Tracking down the origin of neutrino mass

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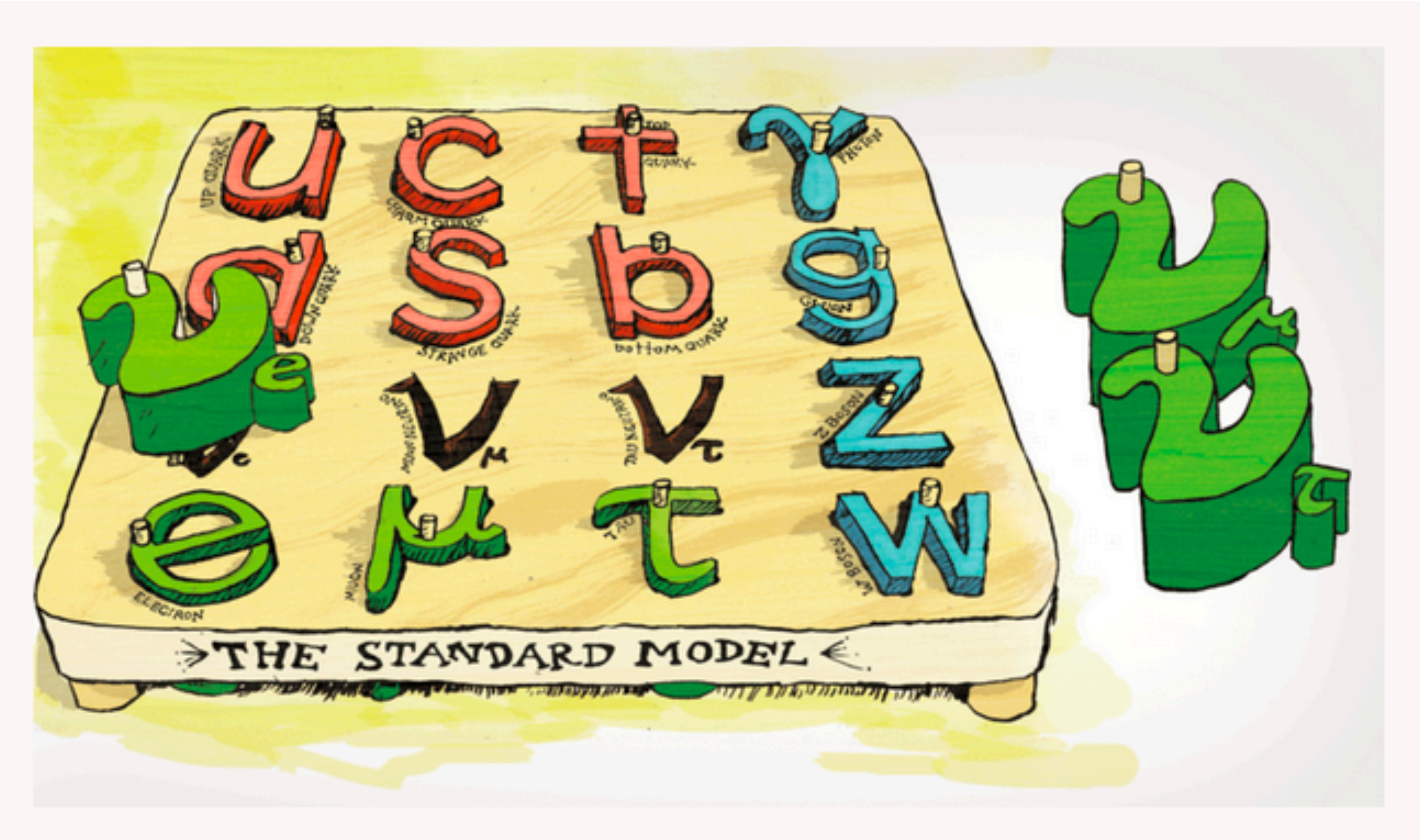
Neutrino oscillations

Observation of neutrino oscillations:

→ Strong evidence of physics beyond the SM

→ introduced more parameters to the model
(3 angles, at least one phase, 3 masses)

→ need to introduce neutrino mass mechanism



Neutrino mass

What is neutrino mass generation mechanism?

Dirac neutrinos

$$m_D = y_\nu \bar{\nu}_L \tilde{H} N_R$$

like other SM fermions

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Majorana neutrinos

$$m_M = M_N \bar{\nu}_L \nu_L^c$$

Neutrinos are the only SM particles that could have such a mass term

Term not gauge invariant!

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Term not gauge invariant!

In any case need new particles!

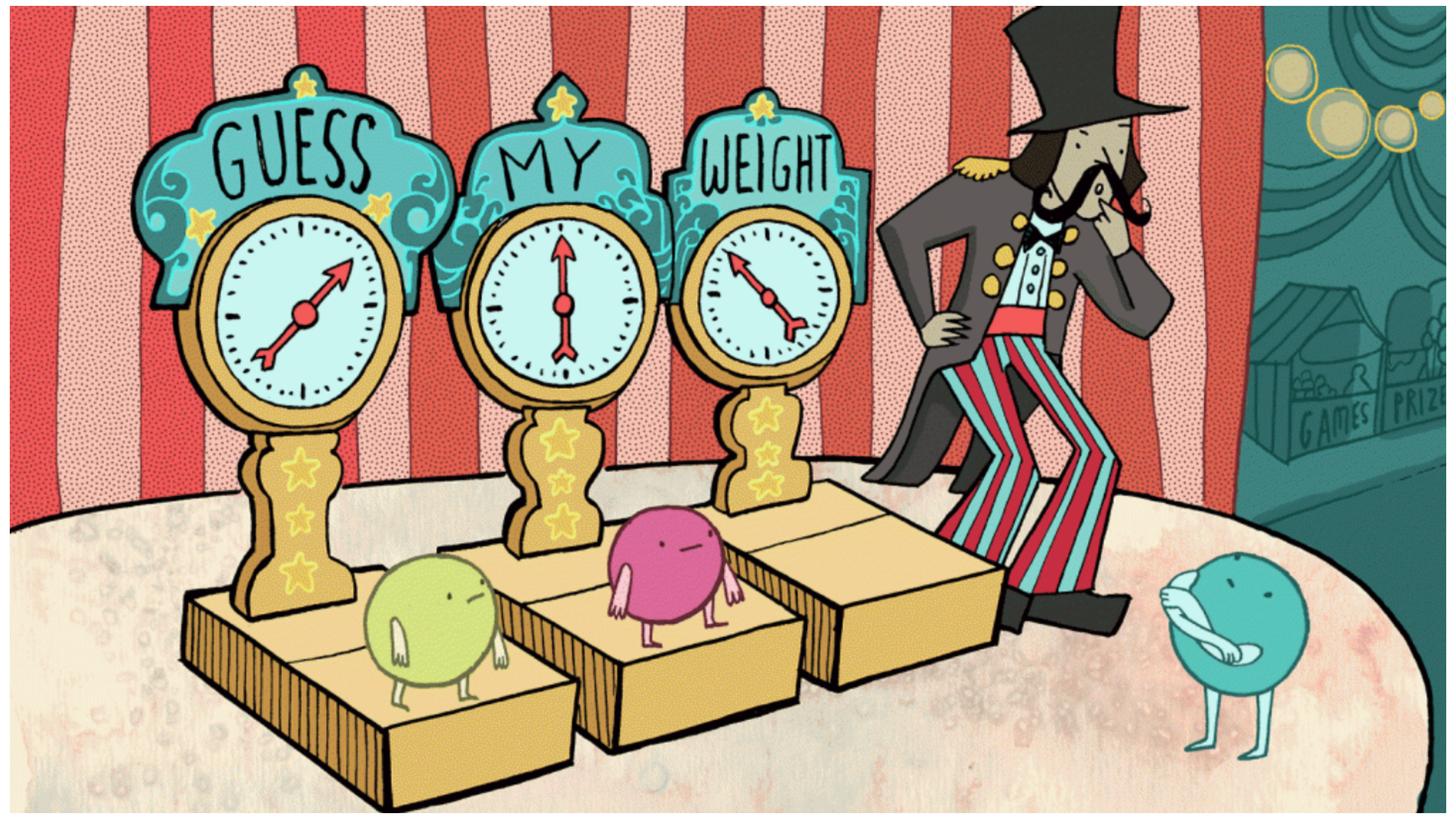
→ observation of neutrino oscillations predicts new particles!

Neutrino mass

What is the neutrino mass scale?

→ learn about required couplings in new interaction

identify promising experimental search strategies



Neutrino mass

What is the neutrino mass scale?

Only upper limit on neutrino mass scale so far!

Cosmological sum of neutrino masses:

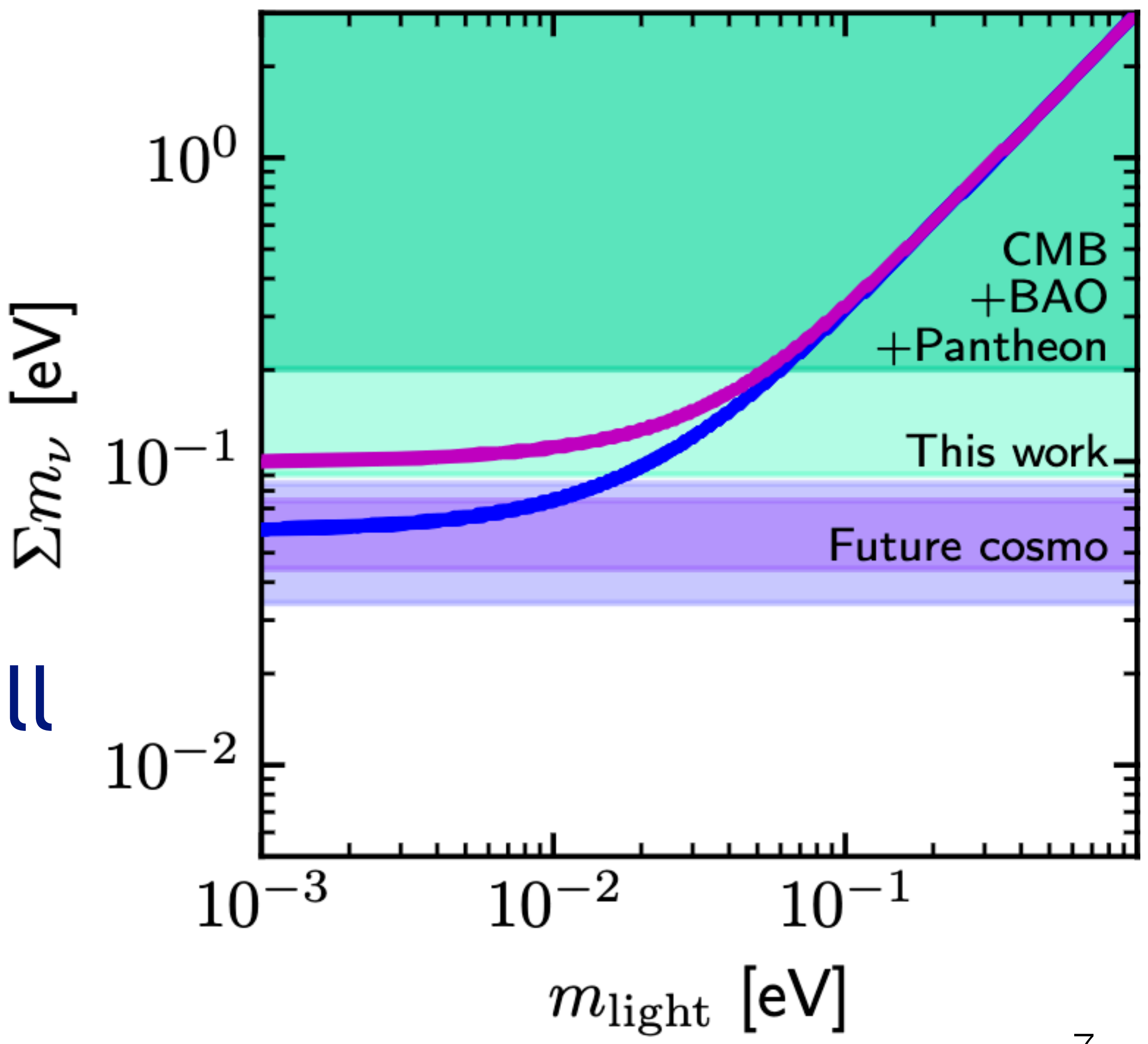
$$\sum m_\nu \lesssim 0.1 \text{ eV}$$

[Di Valentino, Gariazzo, Mena, 2207.05167]

