Neutrino Physics

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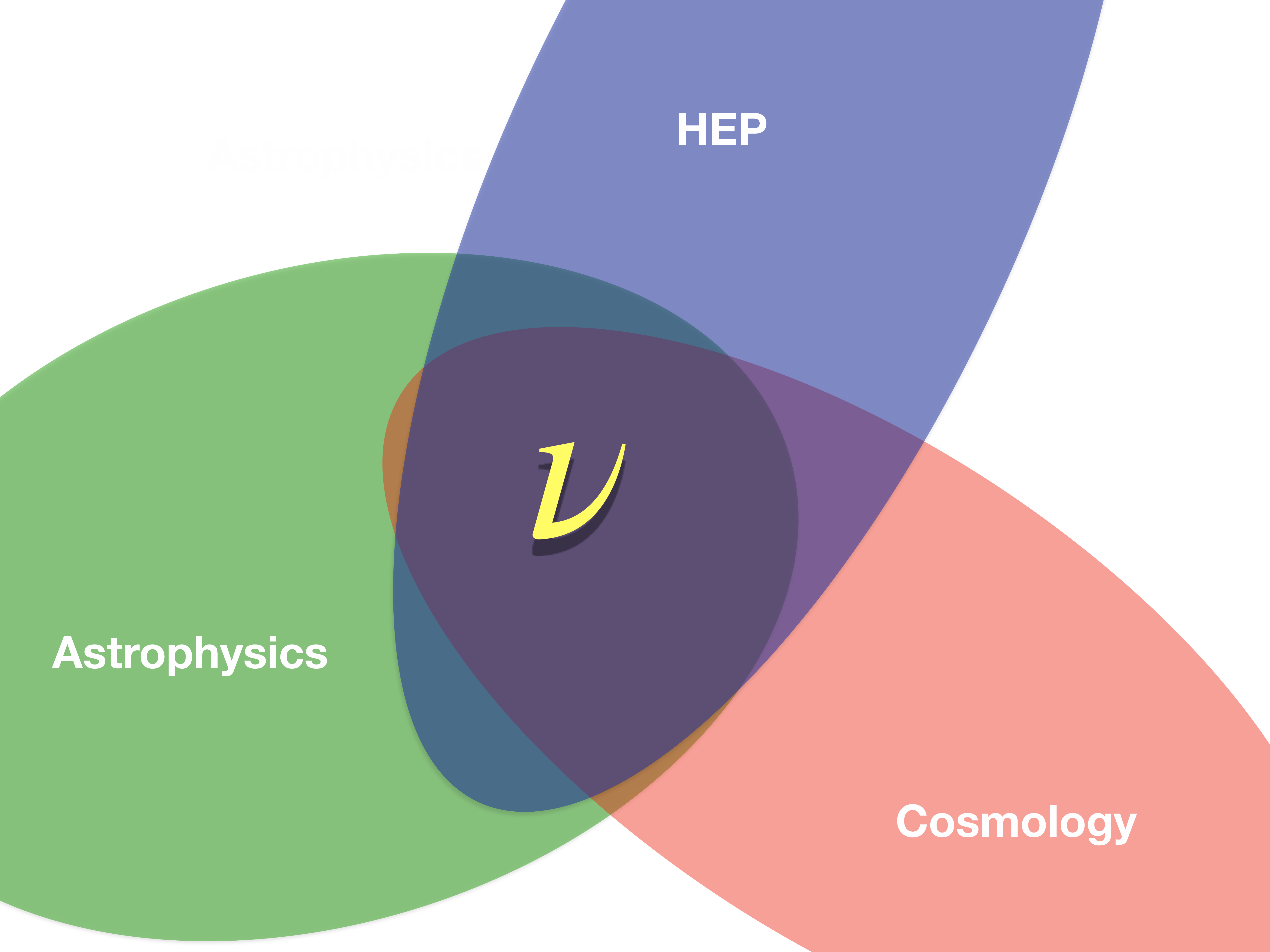
UCL, London. *28/06/2018.*


HEP
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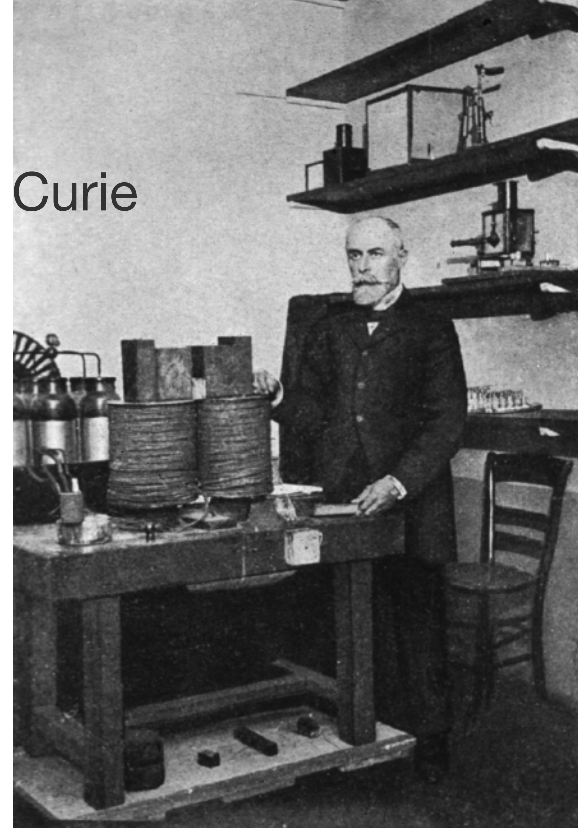
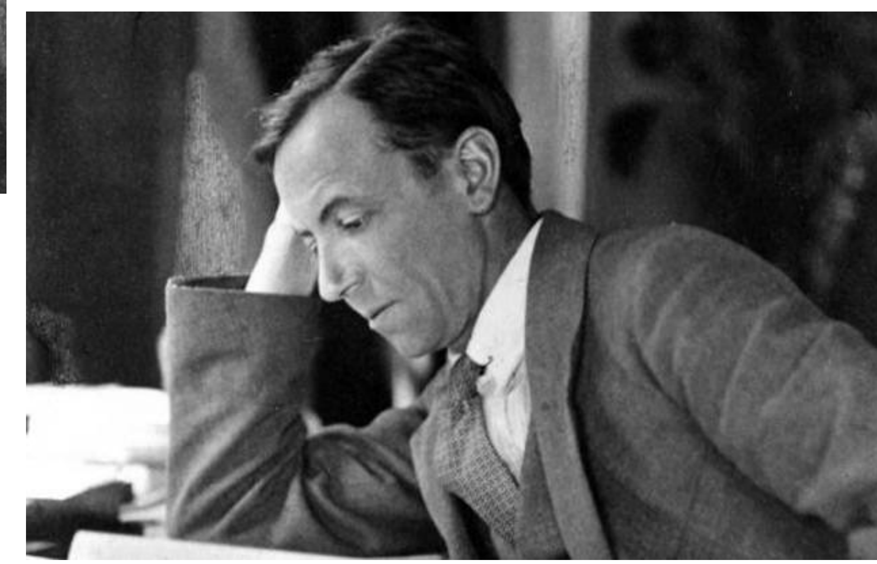
Astrophysics
Cosmology

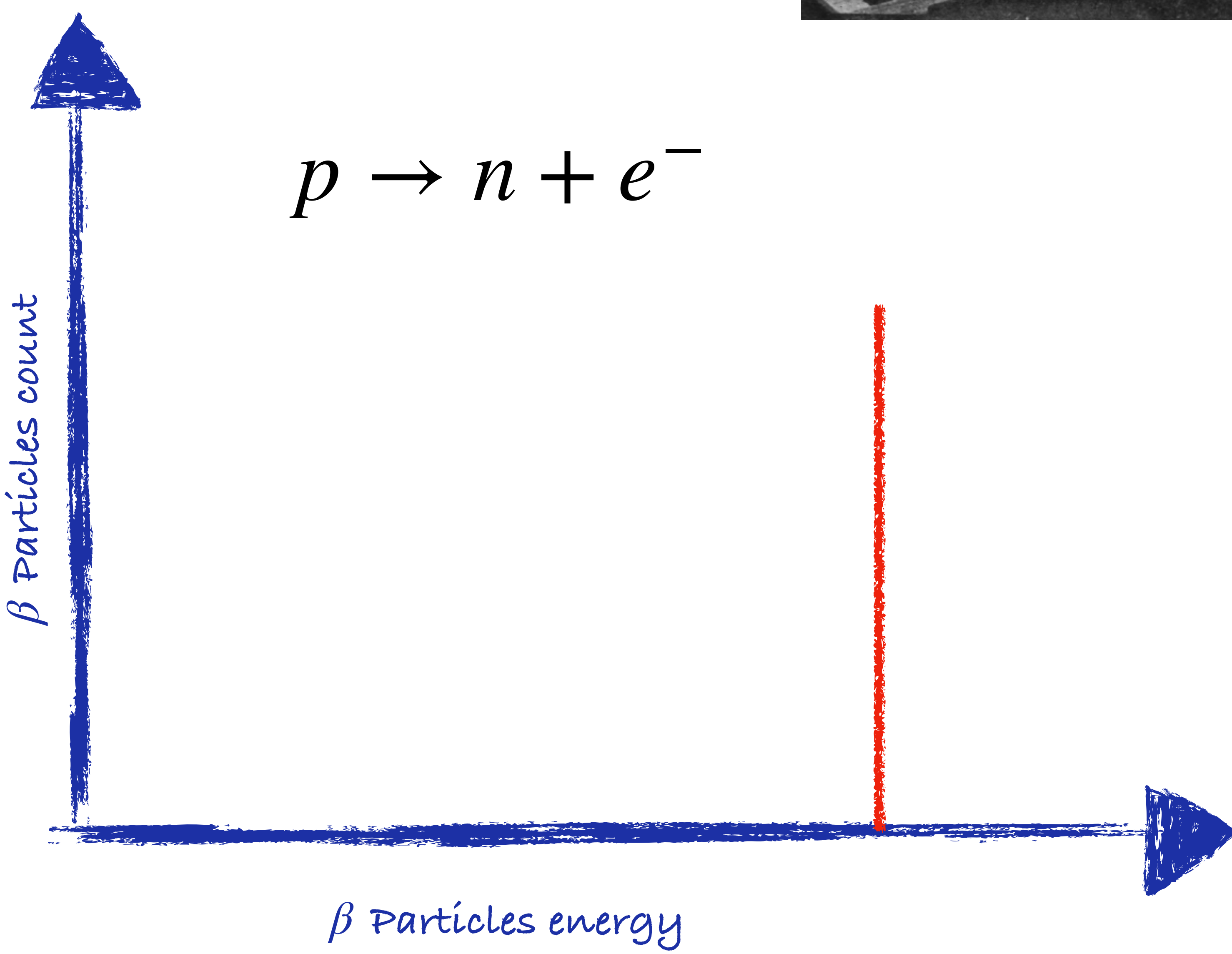
1890' Discovery of radioactivity; Becquerel, the Curie

