Neutrino Physics

1. Neutrino oscillations
2. History of neutrino oscillation
3. T2K neutrino oscillation experiments
4. Current and future neutrino experiments
5. Neutrino astronomy
6. Conclusion

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Teppei Katori
King's College London
JENNIFER2 Summer School
July 22-23, 2020

Mother nature is kind to us

Solar density, solar density gradient, solar neutrino energy are all right value so that we can detect solar neutrino oscillation through MSW effect

Supernova 1987A happens right time when Kamioknade II is online
(6 galactic supernovae in the last 1000 years)

The earth diameter and atmospheric neutrino energy are right values so that we can detect atmospheric neutrino oscillation through up-down asymmetry

θ_{13} is small so that 2 massive neutrino approximation work well to study solar neutrino mixing and atmospheric neutrino oscillation separately

But θ_{13} is big enough so that we can measure it leptonic CP violation

Mass ordering must be inverted so that we can find Dirac or Majorana?????

4. Neutrino oscillations

2. History of neutrino oscillation

3. T2K neutrino oscillation experiments

4. Current and future neutrino experiments

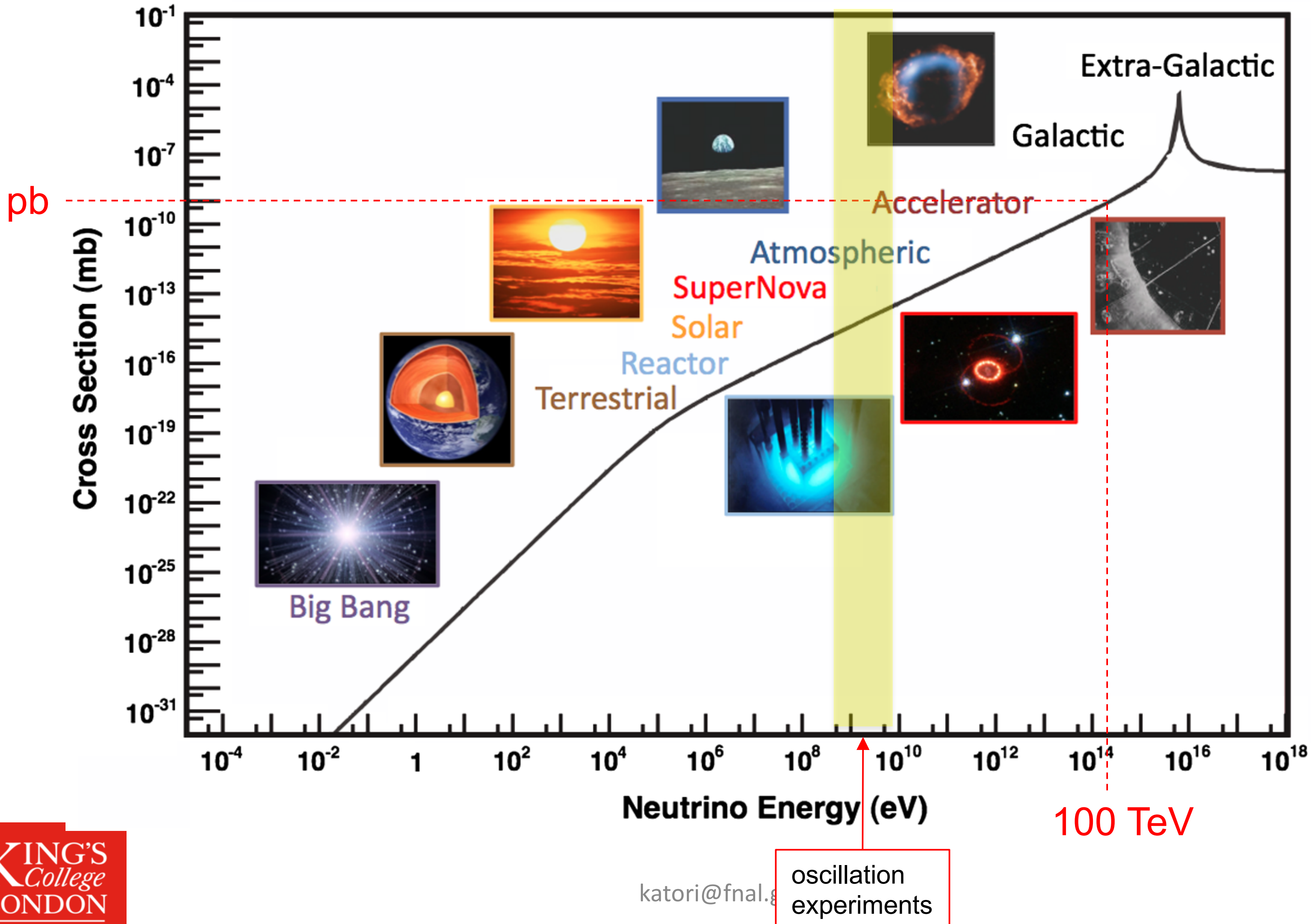
5. Neutrino astronomy

6. Conclusion

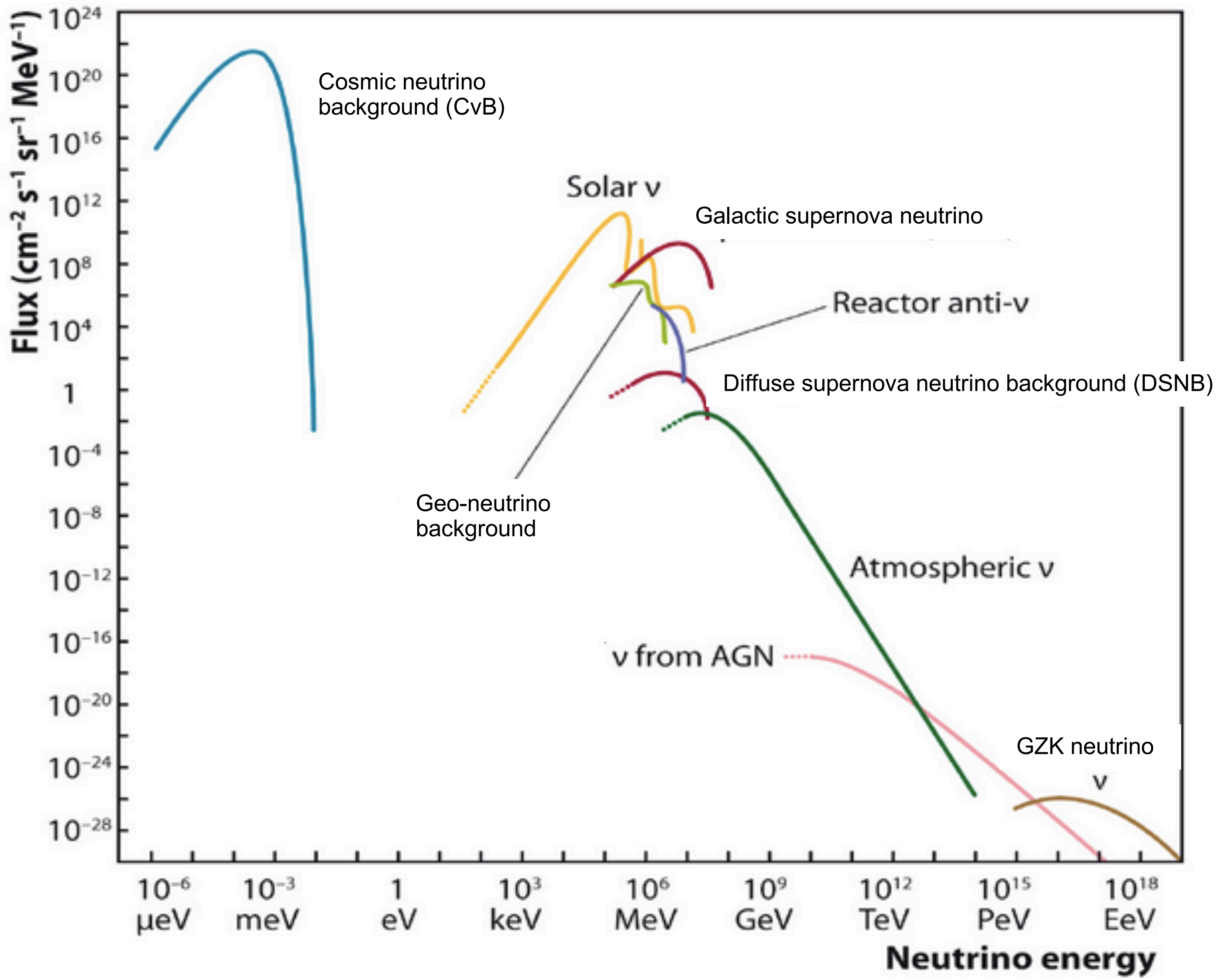
KING'S College LONDON

4.1. Neutrinos – from eV to EeV

electron antineutrino - electron elastic scattering cross section



4.1. Neutrinos – from eV to EeV



4.1. Neutrinos – Limited sources

Type	Source	Production	Energy	Note
Cosmic neutrino background (CvB)	Bing Bang	$\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	~0.1 meV	not detected
Neutrinos from radioactive sources	e-cap/βdec	$\nu_e, \bar{\nu}_e$	~0.7 - 0.8 MeV	
Geo-neutrinos	β-decay	$\bar{\nu}_e$	~ 2 MeV	
Reactor neutrinos	β-decay	$\bar{\nu}_e$	~4 MeV	manmade
Solar neutrinos	fusion	ν_e	~0.4-10 MeV	
Galactic supernova neutrinos	e-cap/thermal	$\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	~10-30 MeV	
Diffused supernova background	e-cap/thermal	$\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	~10 MeV	not detected
Accelerator neutrinos	π,K-decay	$\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	~10 MeV - 1 TeV	manmade
Conventional atmospheric neutrinos	π,K-decay	$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$	~0.1 GeV – 10 TeV	
Prompt atmospheric neutrinos	charm decay	$\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	~1 TeV – 10 PeV	not detected
Solar atmospheric neutrinos	π,K-decay	$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$	~0.1 – 10 PeV	not detected
High-energy astrophysical neutrinos	π-decay? β-decay?	$\nu_e, \nu_\mu, \nu_\tau?, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}$	~10 TeV - 10 PeV	
GZK neutrinos	π-decay?	$\nu_e, \nu_\mu, \nu_\tau?, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}$	~EeV	not detected

(Neutrino mixings allow to produce all flavours from all sources)

4.1. Current and Future neutrino experiments

Not covered in my talk

Accelerator-based long-baseline experiments

- NOvA, Hyper-Kamiokande, DUNE

T2K, P2O, P-ONE, CHIPS, IsoDAR, DAEdALUS, nuSTORM, EMuS, ESSnuSB, ENUBET, NuPRISM, etc

Accelerator-based short-baseline experiments

- MINERvA, MicroBooNE
- FASERnu
- COHERENT

HyperK ND, DUNE ND, SBND, ICARUS, ANNIE, NINJA, WAGASCI-BabyMIND, SHiP, etc

Reactor neutrino experiments

- JUNO
- PROSPECT, Watchman
- BEST

DayaBay, RENO, Double Chooz, STEREO, DANSS, NEOS, Neutrino-4, LENS, Chandler, CONNIE, MIVER, SoLid, BASKET, RICOCHET, RED-100, vGen, CONUS, LENS-sterile, CeLAND, DB Source, LXe-Source, SOX, etc

Neutrino-less double beta decay experiments

EXO-200, nEXO, PANDA-X, Super-NEMO, NEXT, KamLAND-Zen, AXEL, GERDA, MAJORANA, LEGEND, CUORE, CUPID, AMORE, etc

Astrophysical neutrino measurements

- Super-Kamiokande-Gd, Hyper-Kamiokande, Jinping
- PINGU, ORCA
- IceCube, IceCube-Gen2, KM3NeT, ARA
- KATRIN, Project 8

BOREXINO, GVD, DUNE, THEIA, INO, GRAND, ANITA, ARIANNA, RADAR, KATRIN, HOLMES, ECHO, etc

4.1. Neutrino basics

4.2. Accelerator-based long-baseline neutrino experiments

4.3. Accelerator-based short-baseline neutrino experiments

4.4. Reactor-based neutrino experiments

4.5. Neutrino-less double beta decay

4.2. Next goal of neutrino physics

Establish Neutrino Standard Model (νSM)

- SM + 3 active massive neutrinos

Unknown parameters of νSM

1. Dirac CP phase
2. $\theta_{23}<45^o$ "first octant" or $\theta_{23}>45^o$ "second octant"
3. normal ordering (NO) $m_1<m_2<m_3$ or inverted ordering (IO) $m_3<m_1<m_2$
4. Dirac or Majorana
5. Majorana phase (x2)
6. absolute neutrino mass

We need higher precision experiments around 1-10 GeV to measure (1), (2), and (3)

4.2. Standard neutrino oscillation experiments

2-neutrino oscillation approximation,

$$P_{\mu\to\tau}(L,E) = sin^2 2\theta sin^2\left(1.27\Delta m_{32}^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

Use $|\Delta m_{32}^2| \sim 2.5 \cdot 10^{-3} eV^2$, then 1st and 2nd oscillation maximums are L(km)/E(GeV)~500 and 1000

→ 1300km baseline experiment with accelerator neutrino energy 1-4 GeV (=DUNE)

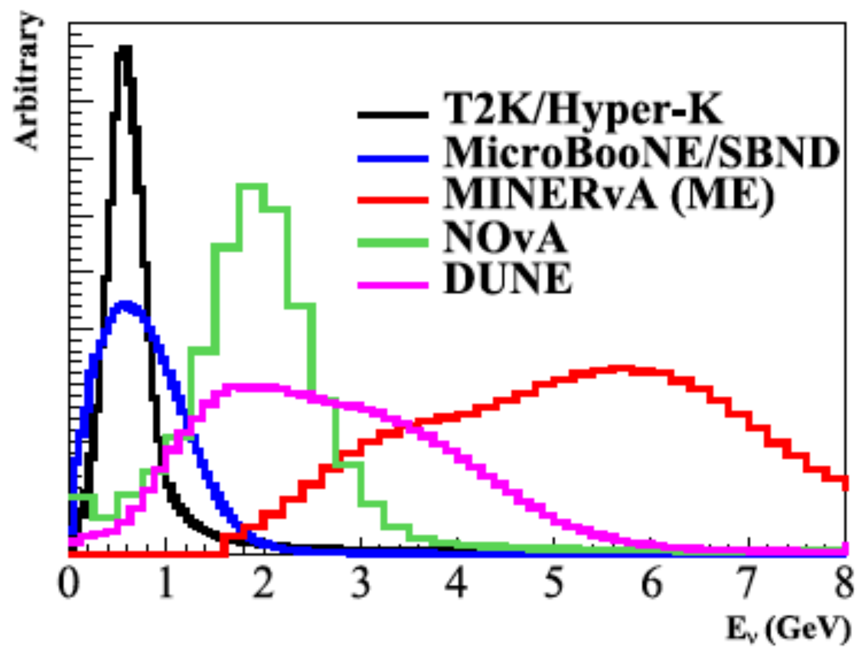
Accelerator-based neutrino oscillation experiments need to tune L/E

Very long baseline (~1000km)
- Large L → high flux reduction
- Large E → higher ν-production, high σ, calorimetric E recon

→ DUNE design

Long baseline (~200km)
- Small L → lower flux reduction
- Small E → low n-production, small σ, kinematic E recon

→ HyperK design



4.2. Accelerator-based neutrino – $\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

π/K Decay-In-Flight (DIF) neutrinos, "superbeam"
- Known spectrum, ~4% precision at best
- Our future

BNB: Mini/Sci/μBooNE, SBND, ICARUS
NuMI: MINOS, NOvA, MINERvA
J-PARC beam: T2K, Hyper-Kamiokande
DUNE beam

π/K Decay-At-Rest (DAR) neutrinos
- Precisely known spectrum (SM, 2-body decays)
- Known production points
- Neutron sources (SNS, JSNS, ESS)

LSND, SNS, JSNS, ESSnuSB

Muon decay neutrinos, "neutrino factory"
- Precisely known spectrum (SM)
- Muon cooling & storage ring for "muon collider"

NuSTORM, EMuS

Isotope decay neutrinos "beta beam"
- Precisely known spectrum
- High-flux low energy beam (=short baseline)

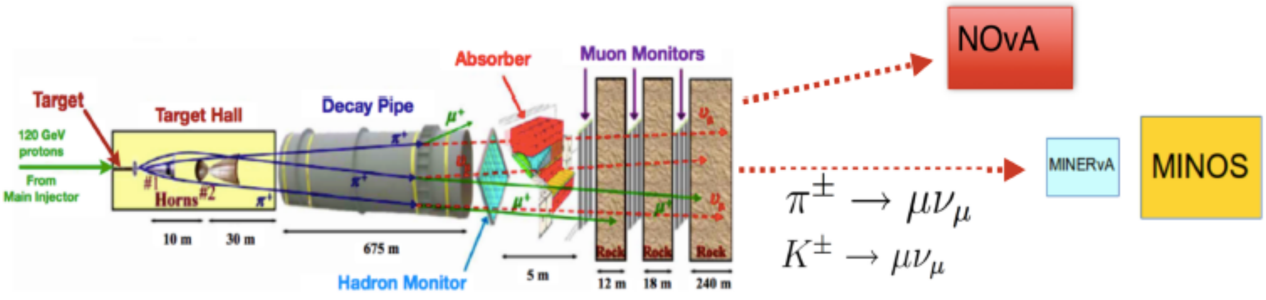
IsoDAR

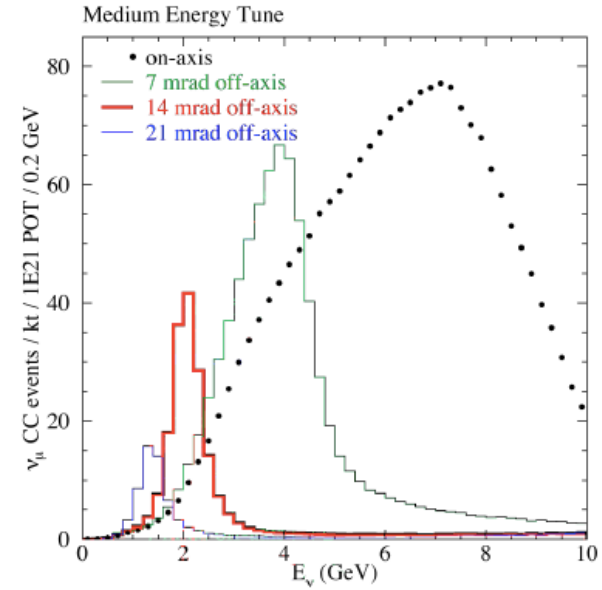
All beams have precise timing (pulsed beam)

2 different approaches
ENUBET: EPJC.75(2015)155
Precise monitoring type projects
NuPRISM: ArXiV:1412.3086
Movable neutrino near detector

4.2. On-axis vs. Off-axis beam

On-axis beam: narrow band, tuned to oscillation maximum
Off-axis beam: broadband, general purpose, measure 1st and 2nd max





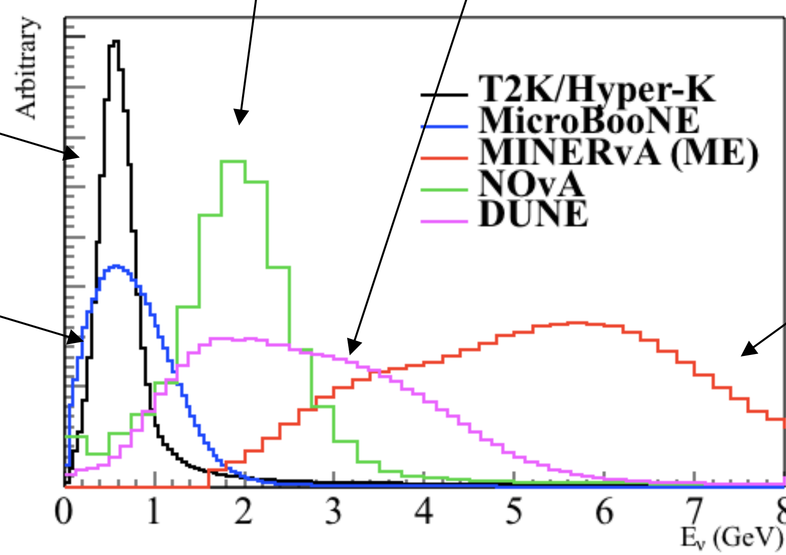
NOvA
NuMI off-axis beam

DUNE on-axis beam

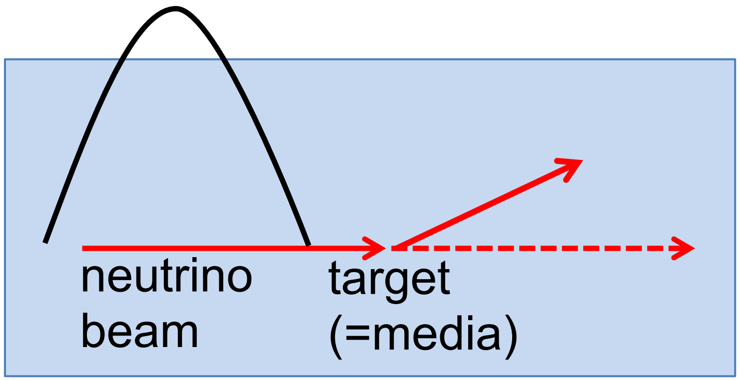
T2K, HyperK
J-PARC off-axis beam

MicroBooNE/SBND/ICARUS
BNB on-axis beam

MINERvA
NuMI on-axis beam



4.2. Typical neutrino detectors



Wide beam spectrum
- Incoming neutrino energy is not known

Coarse detectors
- Volume is maximized with poor instrumentation

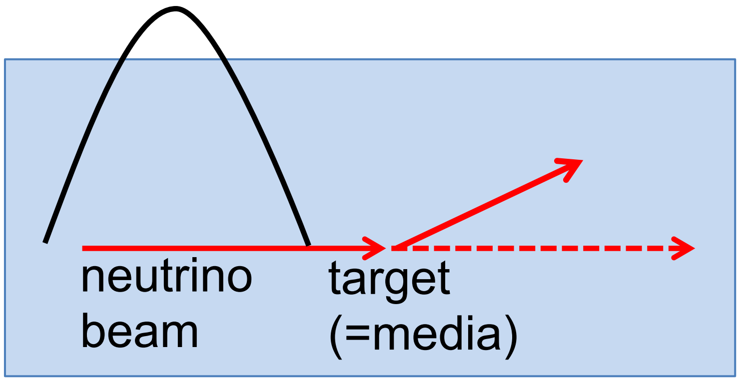
Nuclear target
- Neutrino interacts on nuclei

Incomplete kinematics
- Particle kinematics is under-constraint
- Neutrino energy Ev is reconstructed with assumed interaction (model-dependent)
- All kinematics (Ev, Q2, W, x, y,…) in 1-10 GeV depends on interaction models

Nuclear physics
- Fermi motion (motion of nucleons in muclei)
- Pauli blocking (phase space suppression)
- Final state interaction (re-scattering of outgoing particles in nuclei)
- Nucleon short range correlation, medium range correlation, long range correlation
- Nuclear shadowing, EMC effect, quark-hadron duality

TK and Martini, JPhysG45(2018)013001

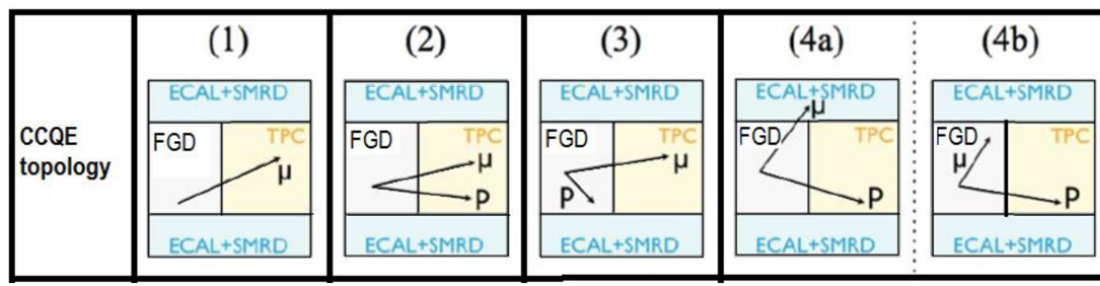
4.2. Typical neutrino detectors

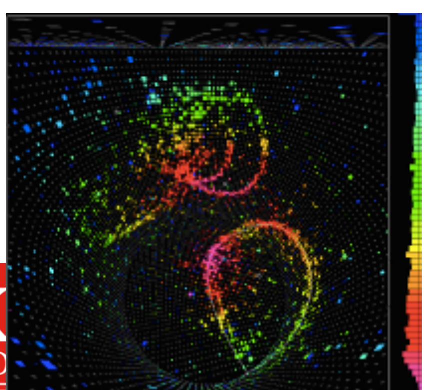


Liquid Scintillator
- JUNO, etc
- 4π coverage
- calorimetric
- low E threshold
- no direction information (in general)

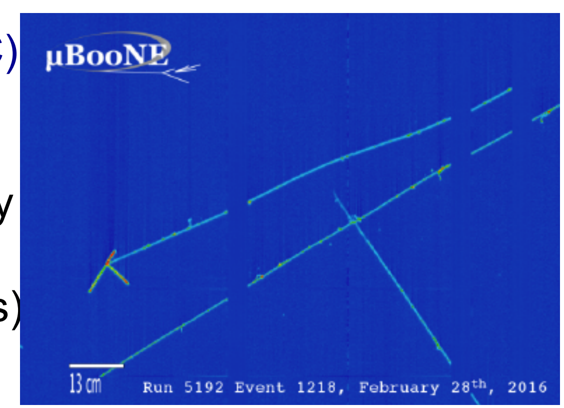
Tracker neutrino detector
- MINERvA, NOvA, etc
- multi-track measurements
- vertex activity measurement
- efficiency depends on topology

Cherenkov neutrino detectors
- Hyper-Kamiokande, etc
- 4π coverage
- Doping (scintillation, neutron capture)
- not good to measure multi-tracks





Liquid argon TPC (LArTPC)
- DUNE, etc
- 4π coverage
- multi-track, vertex activity
- calorimetric (scintillation)
- no timing from TPC (~ms)



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TK and Martini, JPhysG45(2018)013001

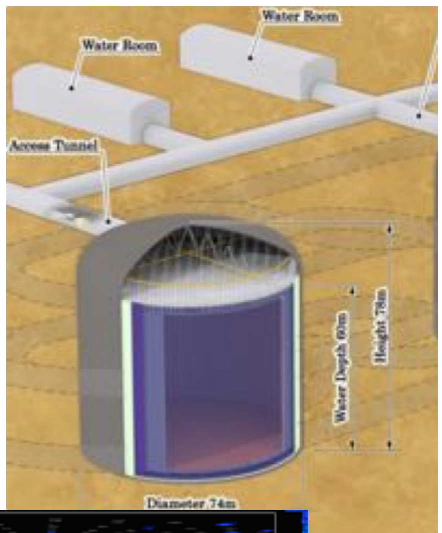
4.2. Hyper-Kamiokande and DUNE far detectors

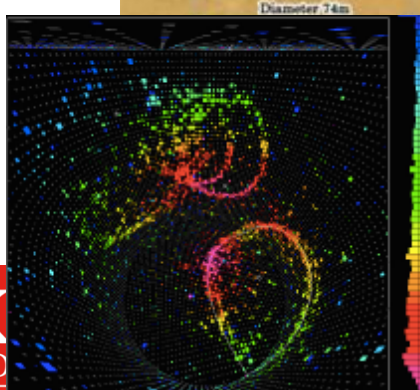
HyperK

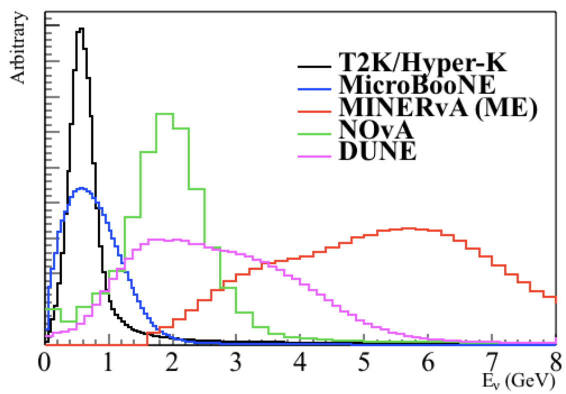
- 260 kton Water Cherenkov
- Narrow band 0.6 GeV
- Low spatial resolution
- High timing resolution
- Kinetic E reconstruction

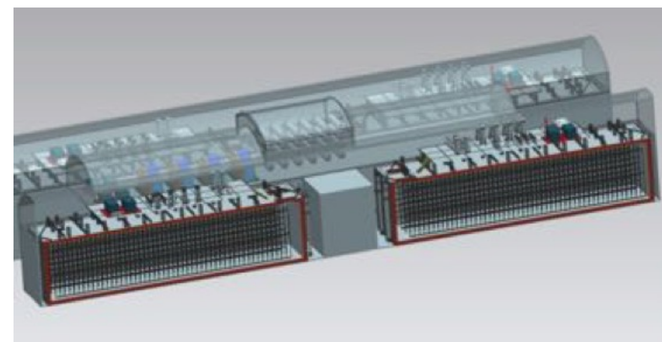
DUNE

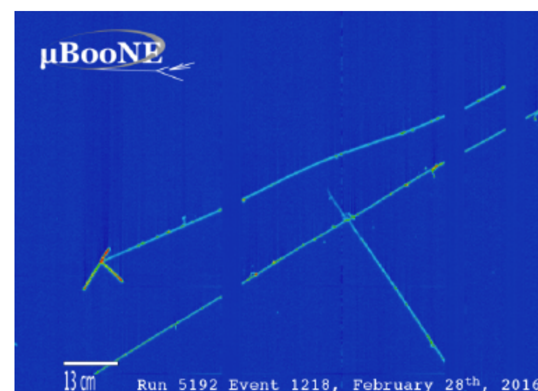
- 40 kton LArTPC
- wide band 1-4 GeV
- High spatial resolution
- Low timing resolution
- Kinematic and Calorimetric E reconstruction









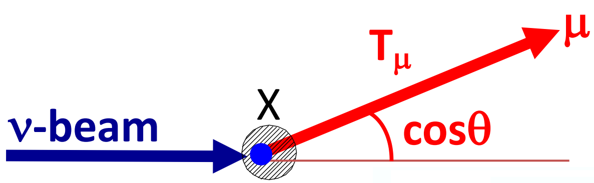


All current and future accelerator-based neutrino experiments are 0.1-10 GeV

4.2. Kinematic E reconstruction vs calorimetric E reconstruction

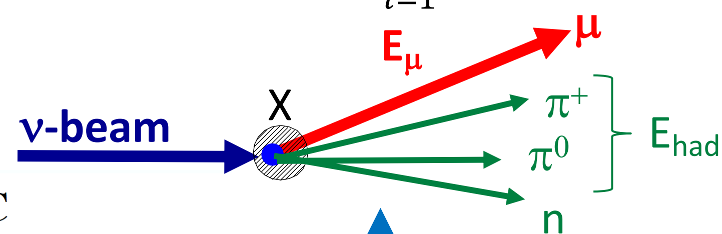
1. Kinematics energy reconstruction
 - It can reconstruct Enu from outgoing lepton kinematics only, but you have to assume neutrino interact type

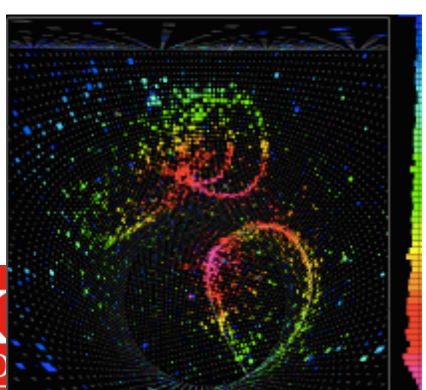
$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

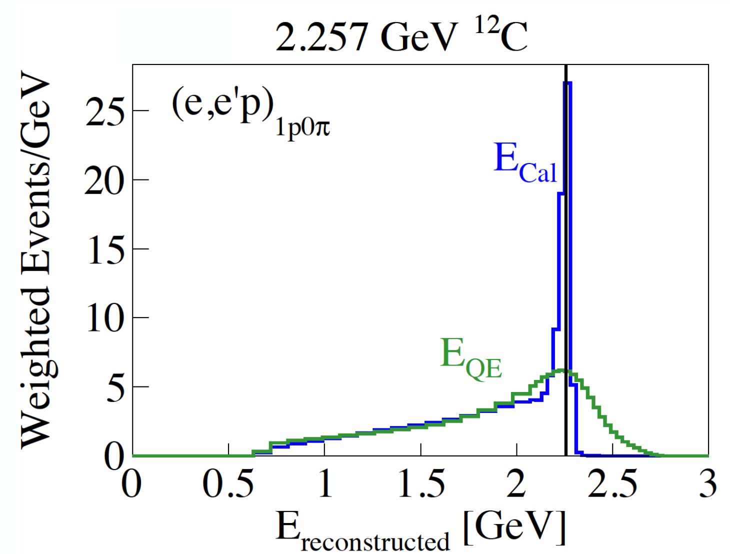


2. Calorimetric energy reconstruction
 - No assumption on interaction type, but you have to measure energy deposit from all outgoing particles (or correctly simulate them)

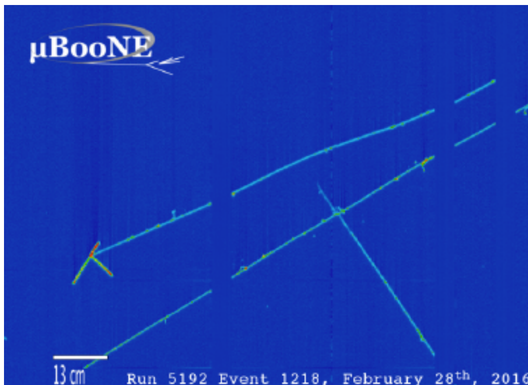
$$E_\nu^{Cal} = E_\mu + \sum_{i=1}^{all} E_{had}^{i}$$





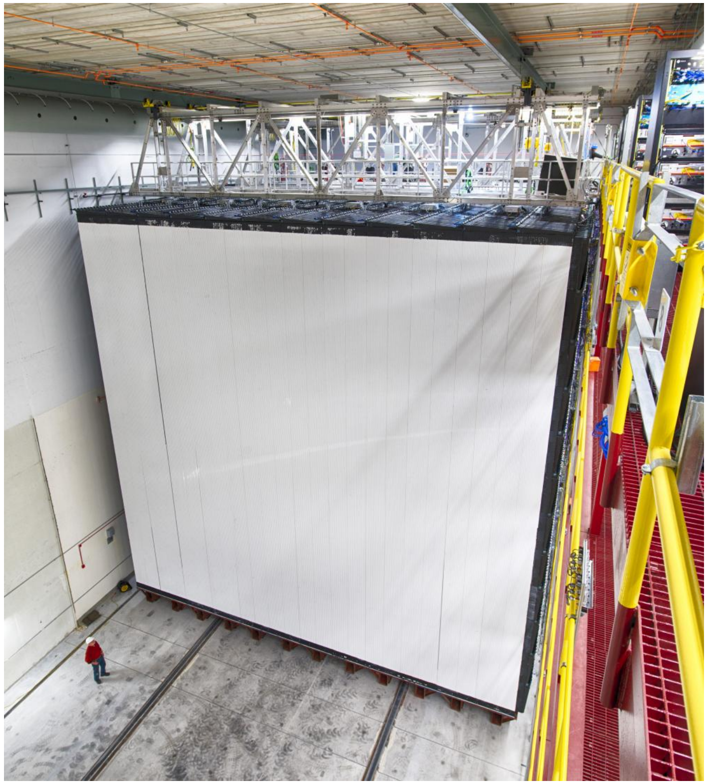


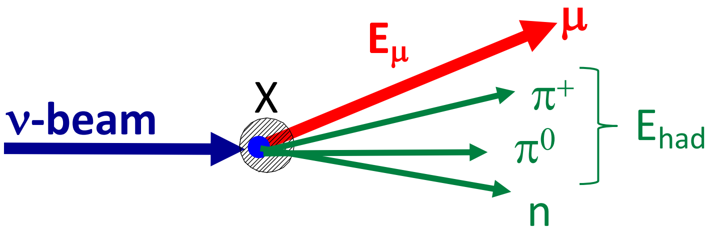
energy reconstruction test using CLAS electron scattering data

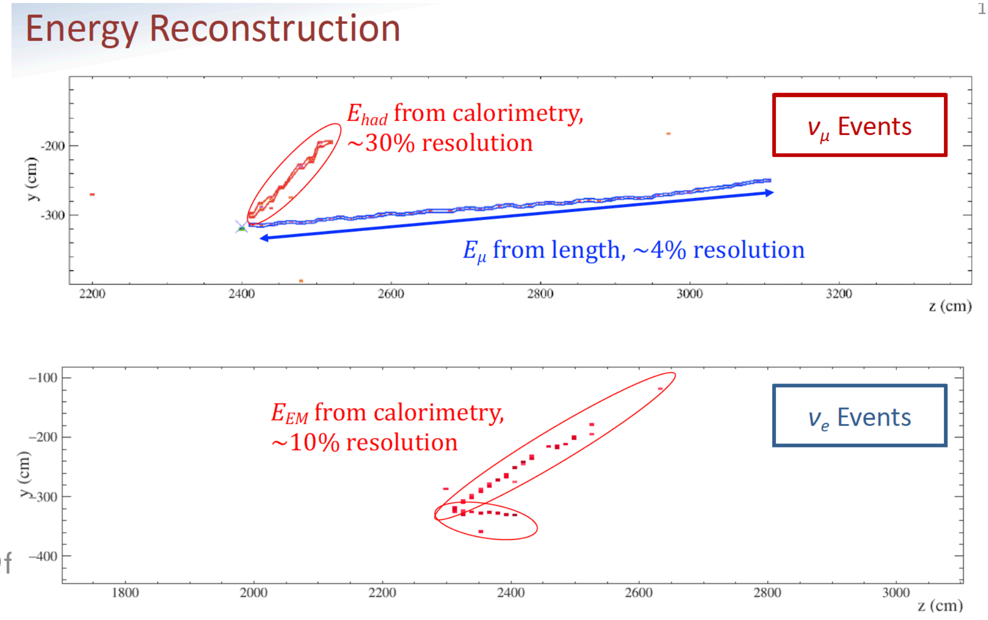


4.2. NOvA

Massive plastic tubes with liquid scintillator
- 14 kton total, 810 km from Fermilab (E~2GeV)
- Longer baseline → nonzero matter effect (mass ordering)
- Calorimetric energy reconstruction







4.2. Oscillation parameter measurements, status and future

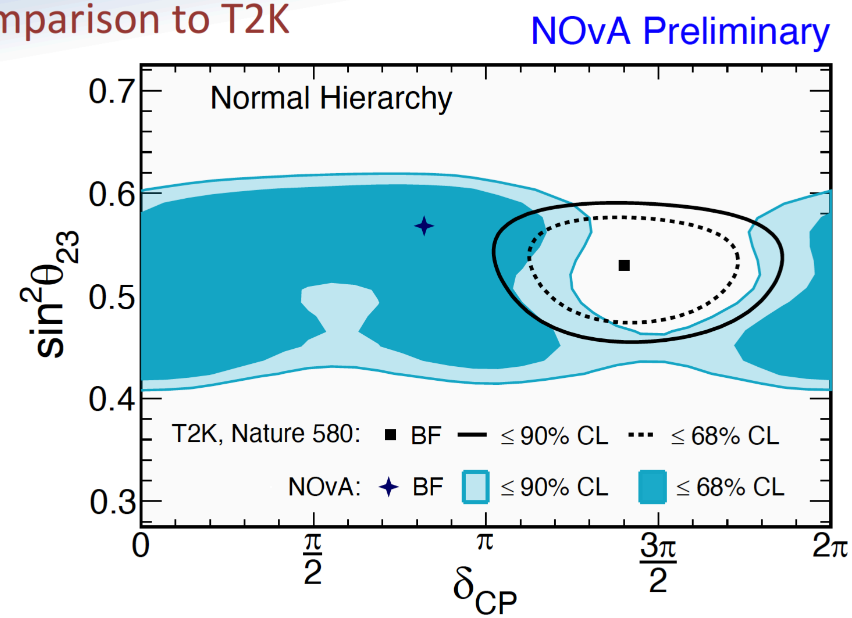
1. T2K prefer upper octant, normal hierarchy, large negative δCP, because data see many ν_e signal

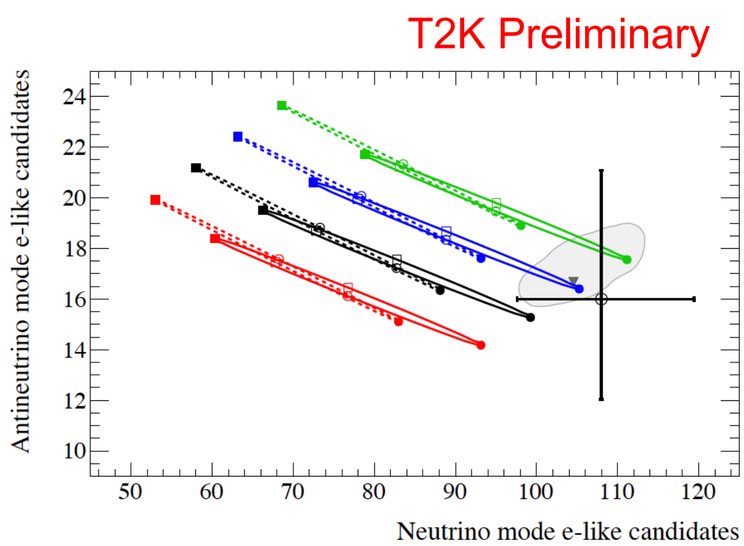
2. NOvA see both ν_e and anti-ν_e events, and the best fit point is the center of the phase space

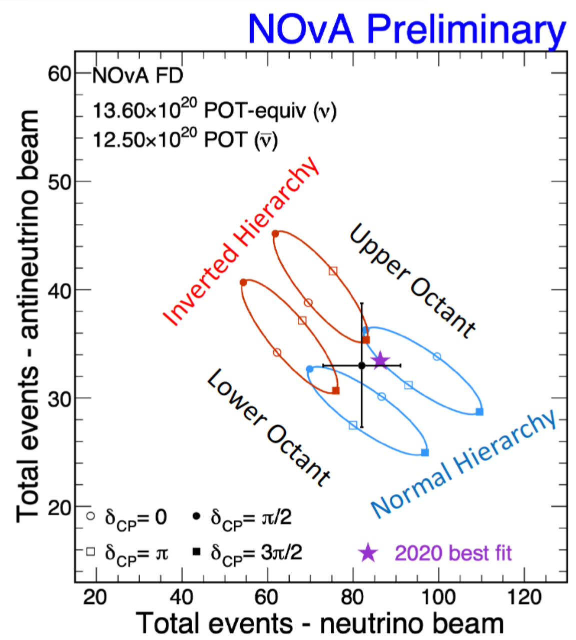
Statistically, both data are consistent, but...
 - Is tension real? Systematics? New Physics?

