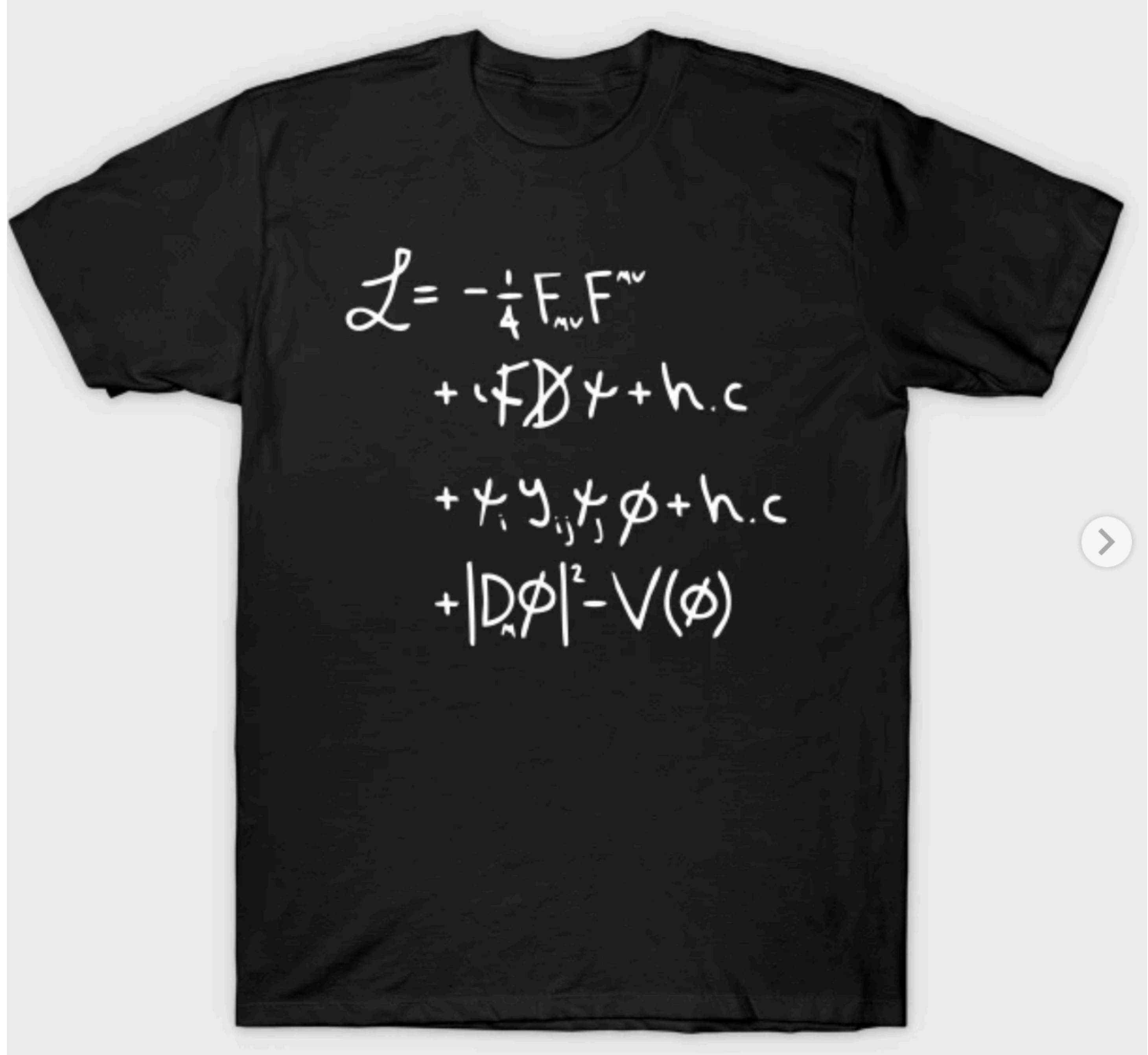
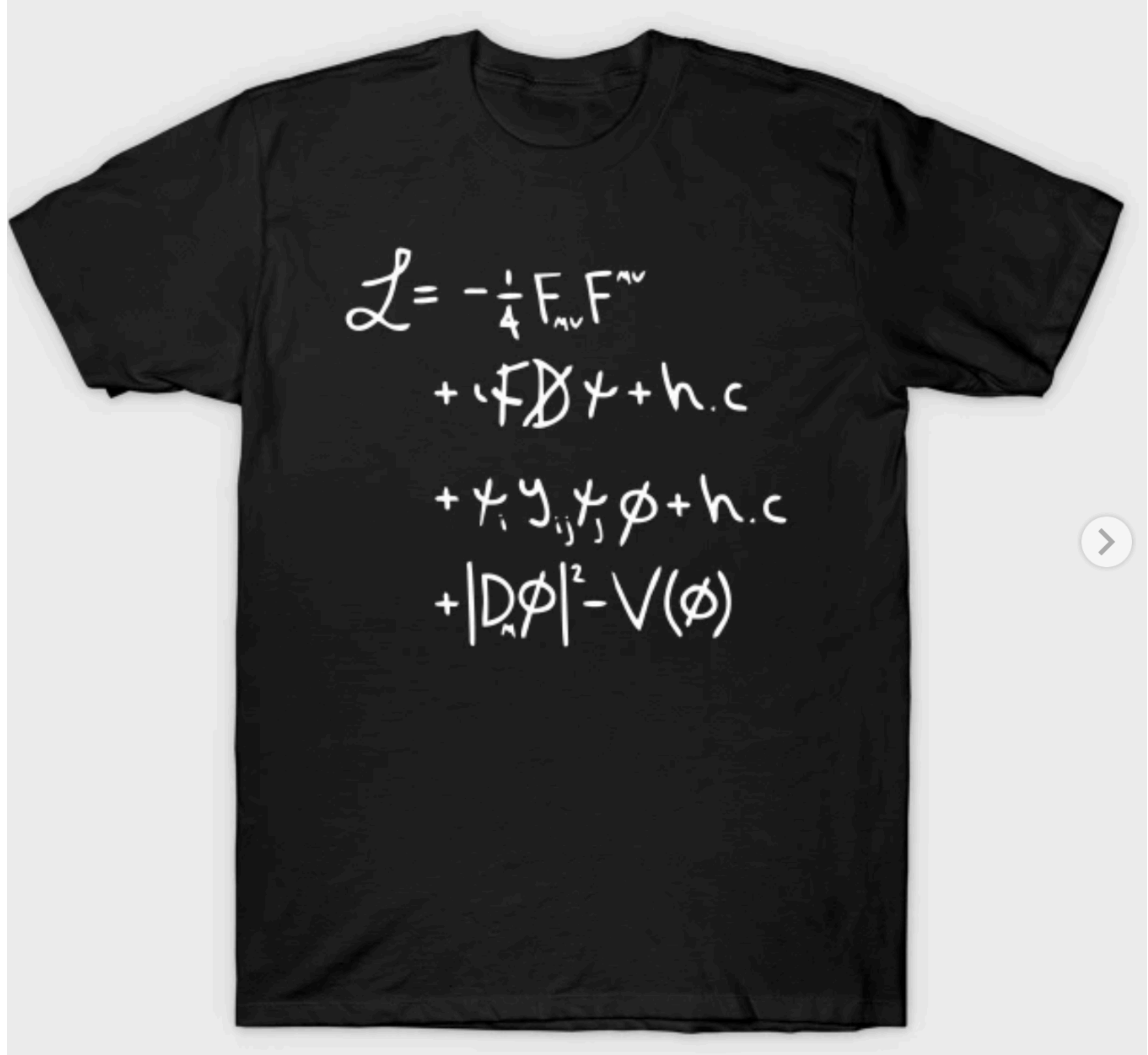
Neutrinoless double beta decay and new physics

David McKeen
TRIUMF


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c$
$+ \psi_i y_{ij} \psi_j \phi + h.c$
$+ |D_\mu \phi|^2 - V(\phi)$

Works great

…but can't explain…



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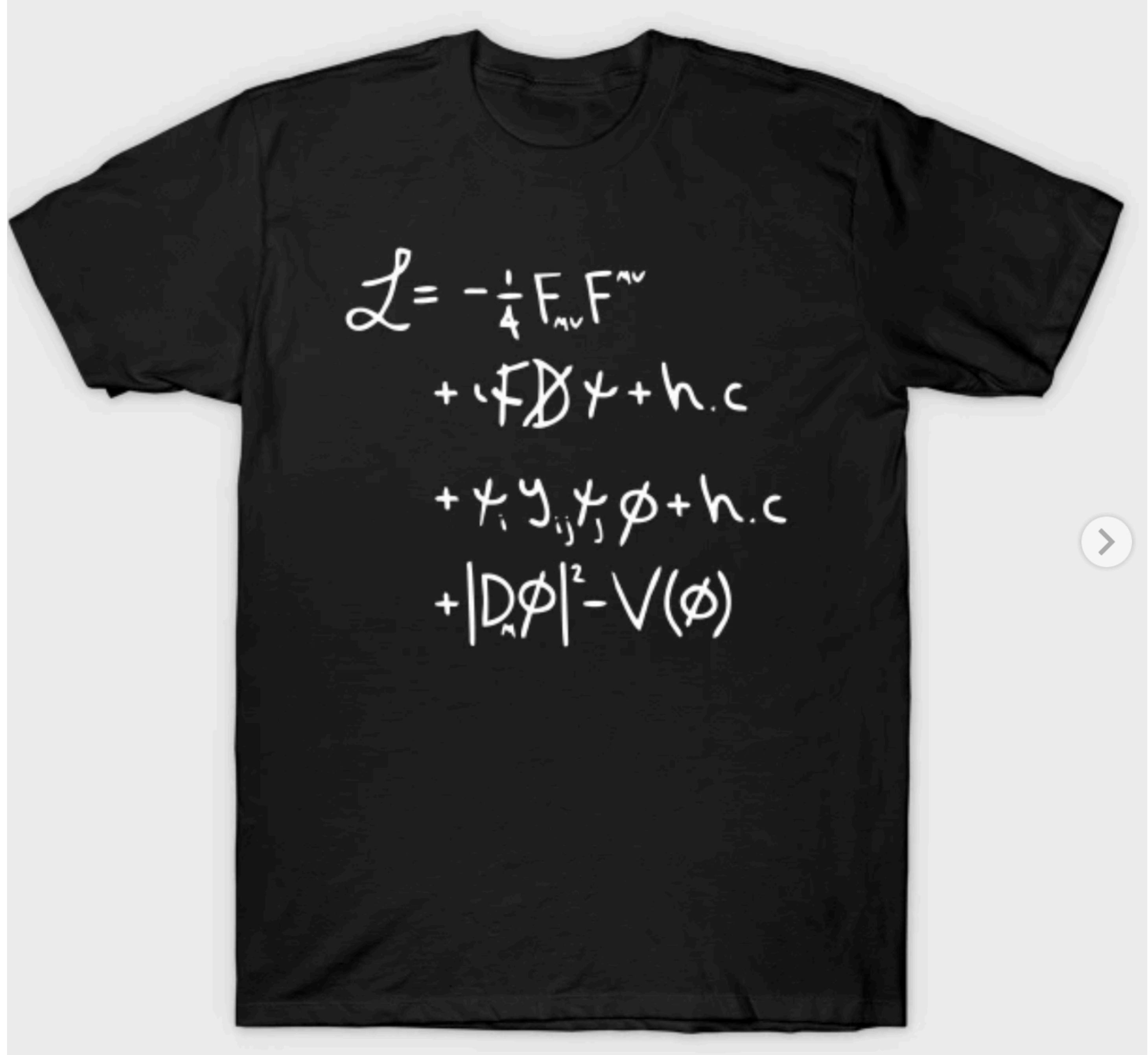

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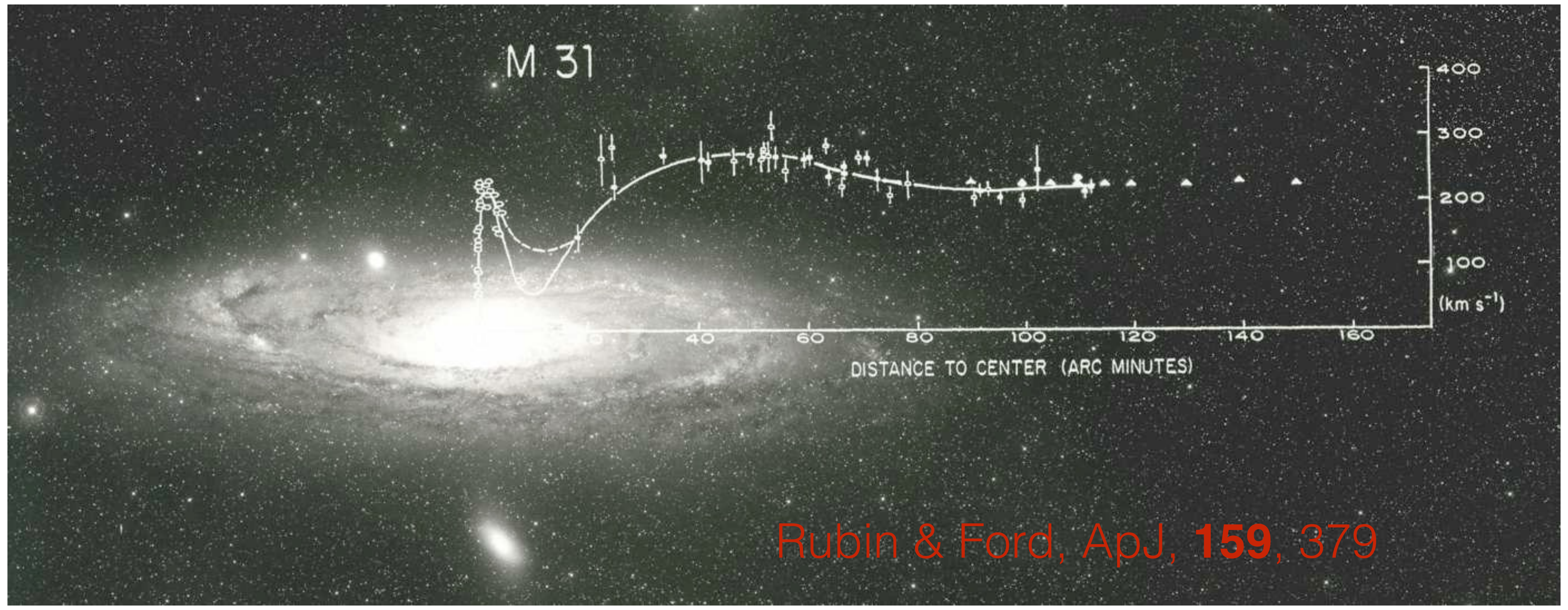
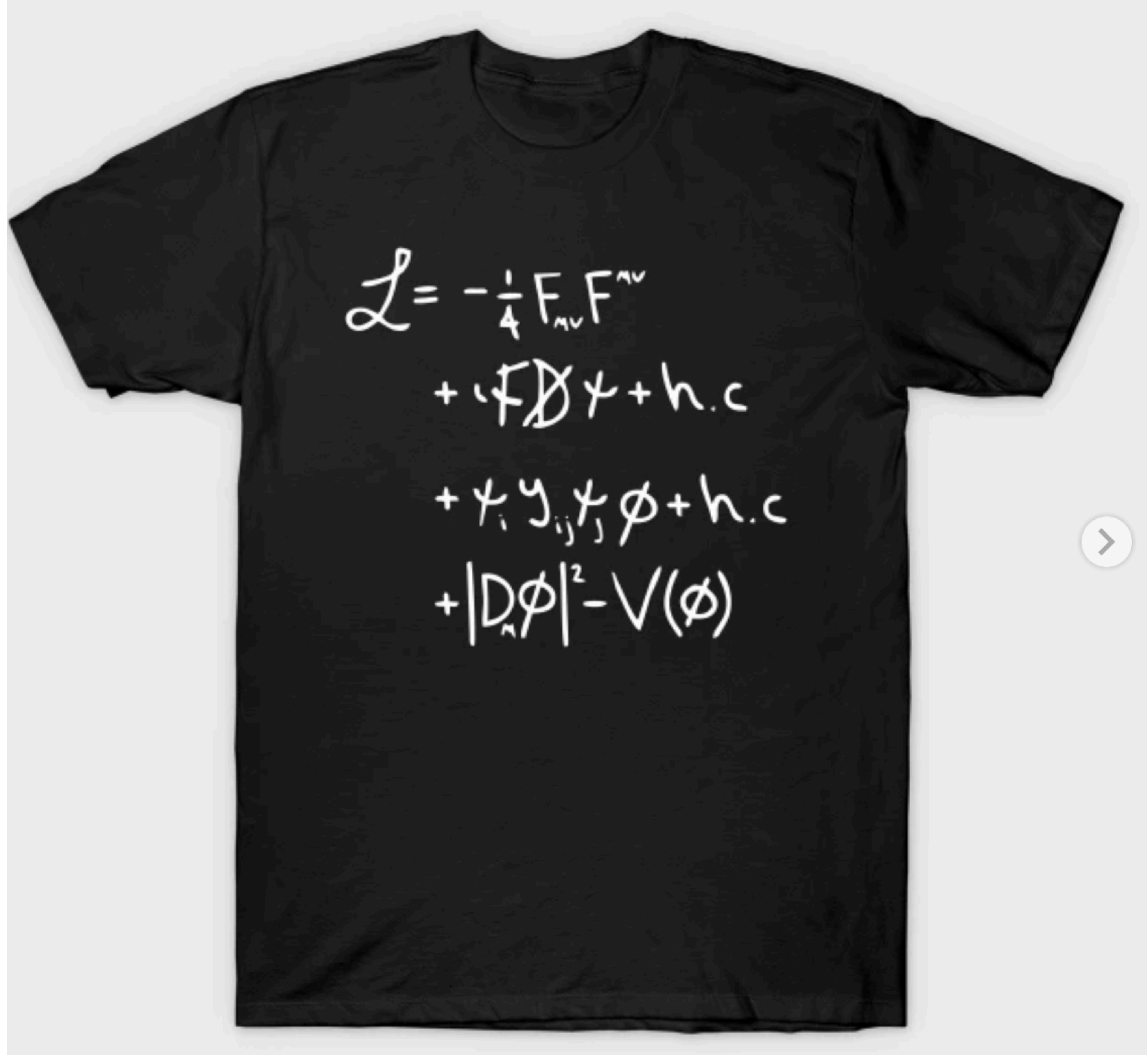


dark matter

…but can't explain…



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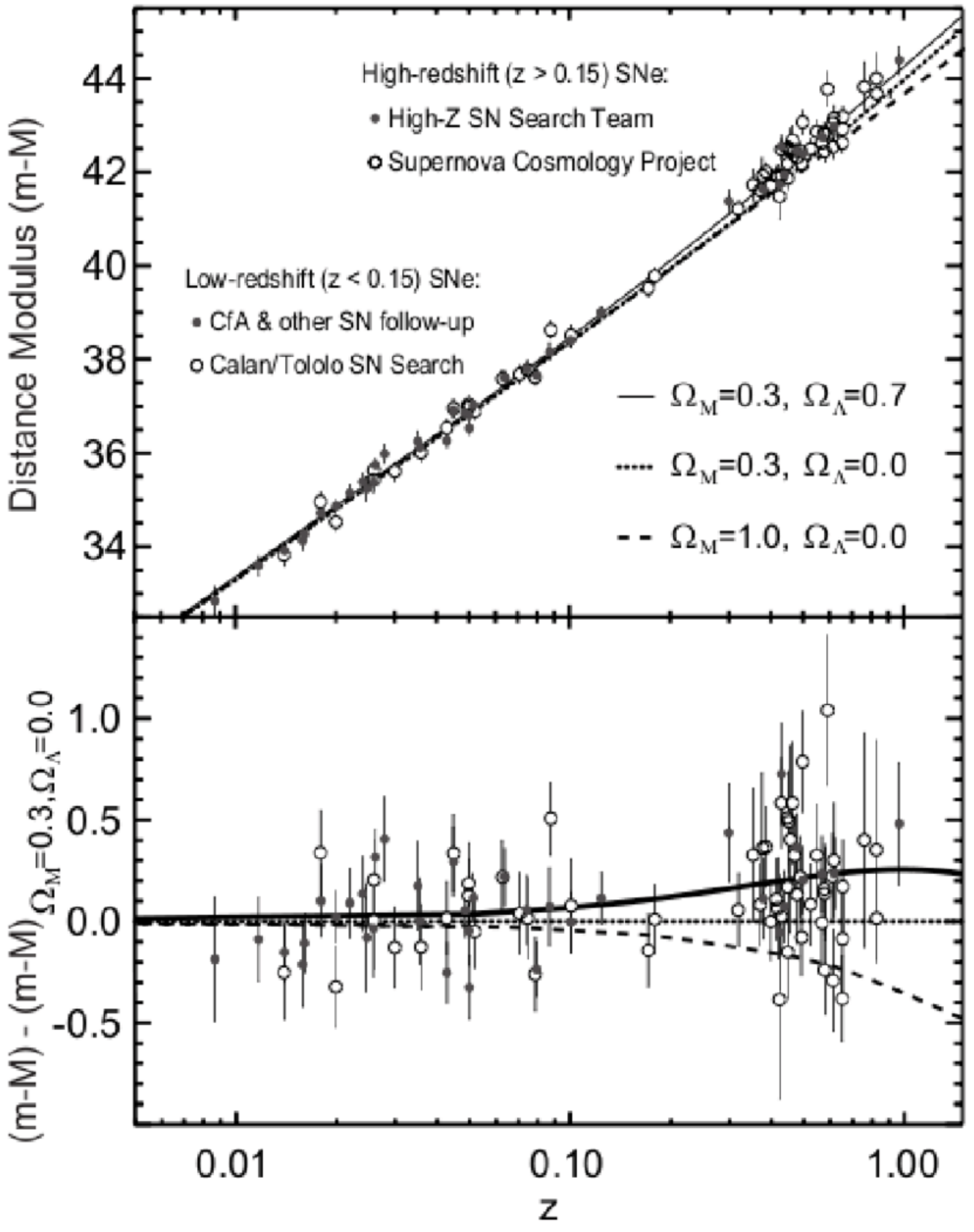
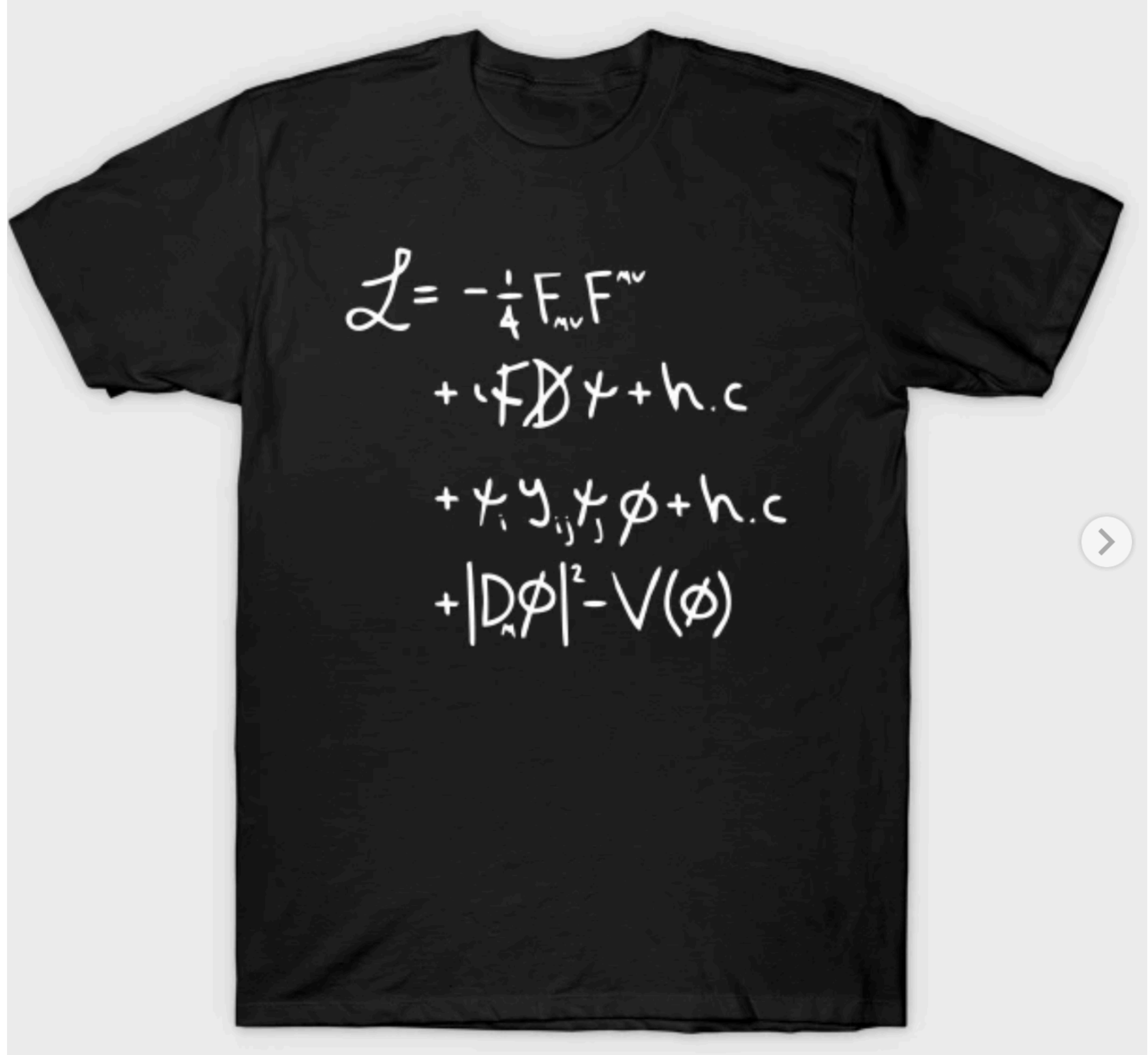


