# Neutrino physics

## Astroparticle School 2024
## Obertrubach-Bärnfels

Juan Pablo Yáñez

j.p.yanez@ualberta.ca

University of Alberta

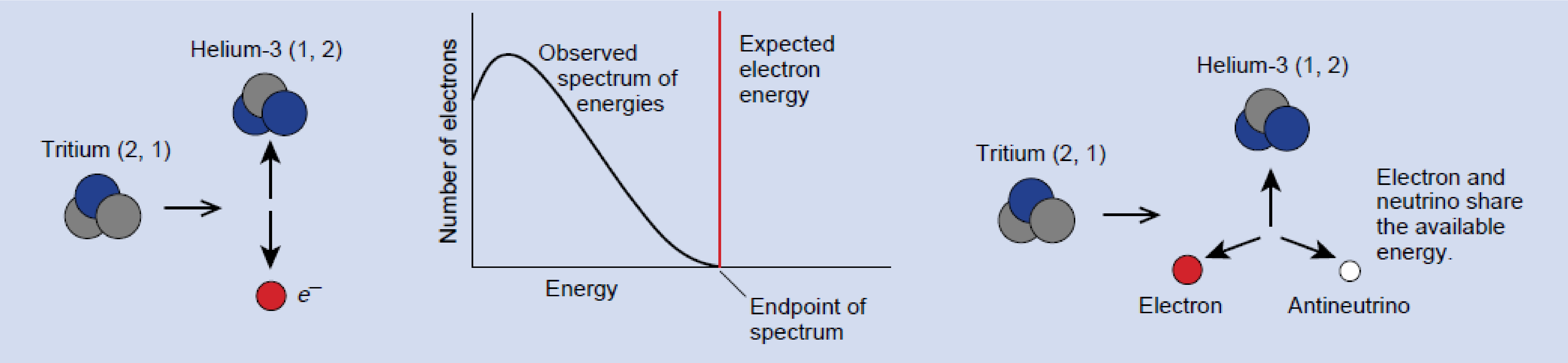
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

# 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 PW

**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 Grossenordnung 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

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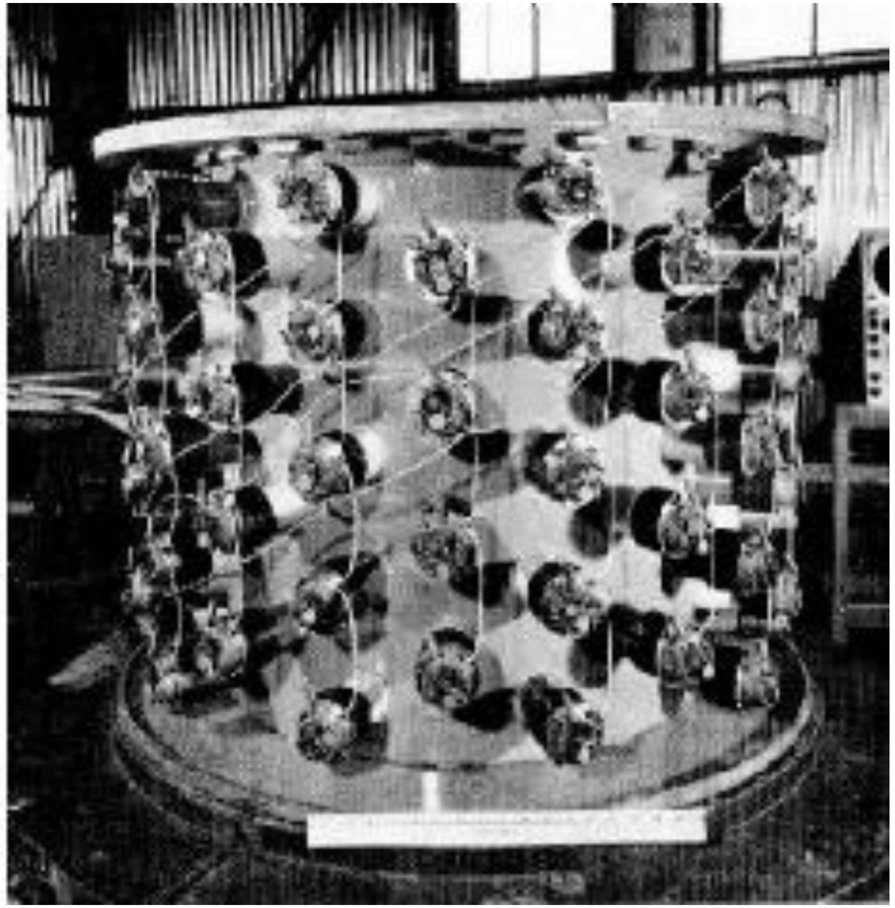
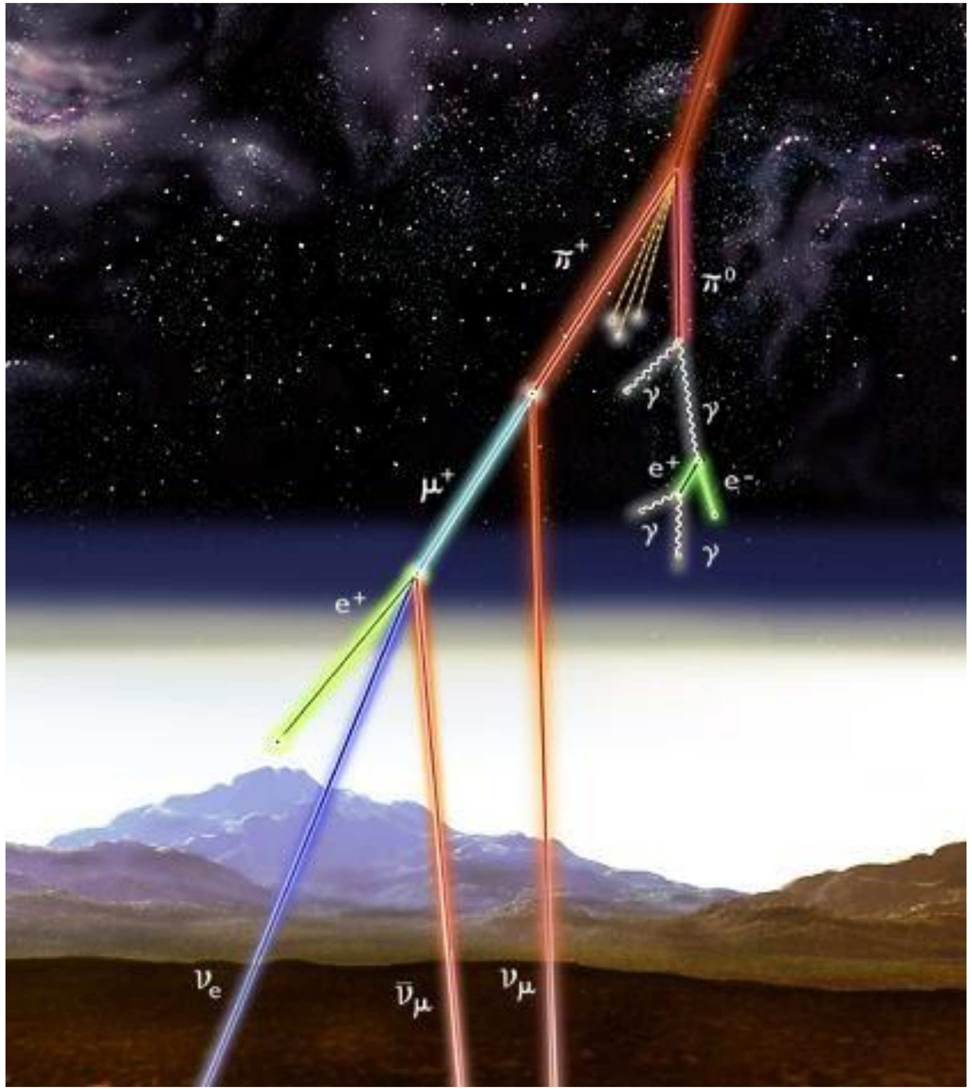
Project *Poltergeist*, Savannah River nuclear reactor

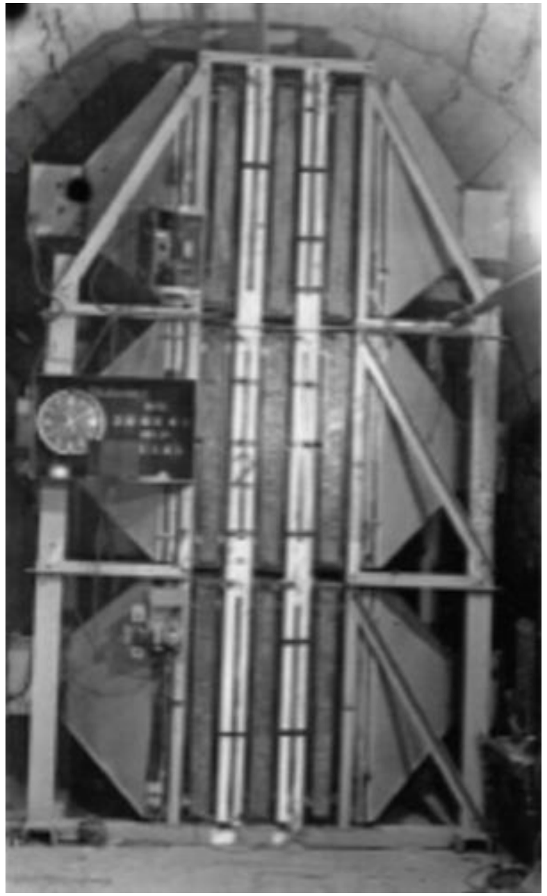



# first neutrino observation, $\bar{\nu}_e$ from a reactor (1956)

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

# discovery of atmospheric neutrinos (1965-68)

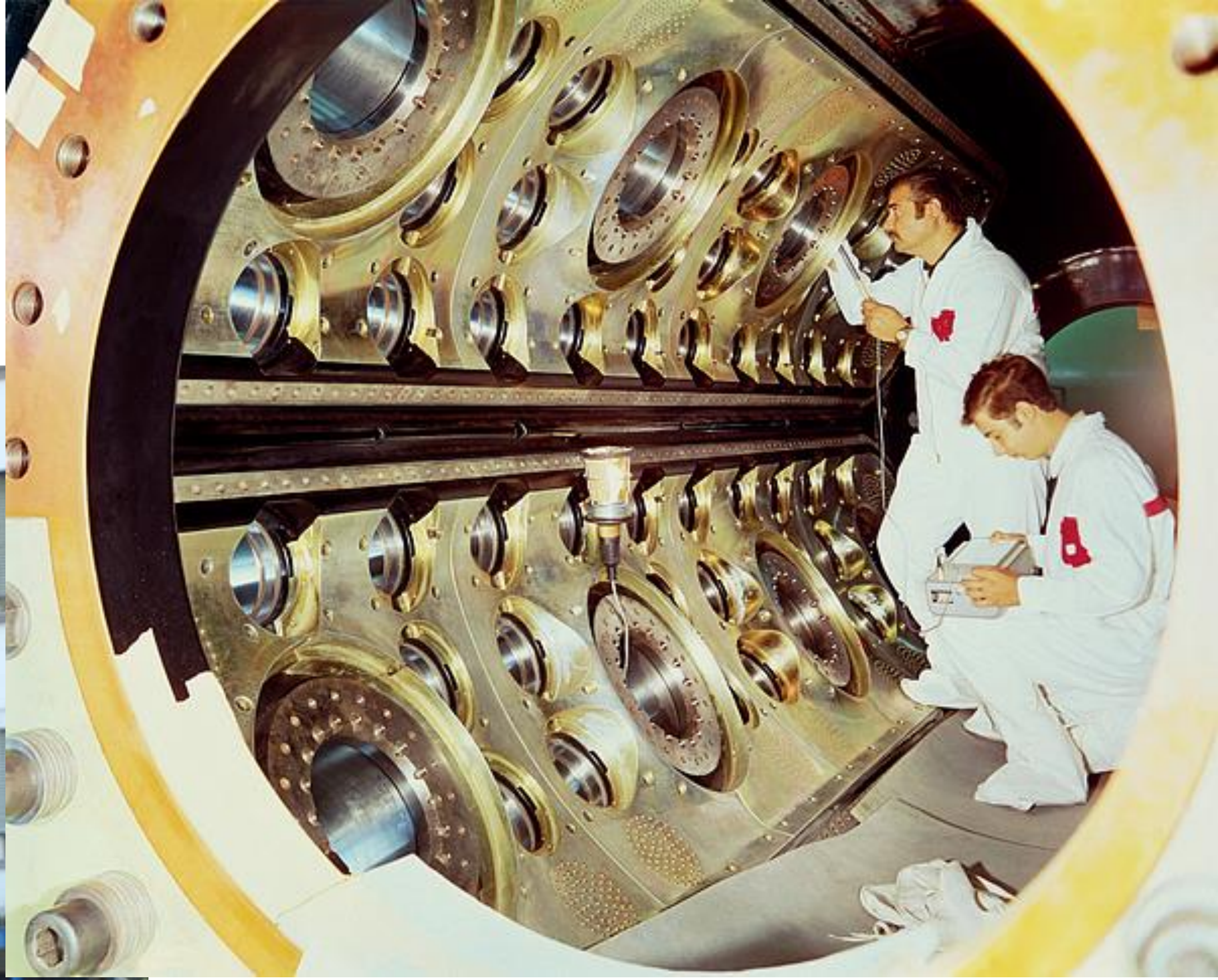


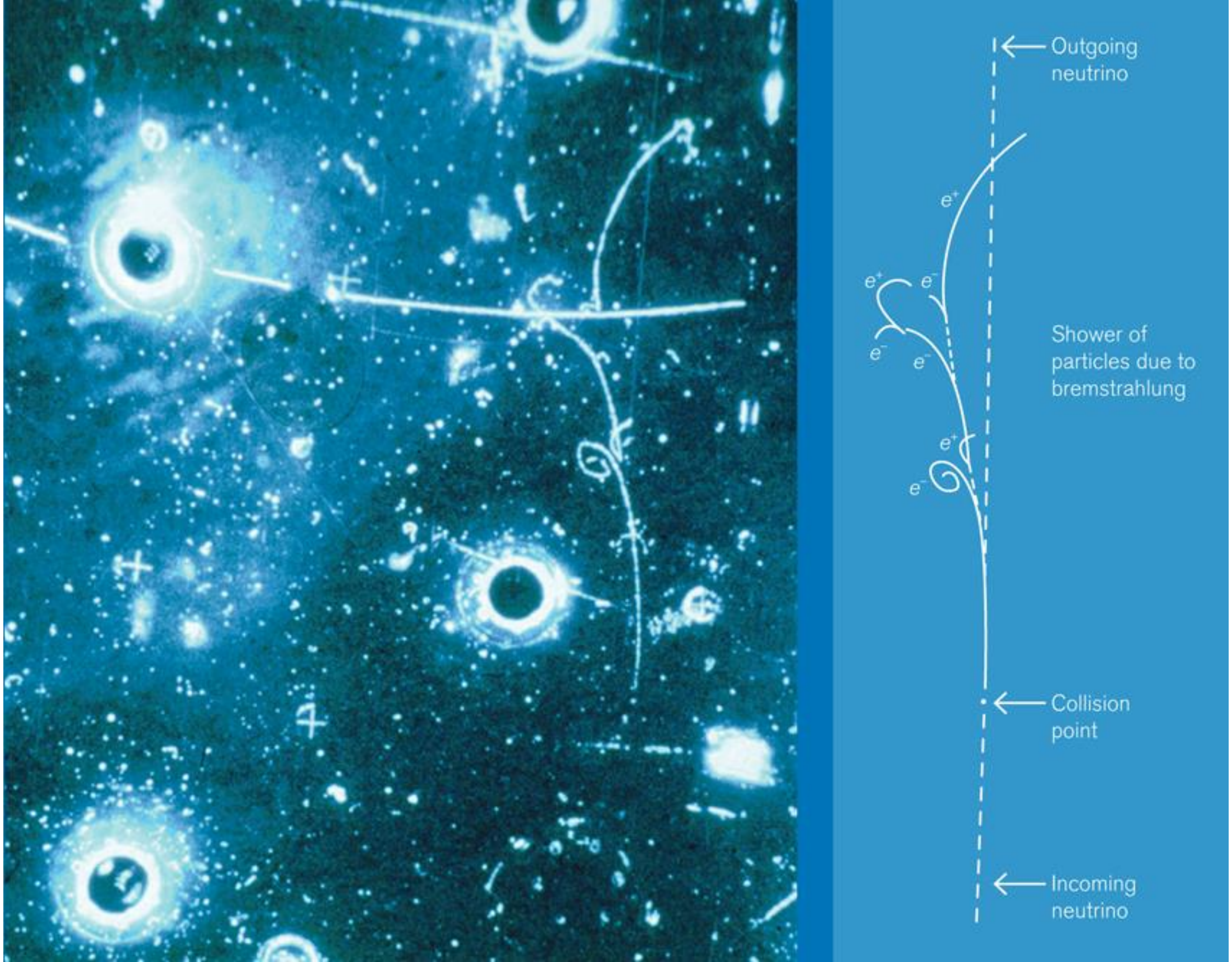
**Kolar Gold Fields detector**

**Case Western Irvine/South Africa Neutrino Detector**

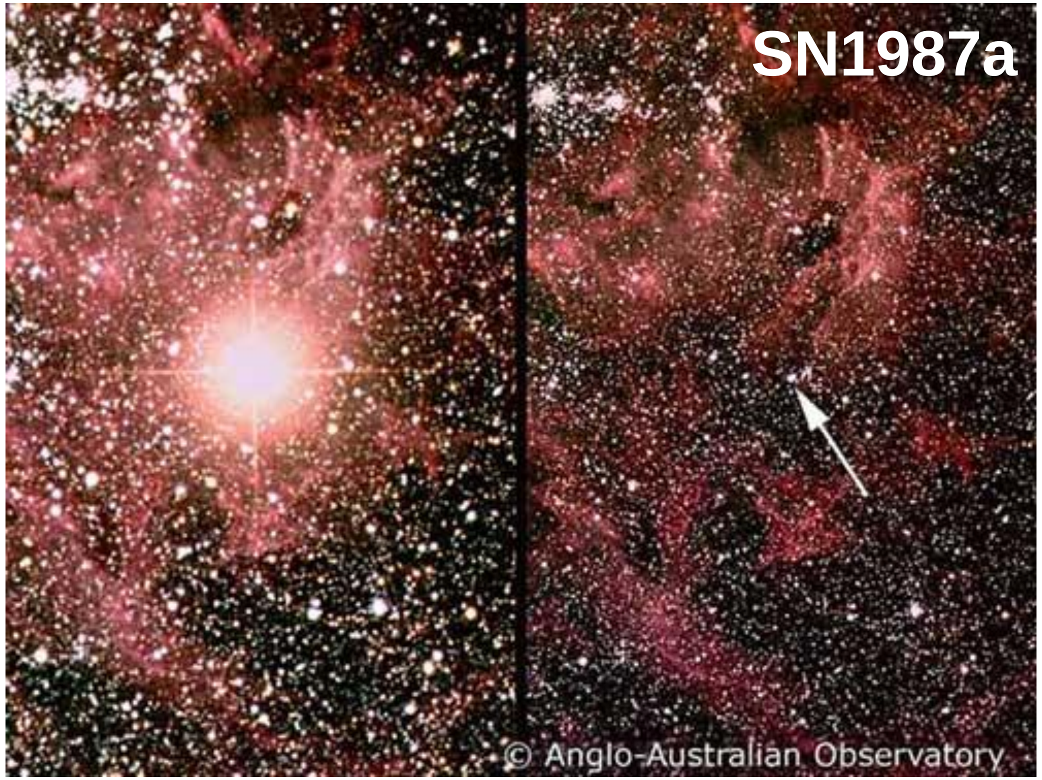
# Gargamelle bubble chamber (1970)



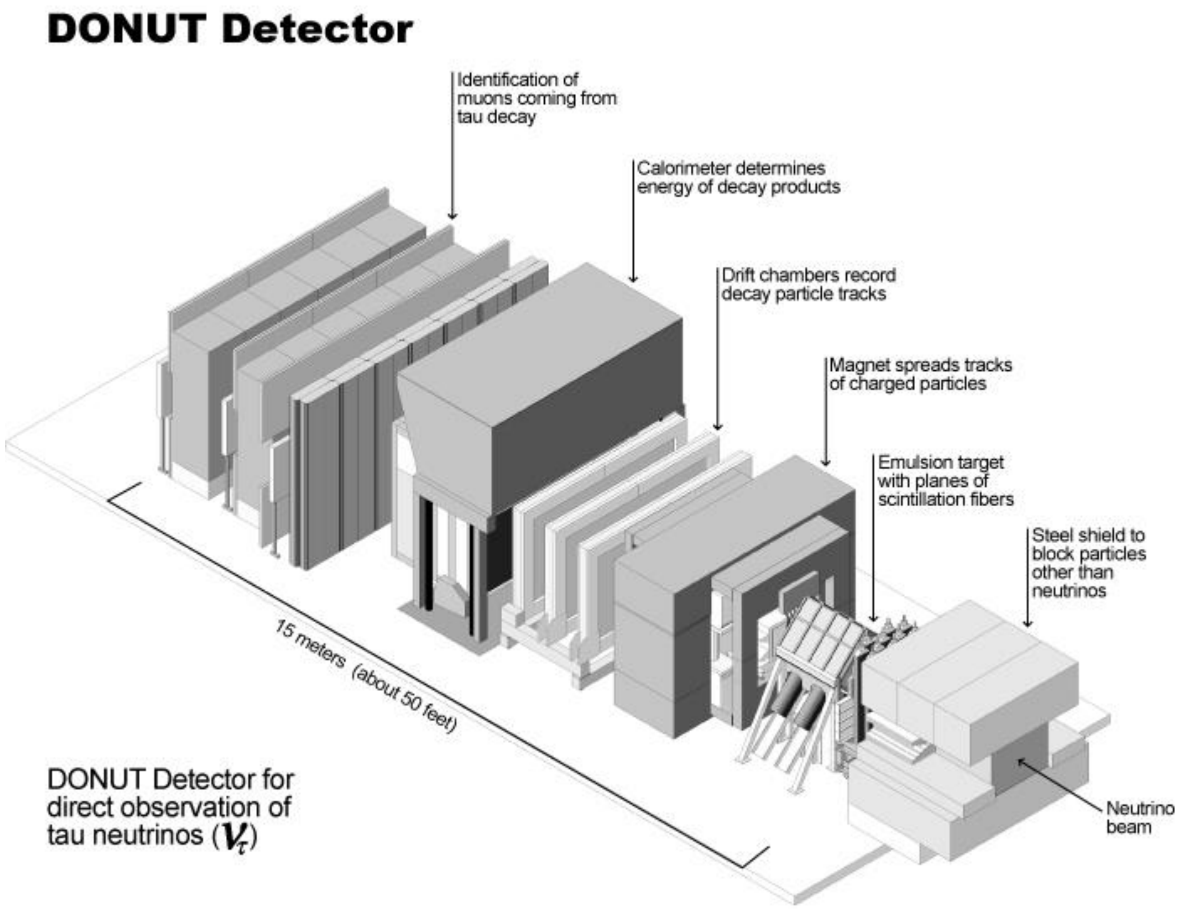
# Gargamelle bubble chamber (1970)