Both HyperK and DUNE promise 5σ rejection of zero δCP with ~few% systematic errors.

Comparison to T2K







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4.1. Neutrino basics

4.2. Accelerator-based long-baseline neutrino experiments

4.3. Accelerator-based short-baseline neutrino experiments

4.4. Reactor-based neutrino experiments

4.5. Neutrino-less double beta decay

4.3. Accelerator-based short baseline neutrino experiments

1. Sterile neutrino search
2. Neutrino cross-section measurement
3. New physics search

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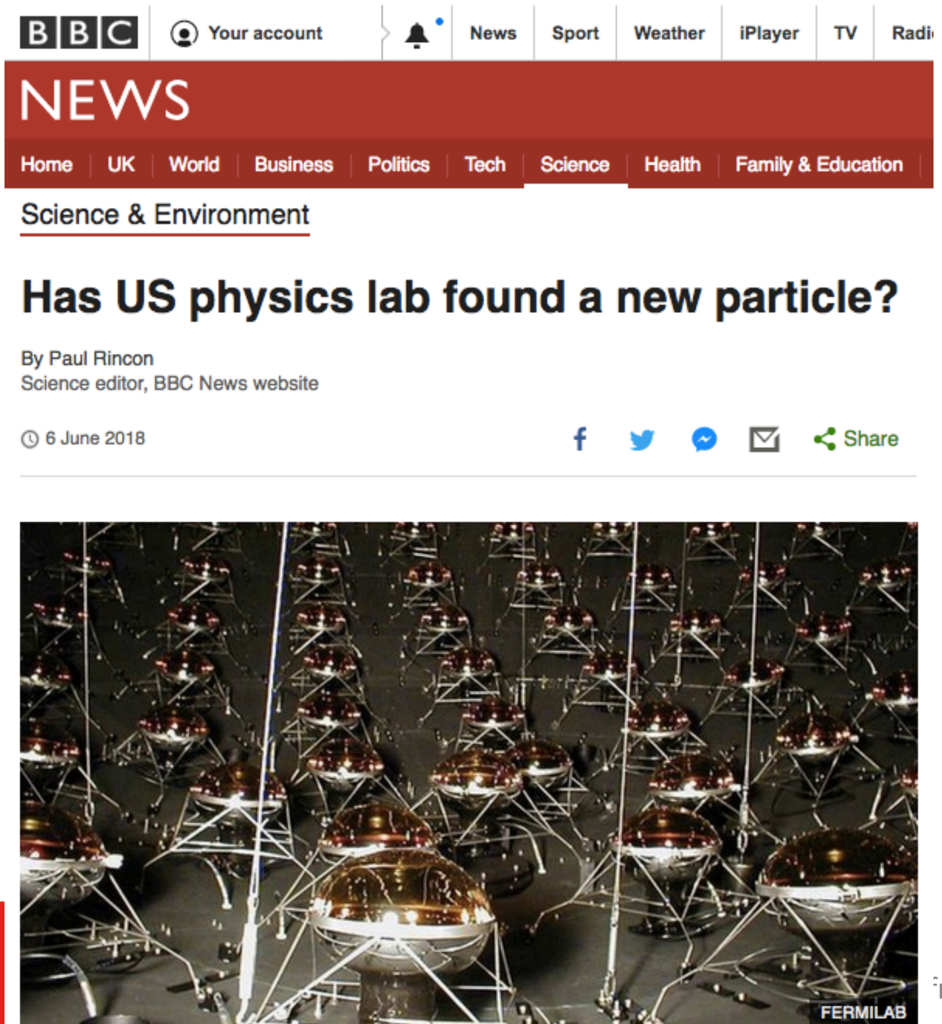
MiniBooNE, ArXiv2006.16883,
Dentler et al, JHEP08(2018)010

4.3. 1eV sterile neutrino search

1. Sterile neutrino search
2. Neutrino cross-section measurement
3. New physics search

- MiniBooNE reaches 4.8σ excess
(Sterile-ν interpretation is rejected by disappearance data)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By Paul Rincon
Science editor, BBC News website

6 June 2018

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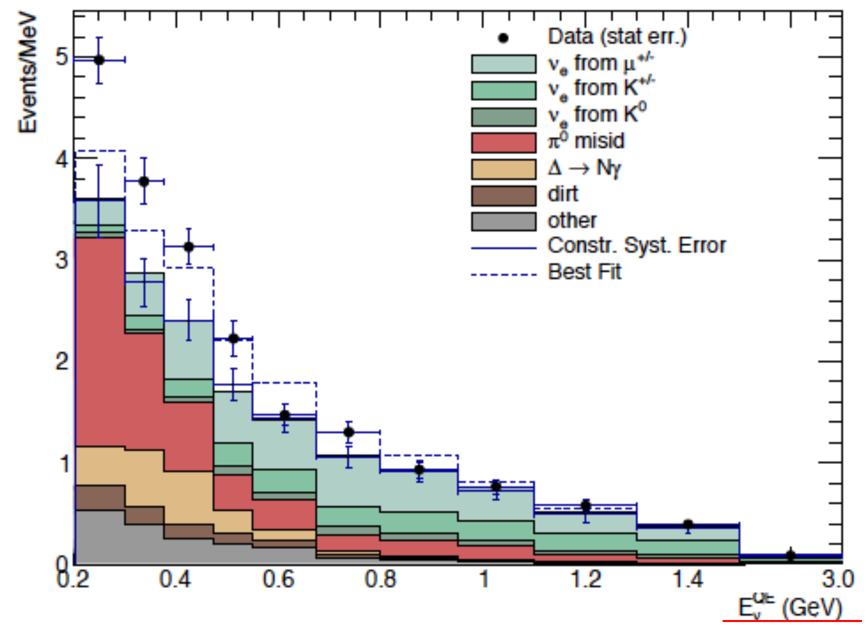
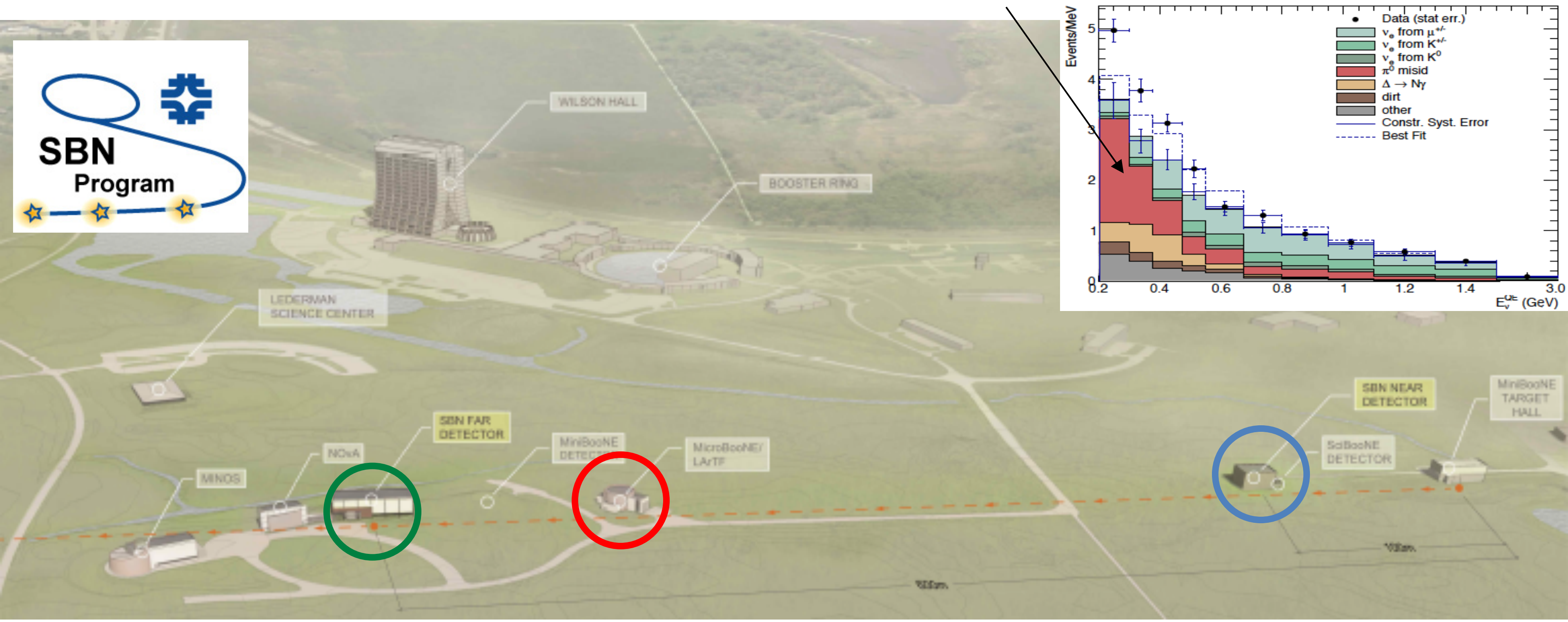


MiniBooNE, PRL121(2018)221801
Fermilab SBN program, arXiv:1503.01520

4.3. Fermilab short baseline neutrino (SBN) program

1. Sterile neutrino search
2. Neutrino cross-section measurement
3. New physics search

- MiniBooNE reaches 4.8σ excess
(Sterile-ν interpretation is rejected by disappearance data)
→ 3 LArTPCs to investigate MiniBooNE signal
(LArTPC= high photon bkgd rejection)



ICARUS
- 600 m
- 476 ton

MicroBooNE
- 470 m
- 85 ton

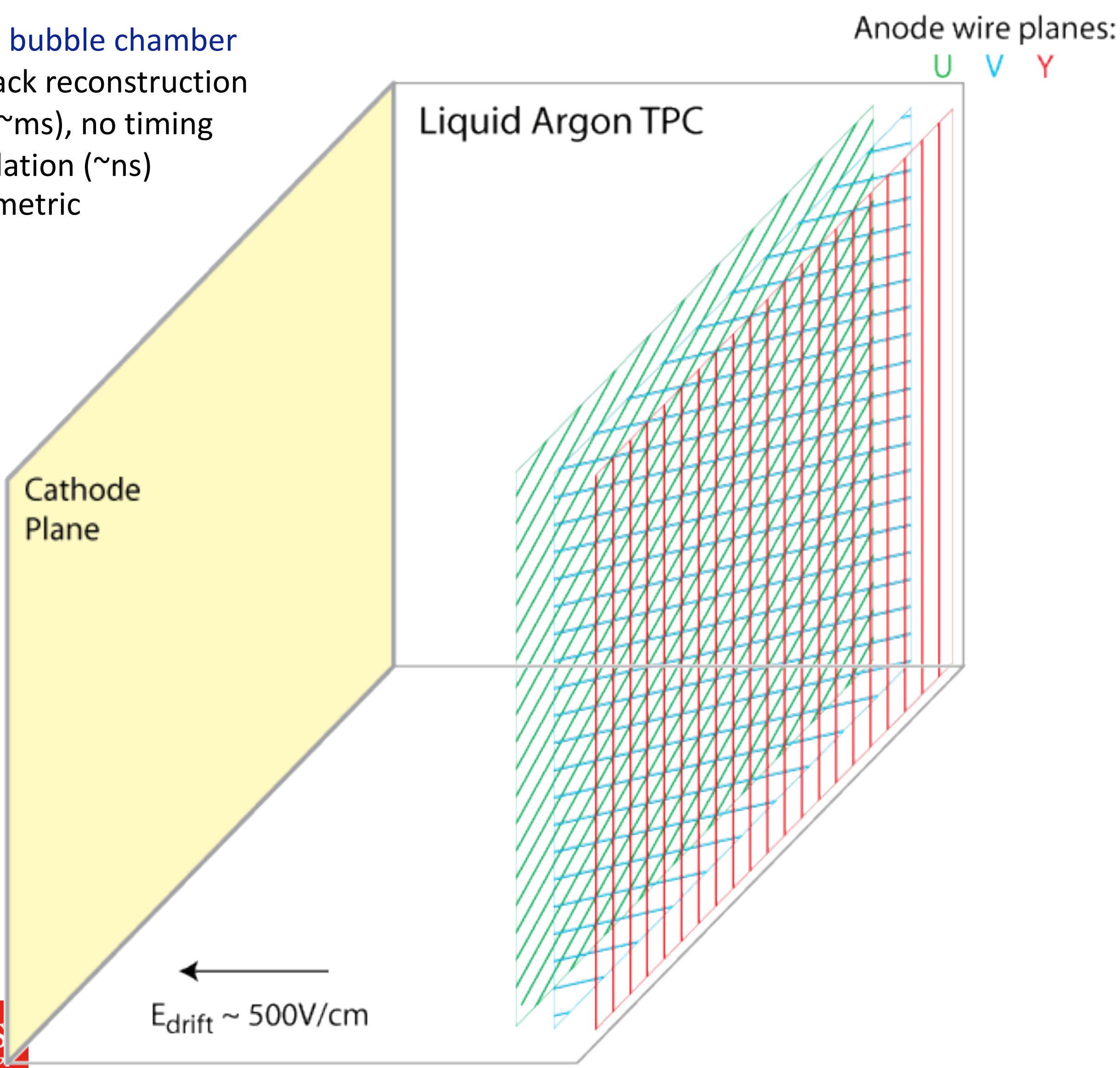
SBND
- 110 m
- 112 ton

← neutrino beam

4.3. LArTPC

Modern bubble chamber

- 3-d track reconstruction
- slow (~ms), no timing
- scintillation (~ns)
- calorimetric



4.3. LArTPC

Modern bubble chamber
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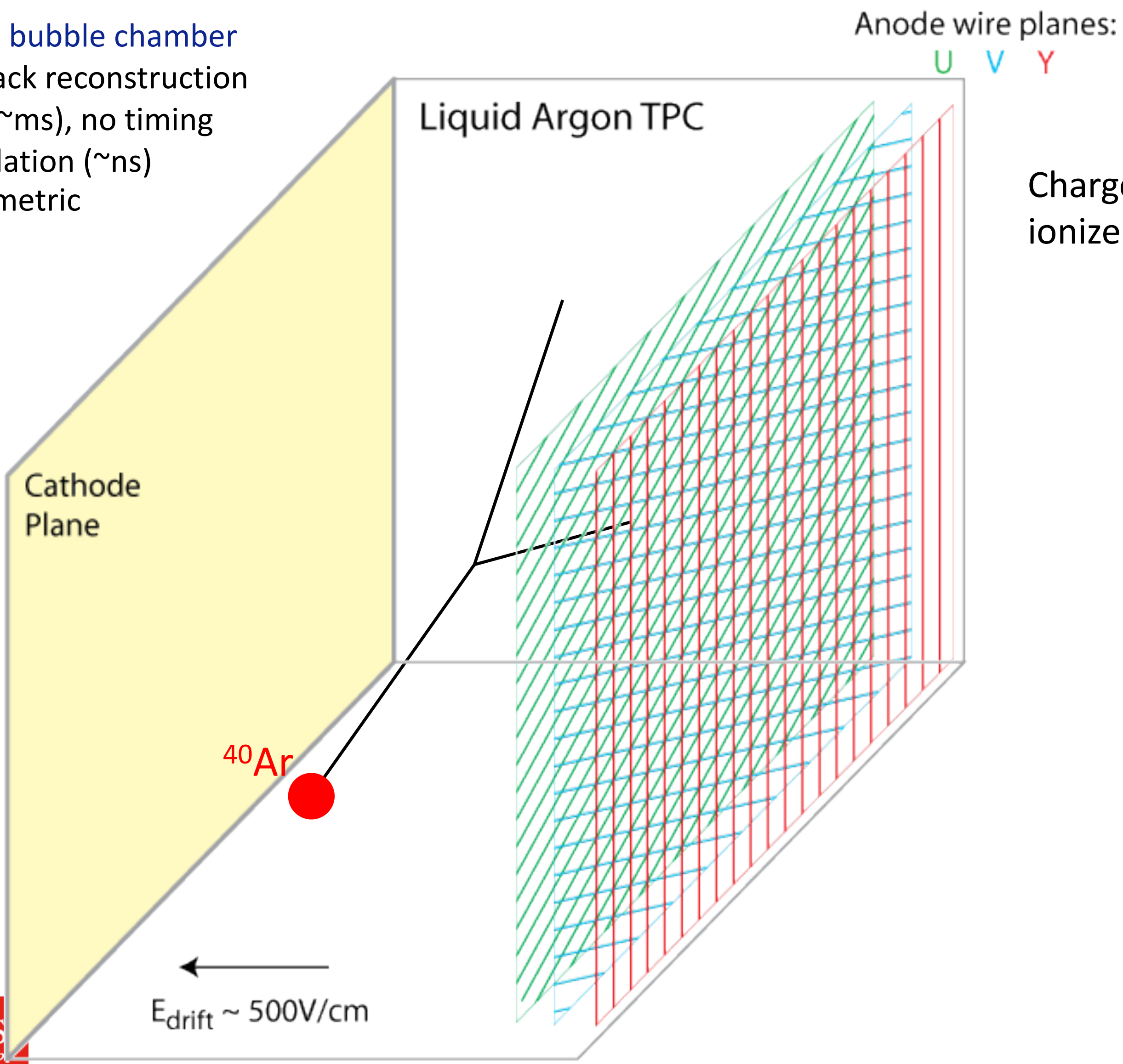
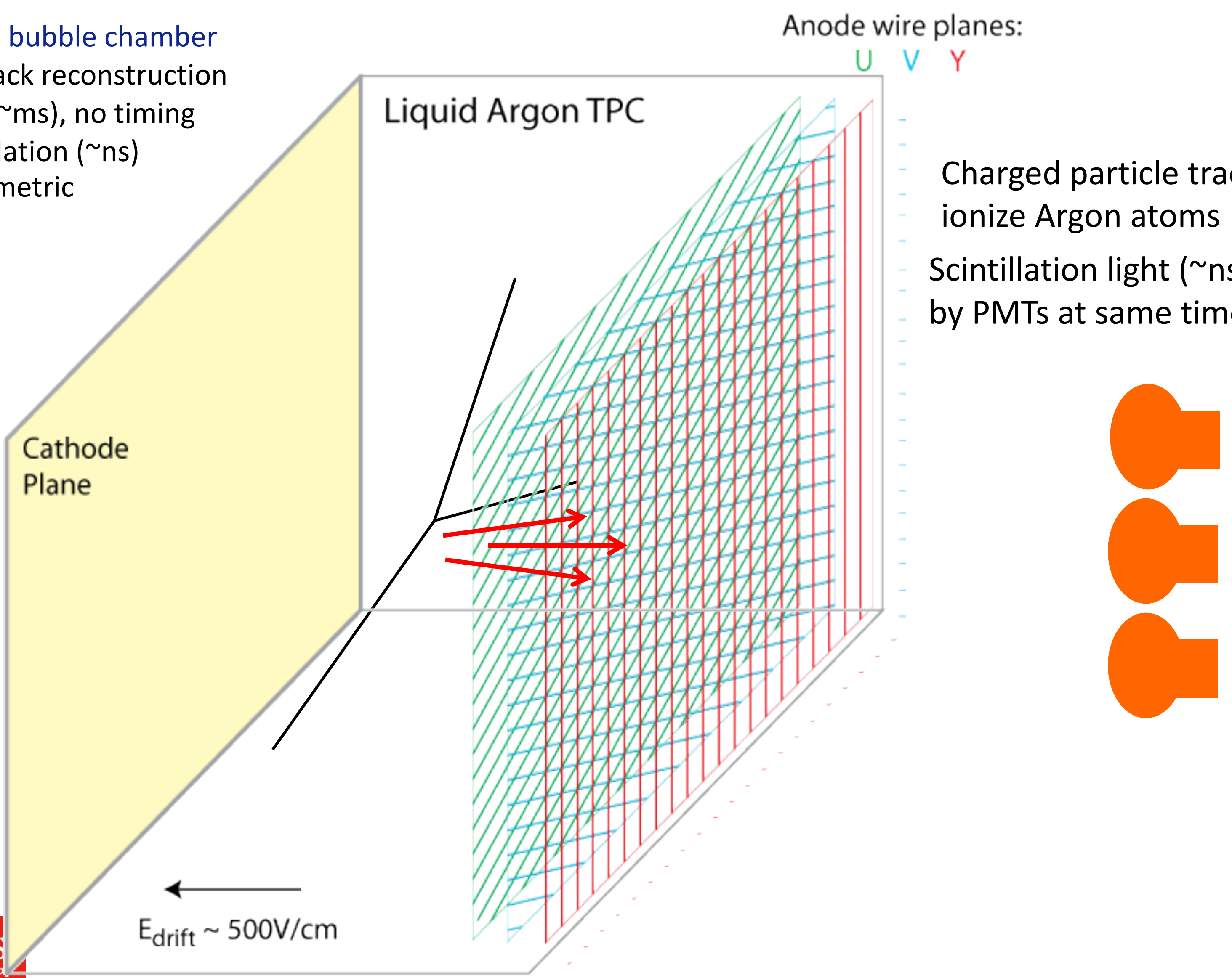


Charged particle tracks ionize Argon atoms

4.3. LArTPC

Modern bubble chamber
- 3-d track reconstruction
- slow (~ms), no timing
- scintillation (~ns)
- calorimetric

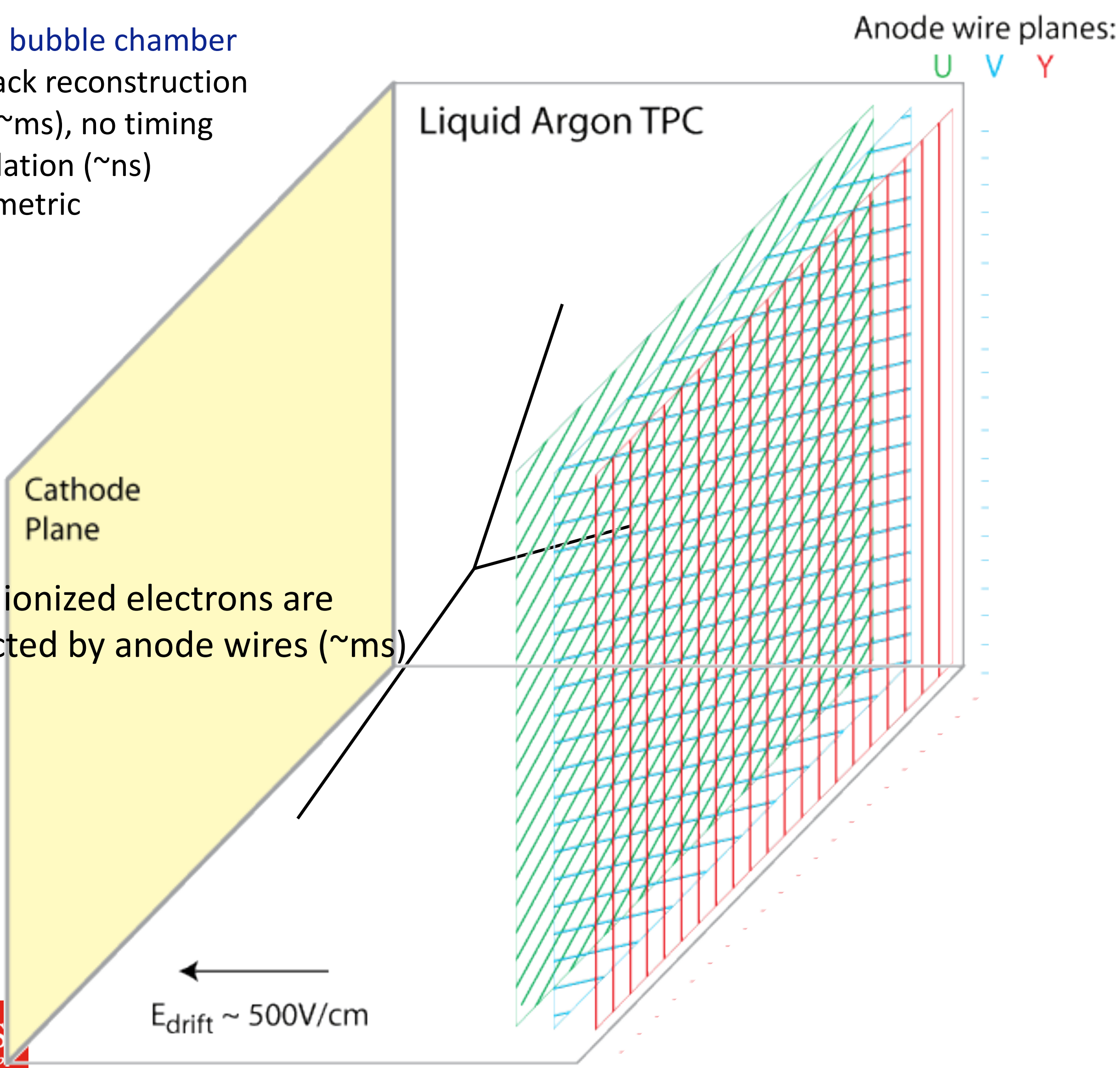


Charged particle tracks ionize Argon atoms

Scintillation light (~ns) is detected by PMTs at same time

4.3. LArTPC

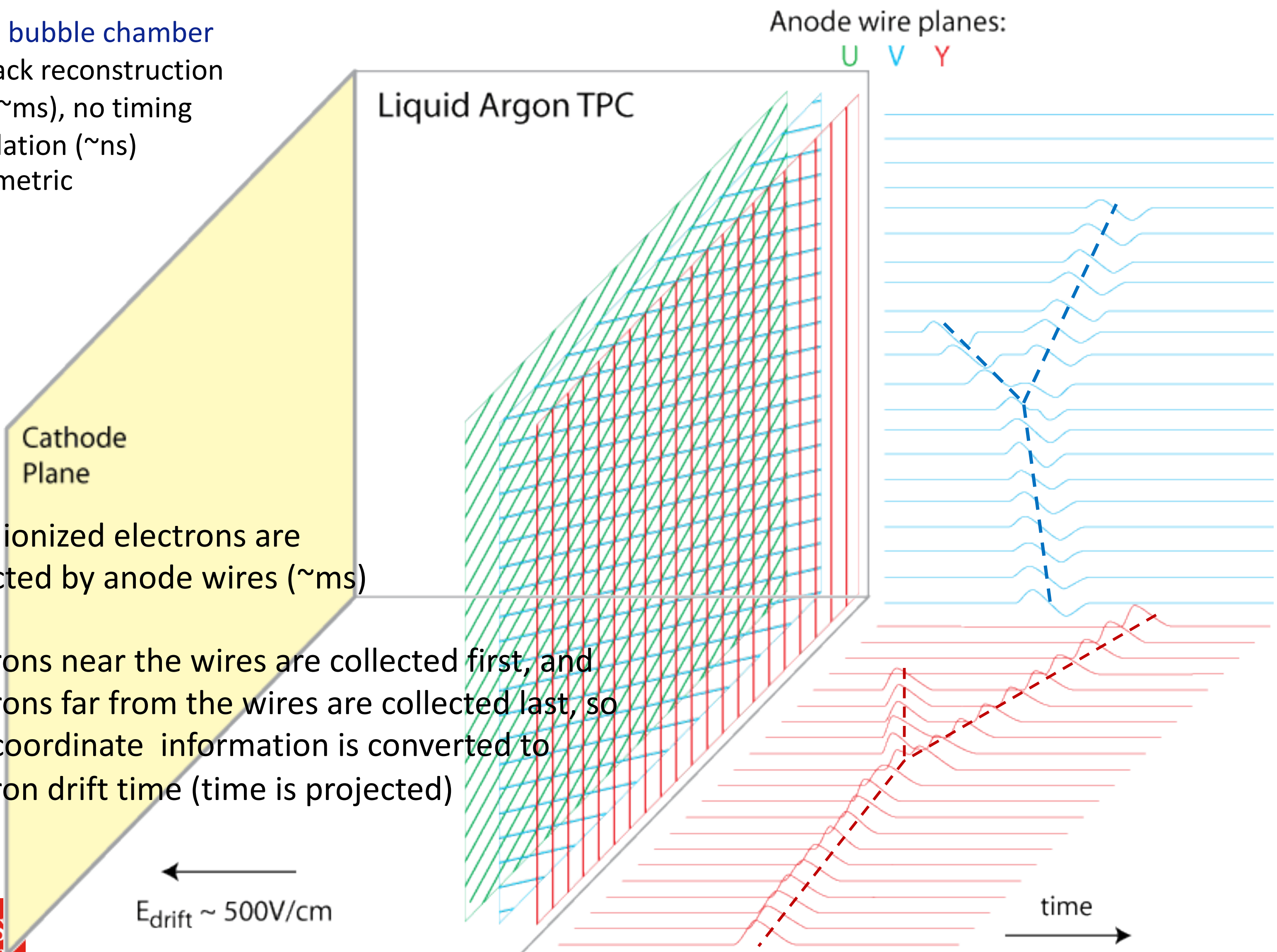
Modern bubble chamber
- 3-d track reconstruction
- slow (~ms), no timing
- scintillation (~ns)
- calorimetric



Then ionized electrons are collected by anode wires (~ms)

4.3. LArTPC

Modern bubble chamber
- 3-d track reconstruction
- slow (~ms), no timing
- scintillation (~ns)
- calorimetric

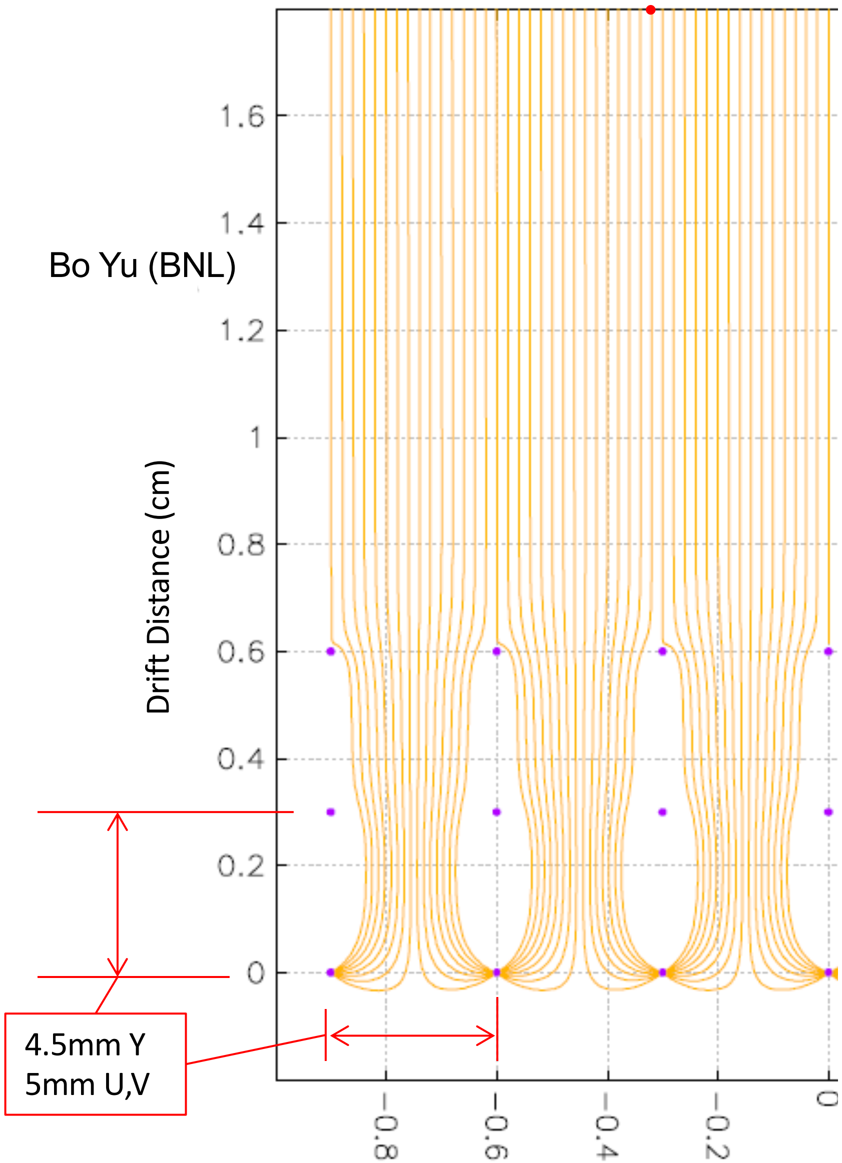


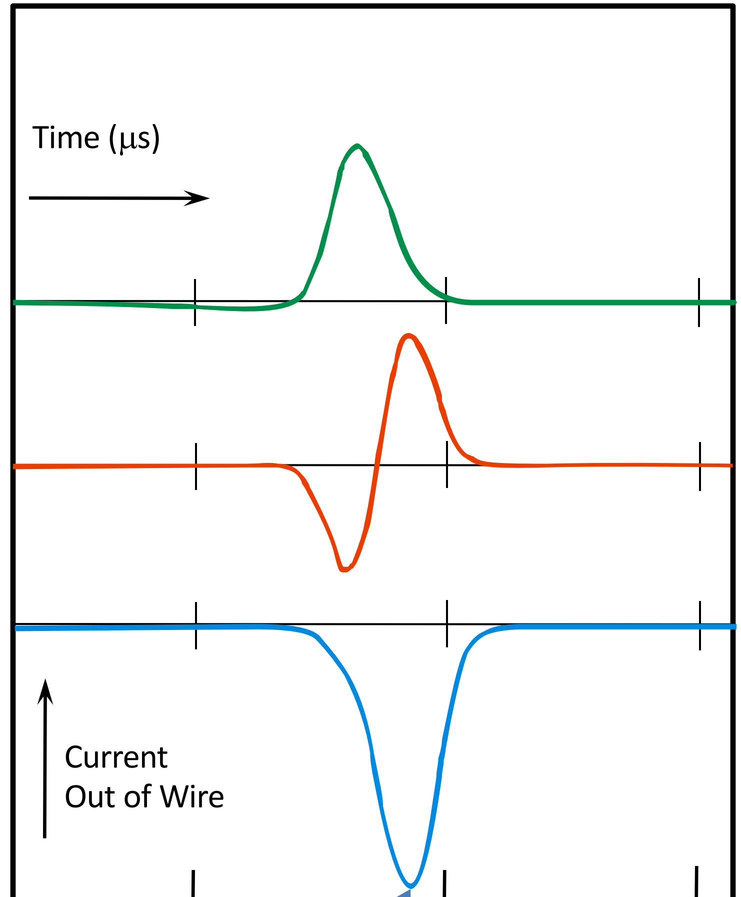
Then ionized electrons are collected by anode wires (~ms)

Electrons near the wires are collected first, and electrons far from the wires are collected last, so drift coordinate information is converted to electron drift time (time is projected)

Charge Signal Formation

Bo Yu (BNL)





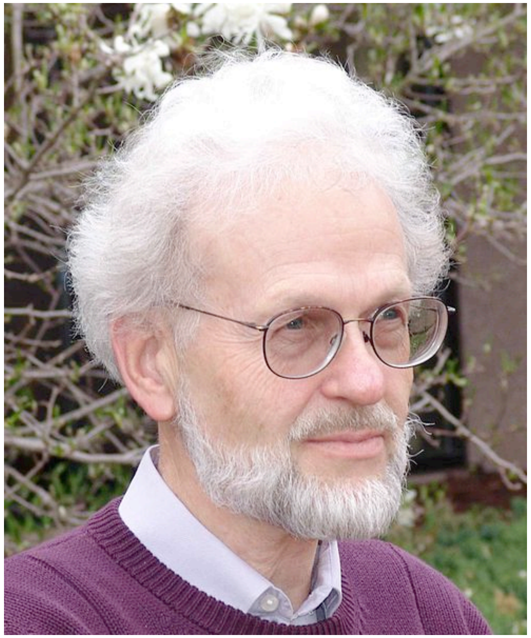
U Induction (small, bipolar)

V Induction (small, bipolar)

Y Collection (large, unipolar)

<u>ArgoNeuT</u>
1 MIP peak ~ 26 ADC counts
Noise rms ~ 1 ADC count

Living legends



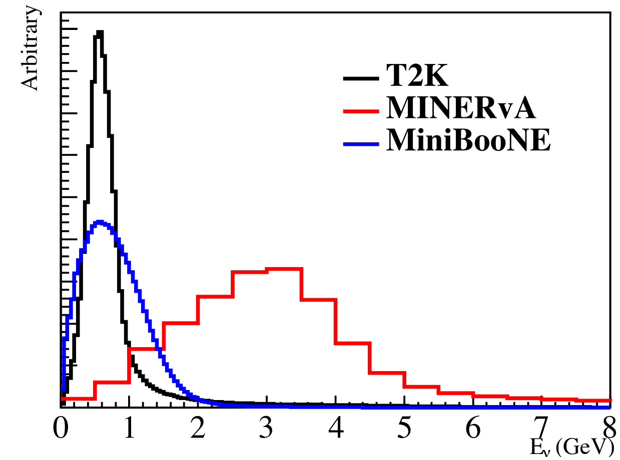
Time Projection Chamber
David Nygren
(Berkeley lab → U. Texas, Arlington)

Liquid Ionization Detector
Veljko Radeka
(Brookhaven national lab)

Liquid Argon Time Projection Chamber
Carlo Rubbia
(CERN → Senator of Italy)
Nobel Prize, 1984