dark energy

…but can’t explain…



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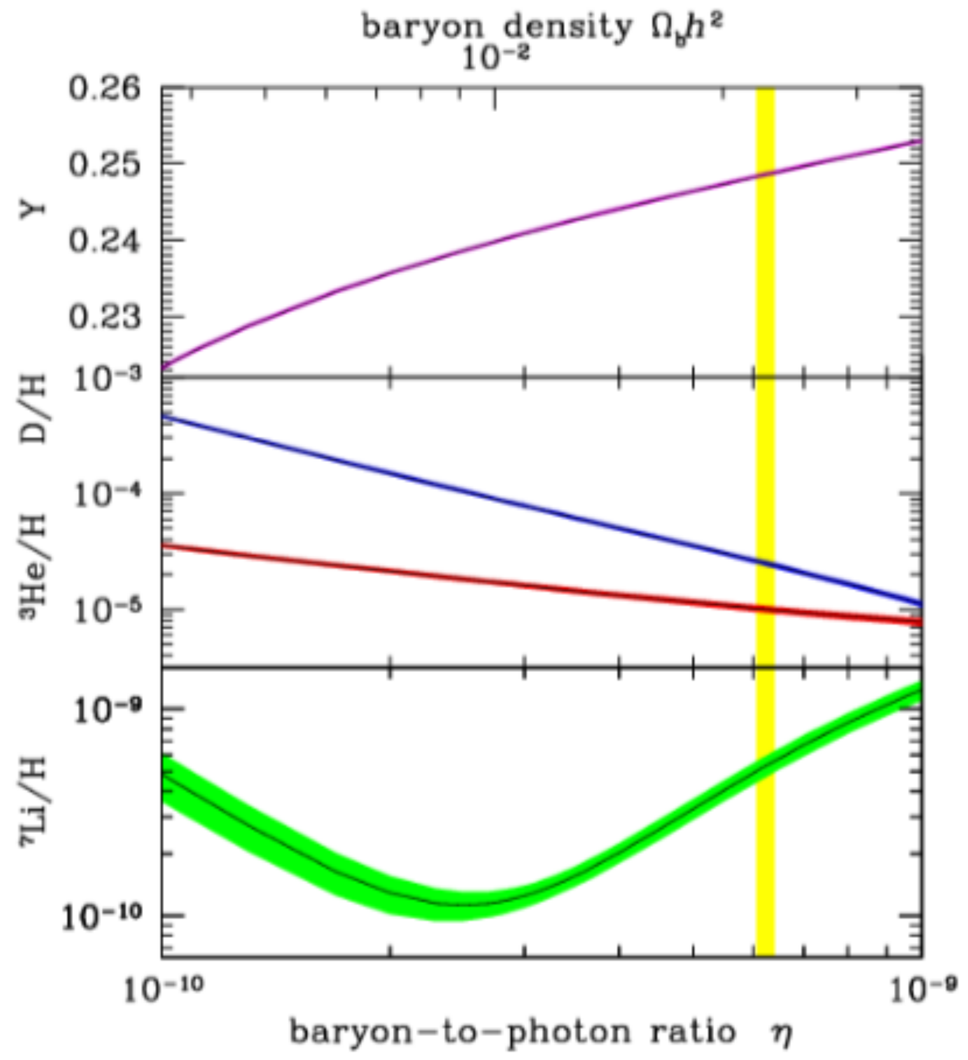
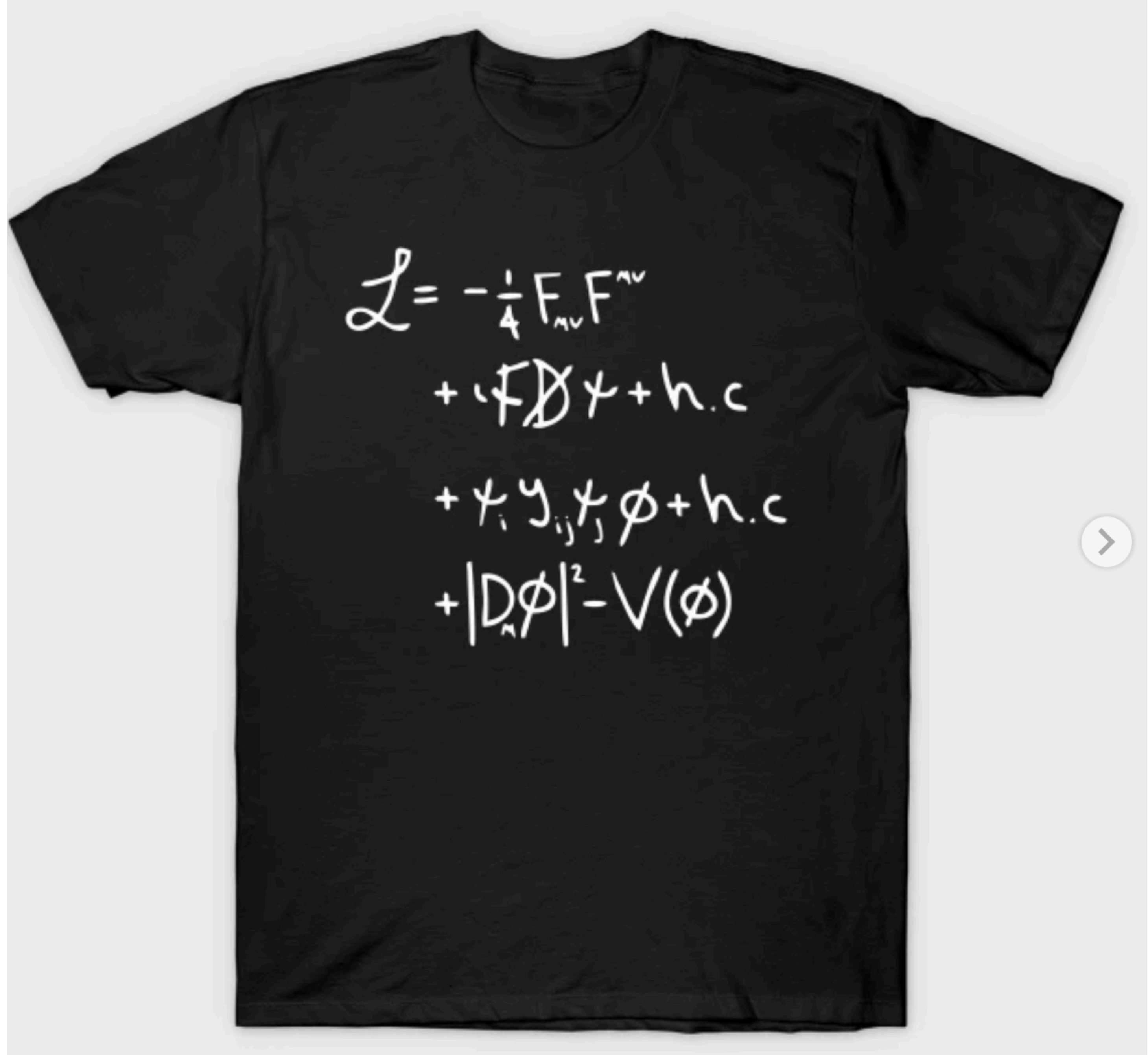


matter asymmetry



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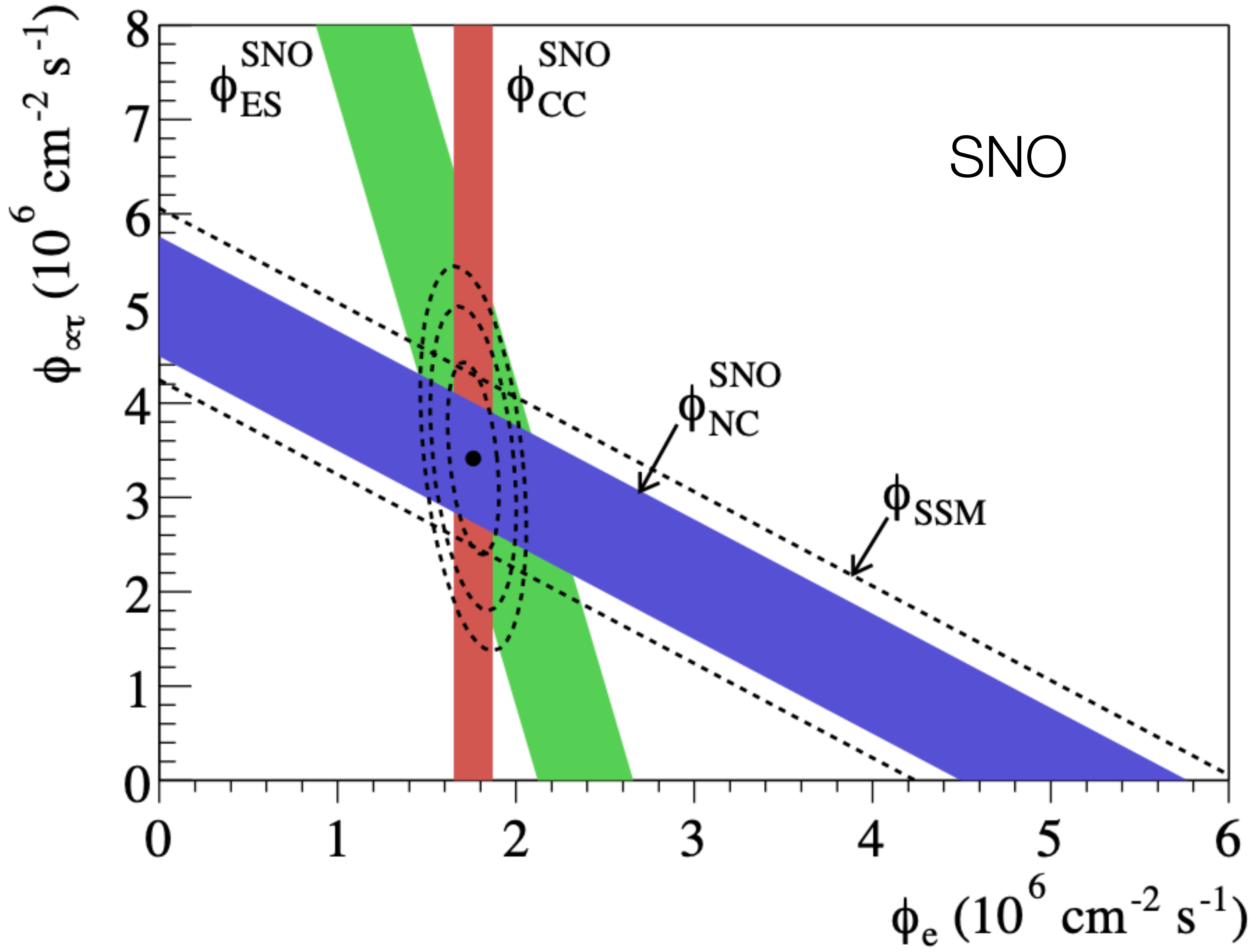
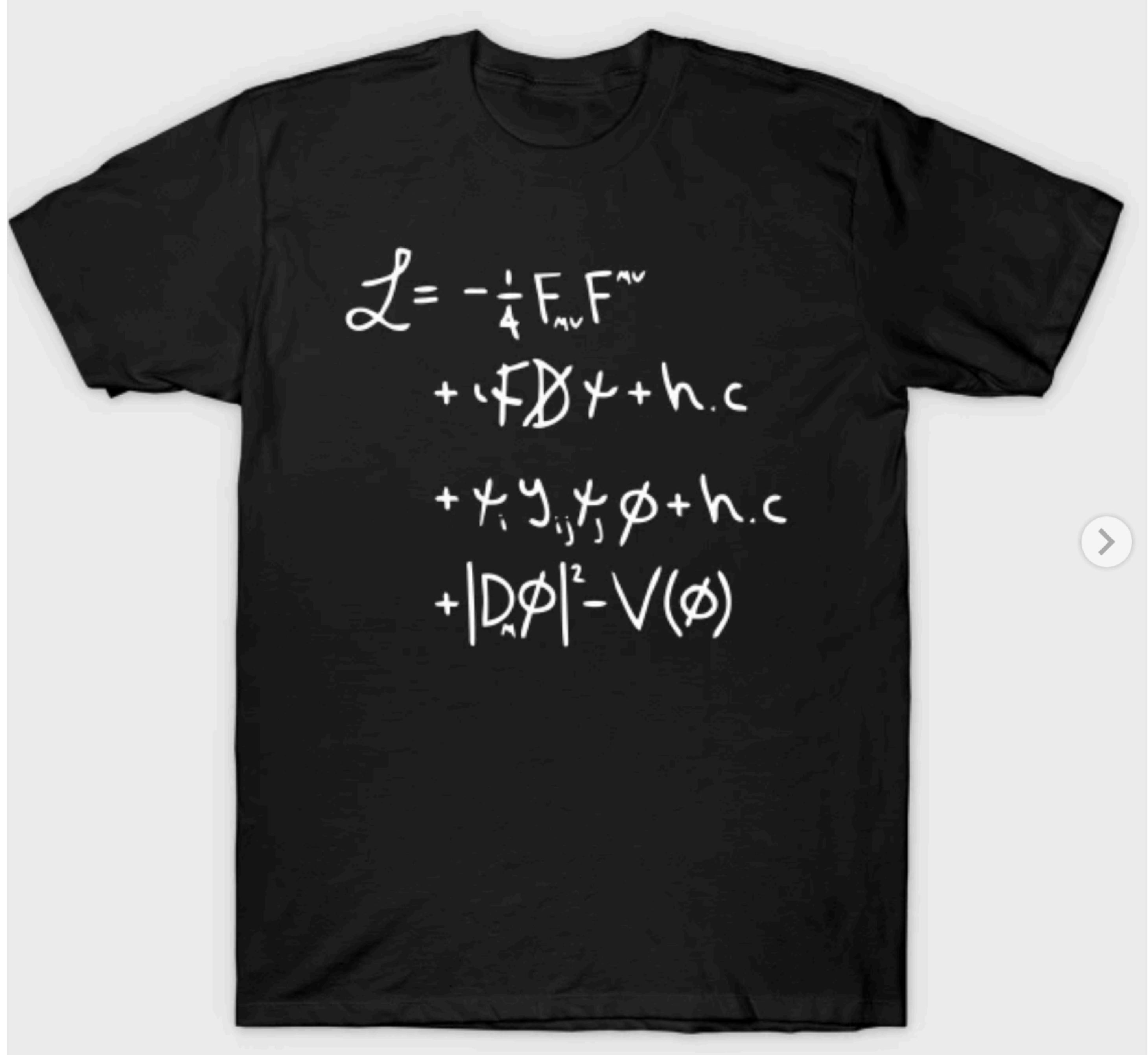


neutrino masses!

…but can’t explain…



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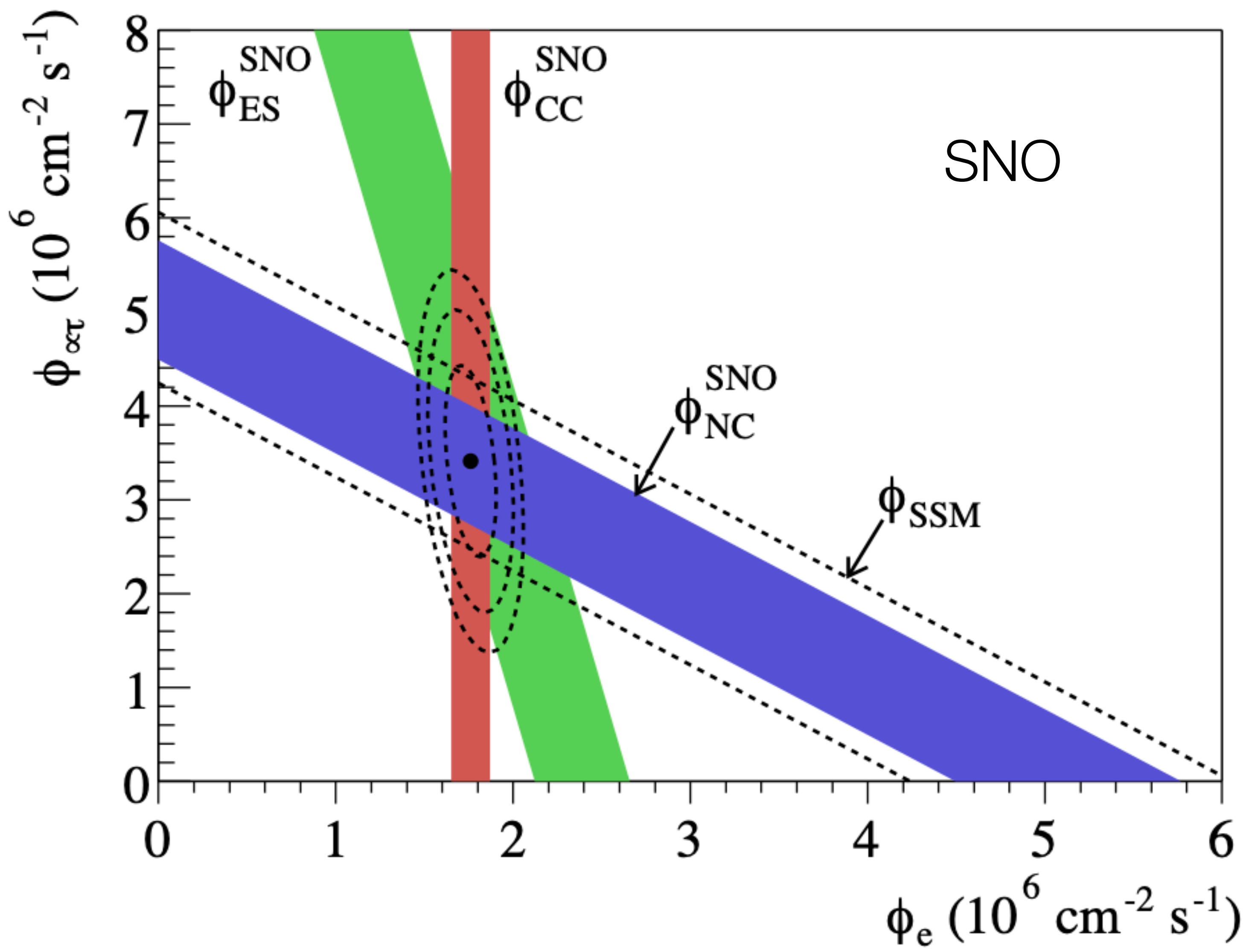


neutrino masses!

How can we tackle (some of) these questions?

Plan

Neutrinos are massive—their masses are **different**

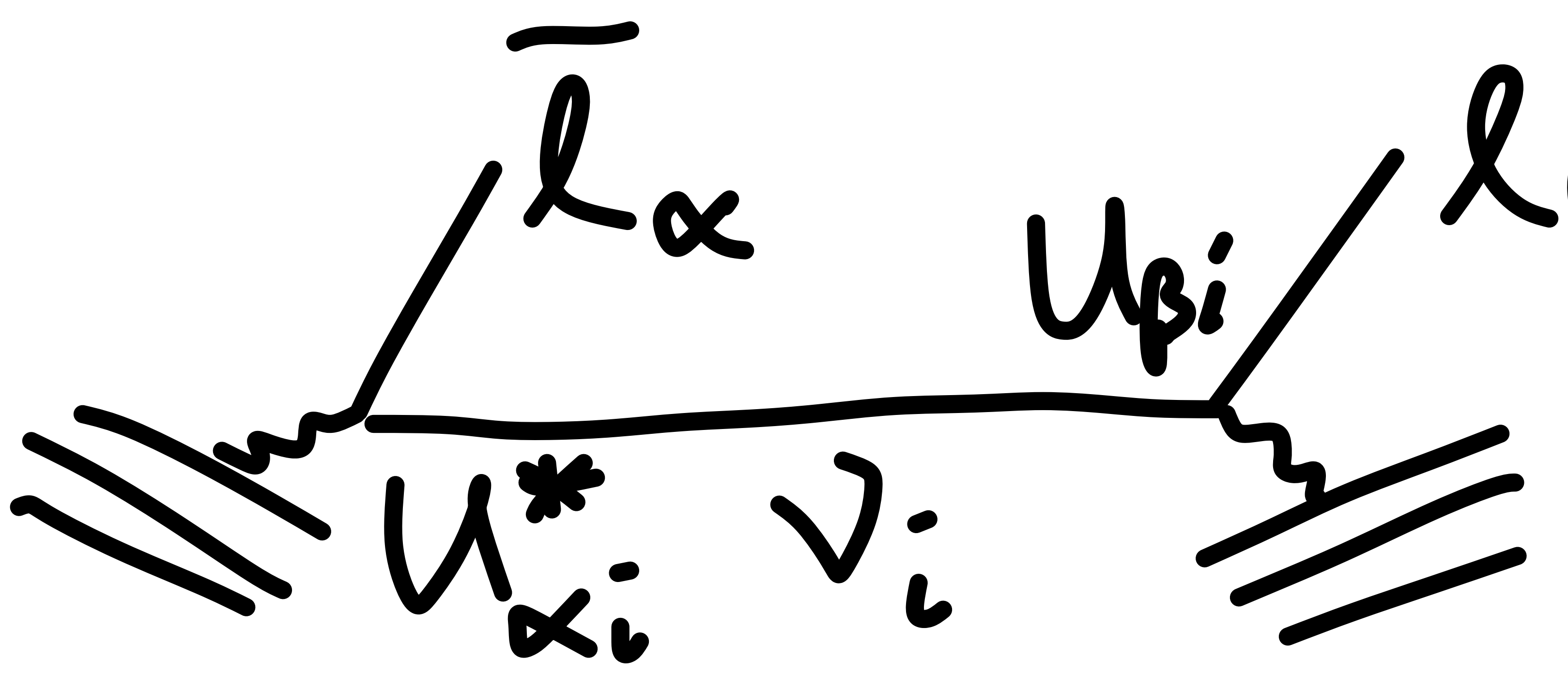
Probing the nature of neutrino masses with $0\nu\beta\beta$

Current status, outlook, and other opportunities

Neutrinos change flavour

Produce them in association with one type of charged lepton, see them in association with another

$$P_{\alpha\to\beta} \sim \left| \sum_i \right.$$



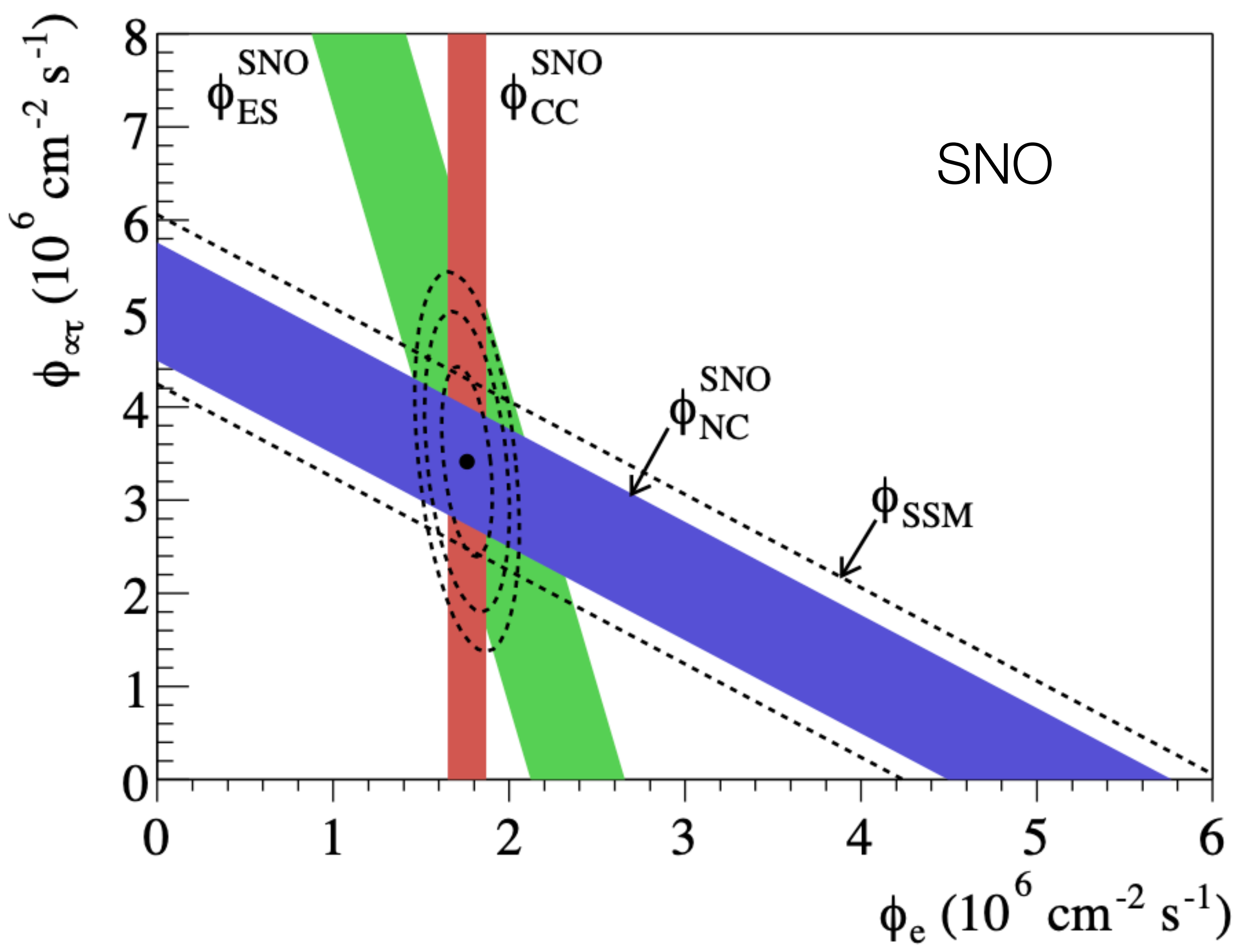
$$\left.\right|^2 \propto \left| \sum_i U^*_{\alpha i} U_{\beta i}\, e^{-i\frac{m_i^2 L}{2E}} \right|^2$$

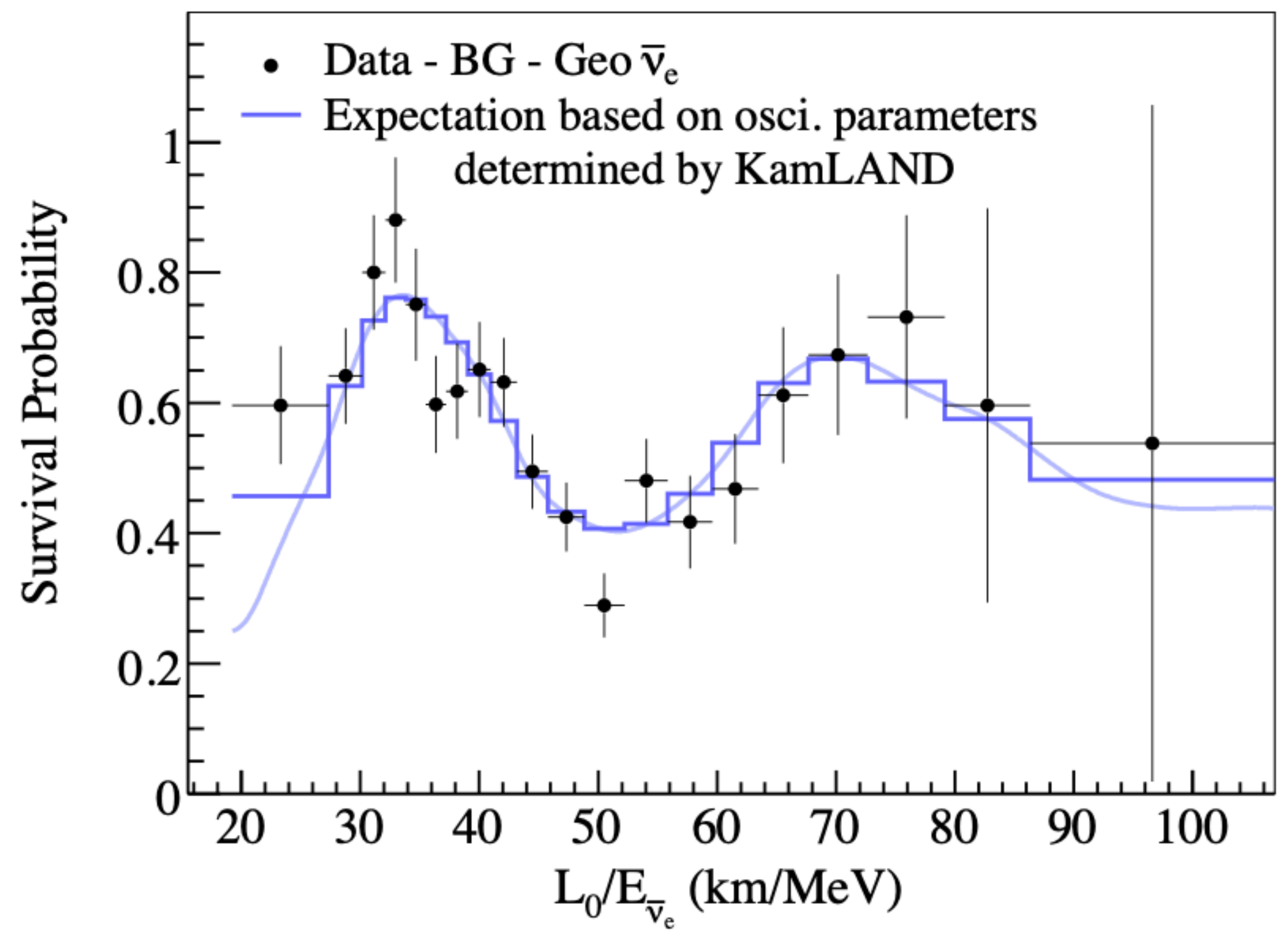
In the simple 2 neutrino case, relation between flavor and mass eigenstates: $U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

