Fermilab

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BSM in neutrino experiments

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Why? - theory

Charged fermion masses seem to come from the Higgs mechanism

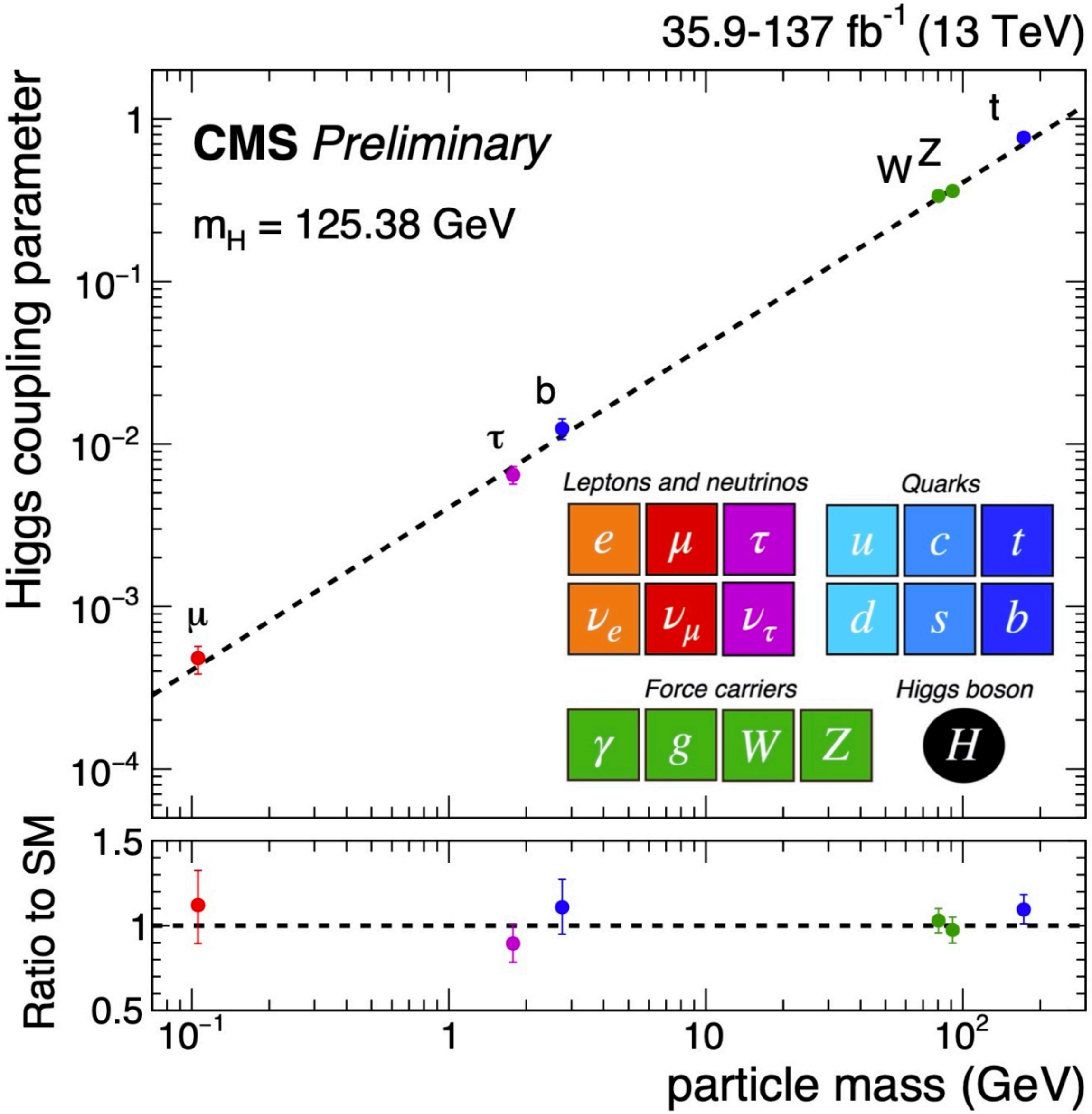
Higgs mechanism: unique prediction for charged fermions

But for neutrinos:

1) New particles required (e.g. RH ν)

2) Additional freedom

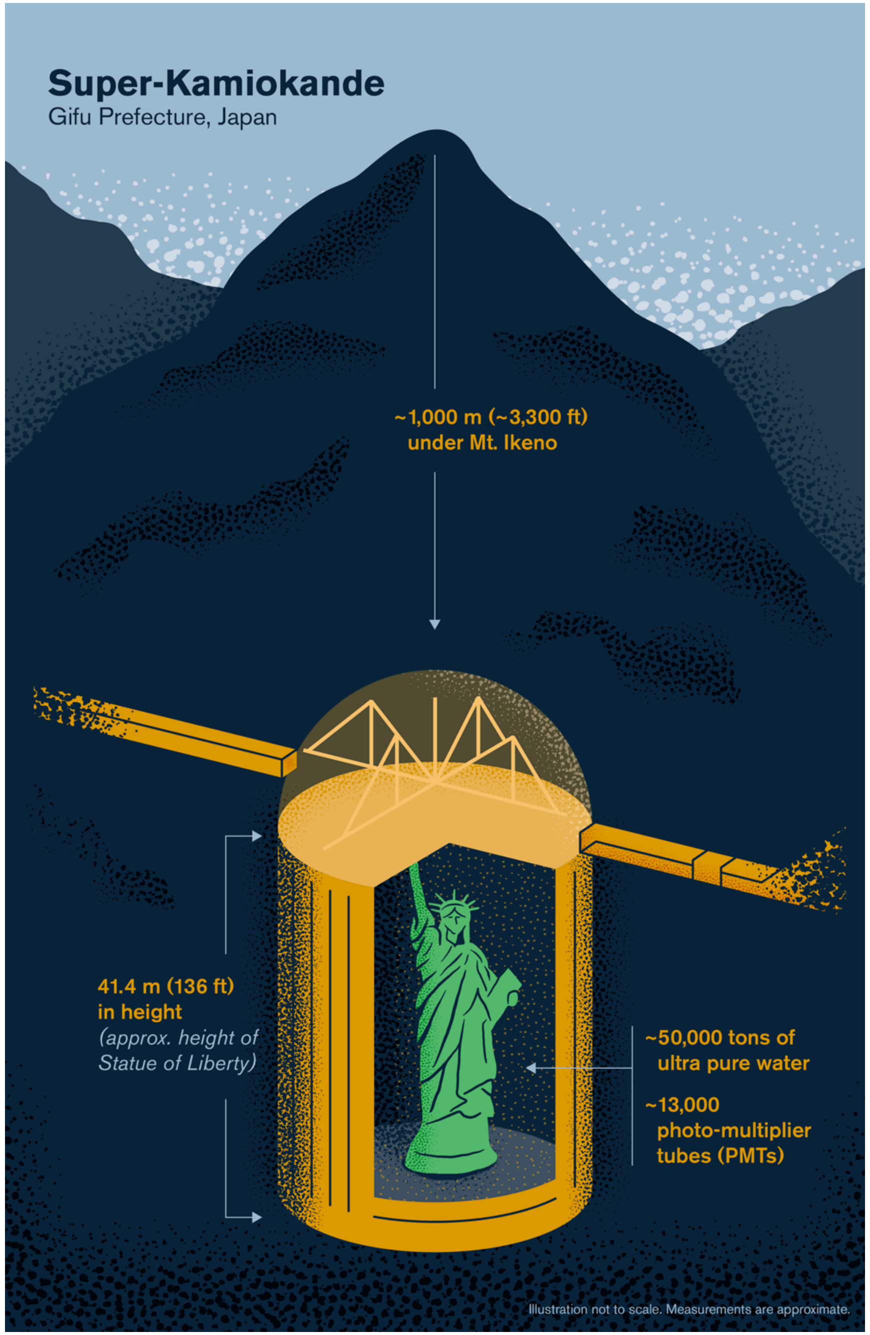
m_ν: only lab-based evidence of BSM...