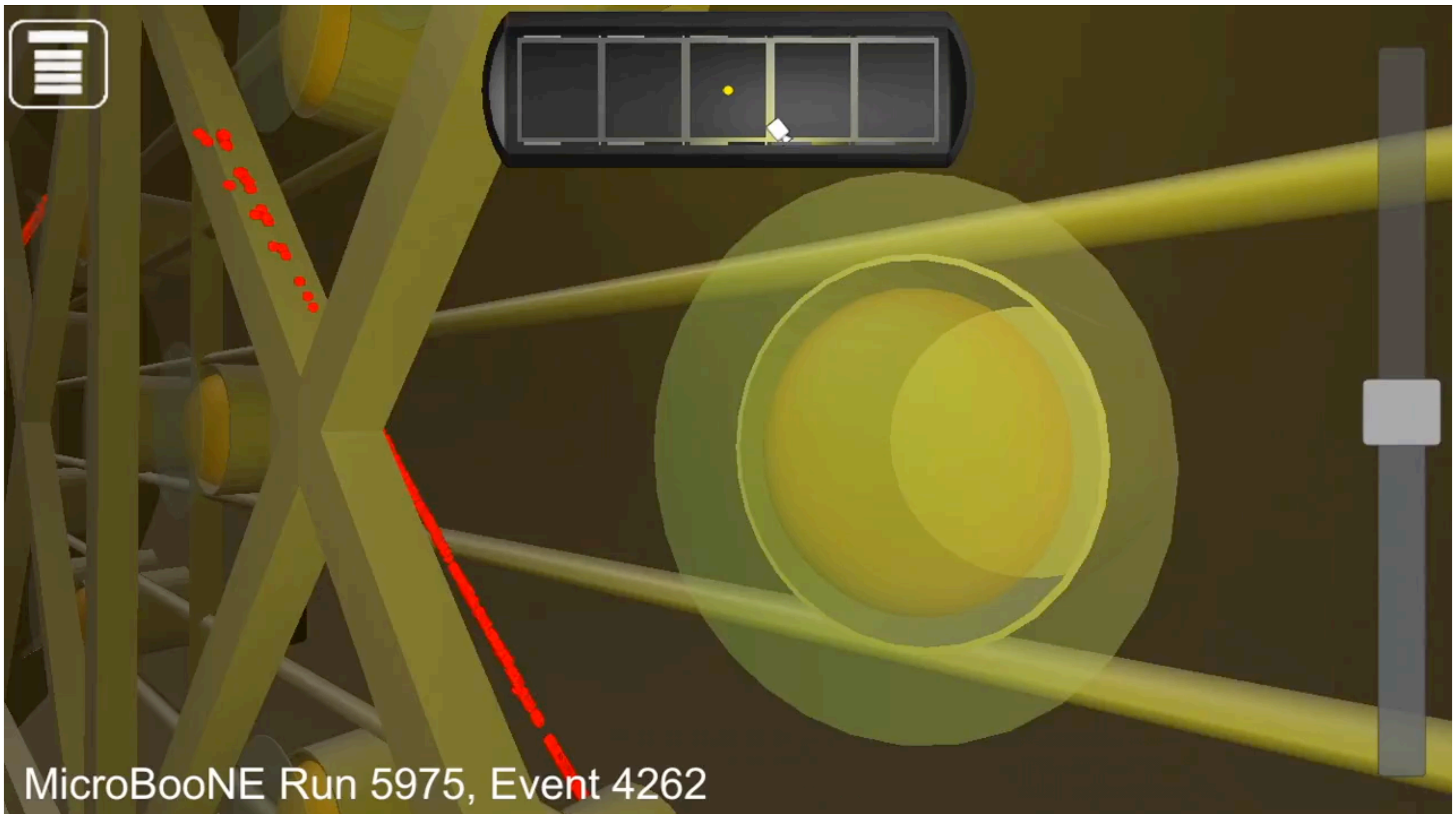
MicroBooNE, JINST12(2018)PO2017
VENu, http://venu.physics.ox.ac.uk/

4.3. MicroBooNE



86ton LArTPC

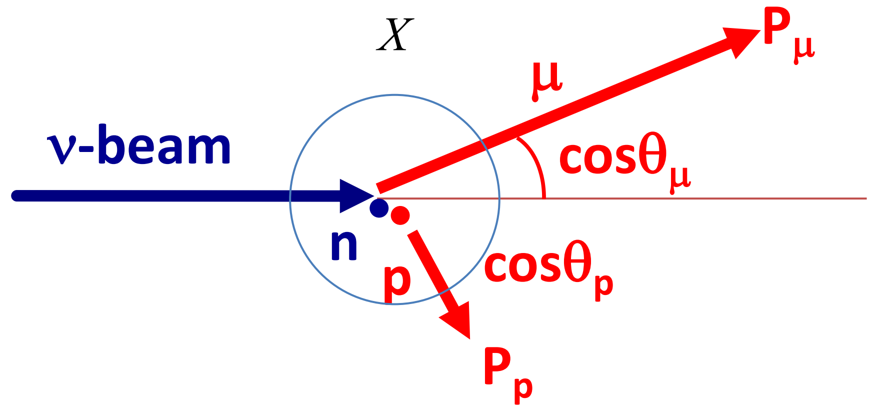
- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- 3mm pitch
- photon detection system
- ArgoNeuT, SBND, protoDUNE, LArIAT…



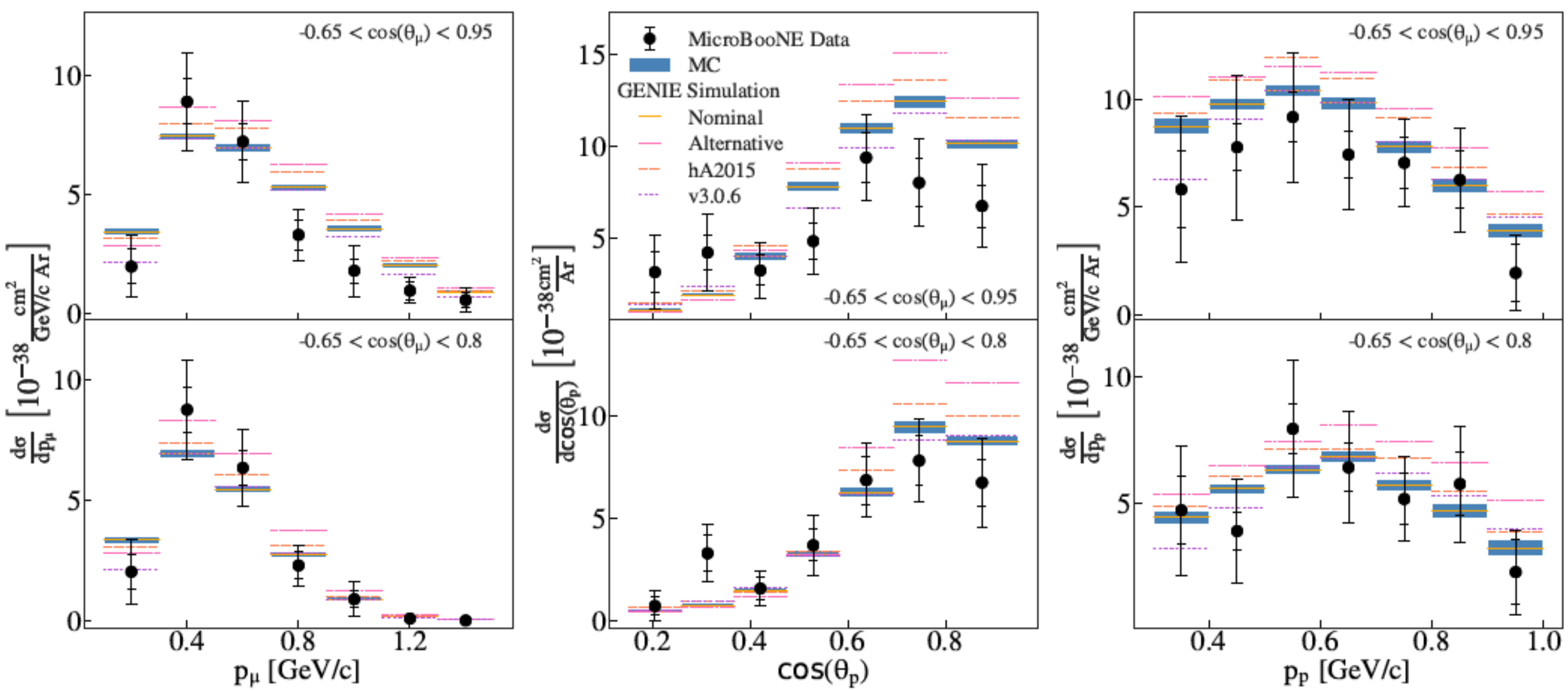
4.3. MicroBooNE

86ton LArTPC

- $\langle E \rangle$~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- 3mm pitch
- photon detection system
- ArgoNeuT, SBND, protoDUNE, LArIAT…



MicroBooNE CC0π1p data



MiniBooNE: PRD81(2010)092005
Martini et al,PRC80(2009)065501

4.3. Neutrino cross section measurements around 1-10 GeV

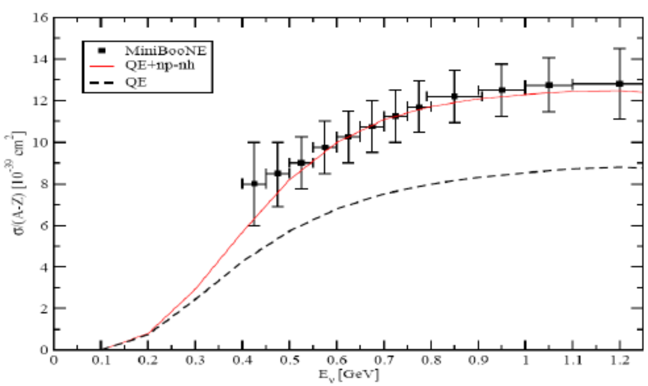
1. Sterile neutrino search
2. Neutrino cross-section measurement
3. New physics search

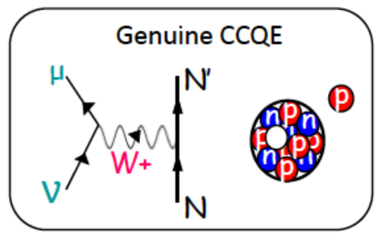
Discovery of nucleon correlation in neutrino scattering:
- Significant enhancement of cross section (10-30%)
- modify lepton kinematics and final state hadrons
- the hottest topic for T2K, MINERvA, MicroBooNE, etc

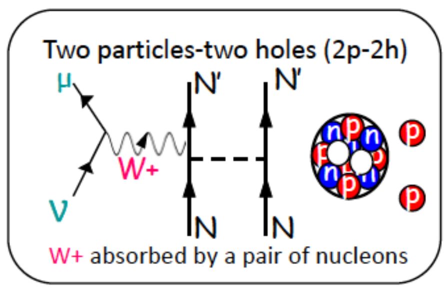
Slide from Marco Martini

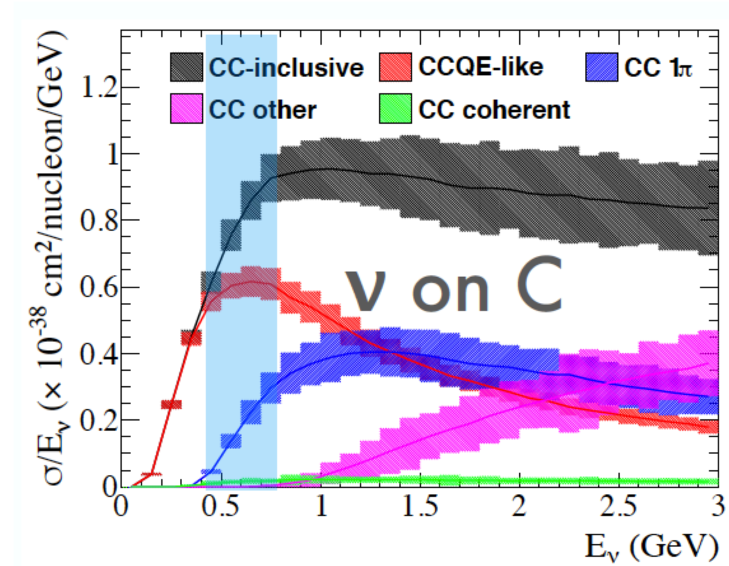
An explanation of this puzzle

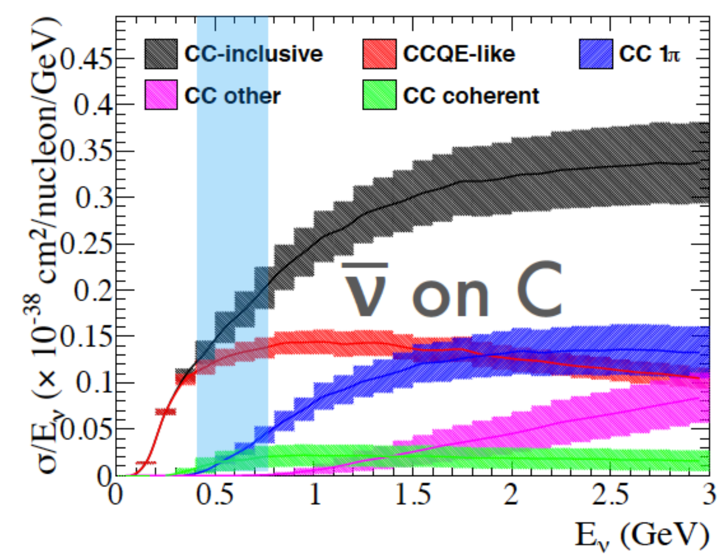
Inclusion of the multinucleon emission channel (np-nh)









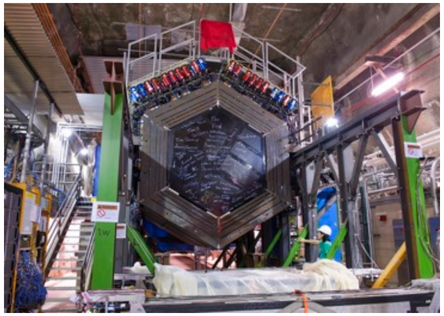


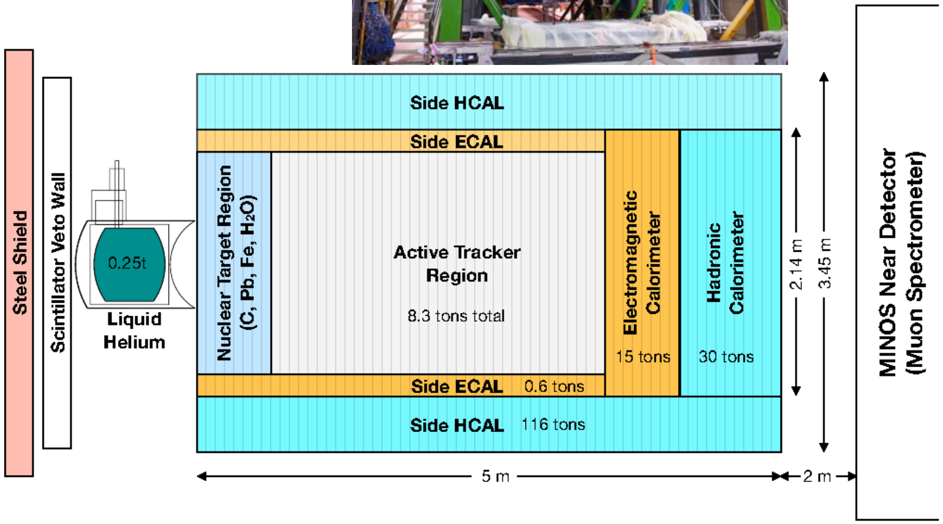
NuSTEC (https://nustec.fnal.gov/)
- Neutrino Scattering Theory-Experiment Collaboration
- Subscribe “NuSTEC News” mailing list
- like @nuxsec (Facebook), use #nuxsec (Twitter)

KING'S College LONDON

4.3. MINERvA

1. Sterile neutrino search
2. Neutrino cross-section measurement
3. New physics search



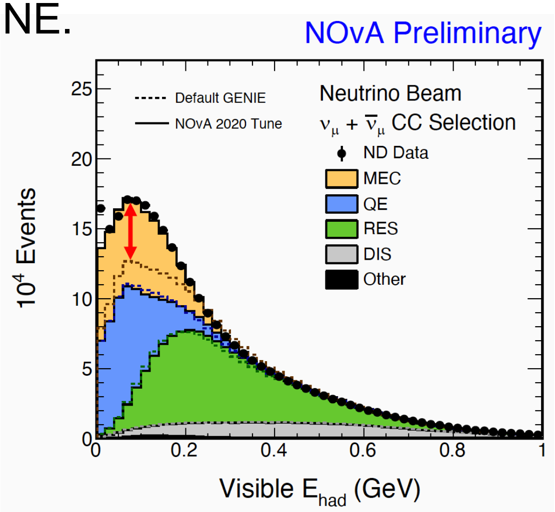


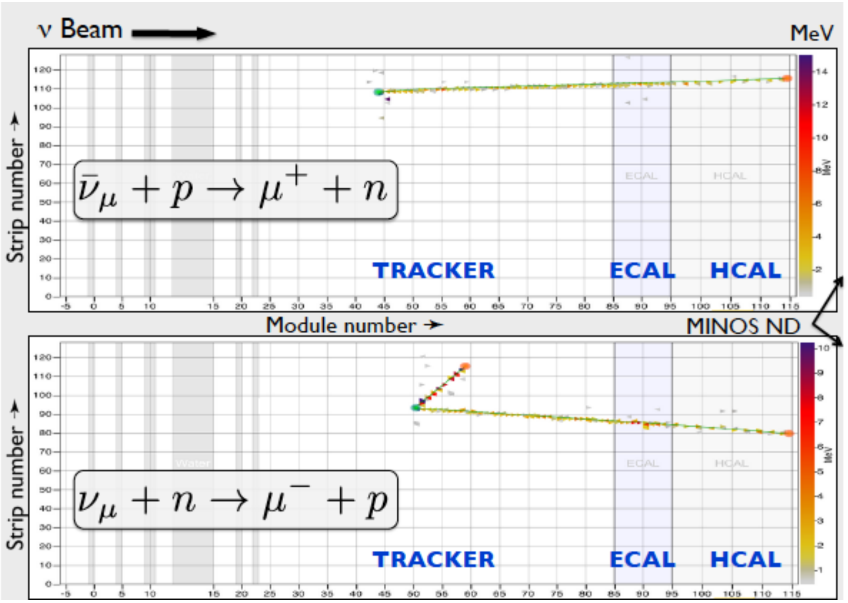
MINERvA Scintillation tracker

- <E>~3.5-7 GeV NuMI on-axis beam
- variety of targets (CH, Pb, Fe)
- Small acceptance due to MINOS ND
- charge separation by MINOS ND
- internal flux constraint (DIS, ν-e)

MINERvA interaction model tuning

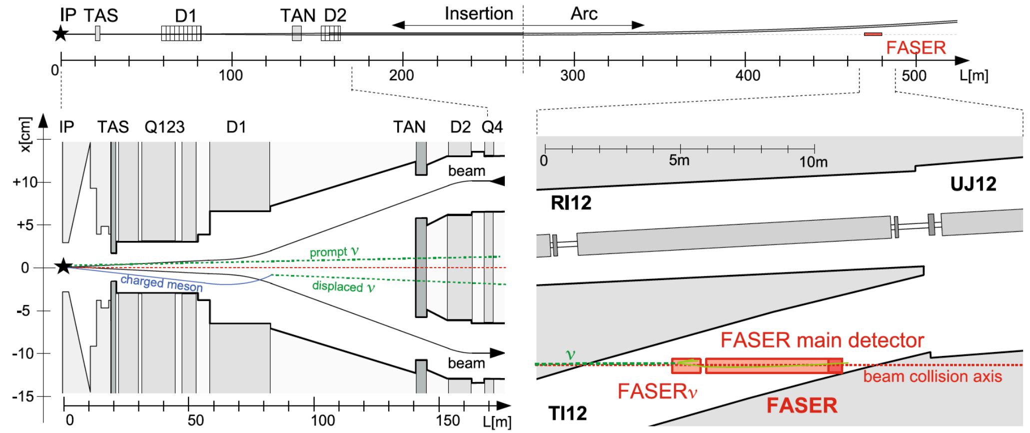
MINERvA developed tuning method for neutrino interaction models ~2 GeV to higher, used by NOvA and DUNE.





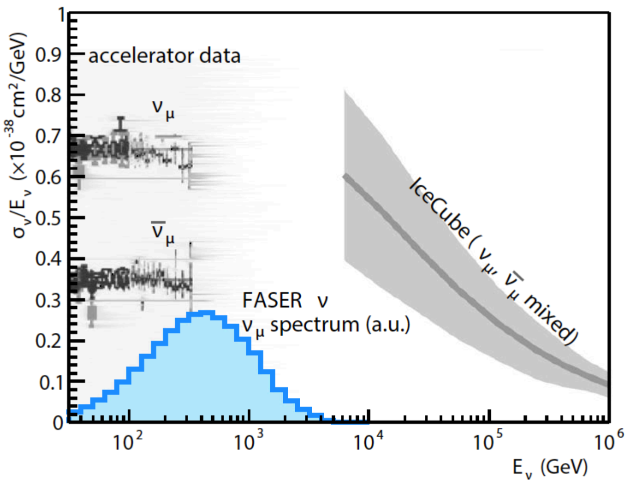
4.3. FASERnu

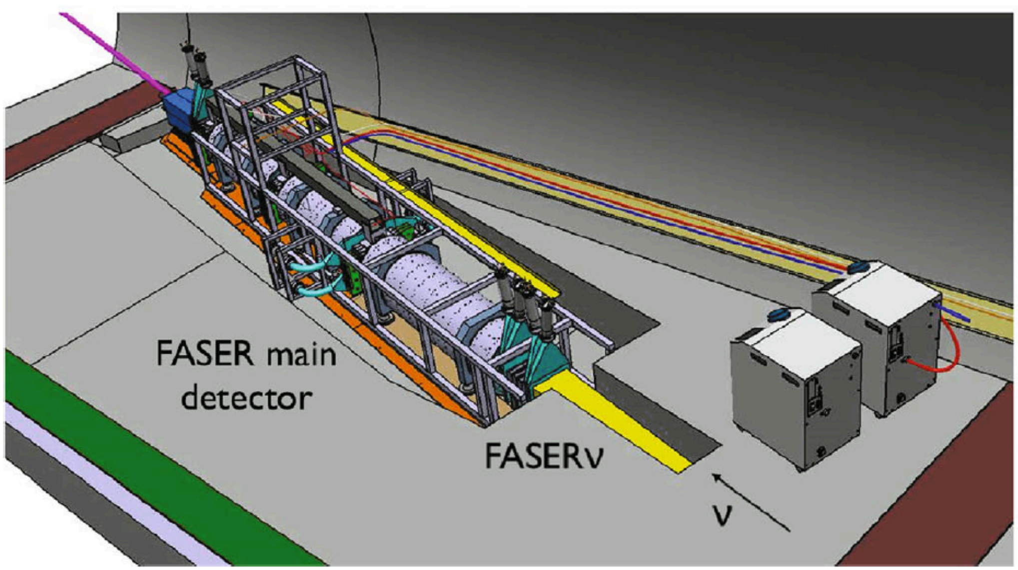
1. Sterile neutrino search
2. Neutrino cross-section measurement
3. New physics search



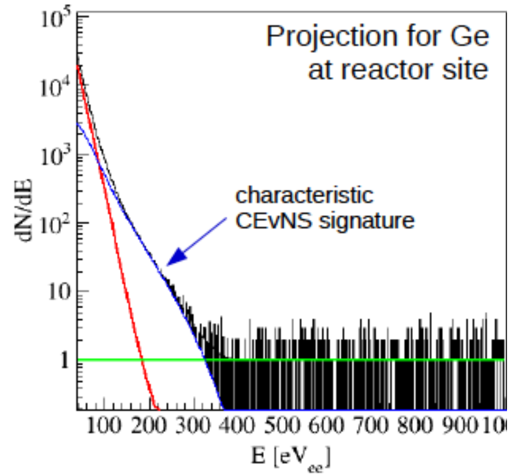
Neutrino experiment ~ dark sector search

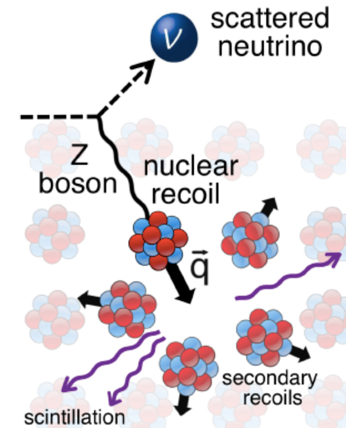
- ν_τ measurement
- high E neutrino measurement
- Rare particle search:
  - boosted DM
  - dark photon
  - heavy neutrinos
  - millicharged particle
  - etc





4.3. Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)





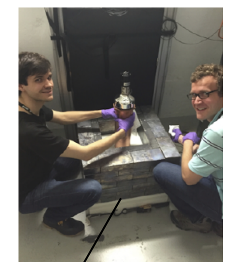
CEvNS

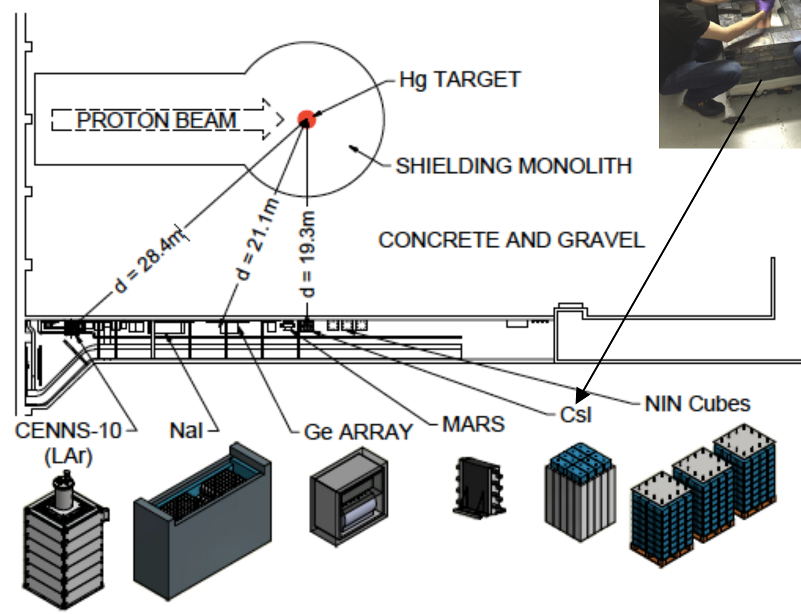
- A fundamental process for supernova physics
- Neutrino floor for WIMP search
- A channel to look for many new physics

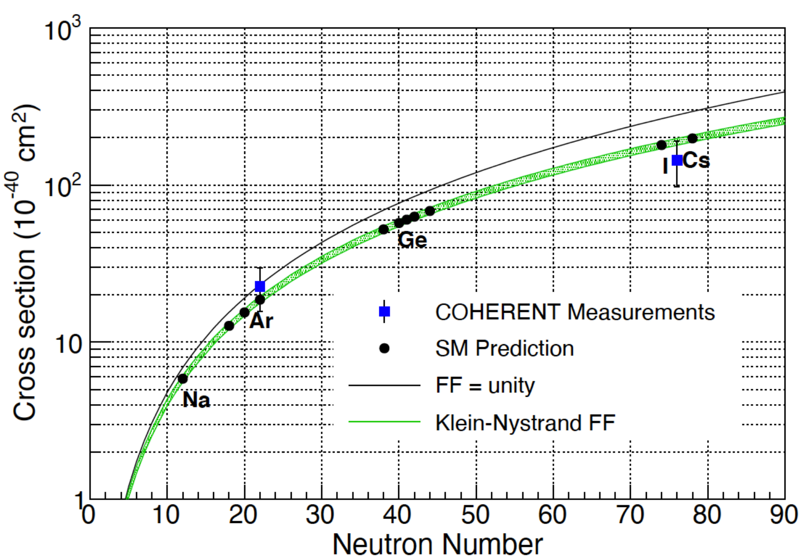
(NC is the home of new physics)

COHERENT

- Neutrinos from neutron spallation source
- Array of small detectors at "neutrino alley'
- First observation by CEvNS (2017)
- More data from other detectors







4.1. Neutrino basics

4.2. Accelerator-based long-baseline neutrino experiments

4.3. Accelerator-based short-baseline neutrino experiments

4.4. Reactor-based neutrino experiments

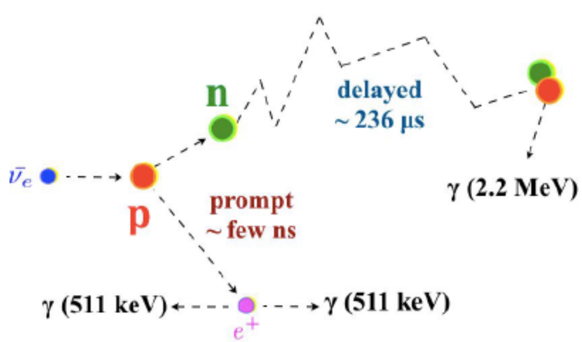
4.5. Neutrino-less double beta decay

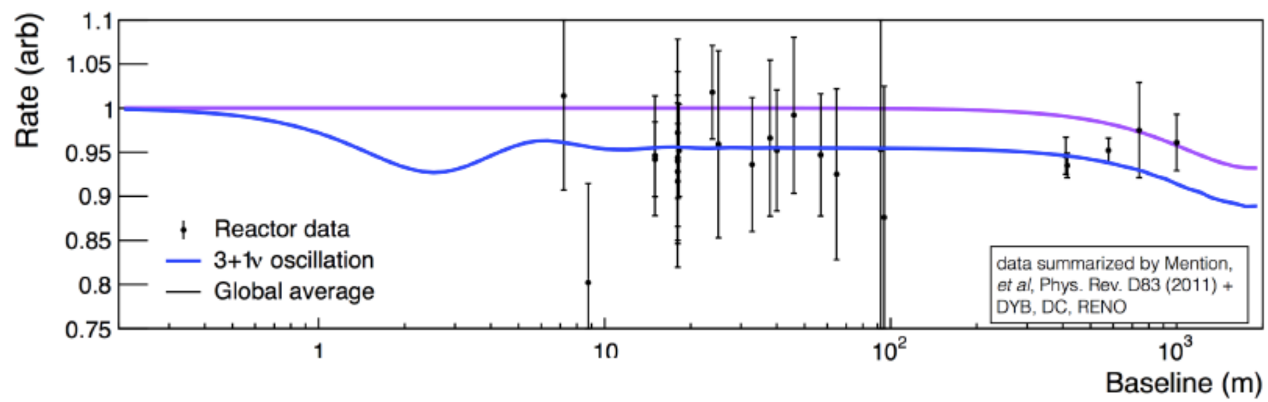
4.4. Reactor neutrinos - $\bar{\nu}_e$

Spectrum is well-known, except 2 open questions
- overall normalization is lower → motivate sterile neutrino oscillation
- shape mismatch around 5 MeV

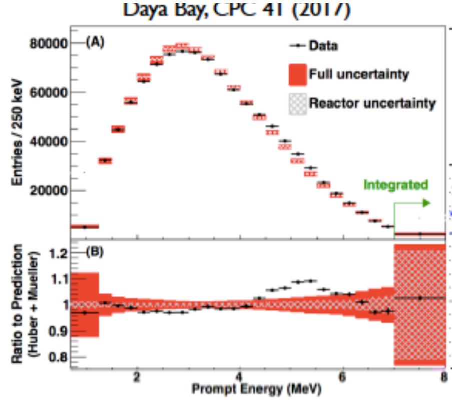
Detection, inverse beta decay (IBD)
- Liquid scintillator (prompt signal)+delayed neutron capture (delayed signal)

Inverse Beta Decay interaction (IBD)

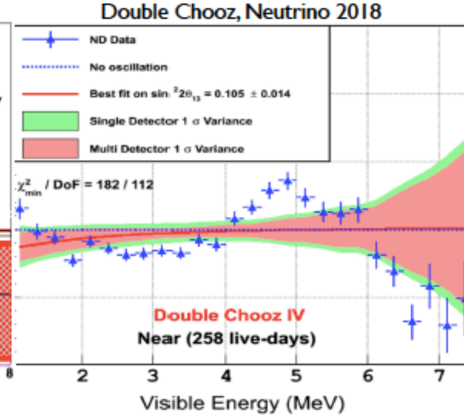




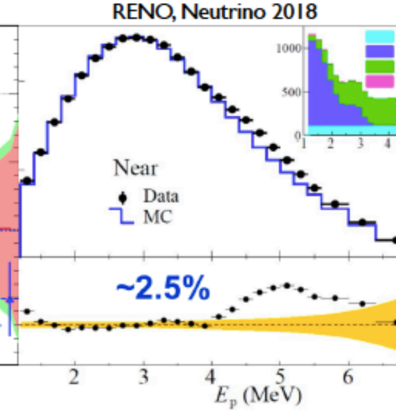
Daya Bay, CPC 41 (2017)



Double Chooz, Neutrino 2018



RENO, Neutrino 2018



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Littlejohn, Yaping, NuPhys 2018
Prospect:PRL122(2019)251801

4.4. Reactor neutrinos - $\bar{\nu}_e$

Spectrum is well-known, except 2 open questions

- overall normalization is lower → motivate sterile neutrino oscillation
- shape mismatch around 5 MeV

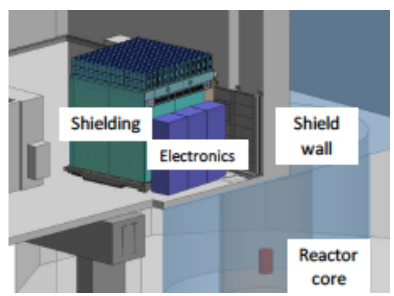
Detection, inverse beta decay (IBD)

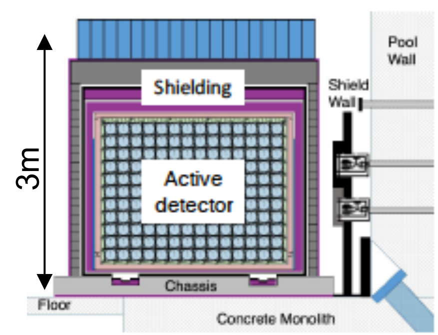
- Liquid scintillator (prompt signal)+delayed neutron capture (delayed signal)

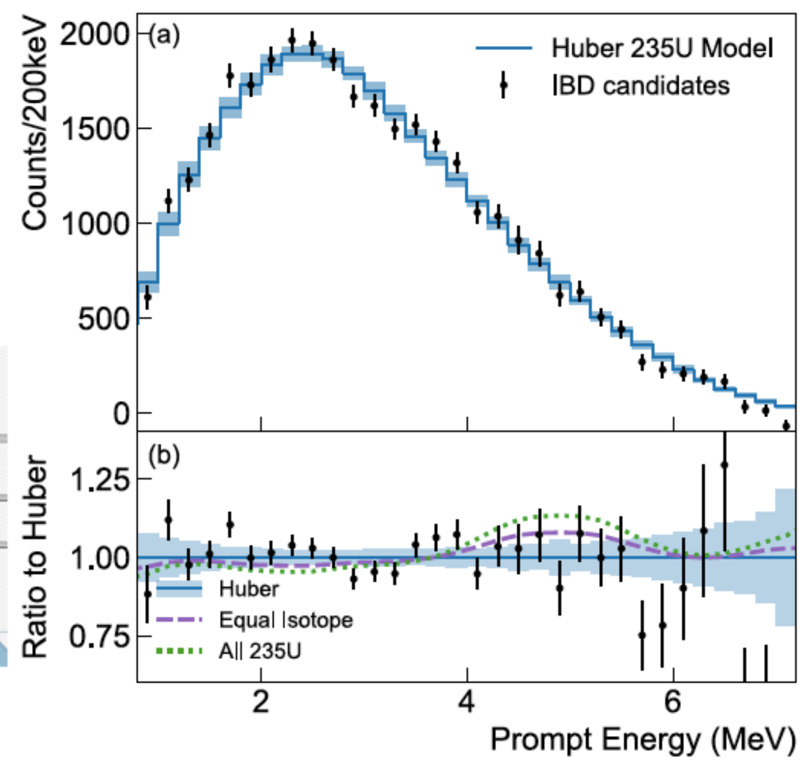
PROSPECT

- segmented liq. scintillator (4 ton)
- ^{6}Li loaded (neutron capture)
- Fission dominated by ^{235}U, easy to predict the neutrino flux

It looks both anomalies are related to the neutrino flux prediction (=nuclear physics)







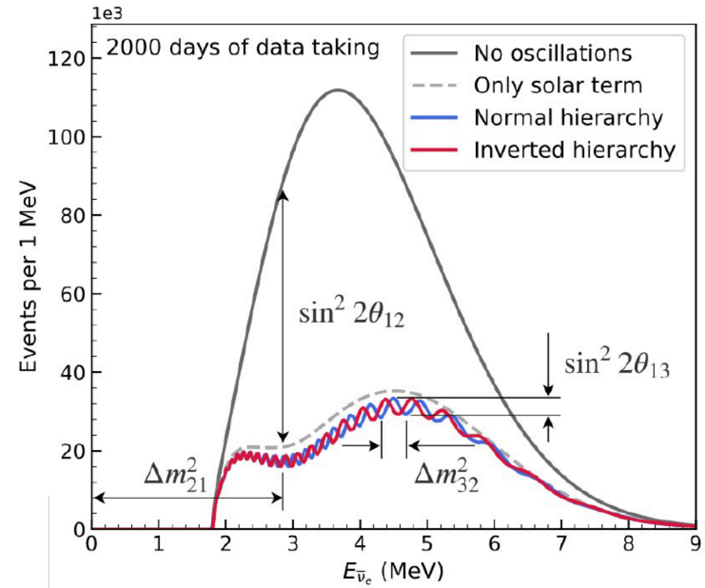
katori@fnal.gov

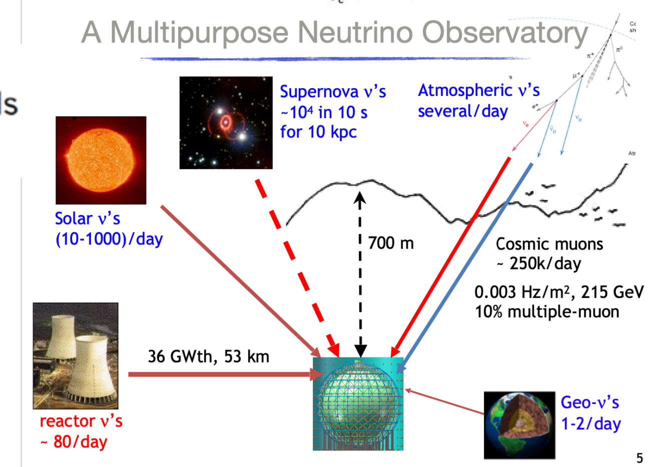
JUNO, JPhysG43(2016)030401
Meng (JUNO), Neutrino 2020

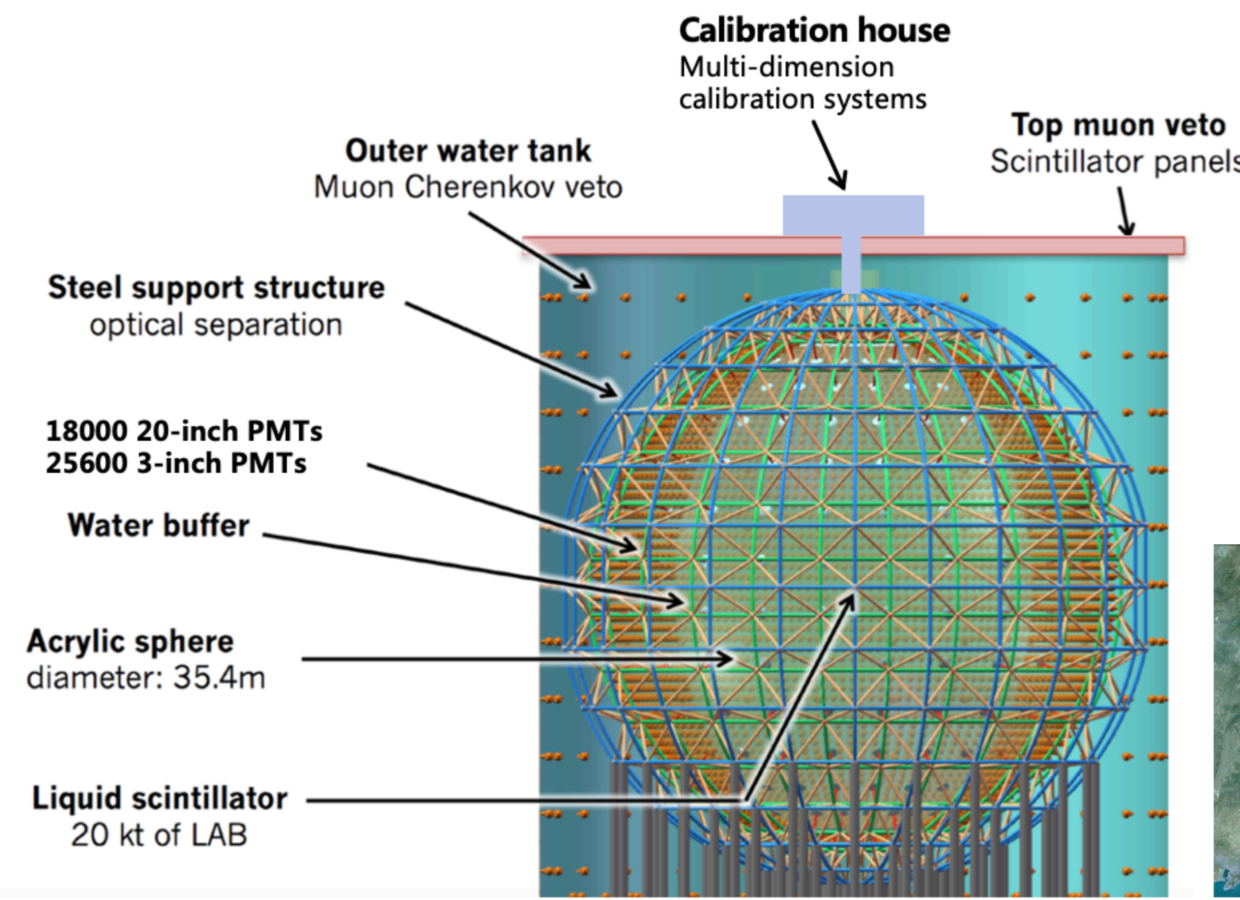
4.4. Neutrino Mass Ordering (NMO)

