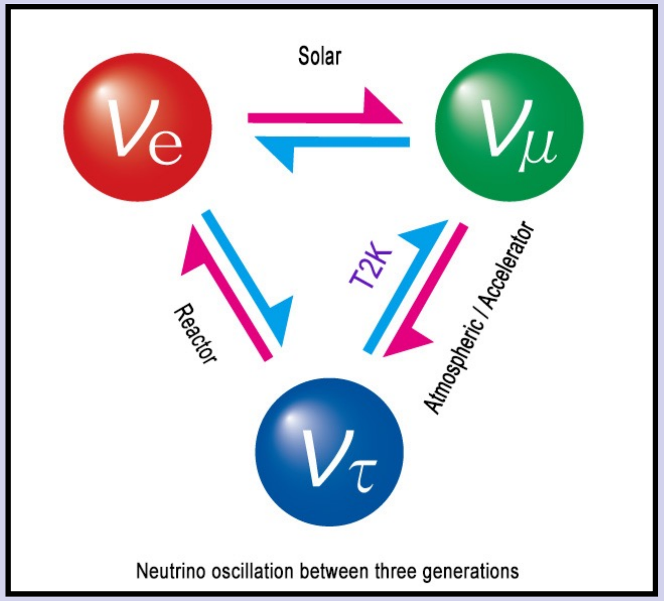
from

Neutrino

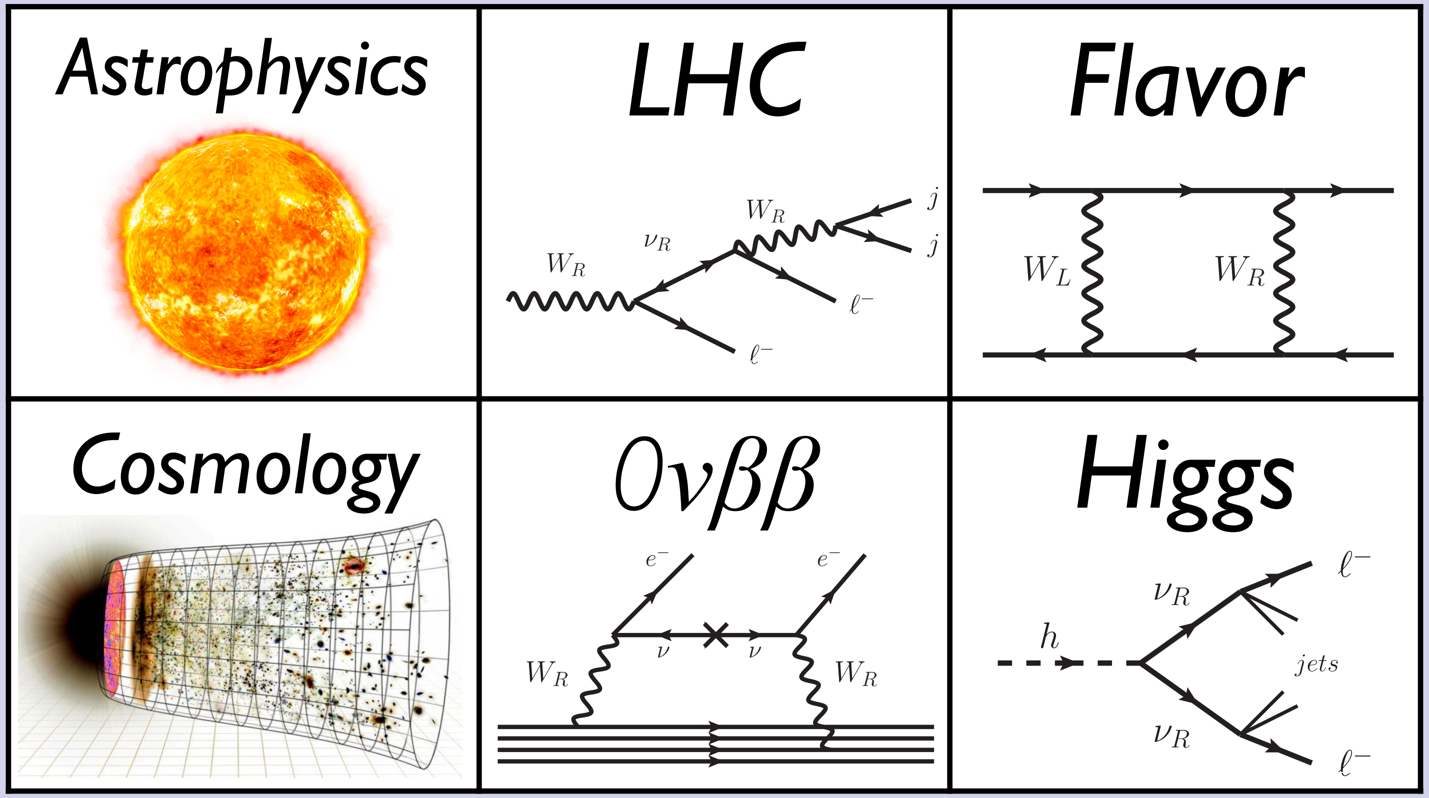
towards new physics

Fabrizio Nesti
L'Aquila University

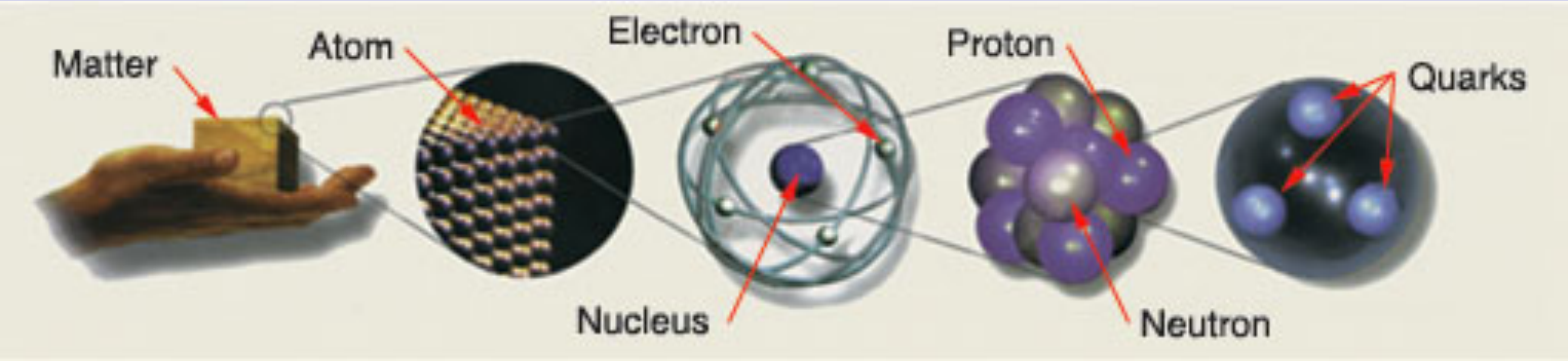
for
Nova Gorica
02/2021



Neutrino oscillation between three generations



Neutrinos, fundamental particles, are invisible



Optical microscope

Cosmology...

Eyes

Electron microscope

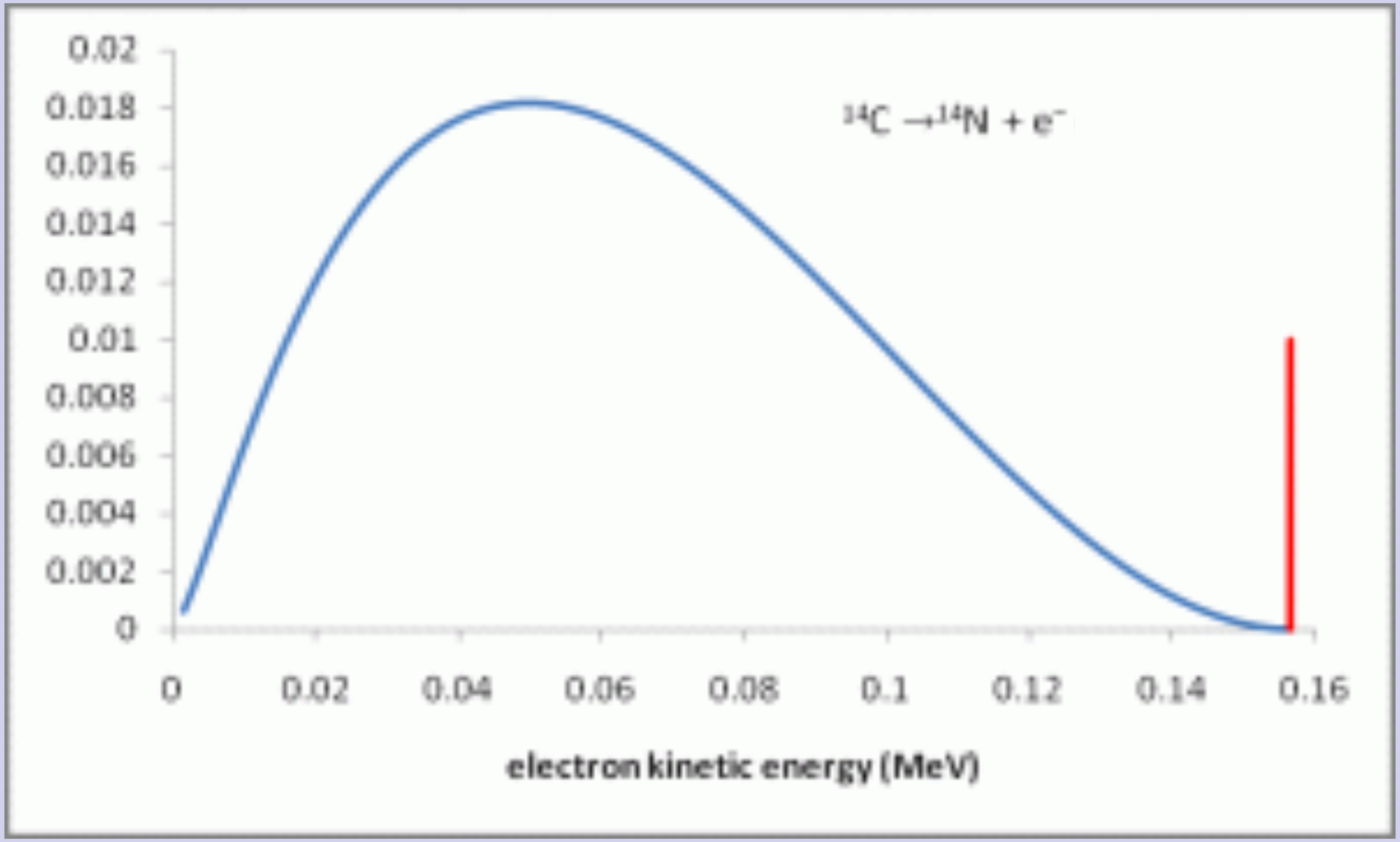
Accelerators....

They don't constitute matter,
but they play an important role in nuclear reactions.

Like radioactivity...

So, the beginning: A Puzzle

1914 James Chadwick measures an unexpected continuous spectrum of beta rays



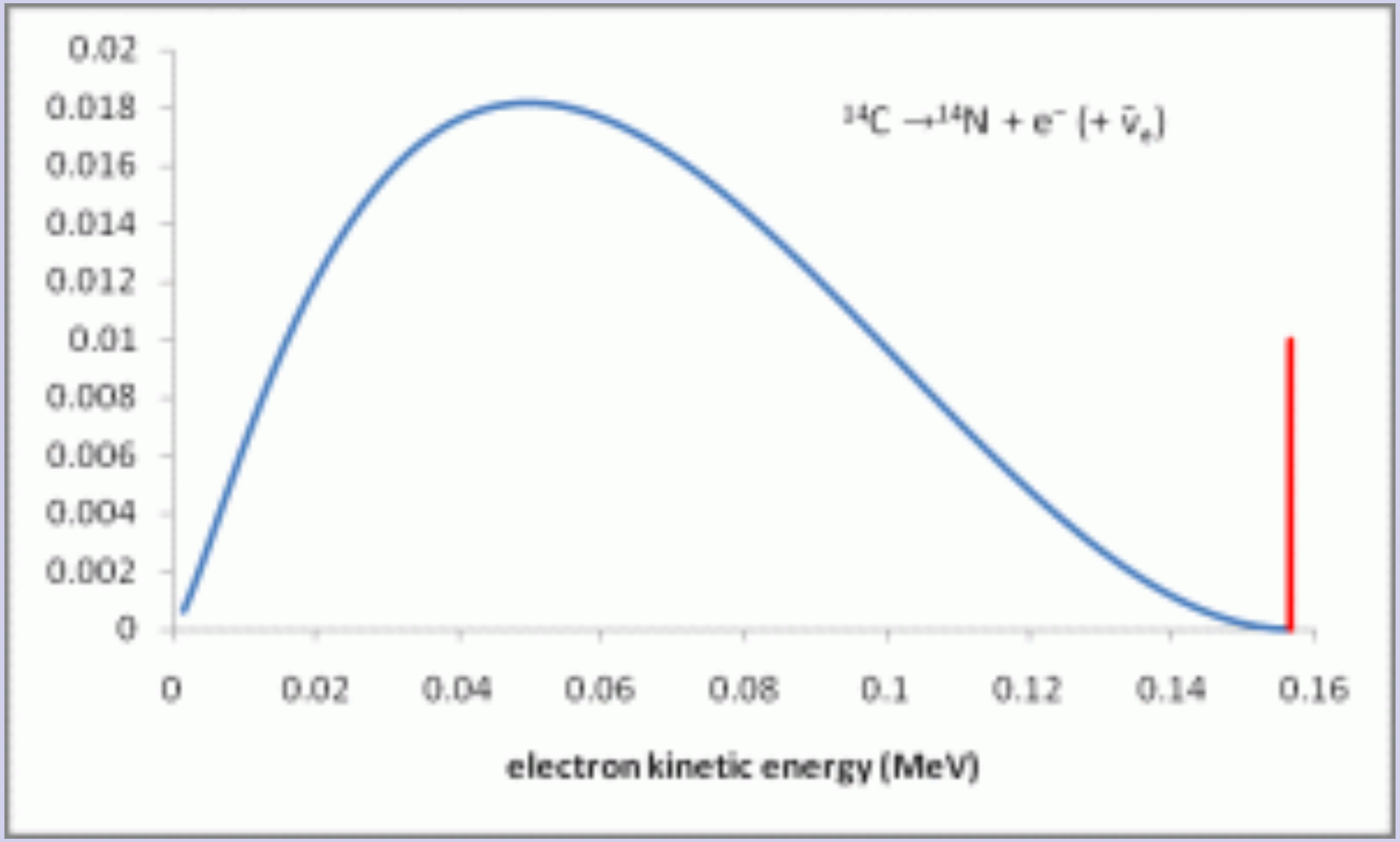
[Chadwick, Verh.Phys.Gesell. 1914]

10 years of controversy. Experiments confirm in mid '20s...

...energy not conserved???

So, the beginning: A Puzzle

1914 James Chadwick measures an unexpected continuous spectrum of beta rays



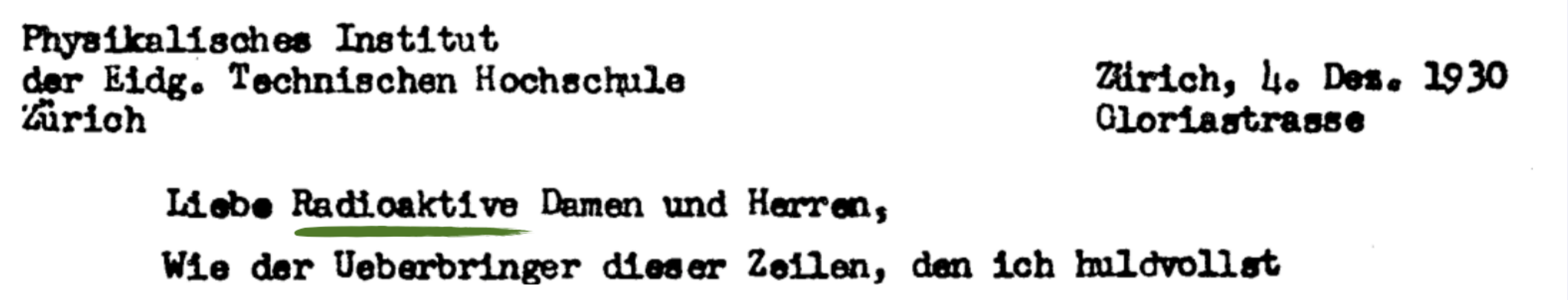
[Chadwick, Verh.Phys.Gesell. 1914]

10 years of controversy. Experiments confirm in mid ‘20s…

…energy not conserved???

The Beginning: Hypothesis

1930 Pauli introduces the missing particle, calls it “neutron”



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst

(…aber nur wer wagt, gewinnt…)

1930-34 Chadwick discovers the real neutron (Nobel 1935)

1932-33 Fermi theory. He coins the new name: Neutrino

(1933-37 Majorana… see later)

How to see neutrinos

They interact with matter Weakly - veeeery weakly:

- Inverse beta decay

  $\nu_e + n \longrightarrow p + e^-$ or $\bar{\nu}_e + p \longrightarrow n + e^+$

- In water, it would take 10^{21}cm

  ~ *1600 light years* to interact

- ...Pauli to his friend Walter Baade:

> *Today I have done something which no theoretical physicist should ever do in his life:*
> *I have predicted something which shall never be detected experimentally!*
>
> Baade, astronomer, apparently had great respect for experimentalists
> and so he bet Pauli that it will one day be detected.