1920' Beta decay spectrum; Ellis-Chadwick





$$p \rightarrow n + e^{-}$$



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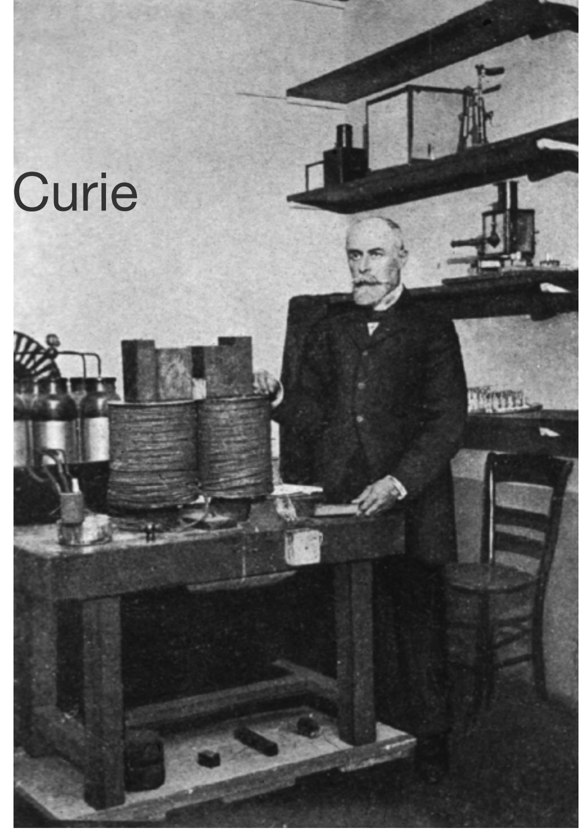

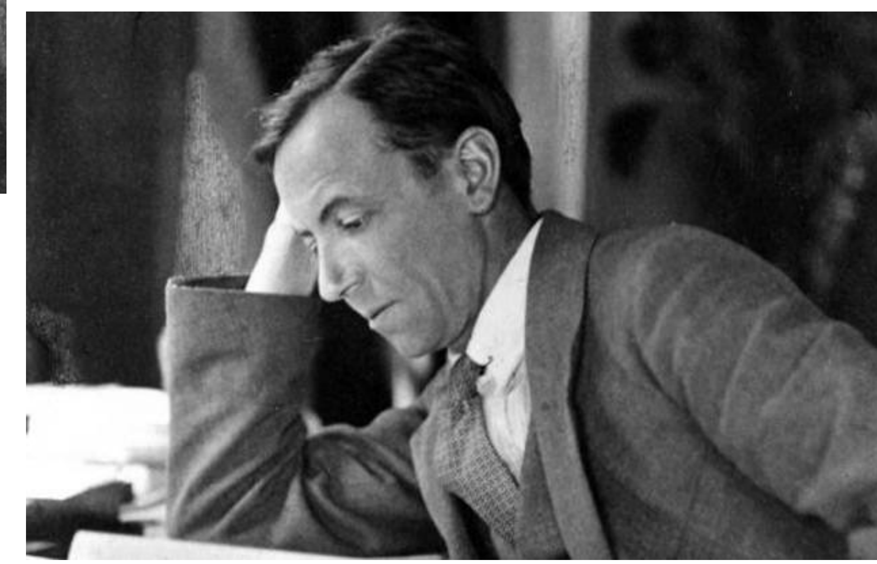

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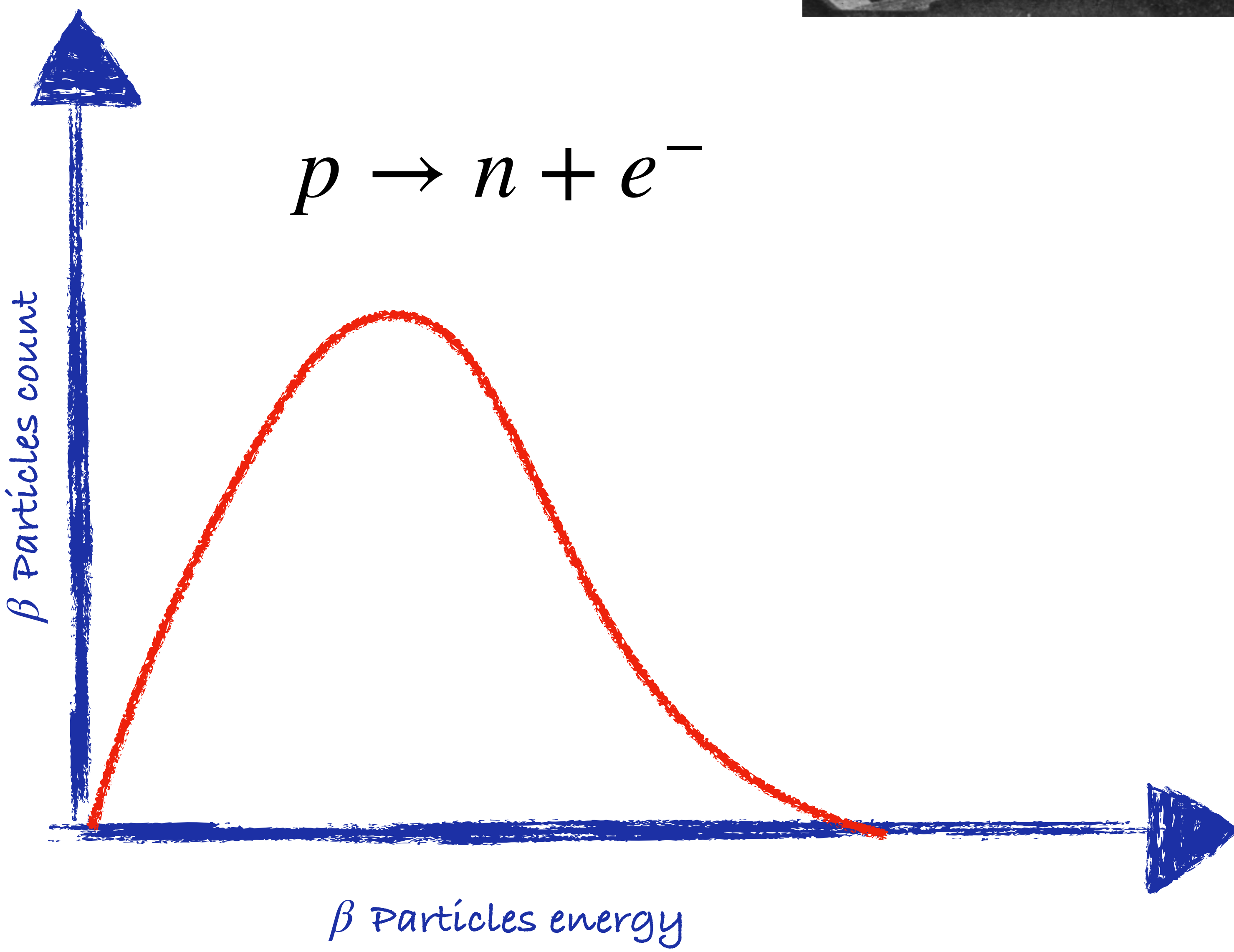

