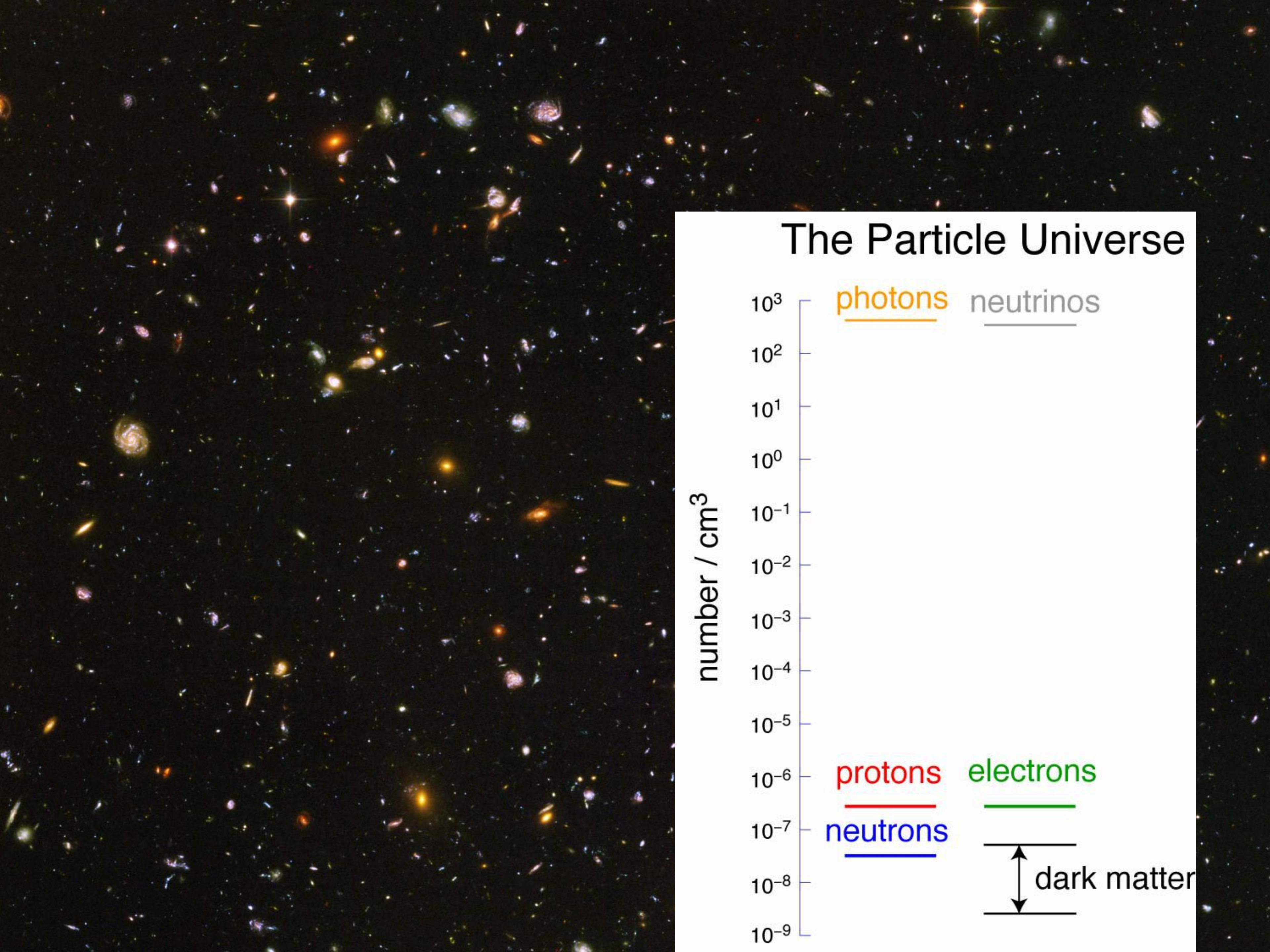
Neutrino Properties and Leptogenesis

Hitoshi Murayama (Berkeley)

July 14, 2024

N3AS Summer School, UCSC


The Particle Universe
number / cm3
10^3
10^2
10^1
10^0
10^−1
10^−2
10^−3
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
photons
neutrinos
protons
electrons
neutrons
dark matter

"Wimpy and Abundant" Neutrinos are Everywhere

- They come from the Big Bang:
  - When the Universe was hot, neutrinos were created equally with any other particles
  - They are still left over: ~300 neutrinos per cm^3
- They come from the Sun:
  - Trillions of neutrinos going through your body every second
- They are shy:
  - If you want to stop them, you need to stack up lead shield up to three light-years

Outline

- Introduction
- Neutrinos in the Standard Model
- Evidence for Neutrino Mass
- Implications of Neutrino Mass
- Solar Neutrinos
- Matter Effect in Solar Neutrinos
- Masses and Mixings
- Leptogenesis
- Conclusions

Neutrinos in the Standard Model

Puzzle with Beta Spectrum

- Three-types of radioactivity: α, β, γ
- Both α, γ discrete spectrum because

$$E_{\alpha,\gamma} = E_i - E_f$$

- But β spectrum continuous

F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

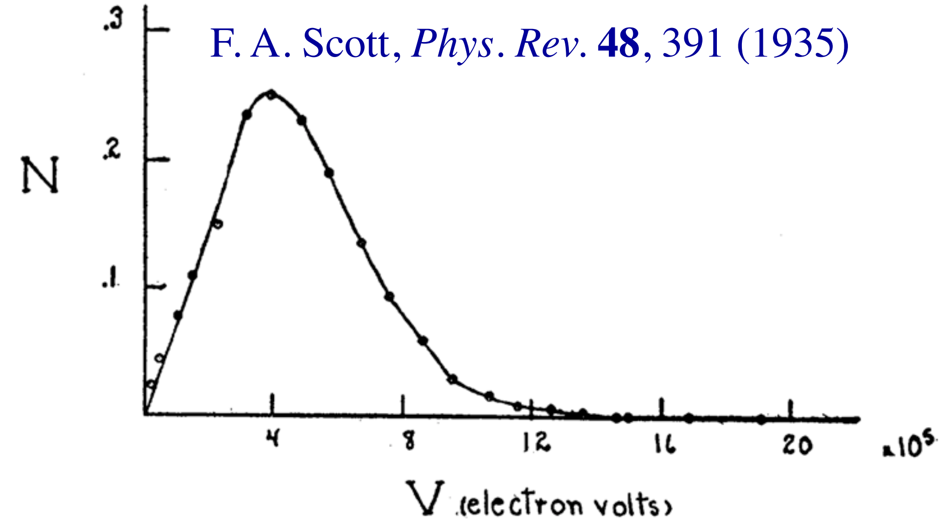


FIG. 5. Energy distribution curve of the beta-rays.

Bohr: *At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations*

Desperate Idea of Pauli

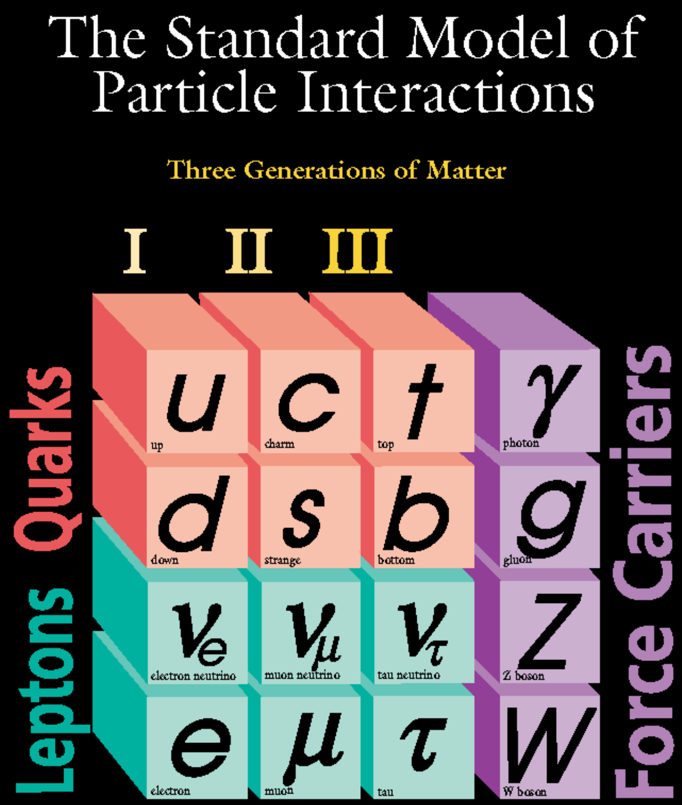
4th December 1930

Dear Radioactive Ladies and Gentlemen,

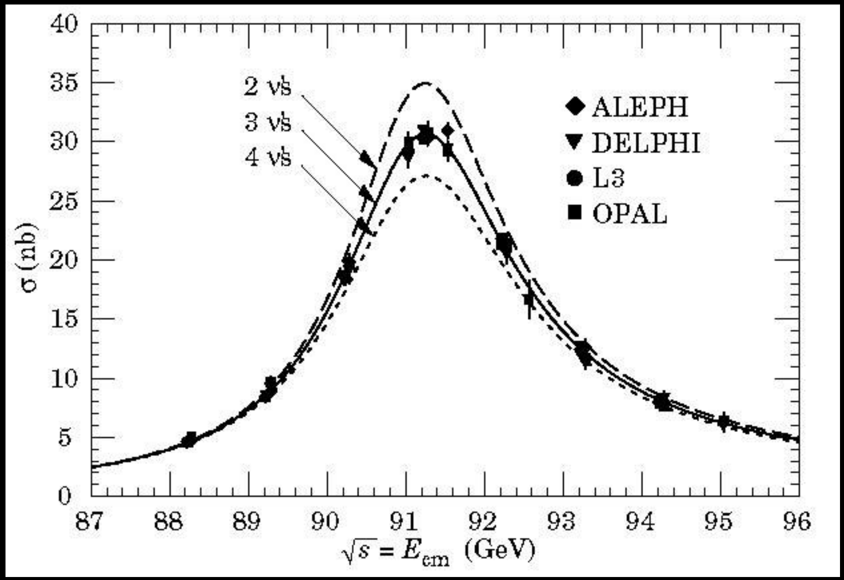
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

Three Kinds of Neutrinos

- There are three



- And no more



Neutrinos are Left-handed

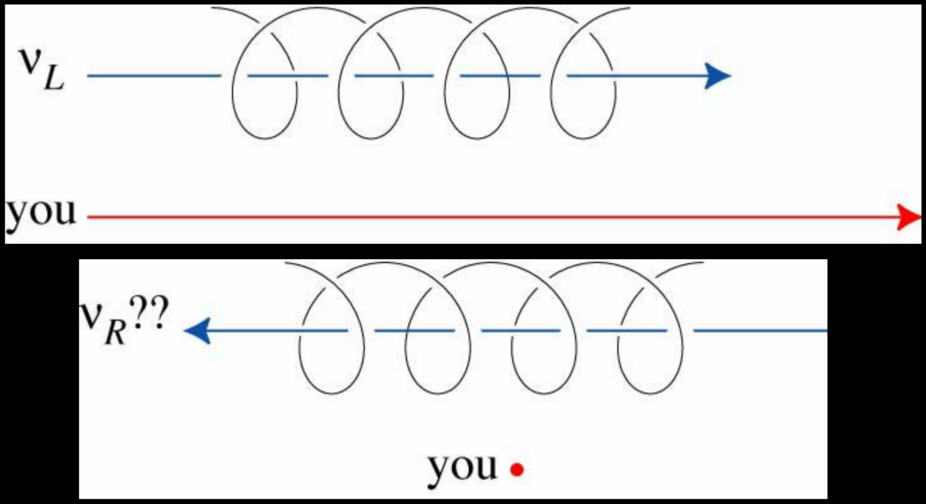
Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Neutrinos must be Massless

- All neutrinos left-handed ⇒ massless
- If they have mass, can't go at speed of light.

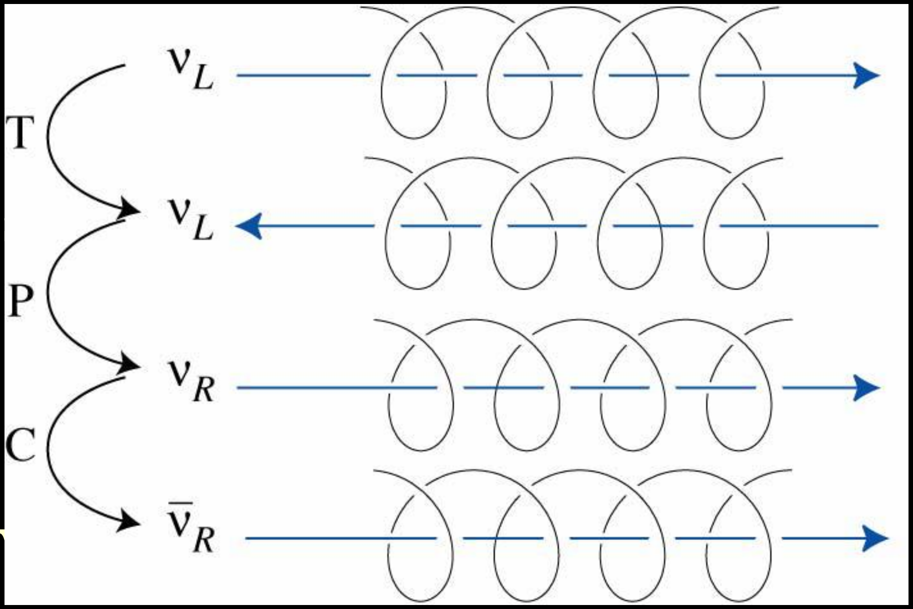


- Now neutrino right-handed??

  ⇒ contradiction ⇒ can't have a mass

Anti-Neutrinos are Right-handed

- CPT theorem in quantum field theory
  - C: interchange particle & anti-particles
  - P: parity
  - T: time-reversal
- State obtained by CPT from ν_L must exist: $\bar{\nu}_R$



$$\mathcal{L} = \bar{\nu} i \partial\!\!\!/ \frac{1-\gamma_5}{2} \nu$$

Other Particles?

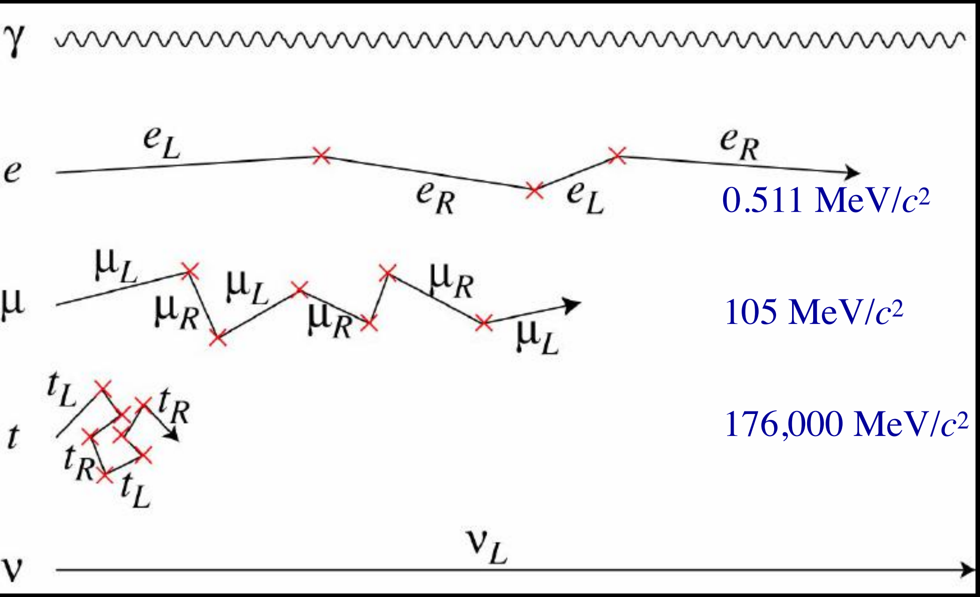
- What about other particles? Electron, muon, up-quark, down-quark, etc
- We say "weak force acts only on left-handed particles" yet they are massive.

Isn't this also a contradiction?

No, because we are swimming in a Bose-Einstein condensate in Universe

Universe is filled with Higgs

- "Empty" space filled with a BEC: cosmic superconductor
- Particles bump on it, but not photon because it is neutral.
- Can't go at speed of light (massive), and right-handed and left-handed particles mix ⇒ no contradiction



But neutrinos can't bump because there isn't a right-handed one ⇒ stays massless

$$\frac{i}{\not{p} - m} = \frac{i}{\not{p}} + \frac{i}{\not{p}}(-im)\frac{i}{\not{p}} + \frac{i}{\not{p}}(-im)\frac{i}{\not{p}}m\frac{1}{\not{p}} + \cdots$$

$$\int \frac{d^4p}{(2\pi)^4}\frac{i}{\not{p}}(-im)\frac{i}{\not{p}}e^{ip\cdot(x_1-x_3)}$$

$$= \int d^4x_2 \frac{1}{2\pi^2}\frac{\gamma\cdot(x_1-x_2)}{((x_1-x_2)^2)^2}(-im)\frac{\gamma\cdot(x_2-x_3)}{((x_2-x_3)^2)^2}$$

Standard Model

- Therefore, neutrinos are strictly massless in the Standard Model of particle physics

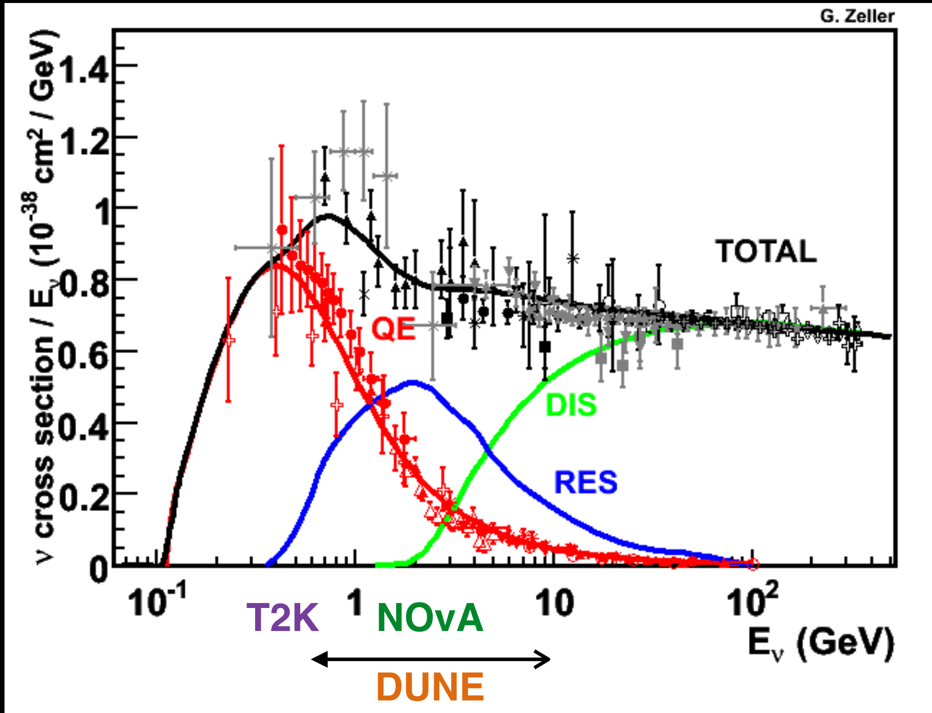
  Finite mass of neutrinos imply the Standard Model is incomplete!

- Not just incomplete but probably a lot more profound

Neutrinos are shy

- Order of magnitude of neutrino cross section on proton at rest:
- Very small, poorly measured

$$\sigma \propto \frac{G_F^2}{\pi} m_p E_\nu \approx 10 \text{ fb} \frac{E_\nu}{\text{GeV}}$$



J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

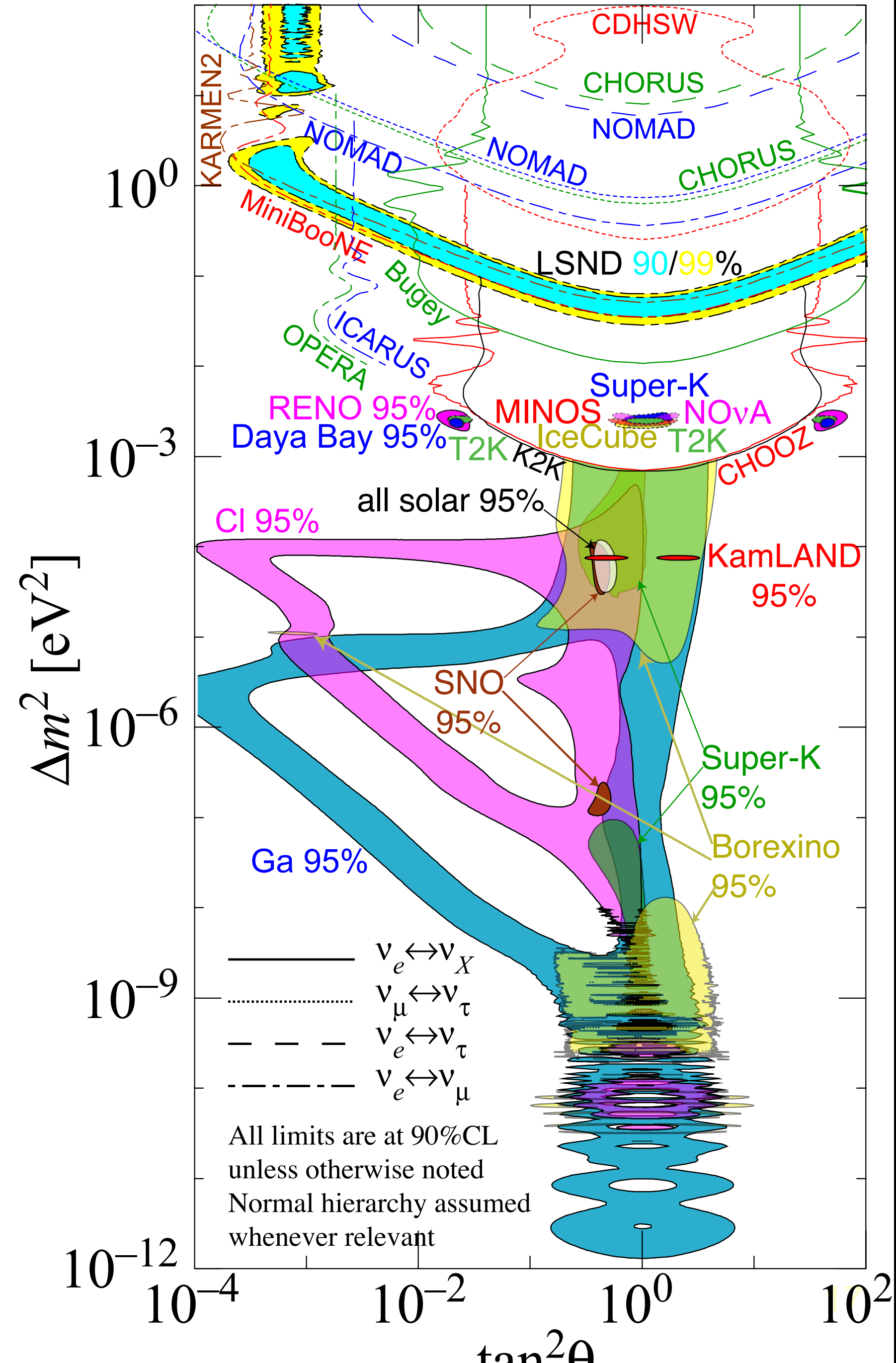
Neutrinos from backstage to center stage

- Pauli bet a case of champagne that noone would discover neutrinos
- Finally discovered by Cowan and Reines using a nuclear reactor in 1958
- Massless Neutrinos in the Standard Model (‘60s)
- Evidence for neutrino mass from SuperK (1998) and SNO (2002)
- *First evidence that the minimal Standard Model of particle physics is incomplete!*
- 2002 Nobel to pioneers: Davis and Koshiba

Lot of effort since ‘60s

Finally convincing evidence for “neutrino oscillation”

Neutrinos appear to have tiny but finite mass

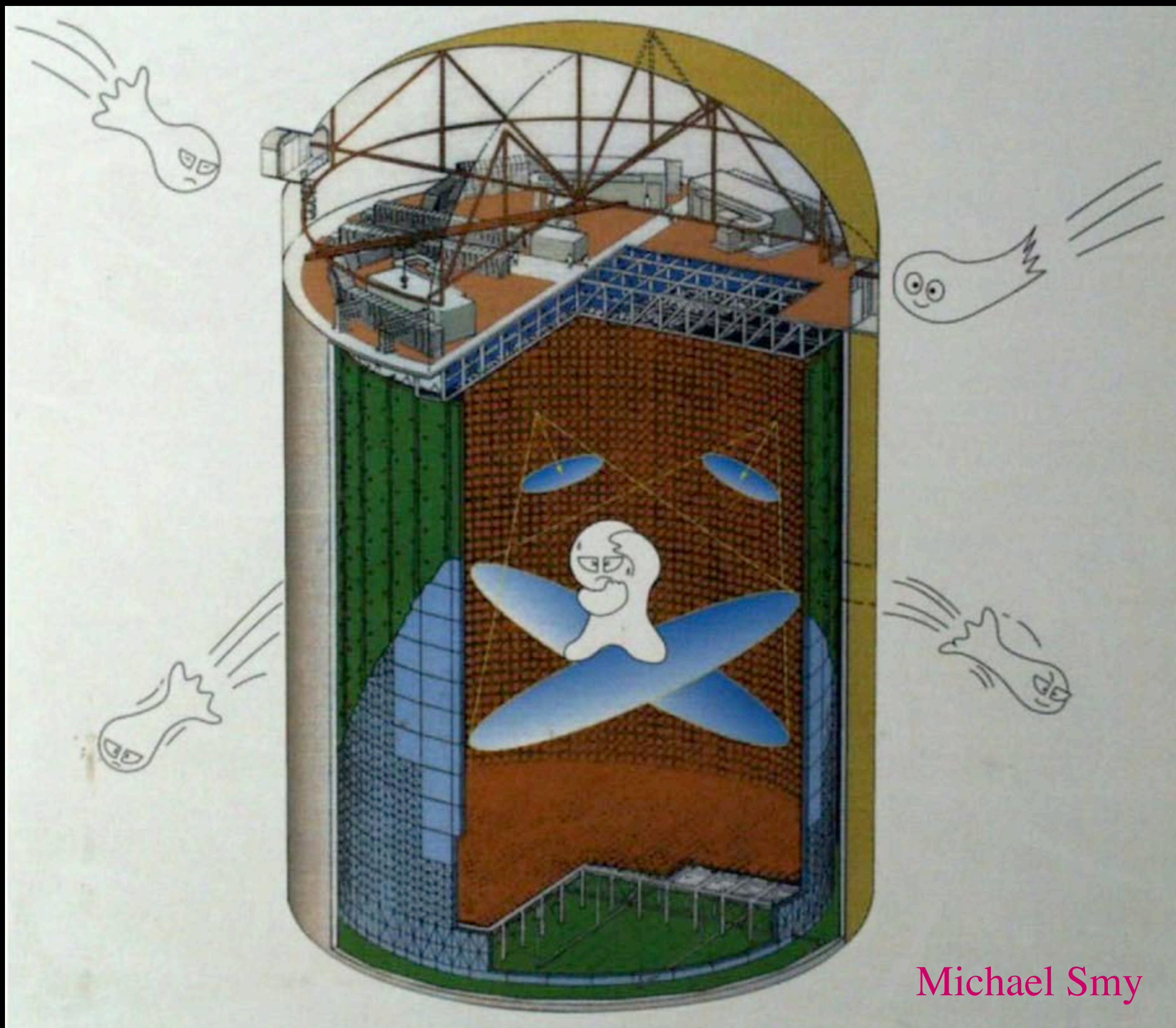


Typical Theorist's View ca. 1990

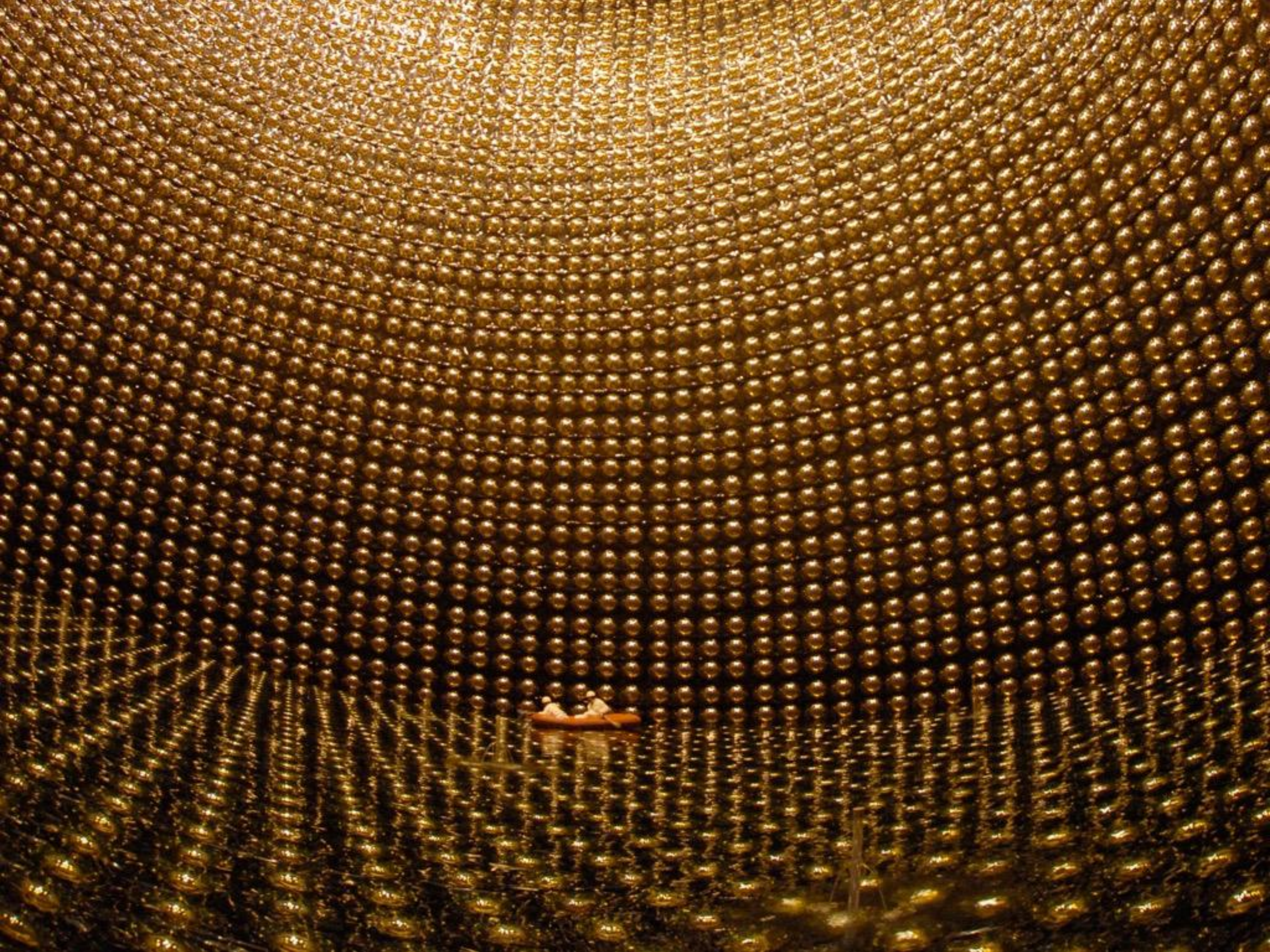
- Solar Neutrino Problem must be solved by Small Angle MSW solution because it is so beautiful Wrong!
- Important scale for oscillation is $\Delta m^2 \approx 10\text{-}100$ eV^2 because it is cosmologically relevant Wrong!
- θ_{23} must be about $\theta_{23} \approx V_{cb} \approx 0.04$ Wrong!
- atmospheric neutrino anomaly must go away because it requires large mixing angle Wrong!