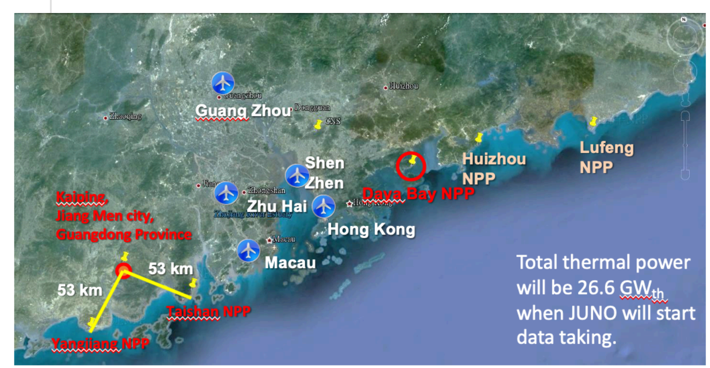
JUNO

- SuperK (~20 kton) + KamLAND (~3%ΔE)
- >3σ signal of NMO
- Data taking ready in 2022







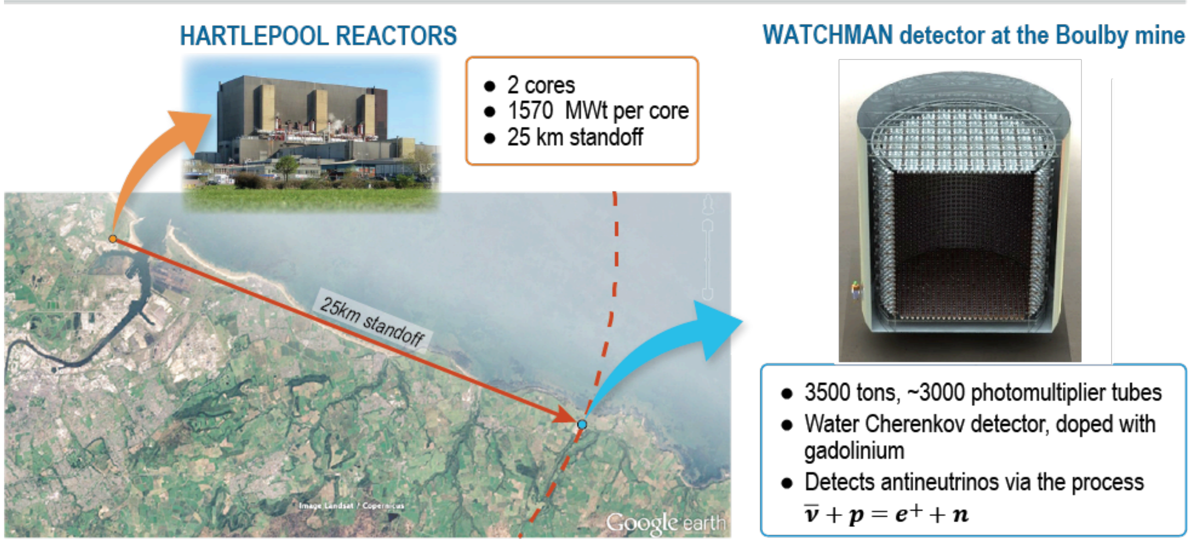


Watchman, arXiv:1502.01132
Akindele, Neutrino 2020

4.4. Neutrino reactor monitoring

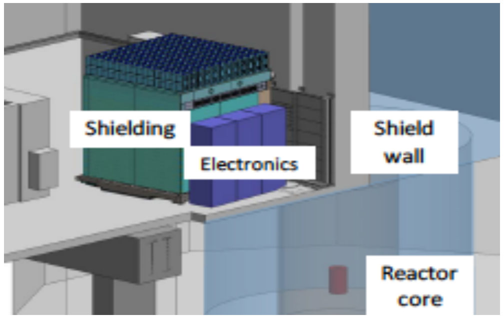
Watchman

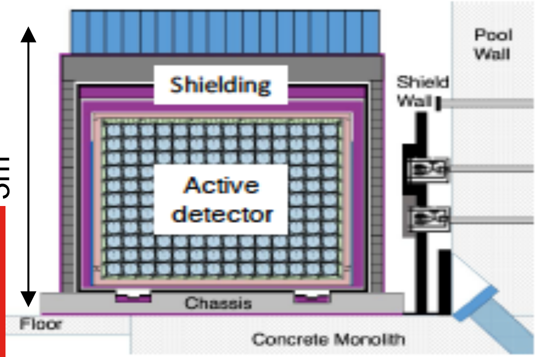
- Water Cherenkov
- Gd-doped for neutron capture
- Far field reactor monitoring



e.g.) PROSPECT

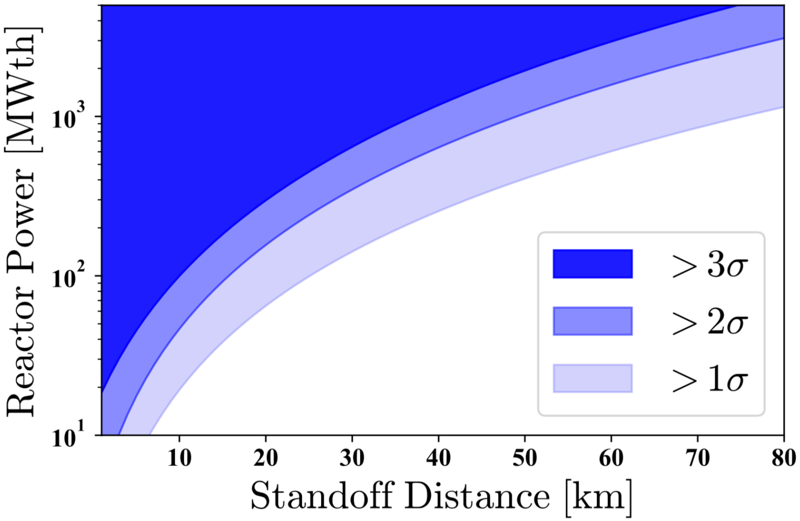
- Near field reactor monitoring





25km is within the range to monitor 1GW nuclear reactor

Watchman 1yr exclusion contour



SOX, JHEP08(2013)038
Link, Neutrino 2018, Gavrin (BEST), Neutrino 2020

4.4. Neutrino source experiment - $\nu_e, \bar{\nu}_e$

Very short-baseline neutrino oscillation experiment
- Test of Gallium anomaly
- E~1 MeV, L~1m
- BEST (Baksan) succssfully provided 3.7 MCi source

Proposed Source Experiments

Many source experiments have been proposed…

Experiment	Source	Detector	Channel	Citation
LENS-Sterile	^{51}Cr	LENS	ν ^{115}In CC	Phys. Rev. D75 (2007) 093006
Baksan	^{51}Cr	SAGE	ν ^{71}Ga CC	arXiv:1006.2103 [nucl-ex]
RICOCHET	^{37}Ar	Bolometers	CEνNS	Phys. Rev. D85 (2012) 013009
CeLAND	^{144}Ce	KamLAND	IBD	Phys. Rev. Lett. 107 (2011) 201801
DB Source	^{144}Ce	Daya Bay	IBD	Phys. Rev. D87 (2013) 093002
Cr-SOX	^{51}Cr	Borexino	νe elastic	JHEP 1308 (2013) 038
Ce-SOX	^{144}Ce	Borexino	IBD	JHEP 1308 (2013) 038
LXe-Source	^{51}Cr	LZ	νe elastic	JHEP 1411 (2014) 042

Yet, no source experiments are actively being pursued.

It can be hard to accumulate statistics; each new run requires a major investment.

For now, let's focus on reactor experiments…

VIRGINIA TECH. Jonathan Link The Center for Neutrino Physics

4.1. Neutrino basics

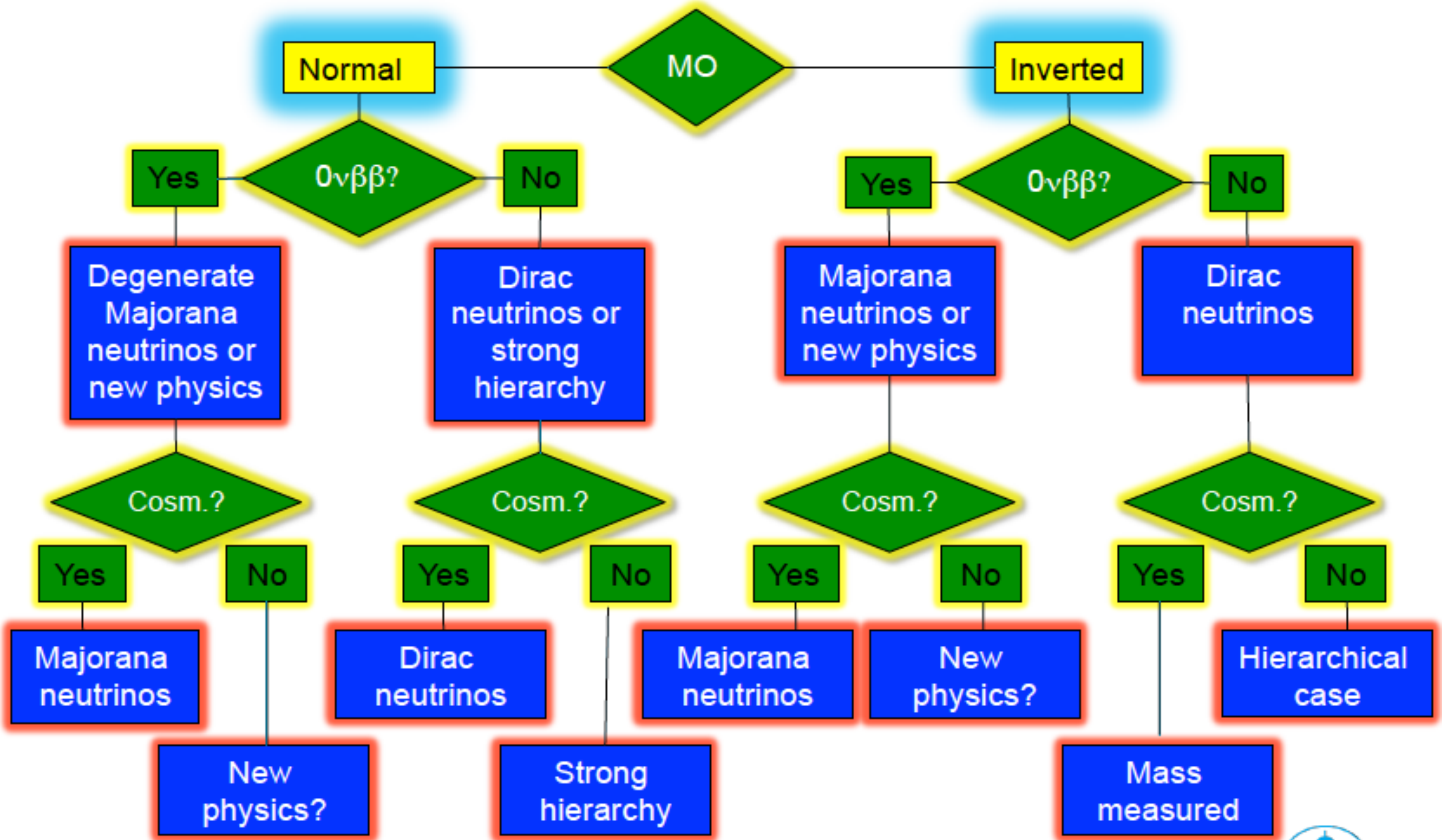
4.2. Accelerator-based long-baseline neutrino experiments

4.3. Accelerator-based short-baseline neutrino experiments

4.4. Reactor-based neutrino experiments

4.5. Neutrino-less double beta decay

Impact of direct mass ordering (MO) measurement



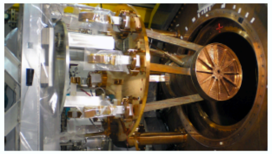
5. Neutrino-less Double Beta Decay

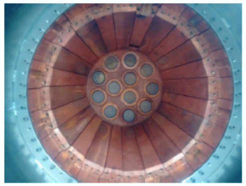
Experimental Techniques

- Bolometers (CUPID, AMoRE, CANDLES IV)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (SuperNEMO)
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + PID
- Scintillators (KamLAND2-Zen, SNO+, Theia, ZICOS)
  - Measure *E* (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (LEGEND, SELENA)
  - Measure *E* (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (nEXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

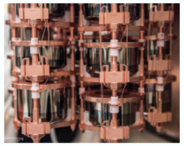

KamLAND-Zen

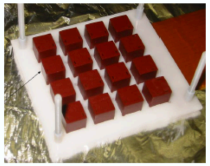

CANDLES

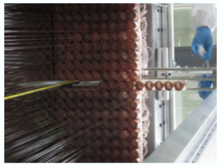

EXO-200


NEXT-100

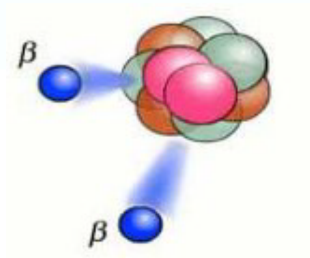

CUORE

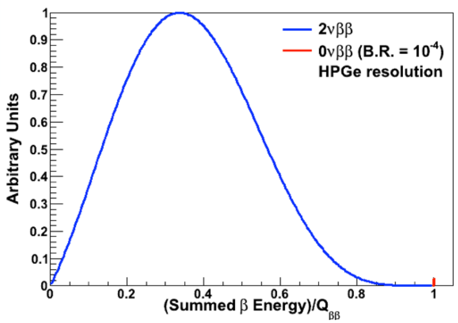

MAJORANA


COBRA

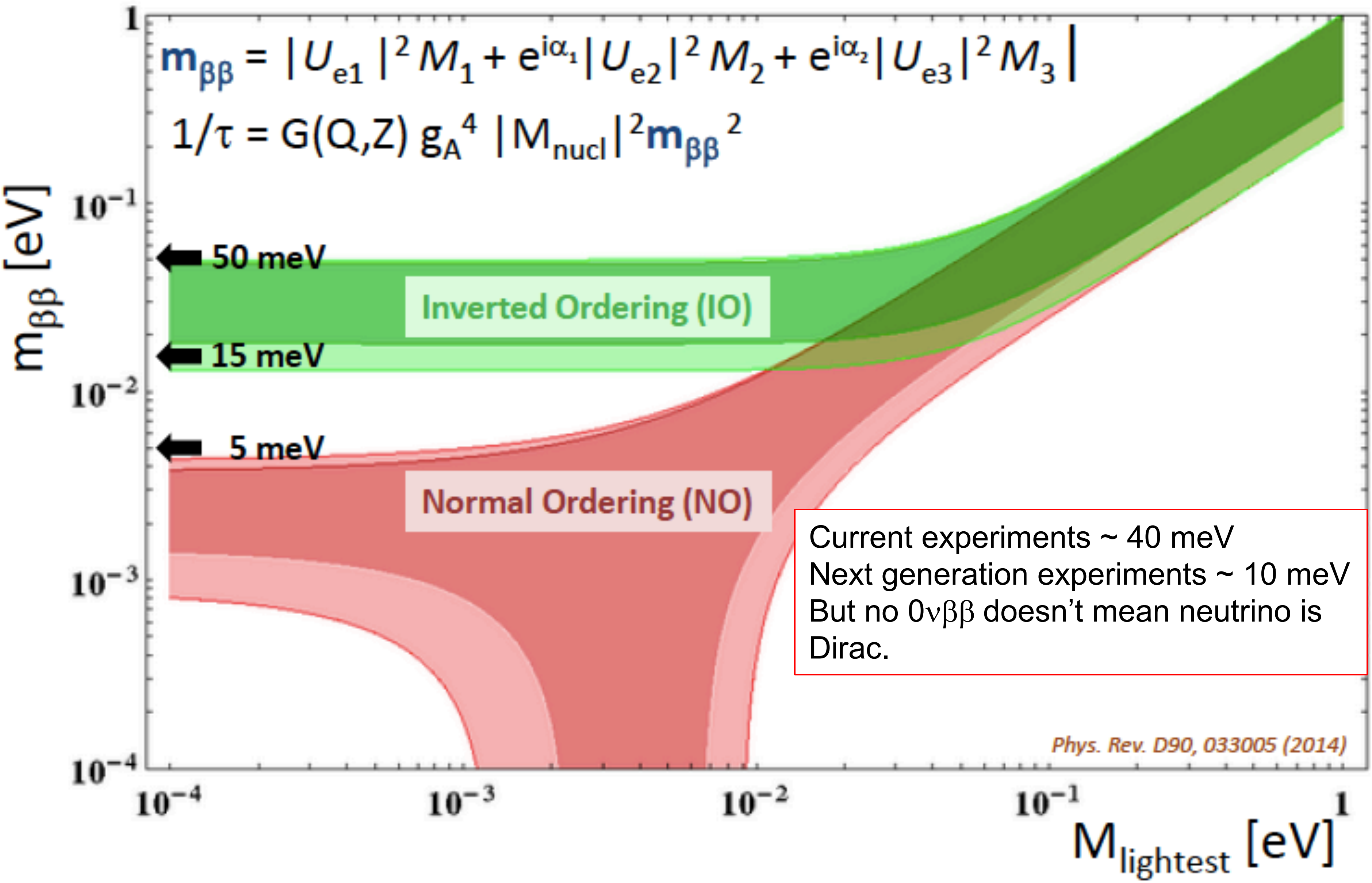

SuperNEMO


NEMO3

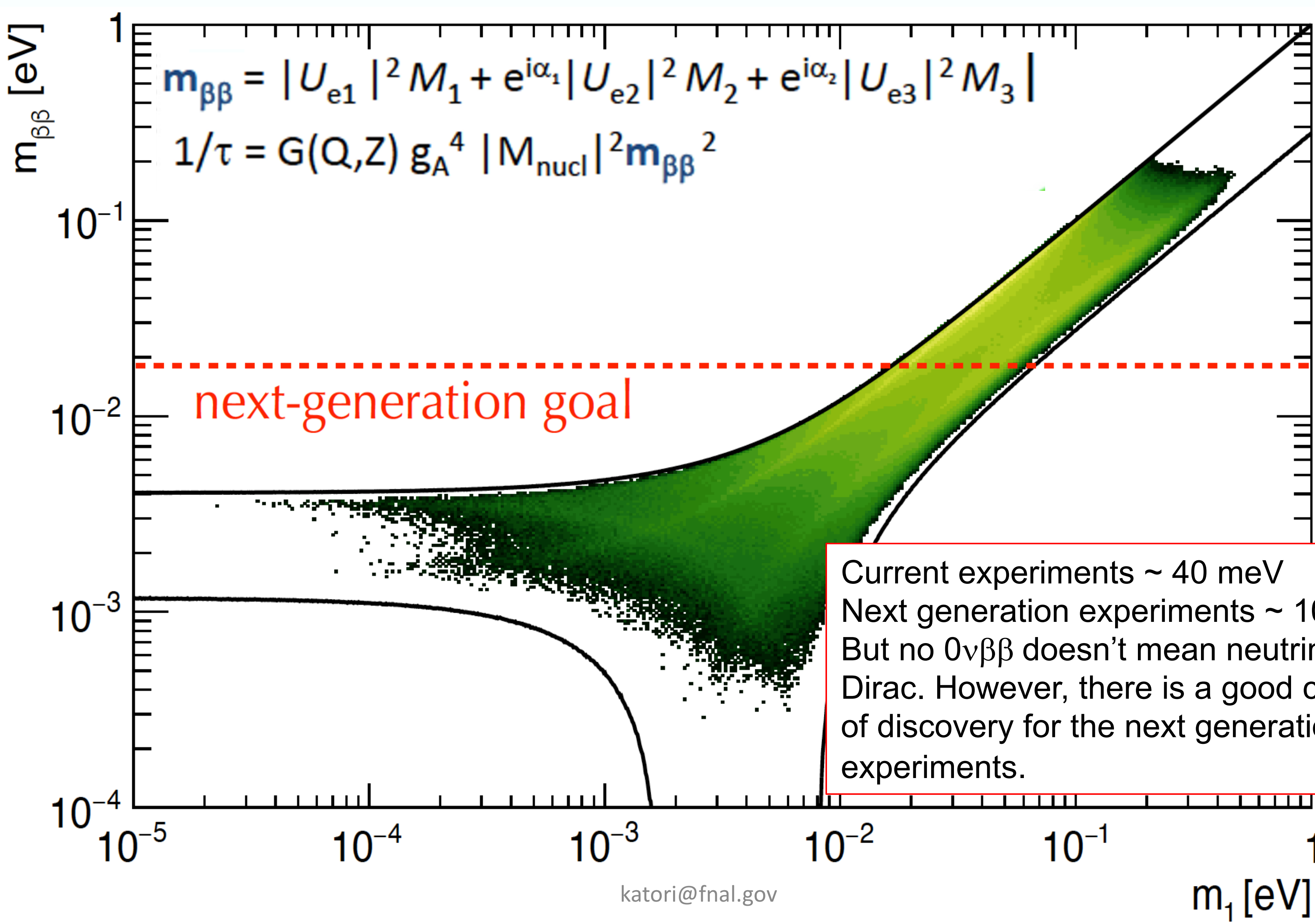




5. Neutrino-less Double Beta Decay



5. Neutrino-less Double Beta Decay

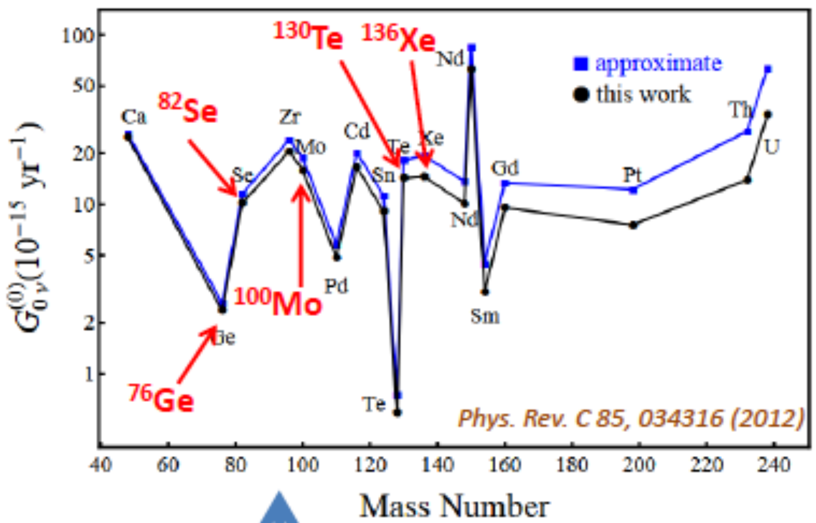


Current experiments ~ 40 meV
Next generation experiments ~ 10 meV
But no $0\nu\beta\beta$ doesn't mean neutrino is Dirac. However, there is a good chance of discovery for the next generation experiments.

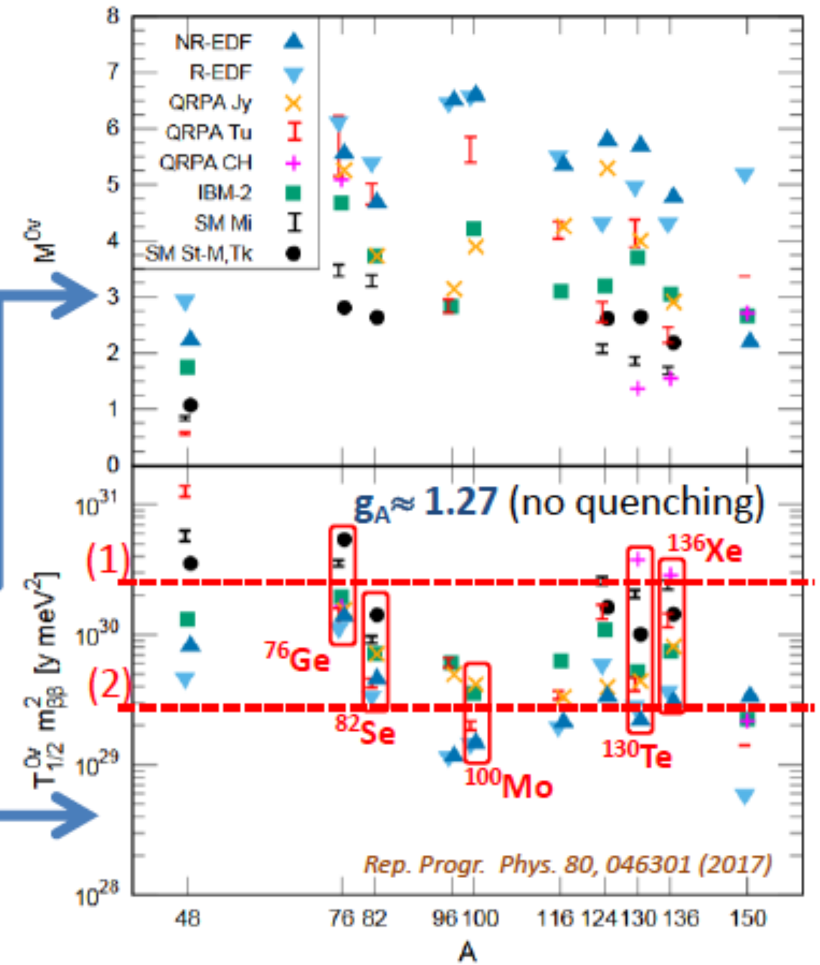
5. Neutrino-less Double Beta Decay

How difficult is it?

Phase space: exactly calculable



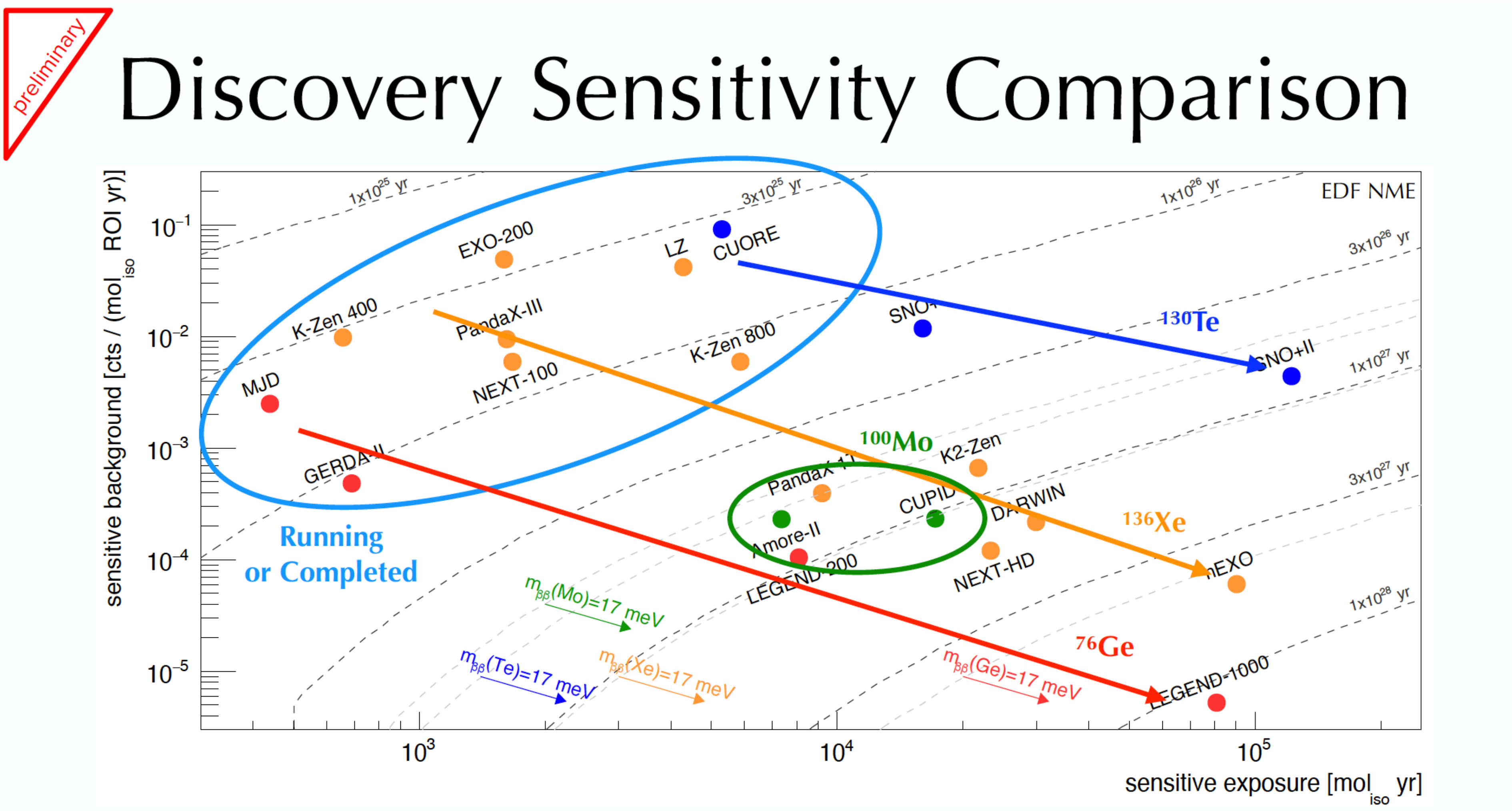
Nuclear matrix elements: several models



$$1/\tau = G(Q,Z)\, g_A^4\, |M_{nucl}|^2\, m_{\beta\beta}^2$$

Nuclear physics gives large systematics
- Nuclear matric element calculation
- Nuclear quenching of g_A

5. Neutrino-less Double Beta Decay



J. Detwiler 38 Agostini, Benato, JD, Menendez, Vissani

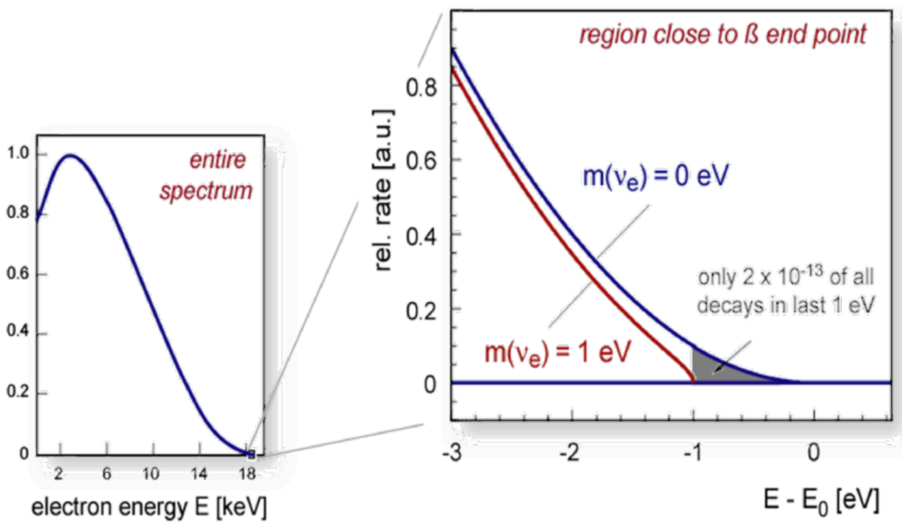
Martens (KATRIN), Neutrino 2020, KATRIN, PRL.123(2019)221802
Knox, Neutrino 2020

5. Direct neutrino mass measurement

KATRIN

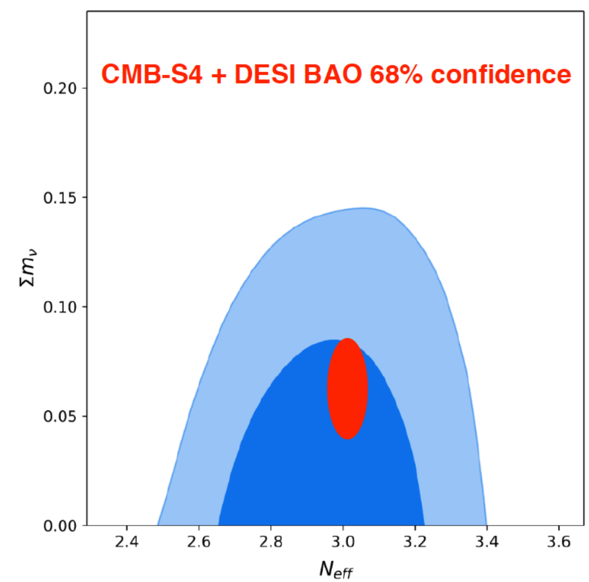
- Tritium β-decay
- Measure end point (18 keV) precisely
- limit ~ 1eV (fit result $m_\nu^2 = -1.0 \pm^{0.9}_{1.0}\ eV^2$)

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



Early universe

- Neutrinos are free-streaming, and neutrinos smear out all energy density fluctuation
- Higher neutrino mass remove more energy



4. Neutrino oscillations

2. History of neutrino oscillation

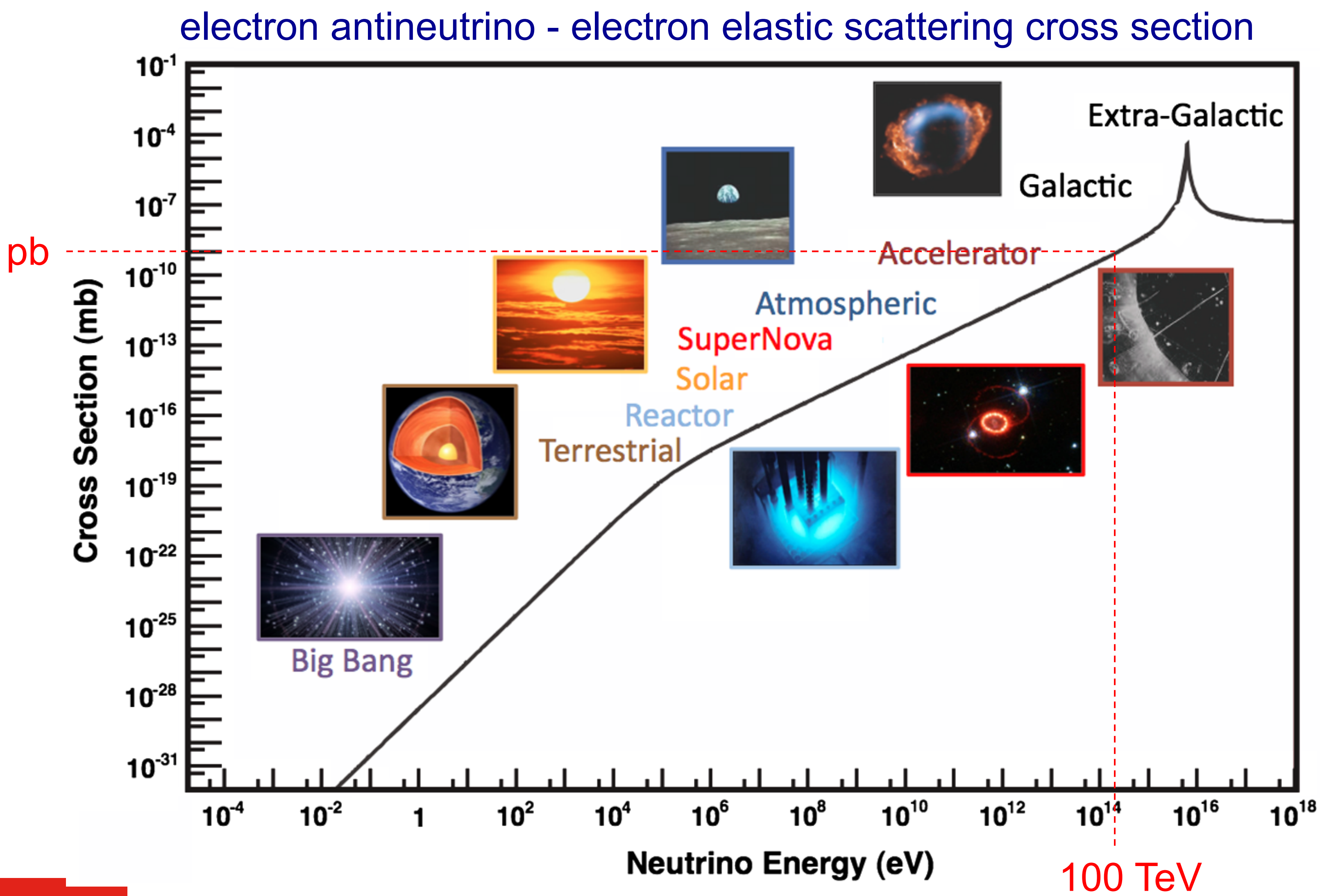
3. T2K neutrino oscillation experiments

4. Current and future neutrino experiments

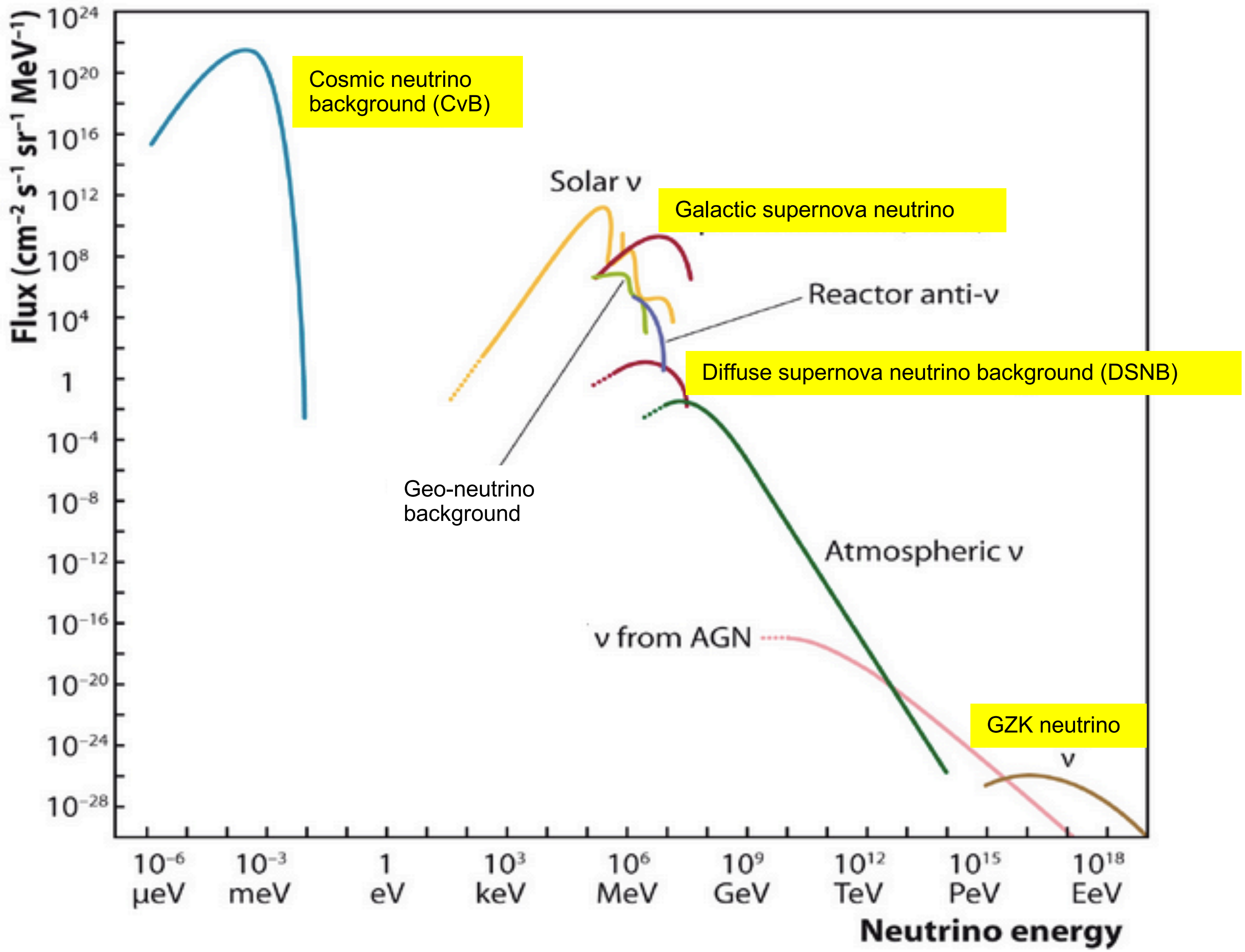
5. Neutrino astronomy

6. Conclusion

5. Neutrinos – from eV to EeV



5. Neutrinos – from eV to EeV

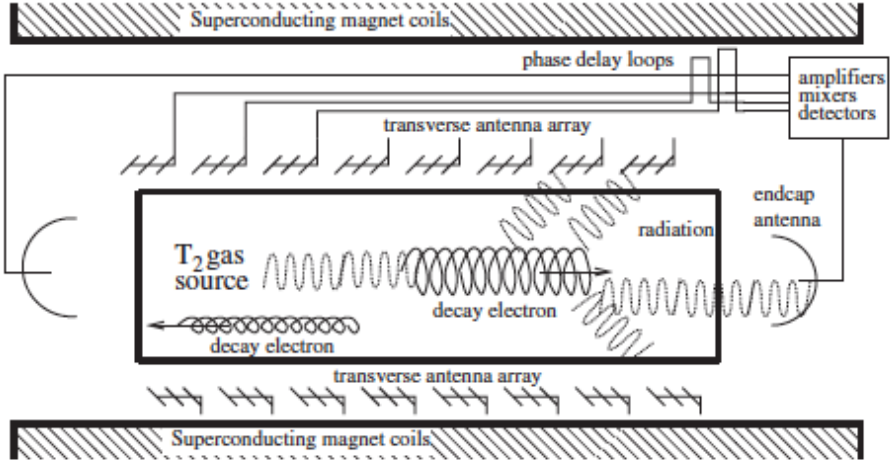


5. Cosmic Neutrino Background (CνB)

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

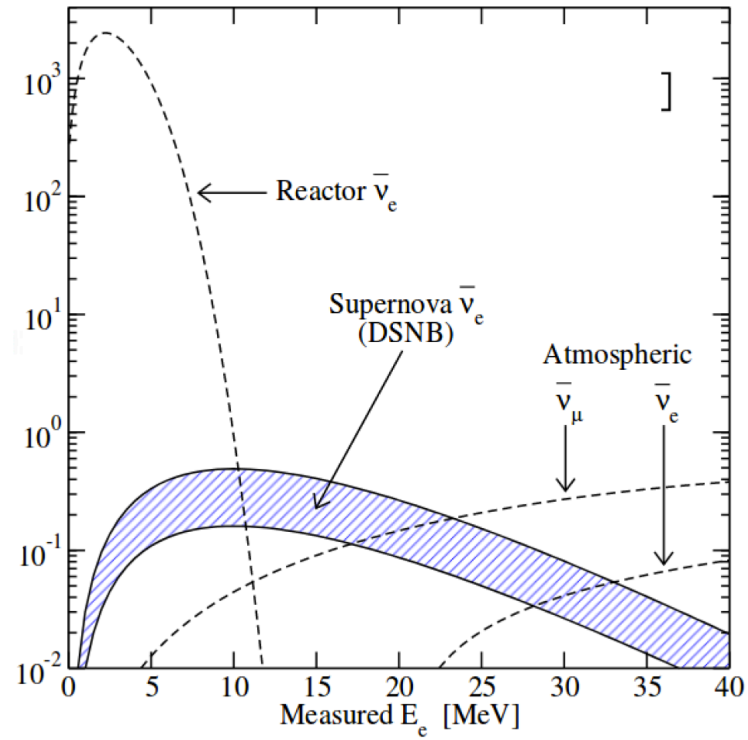
Project 8 concept



Detecting CνB is the holy grail of neutrino physicists! (and we are not very close)