1890’ Discovery of radioactivity

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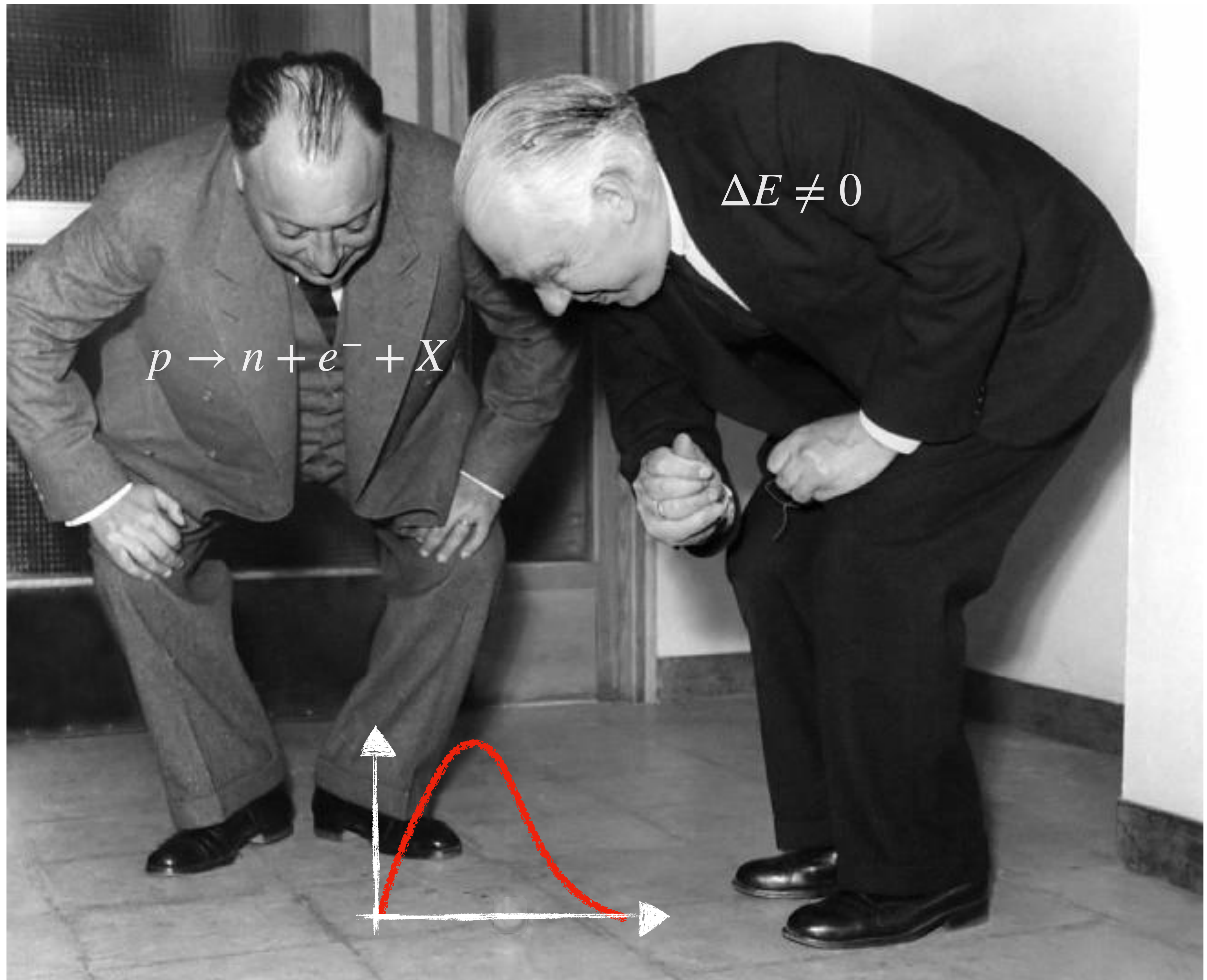
1930’



1890’ Discovery of radioactivity

1920’ Beta decay spectrum; Ellis-Chadwick

1930’
Discovery of the Neutron; Chadwick
Pauli hypothesizes the existence of new fermion
Fermi names it & writes a nice theory for weak interactions

1950’
Electron anti-neutrino is discovered; Reines-Cowan
Neutrinos are left-handed; Goldhaber, Grodzins and Sunyar
Pontecorvo proposes neutrino oscillations

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2018

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δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	**9%**

deSalas et al, 1708.01186 (May 2018)

[M.Tortola]

My goal: A brief overview of neutrino physics from particle theory point of view.

Plan:

- Neutrinos in the SM and Beyond
- Some consequences of neutrinos mixings and masses
- The future of neutrinos

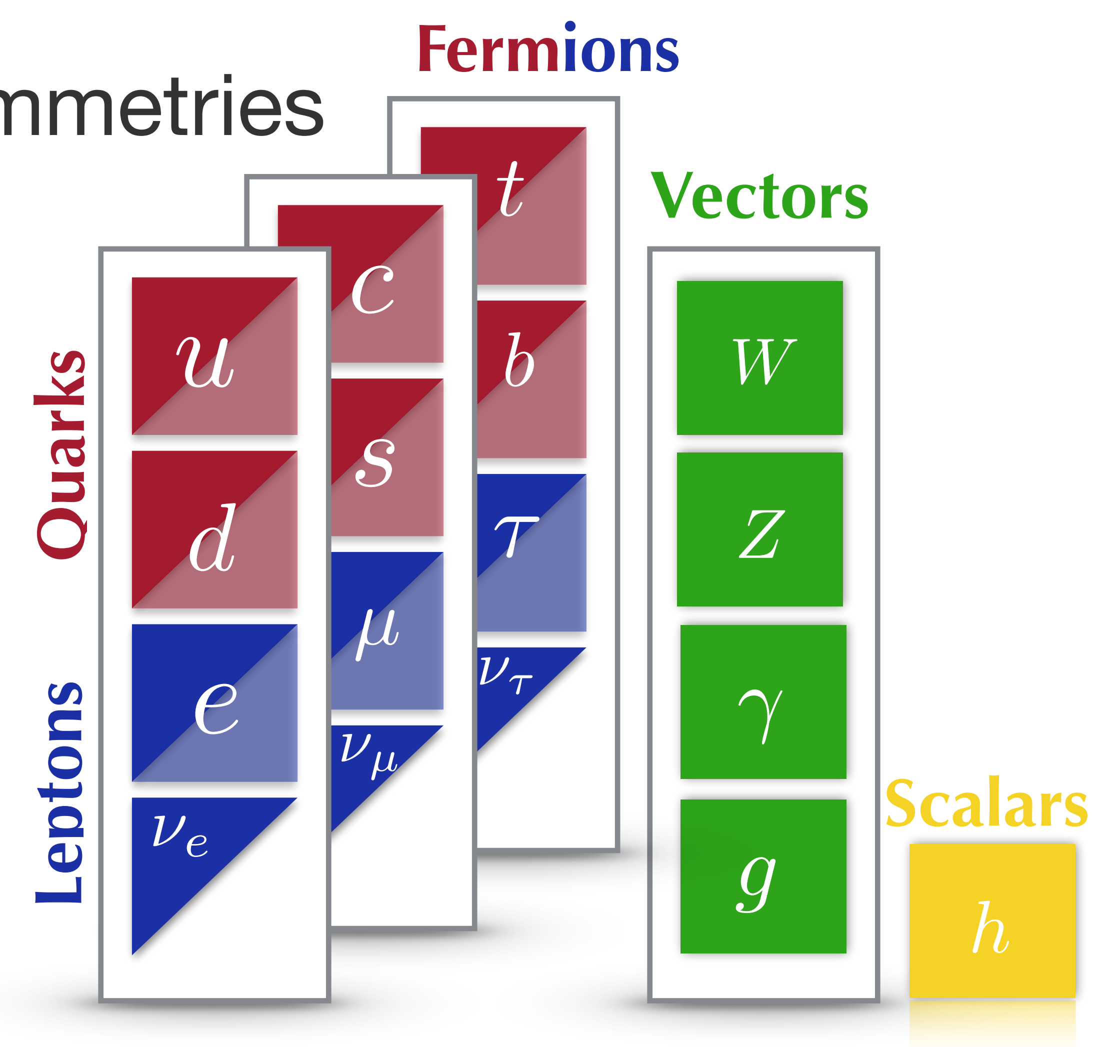
Neutrinos in the SM and Beyond

The Standard Model explains a very vast range of phenomena is explained down to 10^{-16} cm

It is based on a few core concepts:

- Quantum field theory
- Gauge “symmetries”
- Spontaneous breaking of gauge symmetries
- Quark confinement

$$\begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix} \quad e_R \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad u_R \quad d_R$$



SM charged fermions get mass via the Higgs mechanism

A fundamental, charged, fermion is described with two building-blocks; its mass operator looks like this:

$$M_\psi \psi\psi^c$$

However, in the SM the fermions and anti-fermions have different iso-spins!

$$\cancel{M_e \begin{pmatrix} e \\ \nu \end{pmatrix} e^c}$$

We need a coupling that compensates for the iso-spin

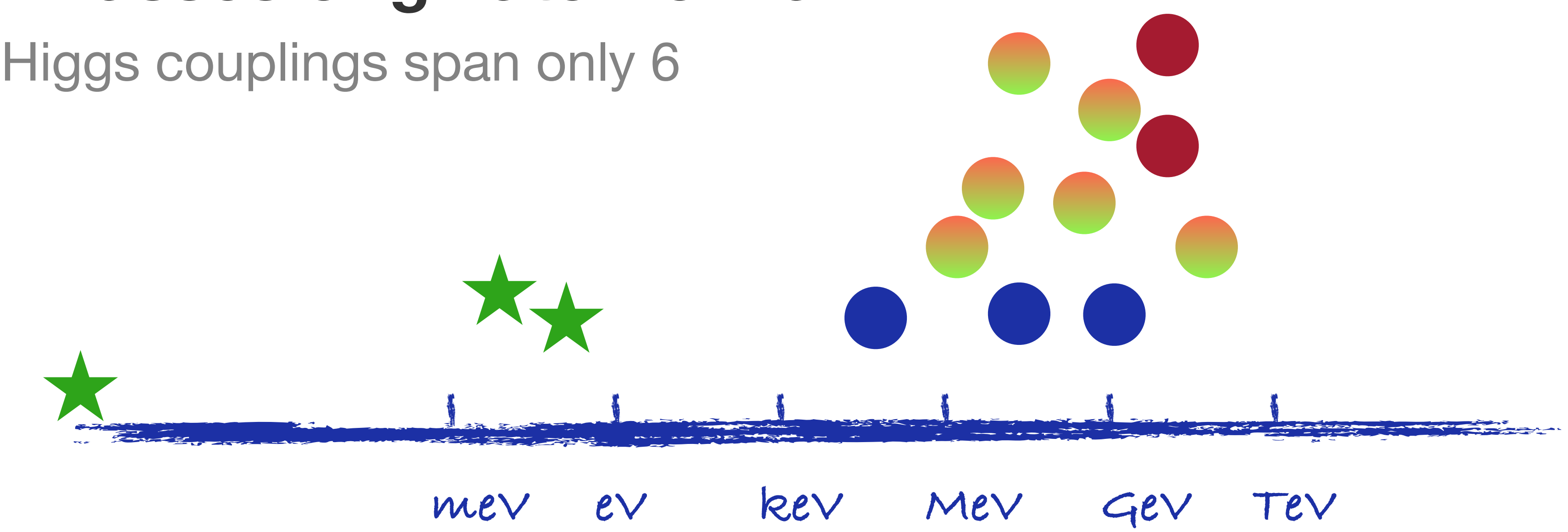
$$y_e \begin{pmatrix} e \\ \nu \end{pmatrix} \begin{pmatrix} 0 \\ h \end{pmatrix} e^c \longrightarrow (y_e h)\, e e^c \longrightarrow M_e\, e e^c$$

This is the **Dirac** mass. Obtained here after Higgs condensation. Neutrinos are so far strictly massless.