Evidence for Neutrino Mass

Super-Kamiokande (SuperK)


Michael Smy

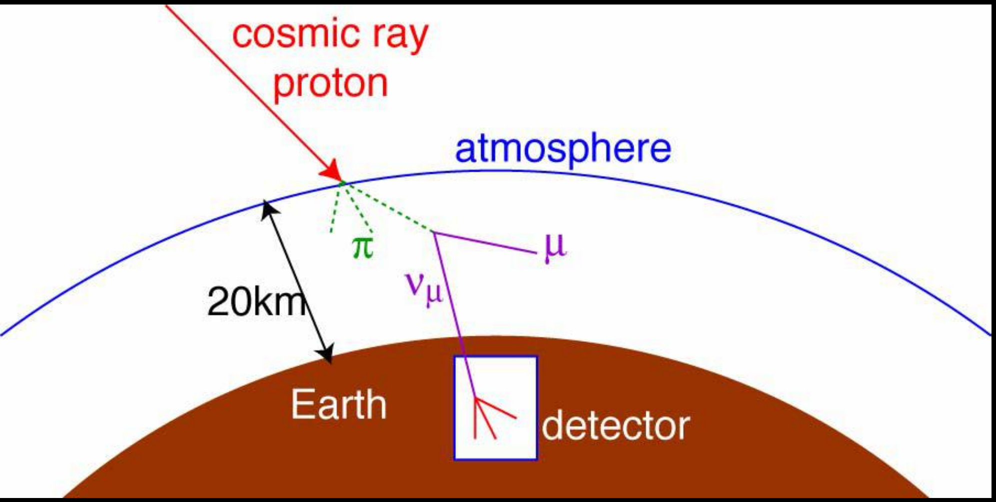
- Kamioka Mine in central Japan
- ~1000m underground
- 50kt water
- Inner Detector
  - 11,200 PMTs
- Outer Detector
  - 2,000 PMTs

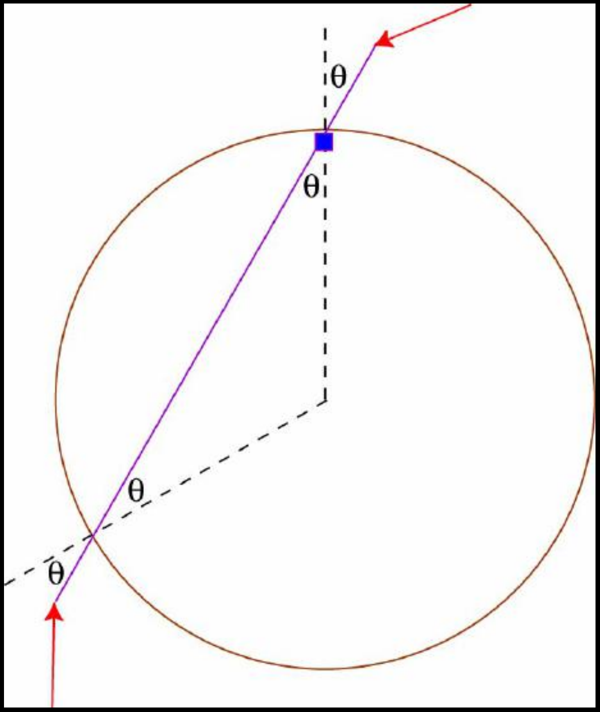



東京大学
東大
東大

SuperKamiokaNDE Nucleon Decay Experiment

- $p \rightarrow e^+\pi^0$, $K^+\nu$, etc
  - So far not seen
  - Atmospheric neutrino main background
- Cosmic rays isotropic
  - Atmospheric neutrino up-down symmetric

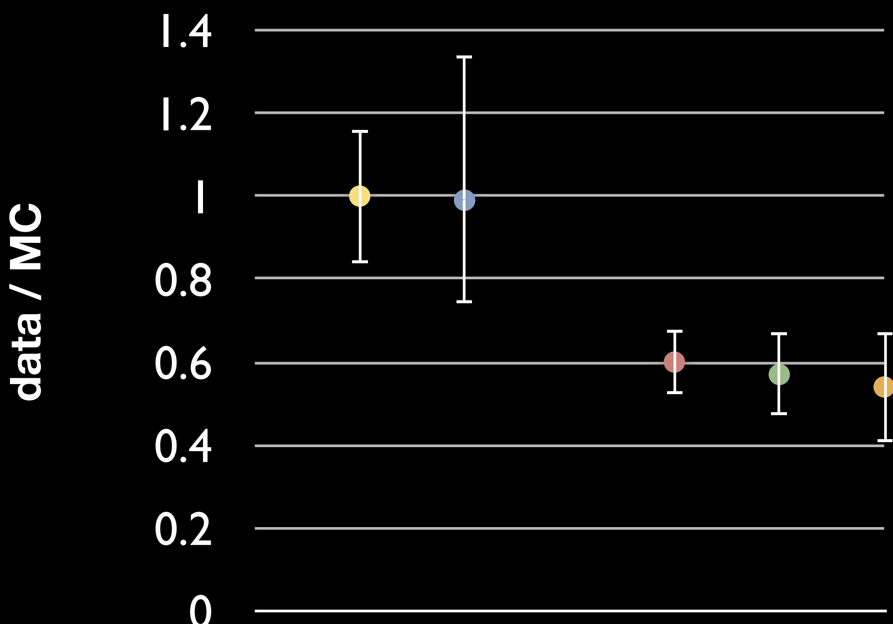




Atmospheric neutrinos

1988

- mu/e ratio
  - problem w/ Water Ch?
  - neutron BG?
  - particle ID?
  - proton decay?



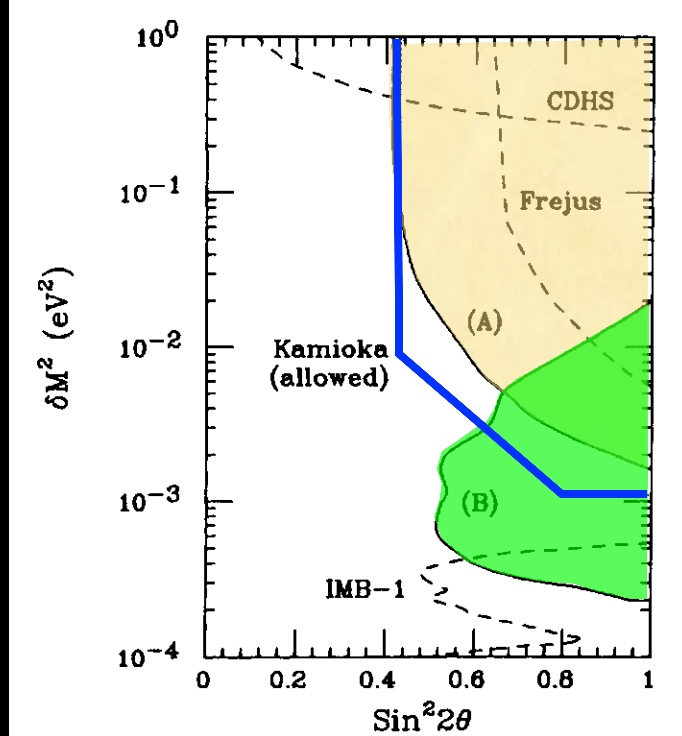
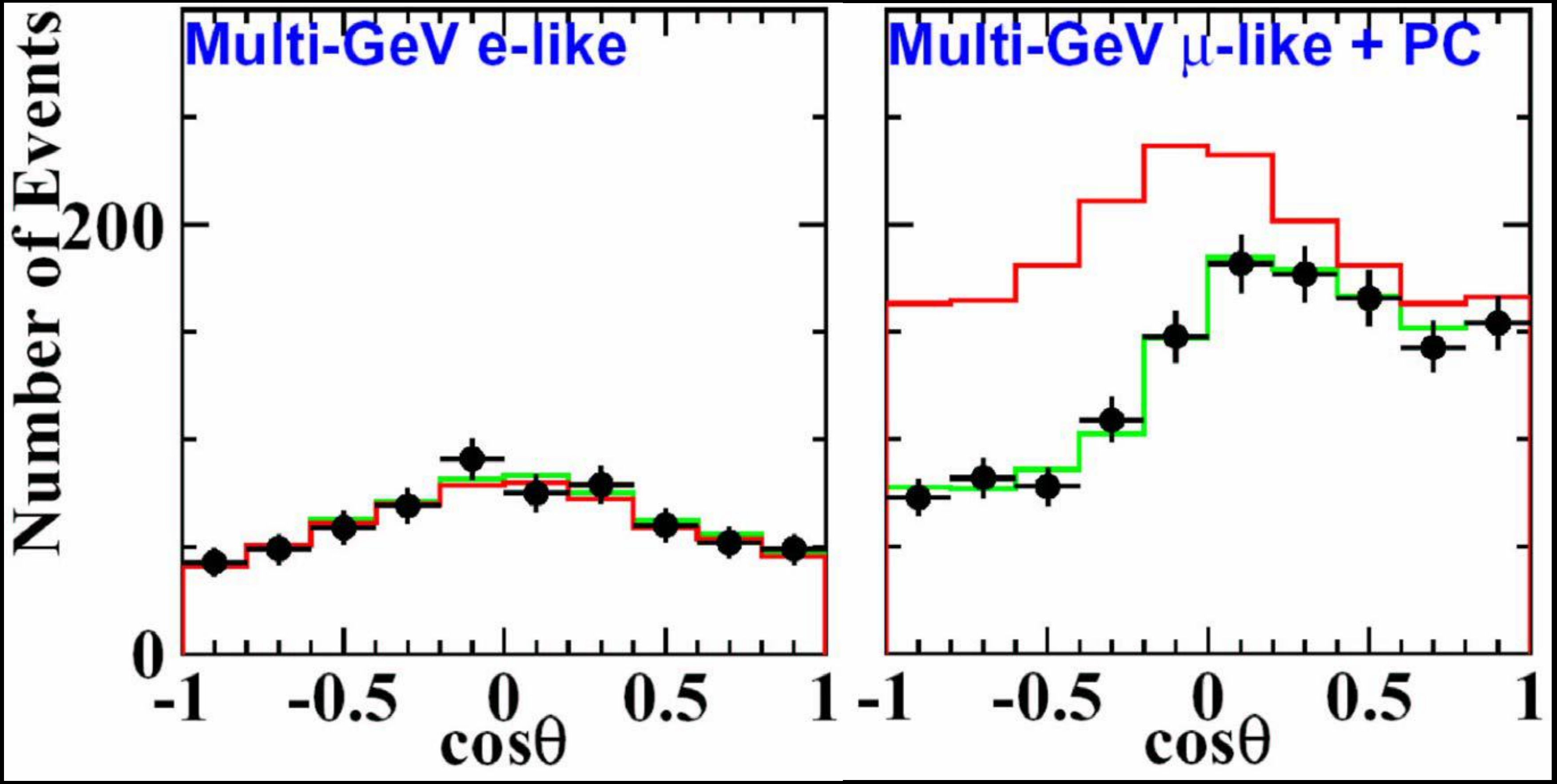


FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (*A*) and stopping fraction (*B*). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

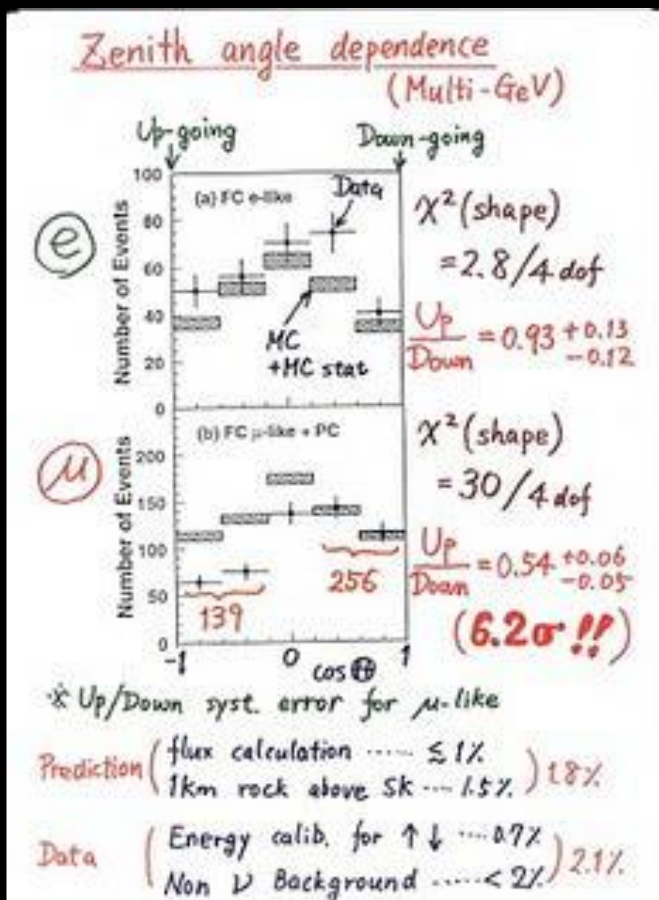
IMB, PRL 69, 1010 (1992)

A half of ν_μ lost!



nospheric neutrinos

1998



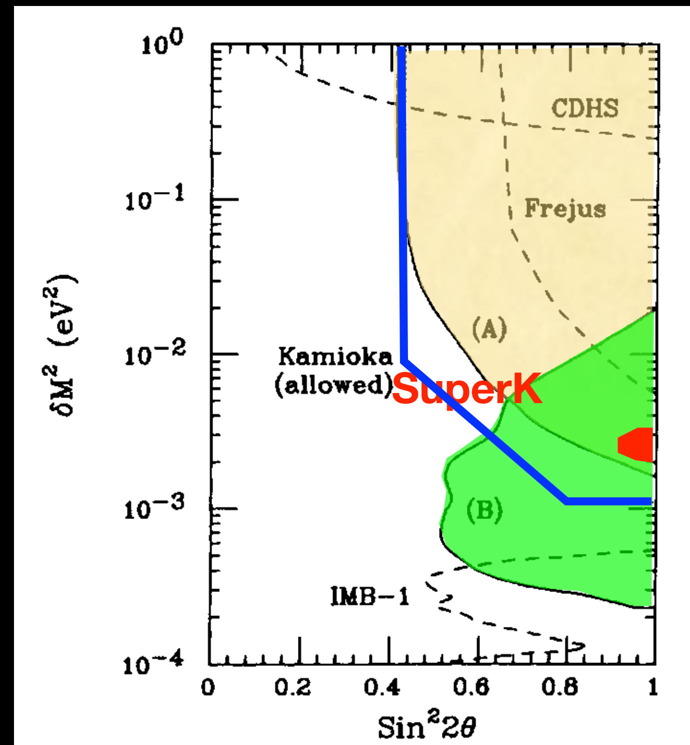


FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (*A*) and stopping fraction (*B*). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

IMB, PRL 69, 1010 (1992)

"All the News That's Fit to Print"

The New York Times

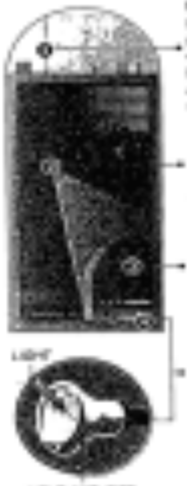
Late Edition

VOL. CXLVII . . . No. 51,179 — NEW YORK, FRIDAY, JUNE 5, 1998 — 60 CENTS

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE



And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

Terry Nichols Gets Life Term In Bombing Plot

By JO THOMAS

TRAINING ORDERED FOR CONTROLLERS AT U.S. AIRPORTS

NEAR MISS PROMPTS MOVE

Two Passenger Planes Averted Collision Above La Guardia by 20 Feet, F.A.A. Says

By MATTHEW L. WALD

Bajram Curri, in northern Albania, has received 4,300 refugees from Yugoslavia in three days. One group ate yesterday in a school building.

Refugees From Kosovo Cite A Bitter Choice: Flee or Die

By CHRIS HEDGES

JUSTICES REBUFF STARR'S REQUEST TO SPEED REVIEW

2 ORDERS WITH NO DISSENT

Court Denies an Early Hearing on Claims of Privilege for 4 in Inquiry on President

By LINDA GREENHOUSE

MIT commencement 6/5/98

Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now that may not mean much to most Americans. But it may change our most fundamental theories, from the nature of the smallest subatomic particles to how the universe itself works, and indeed, how it expands. This discovery was made in Japan, yes, but it had the support of the investment of the US Department of Energy.

This discovery calls into question the decision made in Washington a couple of years ago to disband the superconducting supercollider, and it reaffirms the importance of the work now being done at the Fermi National Accelerating Facility in Illinois.

Neutrino's clock

- Time-dilation: the clock goes slower

$$\Delta t = \Delta\tau\sqrt{1 - \frac{v^2}{c^2}}$$

- At speed of light $v=c$, clock stops
- But something seems to happen to neutrinos *on their own*

- Neutrinos' clock is going
- Neutrinos must be slower than speed of light

⇒Neutrinos must have a mass

The Hamiltonian

- The Hamiltonian of a freely-propagating massive neutrino is simply

$$H = \sqrt{p^2 + m^2} \approx p + \frac{m^2}{2E}$$

- But in quantum mechanics, mass is a matrix in general. 2×2 case:

$$M^2 = \begin{pmatrix} m_{11}^2 & m_{12}^2 \\ m_{12}^{2*} & m_{22}^2 \end{pmatrix}$$

$$M^2|1\rangle = m_1^2|1\rangle$$

$$M^2|2\rangle = m_2^2|2\rangle$$

Two-Neutrino Oscillation

- When produced (*e.g.*, $\pi^+ \rightarrow \mu^+ \nu_\mu$), neutrino is of a particular type

$$|\nu_\mu\rangle = |1\rangle \cos\theta + |2\rangle \sin\theta$$

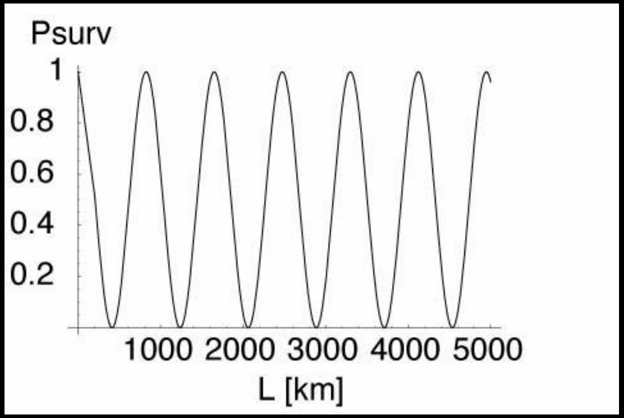
- No longer 100% ν_μ, partly ν_τ!
- "Survival probability" for ν_μ after t

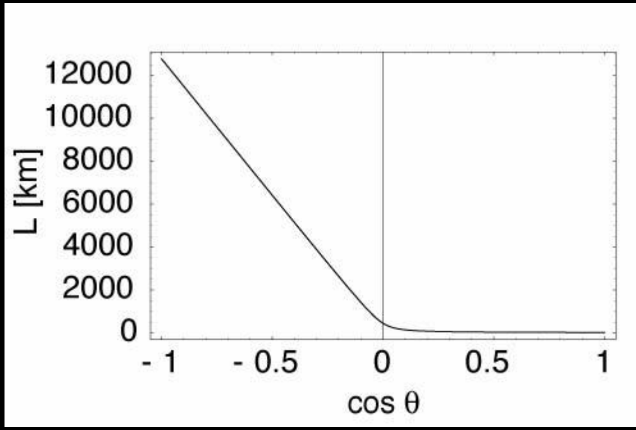
$$P_{\mathrm{surv}} = |\langle \nu_\mu | \nu_\mu, t\rangle|^2 = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2}{\mathrm{eV}^2} \frac{\mathrm{GeV}}{E} \frac{L}{\mathrm{km}}\right)$$

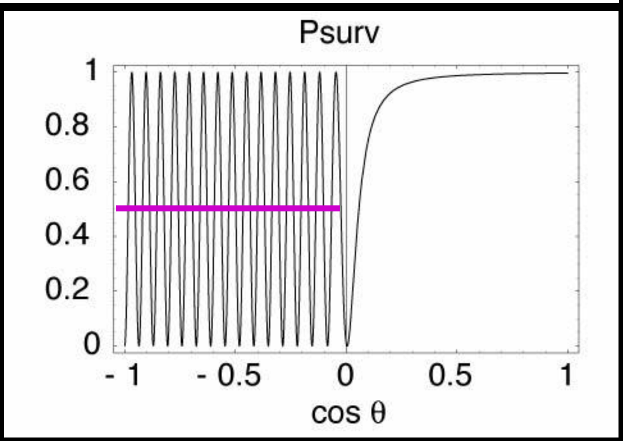
Survival Probability

p=1 GeV/c, $\sin^2 2\theta=1$

$\Delta m^2=2.5\times10^{-3}(\text{eV}/c^2)^2$

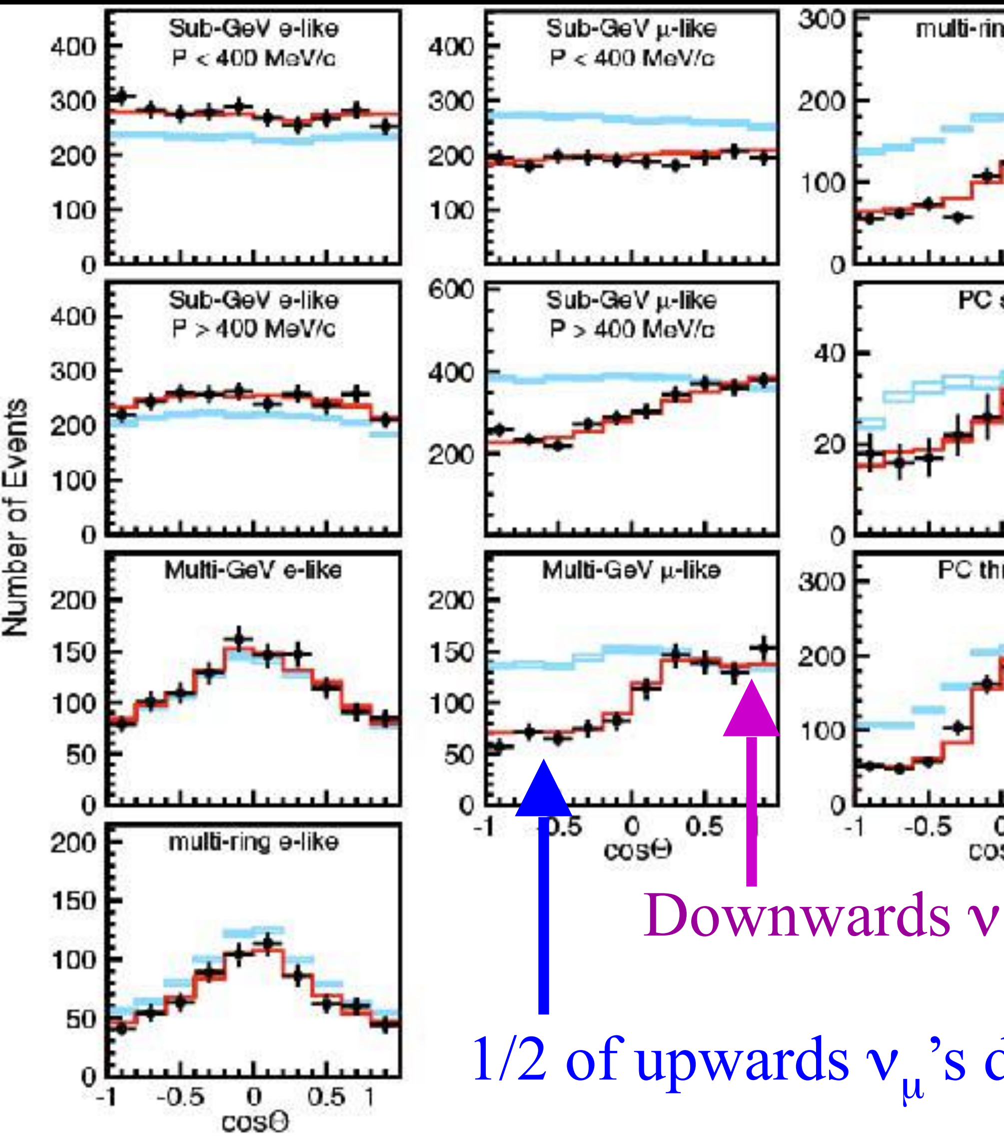


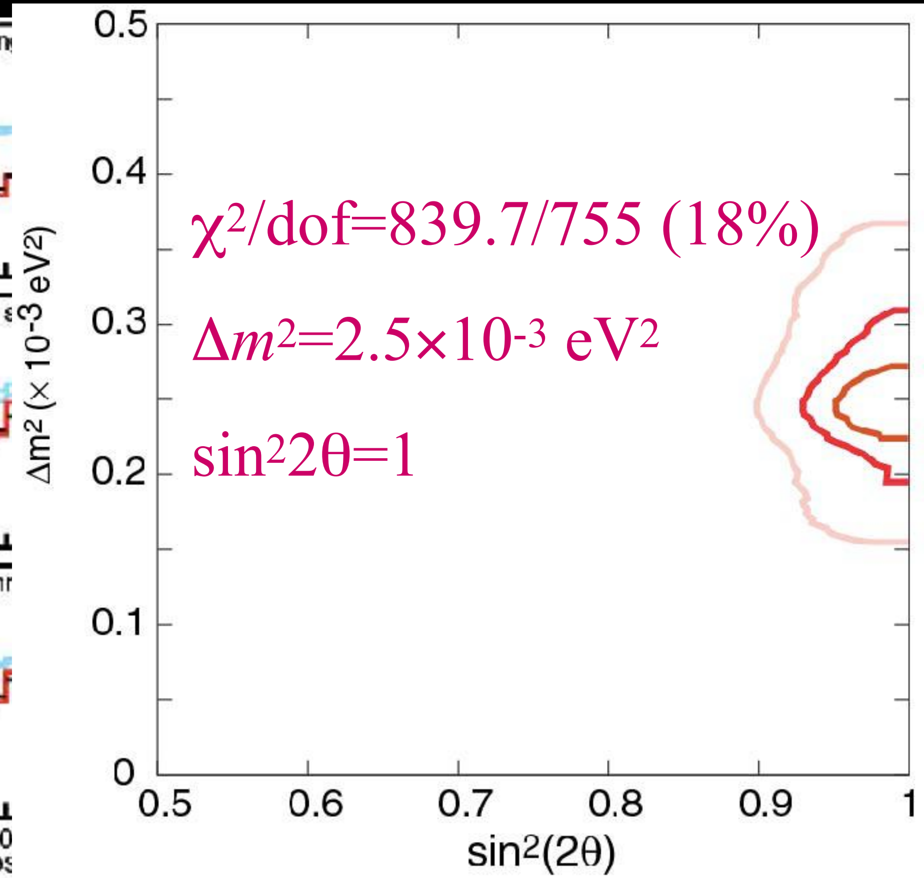




Half of the up-going ones get lost

Excellent Fit

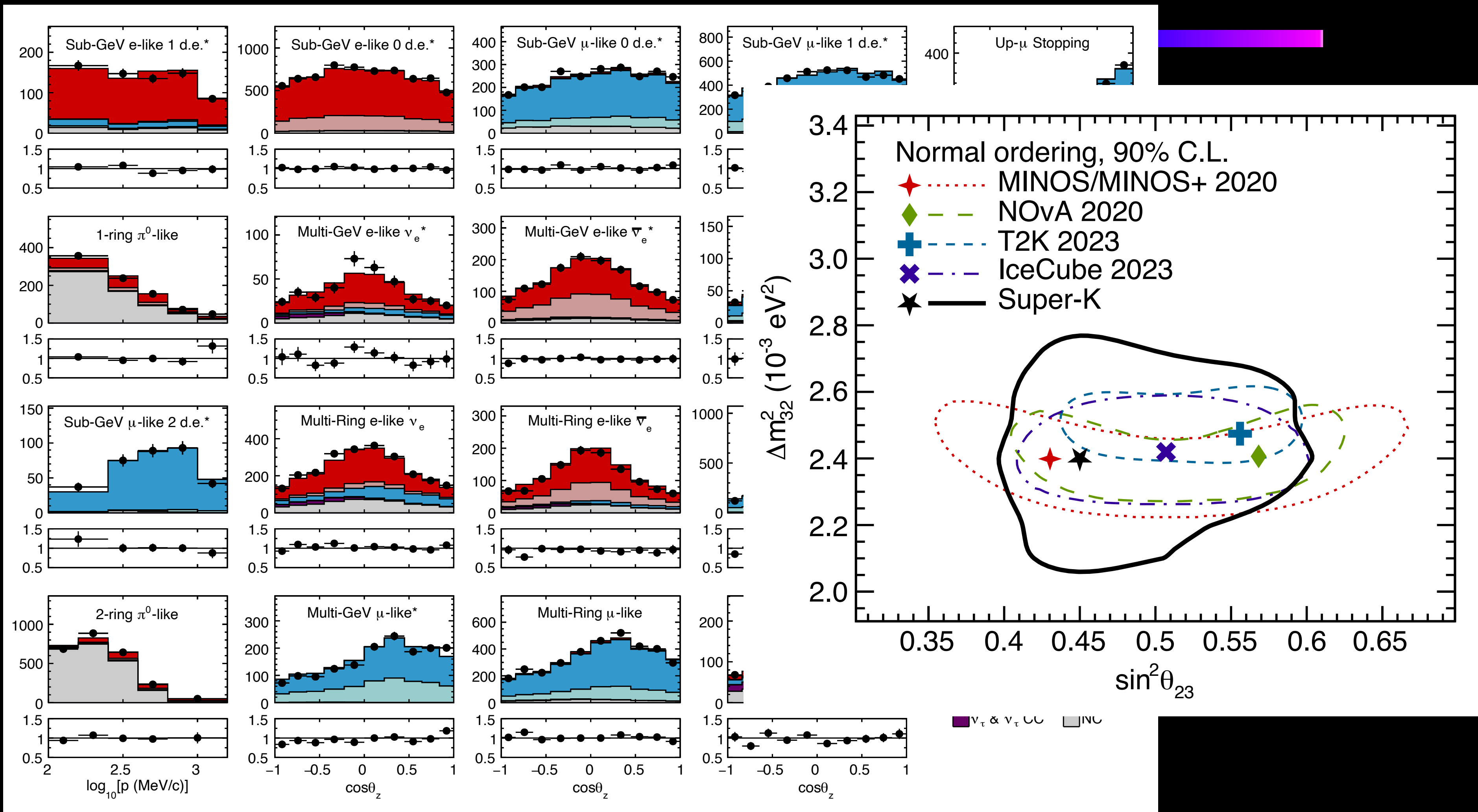




Downwards ν_μ's don't disappear

1/2 of upwards ν_μ's do disappear

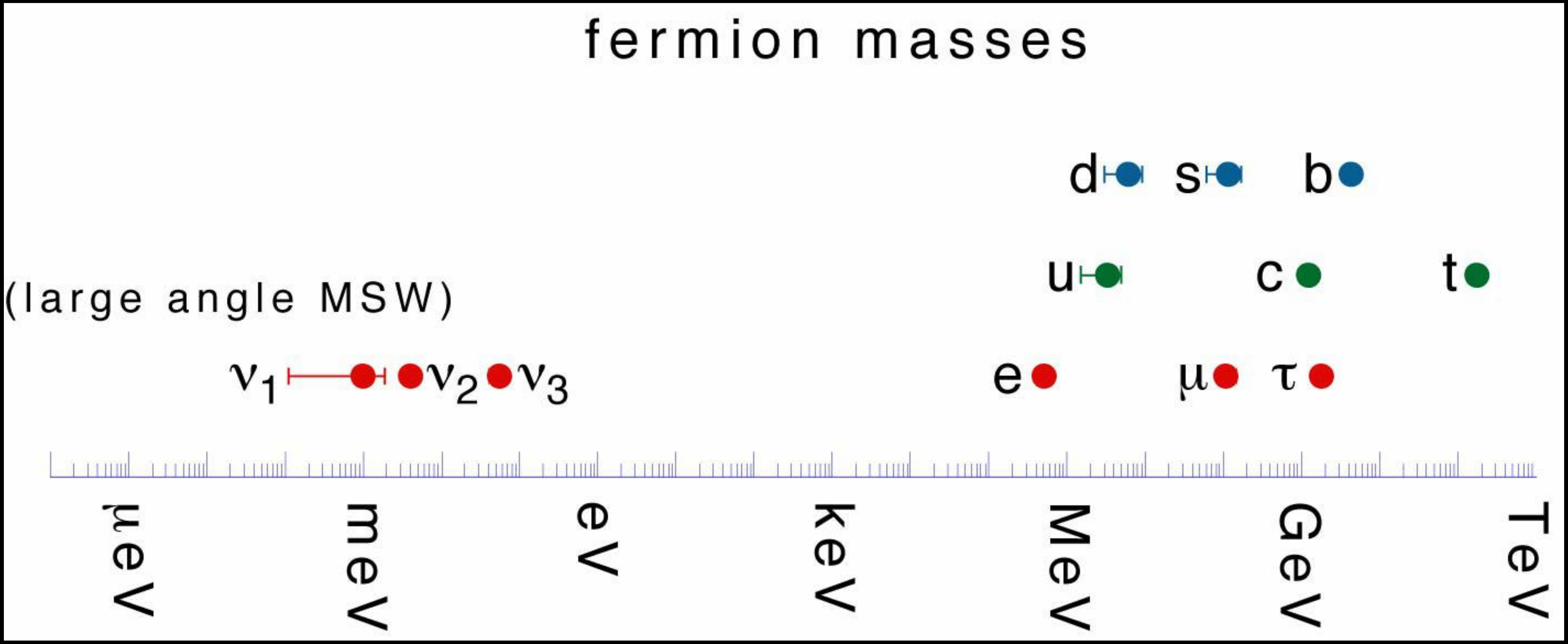
Fit 2023


Sub-GeV e-like 1 d.e.*
Sub-GeV e-like 0 d.e.*
Sub-GeV μ-like 0 d.e.*
Sub-GeV μ-like 1 d.e.*
Up-μ Stopping
1-ring π^0-like
Multi-GeV e-like ν_e*
Multi-GeV e-like $\bar{\nu}_e$*
Sub-GeV μ-like 2 d.e.*
Multi-Ring e-like ν_e
Multi-Ring e-like $\bar{\nu}_e$
2-ring π^0-like
Multi-GeV μ-like*
Multi-Ring μ-like
$\log_{10}$[p (MeV/c)]
$\cos\theta_z$
NC
Normal ordering, 90% C.L.
MINOS/MINOS+ 2020
NOvA 2020
T2K 2023
IceCube 2023
Super-K
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$


SUPER K®
FORTUNE COOKIE
SUPER K®
FORTUNE COOKIE
KARI-OUT CO., NY
1-800-433-8789

Implications of Neutrino Mass

Mass Spectrum



What do we do now?

