Neutrino physics

EXPLORE 2023

Juan Pablo Yáñez

j.p.yanez@ualberta.ca

UNIVERSITY OF ALBERTA

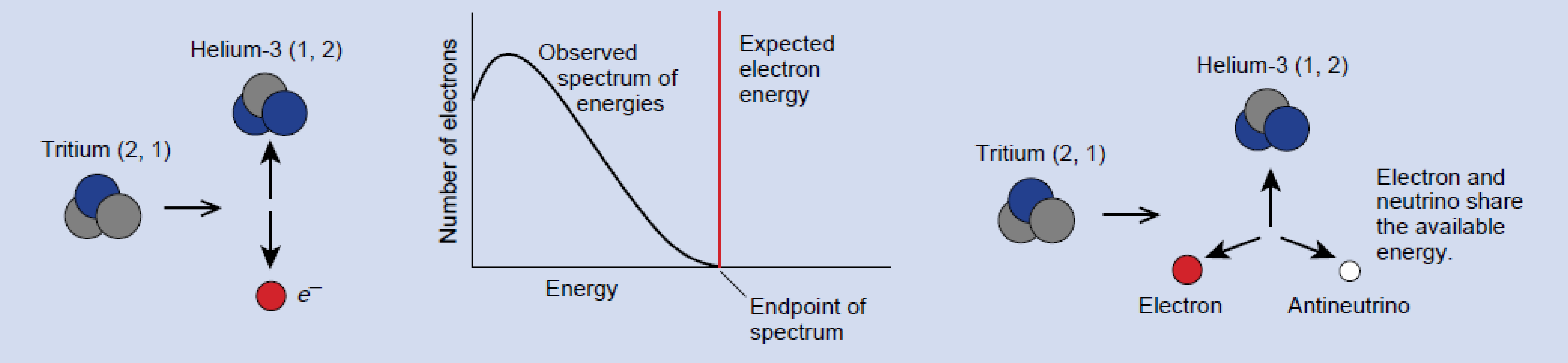
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

outline

-some history
-neutrino masses
-mixing and oscillations
-neutrino flavors
-neutrinos as probes
-some final words

some history

proposed to make sense of radioactive decays




Wolfgang Pauli

Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

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 anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Wolfgang Pauli

the new particle should be
- spin 1/2 (like the electron)
- electrically neutral
- of tiny mass (<0.01 m_p)

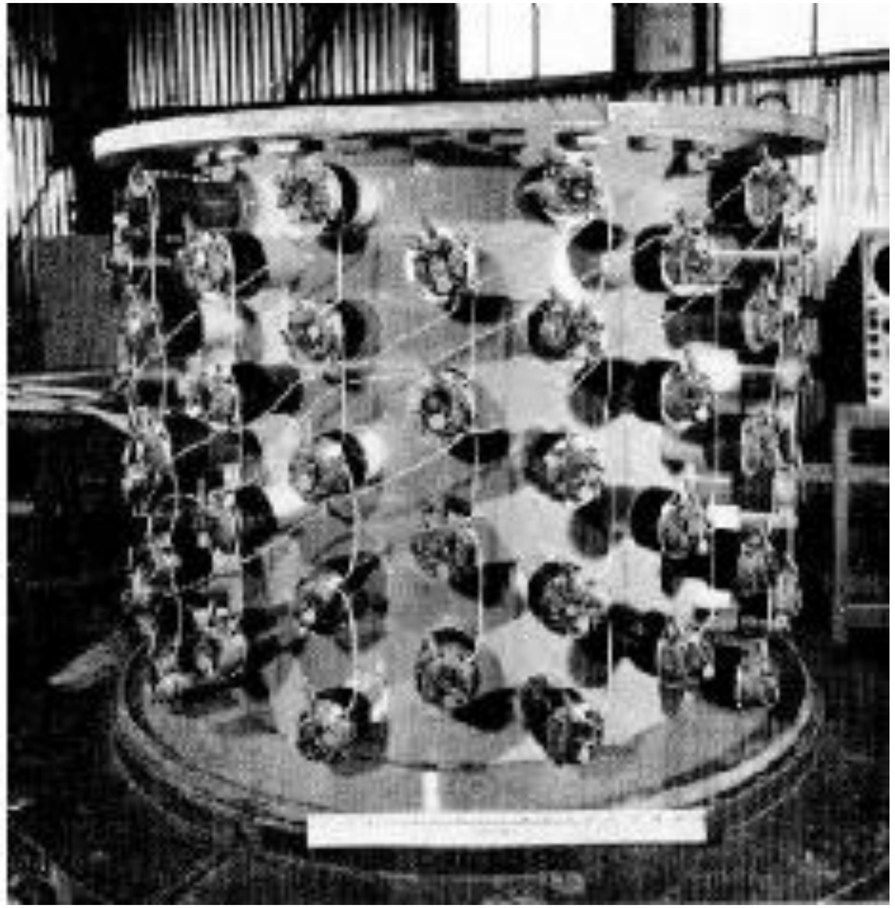
"I have done a terrible thing, I have postulated a particle that cannot be detected." - Pauli, 1930


Wolfgang Pauli

the new particle should be
- spin 1/2 (like the electron)
- electrically neutral
- of tiny mass ($<0.01\ m_p$)

“I have done a terrible thing, I have postulated a particle that ***cannot be detected****.” - Pauli, 1930*

Project *Poltergeist*, Savannah River nuclear reactor

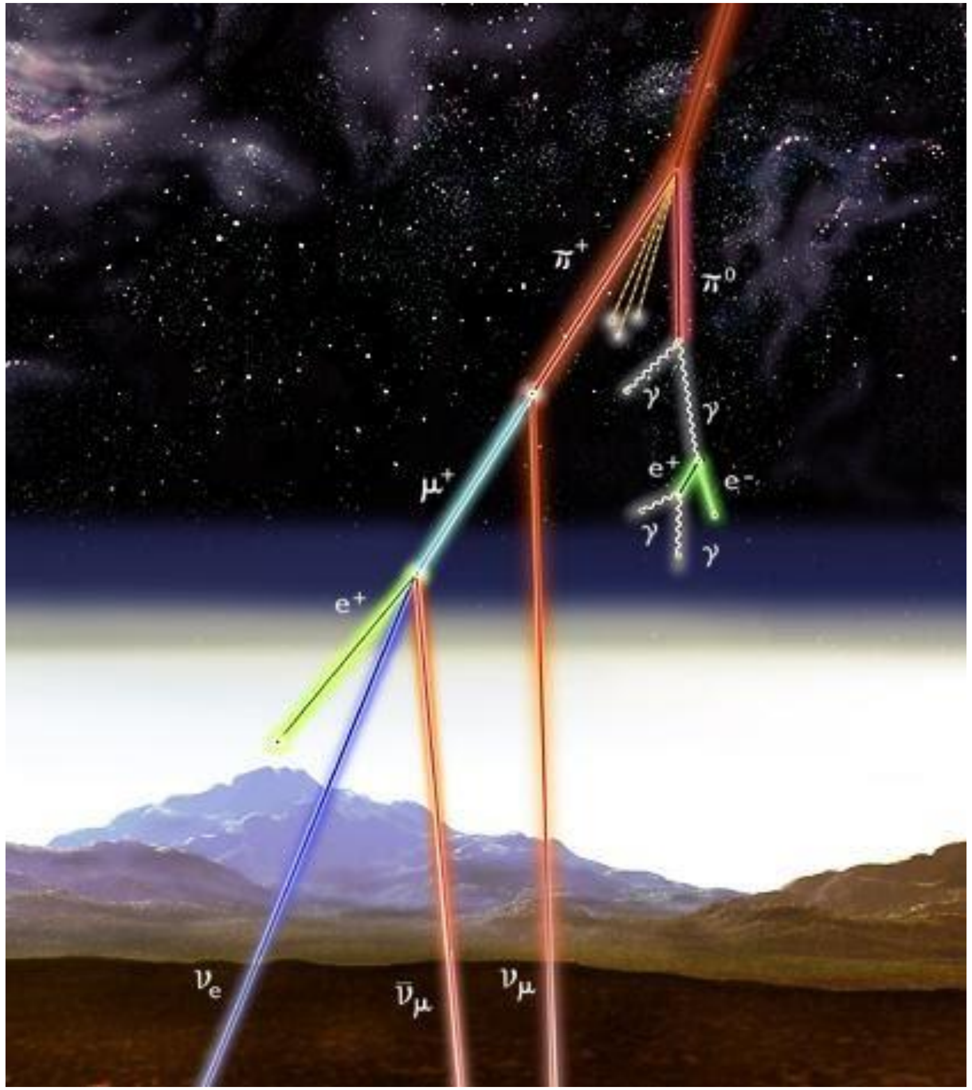


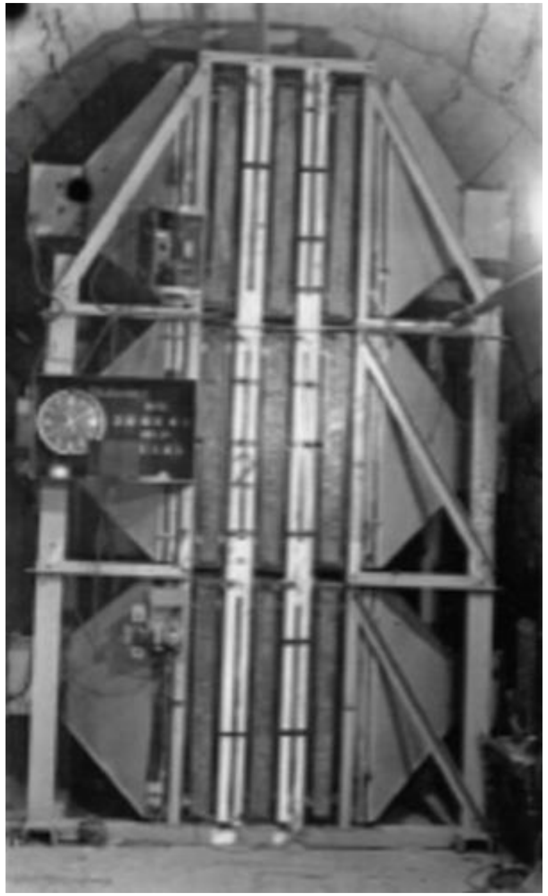
first neutrino observation, $\bar{\nu}_e$ from a reactor (1956)

first detection of the
muon neutrino,
from a particle beam
(1962)

M. Schwartz -
spark chamber
at BNL

discovery of atmospheric neutrinos (1965-68)

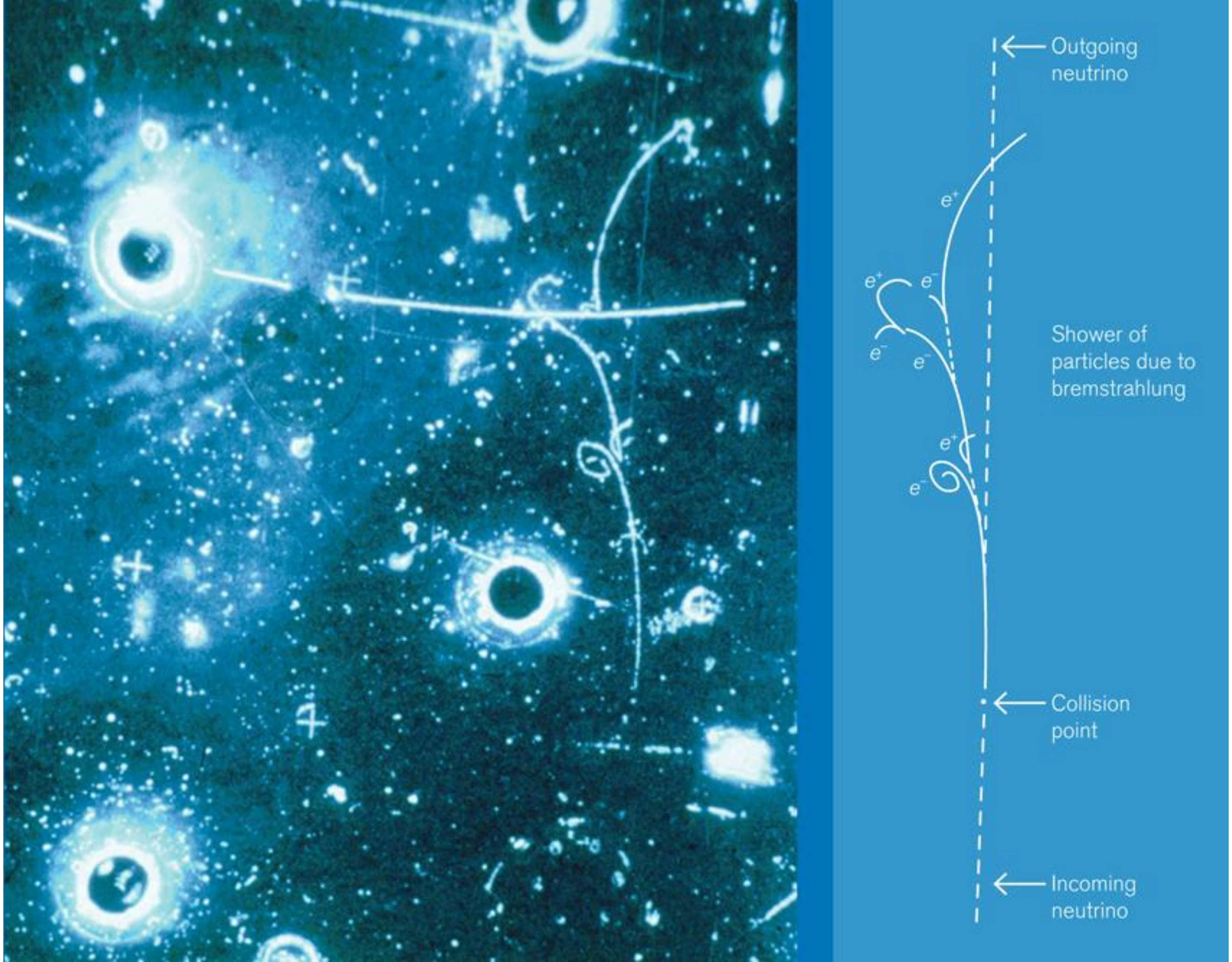




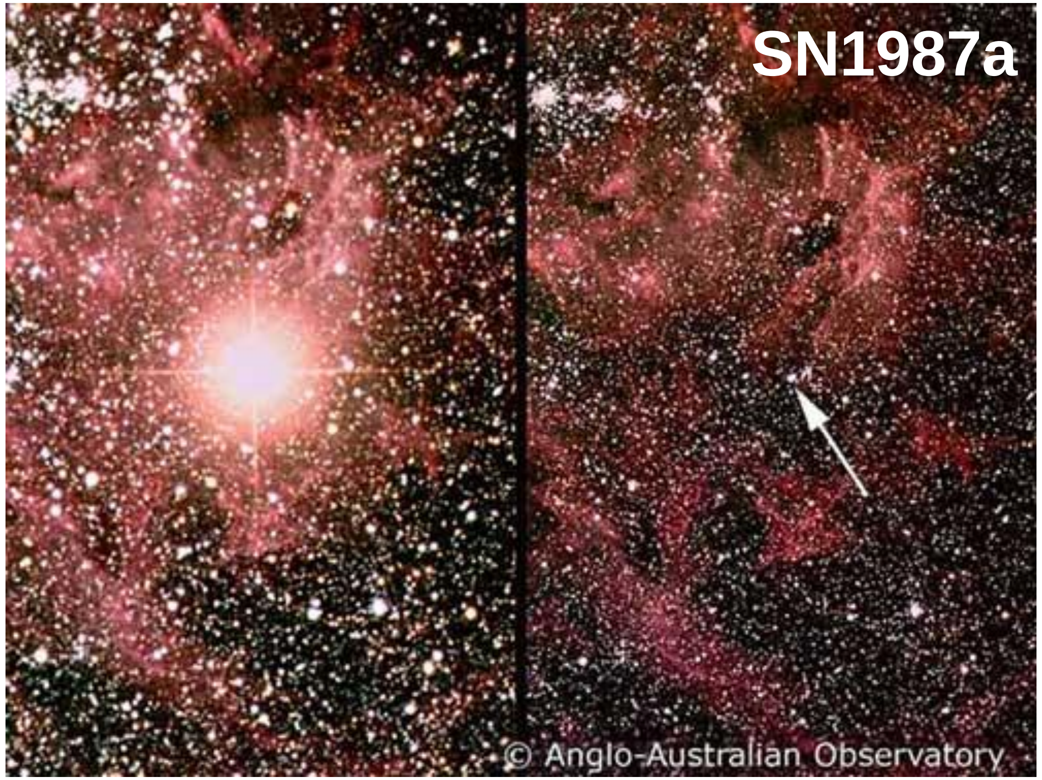
Kolar Gold Fields detector

Case Western Irvine/South Africa Neutrino Detector

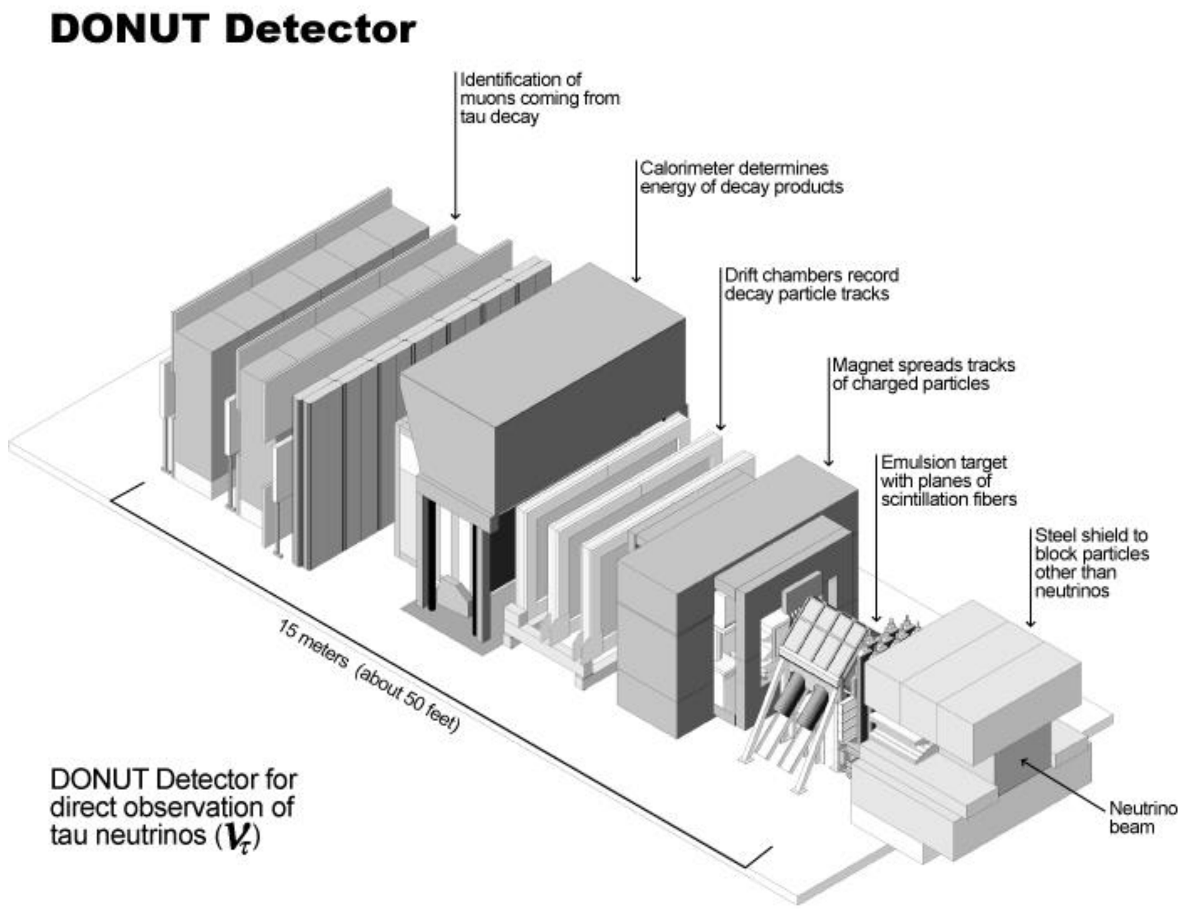
Gargamelle bubble chamber (1970)



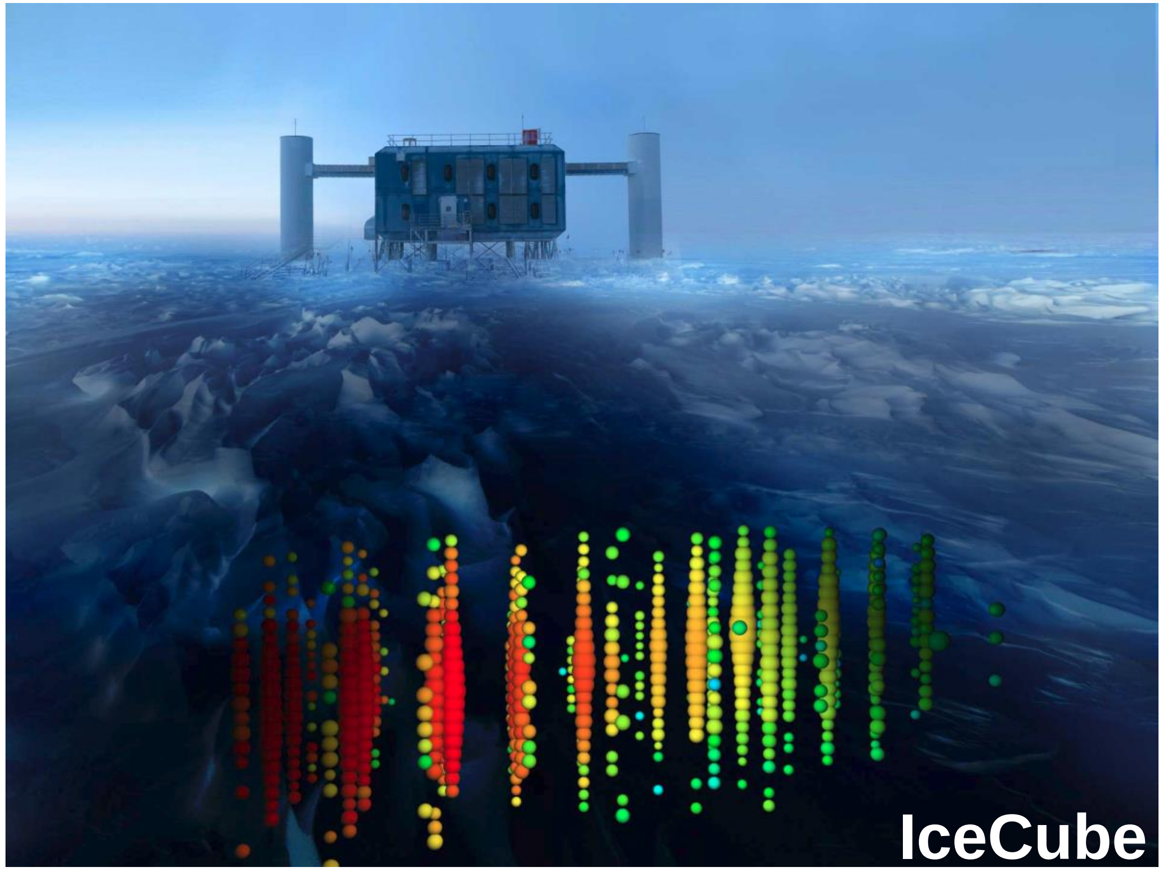
first detection of neutrinos from the Sun – with some odd results (1972)



first and only detection of neutrinos from a supernova (1987)



