Neutrino Observatories

outline

1. **Introduction**
2. **High-energy astrophysical neutrinos**
3. **Particle physics with high-energy neutrinos**
4. **Future**
5. **Conclusion**

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Teppei Katori
King’s College London

UK HEP Forum, Cosener’s house, Abingdon, Nov. 22, 2022

1. Introductions

2. High-energy astrophysical neutrinos

3. Particle physics with high-energy neutrinos

4. Future

5. Conclusion

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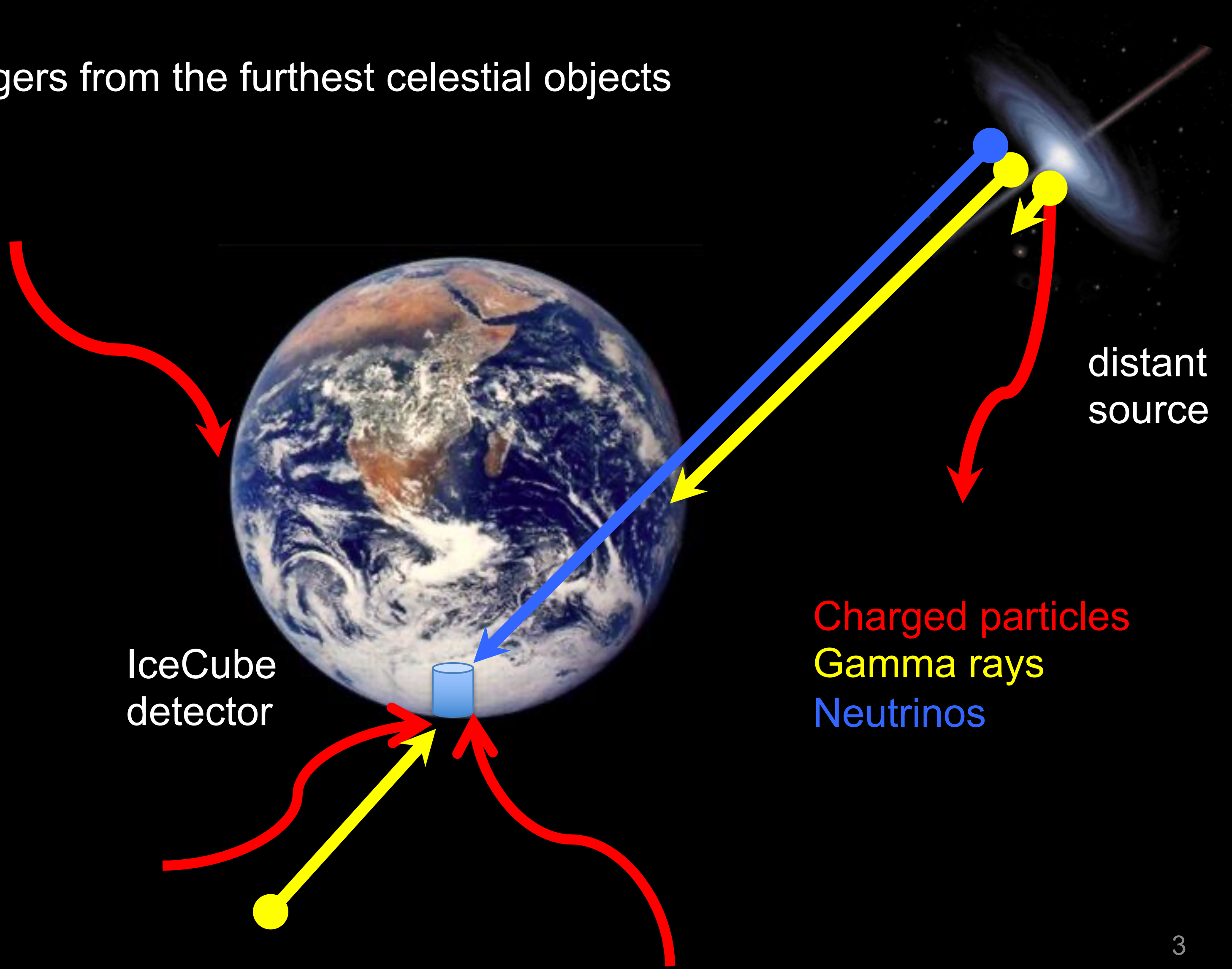
1. High-Energy Astrophysical Neutrinos

Direct messengers from the furthest celestial objects

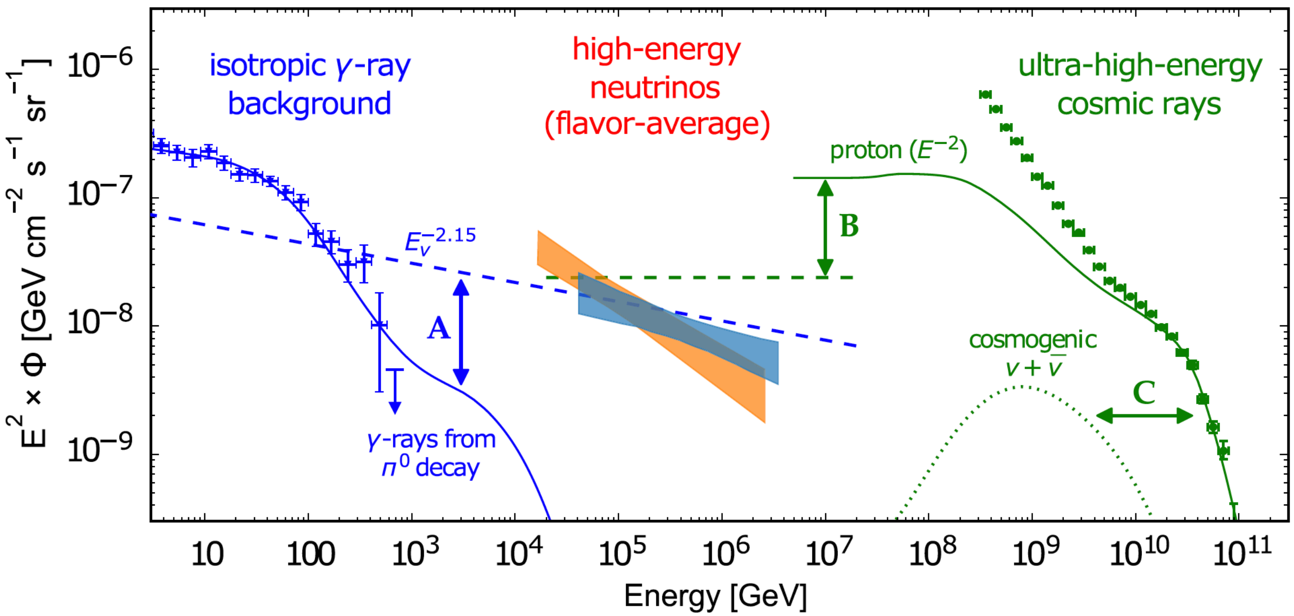


IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378
IceCube-Gen2, J.Phys.G.48(2021) 060501

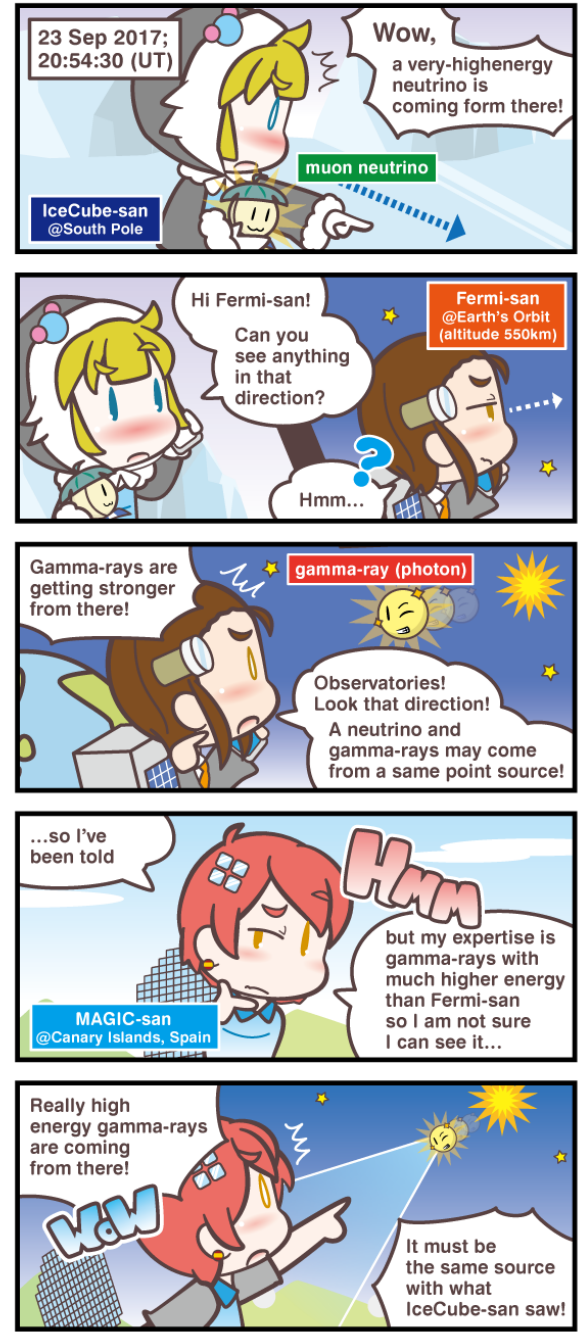
1. Multi-messenger astronomy

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

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



Neutrino☆Multi-messenger



http://higgstan.com/

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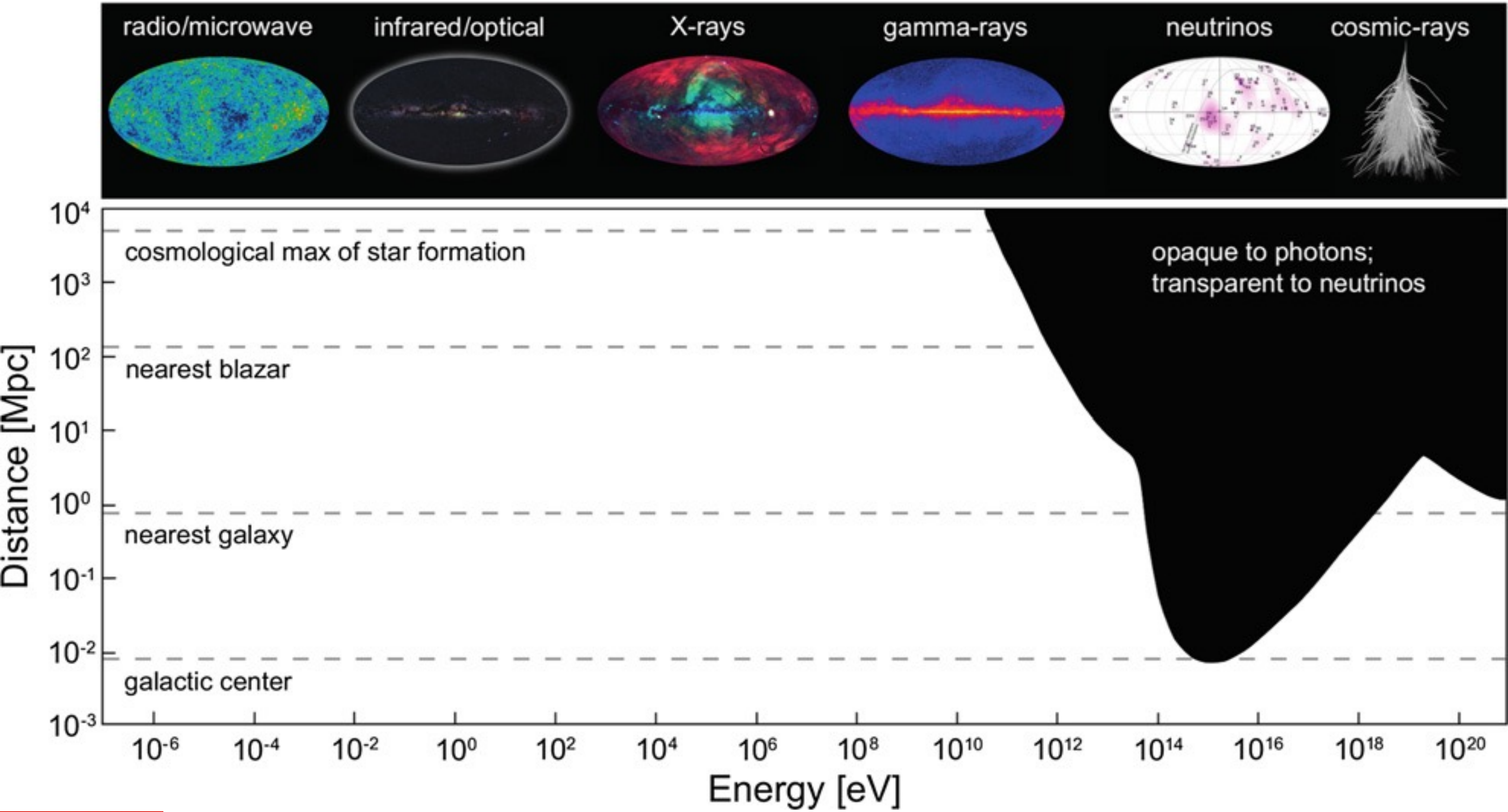
1. High-energy astrophysics

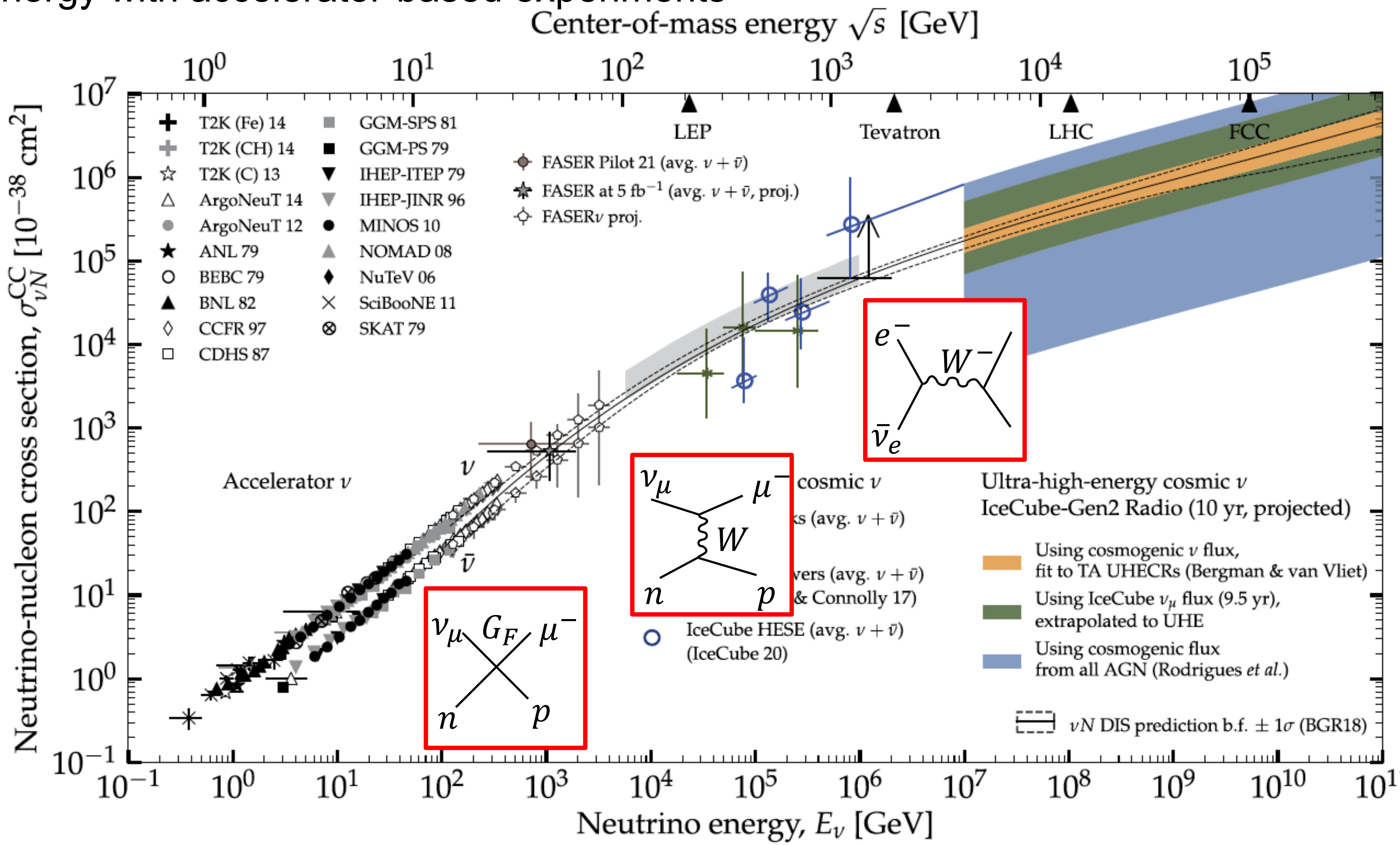
Above ~10-100 TeV neutrinos are only direct extra-galactic messengers



Ackermann,Bustamante,Lu et al.JHEA.36(2022)55

1. High-energy fixed target experiment

Synergy with accelerator-based experiments



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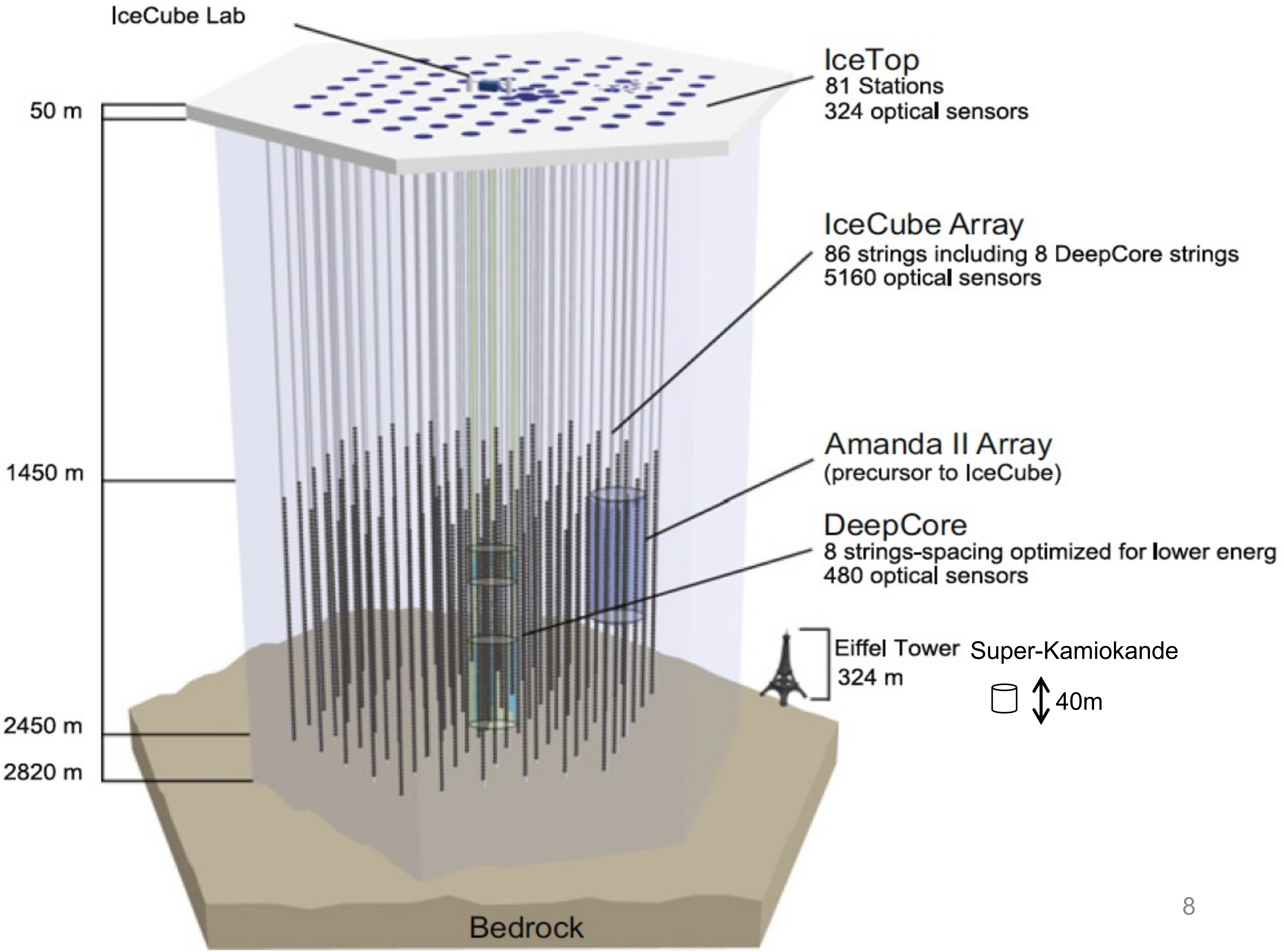
2. IceCube detector



IceCube-Gen2, J.Phys.G.48(2021) 060501

2. IceCube event morphology

Track
ν_μCC

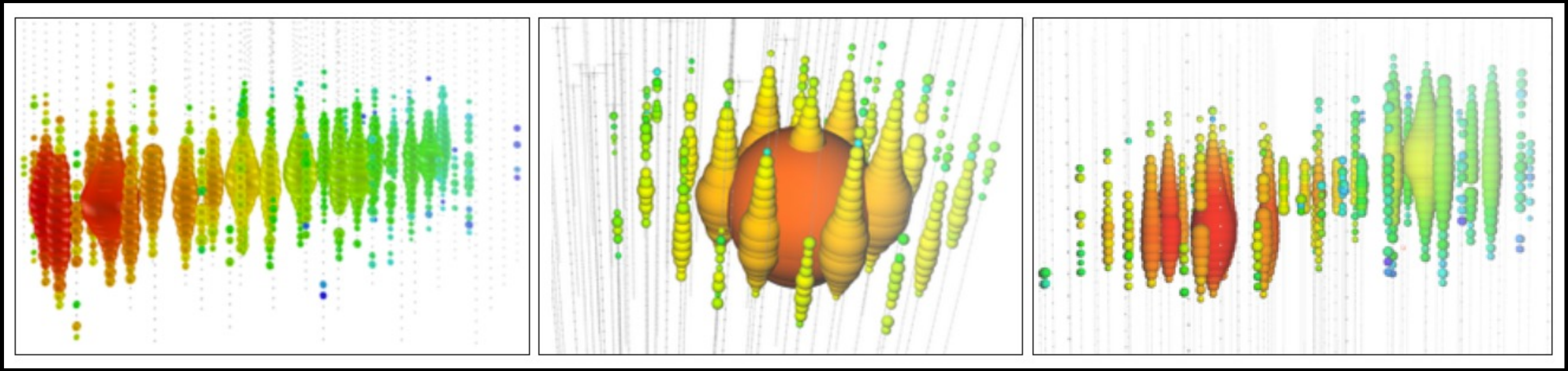
$$\nu_\mu + N \rightarrow \mu + X$$

Cascade
ν_eCC, ν_τCC, NC

$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

Double cascade
ν_τCC (L~50m•E/PeV)