Where do they come from

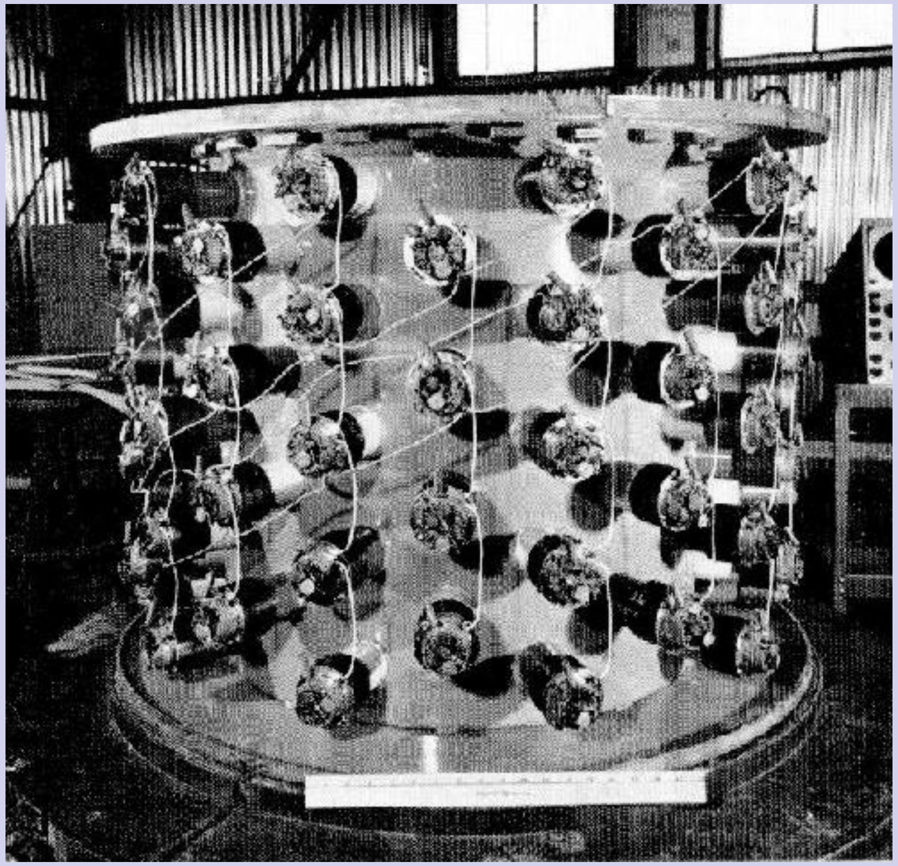
- Big Bang (very low energy, speed ~ 300km/s)
- Stars and Supernovae (a lot but they are far)
- Sun (produces 10^{37} per second....
  here "only" 1–10 billion per cm^2 per second)
- Nuclear plants (> 10^{23} per second !)
- Natural radioactivity, including our body
  (~5000 per second from Potassium)

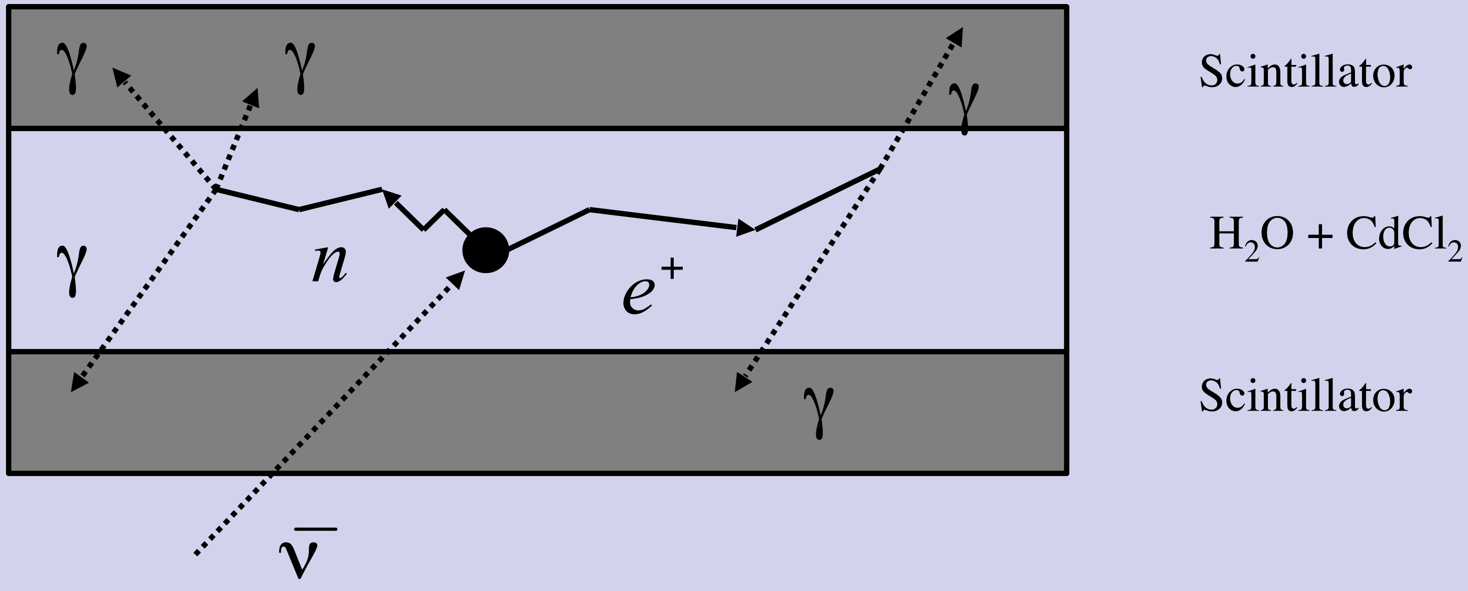
The beginning: Discovery

1956 Reines+Cowan confirm antineutrinos from reactor

(Reines nobel 1995)

Poltergeist experiment: 400 l of a mixture of water and cadmium chloride (Cd)
neutrinos (6 x10^{20} per second) very rarely interacted with the protons in the target (2.8 hr $^{-1}$)





Pauli paid his bet to Baade (a case of Champagne)!

From today
Grand Unified Neutrino Spectrum

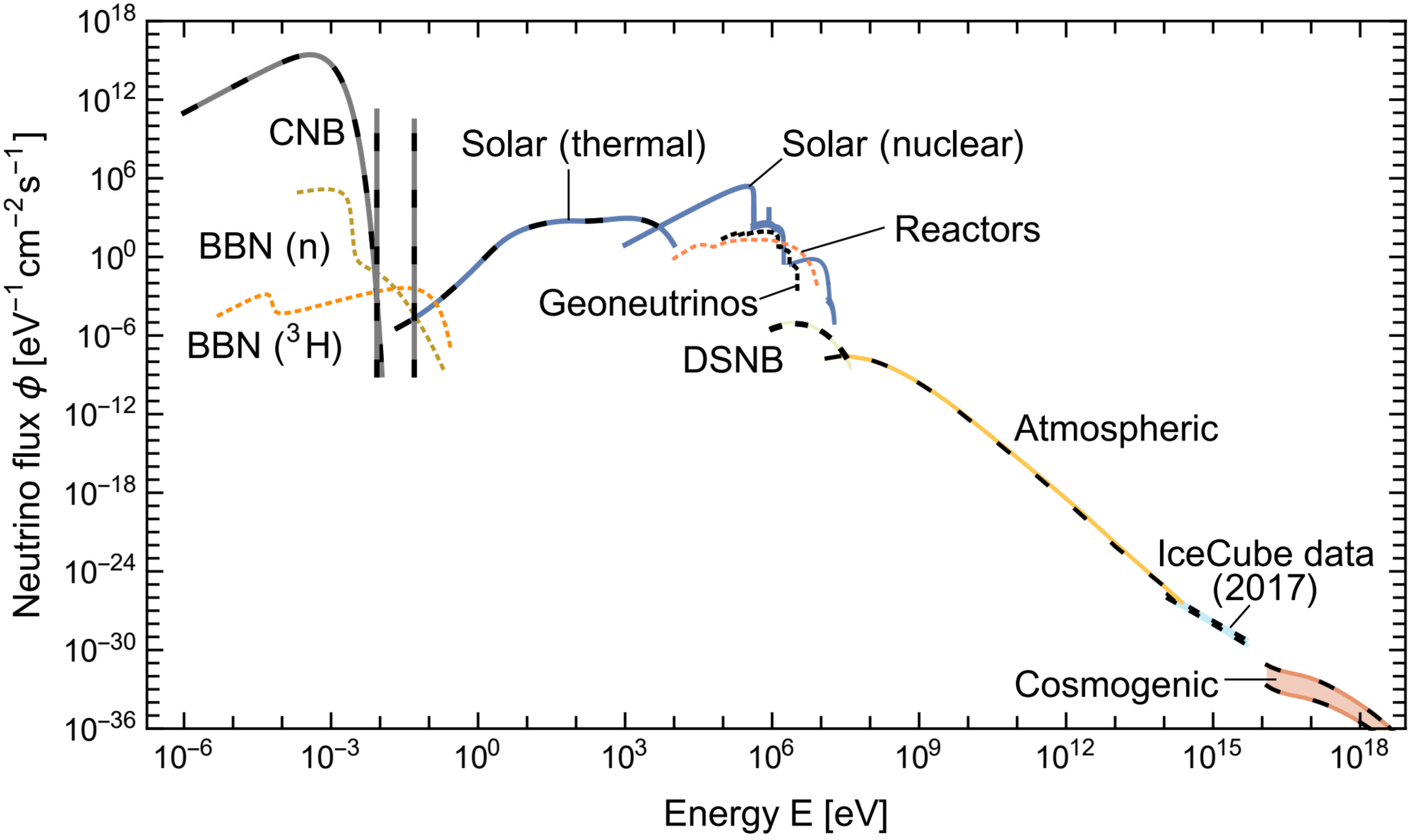


FIG. 1 Grand Unified Neutrino Spectrum (GUNS) at Earth, integrated over directions and summed over flavors. Therefore, flavor conversion between source and detector does not affect this plot. Solid lines are for neutrinos, dashed or dotted lines for antineutrinos, superimposed dashed and solid lines for sources of both ν and $\overline{\nu}$. The fluxes from BBN, the Earth, and reactors encompass only antineutrinos, the Sun emits only neutrinos, whereas all other components include both. The CNB is shown for a minimal mass spectrum of $m_1 = 0$, $m_2 = 8.6$, and $m_3 = 50$ meV, producing a blackbody spectrum plus two monochromatic lines of nonrelativistic neutrinos with energies corresponding to m_2 and m_3. See Appendix D for an exact description of the individual curves. *Top panel:* Neutrino flux ϕ as a function of energy; line sources in units of cm^{-2} s^{-1}. *Bottom panel:* Neutrino energy flux $E \times \phi$ as a function of energy; line sources in units of eV cm^{-2} s^{-1}.

Neutrino cross section

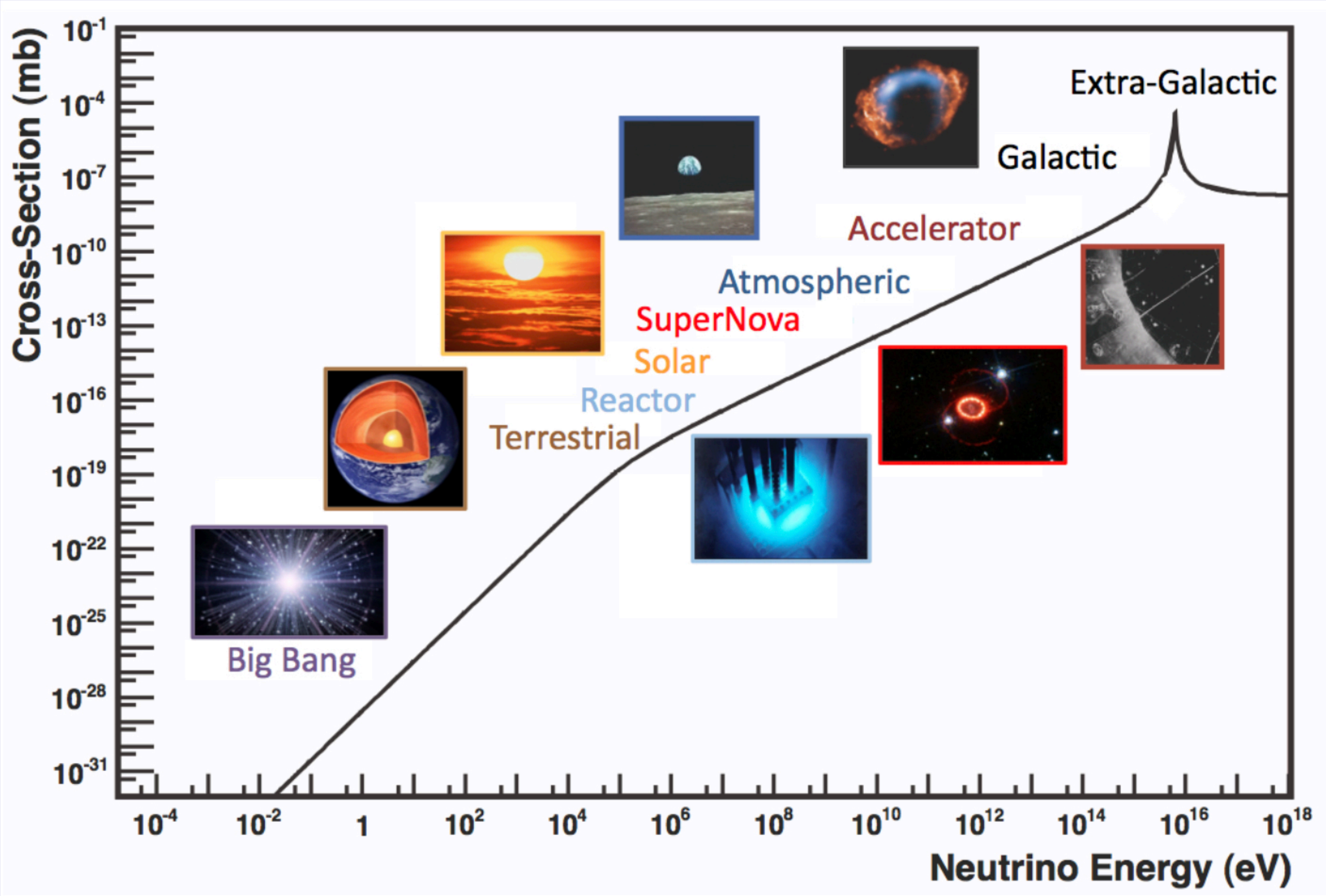
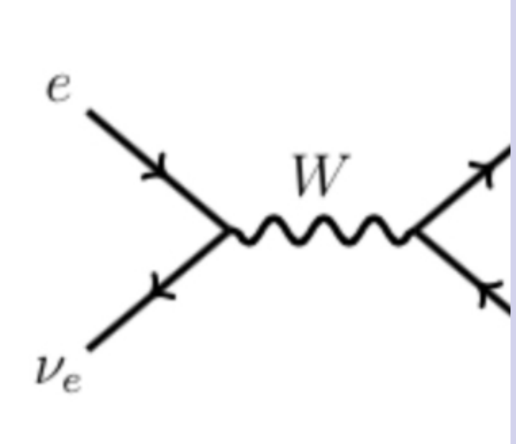


FIG. 1 Representative example of various neutrino sources across decades of energy. The electroweak cross-section for $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$ scattering on free electrons as a function of neutrino energy (for a massless neutrino) is shown for comparison. The peak at 10^{16} eV is due to the W^- resonance, which we will discuss in greater detail in Section VII.