Rare Effects from High-Energies

- Effects of physics beyond the SM as effective operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- Can be classified systematically (Weinberg)

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\begin{aligned}\mathcal{L}_6 &= QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}He, \\ &\epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda}, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \cdots\end{aligned}$$

Unique Role of Neutrino Mass

- Lowest order effect of physics at short distances
- Tiny effect $(m_\nu/E_\nu)^2 \sim (0.1\text{eV}/\text{GeV})^2 = 10^{-20}$!
- Interferometry (*i.e.*, Michaelson-Morley)
  - Need coherent source
  - Need interference (*i.e.*, large mixing angles)
  - Need long baseline

Nature was kind to provide all of them!

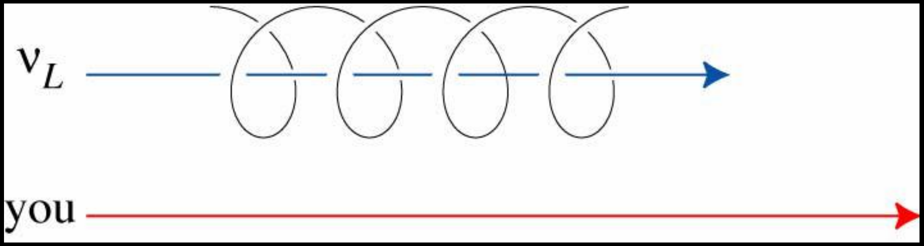
- "neutrino interferometry" (a.k.a. neutrino oscillation) a unique tool to study physics at very high scales

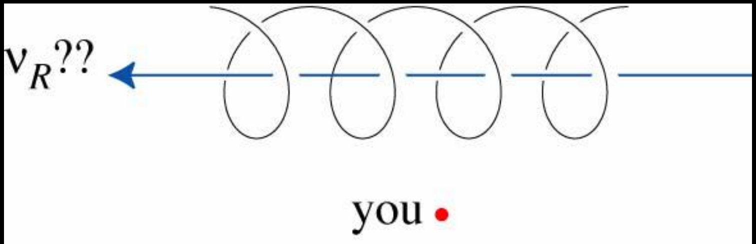
Power of Expedition

courtesy HM & Zoltan Ligeti

Neutrinos have mass

- They have mass. Can't go at speed of light.



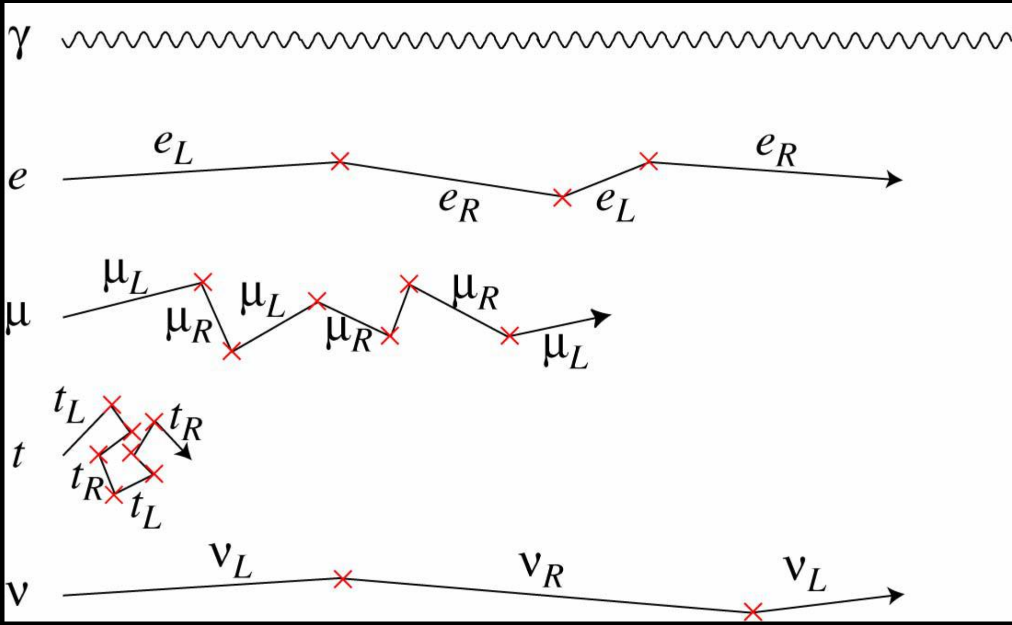


- What is this right-handed particle?
  - New particle: right-handed neutrino (Dirac)
  - Old anti-particle: right-handed anti-neutrino (Majorana)

Two ways to go

(1) Dirac Neutrinos:

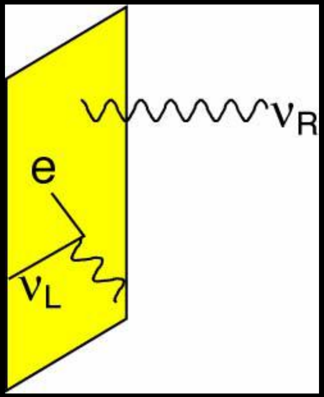
- There are new particles, right-handed neutrinos, after all
- Why haven't we seen them?
- Right-handed neutrino must be *very very weakly coupled*
- Why?



Extra Dimension

- All charged particles are on a 3-brane
- Right-handed neutrinos SM gauge singlet

  ⇒ Can propagate in the "bulk"



- Makes neutrino mass small

  (Arkani-Hamed, Dimopoulos, Dvali, March-Russell; Dienes, Dudas, Gherghetta; Grossman, Neubert; Barbieri, Strumia)

- Or SUSY breaking

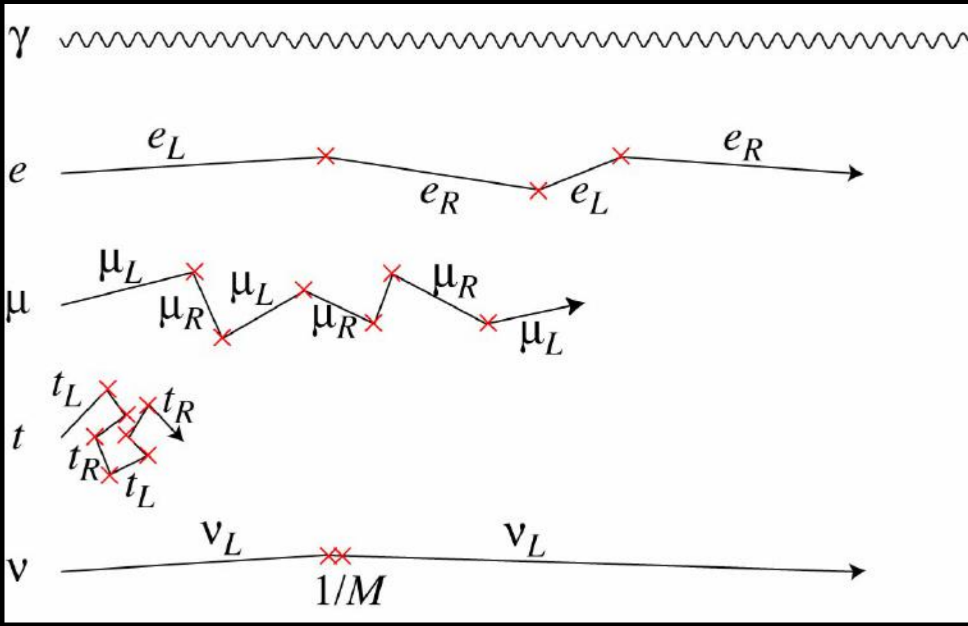
  (Arkani-Hamed, Hall, HM, Smith, Weiner;

  Arkani-Hamed, Kaplan, HM, Nomura)

Two ways to go

(2) Majorana Neutrinos:

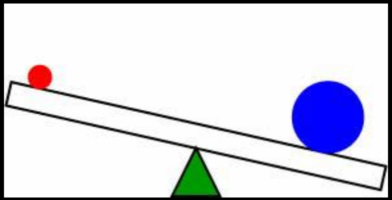
- There are no new light particles
- What if I pass a neutrino and look back?
- Must be right-handed *anti*-neutrinos
- No fundamental distinction between neutrinos and anti-neutrinos!



Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass , but ν_R SM neutral

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$



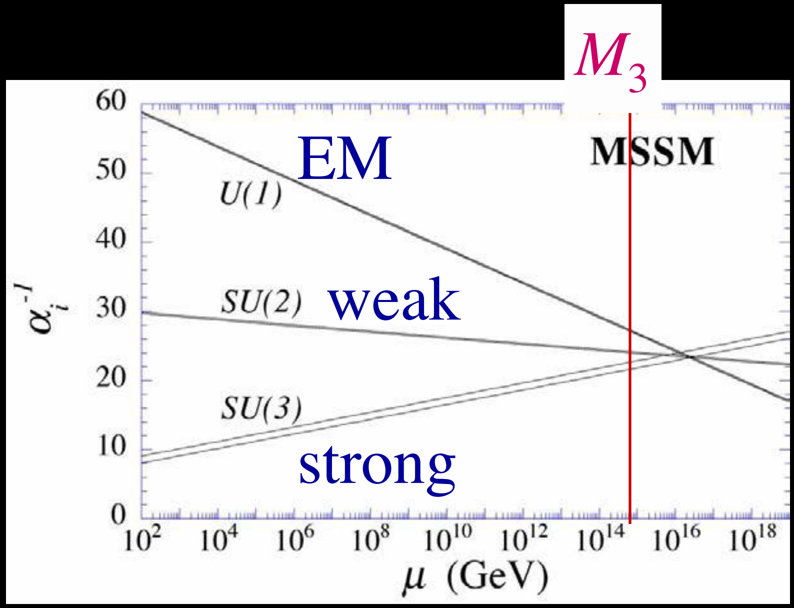
To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

Grand Unification

- electromagnetic, weak, and strong forces have very different strengths
- But their strengths become *the same* at 10^{16} GeV if supersymmetry
- To obtain

$m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$

$\Rightarrow M_3 \sim 10^{15}$GeV!



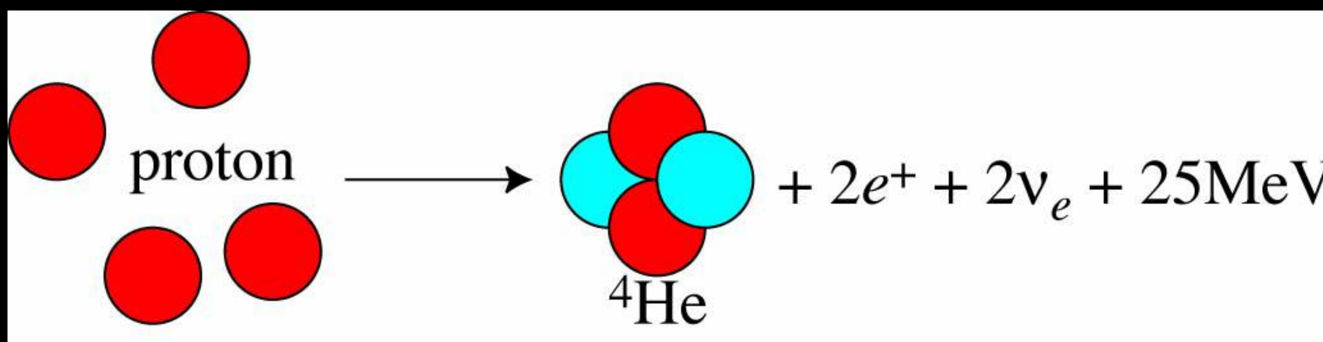
Neutrino mass may be probing unification:

Einstein's dream

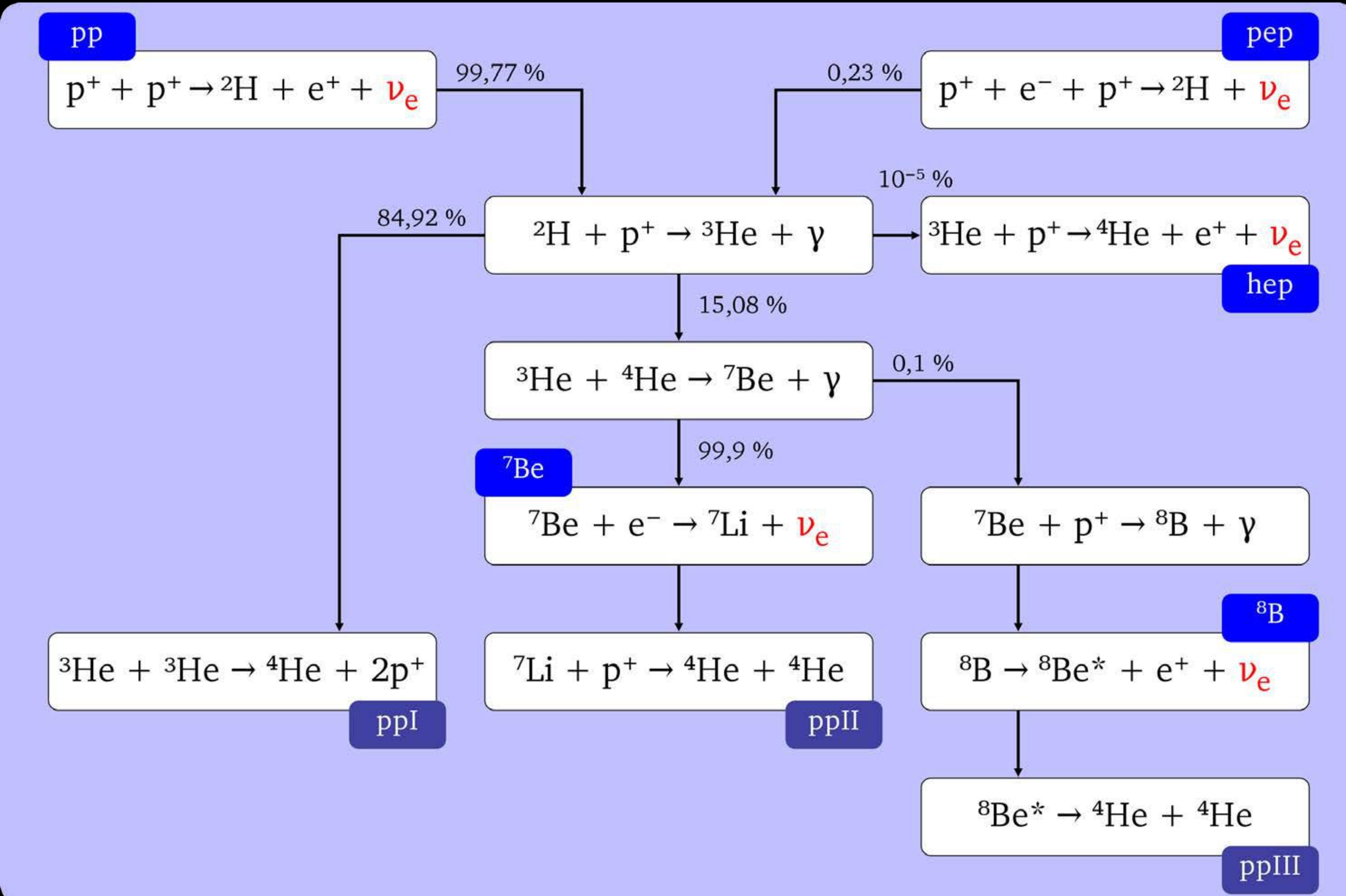
Solar Neutrinos

How the Sun burns

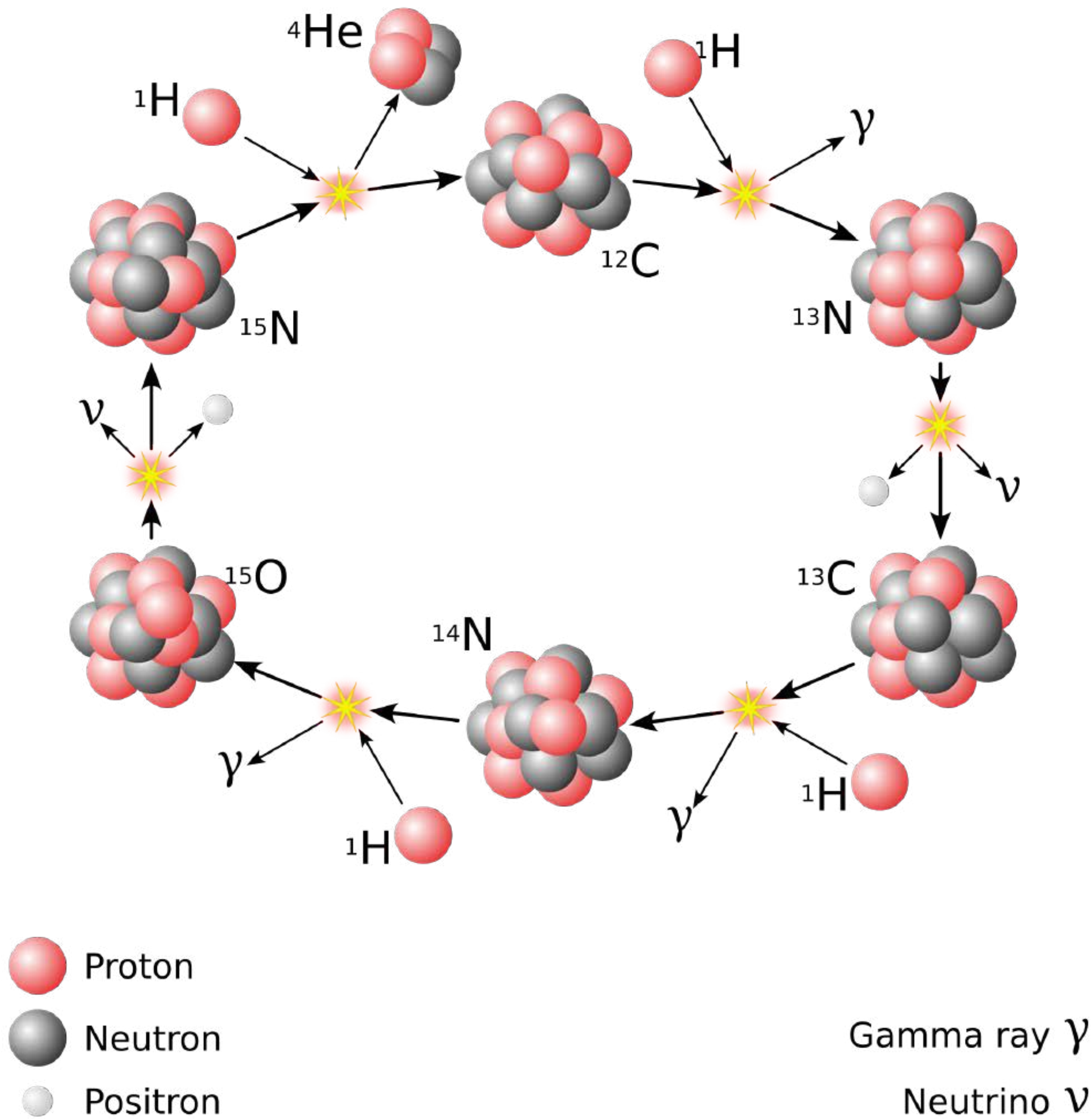
- The Sun emits light because nuclear fusion produces a lot of energy



$$\Phi_\nu = \frac{2L_{\rm Sun}}{25\ {\rm MeV}}\frac{1}{4\pi(1{\rm AU})^2} = 7\times 10^{10}{\rm sec}^{-1}{\rm cm}^{-2}$$



https://en.wikipedia.org/wiki/Proton–proton_chain#/media/File:Proton_proton_cycle.svg



4He
1H
1H
12C
γ
15N
13N
ν
ν
15O
13C
14N
γ
γ
1H
1H
Proton
Neutron
Positron
Gamma ray γ
Neutrino ν

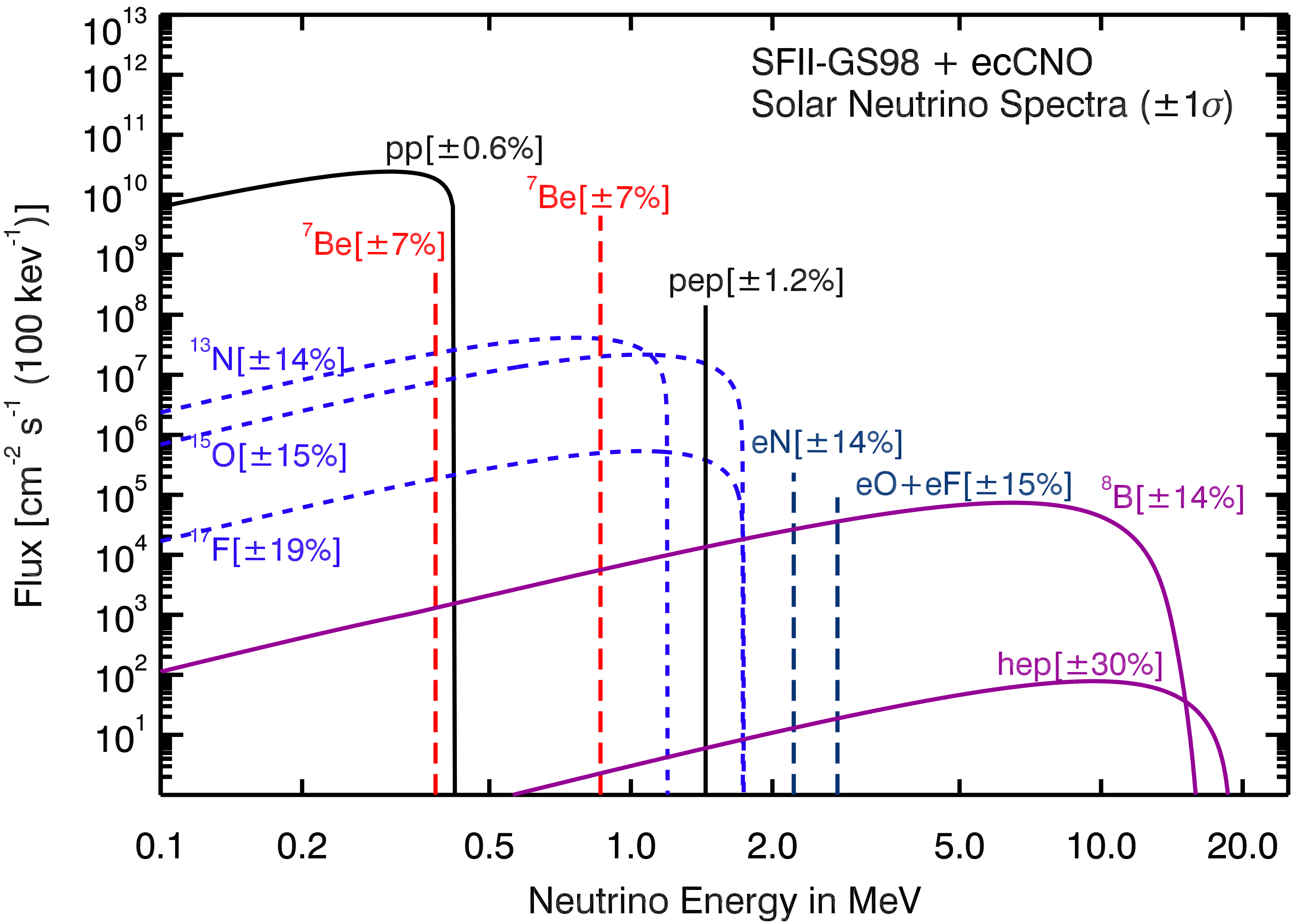
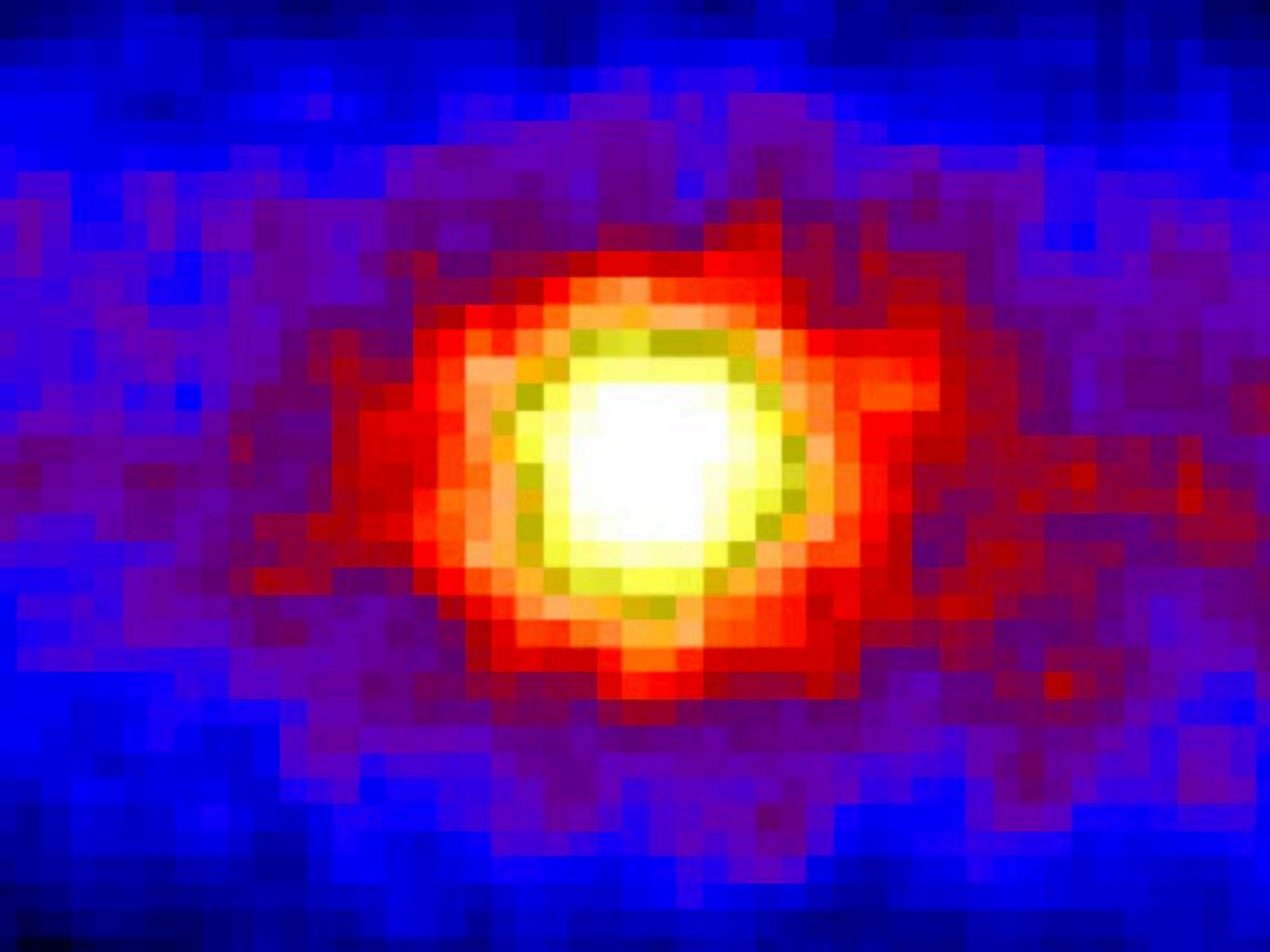
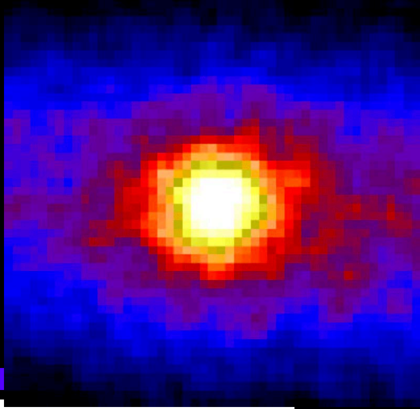
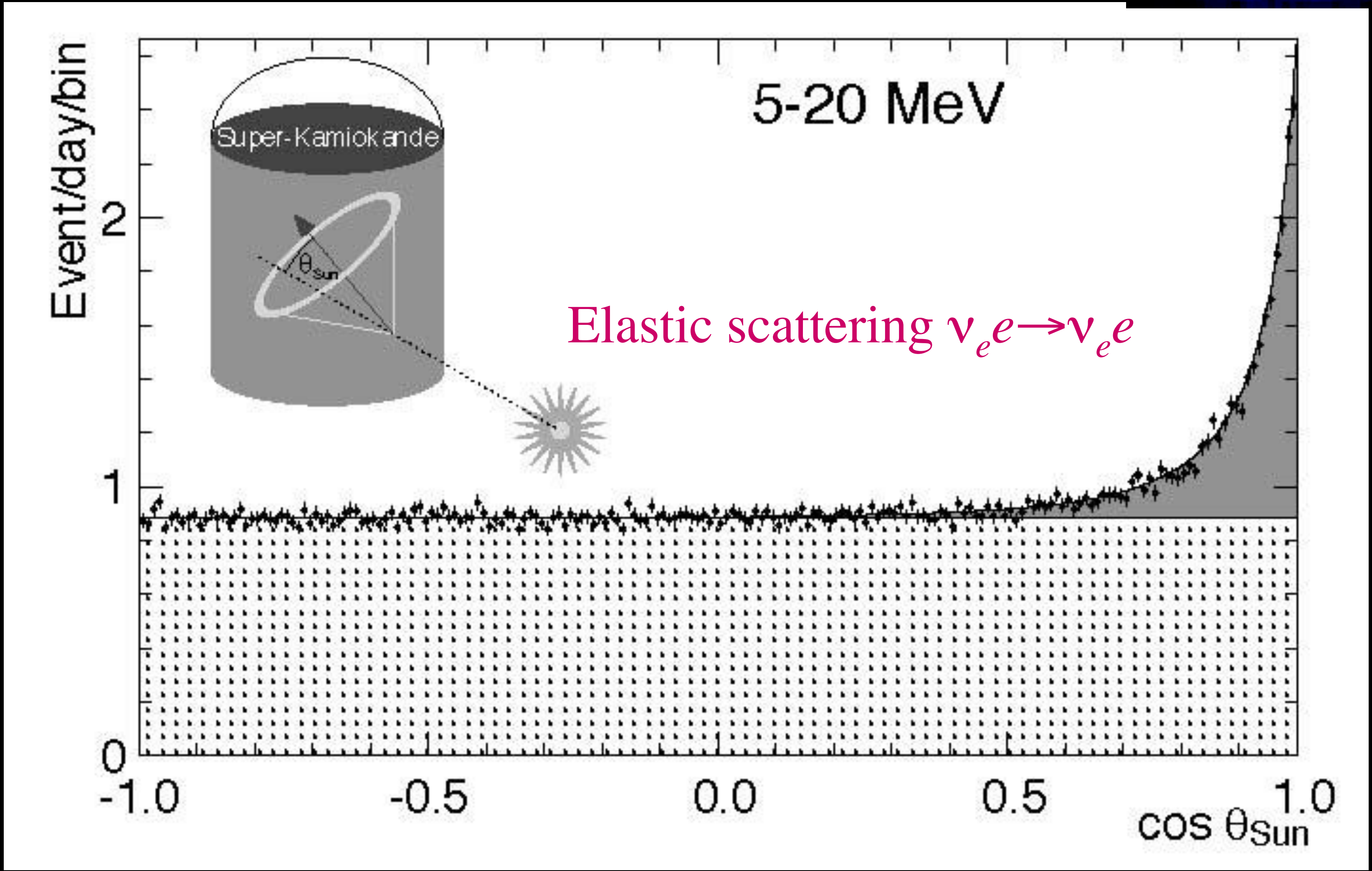


Figure 14.1: Spectrum of solar neutrino fluxes predicted by SSM calculation in [41]. In addition to standard fluxes, ecCNO neutrinos have been added based on [42]. Electron capture fluxes are given in $cm^{-2}s^{-1}$. Taken from [43].