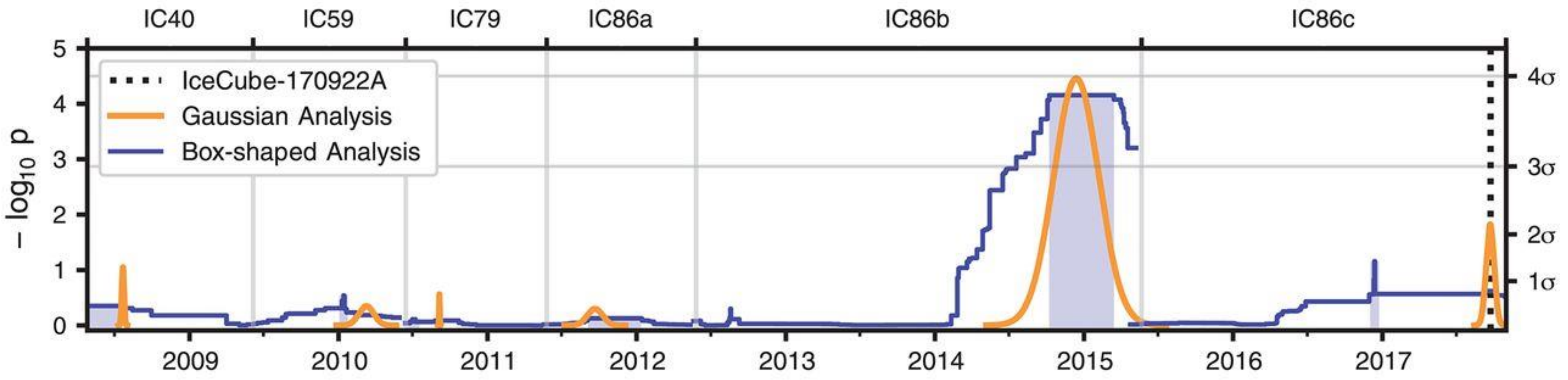
tau neutrino observed for the first time (2000)



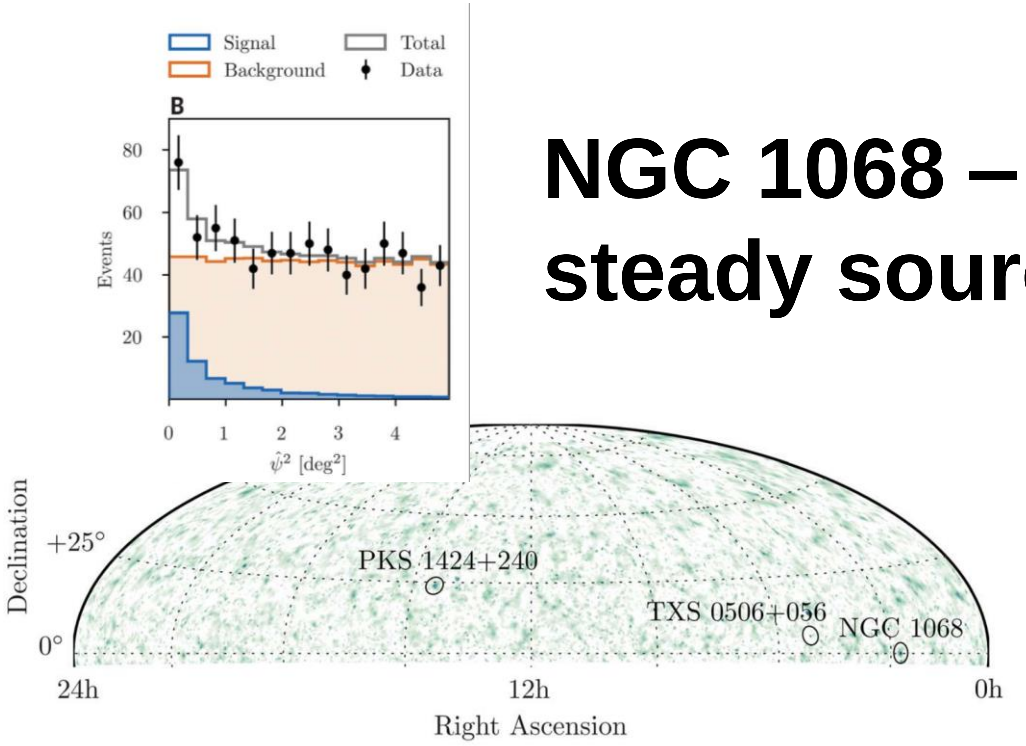
discovery of high energy astrophysical neutrinos (2013)

Astrophysical neutrino sources identified by IceCube

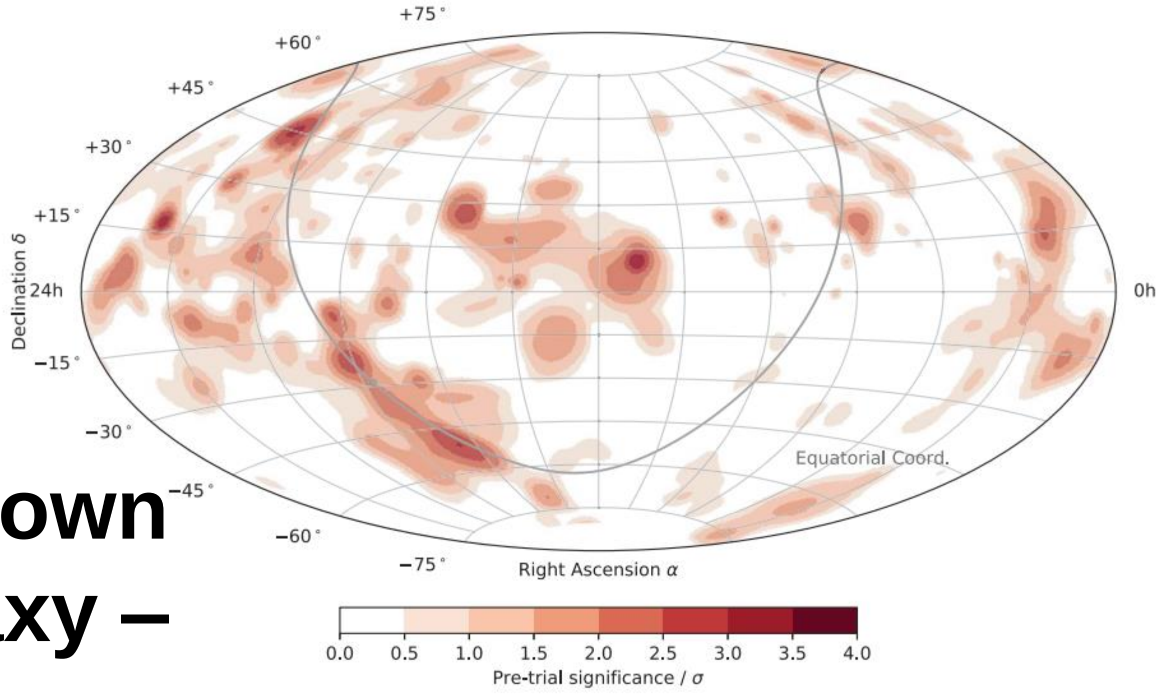
TXS 0506+056 (blazar) – two “flares”



NGC 1068 – steady source

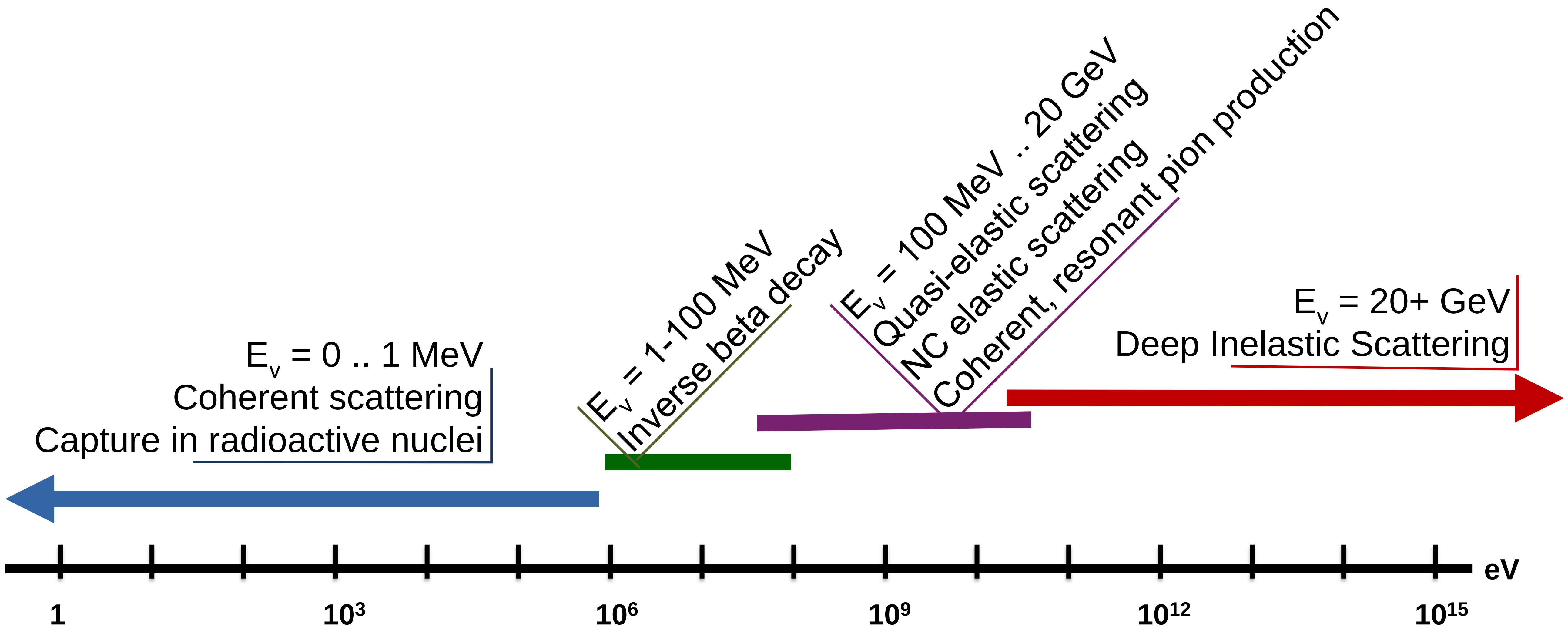


Our own galaxy – steady source

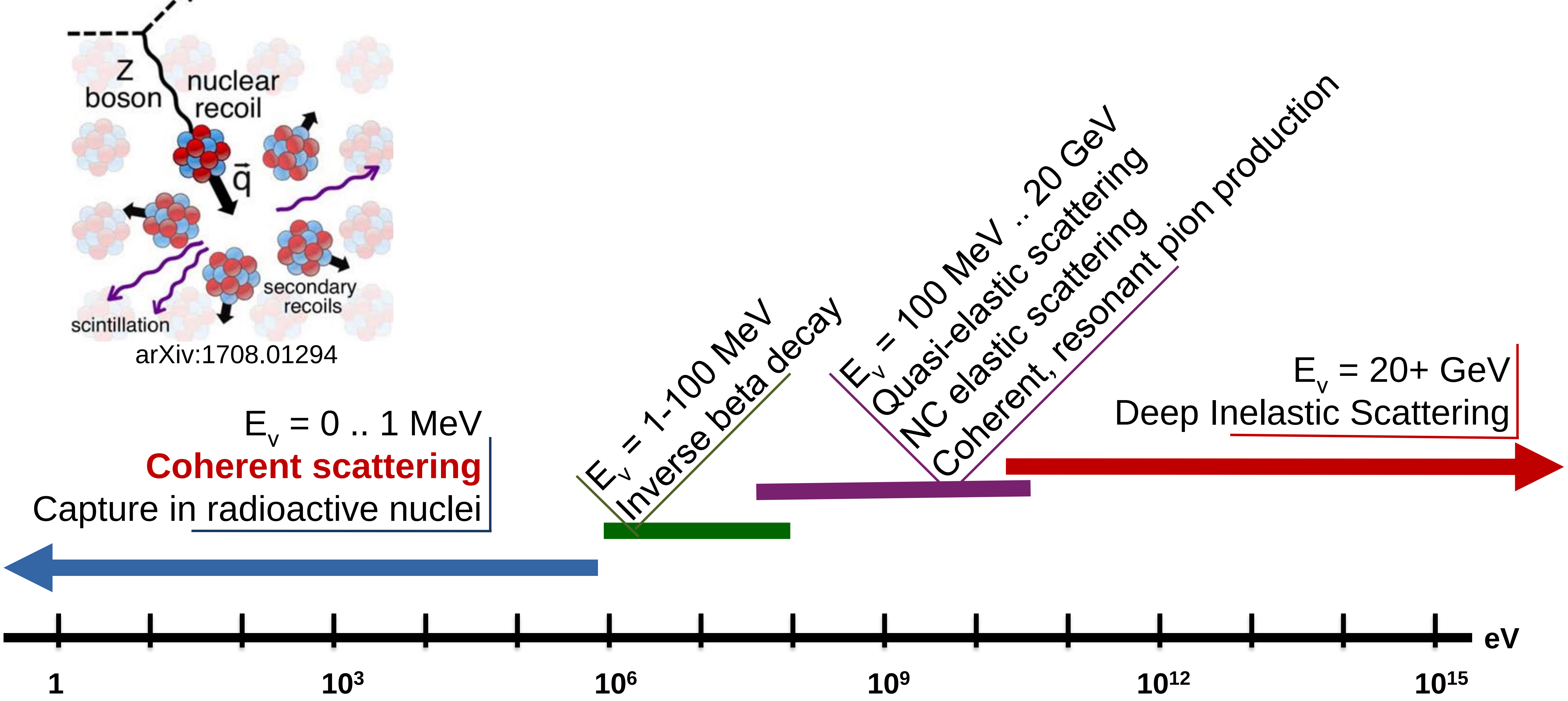


neutrinos can be detected

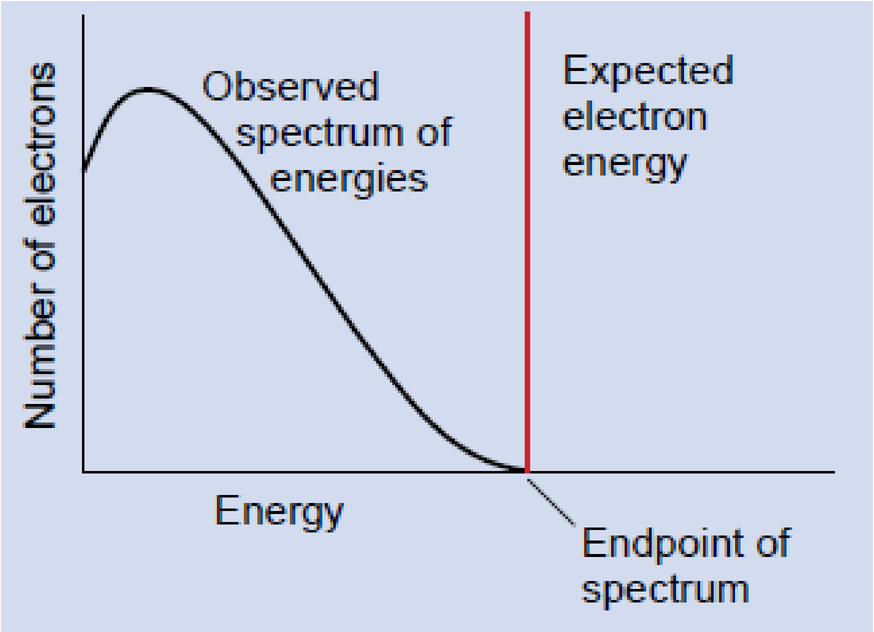
neutrino detection



neutrino detection



what about the neutrino mass?



The β-Spectrum of H^3

G. C. Hanna and B. Pontecorvo
Chalk River Laboratory, National Research Council of Canada, Chalk River, Ontario, Canada

January 28, 1949

THE proportional counter technique previously described[1,2] has been used to study the β-spectrum of H^3 an investigation of which has recently been reported by Curran *et al.*[3]

The two counters *I* and *II* described in reference 2 were used. The fillings are given in Table I.

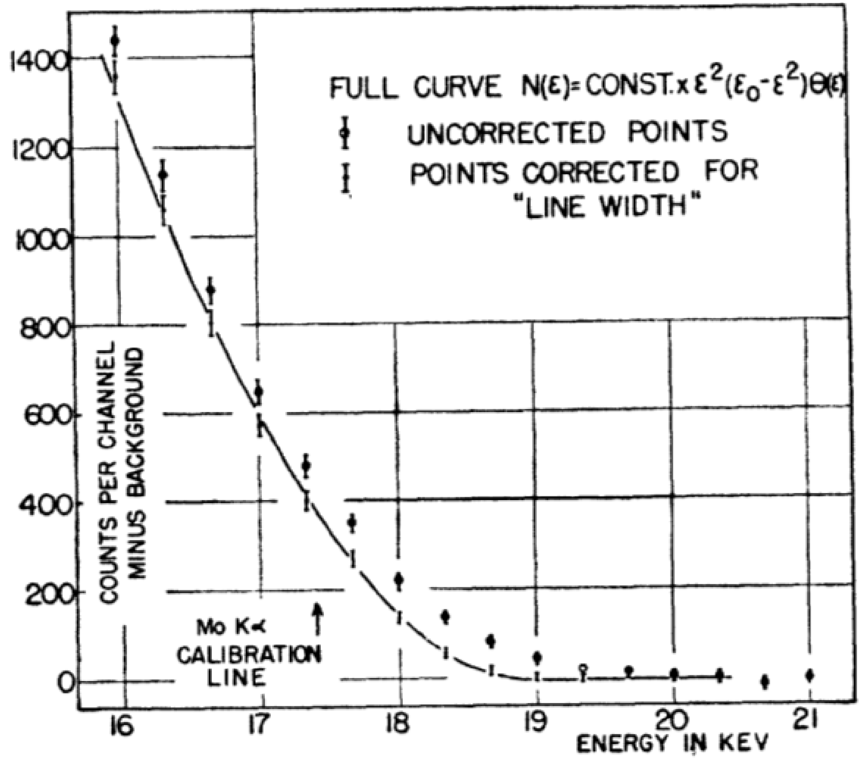


FIG. 1. The spectrum of H^3 in the region of the end

tritium (^{3}H) decay studies show are compatible with neutrinos of zero mass (1949)

Figures 1 and 2 show the experimental and corrected points obtained using counter *I*. The fact that the corrected points lie on the assumed theoretical curve from which the corrections were computed means that our initial assumption of a zero neutrino mass is correct, within our limits of error.

first weak interaction theories assume the neutrino is massless

(1957)

first weak interaction theories assume the neutrino is massless
(1957)

experiments agree with theory

first weak interaction theories assume the neutrino is massless
(1957)

experiments agree with theory

so the Standard Model is built using neutrinos with zero mass

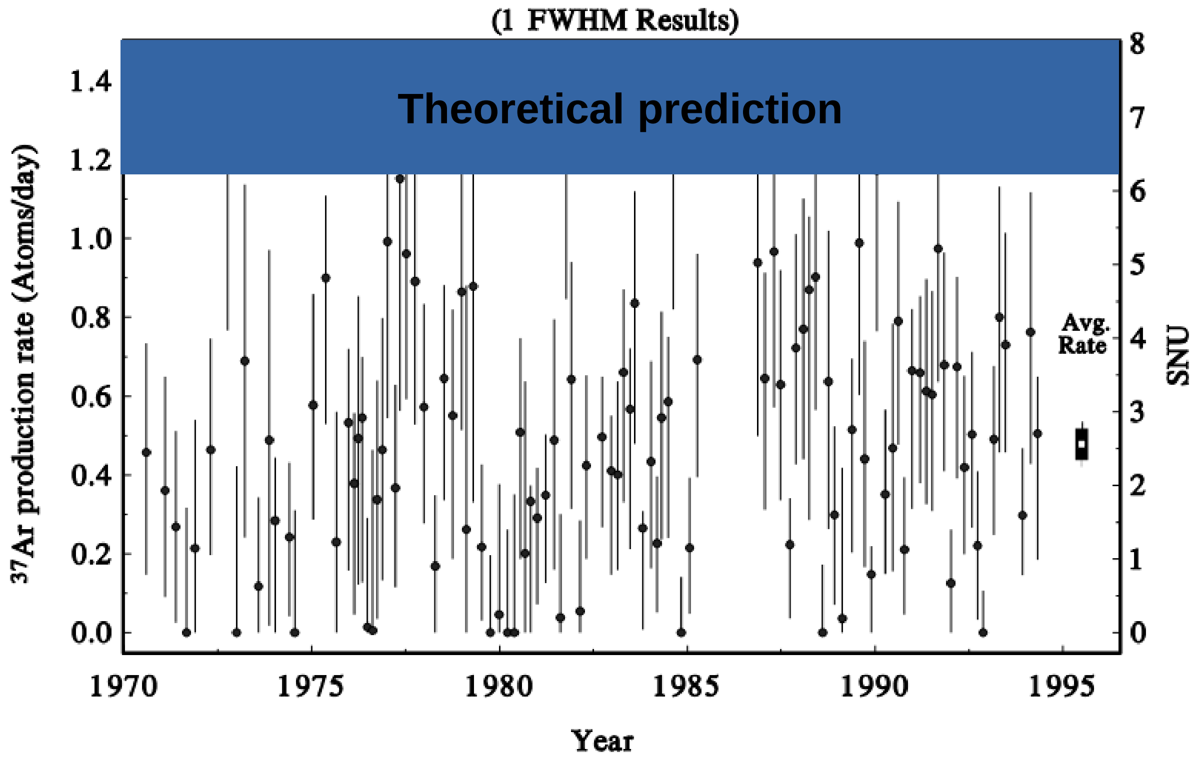
first weak interaction theories assume the neutrino is massless
(1957)

most experiments agree with theory

so the Standard Model is built using neutrinos with zero mass

missing solar neutrinos at Homestake

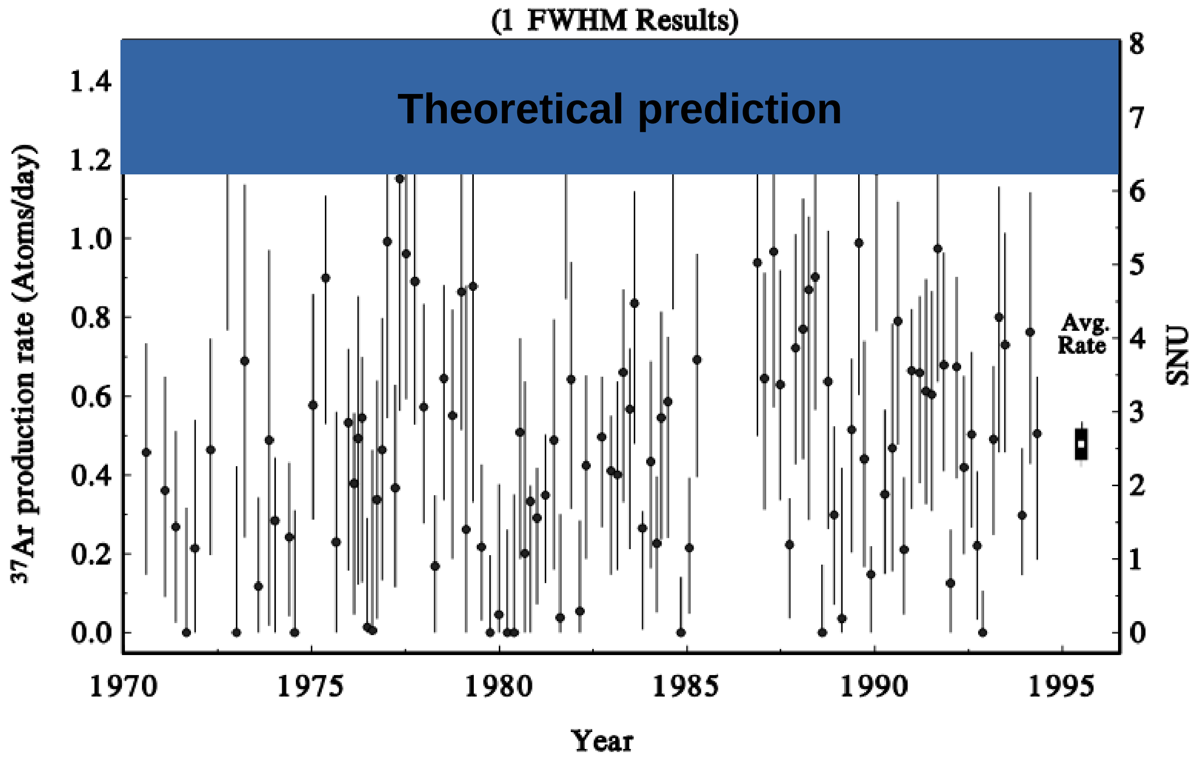
$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$