[All fermions here are 2-components spinors of same chirality.]

But neutrino not really fit into this picture…

It is interesting that the same Higgs doublet “gives” mass to all the charged leptons and quarks (as well as bosons!) of the SM: **all masses originate from a single energy scale.** The Higgs couplings span only 6 orders of magnitude.



However, if we were to treat neutrinos as the other fermions,

$$y_\nu \begin{pmatrix} e \\ \nu \end{pmatrix} \begin{pmatrix} h \\ 0 \end{pmatrix} \nu^c$$

The Higgs coupling would be unnaturally small.
Though its smallness could be explained in some theories, e.g. extra-dimensions.

So how can we explain neutrino masse?

Neutrinos are special: they are neutral ! Under the only unbroken symmetry of nature; electric charge.

Only one block is enough to have a mass:

$$M_\psi \psi\psi$$

This is a **Majorana** mass. There are two generic ways to do that:

1) Renormalizable

$$y_\nu \begin{pmatrix} e \\ \nu \end{pmatrix} \begin{pmatrix} \Delta^{++} & \Delta^{+} \\ \Delta^{+} & \Delta \end{pmatrix} \begin{pmatrix} e \\ \nu \end{pmatrix} \xrightarrow[\Delta \lesssim 1\ \mathrm{GeV}]{} y_\nu \Delta \ \nu\nu$$

2) Effective

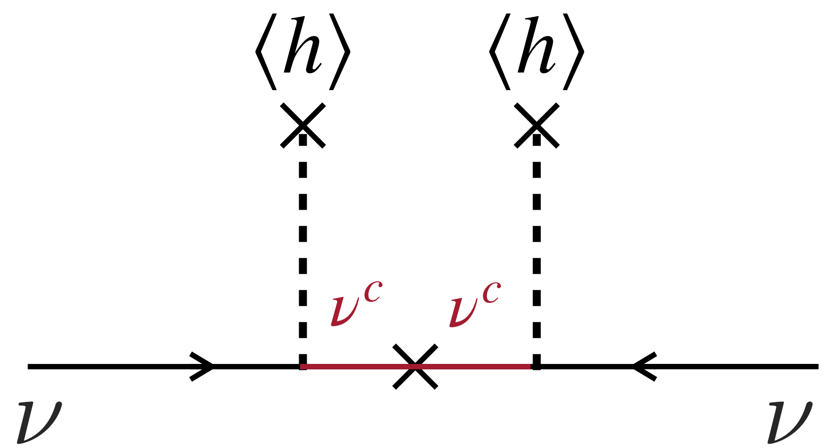
$$\frac{1}{\Lambda} \begin{pmatrix} e \\ \nu \end{pmatrix} \begin{pmatrix} e \\ \nu \end{pmatrix} \begin{pmatrix} h \\ 0 \end{pmatrix} \begin{pmatrix} h \\ 0 \end{pmatrix} \longrightarrow \frac{h^2}{\Lambda} \nu\nu$$

$$\longrightarrow M_\nu \ \nu\nu$$

There are many ways to realize the dim-5 operator, however we can distinguish two main classes:

High-scale models, e.g. seesaw type-I

$$y_\nu \begin{pmatrix} e \\ \nu \end{pmatrix} \begin{pmatrix} h \\ 0 \end{pmatrix} \nu^c + M \nu^c \nu^c$$



$$M_{\nu\nu^c} = \begin{array}{c c} & \begin{array}{cc} \nu & \nu^c \end{array} \\ \begin{array}{c} \nu \\ \nu^c \end{array} & \begin{pmatrix} 0 & y_\nu h \\ y_\nu h & M \end{pmatrix} \end{array} \longrightarrow \quad m_\nu \approx \frac{(y_\nu h)^2}{M} \approx 0.1 \left(\frac{100^2}{10^{14}} \right) \mathrm{eV}$$

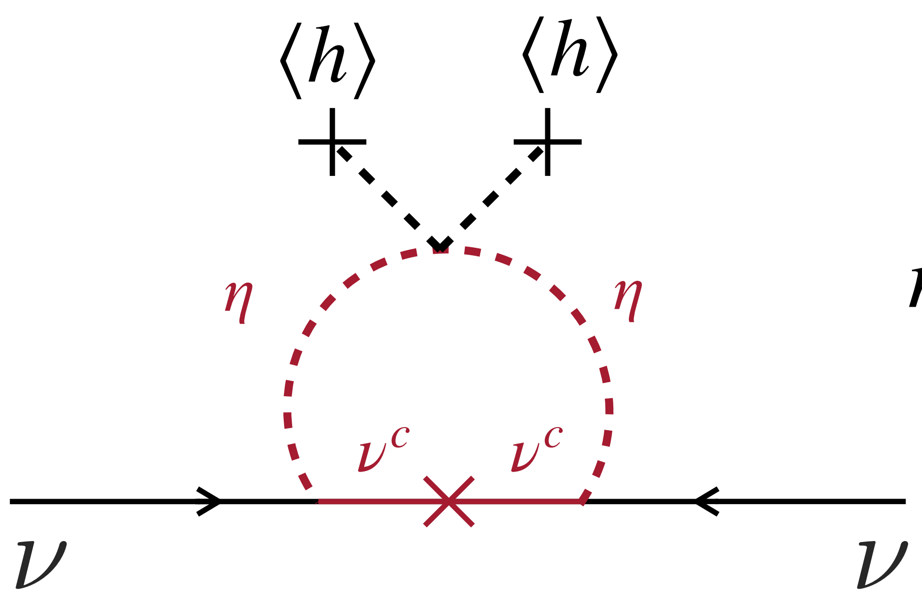
The messengers of high scale models are intriguingly close to unification scale! SO(10) GUT provide a beautiful raison d'être for seesaw variations.

Price: breaking the accidental lepton-number.

[Minkowski '77; Mohapatra, Senjanović '79; Yanagida '79; Glashow '79; Gell-Mann, Ramond, Slansky '79; Schechter, Valle '80]

There are many ways to realize the dim-5 operator, however we can distinguish two main classes:

Low-scale models, e.g. scotogenic model



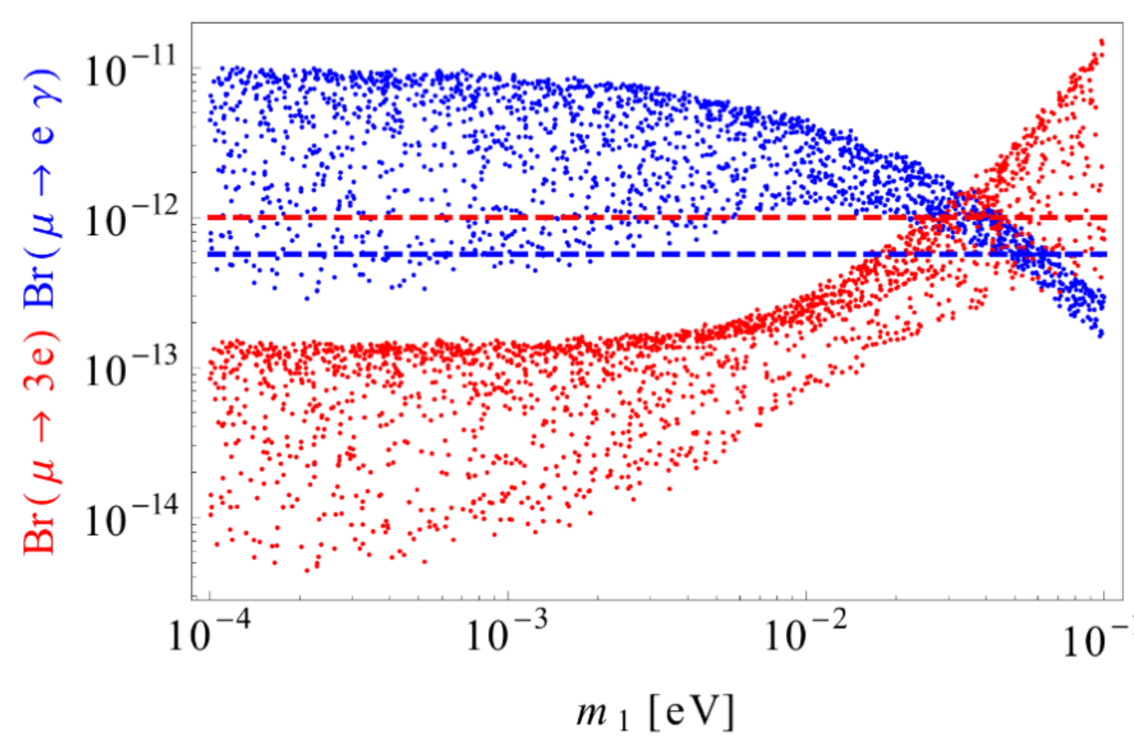
[Ma '06]

$$m_\nu \approx \left(\frac{1}{16\pi^2}\right)\frac{h^2}{M}$$

Radiative model often includes DM!

"Dark" generation of neutrino masses.

Plenty of phenomenology at energy and intensity frontiers.



[Toma&Vicente 1312.2840]

Massive neutrinos have a non-trivial mixing pattern

After turning on the masses, neutrinos can mix in general as

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

This leads to a leptonic mixing matrix, analogous to the CKM in the quarks sector. It can be parameterized with 3 angles and 1+2 phases. We have a total of 7+2 physical parameters.

