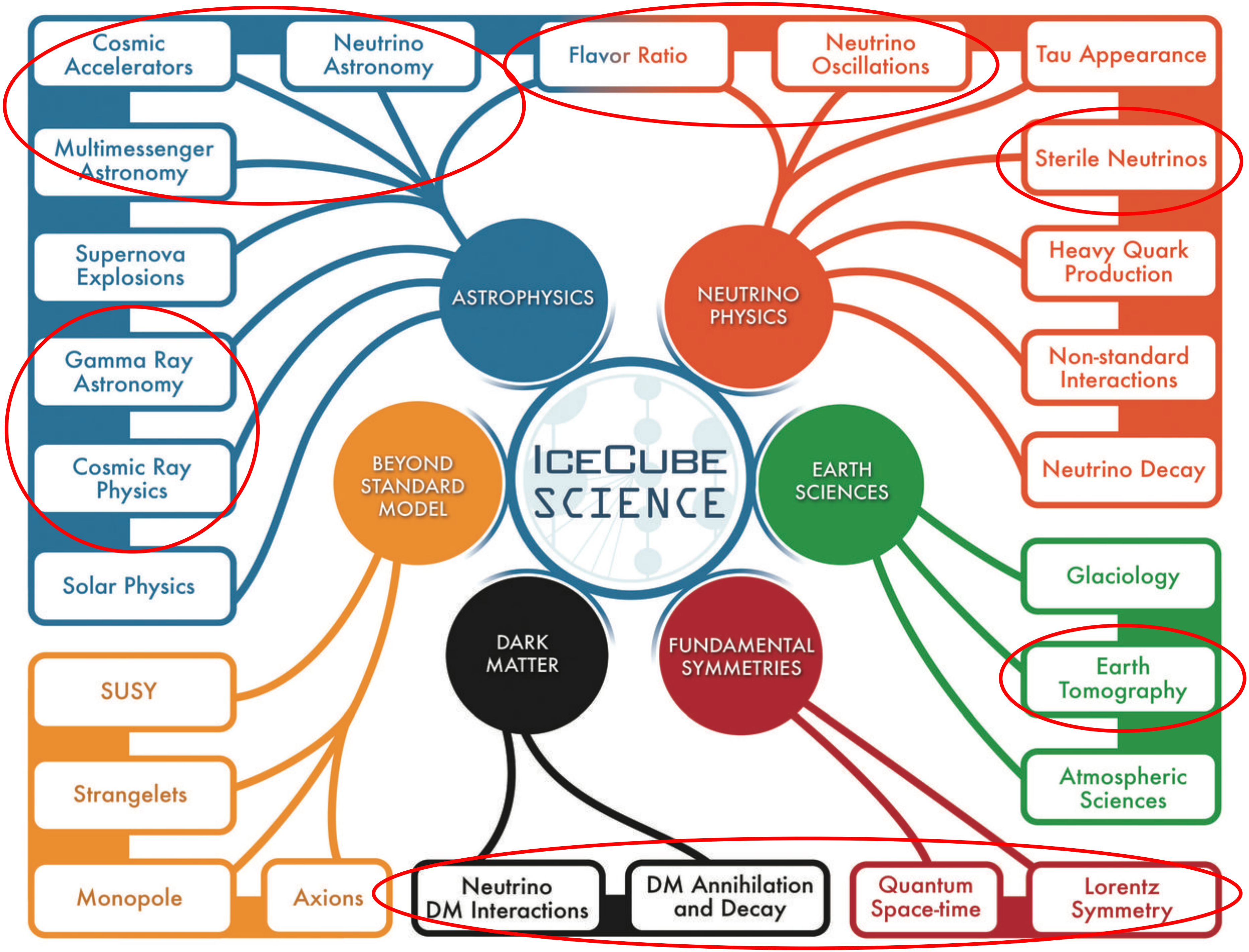
BEYOND STANDARD MODEL
SUSY
Strangelets
Monopole
Axions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High-Energy Neutrino Astronomy

outline

1. Cosmic Ray and Astroparticle Physics
2. High-Energy Neutrino Observations
3. Neutrino Multi-Messenger Astronomy
4. Astrophysical Neutrino Flavour Physics

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Teppei Katori
King’s College London

Vietnam School on Neutrinos (VSON3), ICISE, Quy Nhon, Vietnam, July 12-13, 2019

1. **Cosmic Ray and Astroparticle Physics**

2. High-Energy Neutrino Observations

3. Neutrino Multi-Messenger Astronomy

4. Astrophysical Neutrino Flavour Physics

1. Cosmic ray and astroparticle physics

What are they?

Where are they from?

Why are they so high-energy?

Why neutrinos are important to understand these questions?

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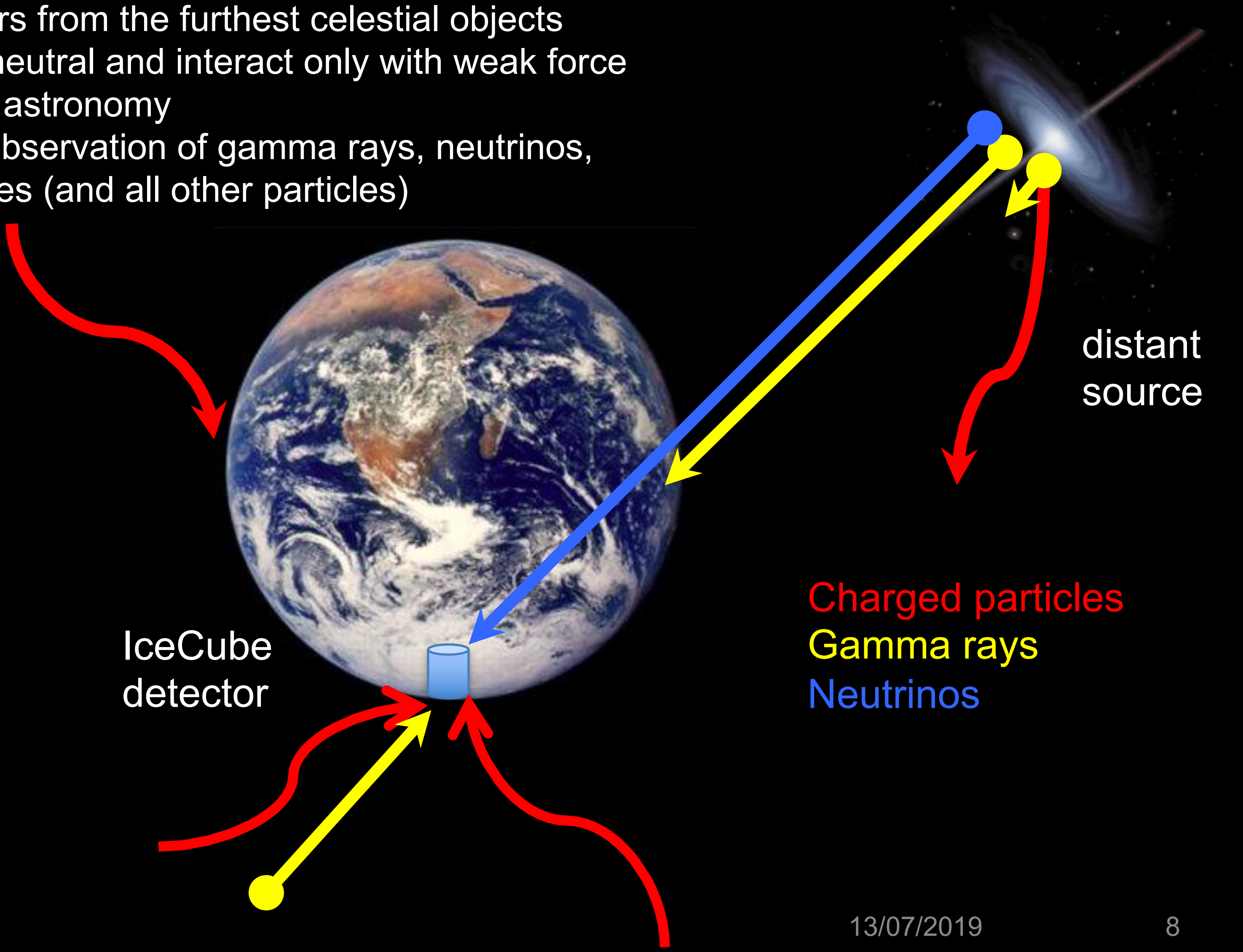
1. High-Energy Neutrino Astronomy

Direct messengers from the furthest celestial objects
- Neutrinos are neutral and interact only with weak force

Multi-messenger astronomy
- simultaneous observation of gamma rays, neutrinos, gravitational waves (and all other particles)

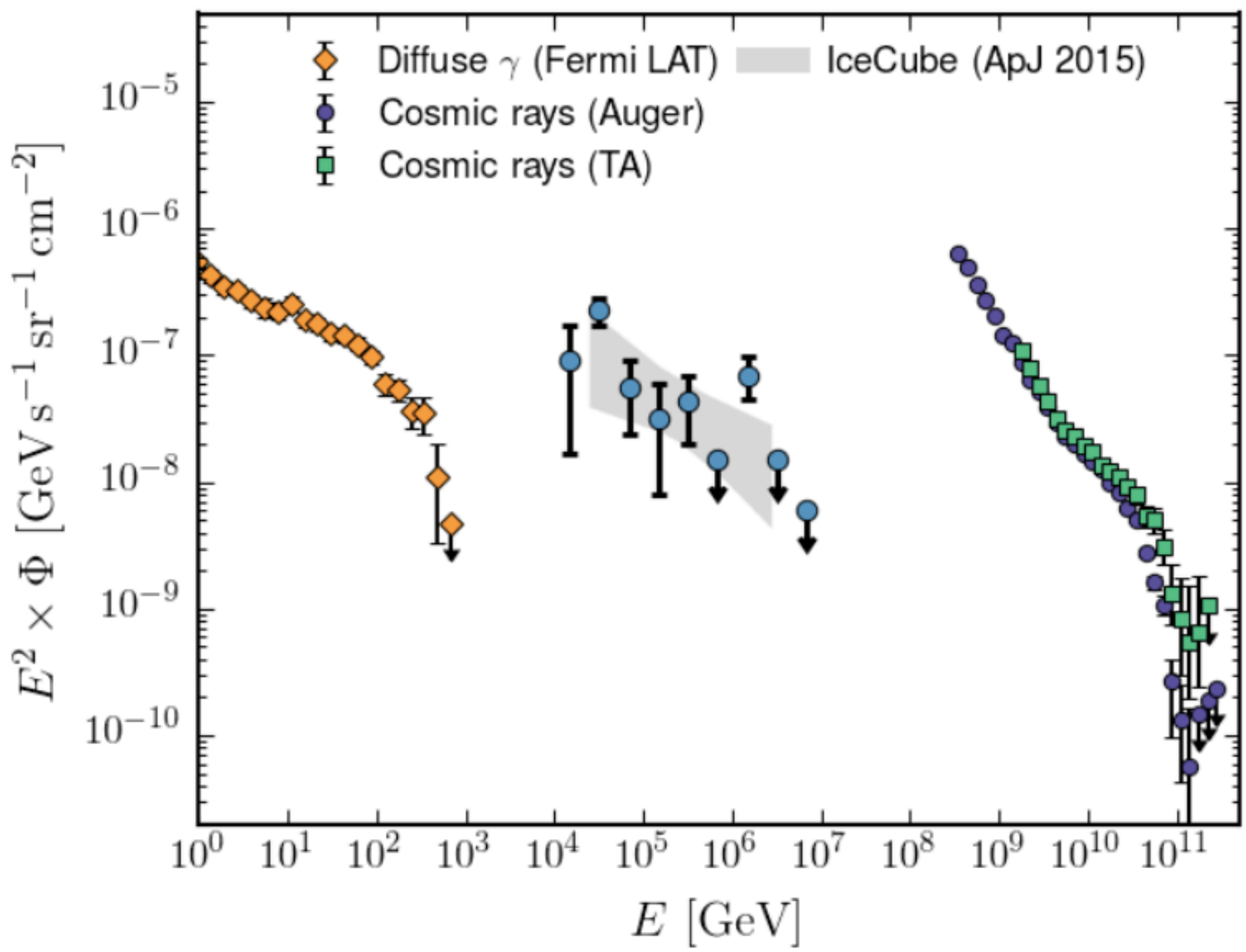


1. High-Energy Neutrino Astronomy

$$\begin{matrix} p+p \\ p+\gamma \end{matrix} \rightarrow X + \pi \begin{cases} \pi^0 \to \gamma\gamma \\ \pi^+ \to \mu^+ + \nu_\mu \\ \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e \\ n \to p + e^- + \bar{\nu}_e \end{cases}$$

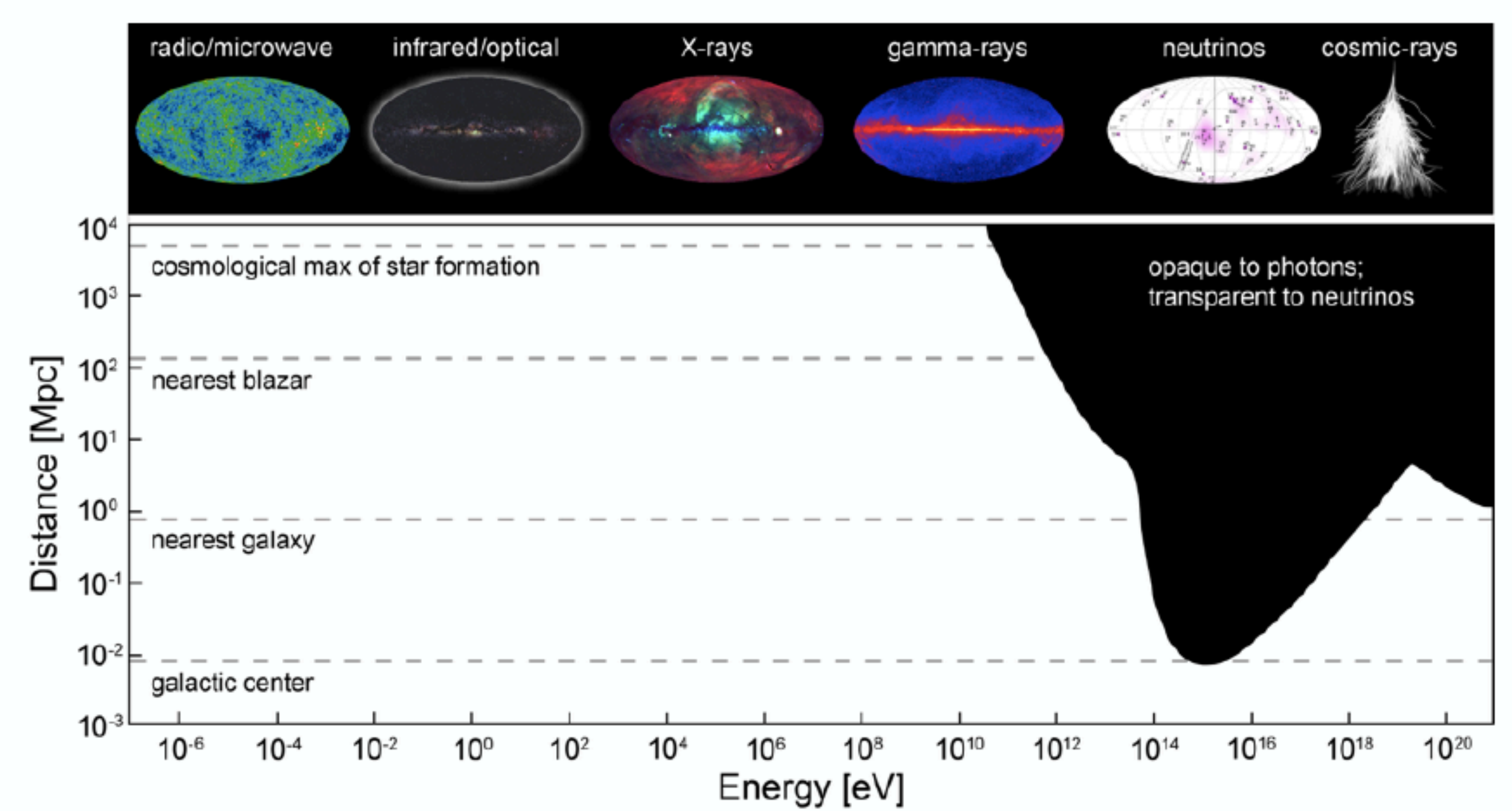
High-energy protons, gamma rays, and neutrinos are related.

→ expected flavour ratio (ν_e:ν_μ:ν_τ)=(1:2:0) (cf. atmospheric neutrinos)



1. High-Energy Neutrino Astronomy

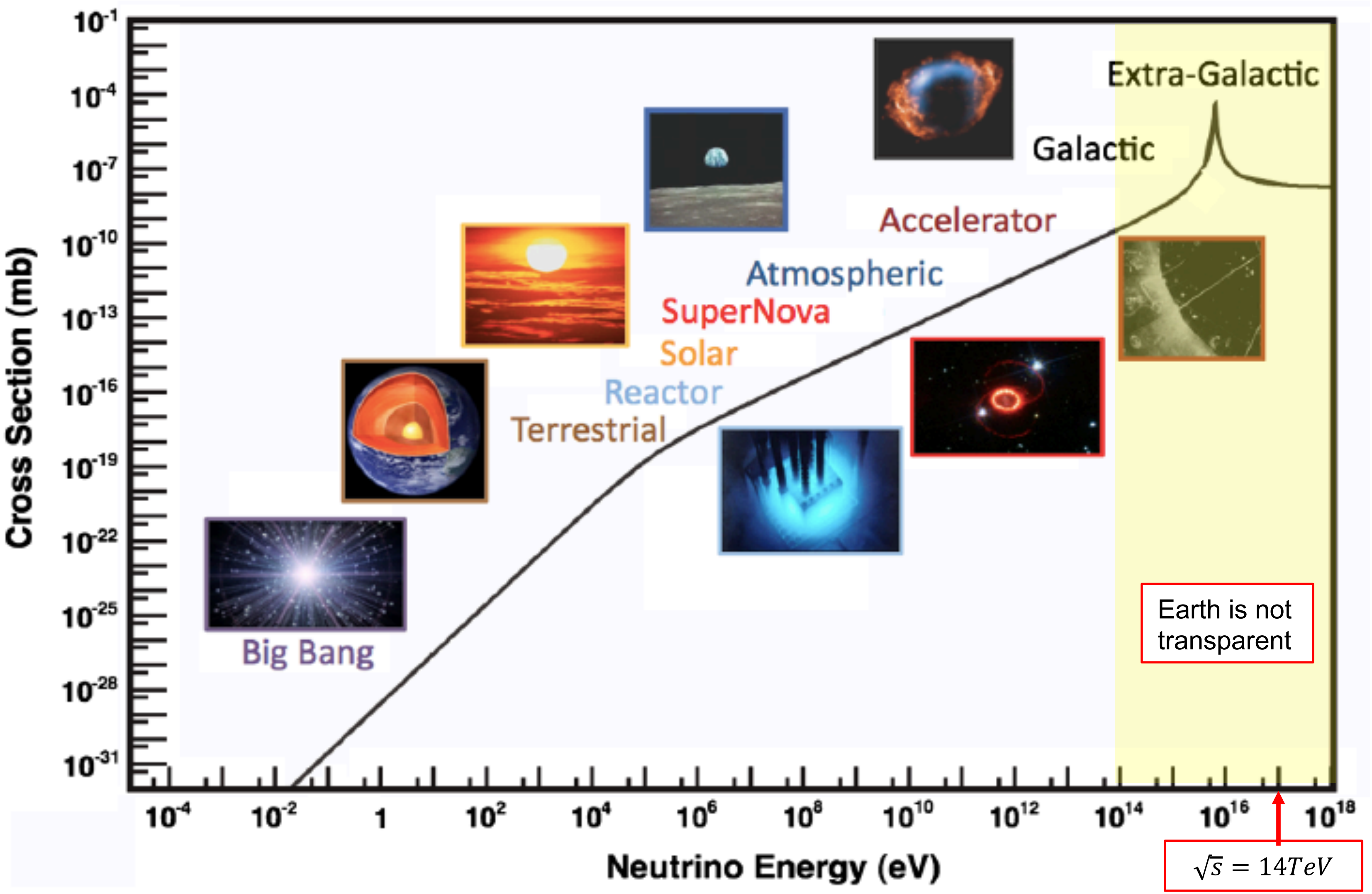
Above ~10-100 TeV neutrinos are only direct messengers



Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

1. High-Energy Neutrino Astronomy

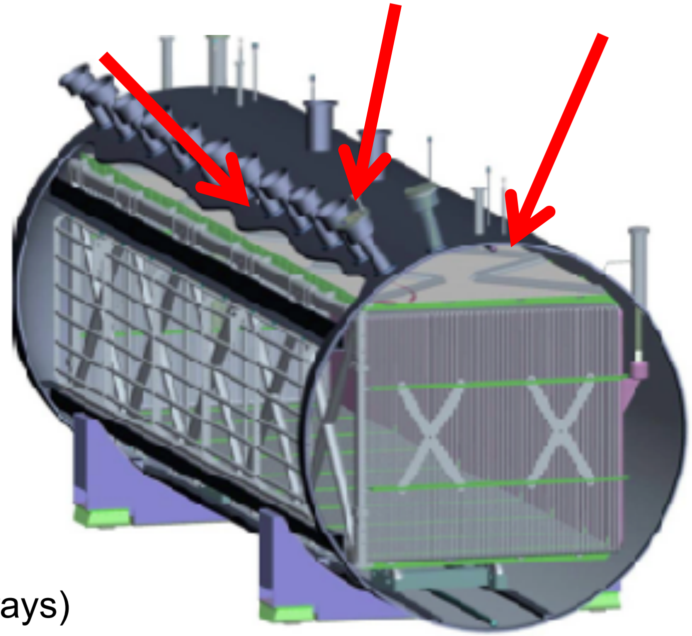
Above ~10-100 TeV neutrinos are only direct messengers



Earth is not transparent

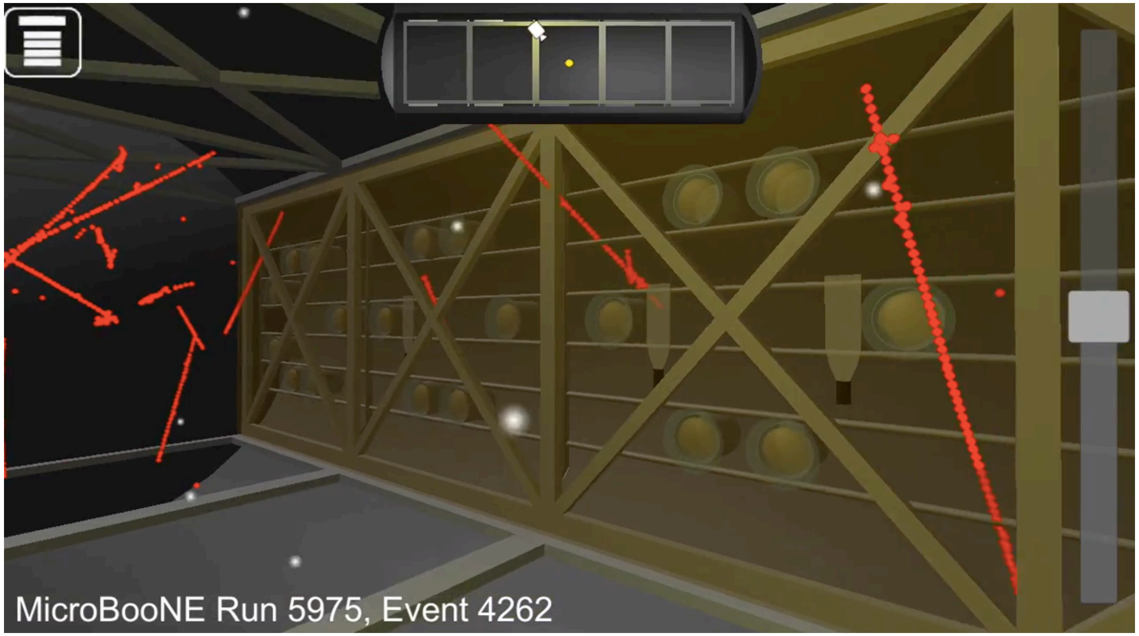
$\sqrt{s} = 14TeV$

1. Cosmic rays in particle physics



On the surface, cosmic ray = atmospheric muons (secondary)
~ 4 GeV (=MIP, stopping power ~ 2 MeV•cm^2/g).
~ 1/10cm^2/s (~ 1 per your hand per second)

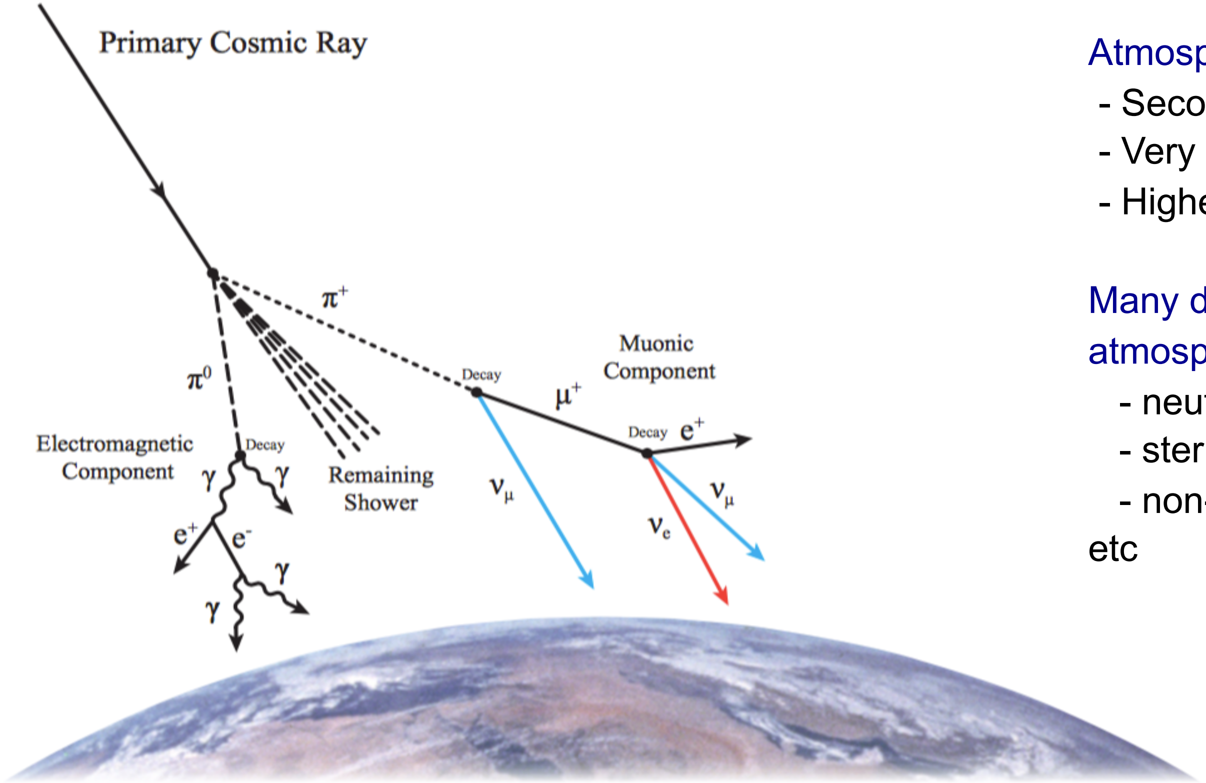
e.g.) MicroBooNE detector
- LArTPC with fiducial volume, ~2m x 2m x 10m
→ ~200,000 cm^2 surface (=20,000 cosmic muons per sec)
- Trigger window is 1.6ms
- 20,000 x 0.0016 ~ 32 cosmic rays per trigger (data ~ 23 cosmic rays)



MicroBooNE Run 5975, Event 4262

1. Cosmic rays, what are they?

Cosmic ray physics
- Secondary: discovery of muon, anti-particle, strange quark, etc
- Primary: what are they? where are they from? why so high energy?



Atmospheric neutrinos
- Secondary particles
- Very high energy (up to ~50 TeV)
- Higher flux at low energy (~$E^{-3.7}$)

Many discovery science with atmospheric neutrinos
- neutrino oscillations
- sterile neutrino search
- non-standard interaction

etc

Gaisser, Stanev, Tilav, Front.Phys.,2103,8(6),748

1. Cosmic rays, what are they?

Cosmic ray physics

- Secondary: discovery of muon, anti-particle, strange quark, etc
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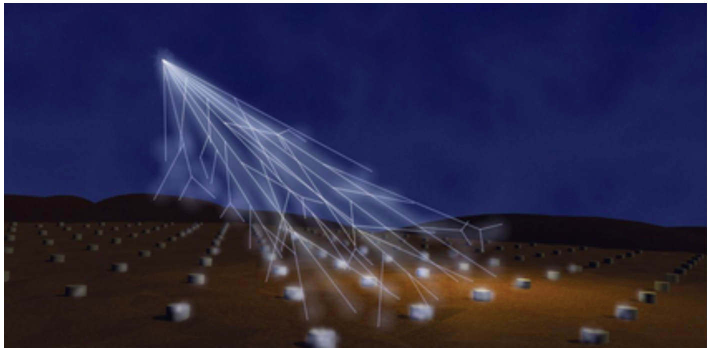
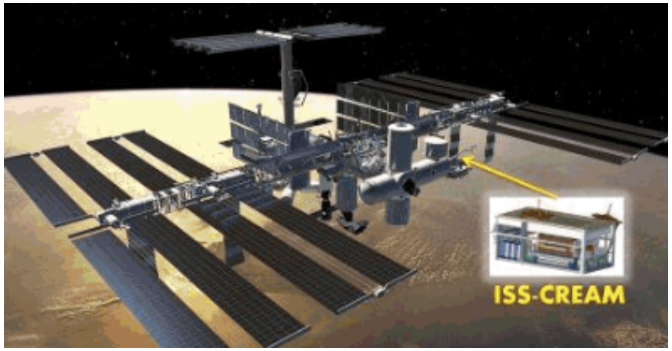


Pierre Auger Observatory

CREAM experiment
(Cosmic Ray Energetics and Mass)



ISS-CREAM

balloon, satellite (direct)

air shower (indirect)

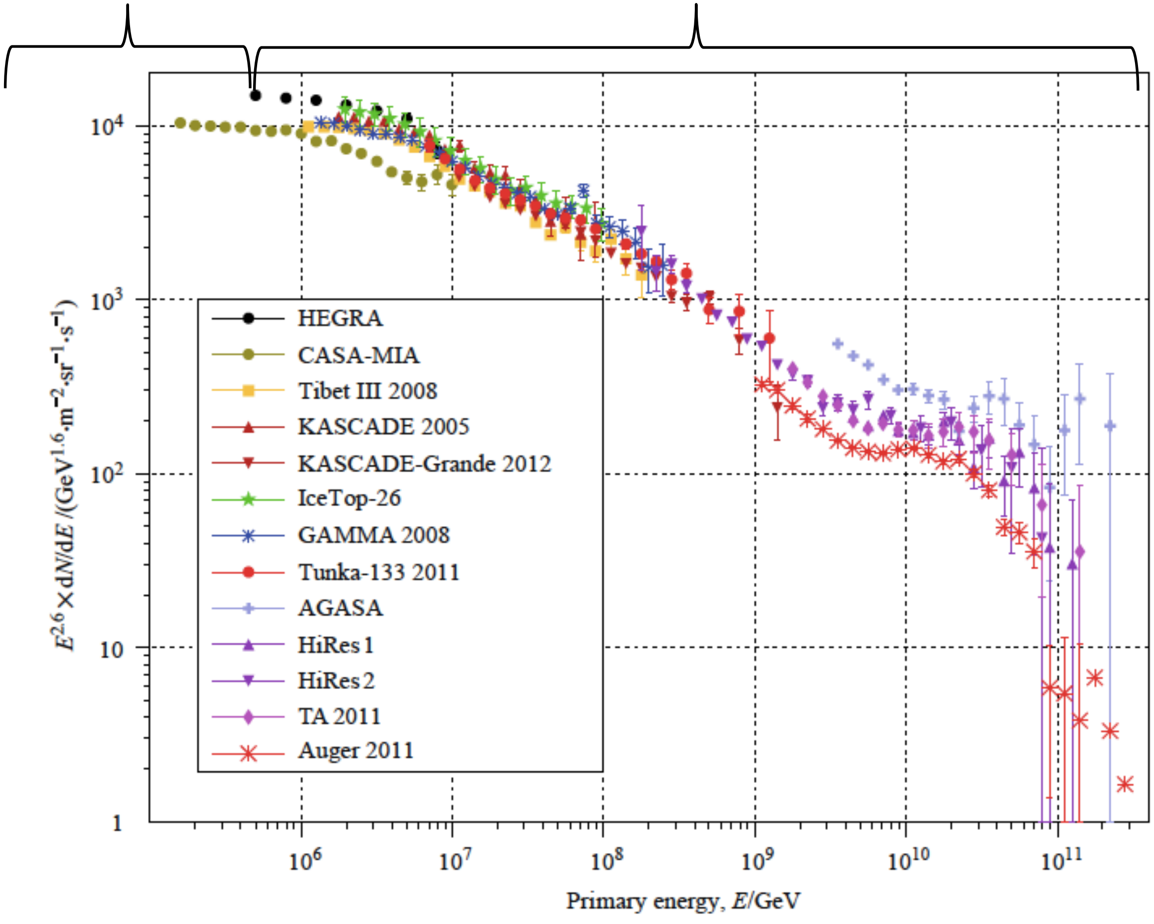
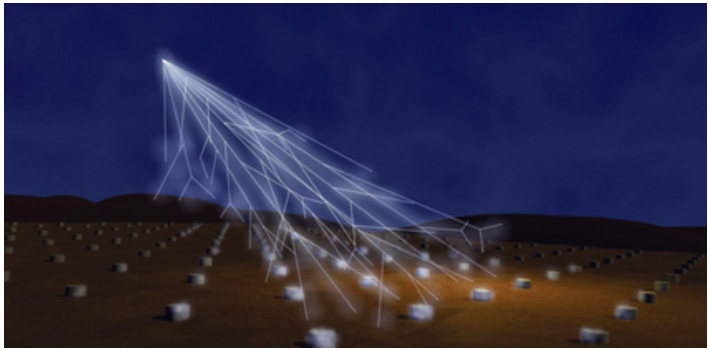


Fig. 1 All particle cosmic ray spectrum from air shower experiments. (References in text.)

Gaisser, Stanev, Tilav, Front.Phys.,2103,8(6),748

1. Cosmic rays, what are they?



Pierre Auger Observatory

Cosmic ray physics
- Secondary: discovery of muon, anti-particle, strange quark, etc
- Primary: what are they? where are they from? why so high energy?

Primary particles
- 90% protons, 9% alphas, 1% all other nuclei
- ~E^{-x} spectrum, x=2.7 (secondary) to 3.0 (primary)
- Energy reaches ~10^{20} eV
- GZK cutoff (~7×10^{19} eV)

$$p + \gamma \rightarrow \Delta \rightarrow \pi + p$$

- $\pi^0 \rightarrow \gamma\gamma$: UHE γ-ray
- $\pi^+ \rightarrow \mu^+ + \nu_\mu$: UHE neutrinos

Presence of UHE γ and ν are natural

Spectrum

$$\frac{dN}{dE} = \frac{dN}{E d\ln E}$$

- spectrum index γ is different “1” for - function of “E” and “lnE”.
- people often multiply number to make it flat.

→ it’s very common to make mistake

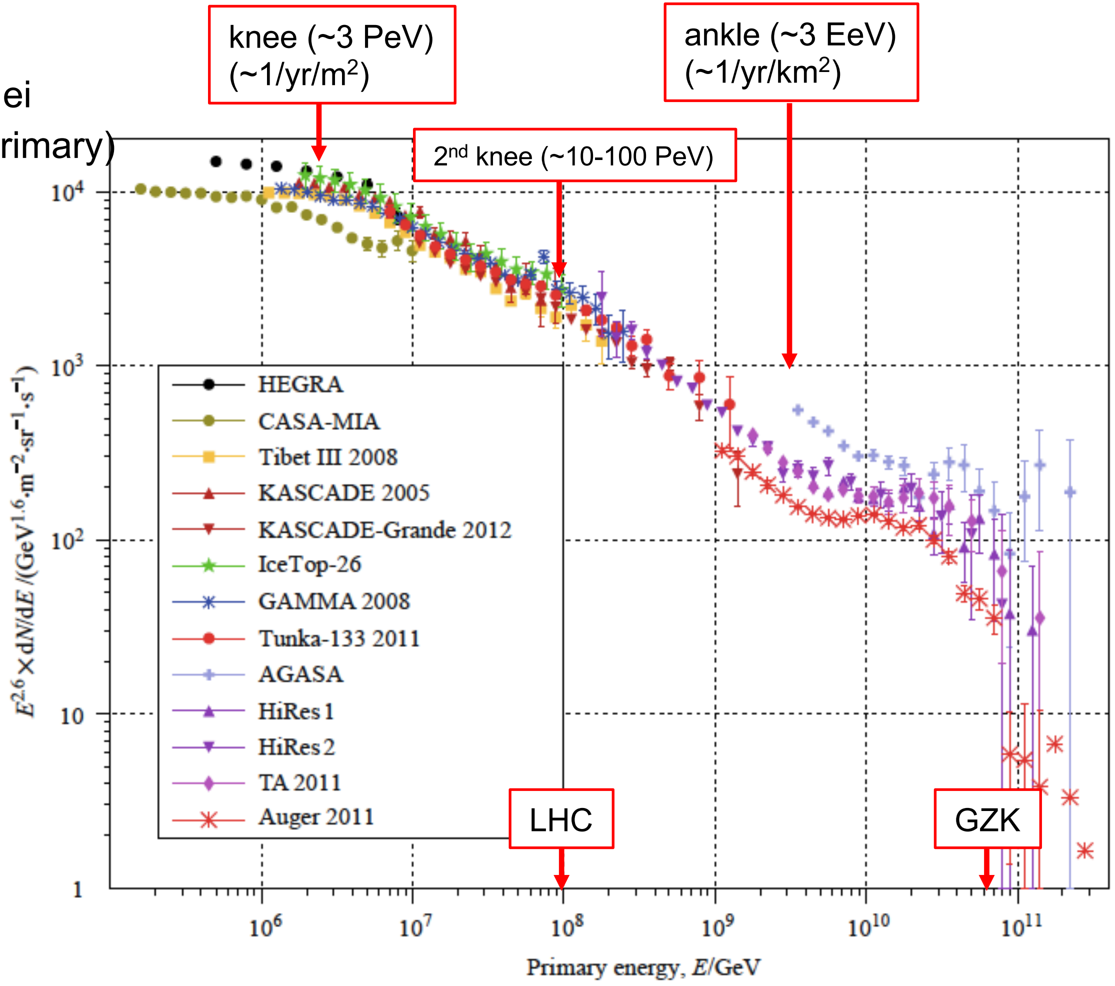


Fig. 1 All particle cosmic ray spectrum from air shower experiments. (References in text.)

Pierre Auger collaboration, PLB762(2016) 288

1. Pierre Auger Observatory

Ultra High Energy Cosmic Rays (UHECRs) have GZK cutoff (~7x10^{19} eV by $p+\gamma\rightarrow\Delta\rightarrow\pi+p$)

- Presence of UHE γ and ν are natural
- $\pi^0\rightarrow\gamma\gamma$: UHE γ-ray
- $\pi^+\rightarrow\mu^++\nu_\mu$: UHE neutrinos

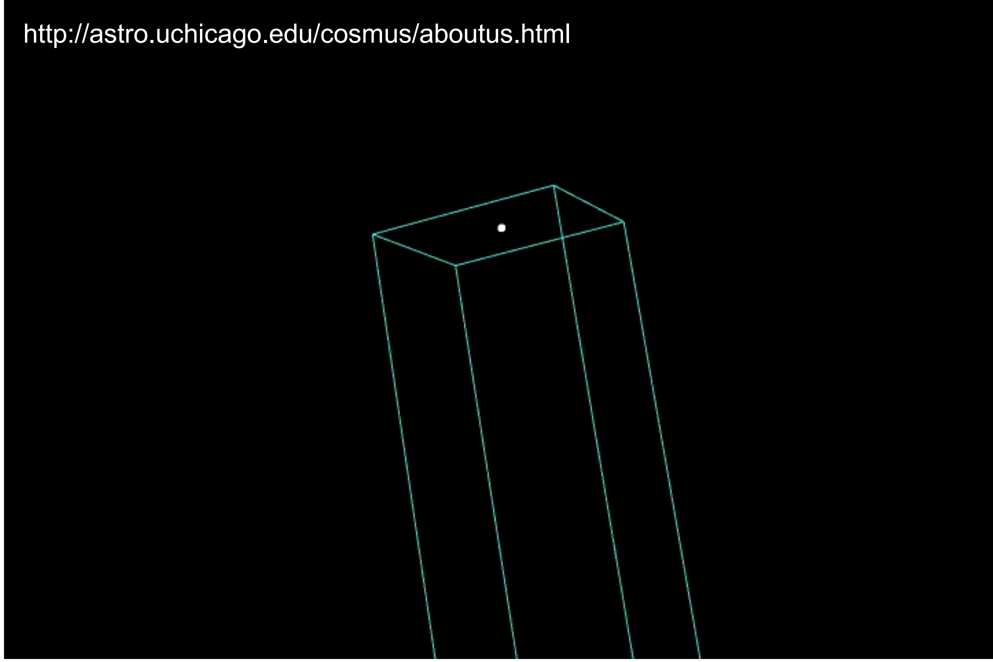
Pierre Auger Observatory

- Surface detector (water Cherenkov array)
  → secondary photons, electrons, muons
- Fluorescence detector (PMT)
  → Shower depth

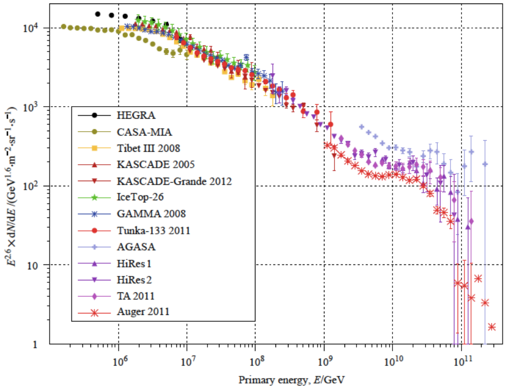
Combination of them can access to the composition of UHECRs

→ mixed, protons and heavy nuclei?

→ No GZK cutoff? No UHE ν?



http://astro.uchicago.edu/cosmus/aboutus.html



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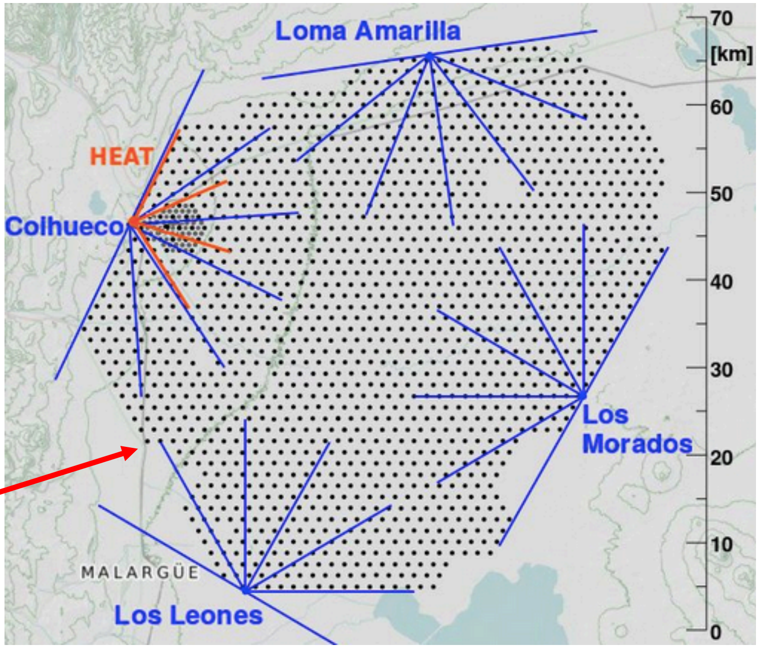


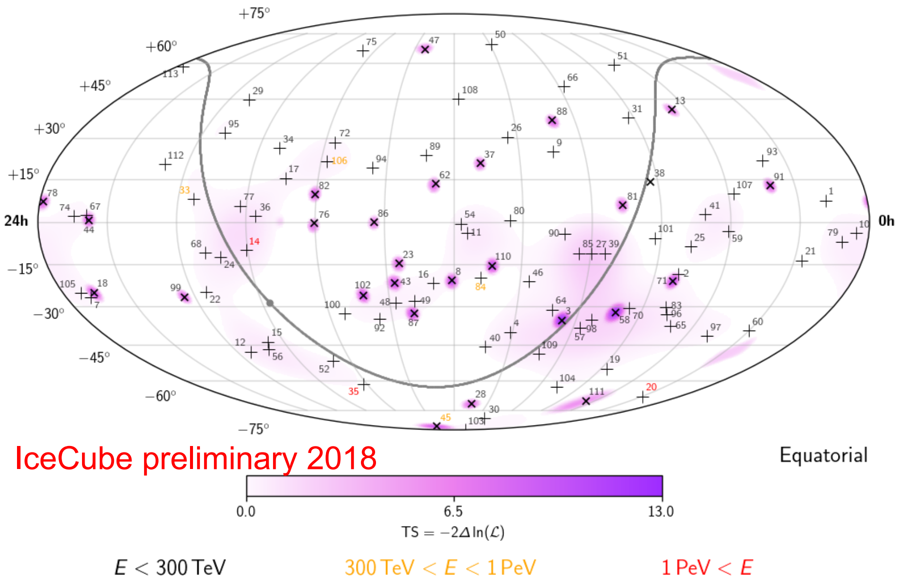
1. Cosmic rays, where are they coming from?

Primary particles

- Mostly from unknown source and isotropic (diffuse)
- Some of them are emitted from known sources (point source)
- Some of them are from only certain time period (transient)

Astrophysical high-energy neutrinos (diffuse flux)

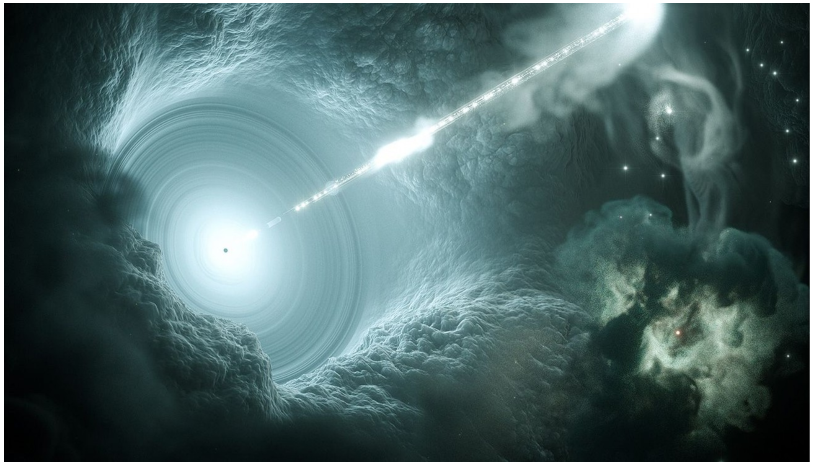
- mostly from unknown source and isotropic



IceCube preliminary 2018

Blazar neutrinos, IC170922A (point source, transient)

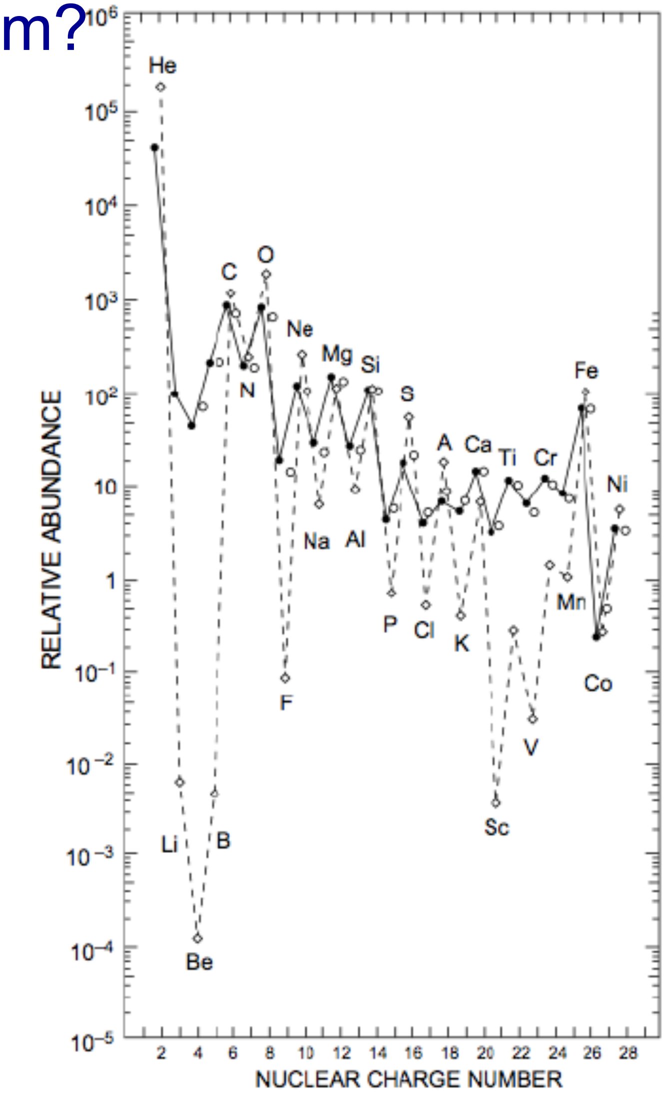
- from TXS0506+056 (blazar)
- coincidence with optical observatories



IceCube, Science361(2018)147
IceCube et al,(2018)eaat1378

R. A. Mewaldt (1983), Rev. Geophys. Space. Phys.(21):295

1. Cosmic rays, where are they coming from?



Primary particles

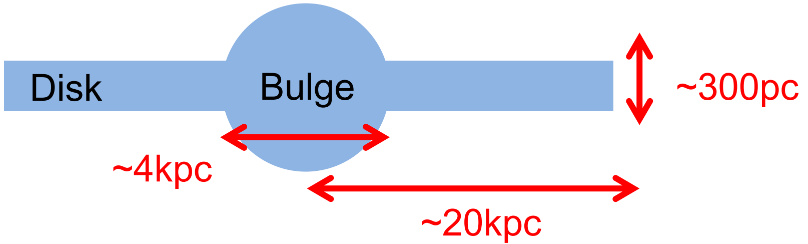
- Mostly from unknown source and isotropic (diffuse)
- Some of them are emitted from known sources (point source)
- Some of them are from only certain time period (transient)

Composition

- Solar system lacks some elements (Li, Be, B,Sc, Ti, V, Cr, Mn, etc)
- Spallation of primary cosmic ray and ISM (interstellar medium)
- From known cross section, cosmic ray traverse X~ 5 g/cm^2
- density of galaxy disc ρ~ 1 proton/cm^3
- L~X/ρ~$\frac{5g}{cm^2} / \frac{1}{N_A \cdot cm^3} \sim 3 \cdot 10^{24} cm \sim 1Mpc$

→ typical cosmic rays are travelling > 1Myr in interstellar medium!

e.g.) Milky Way



1pc = 3.26 lyr = 3x10^{16}m

Brief digression

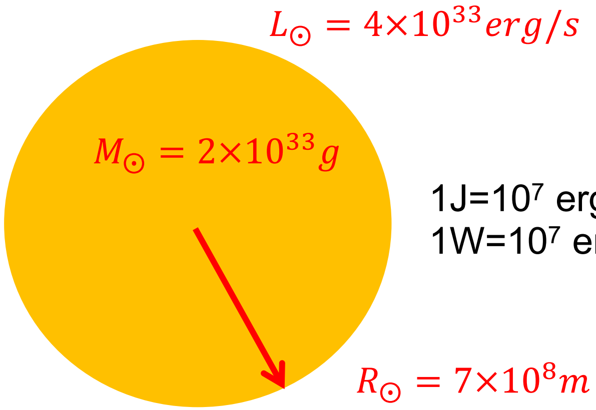
1. Astronomical parameters

Sun (=a typical star)

Solar mass: $M_\odot = 2\times10^{30}kg$ (mass of Sirius = $1M_\odot$)

Solar radius: $R_\odot = 7\times10^{8}m$ (radius of Sirius = $1.7R_\odot$)

Solar luminosity: $L_\odot = 4\times10^{26}W$ (luminosity of Sirius = $25L_\odot$)



1J=10^7 erg
1W=10^7 erg/s

Milky Way

Disk: R: ~ 15-20 kpc
h: ~ 200-300 pc
Solar system ~ 8.5 kpc from the center

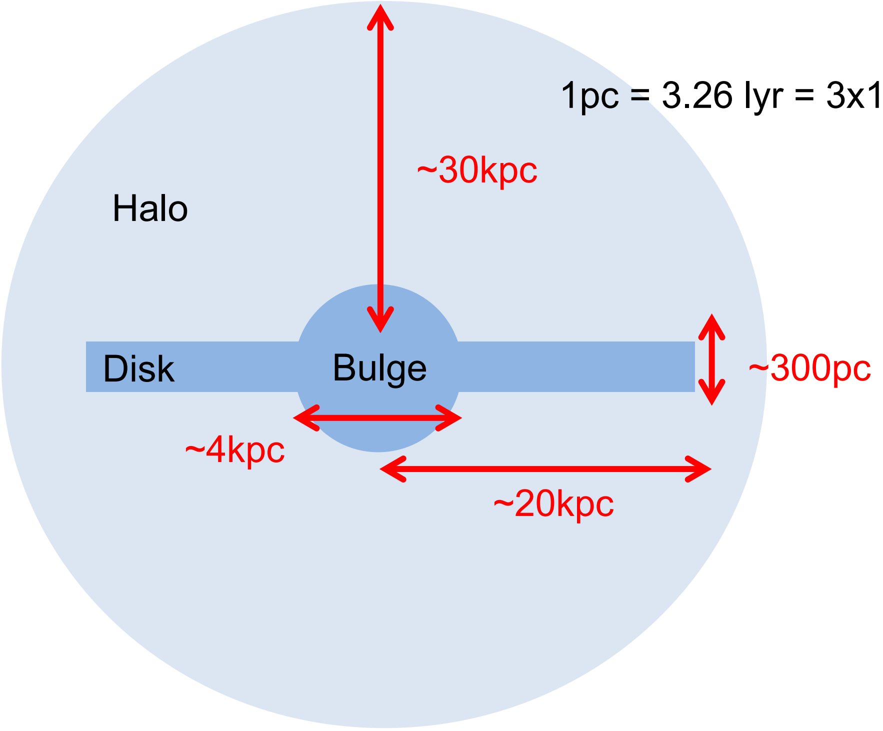
Bulge: ~4-6 kpc

Halo: ~30 kpc

Cosmic ray energy density: ~0.5 eV/cm^3

ISM density: 1 proton/cm^3

B field: 3μG (energy density ~ 0.25 eV/cm^3)



1pc = 3.26 lyr = 3x10^{16}m

Universe

Critical density: $\rho_c = \frac{3H_0}{8\pi G_N} \sim 10^{-29}/cm^3 \sim 5GeV/m^3$

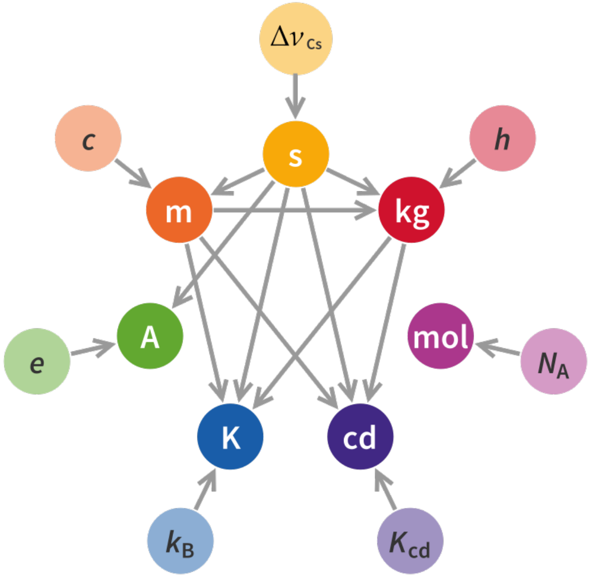
Hubble radius: $R_H = c/H_0 \sim 4400Mpc$

One more brief digression

1. Units and scale

SI base units (2019)

$\Delta\nu_{Cs} = 9192631770\ Hz$	Cesium atom hyperfine transition	second
$c = 299792458\ m/s$	Speed of light	meter
$h = 6.62607015\times10^{-34}\ J\cdot s$	Planck constant	kilogram
$e = 1.602176634\times10^{-19} C$	Electric charge	ampere
$k_B = 1.380649\times10^{-23}\ J/K$	Boltzmann constant	kelvin
$N_A = 6.02214076\times10^{23}$	Avogadro constant	mole
$K_{cd} = 683\ lm/W$	candela	candela


New SI

Scale

yopto	zepto	atto	femto	pico	Ångström	nano	micro	milli	centi	deci	
y	z	a	f	p	Å	n	µ	m	c	d	
10^{-24}	10^{-21}	10^{-18}	10^{-15}	10^{-12}	10^{-10}	10^{-9}	10^{-6}	10^{-3}	10^{-2}	10^{-1}	10^{0}

	deca	hecto	kilo	mega	giga	tera	peta	exa	zetta	yotta
	da	h	k	M	G	T	P	E	Z	Y
10^{0}	10^{1}	10^{2}	10^{3}	10^{6}	10^{9}	10^{12}	10^{15}	10^{18}	10^{21}	10^{24}

Gaisser, Stanev, Tilav, Front.Phys.,2103,8(6),748

1. Cosmic rays, why are they so high energy?

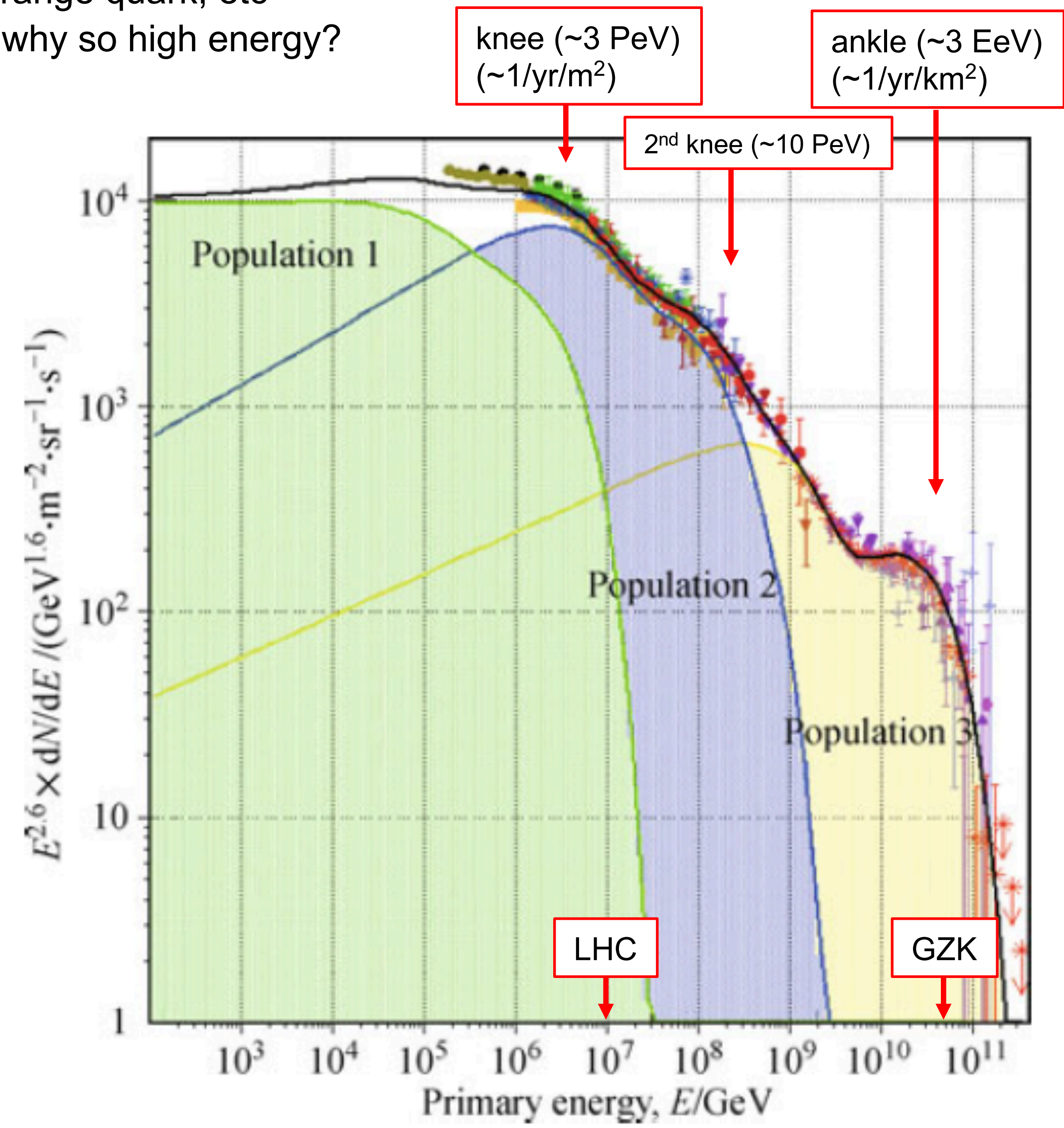
Cosmic ray physics
- Secondary: discovery of muon, anti-particle, strange quark, etc
- Primary: what are they? where are they from? why so high energy?