Cleveland, B.T. et al. Astrophys.J. 496 (1998) 505-526

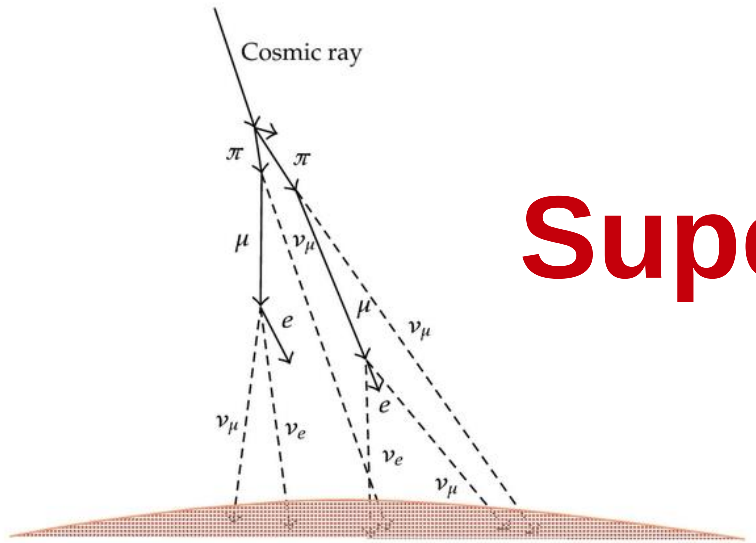
missing solar neutrinos at Homestake

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

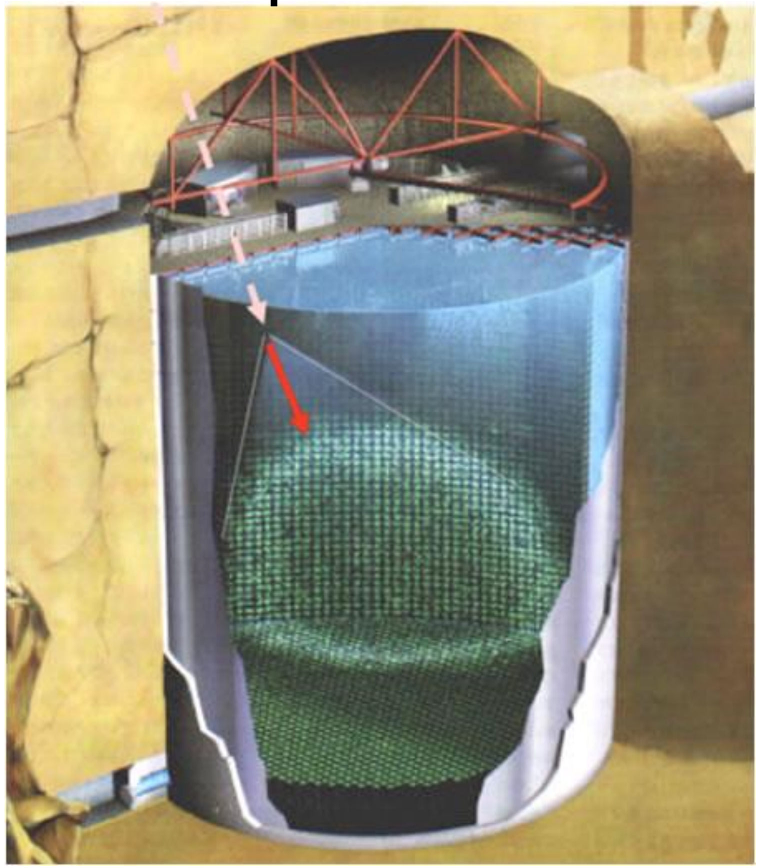


Cleveland, B.T. et al. Astrophys.J. 496 (1998) 505-526

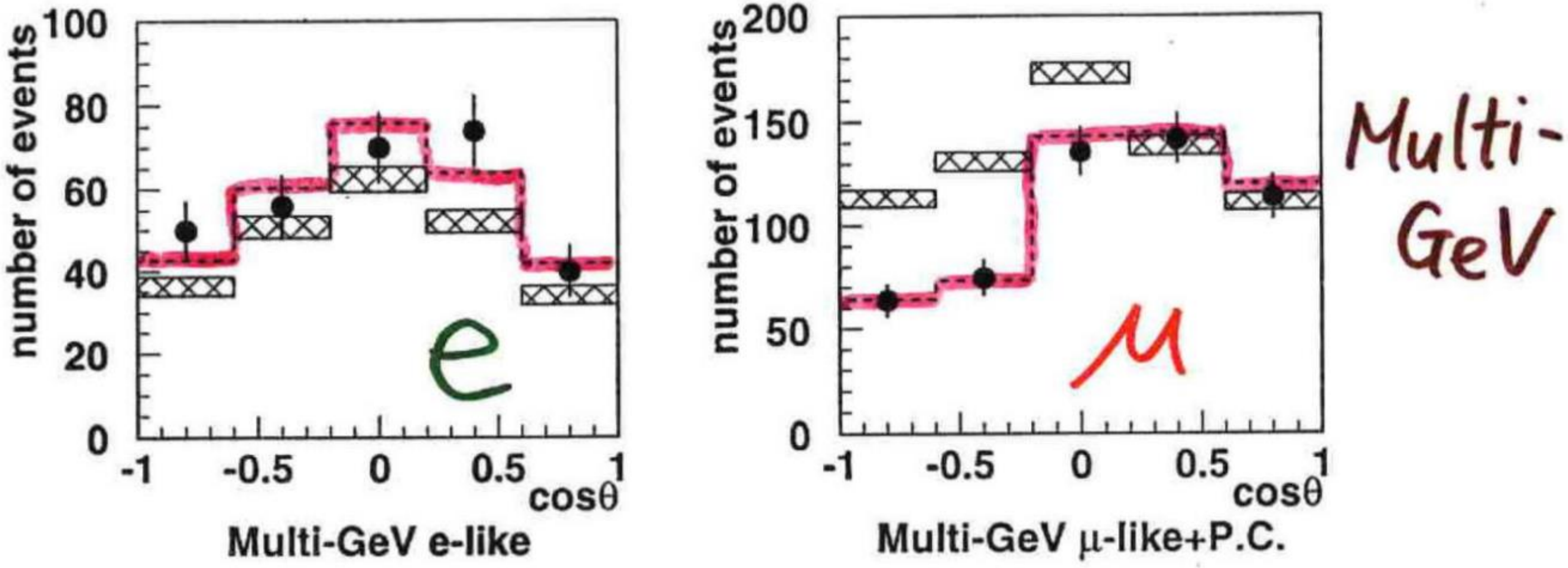
other experiments also see a neutrino deficit



Atmospheric neutrinos



and along came
Super-Kamiokande and SNO
(1998)

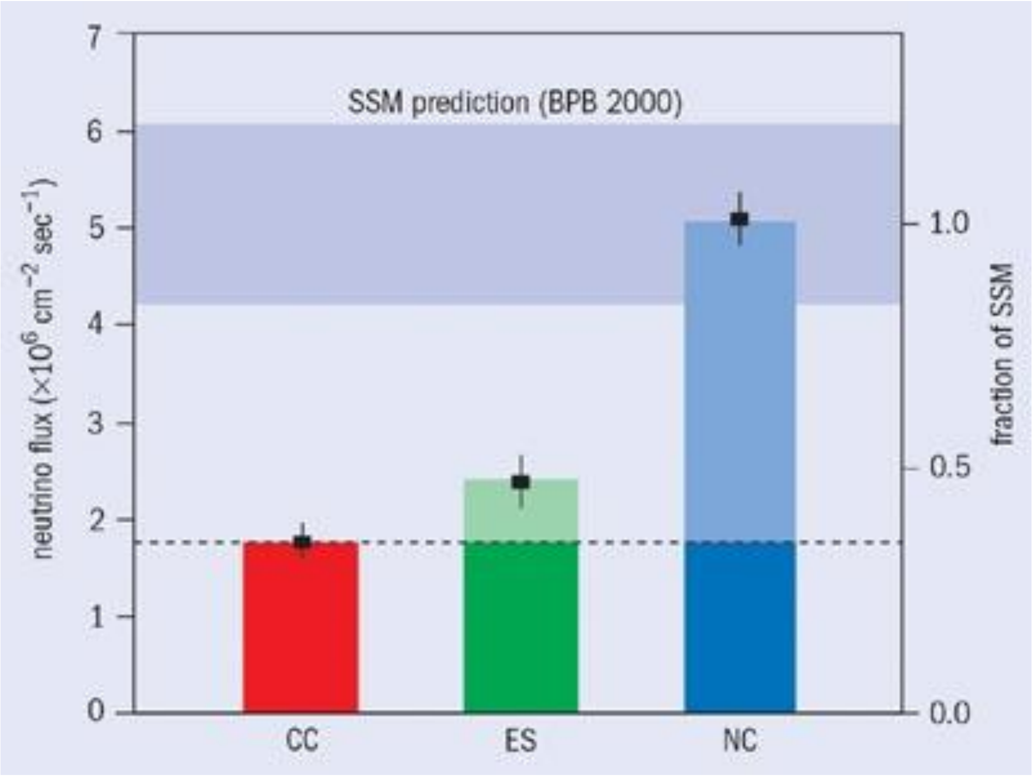


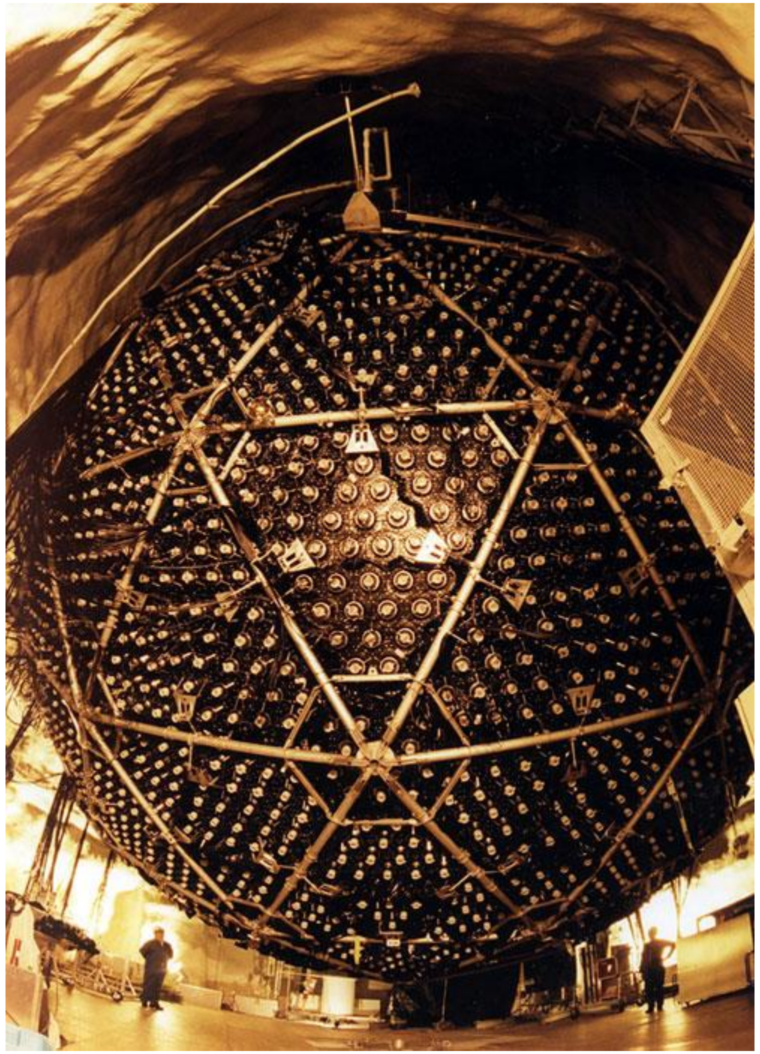
from Neutrino'98 presentation

and along came Super-Kamiokande and SNO (2001)

Solar neutrinos

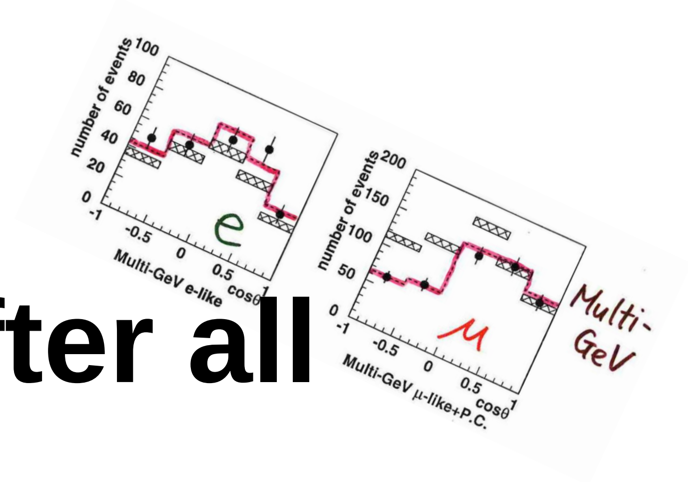
$$\nu_e + d \rightarrow p + p + e^- \qquad \text{(CC)}$$
$$\nu_x + d \rightarrow p + n + \nu_x \qquad \text{(NC)}$$
$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad \text{(ES)}$$

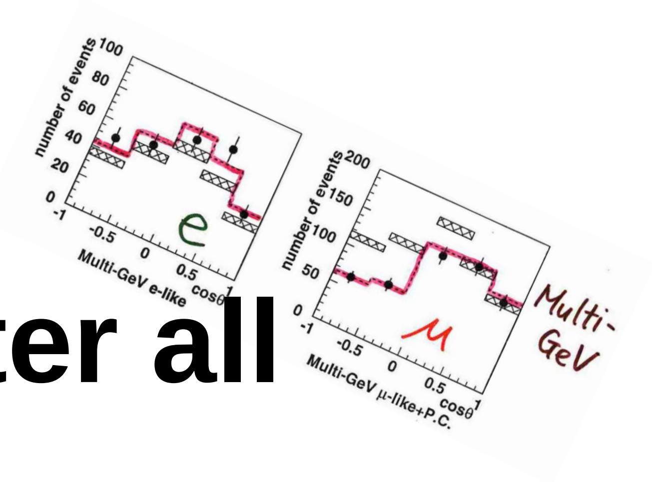




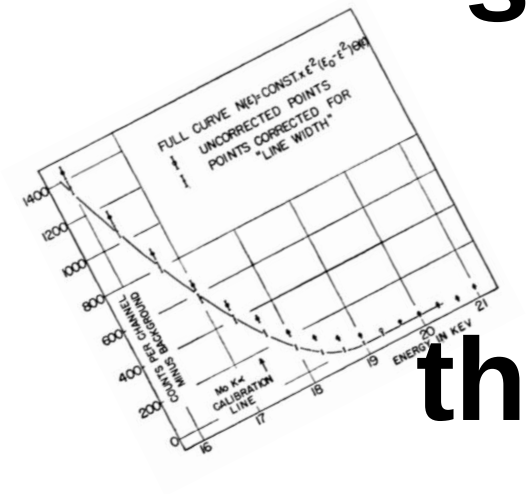
Sudbury Neutrino Observatory

so, neutrinos are massive after all

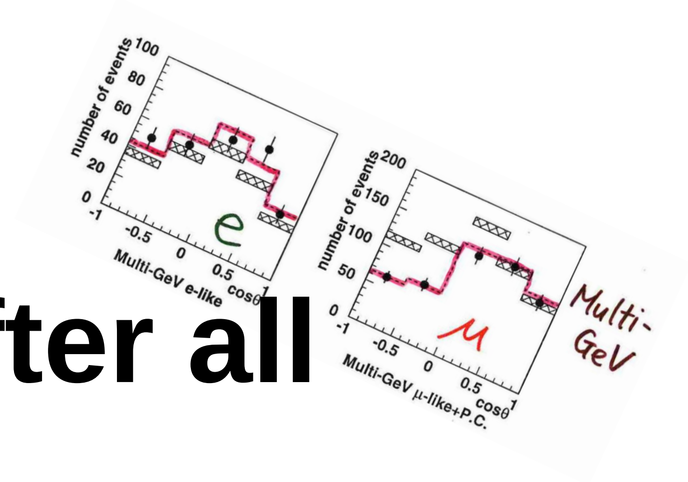




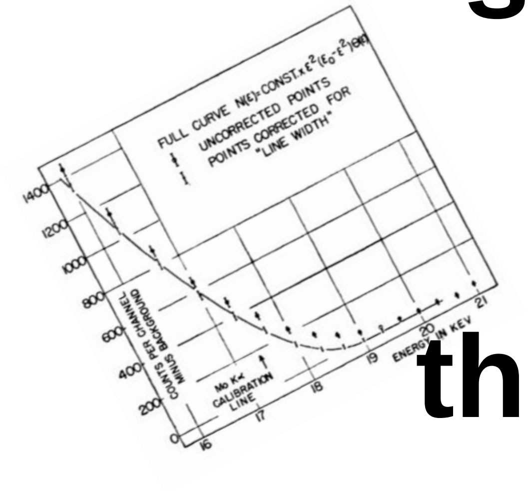
so, neutrinos are massive after all



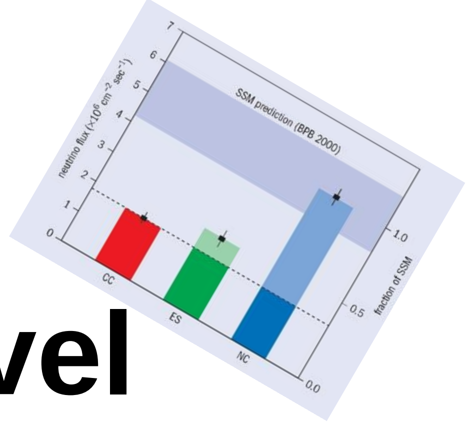
their masses are small, but relevant



so, neutrinos are massive after all



their masses are small, but relevant



their flavors get mixed as they travel

neutrino masses

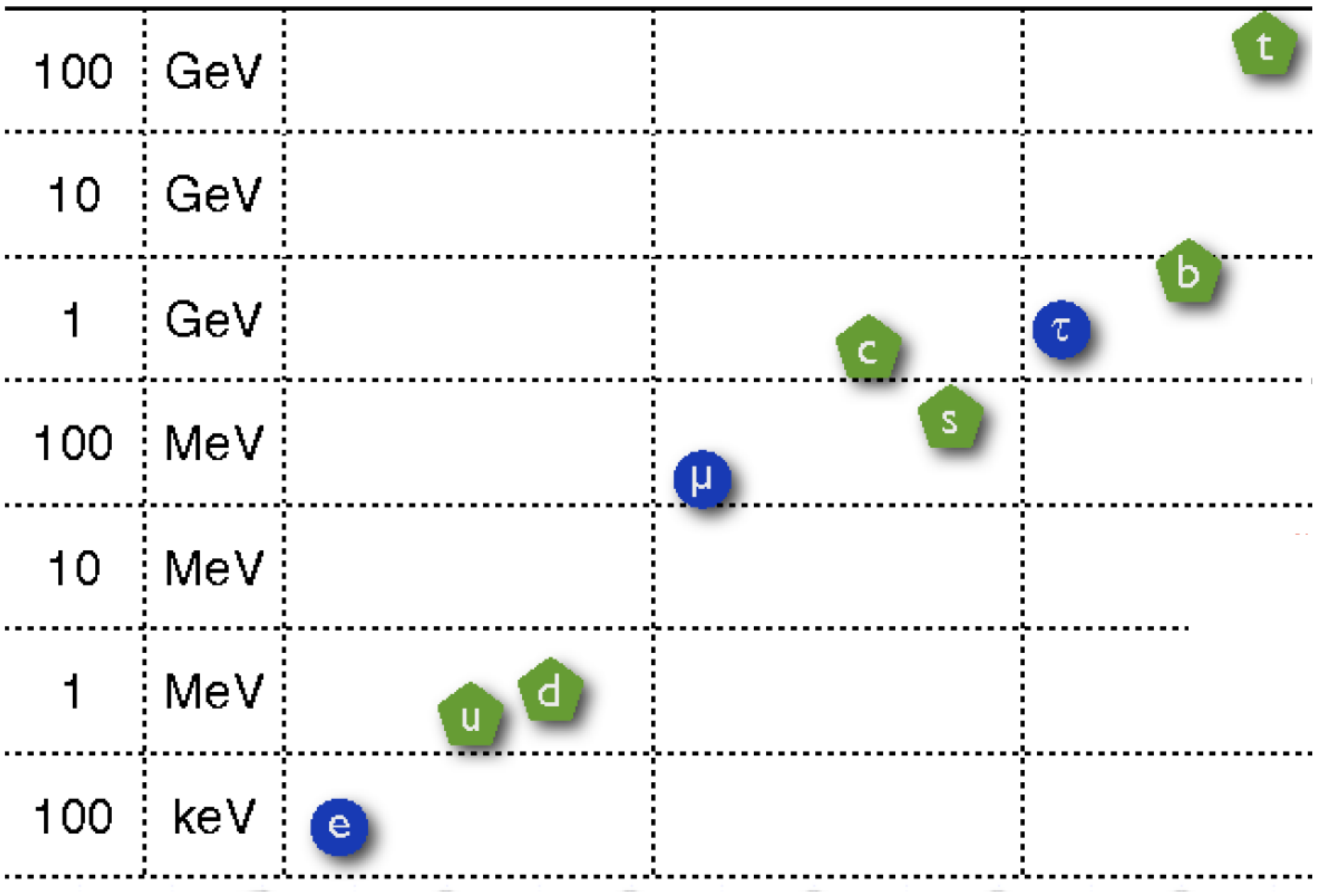
what's the origin of the ν mass?

