Future Neutrino Experiments

Outline

1. Neutrino basics
2. Accelerator-based long-baseline neutrino experiments
3. Accelerator-based short-baseline neutrino experiments
4. Reactor-based neutrino experiments
5. Neutrino-less double beta decay experiments
6. Astrophysical neutrino measurements
7. Conclusion

History of neutrino oscillation physics, see my YETI2014 talk.
https://conference.ippp.dur.ac.uk/event/346/sessions/385/#20140114
Please check Neutrino 2018 talks for more details of each project.
https://www.mpi-hd.mpg.de/nu2018/

Please like "NuSTEC-News"
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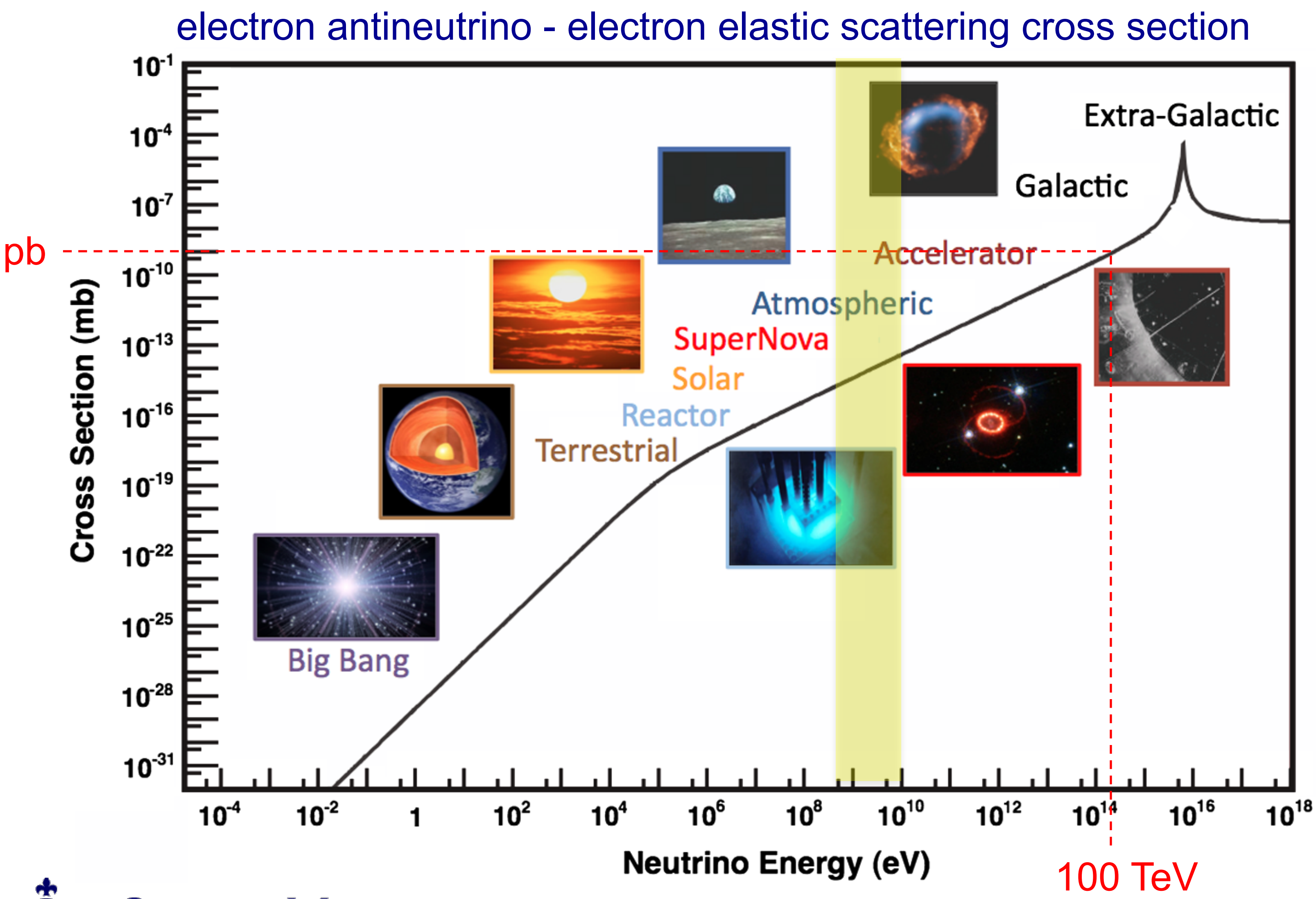
Teppei Katori
Queen Mary University of London
YETI2019, IPPP, Durham, UK, Jan. 7, 2018

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

1. Neutrinos – from eV to EeV

N=σxΦxT



1. Neutrinos – Limited sources

Type	Source	Production	Energy	Note
Cosmic neutrino background	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
Typical accelerator neutrinos	π,K-decay	$\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	~0.1 - 10 GeV	manmade
Typical atmospheric neutrinos	π,K-decay	$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$	~0.1 GeV - 10TeV	
Solar atmospheric neutrinos	π,K-decay	$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$	~0.1 - 10 TeV	not detected
High-energy astrophysical neutrinos	π-decay?	$\nu_e, \nu_\mu, \nu_\tau?, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}$	~50 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)

1. Future neutrino experiments

Not covered in my talk

Accelerator-based long-baseline experiments
- Hyper-Kamiokande, DUNE

T2K, NOvA, P2O, Pacific, CHIPS, IsoDAR, DAEdALUS, nuSTORM, EMuS, ESSnuSB, ENUBET, NuPRISM, etc

Accelerator-based short-baseline experiments
- MINERvA, MicroBooNE, SHiP
- COHERENT

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

Reactor neutrino experiments
- JUNO
- PROSPECT, SoLid, Watchman
- SOX

DayaBay, RENO, Double Chooz, STEREO, DANSS, NEOS, Neutrino-4, LENS, Chandler, CONNIE, MIVER, BASKET, RICOCHET, RED-100, νGen, CONUS, LENS-sterile, CeLAND, DB Source, LXe-Source, Baksan-source, 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
- PINGU, ORCA
- Hyper-Kamiokande, Jinping
- Super-Kamiokande-Gd
- IceCube-Gen2, KM3NeT, ARA
- PTOLEMY

BOREXINO, GVD, DUNE, THEIA, INO, GRAND, ANITA, ARIANNA, RADAR, KATRIN, Project 8 HOLMES, etc

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2. Next goal of neutrino physics

Establish Neutrino Standard Model (νSM)
- SM + 3 active massive neutrinos
- 9 new parameters

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

(4–6: not relevant to neutrino oscillation experiment(?))

We need higher precision experiments around 1-10 GeV.

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)

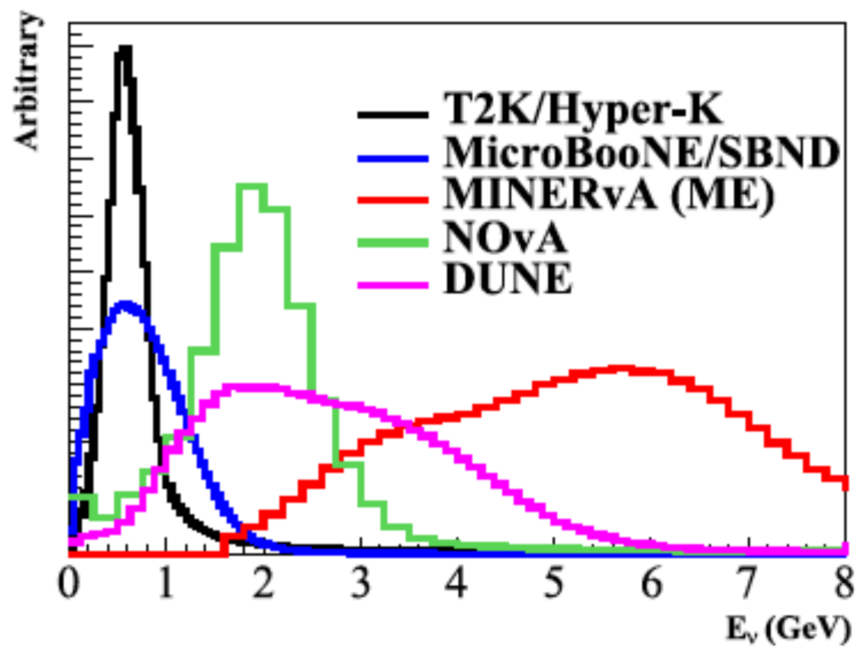
Accelerator-based neutrino oscillation experiments need to tune L/E

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



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

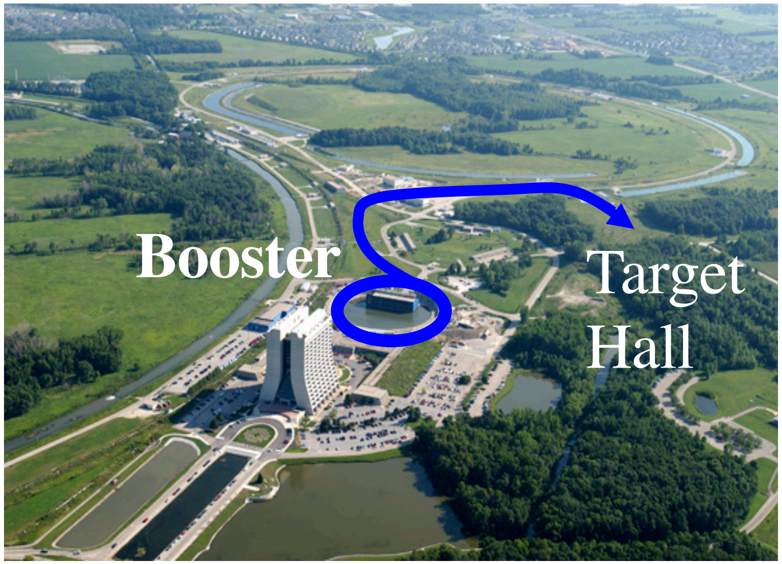
Isotope decay neutrinos "beta beam"
- Precisely known spectrum
- High-flux low energy beam (=short baseline)

IsoDAR

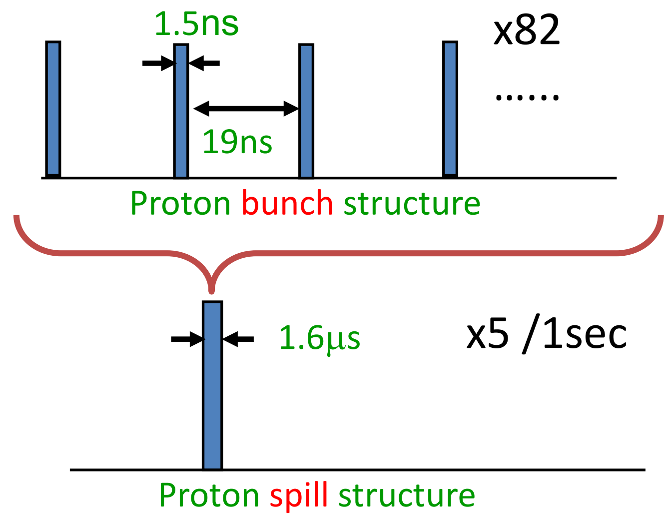
All beams have precise timing

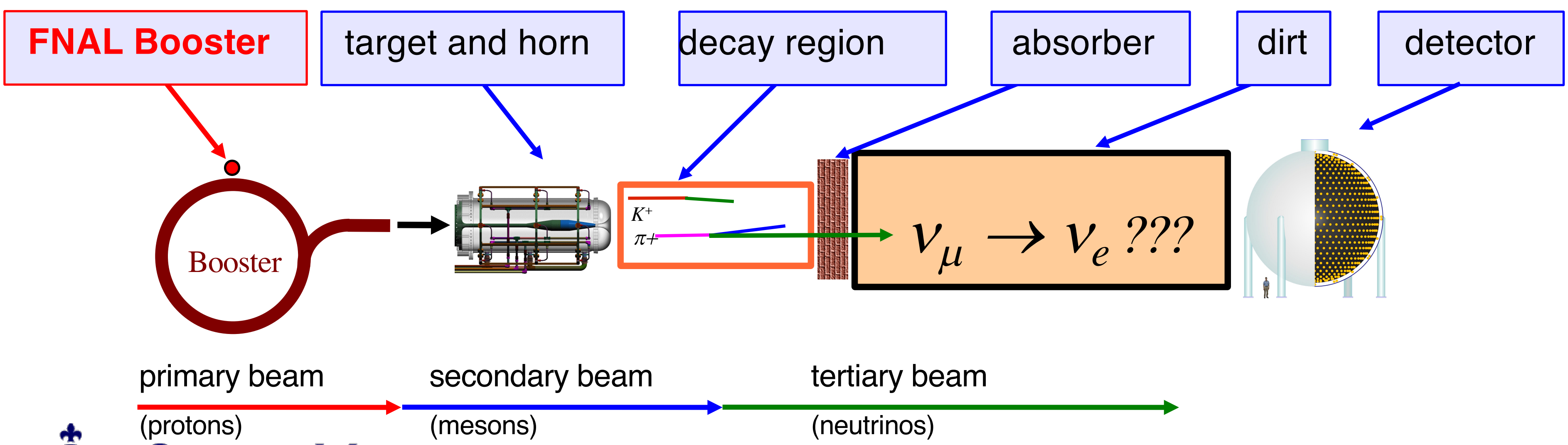
ENUBET: Precise monitoring type projects
NuPRISM: Movable neutrino near detector

2. Booster Neutrino Beamline (BNB)



MiniBooNE extracts beam from the 8 GeV Booster





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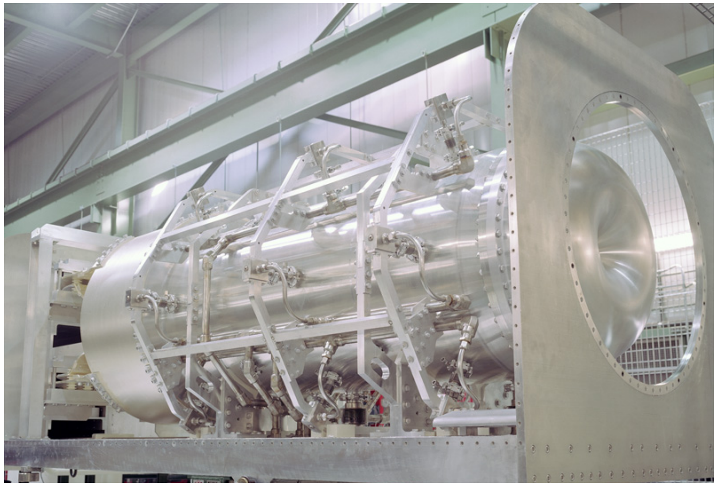
2. Booster Neutrino Beamline (BNB)

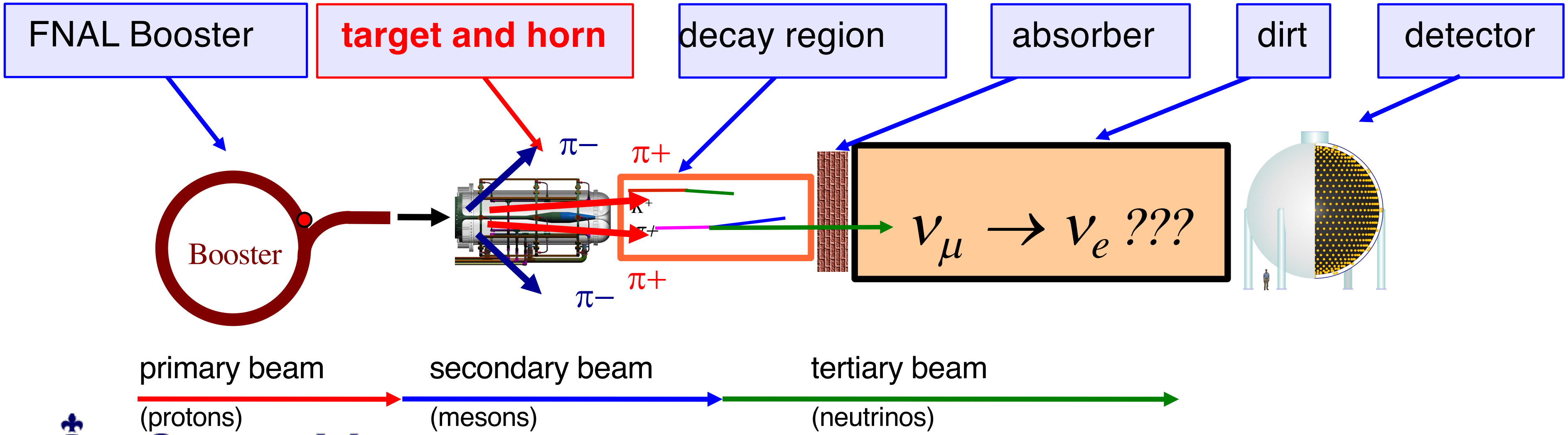
Magnetic focusing horn



8GeV protons are delivered to beryllium target

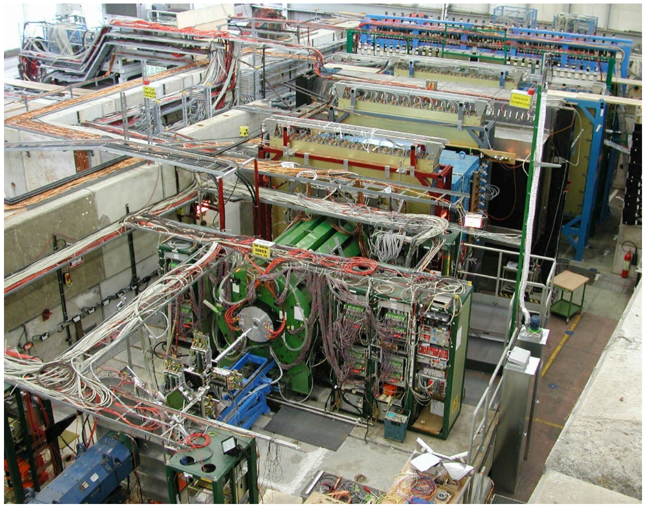
within a magnetic horn (2.5 kV, 174 kA) that increases the flux by × 6

By switching the current direction, the horn can focus either positive (neutrino mode) or negative (antineutrino mode) mesons.



2. Booster Neutrino Beamline (BNB)

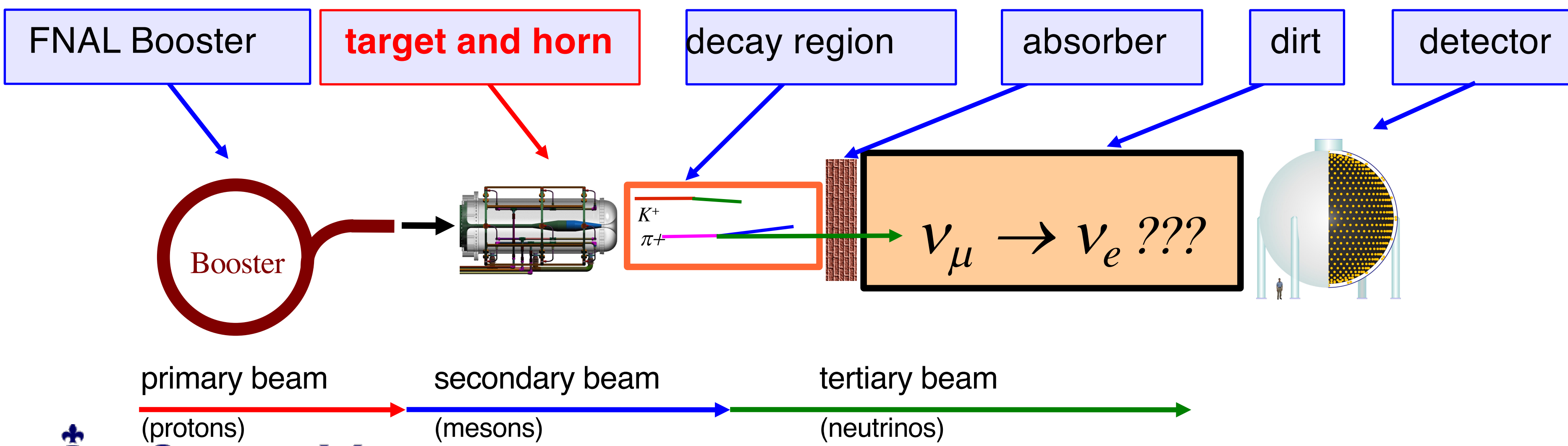
HARP experiment (CERN)



Modeling of meson production is based on the measurement done by HARP collaboration.