Depending on data sets combined

Future cosmological observatories will measure sum of neutrino masses

[Di Valentino, Gariazzo, Mena, 2106.15267]



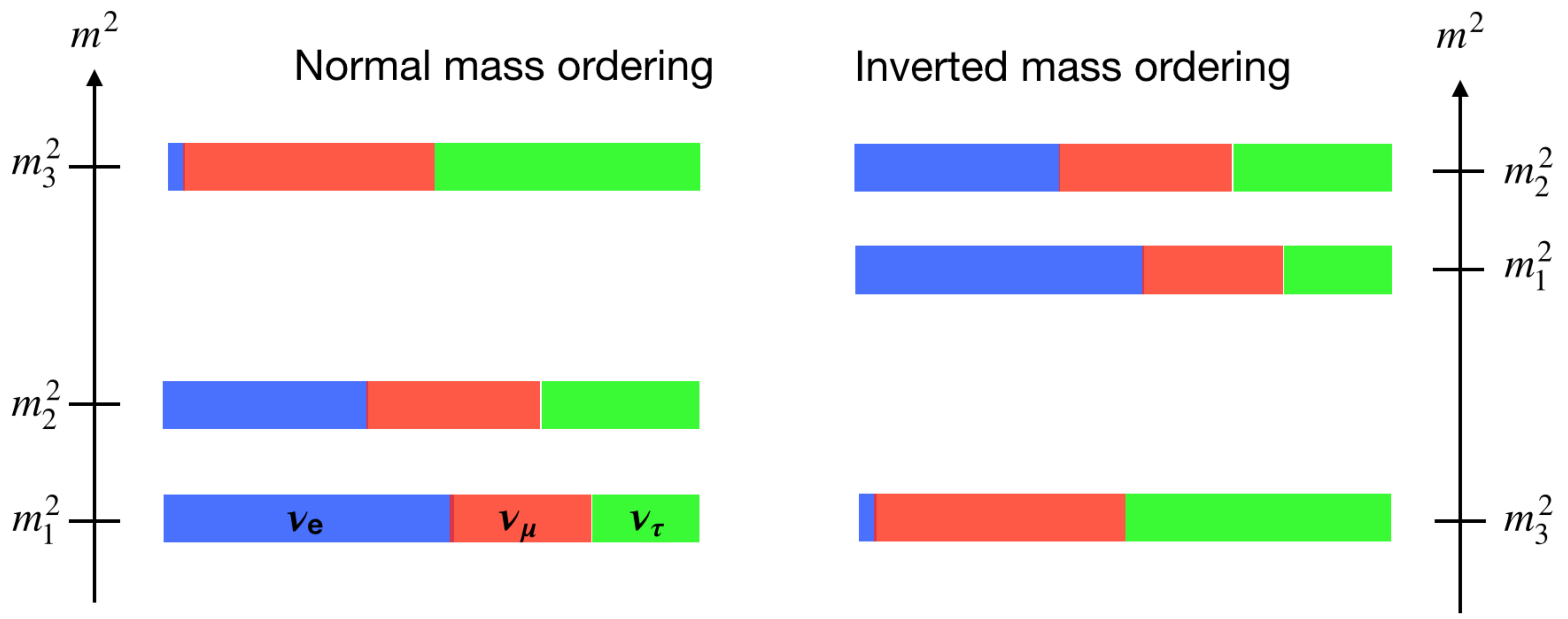
Neutrino mass

What is neutrino mass scale?

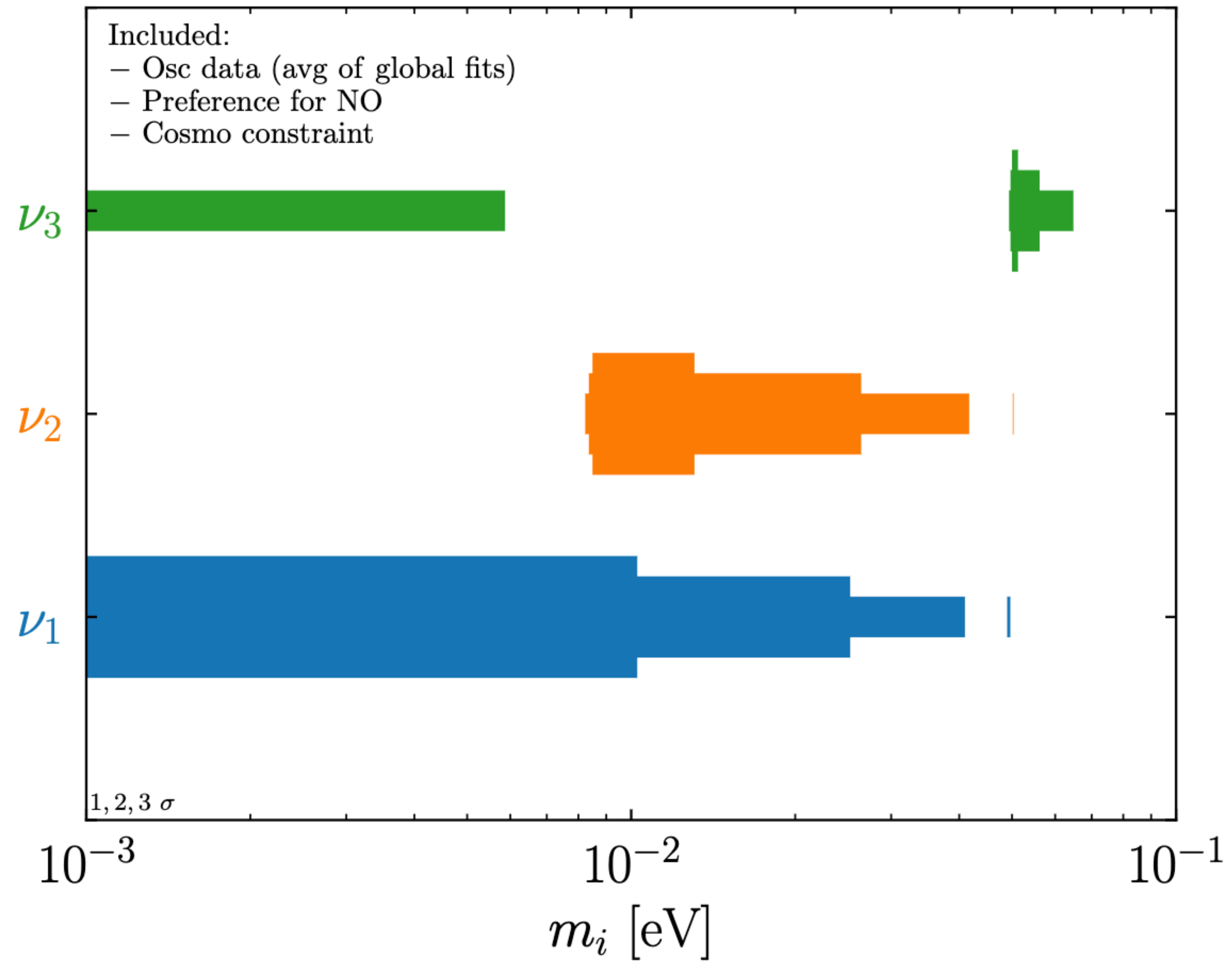
Only upper limit on neutrino mass scale so far!

Mild (1.6 σ) preference for normal mass ordering from oscillation experiments

[nufit v5.2 2007.14792]



[JG, Denton 2308.09737]



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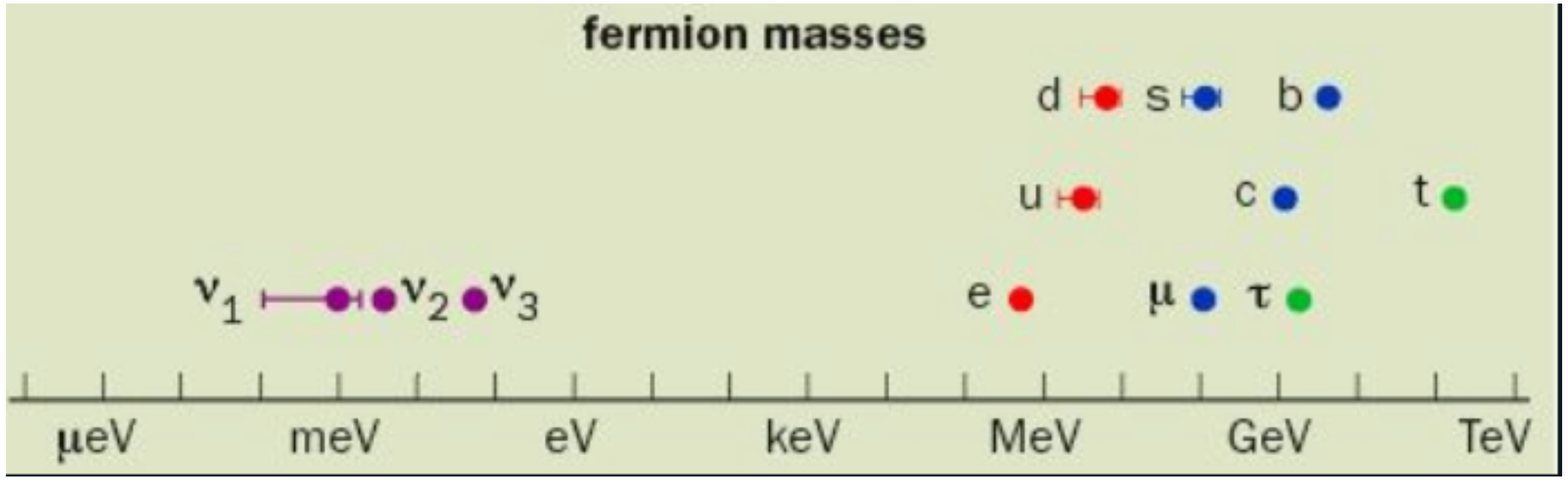
Neutrinos much lighter than other fermions



Is this a clue about underlying mass mechanism?

Neutrino mass

What is neutrino mass scale?

Neutrinos much lighter than other fermions

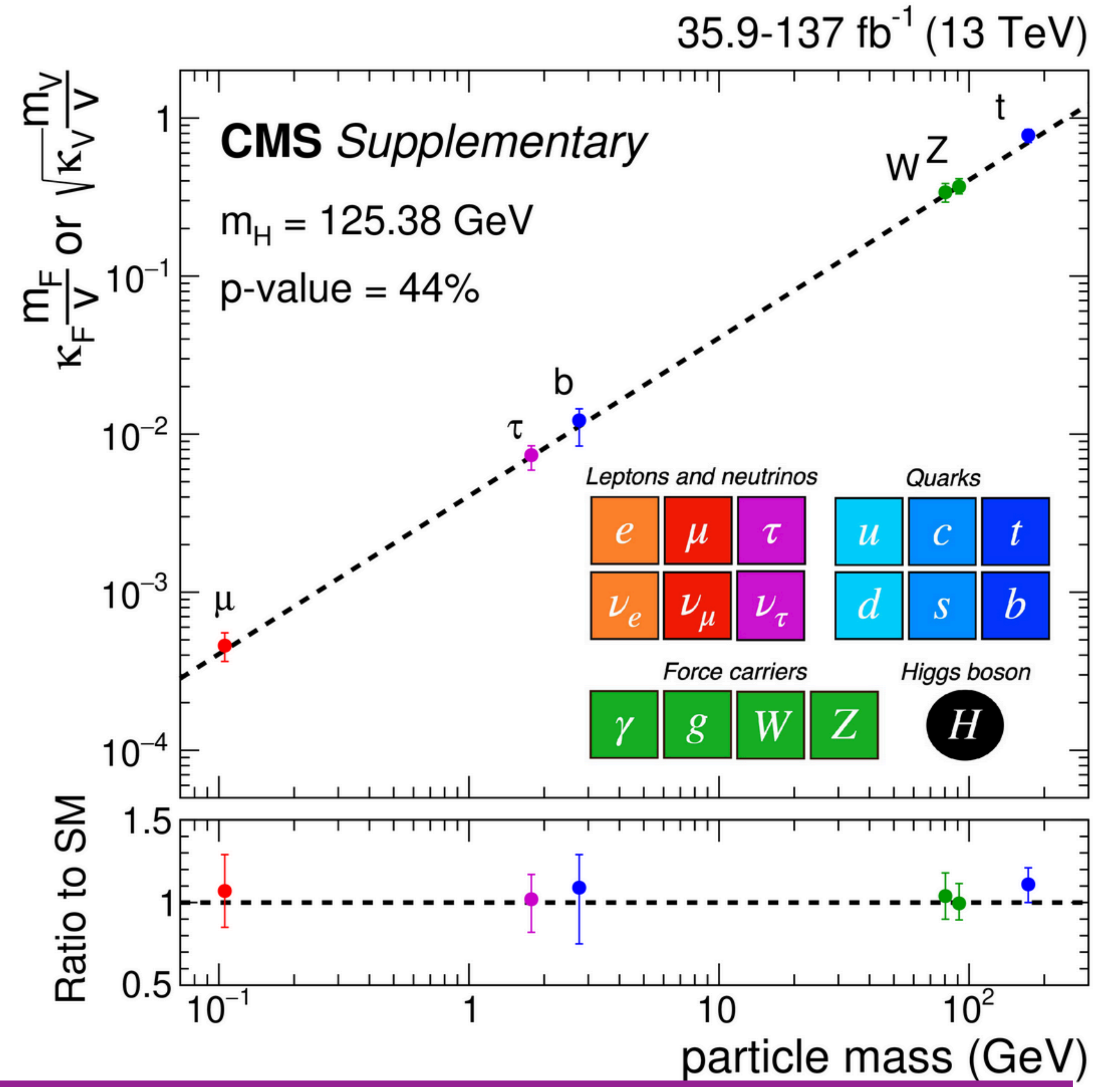
Dirac neutrinos: Yukawa coupling $y_\nu \lesssim 10^{-13}$

Dirac neutrinos would have a much smaller Yukawa coupling than other fermions

Direct probe of $H \to \bar{\nu}\nu$ colliders not possible

Reason for smallness of neutrino mass?