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

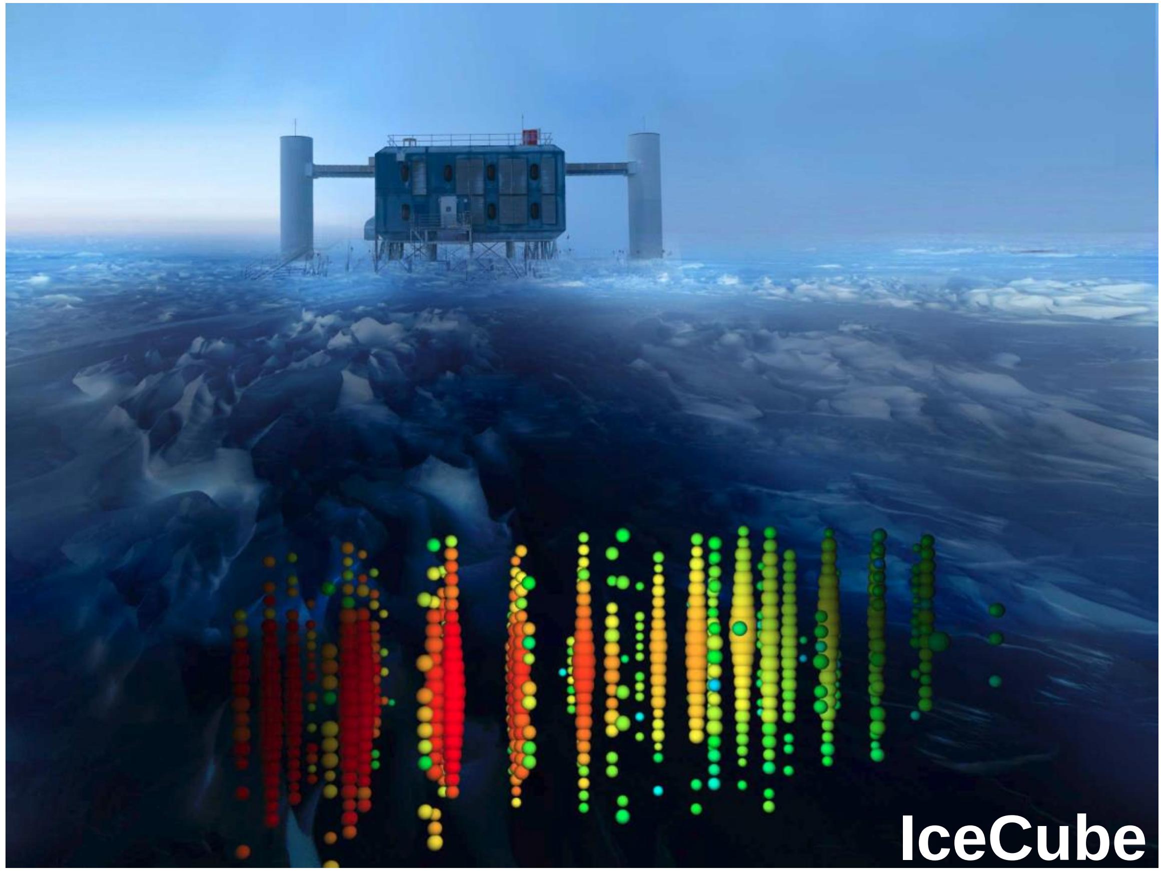




first and only detection of neutrinos from a **supernova** (1987)



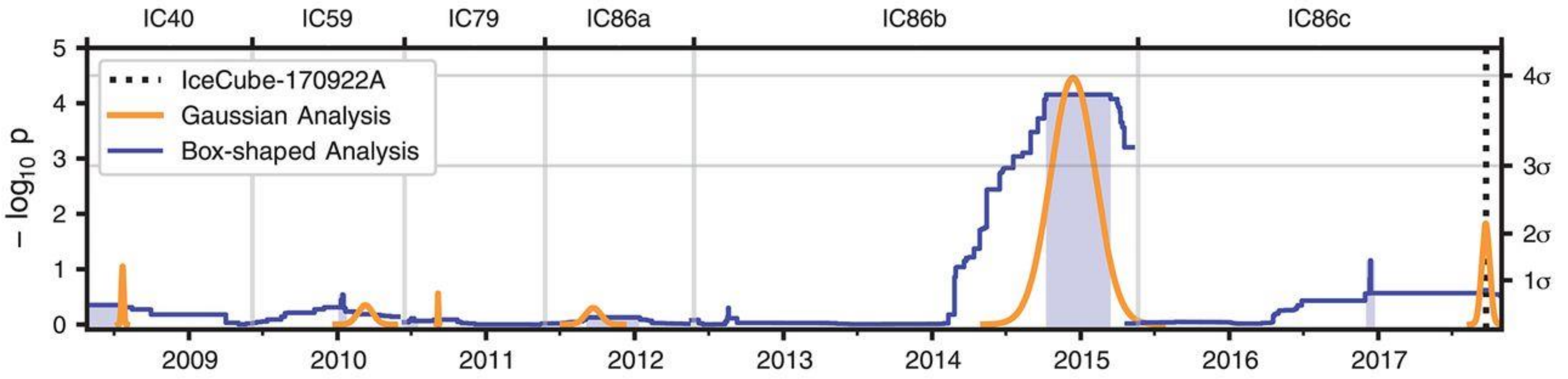

**tau neutrino observed for the first time (2000)**

**discovery of high energy astrophysical neutrinos (2013)**

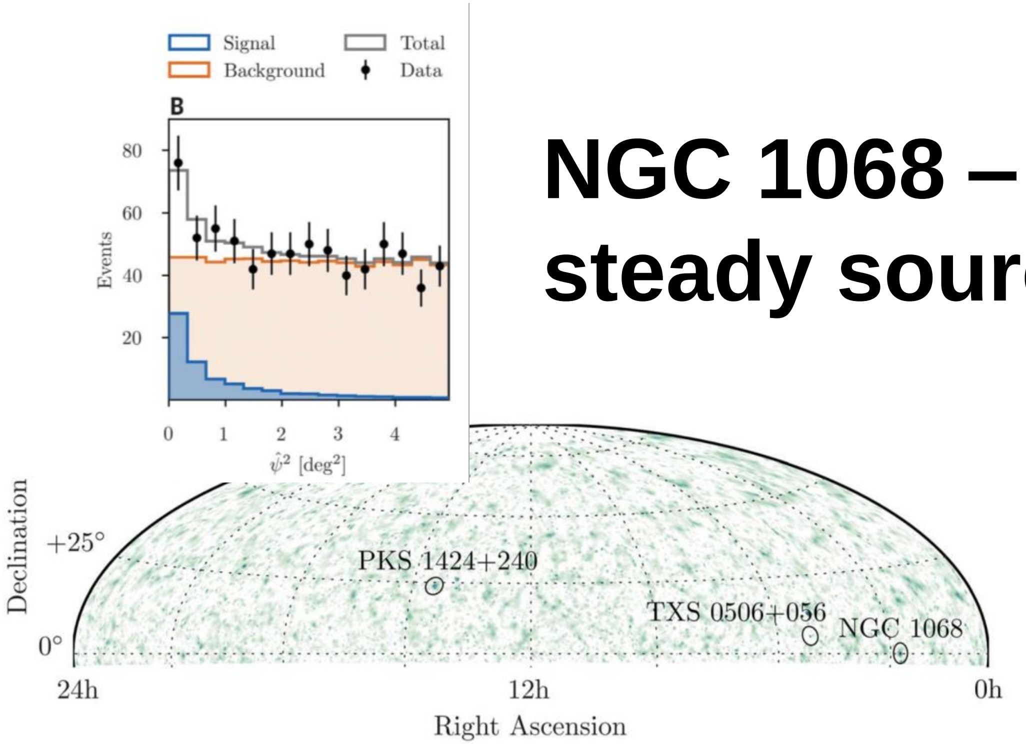


# Astrophysical neutrino sources identified by IceCube

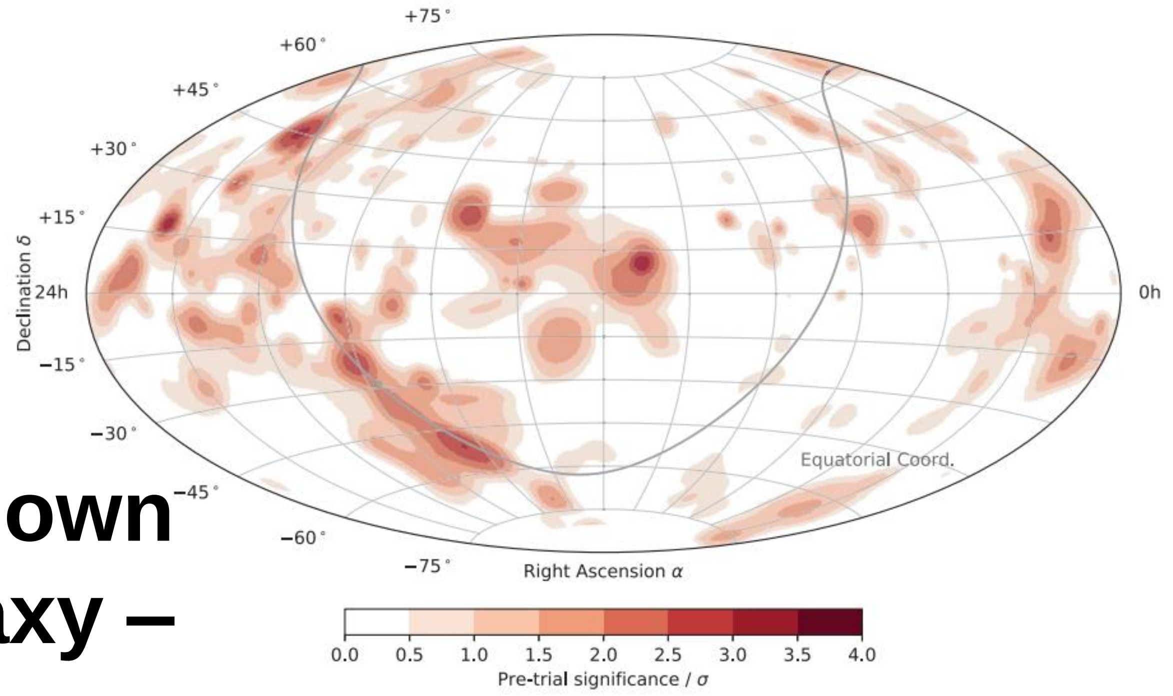
## TXS 0506+056 (blazar) – two "flares"




## NGC 1068 – steady source

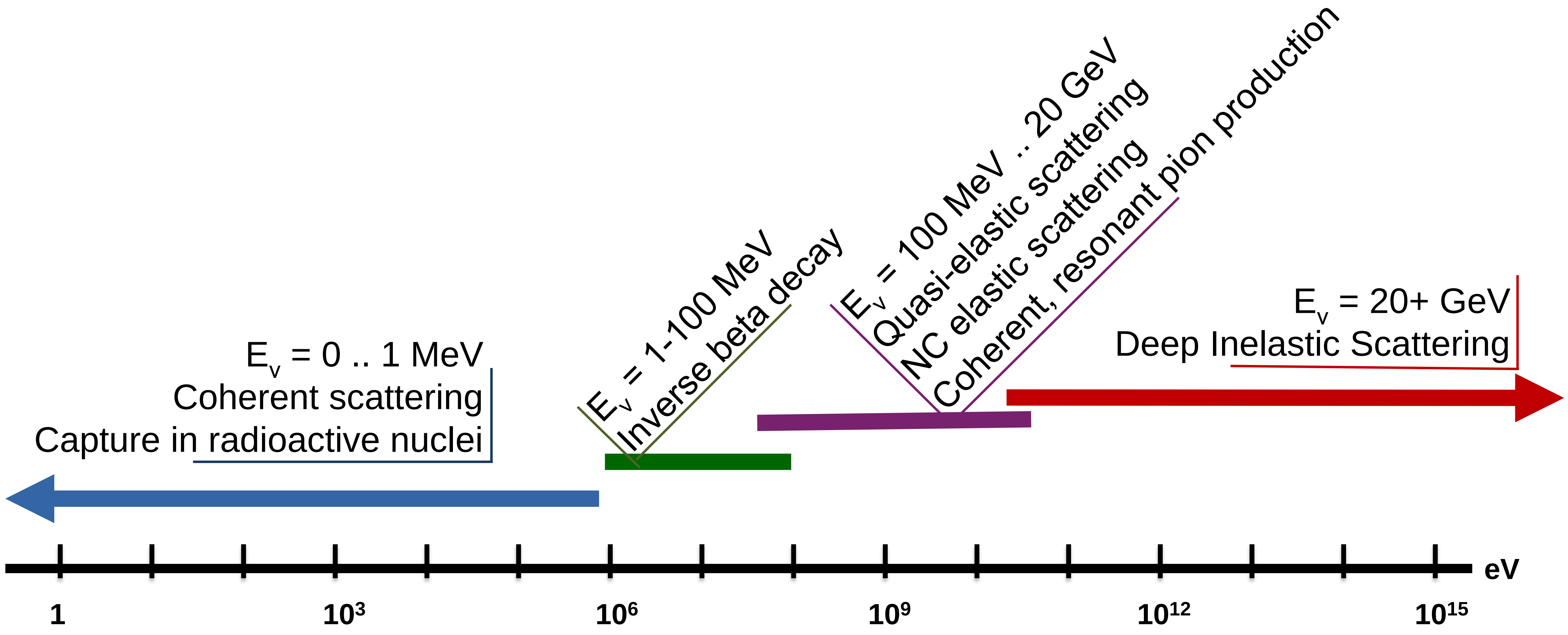



## Our own galaxy – steady source

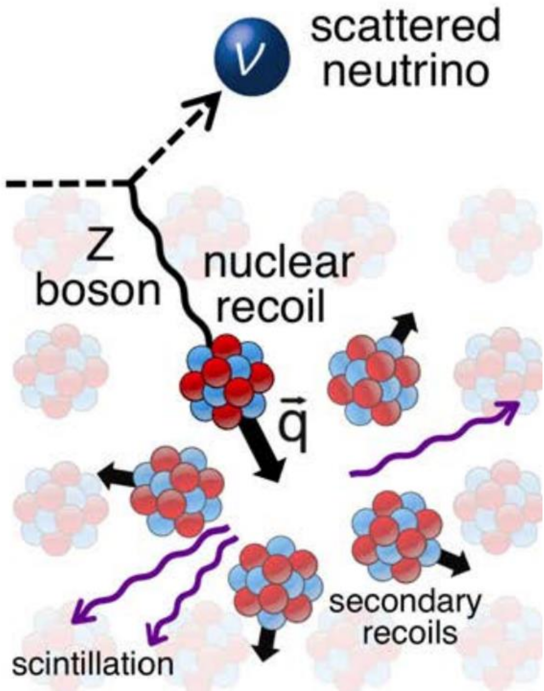


neutrinos can be detected

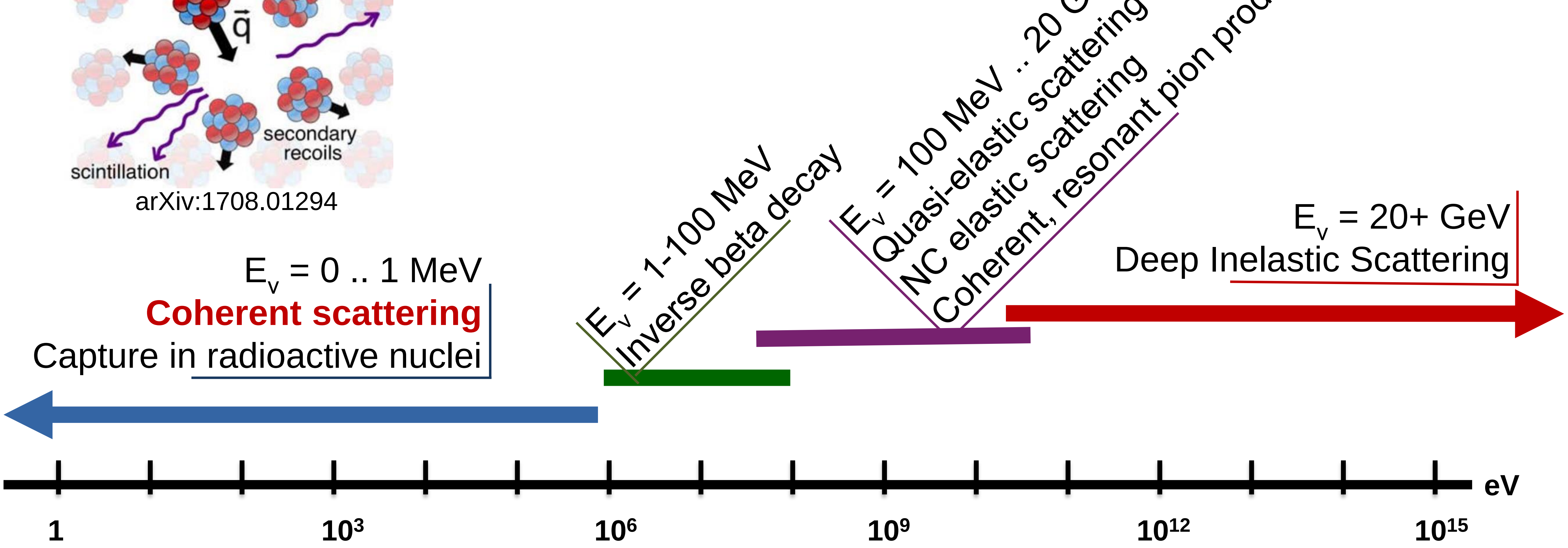
# neutrino detection



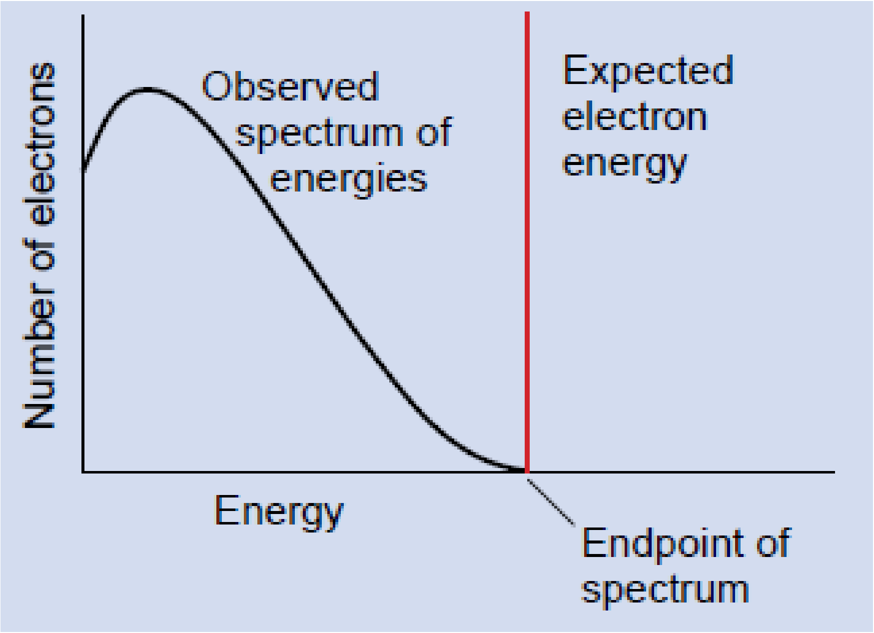
# neutrino detection




arXiv:1708.01294



# what about the neutrino mass?



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

## 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.

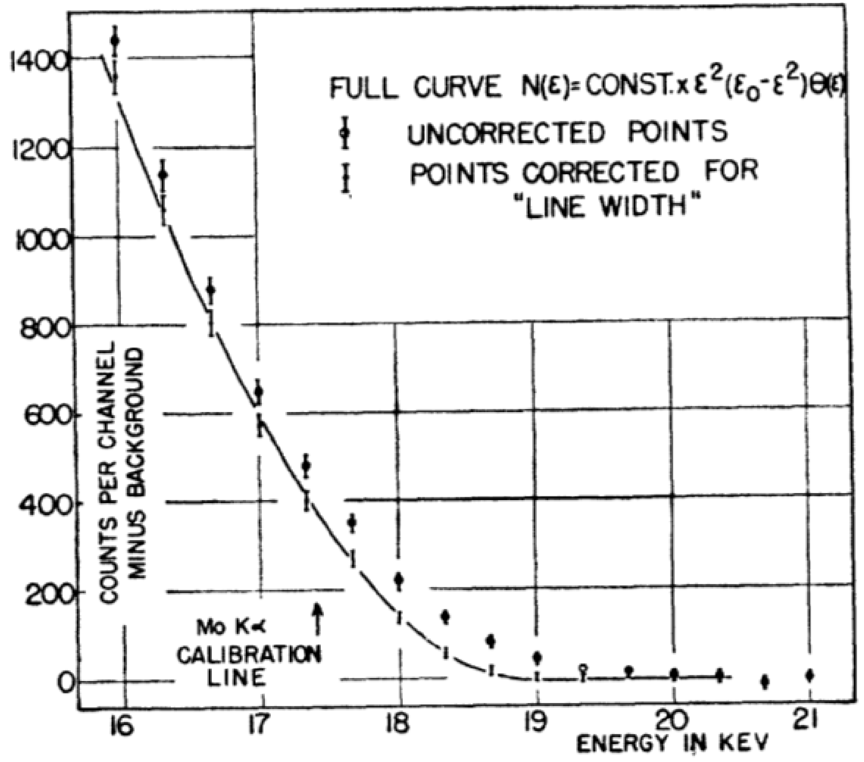



FIG. 1. The spectrum of $H^3$ in the region of the end

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)**

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**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

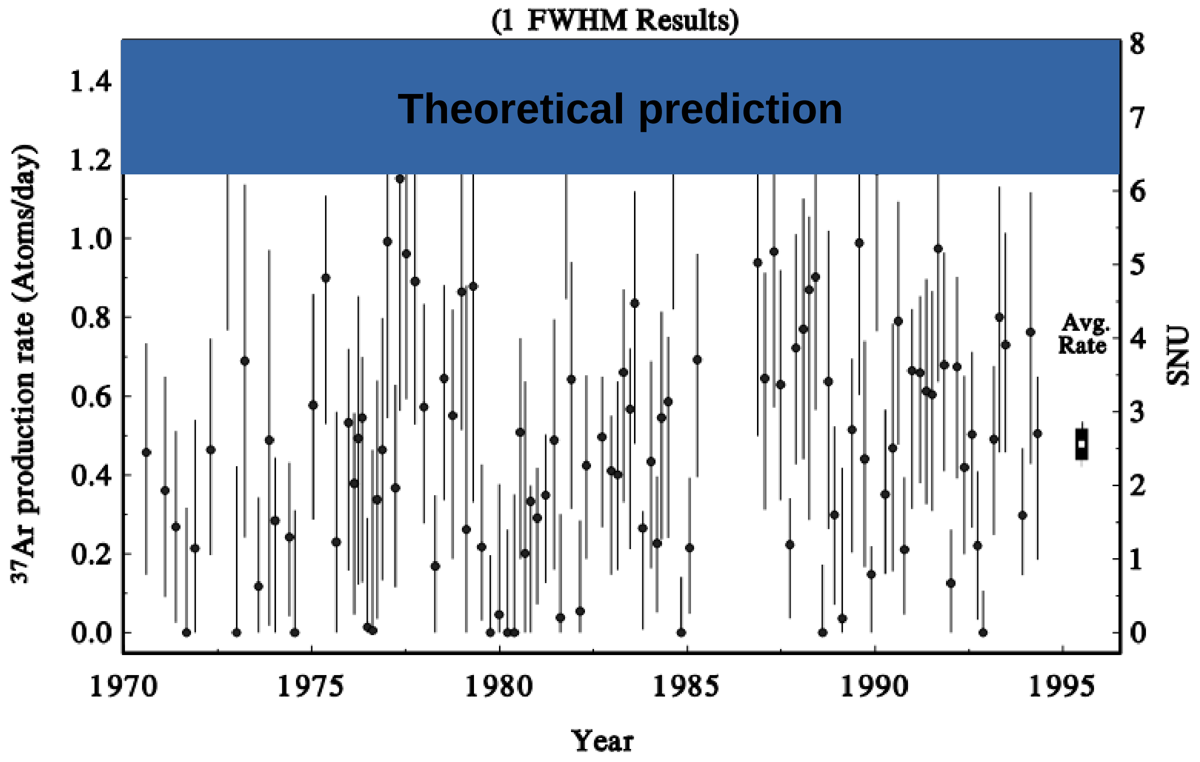
**first weak interaction theories assume the neutrino is massless**
**(1957)**

