Experiments in Neutrinos and Fundamental Symmetries

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National Nuclear Physics Summer School
Granlibakken, Lake Tahoe, CA
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Quick Overview

Part 1:

Introduction to Neutrinos

Neutrino Oscillation

Part 2:

Neutrino Anomalies

Neutrino Mass

Neutrinos as Messengers

Part 3:

The wider world of fundamental symmetries

What are we doing?

Exploring the fundamental laws of nature

The Standard Model of Particle Physics:

- Works remarkably well
- Some obvious issues

How do neutrinos fit?

Matter-antimatter asymmetry

Dark matter, Dark energy

Is there a deeper structure?

Unification with Gravity

What guidance can measurements of neutrinos and tests of fundamental symmetries provide?

How do we do it?

Experimental observations are the final arbiter

Experimental tests of physical laws

- History
- Existing results
- Future directions

Theme: The importance of careful experiments

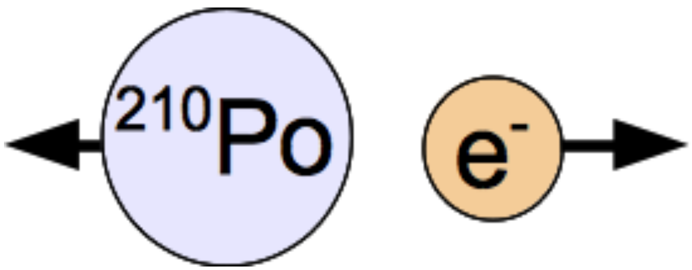
Part 1: Neutrinos and Oscillations

or

The Trouble of Working with Nearly Undetectable Particles

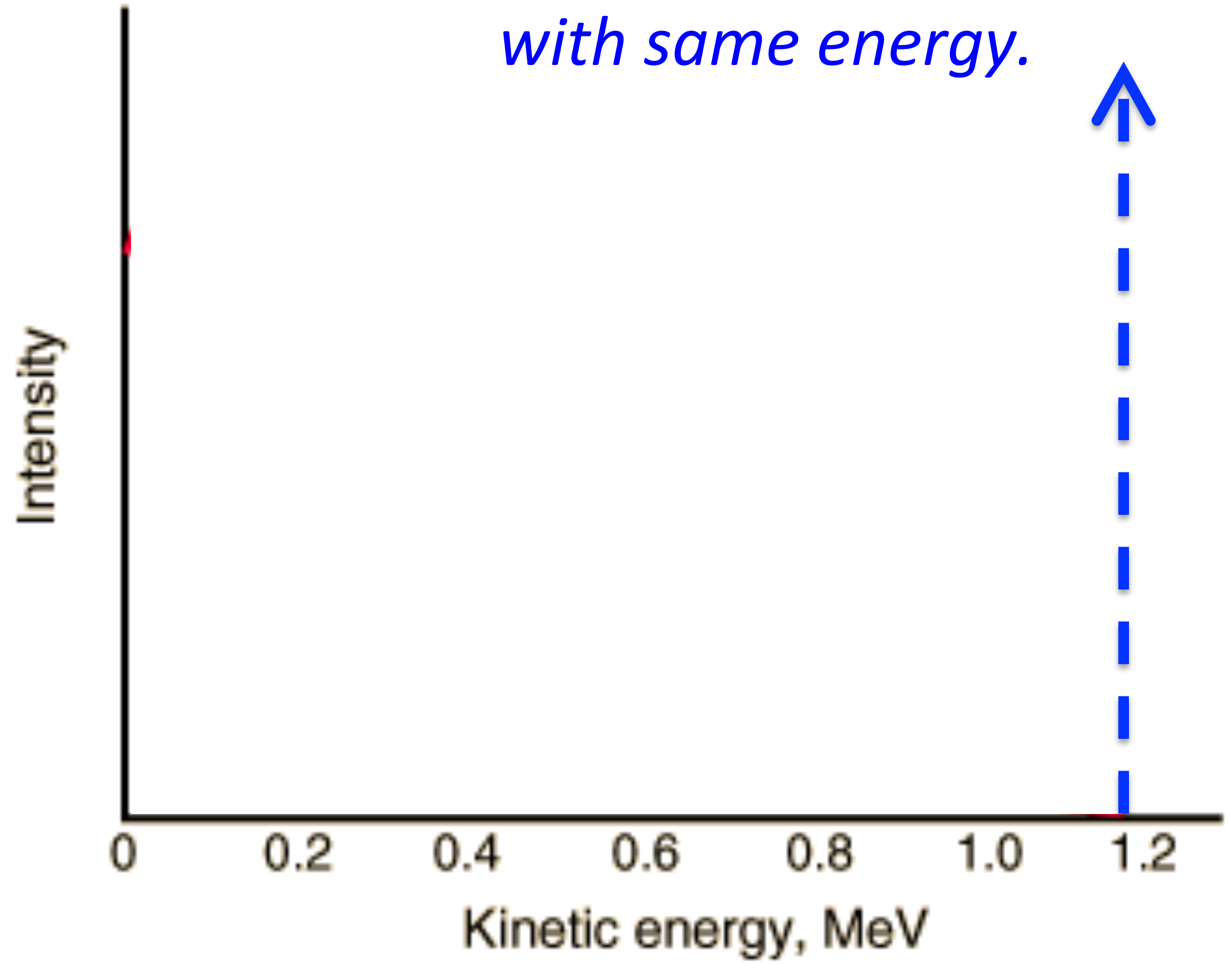
An Energy Crisis…

A problem with nuclear beta decay.



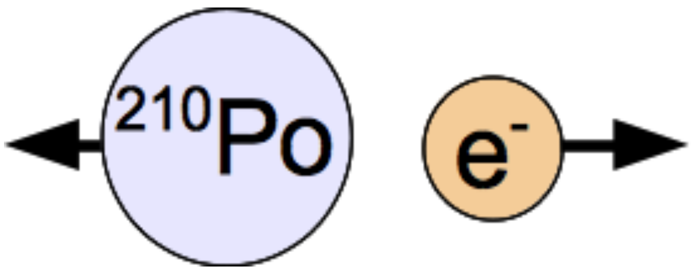
Two-body decay

Expect all electrons emitted with same energy.



An Energy Crisis…

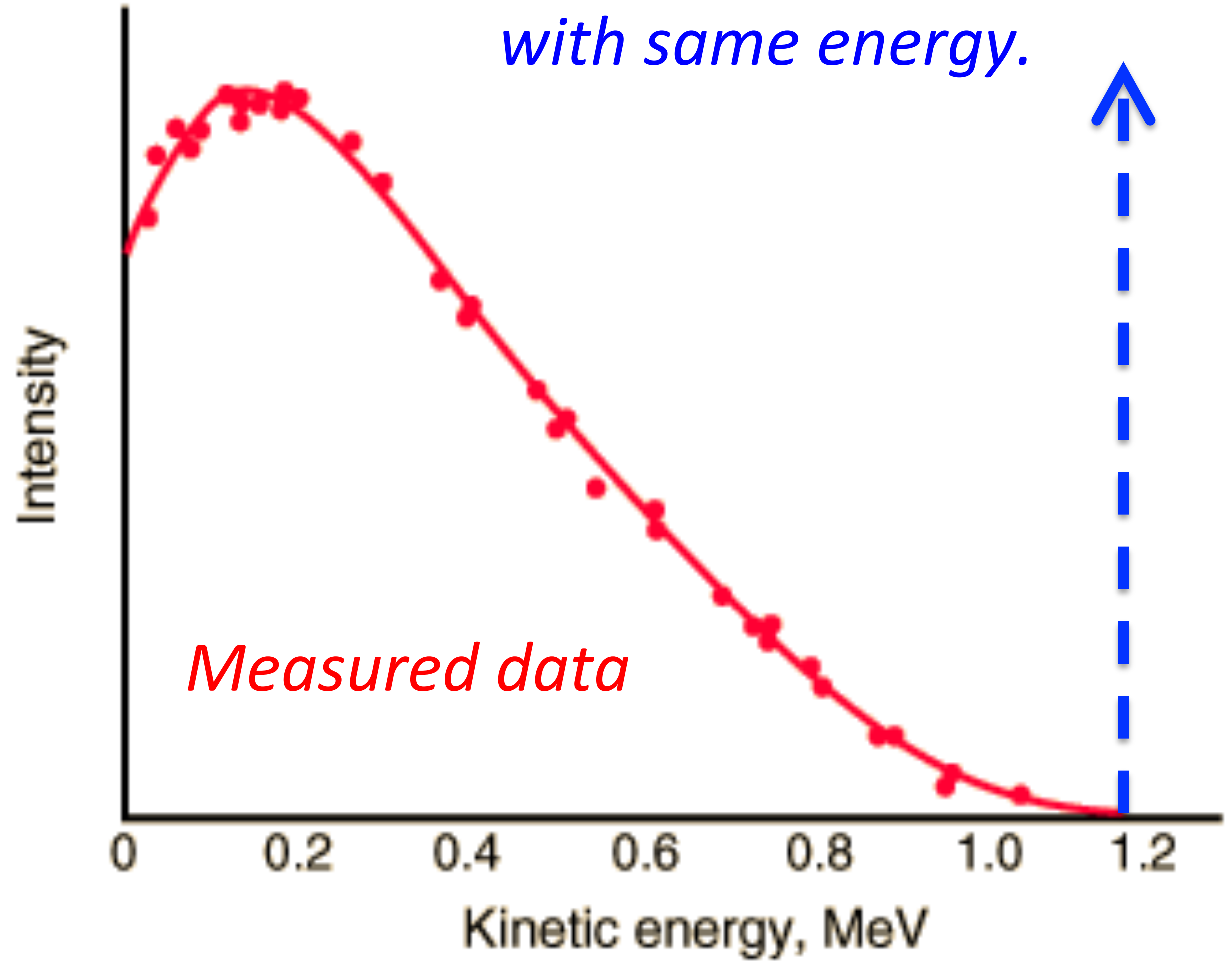
A problem with nuclear beta decay.



Two-body decay

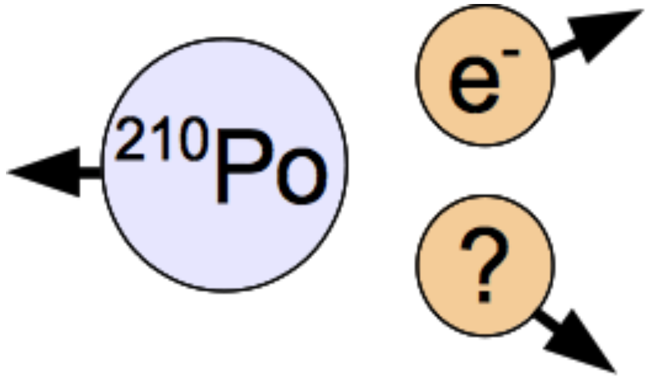
Is energy not conserved!?

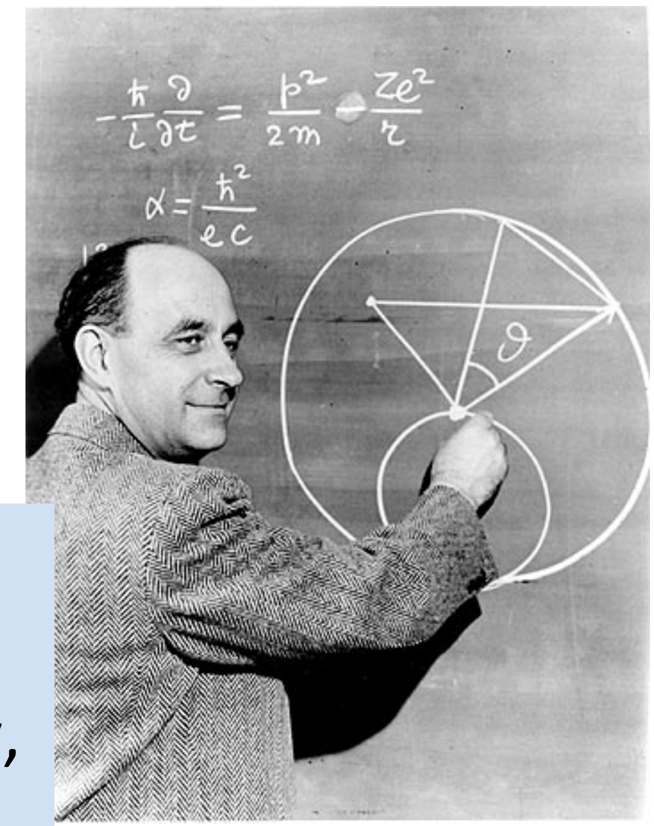
Expect all electrons emitted with same energy.



Early History of Neutrinos

1930:
Pauli proposes neutral fermion.





1933:
Fermi develops theory of beta-decay, names the '*neutrino*'.

Undetectable?

532 NATURE April 7, 1934

Bethe

Peierls

The "Neutrino"

$$\bar{\nu} + p \rightarrow e^{+} + n$$

(Inverse beta decay)

For an energy of $2{\cdot}3 \times 10^6$ volts, t is 3 minutes and therefore $\sigma < 10^{-44}$ cm.^{2} (corresponding to a penetrating power of 10^{16} km. in solid matter). It is

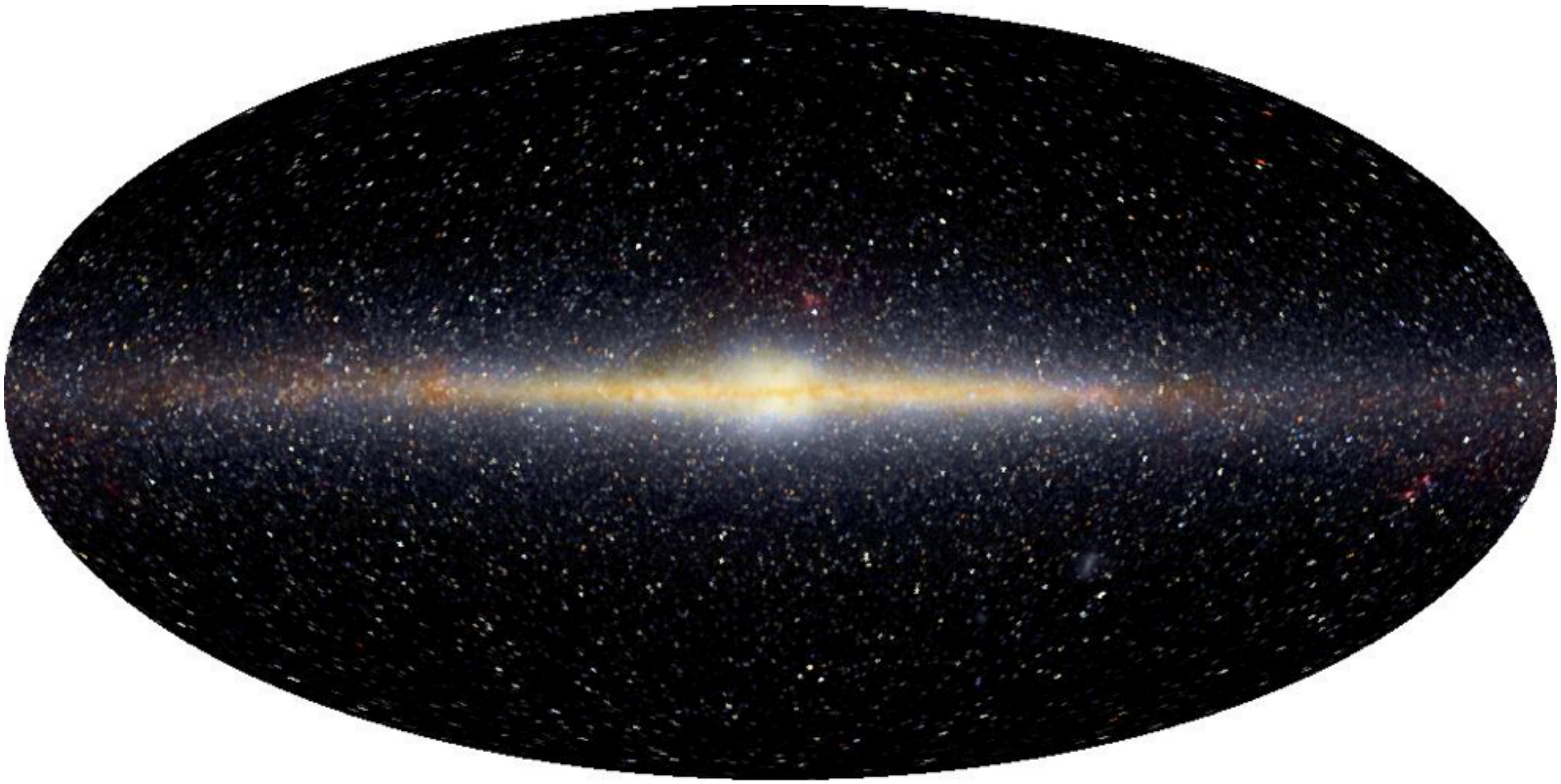
of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

H. Bethe.
R. Peierls.

Transparent

We are transparent to neutrinos.

We’re going to need a bigger detector…



Our distance from the center of the Milky Way ≈ 24×10^{16} km

20 years pass…

Interlude

Concepts behind design of an experiment:

Example case:

- First detection of the neutrino

Detection process / observable:

- What process has the most potential to reveal the neutrino?

Source:

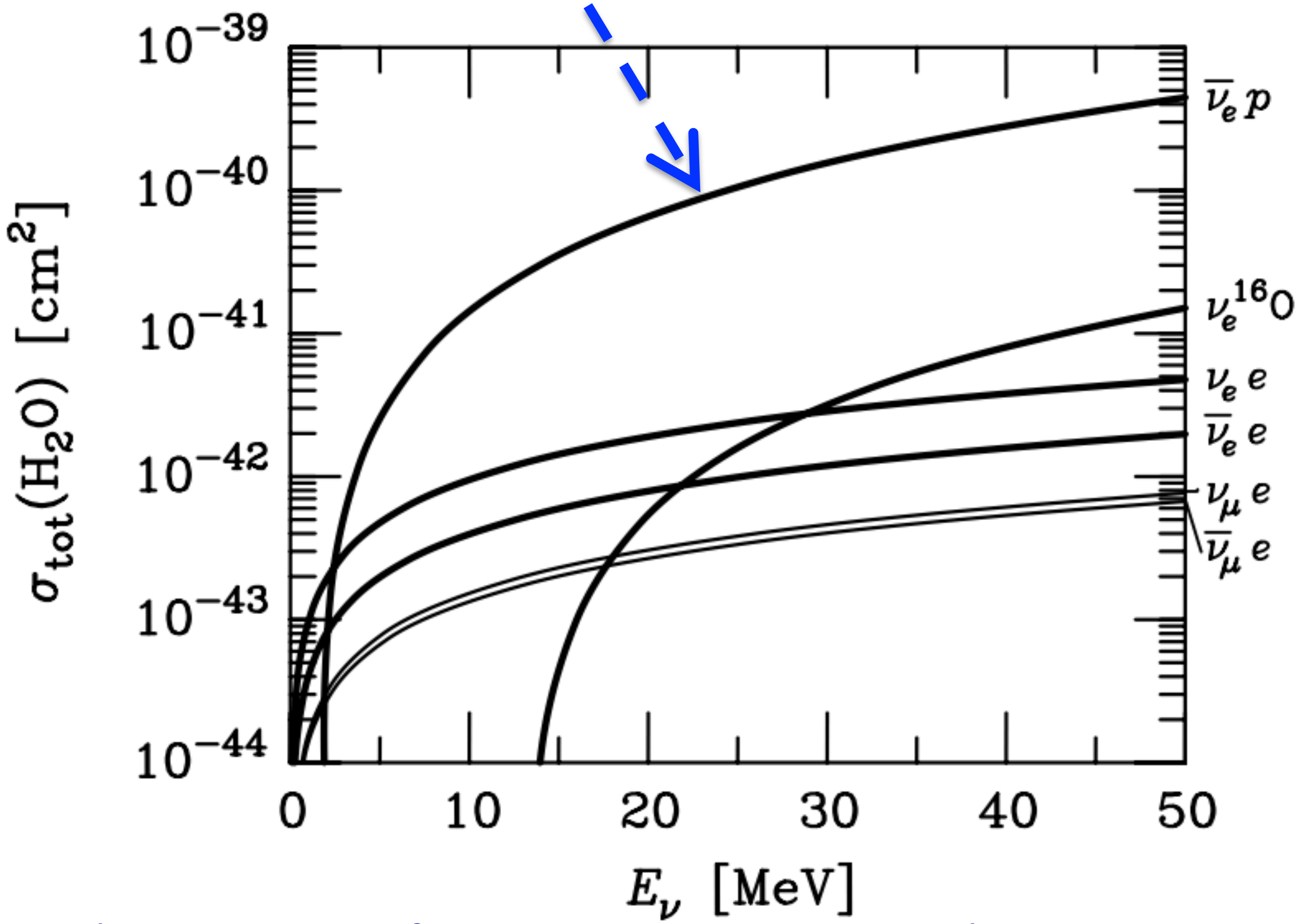
- Which neutrino source is best suited for this experiment?

Detector:

- What detector technique is appropriate for this detection?

Interaction Cross-section

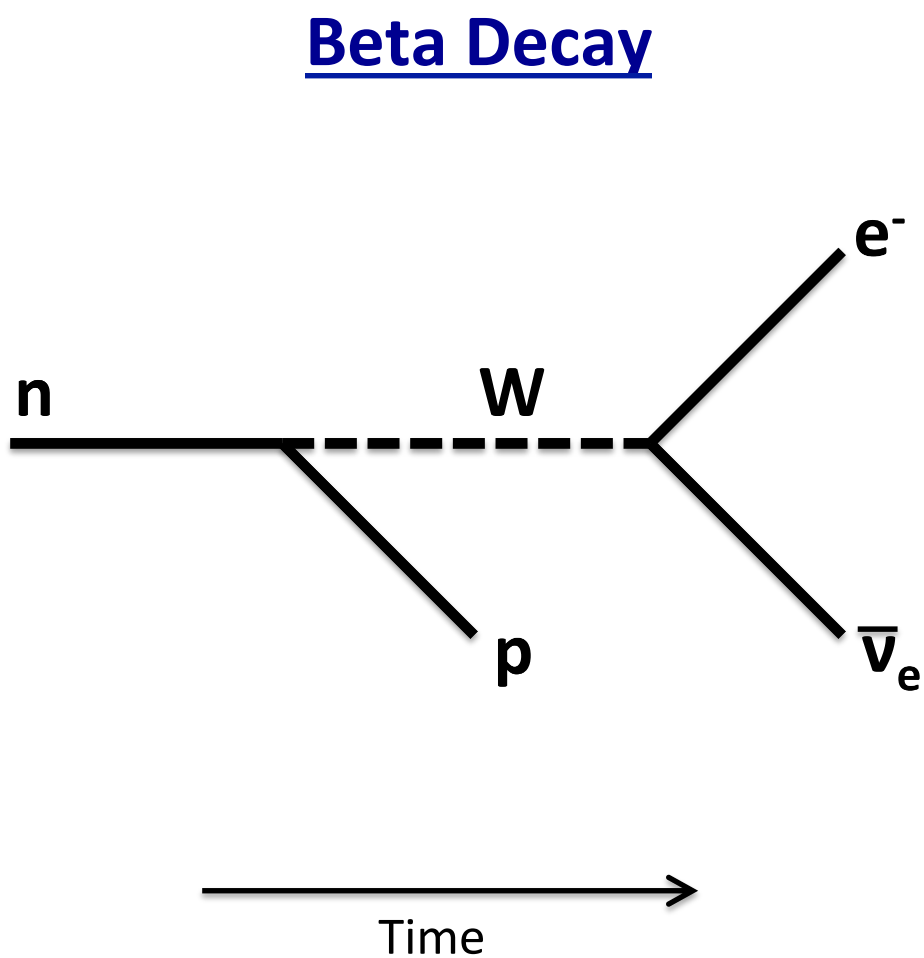
Antineutrino interaction on proton: a giant amongst the tiny.

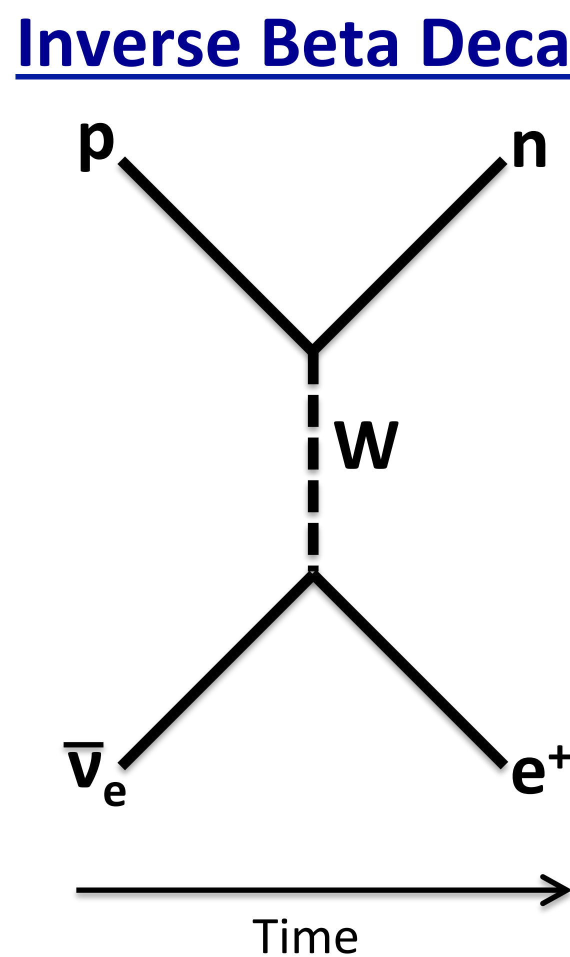


Example total cross-sections for neutrino interactions with water
Proc. Int. Sch. Phys. Fermi 182, 61 (2012)

Inverse-beta decay

Antineutrino interaction on proton: another side of beta decay.





Playing the odds…

Cross section for antineutrino interaction is still small ($\sim 10^{-41}$ cm^2)

$$R_{det} = \sigma_{IBD} \times N_p \times \Phi_\nu$$

But rate of detected neutrinos can still be reasonable…

…if total target protons a and antineutrino flux Is very large.

What kind of detector?

Need a large number of protons (hydrogen)…

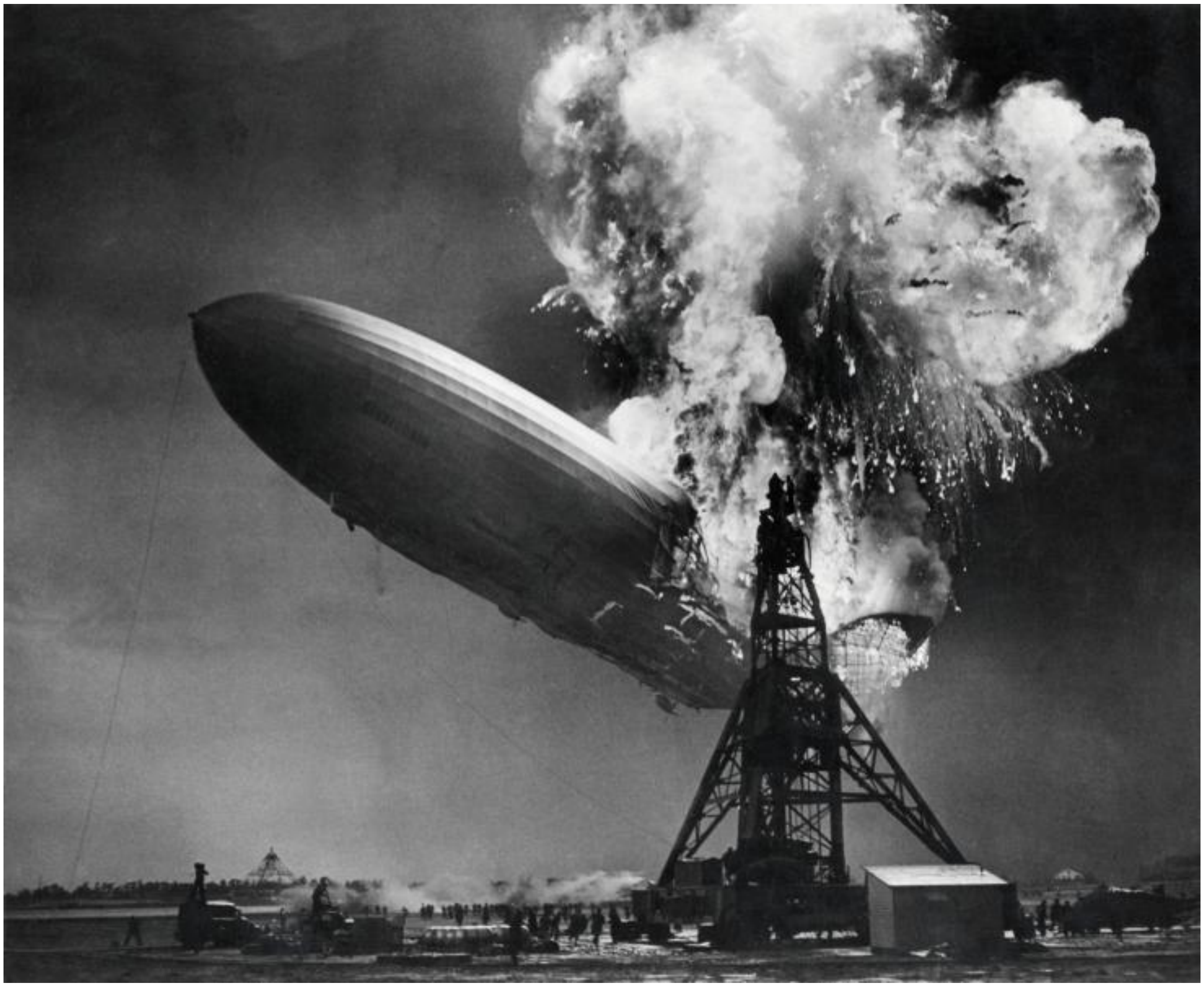
What kind of detector?

Need a large number of protons (hydrogen)…

A very large volume of hydrogen gas?

What kind of detector?

Need a large number of protons (hydrogen)…



Maybe not H_2

What kind of detector?

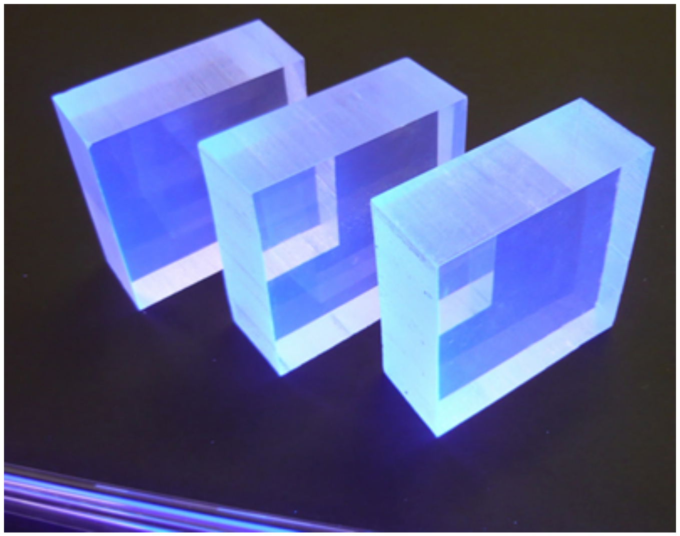
Need a large number of protons (hydrogen)…

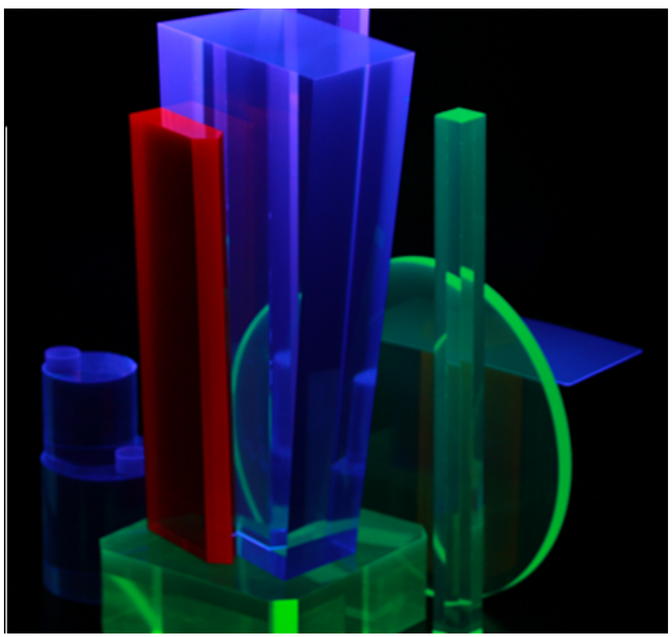
Water?

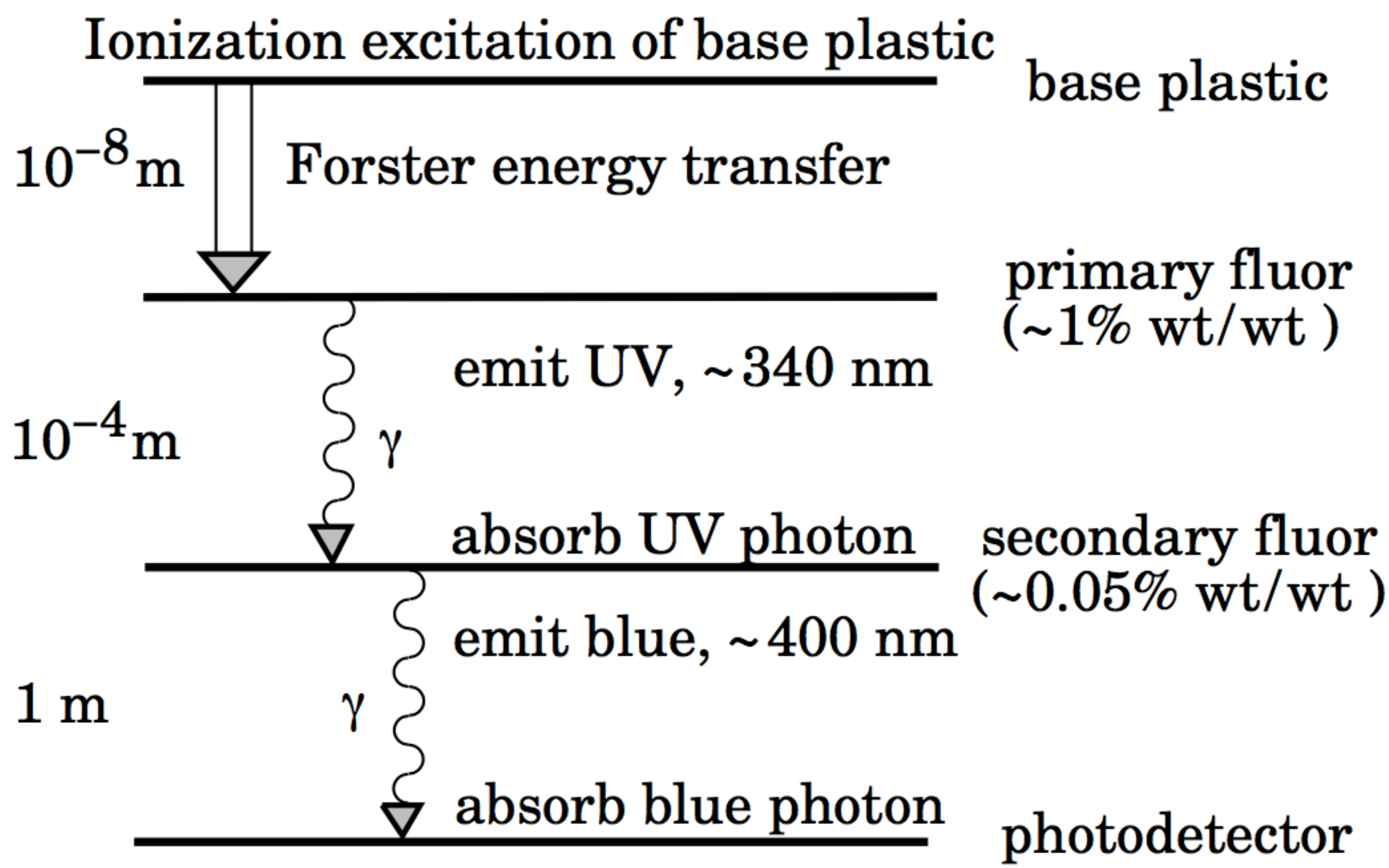
Organics?

What kind of detector?

Organic scintillators provide convenient target + detector material







"Organic Scintillators", Review of Particle Physics

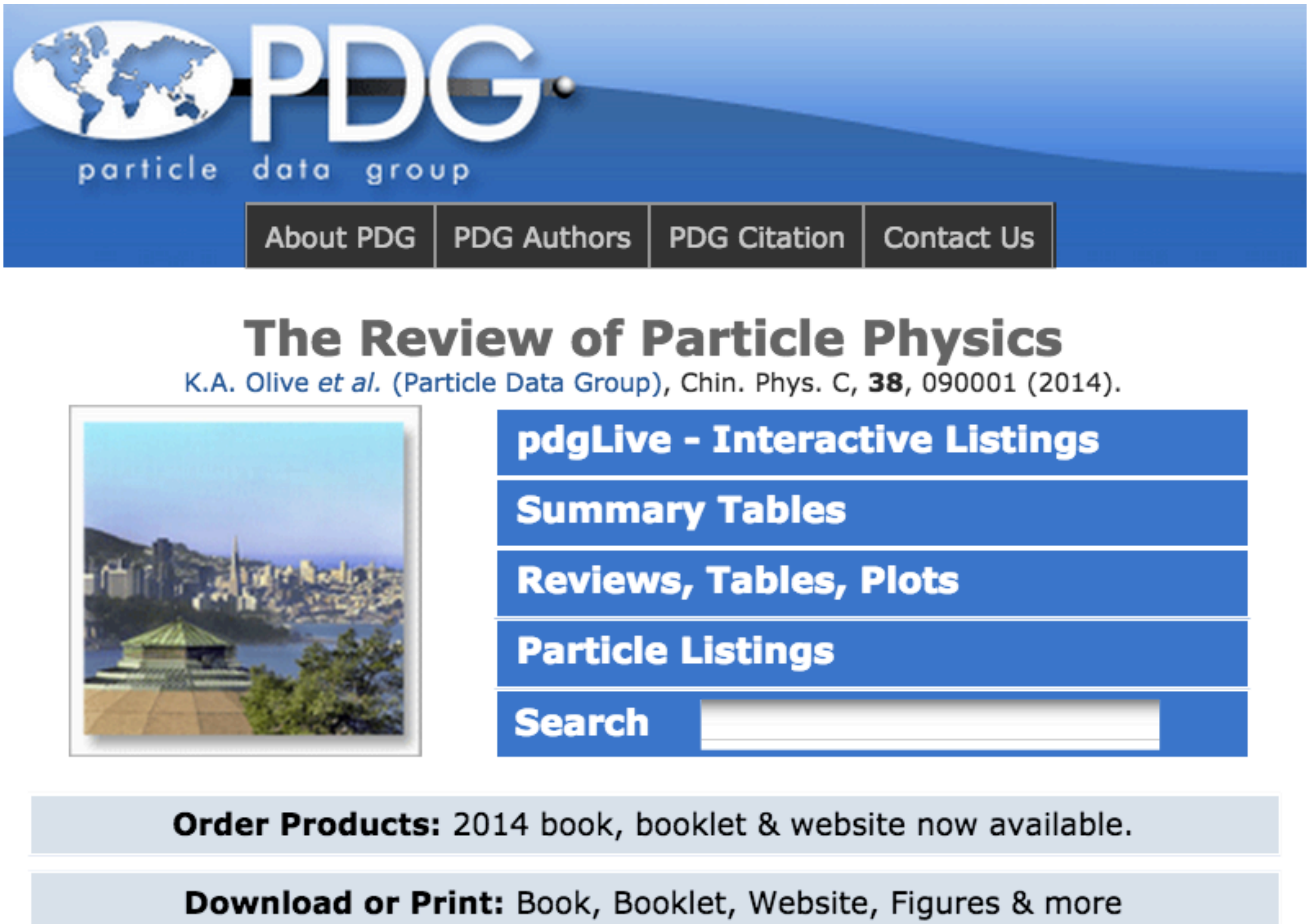
Shameless Advertisement

Read the PDG Reviews of Particle Detectors:

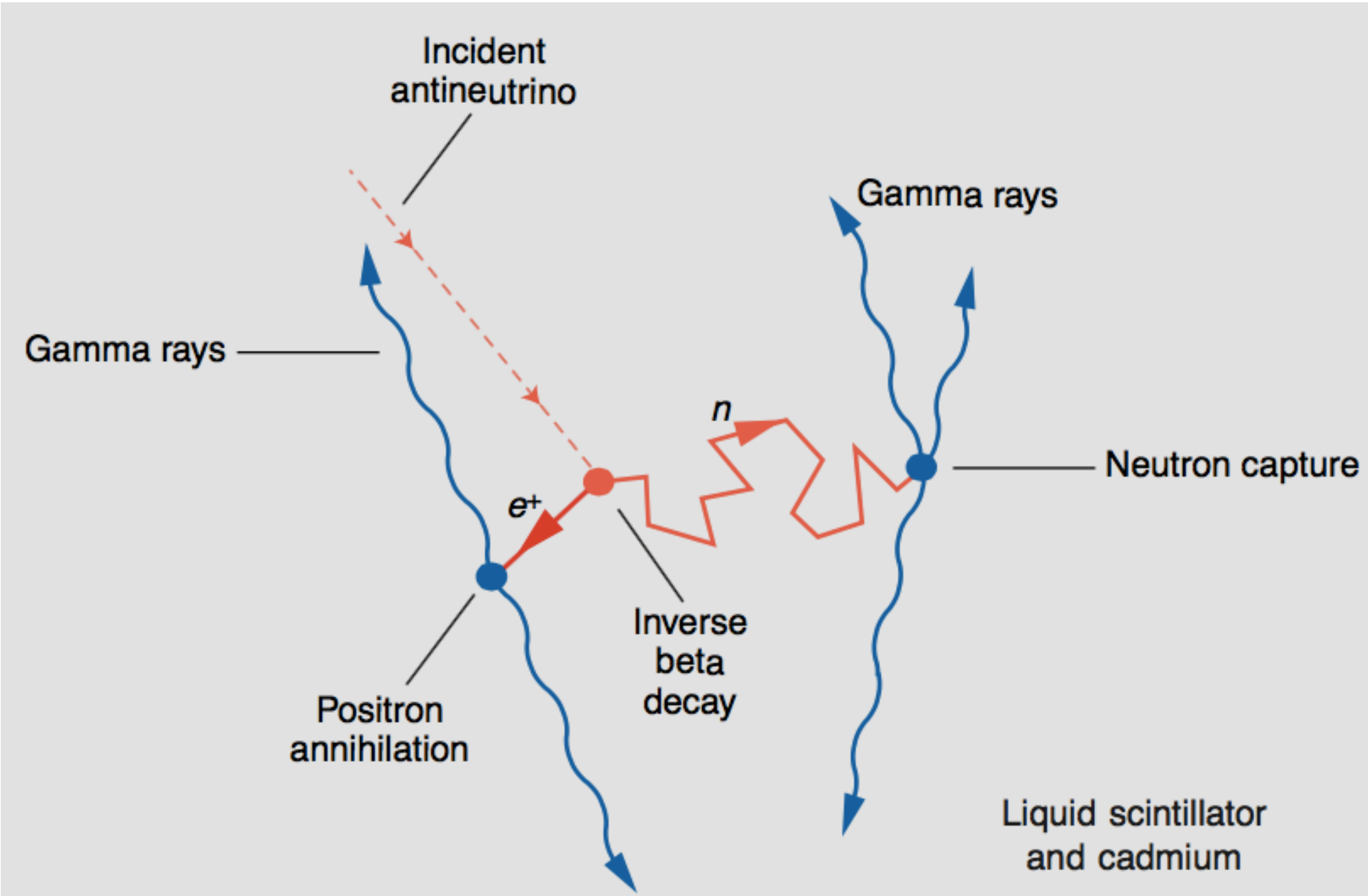
⟶ Particle detectors at accelerators

⟶ Particle detectors for non-accelerator physics

http://pdg.lbl.gov

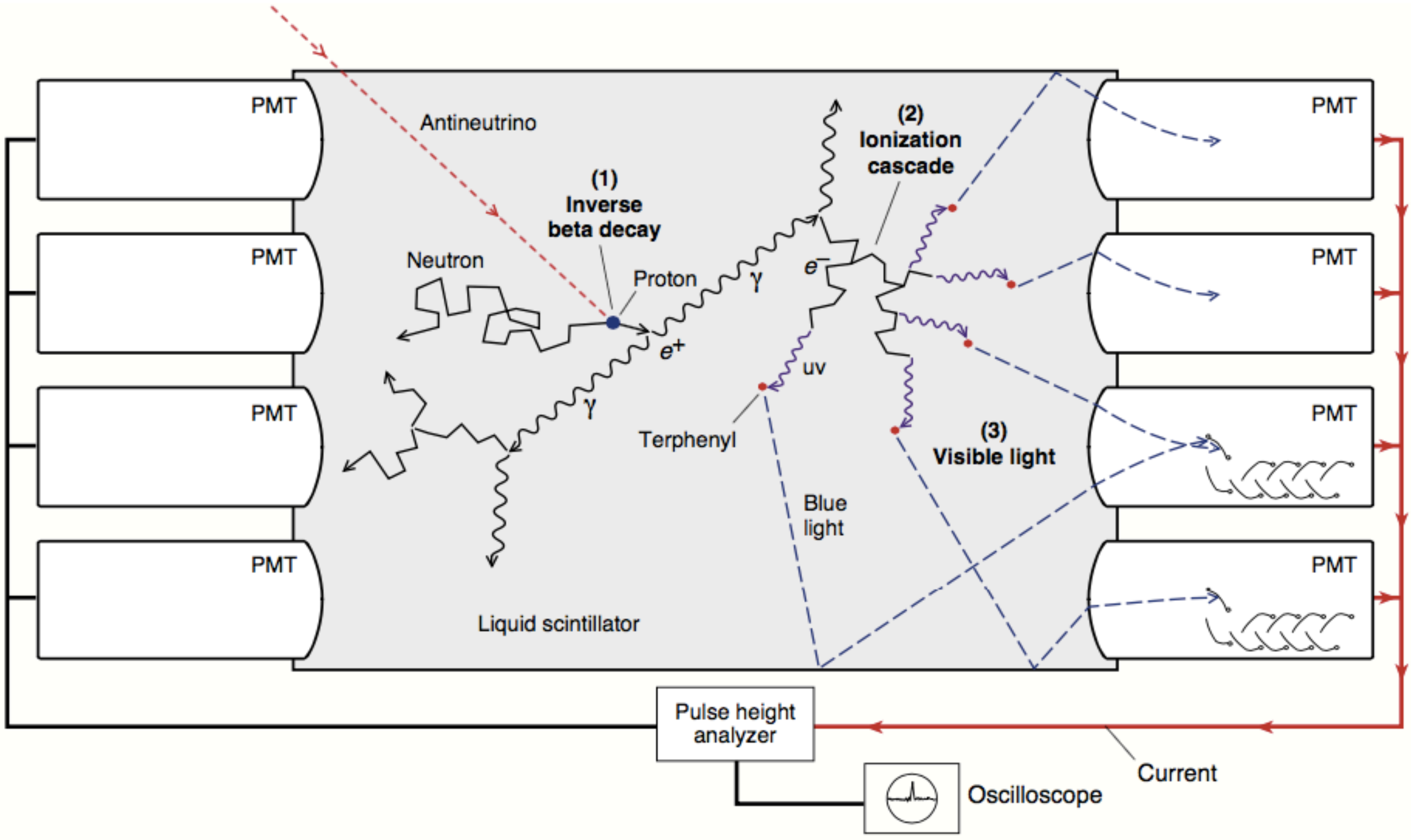


Delayed-Coincidence



The Reines-Cowan Experiments, Los Alamos Science 25, 1997

More detailed…



The Reines-Cowan Experiments, Los Alamos Science 25, 1997

What kind of source?

What are the most intense emitters of antineutrinos?

What kind of source?

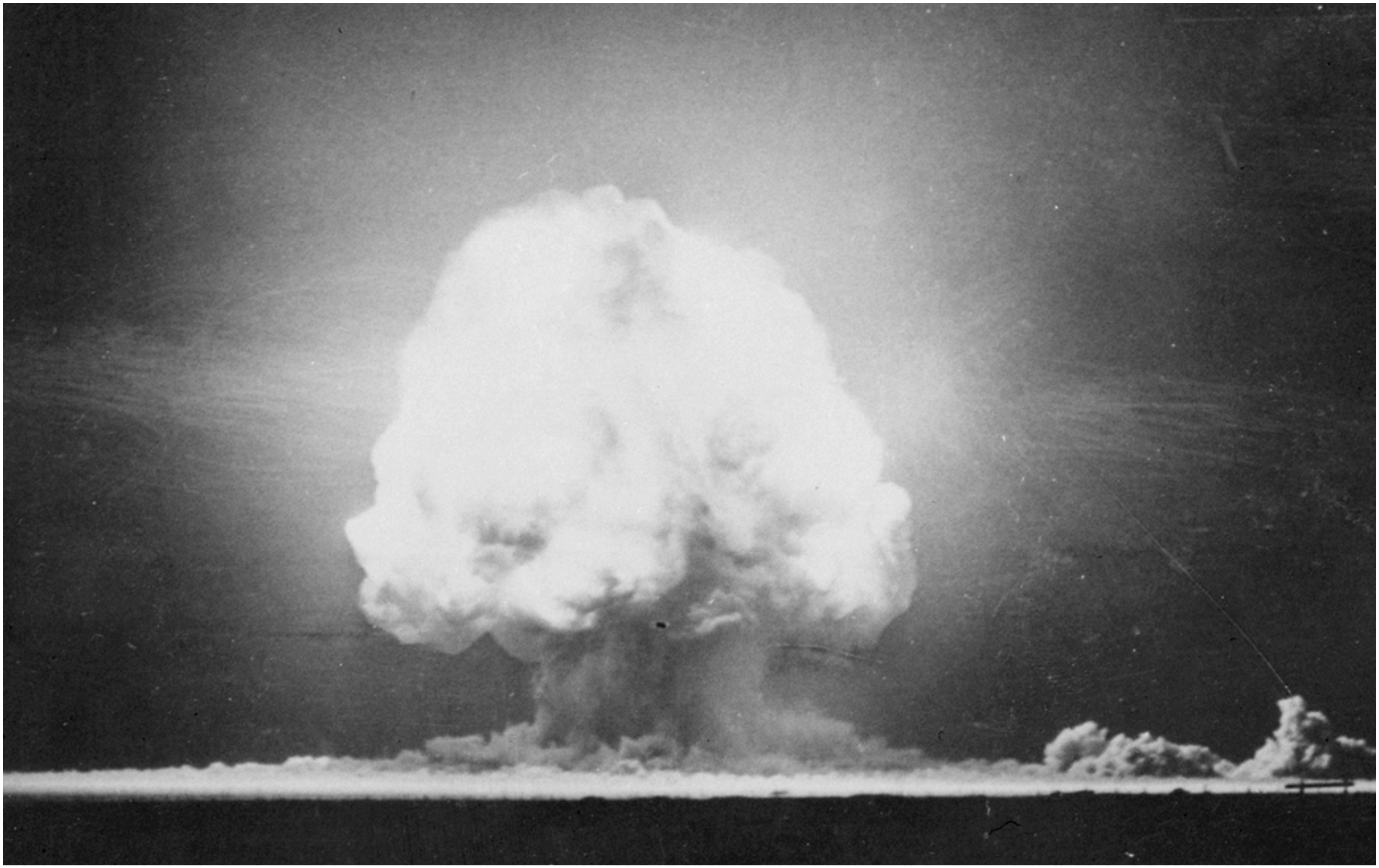
What are the most intense emitters of antineutrinos?

Supernovae?

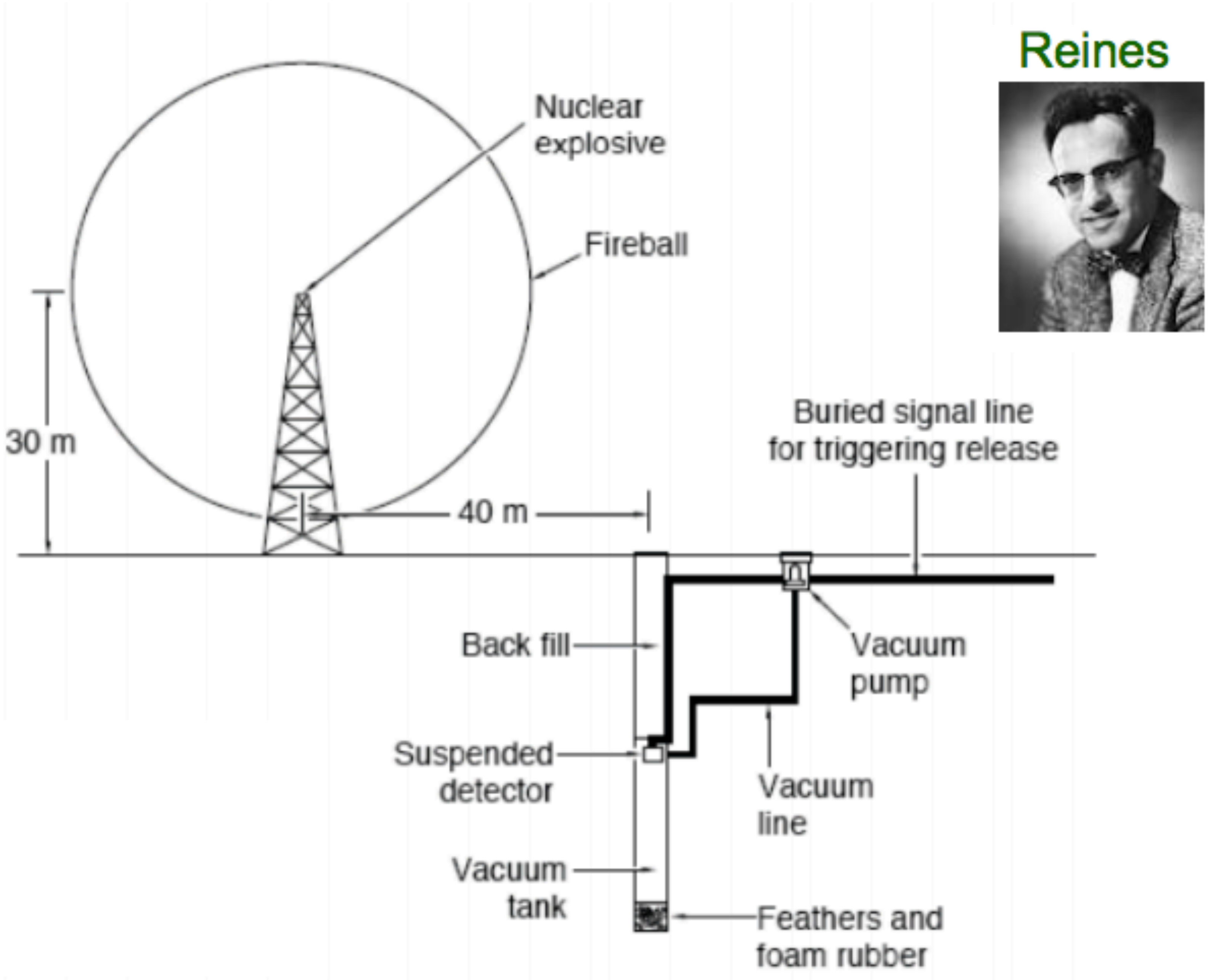
SN1987a

What kind of source?

What are the most intense emitters of antineutrinos?

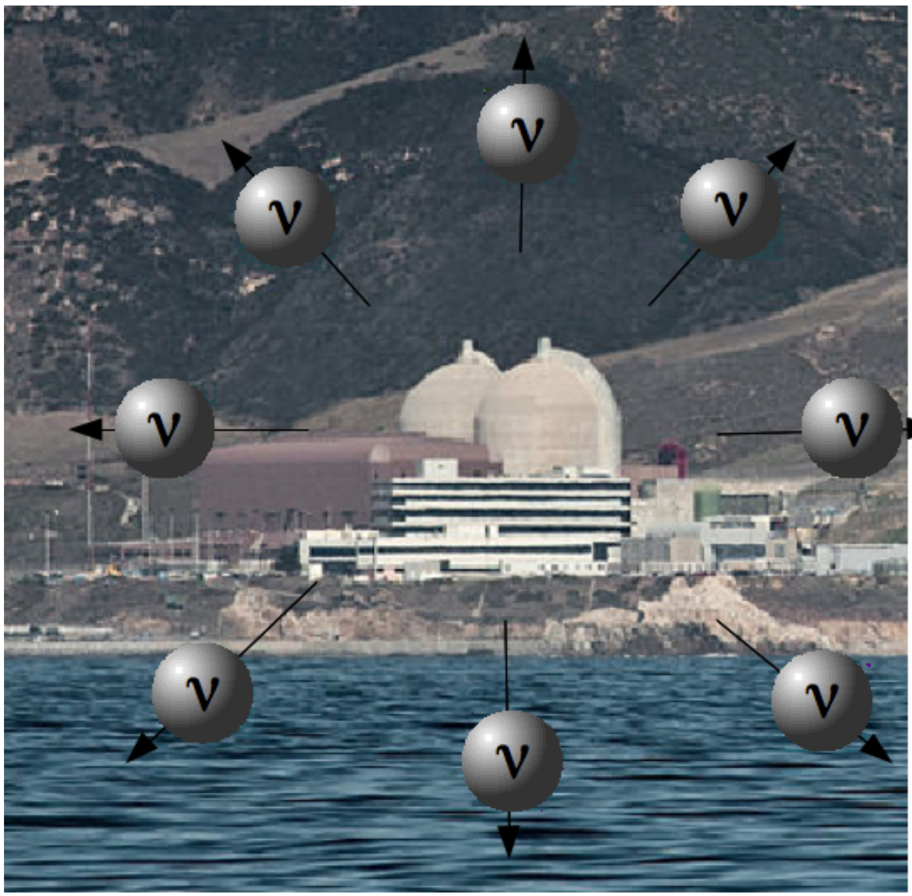


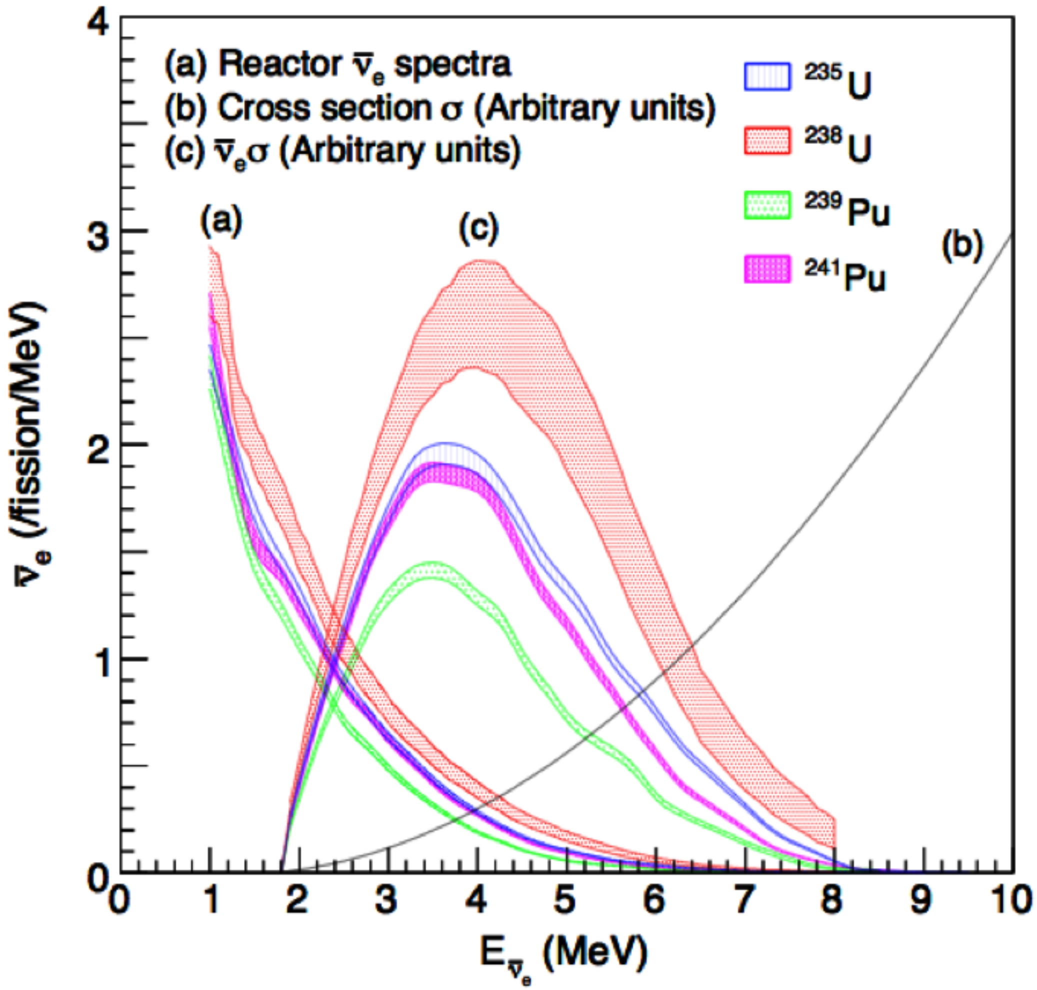
‘Man-made’ Neutrinos



Nuclear Reactors

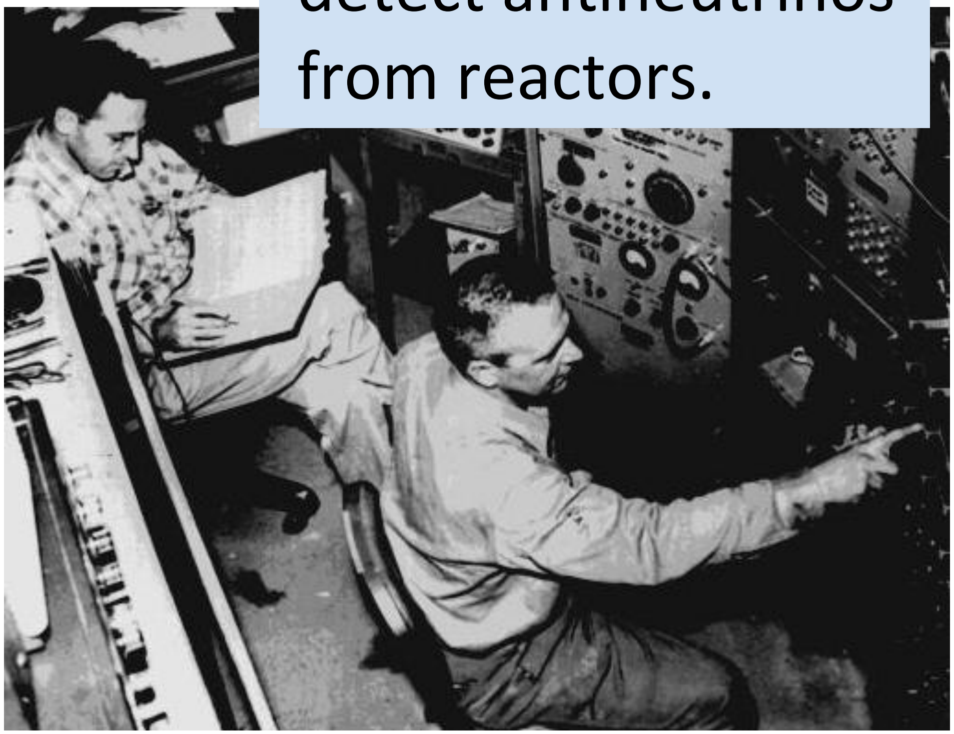
Nuclear fission releases: ~6 antineutrinos/fission
Standard electric power reactor: ~10^{20} fissions/second



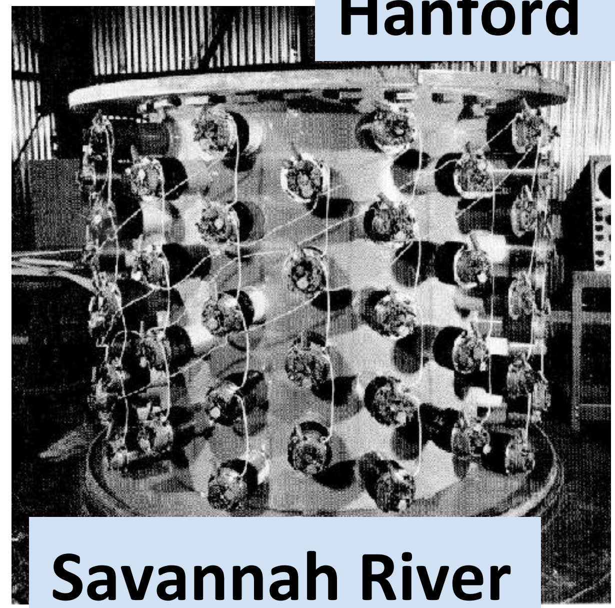


First Detection

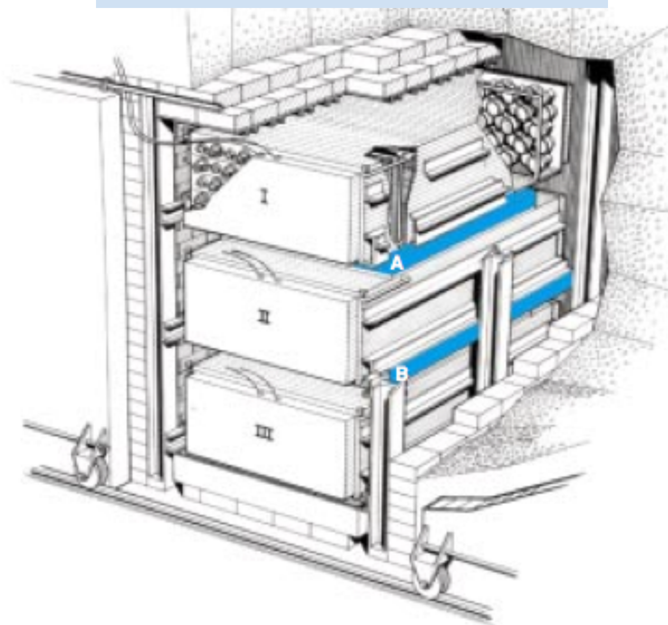
1953-1959:
Reines and Cowan detect antineutrinos from reactors.