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad \text{vs.} \quad |V_{\mathrm{CKM}}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

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

Atm Reactor Solar

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Measuring neutrino parameters

Massive neutrinos experience a funny thing

Neutrino mass states are in general different from neutrino interaction states; with 2 flavors

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

$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

The evolution of these quantum states leads to an oscillatory behavior (in vacuum, ignoring phases),

$$|\nu(L)\rangle = \cos\theta e^{-i\frac{m_1}{2E}L}|\nu_1(0)\rangle + \sin\theta e^{-i\frac{m_2}{2E}L}|\nu_2(0)\rangle$$

No info on absolute
mass scale
And sign of mass diff.

And the probability is

$$\boxed{P^{\text{appear}}_{\nu_e\to\nu_\mu}(L) = |\langle\nu_\mu|\nu(L)\rangle|^2 \approx \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{\text{eV}^2}\frac{L}{\text{km}}\frac{\text{GeV}}{E}\right)}$$

$$\boxed{P^{\text{disappear}}_{\nu_e\to\nu_e}(L) = 1 - P_{\nu_e\to\nu_\mu}(L)}$$

Neutrino oscillations and masses have been confirmed by several experiments

Atmospheric $\nu_\mu, \bar{\nu}_\mu \to \nu_\tau$ (disappearance; Super-K,MINOS, Icecube)

Solar $\nu_e \to \nu_\mu, \nu_\tau$ (conversion; Super-K,SNO, Borexino)

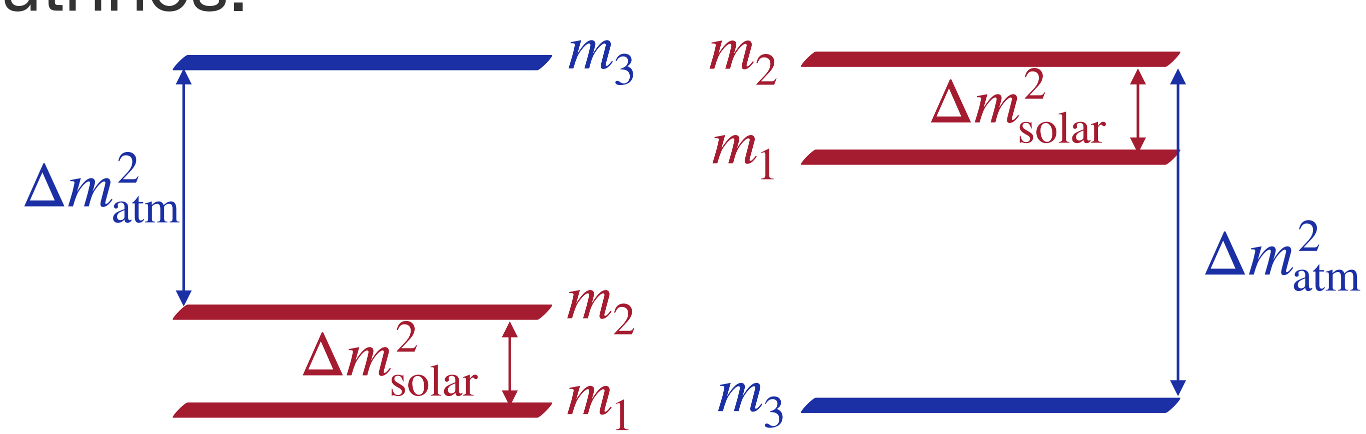
Accelerator $\nu_\mu \to \nu_e$ (appearance; T2K, MINOS,NOvA)

Reactor $\bar{\nu}_e \to$ (disappearance; Daya-Bay, Reno)

…

The **only** explanation which explains all the data is neutrinos oscillations. At least 2 neutrinos are massive: This is a clear signal of New Physics.

However, oscillation exps. do not tell us about the absolute mass scale or the nature of the neutrinos.



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deSalas et al, 1708.01186 (May 2018)

[M.Tortola]

NEVTRINO 2018 Heidelberg 4-9 June

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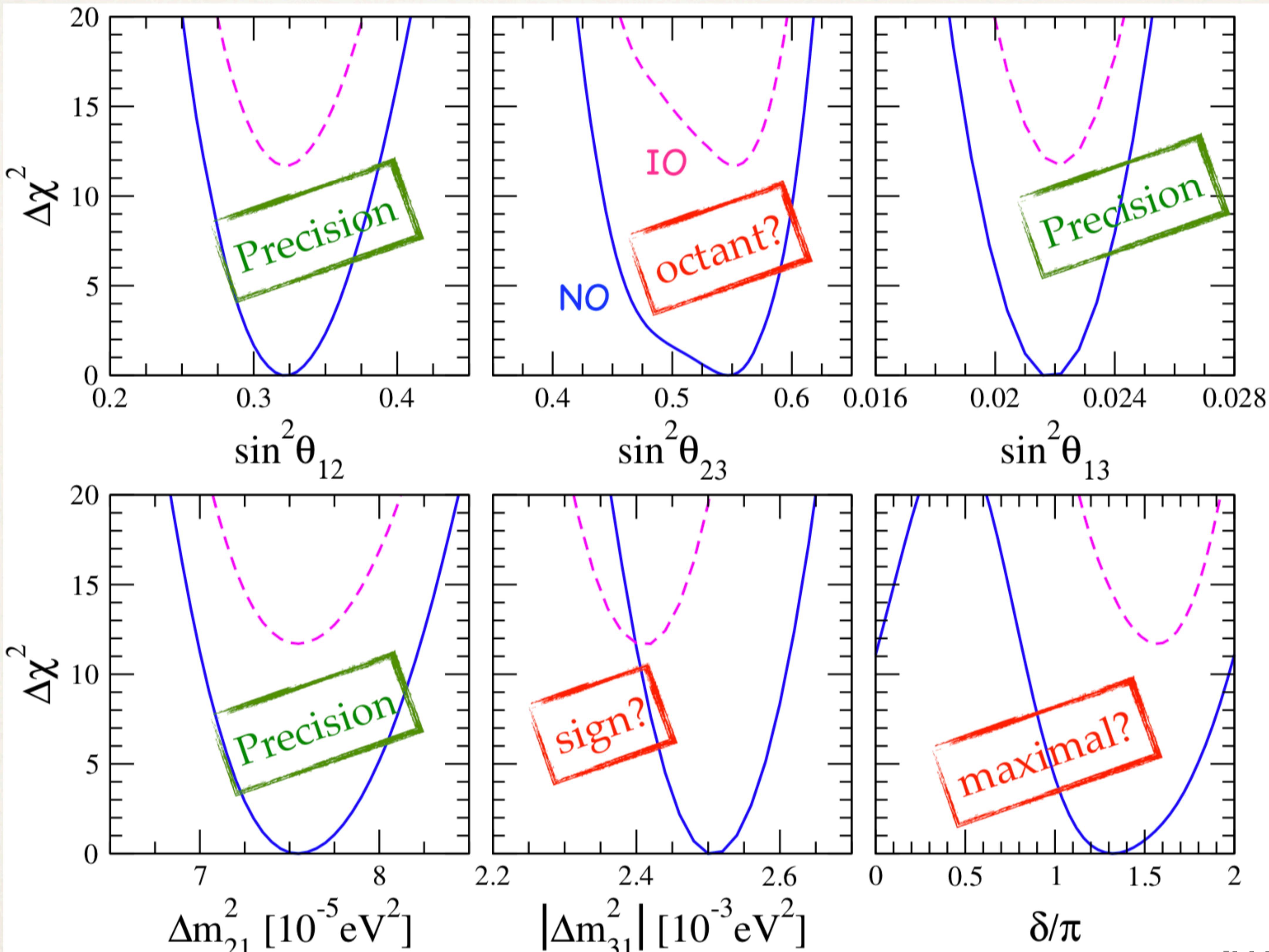


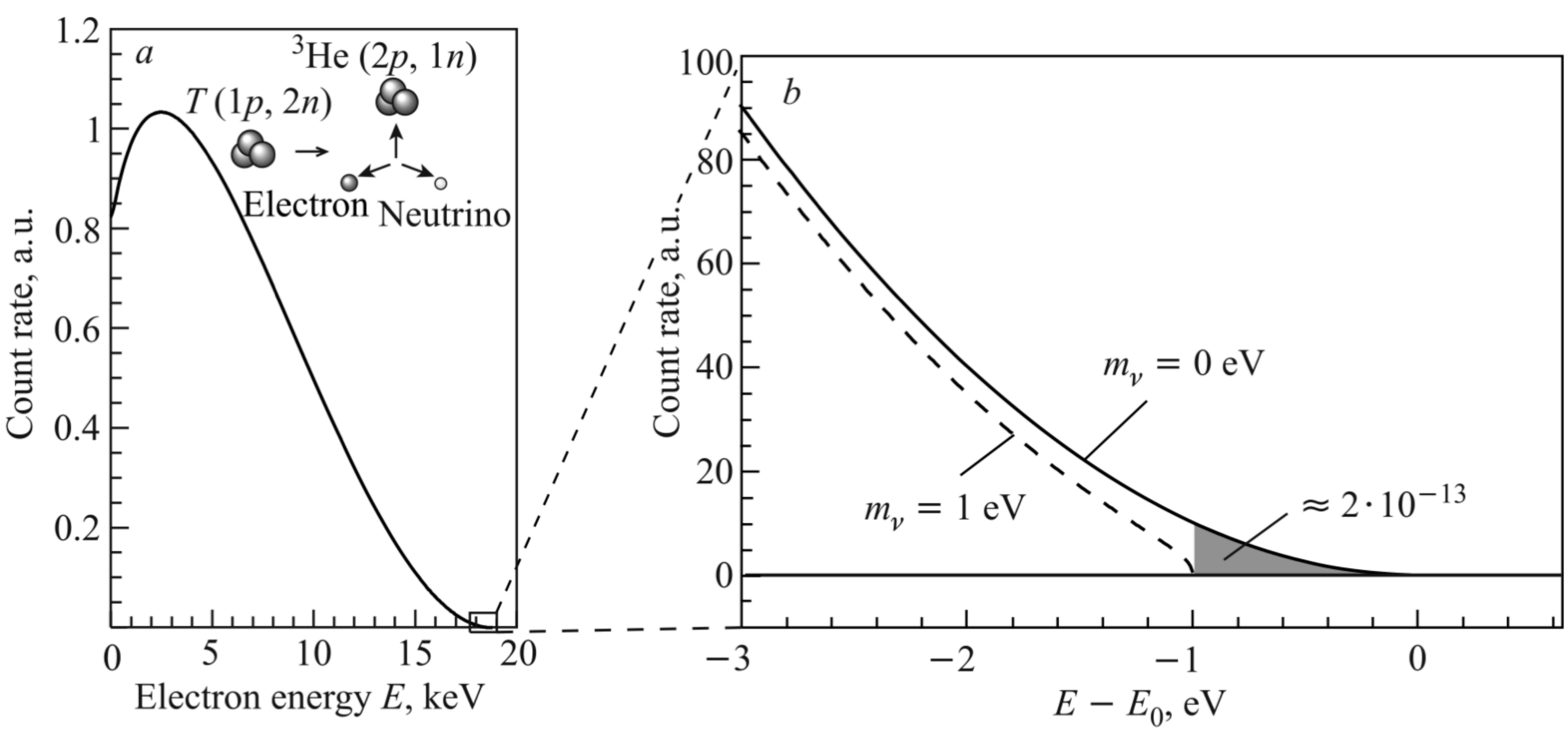
deSalas et al, 1708.01186

[M.Tortola]