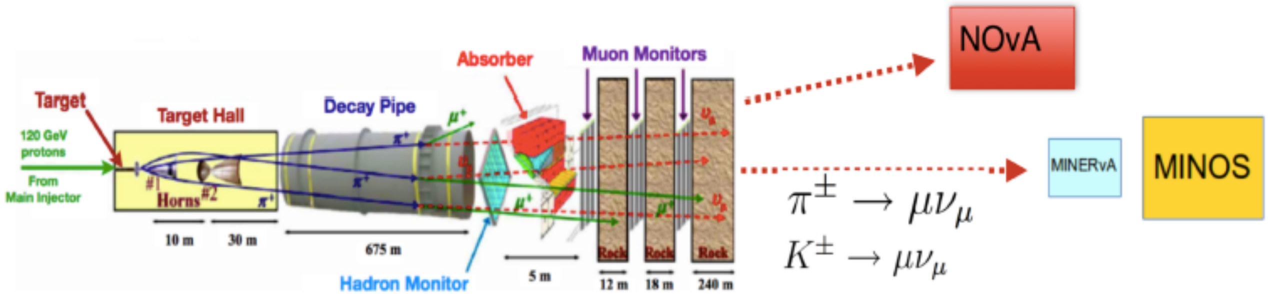
- Identical beryllium target
- 8.9 GeV/c proton beam momentum

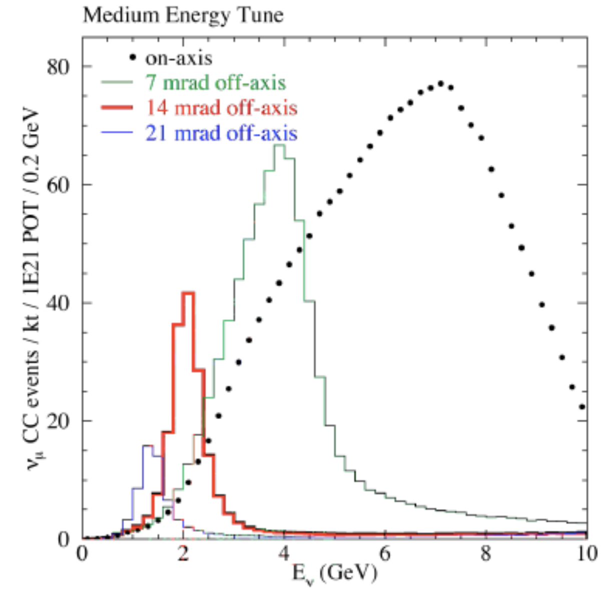
T2K use hadron data from NA61/SHINE (~4% error).



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





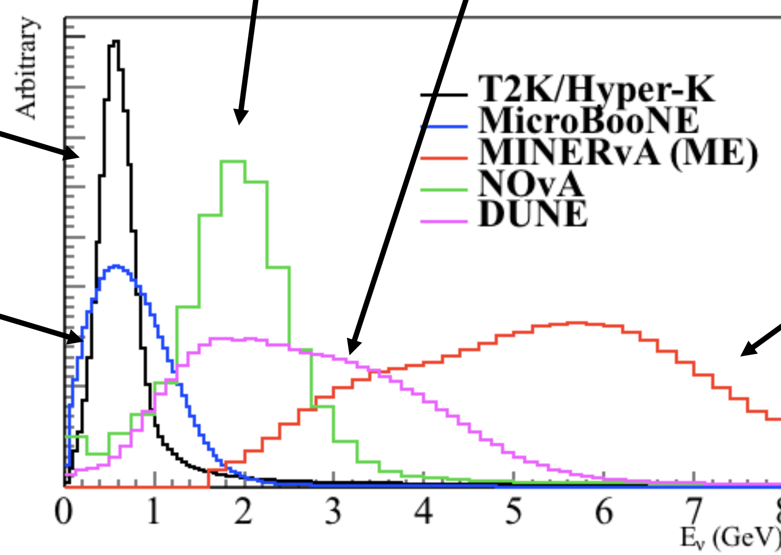
NOvA
NuMI off-axis beam

DUNE on-axis beam

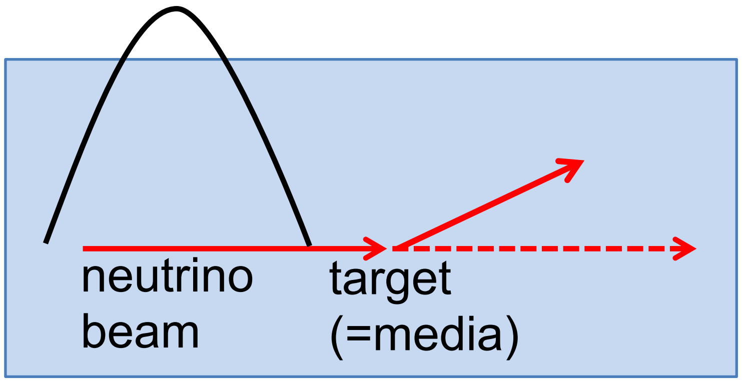
T2K, HyperK
J-PARC off-axis beam

MicroBooNE/SBND/ICARUS
BNB on-axis beam

MINERvA
NuMI on-axis beam



2. Typical neutrino detectors



Wide beam spectrum
- Incoming neutrino energy is not known

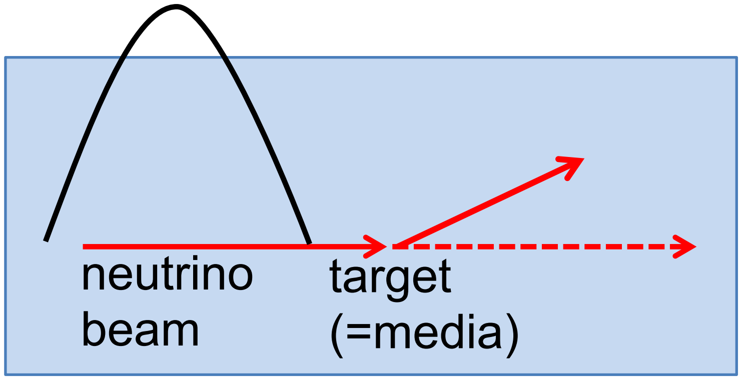
Coarse detectors
- Volume is maximized with poor instrumentation

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

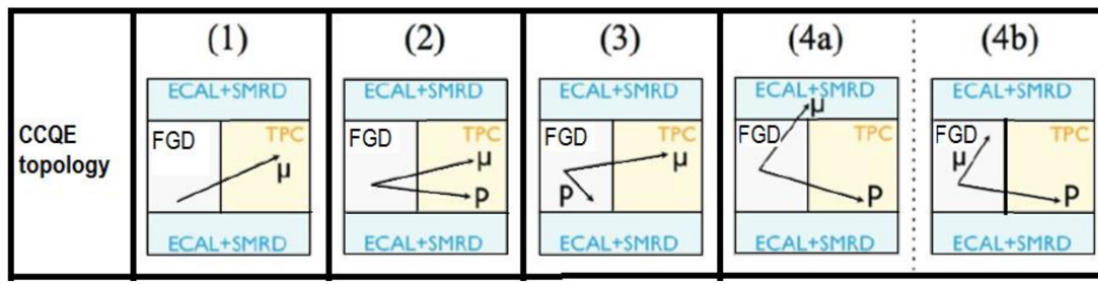
2. Typical neutrino detectors

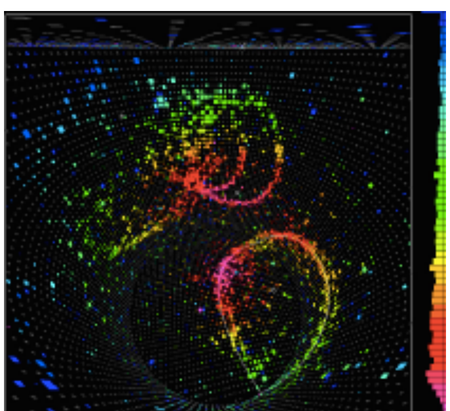


Liquid Scintillator
- JUNO, etc
- 4π coverage
- calorimetric
- low E threshold
- no direction information (in general)

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





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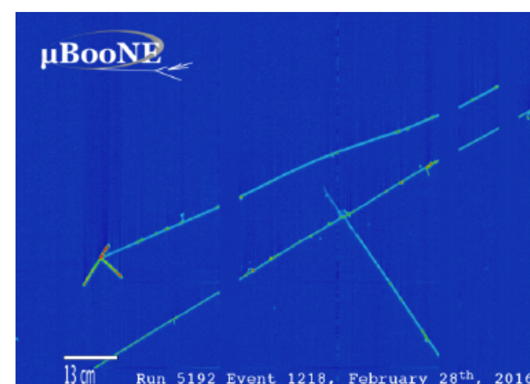
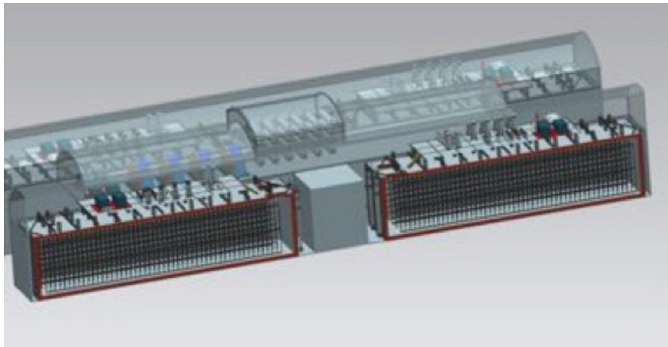
Liquid argon TPC (LArTPC)
- DUNE, etc
- 4π coverage
- multi-track, vertex activity
- calorimetric (scintillation)
- no timing info (~ms)

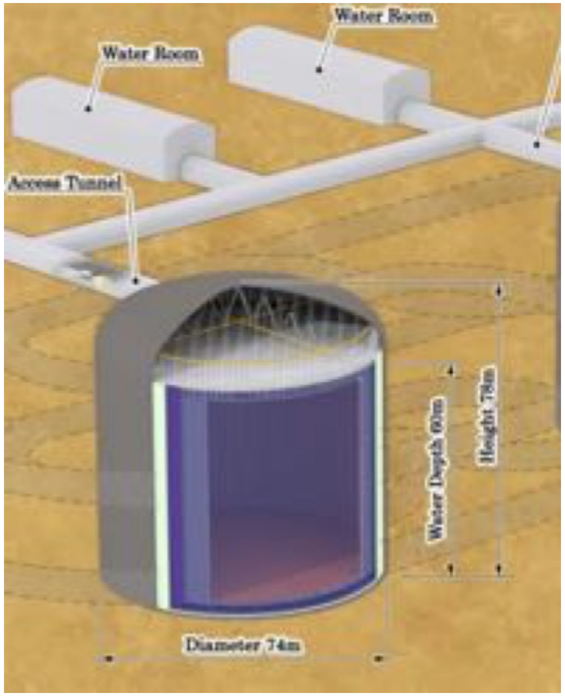


2. Hyper-Kamiokande and DUNE far detectors

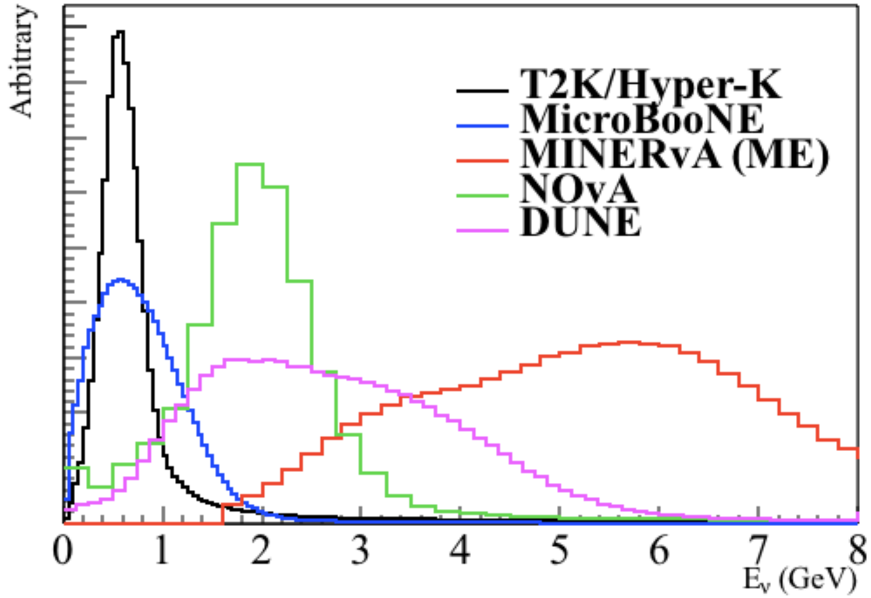
HyperK
- 200 kton Water Cherenkov
- Narrow band 0.6 GeV
- Low spatial resolution
- High timing resolution
- Kinetic E reconstruction

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



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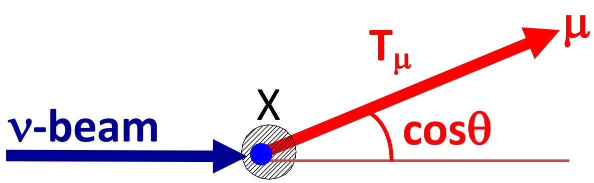
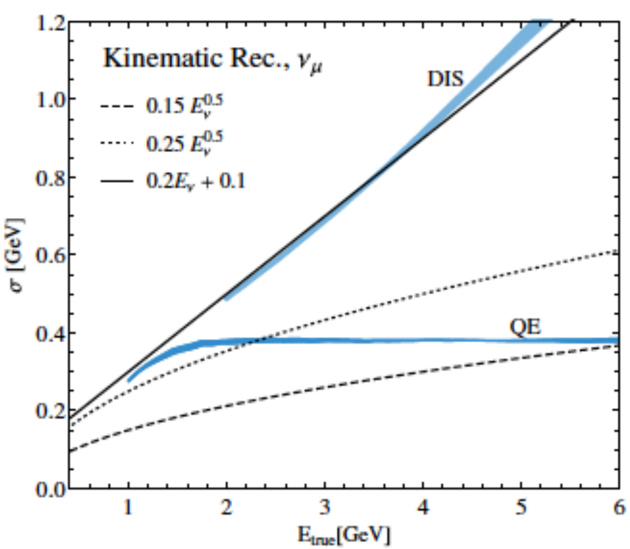
2. Kinematic E reconstruction vs calorimetric E reconstruction

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

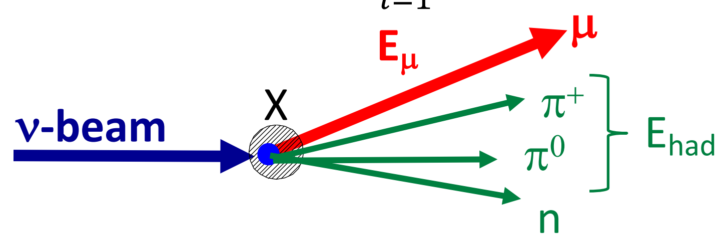
$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

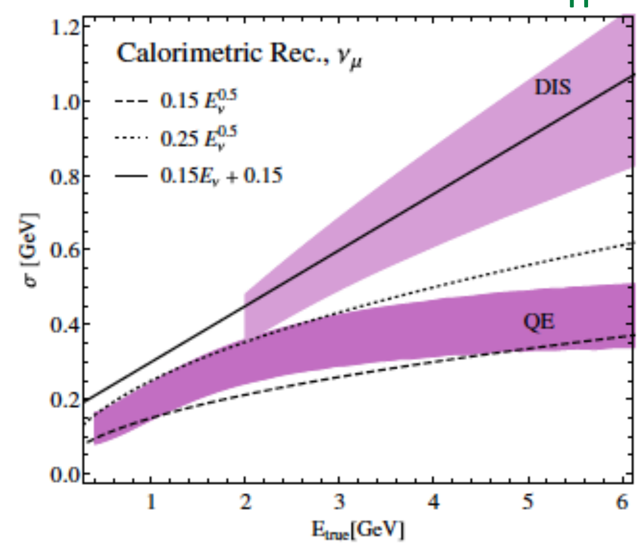




2. Calorimetric energy reconstruction
 - No assumption on interaction type, but you have to measure energy deposit from all outgoing particles (or correctly simulate them)

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





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Neutrino energy (and ν, Q², etc) reconstruction is interaction model-dependent process

T2K, PRD96(2017)092006
NuFit, arXiv:1811.05487

2. Oscillation parameter measurements, status and future

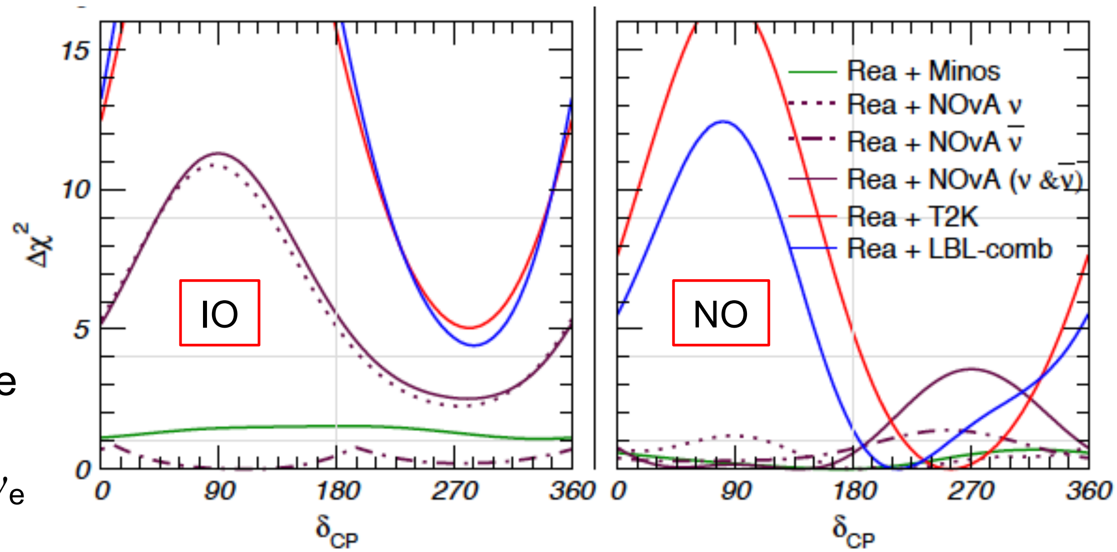
1. T2K and NOvA favor 2nd octant.