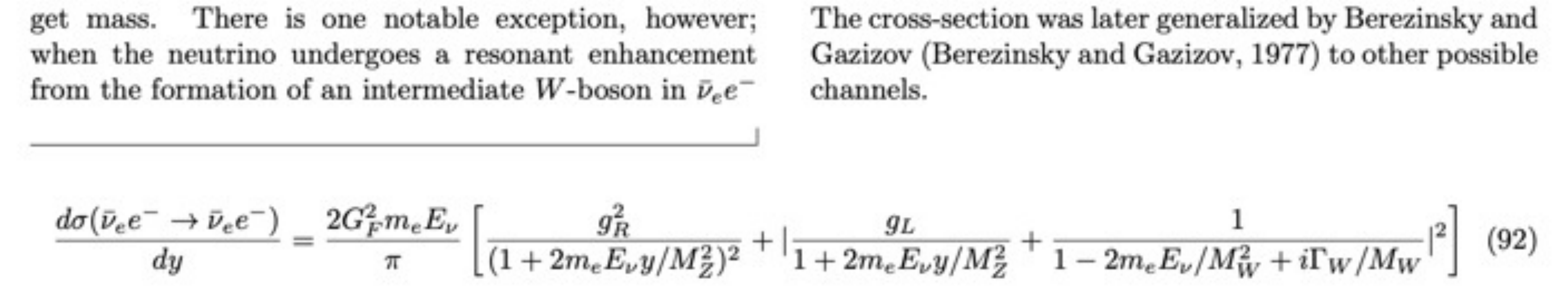
From eV to EeV: Neutrino Cross-Sections Across Energy Scales
A. Formaggio, G. P. Zeller [1305.7513]

The resonant W



$$s = Q^2 = (p_e^\mu + p_{\nu_e}^\mu)^2$$
$$= m_e^2 + m_\nu^2 + 2p_e \cdot p_\nu \simeq 2E_\nu m_e$$

Peak at $E \sim M_W{}^2/2m_e$ ~ $80^2\,10^3$ GeV ~ 6.4 10^{15} eV

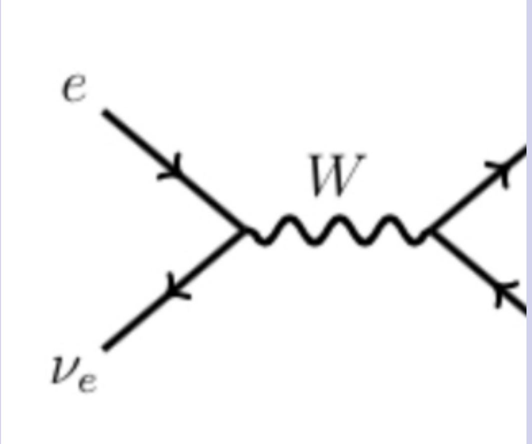


get mass. There is one notable exception, however; when the neutrino undergoes a resonant enhancement from the formation of an intermediate W-boson in $\bar{\nu}_e e^-$

The cross-section was later generalized by Berezinsky and Gazizov (Berezinsky and Gazizov, 1977) to other possible channels.

$$\frac{d\sigma(\bar{\nu}_e e^- \to \bar{\nu}_e e^-)}{dy} = \frac{2G_F^2 m_e E_\nu}{\pi}\left[\frac{g_R^2}{(1+2m_e E_\nu y/M_Z^2)^2} + \left|\frac{g_L}{1+2m_e E_\nu y/M_Z^2} + \frac{1}{1-2m_e E_\nu/M_W^2 + i\Gamma_W/M_W}\right|^2\right] \quad (92)$$

The resonant W



$$s = Q^2 = (p^\mu_e + p^\mu_{\nu_e})^2$$
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Peak at $E \sim M_{\!/}$ … 10^{15} eV

get mass. There is one not … neralized by Berezinsky and
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from the formation of an inter

$$\frac{d\sigma(\bar{\nu}_e e^- \to \bar{\nu}_e e^-)}{dy} = \frac{2G_F^2 m_e}{\pi} \quad \cdots \quad \frac{1}{/M_W^2 + i\Gamma_W/M_W}|^2\Big] \quad (92)$$

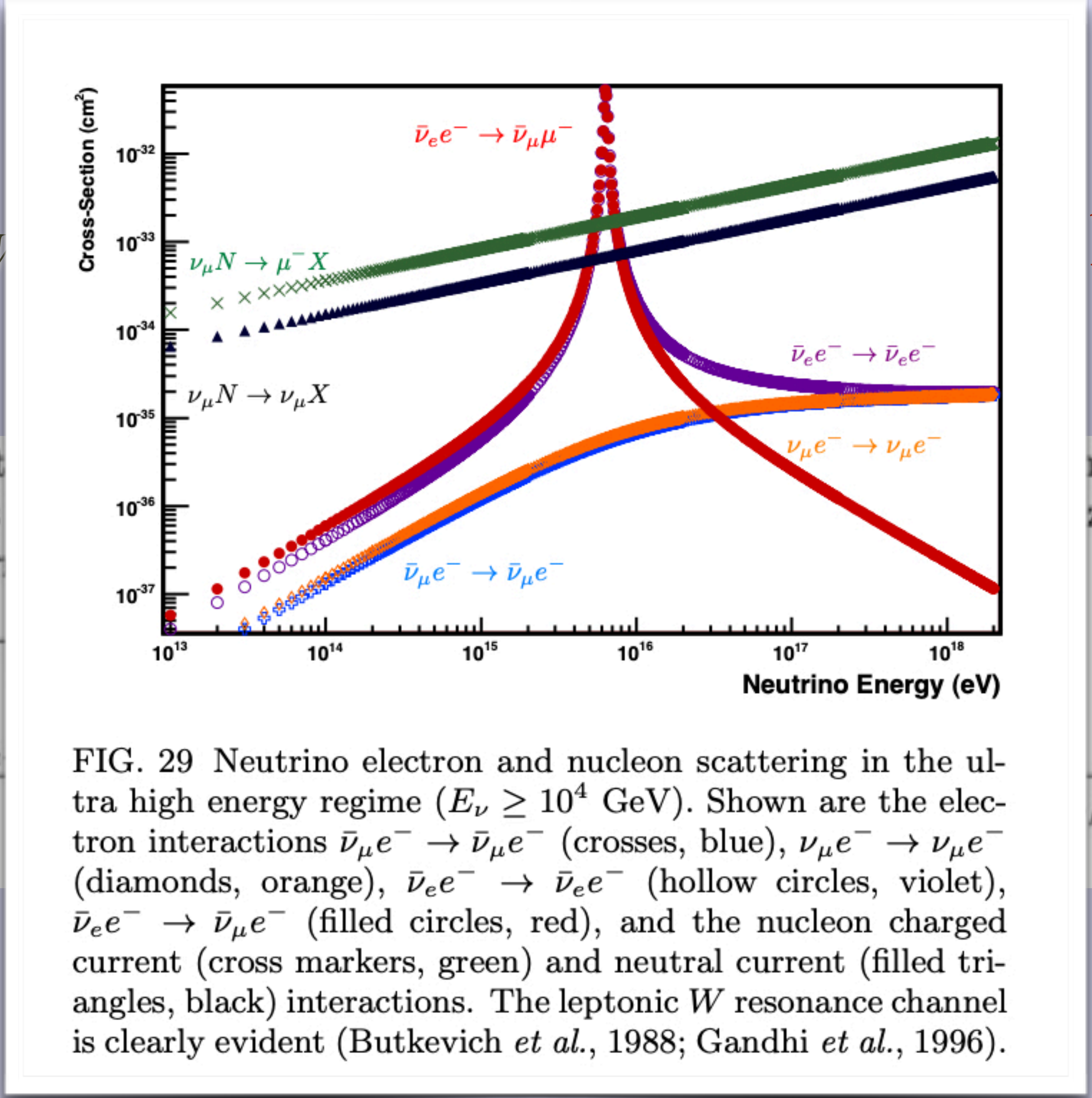
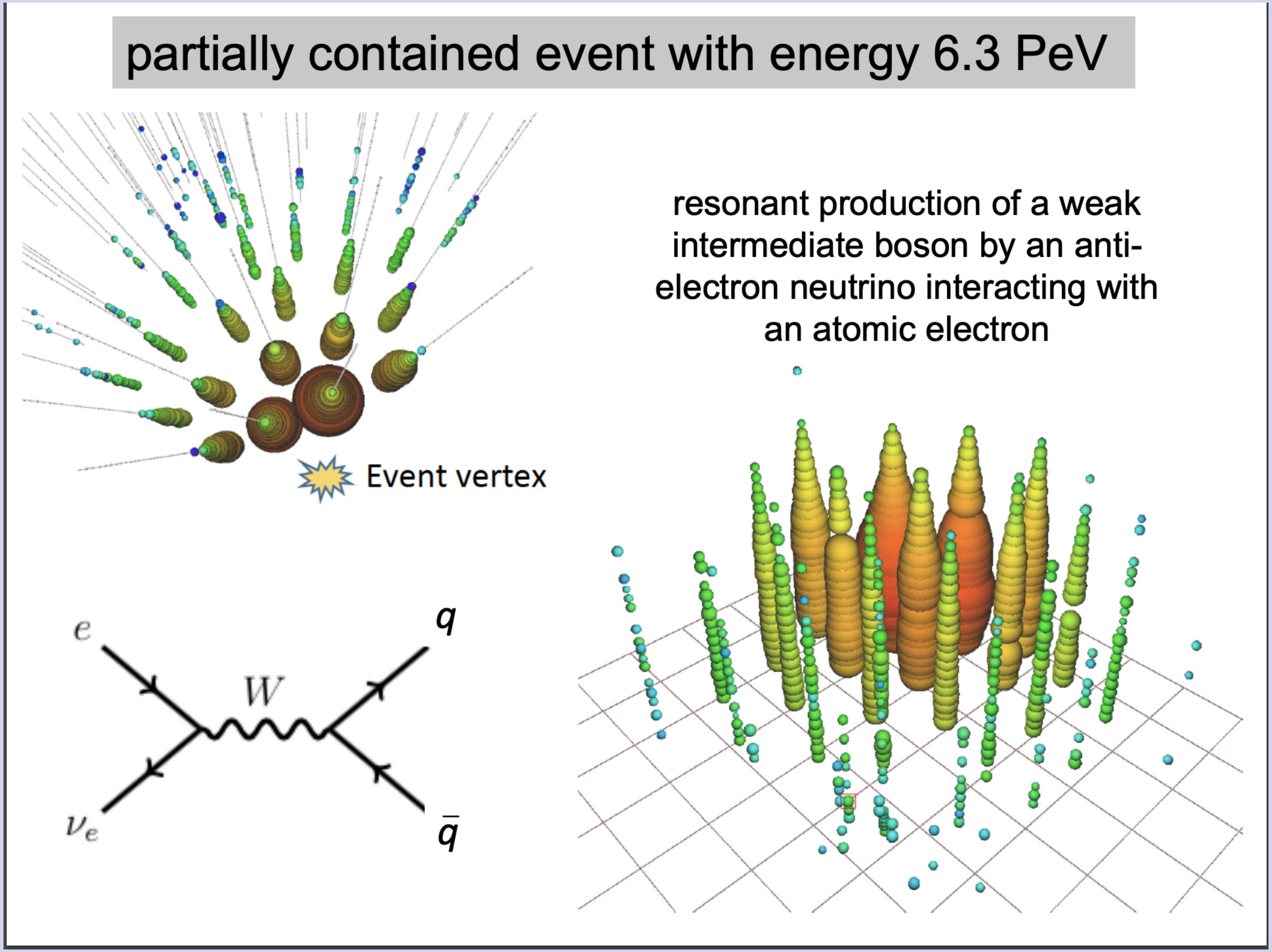


FIG. 29 Neutrino electron and nucleon scattering in the ultra high energy regime ($E_\nu \geq 10^4$ GeV). Shown are the electron interactions $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$ (crosses, blue), $\nu_\mu e^- \to \nu_\mu e^-$ (diamonds, orange), $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$ (hollow circles, violet), $\bar{\nu}_e e^- \to \bar{\nu}_\mu e^-$ (filled circles, red), and the nucleon charged current (cross markers, green) and neutral current (filled triangles, black) interactions. The leptonic W resonance channel is clearly evident (Butkevich *et al.*, 1988; Gandhi *et al.*, 1996).

IceCube finds W !



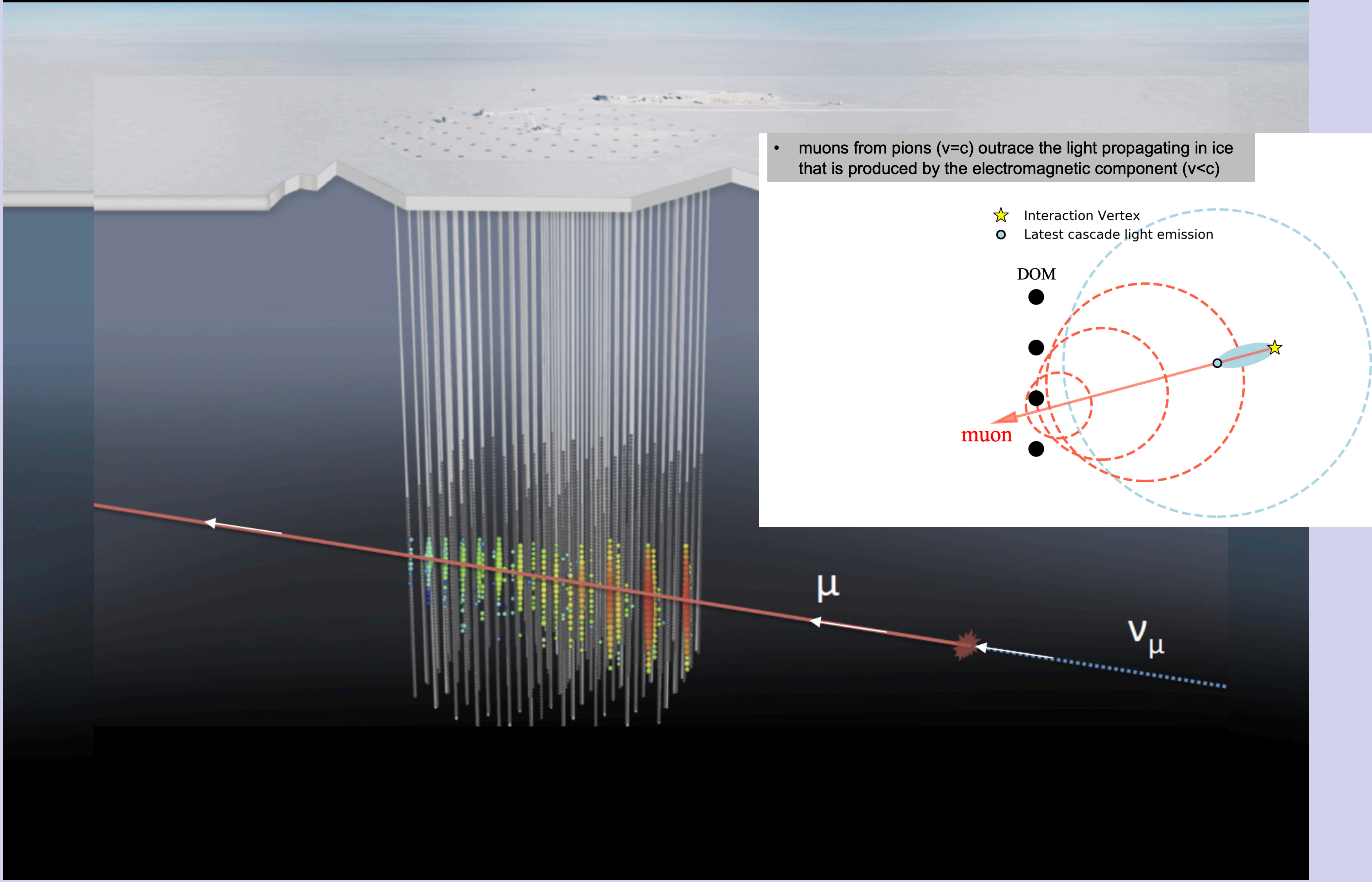
partially contained event with energy 6.3 PeV

resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

[Halzen 2021]

instrument 1 cubic kilometer of natural ice below 1.45 km

- muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)



Their mass and Oscillations

- It was theoretically clear that there had to be more (discovered ν_μ and ν_τ in 1962 and 2000)
- 1957 - Pontecorvo predicts neutrino oscillations ...
- ...if they have mass.
- 1962 - Maki, Nakagawa, Sakata;
  1969 - Gribov, Pontecorvo
  full theory.

What are oscillations...

Neutrino Oscillations

Quantum Mechanics

- Nuclear reactions create superposition of states

$$|\nu_e >= U_{e1}|\nu_1 > +U_{e2}|\nu_2 > +U_{e3}|\nu_3 >$$

evolve with different energies: interference

- Probability of transformation into ν_μ

Distance

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\ \sin^2\left[\frac{(m_1^2 - m_2^2)L}{4E}\right]$$

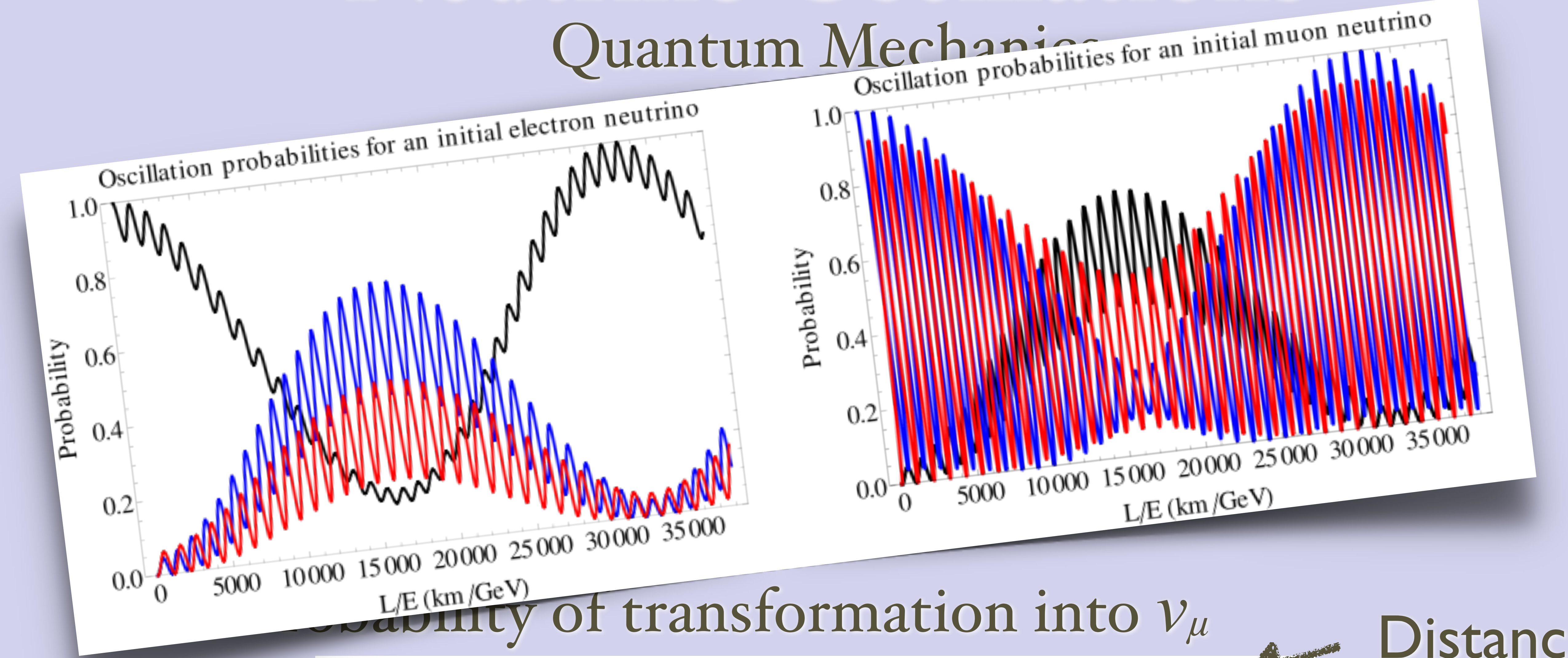
Mass!