Hanford



Savannah River



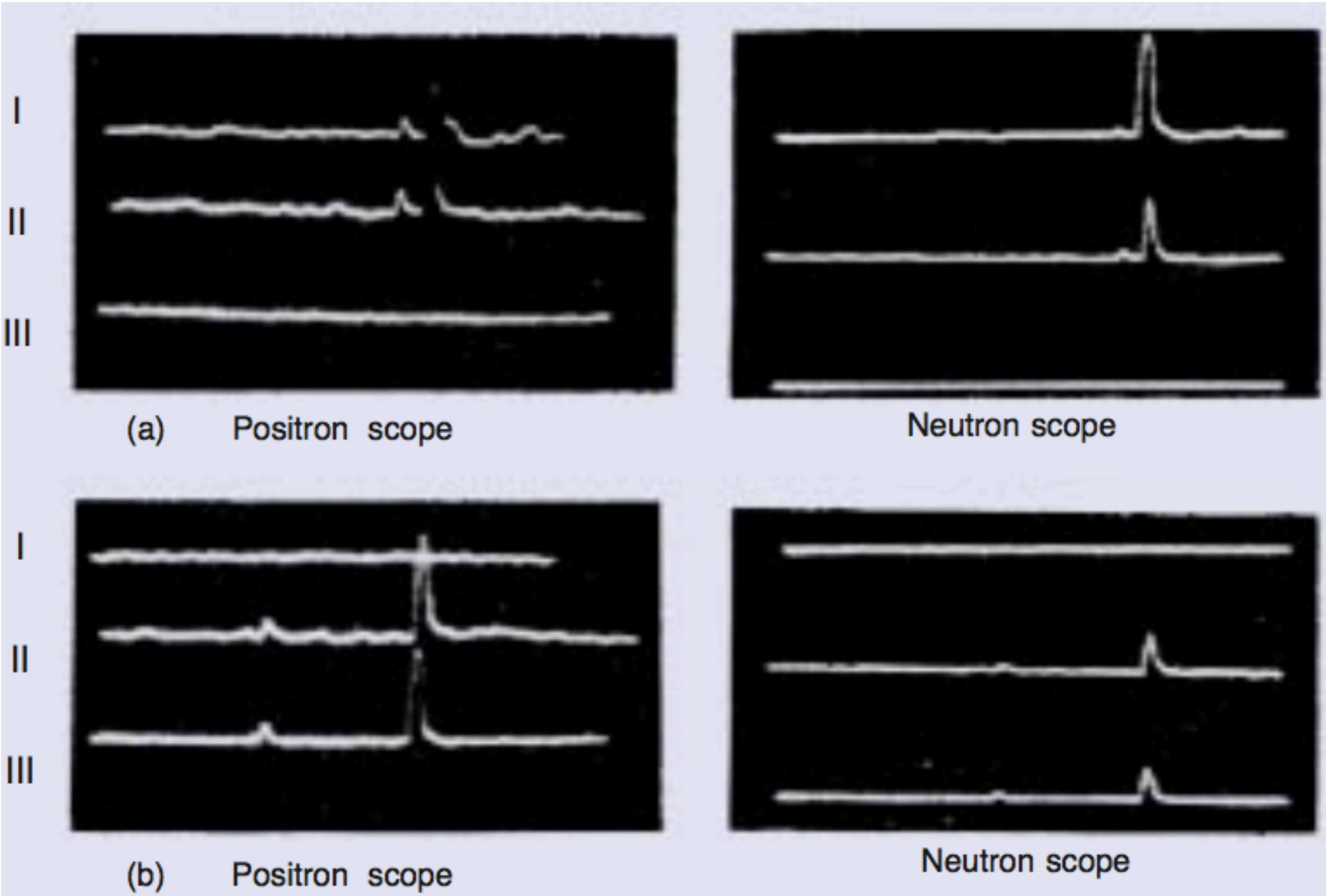
Using:
- Reactors as source
- Inverse-beta decay as signal
- Detectors: Organic liquid scintillator (+water)
  Photomultipliers for light detection

Conclusions from Hanford

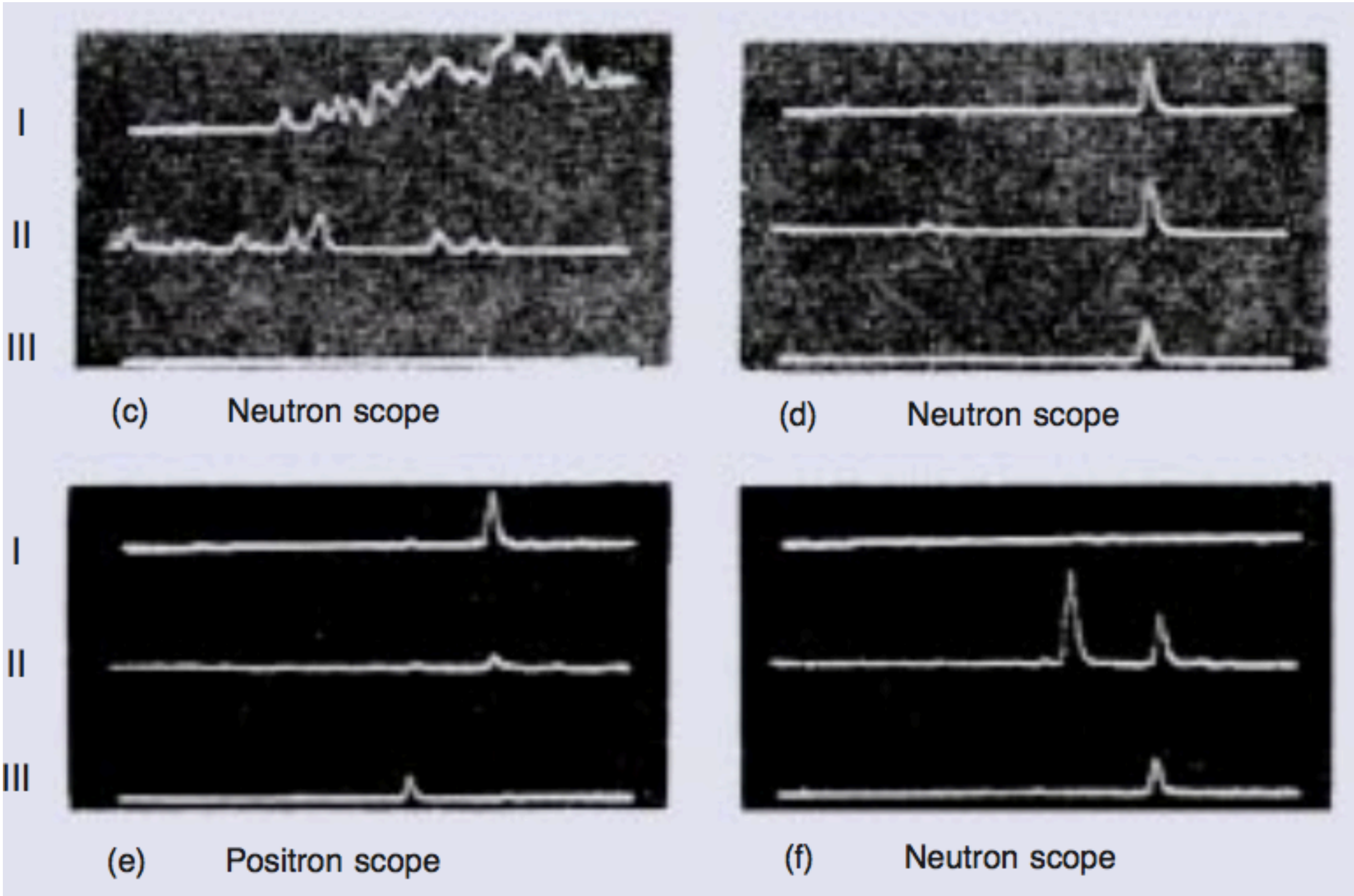
"The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it. We did record neutrino-like signals but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant than were the neutrino signals. We felt we had the neutrino by the coattails, but our evidence would not stand up in court."

The Reines-Cowan Experiments, Los Alamos Science 25, 1997

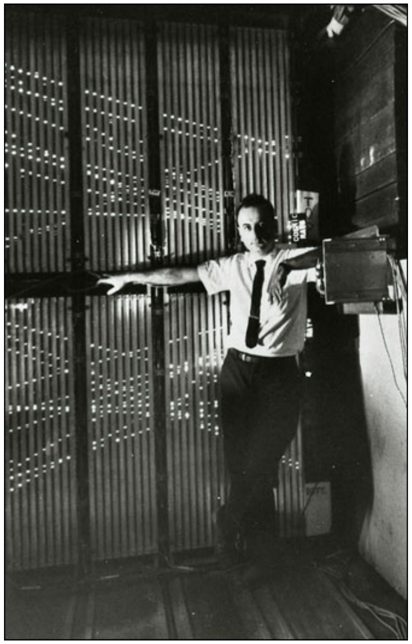
Antineutrino Signals



Background


I
II
III
(c) Neutron scope
(d) Neutron scope
I
II
III
(e) Positron scope
(f) Neutron scope

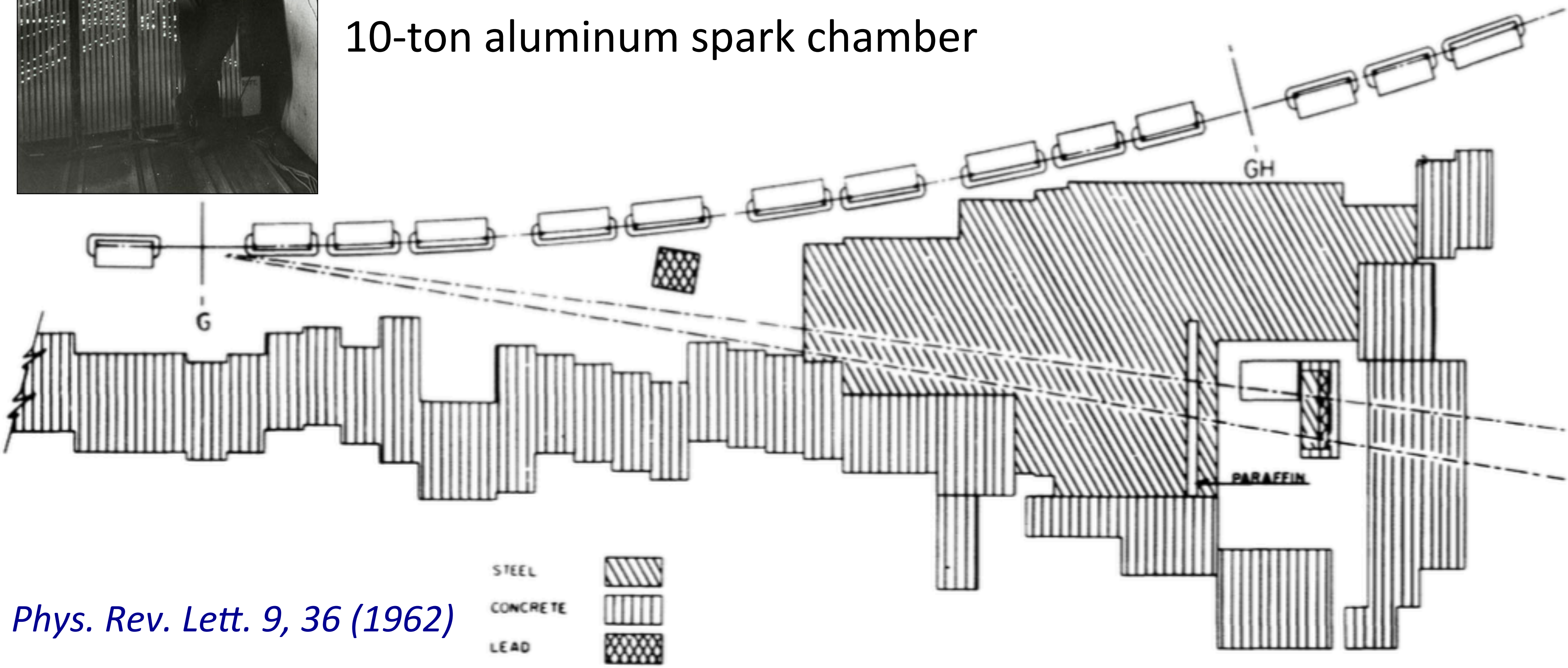
Another Neutrino



1962:

Lederman, Schwartz, Steinberger detect muon neutrino at Brookhaven AGS.

10-ton aluminum spark chamber

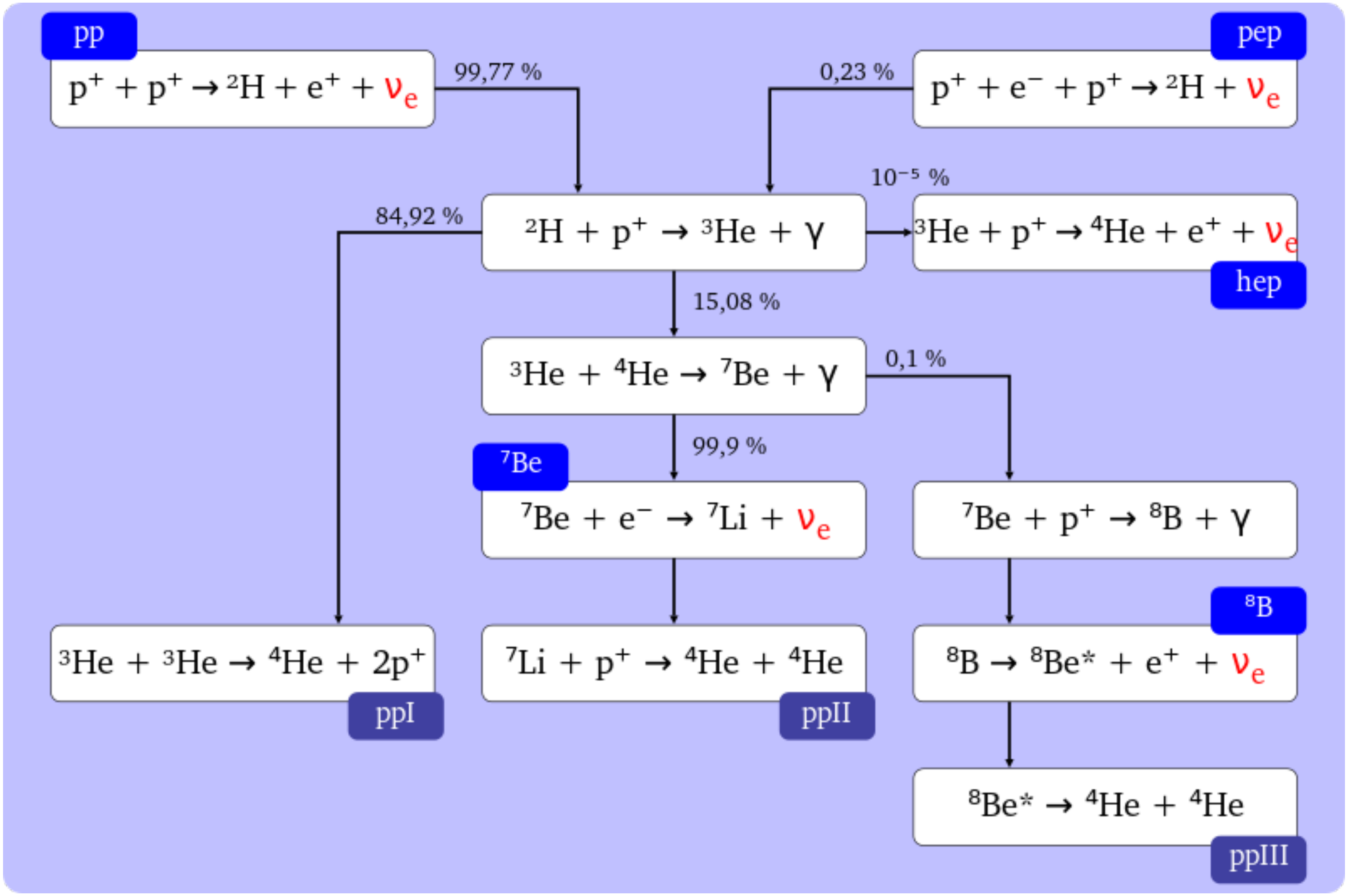


Phys. Rev. Lett. 9, 36 (1962)

FIG. 1. Plan view of AGS neutrino experiment.

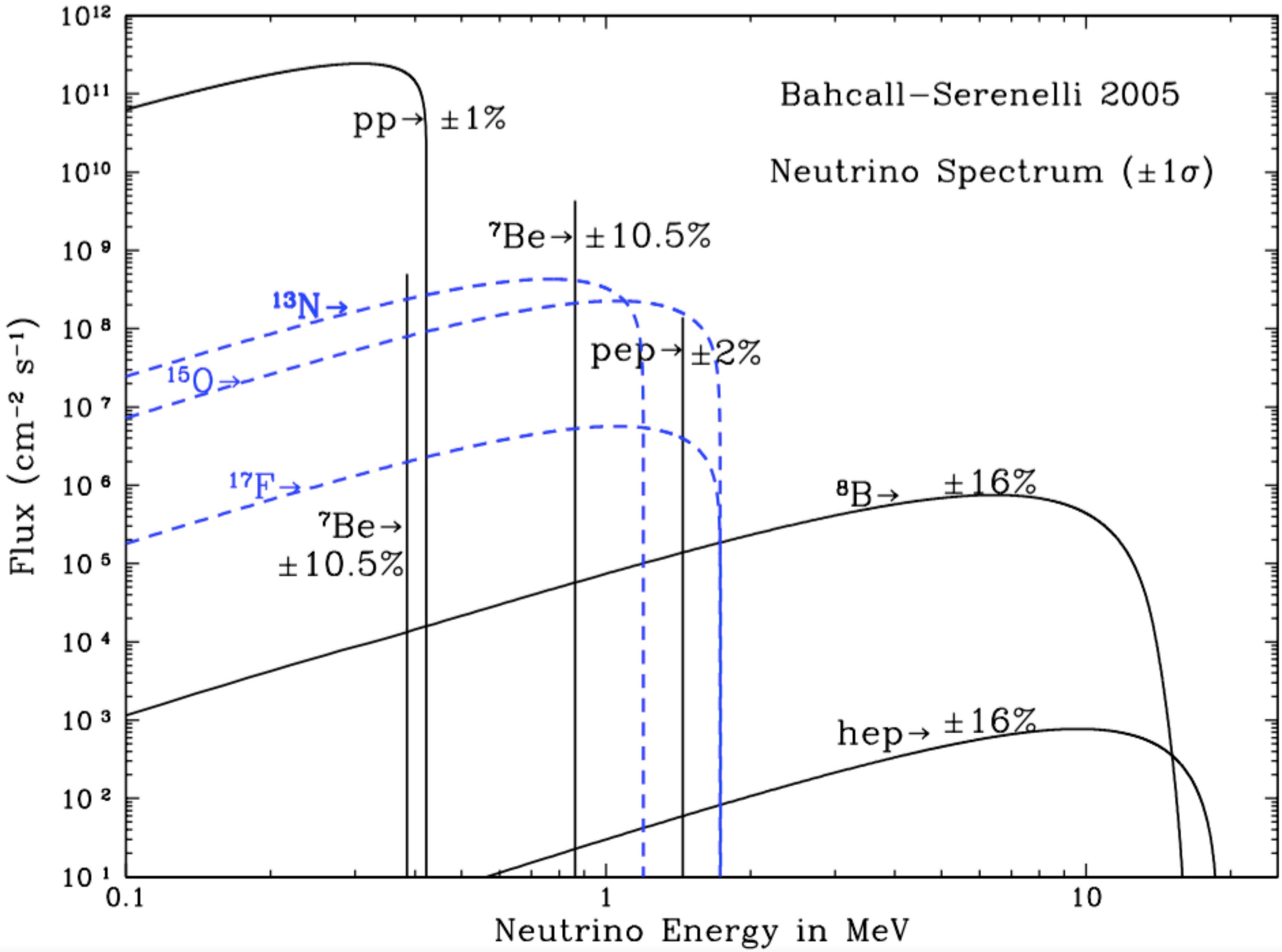
Trouble on the Horizon

Solar Neutrinos



https://en.wikipedia.org/wiki/File:Proton_proton_cycle.svg

Solar Neutrino Spectrum



Better Physics Through Chemistry

Potential for radiochemical solar neutrino detection:

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-. \qquad \text{(Threshold: 0.8 MeV)}$$

Concept:

Step 1:

Fill a tank with 100,000 gallons of cleaning fluid (Chlorine).

Step 2:

Put it ~1 mile underground.

Step 3:

Wait for solar neutrinos to convert a few Cl atoms to Ar.

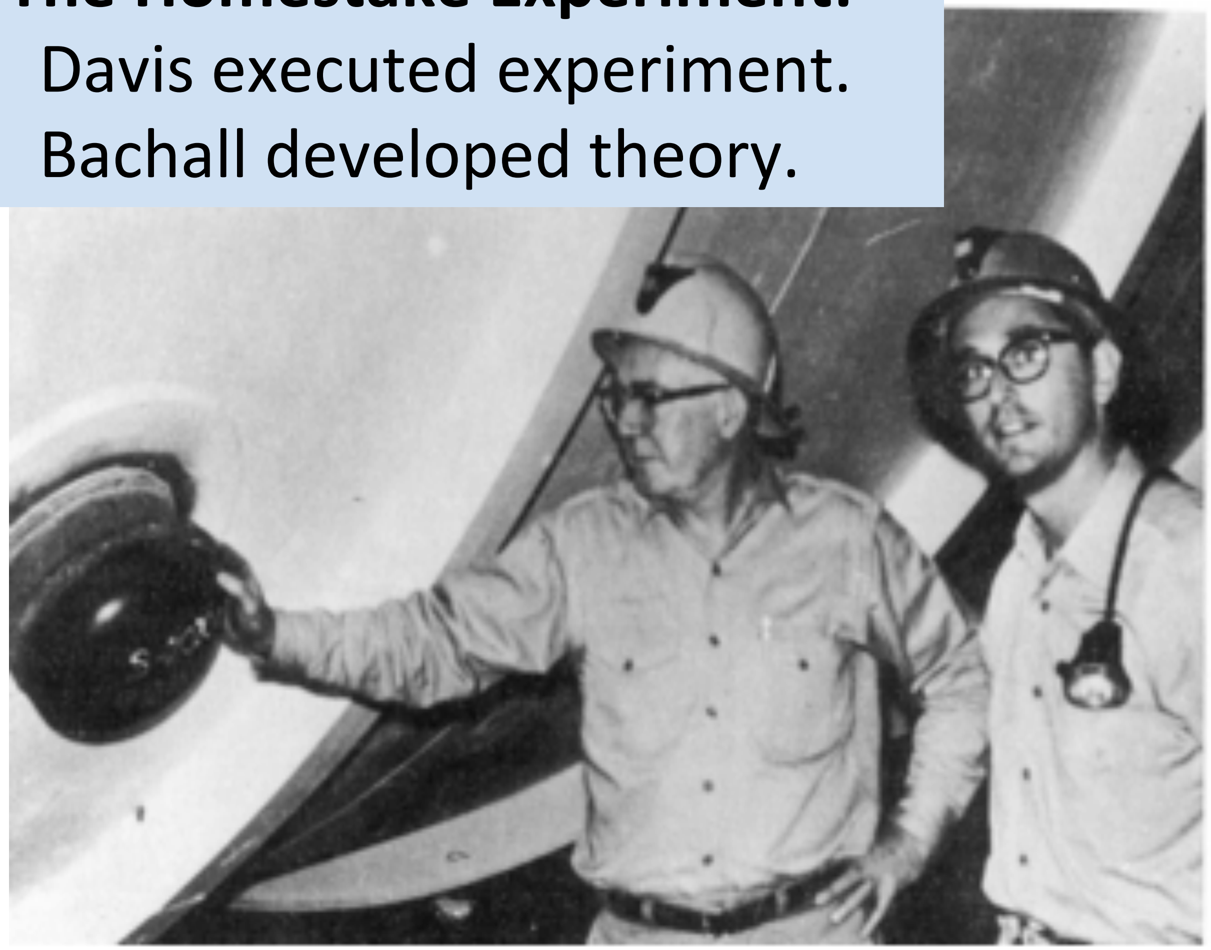
Step 4:

Take Argon atoms out of tank and count them.

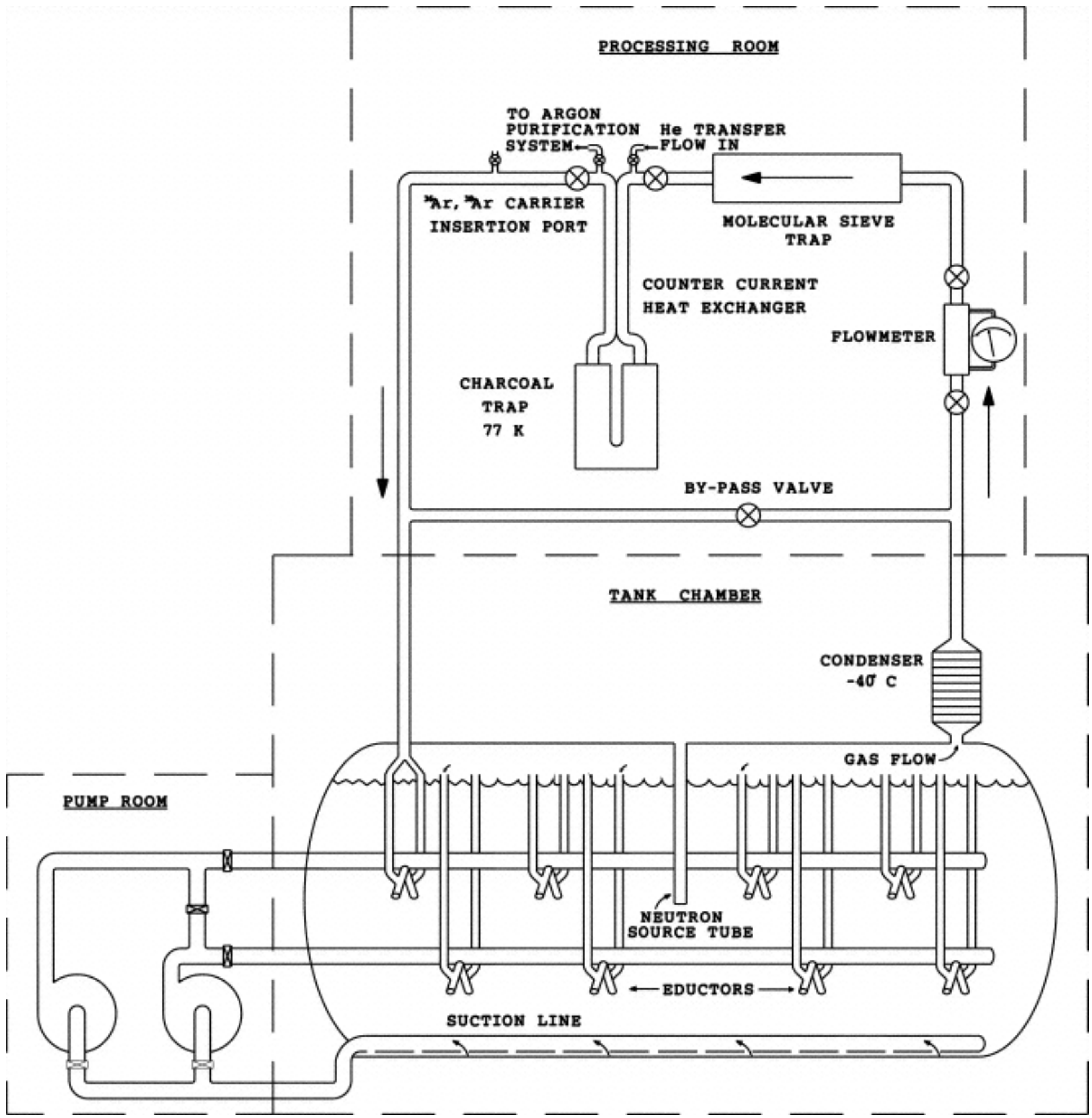
The Homestake Experiment:

Davis executed experiment.

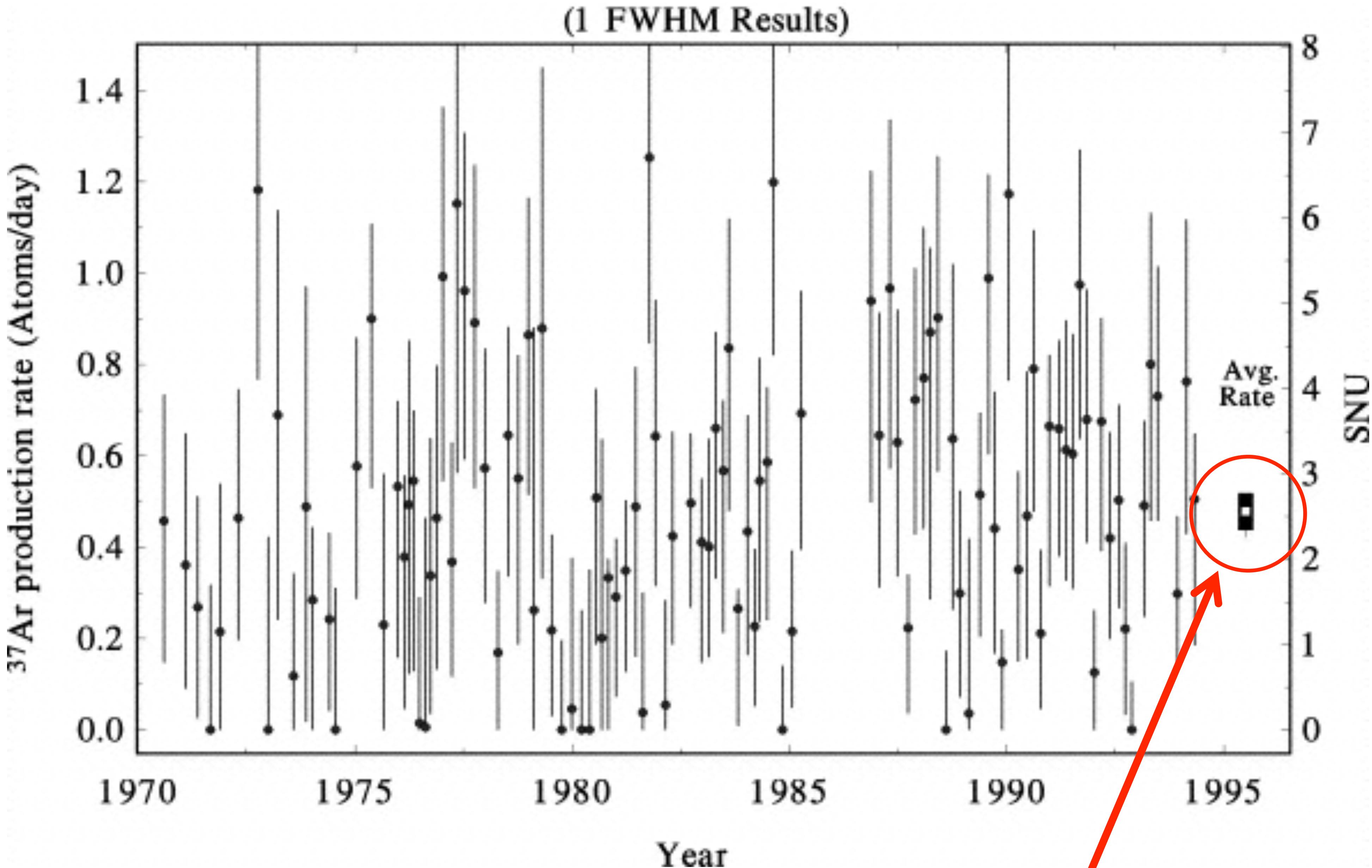
Bachall developed theory.



The Homestake Detector



The Homestake Result

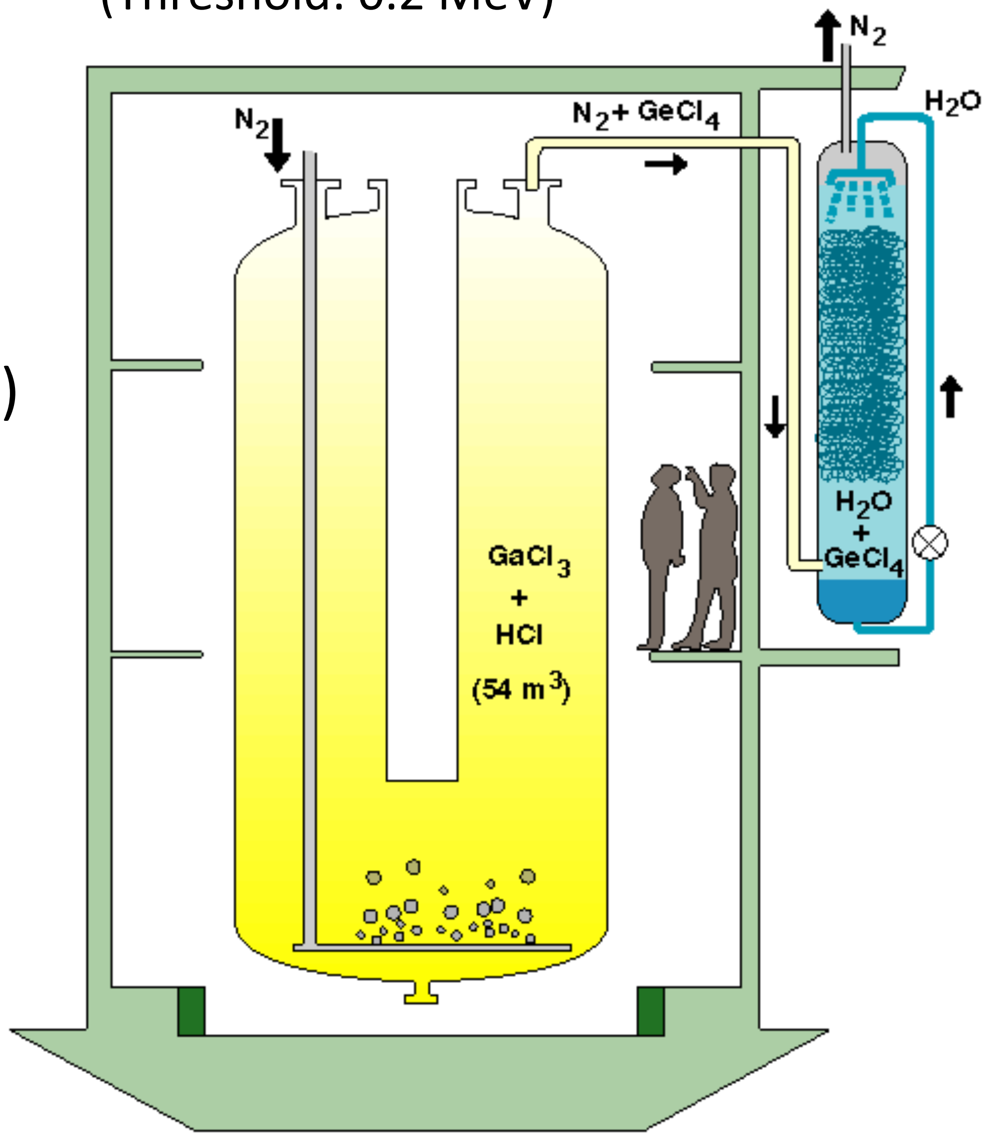


Average rate: 1/3 of that expected from solar models.

SAGE and Gallex/GNO

Radiochemical solar neutrino detection at lower energies:

$$\nu_e + {}^{71}\text{Ga} \mapsto {}^{71}\text{Ge} + e^-$$ (Threshold: 0.2 MeV)



SAGE:

- 50-57 tons liquid gallium metal
- Began operation 1989
- Baksan Observatory (Caucasus, Russia)

Gallex/GNO:

- 101 tons GaCl3+HCl (~30 tons Ga)
- Operated 1991 – 1997, 1998 – 2003
- LNGS (Gran Sasso, Italy)

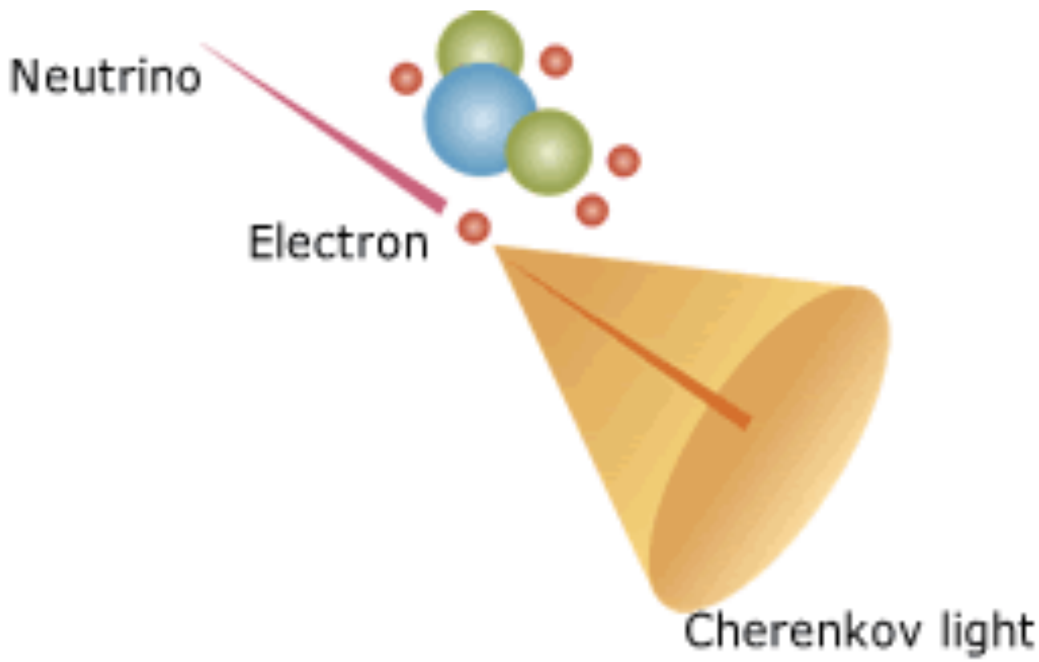
Results:

- Observed 50% of the expected solar neutrino flux.

Water Cherenkov Detectors

Elastic scattering of electrons provide another detection method

$$\nu_x + e^- \rightarrow \nu_x + e^-$$ (Threshold: ~5 MeV, due to backgrounds)



http://www-sk.icrr.u-tokyo.ac.jp/

Details:

- Only sensitive to the high energy tail of the solar ν spectrum (^{8}B, <0.1%)
- Sensitivity to all neutrino flavors (although suppressed for ν_μ, ν_τ)
- Provides 'real-time' measurement
- Light provides neutrino direction
- Requires very large detectors (>kton)

Kamiokande Detector

Details:

- 2.1 kton of ultrapure H_2O (inner det.)
- 948 20” diameter photomultipliers
- Outer layer to reject backgrounds
- Operated 1983 – 1997
- Located in the Kamioka mine, under ~1 km rock. (Gifu, Japan)
- Initially designed to search for proton decay

Prog. in Part. and Nucl. Phys. 40 (1998) 427-441

Kamiokande Results

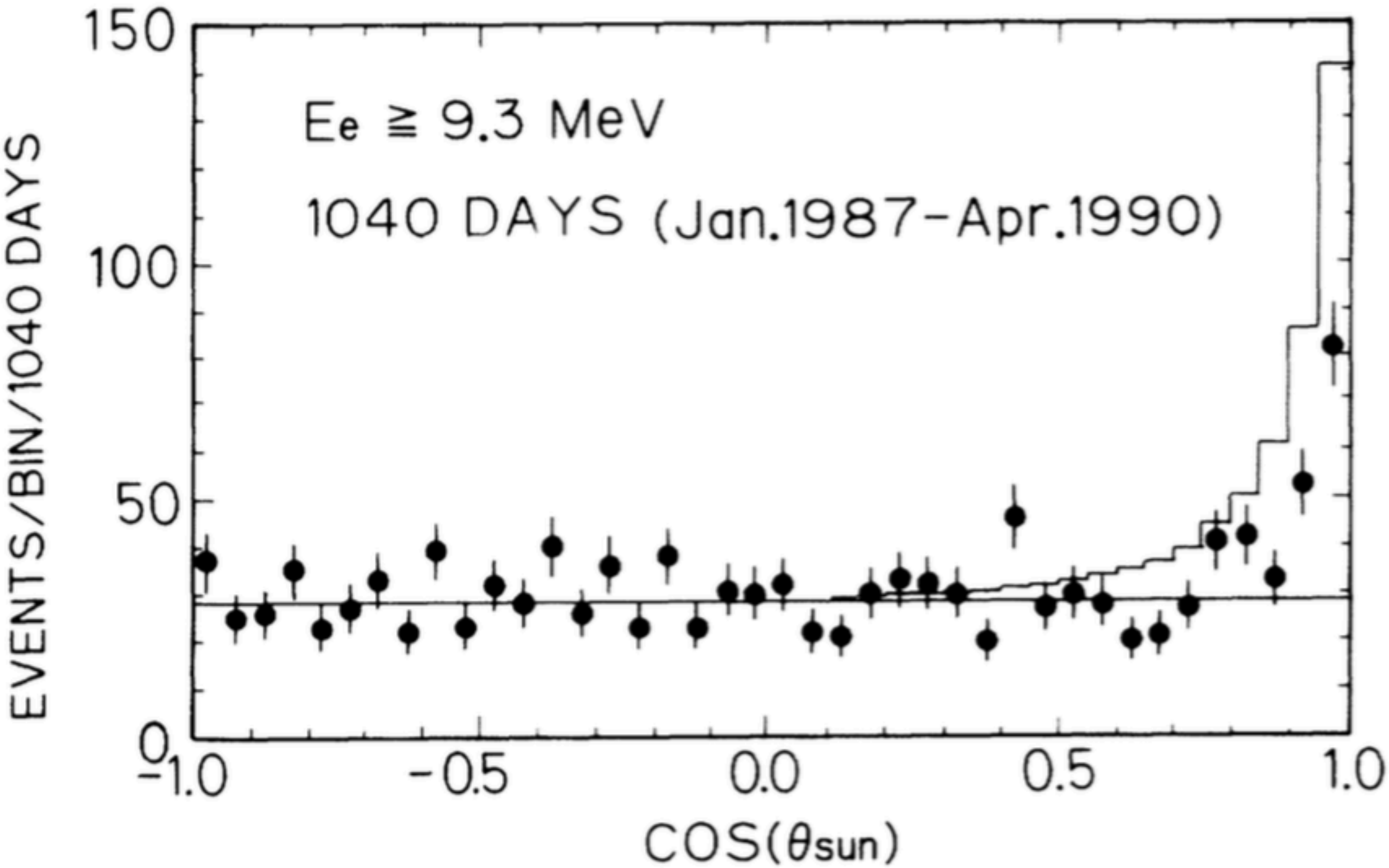
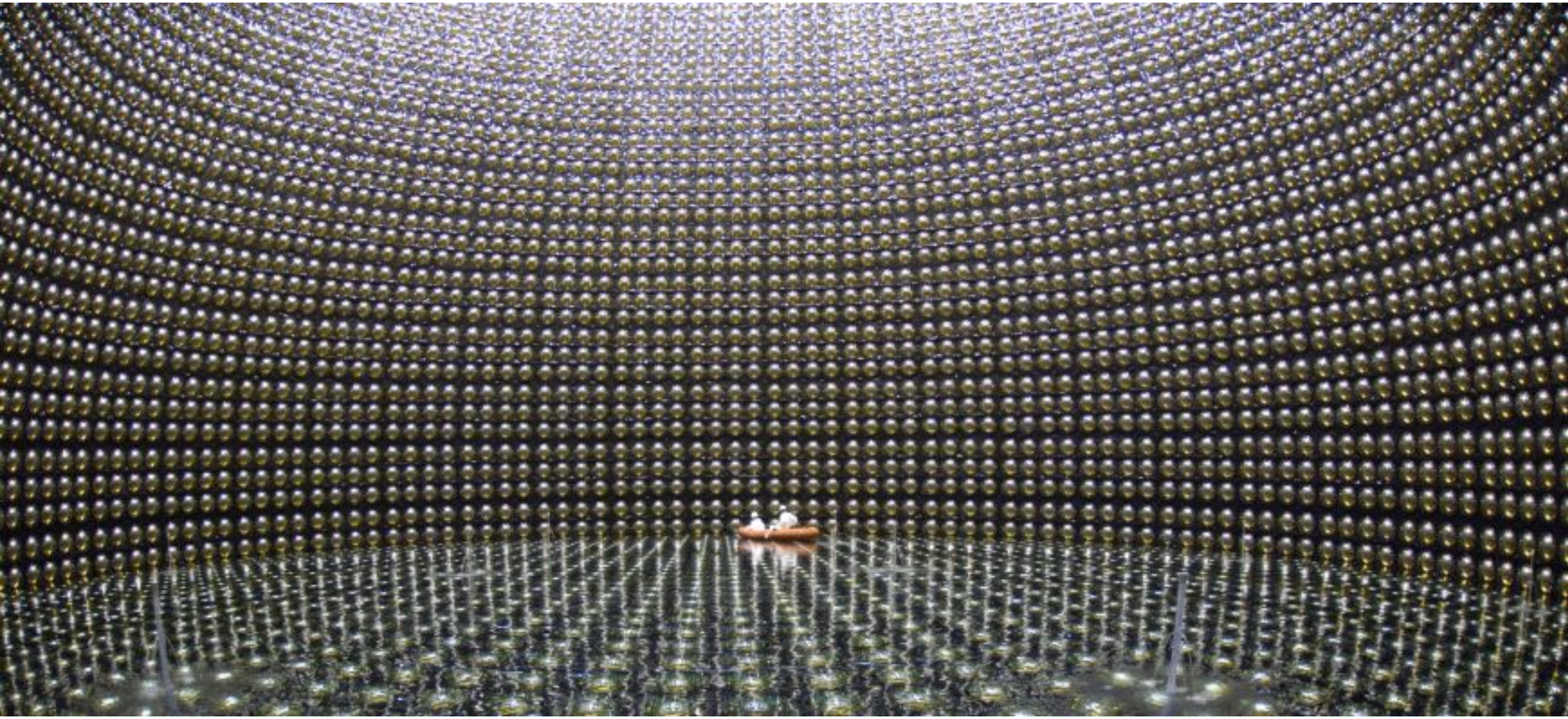


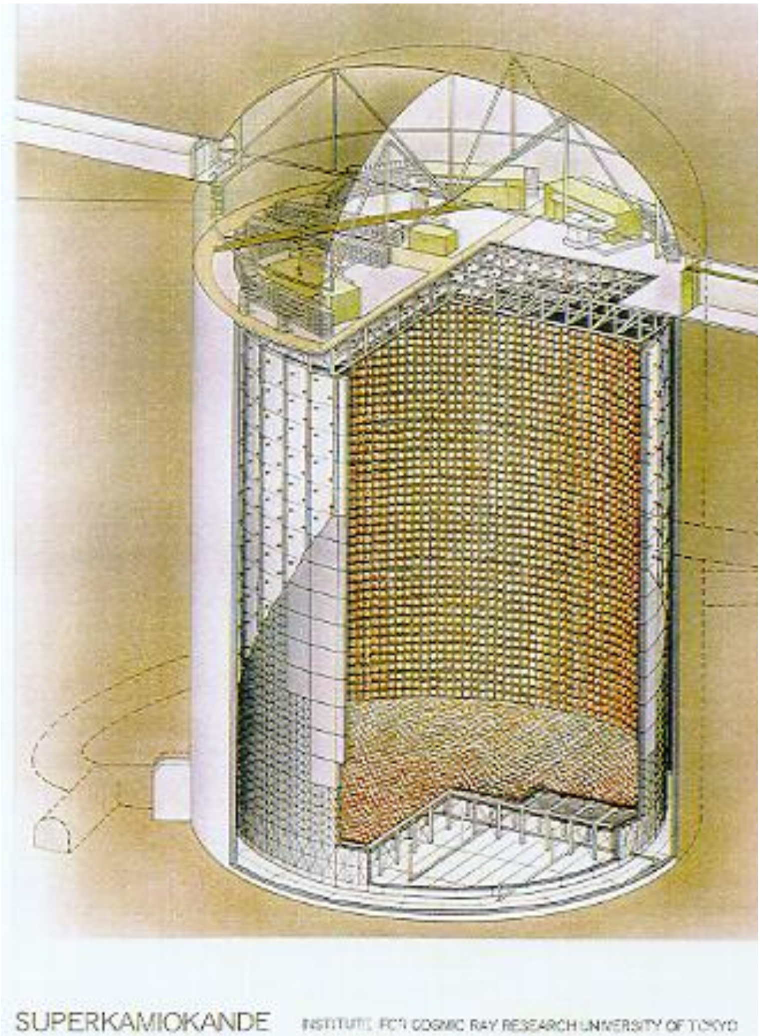
FIG. 3. Distribution in $\cos\theta_{Sun}$ of the combined 1040-day sample for $E_e \geq 9.3$ MeV. The value of the ratio data/SSM from this figure is 0.43 ± 0.06.

Plus other physics to be discussed…

Why Stop There…



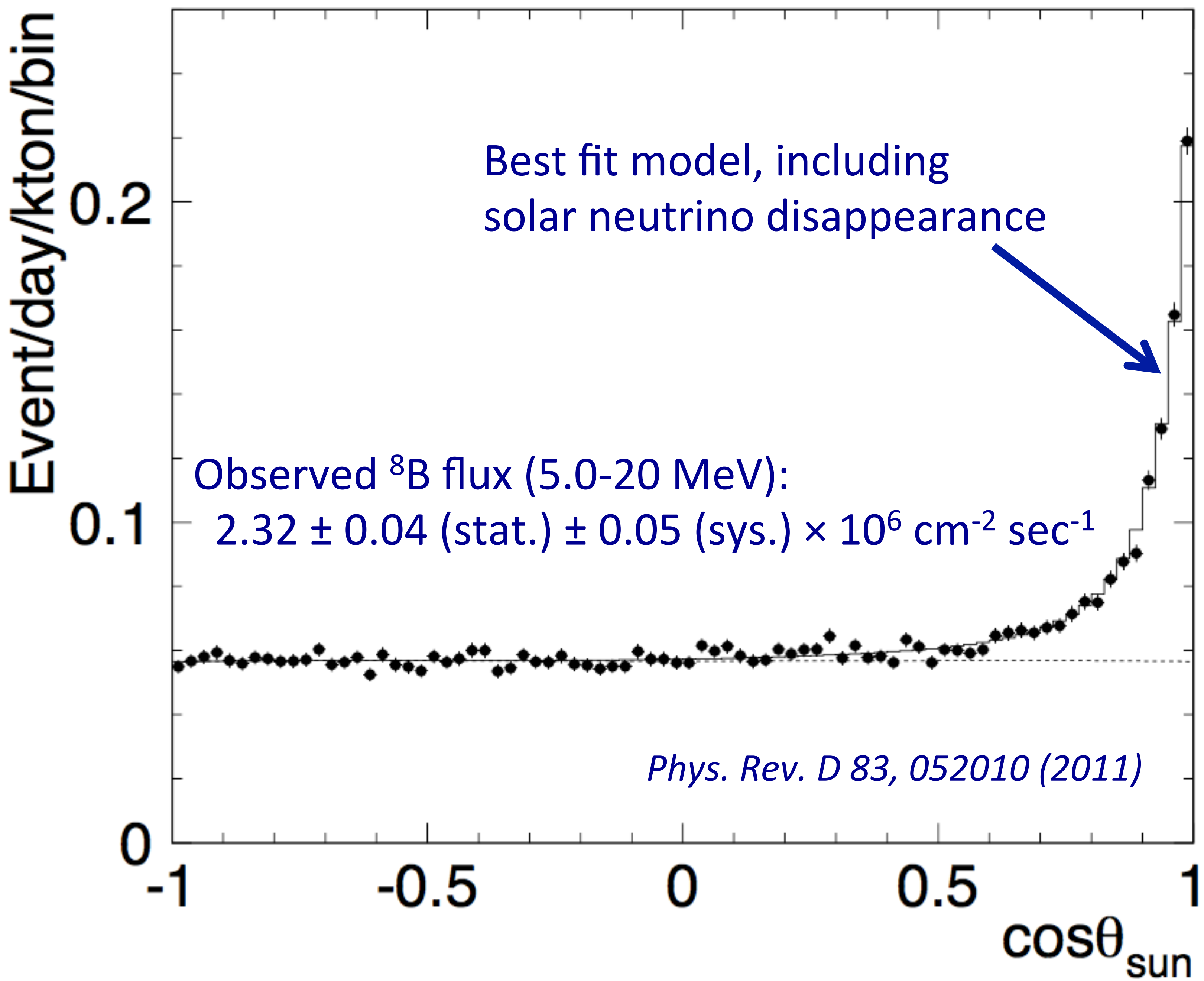
Super-Kamiokande



Details:

- ~~2.1 kton~~ of ultrapure H_2O (inner det.)
  32 kton
- ~~948~~ 20" diameter photomultipliers
  11,146
- Outer layer to reject backgrounds
- Operated 1996 – now
- Located in the Kamioka mine,
  under ~1 km rock. (Gifu, Japan)

Super-Kamiokande: Results



Sudbury Neutrino Observatory

Clever idea: Use heavy water to determine solar neutrino flavor

Interactions in heavy water:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Elastic scattering: ν_e + partial (~1/6) $\nu_{\mu,\tau}$

$$\nu_e + d \rightarrow p + p + e^-$$

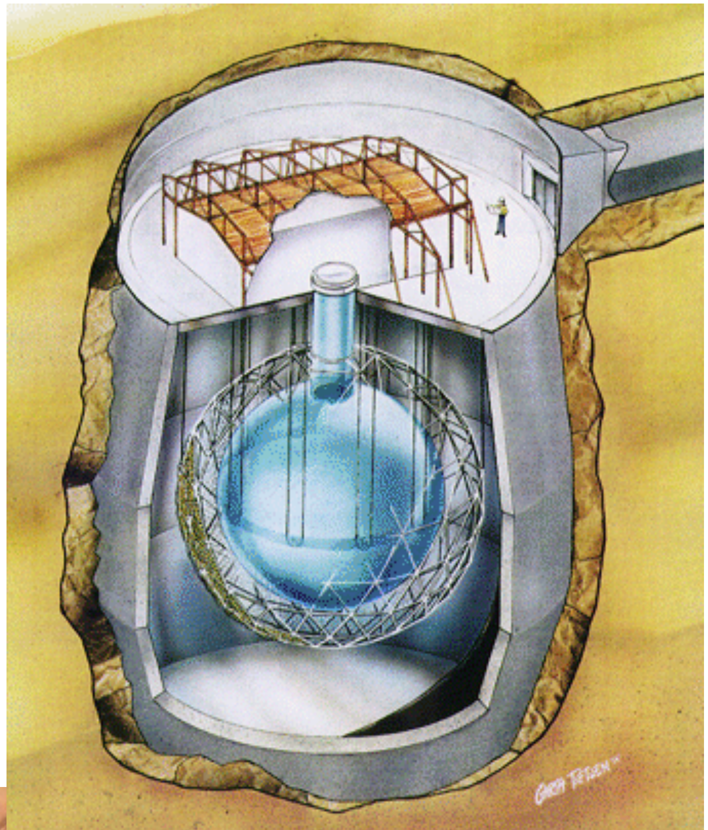
Charged current: Only ν_e

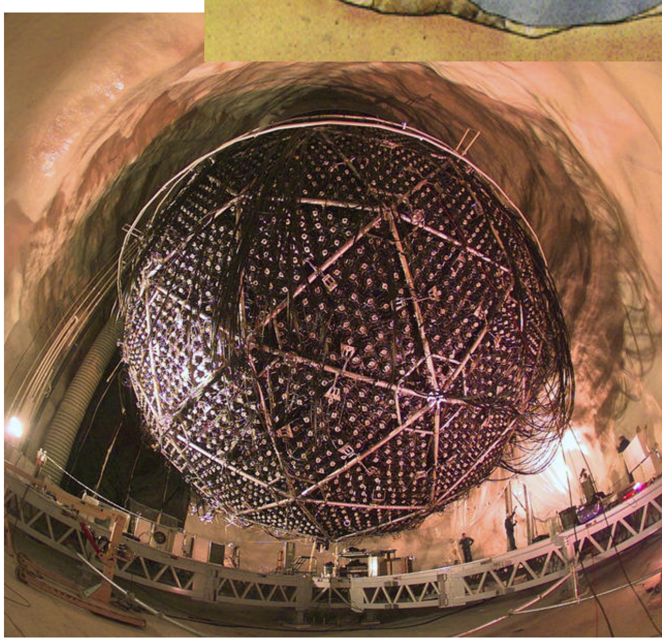
$$\nu_x + d \rightarrow p + n + \nu_x$$

Neutral current: Equal sensitivity $\nu_{e,\mu,\tau}$

By comparing flux measured in each channel,
can determine flavor composition.

SNO Detector





Details:

- 1 kton of ultrapure D_2O (inner det.)

- 9,456 8” diameter photomultipliers

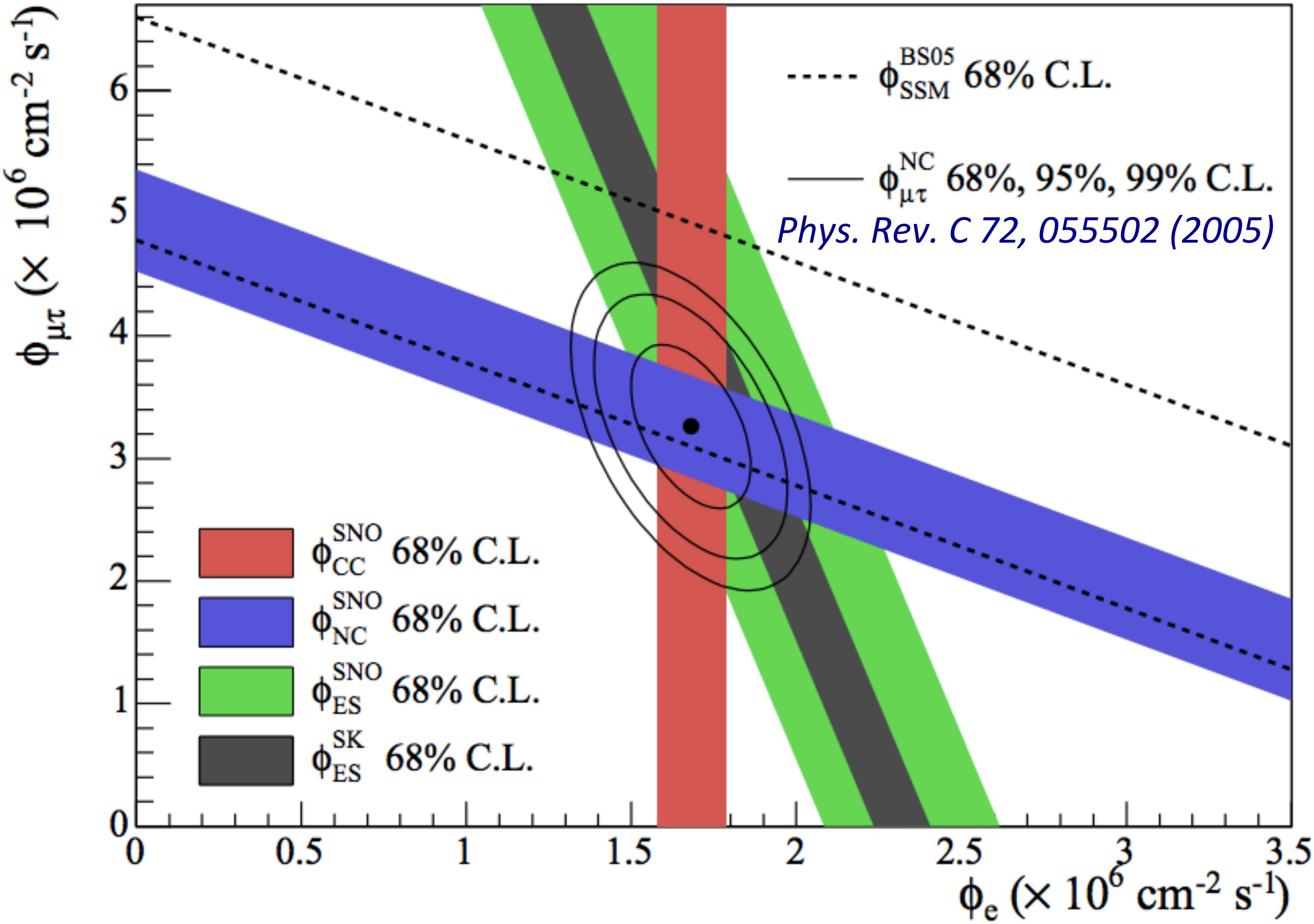
- Operated 1999 – 2006

- Located in the Creighton mine, under ~2 km rock. (Sudbury, Ontario)

Three Phases:

1) Pure D_2O
2) D_20 + NaCl
   -> Increase neutron capture efficiency
3) D_20 + ^{3}He counters
   -> Increase neutron detection purity

SNO: Results



Conclusion: Solar neutrinos are changing flavor!

Neutrino Oscillation

Neutrino Oscillation

Neutrinos change flavor (e,μ,τ) with time

Principle:

Mass eigenstates ≠ Interaction (flavor) eigenstates

$$|\nu_e\rangle = \sum_{m_i} U^*_{ei} \ |\nu_i\rangle$$

Physical Parameters:

θ:

3 angles between mass/flavor eigenstates set **oscillation amplitude**

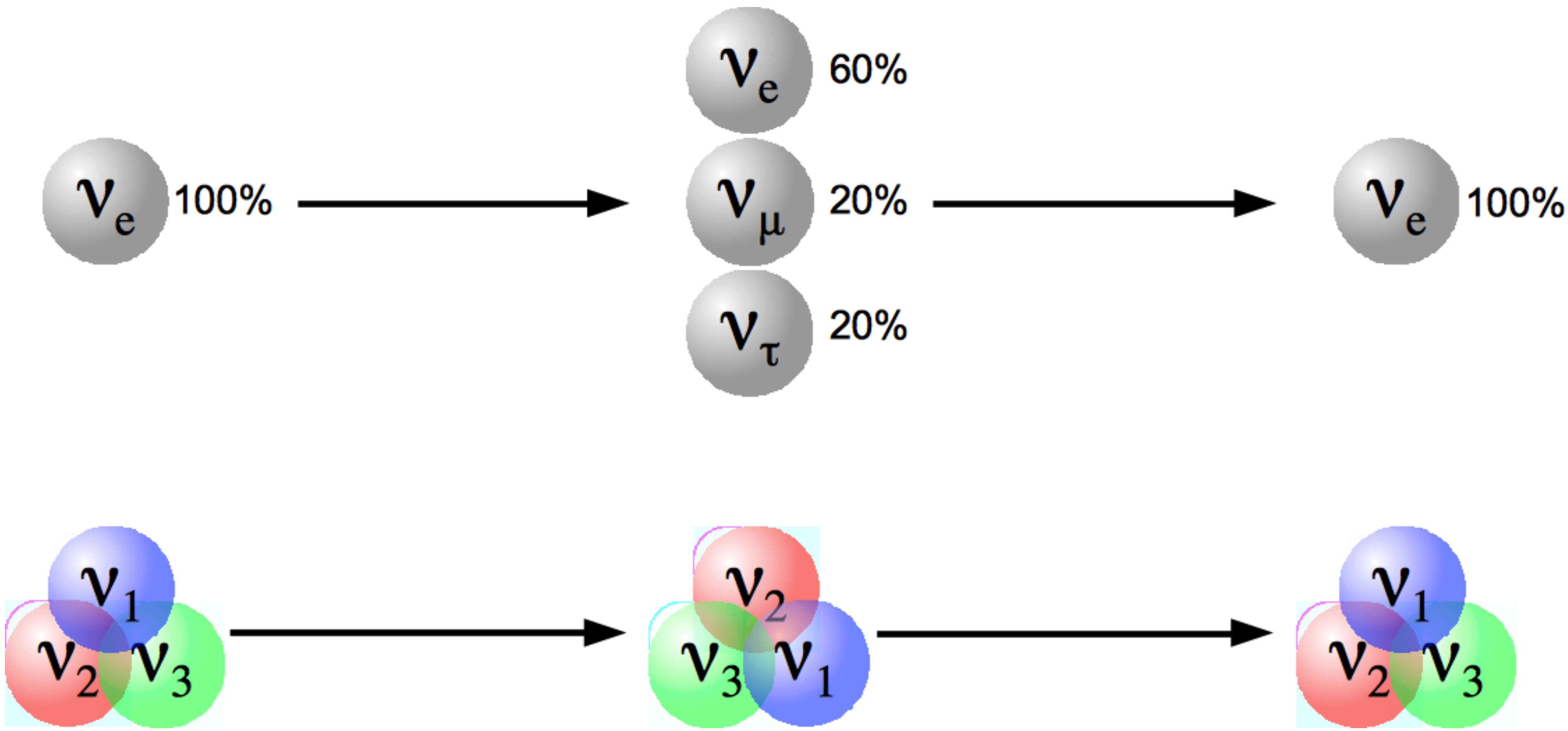
Δm²:

Differences in 3 neutrino masses determine **oscillation frequency** (distance)

We want to know θ and Δm²

Survival Probability: $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m^2_{12} L}{4E}$

Neutrino Oscillations



How can we confirm this model of neutrino oscillation?