SuperK sees the Sun





Homestake Experiment

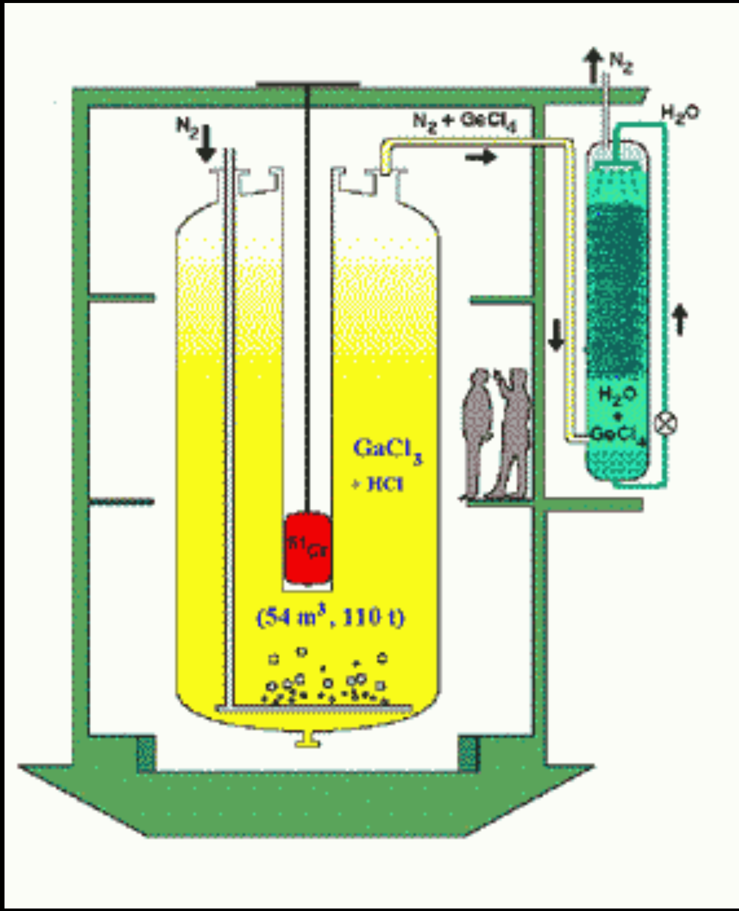
- The first solar neutrino experiment 1970-98
- 600t dry cleaning fluid $Cl_2C{=}CCl_2$ perchloroethylene
- $\nu_e\ {}^{37}Cl\ (24\%) \rightarrow e^-\ {}^{37}Ar$
- Makes ~0.5atom/day
- Extract them by He bubbling every ~2wks
- Count ^{37}Ar decay in a proportional counter $\tau_{1/2}$=35.04 days

2.56±0.23 SNU vs 7.6+1.3−1.1 predicted

1 SNU = 10^{-36} captures/atom/sec

Ga Experiments

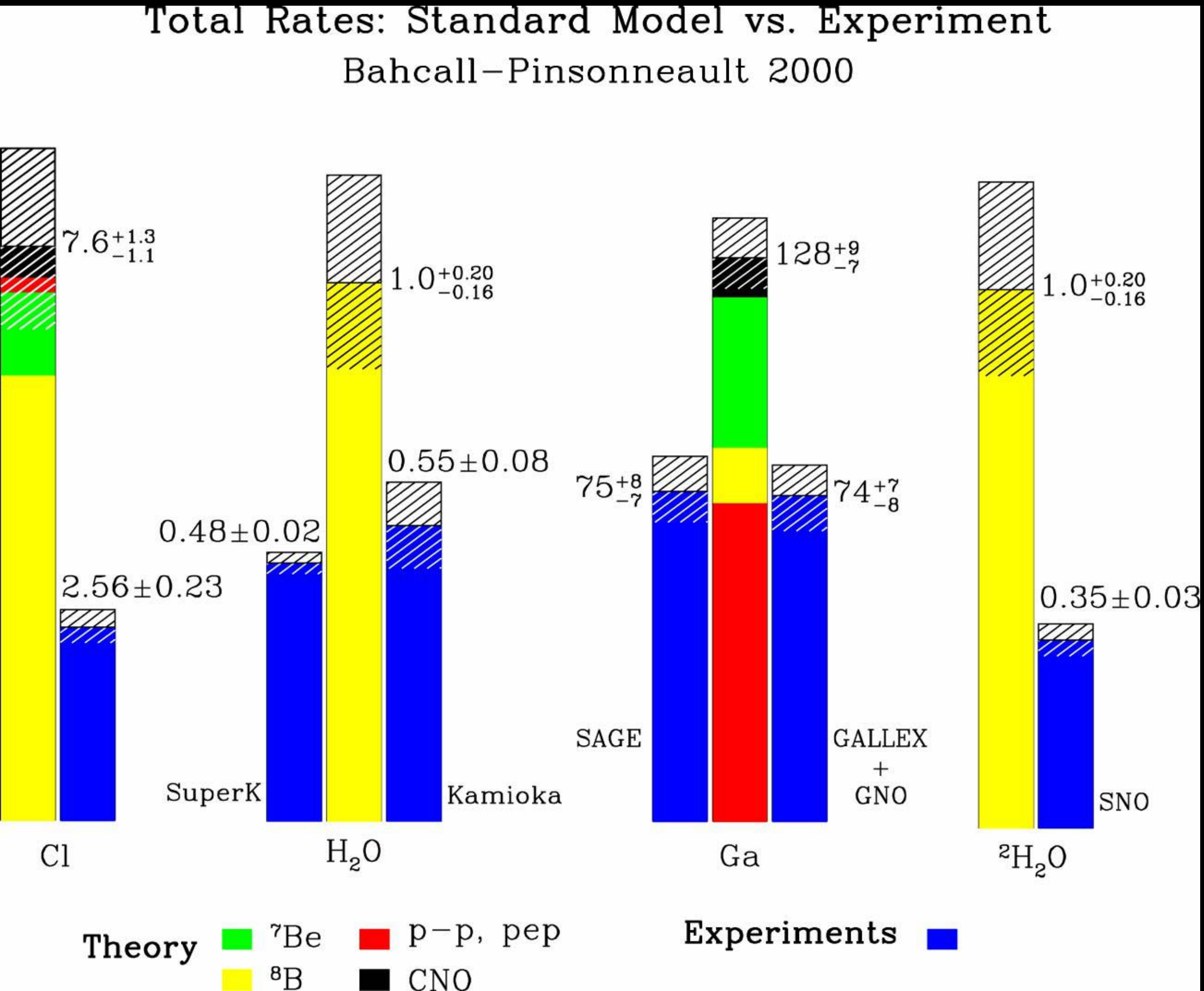
- ν_e ^{71}Ga (40%)→e^- ^{71}Ge
- Low threshold $E_\nu > 0.23$MeV, sensitive to *pp* ν's
- Radiochemical
- GALLEX in Gran Sasso, SAGE in Baksan
- Capture cross section calibrated by ^{51}Cr source (>60 PBq)!



74+7−8 (GALLEX) 75+8−7 (SAGE) SNU

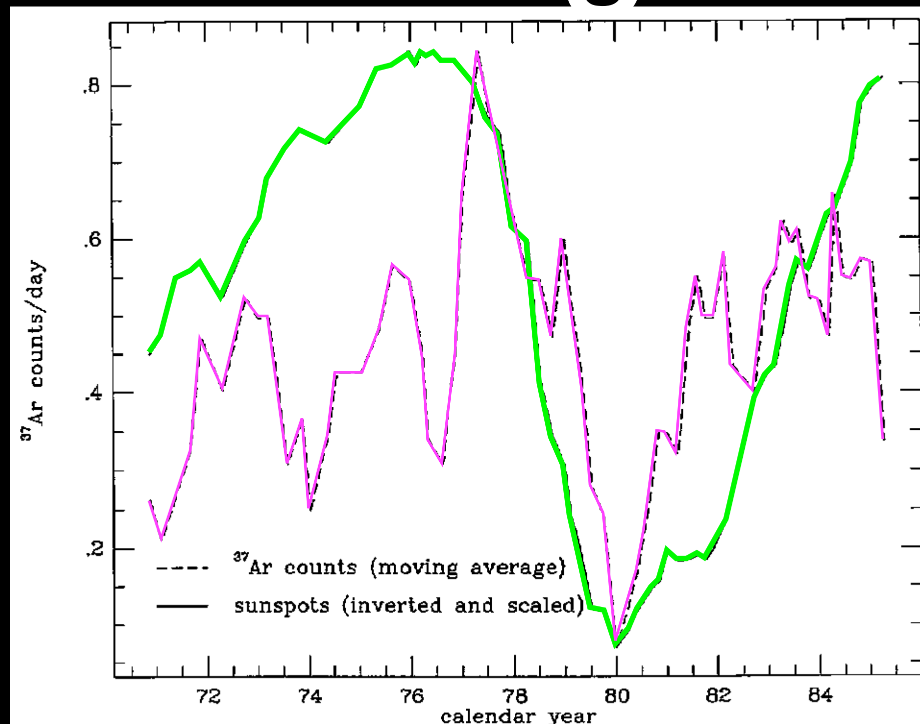
cf. 128+9−7 predicted

We don't get enough



- Neutrino oscillation?
- Something wrong with our understanding of the Sun?

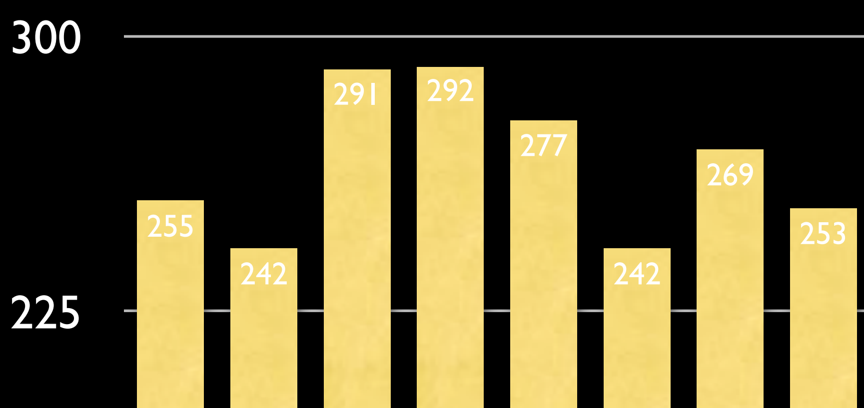
Confusing data



–#sunspot

Homestake

#Democrates in the House



NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY *

Howard GEORGI and Michael LUKE

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 17 April 1990

We identify and exemplify a new mechanism which leads to a nonzero magnetic moment for a neutrino, while suppressing the neutrino's mass. The mechanism requires that the contribution to the neutrino mass of the new particles that are responsible for its magnetic moment is approximately canceled by a contribution from neutral particles, related by a custodial SU(2) symmetry.

1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent modulation of the flux of solar neutrinos with the sun-spot cycle, is certainly intriguing [3]. It is, of course, possible that this is an astrophysical problem rather than a particle physics problem. But that would require a synchronization of cycles of the interior of the sun with those of the convective layer, both in frequency and in *phase*. Thus it seems particularly interesting that there may be a particle physics explanation of this effect [4], involving a magnetic moment of the electron neutrino of the order of $10^{-11}\mu_B$.

Neutrino Properties and Leptogenesis

Hitoshi Murayama (Berkeley)

July 15, 2024

N3AS Summer School, UCSC

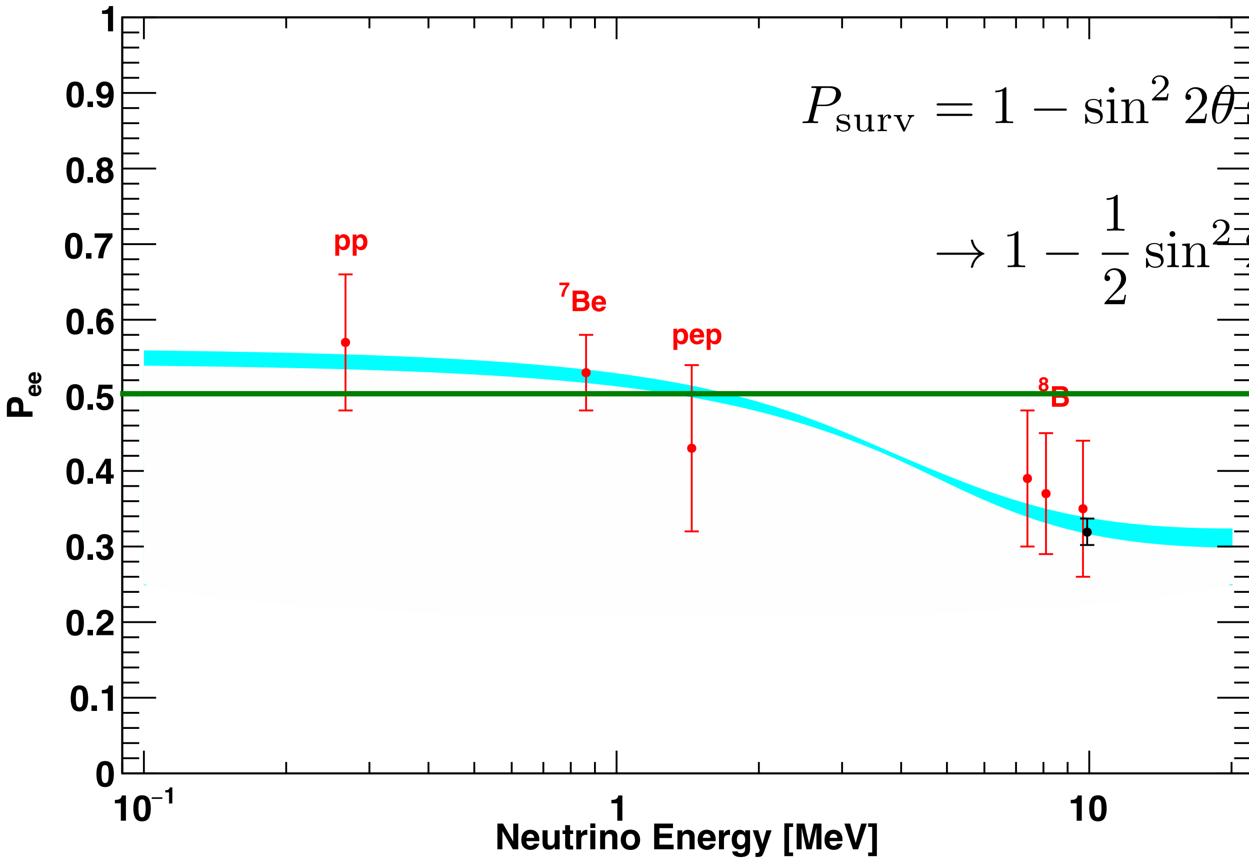
Outline

- Introduction
- Neutrinos in the Standard Model
- Evidence for Neutrino Mass
- Implications of Neutrino Mass
- Solar Neutrinos
- Matter Effect in Solar Neutrinos
- Masses and Mixings
- Leptogenesis
- Conclusions

Outline

- Introduction
- Neutrinos in the Standard Model
- Evidence for Neutrino Mass
- Implications of Neutrino Mass
- Solar Neutrinos
- Matter Effect in Solar Neutrinos
- Masses and Mixings
- Leptogenesis
- Conclusions

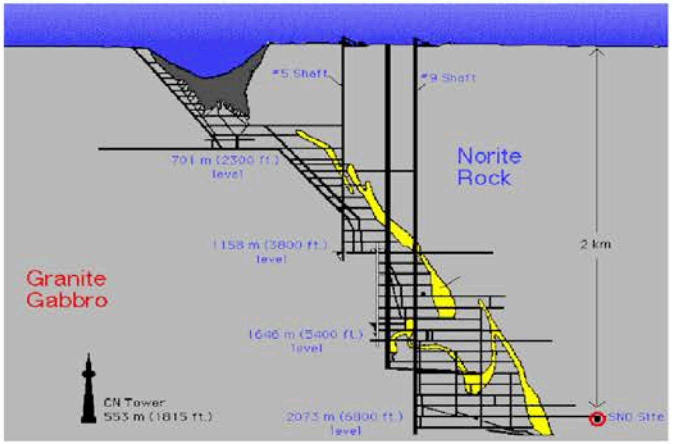
Matter Effect in Solar Neutrinos

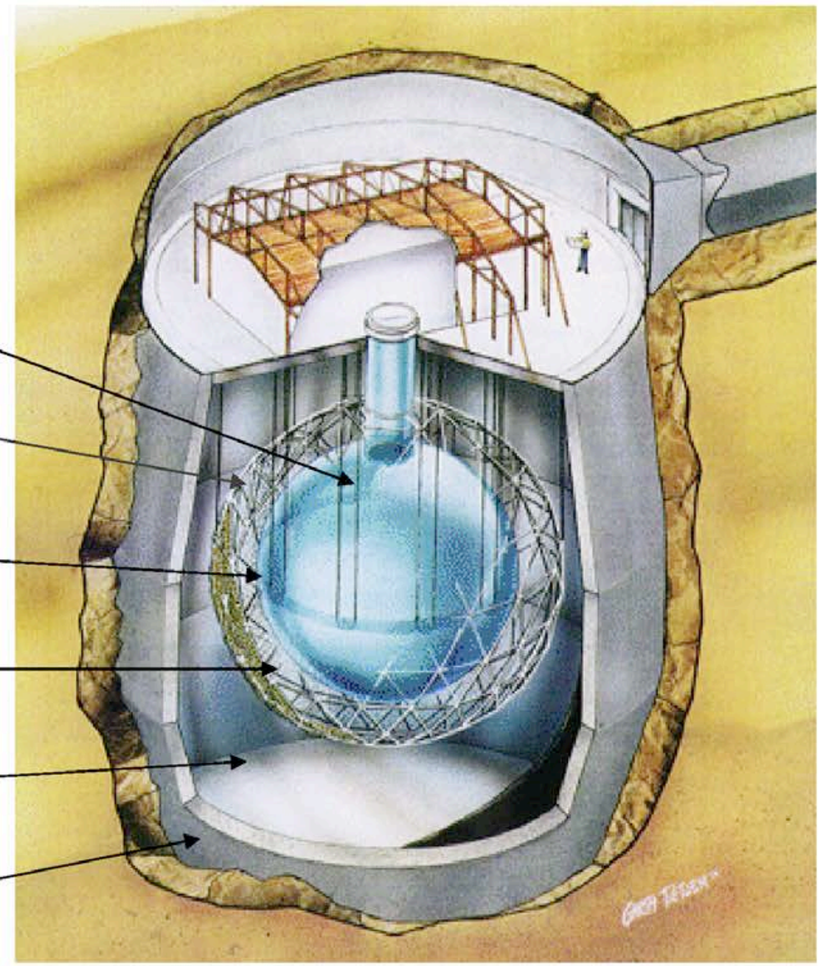


$$P_{\mathrm{surv}} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E}L\right)$$
$$\to 1 - \frac{1}{2}\sin^2 2\theta \geq \frac{1}{2}$$

Figure 14.3: Electron neutrino survival probability as a function of neutrino energy. The points represent, from left to right, the Borexino pp, ^{7}Be, pep, and ^{8}B data (red points) and the SNO+SK ^{8}B data (black point). The three Borexino ^{8}B data points correspond, from left to right, to the low-energy (LE) range, LE+HE range, and the high-energy (HE) range. The electron neutrino survival probabilities from experimental points are determined using a high metallicity SSM from [55]. The error bars represent the $\pm 1\sigma$ experimental + theoretical uncertainties. The curve corresponds to the $\pm 1\sigma$ prediction of the MSW-LMA solution using the parameter values given in [64]. This figure is provided by A. Ianni.

Sudbury Neutrino Observatory





1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

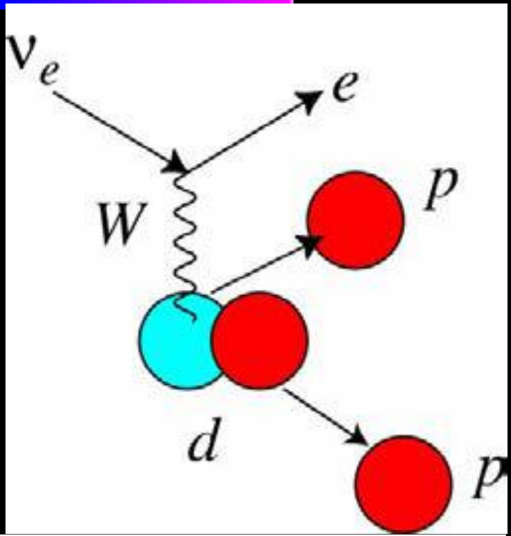
12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

SNO comes to the rescue



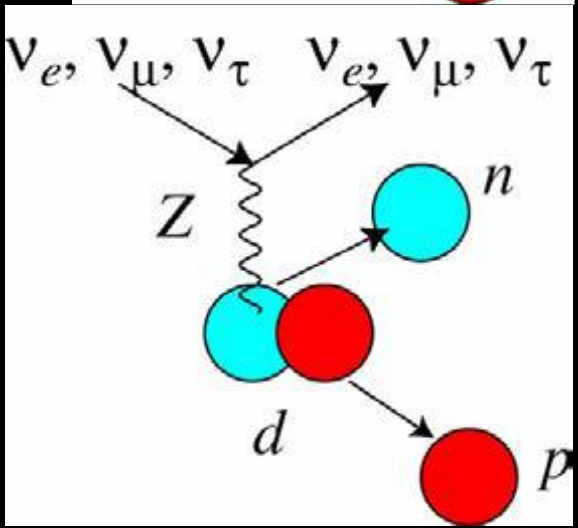
- Charged Current: ν_e

$$\Phi_{\rm CC}^{\rm SNO} = (1.72 \pm 0.05 \pm 0.11){\rm cm}^{-2}{\rm s}^{-1}$$

- Neutral Current: $\nu_e + \nu_\mu + \nu_\tau$

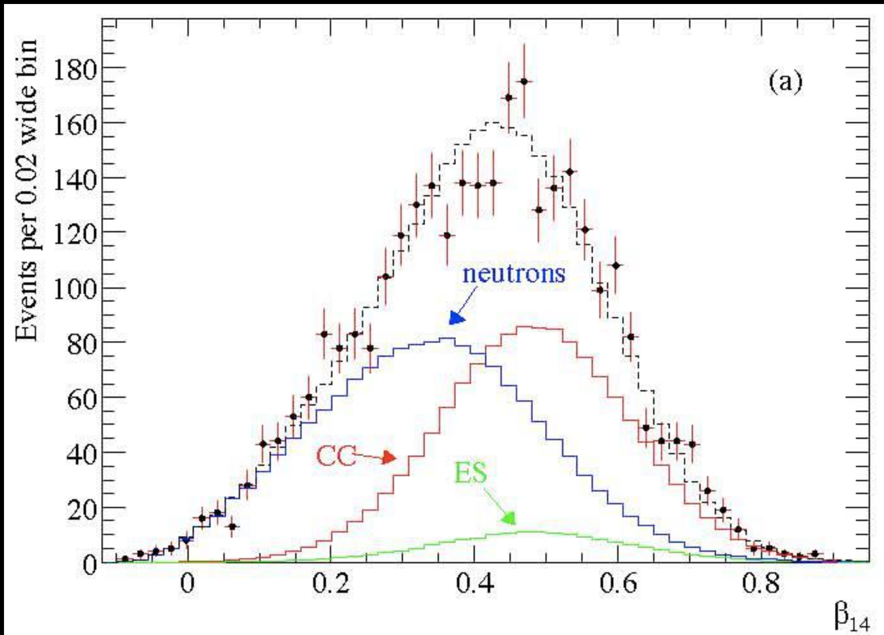
$$\Phi_{\rm NC}^{\rm SNO} = (5.25 \pm 0.16^{+0.11}_{-0.13}){\rm cm}^{-2}{\rm s}^{-1}$$

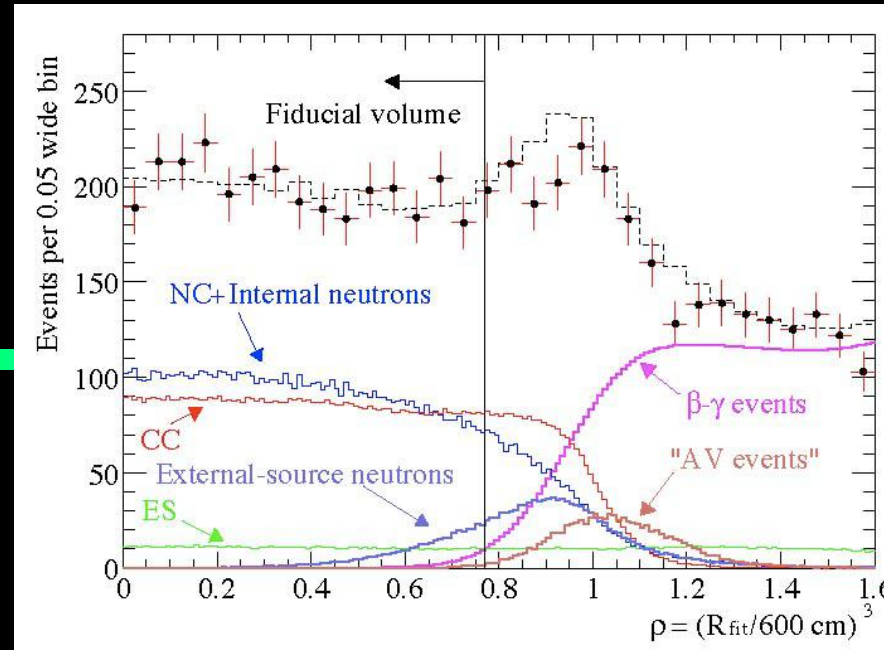
$\Rightarrow \nu_{\mu,\tau}$ are coming from the Sun!

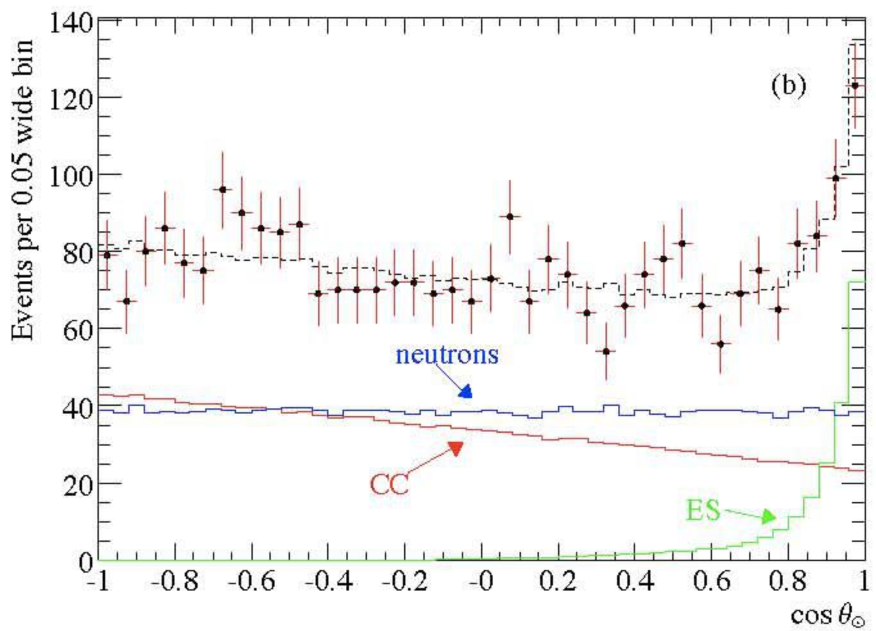


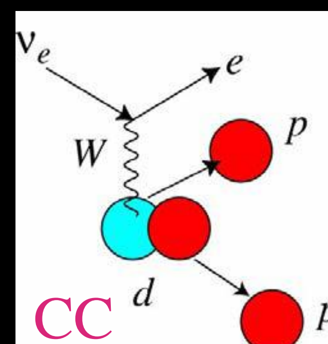
compared to theory prediction

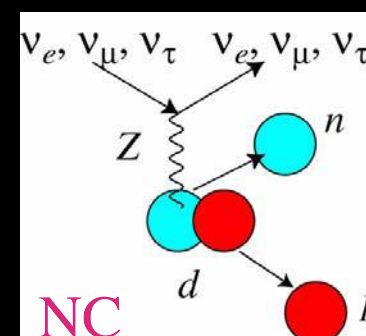
$$\Phi_{\nu_{\rm e}}^{\rm BPS09(GS)} = (5.88 \pm 0.65){\rm cm}^{-2}{\rm s}^{-1}$$

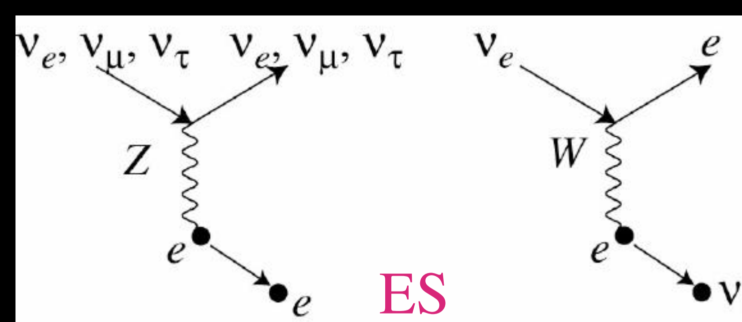

(a)
Events per 0.02 wide bin
neutrons
CC
ES
β_{14}


Events per 0.05 wide bin
Fiducial volume
NC+Internal neutrons
β-γ events
CC
"AV events"
External-source neutrons
ES
$\rho = (R_{fit}/600\ cm)^3$


(b)
Events per 0.05 wide bin
neutrons
CC
ES
$\cos\theta_{\odot}$


ν_e
e
W
p
d
p
CC


ν_e, ν_μ, ν_τ
ν_e, ν_μ, ν_τ
Z
n
d
p
NC

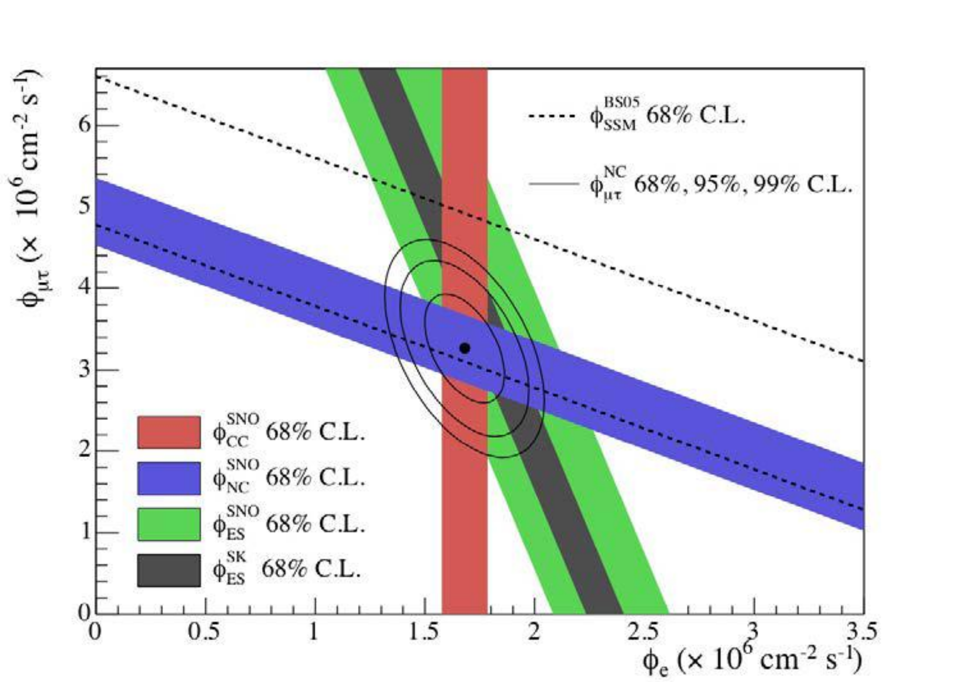

ν_e, ν_μ, ν_τ
ν_e, ν_μ, ν_τ
Z
e
e
ν_e
e
W
e
ν_e
ES


600

Wrong Neutrinos

- Only ν_e produced in the Sun
- Wrong Neutrinos $\nu_{\mu,\tau}$ are coming from the Sun!
- Somehow some of ν_e were converted to $\nu_{\mu,\tau}$ on their way from the Sun's core to the detector

  ⇒ neutrino flavor transformation!