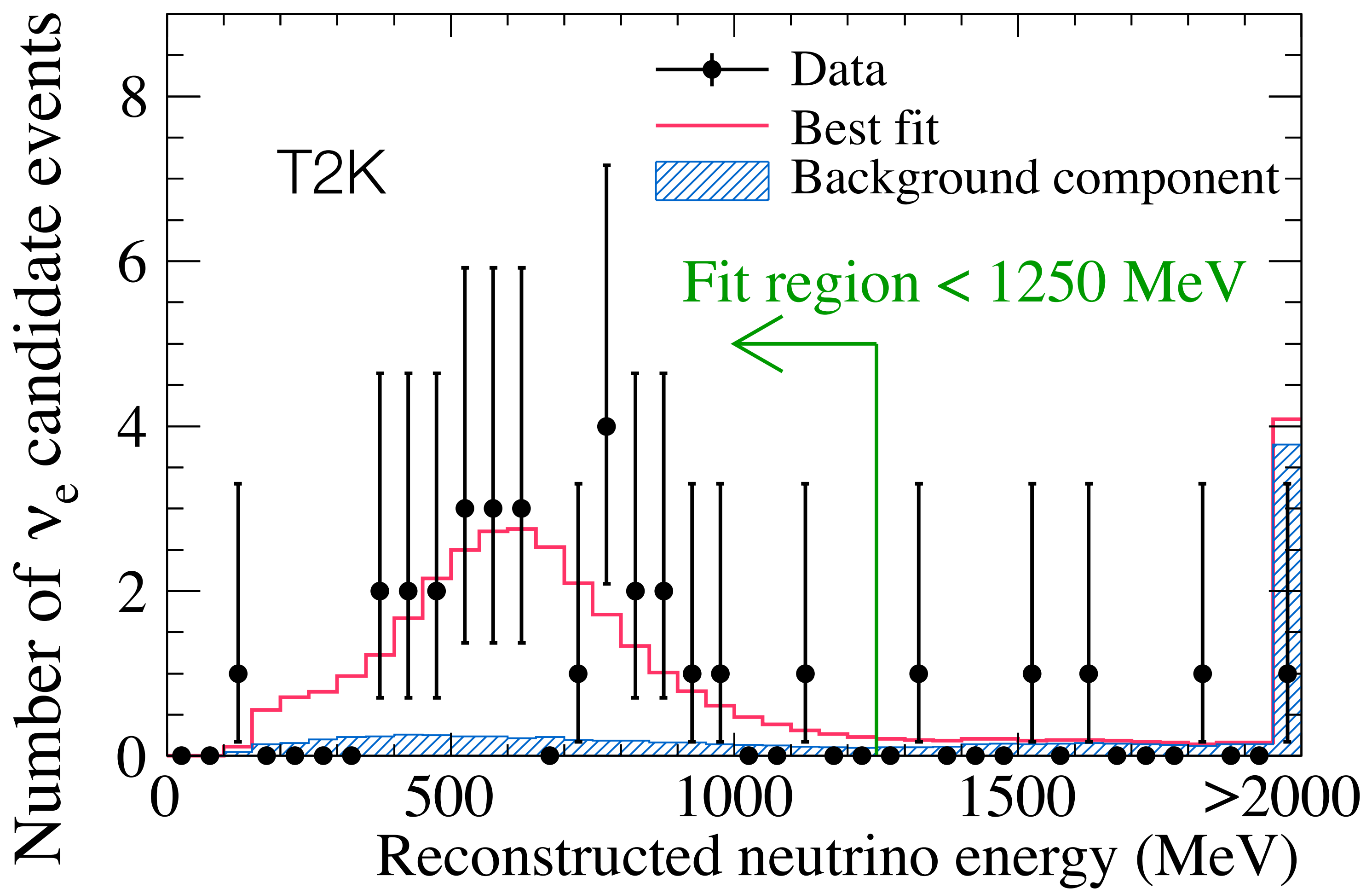
$$\Rightarrow P_{\alpha\to\beta} = 1 - P_{\alpha\to\alpha} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Seeing neutrino oscillations⇒they have mass

Neutrinos have mass





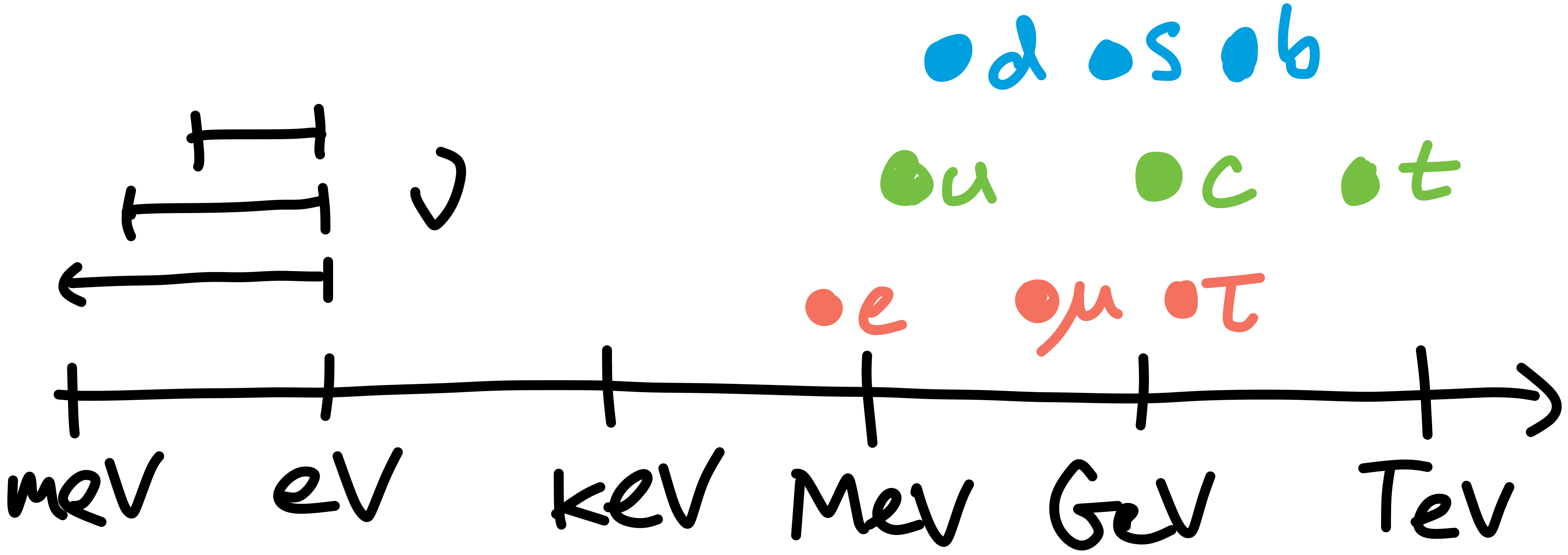


Have seen neutrino oscillations in a number of experimental setups

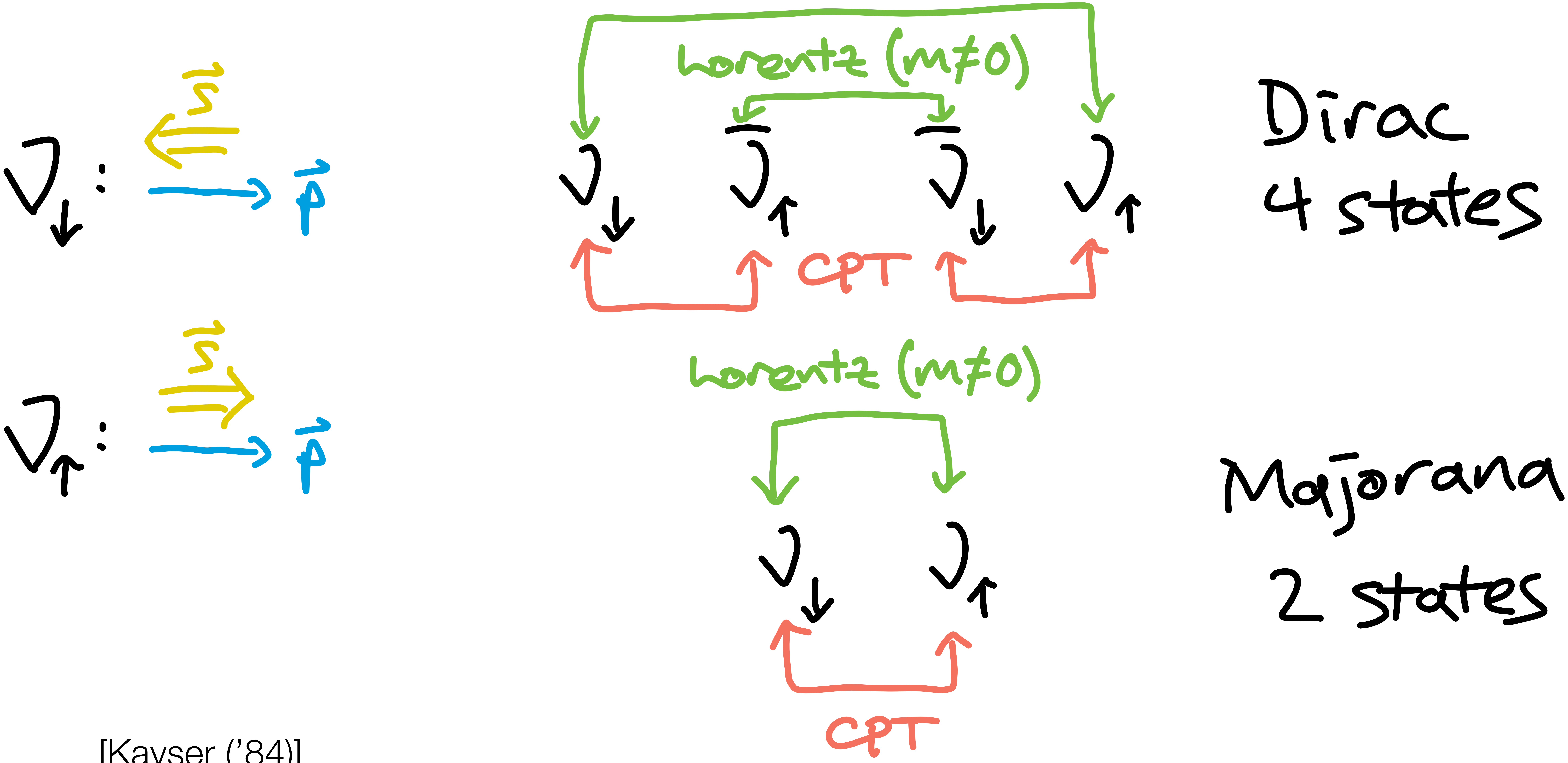
Observed $\Delta m^2_{\text{atm}} = \left|\Delta m^2_{13}\right| \sim 10^{-3}\ \text{eV}^2$ and $\Delta m^2_{\odot} = \Delta m^2_{12} \sim 10^{-5}\ \text{eV}^2$

Neutrinos have mass

But they are **very** light

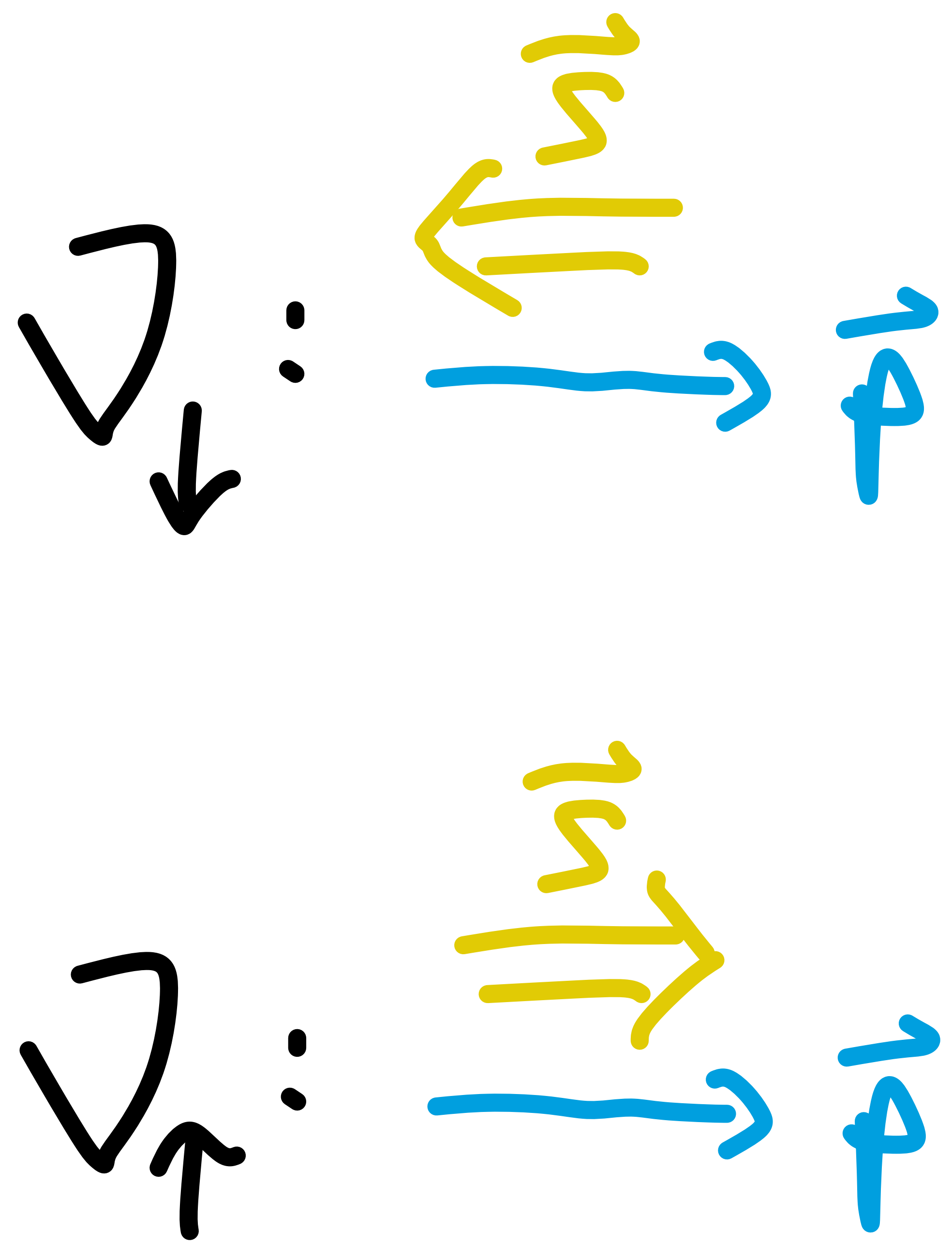


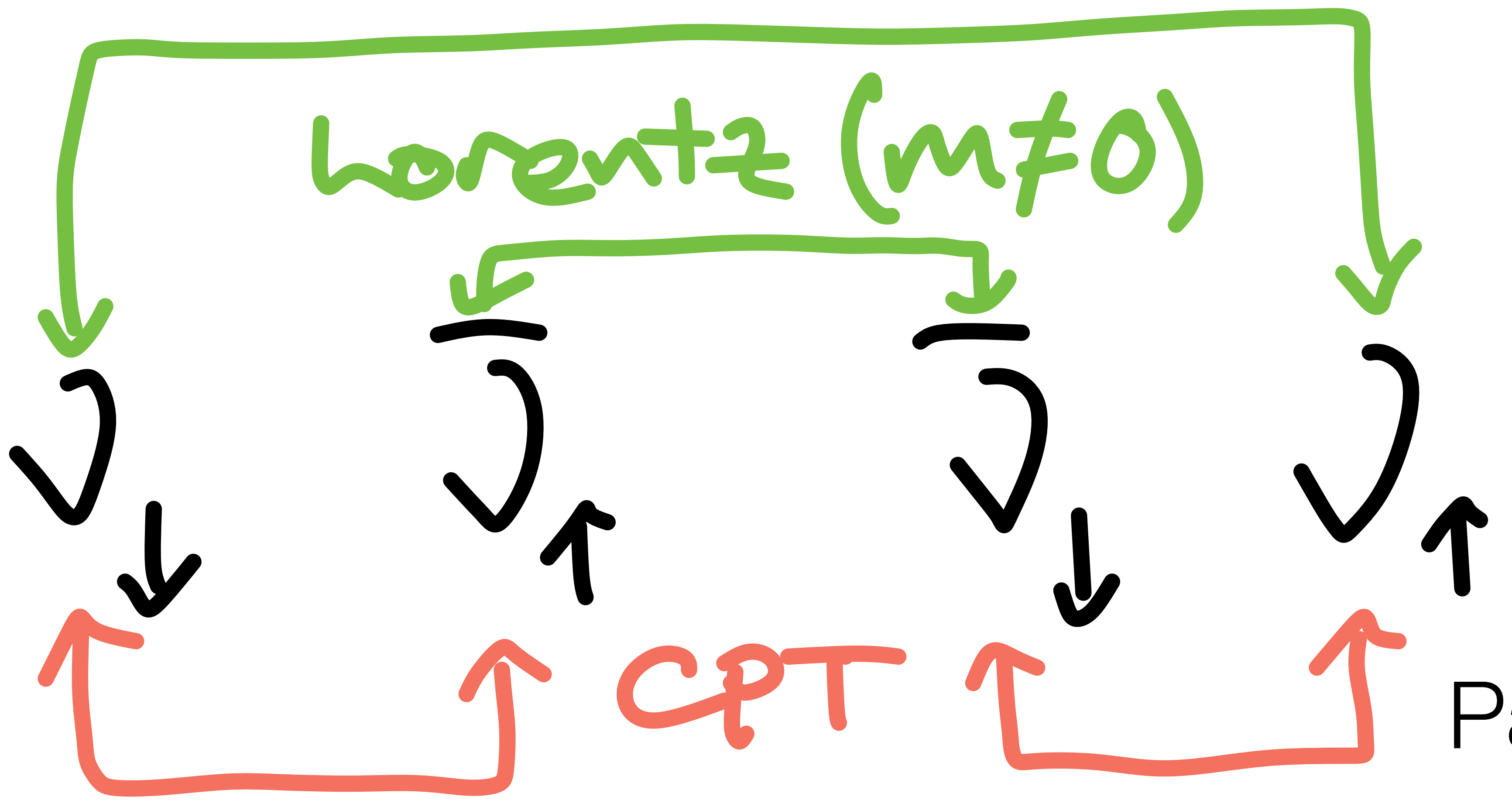
Neutrino masses: Dirac or Majorana?



[Kayser ('84)]

Neutrino masses: Dirac or Majorana?





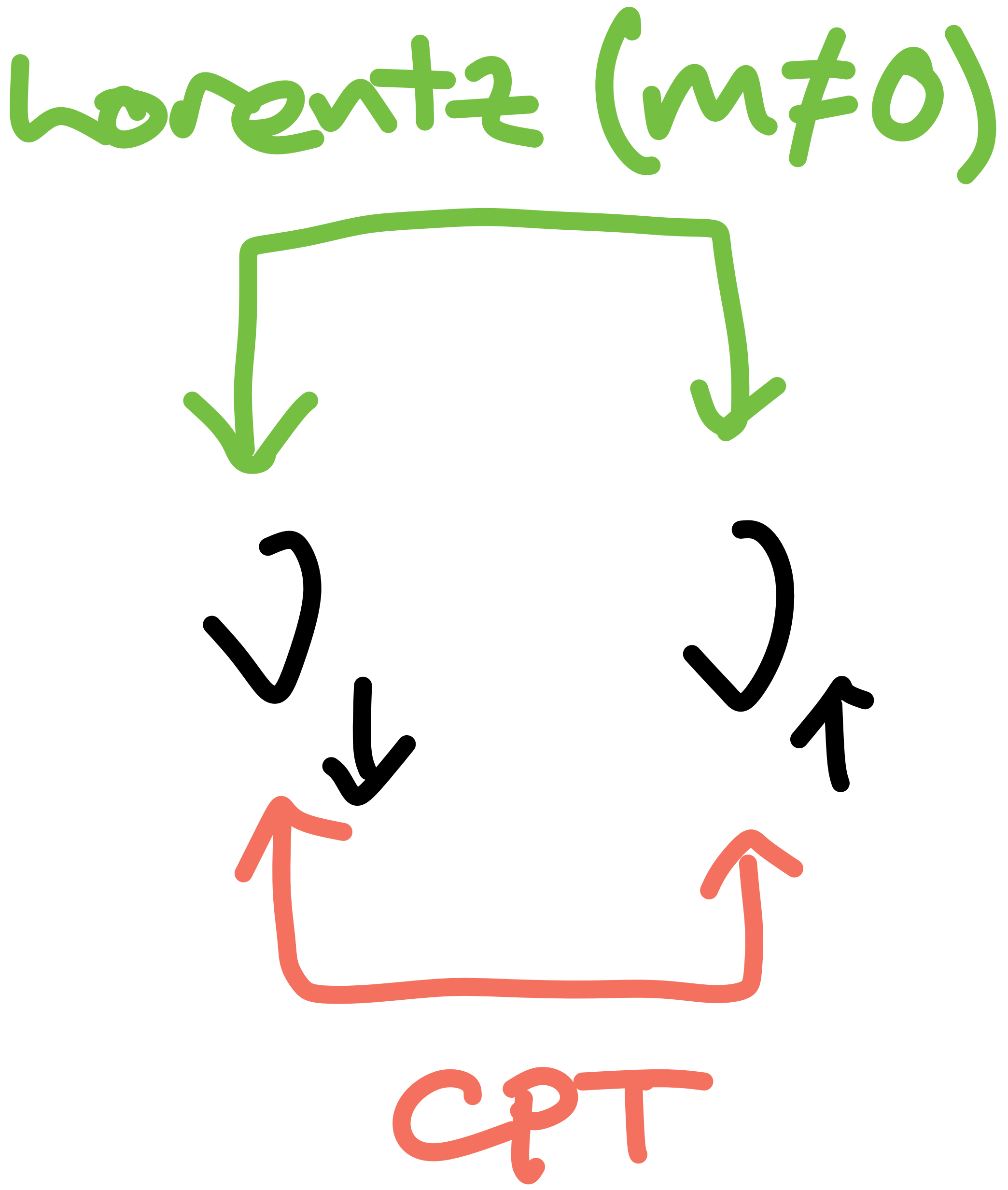
Dirac

4 states

Pair of degenerate Weyl spinors

Degeneracy enforced by $\mathrm{U}(1)$

$\nu \rightarrow e^{i\theta}\nu,\ \bar{\nu} \rightarrow e^{-i\theta}\bar{\nu}$



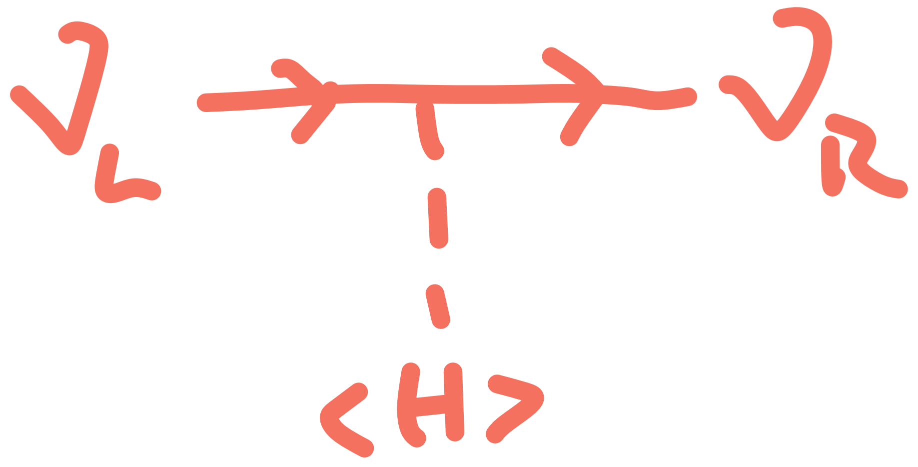
Majorana

2 states

Single Weyl spinor

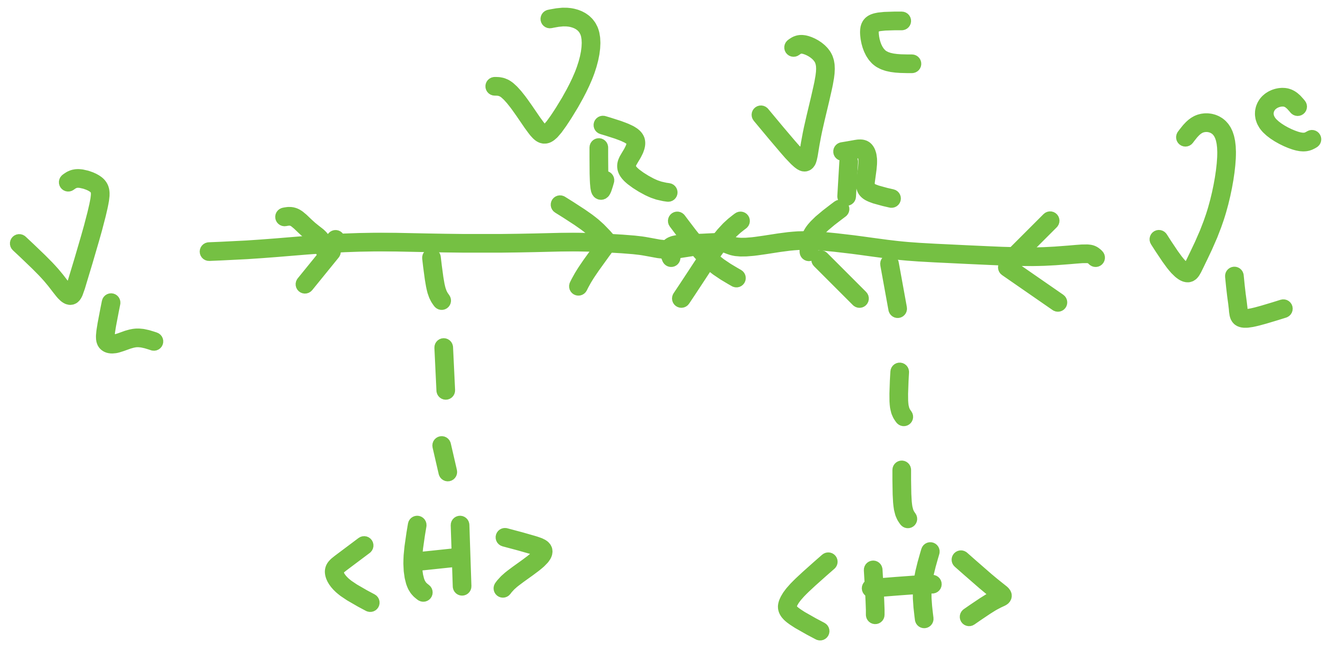
[Kayser ('84)]

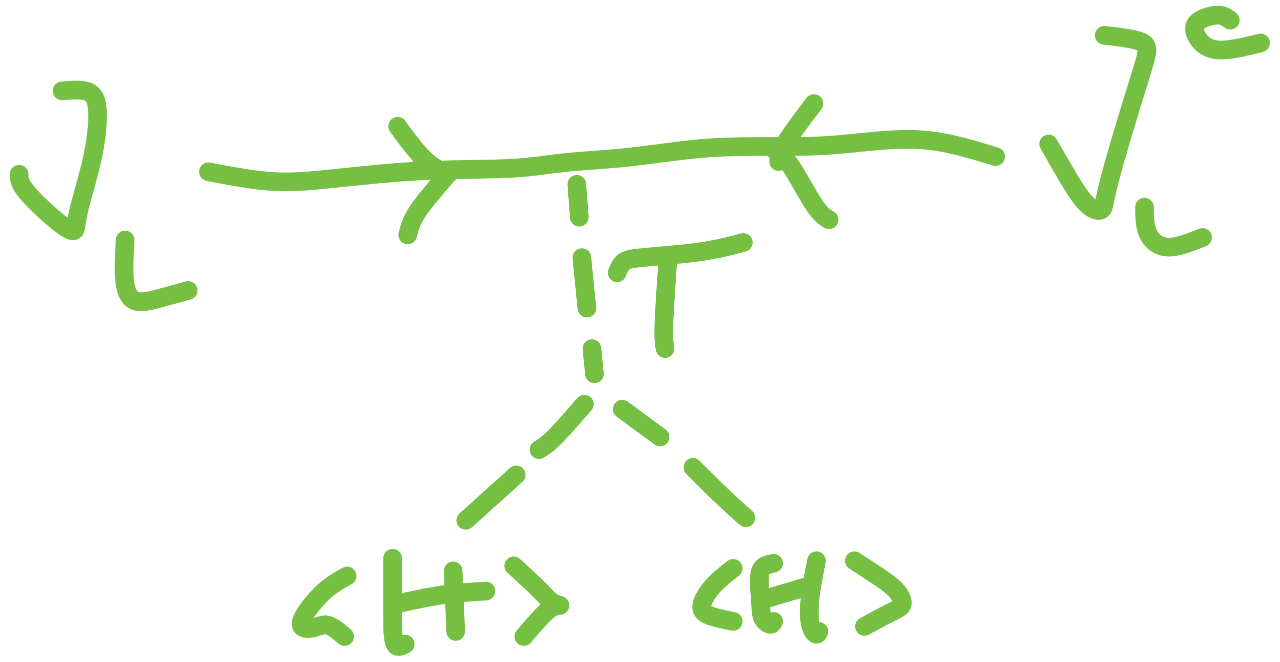
Neutrino masses: Dirac or Majorana?



$$-\mathscr{L} \supset \underbrace{m\bar{\nu}_R \nu_L}_{\Delta L = 0} + \text{h.c.}$$

Dirac
4 states





$$-\mathscr{L} \supset \underbrace{m\bar{\nu}_L^c \nu_L}_{\Delta L = 2} + \text{h.c.}$$

Majorana
2 states

Each option requires degrees of freedom not seen in SM
Neutrino masses are **qualitatively different**

Lepton number

Lepton number is an accidental symmetry of the renormalizable standard model
(it is a consequence of choice of gauge group and charges)

Individual lepton numbers L_e, L_μ, L_τ violated in neutrino oscillation experiments
[similar story for quarks—only total baryon number (accidentally) conserved]

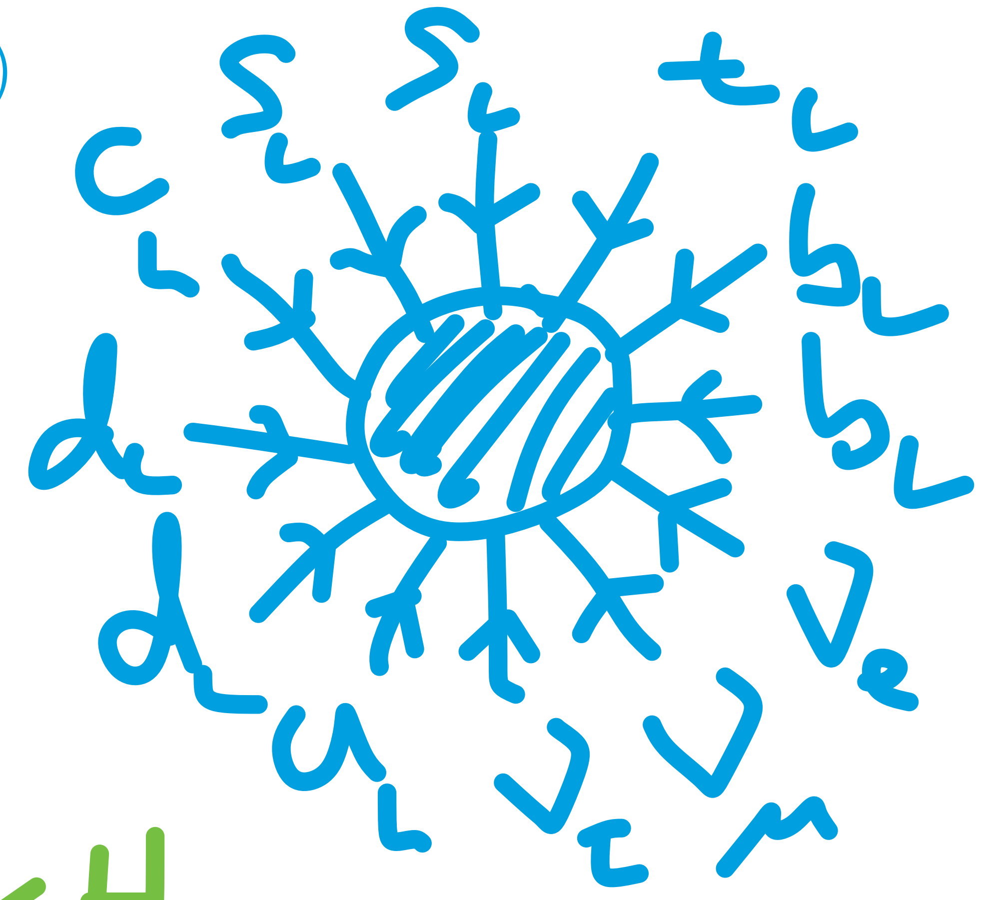
Lepton number is a global symmetry⇒no gauge field associated with it

Should we expect lepton number to be conserved?