E=Energy

(Quantum mechanics at macroscopic distances!)

Neutrino Oscillations

Quantum Mechanic



obability of transformation into ν_μ

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\,\sin^2\left[\frac{(m_1^2 - m_2^2)L}{4E}\right]$$

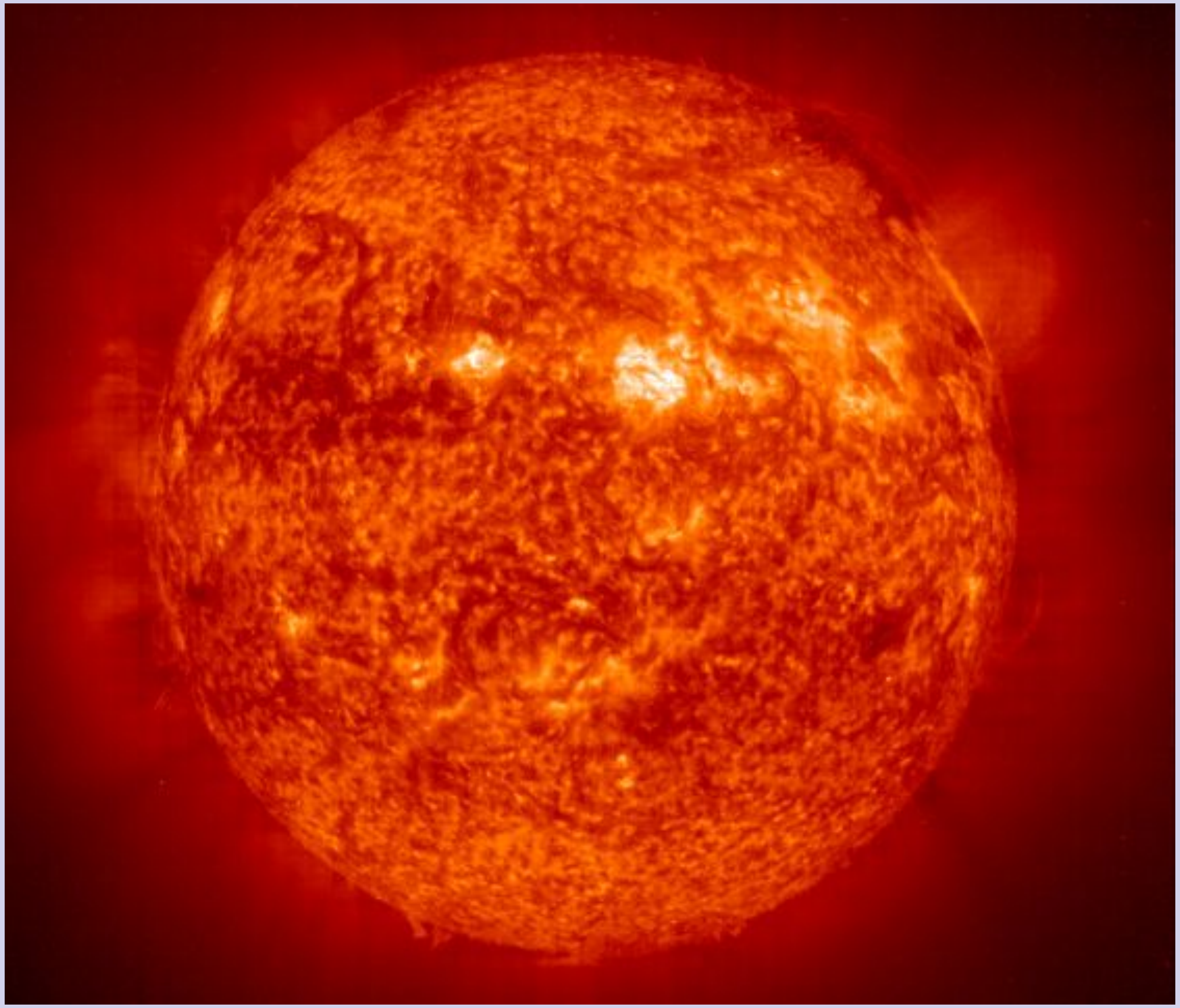
Distance

Mass!

E=Energy

(Quantum mechanics at macroscopic distances!)

Solar & “Atmospheric” neutrinos



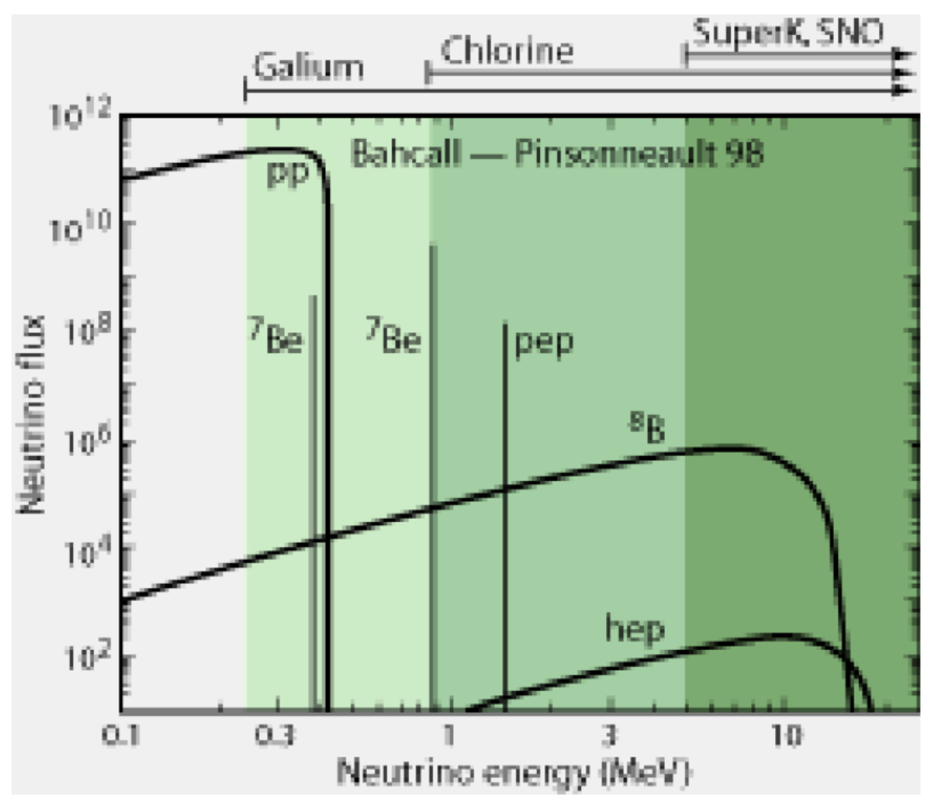
A great flux of ν_e *expected from fusion reactions*

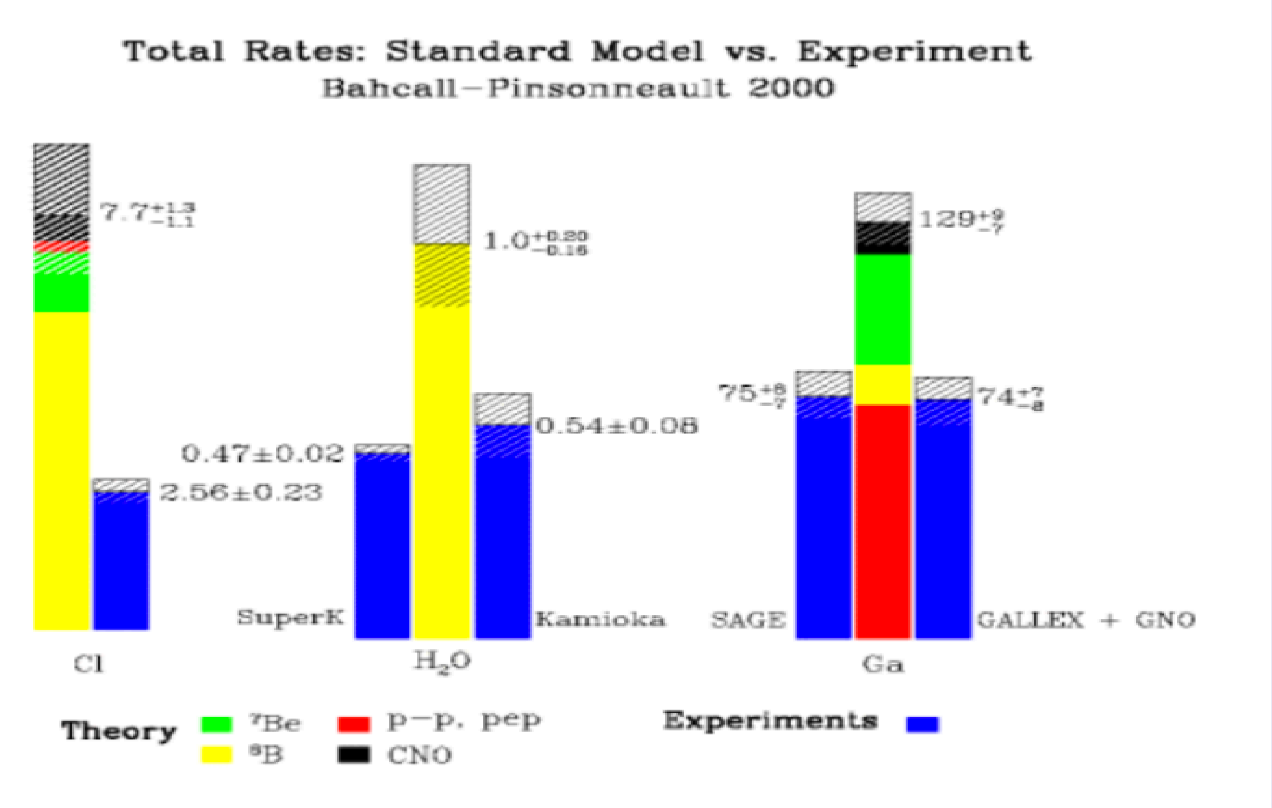
Mystery of solar neutrinos

1960-90 Bahcall predicts, Davis find solar neutrinos

Homestake (Gold Mine in South Dakota) 1,478m underground, 380.000 liters of perchloroethylene, a common dry-cleaning fluid.

…but 2/3 missing…???





2002 Nobel: Davis and Koshiba (Kamiokande) for their pioneering work on solar neutrinos after Bahcall's model.

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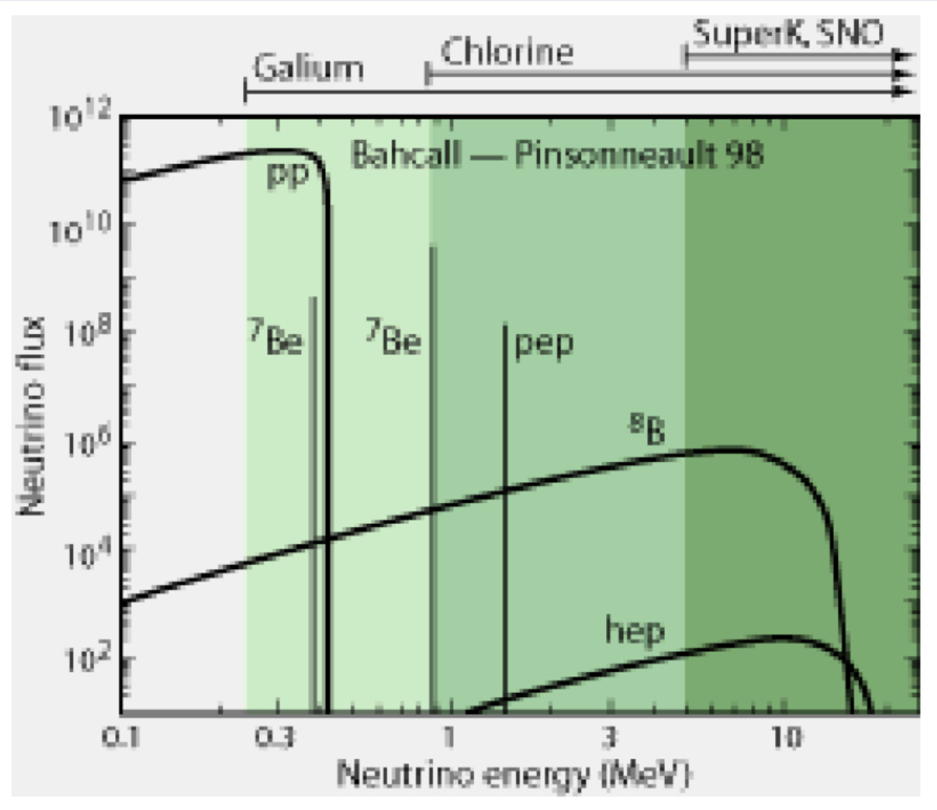