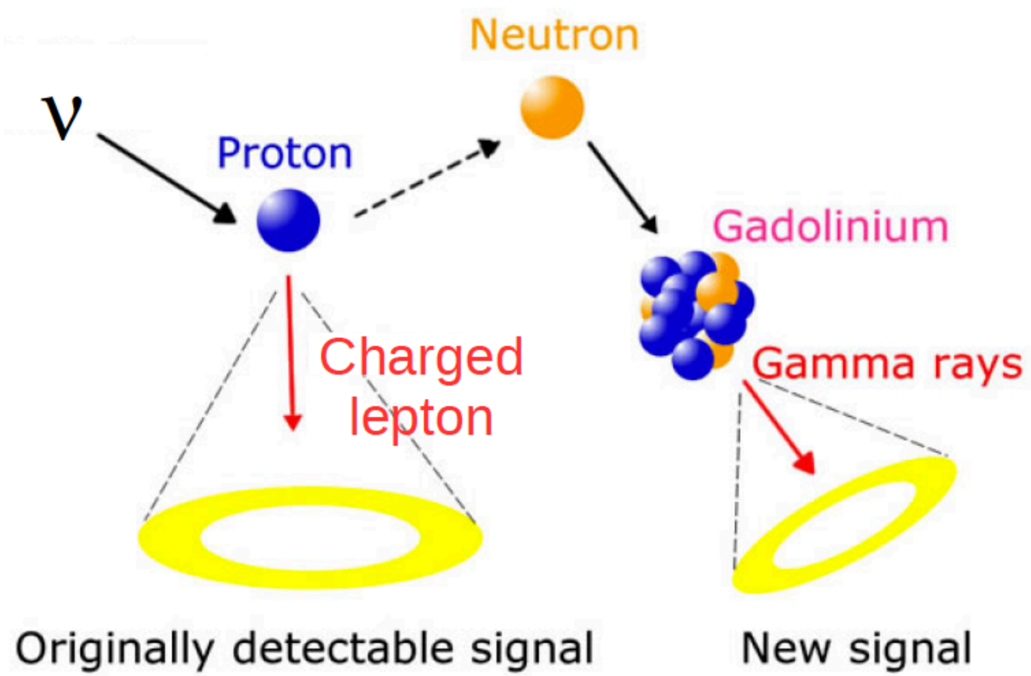
Beacom and Vagins, PRL93(2004)171101
TK, Martini, JPhysG45(2017), TITUS, ArXiv:1606.08114

5. SK-Gd



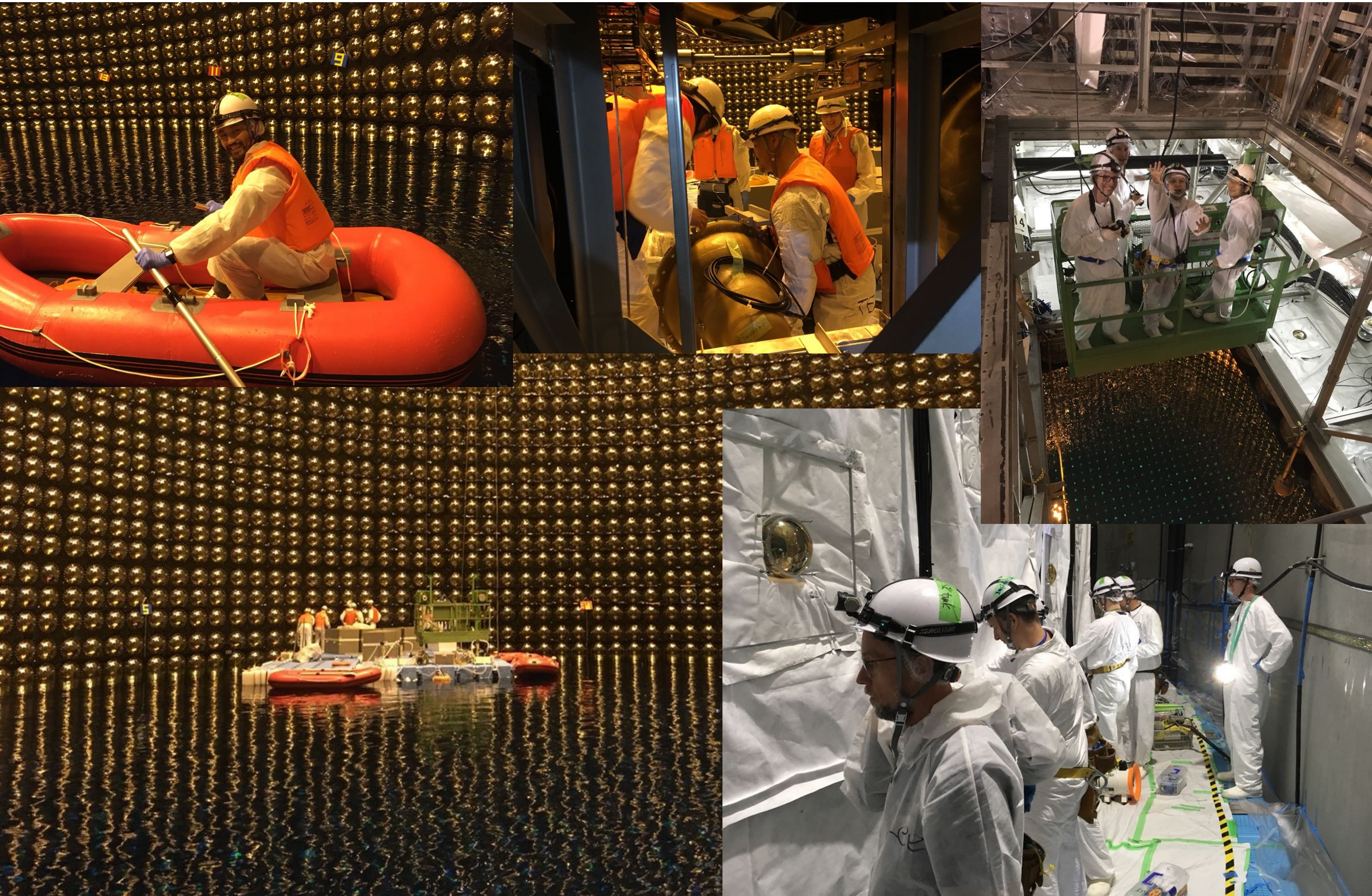
SuperK is planned to be doped with 0.1% of Gd

This improves neutron tagging efficiency to be ~90%, making SK-Gd to be visible for DSNB (diffused supernova neutrino background).



Galactic supernova explosion is ~few per century, but DSNB is always there

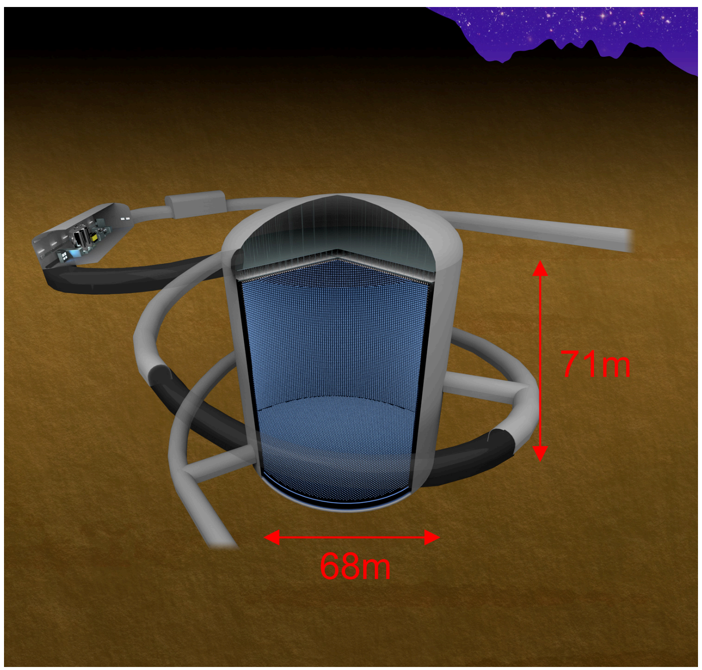
Super-Kamiokande detector refurbishment 2018



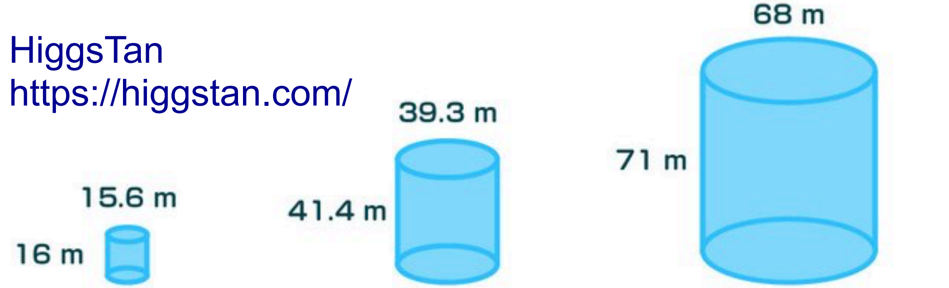
HyperK, ArXiv:1805.04163
Nakayama (HyperK), JPS2020

5. Hyper-Kamiokande

260 kton water Cherenkov tank
- ~x8.4 fiducial volume of SuperK
- Construction starts in this year!
- MeV to TeV physics
- solar, atmospheric, beam neutrinos
- proton decay, new physics search



HiggsTan
https://higgstan.com/



3,000 ton | 50,000 ton | 260,000 ton

~1,000 PMTs | ~11,000 PMTs | ~40,000 PMTs

Kamiokande
1983 start

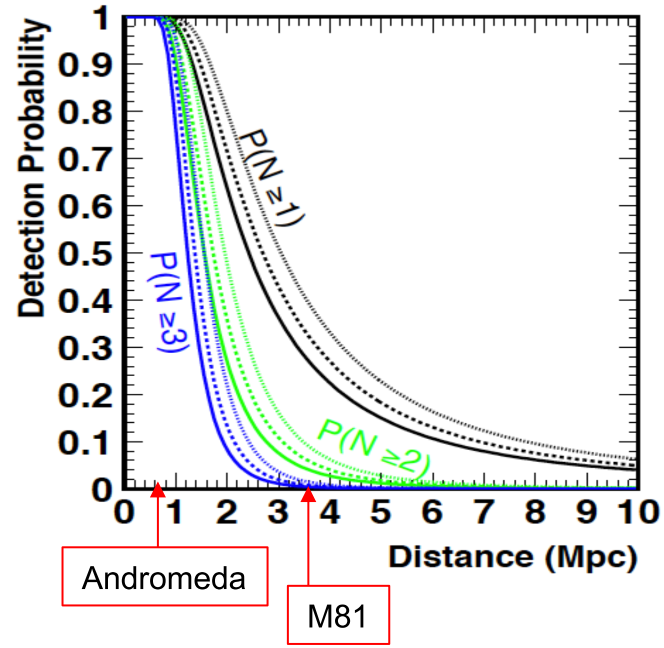
Super-Kamiokande
1996 start

Hyper-Kamiokande
2020 construction start
2027 data taking (plan)

2002 | 2015 | ???

HyperK, ArXiv:1805.04163
Nakayama (HyperK), JPS2020, Ishitsuka (HyperK), Neutrino 2020

5. Hyper-Kamiokande



Galactic supernova neutrinos

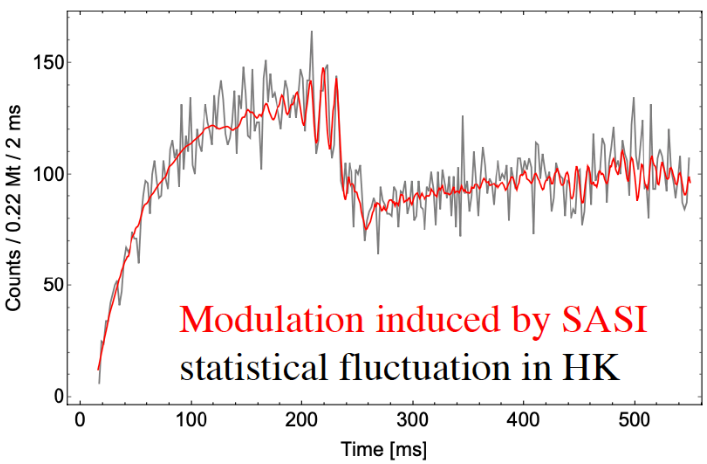
- Search extends to ~Mpc (reach to the next galaxy)
- Time profile is sensitive to explosion mechanism
- Precise pointing (~1 degree) to send alert

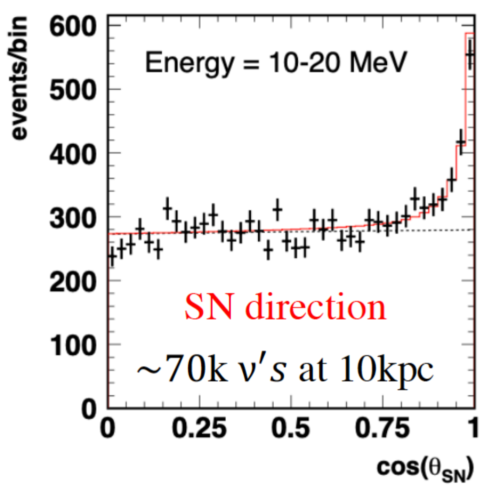
DSNB

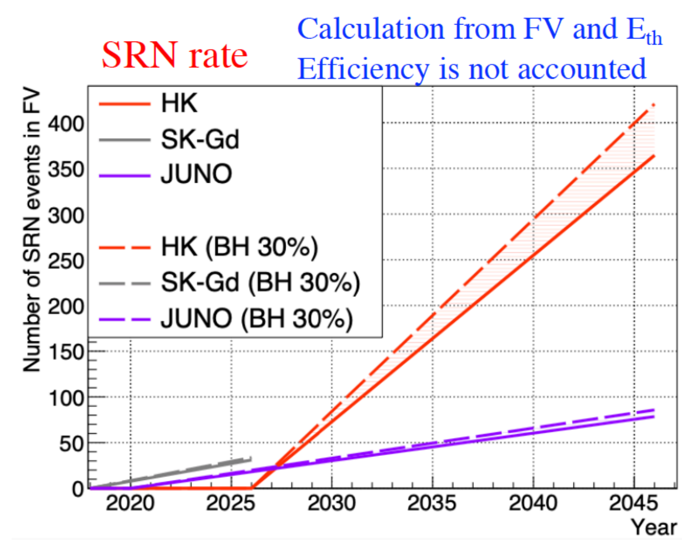
- ~ 20 evts/yr

Solar neutrino

- hep neutrinos, day-night asymmetry







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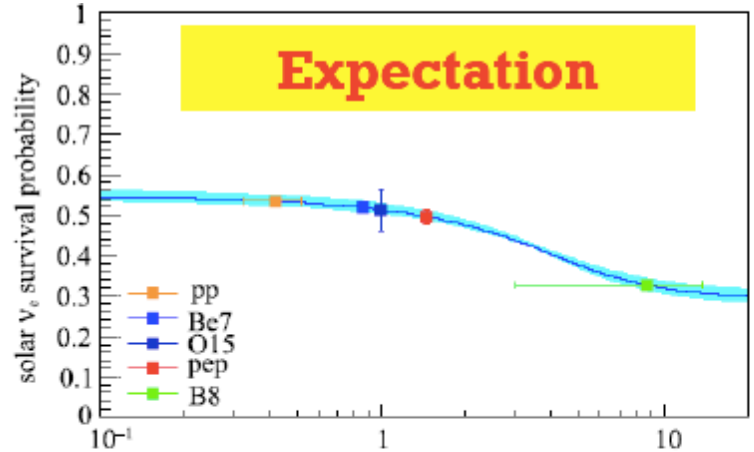
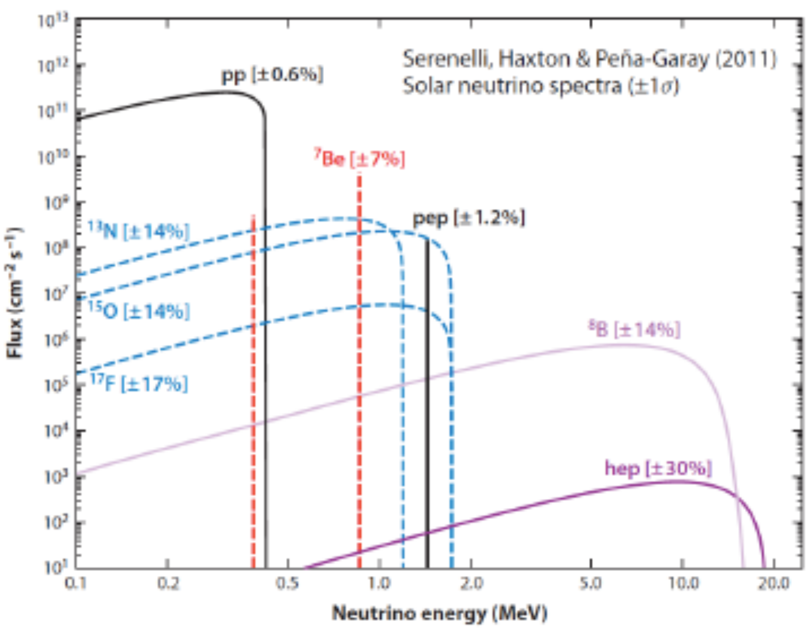
5. Jinping neutrino detector

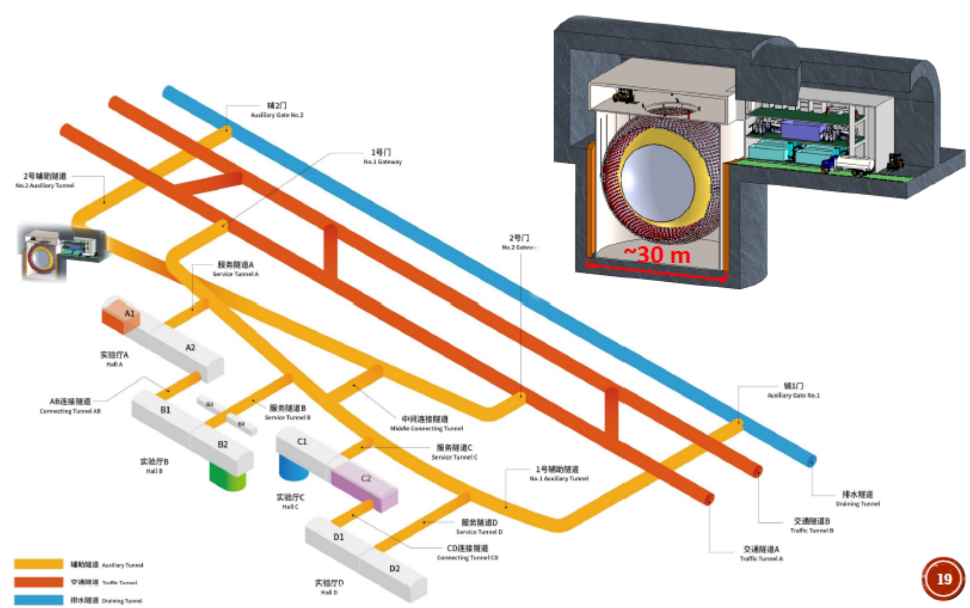
China Jinping underground Laboratory (CJPL)
- 2kton slow Liquid scintillator (directional)

Solar neutrino open questions
- Detection of hep neutrino → HyperK
- Day-night asymmetry measurement → HyperK
- MSW upturn at 3 MeV → Jinping
- Precise CNO neutrino measurement → Jinping





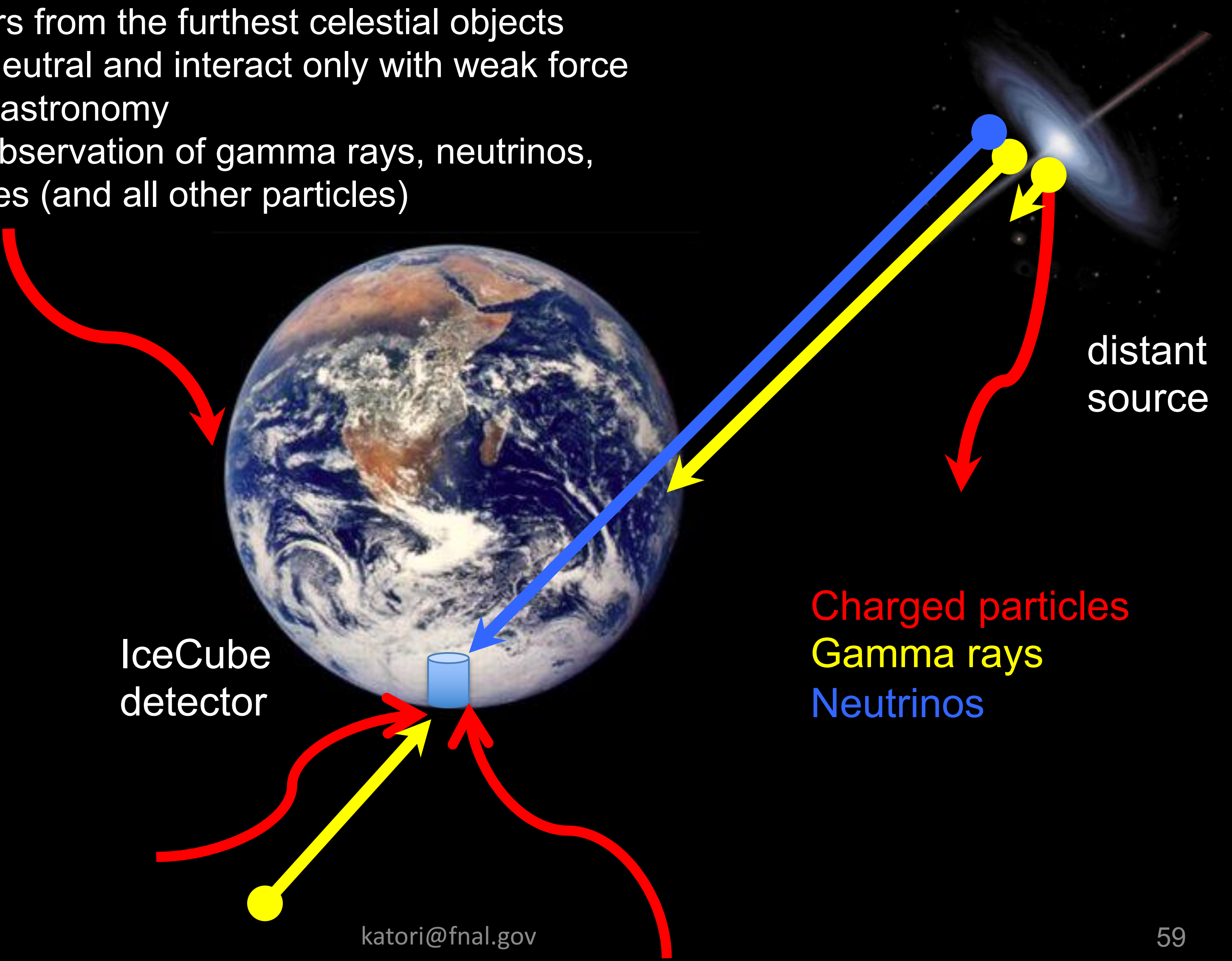
JINPING NEUTRINO DETECTOR



5. High-Energy Neutrino Astronomy

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

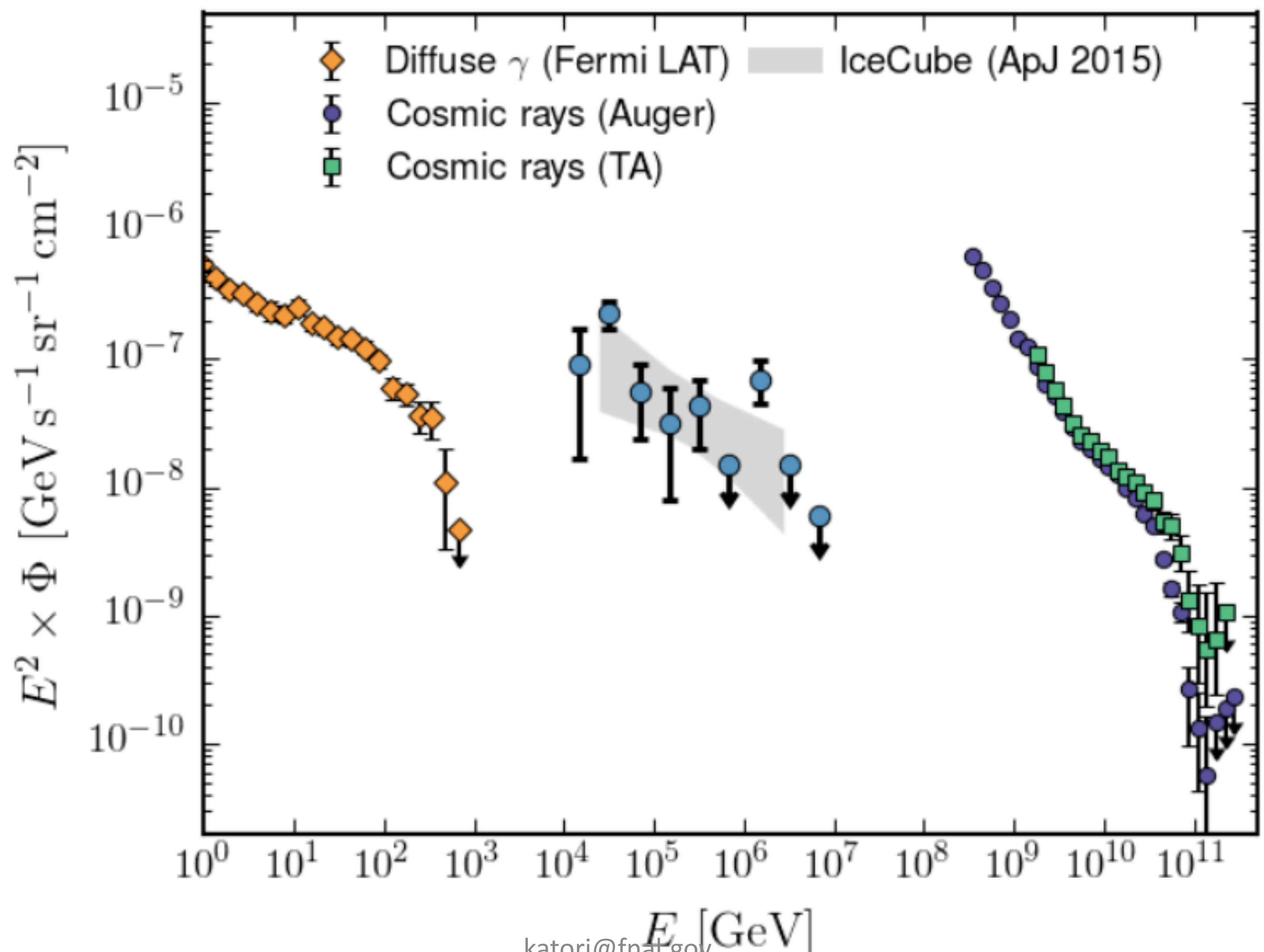
Multi-messenger astronomy
- simultaneous observation of gamma rays, neutrinos, gravitational waves (and all other particles)



5. High-Energy Neutrino Astronomy

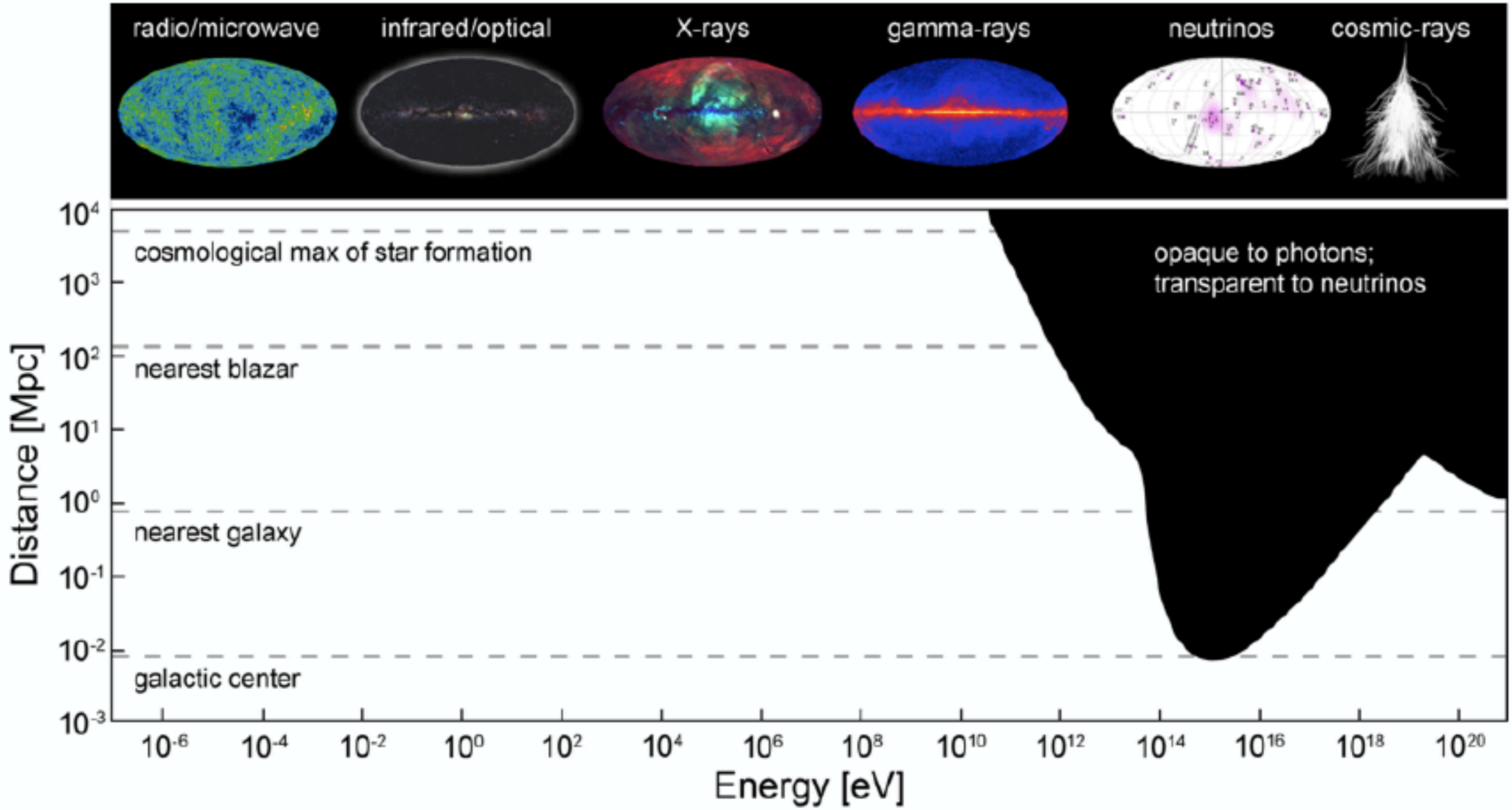
High-energy protons, gamma rays, and neutrinos are related.
→ expected flavour ratio ($\nu_e:\nu_\mu:\nu_\tau$)=(1:2:0) (cf. atmospheric neutrinos)

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



5. High-Energy Neutrino Astronomy

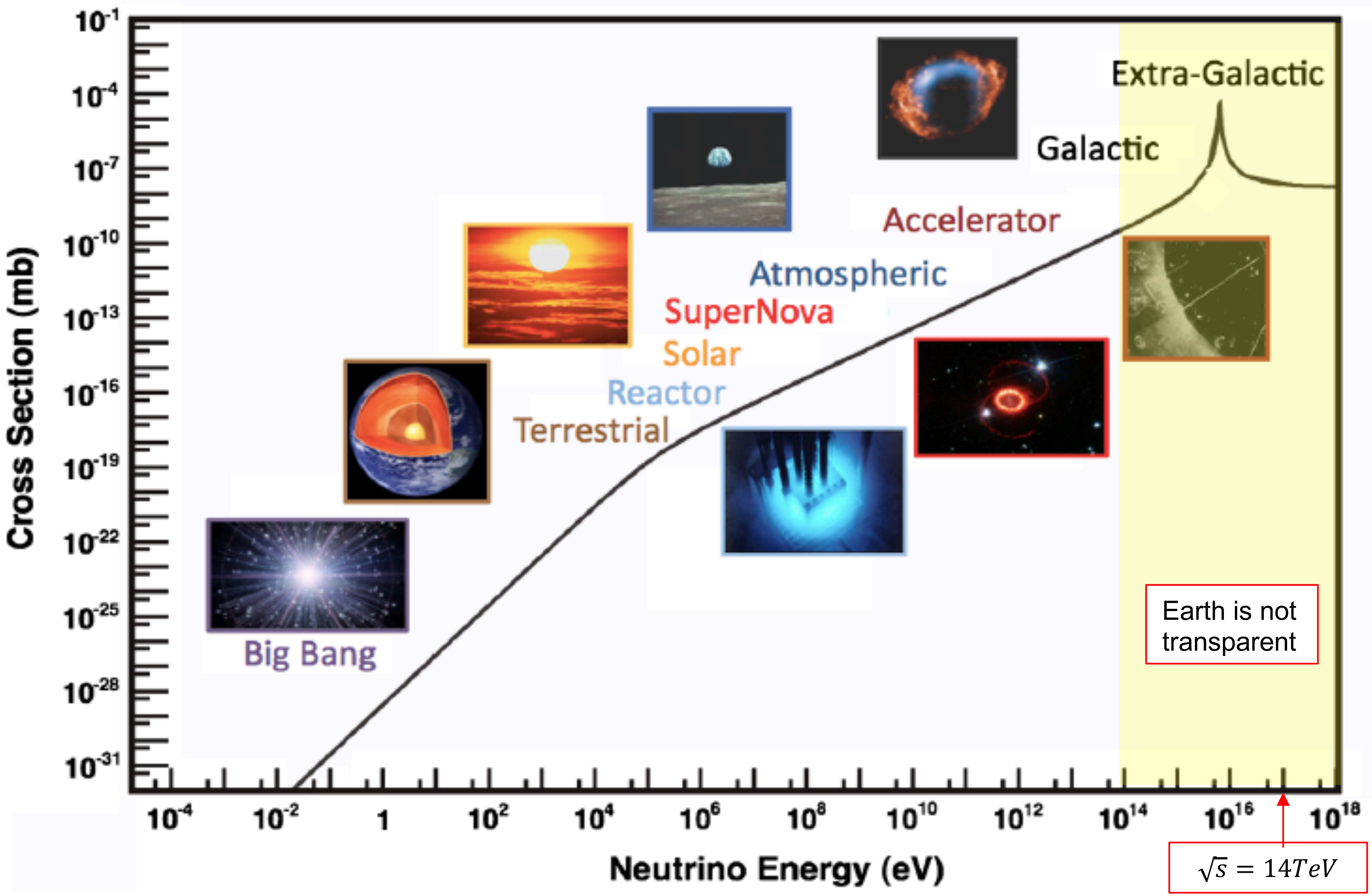
Above ~10-100 TeV neutrinos are only direct messengers



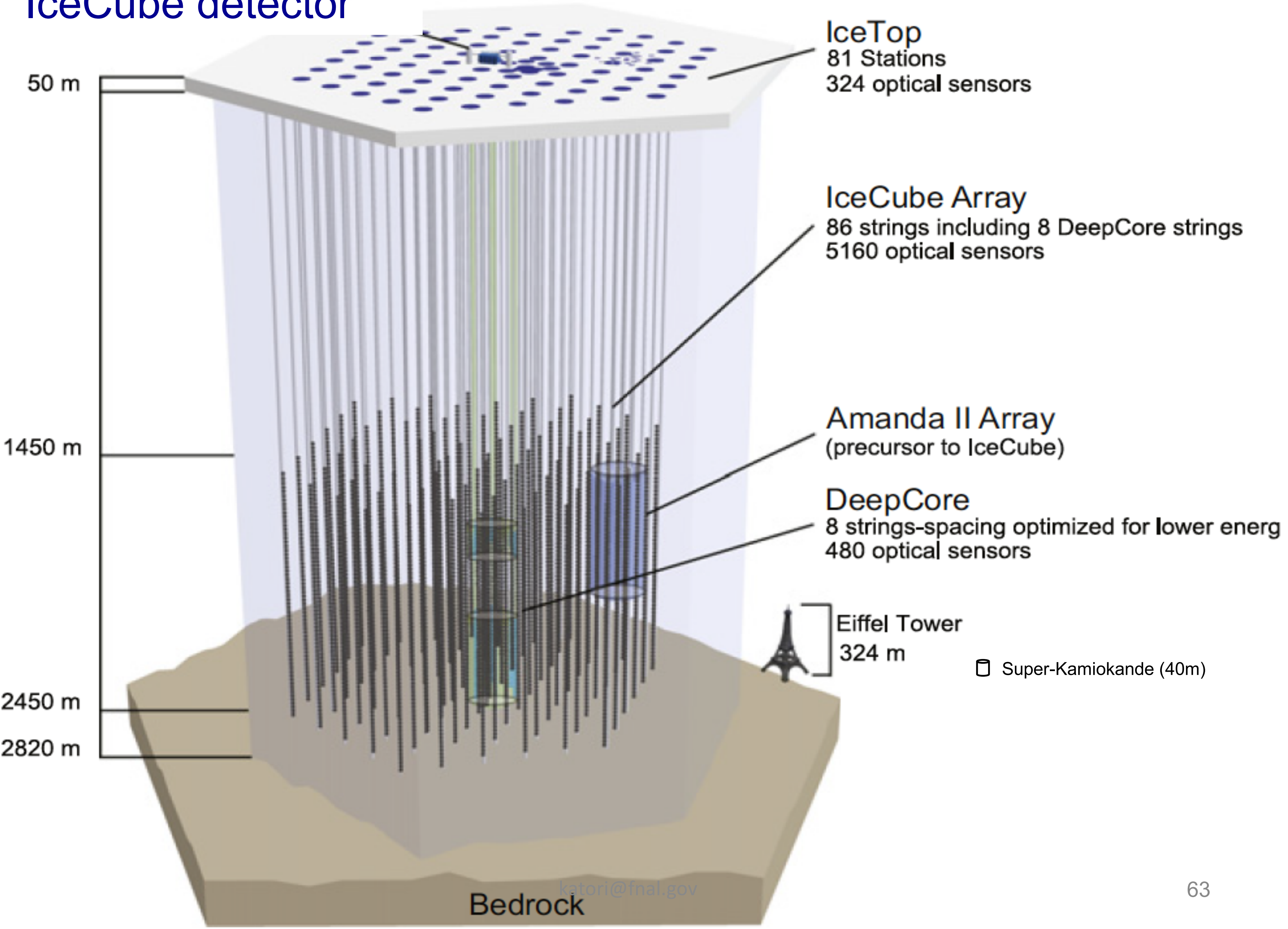
Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

