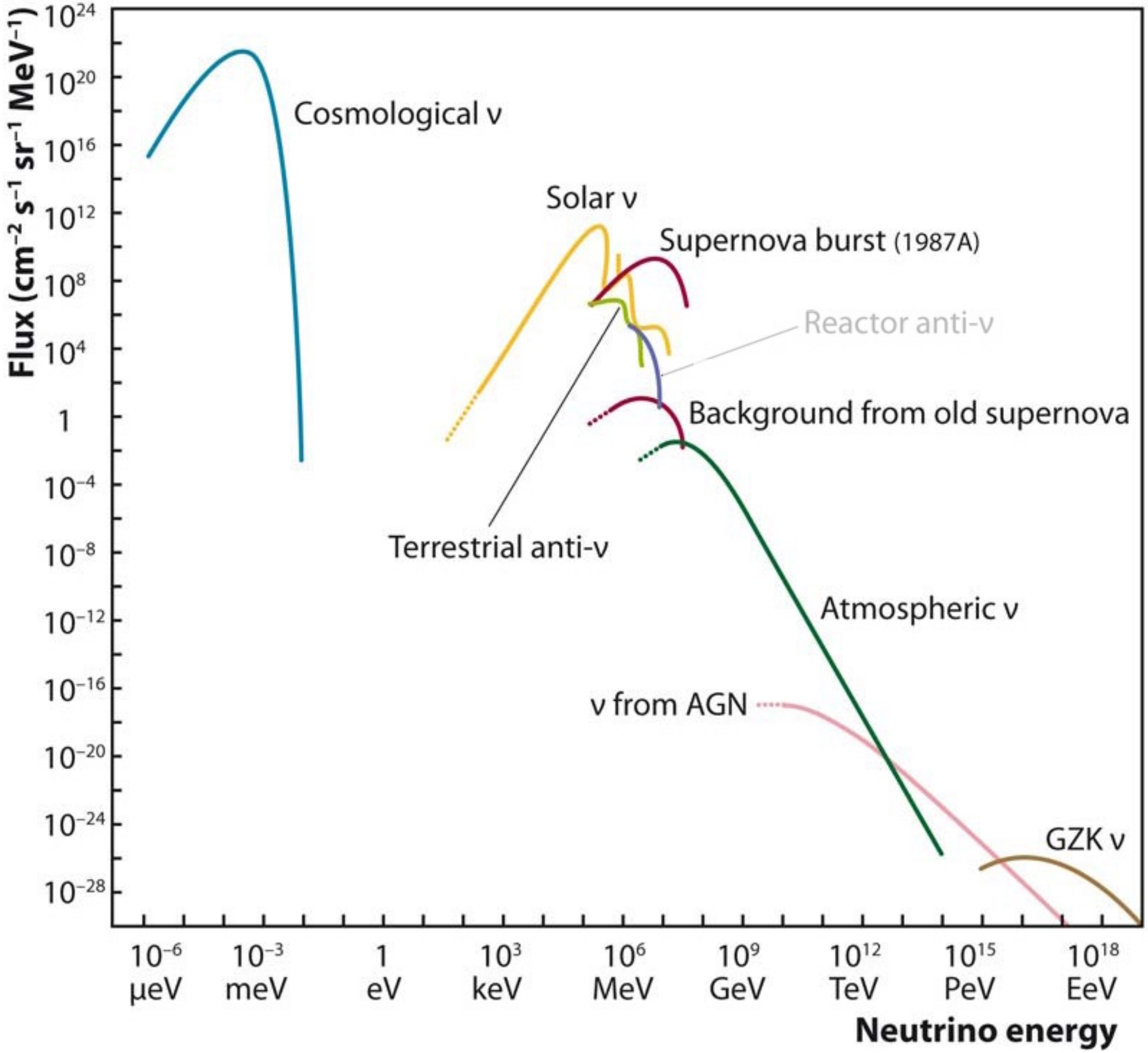
The *Allure* of Natural Neutrinos

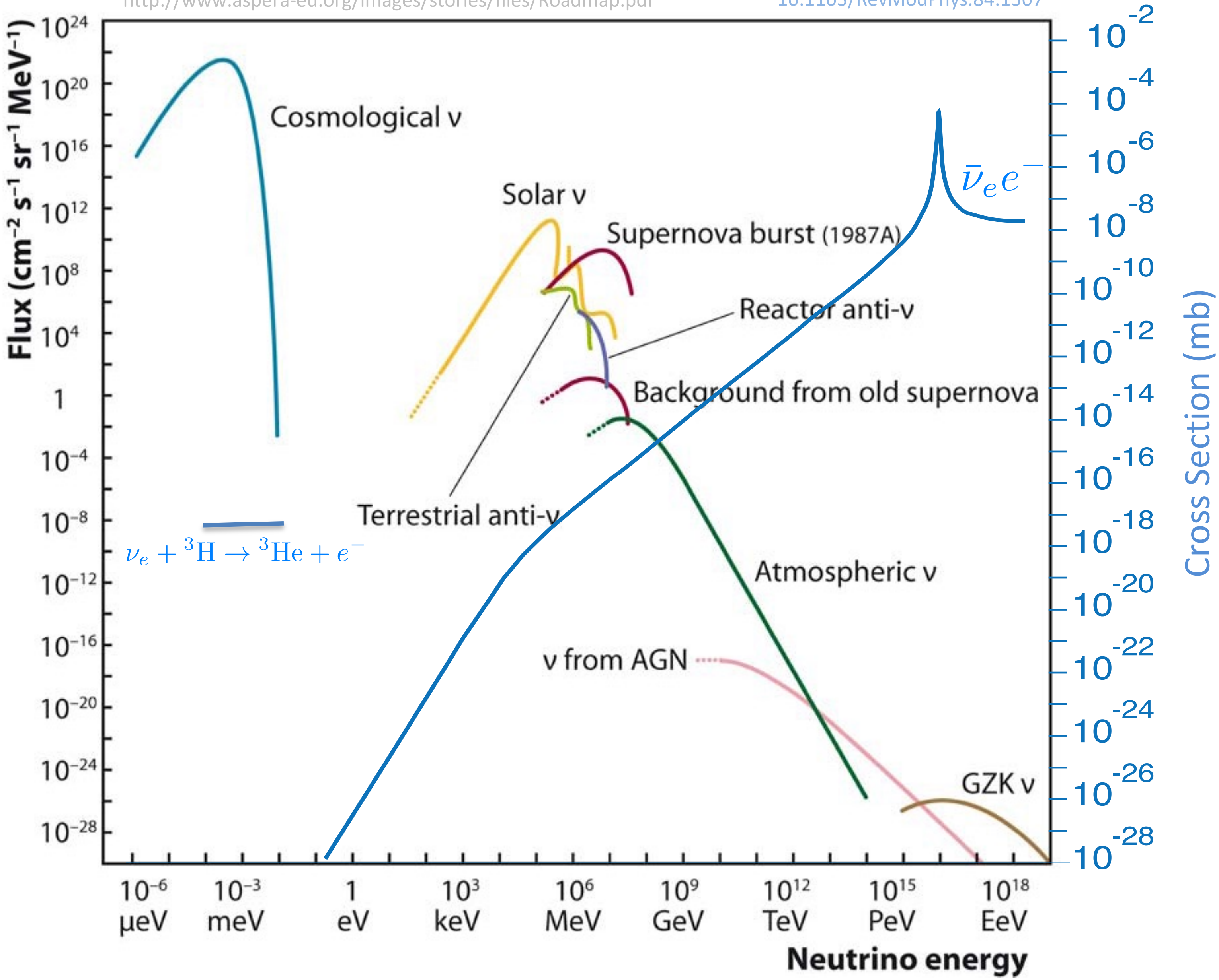
Fermilab Academic Lecture Series
Thursday April 24, 2014
Ed Kearns
Boston University

http://www.aspera-eu.org/images/stories/files/Roadmap.pdf



http://www.aspera-eu.org/images/stories/files/Roadmap.pdf

Formaggio and Zeller
10.1103/RevModPhys.84.1307

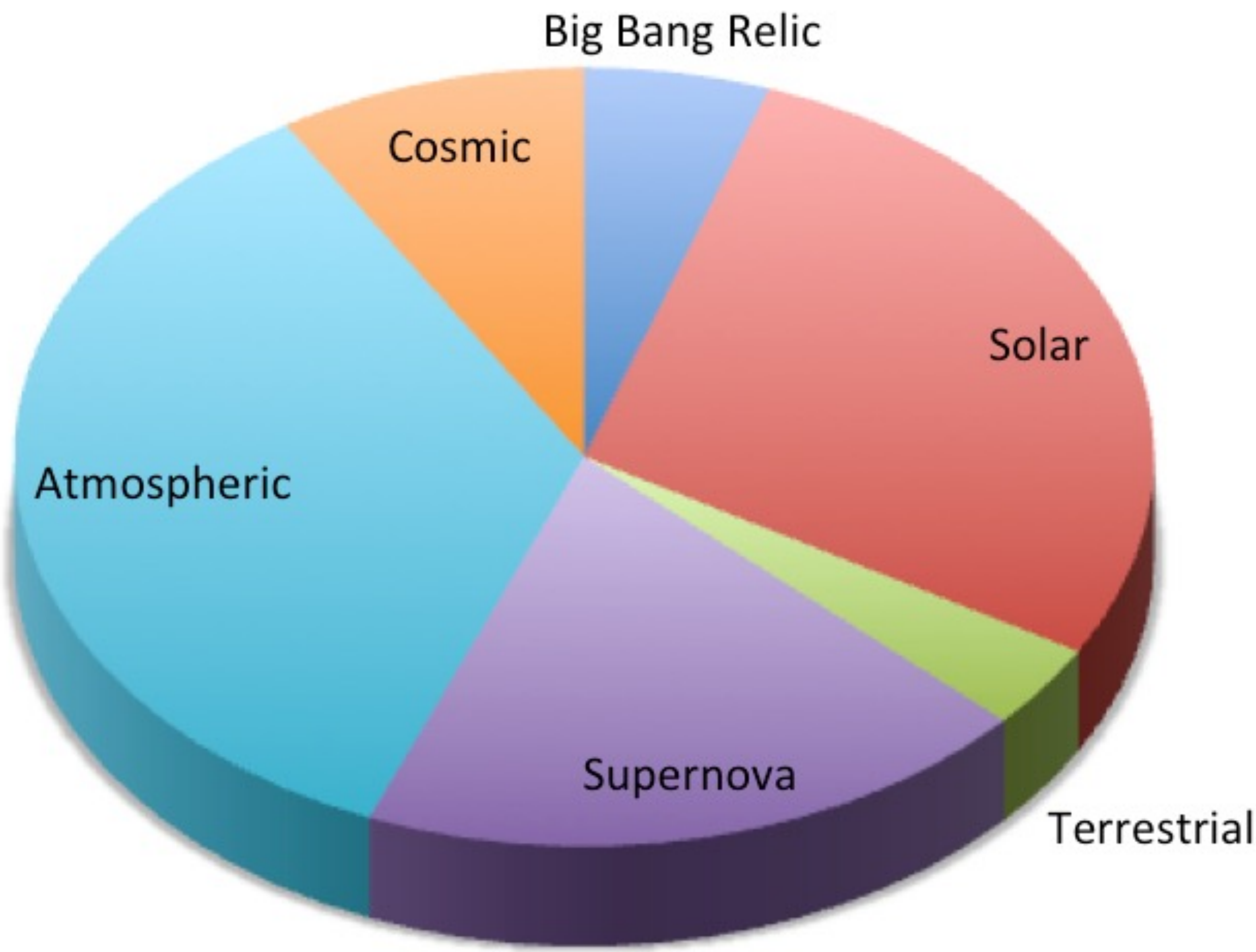


This lecture will be from an experimental perspective…

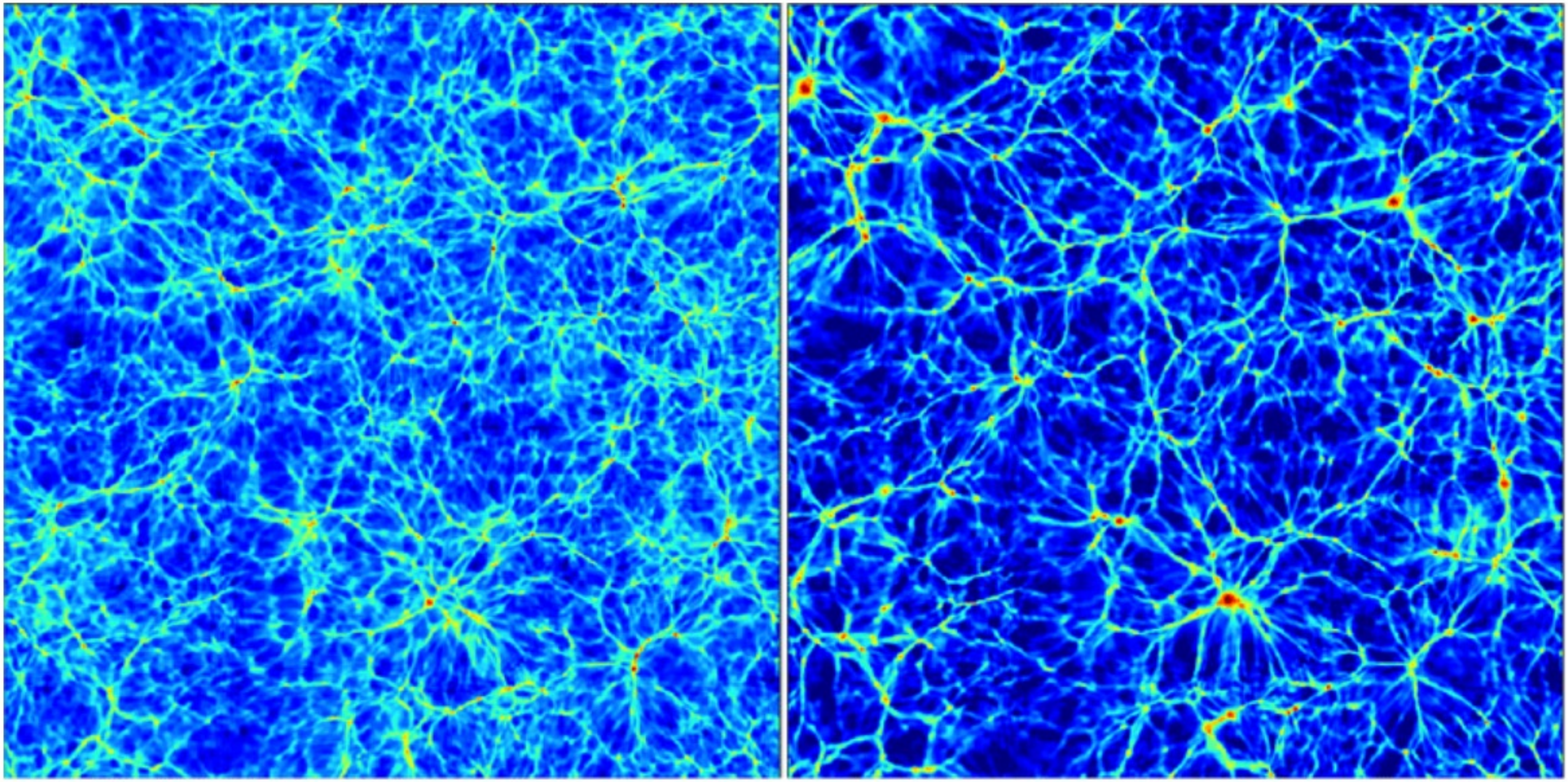
- What have we learned from these natural sources of neutrinos already?
- What are the experimental issues?
- What can we learn from them next?

For local interest: can one study these neutrinos with a massive underground LArTPC ?

Neutrino Composition of this Lecture



Cosmological Relic Neutrinos



$m_\nu = 1.9\ \mathrm{eV}$ $\qquad$ $m_\nu = 0$

http://physics.aps.org/articles/v3/57
Courtesy of Shankar Agarwal and Hume Feldman, University of Kansas; submitted to Mon. Not. R. Astron. Soc.

Cosmological Relic Neutrinos

$$< T_\nu > = 1.9 \text{ K}$$

$$< E_\nu > = 170\ \mu\text{eV}$$

$$\sum m_\nu < 0.3 \text{ eV}$$

> 0.05 eV from ν oscillation

$$n_\nu = 168 \text{ cm}^{-3}$$

x 1-100 from gravitational clustering

(Weinberg, 1962) 10.1103/PhysRev.128.1457

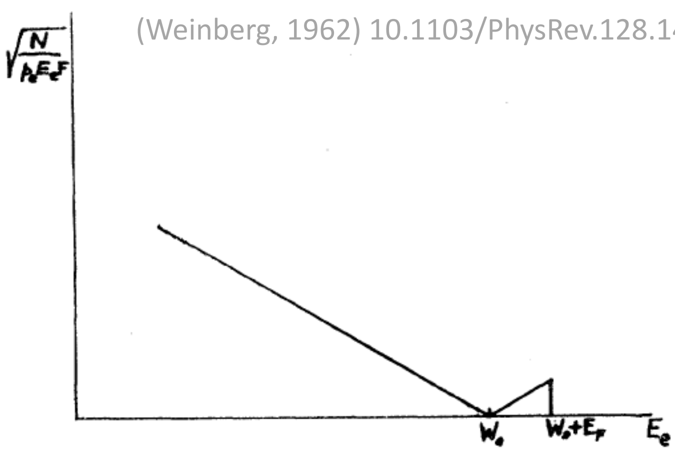


Fig. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

$$\nu_e + {}^3\text{H} \rightarrow {}^3\text{He} + e^-$$

$$T_e = Q_\beta \pm m_\nu$$

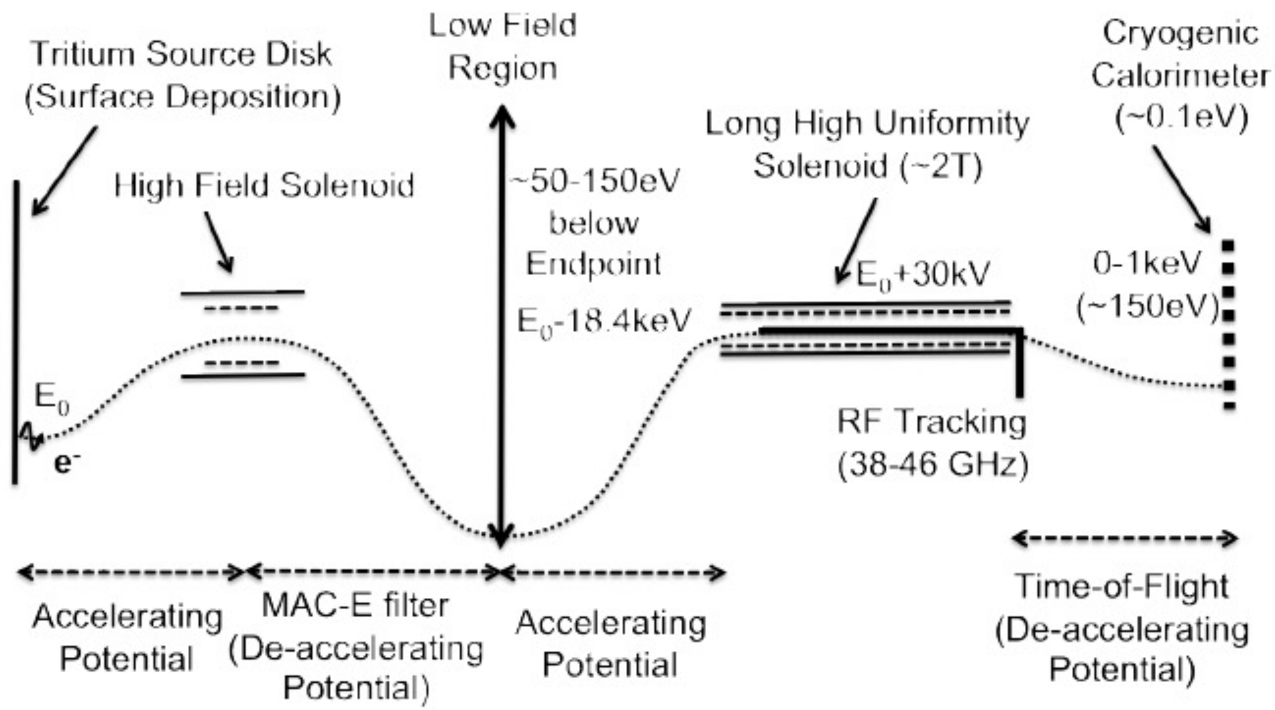
+ for relic neutrino detection

– tritium endpoint resolution

$$\sigma_{\text{NCB}}\left({}^3\text{H}\right) v_\nu = (7.84 \pm 0.03) \times 10^{-45} \text{ cm}^2$$

Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

arXiv:1307.47



Fascinating and challenging experimental techniques:

- 100 g of 3H, large area (graphene substrate)
- magnetic trajectory filter (like KATRIN)
- RF signal from cyclotron motion (like Project 8)
- high resolution calorimeter and TOF
- possible annual modulation

Safti, Lisanti, Spitz, Formaggio arXiv:1404.0680v1

STATUS: prototyping the individual techniques

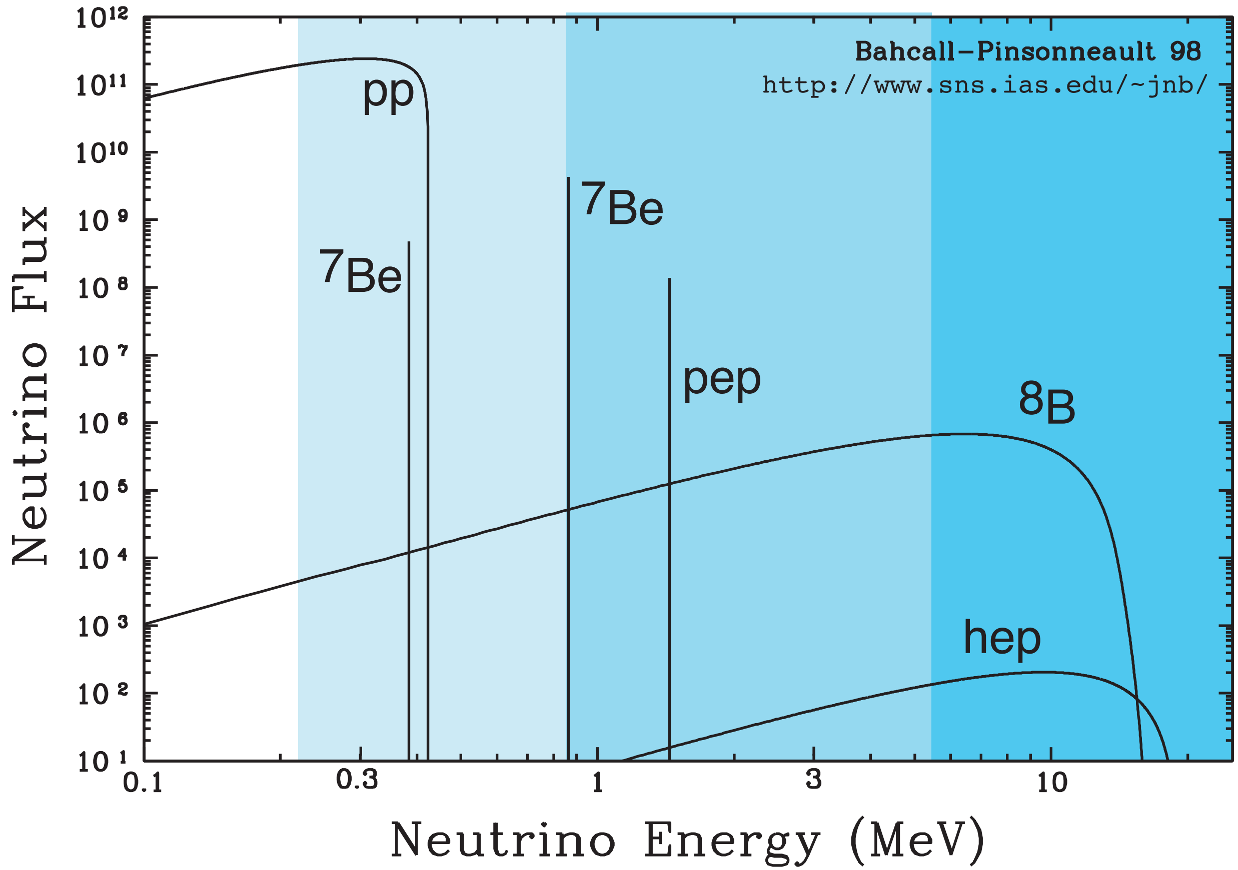
Solar Neutrinos

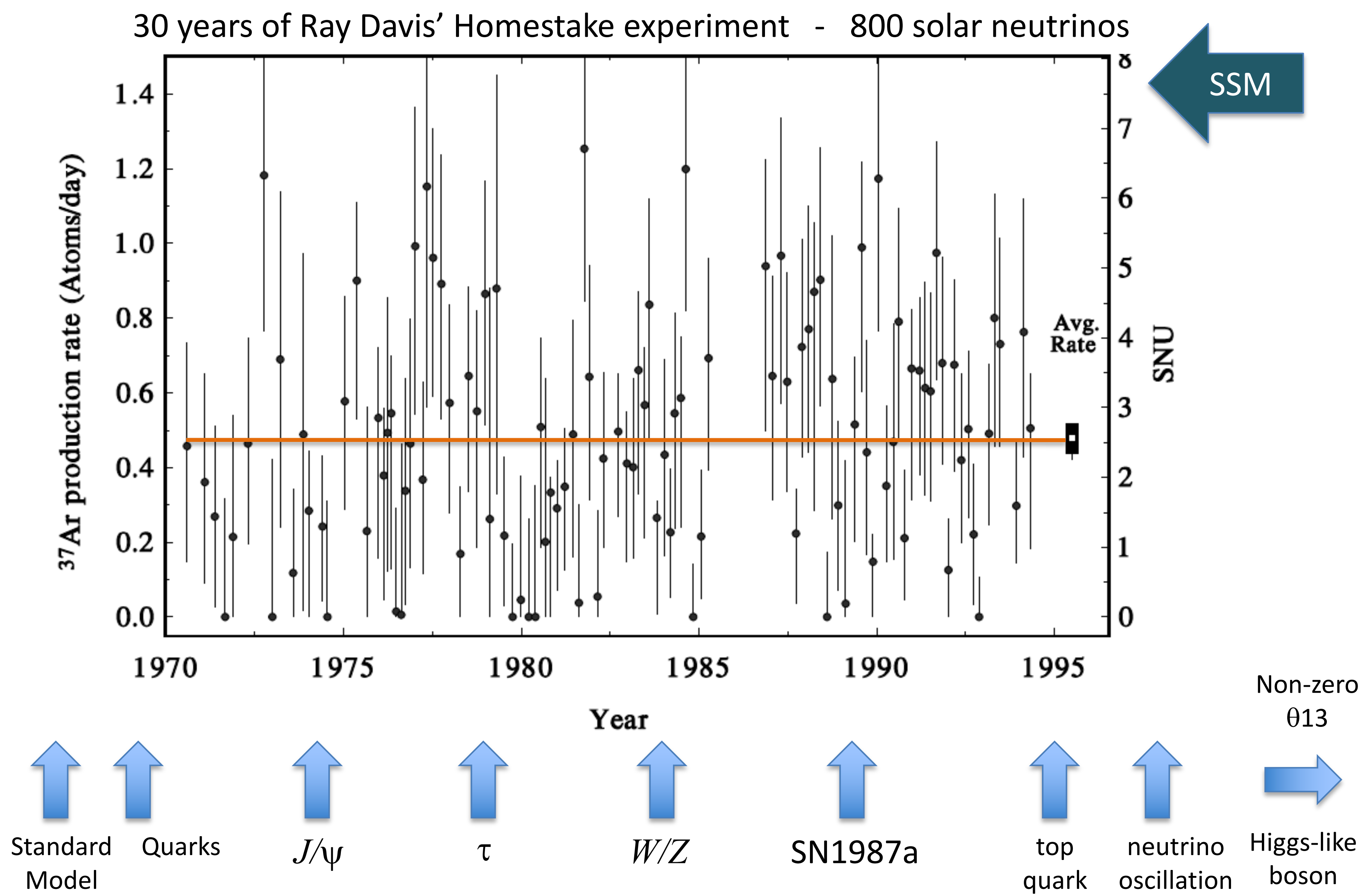
$$4p \rightarrow {}^4\text{He} + 2e^+ + \gamma + 2\nu_e$$