The Nobel Prize in Physics 2015

Takaaki Kajita

Prize share: 1/2

Arthur B. McDonald

Prize share: 1/2

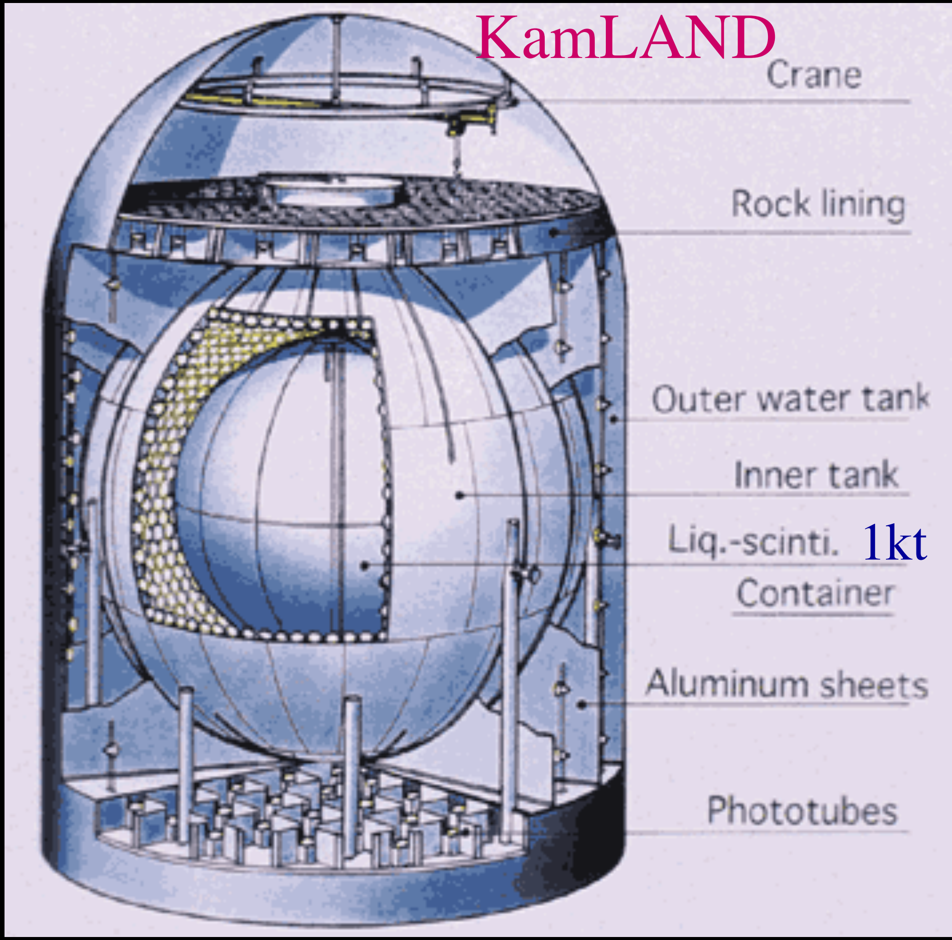
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Terrestrial "Solar Neutrino"

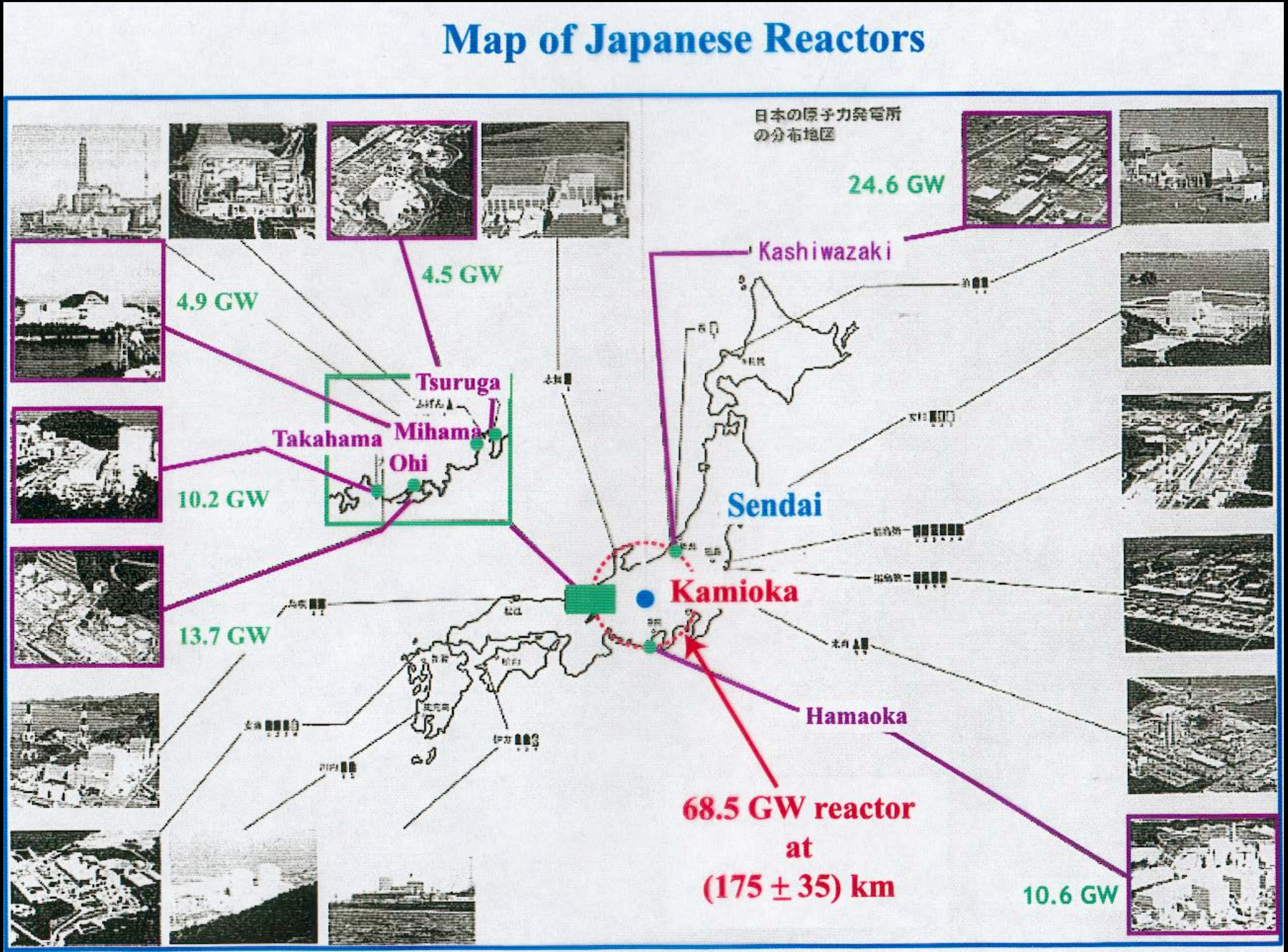
- Can we convincingly verify oscillation with man-made neutrinos?

$$P_{\rm surv} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2}{10^{-5}{\rm eV}^2} \frac{\rm MeV}{E} \frac{L}{100{\rm km}}\right)$$

- Hard for low Δm^2
- To probe $\Delta m^2 \sim 10^{-5}\text{eV}^2$, need L~100km, E_ν~MeV
- Need high Φ_ν
- Use neutrinos from nuclear reactors and detector ~kt

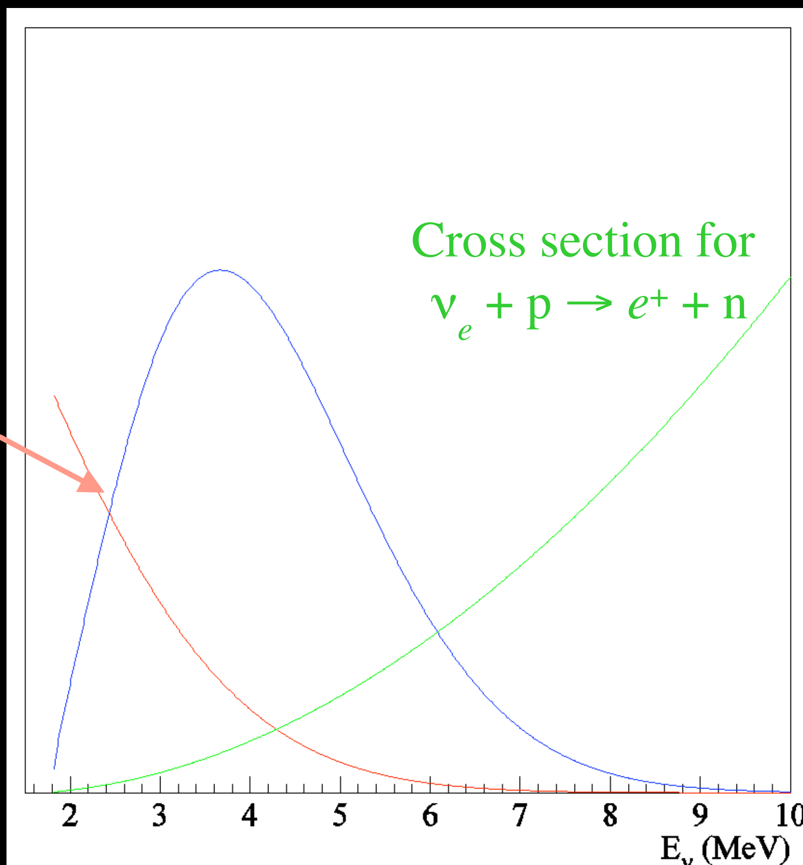


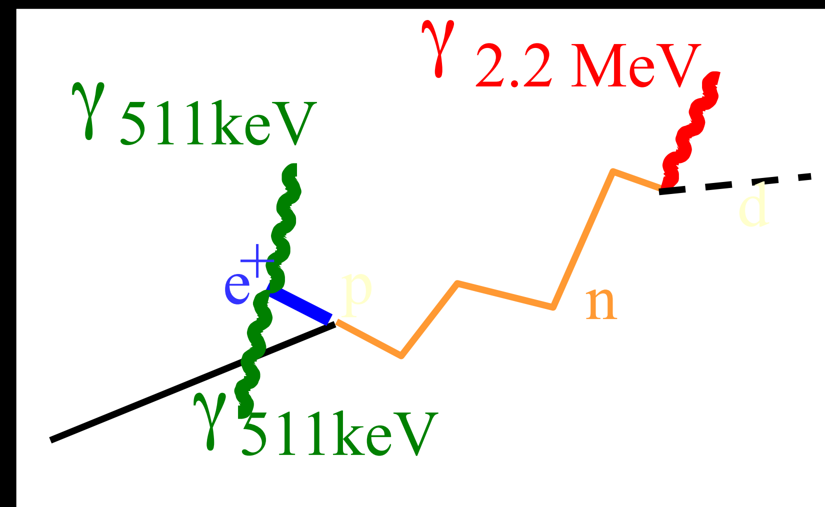
Location, Location, Location



Detection Principle

Reactor ν_e spectrum





Coincidence signal: detect

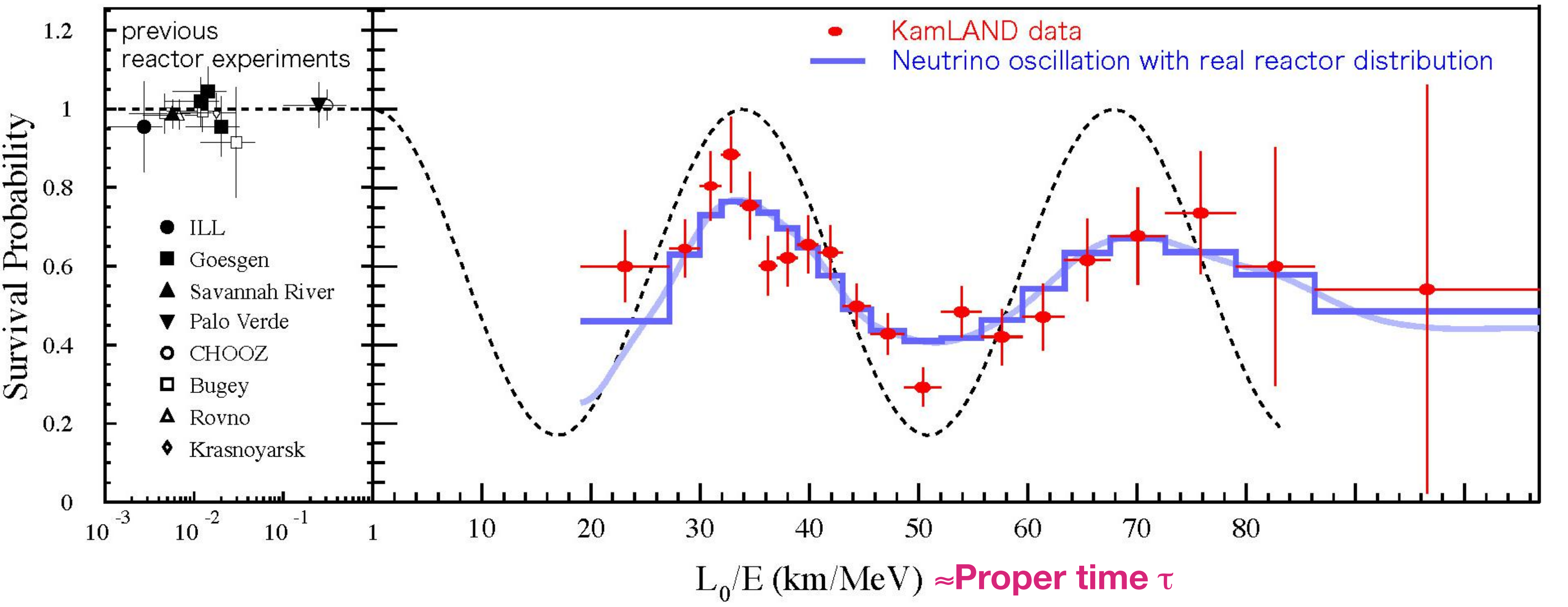
Prompt

Delayed

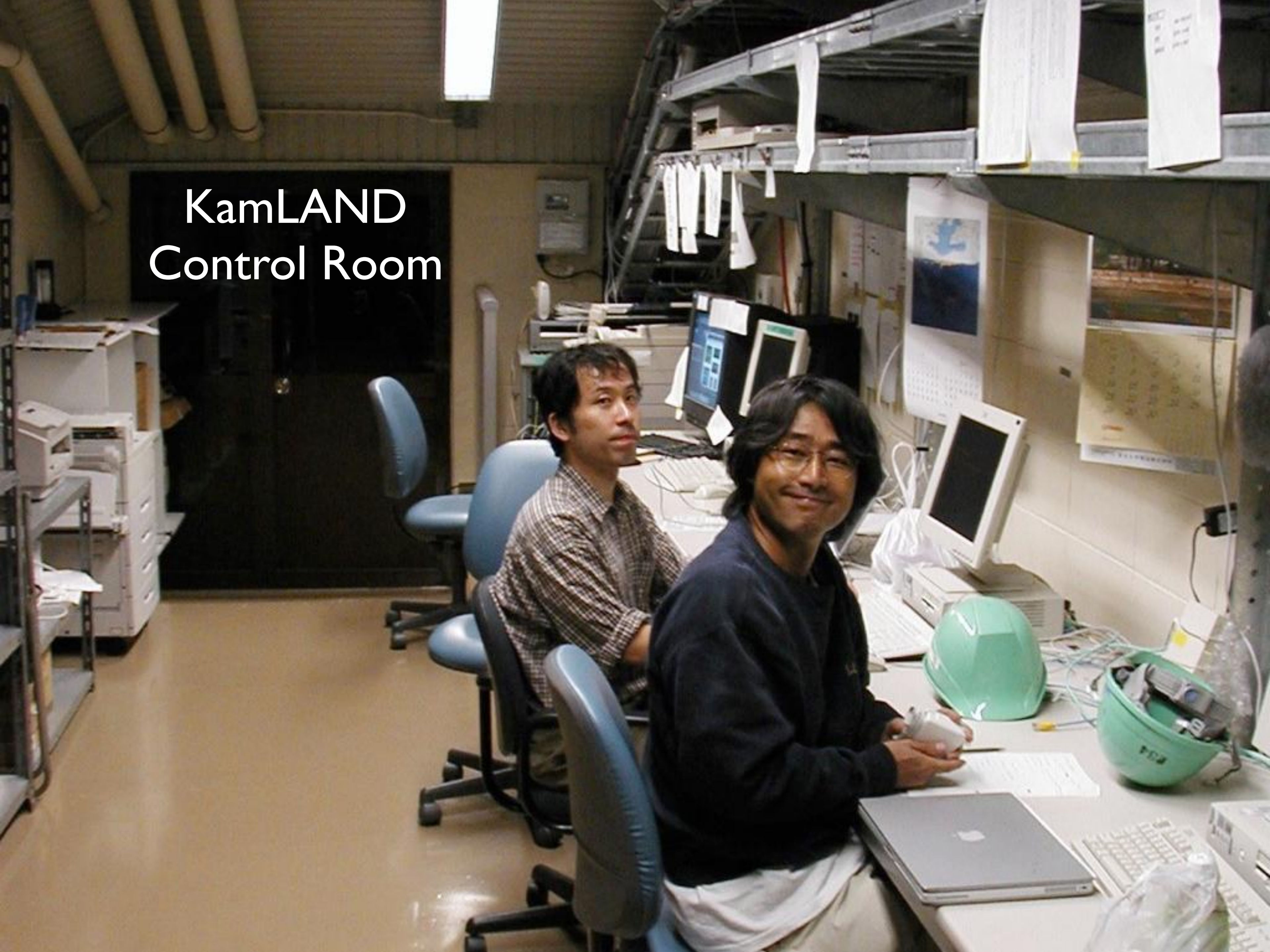
180 μs capture time

$$E_\nu = E_{e^+} + (m_n - m_p)c^2 + \cancel{\frac{\vec{p}_n^{\,2}}{2m_n}}$$

KamLAND neutrinos do oscillate!



L_0=(175±35) km


KamLAND
Control Room

Matter Effect

- CC interaction in the presence of non-relativistic electron

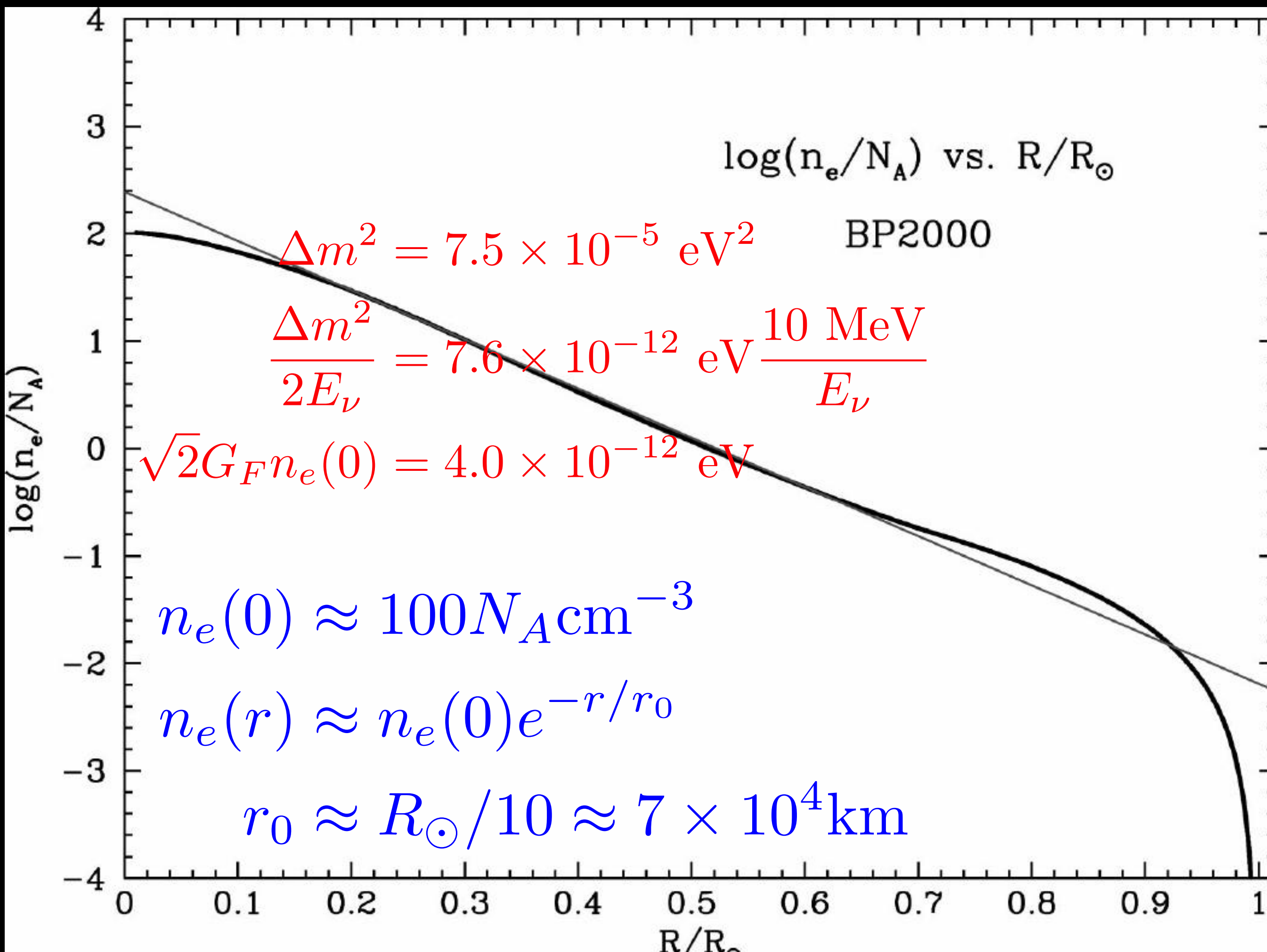
$$\mathcal{L} = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \; \bar{\nu}_e\gamma_\mu(1-\gamma_5)e$$
$$= -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu(1-\gamma_5)e \; \bar{\nu}_e\gamma_\mu(1-\gamma_5)\nu_e$$
$$= -\sqrt{2}G_F n_e \; \bar{\nu}_e\gamma^0\nu_e$$

- Neutrino Hamiltonian

$$H = p + \frac{m_0^2}{2E} + \sqrt{2}G_F n_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

Electron neutrino energy higher in the Sun

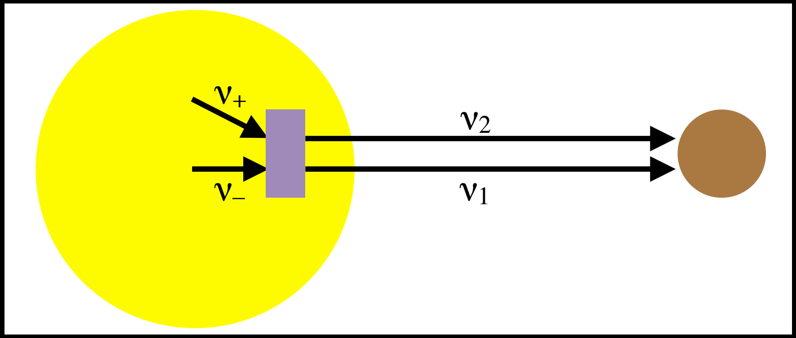
Electron Number Density

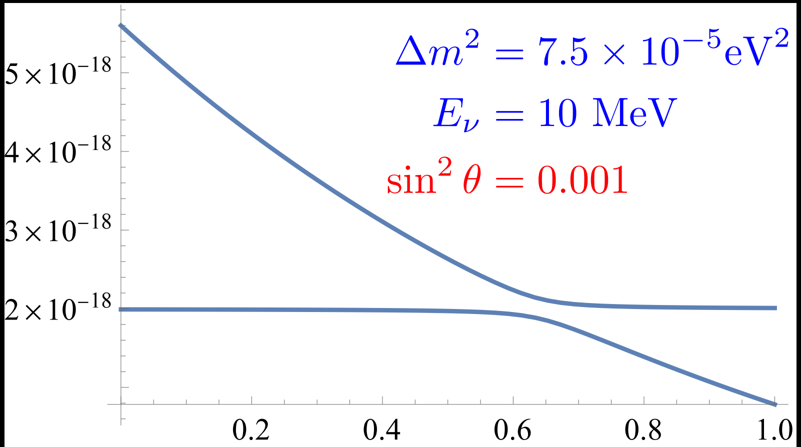


Nearly exponential for most of the Sun's interior $\Rightarrow$ oscillation probability can be solved analytically with Whittaker function

Propagation of ν_e

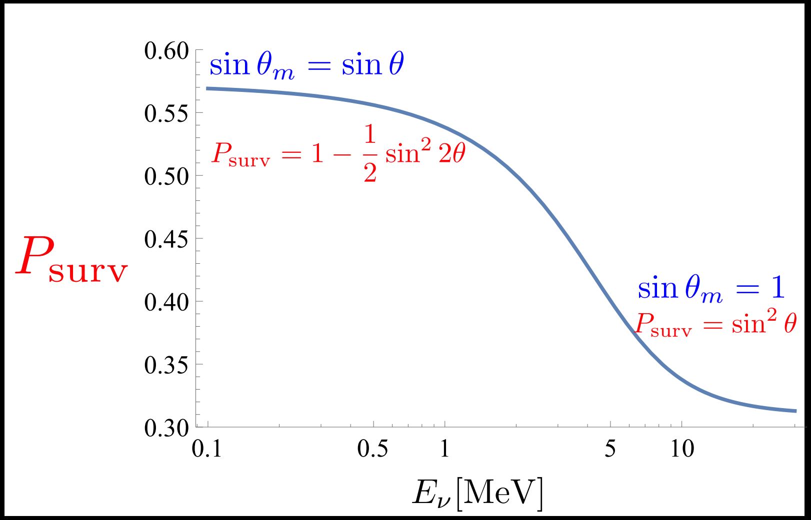
- Use "instantaneous" eigenstates ν_+ and ν_-

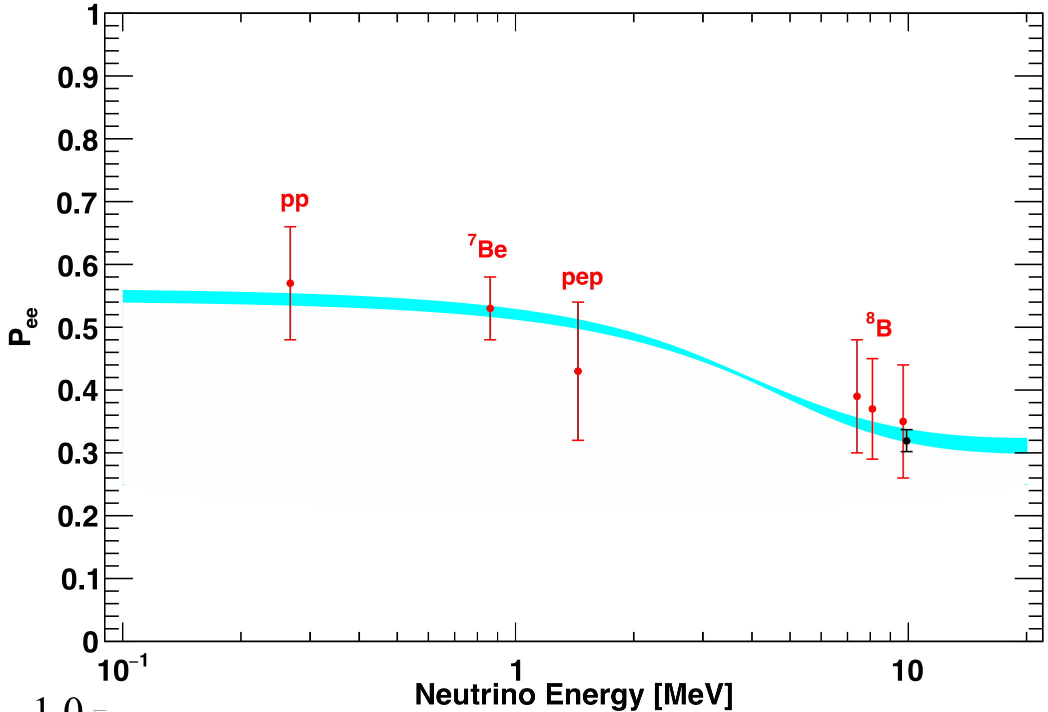




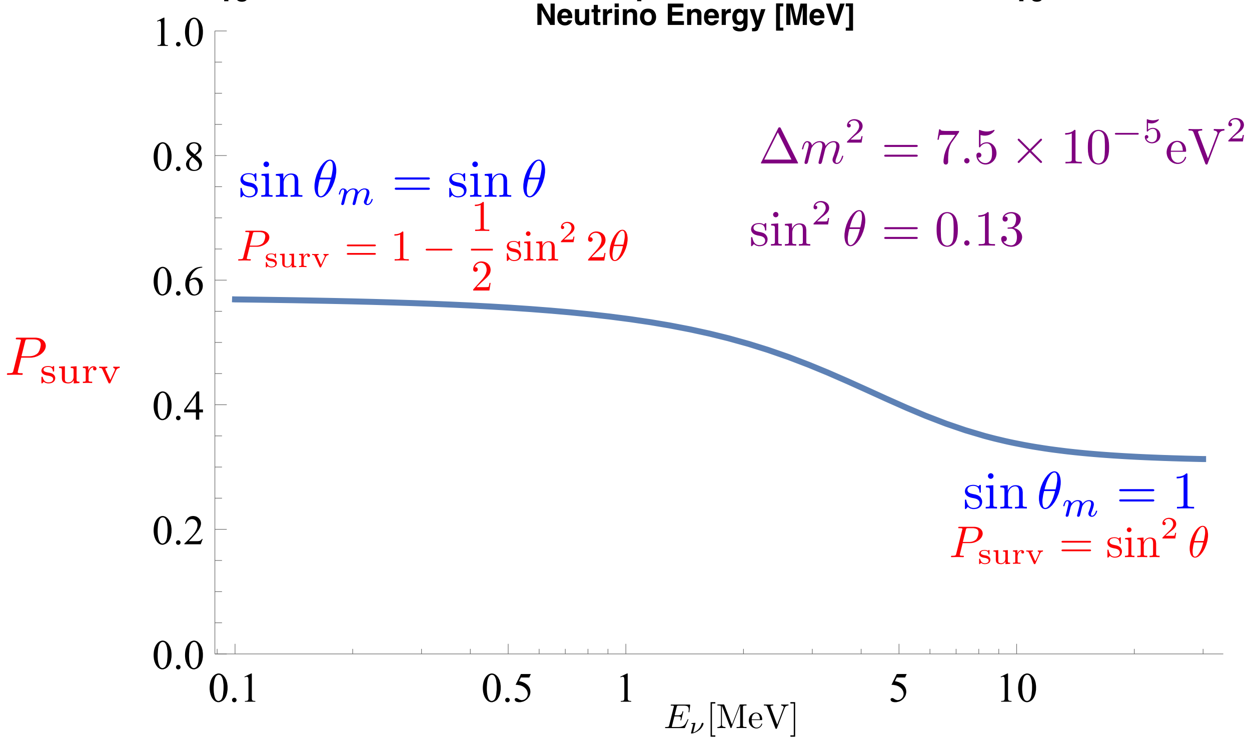
- For the LMA region, the dynamics is adiabatic: there is no hopping between states

$$P_{\mathrm{surv}} = \cos^2\theta\cos^2\theta_m + \sin^2\theta\sin^2\theta_m$$





pp
7Be
pep
8B
Pee
Neutrino Energy [MeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10−1
1
10



$\sin\theta_m = \sin\theta$
$P_{\rm surv} = 1 - \frac{1}{2}\sin^2 2\theta$
$\Delta m^2 = 7.5 \times 10^{-5}{\rm eV}^2$
$\sin^2\theta = 0.13$
$\sin\theta_m = 1$
$P_{\rm surv} = \sin^2\theta$
$P_{\rm surv}$
E_ν[MeV]
0.0
0.2
0.4
0.6
0.8
1.0
0.1
0.5
1
5
10