you can add mass to the neutrino as you do for other matter particles

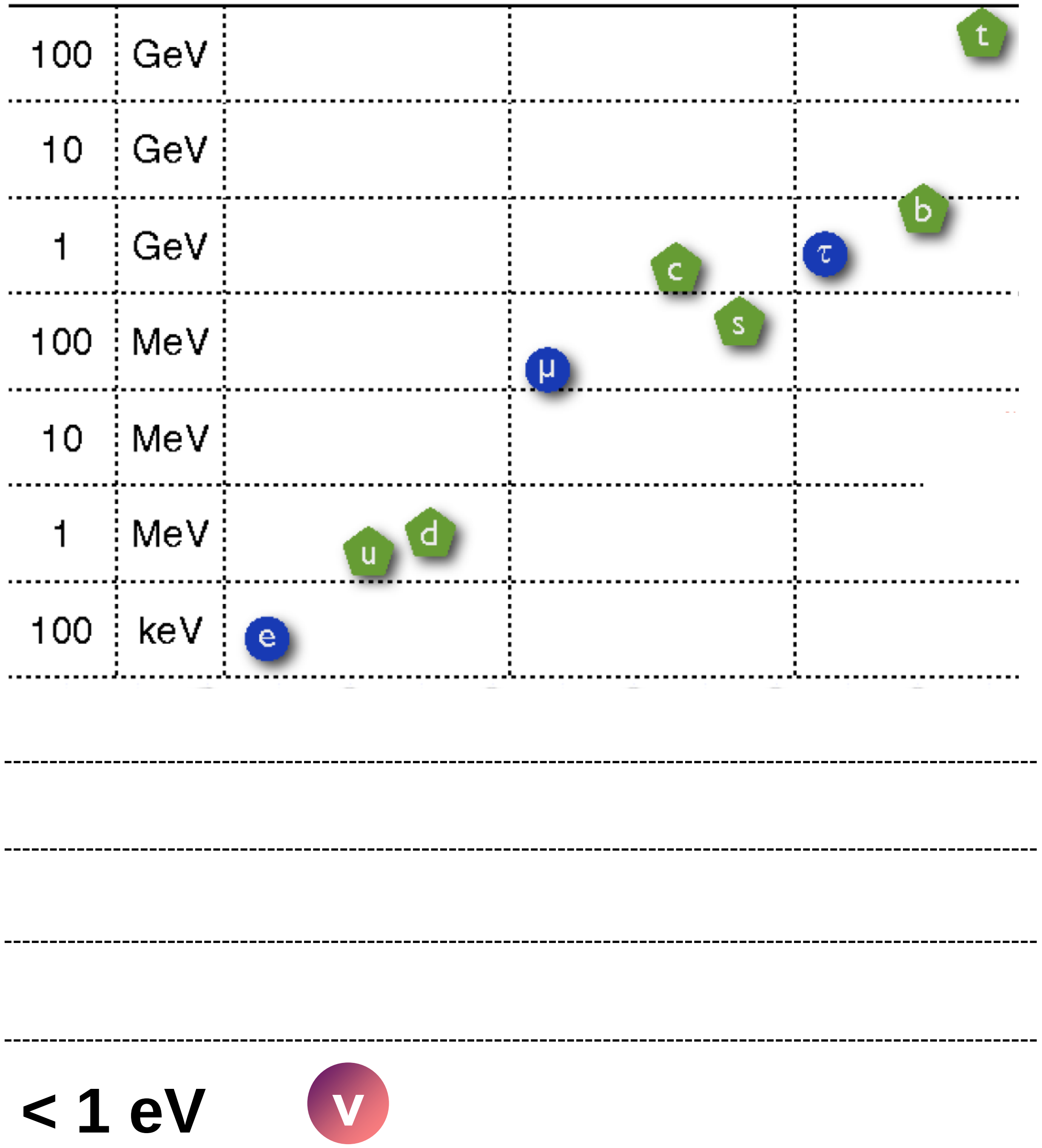
$$m_i = v\, y_i .$$

but

masses of elementary particles

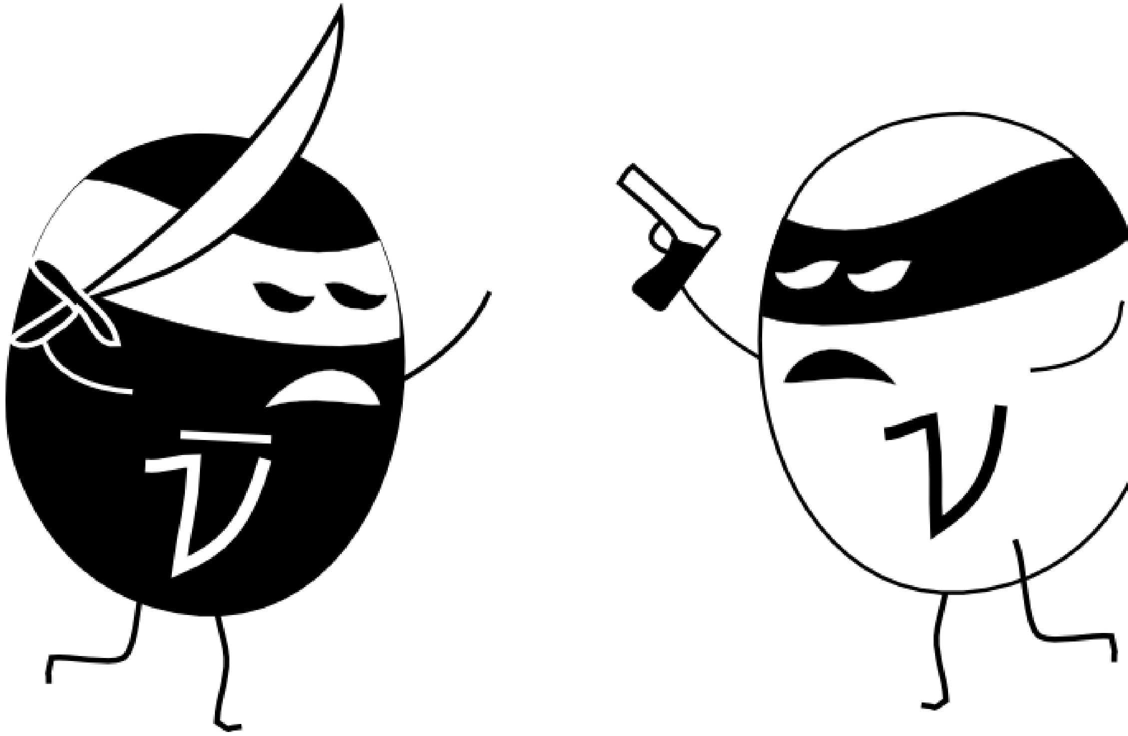


masses of elementary particles

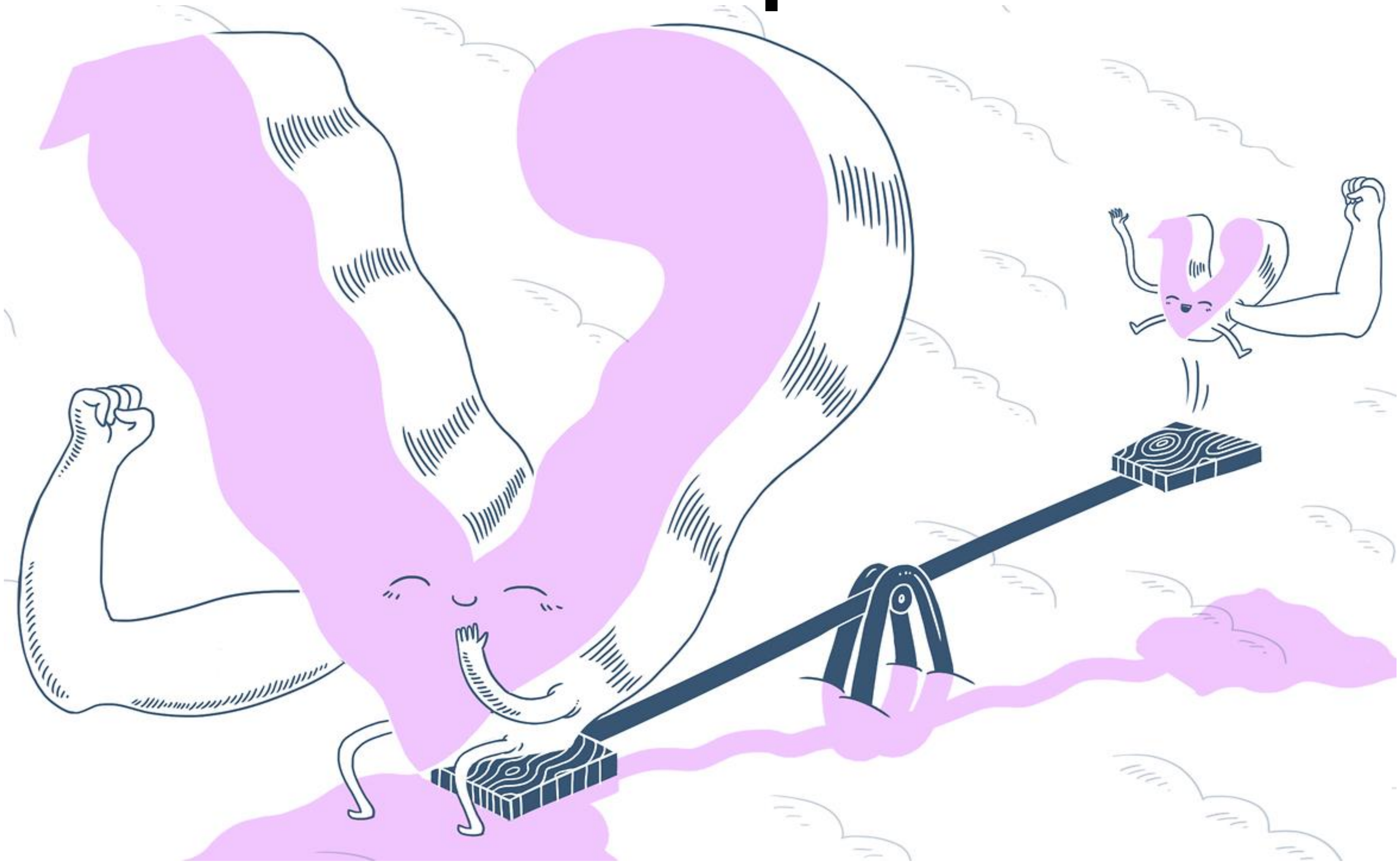


at least 5 orders of magnitude **below**

there's an alternative to gain mass
follow Majorana's recipe: elementary, massive neutral particles that are their own antiparticles
(E. Majorana, 1937)

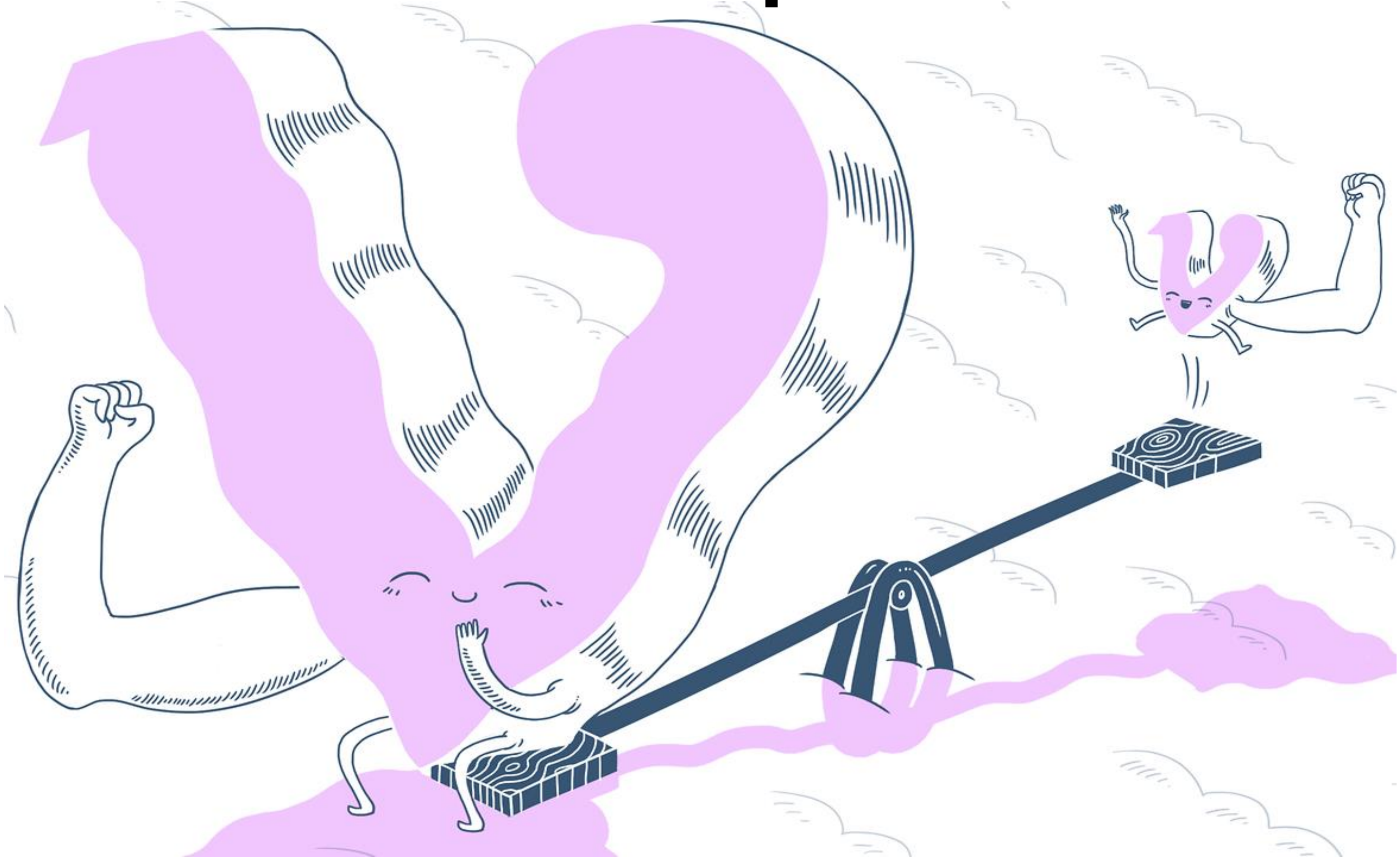


the **mechanism** generating the Majorana neutrino mass explains its **smallness**



$$m_i = \frac{v^2}{\Lambda} \overline{y}_i .$$

the mechanism generating the Majorana neutrino mass explains its smallness

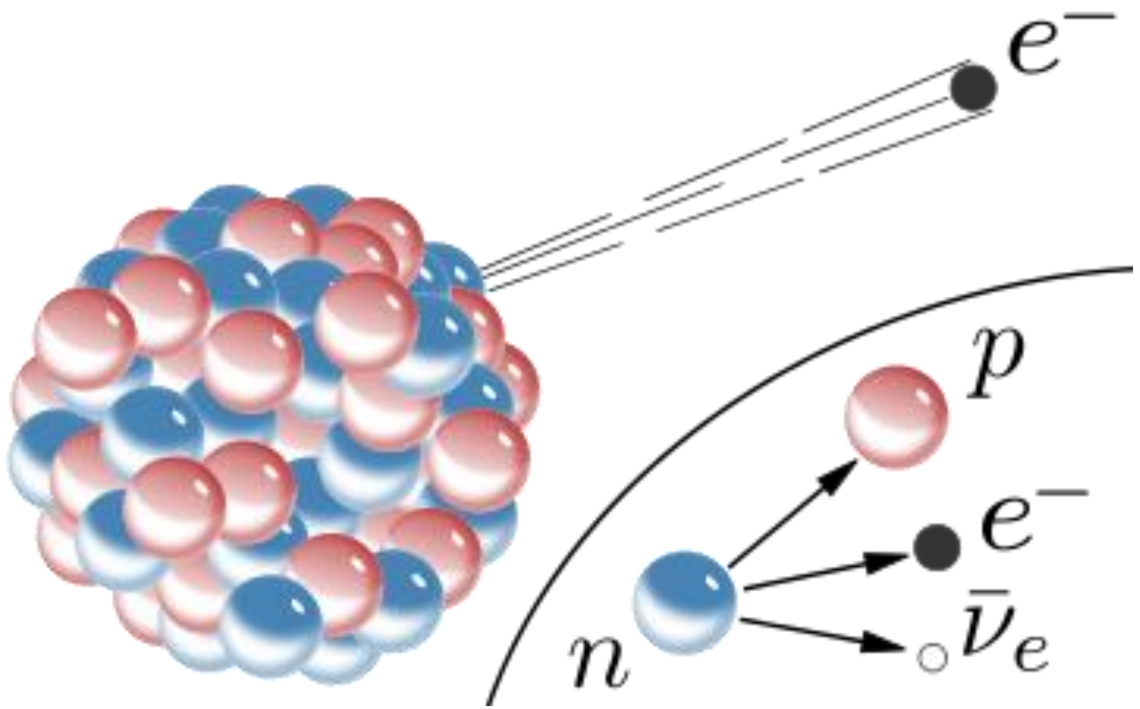


$$m_i = \frac{v^2}{\Lambda}\,\overline{y}_i .$$

New scale

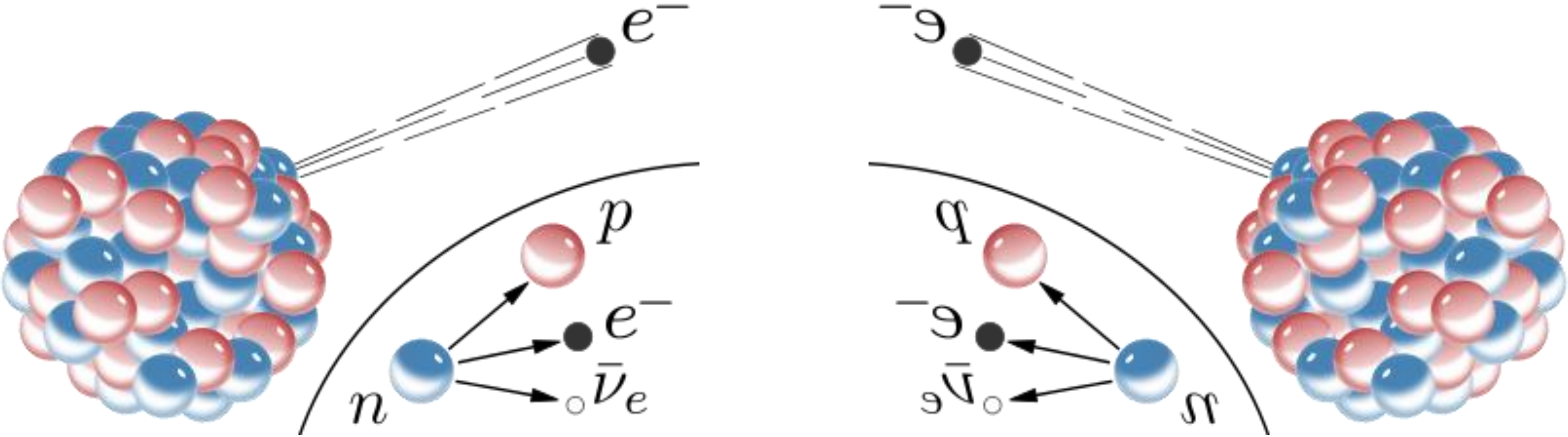
New problem?

