THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

TUNL

Neutrino Physics

Reyco Henning
U. Of North Carolina at Chapel Hill /
Triangle University Nuclear Laboratory

PIRE/GEMADARC Summer School — May 2023

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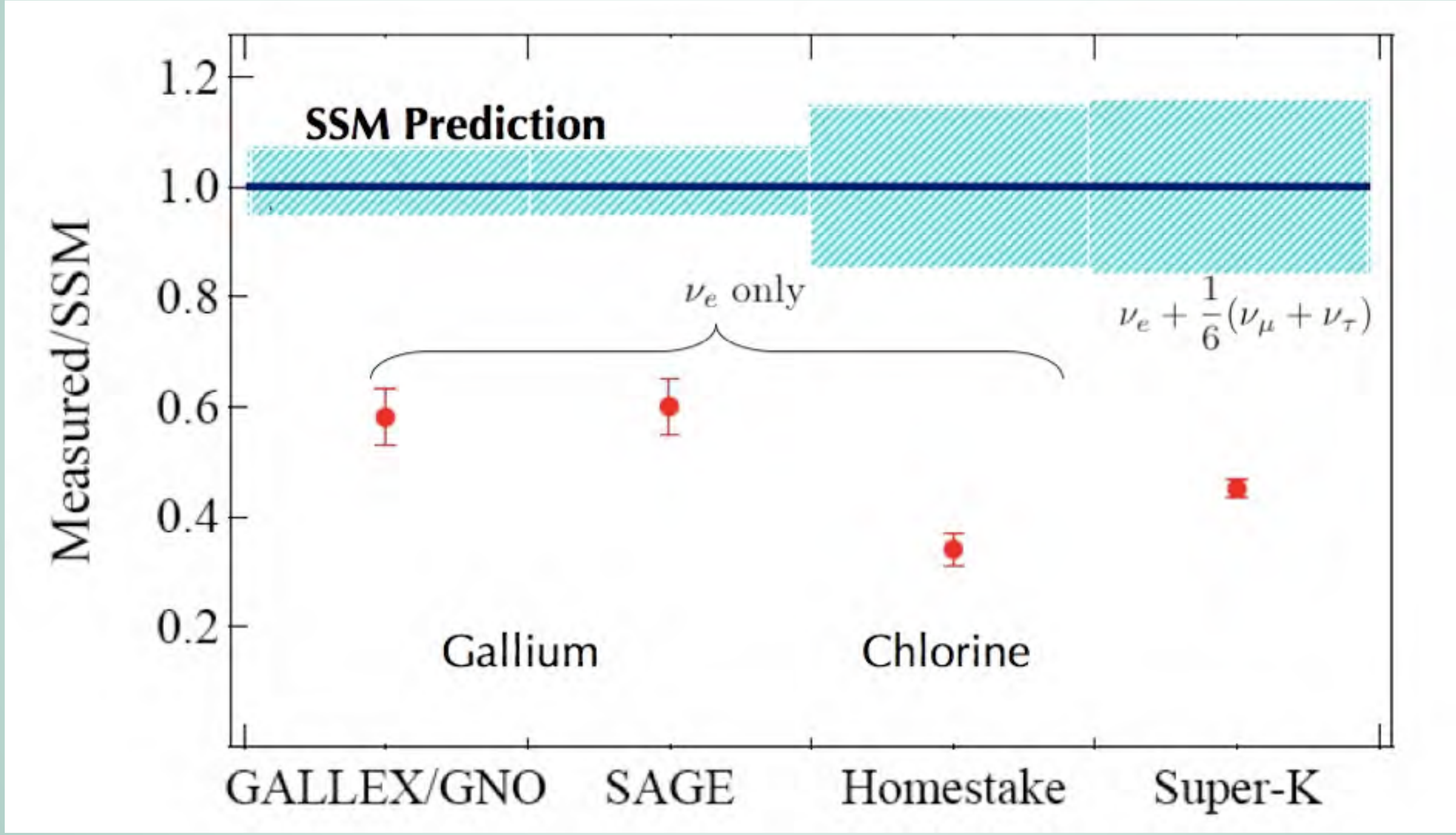
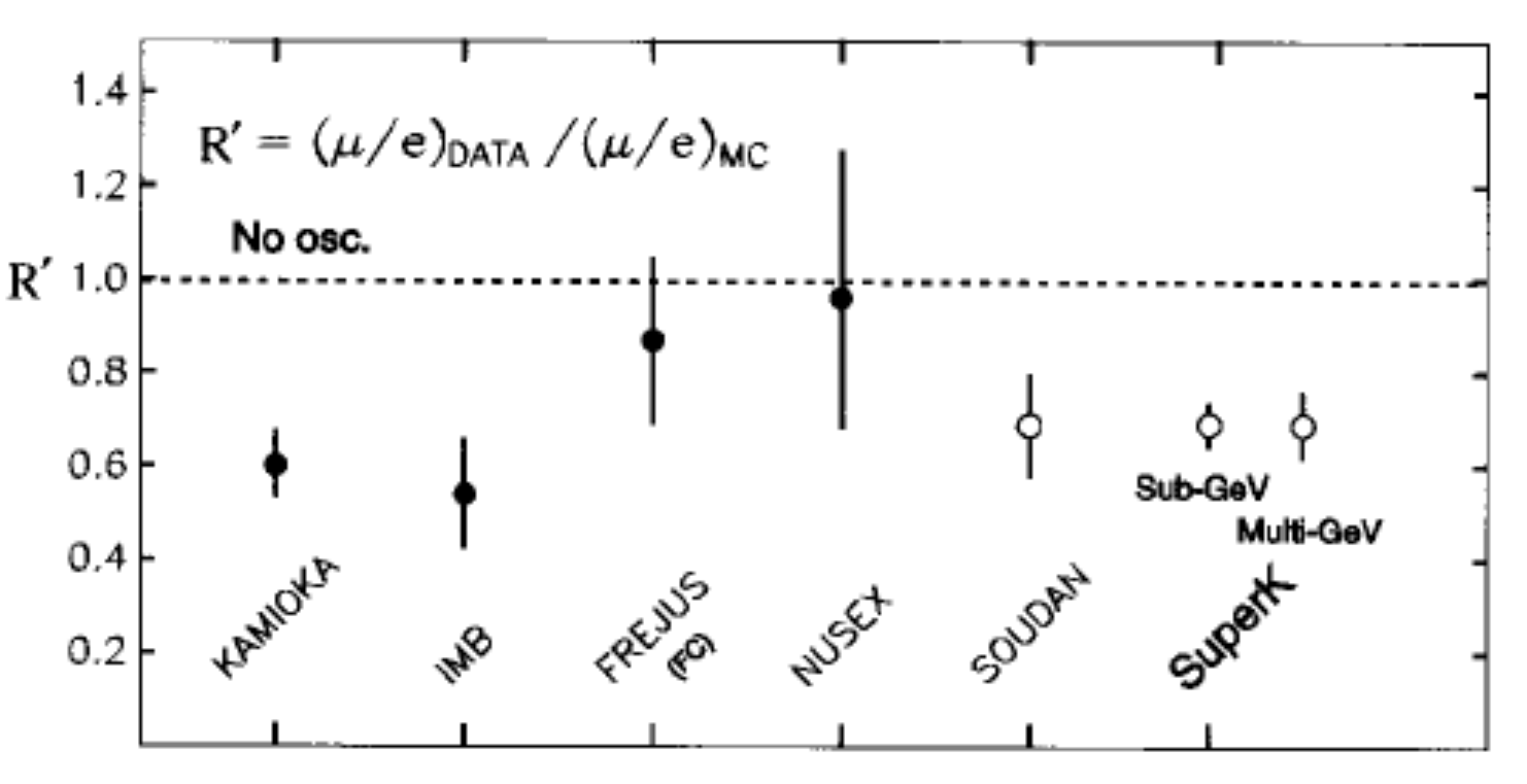
The Solar Neutrino Problem ~2000



A. Poon

Results



Mixing Angle quite large (consistent with maximal)

$\Delta m^2 = 2.5\text{x}10^{-3}\ eV^2$

Verified by Accelerator Experiments

Resolution

SNO
Sudbury Neutrino Observatory

1 kton (\$300M!) D_2O

3 Channels:

Elastic Scattering (ES)

$\nu_{e\tau\mu} + e^- \rightarrow \nu_{e\tau\mu} + e^-$

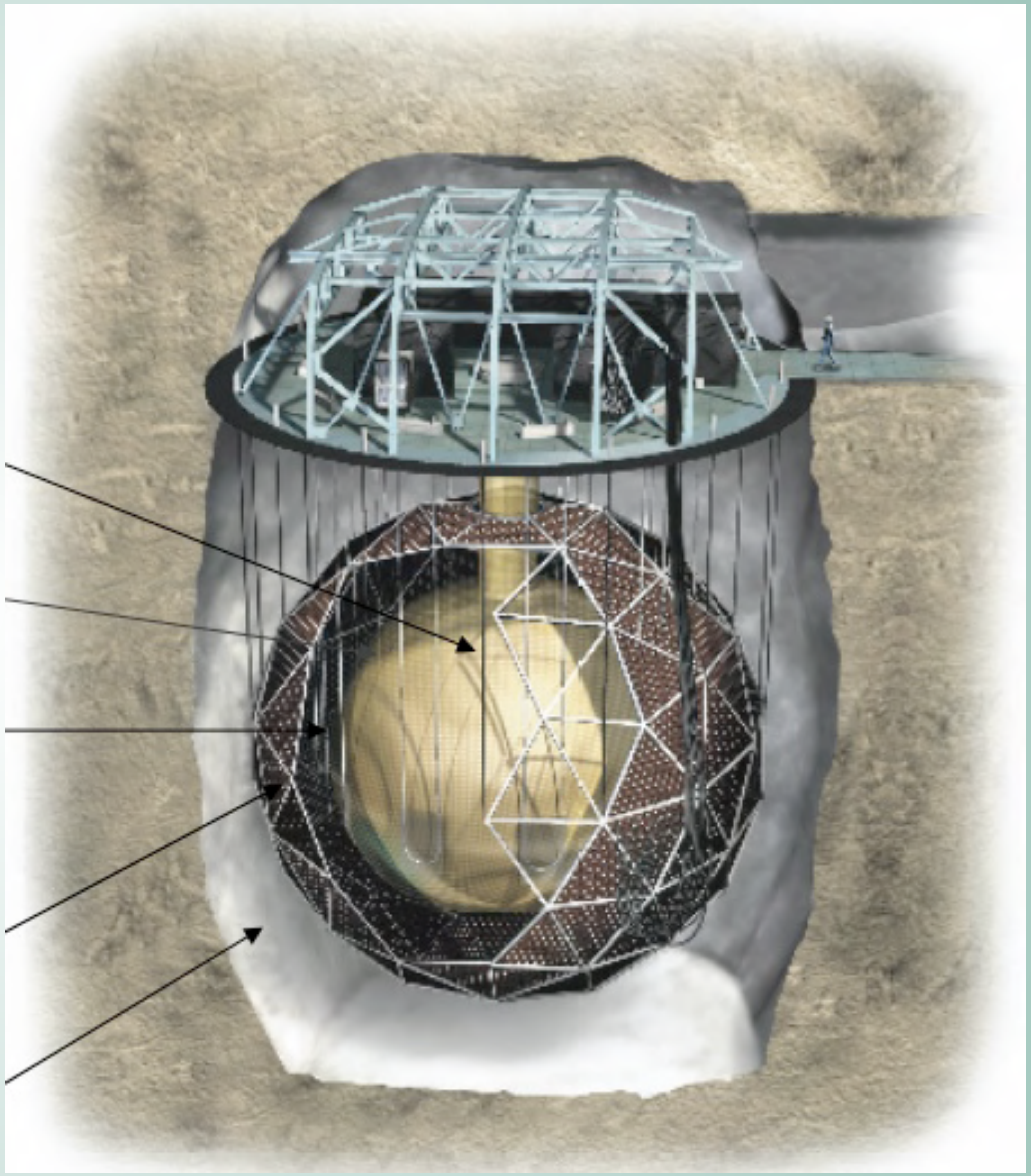
Neutral Current (NC)

$\nu_{e\tau\mu} + d \rightarrow \nu_{e\tau\mu} + p^+ + n$

Charged Current

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

Sensitive to all 3 flavors
Different Signals

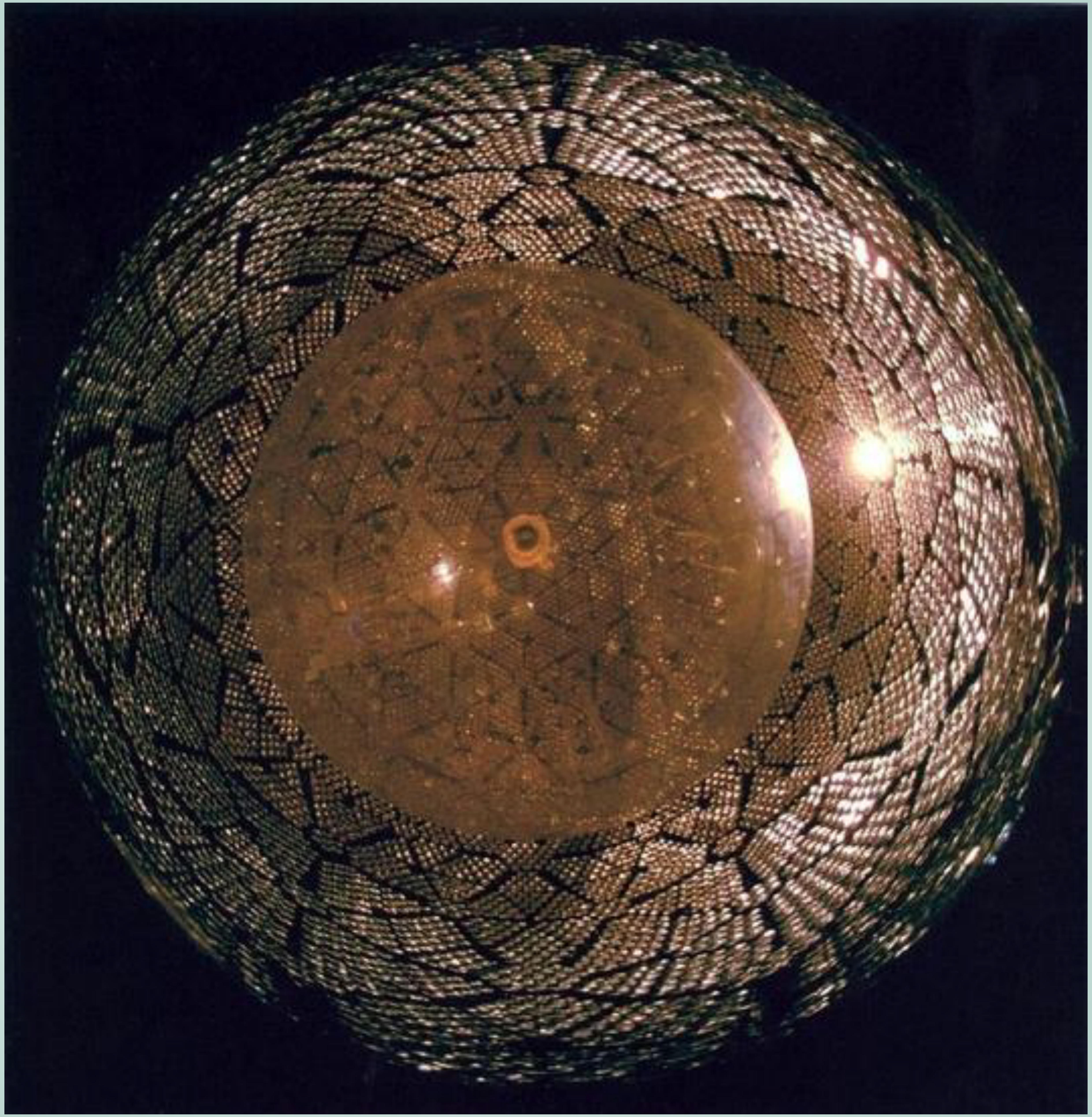


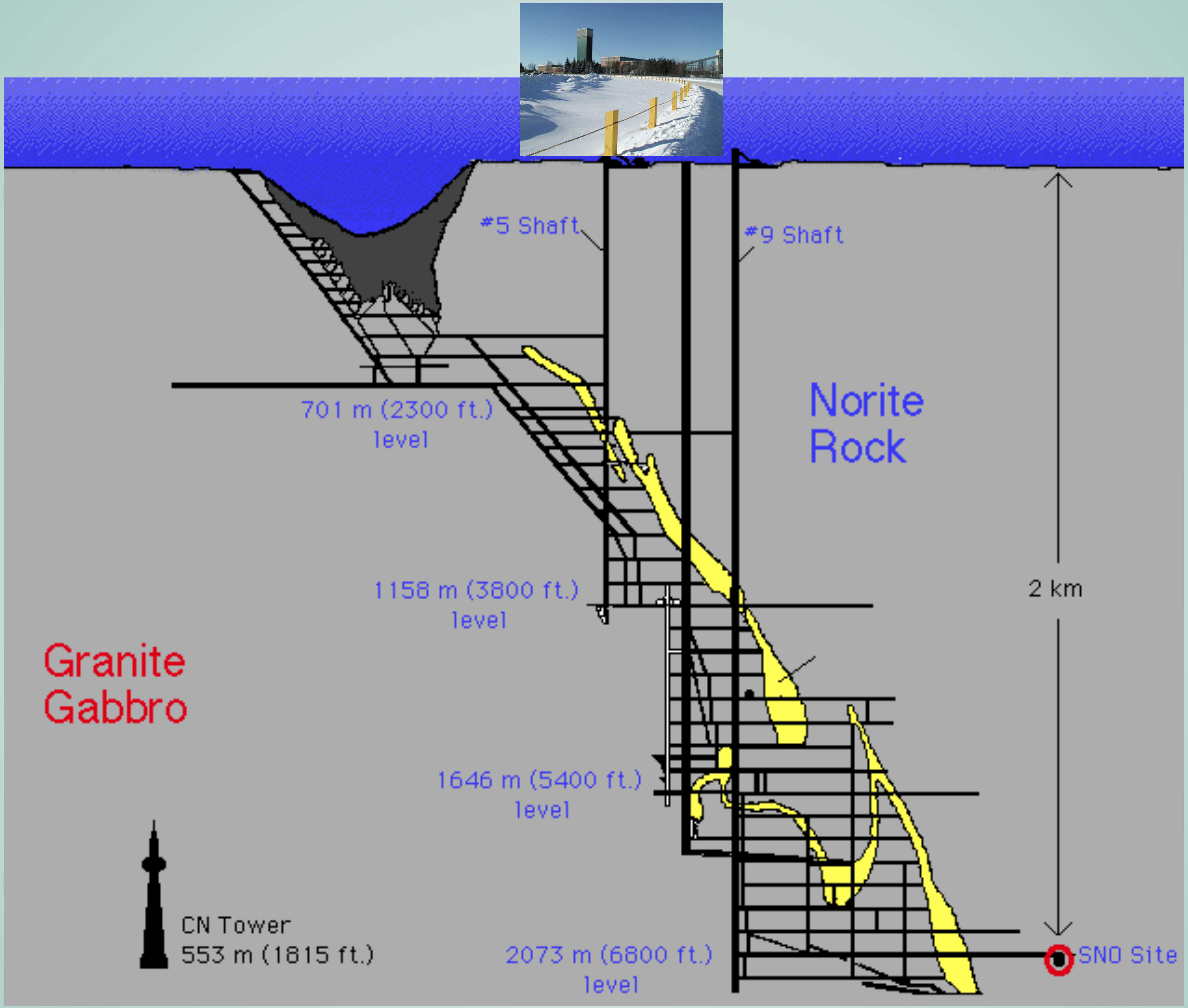
3 Phases:

I: $n + d \rightarrow {}^3H + \gamma + 6.3$ MeV

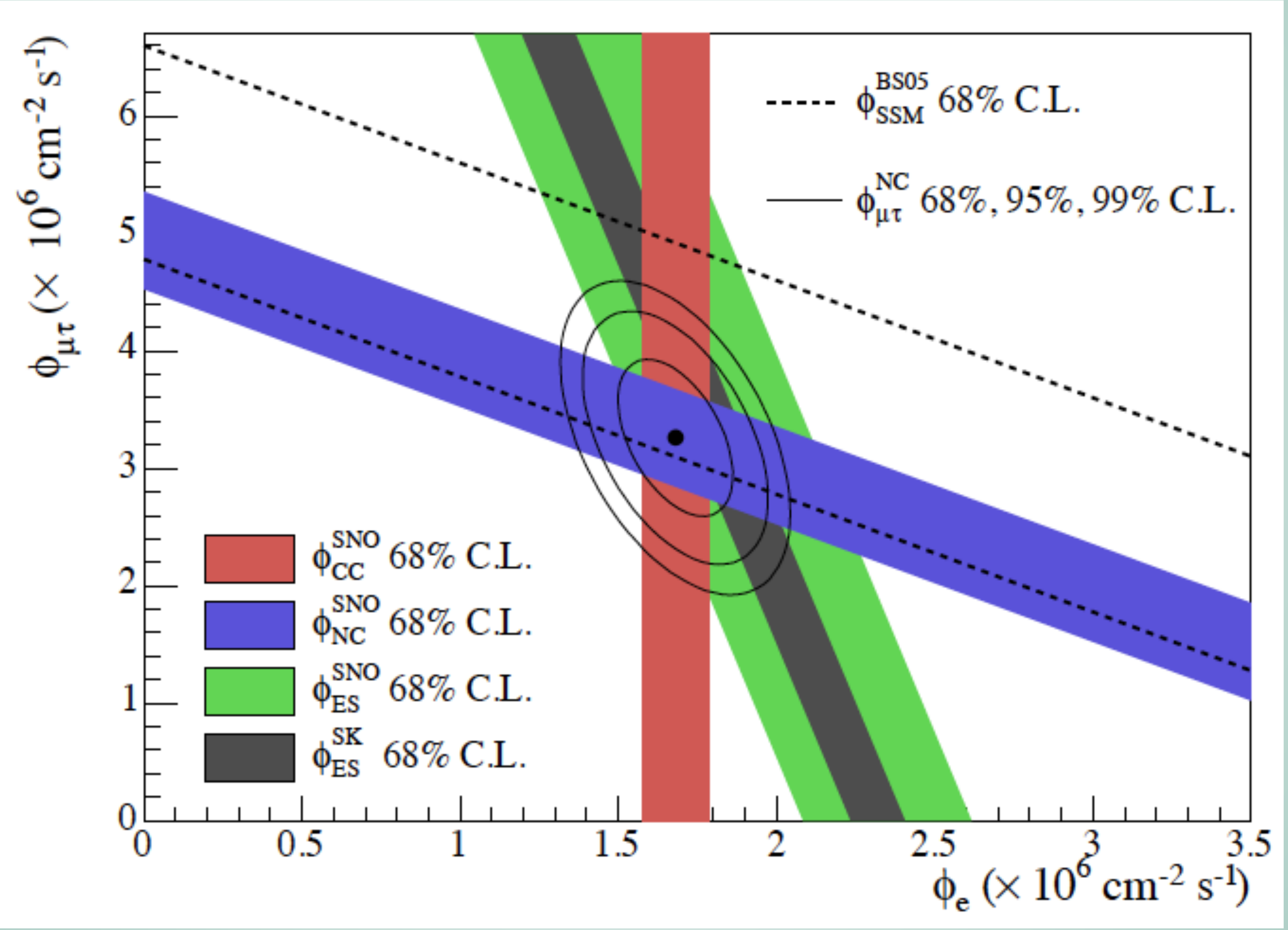
II: $n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6$ MeV

III: $n + {}^3He \rightarrow {}^3H + p + 0.76$ MeV

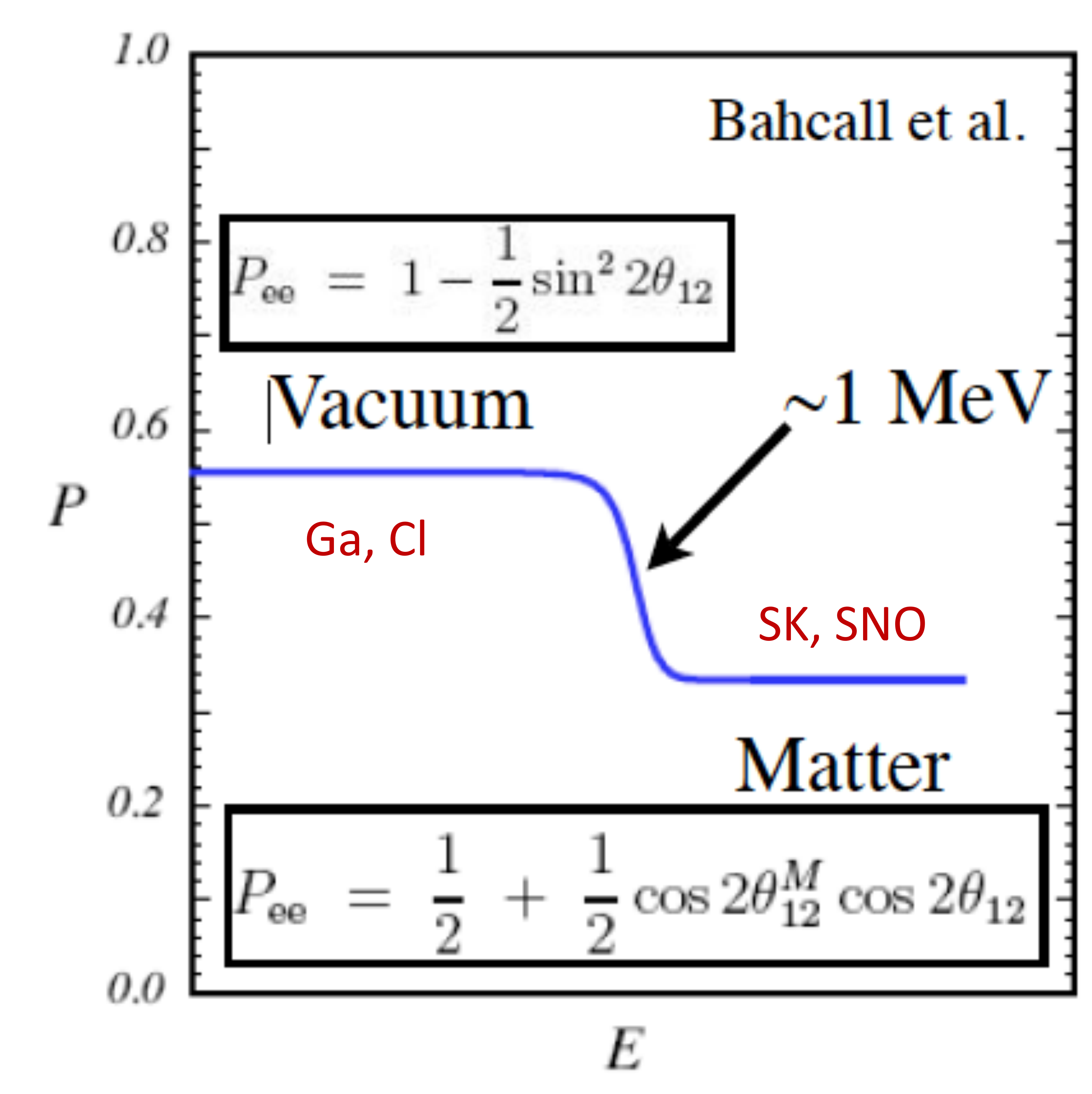



#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
1158 m (3800 ft.) level
2 km
Granite Gabbro
1646 m (5400 ft.) level
CN Tower
553 m (1815 ft.)
2073 m (6800 ft.) level
SNO Site

Solar Neutrino Problem Solved!



Interpretation



2002: Discovery of Reactor Neutrino Oscillations

- Late 90s: Evidence for neutrino oscillations become compelling from solar neutrino and atmospheric neutrinos.
- Not observed in reactor neutrinos yet, though

Probability of ν_e disappearance:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

KamLAND

2800 mwe in Kamioka mine in Japan

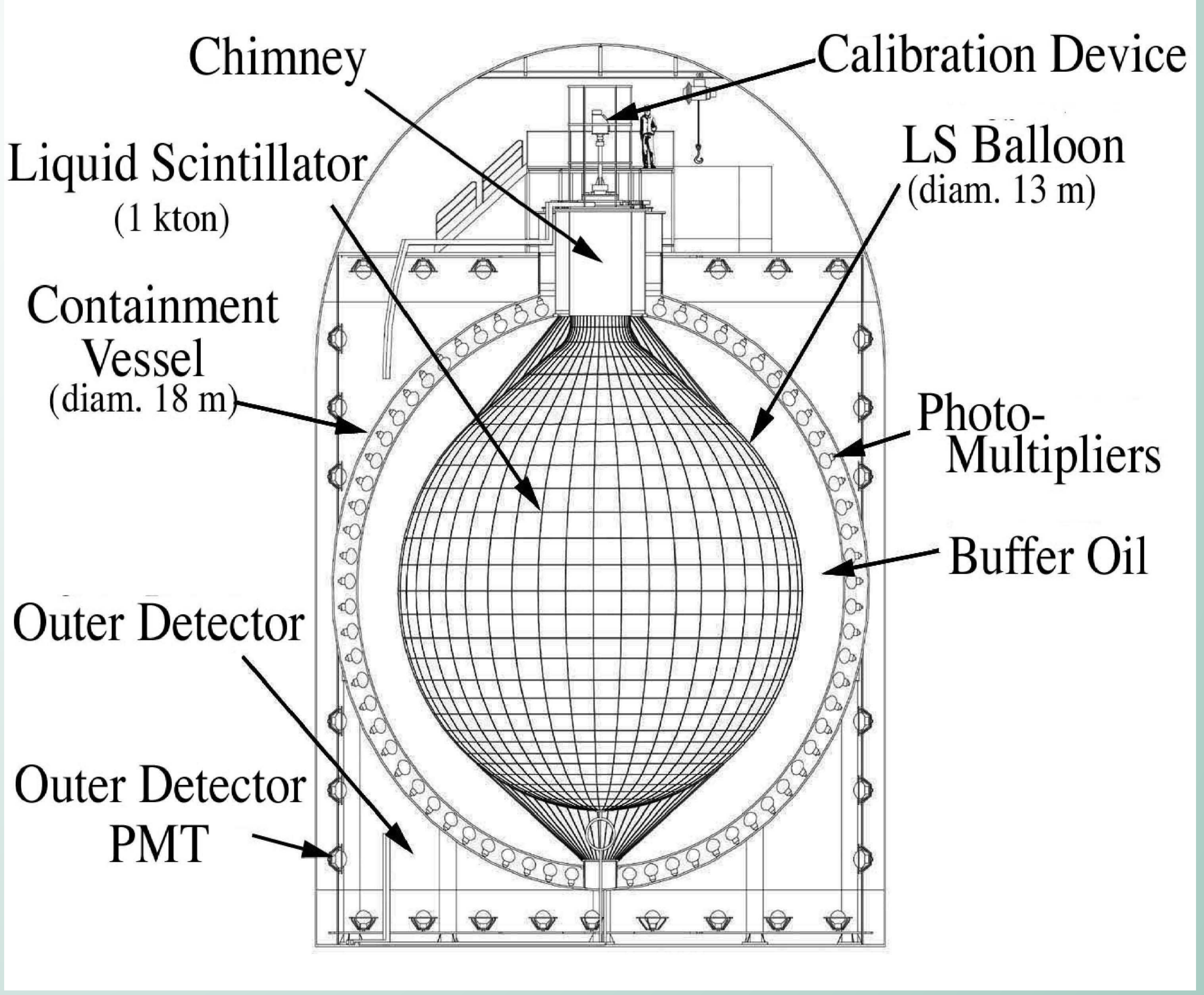
~ 200km from reactors

1 kton ultra pure liquid scintillator (80% dodecane, 20% pseudocumene) doped with fluor (2,5-Diphenyloxazole)

1900 PMTs

Muon veto and buffer shield

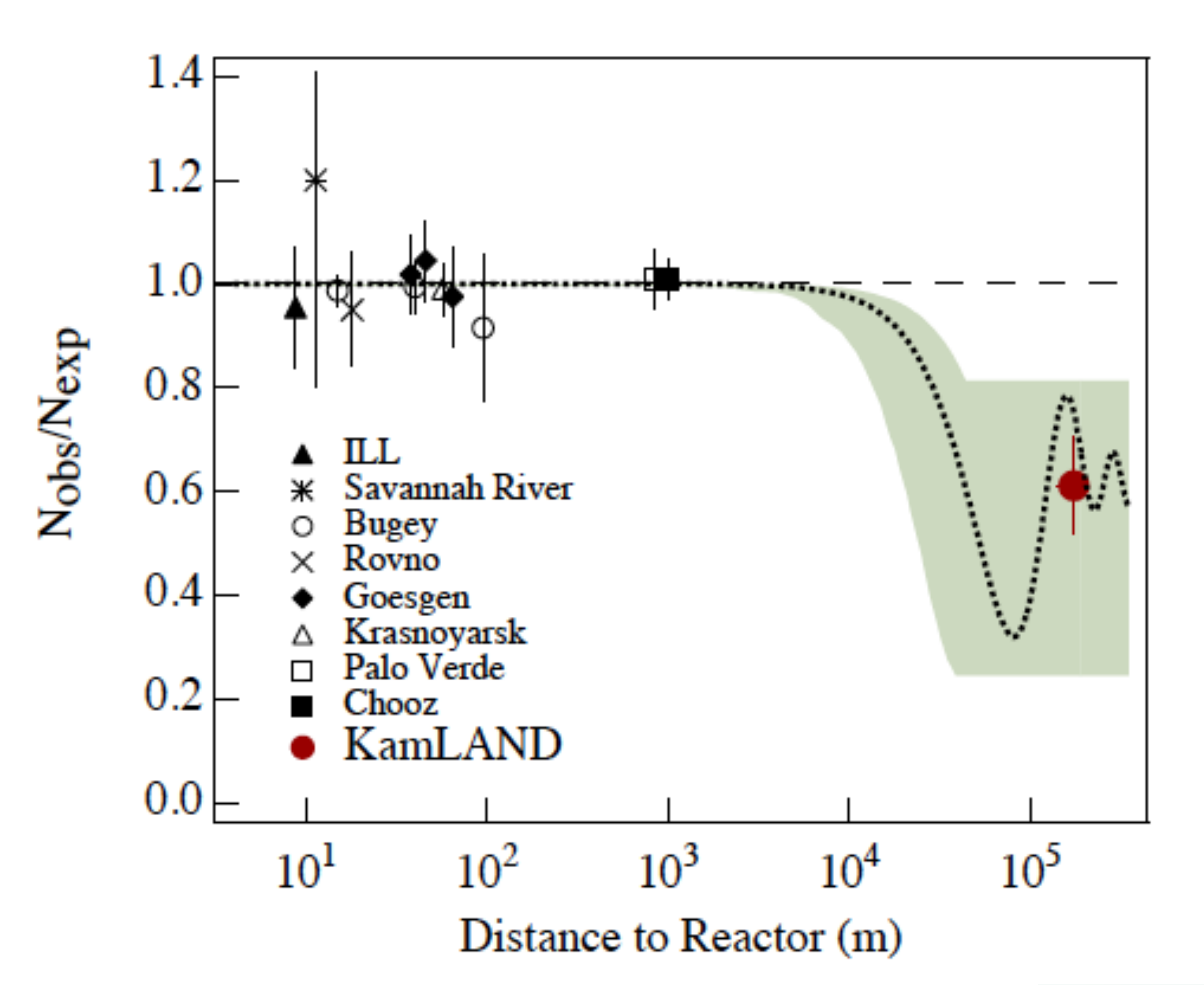
(add map)