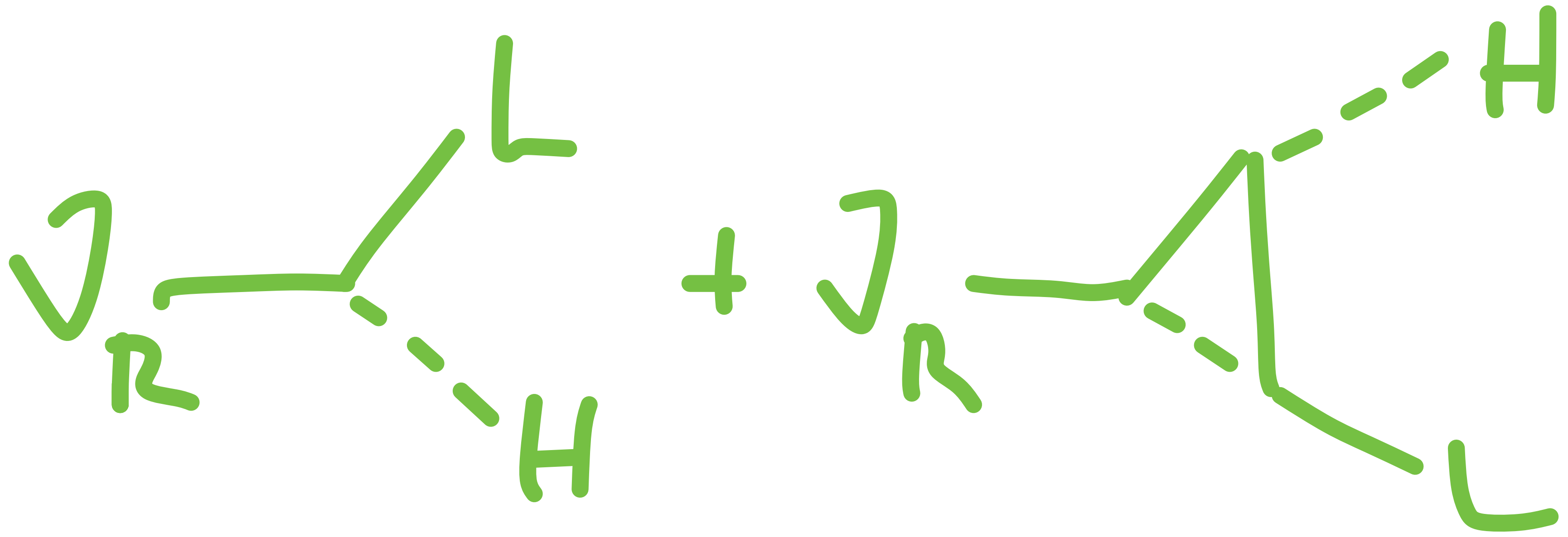
Lepton number violation

(Kuzmin, Rubakov, Shaposhnikov)

Lepton number is violated by the standard model nonperturbatively ($B - L$ conserved)



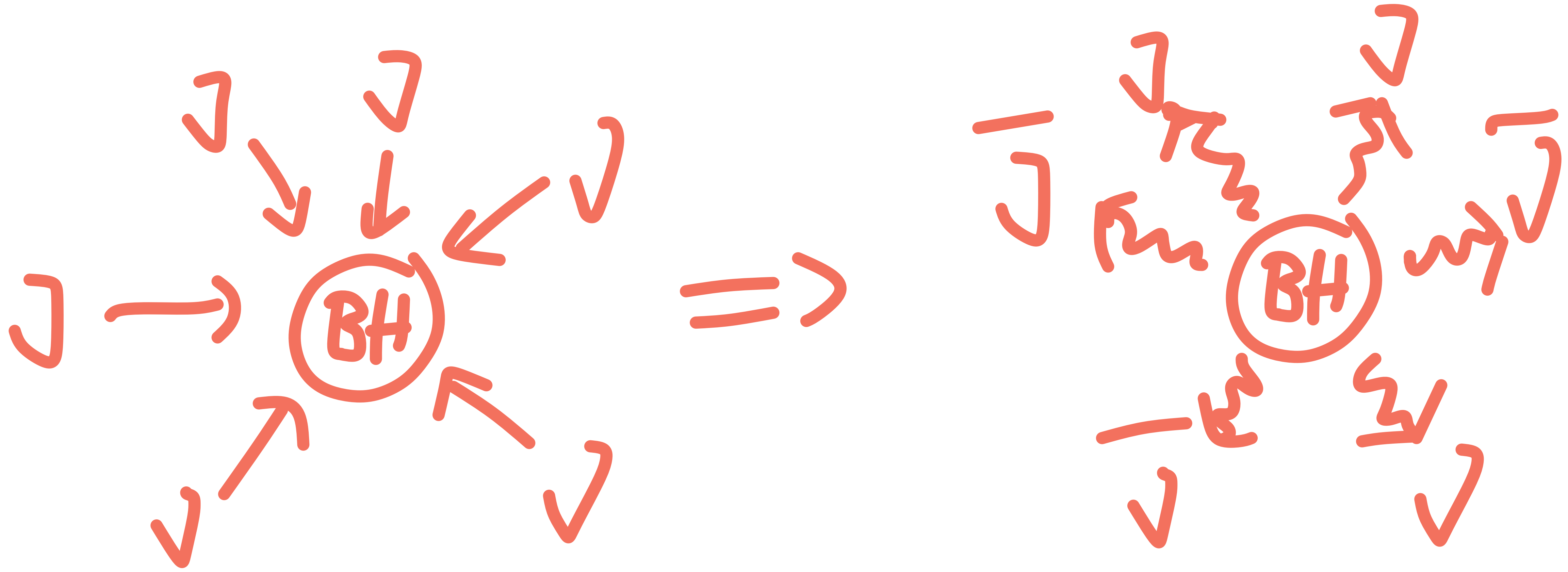
and at dim-5 $(HL)^2$ [Weinberg]



(Fukugita, Yanagida)

Lepton number violation could be intimately related to the baryon asymmetry of the universe

Gravity does not respect global symmetries



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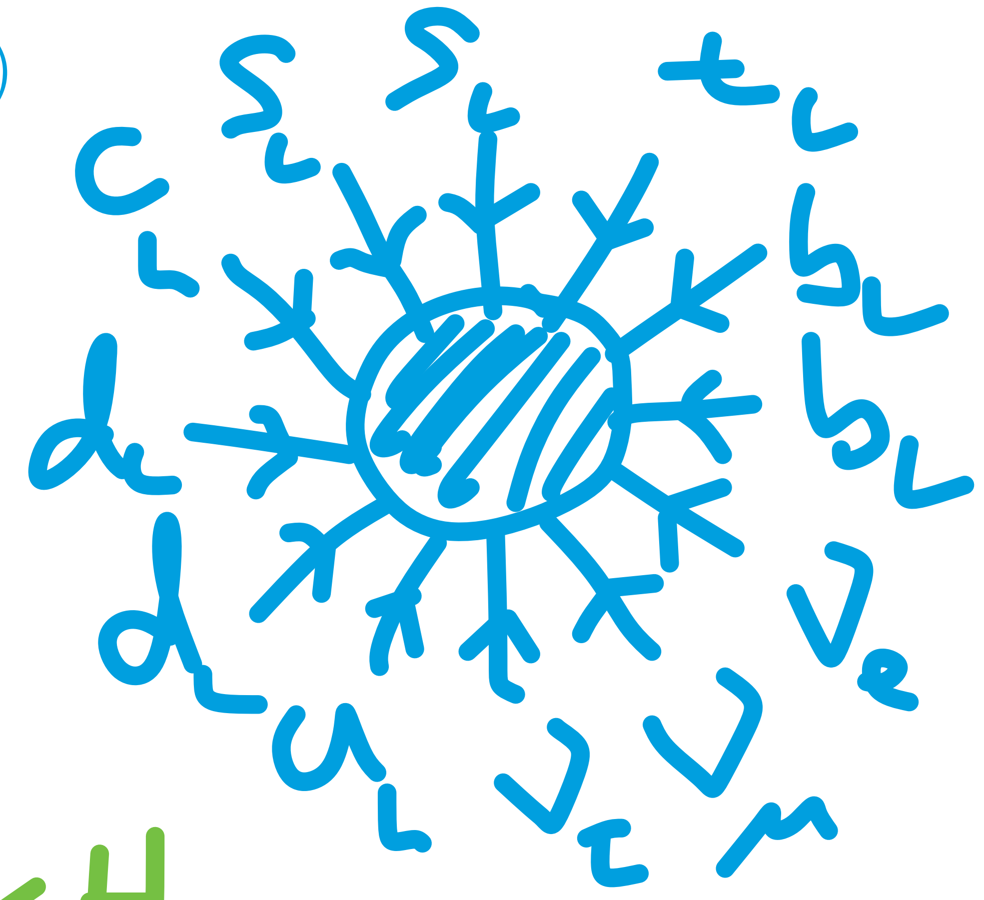

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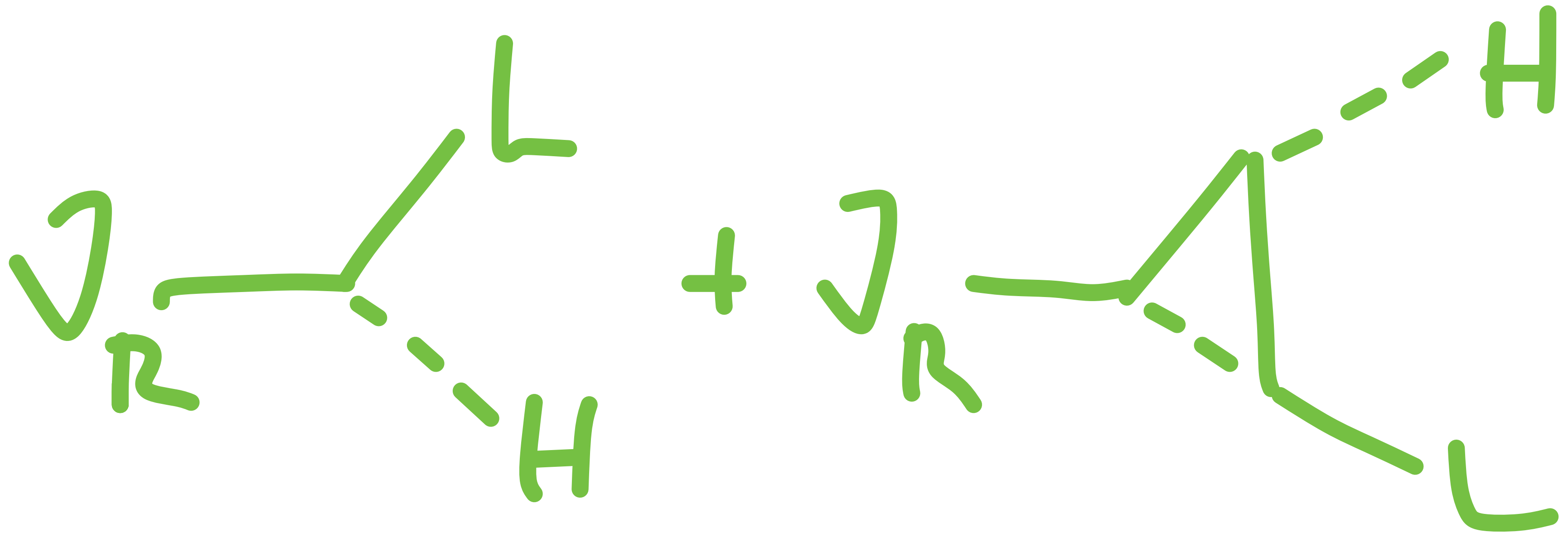
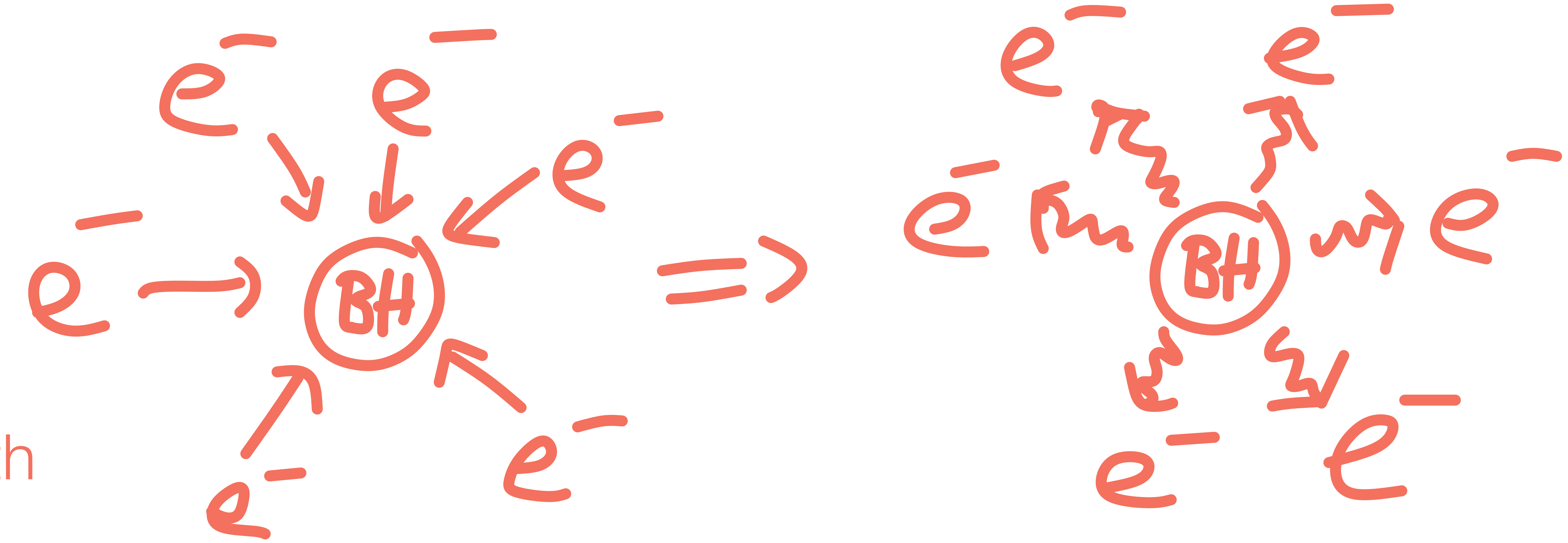


(Fukugita, Yanagida)

Lepton number violation could be intimately related to the baryon asymmetry of the universe

Gravity does not respect global symmetries

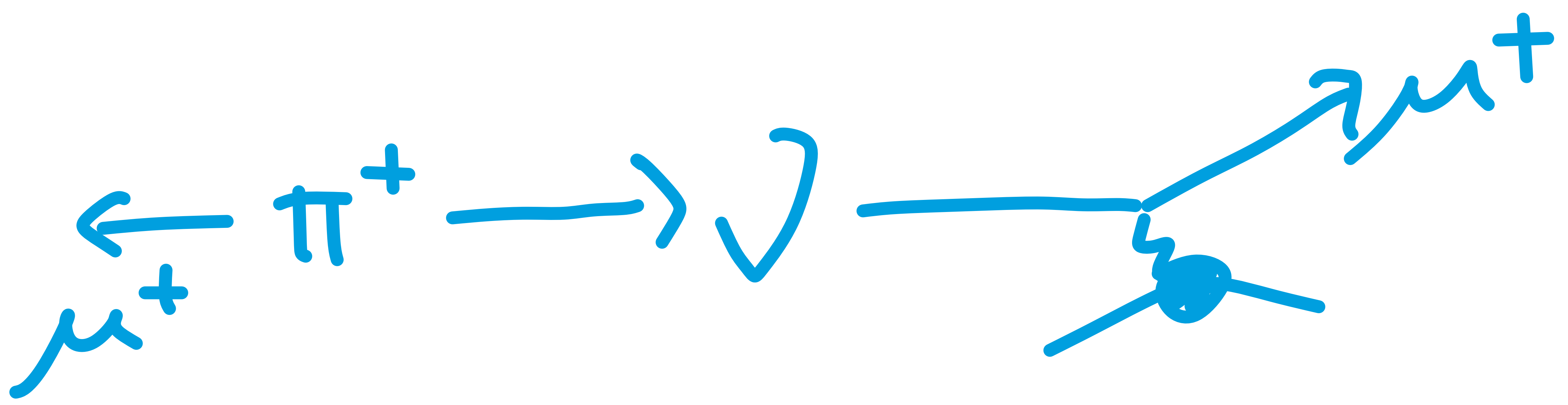
Contrast with



How to find lepton number violation

How would a particle theorist do it? Kayser: use $\pi^+ \to \mu^+ \nu$ to create ν beam.

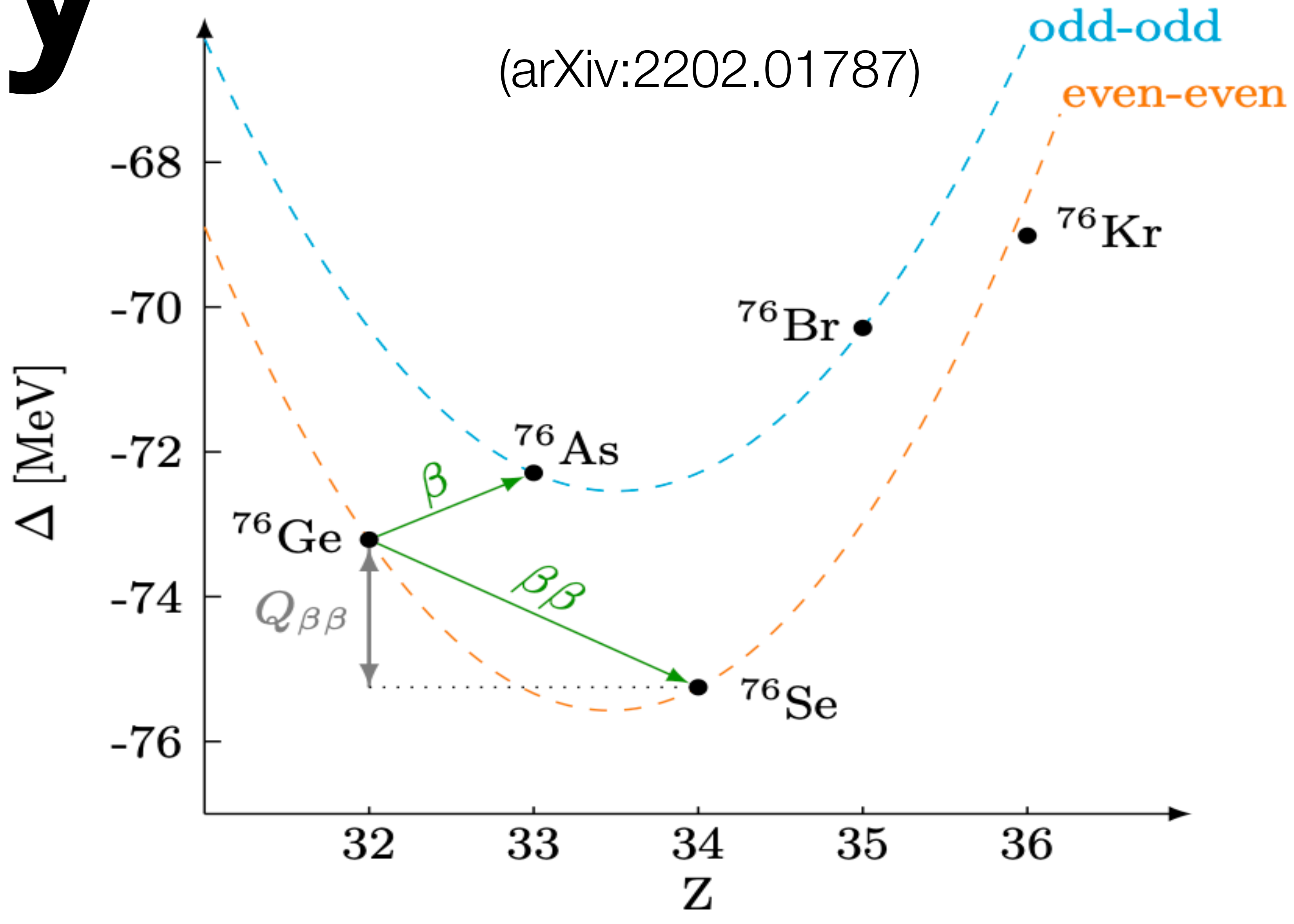
Check if this beam creates μ^+ in scattering on target



Problem: need helicity flip, rate $\propto \left(\frac{m_\nu}{100\ \mathrm{MeV}}\right)^2 \sim 10^{-16}$

Solution: use nuclei and let Avogadro help!

$\beta\beta$ decay



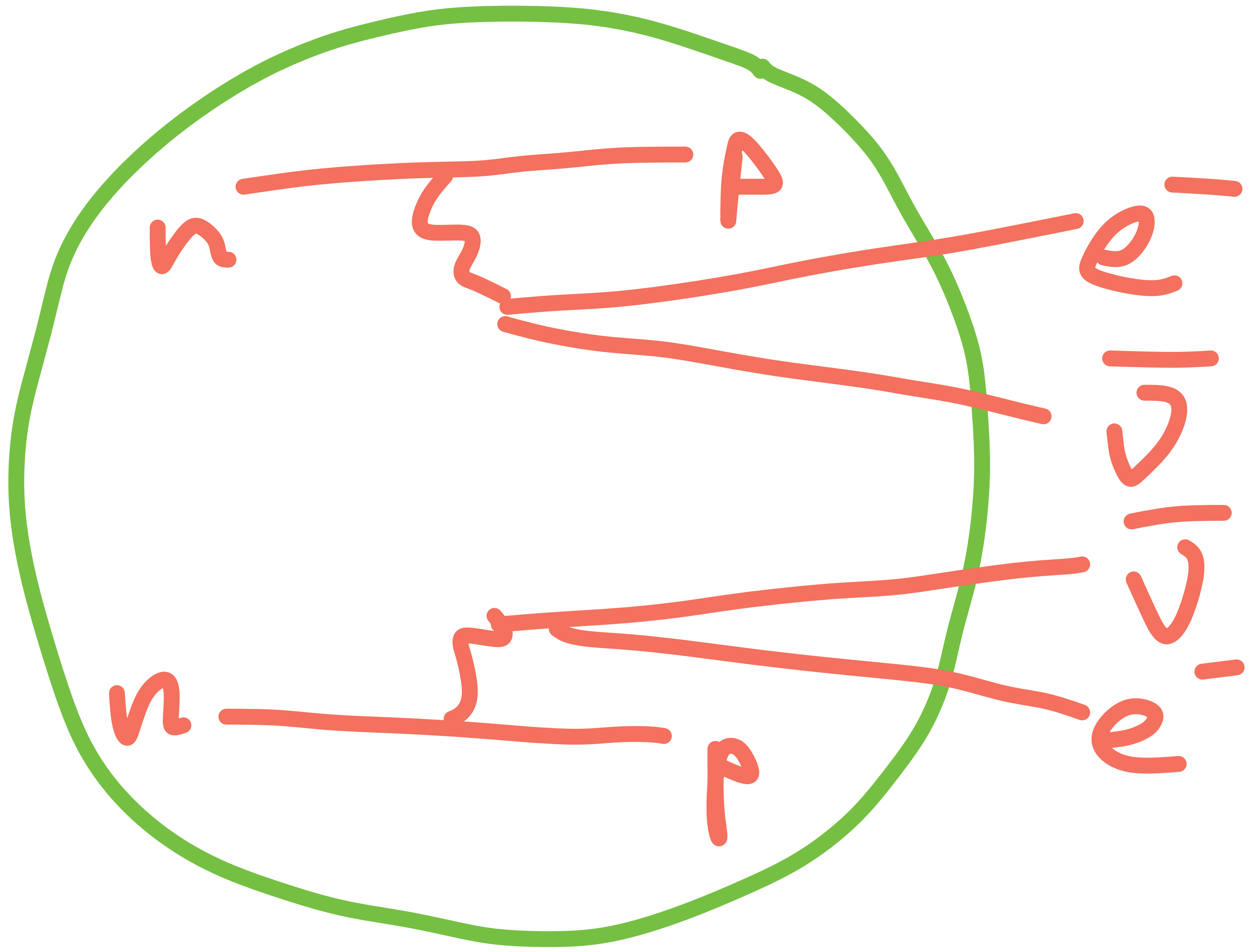
Some even-even nuclei are energetically forbidden from β decay (or it is highly suppressed), have to undergo $\beta\beta$ decay

SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

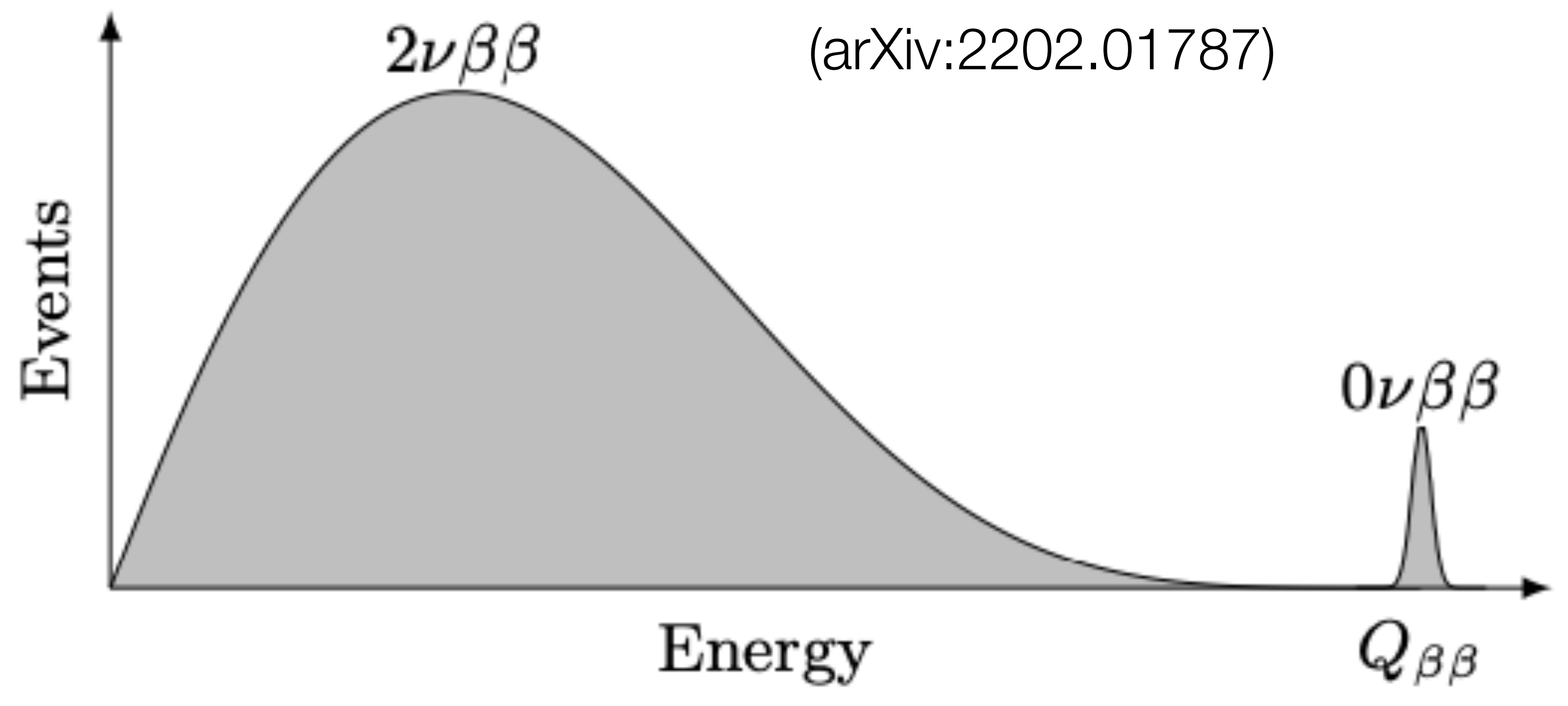
M. Goeppert-Mayer, *The Johns Hopkins University*
(Received May 20, 1935)

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

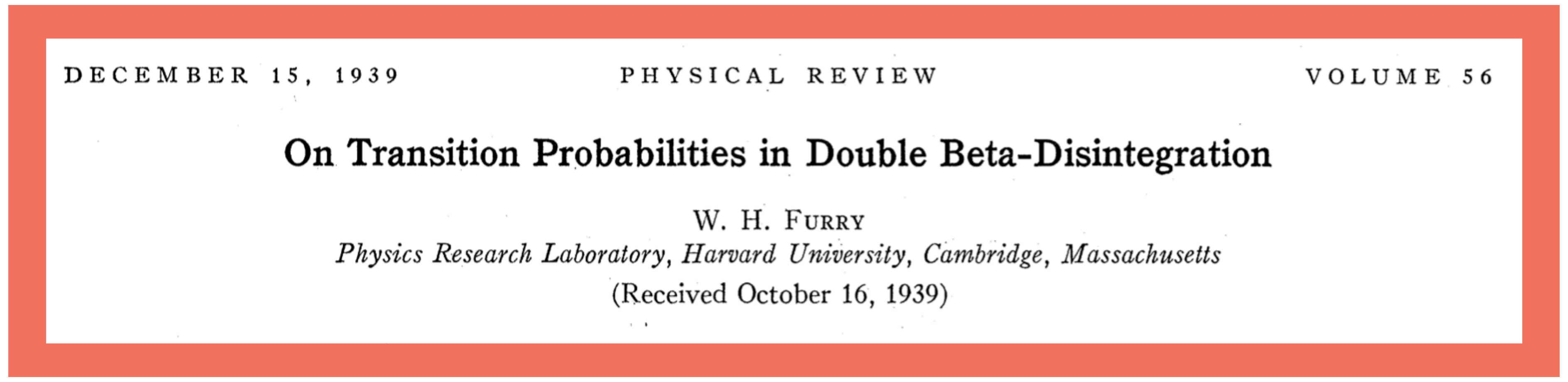


$0\nu\beta\beta$ decay

If lepton number is violated can also have process with no neutrinos emitted



(arXiv:2202.01787)

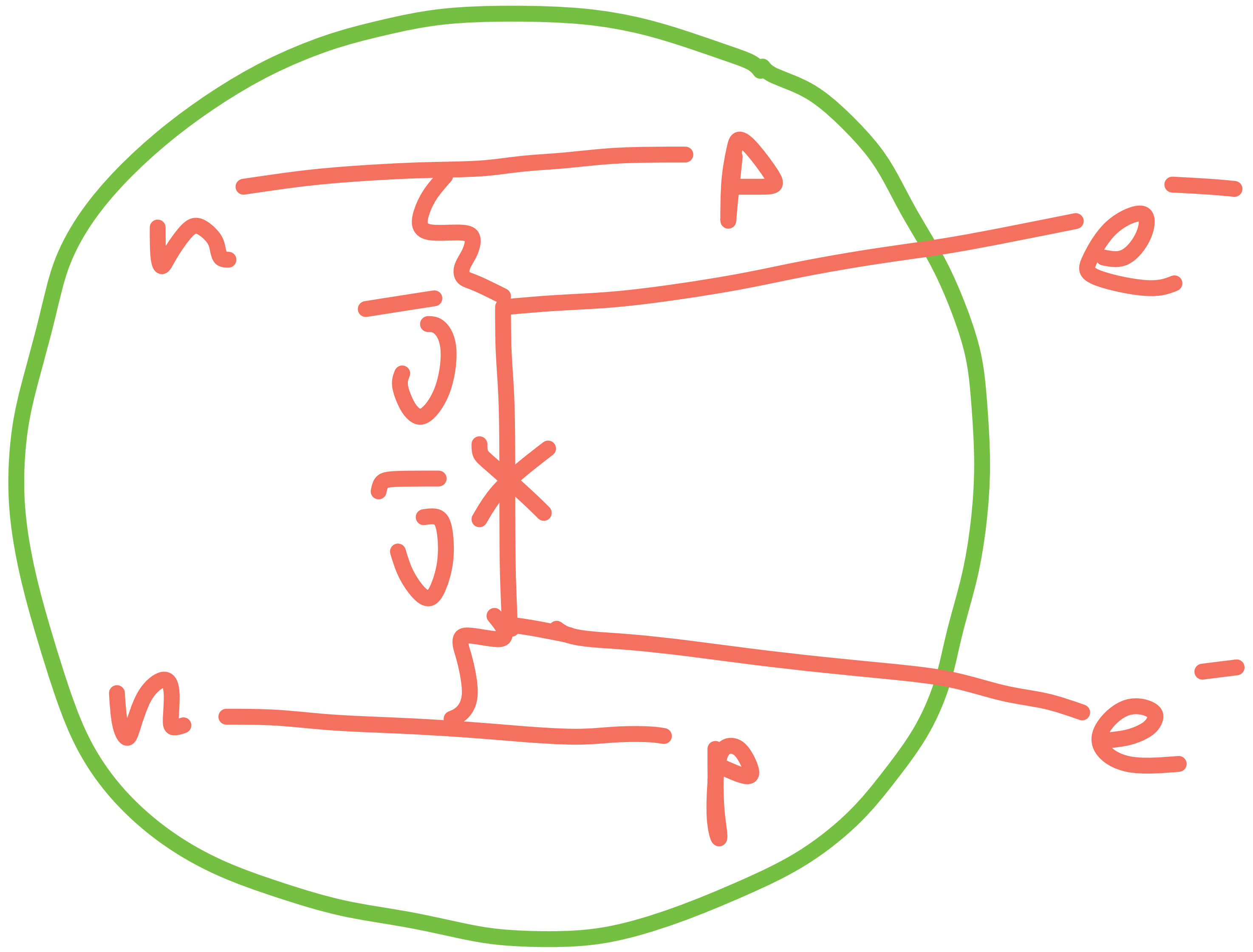


DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

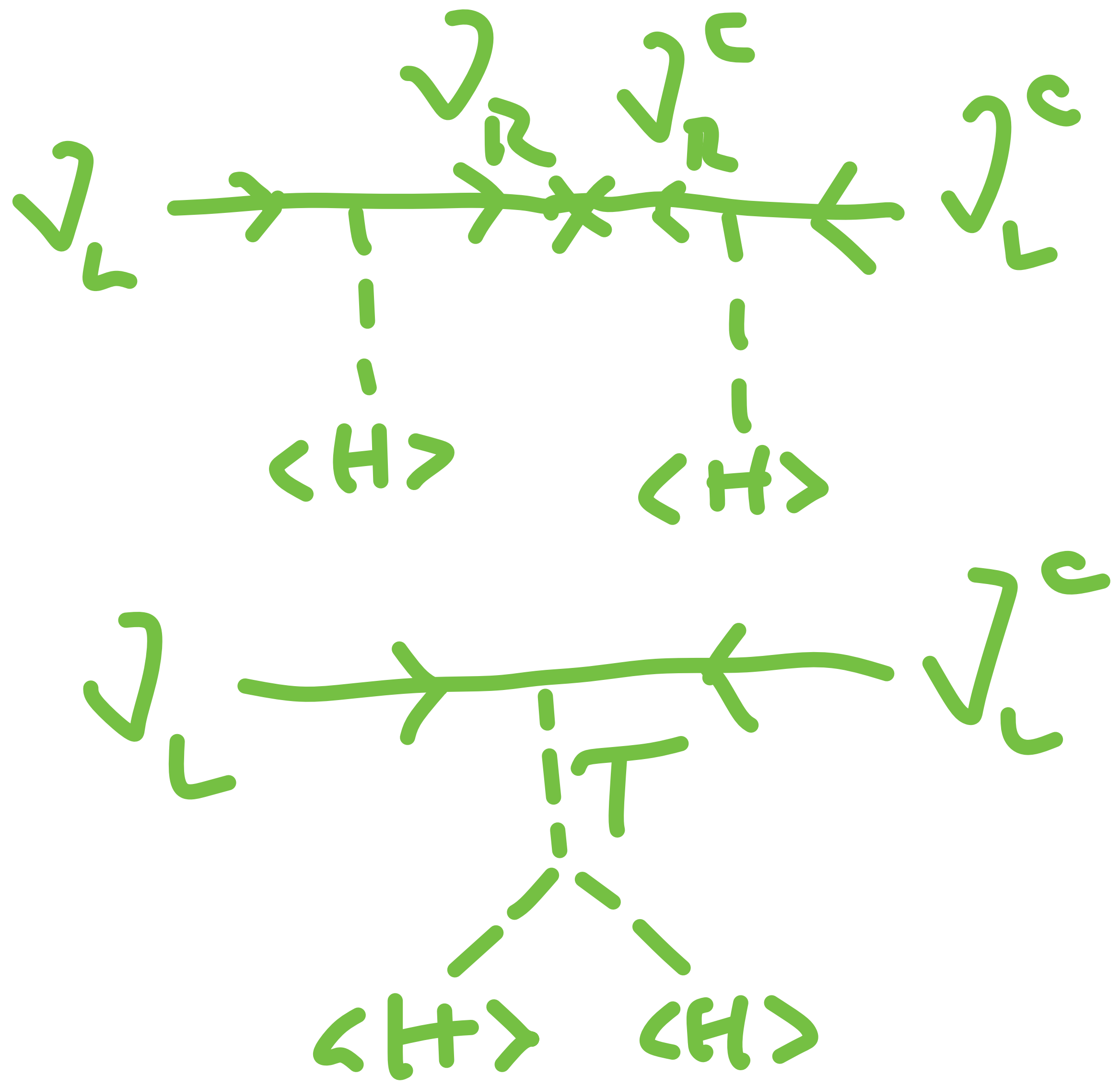
On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 16, 1939)



High-scale seesaw



$$-\mathscr{L} \supset m\bar{\nu}_L^c \nu_L + \mathrm{h.c.}$$

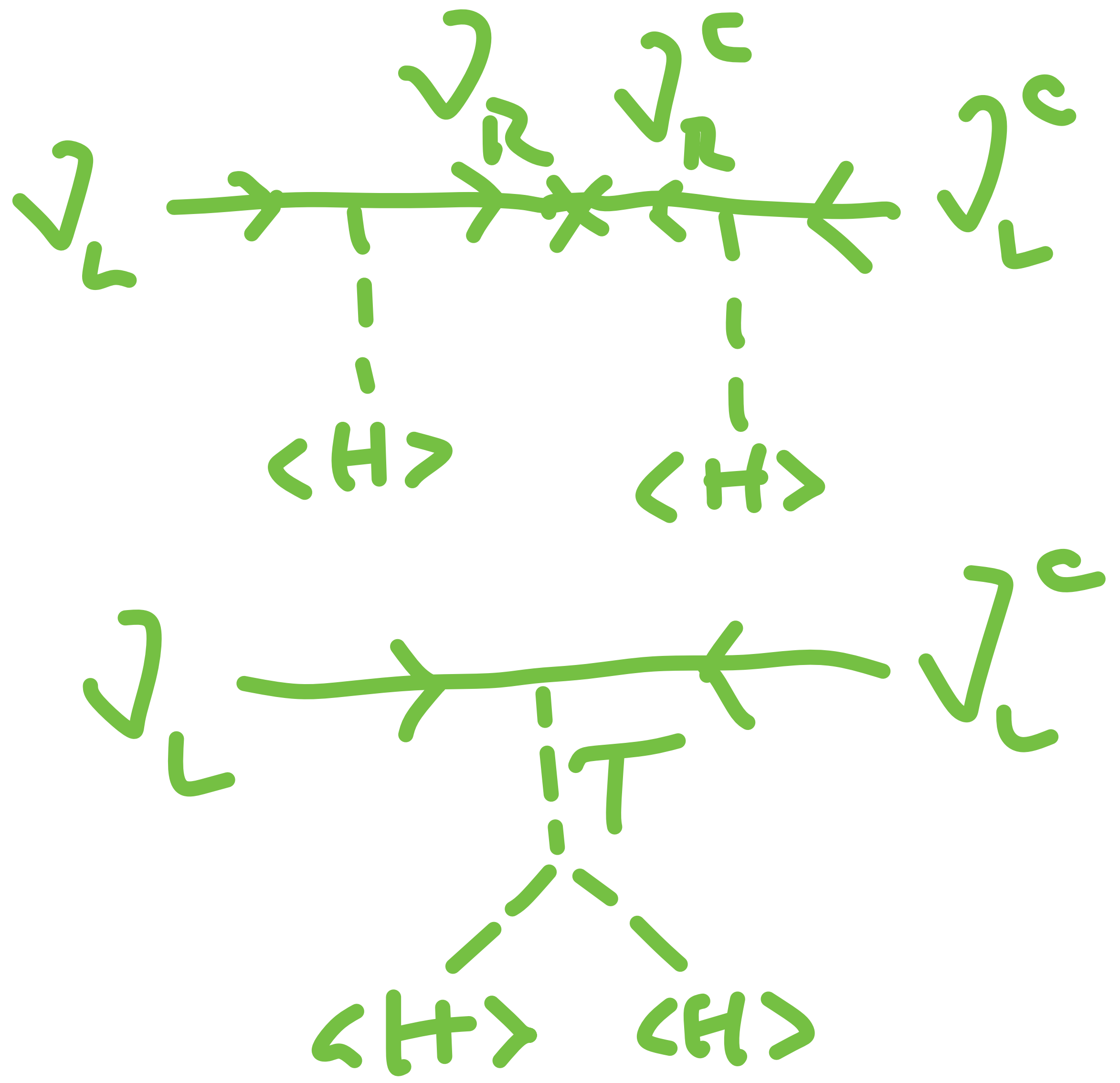
ΔL = 2

Neutrino mass comes from coupling to heavy SM singlets

(can explain smallness of ν masses, $m \sim \frac{y^2 \langle H \rangle^2}{M}$, another reason to expect LNV)

Key prediction of leptogenesis as an explanation of baryon asymmetry of the universe

High-scale seesaw



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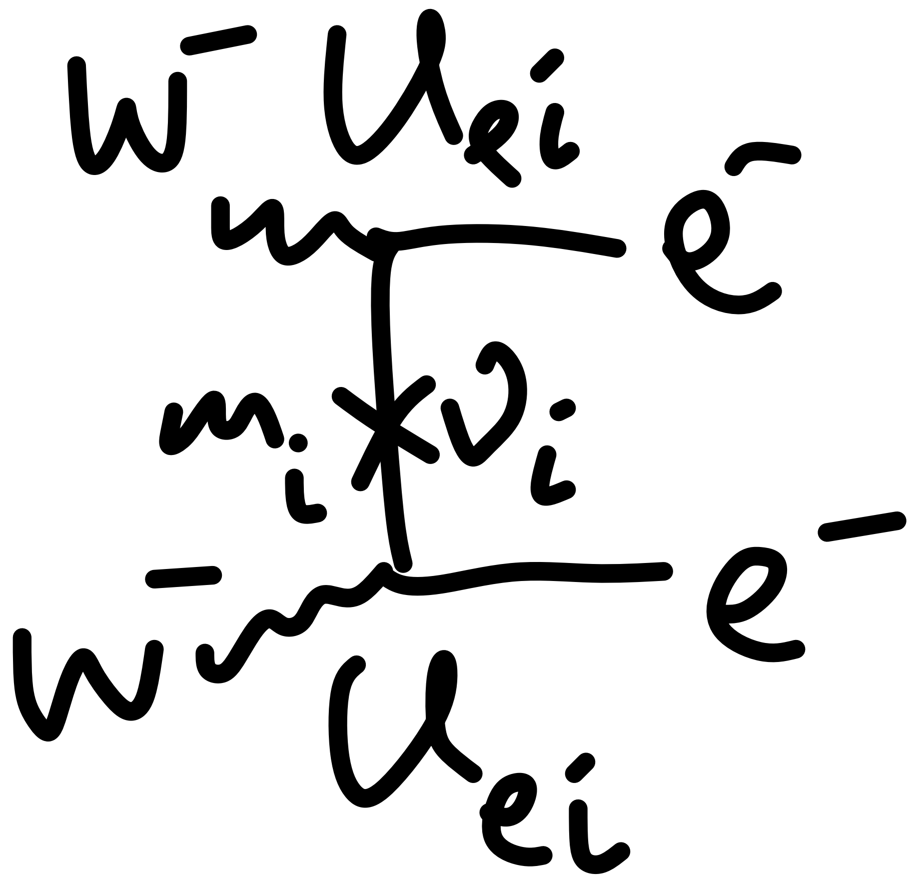
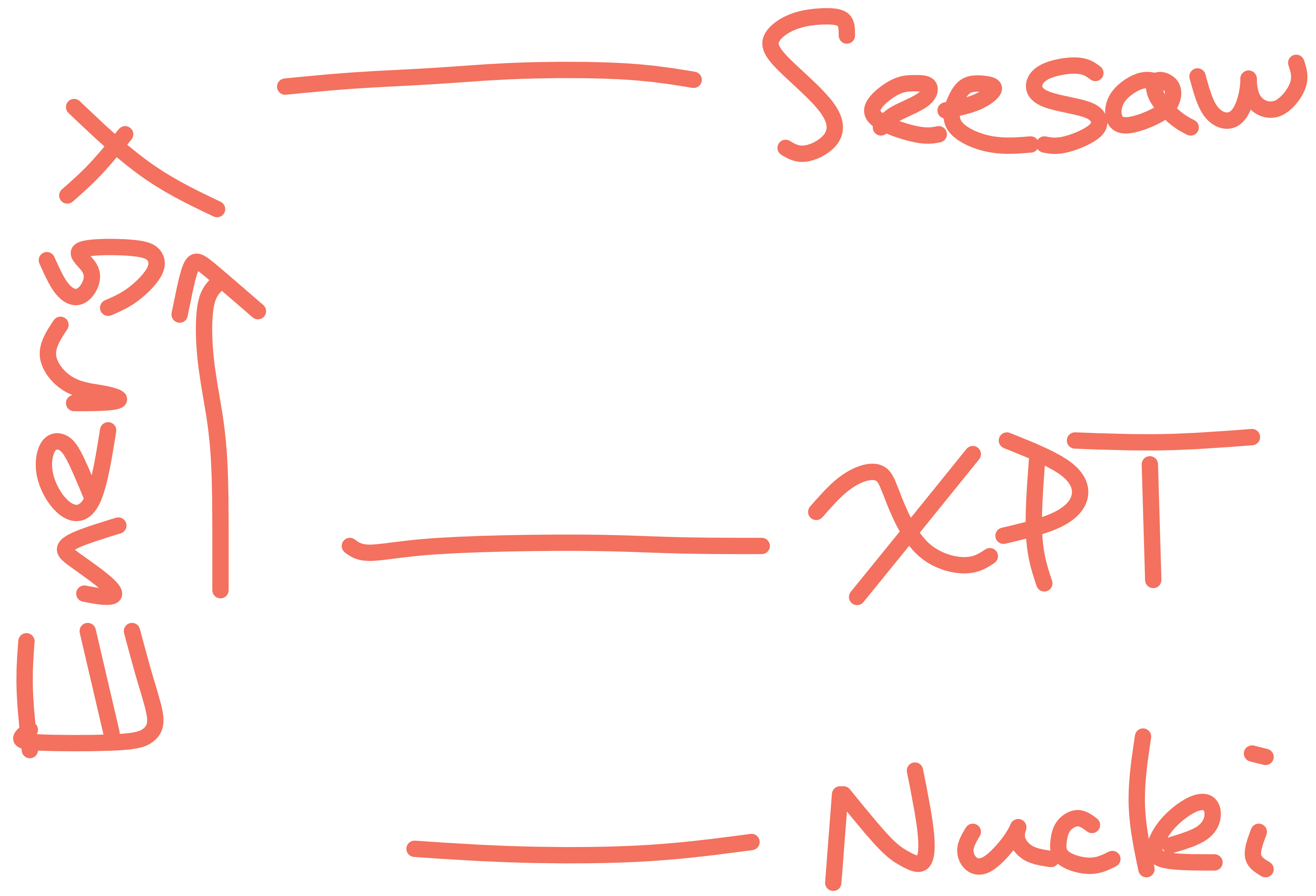
Neutrino mass comes from coupling to heavy SM singlets (can explain smallness of ν masses, another reason to expect LNV)

Short-distance LNV physics

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

and matched onto successively longer scales

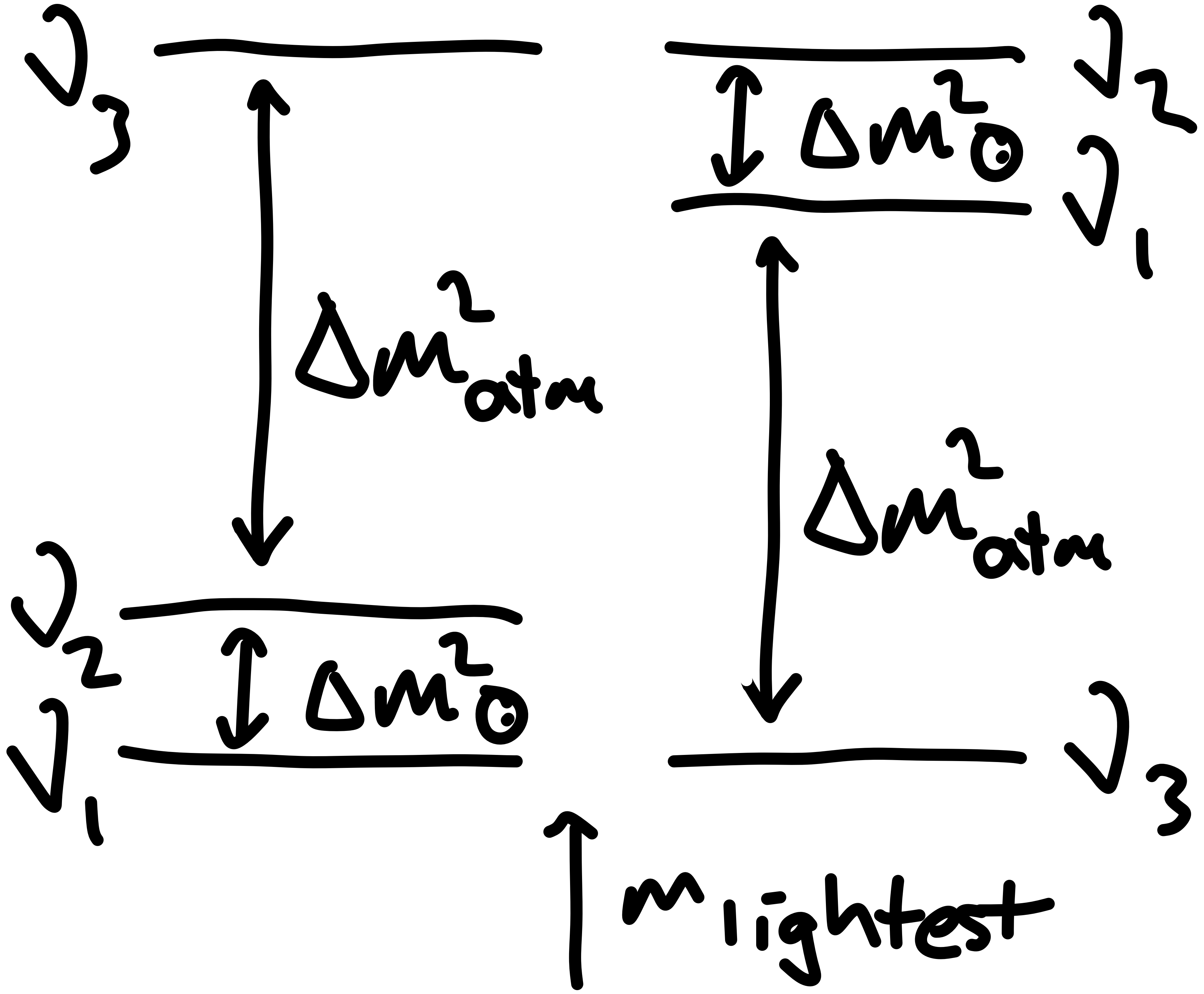




High-scale seesaw

At low energies only remnants are Majorana ν masses

$m_{\beta\beta}$ can be related to lightest ν mass, depends on mass hierarchy, U_{PMNS}



[NuFit 5.2]

$$|U|_{3\sigma}^{\text{with SK-atm}} = \begin{pmatrix} 0.803 \to 0.845 & 0.514 \to 0.578 & 0.143 \to 0.155 \\ 0.244 \to 0.498 & 0.502 \to 0.693 & 0.632 \to 0.768 \\ 0.272 \to 0.517 & 0.473 \to 0.672 & 0.623 \to 0.761 \end{pmatrix}$$

3 angles (known)
1+2 phases (unknown)