NEUTRINO 2018 Heidelberg 4-9 June

Absolute mass scale of neutrino masses?

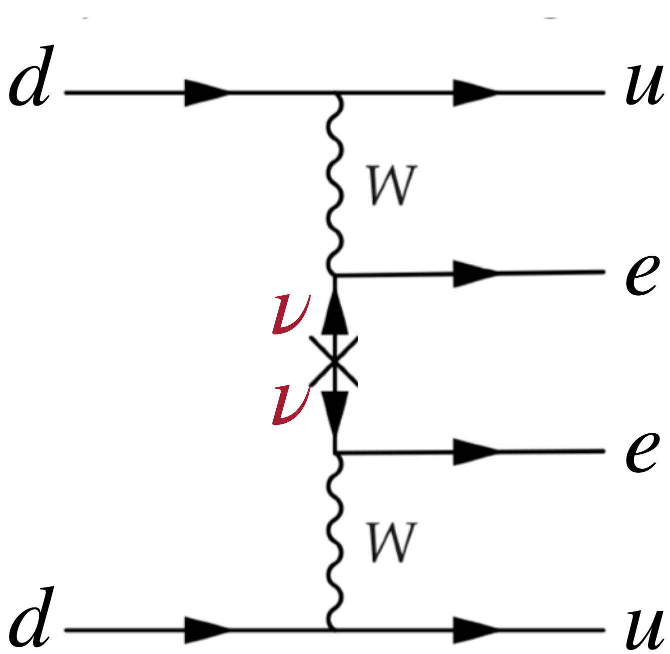
Beta decay is the best hope for direct determination of neutrino mass scale. Current bound is about 2 eV, but Katrin should improve it soon!

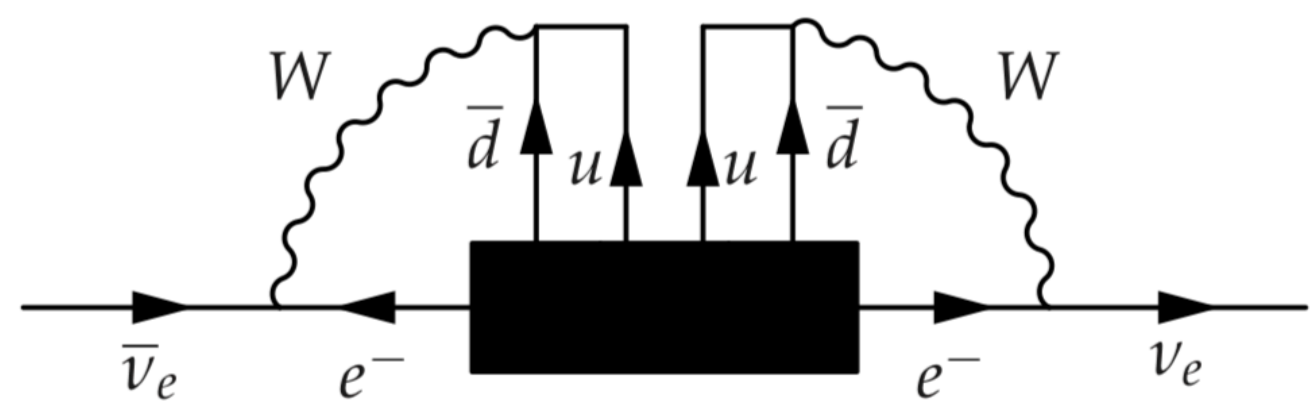


[KATRIN collab.]

Majorana vs. Dirac. How could we tell?

A variant of beta decay; neutrino-less double beta decay can probe the nature of the neutrino (i..e lepton number violation). The process is allowed only if neutrinos are Majorana.





[Shechter-Valle, ’82]

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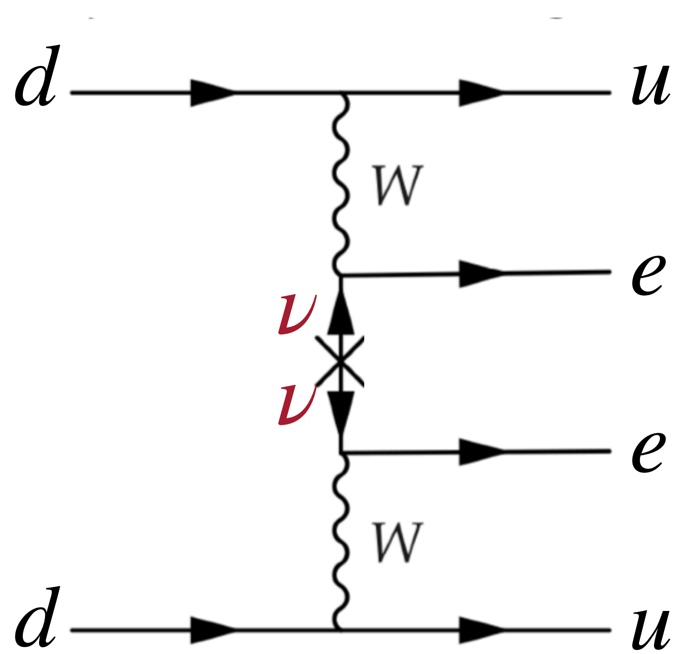
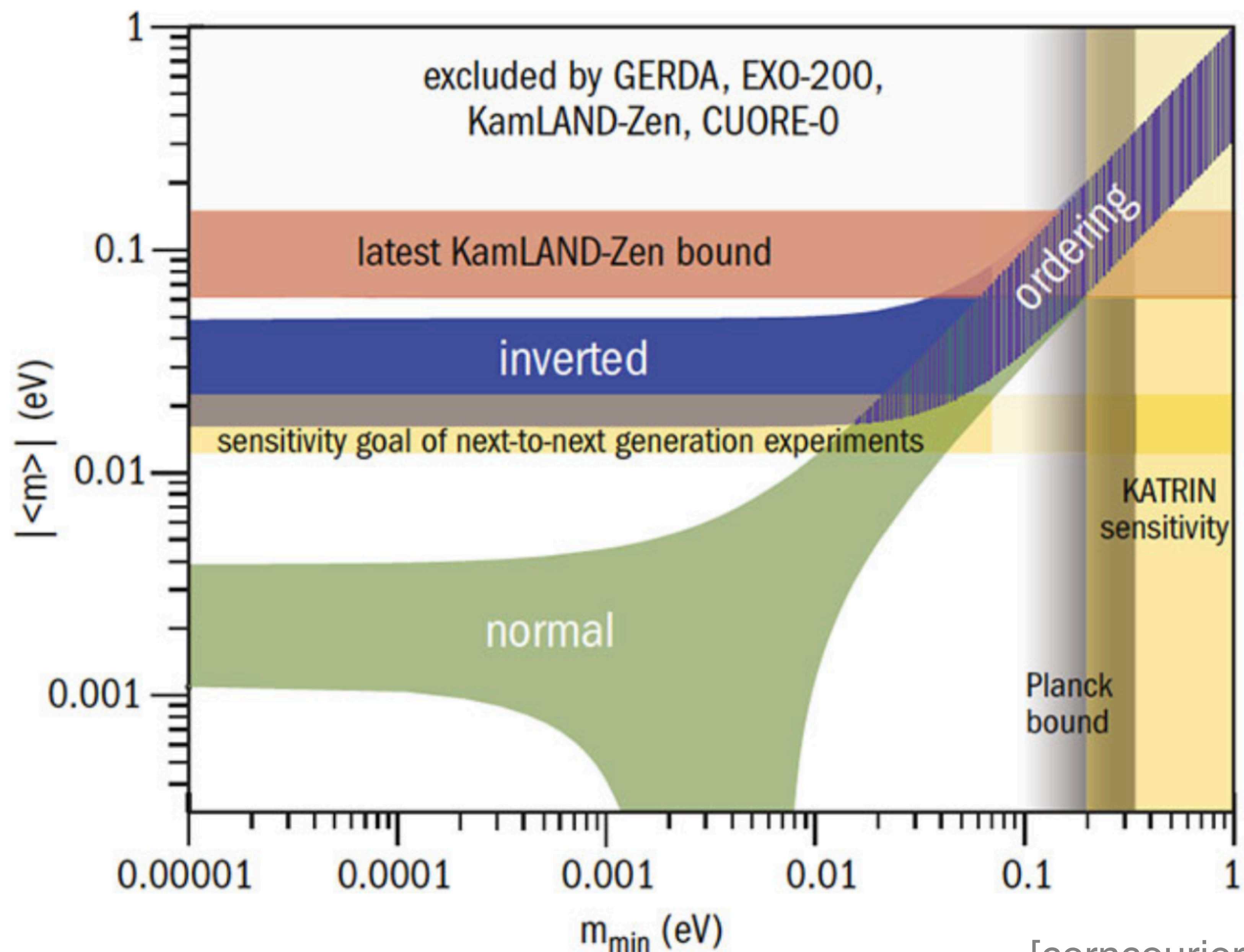