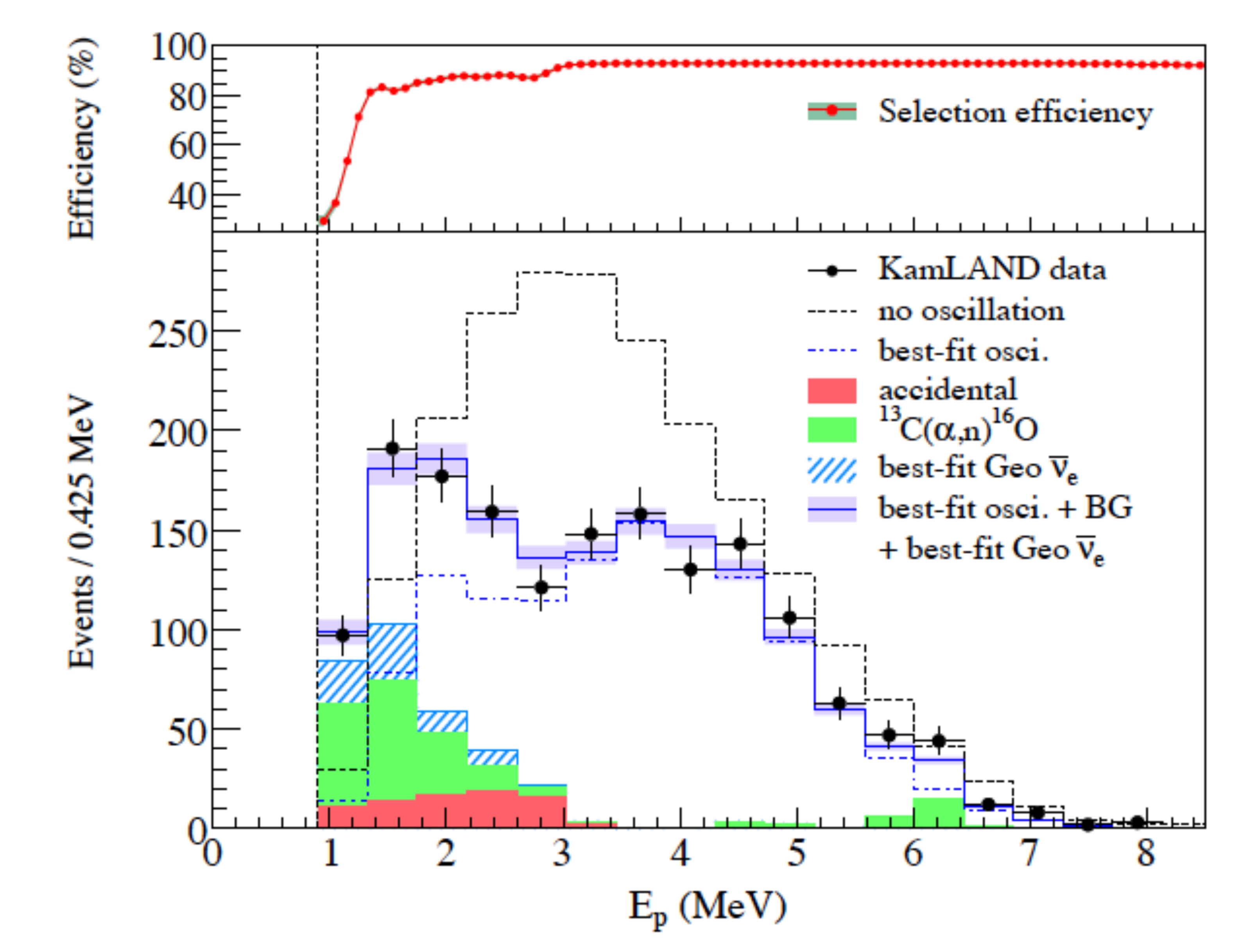


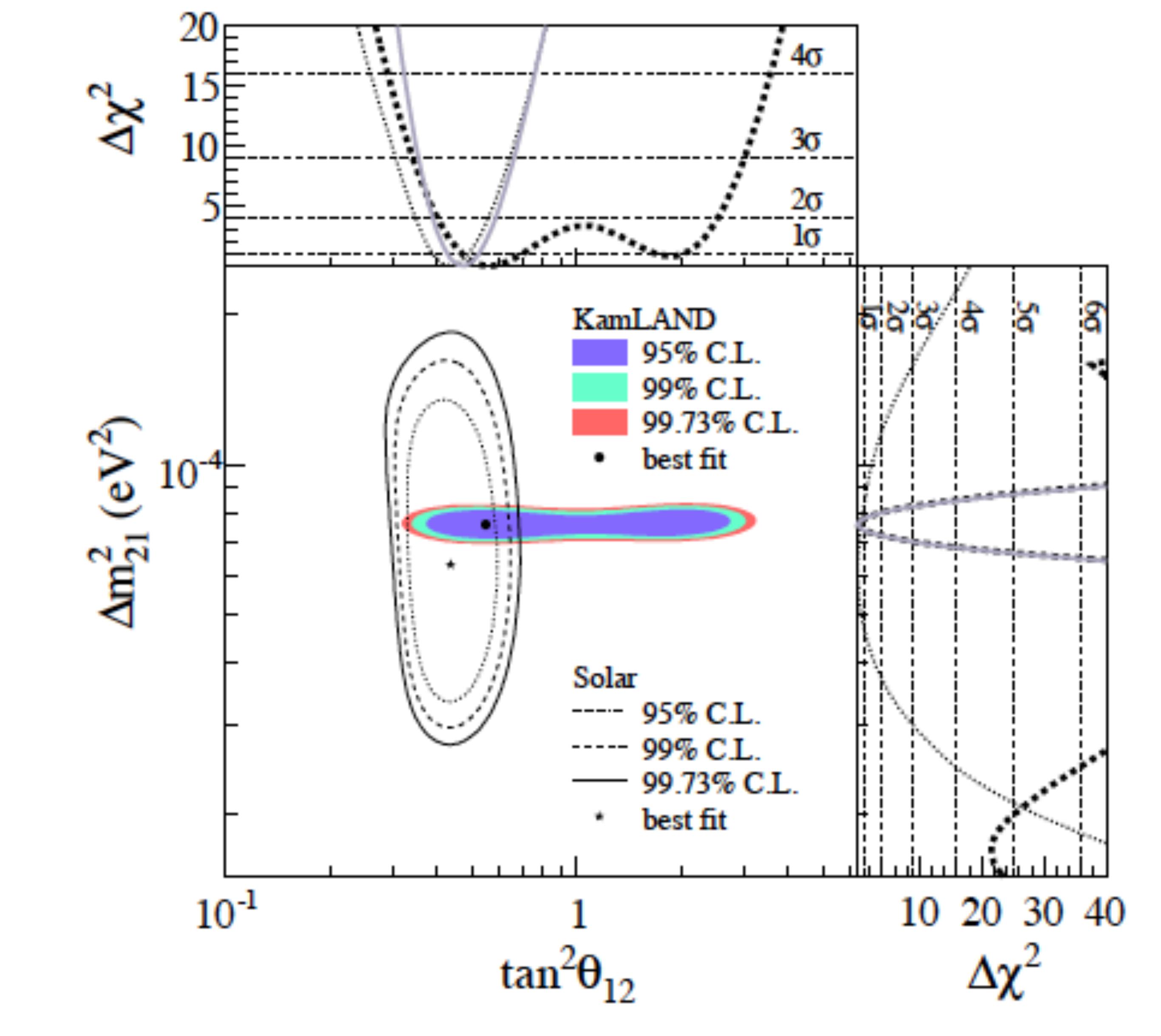
Main KamLAND Results

2002: First observation of ν_e disappearance at very long baselines

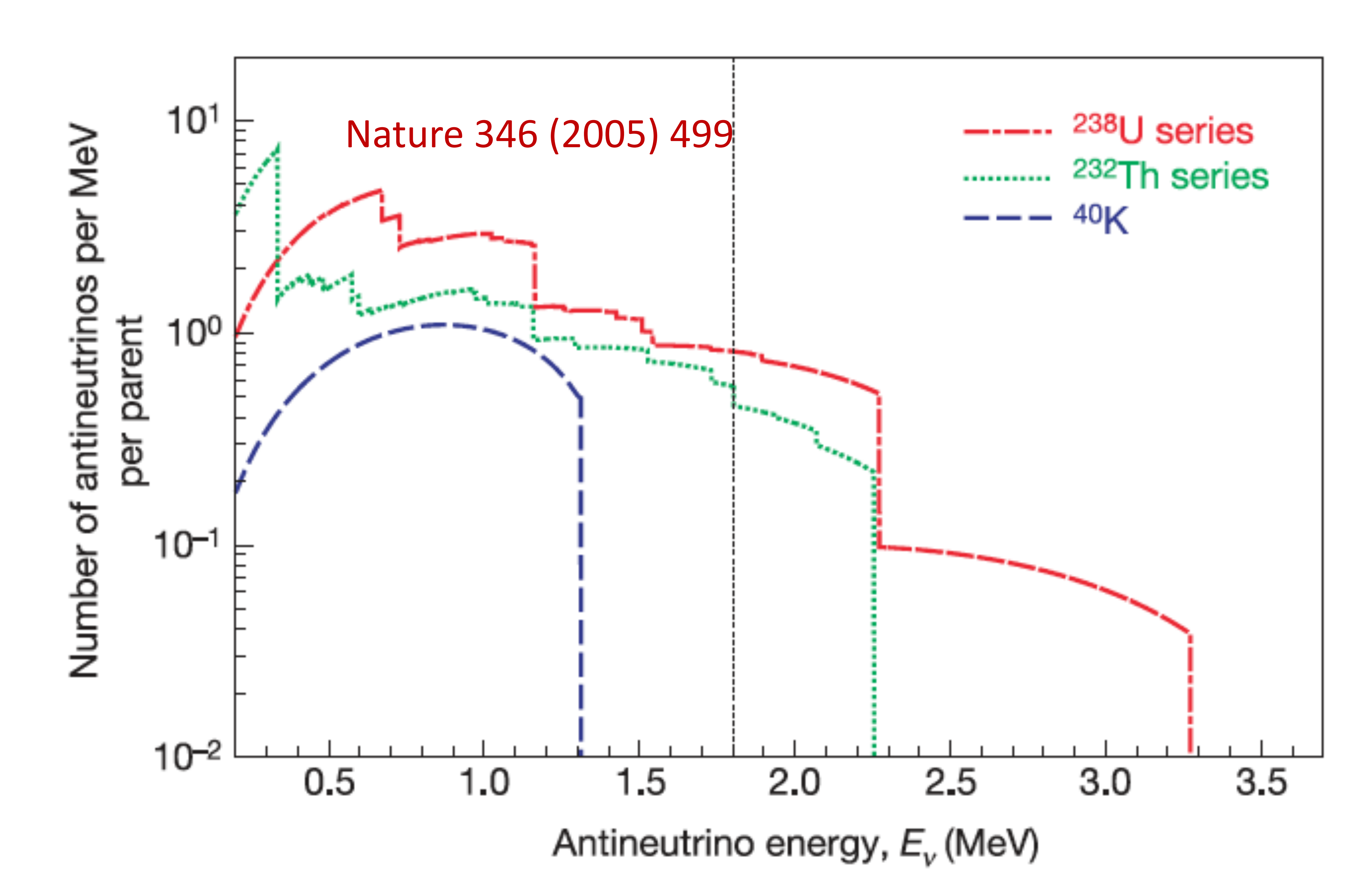
Precision measurements of mixing parameters consistent with solar experiments



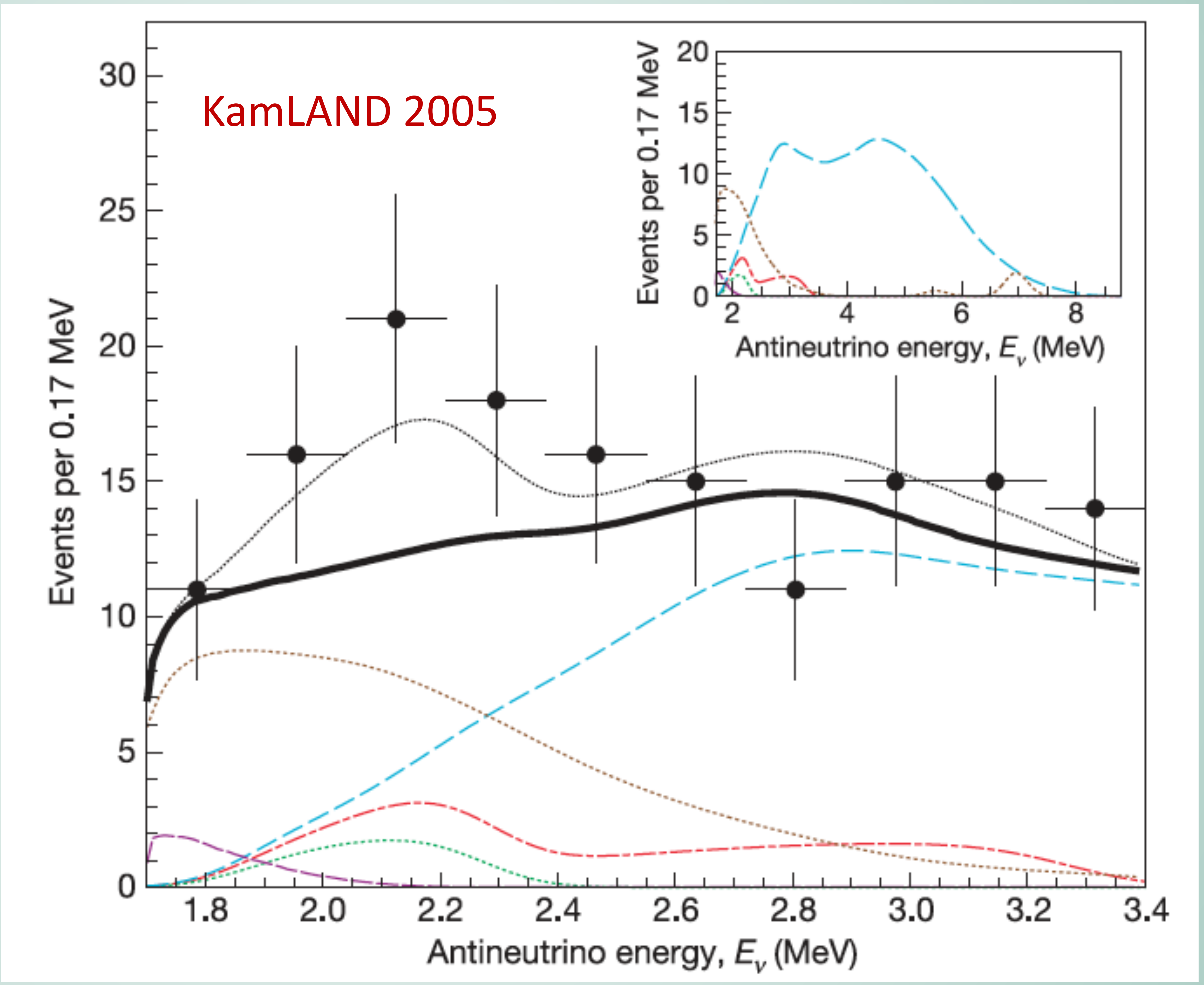




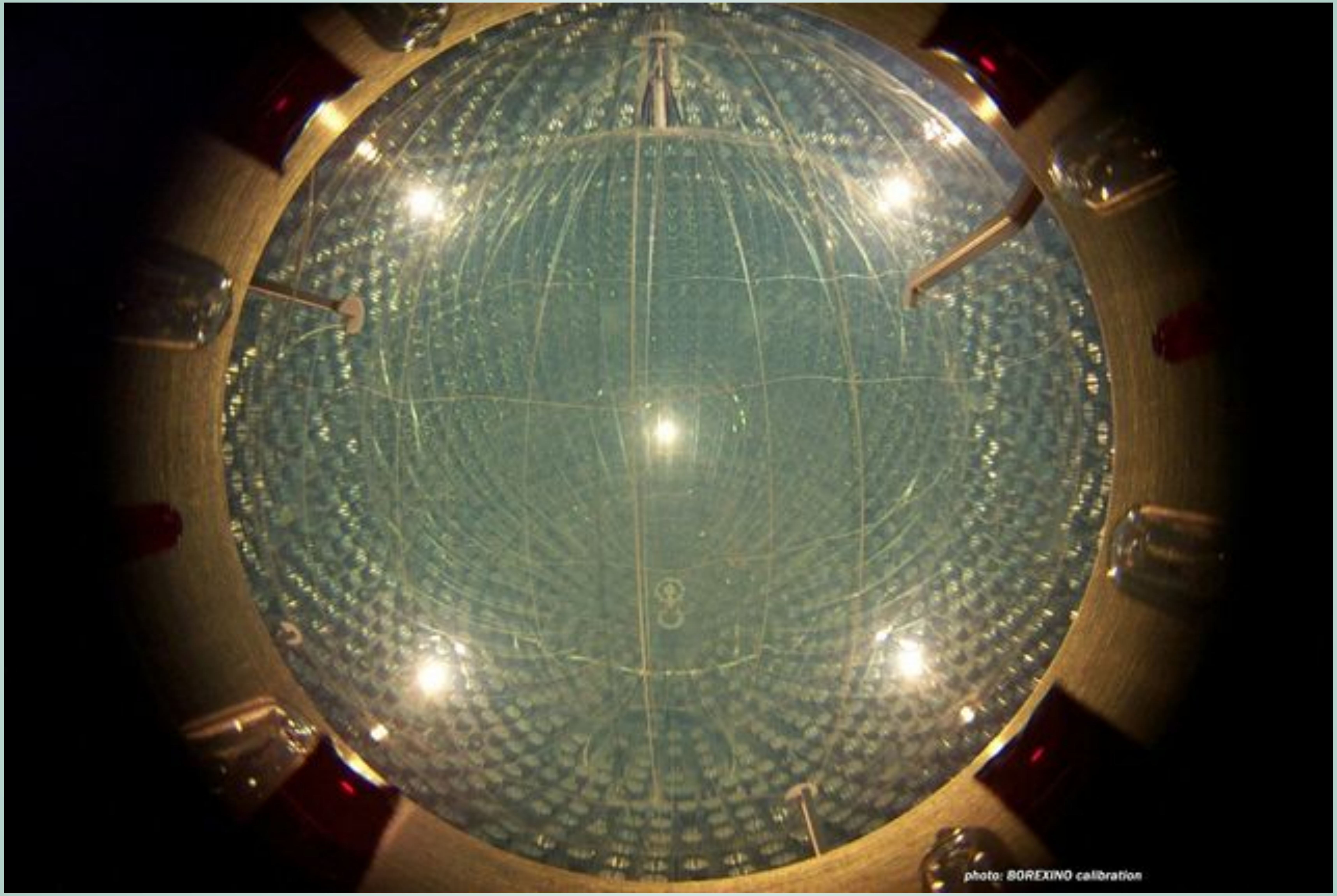
2005: Discover of Geoneutrinos



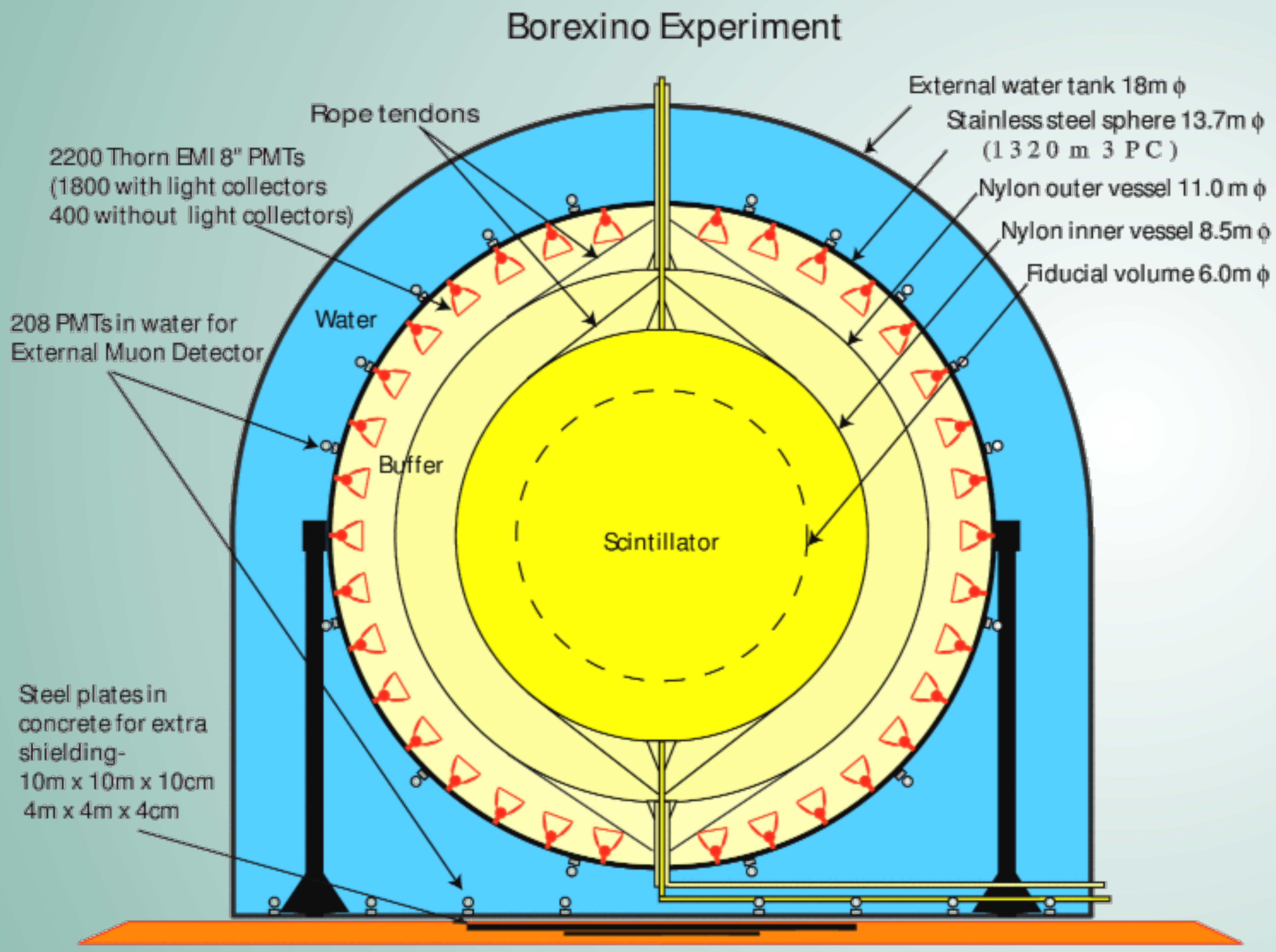
Geoneutrinos Initial Hints

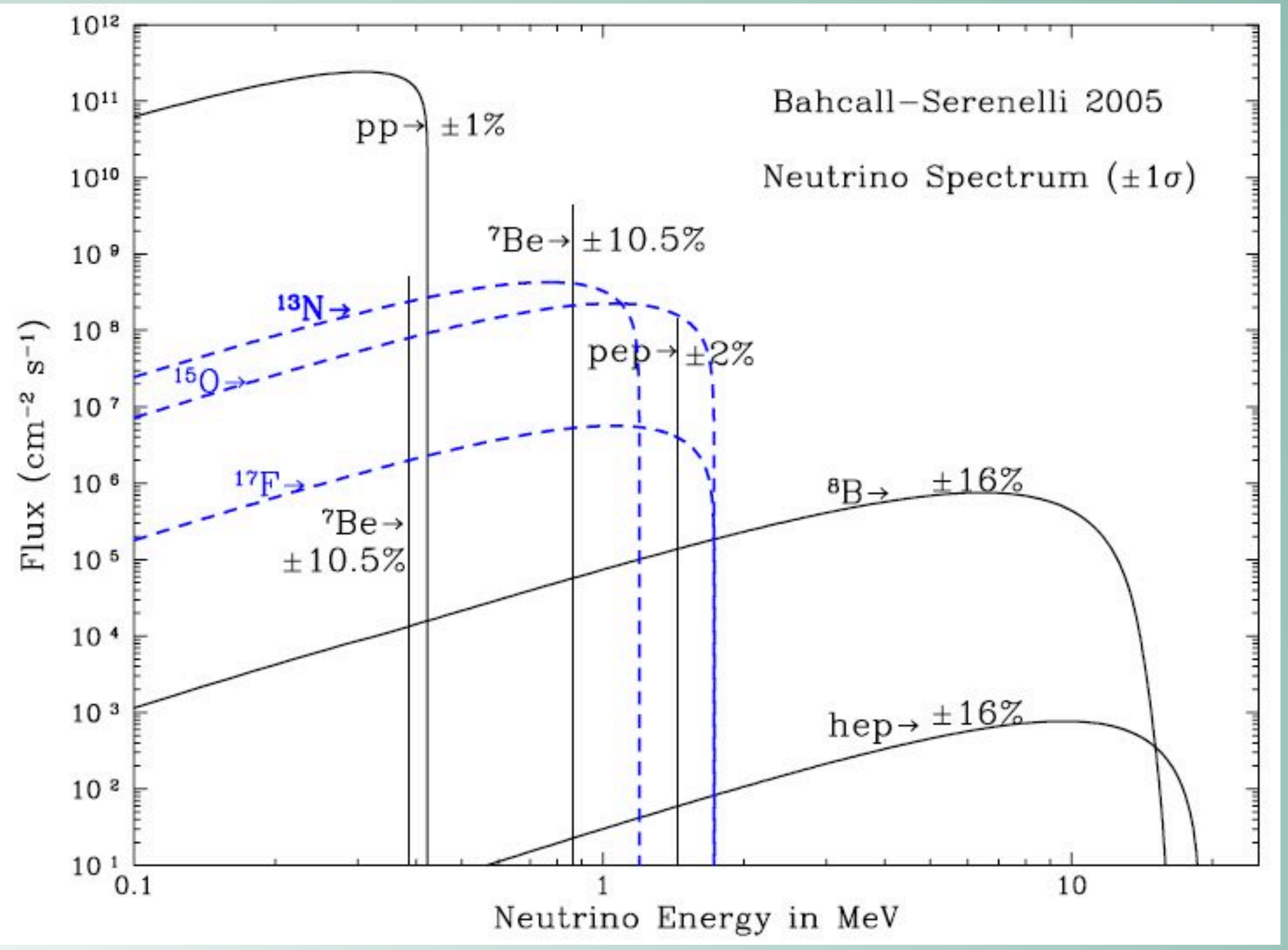


BOREXINO



BOREXINO





Search for ^{7}Be neutrinos via

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

Careful control of backgrounds
First measurements of ^{7}Be (2008) and pep (2011) neutrinos

Geoneutrino Discovery

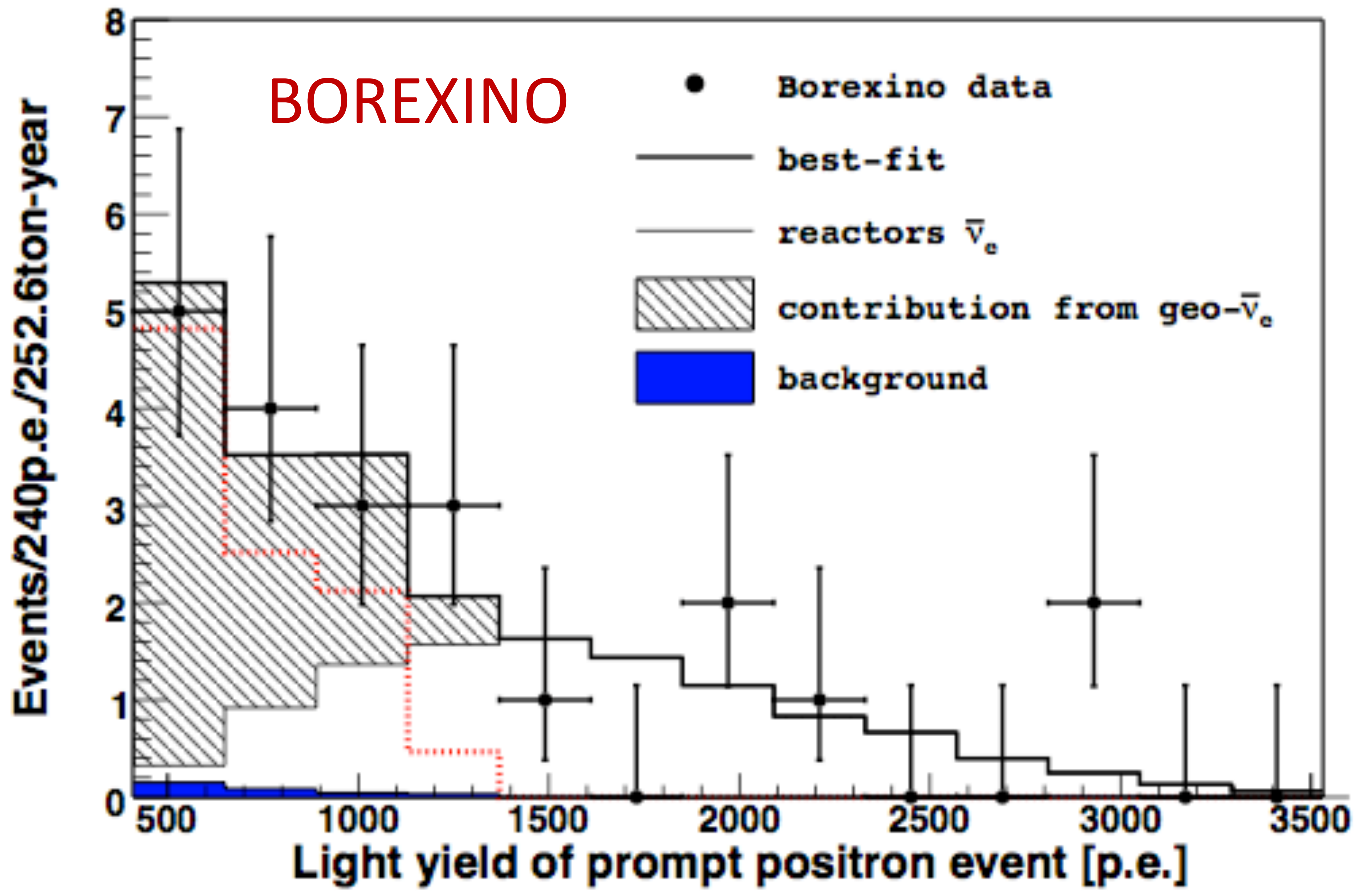
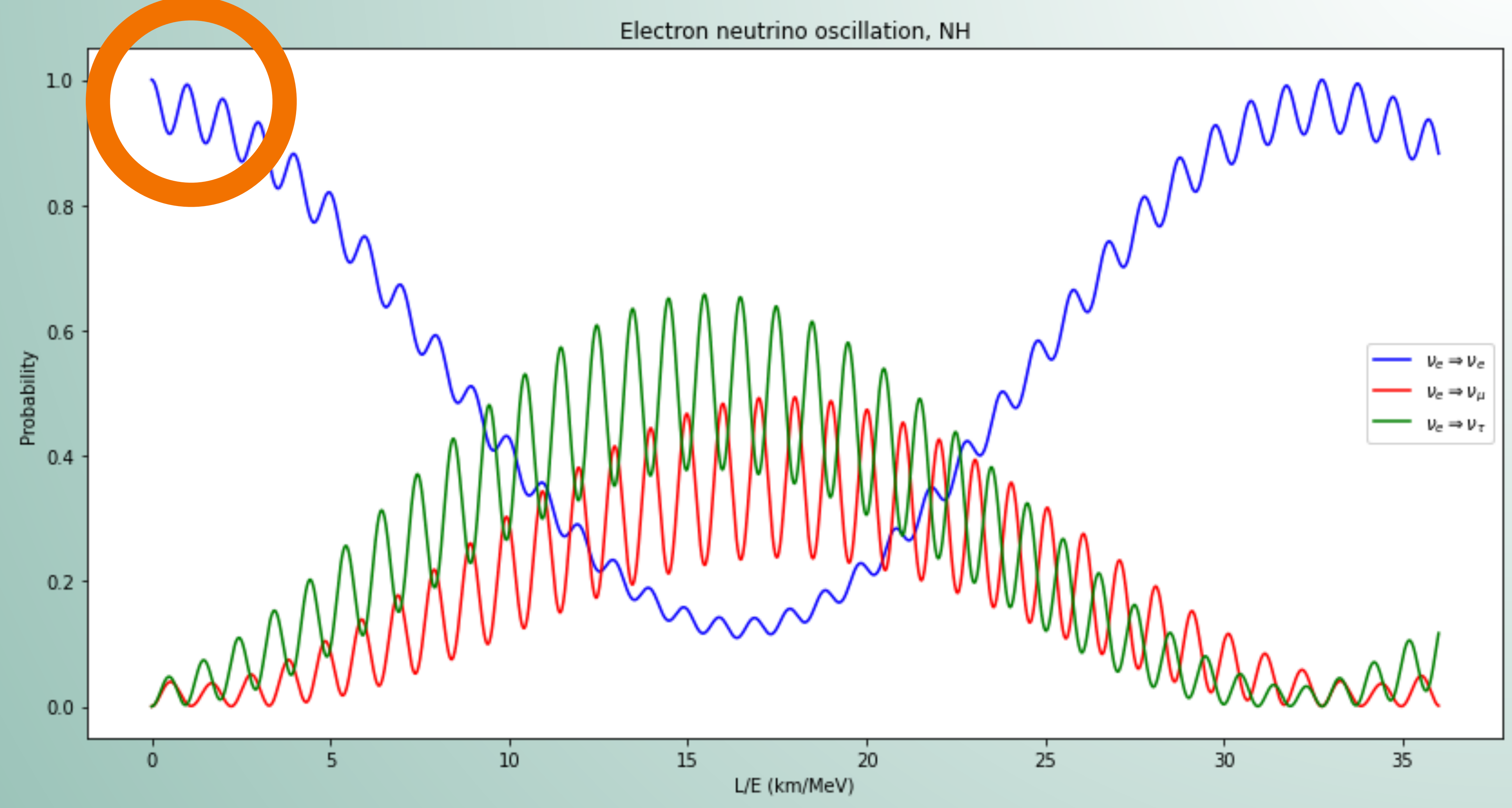


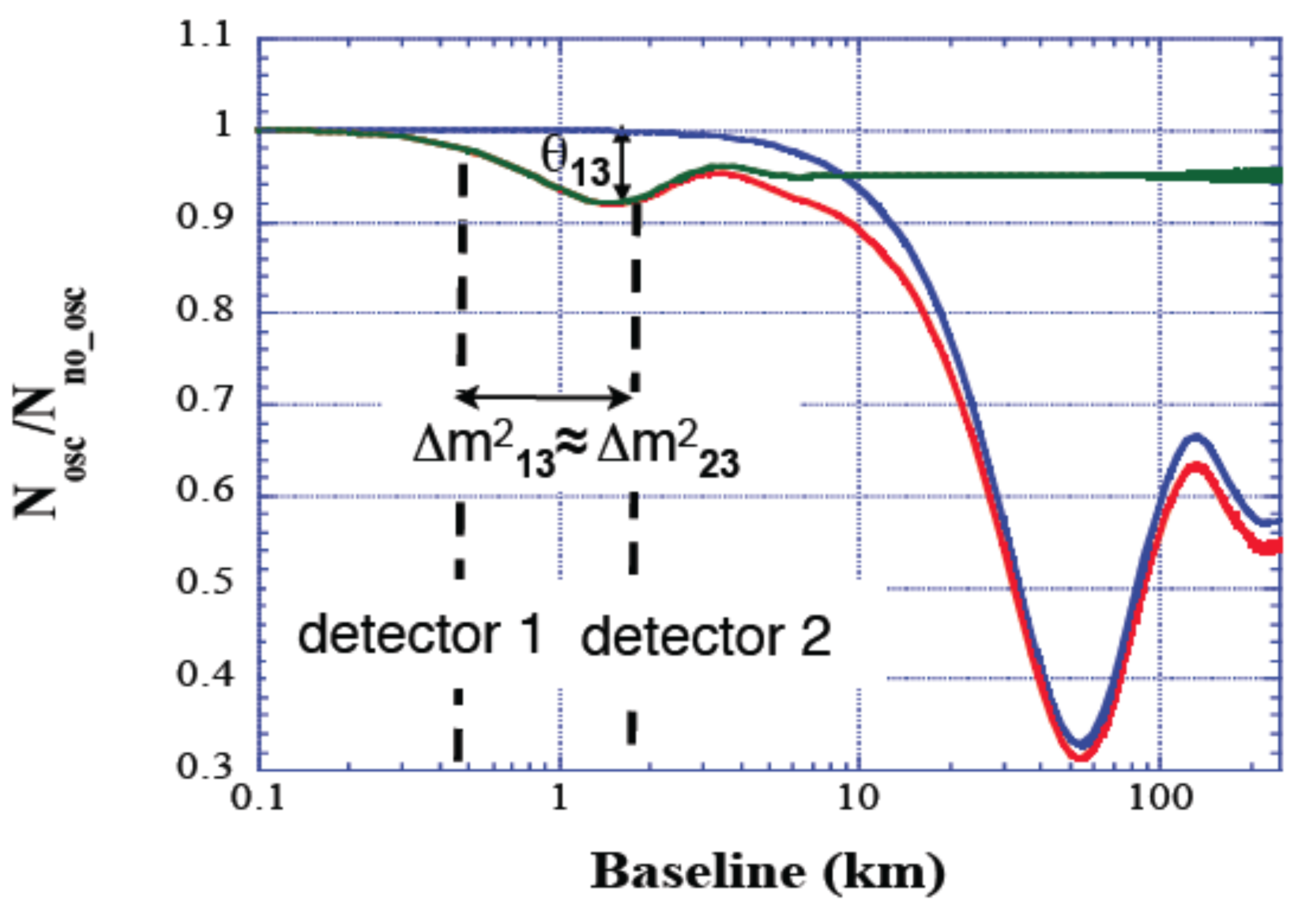
Figure 3: Light yield spectrum for the positron prompt events of the 21 $\bar{\nu}_e$ candidates and the best-fit with Eq. (5) (solid thick line). The horizonal axis shows the number of p.e. detected by the PMTs. The small filled area on the lower left part of the spectrum is the background. Thin solid line: reactor–$\bar{\nu}_e$ signal from the fit. Dotted line (red): geo–$\bar{\nu}_e$ signal resulting from the fit. The darker area isolates the contribution of the geo–$\bar{\nu}_e$ in the total signal. The conversion from p.e. to energy is approximately 500 p.e./MeV.