Why? - experiment

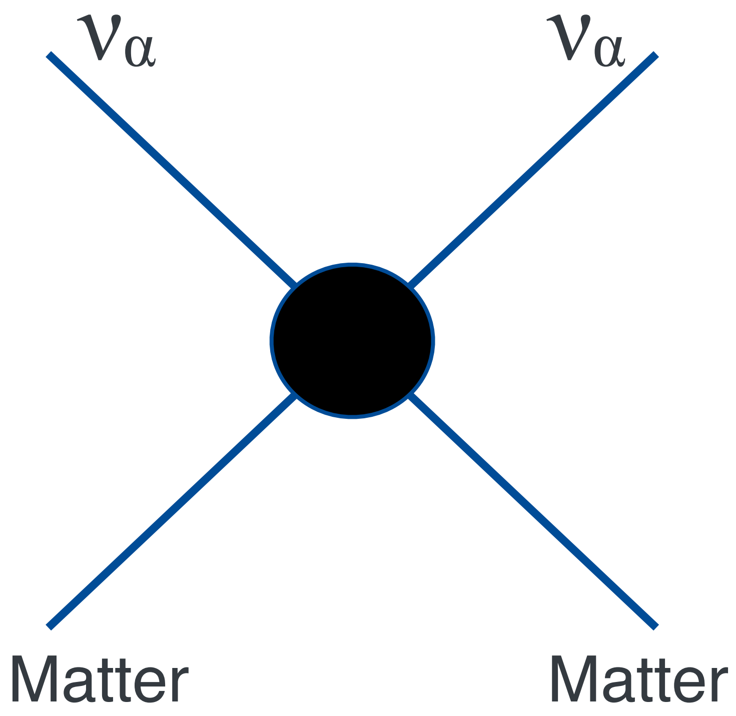
Neutrino experiments inherently have very special setups

1) High intensities
2) Enormous detectors
3) Oscillations: quantum
4) Weak cross sections



Some thoughts before we go in detail

Neutrino matter effects



$$V = \sqrt{2} G_F n_e$$

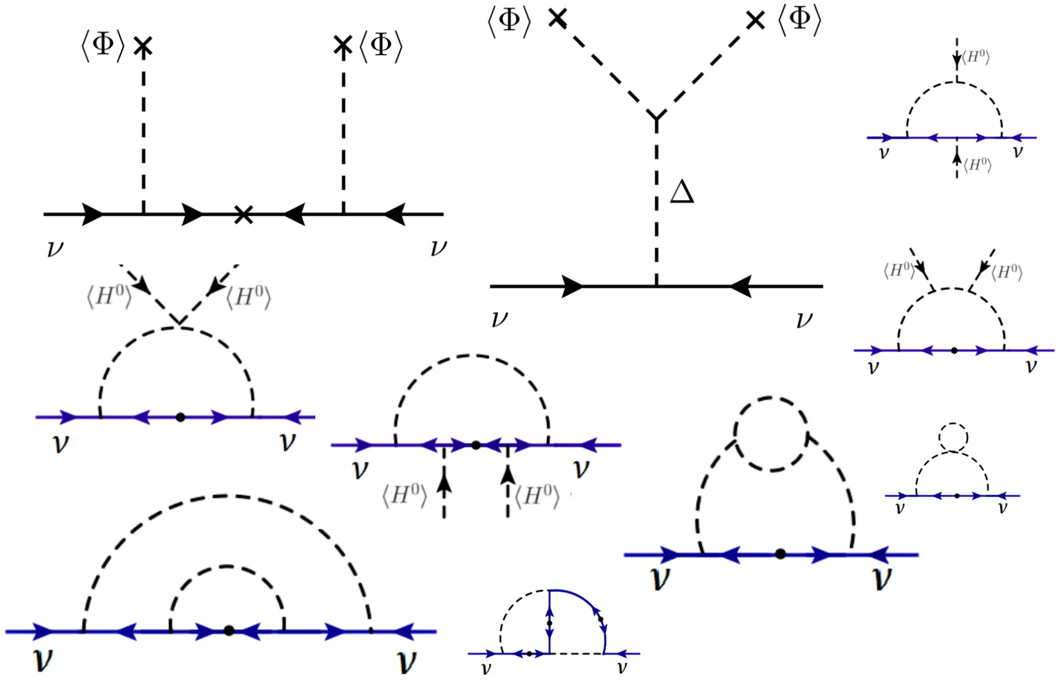
$$G_F = \frac{1}{\sqrt{2} v^2} \sim \frac{1}{(300\ \mathrm{GeV})^2}$$

Measuring the matter potential at 1% level is **probing the several TeV scale in a very nontrivial way**

Some thoughts before we go in detail

Neutrino masses live below the eV scale but could be a consequence of physics living from eV to 10^{13} GeV

$$m_\nu \sim \frac{y^2 v^2}{mN} \;?$$



There is **no reason to believe** that the neutrino mass mechanism is minimal, and it lives at the highest possible scale

Some thoughts before we go in detail

Weak interactions are

a blessing and a curse

It makes experiments much harder

It makes neutrinos excellent probes

in astrophysics and cosmology

On what follows, I'll show you two examples of how neutrinos can probe BSM scenarios from the 10^{-20} eV all the way up to 10^{13} eV

(range could be larger, but no time!)

Let's explore an extremely weakly interacting scenario:

ultralight dark matter coupling to neutrinos

Ultralight Dark Matter

Dark matter could be so light that
its de Broglie wavelength would be **the size of the galaxy**

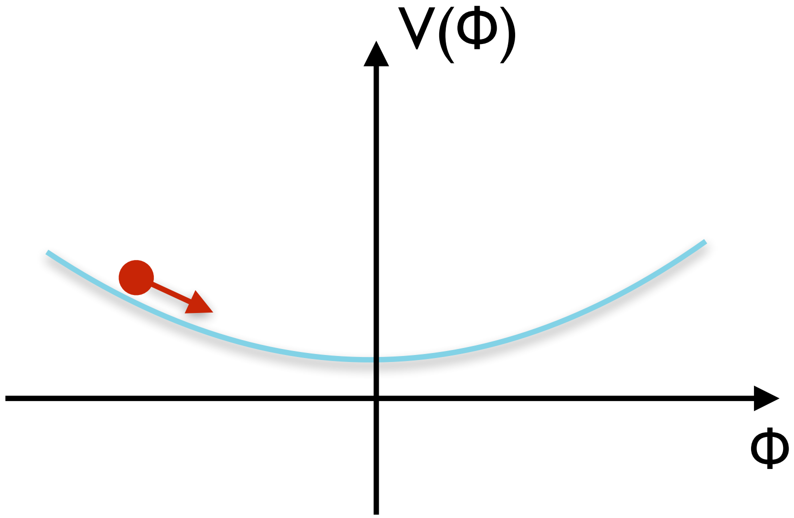
There are many candidates for that: axions, ultralight pseudo-Nambu-Goldstone bosons, vector bosons, ...