Knee:
The end of spectrum of Milky Way galactic acceleration.

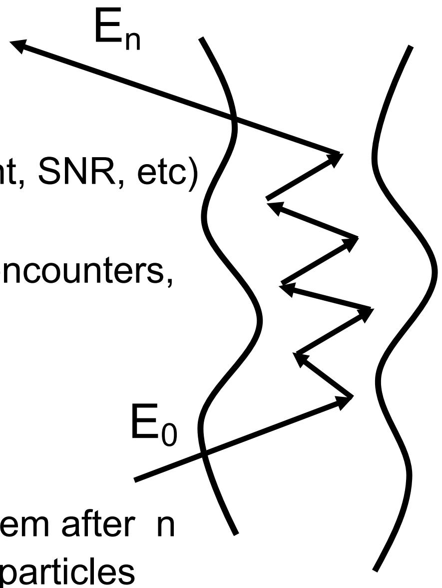
Ankle:
Extragalactic ultra-high-energy acceleration mechanism

2nd knee:
Transition between galactic and extragalactic acceleration.

Basic idea of acceleration
→ Fermi acceleration (shock acceleration)



1. Fermi acceleration



Acceleration of cosmic rays happen in the in the shock plasma (supernova remnant, SNR, etc)

A test particle with energy E_0 gains energy ΔE (=$\xi \times E$) by each encounter. After n encounters,

$$E_n = E_0 \cdot (1+\xi)^n$$

Number of encounter for the test particle to reach energy E is

$$n = ln\left(\frac{E}{E_0}\right)\frac{1}{\ln(1+\xi)}$$

P_{esc} is prob. to escape the system after the collision. Thus, prob. to stay in the system after n encounters is $(1-P_{esc})^n$. This makes the particle to be energy E_n. So the number of particles energy higher than E is proportion to

$$N(>E) \propto \sum_{m=n}^{\infty}\left(1-P_{esc}\right)^m = \frac{\left(1-P_{esc}\right)^n}{P_{esc}} \propto \frac{1}{P_{esc}}\left(\frac{E}{E_0}\right)^{-\gamma}$$

with

$$\gamma = \frac{-ln(1-P_{esc})}{ln(1+\xi)} \sim \frac{P_{esc}}{\xi} \sim \frac{1}{\xi} \cdot \frac{T_{cycle}}{T_{stay}}$$

Here, T_{cycle} is the characteristic time for acceleration cycle, and T_{stay} is the characteristic time to stay in the acceleration system. If the test particle stay t in the system, $n_{max}=t/T_{cycle}$, and

$$E < E_0 \cdot (1+\xi)^{t/T_{cycle}}$$

1. Cosmic ray spectrum follows power law (γ=2)
2. High-energy particles take longer time to accelerate
3. There is a maximum energy depending on how long the particle can stay in the system

IceCube, Adv.Space.Res.62(2018) 2902

1. Hillas plot

Cosmic rays make spiral motions due to magnetic field.
Strong magnetic fields allow to meet more encounters and accelerate to higher energy.

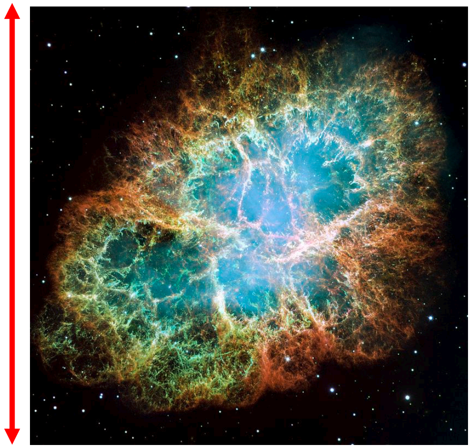
$$E_{max} \leq \beta ZeBR_L$$

R_L: gyro-radius in the acceleration region
In supernova remnant (SNR), E_{max}~10-100 TeV for protons

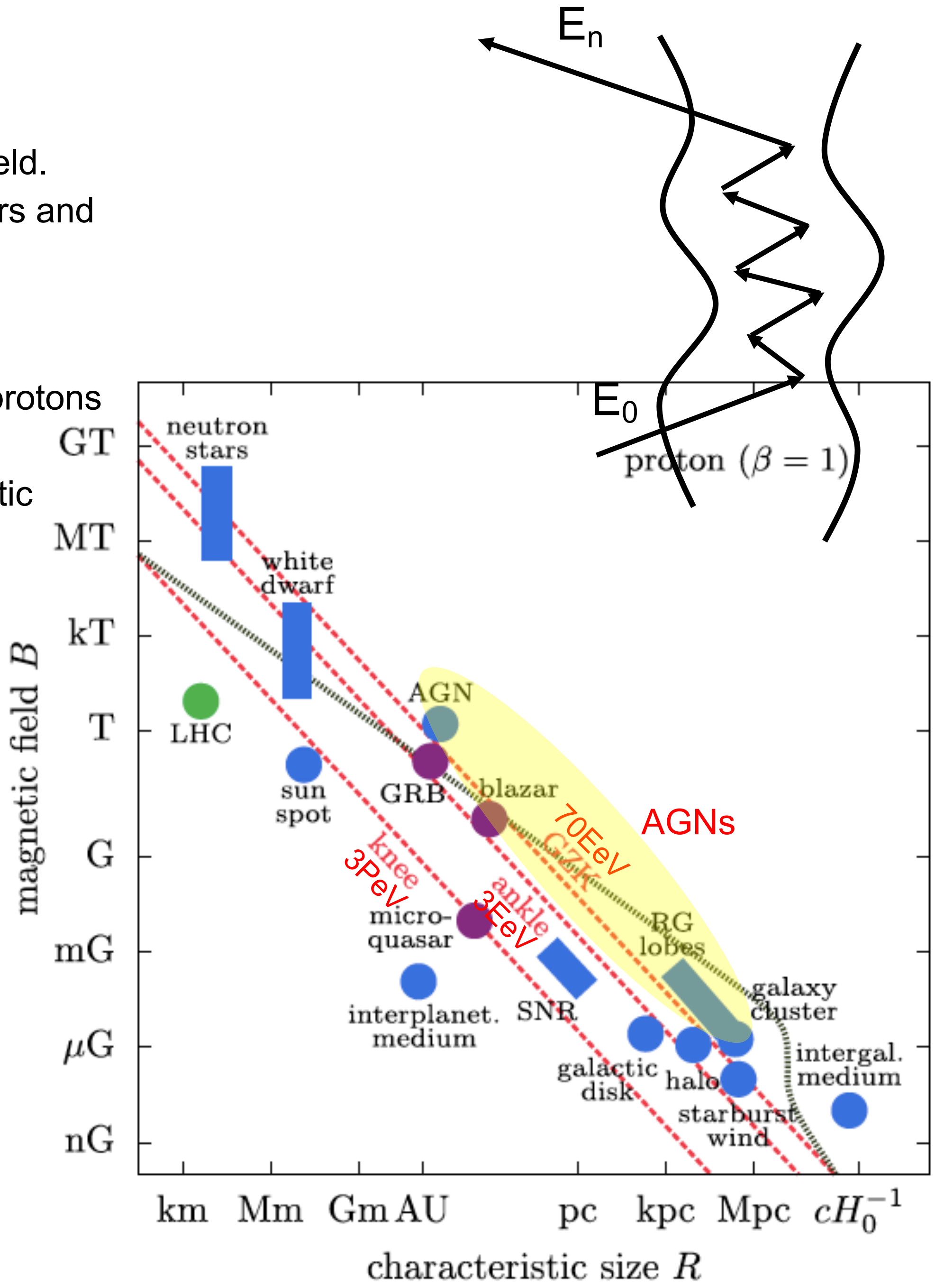
To achieve higher energy, you need stronger magnetic field and large orbit (large "BxR")

- Active Galactic Nuclei (AGN)
- Gamma Ray Burst (GRB)

e.g.) Crab nebula (SNR)



~2pc
(β~0.01)



Gaisser, Stanev, Tilav, Front.Phys.,2103,8(6),748

1. Cosmic rays, why are they so high energy?

Cosmic ray physics

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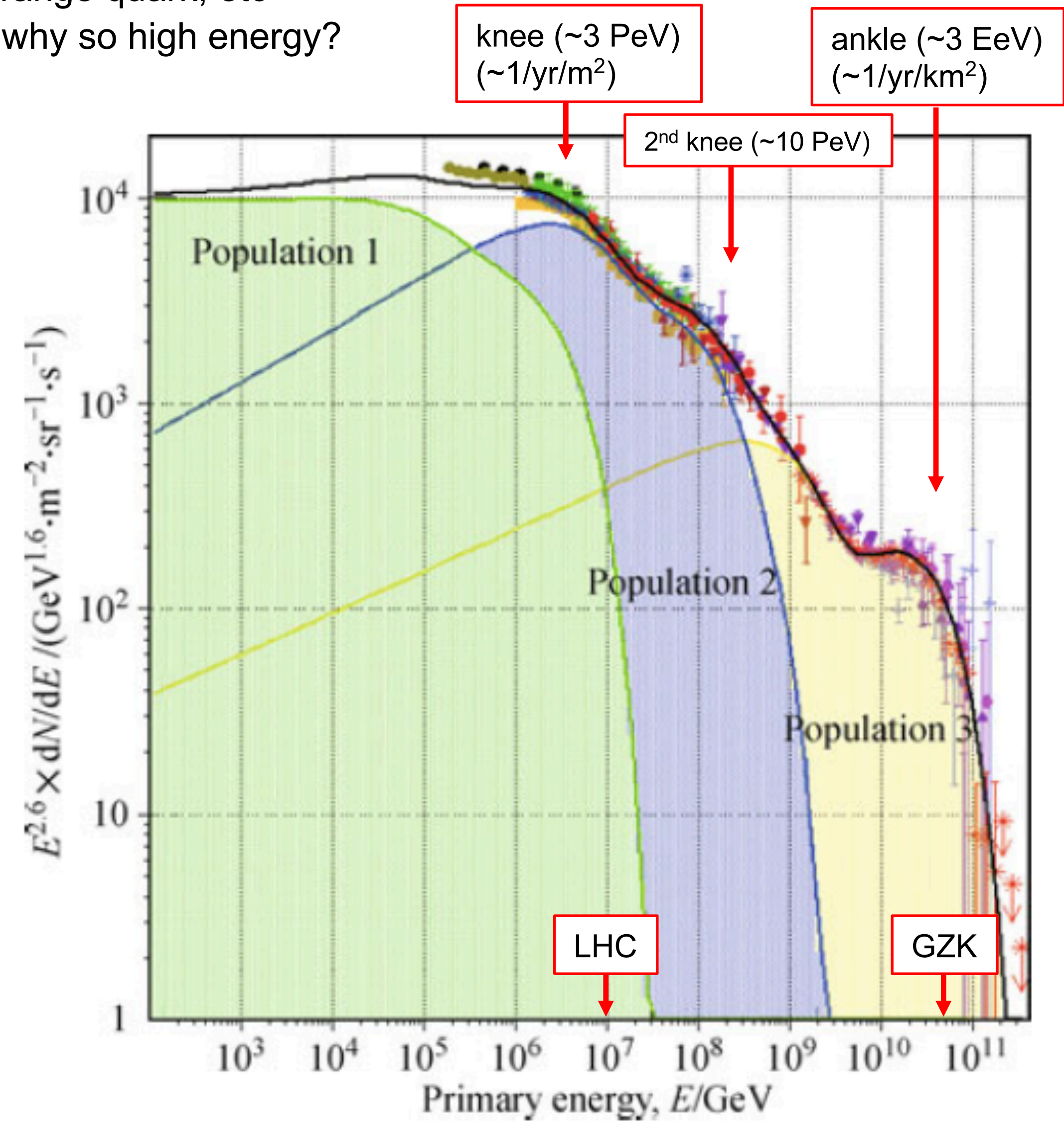
- Primary: what are they? where are they from? why so high energy?

Knee:
The end of spectrum of Milky Way
galactic supernova remnant (SNR)
Fermi acceleration

2nd knee:
New galactic acceleration mechanism

Ankle:
Extragalactic ultra-high-energy
acceleration mechanism

High-energy neutrinos are interesting because they are related to extragalactic UHECRs.



knee (~3 PeV)
(~1/yr/m^2)

2nd knee (~10 PeV)

ankle (~3 EeV)
(~1/yr/km^2)

LHC

GZK

1. Summary

Cosmic rays are everywhere, from low to the highest energy particles. To understand sources and acceleration mechanism, it is important to measure energy, distribution, and types.

High-energy neutrinos are produced naturally in hadronic processes.

The Earth is opaque to high-energy neutrinos (> 50 TeV).

High-energy neutrinos are direct high-energy messengers on the Earth (UHECR measurements are mostly secondary).

High-energy neutrinos are direct messenger of extragalactic ultra-high-energy acceleration mechanisms (extragalactic high-energy objects are opaque for gamma rays).

High-energy neutrinos are useful to learn origin of UHECRs, mechanism of high-energy objects, and fundamental physics (dark matter, space-time symmetry, vacuum properties)

Neutrino telescopes have very rich science programs!

1. Cosmic Ray and Astroparticle Physics

2. **High-Energy Neutrino Observations**

3. Neutrino Multi-Messenger Astronomy

4. Astrophysical Neutrino Flavour Physics

2. High-energy neutrino observations

How to detect high-energy astrophysical neutrinos?

What do we know and do not know about high-energy neutrinos?

What kind of physics can we explore with high-energy neutrinos?

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Katz and Spiering, PPNP67(2012)651
Super-Kamiokande, Astropart.Phys.29(2008)42

2. Requirement of high-energy neutrino detectors

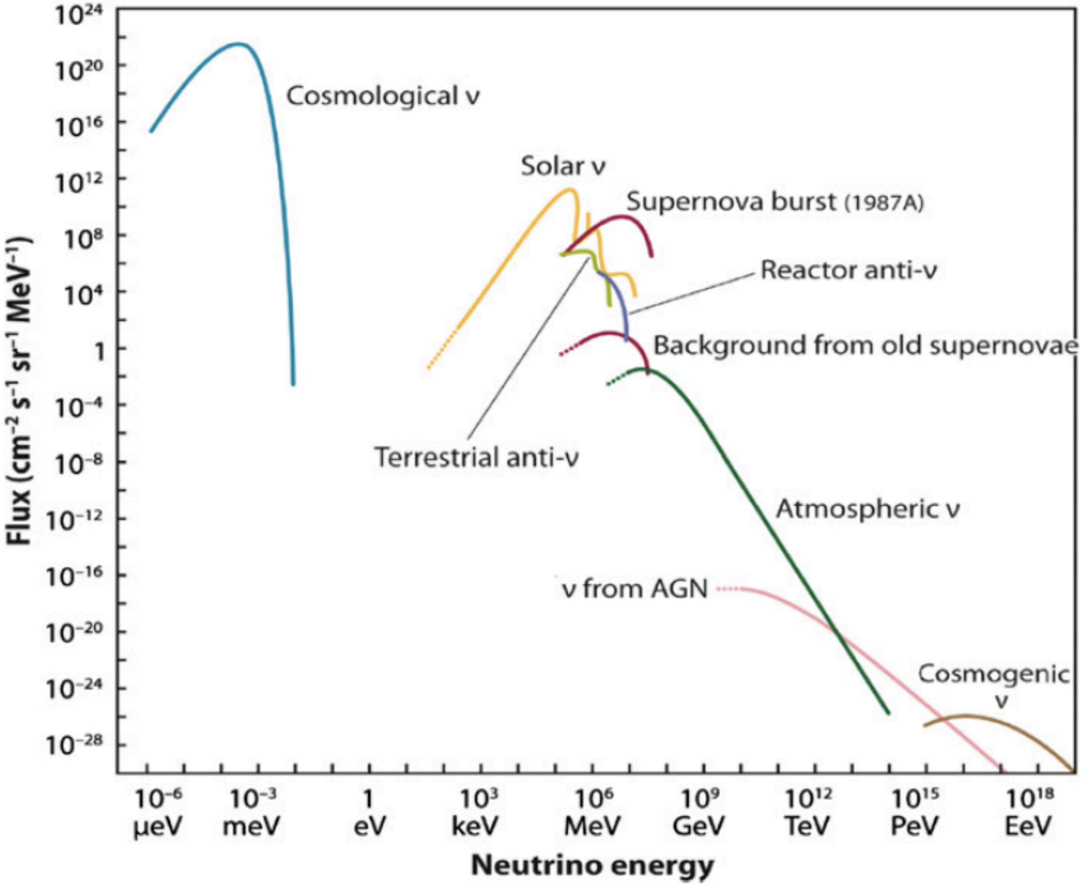
Atmospheric neutrinos flux > astrophysical neutrinos until ~10 TeV

Rate of >1 TeV neutrino events in Super-Kamiokande ~ 3.5 event / day (~1278 evt/yr)
Assuming spectral index of atmospheric neutrinos ($\sim E^{-3.7}$), event rate of 10 TeV is << 1 event

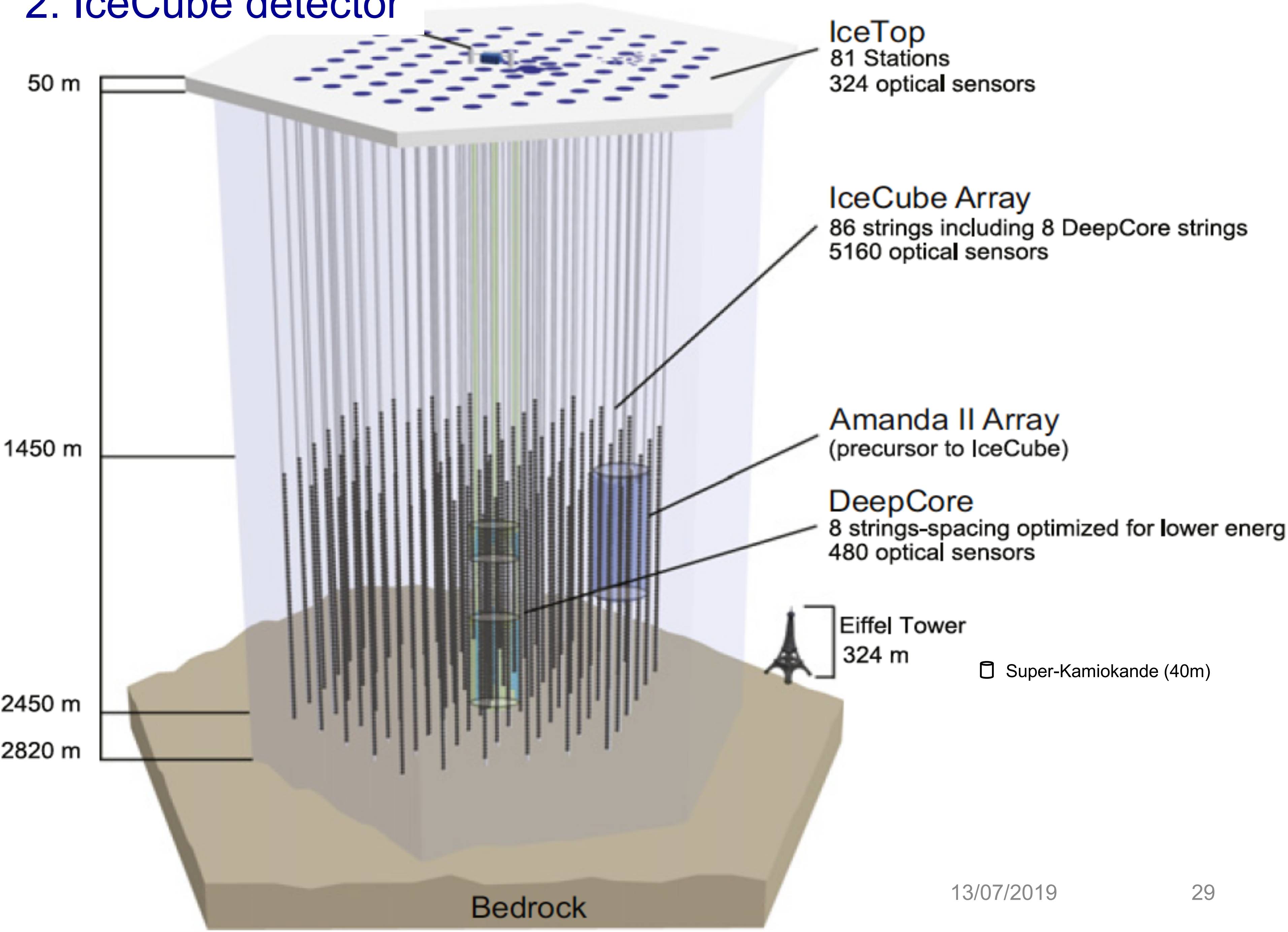
You need significantly larger detector than Super-Kamiokande to see high-energy neutrinos.

Cherenkov detectors
- Ice: IceCube, IceCube-Gen2
- Sea: Antares, KM3NeT, PLEvM
- Lake: Lake Bikal, GVD

Radio-antenna
- Balloon: ANITA
- Ice: ARA, ARRIANNA
- Ground: GRAND



2. IceCube detector



IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

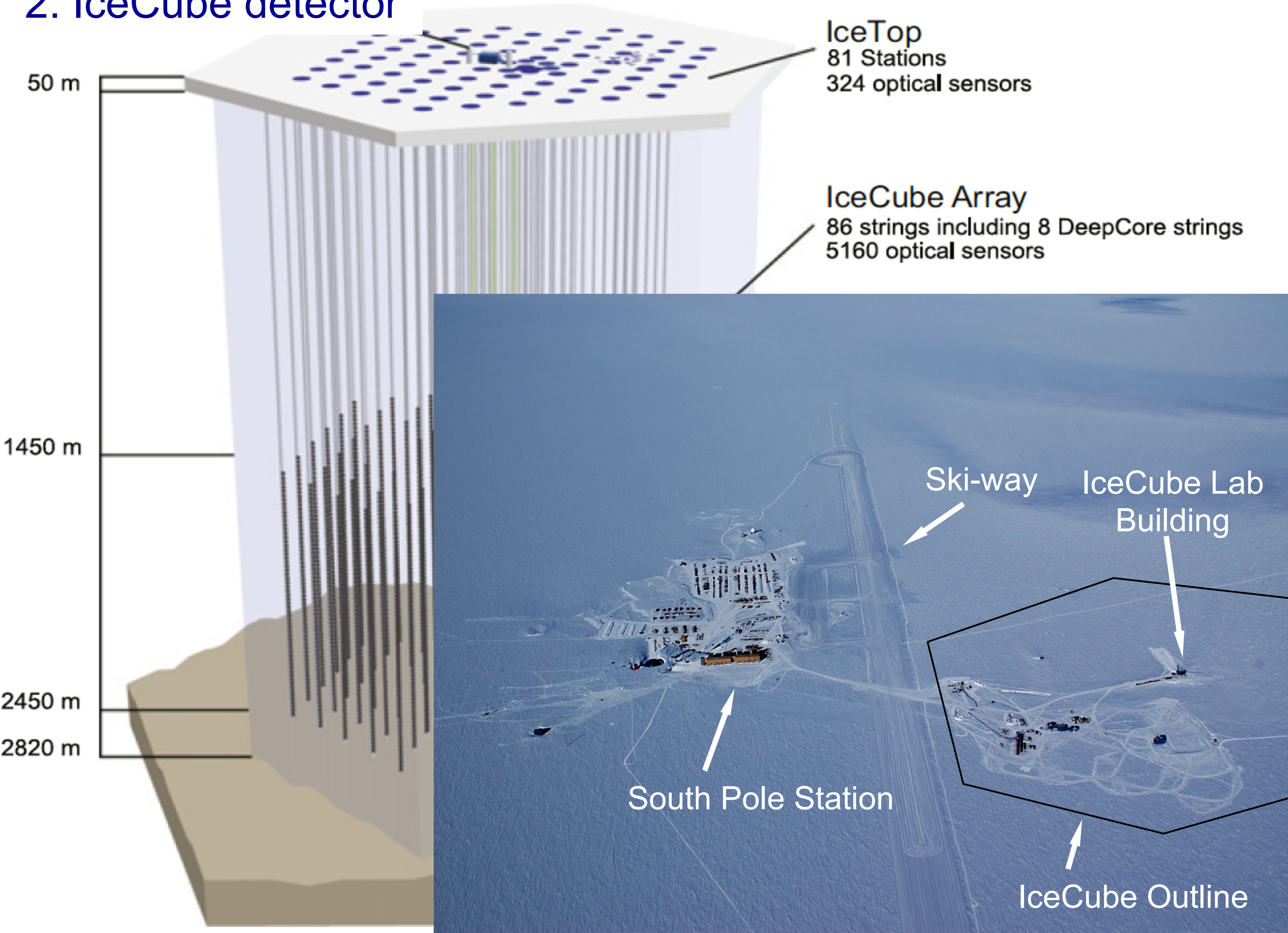
Amanda II Array
(precursor to IceCube)

DeepCore
8 strings-spacing optimized for lower energ
480 optical sensors

Eiffel Tower
324 m

Super-Kamiokande (40m)

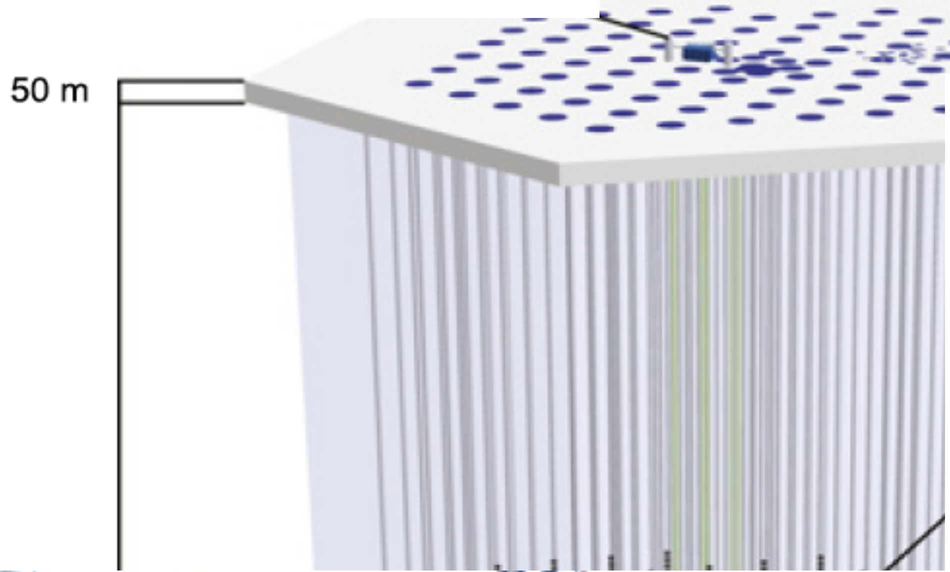
2. IceCube detector



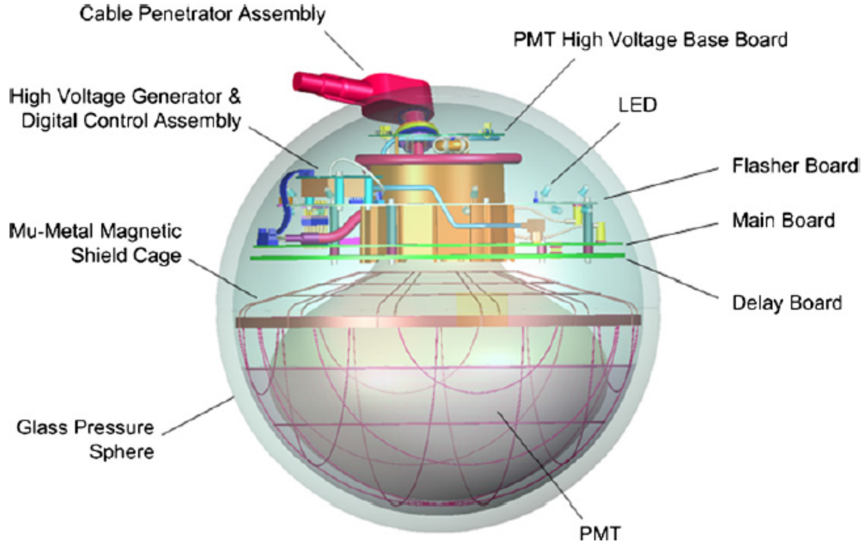
IceTop
81 Stations
324 optical sensors

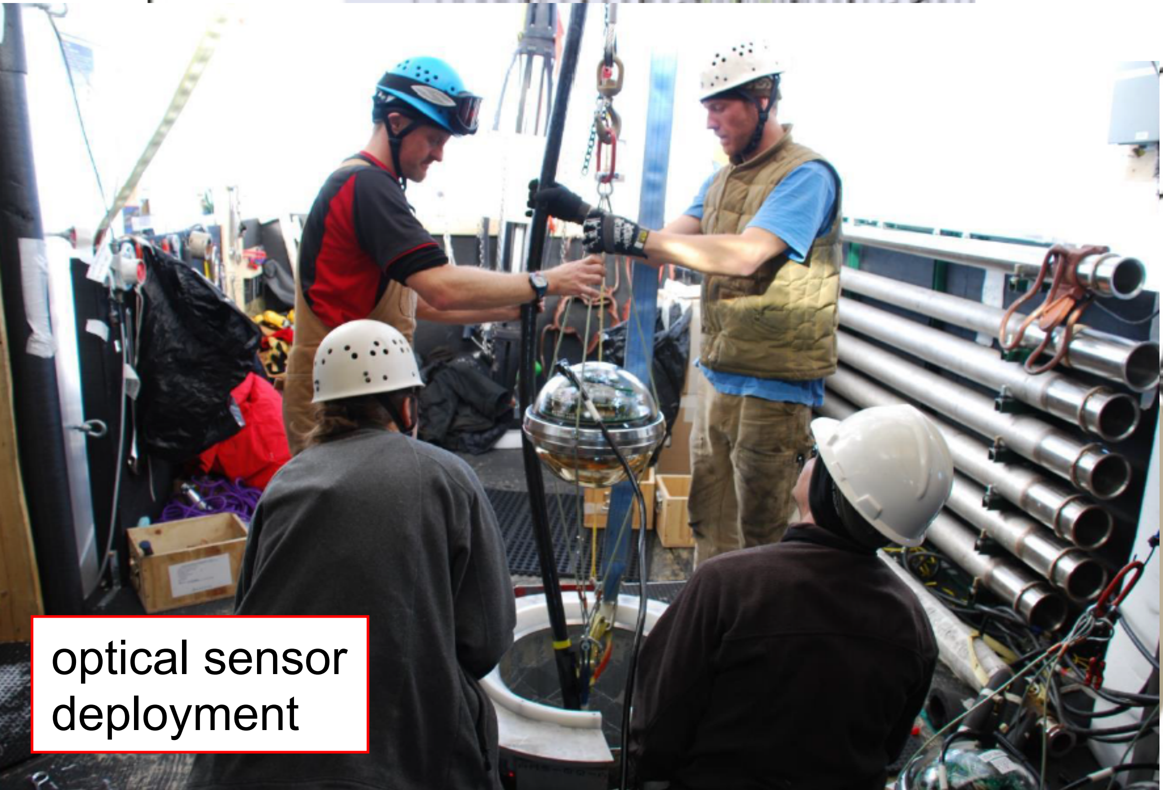
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

2. IceCube detector

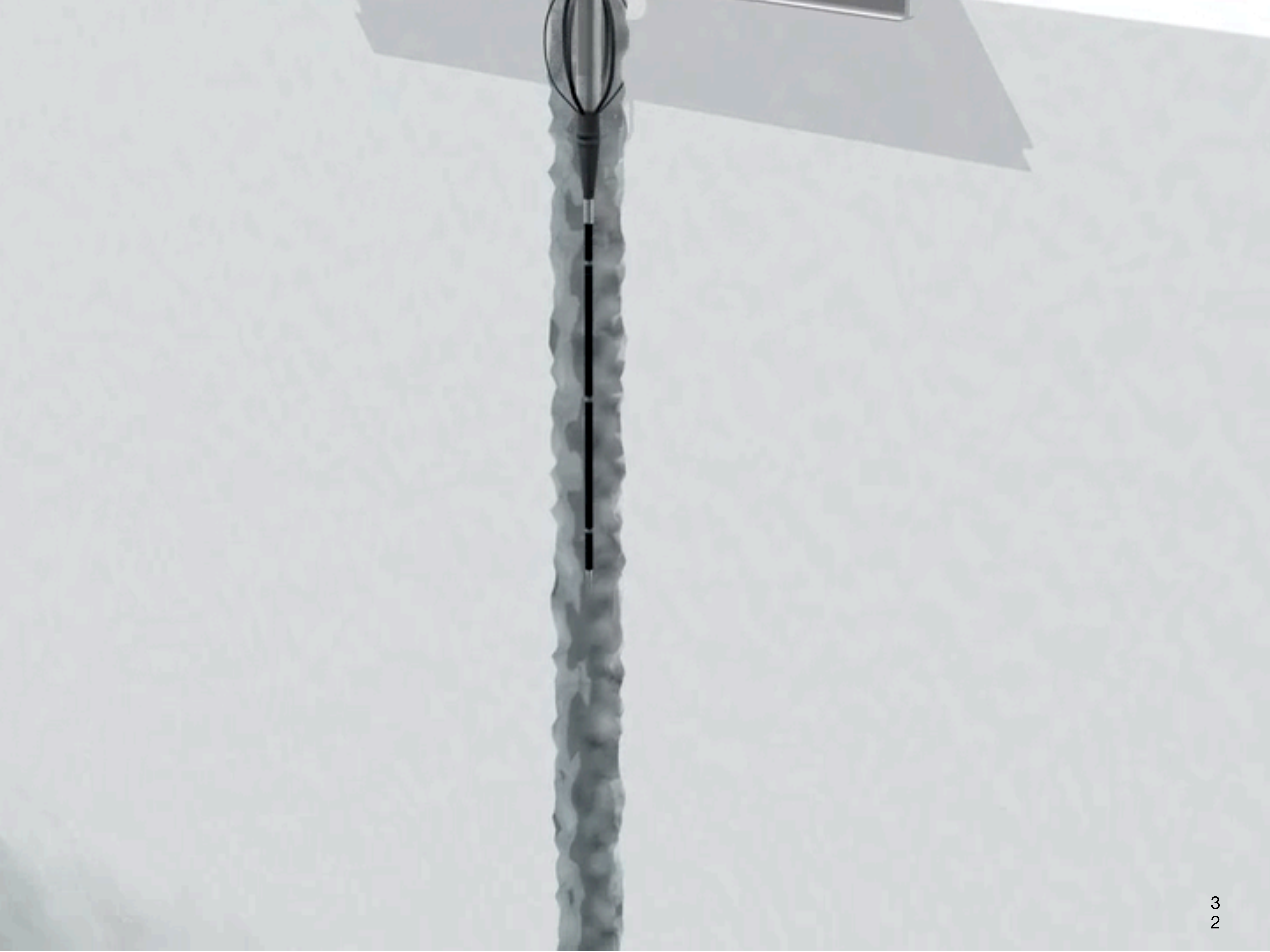


digital optical module (DOM)

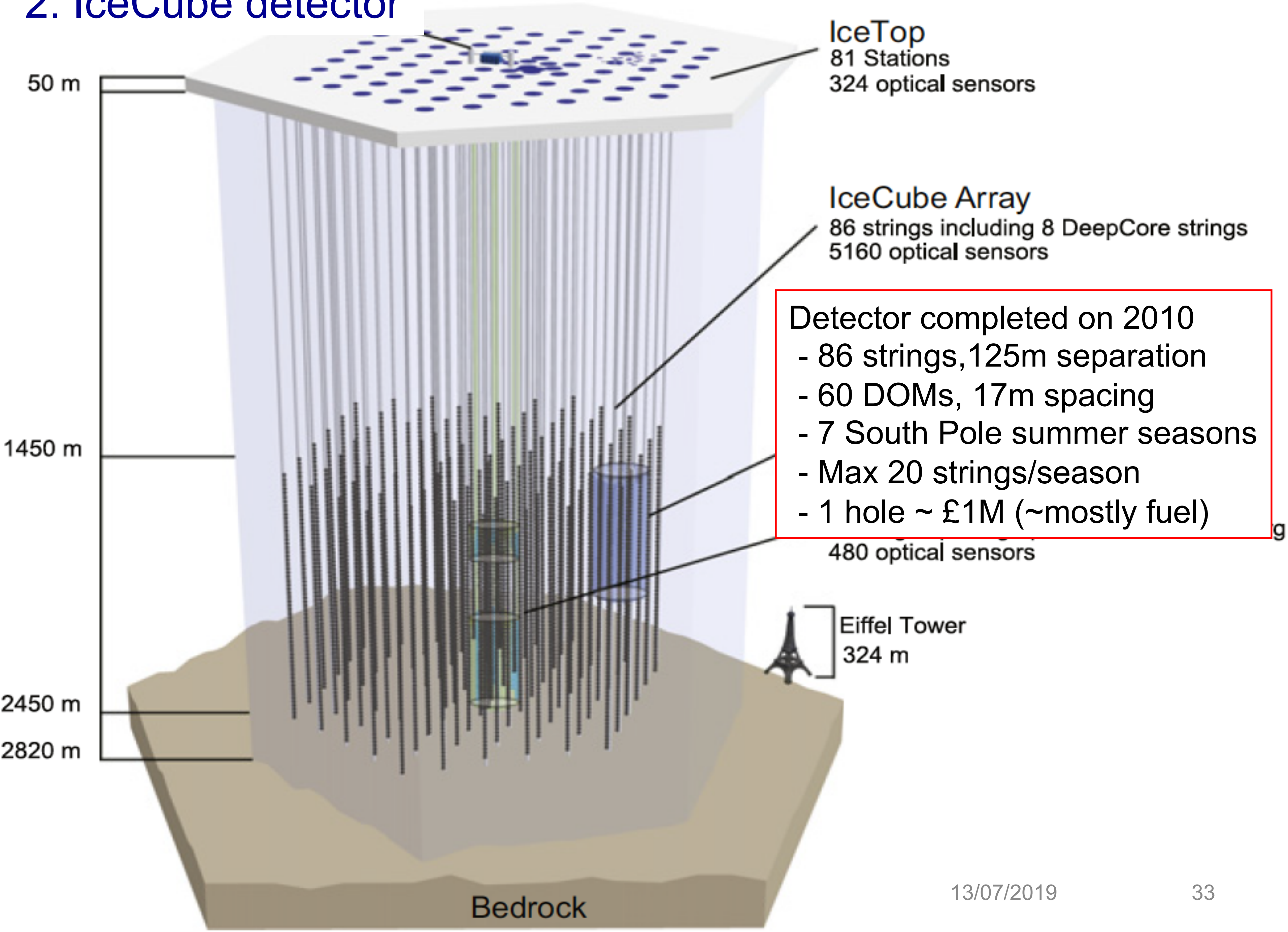




optical sensor
deployment

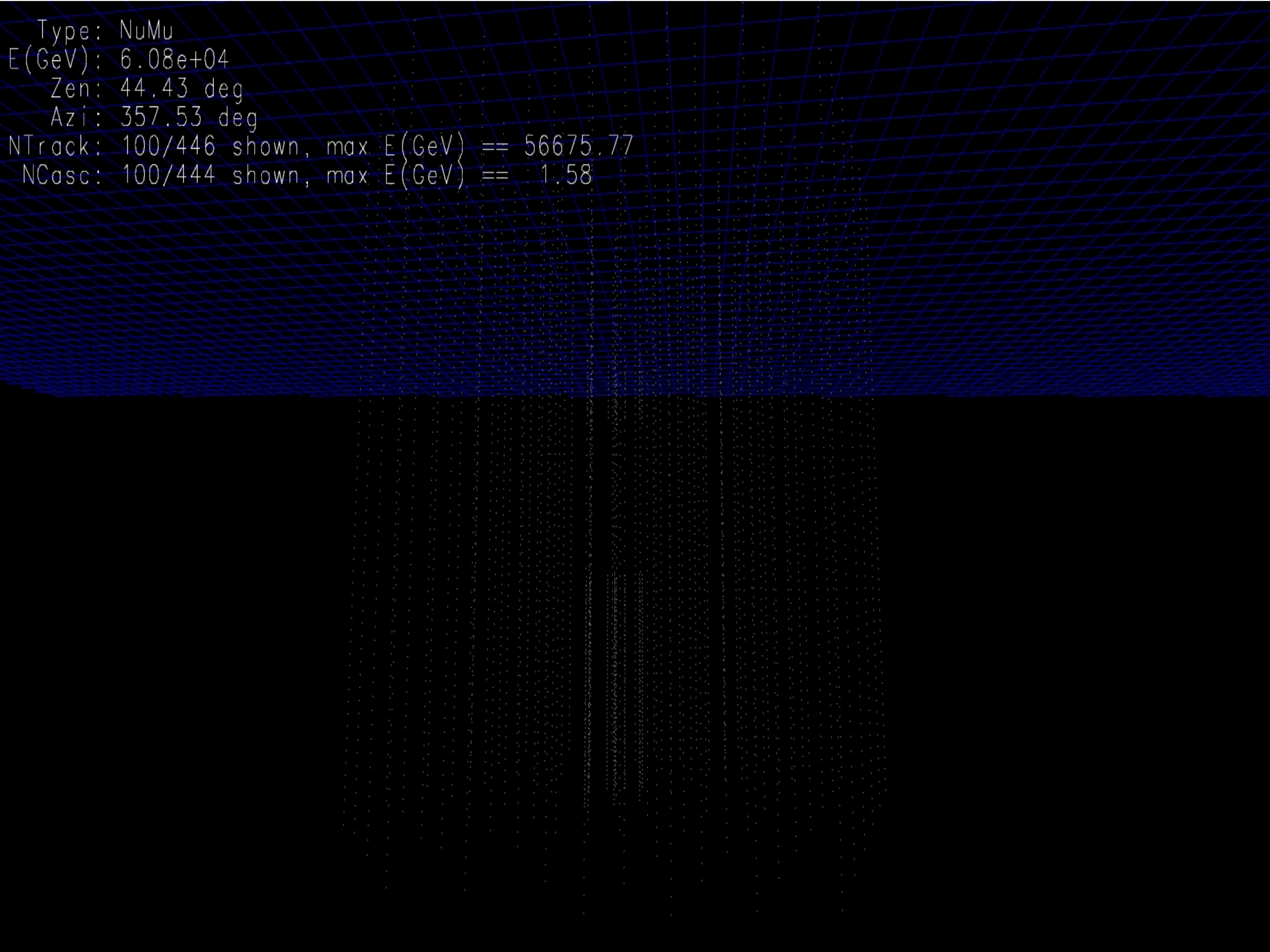


2. IceCube detector



Detector completed on 2010

- 86 strings,125m separation
- 60 DOMs, 17m spacing
- 7 South Pole summer seasons
- Max 20 strings/season
- 1 hole ~ £1M (~mostly fuel)

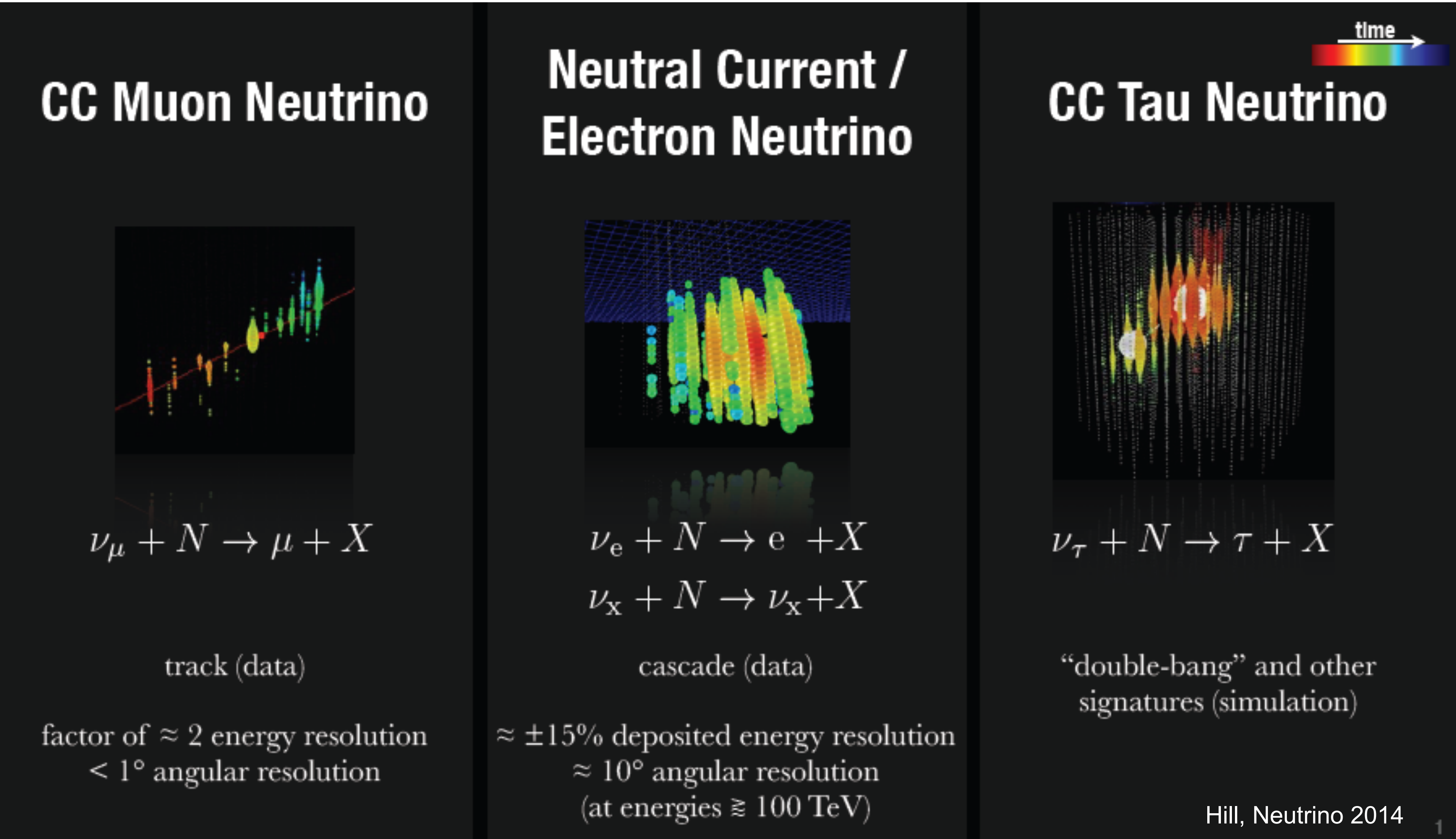


```
  Type: NuMu
E(GeV): 6.08e+04
   Zen: 44.43 deg
   Azi: 357.53 deg
NTrack: 100/446 shown, max E(GeV) == 56675.77
 NCasc: 100/444 shown, max E(GeV) ==  1.58
```

2. Astrophysical High-Energy Neutrinos

Topology

- Track = muon (~ν_μCC)
- Shower (cascade) = electron, tau, hadrons (~, ν_eCC, ν_τCC, NC)



CC Muon Neutrino

$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current / Electron Neutrino

$$\nu_e + N \rightarrow e \ + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

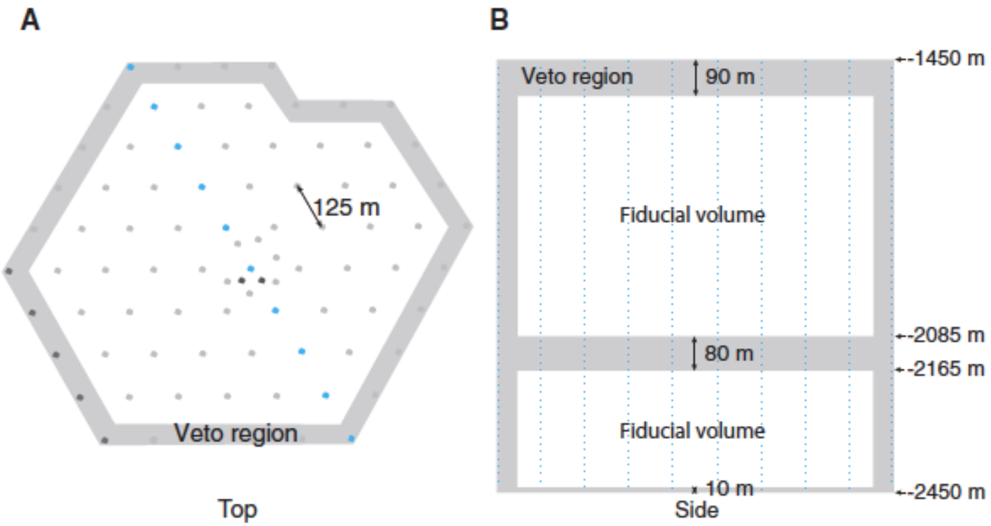
CC Tau Neutrino

$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures (simulation)

Hill, Neutrino 2014

2. Astrophysical High-Energy Neutrinos

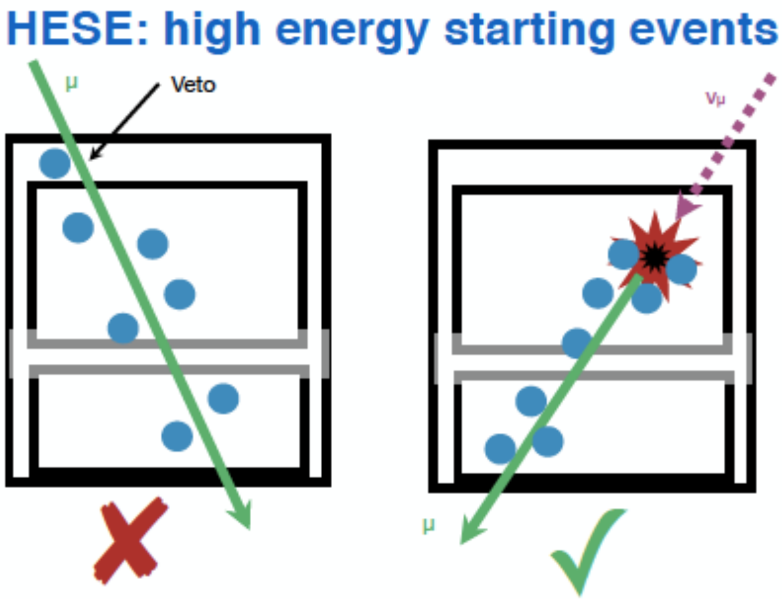


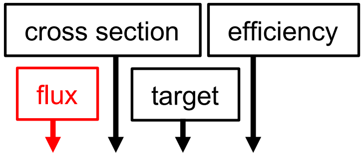
High Energy Starting Event (HESE)
- Veto by surrounding DOMs
- Avoid dust layer from fiducial volume

The detection efficiency is flavour dependent
- ν_eCC: electromagnetic shower (highest PE)
- ν_τCC, NC: hadronic shower
- ν_μCC: muon bremsstrahlung

The simulation takes into account all other details (high-energy muon from tau decay, etc)

The measurement of astrophysical neutrinos assumes the Earth material model and neutrino cross-section model.