2012: First measurement of θ_{13}

- Non-zero θ_{13} required for observable *CP* violation in neutrino sector
  - Long baseline accelerator experiments.
- Important cosmological implications
- ~ 1km baseline
- Exquisite control of systematic errors to ~1%
- Two, identical detector concept:
  - Near detector monitors reactor output
  - Far detector (1 ~km) searches for ν_e disappearance
  - Cancels many systematics

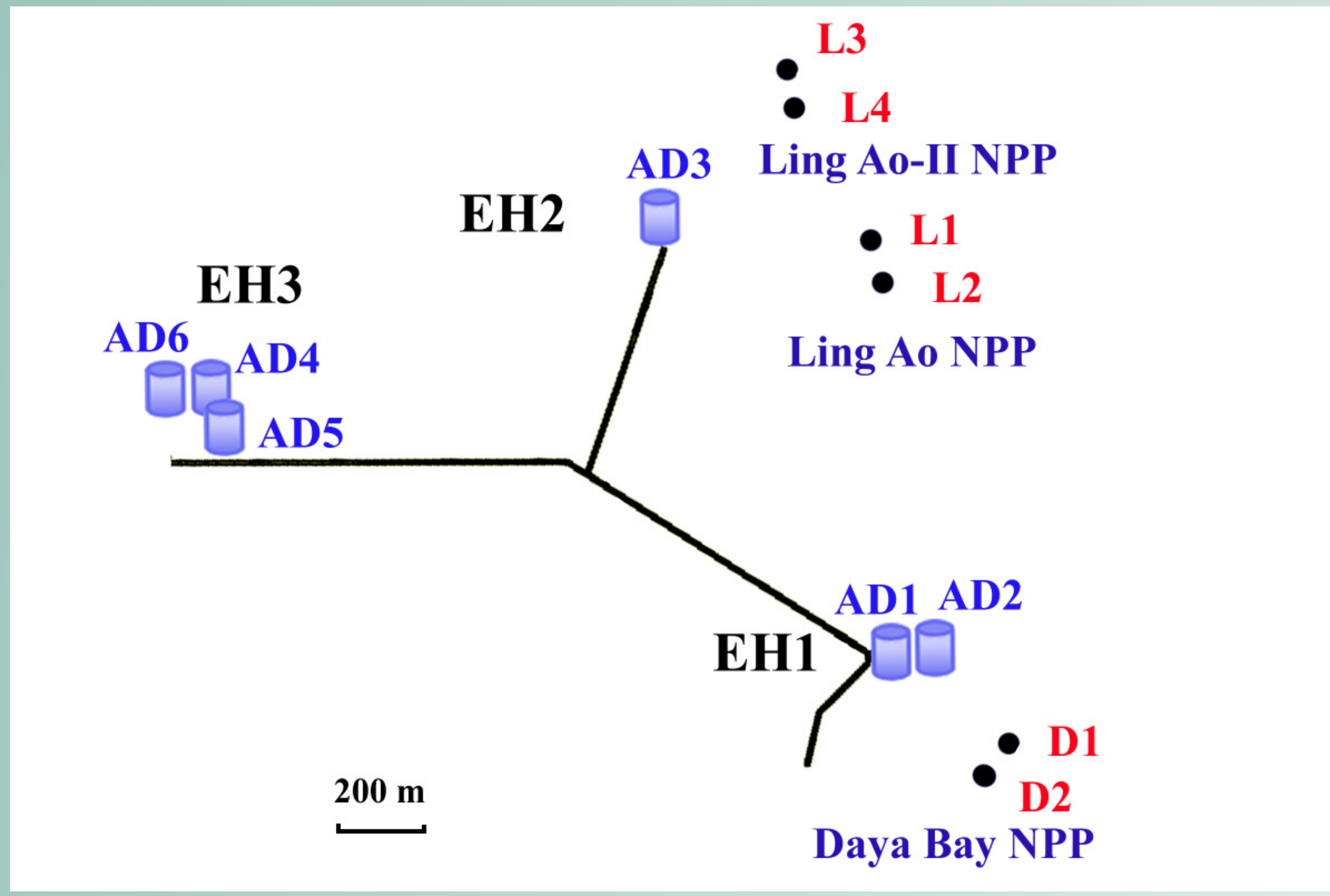
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

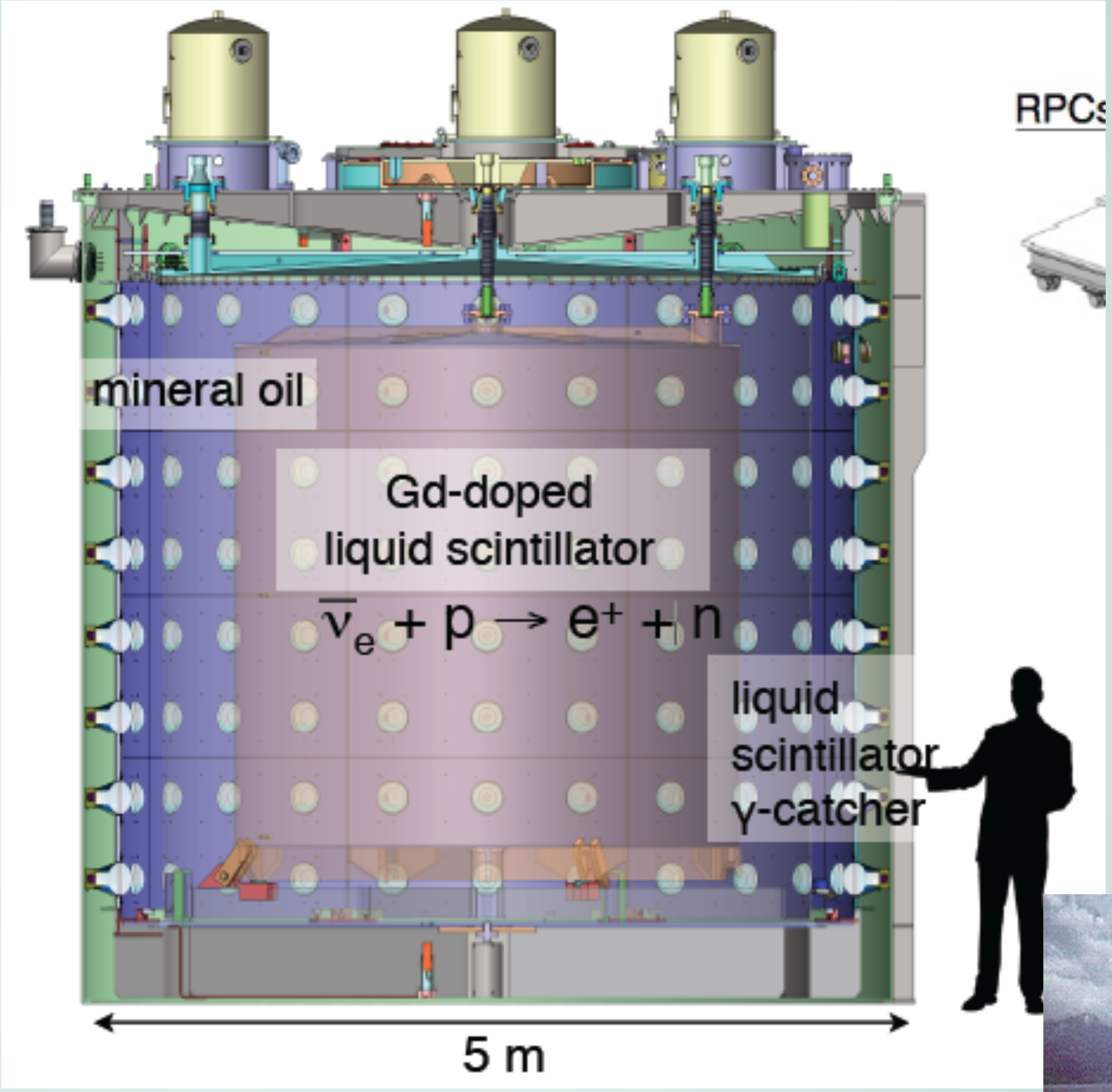




$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

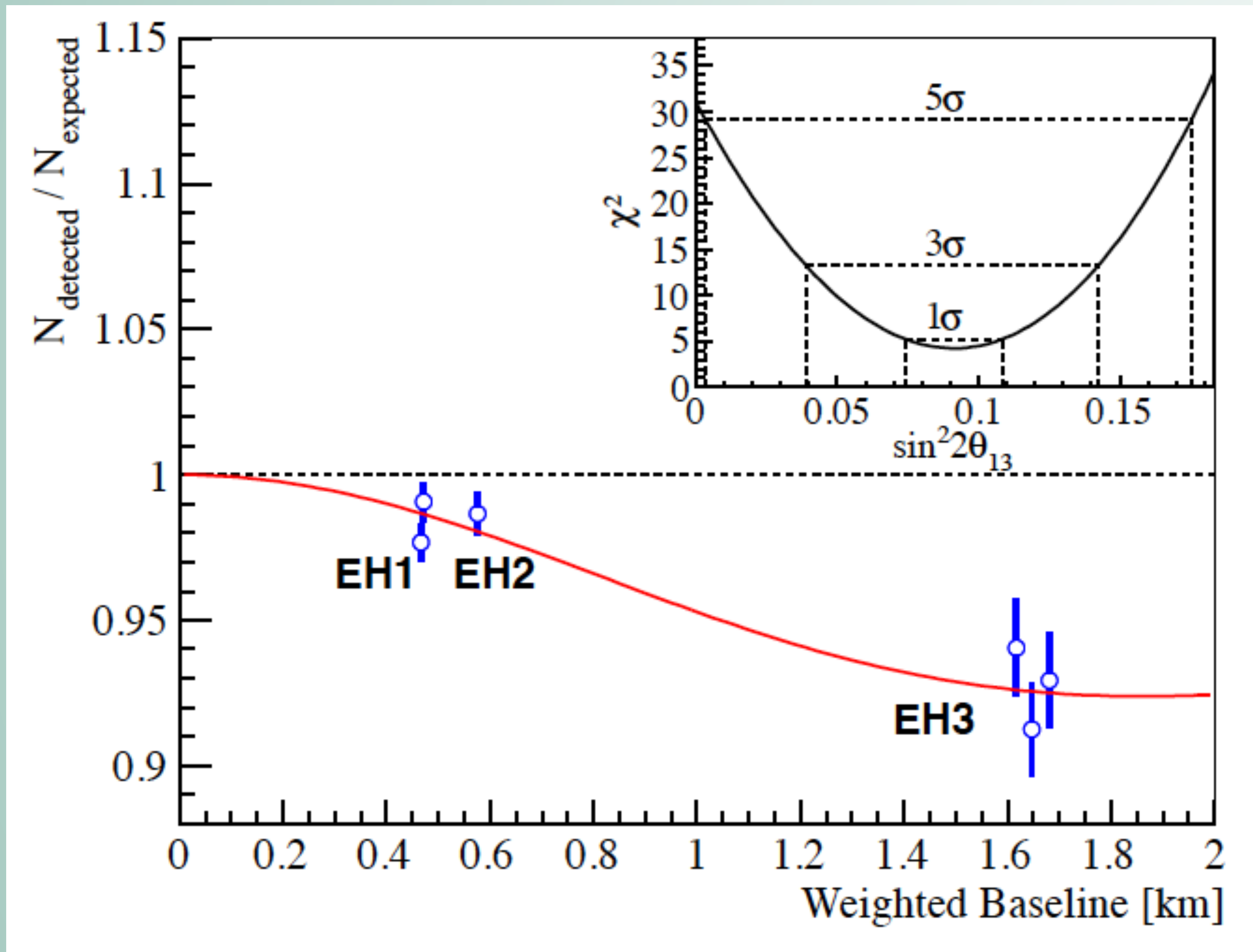
Three Experiments Realized :
Daya Bay

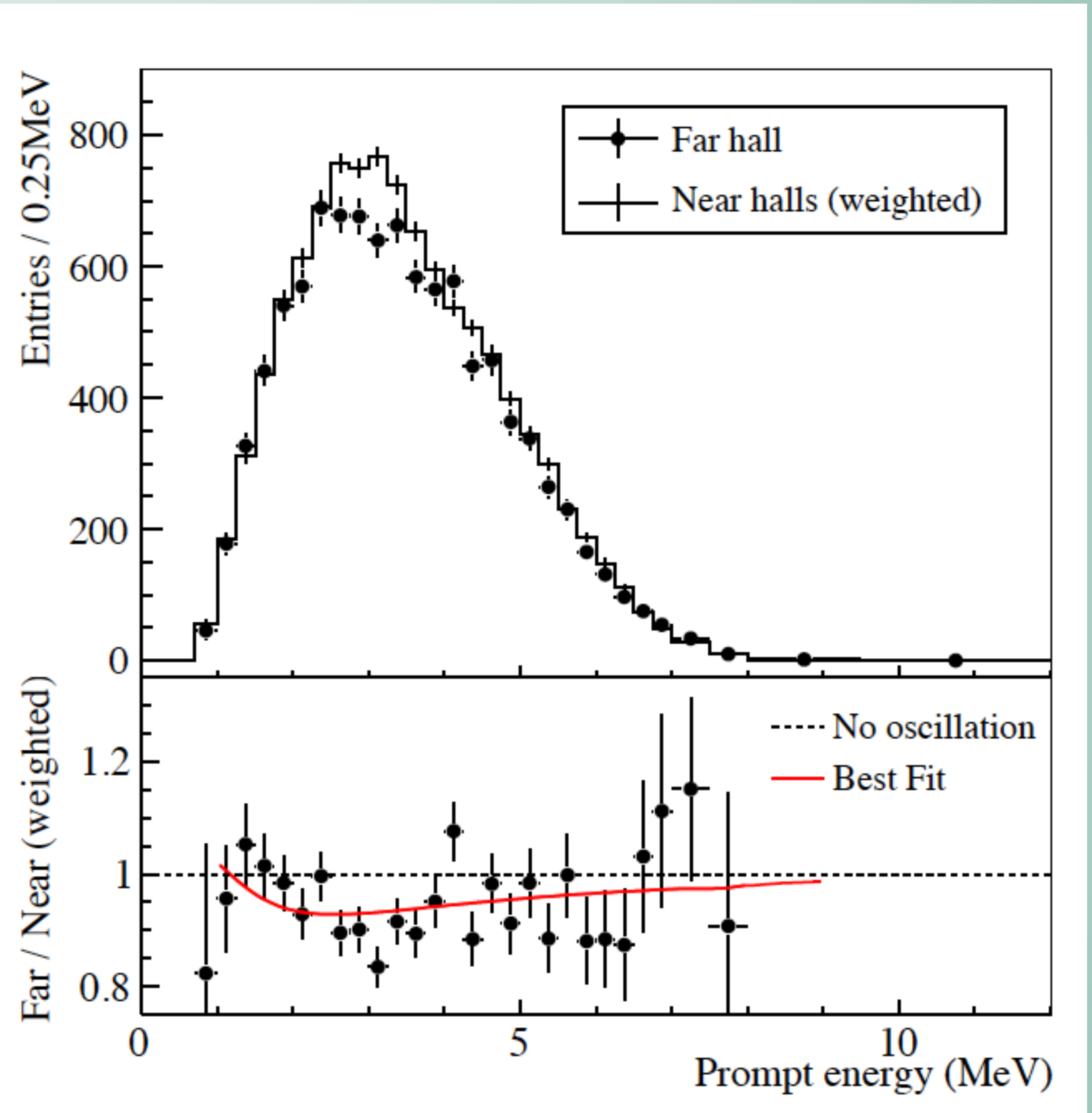




Daya Bay Collaboration

2012: Daya Bay does First measurement of θ_{13}

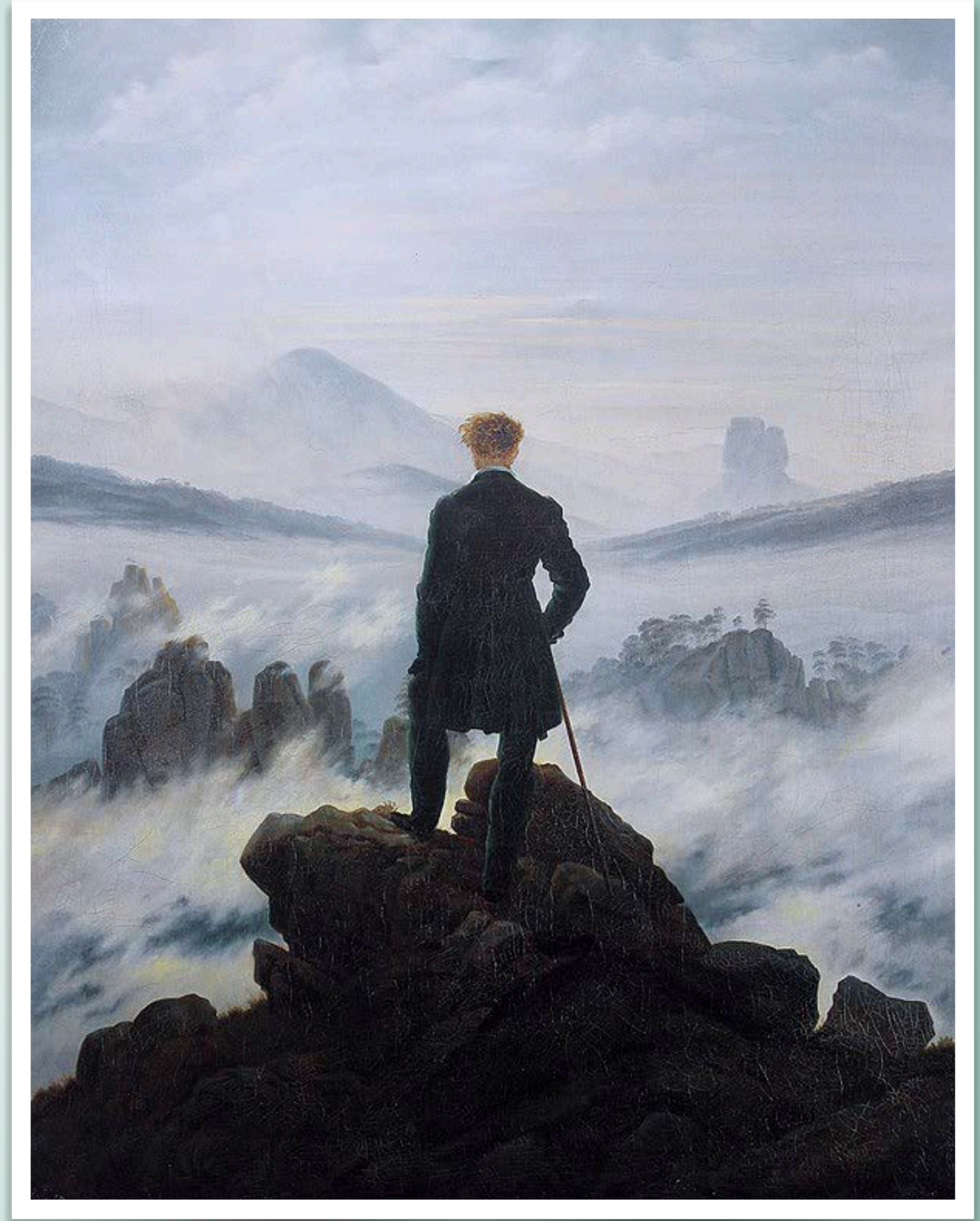




Daya Bay Collaboration

Where We Stand

- 2000: Tau neutrino discovered
- **Neutrinos are massive and have flavor mixing**
- Many questions remain
  - Are neutrinos Majorana or Dirac?
  - What are the neutrino masses?
  - Why are they so light and how are their masses generated?
  - Are neutrino dynamics CP violating? Already violate P…
  - Are there more (sterile) neutrinos?
  - What role did they play in the early universe?
  - How do we detect cosmic relic neutrinos?
  - …

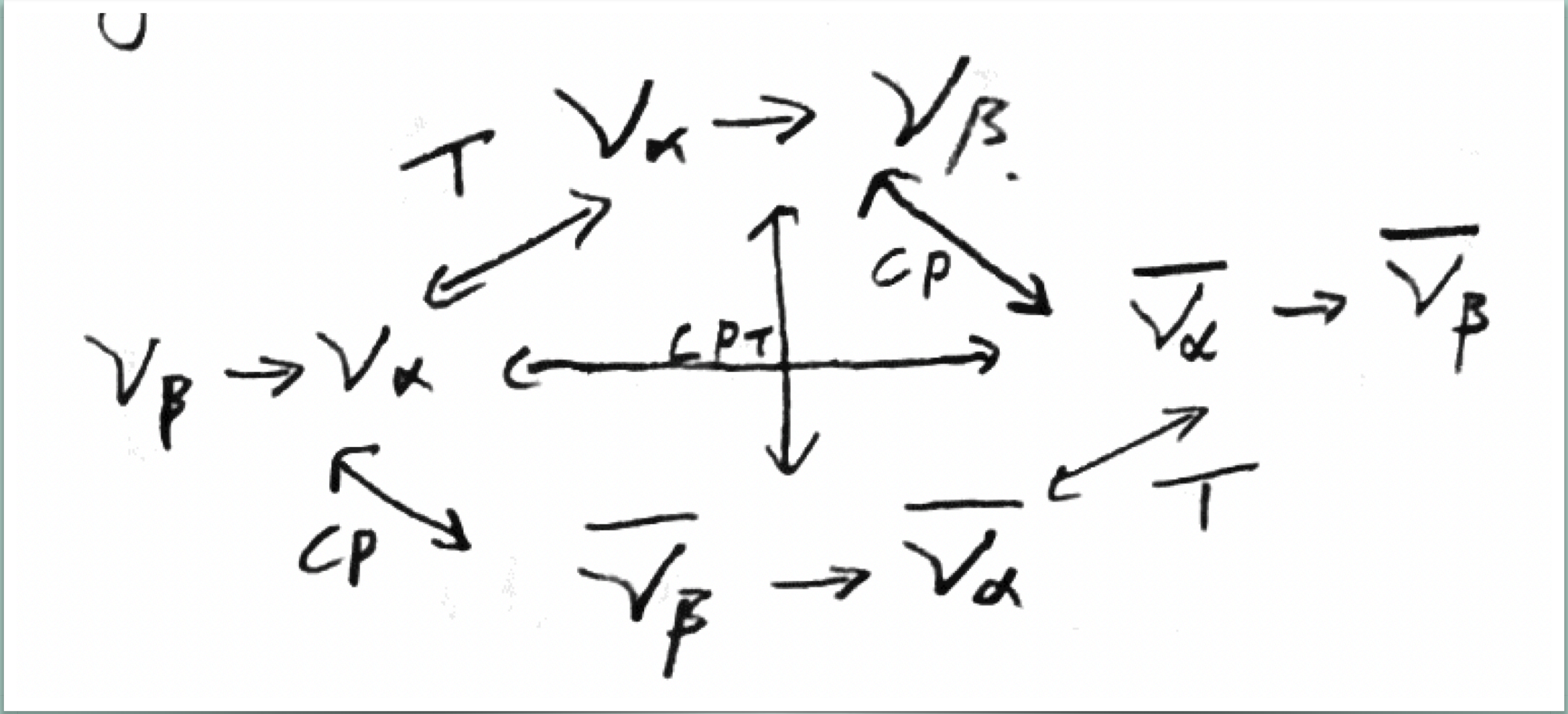


CP Violation

- P Operator changes parity of particle
- C Operator changes particle into anti-particle
- After P-violation was observed, CP was assumed to be conserved
- 1964: Cronin and Fitch showed CP violated by weak force in kaon oscillations.
- **1967: Sakharov Conditions** to Explain Matter/Antimatter Differences in universe (part in 10^{10}):
  - Baryon number violation
  - C and CP violation
  - Thermal non-equilibrium early universe
- Not enough CP violation in SM to explain matter in universe.
- Open question if neutrino dynamics violate CP
- CPT (T = Time Reversal) is still good symmetry.
  - Models that violate CPT difficult in SM framework

Wikipedia

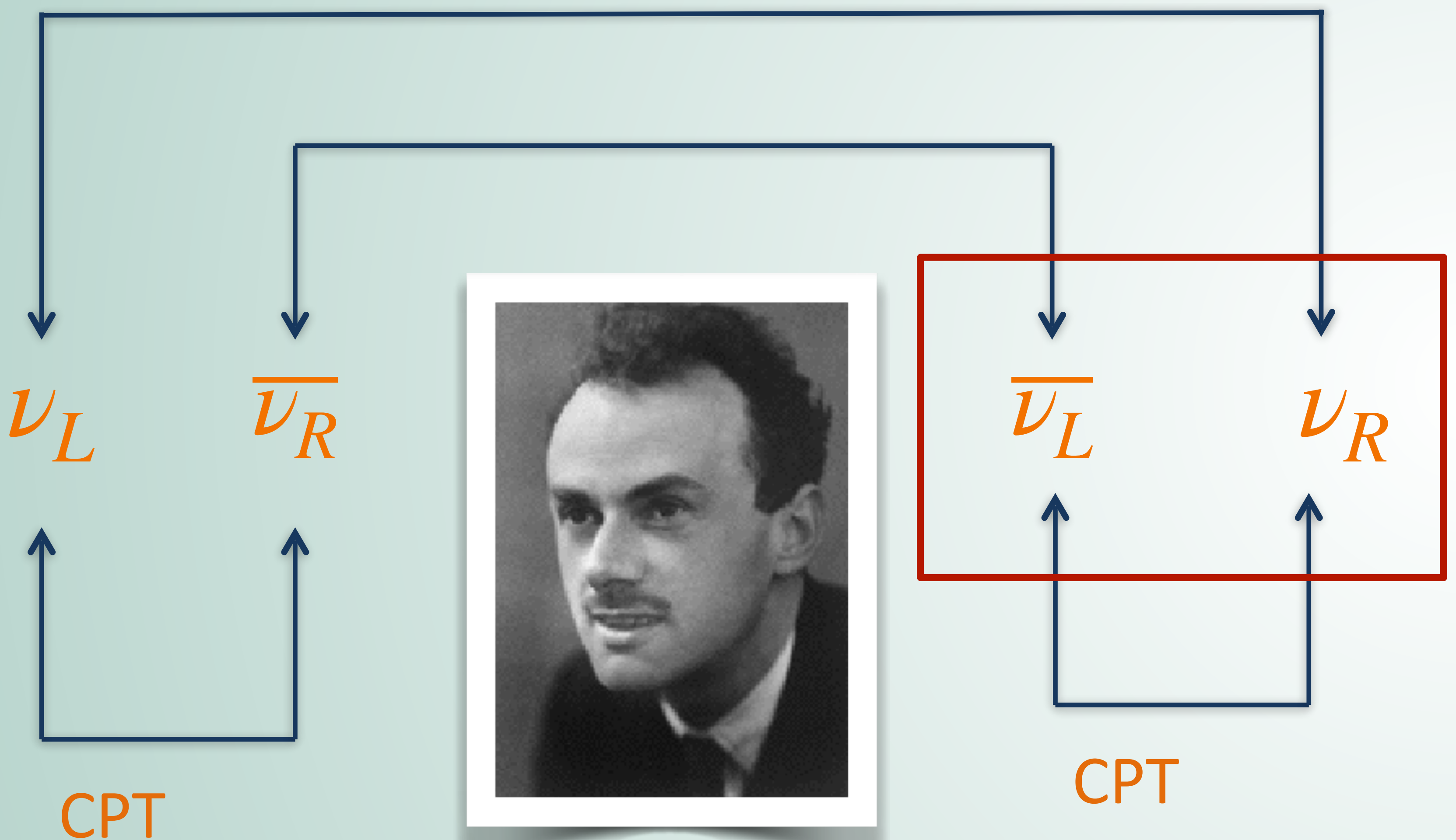
Symmetries in Neutrino Oscillation Probabilities



Symmetries and Majorana/Dirac

Note: Only valid if neutrinos are massive.