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



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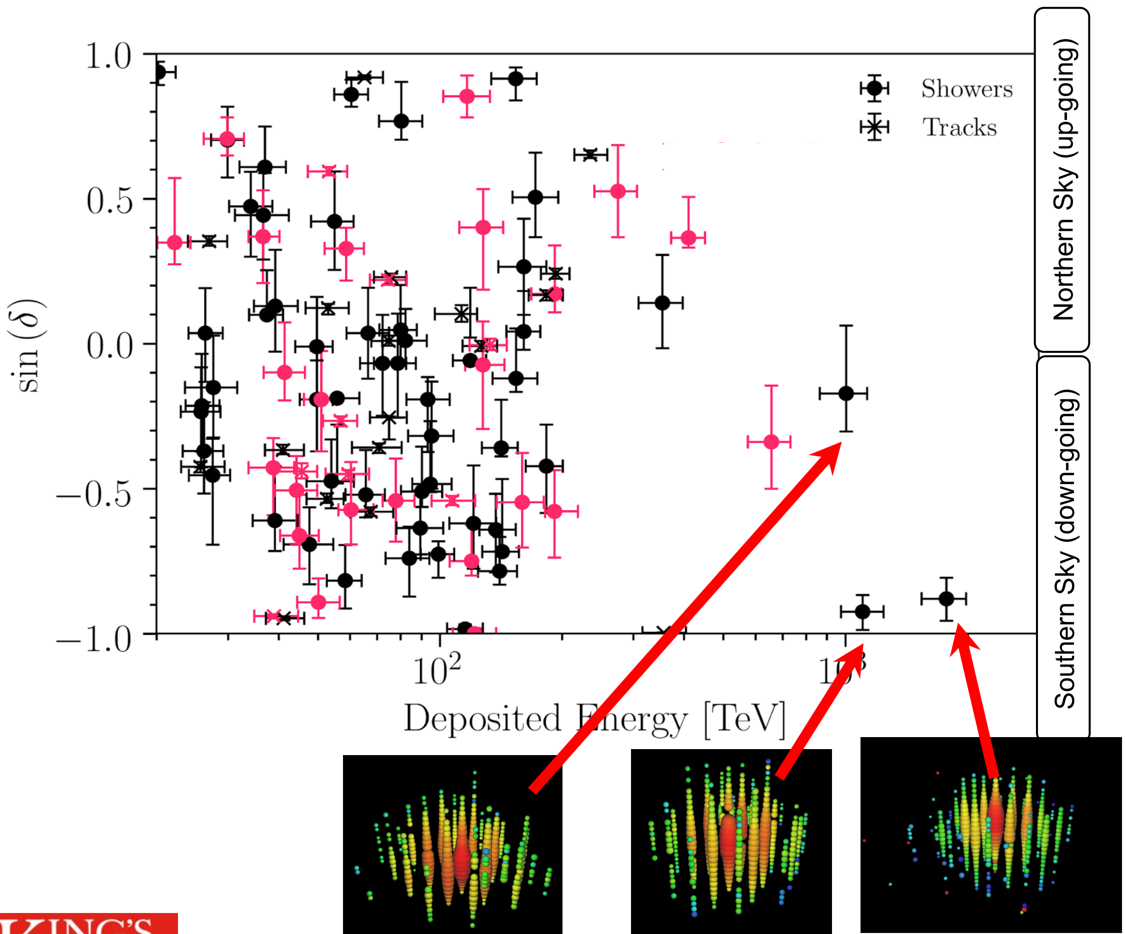
IceCube,Science.342(2013)1242856,PRD104,(2021)022002

2. High-energy astrophysical neutrinos

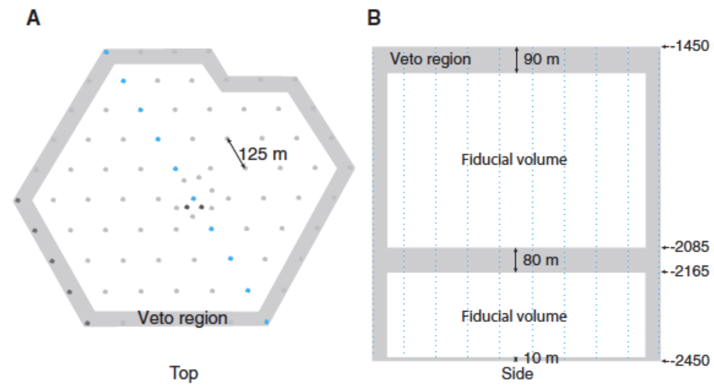
First observation (2013)
- 60-2000 TeV neutrinos



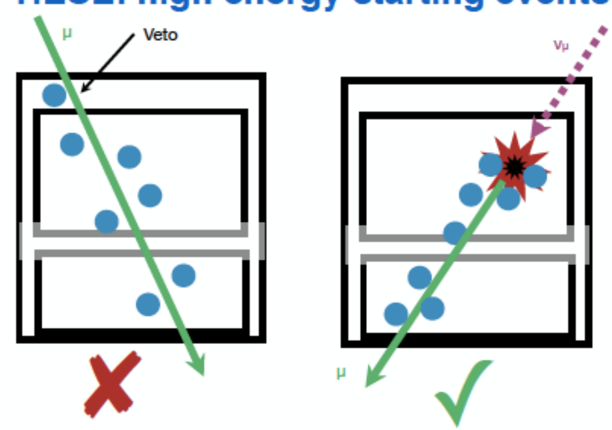
"Bert" 1.1 PeV

"Ernie" 1.0 PeV

"Big Bird" 2.0 PeV



HESE: high energy starting events



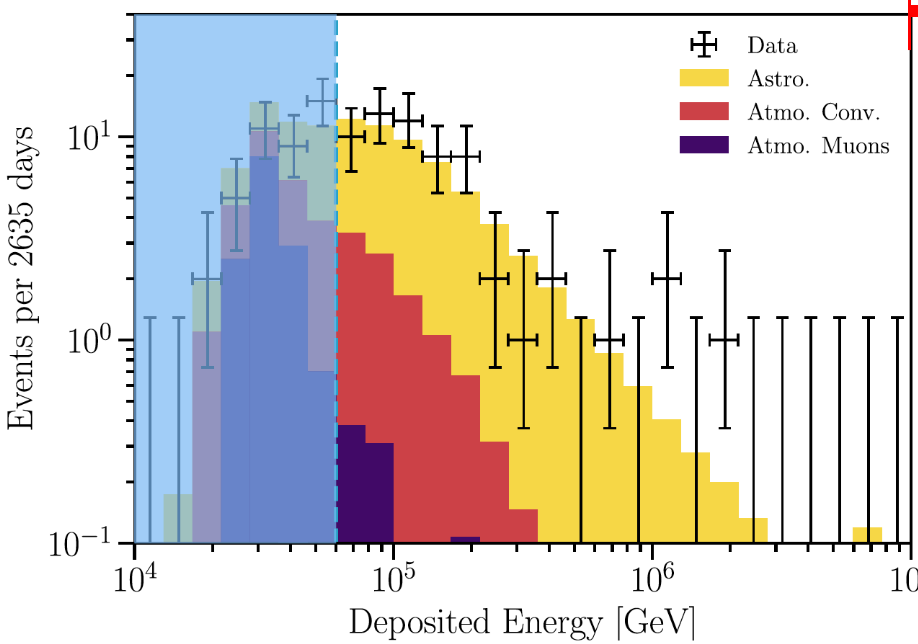
IceCube,Science.342(2013)1242856,PRD104,(2021)022002,ApJ.928(2022)50

2. High-energy astrophysical neutrinos

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

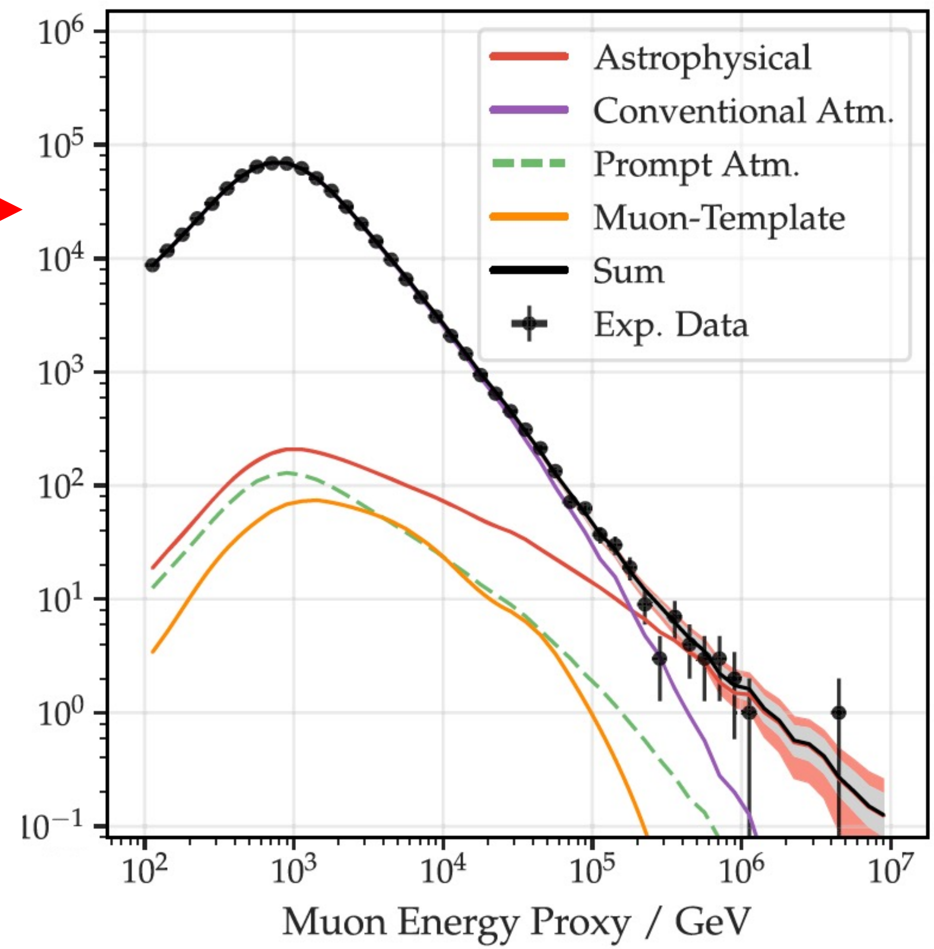
Cosmogenic "UHE" neutrinos

$p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi \rightarrow \nu$



High-energy starting events

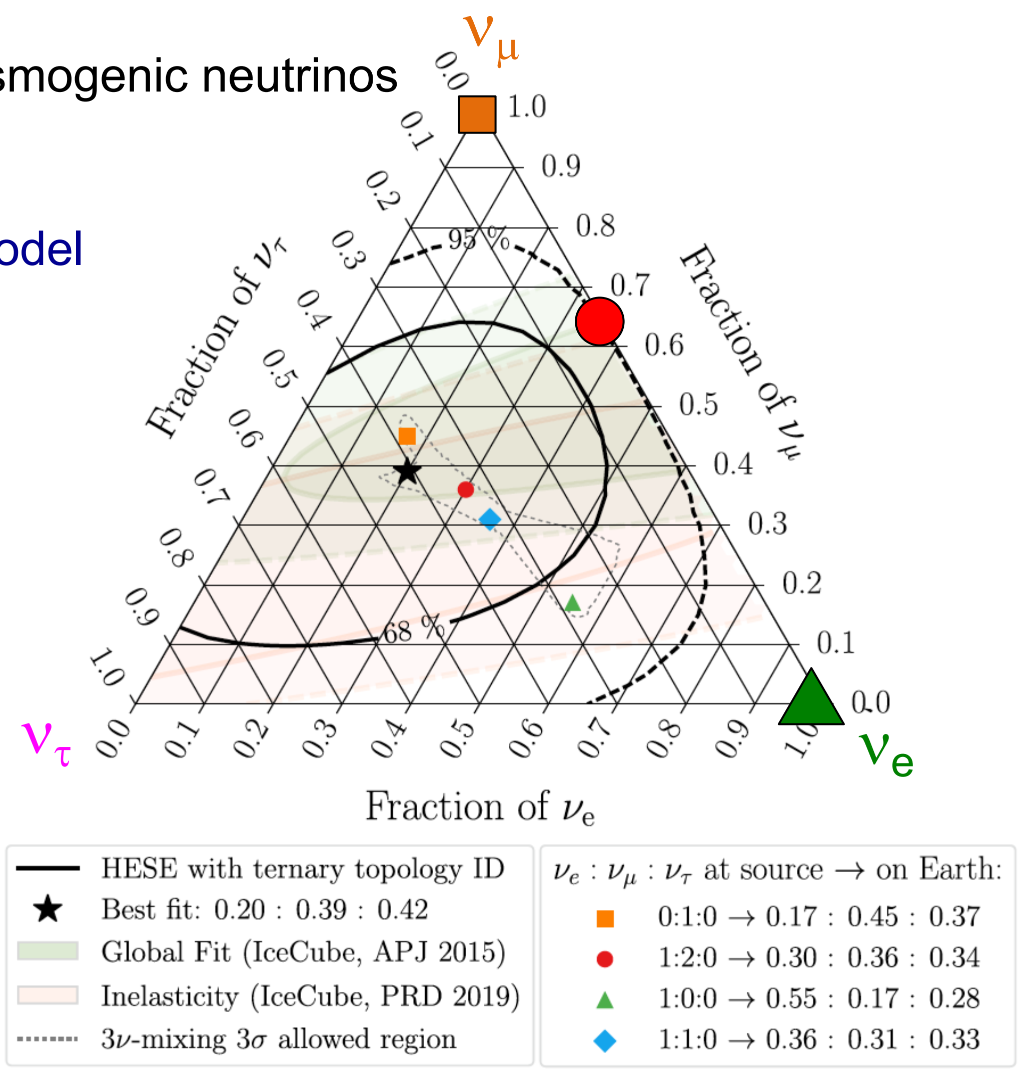
Through going track events



2. High-energy astrophysical neutrinos

First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from atmospheric and cosmogenic neutrinos
- Flavour not understood

Astrophysical neutrino production model
- $\nu_e:\nu_\mu:\nu_\tau \sim 1:2:0$
- After mixing, $\nu_e:\nu_\mu:\nu_\tau \sim 1:1:1$



2. High-energy astrophysical neutrinos

First observation (2013)
- 60-2000 TeV neutrinos
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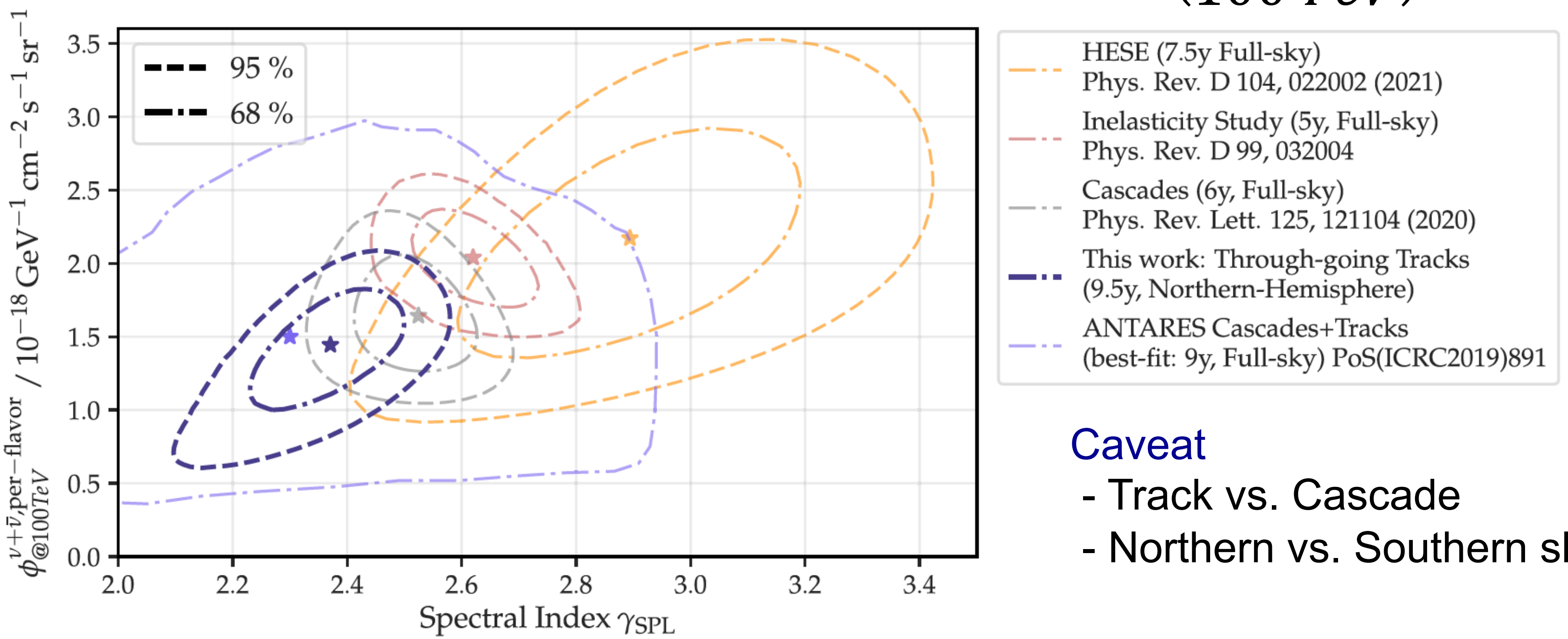
- Flavour not understood
- Spectrum not understood

$$\Phi_\nu \sim \phi_{SPL} \cdot \left(\frac{E_\nu}{100\ TeV}\right)^{-\gamma_{SPL}}$$

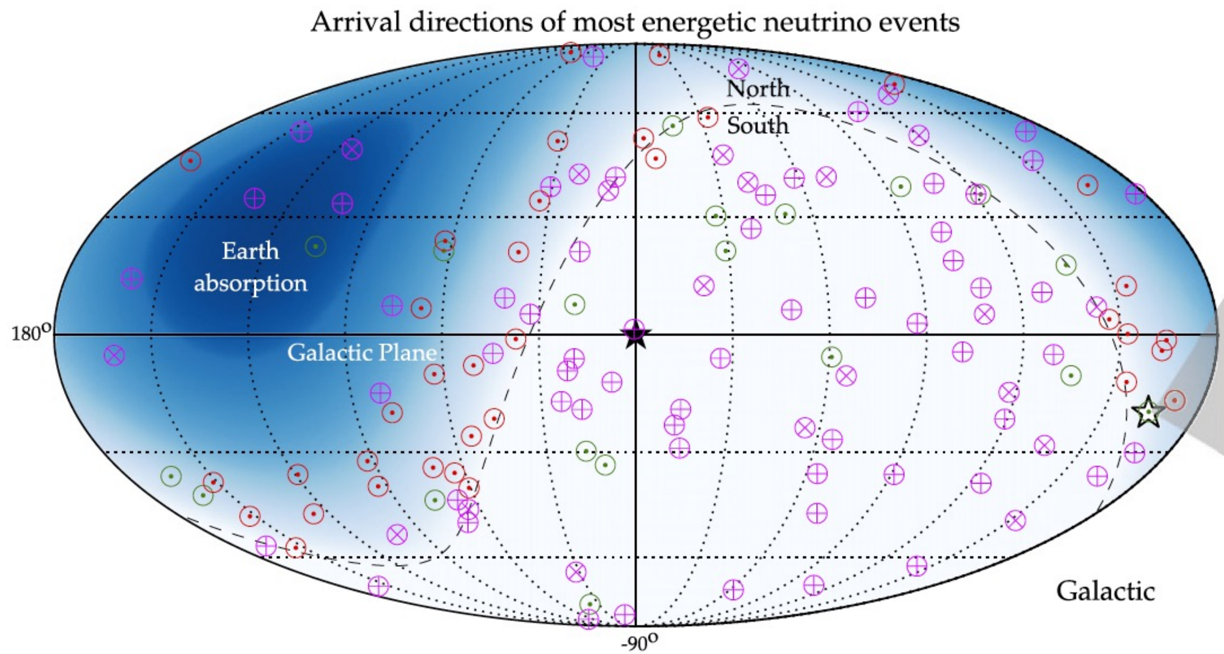


Caveat
- Track vs. Cascade
- Northern vs. Southern sky

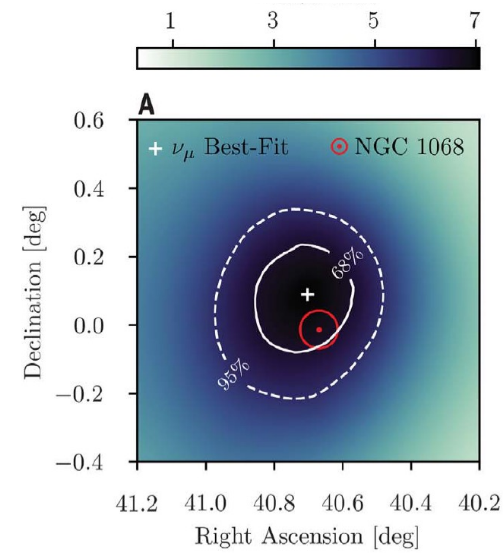
IceCube-Gen2, J.Phys.G.48(2021) 060501
IceCube, Science361(2018)147:378(2022)538

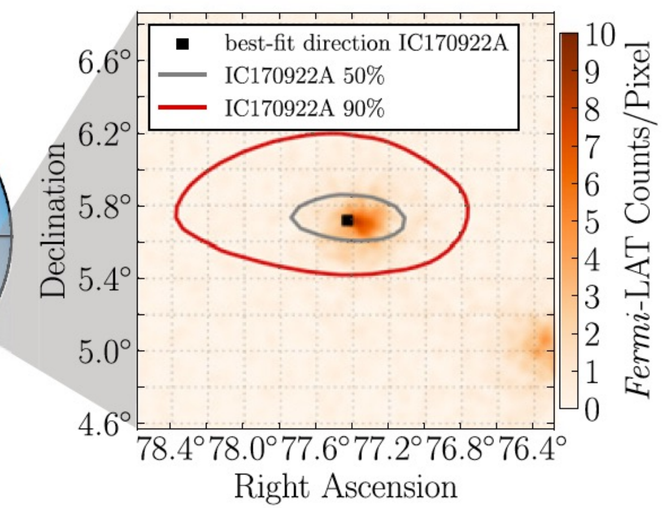
2. High-energy astrophysical neutrinos

First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from atmospheric and cosmogenic neutrinos
- Flavour not understood
- Spectrum not understood
- Sources are mostly unknown (diffuse)



NGC1068 (Radio galaxy)
- Point source

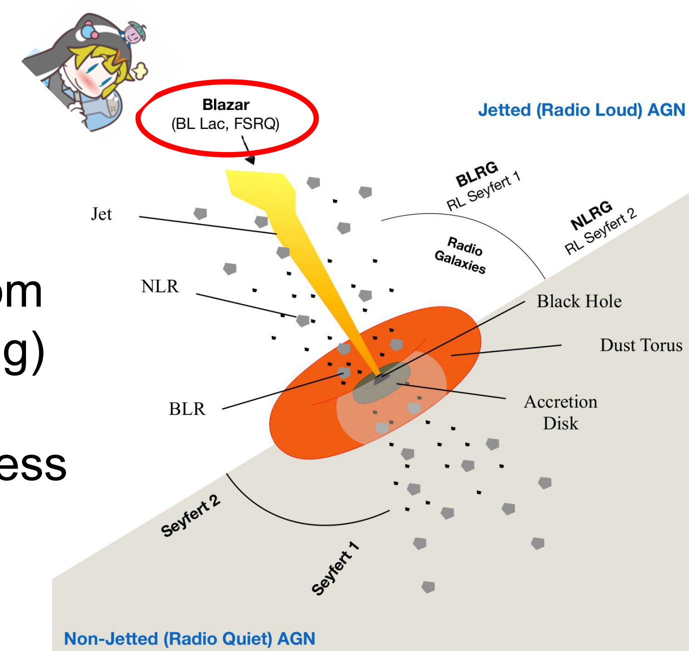




TXS 0506+056 (Blazar)
- Point source

IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378
Gao,Fedynitch,Winter, Pohl, Nature Astronomy 3(2019)88