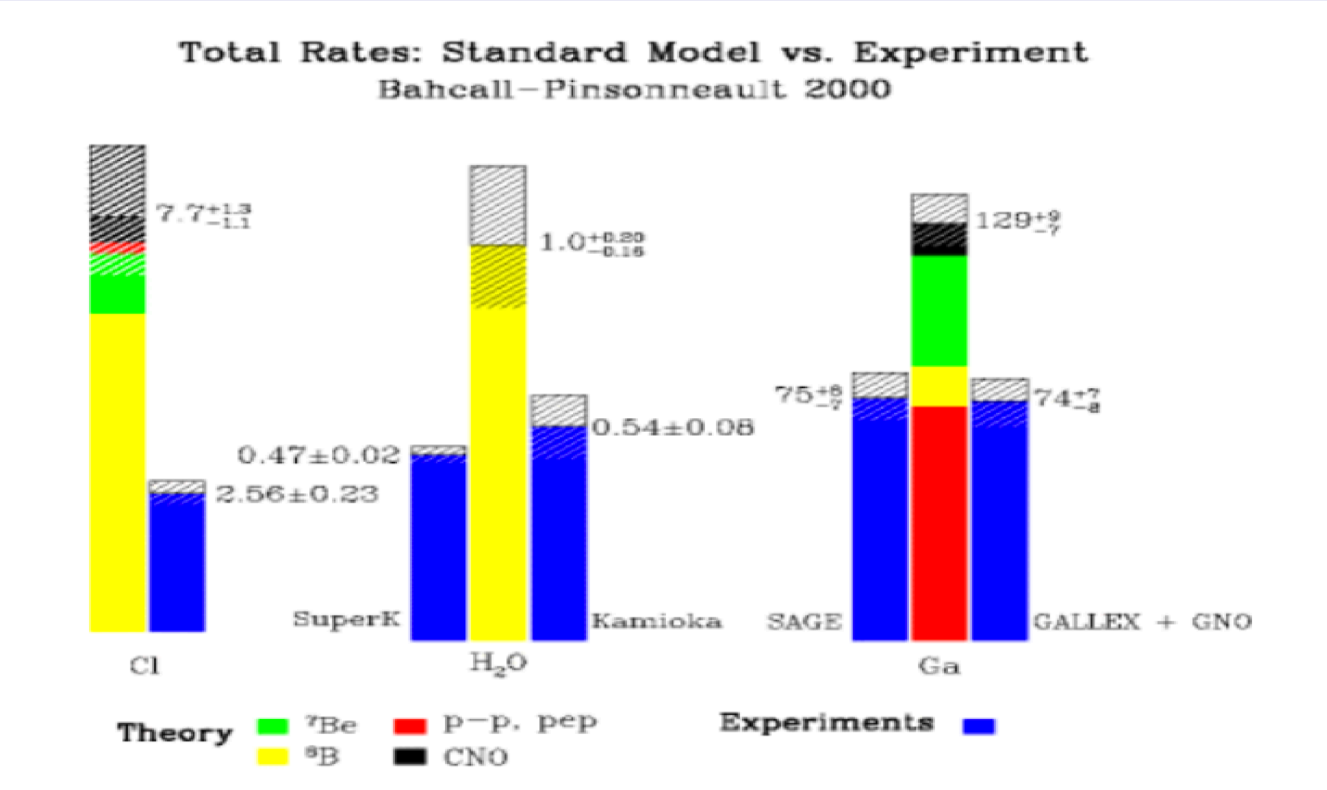

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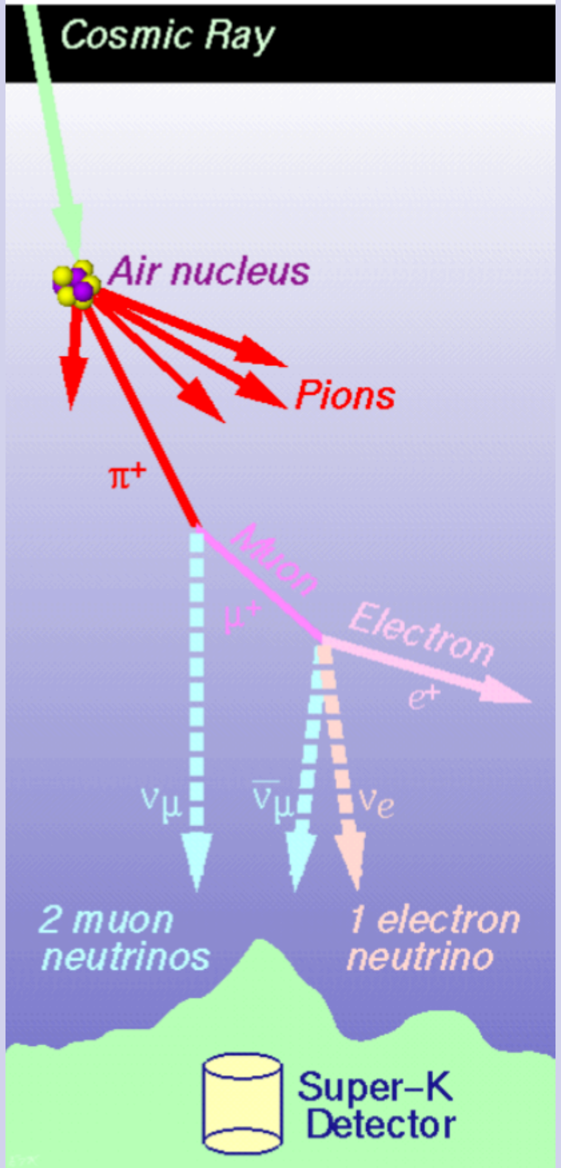
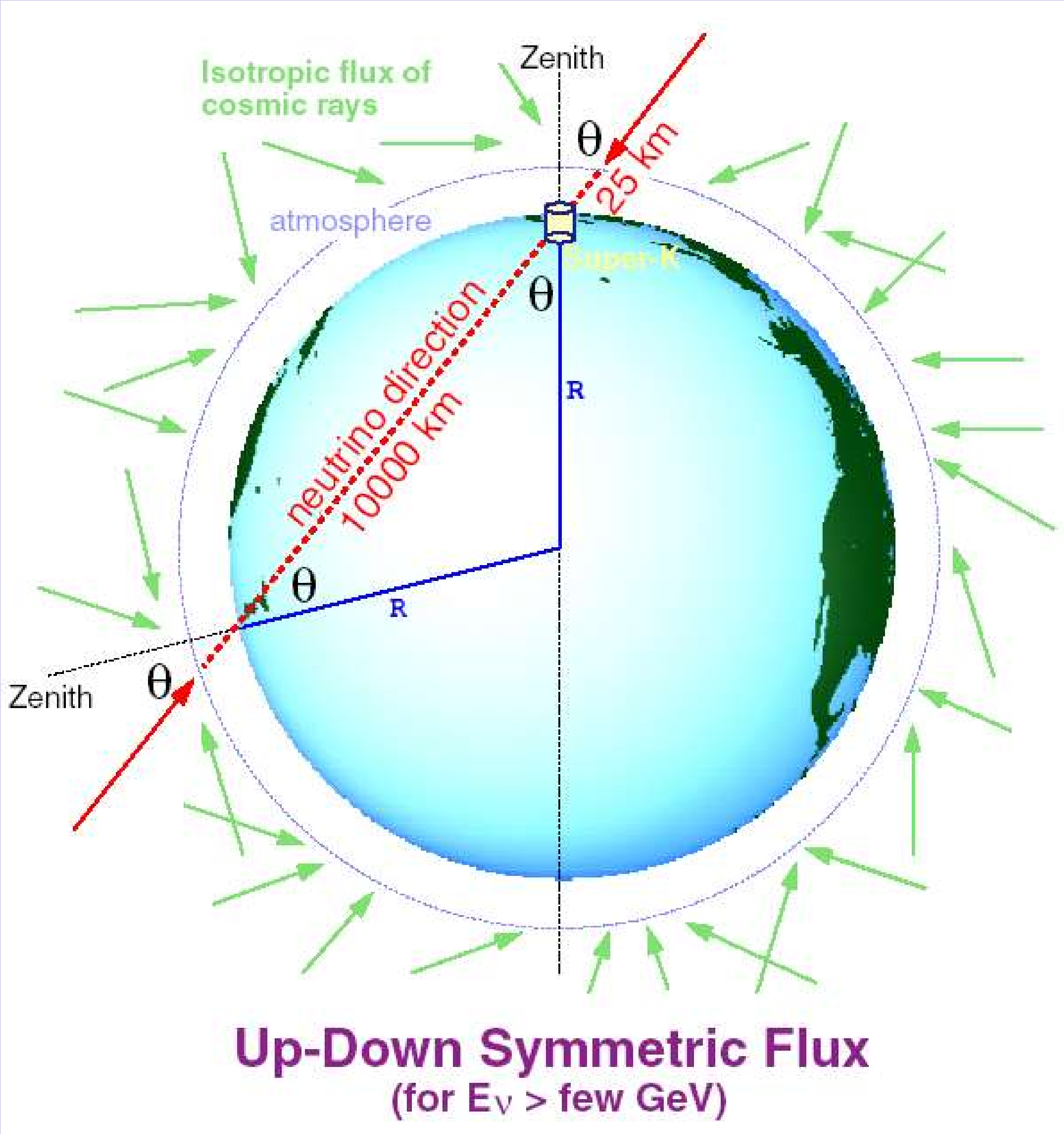
2020: last confirmation, observation of CNO neutrinos @ LNGS, L'Aquila

“Atmospheric” neutrinos



Atmospheric flux of ν_μ

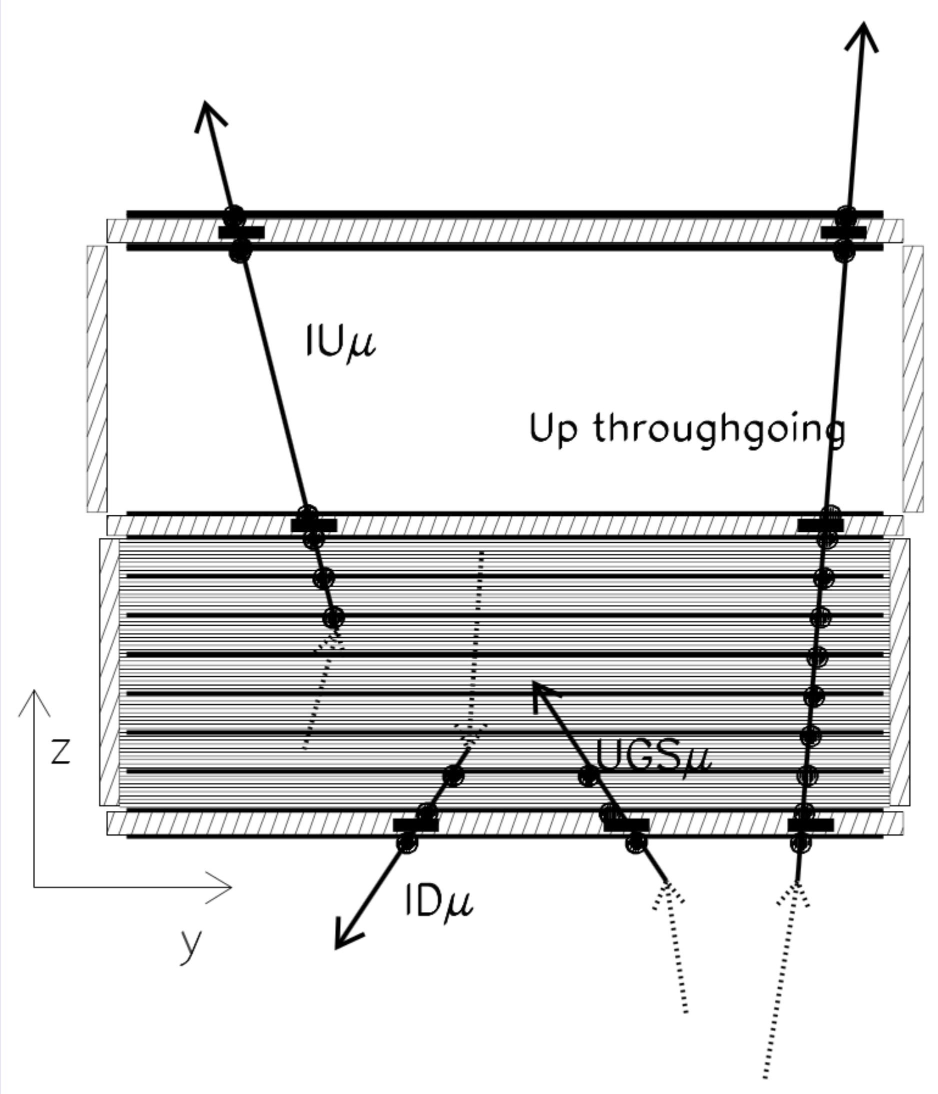


MACRO

- At LNGS, L'Aquila underneath soil as target looking for upgoing muons
- They found ν_μ disappearance!
- .73 ± .09stat. ± .06sys. ± .12th.

[S.Ahlen et al., Phys.Lett.B 1995]

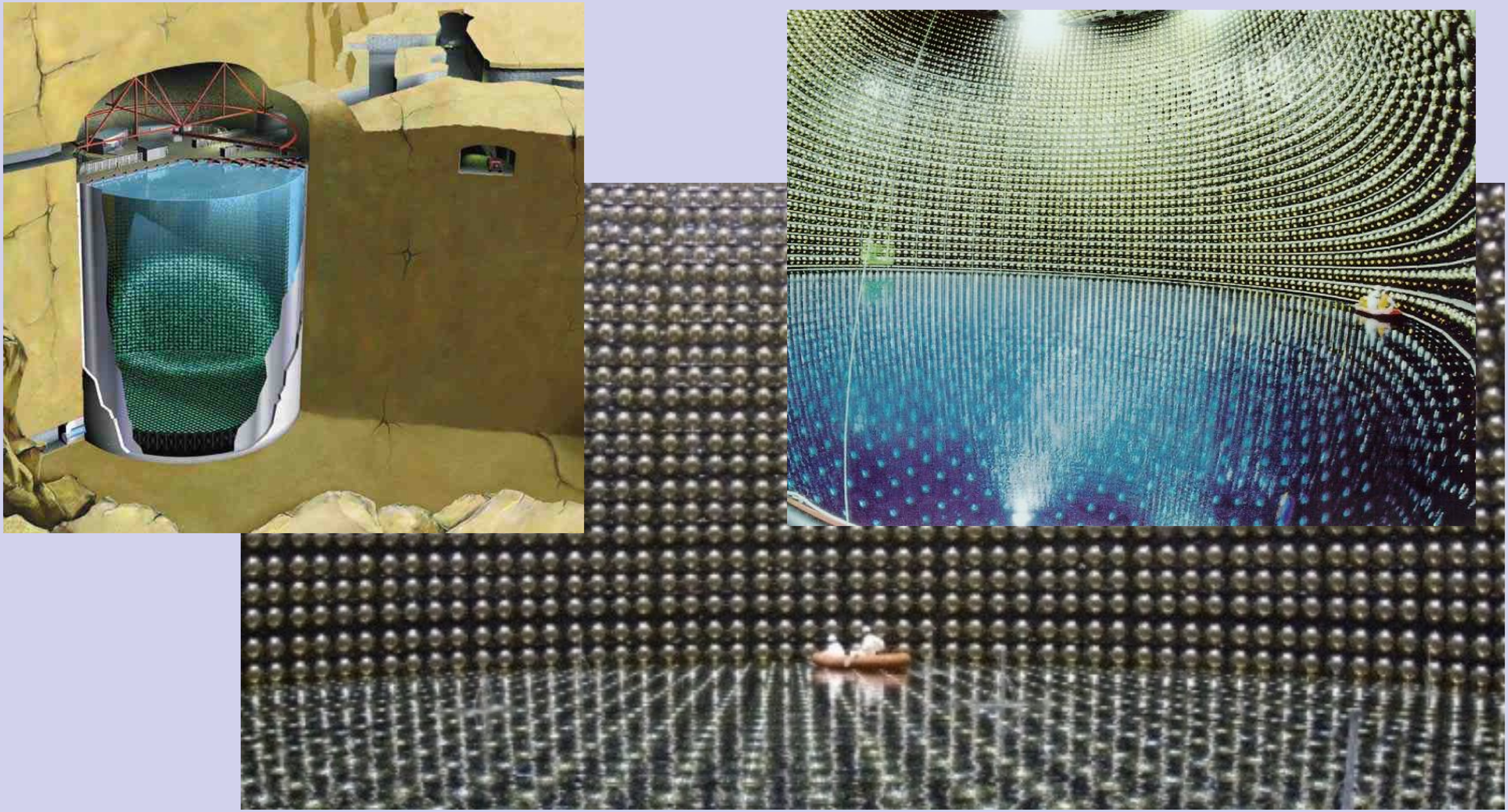
- Needed more statistics...
- They did not claim discovery.



SuperKamiokande

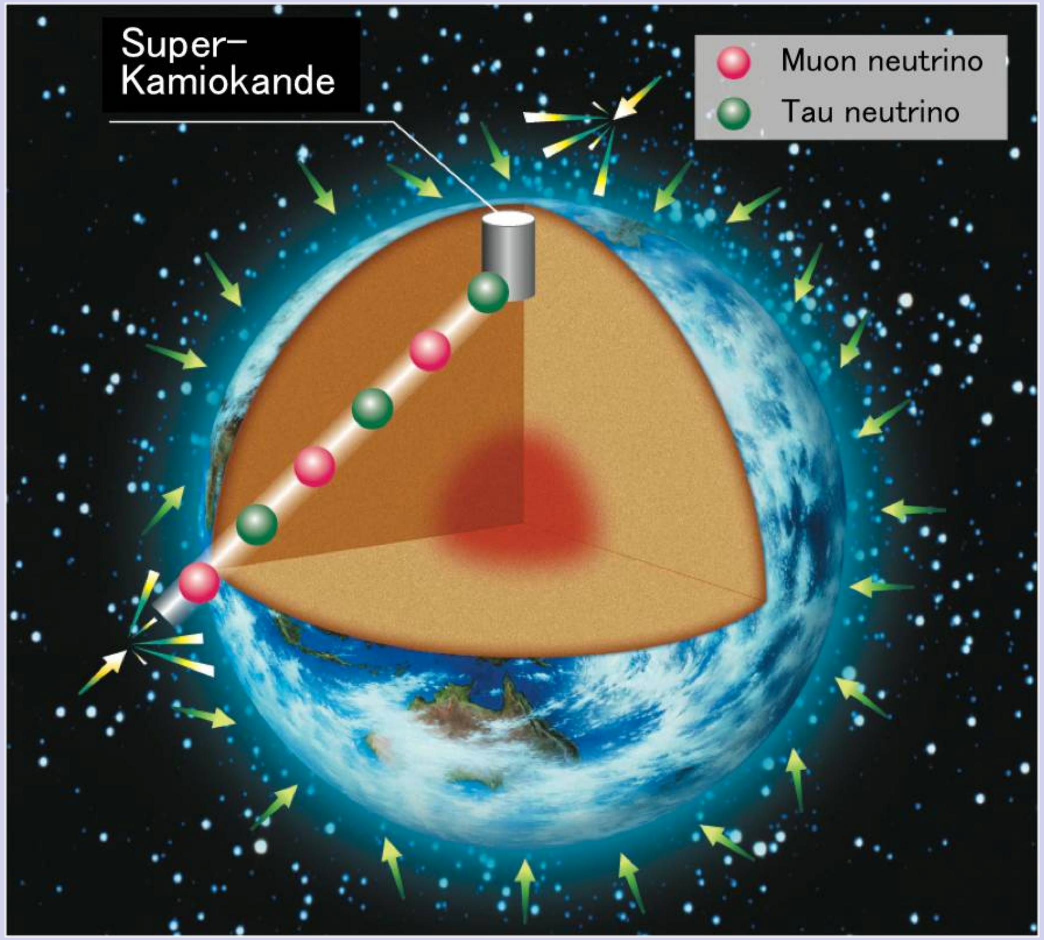
Started 1997 (T Kajita leader experiment, with M. Koshiba)   1,000 metres underground
50,000 tons of water, surrounded by 11,000 phototubes to detect flashes of light in the water.

Actually built to observe Proton Decay - NDE=NucleonDecayExperiment



SuperKamiokande

- ν_μ from above have no time to oscillate
  ν_μ from below yes. Do they disappear?
- Water detector
  = Cherenkov
  = directional!
- cuts background with direction (meaning they see well high energy ν_μ and not well solar ν_μ)



So they measured variation of ν_μ with angle...

SuperKamiokande result

- Up-down asymmetry "less ν_μ from below", confirms the oscillations. (and estimates parameters).

- Joint announcement:

MACRO: M.Ambrosio et al., Phys. Lett. B434(1998)451, hep-ex/9807005.

SOUDAN: Soudan 2 Coll., W.W.M. Allison et al., Phys. Lett. B449 (1999) 137

SuperKamiokande: Y.Fukuda et al., Phys. Rev. Lett. 81(1998)1562; Phys. Lett. B433(1998)9; ...

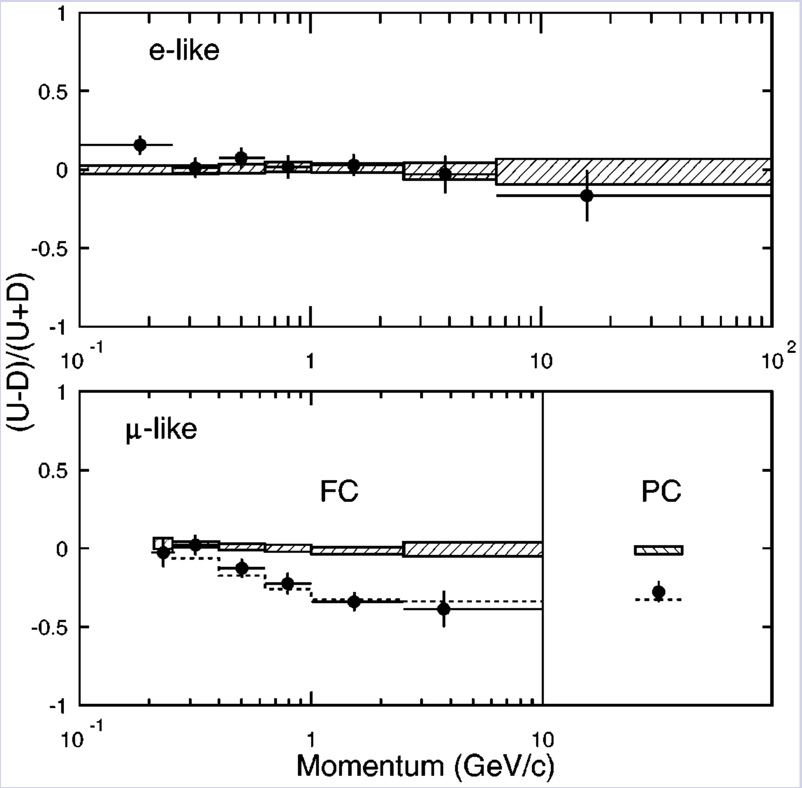


FIG. 1. The $(U - D)/(U + D)$ asymmetry as a functi of momentum for FC e-like and μ-like events and I events. While it is not possible to assign a momentum a PC event, the PC sample is estimated to have a me neutrino energy of 15 GeV. The Monte Carlo expec tion without neutrino oscillations is shown in the hatch region with statistical and systematic errors added in quad ture. The dashed line for μ-like is the expectation $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $(\sin^2 2\theta = 1.0, \Delta m^2 = 2.2$ 10^{-3} eV^2).