[CMS 2009.04363]



Neutrino mass

Majorana mass term arises from higher dimension operators!

→ explains smallness of neutrino mass due to suppression by high scale

Majorana neutrino mass operators occur at odd dimension

[Kobach 1604.05726]

$$\mathcal{O} \propto (LLHH)(H^\dagger H)^n$$

$$\rightarrow m_\nu \propto c\frac{v^2}{\Lambda}\left(\frac{v}{\Lambda}\right)^{d-5}$$

Neutrino mass

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Dimension 5 operator

$$\mathscr{L}_5 = c_5 \frac{(\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L_L)}{\Lambda}$$

Only dim-5 operator that can be build with SM fields alone
Expect first signs of new physics from lowest SMEFT operator
→ neutrino mass

Dimension 7

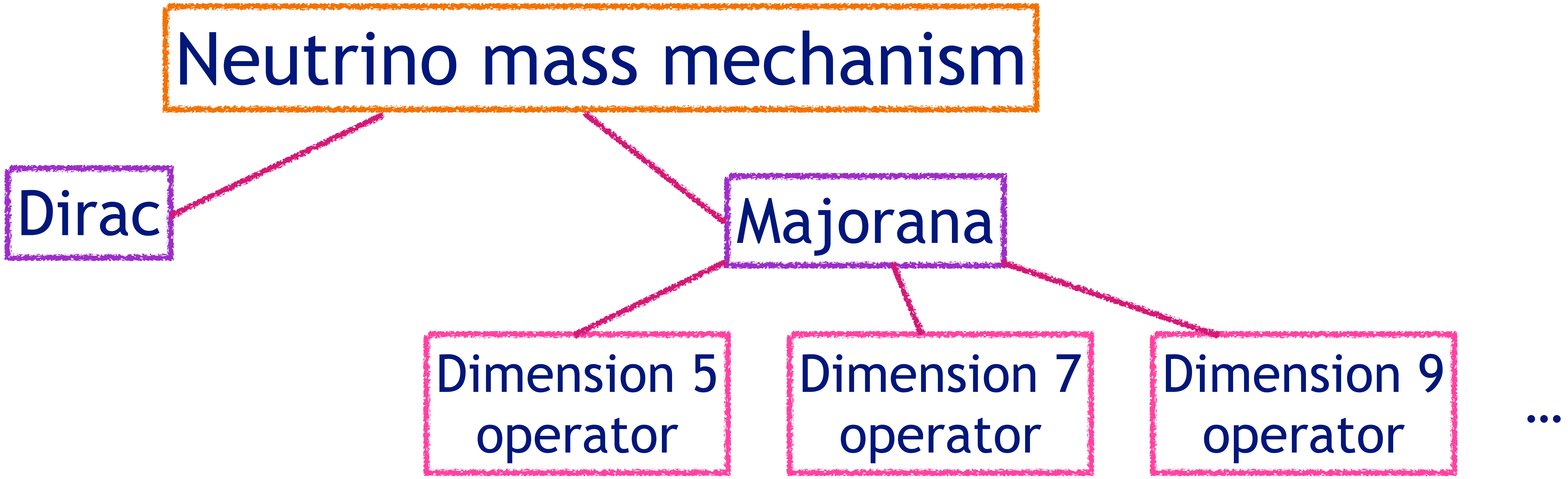
$$\mathscr{L}_7 \propto c_7 \frac{(LLHH)(H^\dagger H)}{\Lambda^3}$$

Dimension 9

$$\mathscr{L}_9 \propto c_9 \frac{(LLHH)(H^\dagger H)(H^\dagger H)}{\Lambda^5}$$

…

Maze of possibilities



Maze of possibilities

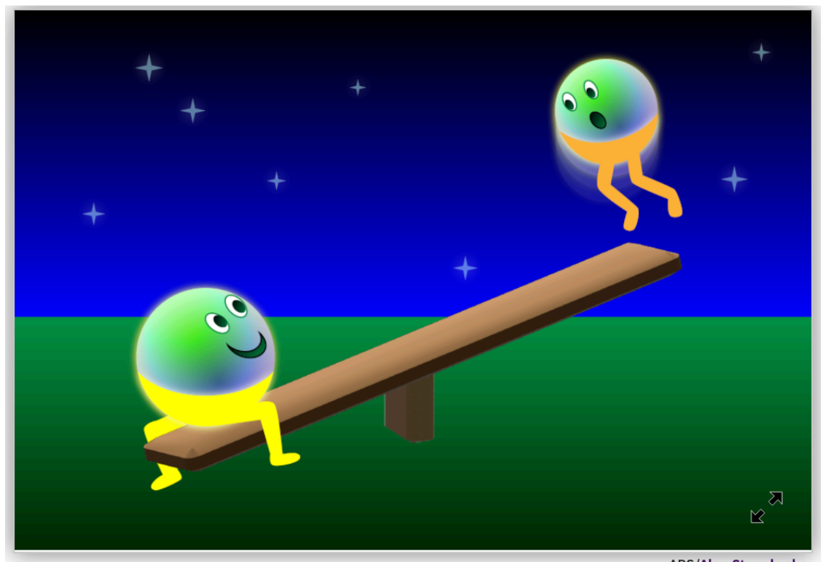
Example dimension 5 operator

$$m_\nu \sim c\frac{v^2}{\Lambda}$$

hierarchy →

Λ large:
small m_ν
due to suppression of scales

→ No direct probe
Hierarchy problem



Type I seesaw
Type II seesaw
Type III seesaw

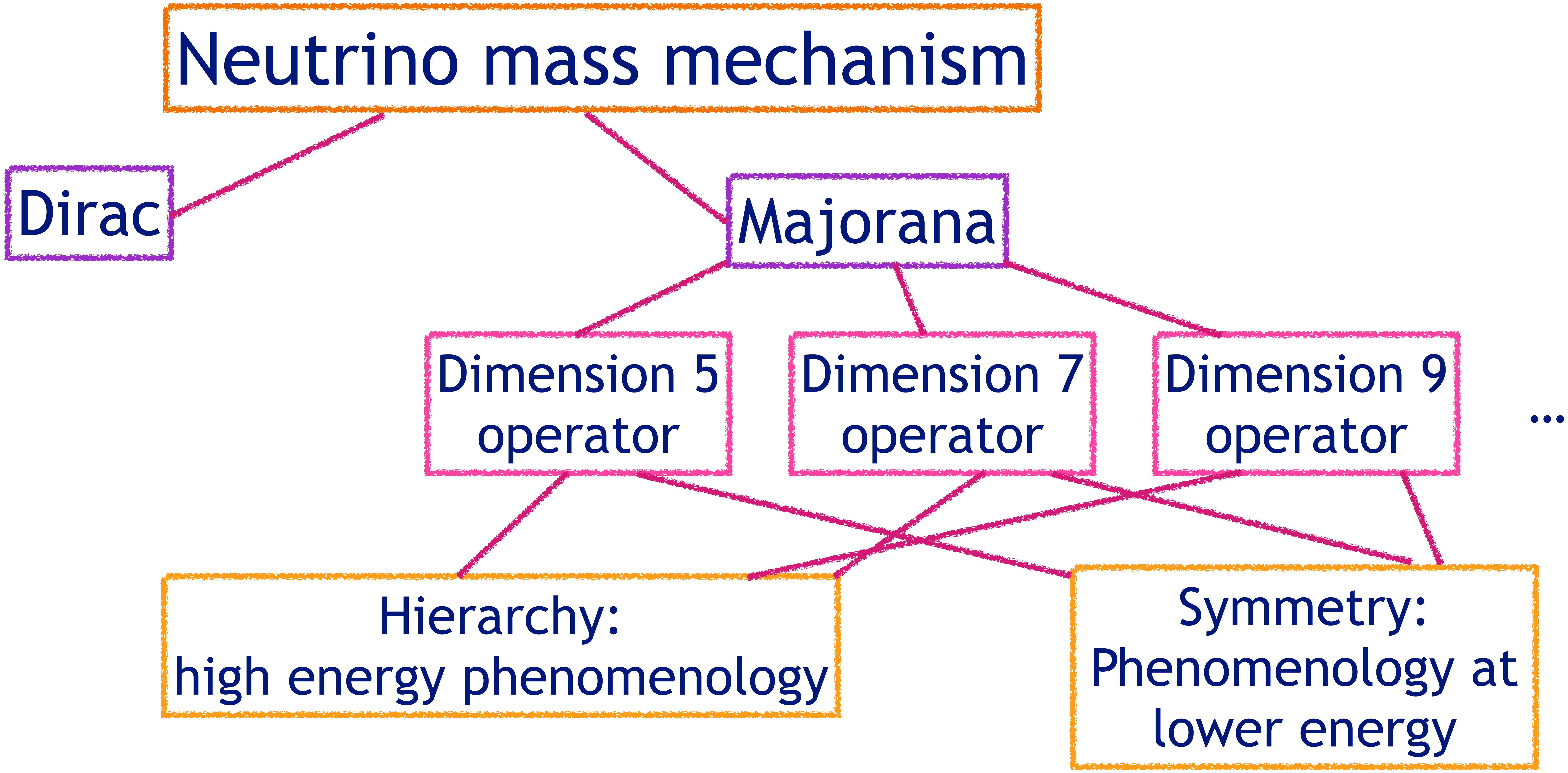
symmetry →

Λ small:
small m_ν
due to small Wilson coefficient c

→ testable

Type II seesaw
inverse seesaw
linear seesaw
extended seesaw

Maze of possibilities



Testing neutrino mass mechanisms

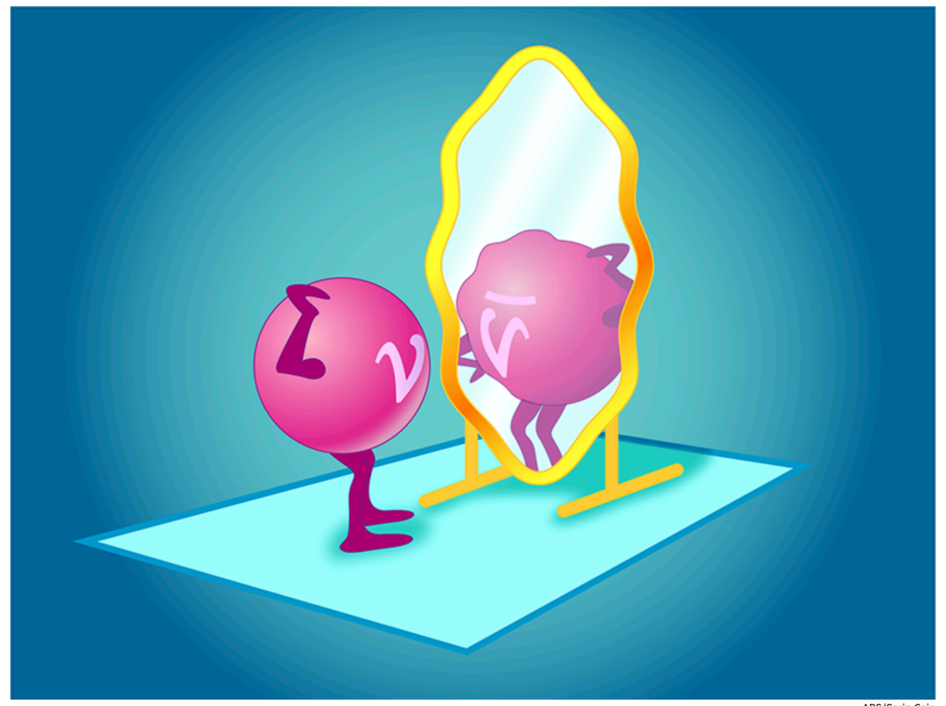
Dirac vs Majorana neutrinos

Dirac

Majorana

Majorana mass term violates lepton number
Dirac mass term conserves lepton number
$\Rightarrow$ search for lepton number violating processes

Effect $\propto$ neutrino mass!