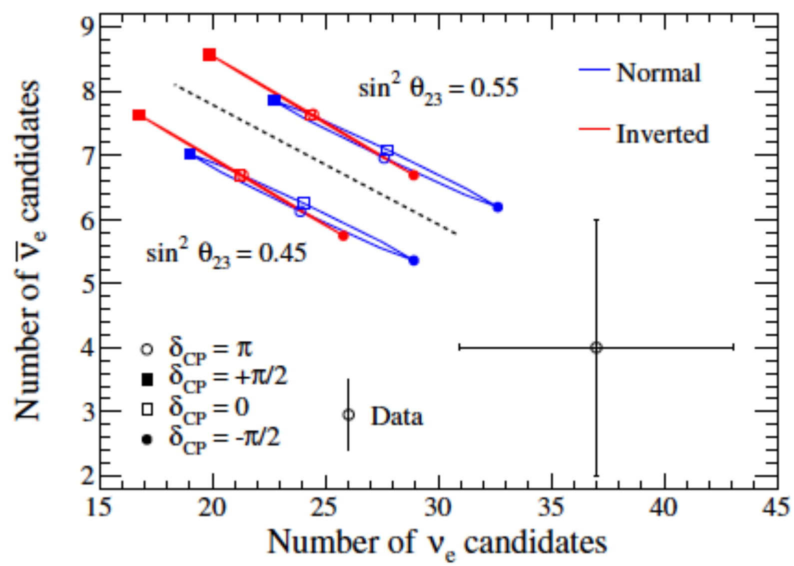
2. T2K, NOvA, and SuperK favor NO.

3. T2K prefers $-\pi/2$ (large ν_e app.), but NOvA prefers $\pi/2$ (large anti-ν_e app.), and combined result reduce significance

→ Oscillation parameters to maximize ν_e app. because T2K see large ν_e excess. Statistics? Systematics? New Physics?

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





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3. Accelerator-based short-baseline neutrino experiments

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5. Neutrino-less double beta decay

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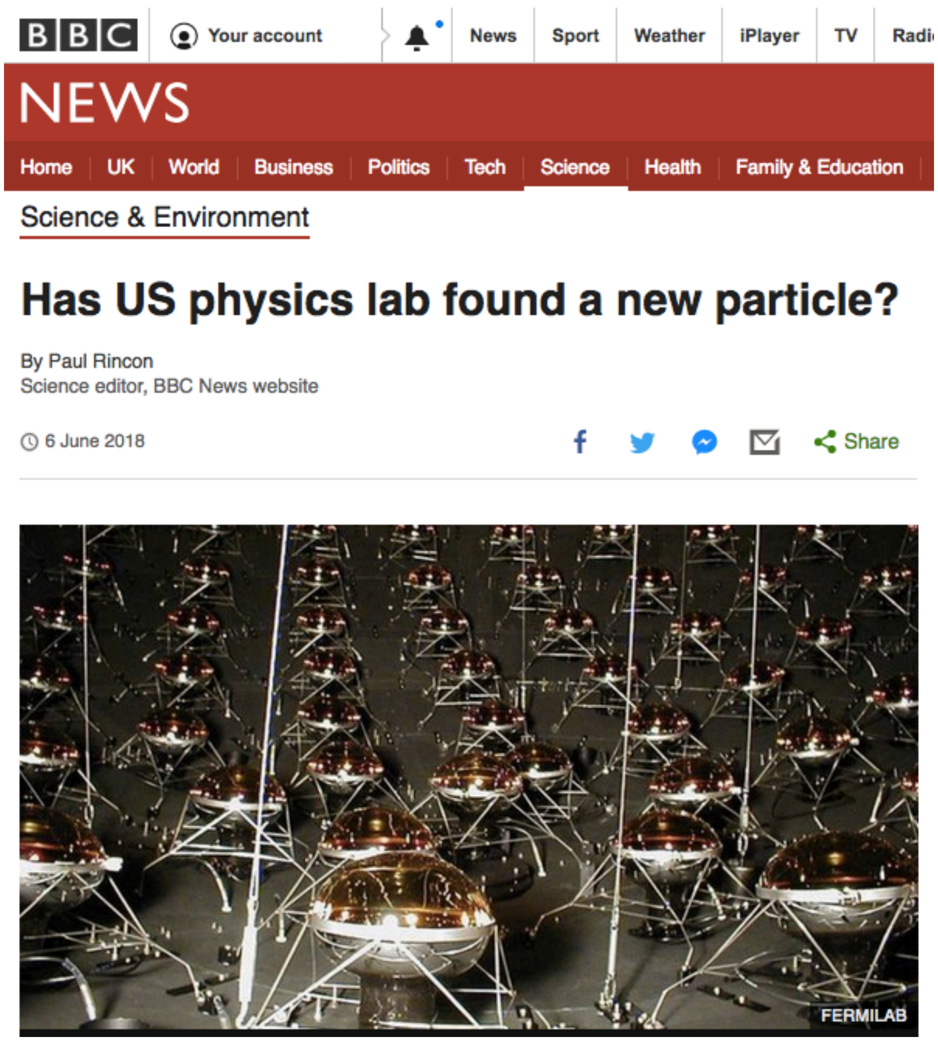
3. Accelerator-based short baseline neutrino experiments

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

3. 1eV sterile neutrino search

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

- MiniBooNE reaches 4.7σ excess
(Sterile-ν interpretation is rejected by disappearance data)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Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

6 June 2018

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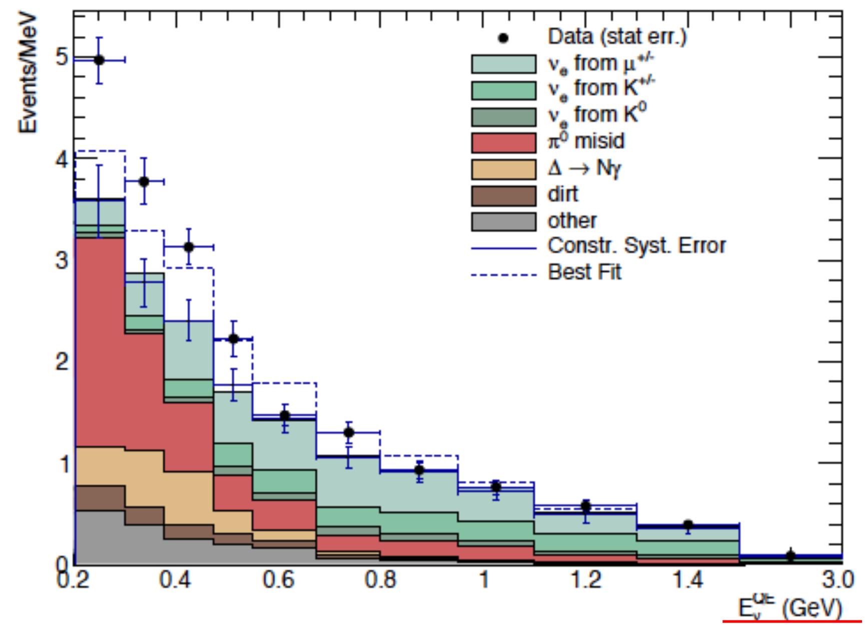
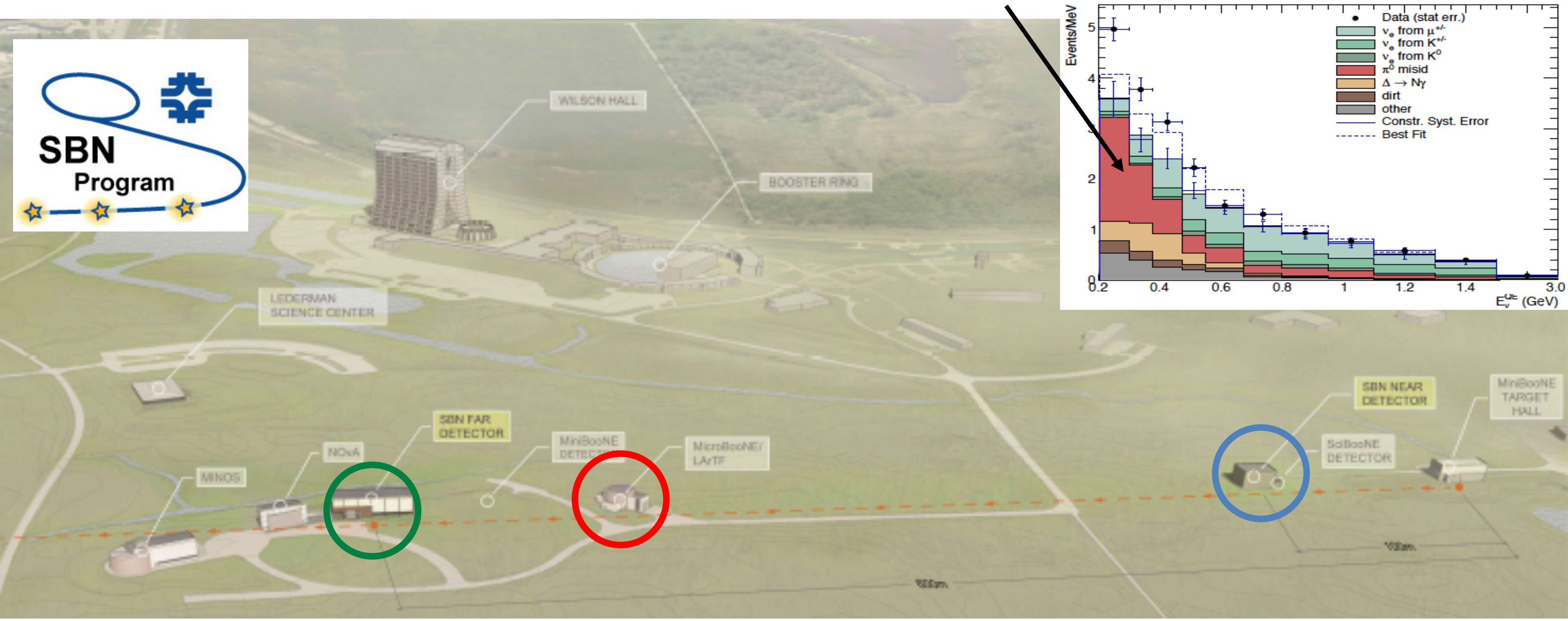


3. Fermilab short baseline neutrino (SBN) program

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

- MiniBooNE reaches 4.7σ 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

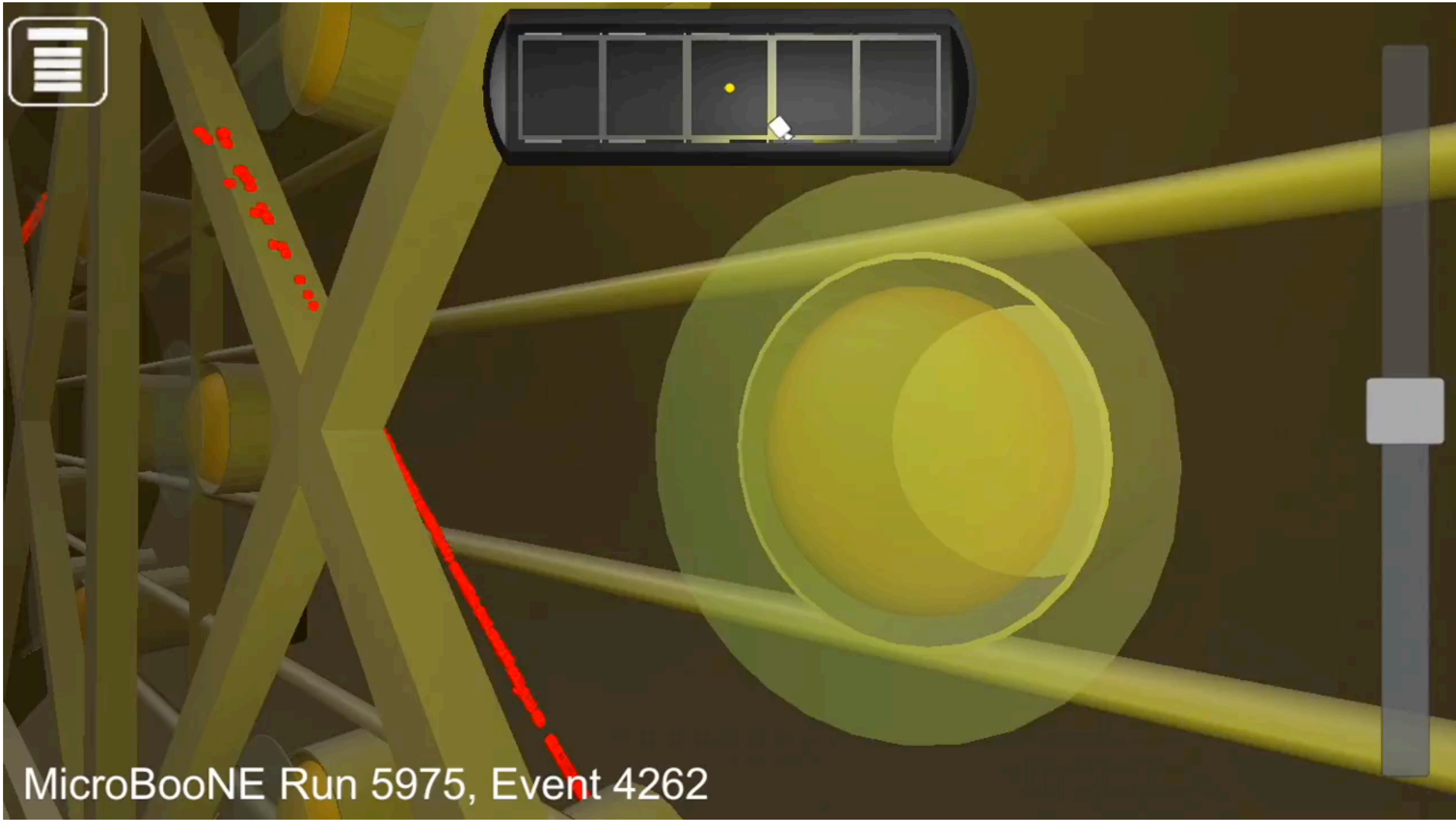
SBND
- 110 m
- 112 ton

← neutrino beam

VENu, Virtual Environment of Neutrinos (iOS/Android app)
http://venu.physics.ox.ac.uk/

3. LArTPC

- High spatial resolution (order few mm)
- Low timing resolution (no "sequence" of events)



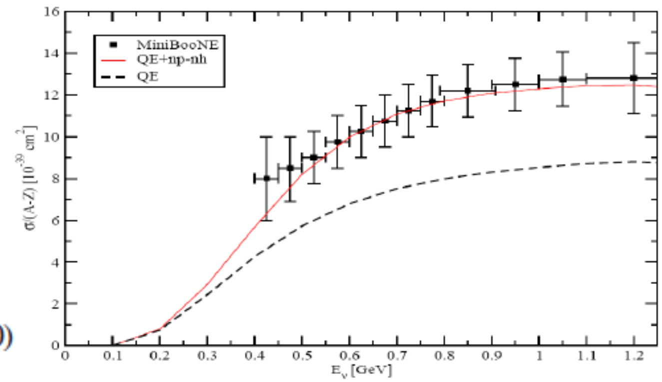
3. Neutrino cross section measurements around 1-10 GeV

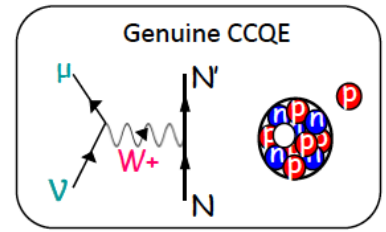
Slide from
Marco Martini

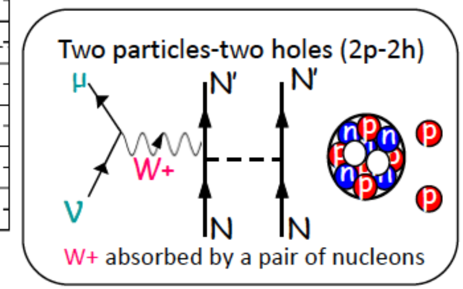
1. Sterile neutrino search
2. Neutrino cross-section measurement
3. New physics search

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)

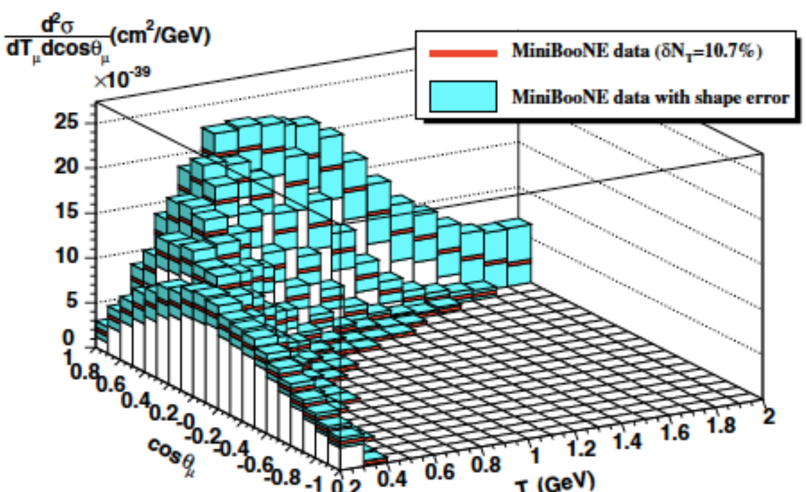






Flux-integrated differential cross section:
Neutrino cross section data is reported in terms of measured kinematics (muon energy, etc) not interaction kinematics (Eν, Q2, x, y, etc)

PHYSICAL REVIEW D 81, 092005 (2010)



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

Particle Data Group
- Section 42, “Monte Carlo Neutrino Generators” (Hugh Gallagher, Yoshinari Hayato)
- Section 50, “Neutrino Cross-Section Measurements” (Sam Zeller)

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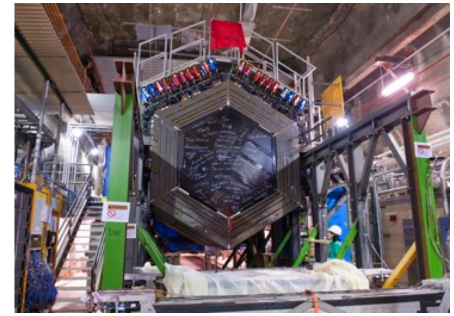
3. MINERvA and MicroBooNE



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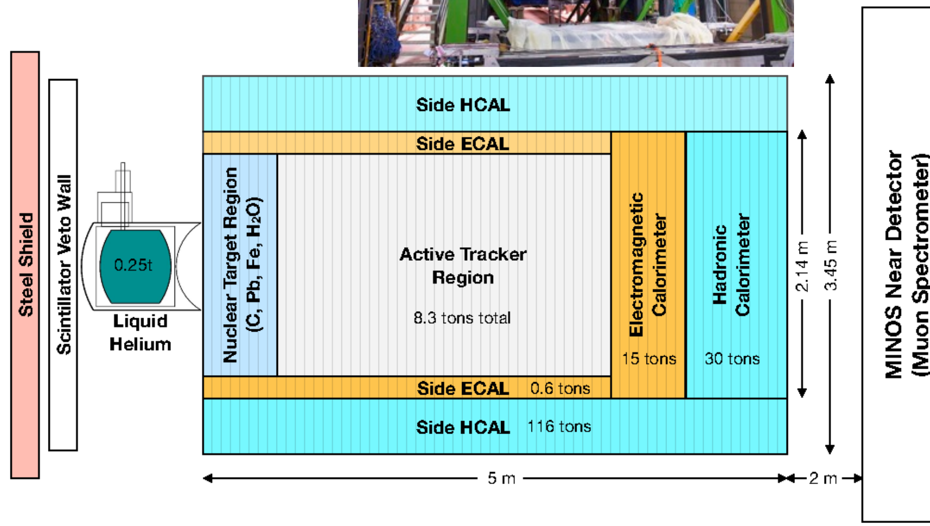
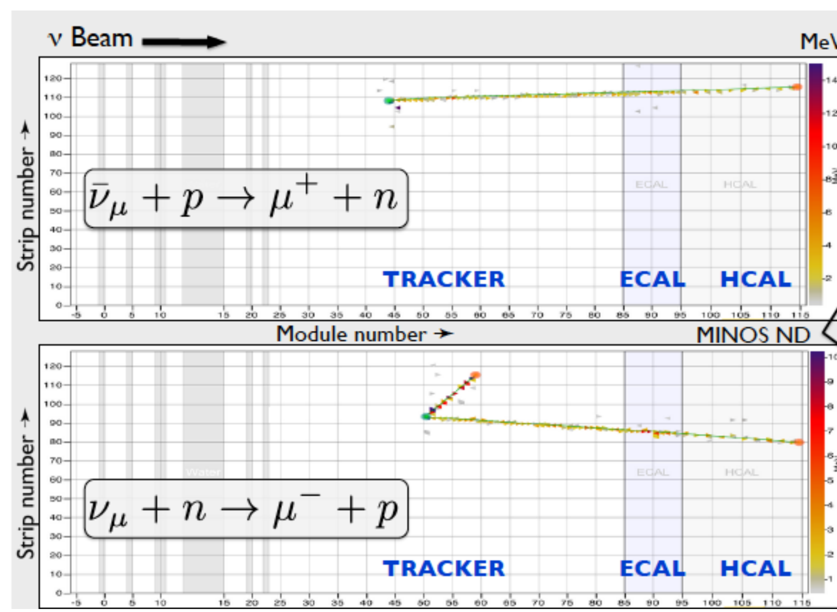