[cerncourier]

Searching for the mass messengers

The mediators at the origin of neutrino masses can be probed by a variety of setups,

[L3, '01]

Beam dump experiments

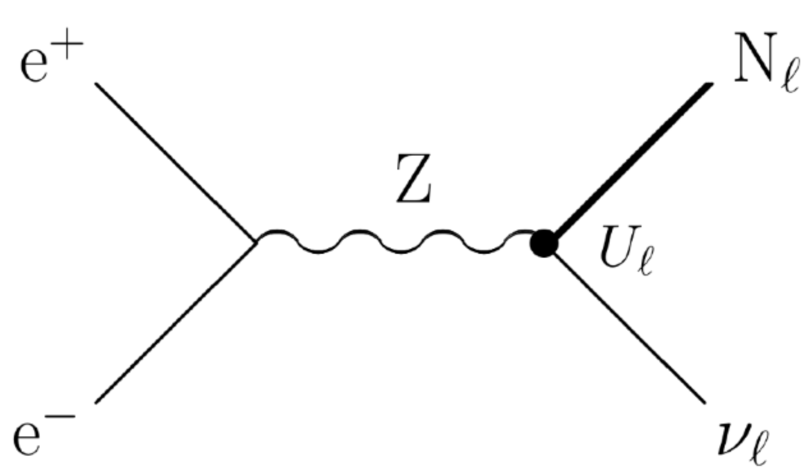
Rare decays & processes

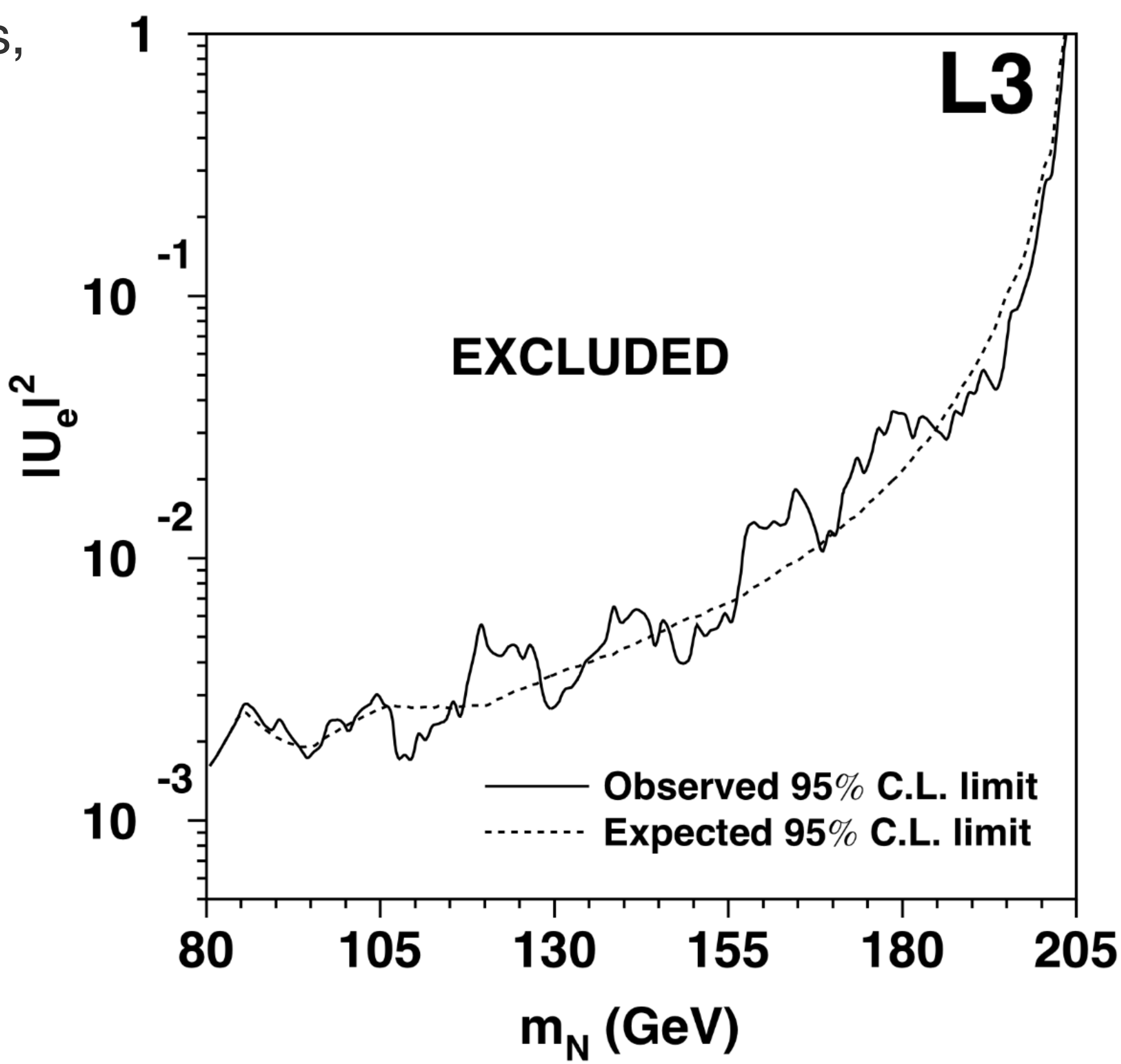
Colliders

Precision tests

Z decays

Unitarity violation





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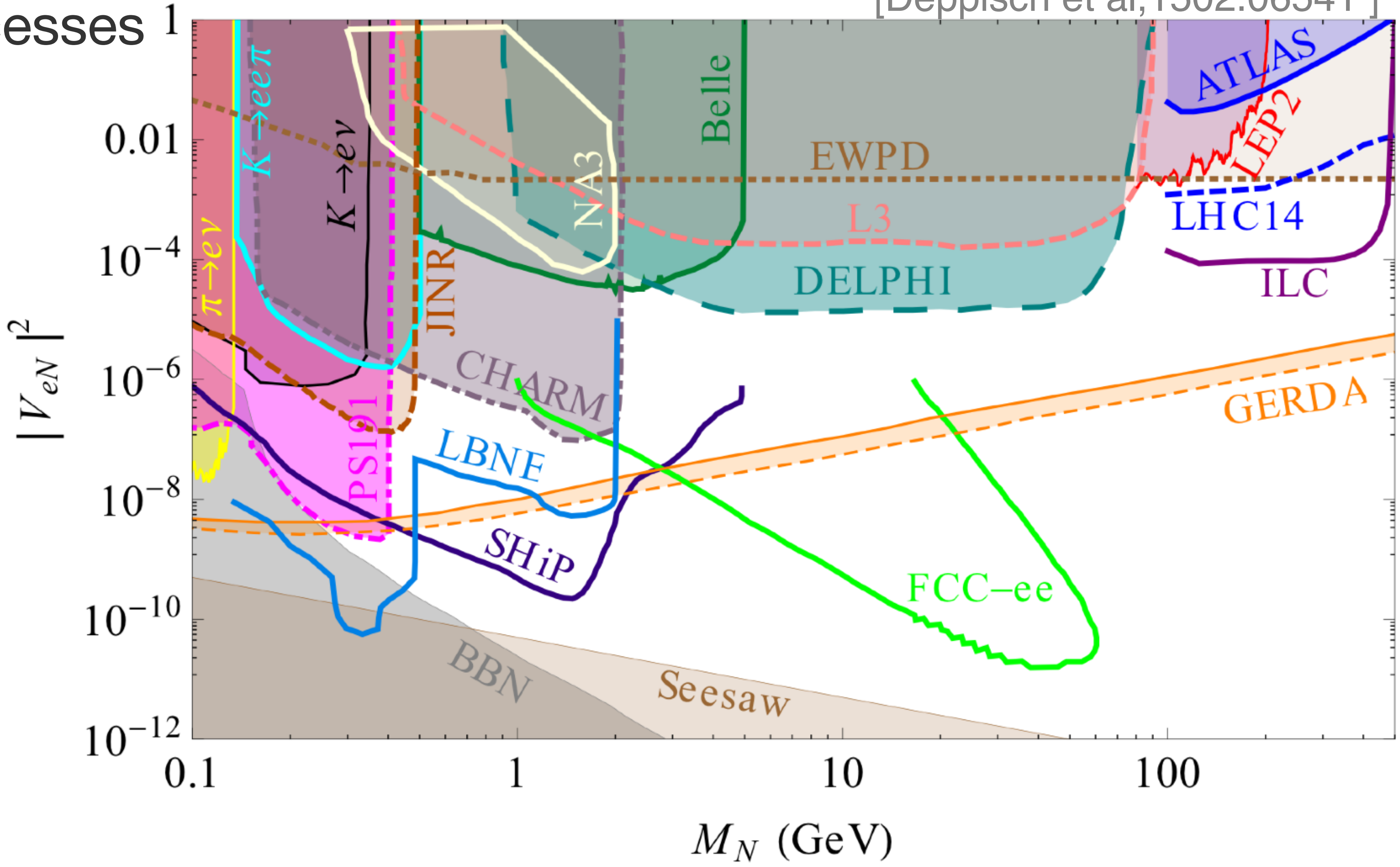
[Deppisch et al,1502.06541]