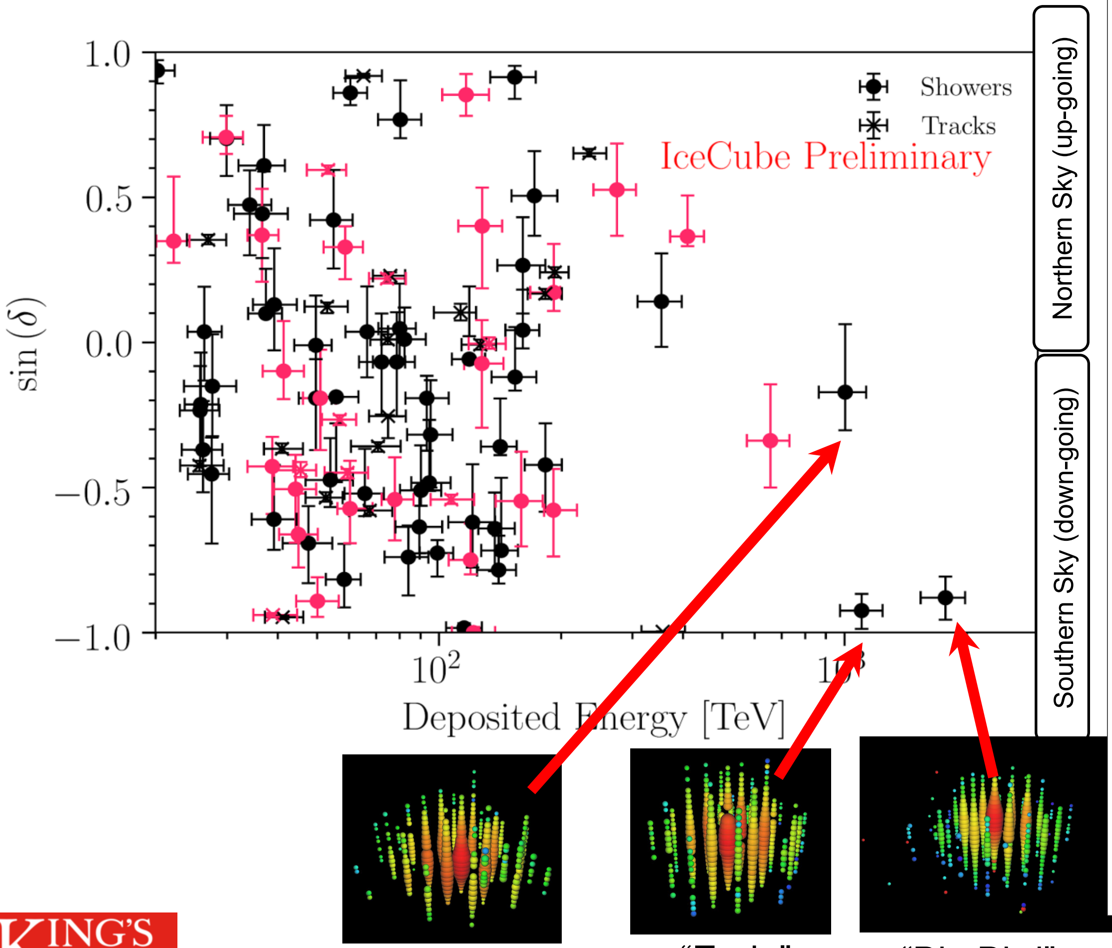


Event rate $\mathrm{N} = \Phi \times \sigma \times T \times \varepsilon$

IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical High-Energy Neutrinos

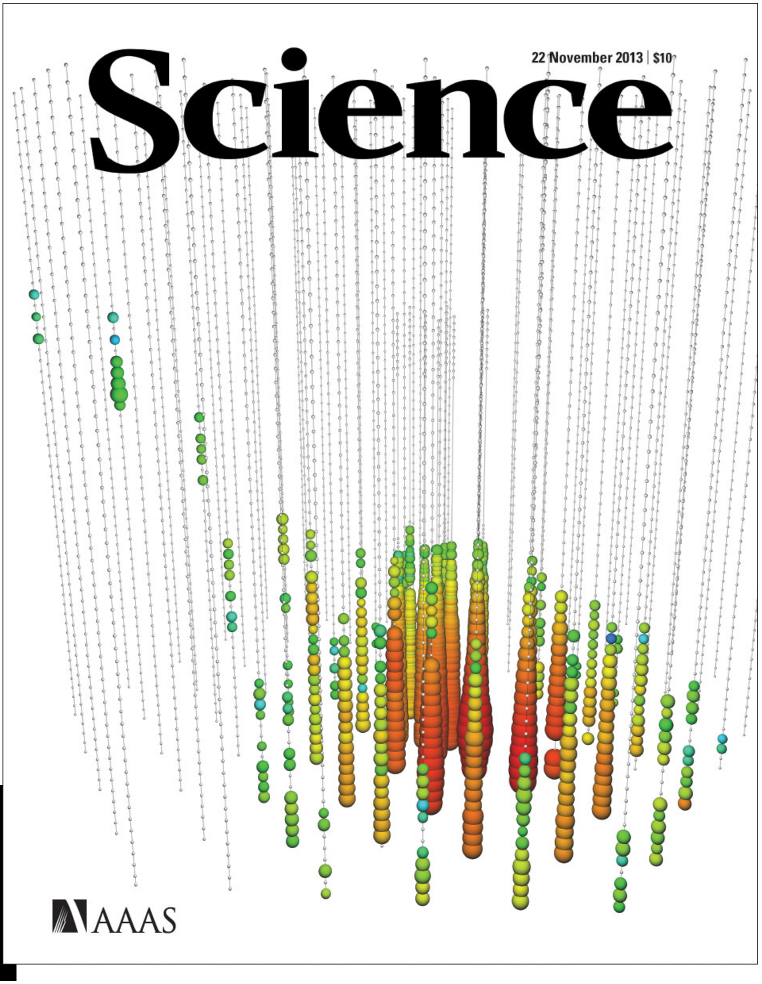
First observation (2013)
- 60-2000 TeV neutrinos



"Bert"
1.1 PeV

"Ernie"
1.0 PeV

"Big Bird"
2.0 PeV



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical High-Energy Neutrinos

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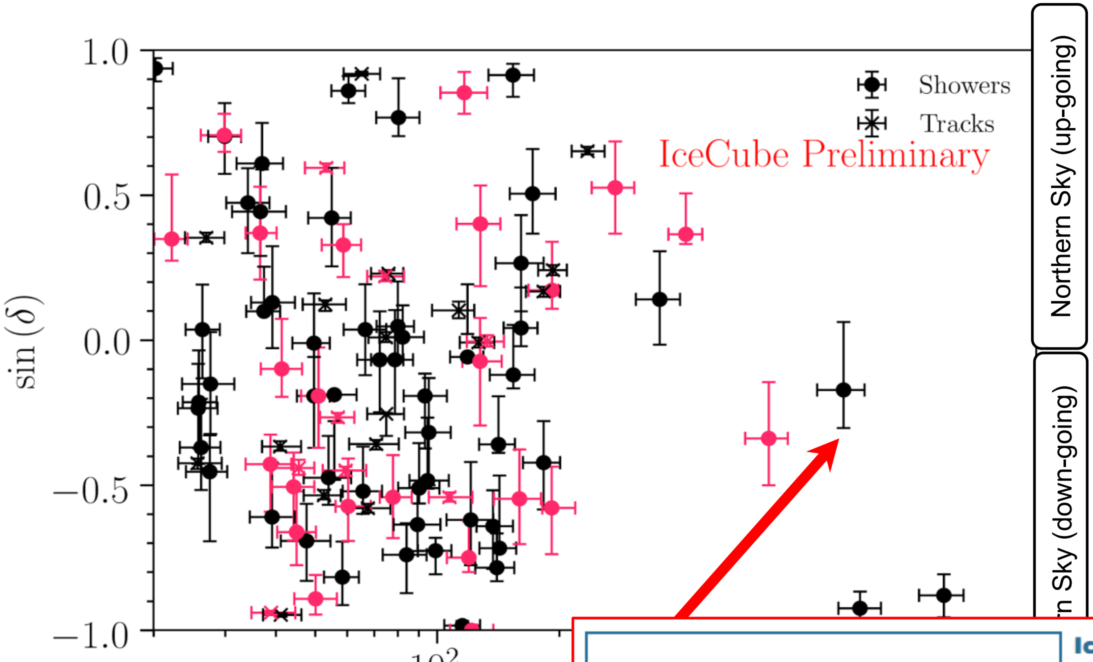
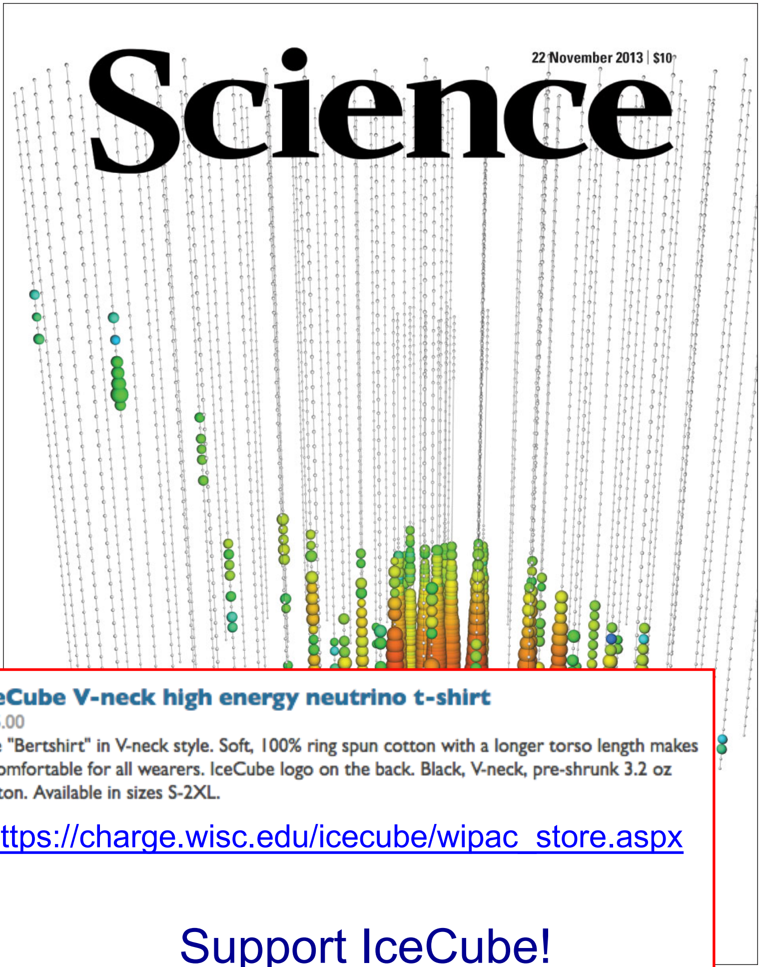
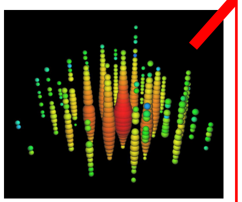






"Bert"
1.1 PeV

IceCube V-neck high energy neutrino t-shirt

$15.00

The "Bertshirt" in V-neck style. Soft, 100% ring spun cotton with a longer torso length makes it comfortable for all wearers. IceCube logo on the back. Black, V-neck, pre-shrunk 3.2 oz cotton. Available in sizes S-2XL.

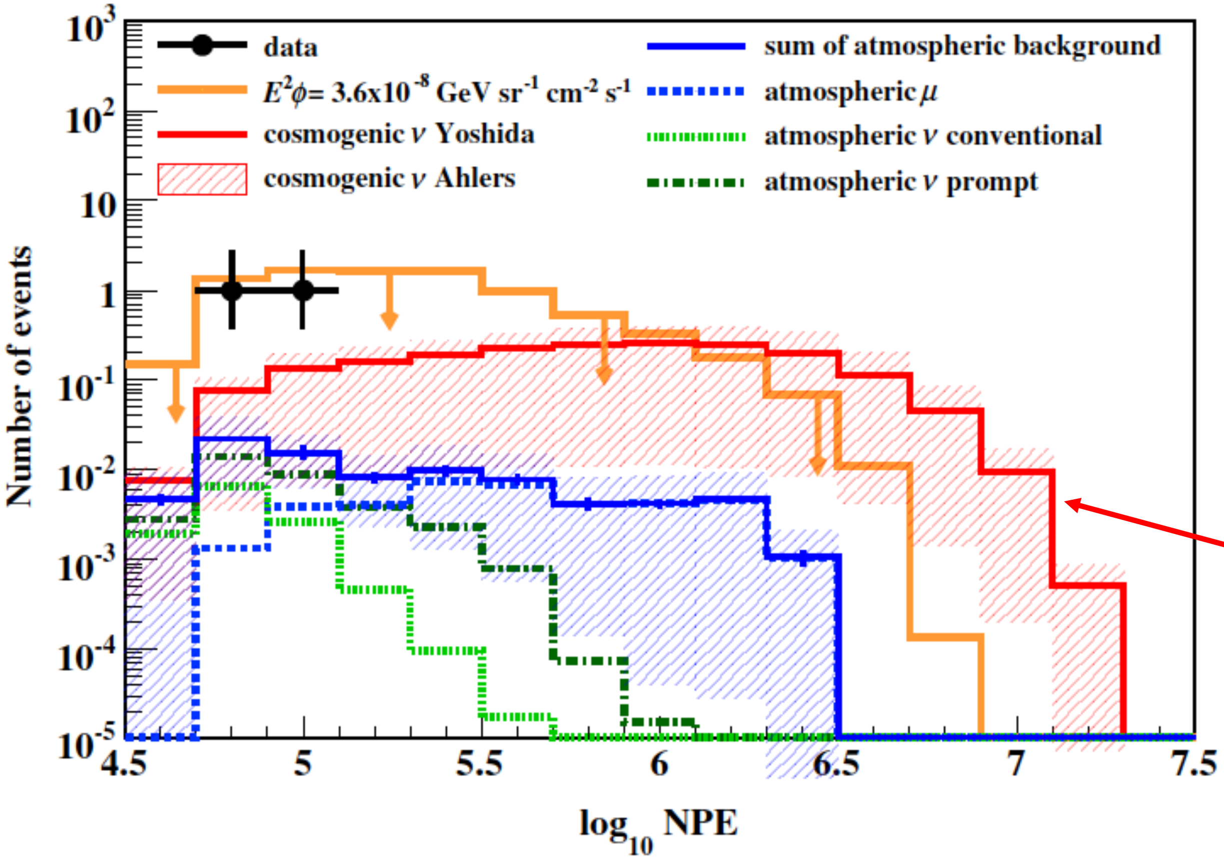
https://charge.wisc.edu/icecube/wipac_store.aspx

Support IceCube!

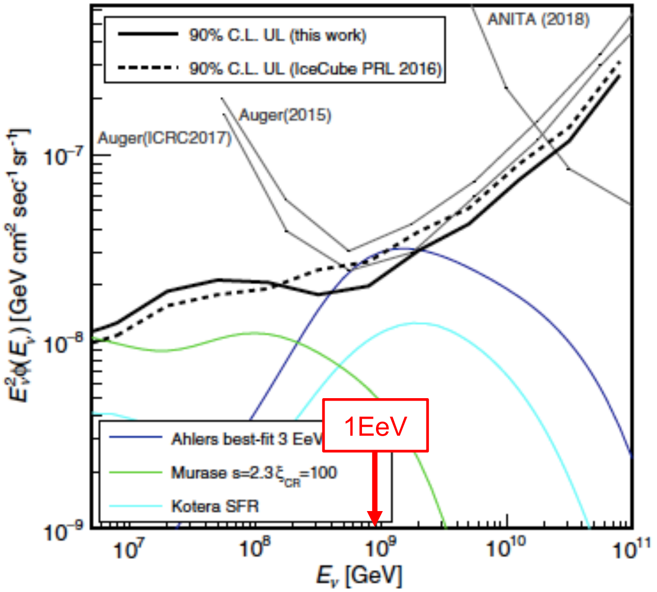
IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical High-Energy Neutrinos

First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from GZK neutrinos



IceCube. PRD98(2018)062003



IceCube limit on extremely-high-energy (EHE) neutrinos

Predicted GZK neutrino flux

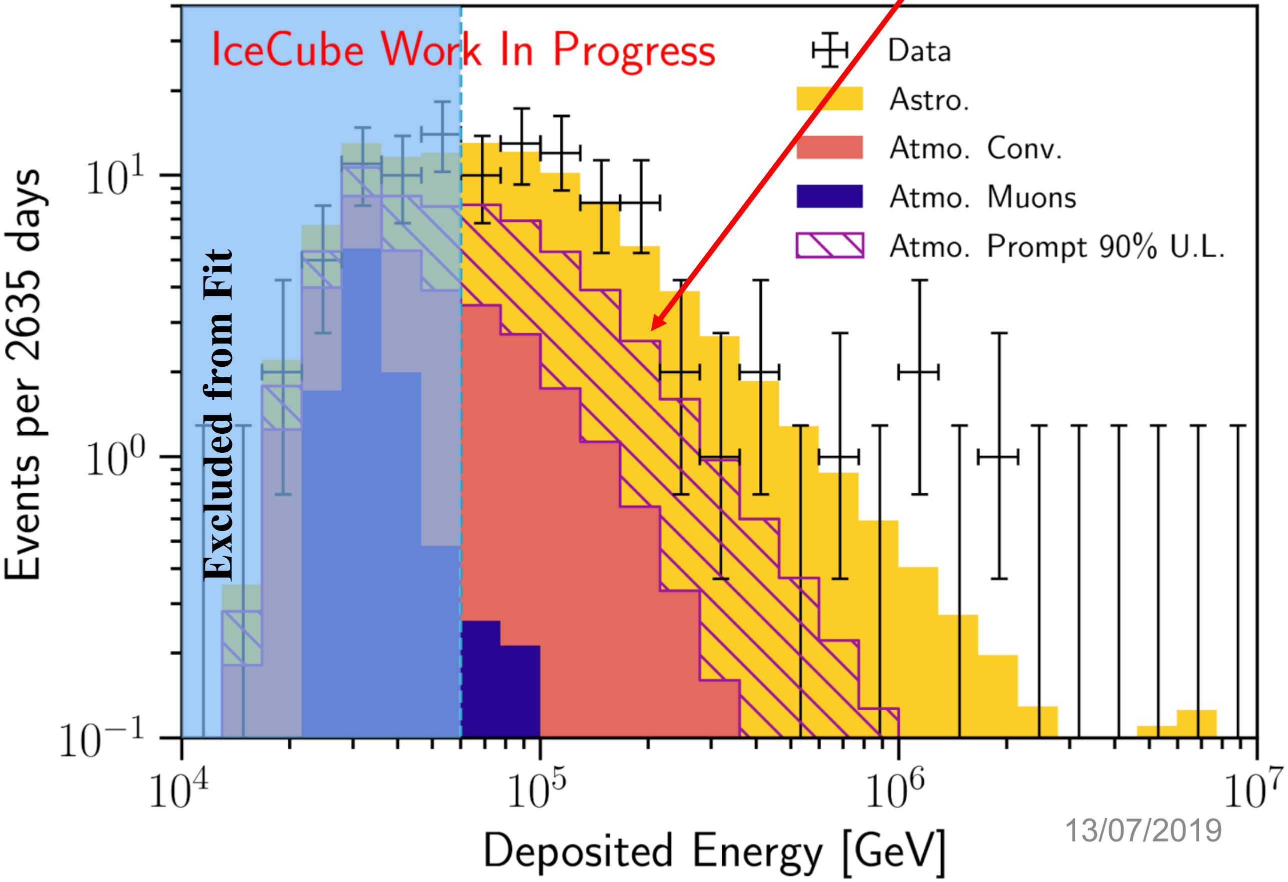
$$p+\gamma \rightarrow \Delta \rightarrow \pi \rightarrow \nu$$

IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical High-Energy Neutrinos

First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from GZK neutrinos
- Unlikely from atmospheric neutrinos

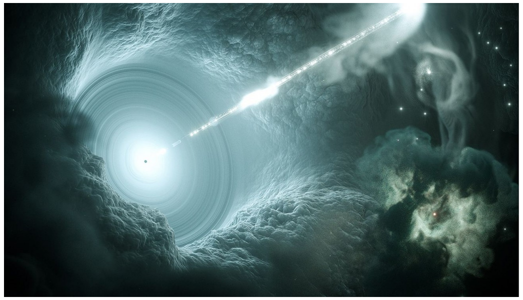
Atmospheric neutrinos
- "conventional", π and K decay neutrinos
- "prompt", D decay neutrinos (not confirmed)



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

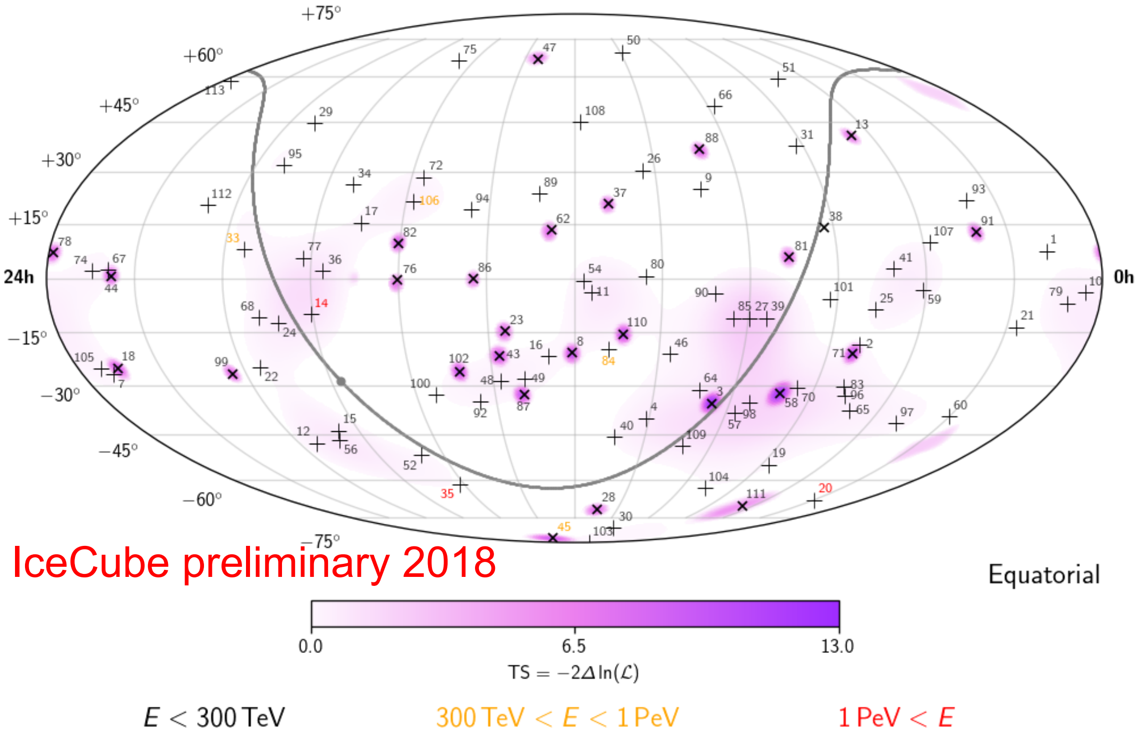
2. Astrophysical High-Energy Neutrinos

Blazar Neutrino (Sec. 3)
- IC170922A
- TXS 0506+056



IceCube, Science361(2018)147
IceCube et al,(2018)eaat1378

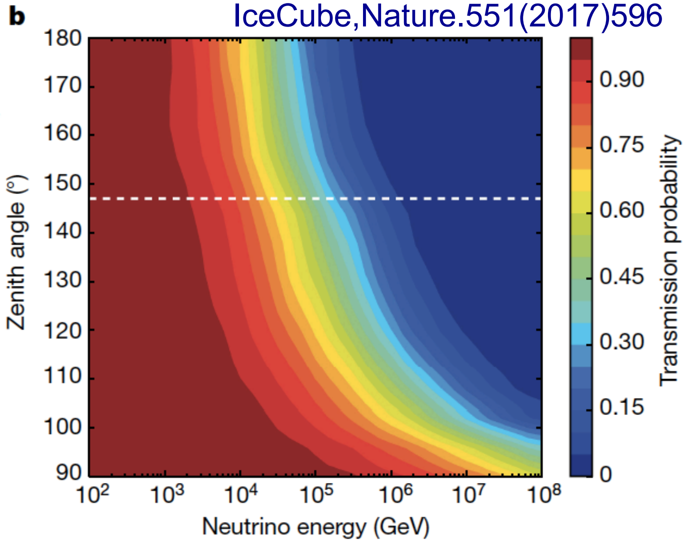
First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)



IceCube preliminary 2018

IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical High-Energy Neutrinos



First observation (2013)
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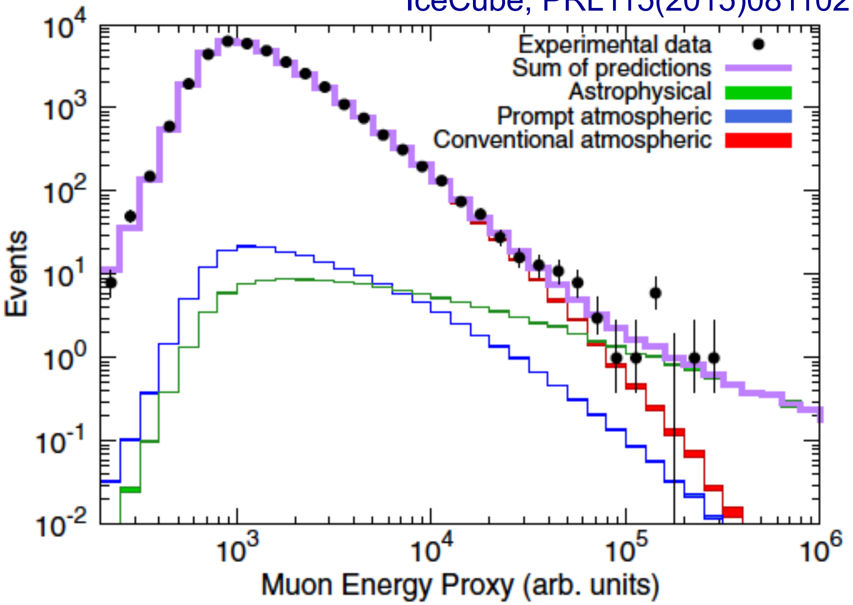
- Unlikely from GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)
- From both southern and northern sky

IceCube efficiency is not uniform
- Southern sky (above) has high atmospheric muon background, and data is mainly cascade
- Northern neutrinos (bottom) are mainly track data samples but attenuated by the earth (visible energy < true energy)

Northern sky track sample with E^{-2} astrophysical spectrum

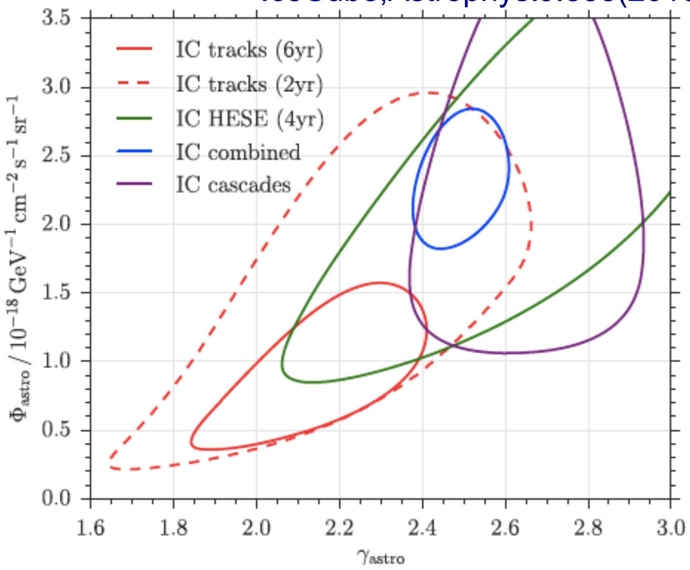
IceCube, PRL115(2015)081102



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical High-Energy Neutrinos

IceCube,Astrophys.J.833(2016)3



First observation (2013)
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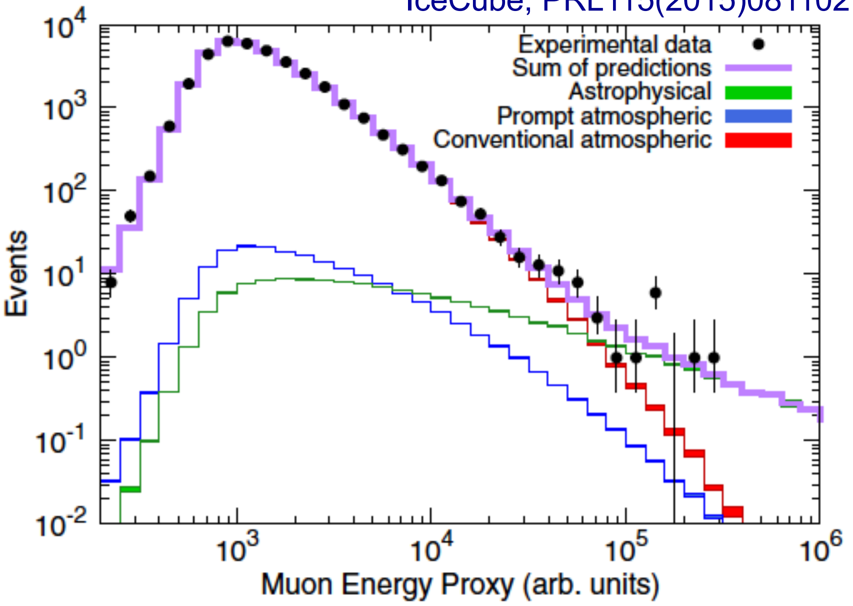
- Unlikely from GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)
- From both southern and northern sky
- Spectrum, no good fit

Each ample prefer different spectral index (Φ~NE$^{-\gamma}$)
- Single power law doesn't fit?
- Southern sky (HESE) has different power law from Northern sky (track dominant)?
- ν_e, ν_μ, and ν_τ have different spectrum?

Northern sky track sample with E^{-2} astrophysical spectrum

IceCube, PRL115(2015)081102



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

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First observation (2013)
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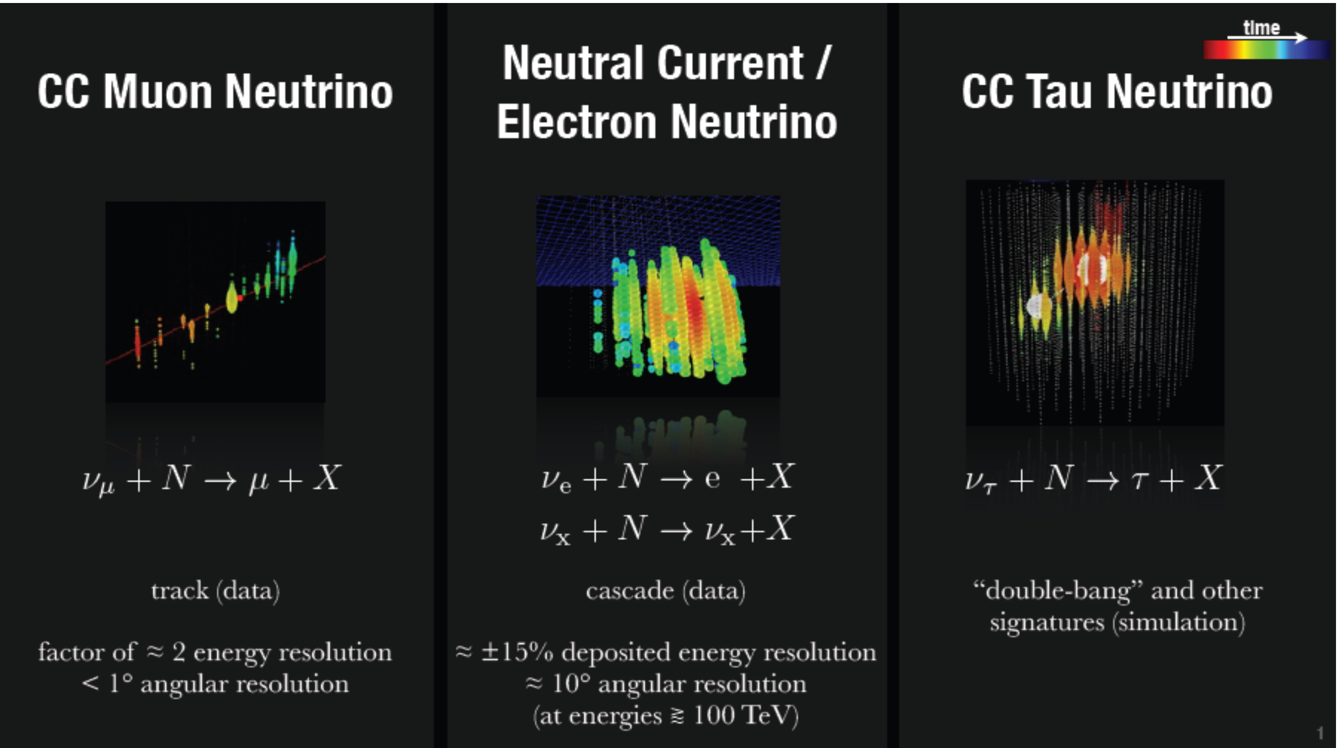
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)
- From both southern and northern sky
- Spectrum, no good fit
- Shower topology is dominant



CC Muon Neutrino

$\nu_\mu + N \rightarrow \mu + X$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current / Electron Neutrino

$\nu_e + N \rightarrow e + X$

$\nu_x + N \rightarrow \nu_x + X$

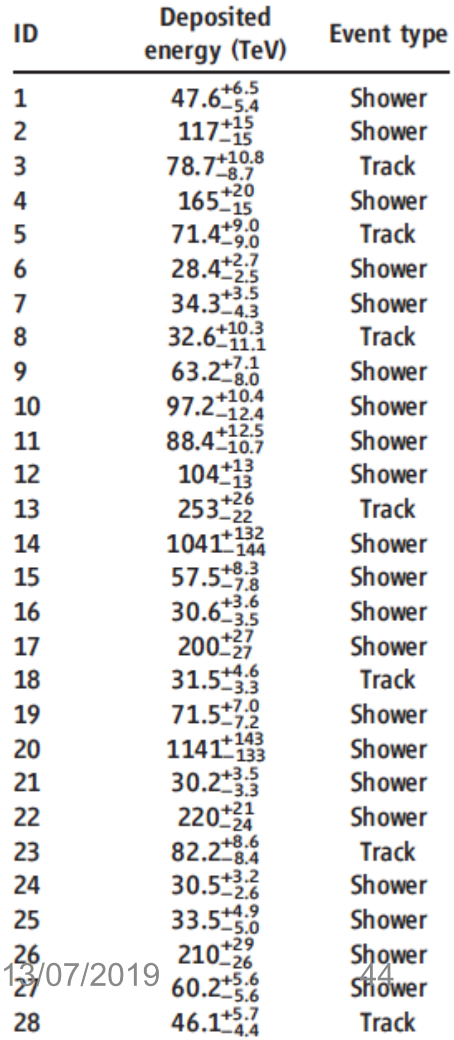
cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

CC Tau Neutrino

$\nu_\tau + N \rightarrow \tau + X$

"double-bang" and other signatures (simulation)



ID	Deposited energy (TeV)	Event type
1	$47.6^{+6.5}_{-5.4}$	Shower
2	117^{+15}_{-15}	Shower
3	$78.7^{+10.8}_{-8.7}$	Track
4	165^{+20}_{-15}	Shower
5	$71.4^{+9.0}_{-9.0}$	Track
6	$28.4^{+2.7}_{-2.5}$	Shower
7	$34.3^{+3.5}_{-4.3}$	Shower
8	$32.6^{+10.3}_{-11.1}$	Track
9	$63.2^{+7.1}_{-8.0}$	Shower
10	$97.2^{+10.4}_{-12.4}$	Shower
11	$88.4^{+12.5}_{-10.7}$	Shower
12	104^{+13}_{-13}	Shower
13	253^{+26}_{-22}	Track
14	1041^{+132}_{-144}	Shower
15	$57.5^{+8.3}_{-7.8}$	Shower
16	$30.6^{+3.6}_{-3.5}$	Shower
17	200^{+27}_{-27}	Shower
18	$31.5^{+4.6}_{-3.3}$	Track
19	$71.5^{+7.0}_{-7.2}$	Shower
20	1141^{+143}_{-133}	Shower
21	$30.2^{+3.5}_{-3.3}$	Shower
22	220^{+21}_{-24}	Shower
23	$82.2^{+8.6}_{-8.4}$	Track
24	$30.5^{+3.2}_{-2.6}$	Shower
25	$33.5^{+4.9}_{-5.0}$	Shower
26	210^{+29}_{-26}	Shower
27	$60.2^{+5.6}_{-5.6}$	Shower
28	$46.1^{+5.7}_{-4.4}$	Track

IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

2. Astrophysical High-Energy Neutrinos

First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)
- From both southern and northern sky
- Spectrum, no good fit
- Shower topology is dominant
- Production flavour structure unknown

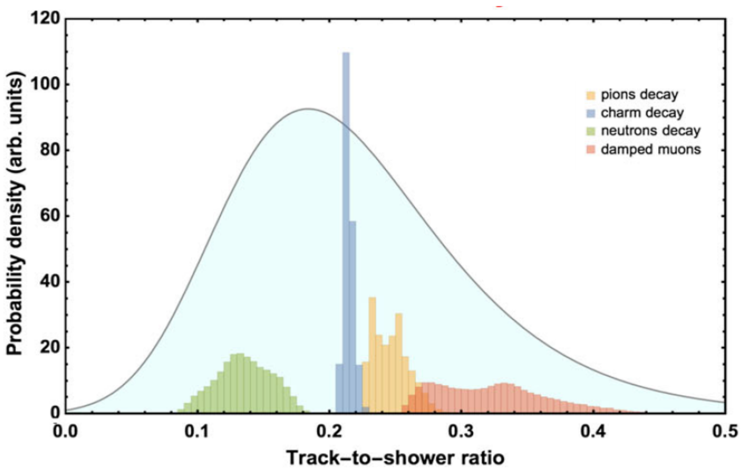
Naively
- Any astrophysical HE neutrino production flavour makes roughly $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$ on the earth
- At very high energy, $\sigma(CC) \sim 3\sigma(NC)$
- Track : Shower ~ 1 : 3 ($N_T/N_S \sim 0.33$)

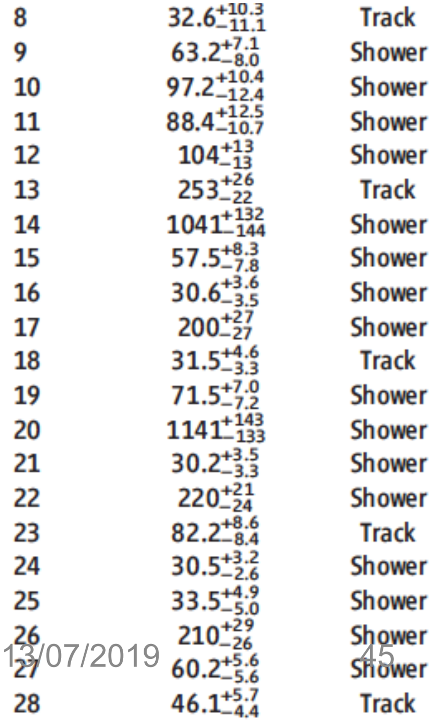
Data
- $N_T/N_S \sim 0.3$ → any production models are compatible with data

Physics of astrophysical neutrino flavor is interesting (Sec. 4)

Palladino et al,PRL114(2015)171101

$$N_S = 8.4F_e + 0.9F_\mu + 6.3F_\tau, \qquad N_T = 3.7F_\mu.$$





8	$32.6^{+10.3}_{-11.1}$	Track
9	$63.2^{+7.1}_{-8.0}$	Shower
10	$97.2^{+10.4}_{-12.4}$	Shower
11	$88.4^{+12.5}_{-10.7}$	Shower
12	104^{+13}_{-13}	Shower
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IceCube, Nature551(2017)596

2. High-energy neutrino cross section measurement

cross section

efficiency

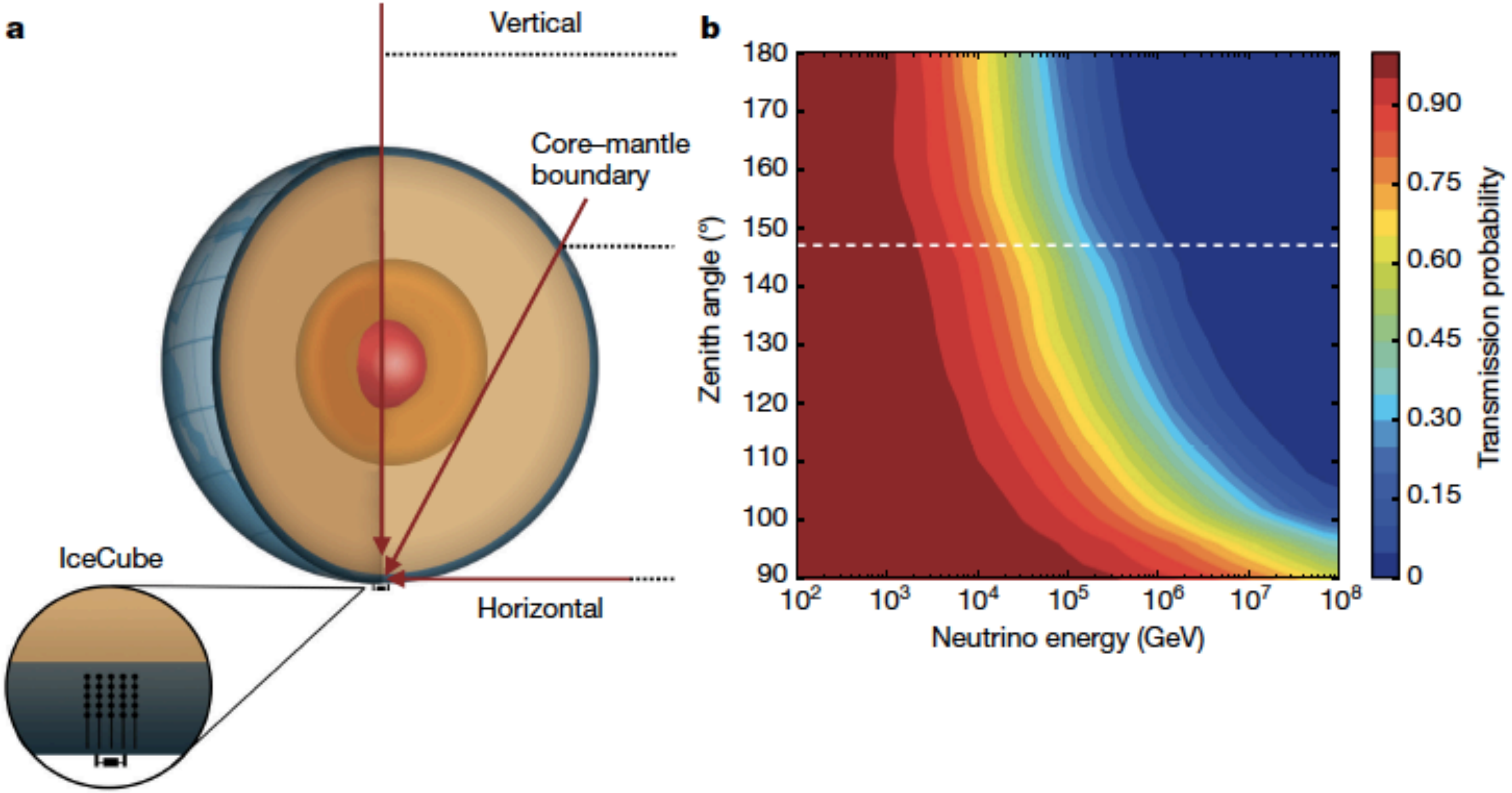
flux

target

Event rate $\mathrm{N} = \Phi \times \sigma \times T \times \varepsilon$

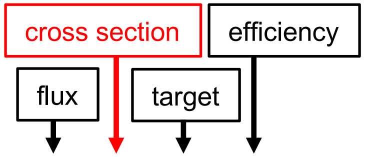
Earth absorption for neutrino cross-section measurement

- high-energy neutrinos have high cross-sections with Earth material.
- Assuming astrophysical neutrino flux, neutrino cross section is extracted from measured event rate.



IceCube, Nature551(2017)596
Bustamante and Connolly, PRL122(2019)041101

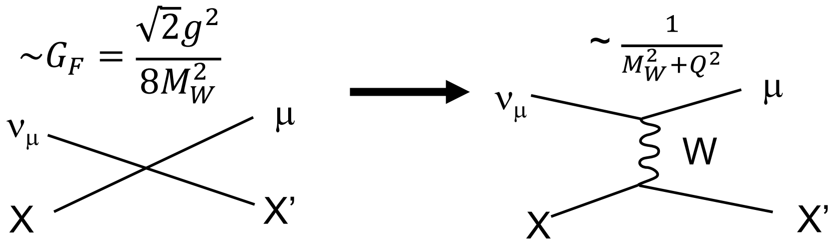
2. High-energy neutrino cross section measurement

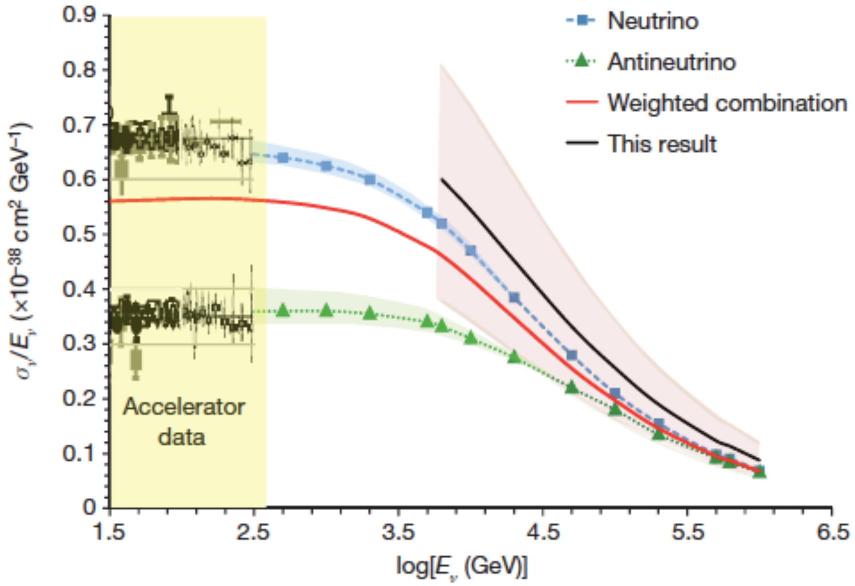


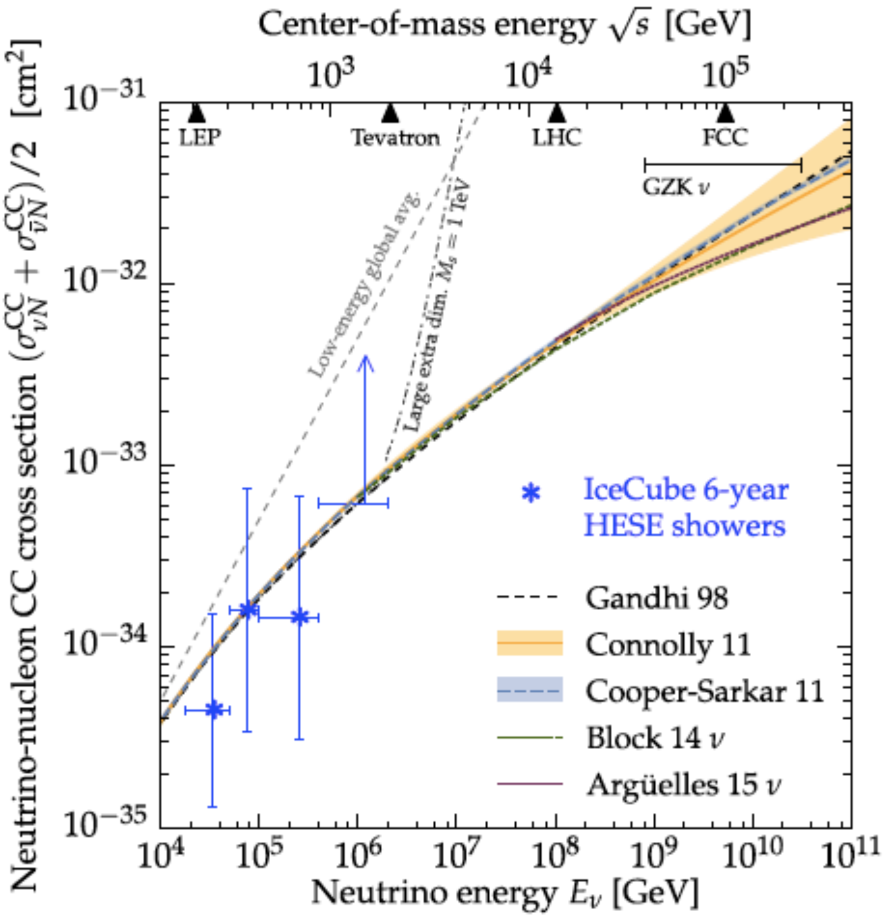
Event rate $N = \Phi \times \sigma \times T \times \varepsilon$

Earth absorption for neutrino cross-section measurement

- high-energy neutrinos have high cross-sections with Earth material.
- Assuming astrophysical neutrino flux, and the Earth model, cross section is extracted from event rate.
- first time Q^2 suppression is observed

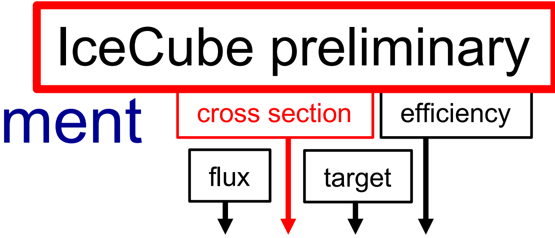

$$\sim G_F = \frac{\sqrt{2} g^2}{8 M_W^2}$$
$$\sim \frac{1}{M_W^2 + Q^2}$$





IceCube, Nature551(2017)596
Bustamante and Connolly, PRL122(2019)041101

2. High-energy neutrino cross section measurement



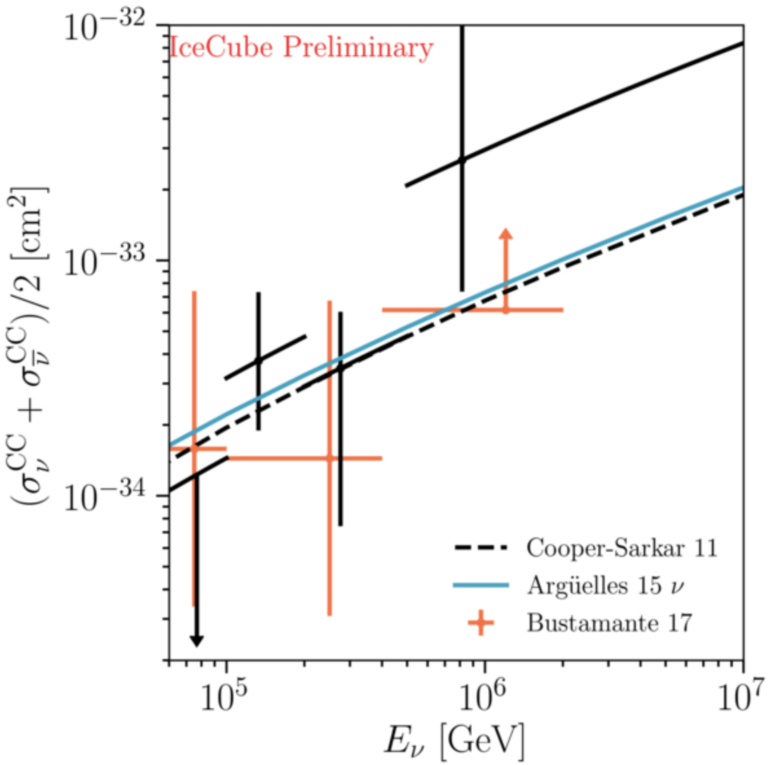
Event rate $\mathrm{N} = \Phi \times \sigma \times T \times \varepsilon$

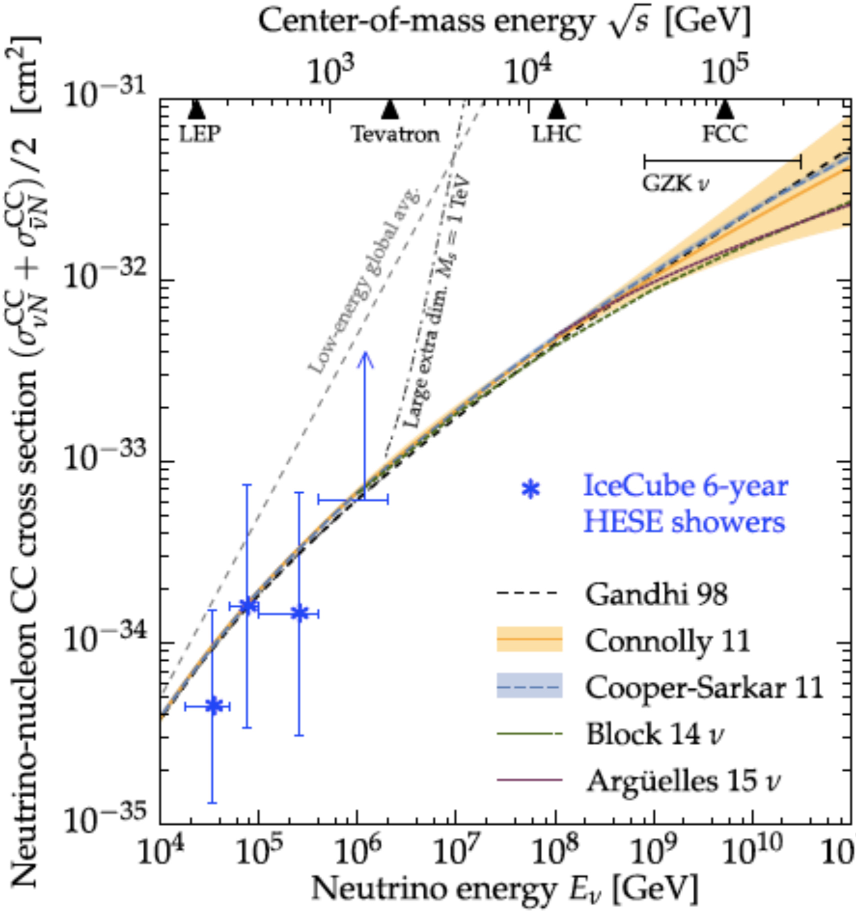
Earth absorption for neutrino cross-section measurement

- high-energy neutrinos have high cross-sections with Earth material.
- Assuming astrophysical neutrino flux, and the Earth model, cross section is extracted from event rate.
- first time Q^2 suppression is observed

Cross section measurement 2019

- Cross section at high energy might may be bigger than we think (exotic scenario?)





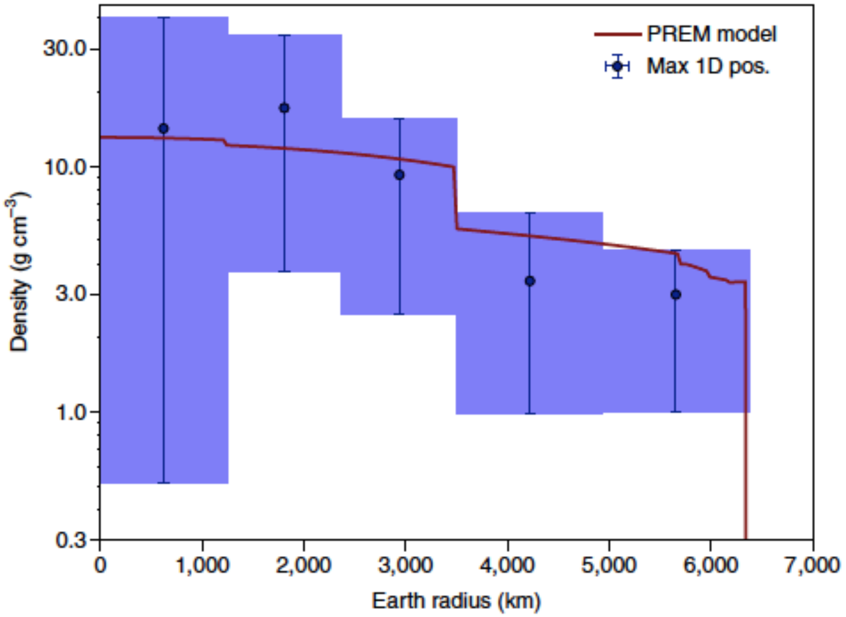
Dziewonski, Anderson (PREM), Phys. Earth Planet.Inter.25,(1981)297
Donini, Palomares-Ruiz, Salvado, Nature Physics 15(2019)37

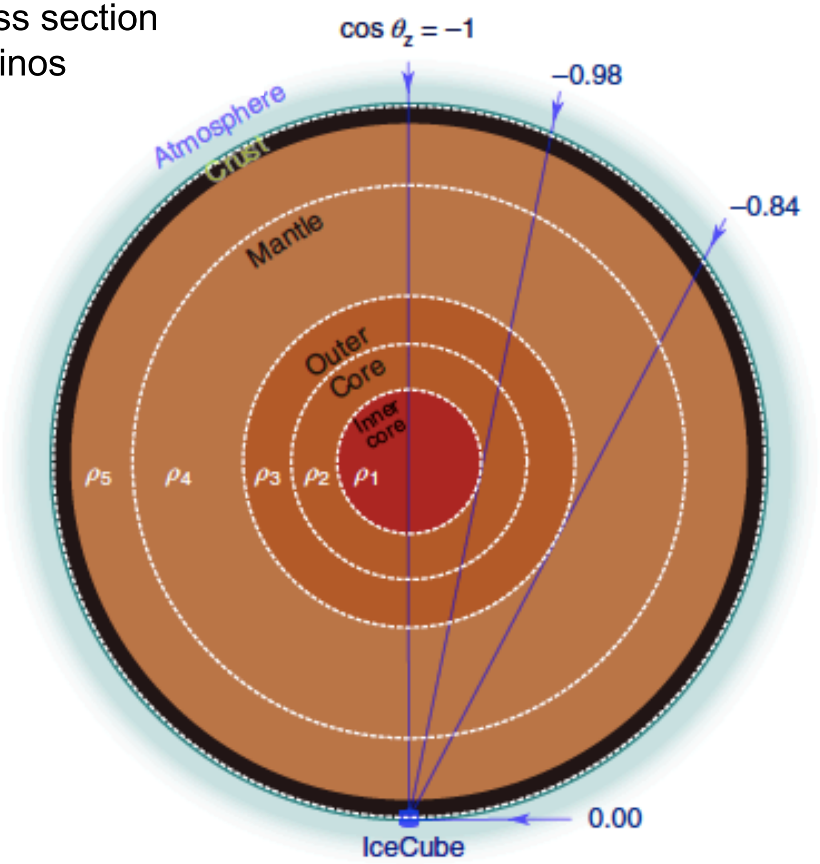
2. Earth tomography

$$\text{Event rate } \mathrm{N} = \overset{\text{flux}}{\Phi} \times \overset{\text{cross section}}{\sigma} \times \overset{\text{target}}{T} \times \overset{\text{efficiency}}{\varepsilon}$$

Earth absorption for Earth density measurement

- PREM (Preliminary reference Earth model)
- Standard earth density model used by T2K, NOvA, etc
- Earth density profile is extracted by assuming flux and cross section
- Measure Earth moment of inertia and Earth mass by neutrinos



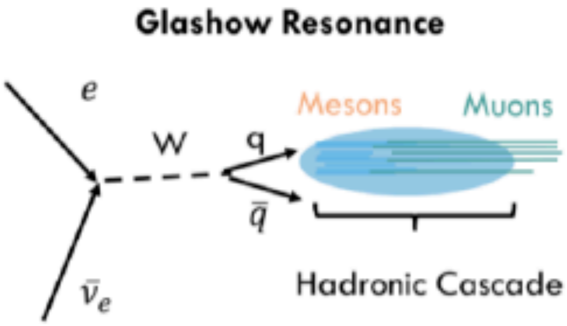


Taboada, Neutrino 2018, IceCube, arXiv:1710.01191

IceCube preliminary

2. Glashow resonance

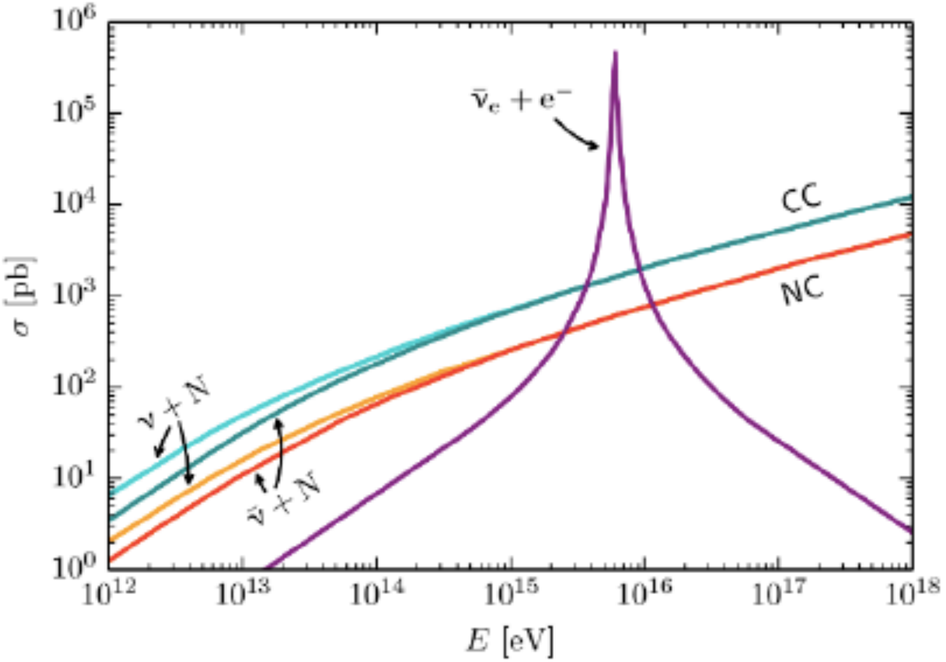
A 5.9 PeV event in IceCube



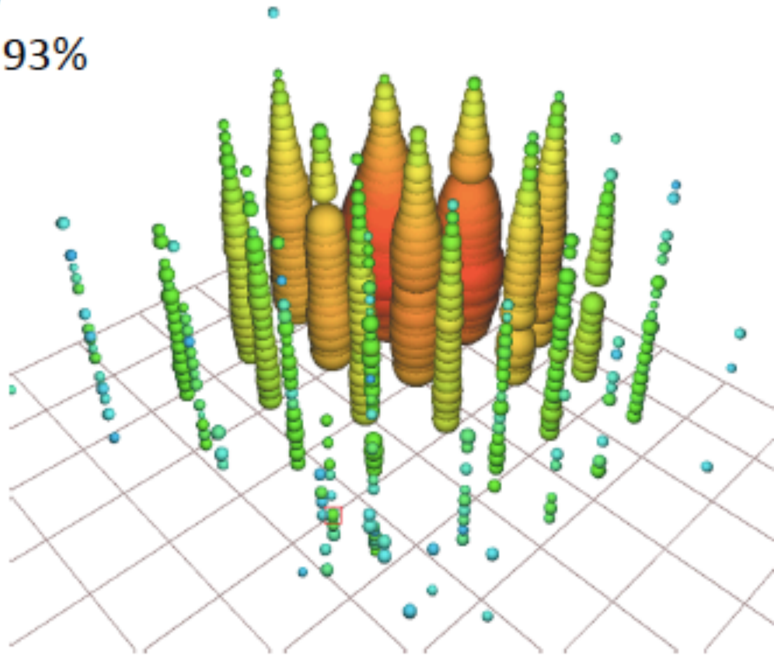
Resonance: E_ν = 6.3 PeV

Typical visible energy is 93%

On-shell production of W with rest electron target



Work in progress



Event identified in a partially-contained PeV search (PEPE)