**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

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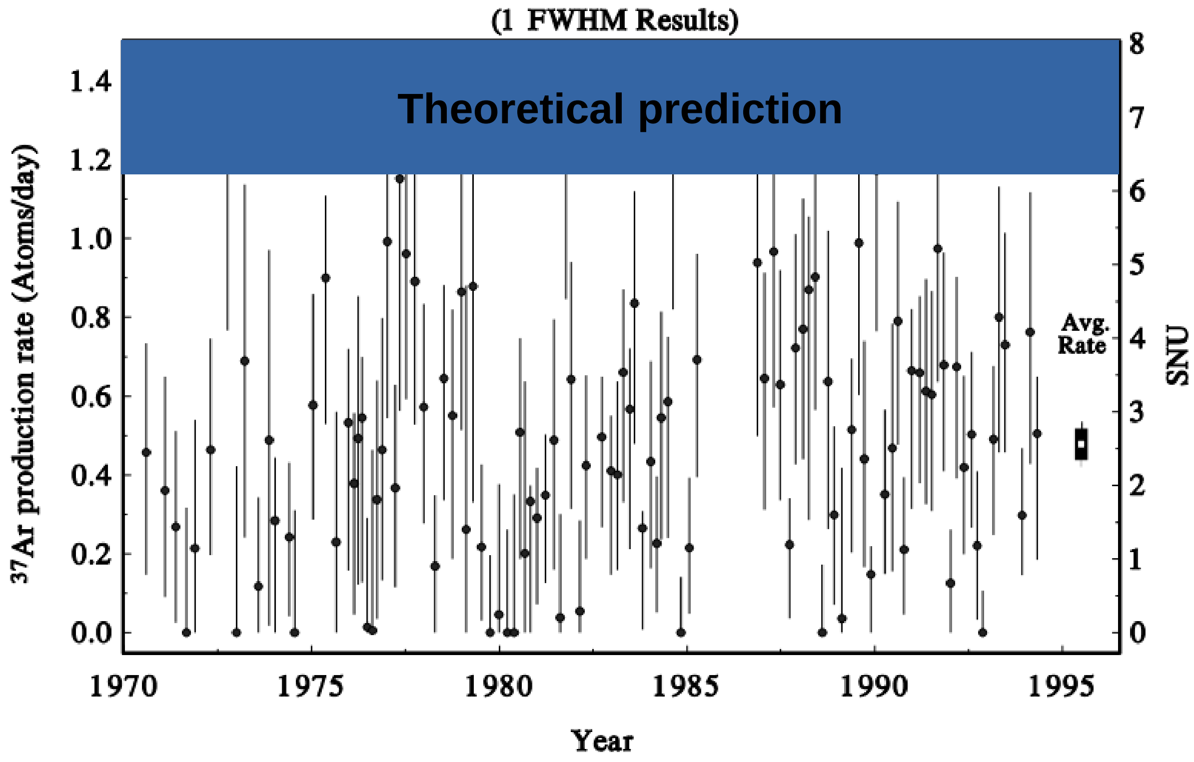
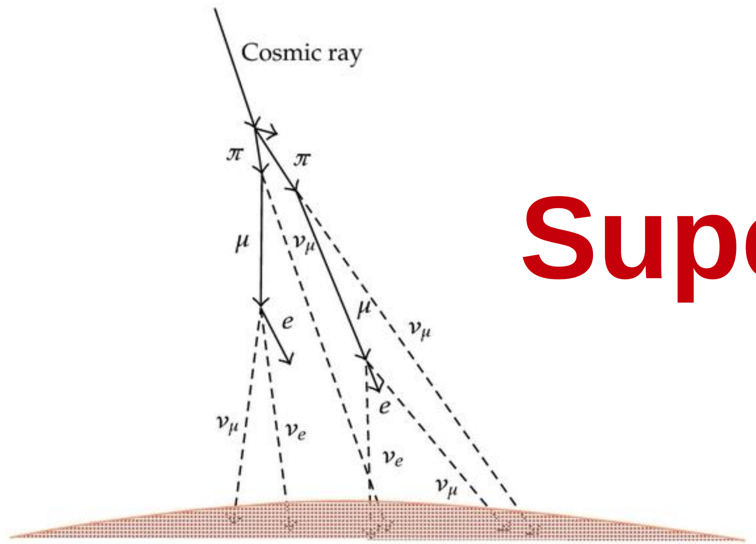


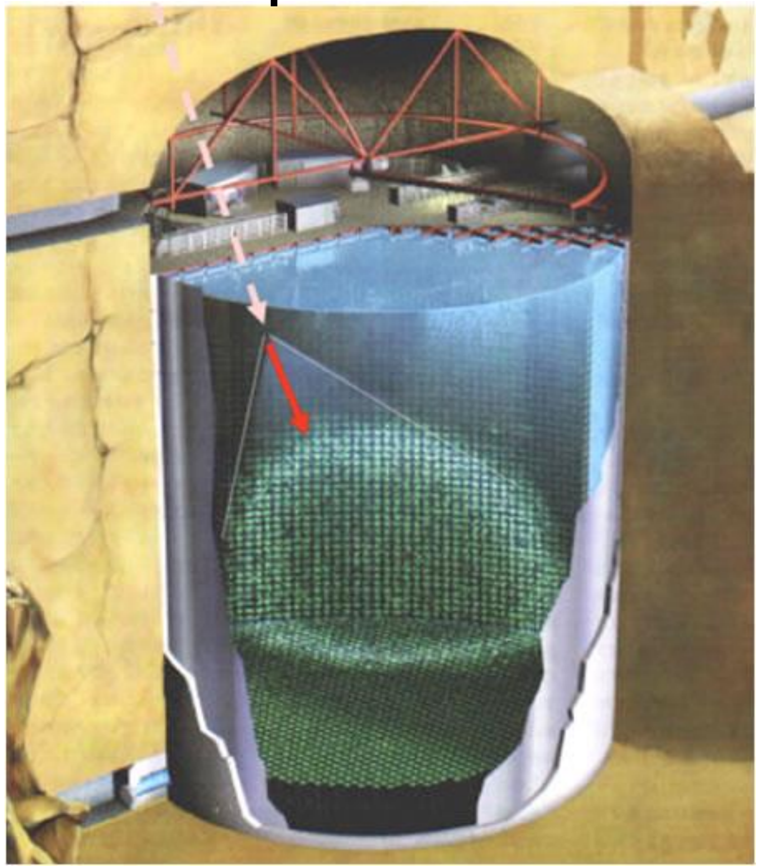

Cleveland, B.T. et al. Astrophys.J. 496 (1998) 505-526

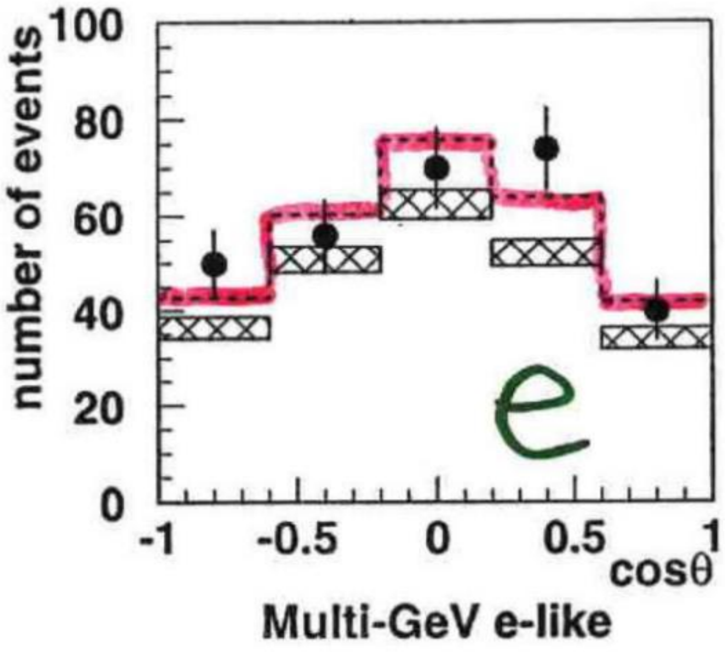
other experiments also see a neutrino deficit

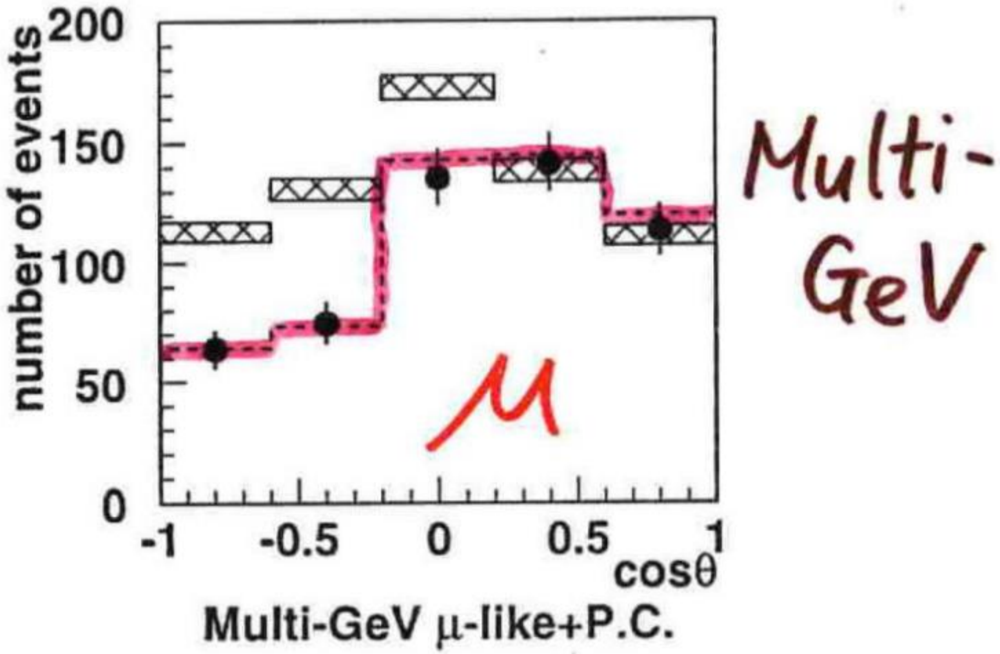
# and along came
# Super-Kamiokande and SNO
# (1998)




**Atmospheric neutrinos**



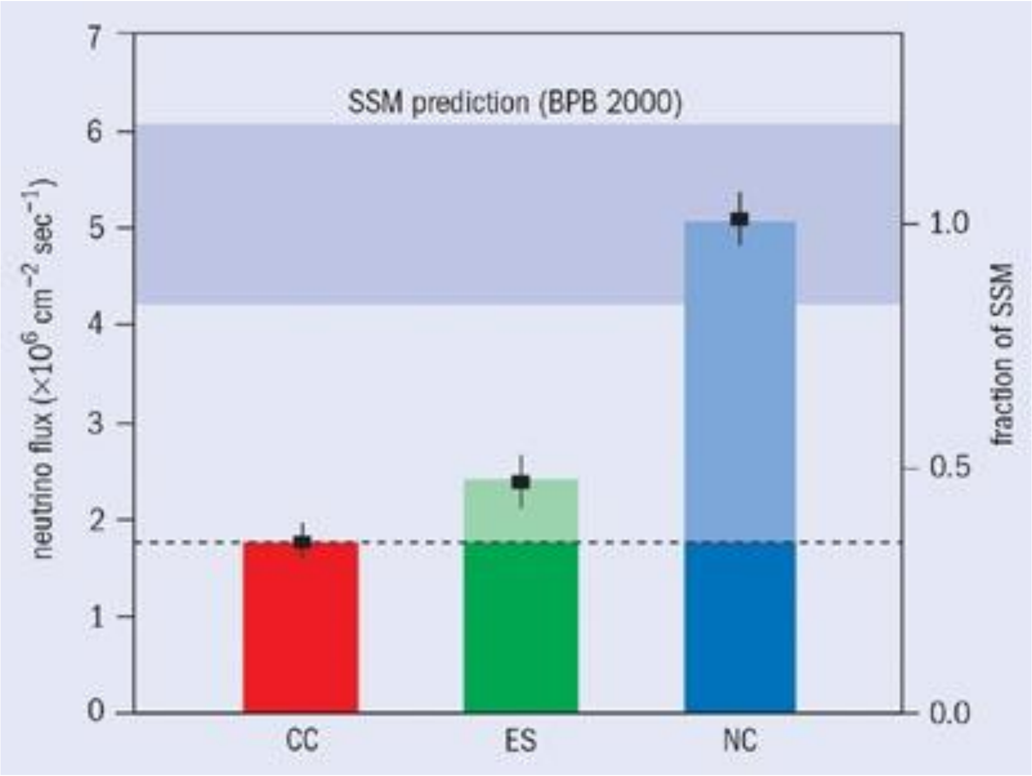


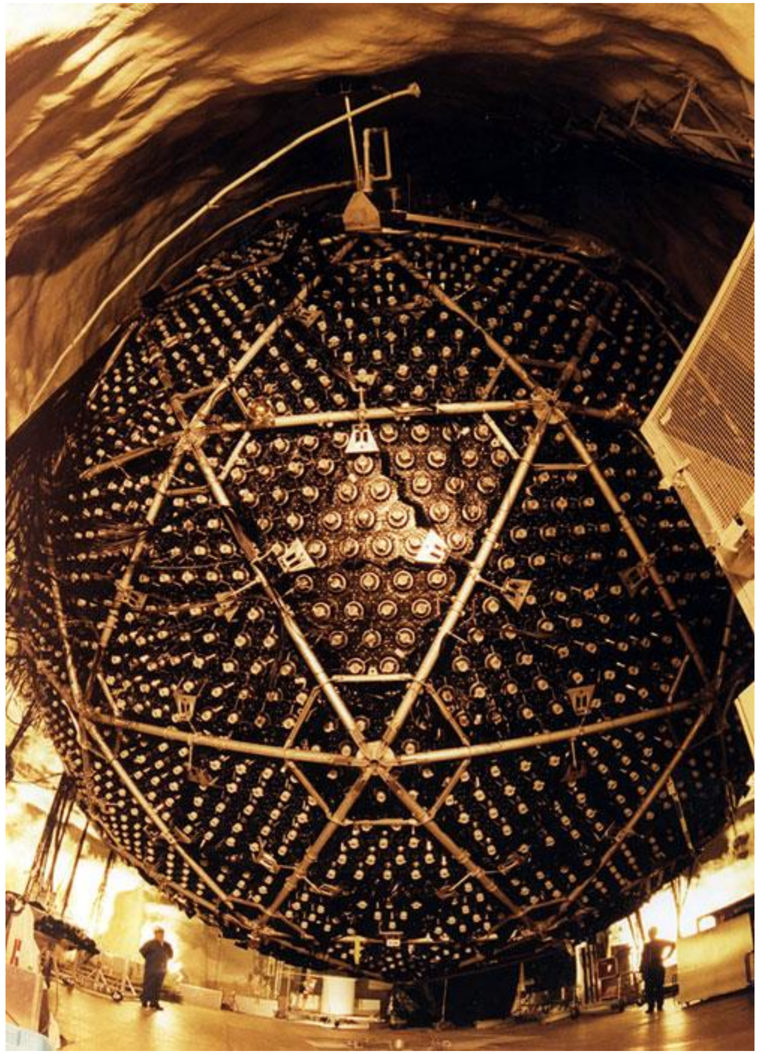

from Neutrino'98 presentation

# and along came Super-Kamiokande and SNO (2001)

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

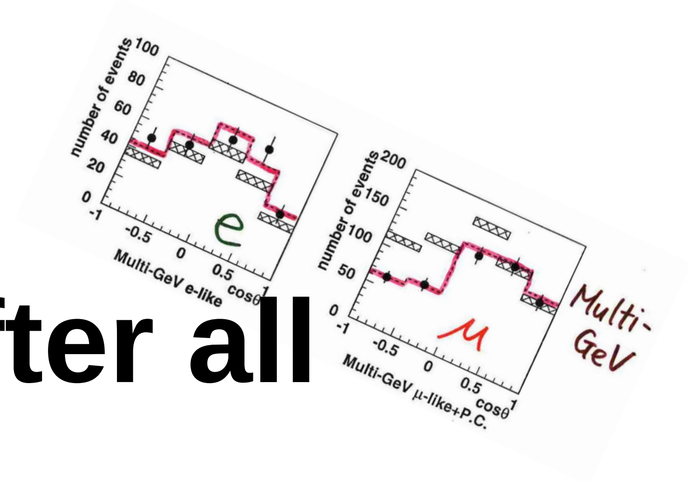



**Solar neutrinos**



Sudbury Neutrino Observatory

# so, neutrinos are massive after all



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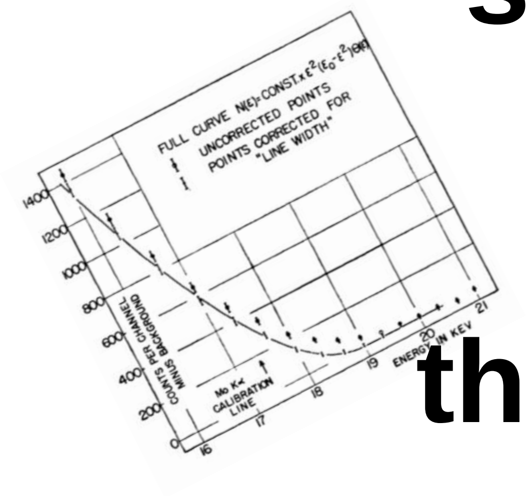
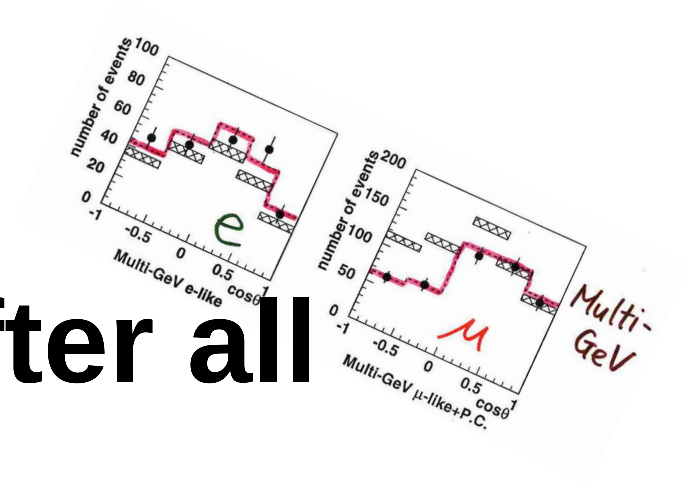
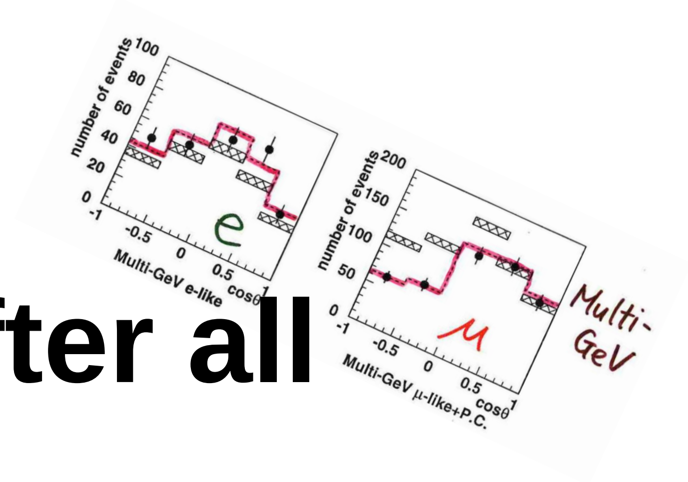
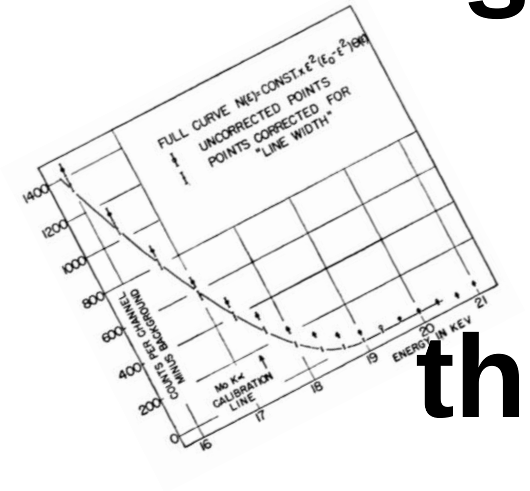