MINERvA Scintillation tracker

- <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, n-e)

MicroBooNE LArTPC

- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- Photon system for timing (scintillator)



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3. MINERvA and MicroBooNE

1. Sterile neutrino search
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3. New physics search

MINERvA Scintillation tracker

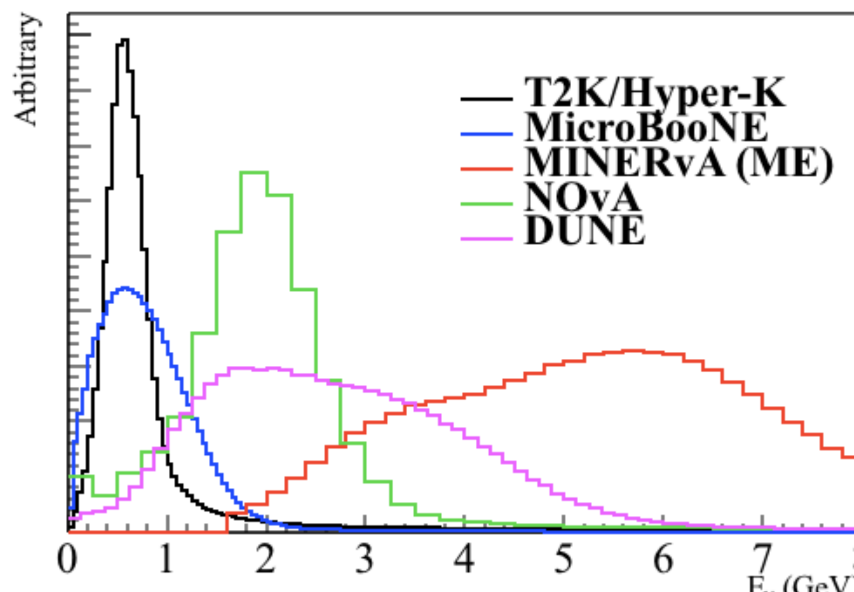
- <E>~3.5-7 GeV NuMI on-axis beam
- variety of targets (CH, Pb, Fe)
- Small acceptance due to MINOS ND
- charge separation by MINOS ND
- internal flux constraint (DIS, n-e)

MicroBooNE LArTPC

- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- Photon system for timing (scintillator)

Concerns

- Many cross section measurements are planned by MicroBooNE, SBND, ICARUS, however, BNB don't cover important energy region of DUNE.
- NOvA+MINERvA could cover DUNE energy region, however, they are not argon target experiments.
- No direct test of DUNE interaction physics before DUNE.
- Main DUNE events are "shallow-inelastic scattering", where higher resonances switch to DIS (quark-hadron duality) in a nuclear environment. Very poorly understood.



MINERvA, PRL111(2013)022501:022502

3. MINERvA and MicroBooNE

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

MINERvA Scintillation tracker

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- variety of targets (CH, Pb, Fe)
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- No direct test of DUNE interaction physics before DUNE.
- Main DUNE events are "shallow-inelastic scattering", where higher resonances switch to DIS (quark-hadron duality) in a nuclear environment. Very poorly understood.

We are very worried about this situation. DUNE requires significant improvements from theory and experiment communities about physics around few GeV, the shallow inelastic scattering.
http://nustec.fnal.gov/nuSDIS18/

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3. SHiP

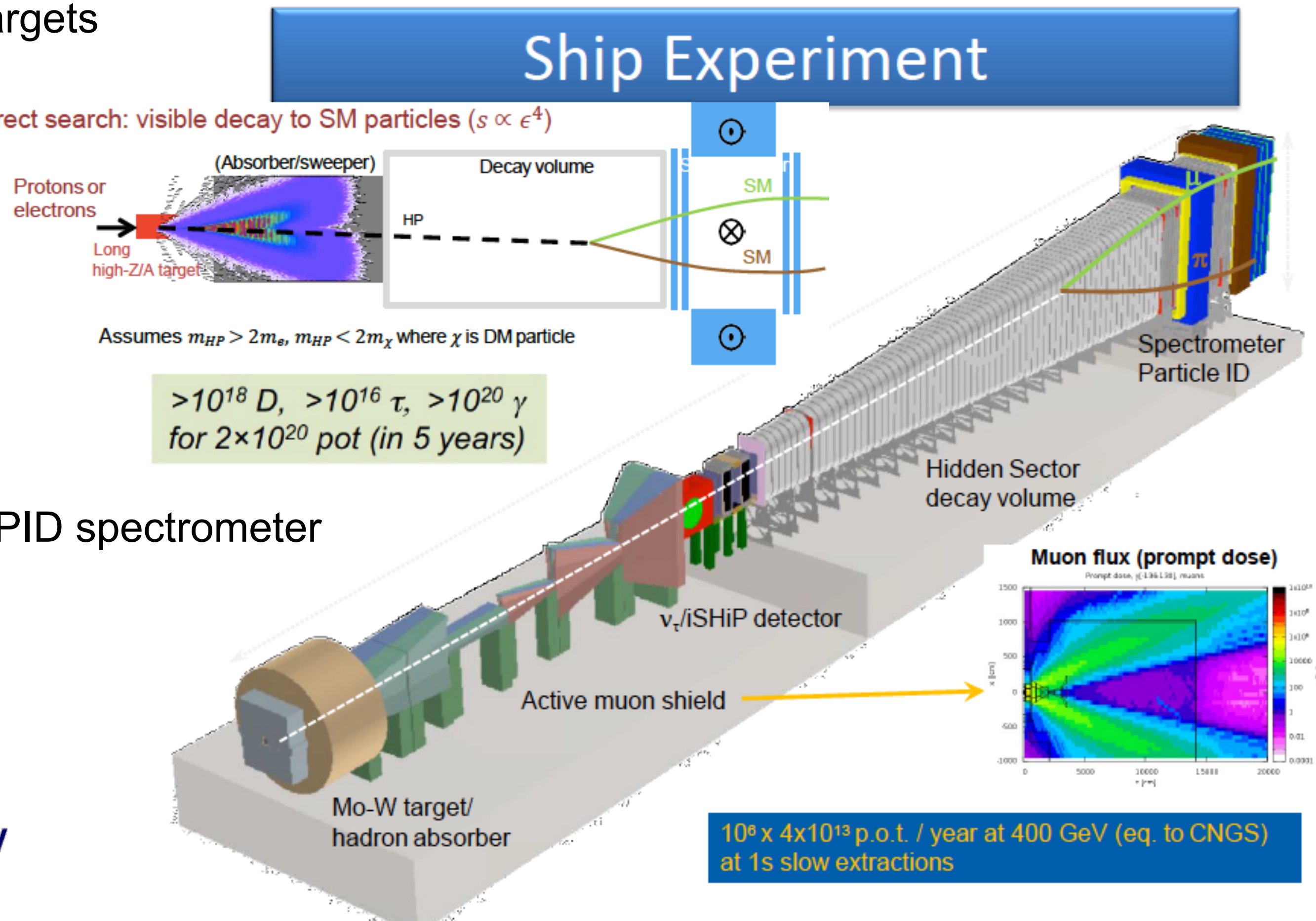
1. Sterile neutrino search
2. Neutrino cross-section measurement
3. New physics search

Neutrino experiment ~ beam dump

- High flux protons hit targets
- Rare particle search:
  - boosted DM
  - dark photon
  - heavy neutrinos
  - millicharged particle

SHiP at CERN

- <E>~400 GeV
- Decay volume with PID spectrometer
- ν_τ physics



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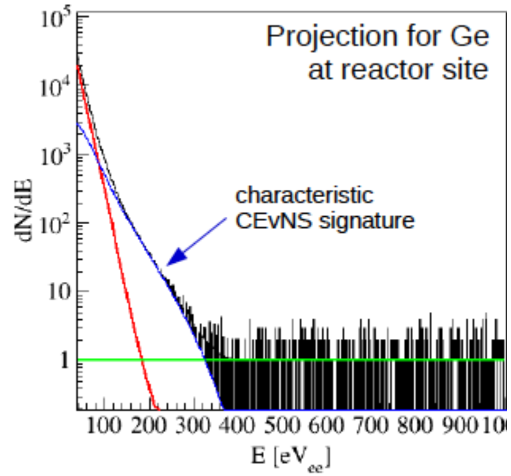
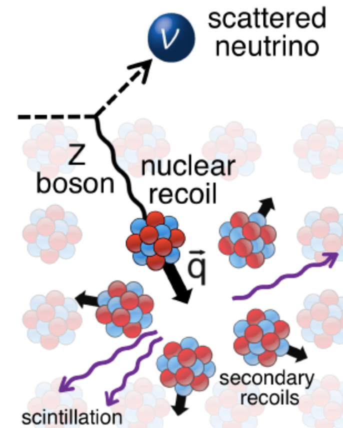
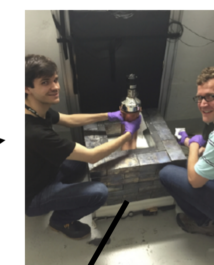
3. Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

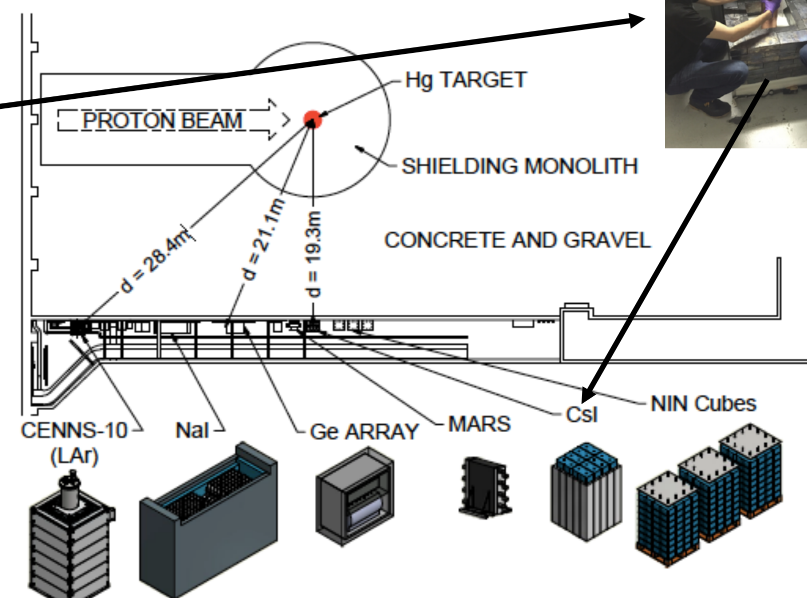
CEvNS
- A fundamental process for supernova physics
- Neutrino floor for WIMP search
- A channel to look for many new physics
(NC is the home of new physics)

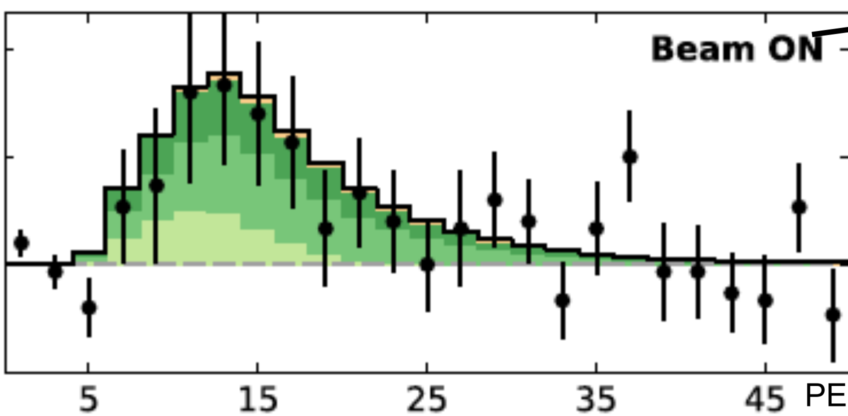
COHERENT
- Neutrinos from neutron spallation source
- Array of small detectors at "neutrino alley'
- First observation by CEvNS (2017)
- More data from other detectors











1. Neutrino basics

2. Accelerator-based long-baseline neutrino experiments

3. Accelerator-based short-baseline neutrino experiments

4. Reactor-based neutrino experiments

5. Neutrino-less double beta decay

6. Astrophysical neutrino measurements

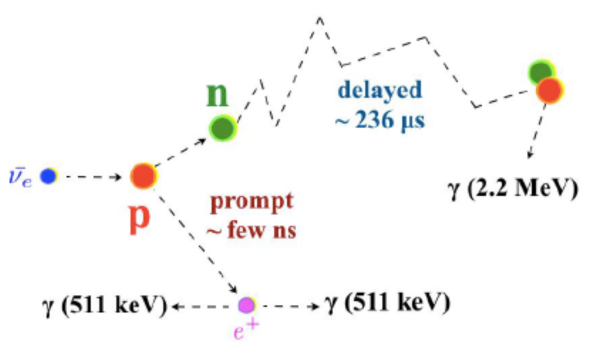
7. Conclusion

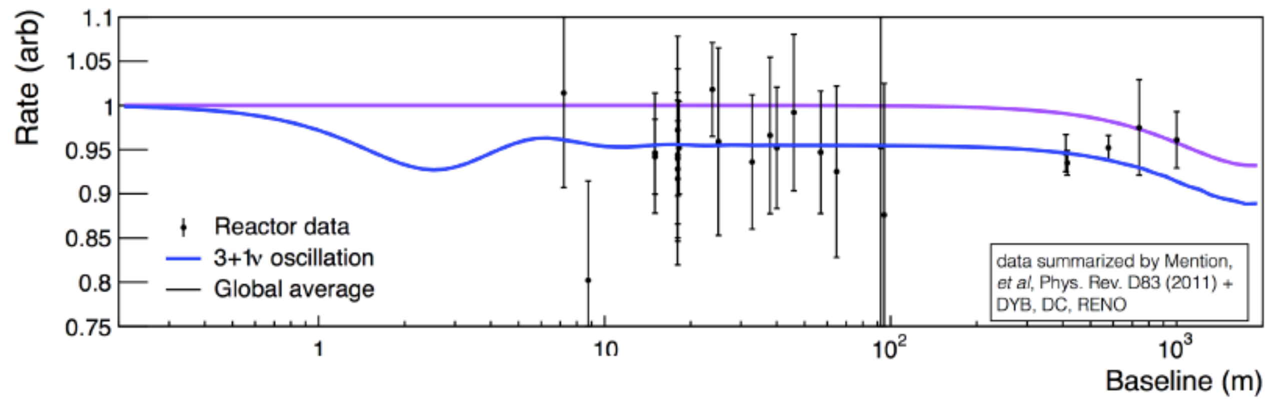
4. Reactor neutrinos - $\bar{\nu}_e$

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

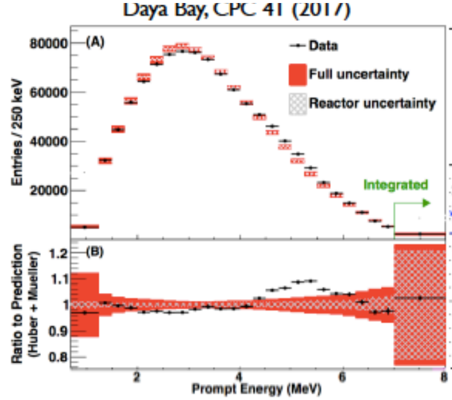
Detection, inverse beta decay (IBD)
- Liquid scintillator (prompt signal)+delayed neutron capture (delayed signal)

Inverse Beta Decay interaction (IBD)

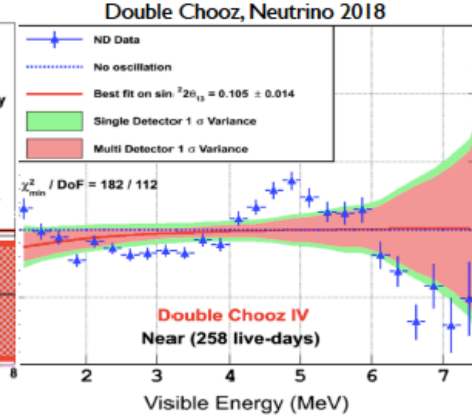




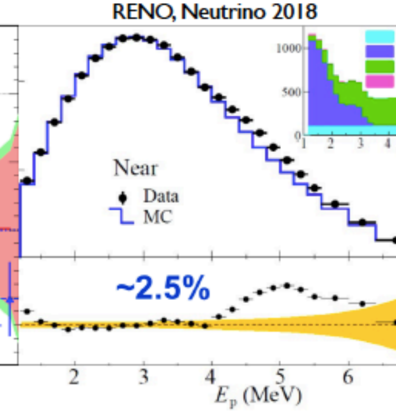
Daya Bay, CPC 41 (2017)



Double Chooz, Neutrino 2018



RENO, Neutrino 2018



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Littlejohn, Yaping, NuPhys 2018
Prospect:1808.00097,1812:10877

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

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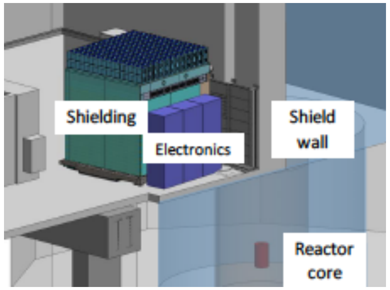
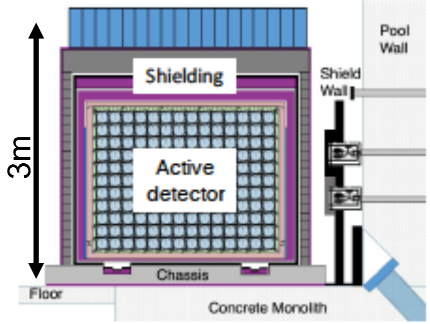
- shape mismatch around 5 MeV
- overall normalization is lower → motivate sterile neutrino oscillation