Let's start with an ultralight scalar that couples to neutrinos

Ultralight Dark Matter

Very light scalar DM (<< eV):

- very high occupation number
- classical field



$$(\partial_t^2 + \underbrace{3H\partial_t}_{\text{friction}} + m_\phi^2)\phi = 0$$

Klein-Gordon

Damped harmonic oscillator

Φ'' << 3 H Φ': slow roll regime

Later times: coherent oscillations

Energy stored: $\rho_\phi = \frac{m_\phi^2 \phi^2}{2}$

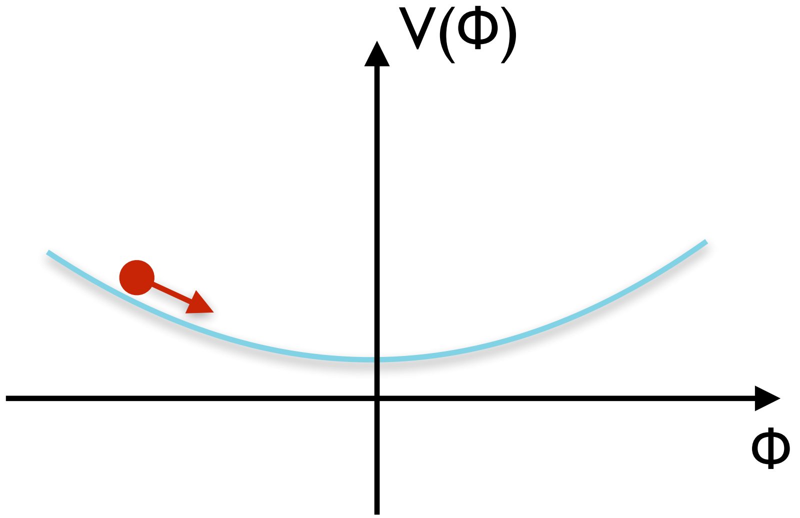
Local field value

$$\phi(x,t) \simeq \frac{\sqrt{2\rho_\phi^\odot}}{m_\phi} \cos[m_\phi(t - \vec{v}\cdot\vec{x})]$$

What if this field couples to neutrinos?

Very light scalar DM (<< eV):

- very high occupation number
- classical field



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Local field value

$$\phi(x,t) \simeq \frac{\sqrt{2\rho_\phi^\odot}}{m_\phi} \cos[m_\phi(t - \vec{v}\cdot\vec{x})]$$

$$\mathscr{L}_{\text{eff}} = -m_\nu \left(1 + y\frac{\phi}{\Lambda}\right)\nu\nu + h.c.$$

(e.g., $\mathscr{L} \supset -y_\nu HLN - (\Lambda - y\phi)NN$)

Toy model

Modulation amplitude (set y = 1):

$$\eta_\phi \equiv \frac{\sqrt{2\rho_\phi^\odot}}{\Lambda m_\phi} = 2.2 \left(\frac{\rho_\phi^\odot}{0.3\ \text{GeV/cm}^3}\right)\left(\frac{\text{TeV}}{\Lambda}\right)\left(\frac{10^{-15}\ \text{eV}}{m_\phi}\right)$$

Ultralight Dark Matter

$m_\nu = m_\nu(t)$

Δm^2 and θ_{ij} modulate!

$$\Delta m^2_{ij}(x,t) \equiv m_i^2 - m_j^2 \simeq \Delta m^2_{ij,0}\left(1 + 2\frac{\phi(x,t)}{\Lambda}\right) \qquad \theta_{ij}(x,t) = \theta_{ij,0} + \frac{\phi(x,t)}{\Lambda}$$

Modulation period $\tau_\phi \equiv \frac{2\pi}{m_\phi} \sim 10 \text{ min}\left(\frac{7\times 10^{-18}\text{ eV}}{m_\phi}\right)$

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Ultralight Dark Matter

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Modulation period

Longer than experiment running time: constant parameters

Shorter than neutrino time of flight: parameters average

Anything between those: striking effects on neutrino oscillations!

~ 10^{-12} eV ←—— interesting region ——→ ~ 10^{-23} eV

2.7 msec ~ 10 years

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Ultralight Dark Matter

Averaged out regime

Two flavor framework:

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

$$\langle P(\nu_\alpha \to \nu_\beta)\rangle = \int_0^{\tau_\phi} \frac{dt}{\tau_\phi} P(\nu_\alpha \to \nu_\beta)$$

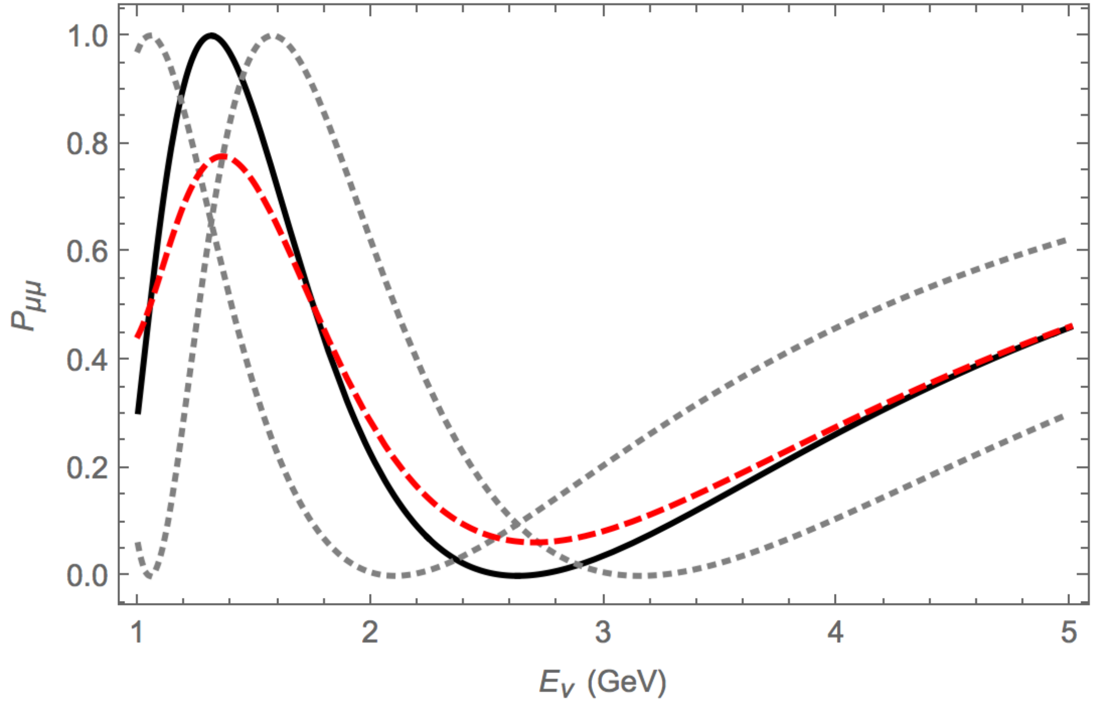
$$\Delta m^2_{ij}(x,t) \equiv m_i^2 - m_j^2 \simeq \Delta m^2_{ij,0}\left(1 + 2\frac{\phi(x,t)}{\Lambda}\right)$$

Mass splittings

$$\int_0^{\tau_\phi} \frac{dt}{\tau_\phi} \sin^2\left[\frac{\Delta m^2 L}{4E}(1 + 2\eta_\phi \cos m_\phi t)\right]$$