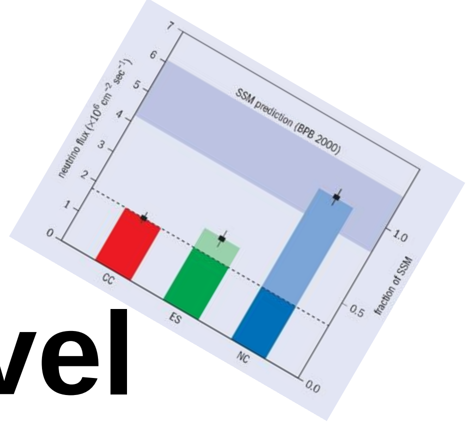

# their masses are small, but relevant




**so, neutrinos are massive after all**




**their masses are small, but relevant**

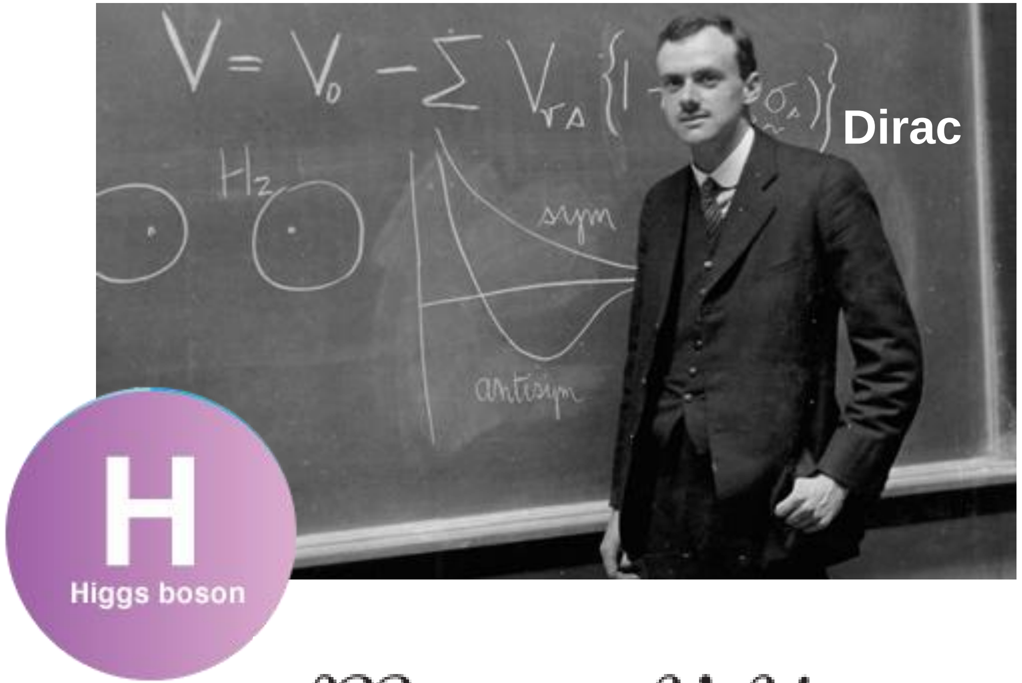



**their flavors get mixed as they travel**

# neutrino masses

# what's the **origin** of the $\nu$ mass?

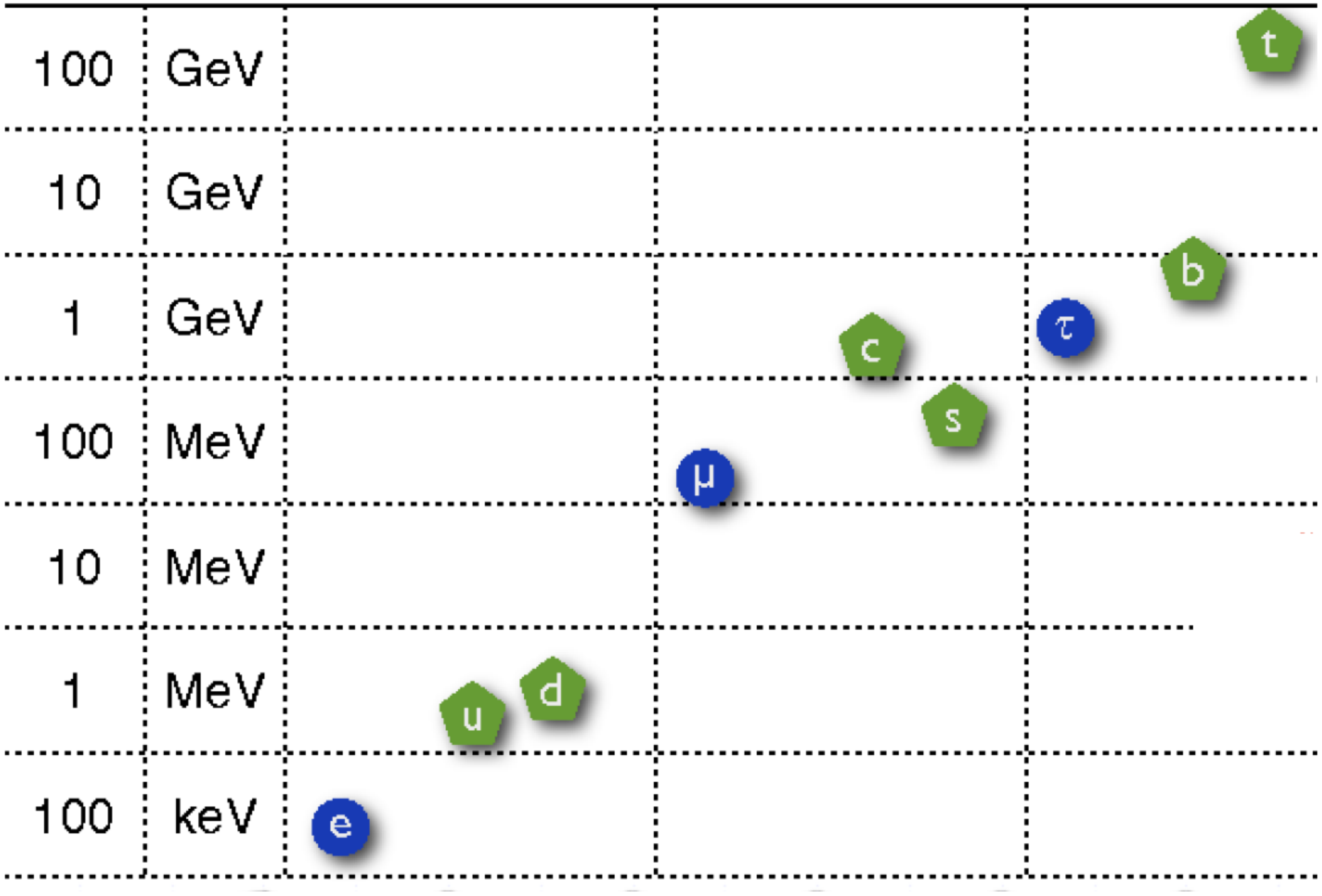
# you can **add mass** to the neutrino as you do for other matter particles



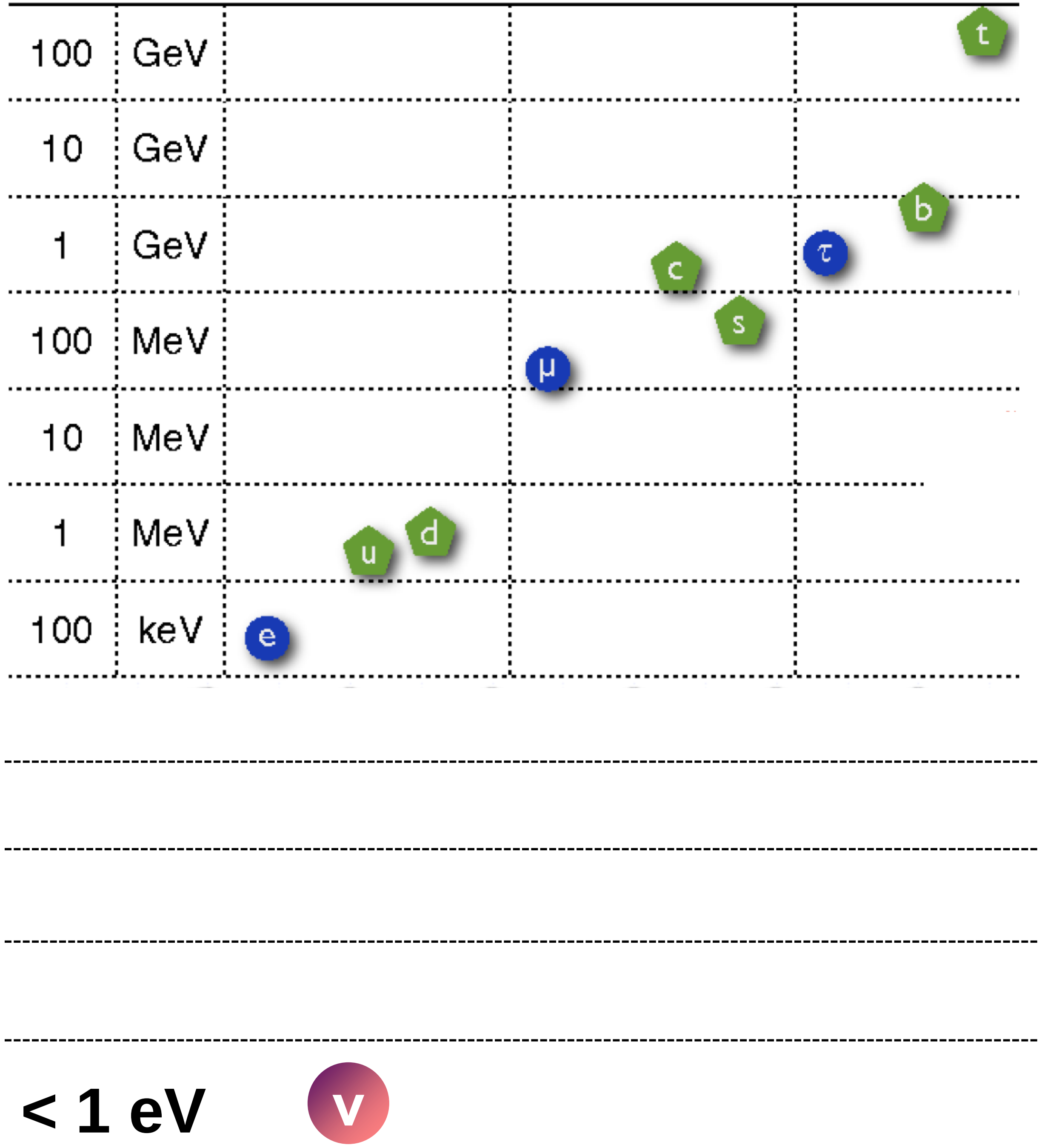

$$m_i = v\, y_i .$$

# but

# masses of elementary particles



# masses of elementary particles

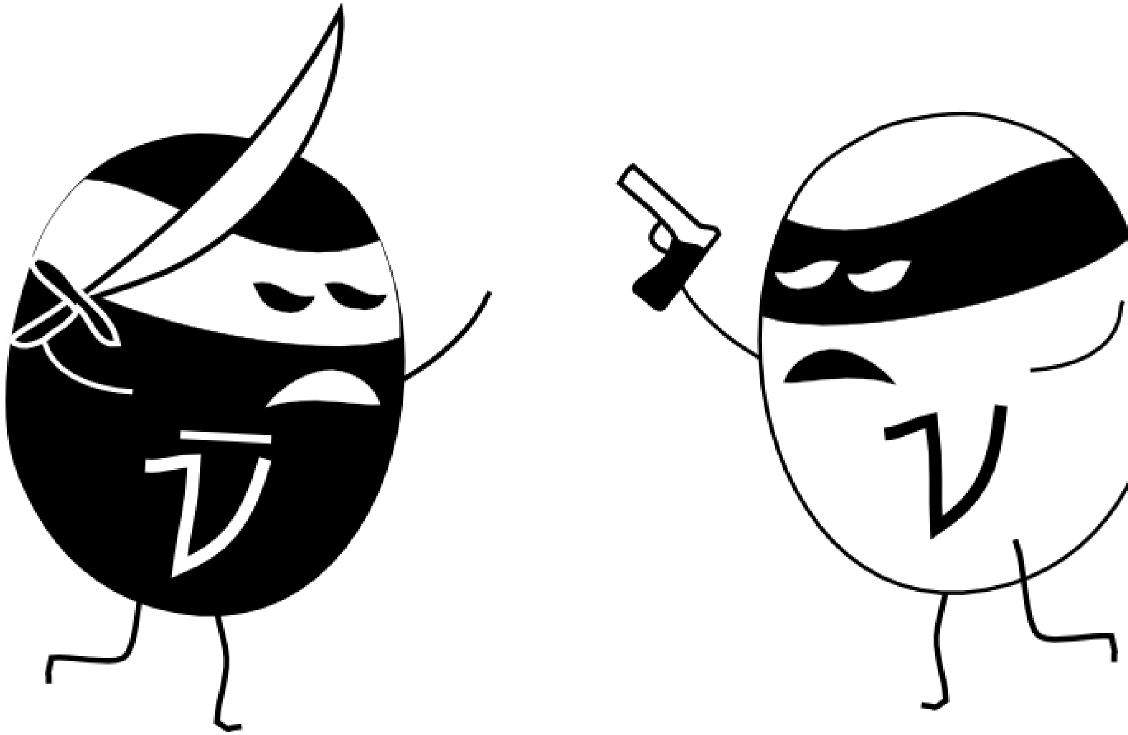



at least 5 orders of magnitude **below**

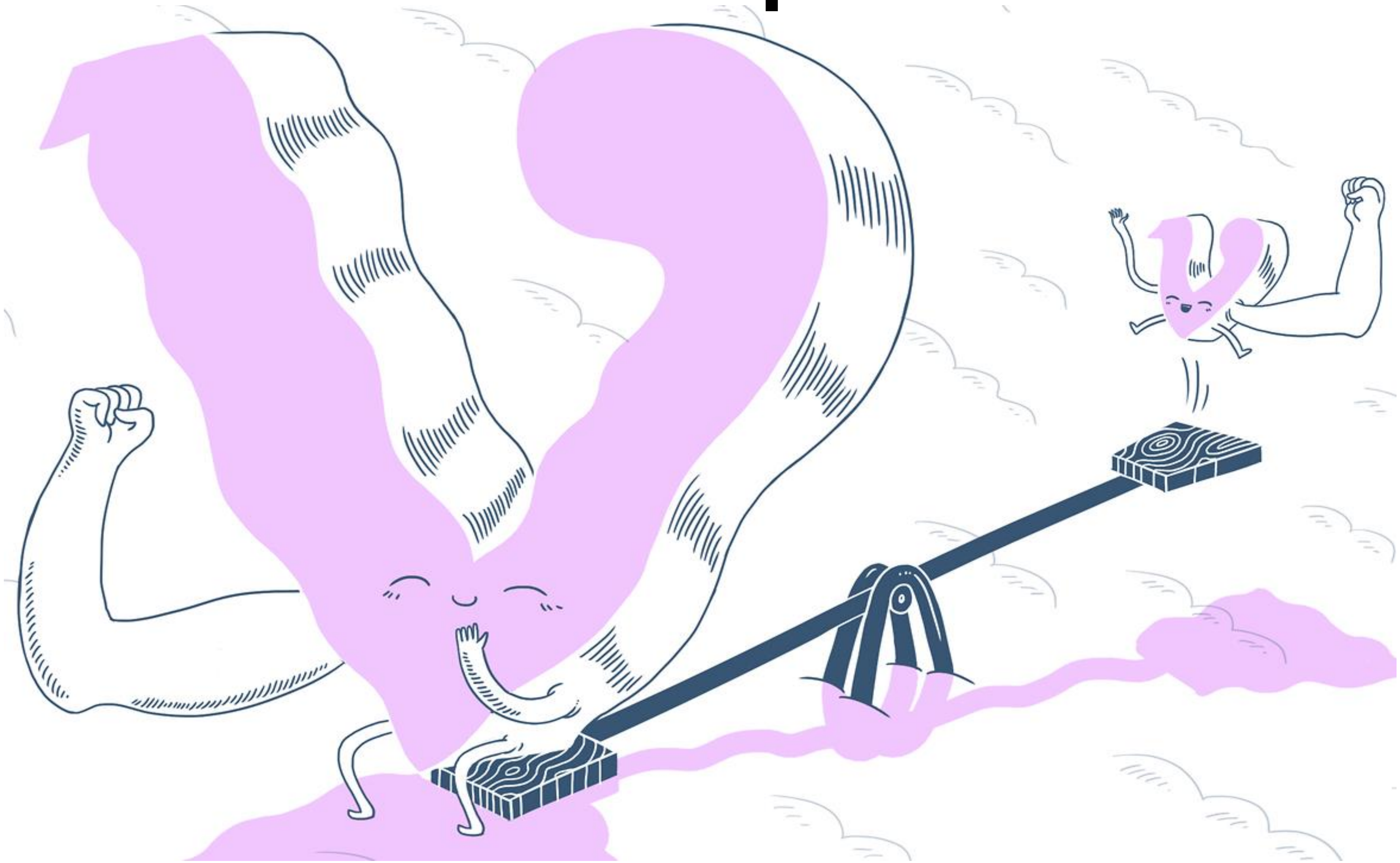
**there’s an alternative to gain mass**

**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



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

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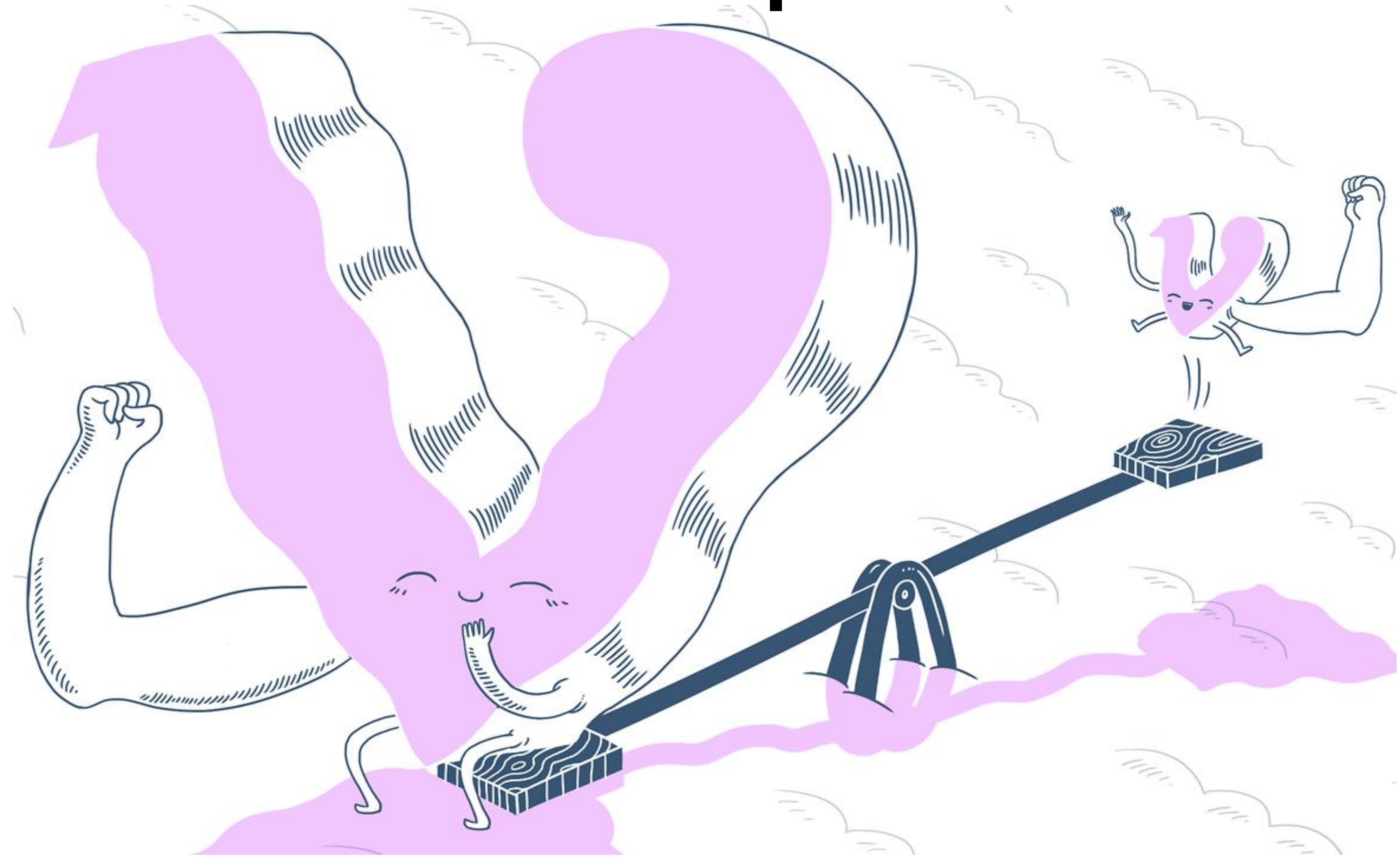
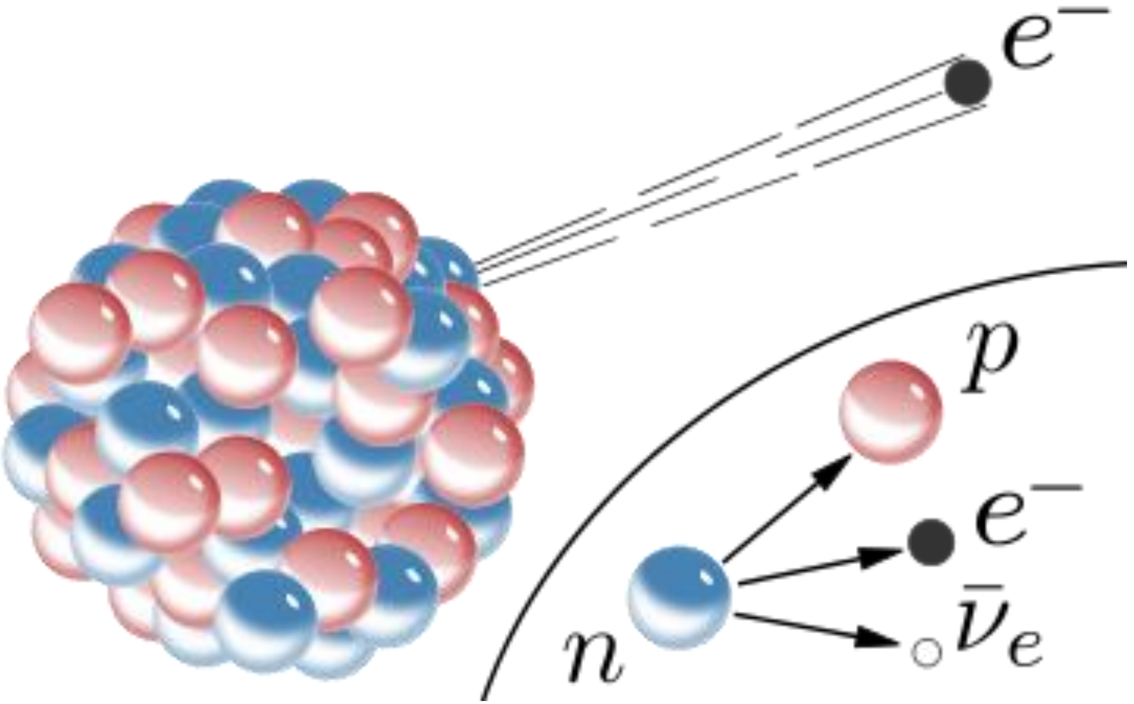


$$m_i = \frac{v^2}{\Lambda}\bar{y}_i.$$

New scale

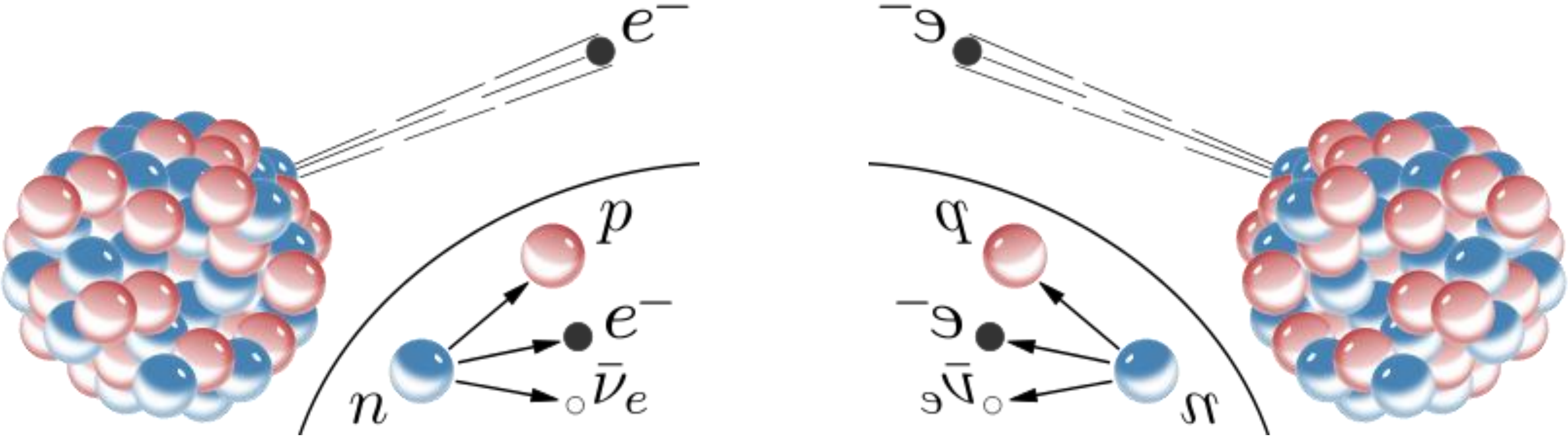
New problem?