$$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$$

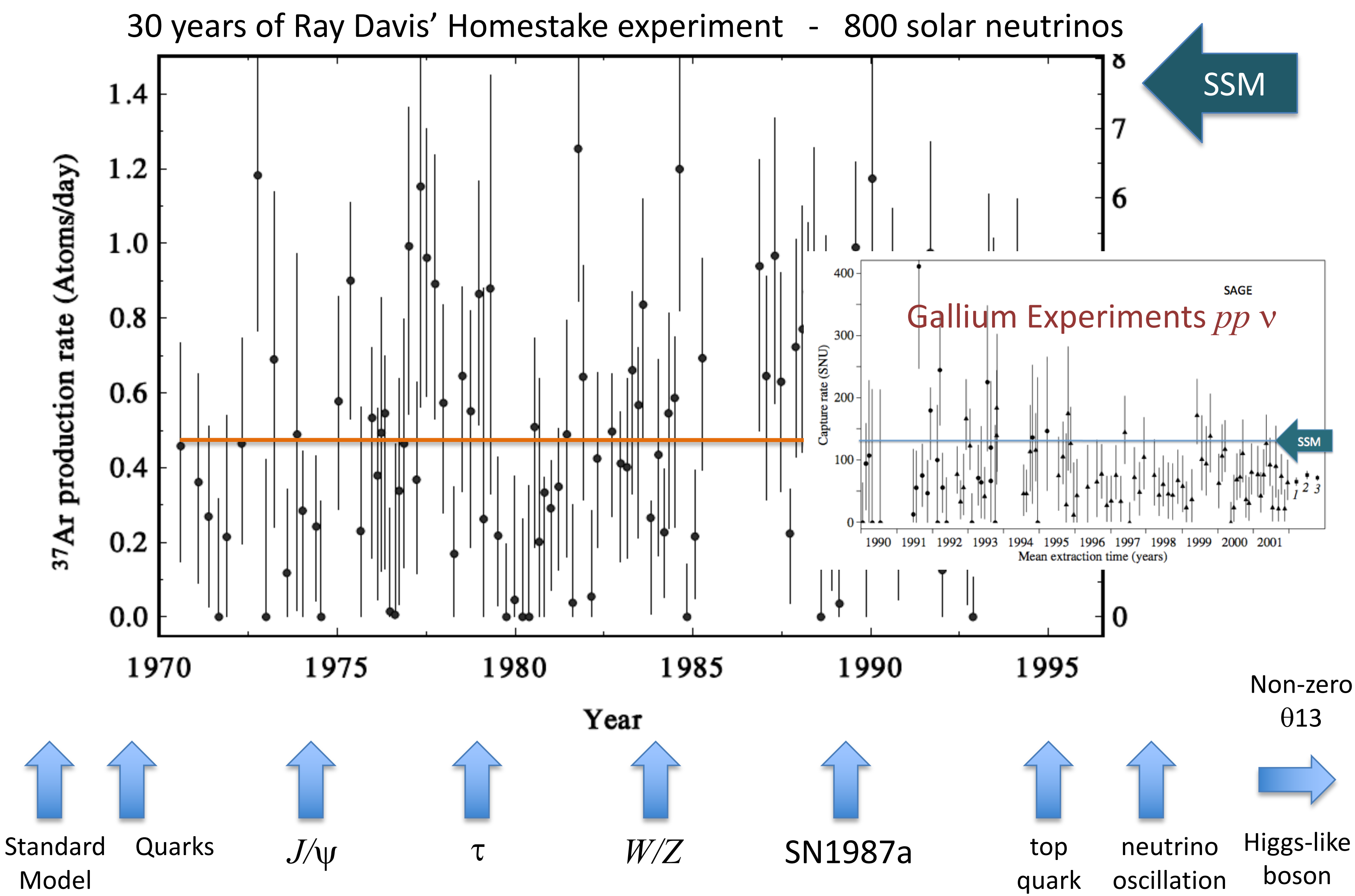
$$^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$$

$$^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$$

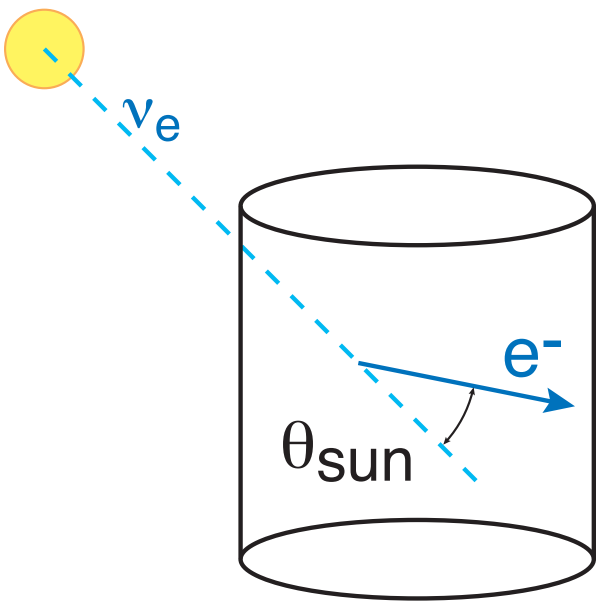




30 years of Ray Davis' Homestake experiment - 800 solar neutrinos
SSM
^{37}Ar production rate (Atoms/day)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
SNU
8
7
6
5
4
3
2
1
0
Avg. Rate
1970
1975
1980
1985
1990
1995
Year
Standard Model
Quarks
J/ψ
τ
W/Z
SN1987a
top quark
neutrino oscillation
Non-zero θ13
Higgs-like boson

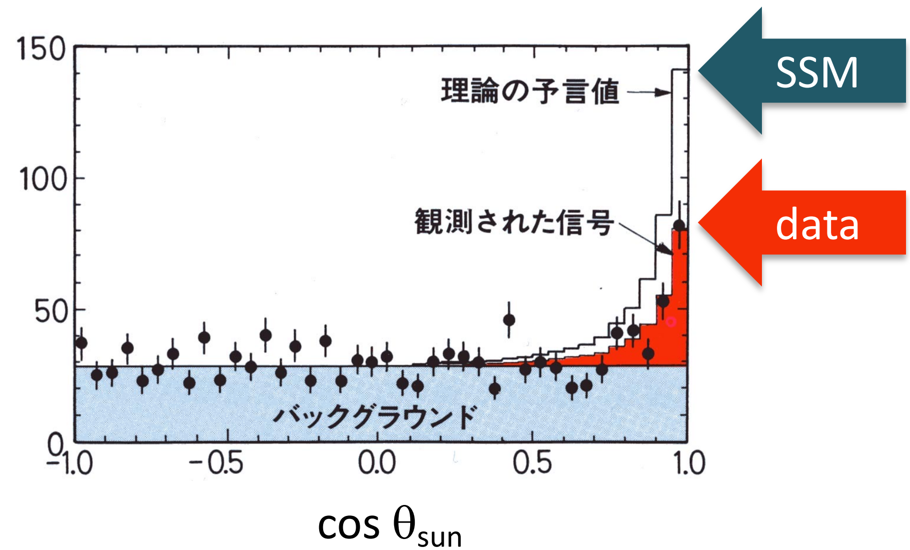

30 years of Ray Davis' Homestake experiment - 800 solar neutrinos
SSM
37Ar production rate (Atoms/day)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
8
7
6
0
1970
1975
1980
1985
1990
1995
Year
SAGE
Gallium Experiments pp ν
Capture rate (SNU)
400
300
200
100
0
SSM
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001
Mean extraction time (years)
Standard Model
Quarks
J/ψ
τ
W/Z
SN1987a
top quark
neutrino oscillation
Non-zero θ13
Higgs-like boson

Kamiokande II and Super-K

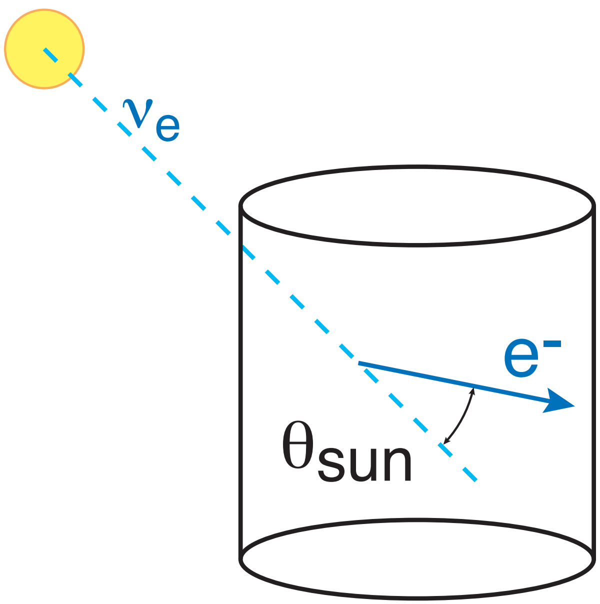


neutrino scattering
off atomic electrons

directional detection

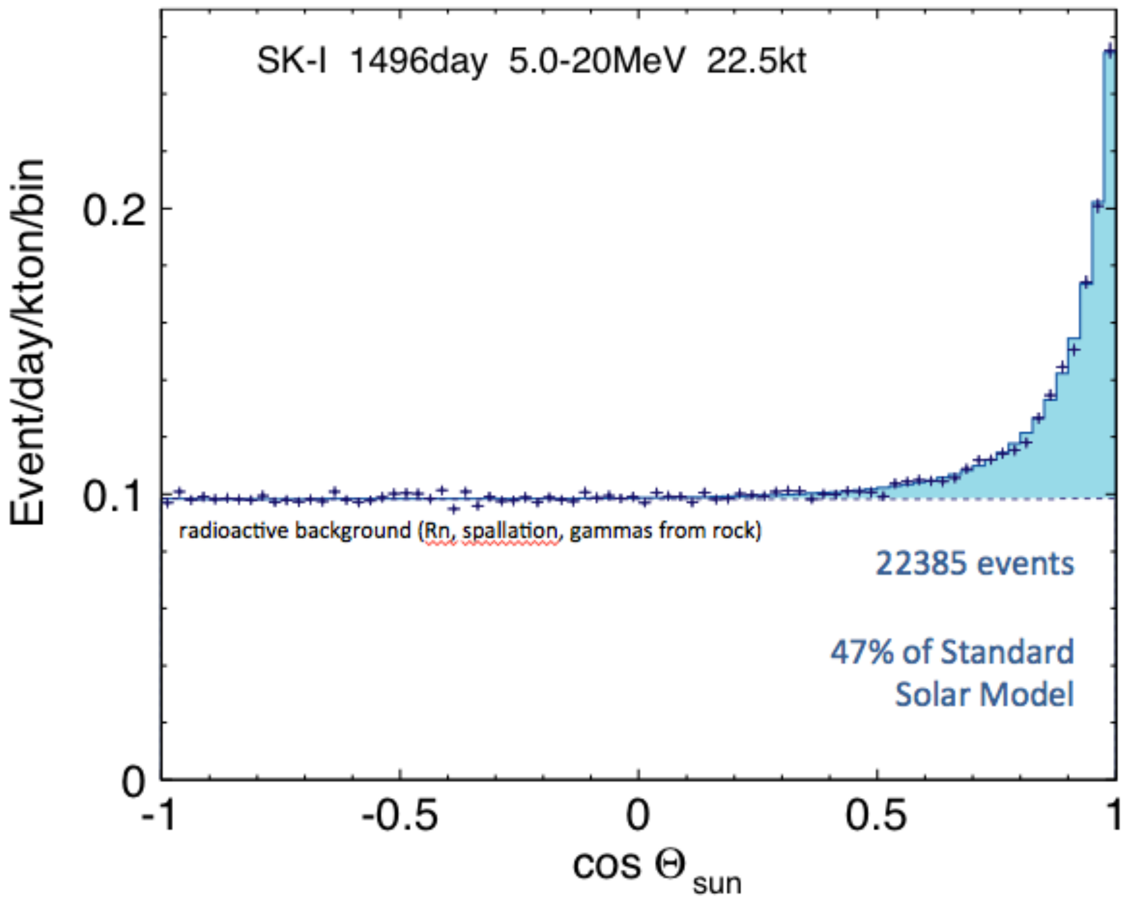


Kamiokande II and Super-K



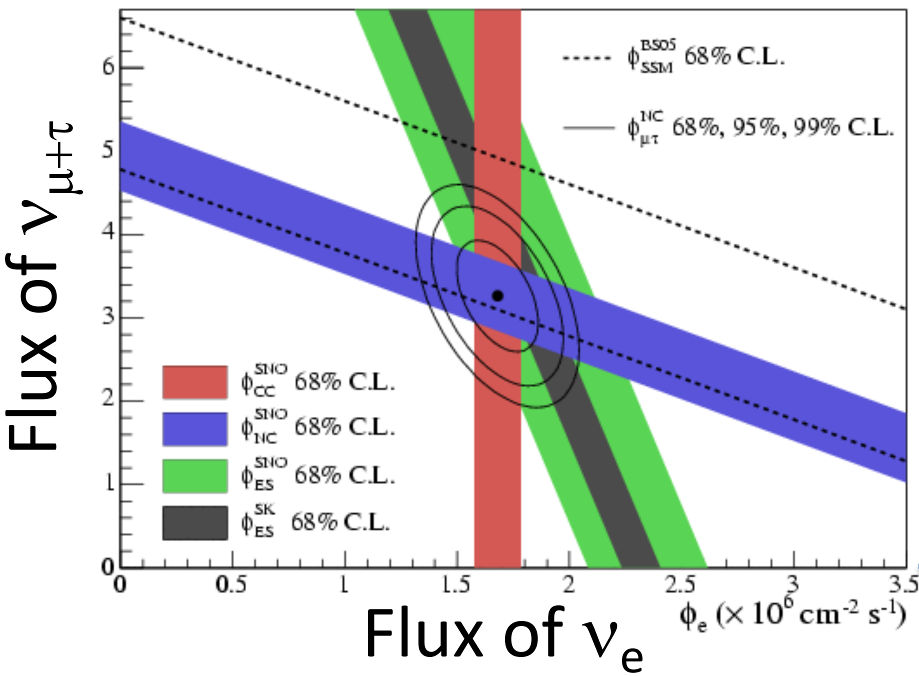
neutrino scattering
off atomic electrons

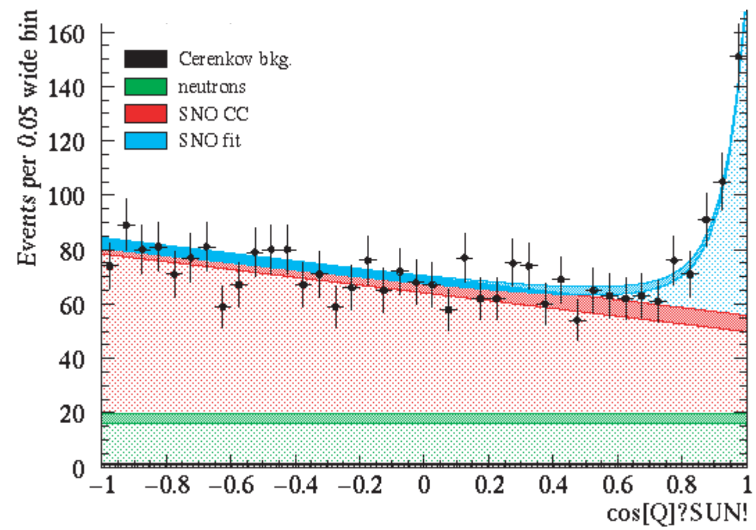
directional detection



SNO

SNO + Super-K



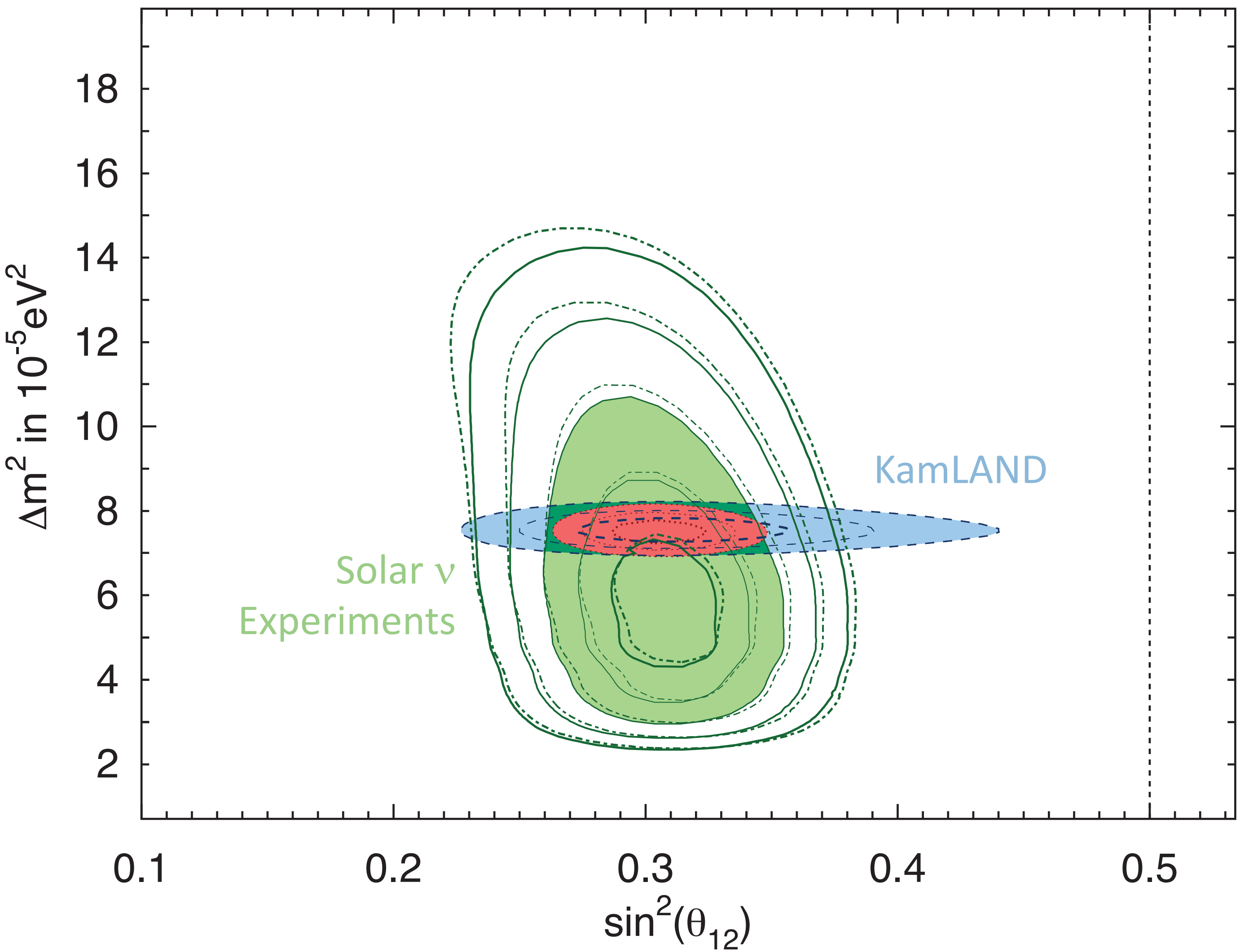


Should measure here if no ν mixing. Standard Solar Model prediction.

(2001)

ν_e only: $\Phi_{CC} = 1.76 \pm 0.11$ x10^{-6} cm^{-1}s^{-1}

$\nu_e + \nu_\mu + \nu_\tau$: $\Phi_{NC} = 5.09 \pm 0.62$ x10^{-6} cm^{-1}s^{-1}



18
16
14
12
10
8
6
4
2
Δm^2 in $10^{-5}eV^2$
0.1
0.2
0.3
0.4
0.5
$\sin^2(\theta_{12})$
KamLAND
Solar ν
Experiments

Solar neutrinos have delivered:

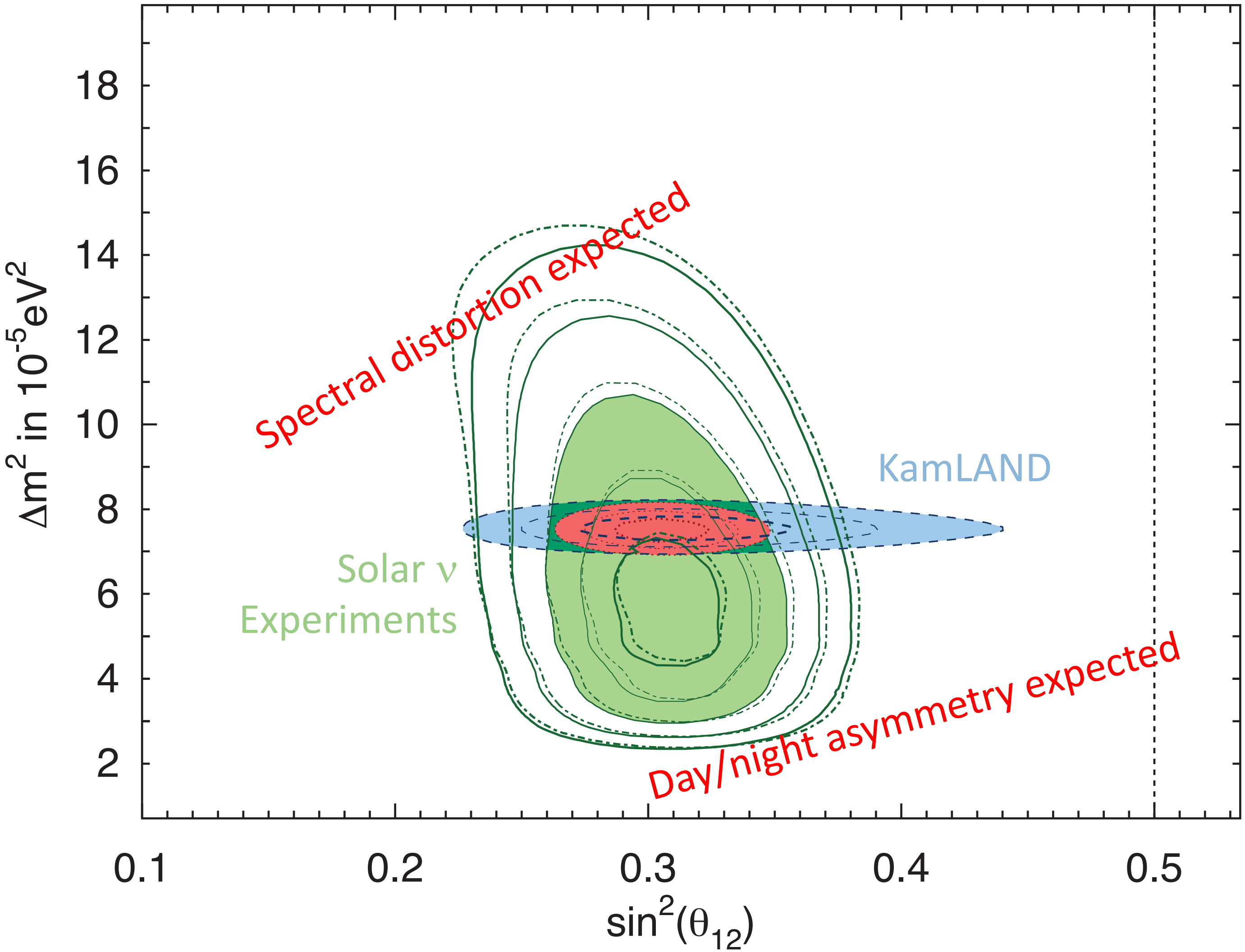
- CC – NC smoking gun
- θ_{12}, Δm_{12} same as KamLAND
- ν_1 ν_2 ordering (mass hierarchy)
- General picture of solar cycle (*pp*, *pep,* ^{7}Be, ^{8}B)

Indications…

- day/night asymmetry from matter effect in the earth

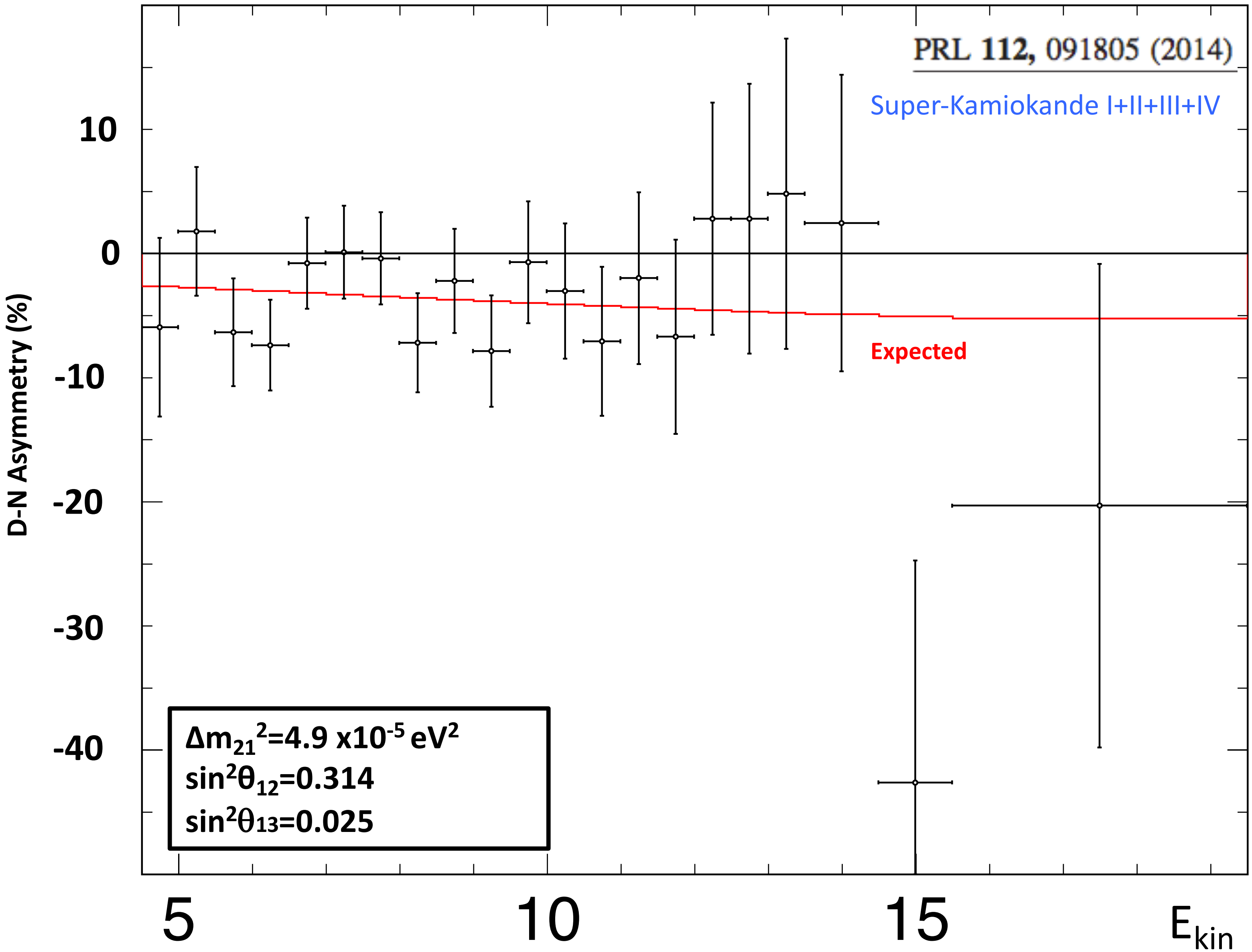
Not yet:

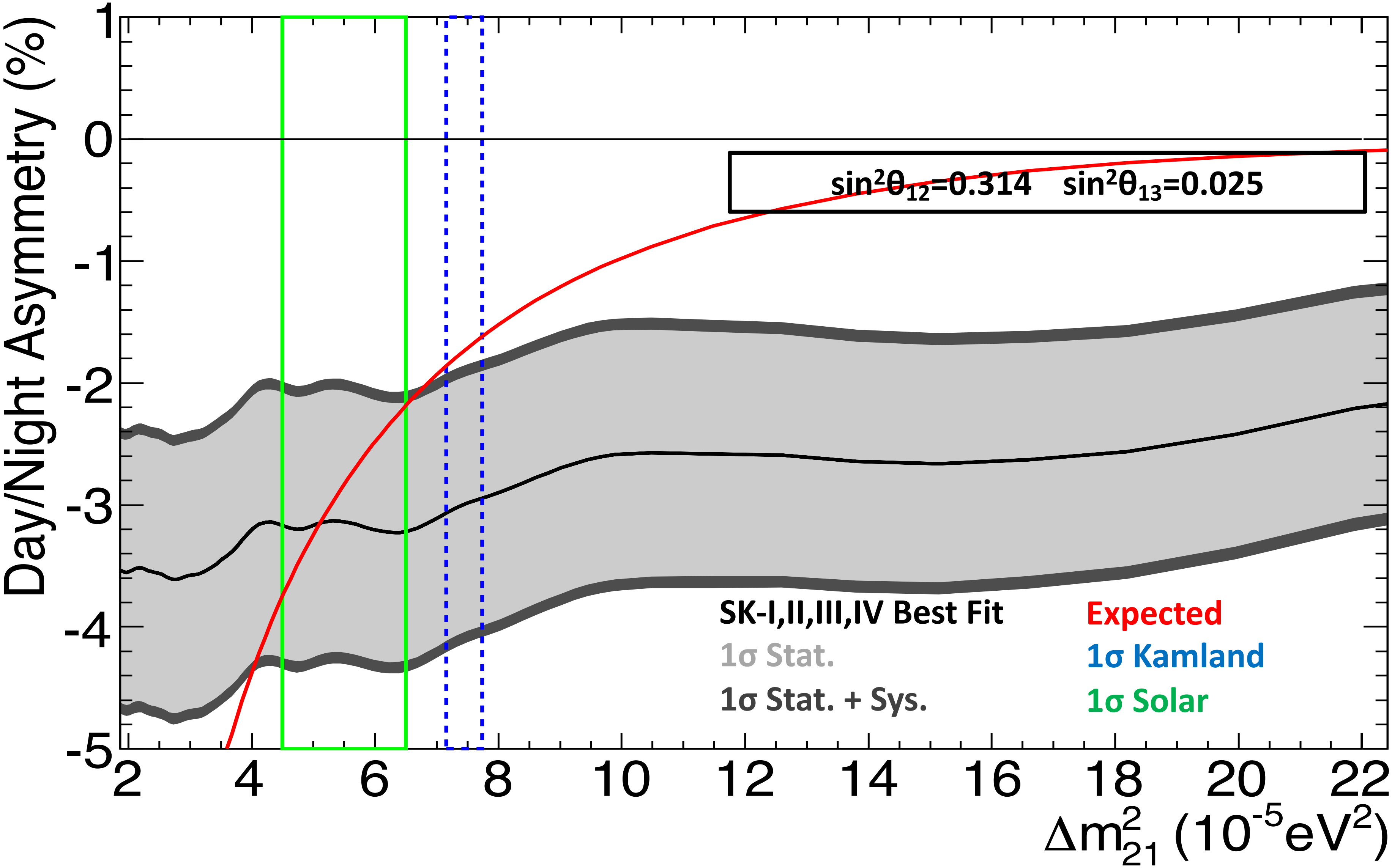
- Spectral distortion of ^{8}B
- *hep* neutrinos
- CNO neutrinos (competing detailed solar models)



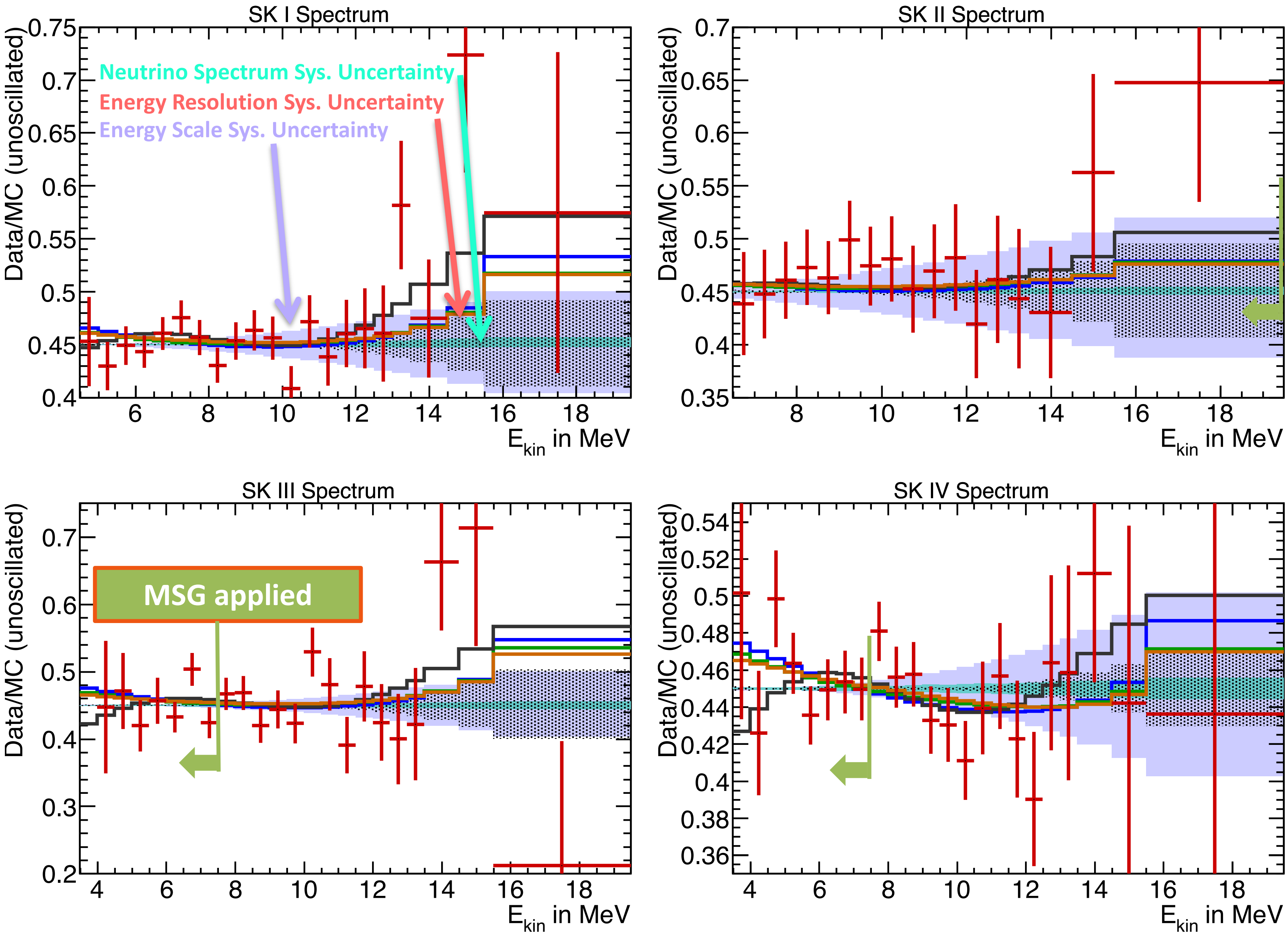
18
16
14
12
10
8
6
4
2
Δm^2 in 10^{-5}eV^2
0.1
0.2
0.3
0.4
0.5
$\sin^2(\theta_{12})$
Spectral distortion expected
KamLAND
Solar ν
Experiments
Day/night asymmetry expected

$$A_{DN}^{fit} = [-3.2 \pm 1.1(\text{stat}) \pm 0.5(\text{syst})]\% \qquad 2.7\sigma$$

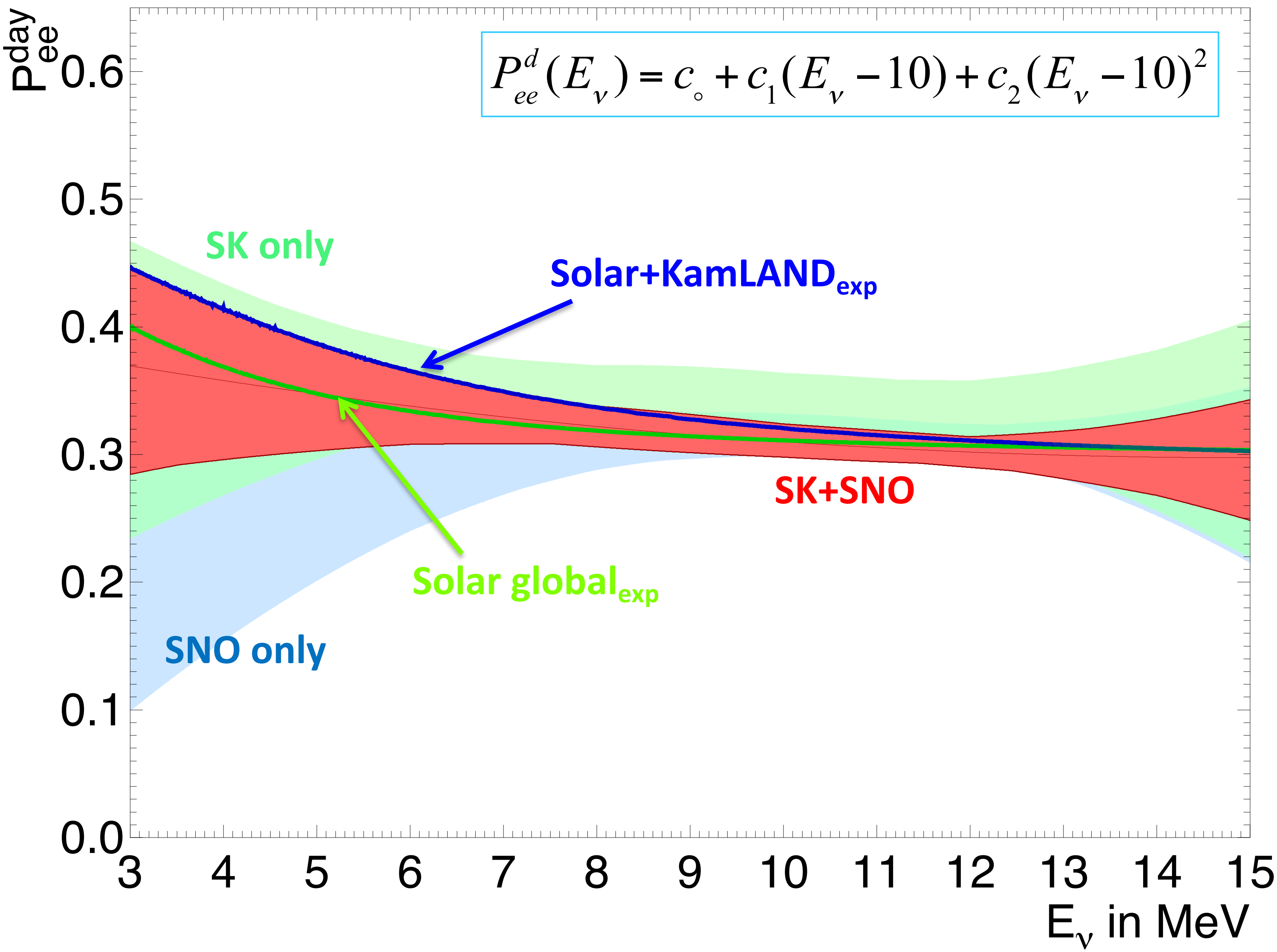




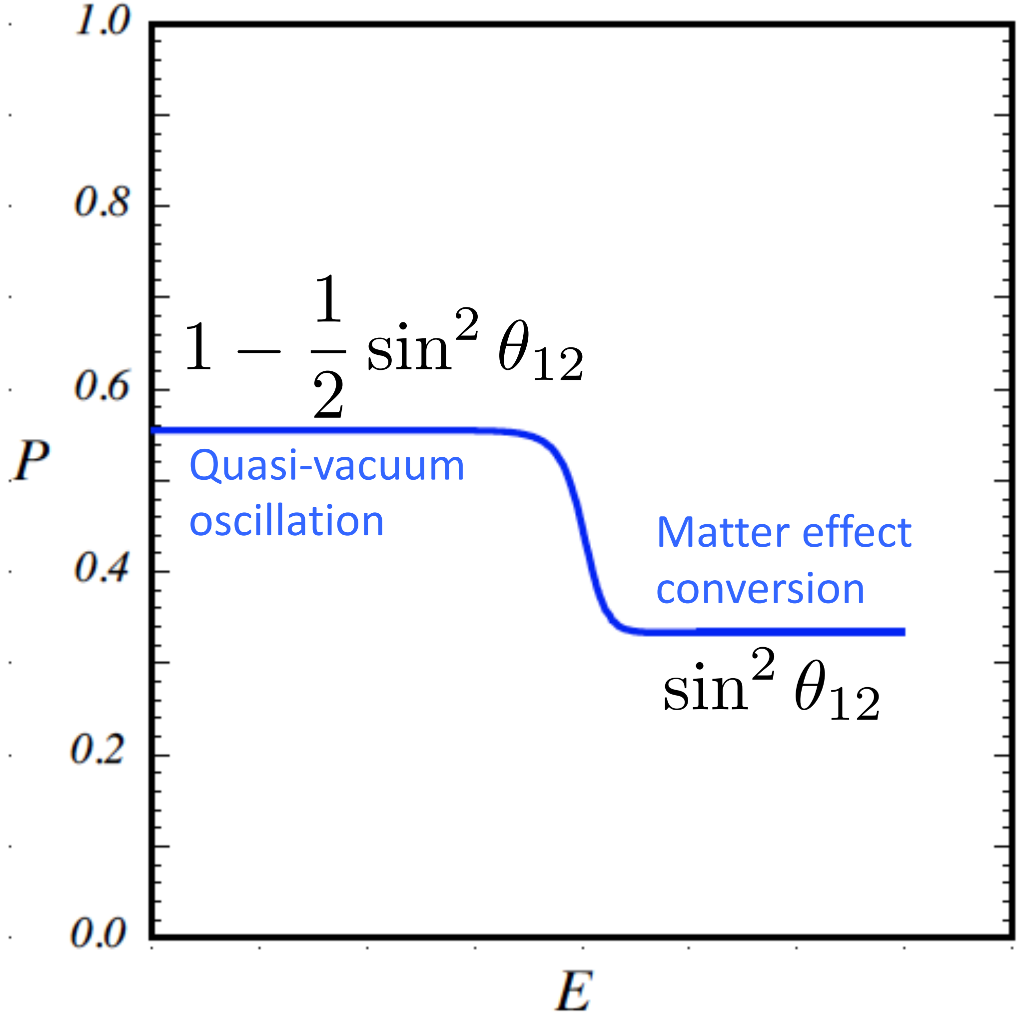
a tiny tension

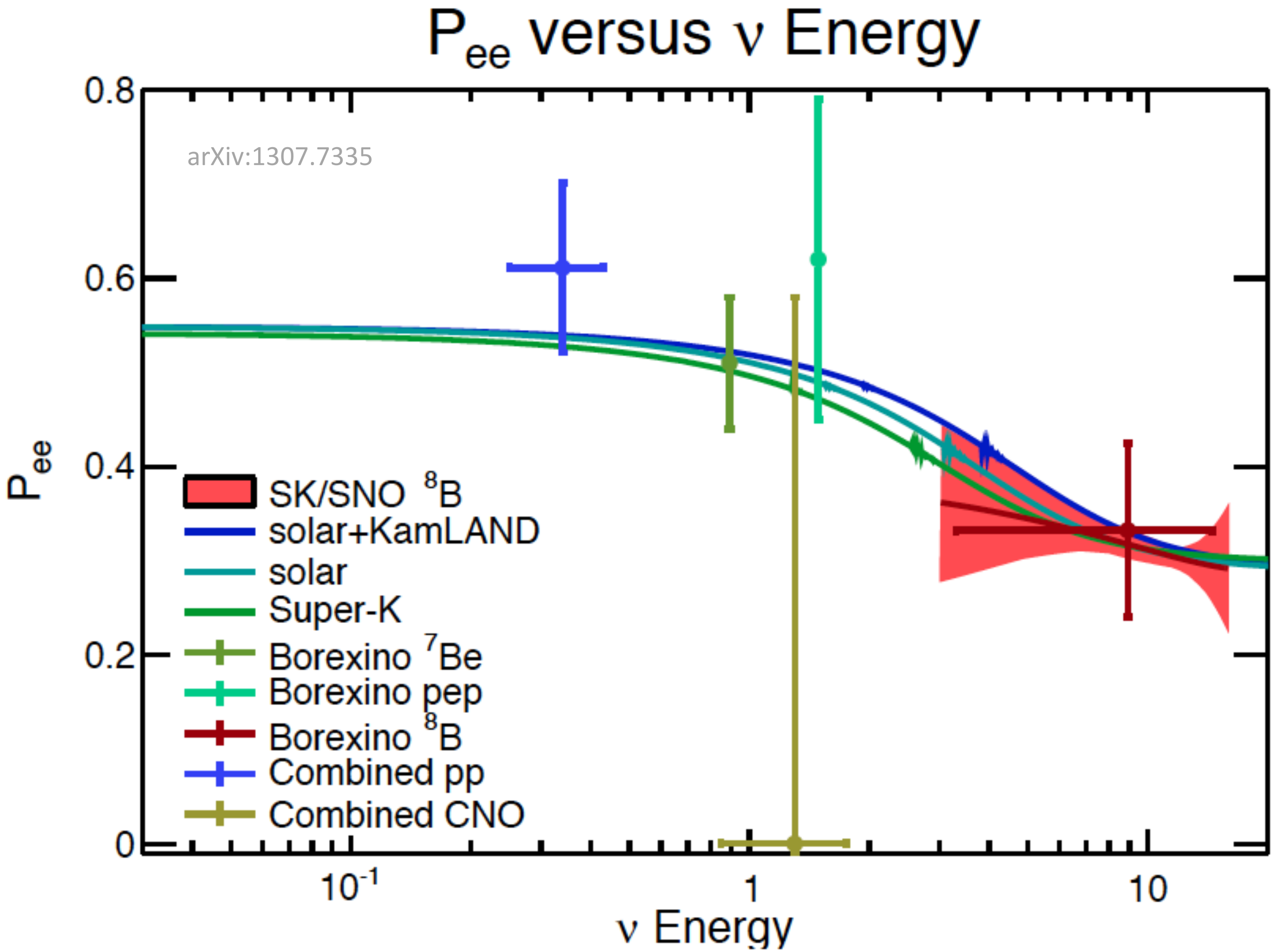


SK I Spectrum
Neutrino Spectrum Sys. Uncertainty
Energy Resolution Sys. Uncertainty
Energy Scale Sys. Uncertainty
Data/MC (unoscillated)
E_kin in MeV
SK II Spectrum
SK III Spectrum
MSG applied
SK IV Spectrum



P_{ee}^{day}
$P_{ee}^{d}(E_\nu) = c_\circ + c_1(E_\nu - 10) + c_2(E_\nu - 10)^2$
SK only
Solar+KamLAND$_{exp}$
SK+SNO
Solar global$_{exp}$
SNO only
0.0
0.1
0.2
0.3
0.4
0.5
0.6
3
4
5
6
7
8
9
10
11
12
13
14
15
E_ν in MeV


1.0
0.8
0.6
0.4
0.2
0.0
P
E
$1 - \frac{1}{2}\sin^2\theta_{12}$
Quasi-vacuum oscillation
Matter effect conversion
$\sin^2\theta_{12}$



Pee versus ν Energy
arXiv:1307.7335
0.8
0.6
0.4
0.2
0
Pee
SK/SNO 8B
solar+KamLAND
solar
Super-K
Borexino 7Be
Borexino pep
Borexino 8B
Combined pp
Combined CNO
10-1
1
10
ν Energy

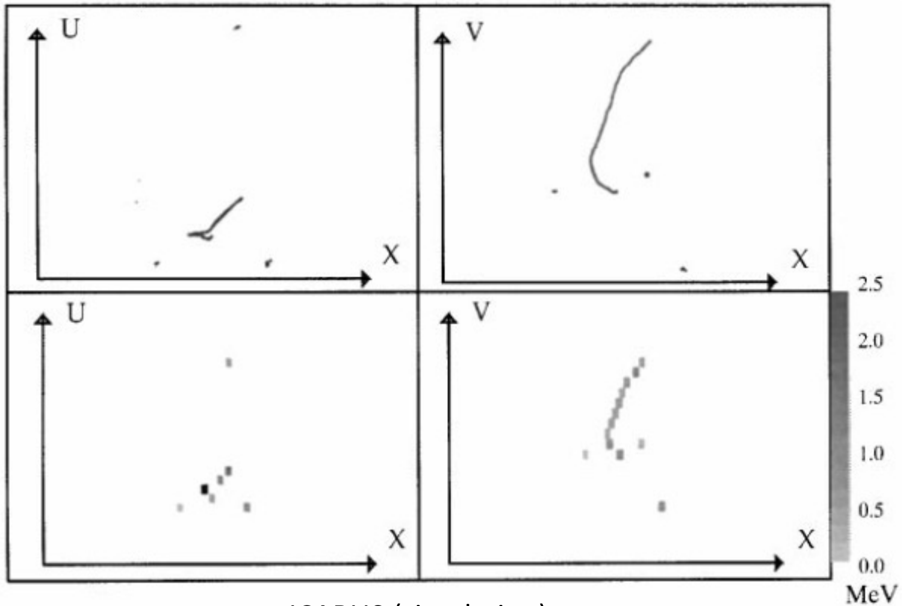
Solar outlook

- Hyper-K: bigger, but shallower, and probably lower photocoverage. $E_{thresh} \approx 7$ MeV
- Borexino and SNO+ will try for pp, pep, CNO
- LArTPC?

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$$

5 MeV threshold
spallation background needs study
photon trigger required

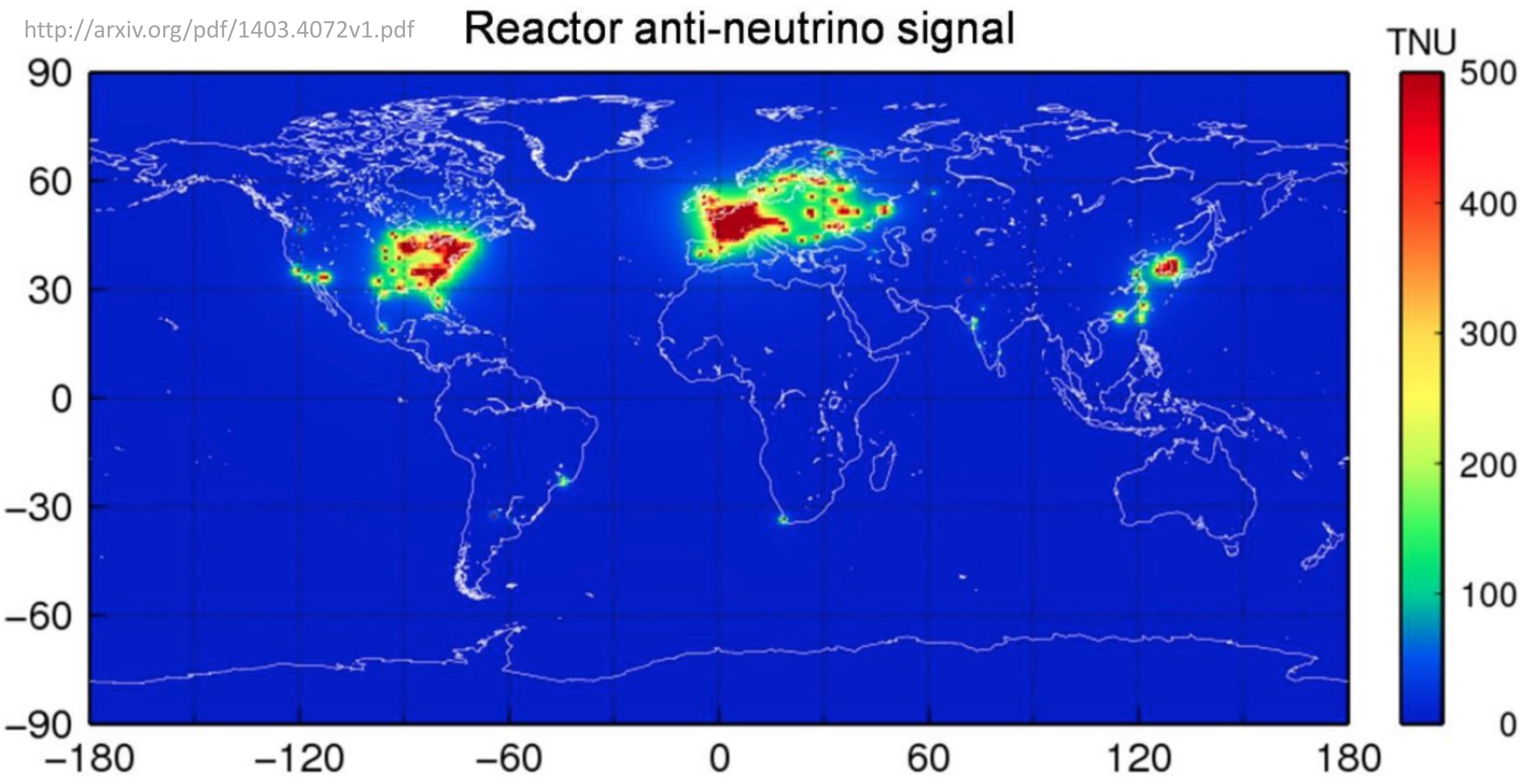
electron energy ∝ Eν
∼ 100 events per day (34 kton)



ICARUS (simulation)

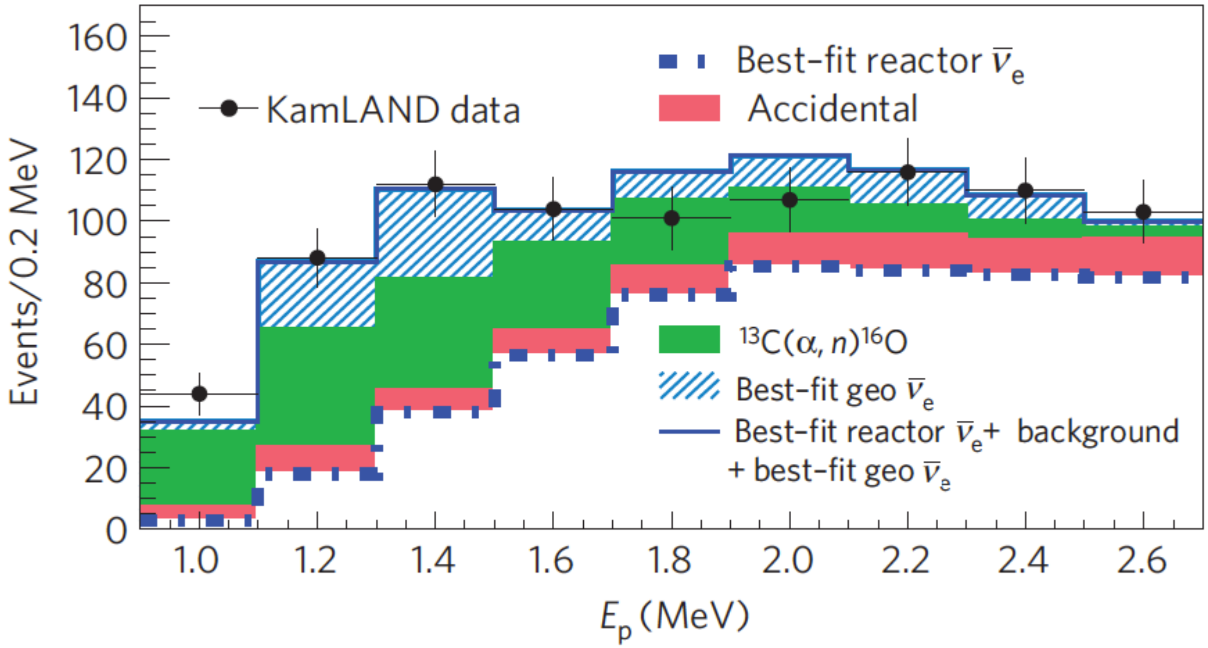
✸ Terrestrial Antineutrinos

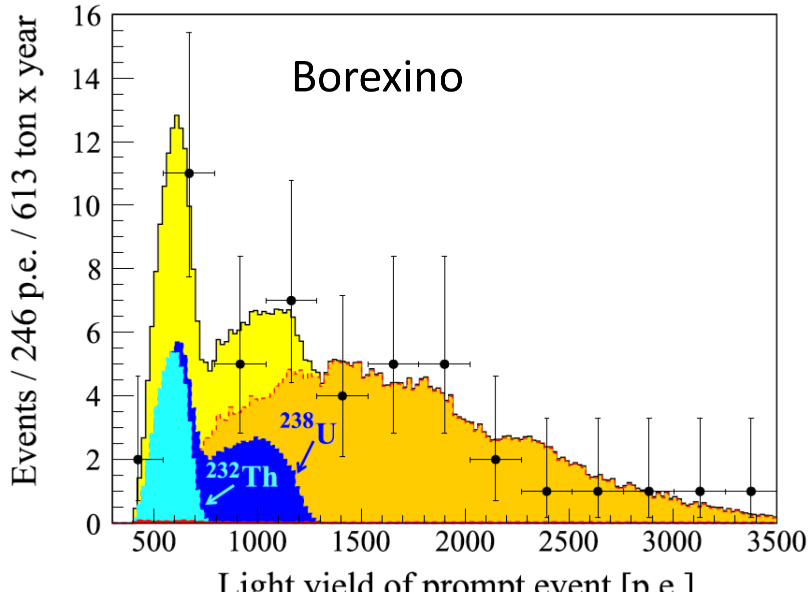
http://arxiv.org/pdf/1403.4072v1.pdf



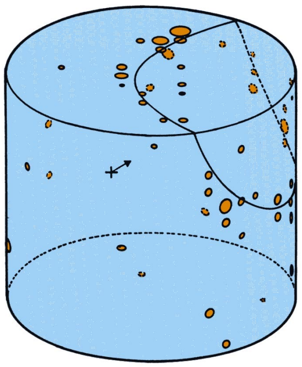
Study heat production in the Earth's interior