another Majorana peculiarity



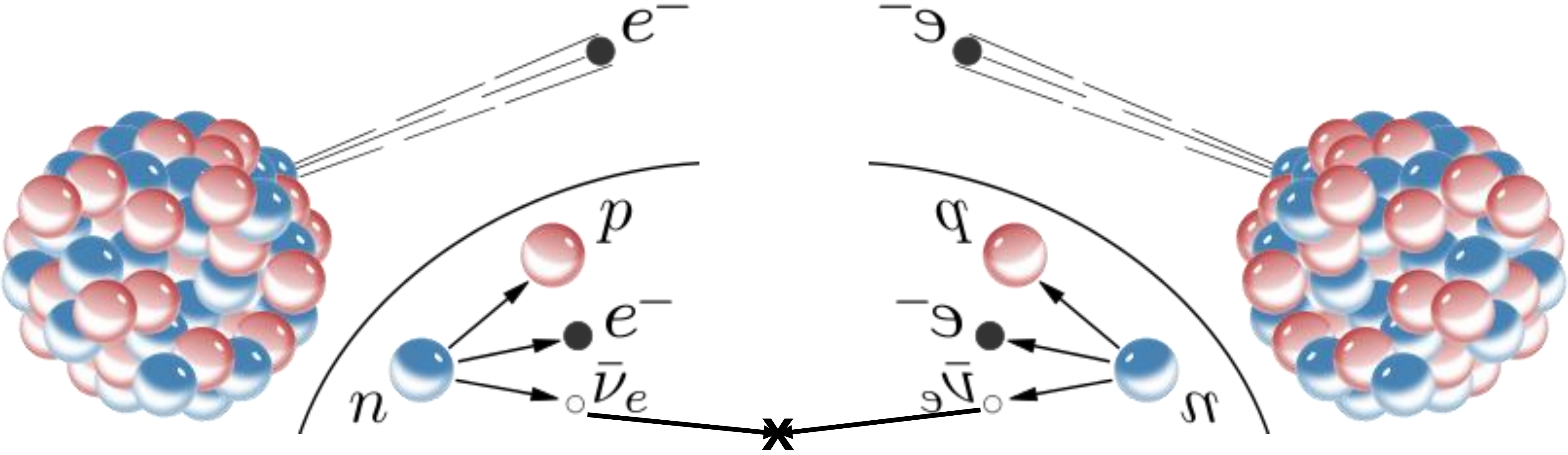
recall the antineutrino emission in beta decay

another Majorana peculiarity



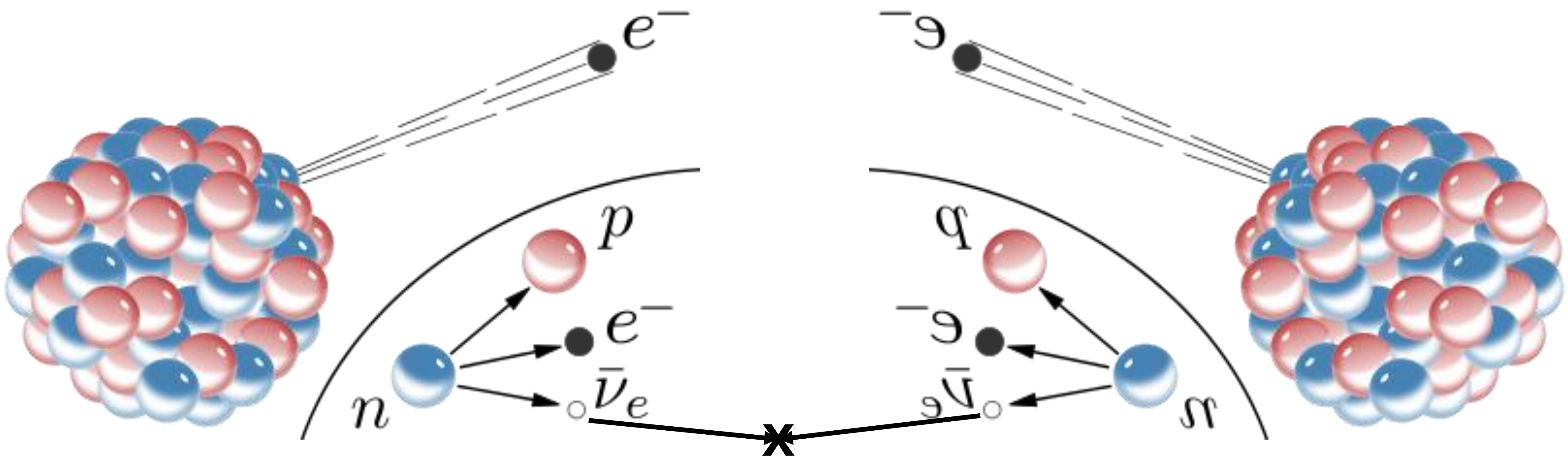
now, let's make it two of them

another Majorana peculiarity



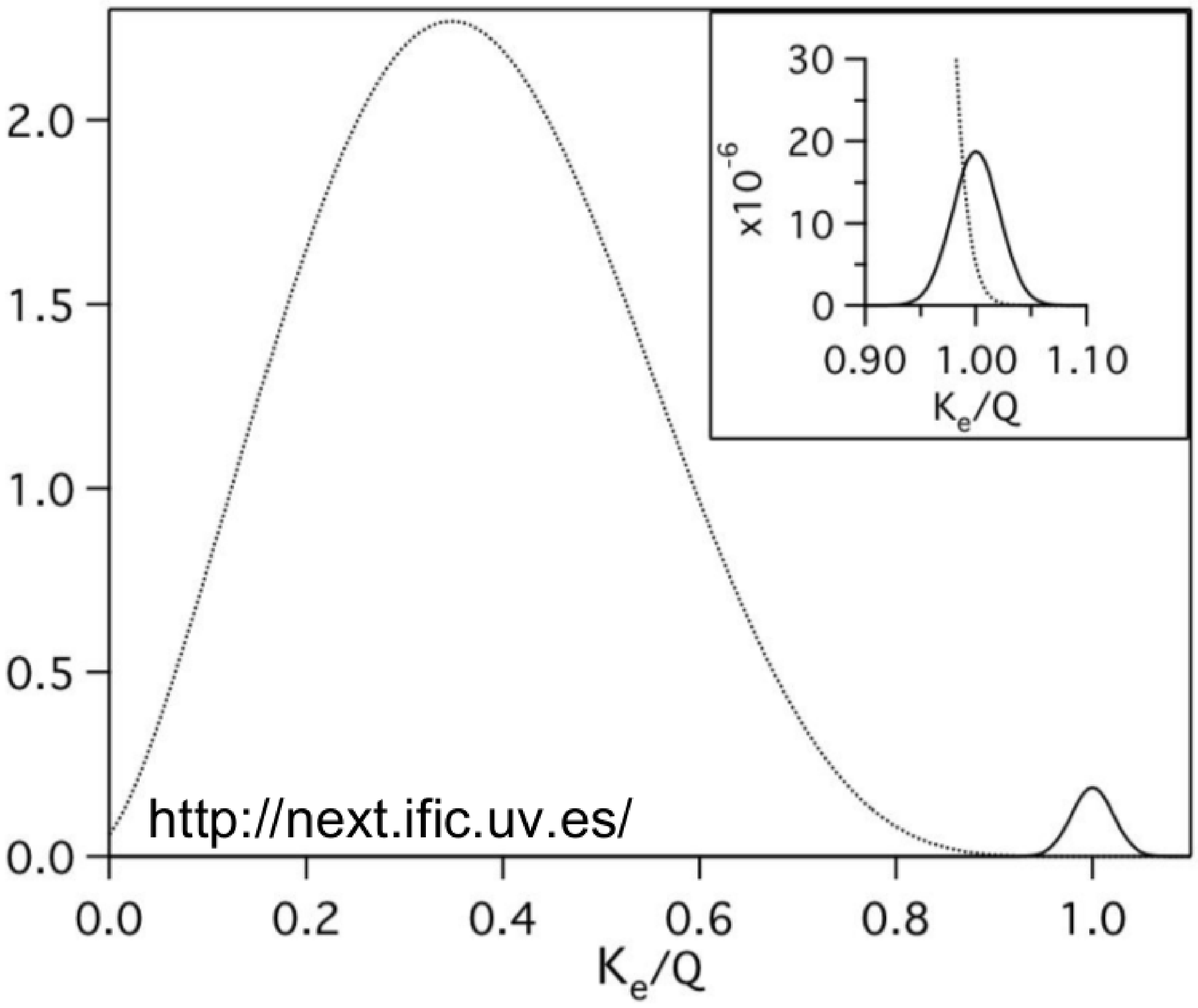
if the neutrino is its own antiparticle
annihilation can occur

another Majorana peculiarity



number of leptons change by 2
violating a law in the Standard Model

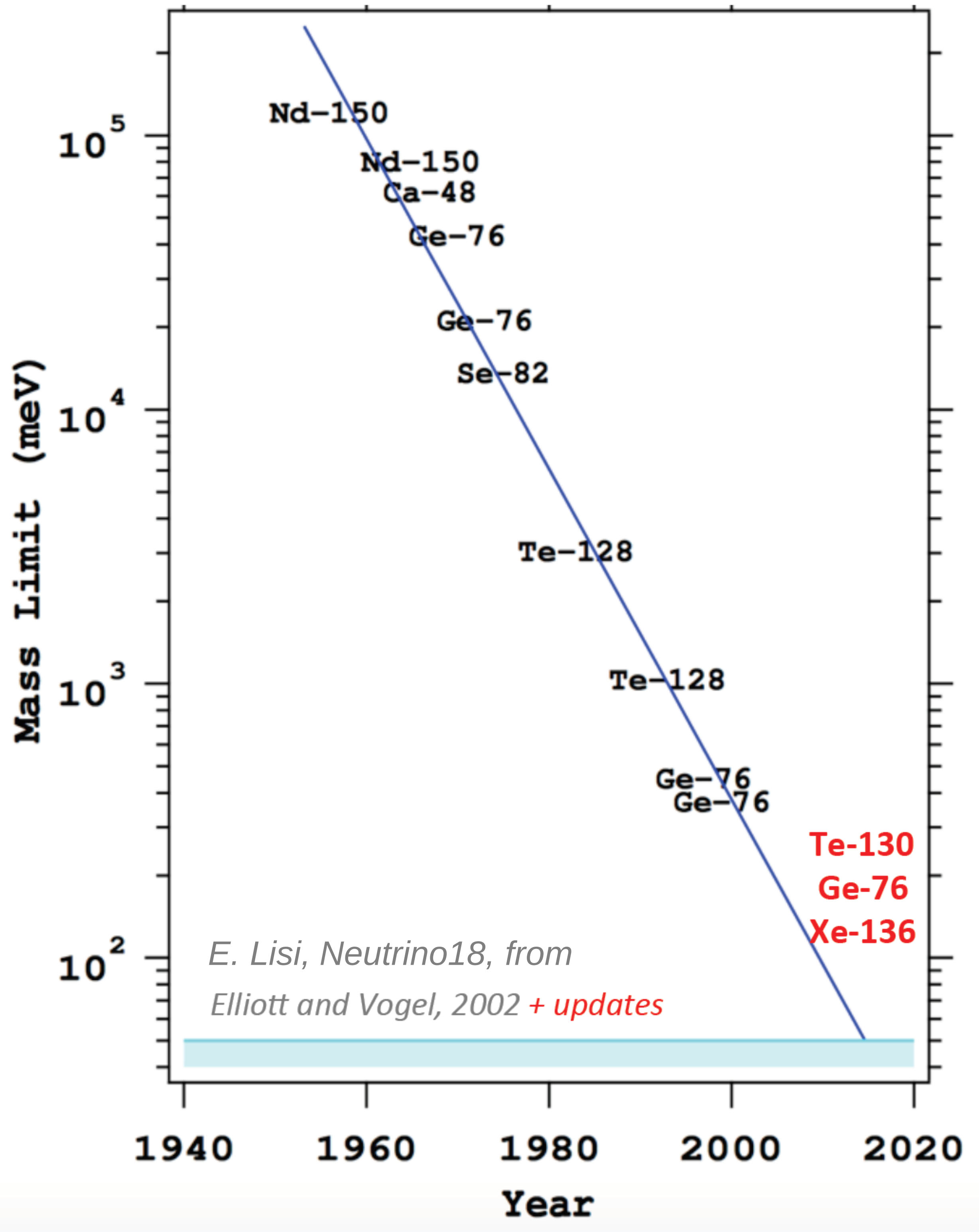
matter-antimatter asymmetry searches aka neutrinoless double-beta decay



$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\ \left|M_{0\nu}\right|^2\ m^2_{\beta\beta},$$

$$m_{\beta\beta} = \left|\sum_i U^2_{ei}\ m_i\right|,$$

evolution of limits

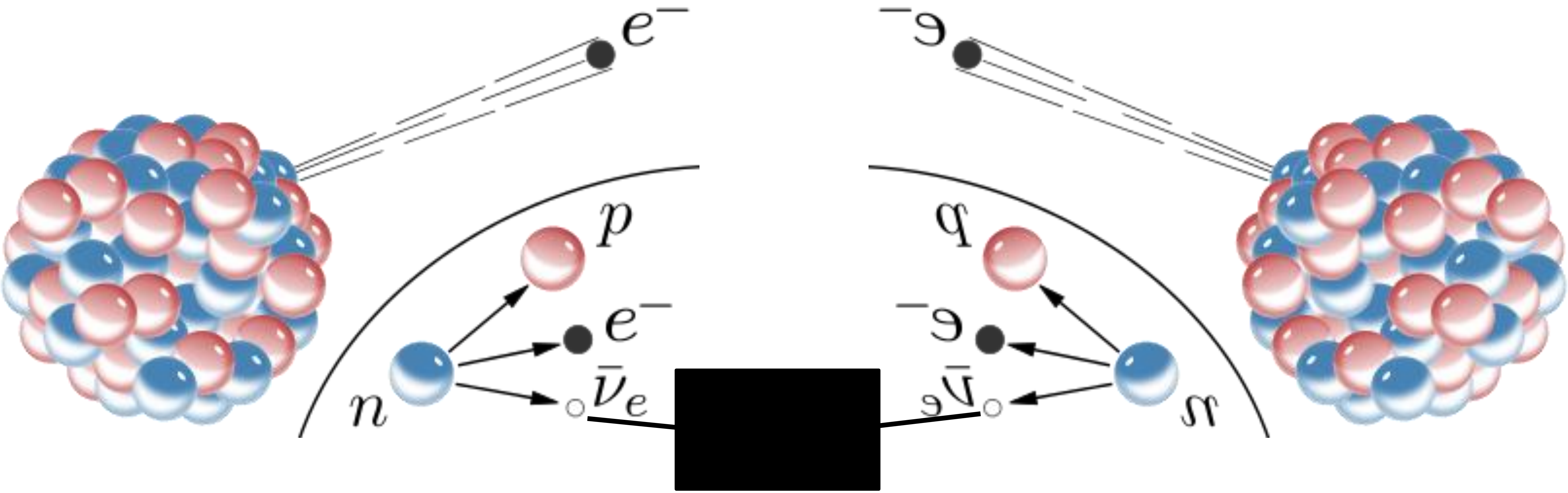


$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \left|M_{0\nu}\right|^2 m^2_{\beta\beta},$$

$$m_{\beta\beta} = \left|\sum_i U^2_{ei}\, m_i\right|,$$

scalability is as crucial as **background** suppression

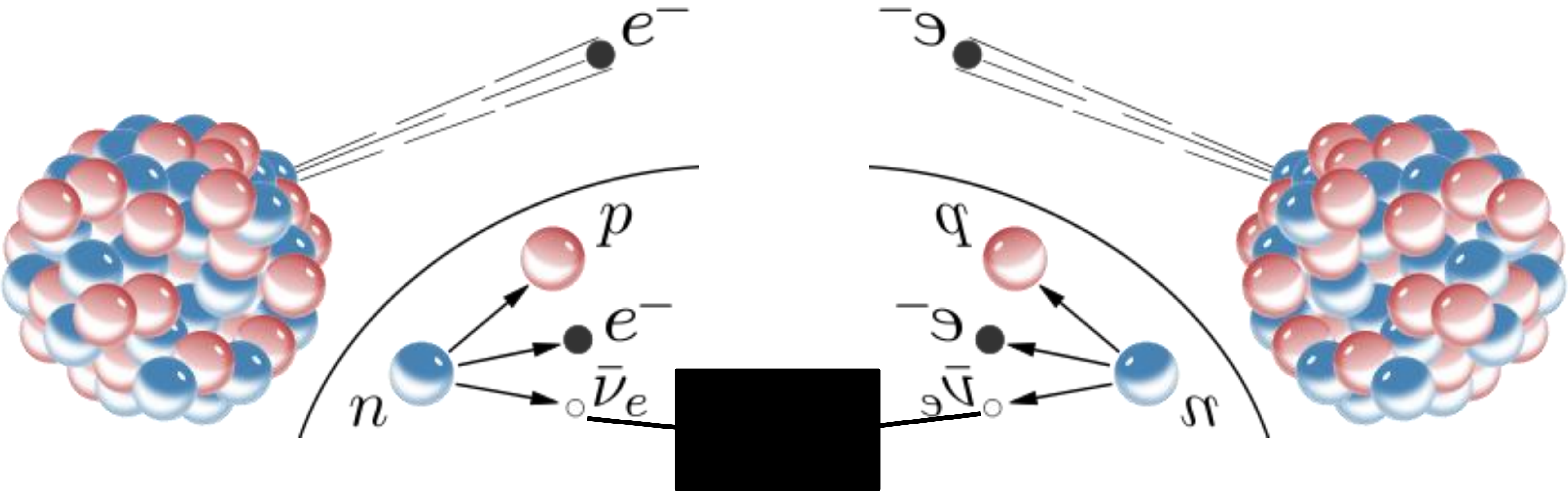
side note on this process



what happens in the box doesn't matter

observation of process → lepton # violation

side note on this process



asymmetry between ℓ & $\bar{\ell}$ $\rightarrow$ leptogenesis

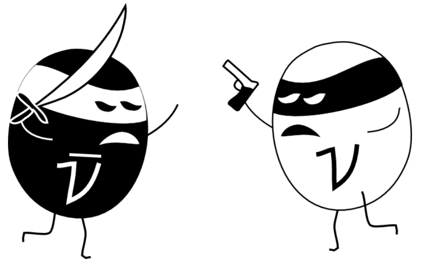
conversion between

baryons to anti-leptons, anti-baryons to leptons

by a Standard Model process known as “sphalerons”

asymmetry between ℓ & $\bar{\ell}$ $\rightarrow$ leptogenesis

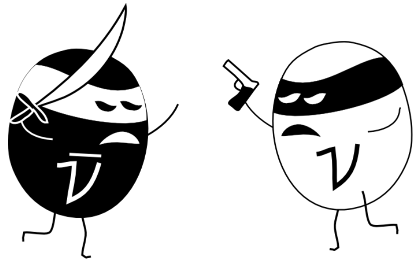
baryon-antibaryon asymmetry → baryogenesis



conversion between
baryons to anti-leptons, anti-baryons to leptons
by a Standard Model process known as “sphalerons”

asymmetry between ℓ & $\bar{\ell}$ → leptogenesis

baryon-antibaryon asymmetry $\rightarrow$ baryogenesis



possible explanation of matter-antimatter asymmetry in the Universe

asymmetry between ℓ & $\bar{\ell}$ $\rightarrow$ leptogenesis

origin still unknown, fine … but what is the mass?

direct mass measurements

The β-Spectrum of H^3

G. C. Hanna and B. Pontecorvo
Chalk River Laboratory, National Research Council of Canada, Chalk River, Ontario, Canada

January 28, 1949

THE proportional counter technique previously described[1,2] has been used to study the β-spectrum of H^3 an investigation of which has recently been reported by Curran *et al.*[3] The two counters *I* and *II* described in reference 2 were used. The fillings are given in Table I.

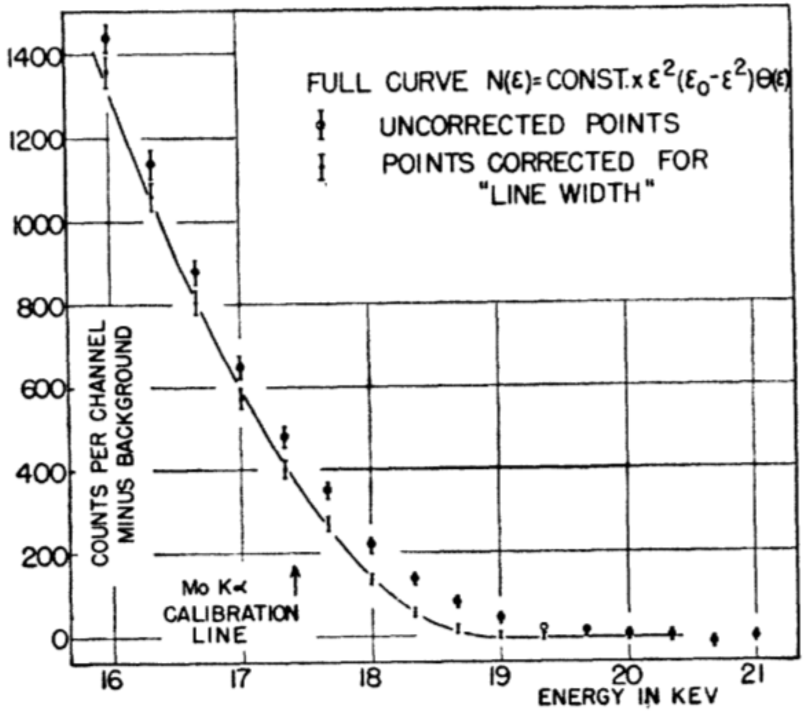
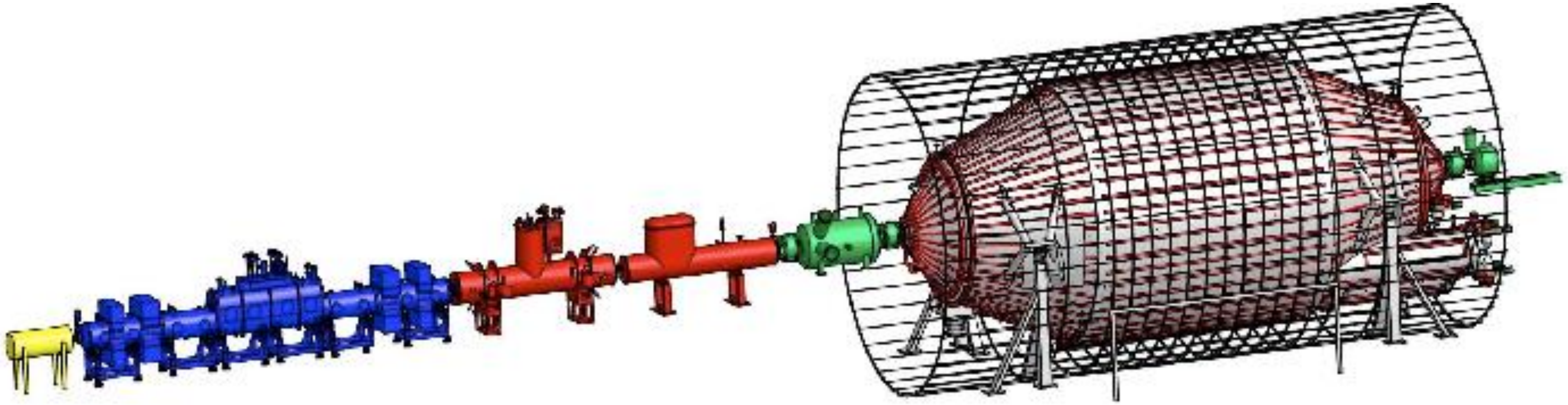


FIG. 1. The spectrum of H^3 in the region of the end



KATRIN – stopping electrons

PROJECT8 – electrons go round and round

ECHo, HOLMES, NuMECS – electron capture ^{163}Ho

direct mass measurements

KATRIN is running and setting new limits

$m_\nu < 0.8$ eV

Nature Physics volume 18, pages160–166 (2022)