2. AGN neutrinos

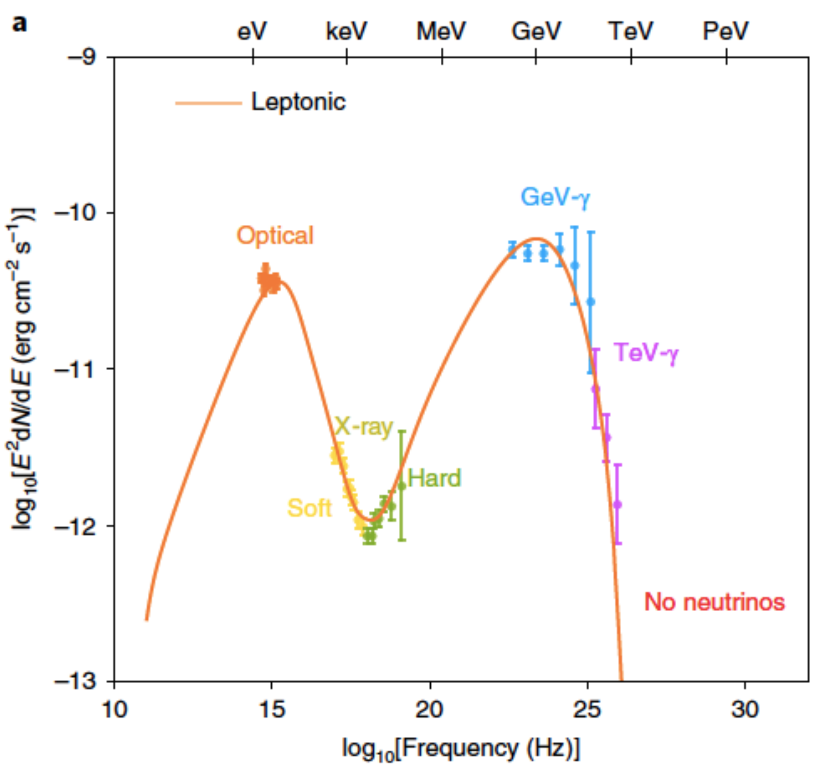


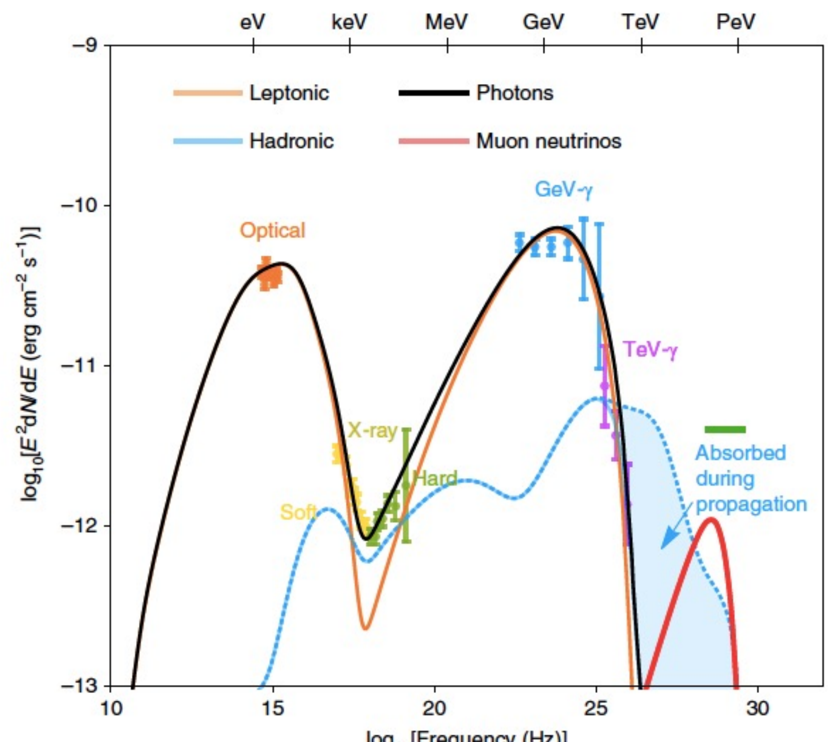
TXS056+0506 (blazar)

- leptonic process can explain all optical signals from TXS0506+056 (Synchrotron self-Compton scattering)

- Neutrino signals imply presence of hadronic process

$$\pi^0 \rightarrow \gamma\gamma$$





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2. AGN neutrinos

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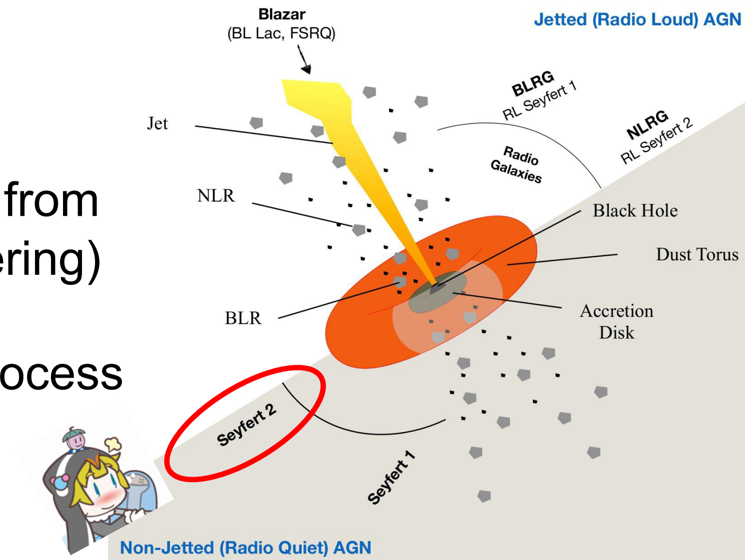
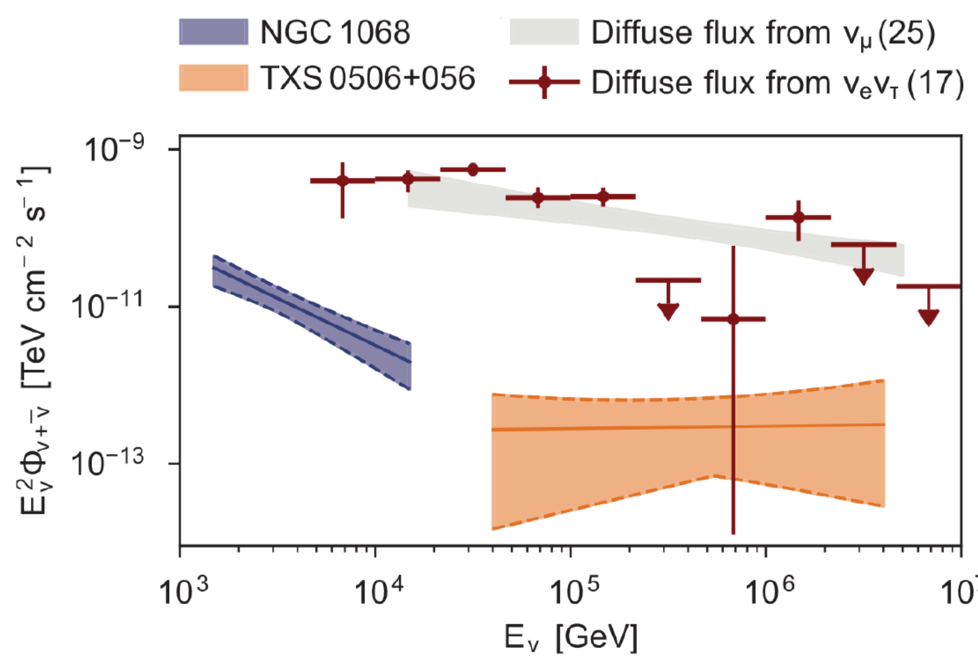


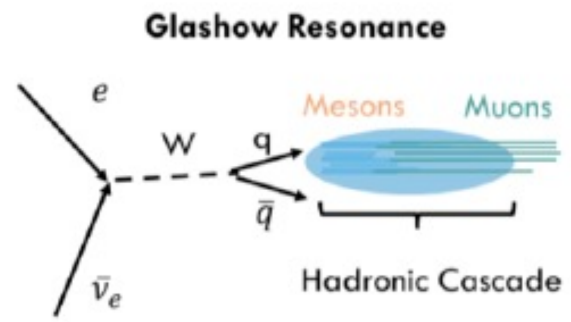
NGC1068 (radio galaxy)

- Nearby AGN (14.4Mpc)
- 1.5 – 15 TeV with γ~3.2±0.2

This suggests we may have more accessible high-energy astrophysical neutrino sources

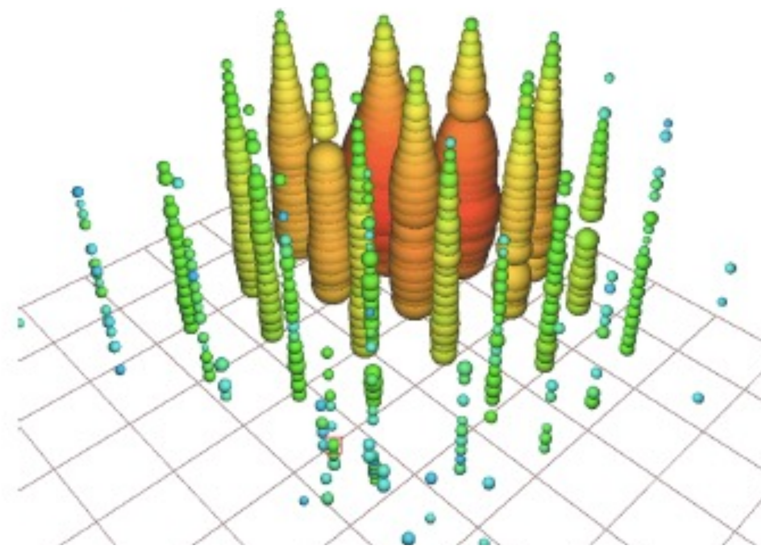


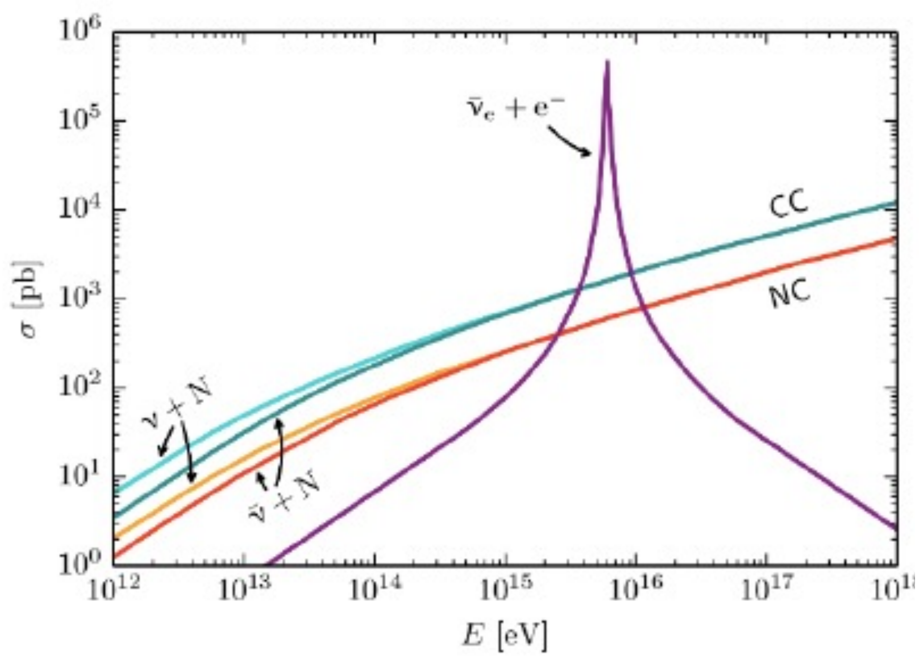
2. Glashow resonance

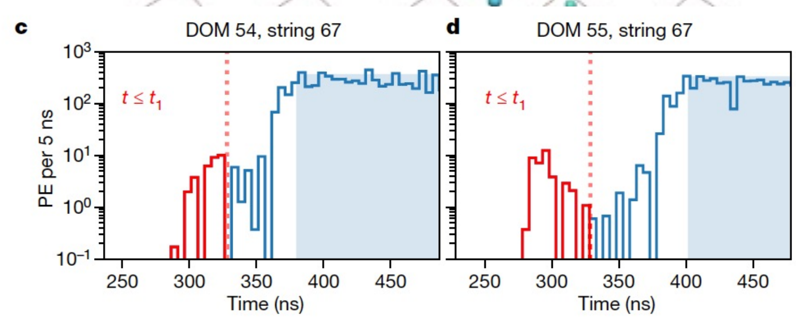


Hydrangea

- Partially contained
- Detected muon from faster than Cherenkov cone
- 5.9±0.2 PeV



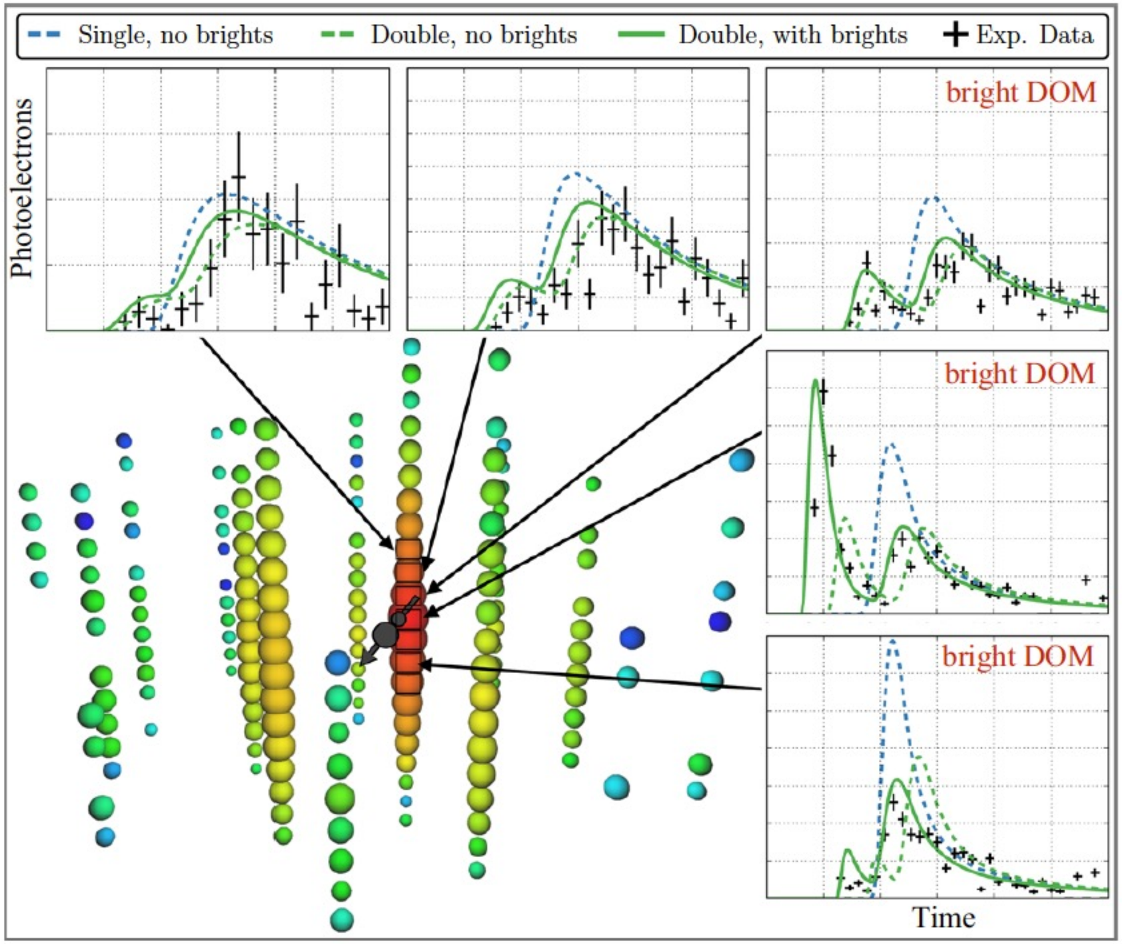




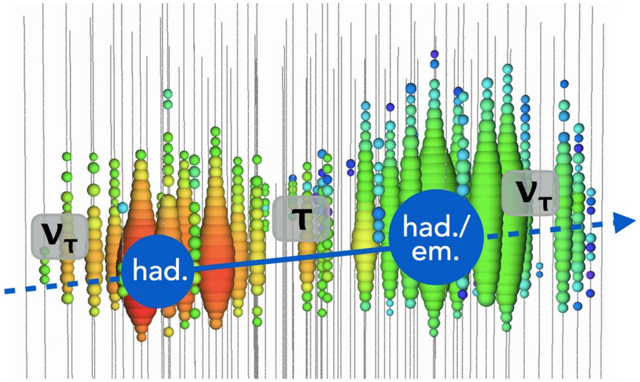
2. Astrophysical tau neutrinos

Double Double

- newly discovered tau neutrino candidate



“Double bang” is rare (~50m xE/1PeV)



Double pulse can be found using timing information.

Improved tau PID algorithm is used for the flavour ratio

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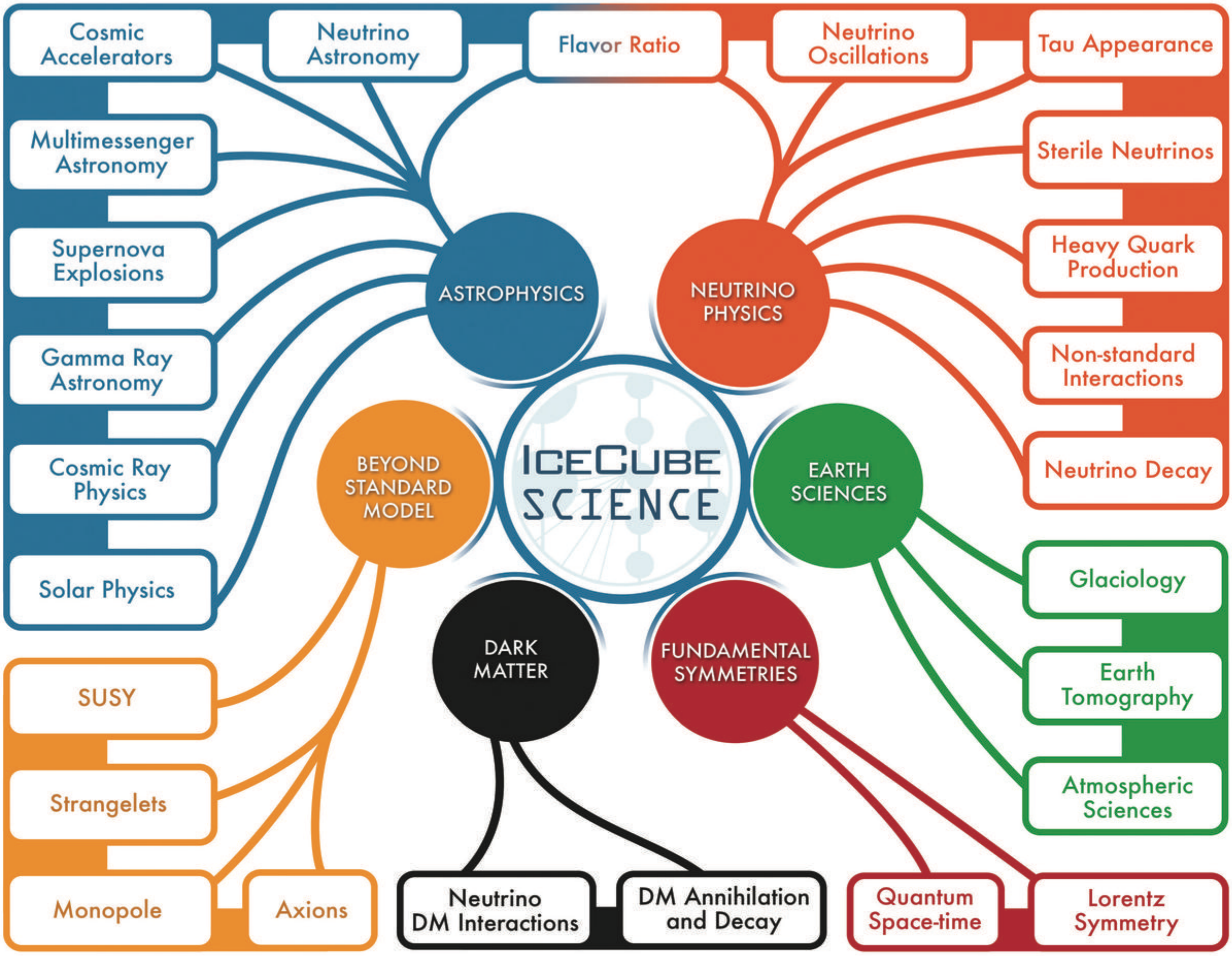
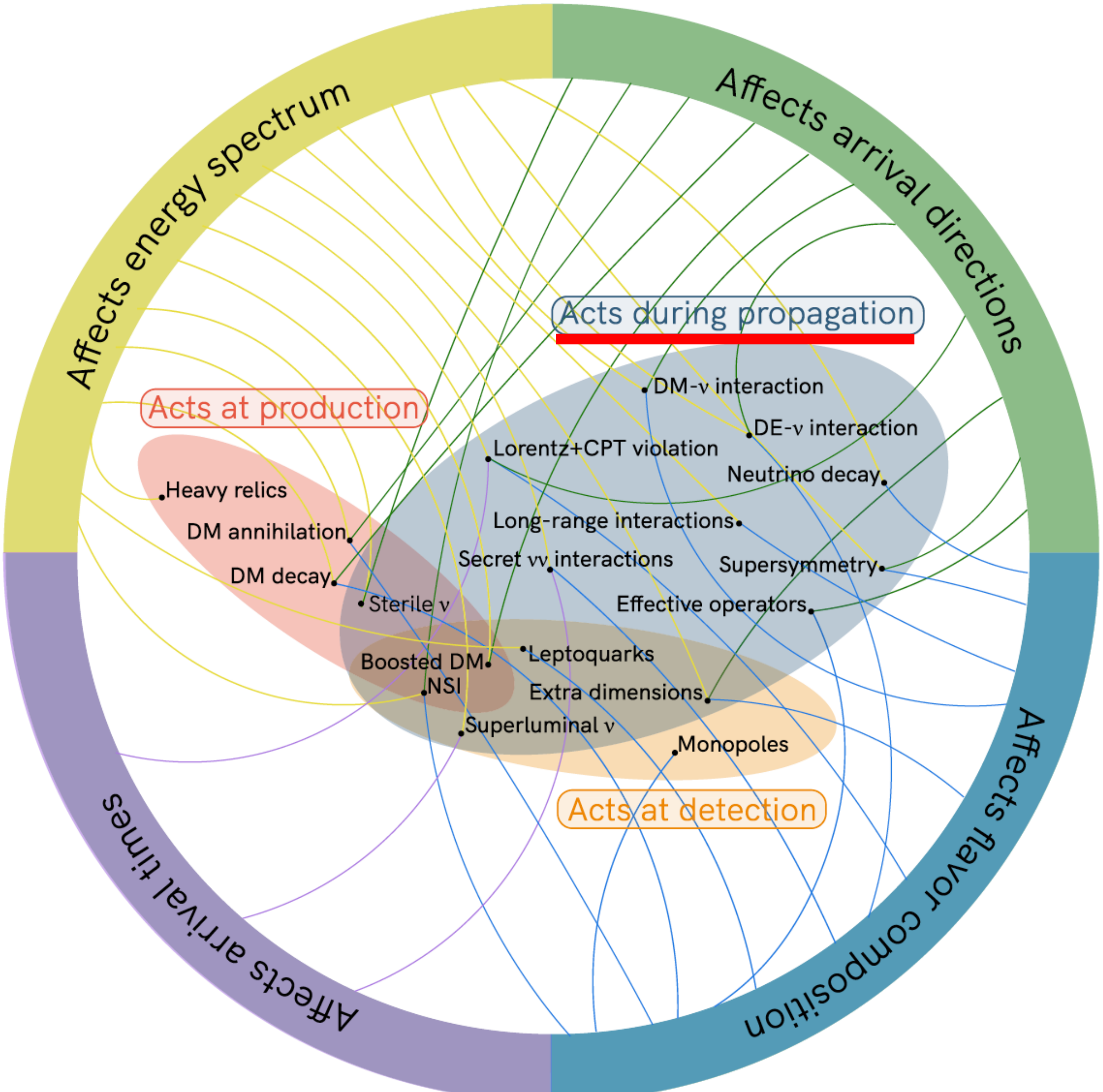