Lorentz Boost



CPT

CPT

Not Observed in Nature

$\nu \neq \overline{\nu}$

Lorentz Boost

CPT

$\nu = \overline{\nu} = \nu^M$

Original argument by Kayser, 1985

3 - Flavor Mixing

$\theta_{12} \approx 30°$ $\delta = ?$

$\theta_{23} \approx 45°$ $\alpha_i = ?$

$\theta_{13} \approx 10°$

Pontecorvo–Maki–Nakagawa–Sakata matrix (PMNS matrix)

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

e.g. $|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$

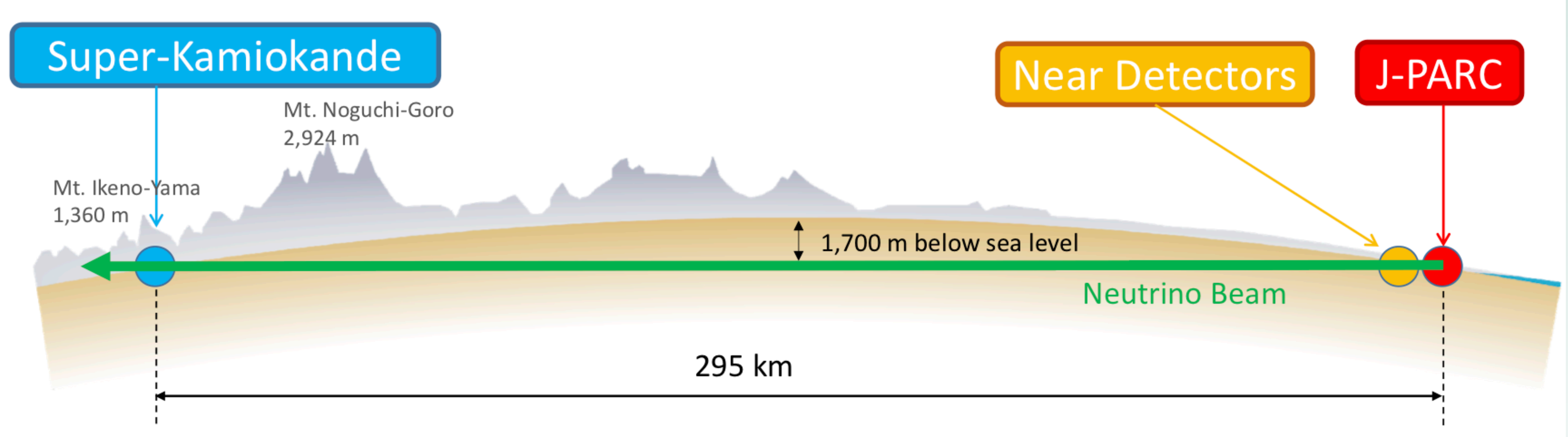
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

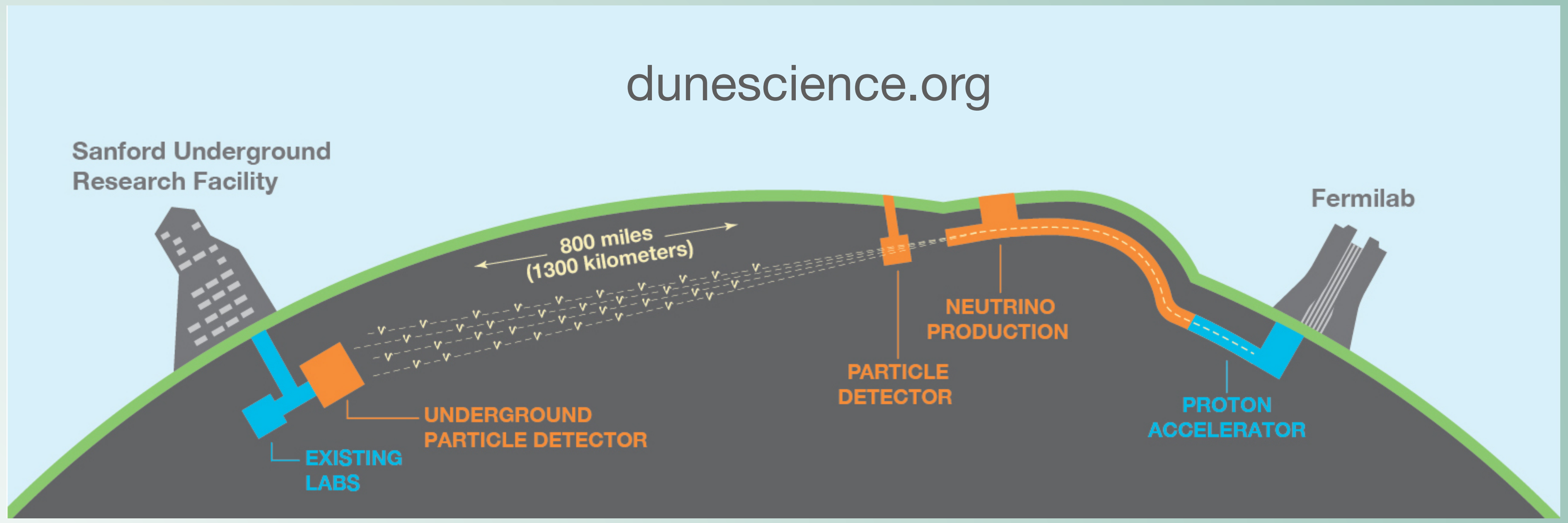
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

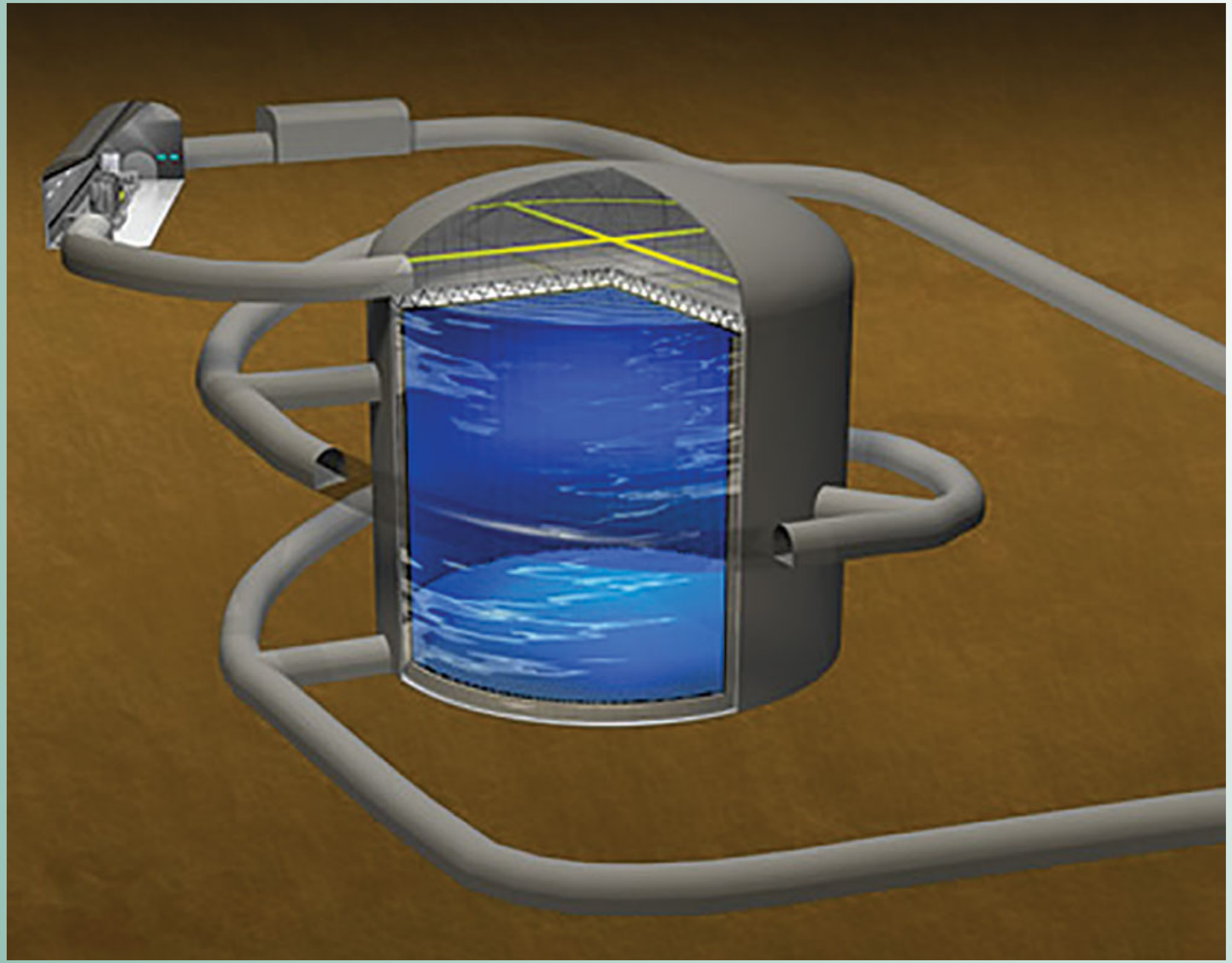
$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

Proposed Long-Baseline Searches: Hyper-K and DUNE

SLAC





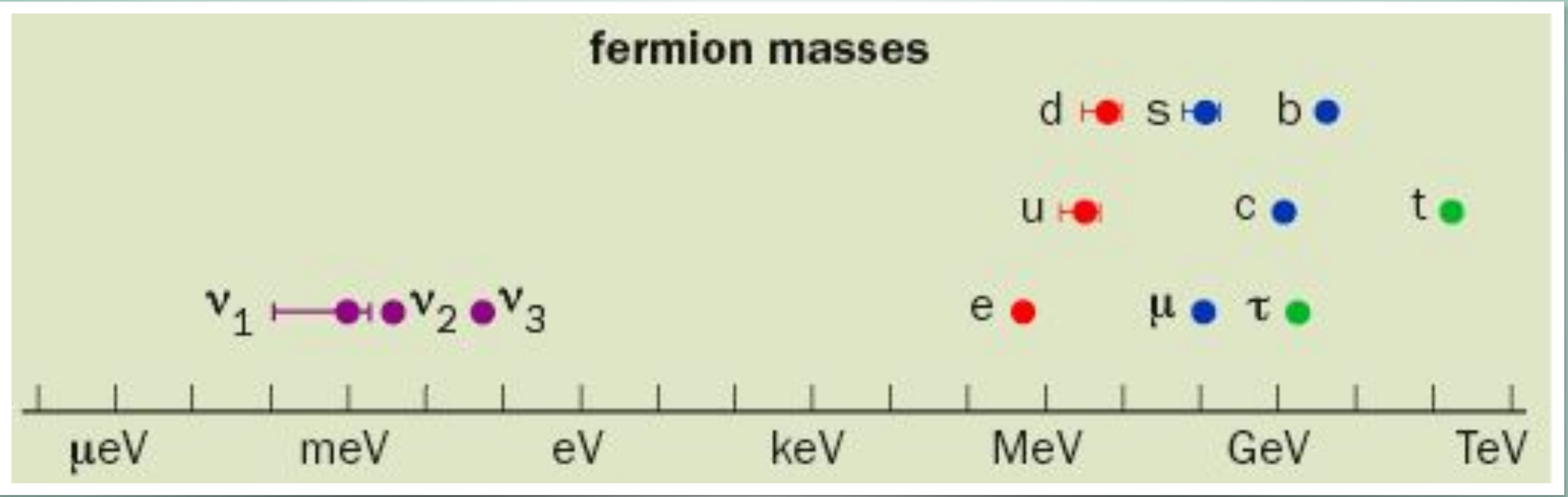


CERN Courier

Direct neutrino mass measurements

Neutrino Masses

Murayama



Experimental Considerations

- Neutrinos are lightest objects in universe.
  - ~ 1×10^{-6} mass of electron
- Relativity makes job tough:
  - $E^2 = p^2 + m^2$
- Approach: Energy distribution of electrons in beta-decay depends on mass of neutrino from kinematics and mixing.

E. Fermi, Z. Physik 88, 161 (1934)

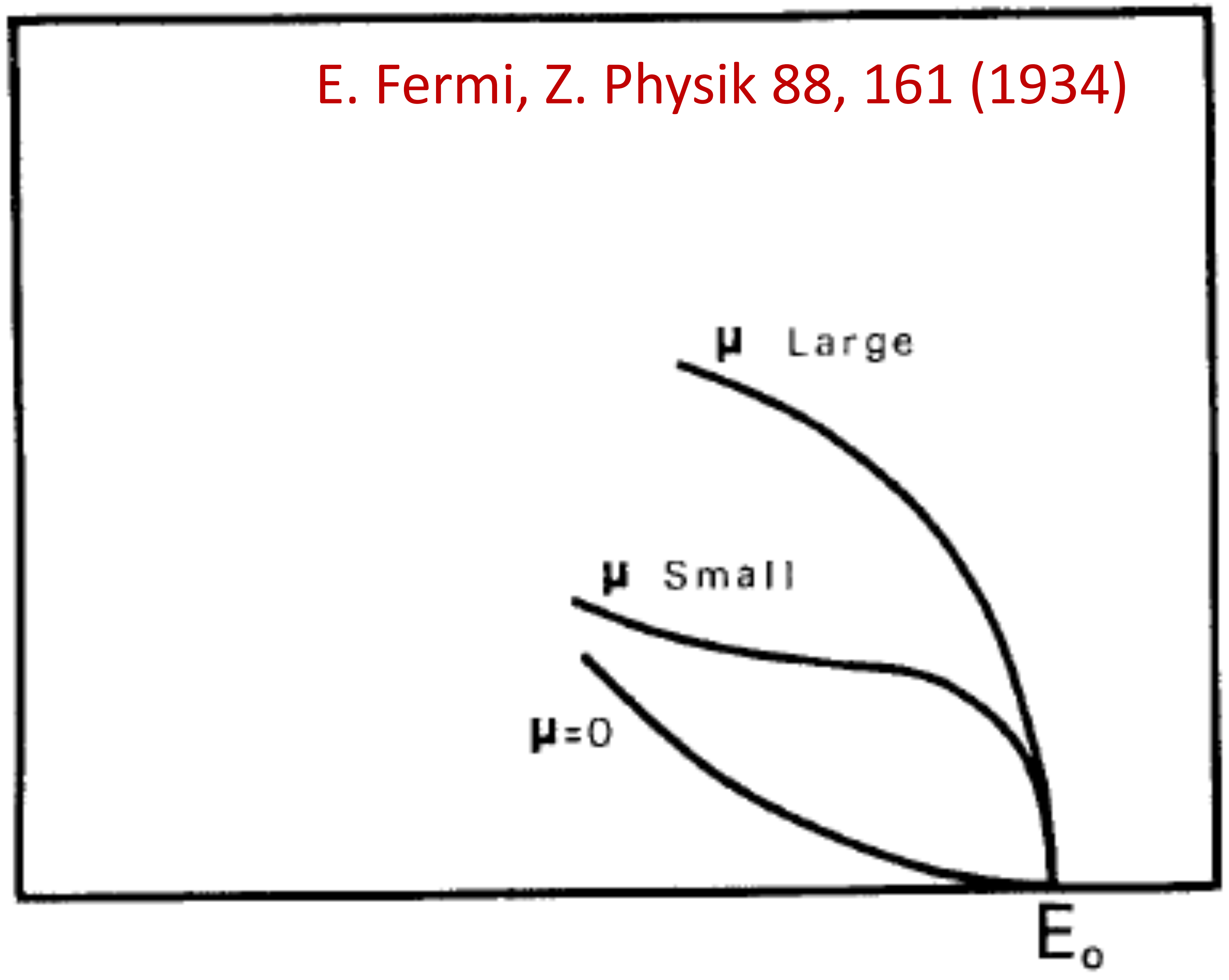
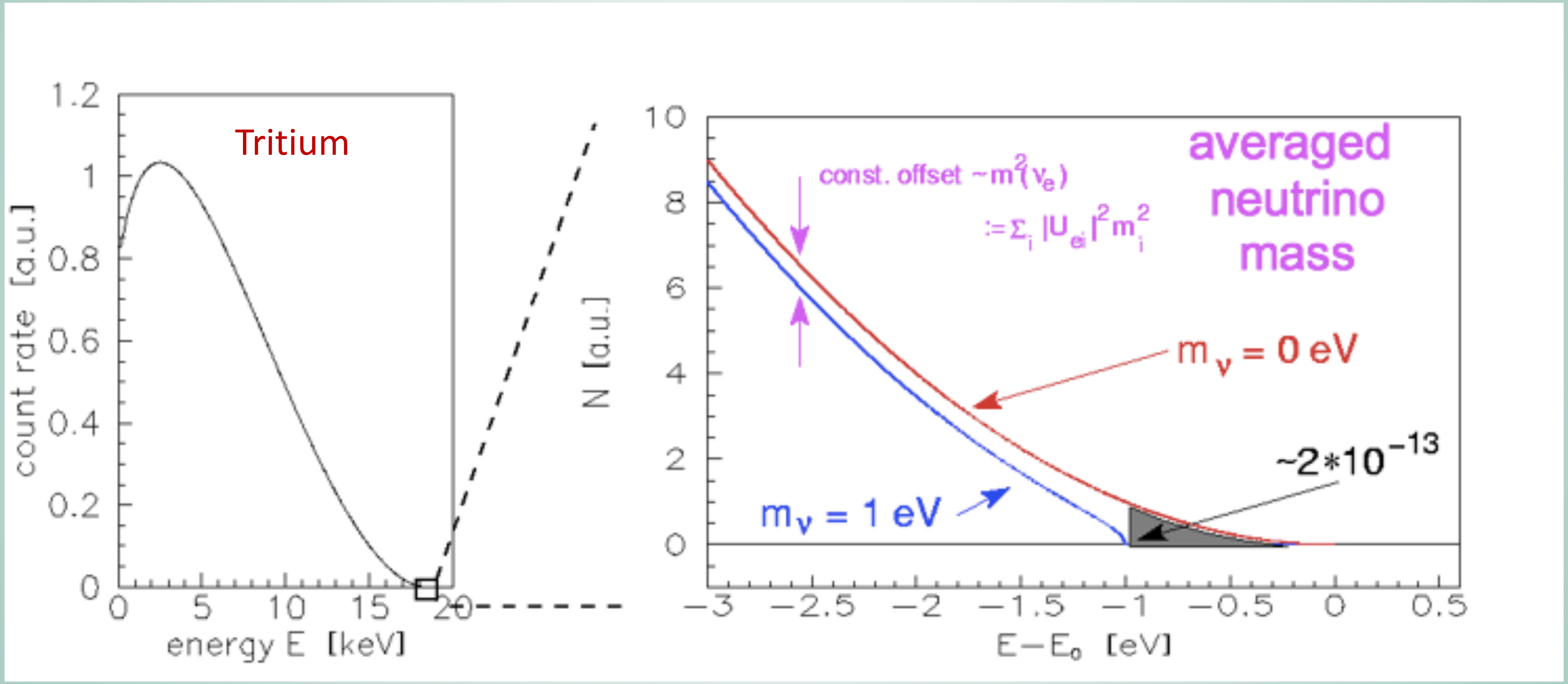


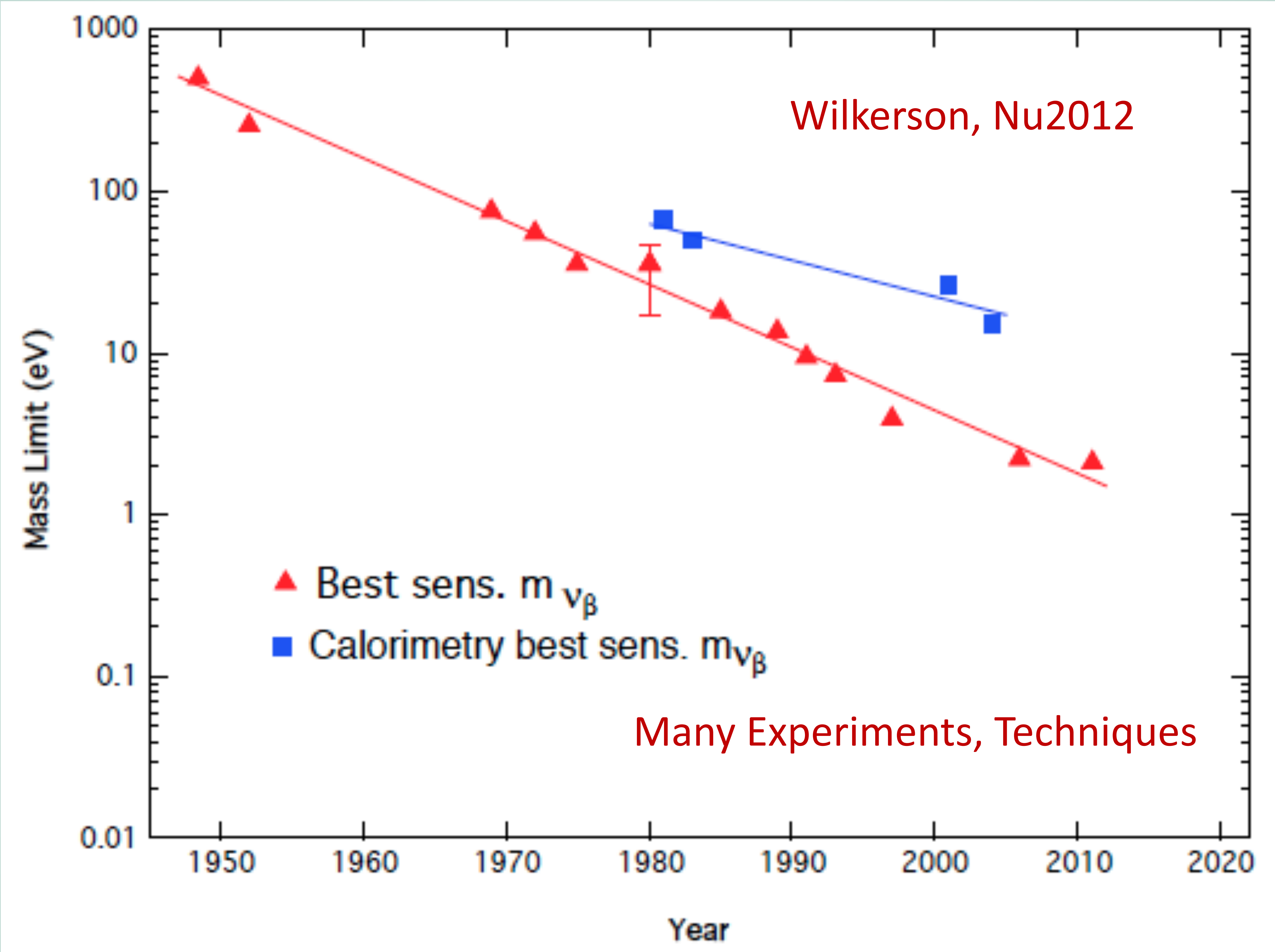
FIG. 1. The end of the distribution curve for $\mu=0$ and for large and small values of μ.

Principle

$$^{3}\mathrm{H} \rightarrow {}^{3}\,\mathrm{He} + e^{-} + \overline{\nu_e}$$

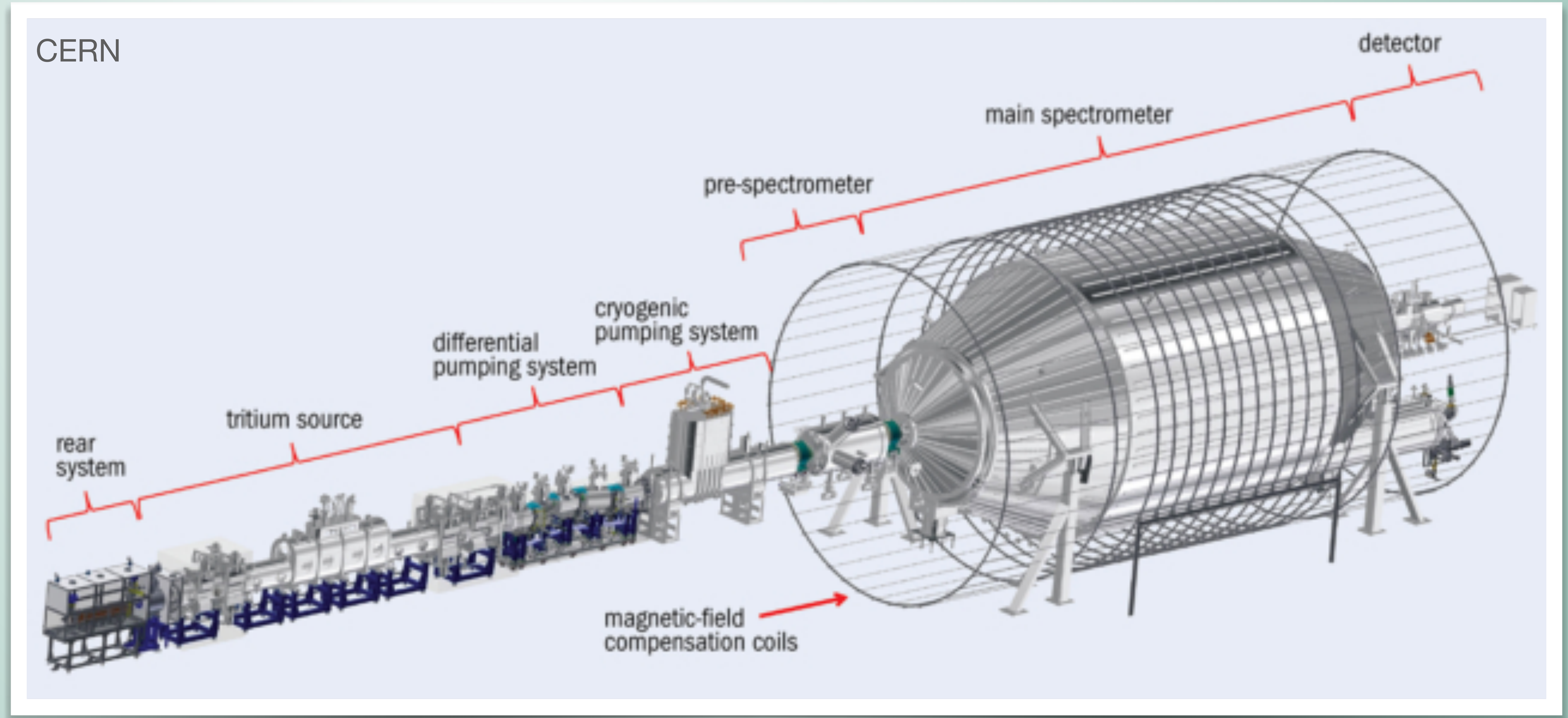


Historic Neutrino Mass Measurements

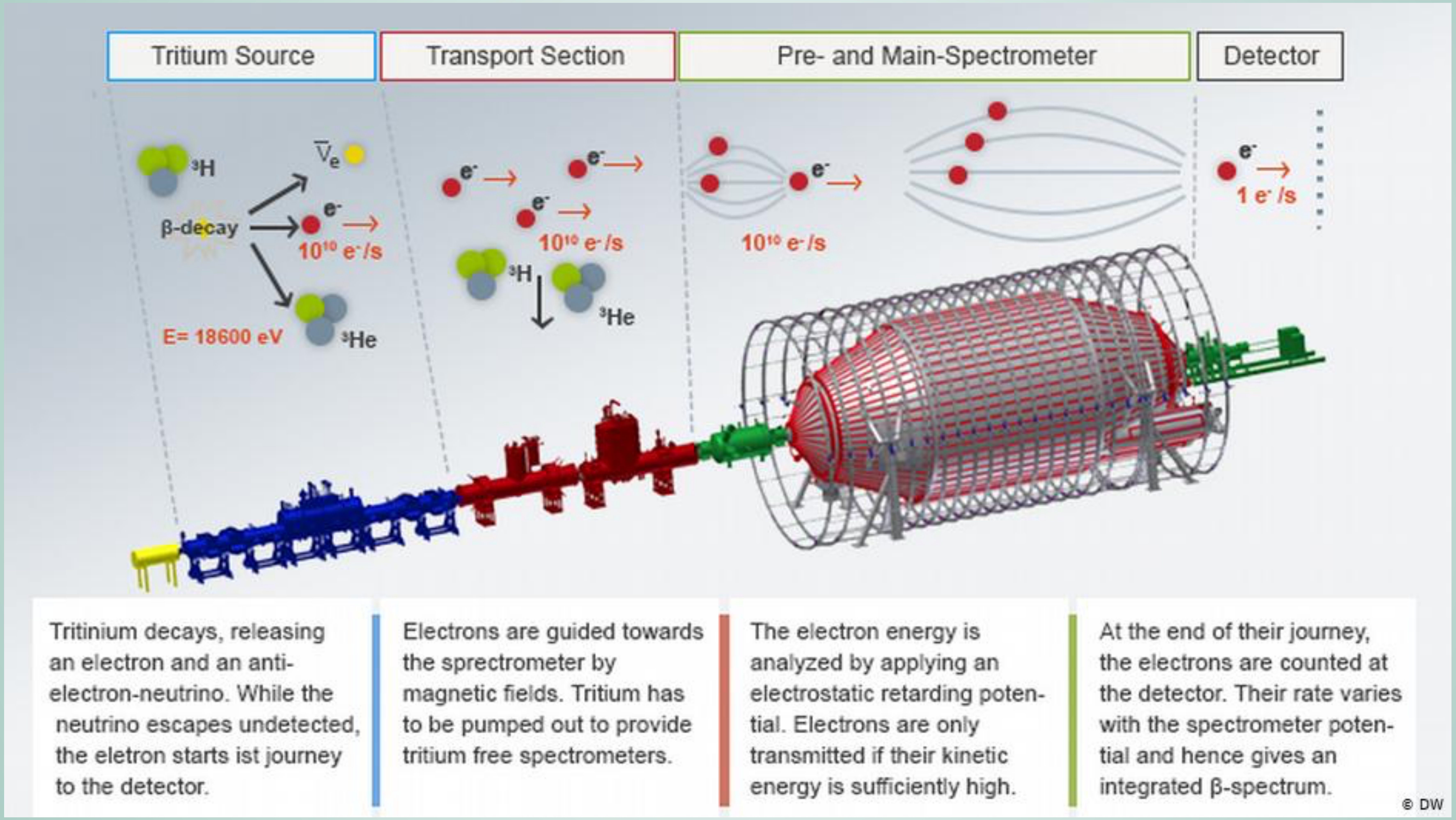


Current Direct Mass Measurements

- Tritium beta decay endpoint measurements
- Current: $m_\beta < 2\text{eV}$
- New Generation: KATRIN (Karlsruhe Tritium Neutrino Experiment)
  - Massive spectrometer
  - Sensitivity to $m_\beta = 0.2\text{eV}$
  - Currently operational

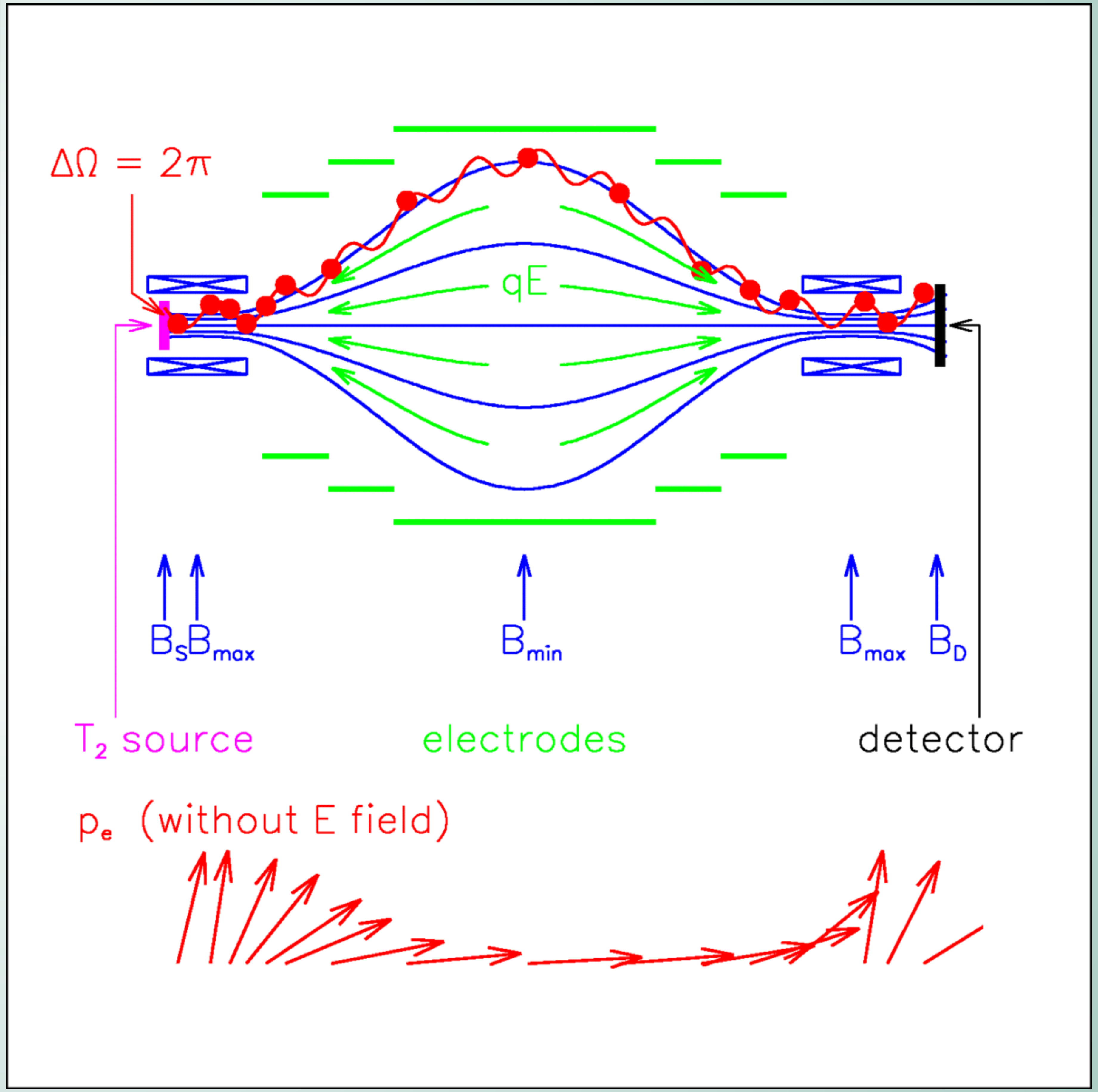


KATRIN Neutrino Mass Experiment (katrin.kit.edu)



dw.com

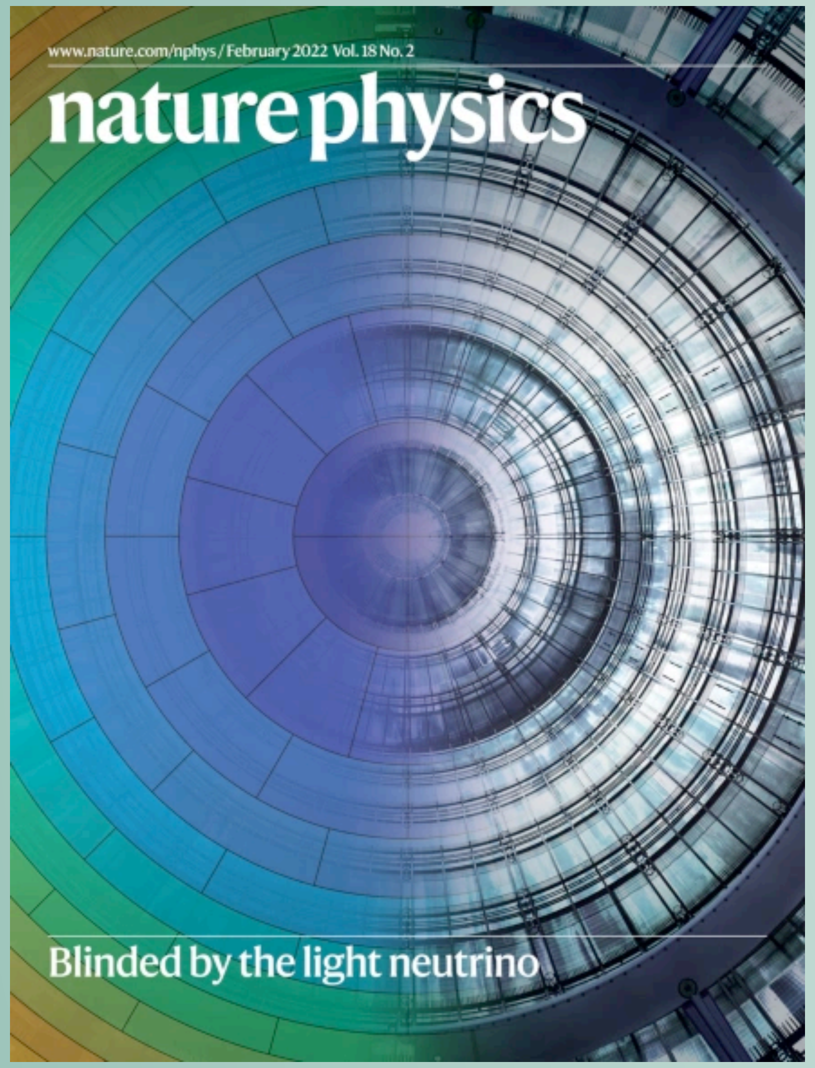
KATRIN Neutrino Mass Experiment (katrin.kit.edu)