$\Delta m^2(t)$ smears $P_{\alpha\beta}$

Better E_ν resolution = stronger constraints



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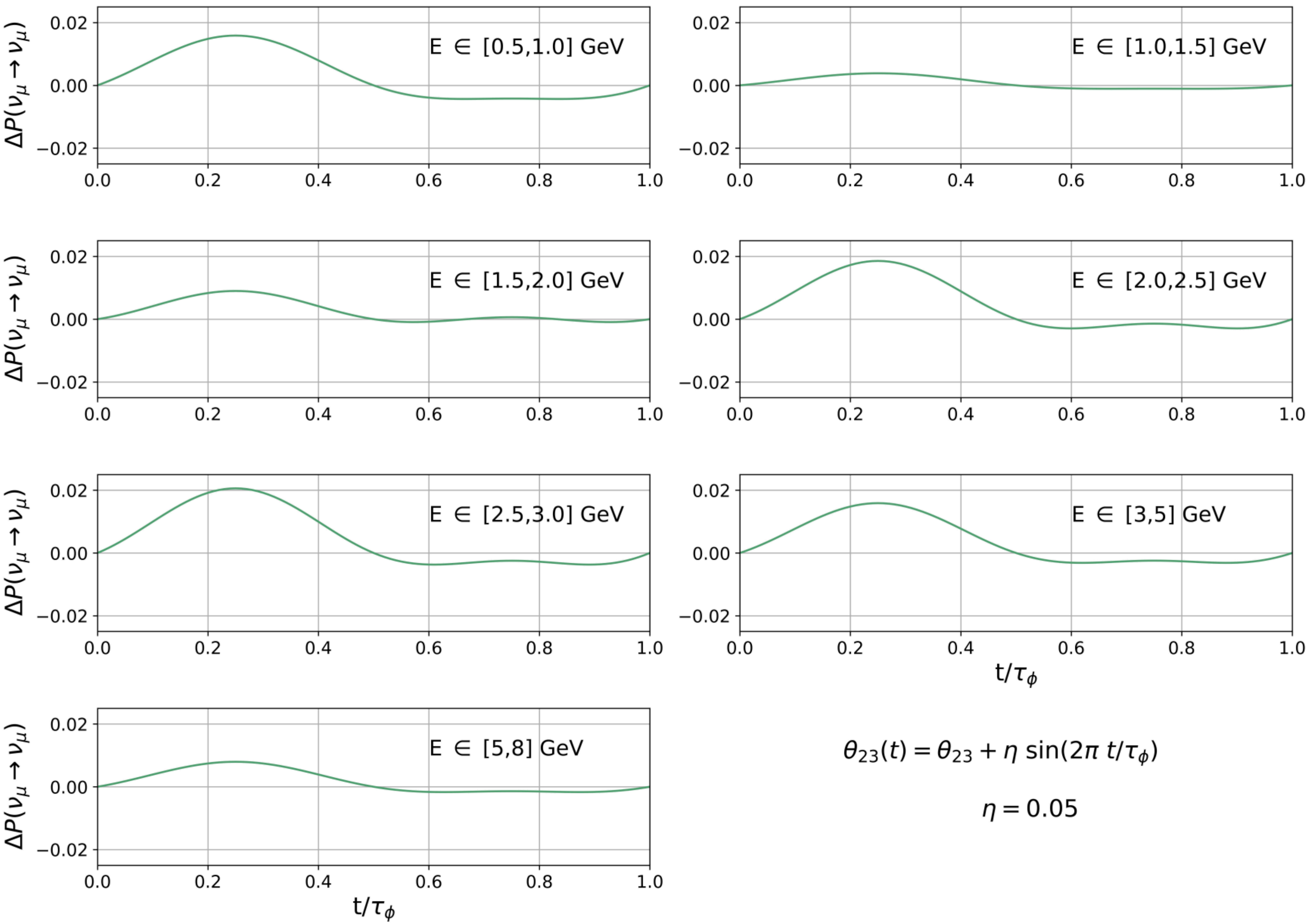
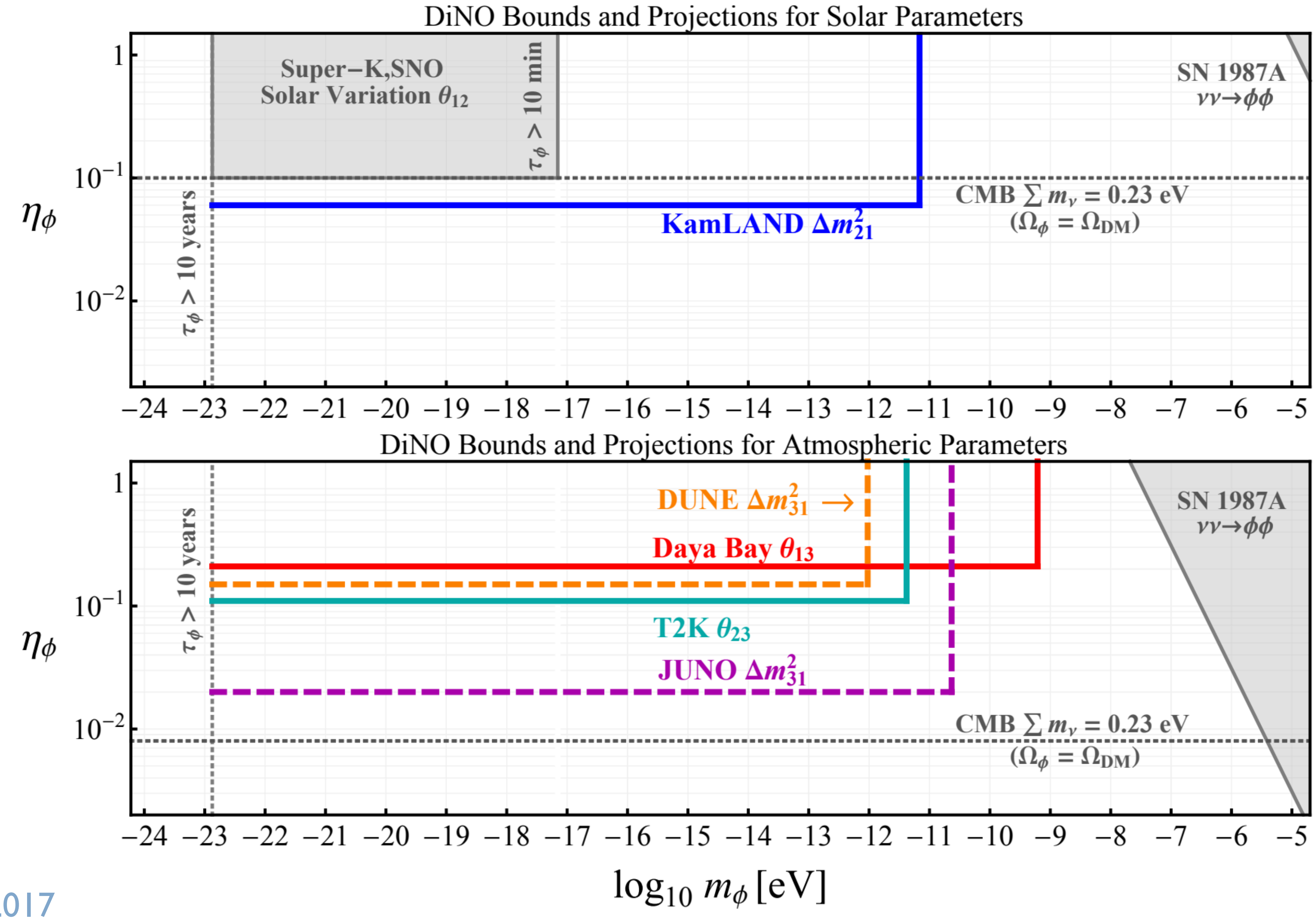
Time modulation signatures



$$\theta_{23}(t) = \theta_{23} + \eta \sin(2\pi\, t/\tau_\phi)$$

$$\eta = 0.05$$

Ultralight Dark Matter



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Ultralight Dark Matter

This scenario can also be mapped on neutrino oscillation decoherence cases

$$\frac{d\rho}{dt} = -i[H, \rho] + \left(2c\rho c^{\dagger} - \rho c^{\dagger}c - c^{\dagger}c\rho\right)$$

It is a bit technical, but this is the first time I have seen
a connection between decoherence effective parameters and a UV complete model