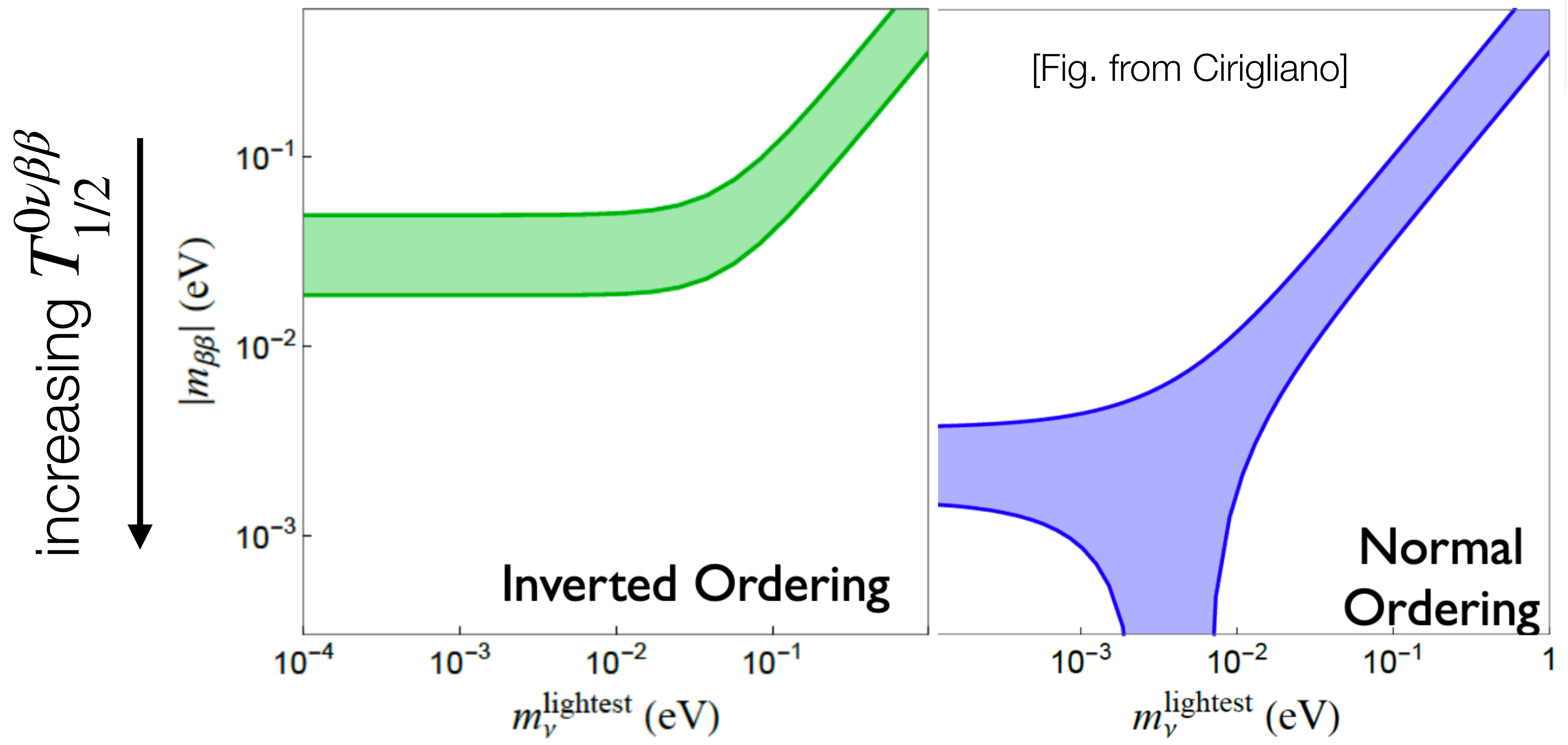
High-scale seesaw

At low energies only remnants are Majorana ν masses

$m_{\beta\beta}$ can be related to lightest ν mass, depends on mass hierarchy, U_{PMNS}

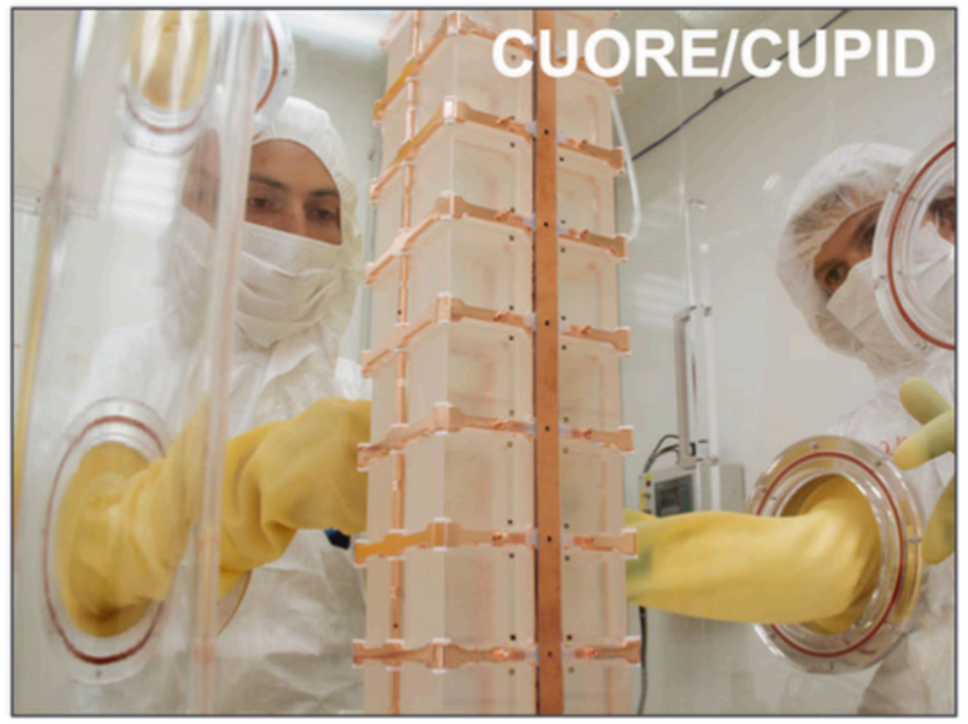
Half-life is related to $m_{\beta\beta}$:

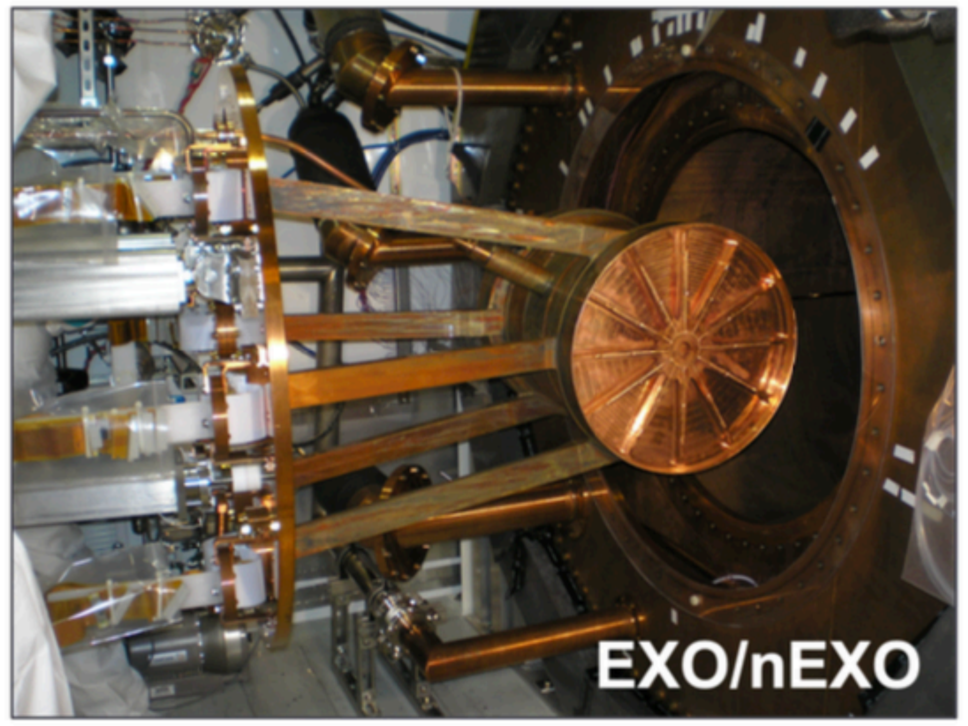
$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = m_{\beta\beta}^2 \times (\text{nuc . matrix element}) \times (\text{phase space})$$

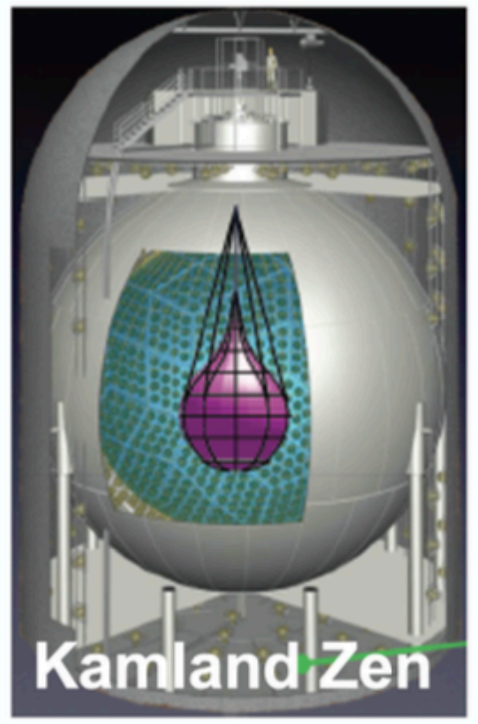


$0\nu\beta\beta$ decay searches are on!

Worldwide effort to search for $0\nu\beta\beta$ with a number of isotopes is underway







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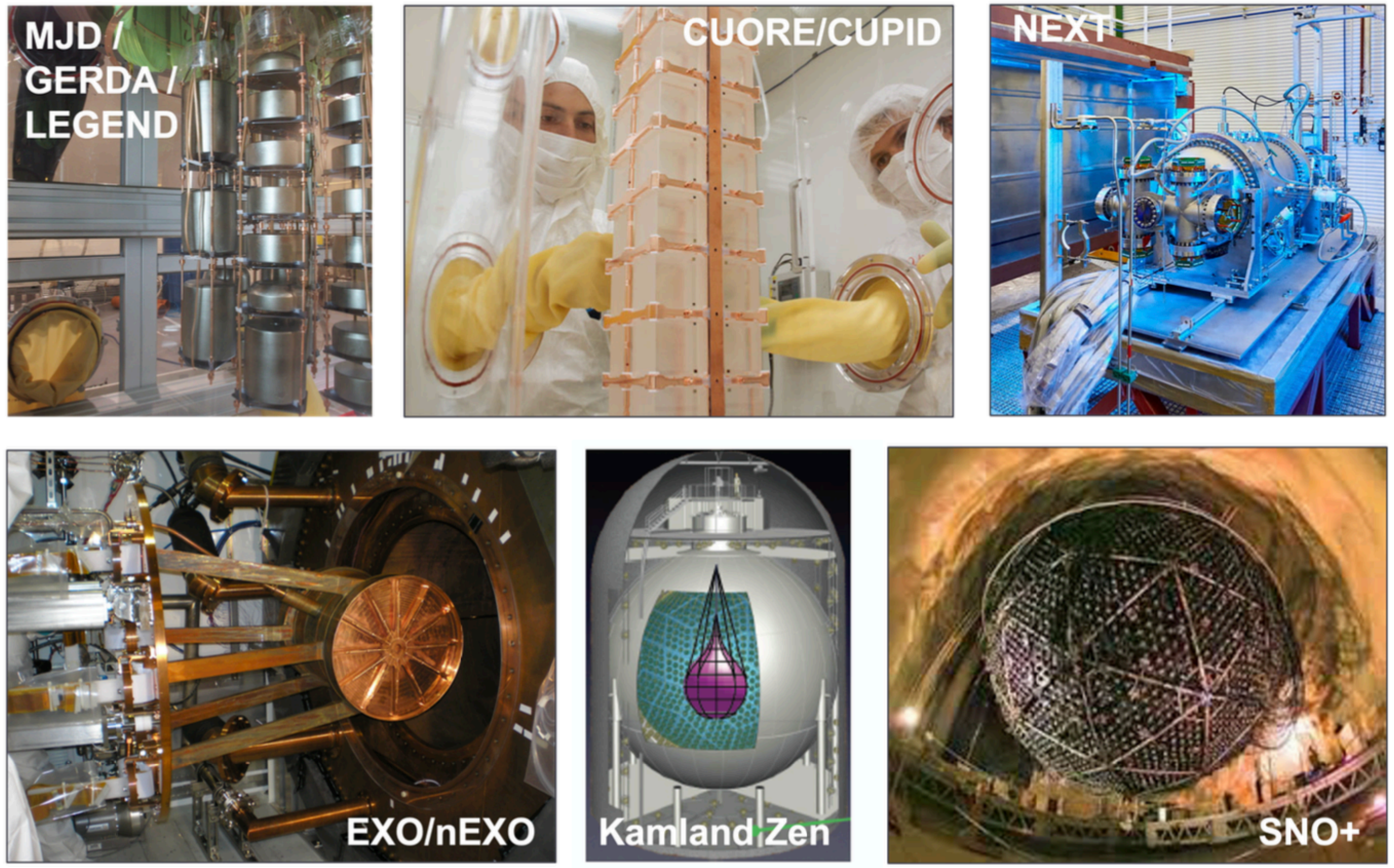


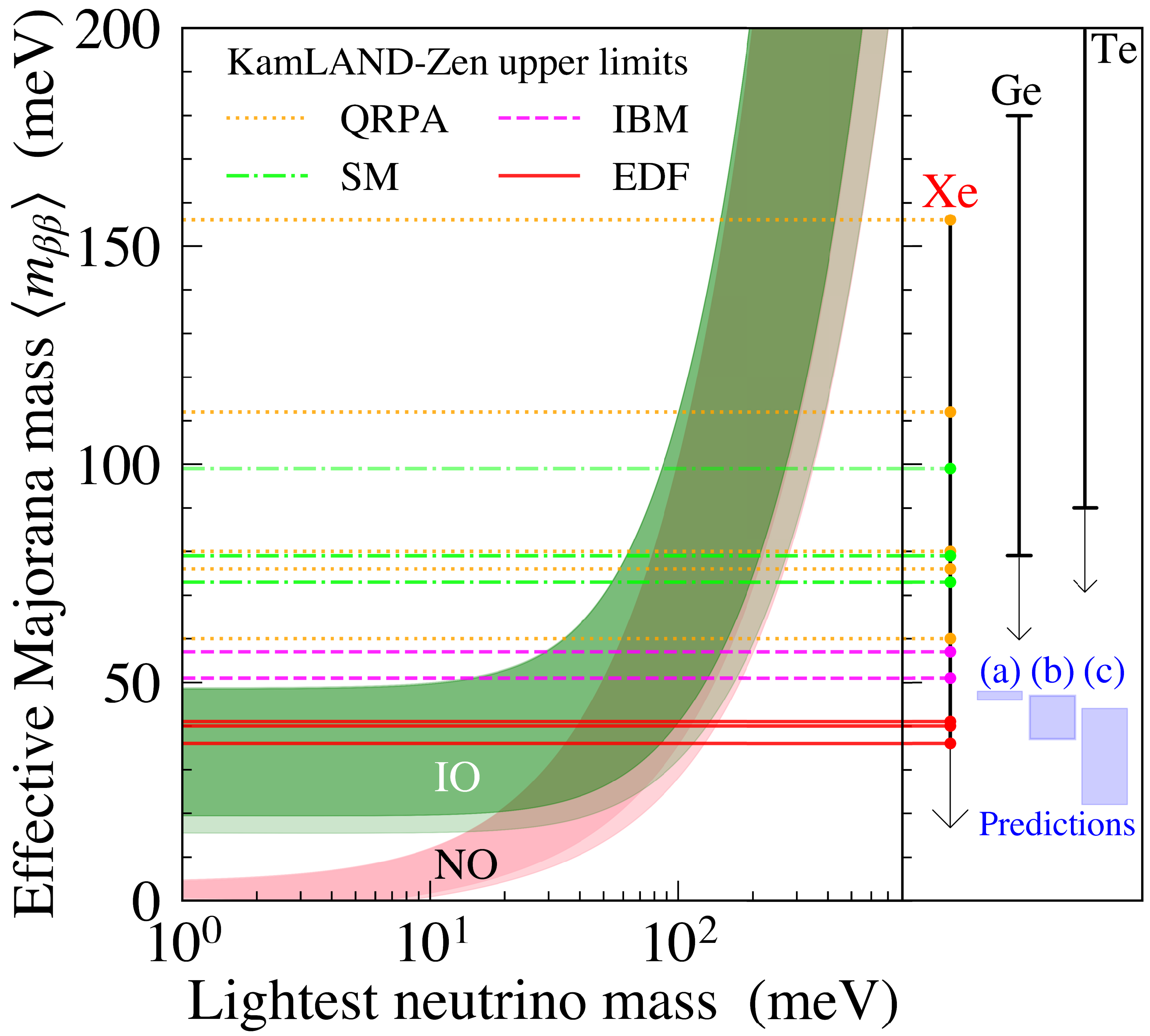
See excellent talks yesterday

$0\nu\beta\beta$ decay searches are on!

KamLAND-Zen

$T_{1/2}^{0\nu\beta\beta}(^{136}\mathrm{Xe}) > 2.6 \times 10^{26}$ yr

arXiv: 2203.02139

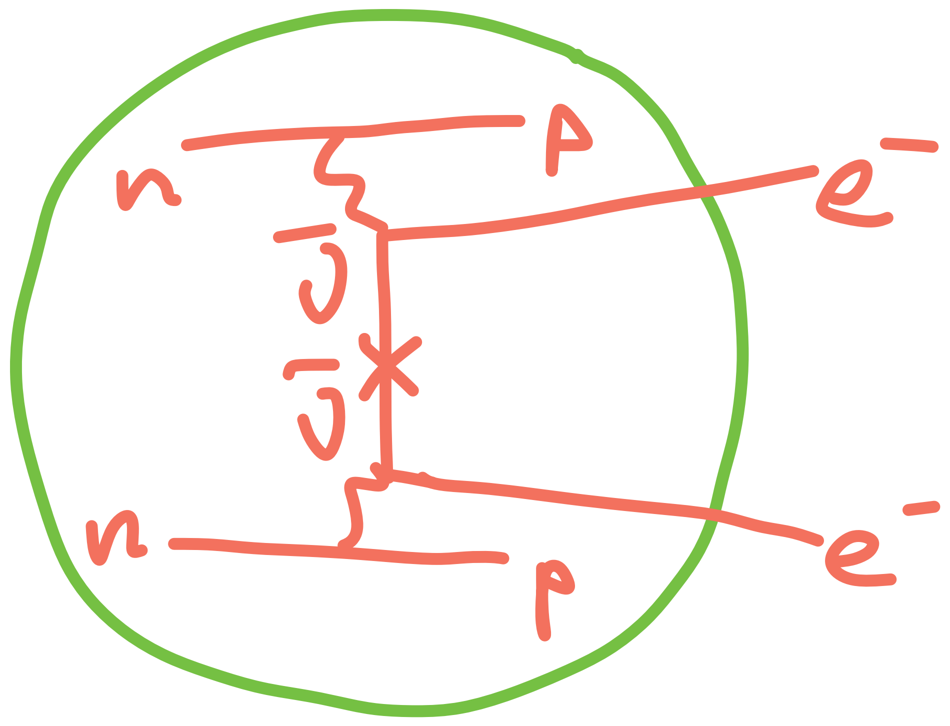


Nuclear matrix elements

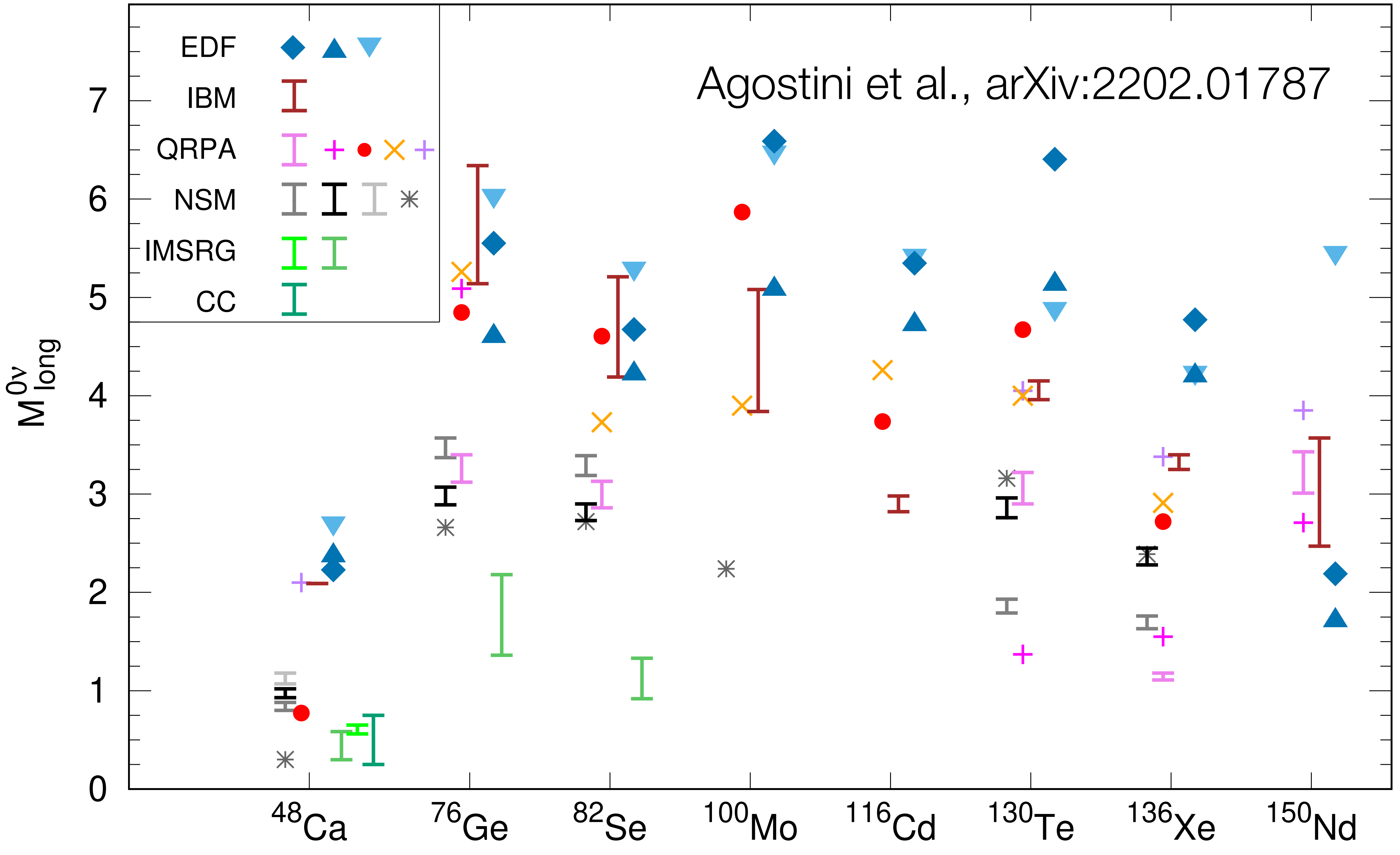
Half-life requires nuclear physics:

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = m_{\beta\beta}^2 \times (\text{nuc . matrix element}) \times (\text{phase space})$$

crucial for prediction



nuclear matrix elements
can vary between
different approaches



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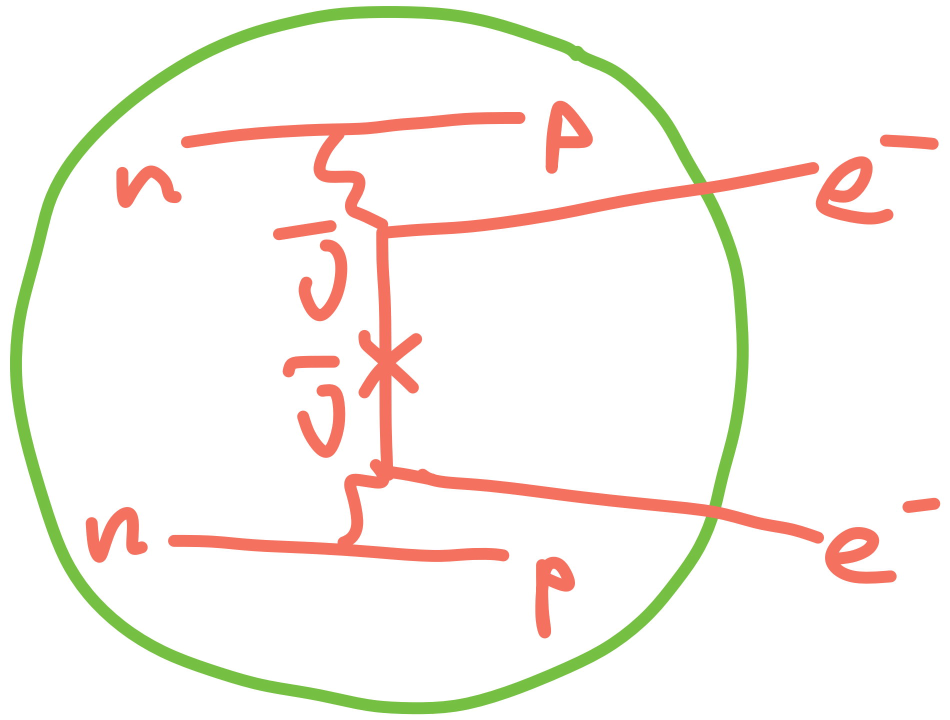
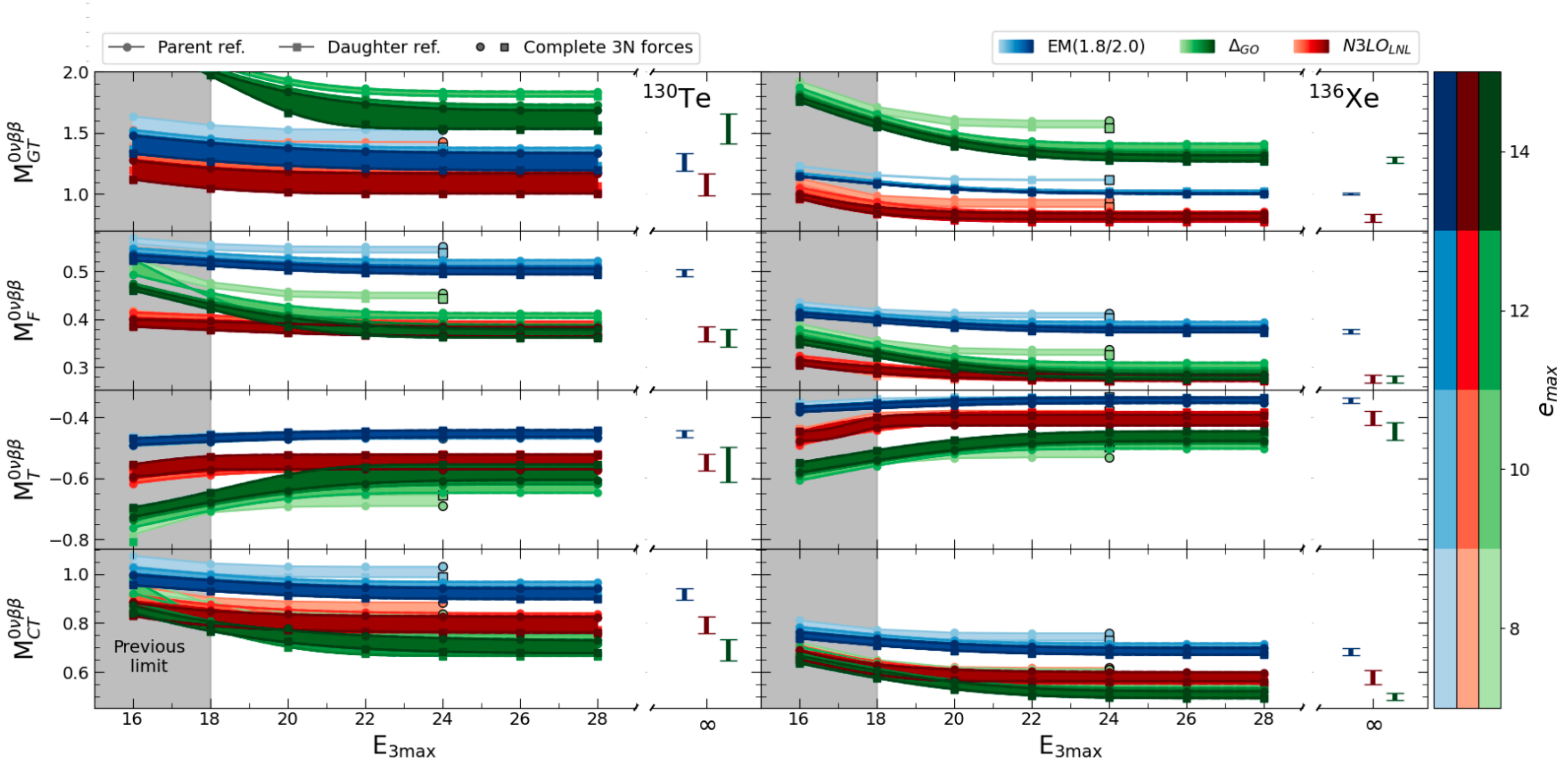
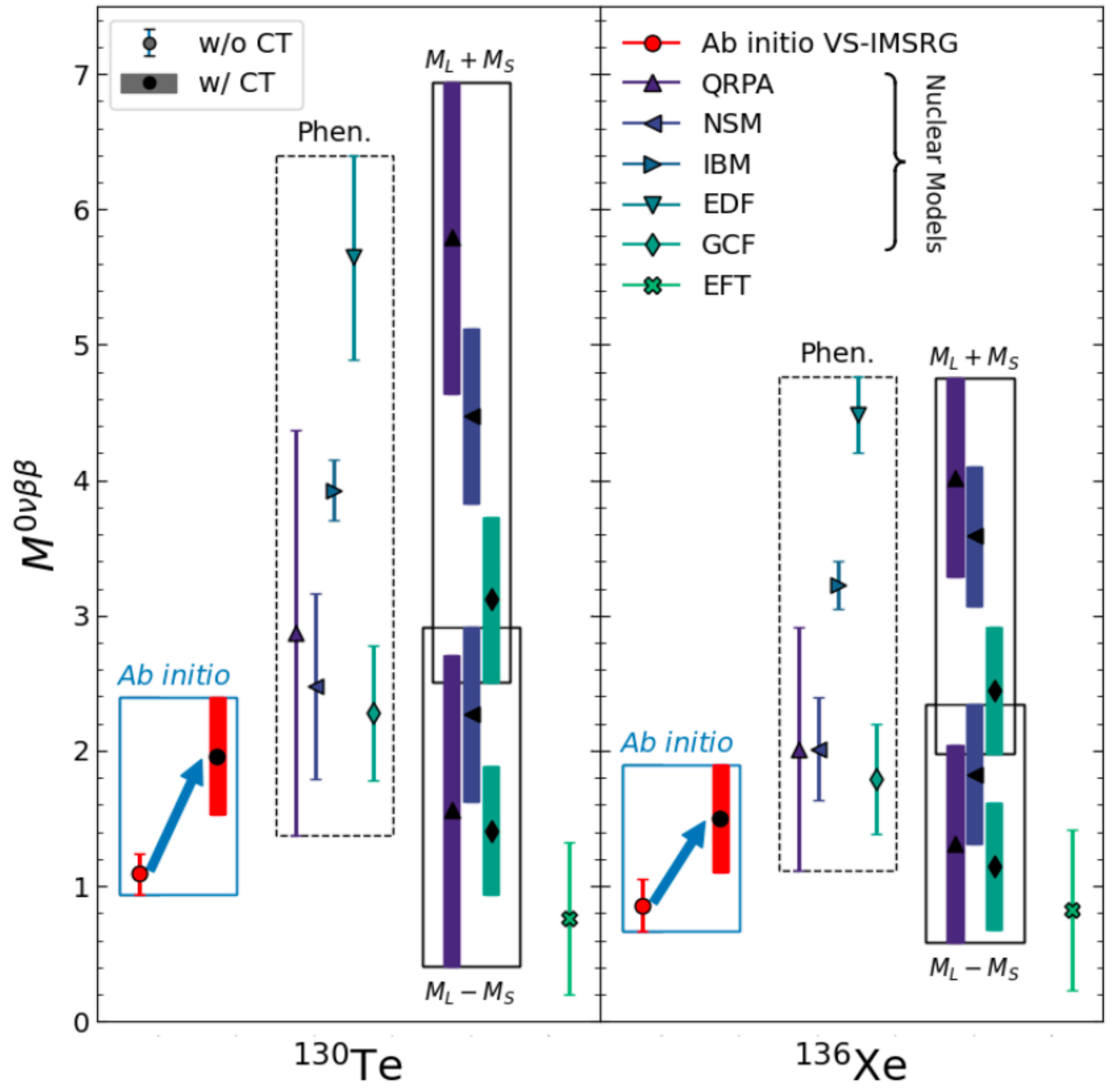