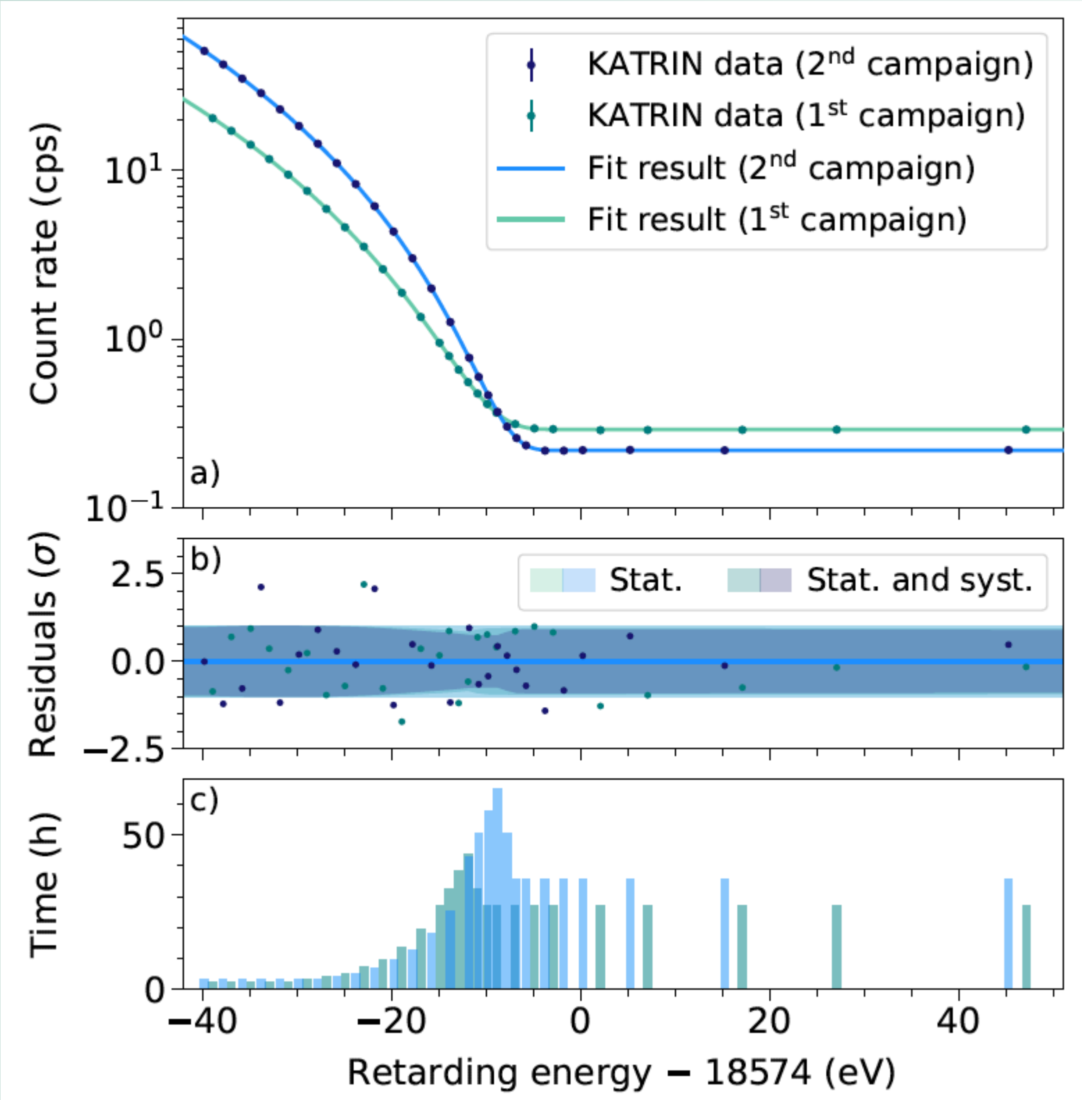


Adiabatic Transport of Electrons

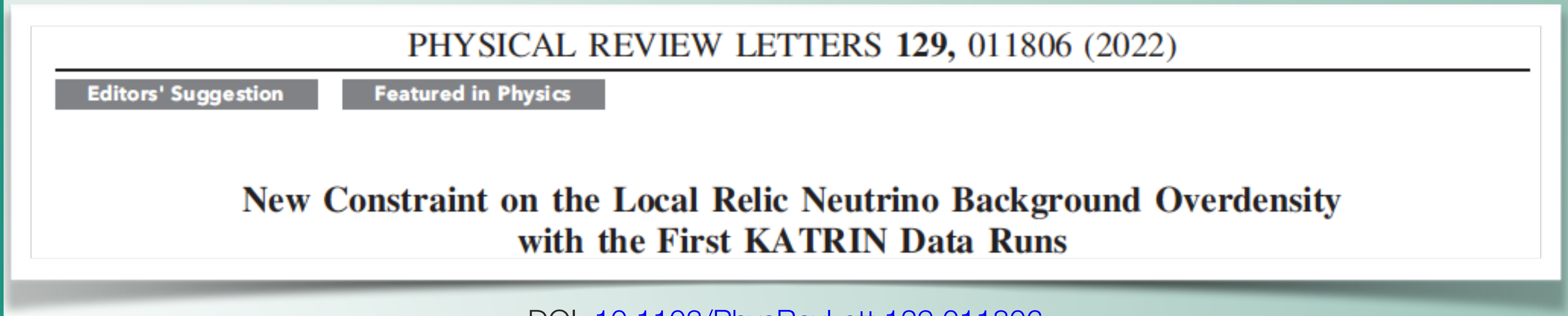
First direct neutrino-mass measurement with sub-eV sensitivity

Nature Physics **18**, 160-166 (2022)
https://doi.org/10.1038/s41567-021-01463-1





Upper Limit (KNM1 & KNM2): $m_\nu < 0.8$ eV/c^2 (90%) CL

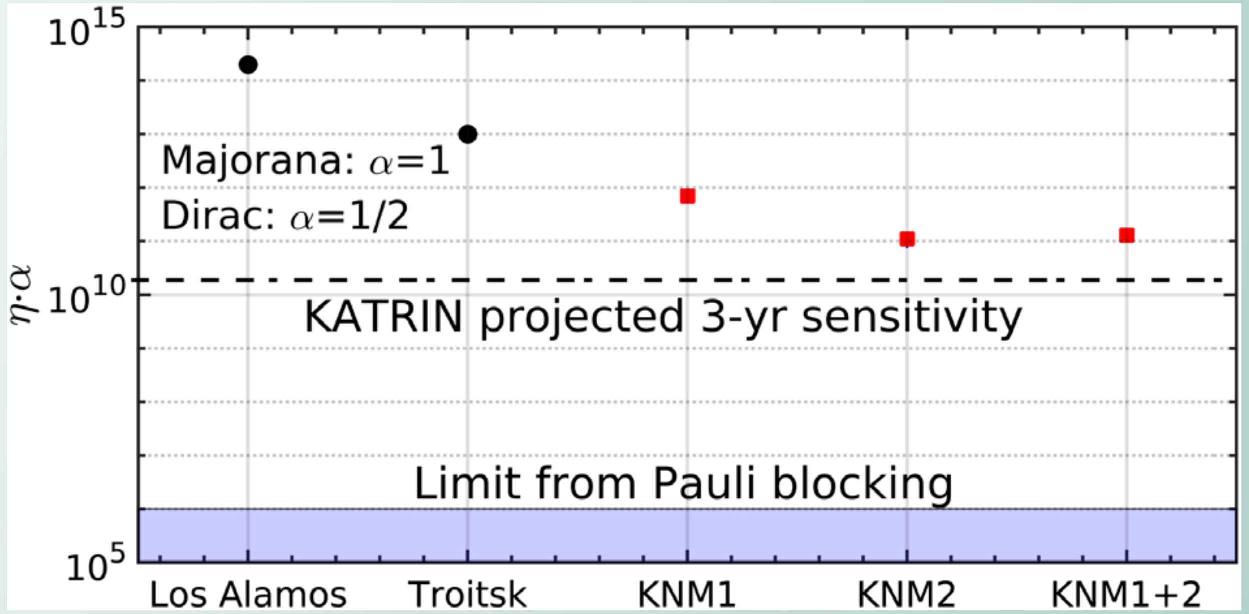

PHYSICAL REVIEW LETTERS **129**, 011806 (2022)

Editors' Suggestion | Featured in Physics

New Constraint on the Local Relic Neutrino Background Overdensity with the First KATRIN Data Runs

DOI: 10.1103/PhysRevLett.129.011806

Direct search for cosmic relic neutrinos using data acquired during the first two science campaigns of the KATRIN experiment

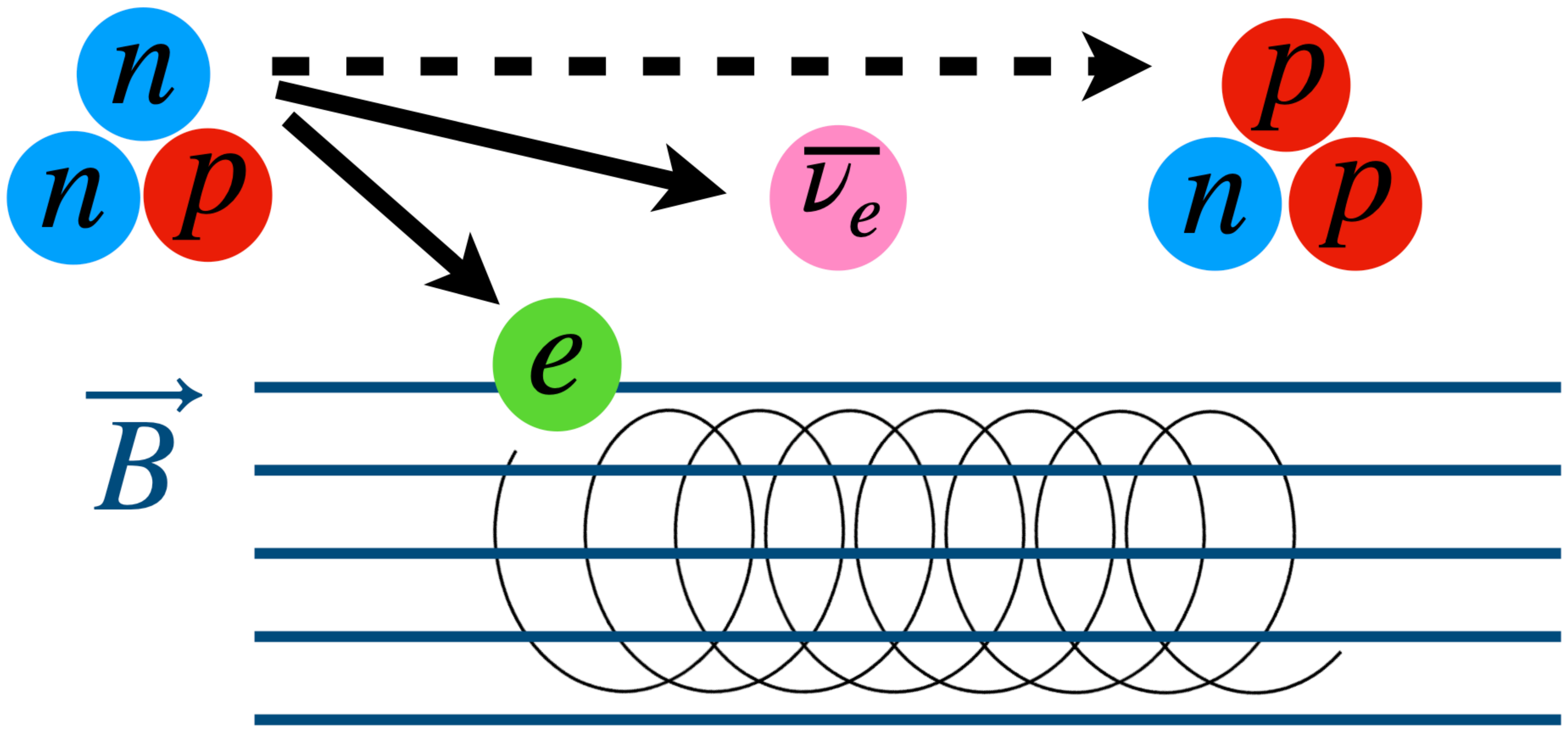


Upper Limit (KNM1 & KNM2): $\eta < 9.7 \times 10^{10}/\alpha$ (90% CL)
$\alpha = 1$ (0.5) for Majorana (Dirac) neutrinos

What about the future?

After KATRIN, it is safe to say that the MAC-E filter design has run its course and cannot be extended
- Hamish Roberton (paraphrased)

PROJECT 8



$$f = \frac{f_0}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$

Figures courtesy Arina Telles and Project 8

Phys.Rev.D80:051301,2009

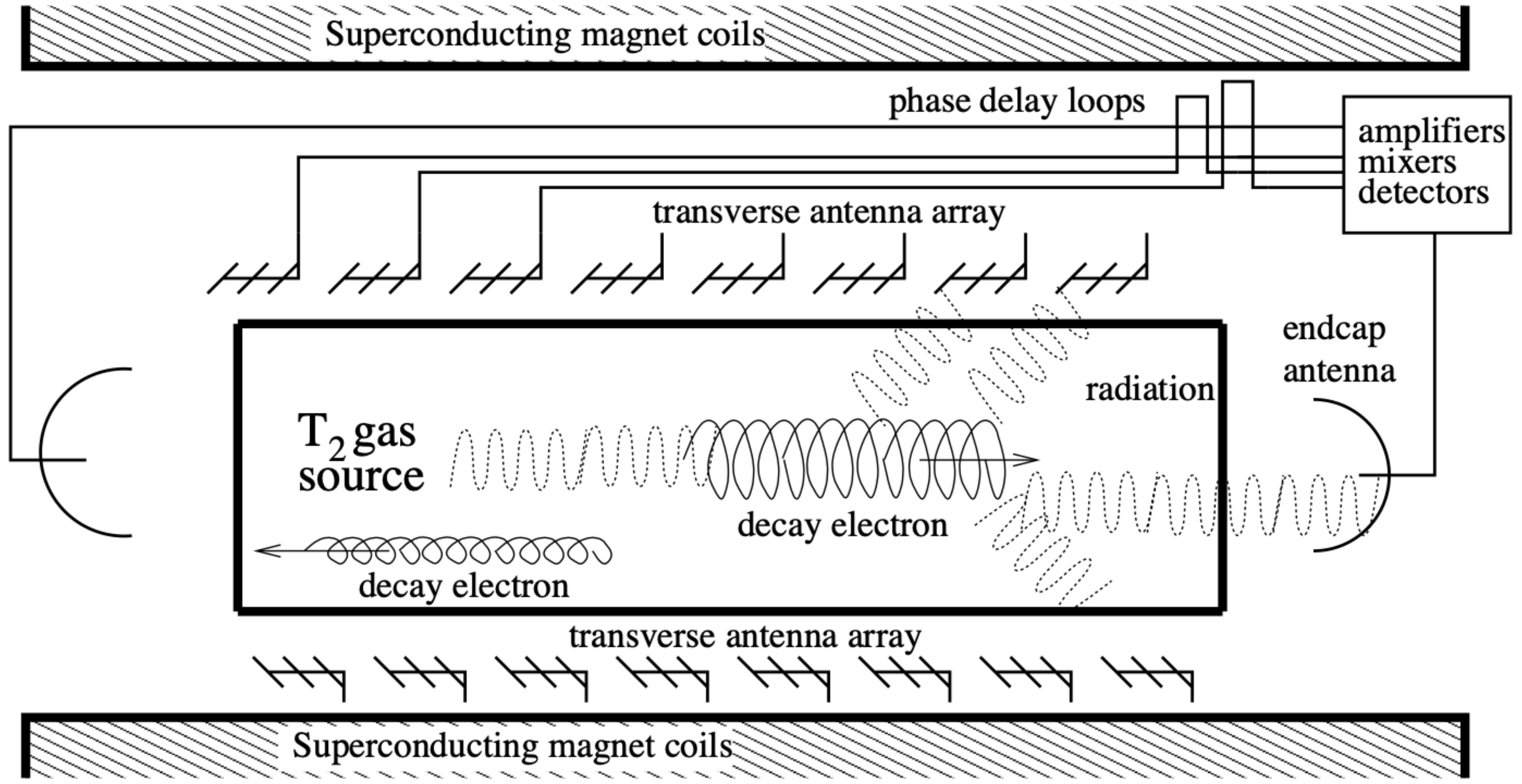


FIG. 1: Schematic of the proposed experiment. A chamber encloses a diffuse gaseous tritium source under a uniform magnetic field. Electrons produced from beta decay undergo cyclotron motion and emit cyclotron radiation, which is detected by an antenna array. See text for more details.

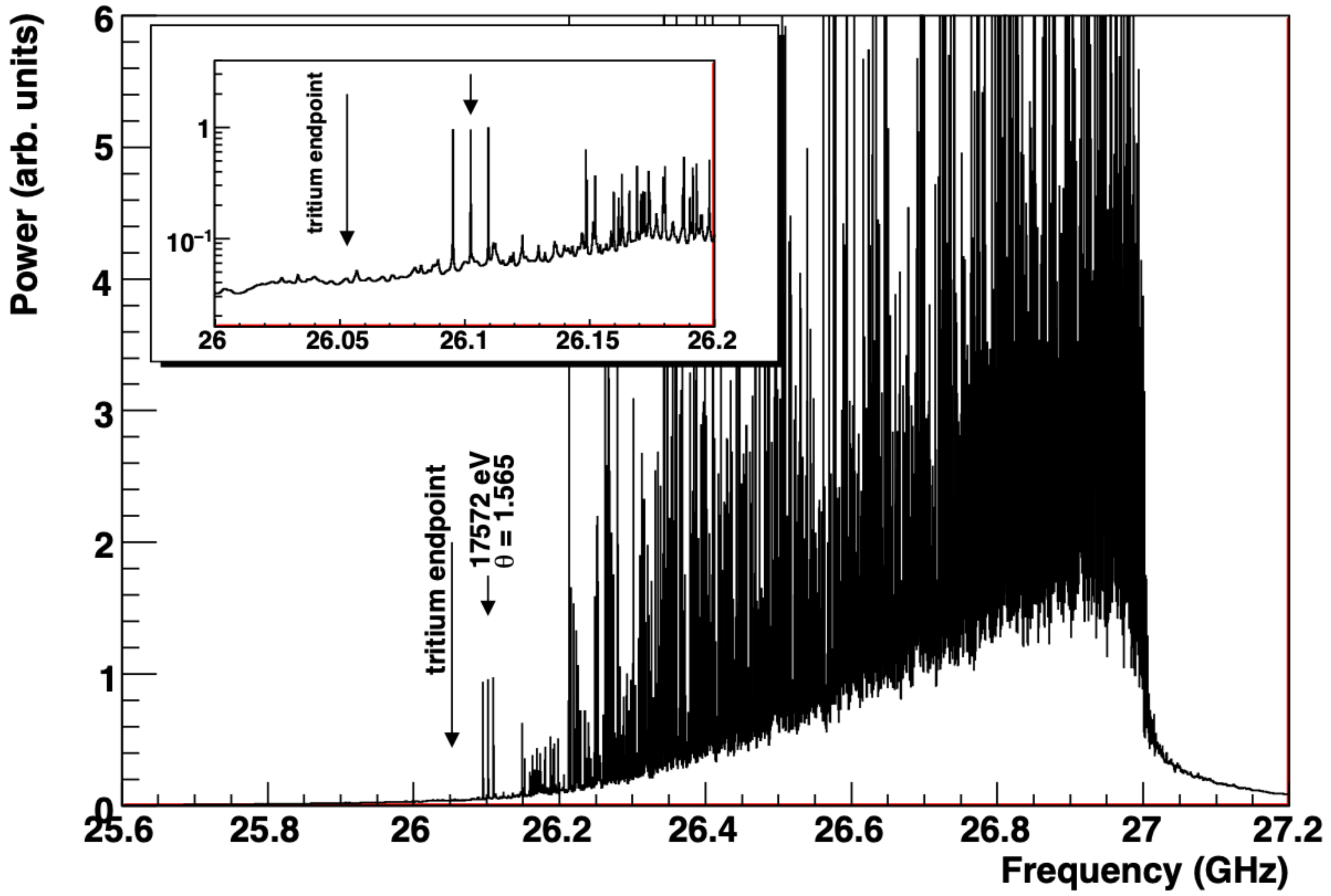
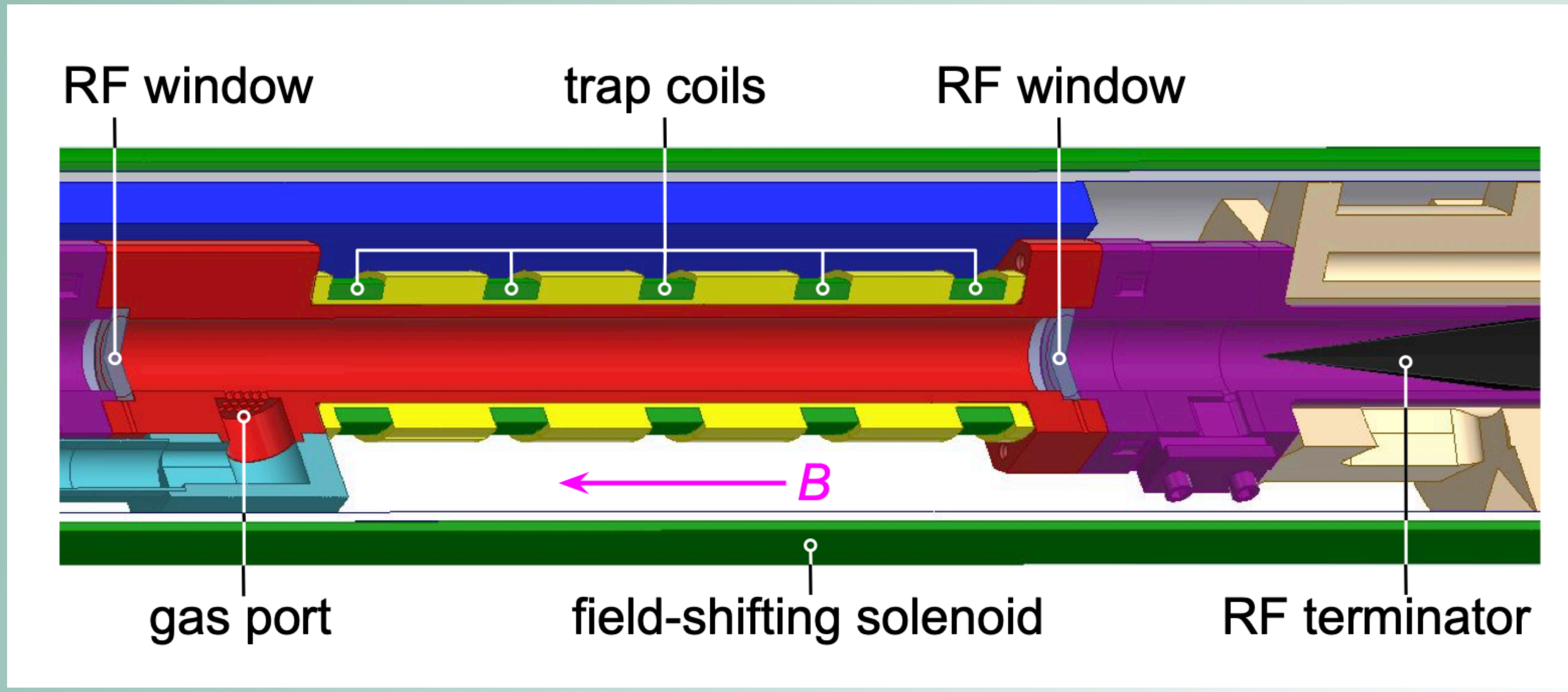
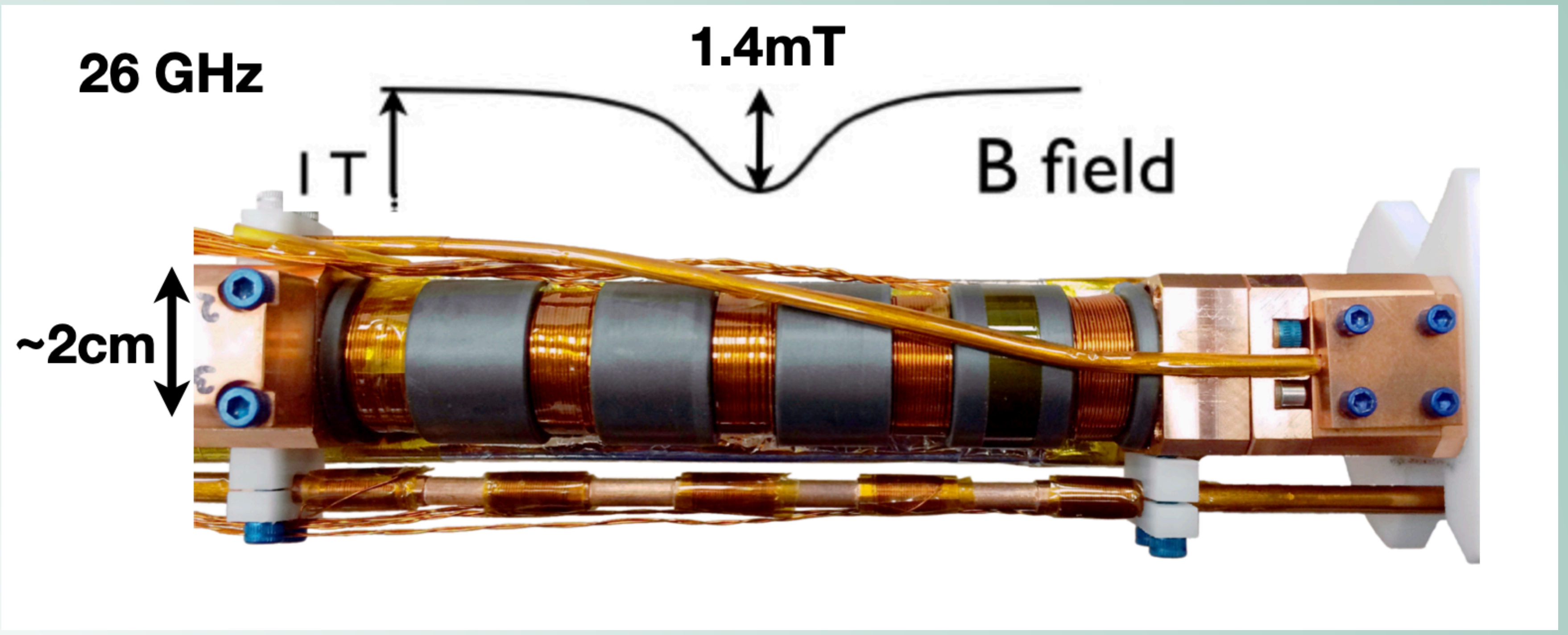


FIG. 2: Simulated microwave spectrum, showing the cyclotron emission of 10^5 tritium decays over 30μs in a 10m long uniform magnet ($\omega_0/2\pi$ = 27 GHz, B $\sim$ 1 T) with a finely-spaced transverse antenna array. e^--T_2 scattering is neglected. The short arrow points out a triplet of spectral peaks generated by an individual high-energy, high-pitch angle electron; the central peak is the cyclotron frequency and the sidebands are due to AM modulation. The log-scale inset zooms in on this electron and the endpoint region.

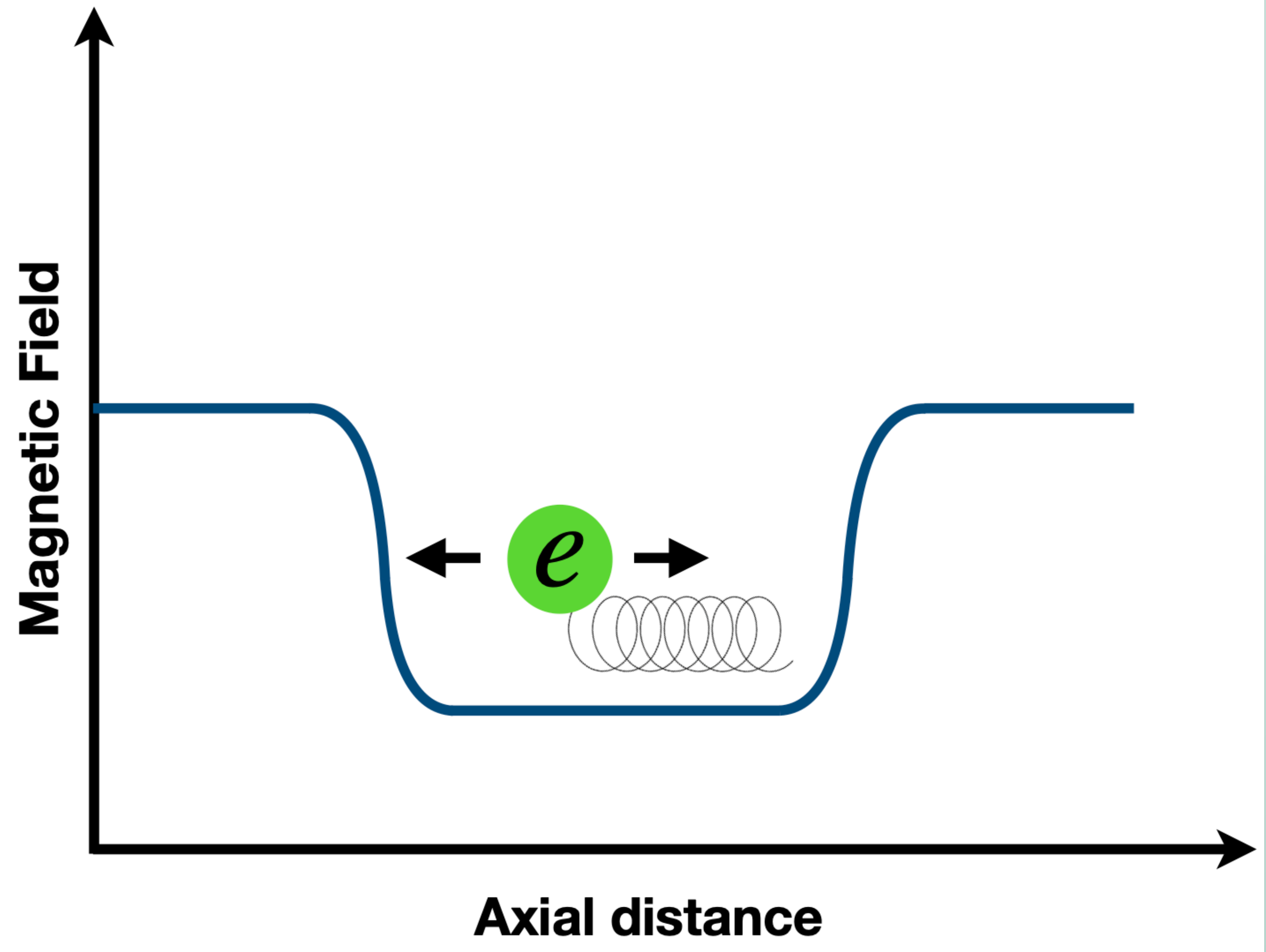
antennae will see Doppler-shifted radiation (one redshift, one blueshift) due to the motion of the guiding center. If we can detect both of these components, both the electron energy and pitch angle are uniquely determined.

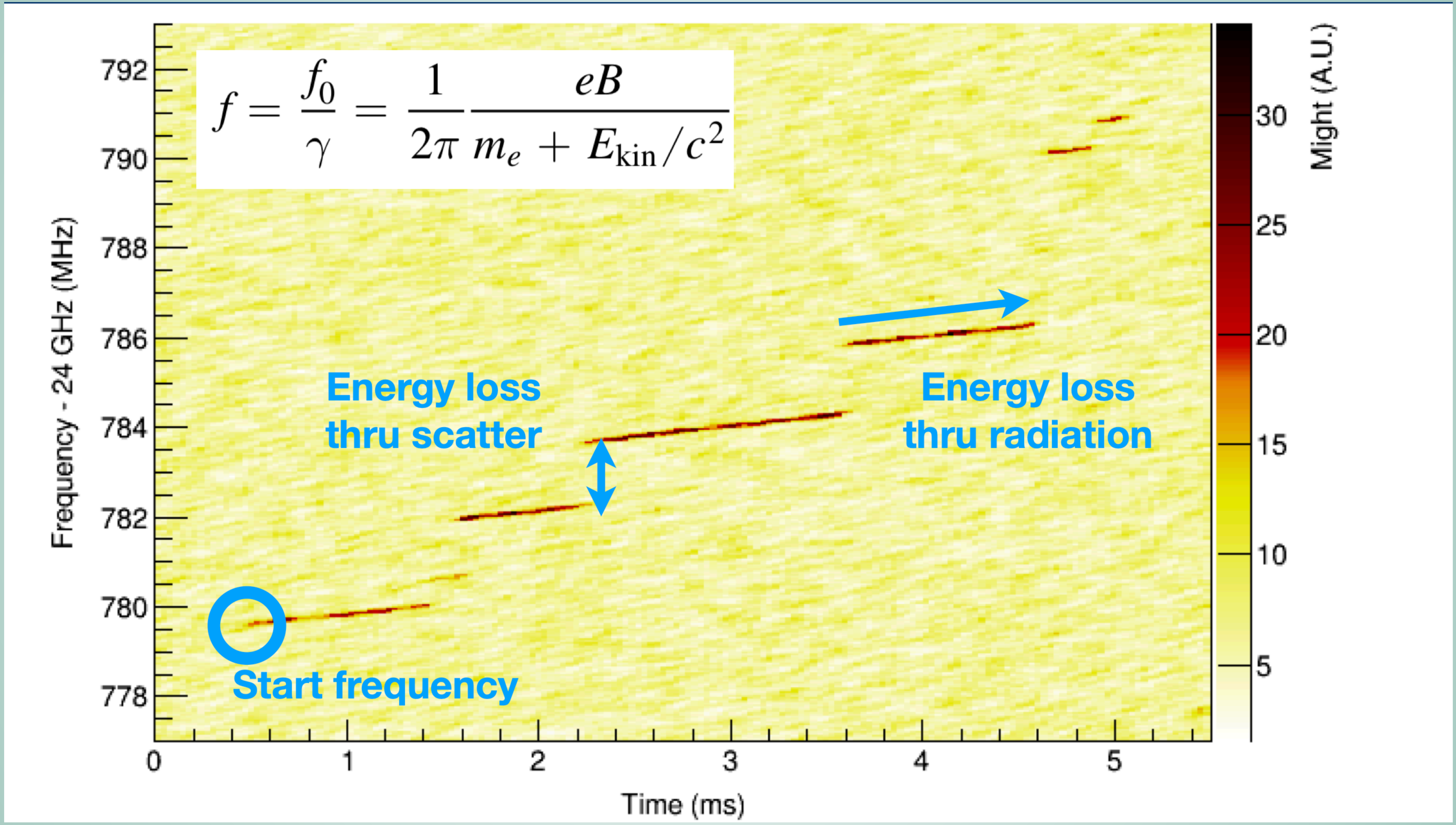




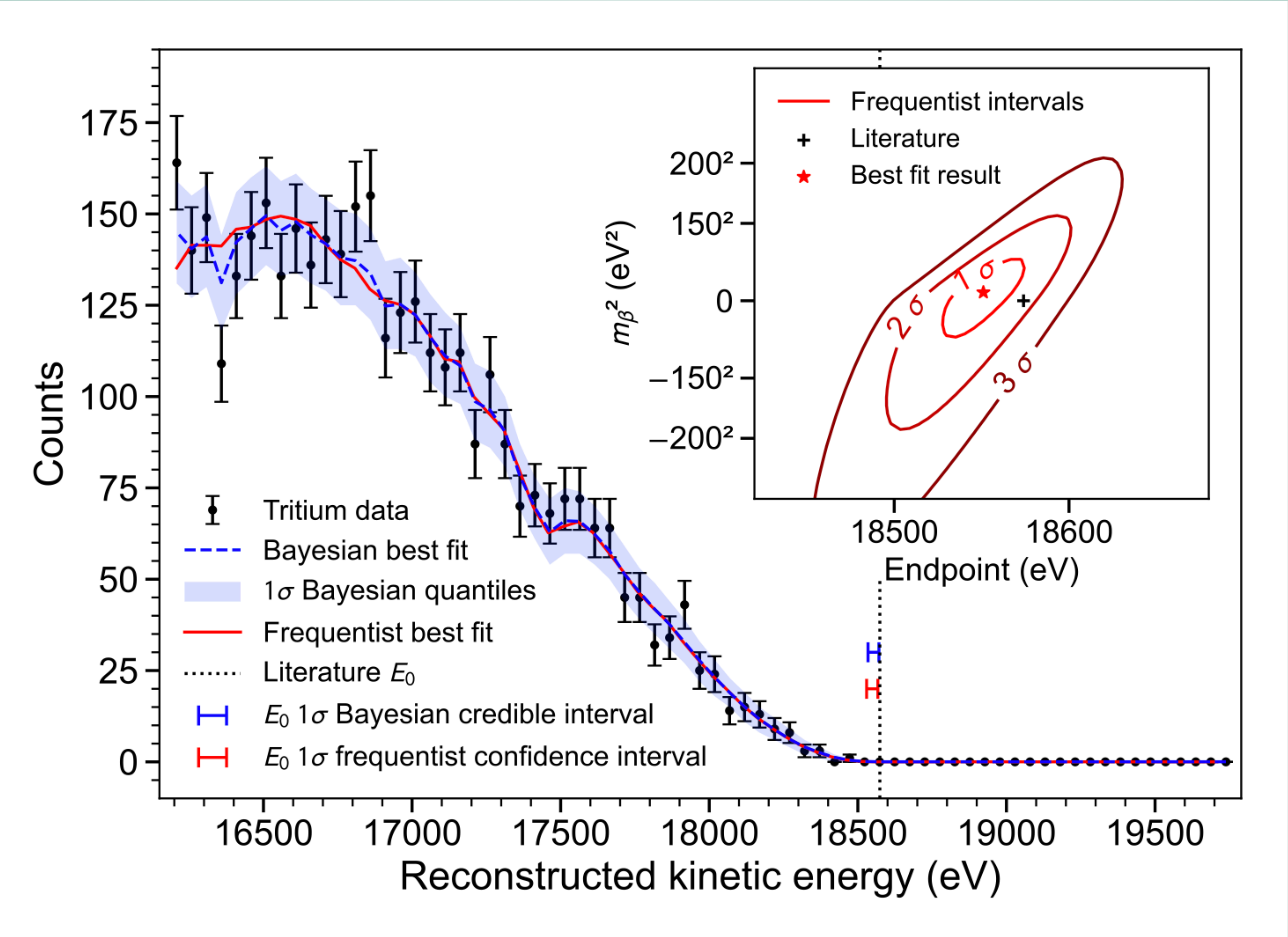
- Magnetic trap (no energy change)
- Extends observation time of electron
- Knowledge of B places limit on energy resolution

$$\triangle E = \frac{\triangle B}{B}(m_e c^2 + E_{kin})$$





$$f = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}/c^2}$$
Energy loss
thru scatter
Energy loss
thru radiation
Start frequency
Frequency - 24 GHz (MHz)
Time (ms)
Might (A.U.)