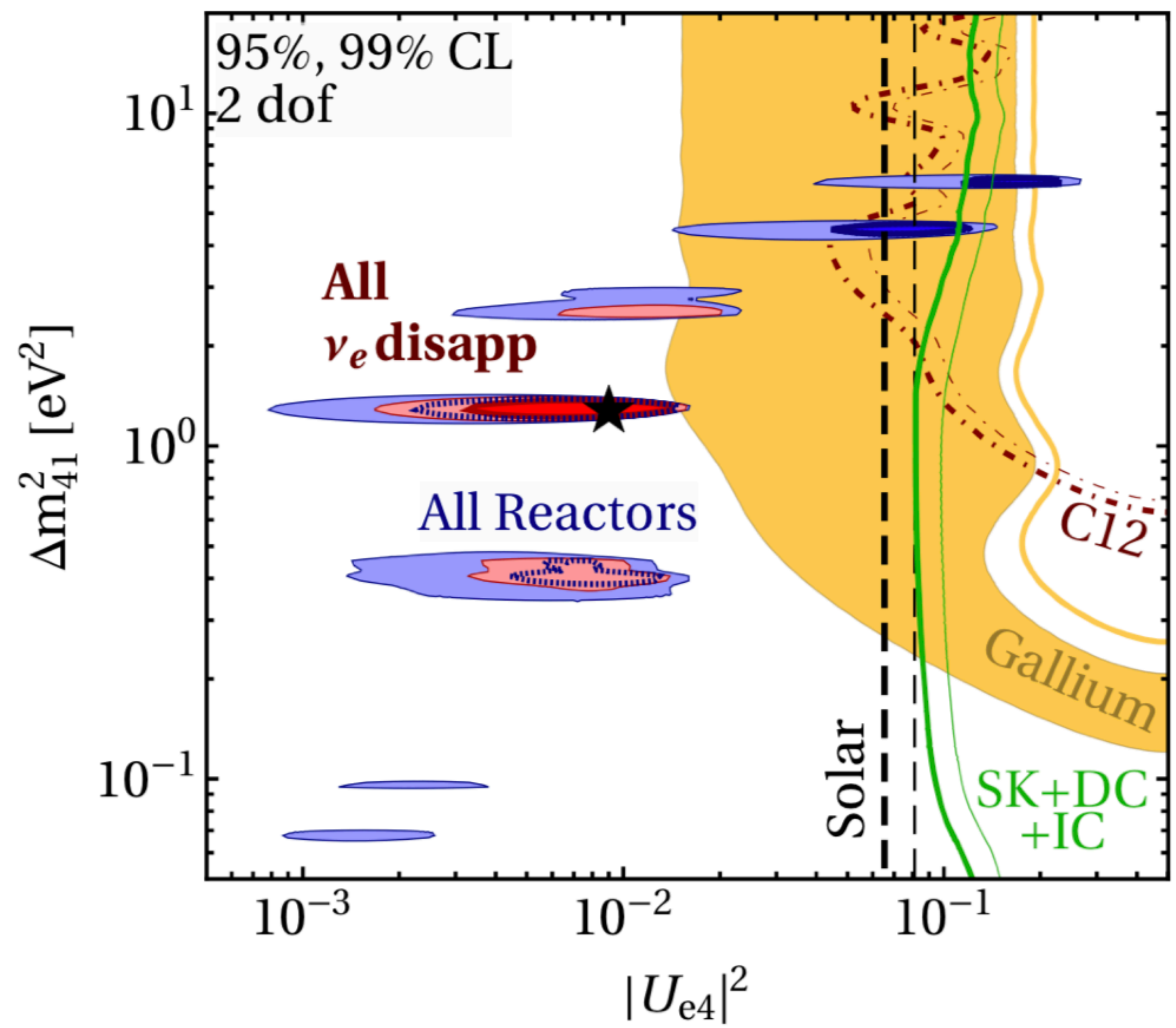


A few anomalies in the data …

Neutrino disappearance channels put constraint on oscillations to sterile neutrinos.

Some experiments seem to *need* such new neutrinos to fit data.

Global fit of e- (anti)neutrino disappearance in 3+1 scenario. Reactor neutrino data show a 3σ preference for sterile neutrino oscillations (DANSS, NEOS)



[Dentler et al, 1803.10661]

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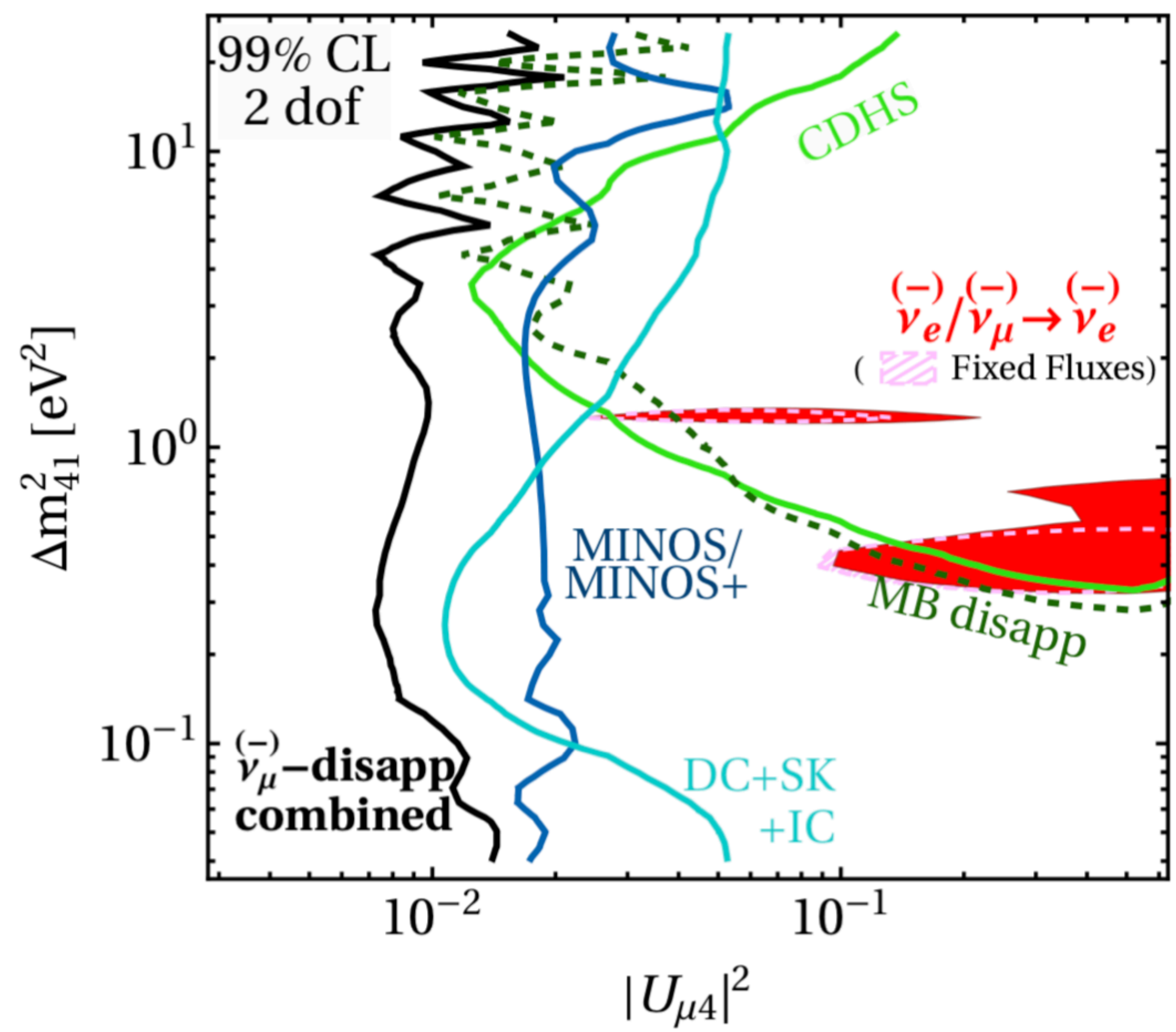
For mu- (anti) neutrino disappearance, strong tensions between the experiments (LSND+miniBoone vs IceCube+MINOS+…).



[Dentler et al, 1803.10661]

Summary and Outlook

Summary

Neutrinos oscillate. At least 2 active neutrinos have mass, and unambiguously establish evidence for BSM physics.

Rich experimental program to unveil mechanism at work.

We can roughly distinguish 2 general classes of models to account for neutrino masses: high-scale, with mediators around unification scale; and low-scale, with mediators around TeV scale.

Neutrinos can be linked to other BSM physics: DM, baryon asymmetry, and inflation.

Hints for a 4th (sterile) neutrino in reactor data.

Most importantly: single and double-beta decay exps. are running!

Known questions about neutrinos

What is their absolute mass scale?

Is CP violated in the leptonic sector?

Are neutrinos their own anti-particles?

Are there sterile neutrinos?

Are there Non-standard interactions?

Is B-L a symmetry of nature?

Is there any relation between neutrinos and baryogengesis?

Is there any relation between neutrinos and DM?

Cosmology+Astrophysics+HEP probes & joined efforts will hopefully answer some of these questions soon!

A selection of references

Textbooks

- Neutrinos in High Energy and Astroparticle Physics, Romao & Valle
- Massive Neutrinos in Physics and Astrophysics, Mohapatra & Pal
- Fundamentals of Neutrino Physics & Astrophysics, Giunti & Kim

Reviews & Lectures:

- Neutrino physics, Akhmedov, hep-ph/0001264
- Theory of Neutrino Masses and Mixings, Grimus, 1101.0137v1
- TASI lectures on neutrino physics, De Gouvea, hep-ph/0411274
- Neutrino masses and mixings and …, Strumia & Vissani, hep-ph/060605
- Neutrinos and collider physics, Deppisch, Dev &Pilaftsis,1502.06541
- The low-scale approach to neutrino masses, SB, Morisi&Valle, 1404.3751
- Non-standard neutrino interactions: current status and future prospects, Miranda & Nunokawa, 1505.06254

Global fits:

- Valencia: https://globalfit.astroparticles.es
- Bari: 1804.09678
- NuFit: http://www.nu-fit.org