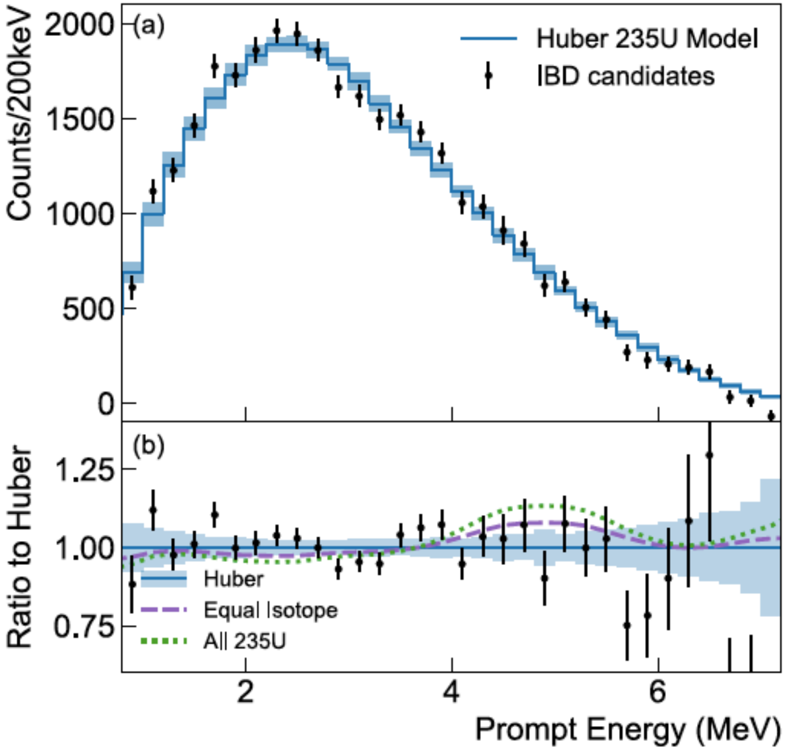
Detection, inverse beta decay (IBD)
- Liquid scintillator (prompt signal)+delayed neutron capture (delayed signal)

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)

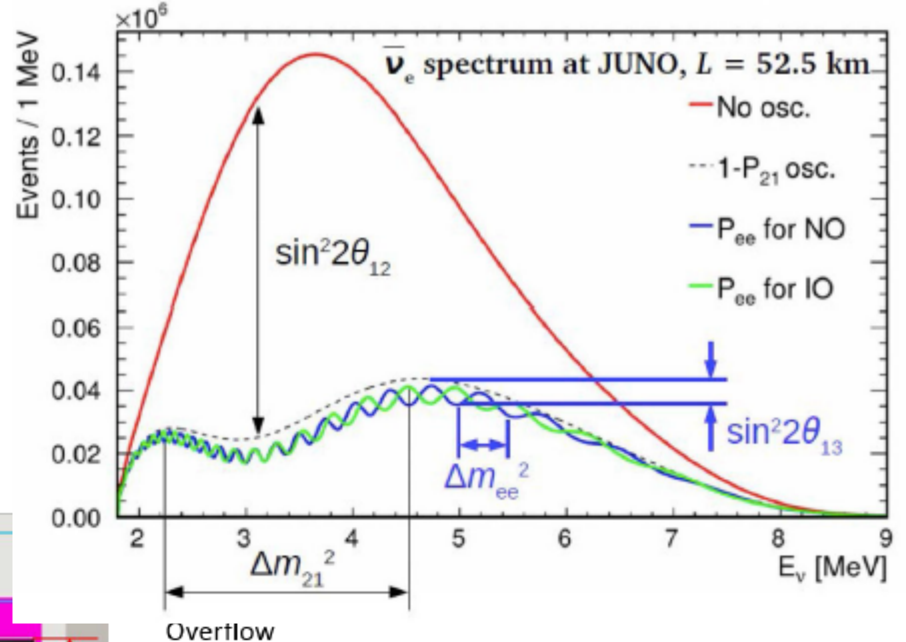






Littlejohn, Yaping, NuPhys 2018
JUNO, JPhysG43(2016)030401

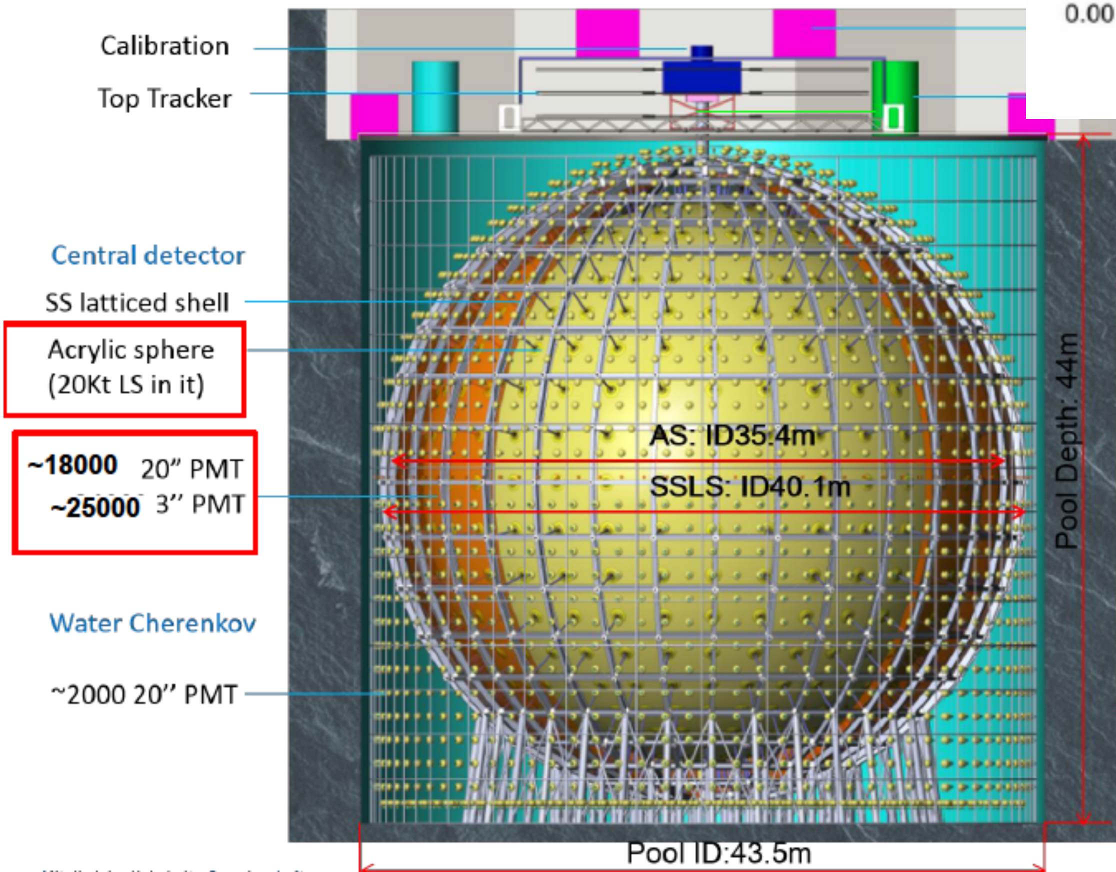
4. Neutrino Mass Ordering (NMO)



JUNO

- SuperK (~20 kton) + KamLAND (~3%ΔE)
- >3σ signal of NMO

JUNO detector

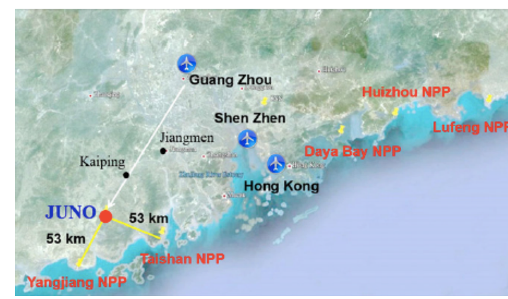


AS: Acrylic sphere; SSLS: stainless steel latticed shell

Acrylic Sphere:
ID: 35.4m
Thickness:120mm

SSLS:
ID: 40.1m
OD: 41.1m

Water pool
ID: 43.5m
Height: 44m
Water Depth: 43.5m



Solid, JINST12 (2017) P04024, Watchman, arXiv:1502.01132
Langenegger et al., Science.362 (2018) 649

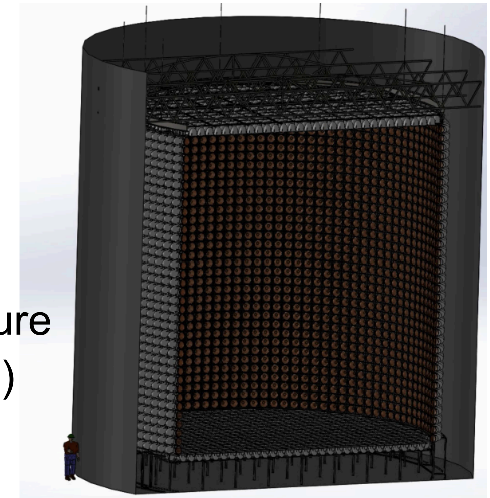
4. Neutrino reactor monitoring

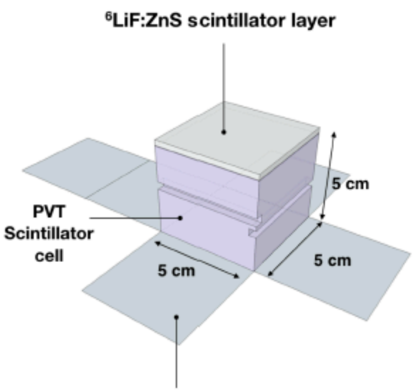
Solid

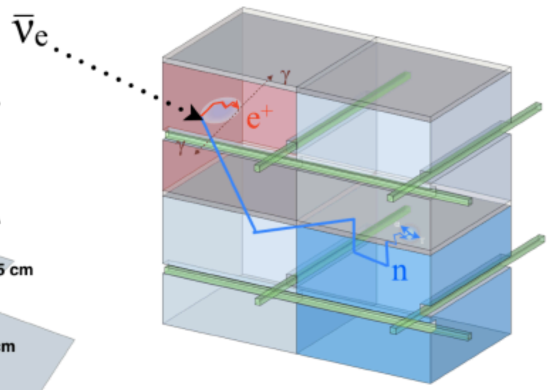
- Motivated by reactor flux anomaly
- Plastic scintillator array
- ^{6}Li doped layer for neutron capture
- WLS fiber + SiPM readout

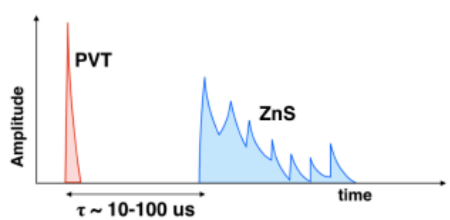
Watchman

- Water Cherenkov
- Gd-doped for neutron capture
- Hosted in UK (Boulby mine)









Edited by **Jennifer Sills**

Denuclearizing North Korea requires trust

In their Policy Forum "Denuclearizing North Korea: A verified, phased approach" (7 September, p. 981) A. Glaser and Z. Mian describe a pathway for verified denuclearization of North Korea. I agree that such an approach is necessary and, equally importantly, technically feasible. However, Glaser and Mian only highlight the disarmament side of the denuclearization agreement, without a plan to develop the mutual trust and the assurances on which such a deal depends. Incentivizing North Korea to reduce nuclear weapons and fissile materials will require confidence-building measures, ease of sanctions, and security guarantees. These elements are strongly related to the disarmament questions and must be regulated with similar precision.

Coordinating with the proposed phased approach, the involved parties could pair

Nations Security Council's sanctions. The structure of this contingency could be similar to the snapback mechanism in Article 37 of the Joint Comprehensive Plan of Action with Iran (*1*). Likewise, North Korea will insist on similar guarantees if it dismantles its nuclear weapons. It is always a challenge to create mechanisms that can credibly assure such guarantees for both parties, and this has become even more difficult after the U.S. withdrawal from the Iran nuclear agreement.

Tobias W. Langenegger
Chair of Negotiation and Conflict Management, ETH Zurich, 8092 Zurich, Switzerland.
Email: tlangenegger@ethz.ch

REFERENCE

1. United Nations Security Council Resolution 2231 (2015); https://undocs.org/S/RES/2231(2015).

10.1126/science.aav4636

Neutrino physics for Korean diplomacy

A freeze in military exercises could help to establish trust during nuclear negotiations with North Korea.

levels and fuel evolution in nuclear reactors, as experiments in South Korea, China, Russia, the United States, and Europe have demonstrated (*1–7*). At Yongbyon, neutrino detectors could be deployed to verify reactor shutdown or civilian operations without the need for operational records or access inside reactor buildings. Shutdown of North Korea's main plutonium production reactor could be verified with a detector in a standard freight container parked outside the reactor building.

Existing neutrino technology may be attractive to all parties in the ongoing talks. North Korea may value a tool for demonstrating treaty compliance while maintaining custody of the reactor buildings. Other parties may value the tamper resistance of the neutrino signal and resilience of neutrino detectors, which require minimal on-site access and can reconstruct reactor operational history even after a data-taking pause. Neutrino projects are also

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SOX, JHEP08(2013)038
Link, Neutrino 2018

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

SOX

- Motivated by Ga-anomaly
- Borexino+144Ce($\bar{\nu}_e$) and 51Cr(ν_e) neutrino sources
- Suddenly terminated…

This moment, there is no active neutrino source experiments (but many ideas)

Proposed Source Experiments

Many source experiments have been proposed…

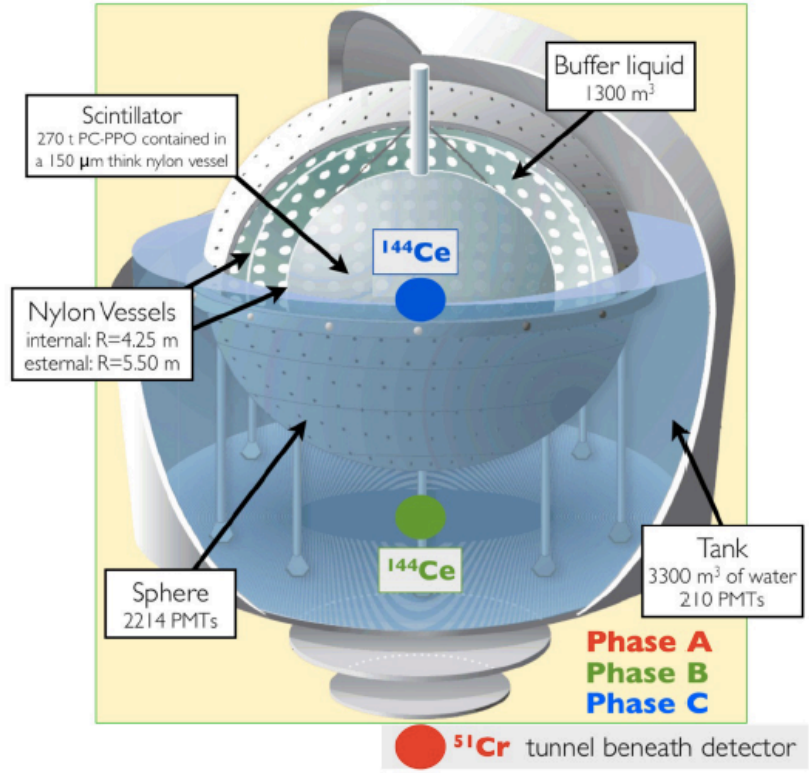
Experiment	Source	Detector	Channel	Citation
LENS-Sterile	^{51}Cr	LENS	ν ^{115}In CC	Phys. Rev. D75 (2007) 093006
Baksan	^{51}Cr	SAGE	ν ^{71}Ga CC	arXiv:1006.2103 [nucl-ex]
RICOCHET	^{37}Ar	Bolometers	CEvNS	Phys. Rev. D85 (2012) 013009
CeLAND	^{144}Ce	KamLAND	IBD	Phys. Rev. Lett. 107 (2011) 201801
DB 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