Counts
175
150
125
100
75
50
25
0
16500
17000
17500
18000
18500
19000
19500
Reconstructed kinetic energy (eV)
Tritium data
Bayesian best fit
1σ Bayesian quantiles
Frequentist best fit
Literature E_0
E_0 1σ Bayesian credible interval
E_0 1σ frequentist confidence interval
Frequentist intervals
Literature
Best fit result
m_β^2 (eV²)
200²
150²
0
−150²
−200²
1σ
2σ
3σ
18500
18600
Endpoint (eV)

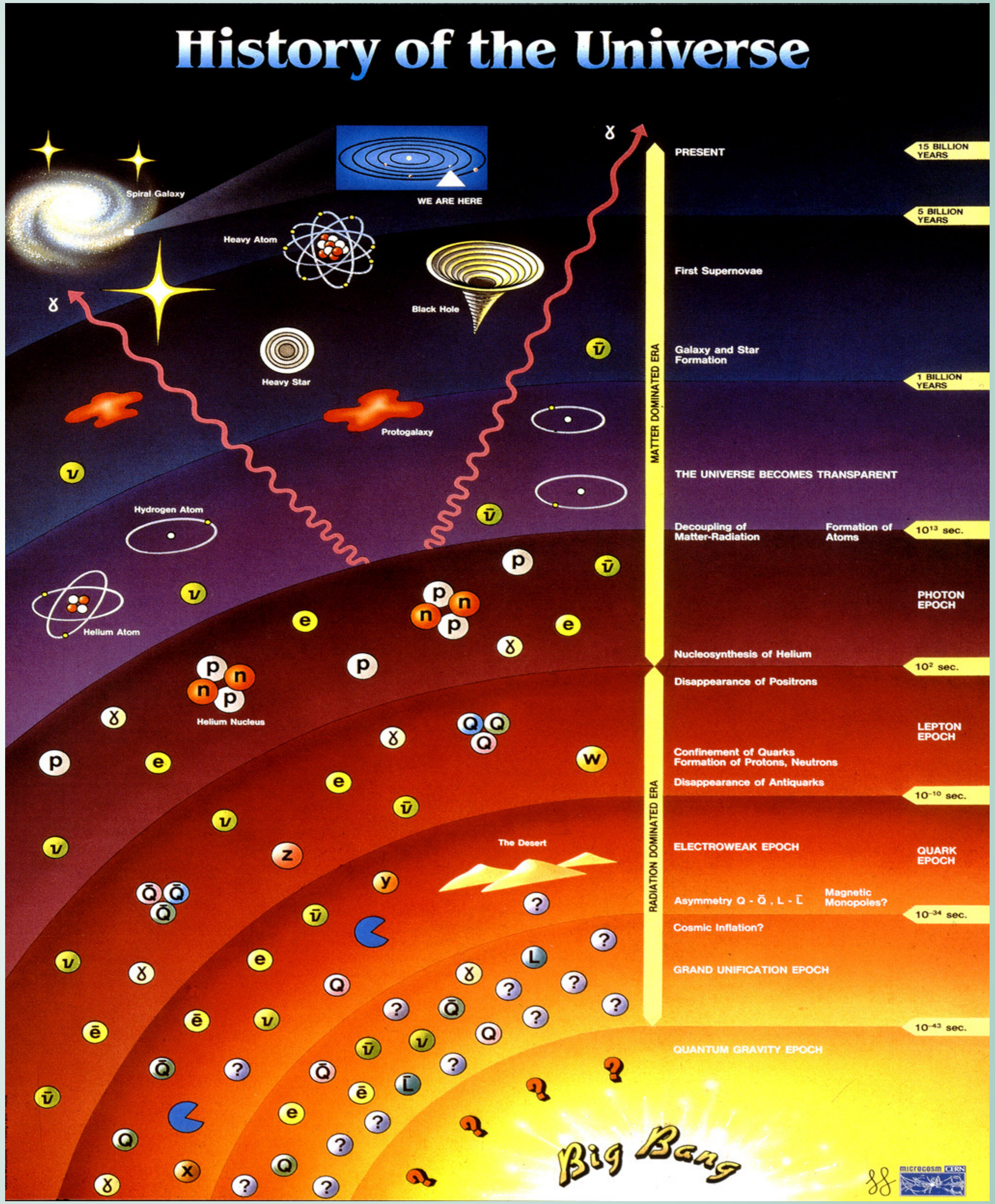
Cosmic relic neutrinos

CMB History
-or- why physics is hard

- **1940's** : Proposal of CMB by Gamow, Dicke, and others. Estimate range for 2K to 50K
- **1965**: Penzias and Wilson measure CMB at 3K. Discarded "Bird-poop" hypothesis to win Nobel prize in 1978.
- **1992:** After 30 years of herculean experimental efforts and theoretical hand-wringing, tiny CMB anisotropy discovered by COBE. Nobel prizes awarded in 2006. (COBE ~10^4x cost of P&W experiment)
- **2000's** Further refinement by BOOMERANG, WMAP, upcoming PLANCK, etc. Precision Observational Cosmology becomes field in own right.
- **2002:** Discovery of CMB Polarization.
- **2013: First announcements from PLANCK**
- **Era of Precision Cosmology**

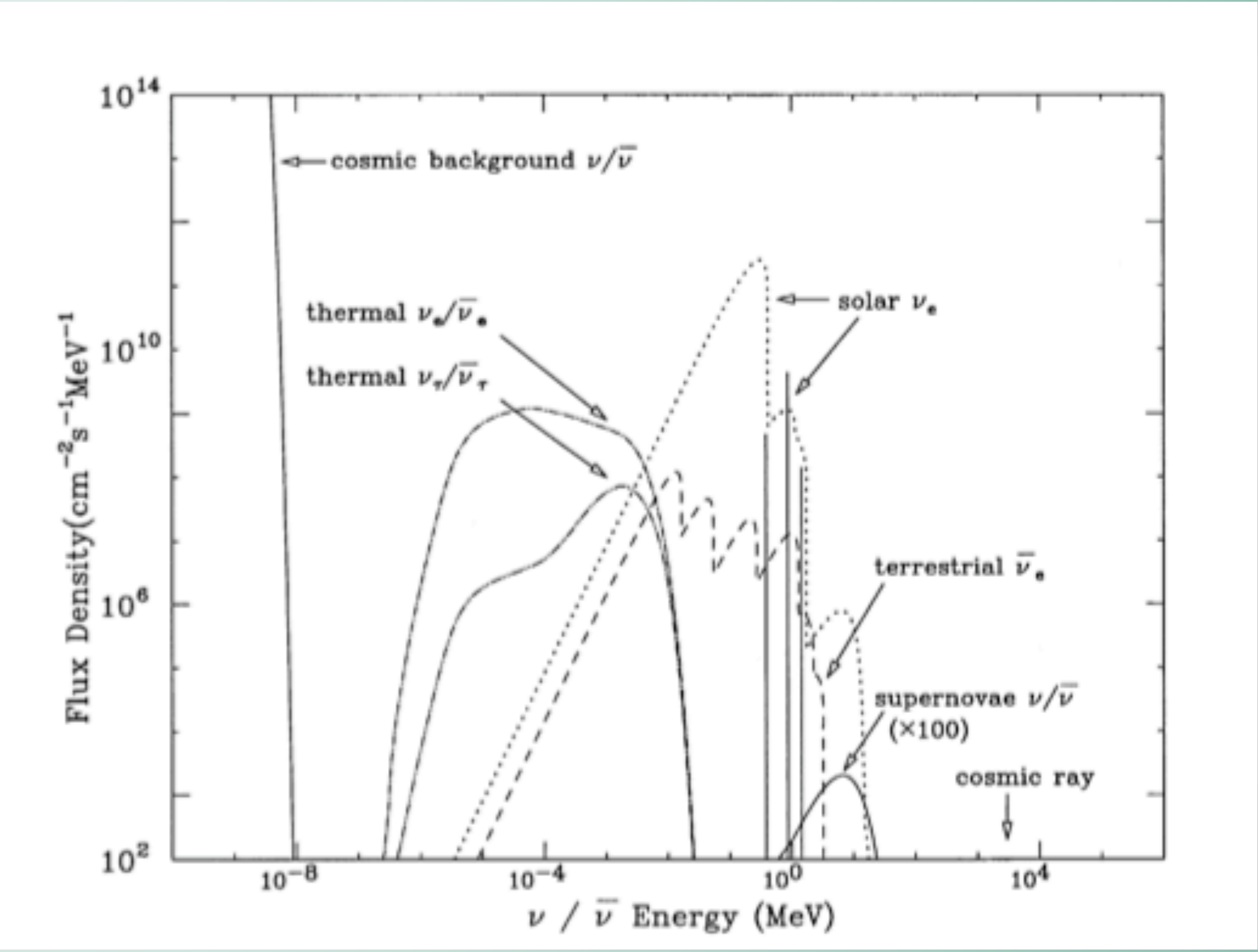
Origin Of Relic Nu

- “Sea” of particles during Big-Bang
- At t < 2 sec. neutrinos are in thermal equilibrium
- At t > 2 sec., neutrinos decouple.
- Free-stream ever since.
- Earliest known relic, predates BBN by far
- CMB formed at 400,000yr



Present Properties

- T ~ 2K (similar to CMB)
- E ~ 100meV, λ_{DB} ~ 2mm
- Density ~ 100 cm^{-3}
- Most abundant particle in universe by number (after CMB)
- Equal contributions from 3 mass eigenstates and particle/anti-particle states
- Clustering properties relevant to experiments



Indirect Evidence

- Big-Bang Nucleosynthesis
  - Relic-nu affect expansion rate
- Cosmic-Microwave Background Anisotropies
- Large-scale Structure
  - Free-streaming neutrinos carry away mass and suppress growth of small structure

Direct Detection?

- Problem:
    - Recoil nuclear E: ~10^{-15}eV
    - Cross-section: ~ 10^{-60} cm^2
    - Corresponds to 1 event per giga-tonne per year. Bwahahaaa….!
- Have to resort to other techniques

UHECR

- Ultra-high energy cosmic-rays
- Flux ~ O(1 per km^2 per year)
- Extensive air show arrays
- Radio detection (Askaryan Effect)
- Cerenkov Telescopes
- IceCube
- Acoustic Detection

PDG

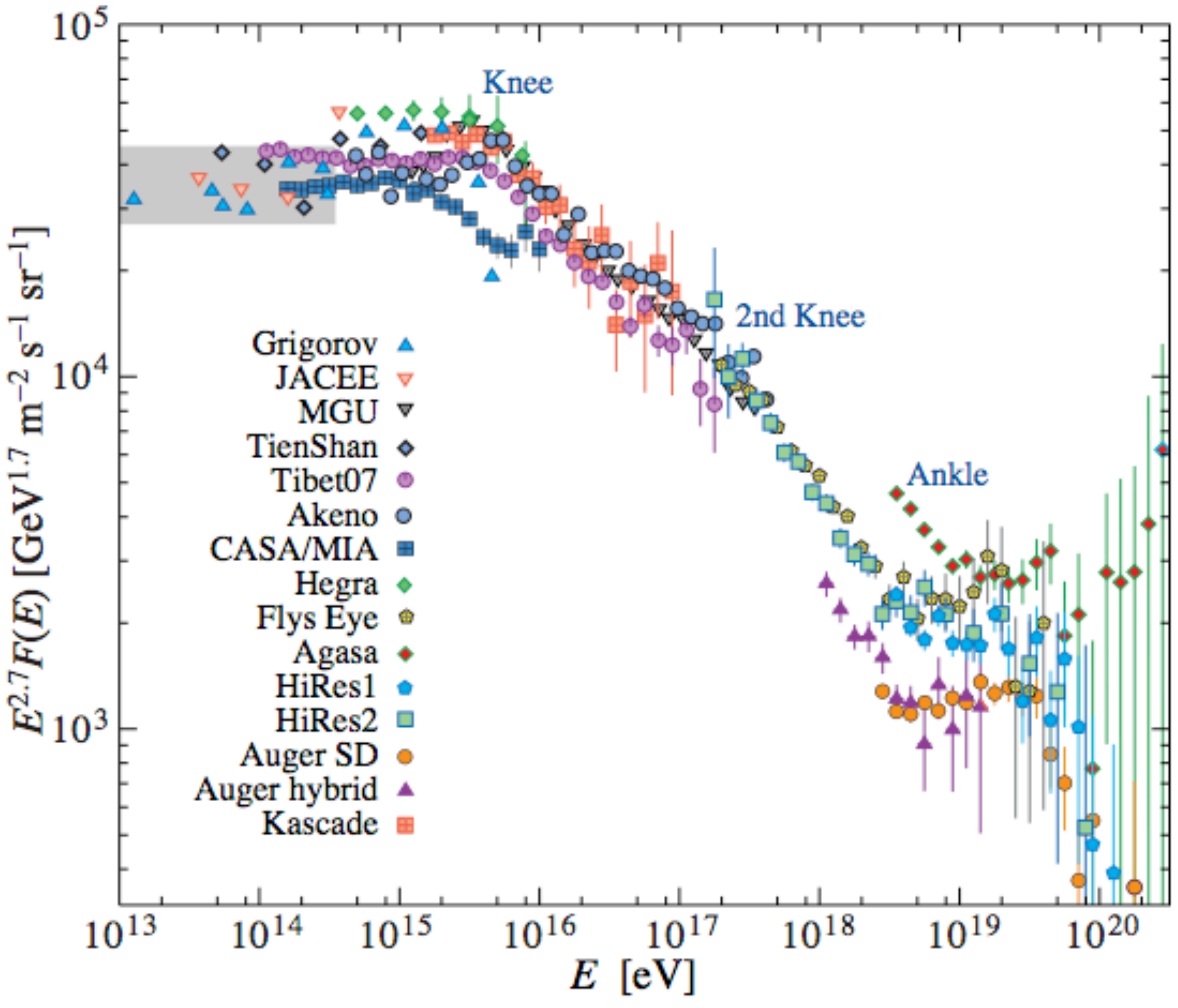


Figure 24.9: The all-particle spectrum from air shower measurements. The shaded area shows the range of the direct cosmic ray spectrum measurements.

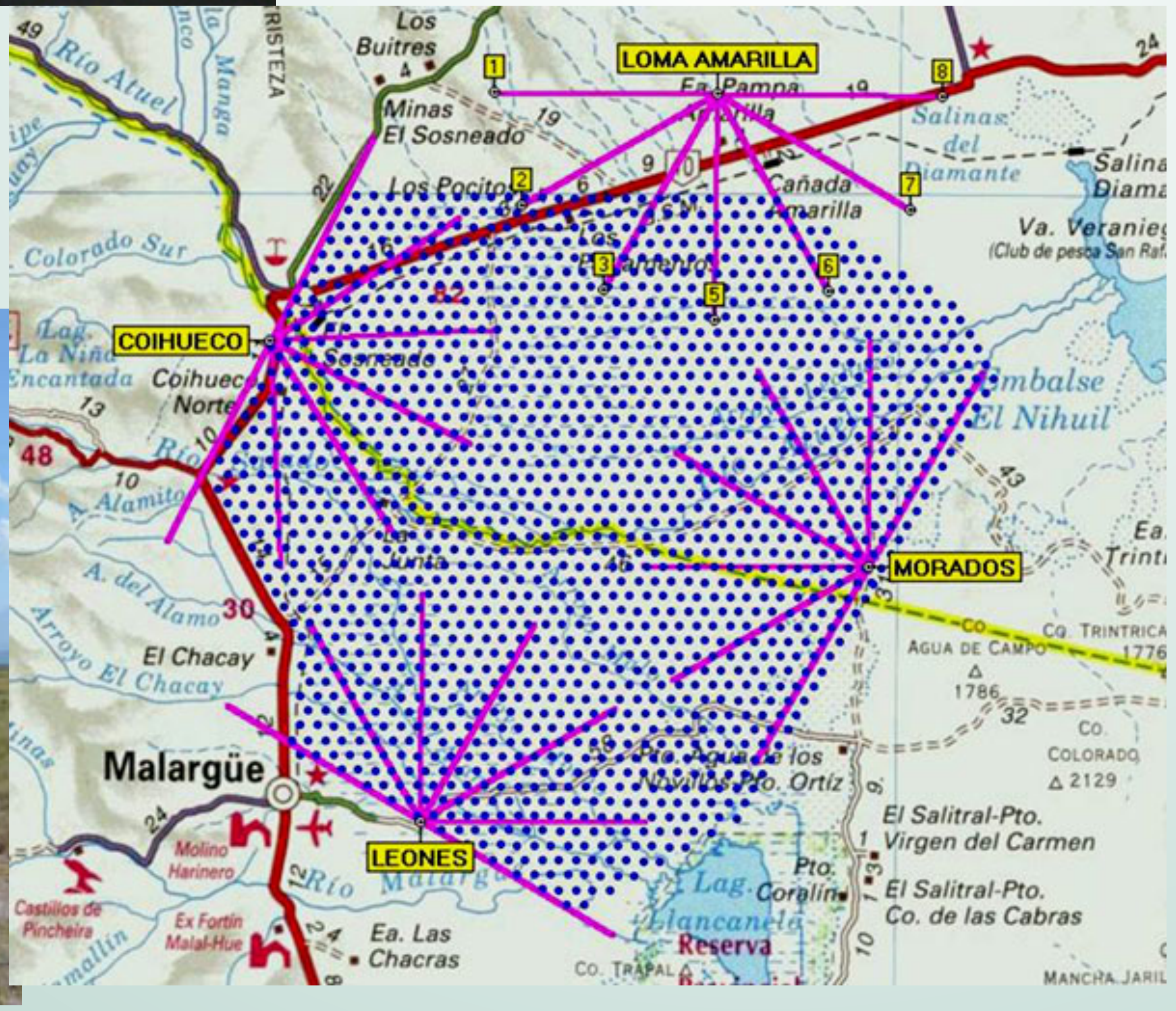
UHECR Facilities

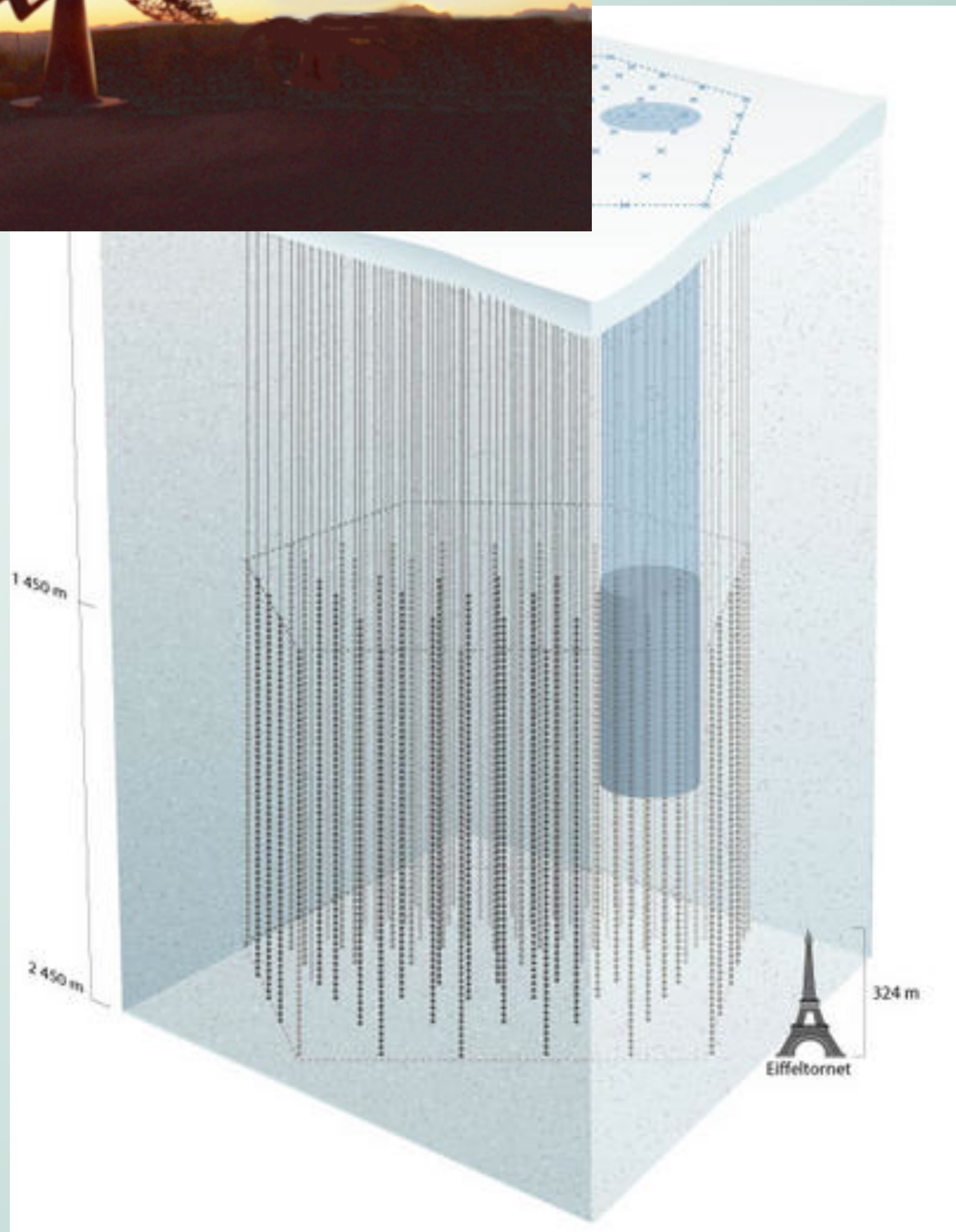
Also: EUSO, OWL, SalSa, RICE, etc.

VERITAS, Gamma-ray and Cerenkov

ANITA, Radio

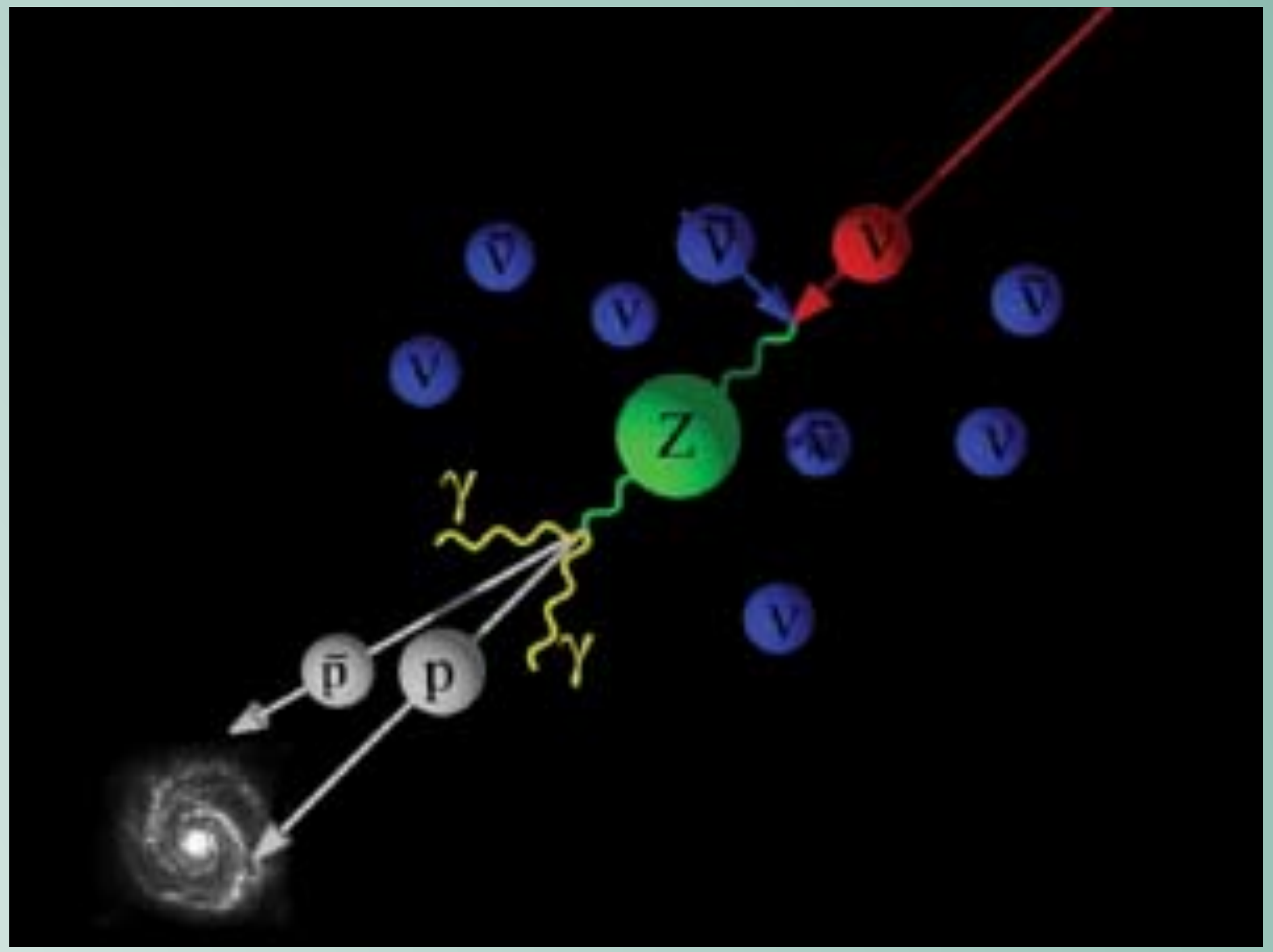
Auger, EAS





Ice-cube Cerenkov

UHECR and Relic Nu



- Significant enhancement of cross-section at Z resonance:

  $\nu + \nu \rightarrow Z(80\text{GeV}/c^2) \rightarrow h, l,$ etc…

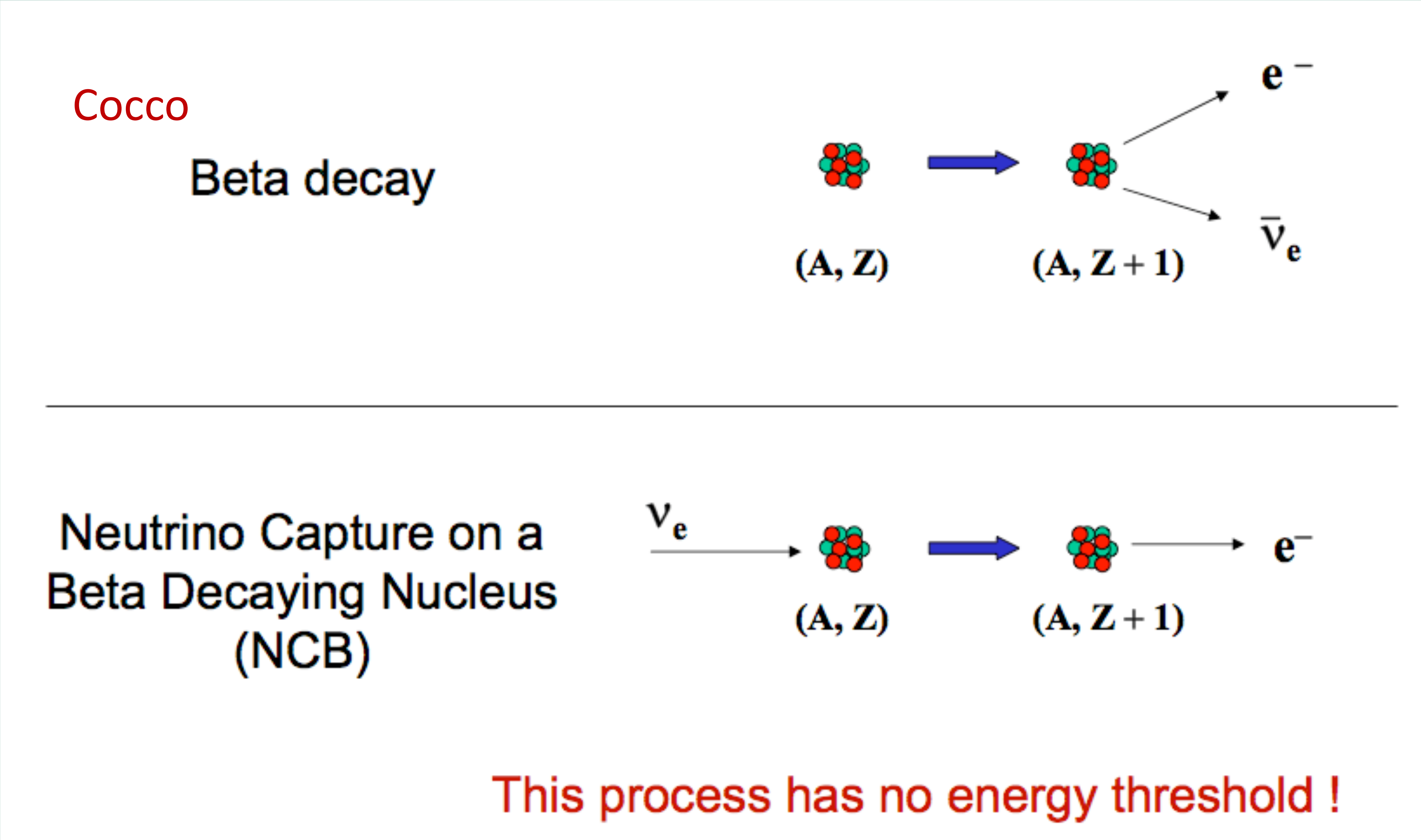
- “Z-burst” Mechanism –or-
- If significant component of UHECR are neutrinos, the expect “dip” in UHECR spectra:

- Future Radio, Satellite, or Acoustic experiments

$$E_{\nu_i}^{\text{res}} = \frac{m_Z^2}{2\,m_{\nu_i}} = 4.2 \times 10^{22}\ \text{eV}\left(\frac{0.1\ \text{eV}}{m_{\nu_i}}\right)$$

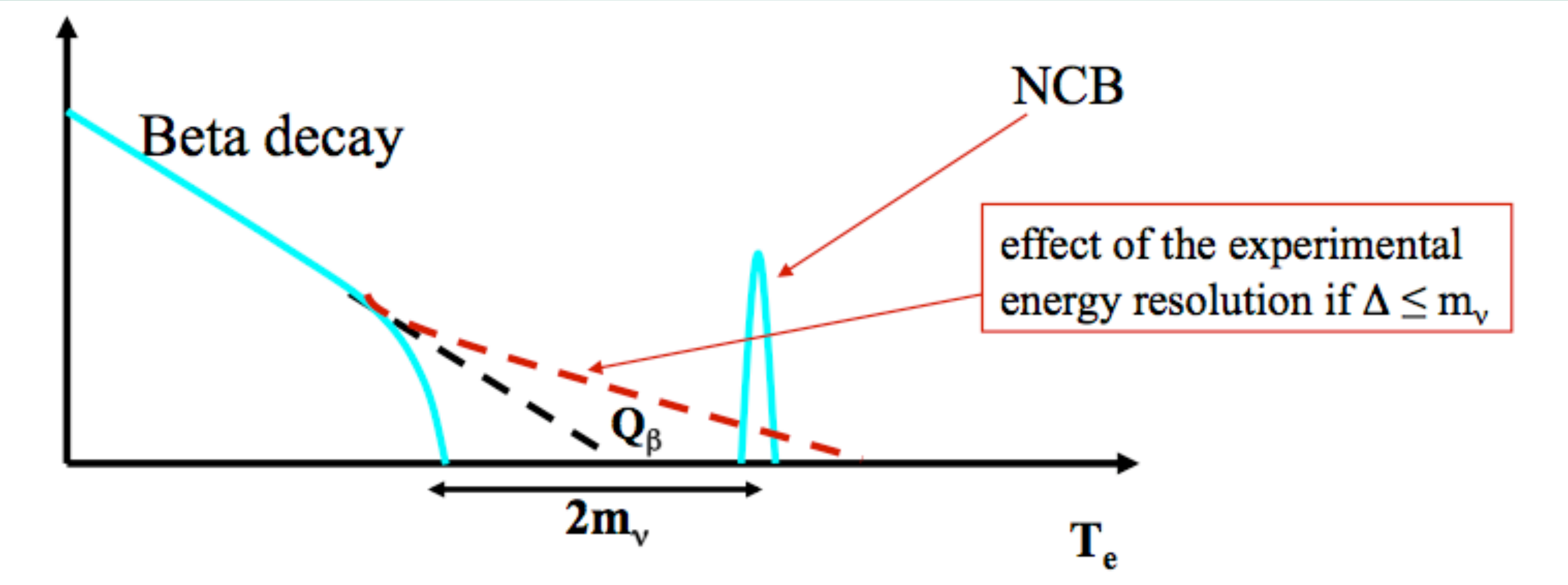
Nuclear Techniques

- Relic neutrinos can “induce” nuclear decays in unstable nuclei. (Weinberg, 1962)



Beta-Decay

Messina



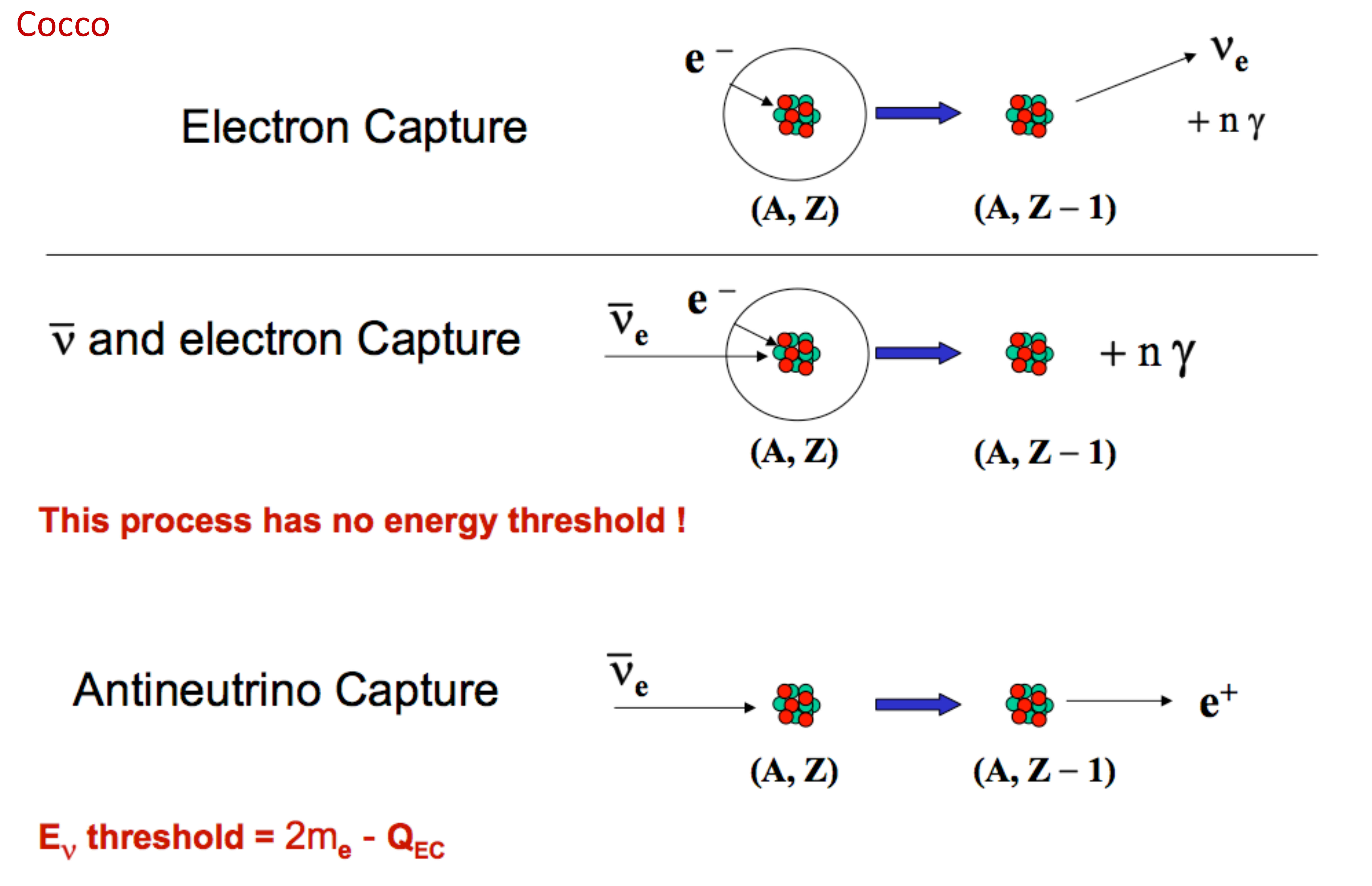
Not so insane: ~7 events per year in 100 g. tritium; however have to reject ~10^{24} normal decays

- KATRIN: Magnetic Spectrometer (tritium)
- RF Cyclotron Measurements (Project 8)
- Geometrically-Metastable Superconducting Strips Detectors

Promising, but still order of magnitude away.