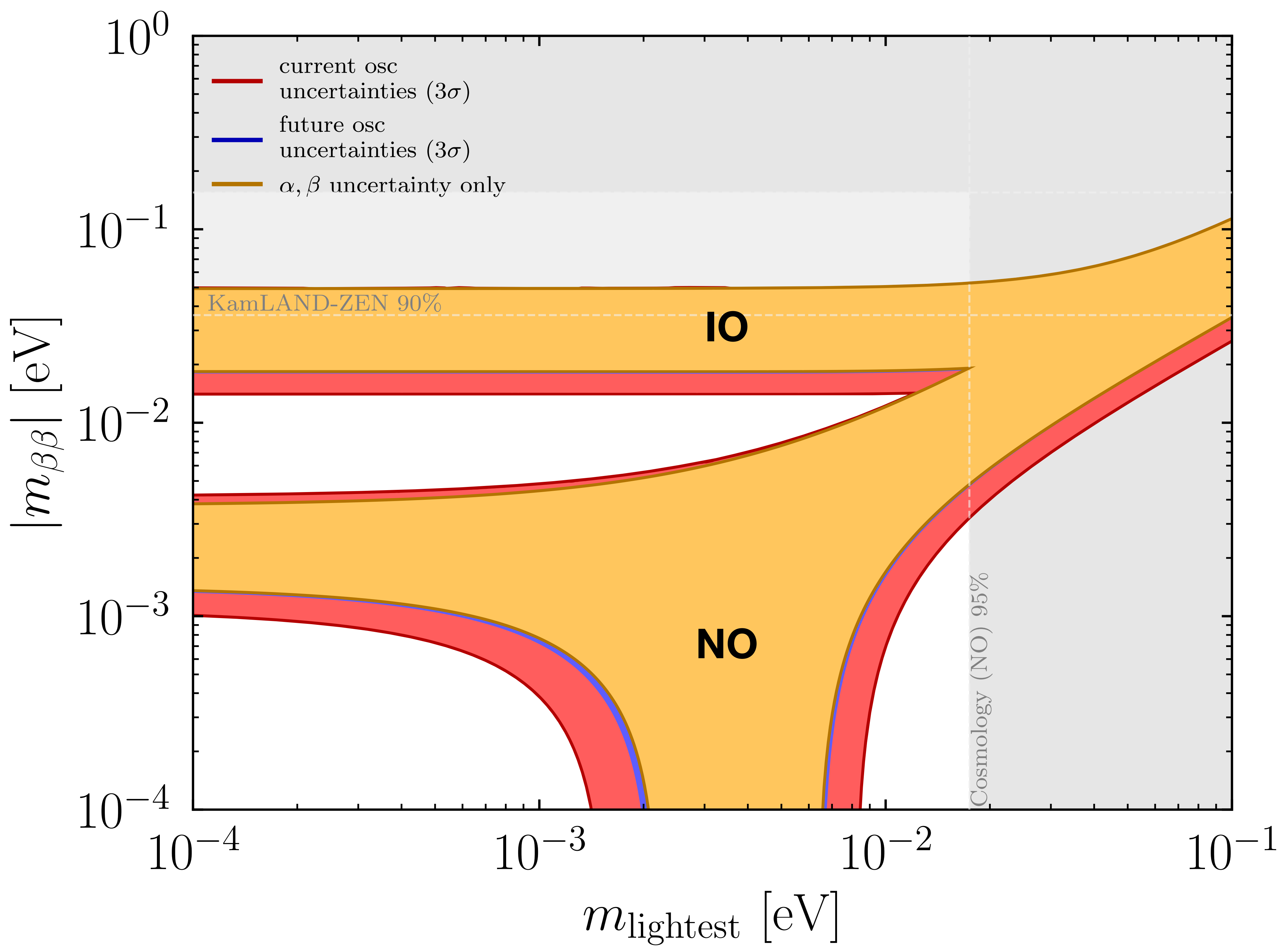


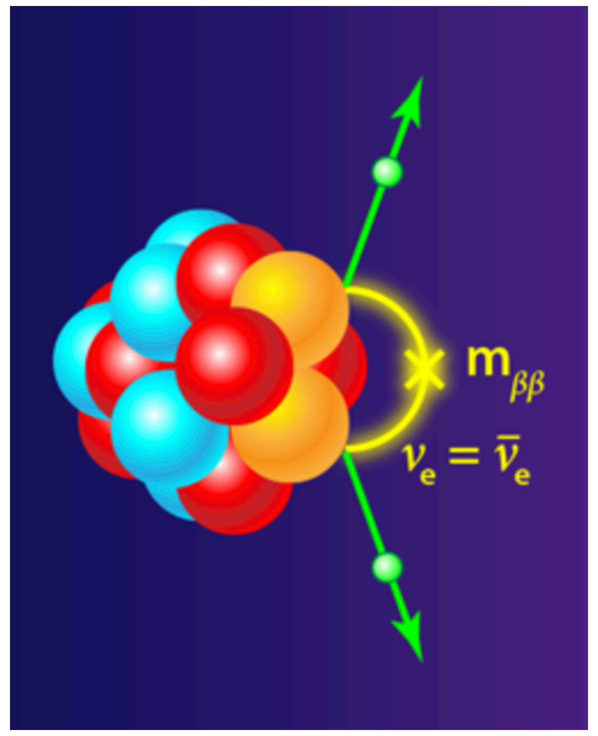
Testing neutrino mass mechanisms

Dirac vs Majorana neutrinos

Neutrinoless double beta decay experiments aim to provide an answer

$$(Z, A) \rightarrow (Z+2, A) + 2\,e^-$$





Currently just upper limit,
no observation

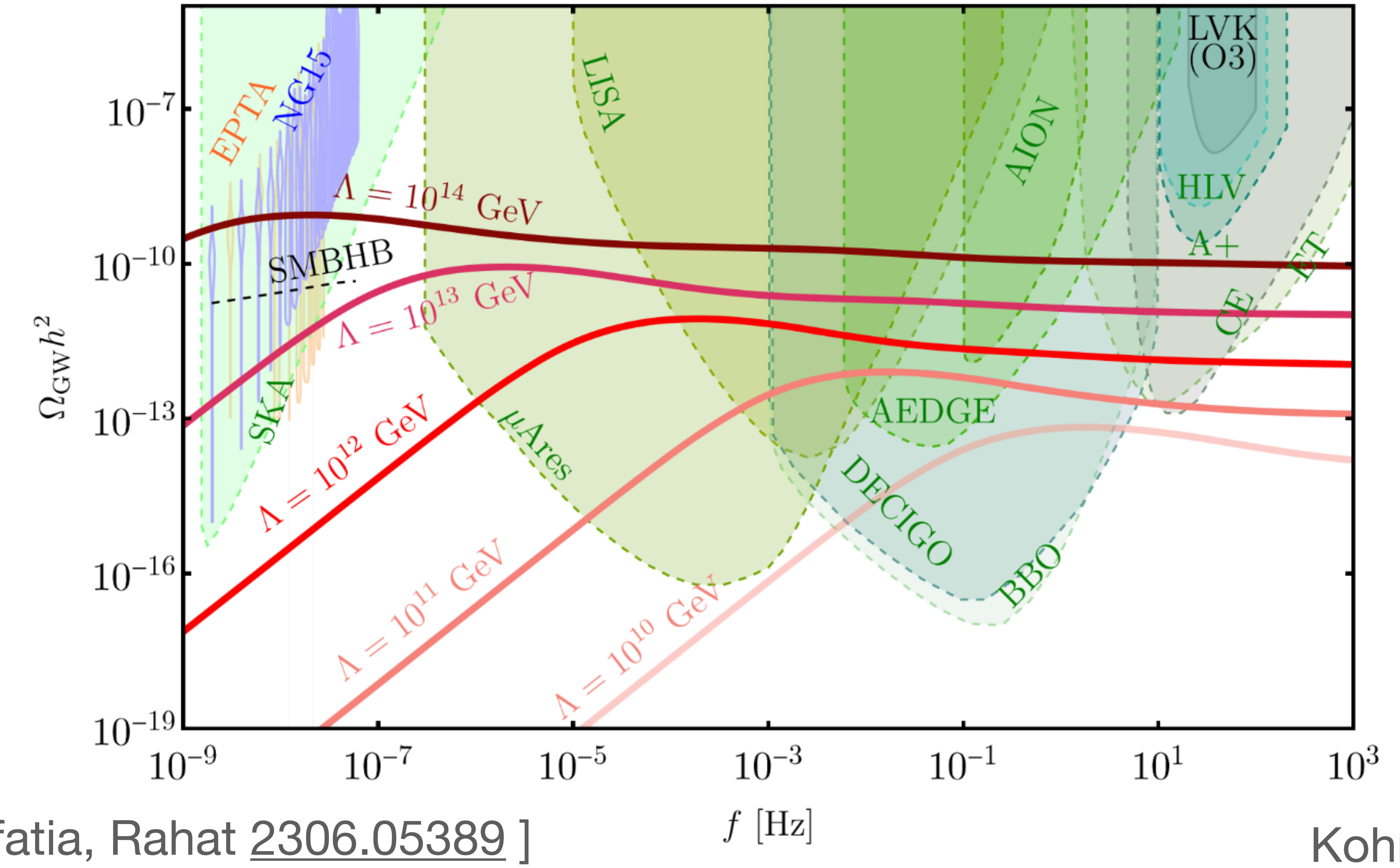
Large parameter space, depending
on absolute mass scale and mass ordering

Width of allowed bands depends on
Majorana phases

Testing neutrino mass mechanisms

Dirac vs Majorana neutrinos

Signs of lepton number breaking in the early Universe
Gravitational waves from decay of cosmic strings from breaking of lepton number symmetry



[King, Marfatia, Rahat 2306.05389]

Signature depends on Lepton number breaking scale

[see also Dror, Hiramatsu, Kohri, Murayama, White 2306.05389]

Testing neutrino mass mechanisms

New particles associated to mass generation

New particles are introduced in neutrino mass generation mechanisms
$\rightarrow$ search for them!