Ultralight Dark Matter

What if the ultralight field is a gauge boson?
Let's take an ultralight B-L gauge boson

$$\mathbf{A}'(t) \simeq \frac{\sqrt{2\rho_{\rm DM}/3}}{m_{A'}} \,\mathrm{Re}\Big[e^{i m_{A'} t} \sum_{i=1}^{3} \alpha_i \, e^{i\phi_i} \, \hat{\boldsymbol{n}}_i\Big]$$

$$\mathscr{L} \supset e' \, A'_\mu \, \nu^\dagger \bar{\sigma}^\mu \nu - \left(\frac{1}{2} m_\nu \, \nu\nu + \mathrm{h.c.}\right)$$

This field couples to the neutrino spin like a magnetic field

Spin-flip for Majorana neutrinos = neutrino to antineutrino conversion

The math gets a little involved, but here is a neat gif

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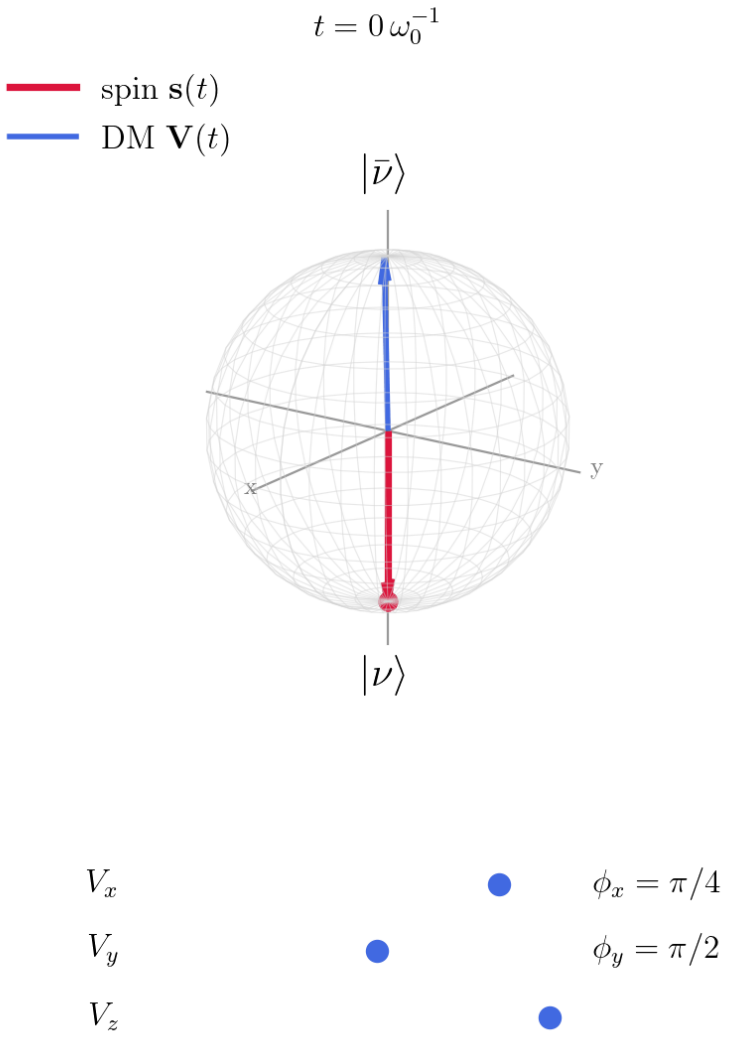
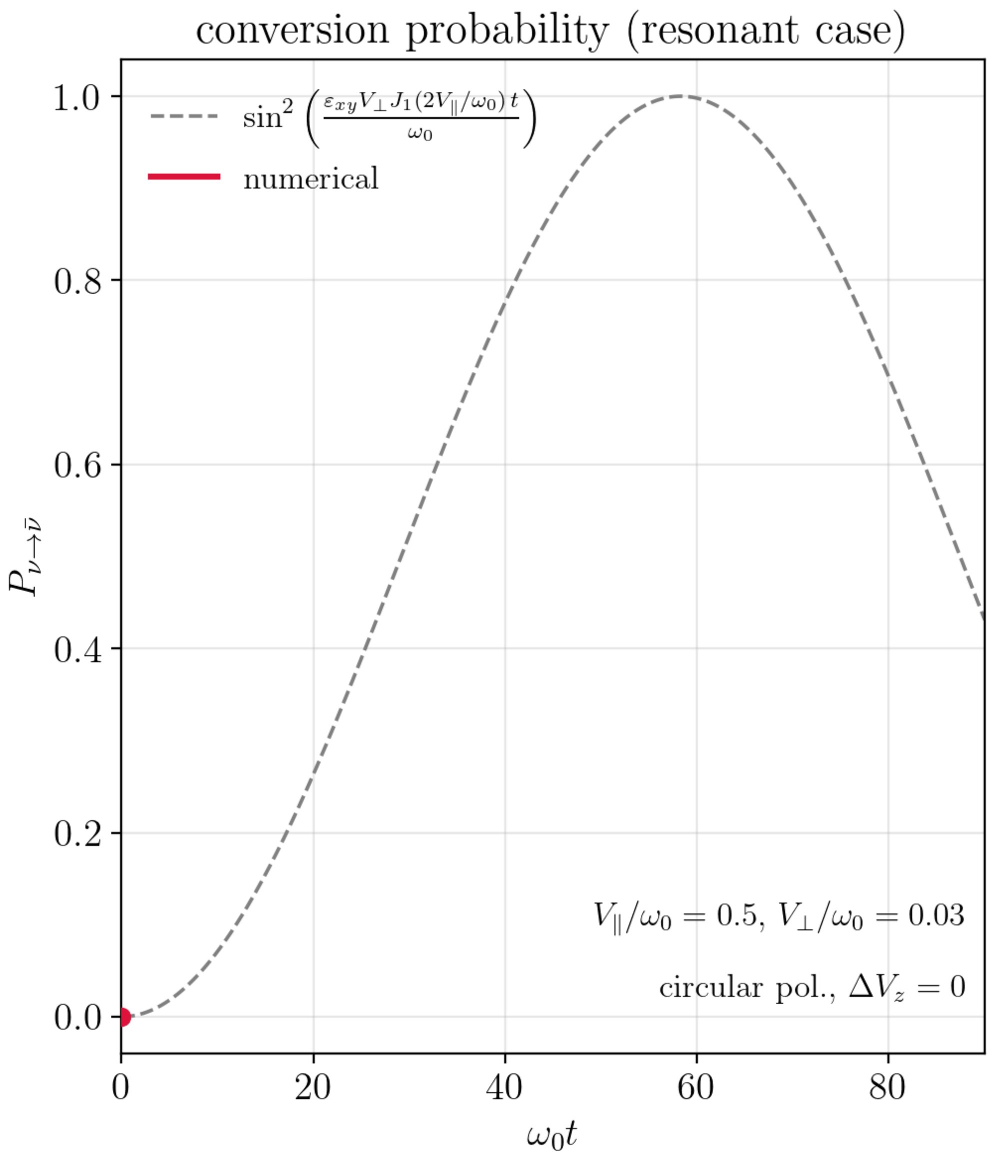
Ultralight Dark Matter