Deposited energy: 5.9±0.18 PeV (stat only)

ICRC 2017 arXiv:1710.01191

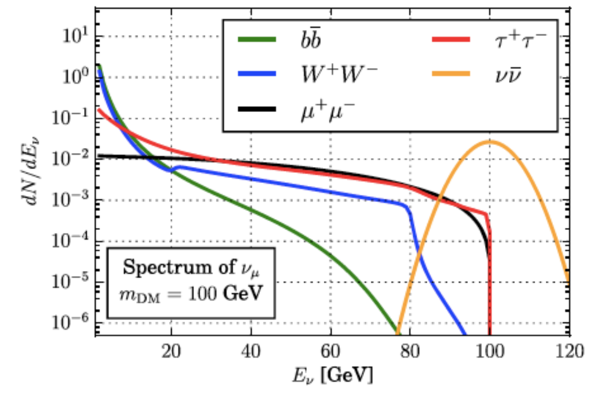
IceCube, EPJC76(2016)531, JCAP04(2016)022

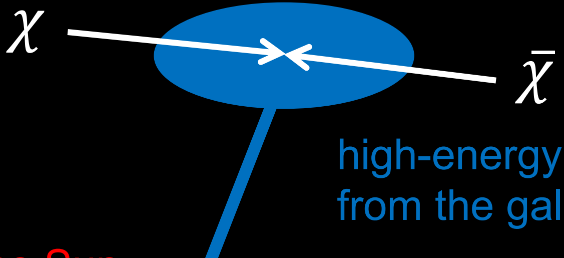
2. Dark matter search

Neutrinos from Earth, Sun, Milky Way center
- Signal of dark matter annihilation to neutrino pair emission

$$\chi + \bar{\chi} \rightarrow \nu + \bar{\nu}$$

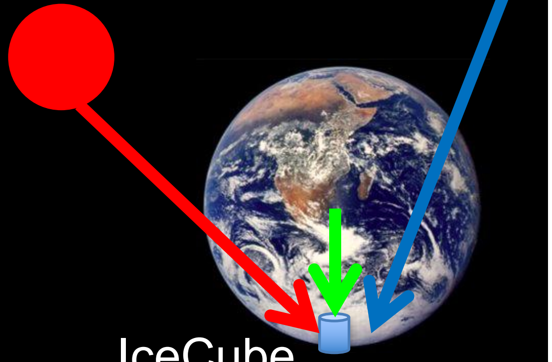
No excess for neutrinos from Earth, Sun, Milky Way center
→ The strongest limits for spin-dependent dark matter-nucleon interaction around m_χ~10-1000 GeV



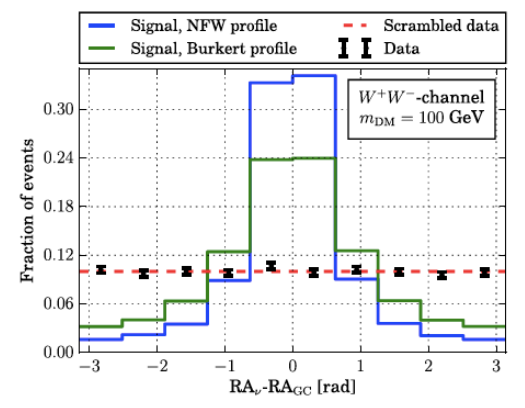


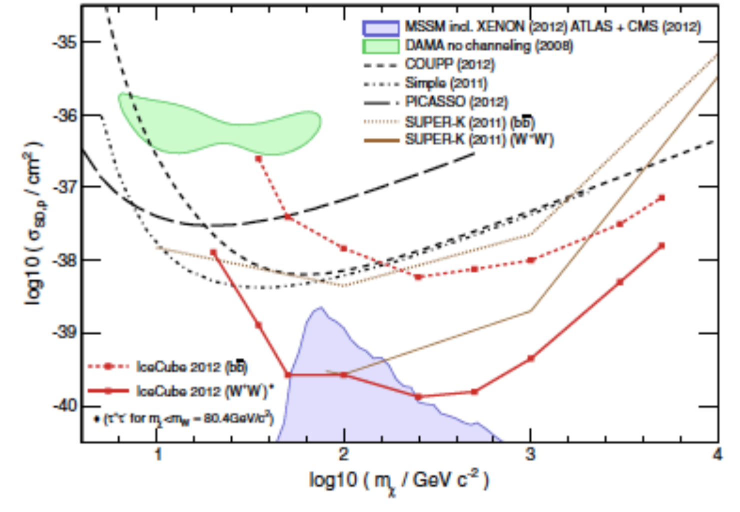
high-energy neutrino from the galactic center

high-energy neutrinos fro the Sun



IceCube



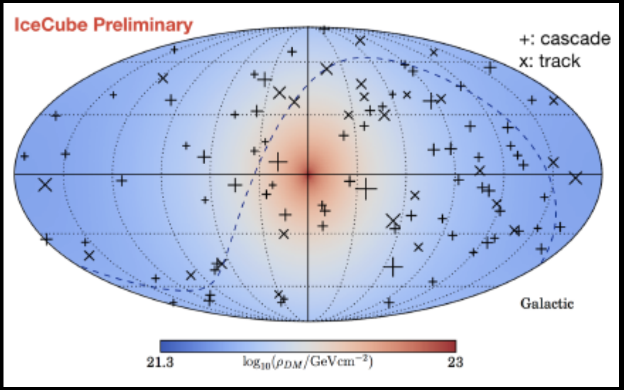


high-energy neutrino from the Earth core

IceCube, EPJC76(2016)531, JCAP04(2016)022
Argüelles, Kheirandish, Vincent, PRL119(2017)201801

IceCube preliminary

2. Dark matter search



Neutrinos from Earth, Sun, Milky Way center
 - Signal of dark matter annihilation to neutrino pair emission

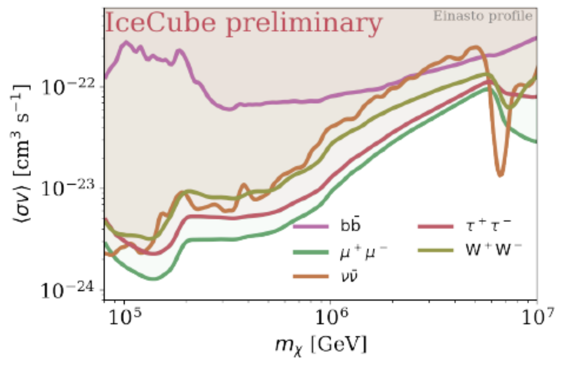
$$\chi + \bar{\chi} \rightarrow \nu + \bar{\nu}$$

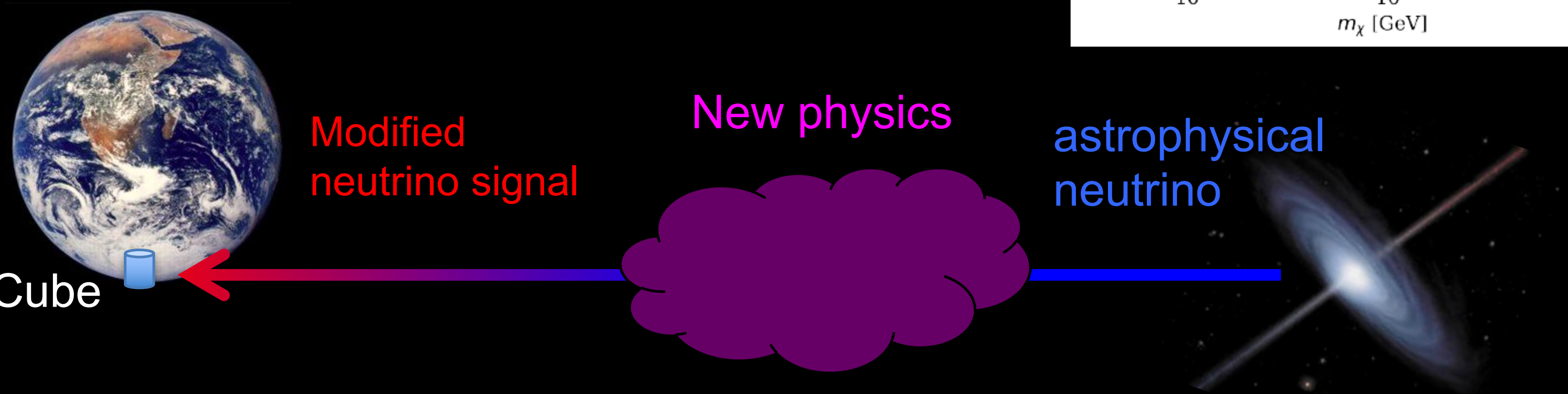
No excess for neutrinos from Earth, Sun, Milky Way center
 → The strongest limits for spin-dependent dark matter-nucleon interaction around m_χ~10 GeV -10PeV

Instead, one can assume dark matters This would modify astrophysical neutrino spectrum

$$\nu + \chi \rightarrow \nu + \chi$$

New techniques to look for light dark matters (m_χ~10-1000 MeV)





Modified neutrino signal

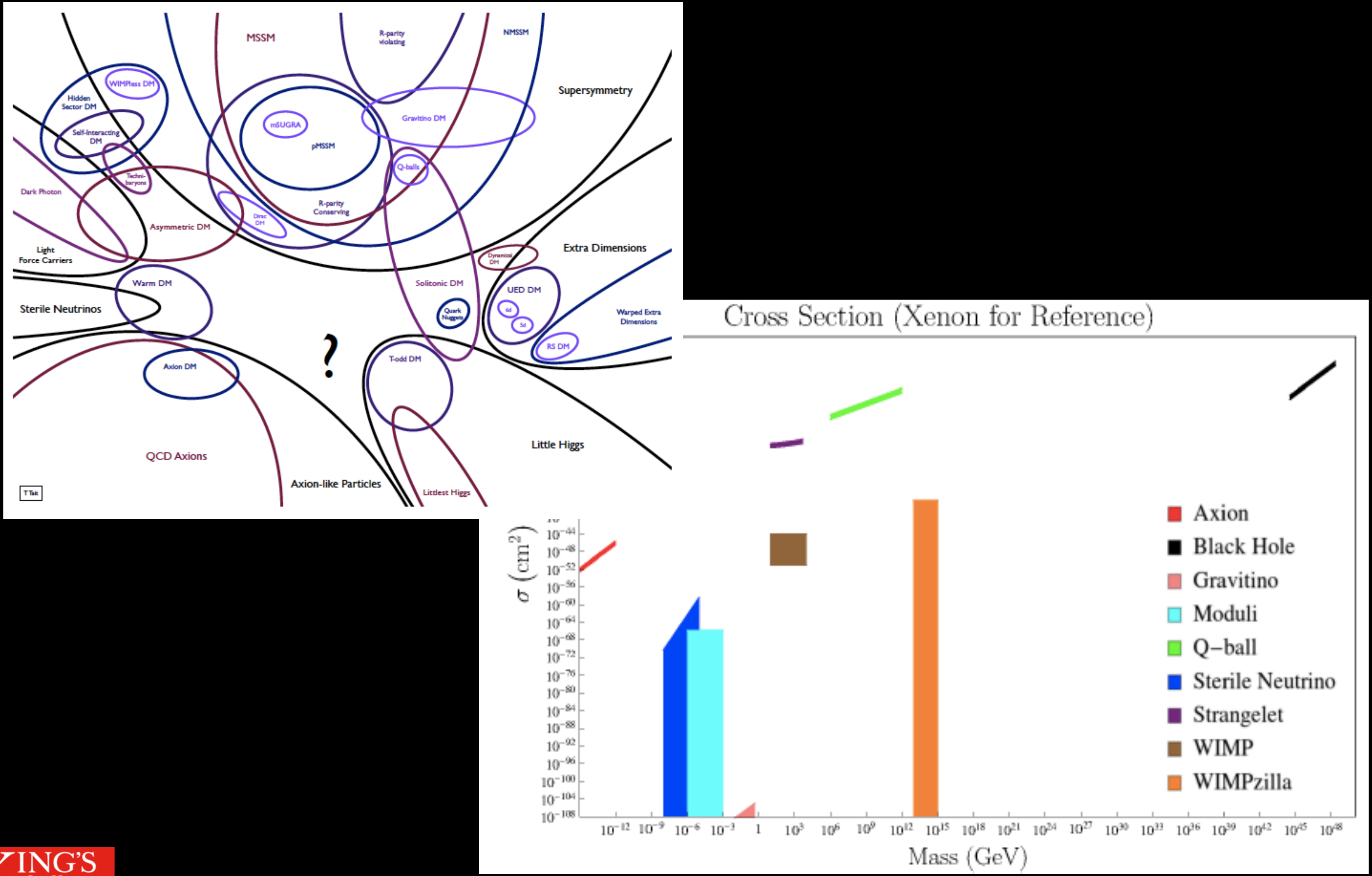
New physics

astrophysical neutrino

IceCube

Snowmass-2013 Cosmic Frontier 3 (CF3) Working Group Summary: Non-WIMP dark matter, ArXiv:1310.8642

2. Dark matter search



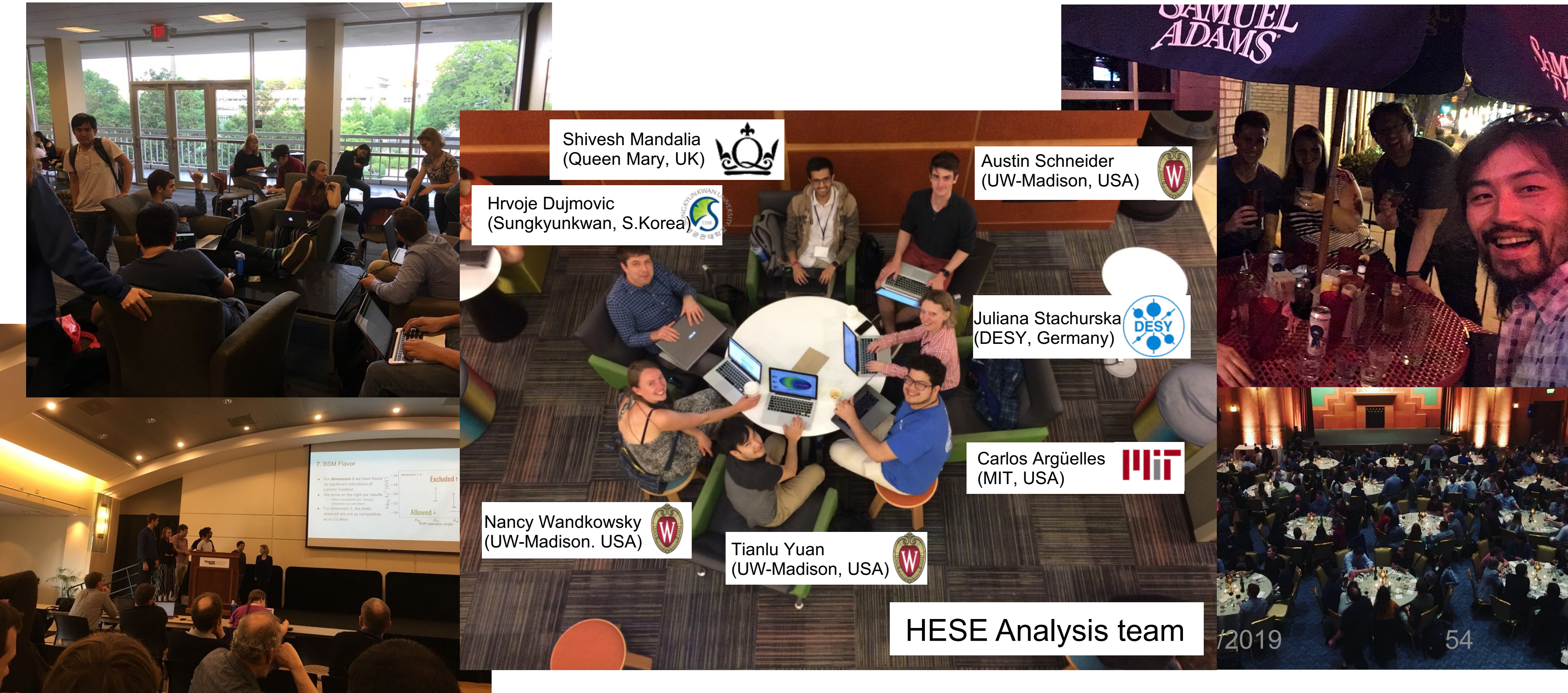
2. Big data science and HESE analysis team

Big data science

Particle physics and astrophysics experiments are large collaborations, and jobs are done by teams
- Detector: design and construction, simulation, operation, detector monitoring system, etc…
- Data analysis: software development, analysis

Students learn innovative technologies (machine learning, etc), and those are useful to get jobs in industry, too

But more importantly, working in a collaboration, with a team, is a lot of fun…



2. Summary

High-energy neutrinos are discovered
- unlikely atmospheric neutrinos, but not high enough to be unlikely GZK neutrinos
- Mostly from unknown source, coming from all directions (diffuse)
- Currently spectrum index is not known precisely, but consistent with -2 ($\Phi \sim E^{-2}$)
- Currently, production flavor structure is not known precisely, but consistent with ($\nu_e : \nu_\mu : \nu_\tau$) ~(1 : 2 : 0)

Physics of high-energy neutrinos
- cross-section is measured up to ~PeV
- Earth moment of inertia and mass are measured by neutrinos
- A variety of dark matter searches are ongoing

Neutrino astronomy is a big data science

1. Cosmic Ray and Astroparticle Physics

2. High-Energy Neutrino Observations

3. **Neutrino Multi-Messenger Astronomy**

4. Astrophysical Neutrino Flavour Physics

3. Neutrino multi-messenger astronomy

What are blazars and TXXS0506+056?

What are sources of astrophysical neutrinos?

What are future projects to study high-energy neutrinos?

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“Institute of Physics Astroparticle Physics”
https://www.facebook.com/IOPAPP

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ニュートリノ☆マルチメッセンジャー

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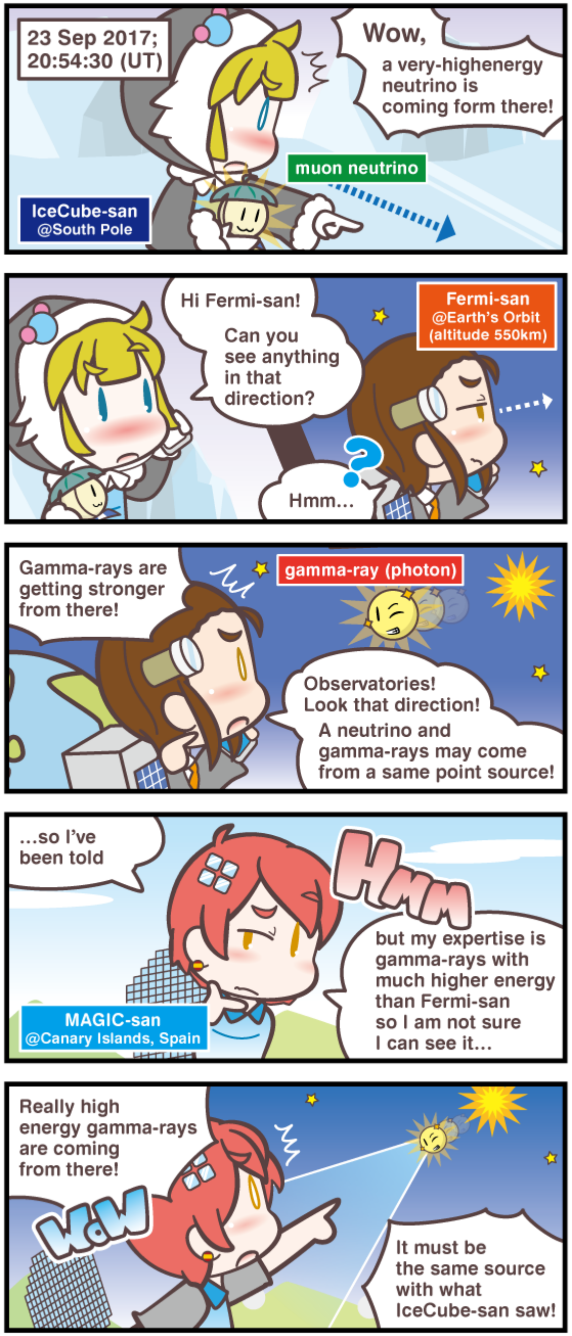
Neutrino☆Multi-messenger



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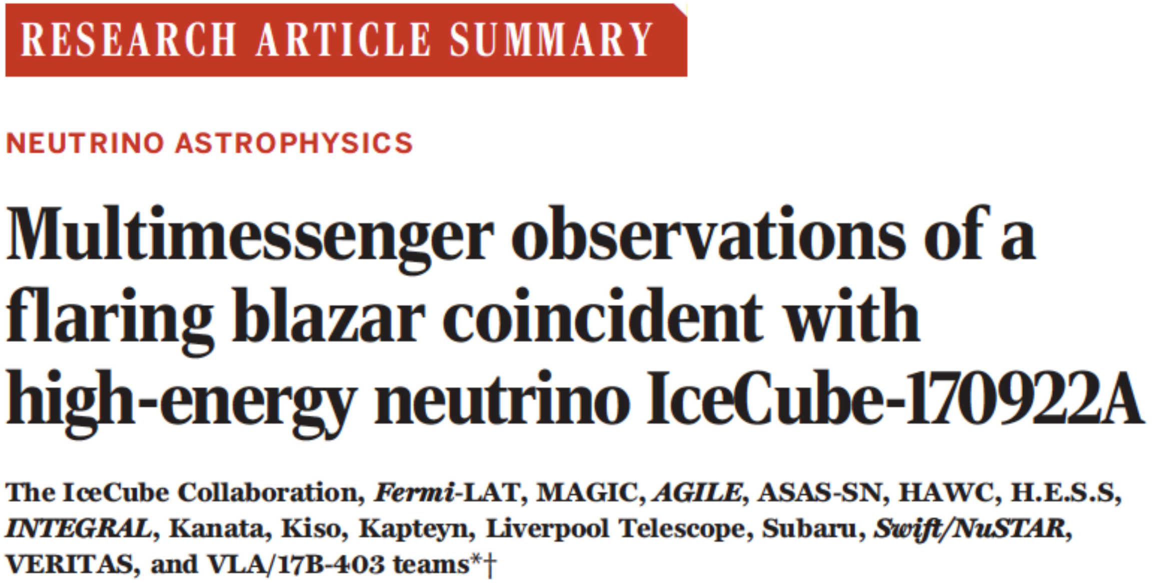
IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378

2 papers about “point source”

“Transient event”
- coincidence with IC170922 and optical signals from blazar TXS0506+056

Not real time “Transient event”
- IceCube search of past data from the direction of blazar TXS0506+056



RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

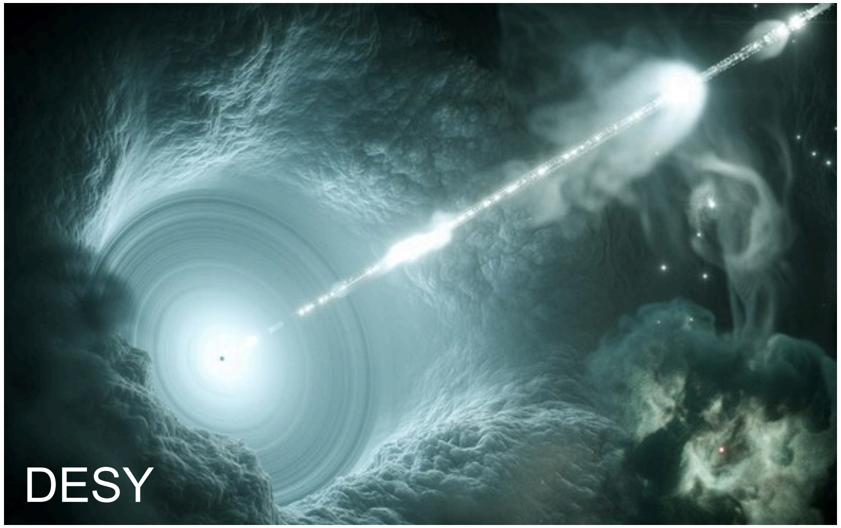
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

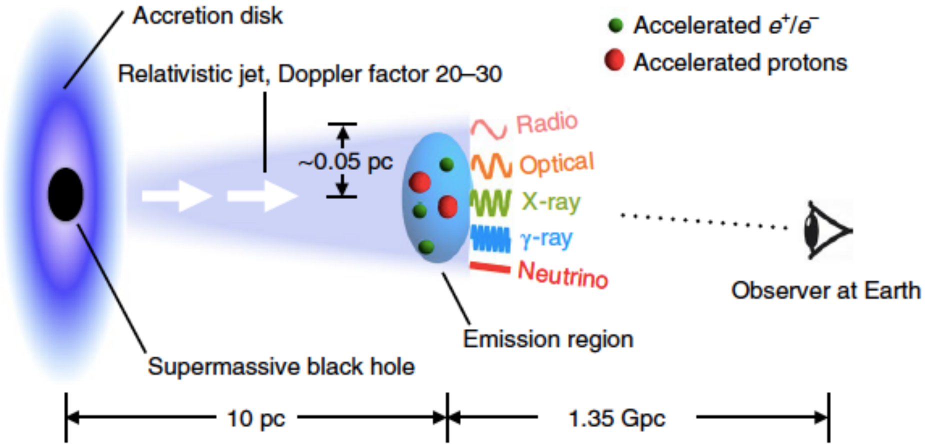
IceCube Collaboration*†

3. High-energy neutrino sources

Blazars

- Active galactic nuclei (AGNs) are galaxies with a bright core.
- Spinning black hole with accretion disk, beyond Eddington luminosity.
- If the jet is oriented toward Earth, it is called a blazar.
- They are known to accelerate particles to the highest observed energies.


DESY



3. High-energy neutrino sources

Blazars

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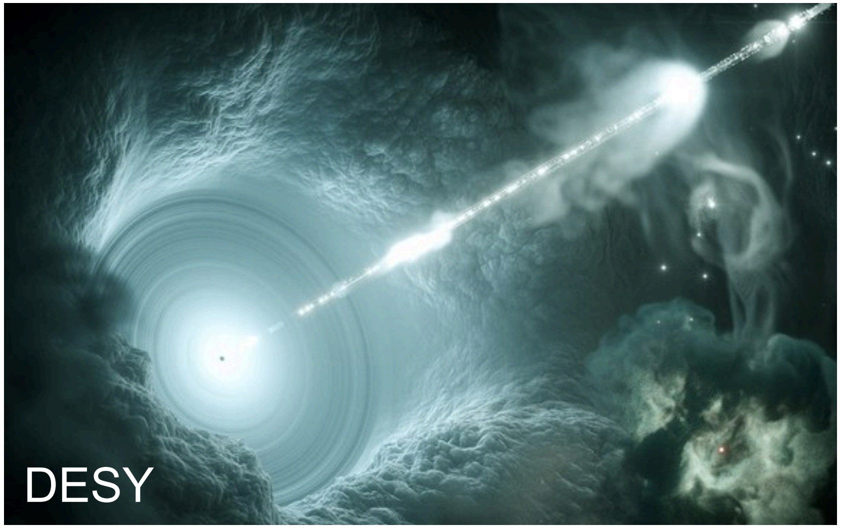
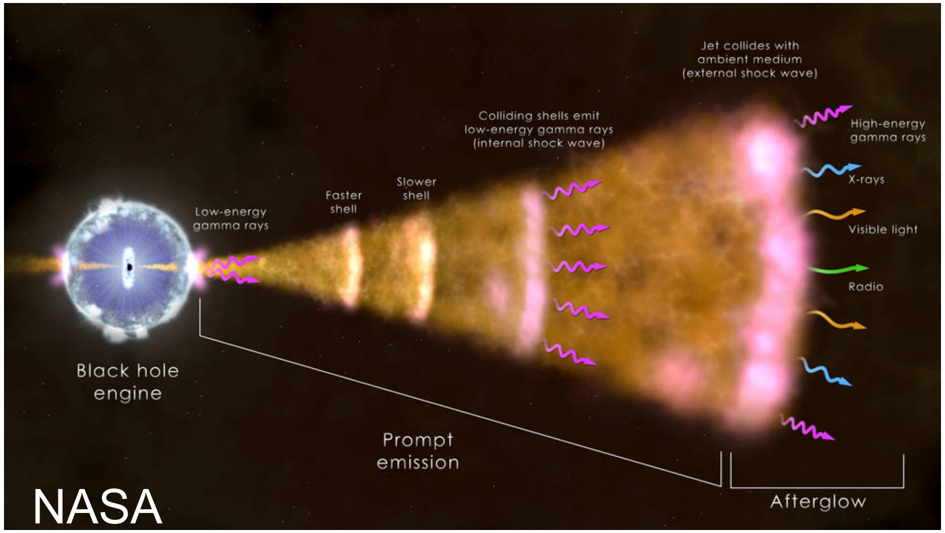
- Spinning black hole with accretion disk, beyond Eddington luminosity.
- If the jet is oriented toward Earth, it is called a blazar.
- They are known to accelerate particles to the highest observed energies.

Gamma Ray Bursts (GRBs)

- Most energetic transient events in the universe.
- Long GRBs (>2 s), collapsars, massive star collapsing to a black hole (?)
- Short GRBs (<2 s), non-collapsars, merger of compact objects (?)



DESY

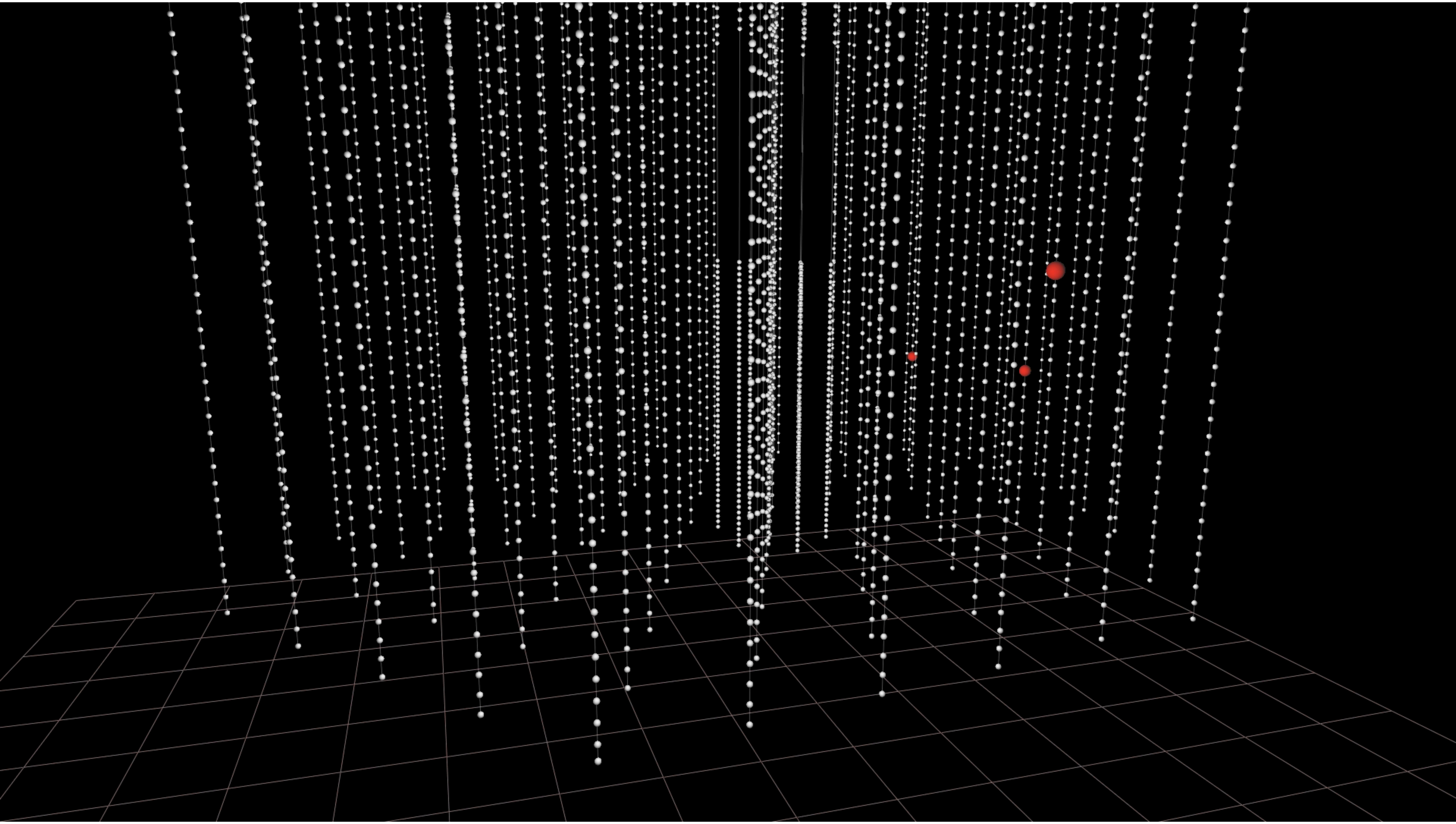


NASA

IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378

3. IC170922

290 TeV, 56.5% astrophysical neutrinos (just by direction and energy)



IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378

3. IC170922

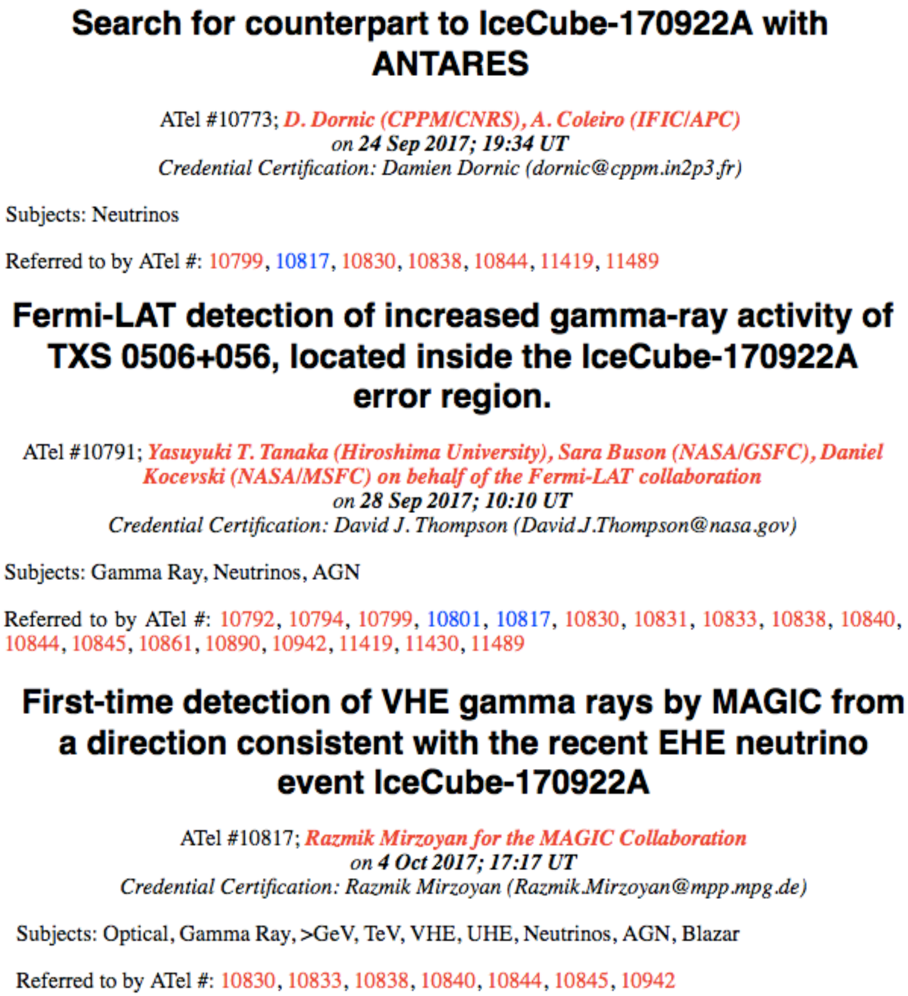
290 TeV, 56.5% astrophysical neutrinos (just by direction and energy)

Within ~1min, public alert was distributed to observatories
- Fermi-LAT found TXS0506+056 is actively flaring
- MAGIC found up to 400 GeV gamma ray flux

Redshift of blazar is ~0.3365 → ~4.6Glyr (1368 Mpc)

Full coverage, radio wavelength to gamma rays by everyone
- Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403

The astronomer's telegram
http://www.astronomerstelegram.org/



Search for counterpart to IceCube-170922A with ANTARES

ATel #10773; *D. Dornic (CPPM/CNRS), A. Coleiro (IFIC/APC)*
on 24 Sep 2017; 19:34 UT
Credential Certification: Damien Dornic (dornic@cppm.in2p3.fr)

Subjects: Neutrinos

Referred to by ATel #: 10799, 10817, 10830, 10838, 10844, 11419, 11489

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

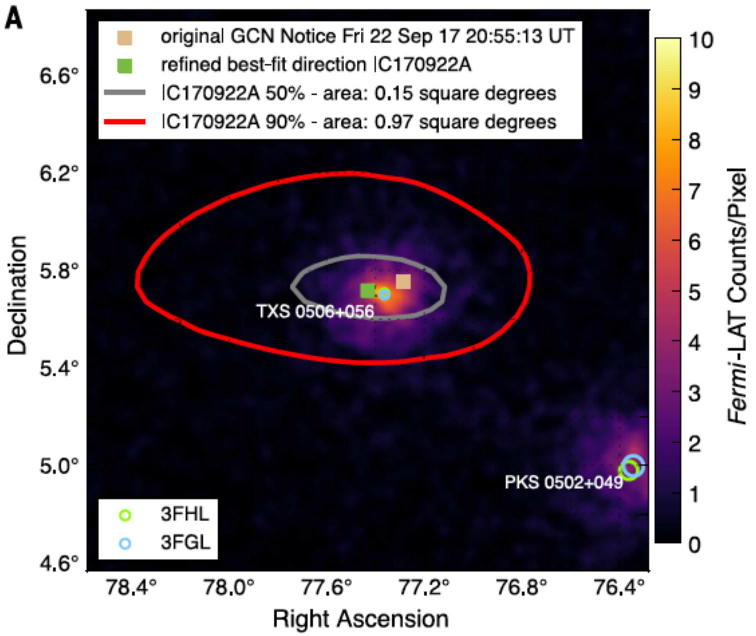
Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

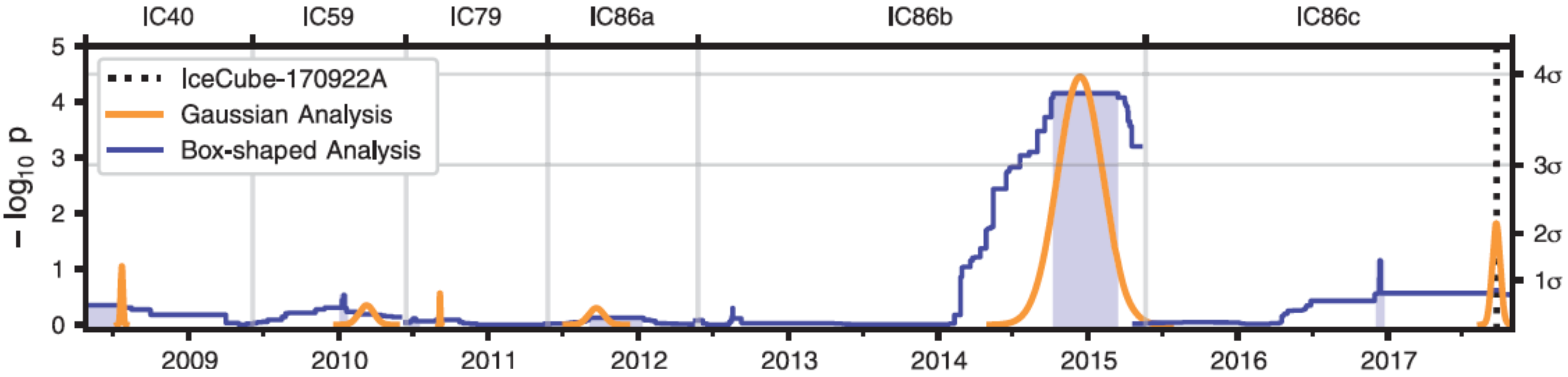


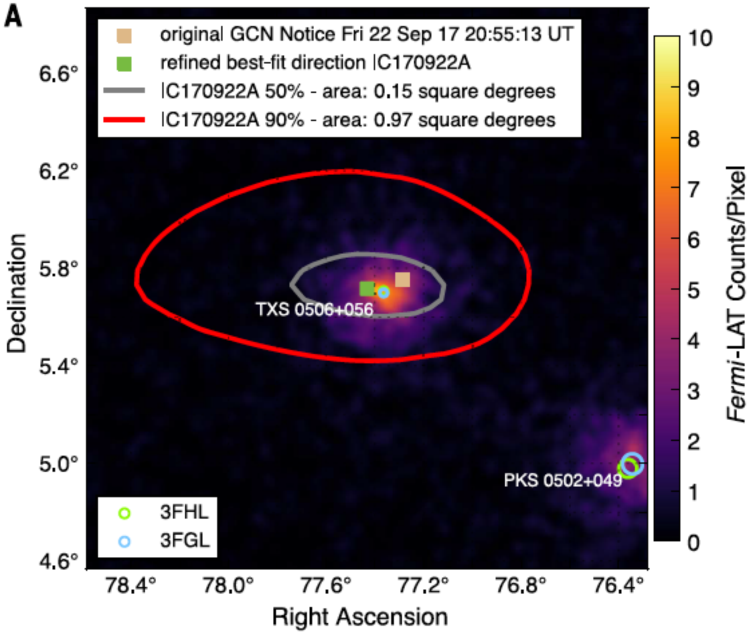
IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378

3. TXS056+0506

2014/15 IceCube data

- When this blazar is active, 13 ± 5 astrophysical VHE neutrinos are identified from this direction.





Is it special blazar?

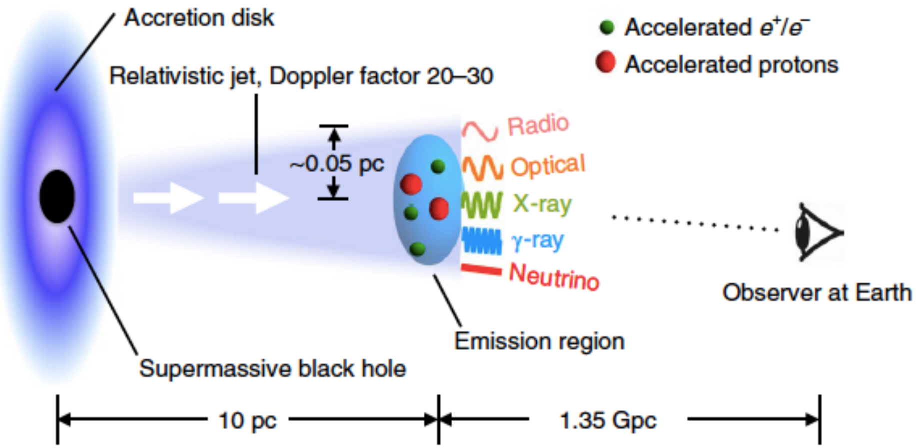
- It is one of the brightest blazars. Among them, TXS 0506+056 is one of the furthest (z=0.33) and the brightest. But other than that we don't know why neutrinos only from this blazar are identified.

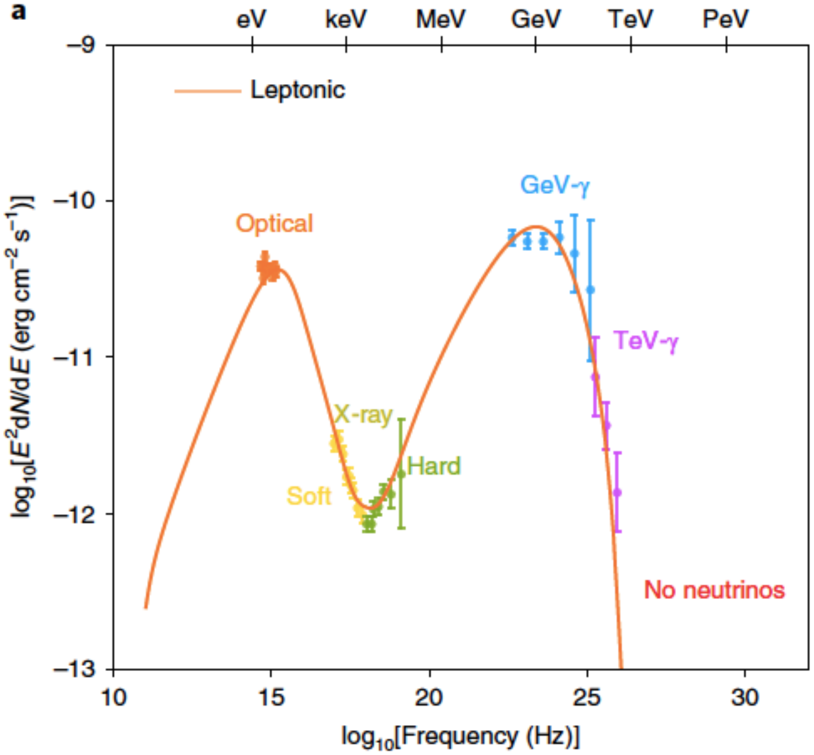
Gao,Fedynitch1,Winter, Pohl, Nature Astronomy 3(2019)88

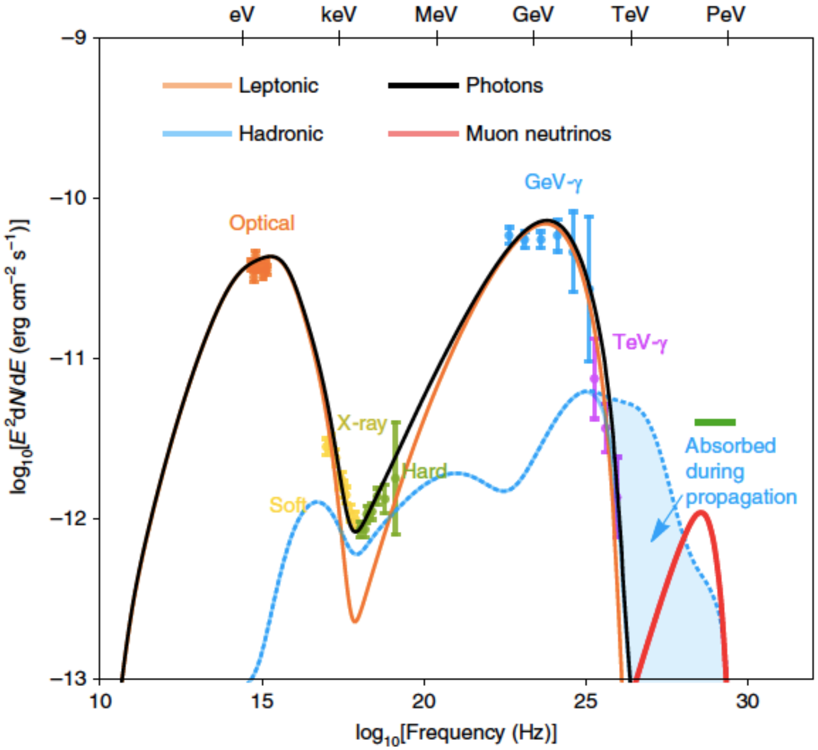
3. TXS056+0506

Origin of photons, hybrid model?

- Pure leptonic process can explain all optical signals from TXS0506+056
- Introducing hadronic process also require to introduce absorption mechanism of photons







3. High-energy neutrino source

What is the source luminosity and source density to produce astrophysical neutrinos?

Assume a class of astrophysical neutrino source has luminosity Lν (erg/s), then neutrino rates per area per steradian on the earth from this source (with density ρ) is

$$\frac{dF_\nu}{d\Omega} = \frac{1}{4\pi}\int_o^{R_H} L_\nu \rho dr = \xi \frac{L_\nu \rho R_H}{4\pi}$$

Here, ξ is for the cosmological evolution of source (~2-3), and R_H is the Hubble radius,

$$R_H = \frac{c}{H_0} = \frac{3\cdot 10^5 km}{72km/s/Mpc} \sim 4000Mpc$$

Now, IceCube data with assumption of E^{-2} flux gives

$$\frac{dF_\nu}{d\Omega} \sim 3\cdot 10^{-8}\frac{GeV}{cm^2\cdot s\cdot sr} \sim 1\cdot 10^{46}\frac{erg}{Mpc^2\cdot yr\cdot sr}$$

Thus, required luminosity-density is

$$\rho L_\nu = \frac{4\pi}{\xi R_H}\cdot\frac{dF_\nu}{d\Omega} \sim 1\cdot 10^{43}\frac{erg}{Mpc^3 yr}$$

A class of astrophysical neutrino source needs to satisfy $\rho L_\nu \geq 1\cdot 10^{43} erg/Mpc^3 yr$

Kowalski, ArXiv:1411.4385

3. Kowalski plot

Transient sources

- Core collapse supernova (SN II) is more plausible source than GRB (SN II is more abundant)

Steady sources

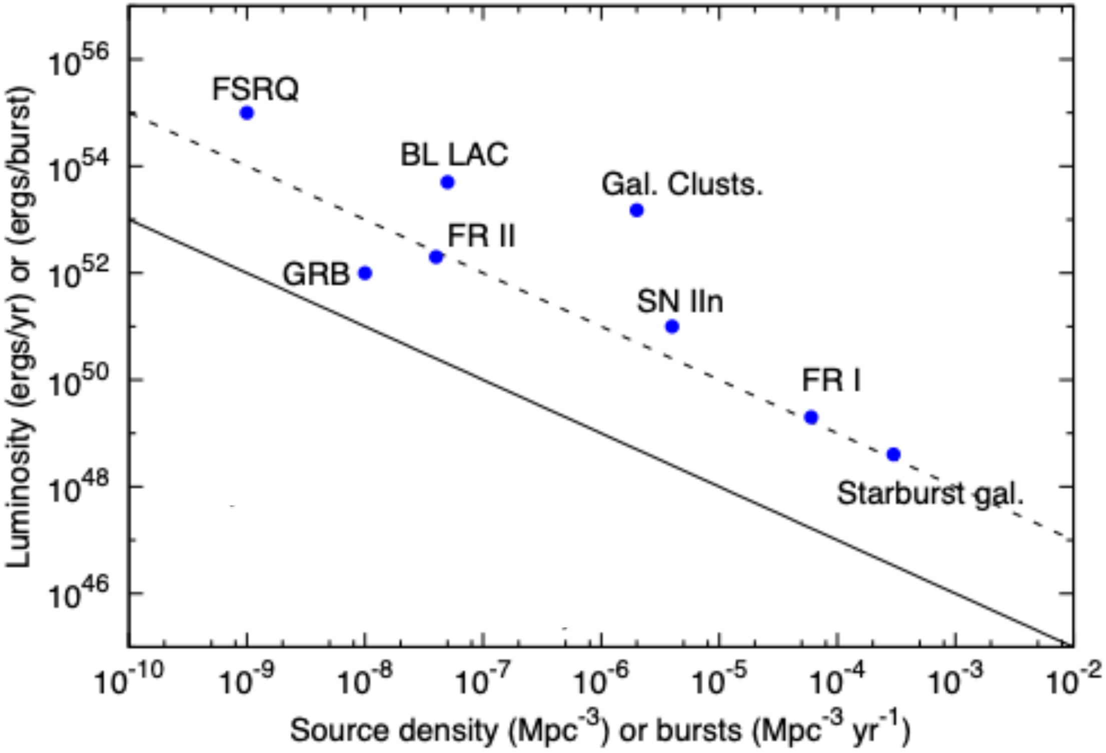
- AGNs include flat-spectrum radio quasar (FSRQ), BL Lac (blazars), Fanaro-Riley (FR) II, FR I
- Starburst galaxy ~ 10% of all galaxies.

AGNs including blazars are very likely sources of astrophysical neutrinos

What did we learn so far?

At least, some cosmic rays are accelerated up to few PeV in blazars. It is conceivable blazars can accelerate up to the highest observed cosmic rays, >10^{19} eV.

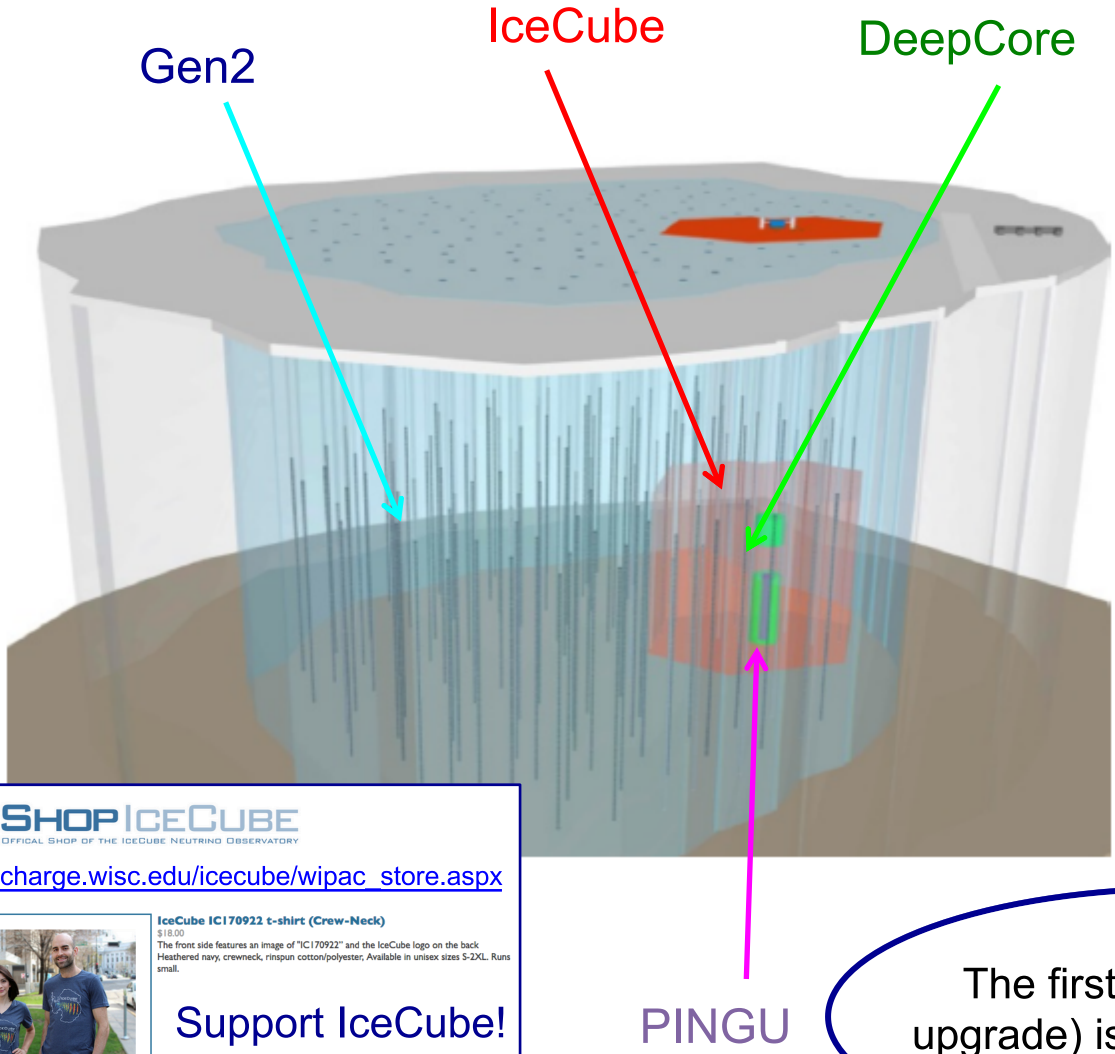
If this is real, **IceCube-Gen2** will see a lot of blazar neutrinos



Dashed line assumes 1% efficiency for production of neutrinos

IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

3. IceCube-Gen2



ICECUBE GEN2

Bigger IceCube and denser DeepCore can push their physics

Gen2
Larger string separations to cover larger area

PINGU
Smaller string separation to achieve lower energy threshold for neutrino mass hierarchy measurement

SHOP ICECUBE
OFFICAL SHOP OF THE ICECUBE NEUTRINO OBSERVATORY

https://charge.wisc.edu/icecube/wipac_store.aspx

IceCube IC170922 t-shirt (Crew-Neck)
$18.00
The front side features an image of "IC170922" and the IceCube logo on the back Heathered navy, crewneck, rinspun cotton/polyester, Available in unisex sizes S-2XL. Runs small.

Support IceCube!