5. High-Energy Neutrino Astronomy

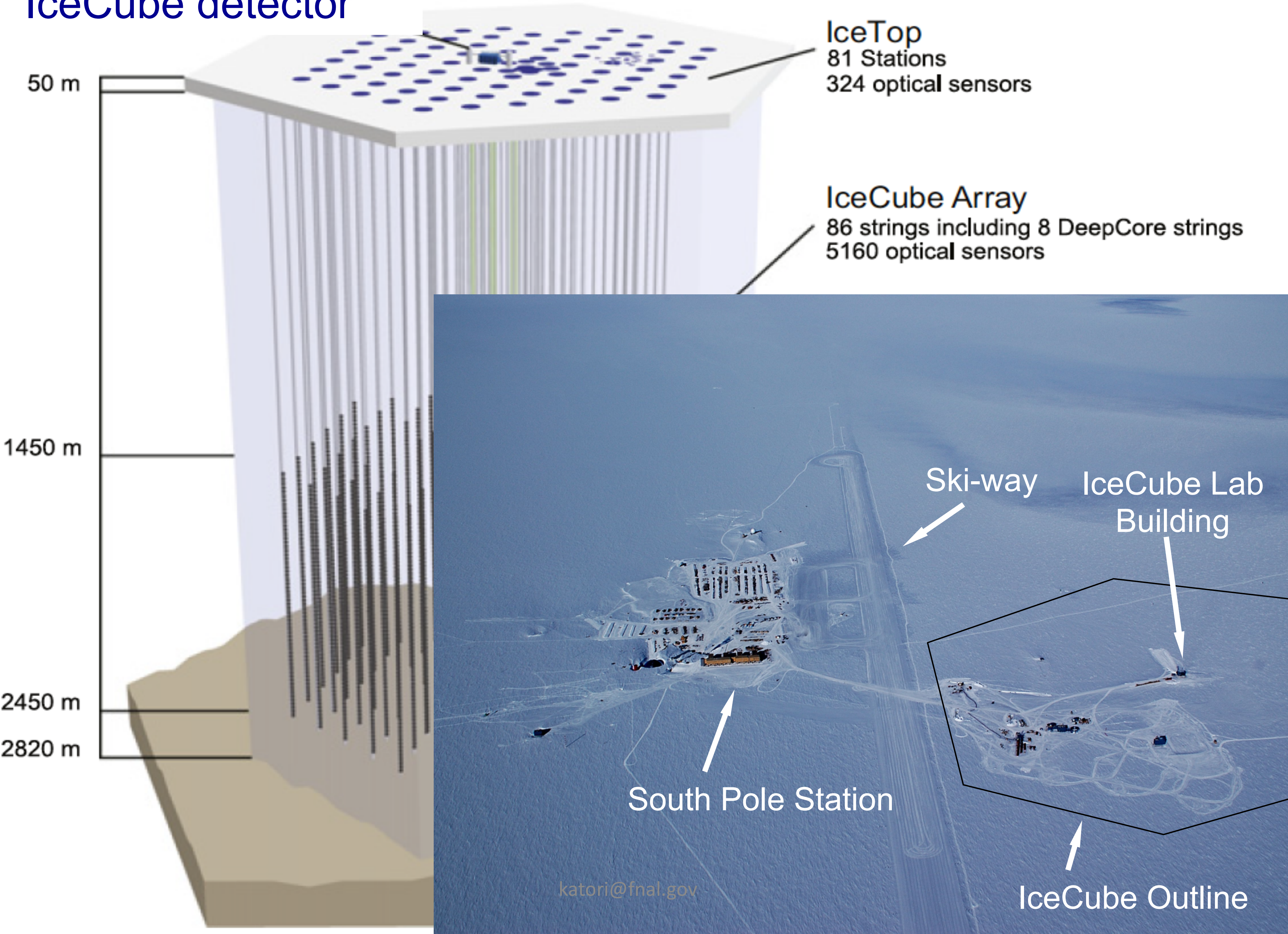
Above ~10-100 TeV neutrinos are only direct messengers



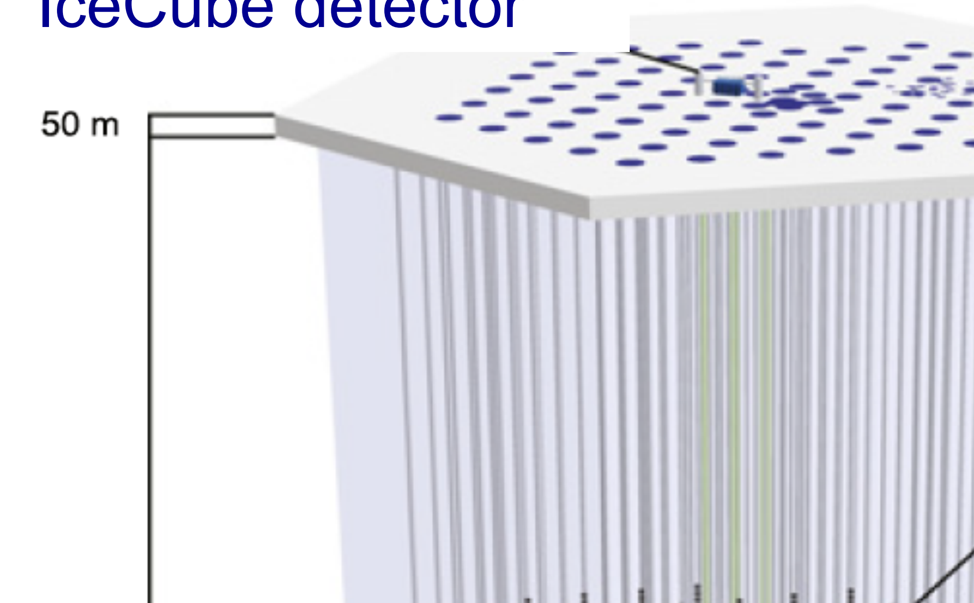
IceCube detector



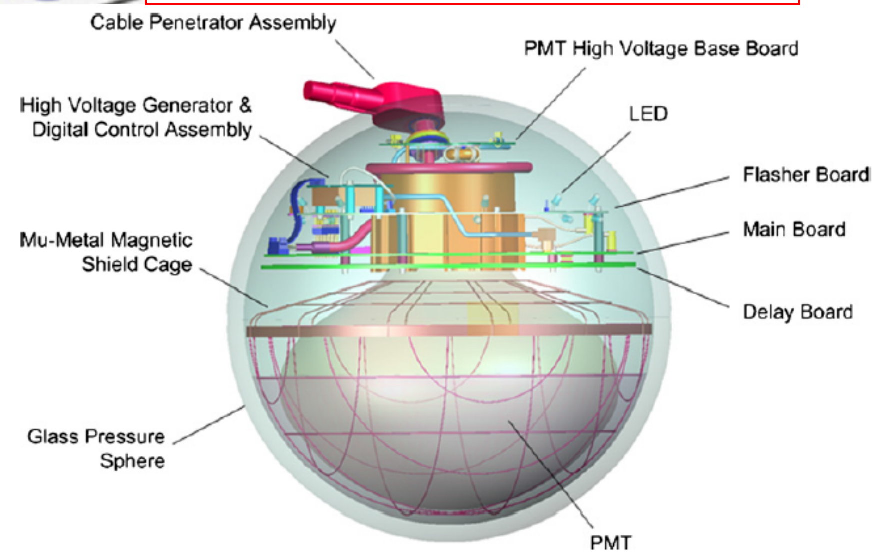
IceCube detector

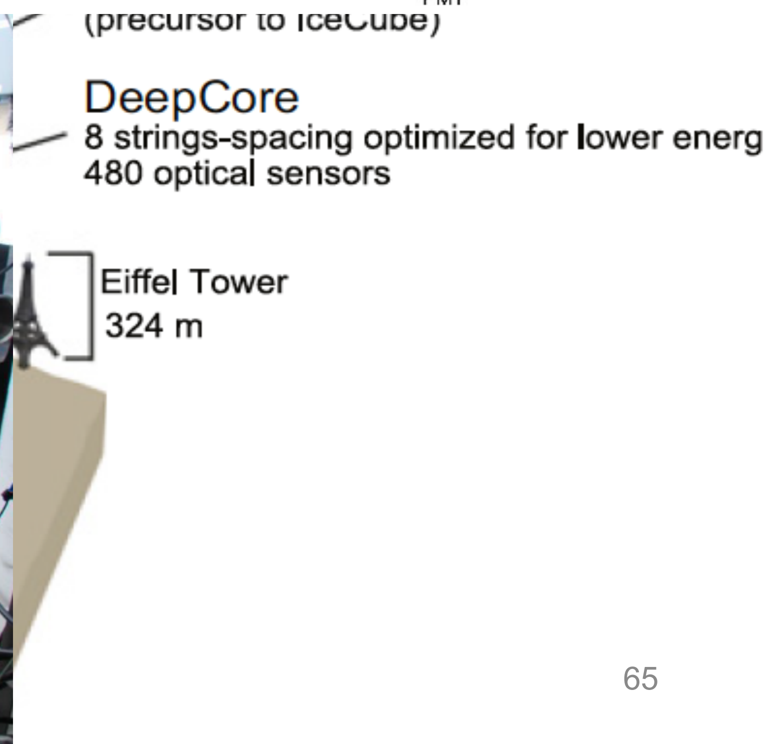


IceCube detector

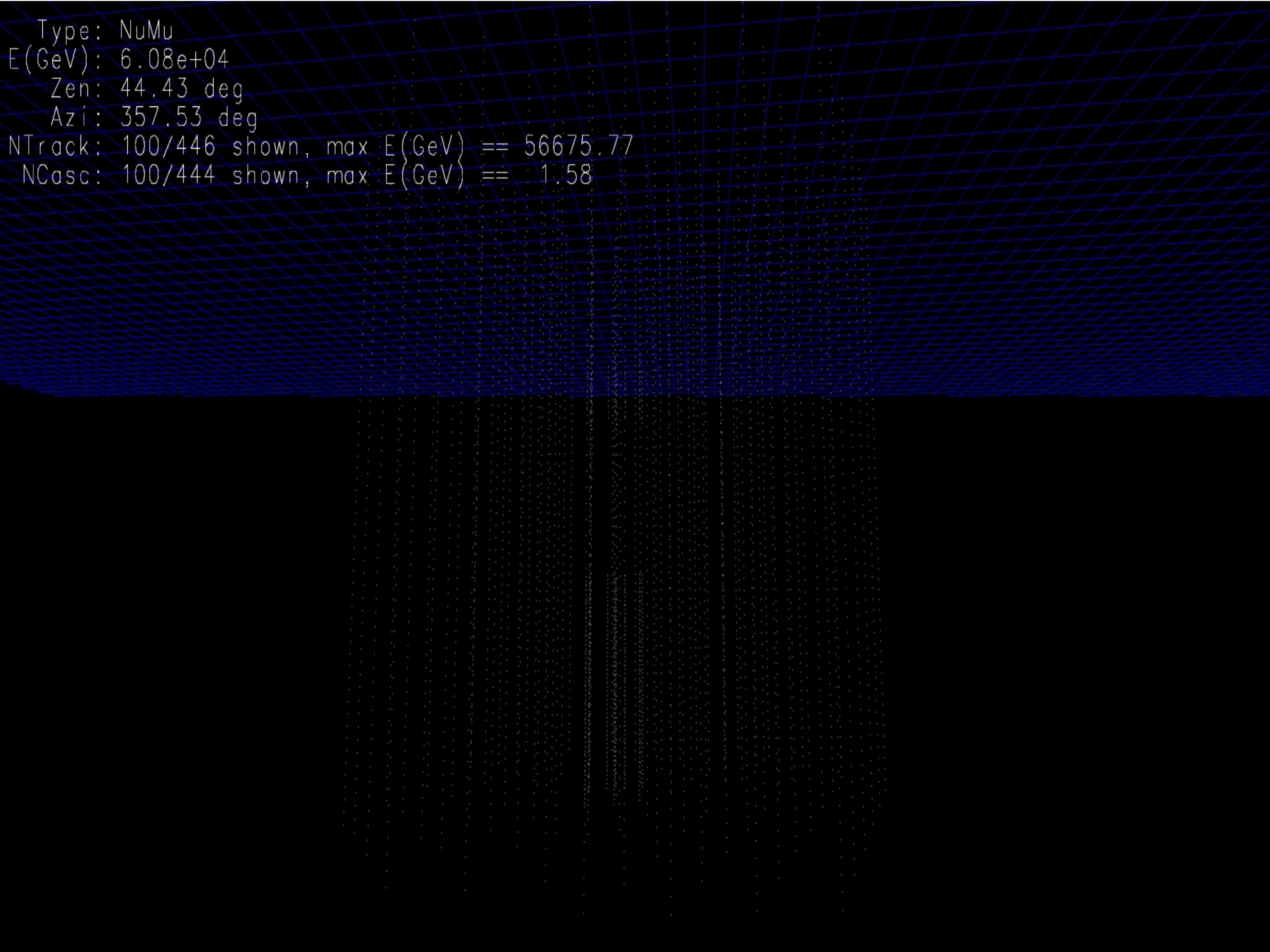


digital optical module (DOM)



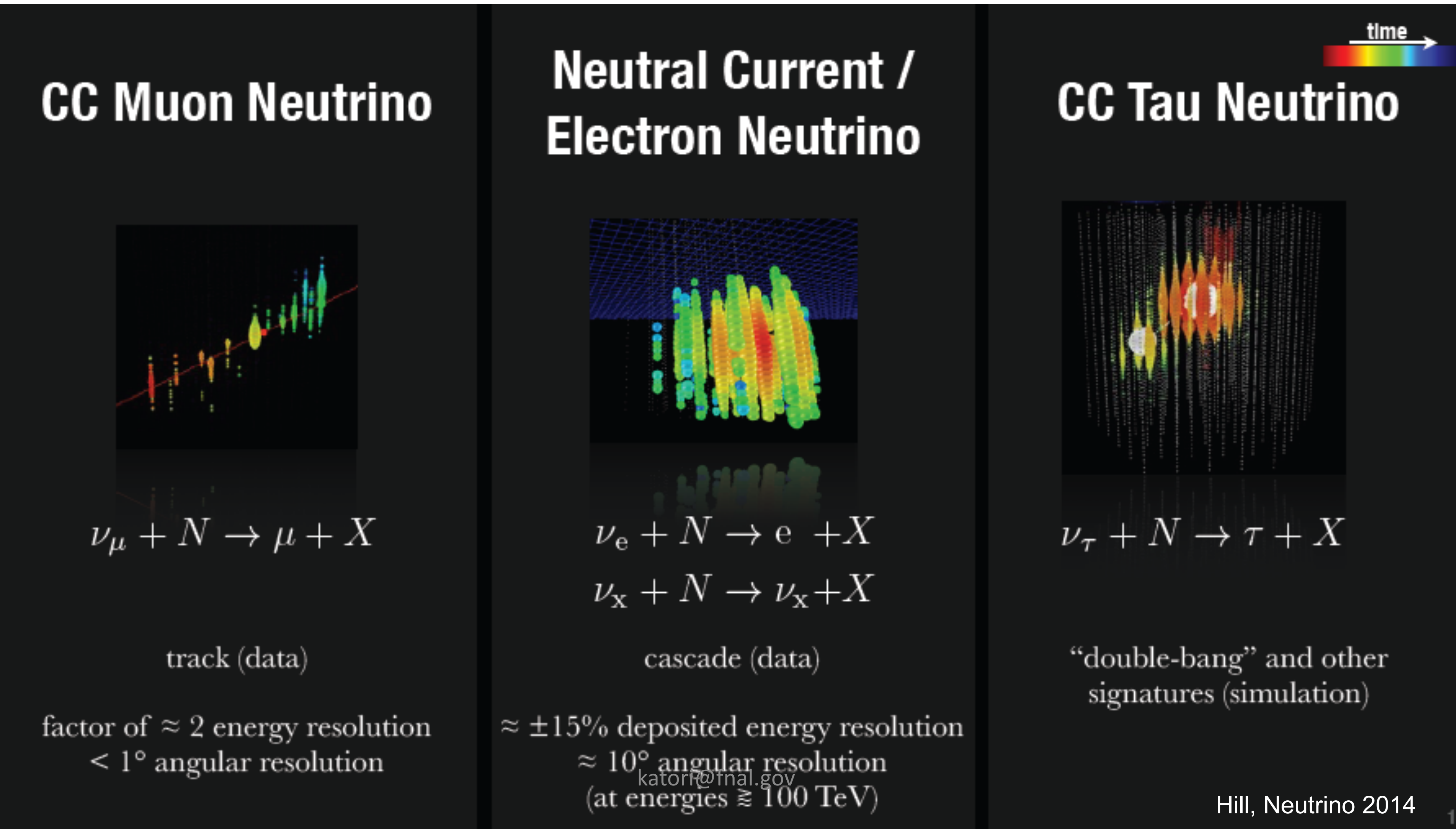


optical sensor deployment


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

5. Astrophysical High-Energy Neutrinos

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



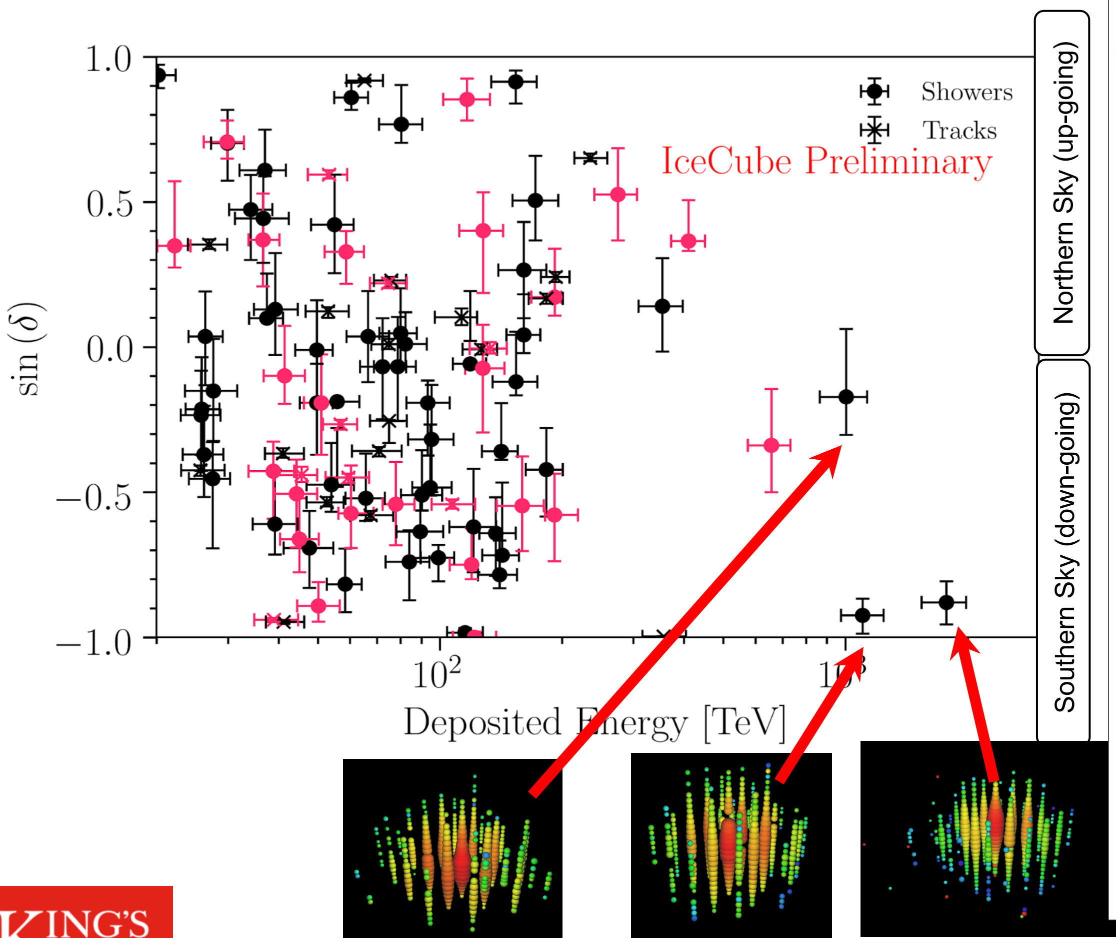
katori@fnal.gov

Hill, Neutrino 2014

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

5. Astrophysical High-Energy Neutrinos

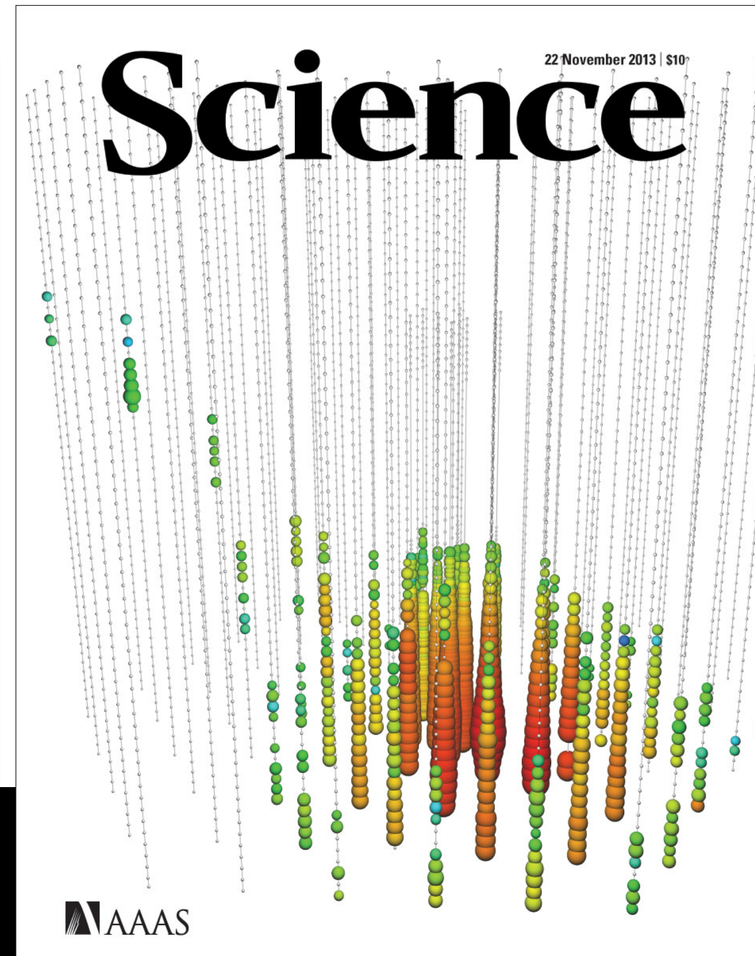
First observation (2013)
- 60-2000 TeV neutrinos



“Bert”
1.1 PeV

“Ernie”
1.0 PeV

“Big Bird”
2.0 PeV



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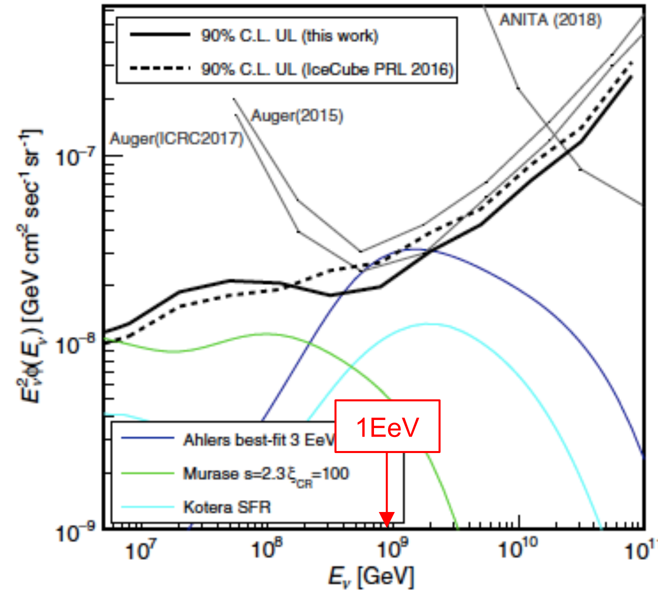
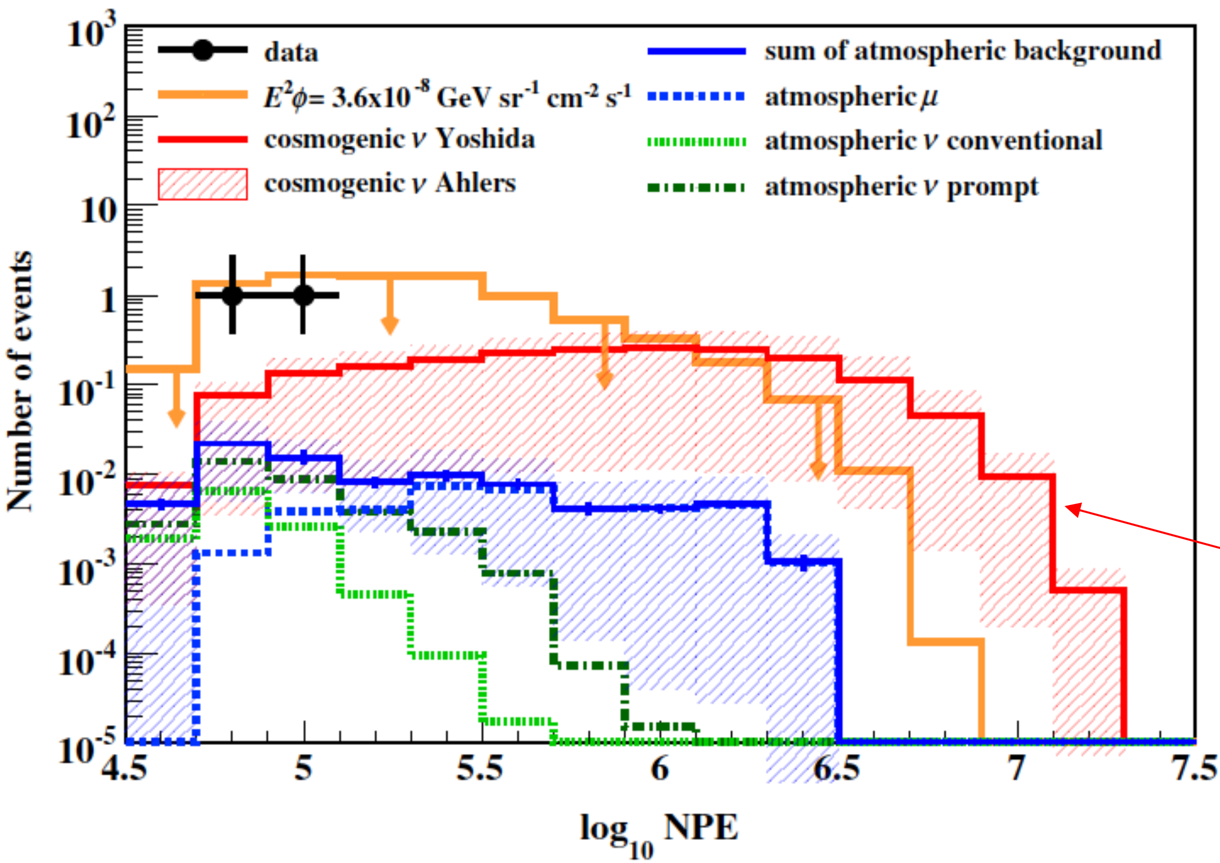
5. Astrophysical High-Energy Neutrinos

IceCube. PRD98(2018)062003



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

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



Predicted GZK neutrino flux

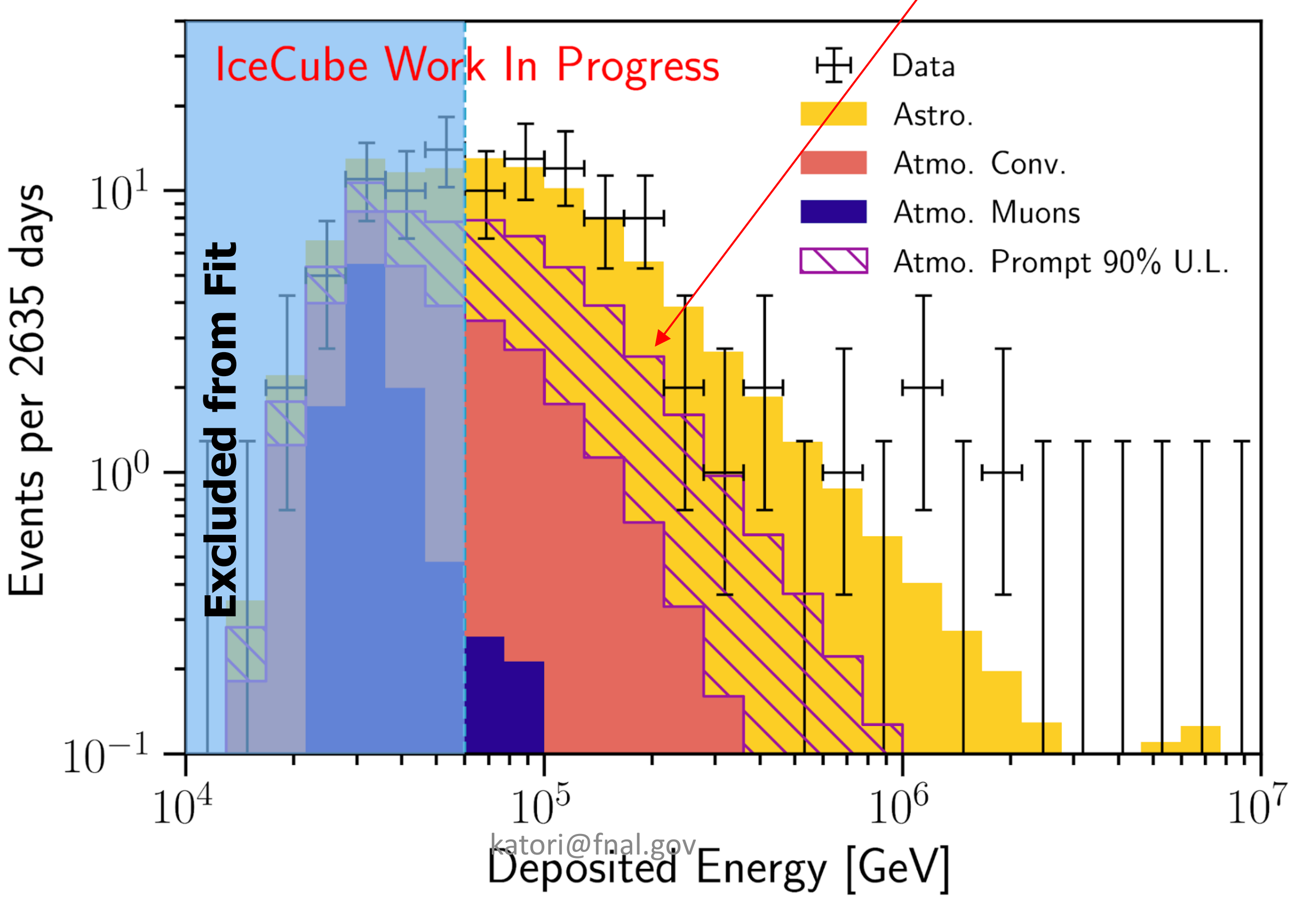
$$p + \gamma \rightarrow \Delta \rightarrow \pi \rightarrow \nu$$

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

5. Astrophysical High-Energy Neutrinos

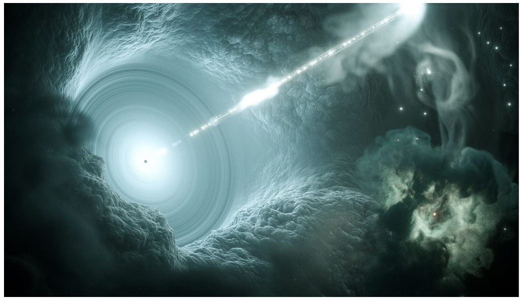
First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from GZK neutrinos
- Unlikely from atmospheric neutrinos

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



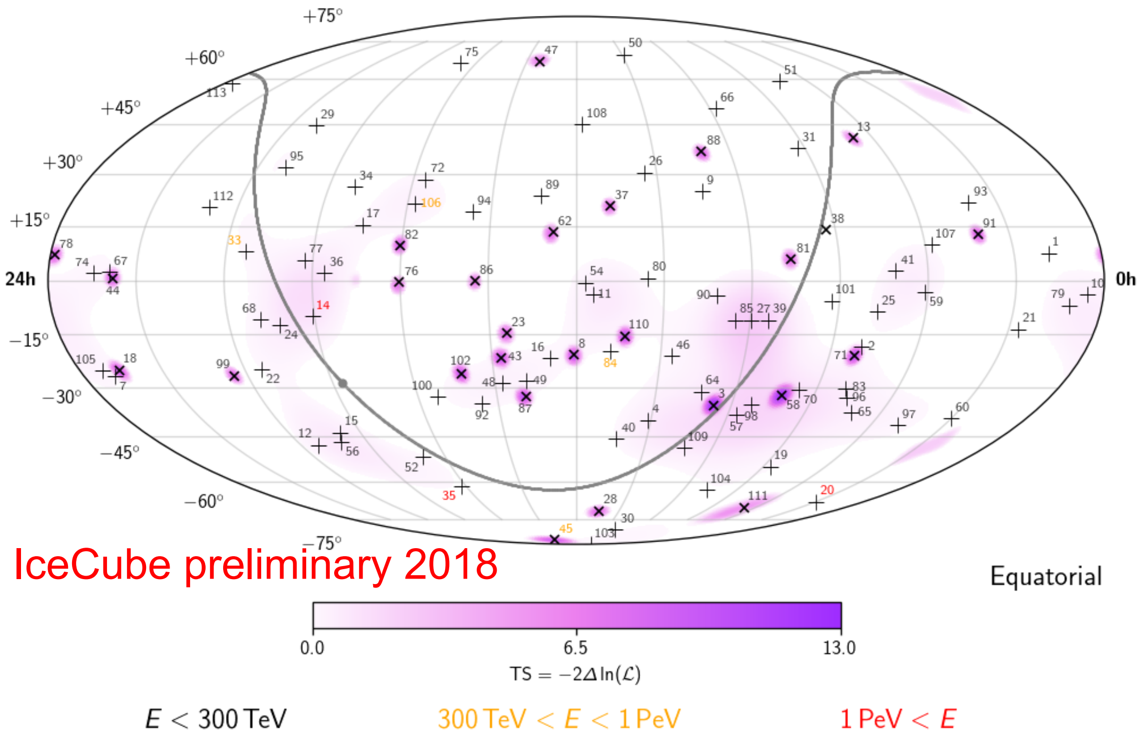
5. Astrophysical High-Energy Neutrinos

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)

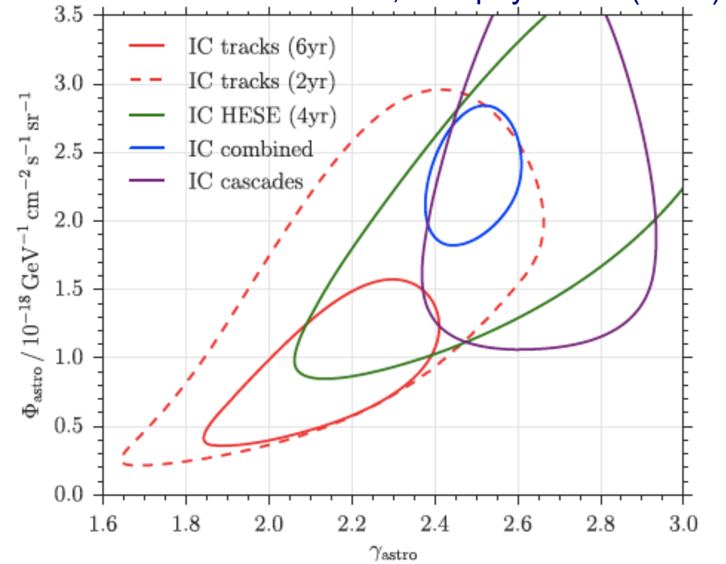


IceCube preliminary 2018

IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102
Santander (IceCube), Neutrino 2020

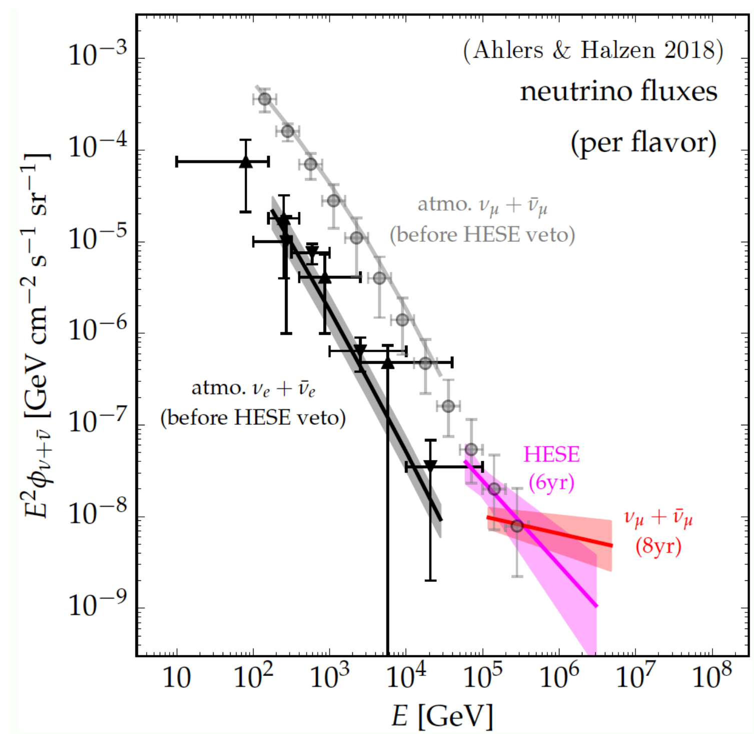
5. Astrophysical High-Energy Neutrinos

IceCube,Astrophys.J.833(2016)3



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



katori@fnal.gov

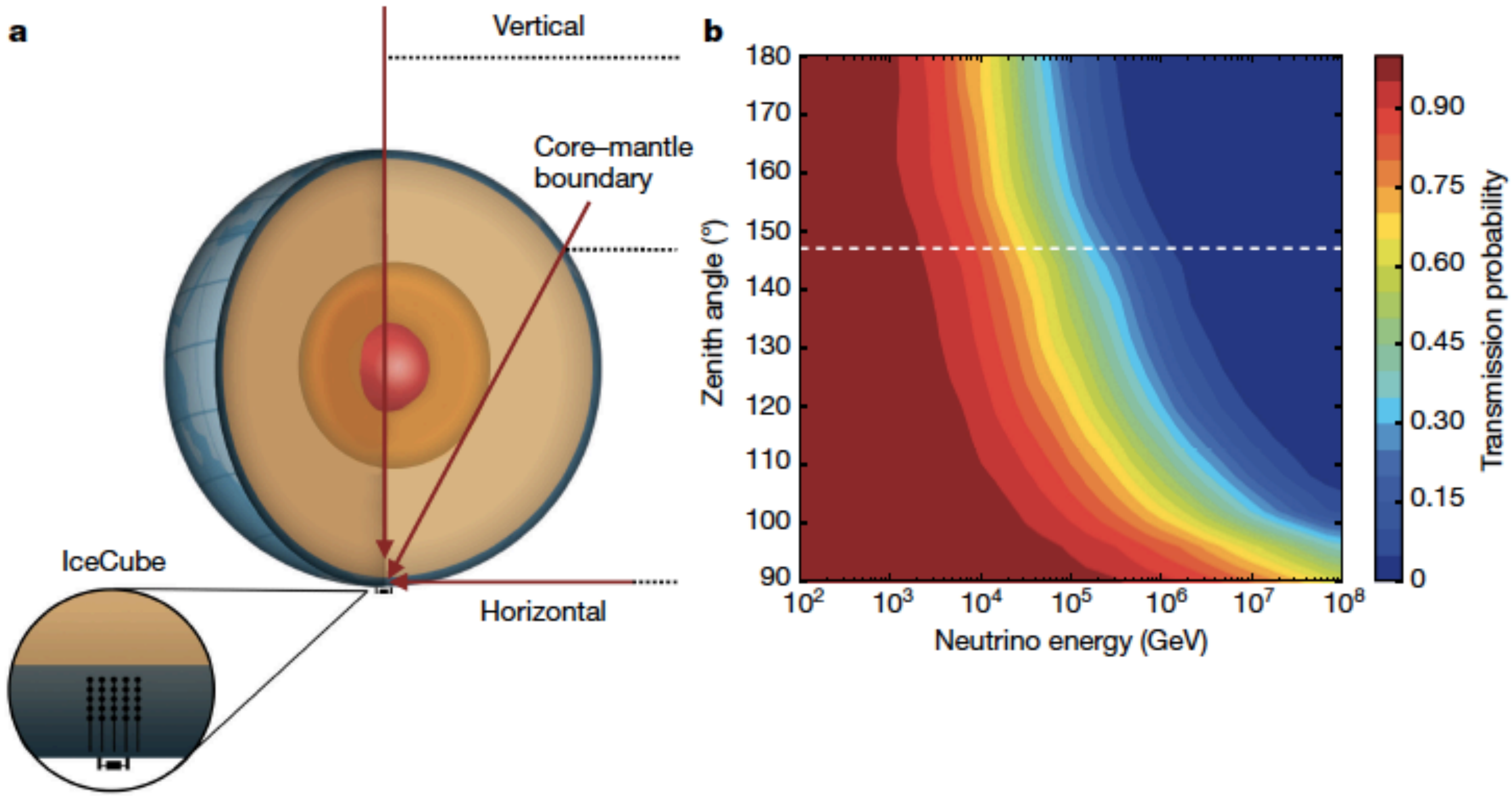
5. High-energy neutrino cross section measurement

cross section | efficiency | flux | target

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, neutrino cross section is extracted from measured event rate.