Identify UV complete models for higher dimensional operators

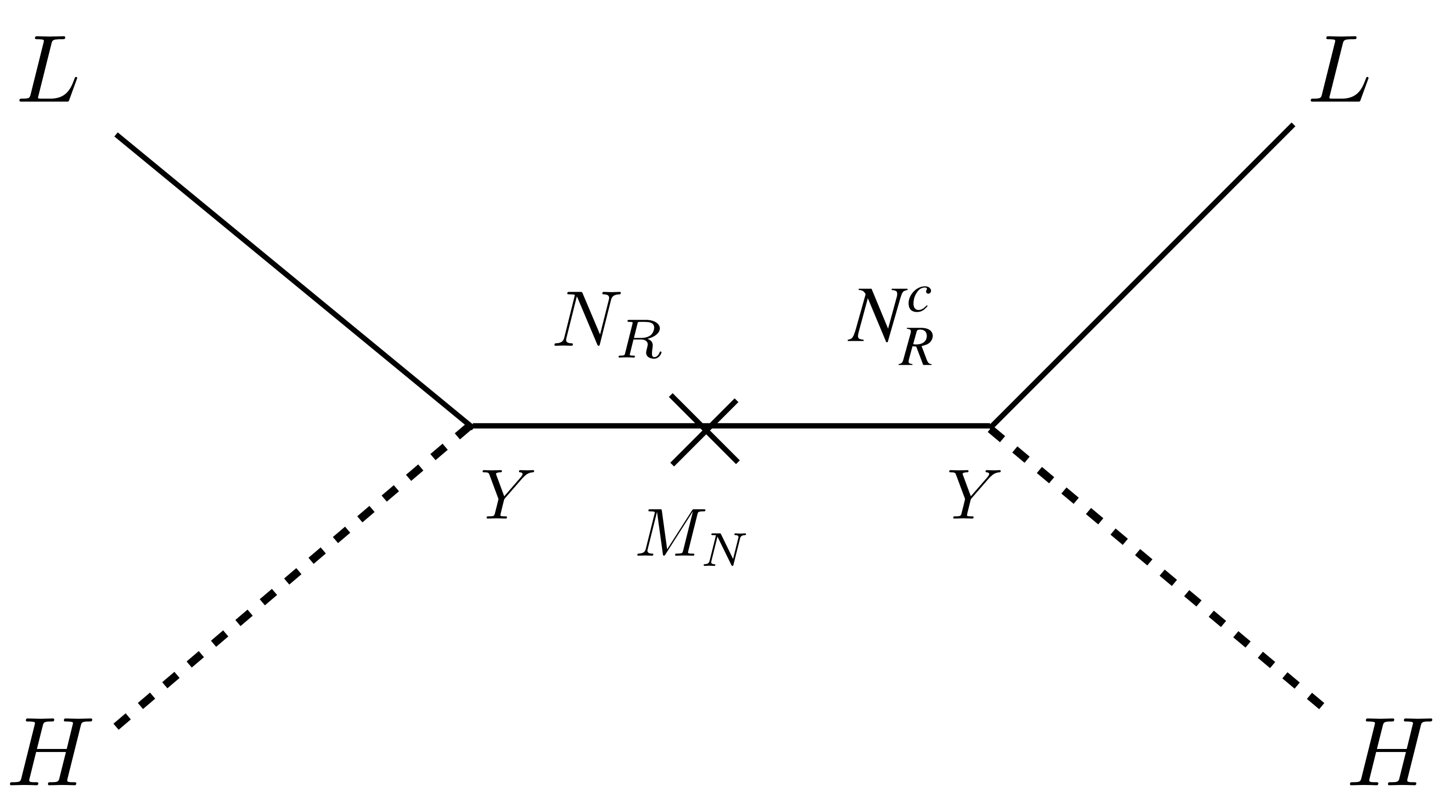
Testing neutrino mass mechanisms

New particles associated to mass generation

Identify UV complete models for higher dimensional operators

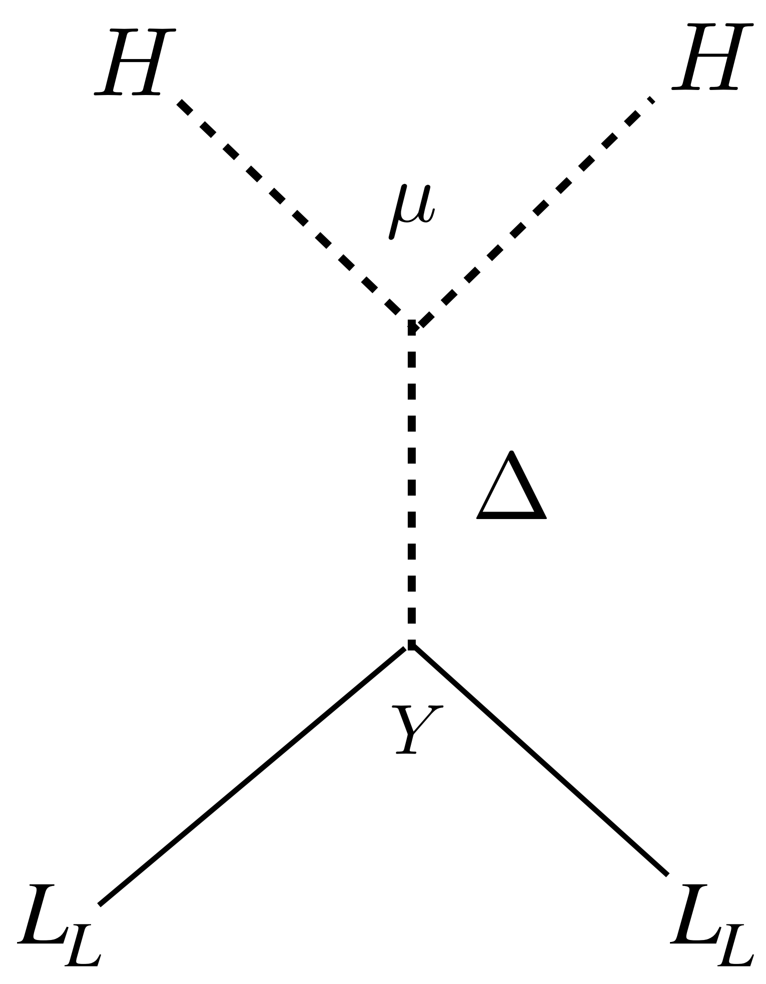
Example: realizations of dim-5 operator

Type I seesaw



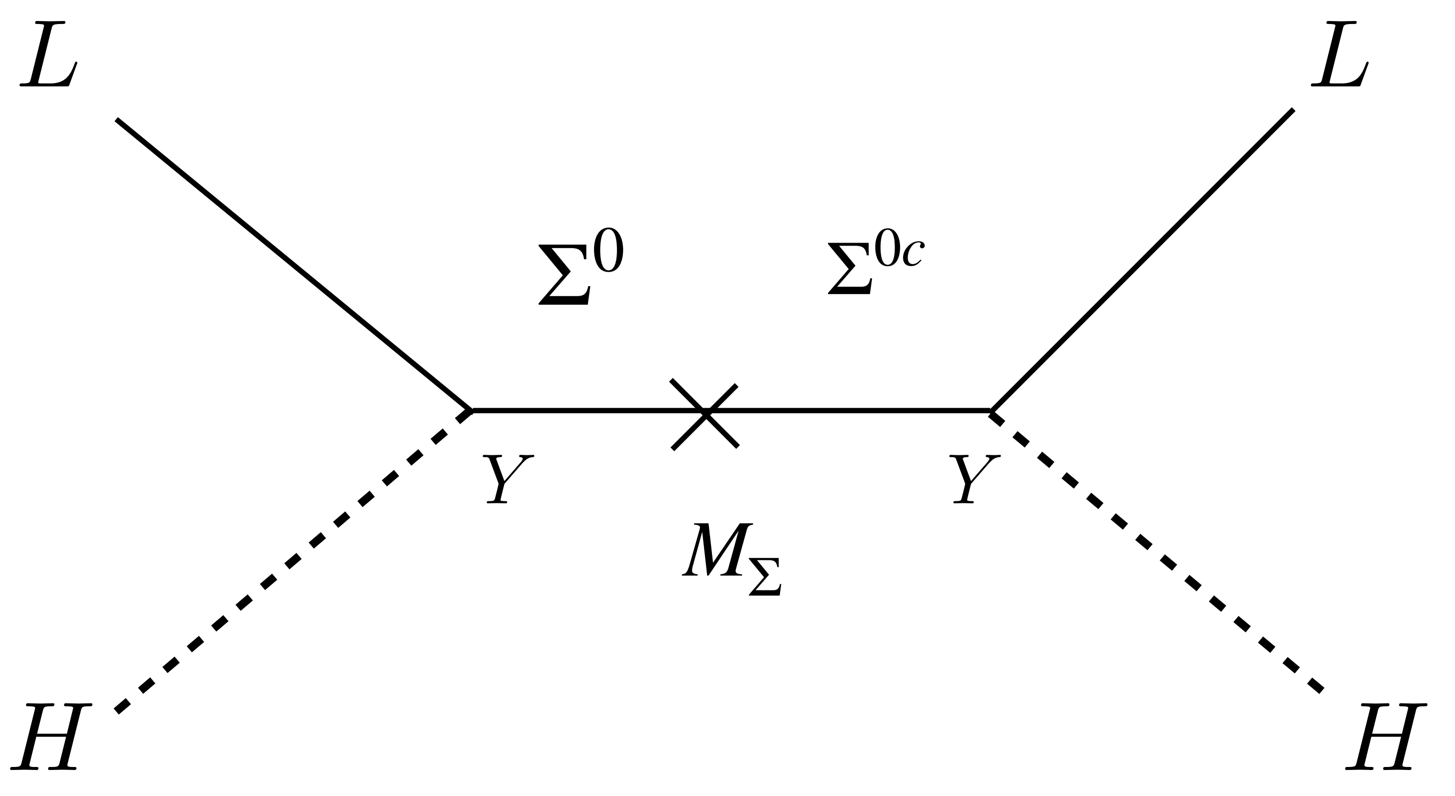
N_R : SM singlet
"Right-handed neutrino"