Reactor antineutrinos

Do we see evidence of flavor change for reactor antineutrinos?

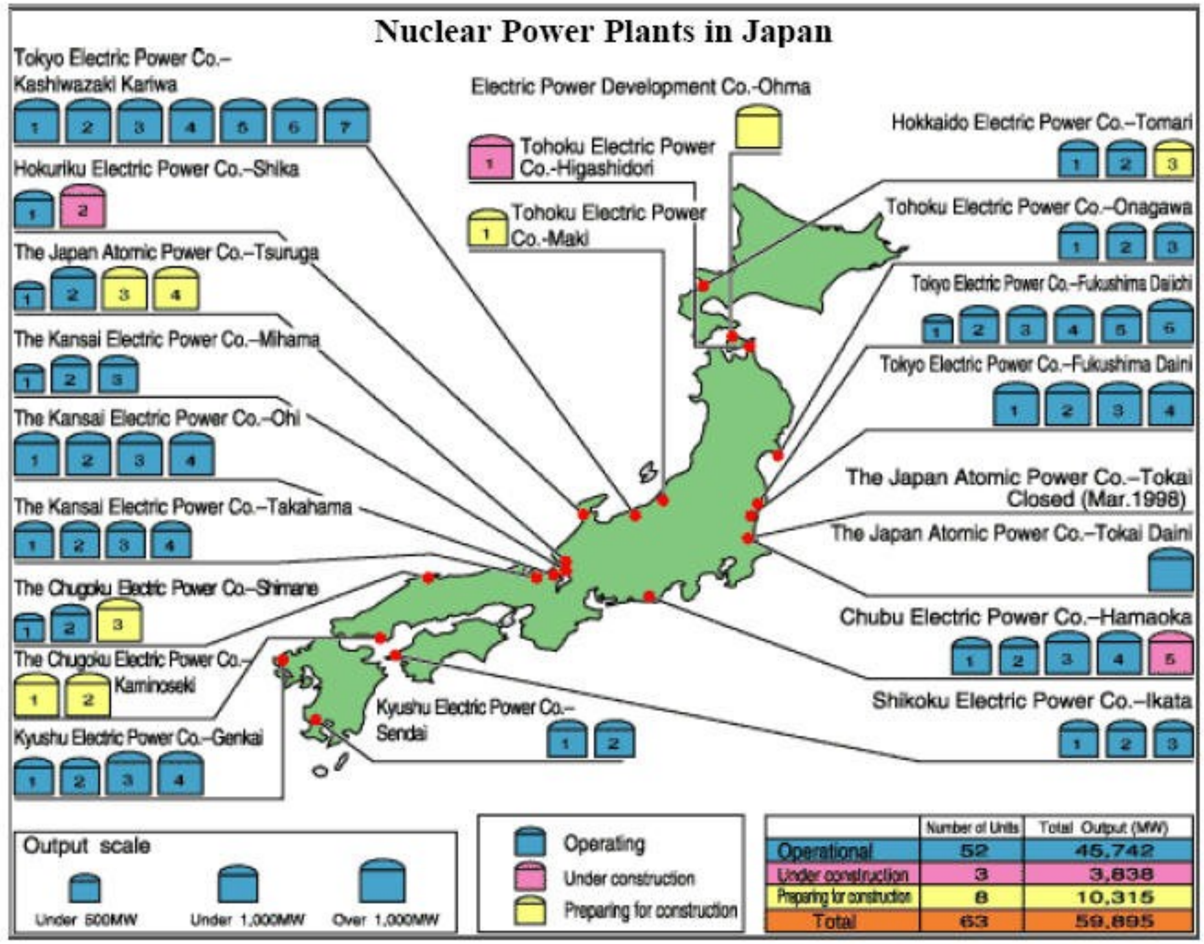
Experiment Needs:

High flux:
Many reactors, small area

Distance for oscillation:
~100 km scale

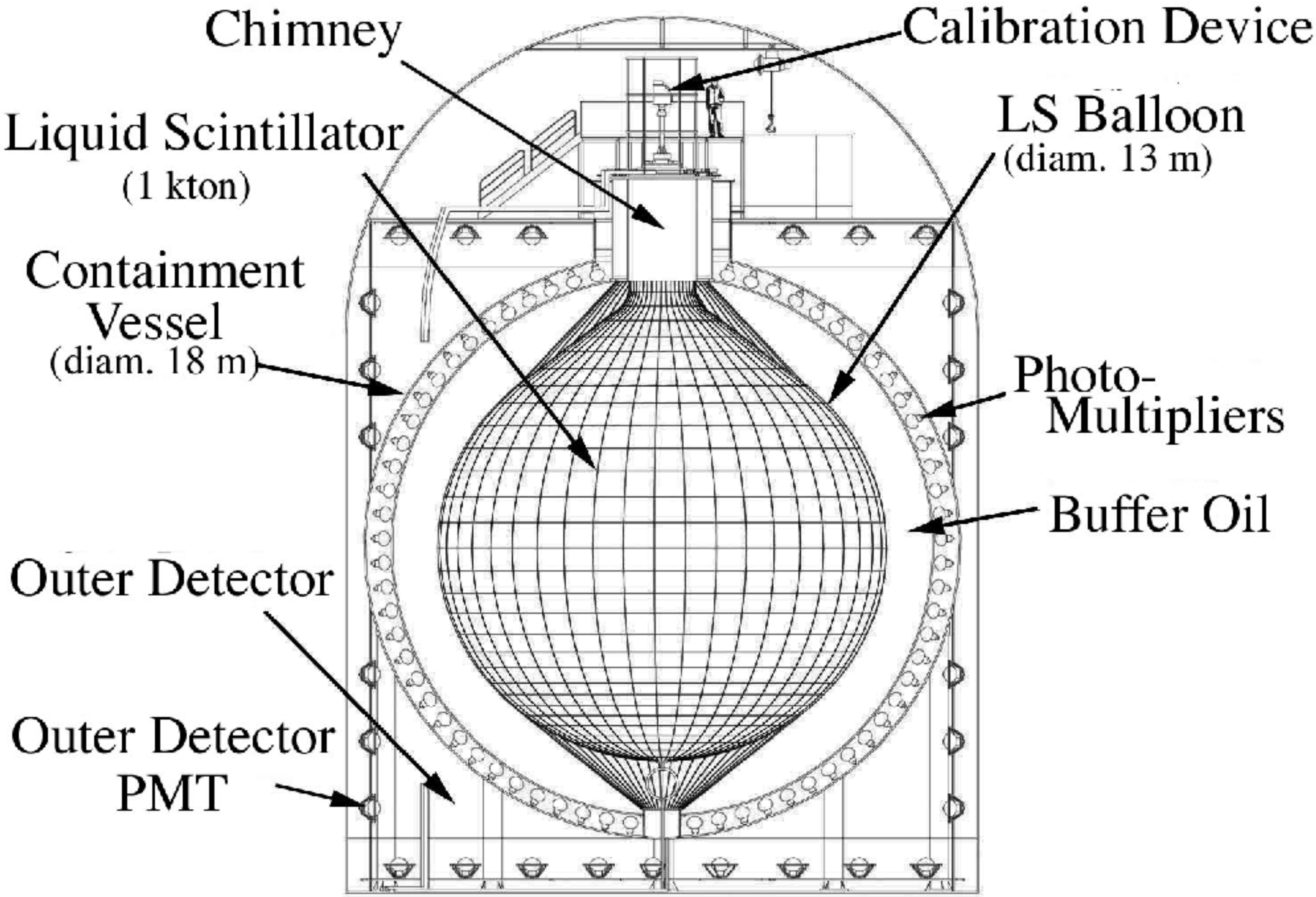
Underground laboratory:
Kamioka

Very large detector:
~kton-scale

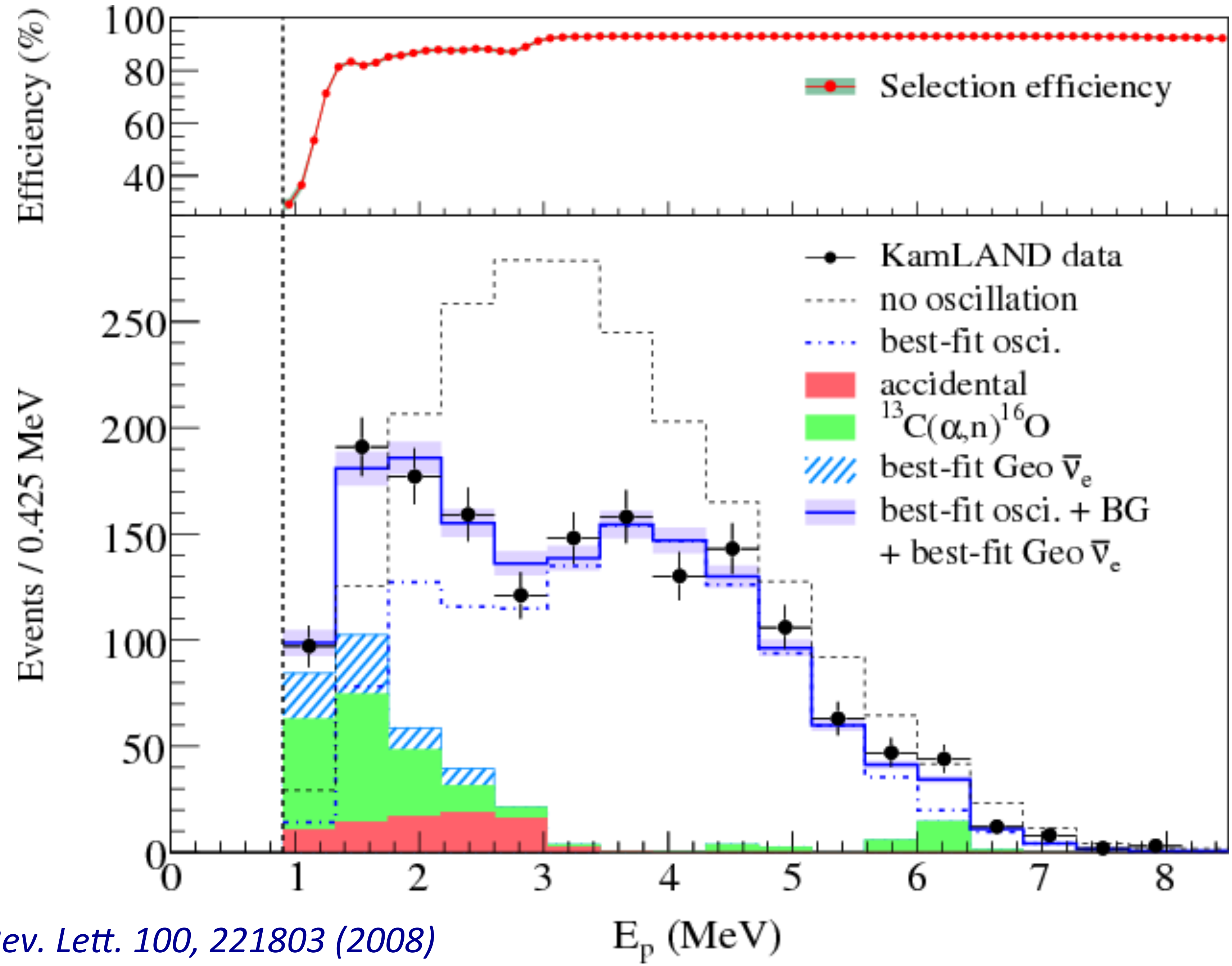


→ The KamLAND experiment

The KamLAND Detector



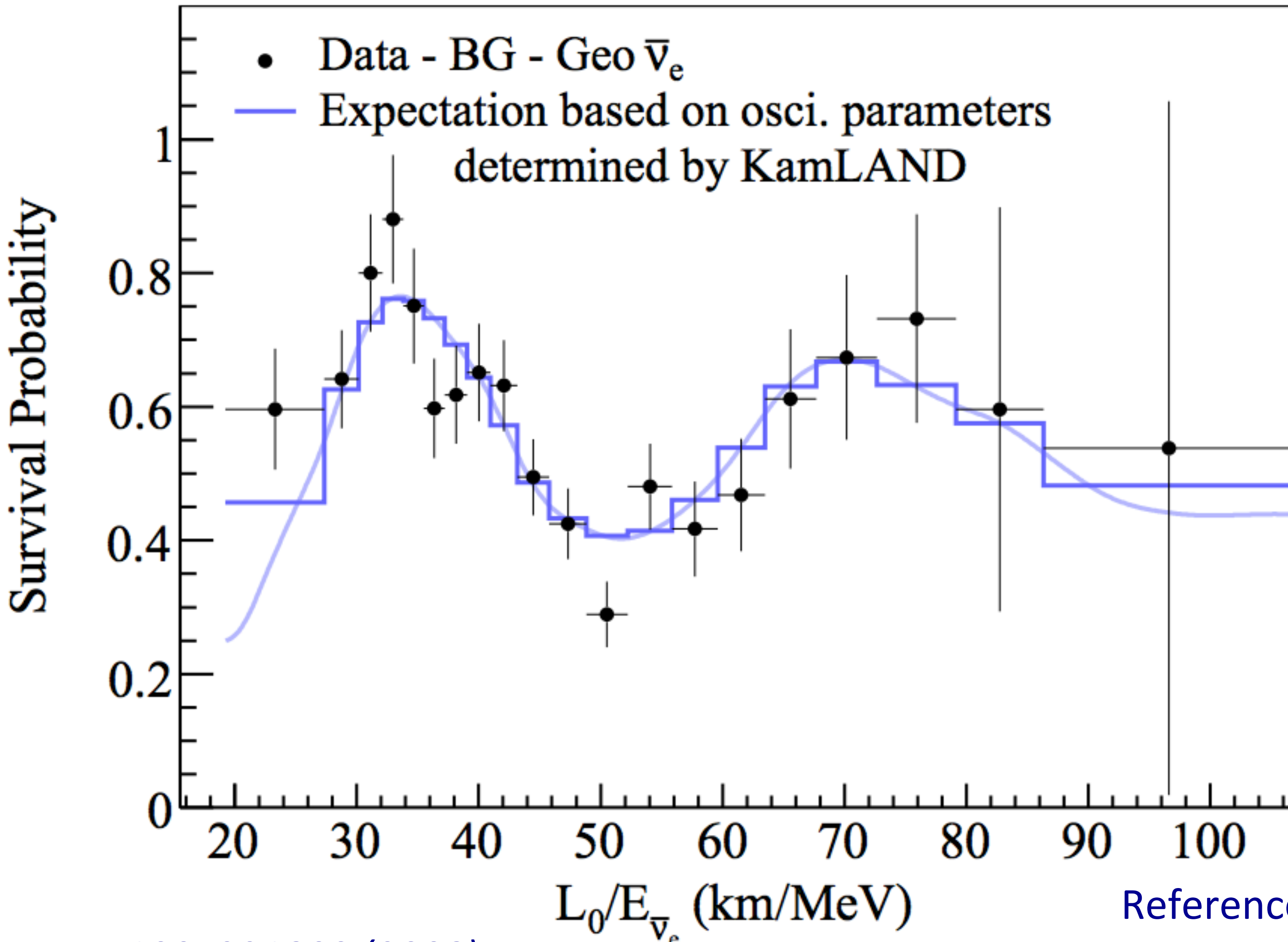
KamLAND: Results



Phys. Rev. Lett. 100, 221803 (2008)

KamLAND: Oscillation!

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$

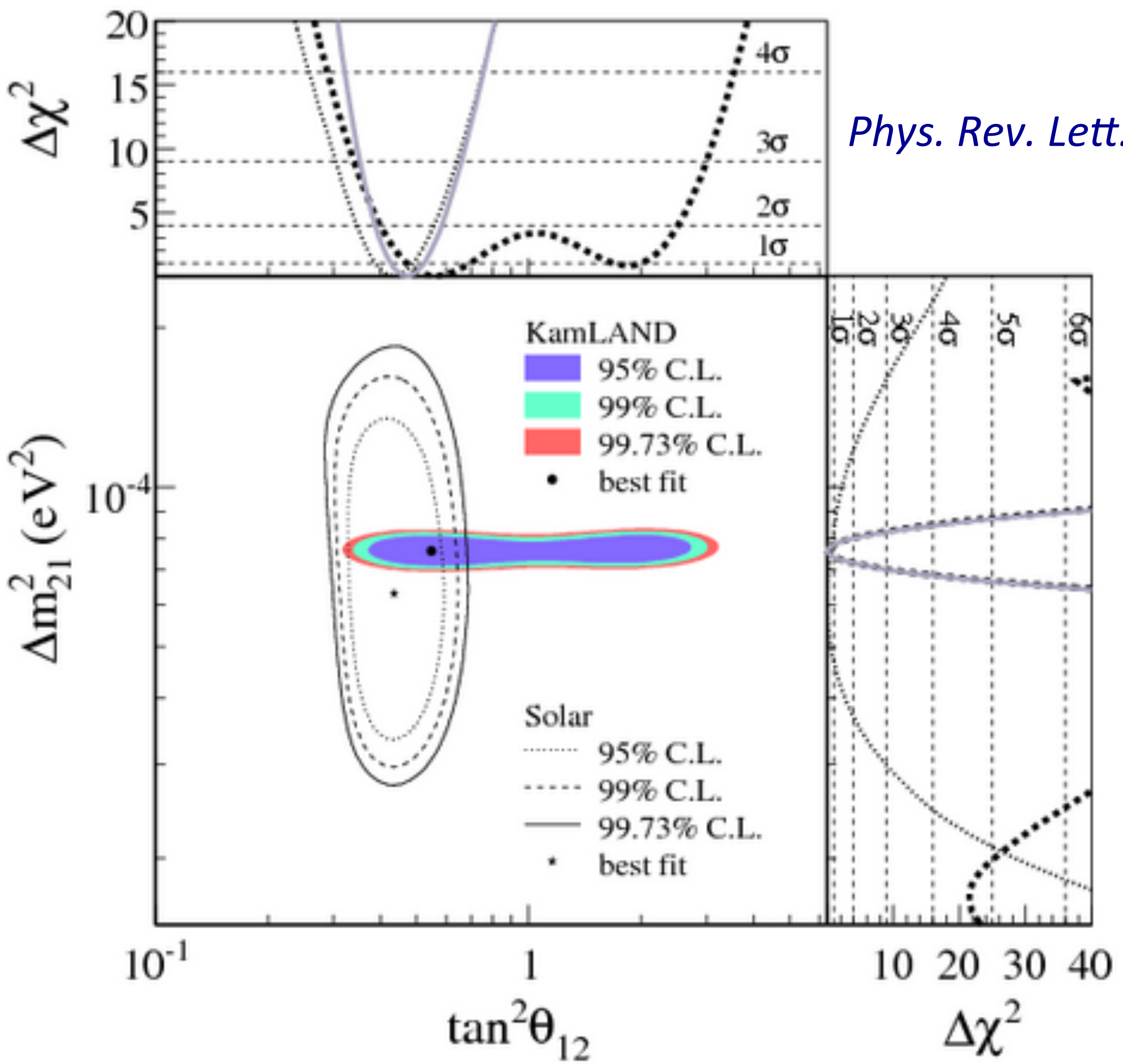


Phys. Rev. Lett. 100, 221803 (2008)

Reference Baseline:
L_0 = 180 km

KamLAND: Oscillation!

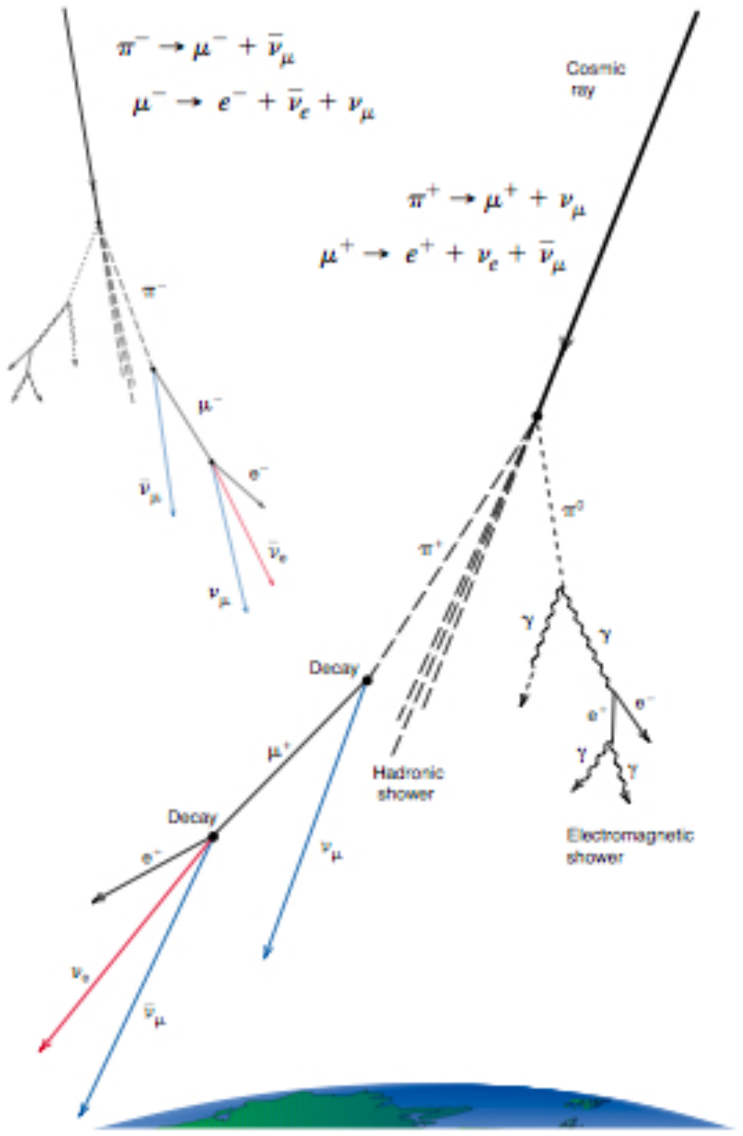
Phys. Rev. Lett. 100, 221803 (2008)



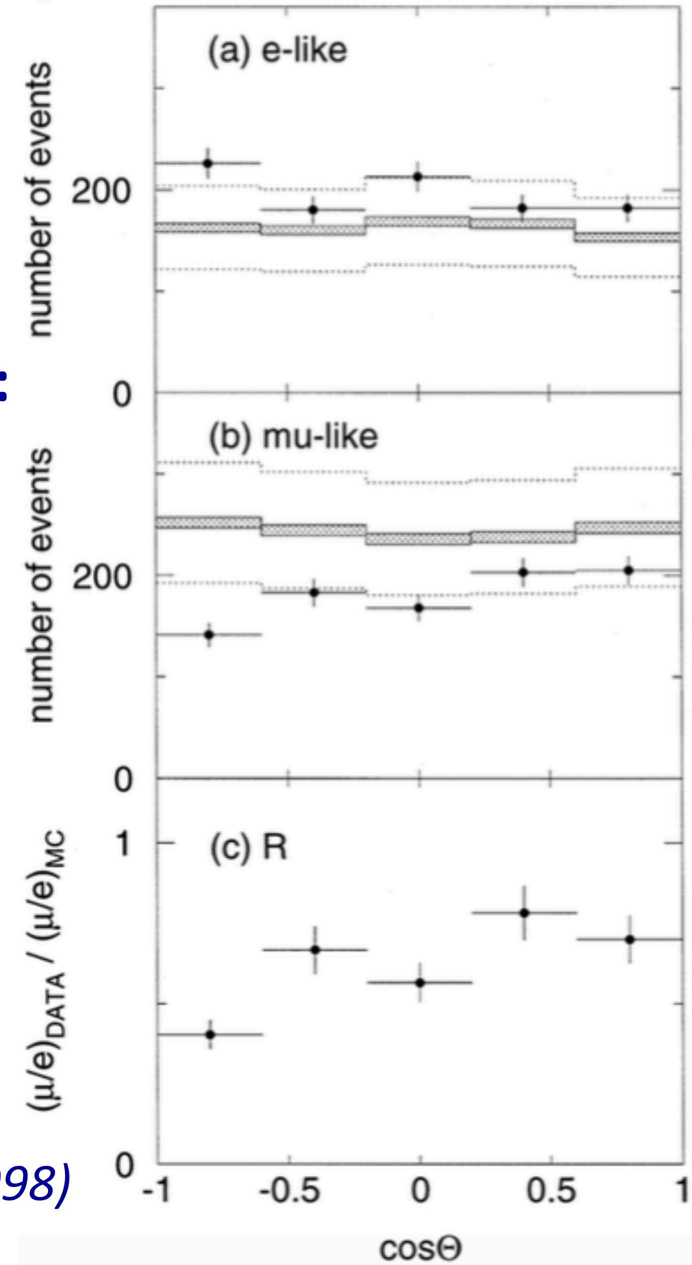
→ Determination of neutrino 2-1 mass difference

In the meantime…

Measurements of atmospheric neutrinos also strange.



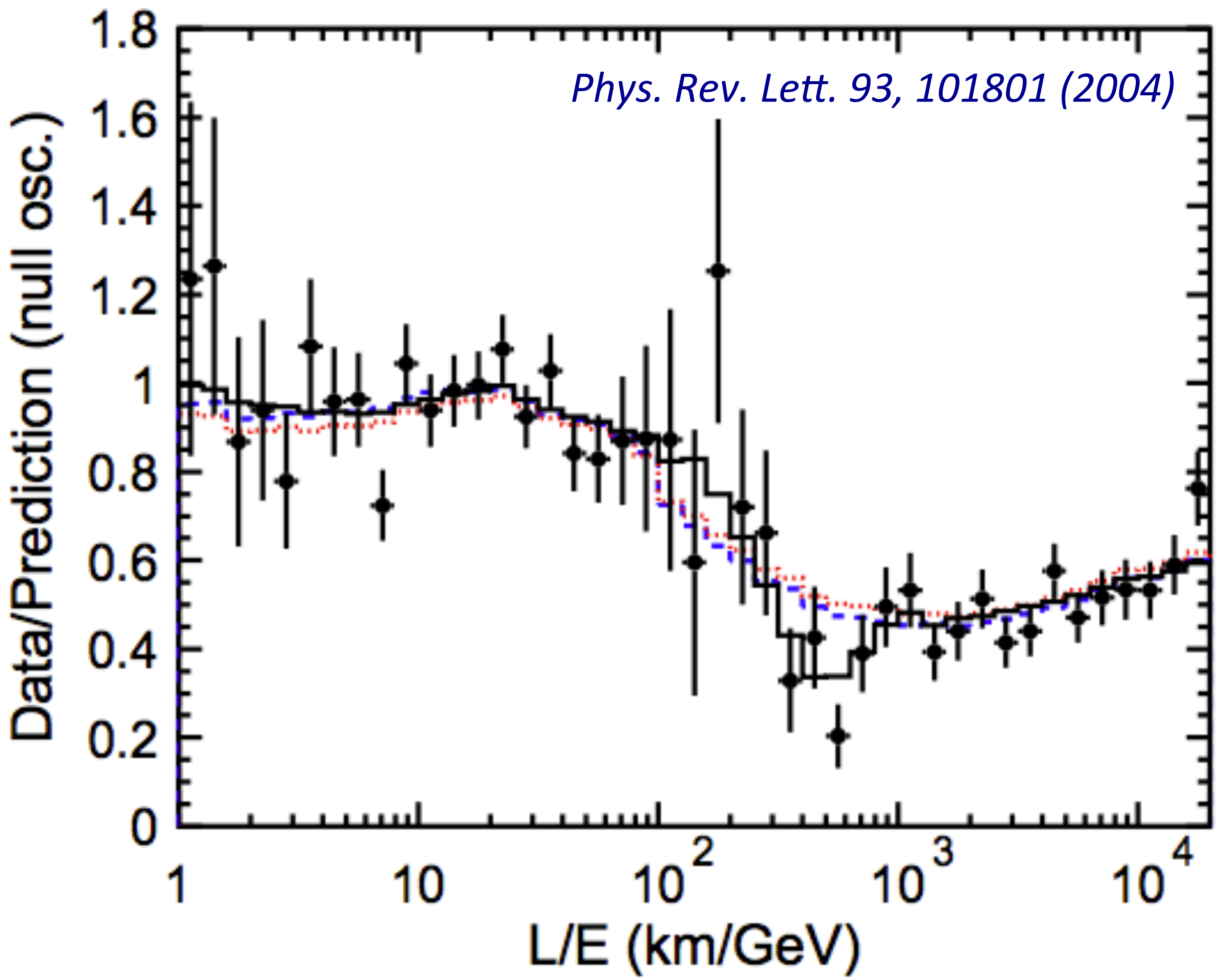
Super-Kamiokande:
ν_μ/ν_e ratio lower than expected



Phys. Lett. B433, 9 (1998)

Muon Neutrino Disappearance

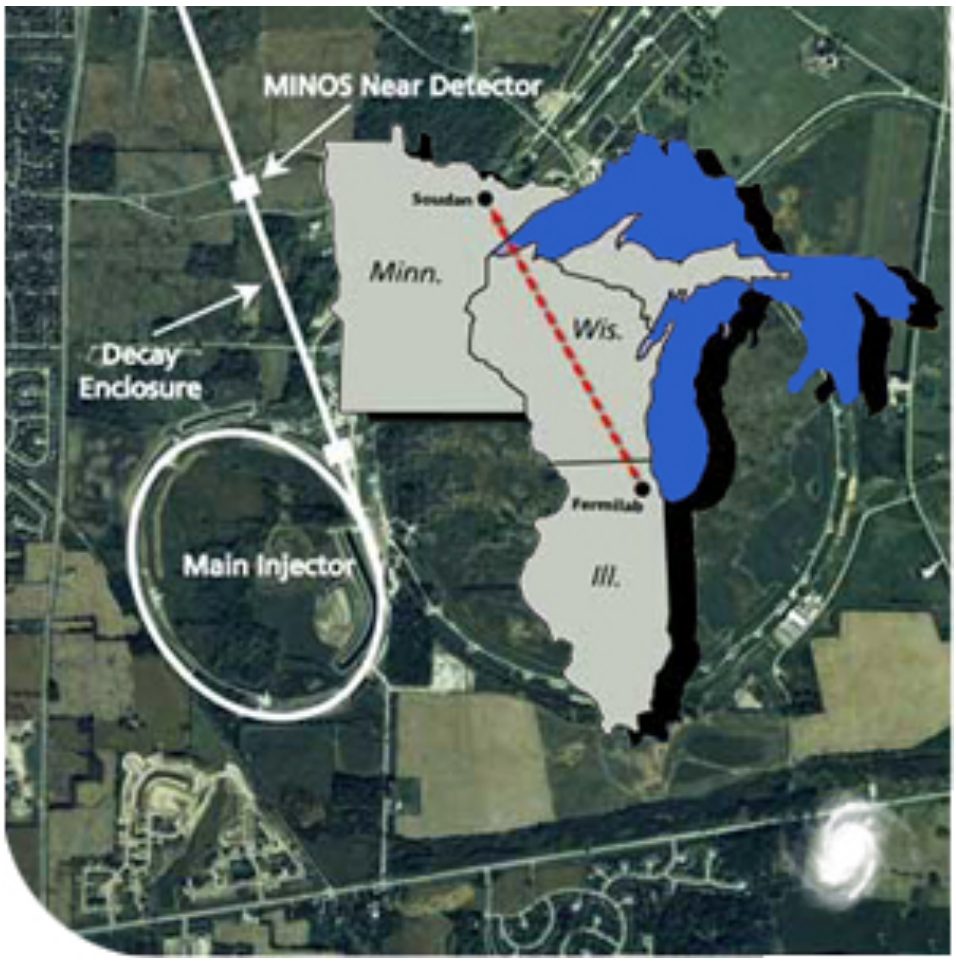
Super-K: Showed disappearance of atmospheric ν_μ versus distance.



Accelerator Neutrinos

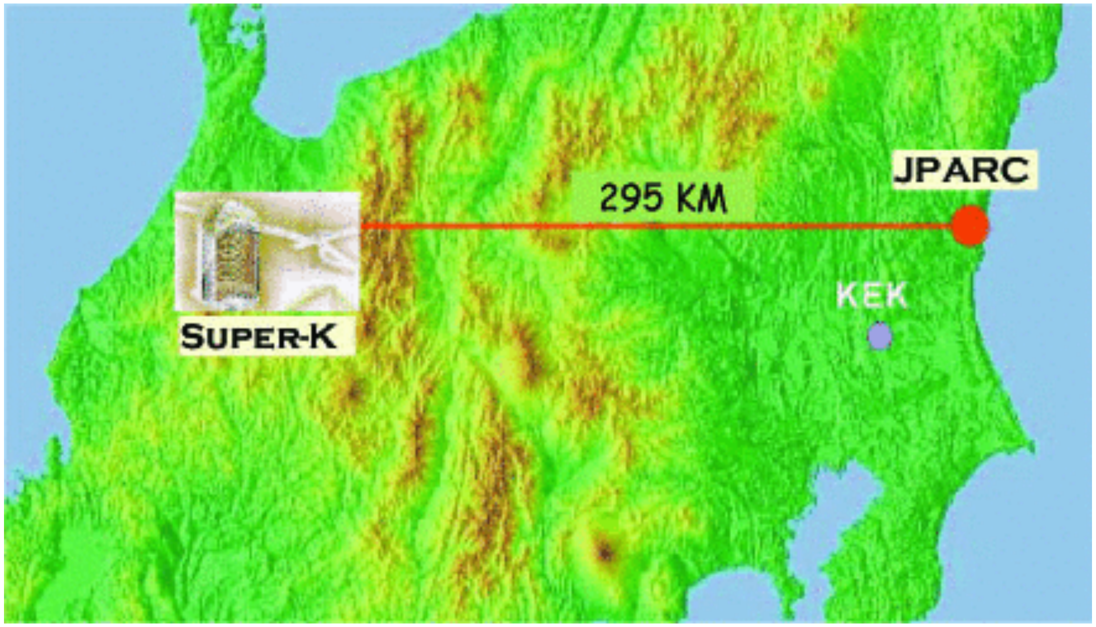
MINOS/MINOS+:

- Beam: Muon decay-in-flight, FermiLAB
- Detector: 5.4 kton steel/scintillator layers
- Distance: 735 km (Soudan Mine, MN)



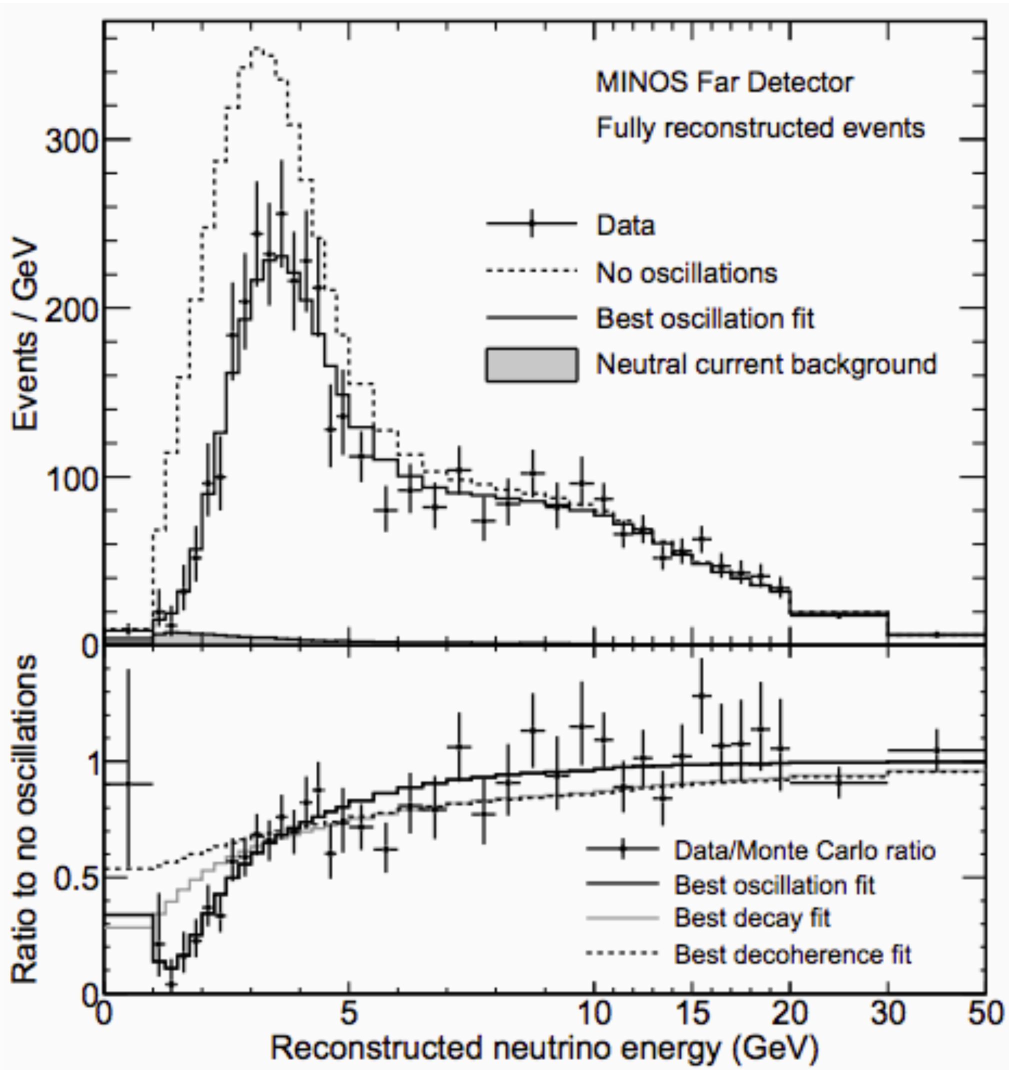
T2K:

- Beam: Muon decay-in-flight, JPARC
- Detector: 32 kton water (Super-K)
- Distance: 295 km (Kamioka, Japan)

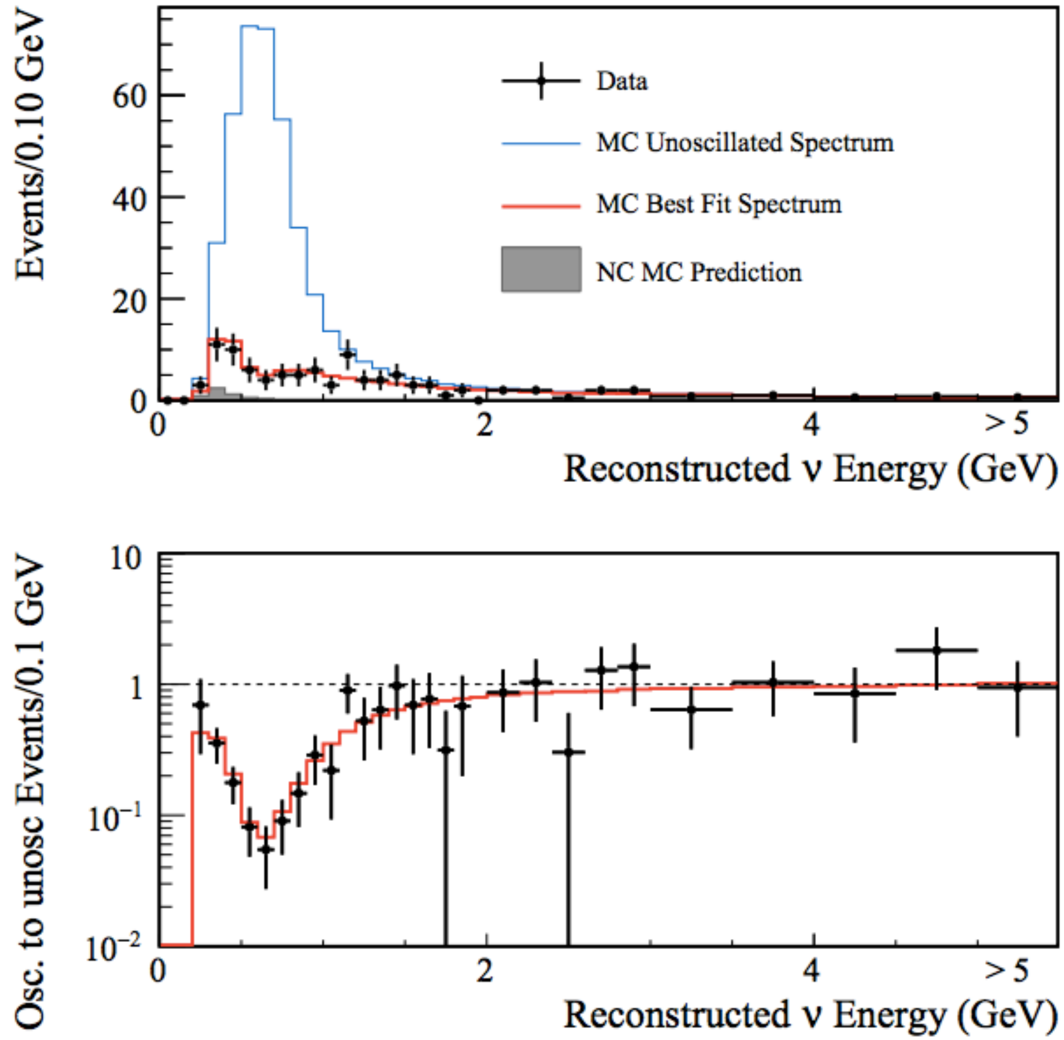


Muon Neutrino Disappearance

MINOS



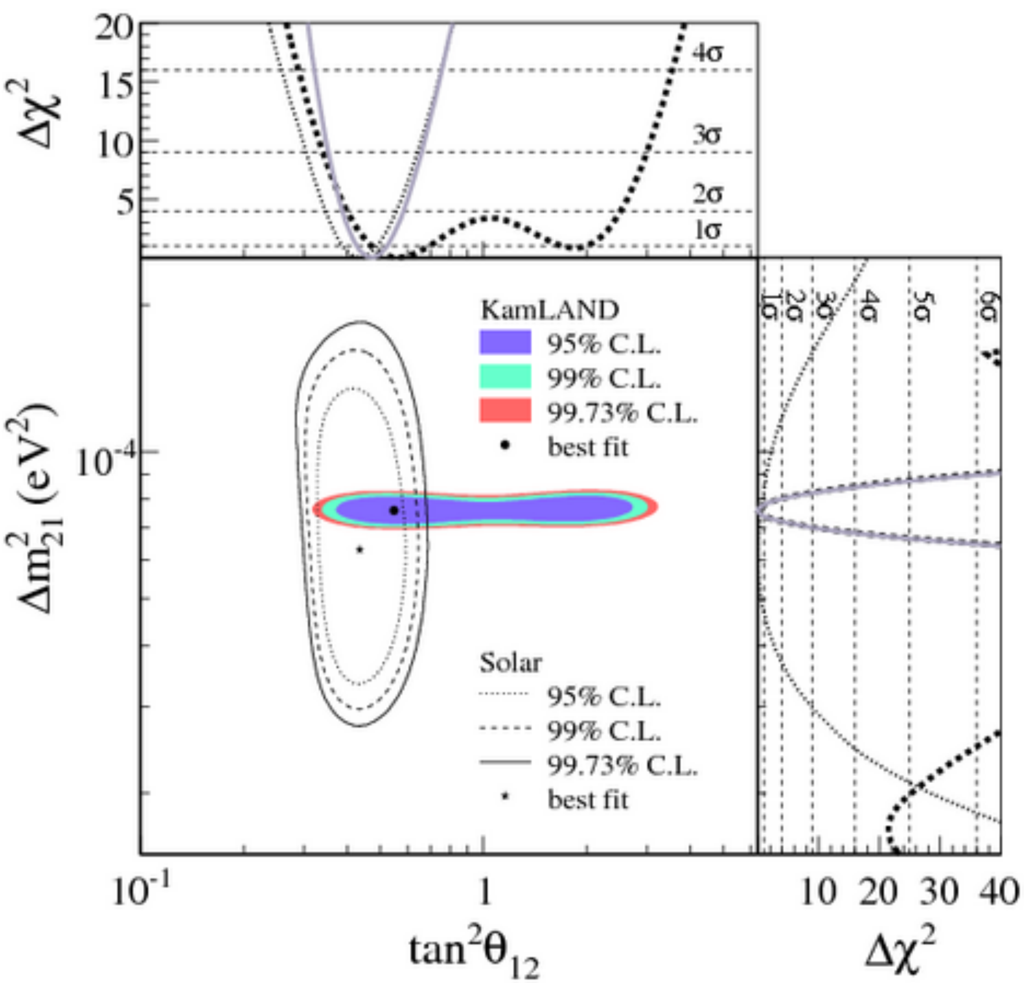
T2K



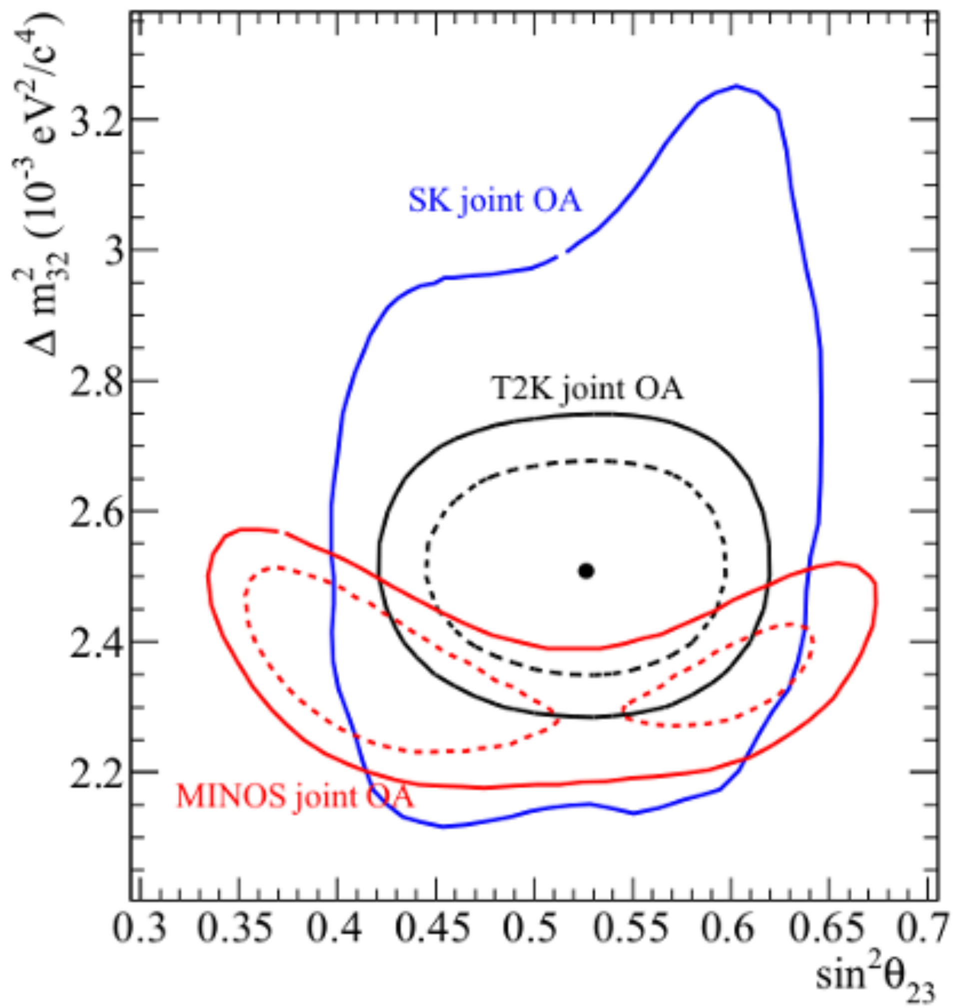
Phys. Rev. D 91, 072010 (2015)

Oscillation Summary

'Solar' Oscillation



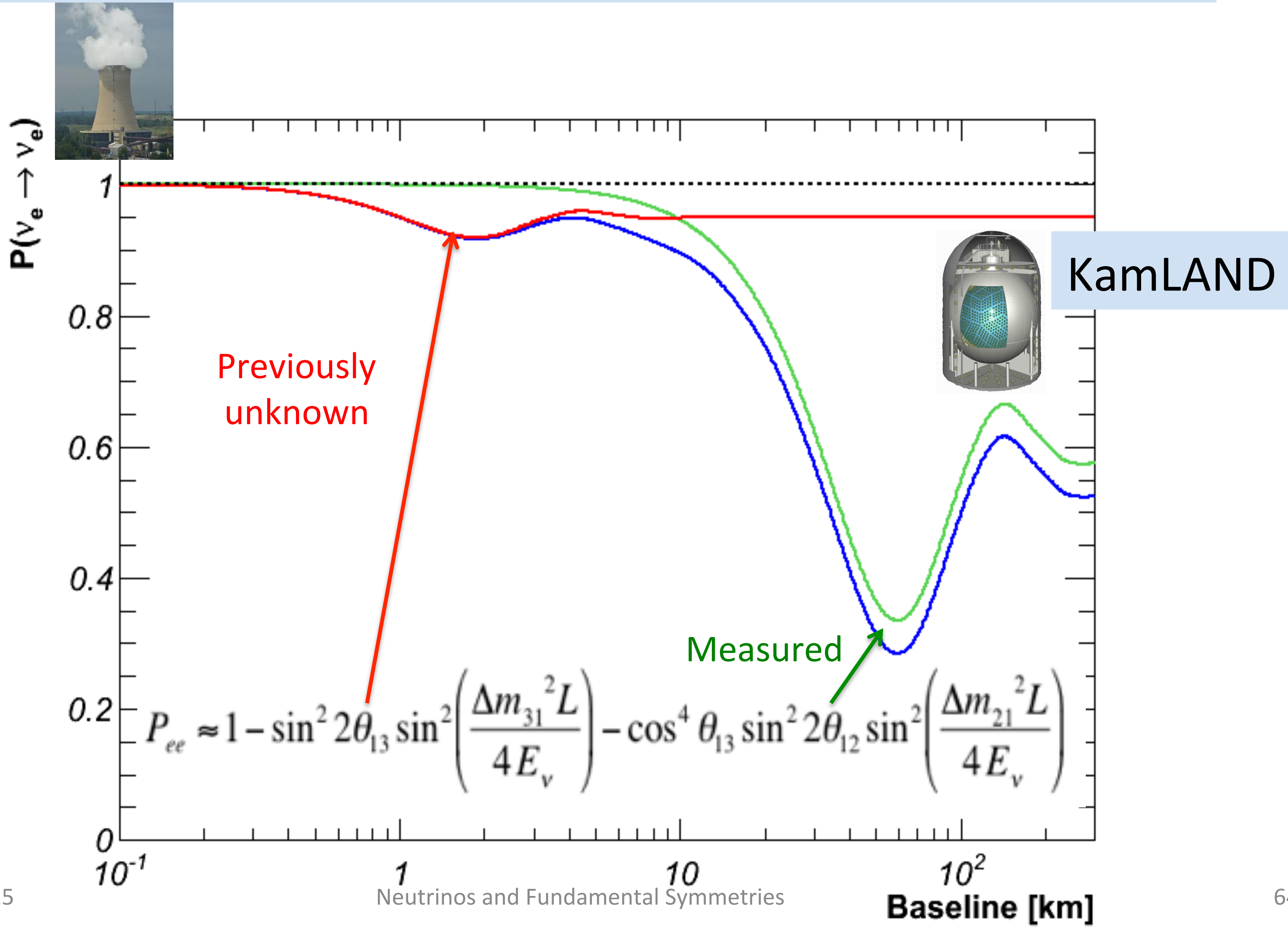
'Atmospheric' Oscillation



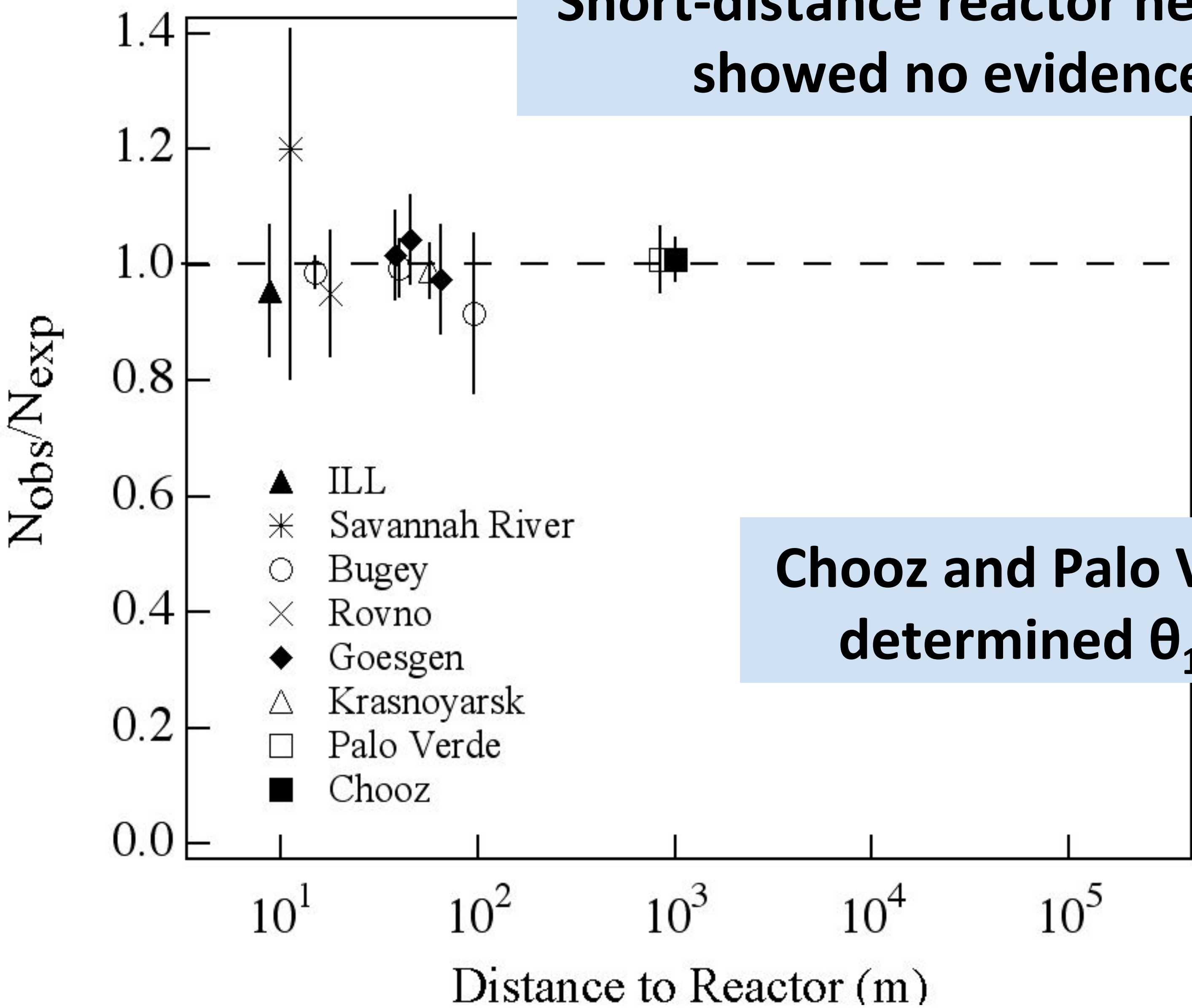
→ Remaining question: Is there mixing due to θ_{13}, Δm^2_{31}?

θ_{13}: Reactor Antineutrinos

θ_{13} revealed by a deficit of reactor antineutrinos at ~2 km.



Short-Distance Reactor ν



Short-distance reactor neutrino experiments showed no evidence of oscillation

Chooz and Palo Verde experiments determined θ_{13} < 11° (90% CL)

Relative Measurement

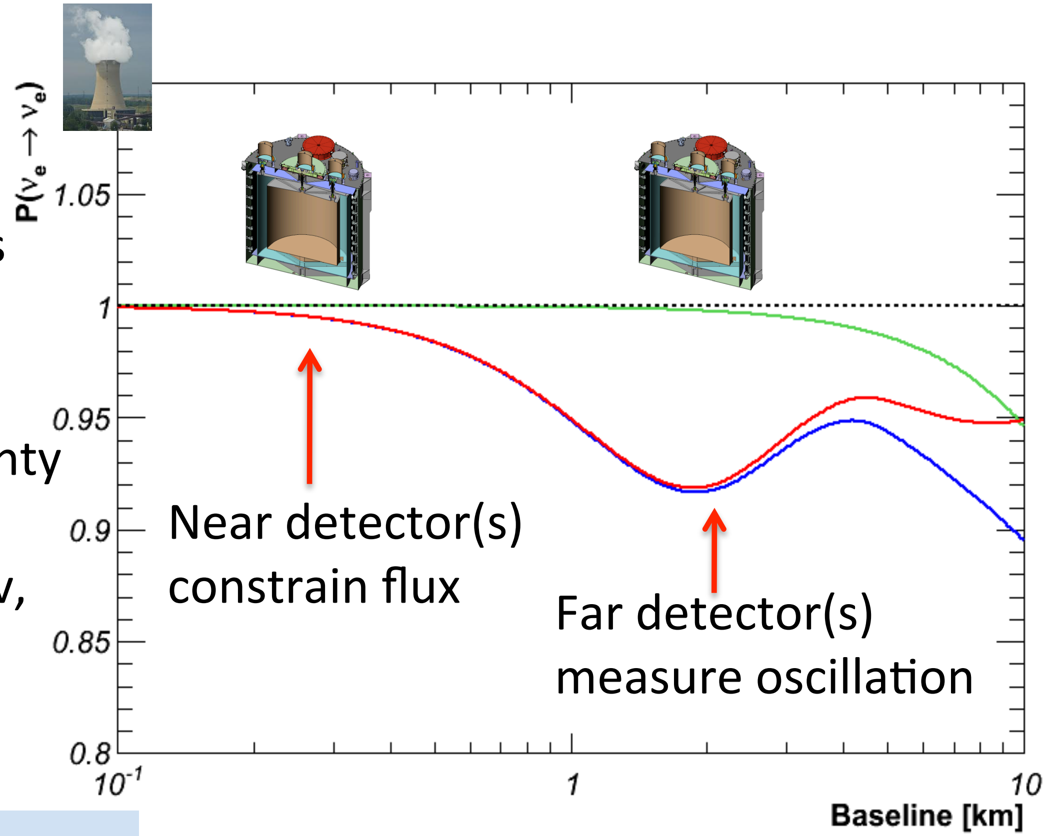
Absolute Reactor Flux:

Largest uncertainty in previous measurements

Relative Measurement:

Multiple detectors removes absolute uncertainty

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)



Far/Near $\bar{\nu}_e$ Ratio

Distances from reactor

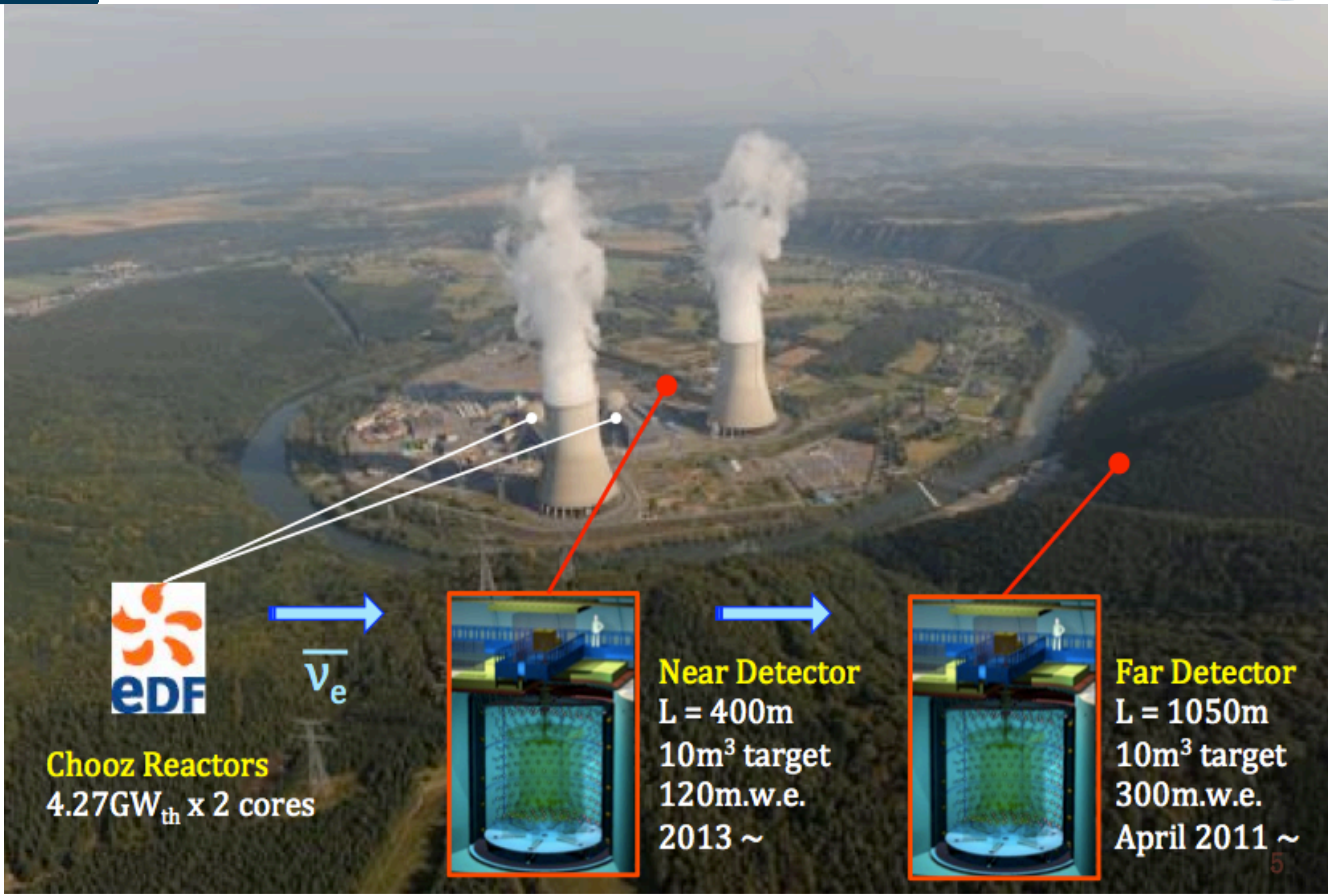
Oscillation deficit

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

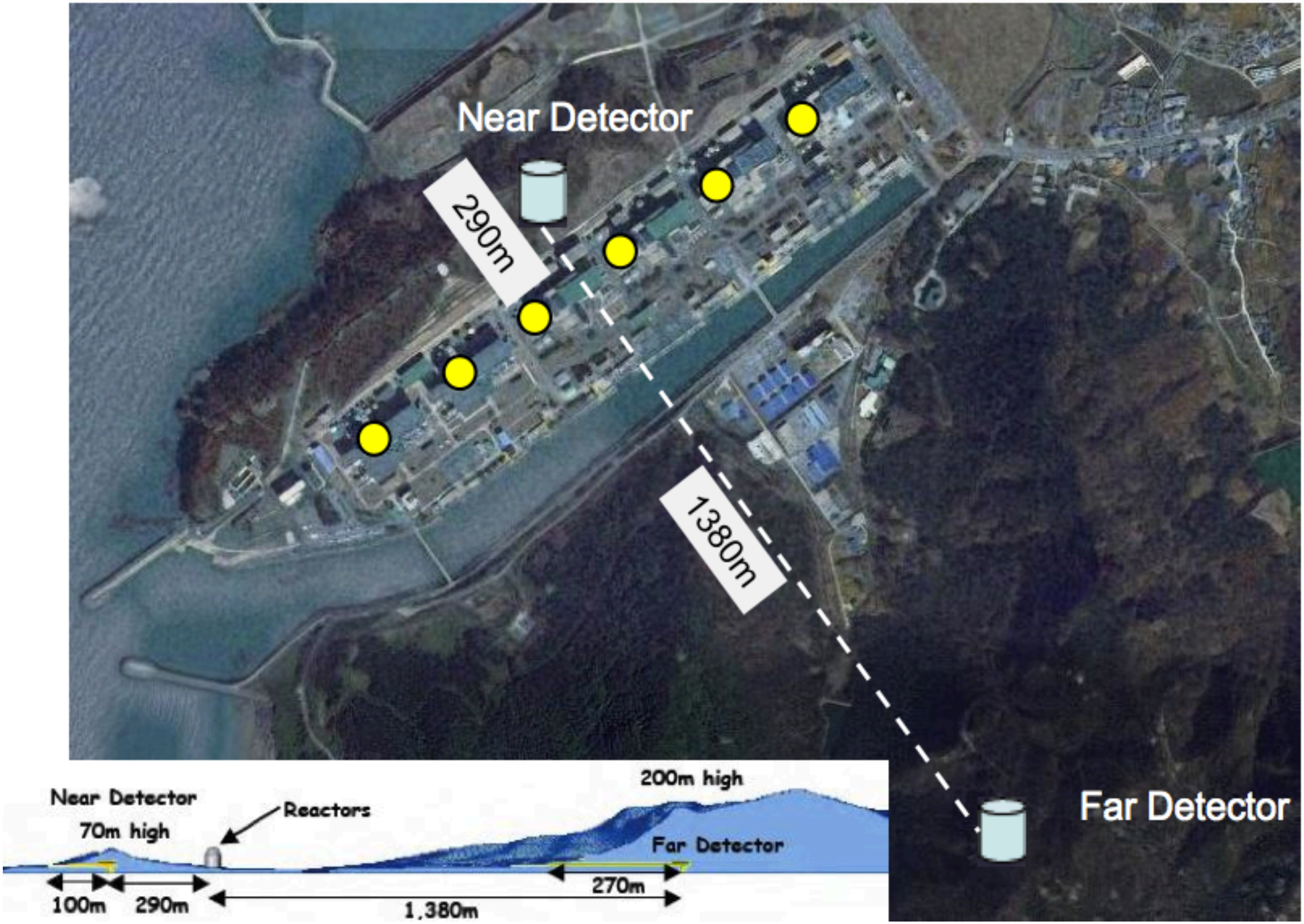
Detector Target Mass

Detector efficiency

Double Chooz



RENO


Near Detector
290m
1380m
Far Detector
Near Detector
70m high
Reactors
200m high
Far Detector
100m
290m
270m
1,380m

The Daya Bay Experiment

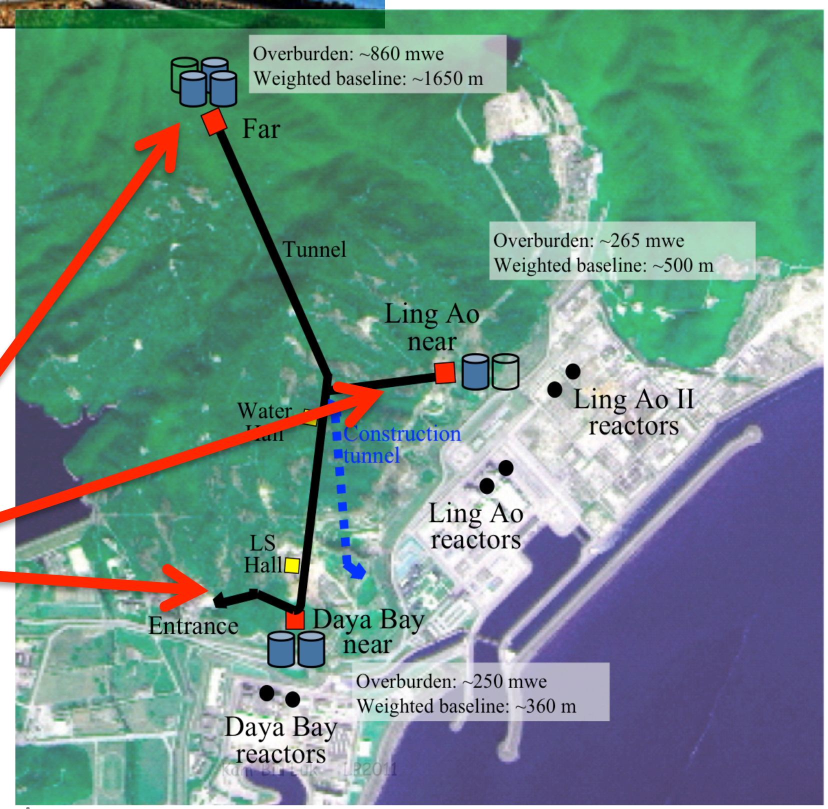
Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

Daya Bay

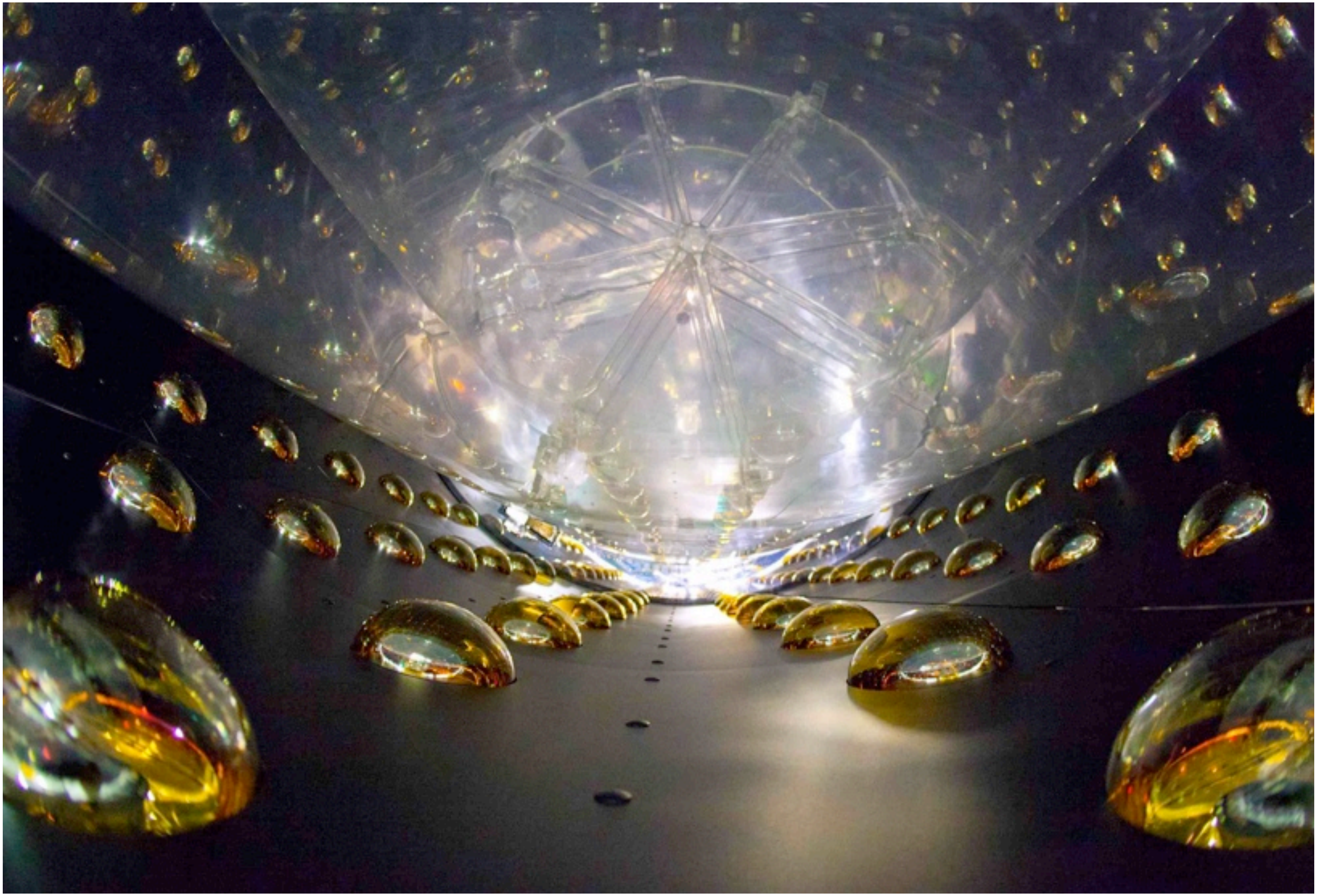
Ling Ao I + II

6 commercial reactor cores with 17.4 GW_{th} total power.