1. Neutrino basics

2. Accelerator-based long-baseline neutrino experiments

3. Accelerator-based short-baseline neutrino experiments

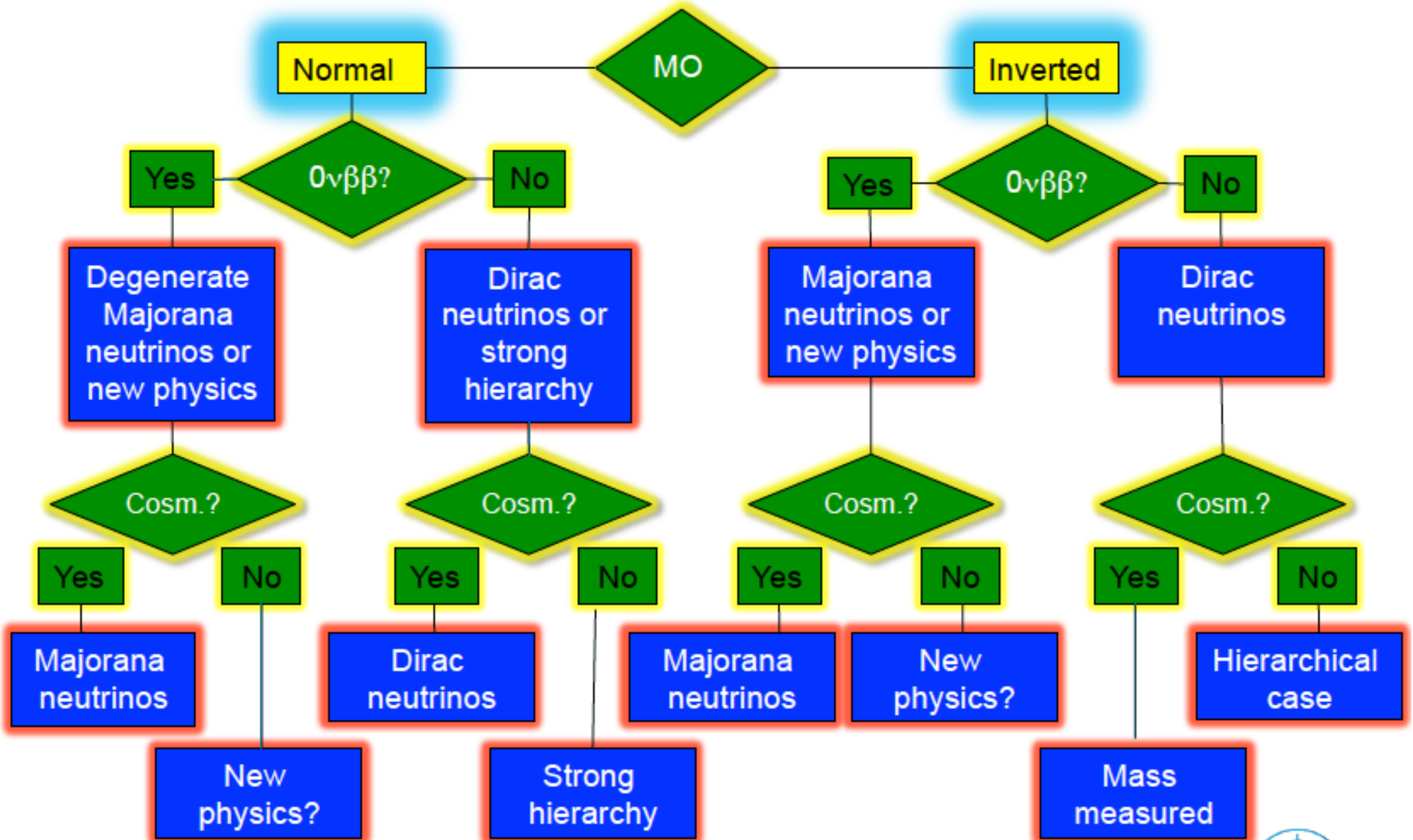
4. Reactor-based neutrino experiments

5. Neutrino-less double beta decay

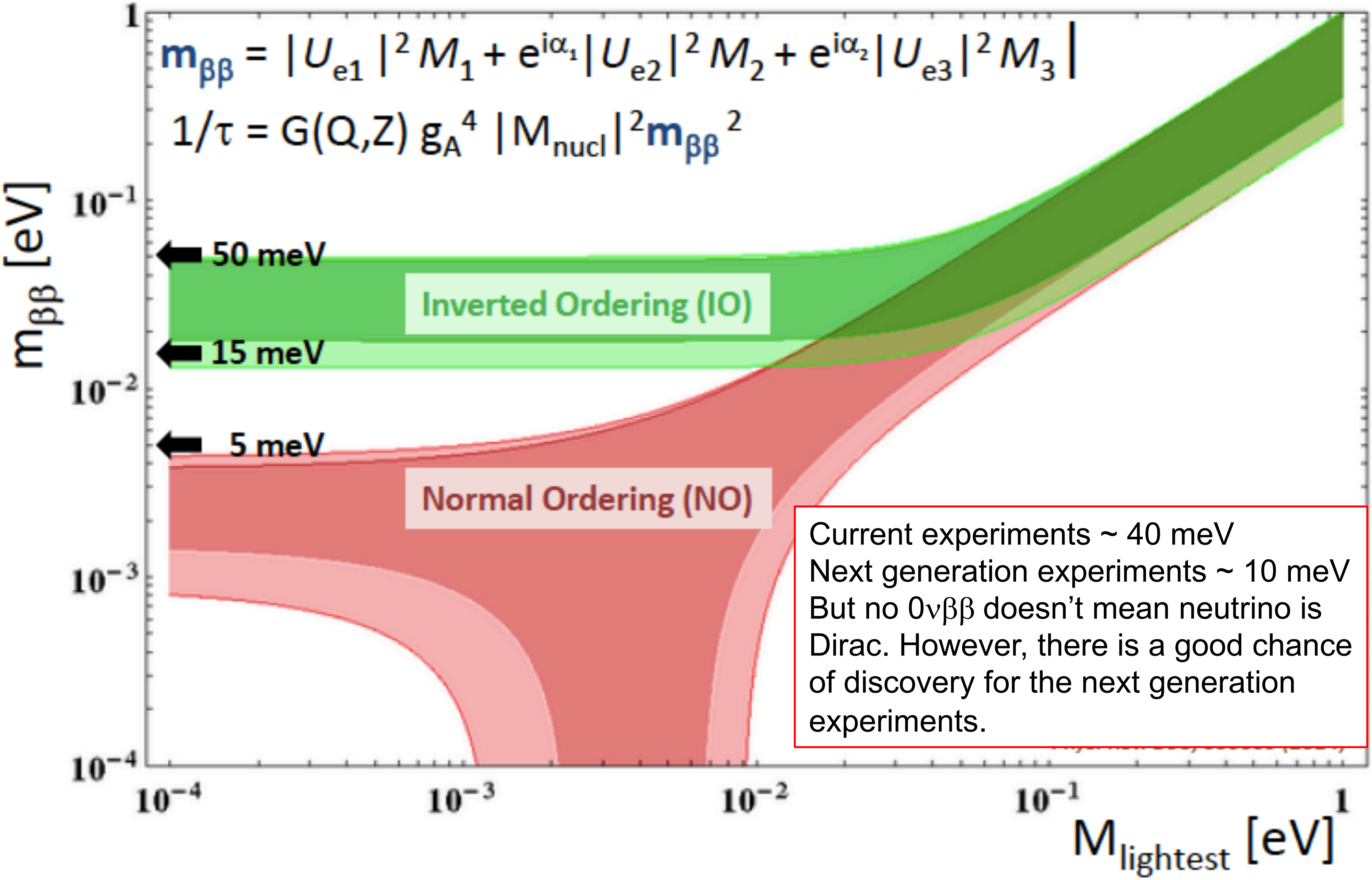
6. Astrophysical neutrino measurements

7. Conclusion

Impact of direct mass ordering (MO) measurement



5. Neutrino-less Double Beta Decay

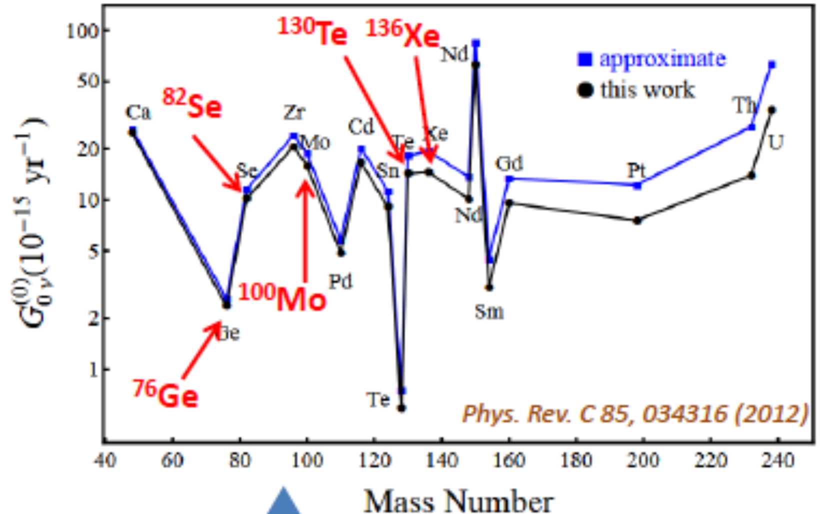


Current experiments ~ 40 meV
Next generation experiments ~ 10 meV
But no $0\nu\beta\beta$ doesn't mean neutrino is Dirac. However, there is a good chance of discovery for the next generation experiments.

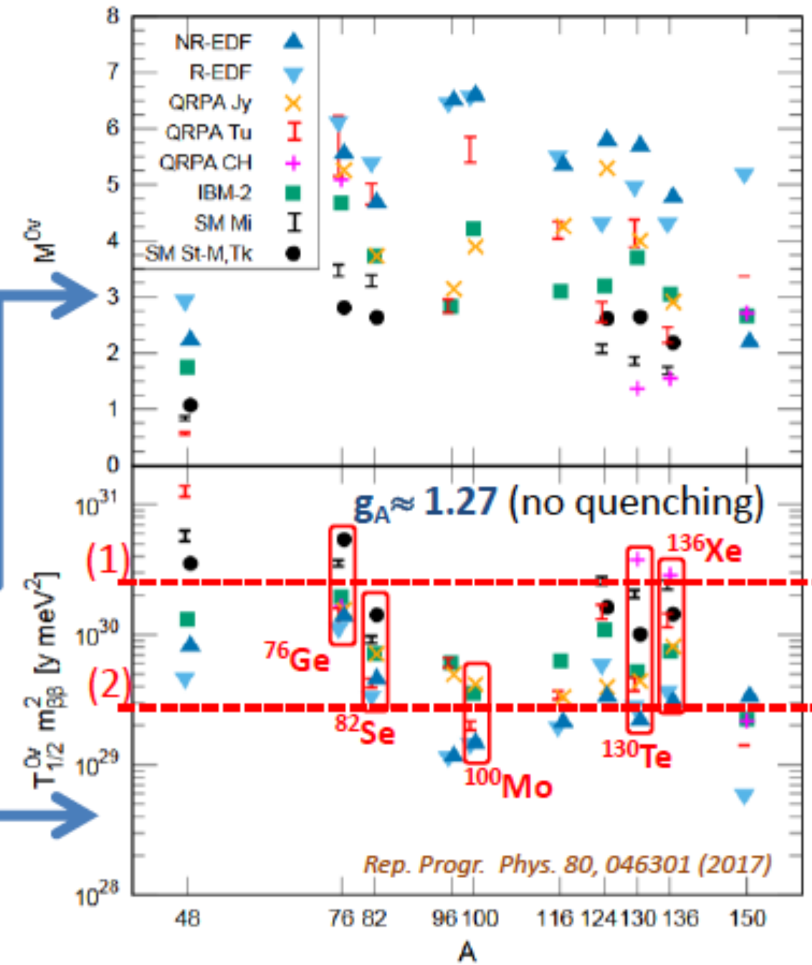
5. Neutrino-less Double Beta Decay

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

Approaches and experiments

source = detector

			NOW	MID-TERM	LONG-TERM
Scalability	**Fluid embedded source**	Xe-based TPC	EXO-200 NEXT-10	NEXT-100 PandaX-III	nEXO NEXT-2.0 PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
High ΔE and ε	**Crystal embedded source**	Germanium diodes	GERDA-II MJD	LEGEND 200	LEGEND 1000
		Bolometers	AMoRE pilot, I CUORE CUPID-0, CUPID-Mo	AMoRE II	CUPID

5. Majorana neutrino scattering experiment?

Dirac neutrino – polarized electron scattering amplitude
- V, A, S, P, T are possible for both left and right chirality

$$
\begin{aligned}
M^D_{\nu_e e^-} = \frac{G_F}{\sqrt{2}}\{ & (\overline{u}_{e'}\gamma^\alpha(c^L_V - c^L_A\gamma_5)u_e)(\overline{u}_{\nu_{e'}}\gamma_\alpha(1-\gamma_5)u_{\nu_e}) \\
& + (\overline{u}_{e'}\gamma^\alpha(c^R_V + c^R_A\gamma_5)u_e)(\overline{u}_{\nu_{e'}}\gamma_\alpha(1+\gamma_5)u_{\nu_e}) \\
& + c^R_S(\overline{u}_{e'}u_e)(\overline{u}_{\nu_{e'}}(1+\gamma_5)u_{\nu_e}) \\
& + c^R_P(\overline{u}_{e'}\gamma_5 u_e)(\overline{u}_{\nu_{e'}}\gamma_5(1+\gamma_5)u_{\nu_e}) \\
& + \frac{1}{2}c^R_T(\overline{u}_{e'}\sigma^{\alpha\beta}u_e)(\overline{u}_{\nu_{e'}}\sigma_{\alpha\beta}(1+\gamma_5)u_{\nu_e}) \\
& + c^L_S(\overline{u}_{e'}u_e)(\overline{u}_{\nu_{e'}}(1-\gamma_5)u_{\nu_e}) \\
& + c^L_P(\overline{u}_{e'}\gamma_5 u_e)(\overline{u}_{\nu_{e'}}\gamma_5(1-\gamma_5)u_{\nu_e}) \\
& + \frac{1}{2}c^L_T(\overline{u}_{e'}\sigma^{\alpha\beta}u_e)(\overline{u}_{\nu_{e'}}\sigma_{\alpha\beta}(1-\gamma_5)u_{\nu_e})\},
\end{aligned} \tag{1}
$$

Majorana neutrino – polarized electron scattering amplitude
- No V and T coupling
- Contribution from A, S, P are doubled

$$
\begin{aligned}
M^M_{\nu_e e^-} = \frac{2G_F}{\sqrt{2}}\{ & -(\overline{u}_{e'}\gamma^\alpha(c_V - c_A\gamma_5)u_e)(\overline{u}_{\nu_{e'}}\gamma_\alpha\gamma_5 u_{\nu_e}) \\
& + (\overline{u}_{e'}\gamma^\alpha(\tilde{c}_V + \tilde{c}_A\gamma_5)u_e)(\overline{u}_{\nu_{e'}}\gamma_\alpha\gamma_5 u_{\nu_e}) \\
& + (\overline{u}_{e'}u_e)\left[c^L_S(\overline{u}_{\nu_{e'}}(1-\gamma_5)u_{\nu_e}) + c^R_S(\overline{u}_{\nu_{e'}}(1+\gamma_5)u_{\nu_e})\right] \\
& + (\overline{u}_{e'}\gamma_5 u_e)\left[-c^L_P(\overline{u}_{\nu_{e'}}(1-\gamma_5)u_{\nu_e}) + c^R_P(\overline{u}_{\nu_{e'}}(1+\gamma_5)u_{\nu_e})\right]\}.
\end{aligned} \tag{2}
$$

Did we explore all possible experiments to find Majorana neutrinos?

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3. Accelerator-based short-baseline neutrino experiments

4. Reactor-based neutrino experiments

5. Neutrino-less double beta decay

6. Astrophysical neutrino measurements

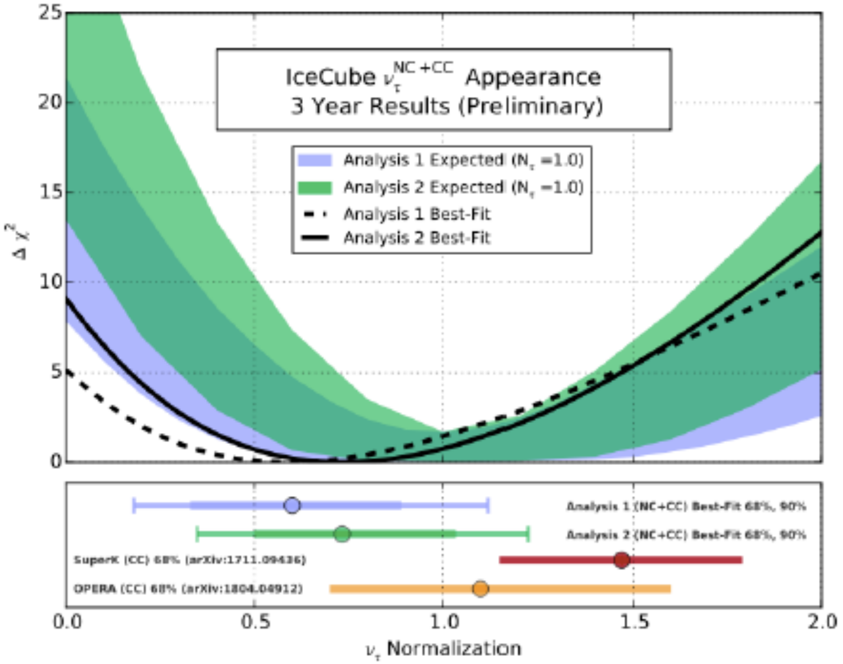
7. Conclusion

6. Atmospheric neutrinos

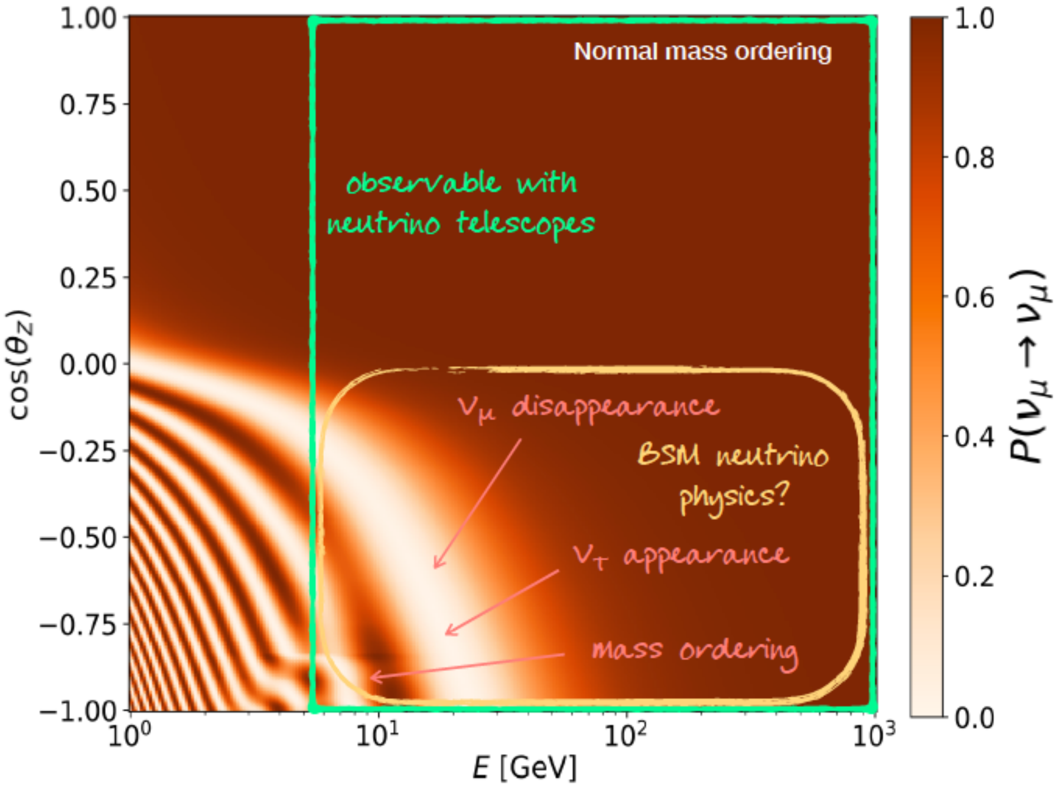
PINGU and ORCA

- 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)

DeepCore $\nu\tau$ appearance result has a small tension with SuperK and OPERA



Oscillograms



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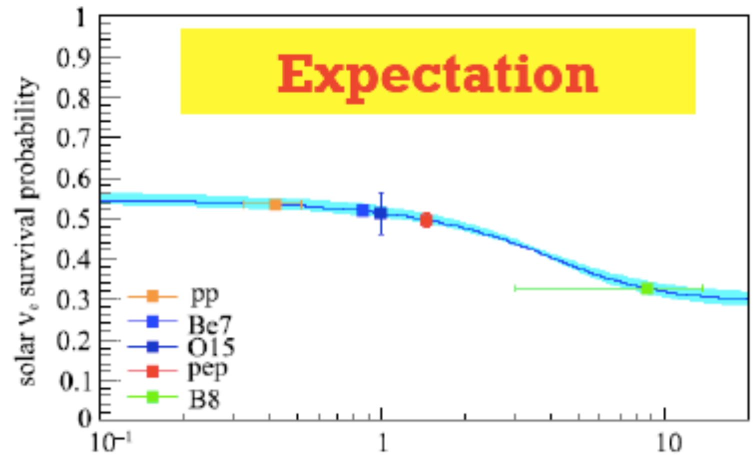
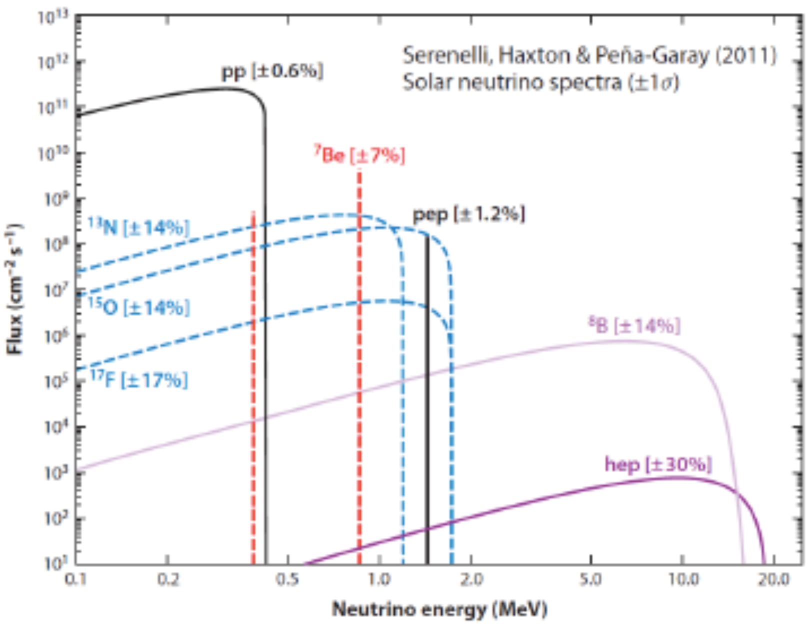
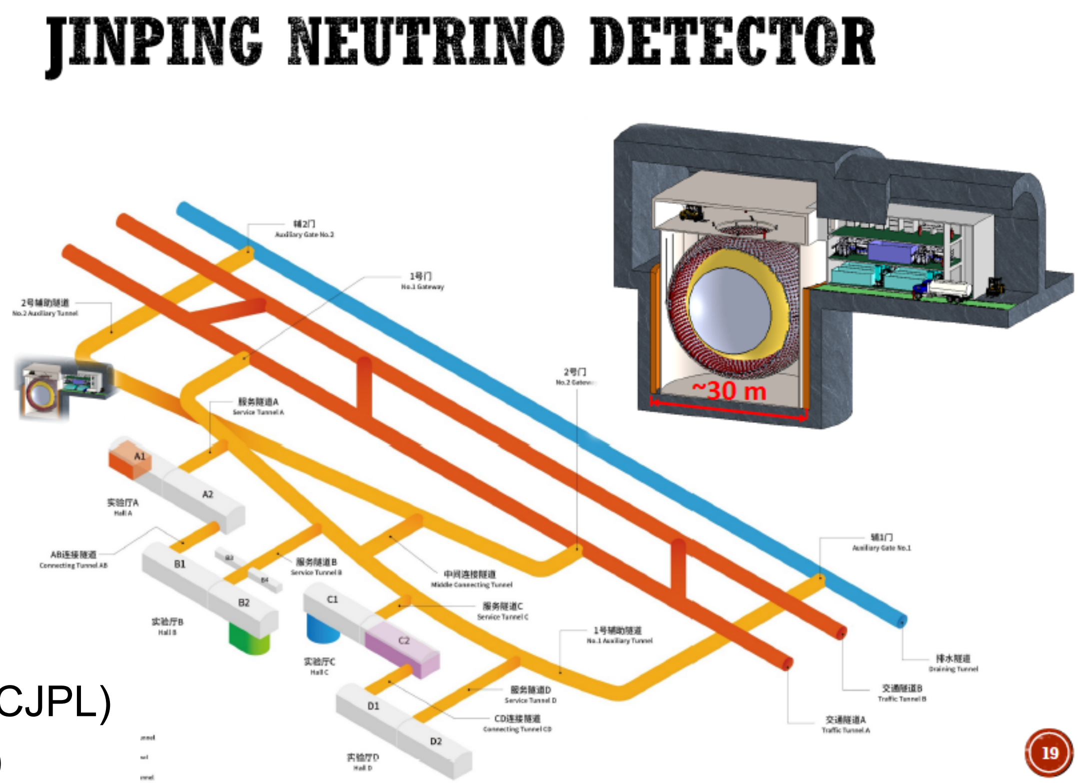
6. Solar neutrinos



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

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

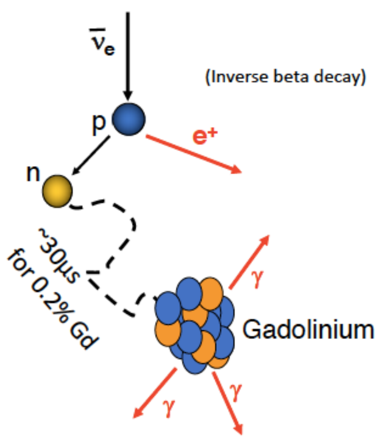
Simpson, Sussex Supernova Nu workshop 2018

6. Supernova neutrinos

Galactic supernova (~3 per century)
- Good luck for HyperK, DUNE, IceCube, etc

Diffused supernova background (DSNB)
- Guaranteed signal, ~few events/yr by SuperK-Gd
- lower ebergy than galactic SN (<20 MeV)

SuperK-Gd
- Gd-loaded (neutron capture)
- Massive refurbishment work during summer 2018



Riding the SuperK boat!
Dream of all neutrino physicists!