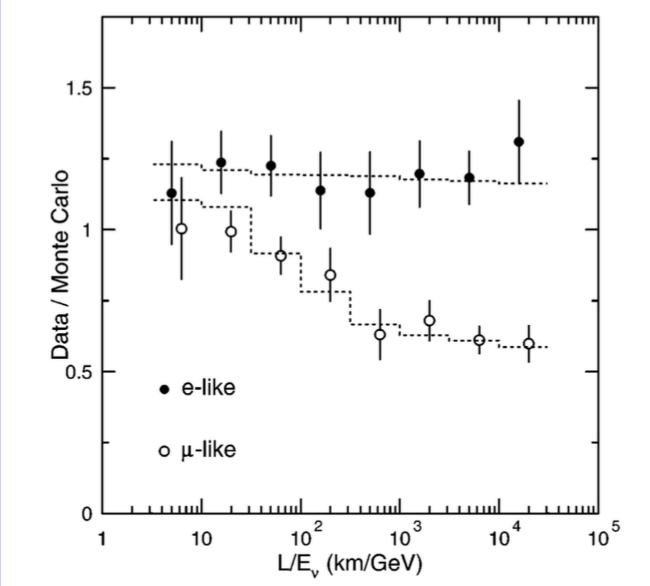
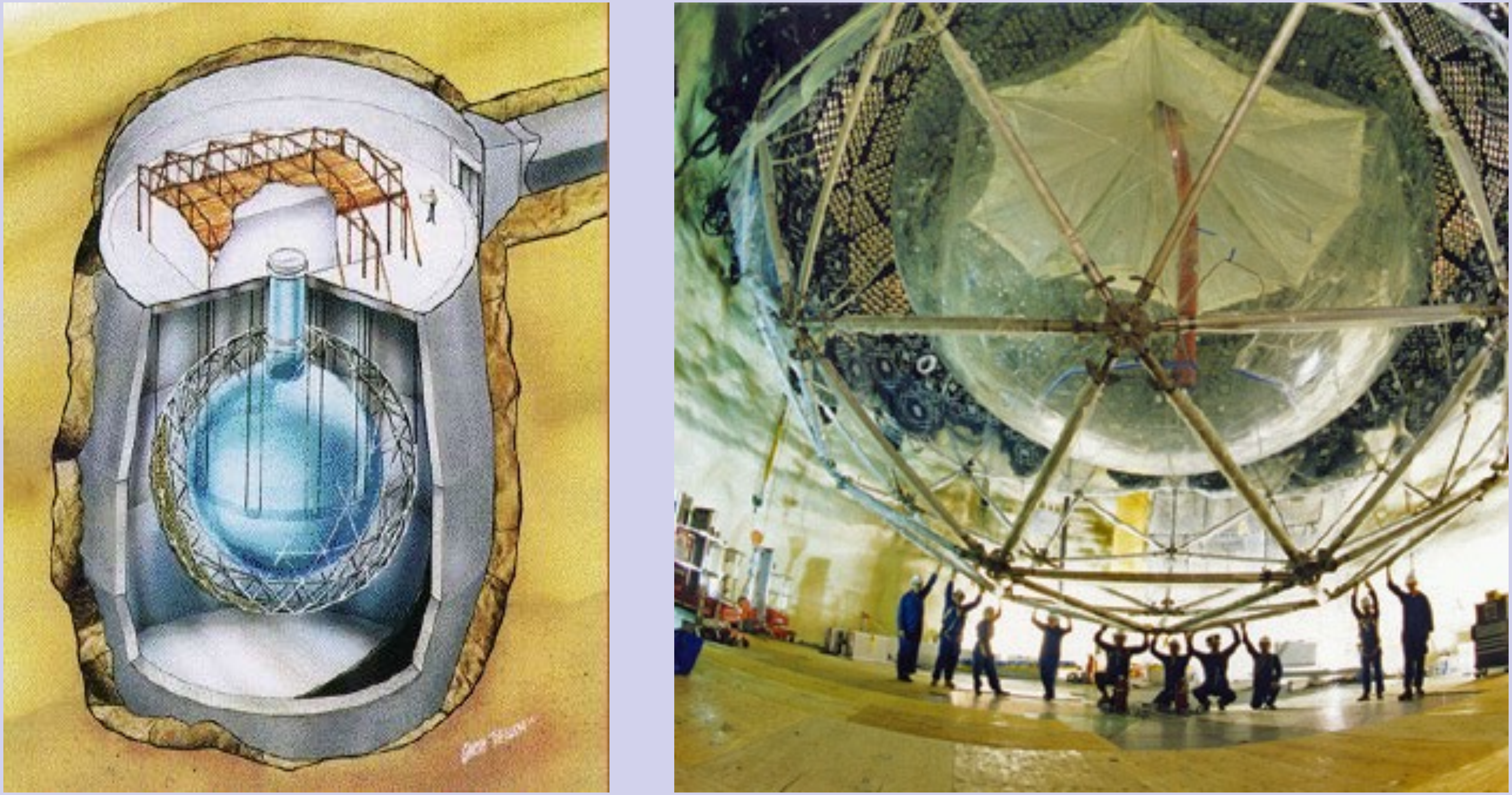


FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2–7%) of ν_μ CC interactions.

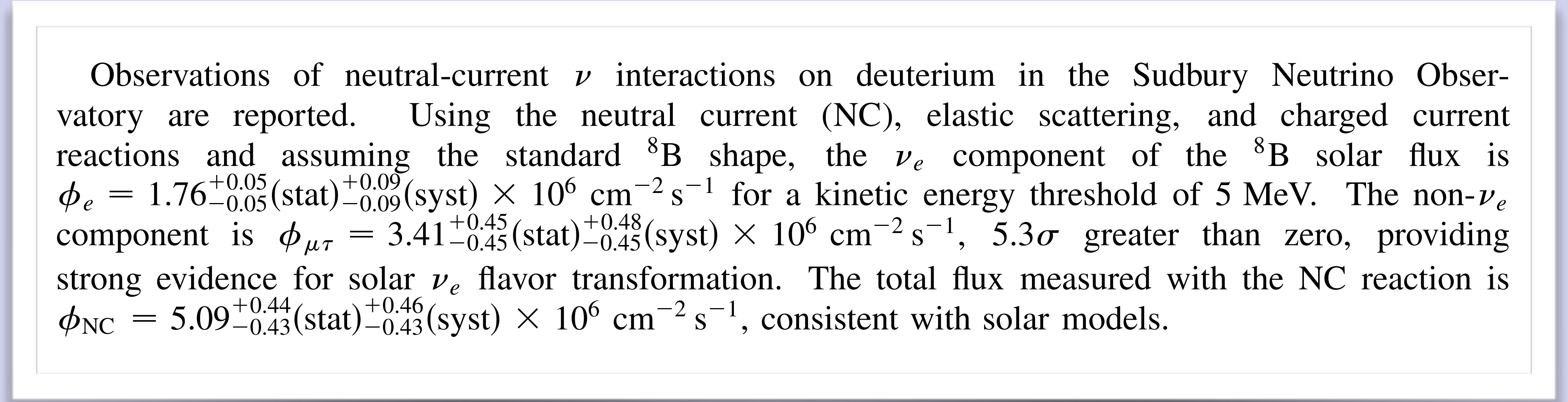
Sudbury Neutrino Observatory
SNO



Sudbury Neutrino Observatory
SNO

- Started 1997 (Arthur McDonald leader experiment)
- 2,000 metres underground,
- 2,000 tons of heavy water,
- 11,000 phototubes to detect flashes of light
- 1 nu per hour one third remain after oscillations

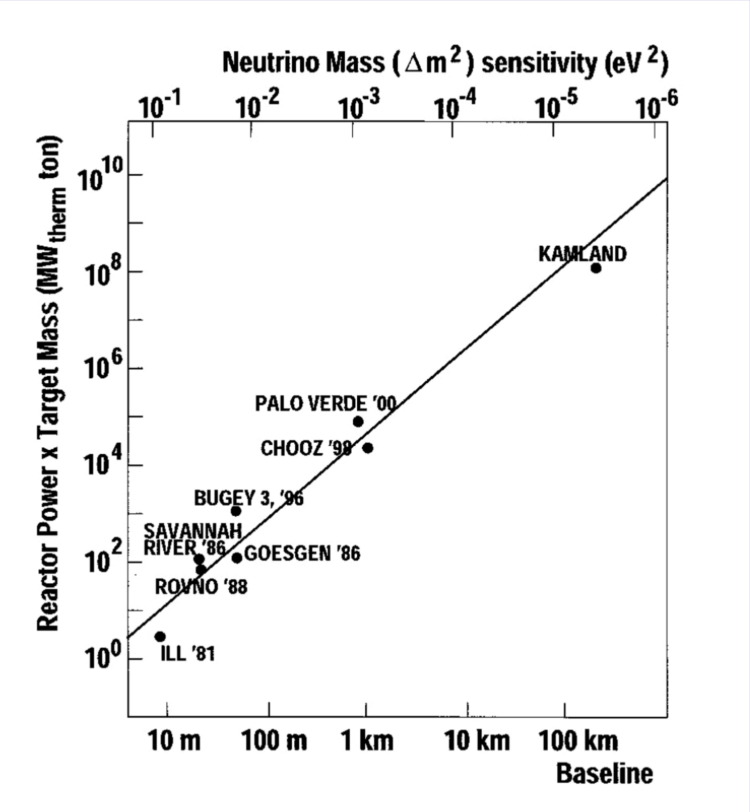
- Heavy water to see the appearance of the missing neutrinos!

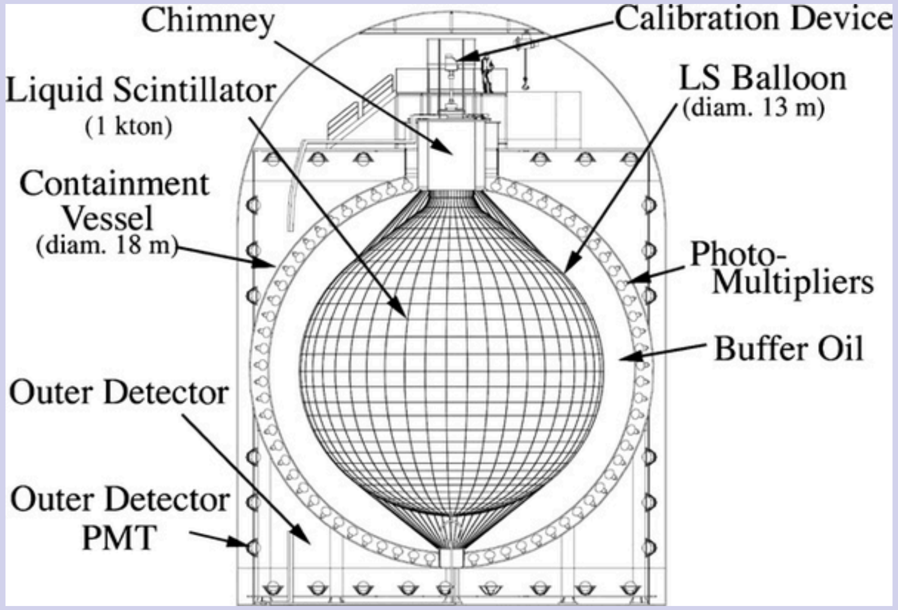


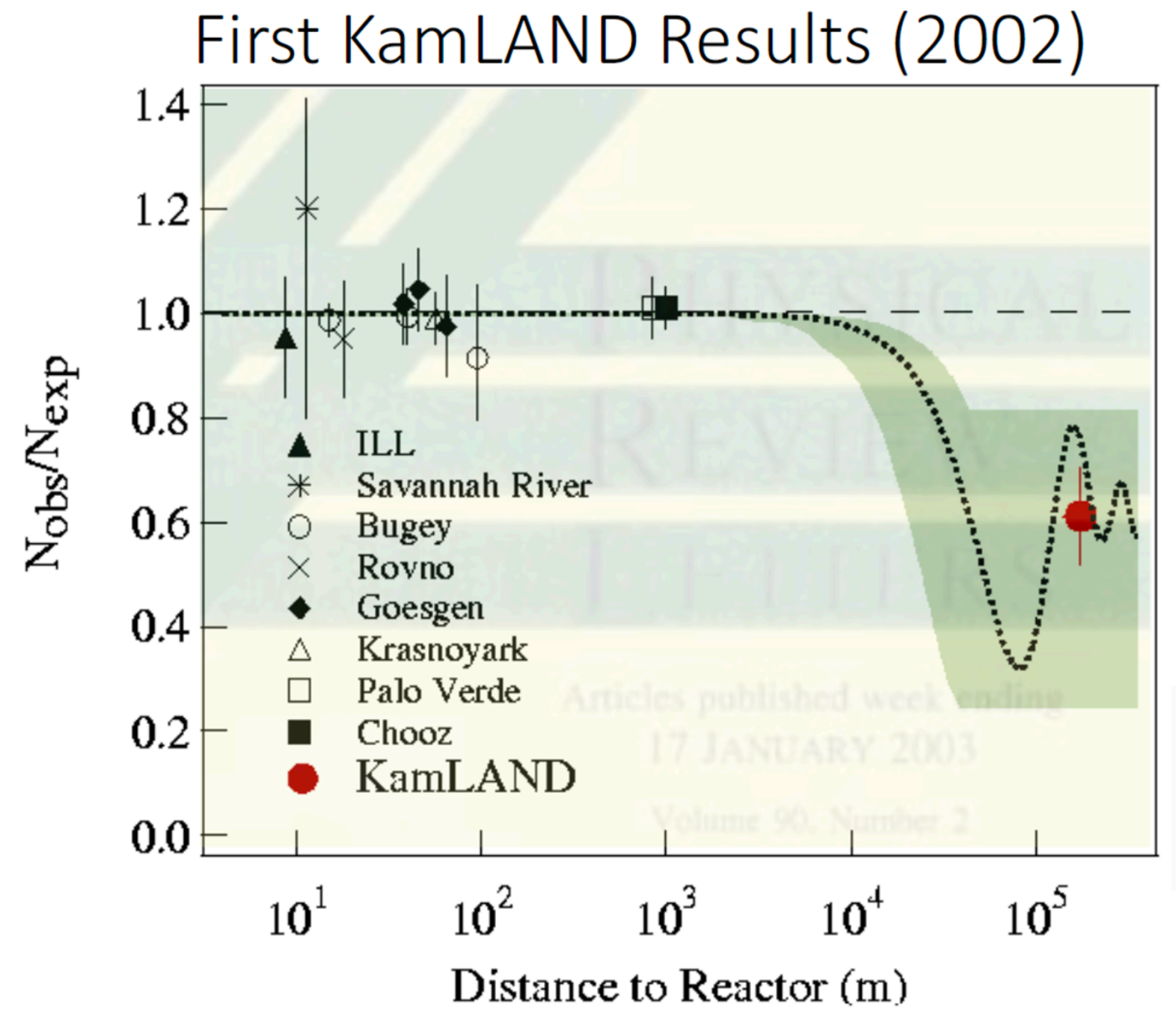
Observations of neutral-current ν interactions on deuterium in the Sudbury Neutrino Observatory are reported. Using the neutral current (NC), elastic scattering, and charged current reactions and assuming the standard ^{8}B shape, the ν_e component of the ^{8}B solar flux is $\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat})^{+0.09}_{-0.09}(\text{syst}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$ for a kinetic energy threshold of 5 MeV. The non-ν_e component is $\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat})^{+0.48}_{-0.45}(\text{syst}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$, 5.3σ greater than zero, providing strong evidence for solar ν_e flavor transformation. The total flux measured with the NC reaction is $\phi_{\text{NC}} = 5.09^{+0.44}_{-0.43}(\text{stat})^{+0.46}_{-0.43}(\text{syst}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$, consistent with solar models.