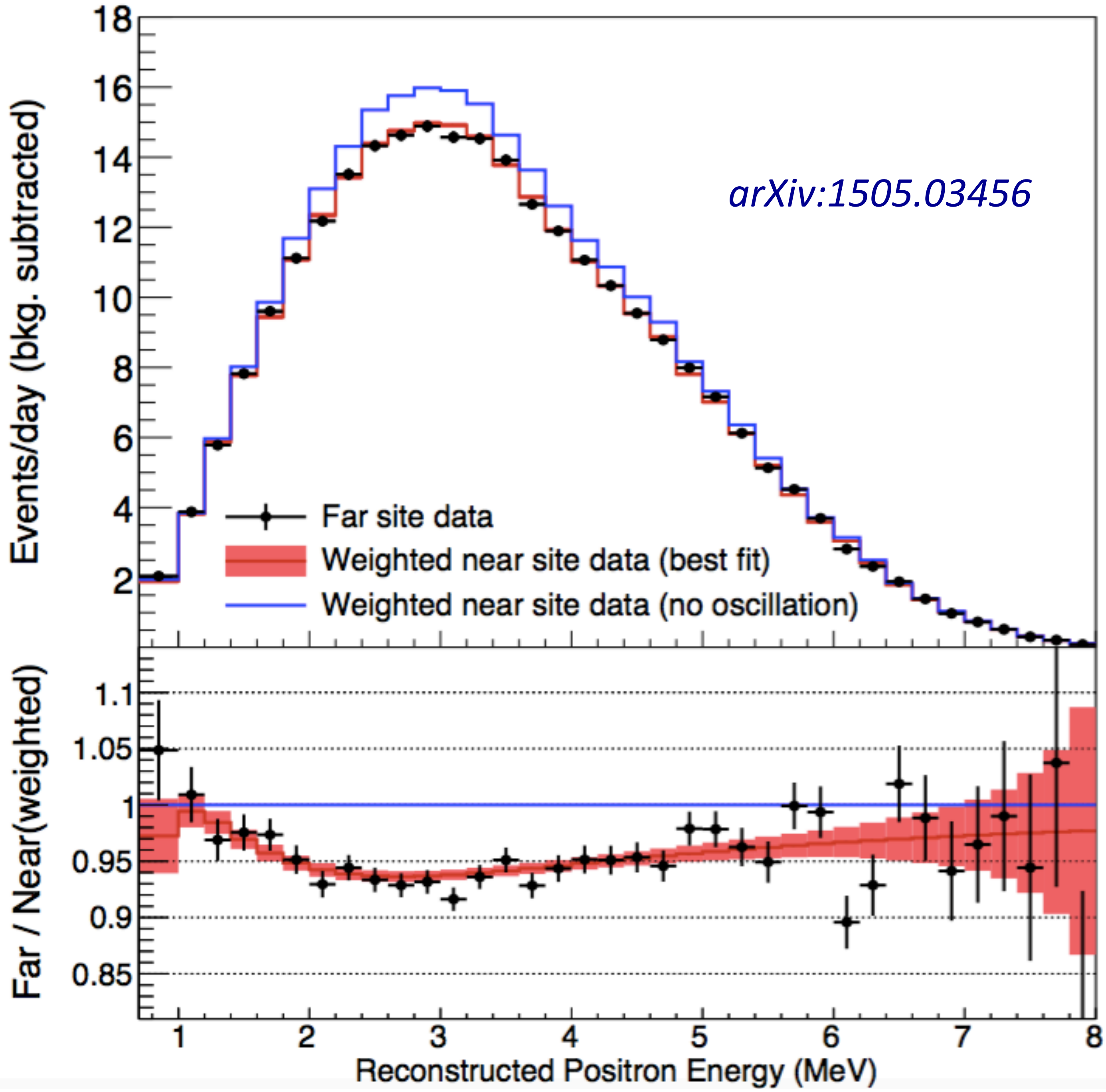
8 Antineutrino Detectors (ADs) give 160 tons total target mass.



Interior of Antineutrino Detector

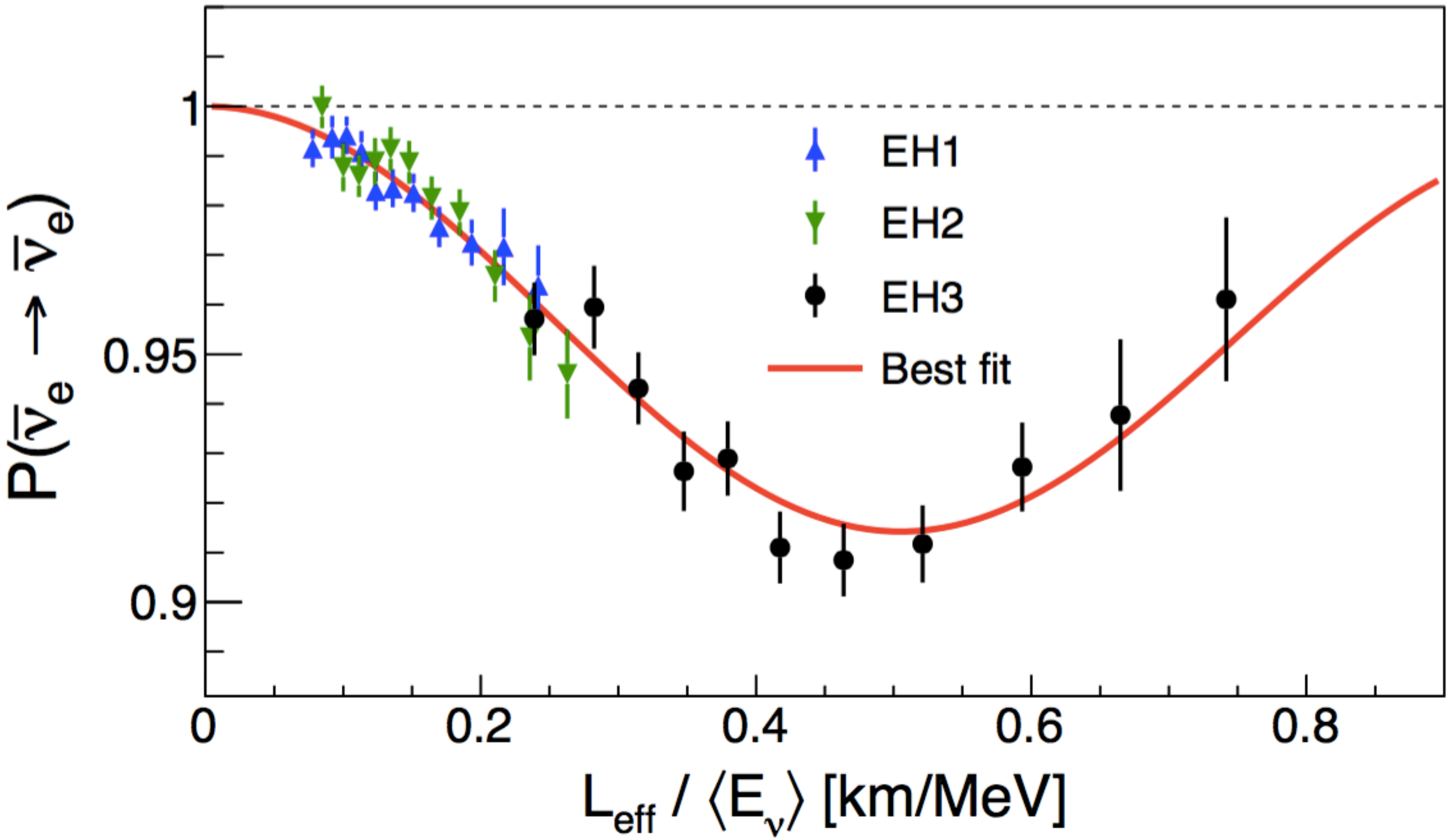


θ_{13}: Latest Daya Bay Results

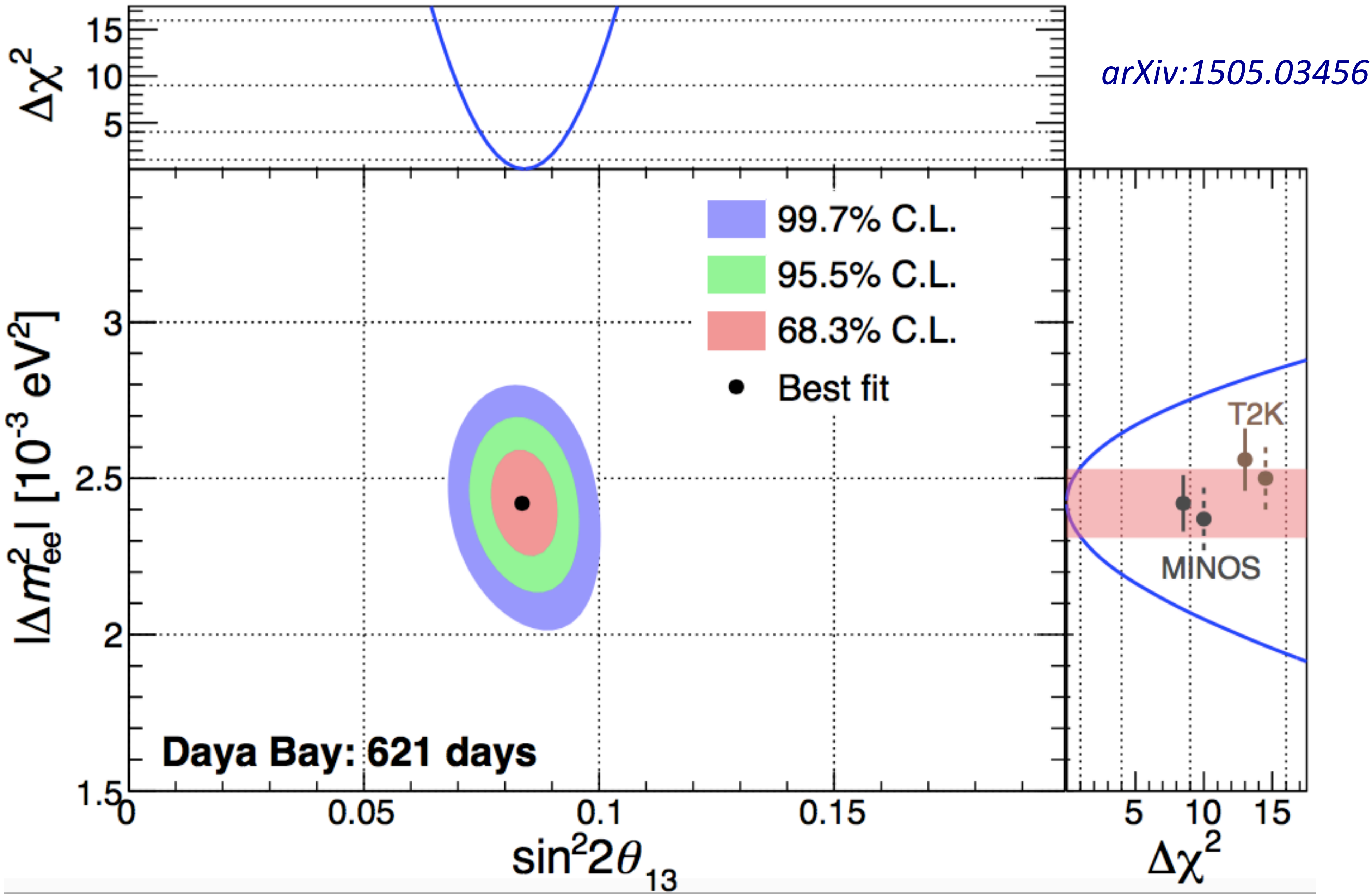


θ_{13}: Latest Daya Bay Results

arXiv:1505.03456



θ_{13}: Latest Daya Bay Results



θ_{13}: Accelerator Neutrinos

Electron Neutrino Appearance Probability

$$P(\nu_\mu \to \nu_e) \simeq$$

$$\sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

$$+\,\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(x\Delta)}{x^2}$$

$$+\,\alpha\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\frac{\sin^2(x\Delta)}{x^2}\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}(\cos\Delta\cos\delta-\sin\Delta\sin\delta)$$

Atmospheric Oscillation

Solar Oscillation

Cross-term

CP-phase

Atmospheric Phase

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

Atmospheric/Solar Ratio

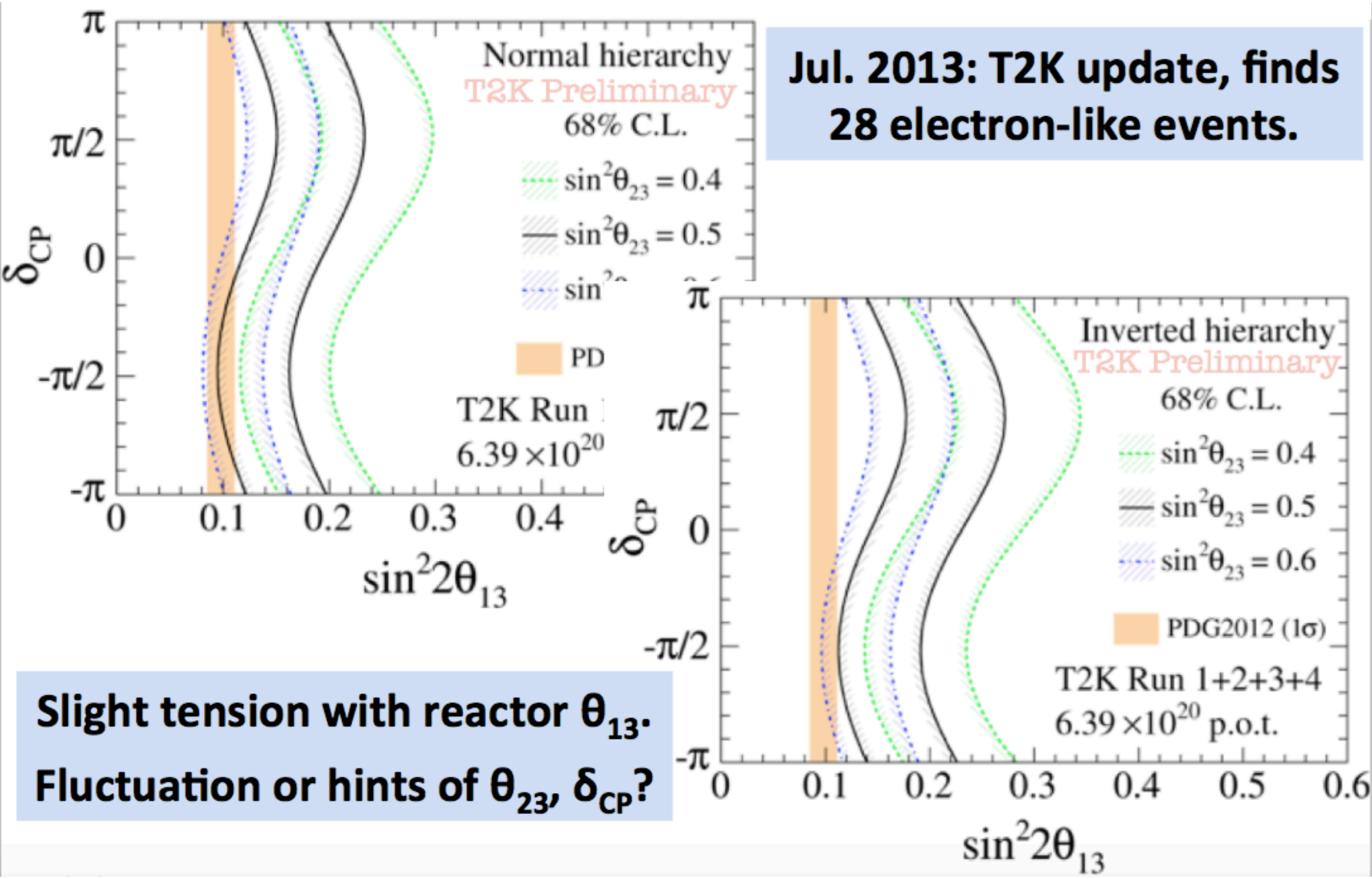
$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Matter Effect

$$x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

Encompasses all neutrino parameters

θ_{13}: Accelerator Neutrinos



Jul. 2013: T2K update, finds 28 electron-like events.

Slight tension with reactor θ_{13}.

Fluctuation or hints of θ_{23}, δ_{CP}?

Neutrino Mixing Matrix

All mixing angles now measured.

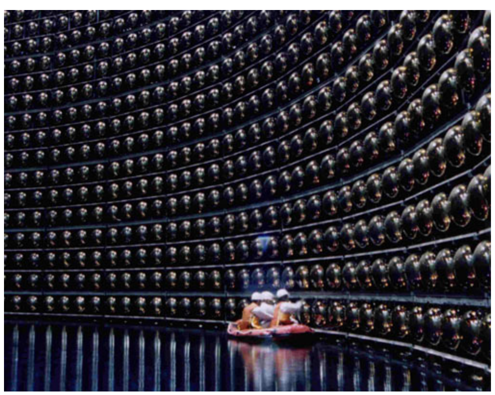
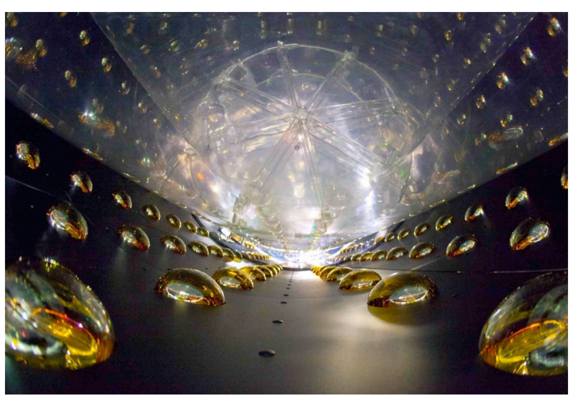
$$c_{ij} \equiv \cos\theta_{ij} \text{ and } s_{ij} \equiv \sin\theta_{ij}$$

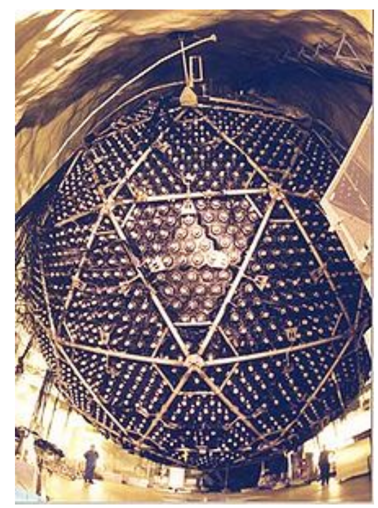
$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^{o}$
Atmospheric ν
Accelerator ν

$\theta_{13} \approx 9^{o}$
Short-Baseline Reactor ν
Accelerator ν

$\theta_{12} \approx 34^{o}$
Solar ν
Long-Baseline Reactor ν



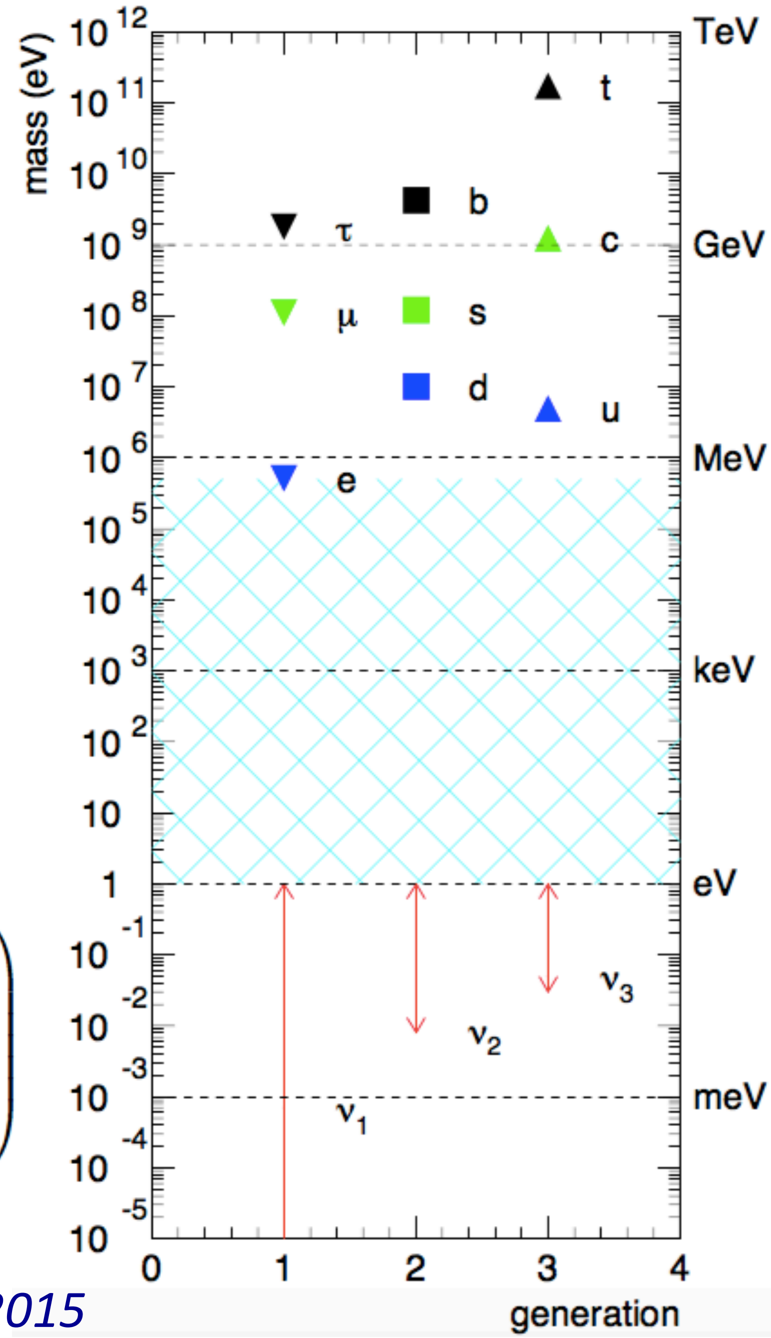
Masses and Mixing?

Big Question:

Is there an underlying theory for
the pattern of neutrino masses and mixing?
Can it be related to quark mixing?

Neutrinos	**Quarks**
$\theta_{12} = 34 \pm 1^{\circ}$	$\theta_{12} = 13.04 \pm 0.05^{\circ}$
$\theta_{13} = 8.7 \pm 0.5^{\circ}$	$\theta_{13} = 0.201 \pm 0.011^{\circ}$
$\theta_{23} = 45 \pm 6^{\circ}$	$\theta_{23} = 2.38 \pm 0.06^{\circ}$
δ_{13} = ???	$\delta_{13} = 1.20 \pm 0.08$ rad

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$



A. De Gouvea, WINP-2015

Open Questions

Prominent questions remaining for neutrino oscillation:

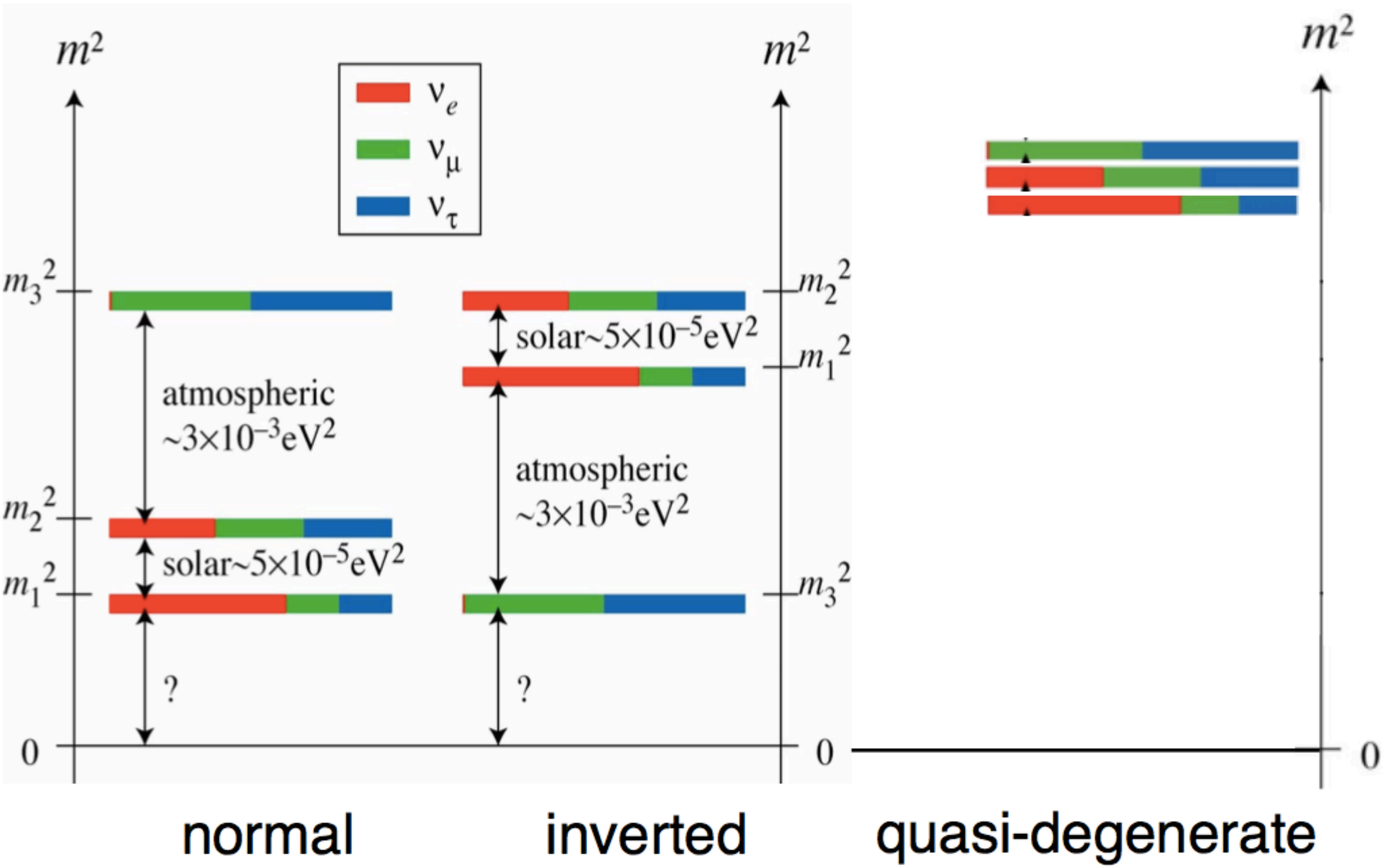
'The Octant':
Is the 'atmospheric' mixing angle <45°, >45° or exactly 45°?

'The Hierarchy': (or more accurately 'The Mass Ordering')
What is the sign of Δm^2_{31} and Δm^2_{32}?

'CP-Violation':
Do neutrinos and antineutrinos oscillate equivalently?

Mass Ordering?

Do we know the proper mass ordering?



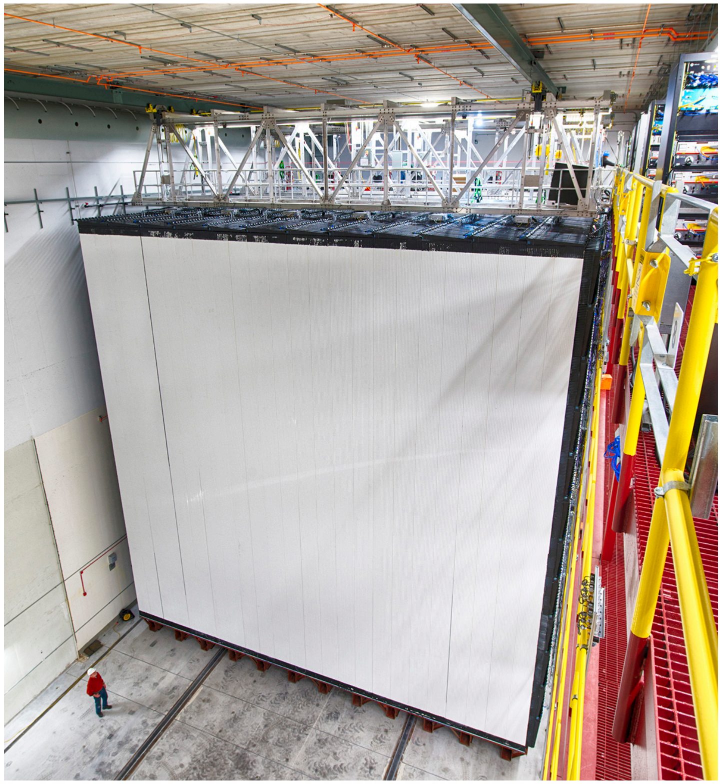
Near-Term Future

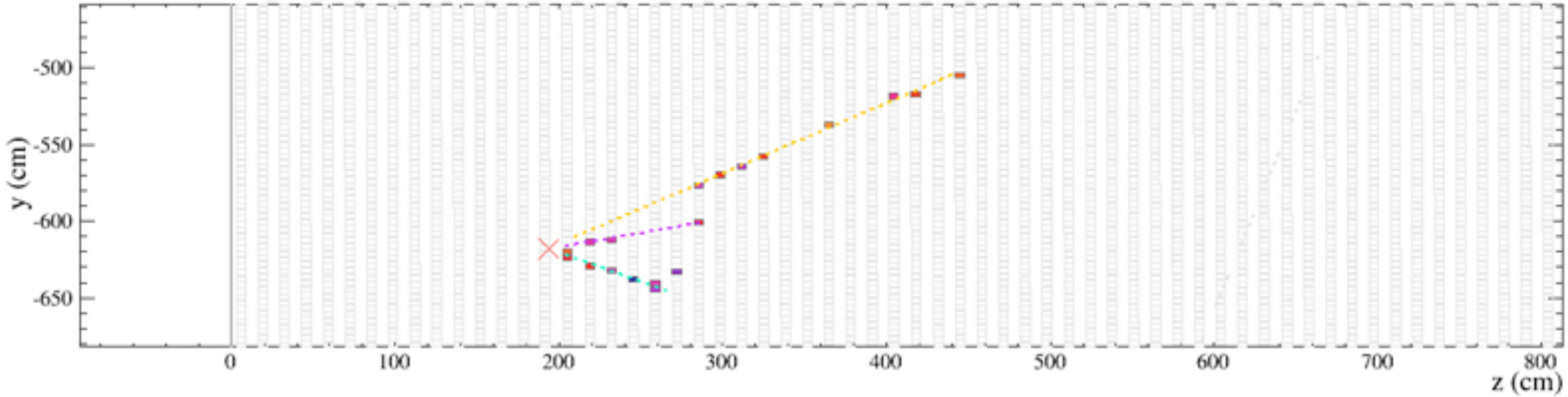
Expect oscillation measurements from T2K and NOvA

NOvA:

- Beam: Muon decay-in-flight, FermiLAB
- Detector: 14 kton plastic/scintillator
- Distance: 810 km (Ash River, MN)

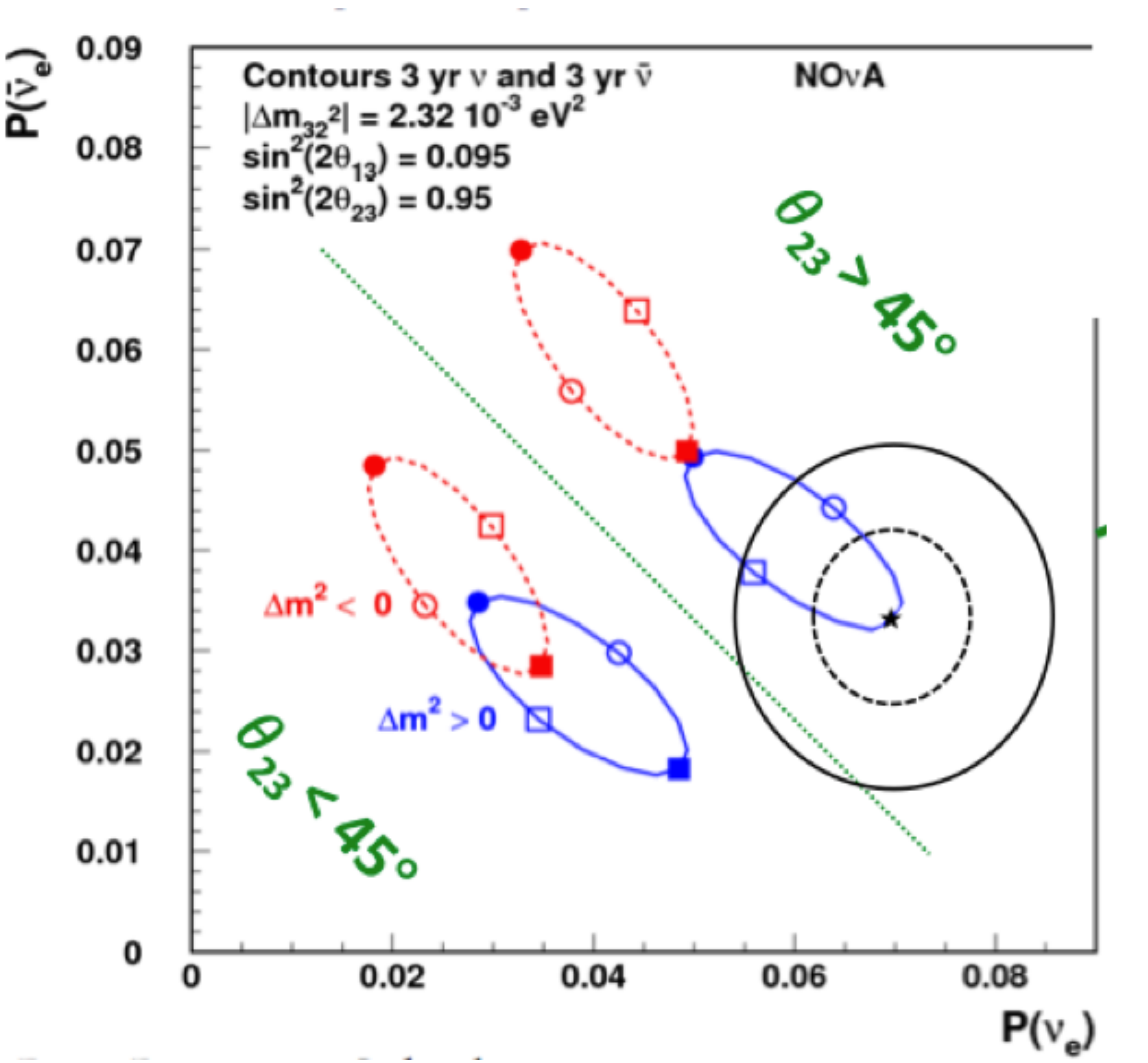
Just collecting first neutrino interactions





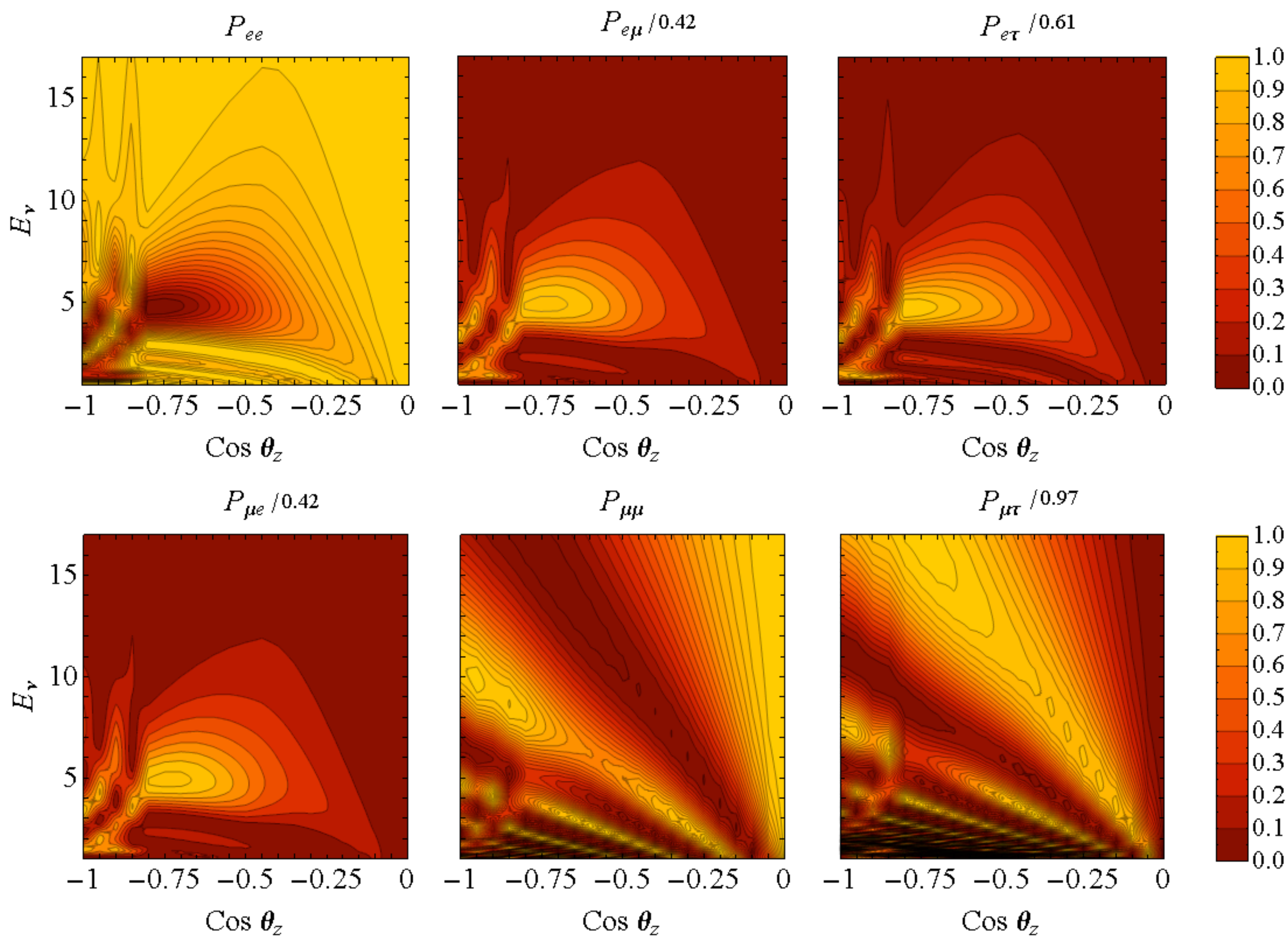
Near-Term Future

Expect oscillation measurements from T2K and NOvA



Mid-Term Future

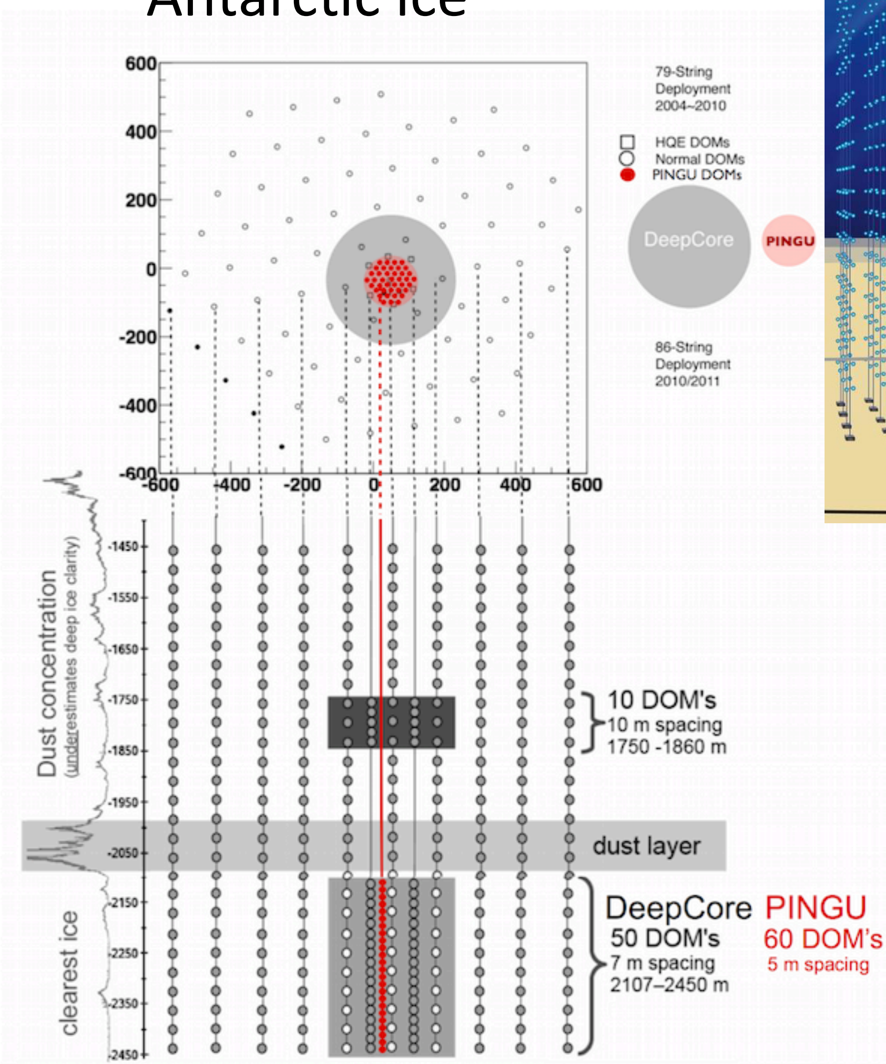
Possible signature of the mass ordering using atmospheric ν

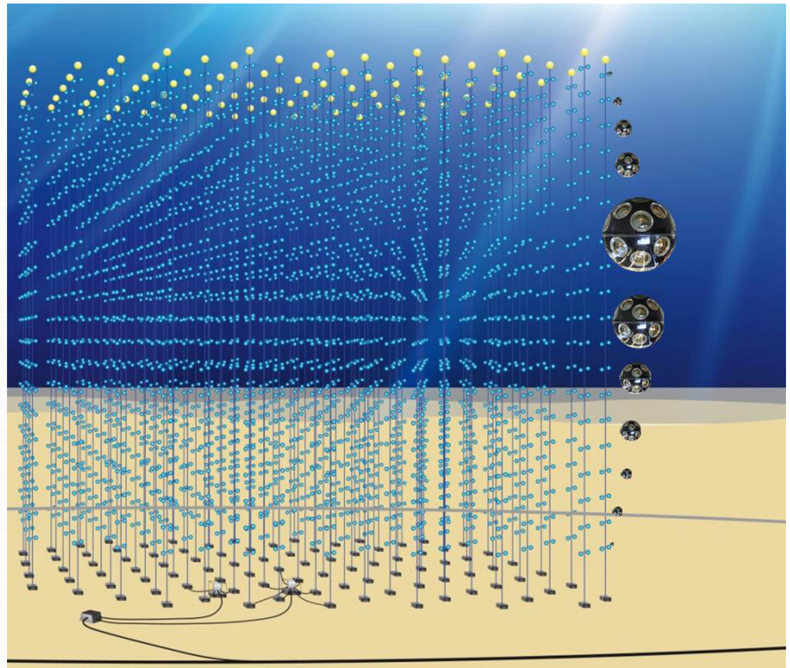


Mid-Term Future

Possible signature of the mass ordering using atmospheric ν

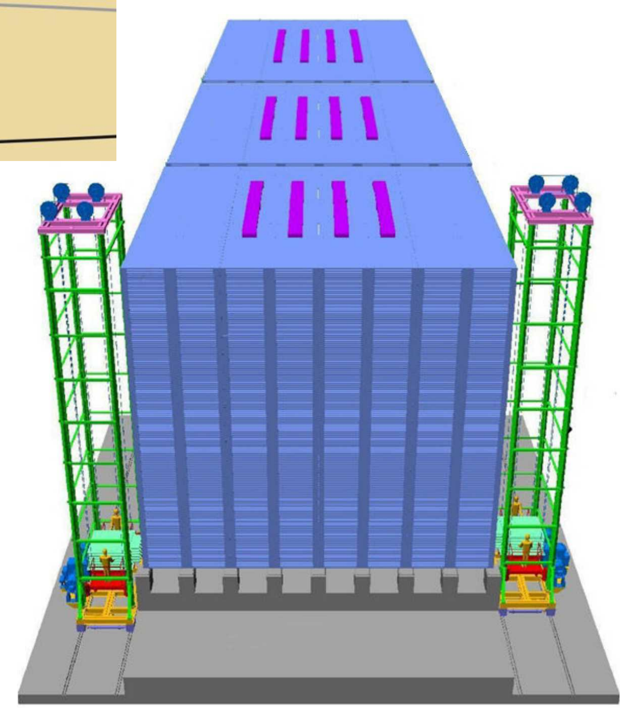
PINGU:
Antarctic ice





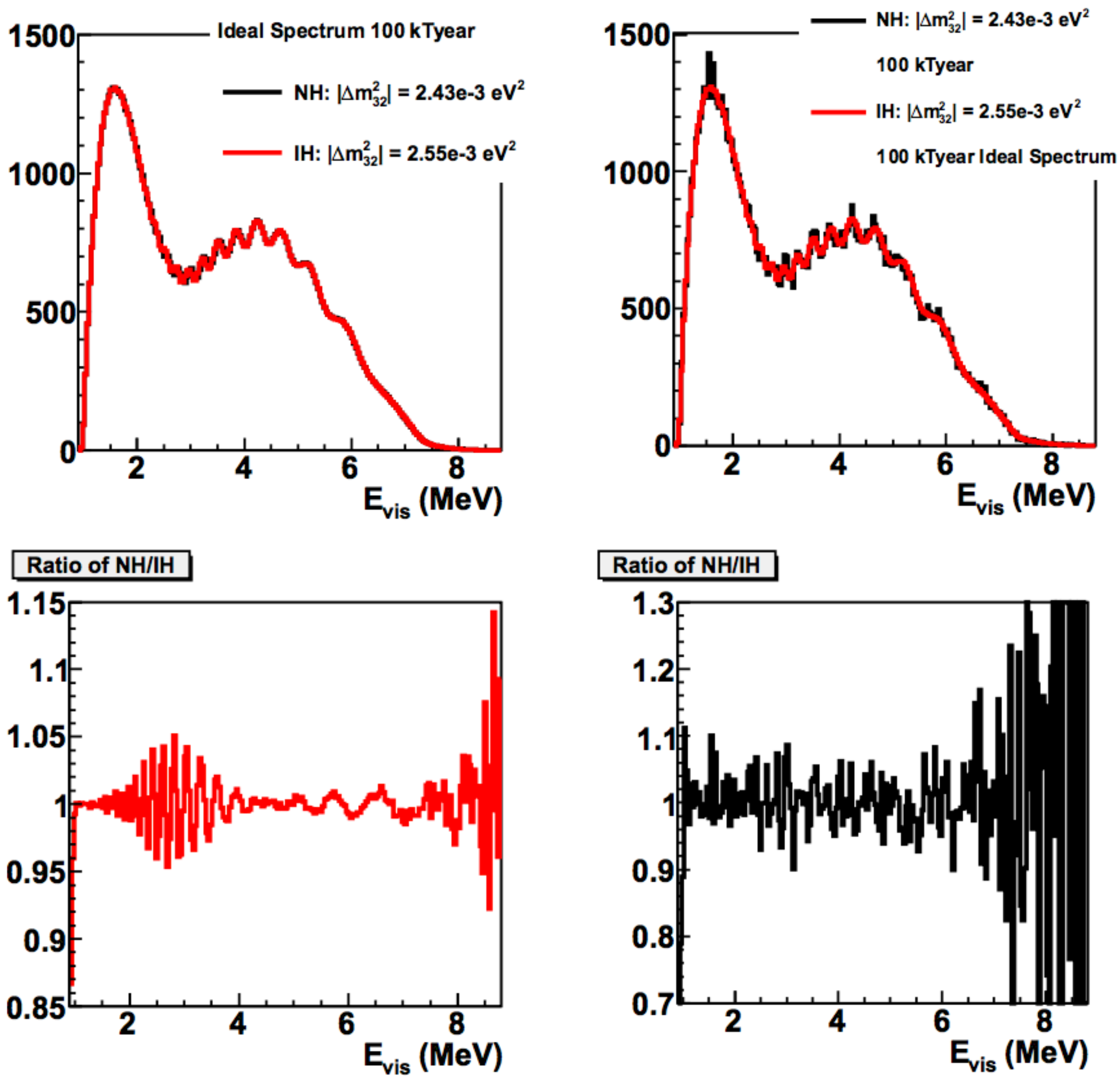
ORCA:
Mediterranean Sea

INO:
50 kton iron
calorimeter



Mid-Term Future

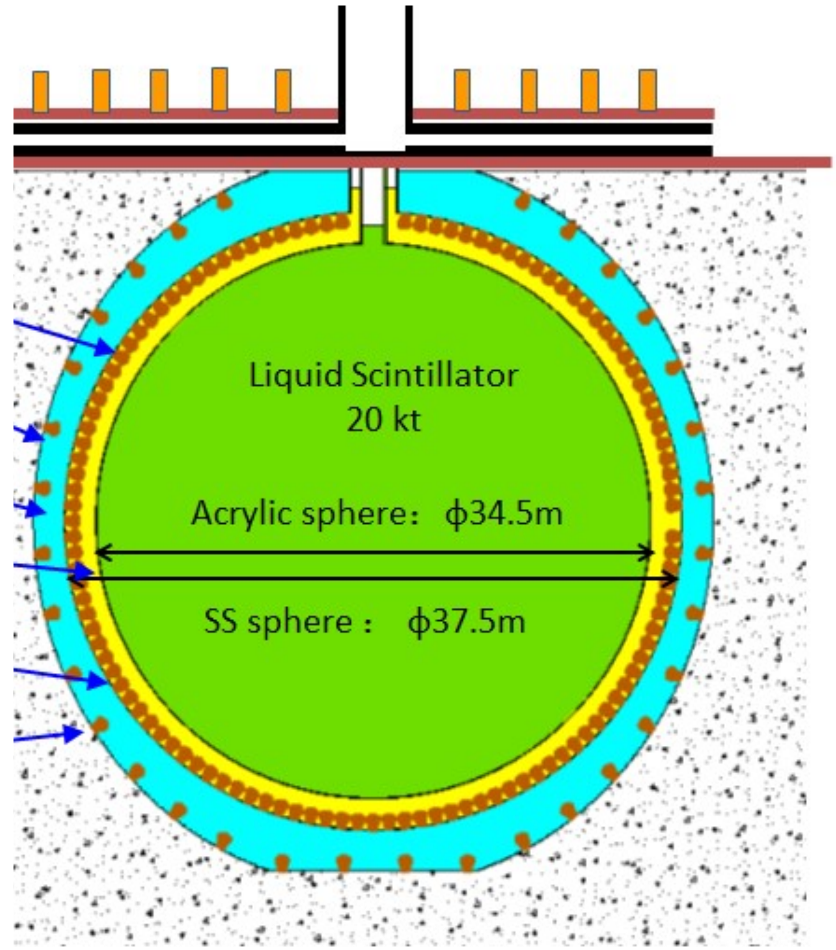
Possible signature of the mass ordering using reactor ν



JUNO/RENO-50:

~20 kton scintillator detectors

~60km from reactors

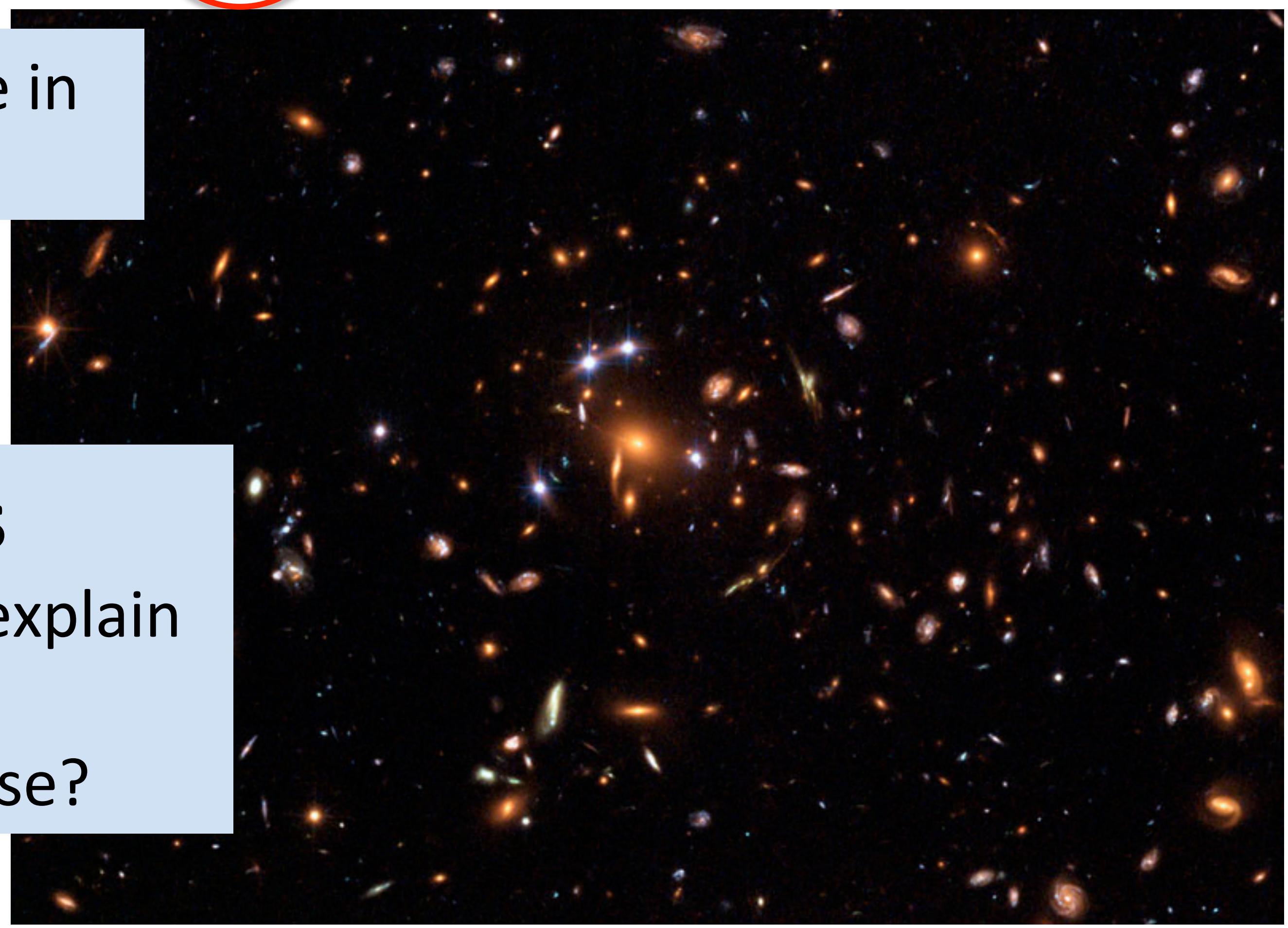


X.Qian, D.Dwyer, et al. PRD 87, 033005 (2013)

CP-Violation?

$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Possible complex phase in mixing matrix



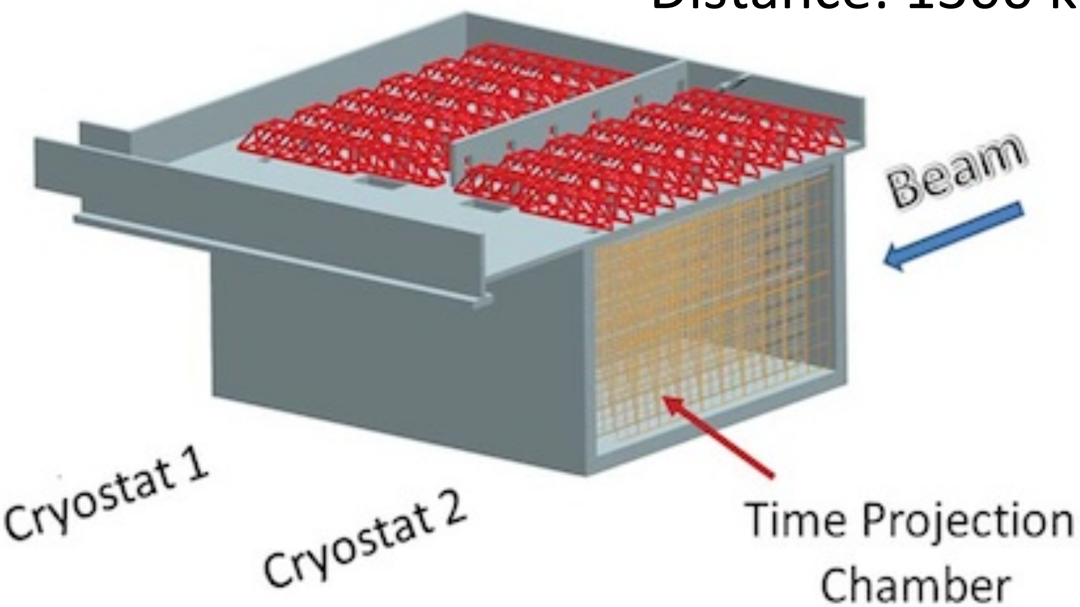
Leptogenesis

Can lepton CP-violation explain the matter/anti-matter asymmetry of the universe?