# another Majorana peculiarity



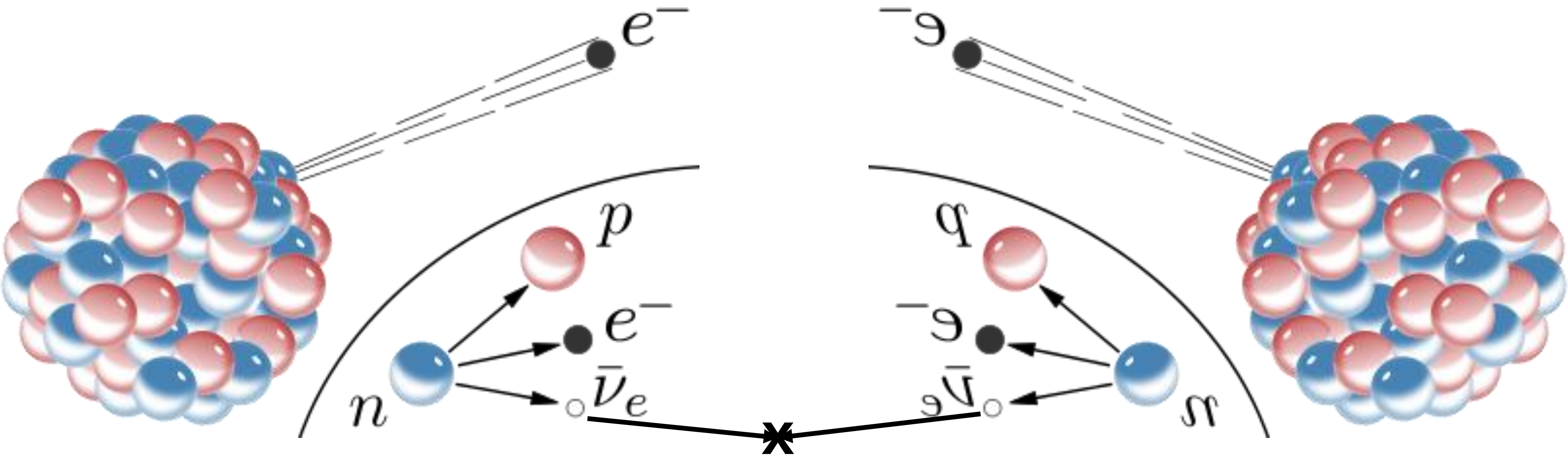

recall the antineutrino emission in beta decay

# another Majorana peculiarity



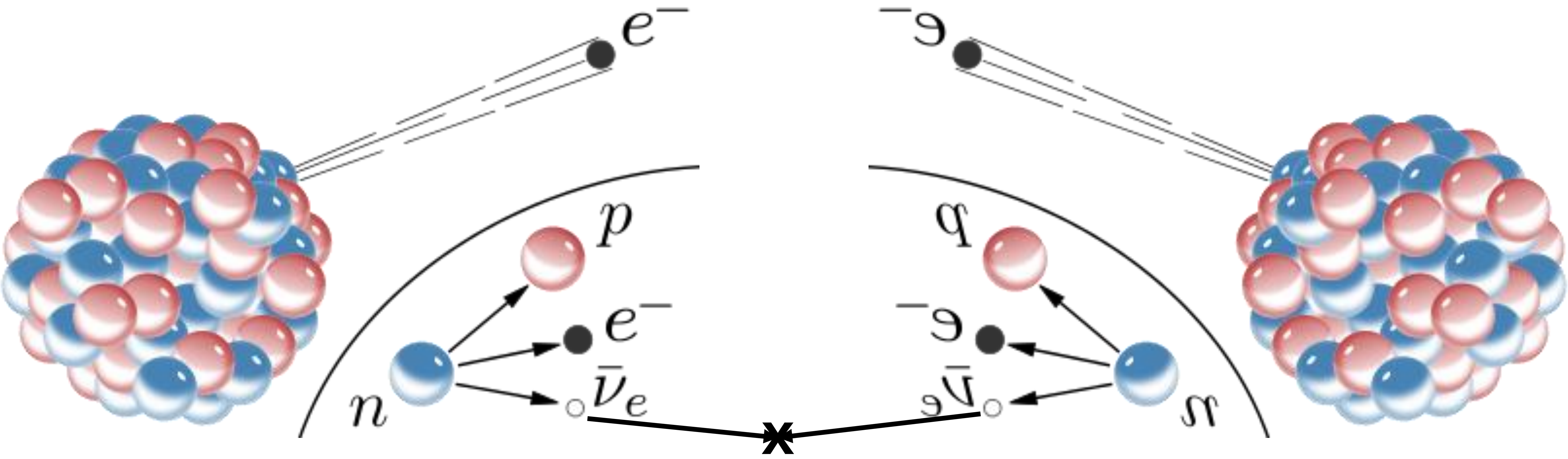

**now, let's make it two of them**

# another Majorana peculiarity



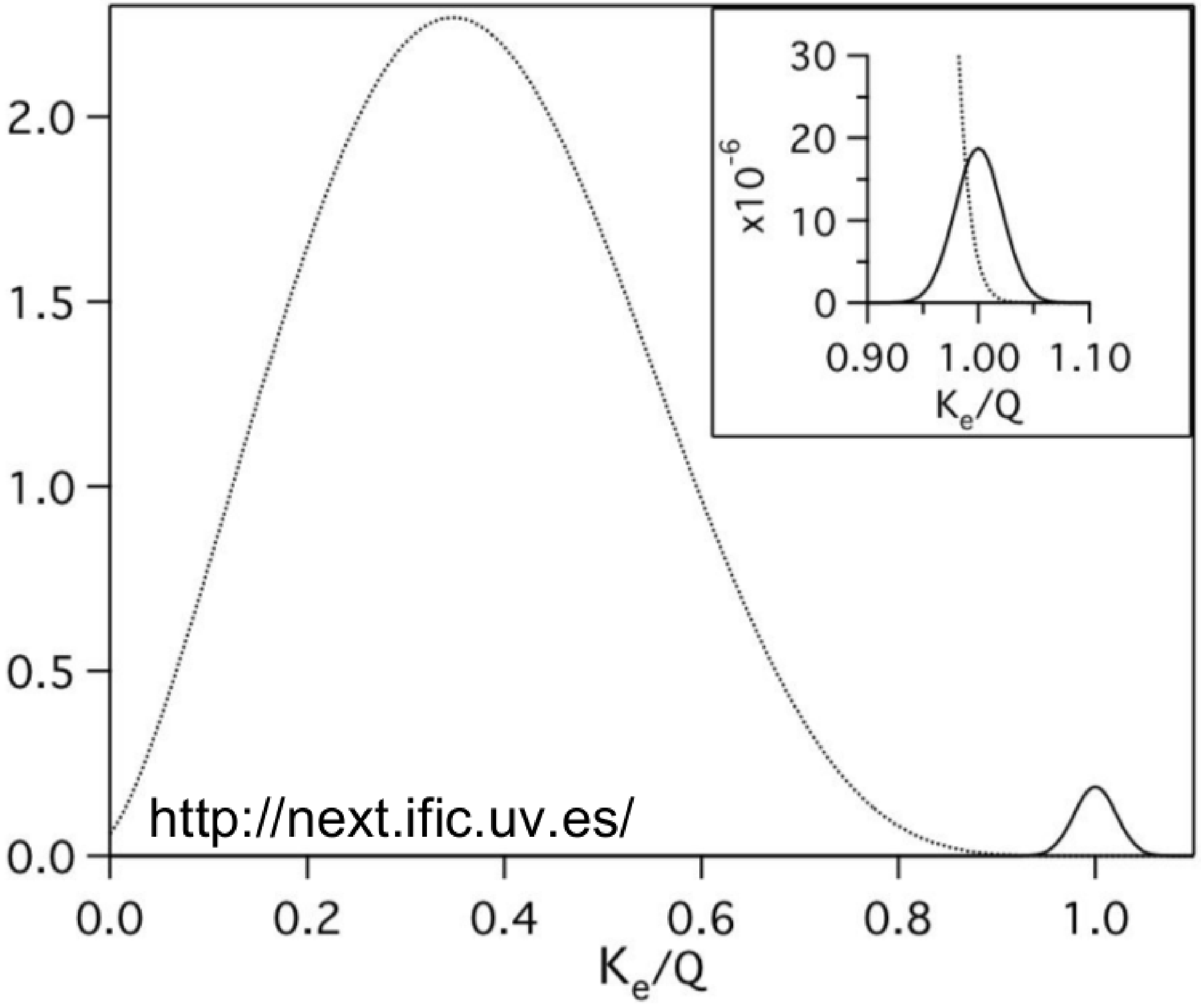

**if the neutrino is its own antiparticle**
**annihilation can occur**

# another Majorana peculiarity




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

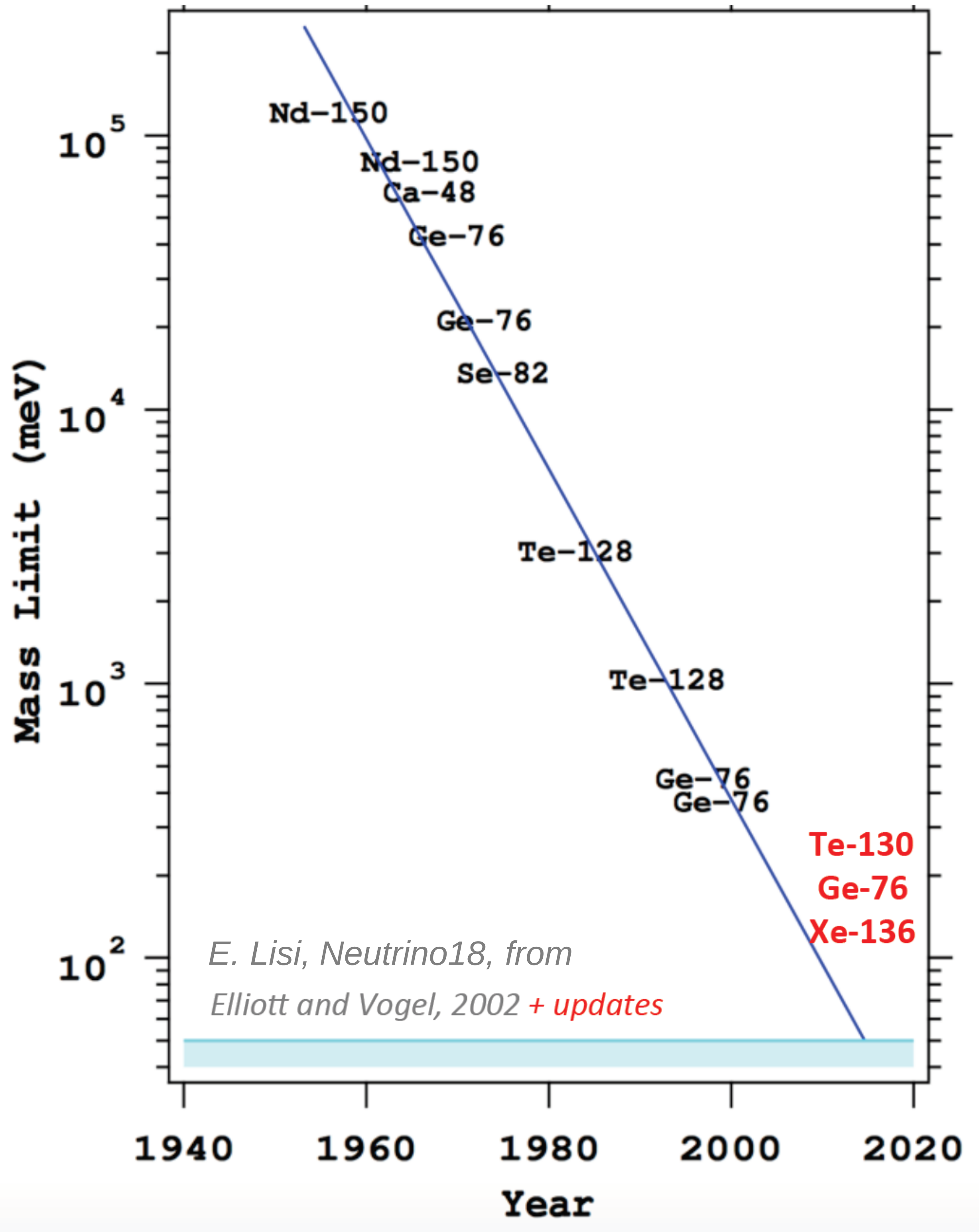
# matter-antimatter asymmetry searches
# aka neutrinoless double-beta decay




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

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

# evolution of limits

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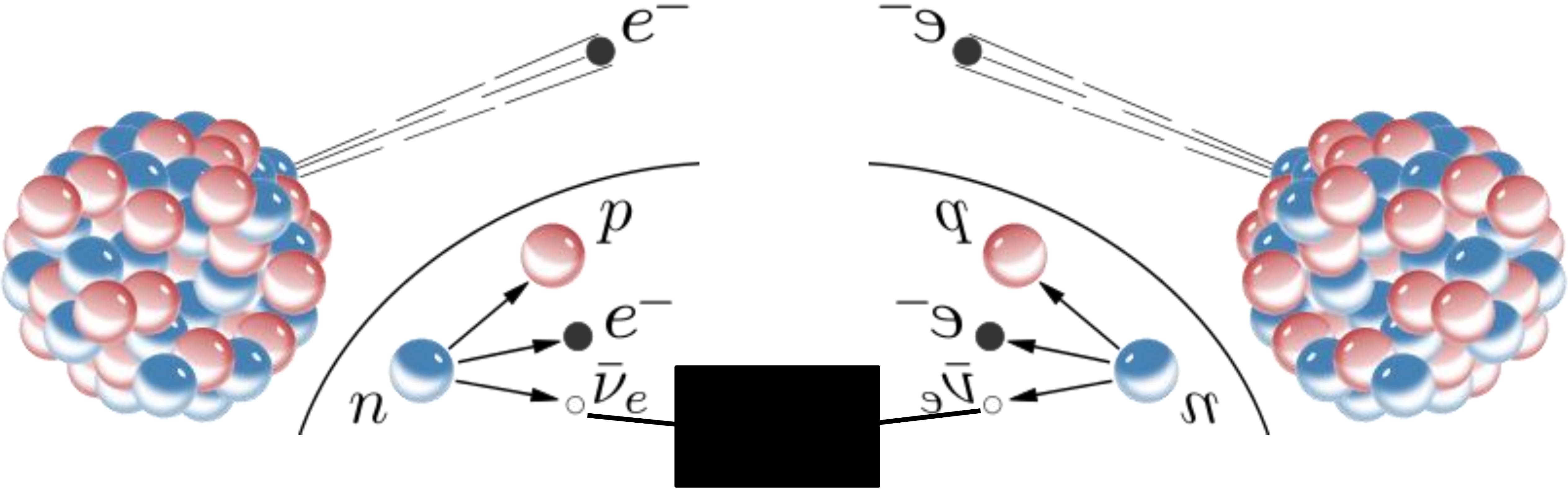
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 \, m_i\right|,$$

**scalability is as crucial as background suppression**

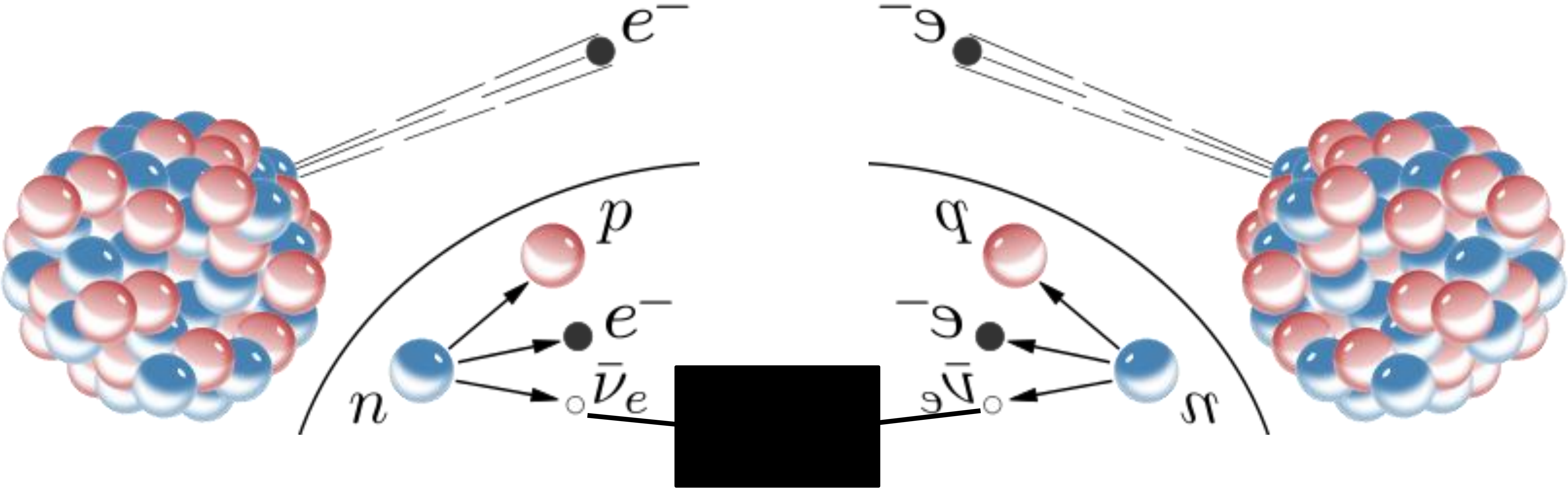
# side note on this process




**what happens in the box doesn’t matter**

**observation of process → lepton # violation**

# side note on this process




**asymmetry between $\ell$ & $\overline{\ell}$ → leptogenesis**

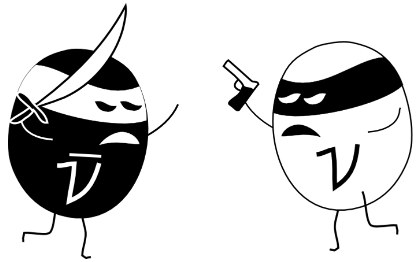
**conversion between**

**baryons to anti-leptons, anti-baryons to leptons**

**by a Standard Model process known as “sphalerons”**

**asymmetry between $\ell$ & $\overline{\ell}$ $\rightarrow$ leptogenesis**

**baryon-antibaryon asymmetry → baryogenesis**

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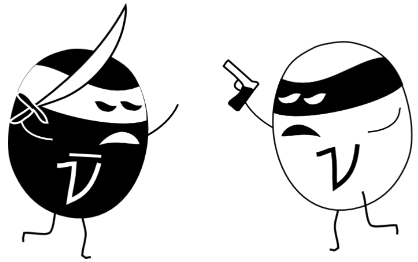



possible explanation of matter-antimatter asymmetry in the Universe

asymmetry between $\ell$ & $\bar{\ell}$ → 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.

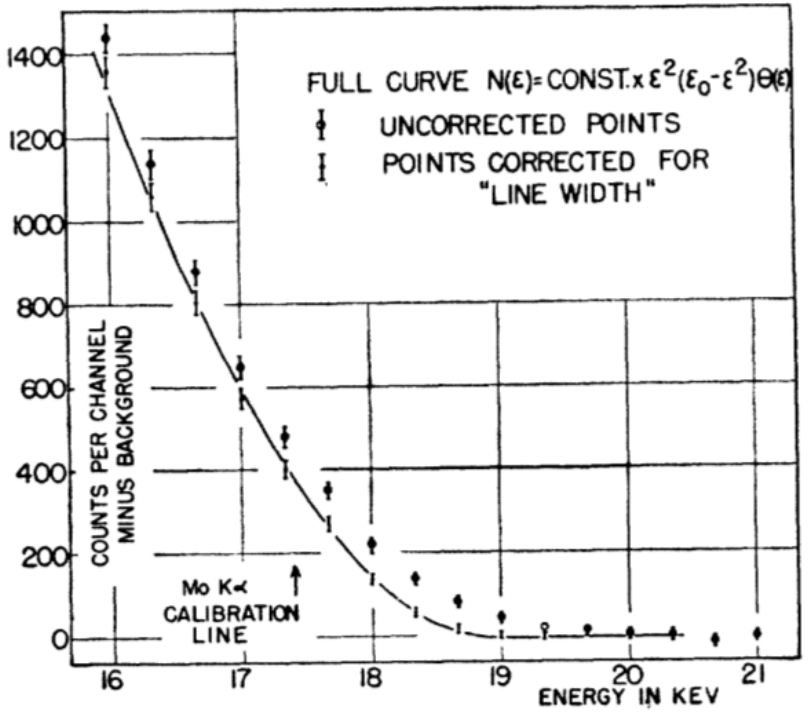
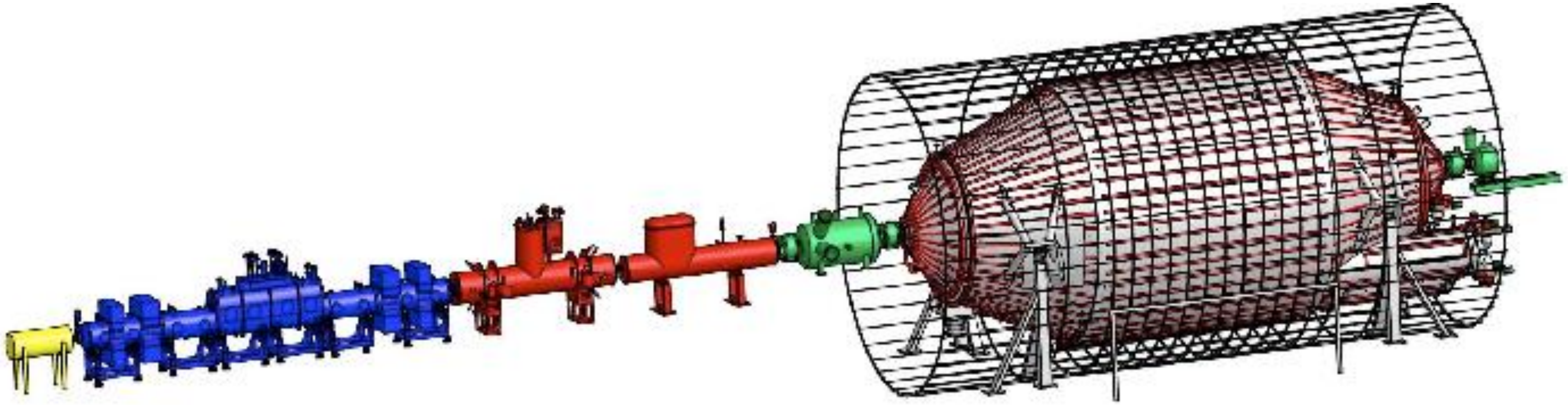