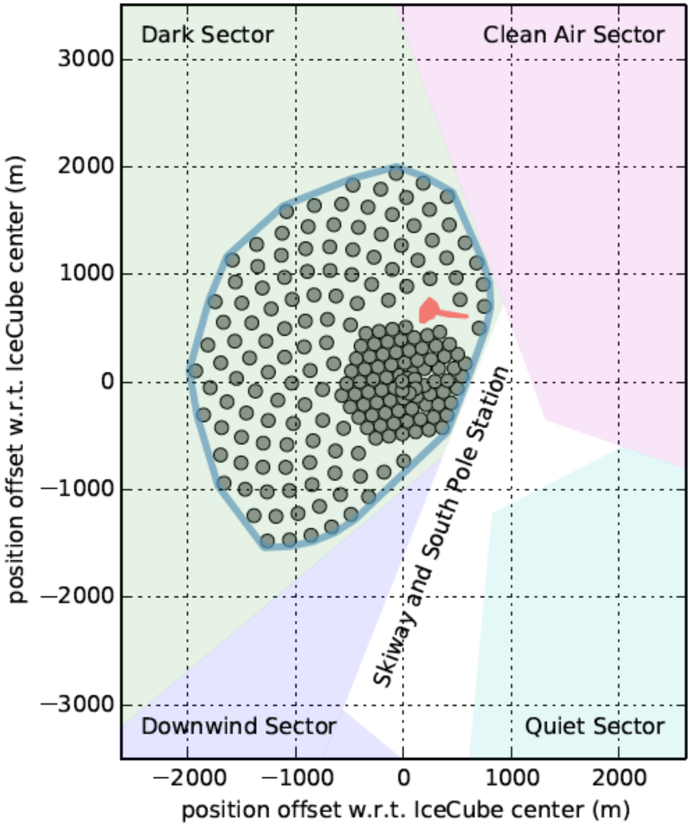
The first stage (IceCube upgrade) is approved by NSF

KING'S College LONDON

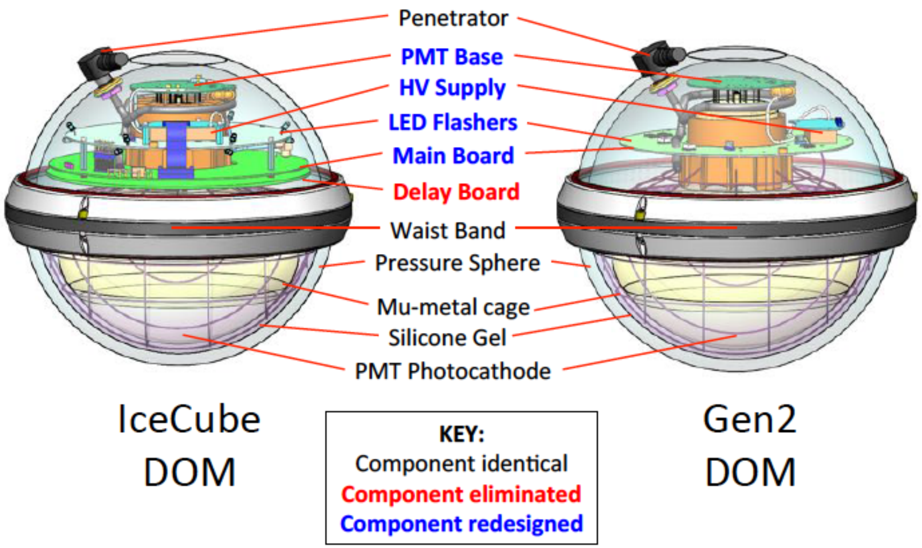
IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

3. IceCube-Gen2

Ice is clear than we thought
→ larger separation (125m → ~200-300m) to cover larger volume
- 120 new strings with 100 sensors, 240 m separation, x10 coverage



pDOM
- Improved IceCube DOM
- baseline design



IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

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→ larger separation (125m → ~200-300m) to cover larger volume
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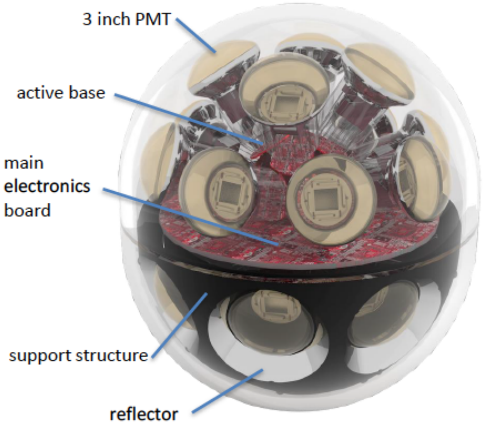
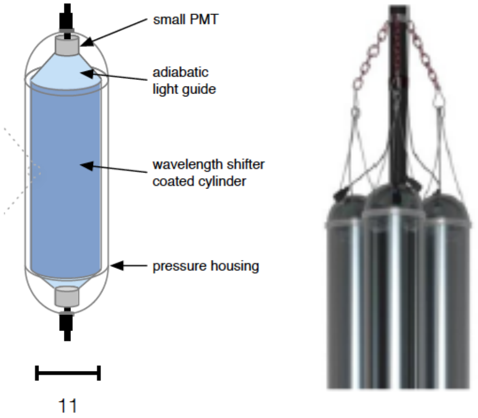
- Variety of new detectors are under development

mDOM
- direction sensitive
- KM3NeT, HyperK, etc

D-Eggs
- 8-inch high-QE PMTs
- cleaner glass window

WOM
- Scintillator light guide
- cheaper per coverage
- small diameter





and more...

IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

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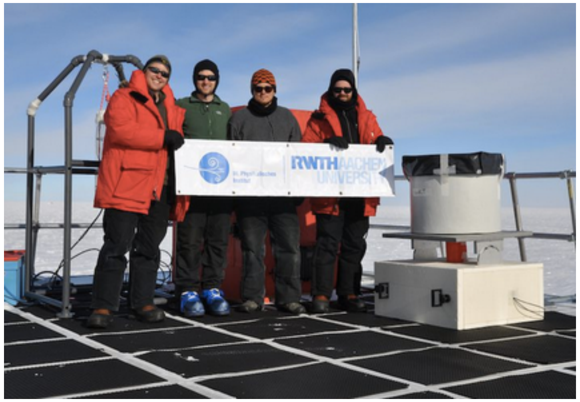
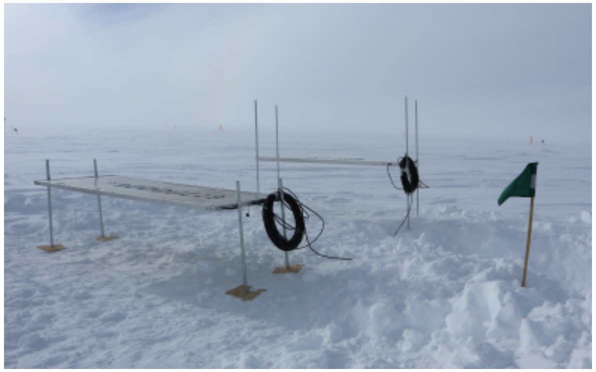
Ice is clear than we thought
→ larger separation (125m → ~200-300m) to cover larger volume
- 120 new strings with 100 sensors, 240 m separation, x10 coverage
- Variety of new detectors are under development
- Variety of new surface array are under development

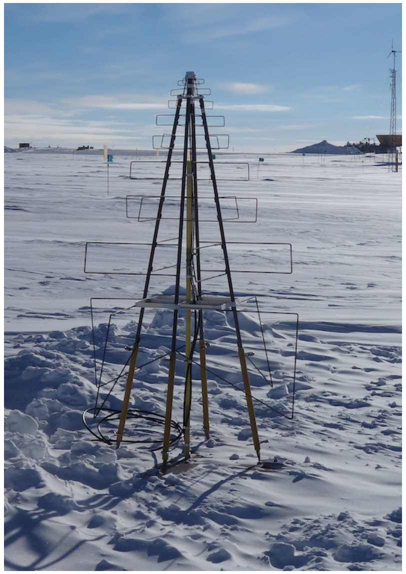
IceACT
- air Cherenkov telescope
- larger coverage with fewer stations



Scintillator panels
- organic scintillator with fibre reading
- cheap, easy deployment



Antenna
- radio frequency from air shower
- cheap, different phase space



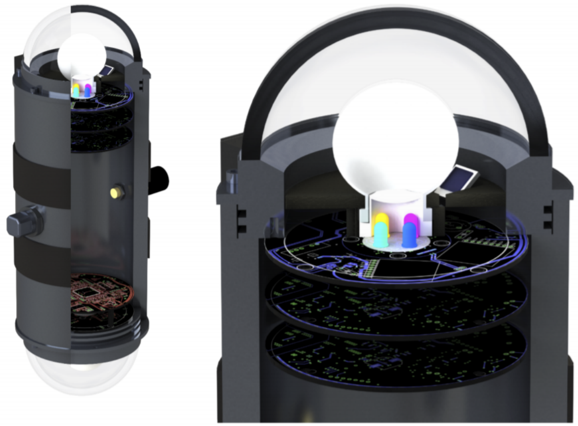
Prototypes of surface detectors are installed at South Pole

IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

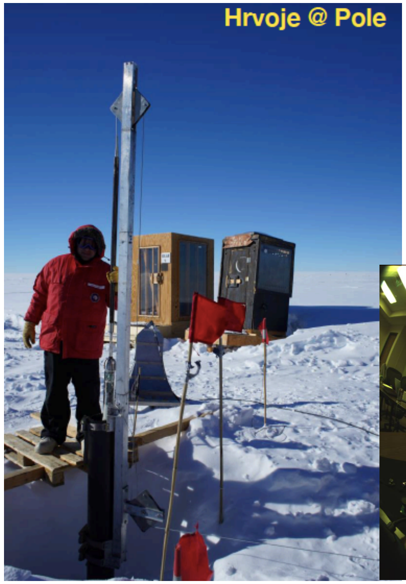
3. IceCube-Gen2

Ice is clear than we thought
→ larger separation (125m → ~200-300m) to cover larger volume
- 120 new strings with 100 sensors, 240 m separation, x10 coverage
- Variety of new detectors are under development
- Variety of new surface array are under development
- Variety of new calibration devices are under development

POCAM
- isotropic light source
- large dynamic range, multiple LEDs
- prototype deployed in lake, ocean



New camera system
- modern electronics
- monitor ice quality
- prototype deployed



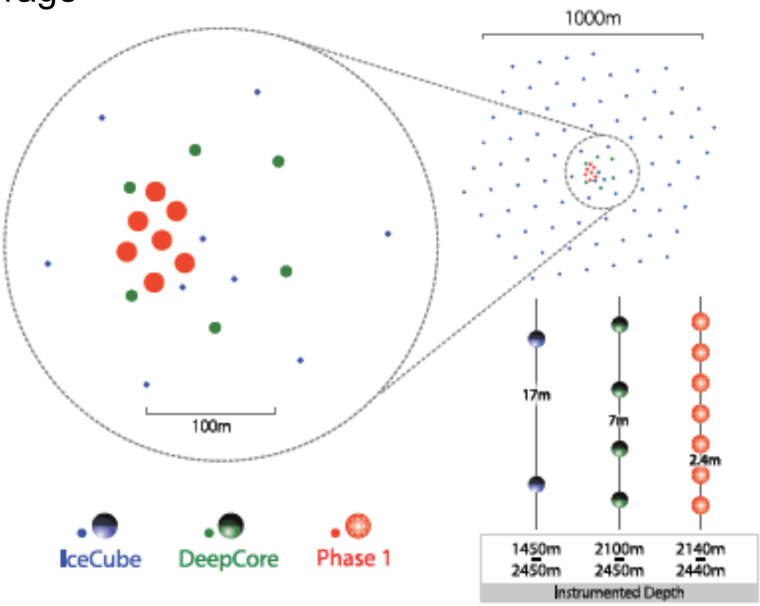
camera project review process including group photo quality check

IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

3. IceCube-Upgrade

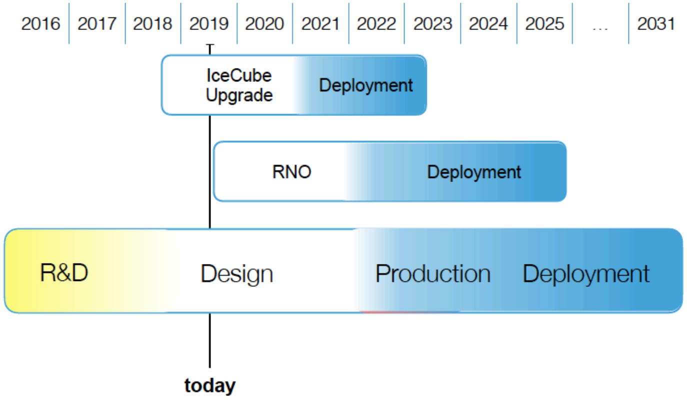
ICECUBE
GEN2

Ice is clear than we thought
→ larger separation (125m → ~200-300m) to cover larger volume
- 120 new strings with 100 sensors, 240 m separation, x10 coverage
- Variety of new detectors are under development
- Variety of new surface array are under development
- Variety of new calibration devices are under development



IceCube-Upgrade

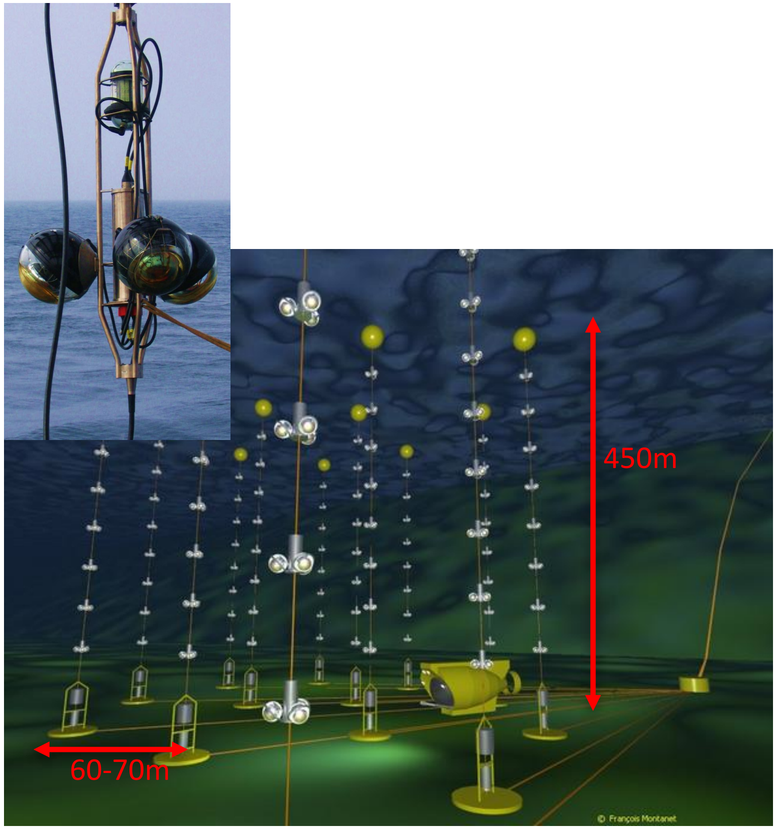
- Proposal accepted
- 7 new strings (part of PINGU array)
- Test new devices for high energy physics
- ν_τ appearance to constrain unitary triangle

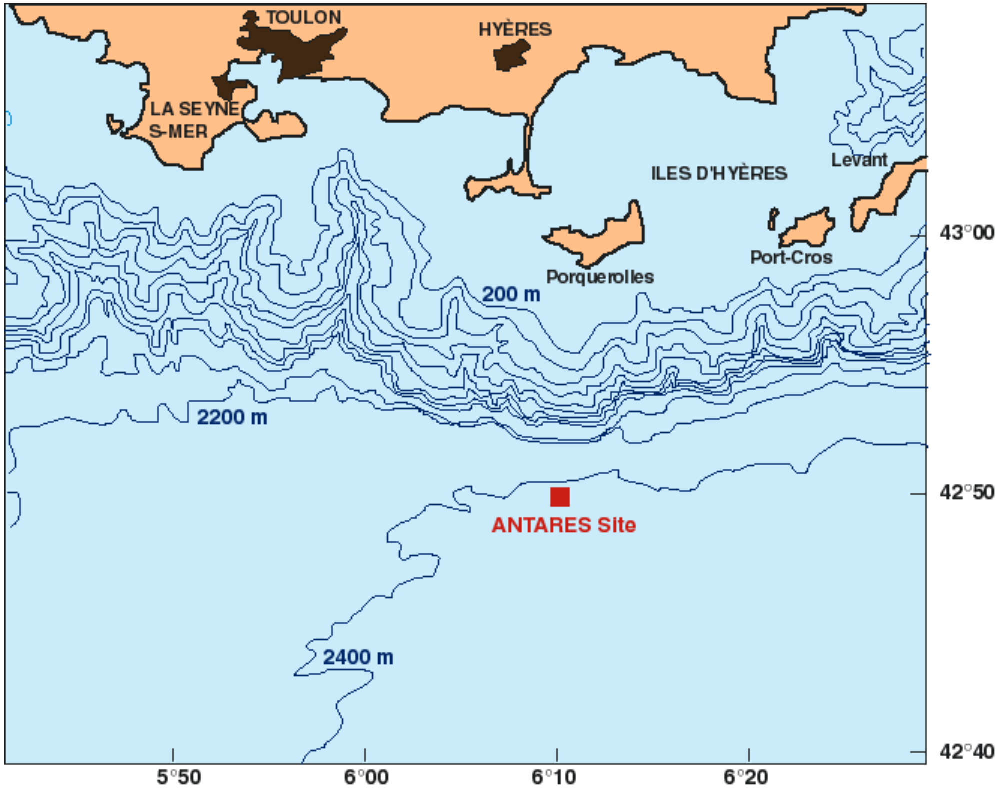


ANTARES, http://antares.in2p3.fr/

3. ANTARES

Photo-sensor array in the ocean.
- 12 lines, ~70m spacing
- 25 storeys per line, 3 10-inch PMTs /storey





KM3NeT, J.Phys.G43(2016)084001

3. ANTARES → KM3NeT

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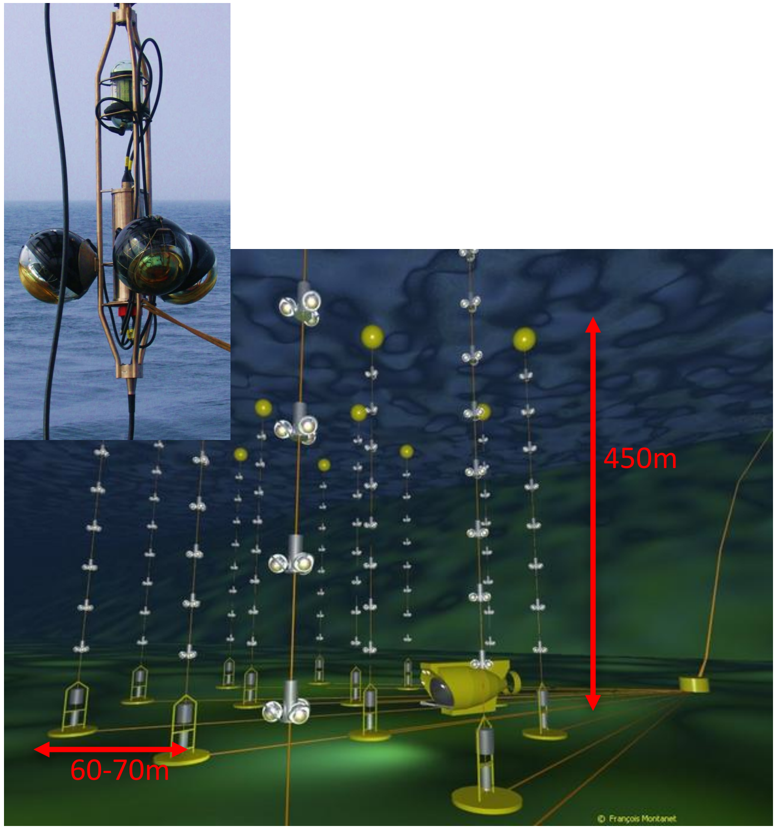
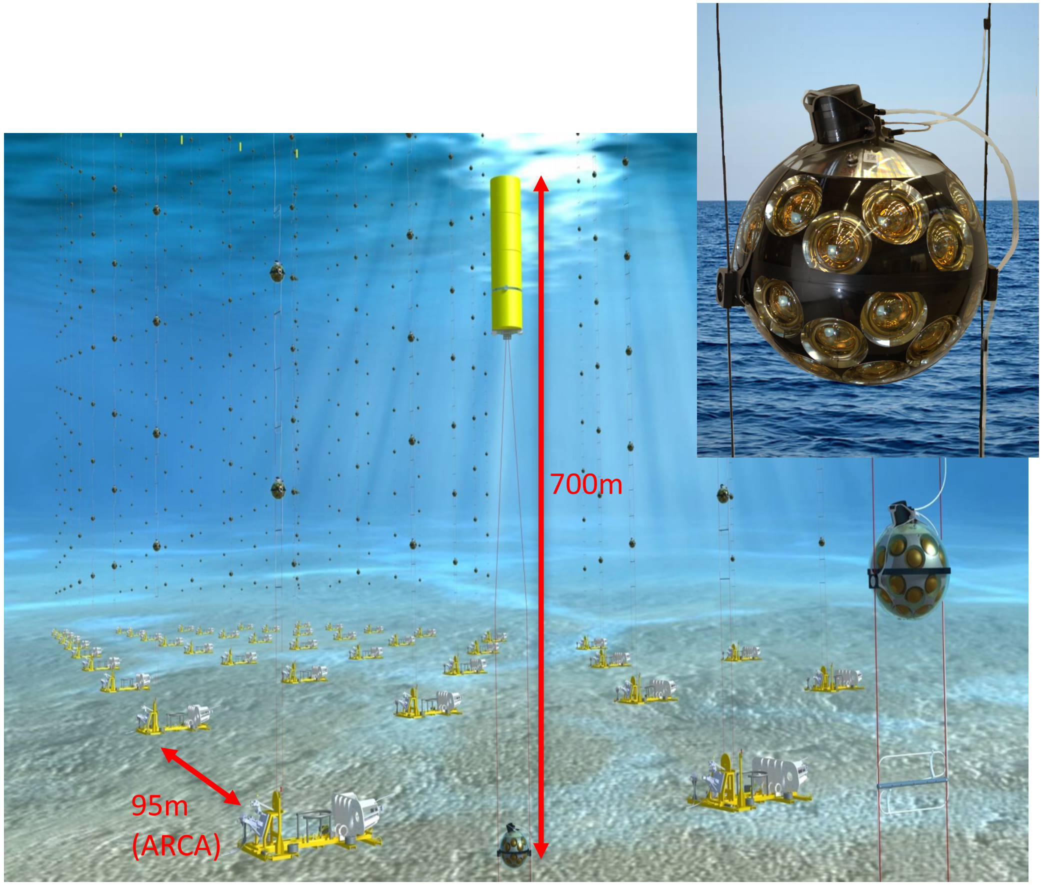


Multi-DOM (mDOM) system
- 115 lines x 3 blocks, ~2000 mDOMs per block (~IceCube)
- 18 mDOMs per string
- 4π coverage by 31-inch PMTs per mDOM
- good background rejection, energy and direction resolution
- Hyper-Kamiokande, IceCube-Gen2, R&D mDOMs



KM3NeT, J.Phys.G43(2016)084001

3. ANTARES → KM3NeT

KM3NeT is ARCA and ORCA
- ARCA: Astroparticle Research with Cosmics in the Abyss, IceCube-like neutrino telescope
- ORCA: Oscillation Research with Cosmics in the Abyss, more lines in small region for low energy (<20 GeV) neutrino oscillation physics
- string installation ongoing

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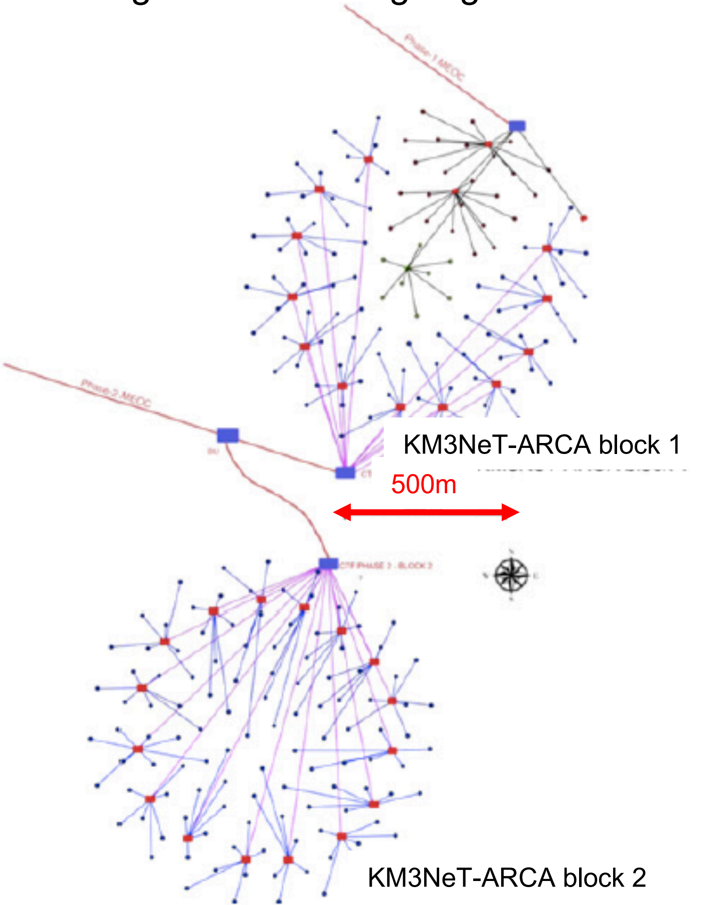

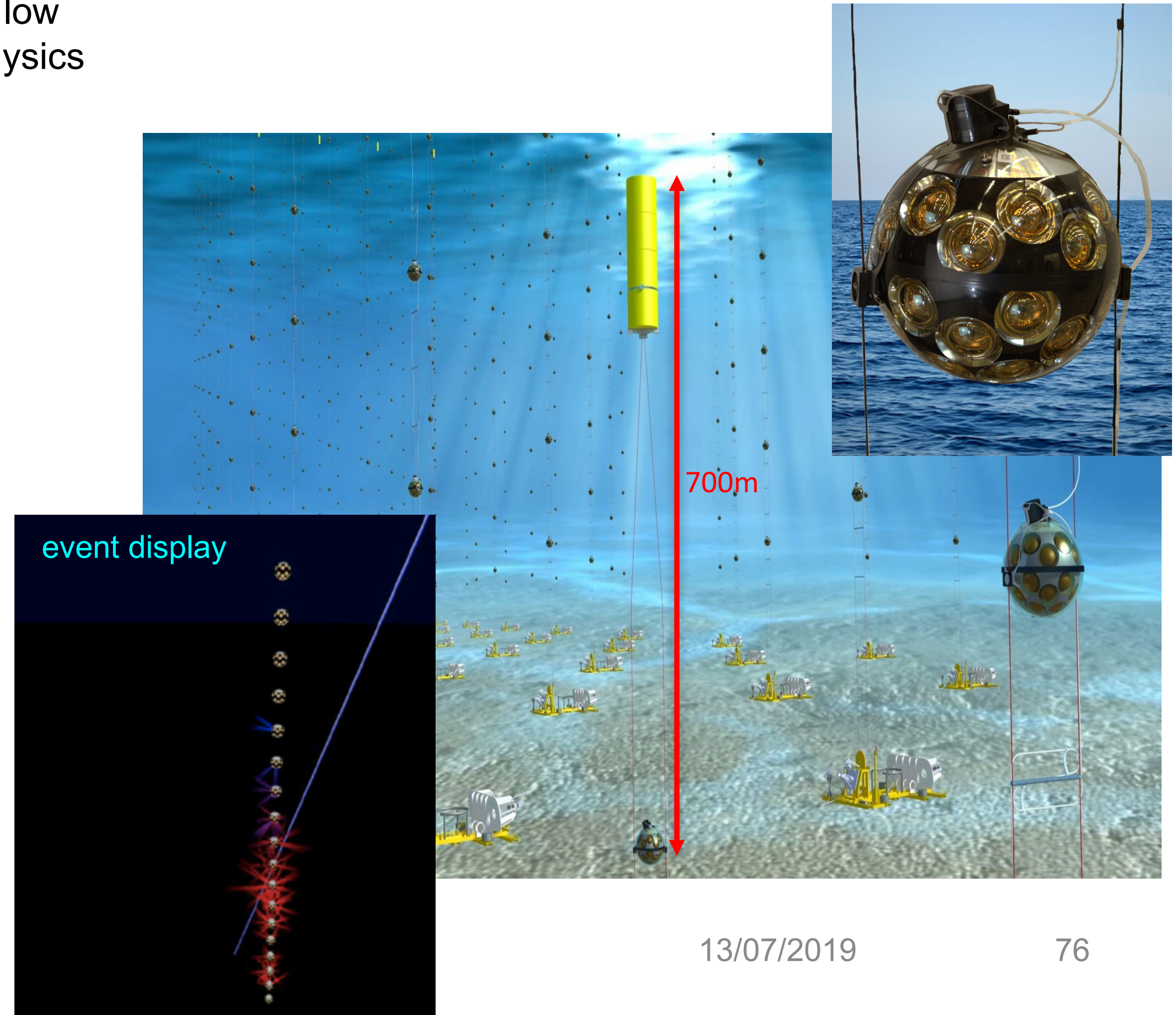

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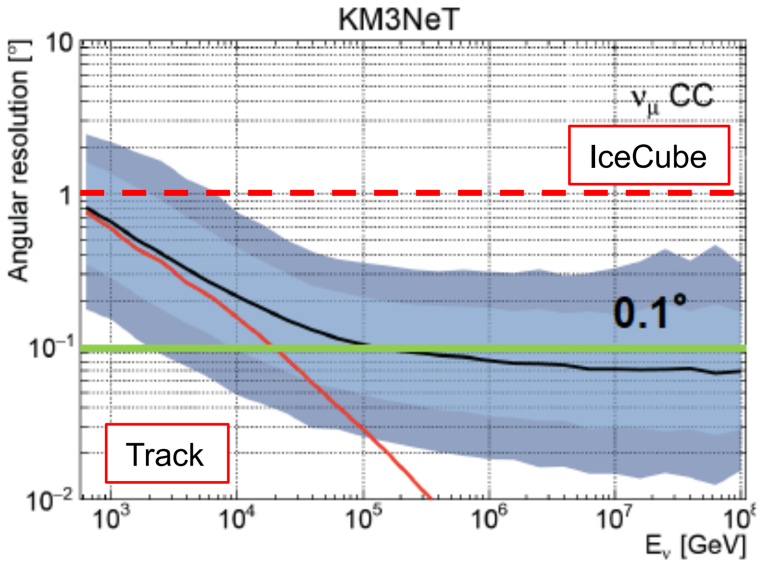
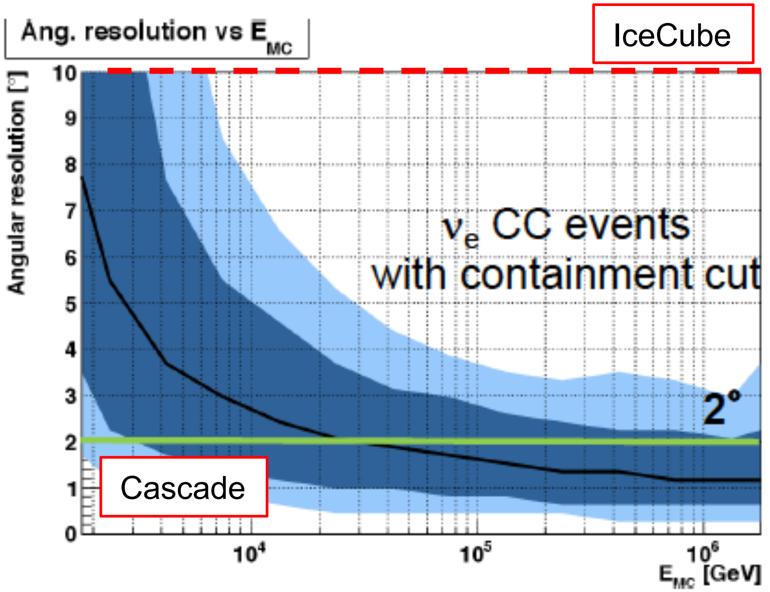
Angular resolution

- scattering length of water ~80m (ice ~20m)
- significantly better angular resolution than IceCube

→ good to find point sources



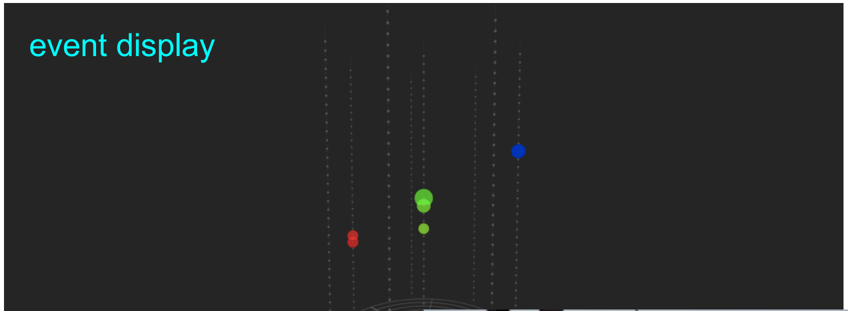


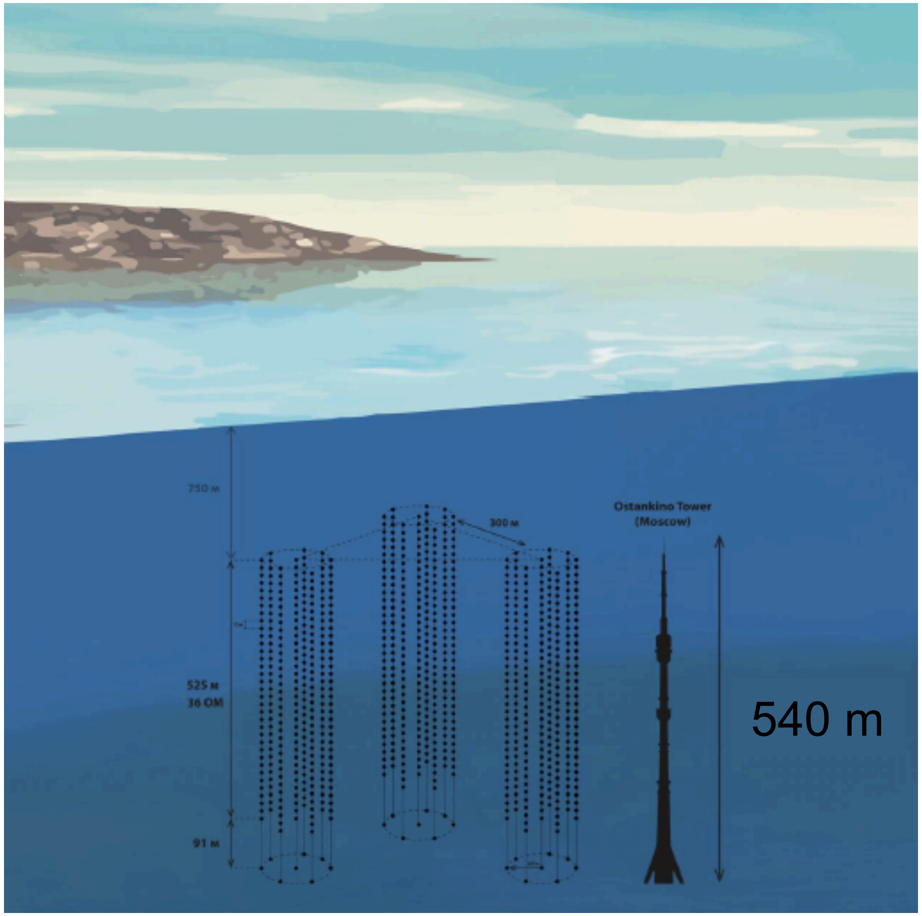
Baikal-GVD, ArXiv:1808.10353

3. Lake Baikal → GVD

GVD (Gigaton Volume Detector)

- 2 cubic km volume coverage by ~10,000 optical modules (OMs)
- 1 cluster = 8 strings with 36 OMs per string
- 5 clusters installed

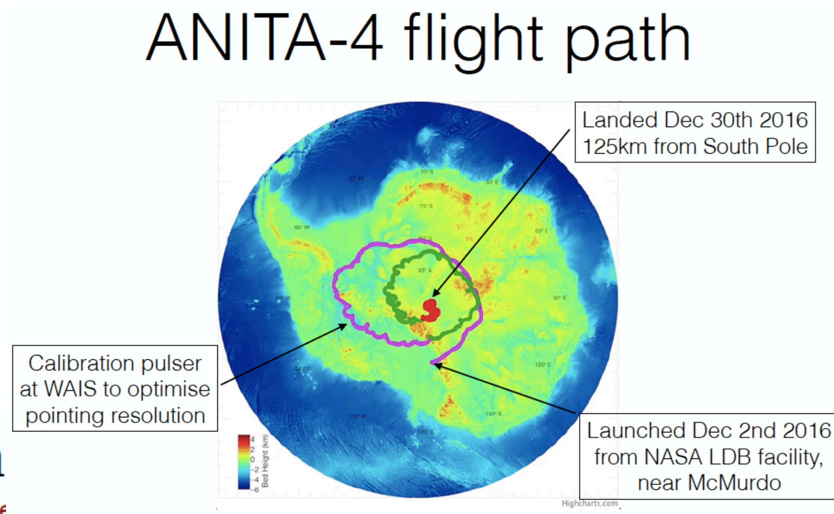




Linda Cremonesi (2018)

3. ANITA

Detector volume = entire Antarctic ice-sheet



ANITA-4 flight path

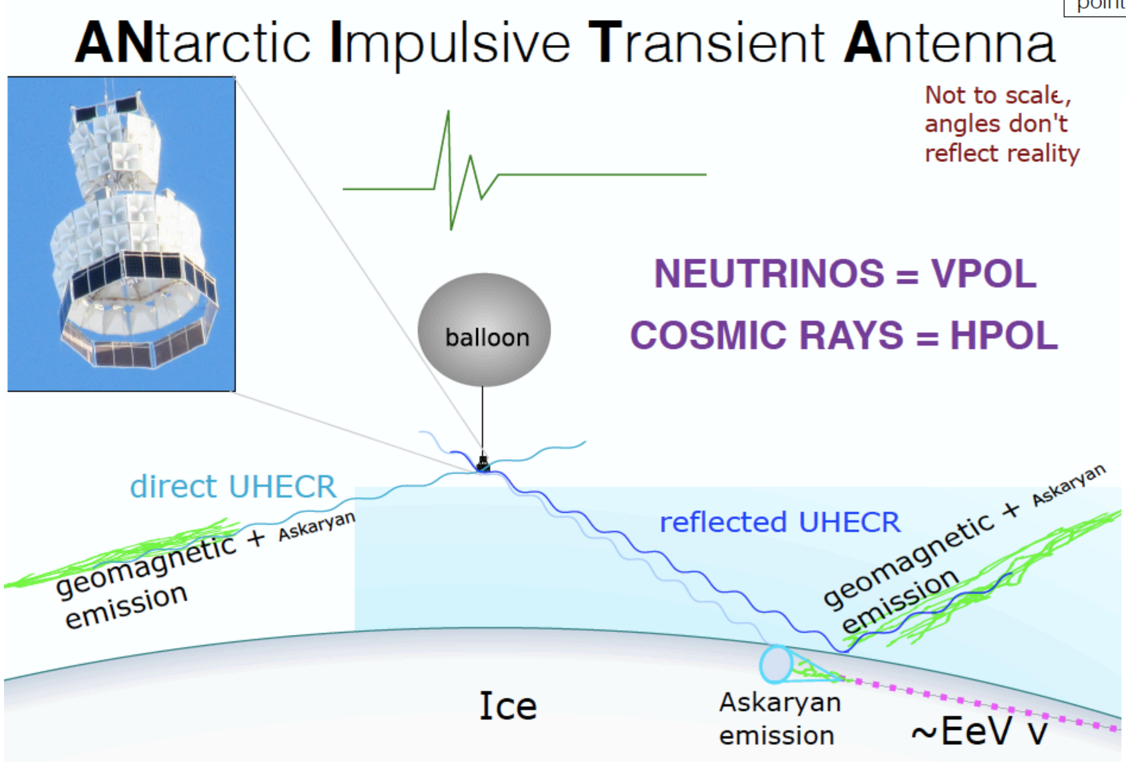
Landed Dec 30th 2016
125km from South Pole

Calibration pulser
at WAIS to optimise
pointing resolution

Launched Dec 2nd 2016
from NASA LDB facility,
near McMurdo

Askaryan radiation (~Cherenkov radiation)

- radio emission from E&M shower in dielectric
- effective to measure EeV range astrophysical neutrinos
- Antennas balloon, in ice, on ice, etc
- GZK neutrinos (EeV neutrinos) not discovered yet

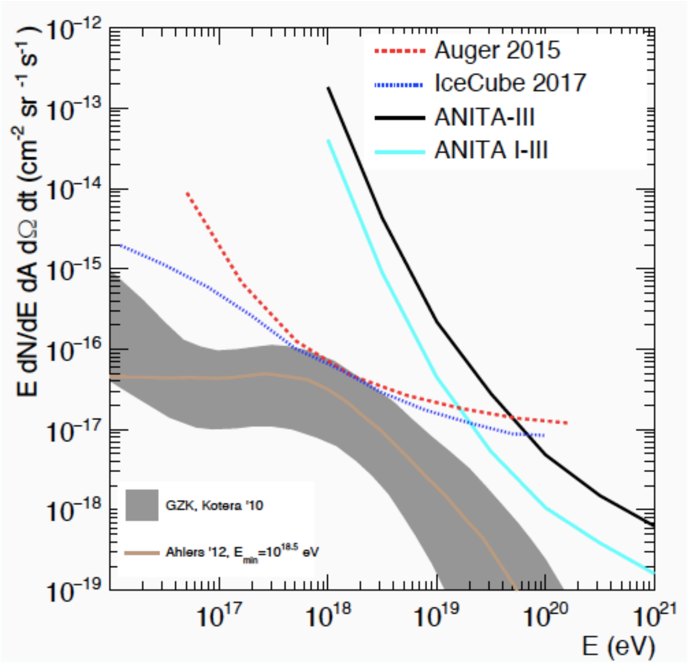


ANtarctic **I**mpulsive **T**ransient **A**ntenna

Not to scale,
angles don't
reflect reality

NEUTRINOS = VPOL

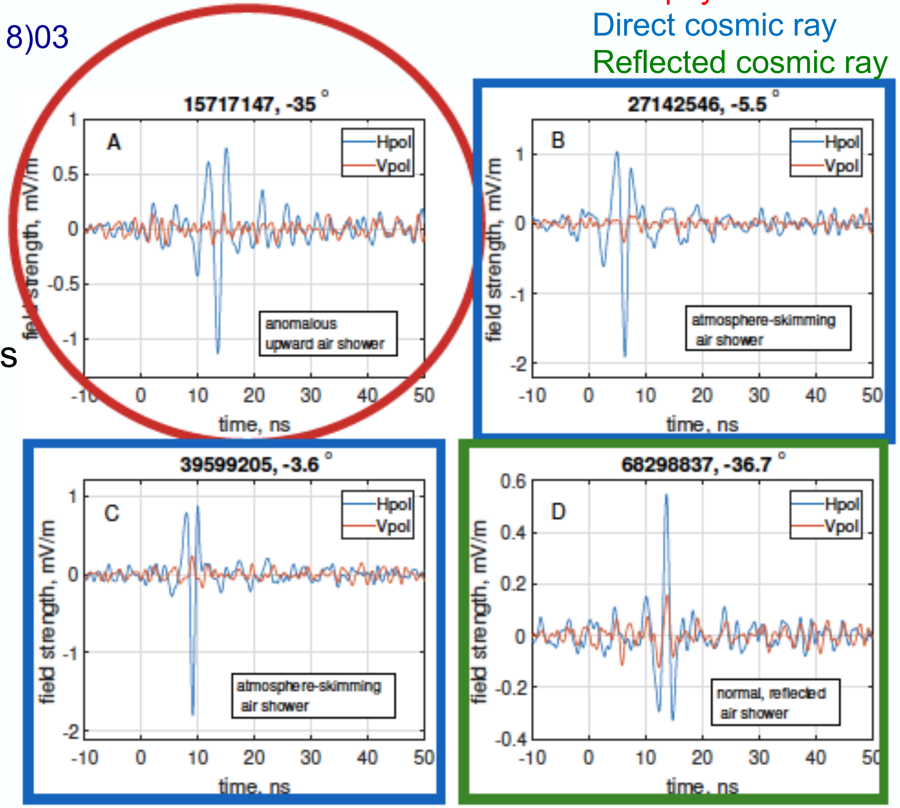
COSMIC RAYS = HPOL



Linda Cremonesi (2018)
ANITA, PRL121(2018)161102 (2018), Anchordoqui et al, LHEP01(2018)03

3. ANITA

New physics?
Direct cosmic ray
Reflected cosmic ray



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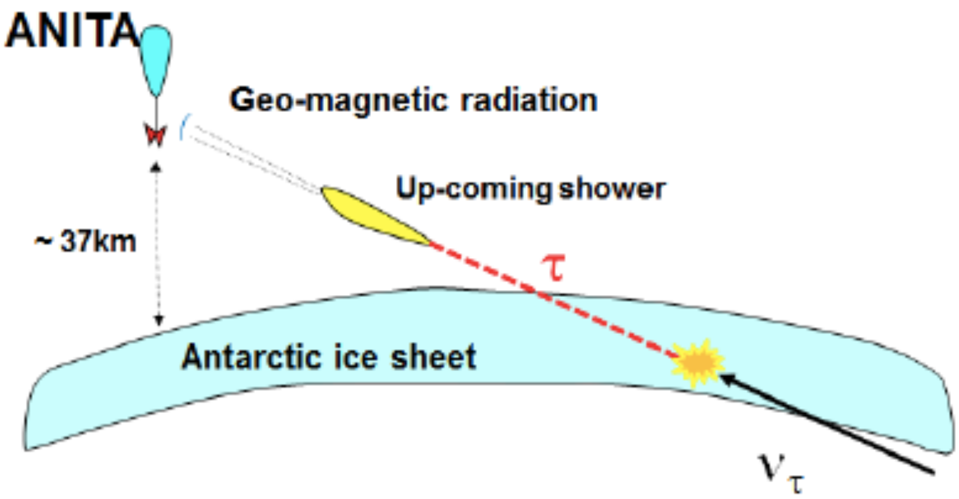
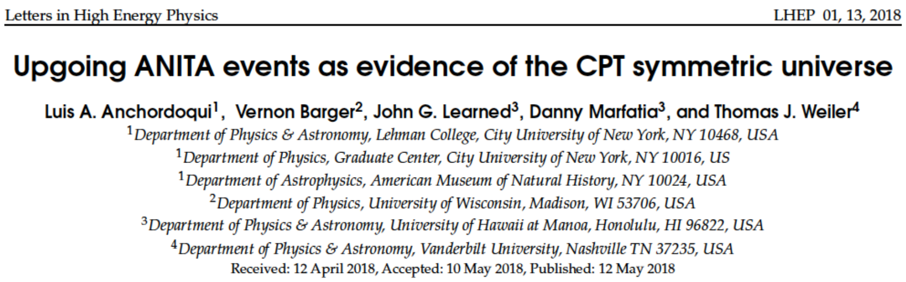
Unusual ultra-high-energy neutrino signal?

- 0.5 EeV τ-neutrino from the bottom
- EeV neutrino cannot penetrate such long distance
- new physics?



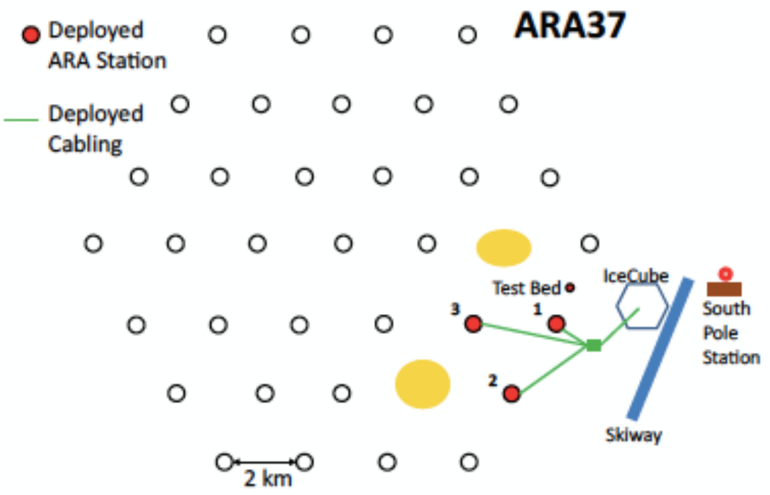

Letters in High Energy Physics LHEP 01, 13, 2018

Upgoing ANITA events as evidence of the CPT symmetric universe

Luis A. Anchordoqui[1], Vernon Barger[2], John G. Learned[3], Danny Marfatia[3], and Thomas J. Weiler[4]
[1] Department of Physics & Astronomy, Lehman College, City University of New York, NY 10468, USA
[1] Department of Physics, Graduate Center, City University of New York, NY 10016, US
[1] Department of Astrophysics, American Museum of Natural History, NY 10024, USA
[2] Department of Physics, University of Wisconsin, Madison, WI 53706, USA
[3] Department of Physics & Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA
[4] Department of Physics & Astronomy, Vanderbilt University, Nashville TN 37235, USA
Received: 12 April 2018, Accepted: 10 May 2018, Published: 12 May 2018

ARA,PRD93(2016)082003

3.ARA, ARIANNA



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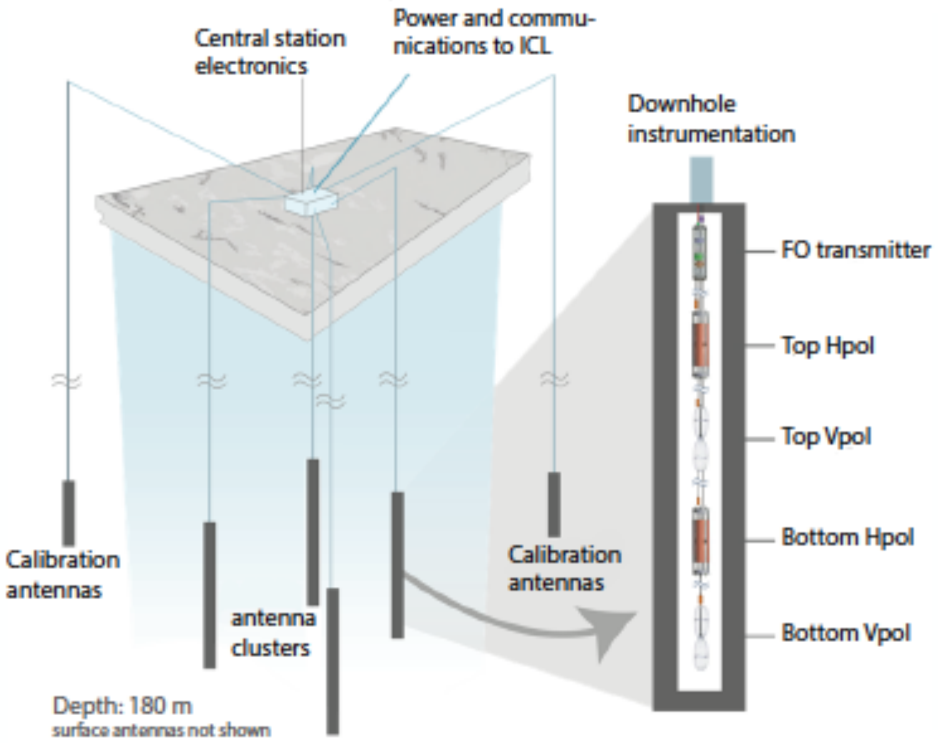
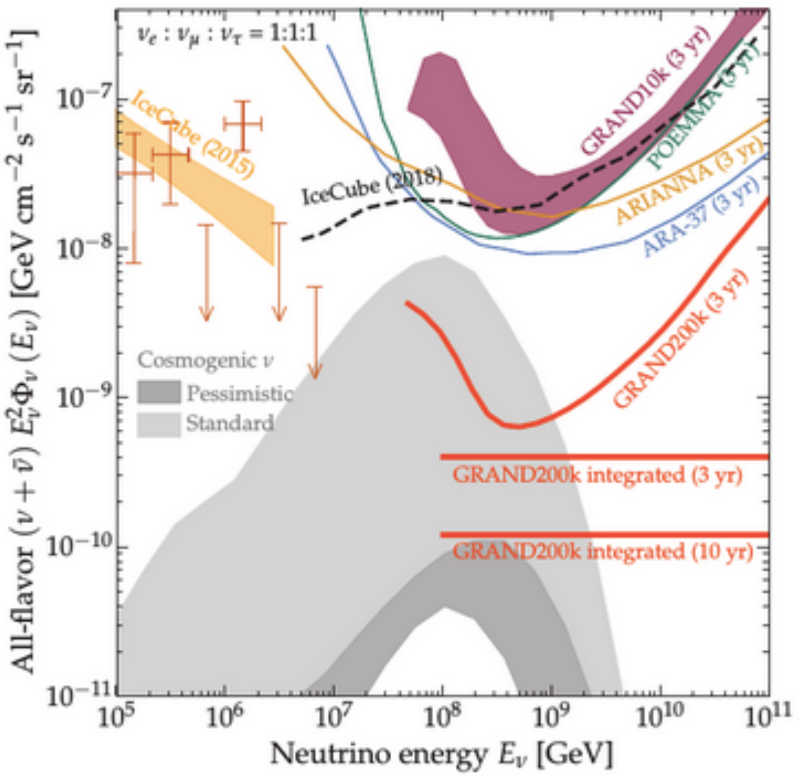


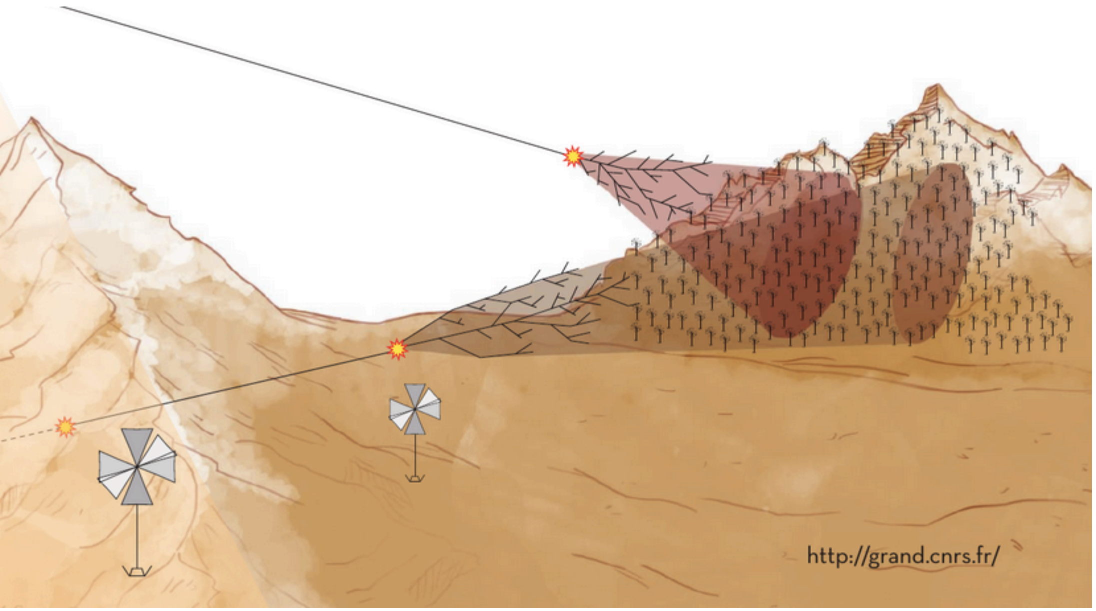


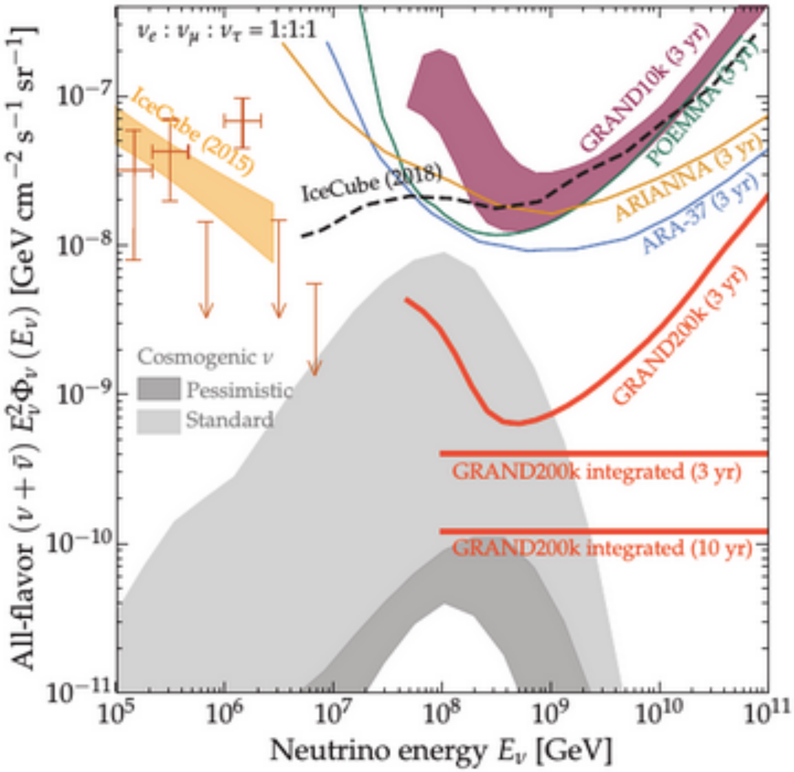
3. GRAND

Candidate site: Qinghai Province (青海省)

Giant Radio Array for Neutrino Detection

- Arrays of antennas to detect air shower radiation
- 200,000 antennas over 200,000km^2
- promising to detect GZK neutrinos
- horizontal tau neutrinos (“skimming tau”), special target

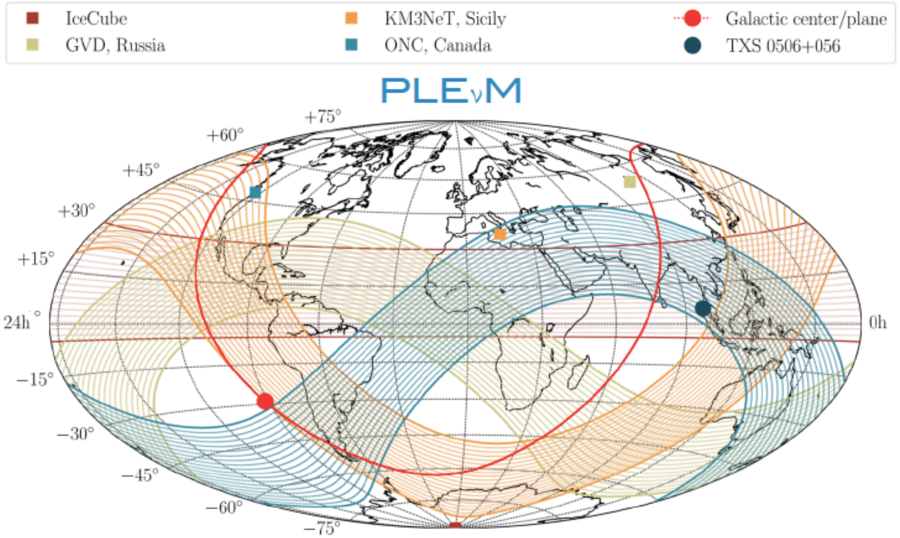


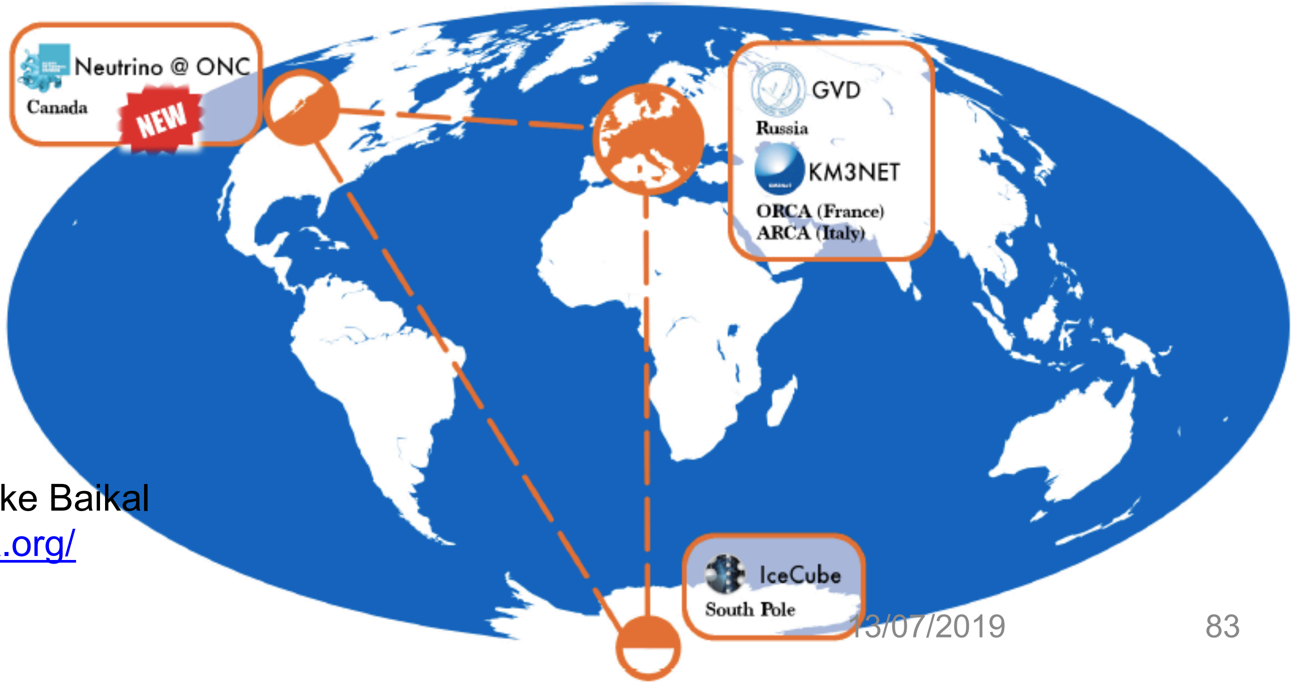


3. Global neutrino telescope network?

High-energy neutrinos cannot penetrate the Earth
→ We need a network to cover all sky

Pacific ocean is empty
→ Need a neutrino telescope near Vietnam or Japan





Global Neutrino Network
- IceCube, KM3NeT, Antares, Lake Baikal

http://www.globalneutrinonetwork.org/

Ellis et al., PLB 789 (2019) 352

3. Astrophysical neutrino time-of-flight

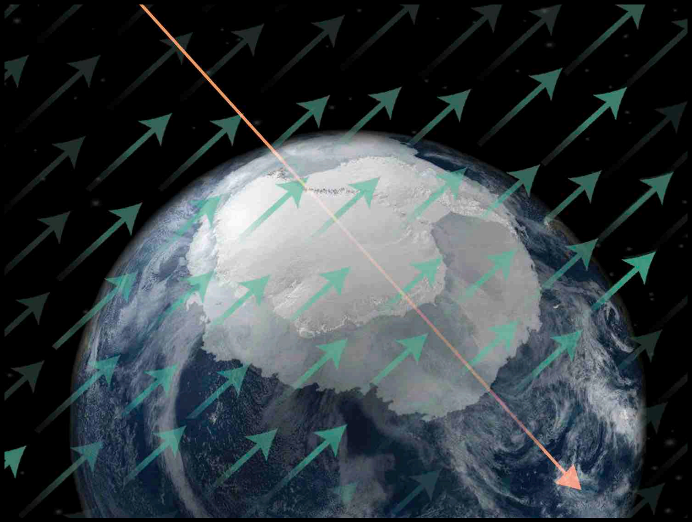
Quantum gravity ~ QFT+GR
- Quantum Field Thoery (QFT) → particle physics, microscopic scale
- General Relativity (GR) → gravity, large scale

Quantum gravity motivates new space-time structure
- ~10^{19} GeV (Planck energy), the energy of the Big Bang and no machines can replicate
- Quantum gravity effect may be suppressed with inverse of Planck scale
  - $(10^{19}\ \mathrm{GeV})^{-1}$ = dimension-5 operator (cf. neutrino mass term)
  - $(10^{19}\ \mathrm{GeV})^{-2}$ = dimension-6 operator (cf. Fermi coupling)

New physics is often higher-dimension operators of the SM

quantum foam
- quantum fluctuation of space time

Lorentz violating field
- new field saturating the universe (aether)



Ellis et al., PLB 789 (2019) 352

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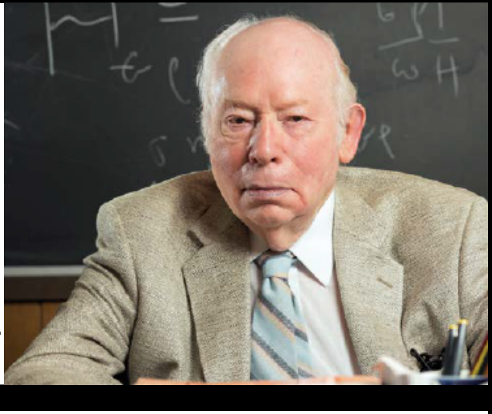
New physics is often higher-dimension operators of the SM

"In a sense it is beyond the SM, but I would rather say it is beyond the leading terms – the renormalisable, unsuppressed part of the SM. But hell – so is gravity! The symmetries of general relativity don't allow any renormalisable interactions of massless spin-2 particles called gravitons."
Steve Weinberg (CERN Courier, Nov 2017)
https://home.cern/resources/courier/physics/cern-courier-november-2017



Search of higher dimension operator is a reasonable approach to look for new physics, or gravity effect in particle physics

Ellis et al., PLB 789 (2019) 352, Huang, Ma, Comm. Phys.1:62(2018)

3. Astrophysical neutrino time-of-flight

Modified dispersion

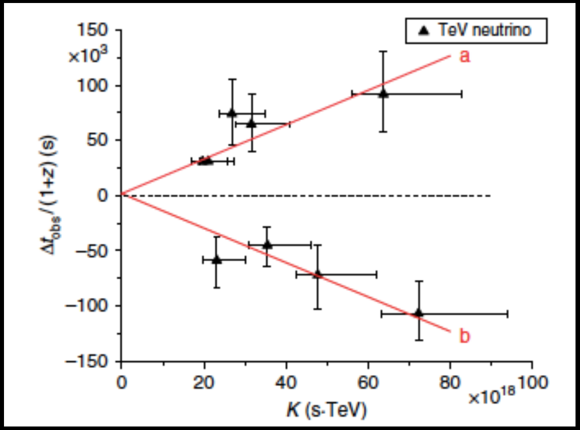
- Fuzzy quantum gravity space-time may speed up or slow down neutrinos

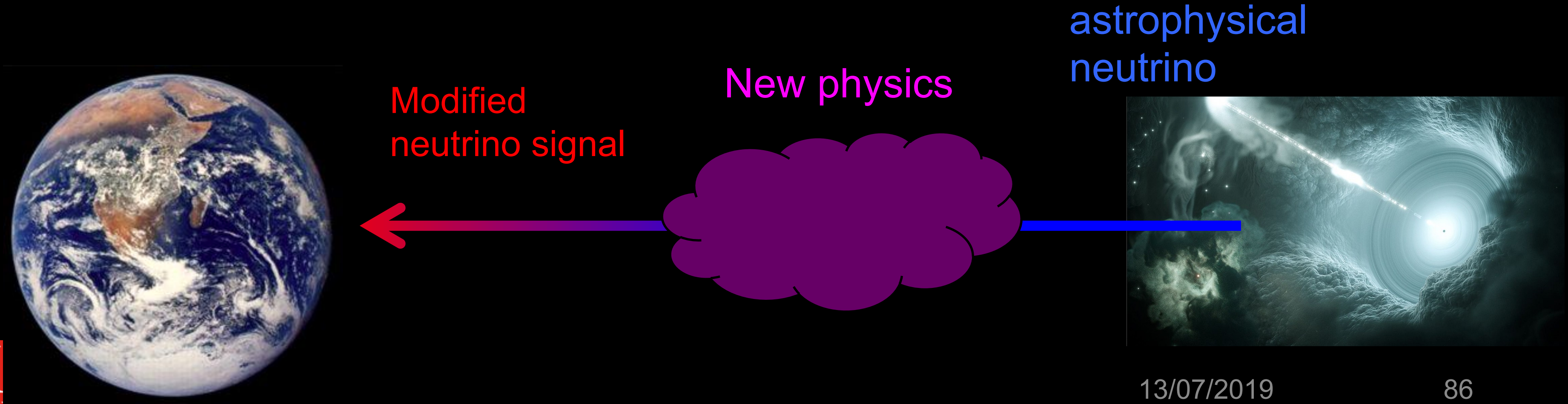
$$v_g \sim 1 \pm \frac{E}{M_1}$$

- From the distance of TXS0506+056 (1.3 Gpc), energy of astrophysical neutrinos (>200 TeV), and time delay (~10 days),quantum fluctuation of space-time is investigated up to $M_1 \sim 10^{16}$ GeV

Assuming quantum gravity neutrino and GRB data have better match(?!)