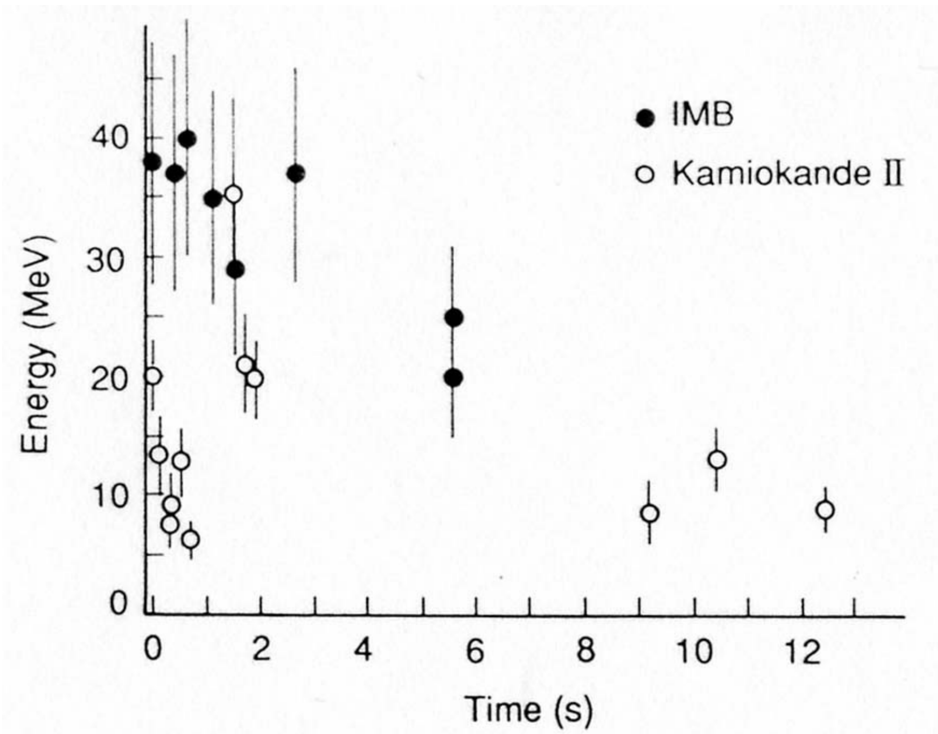
Terrestrial Antineutrinos have been observed

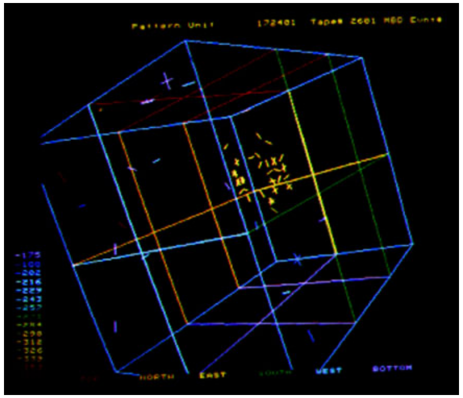




✷ Supernova Neutrinos



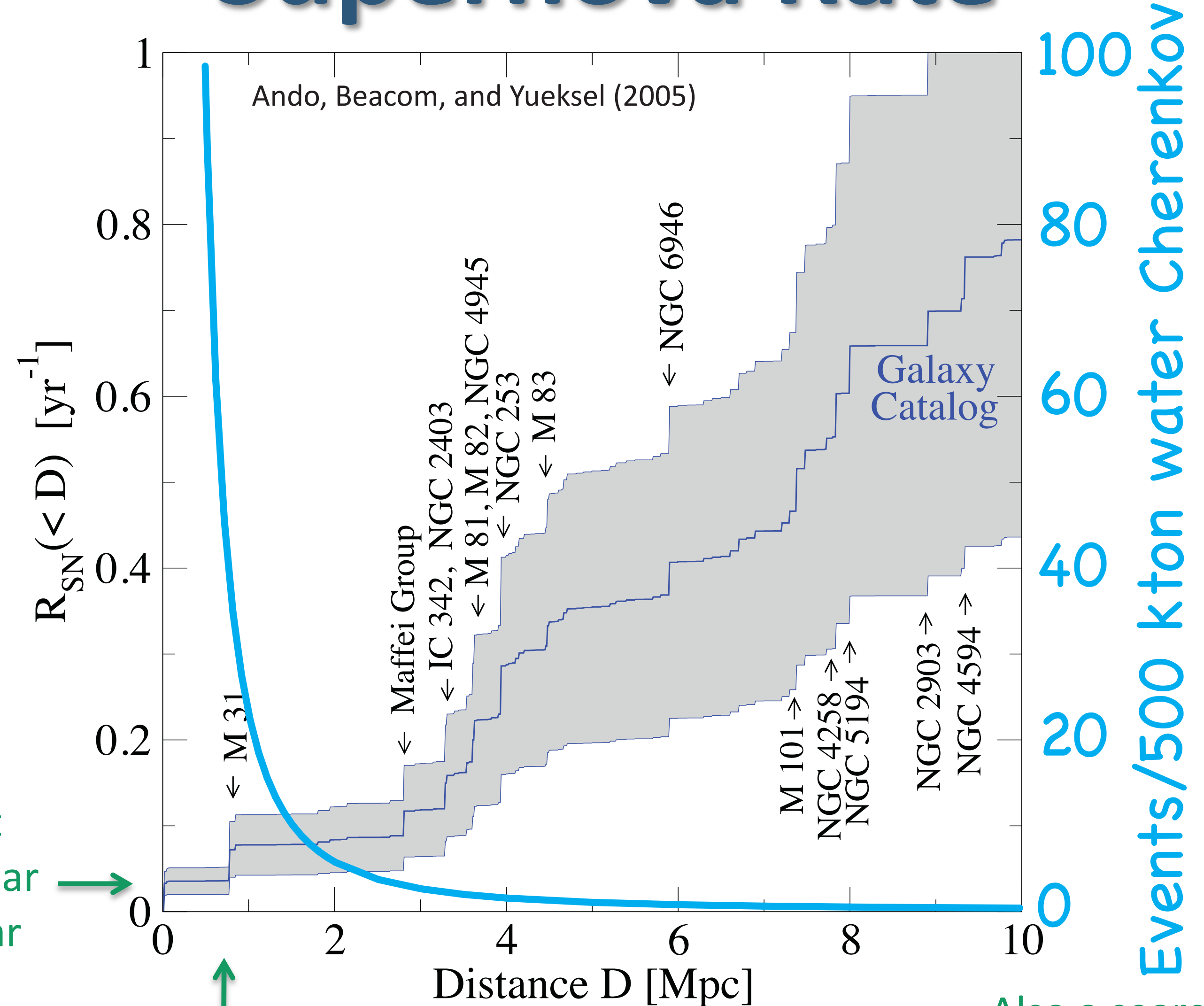




Supernova Neutrinos

- Guaranteed signal – if you run long enough.
- Enormous statistics in a megaton-scale detector.
- Early warning before light and directional pointing
- Time profile and spectra of great astrophysical interest. Possibilities such as Si-burning and black hole formation.
- Standard picture: Initial burst of ν_e and cooling tail of equal flavors
- Matter effects in SN and in earth may be revealed.
- May reveal fundamental neutrino physics as well.

Supernova Rate

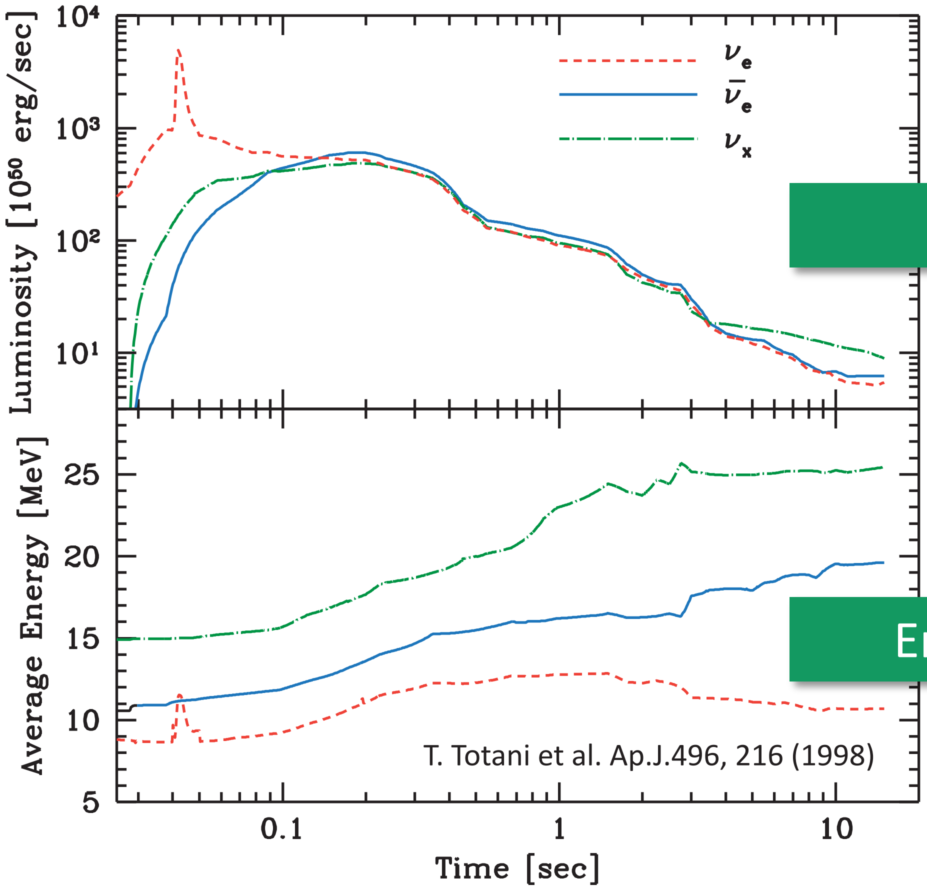


Milky Way: few percent chance per year of spectacular signal

500 kton detector adds 30-50 event burst from Andromeda (M31)

Also a search strategy of time coincidence of 1-2 events from more distant galaxies

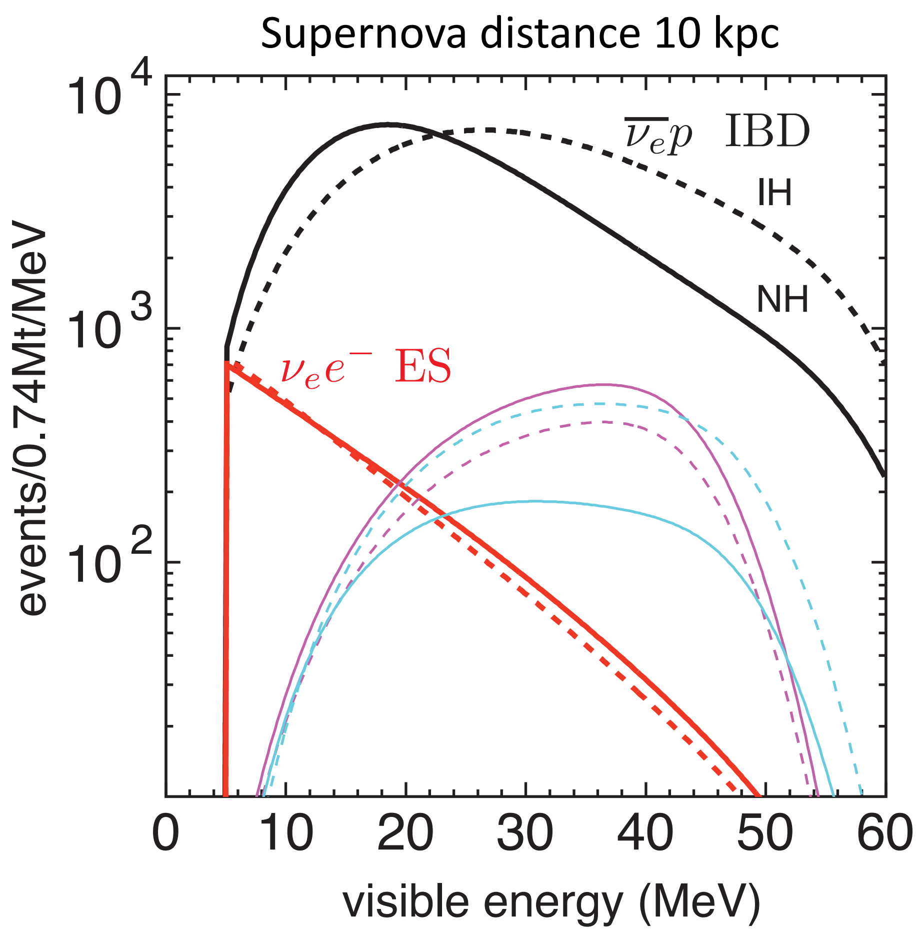
Supernova Observables



Time profile

Energy Spectrum

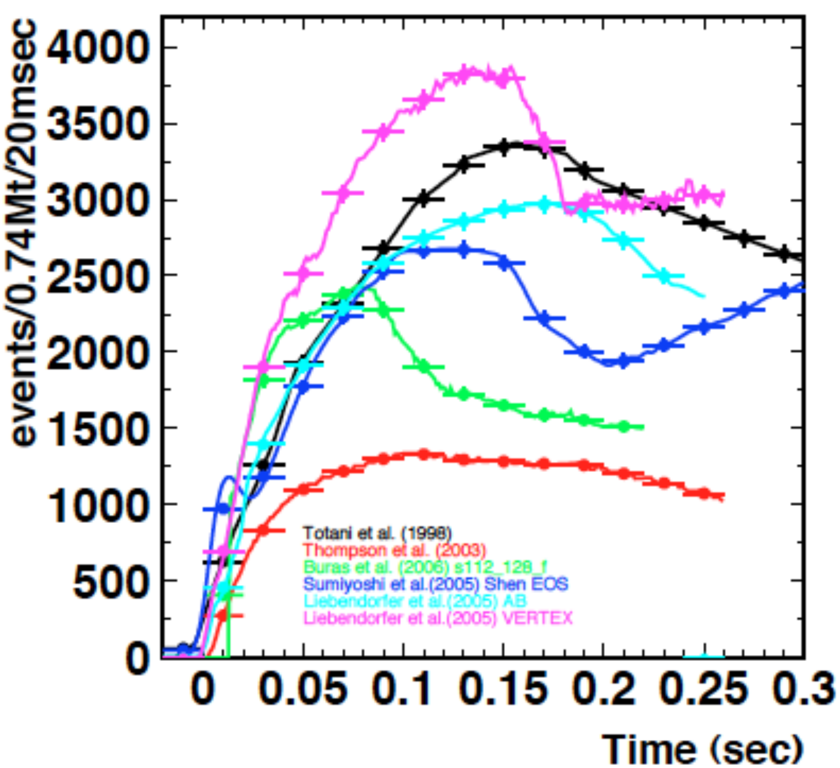
Event Rates in Hyper-K

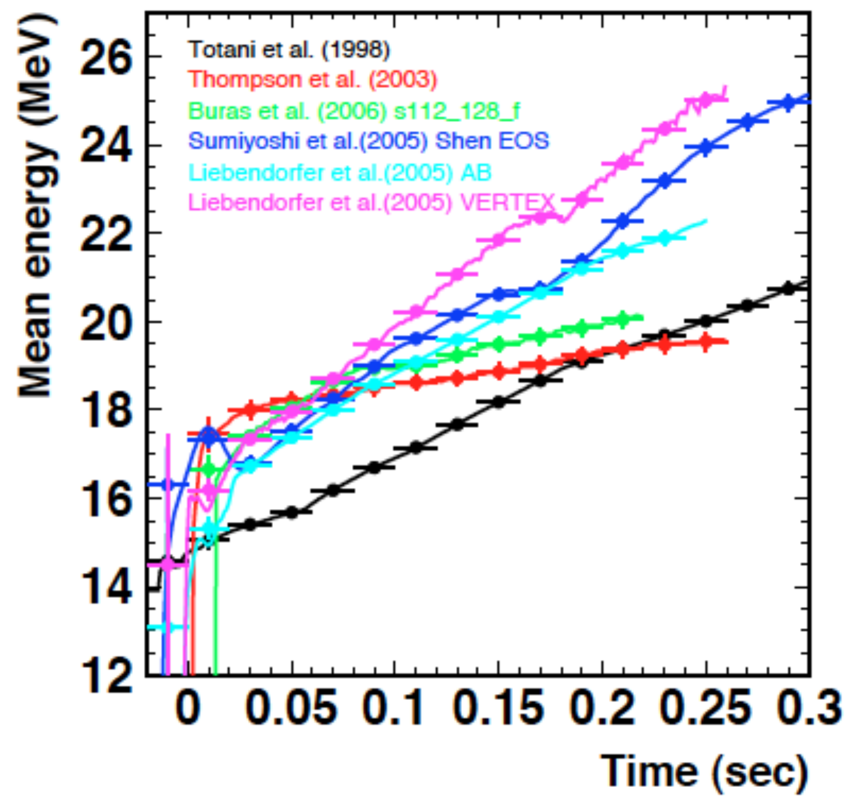


Entire inner volume (0.74 Mton) should be useable for SN burst.

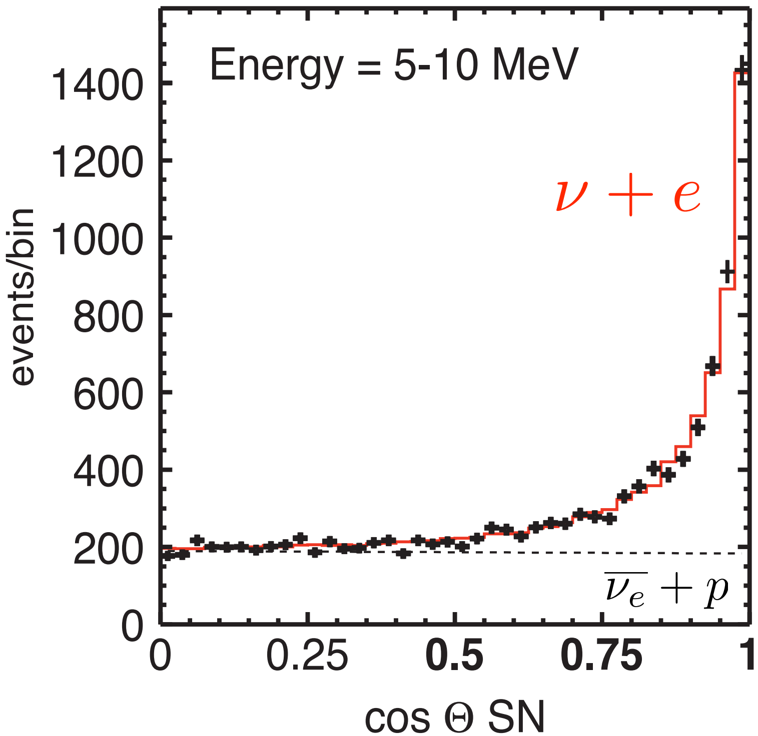
165K – 230K IBD events
7K – 8K ES events

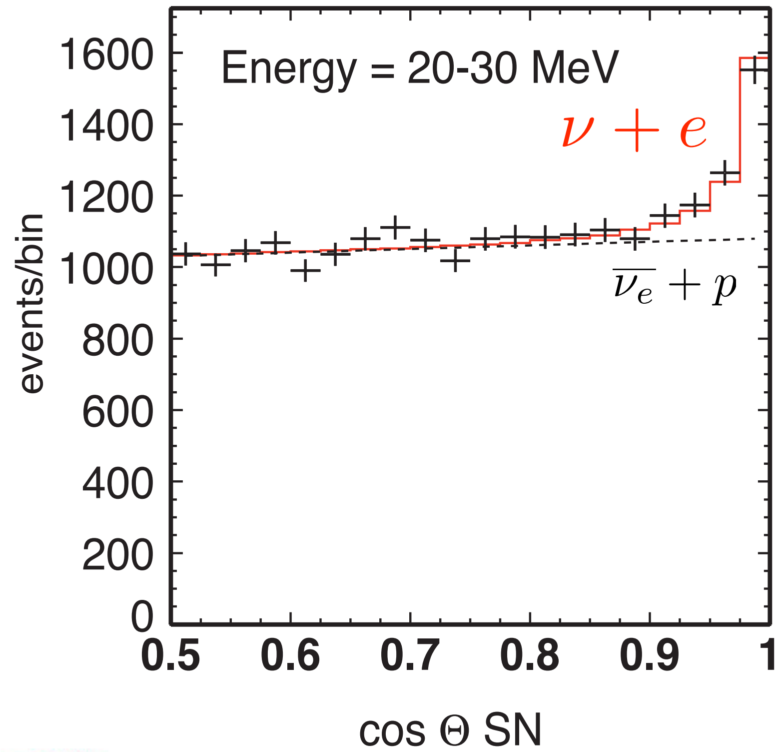
Enough Statistics to Distinguish SN Models

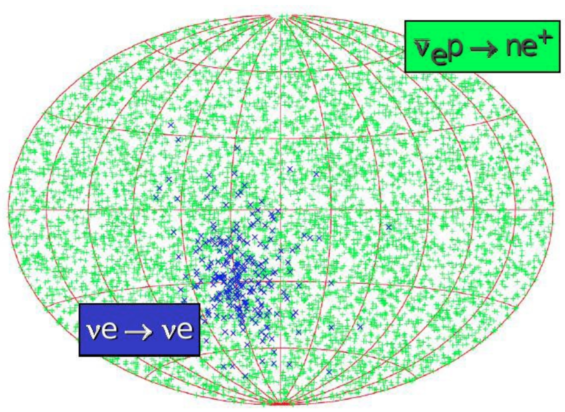




Directional Pointing



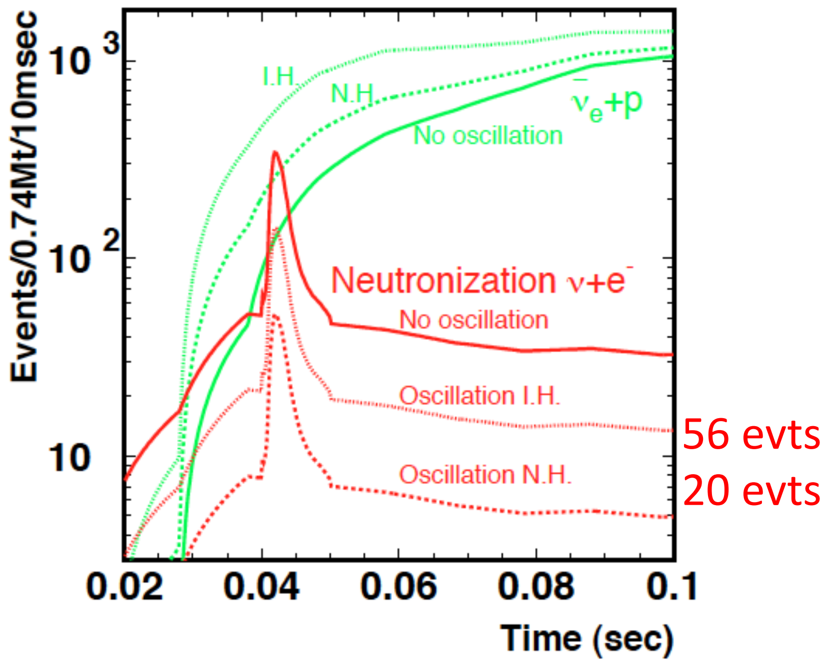


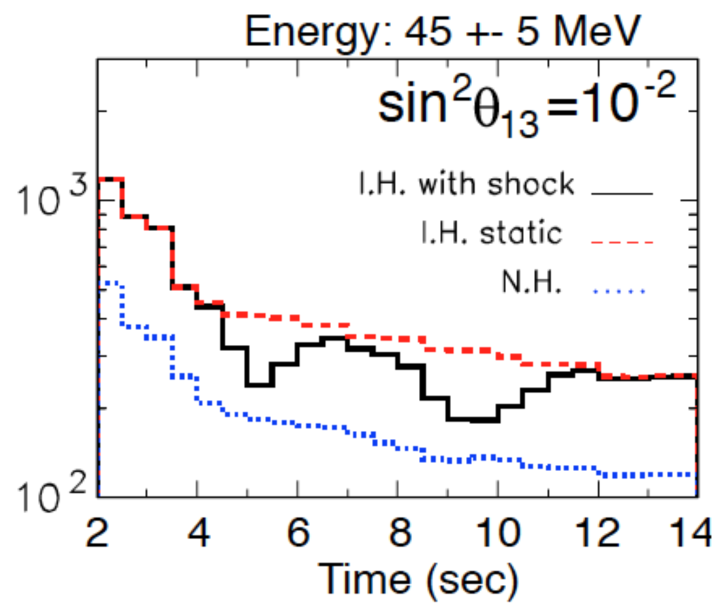


Accuracy of
1-2 degrees

Mass Hierarchy Determination

Neutrino – antineutrino matter resonance swaps with Normal – Inverted Hierarchy



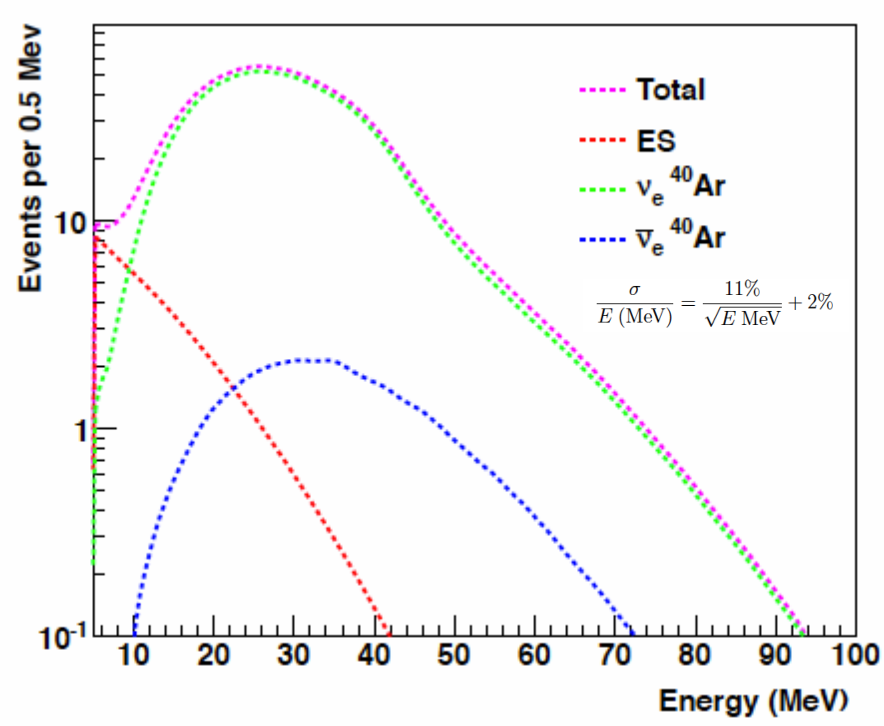


Size of neutronization burst
may suggest hierarchy

Observation of shock wave
in IBD events favors IH

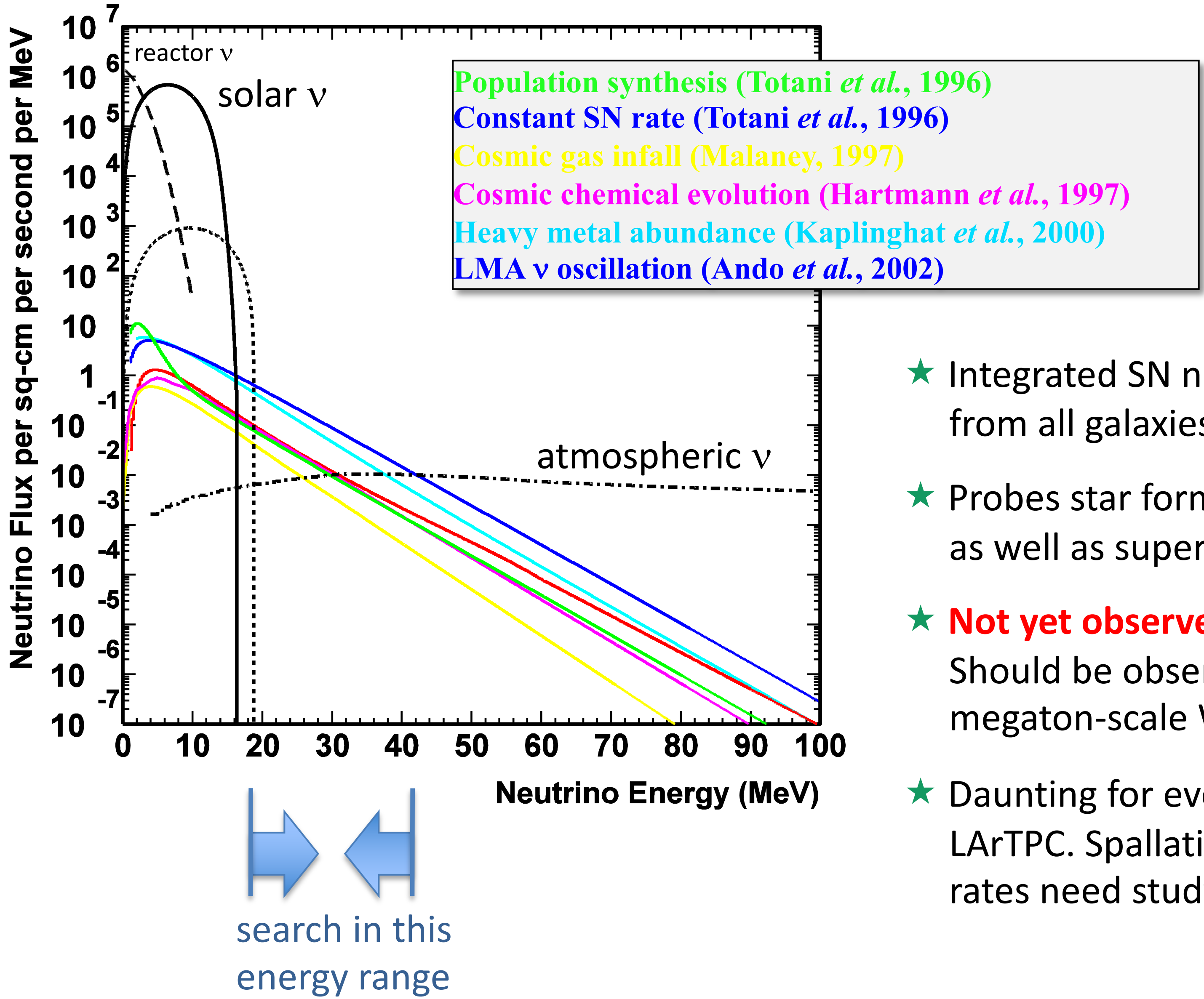
LArTPC?