Lots of recent work on *ab initio* predictions of experimentally relevant matrix elements





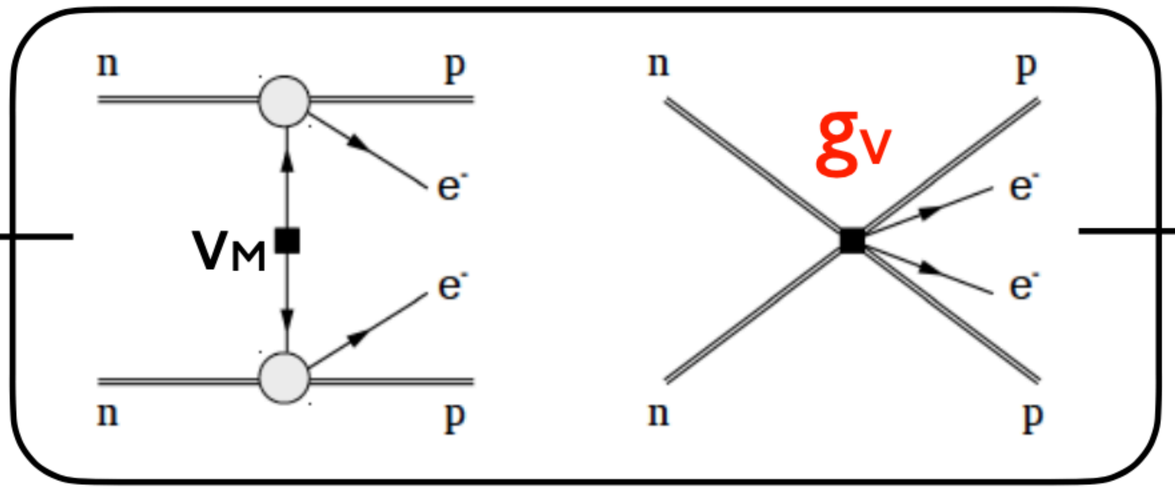
Belley, Miyagi, Stroberg, Holt, in prep.

Nuclear matrix elements

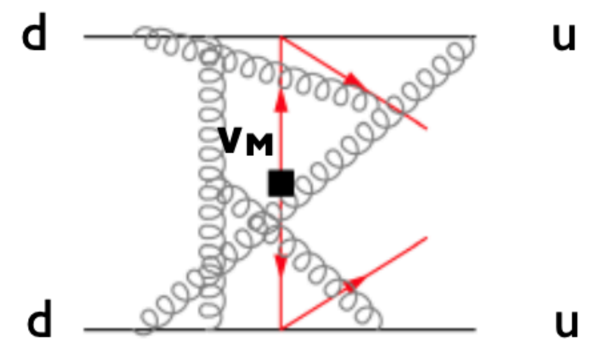
Cirigliano et al., 1802.10097

Additional complication in χPT— short distance contribution that is difficult to relate to data

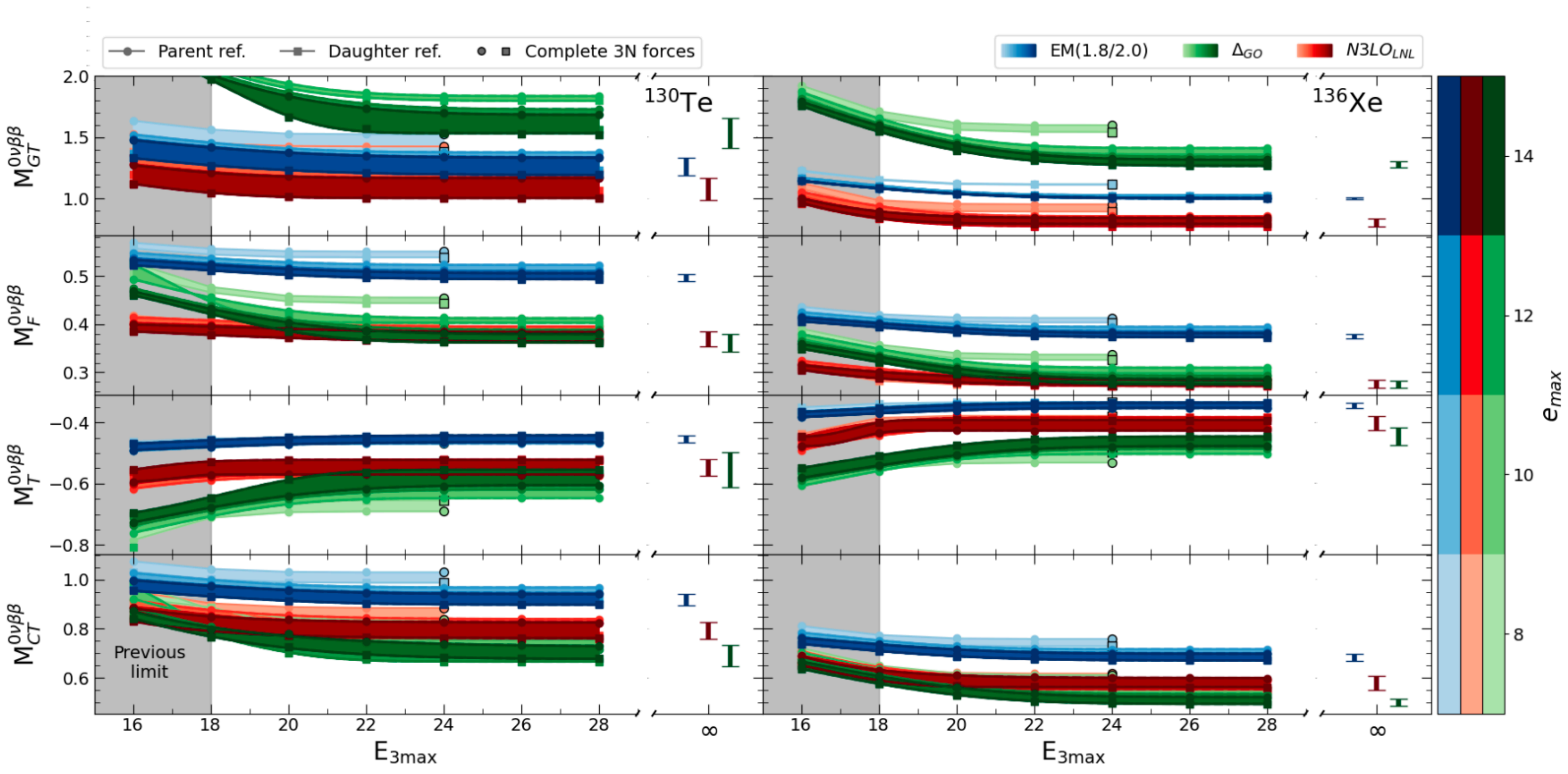
'Usual' v_M exchange $\sim 1/k_F^2 \sim 1/Q^2$ Coulomb-like potential

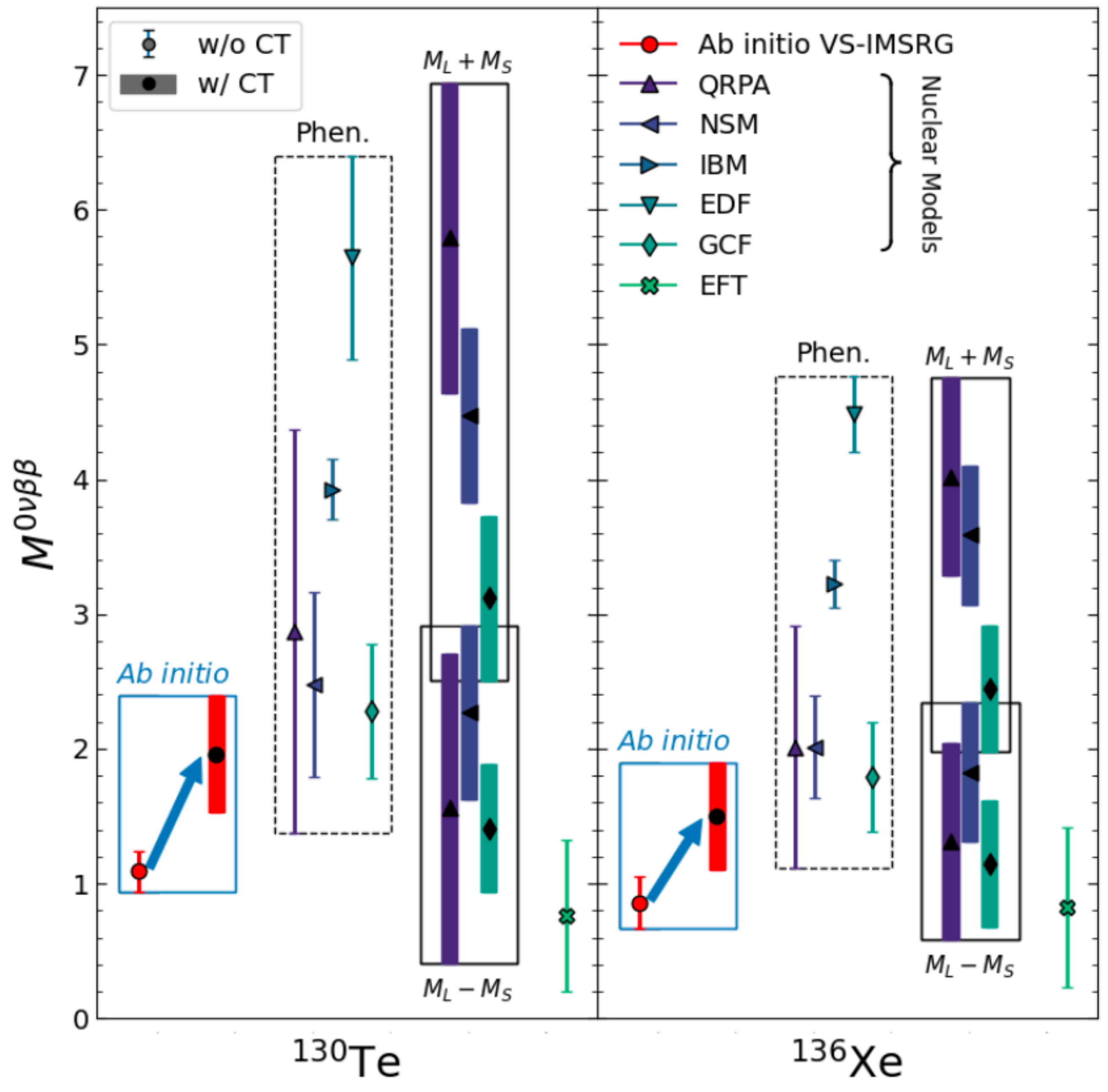


'New': short-range coupling $g_V \sim 1/Q^2$



Contact term is an important ingredient in predictions



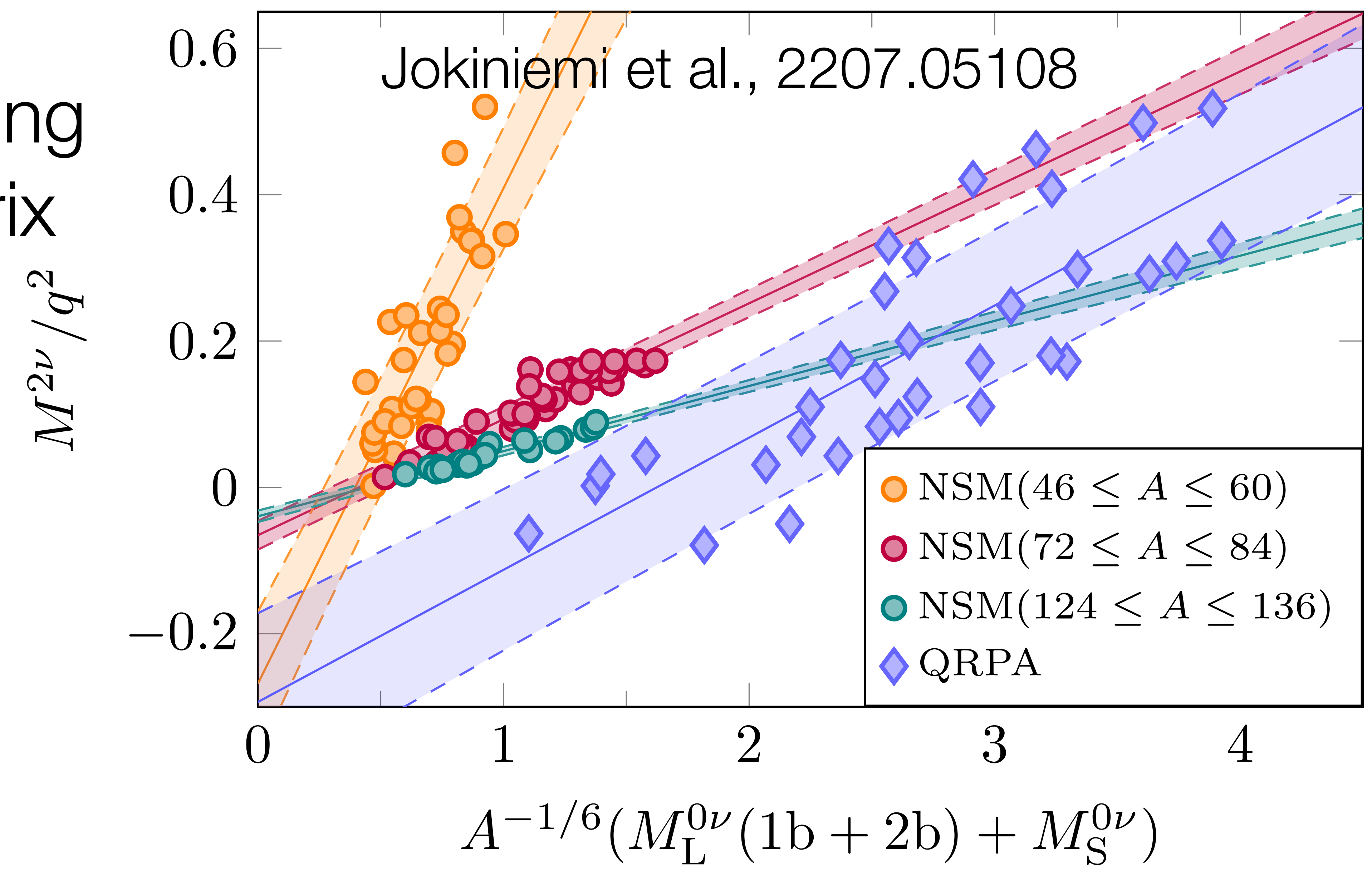


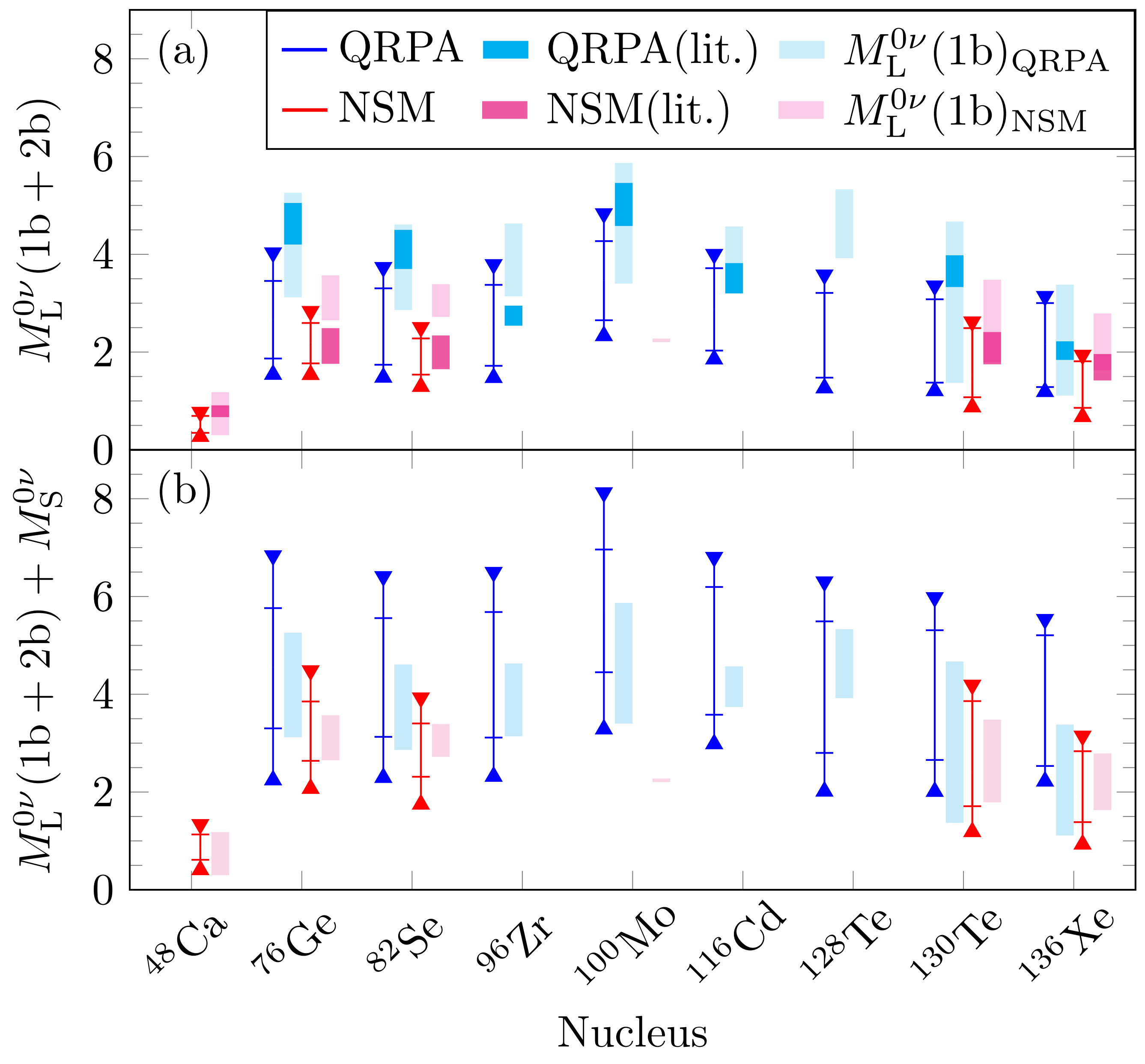
Belley, Miyagi, Stroberg, Holt, in prep.

Nuclear matrix elements

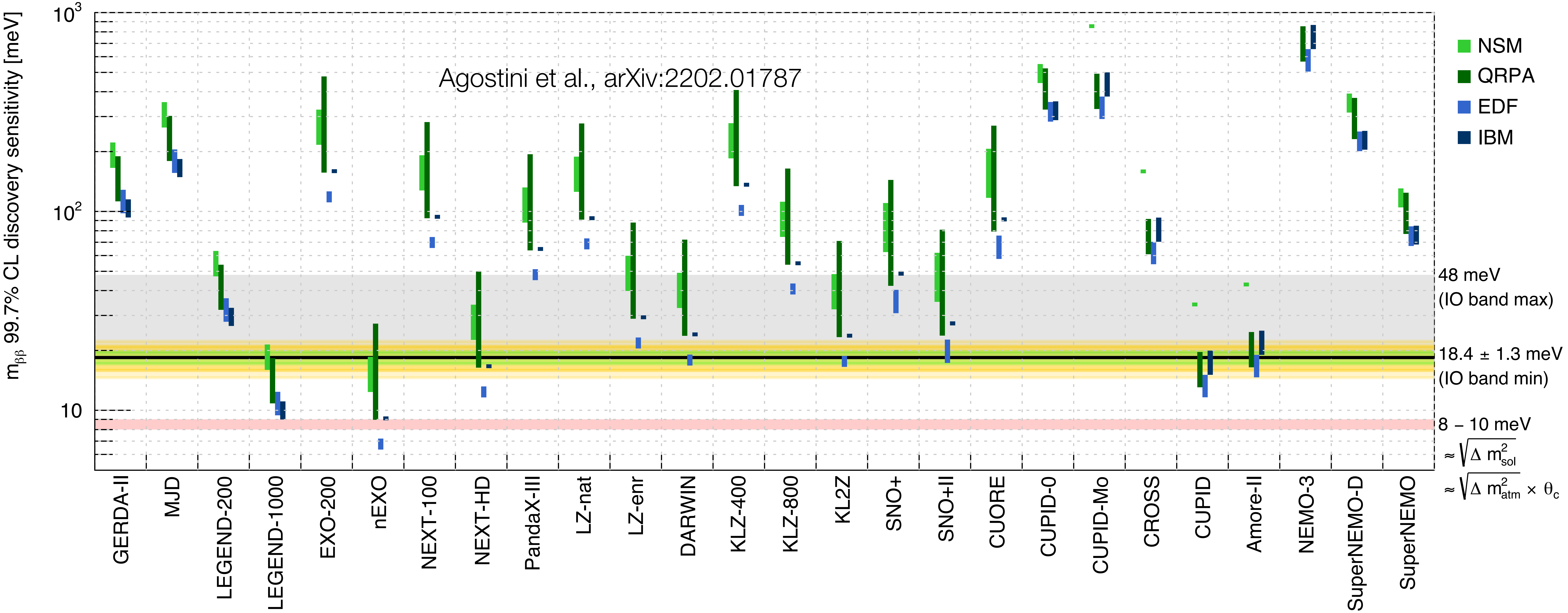
Other approaches to characterizing and understanding nuclear matrix elements

correlation between $0\nu\beta\beta$ & $2\nu\beta\beta$



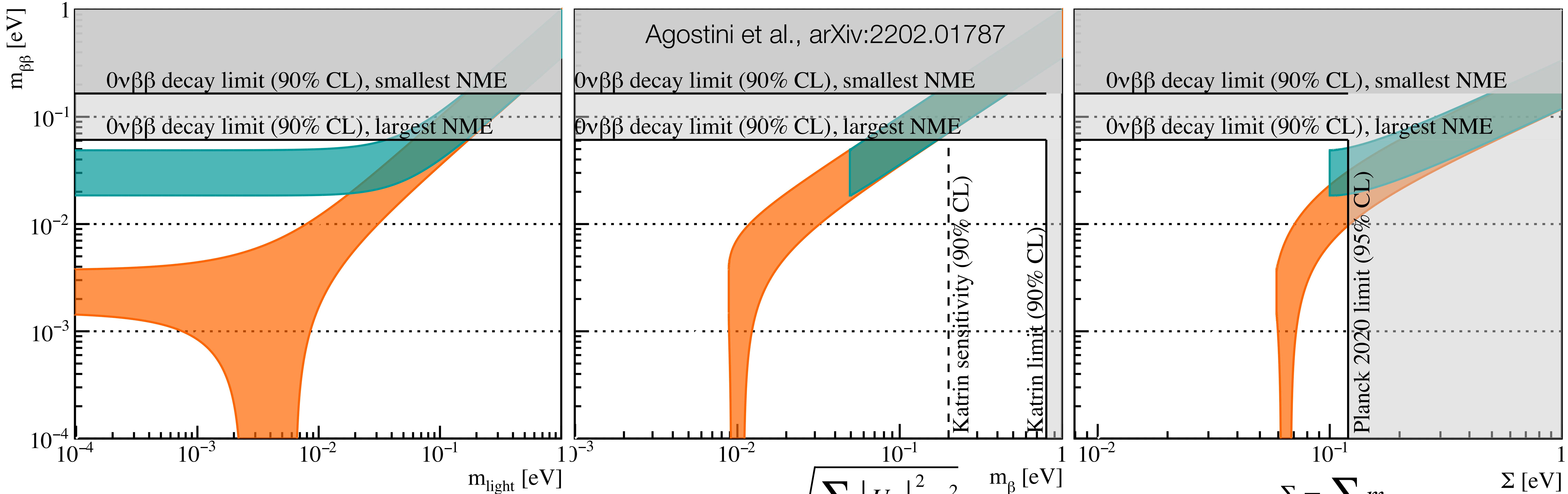


Experimental outlook



Tonne-scale experiments will probe much of the inverted hierarchy region of $m_{\beta\beta}$

Relation to other probes of neutrino mass



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

$$\Sigma = \sum_i m_i$$

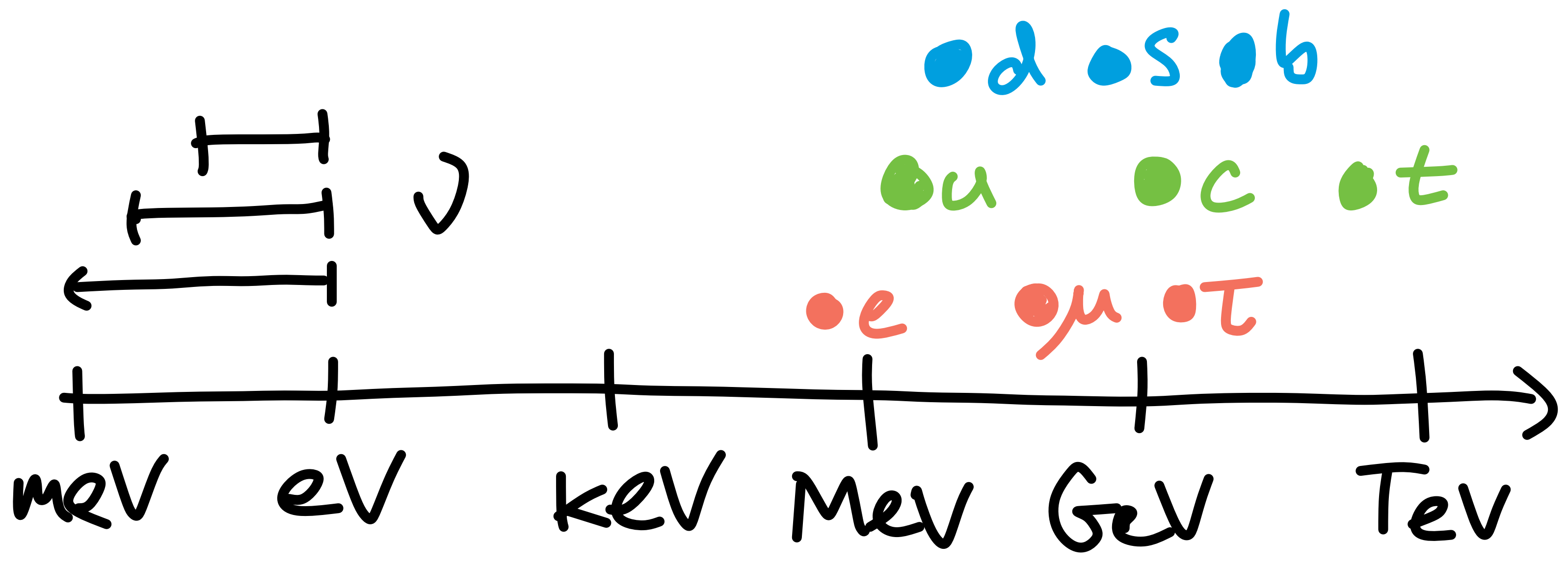
$0\nu\beta\beta$ is complementary to β-decay endpoint and cosmology but is **uniquely** sensitive to $\Delta L \neq 0$!