Aside: Cannot cause annual modulation of rate, since σ *v* = const.

Neutrino-induced EC



Neutrino-induced EC

$\bar{\nu}_e + e^- + (A,Z) \rightarrow (A,Z-1) + X$

The lack of a suitable final state prevents the use of this reaction to detect CνB unless either:

1) there exist an excited level (either atomic or nuclear) with energy $E_o = Q_{EC} - E_K + m_\nu$

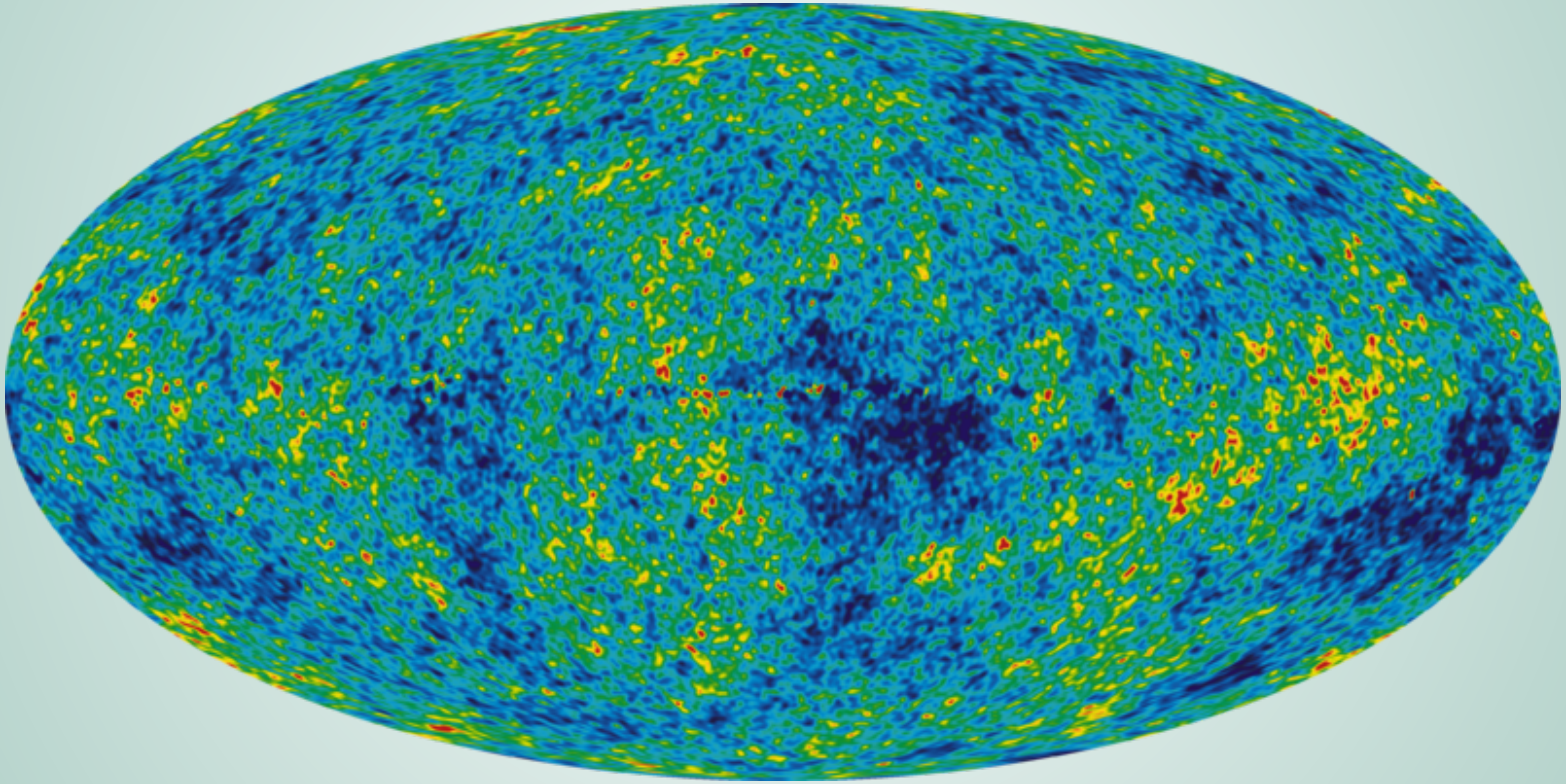
2) the captured electron is “off-mass” shell $m_{eff} = m_e - E_o$

3) it exist a nucleus A (stable) for which $Q_{EC} = E_K - m_\nu$

Relic Neutrino History
-or- why physics is *really* hard

- **1940's** : Proposal by Gamow, Dicke, and others. Estimate range for 2K to 50K
- **2023:** yep, still here. A few ideas, but not much to report.

Relic nu map in 2150?
(apologies to Cocco)



Bonus

A cautionary tale of false starts in neutrino physics

The 17 keV Neutrino

A little Background

For nuclear beta-decay, the spectrum is given by:

$$\frac{dN(E,m_\nu)}{dE} \propto F(Z,E)pE(Q-E)\left[(Q-E)^2 - m_\nu^2\right]^{1/2}$$

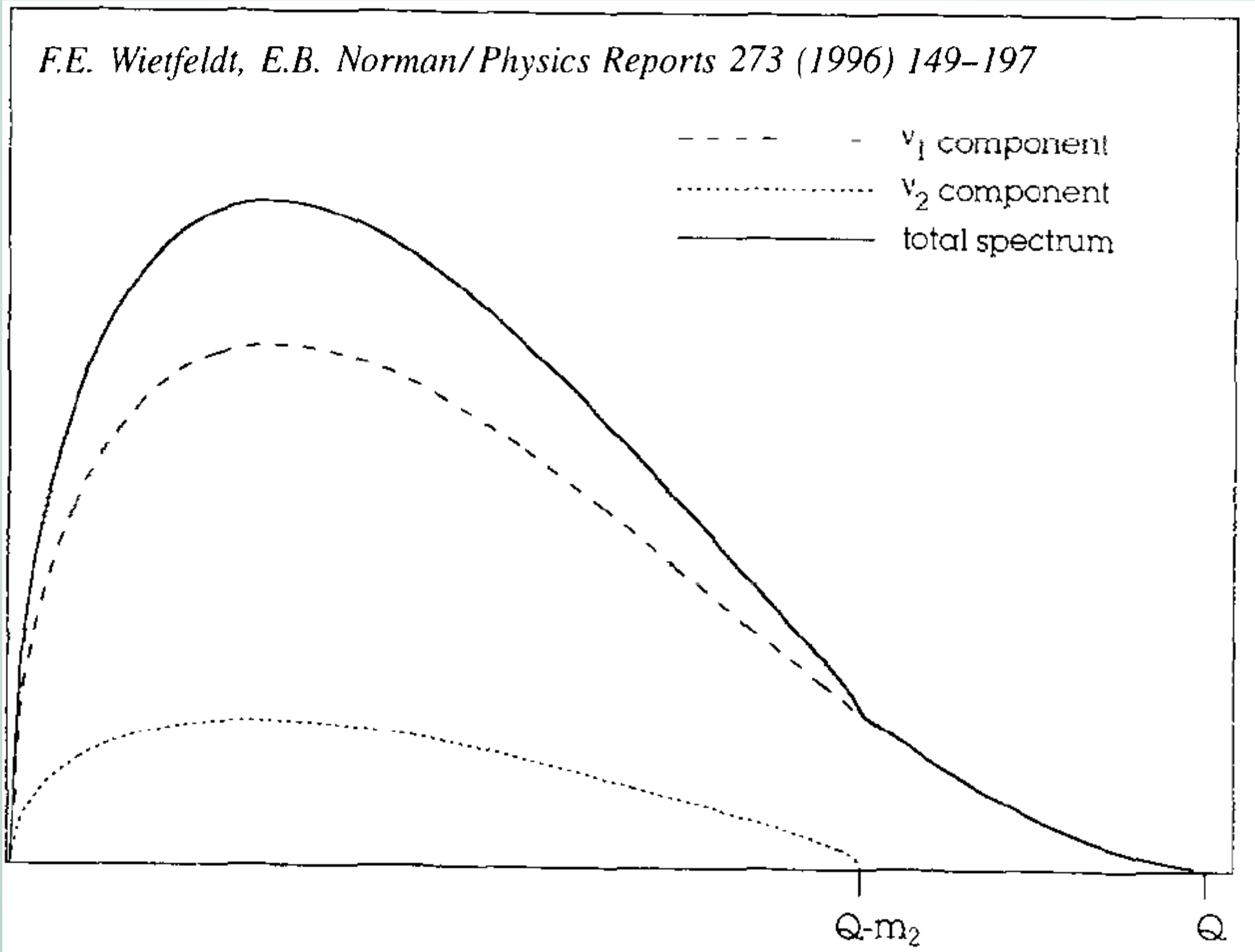
However, the emitted neutrino is in a superposition of mass eigenstates.
For example, in a simple two state mixing model:

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

This modifies the spectrum to:

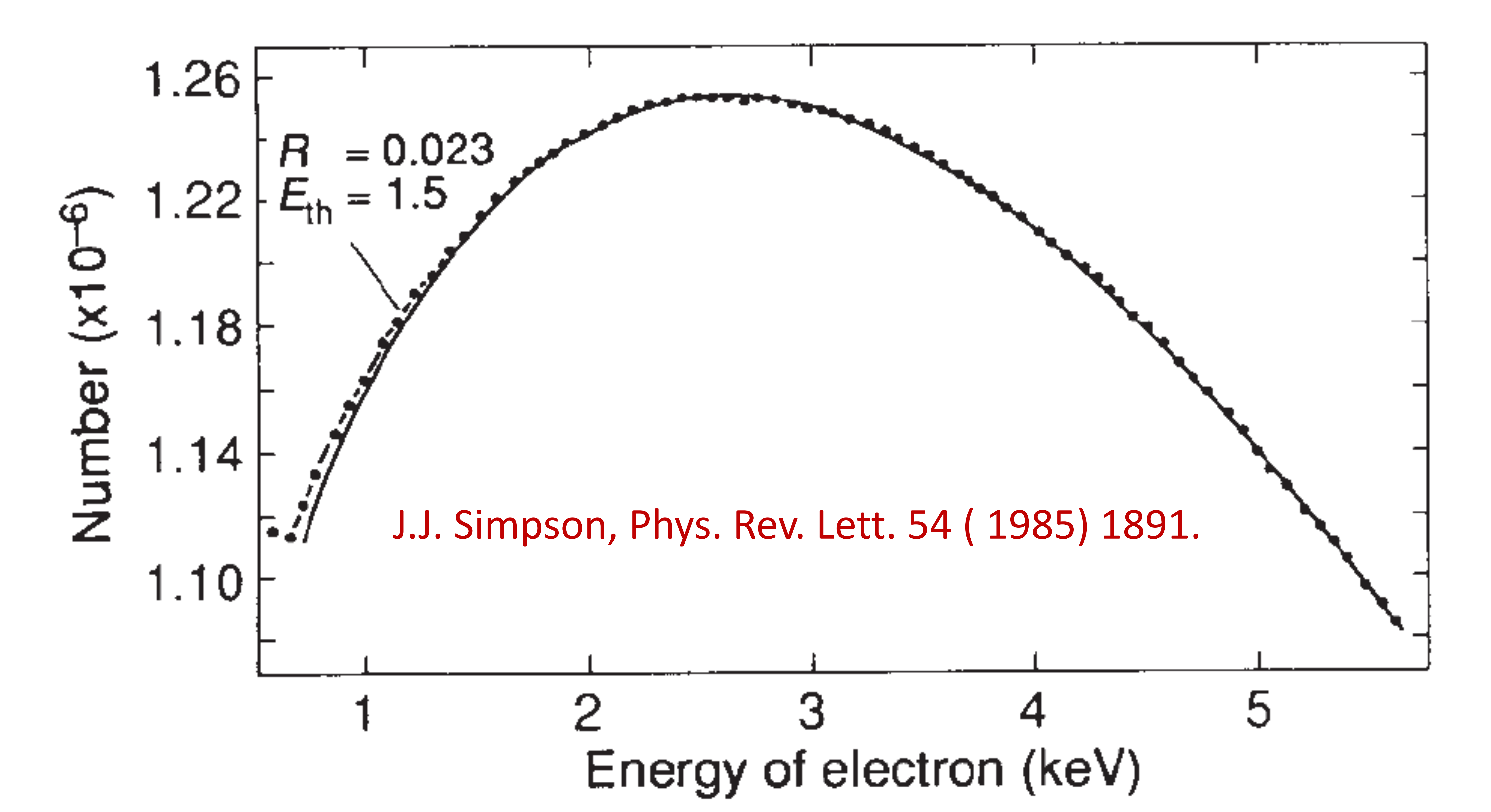
$$\frac{dN(E)}{dE} = \cos^2\theta\frac{dN(E,m_1)}{dE} + \sin^2\theta\frac{dN(E,m_2)}{dE}$$

Leads to "kinks" in beta spectrum



1985: “Kink” is observed by Simpson at U. of Guelph

Si(Li) detector implanted with Tritium via Tandem.
Only directly calibrated above 8 keV
Consistent with m_2 = 17.1 +- 0.2 keV and $\sin^2 \vartheta$ = 0.03 +- 0.01



J.J. Simpson, Phys. Rev. Lett. 54 (1985) 1891.

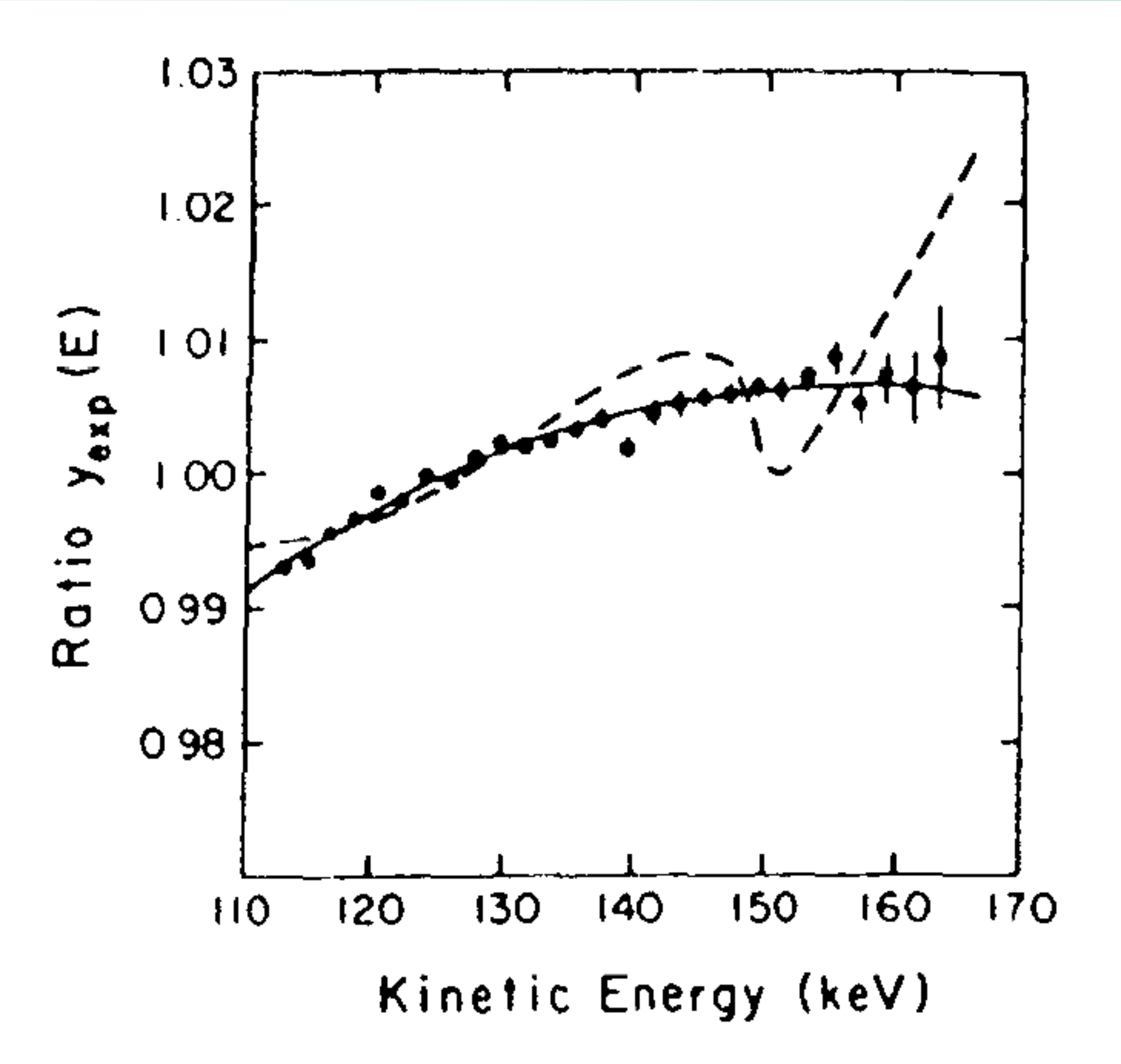
Initial Negative Results (1)

- Shortly ruled out by 4 magnetic Spectrometer experiments using ^{35}S (Q=167keV):
  - Princeton
  - ITEP- Moscow
  - Caltech
  - Chalk River (^{63}Ni)

  Applied shape

  Correction – Criticized by

  Simpson and others



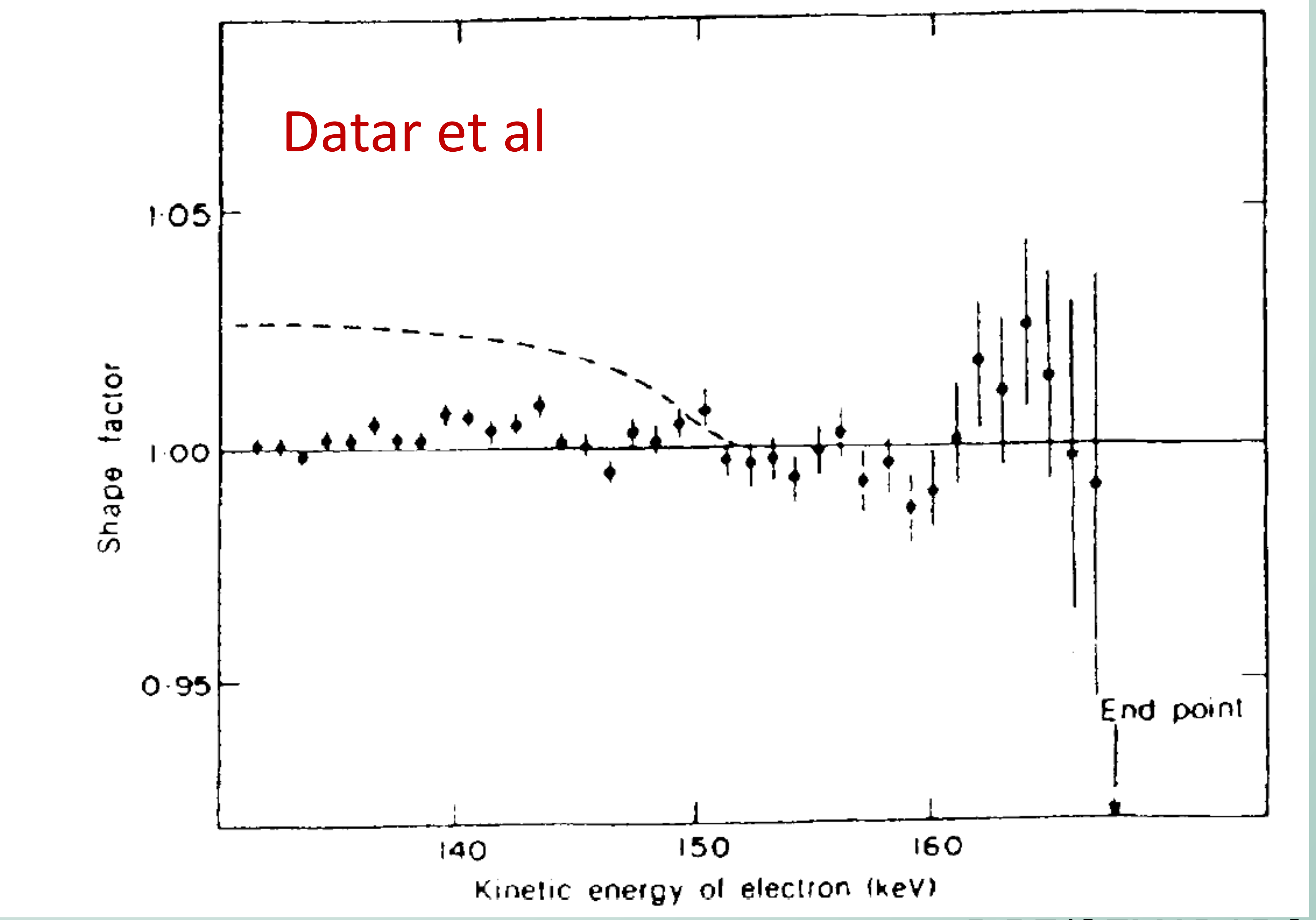
T. Altzitzoglou, F. Calaprice, M.S. Dewey, L. Lowry, L. Piilonen, J. Brorson, S. Hagen and F. Loeser, Phys. Rev. Lett. 55 (1985) 799.

Initial Negative Results (2)

- 1985: 2 Experiments using Si(Li) detectors and ^{35}S observe no indication of 17 keV neutrino

V.M. Datar, C.V.K. Baba, S.K. Bhattacherjee, C.R. Bhuinya and A. Roy, Nature 318 (1985) 547.
T. Ohi, M. Nakajima, H. Tamura, M. Matsuzaki, T. Yamazaki, O. Hashimoto and R.S. Hayano, Phys. Lett. B 160 (1985) 322.

However, there were issues with fit applied and normalization
Simpson re-analyzed data and claimed Ohi et al is consistent with 17 keV neutrino!



The 17 keV Neutrino Returns!

- 1989: Simpson and his student A. Hime publish results from two experiments confirming existence of 17 keV Neutrino
- #1 Si(Li) detector + ^{35}S source

J.J. Simpson and A. Hime, Phys. Rev. D 39 (1989) 1825.

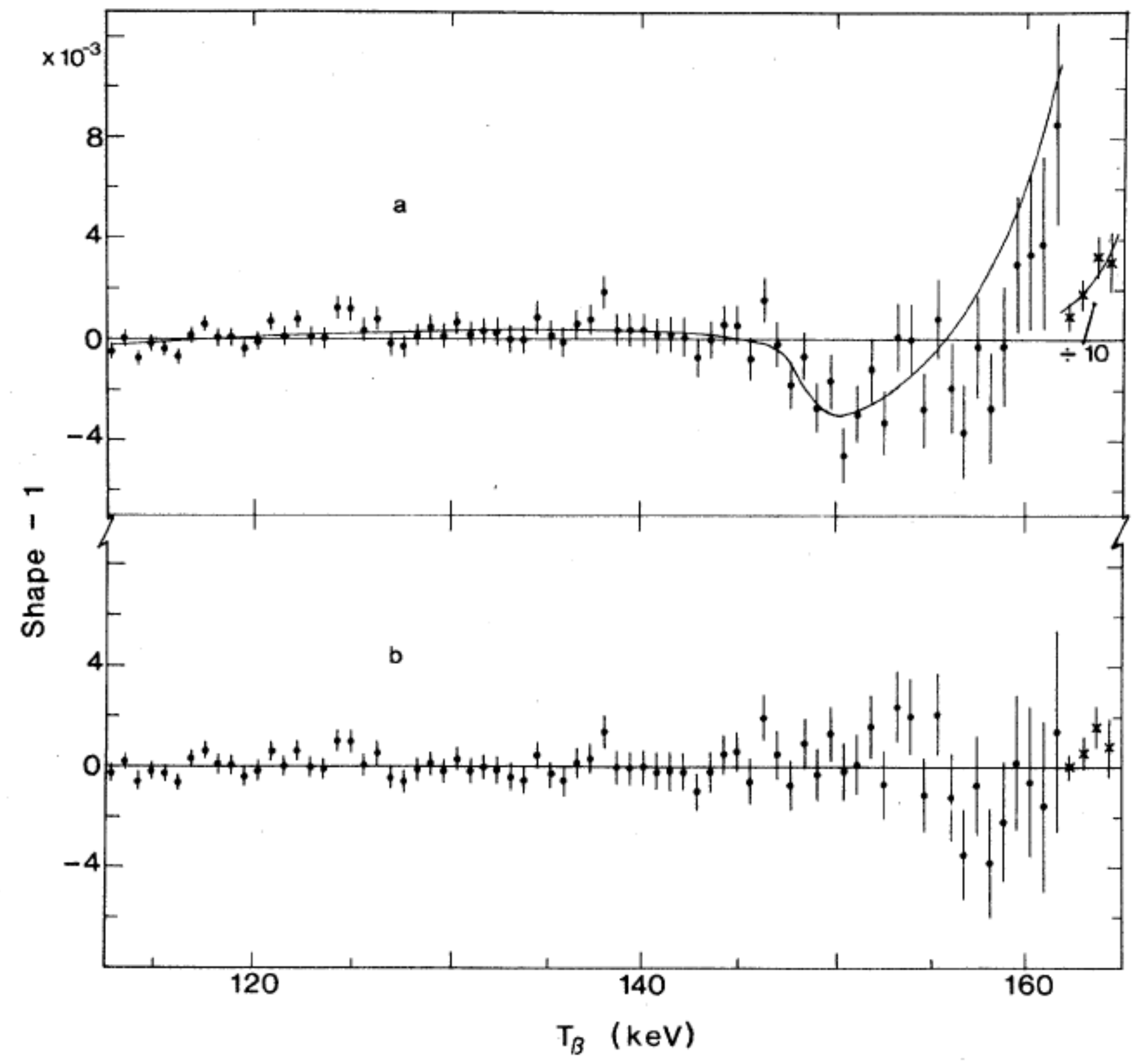


FIG. 6. The deviation of the shape function from a constant for the combined data of runs B and C. In (a) the theoretical spectrum has $\sin^2\theta=0$. $\chi^2/\nu=2.0$. The smooth curve shows the shape expected for $M_2=17$ keV and $\sin^2\theta=0.008$. In (b) the experimental data are divided by a theoretical fit with $M_2=17$ keV and $\sin^2\theta=0.0075$. $\chi^2/\nu=1.0$.

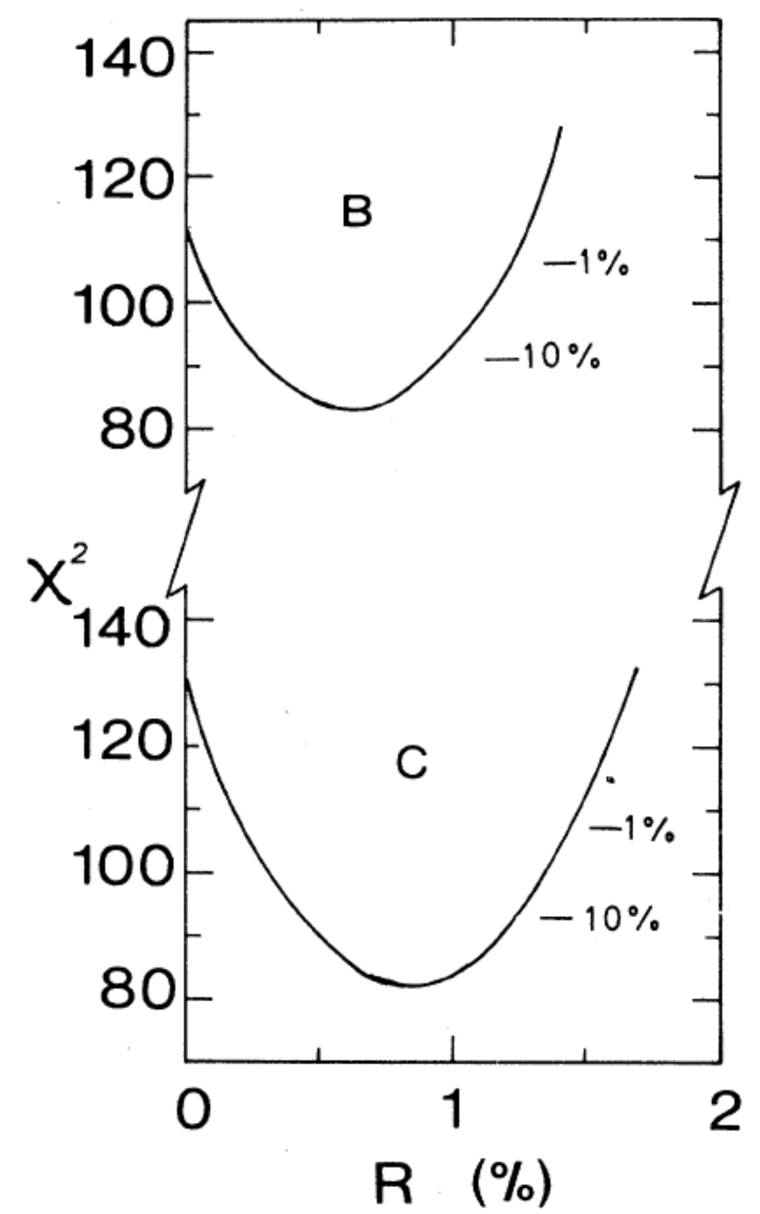


FIG. 7. χ^2 curves for fits to the two ^{35}S experiments B (number of degrees of freedom $\nu=75$) and C ($\nu=77$) vs 17-keV neutrino mixing probability $R\equiv\sin^2\theta$ over the energy region 110–166 keV. For each value of R used to attempt a fit, the normalization, end-point energy, and the tail of the response function were varied.