ICECUBE SCIENCE
ASTROPHYSICS
Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Multimessenger Astronomy
Supernova Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
NEUTRINO PHYSICS
Neutrino Oscillations
Tau Appearance
Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
Neutrino Decay
BEYOND STANDARD MODEL
SUSY
Strangelets
Monopole
Axions
DARK MATTER
Neutrino DM Interactions
DM Annihilation and Decay
FUNDAMENTAL SYMMETRIES
Quantum Space-time
Lorentz Symmetry
EARTH SCIENCES
Glaciology
Earth Tomography
Atmospheric Sciences

Snowmass21 white paper, “Beyond the Standard Model effects on Neutrino Flavor”, ArXiv:2203.10811
Ackermann,Bustamante,Lu et al.JHEA.36(2022)55

3. Particle physics with high-energy neutrinos



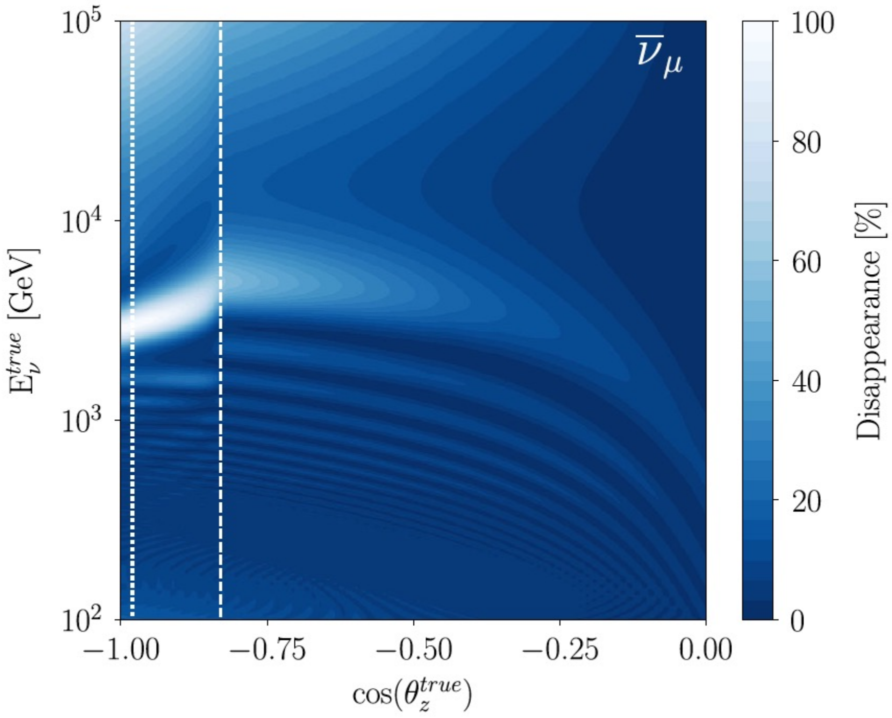
Snowmass21 white paper, "Beyond the Standard Model effects on Neutrino Flavor", ArXiv:2203.10811
IceCube, PRL125(2020)141801,PRD102(2020)052009

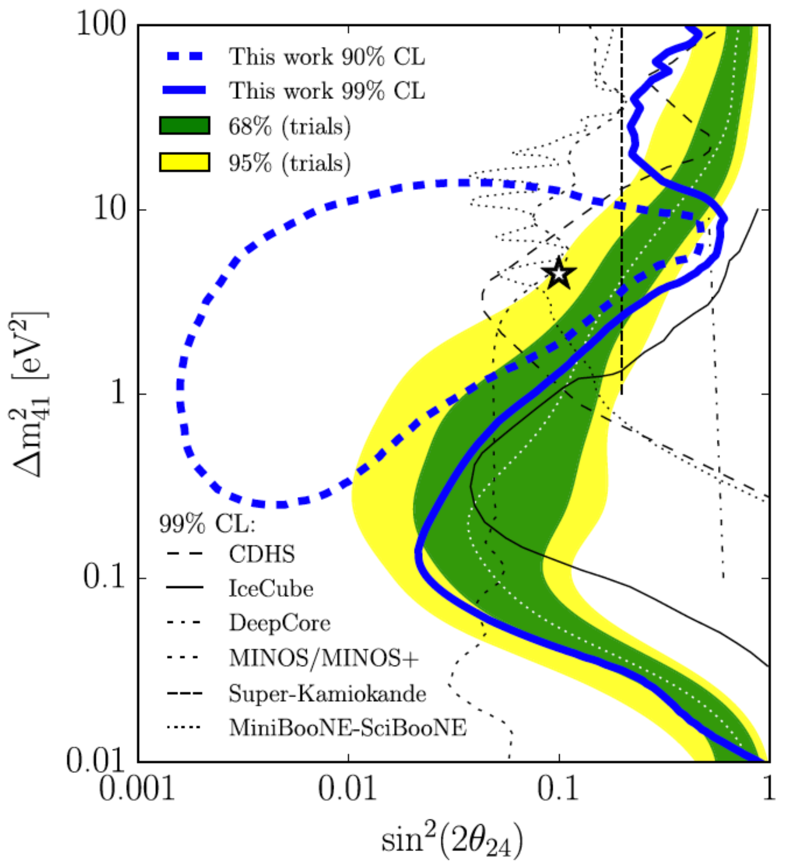
3. High-energy atmospheric neutrinos

1eV sterile neutrinos

- MSW resonance around 1 TeV with 12700 km (earth diameter)
- All disappearance experiments (including IceCube) disfavour 1eV sterile neutrinos

$\bar{\nu}_\mu$ disappearance with
Δm^2_{41}=1.3 eV^2, $\sin^2\theta_{24}$=0.07, $\sin^2\theta_{34}$=0





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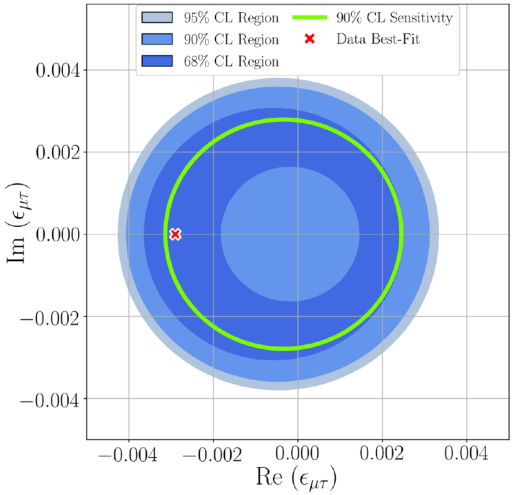
3. High-energy atmospheric neutrinos

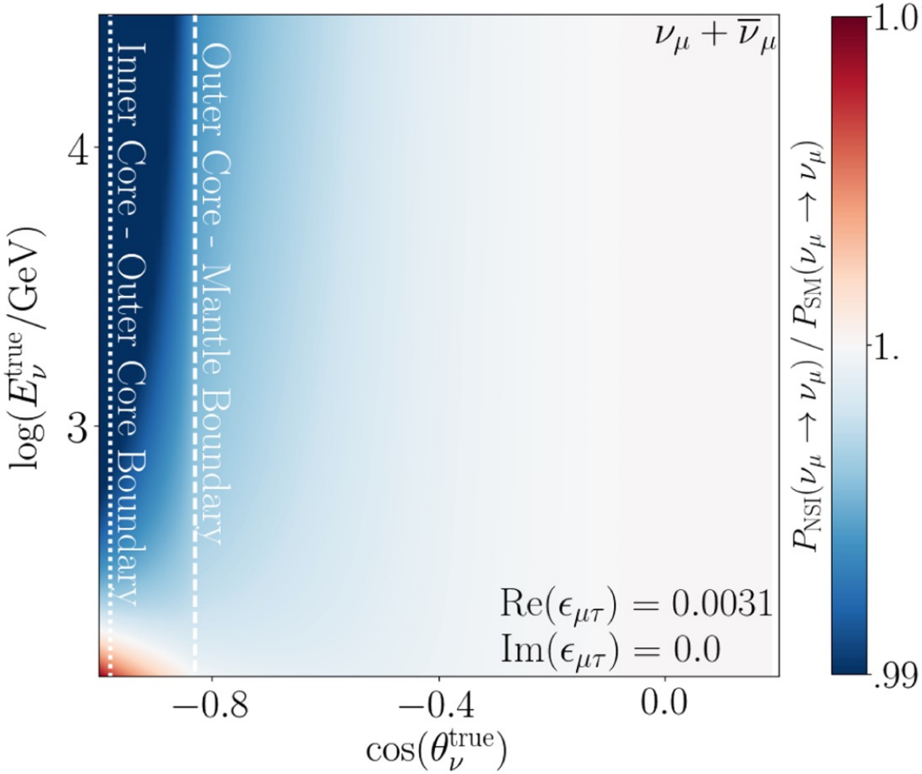
Non-standard interactions (NSIs)

- High energy (~20 TeV)
- Long baseline (~12700m)

$$P \sim sin^2\left[\left(\frac{\Delta m^2}{2E} + new\ physics\right)\cdot L\right]$$



ν_μ disappearance with nonzero NSI
Re($\varepsilon_{\mu\tau}$)=0.0031, Im($\varepsilon_{\mu\tau}$)=0.0031



ε~0.003 → ~10^{-25} GeV new physics

cf) The highest precision hydrogen 1S-2S transition (PRL107(2011)203001)
Fractional frequency uncertainty ~ 4×10^{-15}
→ new physics sensitivity ~10^{-23} GeV

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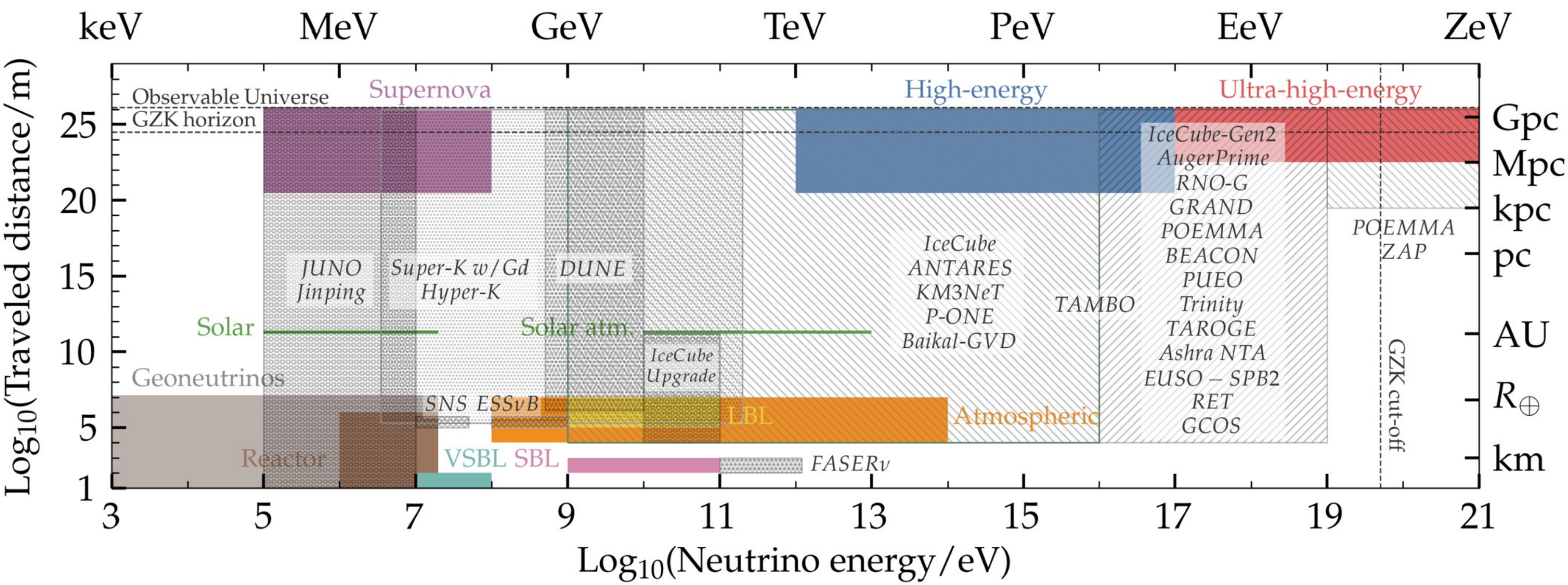
3. High-energy astrophysical neutrinos

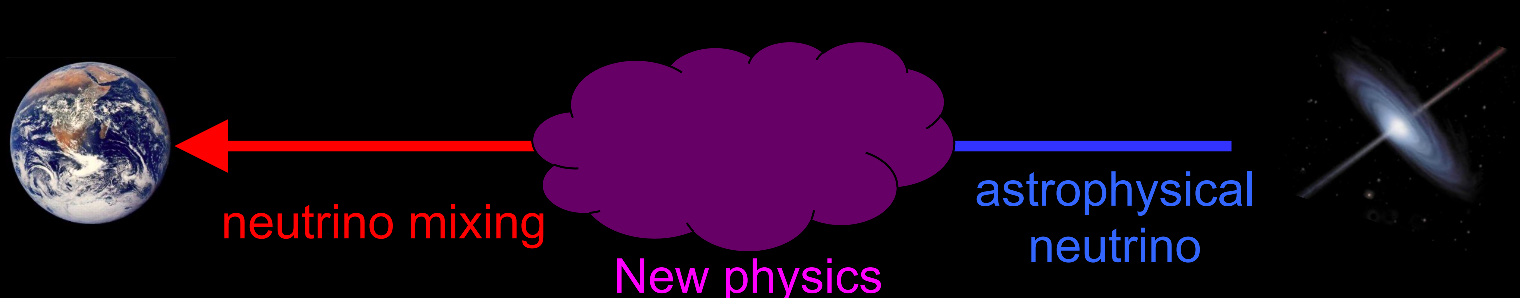
Astrophysical neutrino flavour physics

- High energy (~ PeV)
- Long baseline (~Mpc)



3. Propagations of high-energy astrophysical neutrinos

High-energy particles (>100 TeV) propagating a long distance (>1 Mpc)
- Neutrinos can probe new physics in the universe



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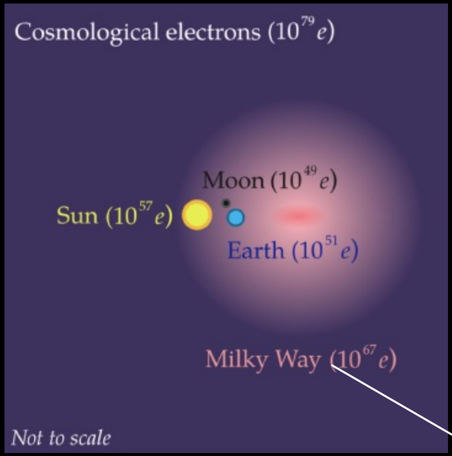
3. Propagations of high-energy astrophysical neutrinos

High-energy particles (>100 TeV) propagating a long distance (>1 Mpc)

- Neutrinos can probe new physics in the universe

new long-range force

Bustamante,Agarwalla PRL122(2019)061103

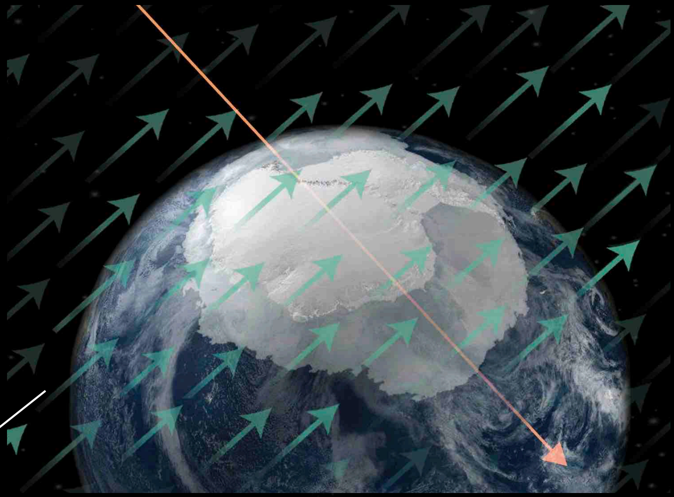


Quantum foam

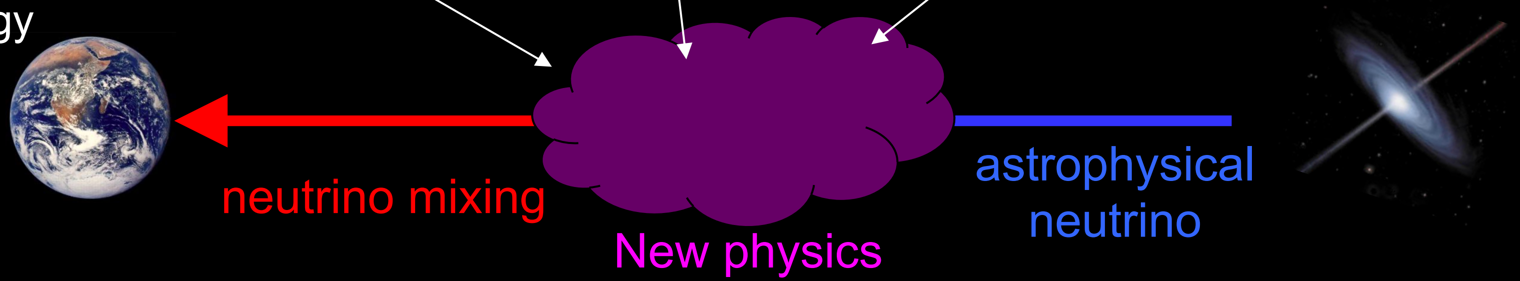
Ellis,Mavromatos,NanopoulosPLB293(1992)37

Lorentz violating field

Argüelles,TK,Salvado,PRL115(2015)161303



ultra-light dark matter
dark energy
etc



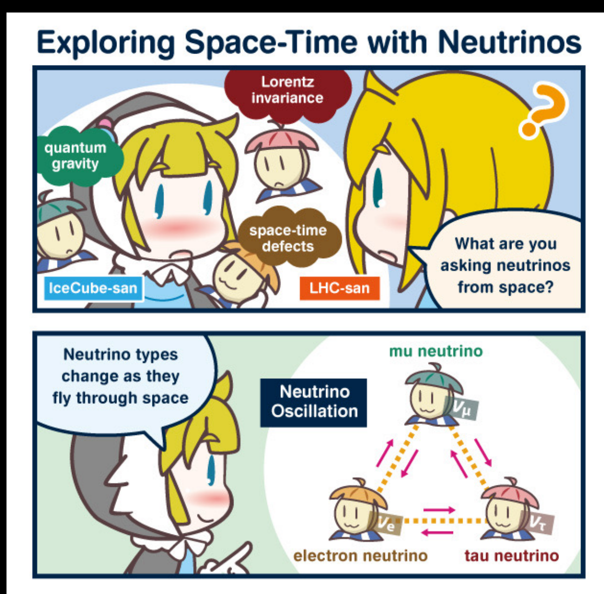
3. Quantum gravity-motivated physics search

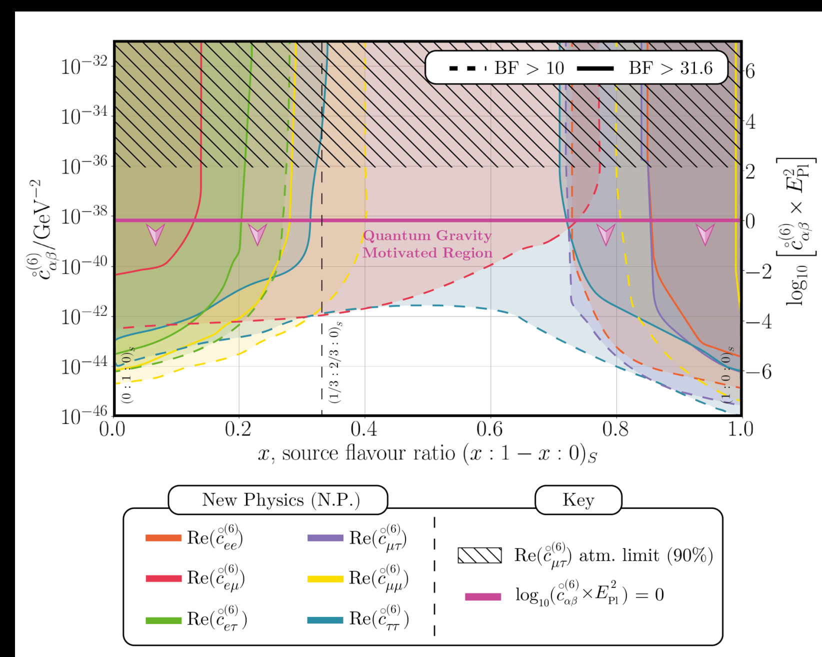
High-energy particles (>100 TeV) propagating a long distance (>1 Mpc)
- Neutrinos can probe new physics in the universe
- IceCube demonstrated sensitivity of vacuum dimension-six operators go beyond 10^{-38} GeV^{-2} (naive Planck physics scale)

Standard Model | New physics (renormalizable) | higher dimension operator (non-renormalizable)

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

No new physics found yet





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High-energy particles (>100 TeV) propagating a long distance (>1 Mpc)
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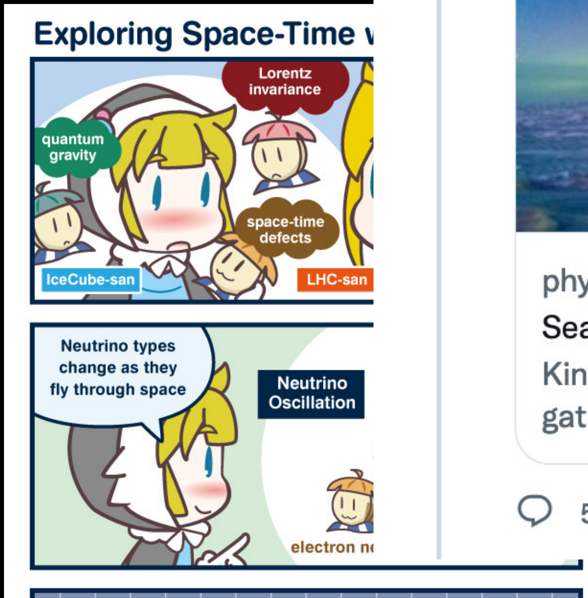
10^{-38} GeV^{-2} (naive Planck