[Phys Rev. Letters (2002)]

Kamland (2002)

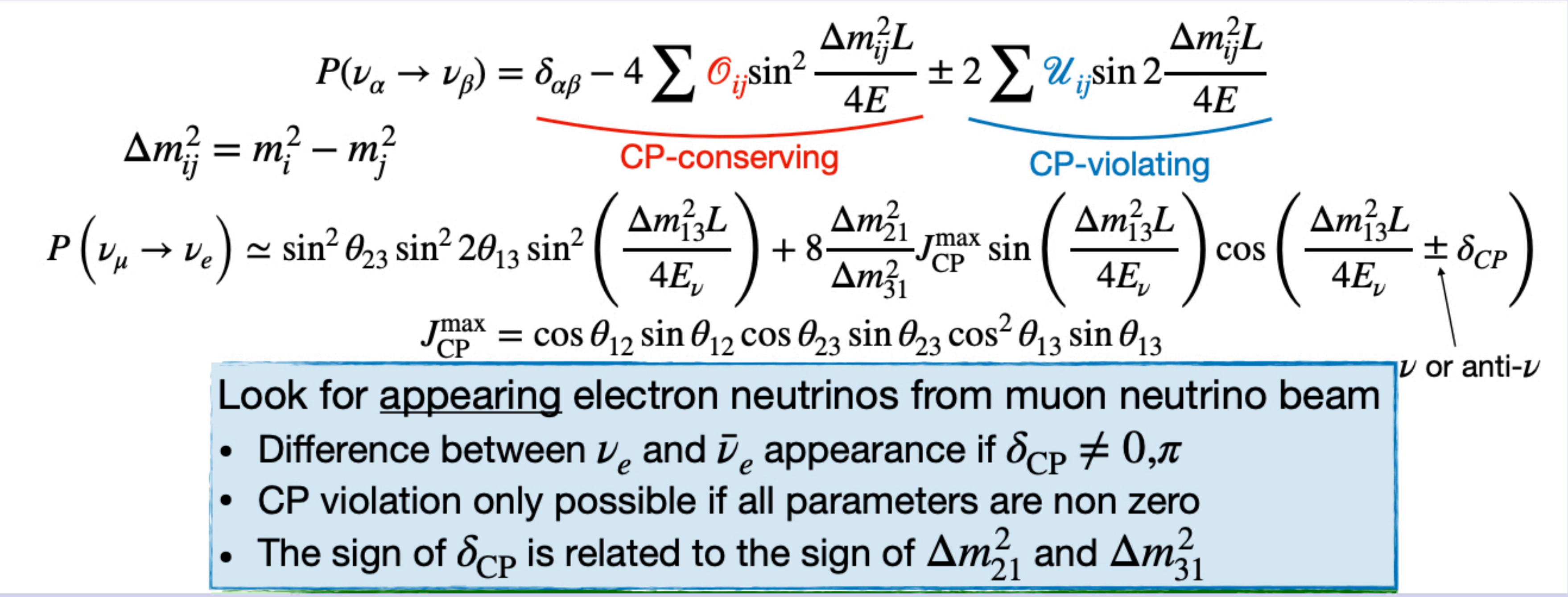






T2K (now)

Beam of 0.6 GeV muon neutrinos



$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} \underbrace{- 4 \sum \mathcal{O}_{ij} \sin^2 \frac{\Delta m^2_{ij} L}{4E}}_{\text{CP-conserving}} \underbrace{\pm 2 \sum \mathcal{U}_{ij} \sin 2 \frac{\Delta m^2_{ij} L}{4E}}_{\text{CP-violating}}$$

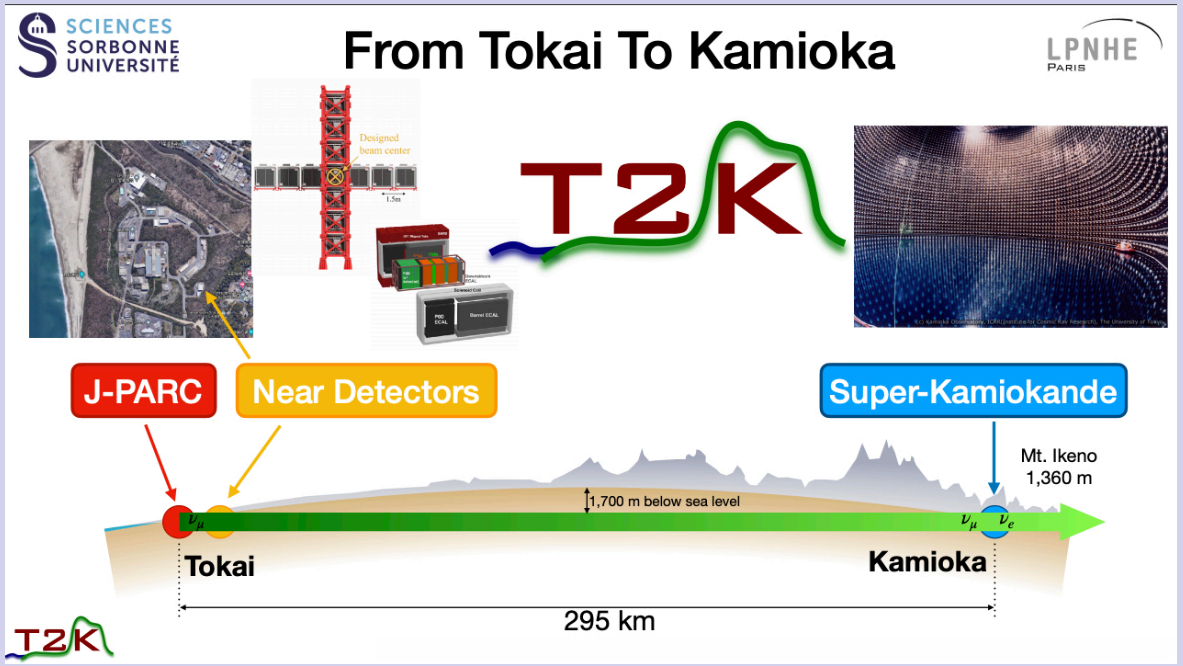
$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

$$P\left(\nu_\mu \to \nu_e\right) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E_\nu}\right) + 8 \frac{\Delta m^2_{21}}{\Delta m^2_{31}} J^{\max}_{\mathrm{CP}} \sin\left(\frac{\Delta m^2_{13} L}{4E_\nu}\right) \cos\left(\frac{\Delta m^2_{13} L}{4E_\nu} \underset{\nu \text{ or anti-}\nu}{\pm} \delta_{CP}\right)$$

$$J^{\max}_{\mathrm{CP}} = \cos\theta_{12} \sin\theta_{12} \cos\theta_{23} \sin\theta_{23} \cos^2\theta_{13} \sin\theta_{13}$$

Look for <u>appearing</u> electron neutrinos from muon neutrino beam

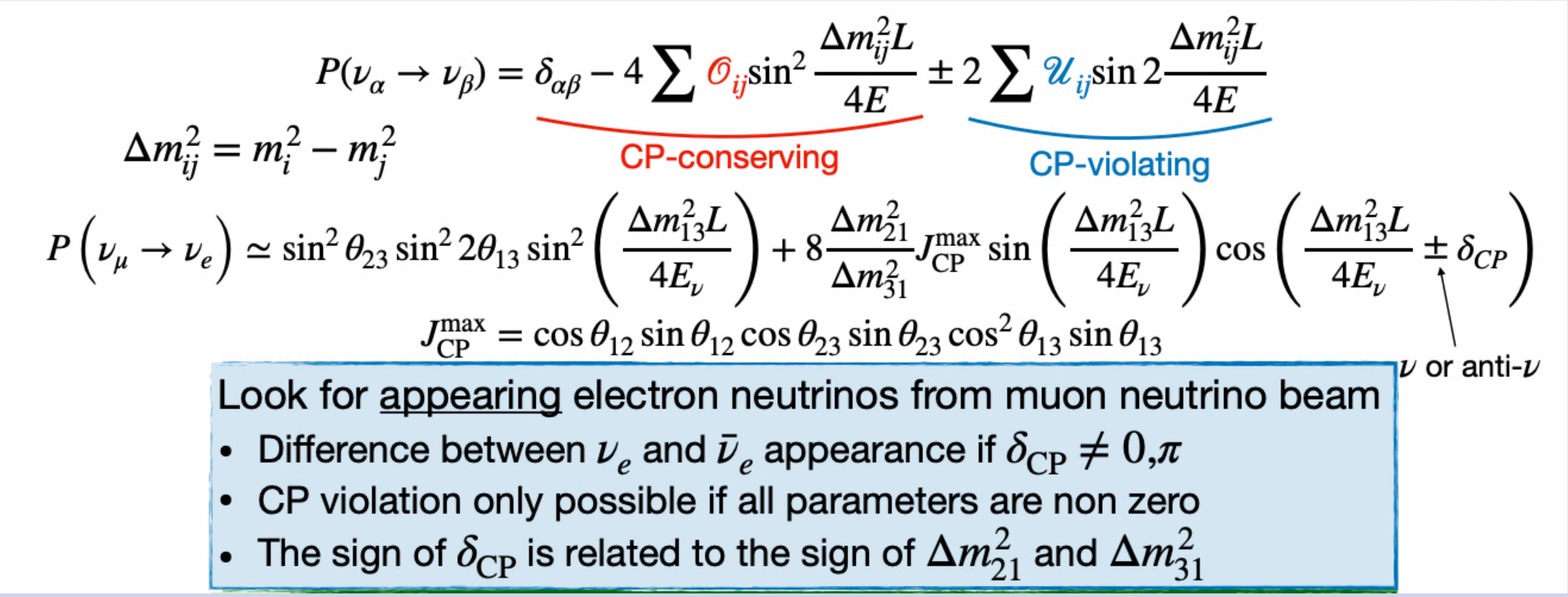
- Difference between ν_e and $\bar{\nu}_e$ appearance if $\delta_{\mathrm{CP}} \neq 0, \pi$
- CP violation only possible if all parameters are non zero
- The sign of δ_{CP} is related to the sign of Δm^2_{21} and Δm^2_{31}



From Tokai To Kamioka

T2K (now)

Beam of 0.6 GeV muon neutrinos



$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\underbrace{\sum \mathcal{O}_{ij}\sin^2\frac{\Delta m^2_{ij}L}{4E}}_{\text{CP-conserving}} \pm 2\underbrace{\sum \mathcal{U}_{ij}\sin 2\frac{\Delta m^2_{ij}L}{4E}}_{\text{CP-violating}}$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

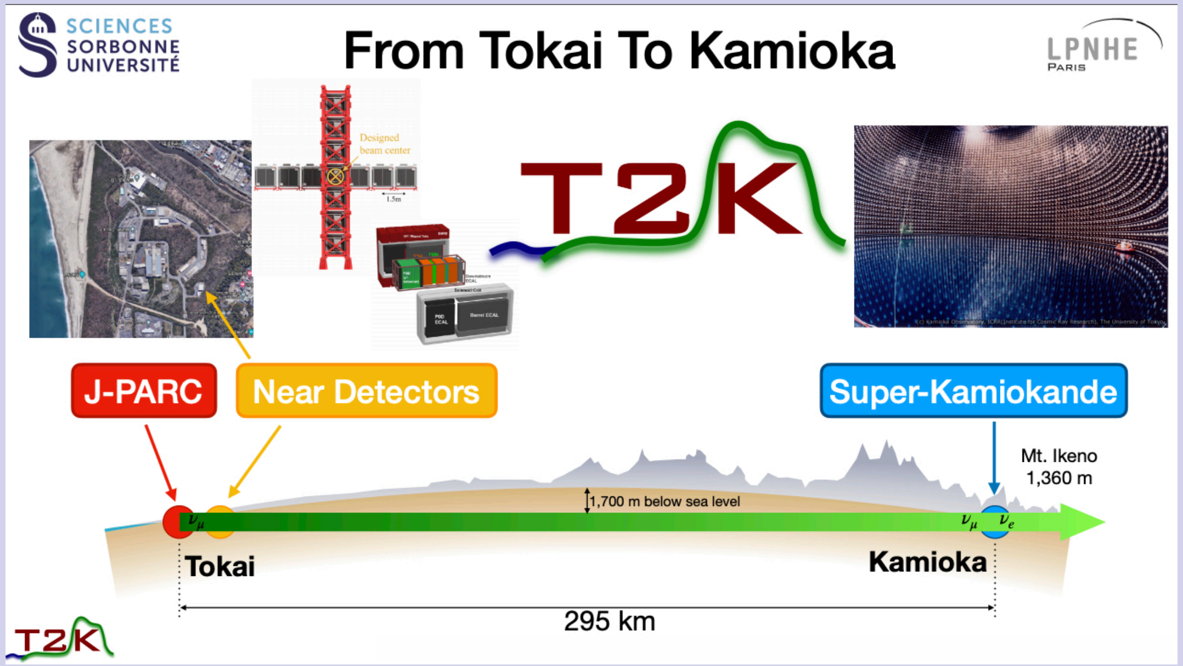
$$P\left(\nu_\mu \to \nu_e\right) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{13}L}{4E_\nu}\right) + 8\frac{\Delta m^2_{21}}{\Delta m^2_{31}}J^{\max}_{\mathrm{CP}}\sin\left(\frac{\Delta m^2_{13}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{13}L}{4E_\nu} \pm \delta_{CP}\right)$$

$$J^{\max}_{\mathrm{CP}} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

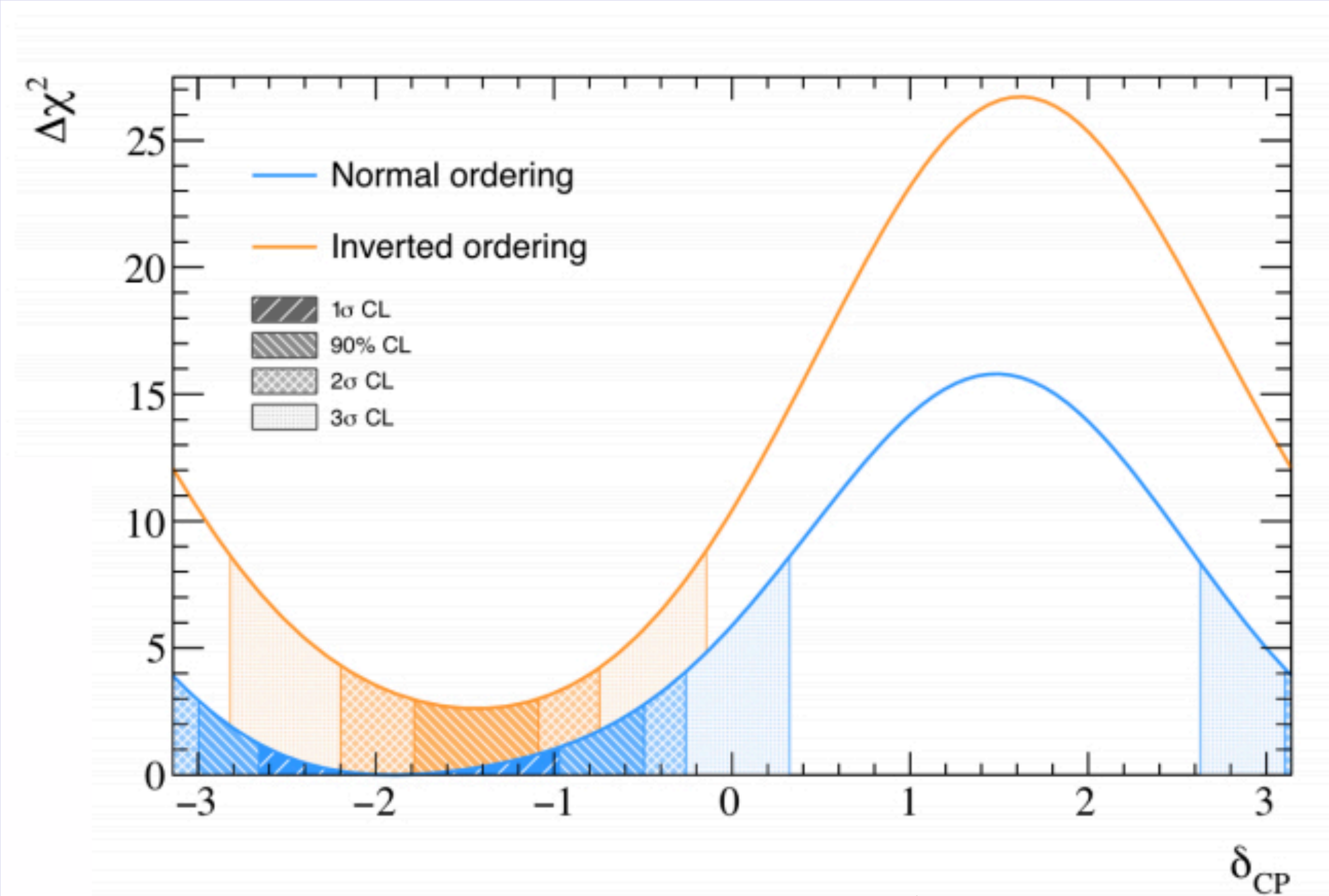
ν or anti-ν

Look for appearing electron neutrinos from muon neutrino beam

- Difference between ν_e and $\bar{\nu}_e$ appearance if $\delta_{\mathrm{CP}} \neq 0,\pi$
- CP violation only possible if all parameters are non zero
- The sign of δ_{CP} is related to the sign of Δm^2_{21} and Δm^2_{31}

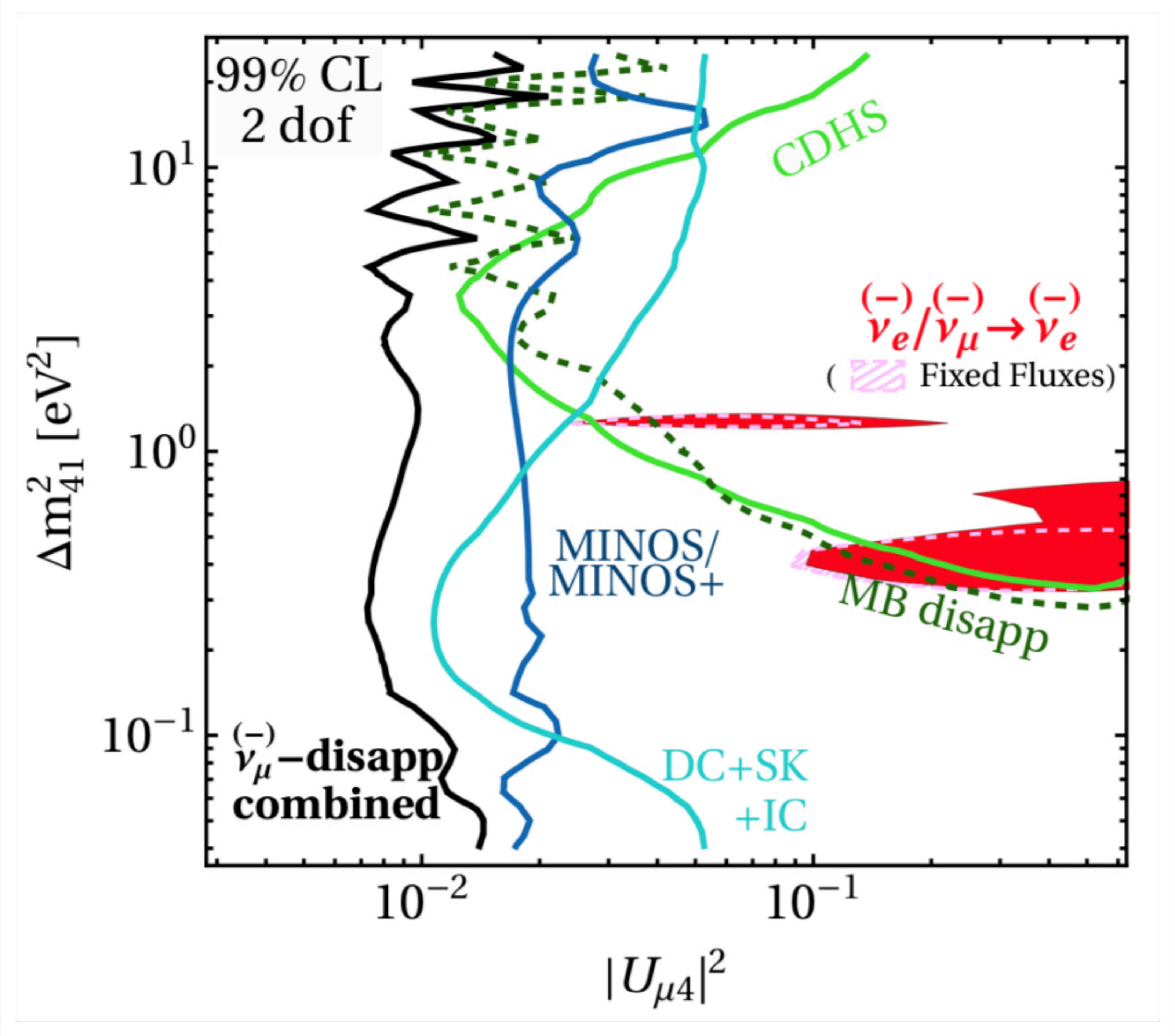


From Tokai To Kamioka



Latest results

Still (Reactor) anomalies….