Type II seesaw



Δ: $SU(2)_L$ scalar triplet

Type III seesaw

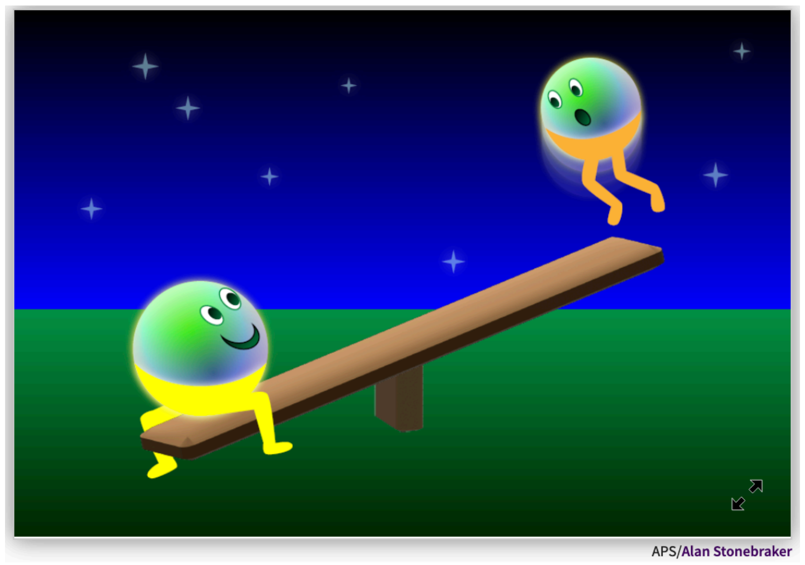


Σ: $SU(2)_L$ fermion triplet

Testing neutrino mass mechanisms

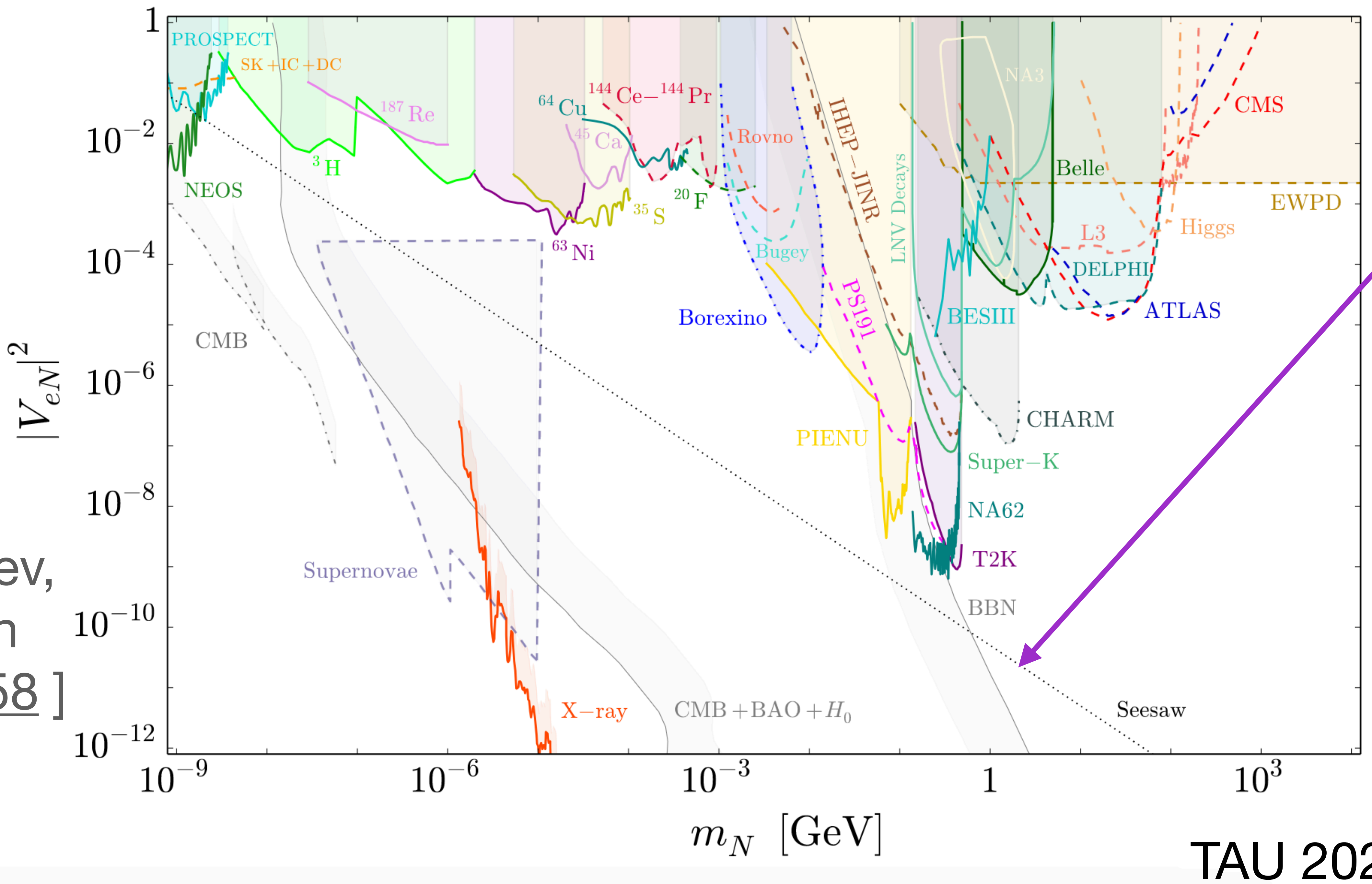
New particles associated to mass generation

Probing the Type I seesaw



Interaction of sterile with SM governed by active-sterile mixing angle

$$\theta \propto \frac{yv}{M_N}$$, neutrino mass $m_\nu \propto \theta \times (yv)$



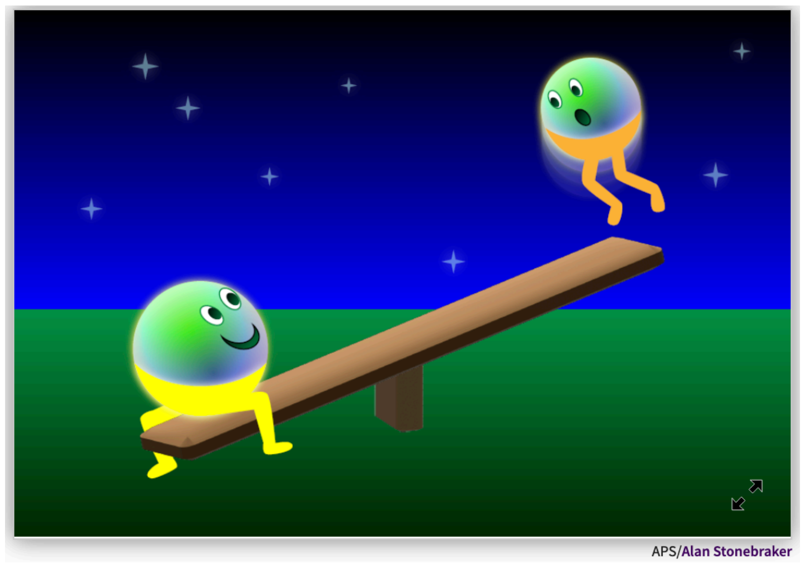
[Bolton, Dev, Deppisch 1912.03058]

Phenomenology depends on mass of sterile

Light sterile: produced at experiments + cosmology

Heavy sterile: unitarity of neutrino mixing matrix

Testing neutrino mass mechanisms

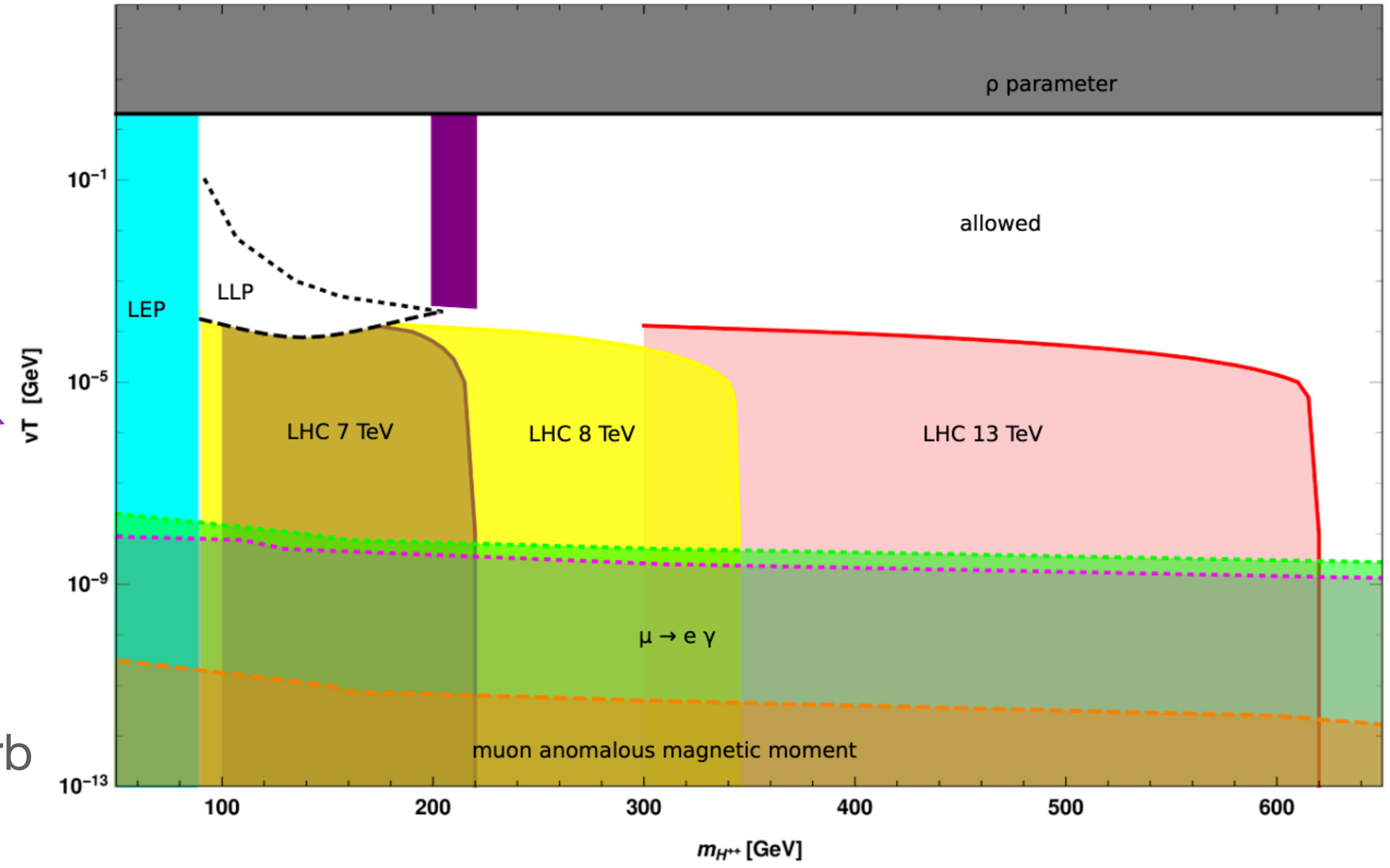


New particles associated to mass generation

Probing the Type II seesaw

Introduce new field charged under $SU(2)_L,\ U(1)_Y$
new neutral, singly and doubly charged scalar particles

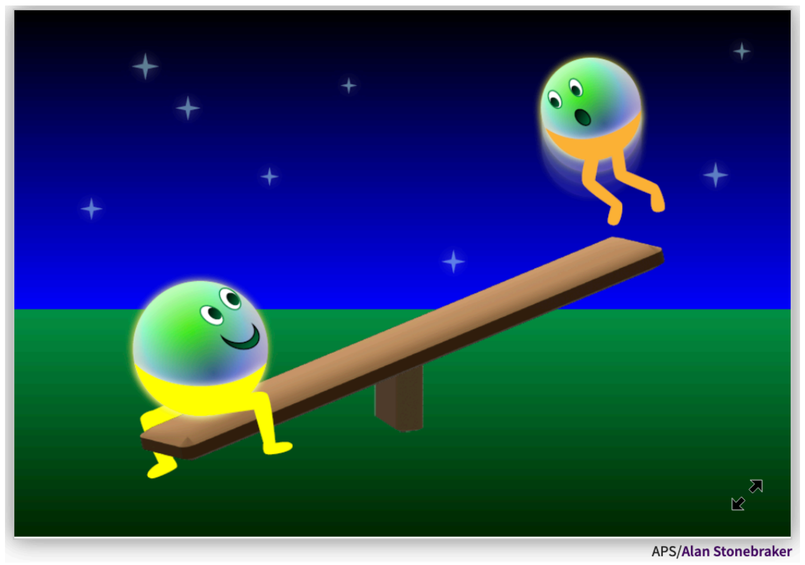
$$m_\nu \propto y\frac{\mu v^2}{M_\Delta^2}$$



EWPO, collider phenomenology, cLFV, g-2

[Antusch, Fischer, Hammad, Scherb 1811.03476]

Testing neutrino mass mechanisms



New particles associated to mass generation

Probing the Type III seesaw

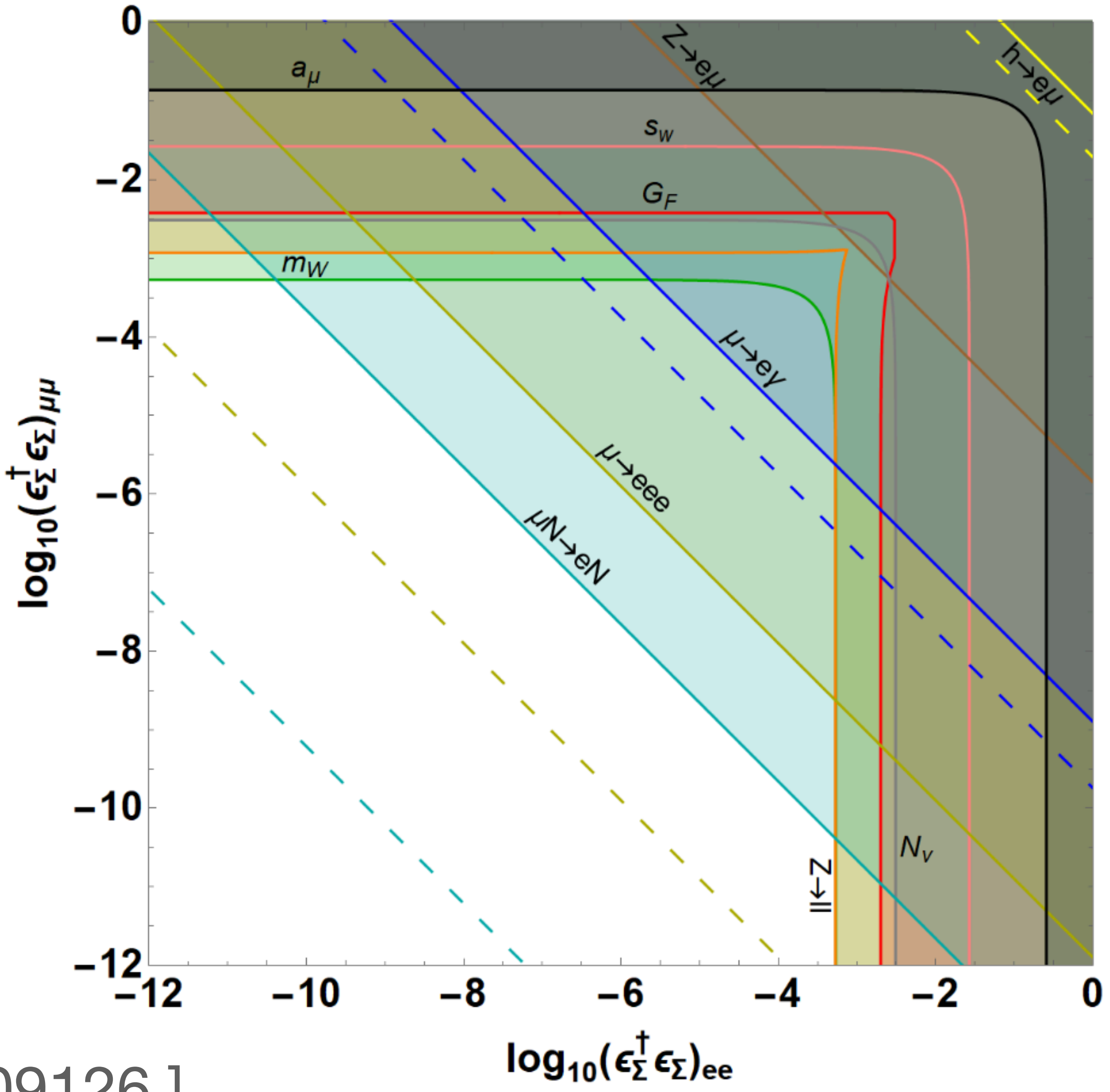
Introduce new field charged under $SU(2)_L,\ U(1)_Y$
new neutral, charged fermions with EW gauge interactions

$$m_\nu \propto yv\frac{yv}{M_\Sigma}$$

(similar to type I seesaw however
Σ^0 couples to EW bosons)

Charged fermion mixing!