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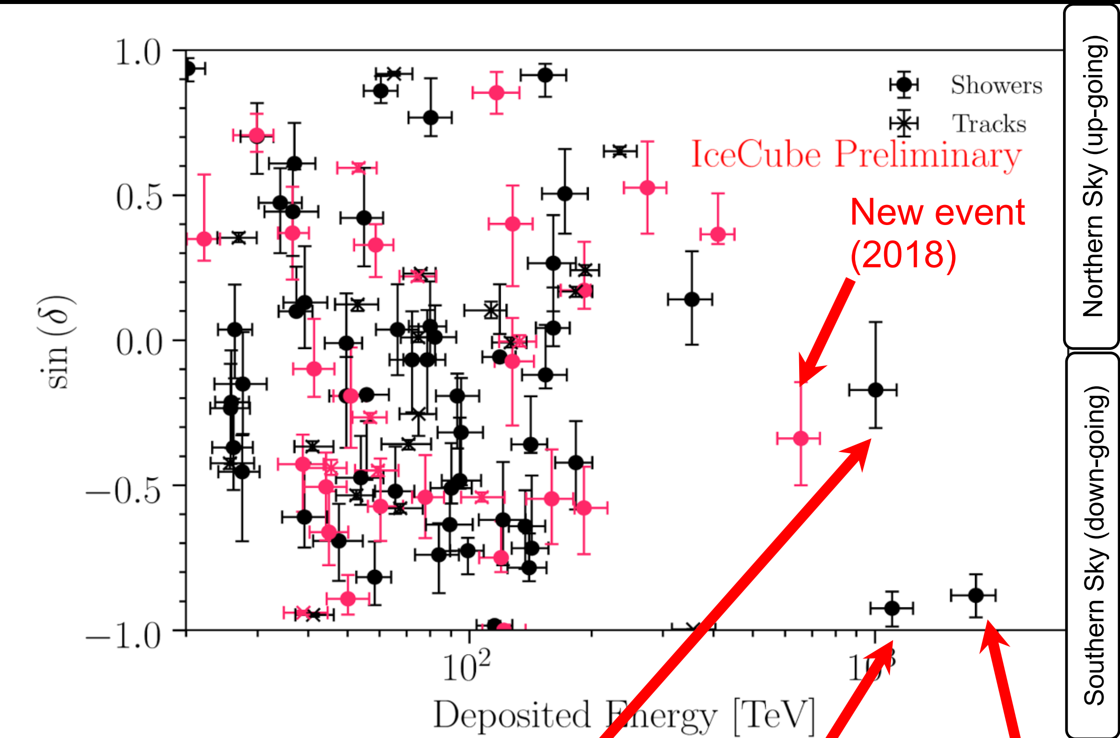
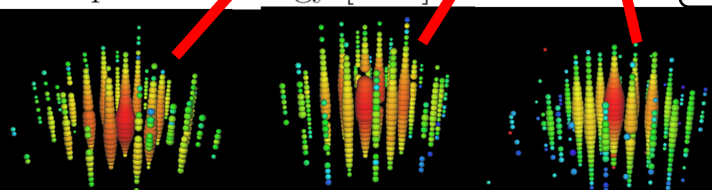
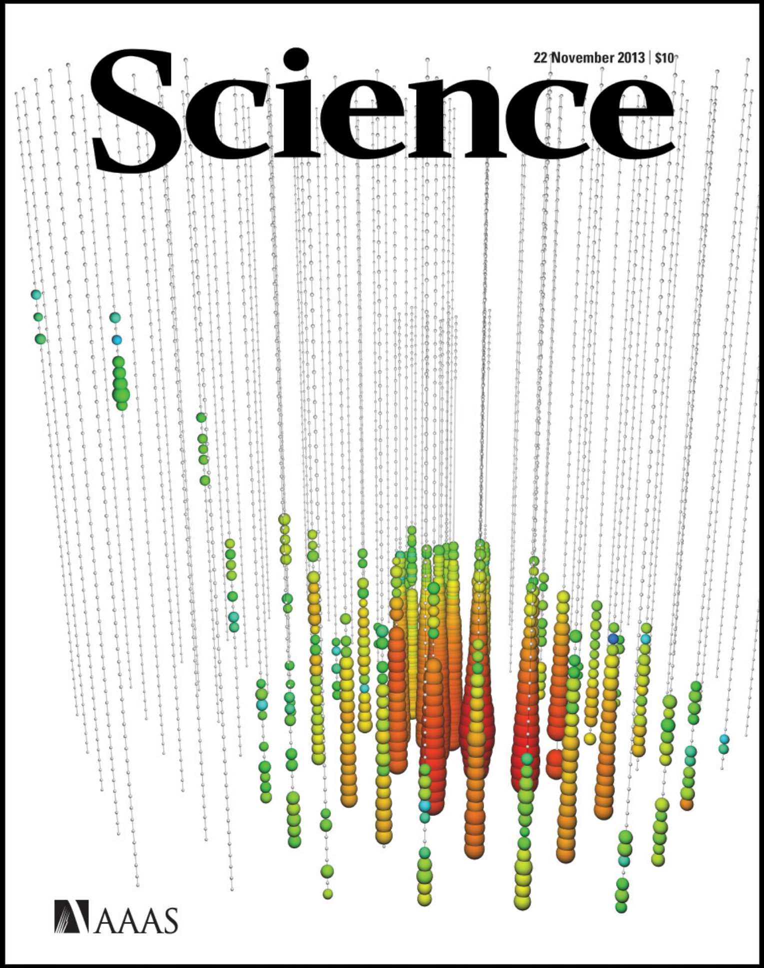
6. Astrophysical Very-High-Energy Neutrinos

First observation (2013)
 - 30-2000 TeV neutrinos

Taboada, Neutrino 2018

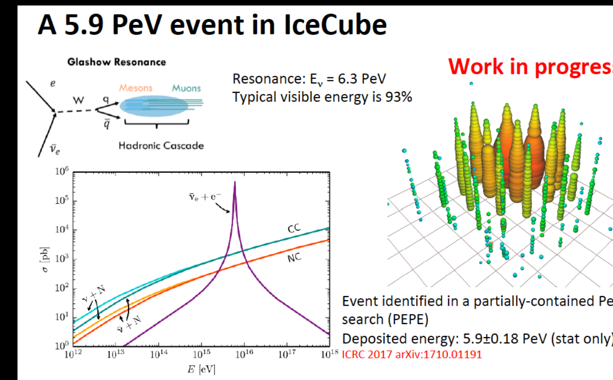






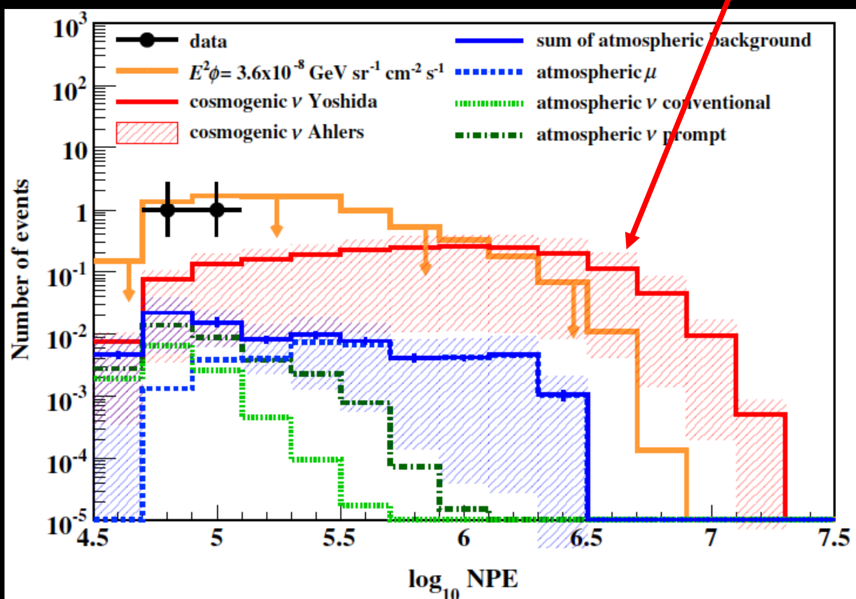
6. Astrophysical Very-High-Energy Neutrinos

First Glashow resonance?
(Taboada, Neutrino 2018)

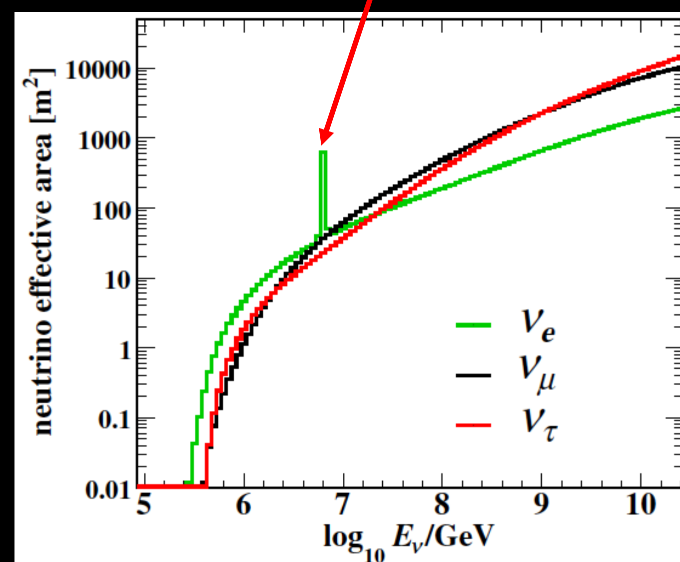


First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from GZK neutrinos or Glashow resonance

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



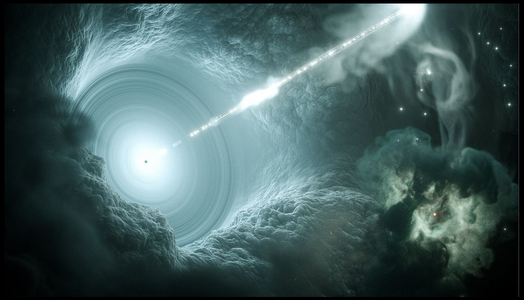
$\bar{\nu}_e(6.2PeV)+e \rightarrow W$



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

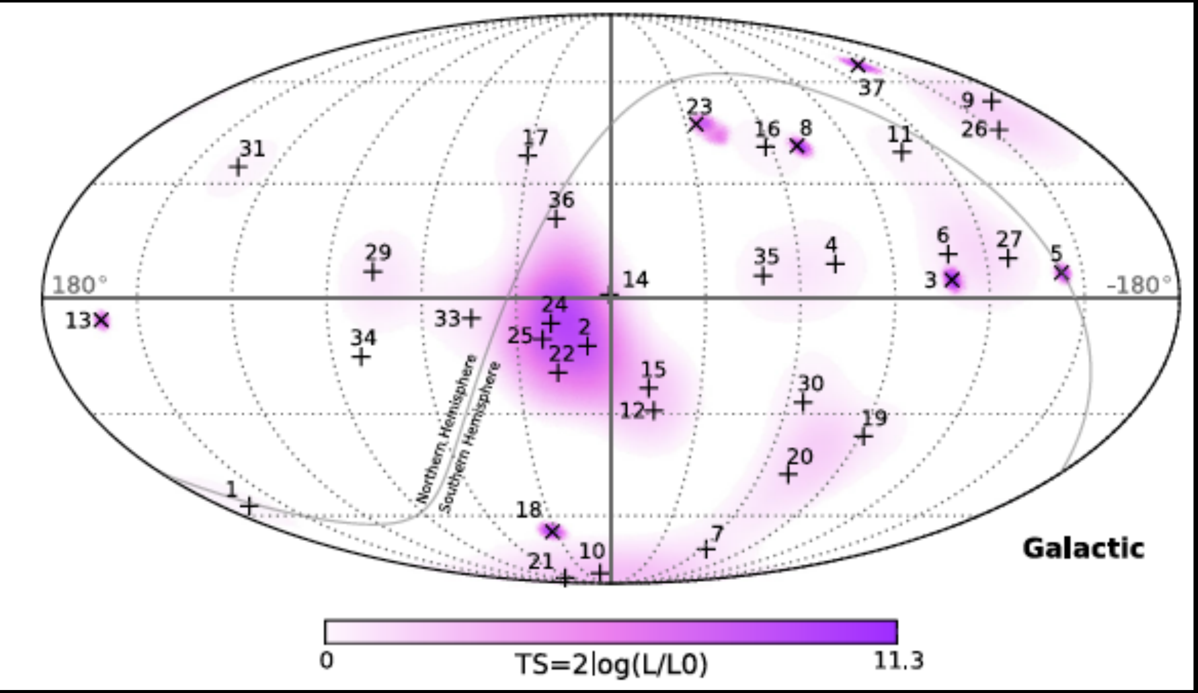
6. Astrophysical Very-High-Energy Neutrinos

Evidence of Blazar Neutrino
- IC170922A
- TXS 0506+056



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

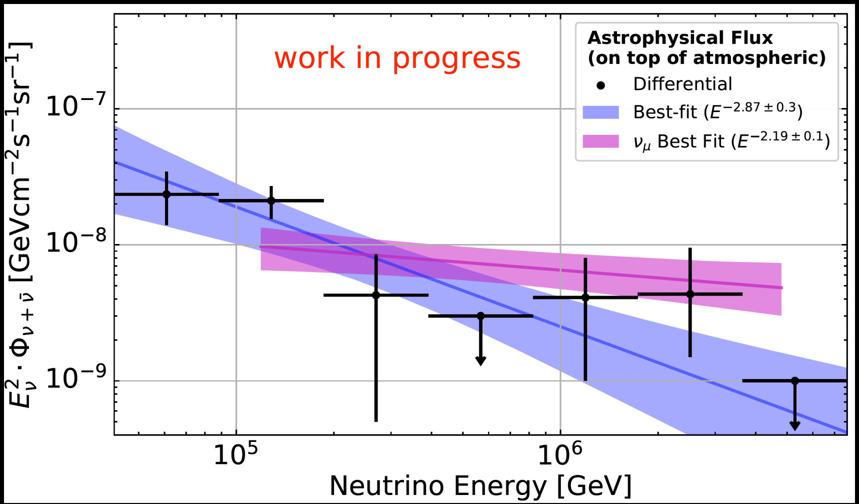
First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from GZK neutrinos or Glashow resonance
- Sources are mostly unknown

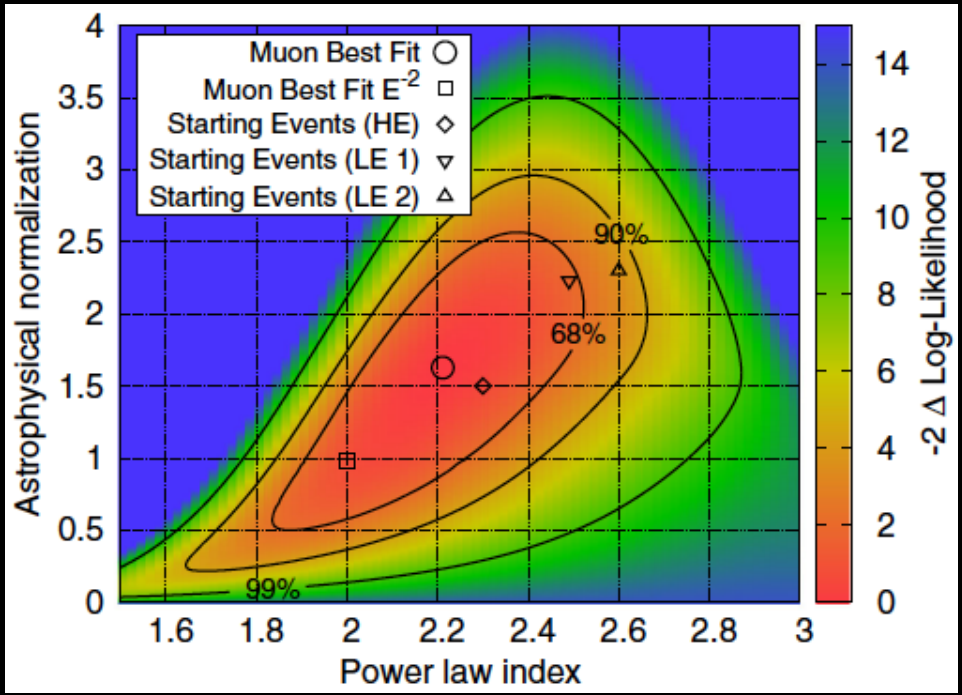


6. Astrophysical Very-High-Energy Neutrinos

First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from GZK neutrinos or Glashow resonance
- Sources are mostly unknown
- Spectrum is poorly constrained

Data prefer broken power law?
(Taboada, Neutrino 2018)