Stand

$$h_{eff} \sim \frac{1}{2E} U$$

No new physics found yet



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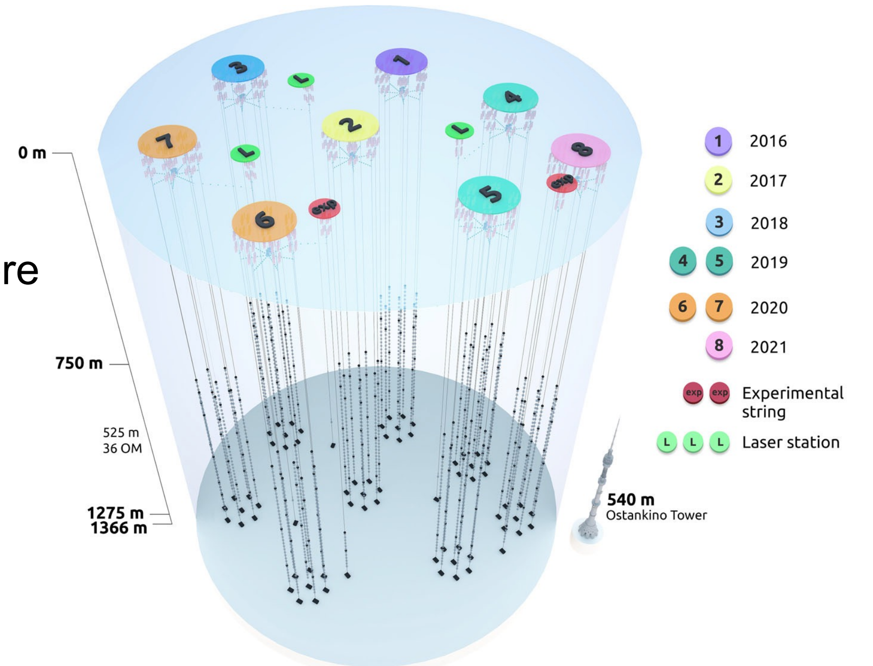
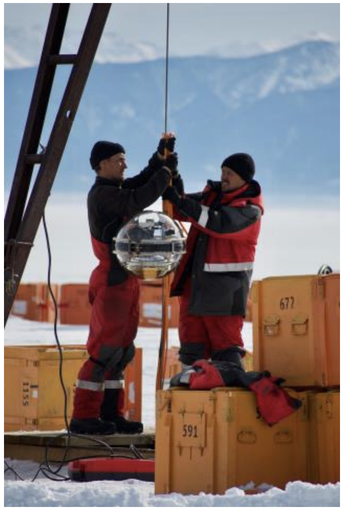
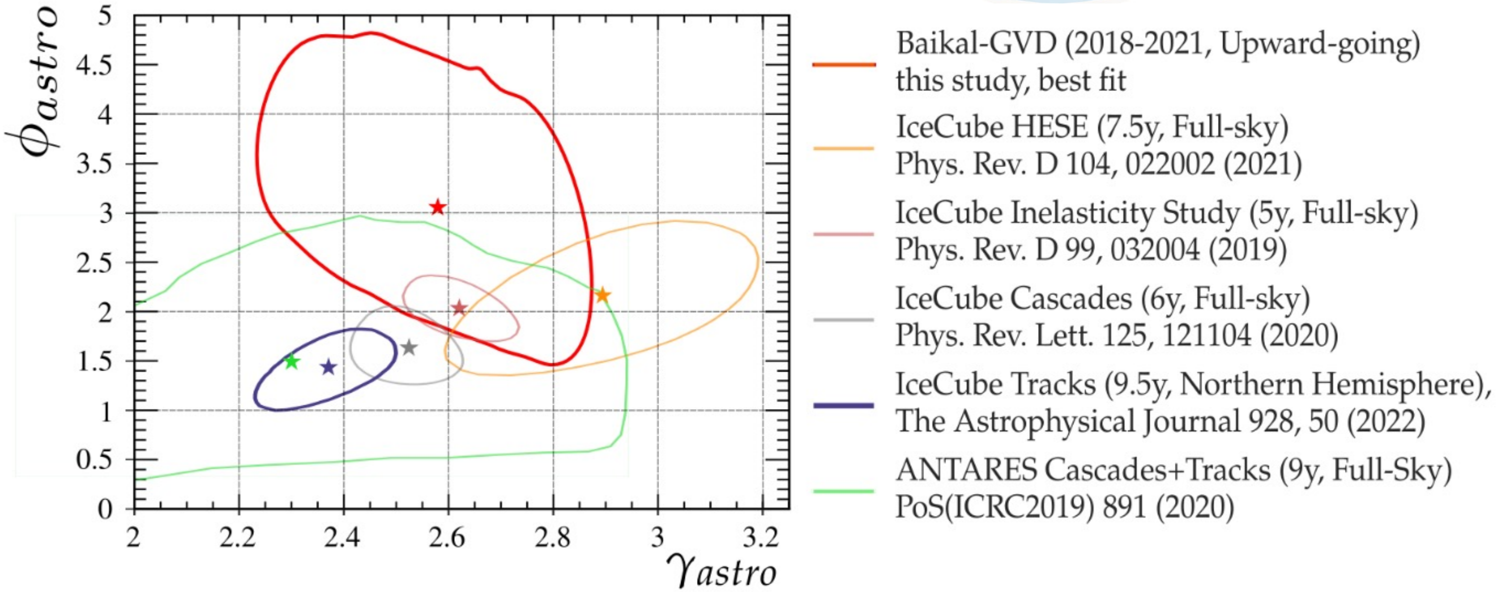
4. Baikal-GVD

GVD (Gigaton Volume Detector)
- Southern part of Lake Baikal, ~4km from the shore
- 1 cluster = 8 strings with 36 OMs per string
- 10 clusters (2022), ~250-300m separation
- Goal is 27 clusters to cover ~1.5 km^3



Excess from astrophysical neutrinos (3σ)
- Upgoing cascade
- γ~2.6±0.3





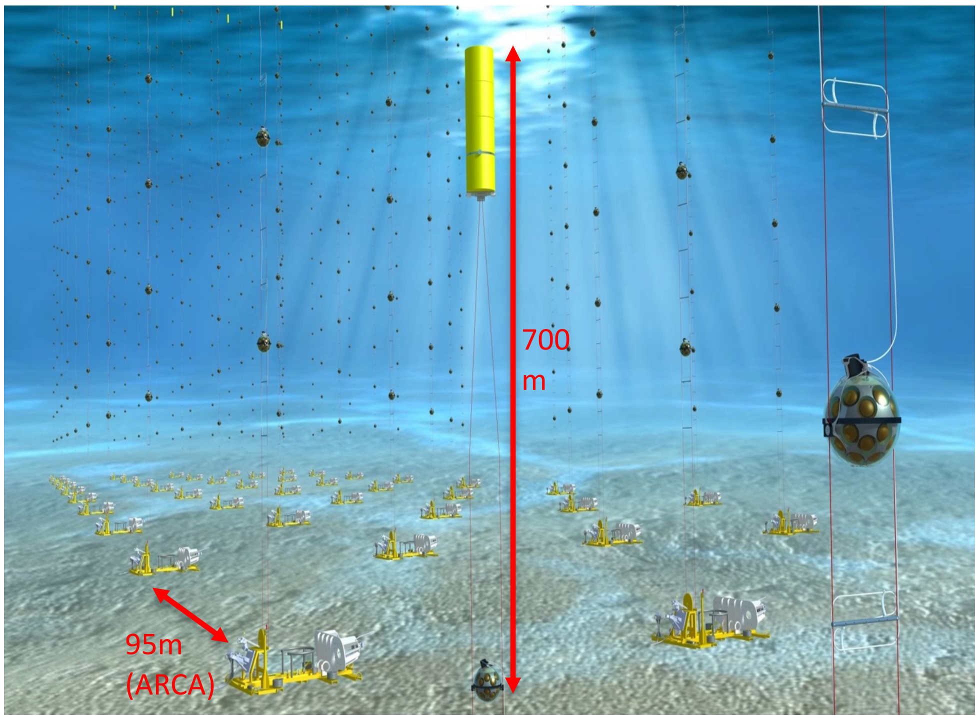
KM3NeT, J.Phys.G43(2016)084001

4. KM3NeT

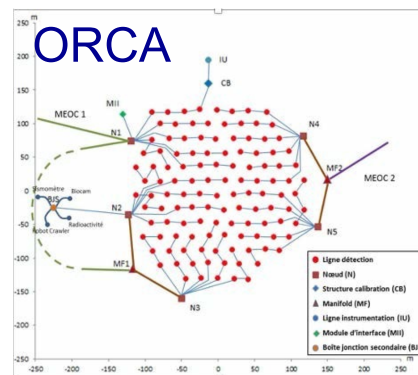
Carla Distefano (INFN LNS)
Gwen De Wasseige (Louvain)

Oscillation Research with Cosmics in the Abyss (ORCA), France
- low energy (<100 GeV), oscillation physics (~7 Mton)

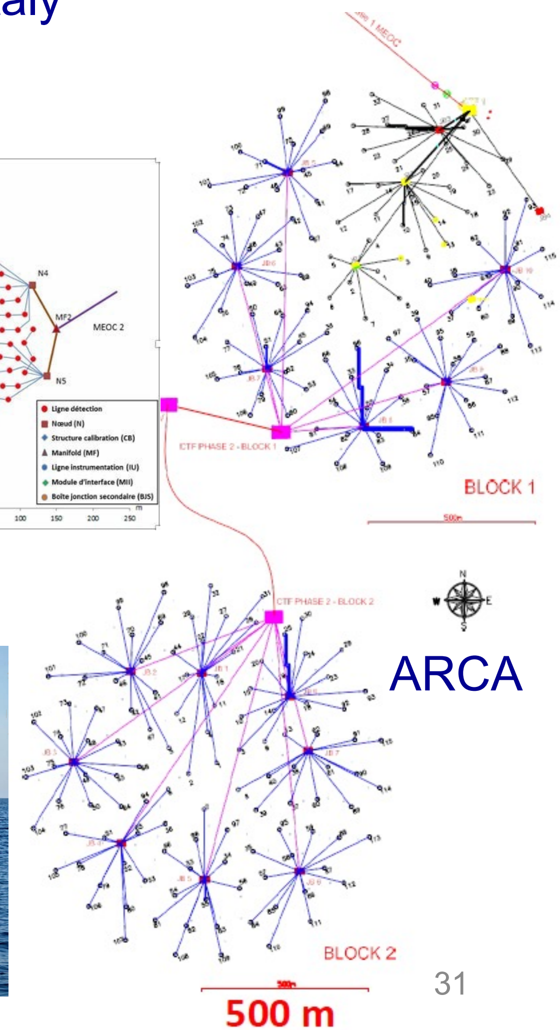
Astroparticle Research with Cosmics in the Abyss (ARCA), Italy
- high energy (>100 GeV), astrophysics (~1 Gton)



1 detector unit = 18 mDOMs
1 building block (0.5Mton) = 115 detector units



mDOM



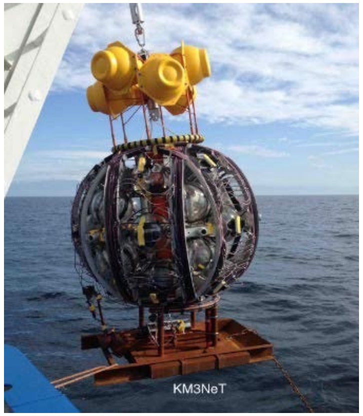
KM3NeT, J.Phys.G43(2016)084001
KM3NeT and JUNO (VLVnT2021), JINST16 (2021)C11007

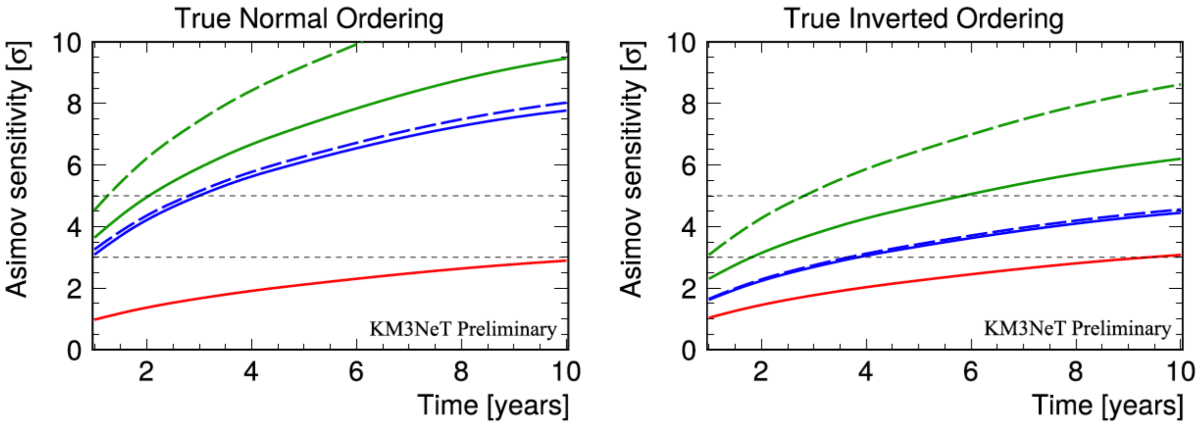
4. KM3NeT

Carla Distefano (INFN LNS)
Gwen De Wasseige (Louvain)

Status

- 32 lines operation
- funded up to 130 lines for ARCA
- Physics analysis (oscillation, mass ordering, etc)
- point source, extended source, diffuse flux searches
- multi-messenger framework (GW, SN)





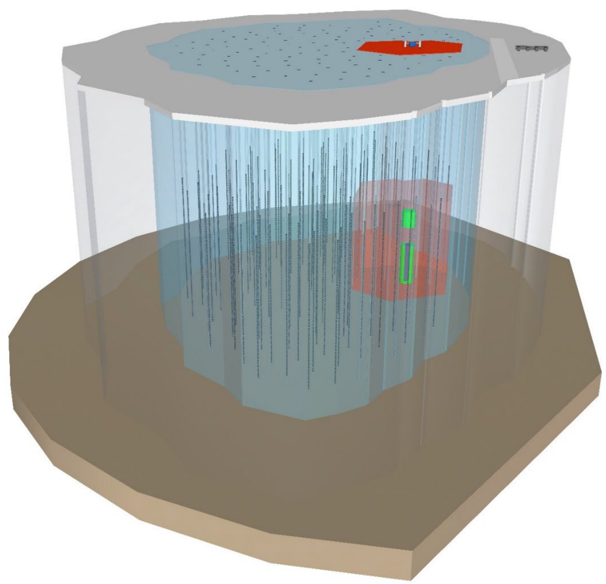
Red = JUNO only
Blue = KM3NeT only
Green = combined

IceCube-Gen2, JPhysG.44 (2017) 054006
Clark (VLVnT2021), ArXiv:2108.05292

4. IceCube-Gen2

larger separation (125m → ~200-300m) to cover larger volume (x8)

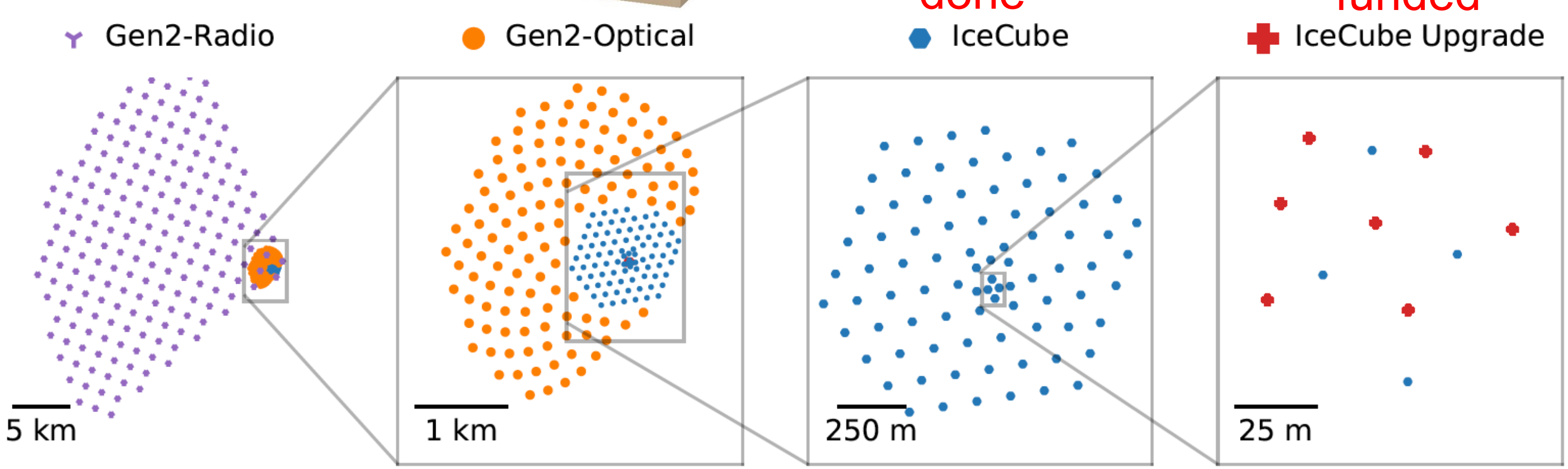
R&D is underway for ~2026 starts
- Gen2 optical
- Gen2 surface
- Gen2 radio



IceCube-Upgrade
- 7 new strings
- Test new devices
- ν_τ appearance, etc

done

funded



IceCube-Gen2, JPhysG.44 (2017) 054006
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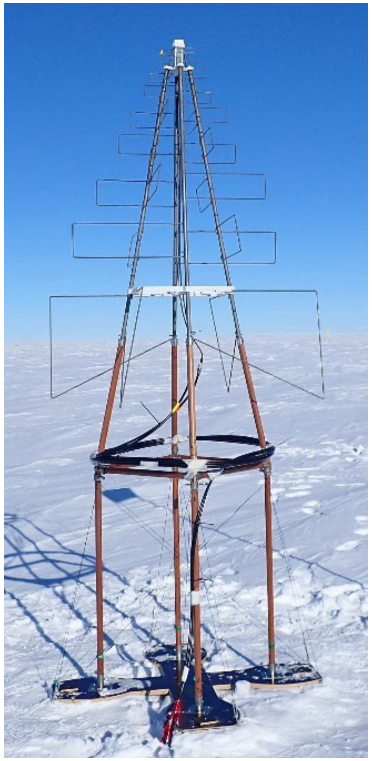
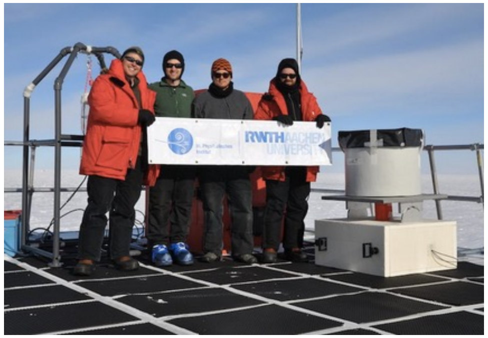
Scintillator panels
- fibre reading
- cheap, easy deployment

Antenna
- radio from air shower
- cheap, high-energy



mDOM
- direction sensitive
- KM3NeT, HyperK, etc

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



IceACT
- air Cherenkov telescope
- larger coverage

4. P-ONE

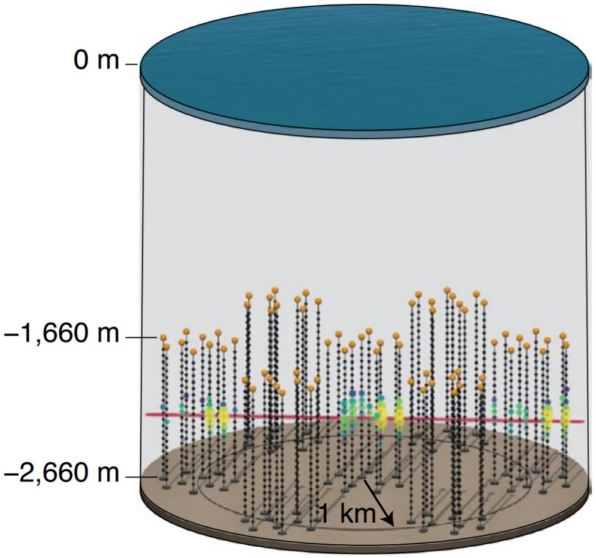
Matteo Agostini (UCL)

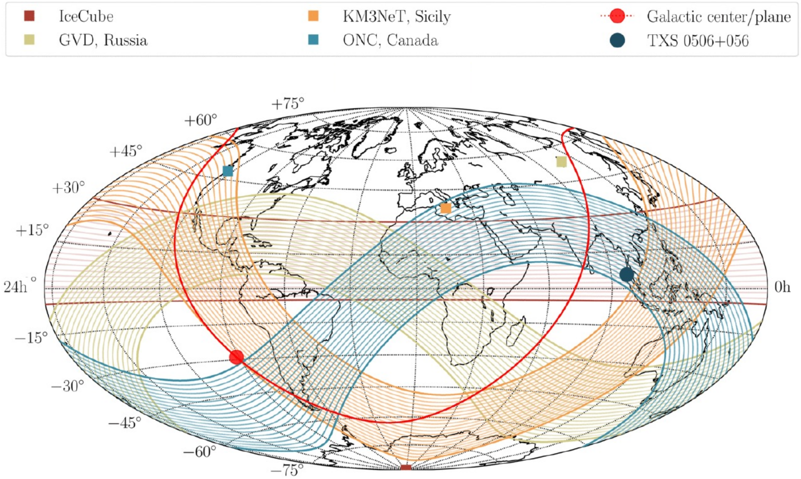
P-ONE:

- Optimized for horizontal tracks, effective ~ IceCube
- **Reliable** underwater infrastructure & detector installation provided by Ocean Network Canada (Vancouver)
- Sensitive to galactic center

Status:

- 2018: first string in situ, **verified** water properties (STRAW)
- 2023: installation of 10 strings
- 2028: completion of detector



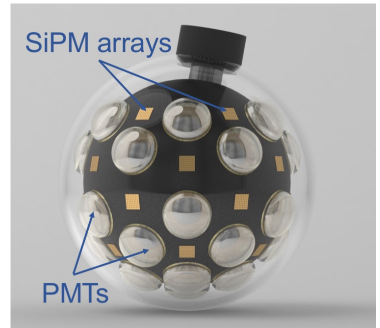


4. Trident (海鈴)

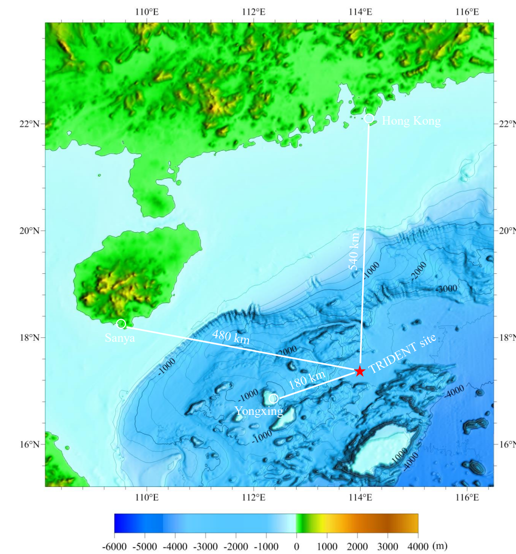
Donglian Xu (TDLI, SJTU)