FIG. 1. The spectrum of $H^3$ in the region of the end



**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**

**$m_{\nu} < 0.45$ eV**

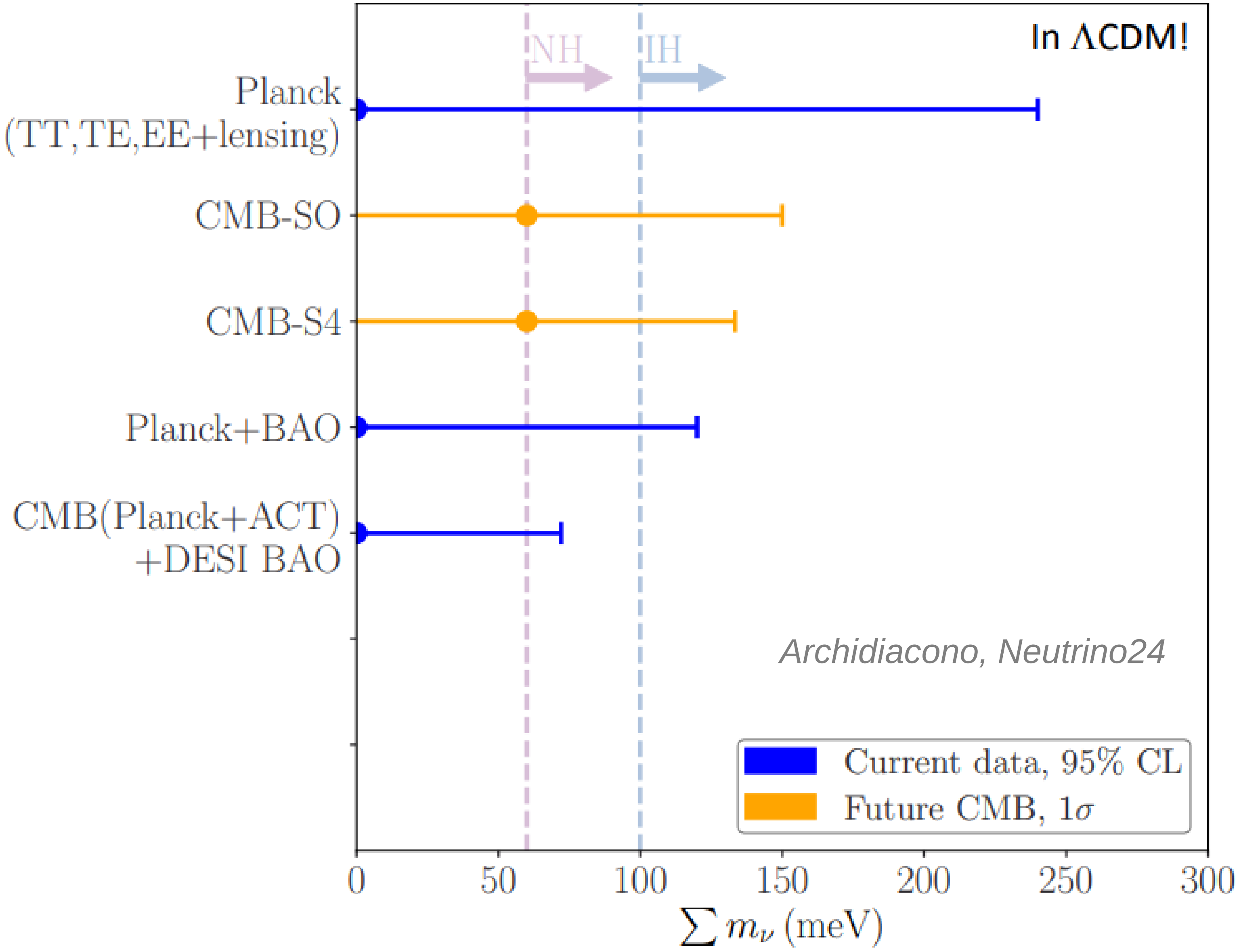
**Presented at Neutrino'24 (arXiv 2406.13516)**

**KATRIN – stopping electrons**

**PROJECT8 – electrons go round and round**

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

# **indirect** mass measurements




**neutrino masses are a parameter in interpretation of cosmological data**

**results depend on details of the cosmological model**

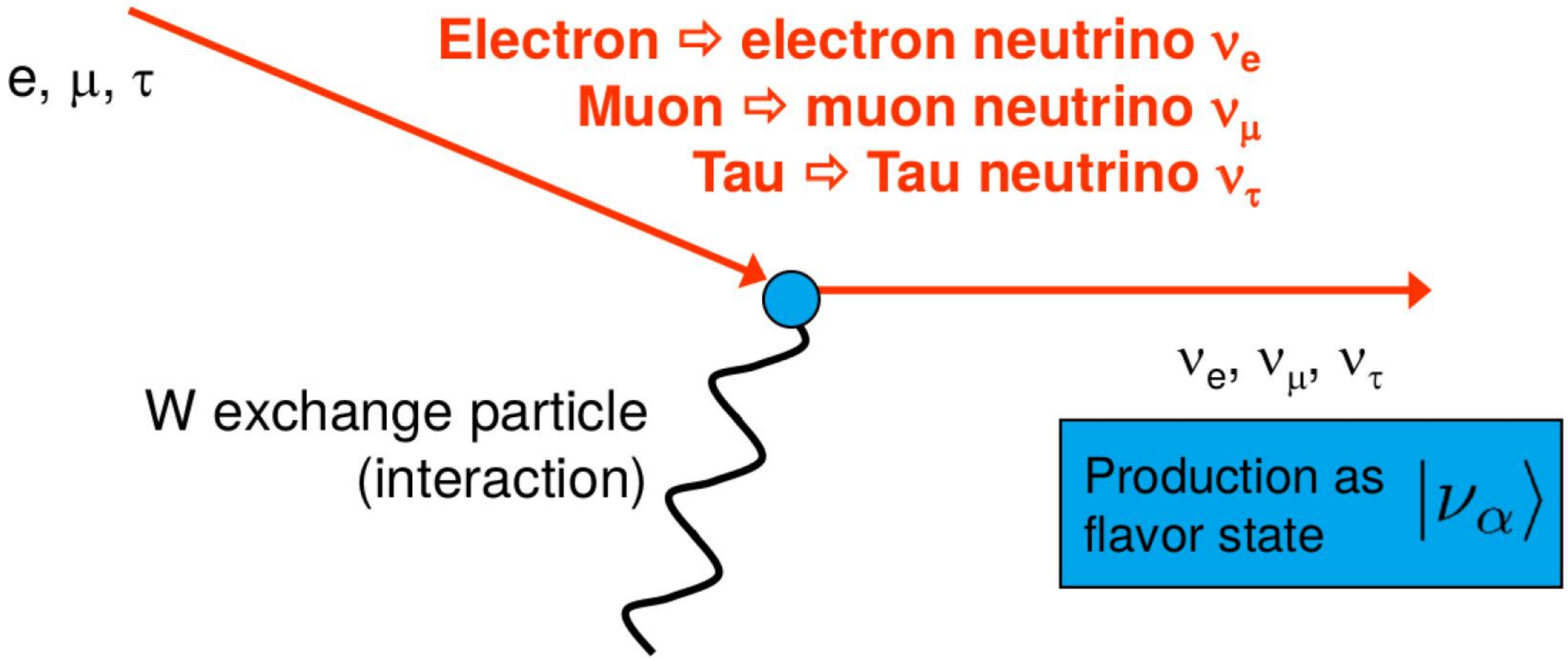
$m_\nu$ **< 72 meV**

**see arXiv:2404.03002**

**(in)direct measurements see**
**no evidence for neutrino mass**

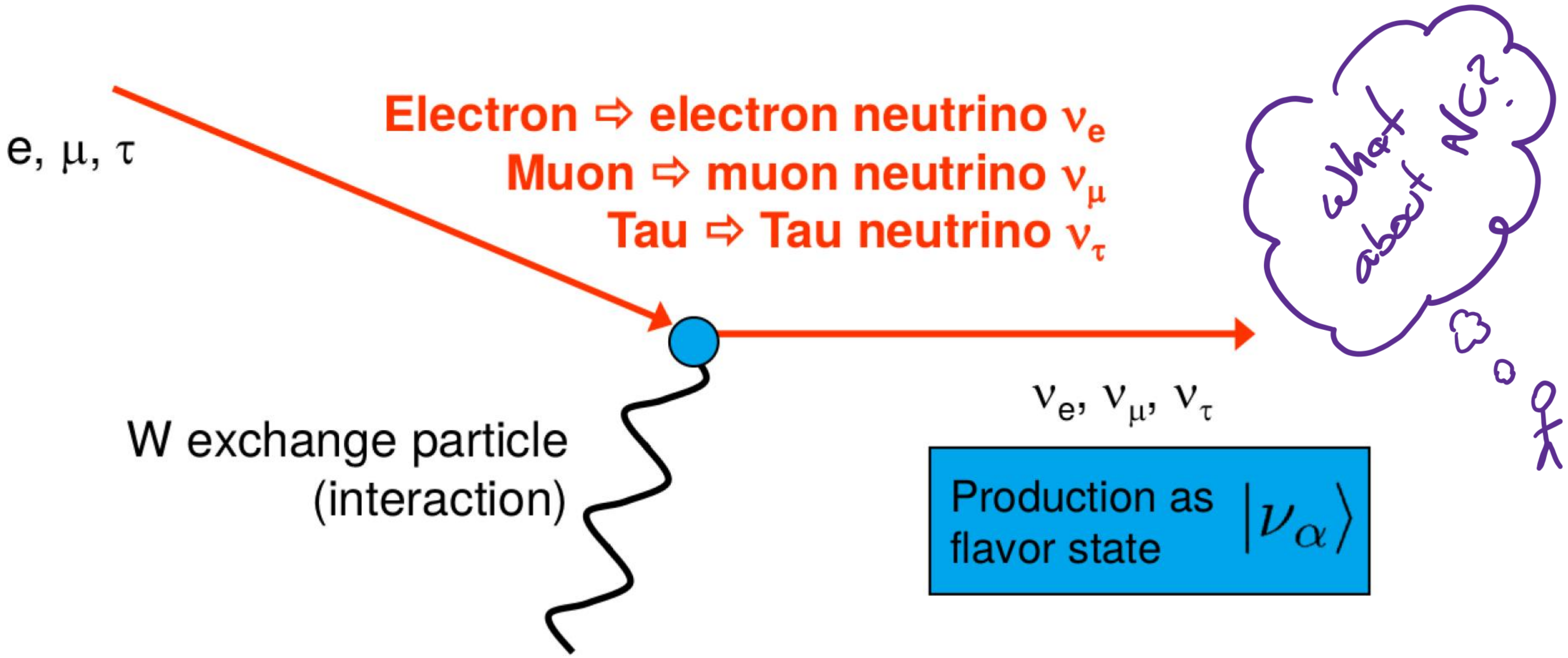
# mixing and oscillations

# neutrinos are detected/produced in weak interactions




**cannot assign mass to the $\nu_e$ $\nu_\mu$ $\nu_\tau$ states!**

# neutrinos are detected/produced in weak interactions




**cannot assign mass to the $\nu_e$ $\nu_\mu$ $\nu_\tau$ states!**

**postulate states $\nu_1$ $\nu_2$ $\nu_3$ with well defined masses**

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

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

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**production → flavor eigenstates**

**propagation → mass eigenstates**

**interaction → flavor eigenstates**

postulate states $\nu_1$ $\nu_2$ $\nu_3$ with **well defined masses**

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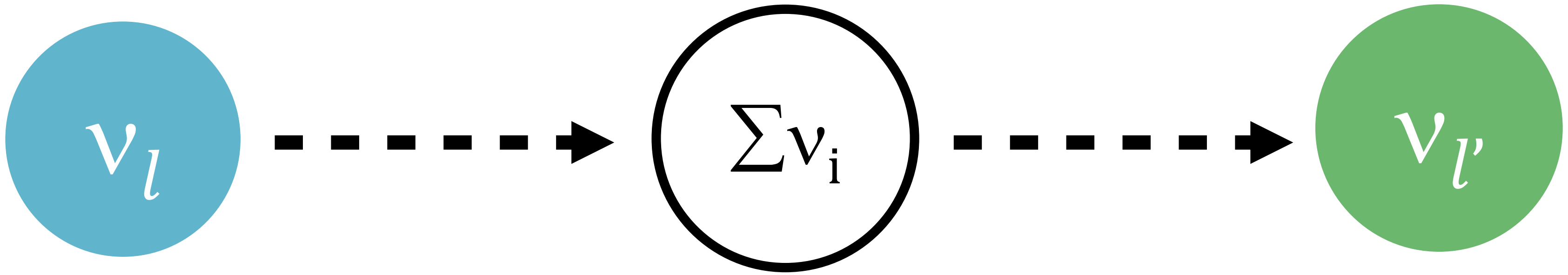
production $\longrightarrow$ **flavor** eigenstates

propagation $\longrightarrow$ **mass** eigenstates

interaction $\longrightarrow$ **flavor** eigenstates

if **flavor ≠ mass** eigenstates




**mixing!**

postulate states $\nu_1$ $\nu_2$ $\nu_3$ 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 $\nu_1$ $\nu_2$ $\nu_3$ with well defined masses**

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**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 $\nu_1$ $\nu_2$ $\nu_3$ 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**

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

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MASS DIFFERENCE INSIDE AN EVEN FUNCTION

NO SIGN INFORMATION

**valid when**

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

SUFFICIENT TO EXPLAIN MOST EXPERIMENTS

## considering propagation in vacuum

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

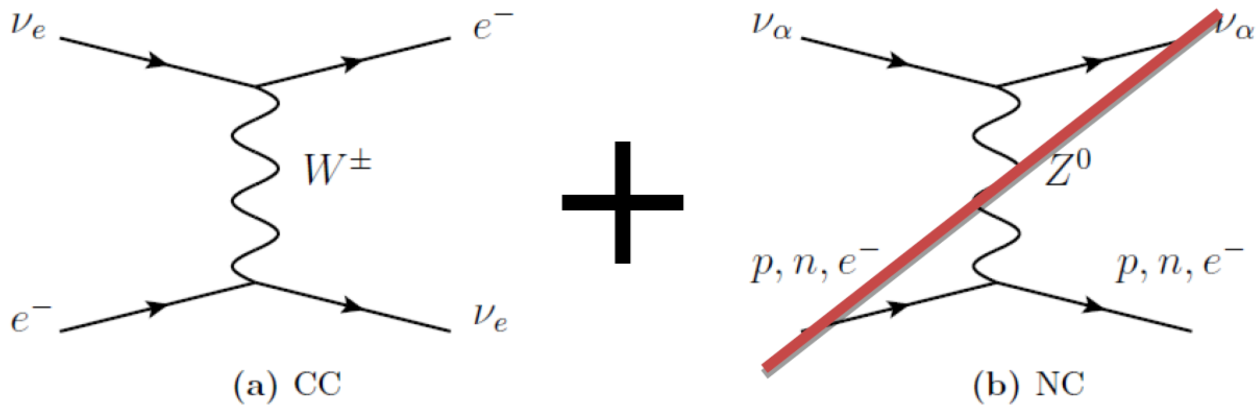
## the master formula (for N species)

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

## matter adds some complications

# considering propagation in matter

## scattering processes in ordinary matter




$$\mathcal{H}_0 \to \mathcal{H} = \mathcal{H}_0 + V(n_e) \qquad V(n_e) = \pm\sqrt{2}\,G_F\,n_e(x)\,\beta,$$

## recycling the formalism: effective parameters in matter

### in constant electron density:

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{\rm CC})^2 + (\Delta m^2 \sin 2\theta)^2}\,,$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \dfrac{A_{\rm CC}}{\Delta m^2 \cos 2\theta}}.$$

$$A = \pm 2\sqrt{2}\,E\,G_F\,n_e.$$

*See Phys.Rev.D64:053003,2001 for a full derivation

# matter effects in oscillations

## MSW resonance and saturation, a local effect

if $A_{\rm R} = \Delta m^2_{31}\cos(2\theta_{13})$. → $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ → $\theta^{\rm M}_{13} = \dfrac{\pi}{4}$ maximal (resonance)

goes to zero

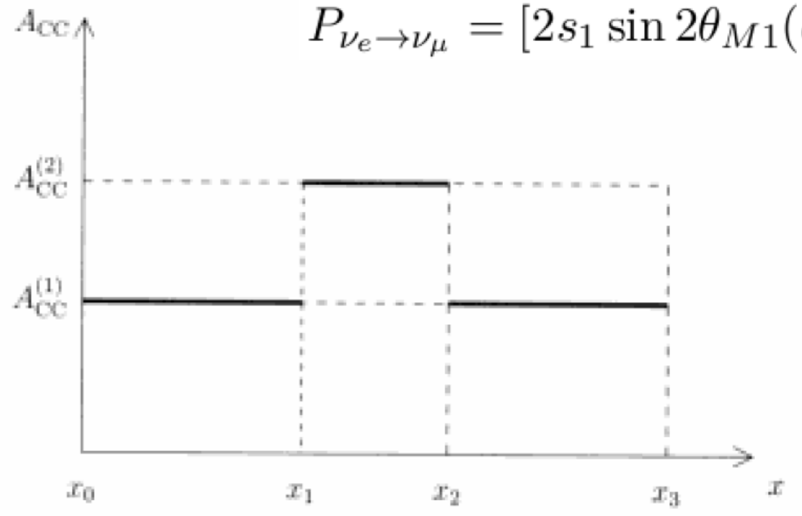
---

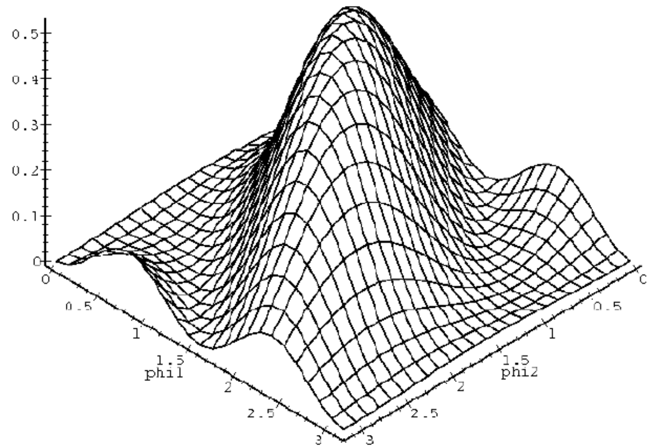
if $|A_{\rm R}| \gg \Delta m^2_{31}\cos(2\theta_{13})$. → $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ → $\theta^{\rm M}_{13} = \dfrac{\pi}{2}$ no mixing (saturation)

becomes large

## parametric resonance, a global effect

$$P_{\nu_e\to\nu_\mu} = [2s_1\sin 2\theta_{M1}(c_1c_2 - s_1s_2\cos 2(\theta_{M1} - \theta_{M2})) + s_2\sin(2\theta_{M2})]^2$$

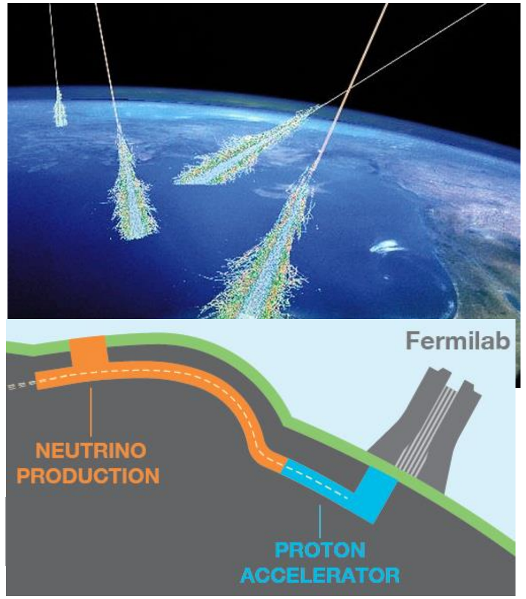


# current knowledge

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

# current knowledge

$U =$ ( 

) (  ) (  )

mostly in disappearance mode

appearance experiments are tough but help complete the picture

# current knowledge

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

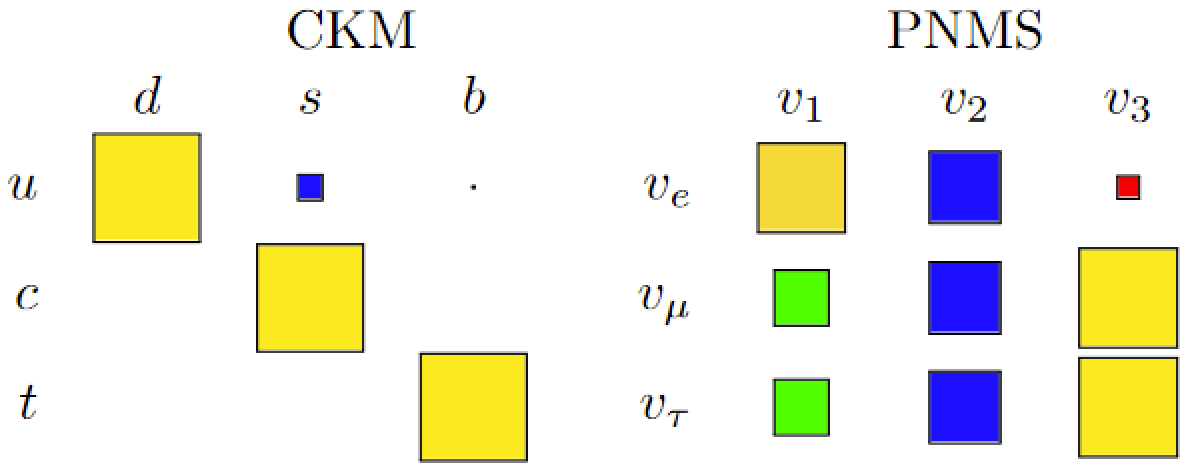
NuFIT 5.3 (2024)

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.801 \to 0.842 & 0.518 \to 0.580 & 0.142 \to 0.155 \\ 0.236 \to 0.507 & 0.458 \to 0.691 & 0.630 \to 0.779 \\ 0.264 \to 0.527 & 0.471 \to 0.700 & 0.610 \to 0.762 \end{pmatrix}$$

**close to maximal mixing possible**

**why? another symmetry?**

# current knowledge

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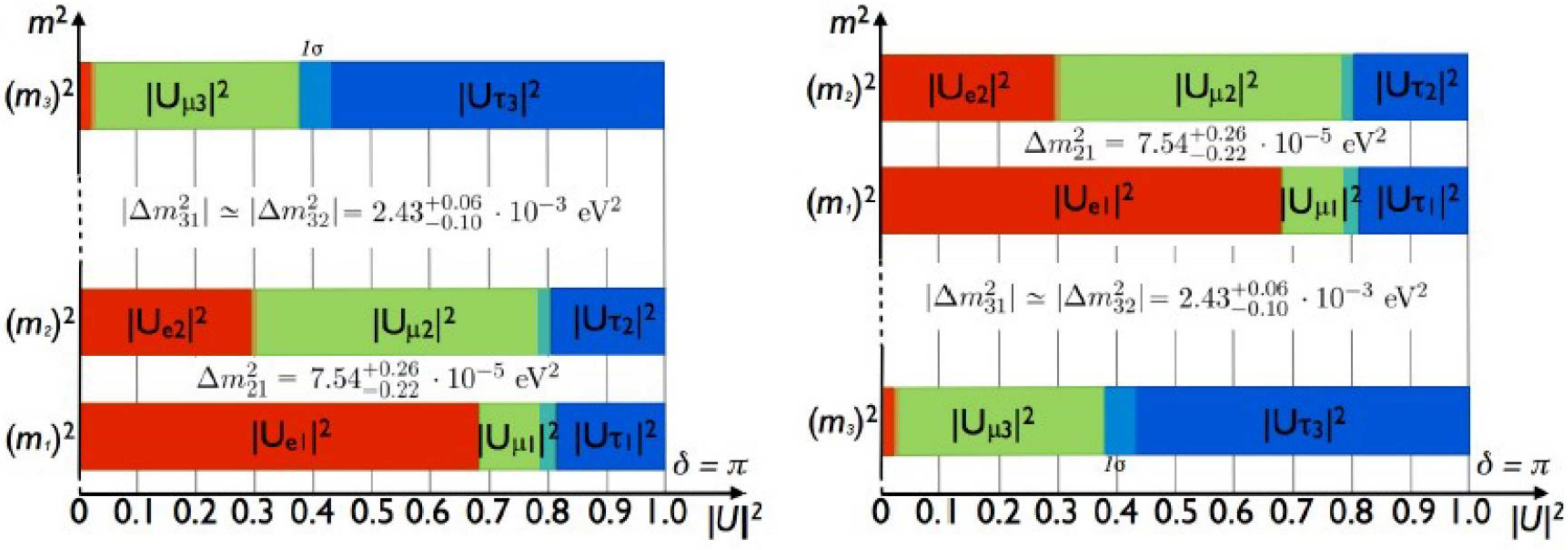
**need better precision**