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

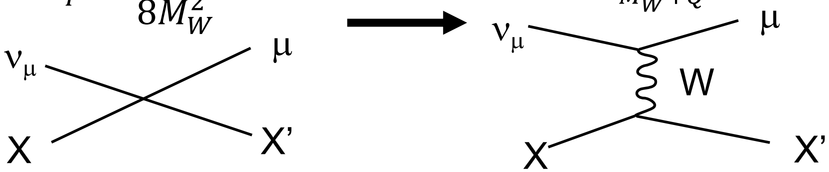
5. High-energy neutrino cross section measurement

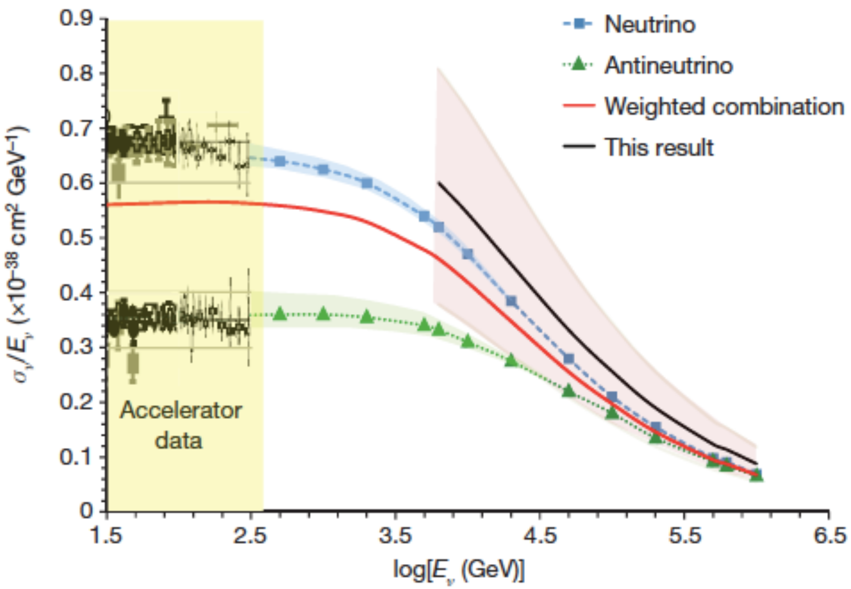
Event rate $N = \Phi \times \sigma \times T \times \varepsilon$ (flux, cross section, target, efficiency)

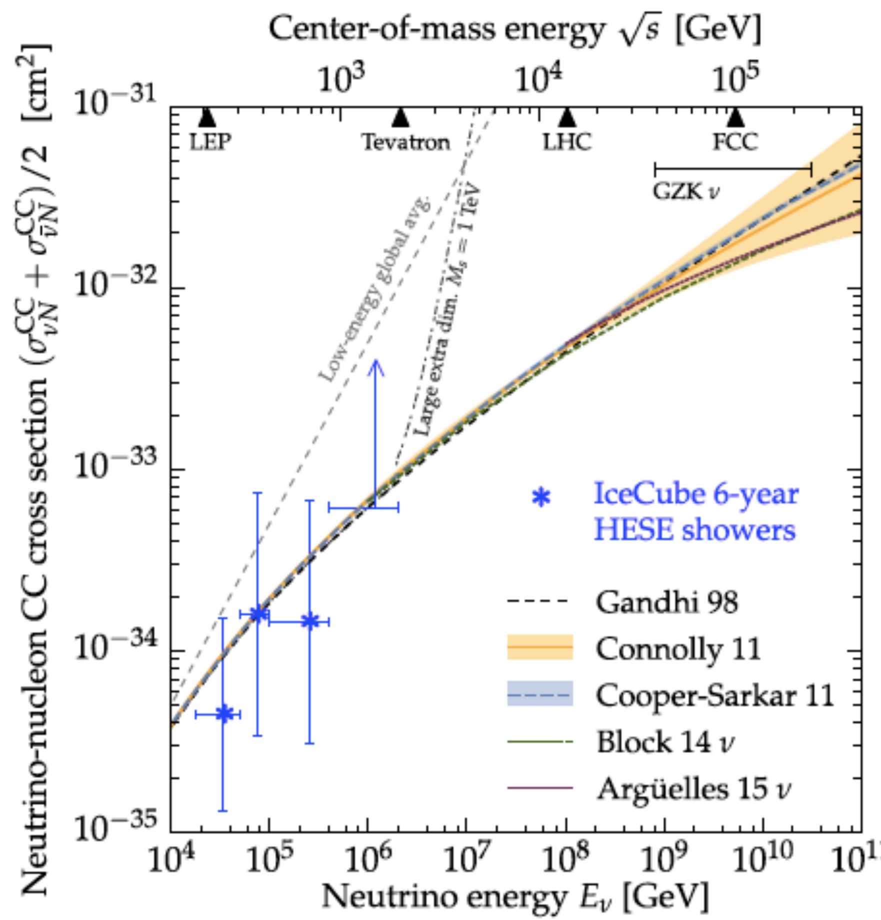
Earth absorption for neutrino cross-section measurement

- 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

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







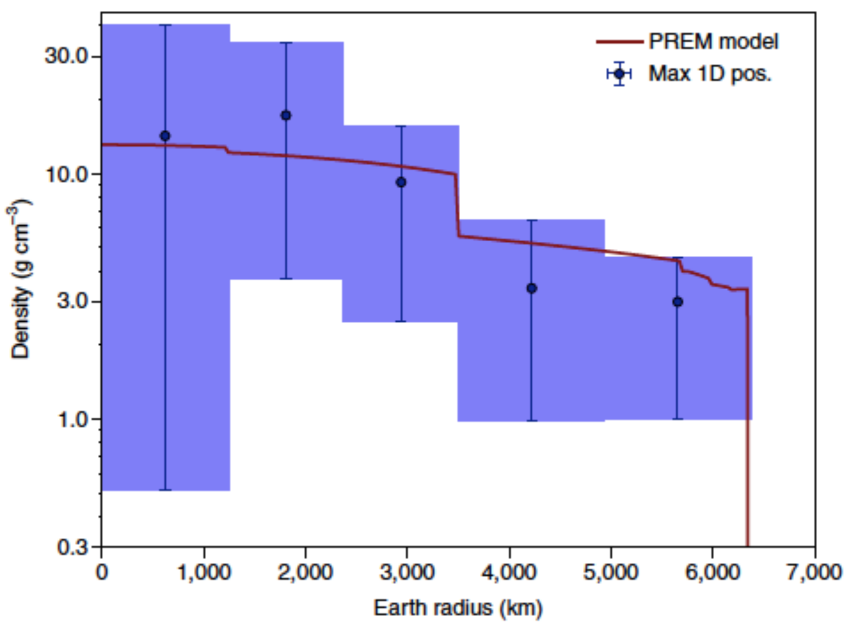
Dziewonski, Anderson (PREM), Phys. Earth Planet.Inter.25,(1981)297
Donini, Palomares-Ruiz, Salvado, Nature Physics 15(2019)37

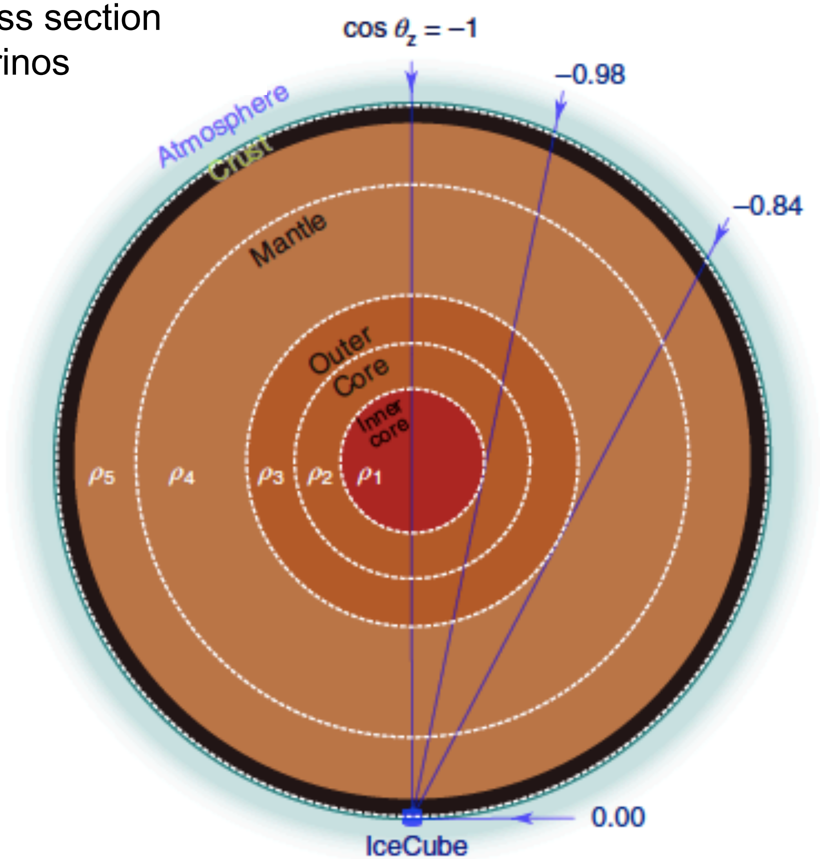
5. Earth tomography

cross section | efficiency | flux | target

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

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

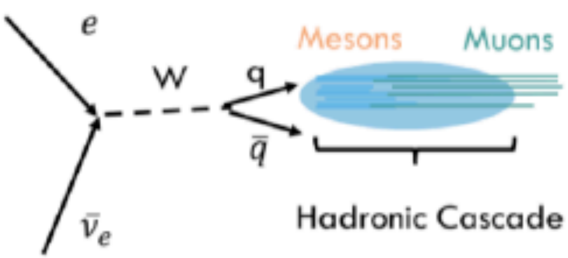




5. Glashow resonance

A 5.9 PeV event in IceCube

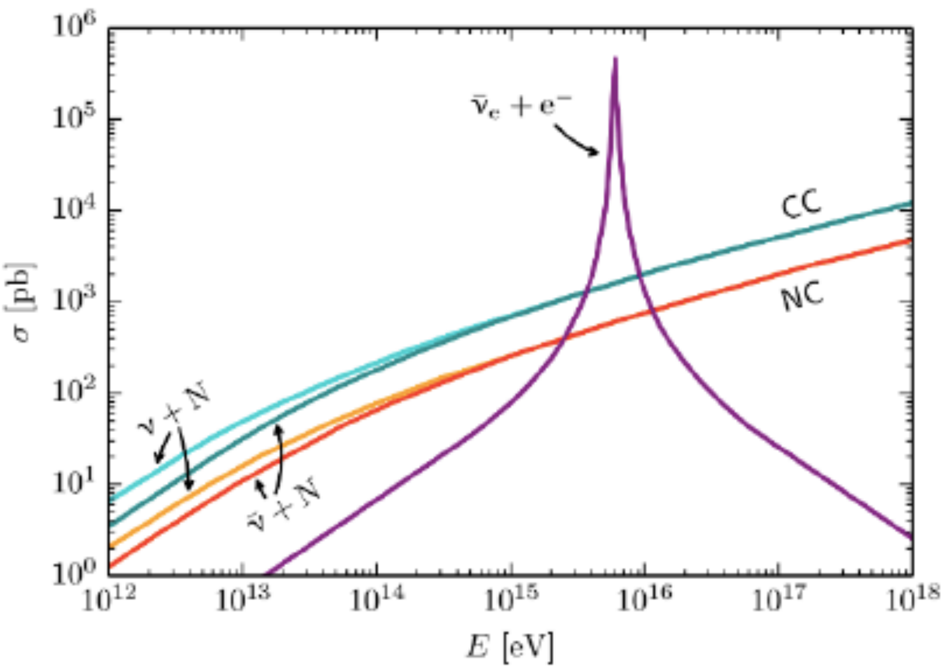
Glashow Resonance

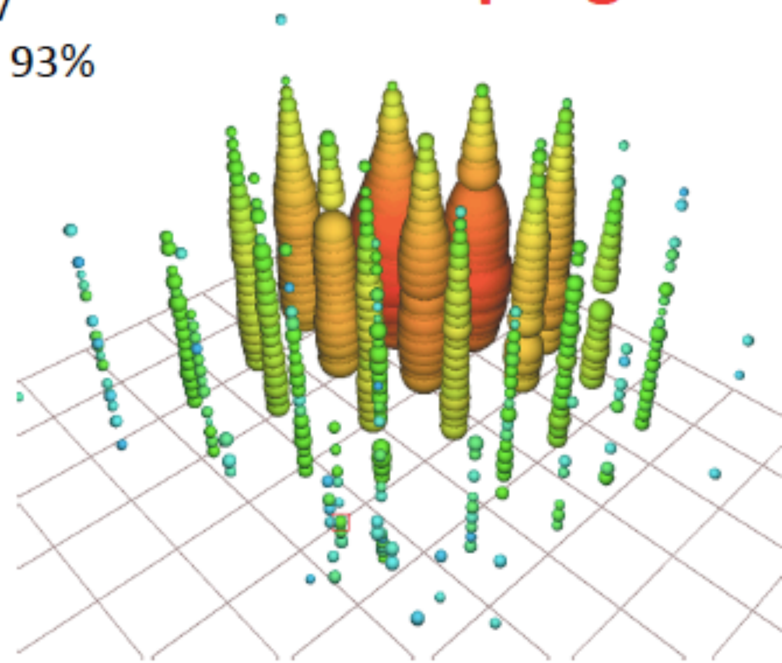


Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%

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

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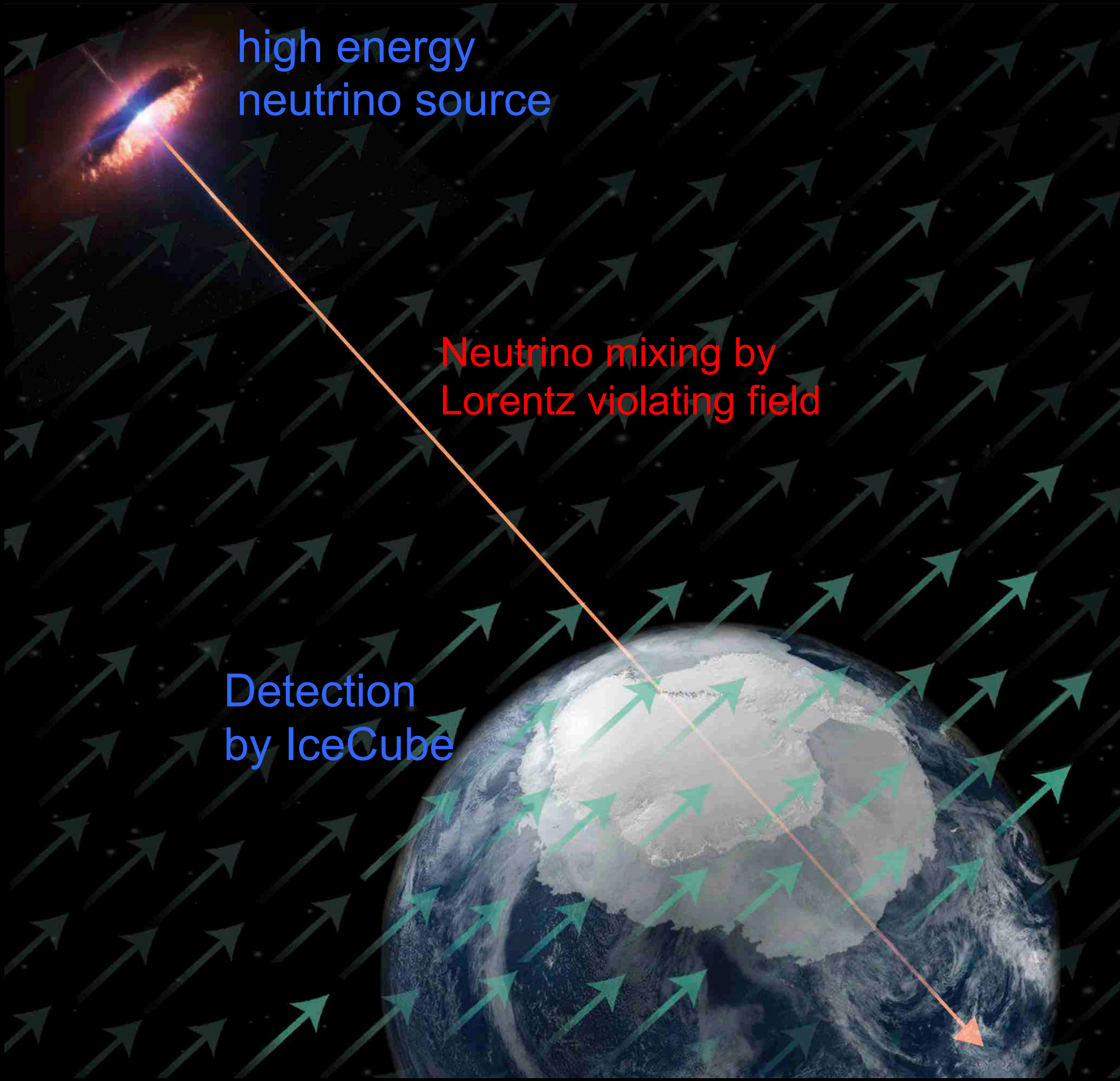
IceCube, Nature Physics 14(2018)961
TK, ArXiv:1906.09240, Argüelles et al, arXiv:1907.08690

5. New physics

Test of fundamental physics
- Quantum gravity = QFT+GR
- Quantum Field Thoery (QFT) → particle physics, microscopic scale
- General Relativity (GR) → gravity, large scale

High-energy astrophysical neutrinos are sensitive to small deficit of vacuum
- new interaction in vacuum
- new space-time structure
- new vacuum structure



IceCube, Nature Physics 14(2018)961
TK, ArXiv:1906.09240, Argüelles et al, arXiv:1907.08690

5. New physics

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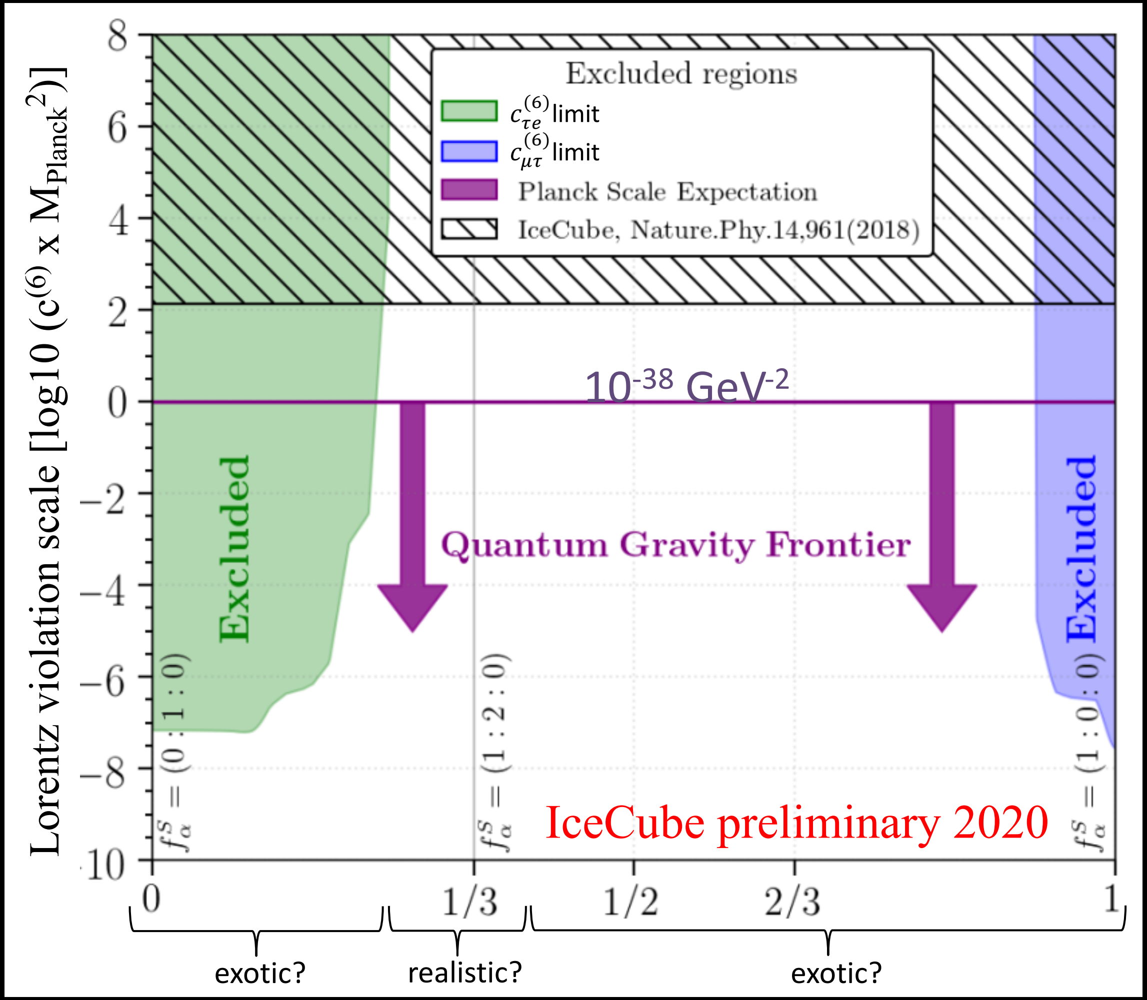
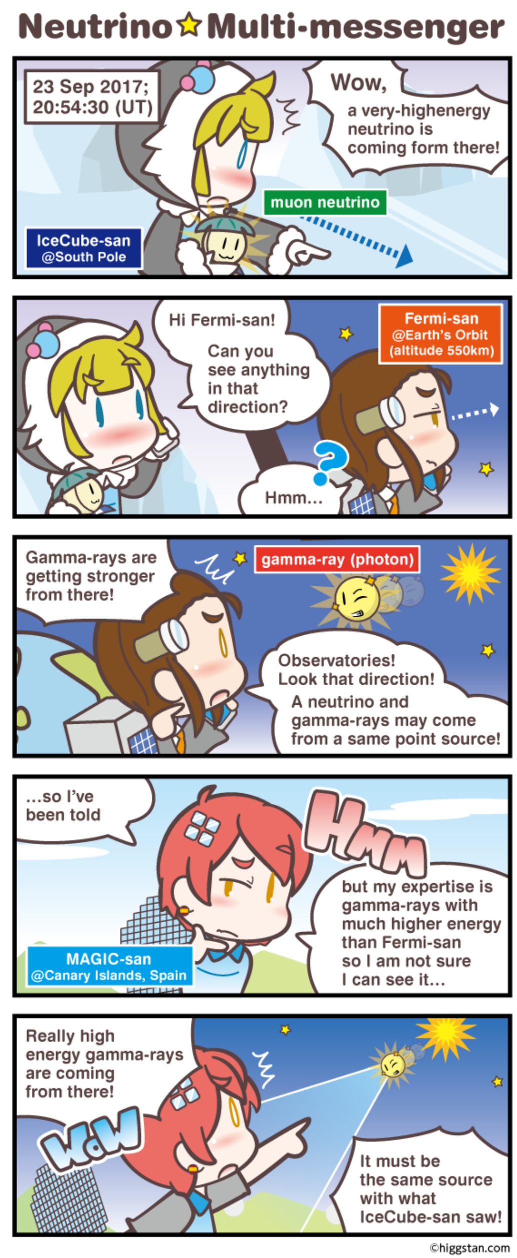
High-energy astrophysical neutrinos are sensitive to small deficit of vacuum
- new interaction in vacuum
- new space-time structure
- new vacuum structure

It looks IceCube achieves to enough sensitivity to explore quantum gravity physics



5. Multi-messenger astronomy



5. Multi-messenger astronomy

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

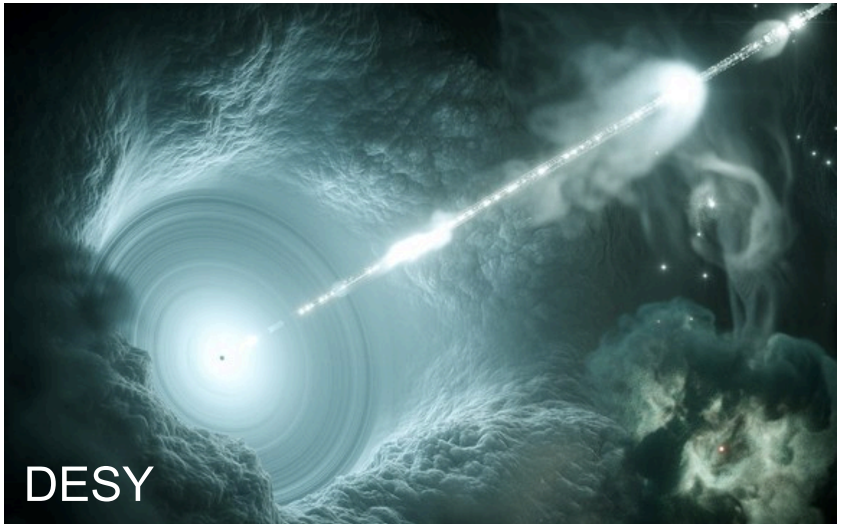
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

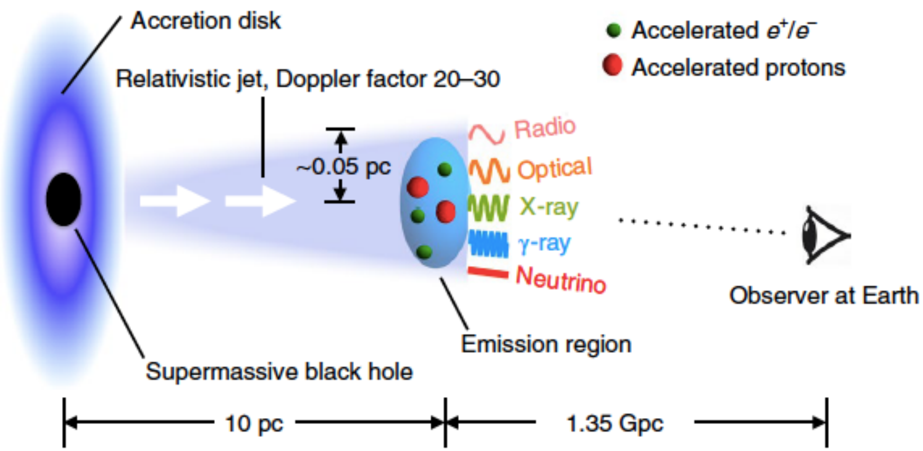
IceCube Collaboration*†

5. Multi-messenger astronomy

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.





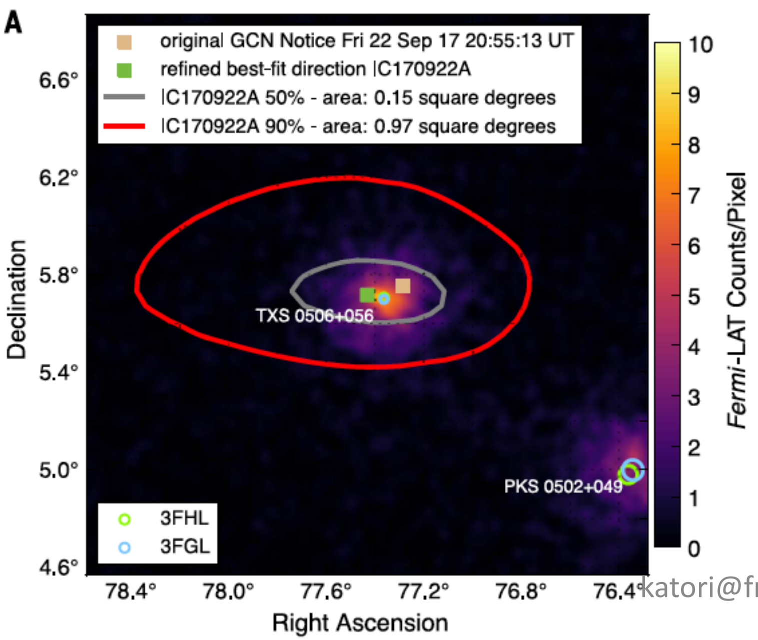
IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378

5. Multi-messenger astronomy

IC170922
- 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)

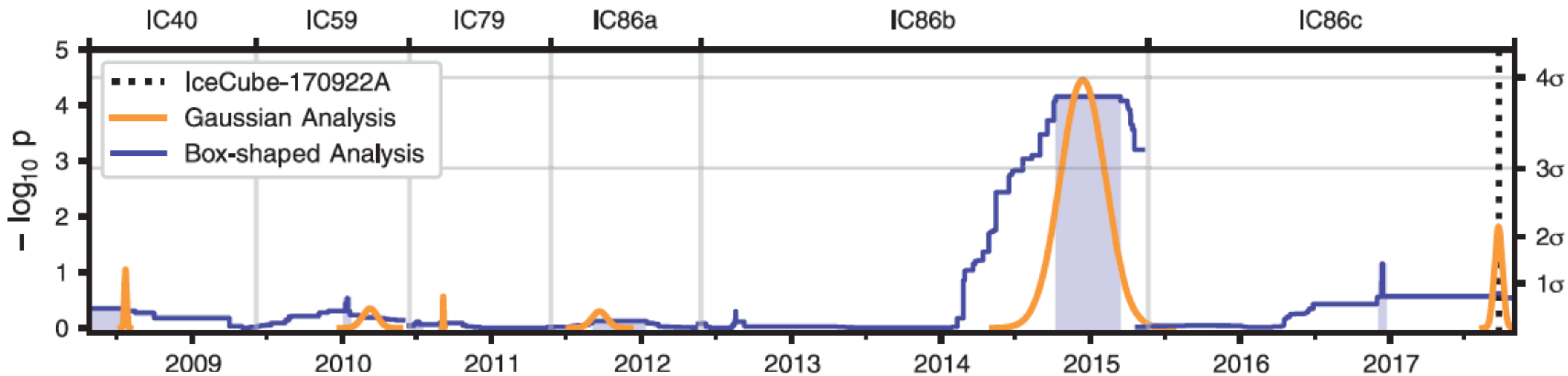
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

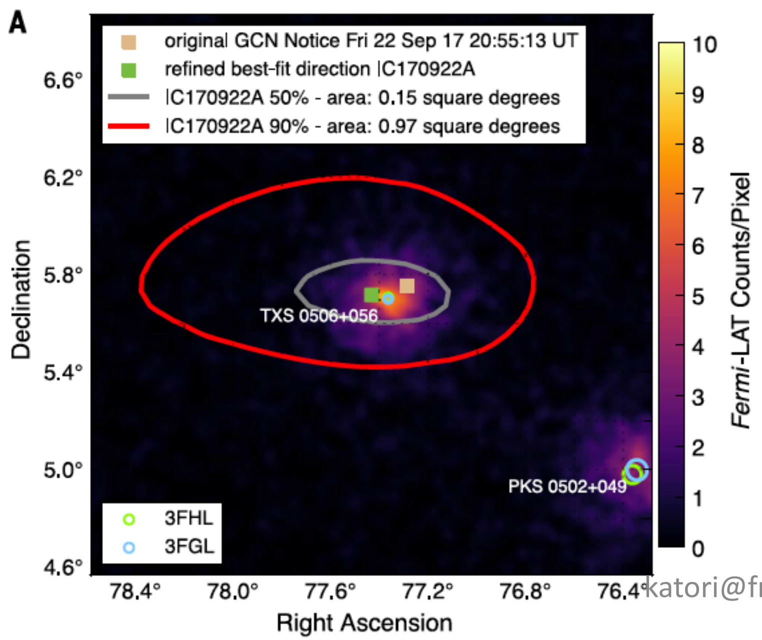
Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

5. TXS056+0506

2014/15 IceCube data

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





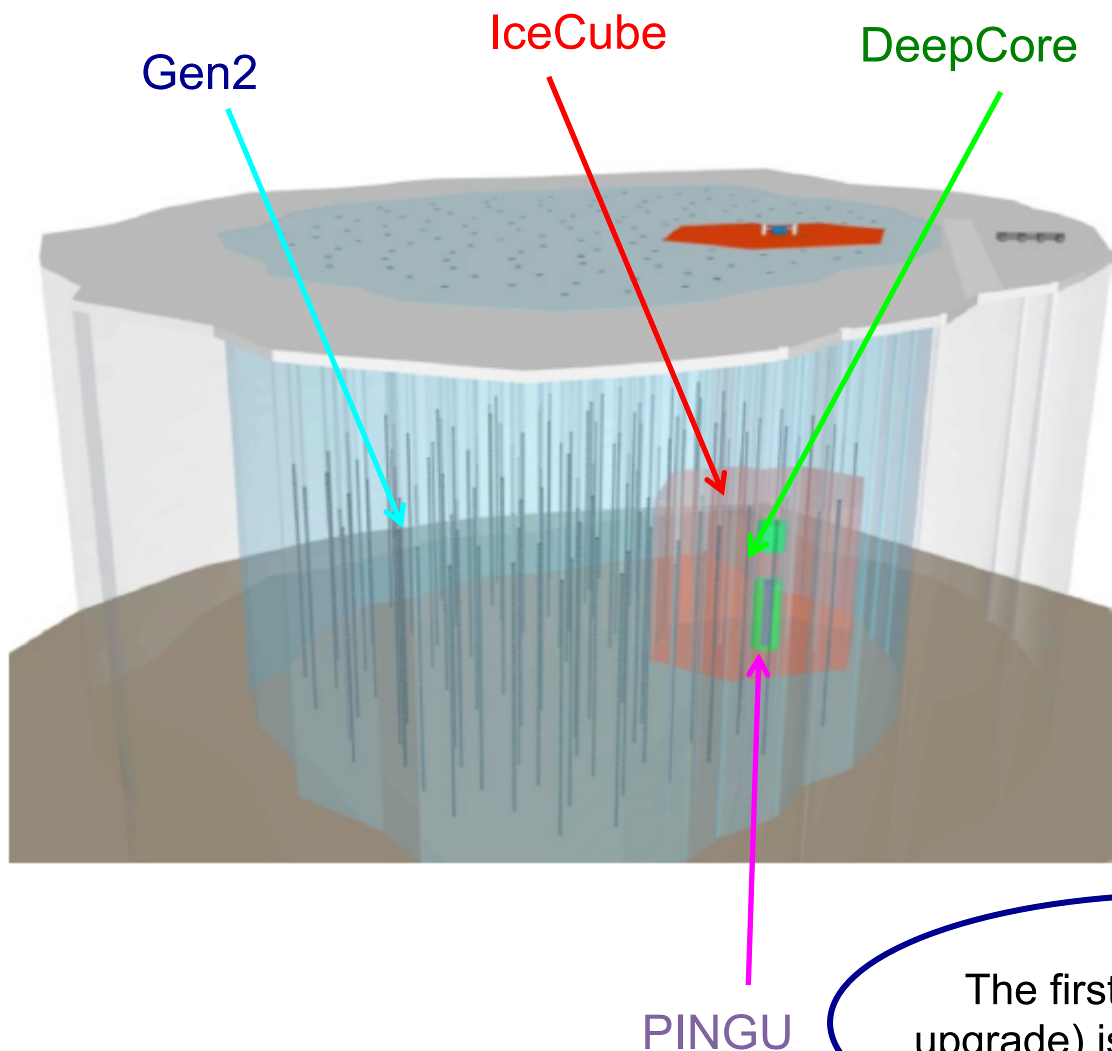
Is it special blazar?

- 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.

IceCube-Gen2 will see a lot of blazar neutrinos!