L violating and L conserving processes:
Collider constraints, cLFV



[Coy, Frigerio 2110.09126]

Testing neutrino mass mechanisms

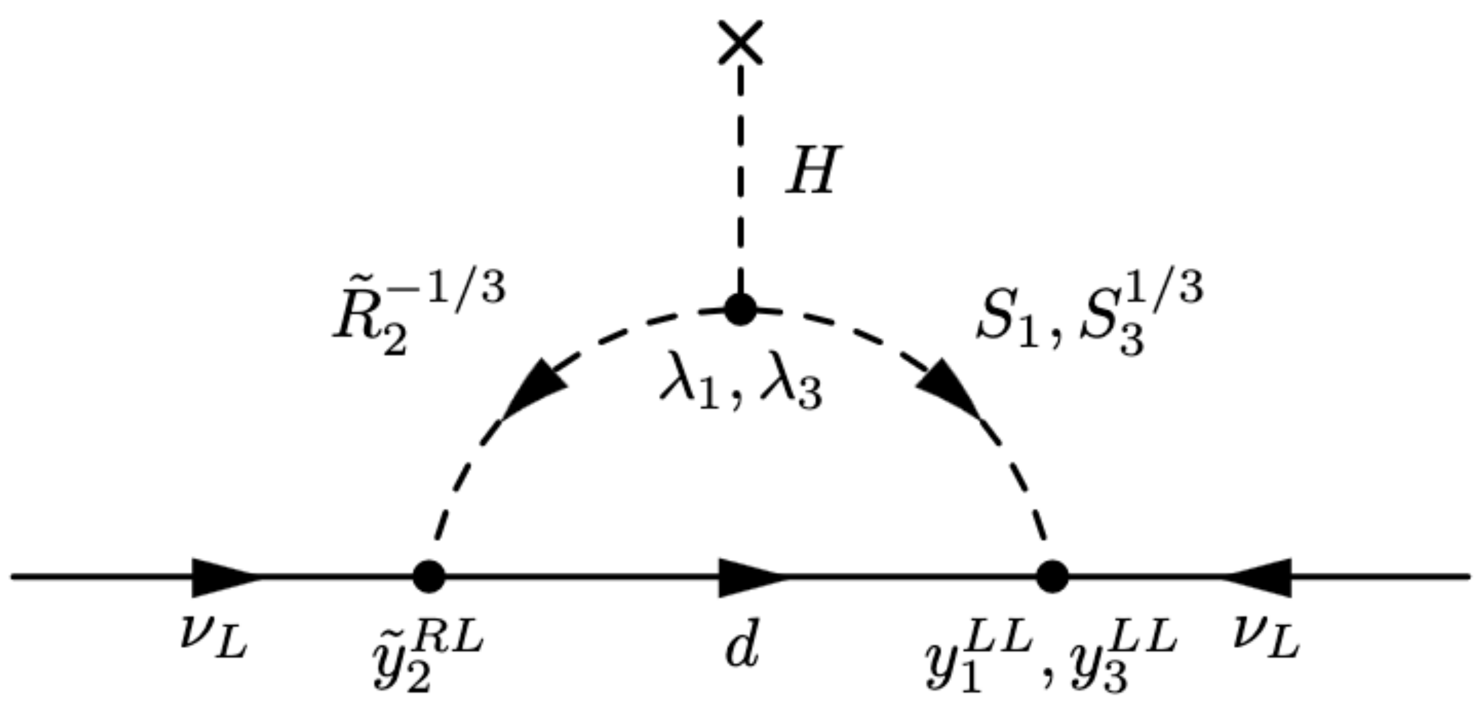
New particles associated to mass generation

Alternative neutrino mass mechanisms: radiative neutrino mass models

Smallness of m_ν due to loop factor

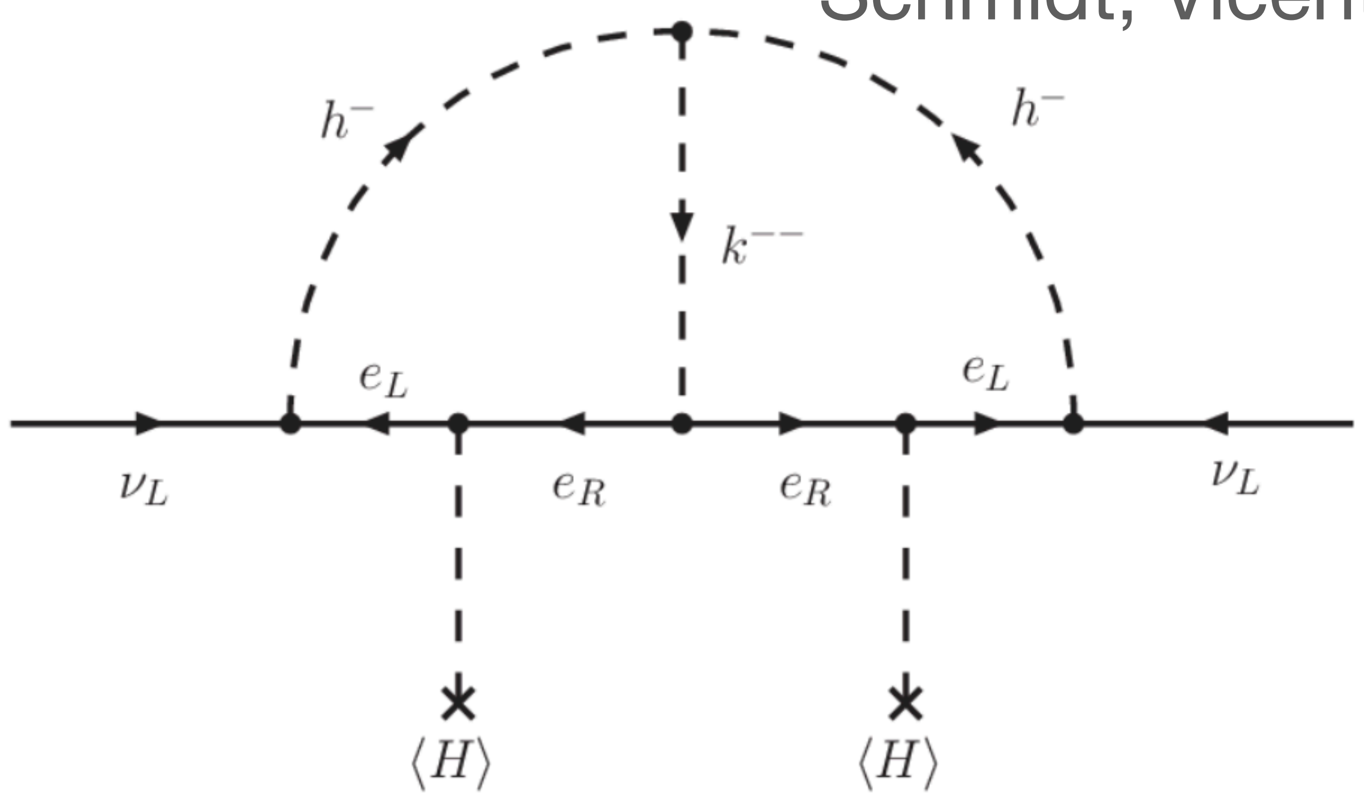
1-, 2-, 3-loop mass models available in literature

[for a review see Cai, Herrero-Garcıa, Schmidt, Vicente. Volkas 1706.08524]



[Doršner, Fajfer, Košnik 1701.08322]

Leptoquark model



[Zee '86, Babu ‘88]

Zee-Babu model (new charged scalars)

Testing neutrino mass mechanisms

Connection to other open questions of SM

Dark Matter

DM particles introduced scotogenic neutrino mass model, realization of inverse seesaw

[Ma, 0601225, De Romeri, Fernandez-Martinez, Machado, Niro, JG 1707.08606]

Baryon asymmetry of the Universe

Leptogenesis:
lepton number violating decays of heavy sterile neutrinos

→ can be realized in parameter space of high scale type I seesaw

Unification of forces

Right-handed neutrinos automatically introduced in SO(10) GUT

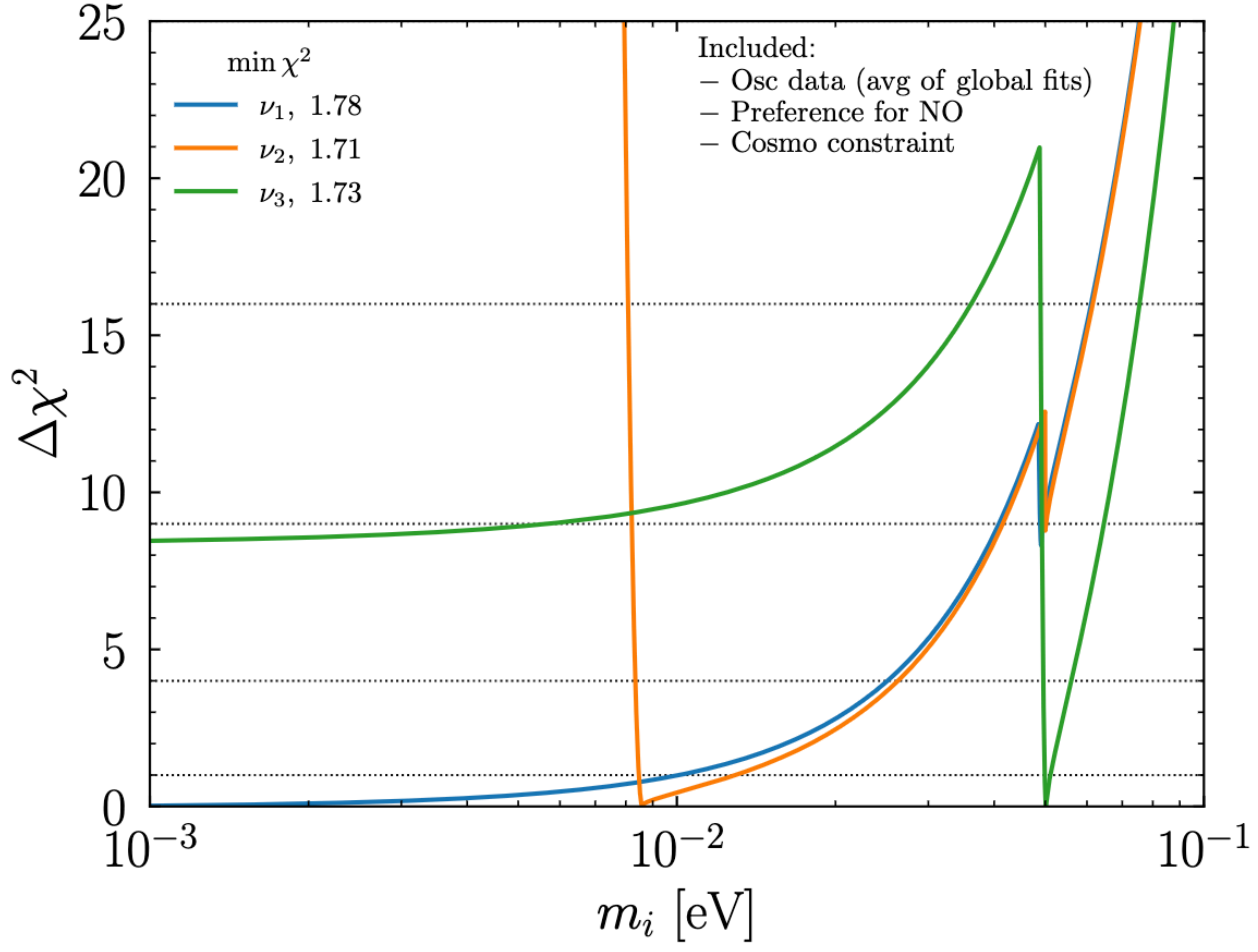
High scale type I seesaw scale ≈ scale of unification