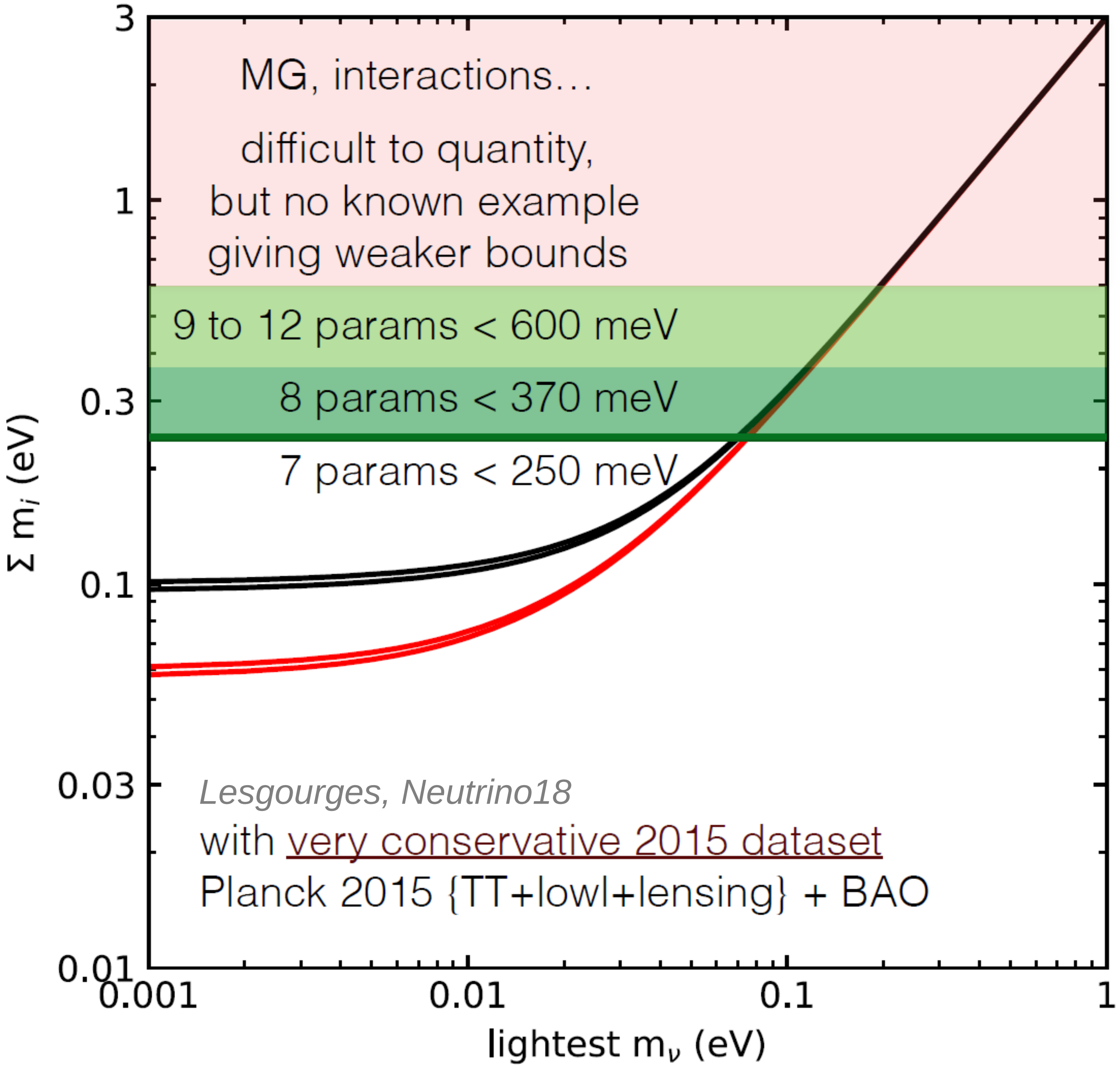
KATRIN – stopping electrons

PROJECT8 – electrons go round and round

ECHo, HOLMES, NuMECS – electron capture ^{163}Ho

indirect mass measurements

summed mass



neutrino masses are a parameter in interpretation of cosmological data

results depend on details of the cosmological model

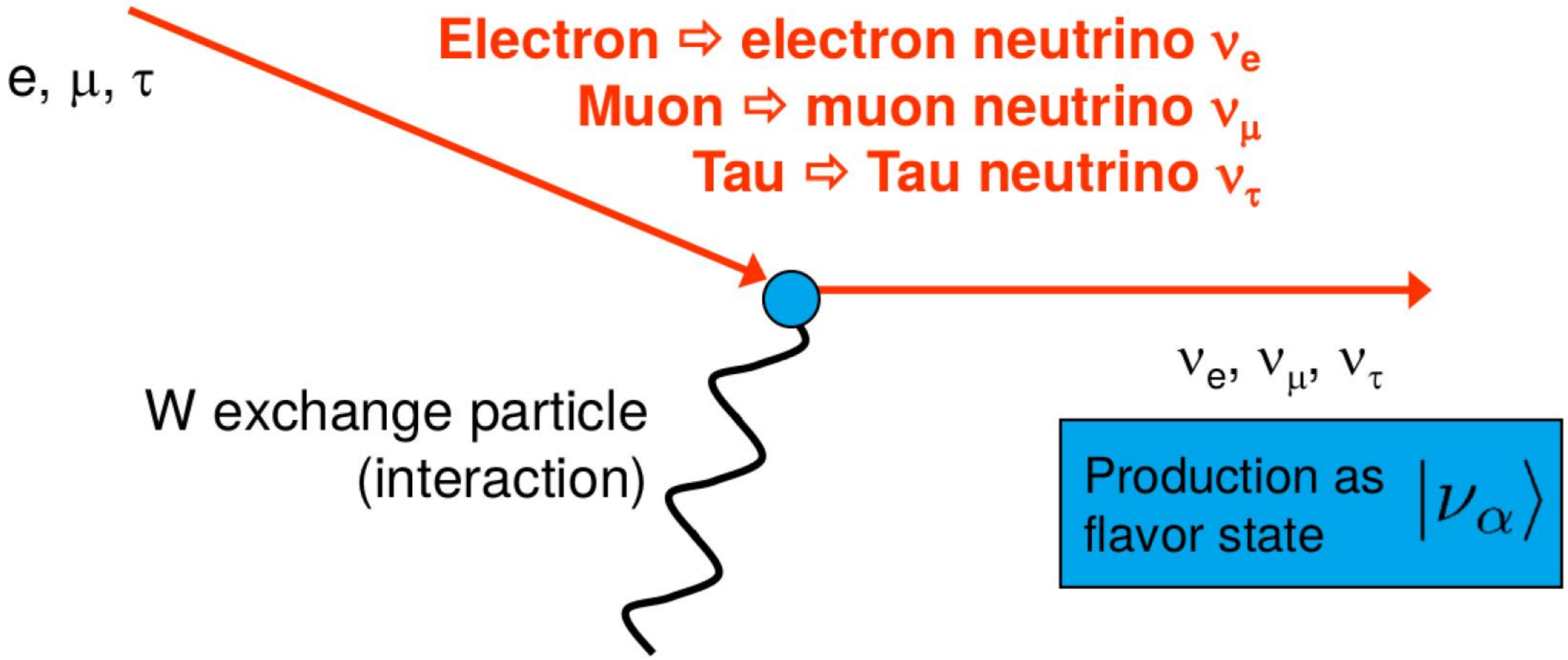
m_ν < 250-600 meV

see arXiv:1502.01589

(in)direct measurements see
no evidence for neutrino mass

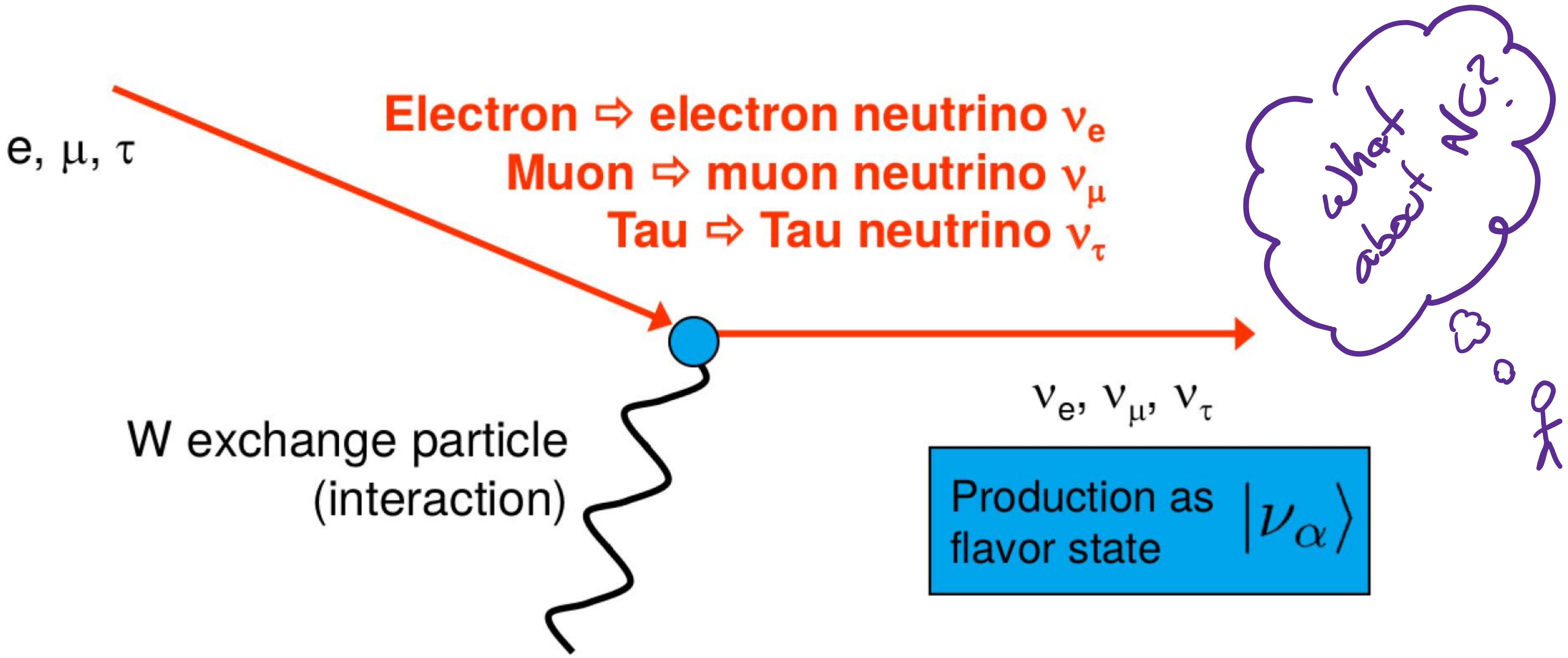
mixing and oscillations

neutrinos are detected/produced in weak interactions



cannot assign mass to the ν_e ν_μ ν_τ states!

neutrinos are detected/produced in weak interactions



cannot assign mass to the ν_e ν_μ ν_τ states!

postulate states ν_1 ν_2 ν_3 with well defined masses

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U^*_{\alpha k} |\nu_k\rangle$$

postulate states ν_1 ν_2 ν_3 with well defined masses

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

postulate states ν_1 ν_2 ν_3 with well defined masses

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

production $\longrightarrow$ flavor eigenstates

propagation $\longrightarrow$ mass eigenstates

interaction $\longrightarrow$ flavor eigenstates

postulate states ν_1 ν_2 ν_3 with well defined masses

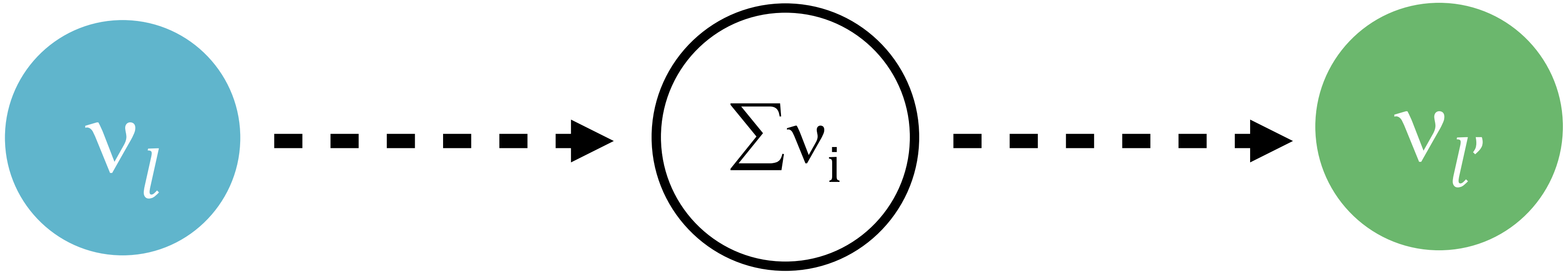
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

production $\rightarrow$ flavor eigenstates

propagation $\rightarrow$ mass eigenstates

interaction $\rightarrow$ flavor eigenstates

if flavor ≠ mass eigenstates



mixing!

postulate states ν_1 ν_2 ν_3 with well defined masses

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

the SM gives you the matrix structure

postulate states ν_1 ν_2 ν_3 with well defined masses

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

the SM gives you the matrix structure

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

3 real parameters (mixing angles)

1 imaginary phase

2 Majorana-only imaginary phases

postulate states ν_1 ν_2 ν_3 with well defined masses

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

the SM gives you the matrix structure

nothing to say about the actual values
need to be determined by experiment

considering propagation in vacuum

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t) = \langle \nu_\beta | \nu(t) \rangle = \langle \nu_\beta | e^{-i\mathcal{H}_0 t} | \nu_\alpha \rangle .$$

assuming 2 neutrinos for simplicity

$$P^{2\nu}_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

valid when

$$|\Delta m^2_{\mathrm{large}}| \gg |\Delta m^2_{\mathrm{small}}|$$

considering propagation in vacuum

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t) = \langle \nu_\beta | \nu(t) \rangle = \langle \nu_\beta | e^{-i\mathcal{H}_0 t} | \nu_\alpha \rangle .$$

assuming 2 neutrinos for simplicity

$$P^{2\nu}_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

MASS DIFFERENCE INSIDE AN EVEN FUNCTION

NO SIGN INFORMATION

valid when

$$|\Delta m^2_{\text{large}}| \gg |\Delta m^2_{\text{small}}|$$

SUFFICIENT TO EXPLAIN MOST EXPERIMENTS

considering propagation in vacuum

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t) = \langle \nu_\beta | \nu(t) \rangle = \langle \nu_\beta | e^{-i\mathcal{H}_0 t} | \nu_\alpha \rangle .$$

the master formula (for N species)

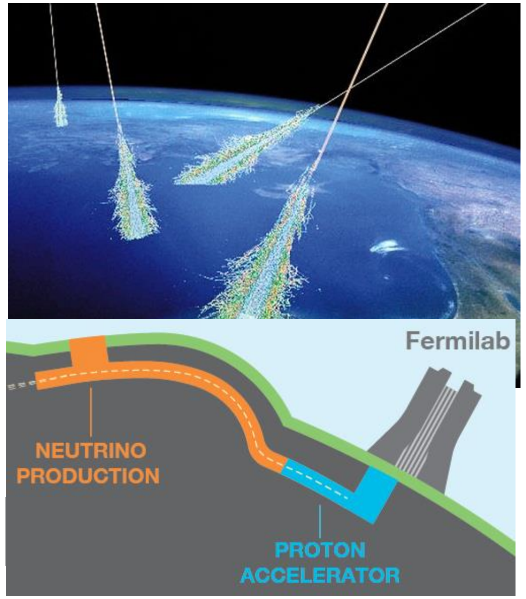
$$\begin{aligned} \mathrm{P}_{\nu_l \to \nu_{l'}}(L,E) = \delta_{l'l} &- 4 \sum_{i>j} \Re[U_{li}^* U_{l'i} U_{lj} U_{l'j}^*] \sin^2\left(\frac{\Delta m_{ij}^2}{4E} L\right) \\ &\pm 2 \sum_{i>j} \Im[U_{li}^* U_{l'i} U_{lj} U_{l'j}^*] \sin\left(\frac{\Delta m_{ij}^2}{2E} L\right) \end{aligned}$$

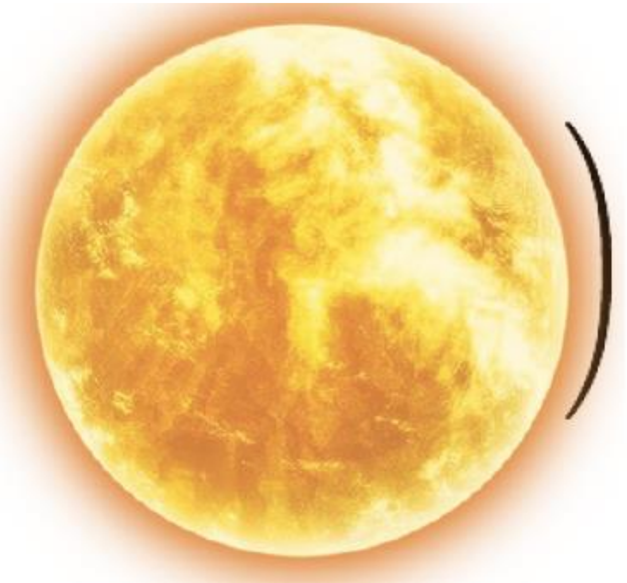
matter adds some complications

current knowledge

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

current knowledge

$U =$ 



mostly in disappearance mode

appearance experiments are tough but help complete the picture

current knowledge

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

NuFIT 5.2 (2022)

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.803 \to 0.845 & 0.514 \to 0.578 & 0.142 \to 0.155 \\ 0.233 \to 0.505 & 0.460 \to 0.693 & 0.630 \to 0.779 \\ 0.262 \to 0.525 & 0.473 \to 0.702 & 0.610 \to 0.762 \end{pmatrix}$$

close to maximal mixing possible

why? another symmetry?

current knowledge

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

NuFIT 5.2 (2022)

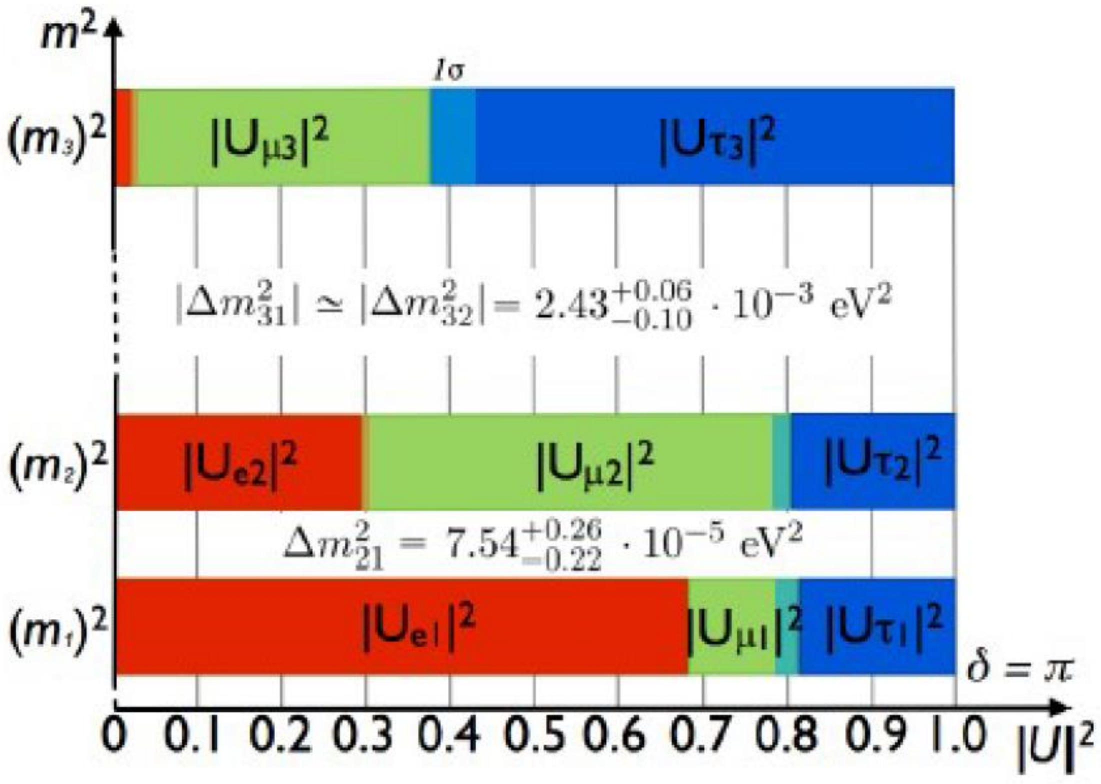
$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.803 \to 0.845 & 0.514 \to 0.578 & 0.142 \to 0.155 \\ 0.233 \to 0.505 & \text{[illegible]} & 0.630 \to 0.779 \\ 0.262 \to 0.525 & 0.473 \to 0.702 & 0.610 \to 0.762 \end{pmatrix}$$

need better precision

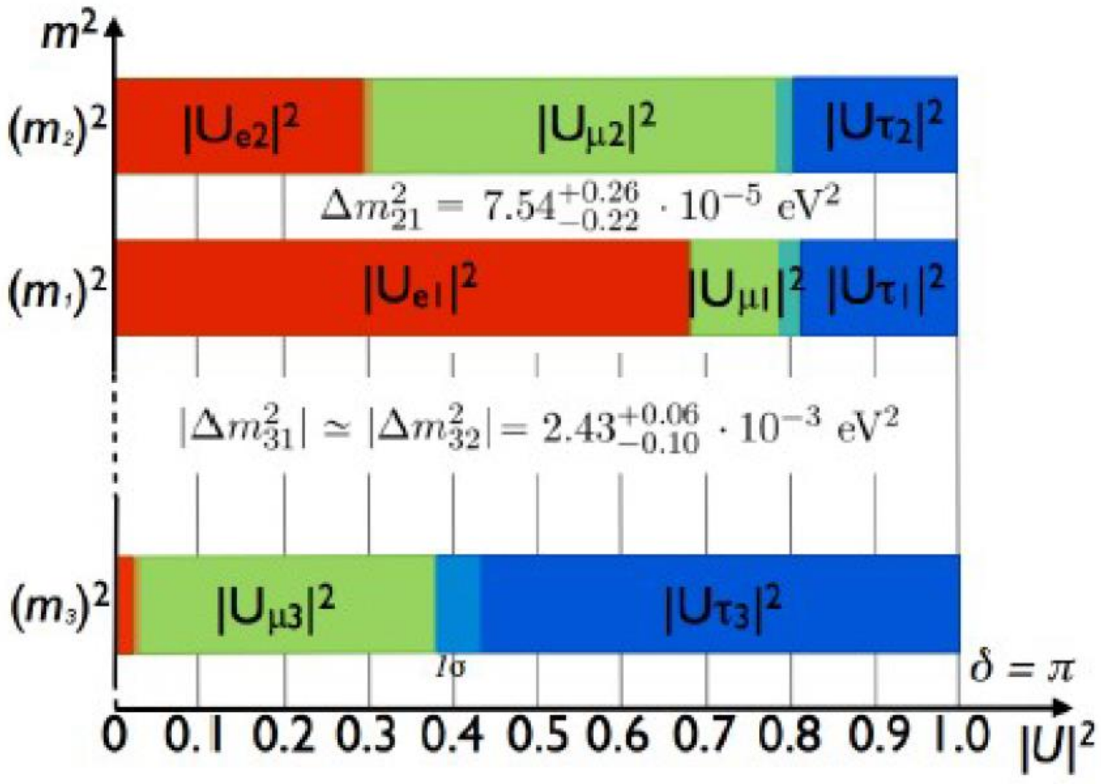
close to maximal mixing possible

why? another symmetry?