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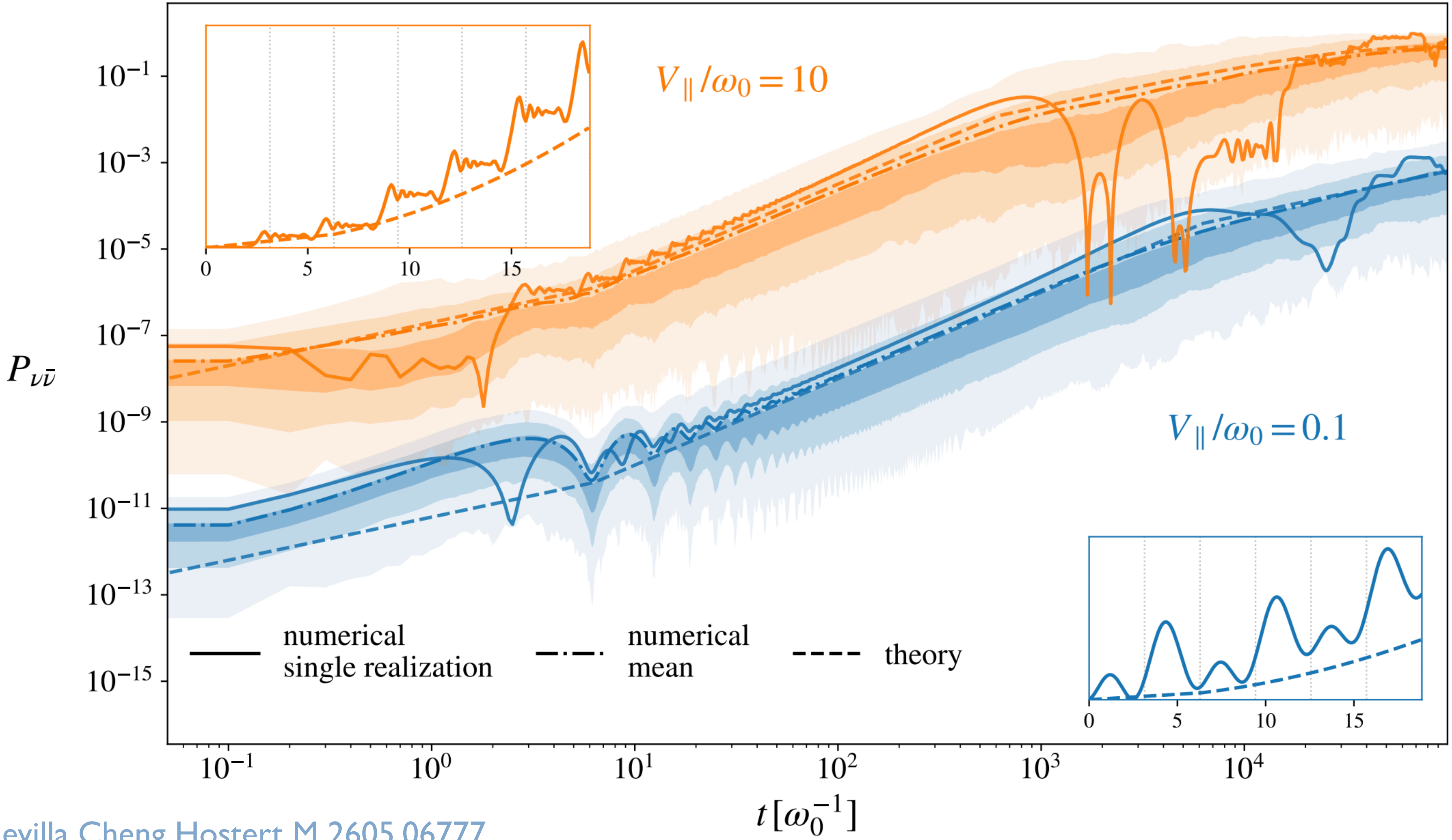
Ultralight Dark Matter



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Ultralight Dark Matter

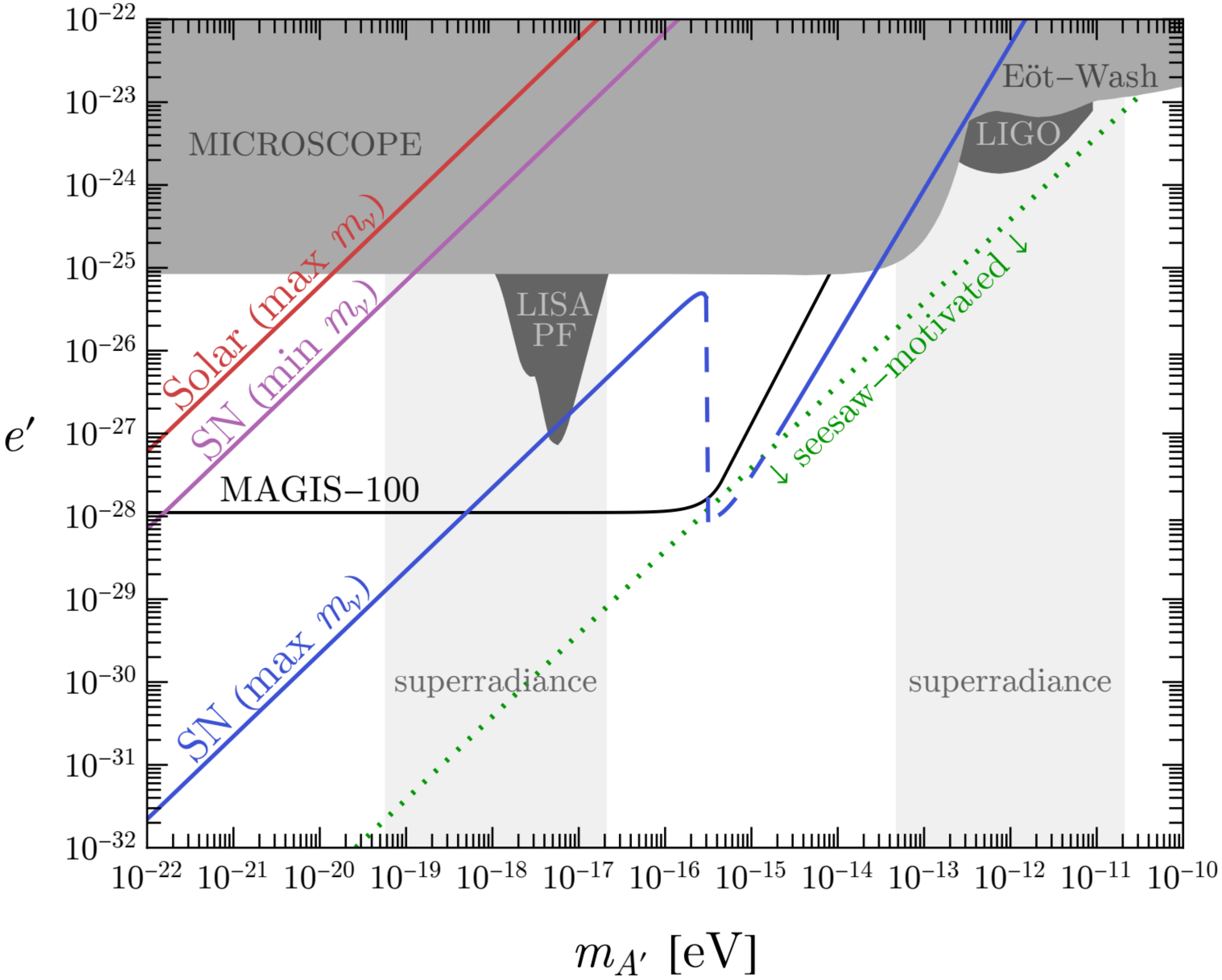
Two main probes

Solar neutrinos

Only produce neutrinos, any antineutrino would be a sign of new physics

Supernova neutrinos

Temperature between neutrinos and antineutrinos should be different, identical spectra would be new physics



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Let's move to the complete opposite scenario:

strongly interacting physics

Neutrino Masses and New Physics

Two possibilities for neutrino masses

Dirac	Majorana
$\mathcal{L} = -y_\nu \overline{L}\widetilde{H}\nu_R + \text{h.c.}$	???