- Complementary to WC (ν_e not anti-ν_e)
- 1000's of events in 34kt
- Good energy correlation
- Photon trigger?
  Or trigger by nearby modest sized WC?

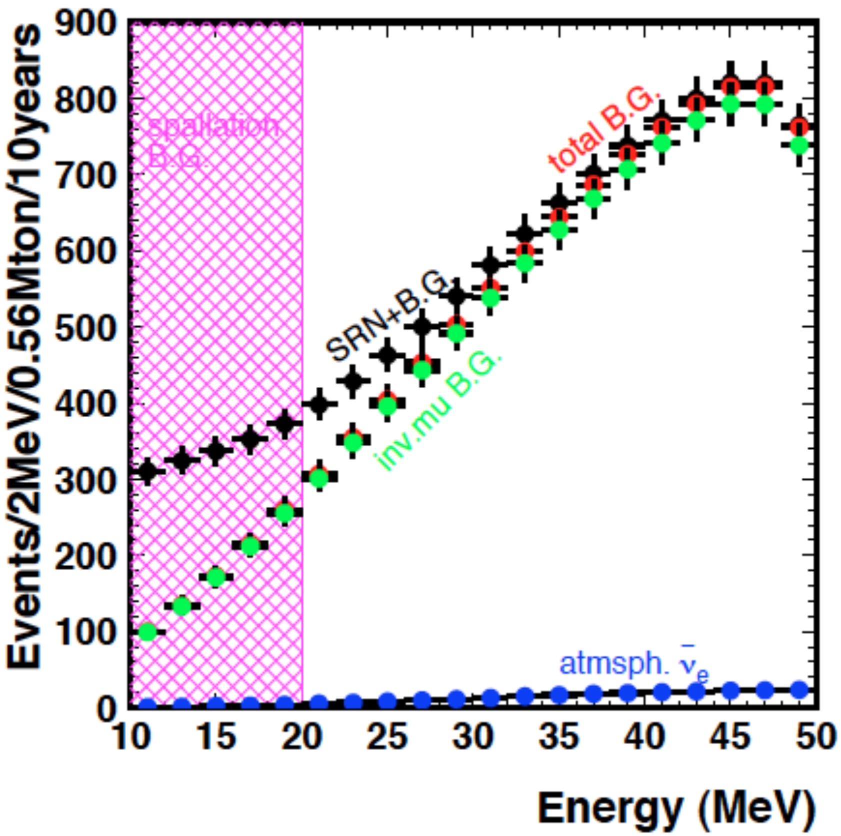


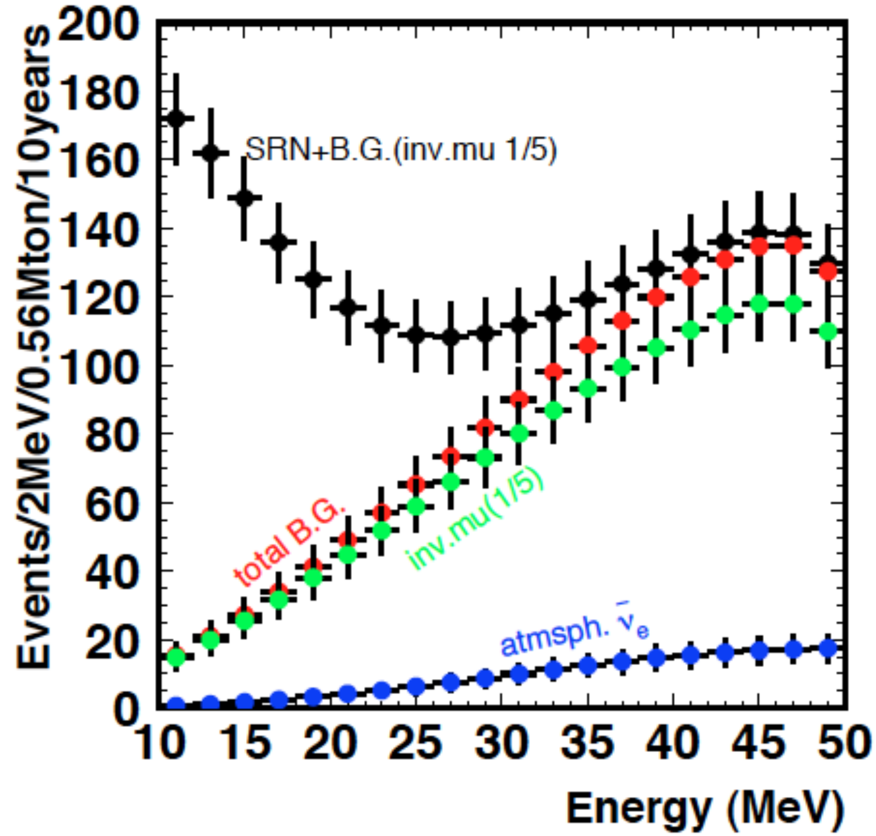
Channel	Events *Livermore* model	Events *GKVM* model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2308	2848
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	**2794**	**3160**

✸ Diffuse Relic Supernova Neutrinos



- Integrated SN neutrino flux from all galaxies (to $z \approx 1$)
- Probes star formation models as well as supernova models.
- **Not yet observed!** Should be observable by megaton-scale WC detector.
- Daunting for even a massive LArTPC. Spallation background rates need study.



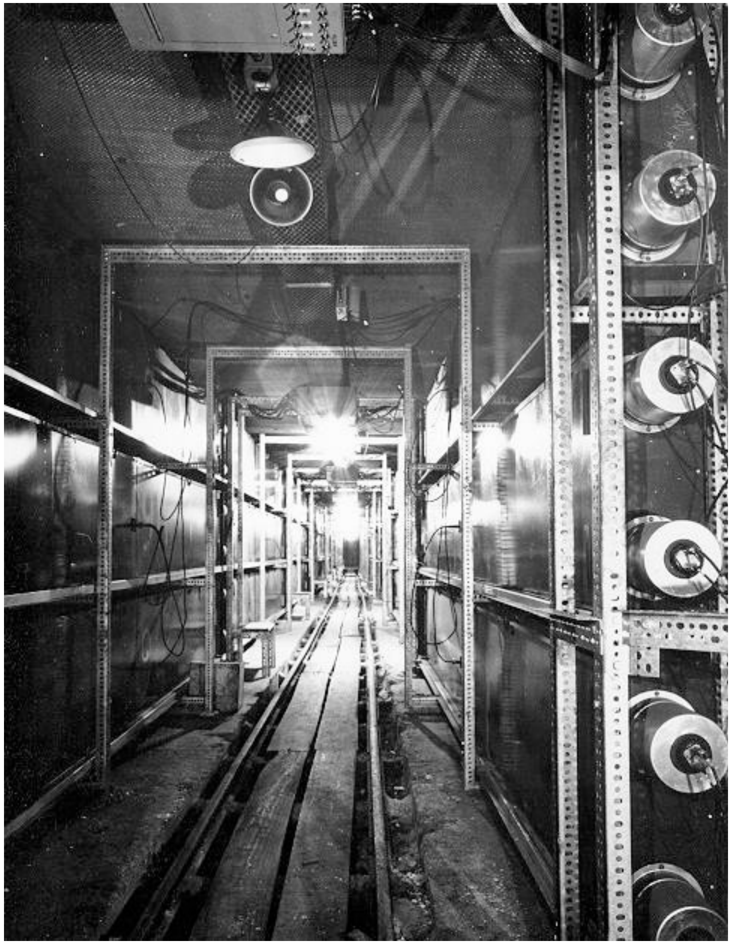


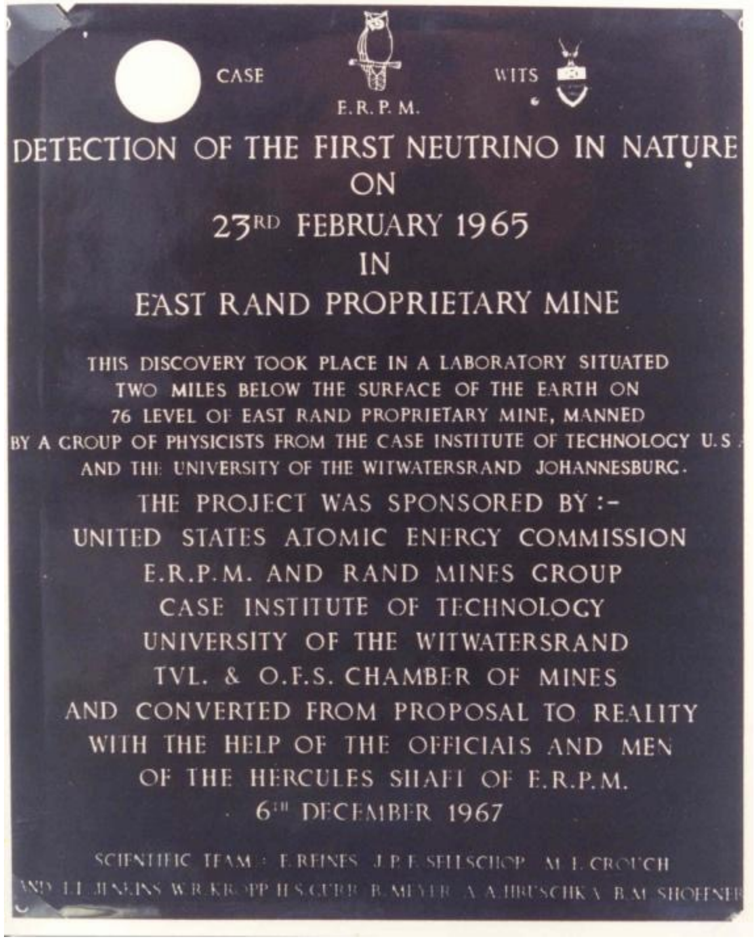
Remarkable improvement with Gd tagging of neutron.

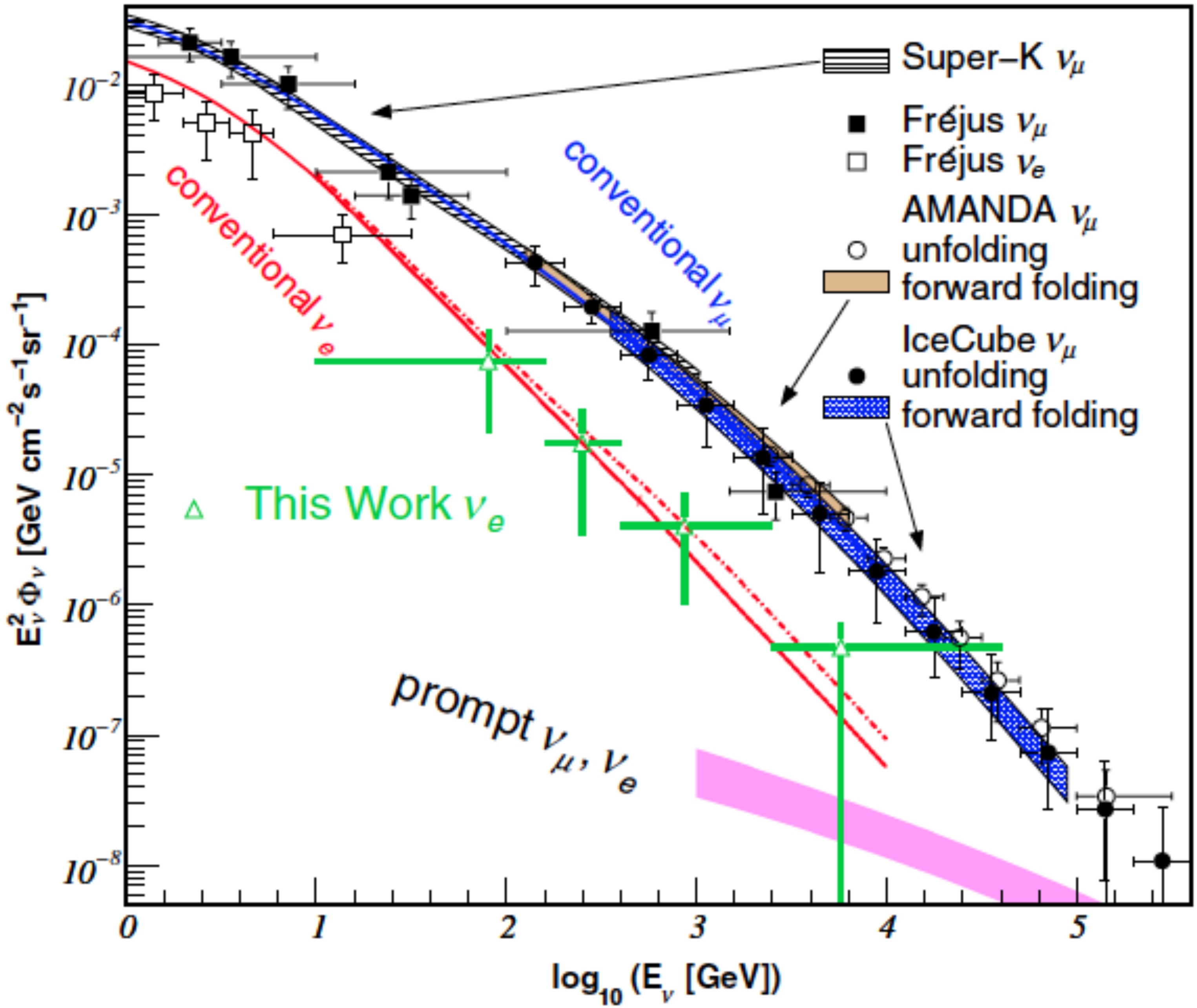
Hyper-K LOI arXiv:1109.3262v1

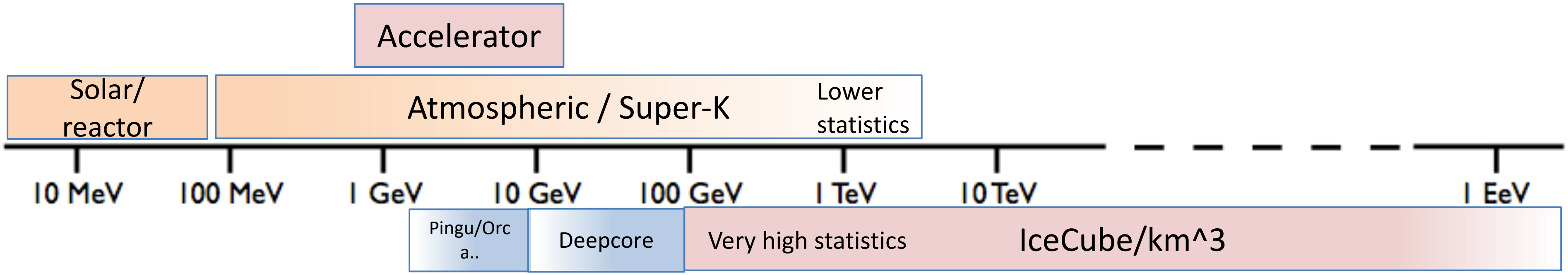
LArTPC? See challenges for solar neutrinos.
Roughly 40 events in a 34 kt x 10 year exposure

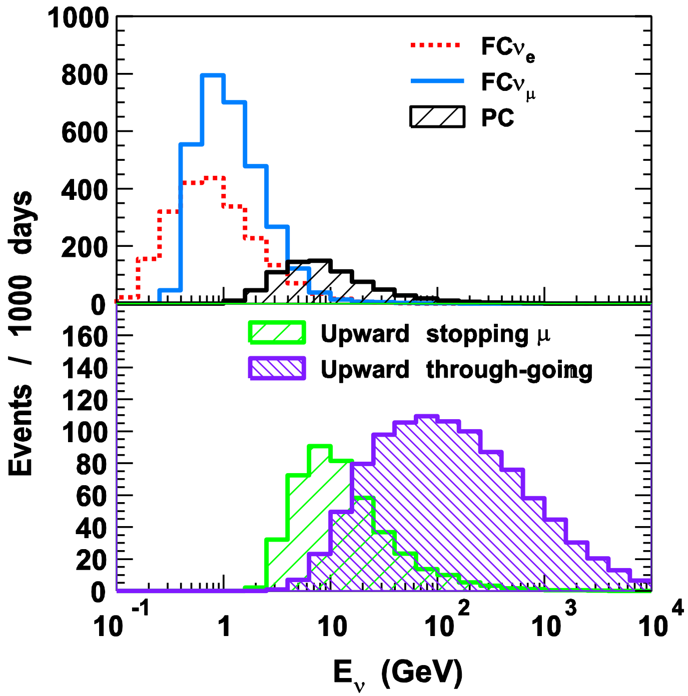
Atmospheric Neutrinos



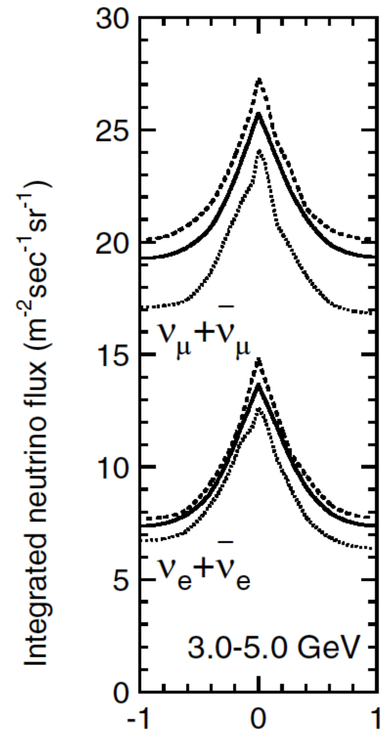


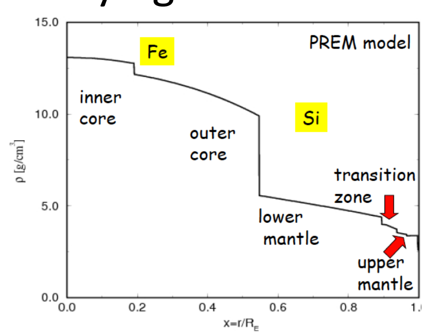

Super–K ν_μ
Fréjus ν_μ
Fréjus ν_e
AMANDA ν_μ
unfolding
forward folding
IceCube ν_μ
unfolding
forward folding
conventional ν_μ
conventional ν_e
This Work ν_e
prompt ν_μ, ν_e
$E_\nu^2 \Phi_\nu$ [GeV cm^{-2}s^{-1}sr^{-1}]
$\log_{10}$ (E_ν [GeV])



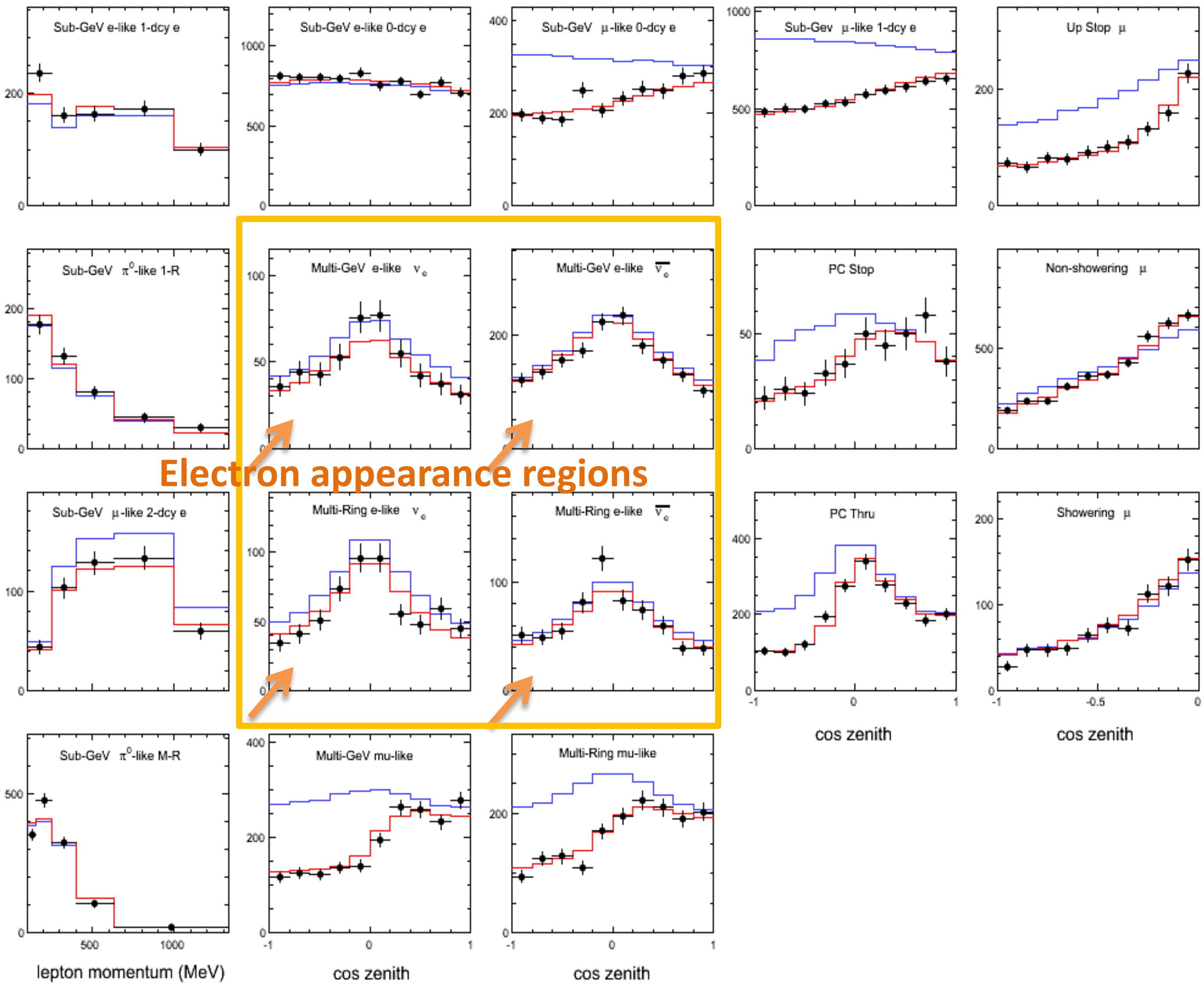


- Exponential energy spectrum energies 100 MeV – 10 TeV
- Flux ratios (well estimated and self-calibrated)
  - mu/e
  - up/down
- Pathlength: 15-13000 km
- Varying matter density

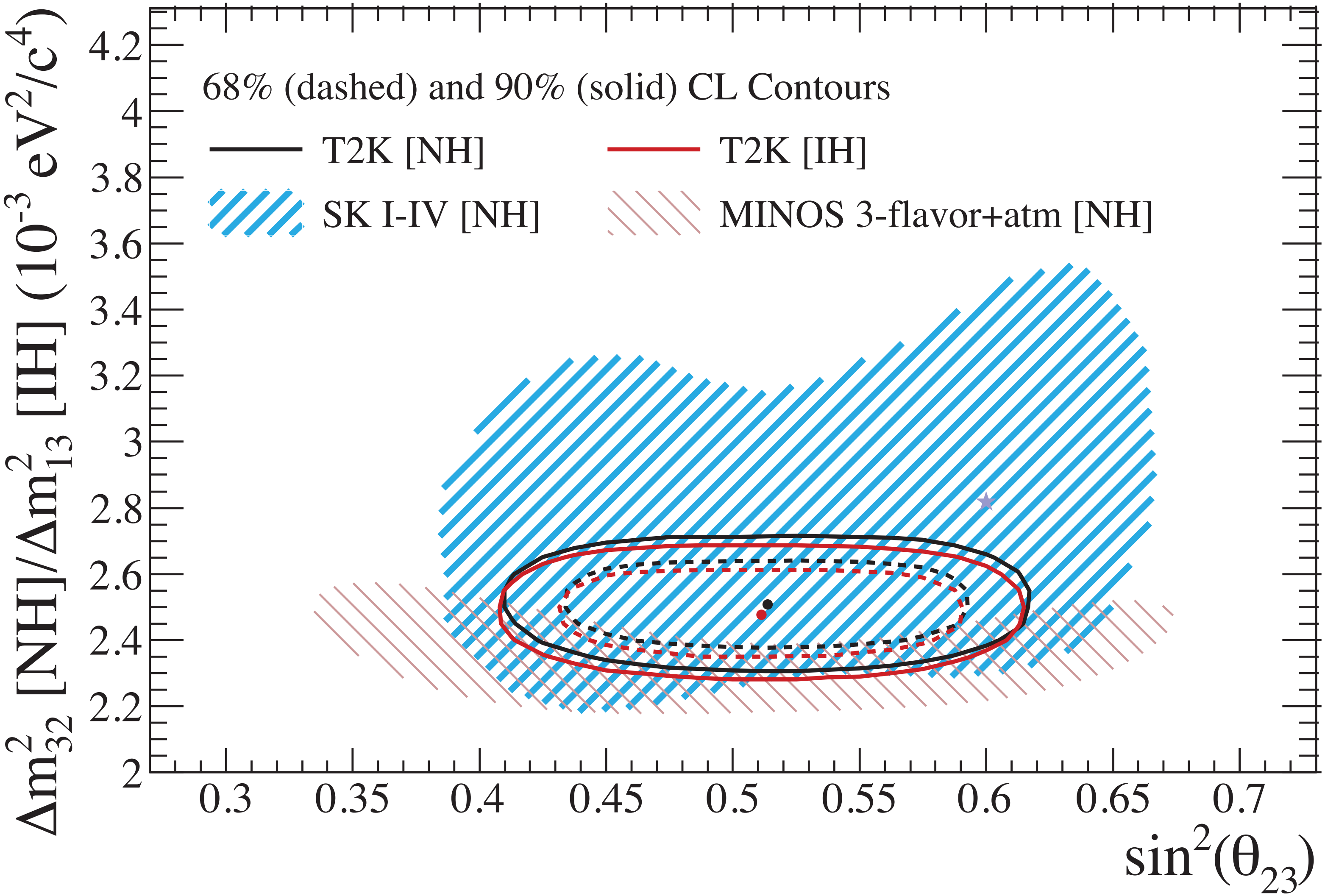




Super-K I+II+III+IV Combined Dataset



Until recently, atmospheric neutrinos provided tightest constraint on θ_{23}

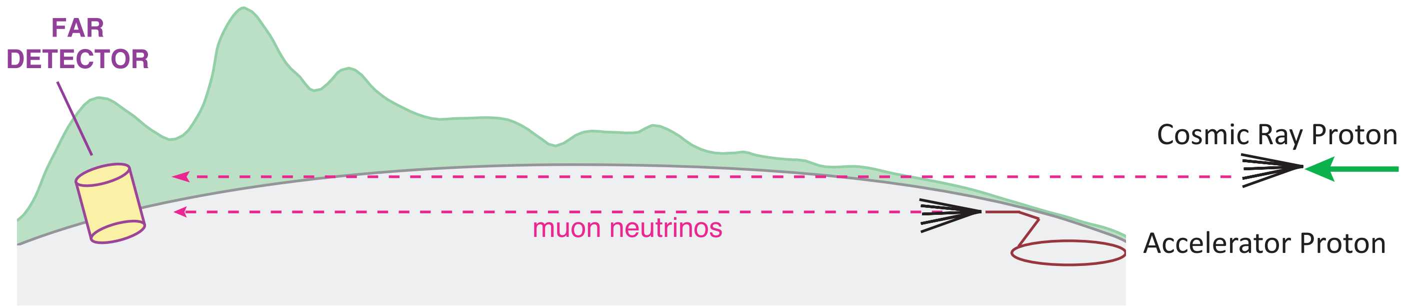


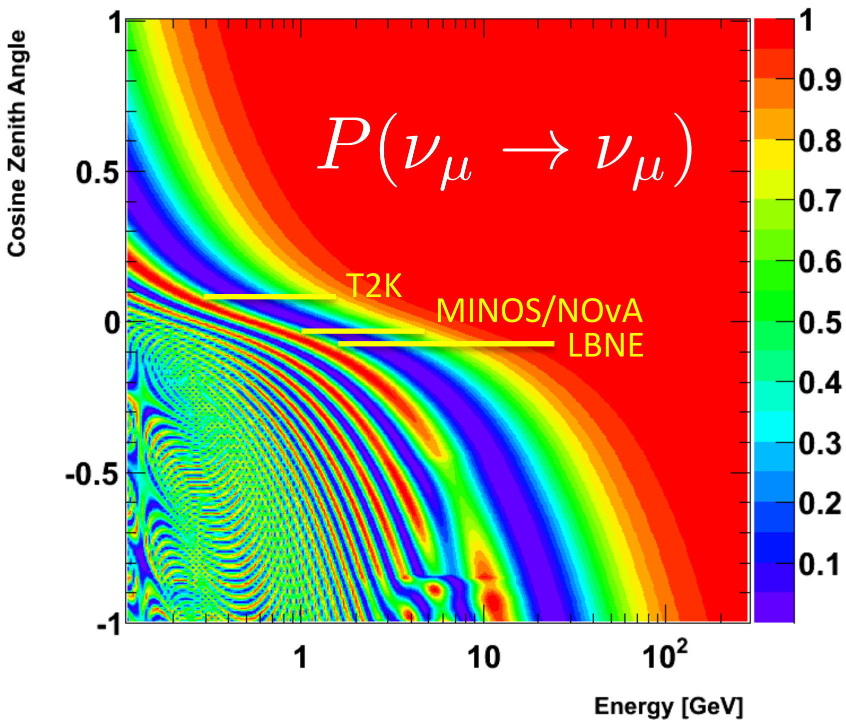
Atmospheric neutrinos have delivered:

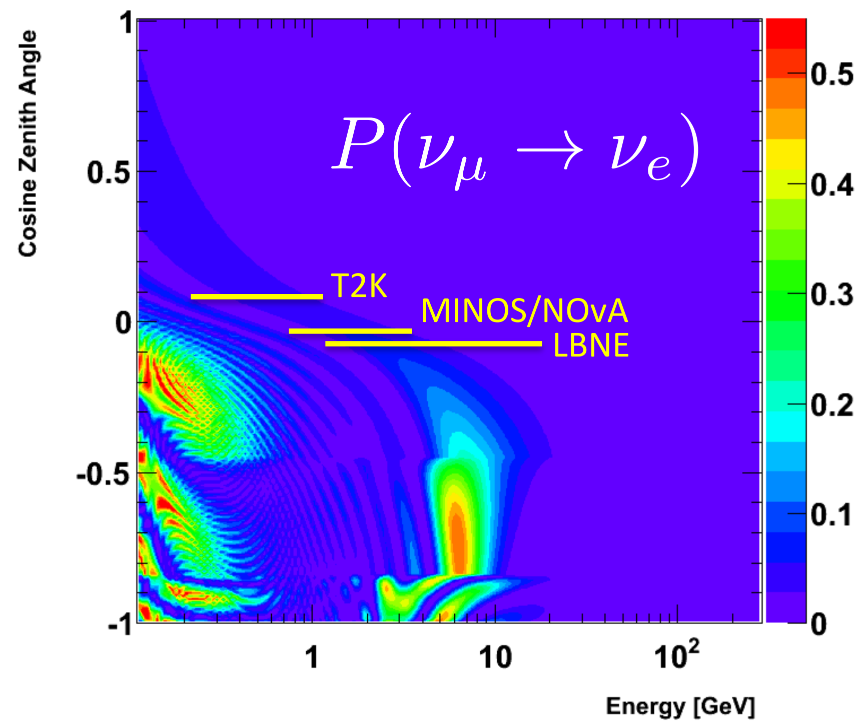
- Discovery of neutrino oscillation
- θ_{23}, Δm^2_{23} same values as long-baseline experiments
- Oscillation pattern
- ν_τ appearance (3.8σ)

Not yet:

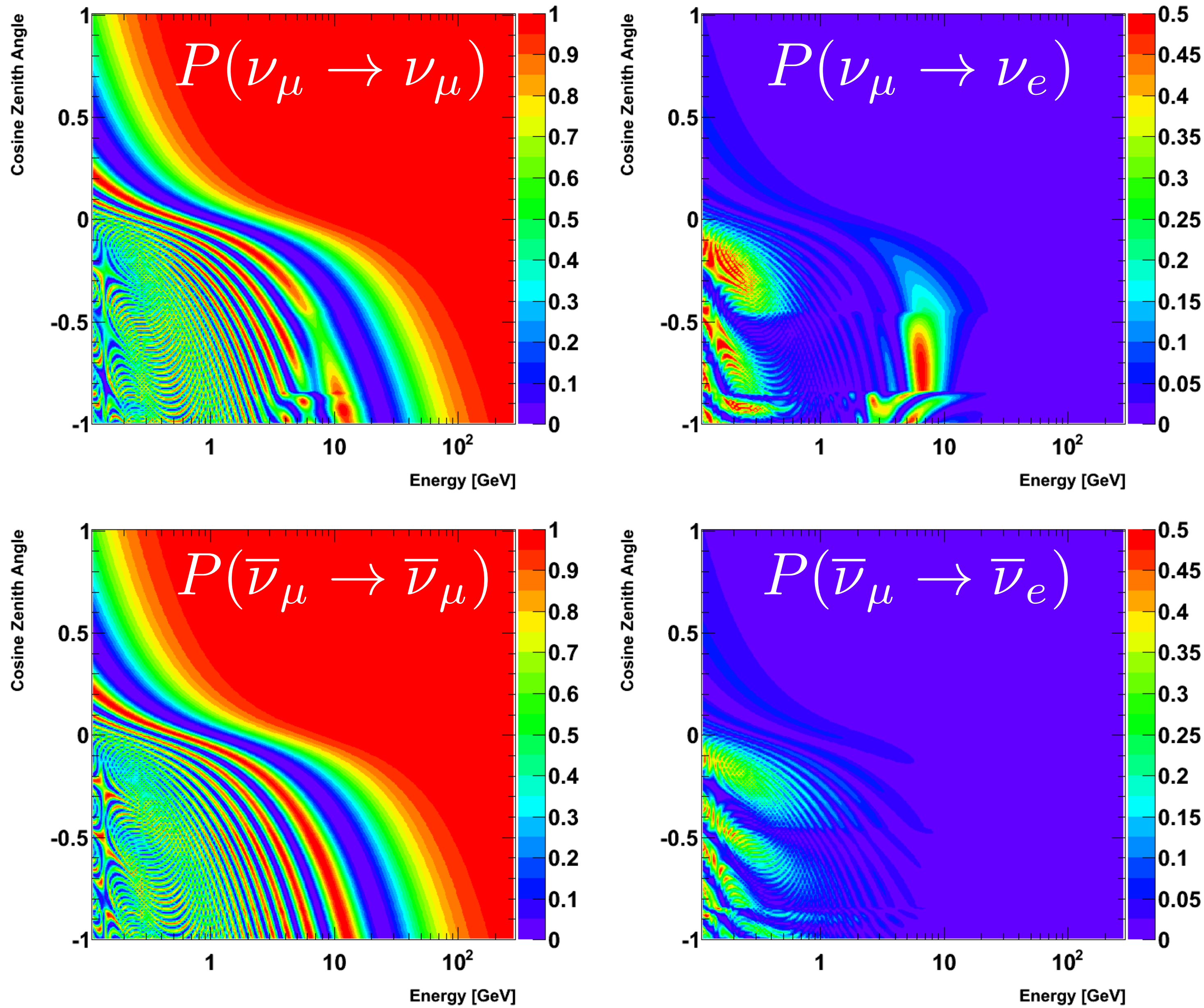
- Independent measurement of θ_{13}
- Mass hierarchy
- Octant of θ_{23}
- CP violation δ


FAR
DETECTOR
Cosmic Ray Proton
muon neutrinos
Accelerator Proton


$P(\nu_\mu \to \nu_\mu)$
T2K
MINOS/NOvA
LBNE
Cosine Zenith Angle
Energy [GeV]

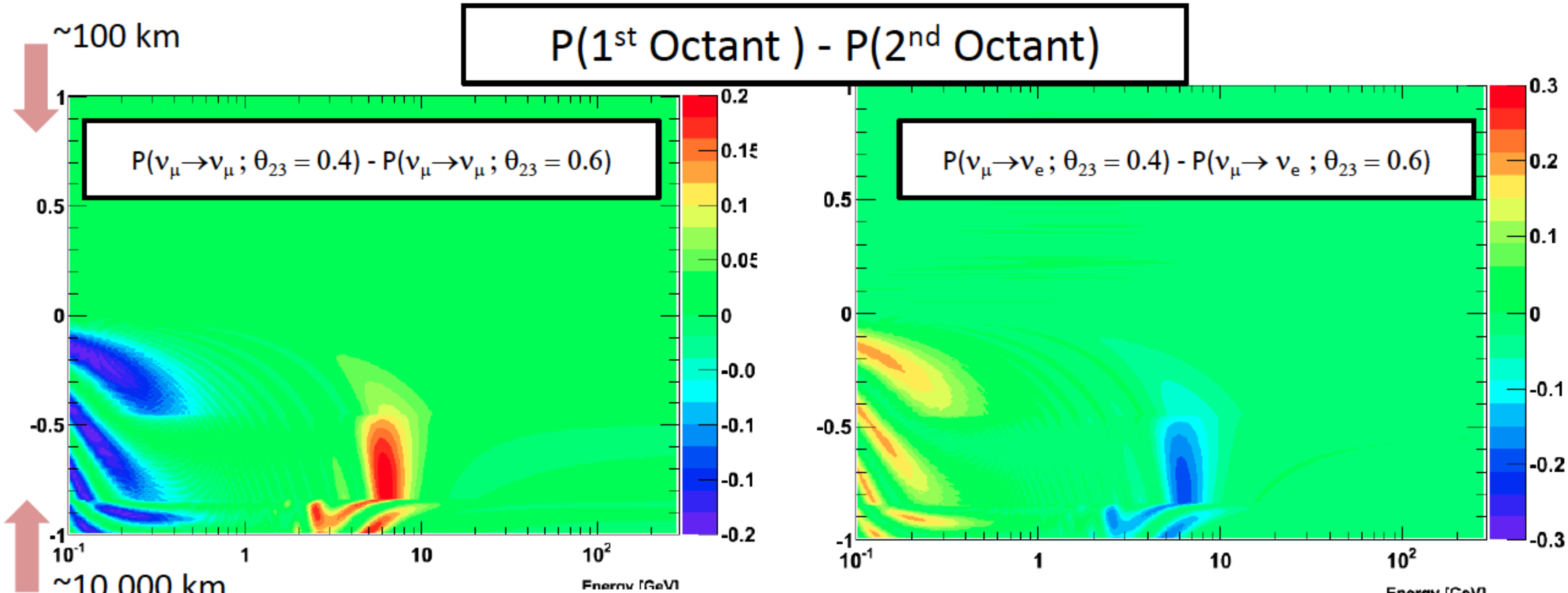

$P(\nu_\mu \to \nu_e)$
T2K
MINOS/NOvA
LBNE
Cosine Zenith Angle
Energy [GeV]

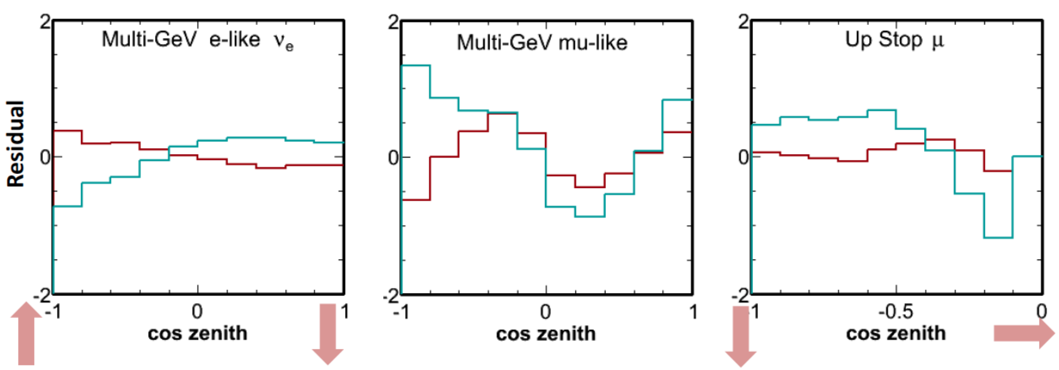
Oscillograms: Graphical representations of neutrino mixing probability



Resonance
in ν_μ–ν_e
for NH
...
(in antinu
for IH)

First Octant minus Second Octant





θ_{23} = **0.4** vs. θ_{23} = 0.5

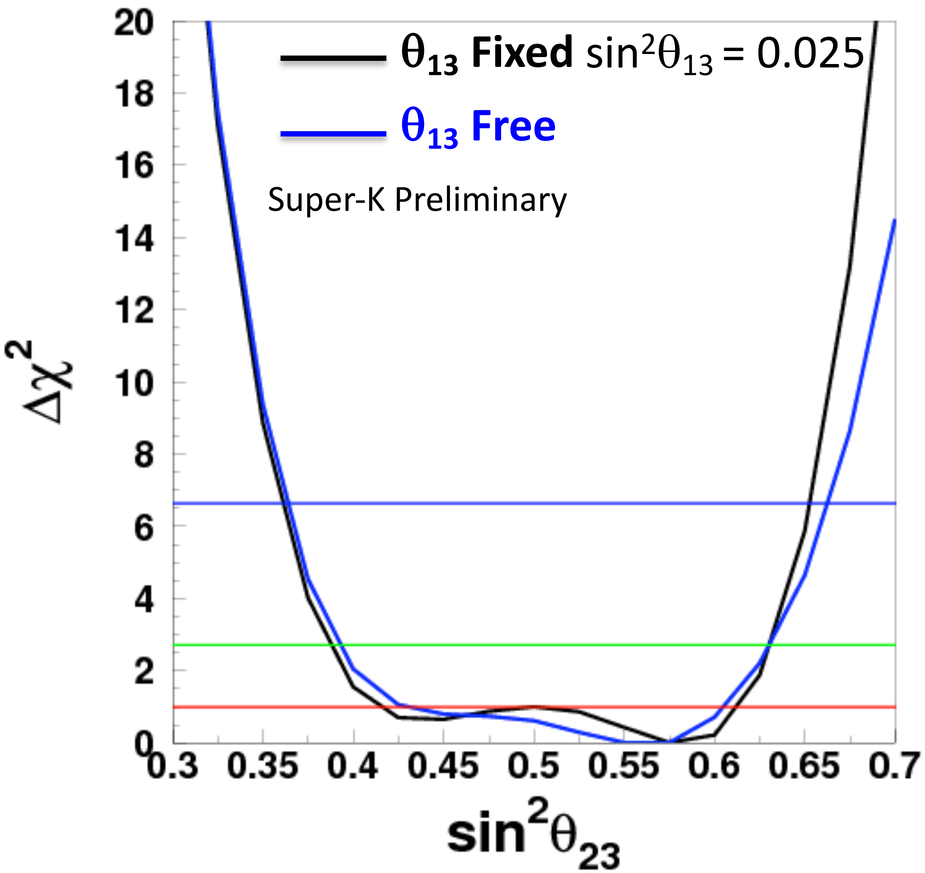
θ_{23} = **0.6** vs. θ_{23} = 0.5

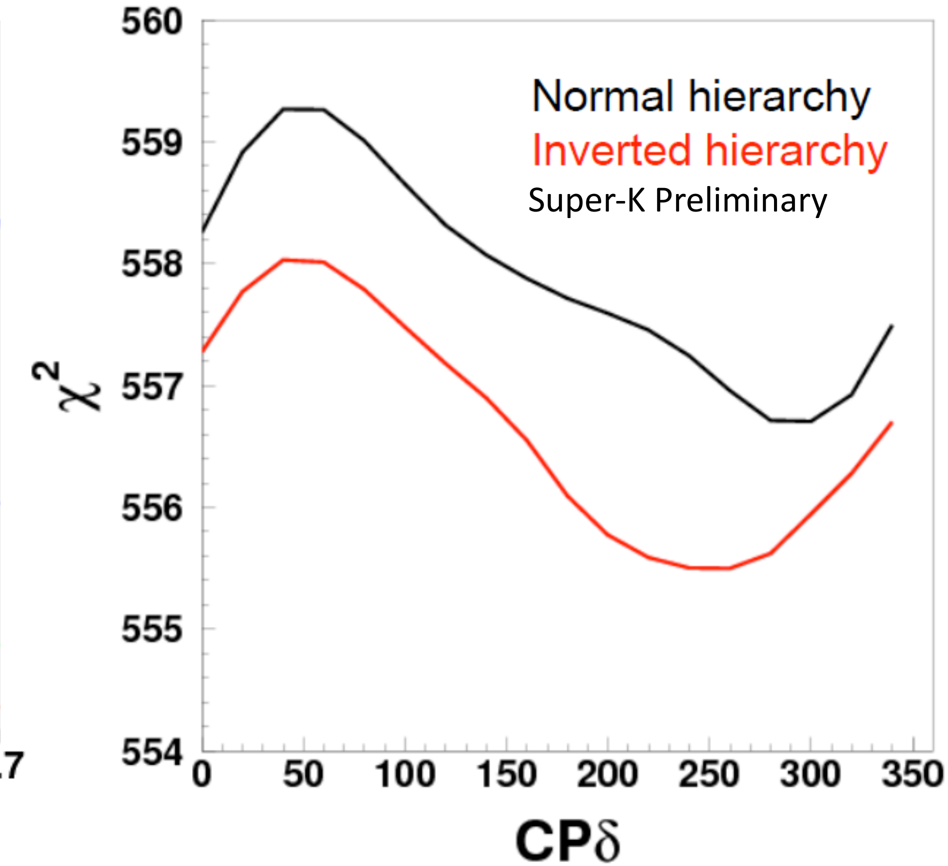
In 1st Octant:

More multi-GeV muon survival

Less electron appearance

Results: using reactor θ_{13} constraint

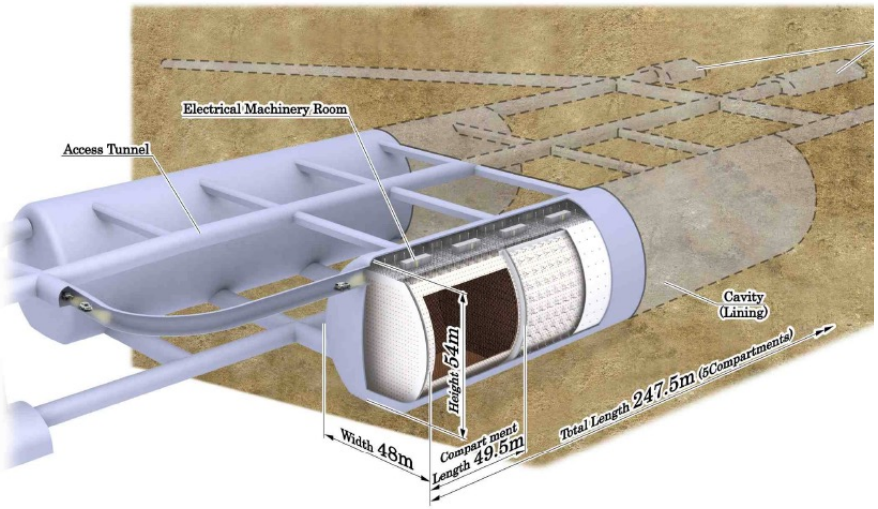




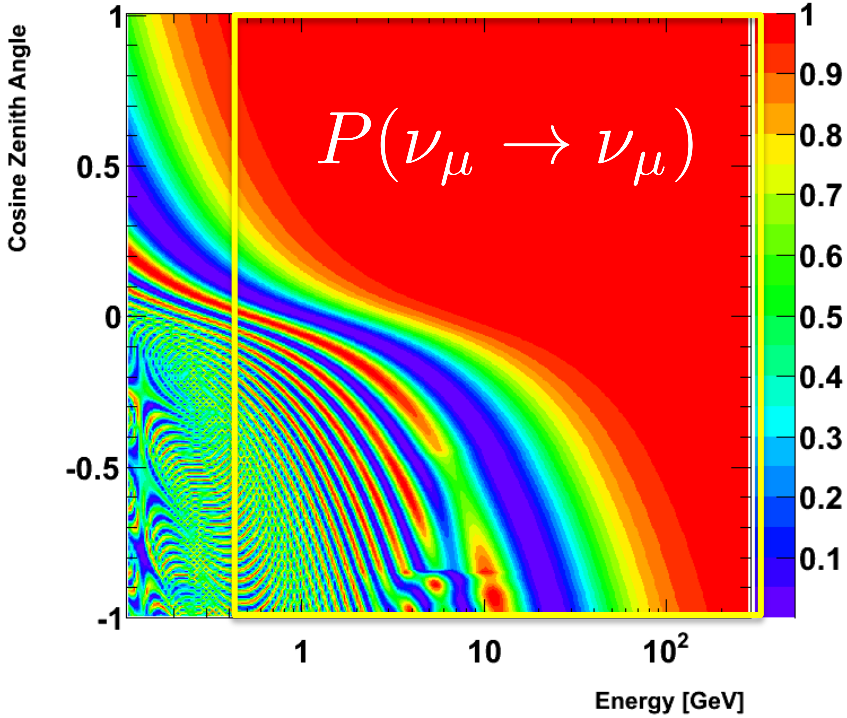
- Both free and constrained fits prefer 2nd octant
- 1.2σ preference for inverted hierarchy sensitivity is 0.9σ

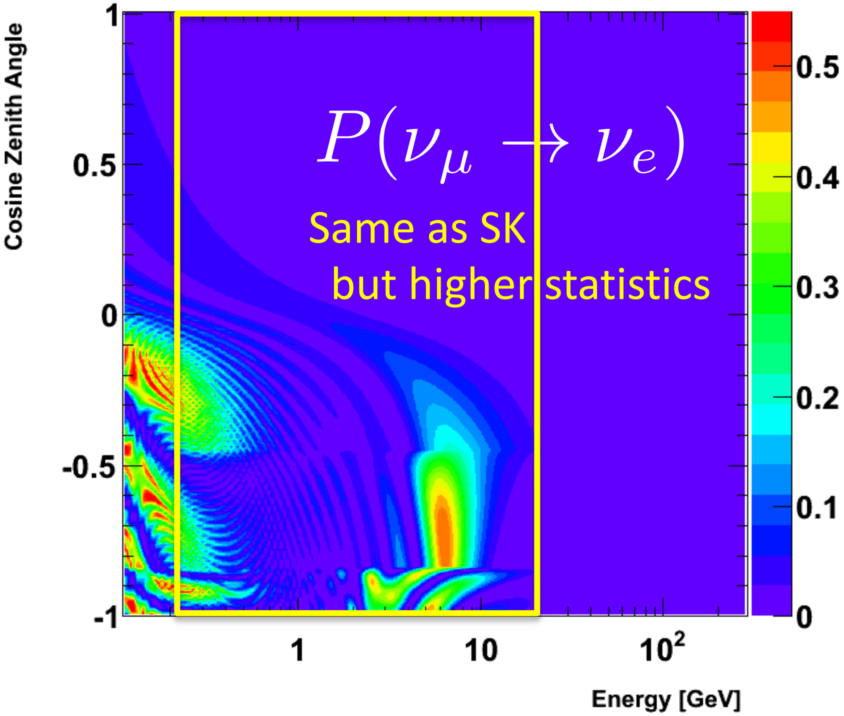
} Not significant!