missing measurements



(a) Normal ordering



(b) Inverted ordering

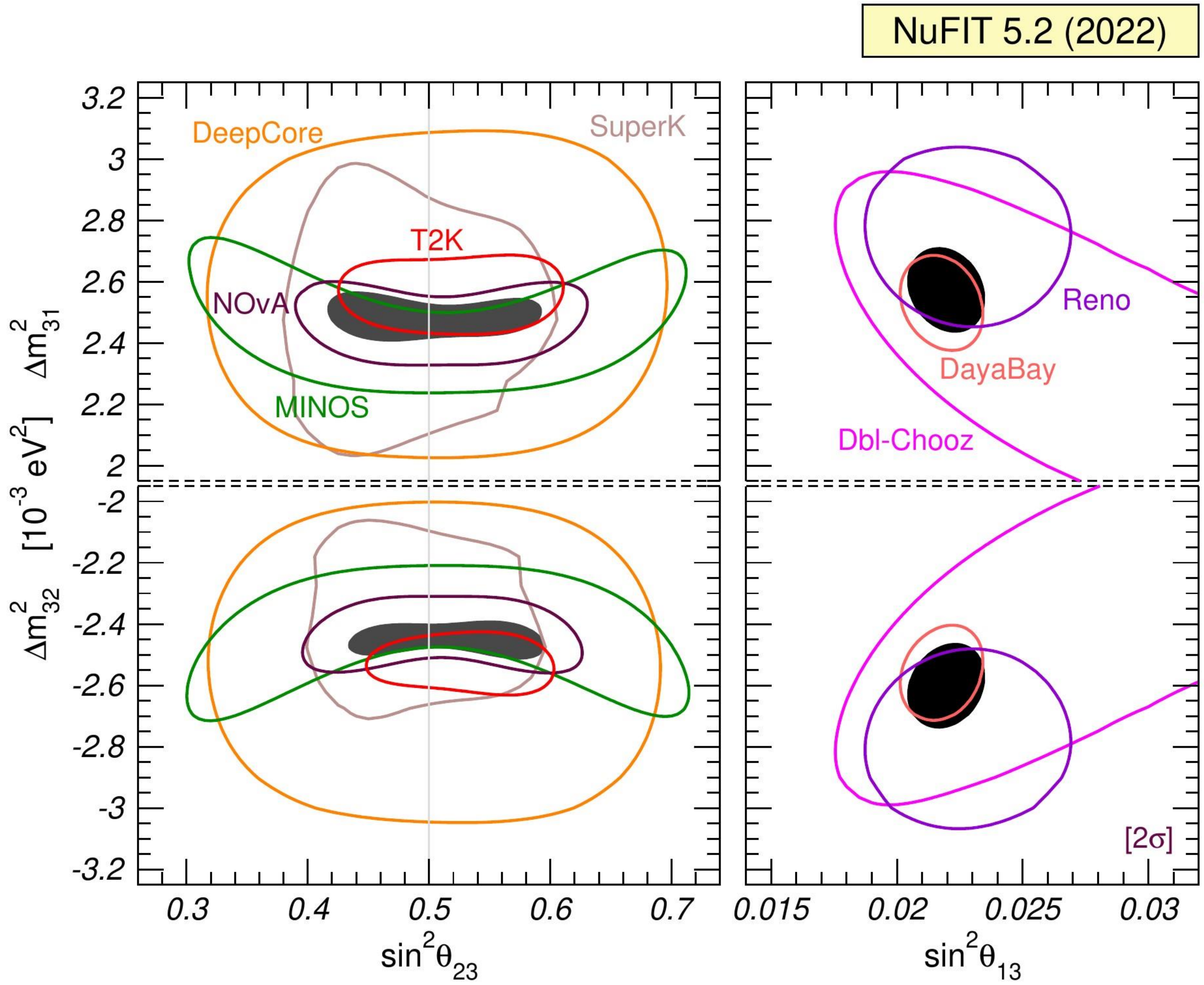
mass ordering – which is the lightest mass state?

missing measurements

$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

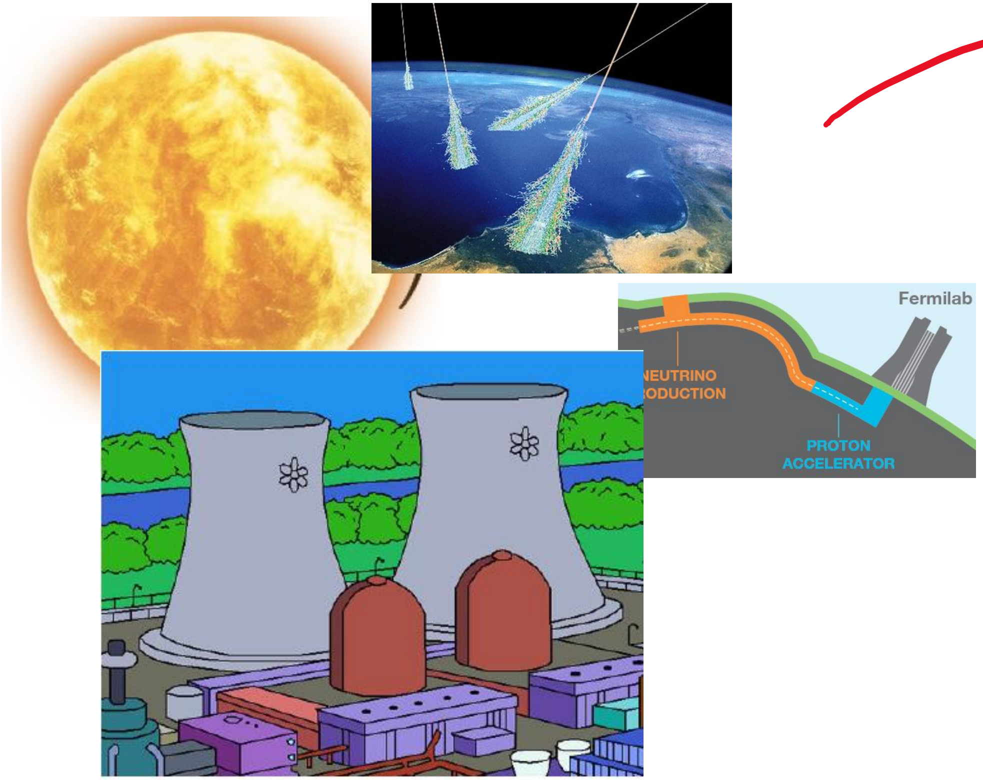
CP violation – nu vs anti-nu oscillations

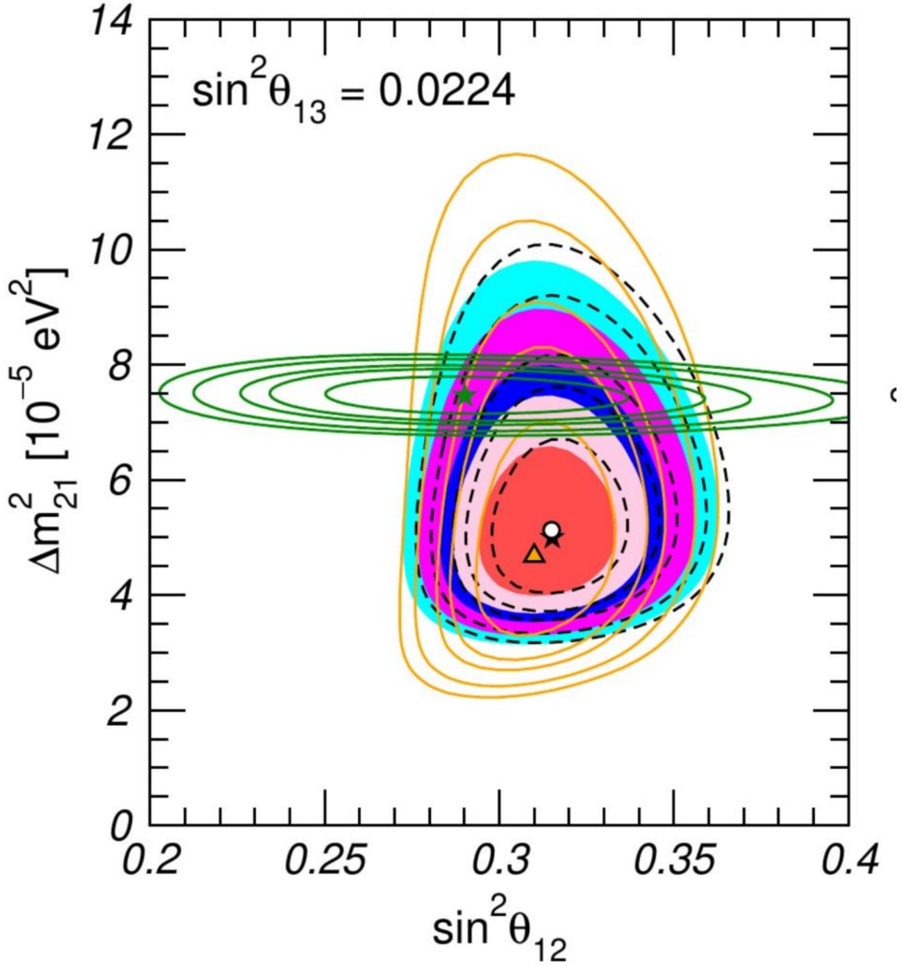
global fits chiming in



multiple experiments measure the same parameters

global fits chiming in





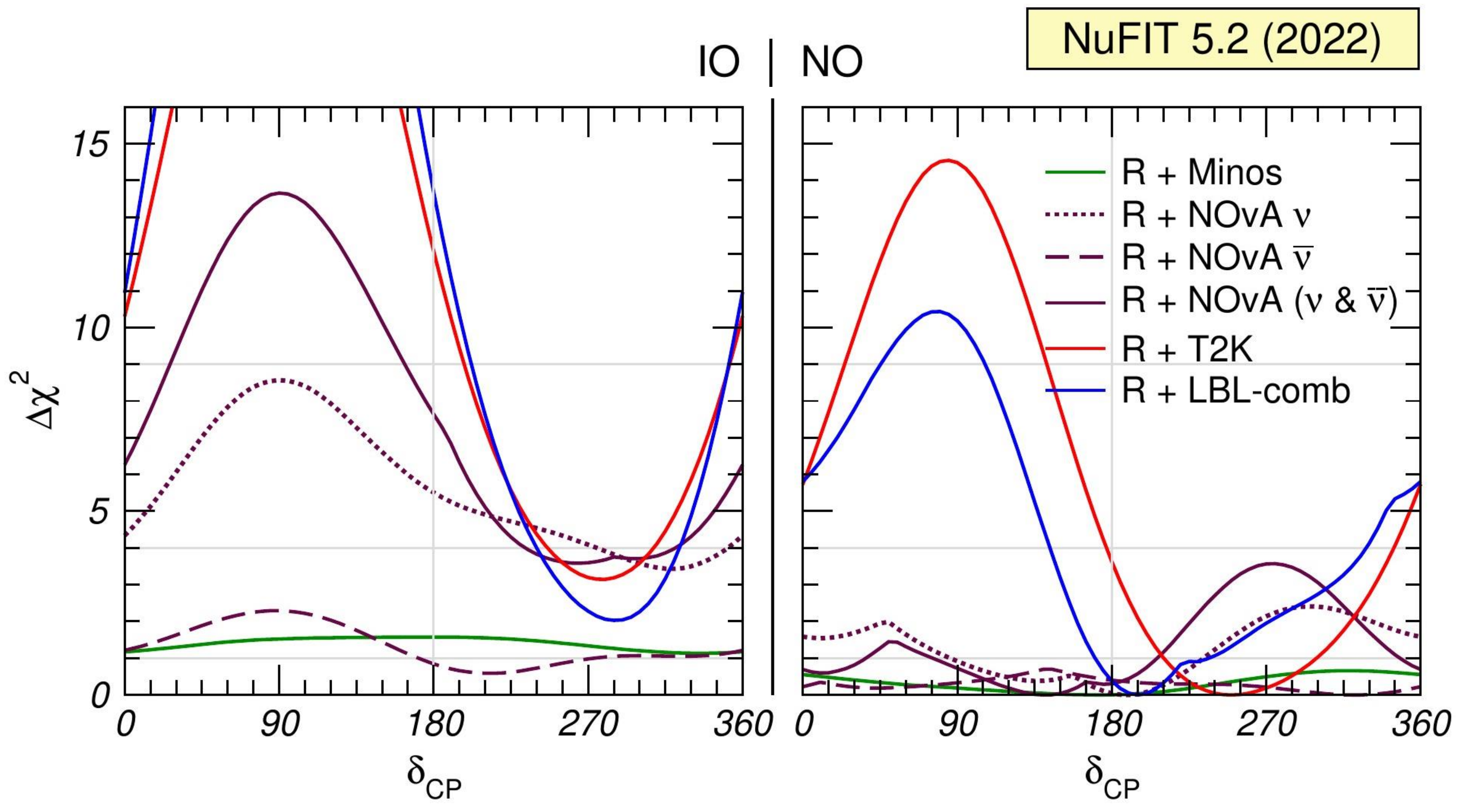
analysis of all data available including correlations

global fits chiming in

-NuFit (Esteban, Gonzalez-Garcia, Hernandez, Maltoni, Schwetz)

-“Bari” group (Capozzi, Lisi, Marrone, Montanino, Palazzo)

-“Valencia” group (Salas, Forero, Ternes, Tortola, Valle)



hints of

-normal ordering

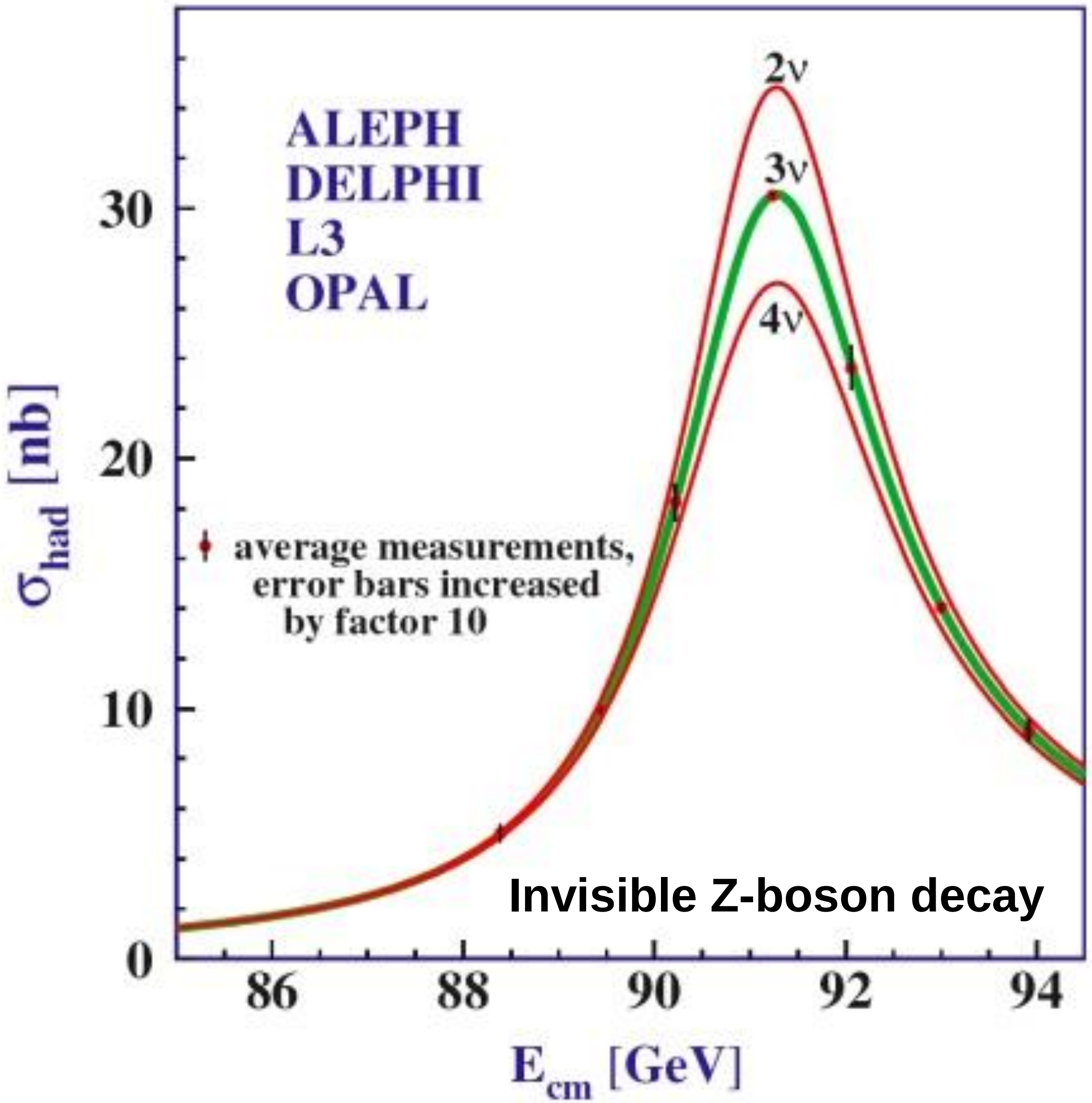
-some CP violation

good knowledge of oscillation parameters but relevant details still missing

neutrino flavors

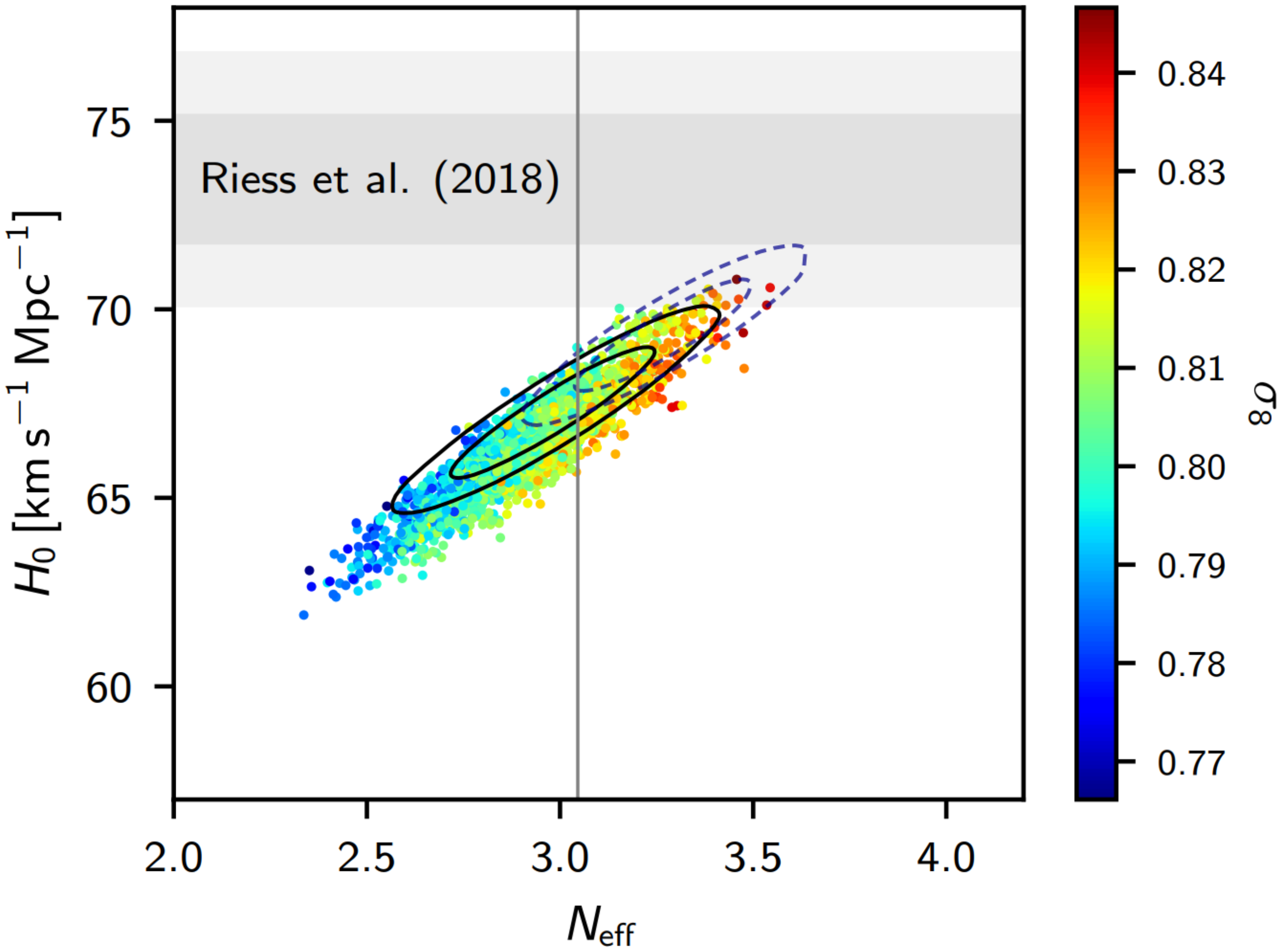
neutrino flavors

evidence of 3 light, active neutrinos in invisible Z-decay



neutrino flavors

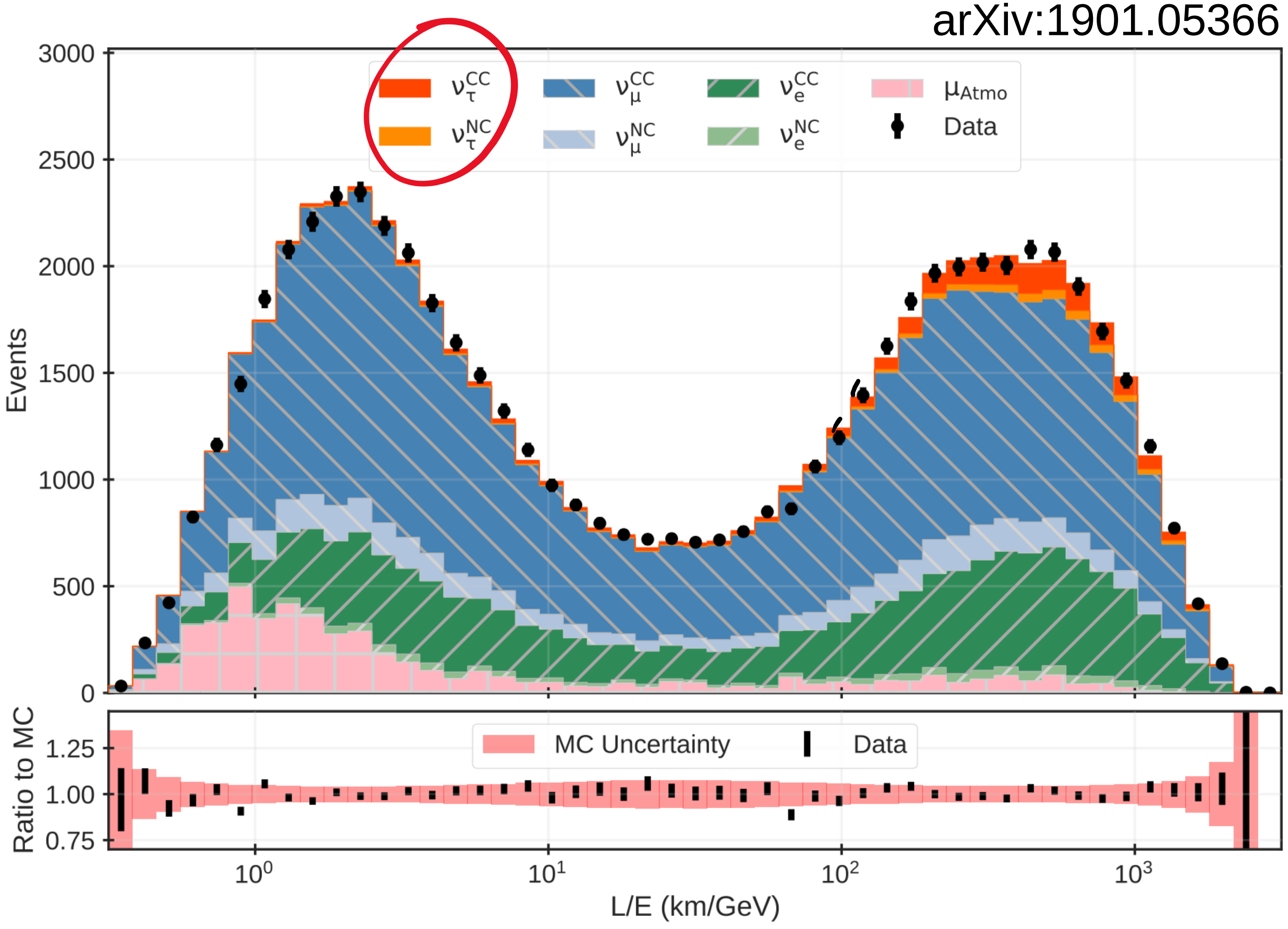
evidence of 3 light, active neutrinos in cosmological data from Planck