Other new physics: light ν_R

Large ν_R Majorana mass could explain light neutrino masses

$$-\mathscr{L} \supset M\nu_R\nu_R + \mathrm{h.c.} \Rightarrow m \sim \frac{y^2\langle H\rangle^2}{M}$$

But Yukawa couplings could be small (we see $\sim 10^5$ variation in the case of charged fermions)

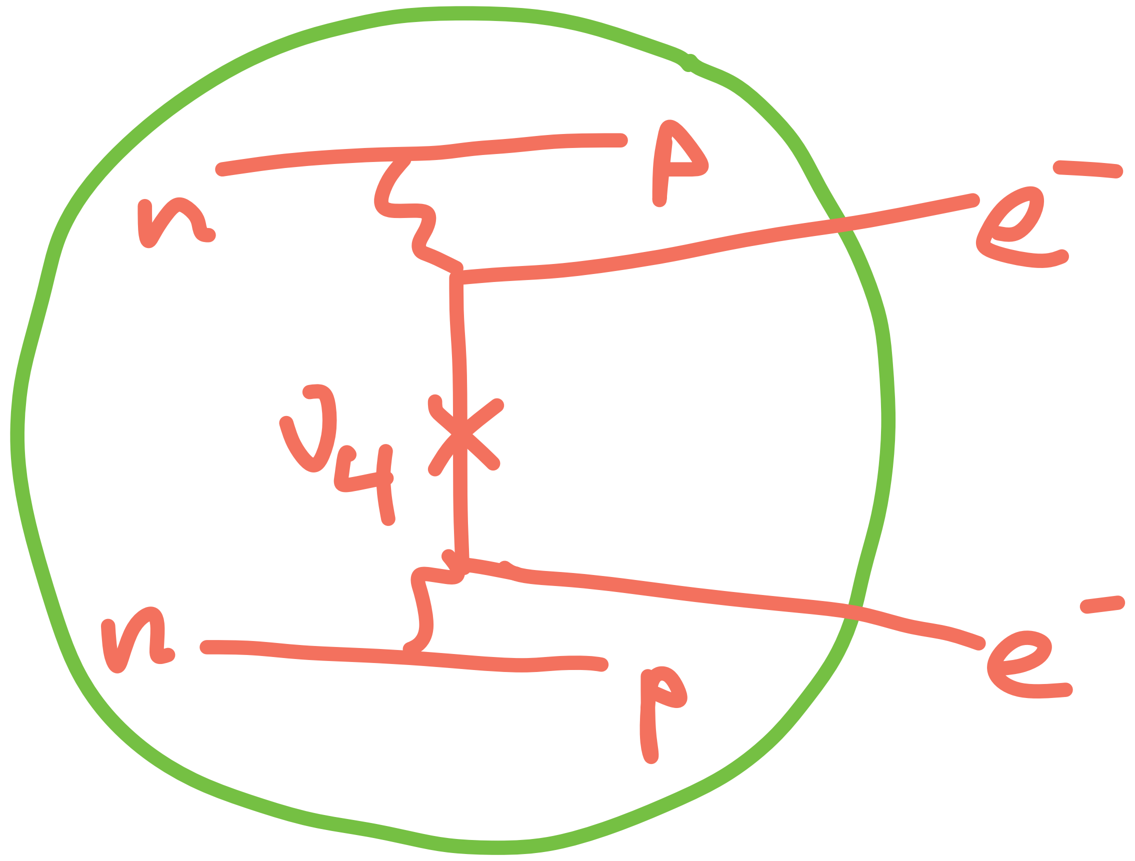


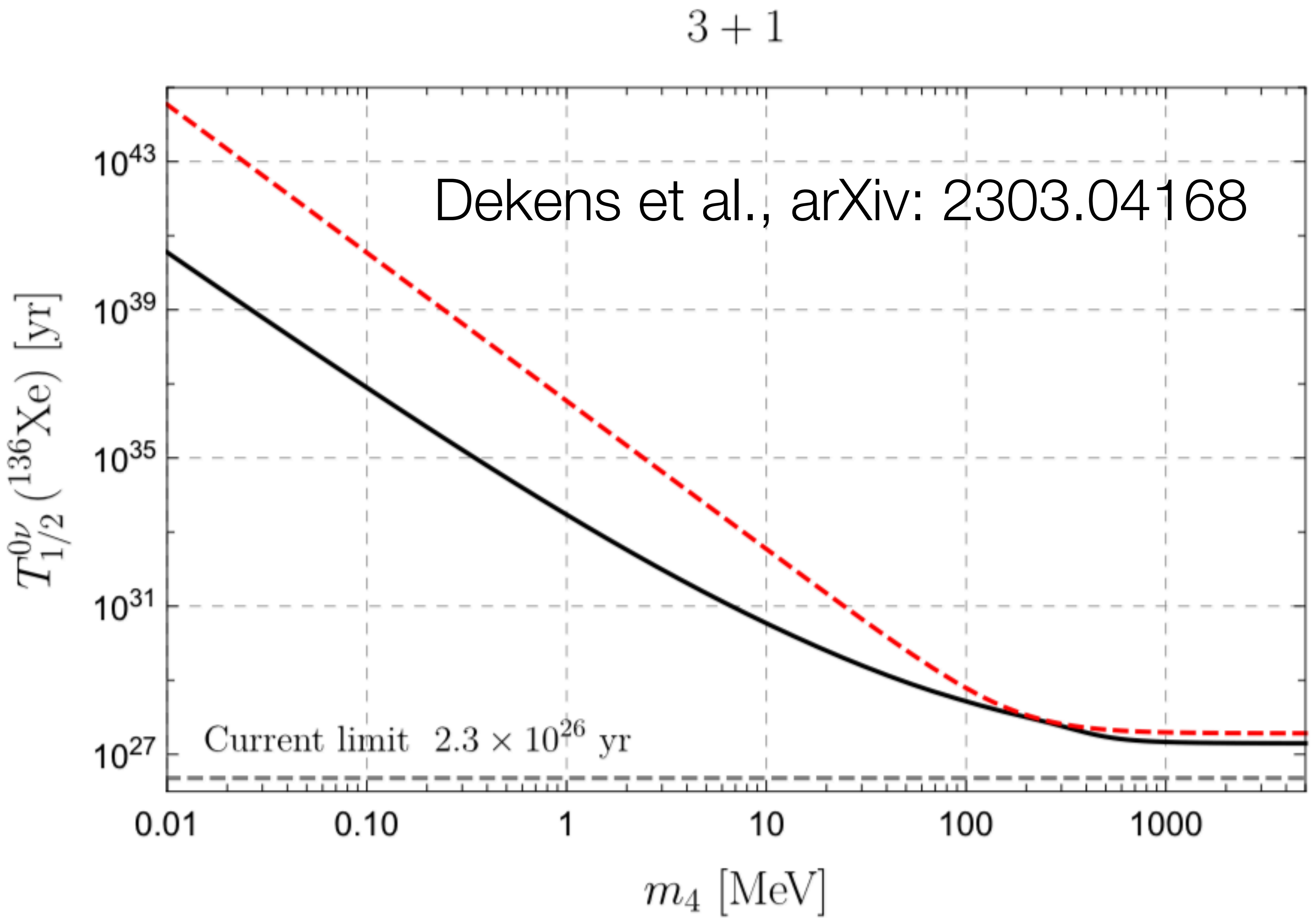
$\Rightarrow$(mostly) sterile neutrinos may not be so heavy, with $M \sim k_F$

Can affect nuclear matrix elements

Other new physics: light ν_R

Heuristically $\mathscr{M} \sim \dfrac{1}{p^2 - m_4^2}$



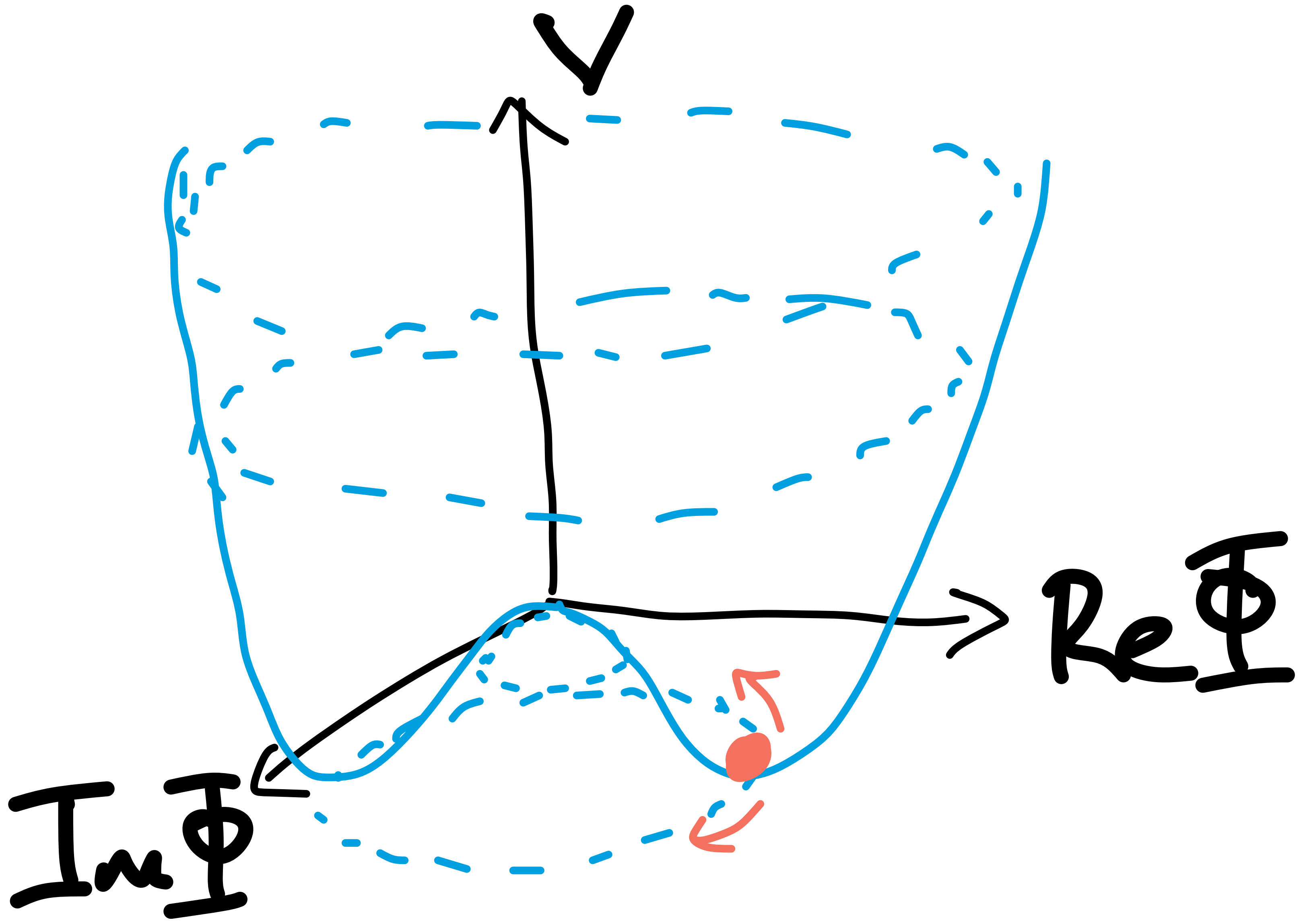


Detailed study shows rates can be impacted

Other new physics: Majorons

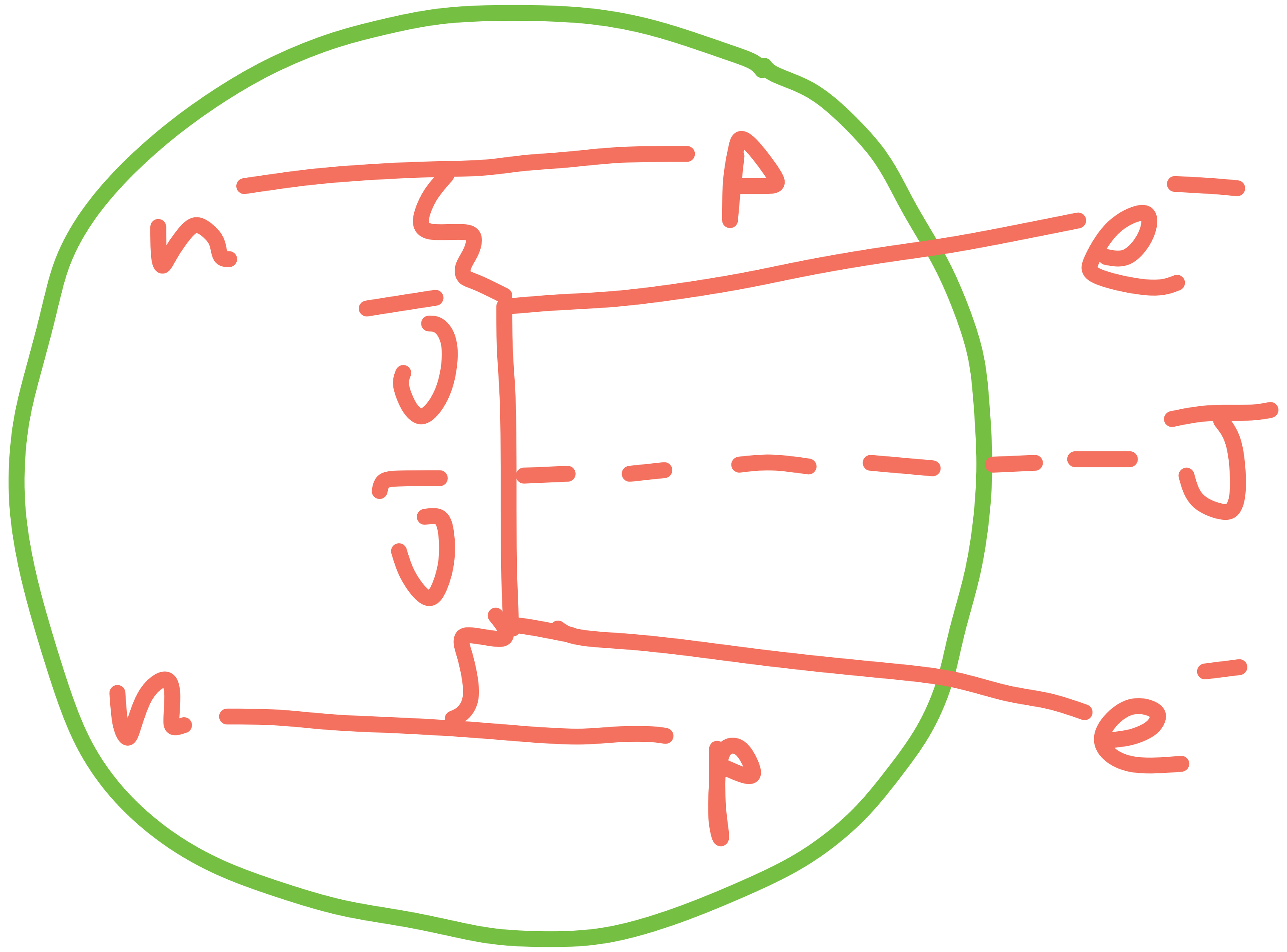
ν_R Majorana mass could be associated with vev of a scalar that spontaneously breaks $\mathrm{U}(1)_L$

$$-\mathscr{L} \supset g\Phi\nu_R\nu_R + \mathrm{h.c.} = Me^{iJ/f}\nu_R\nu_R + \mathrm{h.c.}$$



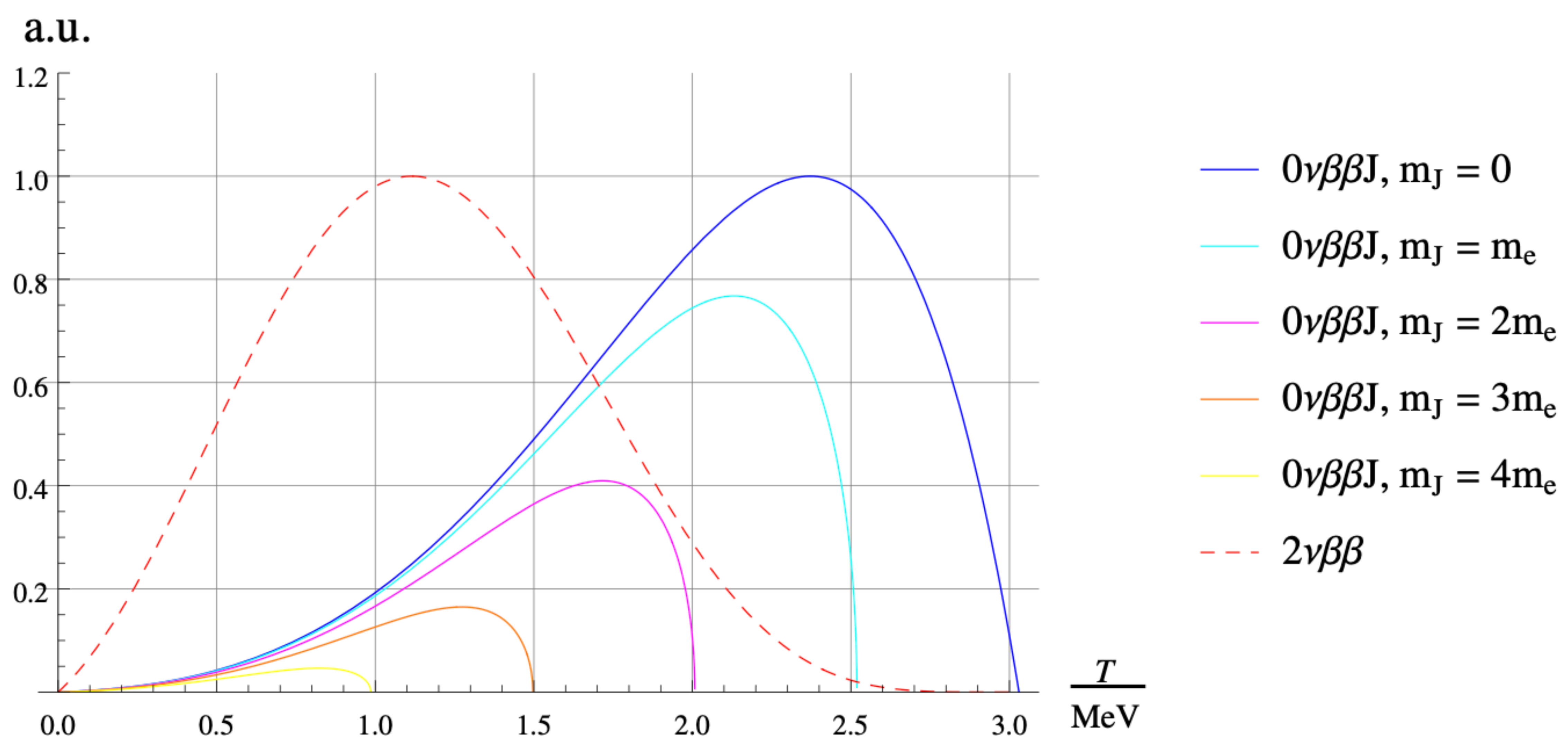
Light pseudo-Nambu-Goldstone boson could then be emitted in $\beta\beta$ decay

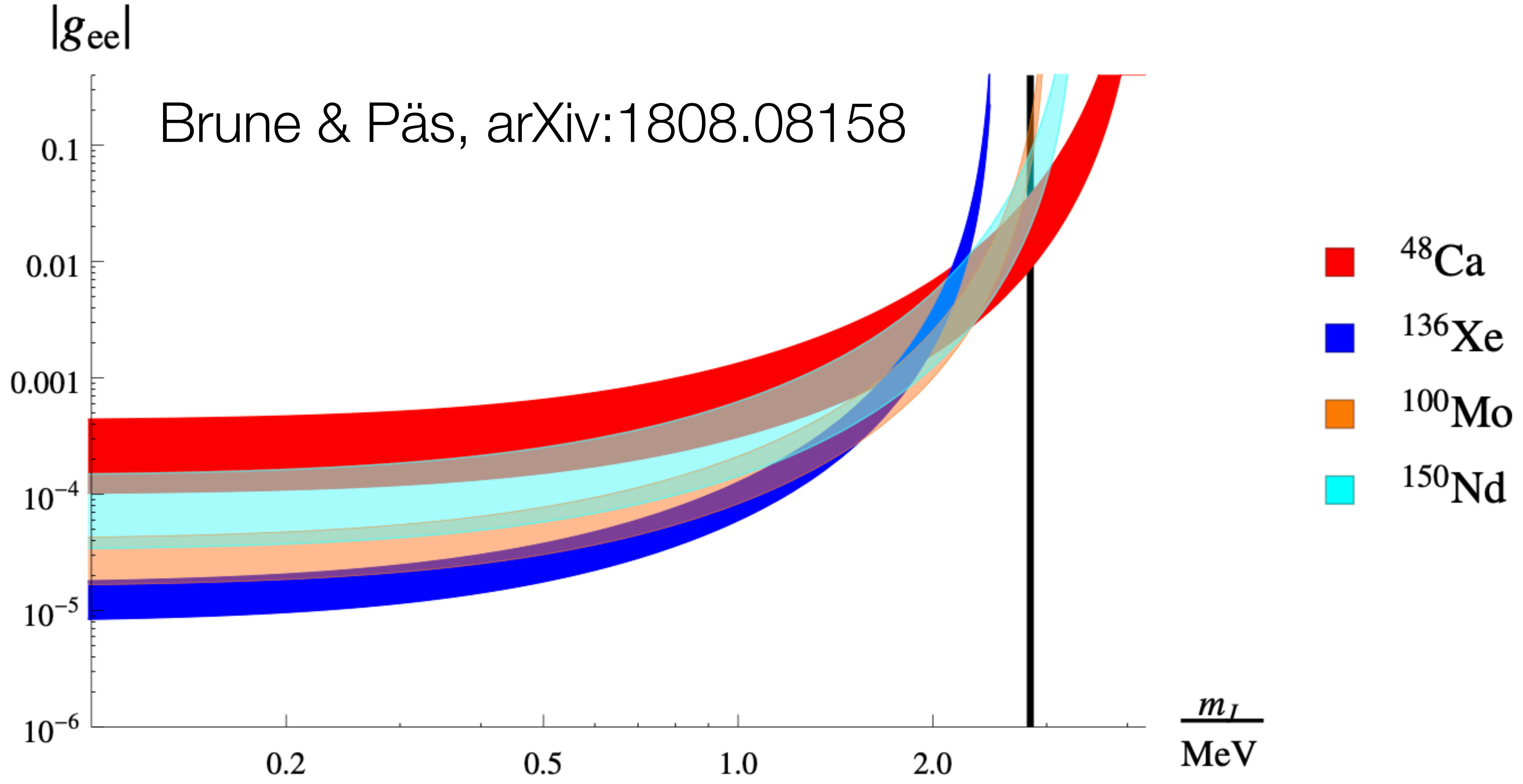
(Georgi, Glashow, Nussinov)



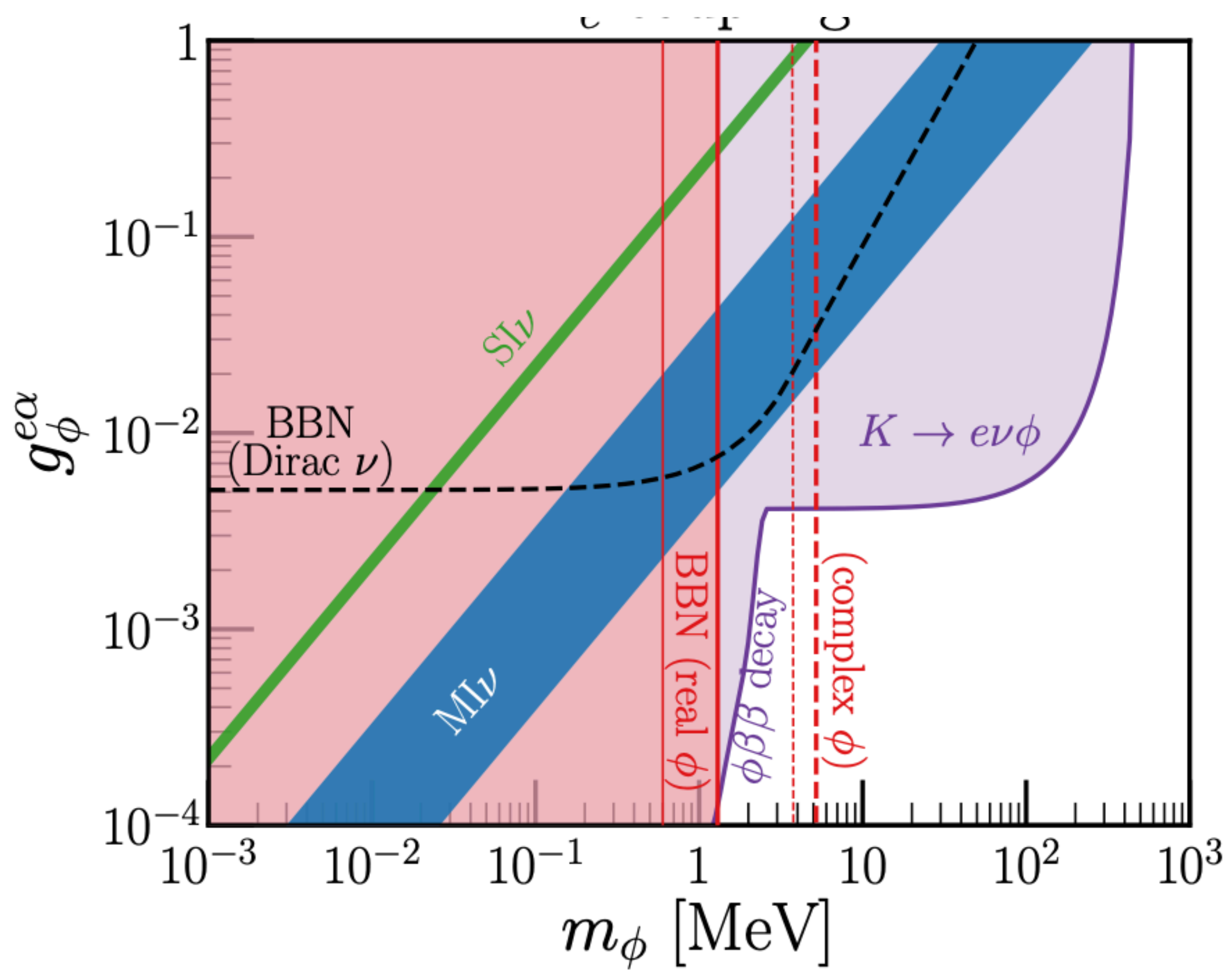
Other new physics: Majorons

Can be constrained with existing data/searches





Interesting because of impact on cosmology tensions!



Blinov et al. arXiv:1905.02727

Wrap up

Neutrino masses are only terrestrial evidence of physics beyond SM

Adding neutrino masses to SM is qualitatively different—connected to existence of a global symmetry

Ongoing effort to study the nature of neutrino masses with $0\nu\beta\beta$ decay searches

This effort is profoundly important—impacts our understanding of ν masses themselves, the matter asymmetry of the universe, cosmology, quantum gravity, …

It's vitally important that we push these searches forward

Backup: back of the t-shirt