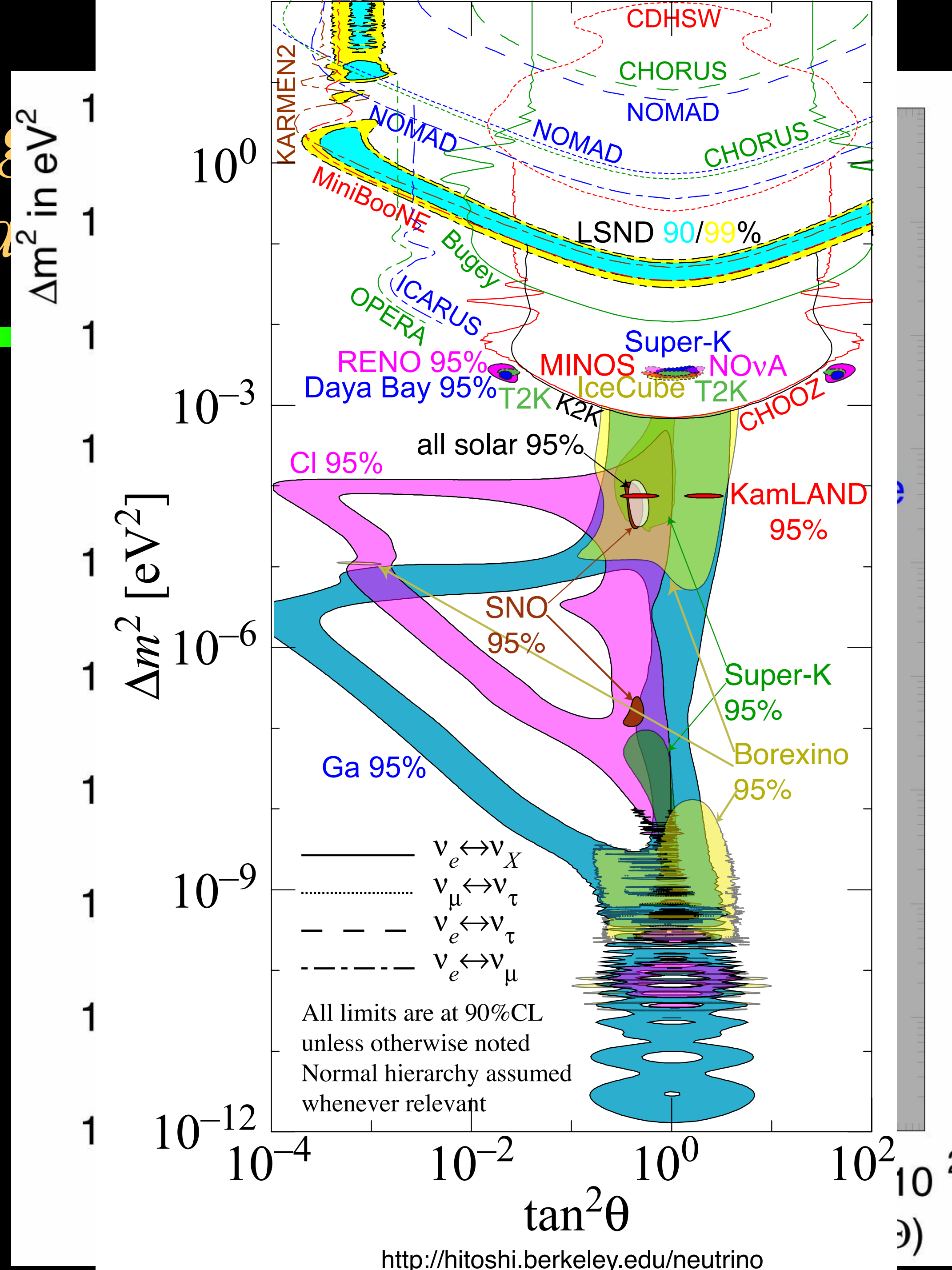
Prog
on the Sola

March 2002

April 2002
with SNO

Dec 2002
with KamLAND

June 2004
with KamLAND



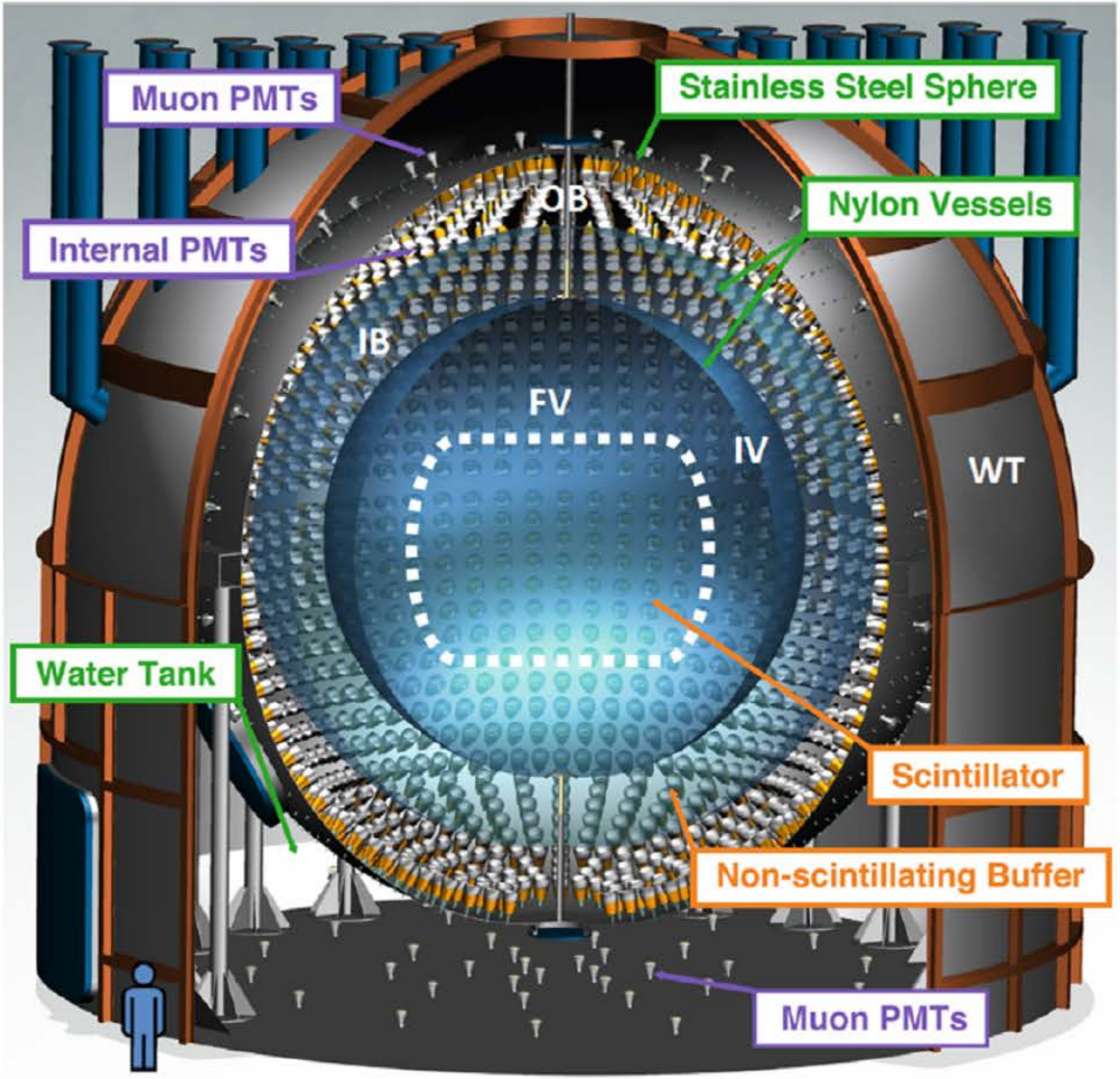
The Borexino detector @ LNGS

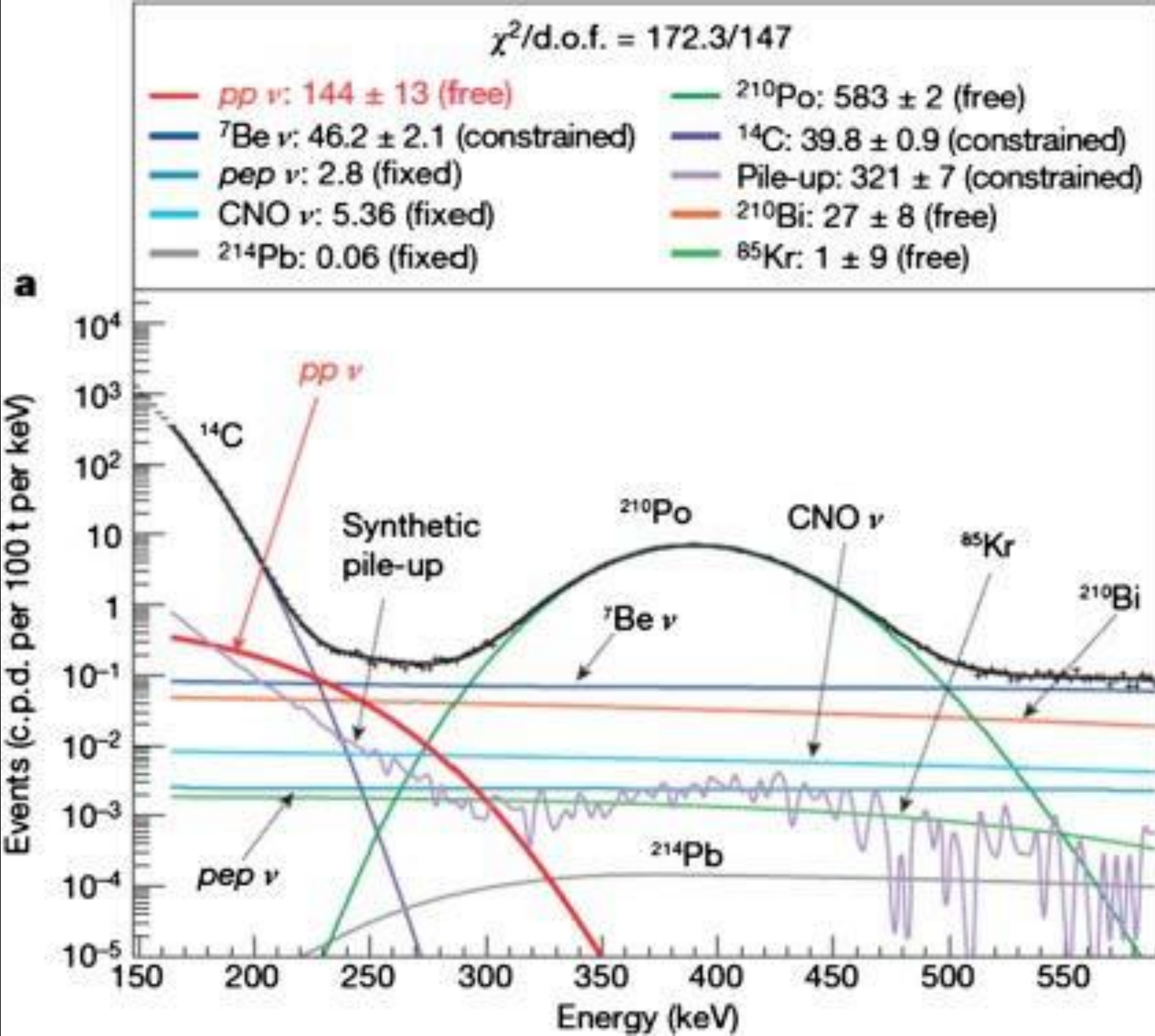
Active volume:
280 tons of liquid scintillator.

Detection principle

$$\nu_x + e \rightarrow \nu_x + e$$

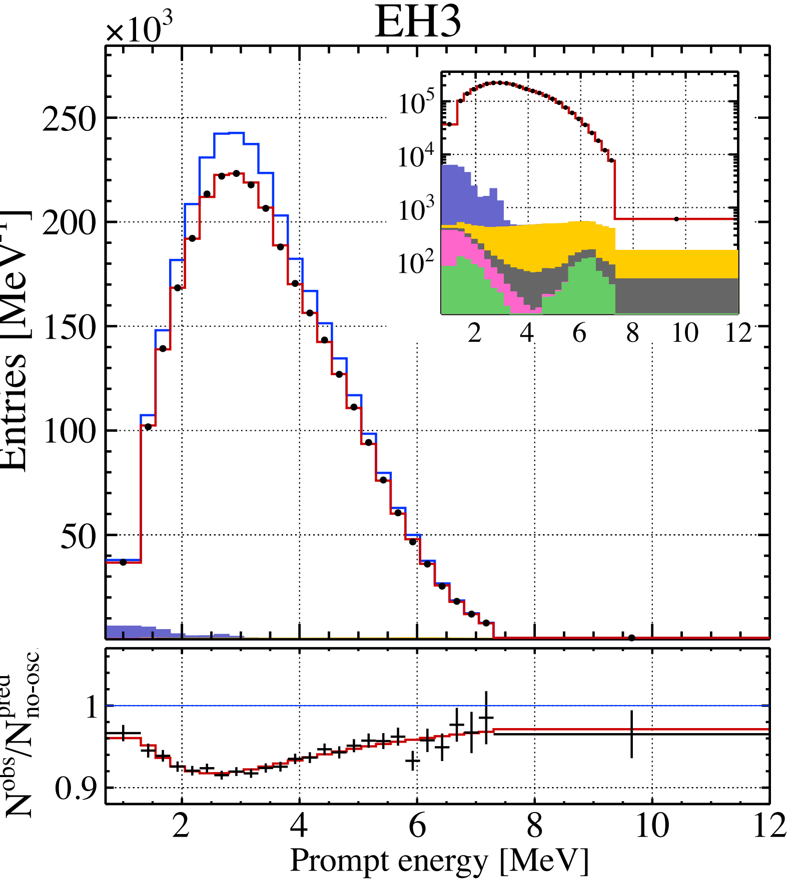
Elastic scattering off the electrons of the scintillator.
Threshold at ~ 60 keV (electron energy)





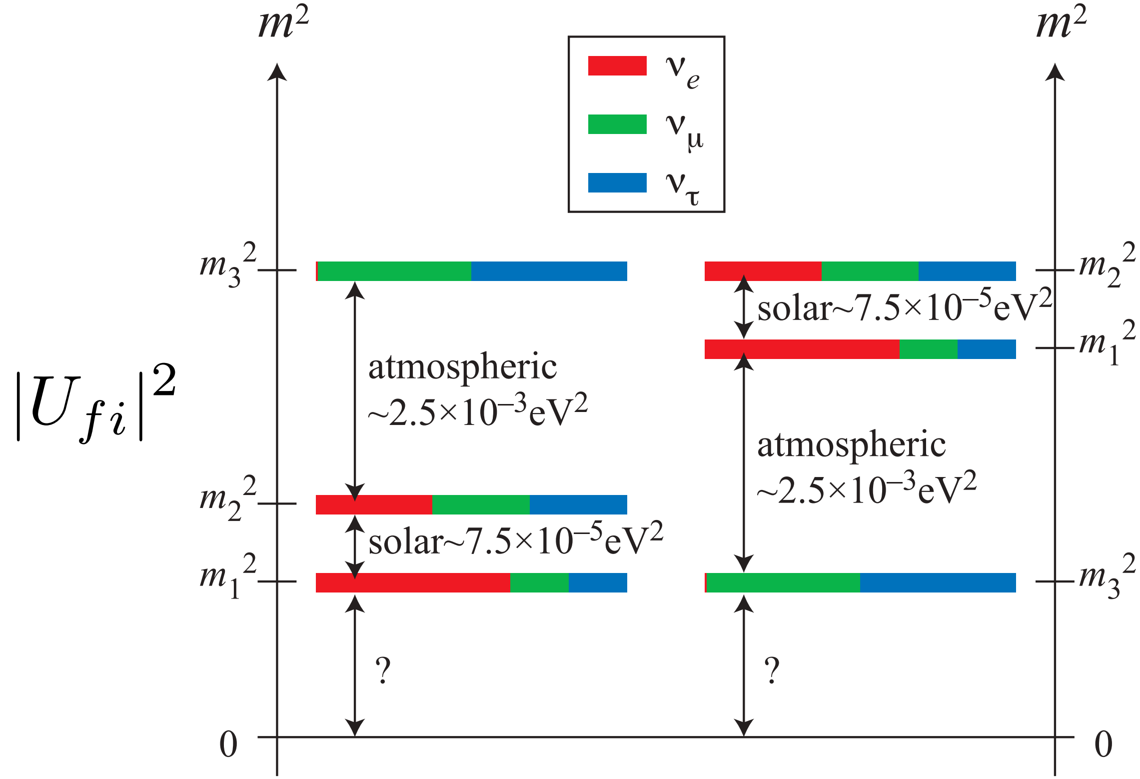
χ²/d.o.f. = 172.3/147
pp ν: 144 ± 13 (free)
⁷Be ν: 46.2 ± 2.1 (constrained)
pep ν: 2.8 (fixed)
CNO ν: 5.36 (fixed)
²¹⁴Pb: 0.06 (fixed)
²¹⁰Po: 583 ± 2 (free)
¹⁴C: 39.8 ± 0.9 (constrained)
Pile-up: 321 ± 7 (constrained)
²¹⁰Bi: 27 ± 8 (free)
⁸⁵Kr: 1 ± 9 (free)
a
Events (c.p.d. per 100 t per keV)
Energy (keV)
pp ν
¹⁴C
Synthetic pile-up
²¹⁰Po
CNO ν
⁸⁵Kr
²¹⁰Bi
⁷Be ν
pep ν
²¹⁴Pb

Masses and Mixings


EH3
×10^3
Entries [MeV^-1]
Prompt energy [MeV]
N^obs/N^pred_no-osc


Entrance portal


aya Bay
Empty detectors: moved to underground halls through access tunnel.
Filled detectors: swapped between underground halls via horizontal tunnels.
Ling Ao Near
500 m from Ling Ao
Overburden: 98 m
910 m
570 m
730 m
230 m
290 m
Ling Ao-II NPP
(under const.)
Ling Ao
NPP
Daya Bay Near
360 m from Daya Bay
Overburden: 97 m
Daya Bay
NPP
Total tunnel length: ~2700 m



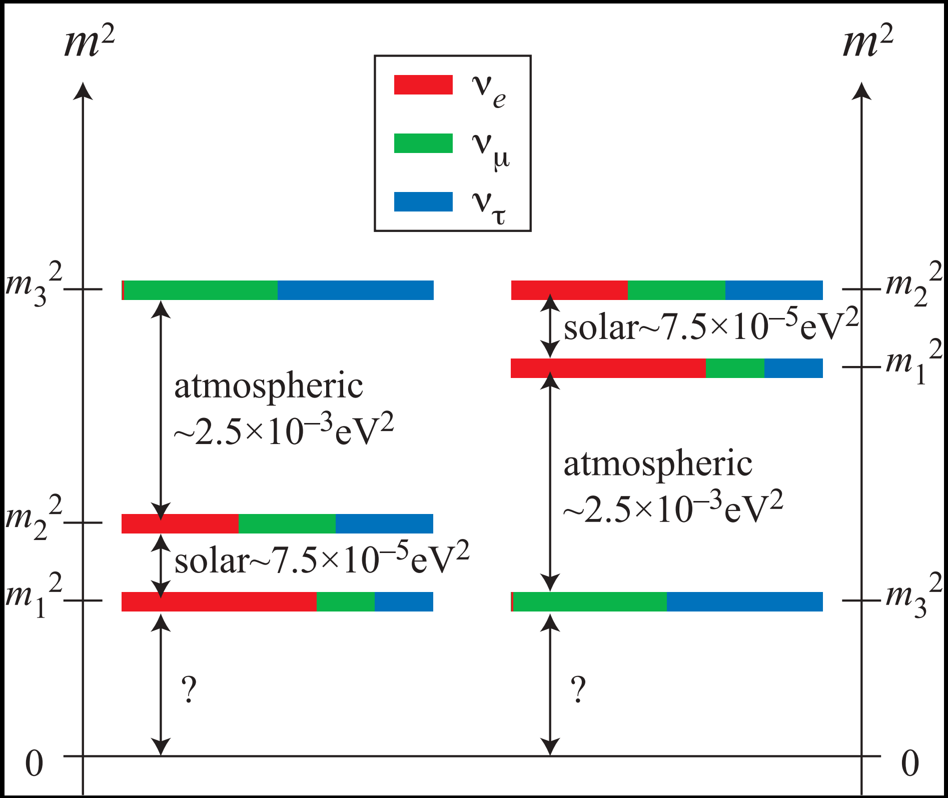
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 0.82 & 0.55 & 0.15e^{i\delta} \\ -0.41 & 0.62 & 0.66 \\ 0.37 & -0.56 & 0.73 \end{pmatrix}$$

Seven Questions

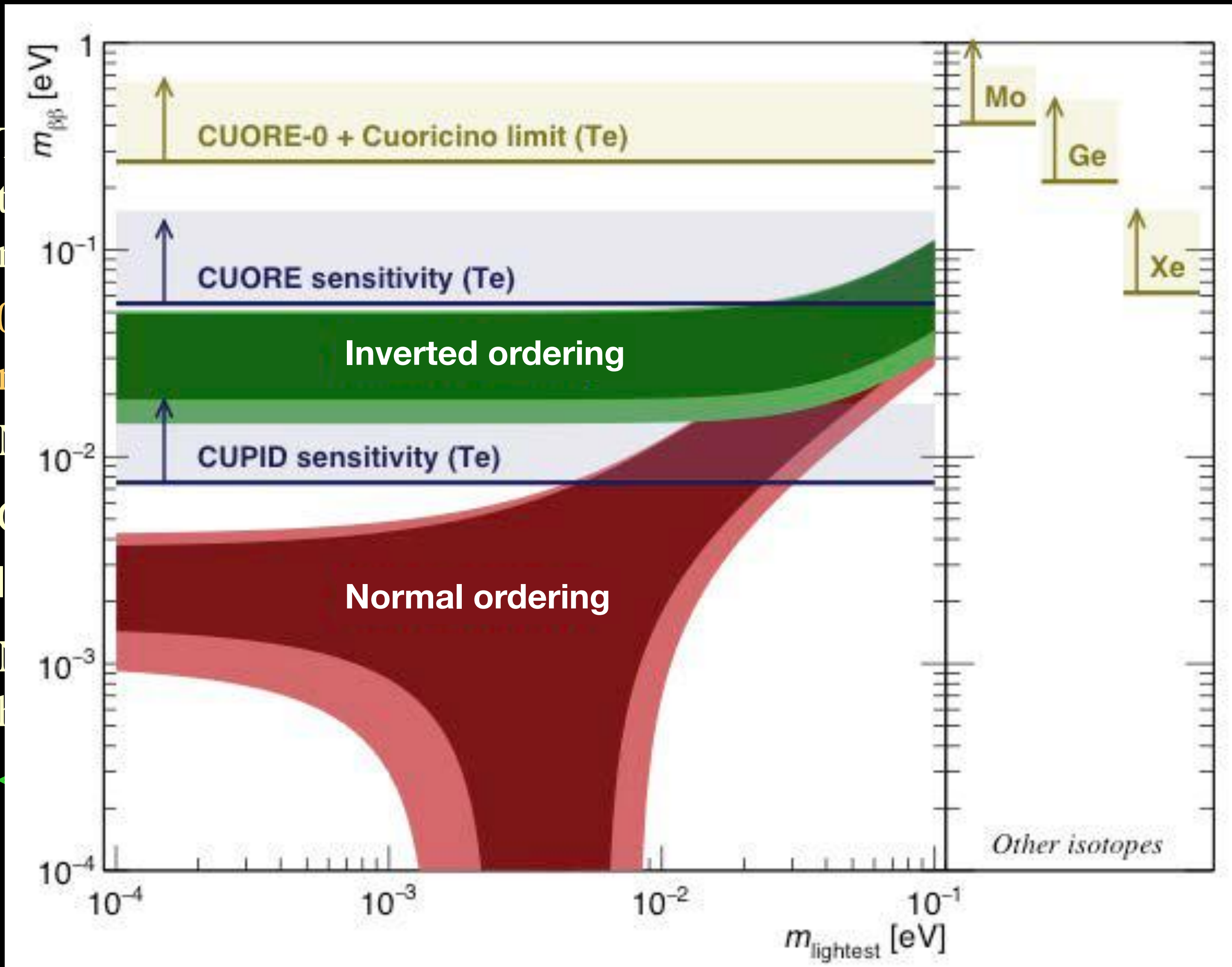
- Dirac or Majorana?
- Absolute mass scale?
- Mass ordering?
- CP Violation?
- Is θ_{23} maximal?
- Sterile neutrino(s)?
- Baryon asymmetry?



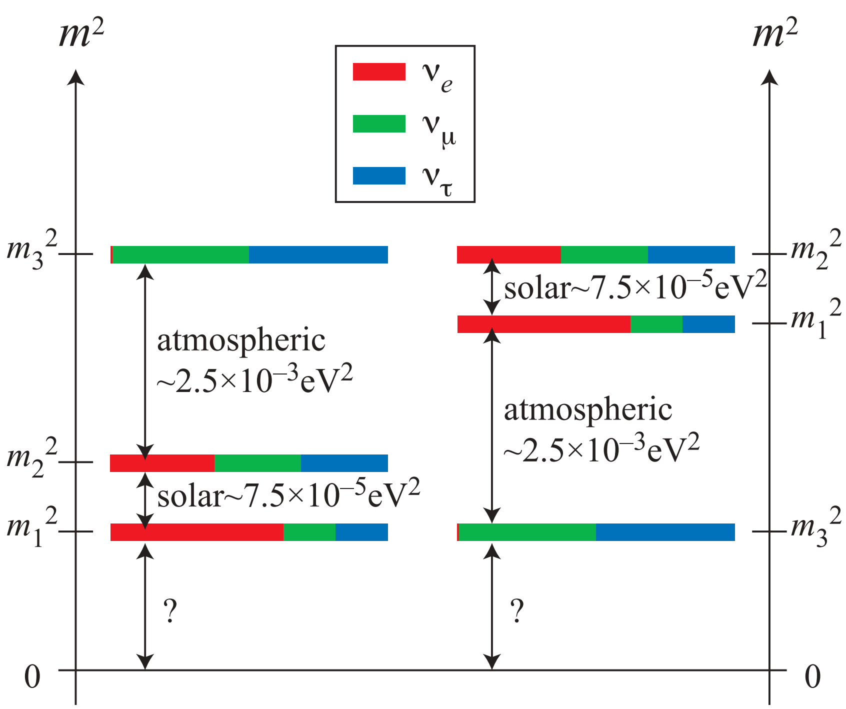
Seven Questions

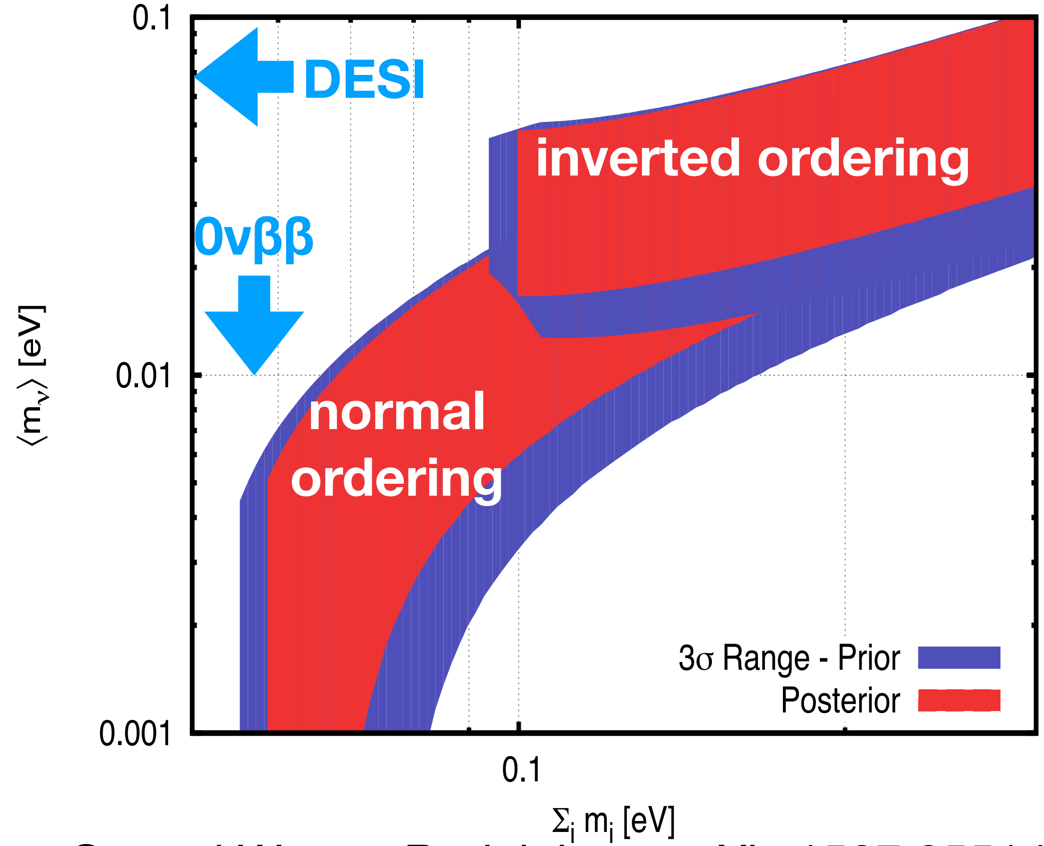
- Dirac or Majorana? ⇒ neutrino less double β decay
- Absolute mass scale? ⇒ cosmology, Project 8
- Mass ordering? ⇒ JUNO, DUNE
- CP Violation? ⇒ Hyper-K, DUNE
- Is θ_{23} maximal? ⇒ DUNE, Hyper-K
- Sterile neutrino(s)? ⇒ SBN program @ Fermilab
- Baryon asymmetry? ⇒ Leptogenesis

Neutrinoless Double-beta Decay



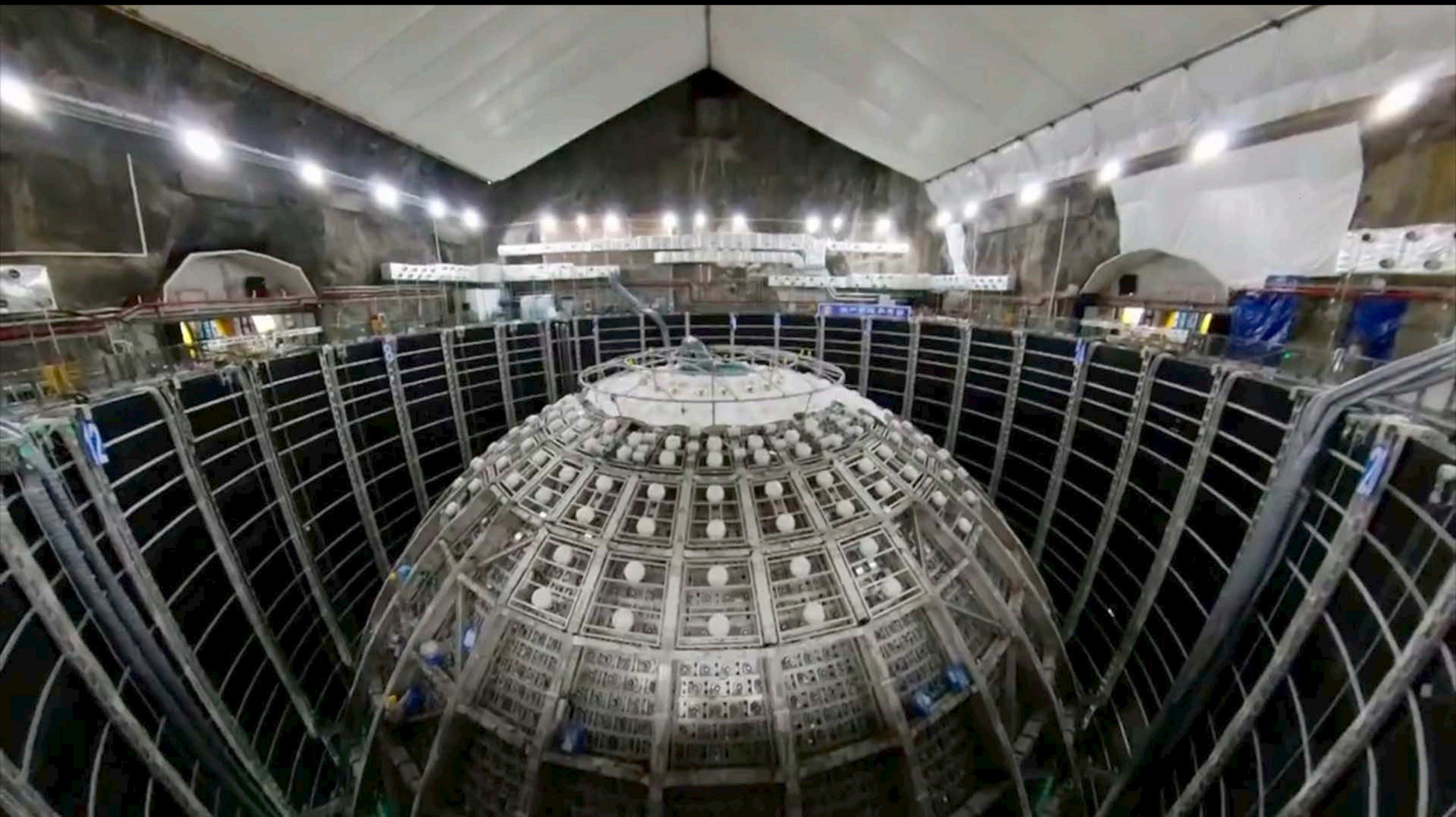
Lab vs Universe



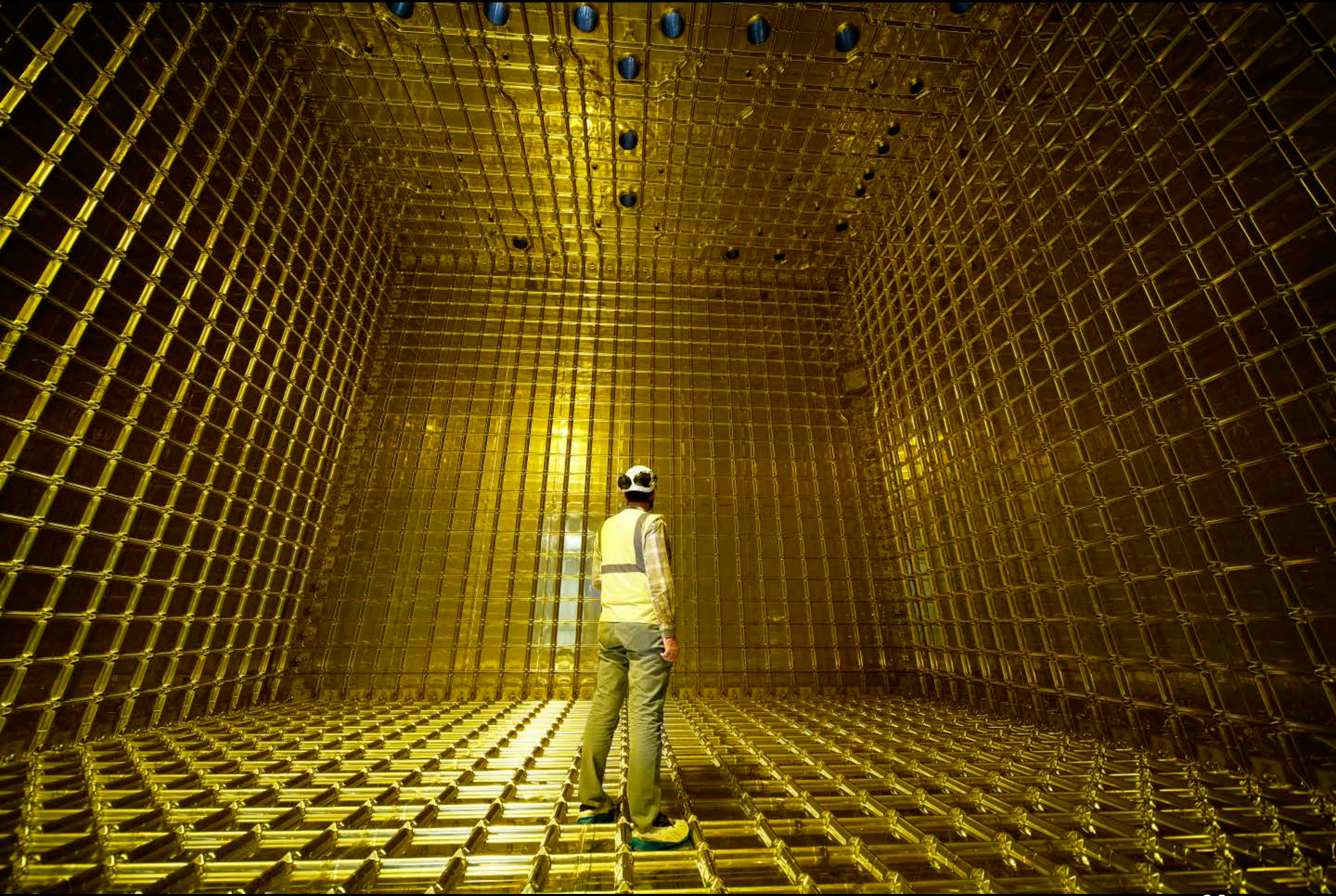


Shao-Feng Ge and Werner Rodejohann arXiv:1507.05514

Jiangmen Underground Neutrino Observatory (JUNO)