neutrino flavors

evidence of 3 light, active neutrinos in most oscillation experiments

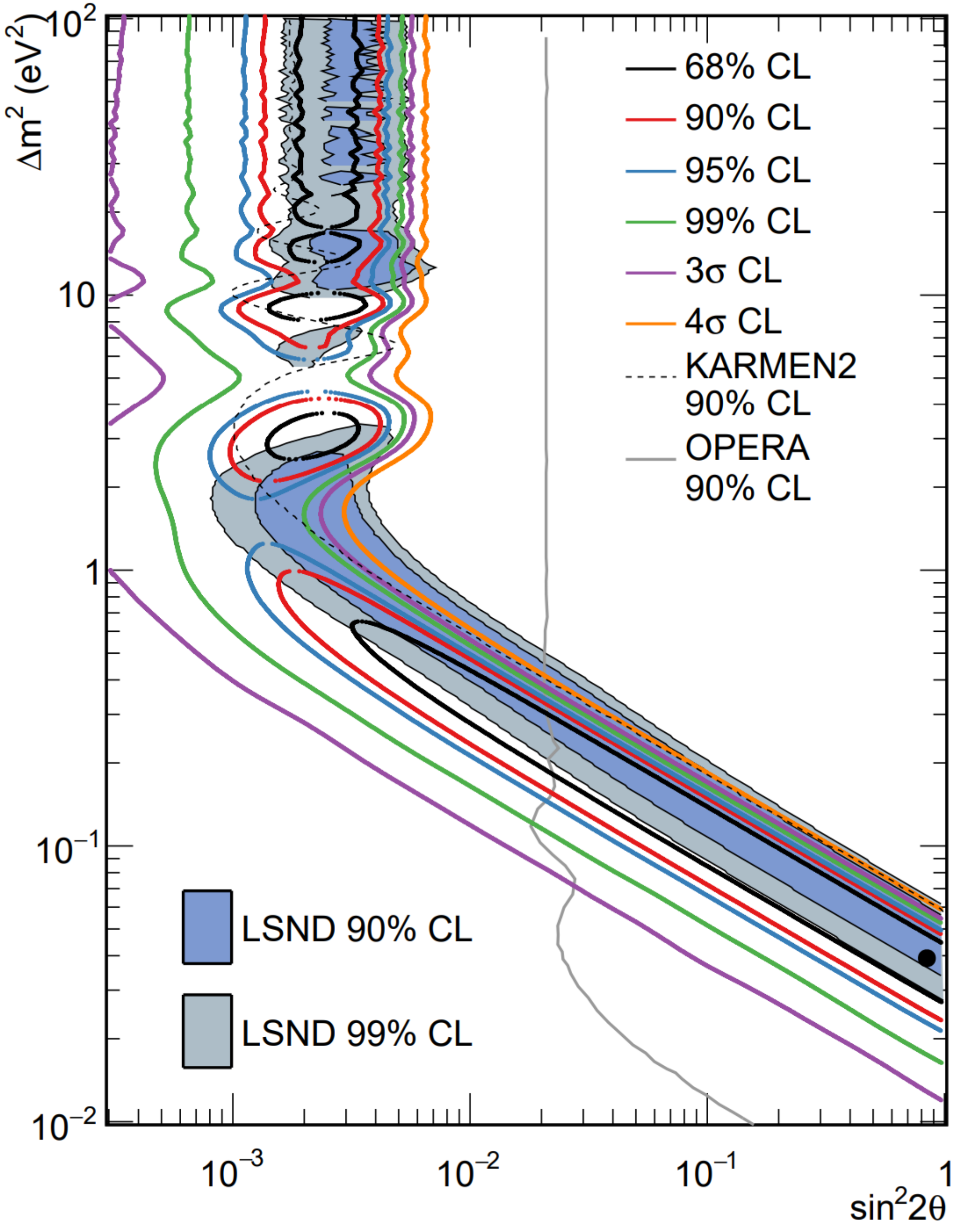
IceCube DeepCore
arXiv:1901.05366



neutrino flavors

except LSND, MiniBooNE which suggest a sterile state might be there

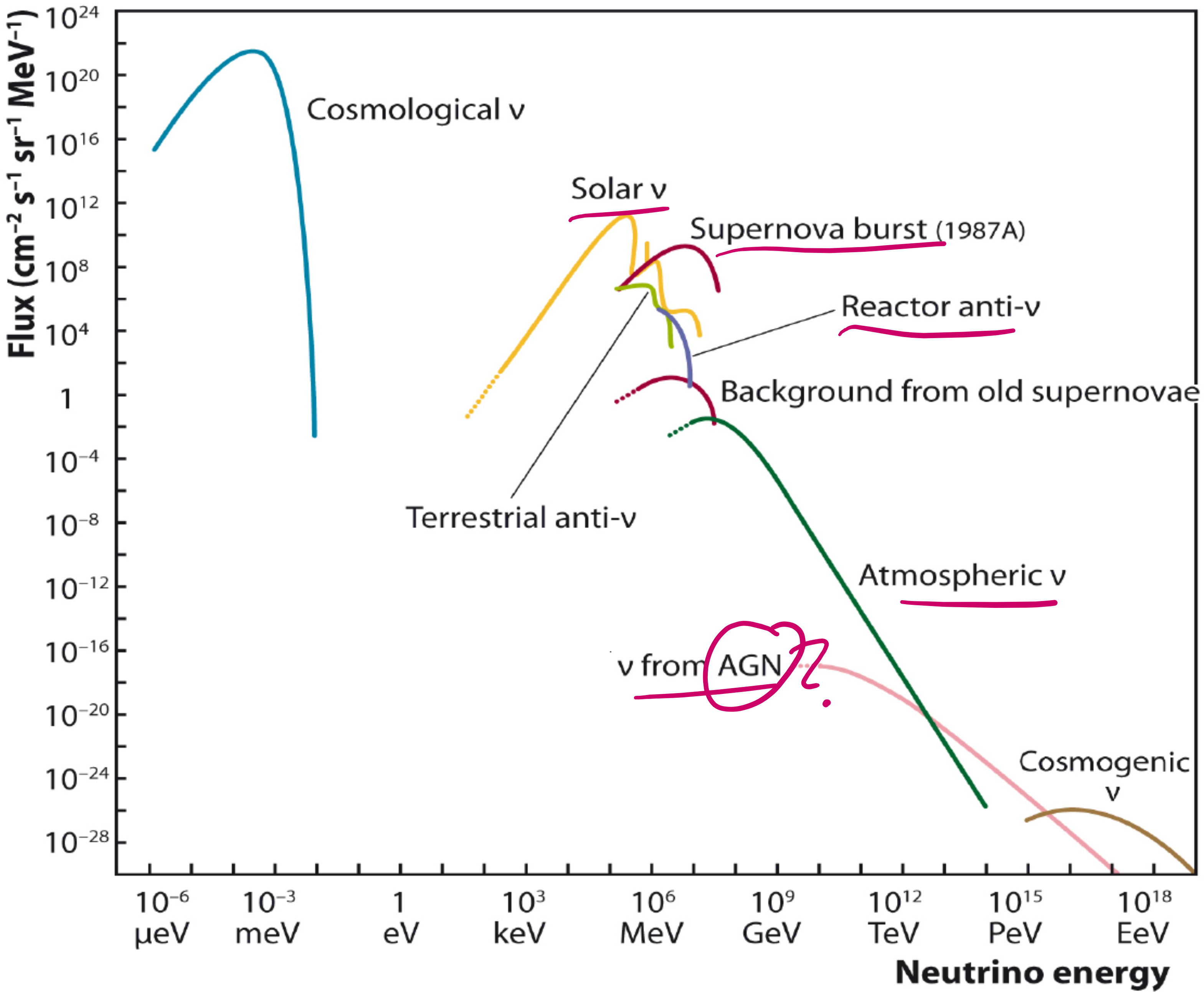
or that low energy neutrino interactions are hard to measure



3+ flavors? would be exciting but could be symptoms of experimental problems

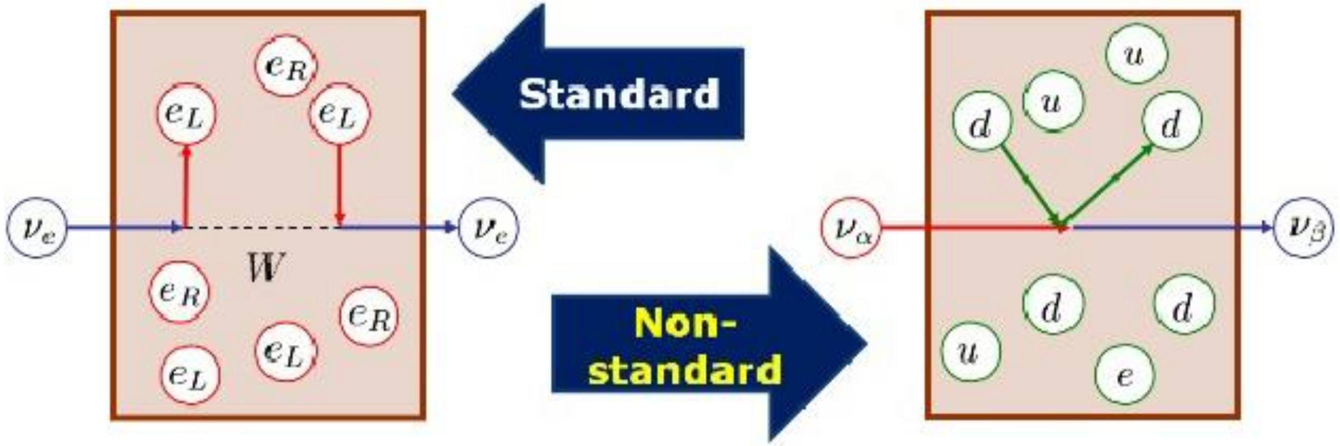
neutrinos as probes

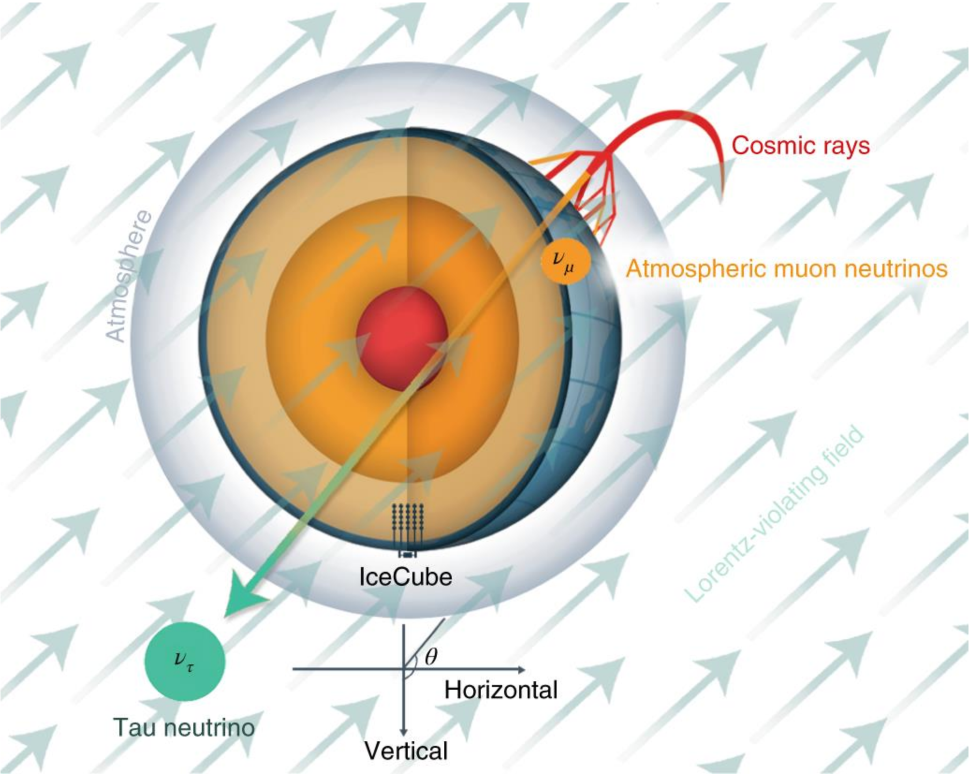
neutrino sources



searching for **exotic physics** with ν

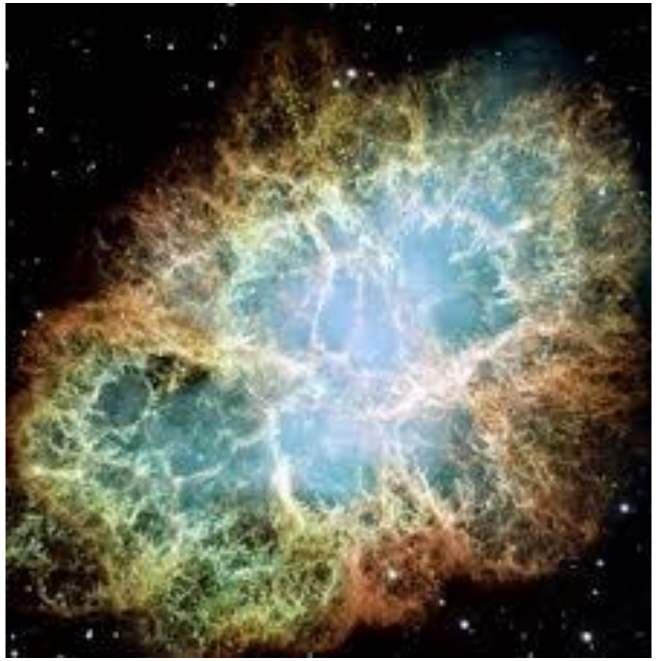
non-standard interactions

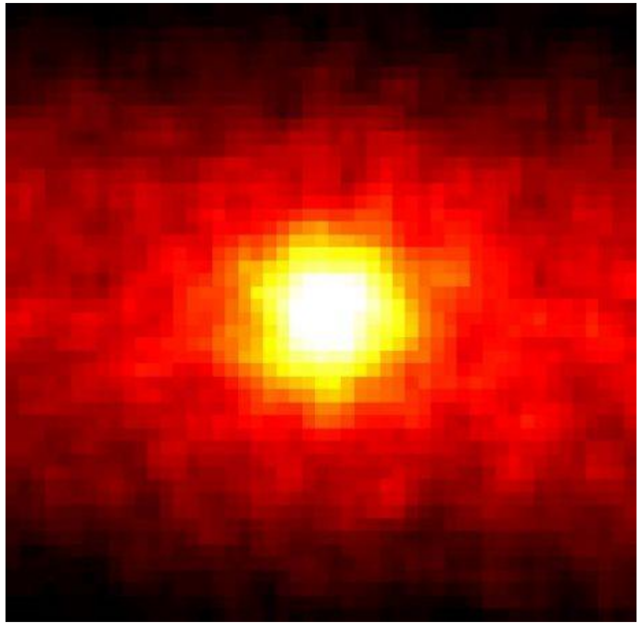




Lorentz invariance violation

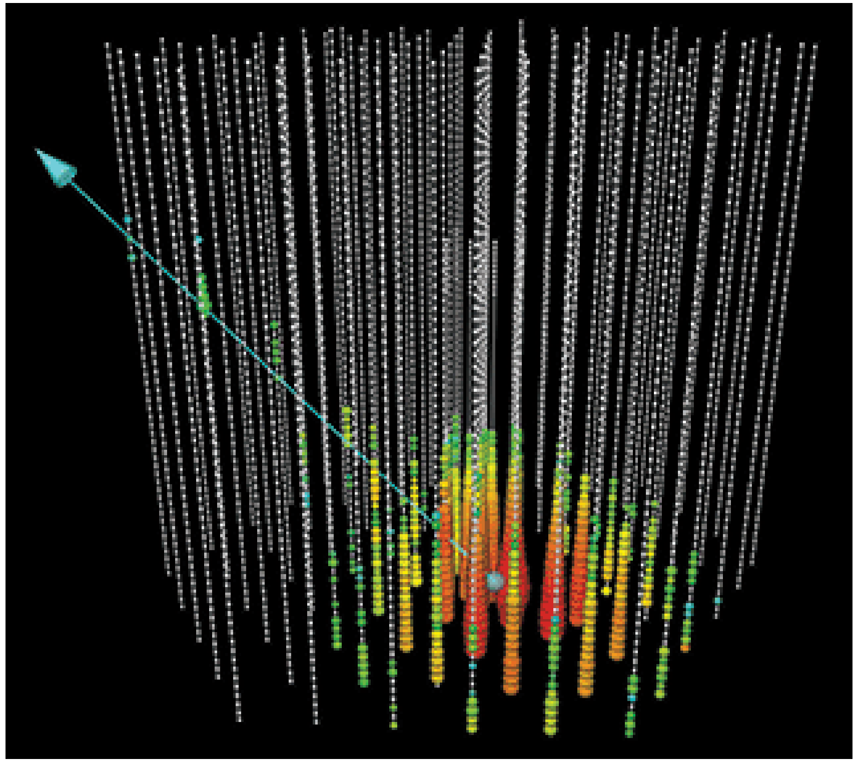
studying astrophysical objects





solar neutrinos

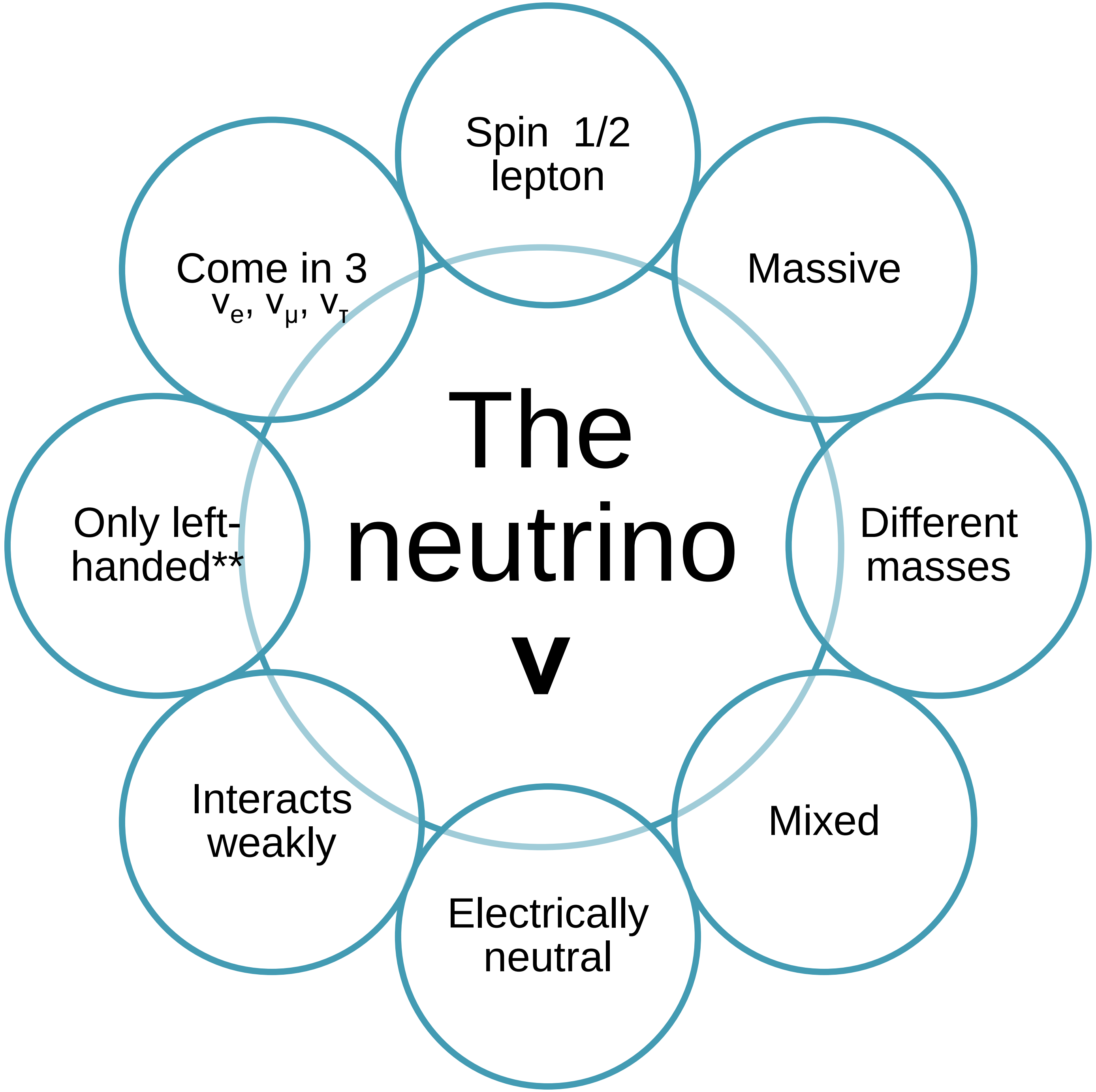
supernova
neutrinos



HE neutrinos from
violent sources

let’s wrap it up

neutrino summary



experiments testing all of these knowledge

+the potential uses of ν's

searching for the next breakthrough

symmetry
magazine

thank you