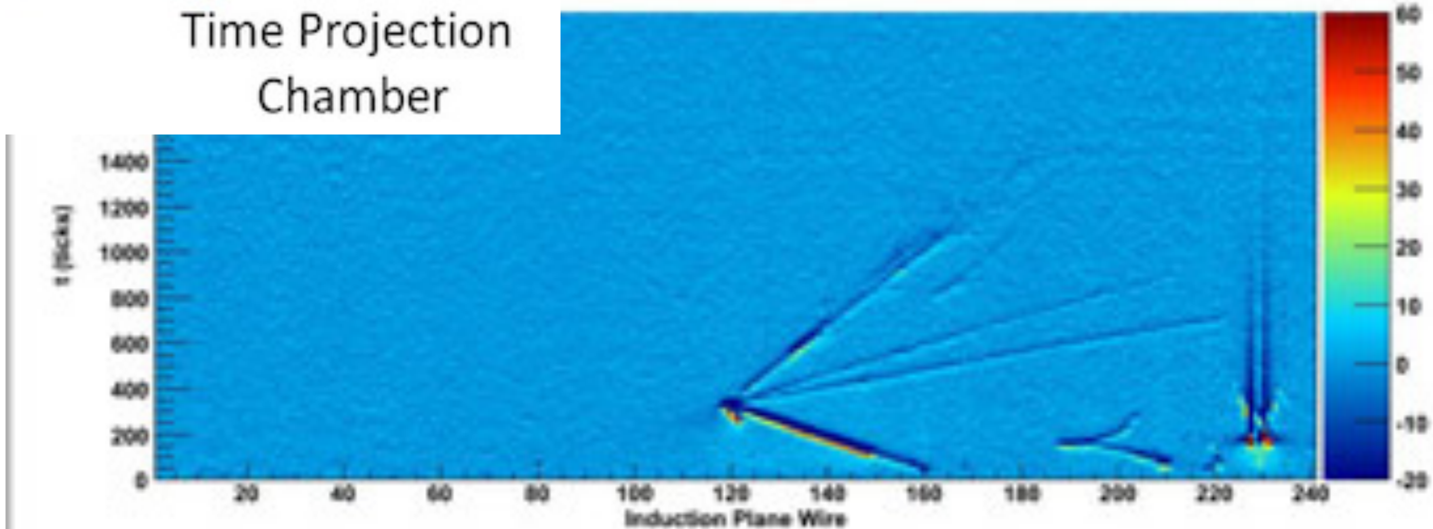
Longer-Term Future

DUNE:

- Beam: Muon decay-in-flight, LBNF beam, FermiLAB
- Detector: 34 kton liquid argon TPC
- Distance: 1300 km (Homestake, SD)



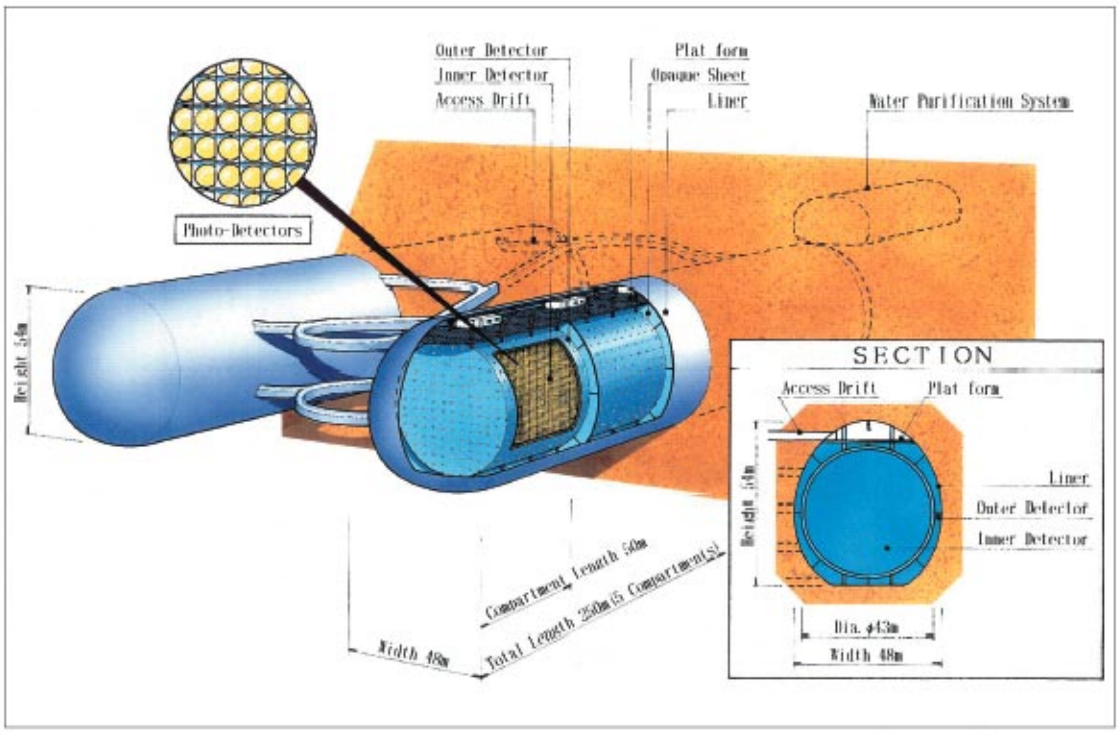
Example LAr event: ArgoNeut

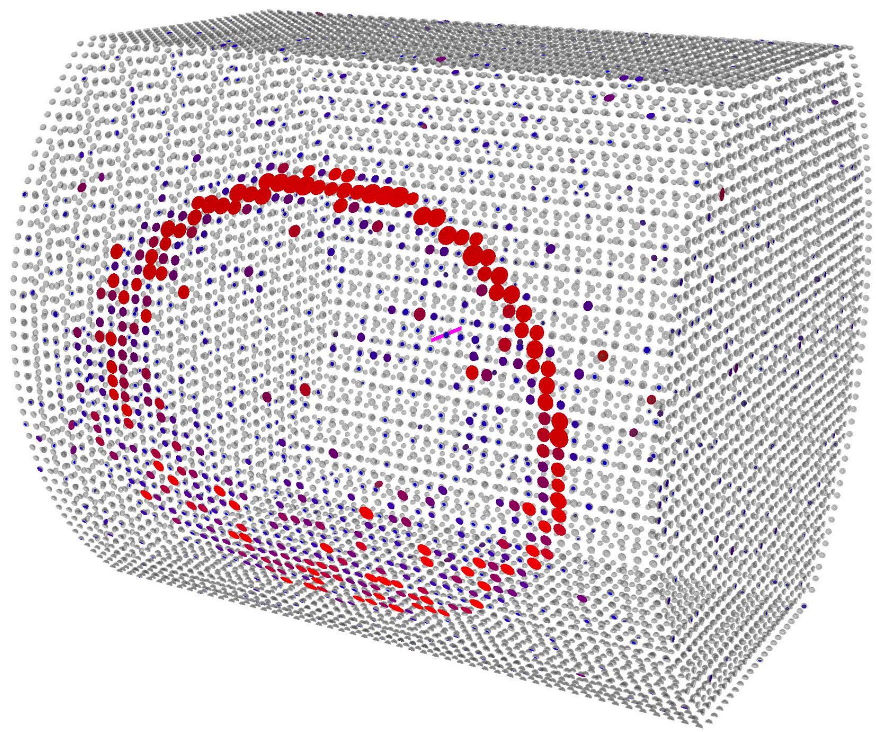


Longer-Term Future

Hyper-Kamiokande:

- Detector: 1 Mton water Cherenkov detector viewed by 10^5 20” PMTs
- Beam: Muon decay-in-flight (J-PARC), Atmospheric neutrinos, Supernovae
- Distance: 295 km (Kamioka, Japan)





Reality Check

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$ – solar data;
- $|U_{e2}|^2|U_{e1}|^2$ – KamLAND;
- $|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2(1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2|U_{\mu 3}|^2$ (upper bound $\rightarrow$ evidence) – MINOS, T2K.

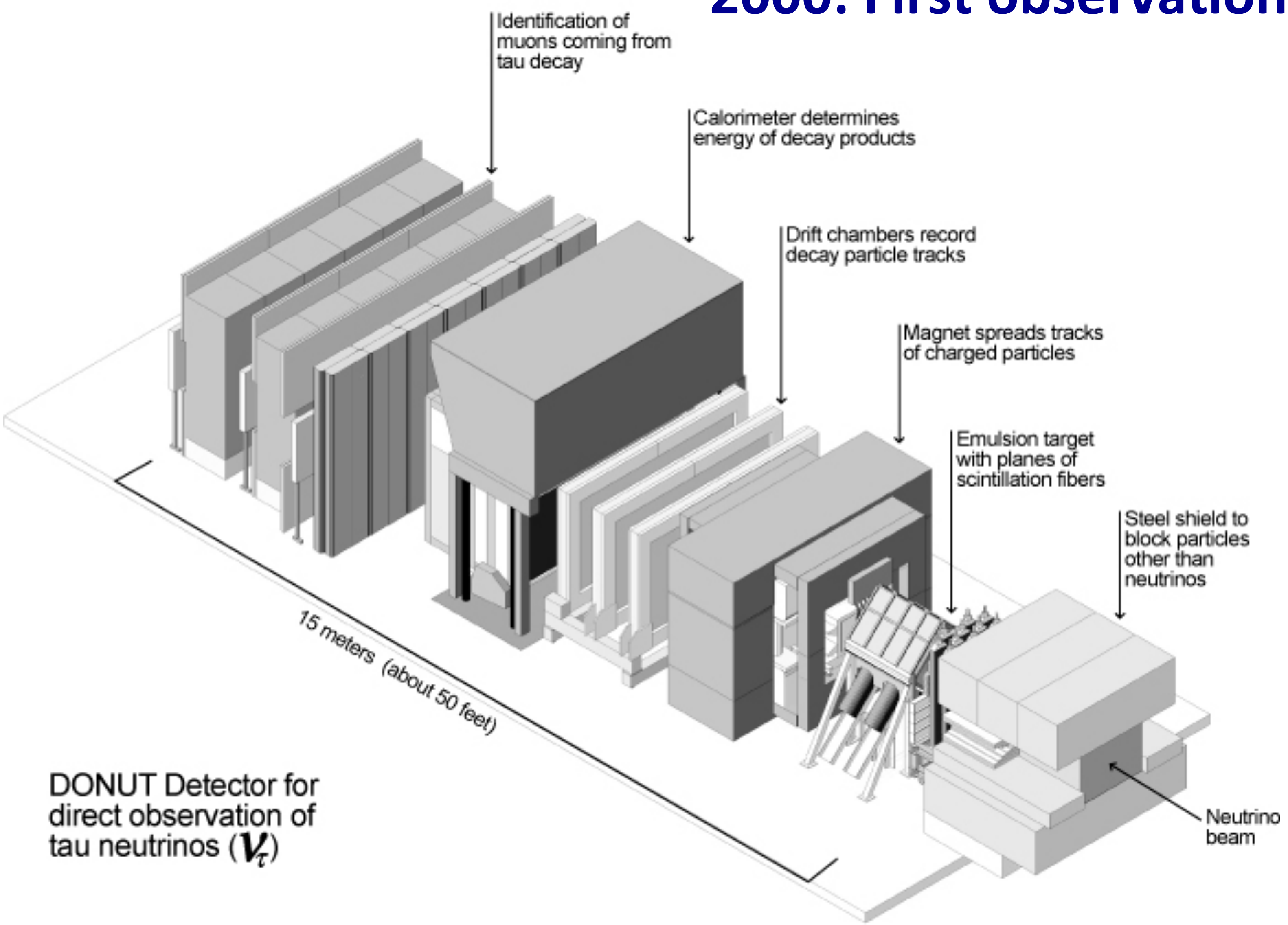
We still have a ways to go!

A. De Gouvea, WINP-2015

Tau Neutrinos

DONUT Detector

2000: First observation of ν_τ



Phys. Lett. B 504, 218 (2001)

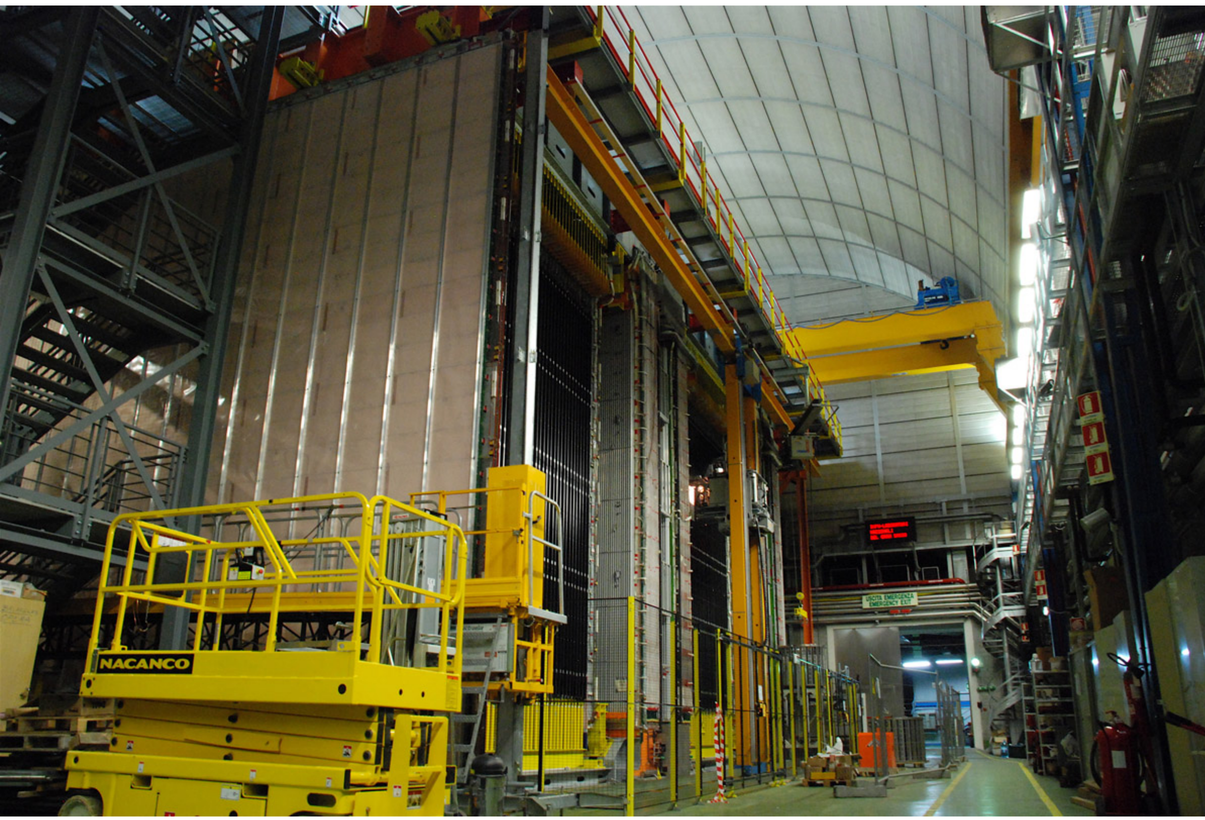
Tau Neutrinos

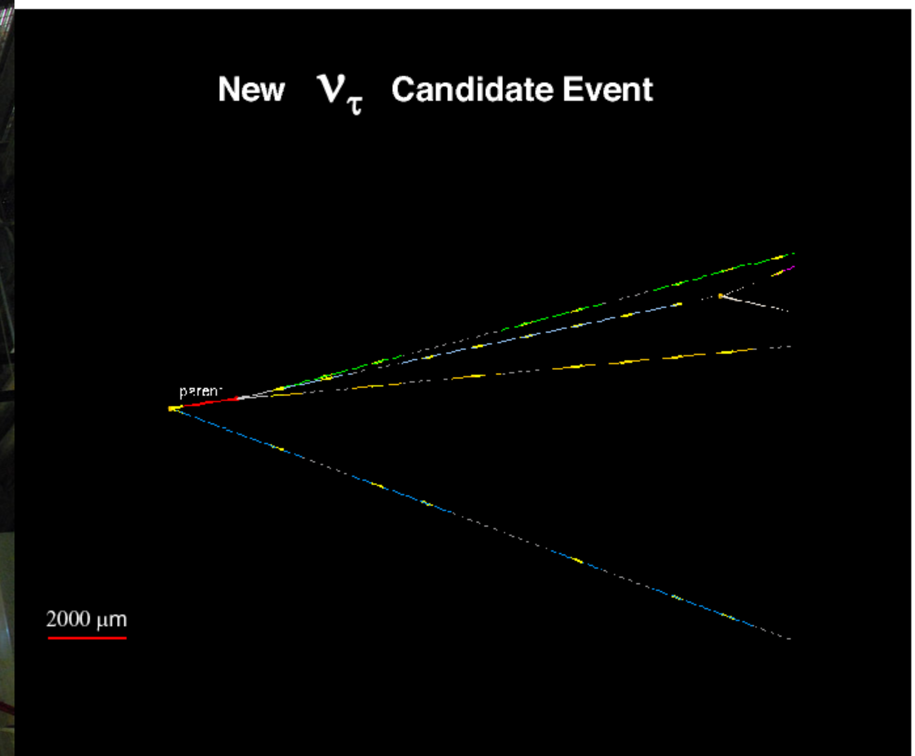
2010: First observation of ν_τ appearance in a ν_μ beam.

OPERA:

150,000 'bricks': 8kg interleaved sheets of Pb and photo film

Plastic scintillator layers to trigger and identify which brick to 'develop'





Phys. Lett. B 691, 138 (2010)

Detected 5 tau neutrinos as of June 2015.

Part 2: Neutrino Anomalies and Neutrino Mass

or

Why we still don't really understand neutrinos

Neutrinos Anomalies

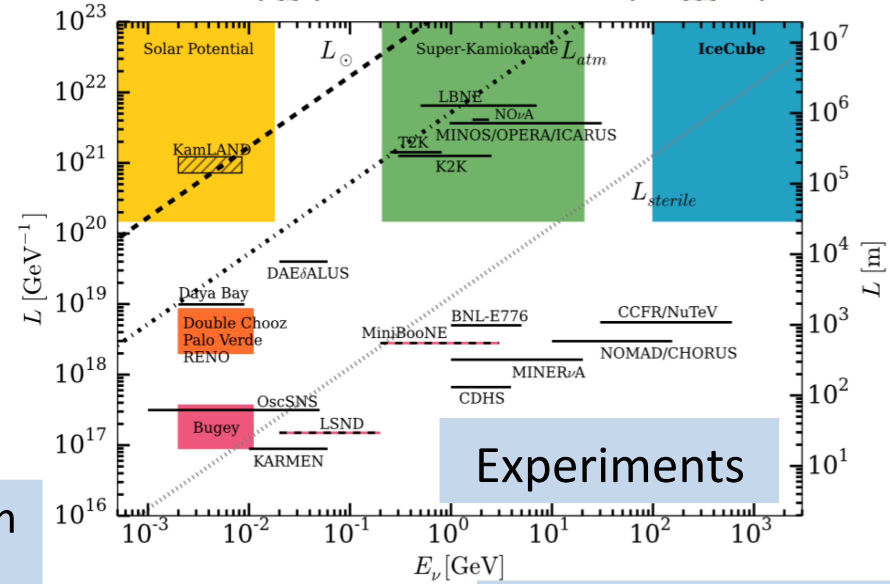
Neutrino Anomalies

Overview of Sterile Neutrino Phenomenology: *Jordi Salvado, CIPANP-2015*

Discussion of anomalies:

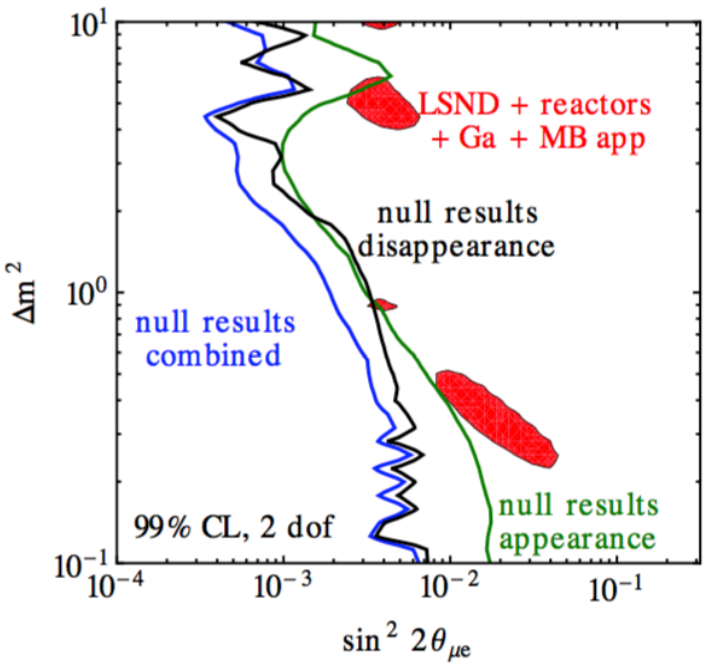
- LSND: e- antineutrino excess
- MiniBooNE: low-energy excess
- SAGE/GALLEX: e- neutrino deficit
- Reactors: e- antineutrino deficit

$$P_{\nu_\alpha \to \nu_\alpha}\left(\frac{L}{E}\right) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Experiments

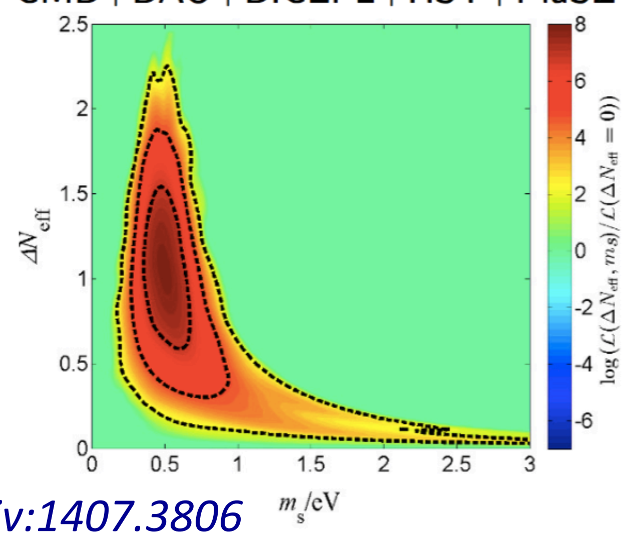
Global Picture



arXiv:1303.3011

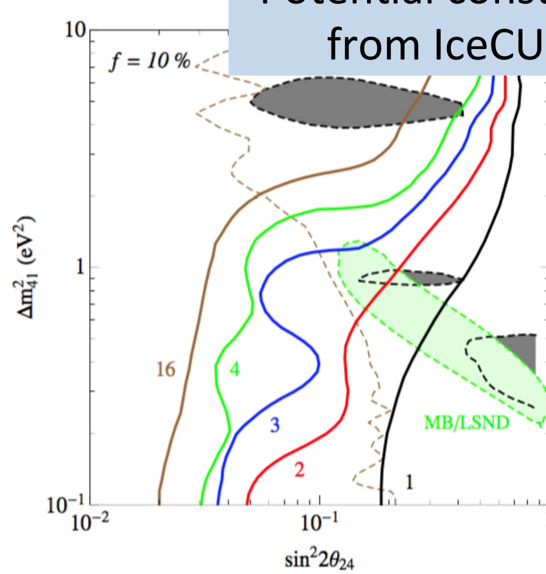
Constraints from Cosmology

CMB+BAO+BICEP2+HST+PlaSZ



arXiv:1407.3806

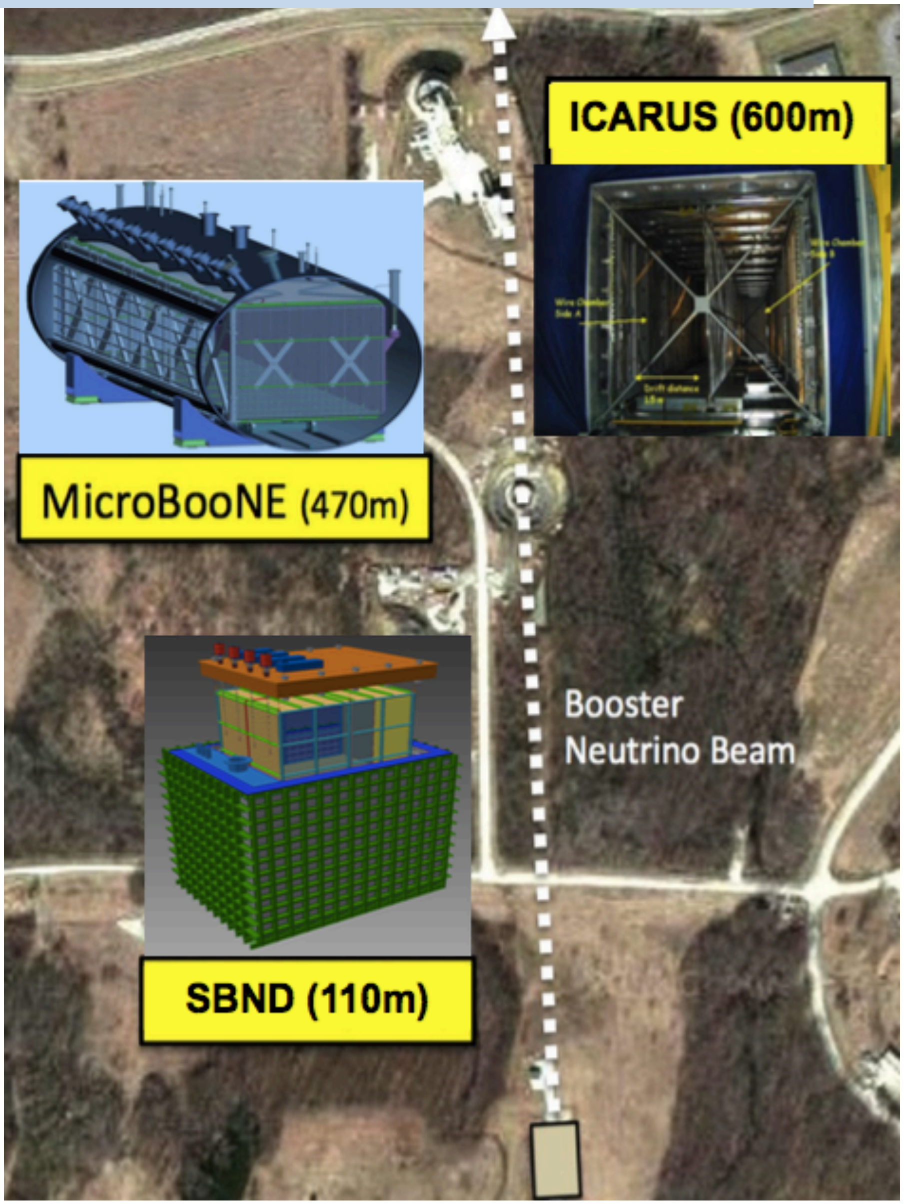
Potential constraints from IceCUBE



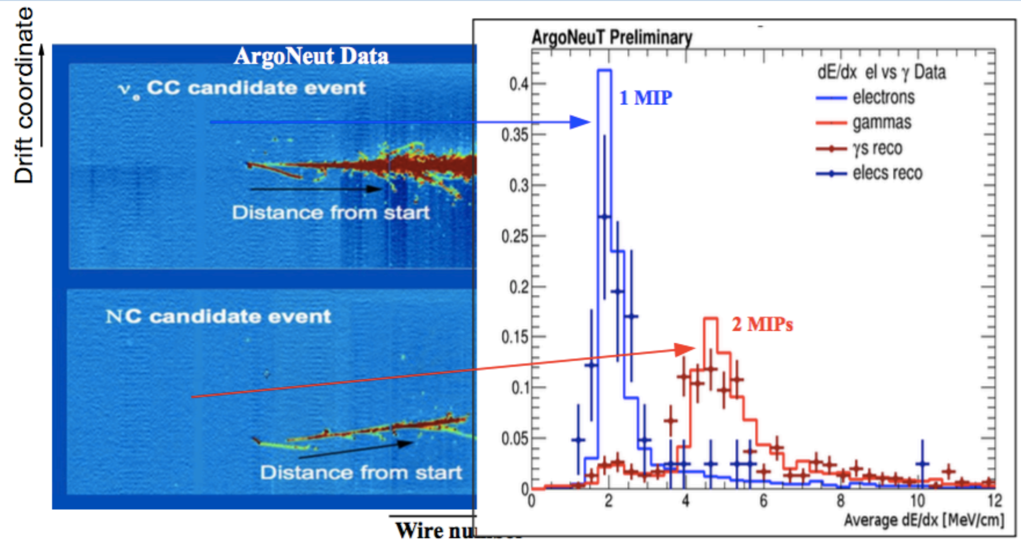
Sterile Neutrinos

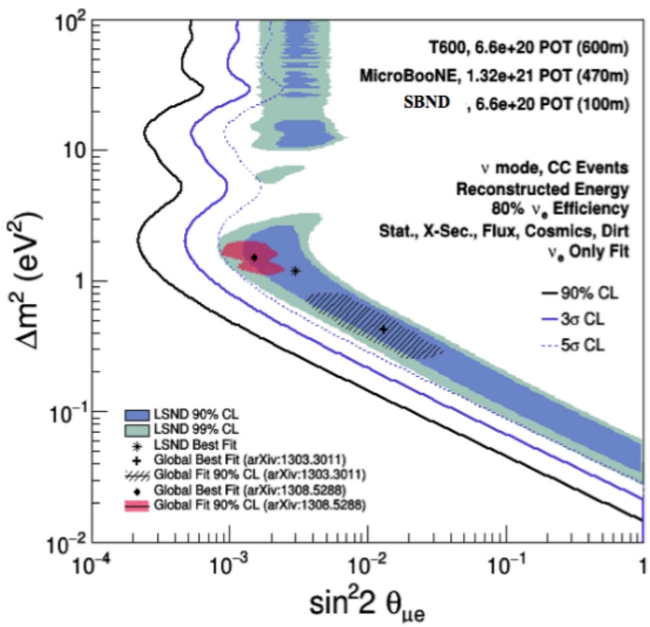
Searches using Accelerator Neutrinos: *Sowjanya Gollapinni, CIPANP-2015*

Fermilab Short-baseline Program



LAr TPC: Potential e/gamma discrimination





Potential reach for sterile oscillation

Sterile Neutrinos

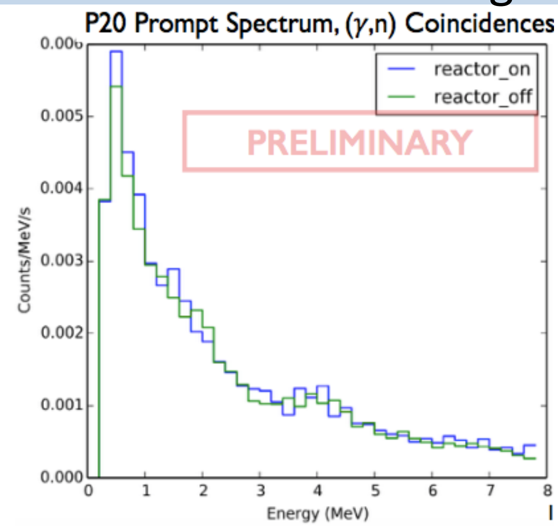
Searches using Reactor Antineutrinos: *Bryce Littlejohn, CIPANP-2015*

Experiment Program

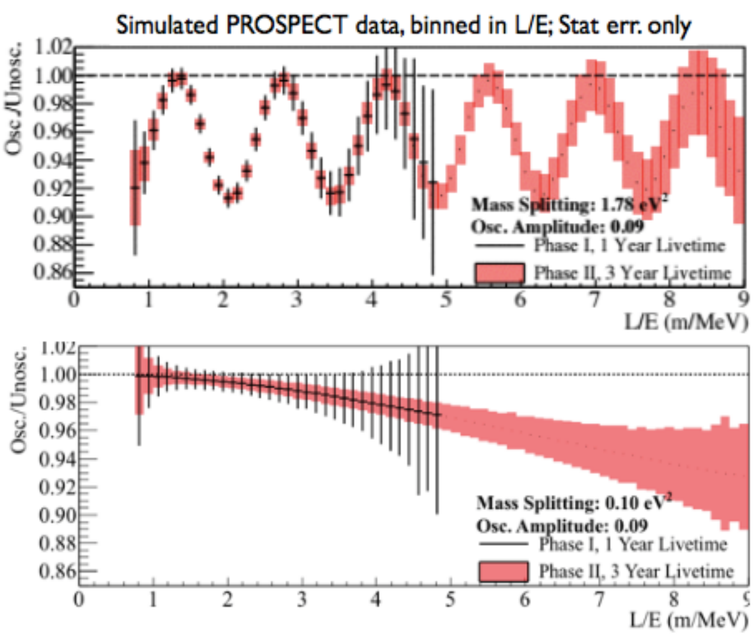
My (biased) overview of global efforts — Good : OK : Not Good

	Effort	Good X-Res	Good E-Res	L Range (meters)	Fuel	Exposure, MW*ton	Running at intended reactor?
US	**PROSPECT**	**Yes**	**Yes**	**6.5-20**	**HEU**	**185**	**Yes**
	NuLat	Yes	OK?	TBD	TBD	TBD	No
EU	STEREO	Yes	OK?	9-11	HEU	100	Yes
	SoLid	Yes	No	6-8	HEU	155	Yes
Russia	DANSS	Yes	No	9.7-12	LEU	2700	Yes
	Neutrino4	Yes	OK?	6-12	HEU	150	Yes
Asia	Hanaro	No	Yes	20-ish	LEU	30	No

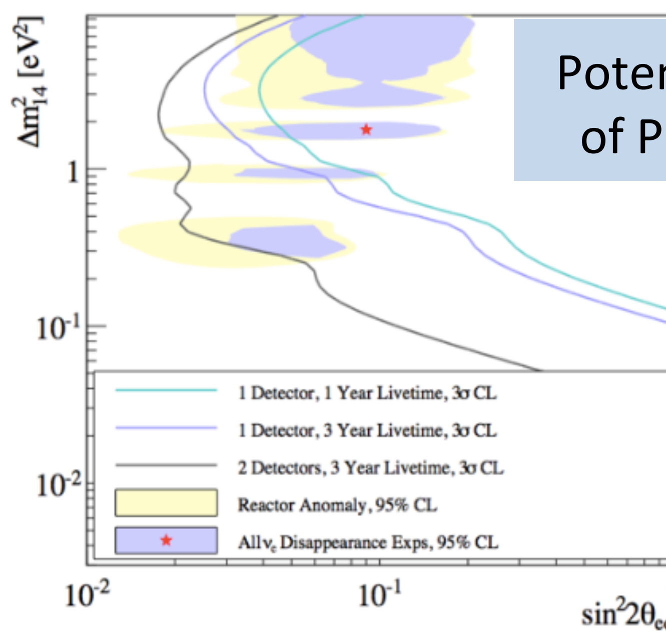
PROSPECT-20: Prototype shows no evidence for reactor background



Searching for 'smoking gun': L/E oscillation signal



Potential reach of PROSPECT

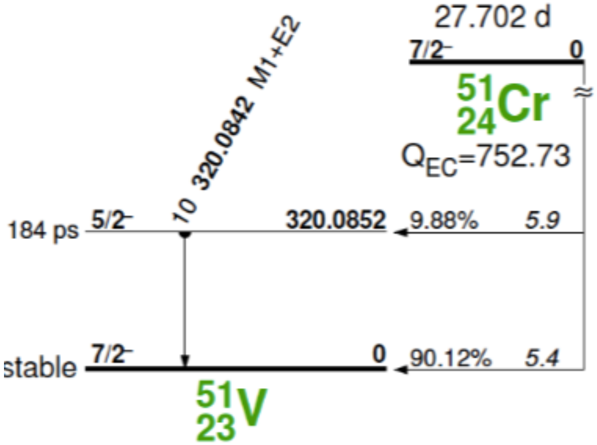


Sterile Neutrinos

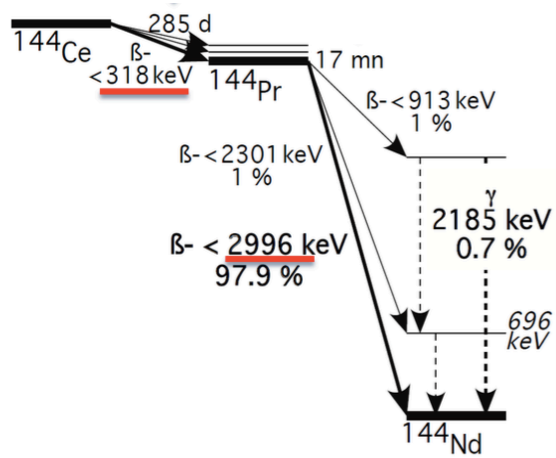
Searches using Radioactive Sources: *Jelena Maricic, CIPANP-2015*

Neutrino Source Options

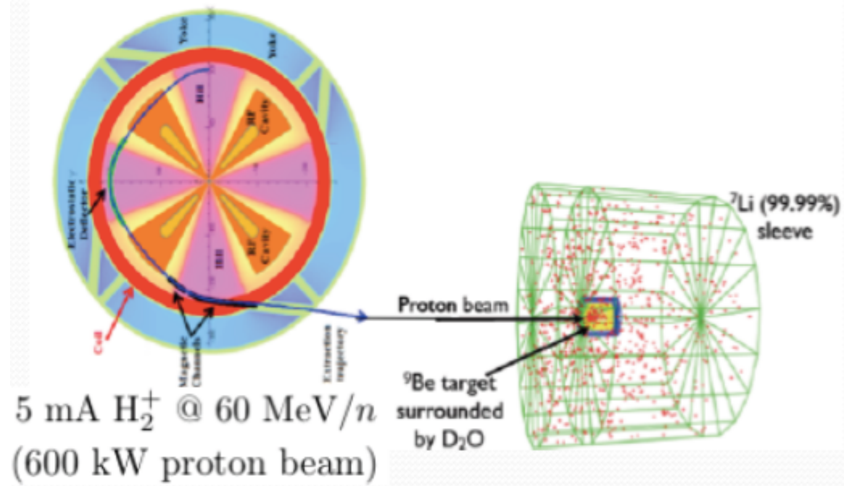
10 MCi ^{51}Cr



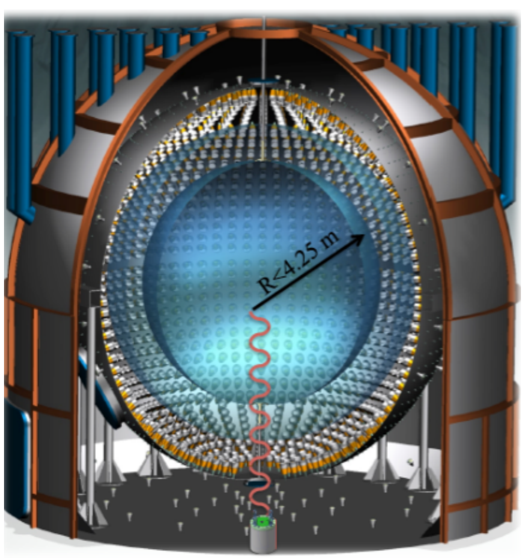
10 kCi ^{144}Ce-^{144}Pr



Cyclotron-generated ^{8}Li



Search for L/E oscillation within ~kton scintillator detector

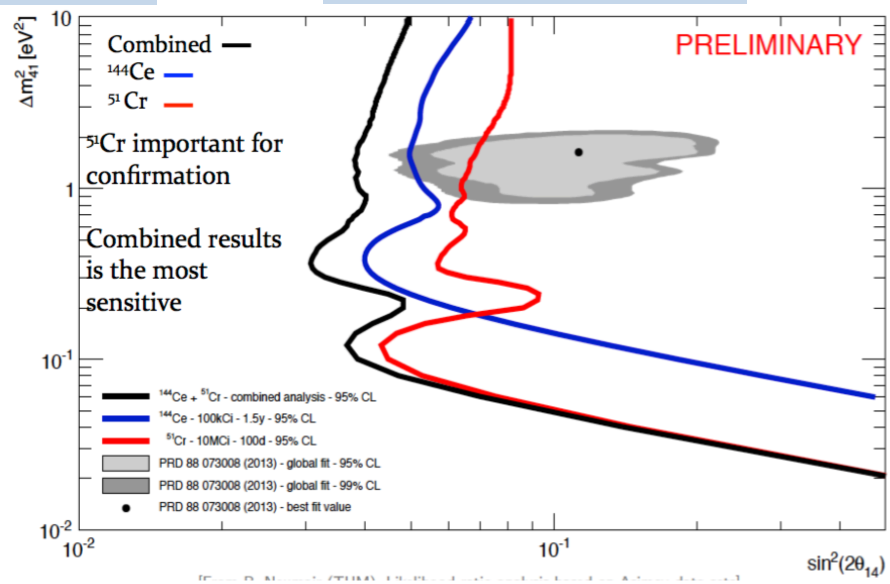


Candidate Detectors:

- Borexino
- KamLAND
- JUNO, SNO+?

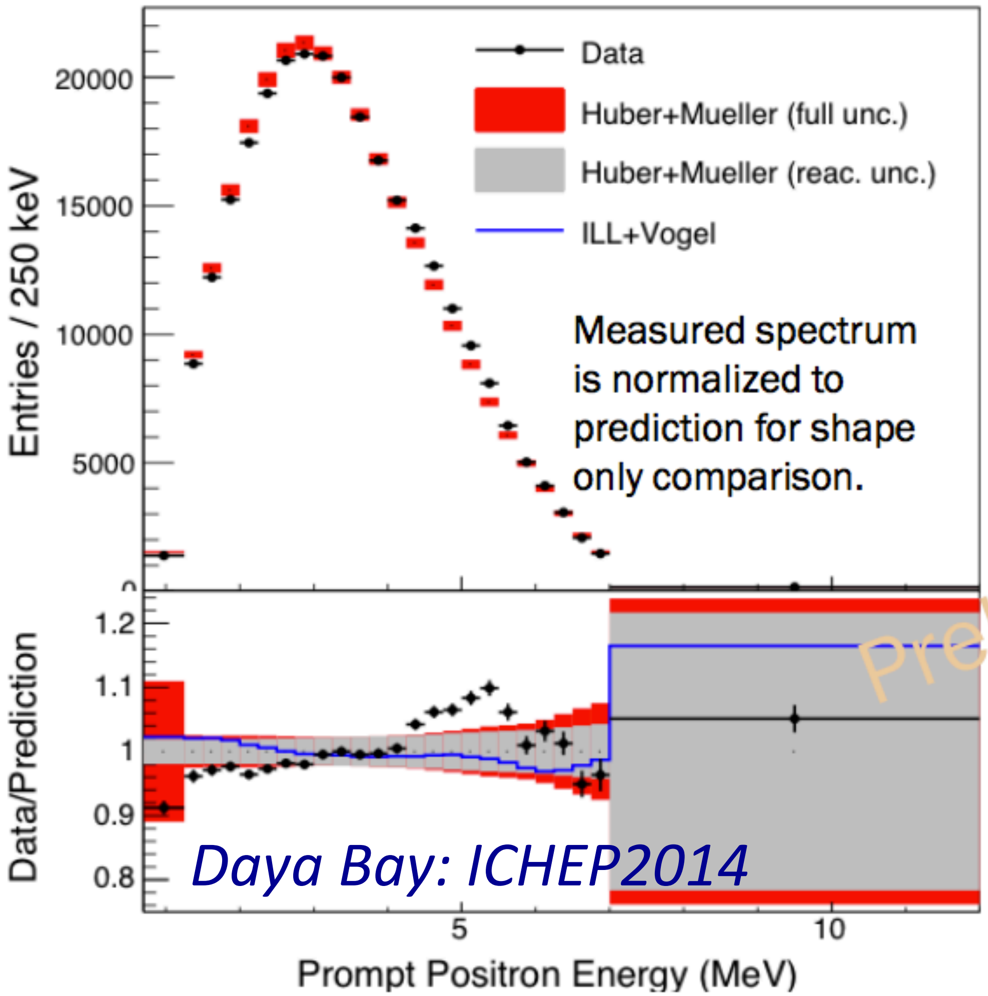
CeSOX: Borexino + ^{144}Ce
Source in production.
Planning for data in 2016.

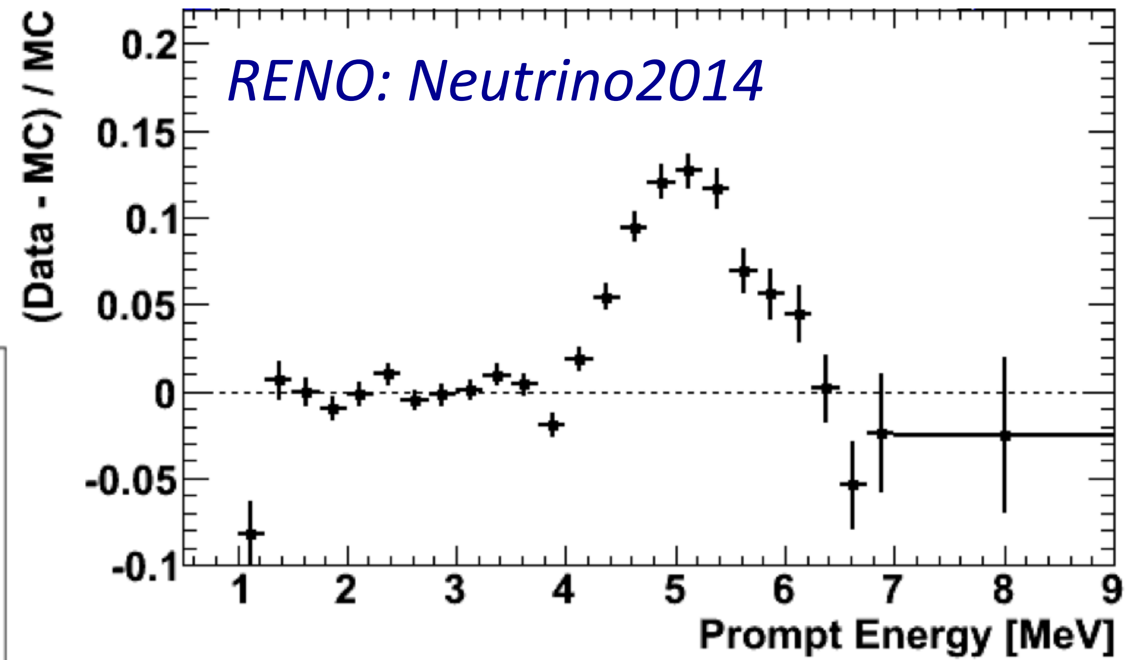
SOX Sensitivity

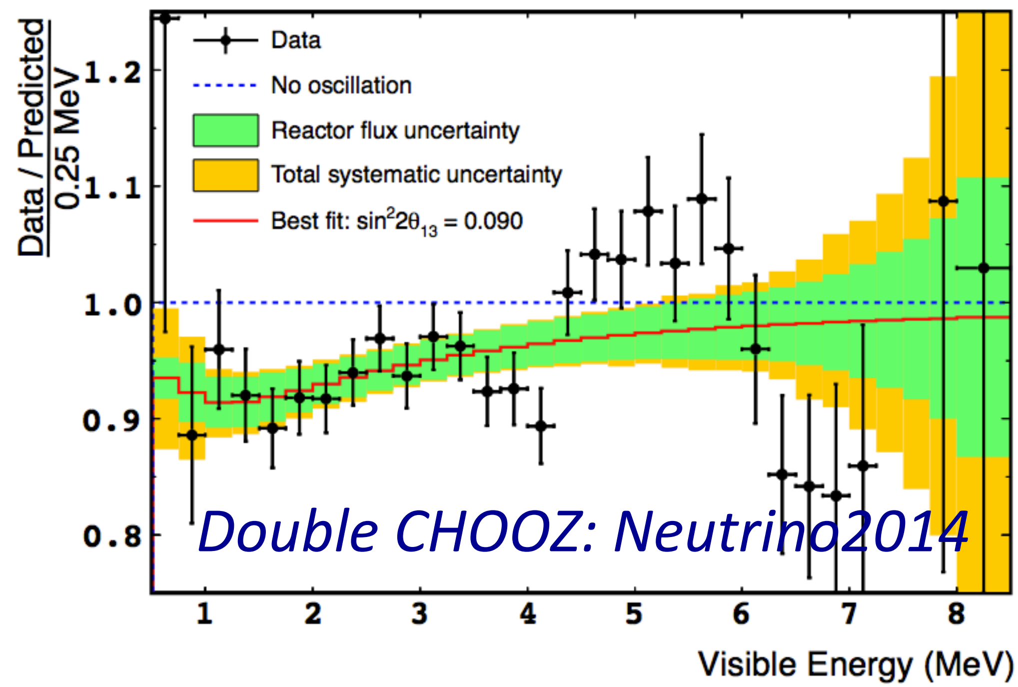


Reactor $\overline{\nu}_e$ Spectrum

Recent $\overline{\nu}_e$ measurements also disagree with existing models.







β^- Conversion

Standard: Use cumulative β^- spectrum to predict $\overline{\nu}_e$ spectrum

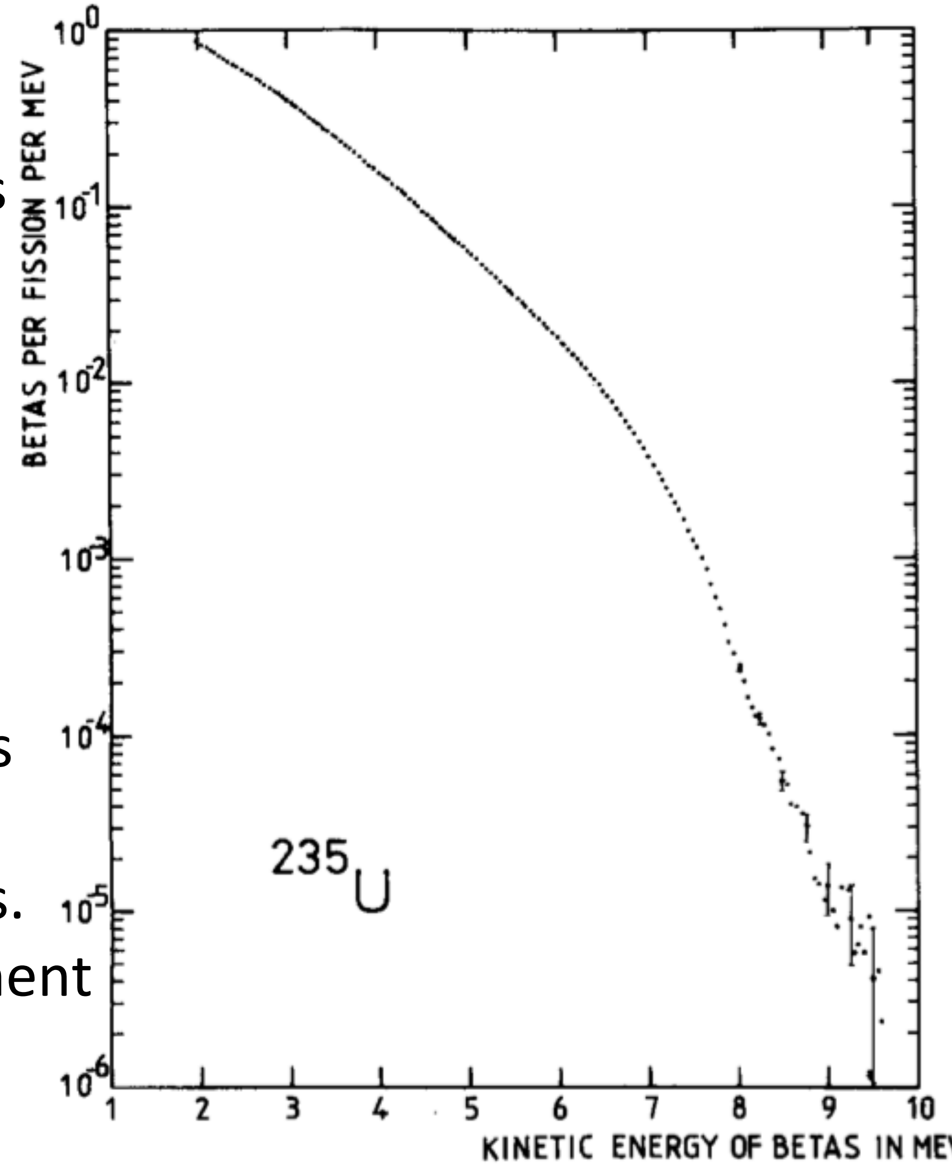
Method:

Expose fission parents to thermal neutrons

Measure total outgoing β- energy spectra

Predict corresponding $\overline{\nu}_e$ spectra

Phys. Lett. B160, 325 (1985), Phys. Lett. B118, 162 (1982)
Phys. Lett. B218, 365 (1989), Phys. Rev. Lett. 112, 122501 (2014)
Phys. Rev. C83, 054615 (2011)
Phys. Rev. C84, 024617 (2011)



Results:

More precise than nuclear data predictions

Standard approach for ~30 years

Predicts 6% higher flux than reactor msmts.

Spectrum disagrees with recent measurement

Reactor Anomaly, Sterile Neutrinos?

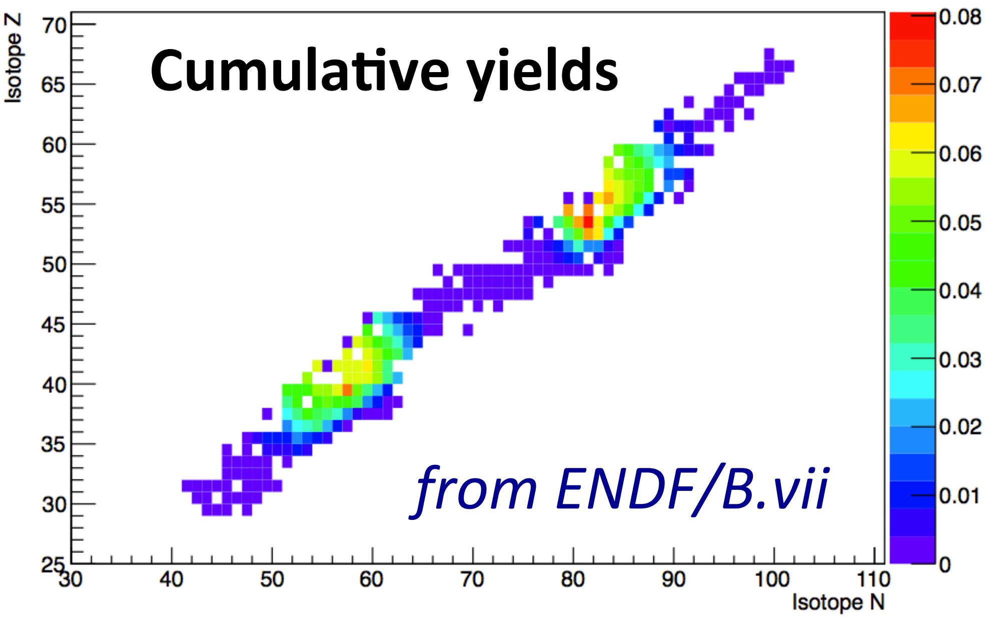
Phys. Rev. D83, 073006 (2011)

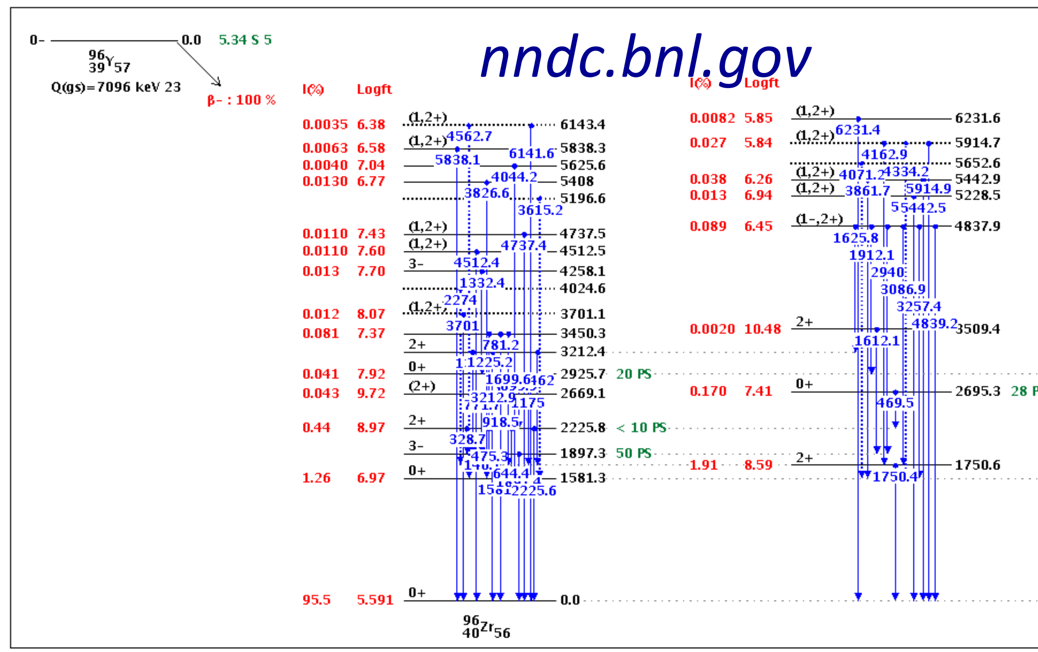
Guidance from Nuclear Data?

Does evaluated nuclear data suggest an explanation for anomalies?

To estimate antineutrino emission from a reactor:

Decay Rates (of beta emitters) **+** **Antineutrino Spectra** (from beta decay)





Estimated using:

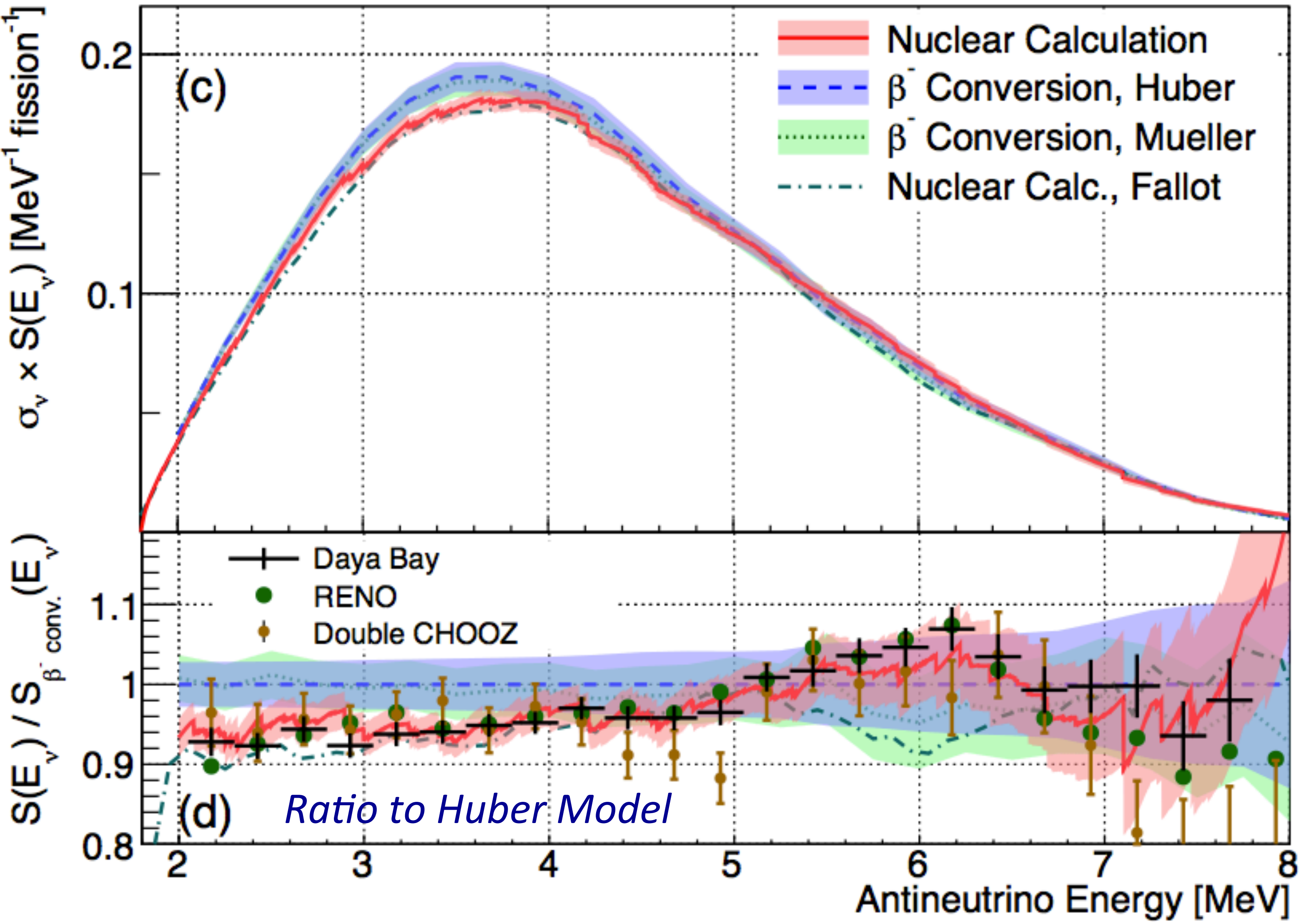
- Fission parent rates
- Cumulative fission yields per parent

Estimated using:

- Evaluated nuclear data (levels, feeding)
- Estimated beta decay spectrum

Reactor $\overline{\nu}_e$ Spectrum

Direct calculation unexpectedly agrees with preliminary msmts.



D.Dwyer, T.Langford
PRL 114, 012502 (2015)

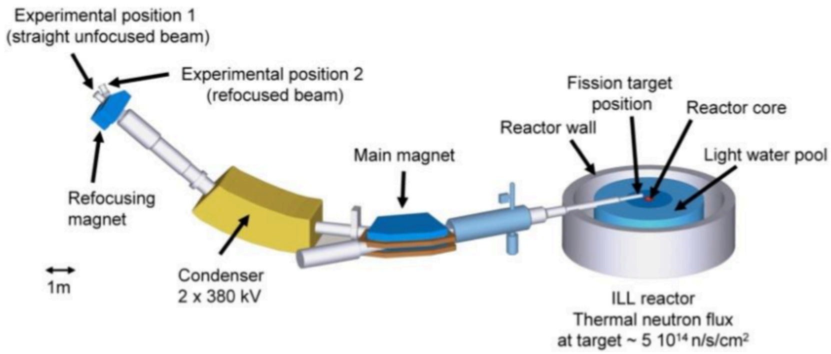
Note:
Preliminary data compared using approx. $E_\nu \approx E_{e+} + 0.8$ MeV

Data normalization adjusted to accurately compare shape.

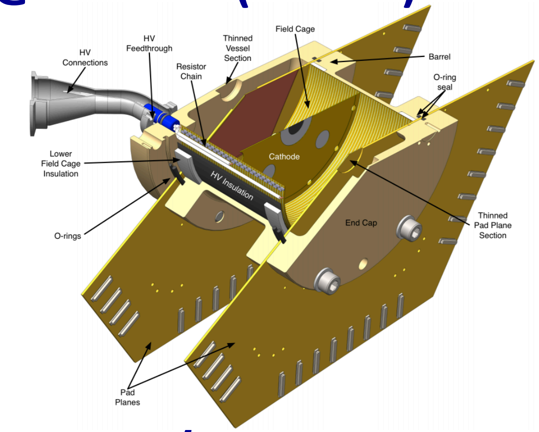
How do large calc. uncertainties not cause more tension with measurements?

Nuclear Measurements

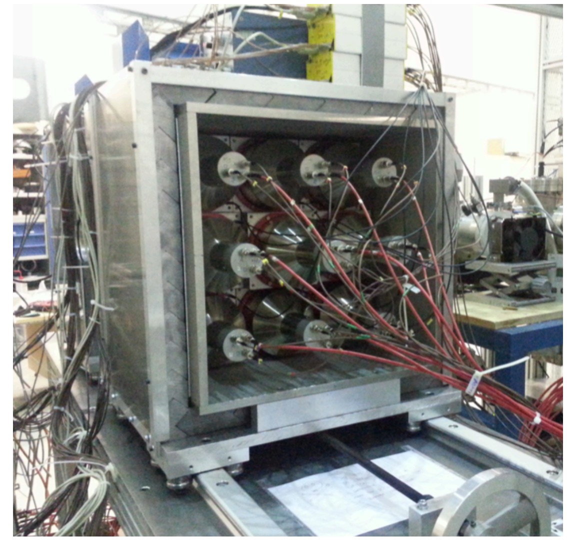
Fission Yields @ ILL (Lohengrin)



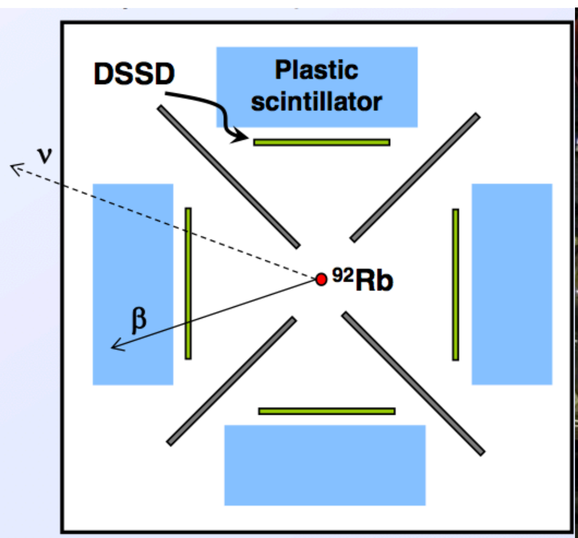
Fission Yields @ LANSCE (NIFFTE)

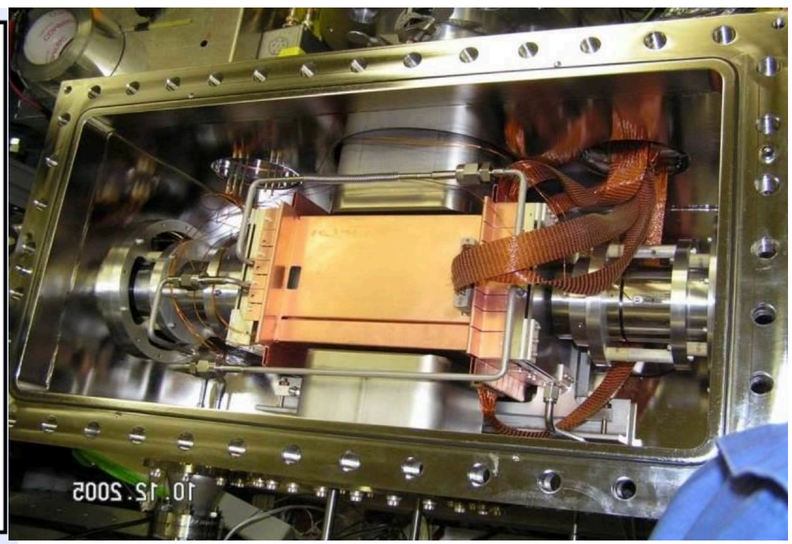


Total Absorp. Spec. @ IGISOL (DTAS)



Precision β$^-$ Spec. with Trapped Ions @ ANL/CARIBU





Total Absorp. Spec. @ ORNL (MTAS)

Some examples of planned measurements of these decays:

N.D. Scielzo, private comm. [G.Li et al., PRL 110, 092502 (2013)]
A.-A. Zakari-Issoufou et al., EPJ Web of Conferences 66, 10019 (2014)
M. Heffner et al. (NIFFTE Collaboration), arXiv:1403.6771

Consequences…

You broke the Standard Model, now fix it!