We need more astrophysical neutrino data to confirm these exciting ideas!





astrophysical neutrino

New physics

Modified neutrino signal

3. Summary

TXS0506+056 is the first identified point source of high-energy astrophysical neutrinos
- Optical coincidence (time, location) is observed with IC170922A
- TXS0605+056 is the 3rd point source of astrophysical neutrinos (Sun, SN1987A)
- Currently, we do not know if TXS0506+056 is a special blazar or not

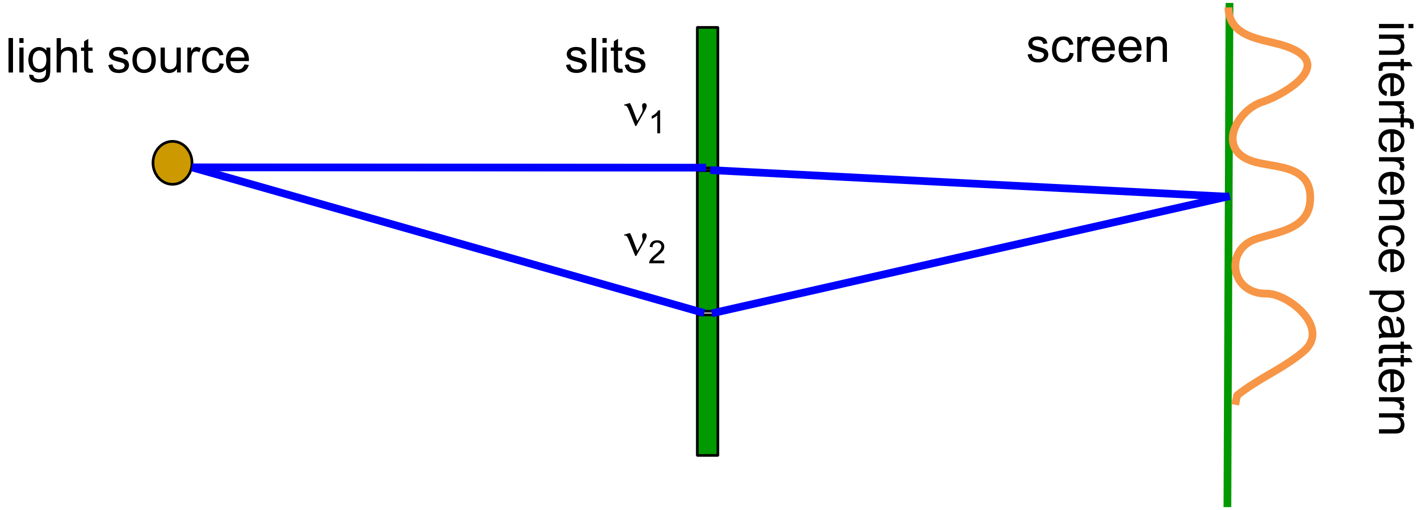
Point source of

More astrophysical high-energy neutrinos can be detected by other gigantic detectors
- IceCube-Gen2 (ice Cherenkov)
- KM3NeT, GVD (water Cherenkov)
- ANITA, ARA, ARIANNA, GRAND, etc (radio array)

1. Cosmic Ray and Astroparticle Physics
2. High-Energy Neutrino Observations
3. Neutrino Multi-Messenger Astronomy
4. **Astrophysical Neutrino Flavour Physics**

4. Neutrino oscillations

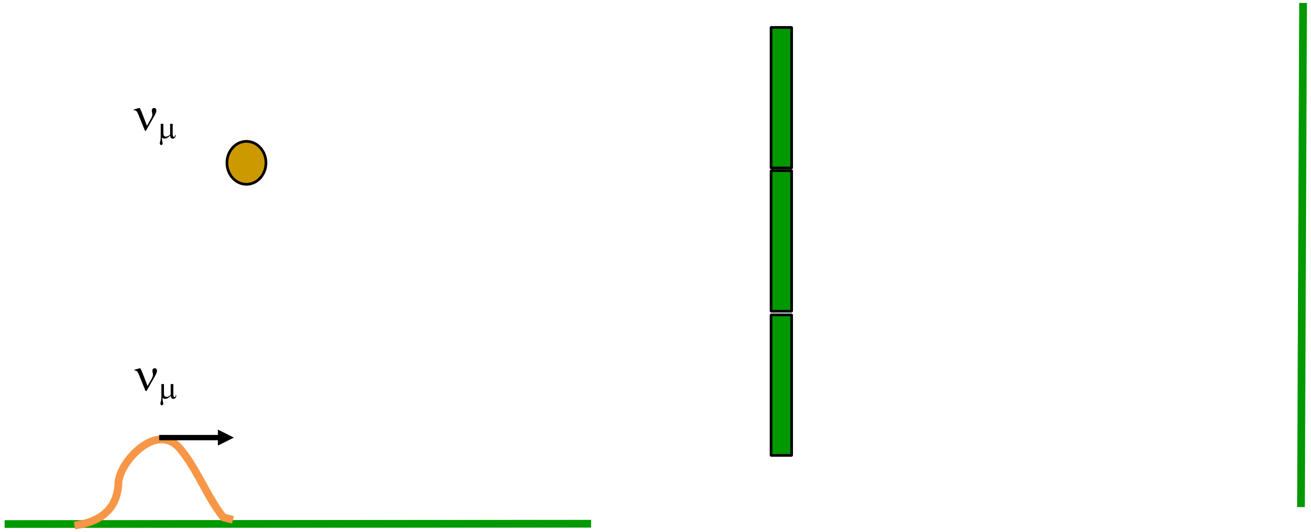
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

4. Neutrino oscillations

Neutrino oscillation is an interference experiment (cf. double slit experiment)



If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

4. Neutrino oscillations

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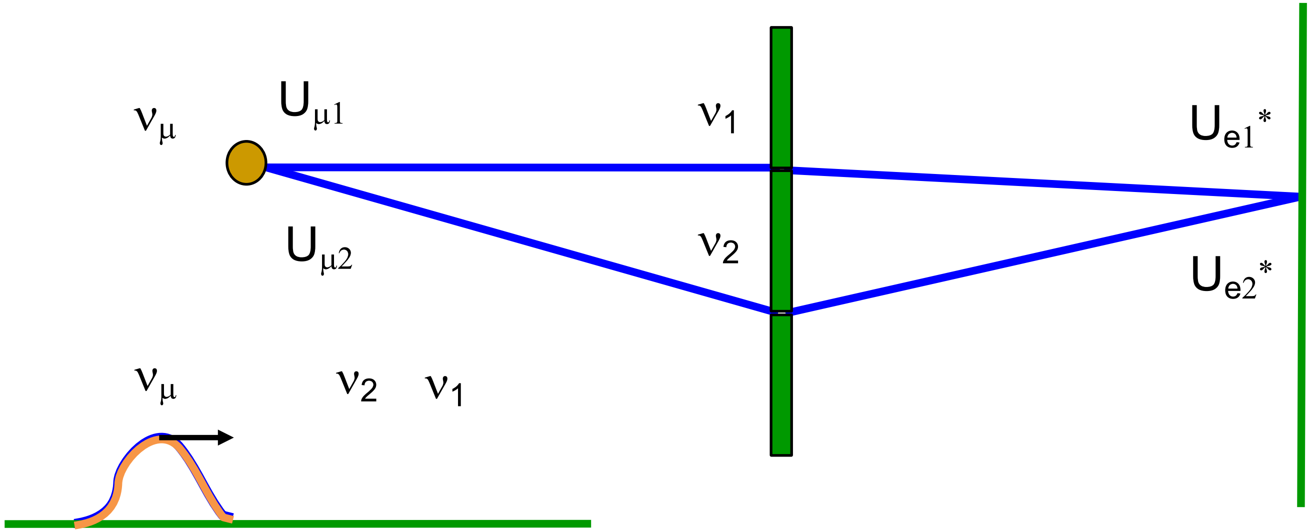

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If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

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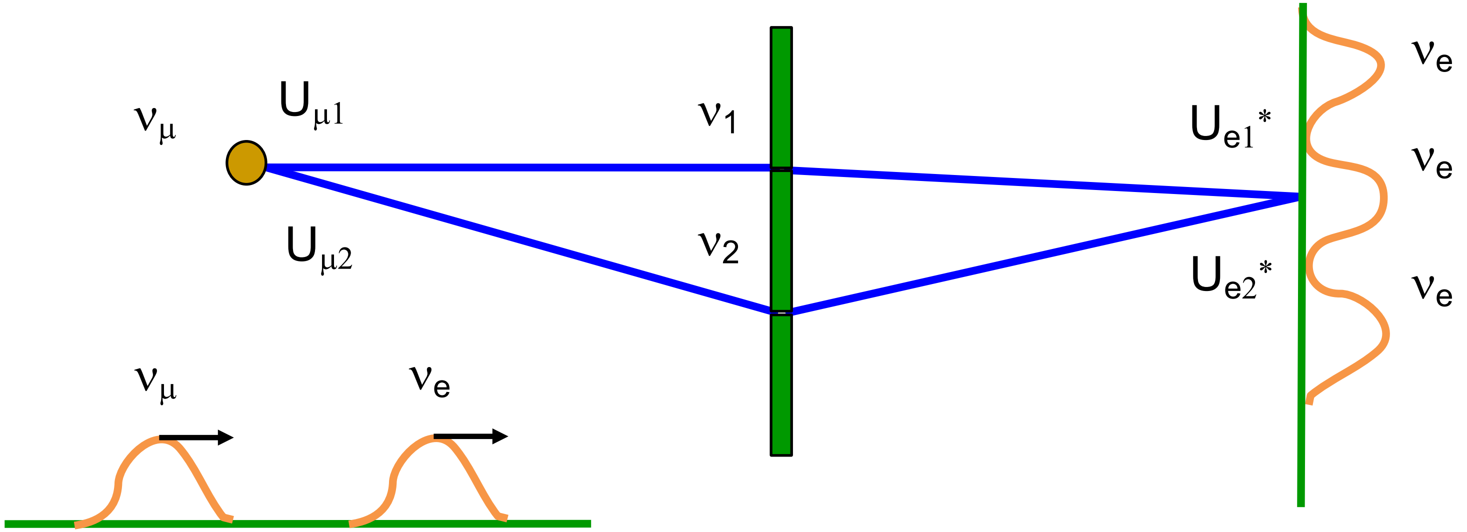
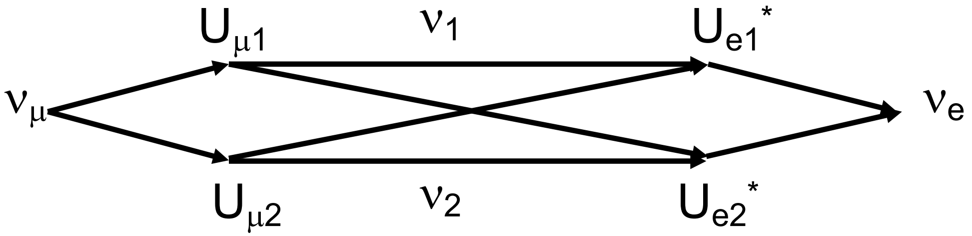


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation. The detection may be different flavour (neutrino oscillations).

4. Neutrino oscillations



2 neutrino mixing

The neutrino weak interaction eigenstate (flavour eigenstate) is described by neutrino Hamiltonian eigenstates, ν_1 and ν_2, and their mixing matrix elements.

$$|\nu_\mu\rangle = U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle$$

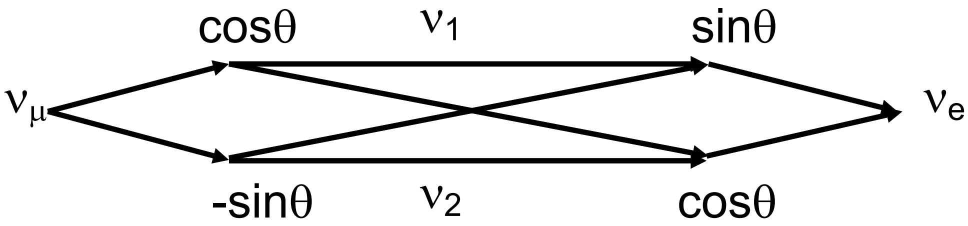
The time evolution of flavour eigenstate is written by Hamiltonian mixing matrix elements and eigenvalues of ν_1 and ν_2 .

$$|\nu_\mu(t)\rangle = U_{\mu 1}e^{-i\lambda_1 t}|\nu_1\rangle + U_{\mu 2}e^{-i\lambda_2 t}|\nu_2\rangle$$

Then the transition probability from weak eigenstate ν_μ to ν_e is,

$$P_{\mu\to e}(t) = \left|\langle\nu_e|\nu_\mu(t)\rangle\right|^2 = -4U_{e1}^* U_{e2}^* U_{\mu 1}U_{\mu 2}sin^2\left(\frac{\lambda_1-\lambda_2}{2}t\right)$$

4. Neutrino oscillations



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In the vacuum, 2 neutrino effective Hamiltonian has a mass term,

$$H_{eff}\sim\begin{pmatrix}\frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E}\\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E}\end{pmatrix} = \begin{pmatrix}cos\theta & -sin\theta\\ sin\theta & cos\theta\end{pmatrix}\begin{pmatrix}\frac{m_1^2}{2E} & 0\\ 0 & \frac{m_2^2}{2E}\end{pmatrix}\begin{pmatrix}cos\theta & sin\theta\\ -sin\theta & cos\theta\end{pmatrix}$$

Therefore, 2 massive neutrino oscillation model is ($\Delta m^2=|m_1^2-m_2^2|$, t~L)

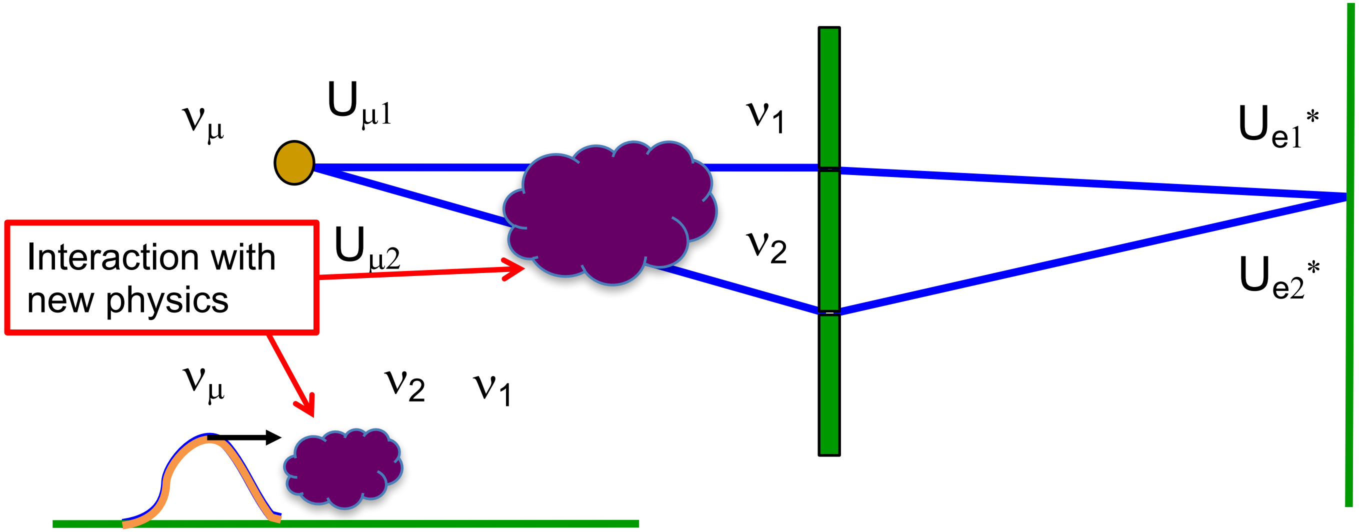
$$P_{\mu\to e}(L/E) = sin^2 2\theta sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

After adjusting the unit, 2 neutrino oscillation formula

$$P_{\mu\to e}(L/E) = sin^2 2\theta sin\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

4. Neutrino interferometry as a probe of new physics

Neutrino oscillation is an interference experiment (cf. double slit experiment)



If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation. The detection may be different flavour (neutrino oscillations).

Any BSM physics coupling to neutrinos can contribute the phase shift of neutrino oscillation, and it appears as anomalous flavour structure of neutrinos.

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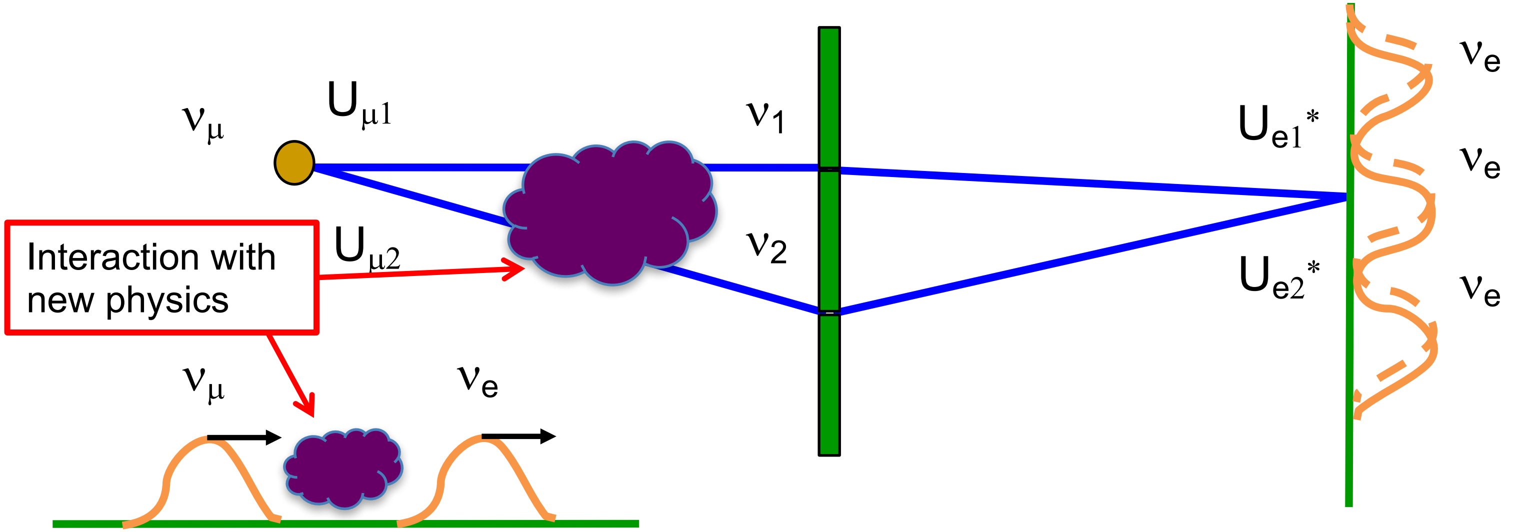

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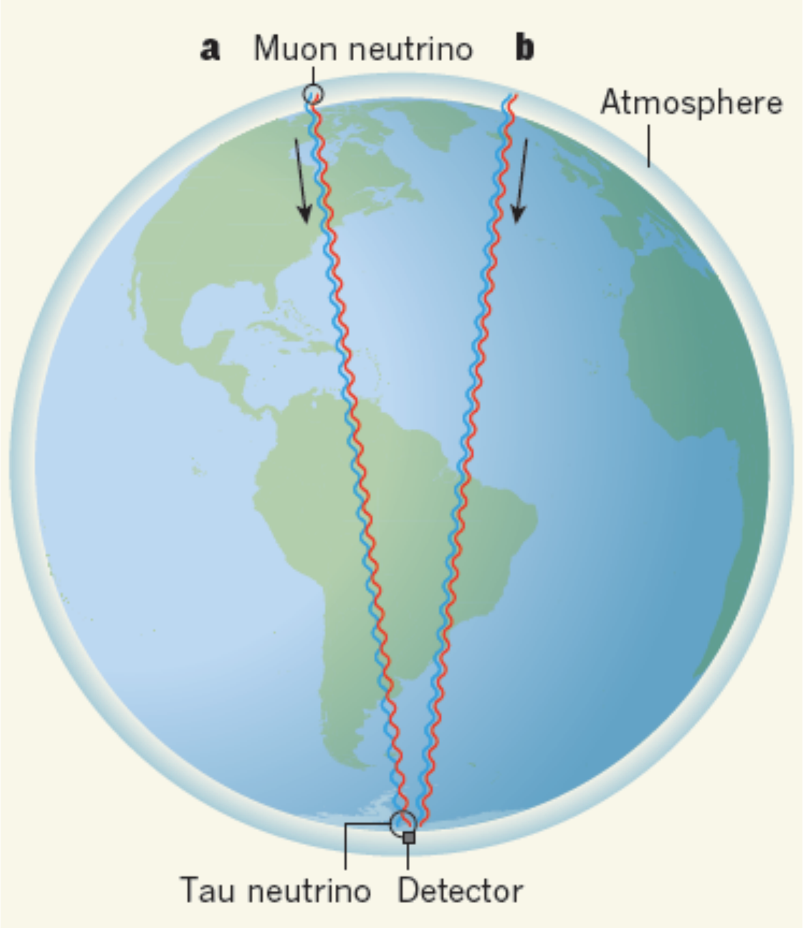
longer baseline and higher energy means better neutrino interferometer

IceCube, Nature Physics 14 (2018) 961
Mewes, Nature 560 (2018) 316

4. Neutrino interferometry with atmospheric neutrinos



The biggest interferometer on the Earth is the size of Earth diameter (12700km, cf. LIGO~4km)

The highest-energy terrestrial particles are atmospheric neutrinos (up to ~20 TeV)

Using atmospheric neutrinos produced on other side of the Earth, we can test violation of Lorentz invariance with the highest precision.

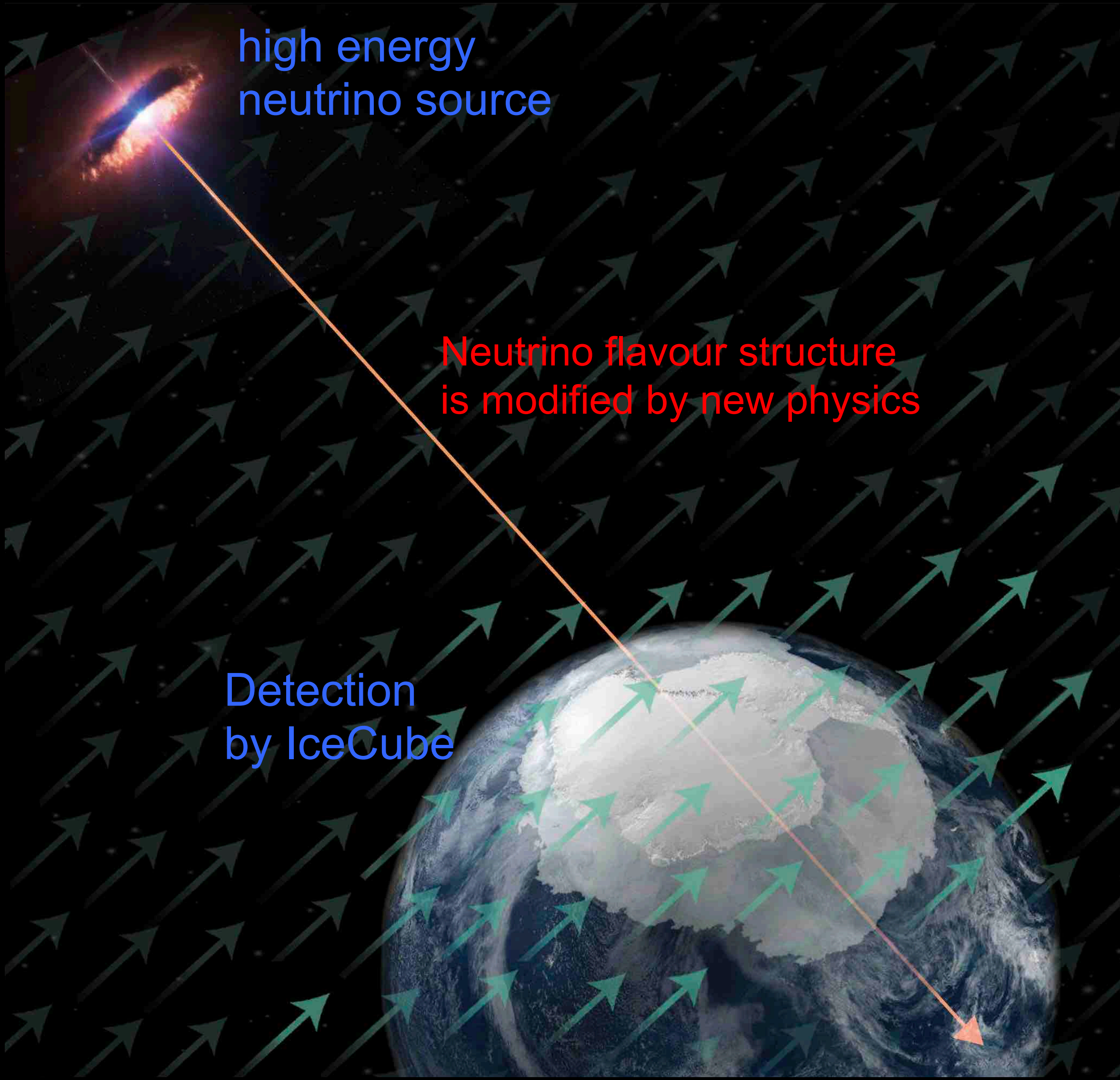
There is no anomalous neutrino oscillation, Lorentz invariance is valid with very high-precision
e.g.)
Dimension-4 new physics operator in vacuum < 10^{-28}
(~speed of neutrino deviation from c is order 10^{-28}, order 20 better than Michelson-Morley experiment)

What can be a better test? Astrophysical neutrinos!
- baseline: 12700km → 100Mpc
- energy: 20TeV → 1 PeV

4. Neutrino interferometry with astrophysical neutrinos

Neutrinos are produced, and detected with flavour eigenstates. However, the propagation is Hamiltonian eigenstates. Thus neutrinos make a natural interferometric system.

Combination of longer baseline and higher energy makes astrophysical neutrinos to be extremely sensitive tool to look for tiny space-time effects.



4. Neutrino interferometry with astrophysical neutrinos

Quantum gravity ~ QFT+GR
- Quantum Field Thoery (QFT) → particle physics, microscopic scale
- General Relativity (GR) → gravity, large scale

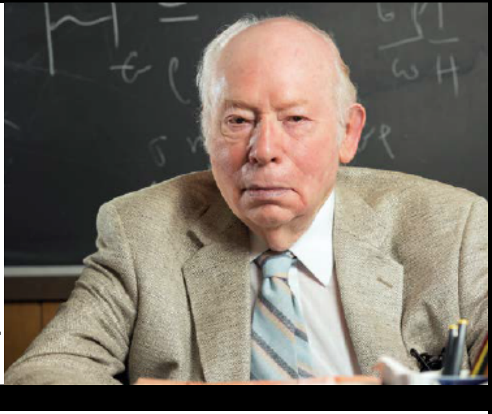
Quantum gravity motivates new space-time structure
- ~10^{19} GeV (Planck energy), the energy of the Big Bang and no machines can replicate
- Quantum gravity effect may be suppressed with inverse of Planck scale
  - $(10^{19}\ \text{GeV})^{-1}$ = dimension-5 operator (cf. neutrino mass term)
  - $(10^{19}\ \text{GeV})^{-2}$ = dimension-6 operator (cf. Fermi coupling)

New physics is often higher-dimension operators of the SM

"In a sense it is beyond the SM, but I would rather say it is beyond the leading terms – the renormalisable, unsuppressed part of the SM," says Weinberg. "But hell – so is gravity! The symmetries of general relativity don't allow any renormalisable interactions of massless spin-2 particles called gravitons.

Steve Weinberg (CERN Courier, Nov 2017)

https://home.cern/resources/courier/physics/cern-courier-november-2017



Search of higher dimension operator is a reasonable approach to look for new physics, or gravity effect in particle physics

4. Neutrino oscillation and neutrino mixing

Any arbitrary 3x3 effective Hamiltonian can be diagonalized with mixing matrix V

$$h_{eff} \sim V^{\dagger} D V, D = diag(\lambda_1, \lambda_2, \lambda_3)$$

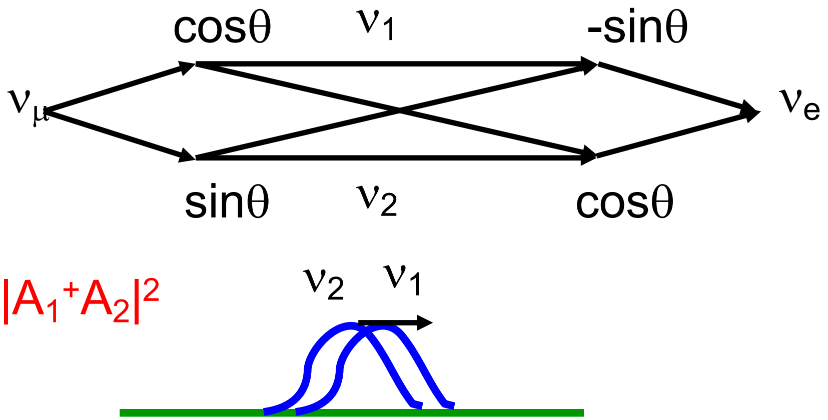
Neutrino oscillation formula is written with mixing matrix elements and eigenvalues

$$P_{\alpha\to\beta}(E,L) = 1 - 4\sum_{i>j} Re\left(V_{\alpha i}^* V_{\beta i}^* V_{\alpha j} V_{\beta j}\right) sin^2\left(\frac{\lambda_i - \lambda_j}{2} L\right) + 2\sum_{i>j} Im\left(V_{\alpha i}^* V_{\beta i}^* V_{\alpha j} V_{\beta j}\right) sin\left((\lambda_i - \lambda_j)L\right)$$

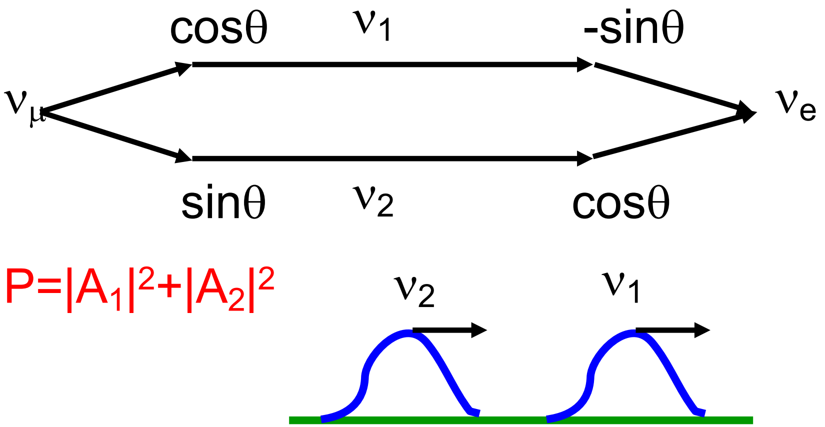
However, if neutrinos propagate long distance, they lose coherence and don’t oscillate

$$P_{\alpha\to\beta}(E,\infty) \sim 1 - 2\sum_{i>j} Re\left(V_{\alpha i}^* V_{\beta i}^* V_{\alpha j} V_{\beta j}\right) = \sum_i |V_{\alpha i}|^2 |V_{\beta i}|^2$$

This is called time-averaged oscillation, or neutrino mixing



P=|A1+A2|2



P=|A1|2+|A2|2

4. Neutrino oscillation and neutrino mixing

2 neutrino oscillation formula is

$$P_{\mu\rightarrow e}(L/E) = sin^2 2\theta sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

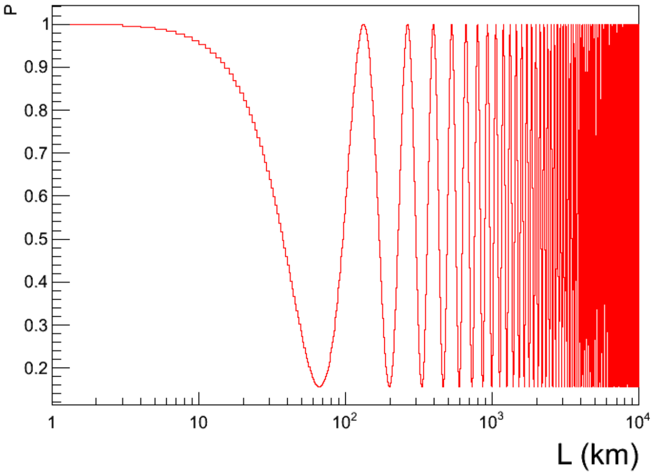
If the oscillation is really fast, time-averaged oscillation is

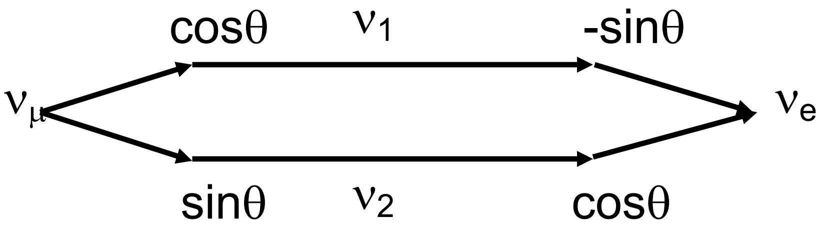
$$P_{\mu\rightarrow e}(L/E) = \frac{1}{2} sin^2 2\theta$$

On the other hand, if 2 paths are incoherent, transition probability is a incoherent sum of 2 amplitudes

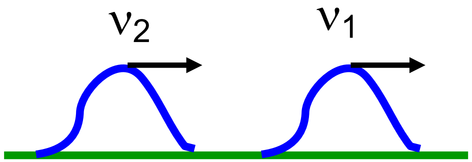
$$P_{\mu\rightarrow e}(L/E) = |A_1|^2 + |A_1|^2 = 2cos^2\theta sin^2\theta = \frac{1}{2} sin^2 2\theta$$

Thus, time-averaged oscillation is the incoherent neutrino mixing





$P=|A_1|^2+|A_2|^2$



Smirnov, arXiv:1609.02386

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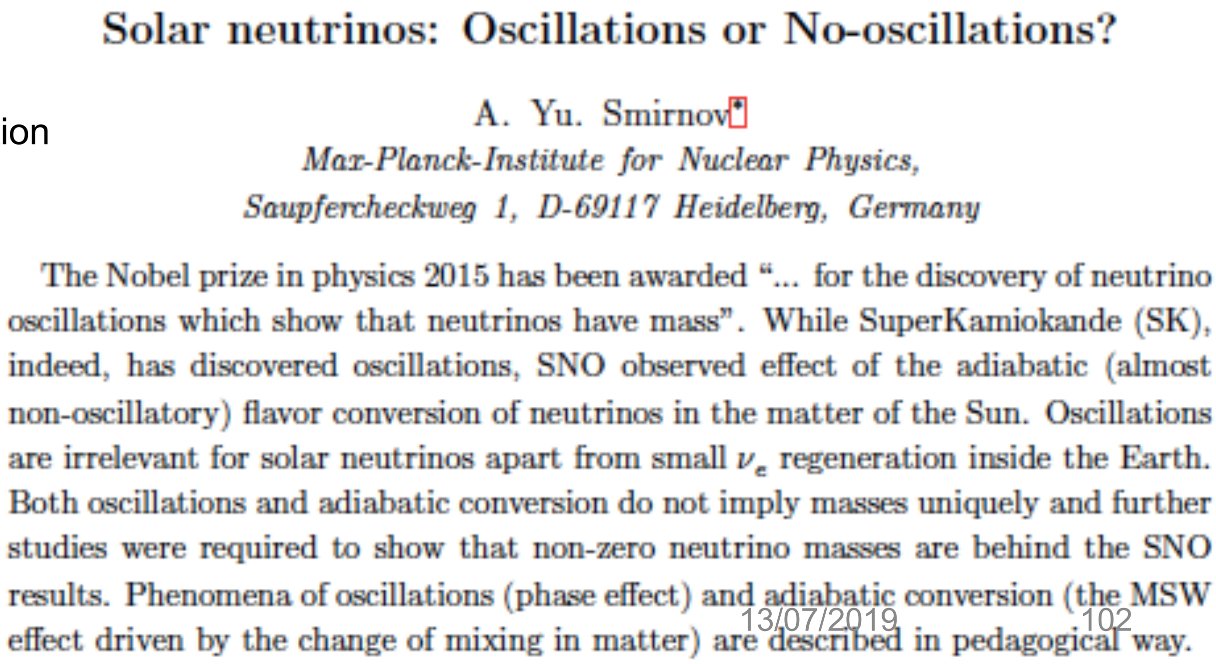
Thus, time-averaged oscillation is the incoherent neutrino mixing

Atmospheric neutrino = neutrino oscillation
Solar neutrino = neutrino mixing

Astrophysical neutrinos (O(100 Mpc) propagation) do not oscillate, but mix
→ phase information is washed out



Solar neutrinos: Oscillations or No-oscillations?

A. Yu. Smirnov*
Max-Planck-Institute for Nuclear Physics,
Saupfercheckweg 1, D-69117 Heidelberg, Germany

The Nobel prize in physics 2015 has been awarded "... for the discovery of neutrino oscillations which show that neutrinos have mass". While SuperKamiokande (SK), indeed, has discovered oscillations, SNO observed effect of the adiabatic (almost non-oscillatory) flavor conversion of neutrinos in the matter of the Sun. Oscillations are irrelevant for solar neutrinos apart from small ν_e regeneration inside the Earth. Both oscillations and adiabatic conversion do not imply masses uniquely and further studies were required to show that non-zero neutrino masses are behind the SNO results. Phenomena of oscillations (phase effect) and adiabatic conversion (the MSW effect driven by the change of mixing in matter) are described in pedagogical way.

Kostelecký and Mewes, PRD85(2012)096005

4. Astrophysical neutrino flavour with Lorentz violation

We introduce effective operators motivated by SME formalism (effective field theory)

$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + a^{(3)}_{\alpha\beta} - E c^{(4)}_{\alpha\beta} + E^2 a^{(5)}_{\alpha\beta} - E^3 c^{(6)}_{\alpha\beta} + E^4 a^{(7)}_{\alpha\beta} - E^5 c^{(8)}_{\alpha\beta} \cdots$$

Astrophysical neutrinos mixing can be written under this effective Hamiltonian

$$P_{\alpha\rightarrow\beta}(E,\infty) \sim 1 - 2 \sum_{i>j} Re\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) = \sum_{i} |V_{\alpha i}|^2 \left|V_{\beta i}\right|^2$$

→ Information of small new physics is encoded on neutrino mixing probability, so by measuring astrophysical neutrino flavours, you can access potential new physics

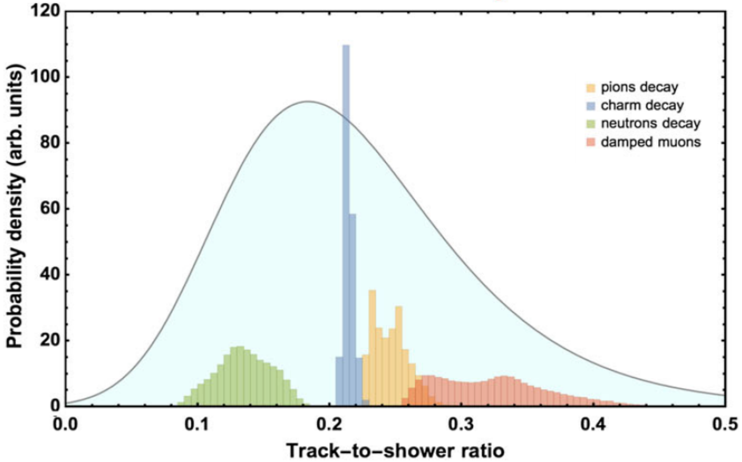
By using effective operator approach, IceCube can perform generic new physics search (we will discuss the interpretation of these new terms later)

IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

4. Astrophysical High-Energy Neutrinos

Palladino et al,PRL114(2015)171101

$$N_S = 8.4F_e + 0.9F_\mu + 6.3F_\tau, \qquad N_T = 3.7F_\mu.$$



First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)
- From both southern and northern sky
- Spectrum, no good fit
- Shower topology is dominant
- Production flavour structure unknown

Naively
- Any astrophysical HE neutrino production flavour makes roughly $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$ on the earth
- At very high energy, $\sigma(CC) \sim 3\sigma(NC)$
- Track : Shower ~ 1 : 3 ($N_T/N_S \sim 0.33$)

Data
- $N_T/N_S \sim 0.3$ → any production models are compatible with data

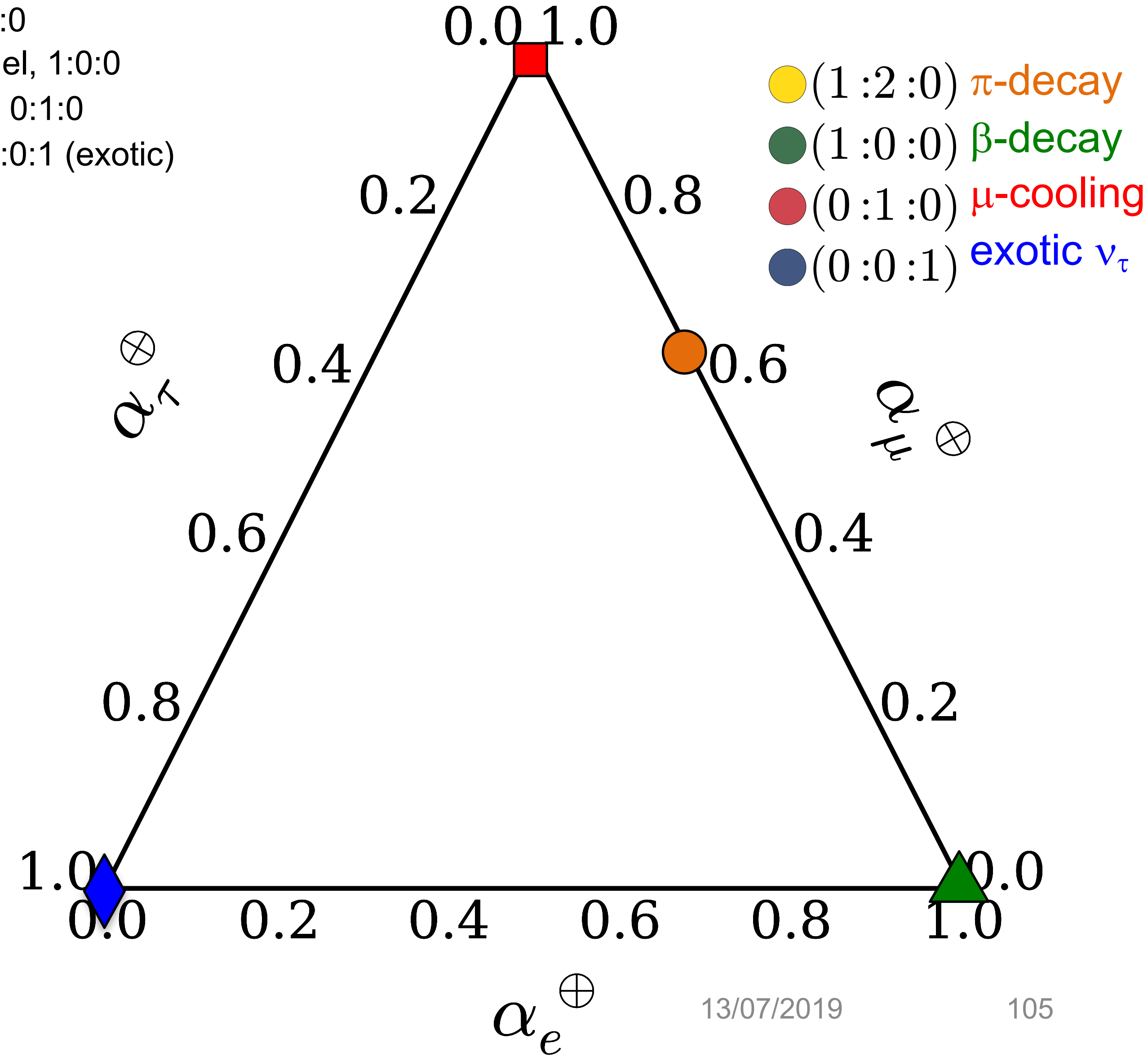
Physics of astrophysical neutrino flavor is interesting (Sec. 4)

8	$32.6^{+10.3}_{-11.1}$	Track
9	$63.2^{+7.1}_{-8.0}$	Shower
10	$97.2^{+10.4}_{-12.4}$	Shower
11	$88.4^{+12.5}_{-10.7}$	Shower
12	104^{+13}_{-13}	Shower
13	253^{+26}_{-22}	Track
14	1041^{+132}_{-144}	Shower
15	$57.5^{+8.3}_{-7.8}$	Shower
16	$30.6^{+3.6}_{-3.5}$	Shower
17	200^{+27}_{-27}	Shower
18	$31.5^{+4.6}_{-3.3}$	Track
19	$71.5^{+7.0}_{-7.2}$	Shower
20	1141^{+143}_{-133}	Shower
21	$30.2^{+3.5}_{-3.3}$	Shower
22	220^{+21}_{-24}	Shower
23	$82.2^{+8.6}_{-8.4}$	Track
24	$30.5^{+3.2}_{-2.6}$	Shower
25	$33.5^{+4.9}_{-5.0}$	Shower
26	210^{+29}_{-26}	Shower
27	$60.2^{+5.6}_{-5.6}$	Shower
28	$46.1^{+5.7}_{-4.4}$	Track

4. Neutrino flavour ratio

There are 3 astrophysical neutrino production models

i. pion decay dominant model, 1:2:0
ii. electron neutrino dominant model, 1:0:0
iii. muon neutrino dominant model, 0:1:0
iv. tau neutrino dominant model, 0:0:1 (exotic)



Argüelles, TK, Salvado, PRL115(2015)161303

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1. pion decay dominant model, 1:2:0
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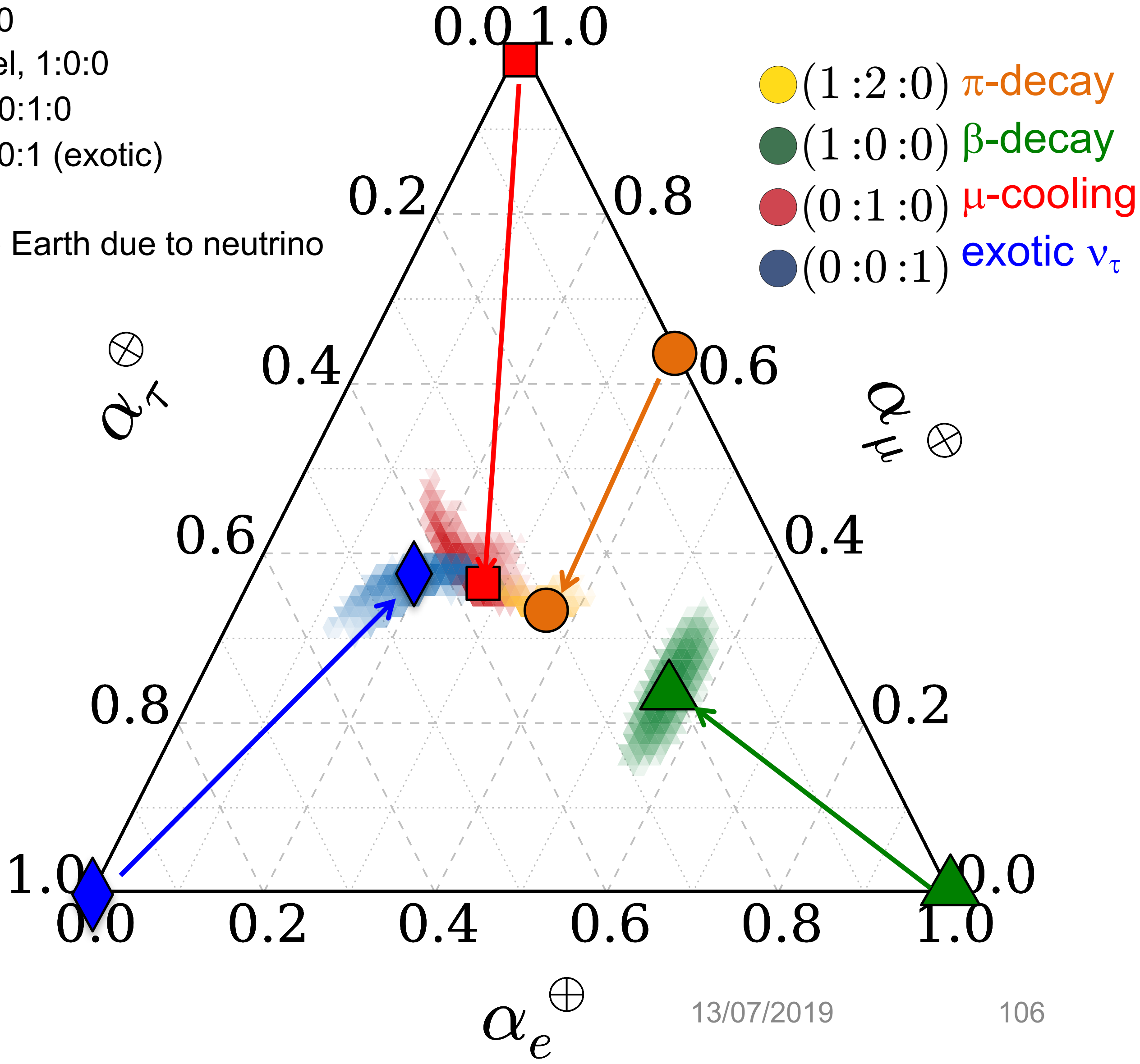
3. muon neutrino dominant model, 0:1:0
4. tau neutrino dominant model, 0:0:1 (exotic)

Initial flavour ratio is modified on the Earth due to neutrino mixing



Argüelles, TK, Salvado, PRL115(2015)161303

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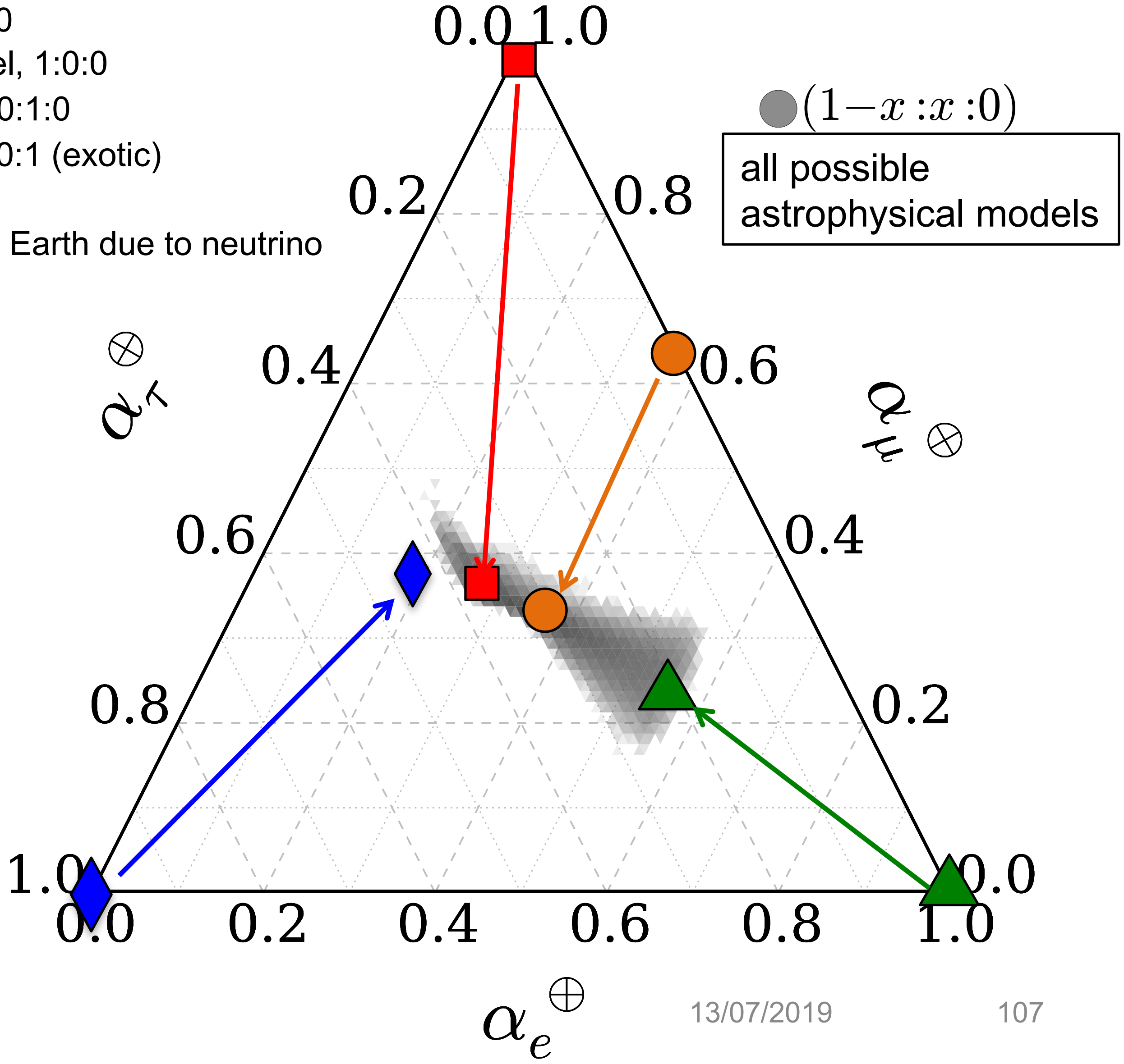
Initial flavour ratio is modified on the Earth due to neutrino mixing

Astrophysical neutrinos = hadronic (pion) process → (1:0:0) and (0:1:0) are too extreme astrophysical neutrino flavour models and all realistic models are between them

All possible flavour ratio is confined in a small space.