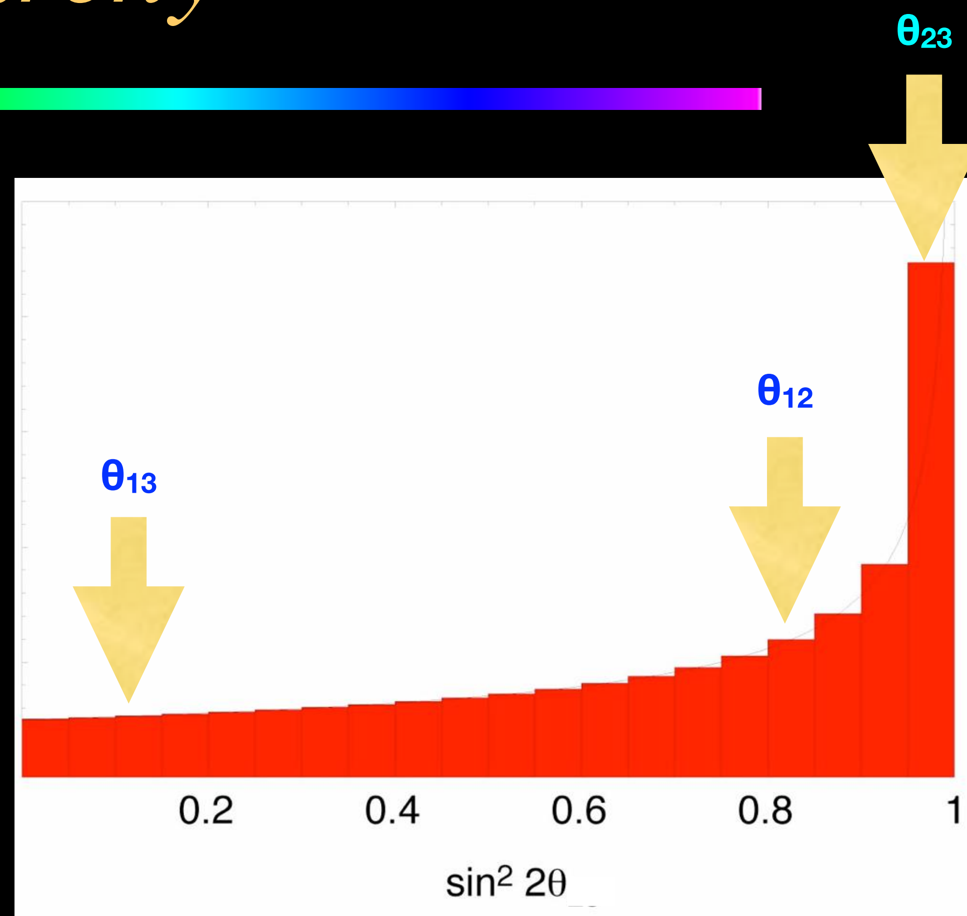
matter effect



CP violation

Hall, HM, Weiner

Anarchy



Kolmogorov-Smirnov test (de Gouvêa, HM)

nature has 47% chance to choose this kind of numbers

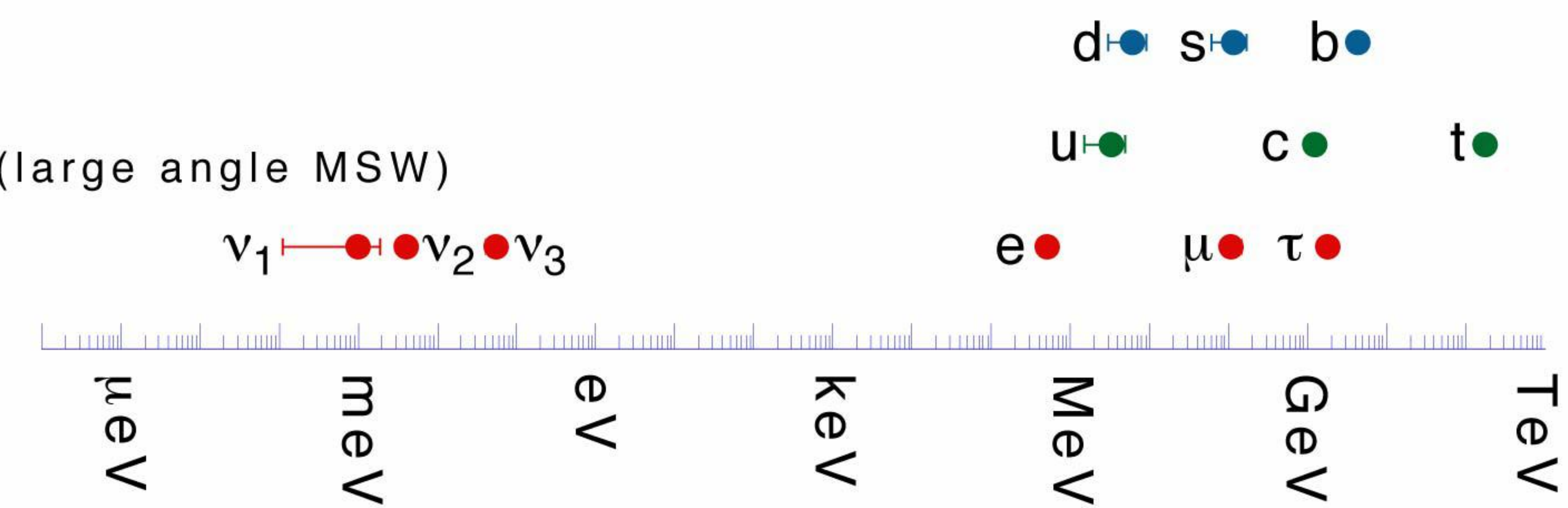
Anarchy and Hierarchy

- Consider a simple U(1) flavor symmetry broken by ε(–1)

generation	3rd	2nd	1st
Q, u^c, e^c	$+0$	$+1$	$+2$
L, d^c	$+1$	$+1$	$+1$
N	$+0$	$+1$	$+2$

$$M_u \approx \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^1 \\ \varepsilon^2 & \varepsilon^1 & 1 \end{pmatrix} \qquad M_\nu \approx \varepsilon^2 \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

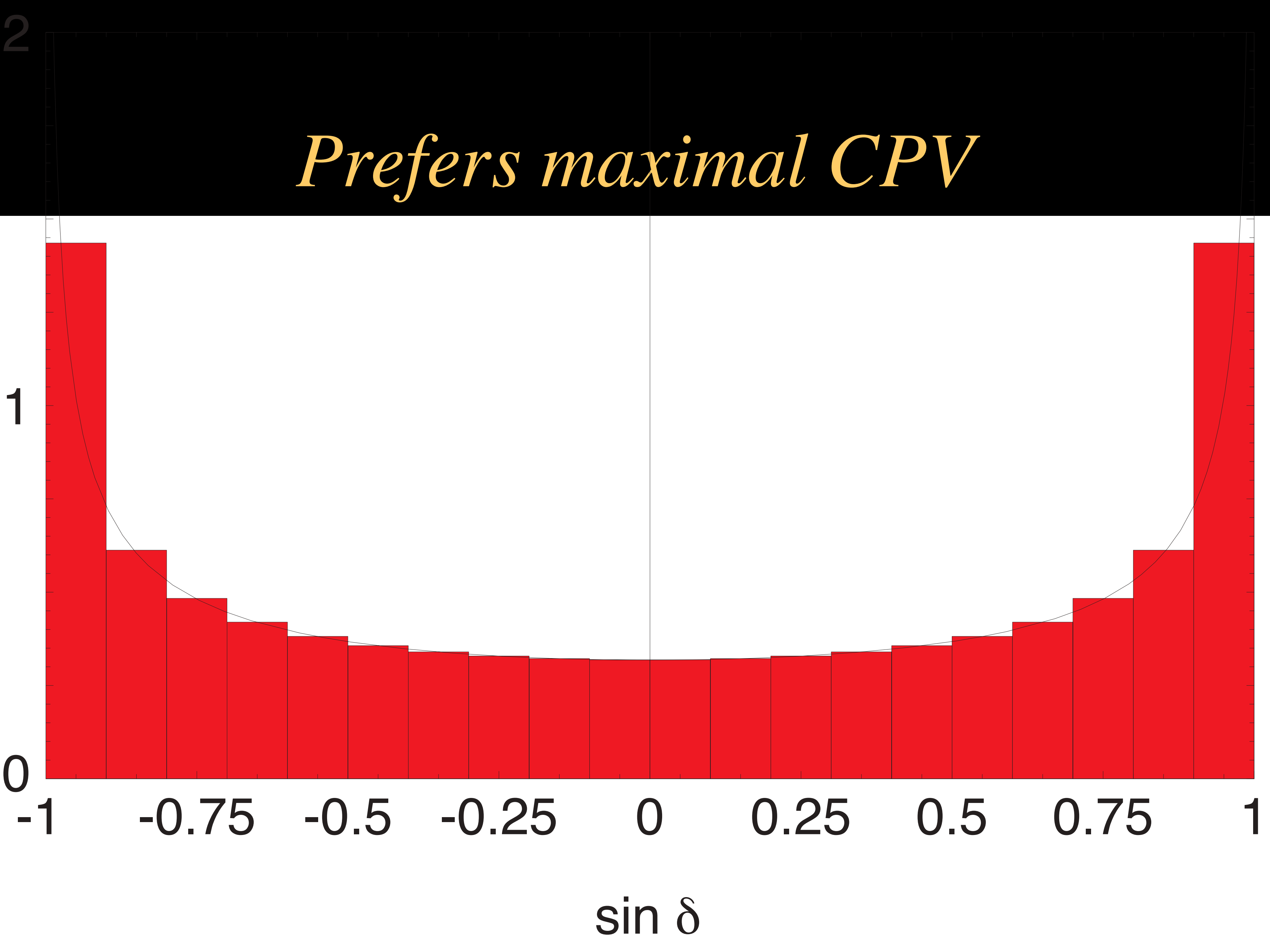
$$M_d \approx M_e^T \approx \begin{pmatrix} \varepsilon^3 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^1 & \varepsilon^1 & \varepsilon^1 \end{pmatrix}$$



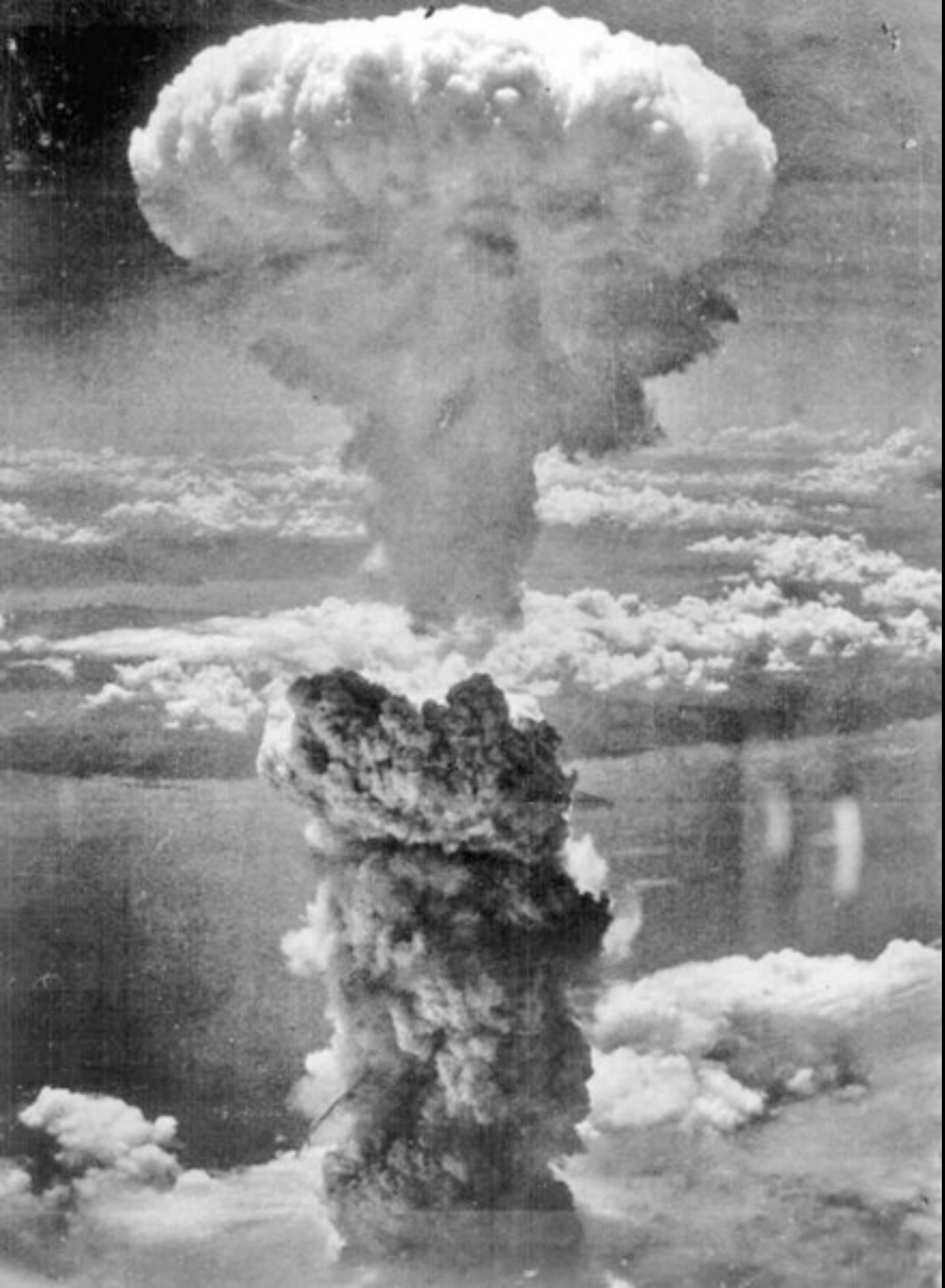
$$M_u \approx \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^1 \\ \varepsilon^2 & \varepsilon^1 & 1 \end{pmatrix} \qquad M_\nu \approx \varepsilon^2 \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

$$M_d \approx M_e^T \approx \begin{pmatrix} \varepsilon^3 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^1 & \varepsilon^1 & \varepsilon^1 \end{pmatrix}$$

$$V_{CKM} \approx \begin{pmatrix} 1 & \varepsilon^2 & \varepsilon^4 \\ \varepsilon^2 & 1 & \varepsilon^2 \\ \varepsilon^4 & \varepsilon^2 & 1 \end{pmatrix} \qquad U_{PMNS} \approx \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$


Prefers maximal CPV
2
1
0
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
sin δ

Leptogenesis



- a scientist at CERN created 0.25g of antimatter without the knowledge of DG
- it will fall into the hands of an evil guy

a billion billion dollars


BASED ON THE BEST-SELLING NOVEL
BY THE AUTHOR OF
THE DAVINCI CODE


2008 Nobel Prize

CP Violation

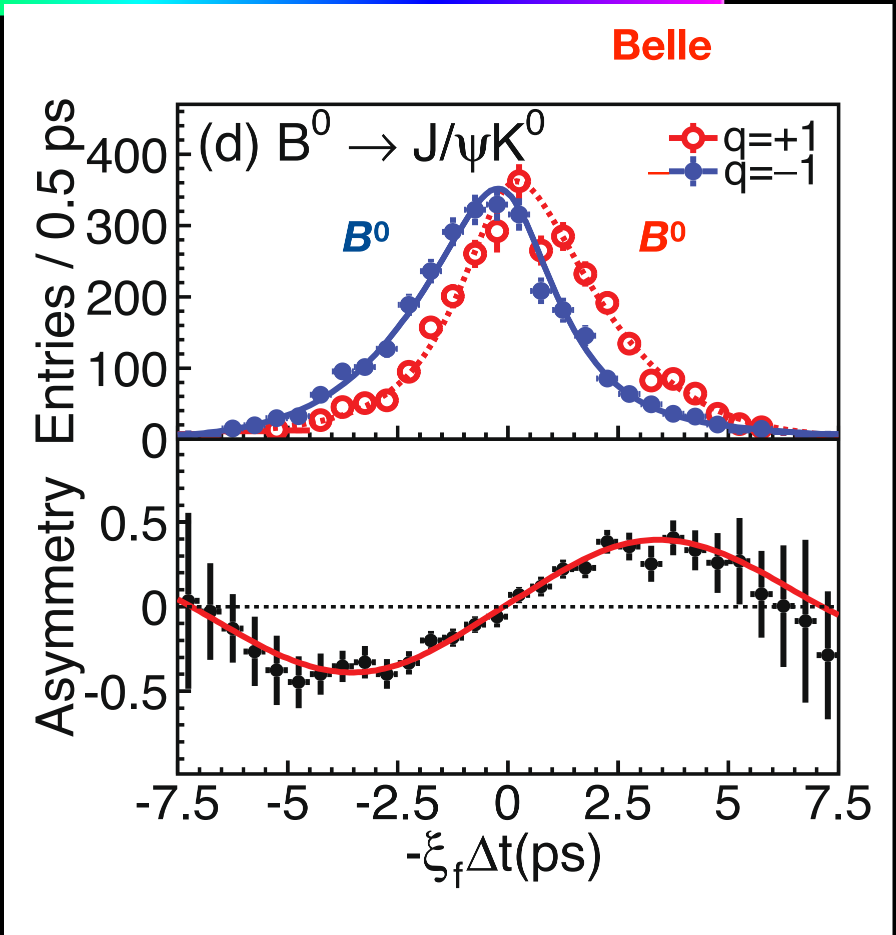
- Is anti-matter the exact mirror of matter?

1964 discovery of CP violation

- But only one system, hard to tell what is going on.

2001, 2002 Two new CP-violating phenomena

- But CP violation observed so far is too small by a factor of 10^{-16} to explain the absence of anti-matter
- doesn't look like quarks are important here (LHCb, Belle2)



End of Inflation

matter *anti-matter*

Reheating

1,000,000,000 | 1,000,000,000

matter | *anti-matter*

Empty Universe?

matter *anti-matter*

Beginning of Universe

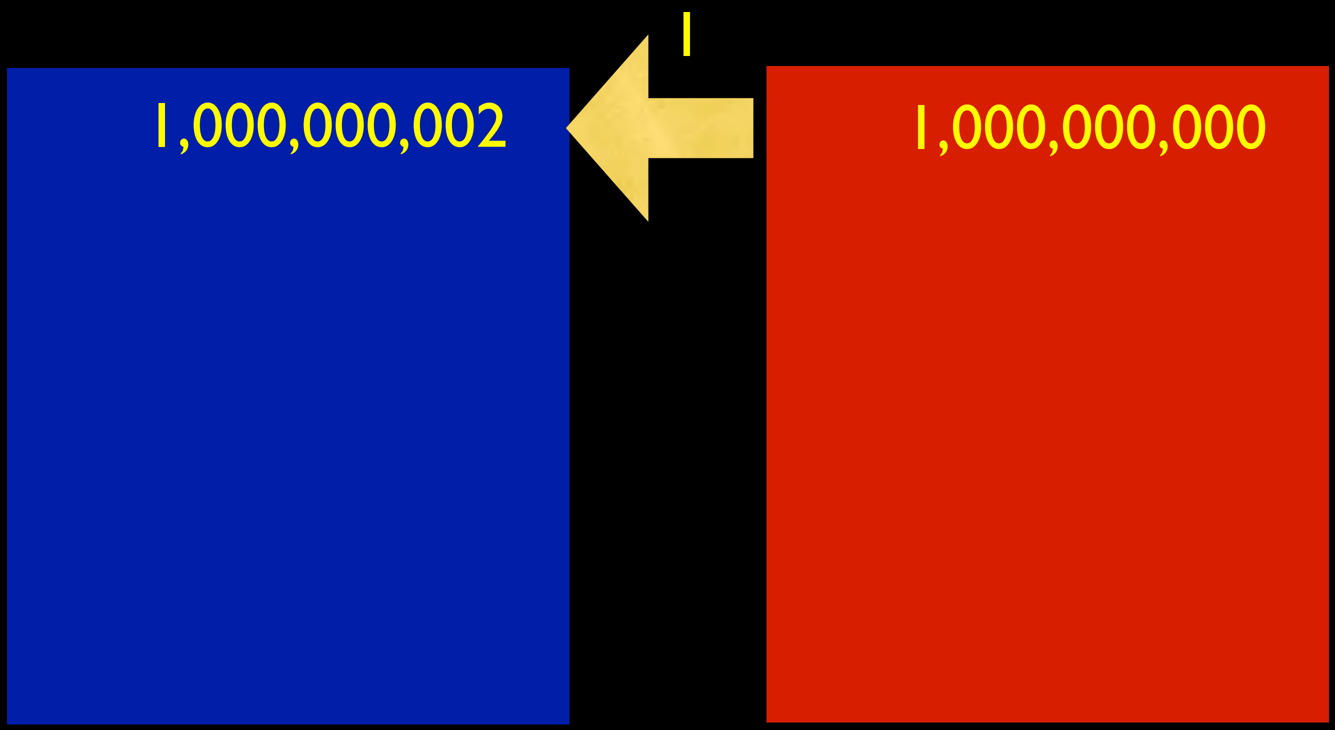
1,000,000,001

1,000,000,001

matter

anti-matter

fraction of second later



matter *anti-matter*

Universe Now

2
•
us

matter *anti-matter*

Sakharov's Three Conditions

- If you take inflation seriously, asymmetry cannot be the initial condition
- microphysical mechanism is needed

  (1) baryon number violation

  (2) C and CP violation

  (3) departure from equilibrium

2008 Nobel Prize

CP Violation

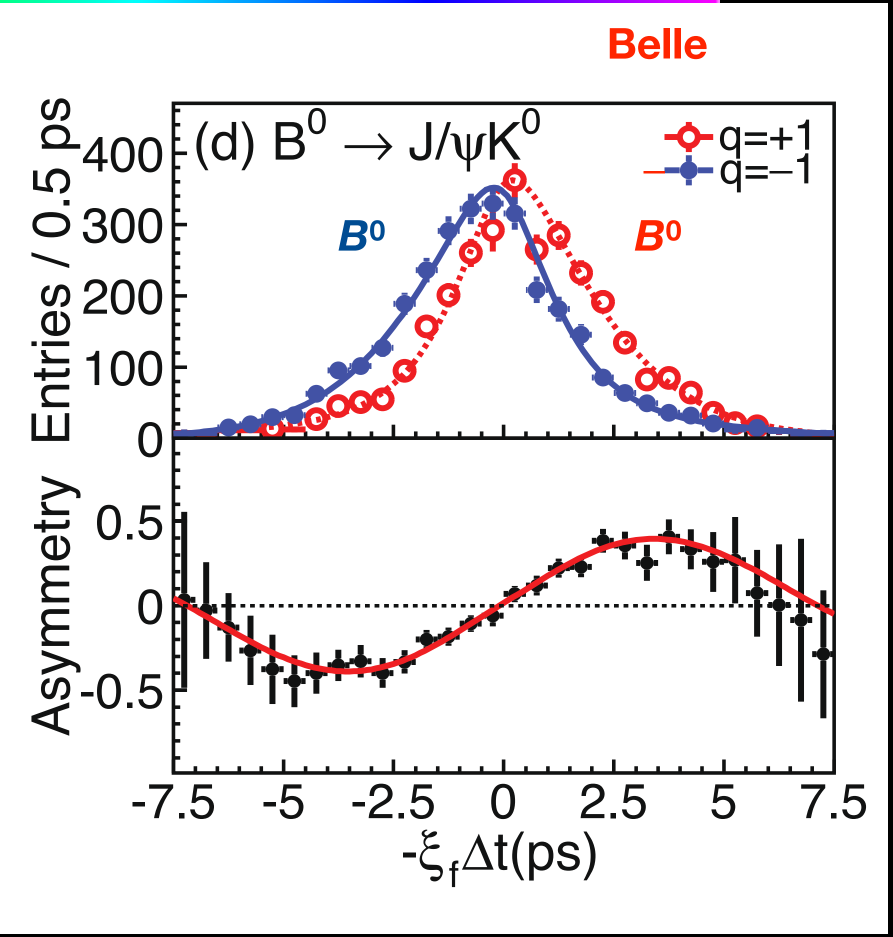
- Is anti-matter the exact mirror of matter?

1964 discovery of CP violation

- But only one system, hard to tell what is going on.

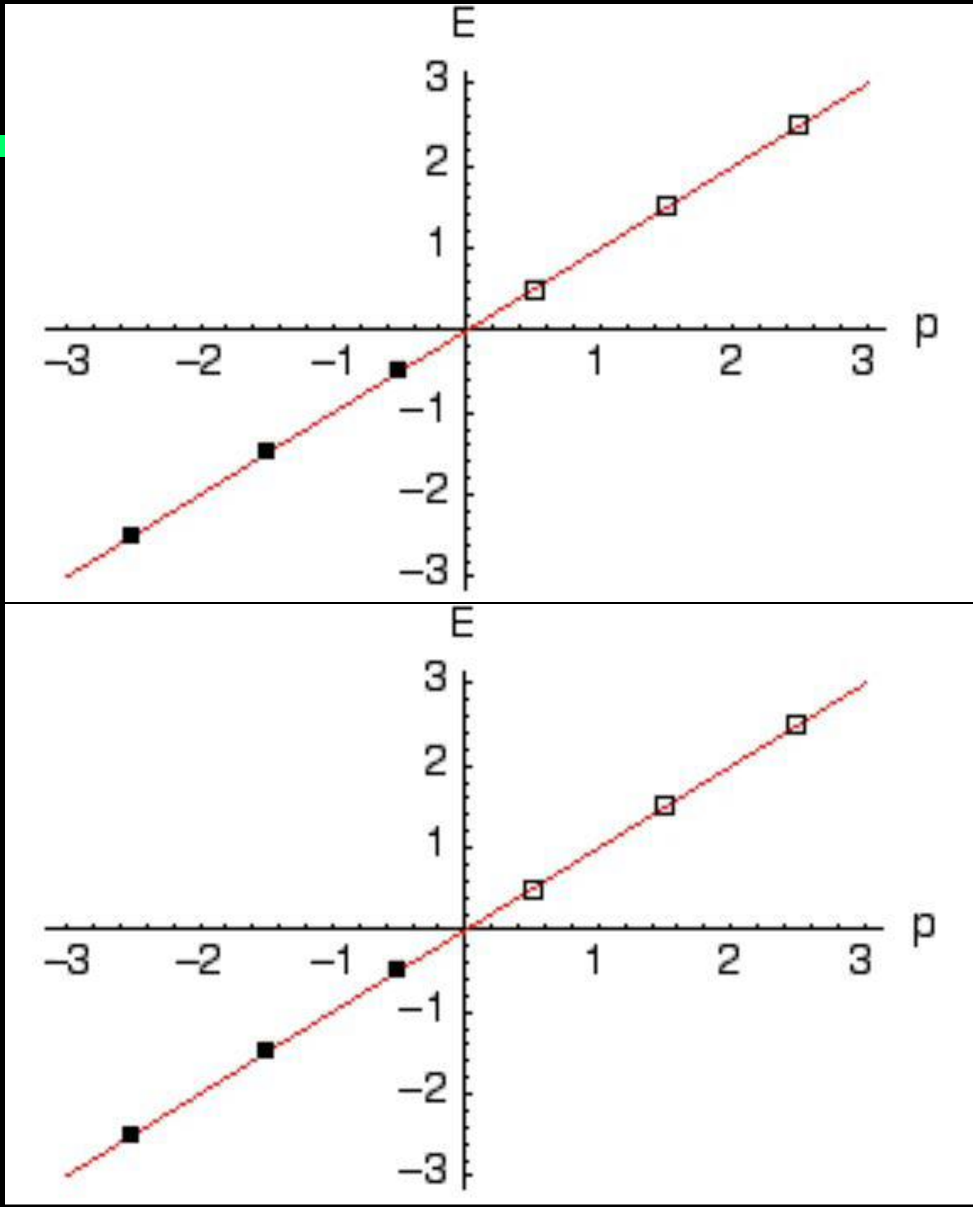
2001, 2002 Two new CP-violating phenomena

- But CP violation observed so far is too small by a factor of 10^{-16} to explain the absence of anti-matter
- doesn't look like quarks are important here



Anomaly!