Neutrino oscillation implies:

-> Must add mixing matrix into weak interaction.

…but is the mixing matrix complete?

-> Lepton flavor is no longer conserved!

…but at least total lepton number is possibly still conserved.

-> Neutrinos have mass!

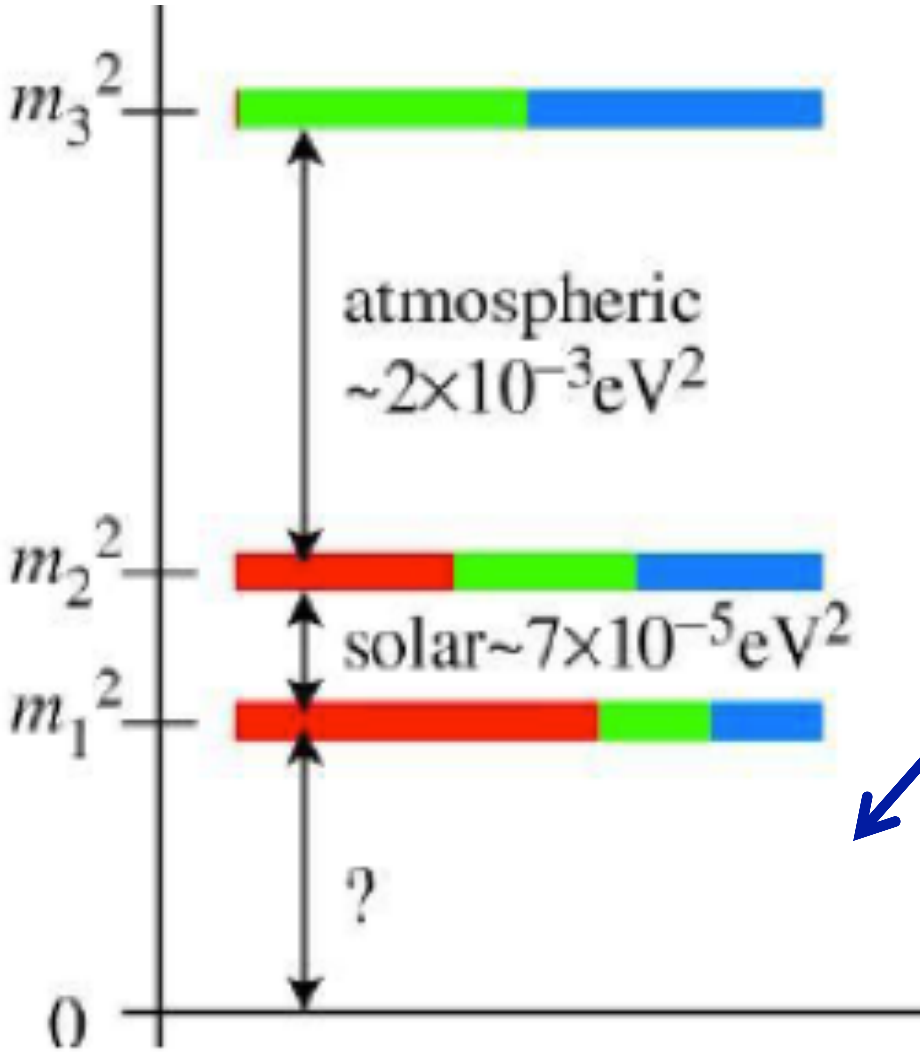
…but how do we add it to the Standard Model?

Neutrinos Mass

Neutrino Mass

Oscillation implies neutrinos have mass,

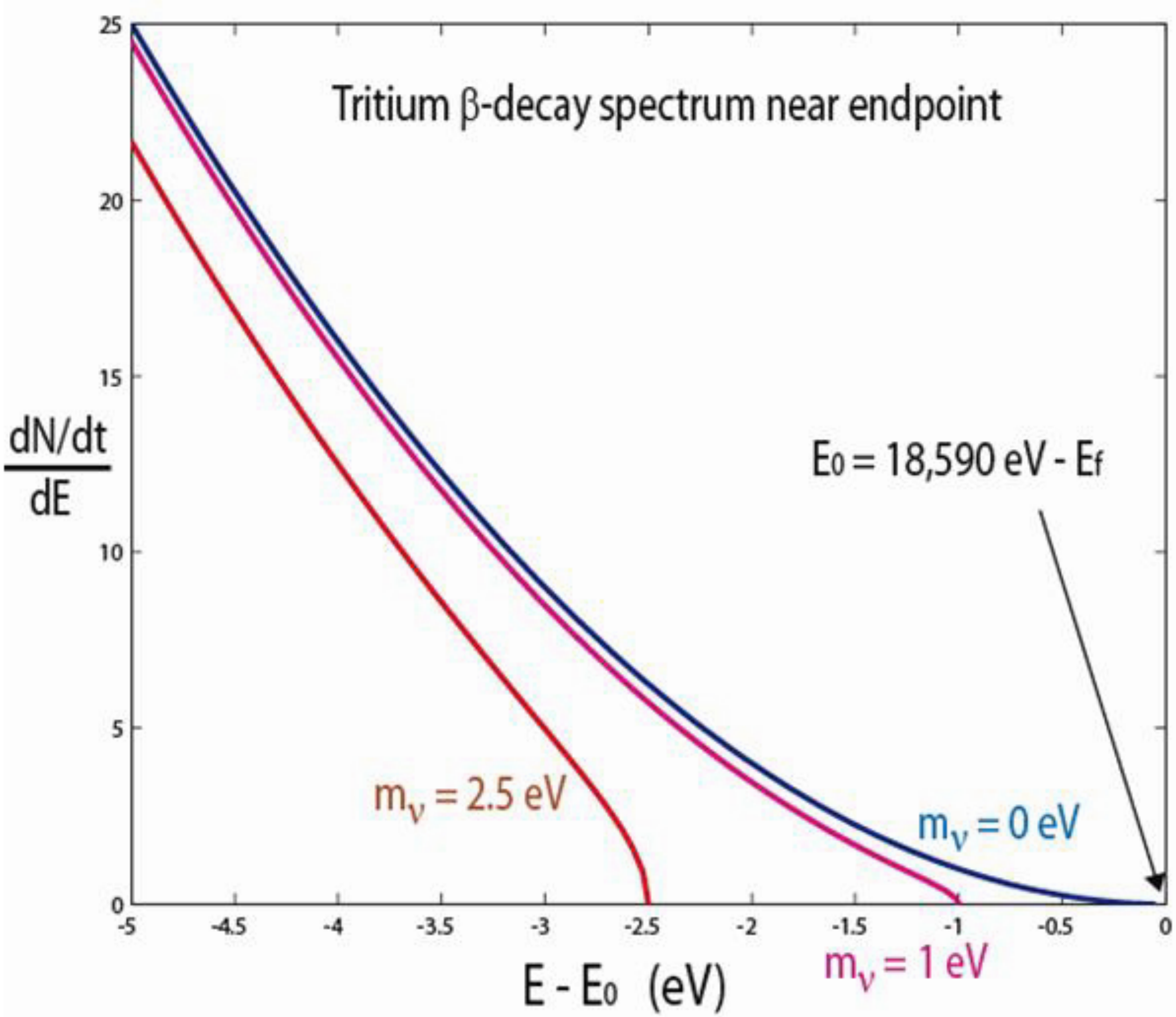
…but only provides mass differences.



What are the prospects for measuring the absolute mass?

Kinematics

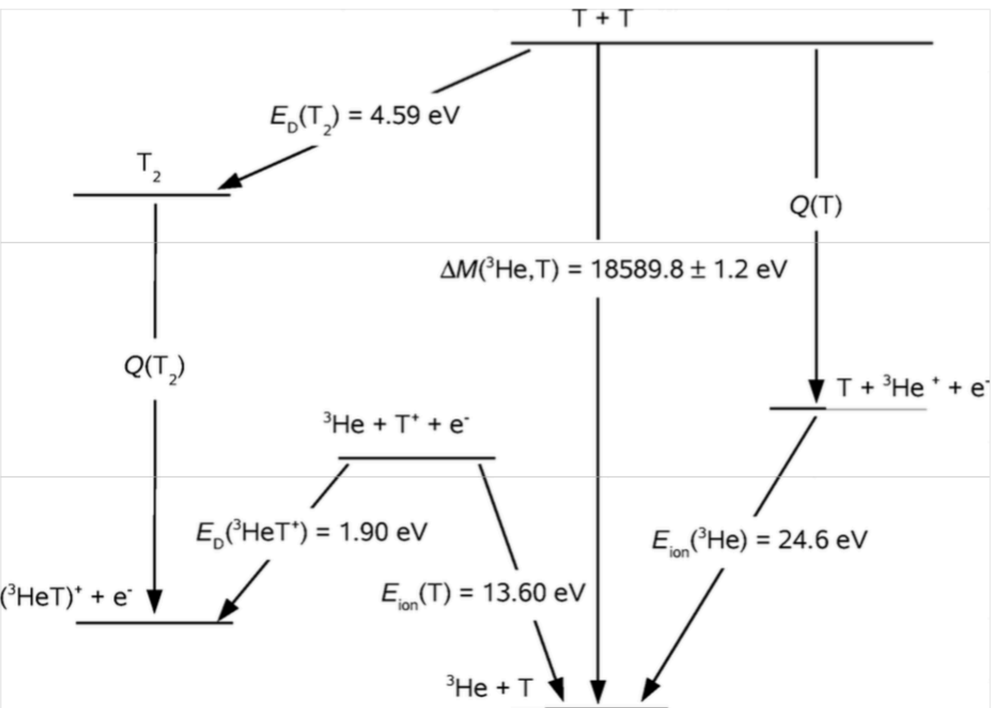
Neutrino mass impacts the e- energy spectrum from beta decay

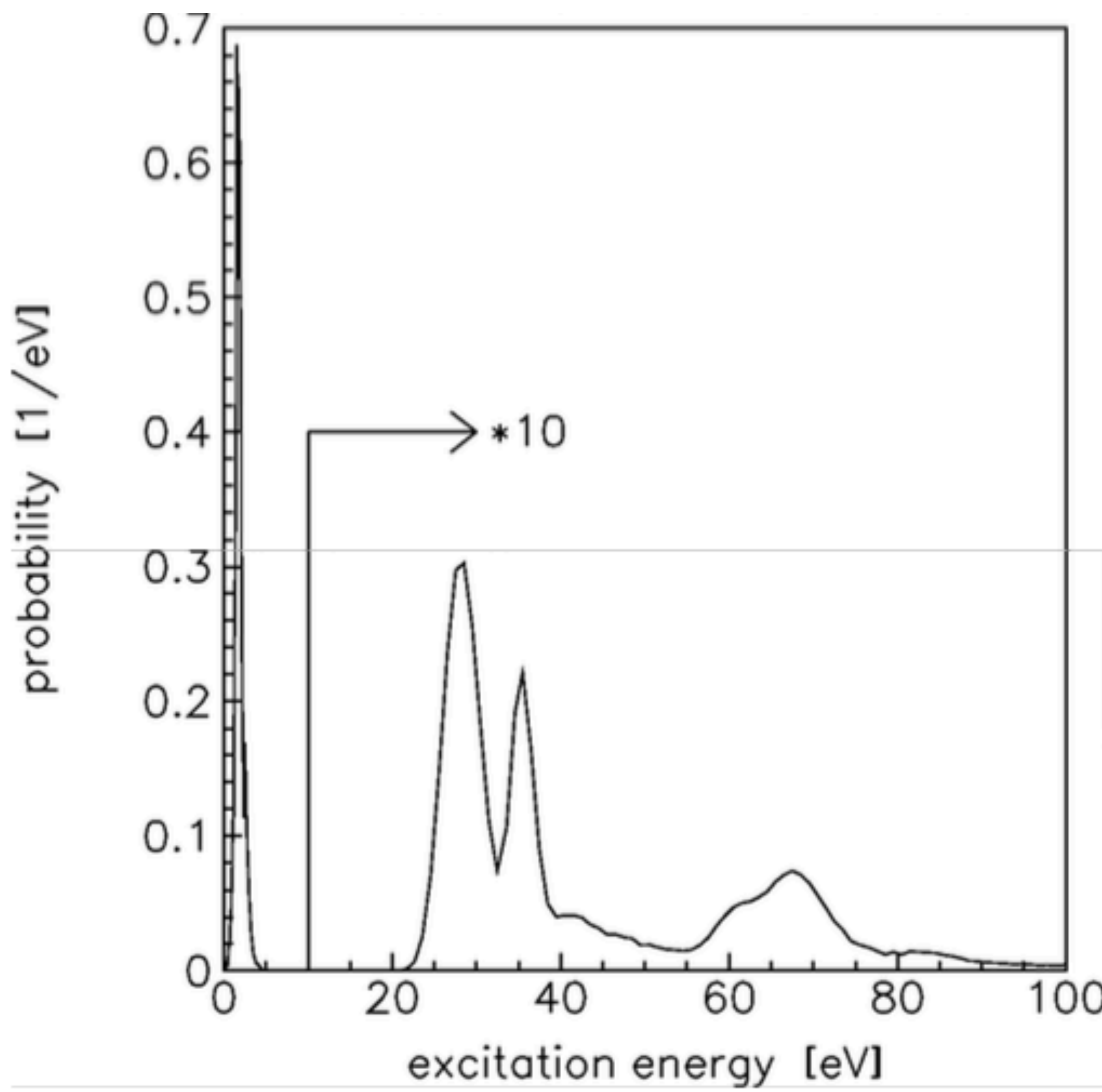


Systematics

Significant systematics when measuring decays at the eV scale.

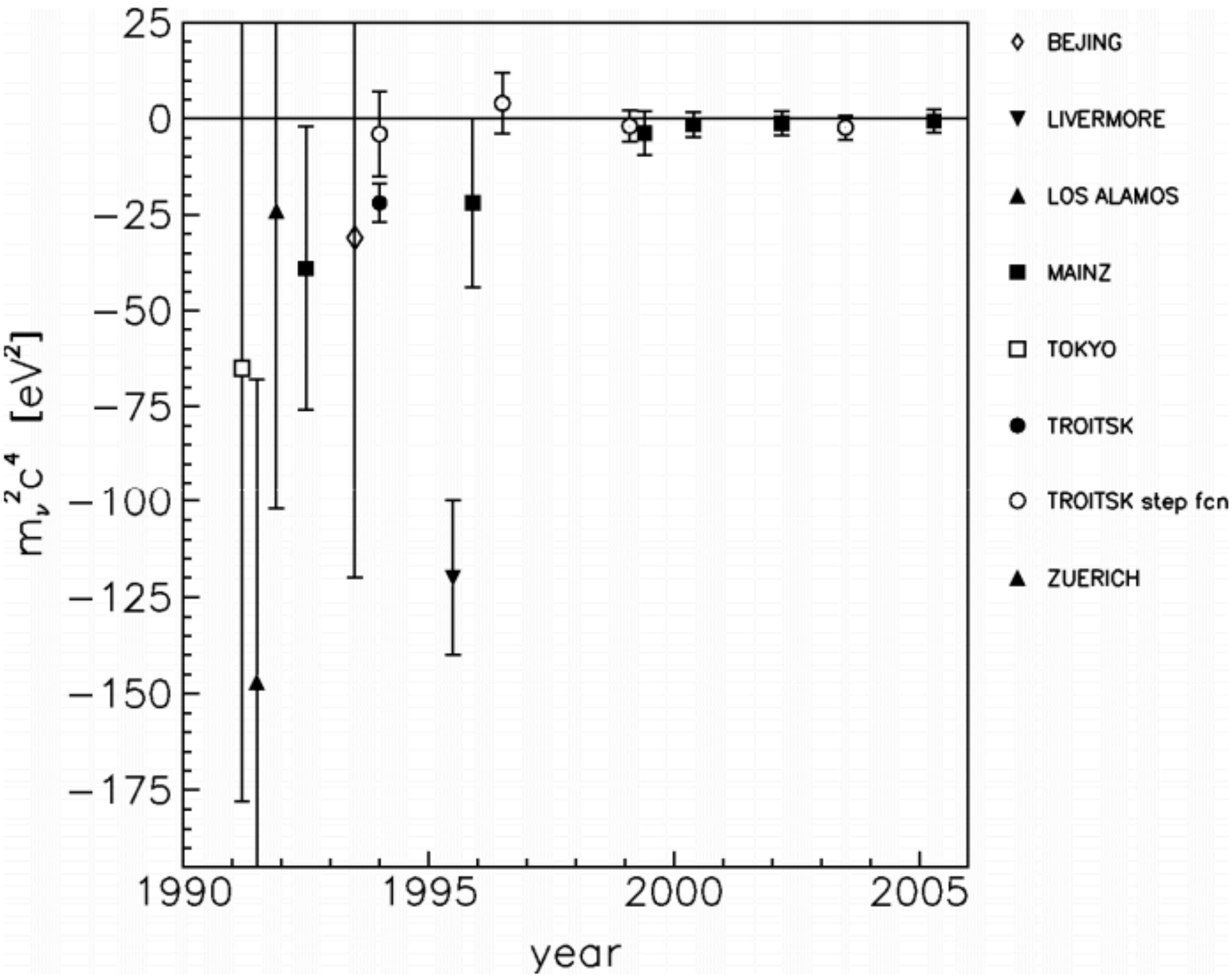
Intrinsic offsets and resolution due to molecular T_2 states.





Increasing Precision

Incremental improvements using beta decay spectrometers.



$$m^2(\nu_e) = \sum_{i=1}^{3} |U_{ei}^2|^2 \, m_i^2$$

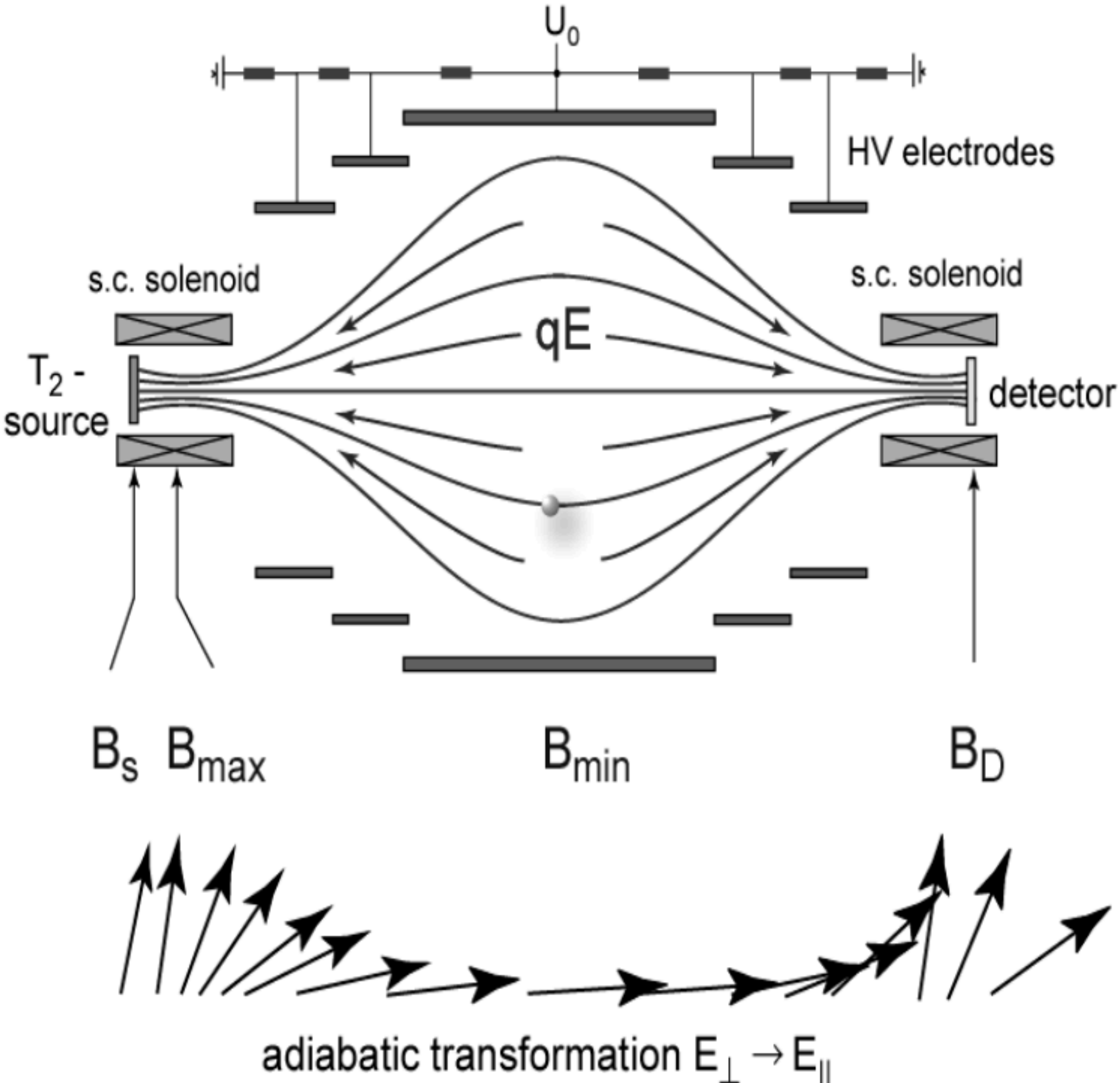
Conclusion:

$m_\nu < 2$ eV

Rept. Prog. Phys. 71, 086201 (2008)

Electrostatic Filter

Electrostatic filter allows increased energy resolution.



Too big to fail

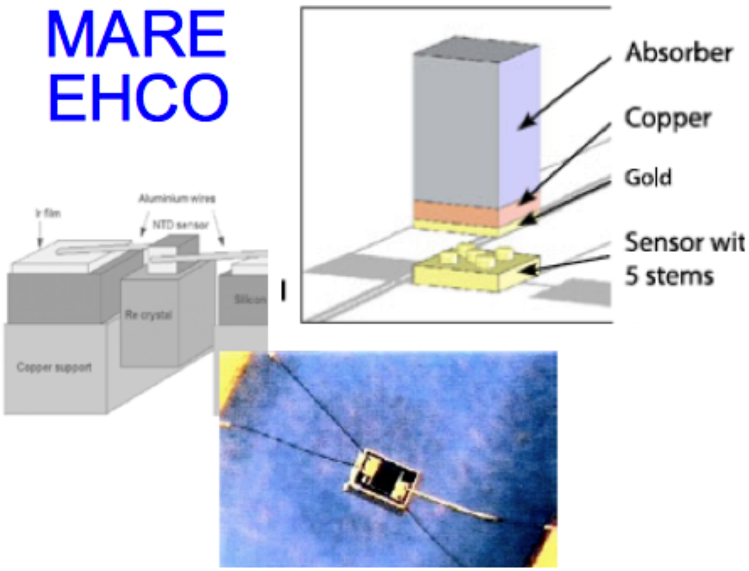
KATRIN: The world's largest electrostatic filter

Absolute Mass?

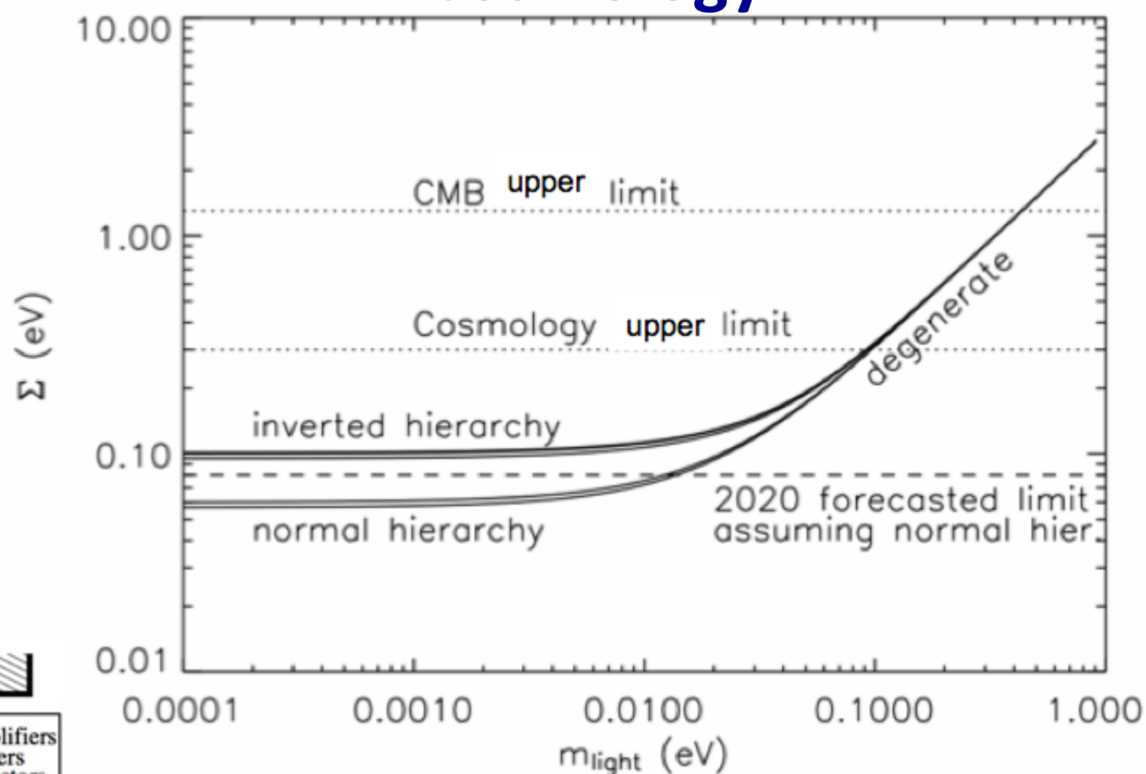
Other experimental approaches

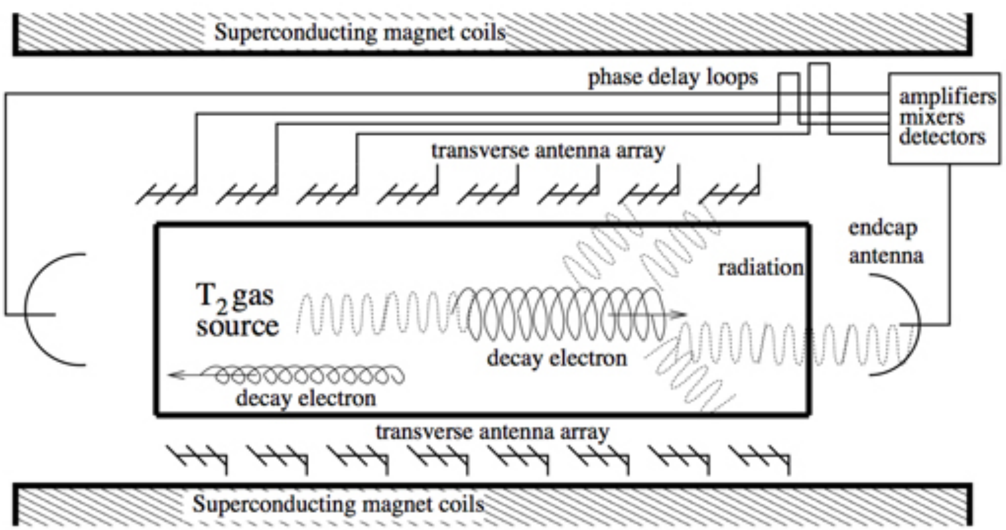
Microcalorimeters

MARE
EHCO



Cosmology





Project-8: Cyclotron Spectrometer

Even if we measure the mass…
…what kind of mass we are measuring?

Dirac vs. Majorana

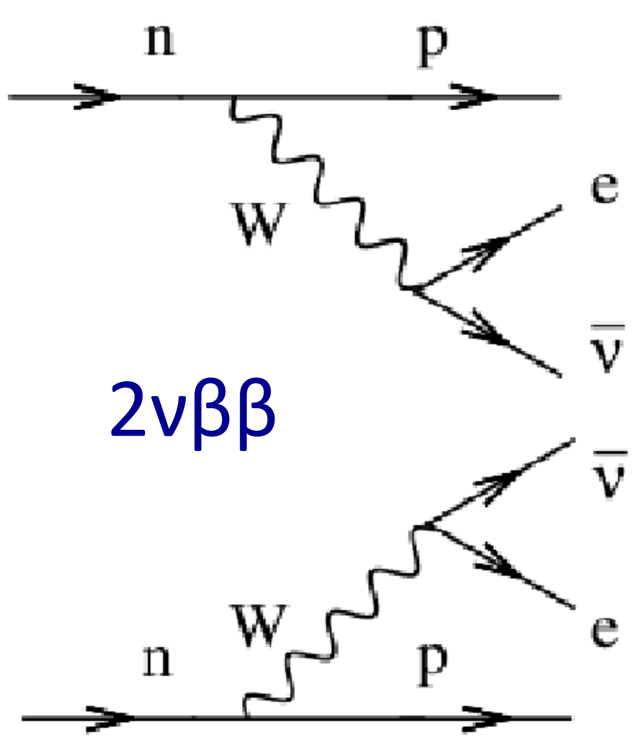
Even if we know the mass, what kind of mass is it?

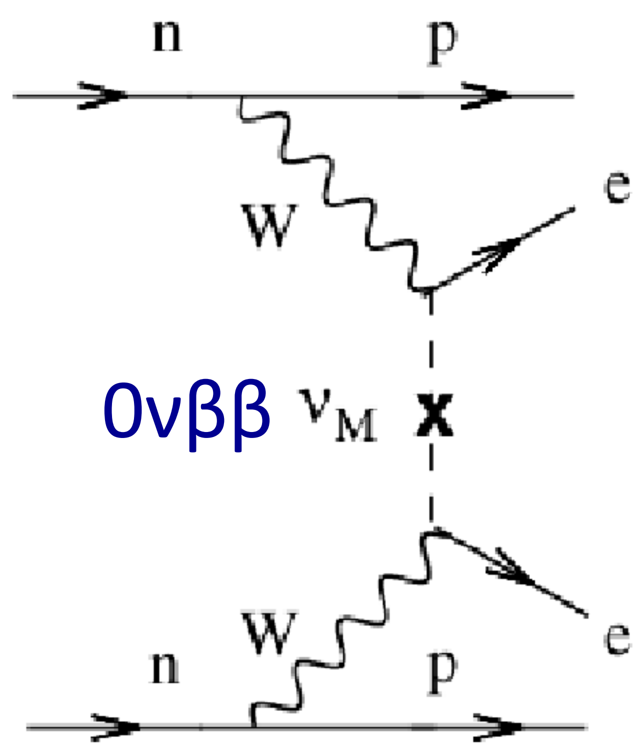
Dirac mass:

$$- m\bar{\psi}_R\psi_L - m\psi_R\bar{\psi}_L$$

Majorana mass:

$$- m_L\bar{\chi}_L\chi_L - m_R\bar{\chi}_R\chi_R$$





Observed:
$t_{1/2} \sim 10^{19}$ to 10^{21} years

Unobserved:
$t_{1/2} > 10^{24}$ years

Violates lepton number

Majorana Physics

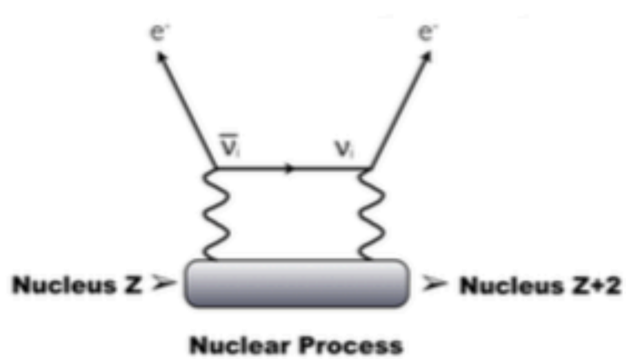
B-L conserved in Standard Model

$0\nu\beta\beta$ is the most powerful and comprehensive probe of Lepton Number Violation, sensitive to new physics over a vast range of scales, with far reaching implications

Observation of $0\nu\beta\beta$ would be direct evidence for new physics

Demonstrate that **neutrinos are Majorana fermions**

Probe **new mechanism of neutrino mass generation,** reaching up to GUT scale



Probe key **ingredient needed to generate cosmic baryon asymmetry** via leptogenesis. Sakharov conditions.

1. Baryon number violation
2. Out of thermal equilibrium
3. CP violation

Proposed experiments have discovery potential in a variety of mechanisms

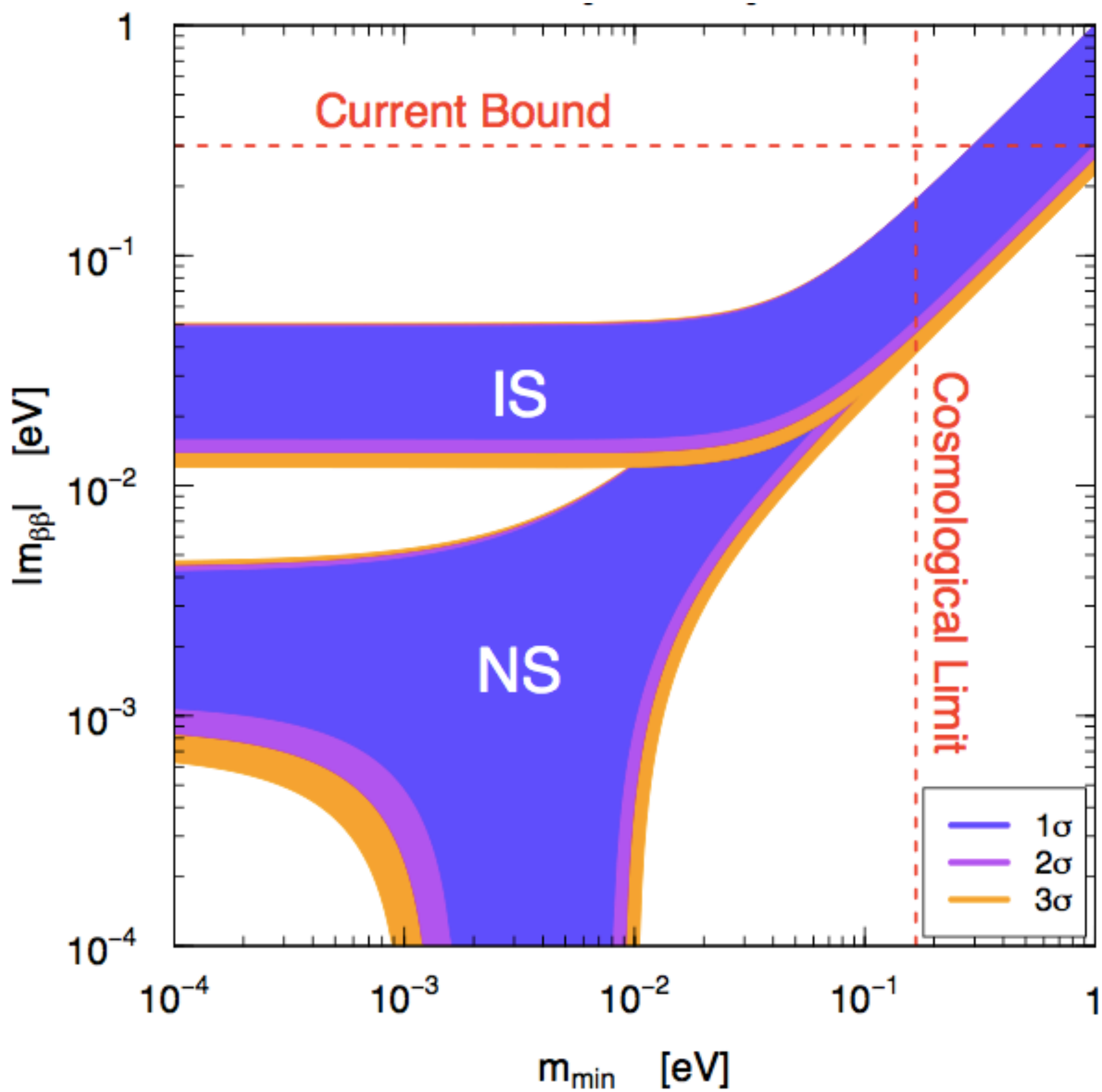
K. Heeger, CIPANP-2015

Majorana Mass

Majorana mass:

Coherent sum of masses

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$



Mod. Phys. Lett. A 27, 1230015 (2012)

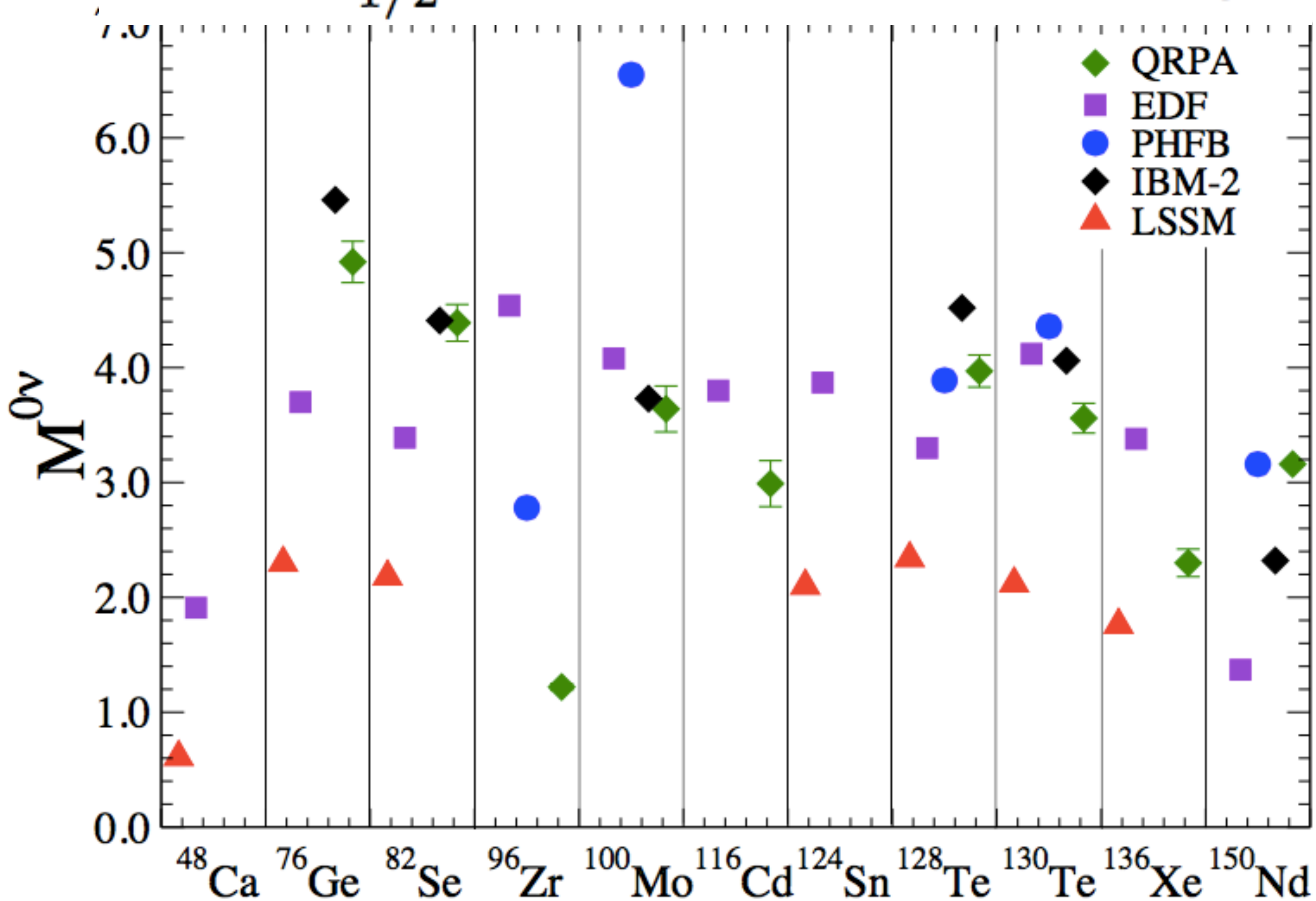
Isotopes

$\beta\beta$-decay	$G^{0\nu}$ [10^{-14} y^{-1}]	Q [keV]	nat. abund. [%]	experiments
$^{48}Ca \to {}^{48}Ti$	6.3	4273.7	0.187	CANDLES
$^{76}Ge \to {}^{76}Se$	0.63	2039.1	7.8	GERDA, Majorana
$^{82}Se \to {}^{82}Kr$	2.7	2995.5	9.2	SuperNEMO, Lucifer
$^{100}Mo \to {}^{100}Ru$	4.4	3035.0	9.6	MOON, AMoRe
$^{116}Cd \to {}^{116}Sn$	4.6	2809	7.6	Cobra
$^{130}Te \to {}^{130}Xe$	4.1	2530.3	34.5	CUORE
$^{136}Xe \to {}^{136}Ba$	4.3	2461.9	8.9	EXO, KamLAND-Zen, NEXT, XMASS
$^{150}Nd \to {}^{150}Sm$	19.2	3367.3	5.6	SNO+, DCBA/MTD

Mod. Phys. Lett. A 27, 1230015 (2012)

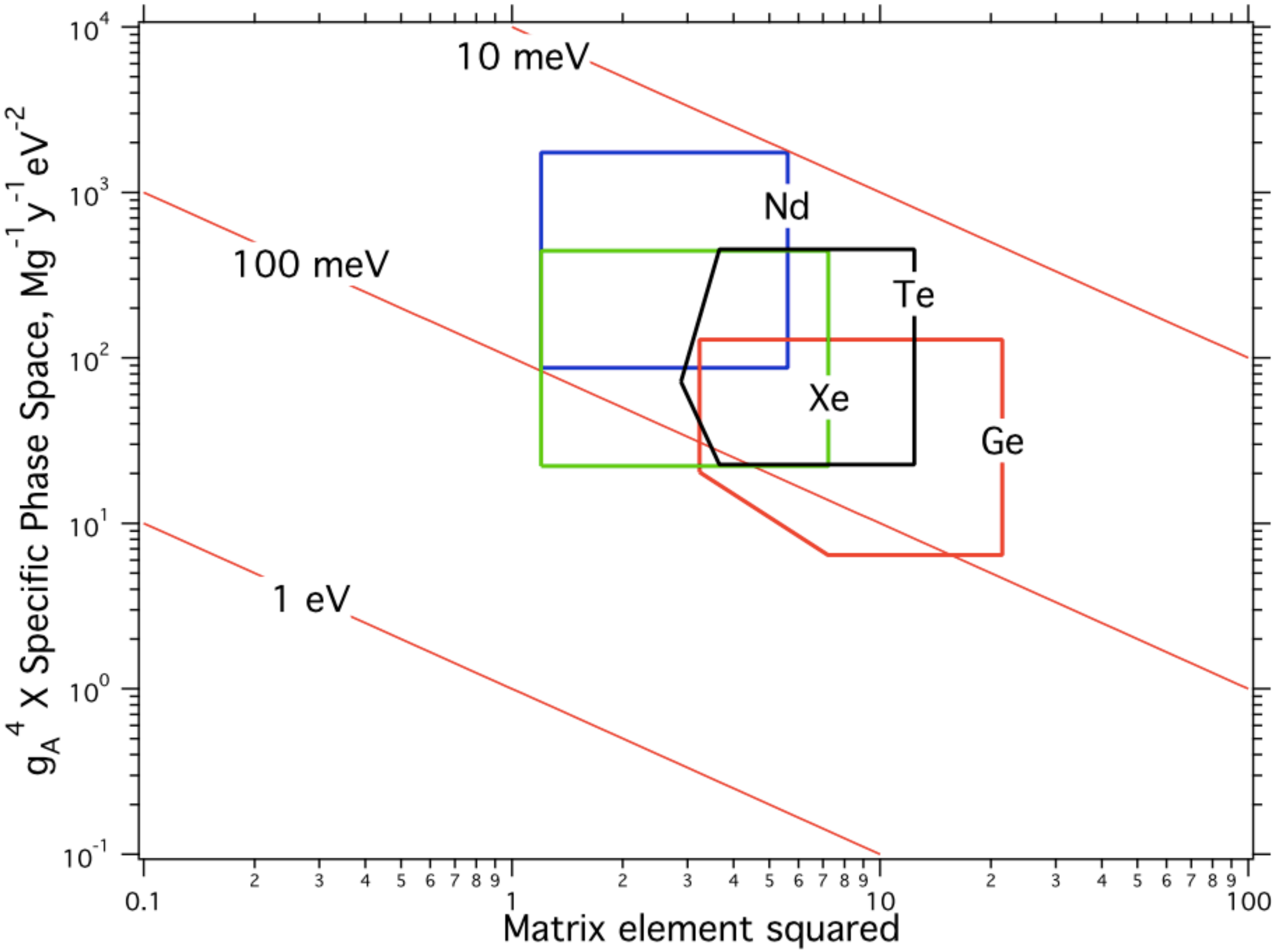
Nuclear Matrix Element

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|m_{\beta\beta}|^2}{m_e^2}$$



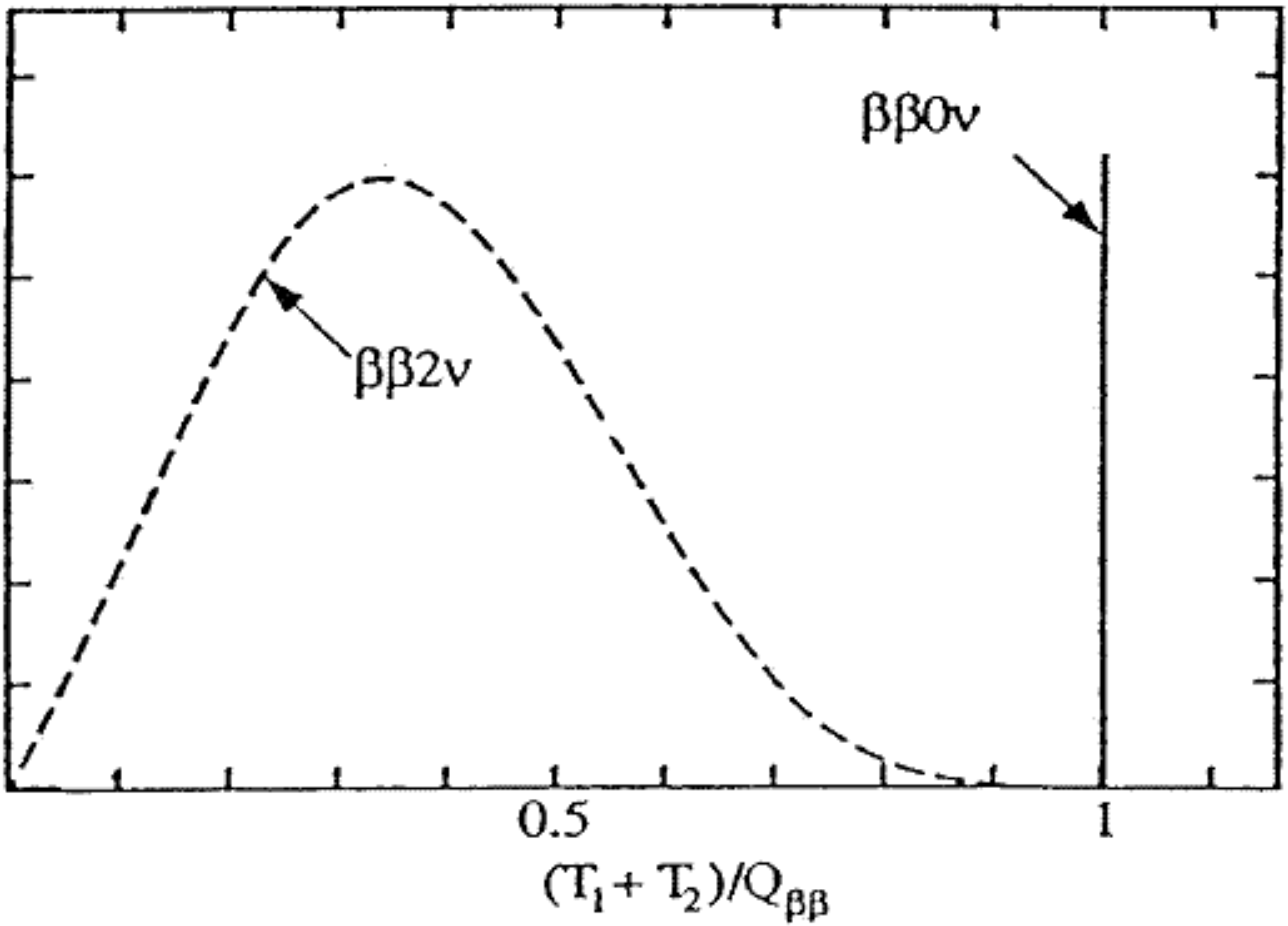
Mod. Phys. Lett. A 27, 1230015 (2012)

Expected Rates



Mod. Phys. Lett. A 28, 1350021 (2013)

Signal



Measurement Sensitivity

Maximize:

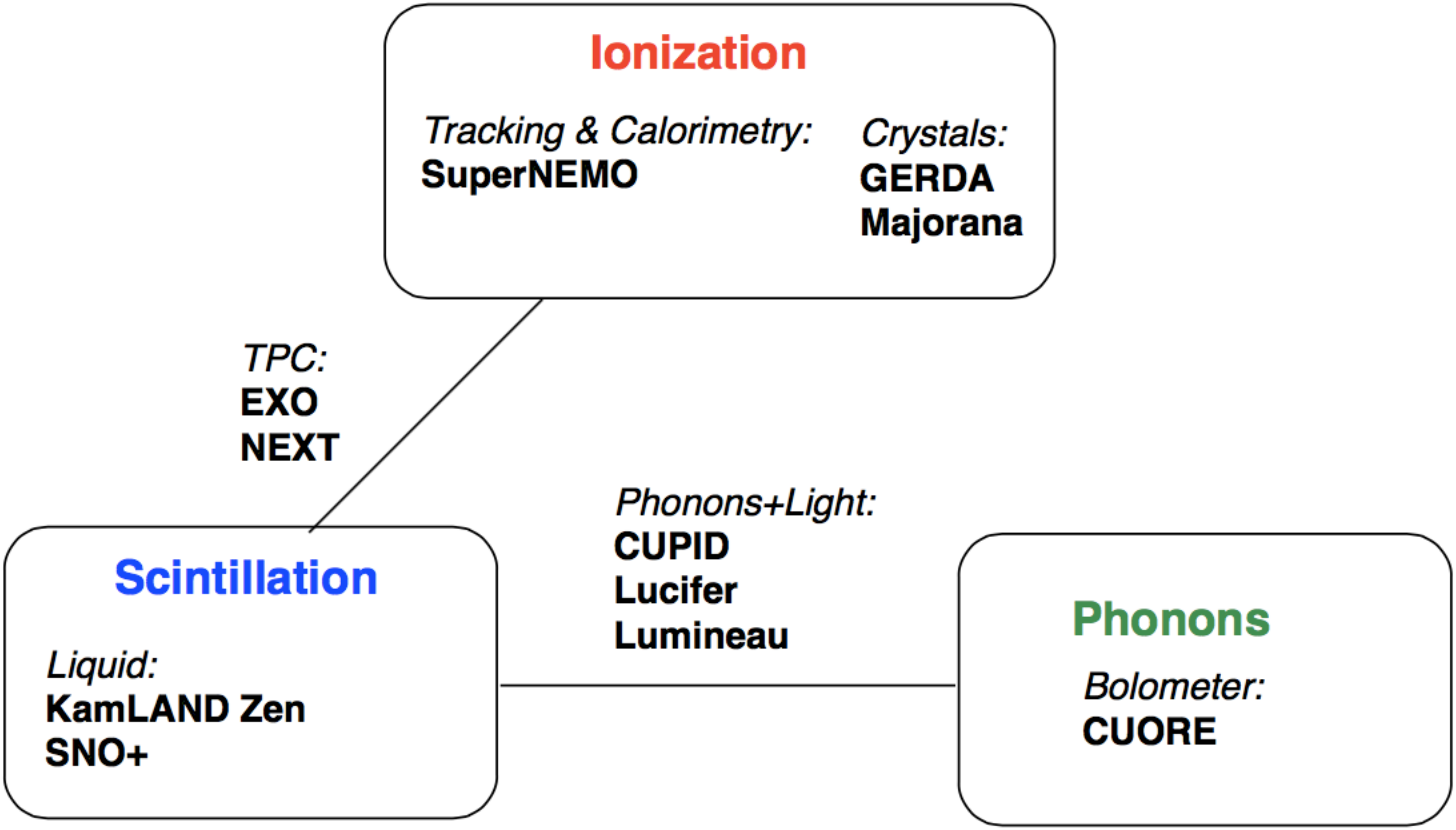
Abundance, Efficiency, Mass, Time

$$T_{1/2}^{0\nu} \text{ sensitivity} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

Minimize: Background, Energy Resolution

Techniques

A rich field of techniques for 0νββ detection.



K. Heeger, CIPANP-2015

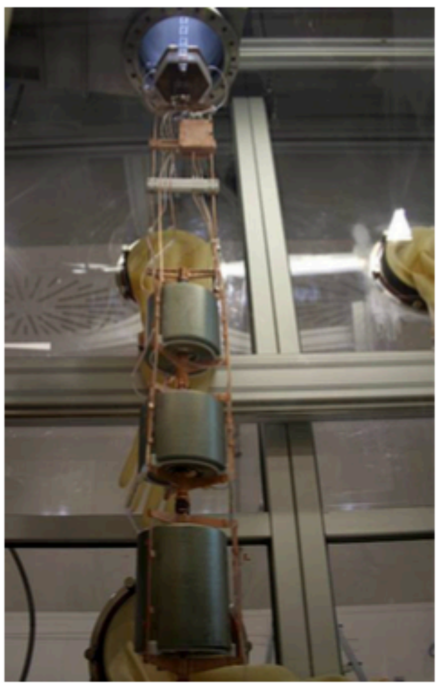
Example Experiments

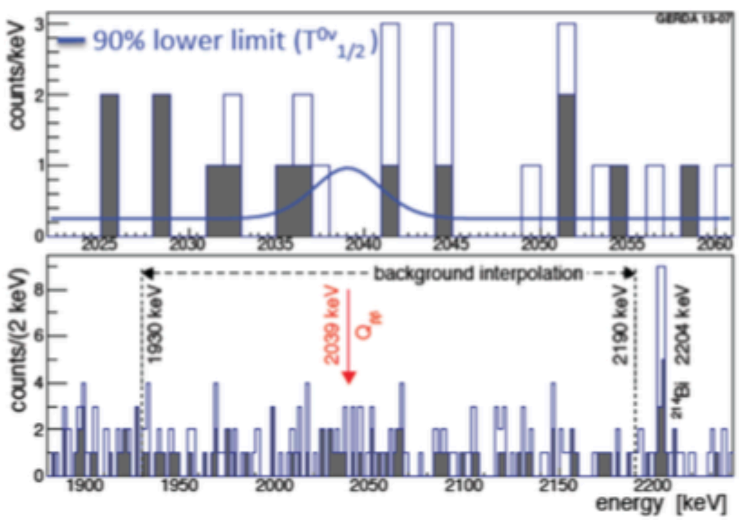
Experiment	Isotope	Isotopic Mass	Start of Operations
CUORE0 CUORE	130	~11 Kg ~210 Kg	2013 (Running) 2015
EXO-200	136	~200 Kg	2011
GERDA I/II	76	~34 Kg	2011/15
KamLAND-Zen	136	~300 Kg	2012 (Running)
MAJORANA	76	~30 Kg	2015
NEXT	136	~100 Kg	2016
SNO+	130	~800 Kg	2016 ?
SuperNEMO	82	~7 Kg	2016

K. Heeger, CIPANP-2015

GERDA, Phase I (^{76}Ge)

- 87% enriched ^{76}Ge detectors in LAr
- $Q_{\beta\beta}$ = 2039 keV
- 14.6 kg of 86% enriched Ge detectors from H-M, IGEX (4.8 keV FWHM @ $Q_{\beta\beta}$
- 3 kg of 87% enriched BEGe enriched detectors (3.2 keV FWHM @ $Q_{\beta\beta}$)
- Single-site, multi-site pulse shape discrimination





GERDA Collaboration, PRL 111 (2013) 122503
Eur. Phys. J. C (2014) 74:2764

- 21.6 kg-year exposure
- Frequentist
  $T_{1/2} > 2.1 \times 10^{25}$ y (90% CL)
- Bayesian
  $T_{1/2} > 1.9 \times 10^{25}$ y (90% CL)

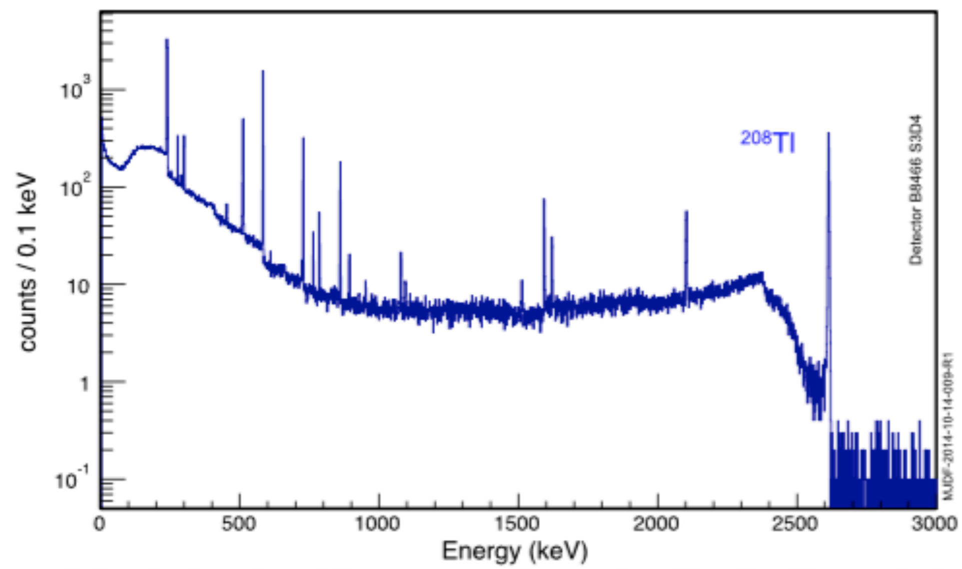
→G. Benato

CIPANP-2015

Majorana Demonstrator (^{76}Ge)

- MJD Prototype module installed and taking data in shield since July 2014. Simulations and analysis of data are underway .