**close to maximal mixing possible**

**why? another symmetry?**

# missing measurements



(a) Normal ordering

(b) Inverted ordering

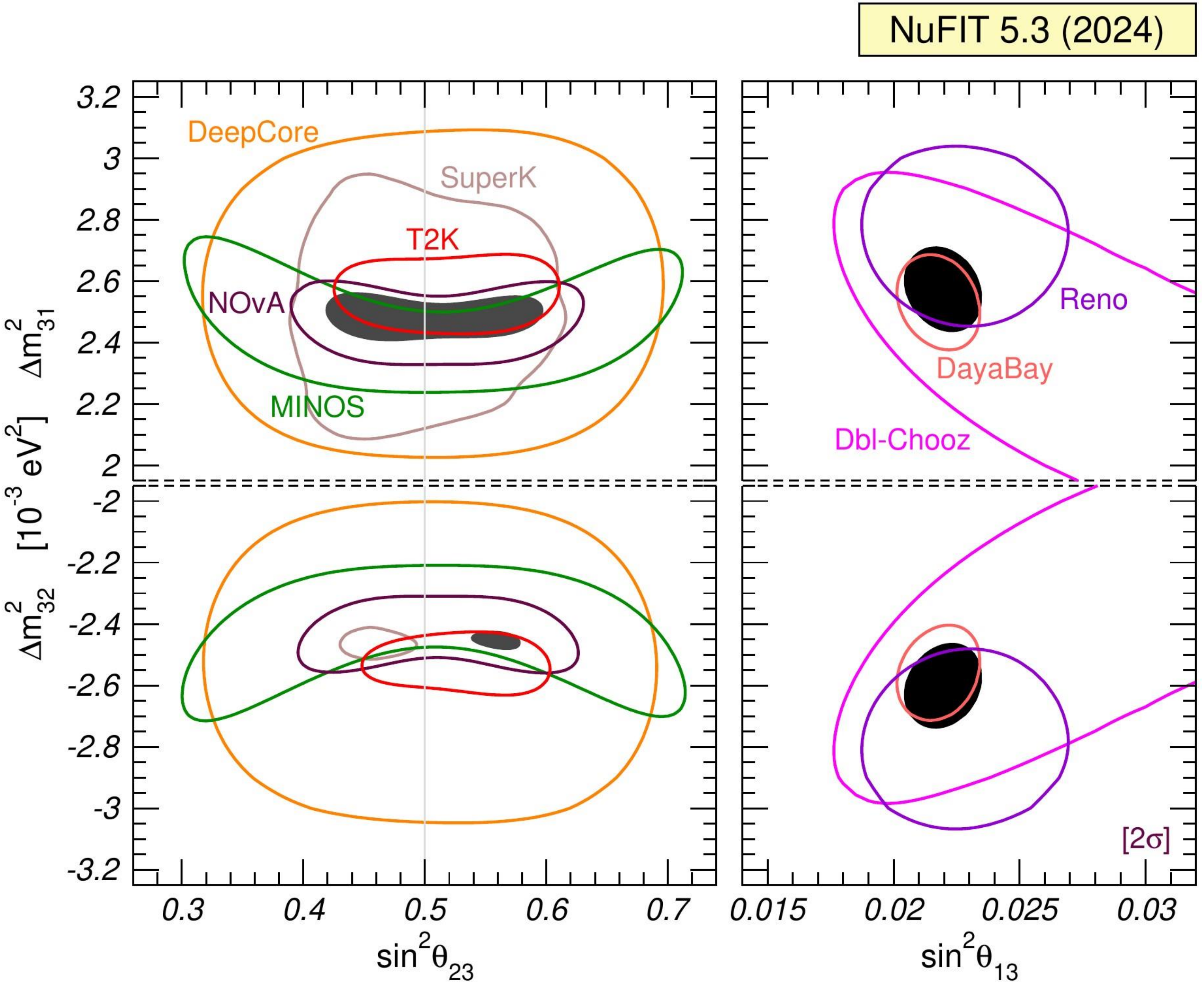
**mass ordering – which is the lightest mass state?**

# missing measurements

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

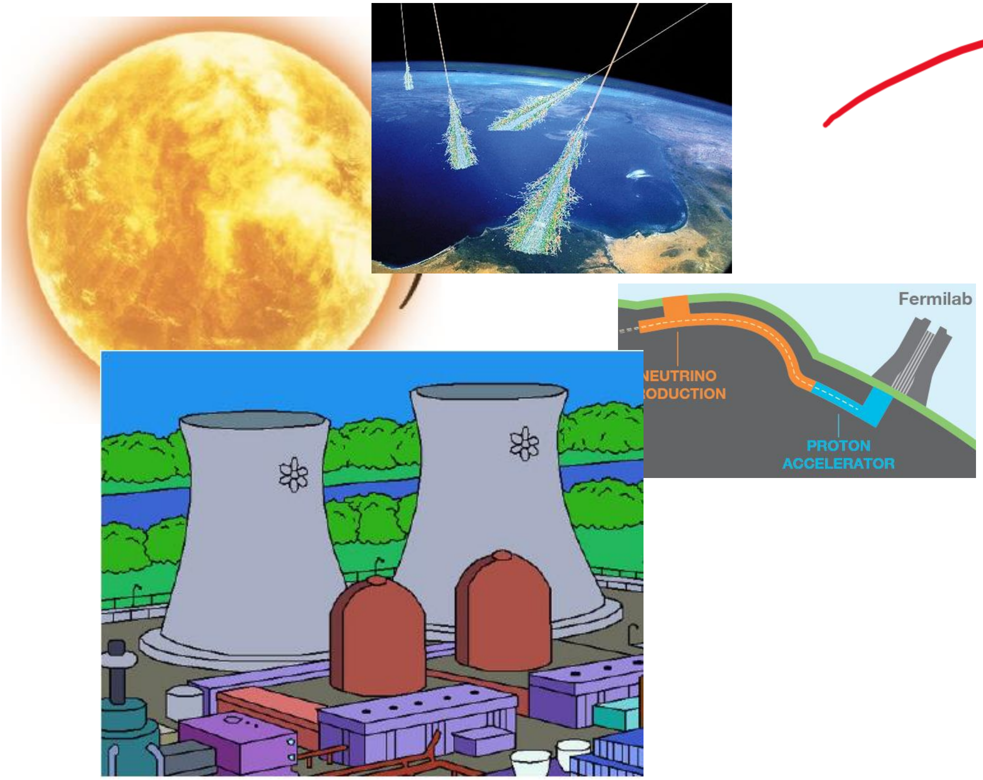
**CP violation – nu vs anti-nu oscillations**

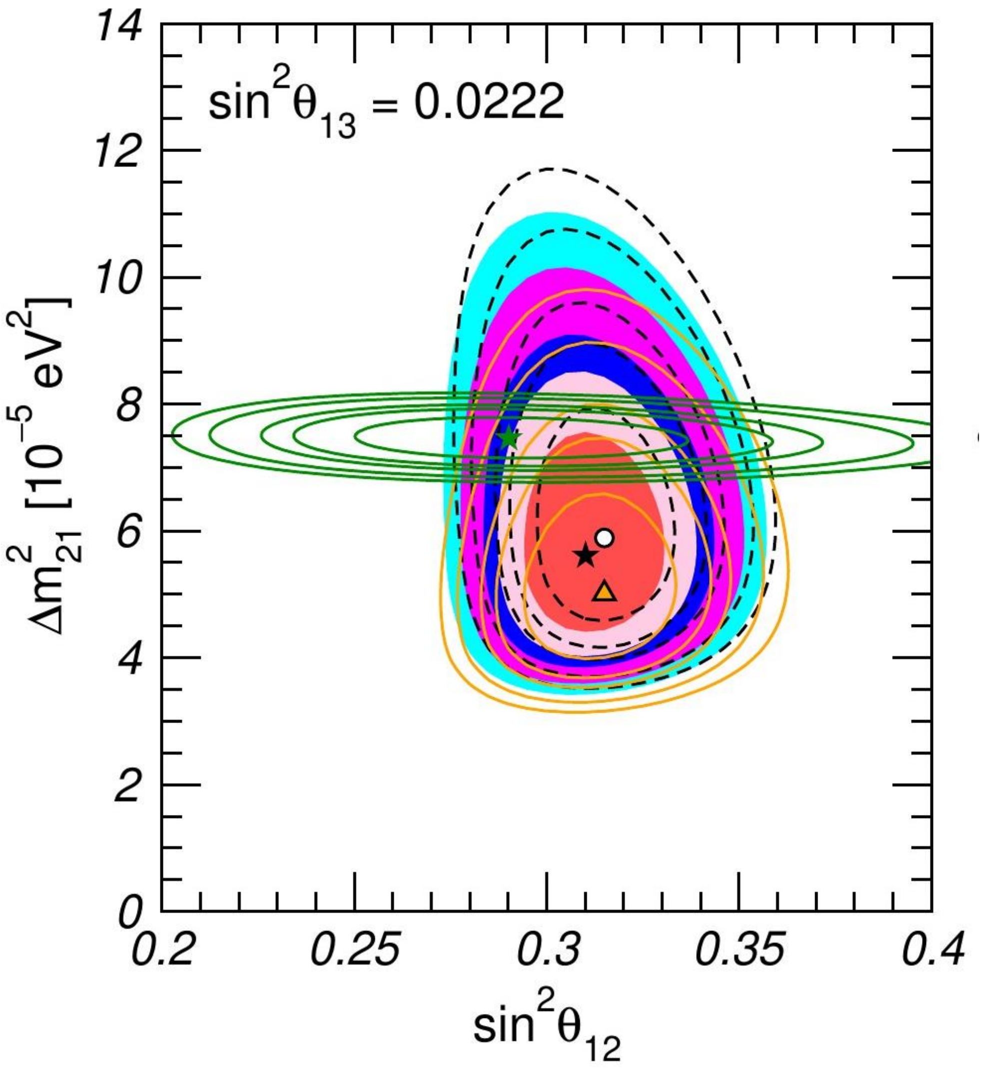
# global fits chiming in




**multiple experiments measure the same parameters**

# global fits chiming in



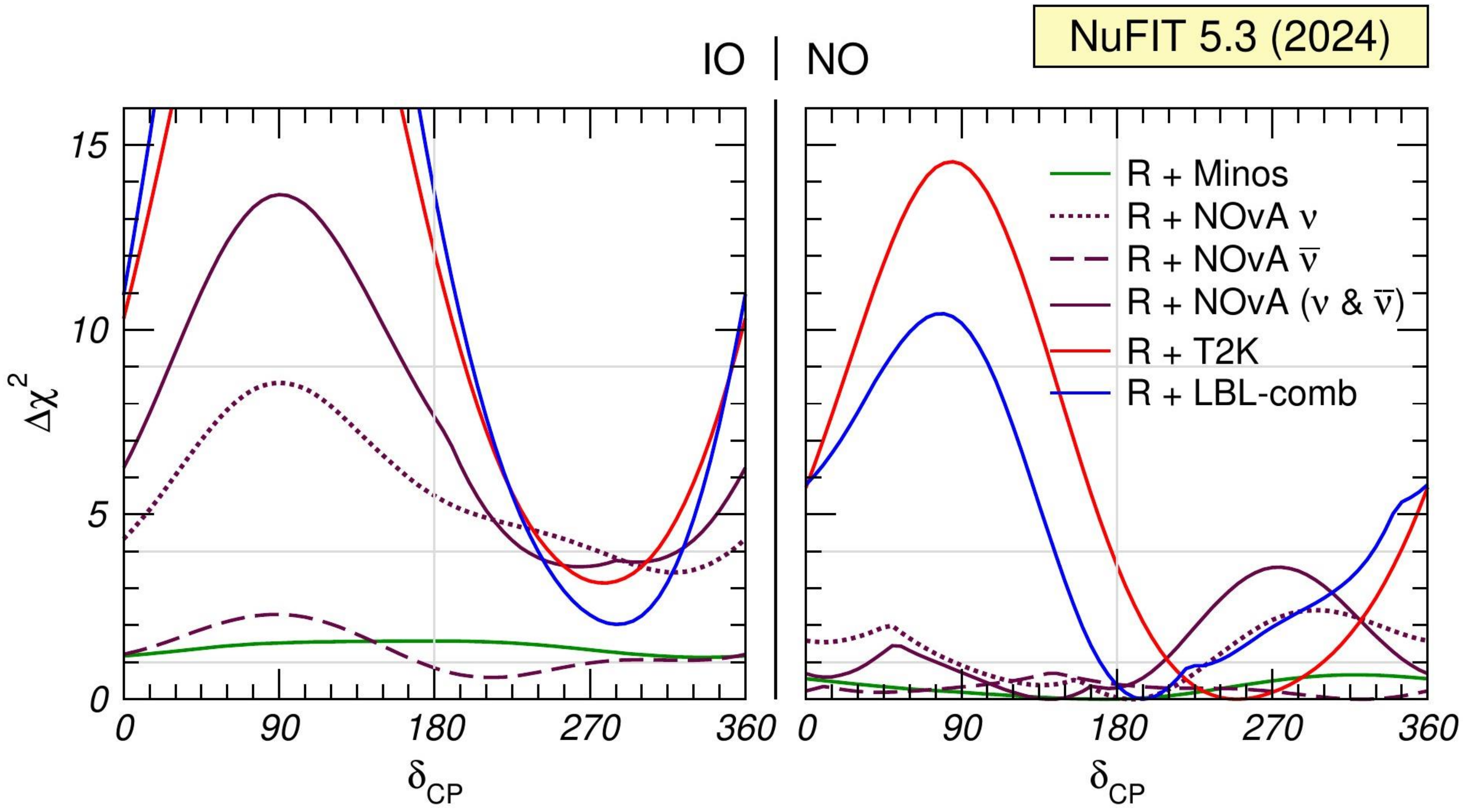

**analysis of all data available including correlations**

# 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**

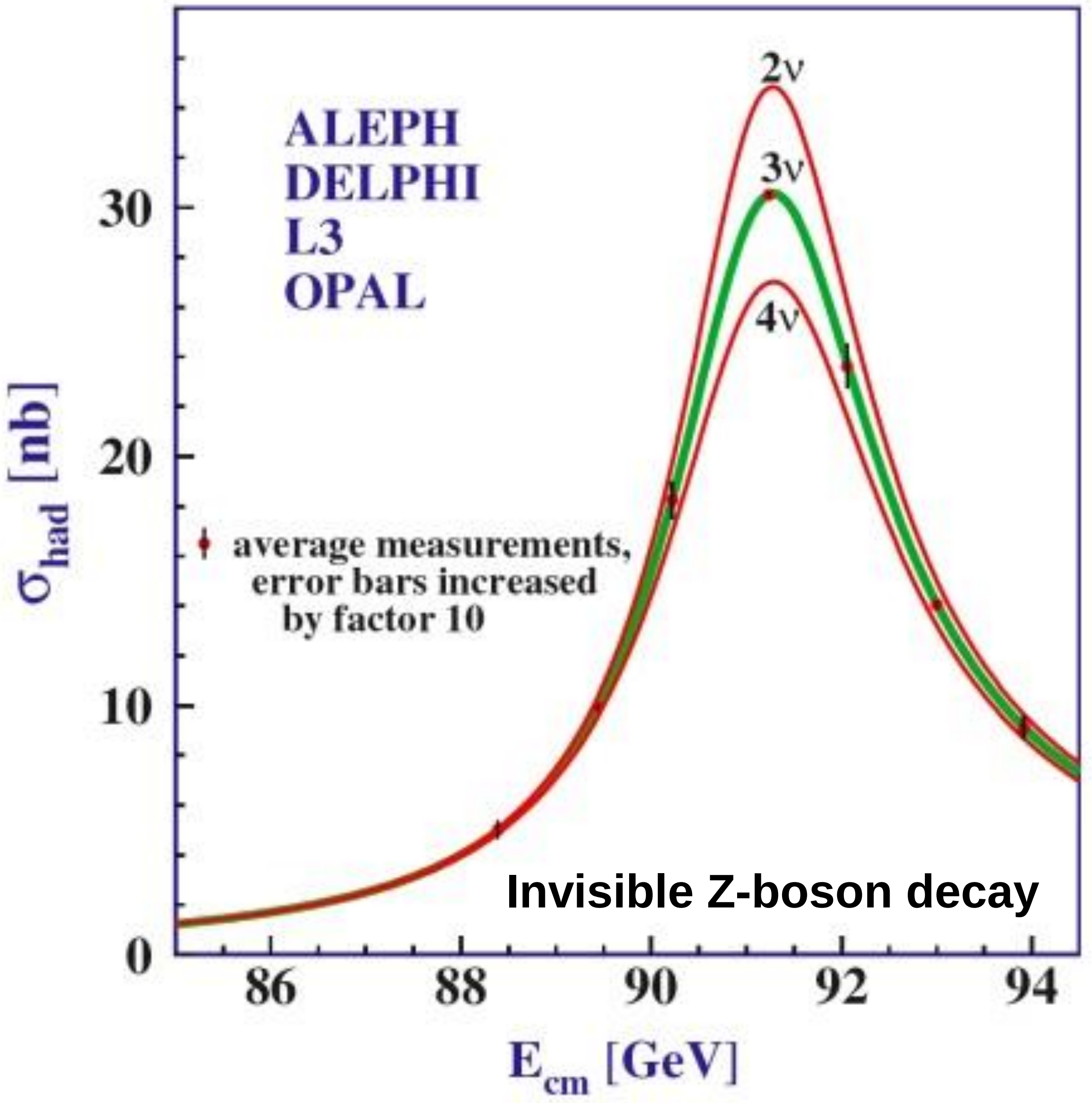
**-some CP violation**

**good knowledge of oscillation parameters but relevant details still missing**

# neutrino flavors

# neutrino flavors

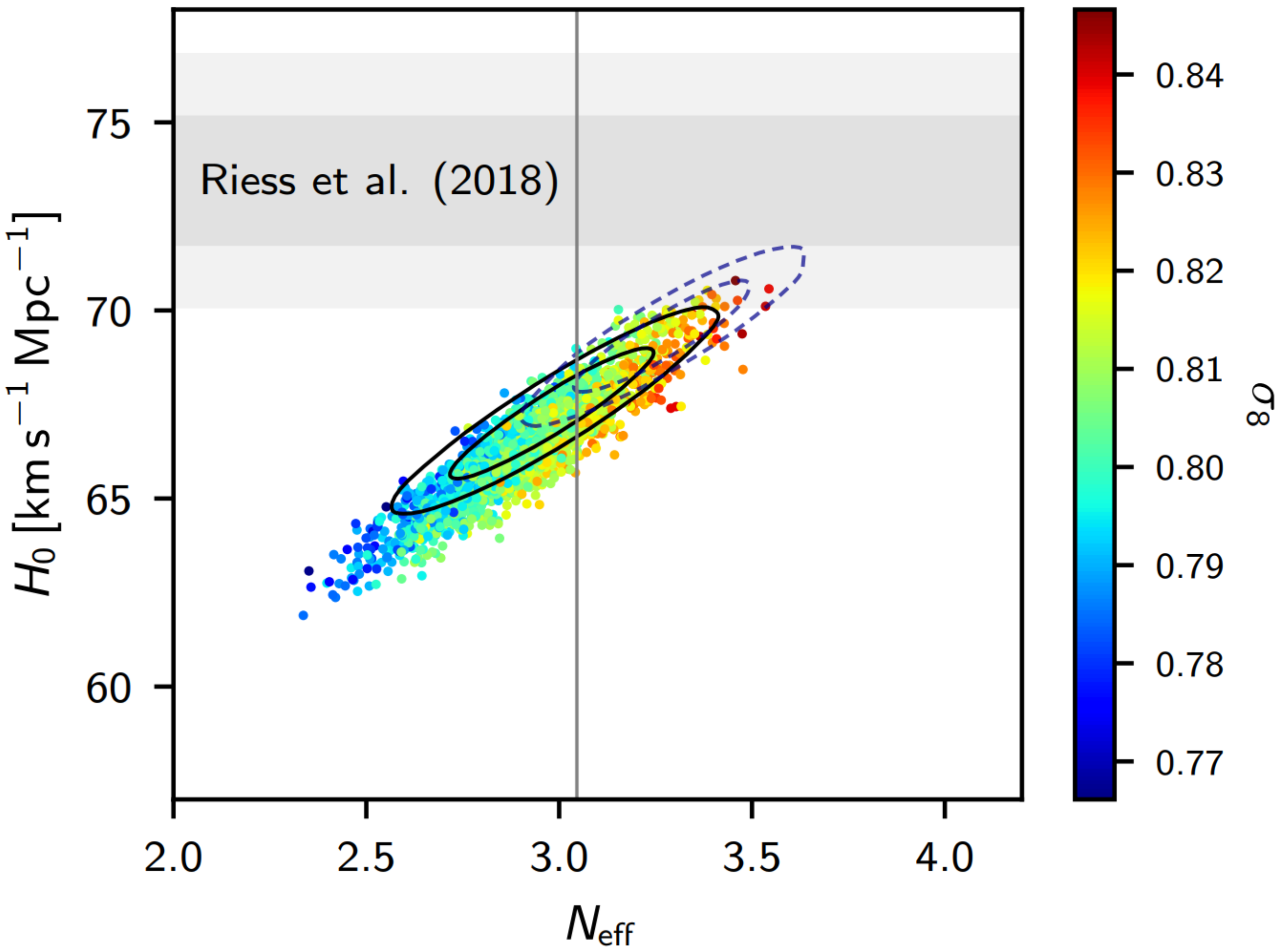
evidence of 3 light, active neutrinos in invisible Z-decay