Gravity effect **could** break global symmetries

$$\frac{1}{M_{\text{Pl}}}(LH)^2$$

This Planck correction is **ruled out by 6 orders of magnitude**

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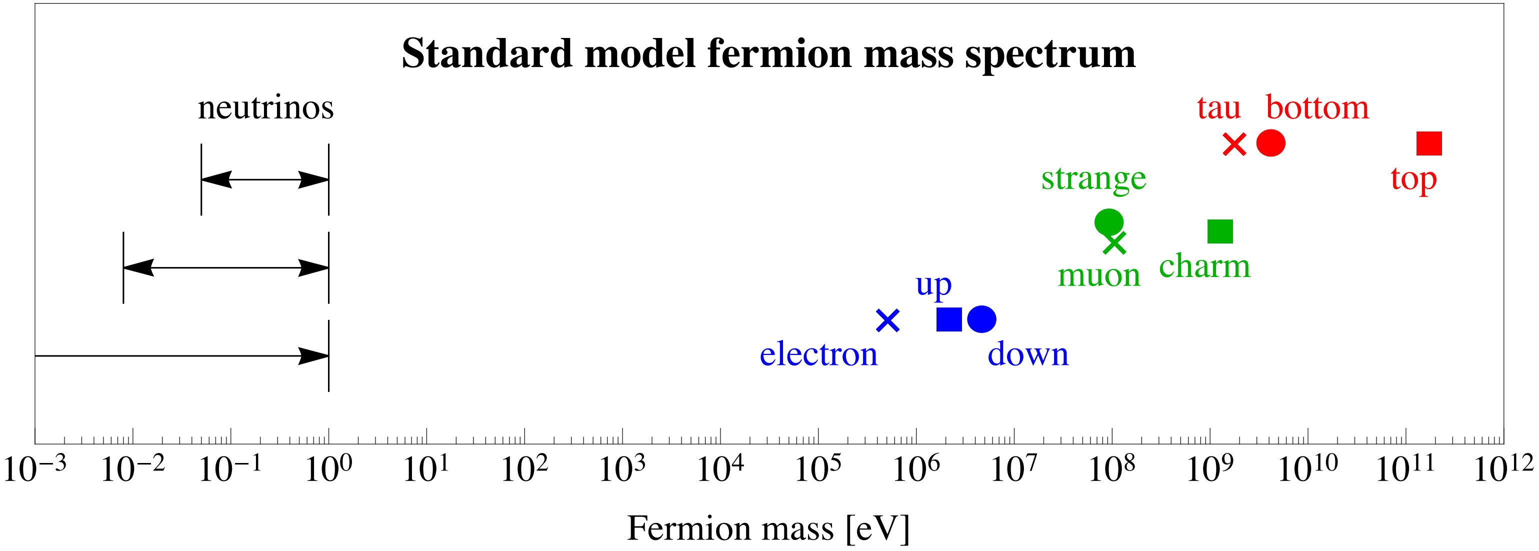
Neutrino Masses and New Physics

For Majorana neutrinos, there is no experimental indication of what should be the neutrino mass mechanism

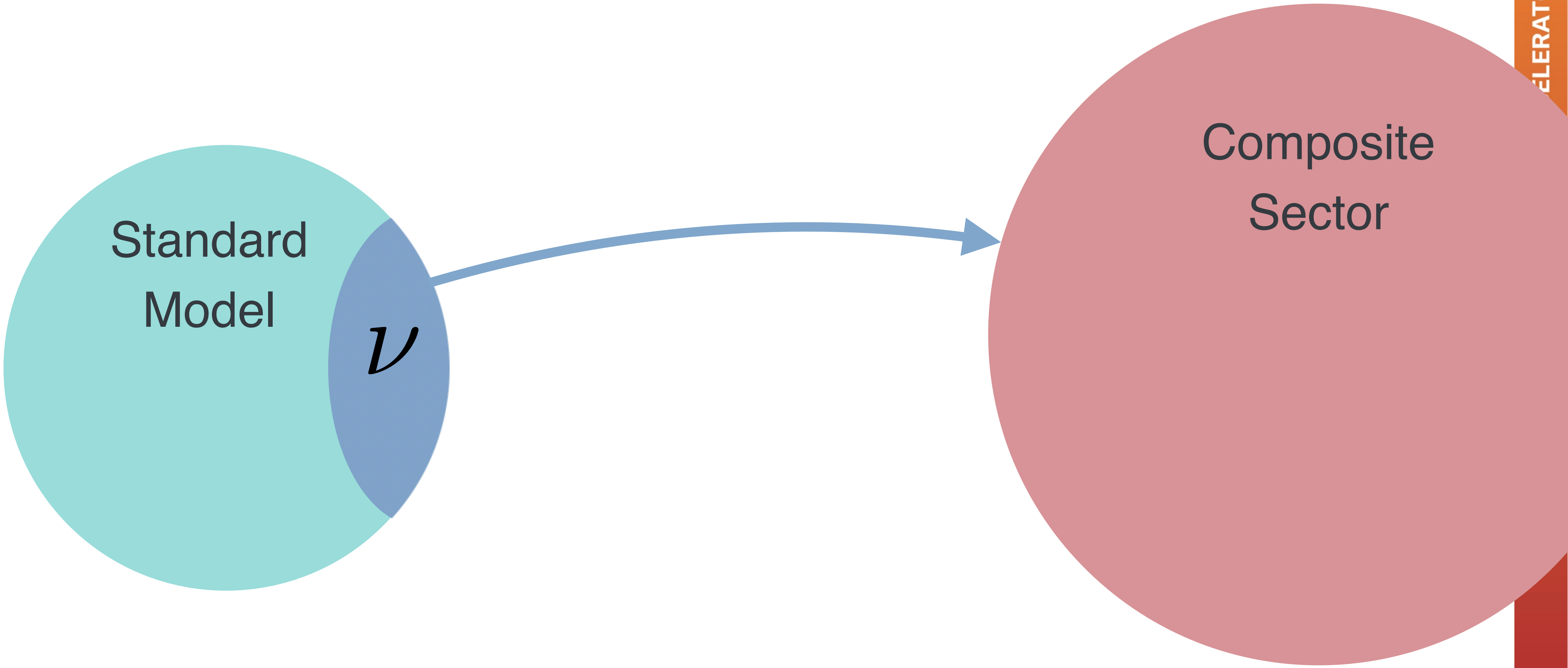
We know it must involve the Higgs

But we don't know much more...



Neutrino Masses and New Physics

What if neutrino masses come from a composite sector?



**We describe the connection with an unparticle framework*

Neutrino Masses and New Physics

Composite operator ~N

$$\mathcal{L}_{\rm UV} \supset \frac{\hat{\lambda}}{M_{\rm UV}^{\Delta_{\rm N}-3/2}} L H \mathcal{O}_{\rm N} + {\rm h.c.}$$

Composite operator ~NN^c

$$\mathcal{L}_{\rm UV} \supset \frac{\hat{\mu}^c}{M_{\rm UV}^{\Delta_{2{\rm N}^c}-4}} \mathcal{O}_{2{\rm N}^c} + {\rm h.c.}$$

Anomalous dimension:

tells you about degree of compositeness

Sit tight and calculate

$$\int d^4x\, e^{ipx} \langle 0 | T \left[\mathcal{O}_{\rm N}(x) \mathcal{O}^\dagger_{\rm N}(0) \right] | 0 \rangle = \int_0^\infty dM^2\, \rho(M^2)\, \frac{i\,\sigma^\mu p_\mu}{p^2 - M^2 + i\epsilon}$$