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

5. 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

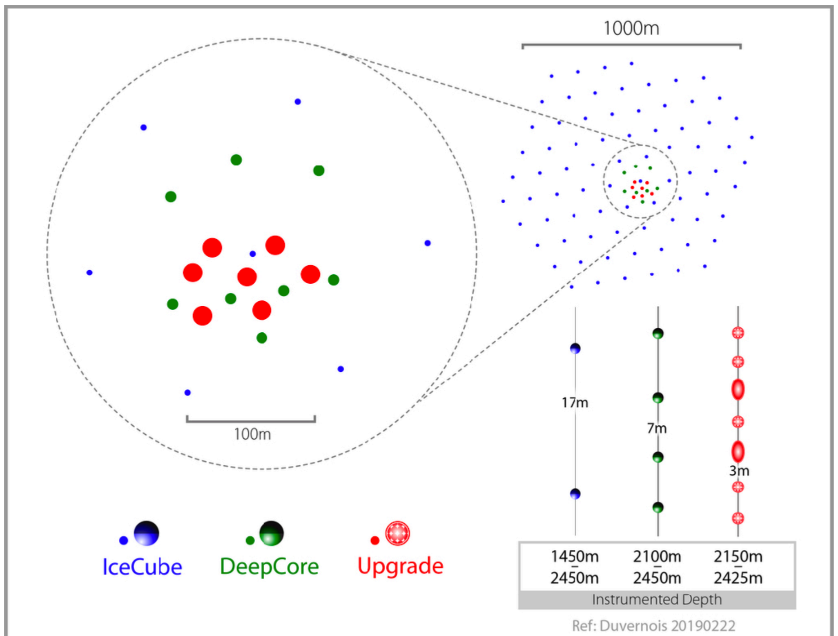
The first stage (IceCube upgrade) is approved by NSF

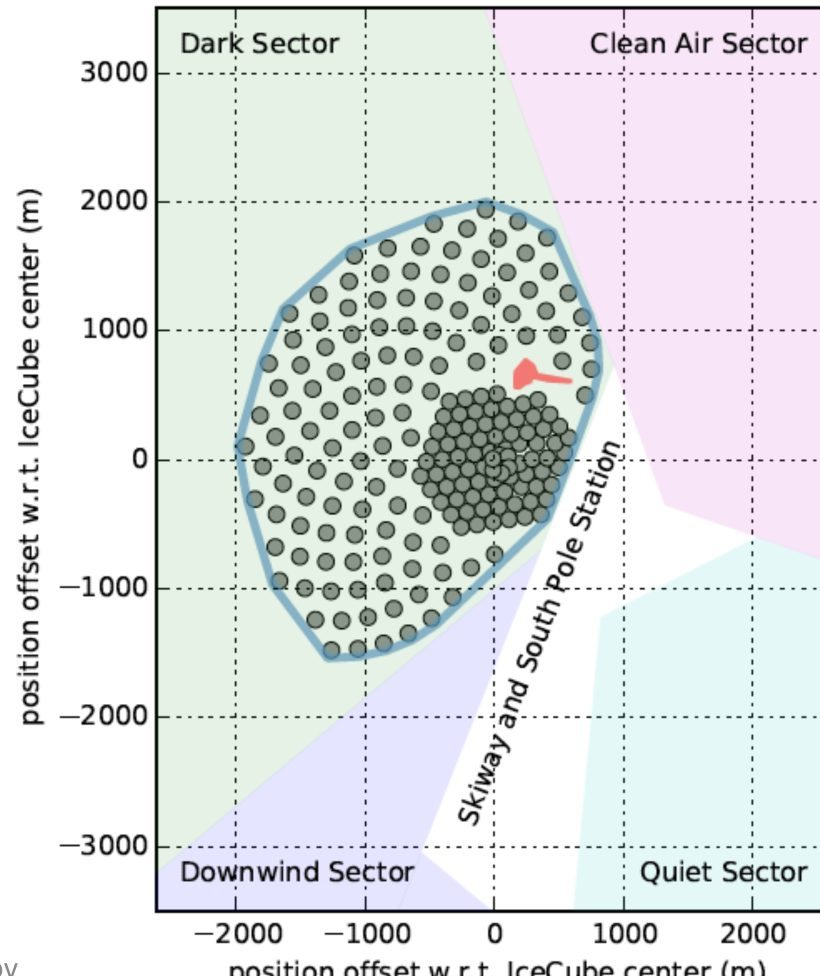
IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

5. 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

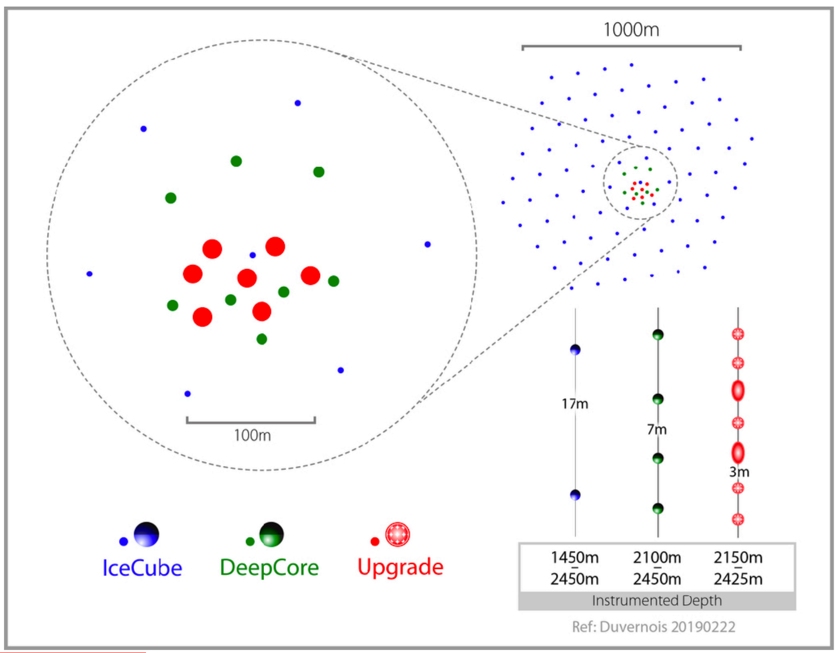
IceCube-Upgrade
- 7 new strings (part of PINGU array)
- Test new devices for high energy physics
- ν_τ appearance to constrain unitary triangle



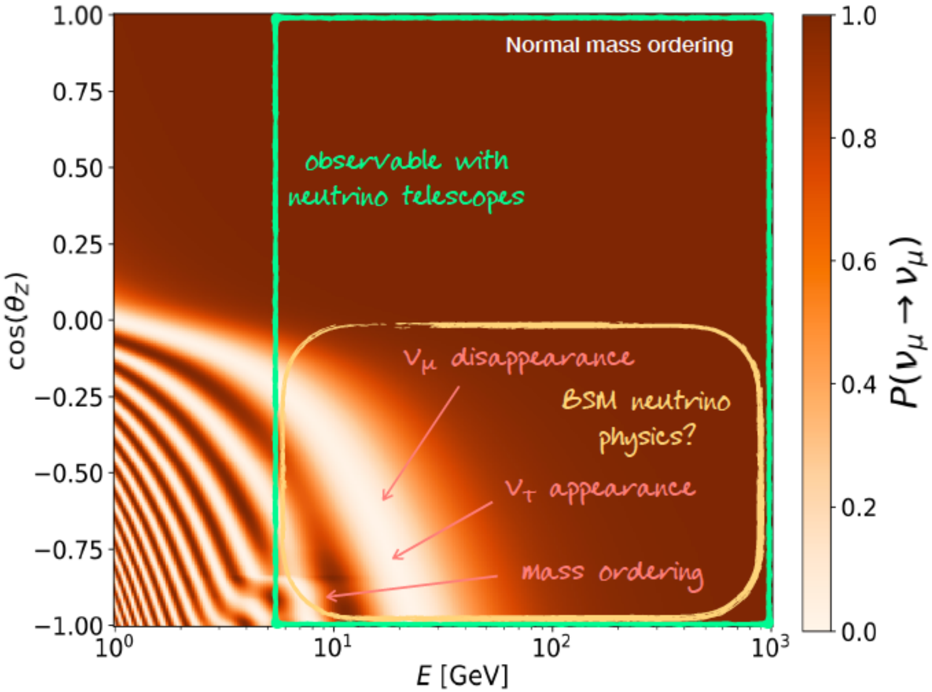


5. High-precision atmospheric neutrino physics

PINGU and ORCA
- PINGU is a part of IceCube-Gen2, ORCA is a part of KM3NeT
- Dense arrays of PMTs in South Pole ice or Medetrrenian sea water (=lower threshold)
- NMO by MSW effect around 4-6 GeV.
- Large ν_τ appearance data (PMNS unitary test)



Oscillograms

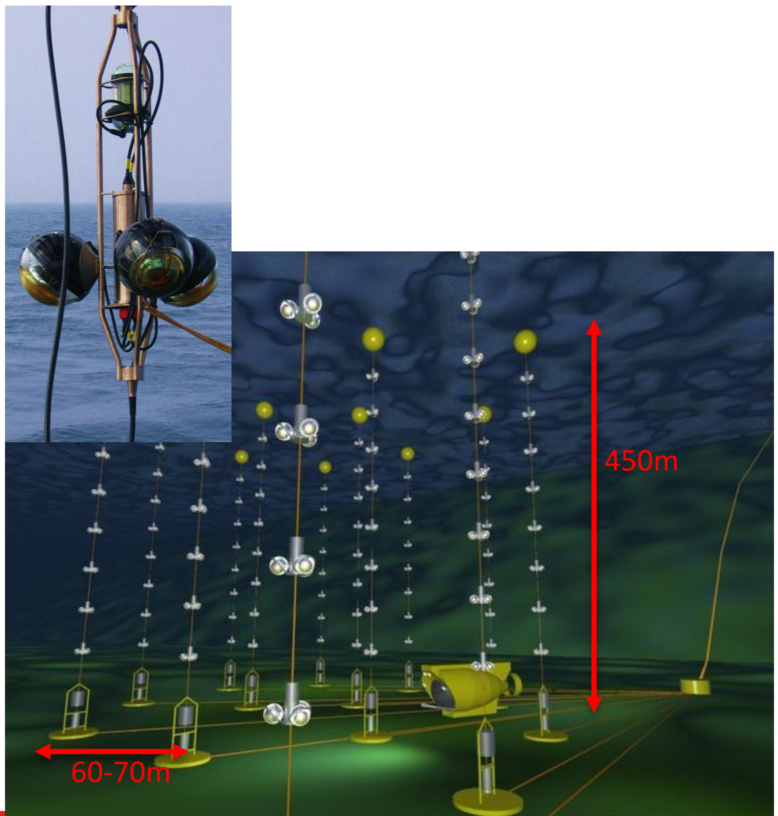


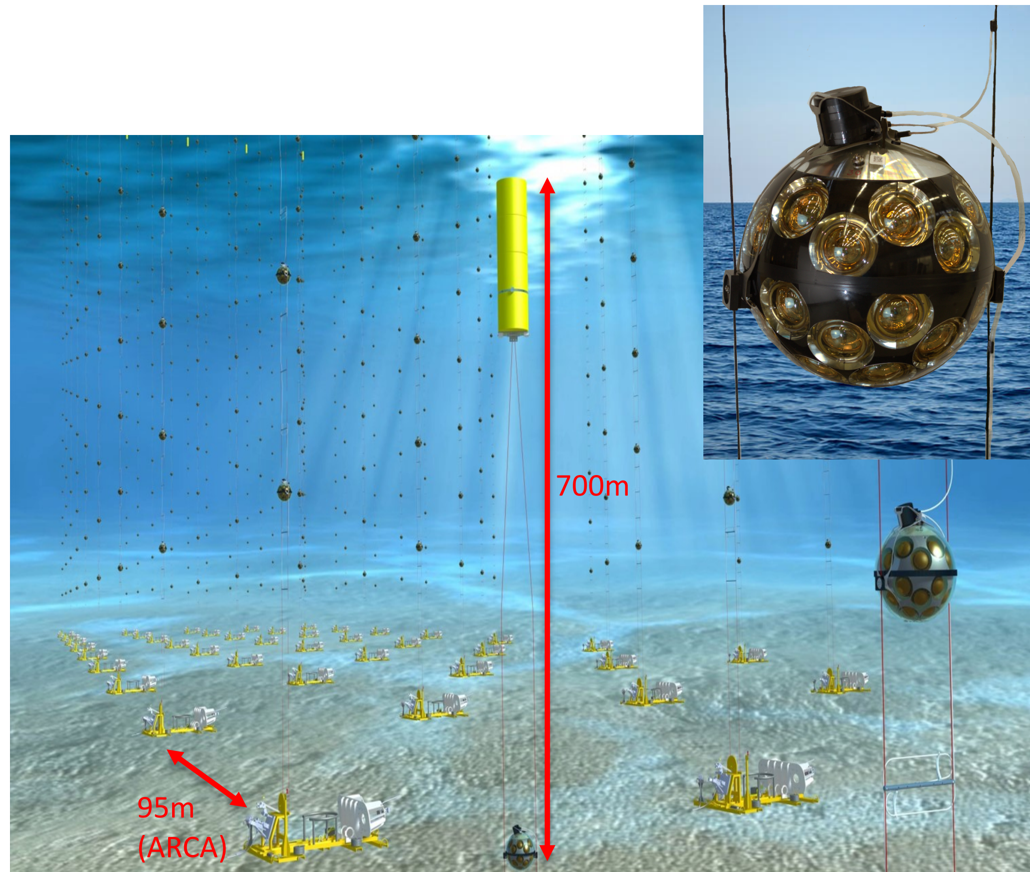
KM3NeT, J.Phys.G43(2016)084001

5. ANTARES → KM3NeT

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

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

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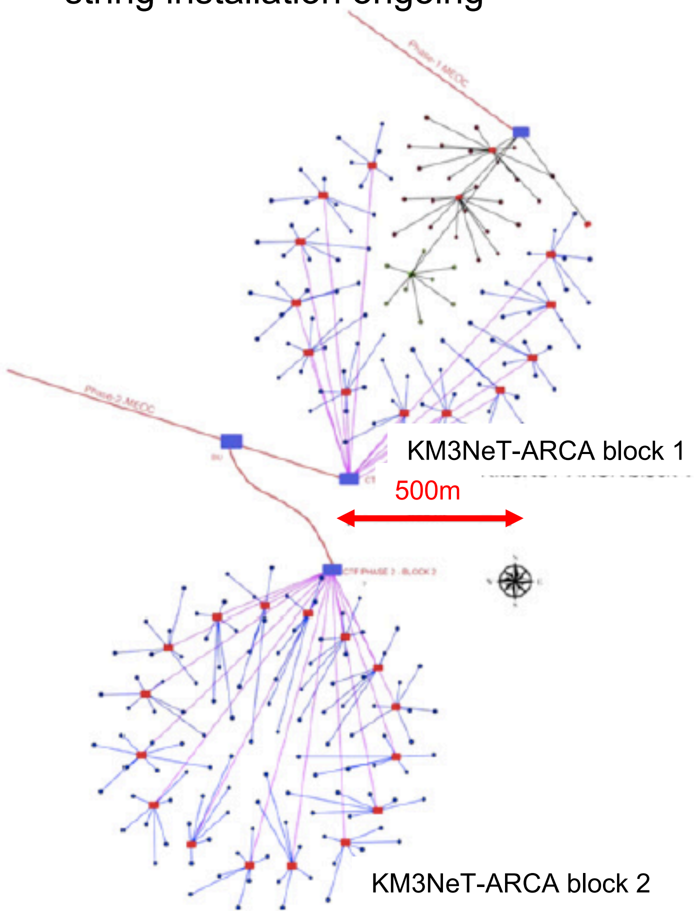
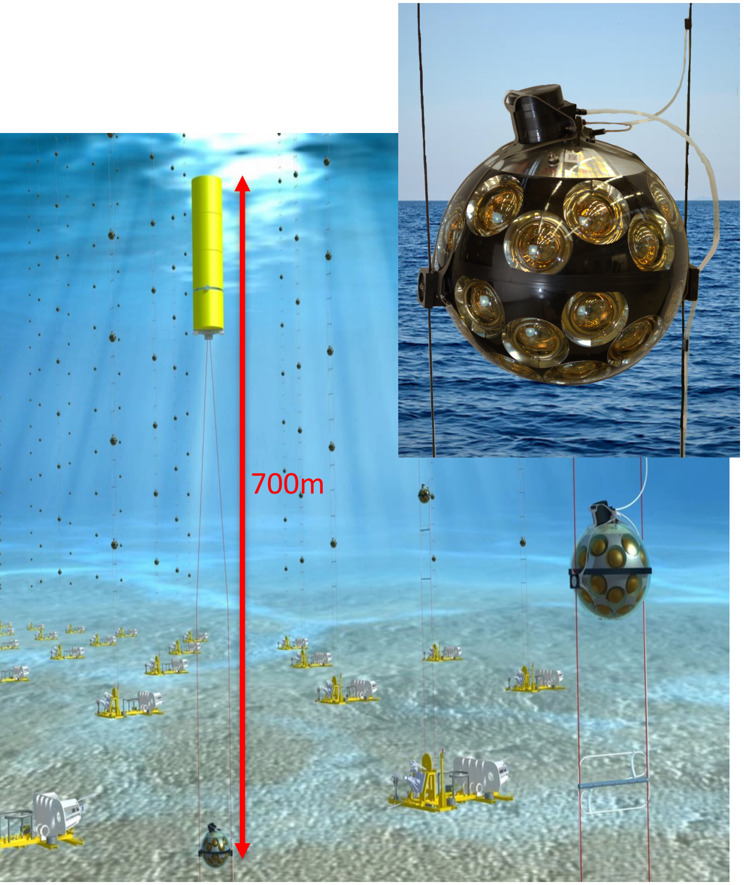
KM3NeT is ARCA and ORCA
- ARCA: Astroparticle Research with Cosmics in the Abyss, IceCube-like neutrino telescope
- ORCA: Oscillation Research with Cosmics in the Abyss, more lines in small region for low energy (<20 GeV) neutrino oscillation physics
- string installation ongoing





KM3NeT, J.Phys.G43(2016)084001

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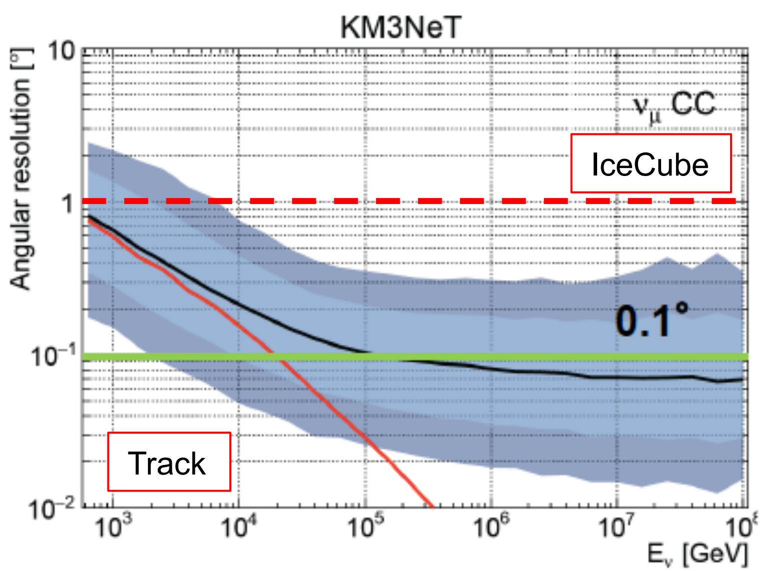
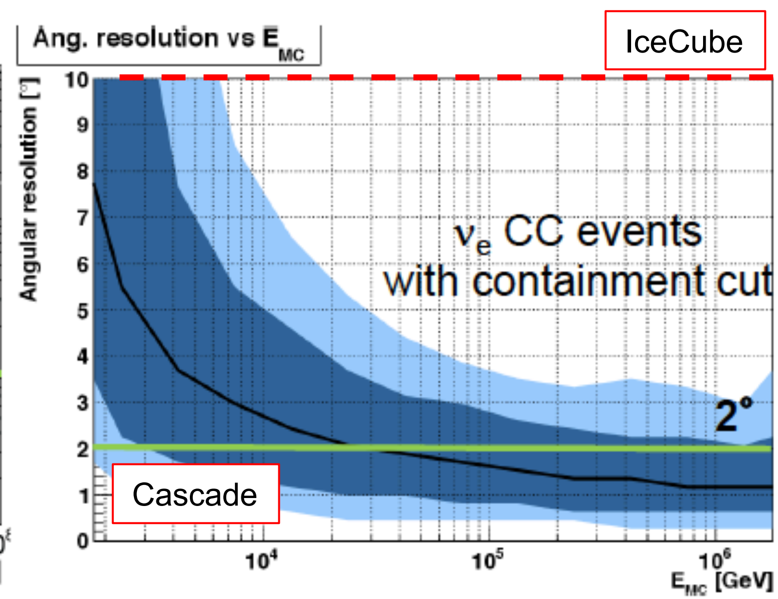
Angular resolution

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

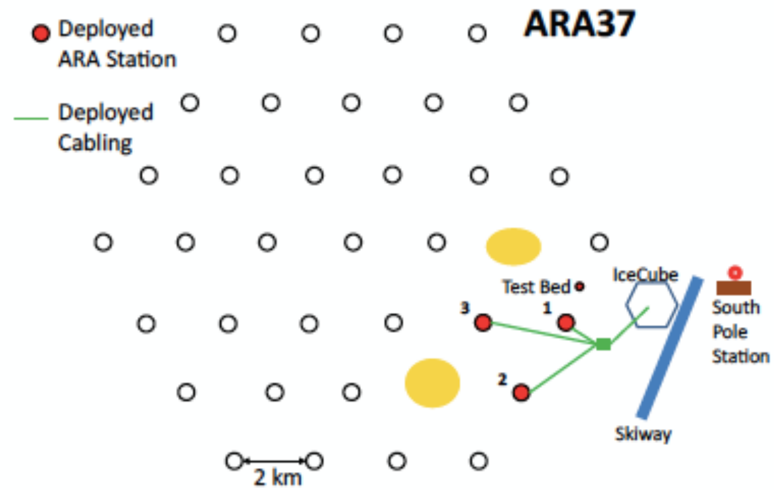
→ good to find point sources





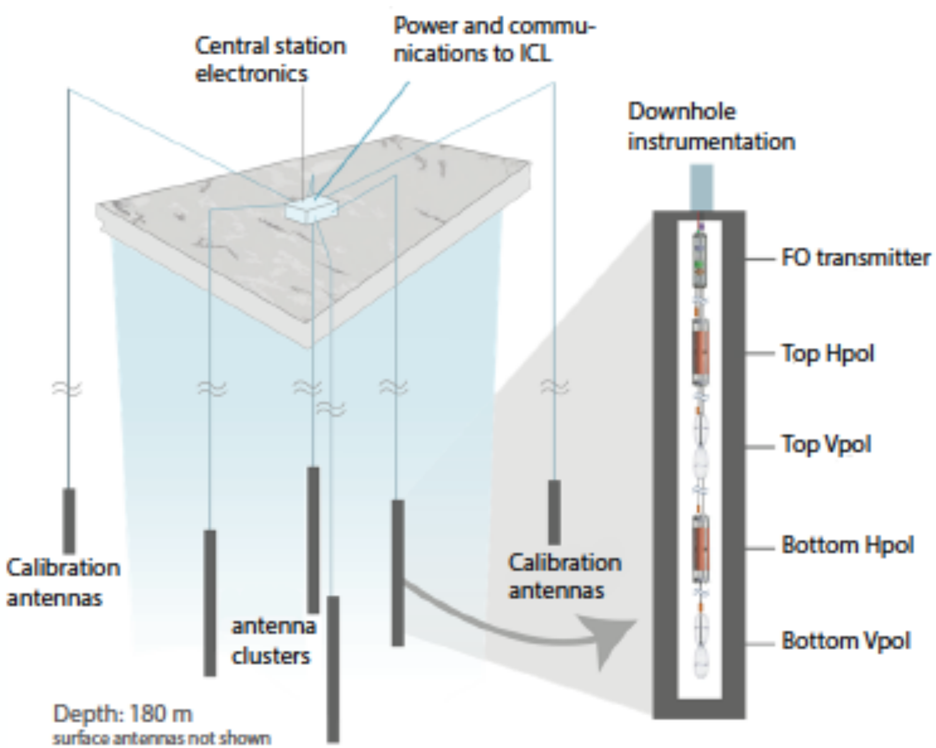
ARA,PRD93(2016)082003

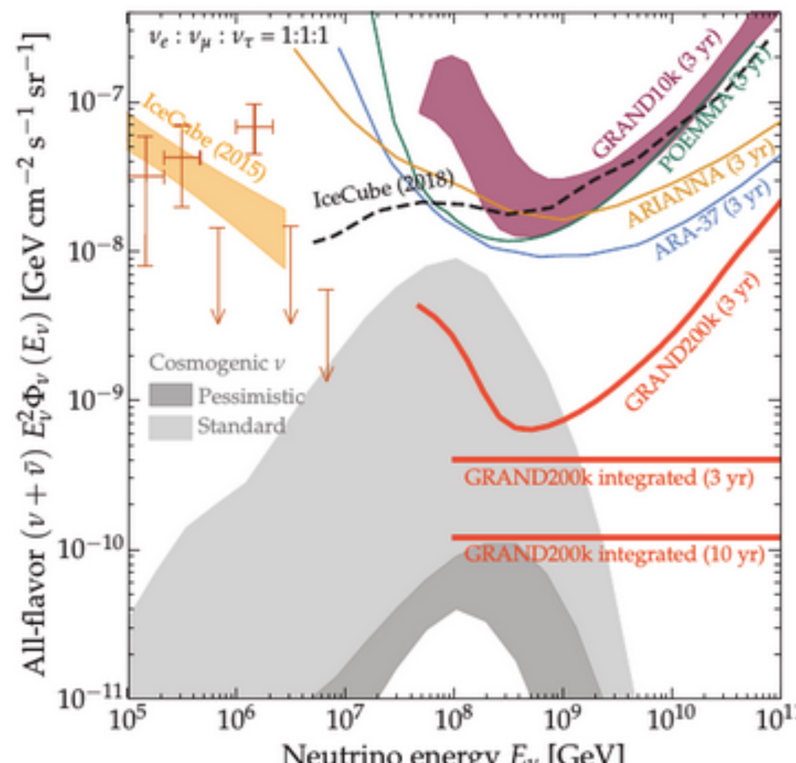
5.ARA



Askaryan radiation (~Cherenkov radiation)

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

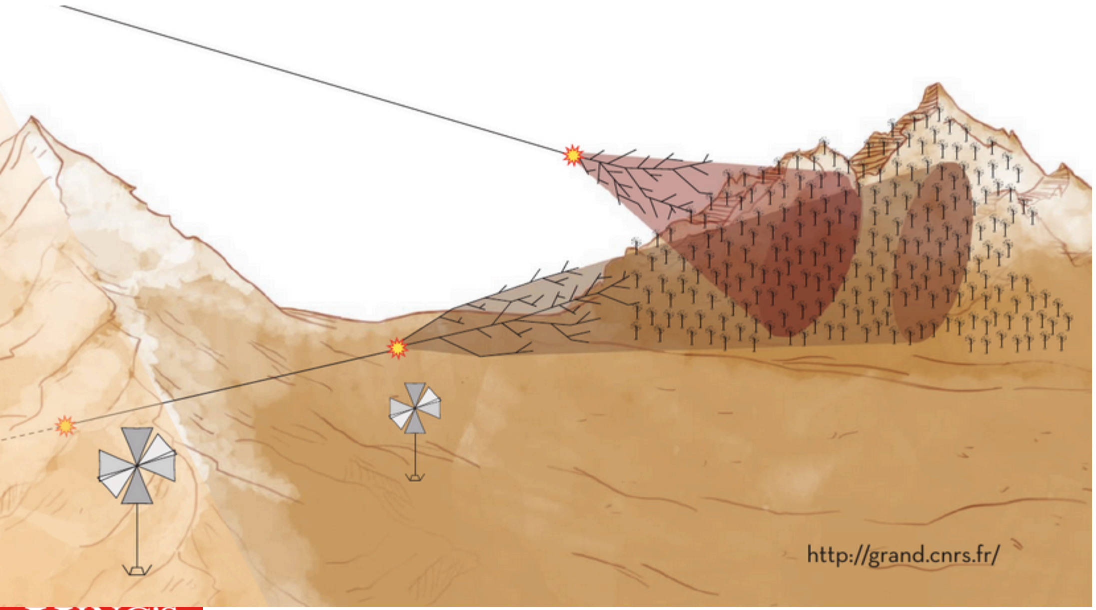


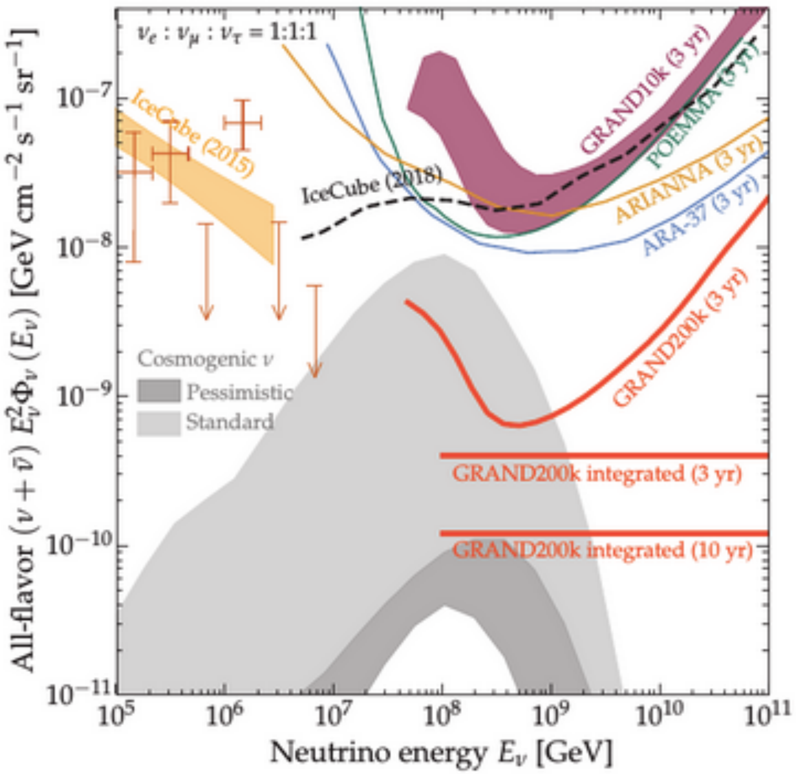


5. GRAND

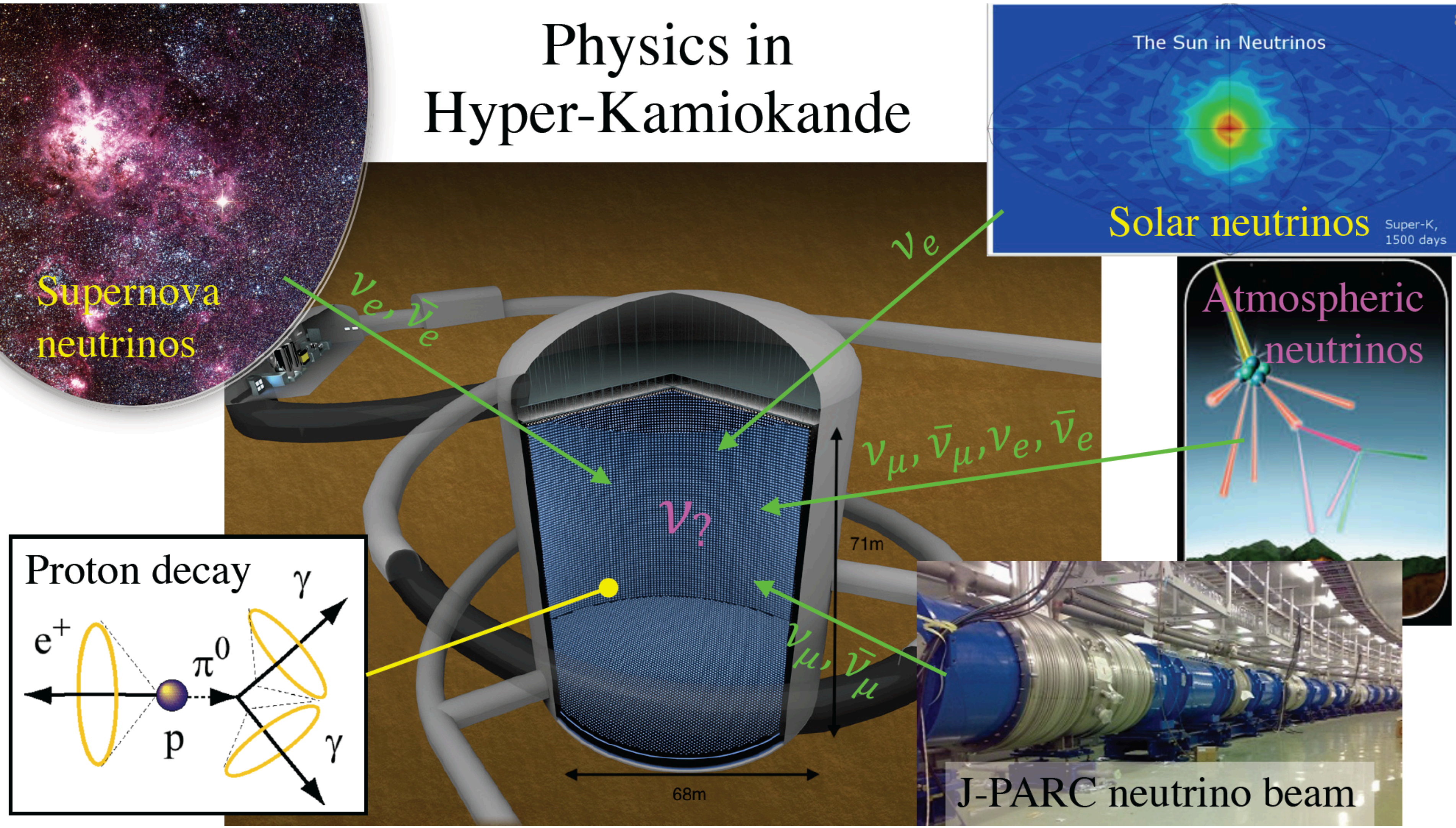
Candidate site: Qinghai Province (青海省)

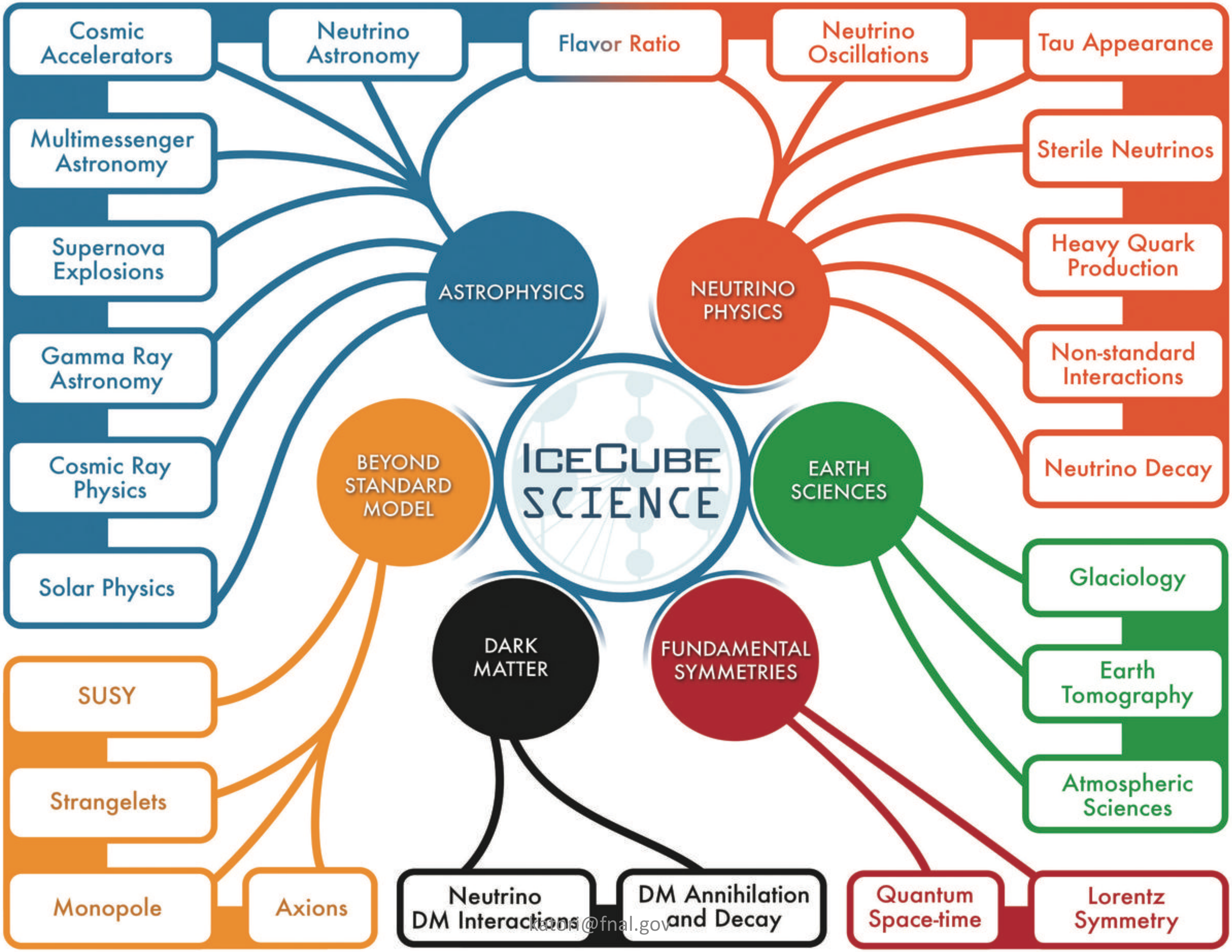
Giant Radio Array for Neutrino Detection
- Arrays of antennas to detect air shower radiation
- 200,000 antennas over 200,000km^2
- promising to detect GZK neutrinos
- horizontal tau neutrinos ("skimming tau"), special target



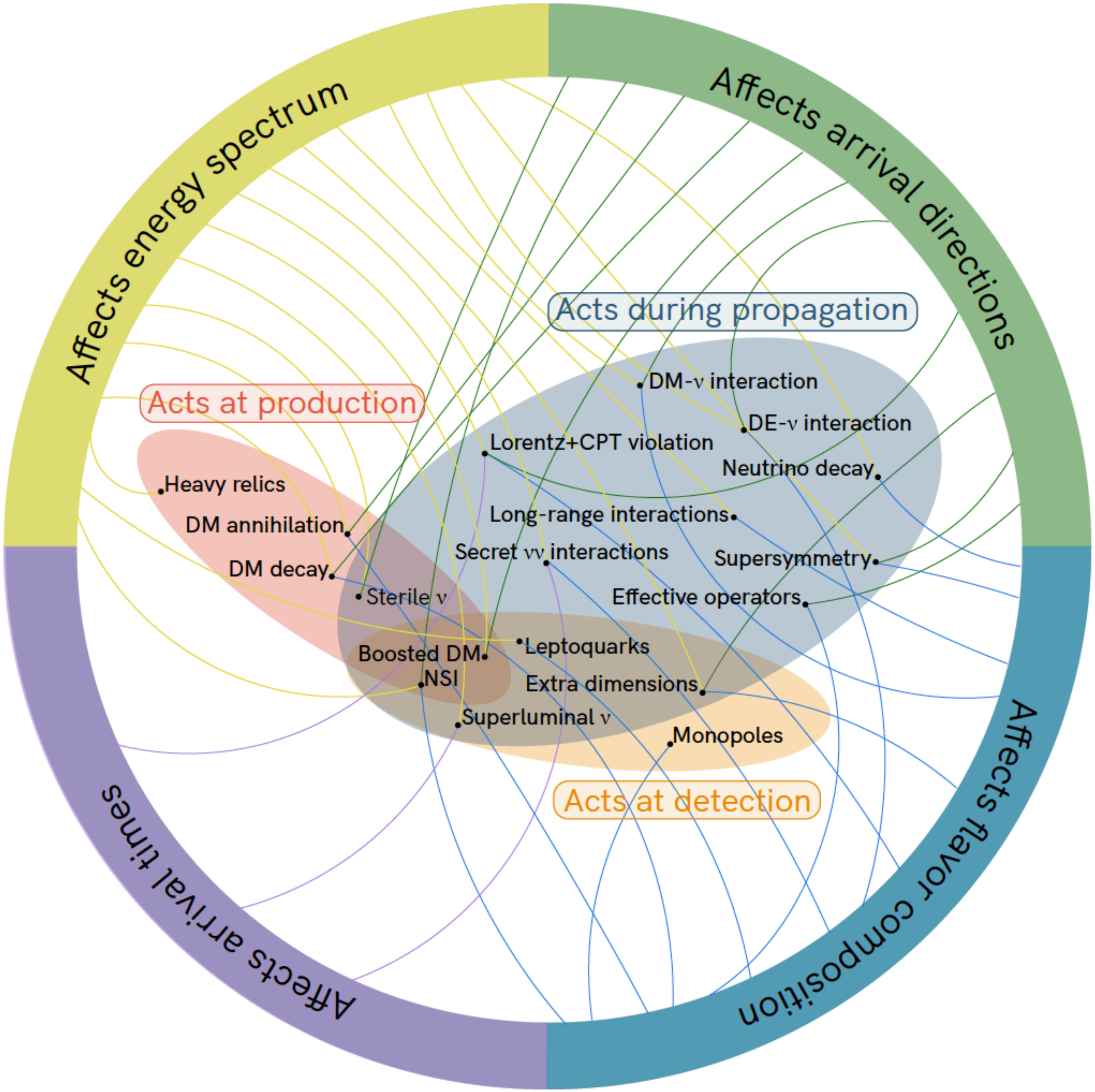


Physics in Hyper-Kamiokande




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

Argüelles et al, arXiv:1907.08690



Conclusion

Unknown parameters of νSM
- δ_{CP}
- θ_{23}
- mass ordering
- Majorana phase
- Dirac or Majorana
- Absolute neutrino mass

Unsolved anomalies
- Solar-KamLAND tension
- LSND signal
- MiniBooNE signal
- Reactor anomaly
- Gallium anomaly

Unmeasured neutrinos
- CνB
- DSNB
- hep solar neutrinos
- Solar atmospheric neutrinos
- Prompt atmospheric neutrinos
- GZK neutrinos

Unmeasured effects
- Upturn of solar neutrino
- Day-night effect
- PMNS matrix unitarity test

Next generation oscillation experiments (~10yrs) can find δ_{CP}, θ_{23}, mass ordering and solve all anomalies, and perform high precision PMNS matrix unitarity test

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Next generation neutrino astronomy (~10yrs) can measure upturn and day-night effect, then discover DSNB and hep neutrino. They may discover all other neutrinos except CvB.

All these experiments have a chance to discover new physics!

Thank you for your attention!

Backup