Hyper-Kamiokande

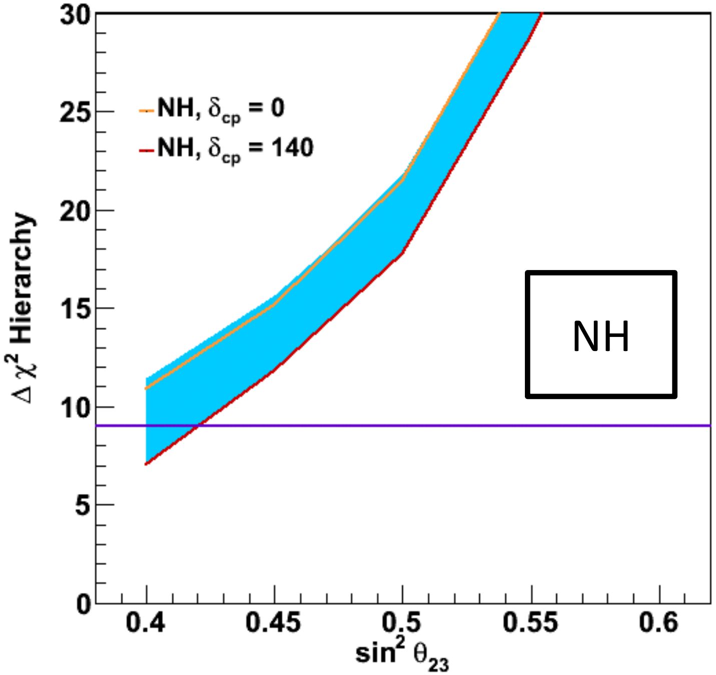


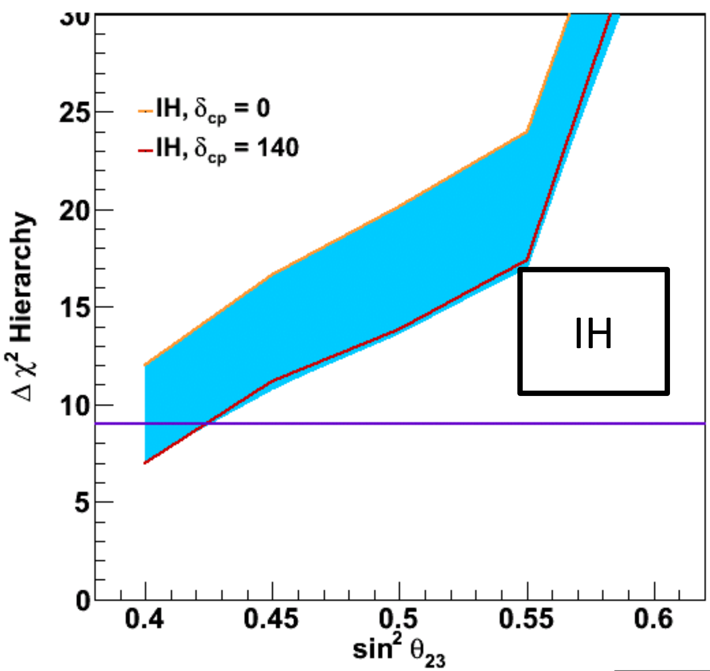
Sensitivity studies simply scale SK result to large exposure, i.e. assume the same detector performance

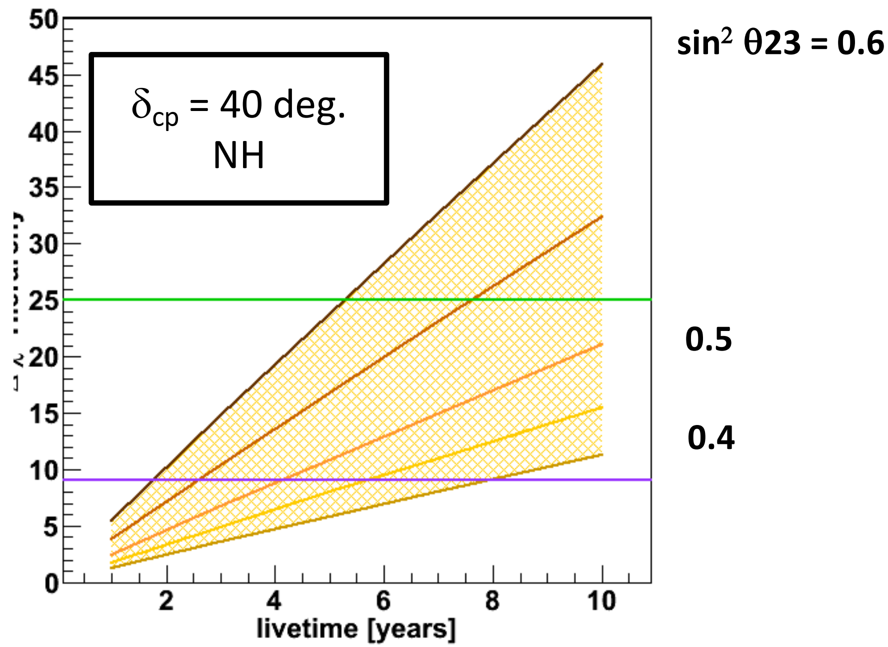




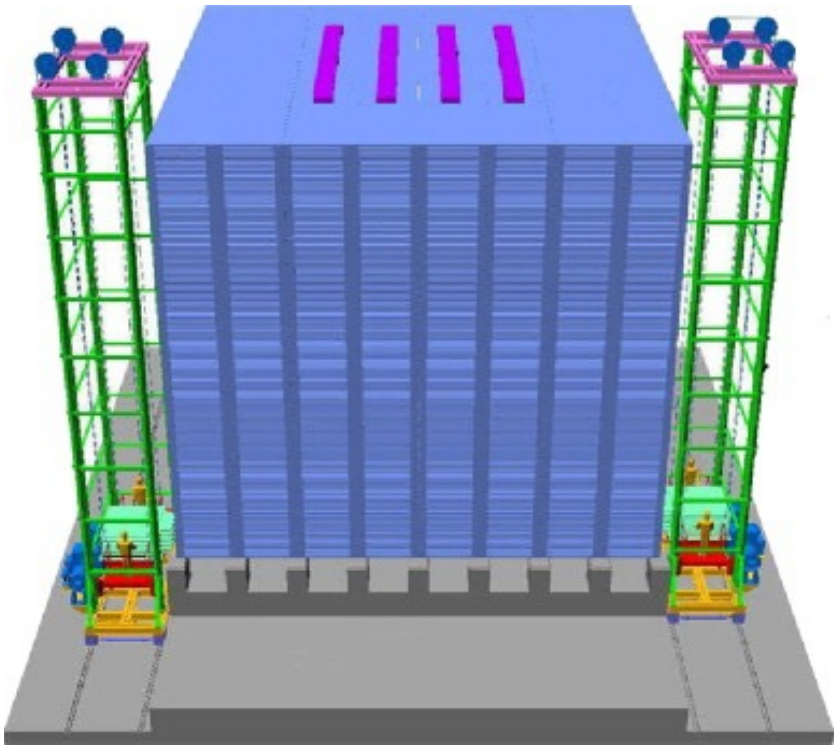
Octant and CP-δ dependency

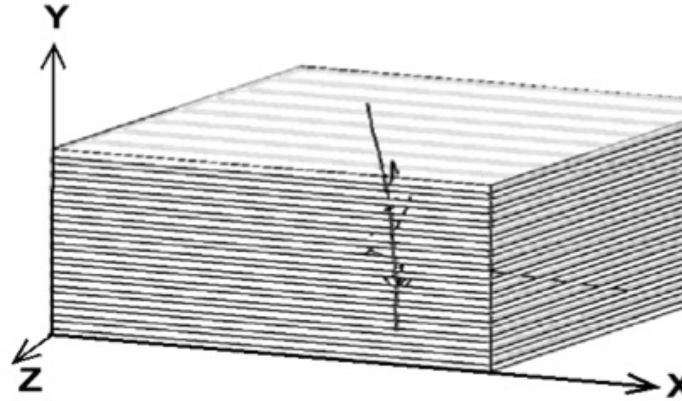


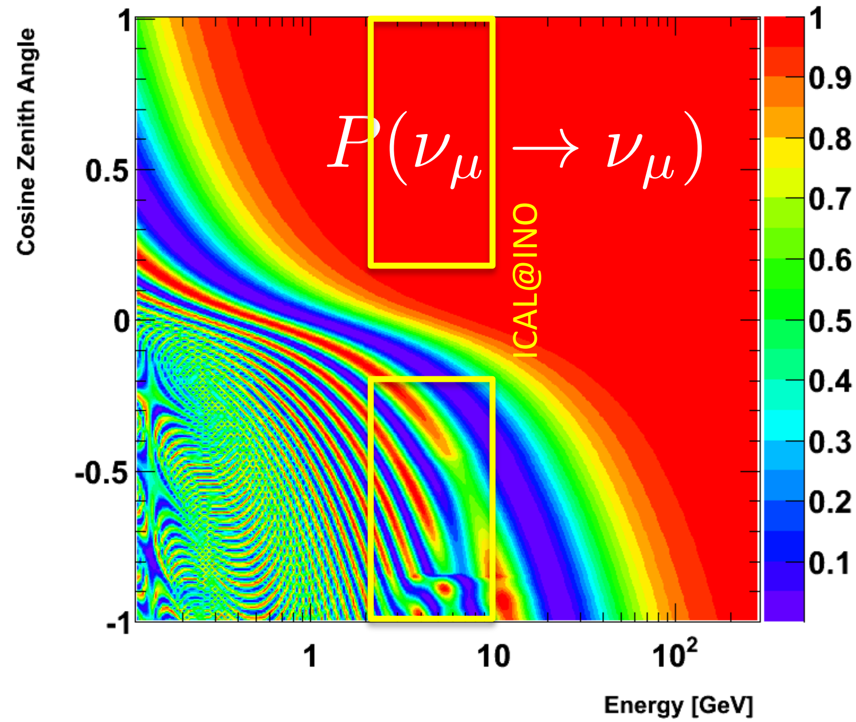




ICAL @ INO (Iron Calorimeter at India-based Neutrino Observatory)



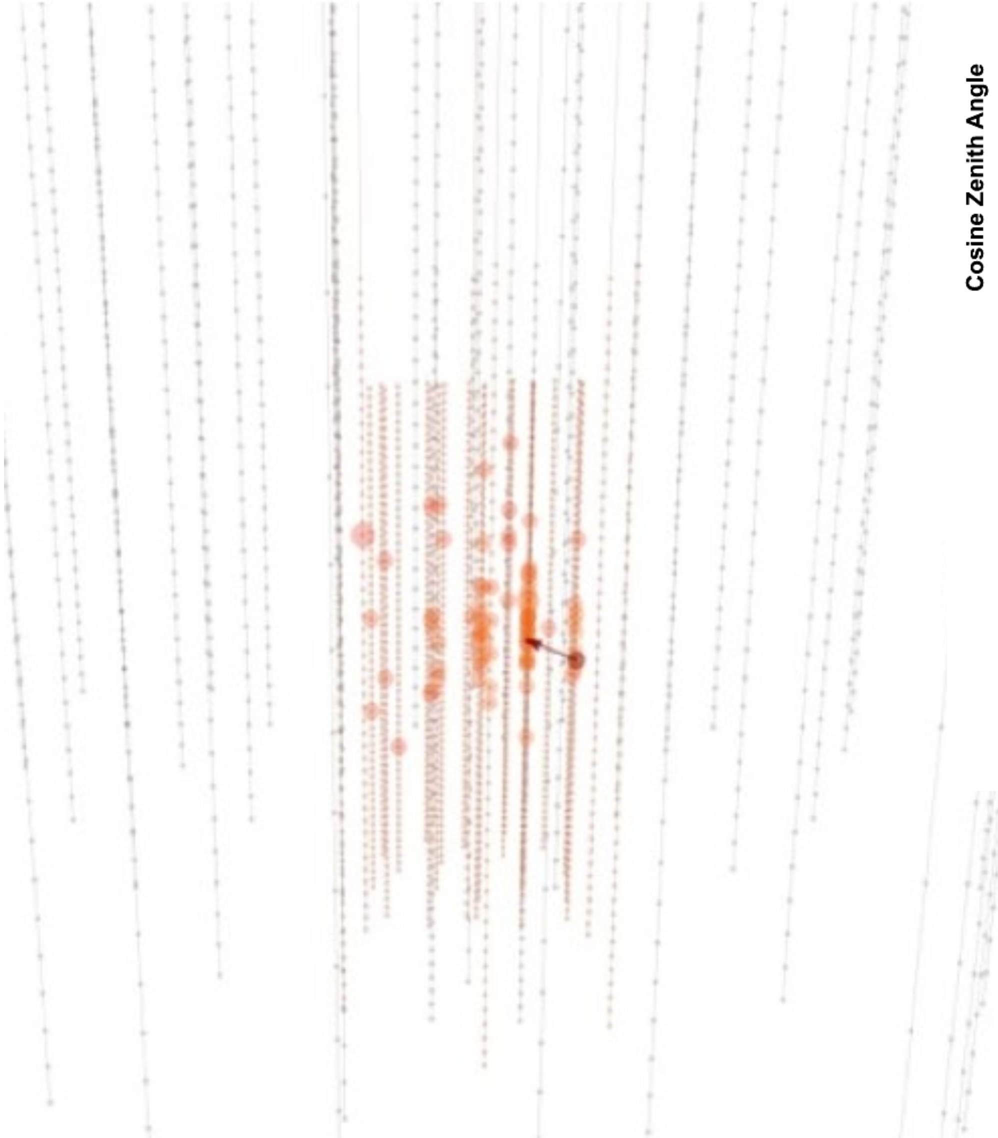


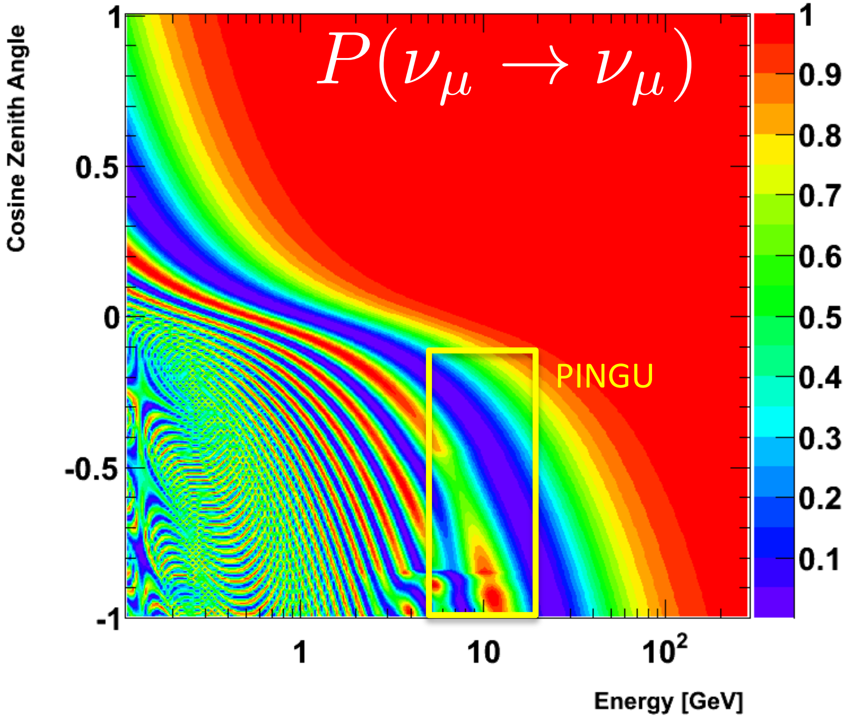


- 50 kton mass
- 29000 RPCs
- 1.3T magnetic field
- Best acceptance for vertical muons
- 2-3σ MH in 5-10 years

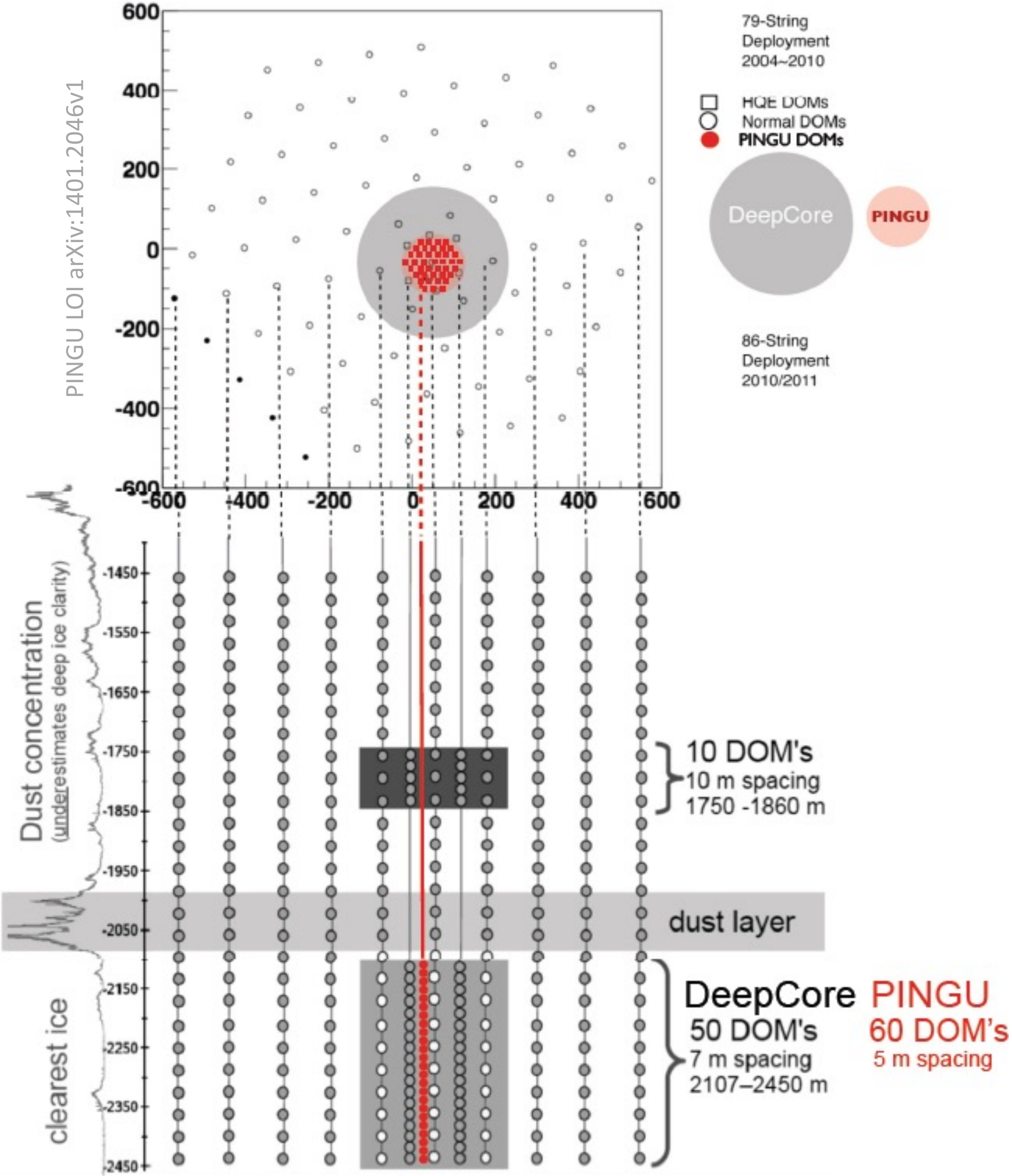
http://dx.doi.org/10.1016/j.nima.2012.03.017

PINGU (Precision IceCube Next Generation Upgrade)

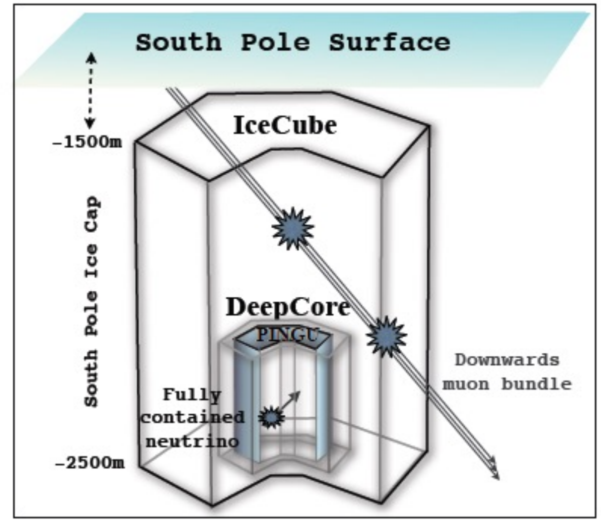




- \+ Enormous statistics (25K evt/yr)
- \+ Full containment of 10 GeV ν_μCC
- \+ Possible ν/antiν by $d\sigma/dy$ (ArXiv:1303.0758)
- \+ Recent work includes shower (CC nu e)
- − No up/down normalization
- − Zenith acceptance & detector response may be challenging to control



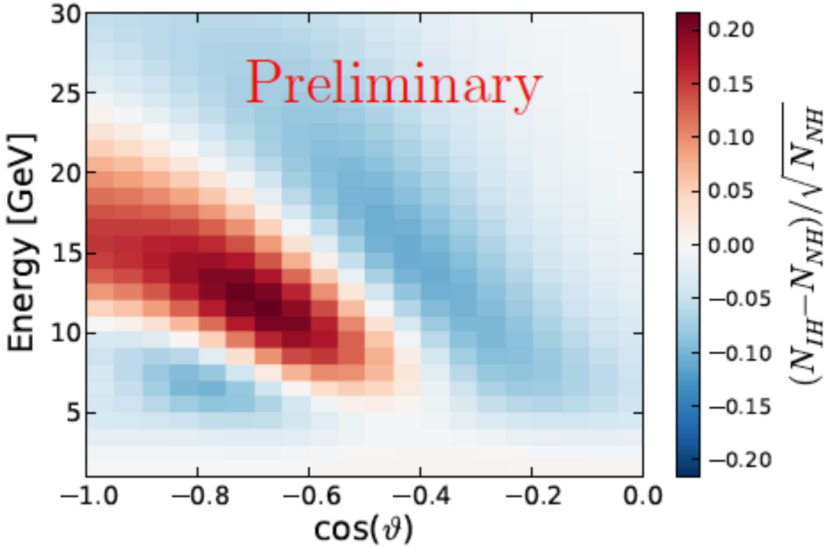
Use IceCube and DeepCore as an active veto



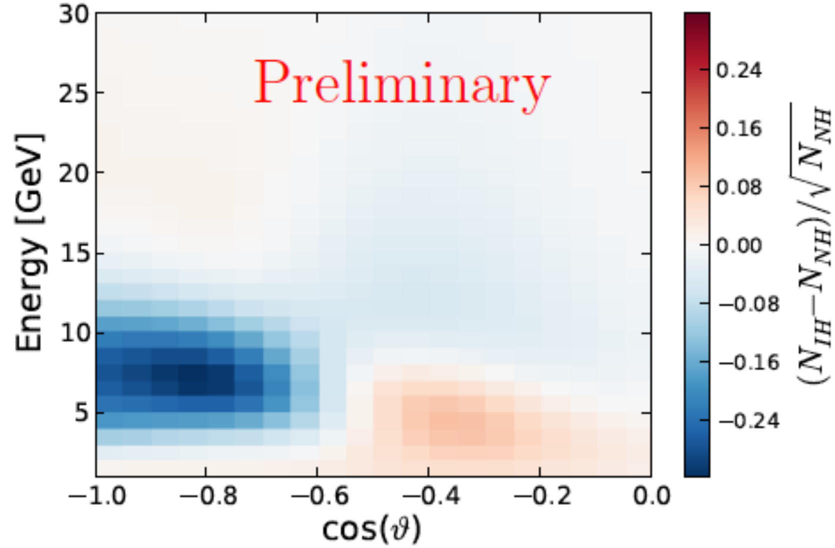
3-4 Mton effective volume

10 GeV neutrinos – ideal for core resonance

PINGU LOI arXiv:1401.2046v1

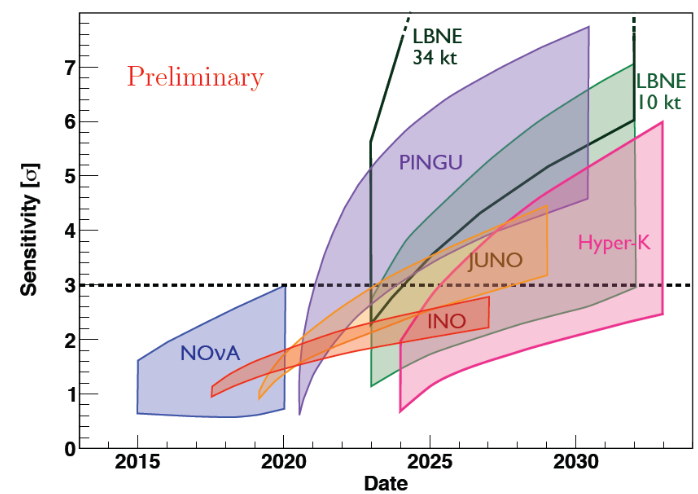


(a) Track-like events.

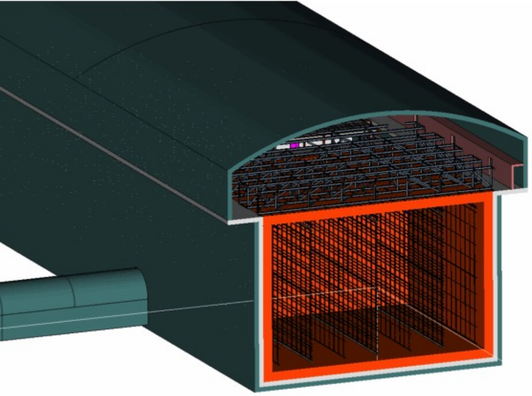


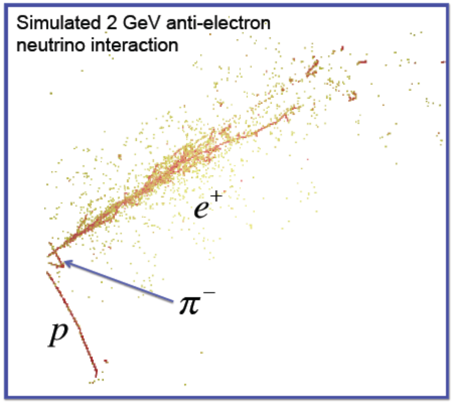
(b) Cascade-like events.

3σ for MH in < 3 years

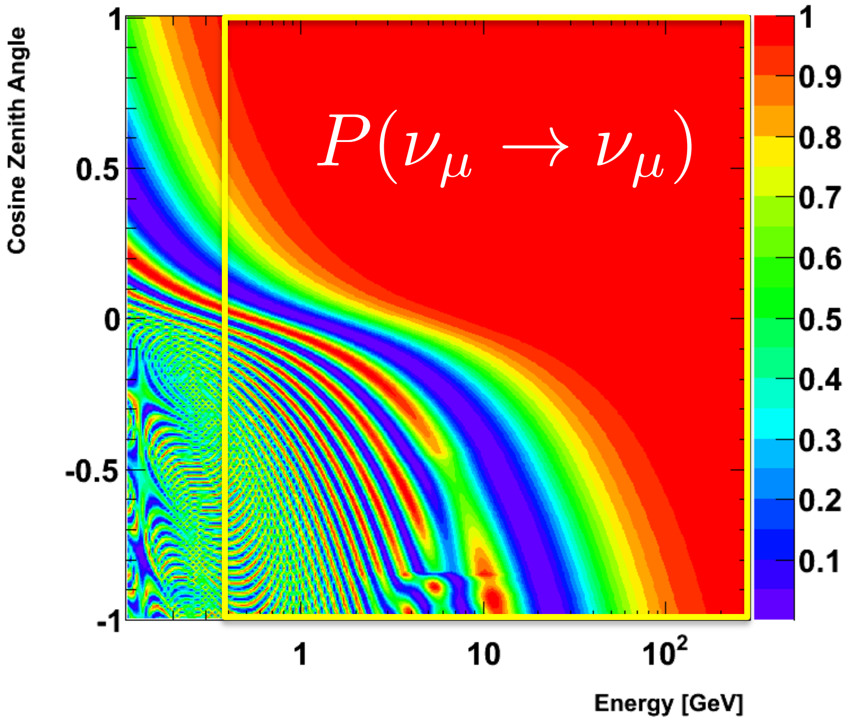


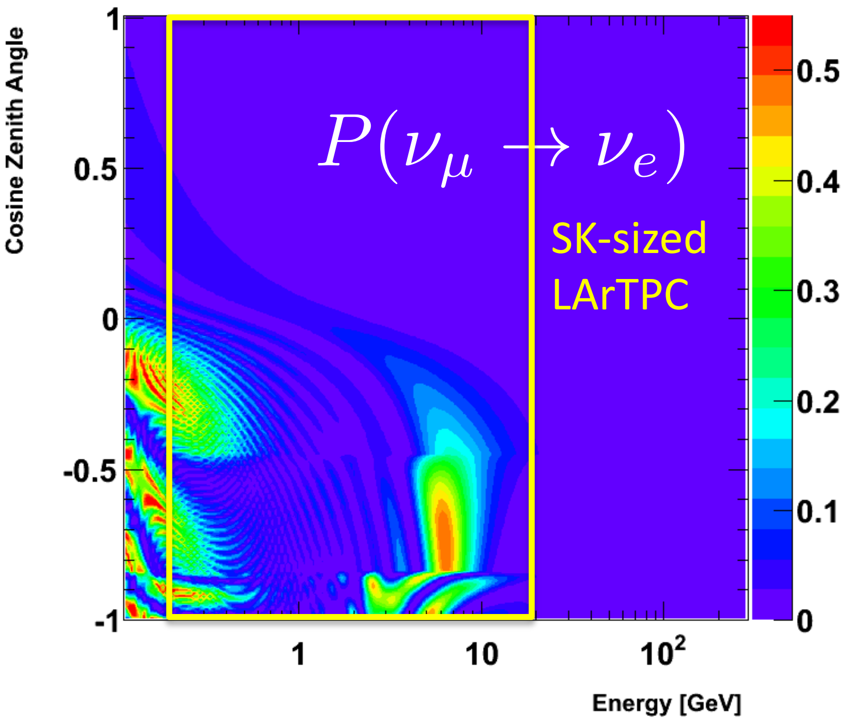
LArTPC





- High resolution:
- NC BG rejection
- Direction/energy (see all charged)
- ν/anti-ν handles
- Above are needed to compensate for modest mass
- Magnetize?