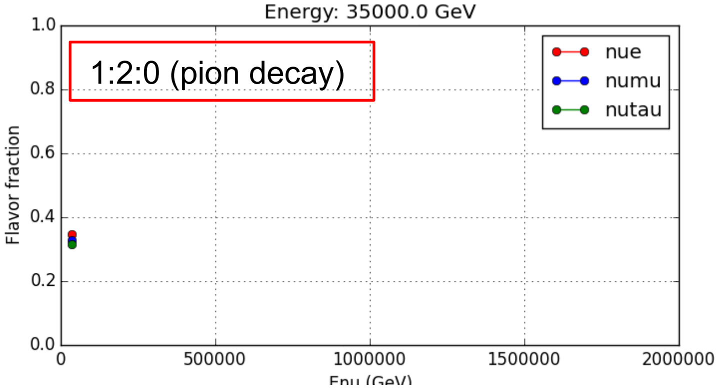
Argüelles, TK, Salvado, PRL115(2015)161303

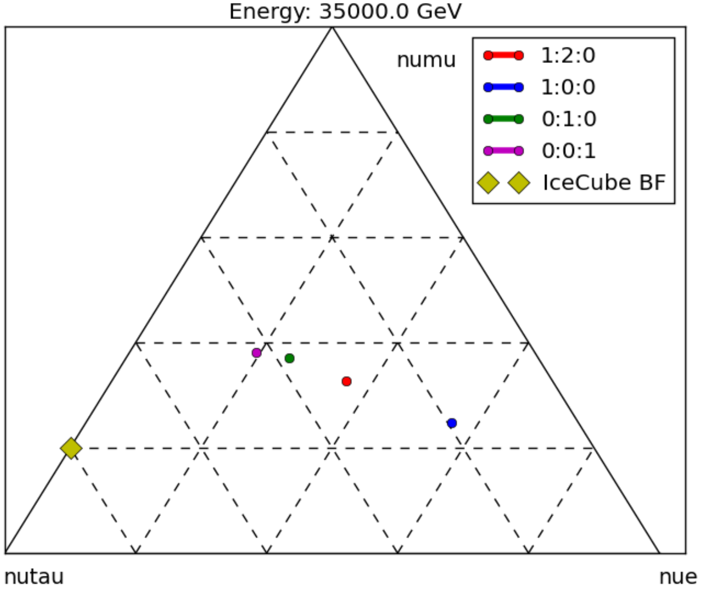
4. Neutrino flavour ratio with new physics

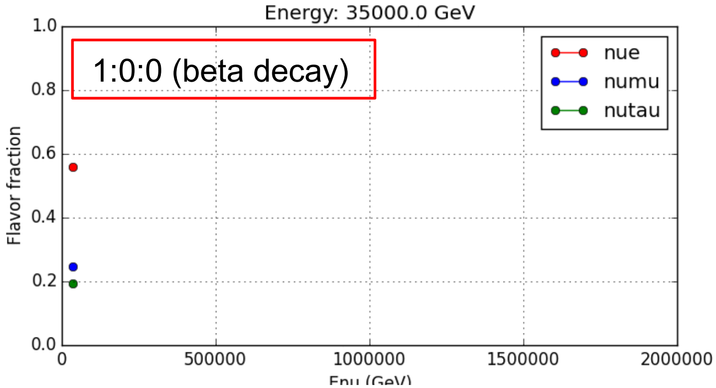
An example Hamiltonian with new physics term (~10^{-28} CPT even Lorentz violation)

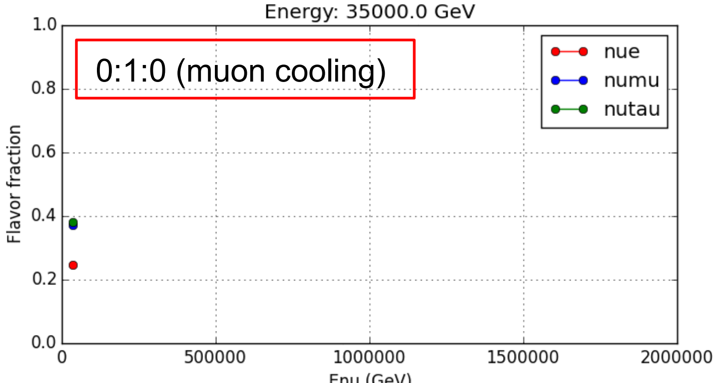
$$h_{eff} = \frac{1}{2E}\begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{e\tau}^2 \\ m_{e\mu}^{2*} & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{e\tau}^{2*} & m_{\mu\tau}^{2*} & m_{\tau\tau}^2 \end{pmatrix} + E\cdot\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c_{\mu\tau} \\ 0 & c_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$

It looks nature could choose any flavor ratio if there were new physics coupled with neutrinos just below sensitivities of terrestrial experiments









4. Neutrino flavour ratio with new physics

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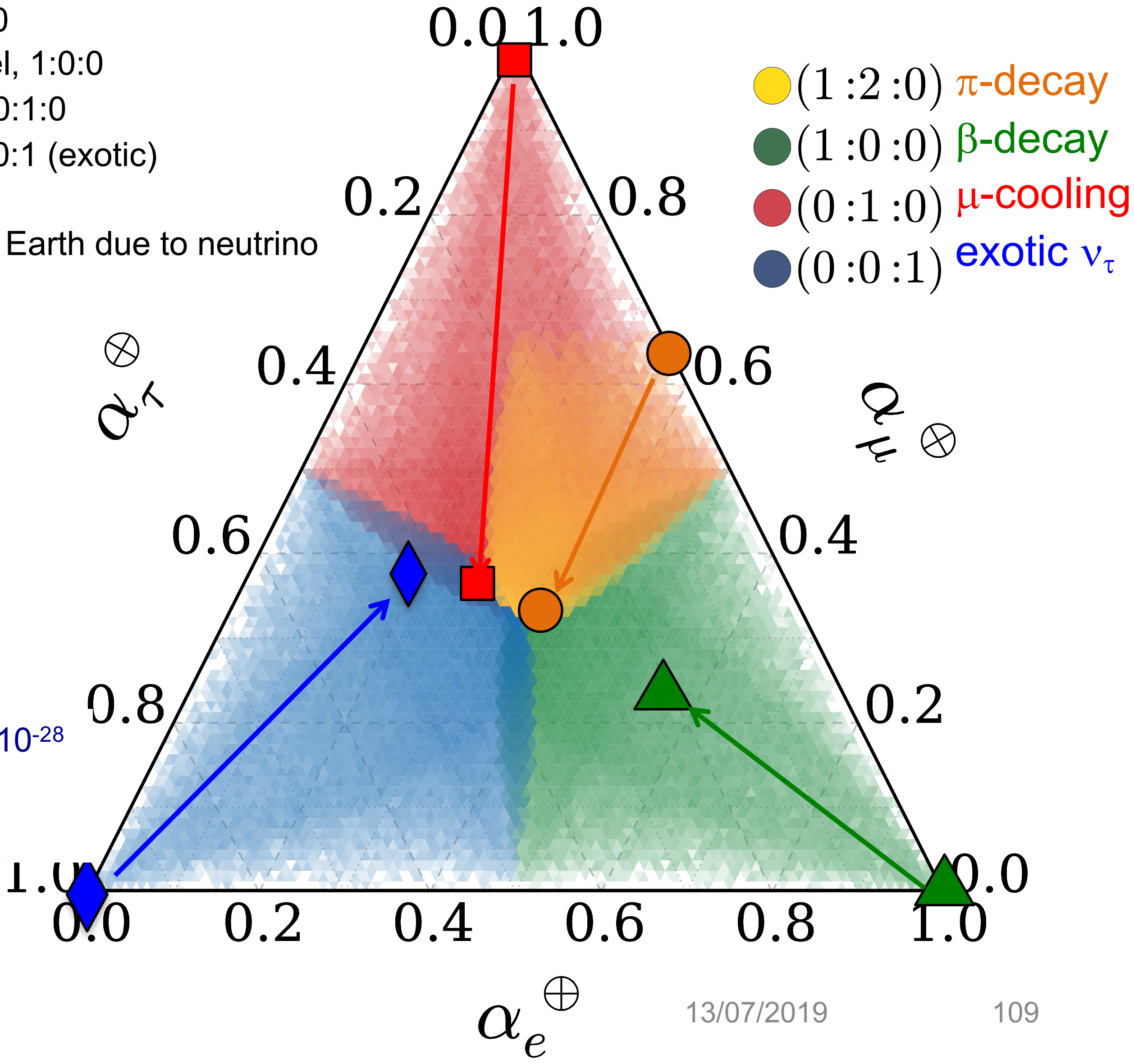
Initial flavour ratio is modified on the Earth due to neutrino mixing

Astrophysical neutrinos = hadronic (pion) process → (1:0:0) and (0:1:0) are too extreme astrophysical neutrino flavour models and all realistic models are between them

All possible flavour ratio is confined in a small space.

E.g.) dim-4 new physics operator ~ 10^{-28}
- just below experimental limit
- new method to study new physics



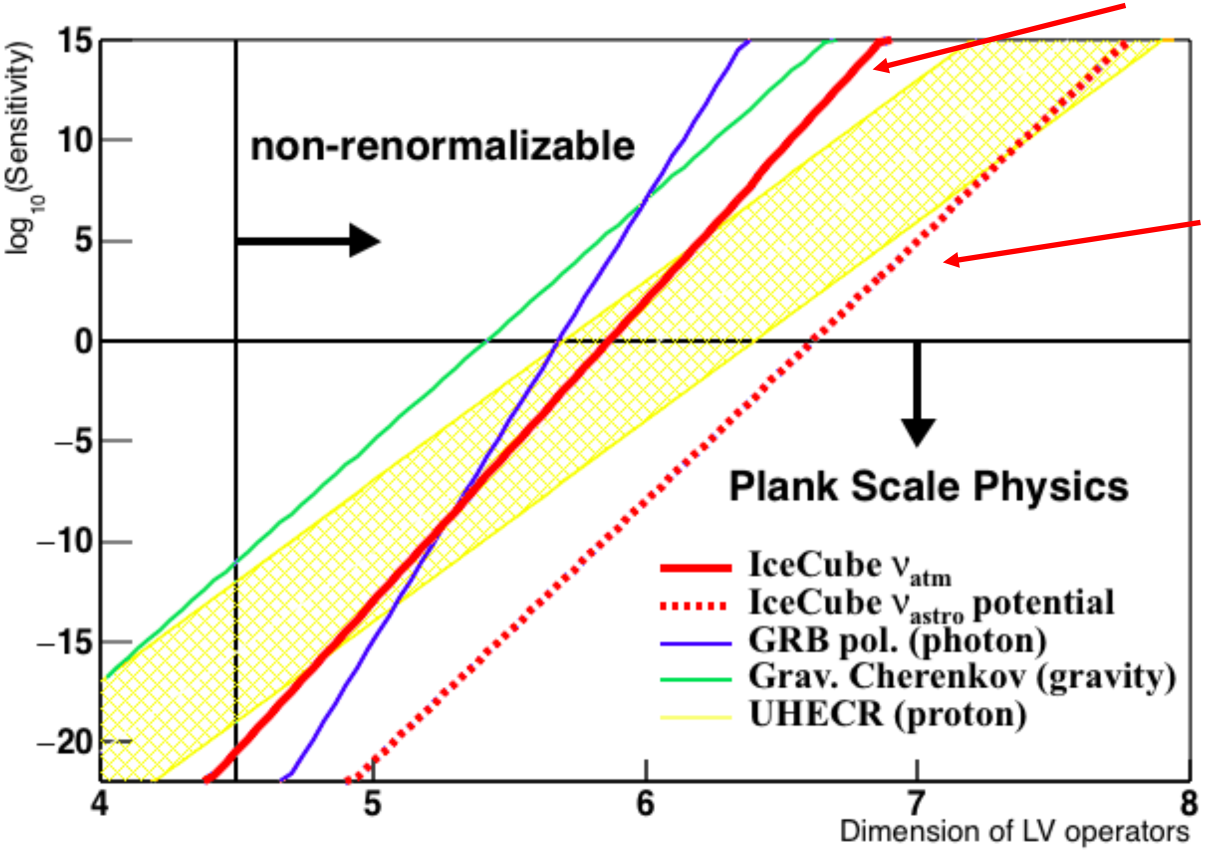
Argüelles, TK, Farrag, Mandalia, ArXiv:1906.09240

4. Neutrino flavour ratio with new physics

Combination of longer baseline and higher energy makes extra-terrestrial neutrino to be the most sensitive source of fundamental physics.

new physics sensitivity (normalized with M_{Planck})

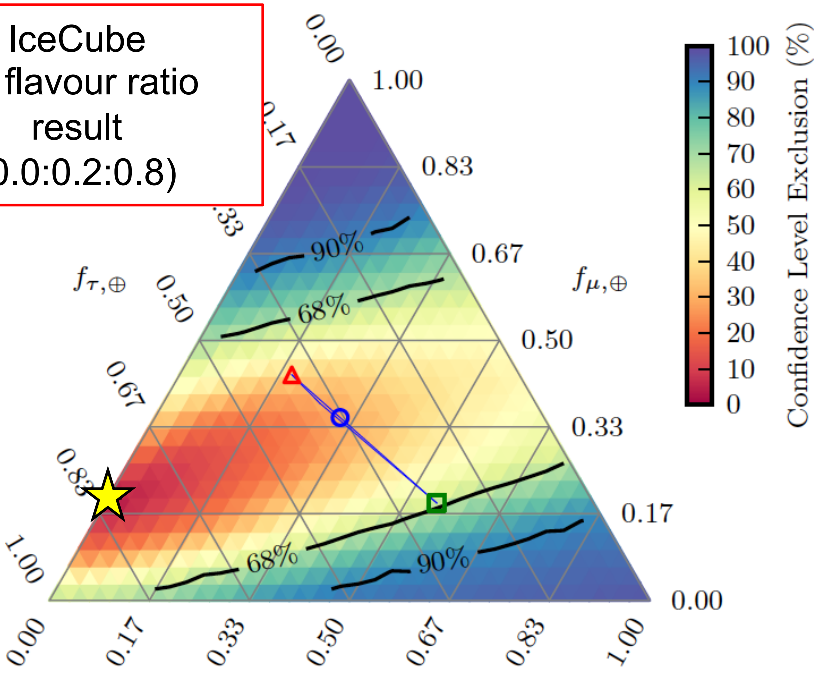
IceCube atmospheric neutrino Lorentz violation limit
Nature Physics 14(2018)961



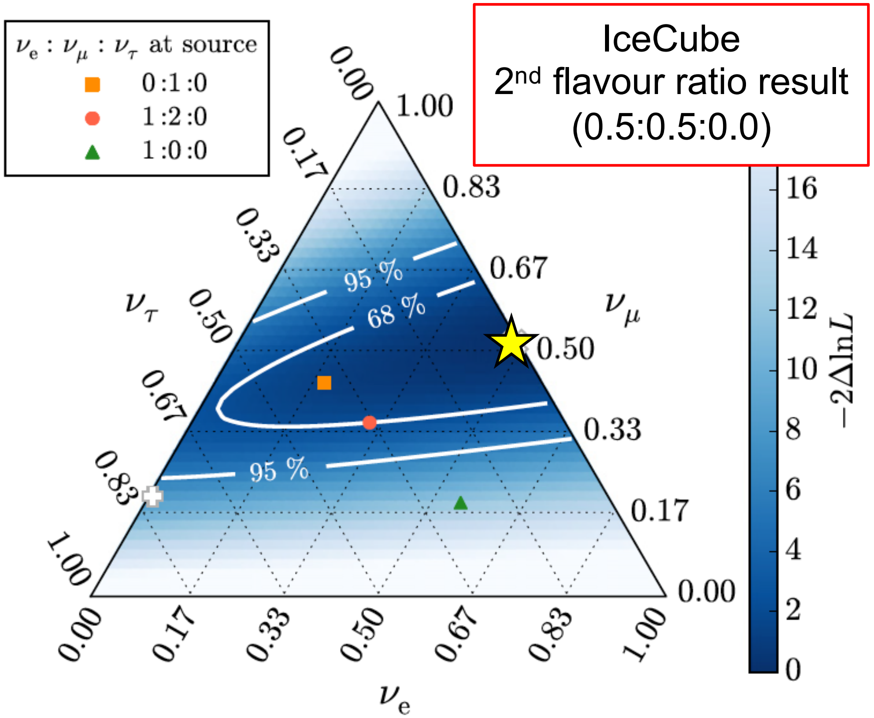
IceCube astrophysical neutrino new physics sensitivity

IceCube, PRL114(2015)171102, Astro.J.809:98(2015)

4. IceCube flavor ratio



IceCube
1st flavour ratio result
(0.0:0.2:0.8)



IceCube
2nd flavour ratio result
(0.5:0.5:0.0)

Shallow χ^2 minimum

- Only 2 measured event type (track and cascade) → classified to 4 groups ν_eCC, ν_μCC, ν_τCC, NC)
- Large confusion between ν_e and ν_τ flavour content (shallow likelihood to find the best fit points).

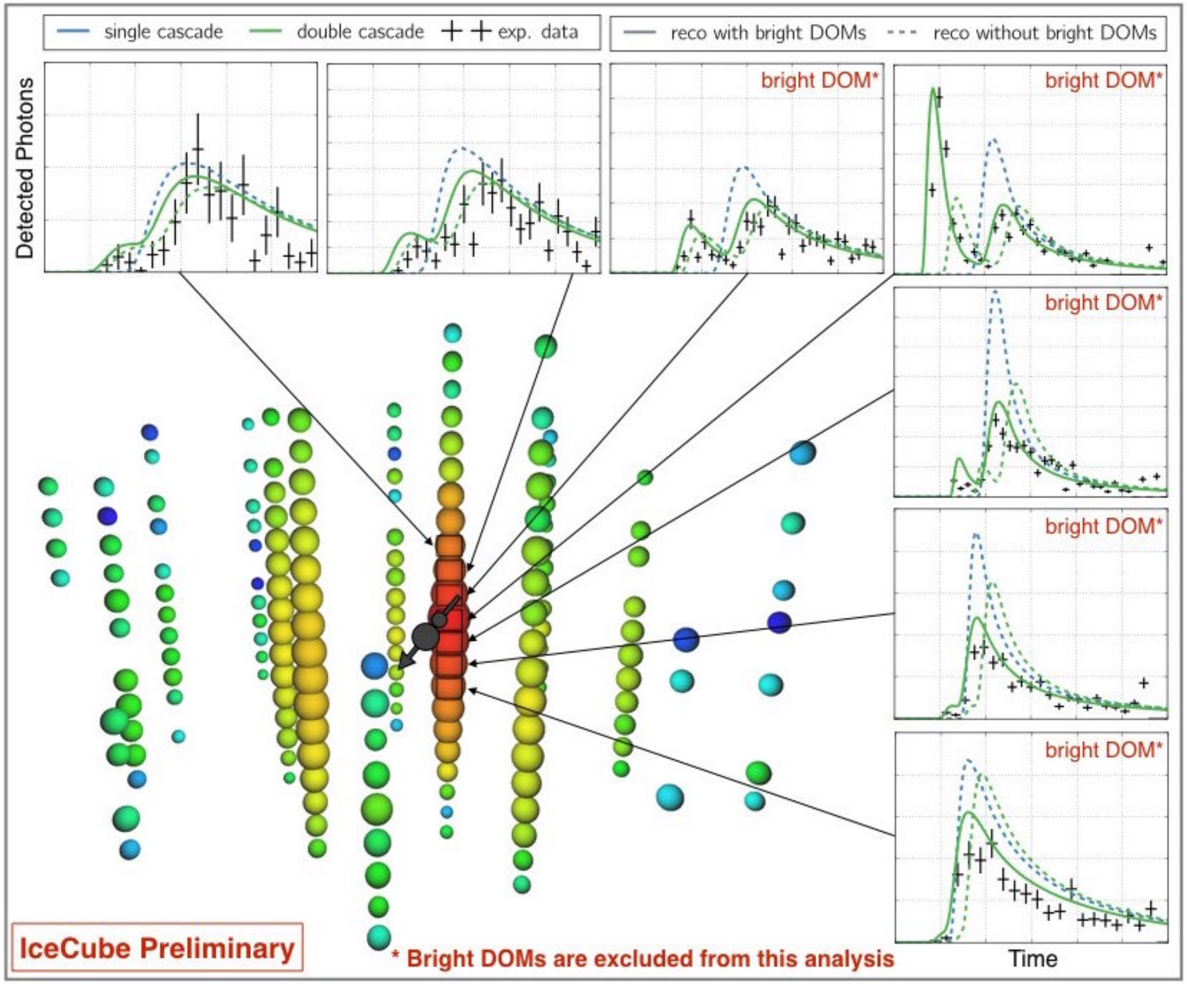
→ flavour ratio fit needs to have a better particle ID

IceCube preliminary

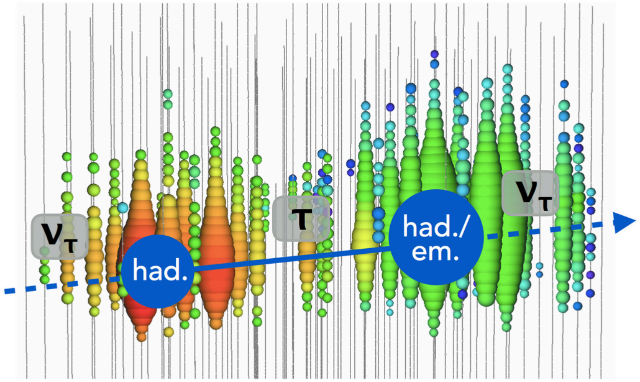
4. HESE 7-yr data (2018)

Double Double

- newly discovered tau neutrino candidate



"Double bang" is extremely rare (bang separation~50m xE/1PeV)



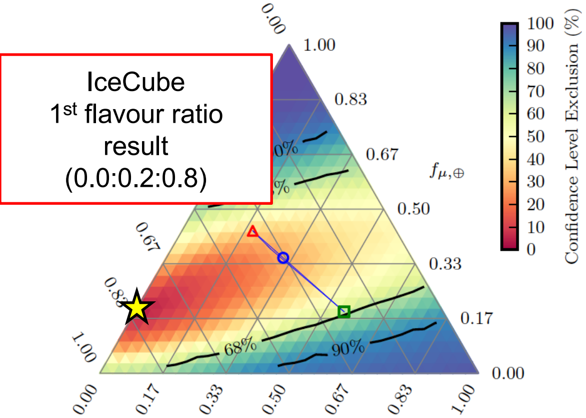
But double pulse can be found using timing information.

Improved tau PID algorithm is used to calculate the flavour ratio

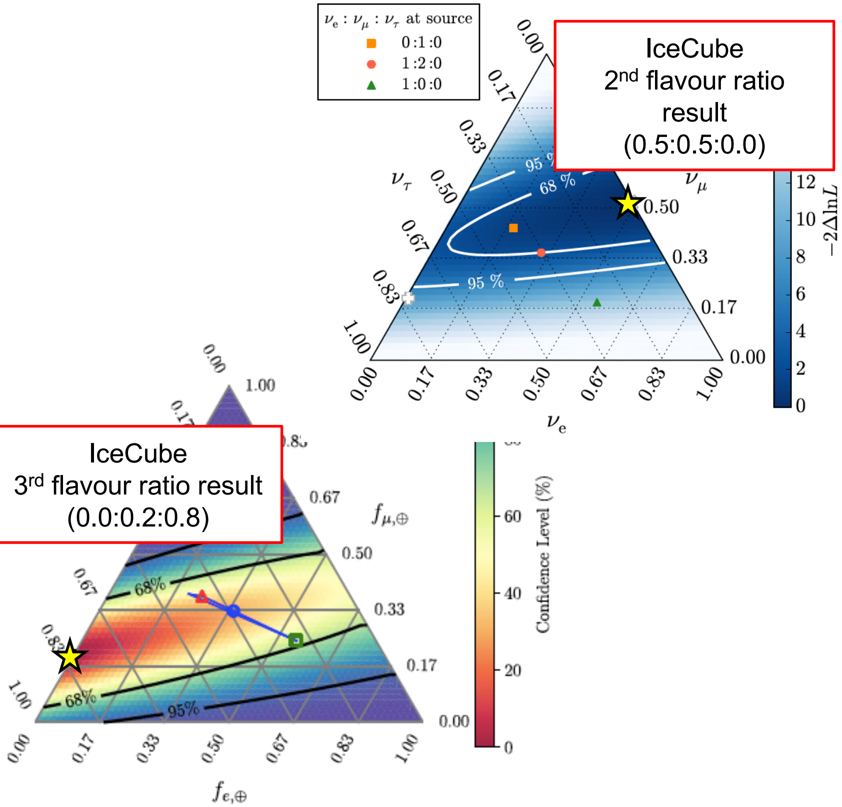
Taboada (IceCube), Neutrino 2018
IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004

4. HESE 7-yr data (2018)

IceCube preliminary



IceCube
1st flavour ratio result
(0.0:0.2:0.8)

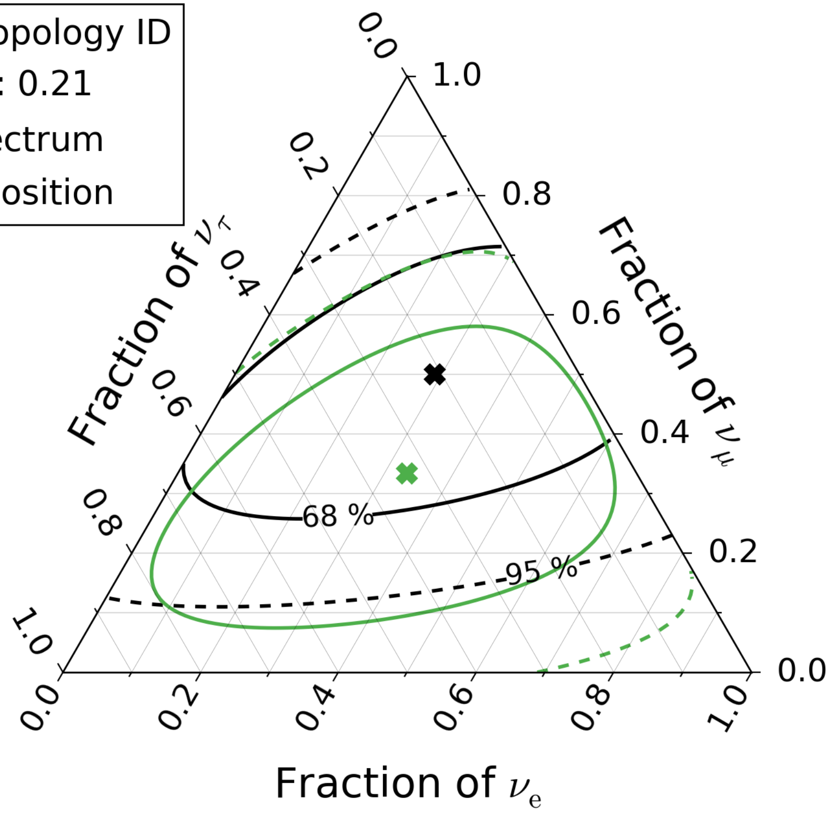


IceCube
2nd flavour ratio result
(0.5:0.5:0.0)

IceCube
3rd flavour ratio result
(0.0:0.2:0.8)

—	HESE with ternary topology ID
✖	Best fit: 0.29 : 0.50 : 0.21
—	Sensitivity, $E^{-2.9}$ spectrum
✖	1 : 1 : 1 flavor composition

WORK IN PROGRESS



New flavour ratio measurement

- Sensitivity reaches nonzero ν_τ component
- New flavour ratio result has some power to distinguish ν_e and ν_τ, Likelihood is still very shallow and fit confuses between ν_e and ν_τ

Taboada (IceCube), Neutrino 2018
IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004

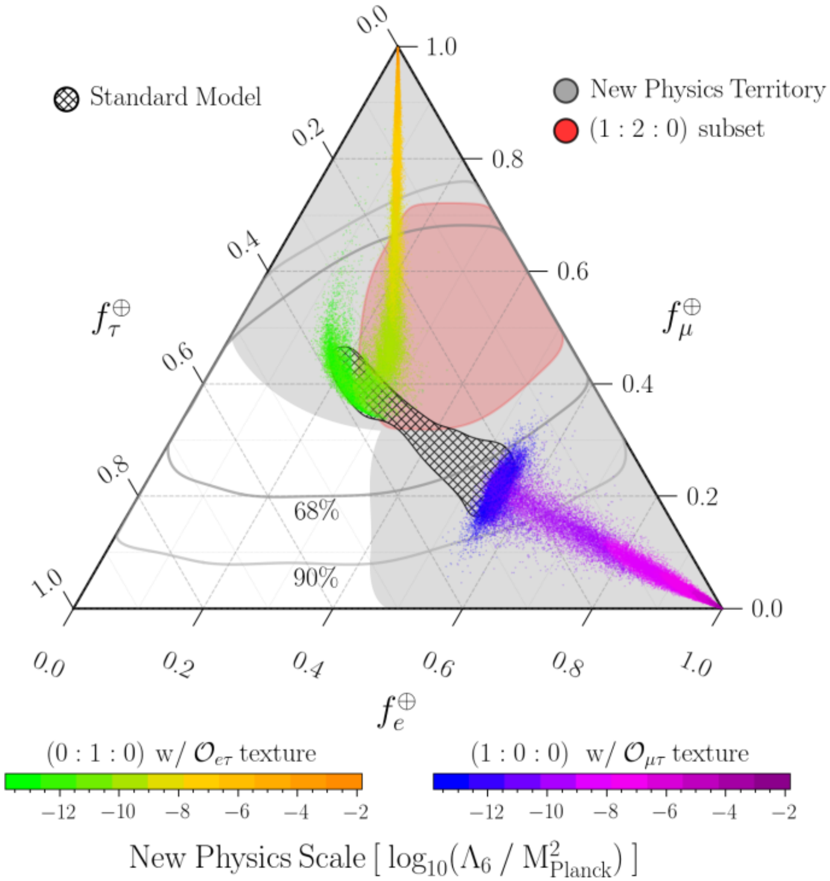
IceCube preliminary

4. HESE 7-yr data (2018)

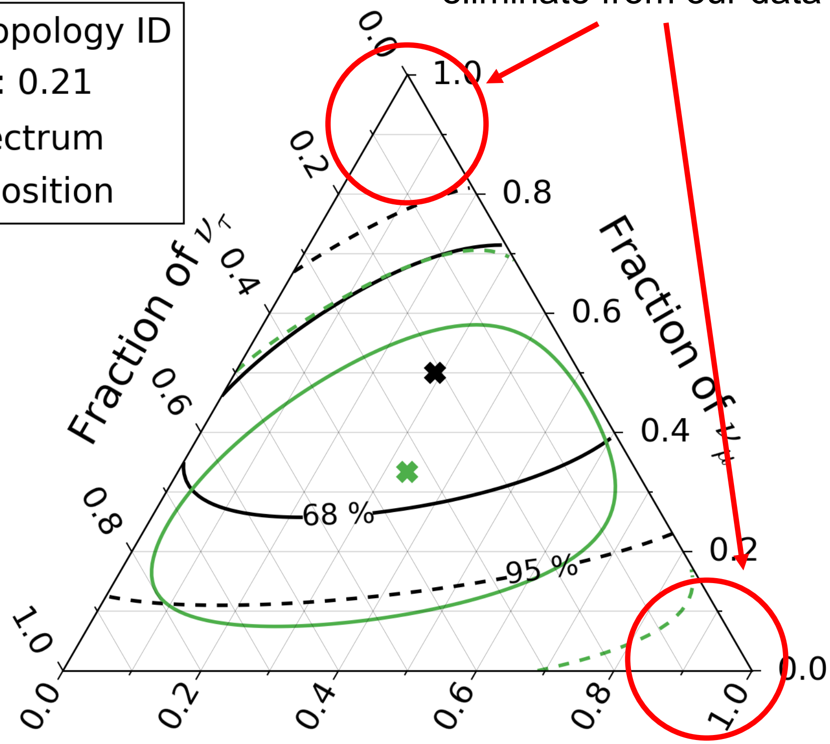
We can only exclude models if Lorentz violation make flavour ratios at those corners

— HESE with ternary topology ID
✖ Best fit: 0.29 : 0.50 : 0.21
— Sensitivity, E$^{-2.9}$ spectrum
✖ 1 : 1 : 1 flavor composition

WORK IN PROGRESS



Phase space we can eliminate from our data



1. Astrophysical neutrino is pre-dominantly produced as muon neutrinos (~0:1:0), and new physics causes ν_e-ν_τ transition (nonzero $c^{(6)}_{\tau e}$)

2. Astrophysical neutrino is pre-dominantly produced as electron neutrinos (~1:0:0), and physics causes ν_μ-ν_τ transition (nonzero $c^{(6)}_{\mu\tau}$)

IceCube preliminary

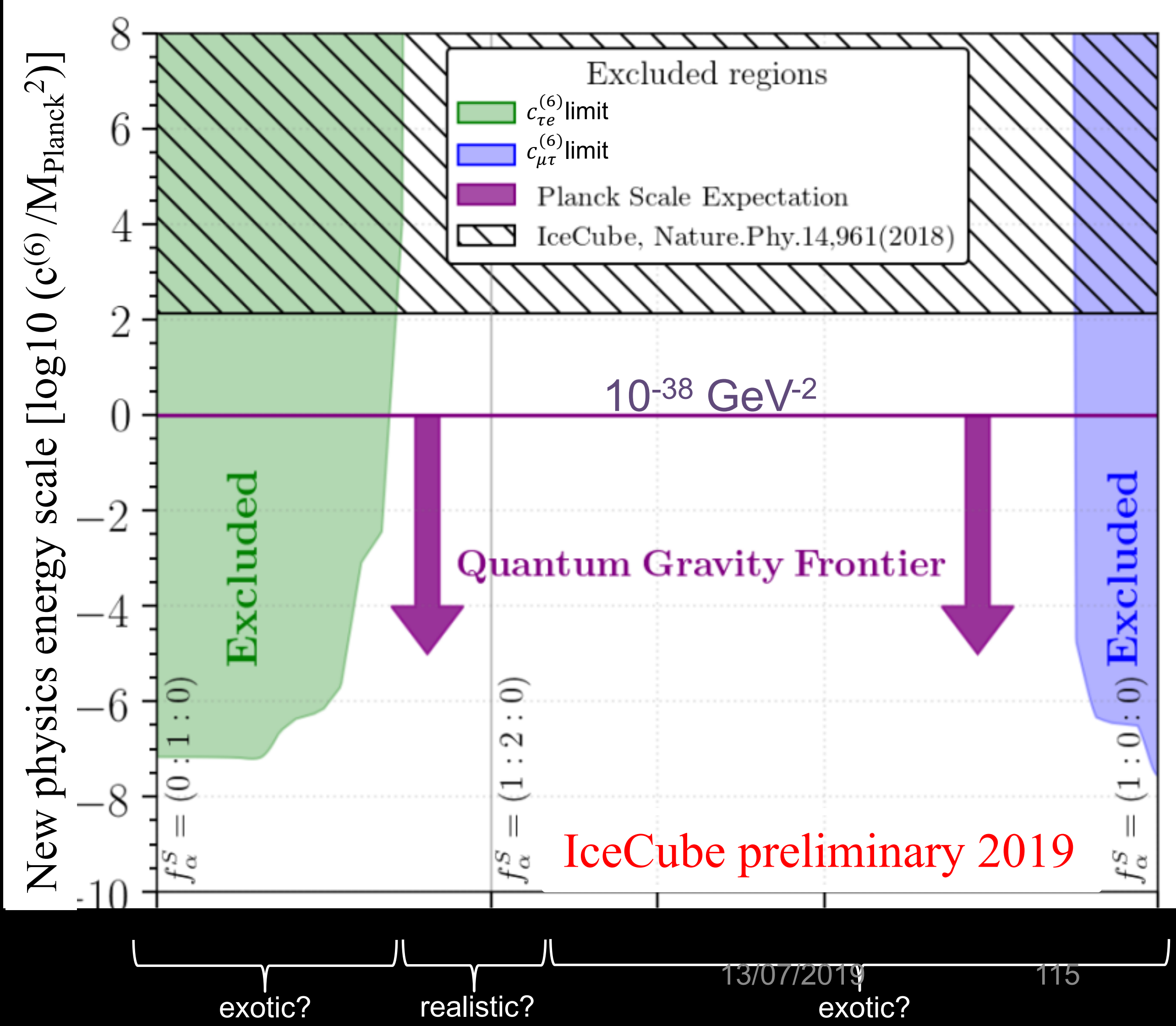
4. Astrophysical Neutrino Flavour Lorentz Violation search

We start to exclude possible new physics in Planck scale signal region

- This moment, we focus to search max e↔τ mixing or max μ↔τ mixing by LV

- dim-3 LV limit ~ 10^{-26} GeV
- dim-4 LV limit ~ 10^{-32}
- dim-5 LV limit ~10^{-40} GeV^{-1}
- dim-6 LV limit ~10^{-46} GeV^{-2}
- dim-7 LV limit ~10^{-51} GeV^{-3}
- dim-8 LV limit ~10^{-58} GeV^{-4}

We start to explore quantum gravity-motivated region, but so far we didn't discover any new physics operators

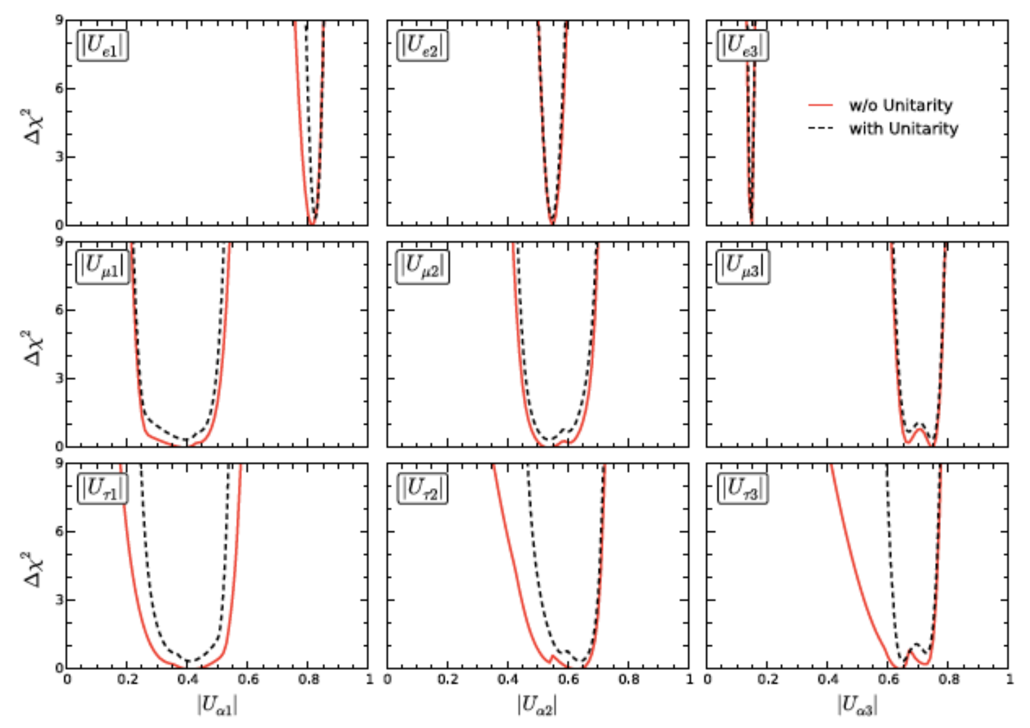


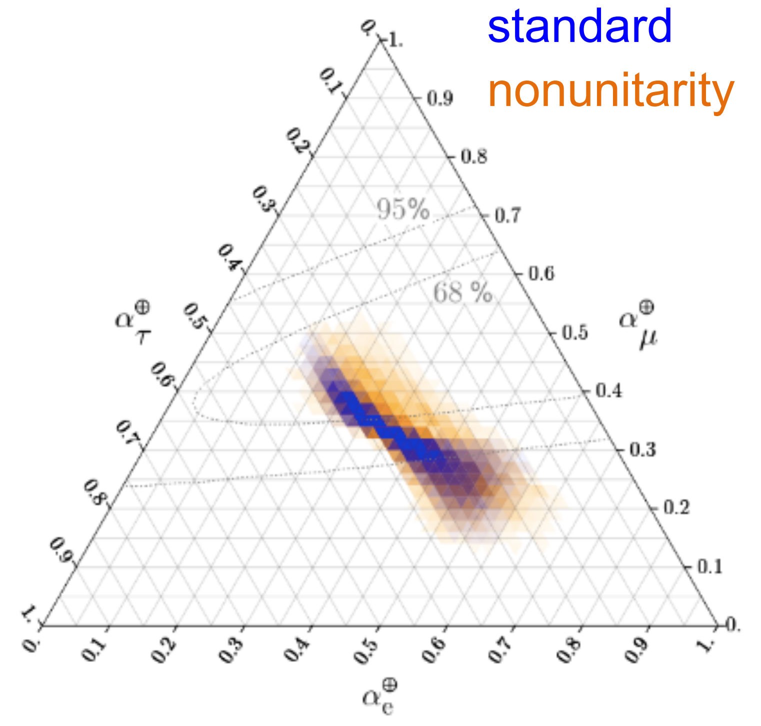
Parke, Ross-Lonergan,PRD93(2016)113009
TK et al, to be published (2019)

4. 4th neutrino (sterile neutrino)

Current data allow large amount of non-unitarity in neutrino mixing matrix. 4th neutrino contribute non-unitarity of PMNS matrix.

If 4th neutrino exists and mixing is nonzero, astrophysical neutrino flavour is sensitive regardless the size of mass. We may be able to find that from next generation flavour ratio measurement.





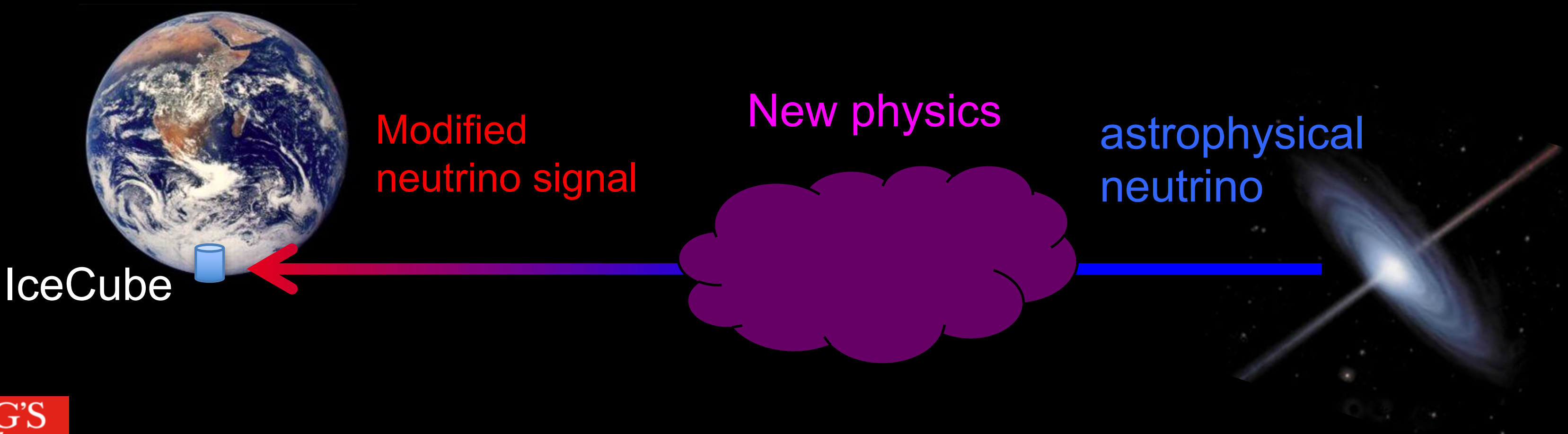
Berlin, PRL117(2016)231801
Farzan,Palomares-Ruiz, PRD99(2019)051702(R)

4. Ultra-light dark matter

3 dark matter searches with neutrinos
- Neutrinos from Earth, Sun, Milky Way center, $\chi + \bar{\chi} \rightarrow \nu + \bar{\nu}$ (WIMP, m_χ~100 GeV)
- Spectrum distortion of astrophysical neutrinos, $\nu + \chi \rightarrow \nu + \chi$ (light WIMP, m_χ~100 MeV)
- Anomalous flavor ratio by dark-matter potential (ultra-light dark matter)

Dark matter may be ultra-light and make a classical field, and coupling of this and neutrinos make an effective potential.

This method is sensitive to dark matter mass down to $m_\chi \sim 10^{-21}$ eV.

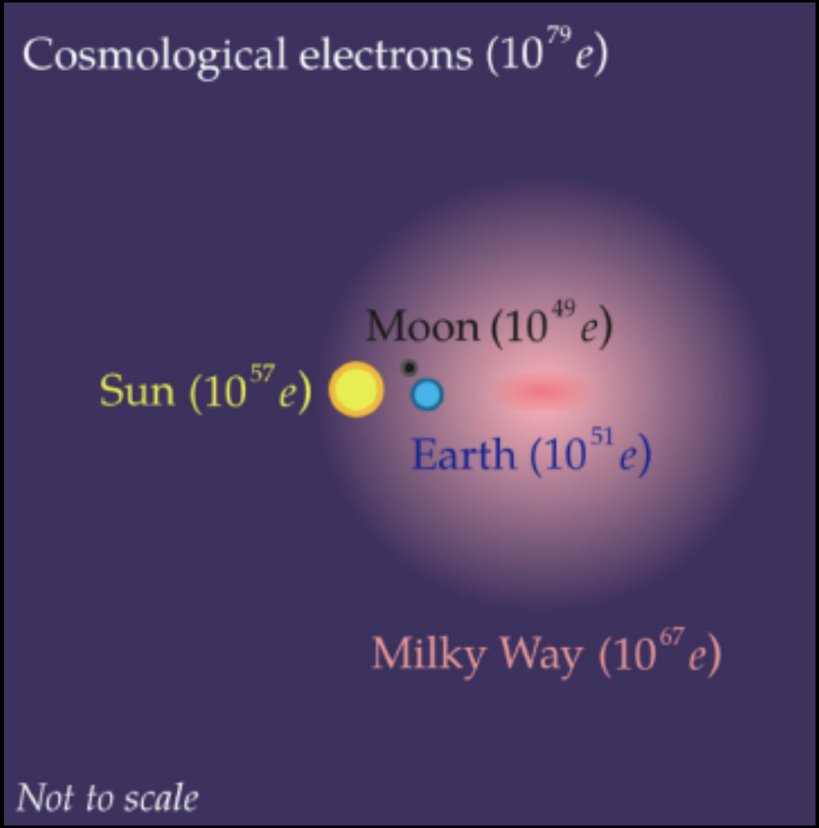


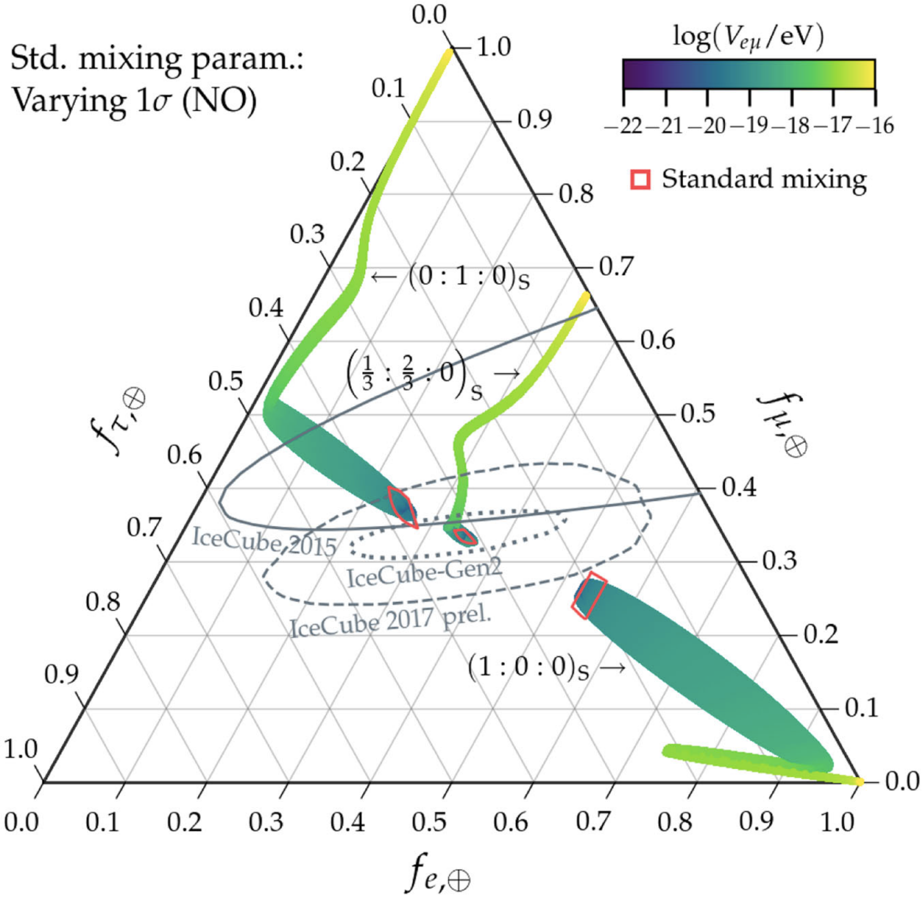
Bustamante,Agarwalla, PRL122(2019)061103

4. Long range 5th force

New long range force, if existed, can contribute an effective potential.

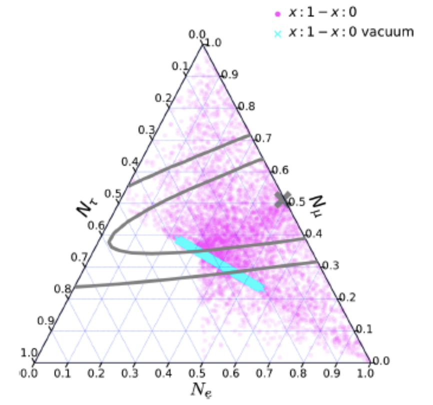
If the range is really long, all particles in the universe can contribute to modify the astrophysical neutrino flavor ratio!





Klop,Ando,PRD97(2018)063006

4. Neutrino-dark energy coupling



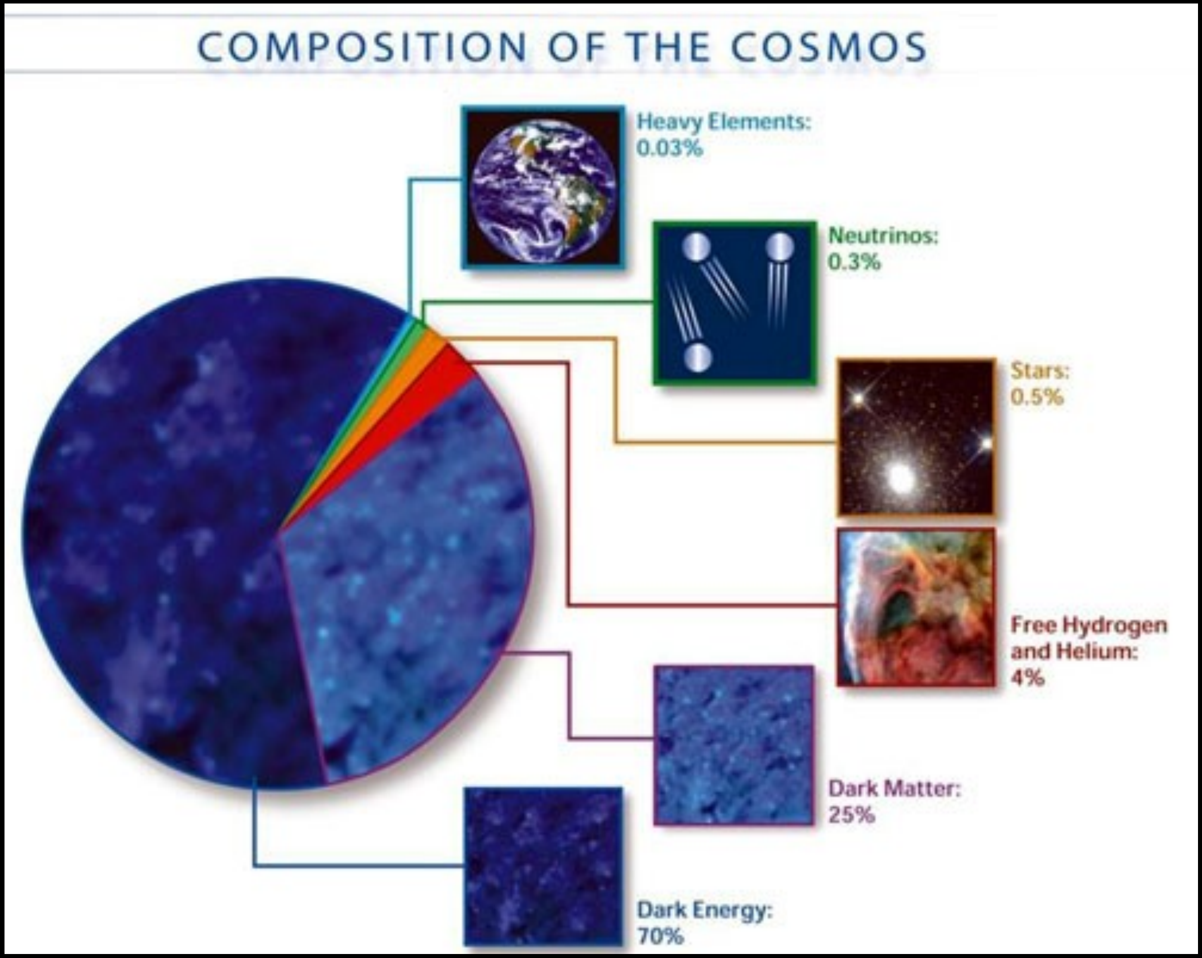
Dark energy makes up ~70% of energy density of the universe

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

Or Einstein equation doesn't describe the universe (modified gravity)

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

Dark energy can be a classical field, and it may couple with normal matter very weakly. If it couples with neutrinos, this may modify the astrophysical neutrino flavor ratio.



Kostelecký and Mewes, PRD85(2012)096005

4. Search of effective couplings

In fact, any models written by effective couplings by effective field theory can be tested by astrophysical neutrino flavor

$$\sim\bar{\psi}\gamma_\mu a^\mu\psi$$

- Lorentz violation
- CPT violation
- Neutrino-dark matter coupling
- Neutrino-dark energy coupling
- Neutrino-torsion coupling
- Neutrino velocity ≠ c
- Violation of equivalent principle
- New long range force, etc

These physics are motivated by

- String theory
- Loop quantum gravity
- Horava-Lifshitz gravity
- Lee-Wick theory
- Non-commutative field theory
- Supersymmetry, etc

Standard Model Extension

- An effective field theory formalism to look for Lorentz violation
- Community standard to report results and compare with others

Conclusion

Neutrino interferometry is a powerful technique to look for new physics if new physics couple with neutrinos and they cause neutrino mixings.