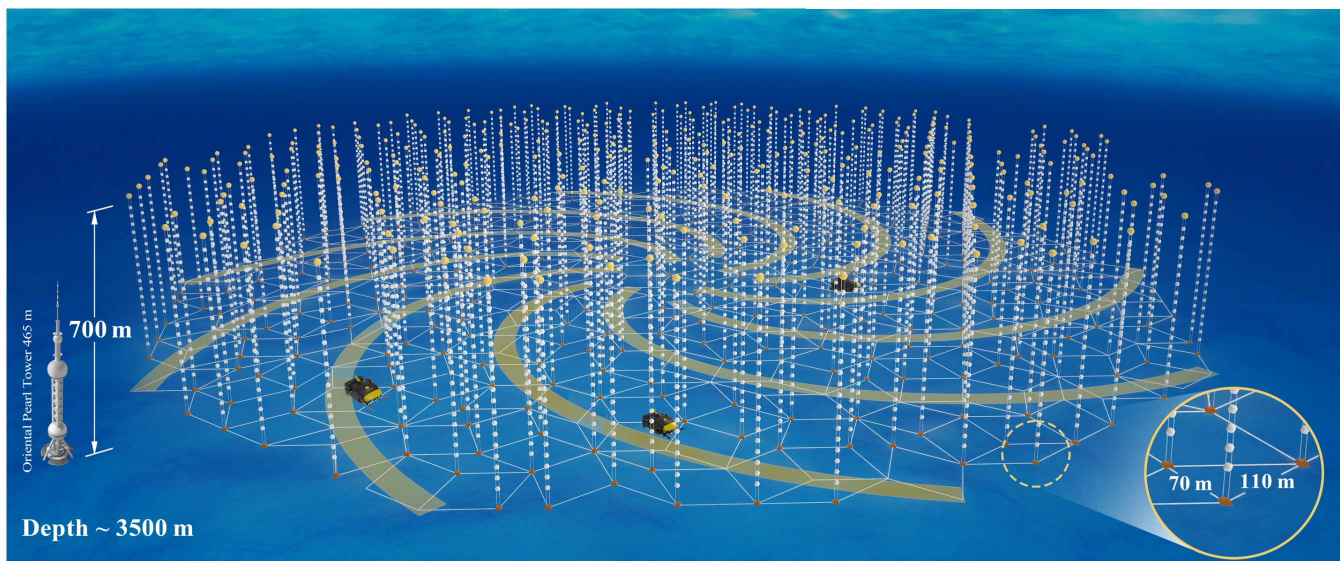
South China sea neutrino telescope

- 180km from Yongxing island (永興島)
- 3500 m seabed
- 1211 strings, 70-100m to cover ~8 km^3
- 20 hDOM per string
- hDOM = hybrid digital optical module



Conceptual Design of hDOM





Trident, ArXiv:2207.04519

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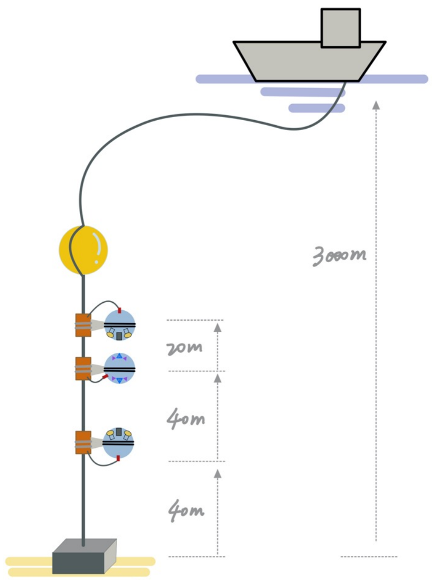
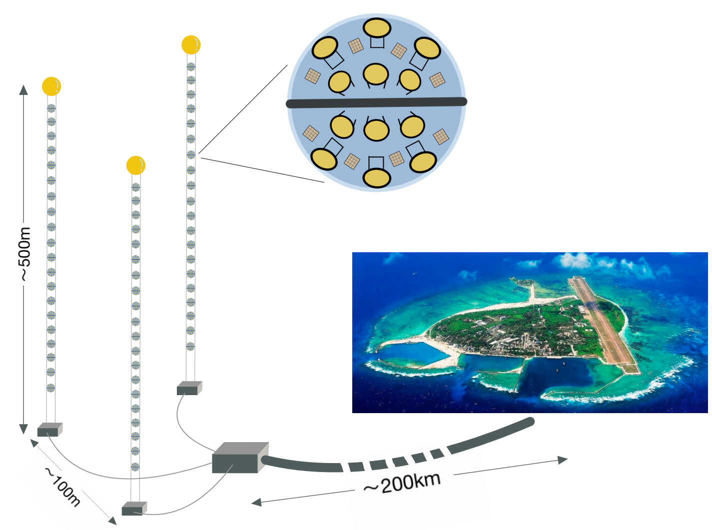
- 20 hDOM per string
- hDOM = hybrid digital optical module

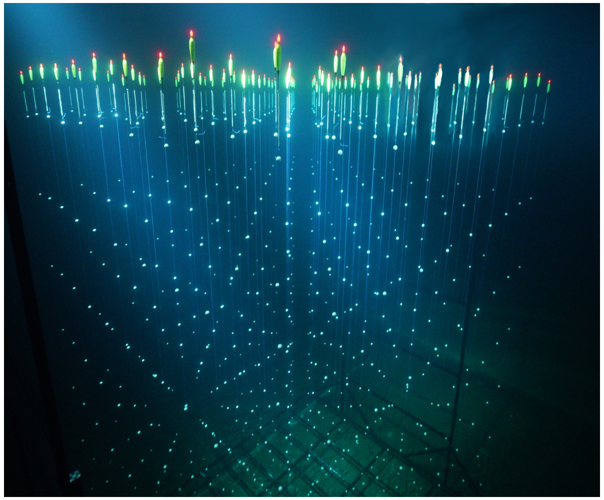
Status

- Measurements including sea current, radioactive background, attenuation
- Mechanical model to study sea current
- hDOM study





Mechanical model



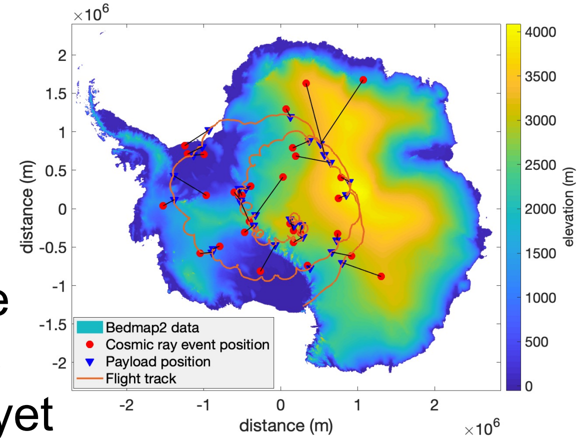
done

funded

Pathfinder: 2019-2021 海铃探路者	Pilot project: 2022-2025 海铃先导项目	Big array construction: 2026- 海铃大阵列

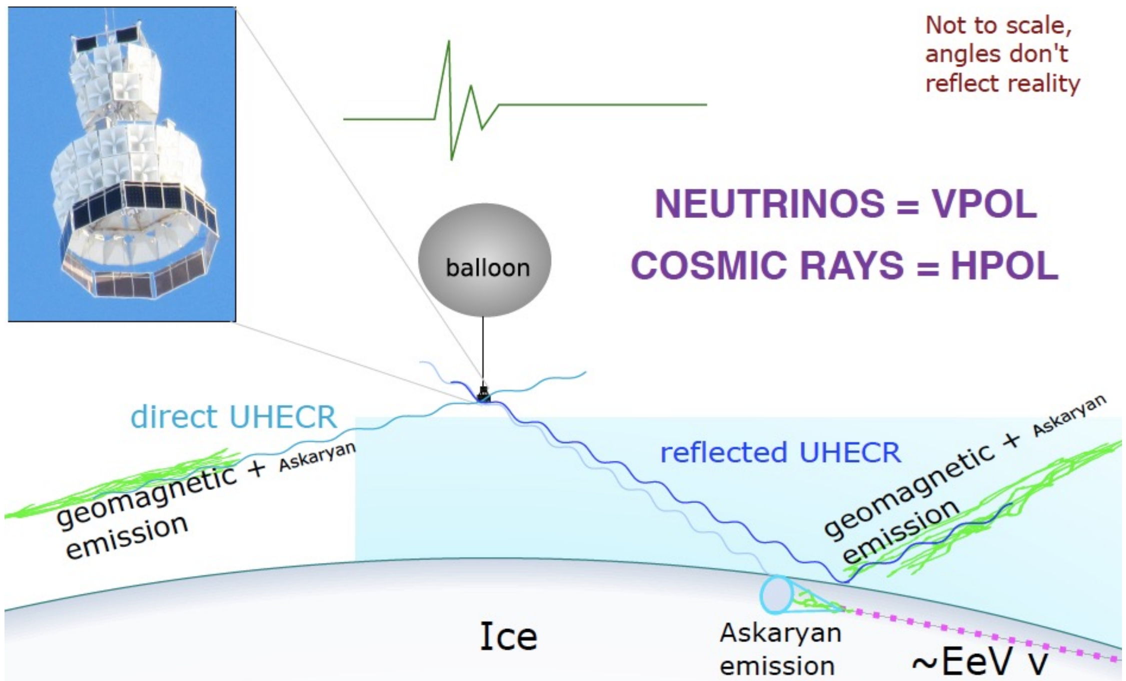
ANITA, PRL121(2018)161102,126 (2021)071103, PRD99(2019)122001

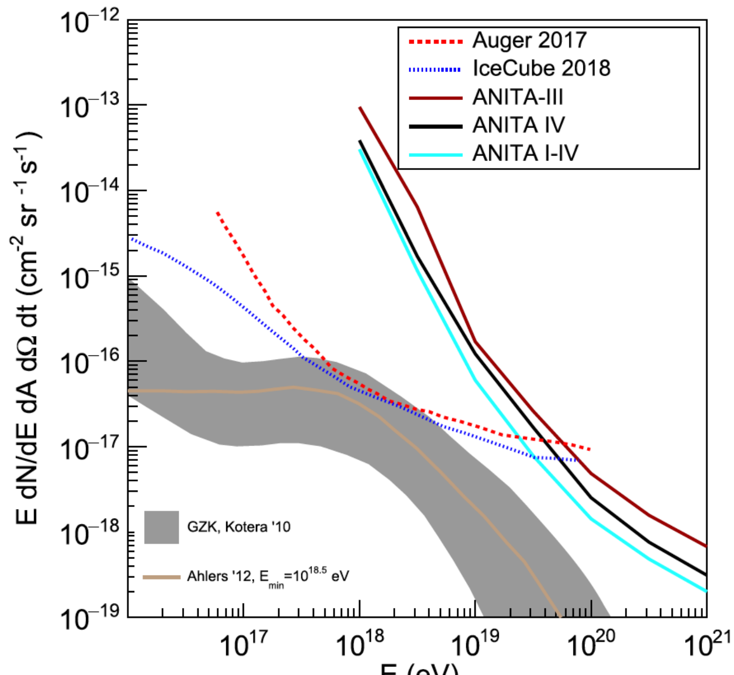
4. ANITA/PUEO



ANtarctic Impulse Transient Antenna (ANITA)

- Askaryan effect, radio emission from E&M shower in ice
- effective to measure EeV range astrophysical neutrinos
- Cosmogenic neutrinos (EeV neutrinos) not discovered yet
- Several anomalous signals





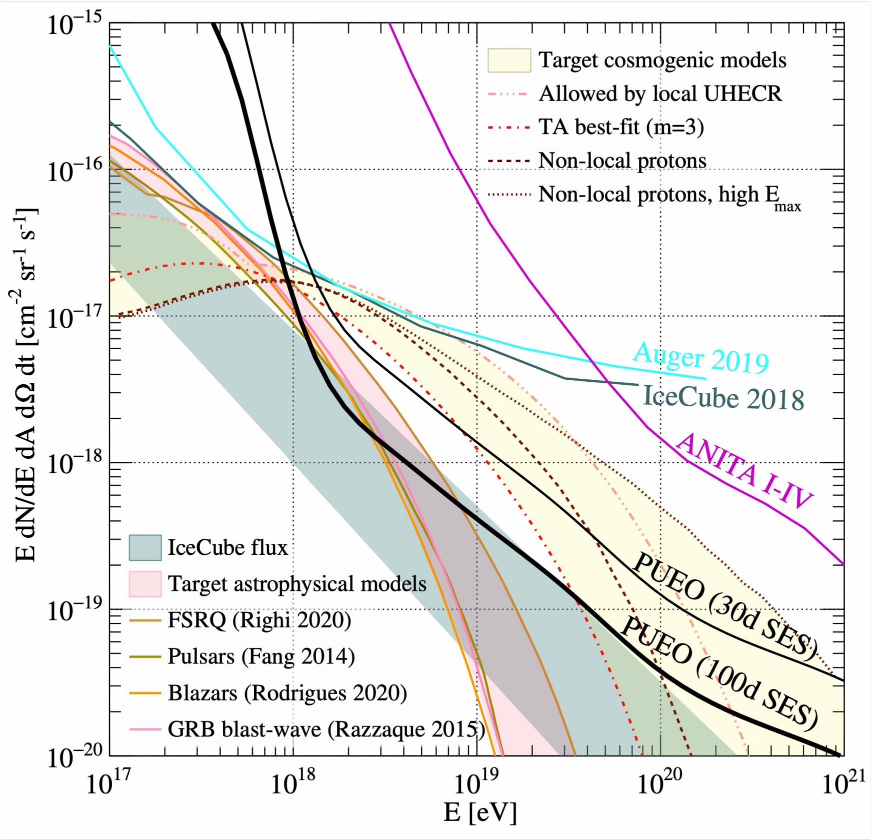
$\log_{10}(E(eV))$	18	18.5	19	19.5	20	20.5	21
A $(km^2 \cdot sr)$	0.0032	0.033	0.43	3.1	21	68	167

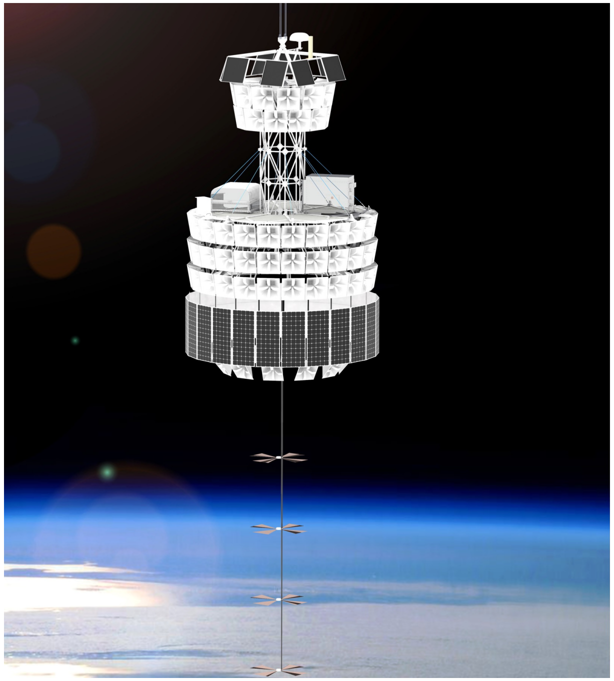
Ryan Nichol (UCL)
Linda Cremonesi (Queen Mary)

4. ANITA/PUEO

Payload for Ultrahigh Energy Observations (PUEO)

- Significant sensitivity improvement below 30 EeV
- Scheduled to fly in 2024





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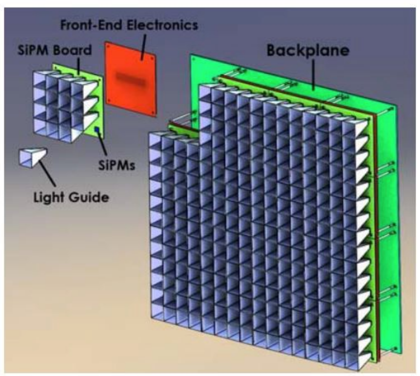
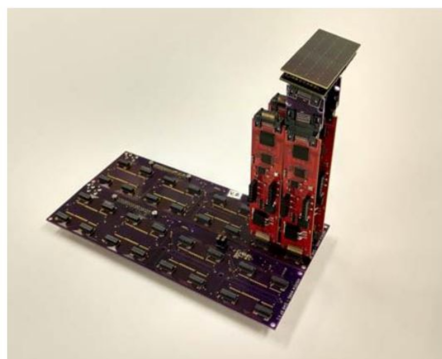
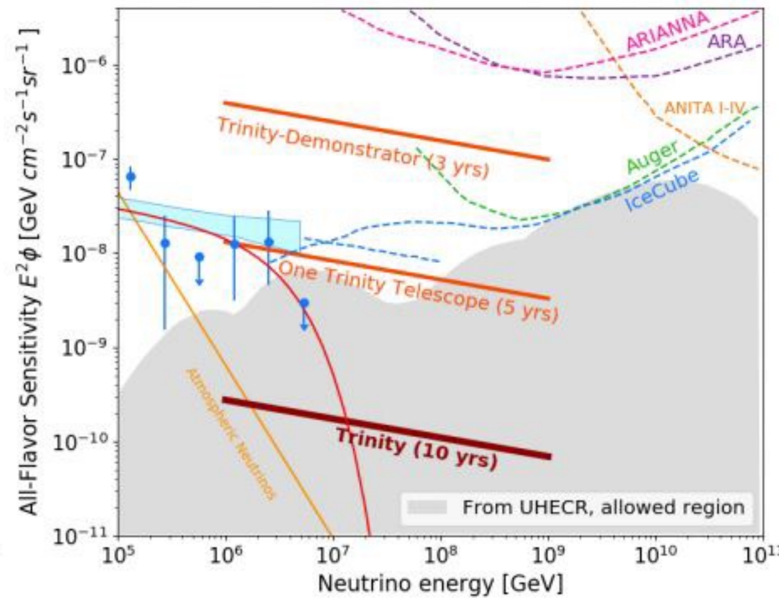
Ryan Nichol (UCL)
Linda Cremonesi (Queen Mary)

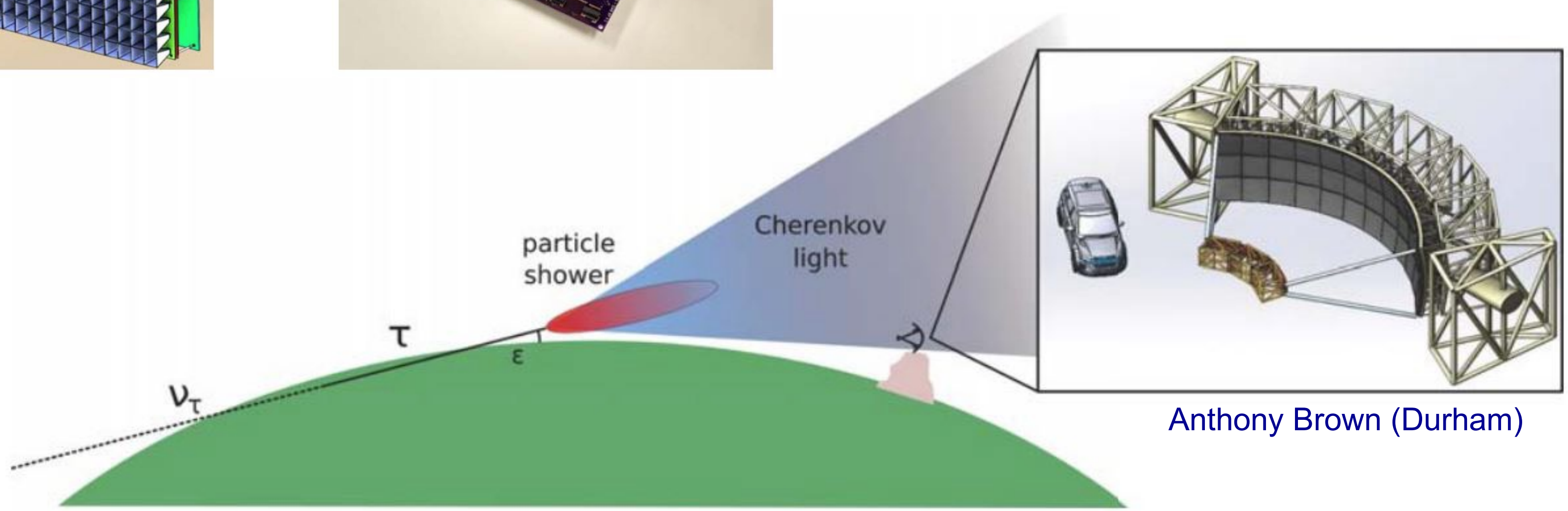
4. Trinity

Skimming tau induced air shower
- SiPM Image Air-Cherenkov Telescope (IACT)
- 1 IACT covers 5º x 60º FoV
- 5yr operation of 1 telescope can see 1 PeV neutrino!









Anthony Brown (Durham)

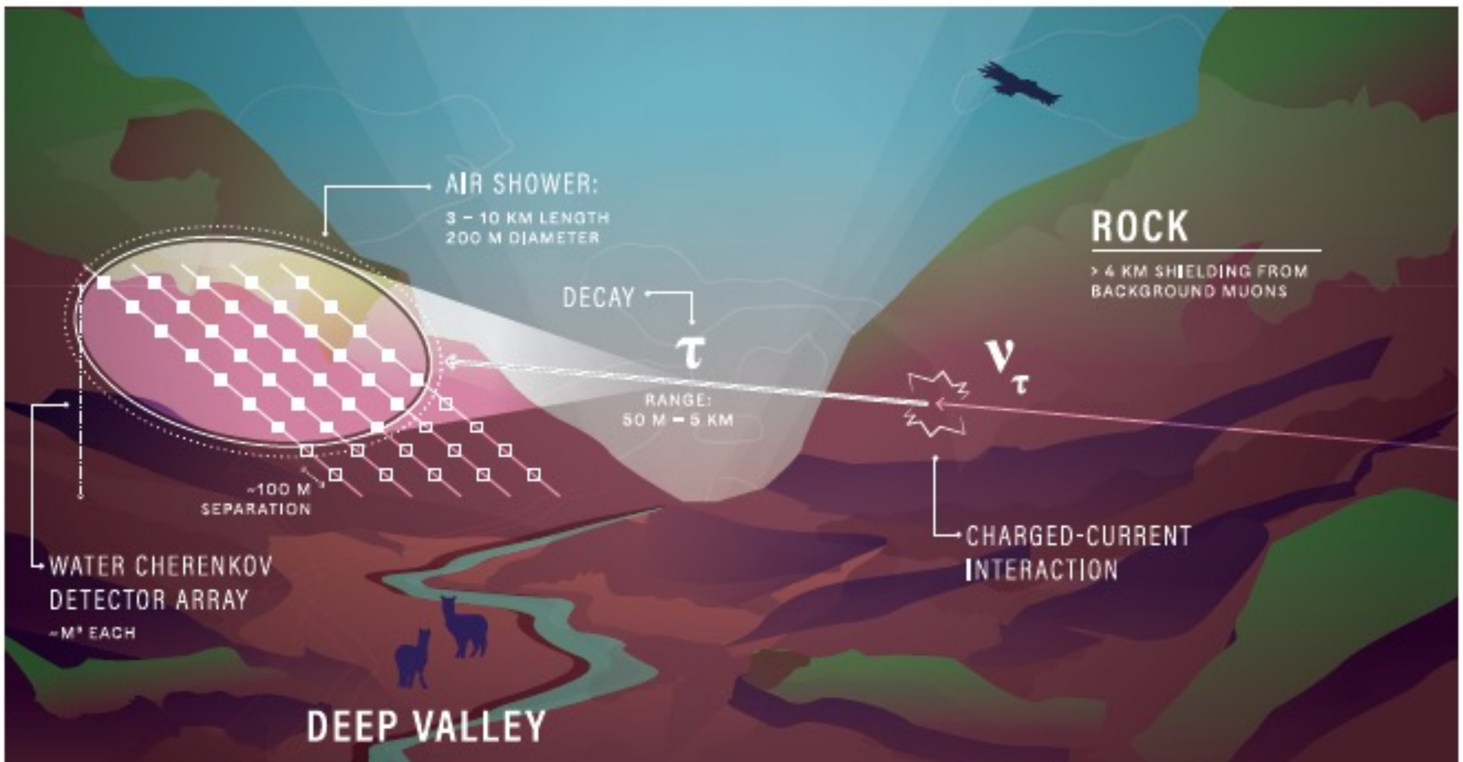
4. TAMBO

Looking for the experiment site!
(Harvard group at Tambo valley)