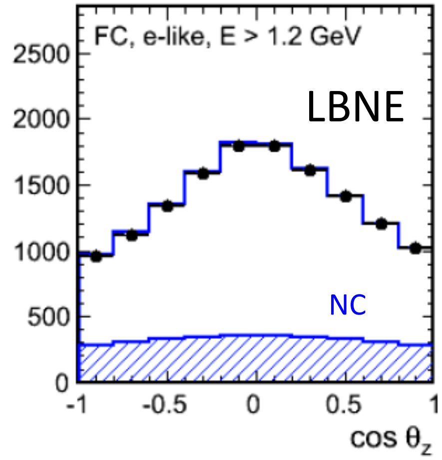




LBNE Sensitivity Studies via Performance Estimates

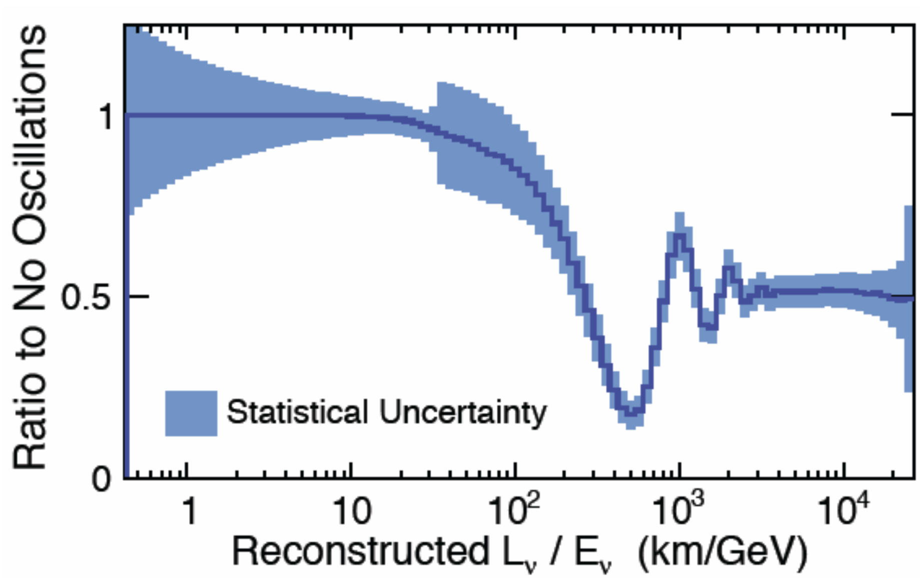
	Lepton (electron)	Lepton (muon)	Hadronic System
Angular Resolution	2°	2°	10°
Energy Resolution	$10\% / \sqrt{E}$	2% (FC) 15% (PC)	$30\% / \sqrt{E}$

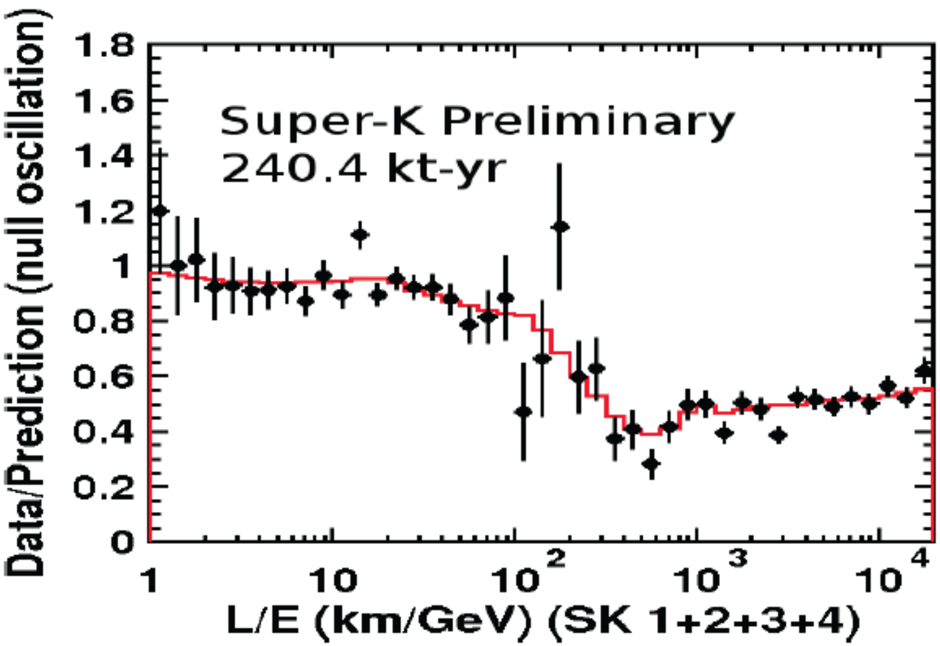
A. Guglielmi, Neutrino 2010, Ghandi et al., hep-ph/0807.2759.

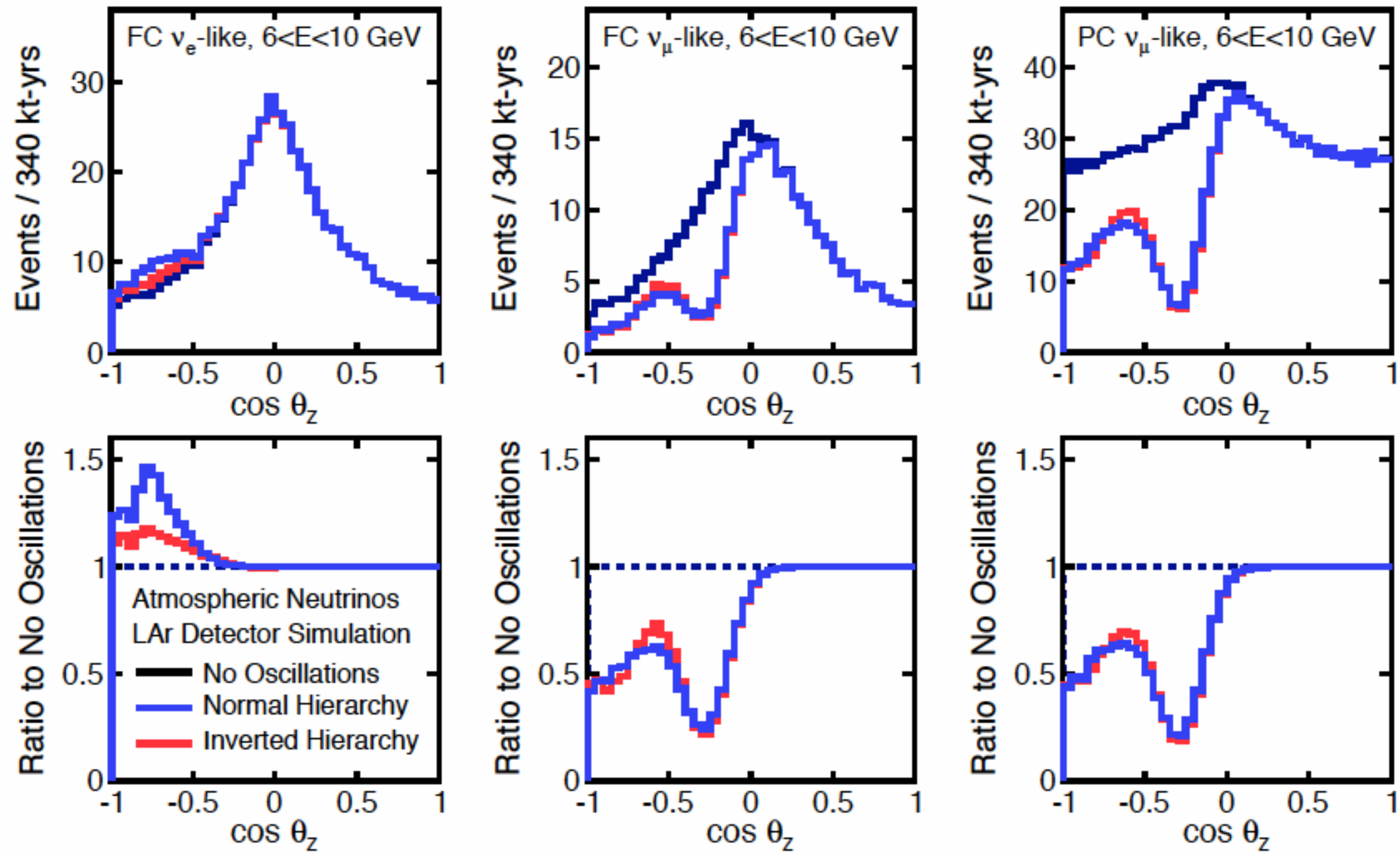


A. Blake, LBNE

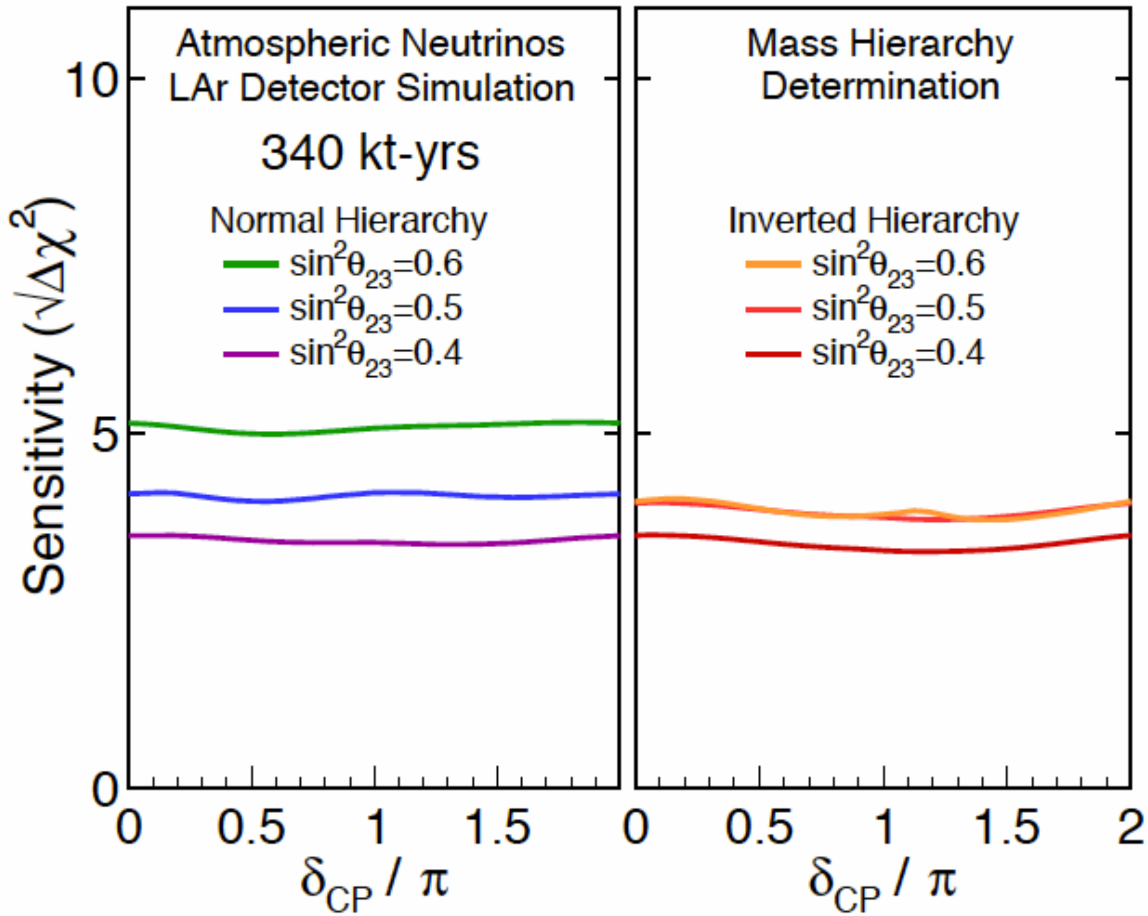
LBNE study	Neutrino (true)	Antineutrino (true)	Tag method(s)
ν_e-like	30%	6%	p ID only
Anti ν_e-like	43%	22%	p ID only
ν_μ-like	27% / 57%	5% / 0%	p ID / μ-e decay
Anti ν_μ-like	49% / 19%	19% / 24%	p ID / μ-e decay


Ratio to No Oscillations
1
0.5
0
Statistical Uncertainty
1
10
10^2
10^3
10^4
Reconstructed L_ν / E_ν (km/GeV)


Data/Prediction (null oscillation)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Super-K Preliminary
240.4 kt-yr
1
10
10^2
10^3
10^4
L/E (km/GeV) (SK 1+2+3+4)

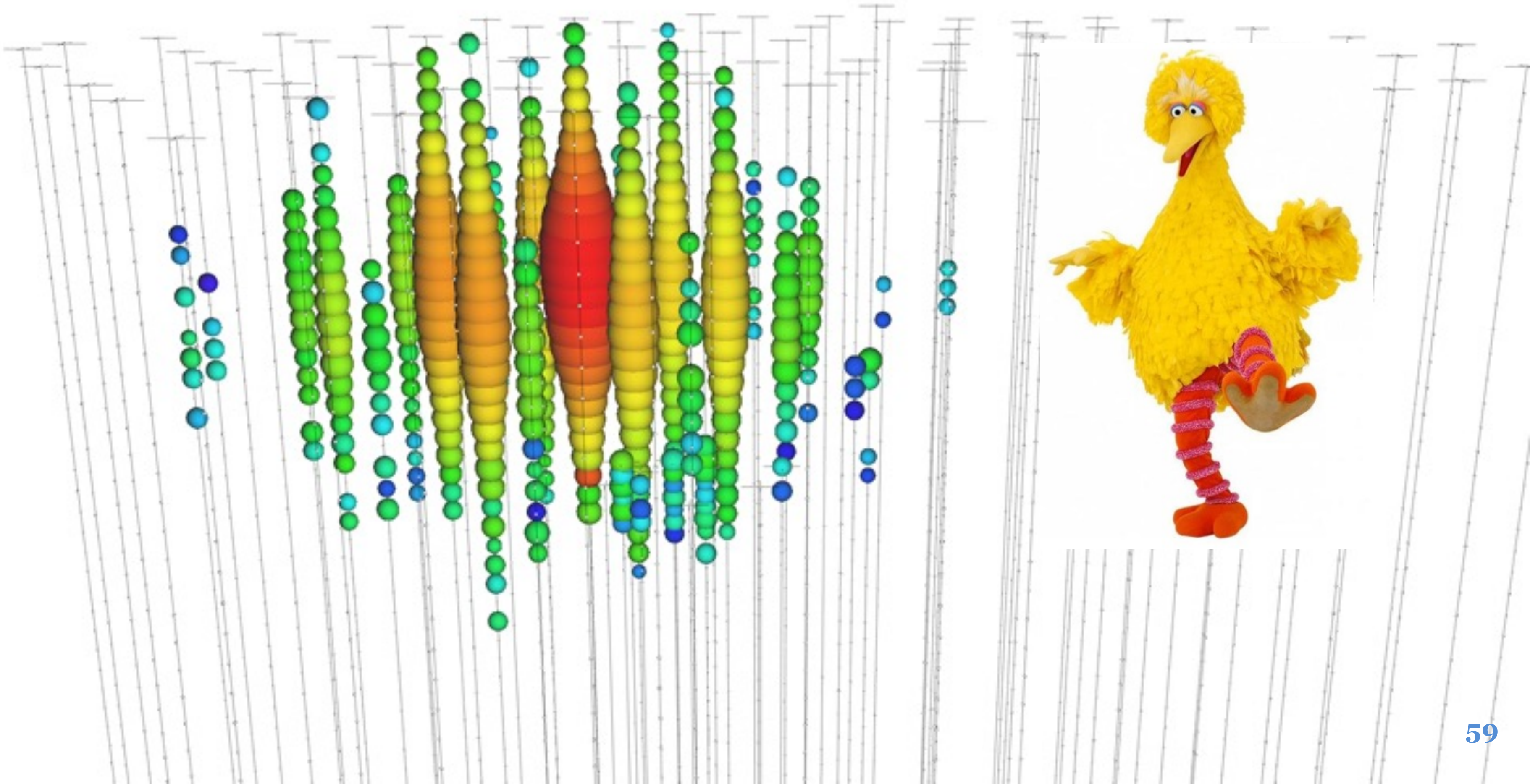


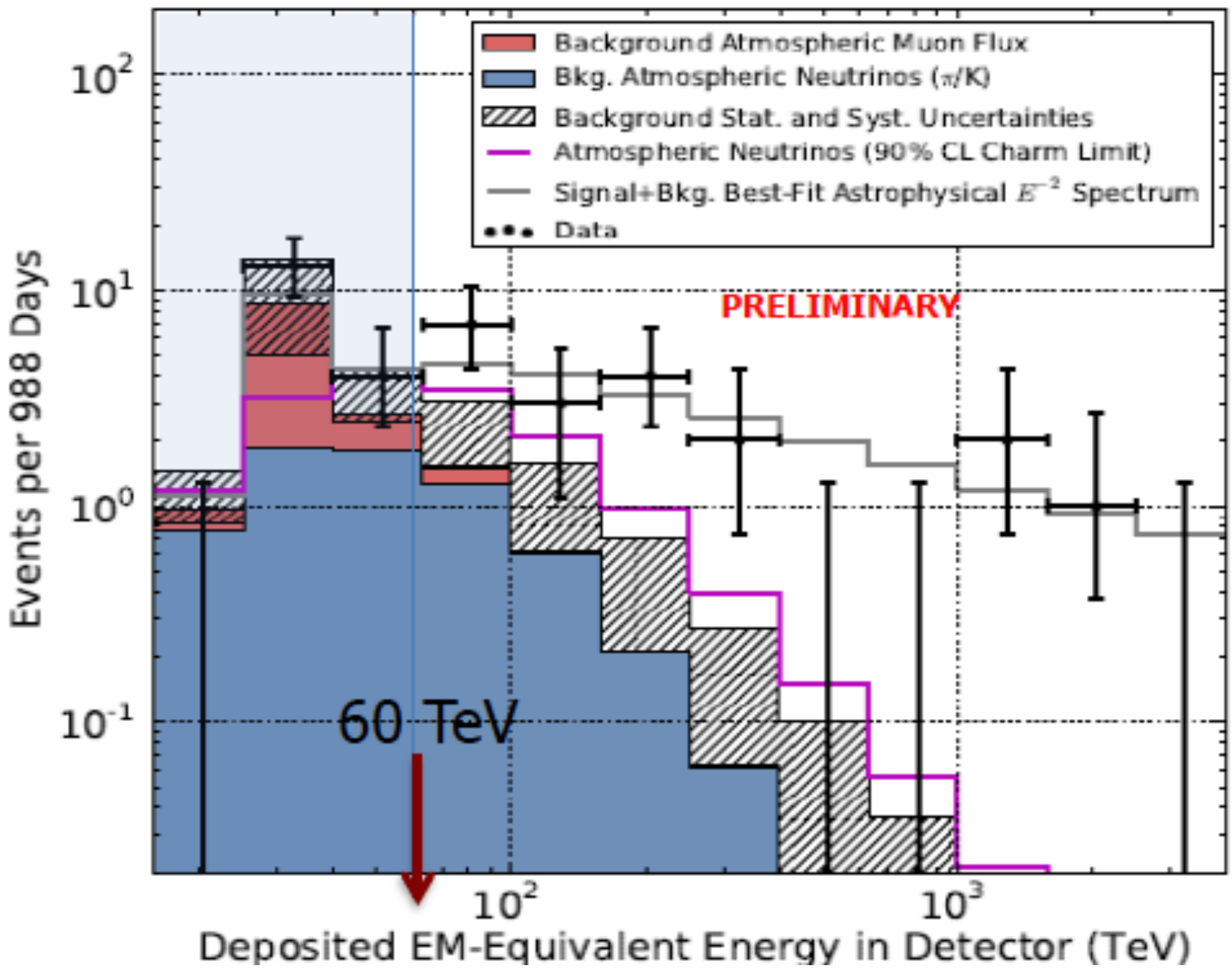
Arguably – 34 kton LArTPC is more interesting than 500 kton WC!

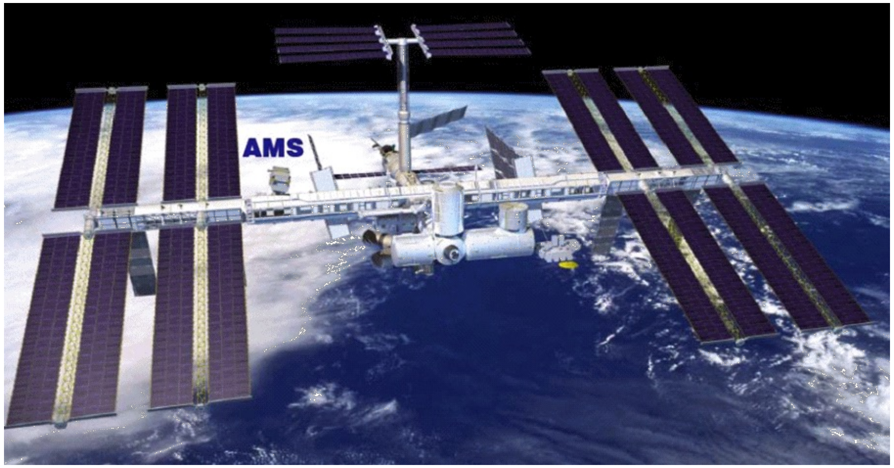


Atmospheric Neutrinos
LAr Detector Simulation
340 kt-yrs
Normal Hierarchy
$\sin^2\theta_{23}$=0.6
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{23}$=0.4
Mass Hierarchy
Determination
Inverted Hierarchy
$\sin^2\theta_{23}$=0.6
$\sin^2\theta_{23}$=0.5
$\sin^2\theta_{23}$=0.4
Sensitivity ($\sqrt{\Delta\chi^2}$)
10
5
0
0
0.5
1
1.5
0
0.5
1
1.5
2
δ_{CP} / π
δ_{CP} / π

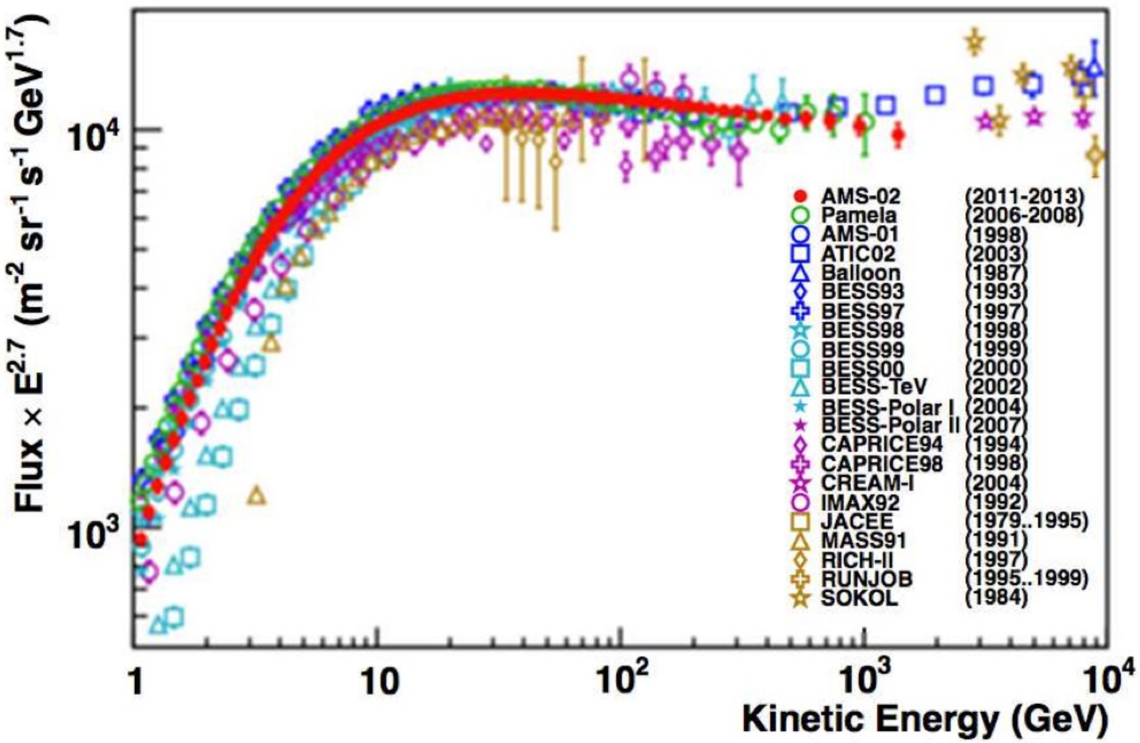
✷ High Energy Cosmic Neutrinos




Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
PRELIMINARY
60 TeV
Events per 988 Days
Deposited EM-Equivalent Energy in Detector (TeV)
10^2
10^1
10^0
10^{-1}
10^2
10^3



http://arxiv.org/abs/1402.0467v2



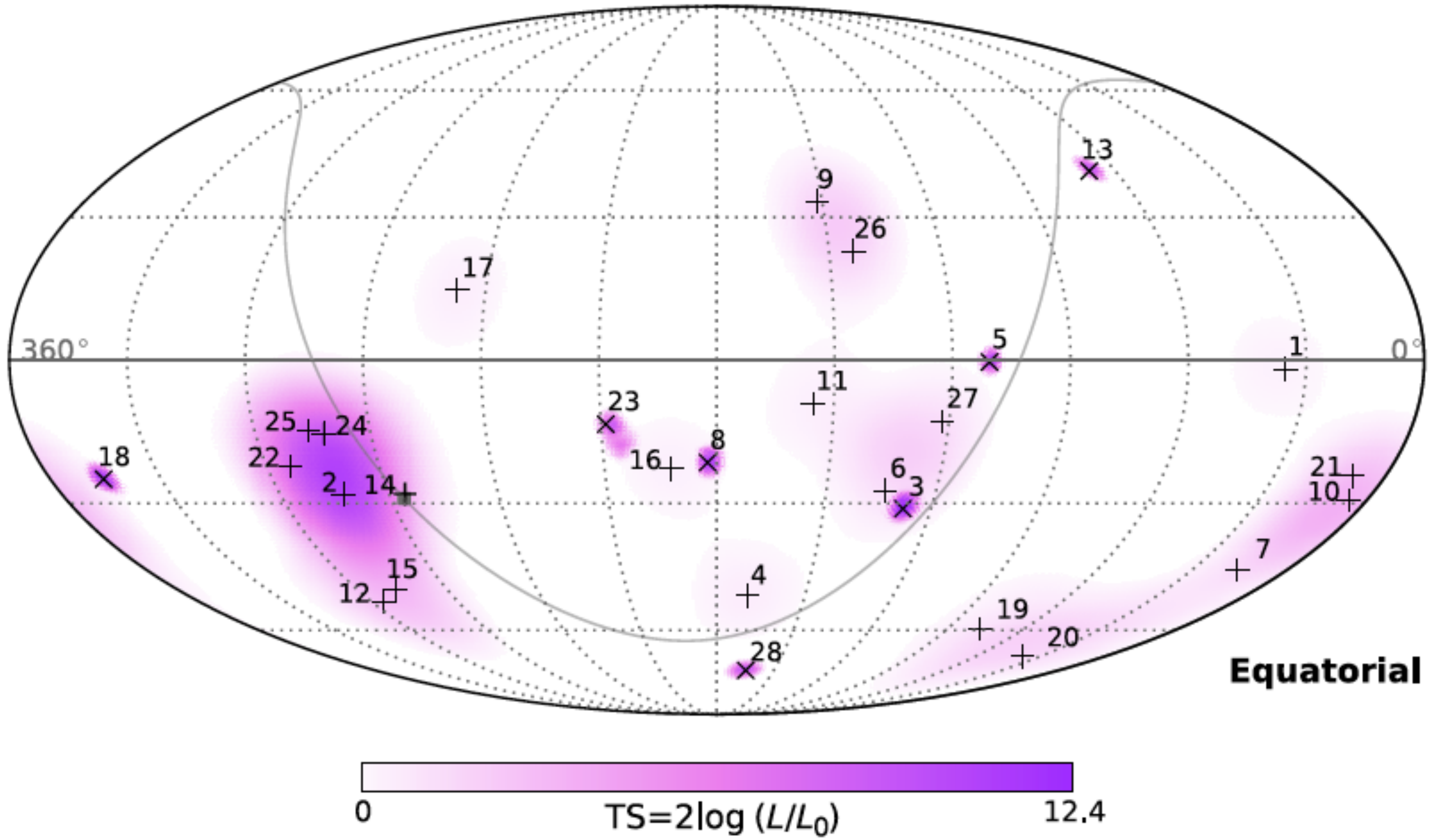
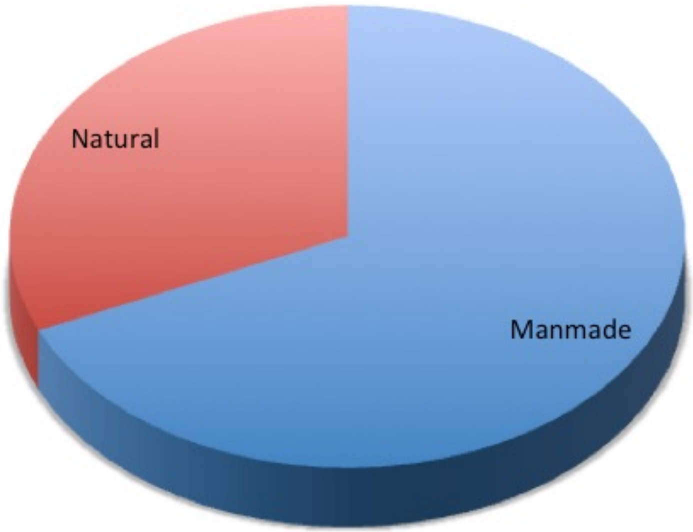


Fig. 5. Sky map in equatorial coordinates of the TS value from the maximum likelihood point source analysis. The most significant cluster consists of five events—all showers and including the second highest energy event in the sample—with a final significance of 8%. This is not sufficient to identify any neutrino sources from the clustering study. The galactic plane is shown as a curved gray line with the galactic center at the bottom left denoted by a filled gray square. Best-fit locations of individual events (listed in Table 1) are indicated with vertical crosses (+) for showers and angled crosses (×) for muon tracks.

IceCube Collaboration, DOI: 10.1126/science.1242856

Neutrino Composition
of Neutrino 2014 Boston –
See you again soon!



http://neutrino2014.bu.edu/

Registration fee goes up May 1! Hotels are pricey and filling up!