- *W* and *Z* bosons massless at high temperature
- *W* field fluctuates just like in thermal plasma
- solve Dirac equation in the presence of the fluctuating *W* field



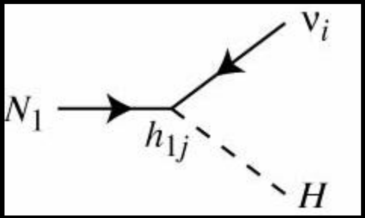
$$\Delta q=\Delta q=\Delta q=\Delta B=\Delta L$$

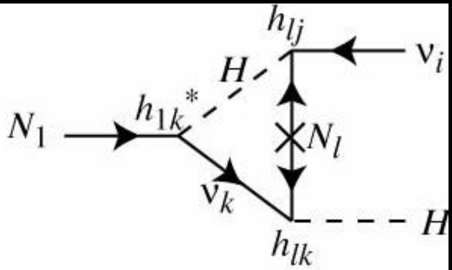

Fukugita


Yanagida

Leptogenesis

- both neutrinos and anti-neutrinos have charge ±0, can reshuffle matter & antimatter





$$\frac{1}{\Gamma(N_1)}(\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H))$$

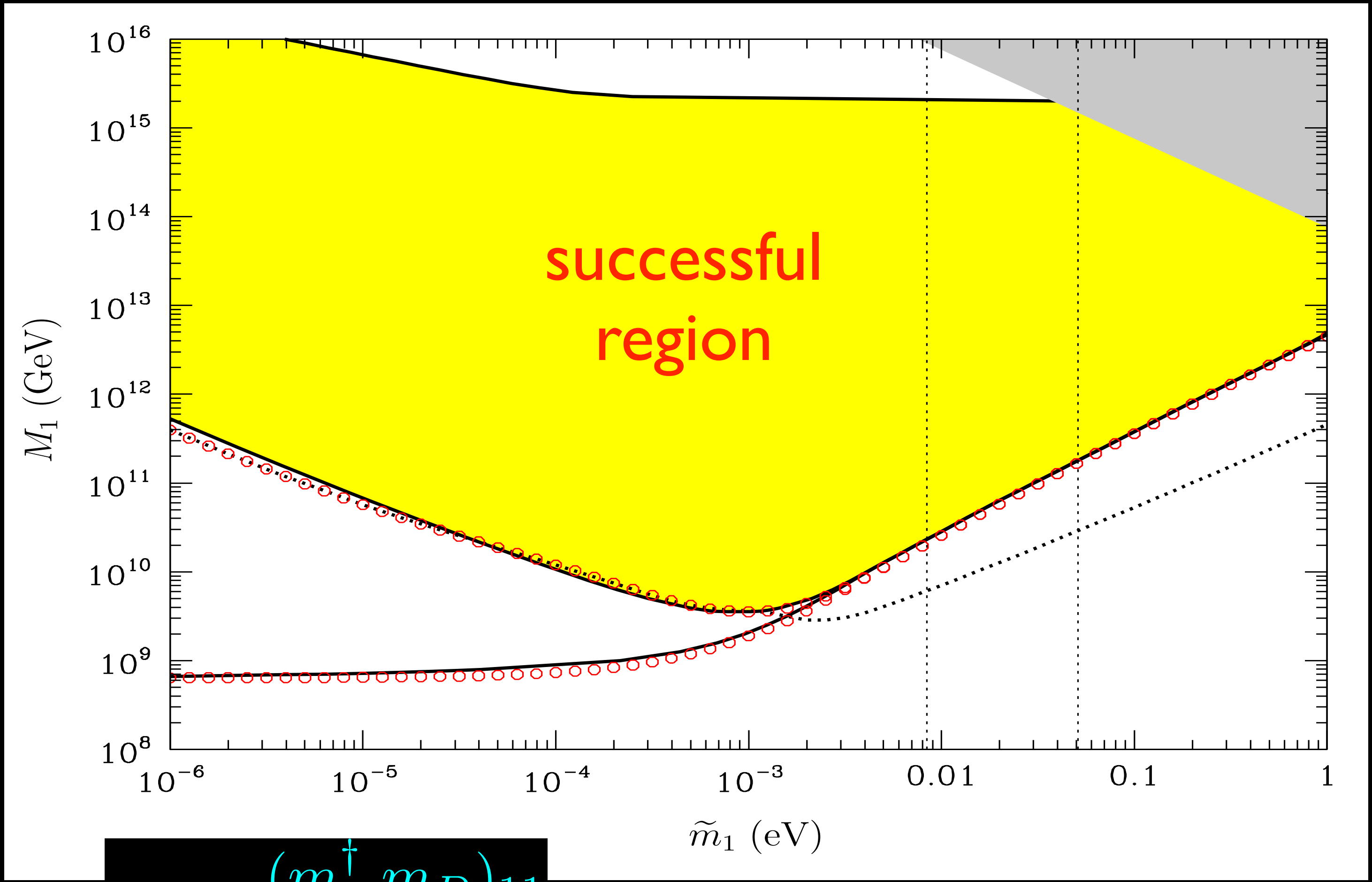
$$\propto \frac{1}{|h_{1i}|^2}\left(\left|h_{1i} + i\pi\frac{1}{16\pi^2}h_{1k}^* h_{lk} h_{li}\frac{M_1}{M_l}\right|^2 - \left|h_{1i}^* + i\pi\frac{1}{16\pi^2}h_{1k} h_{lk}^* h_{li}^*\frac{M_1^*}{M_l^*}\right|^2\right)$$

$$= \frac{1}{4\pi\,|h_{1i}|^2}\mathrm{Im}\left(h_{1i}h_{1k}h_{lk}^*h_{li}^*\frac{M_1}{M_l}\right)$$

- saved us from complete annihilation?


Disney presents a PIXAR film
THE IvCREDIBLES
NOW PLAYING
© Disney Enterprises, Inc./Pixar Animation Studios. All Rights Reserved.

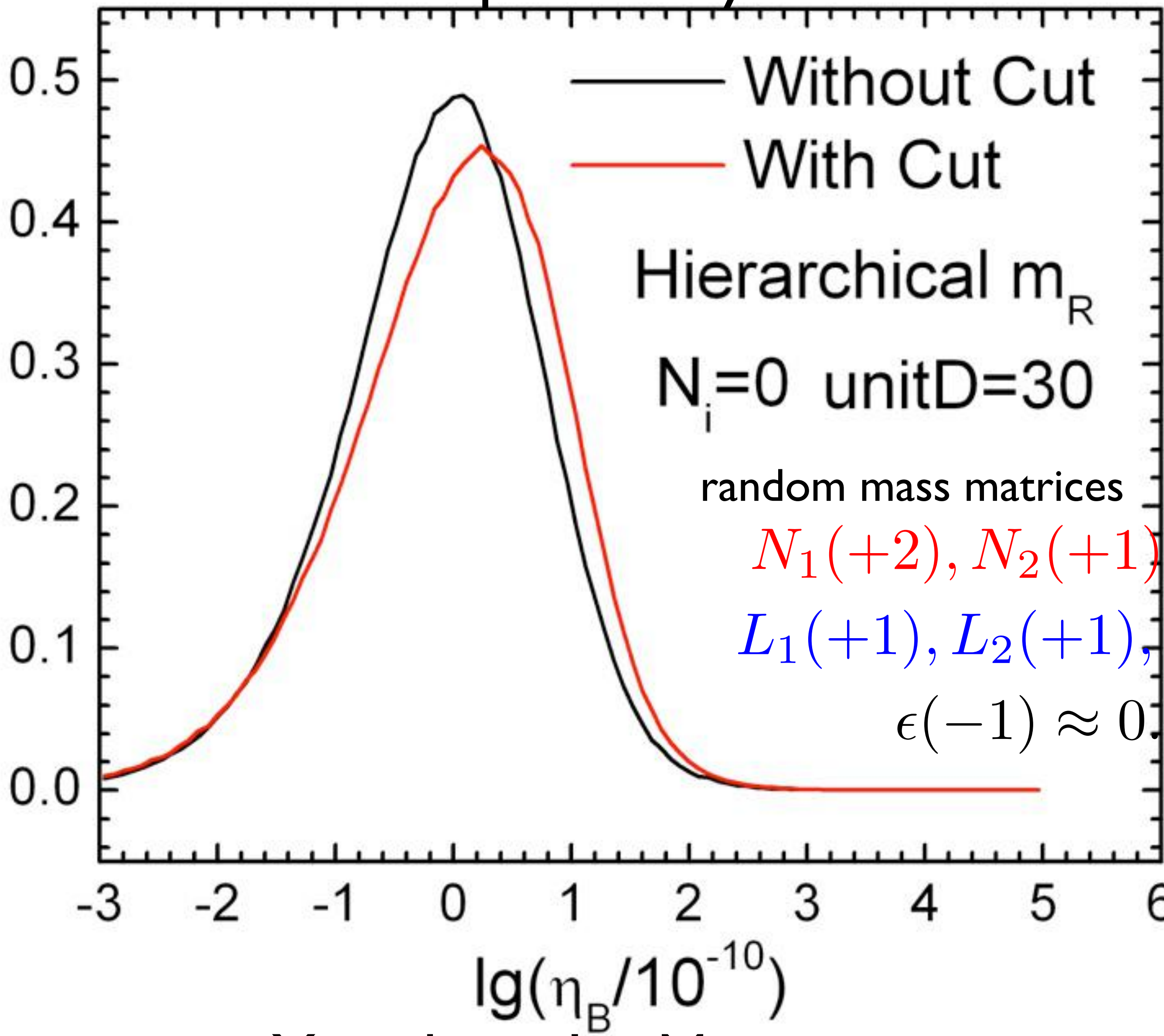
Leptogenesis



$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

di Bari, Plümacher, Buchmüller

no direct connection to CP violation in oscillation
but a plausibility test



random mass matrices

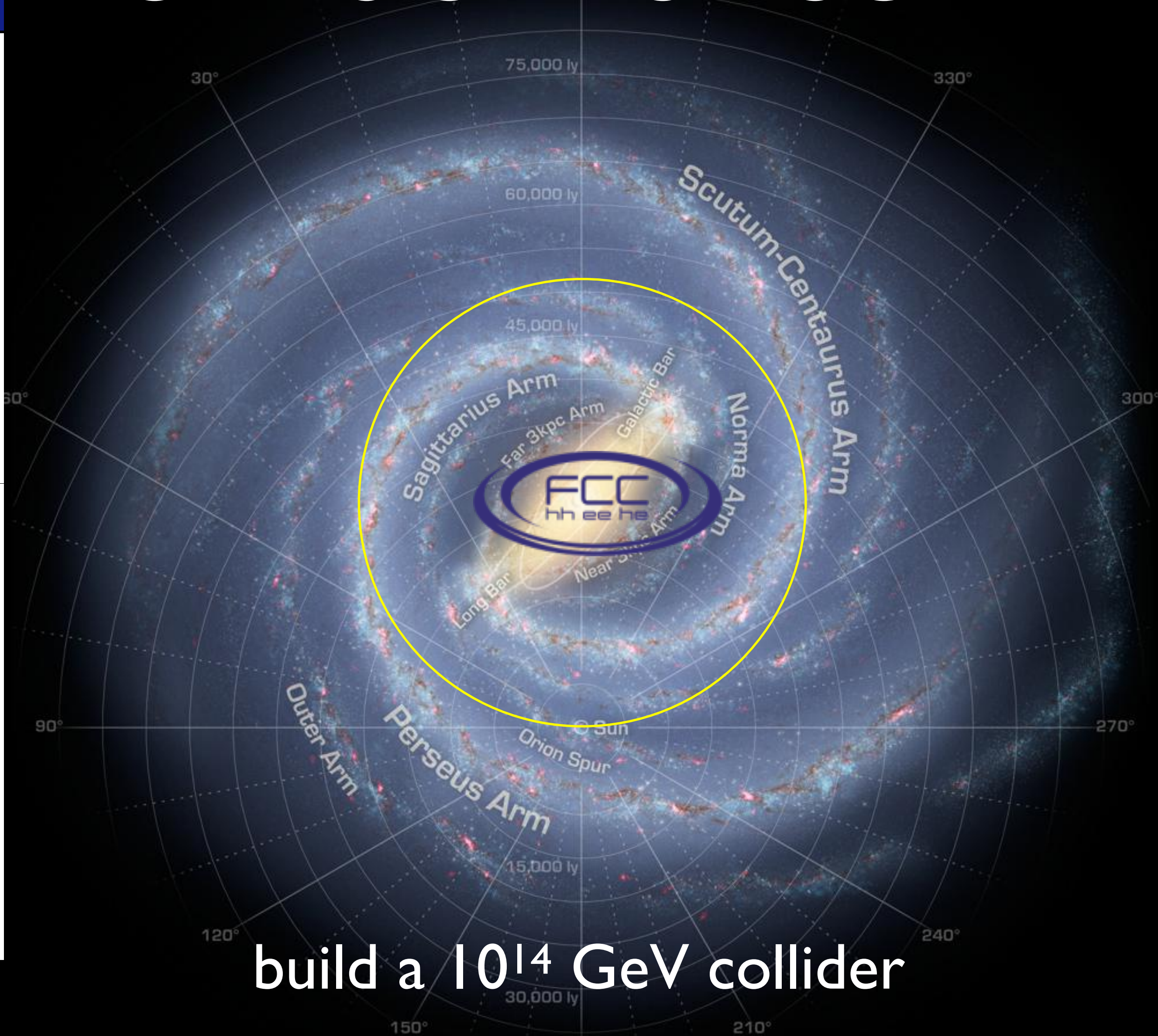
$N_1(+2), N_2(+1), N_3(0)$

$L_1(+1), L_2(+1), L_3(+1)$

$\epsilon(-1) \approx 0.1$

Xiaochuan Lu, Murayama

How do we test it?



build a 10^{14} GeV collider

JAXA
Japan Aerospace Exploration Agency

文部科学省
MEXT
MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

NASA

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

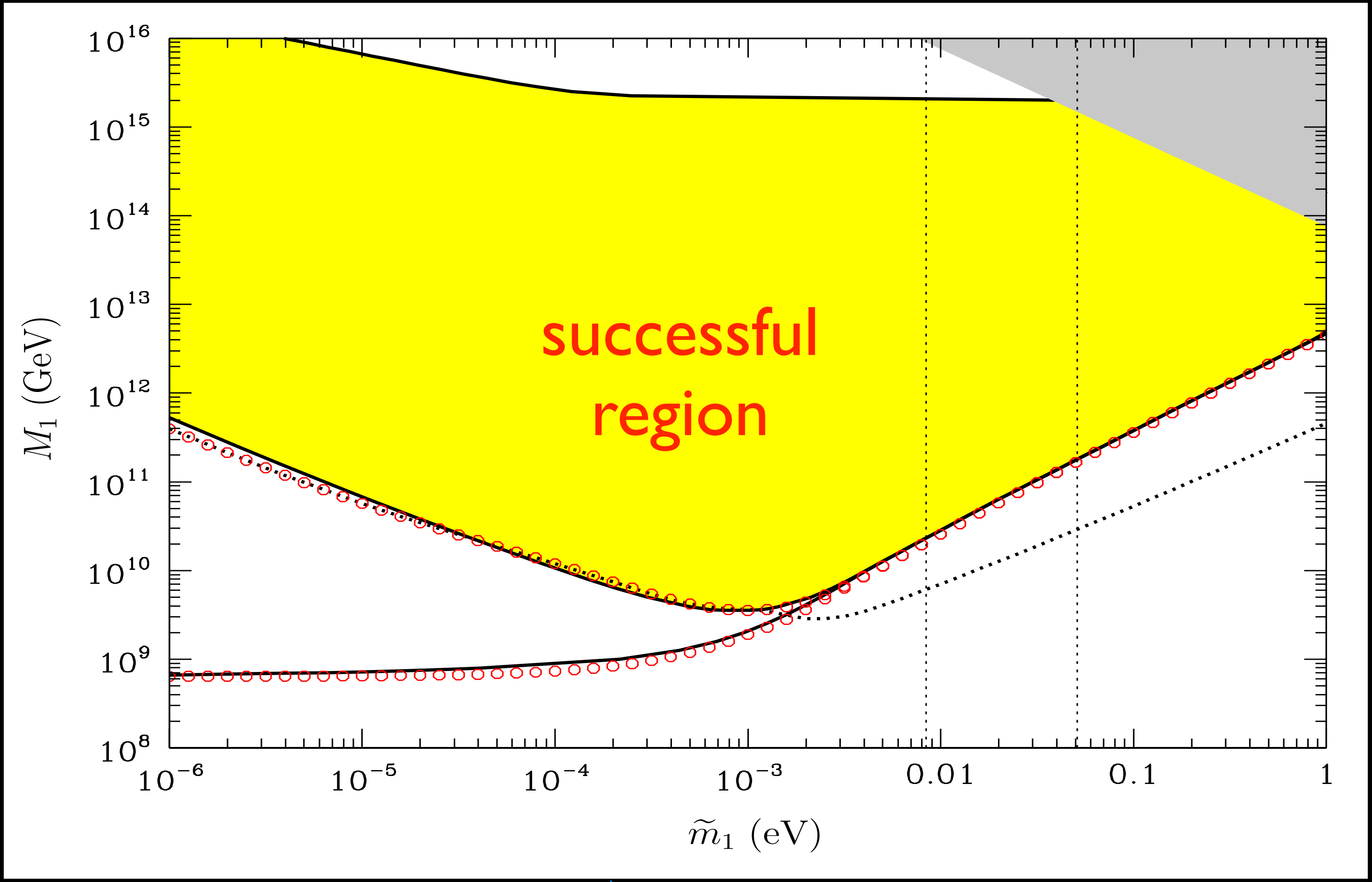
NSF

how do we test it?

- possible three circumstantial evidences
  - $0\nu\beta\beta$
  - CP violation in neutrino oscillation
  - other impacts *e.g.* LFV (requires new particles/ interactions < 100 TeV)
- *archeology*
- any more circumstantial evidences?

M_{Pl}

Natural to think M is induced from symmetry breaking
e.g. $\mathcal{L}=-y\langle\varphi\rangle N\,N$



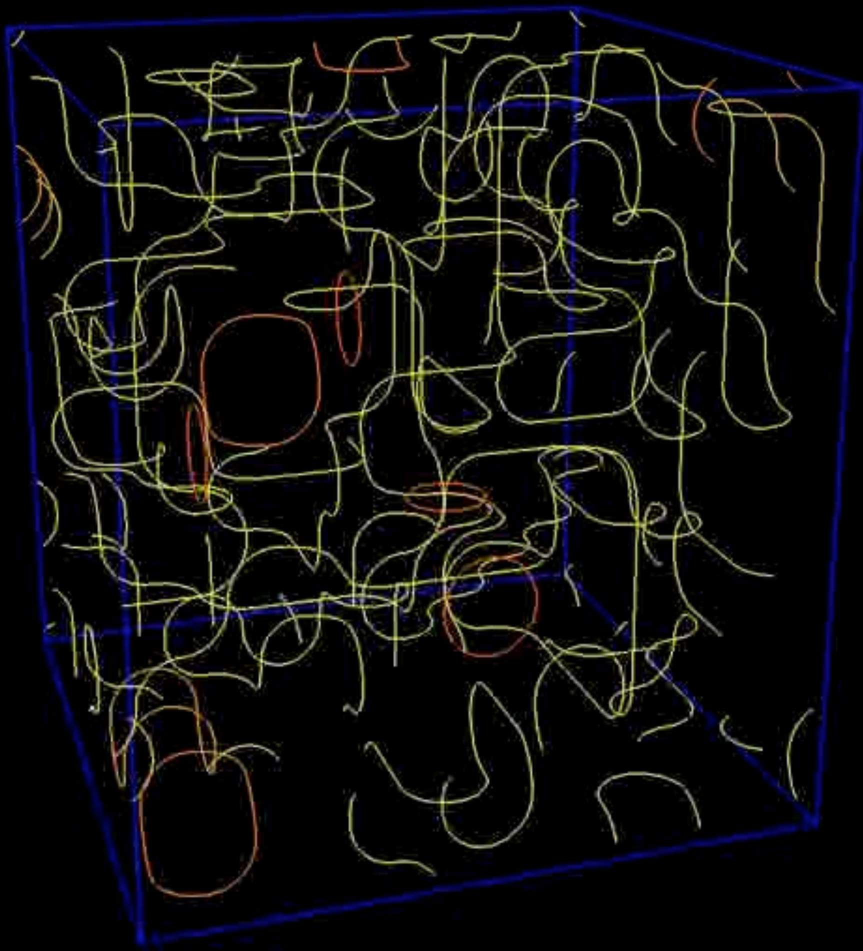
Phase Transition → **Gravitational Waves?**

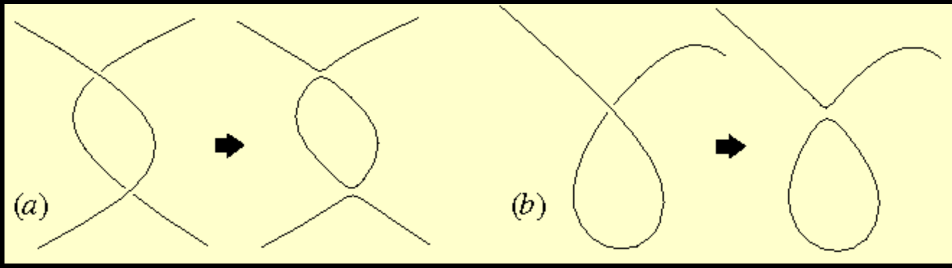
$U(1)_{B-L}$

- Consider $<\phi>\neq 0$
  - M_R from $<\phi>\nu_R\nu_R$ or $<\phi^2>\nu_R\nu_R/M_{Pl}$
- U(1) breaking produces cosmic strings because $\pi_1(U(1))=Z$
- nearly scale invariant spectrum
- simplification of the network produces gravitational waves
- stochastic gravitational wave background

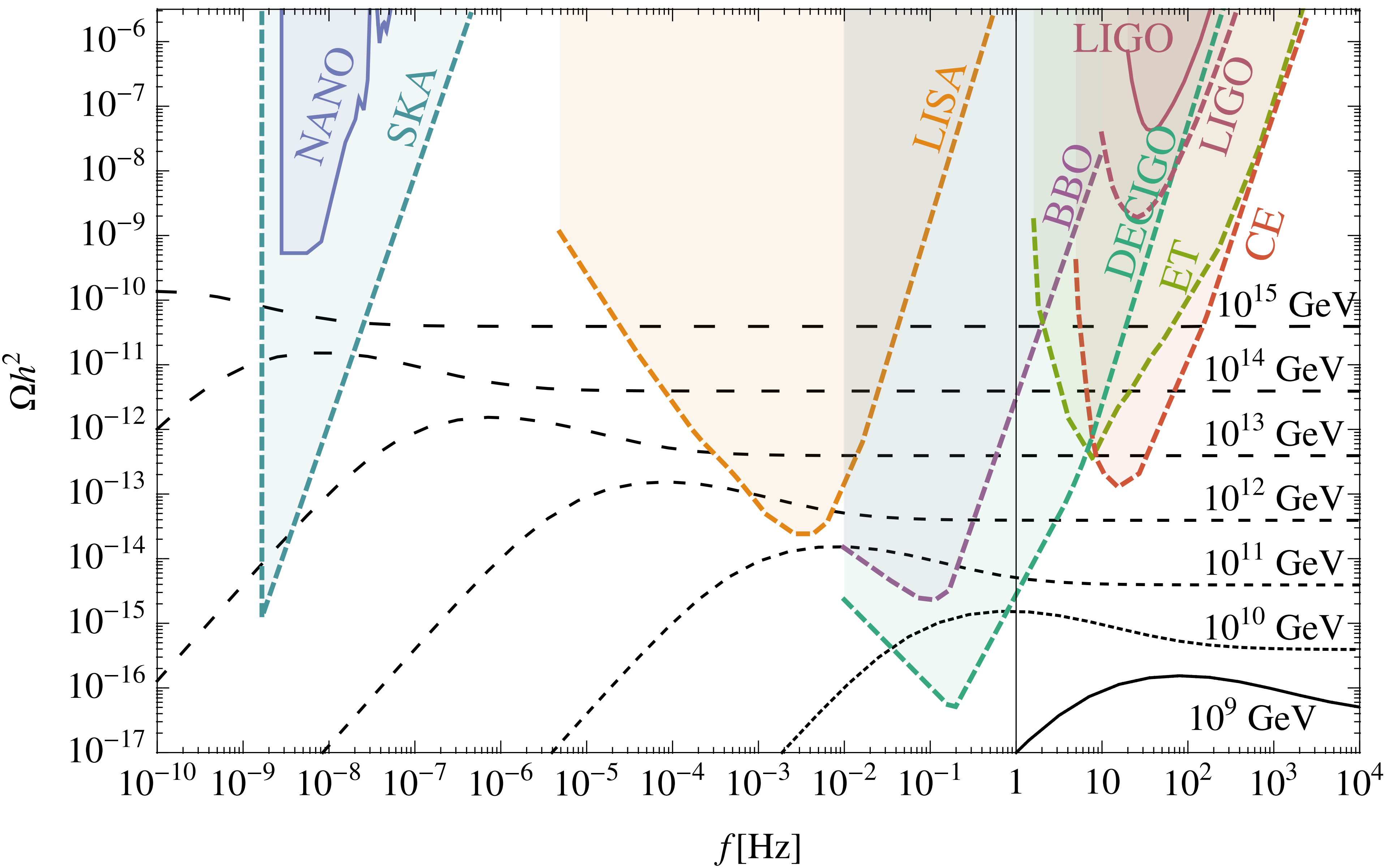
https://www.ligo.org/science/Publication-S5S6CosmicStrings/index.php

cosmic strings





$G_N \mu \sim v^2/M_{Pl}^2$



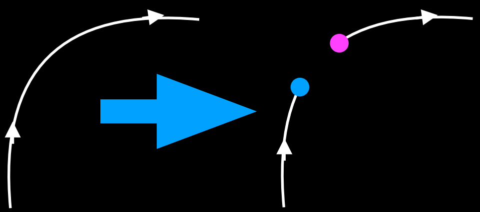
J. Dror, T. Hiramatsu, K. Kohri, HM, G. White, arXiv:1908.03227

covers pretty much the entire range for leptogenesis!

caveat: particle emission from cosmic strings

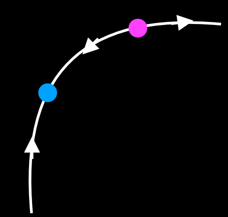
SO(10)

- It is natural to embed $U(1)_{B-L}$ etc into SO(10)
- However, SO(10)→SU(3)×SU(2)×U(1) doesn't lead to cosmic strings because $\pi_1(SO(10)/SU(3)\times SU(2)\times U(1))=0$
- SO(10)→SU(3)×SU(2)×U(1)×$U(1)_{B-L}$ produces monopoles
  - SO(10) scale is presumably $V\sim 10^{16}$GeV $\gg v$
  - need inflation below this scale
- SU(3)×SU(2)×U(1)×$U(1)_{B-L}$→SU(3)×SU(2)×U(1) produces strings
  - strings can be *cut* by monopole-anti-monopole pairs through a tunneling process



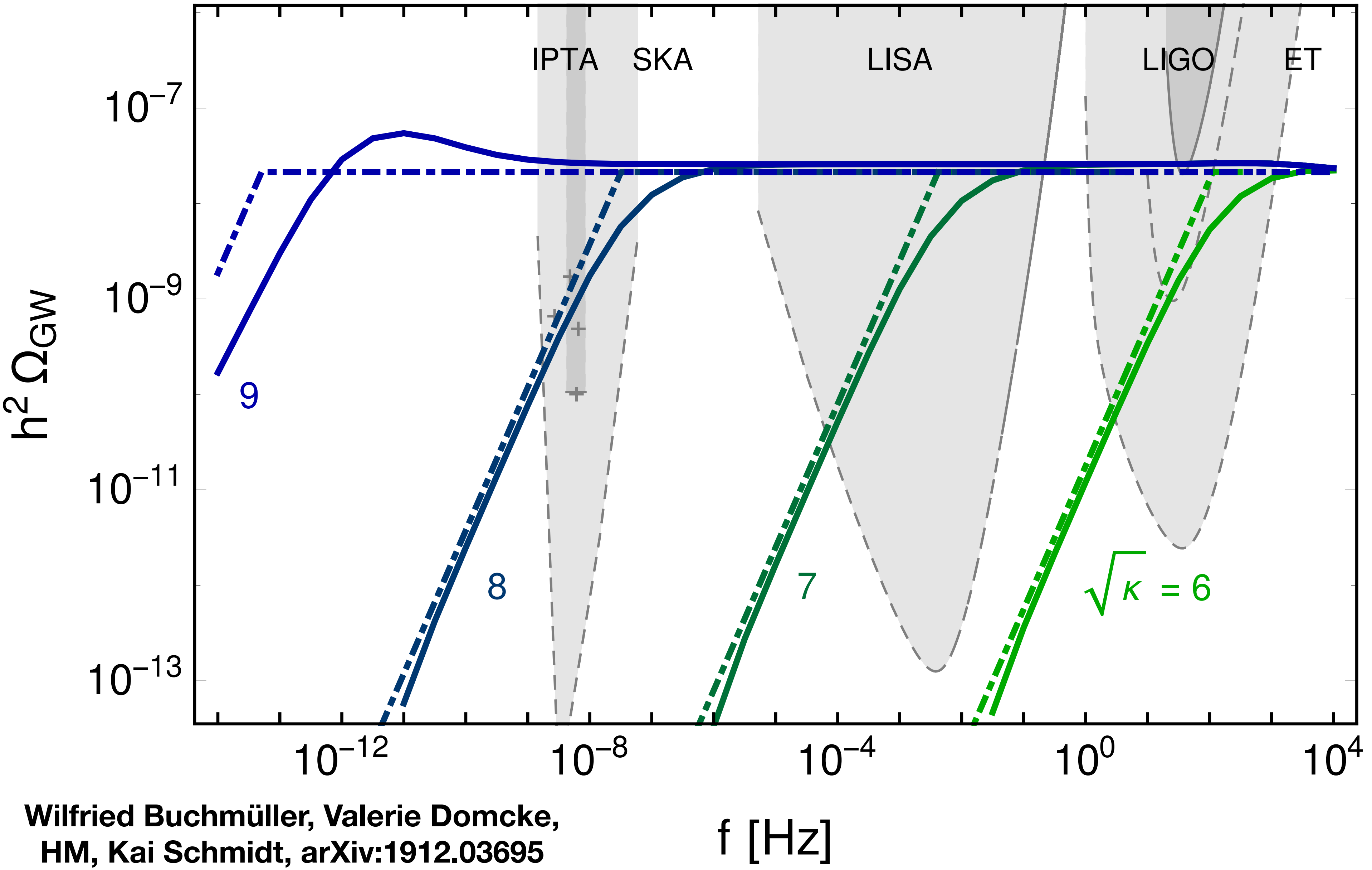
monopoles

- string from $U(1)_{B-L}$ breaking is basically Abrikosov flux in a superconductor
  - For the Higgs $\phi(\pm Q)$
  - magnetic flux $h/(g\ Q) \times$ integer (Q=1, 2, …)
  - minimum monopole charge h/g
  - If Q=1, monopole can saturate the flux and cut the string



  - If Q=2, the minimum string cannot be cut by monopoles

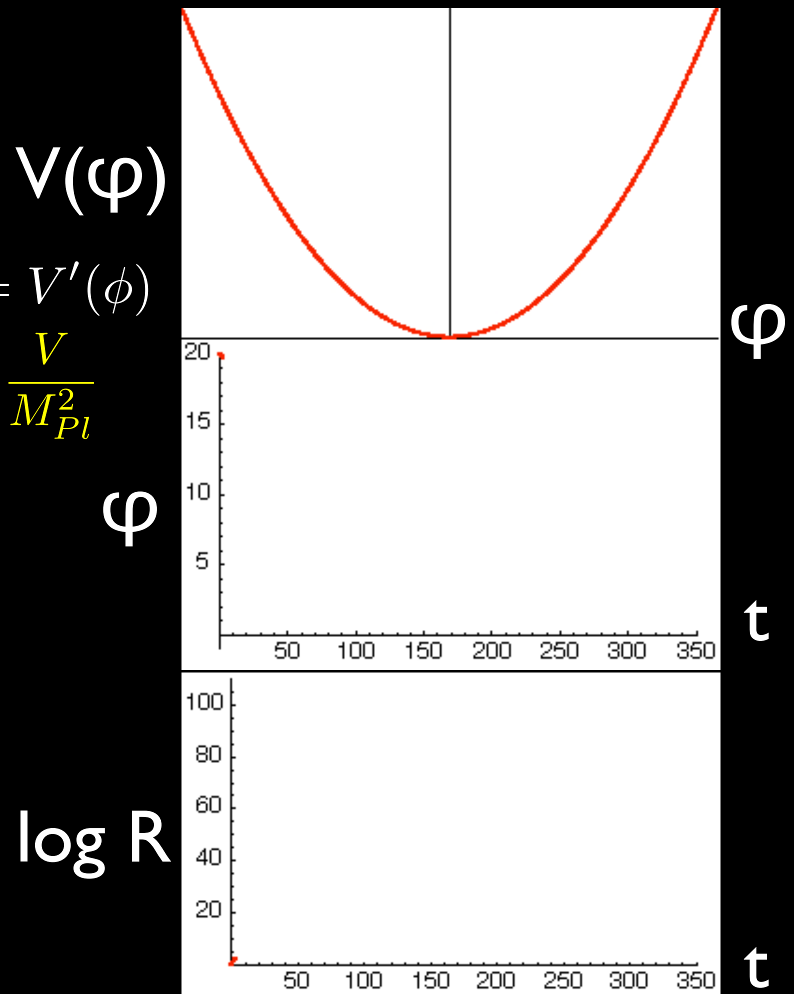
hybrid inflation



Wilfried Buchmüller, Valerie Domcke, HM, Kai Schmidt, arXiv:1912.03695

SNeutrino Inflaton

- Superpartner of a heavy neutrino
- displaced from the minimum at the beginning $\ddot{\phi} + 3H\dot{\phi} = V'(\phi)$
- rolls down slowly: inflation $|\ddot{\phi}| \ll |\dot{\phi}| = V'(\phi)$
- quantum fluctuation source of later structure $H^2 = \frac{8\pi}{3}\frac{V}{M_{Pl}^2}$
- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter



HM, Suzuki, Yanagida, Yokoyama

Outline

- Introduction
- Neutrinos in the Standard Model
- Evidence for Neutrino Mass
- Implications of Neutrino Mass
- Solar Neutrinos
- Matter Effect in Solar Neutrinos
- Masses and Mixings
- Leptogenesis
- Conclusions


Disney PRESENTS A PIXAR FILM
THE IvCREDIBLES
NOW PLAYING
© Disney Enterprises, Inc./Pixar Animation Studios. All Rights Reserved.