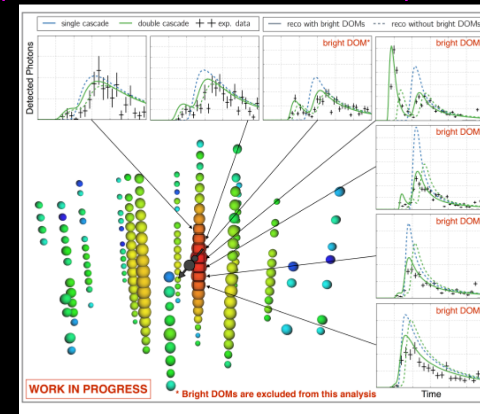




Palladino et al,PRL114(2015)171101

6. Astrophysical Very-High-Energy Neutrinos

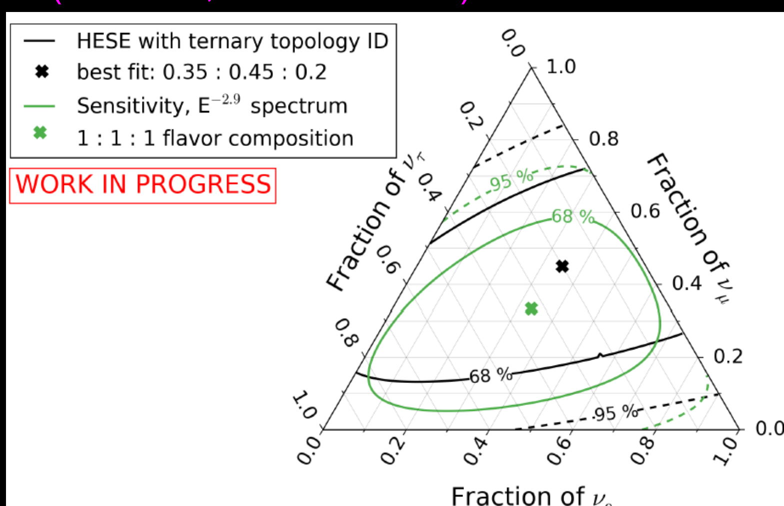
First astrophysical tau neutrino?
(Taboada, Neutrino 2018)



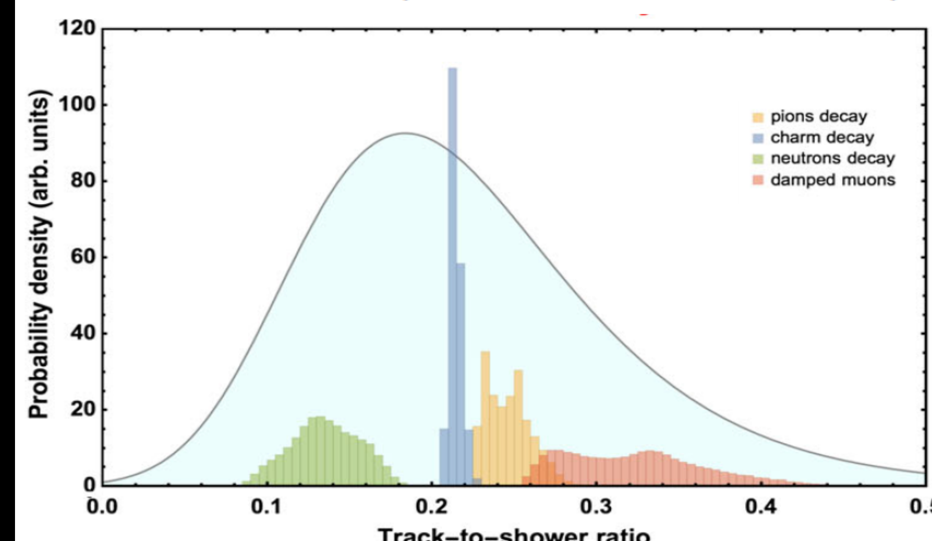
Double cascade Event #2

First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from GZK neutrinos or Glashow resonance
- Sources are mostly unknown
- Spectrum is poorly constrained
- Production flavor structure unknown

Latest flavor ratio measurement
(Taboada, Neutrino 2018)

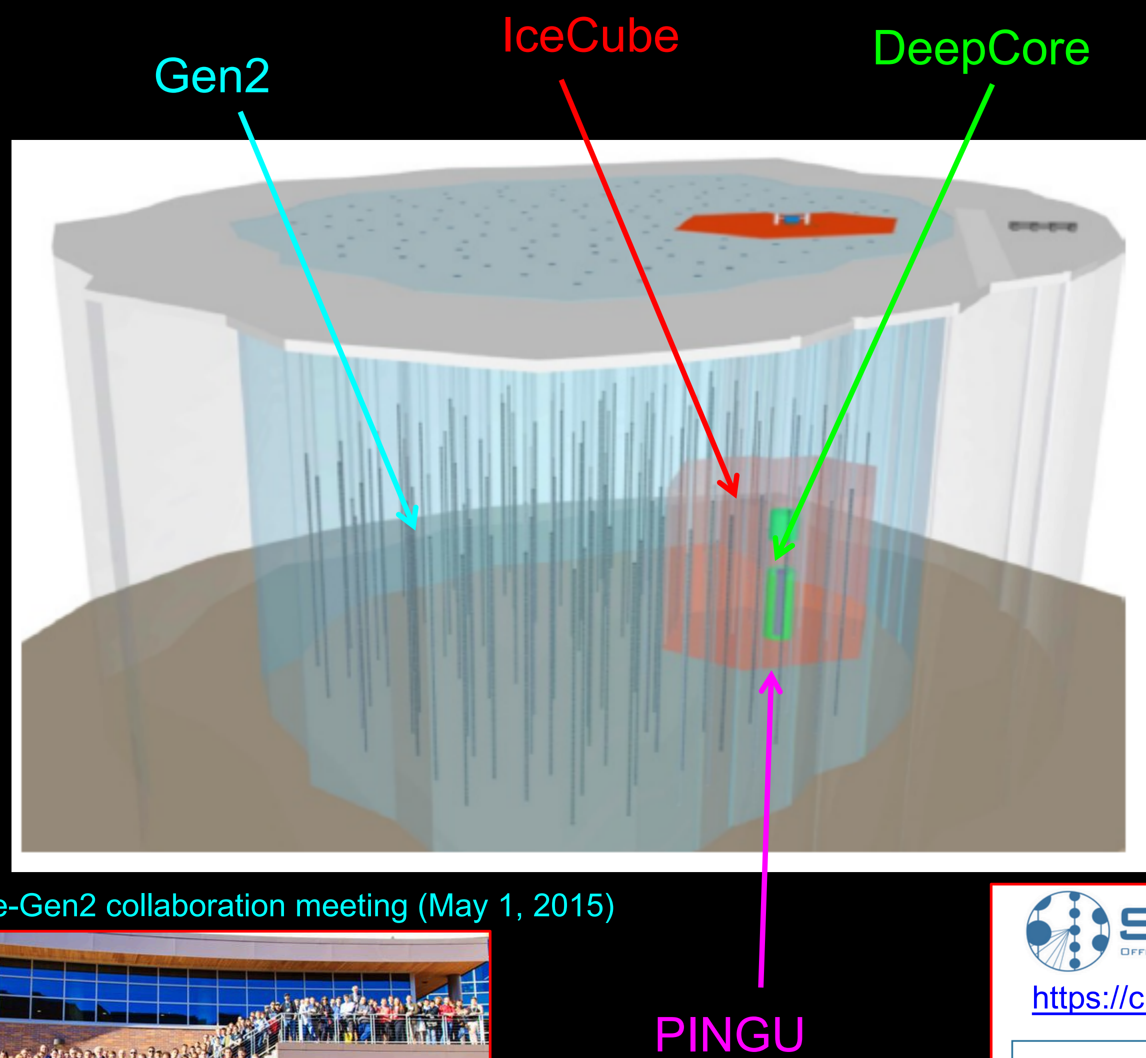


$$N_S = 8.4F_e + 0.9F_\mu + 6.3F_\tau, \qquad N_T = 3.7F_\mu.$$



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

6. 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

IceCube-Gen2 collaboration meeting (May 1, 2015)

SHOP ICECUBE
OFFICAL SHOP OF THE ICECUBE NEUTRINO OBSERVATORY

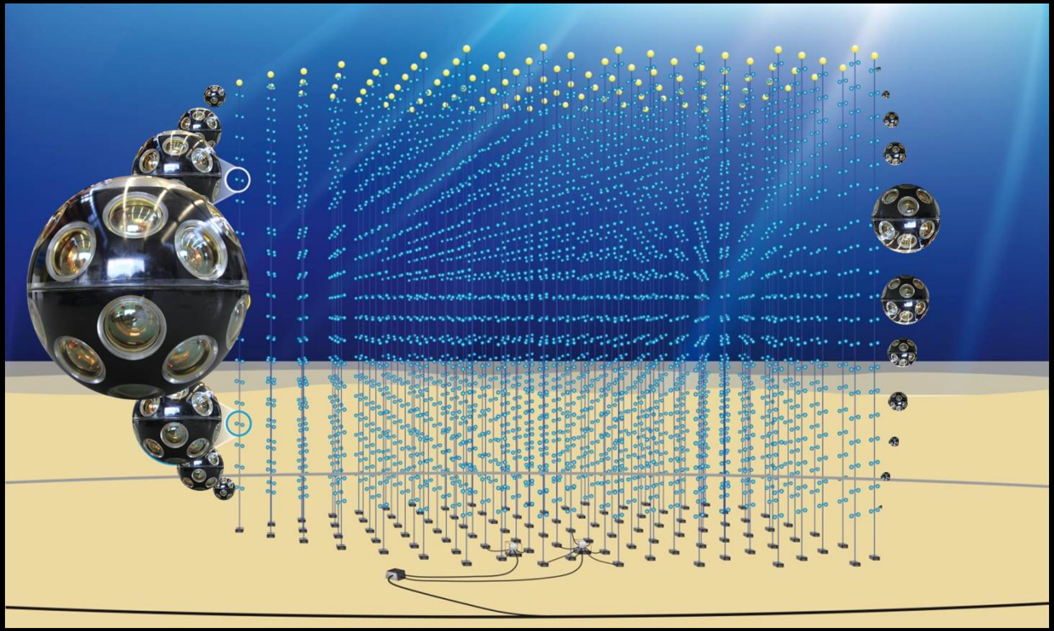
https://charge.wisc.edu/icecube/wipac_store.aspx

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

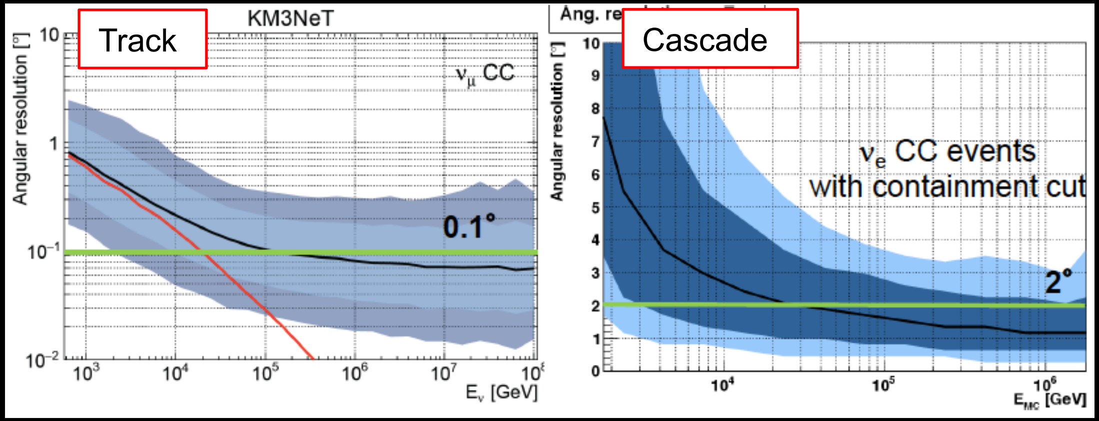
Support IceCube!

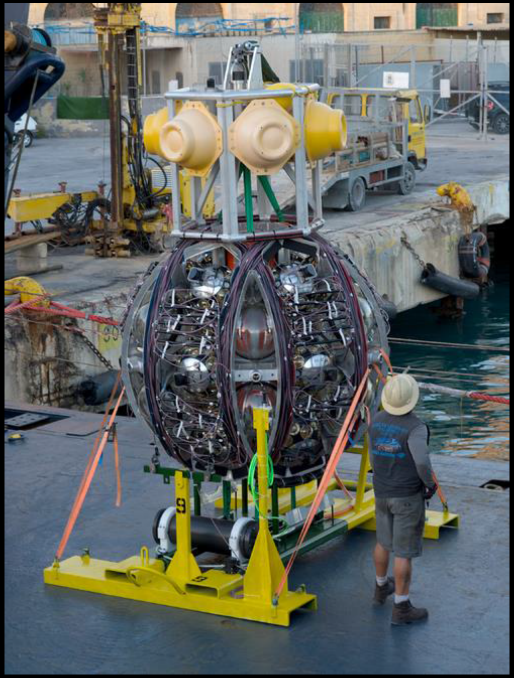
KM3NeT, JPhysG.43 (2016) 084001
Katz, Neutrino 2018

6. KM3NeT



mDOM design
- 31 3" PMT in one module
- Cover roughly IceCube volume
- Better angular resolution
- Candidate design for HyperK and IceCube-Gen2

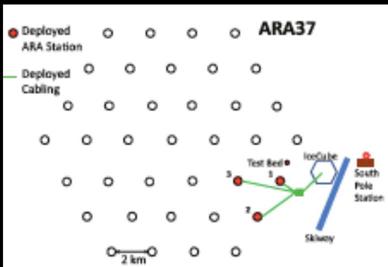


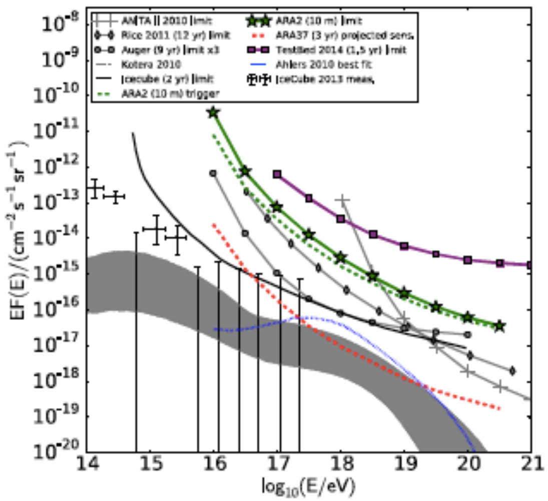


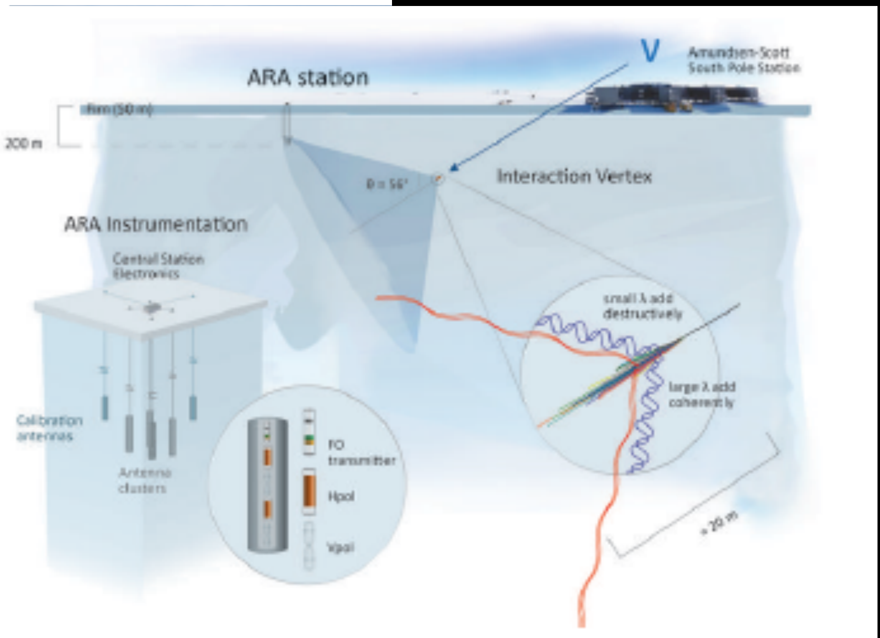
Connolly, Neutrino 2018
Anchordoqui et al, LHEP01(2018)03

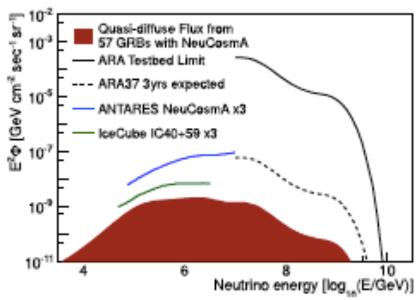
6. ARA

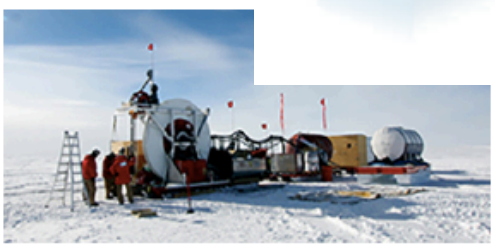
Askaryan Radio Array (ARA)











- Target: EeV neutrinos
- ARA is a part of IceCube-Gen2
- ANITA motivates new physics

Letters in High Energy Physics LHEP 01, 13, 2018

Upgoing ANITA events as evidence of the CPT symmetric universe

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Queen Mary
University of London

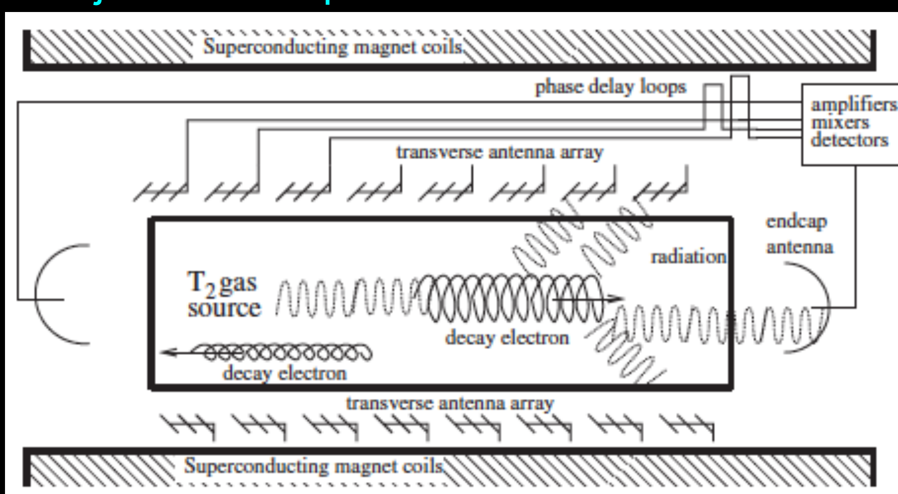
PTOLEMY, arXiv:1808.01892
Project 8, PRD80(2009)051301

6. Cosmic Neutrino Background (CνB)

PTOLEMY and Project 8
- Motivated by KATRIN
- Tritium ν_e capture (no threshold)
- Measure end point of tritium (18 keV) from cyclotron radiation of single electron RF
- Target: ~meV shift of end point due to neutrino mass.

$Q-m_\nu$ → neutrino mass effect on β-decay
$Q+m_\nu$ → CνB capture

Project 8 concept



Conclusions

Neutrino physics spans from few meV to EeV, but 2 fields are very popular
- reactor neutrinos (~4 MeV)
- accelerator-based neutrinos (1-10 GeV)

NC is useful to look for new physics, but often ignored at the design stage of oscillation experiments.

Nuclear physics is important for many experiments; nuclear effects for oscillation experiments, reactor flux prediction for rector experiments, nuclear matrix element and g_A calculations for double beta experiments, etc
- If you can avoid nuclear physics, you should
- If you cannot avoid, you deal it and don't ignore

For students in large collaborations
- Don't be a part of the system. It's YOU to make your experiment more interesting!

(new ideas never come from old people, change the future if you don't like)

Thank you for your attention!