- #2: Tritium implanted in HPGe detector (Better calibration, annealing to repair radiation damage)

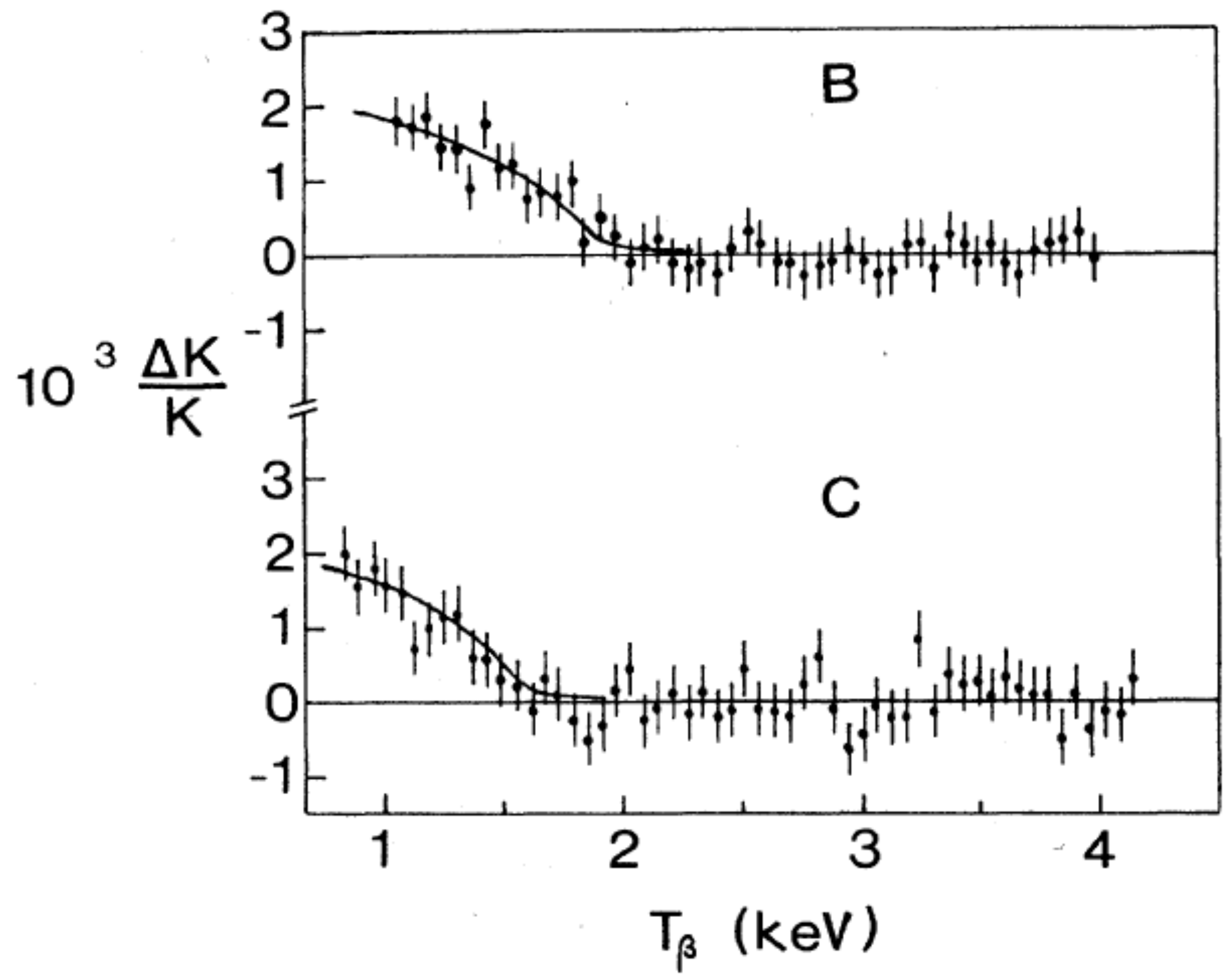


FIG. 14. The fractional deviations $\Delta K/K$ in the Kurie plots of spectrum B and spectrum C from a straight line using an effective screening potential of 42.6 eV. The smooth curves are as predicted in Eq. (5) for the emission of a heavy neutrino after accounting for resolution smearing. $M_2 = 16.85$ keV with $\sin^2\theta = 1.1\%$ in the case of spectrum B with FWHM$\simeq$405 eV. $M_2 = 17.00$ with $\sin^2\theta = 1.3\%$ in the case of spectrum C with FWHM$=$310 eV.

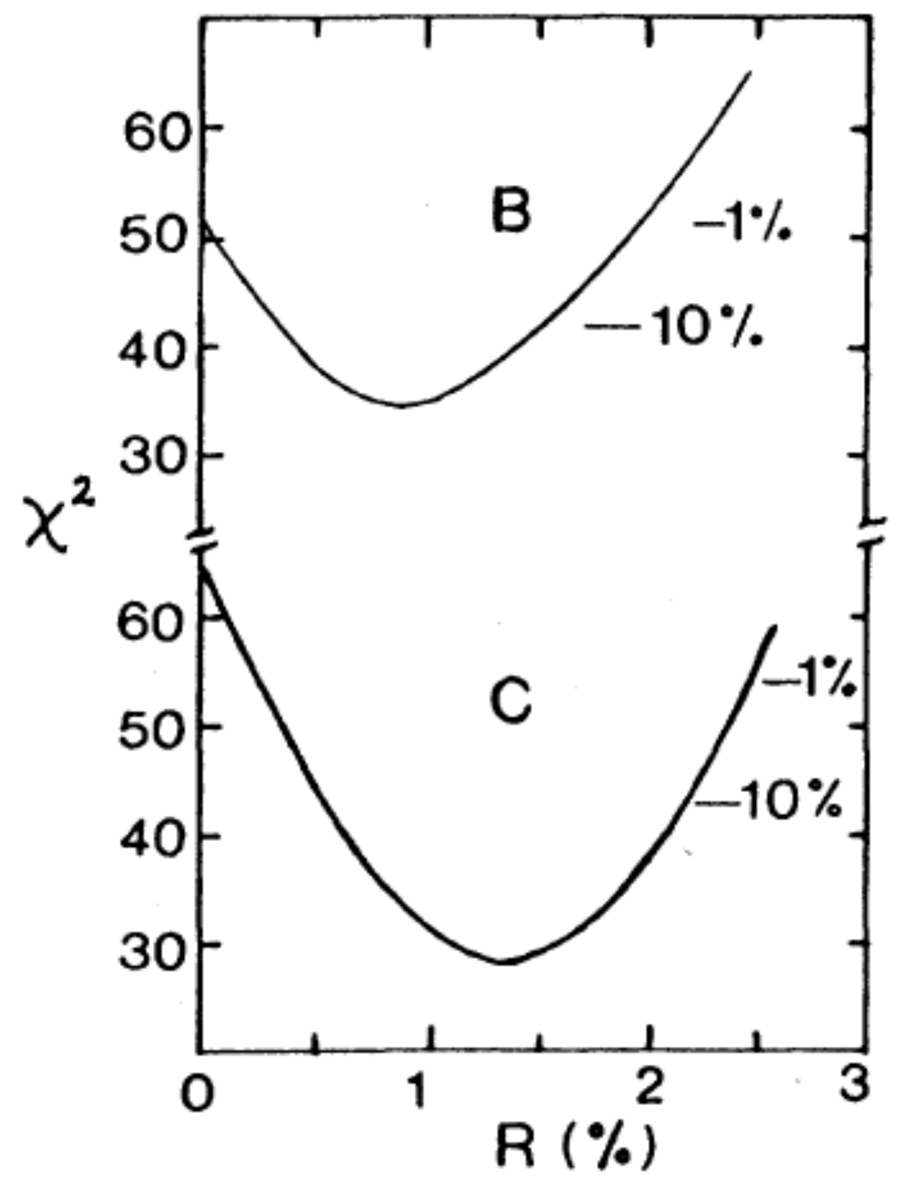


FIG. 13. χ^2 plots obtained by fitting spectrum B and spectrum C to a two-state model of the electron neutrino using an effective screening potential of 42.6 eV. A combined χ^2 indicates that the data are best described by the emission of 16.93±0.10 keV neutrino with a (1.1±0.2)% mixing probability.

A. Hime and J.J. Simpson, Phys. Rev. D 39 (1989) 1837.

Independent Confirmation!

E.E. Haller, W.L. Hansen, P. Luke, R. McMurray and B. Jarrett, IEEE Trans. Nucl. Sci. 29 (1982) 745.

B. Sur, E.B. Norman, K.T. Lesko, M.M. Hindi, R.M. Larimer, N. Luke, W.L. Hansen and E.E. Haller, Phys. Rev. Lett. 66 (1991) 2444.

- HPGe detector doped with ^{14}C (Q=156 keV)
- Large background subtraction

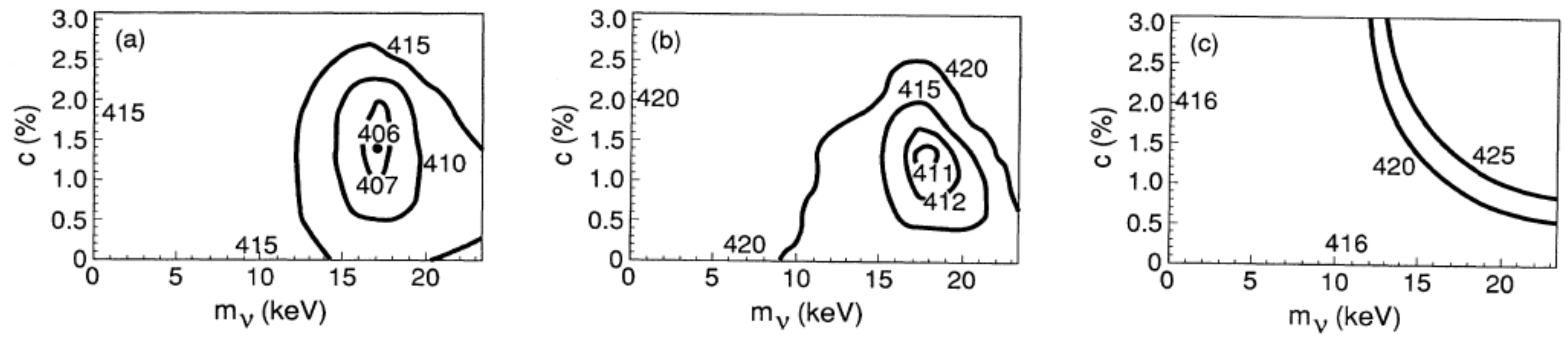


FIG. 2. Contour plots of χ^2 as a function of the neutrino mass m_ν and c. The curves are labeled by the values of χ^2. (a) Analysis of our type-(2) data; (b) analysis of Monte Carlo-generated data which contains a 1.4% fraction of a 17-keV neutrino; (c) analysis of Monte Carlo-generated data which contains only a zero-mass neutrino.

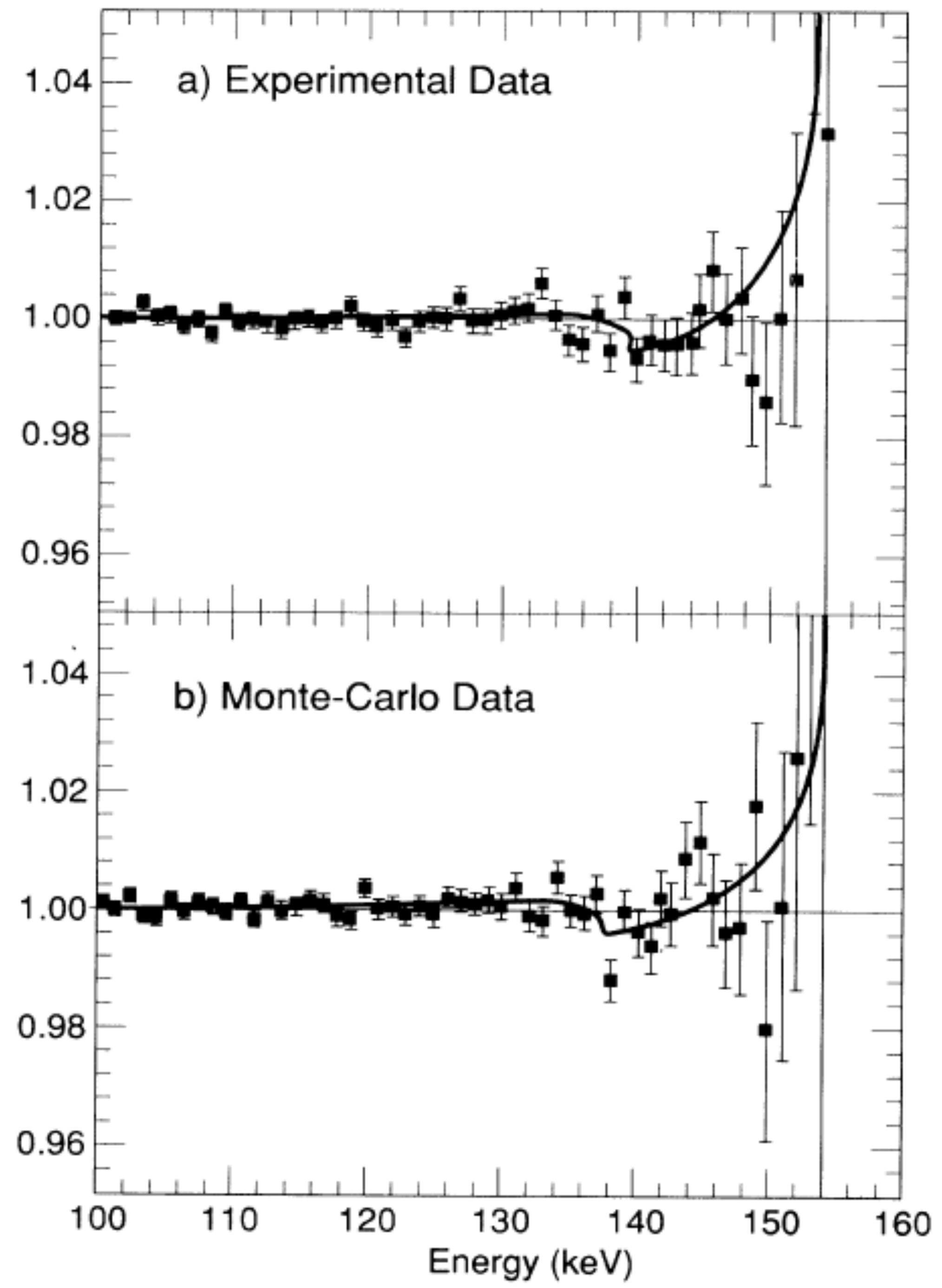


FIG. 3. The ratio of the data to a theoretical fit assuming the emission of only zero-mass neutrinos. The data were compressed to 1 keV/channel. The horizontal line is the shape expected for zero-mass neutrinos. The curves illustrate the shape expected from the best fits to the data. (a) Analysis of our type-(2) data; (b) analysis of Monte Carlo-generated data which contain a 1% fraction of a 17-keV neutrino.

1991: Experimental Controversy

- More confirmation followed:
  - Zagreb
  - Hime & Jelley at Oxford

take the prospect of a 17 keV neutrino more seriously. A world average of the positive experiments, weighted by their reported uncertainties, gives $m_2 = 16.9 \pm 0.1$ keV and $\sin^2\theta = 0.83 \pm 0.06\%$. A fit of these points to the average yields a χ^2_ν of 0.17 for the mass and 0.92 for the mixing, remarkably good agreement considering the variety of techniques and isotopes used. This consistency was probably the

Table 1
17 keV neutrino results as of December 1991 (see text for references).

Group	Method	Isotope	m_2(keV)[a]	$\sin^2\theta$(%)[a]
Positive:				
Guelph	Int. Si(Li)	^{3}H	17.1 ± 0.2	2–4[b]
	Ext. Si(Li)	^{35}S	16.9 ± 0.4	0.73 ± 0.11
	Int. Ge	^{3}H	16.9 ± 0.1	0.6–1.6
LBL	Int. Ge	^{14}C	17 ± 2	1.4 ± 0.5
Oxford	Ext. Si(Li)	^{35}S	17.0 ± 0.4	0.8 ± 0.08
	Ext. Si(Li)	^{63}Ni	16.8 ± 0.4	1.0 ± 0.2
Zagreb	IBEC	^{71}Ge	17.2 ± 0.7	1.6 ± 0.5
Negative:				
Princeton	Mag. Spec.	^{35}S	17	< 0.4 (99% CL)
ITEP	Mag. Spec.	^{35}S	17	< 0.17 (90% CL)
INS Tokyo	Ext. Si(Li)	^{35}S	17	< 0.15 (90% CL)
Bombay	Ext. Si(Li)	^{35}S	17	< 0.6 (90% CL)
Caltech	Mag. Spec.	^{35}S	17	< 0.3 (90% CL)
ISOLDE	IBEC	^{125}I	17	< 2 (98% CL)
Chalk River	Mag. Spec.	^{63}Ni	17	< 0.3 (90% CL)
Zagreb	IBEC	^{55}Fe	17	< 0.74 (99.7% CL)
ILL Grenoble[c]	Mag. Spec.	^{177}Lu	17	< 0.4 (68% CL)
U. Oklahoma	Int. gas	^{3}H	17	< 0.4 (99% CL)
Other:				
LBL	IBEC	^{55}Fe	21 ± 2	0.85 ± 0.45
Buenos Aires	IBEC	^{71}Ge	13.8 ± 1.8	0.8 ± 0.3

F.E. Wietfeldt, E.B. Norman/Physics Reports 273 (1996) 149–197

D.R.O Morrison, *Nature*, 366 (1993) 29

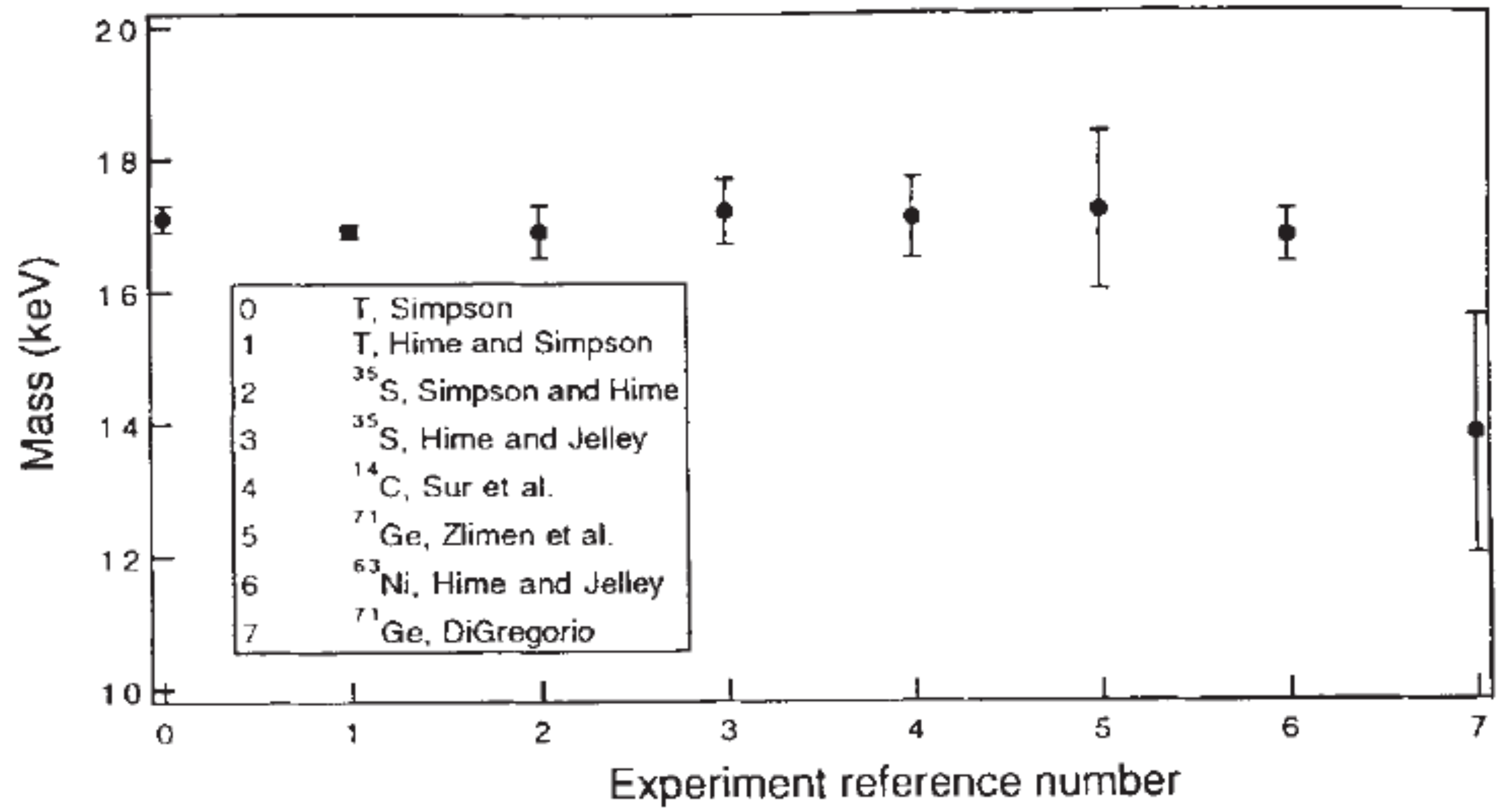
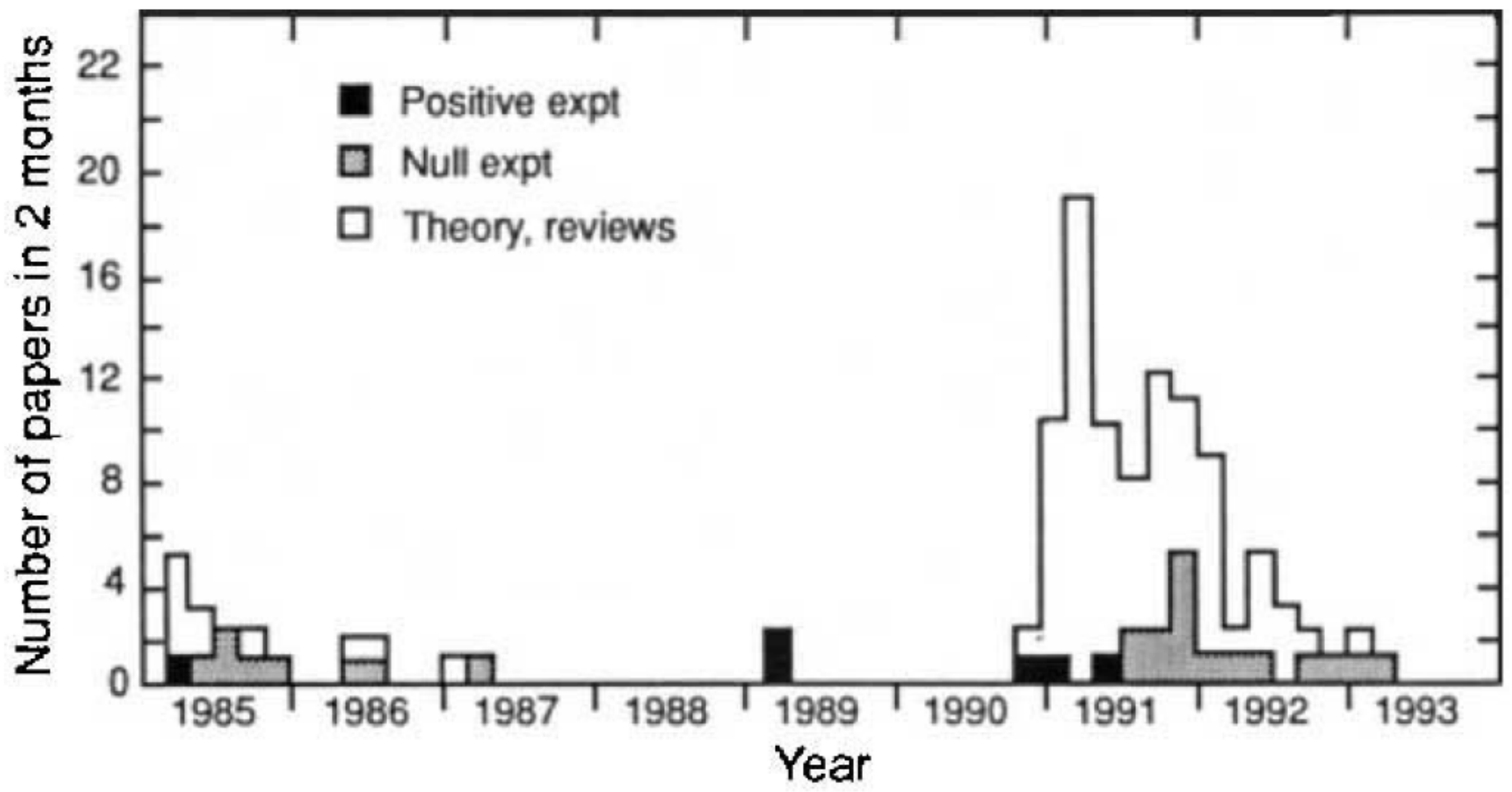


FIG. 4 Values of the mass of a heavy neutrino from positive determinations, from ref. 43.



What about theory?

- Initially (1985), a 17 keV neutrino had significant theoretical inconsistencies with:
  - LEP Data
  - Cosmology
  - SN 1987A
- However, by 1991:

It is a tribute to theoretical ingenuity that in spite of the severe constraints a number of viable, if somewhat contrived, models for the 17 keV neutrino were developed. See [83,85,88,89] for interesting and more detailed discussions. Although the theoretical debate over the 17 keV neutrino was fascinating, the question of its existence remained an experimental issue. In the summary talk at the Workshop on the 17 keV Neutrino Question convened in Berkeley in December 1991, Bernard Sadoulet concluded, "The 17 keV neutrino may not exist, but it will not be because it cannot exist."

F.E. Wietfeldt, E.B. Norman/Physics Reports 273 (1996) 149–197

The tide turns

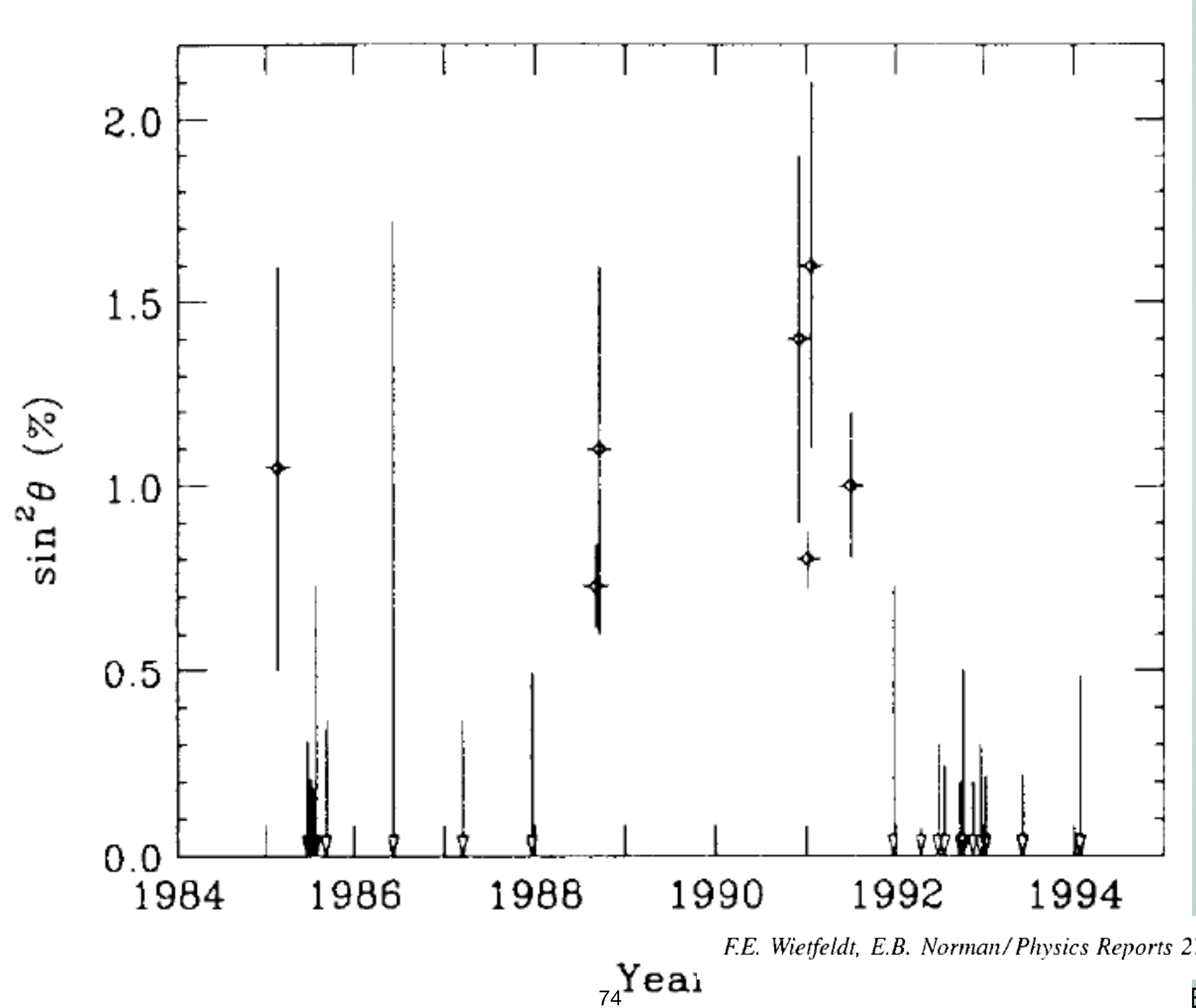
- 1992-1994. Experiments gather compelling evidence against 17 keV neutrino.

Table 2
Second generation 17 keV neutrino experiments (see text for references).

Group	Method	Isotope	m_2(keV)	$\sin^2\theta$(%)
INS Tokyo	Mag. Spec.	^{63}Ni	17	< 0.073 (95% CL)
Caltech	Mag. Spec.	^{35}S	17	< 0.2 (90% CL)
Argonne	Ext. Si(Li)	^{35}S	17	< 0.2 (95% CL)
Buenos Aires	IBEC	^{71}Ge	17	< 0.5 (95% CL)
Berkeley	IBEC	^{55}Fe	17	< 0.2 (95% CL)
Princeton	Mag Spec.	^{35}S	17	< 0.3 (95% CL)[a]
U. Oklahoma	Int. gas	^{3}H	17	< 0.28 (99% CL)
Zürich	Mag. Spec.	^{63}Ni	17	< 0.15 (95% CL)[a]
ILL Grenoble	Ext. Si	^{35}S	17	< 0.18 (90% CL)
Tenn. Tech	IBEC	^{125}I	17	< 0.4 (90% CL)

F.E. Wietfeldt, E.B. Norman/Physics Reports 273 (1996) 149–197

World summary of results



F.E. Wietfeldt, E.B. Norman / Physics Reports 273 (1996) 149–197

What happened?

- T experiments: Cause still unknown, probably non-linear energy response
- Oxford and Guelph ^{35}S and ^{63}Ni experiments: electron scattering from annular baffles + finite thickness of source
  - Hime – “baffled” by result
- LBNL: Events in Guard ring of Ge detector
- Zagreb not explained, could be statistical

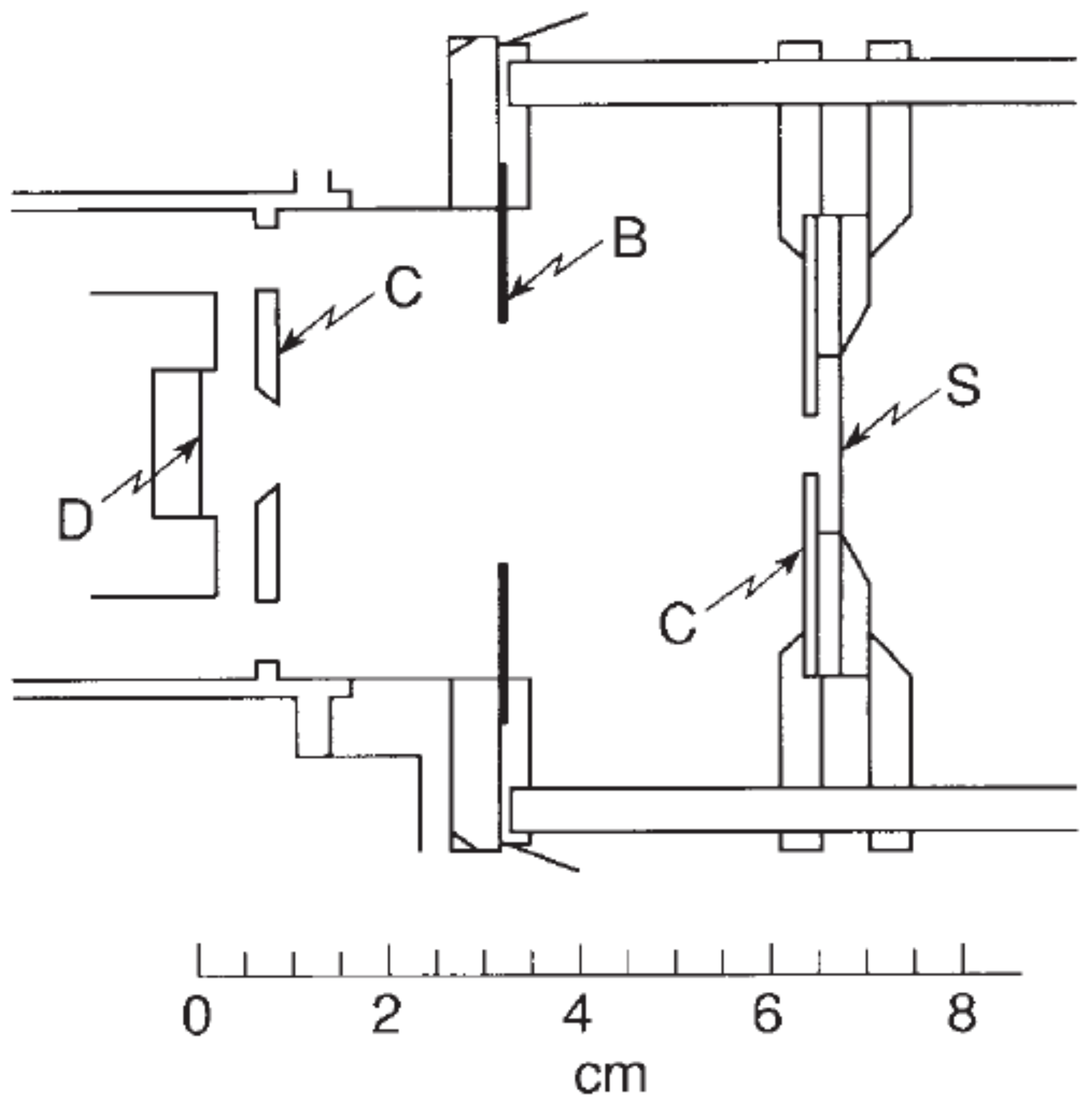


FIG. 3 Inner part of the experimental apparatus used by Hime and Jelley[17,19]. B is the annular baffle that caused problems, S is the source from which the decay electrons emerge, D is the solid-state detector and C represents the two collimators around the source and the detector.

F.E. Wietfeldt, E.B. Norman/Physics Reports 273 (1996) 149–197

Other extraordinary claims in neutrino physics

- Disproven:
  - ~10 claims of neutrinoless double-beta decay! (Tretyak, MEDEX 2011)
  - T endpoint anomalies
  - Superluminal neutrinos
- Proven:
  - Solar neutrino problems (20+ years) (Nobel)
  - Atmospheric neutrino oscillations
- Still out there:
  - KKDC claim for DBD
  - Sterile neutrinos (LSND, MiniBOONE, reactor anomaly)
  - Dark matter claims (CoGeNT, CRESST)

Lessons learned

The 17 keV neutrino experiments taught how easily a systematic effect can masquerade as the signature for a new physical process. Obtaining a good χ^2 fit with the experimental spectral shape is not sufficient; a convincing experiment must independently demonstrate its sensitivity to the effect in question. Seemingly negligible influences on the spectrum must not be taken for granted. A fundamental problem in all of the positive experiments was a high sensitivity to the detailed shape of the energy response of the apparatus, and the failure to measure this response function in the energy region analyzed. In the Guelph and Oxford ^{35}S experiments the response was measured at low energies

- **Systematic errors must be well quantified (calibration)**
- Do not extrapolate into regions where you cannot calibrate
- Psychology
- Blind Analysis