Carlos Argüelles (Harvard)

Tau-Air-shower Mountain-Based Observatory (Peru)

- UHE tau induced air shower
- Water Cherenkov detector array
- Relatively low energy threshold (~1PeV)



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) • COLCA VALLEY, PERU

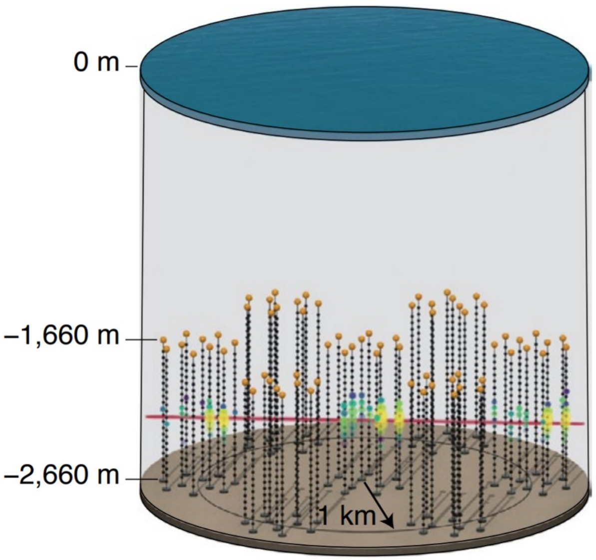
King's College London

4. High-Energy Astrophysical Neutrinos

Many planned experiments targeting PeV-EeV neutrinos

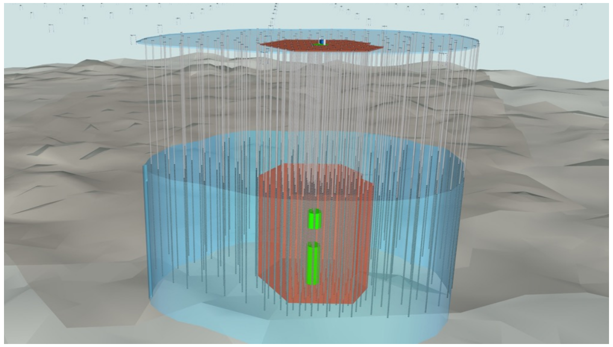
Energy Range	Experiment	Technology	Detected Flavor	Ref.
$\lesssim 10^3$ GeV	JUNO	Liquid scintillator	All Flavors	[234]
$\lesssim 10^3$ GeV	DUNE	LArTPC	All Flavors	[671]
$\lesssim 10^3$ GeV	THEIA	WbLS	All Flavors	[486]
$\lesssim 10^3$ GeV	Super-Kamiokande	Gd-loaded Water C	All Flavors	[645]
$\lesssim 10^4$ GeV	Hyper-Kamiokande	Water Cherenkov	All Flavors	[483]
$\lesssim 10^5$ GeV	ANTARES	Sea-Water Cherenkov	ν_μ, $\bar{\nu}_\mu$ (CC)	[672]
$\lesssim 10^6$ GeV	IceCube/IceCube-Gen2	Ice Cherenkov	All Flavors	[433, 673]
$\lesssim 10^6$ GeV	KM3NeT	Sea-Water Cherenkov	All Flavors	[674]
$\lesssim 10^6$ GeV	Baikal-GVD	Lake-Water Cherenkov	All Flavors	[675]
$\lesssim 10^6$ GeV	P-ONE	Sea-Water Cherenkov	All Flavors	[676]
$1 - 100$ PeV	TAMBO	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)	[677]
$\gtrsim 1$ PeV	Trinity	Earth-skimming Image	ν_τ, $\bar{\nu}_\tau$ (CC)	[678]
$\gtrsim 10$ PeV	RET-N	Radar echo	All Flavors	[679]
$\gtrsim 10$ PeV	IceCube-Gen2	In-ice Radio	All Flavors	[433]
$\gtrsim 10$ PeV	ARIANNA-200	On-ice Radio	All Flavors	[680]
$\gtrsim 20$ PeV	POEMMA	Space Air-shower Image	ν_τ, $\bar{\nu}_\tau$ (CC)	[681]
$\gtrsim 100$ PeV	RNO-G	In-ice Radio	All Flavors	[682]
$\gtrsim 100$ PeV	ANITA/PUEO	Balloon Radio	All Flavors	[683, 684]
$\gtrsim 100$ PeV	Auger/GCOS	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)	[685, 686]
$\gtrsim 100$ PeV	Beacon	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)	[687]
$\gtrsim 100$ PeV	GRAND	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)	[688]

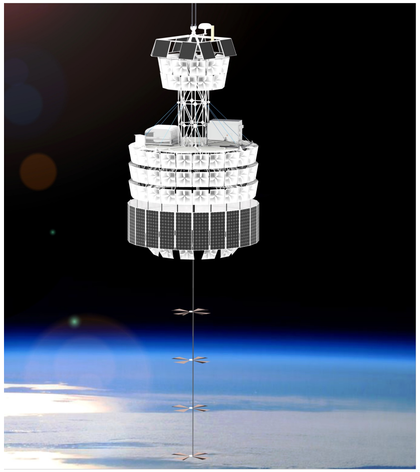
4. UK-High-energy astrophysical neutrino (UK-HEAN) consortium

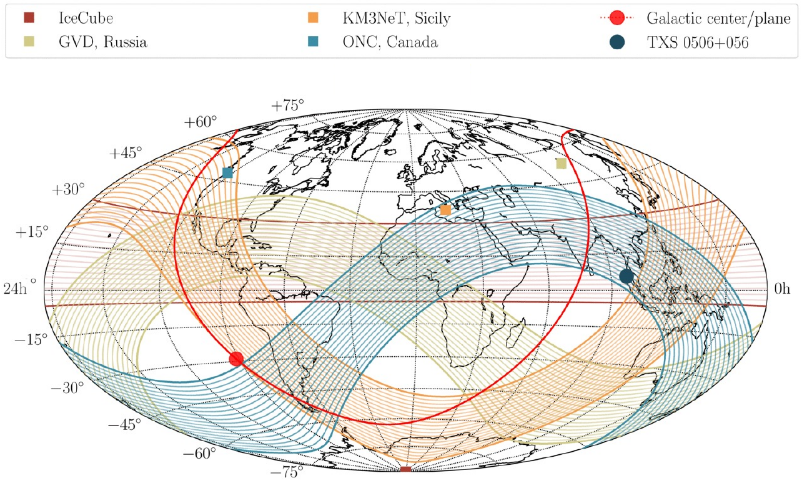


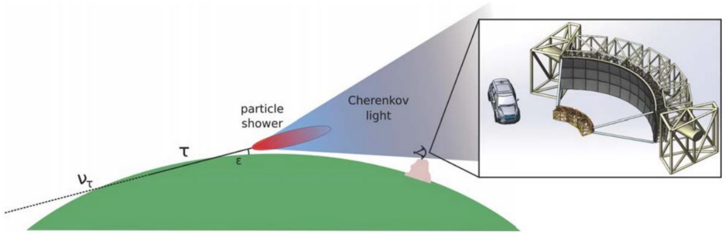
PAAP roadmap plan

- UK groups participate many HEAN projects.
- We are in the process to form a group beyond each collaboration.
- We will make a realistic plan for future
- Everyone is welcome!









Conclusion

Neutrino telescopes are successful experiments

High-energy astrophysical neutrinos offer very exciting science for both particle physics and astrophysics

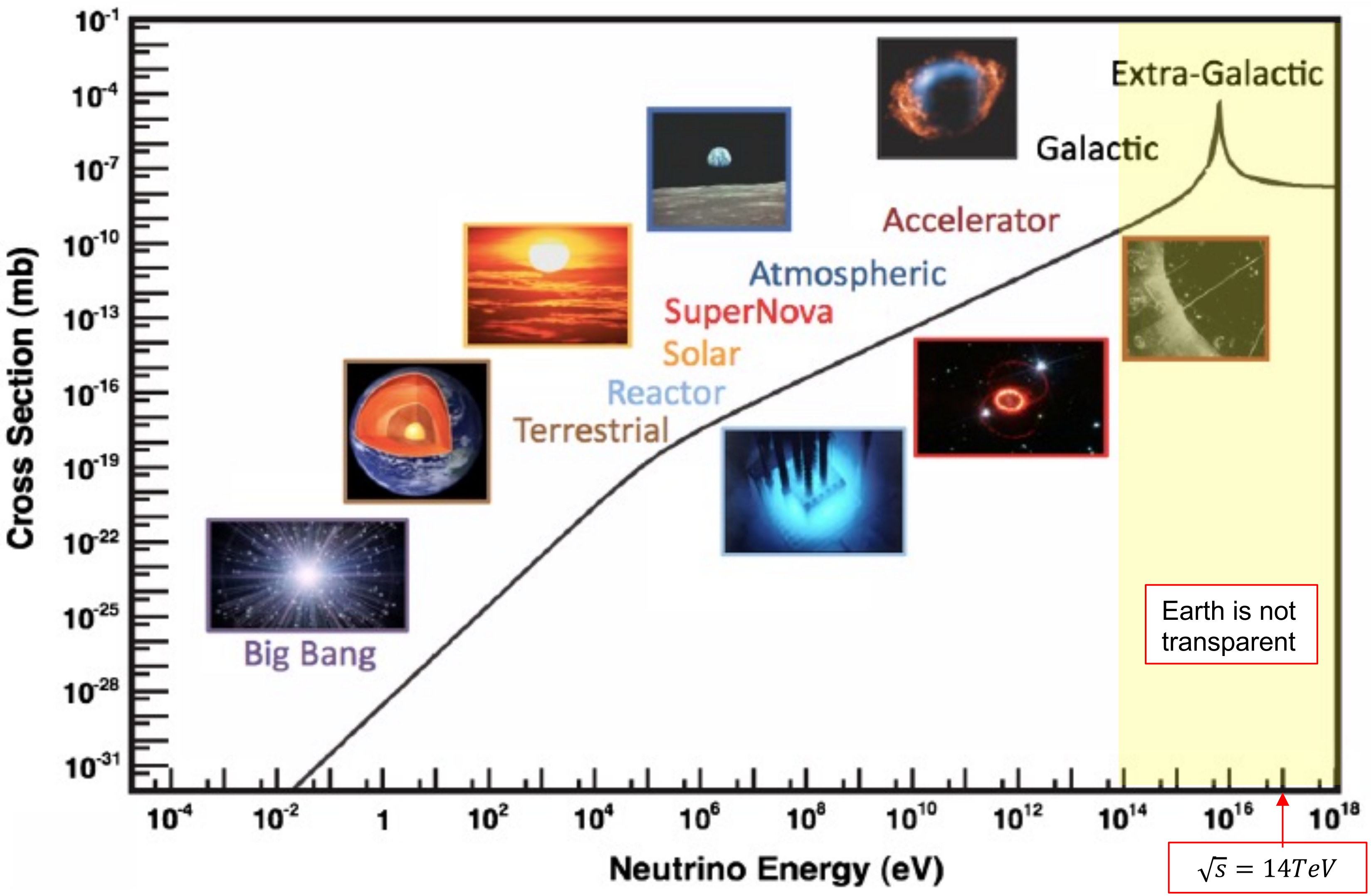
There are many planned projects with discovery potentials

Thank you for your attention!

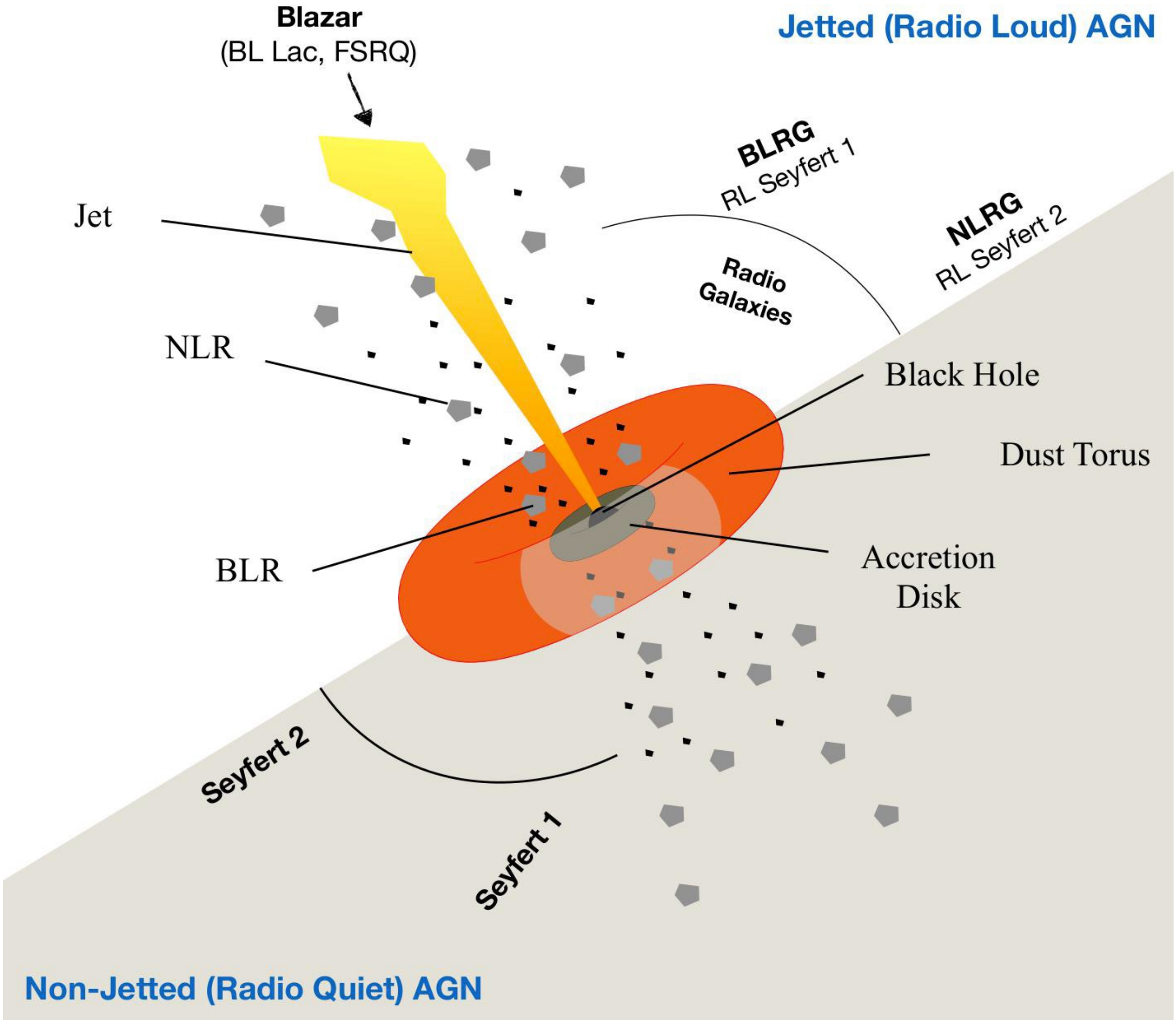
Backup

1. High-Energy Astrophysical Neutrinos

Above ~10-100 TeV neutrinos are only direct messengers



2. Active Galactic Nuclei (AGNs)



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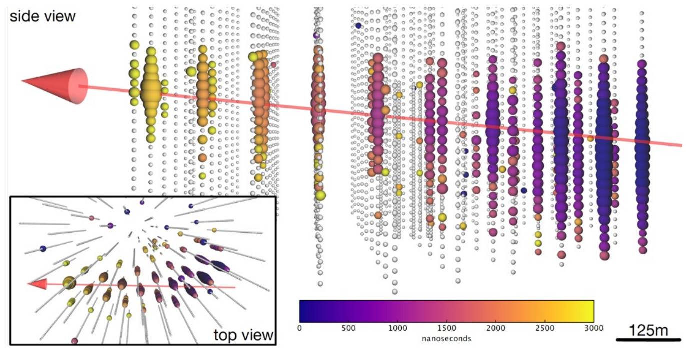
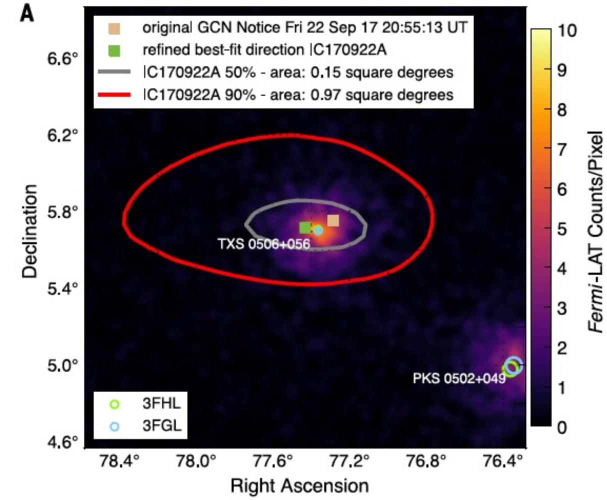
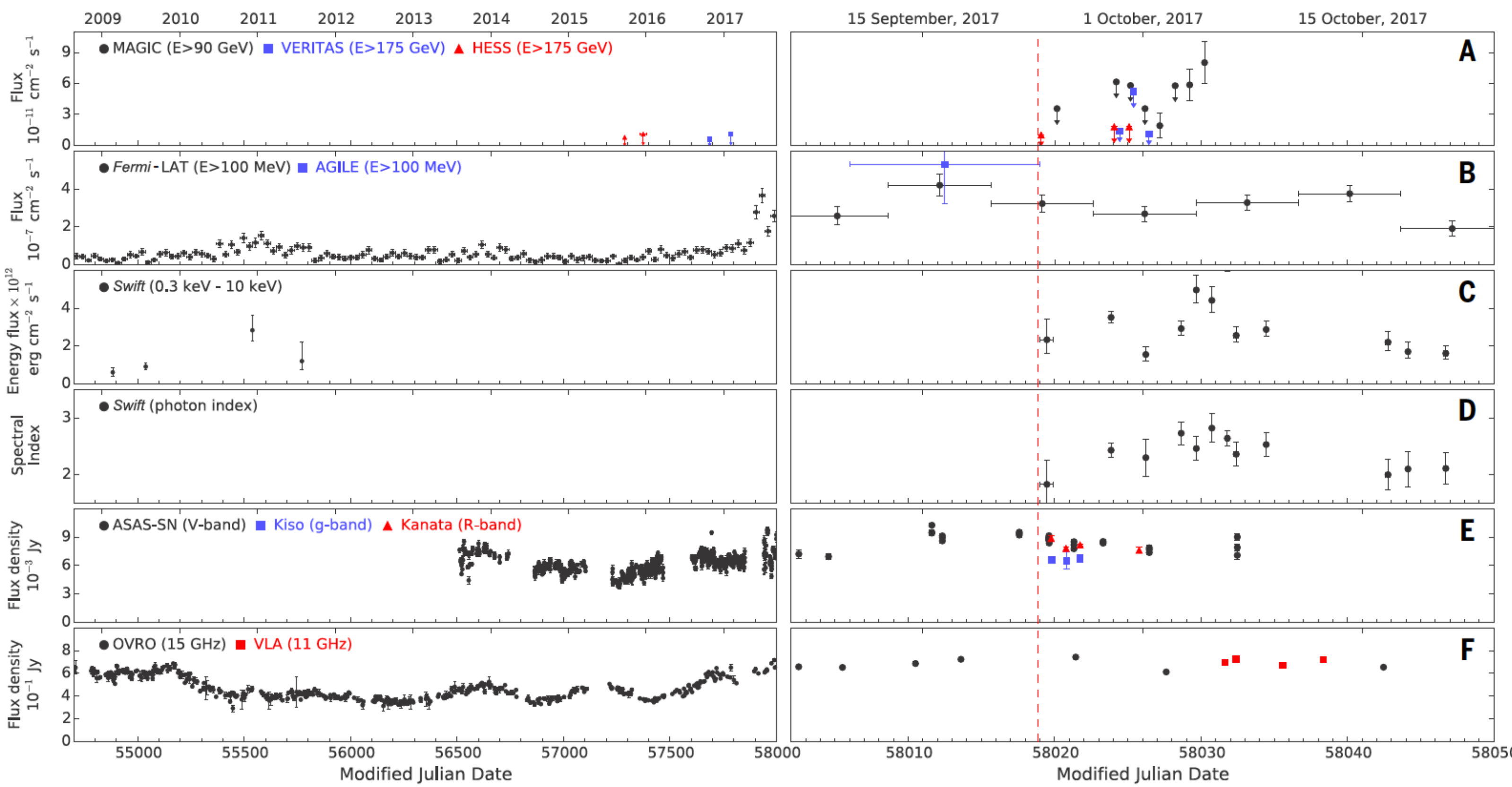
IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378