Invisible Z-boson decay

# neutrino flavors

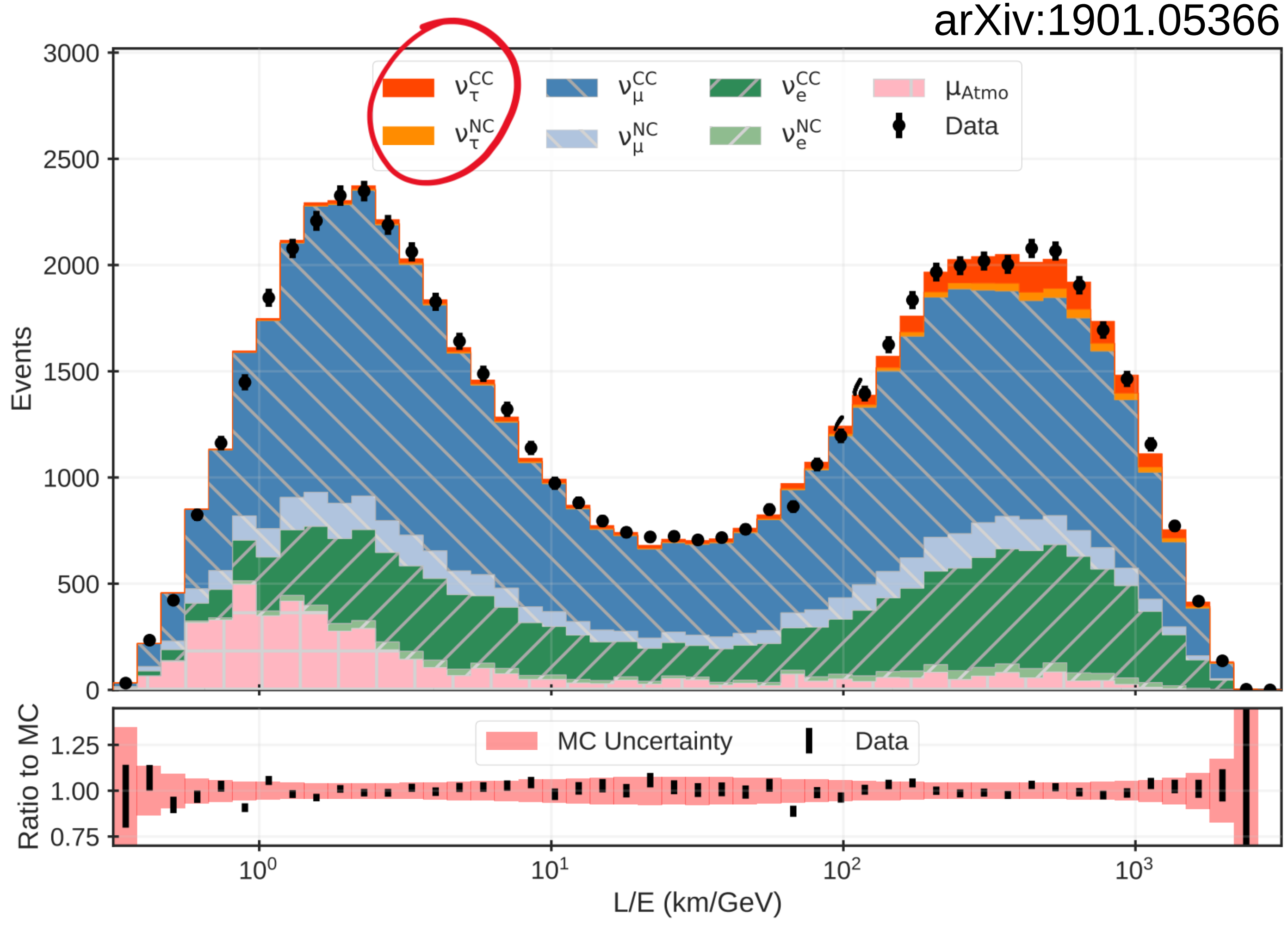
**evidence of 3 light, active neutrinos in cosmological data from Planck**



# neutrino flavors

## evidence of 3 light, active neutrinos in most oscillation experiments

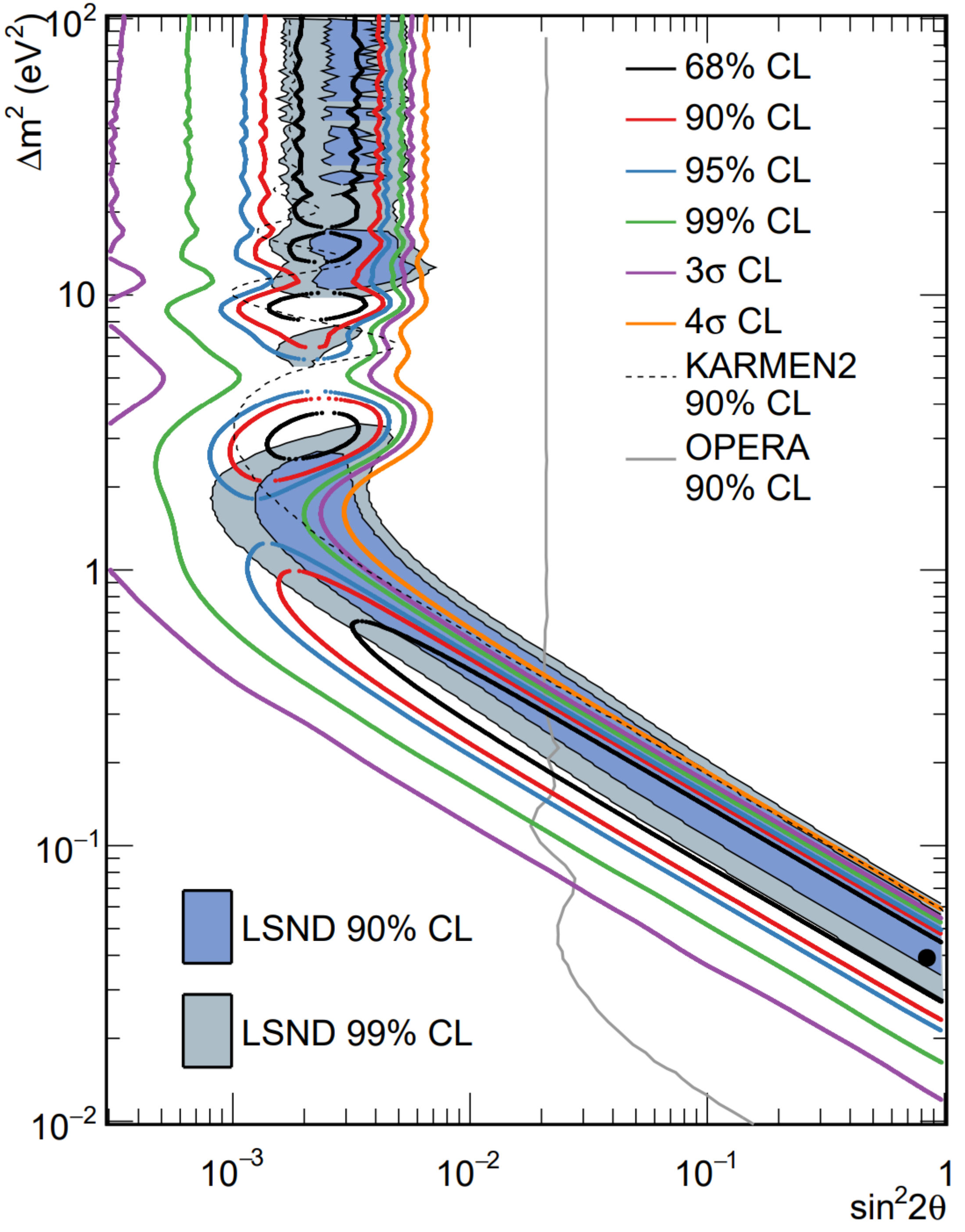
IceCube DeepCore
arXiv:1901.05366



# neutrino flavors

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

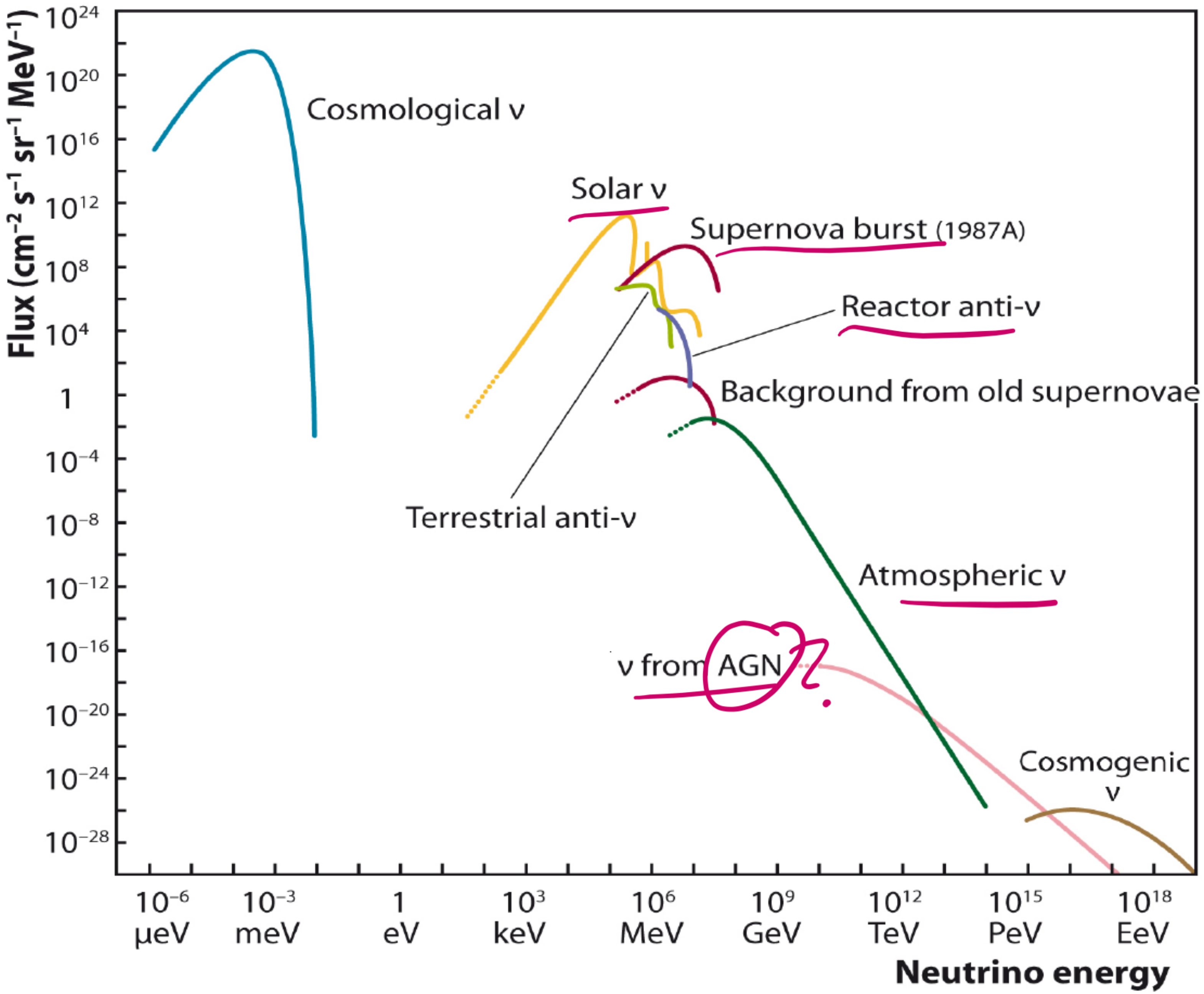
**or that low energy neutrino interactions are hard to measure**



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

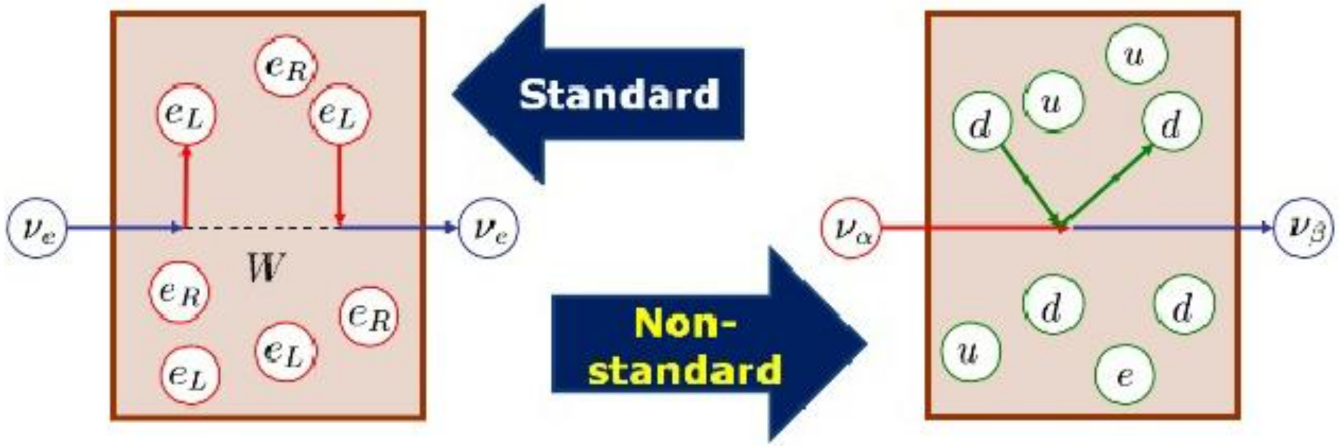
# neutrinos as probes

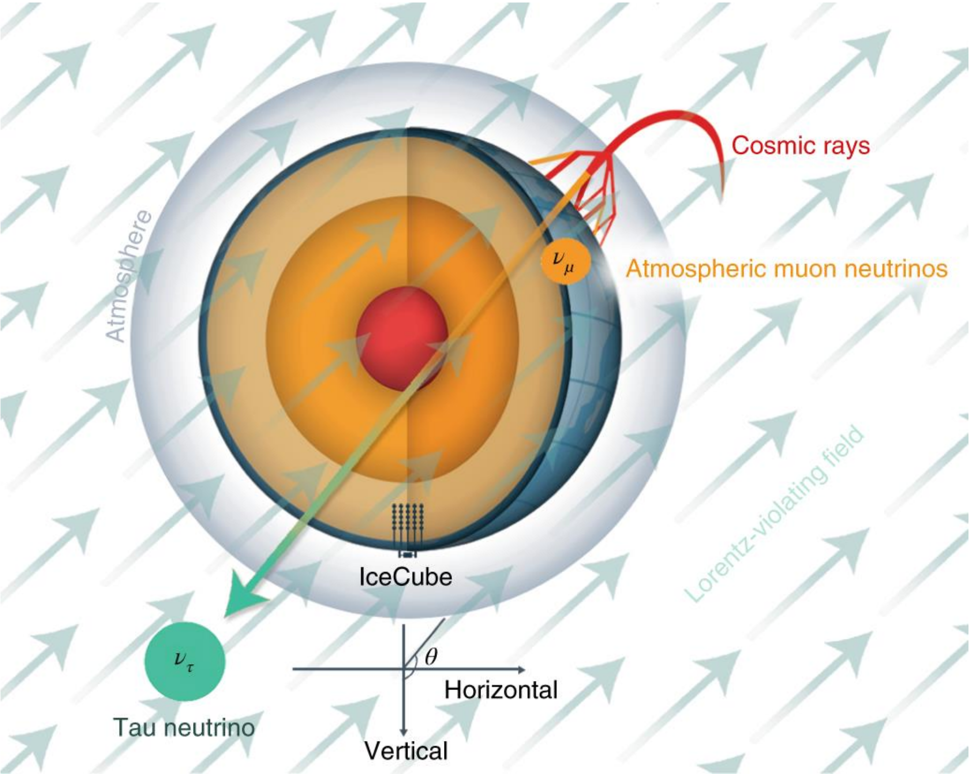
# neutrino sources



# searching for exotic physics with ν

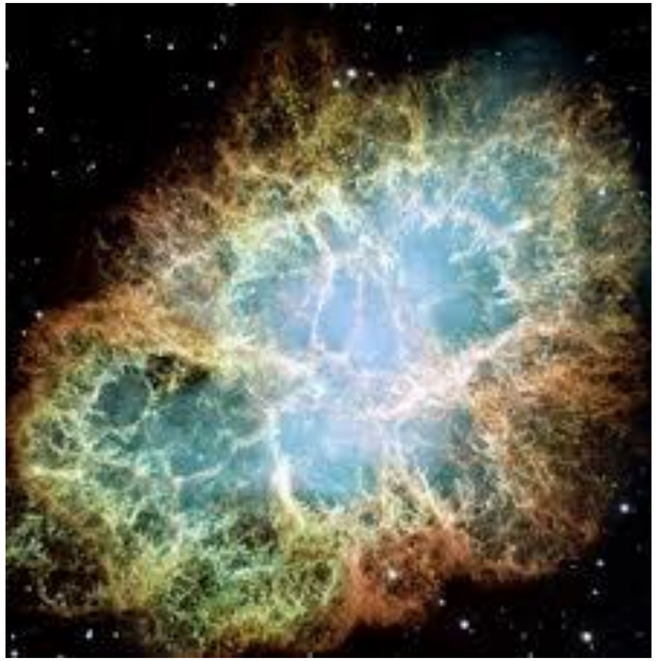
non-standard interactions



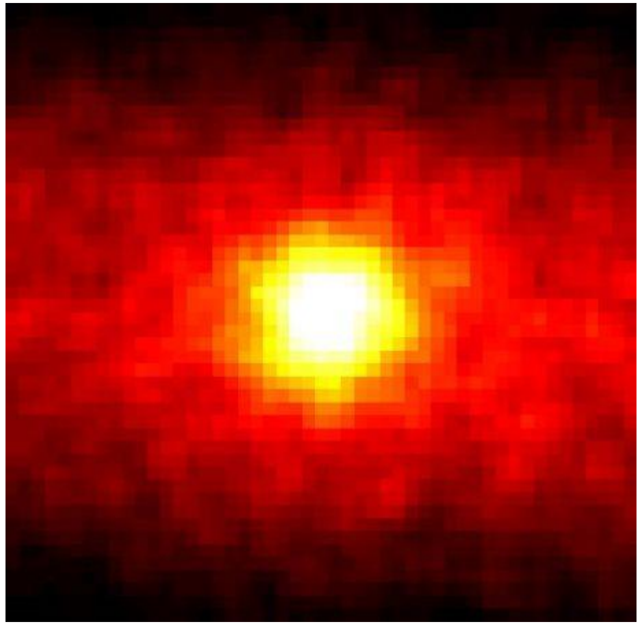




Lorentz invariance violation

# studying astrophysical objects

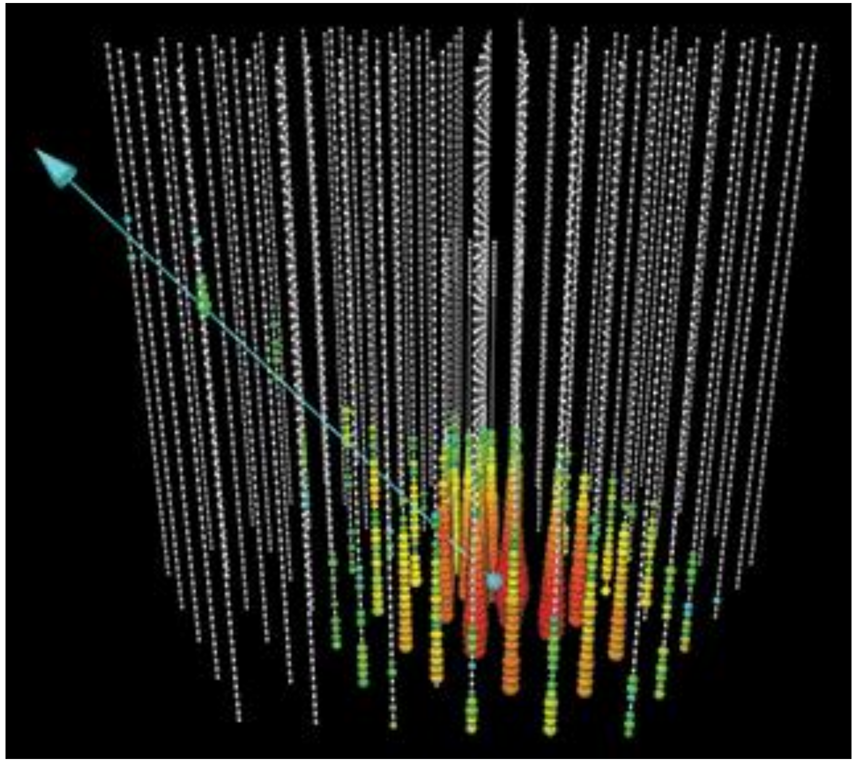


supernova
neutrinos



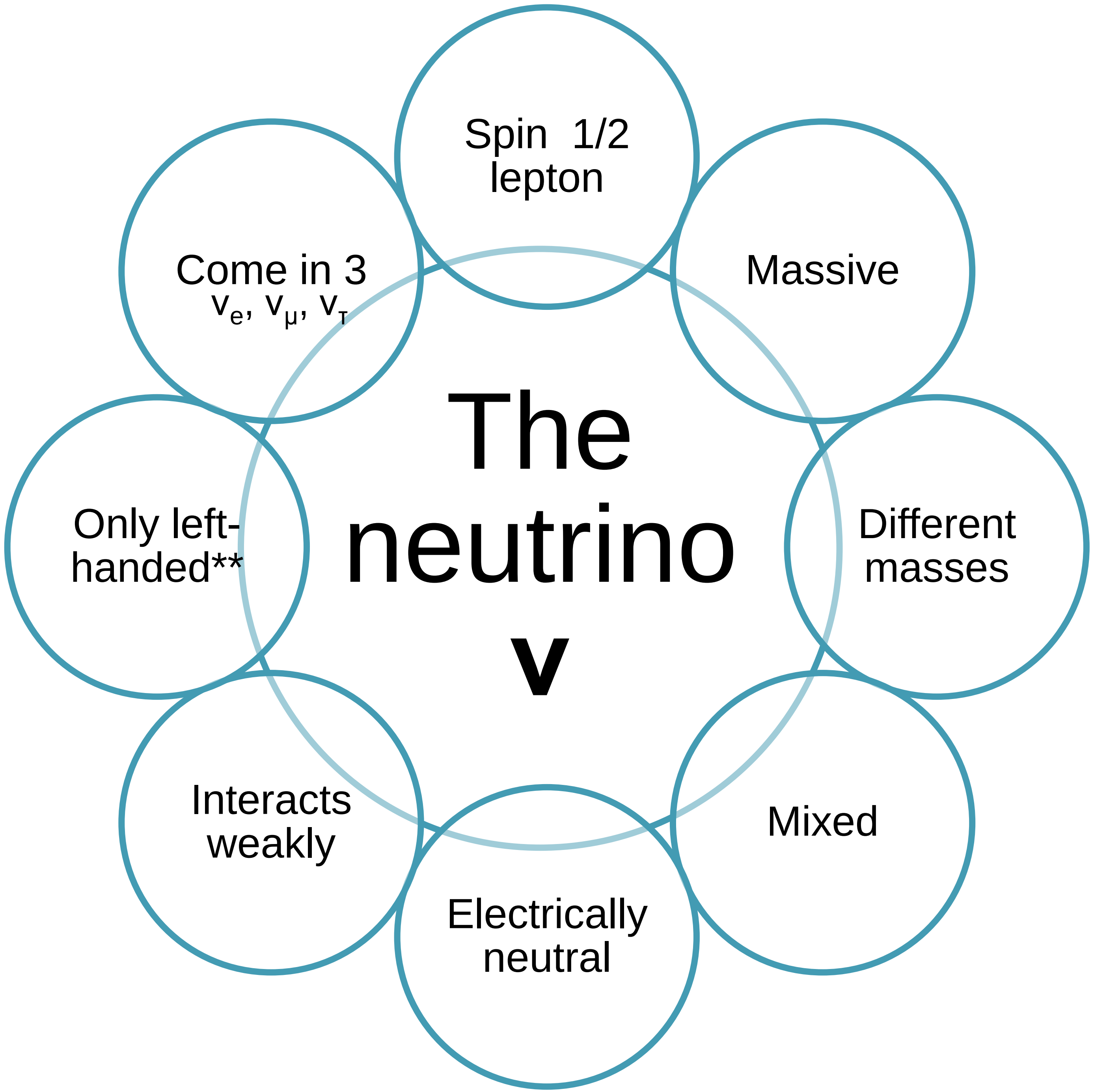
solar neutrinos

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**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thank you