[Dentler Hernandez JK Machado Maltoni Martinez Schwetz, 1803.10661]

Oscillations nowadays confirmed completely

- Gallex/GNO-SAGE (solar ν_e, low E_ν) (1990)
- SK (ν_{atm}), K2K & MINOS (ν_μ accel.) (1998) $\theta_{23} \sim 45^\circ$
- KamLAND (anti ν_e react.) (2002) $\theta_{12} \sim 34^\circ$
- Daya Bay and RENO T2K (anti ν_e react.) (2012) $\theta_{13} \sim 8.5^\circ$
- T2K (2020-21) excludes zero CP violation $\delta_{CP} \sim -2 \pm 1.5$
- LSND (ν_e from $\pi+$ at rest) DayBay 1eV, $\theta_{14} \sim$ few° ???

Oscillations nowadays confirmed completely

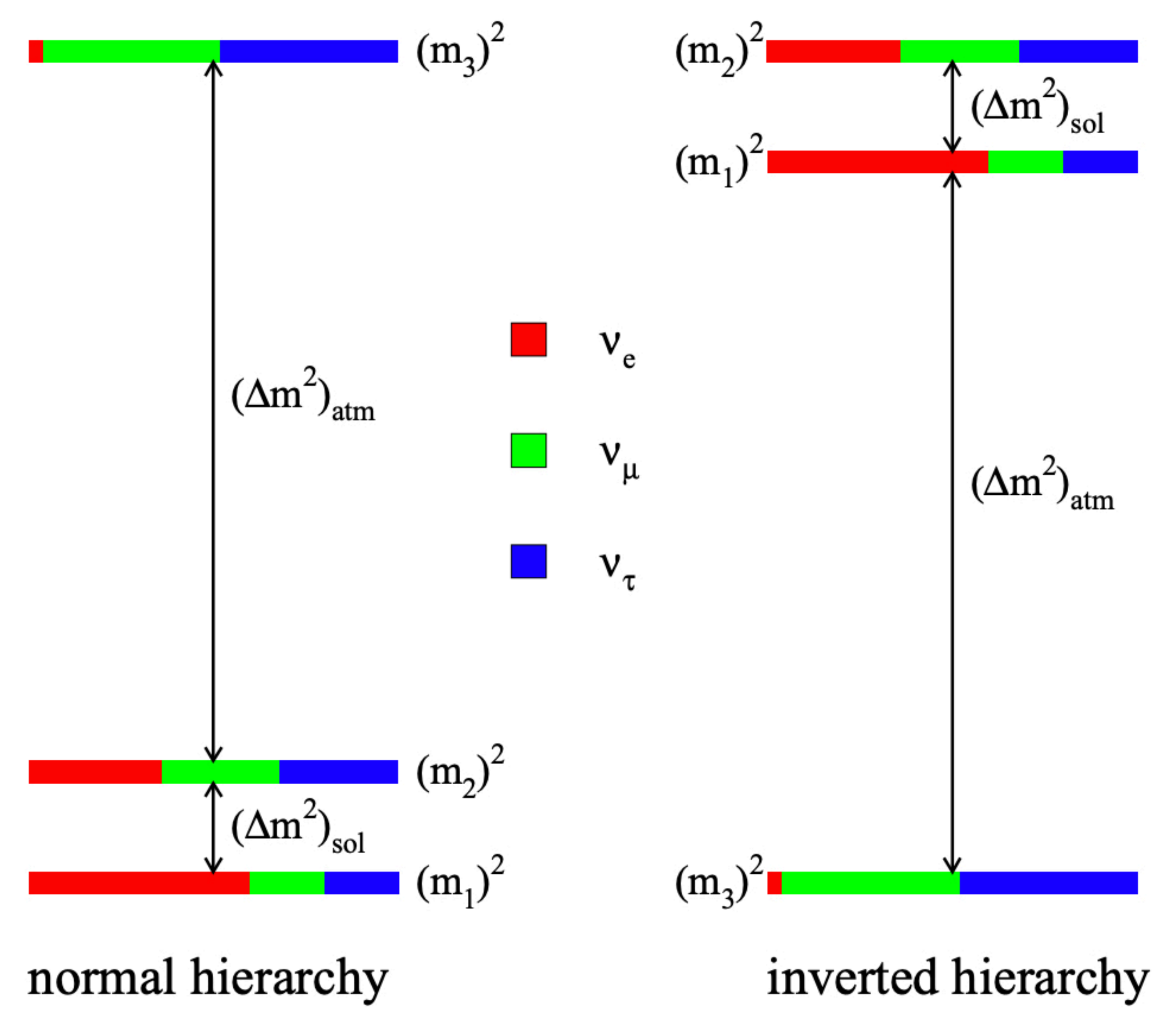
- Thus neutrinos have a mass.
- We find their mass differences, very tiny

$$\Delta m^2_{12} \simeq (0.01\mathrm{eV})^2 \qquad \Delta m^2_{23} \simeq (0.05\mathrm{eV})^2$$

- The absolute value is still unknown

(limited to be below ~0.2-0.5eV... cosmology, etc.)

Graphical representation

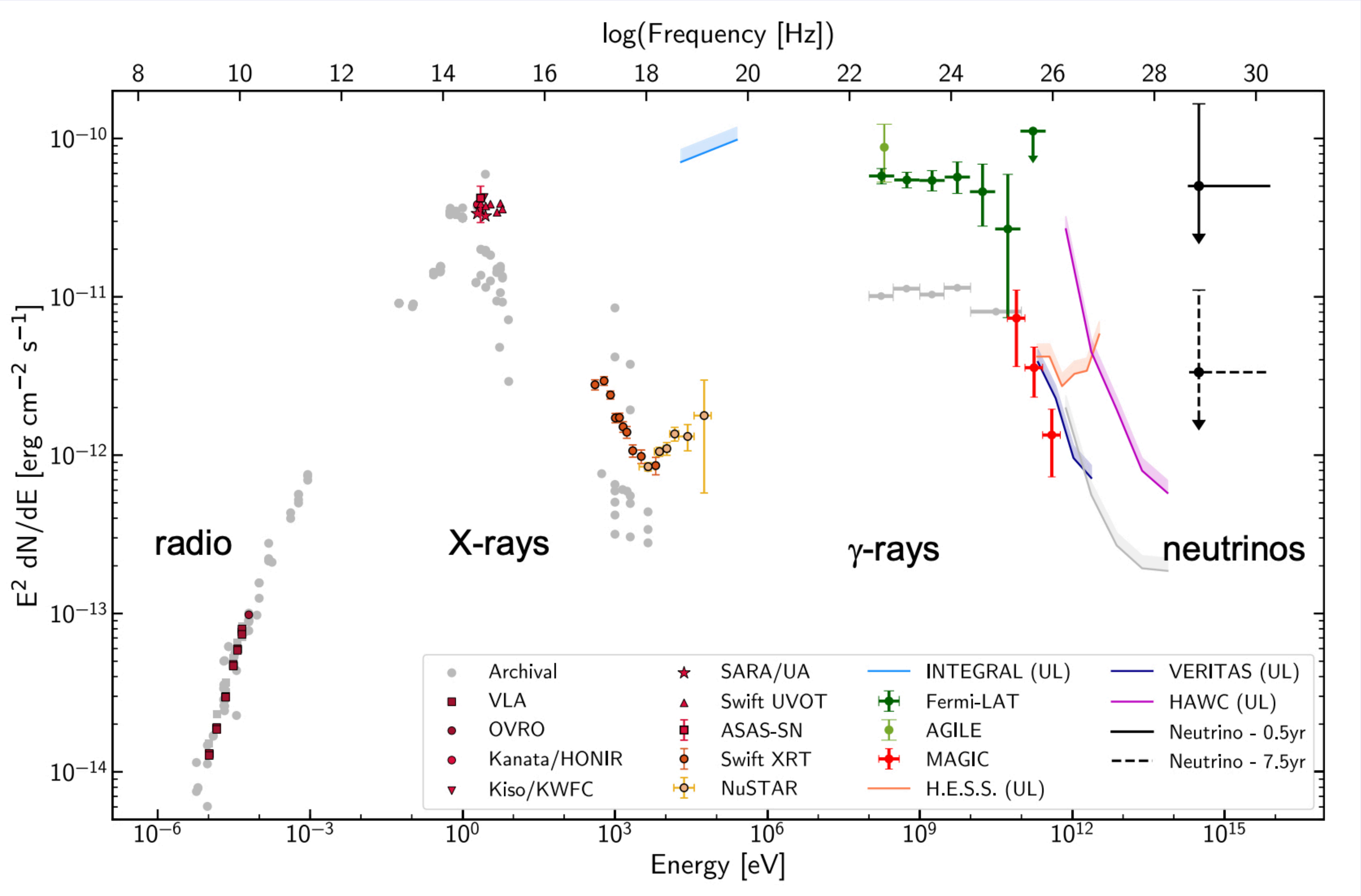


(T2K preliminary result, mildly prefers normal ordering...)

Intermezzo - Applications ? :)

- Probing inside the sun and stars (present)
  help understanding nuclear reactions, e.g. fusion
- Neutrino astronomy (ongoing)
  e.g. IceCube - high energy neutrinos from outside our galaxy
- Earth: Geoneutrinos, Earth Oscillograms
  Radiogenic composition, study of Earth's density distribution... http://arxiv.org/abs/hep-ph/0612285   http://arxiv.org/abs/1201.6080
- Detection of undeclared nuclear plants (maybe?)
  (Secret Neutrino Interactions Finder - http://arxiv.org/abs/1011.3850)
- Communication... (hard)
  Demonstration of Communication using Neutrinos
  http://arxiv.org/abs/1203.2847
- As energy source (flat-earthers - high-profile pirates 🥺)
  https://neutrino-energy.com/

Multimessenger



Next frontier, neutrino + gravitational waves :)

Theory...

Theory is lagging behind.

After 60 years,
still no theory of neutrino masses,
we ignore whether they are Majorana particles...

Note

- It would be easy to see the difference if one could stop them...
- but the small mass and cross section makes this almost impossible

...theory

Theory for fundamental masses

Look at the Standard Model

- Higgs field spontaneously breaks the symmetry

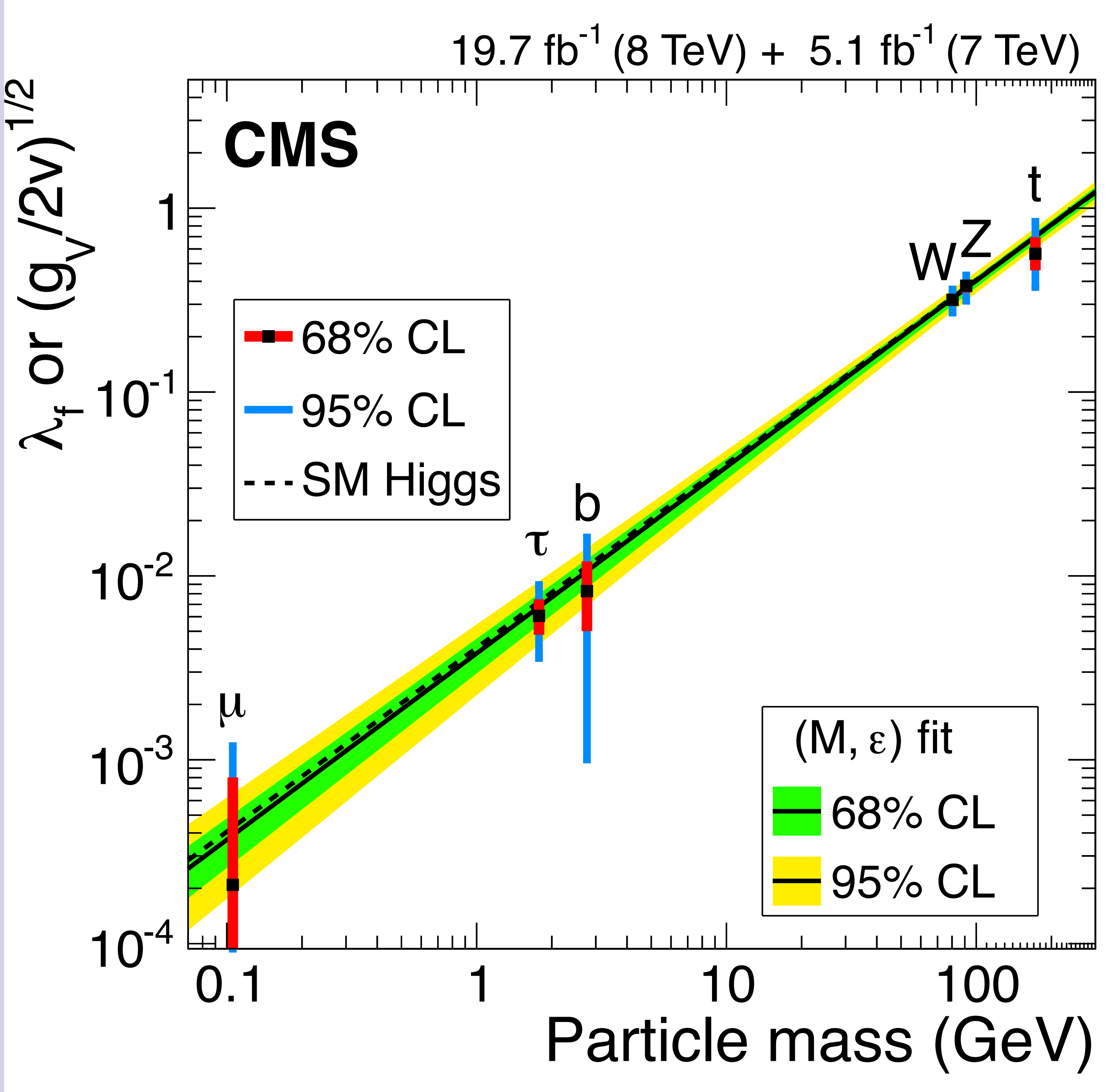
[Nambu ‘60 Goldstone ’61 Higgs ’64 Weinberg ’67]

- ...and provides the mass. Electron:

coupling: $\lambda_e H \; e_L \, e_R$ $\longleftrightarrow$ mass: $m_e \, e_L \, e_R$

Mass m and coupling should be related...

LHC - The last triumph of the SM



Masses versus
Higgs decays
as expected

Anything similar for neutrino masses?

- We saw: neutrino mass differences (oscillations)
  ...thus nonzero neutrino mass.

- SM has only *left* neutrinos...
  ...no Higgs coupling

$$M_\nu = 0$$

Need to go Beyond the Standard Model...

1937 Majorana disappears

Chi l'ha visto?

Ettore Majorana, ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

Who saw him?

His legacy goes on...

Neutrino mass choice

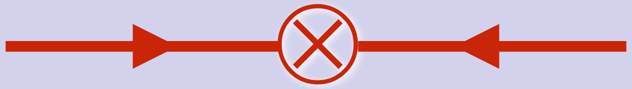
- 1928 - Dirac theory of the electron e^- , mass defined by:

$$m_D\,\bar{e}_L e_R$$

it predicts antimatter, i.e. the positron e^+
(1932 - Anderson discovers it!)

- 1937 Majorana theory of neutral particles

$$m_M\,\nu_L \nu_L$$



neutrinos can be their own antiparticles $\nu \equiv \bar{\nu}$

Difference intimately linked to breaking of Parity...