2. IC170922

290 TeV





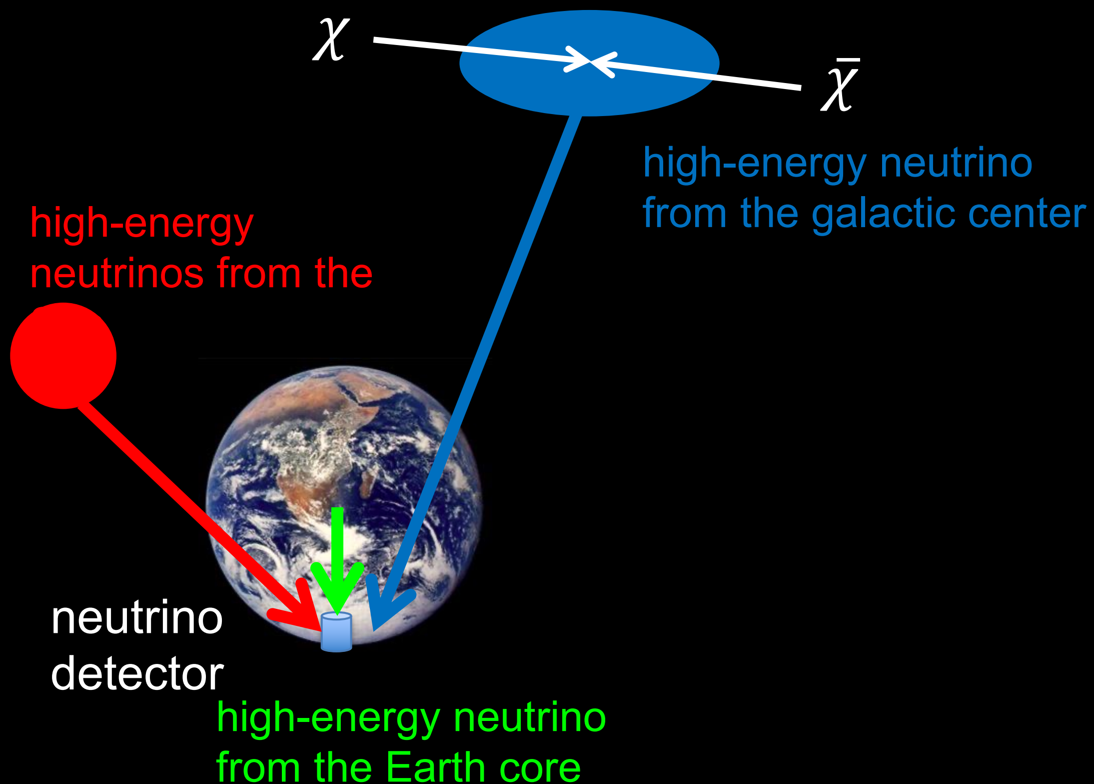


3. Dark matter annihilation neutrinos

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

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

- No excess for neutrinos



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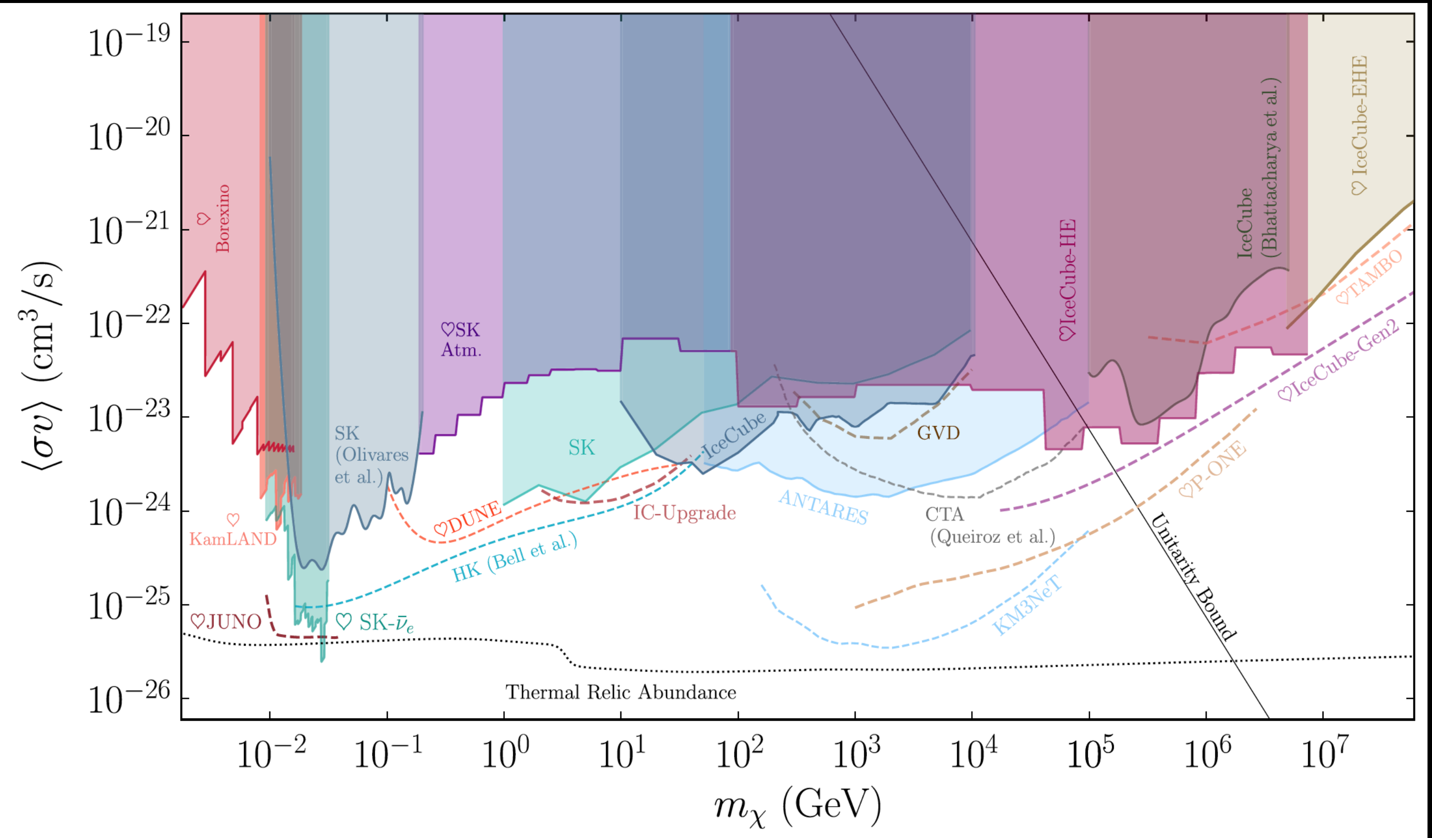
Neutrinos from Earth, Sun, Milky Way center

- Signal of dark matter annihilation to neutrino emission

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

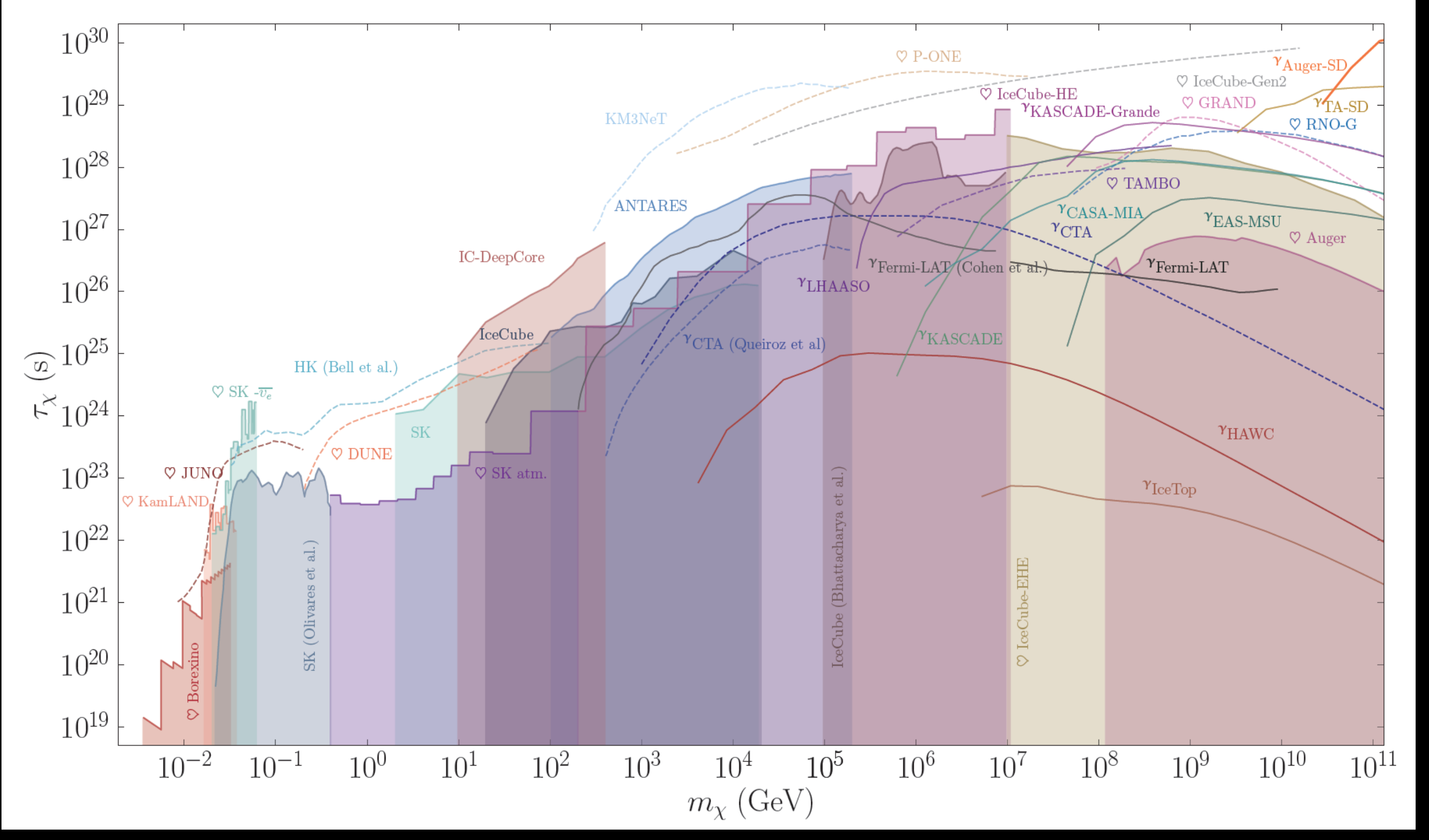
8 order of dark matter limits by neutrino telescope

- Sensitivity decreases for heavier dark matter particles
- Next generation neutrino telescopes can reach to the thermal relic DM limits



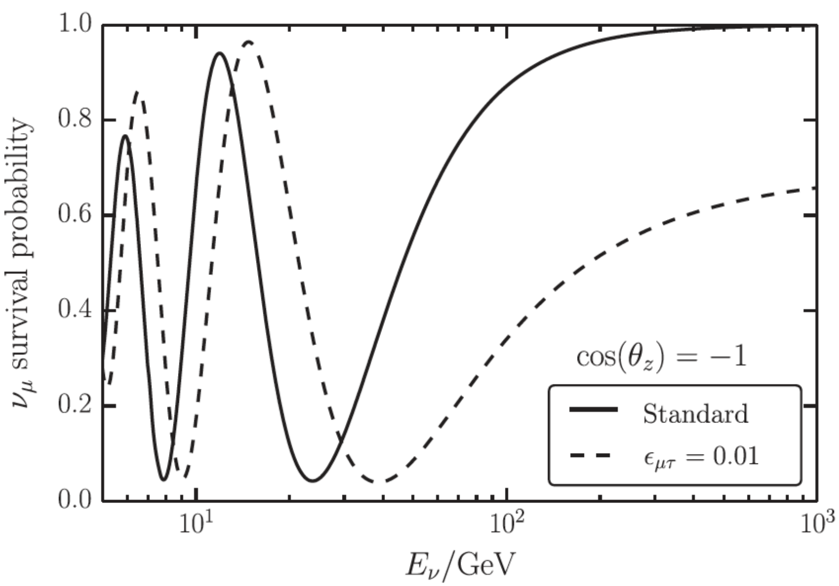
3. Dark matter decay neutrinos

Dark matter decay to neutrinos
- Sensitivity is higher for heavier dark matter particles



3. Non-standard interactions

Atmospheric neutrinos cover ~100MeV - 20 TeV (conventional) coming from all direction (diffuse). However, direction is related to the propagation distance.
→ They are the highest energy particles (~20 TeV) with the longest baseline (12700km) propagating the high-density material (~13g/cm^3) on Earth.



$$h_{eff} \sim \frac{1}{2E} M^2 + V_{CC}, \quad P_{\alpha\beta} = \left|\langle \nu_\alpha | U(h_{eff}, t) | \nu_\beta \rangle\right|^2$$

$$M^2 = \begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{\tau e}^2 \\ (m_{e\mu}^2)^* & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ (m_{\tau e}^2)^* & (m_{\mu\tau}^2)^* & m_{\tau\tau}^2 \end{pmatrix}, V_{CC} = \begin{pmatrix} \sqrt{2} G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Non-standard interaction limits in IceCube is order ~10^{-25} GeV

cf) The highest precision hydrogen 1S-2S transition (PRL107(2011)203001)
Fractional frequency uncertainty ~ 4x10^{-15} → new physics sensitivity ~10^{-23} GeV

3. Flavor new physics search with effective operators

Standard Model Extension (SME) is an effective field theory to look for Lorentz violation

Standard Model | New physics

$$L = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi + \bar{\psi}\gamma^{\mu}a_{\mu}\,\psi + \bar{\psi}\gamma^{\mu}c_{\mu\nu}\partial^{\nu}\psi \cdots$$

Effective Hamiltonian can be written from here

Standard Model | New physics (renormalizable) | higher dimension operator (non-renormalizable)

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

Astrophysical neutrino flavour sensitivity of dim-6 operator

goes beyond the natural scale $c^{(6)} \sim \frac{1}{M^{2}_{Planck}} \sim 10^{-38}GeV^{-2}$,

first time in any known scientific system

3. Flavor new physics search with effective operators

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

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

Astrophysical neutrino flux of flavour α at production is $\phi_{\alpha}^{p}(E)\sim\phi_{\alpha}^{P}\cdot E^{-\gamma}$. Since it's low statistics, we consider energy-averaged flavour composition β on Earth

$$\bar{\phi}_{\beta}^{\oplus} = \frac{1}{\Delta E}\int_{\Delta E}\sum_{\alpha} P_{\alpha\to\beta}(E,\infty)\,\phi_{\alpha}^{p}(E)dE$$

We take the fraction of this for each flavour.

$$f_{\beta}^{\oplus} = \frac{\bar{\phi}_{\beta}^{\oplus}}{\sum_{e,\mu,\tau}\bar{\phi}_{\gamma}^{\oplus}}$$

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3. HESE 7.5-yr Flavor new physics search

Data, 2635 days HESE sample IceCube, ArXiv: 2011.03545

- 17 track events, 20 log(E) bins [60 TeV, 10 PeV], 10 cosθ bins [-1.0, +1.0]
- 41 cascade events, 20 log(E) bins [60 TeV, 10 PeV], 10 cosθ bins [-1.0, +1.0]
- 2 double cascades, 20 log(E) bins [60 TeV, 10 PeV], 10 log(L) bins [10m, 100m]

Simulation

Bhattacharya et al.,JHEP06(2015)110

- Foregrounds, conventional (Honda flux), prompt (BERSS model), muon (CORSIKA)
- Astrophysical neutrinos, simple power law
- Interaction, NLO PDF DIS (CSMS model) Cooper-Sarkar et al., JHEP08(2011)042

Systematics (15 nuisance parameters)

- oscillation parameters (6)
- normalization of flux : conventional (40%), prompt (free), muon (50%), astrophysical (free)
- spectrum index : primary cosmic ray (5%) astrophysical neutrinos (free)
- Ice model : (20%)
- DOM efficiency : overall (10%), angular dependence (50%)

Limits

Feroz et al., Mon. Not. Roy. Astron. Soc. 398,1601(2009)1601

- Bayesian: MCMC with Multinest, Bayes factor with Jefferey' scale "strong" limit
- Frequentist: Wilks' theorem

3. Systematic errors

Parameter	Prior (constraint)	Range	Description
Astrophysical neutrino flux:			
$\Phi_{\texttt{astro}}$	-	$[0, \infty)$	Normalization scale
$\gamma_{\texttt{astro}}$	-	$(-\infty, \infty)$	Spectral index
Atmospheric neutrino flux:			
$\Phi_{\texttt{conv}}$	1.0 ± 0.4	$[0, \infty)$	Conventional normalization scale
$\Phi_{\texttt{prompt}}$	-	$[0, \infty)$	Prompt normalization scale
$R_{K/\pi}$	1.0 ± 0.1	$[0, \infty)$	Kaon-Pion ratio correction
$2\nu / (\nu + \bar{\nu})_{\texttt{atmo}}$	1.0 ± 0.1	$[0, 2]$	Neutrino-anti-neutrino ratio correction
Cosmic-ray flux:			
$\Delta\gamma_{\texttt{CR}}$	0.0 ± 0.05	$(-\infty, \infty)$	Cosmic-ray spectral index modification
Φ_{μ}	1.0 ± 0.5	$[0, \infty)$	Muon normalization scale
Detector:			
$\epsilon_{\texttt{DOM}}$	0.99 ± 0.1	$[0.80, 1.25]$	Absolute energy scale
$\epsilon_{\texttt{head-on}}$	0.0 ± 0.5	$[-3.82, 2.18]$	DOM angular response
$a_{\texttt{s}}$	1.0 ± 0.2	$[0.0, 2.0]$	Ice anisotropy scale

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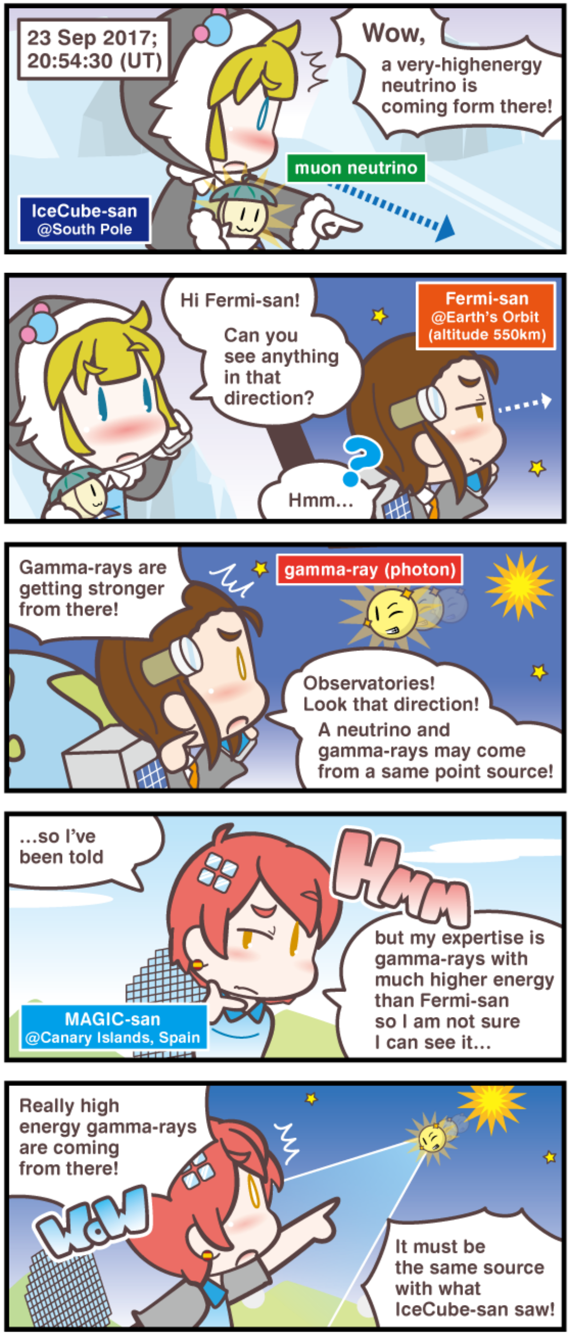
Neutrino☆Multi-messenger



ニュートリノ☆マルチメッセンジャー

KING'S College LONDON

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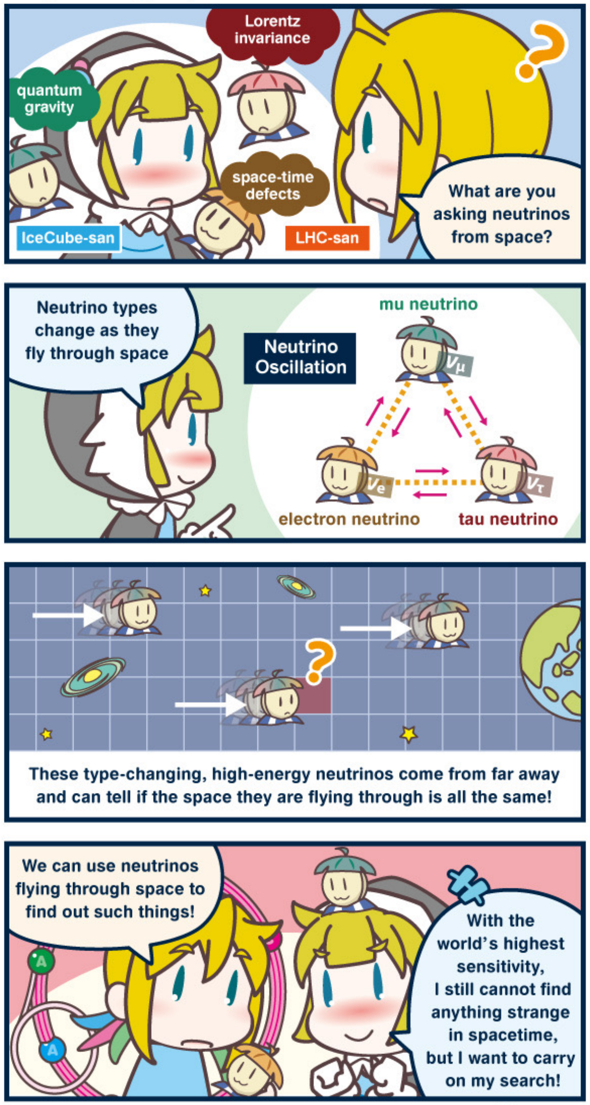
Exploring Space-Time with Neutrinos



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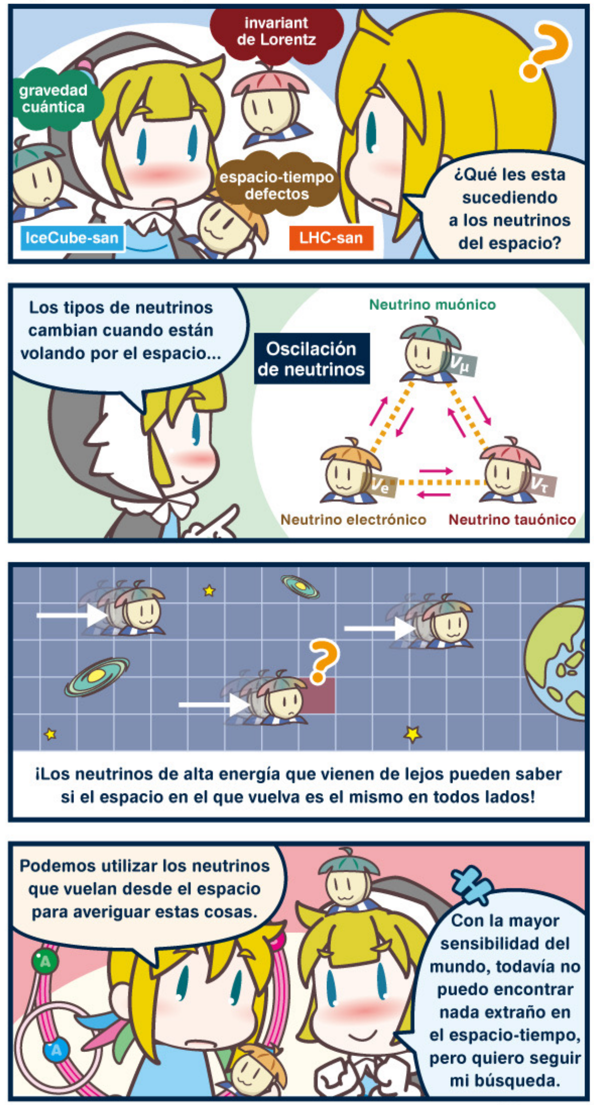
Explorar el espacio-tiempo con los neutrinos



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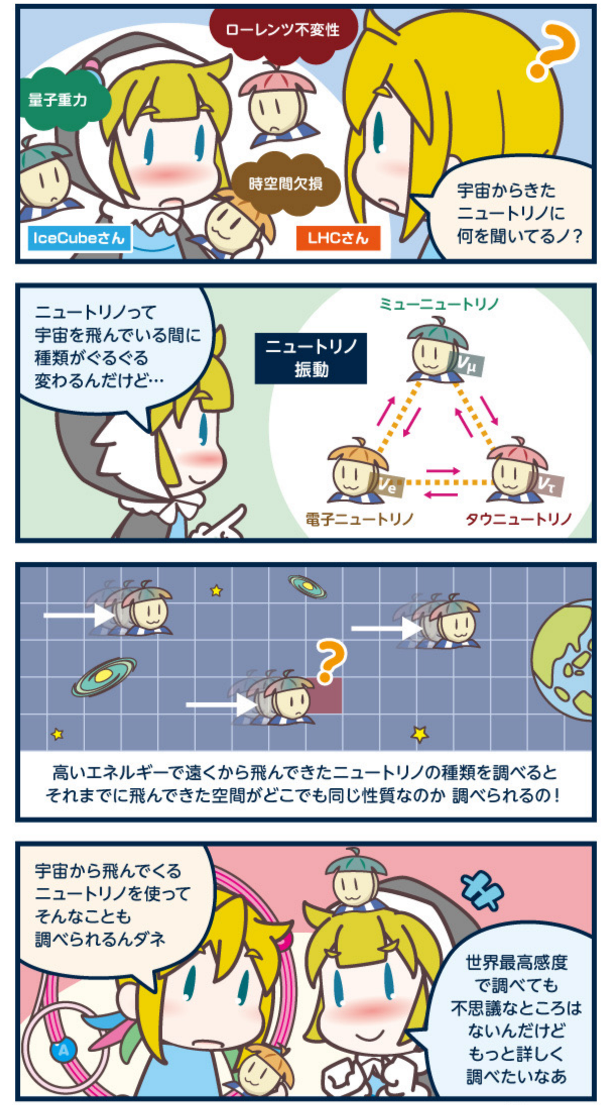
ニュートリノで調べる時空の性質



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