One detector spectrum within a string mounted in the prototype cryostat and inside shield. FWHM 3.2 keV at 2.6 MeV



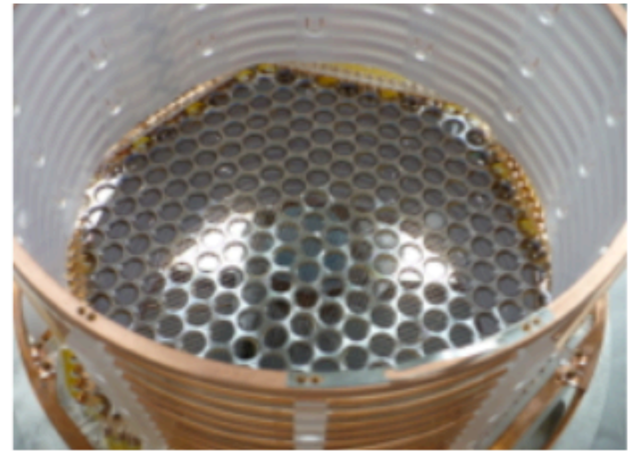
- Module 1 with more than half of all enriched detectors will go in-shield in a few days and start operation soon.
- Assembly of strings for Module 2 is underway. Anticipate completion by end of 2015.
- **Expecting data from the completed Demonstrator in 2016.**

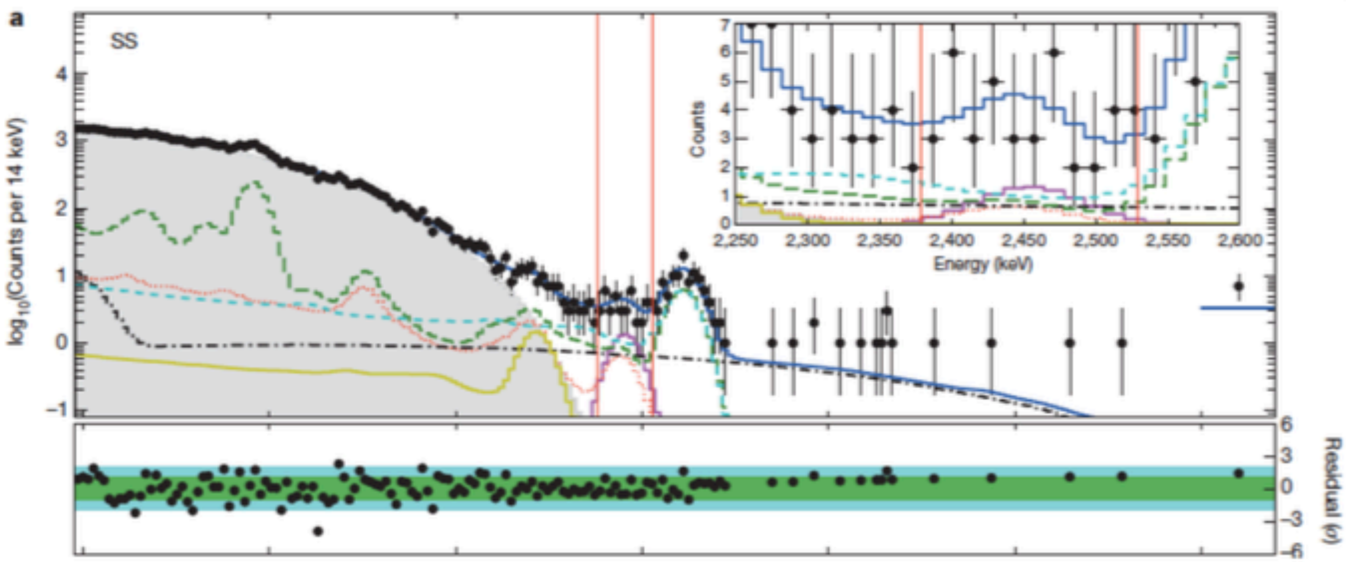
→Wenqin Xu
CIPANP-2015

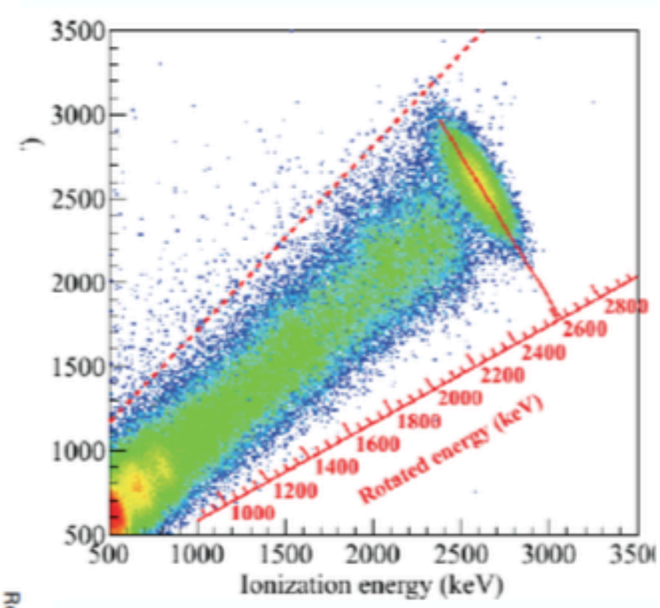
EXO-200 (^{136}Xe)

- Enriched Liquid Xe in TPC
  - $Q_{\beta\beta}$=2457.8 keV
  - 200 kg of 80.6 % enriched ^{136}Xe
  - 75.6 kg fiducial mass,
  - 100 kg years exposure
  - Combine Scintillation-Ionization signal for improved resolution (88 keV FWHM @ $Q_{\beta\beta}$)
  - Single site - Multisite discrimination

$T_{1/2} > 1.1 \times 10^{25}$ y (90% CL)







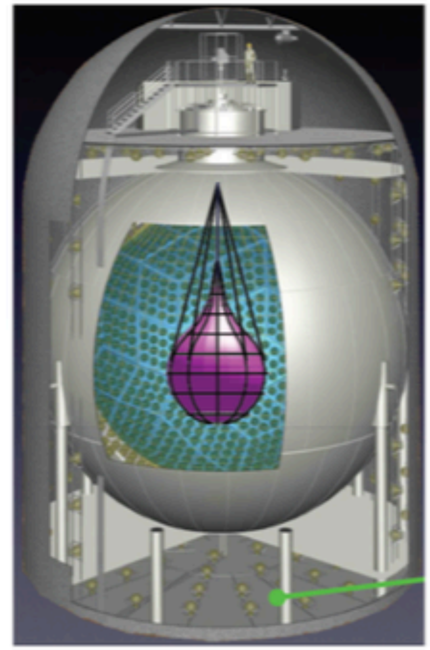
EXO-200 Collaboration, Nature **510** 229 (2014)

→M. Tarka
CIPANP-2015

KamLAND-Zen

- ^{enr}Xe in liquid scintillator, balloon of R=1.5 m
- $Q_{\beta\beta}$=2457.8 keV
- Phase 1
  - 179 kg (2.44% by Xe wt.) 91.7% enriched ^{136}Xe
  - R=1.35 m fiducial cut
  - 213.4 days, with 89.5 kg years exposure
  - 400 keV FWHM @ $Q_{\beta\beta}$
  - evidence for ^{110m}Ag contamination

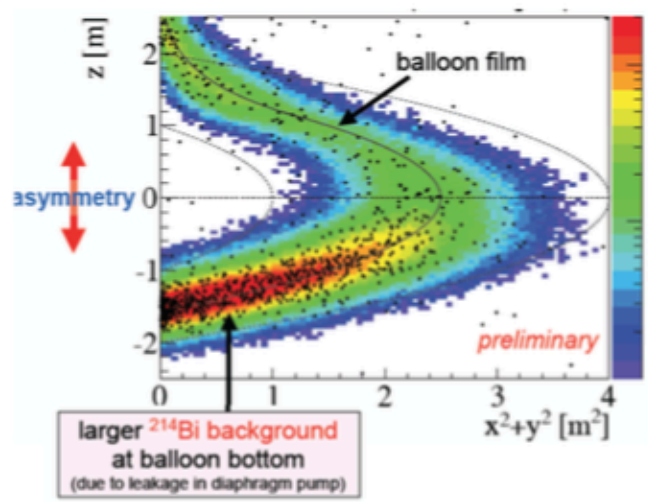
    $T_{1/2} > 1.9 \times 10^{25}$ y (90% CL)



- Phase 2
  - 383 kg (2.96% by Xe wt.)
  - R=1 m fiducial cut
  - 114.8 days, with 27.6 kg years exposure
  - ^{110m}Ag contamination reduced by x10

    $T_{1/2} > 1.3 \times 10^{25}$ y (90% CL)

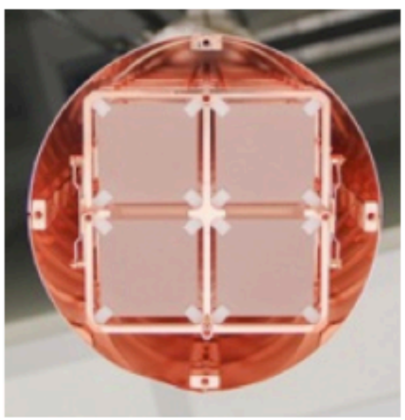
Combined (1&2) $T_{1/2} > 2.6 \times 10^{25}$ y (90% CL)

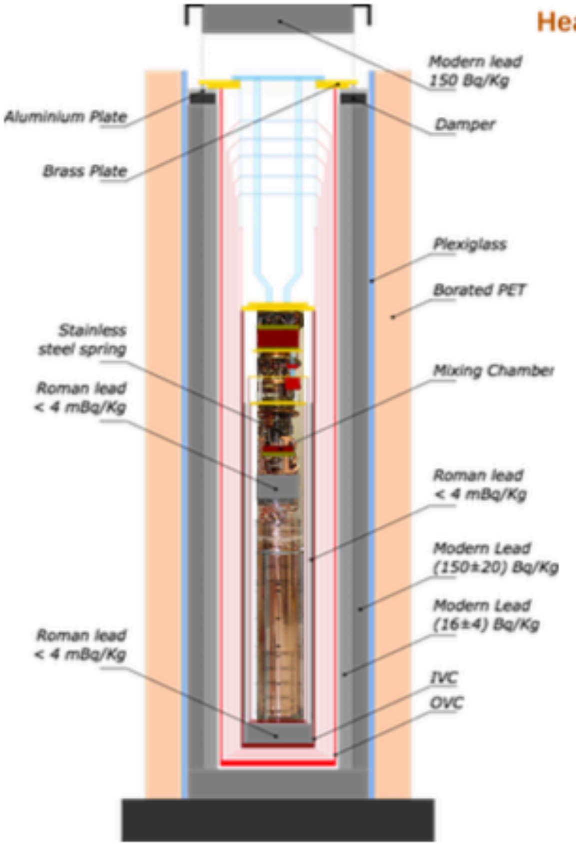


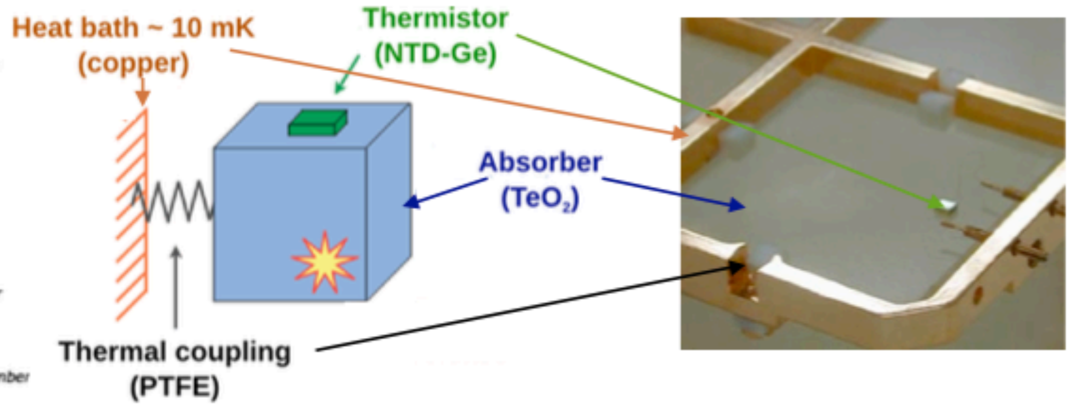
KamLAND ZEN Collaboration, Shimizu, Neutrino 2014

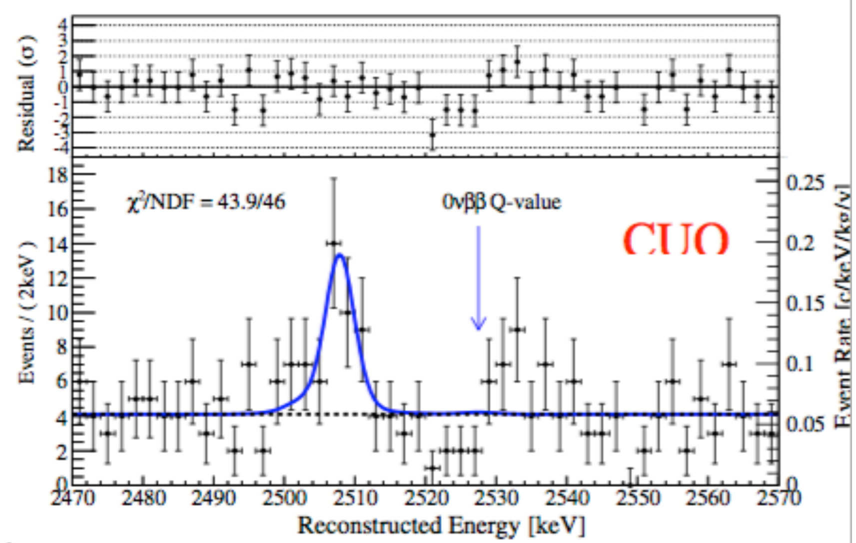
→B. Berger
CIPANP-2015

CUORE (^{130}Te)









- 11kg ^{130}Te (34% nat.) bolometer (10 m
- $Q_{\beta\beta}$=2527.5 keV
- Array of 52 5x5x5 cm^3 TeO_2 crystals
- 9.8 kg - years exposure
- FWHM of 5.1 keV

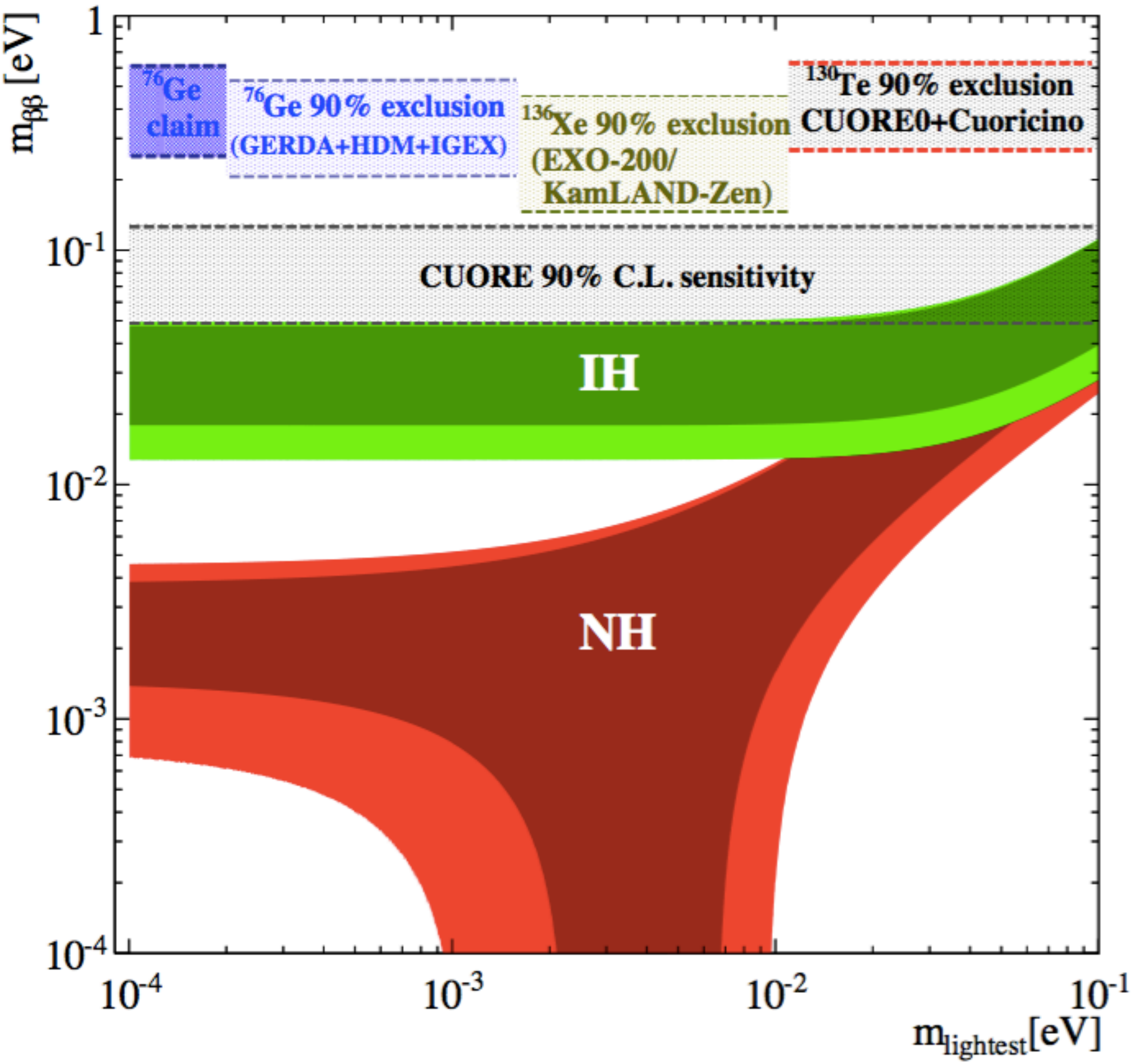
$T_{1/2}$ > 2.7 x 10^{24} y (90% CL) CUORE-0

$T_{1/2}$ > 4.0 x 10^{24} y (90% CL) CUORE-0 & Cuoricino

arXiv: 1504.2454

→T. O'Donnell
CIPANP-2015

Current Limits



K. Heeger, CIPANP-2015

Future Direction

Goals/Requirements

- Expect signals of **1 count/tonne-year for half-lives of 10^{27} years,** or **$\langle m_{\beta\beta}\rangle \sim$ 15 meV.**
  - For discovery aim for S:B of better than 1:1 in region of interest
  - Region of interest can be single dimension (e.g. energy) or multi-dimensional (e.g. energy+fiducial)

Next Steps

International collaborations are building on current efforts using multiple isotopes:

- **^{76}Ge**: large Ge experiment, HPGE crystals, ton-scale
- **^{82}Se:** SuperNEMO, tracking and calorimeter, 100kg scale
- **^{136}Xe:**
  - nEXO, liquid TPC, 5 tonnes
  - NEXT/BEXT, high pressure gas TPC, tonne-scale
  - KamLAND-Zen, scintillator
- **^{130}Te:**
  - CUPID, bolometers+scintillation/Cherenkov light
  - SNO+ phase II, scintillator
- other efforts worldwide
- staged approach possible, some experiments pursue isotopic enrichment

K. Heeger, CIPANP-2015

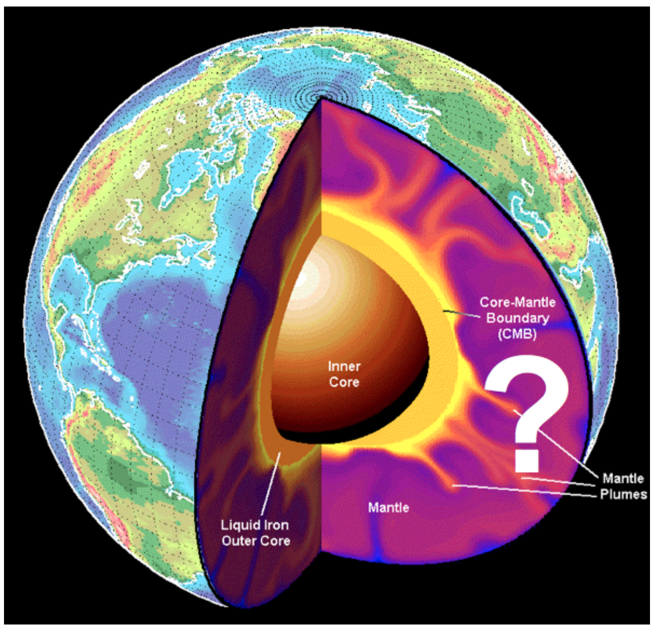
Neutrinos as Messengers

Geoneutrinos

Question: what fraction of Earth's heat is generated from radioactive decays?

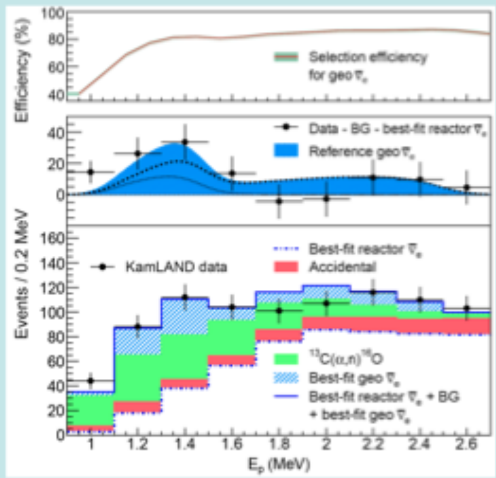
KamLAND and Borexino have made initial measurements. SNO+ expected to also measure.

^{40}K, ^{238}U, ^{232}Th



KamLAND

Mar-02 to Nov-09 : 3.49±0.07 TNU^{-1}

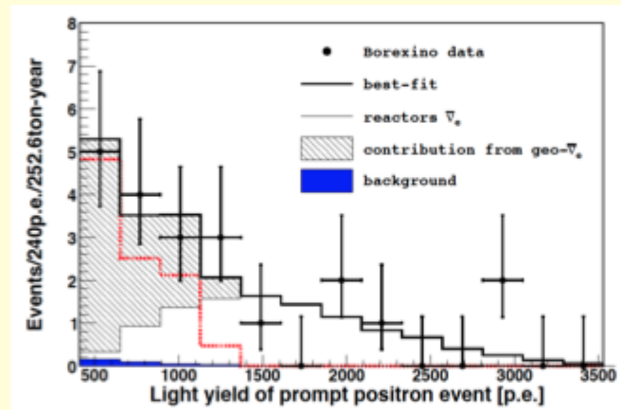


Total events- 841
Background- 730±32
Geo-nu- 111±43

Gando et al., 2011
Nature Geoscience **4**, 647

Borexino

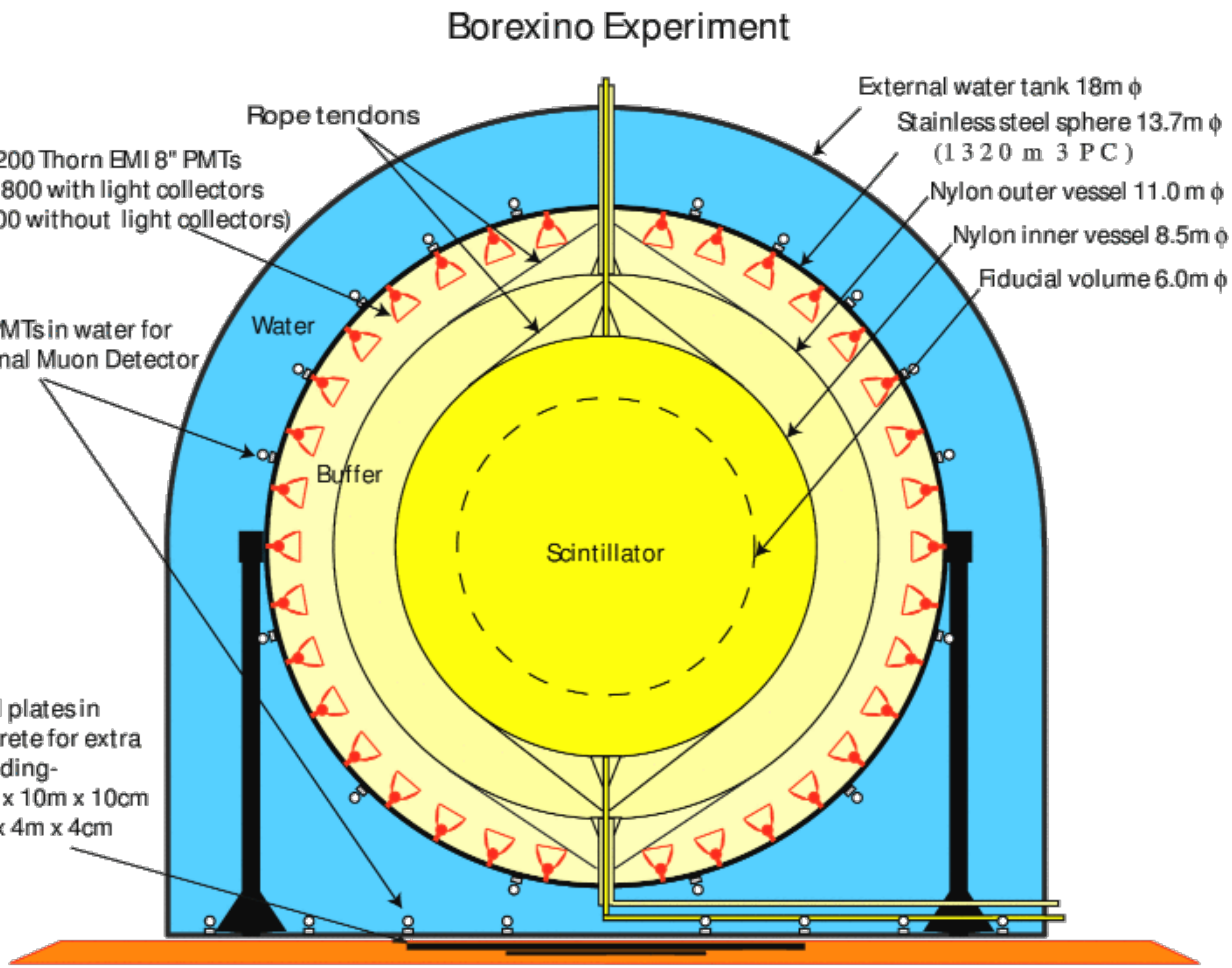
Dec-07 to Dec-09 : 0.152 TNU^{-1}



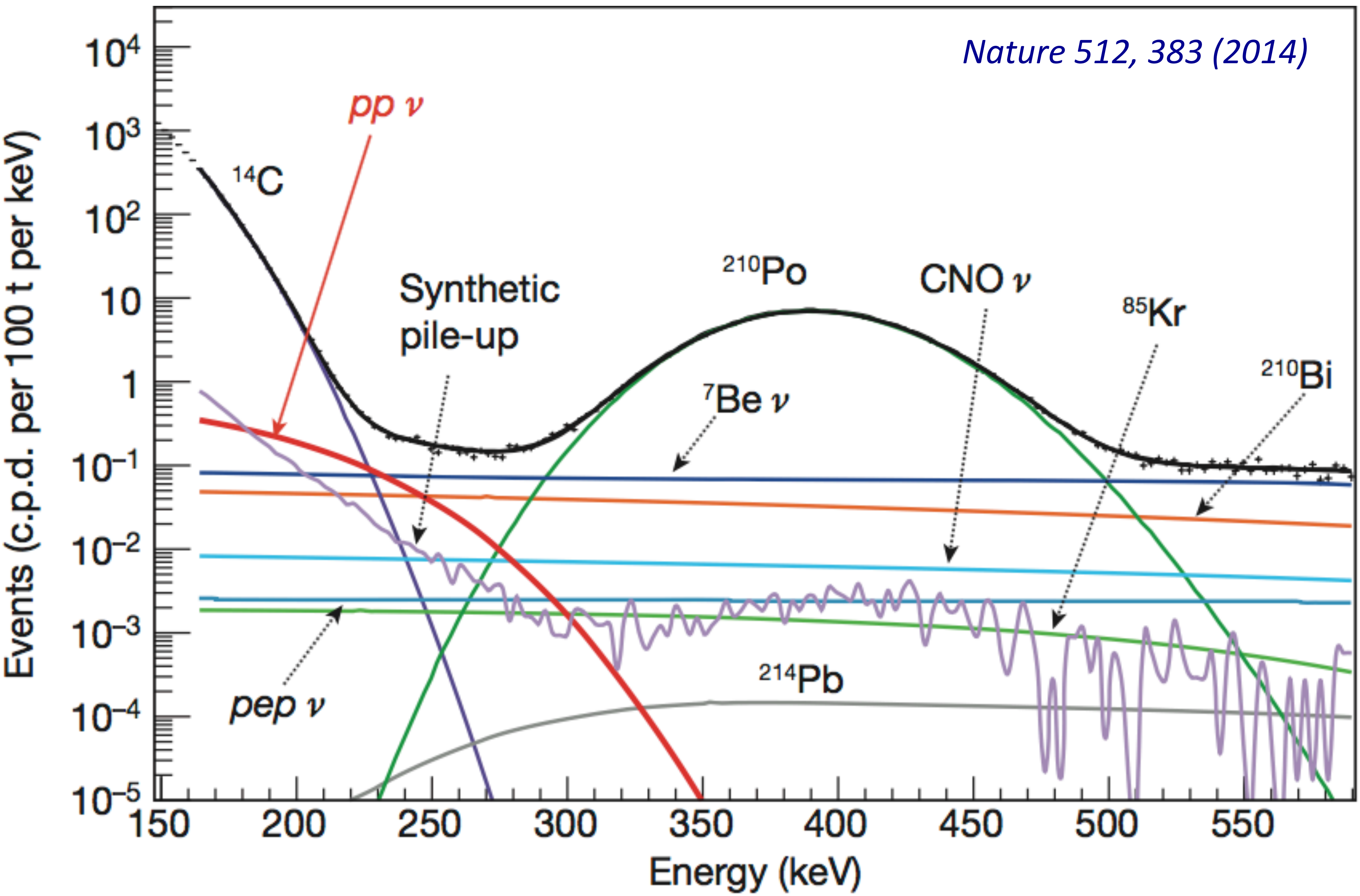
Total events- 15
Background- 5.3±0.3
Geo-nu- 9.7±3.9

Bellini et al., 2010
Phys. Lett. B **687**, 299

Borexino Experiment



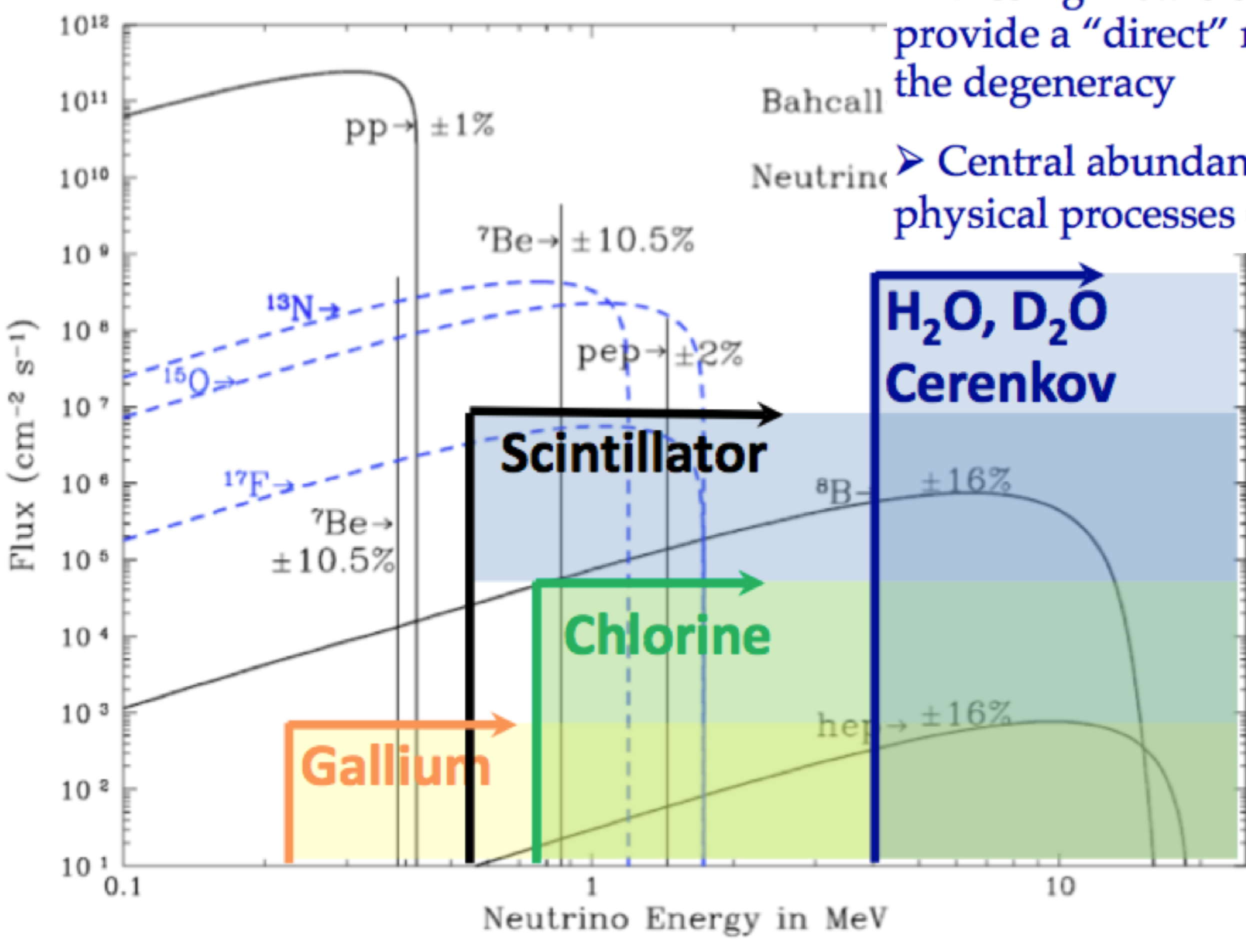
Borexino Results



Solar Physics

Request for experimental data from A. Serenelli:

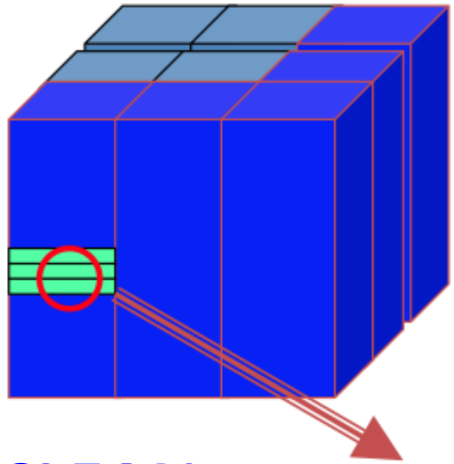
- Best SSM (high-Z) and best solar atmosphere models (low-Z) lead to contradicting results: solar abundance problem
- Solar abundance problem: missing metals, missing opacity, missing (relevant) physics?
- Current data on solar fluxes do not discriminate between abundances.
- Missing metals or missing opacity? CNO neutrinos can provide a “direct” measurement of C+N abundance and break the degeneracy
- Central abundance of C+N will help constrain solar (stellar) physical processes (gravitational settling, mixing)



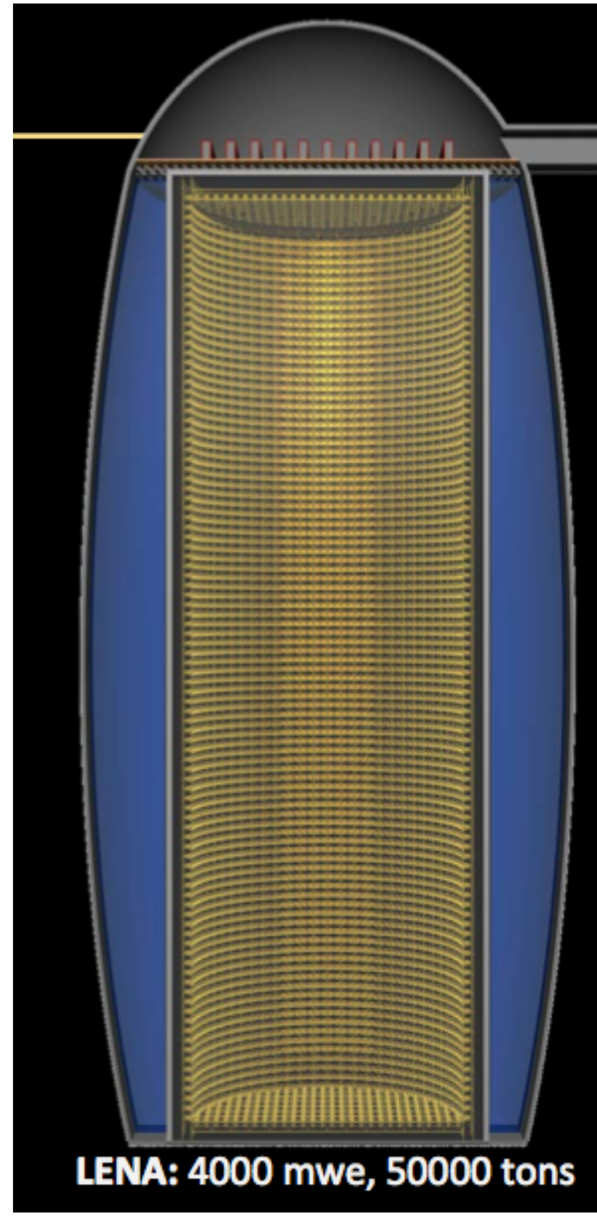
Borexino and SNO+ will provide some data, but CNO neutrinos difficult to reach.

Solar Physics

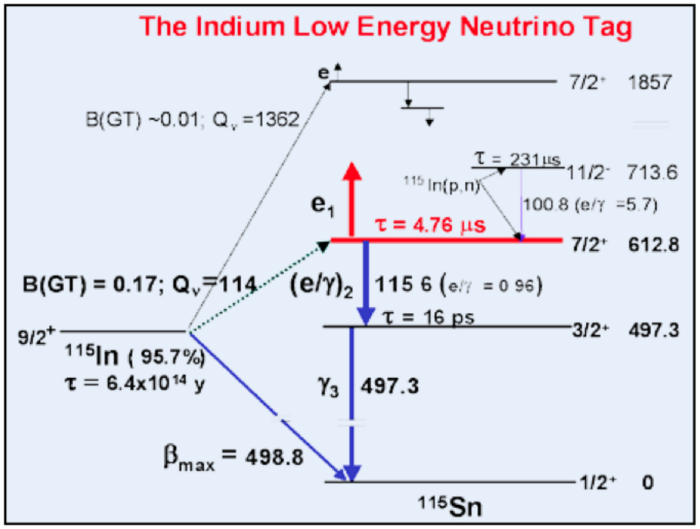
MOON

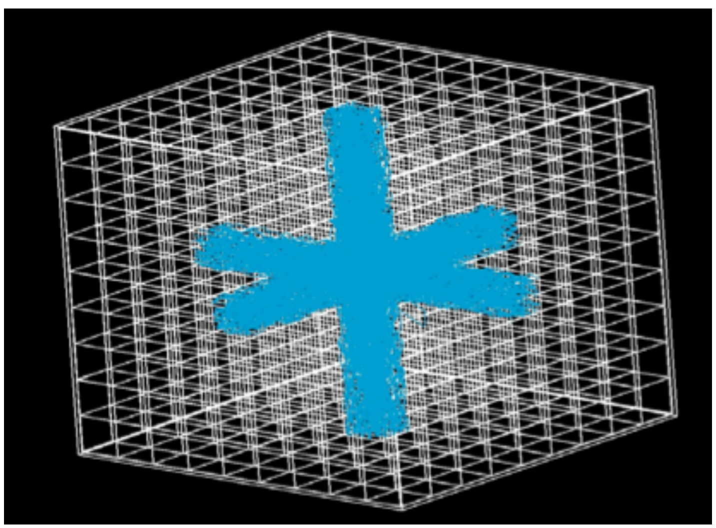


LENA/THEIA

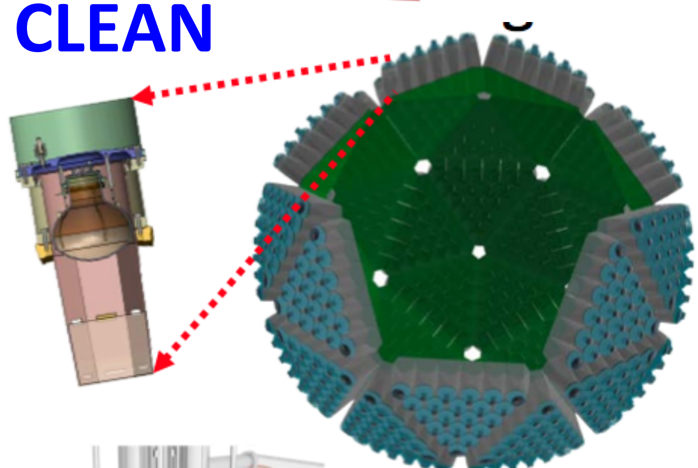


LENS





CLEAN



XMASS

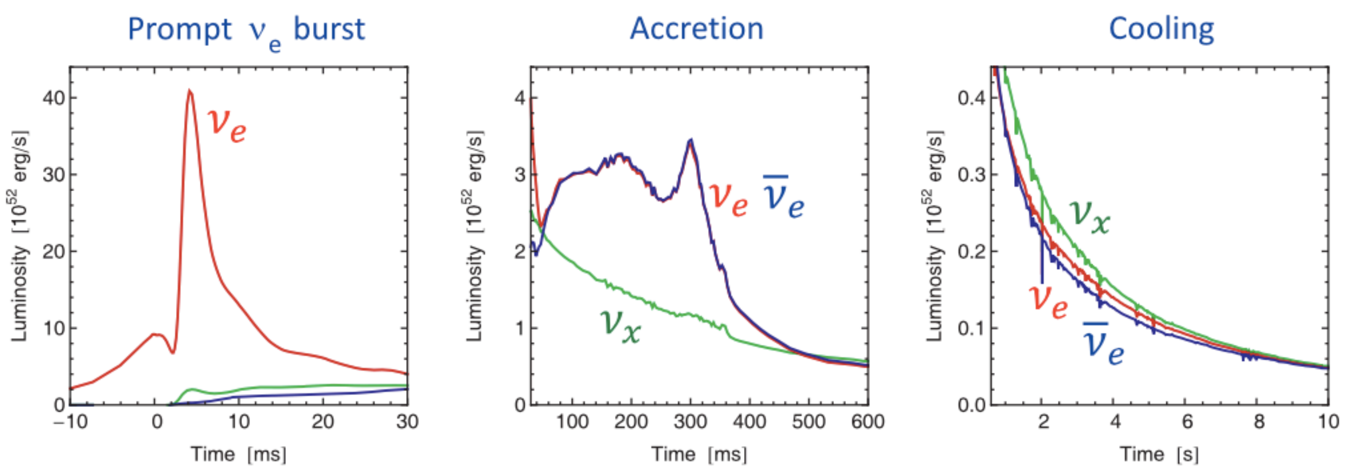
Supernova Neutrinos

Provide unparalleled data on supernova and neutrinos

99% of supernova energy (10^{53} ergs) emitted in neutrinos.

Neutrinos precede light signal by ~hours.

'Neutrinosphere':
 Neutrino-neutrino interactions relevant.
 Very sensitive probe of neutrino properties.

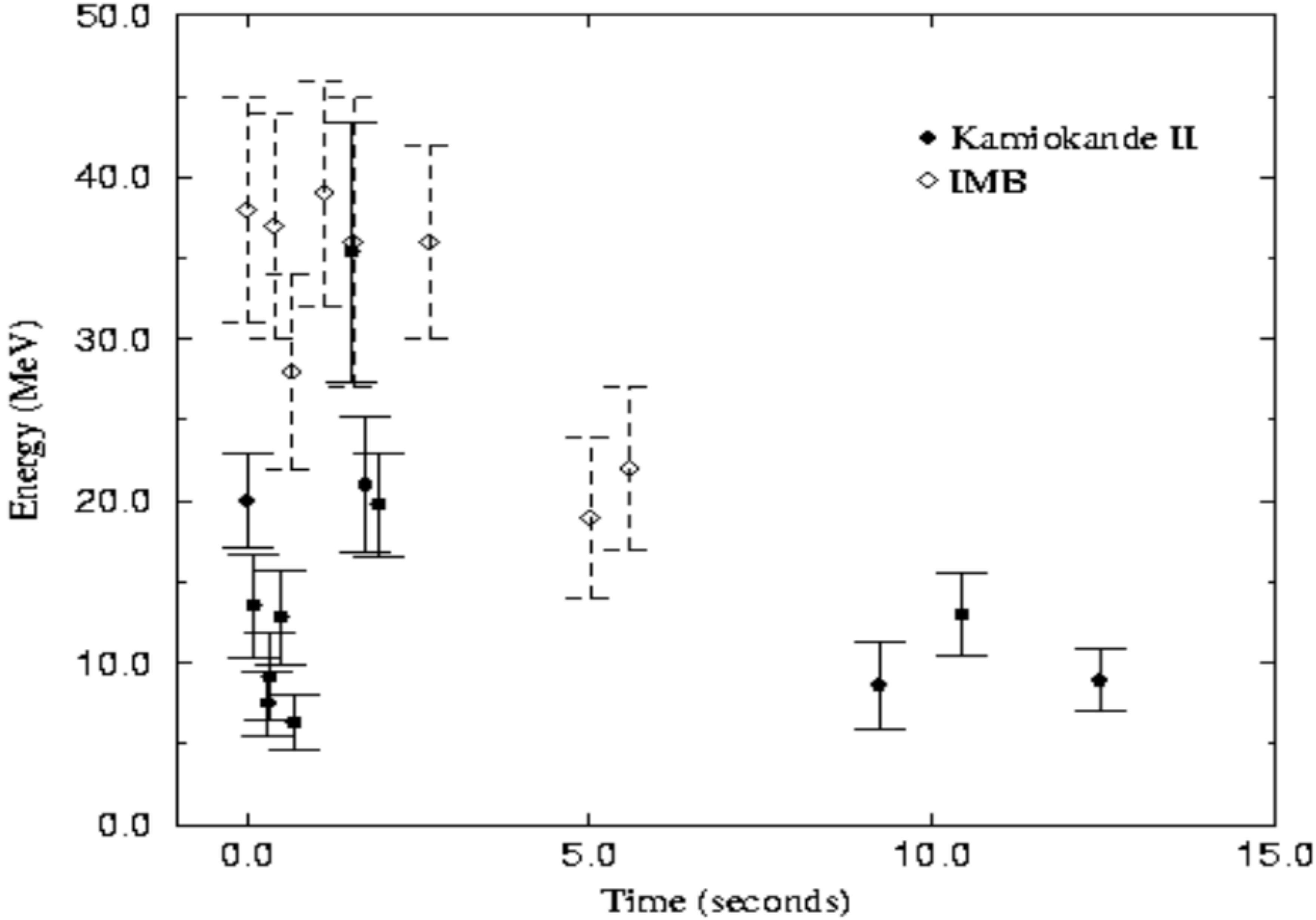


A supernova in our galaxy:
~300 interactions / kton
 → *When?*

Diffuse signal from all past SN:
~0.1 interaction / (kton yr)

Supernova Neutrinos

SN1987A in the Large Magellanic Cloud



Supernova ν Detectors

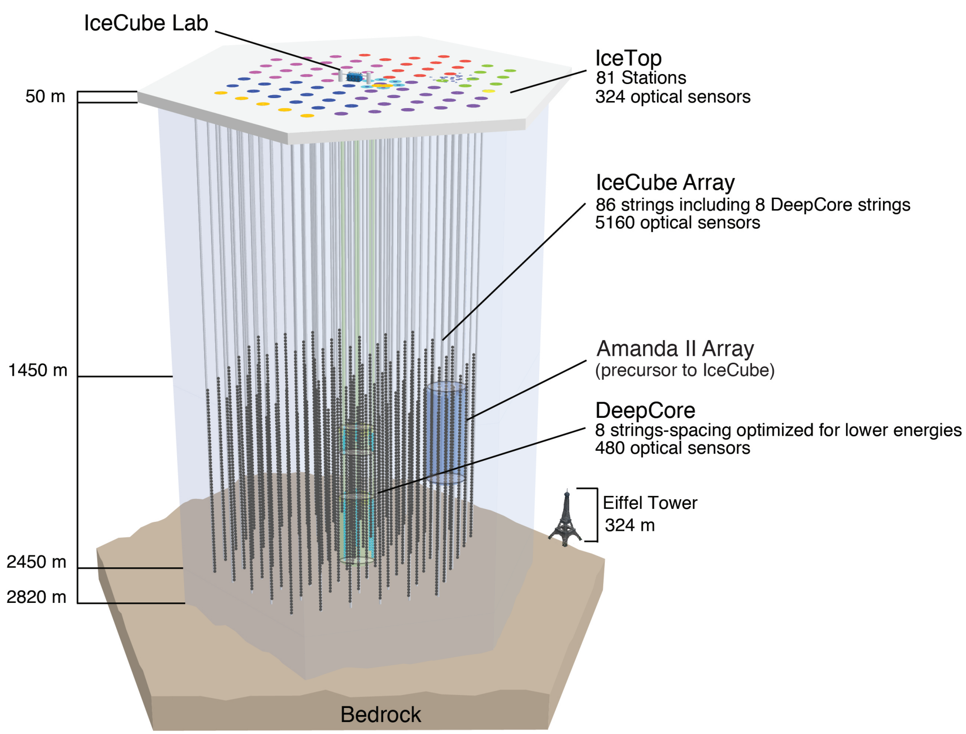
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BooNE	Scintillator	USA	0.7	200	(Running)
HALO	Lead	Canada	0.079	20	Running
Icarus	Liquid argon	Italy	0.6	(60)	(Running)
NOνA	Scintillator	USA	15	3000	Turning on
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction
LBNE LAr	Liquid argon	USA	34	3000	Proposed
Hyper-K	Water	Japan	540	110,000	Proposed
JUNO	Scintillator	China	20	6000	Proposed
RENO-50	Scintillator	South Korea	18	5400	
LENA	Scintillator	Europe	50	15,000	Proposed

K. Scholberg

Ultra-High Energy Neutrinos

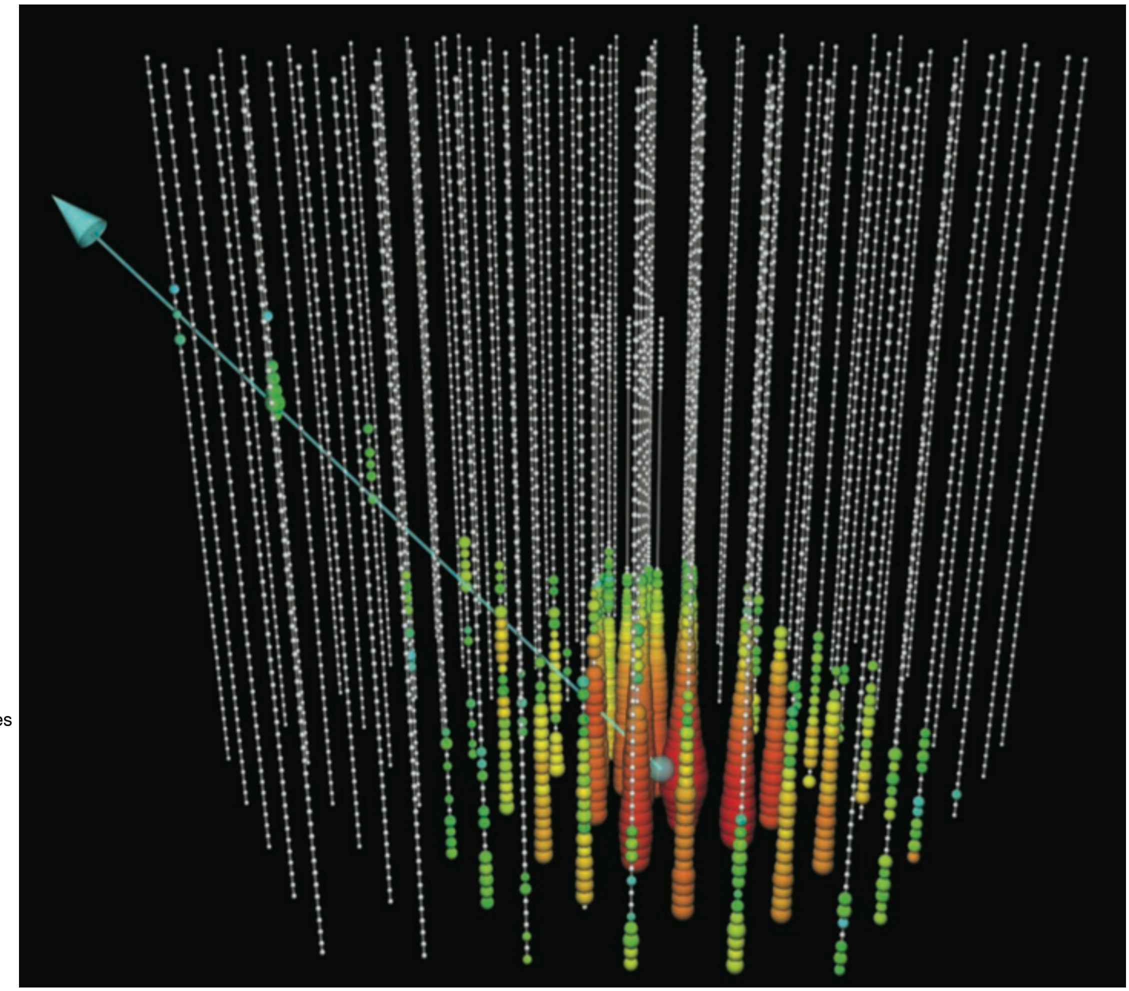
IceCUBE Experiment:

Instrument 1 km^3 of Antarctic ice to detect Cherenkov light using 5160 photomultipliers



Detected 28 neutrinos above 30 TeV

Example 250 TeV neutrino interaction

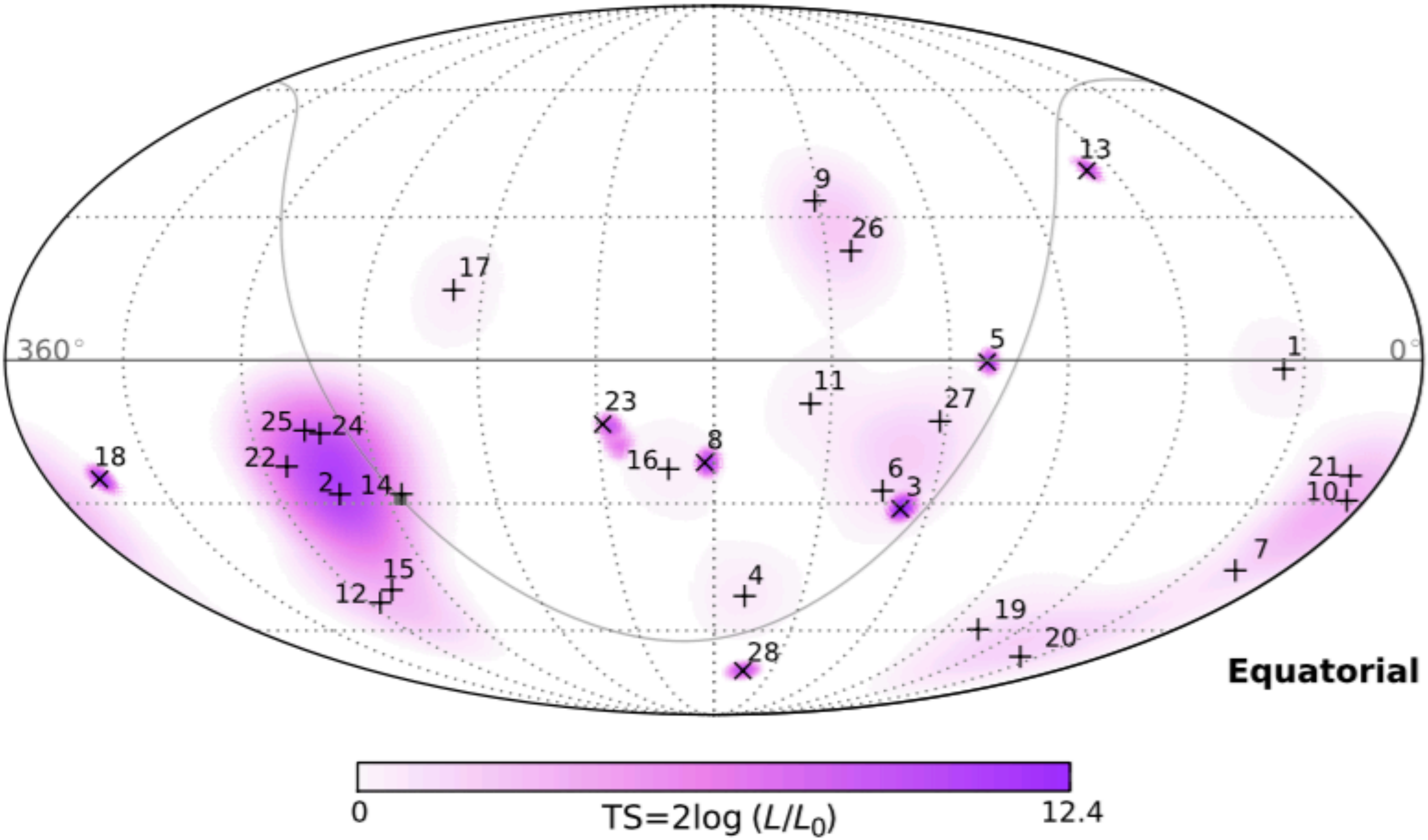


Inconsistent with atmospheric neutrinos

Science 342, 1242856 (2013)

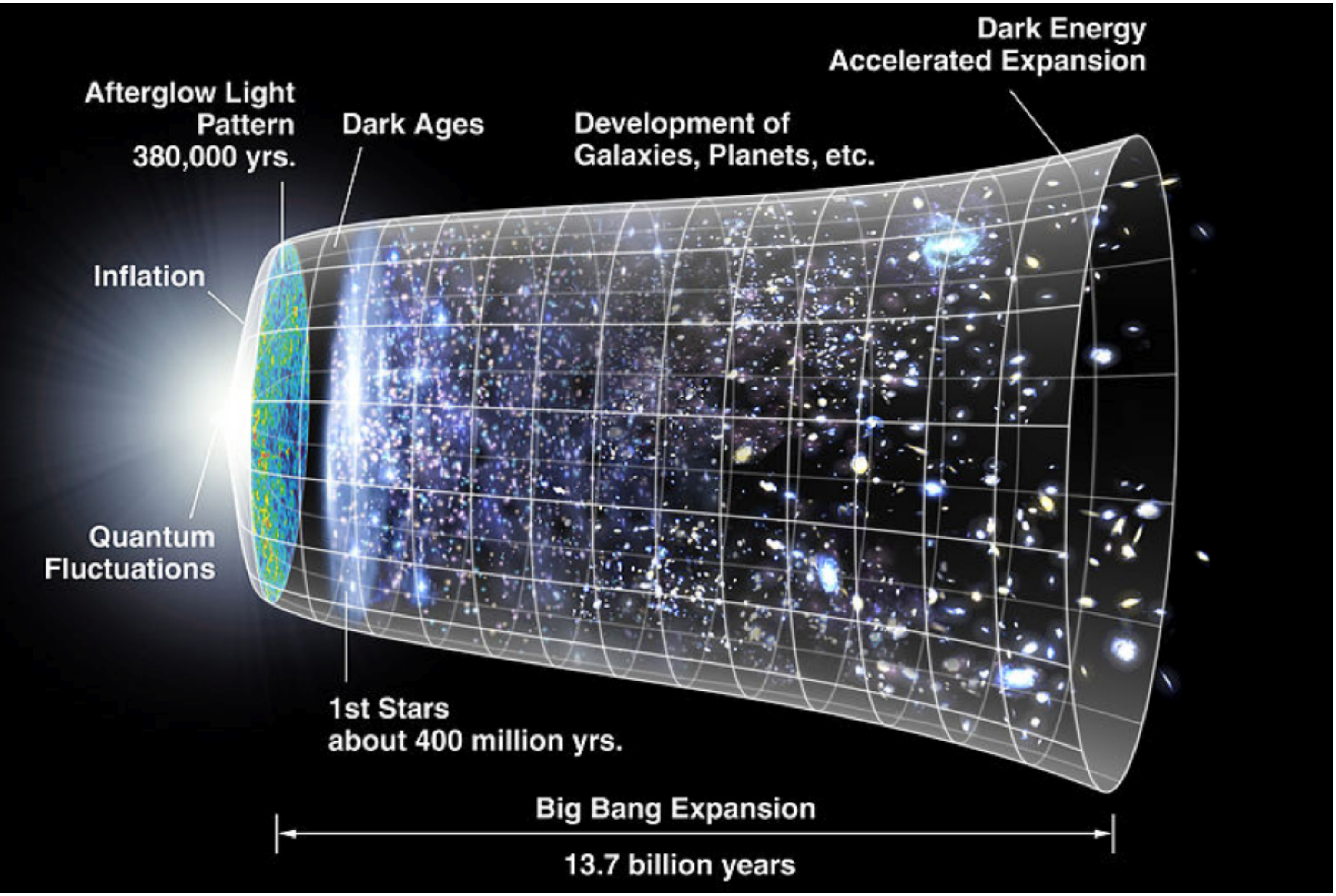
Point Sources?

No statistically-significant point sources



Cosmic Neutrino Background

Similar to CMB photons, except neutrinos show the universe at ~1 second after the Big Bang.



Estimates:

Current density:

~300 / cm^3

Current temp:

~1.95 K

May be as much mass as all stars combined…

Part 3: Fundamental Symmetries

or

Trying to seriously break the Standard Model

Charged Lepton Flavor

Neutral Leptons:

Neutrinos show significant change of flavor: ($\nu_{e,}$ $\nu_{\mu,}$ ν_{τ})

Charged Leptons:

Do we find any similar change for charged leptons (e, μ, τ)?

Prominent CLFV Processes

$\mu \longrightarrow e\,\gamma$

Now allowed within the Standard Model due to neutrino mixing:

$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W}\right|^2 \sim 10^{-52}$$

$\mu^+ \longrightarrow e^+ e^- e^+$

Relative rate strongly constrains extension of Standard Model.

e.g. If dipole terms dominate:

$$\frac{B(\mu^+ \to e^+ e^- e^+)}{B(\mu^+ \to e^+\gamma)} \simeq \frac{\alpha}{3\pi}\left(\ln(\frac{m^2_\mu}{m^2_e}) - \frac{11}{4}\right) = 0.006$$

$\mu^- N \longrightarrow e^- N$

Muon conversion in the field of a nucleus.

e.g. If dipole terms dominate:

$$\frac{B(\mu^+ \to e^+\gamma)}{B(\mu^- N \to e^- N)} = \frac{96\pi^3\alpha}{G_F^2 m_\mu^4} \cdot \frac{1}{3 \cdot 10^{12} B(A,Z)} \simeq \frac{428}{B(A,Z)}$$

~1 to ~2, depending on nucleus

Current and Proposed Experiments

Experiment	Beam	Momentum [MeV/c]	Rates [s^{-1}]	BBeamline
MEG ($\mu \to e\gamma$) [25]	μ^+	29.8	$3 \cdot 10^7$	πE5 at PSI
MuLan [24]	μ^+	29.8	$8 \cdot 10^6$	πE3 at PSI
TWIST [26]	μ^+	29.8	$< 5 \cdot 10^3$	TRIUMF
MEG upgrade* ($\mu \to e\gamma$) [27]	μ^+	29.8	$7 \cdot 10^7$	πE5 at PSI
Mu2e* ($\mu^- \to e^-$) [9]	μ^-	~ 40	10^{10}	FNAL
$\mu^+ \to e^+e^-e^+$ (Phase 1)* [29]	μ^+	29.8	$< 1 \cdot 10^8$	πE5 at PSI
$\mu^+ \to e^+e^-e^+$ (Phase 2)* [29]	μ^+	29.8	$2 \cdot 10^9$	HIMB at PSI

arXiv:1311.5278

Mu2e Experiment

Principle:

Determine or limit branching ratio for muon conversion.

$$R_{\mu e} = \frac{\Gamma(\mu^- \; N(A,Z) \rightarrow e^- \; N(A,Z))}{\Gamma(\mu^- \; N(A,Z) \rightarrow \nu_\mu \; N(A,Z-1))}$$

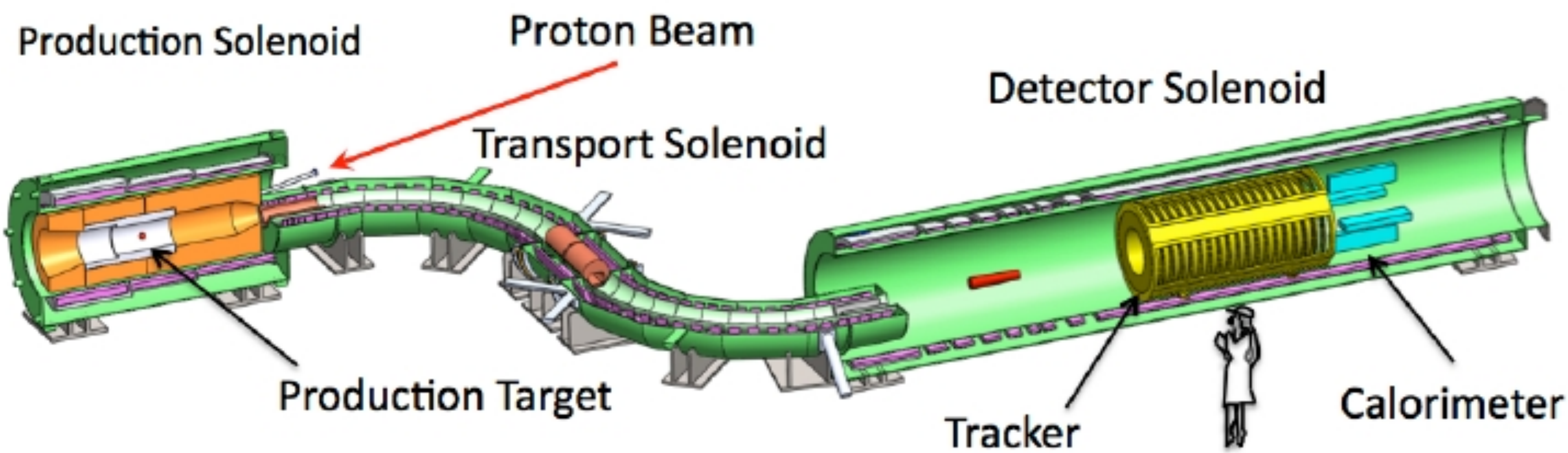
Signal:

Emission of mono-energetic electron: 105 MeV.

Current Limit: $R_{\mu e} < 7 \times 10^{-13}$

Aim to surpass this limit by 4 orders of magnitude!

Mu2e Detector



Goal:

Stop 10^{18} muons in Al target.

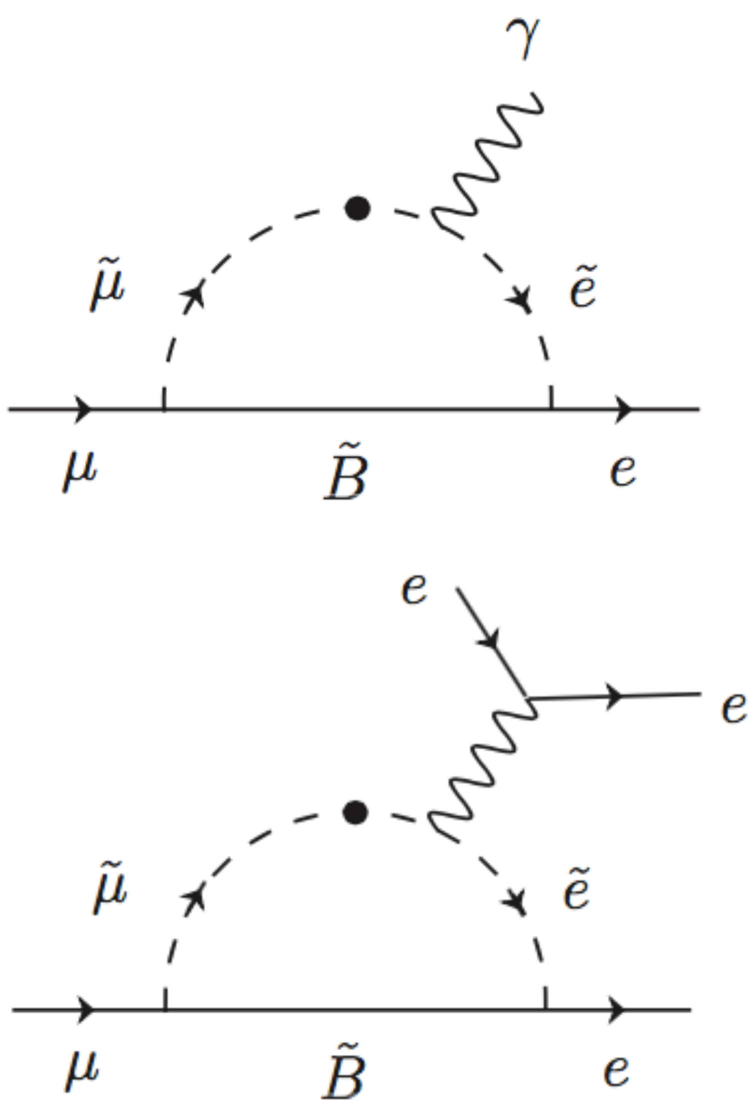
Search for emission of a few electrons with energy of 105 MeV.

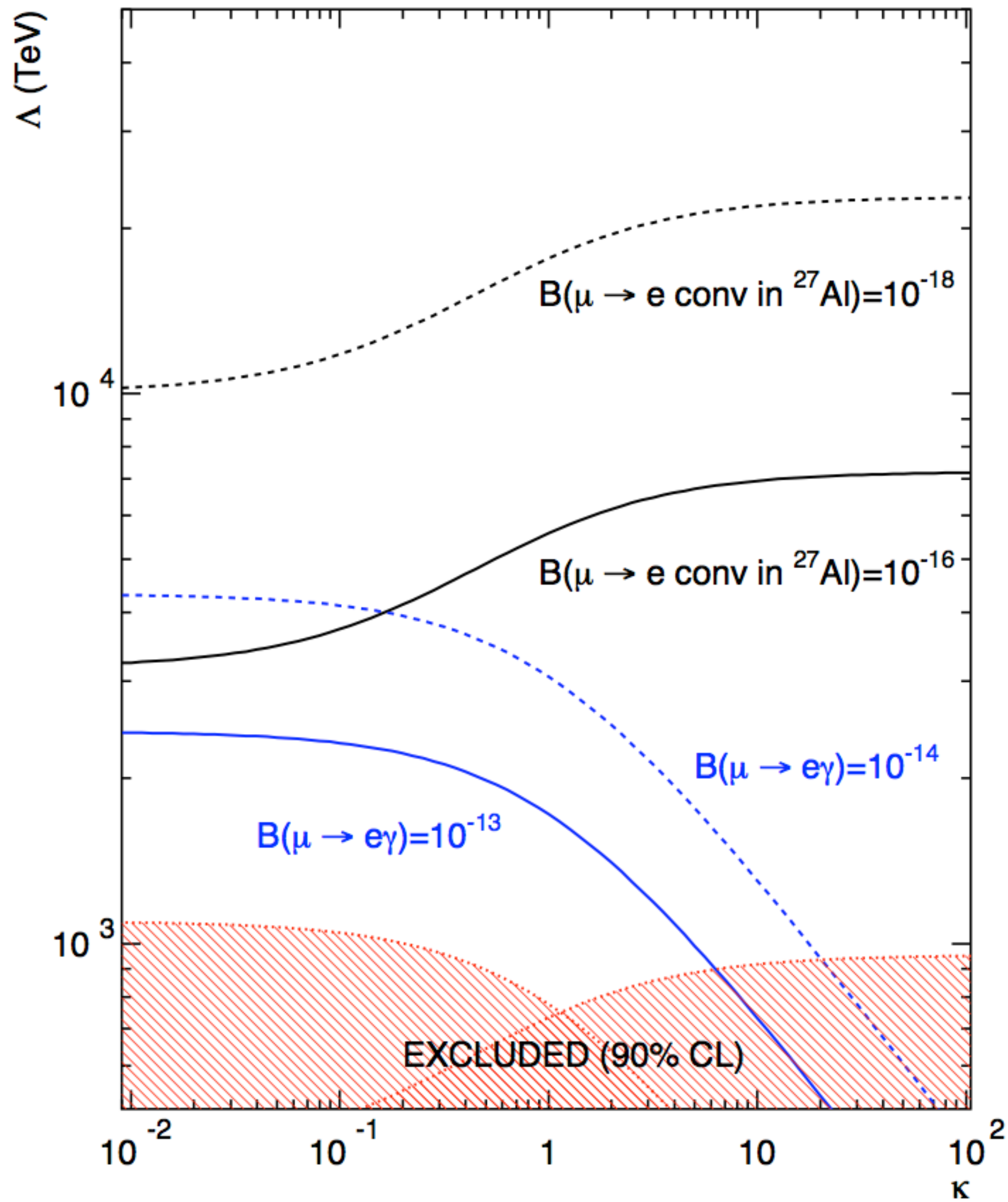
Keep background below 1 count during entire operation.