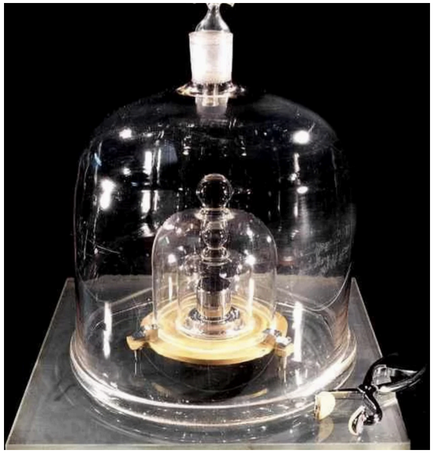
Astrophysical neutrino mixing sensitivity reaches to naïve expectation of Planck scale physics. However, in this moment, the sensitivity is limited and we didn’t discover Lorentz violation.

IceCube-Gen2 collaboration

Thank you for your attention!

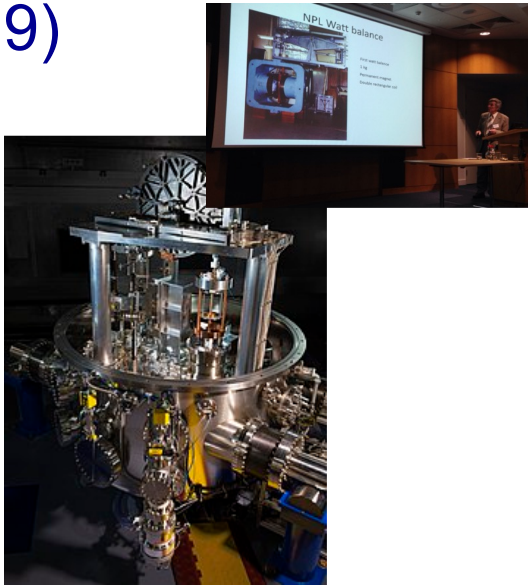
Backup

1. SI base units (2019)

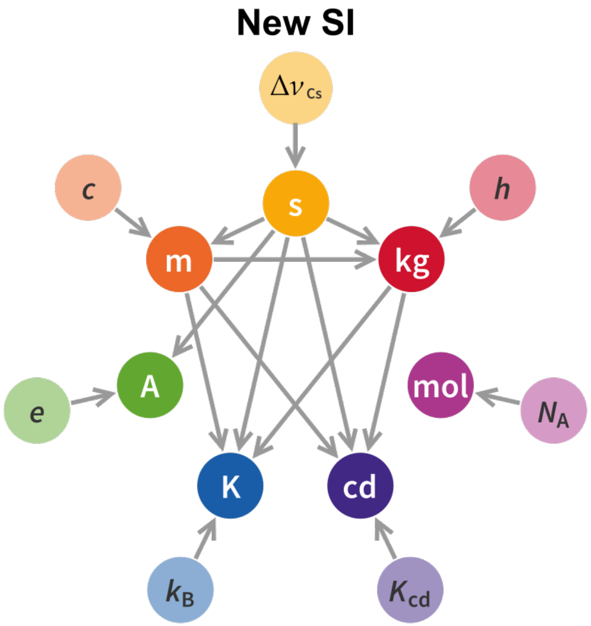


International prototype of kilogram

Bryan Kibble
1938–2016

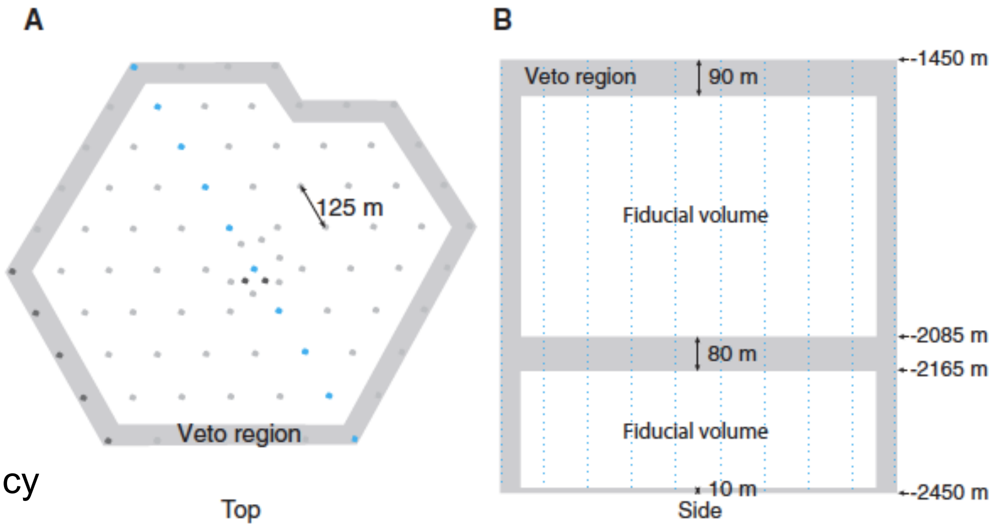


Kibble balance



$\Delta\nu_{Cs} = 9192631770\ Hz$	Cesium atom hyperfine transition	second
$c = 299792458\ m/s$	Speed of light	metre
$h = 6.62607015{\times}10^{-34}\ J \cdot s$	Planck constant	kilogram
$e = 1.602176634{\times}10^{-19} C$	Electric charge	ampere
$k_B = 1.380649{\times}10^{-23}$	Boltzmann constant	kelvin
$N_A = 6.02214076{\times}10^{23}$	Avogadro constant	mole
$K_{cd} = 683\ lm/W$	candela	candela

2. Astrophysical High-Energy Neutrinos



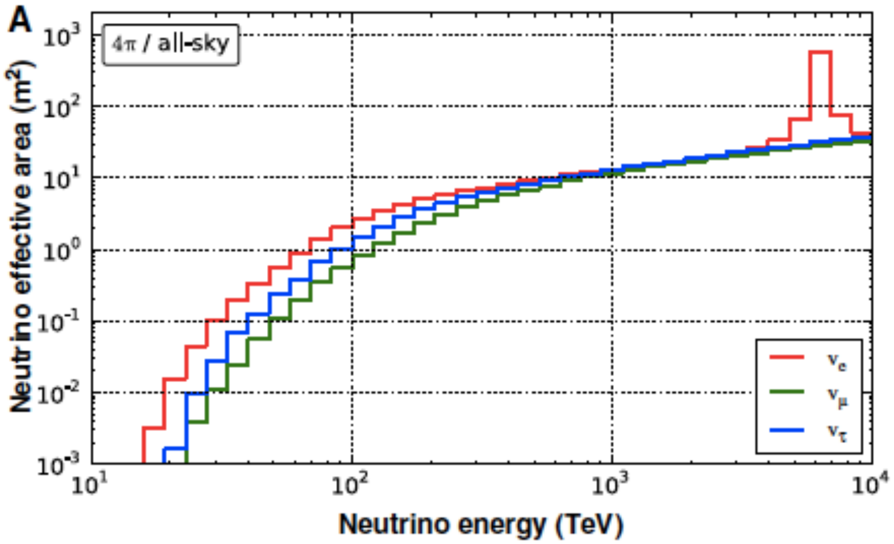
High Energy Starting Event (HESE)

- Veto (3PE veto threshold)
- Total 6000PE (> 60 TeV)
- 250PE for “starting”
- Avoid dust layer from fiducial volume

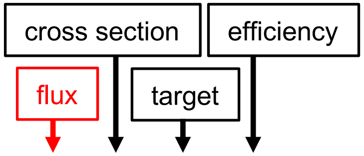
Effective area

- cross-section x target number x efficiency
- larger effective area → higher detection efficiency
- detection efficiency is flavour dependent
  - ν_eCC: electromagnetic shower (highest PE)
  - ν_τCC, NC: hadronic shower
  - ν_μCC: muon bremsstrahlung

The simulation takes into account all other details (high-energy muon from tau decay, etc)



The measurement of astrophysical neutrinos assumes the Earth material model and neutrino cross-section model.



cross section

efficiency

flux

target

Event rate $N = \Phi\times\sigma\times T\times\varepsilon$

1. Hertzsprung-Russel (H-R) diagram

Sun (=a typical star)

Solar mass: $M_{\odot} = 2\times10^{30}kg$ (mass of Sirius = $2M_{\odot}$)

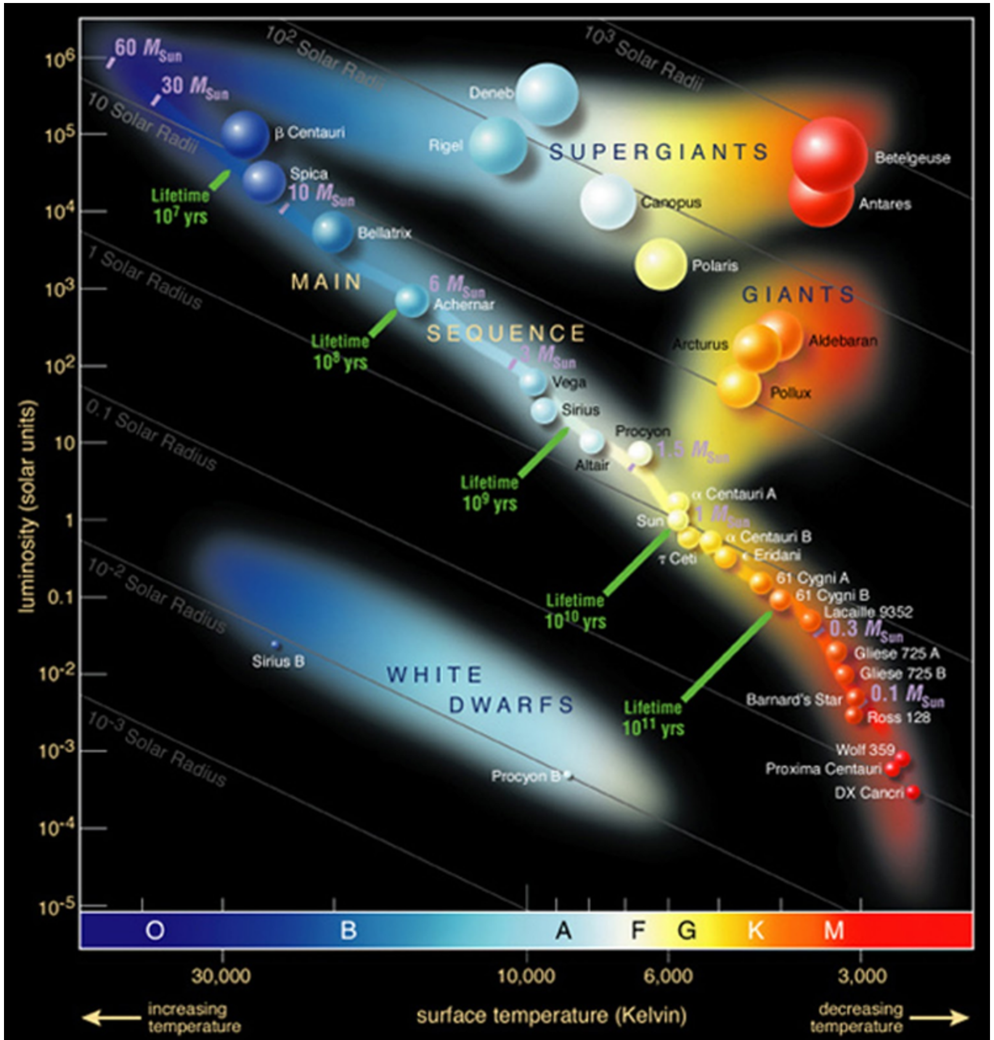
Solar radius: $R_{\odot} = 7\times10^{8}m$ (radius of Sirius = $1.7R_{\odot}$)

Solar luminosity: $L_{\odot} = 3.8\times10^{26}W$ (luminosity of Sirius = $25L_{\odot}$)

Sun is literally a typical star

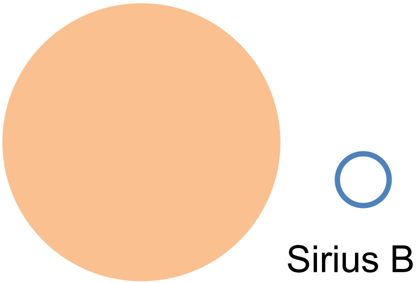
All stars are more or less same size and mass.
→ Crude approximation, all stars are Sun.
(Stefan-Boltzmann law: $L = 4\pi\sigma R^2 T_{eff}^4$)

European Southern Observatory
http://www.eso.org/public/images/



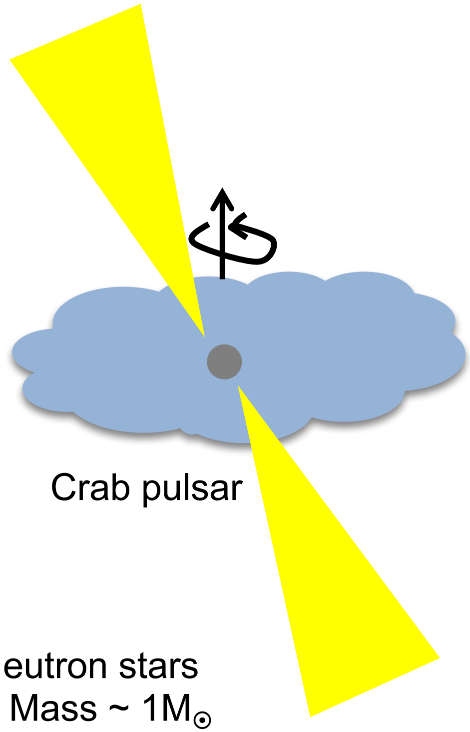
KING'S College LONDON

1. Compact objects

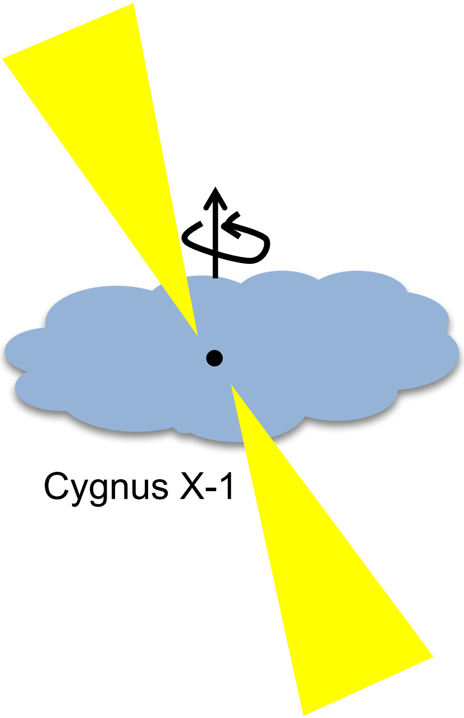


Sirius B, $1M_\odot$

Sirius A, $2M_\odot$



Crab pulsar



Cygnus X-1

White dwarf
- Mass ~ $1M_\odot$
- Radius ~ $1R_{Earth}$
- density ~ 10^6 g/cm^3

- Supported by degenerated gas (electron Fermi gas)

The most famous examples
- Sirius B
- Procyon B

Neutron stars
- Mass ~ $1M_\odot$
- Radius ~ 10km
- density ~ 10^{14} g/cm^3 ~ ρ_{nucl}

- Supported by degenerated gas (neutron Fermi gas)

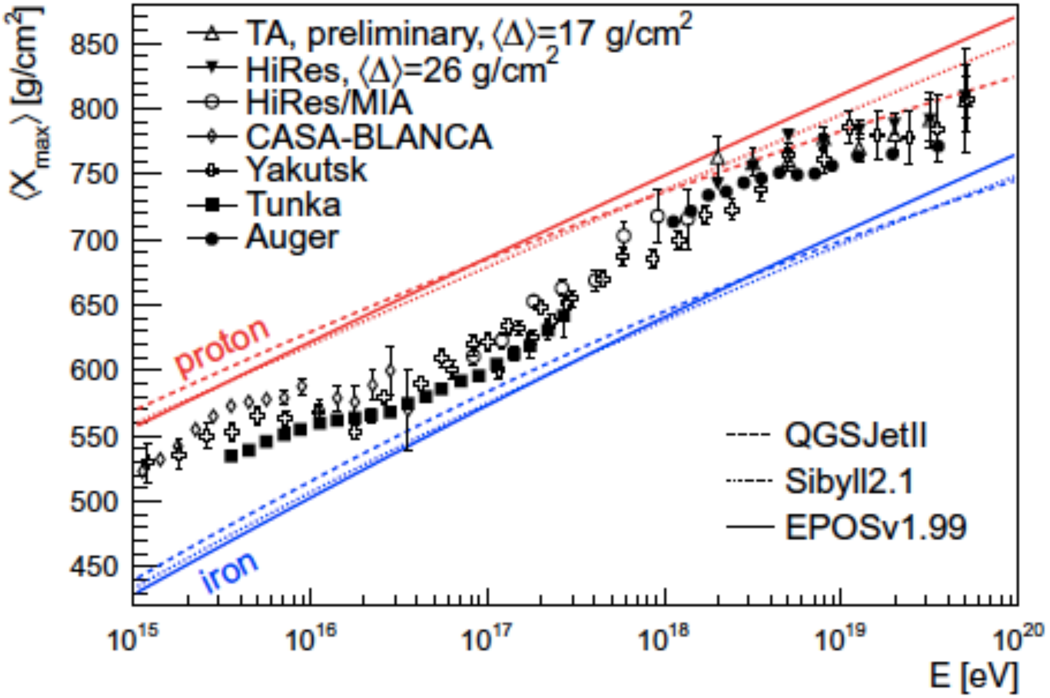
The most famous examples
- Crab pulsar
- Hulse-Taylor binary pulsar

Black hole
- Mass ~ any
- Radius ~ Schwarzschild radius (event horizon)
- density ~ ???

The most famous examples
- Cygnus X-1
- all small stars with $>10M_\odot$

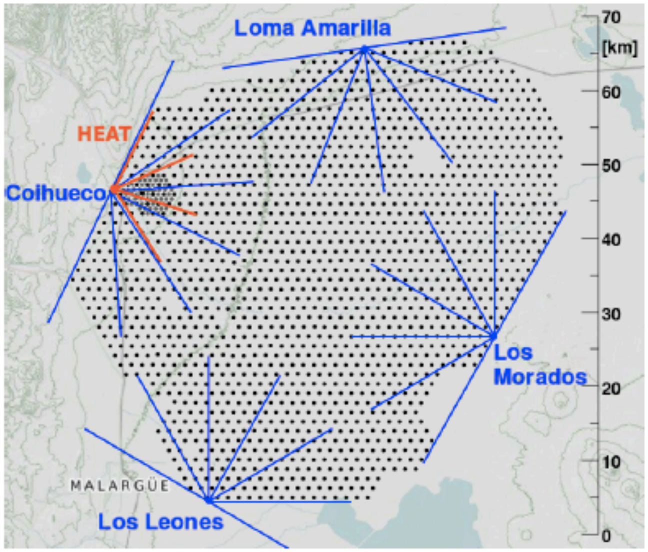
Kampert and Unger, Astropart.Phys. 35(2012)660

1. Pierre Auger Observatory

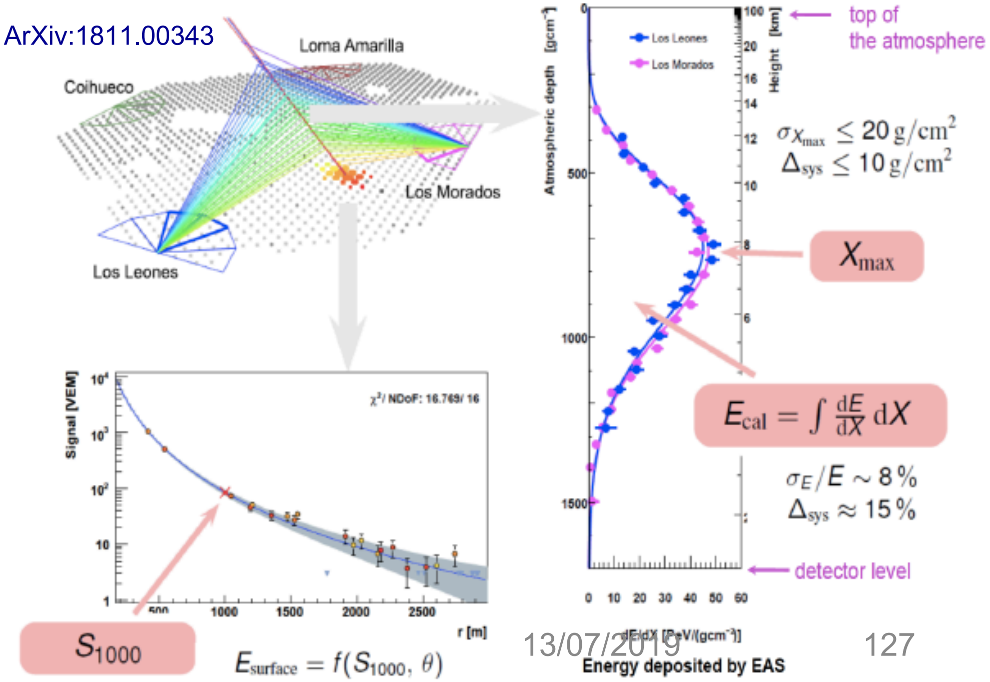


Pierre Auger Observatory
- Surface detector (water Cherenkov array)
  → secondary photons, electrons, muons
- Fluorescence detector (PMT)
  → Shower depth

Showers made by heavy elements reach maximum at upper atmosphere (less depth)
Combination of them can access to the composition of UHECRs
→ mixed, protons and heavy nuclei?
→ No GZK cutoff? No UHE ν?



Gora, ArXiv:1811.00343



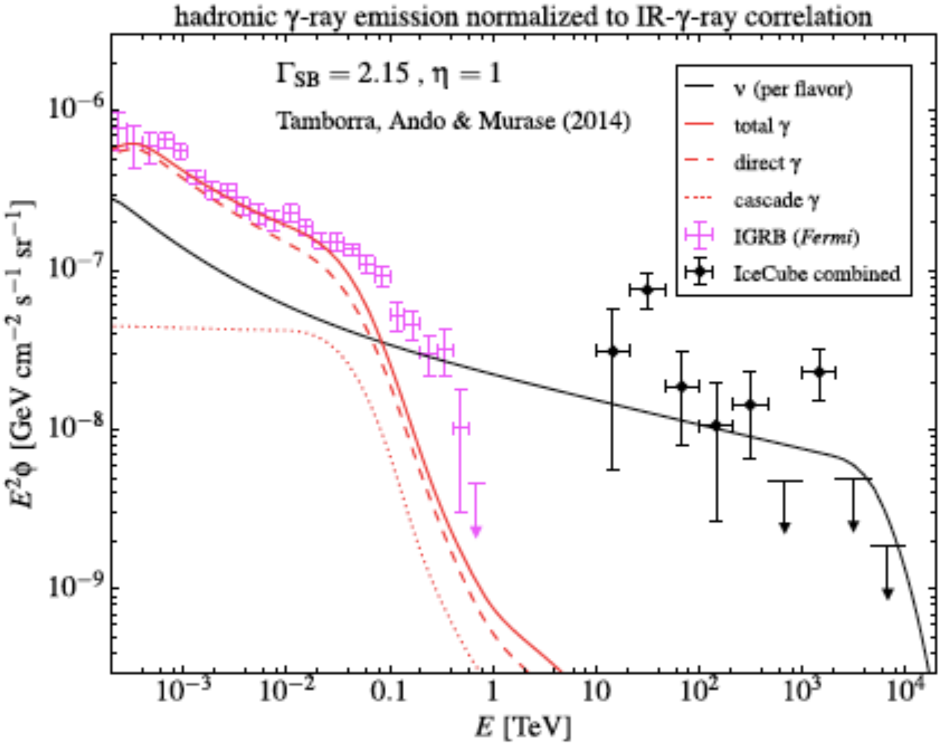
DeYoung, VSON2017
Bechtol et al., Astrophys. J, 836:47 (2017)

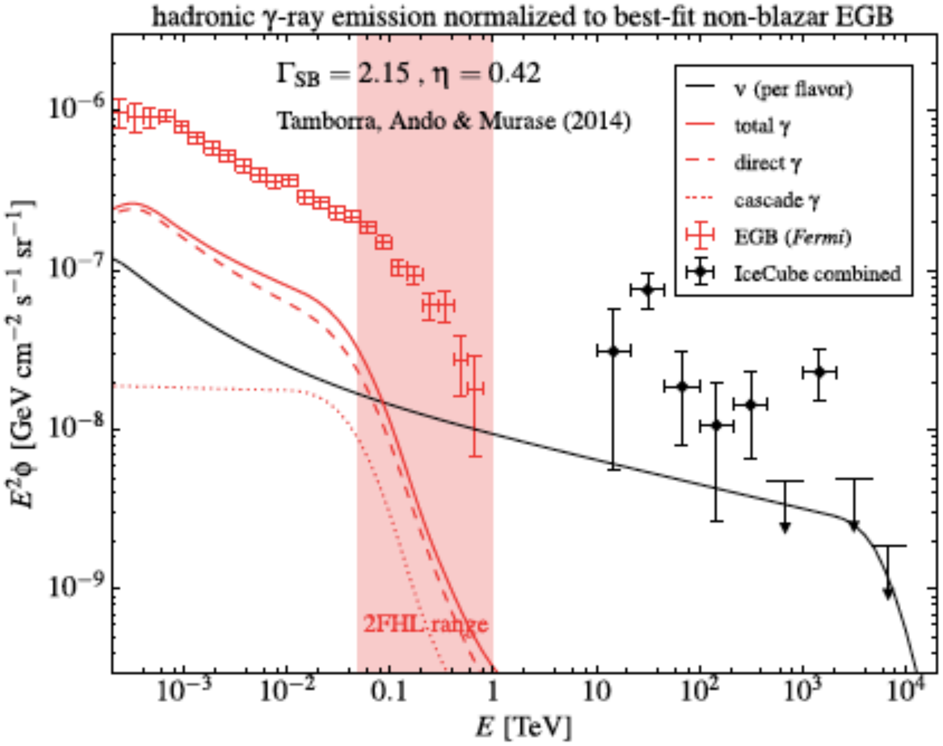
1. Fermi gamma data

A significant fraction of the energy in the non-thermal Universe is due to hadronic accelerators

If neutrino sources produce gamma rays, most of the Fermi isotropic gamma ray background comes from these sources…

…but if blazars don’t produce neutrinos, the remaining gamma ray background is too low for the observed neutrino flux


hadronic γ-ray emission normalized to IR-γ-ray correlation


hadronic γ-ray emission normalized to best-fit non-blazar EGB

PTOLEMY, arXiv:1808.01892
Project 8, PRD80(2009)051301

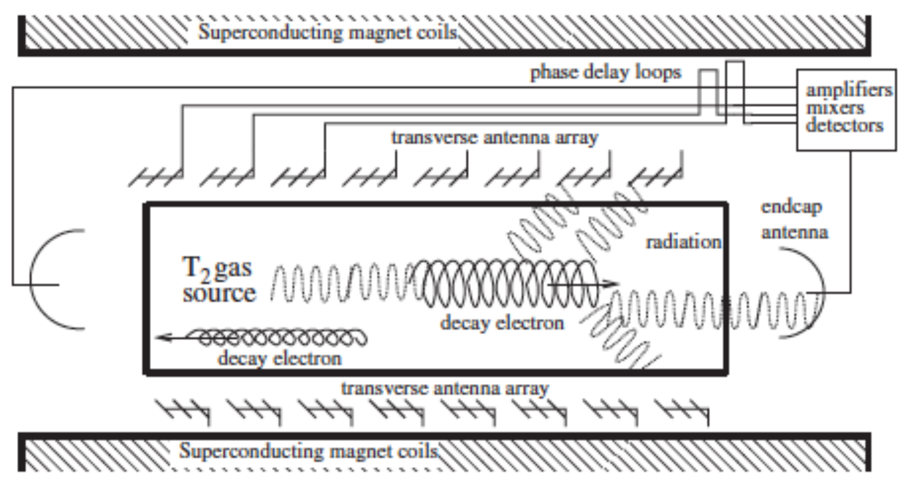
6. Cosmic Neutrino Background (CνB)

PTOLEMY and Project 8

- Motivated by KATRIN
- Tritium ν_e capture (no threshold)
- Measure end point of tritium (18 keV) from cyclotron radiation of single electron RF
- Target: ~meV shift of end point due to neutrino mass.

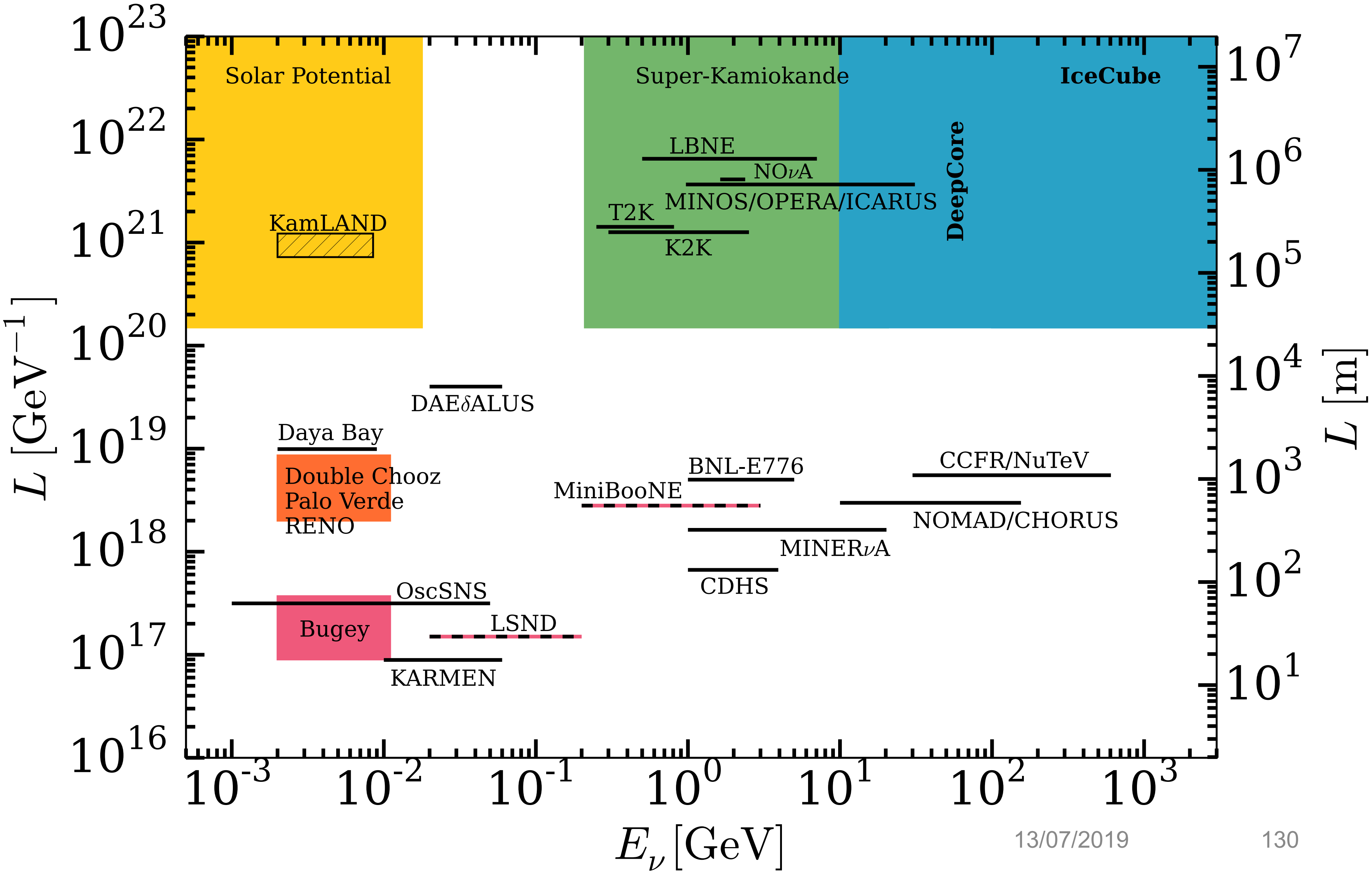
Q-m_ν → neutrino mass effect on β-decay
Q+m_ν → CνB capture

Project 8 concept



Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

4. New physics phase space by neutrino interferometry



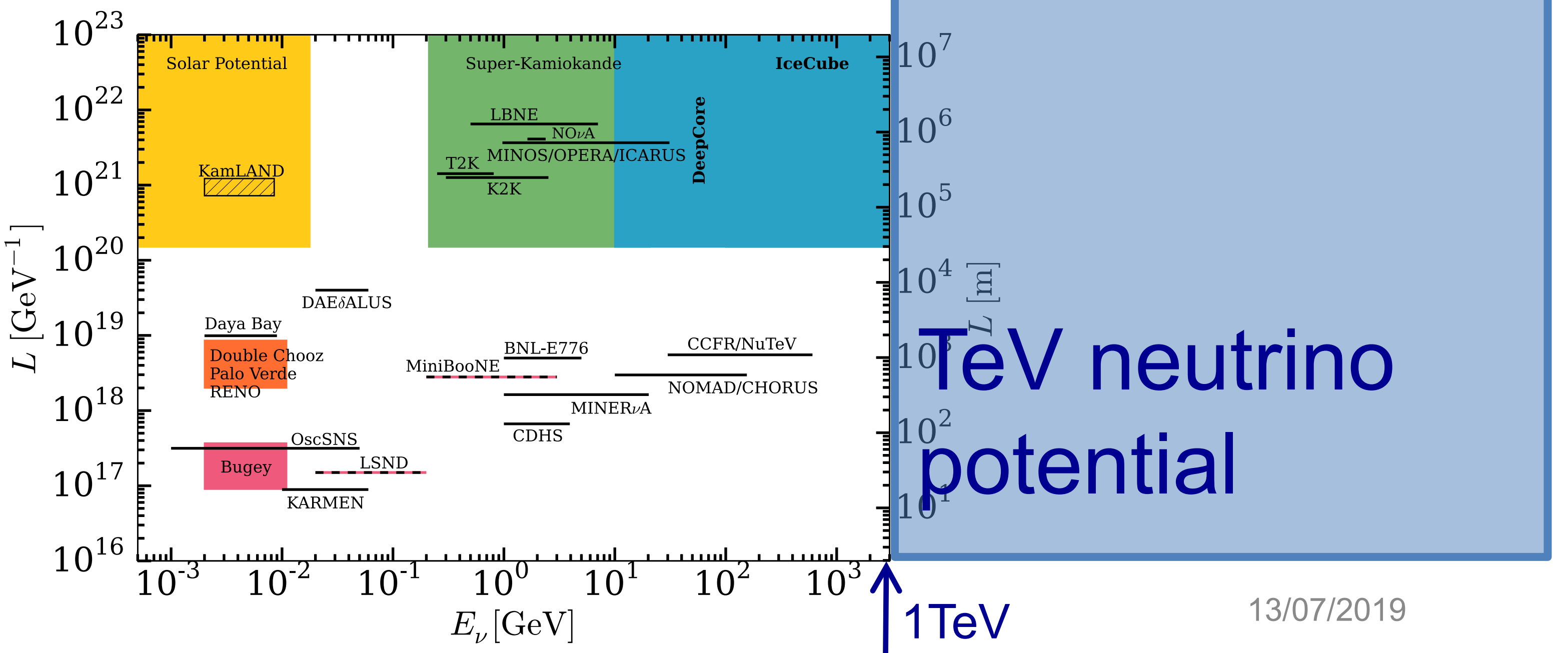
Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

4. New physics phase space by neutrino interferometry

extra galactic
neutrino potential

?

1Mpc(~Andromeda)



TeV neutrino
potential

1TeV

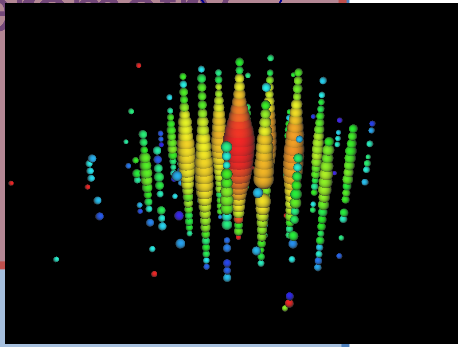
Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

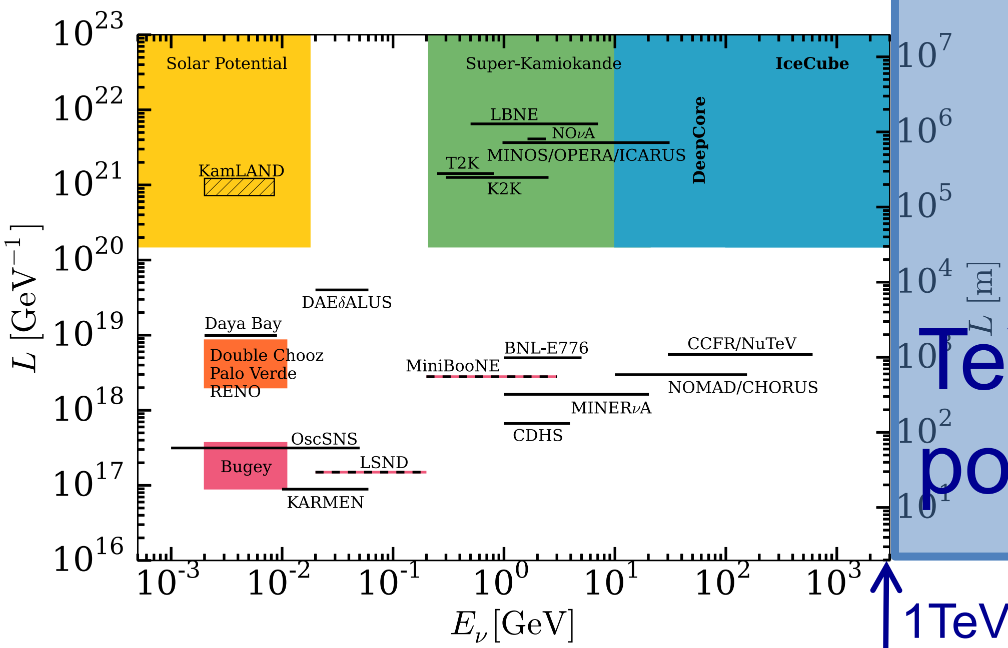
4. New physics phase space by neutrino interferometry

extra galactic
neutrino potential

1Mpc(~Andromeda)

IceCube collaboration
PRL111(2013)021103





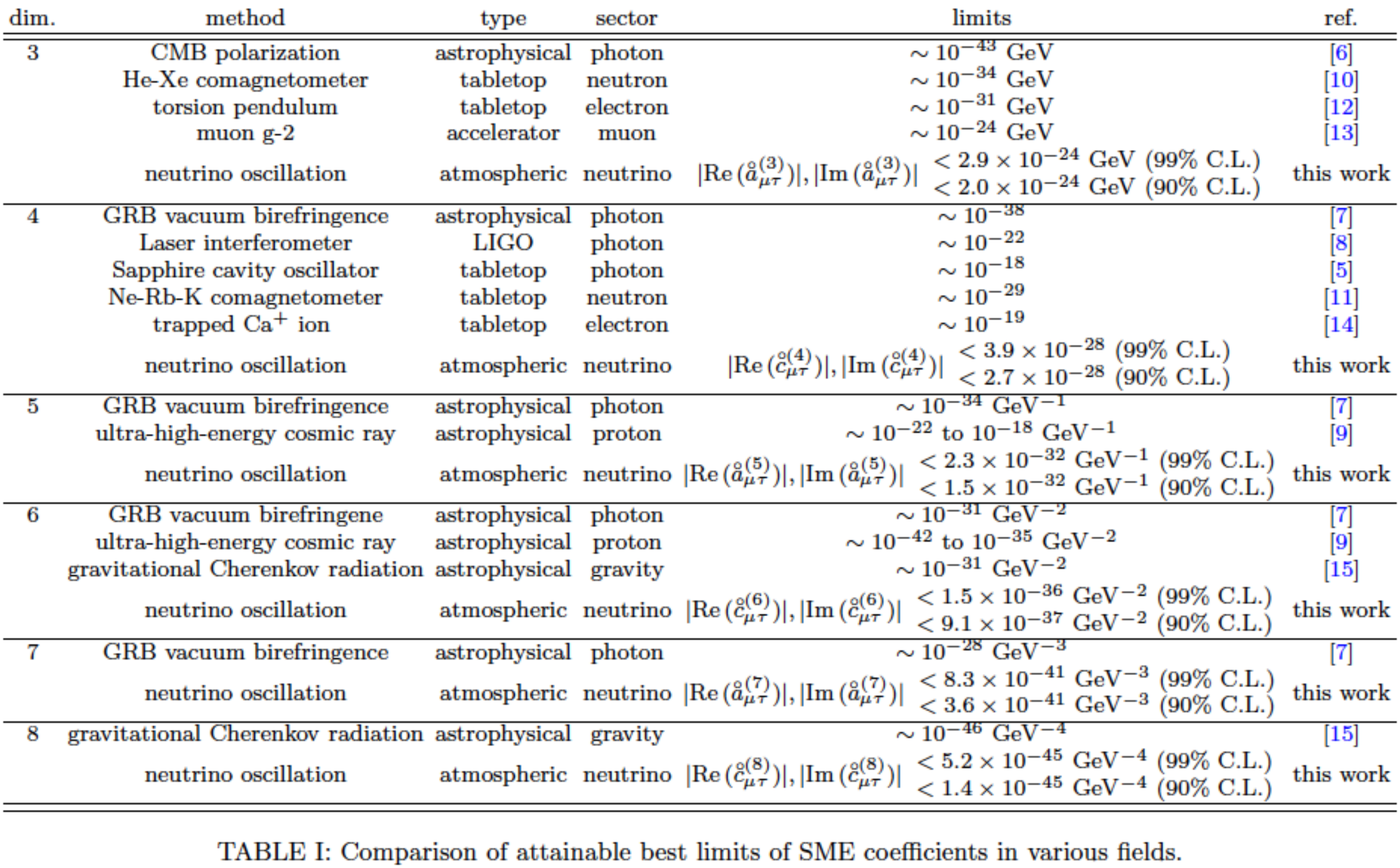
TeV neutrino
potential

1TeV

IceCube, Nature Physics 14 (2018) 961

5. Results

The main results of this paper are new limits on Lorentz violation and to demonstrate the potential of neutrino interferometry. Note, we don't know which sector has Lorentz violation, so there is no straightforward way to compare results from different sectors.



dim.	method	type	sector	limits	ref.
3	CMB polarization	astrophysical	photon	$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron	$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron	$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon	$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$ $< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon	$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon	$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron	$\sim 10^{-29}$	[11]
	trapped Ca^{+} ion	tabletop	electron	$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$ $< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-34}$ GeV^{-1}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$ $< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon	$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$ $< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$ $< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$ $< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

IceCube, Nature Physics 14 (2018) 961

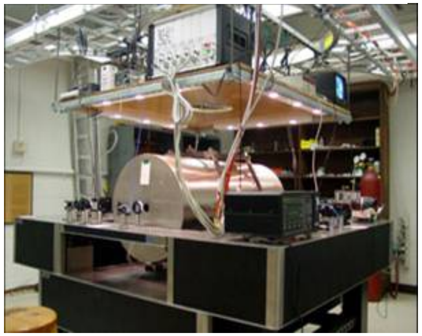
5. Results

Atomic physics results dominate LV test with low dimension operators (effective field theory approach)

dim.	method	type	sector		limits	ref.
3	CMB polarization	astrophysical	photon		$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron		$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron		$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon		$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$	$< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca^{+} ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	
		astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	
		atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (9 $< 1.5 \times 10^{-32}$ GeV^{-1} (9	
6		astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	
		ast				
	gra	ast				
		at		)|, |In	2 (9 2 (9	
7		ast				
		at		)|, |In	(99% C.L.) (90% C.L.)	this work
8	gra	ast				[15]
		at		)|, |In	(99% C.L.) (90% C.L.)	this work

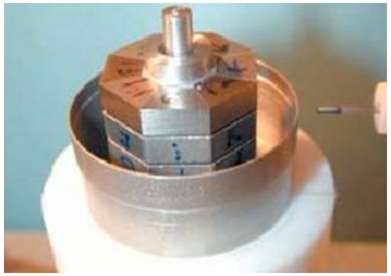
TABLE I: Comparison of attainable best limits of SM lds.

Double gas maser
$b_n < 10^{-34}$GeV
$c_n < 10^{-29}$



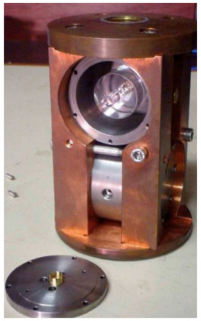
PRL107(2011)171604
PRL112(2014)110801

Spin torsion pendulum
$b_e < 10^{-30}$ GeV



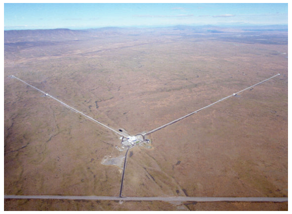
PRL97(2006)021603

Crystal oscillator
$\Delta c/c < 10^{-18}$



Nature.Comm.6(2015)8174

LIGO
$c^{(4)} < 10^{-22}$



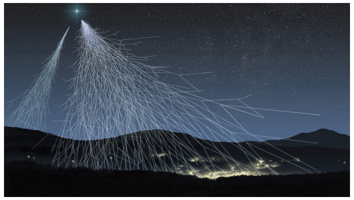
PLB761(2016)1

IceCube, Nature Physics 14 (2018) 961

5. Results

Astrophysical observations dominate LV test with high dimension operators (quantum gravity motivated models)

UHECR
$c^6 < 10^{-42}$ GeV^{-2}
$s^8 < 10^{-46}$ GeV^{-4}



JCAP0904(2009)022
PLB749(2015)551

GRB vacuum birefringence
$\kappa_{e+}, \kappa_{o-} < 10^{-37}$

PRL110(2013)201601

		type	sector		li	
	tion	astrophysical	photon		~ 10	[6]
	ometer	tabletop	neutron		~ 10	10]
	lum	tabletop	electron		~ 10	12]
		accelerator	muon		~ 10	13]
	ation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$	< 2 < 2	work
	fringence	astrophysical	photon		$\sim$	[7]
	meter	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca$^+$ ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$	$< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$	$< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$	$< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

Kostelecký and Mewes, PRD85(2012)096005

4. Astrophysical neutrino flavour with Lorentz violation

We introduce effective operators (motivated by SME formalism)

$$h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U + a_{\alpha\beta}^{(3)} - E c_{\alpha\beta}^{(4)} + E^2 a_{\alpha\beta}^{(5)} - E^3 c_{\alpha\beta}^{(6)} + E^4 a_{\alpha\beta}^{(7)} - E^5 c_{\alpha\beta}^{(8)} \cdots$$

dim-6 operator (lowest order new interaction)

scale

O(1) diagonal element

$$E^3 c_{\alpha\beta}^{(6)} = E^3 \frac{1}{\sqrt{4\pi}} \left(c_{\alpha\beta}^{(6)} \right)_{00} = E^3 \begin{pmatrix} c_{ee}^{(6)} & c_{e\mu}^{(6)} & c_{\tau e}^{(6)} \\ c_{e\mu}^{(6)*} & c_{\mu\mu}^{(6)} & c_{\mu\tau}^{(6)} \\ c_{\tau e}^{(6)*} & c_{\mu\tau}^{(6)*} & c_{\tau\tau}^{(6)} \end{pmatrix} = E^3 c^{(6)} \widetilde{U}_6^\dagger O_6 \widetilde{U}_6$$

mixing matrix

and so on…

We test dim-3 to dim-8 operators one by one to find nonzero scale (or set limit on scale)

$$h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U - E^3 c_{\alpha\beta}^{(6)} = V^\dagger(E) \Delta V(E)$$

$$V(E) = \begin{pmatrix} V_{e1}(E) & V_{e2}(E) & V_{e3}(E) \\ V_{\mu 1}(E) & V_{\mu 2}(E) & V_{\mu 3}(E) \\ V_{\tau 1}(E) & V_{\tau 2}(E) & V_{\tau 3}(E) \end{pmatrix}, \qquad \Delta = \begin{pmatrix} \lambda_1(E) & 0 & 0 \\ 0 & \lambda_2(E) & 0 \\ 0 & 0 & \lambda_3(E) \end{pmatrix}$$

2. Astrophysical neutrino flavour with Lorentz violation

We introduce effective operators (motivated by SME formalism)

$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + a^{(3)}_{\alpha\beta} - E c^{(4)}_{\alpha\beta} + E^2 a^{(5)}_{\alpha\beta} - E^3 c^{(6)}_{\alpha\beta} + E^4 a^{(7)}_{\alpha\beta} - E^5 c^{(8)}_{\alpha\beta} \cdots$$

Neutrino oscillation formula is written with mixing matrix elements and eigenvalues

$$P_{\alpha\to\beta}(E,L) = 1 - 4\sum_{i>j} Re\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) sin^2\left(\frac{\lambda_i - \lambda_j}{2} L\right) + 2\sum_{i>j} Im\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) sin\left((\lambda_i - \lambda_j) L\right)$$

However, astrophysical neutrinos propagate O(100Mpc) → lost coherence

$$P_{\alpha\to\beta}(E,\infty) \sim 1 - 2\sum_{i>j} Re\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) = \sum_{i} |V_{\alpha i}|^2 \left|V_{\beta i}\right|^2$$

→ Information of small new physics is encoded on neutrino mixing probability, so by measuring astrophysical neutrino flavours, you can access potential new physics

2. Spontaneous Lorentz symmetry breaking (SLSB)

Every fundamental symmetry needs to be tested, including Lorentz symmetry.

After the recognition of theoretical processes that create Lorentz violation, testing Lorentz invariance becomes very exciting

Lorentz and CPT violation has been shown to occur in Planck scale theories, including:
- string theory
- noncommutative field theory
- quantum loop gravity
- extra dimensions
- etc

However, it is very difficult to build a self-consistent theory with Lorentz violation...

Spontaneous Symmetry Breaking (SSB)!

Y. Nambu
(Nobel prize winner 2008),
picture from CPT04 at
Bloomington, IN

2. Spontaneous Lorentz symmetry breaking (SLSB)

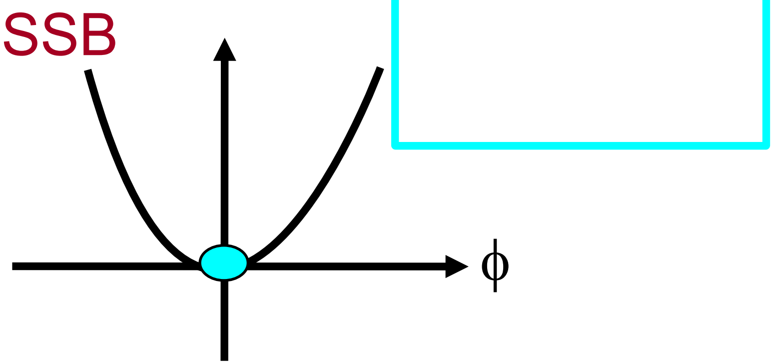
vacuum Lagrangian for fermion $L = i\overline{\Psi}\gamma_{\mu}\partial^{\mu}\Psi$

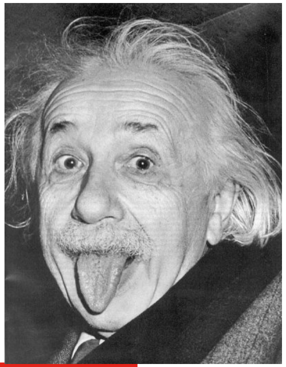
e.g.) SSB of scalar field in Standard Model (SM)

- If the scalar field has Mexican hat potential

$$L = \frac{1}{2}(\partial_{\mu}\varphi)^2 - \frac{1}{2}\mu^2(\varphi^*\varphi) - \frac{1}{4}\lambda(\varphi^*\varphi)^2$$

$$M(\varphi) = \mu^2 < 0$$





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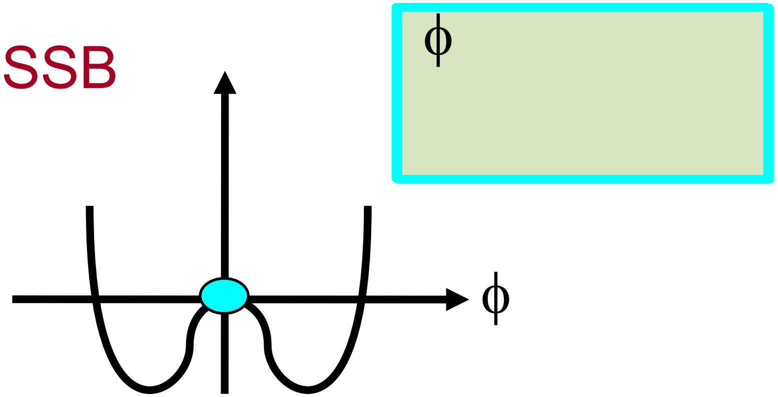
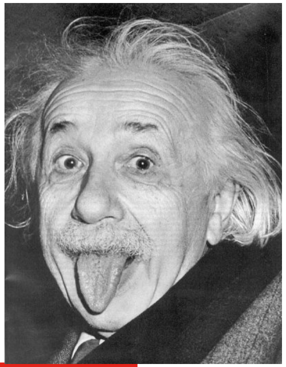
SSB





Particle acquires
mass term!

Kostelecký and Samuel,PRD39(1989)683

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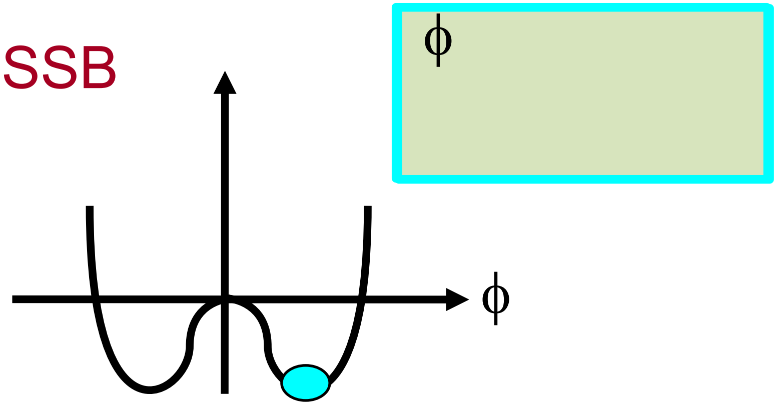
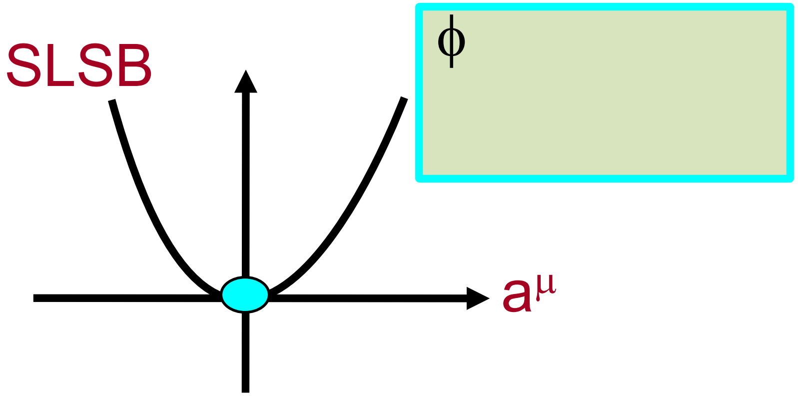
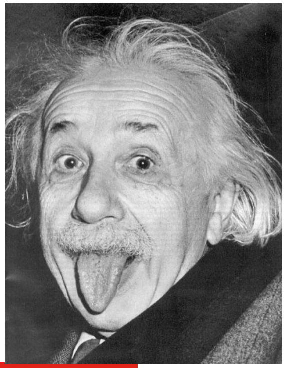


e.g.) SLSB in string field theory

- There are many Lorentz vector fields
- If any of vector field has Mexican hat potential

$$M(a^\mu) = \mu^2 < 0$$





Kostelecký and Samuel,PRD39(1989)683

2. Spontaneous Lorentz symmetry breaking (SLSB)

vacuum Lagrangian for fermion $L = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi - m\bar{\Psi}\Psi + \bar{\Psi}\gamma_\mu a^\mu\Psi$

e.g.) SSB of scalar field in Standard Model (SM)

- If the scalar field has Mexican hat potential

$$L = \frac{1}{2}(\partial_\mu \varphi)^2 - \frac{1}{2}\mu^2(\varphi^*\varphi) - \frac{1}{4}\lambda(\varphi^*\varphi)^2$$

$$M(\varphi) = \mu^2 < 0$$

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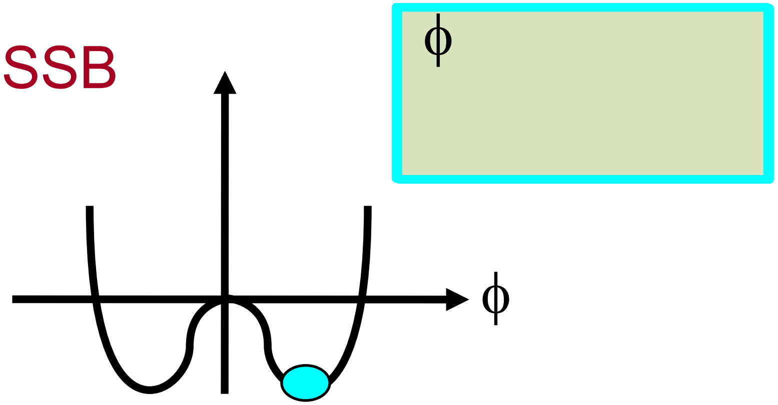

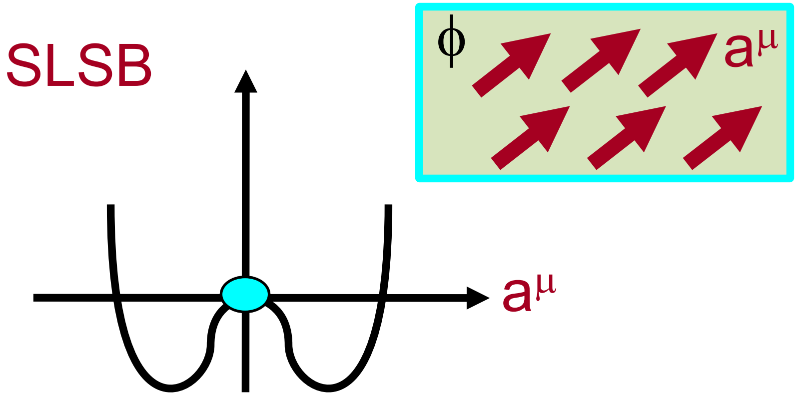

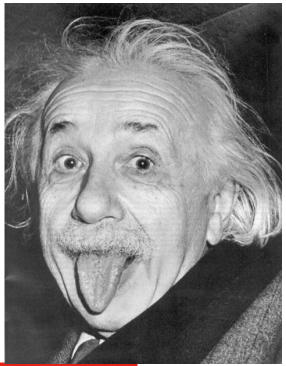

Lorentz symmetry is spontaneously broken!