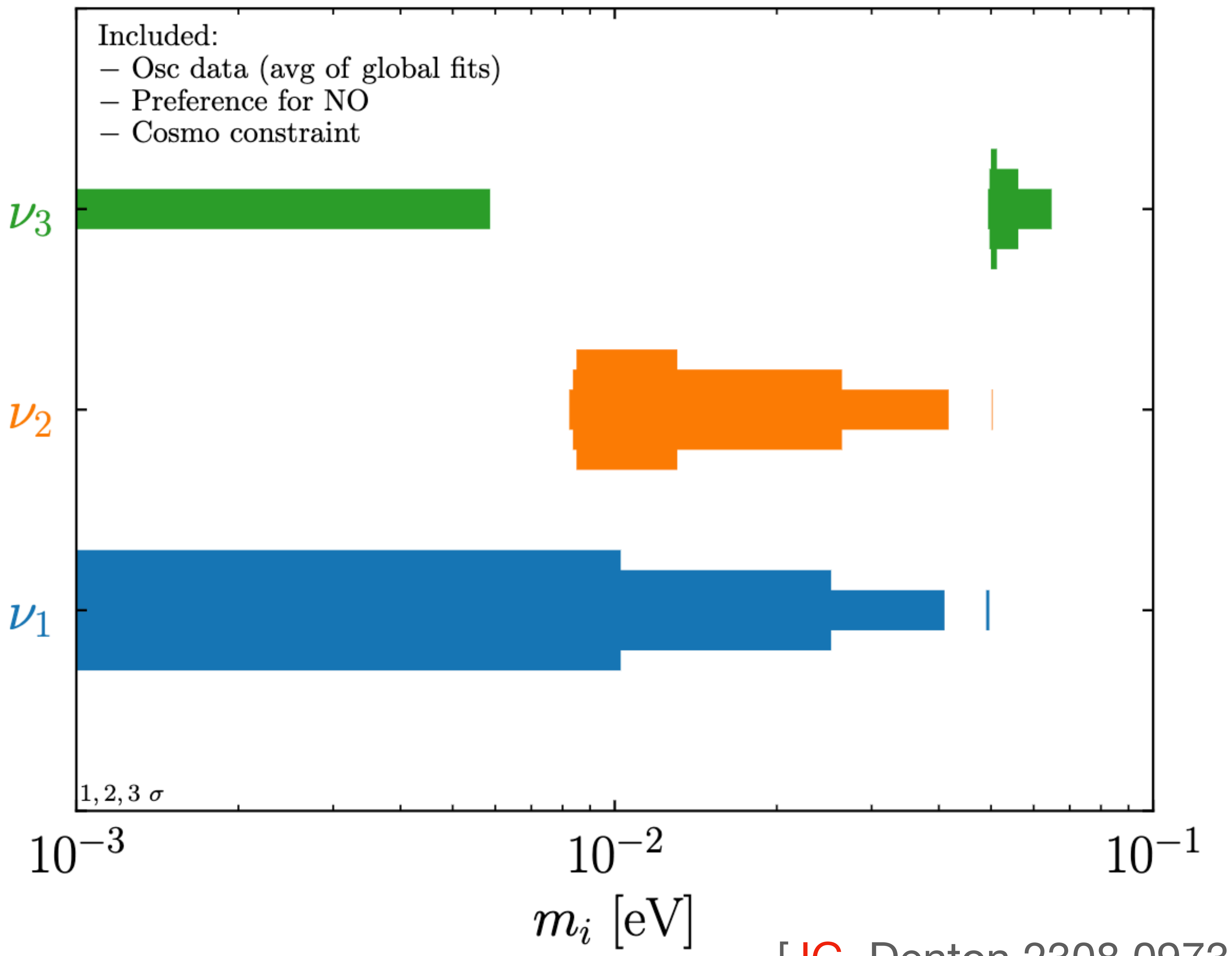
Summary & Conclusion

- Neutrino oscillations $\rightarrow$ Very strong evidence for need for additional particles related to neutrino mass generation
- Many possible mass mechanisms with rich phenomenology
- So far no sign of new particles
- If new particle is discovered, need to test if it can reproduce measured neutrino masses and mixing
- Future improved experimental sensitivities and new testable models will hopefully bring us closer to find neutrino mass generation mechanism

Thanks for your attention!

Appendix: Neutrino mass

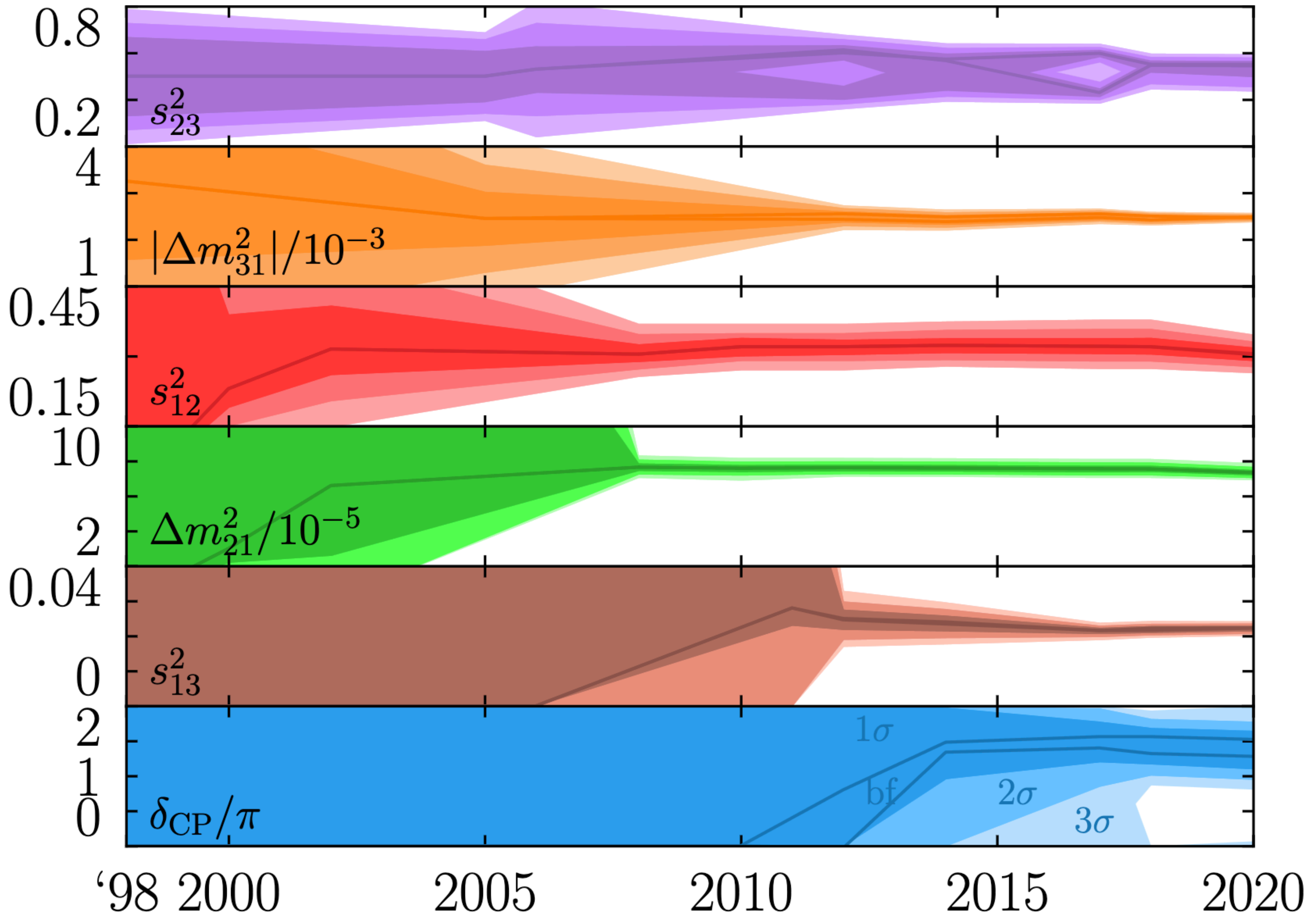




[JG, Denton 2308.09737]

Appendix: Neutrino oscillation parameters

Neutrino oscillation parameters measured over years



[Denton et al 2212.00809]

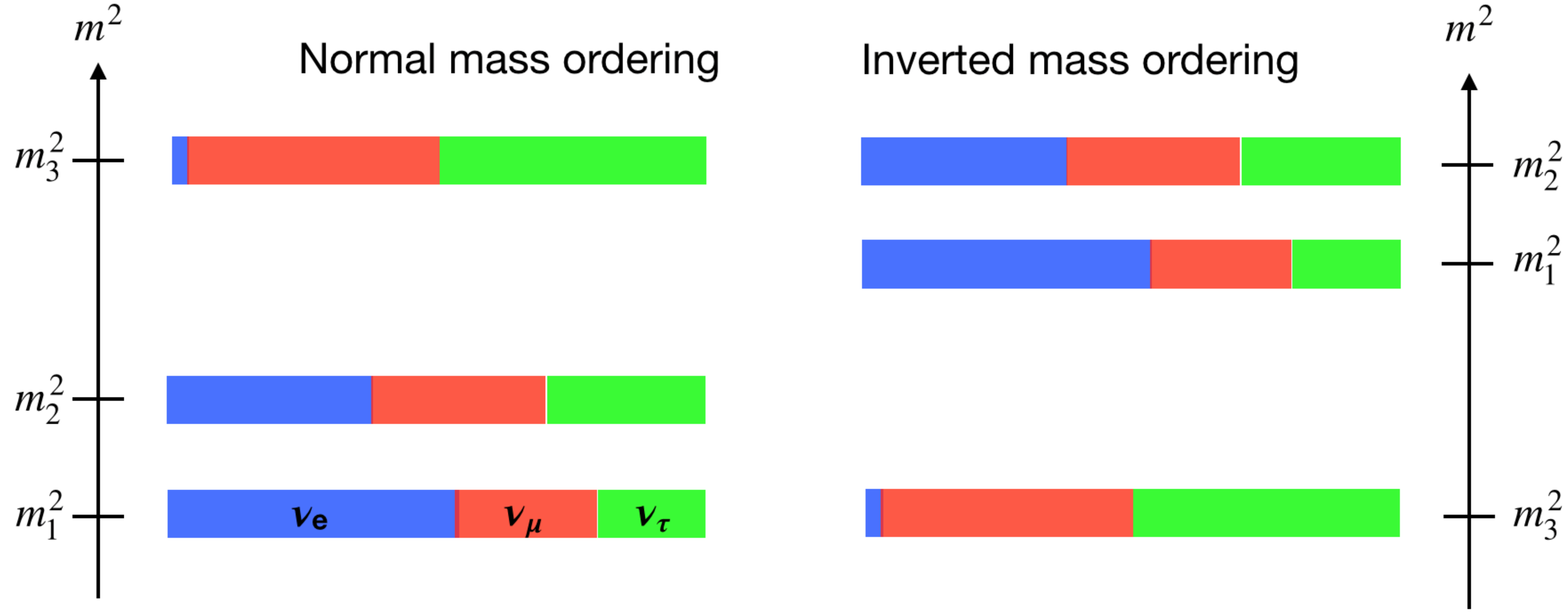
Appendix: Neutrino oscillation parameters

Global fits to oscillation data:

mass splittings: $|\Delta m^2_{32}| = 2.5 \cdot 10^{-3}\ \text{eV}^2,\ \Delta \text{m}^2_{21} = 7.4 \cdot 10^{-5}\ \text{eV}^2$

[nufit v5.1]

mass ordering unknown



$m_1 < m_2 < m_3$ $\qquad$ $m_3 < m_1 < m_2$