Sensitivity to New Physics

Examples:

New particles induce CLFV





Flavor Conservation

Flavor conserving processes:

Can also inform us of physics beyond the Standard Model

$\longrightarrow$ Dipole Moments!

$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)\vec{s}\,, \qquad \vec{d} = \eta\left(\frac{Qe}{2mc}\right)\vec{s}$$

Including radiative corrections:

Phys. Rev. D 73, 072003 (2006)

$$a = \frac{g-2}{2}$$

$$a_\mu(\mathrm{Expt}) = 116\,592\,089(54)(33) \times 10^{-11}$$

$$a_\mu(\mathrm{SM}) = 116\,591\,802(42)(26)(02) \times 10^{-11}$$

(At zero'th order, g ≡ 2.)

Disagrees at ~3.6σ sigma

Loops within loops

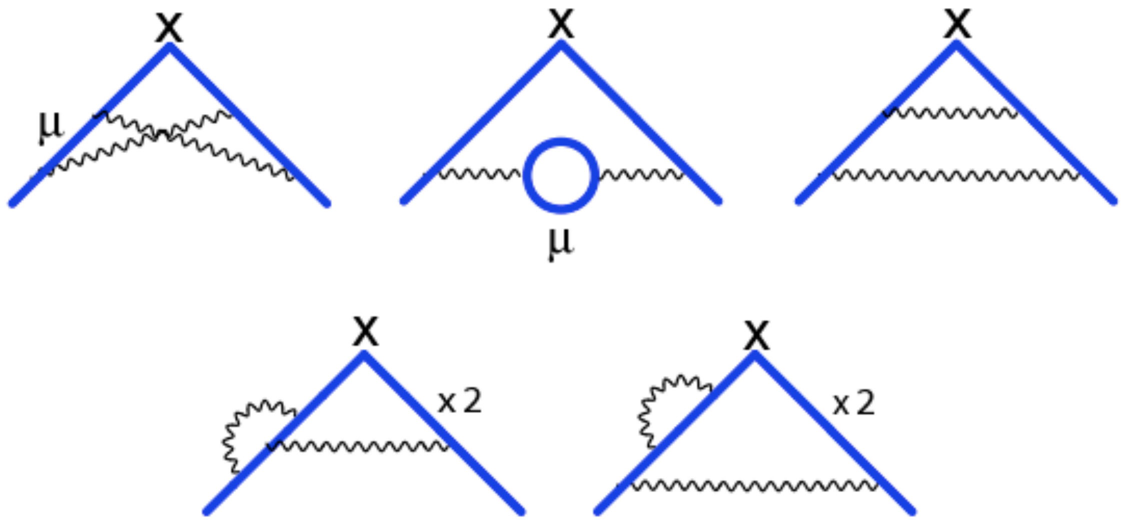


Figure 32. Two-loop QED Feynman diagrams with the same lepton flavor.

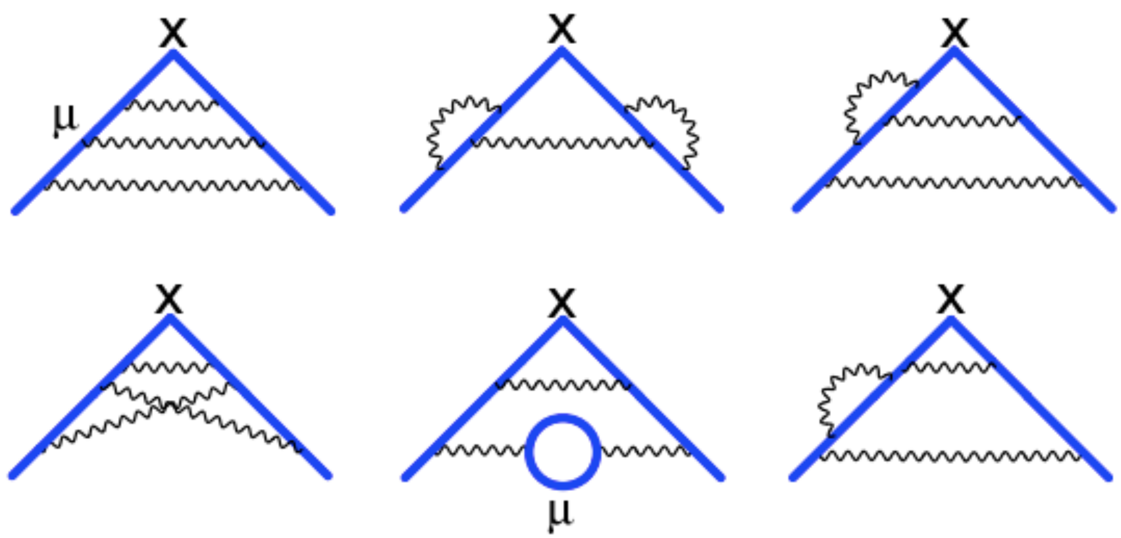


Figure 33. A few Feynman diagrams of the three-loop type. In this class the flavor of the internal fermion loops is the same as the external fermion.

Rept. Prog. Phys. 70, 795 (2007)

Loops within loops

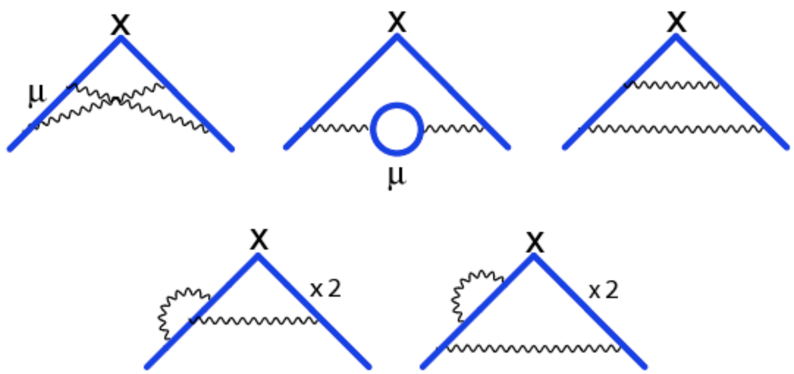


Figure 32. Two-loop QED Feynman diagrams with the same lepton flavor.

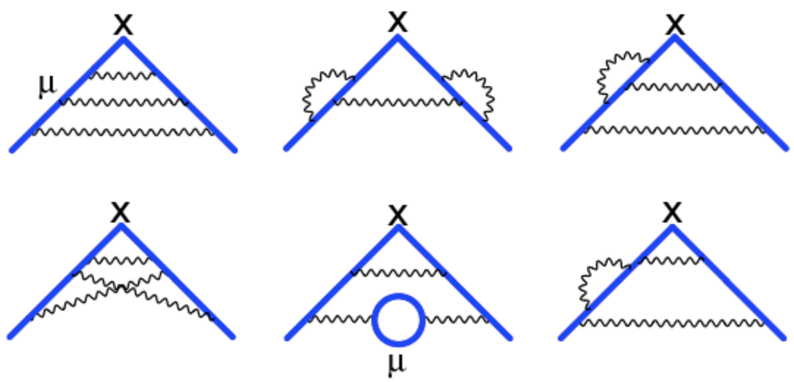
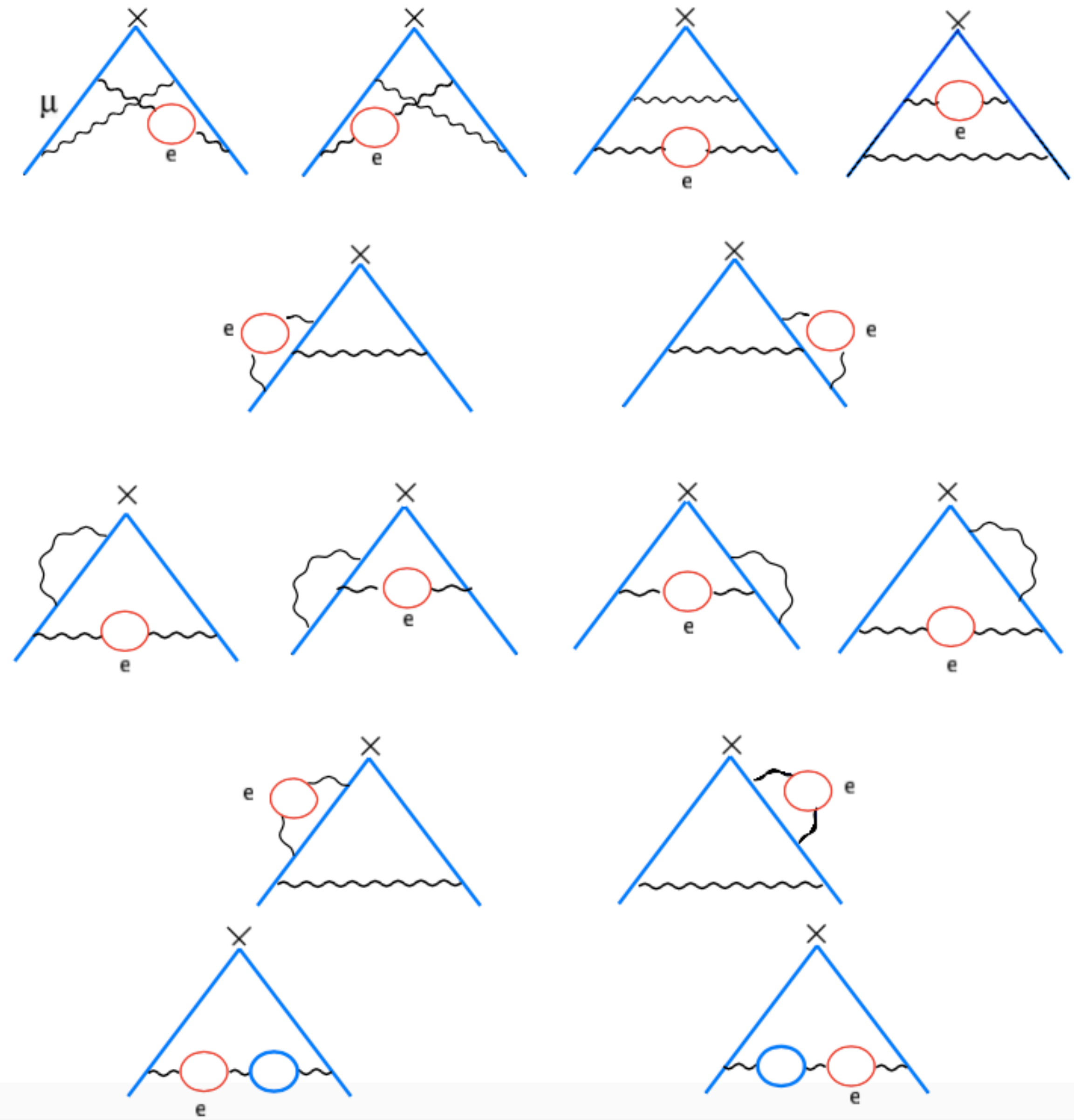


Figure 33. A few Feynman diagrams of the three-loop type. In this class the flavor of the internal fermion loops is the same as the external fermion.



Rept. Prog. Phys. 70, 795 (2007)

Loops within loops

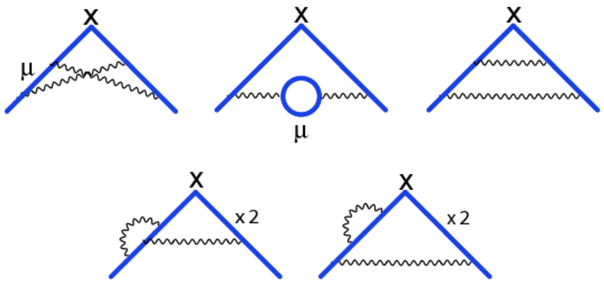
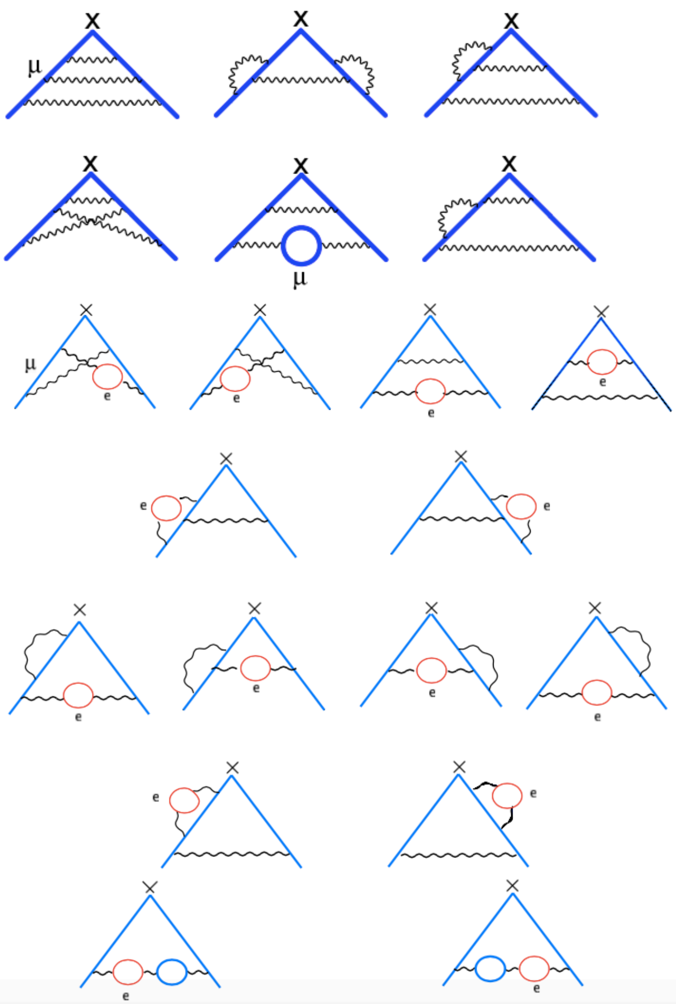
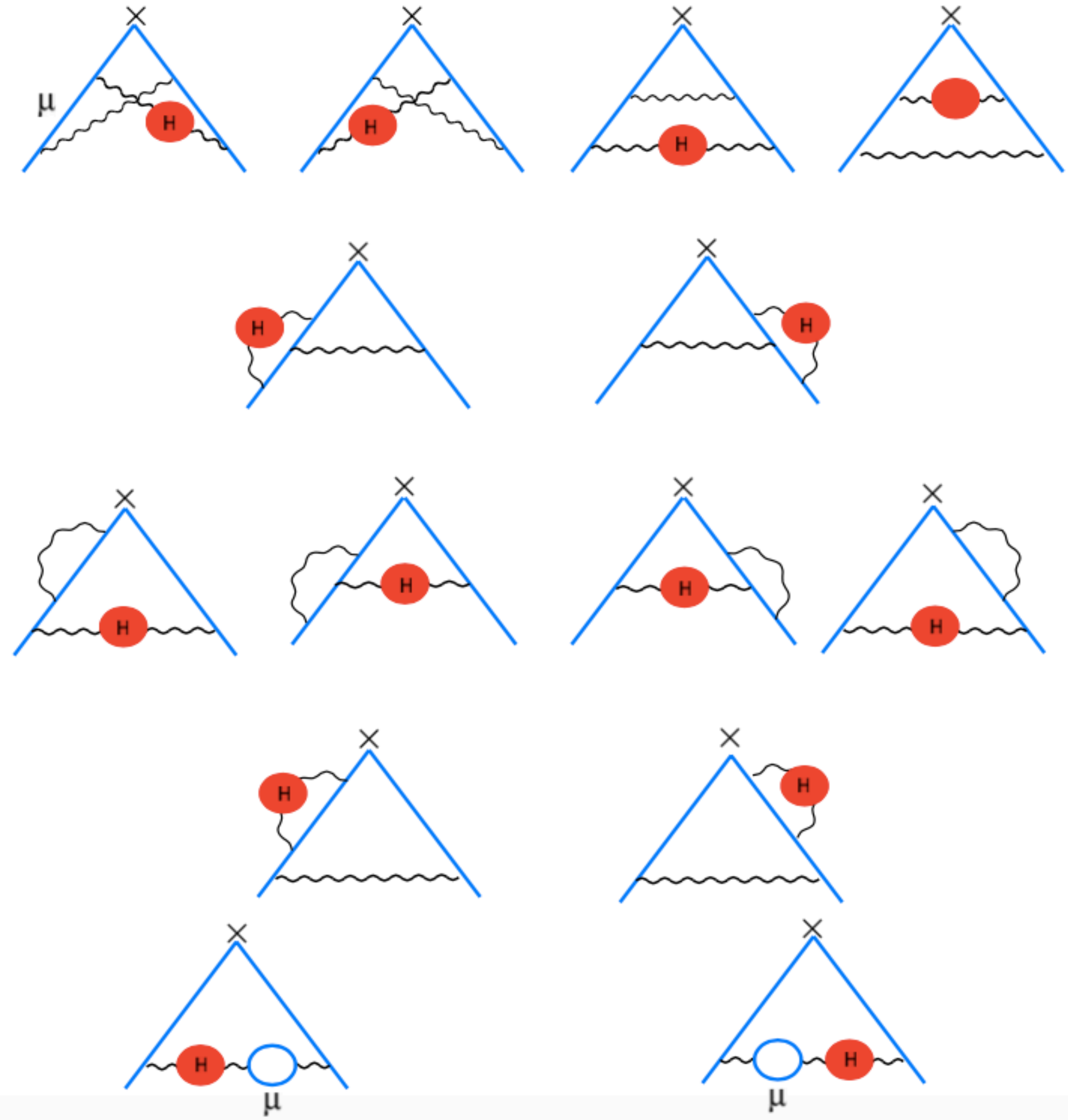


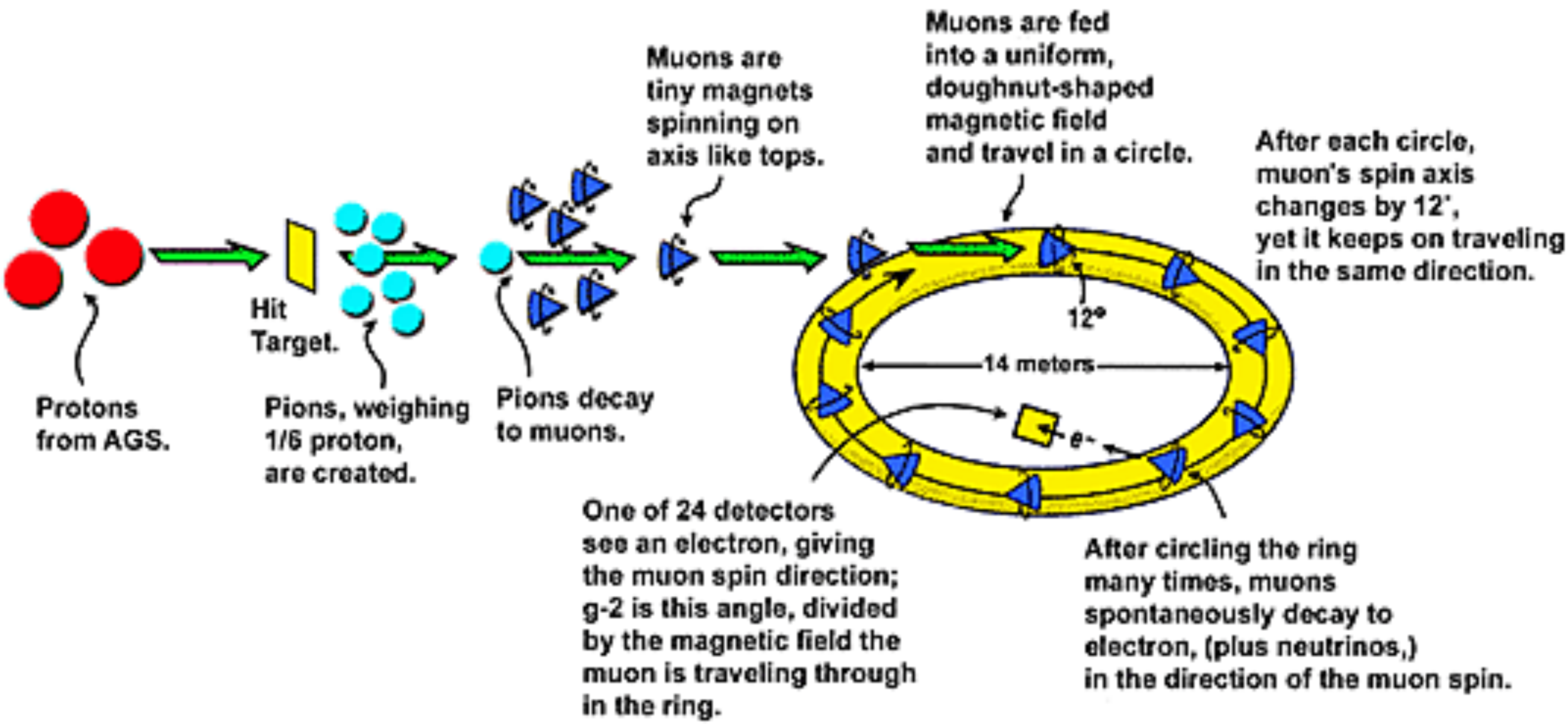
Figure 32. Two-loop QED Feynman diagrams with the same lepton flavor.





Rept. Prog. Phys. 70, 795 (2007)

Measuring g-2



g-2: On the road

g-2 moving from Brookhaven to Fermilab

Aim to improve current precision by a factor of 4.

Experiment also at J-PARC…

Electric Dipole Moments

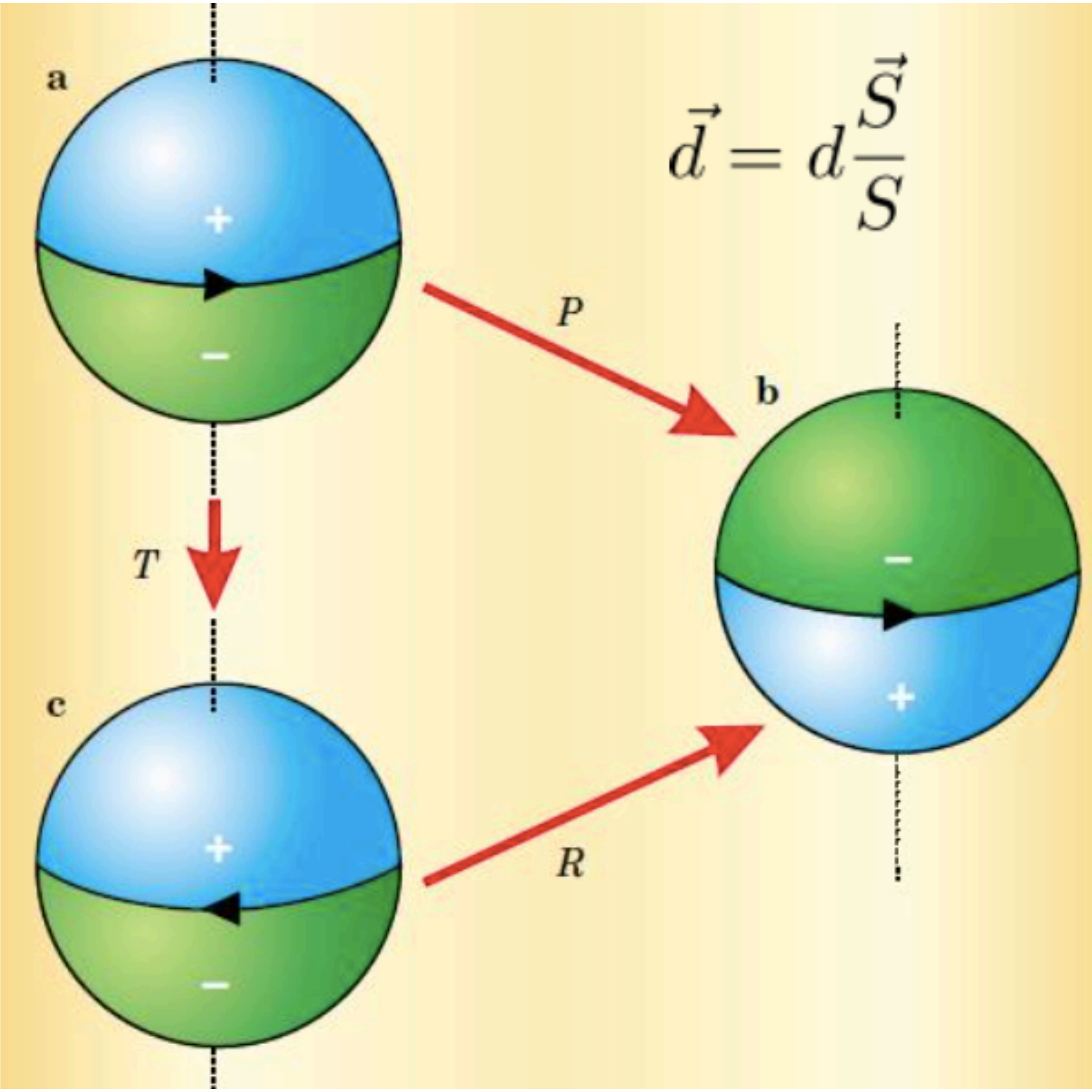
Violate:

Time-reversal symmetry
Parity-reversal symmetry
(and CP via CPT theorem)

Standard Model predicts exceedingly small EDMs:

$d_e = 10^{-38}$ e × cm
$d_n = 10^{-32}$ e × cm
$d_{Hg} = 10^{-34}$ e × cm

Any observation:
⟶ *New physics.*



Prog. in Part. and Nucl. Phys. 71, 21 (2013)

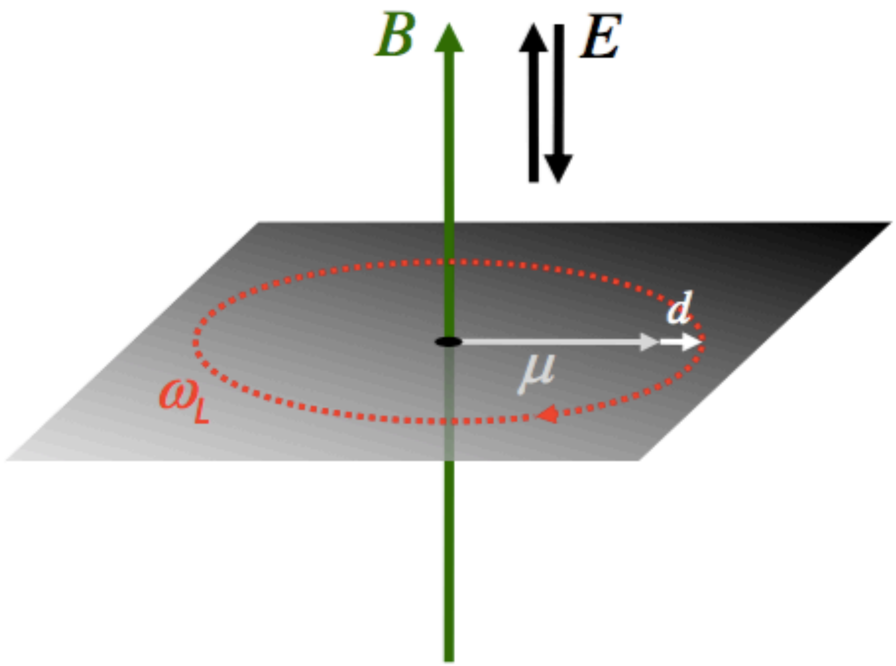
EDM Experiments

Leptonic EDMs		Hadronic EDMs	
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	U. Texas	n (UCN)	ILL-PNPI
Cs (fountain)	LBNL	n (UCN)	PSI
^{210}Fr (trapped)	Cyric	n (UCN)	KEK-Triumph
		n (UCN)	Munich
YbF (beam)	Imperial College	p (ring)	BNL
HfF+ (trapped)	JILA	d (ring)	COSY
ThO (beam)	Harvard-Yale		
PbF (trapped)	U. Oklahoma	^{129}Xe (liquid)	Princeton
WC (beam)	U. Michigan	^{129}Xe (cell)	GUMainz
		^{129}Xe (cell)	TUMunich
GGG (solid)	Indiana	^{129}Xe (cell)	Tokyo Inst. Tech.
		^{199}Hg (cell)	Seattle
muon (ring)	J-PARC	^{223}Rn (trapped)	TRIUMF
		^{225}Ra (trapped)	Argonne
		^{225}Ra (trapped)	KVI

Partial List from B. Heckel, CIPANP-2015

EDM Measurement

Larmor Precession



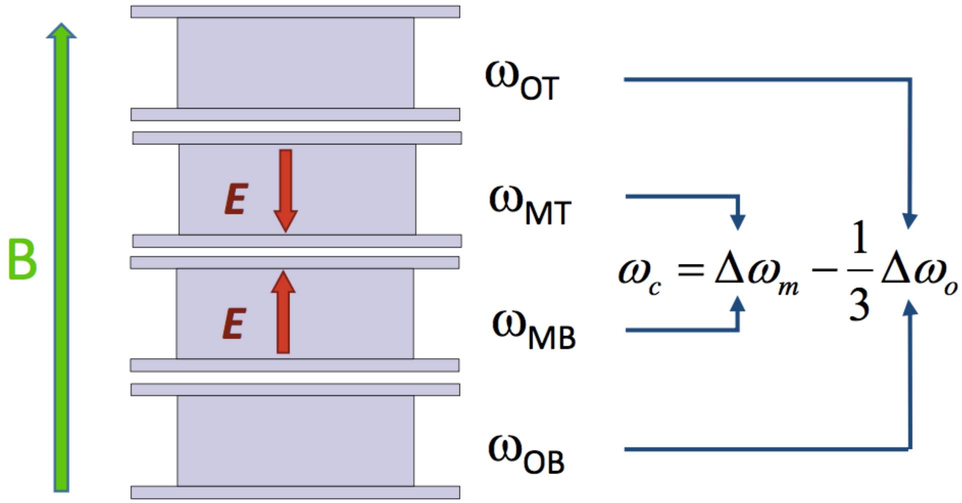
$$\omega_1 = \frac{2\vec{\mu}\cdot\vec{B} + 2\vec{d}\cdot\vec{E}}{\hbar} \quad \left(\frac{\mathrm{B}\cdot\mathrm{E}}{\|\mathrm{B}\cdot\mathrm{E}\|}=1\right)$$

$$\omega_2 = \frac{2\vec{\mu}\cdot\vec{B} - 2\vec{d}\cdot\vec{E}}{\hbar} \quad \left(\frac{\mathrm{B}\cdot\mathrm{E}}{\|\mathrm{B}\cdot\mathrm{E}\|}=-1\right)$$

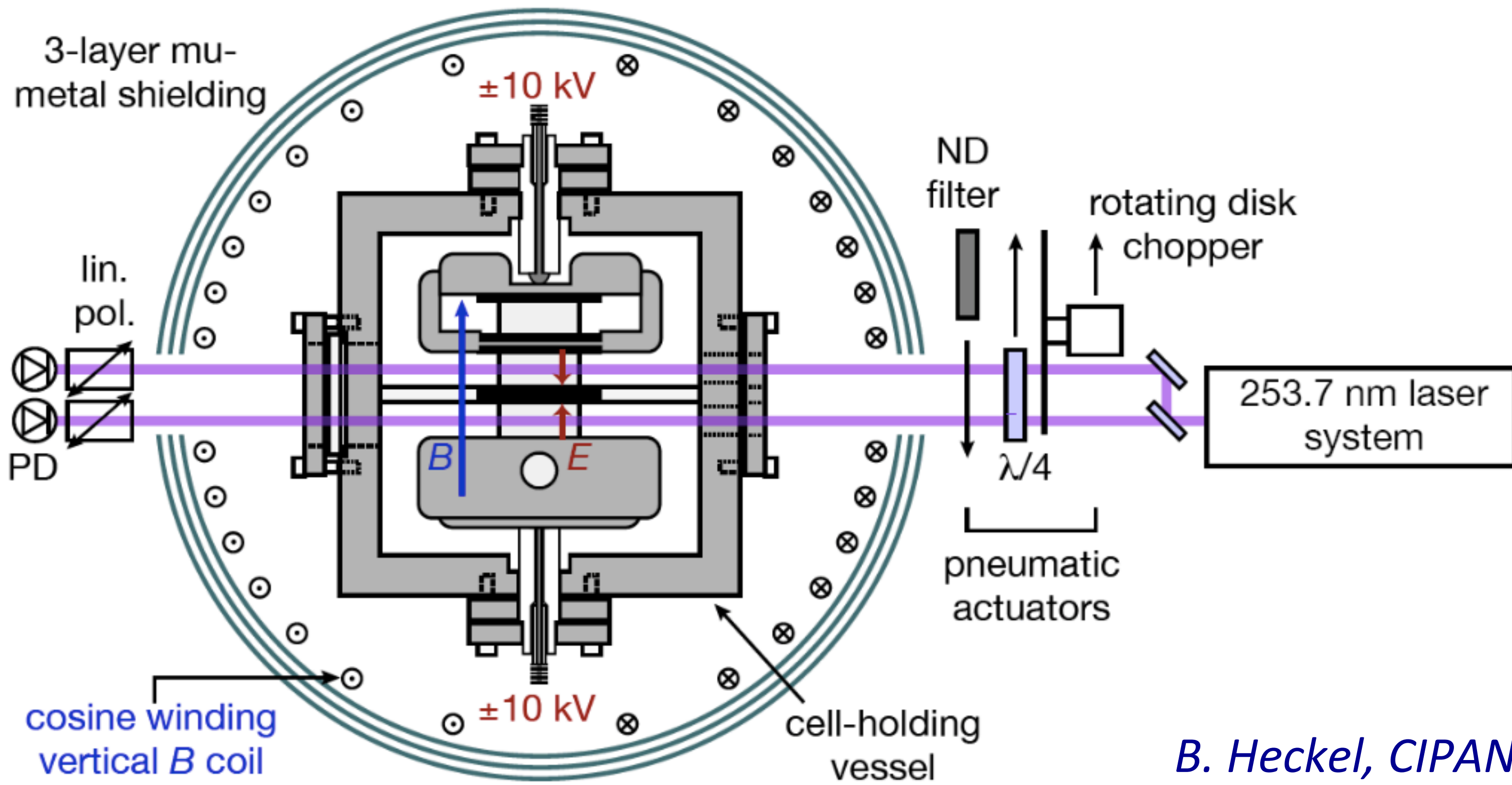
$$\omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

B. Heckel, CIPANP-2015

Example: ^{199}Hg



$$\omega_c = \frac{\mu}{\hbar}\left(-\frac{8}{3}\frac{\partial^3 B}{\partial z^3}\Delta z^3\right) + \frac{4dE}{\hbar}$$



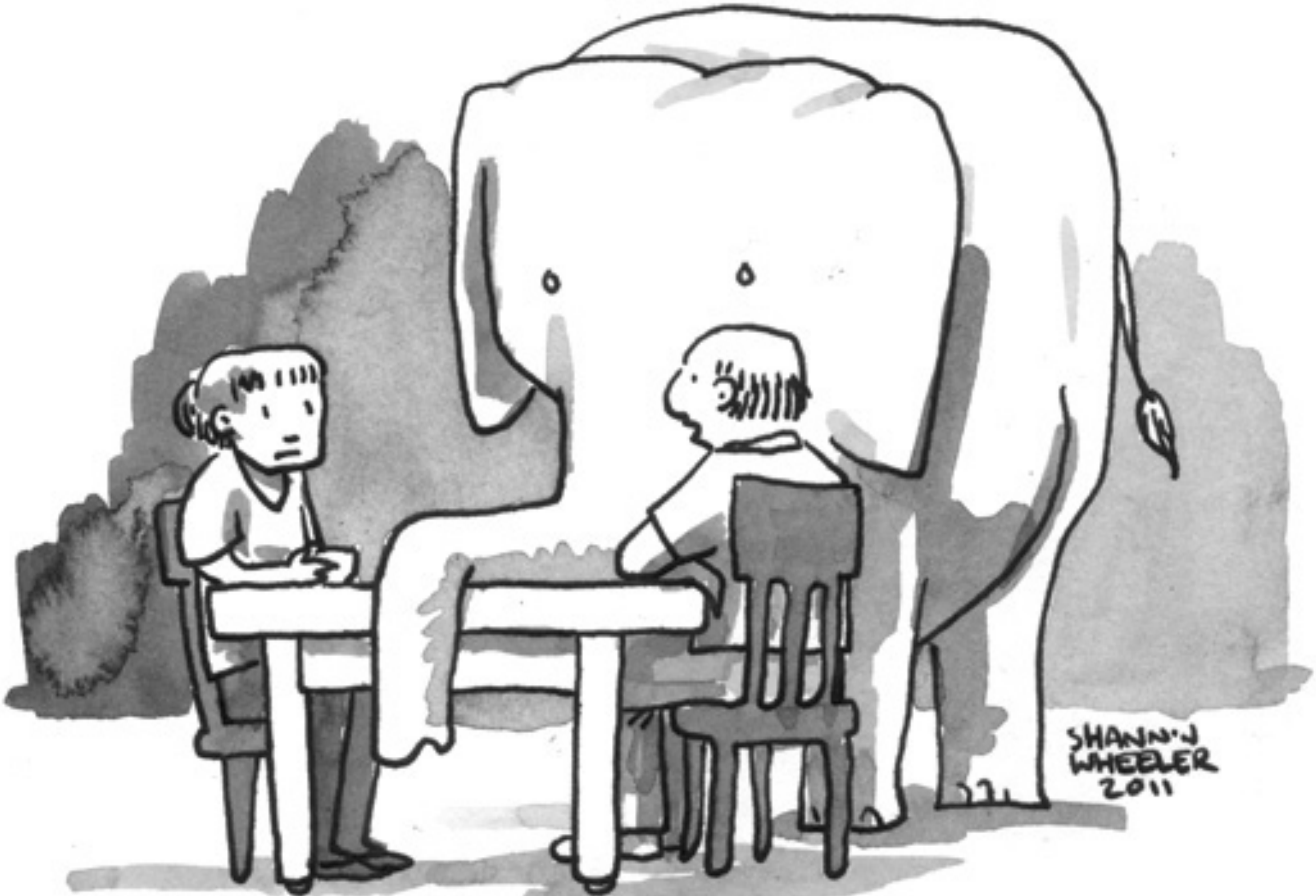
B. Heckel, CIPANP-2015

EDM: Current Best Limits

System	Limit	E_{eff}	co-magnetometer	Freq. res.
ThO[1]	$\|d_e\| < 8.7 \times 10^{-29}$ e-cm	84 GV/cm	Omega doublet states	1 mHz
Neutron[2]	$\|d_n\| < 2.9 \times 10^{-26}$ e-cm	15 kV/cm	^{199}Hg vapor	2 μHz
^{199}Hg[3]	$\|d_{Hg}\| < 3.1 \times 10^{-29}$ e-cm	10 V/cm	Adjacent vapor cells	0.1 nHz

1. J. Baron *et al.*, (ACME Collaboration), Science **343**, 269 (2014)
2. C. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006)
3. W. C. Griffith *et al.*, Phys. Rev. Lett. **102**, 101601 (2009)

B. Heckel, CIPANP-2015



"HONESTLY? I PREFERRED WHEN WE DIDN'T TALK ABOUT THE ELEPHANT"

What is the lifetime of the proton?

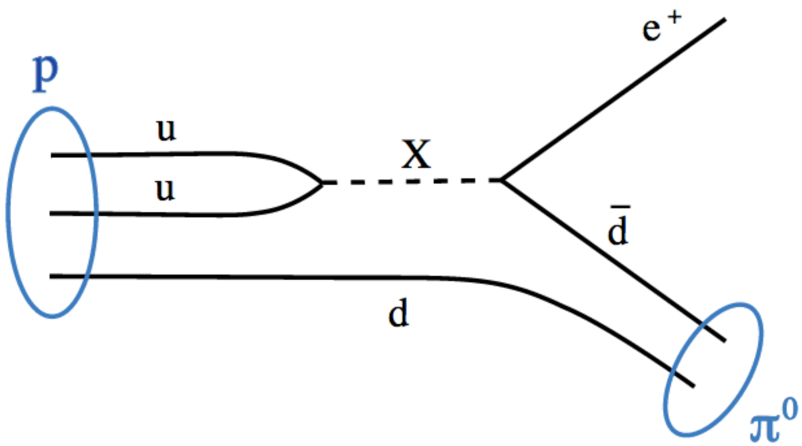
Proton Decay

Sensitive probe of new physics up to GUT scale (10^{16} GeV)

Decay to charged lepton:

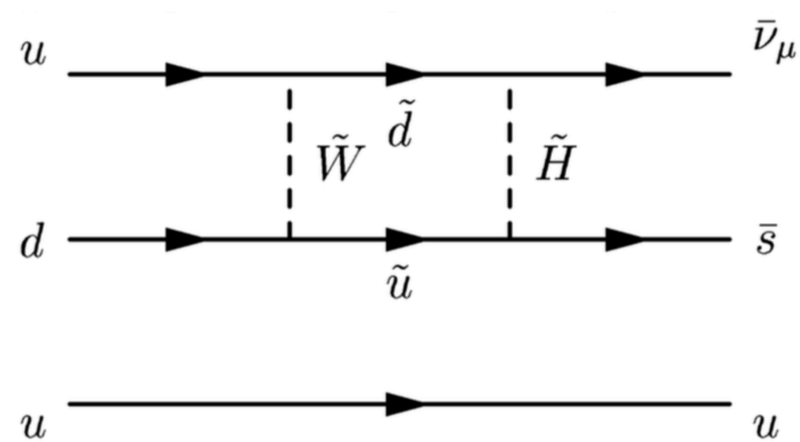
$p \longrightarrow e^{+} \pi^{0}$

$p \longrightarrow \mu^{+} \pi^{0}$



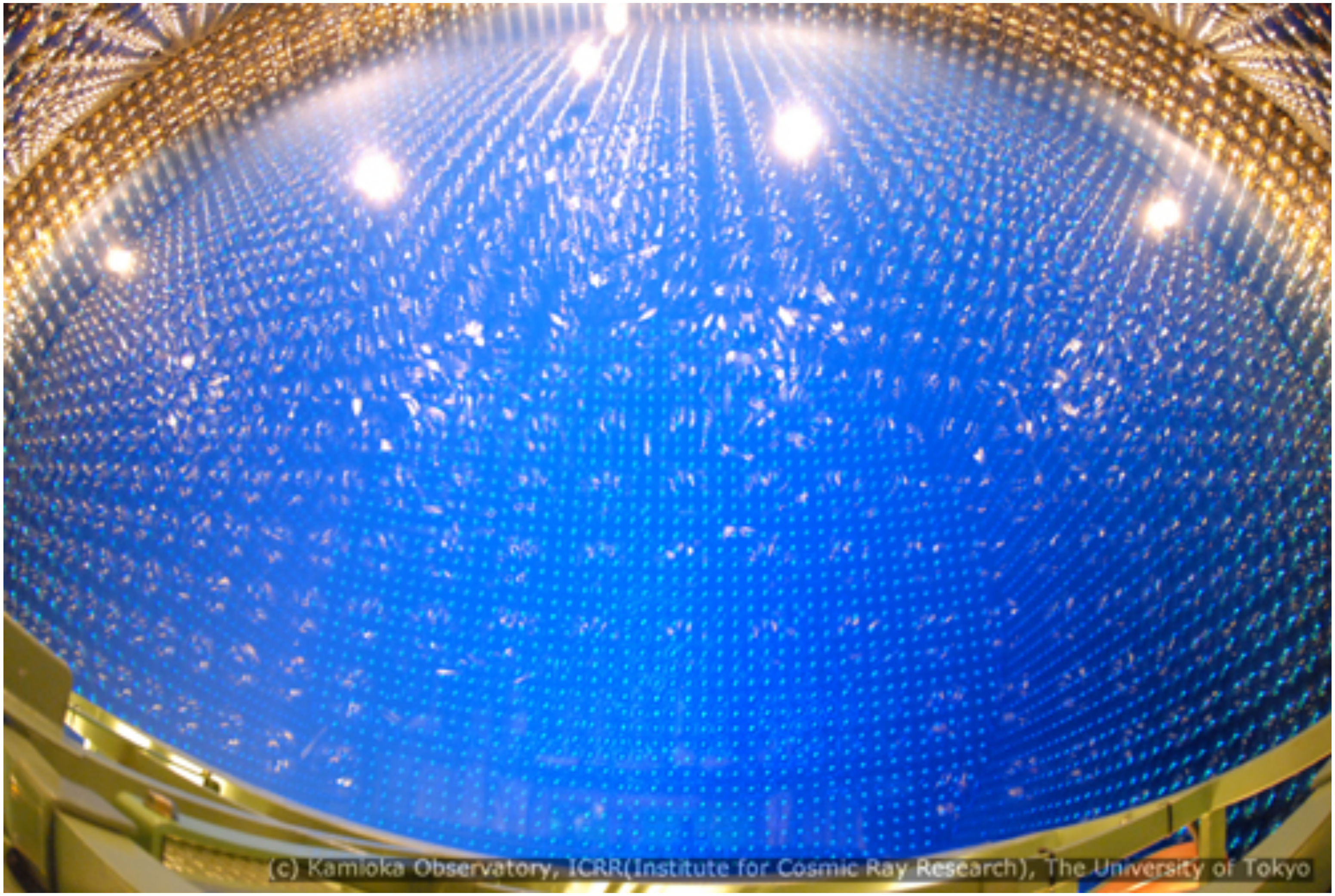
Decay to neutral lepton:

$p \longrightarrow \bar{\nu} K^{+}$



Super-Kamiokande

Has watched 32 ktons of water for 20 years. No decays.



$p \longrightarrow e^+ \pi^0$

$\tau > 8.2 \times 10^{33}$ years

$p \longrightarrow \mu^+ \pi^0$

$\tau > 6.6 \times 10^{33}$ years

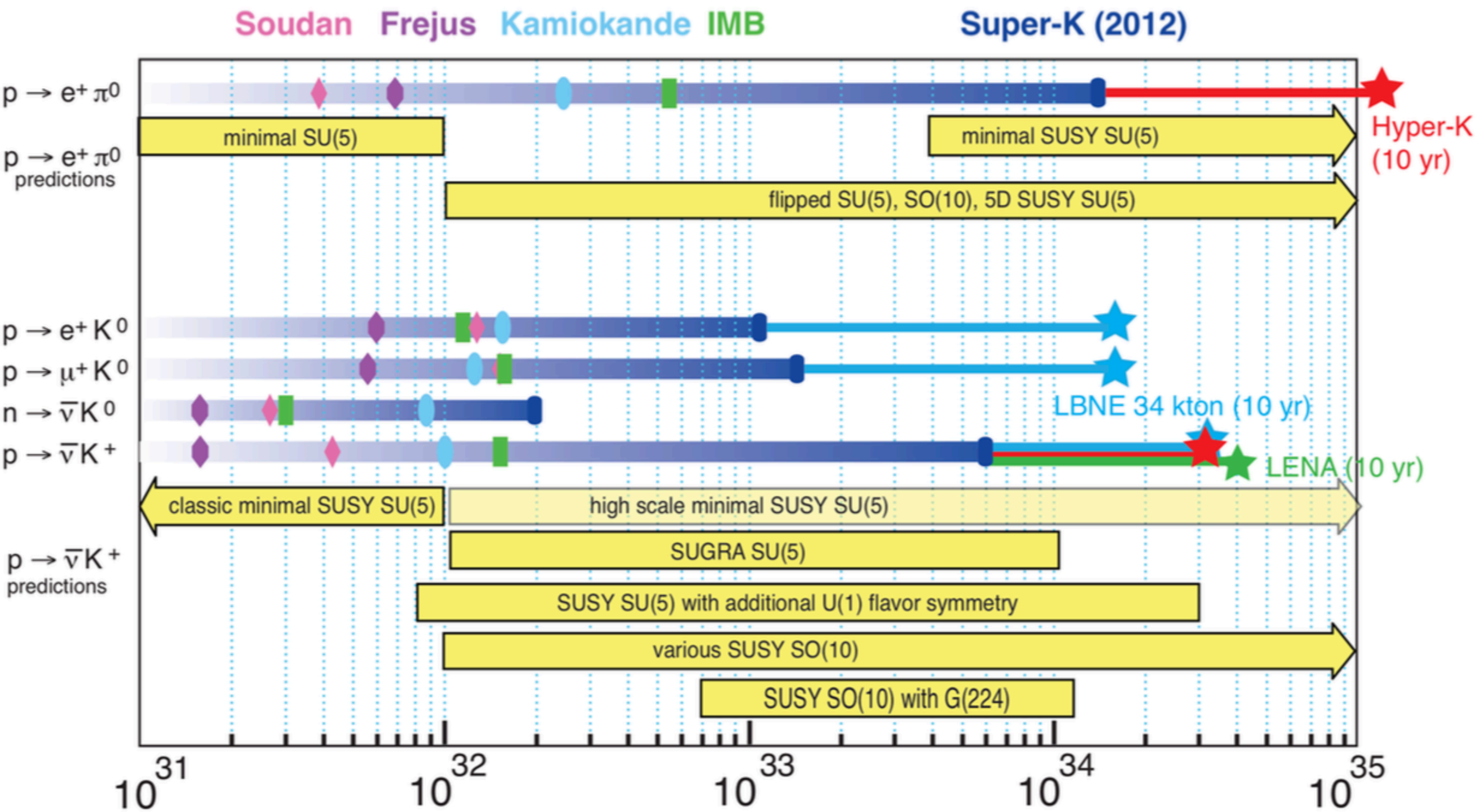
Phys. Rev. Lett. 102, 141801 (2009)

$p \longrightarrow \bar{\nu} K^+$

$\tau > 5.9 \times 10^{33}$ years

Phys. Rev. D 90, 072005 (2014)

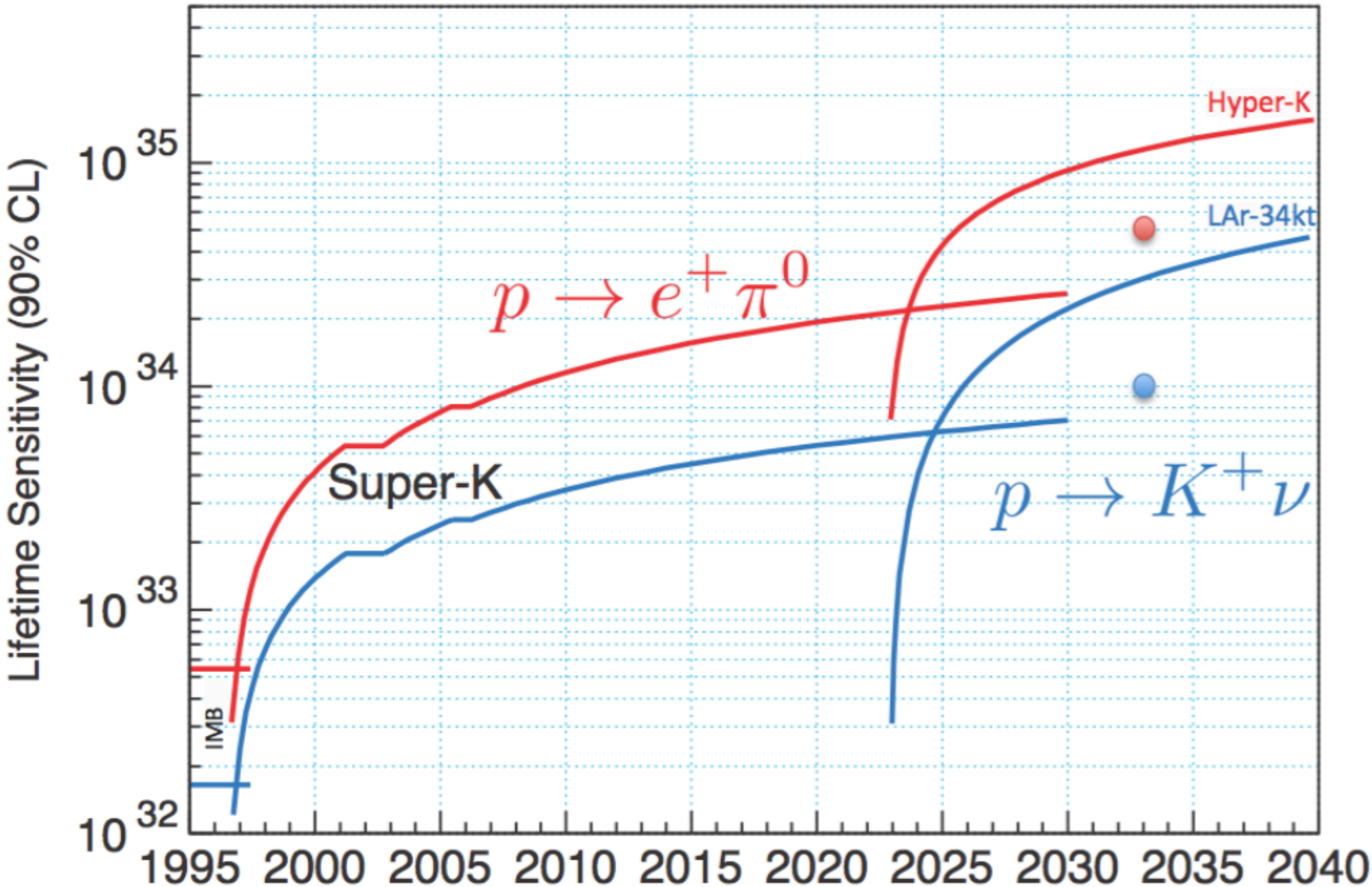
Proton Decay



Lifetime (years)

Ed Kearns

Proton Decay



Ed Kearns

Conclusions

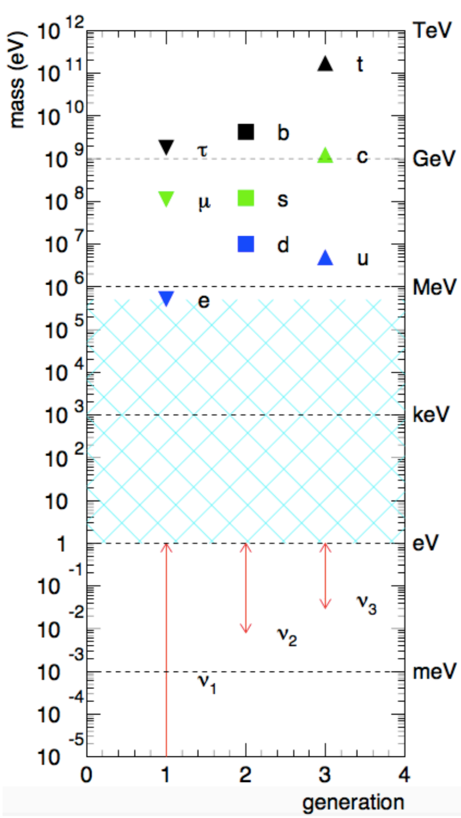
Clear limits to our understanding of physical laws:

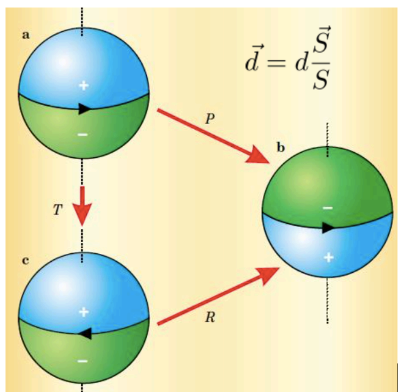
What are the characteristics of the known particles?

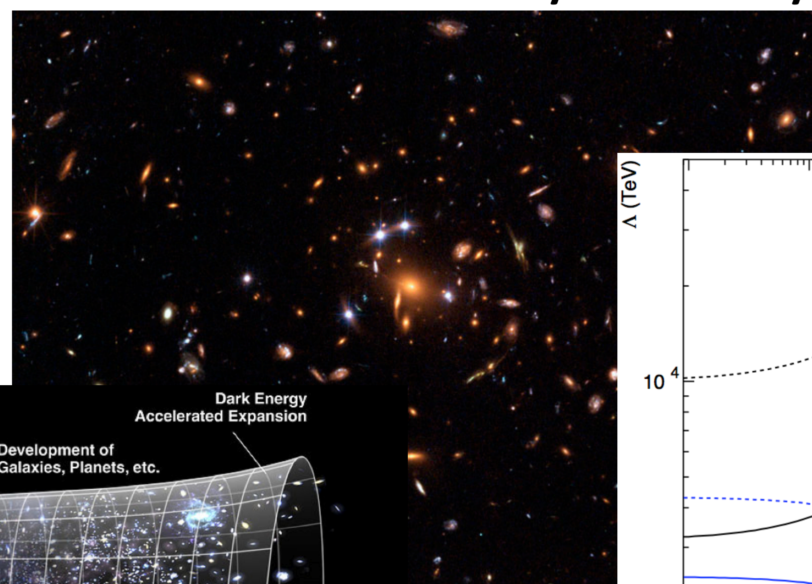
What about the unknown particles (dark matter, energy?)

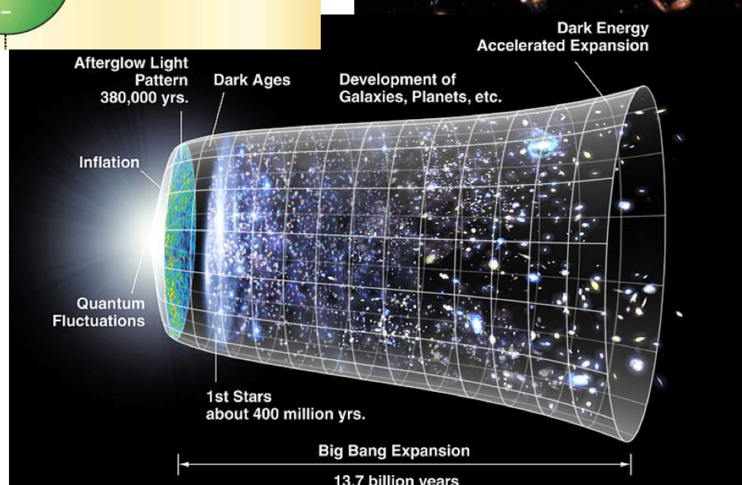
Is there a deeper underlying structure?

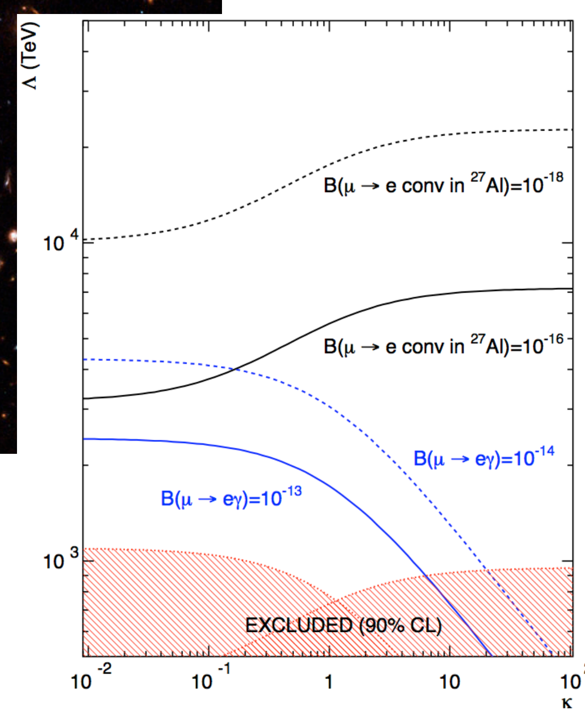
How do we explain the matter-antimatter asymmetry?





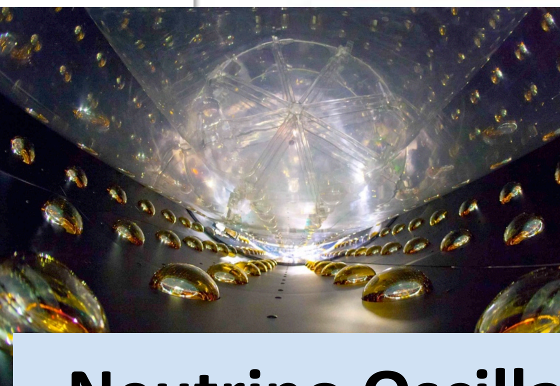


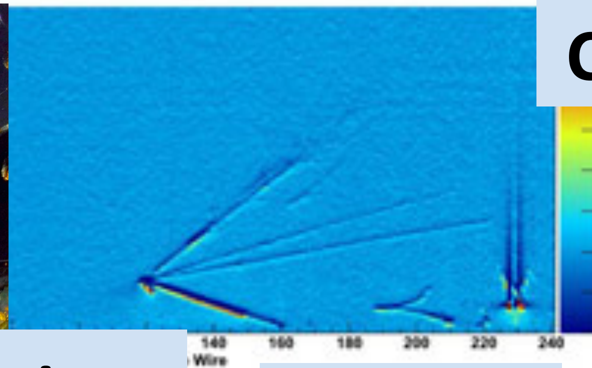




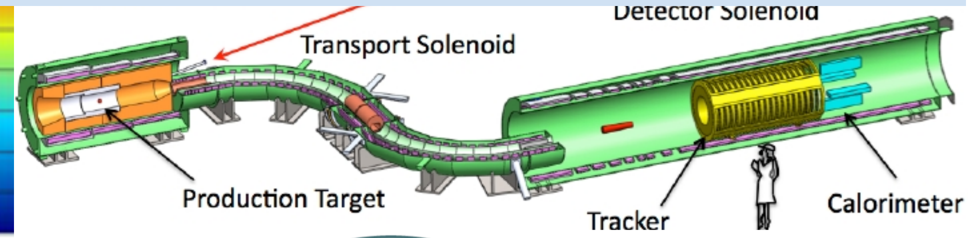
Conclusions

Many interesting experimental routes to explore:

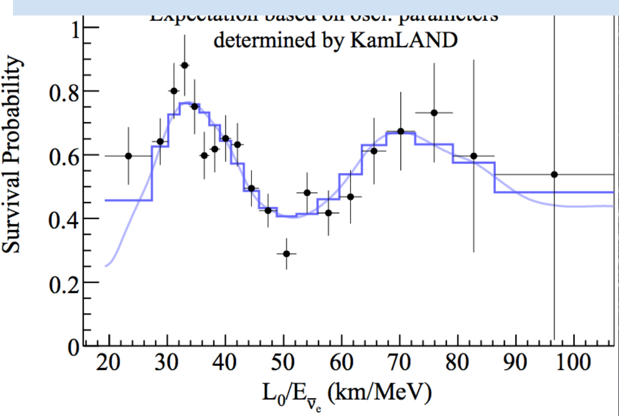




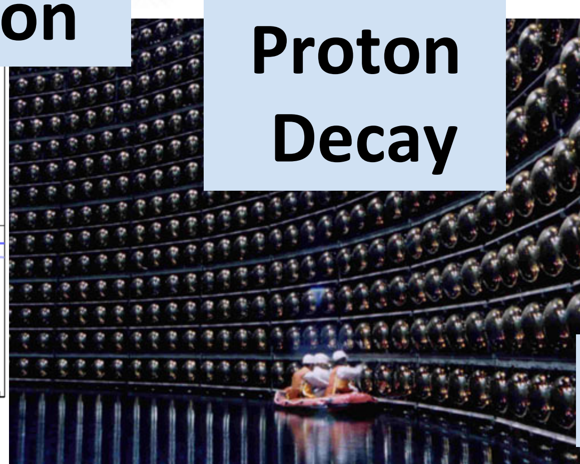
Charge Lepton Flavor Violation

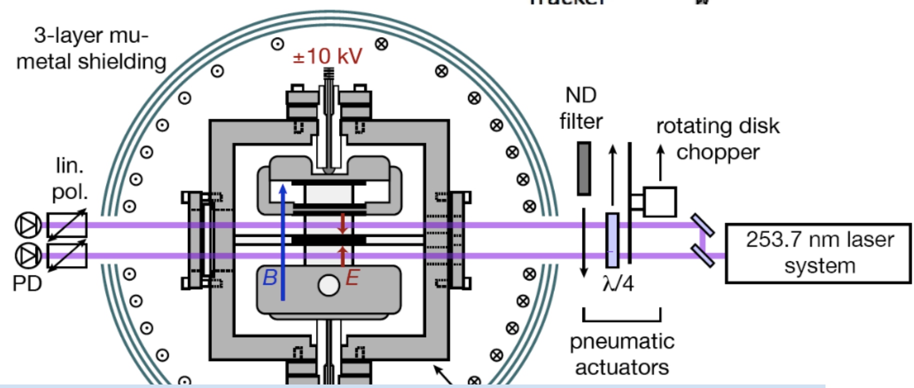


Neutrino Oscillation

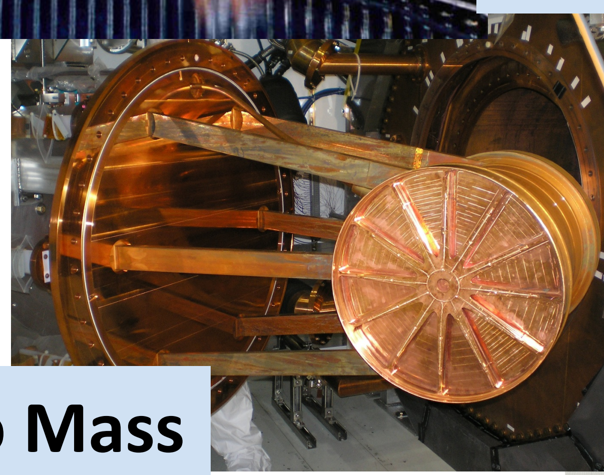


Proton Decay





Electric Dipole Moments



Neutrino Mass

Muon g-2