Eventually arrive at

$$m_\nu \sim \mu^c \left(\frac{\lambda v_{\rm EW}}{M_N} \right)^2 \sim \Lambda \left[C_\mu \hat{\mu}^c \left(\frac{\Lambda}{M_{\rm UV}} \right)^{\Delta_{2{\rm N}^c}-4} \right] \left[C_\lambda \hat{\lambda} \left(\frac{v_{\rm EW}}{\Lambda} \right) \left(\frac{\Lambda}{M_{\rm UV}} \right)^{\Delta_{\rm N}-3/2} \right]^2$$

$$m_\nu \sim \mathcal{O}(1) \times \Lambda \left(\frac{v_{\rm EW}}{\Lambda} \right)^2 \times \varepsilon^{\Delta_{2{\rm N}^c}+2\Delta_{\rm N}-7}$$

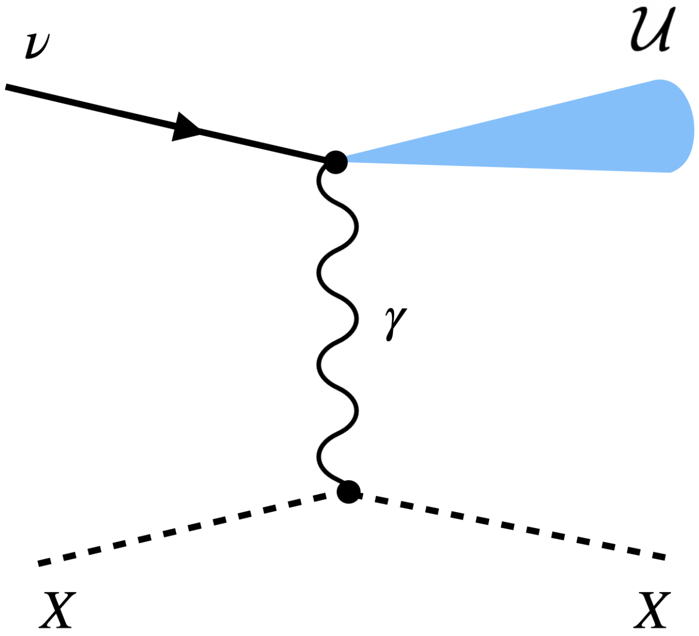
Chacko et al 2020

Λ: infrared scale (e.g. mass of RH neutrinos)

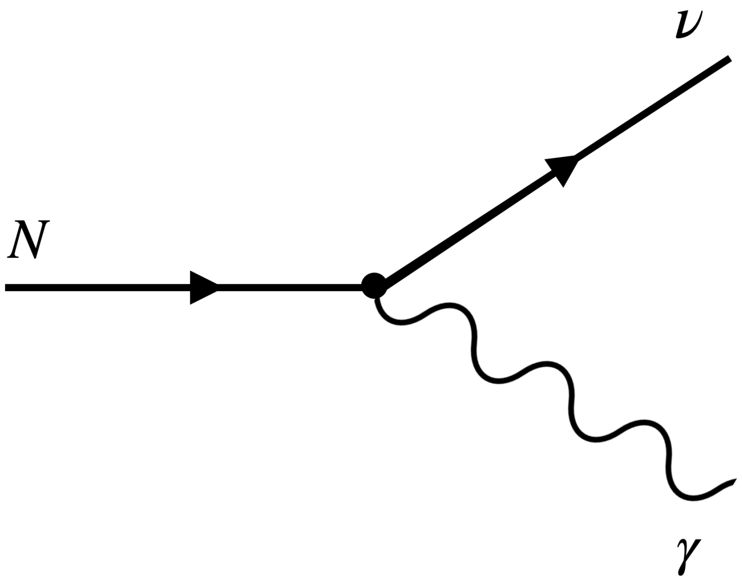
Neutrino Masses and New Physics

Transition dipole operator

$$\mathcal{L}_{\rm UV} \supset \frac{\hat{c}_D}{M_{\rm UV}^{\Delta_N+1/2}} L H F^{\mu\nu}\sigma_{\mu\nu}\mathcal{O}_N + \text{h.c.}$$



Travel, decay to photons



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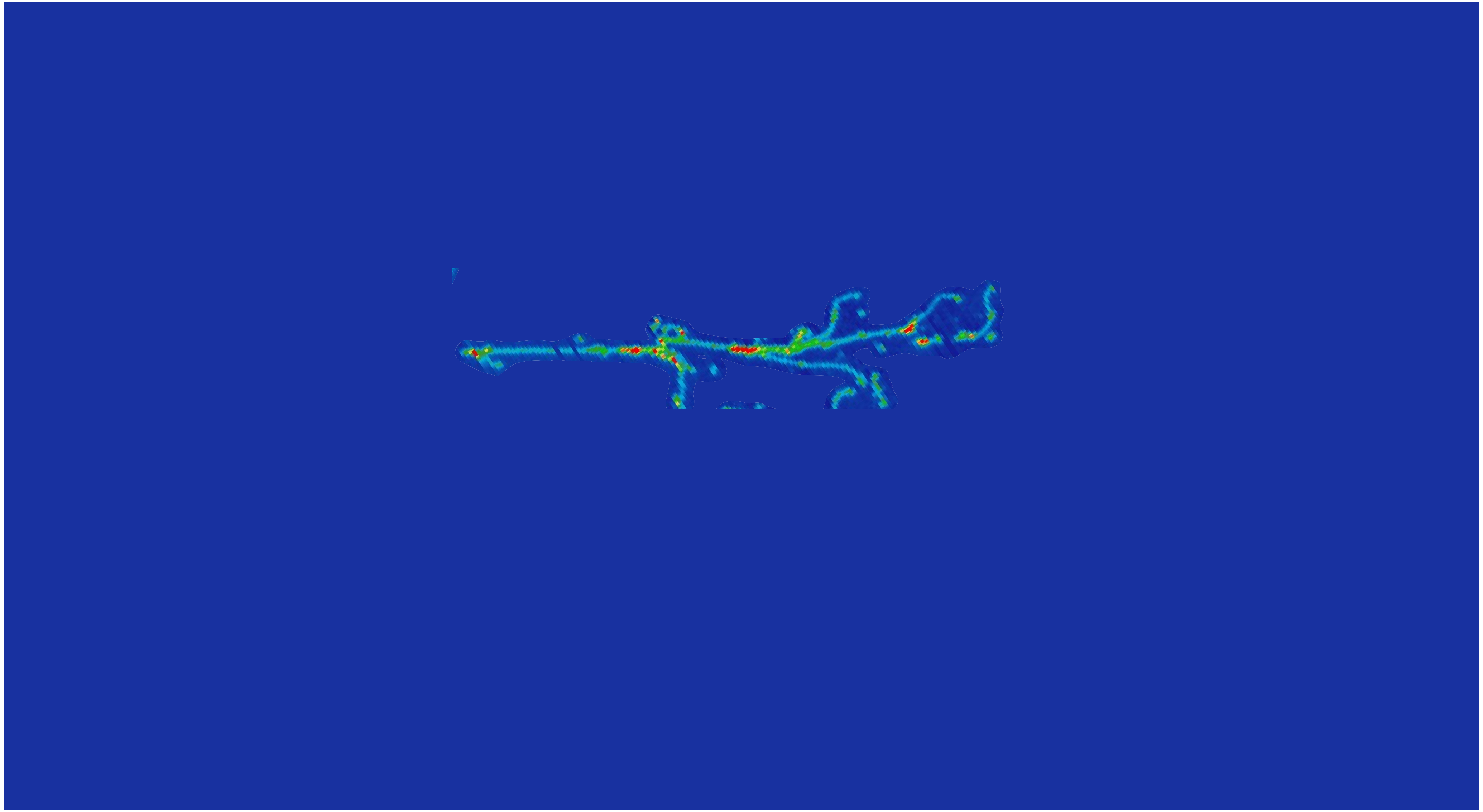
Neutrino Masses and New Physics



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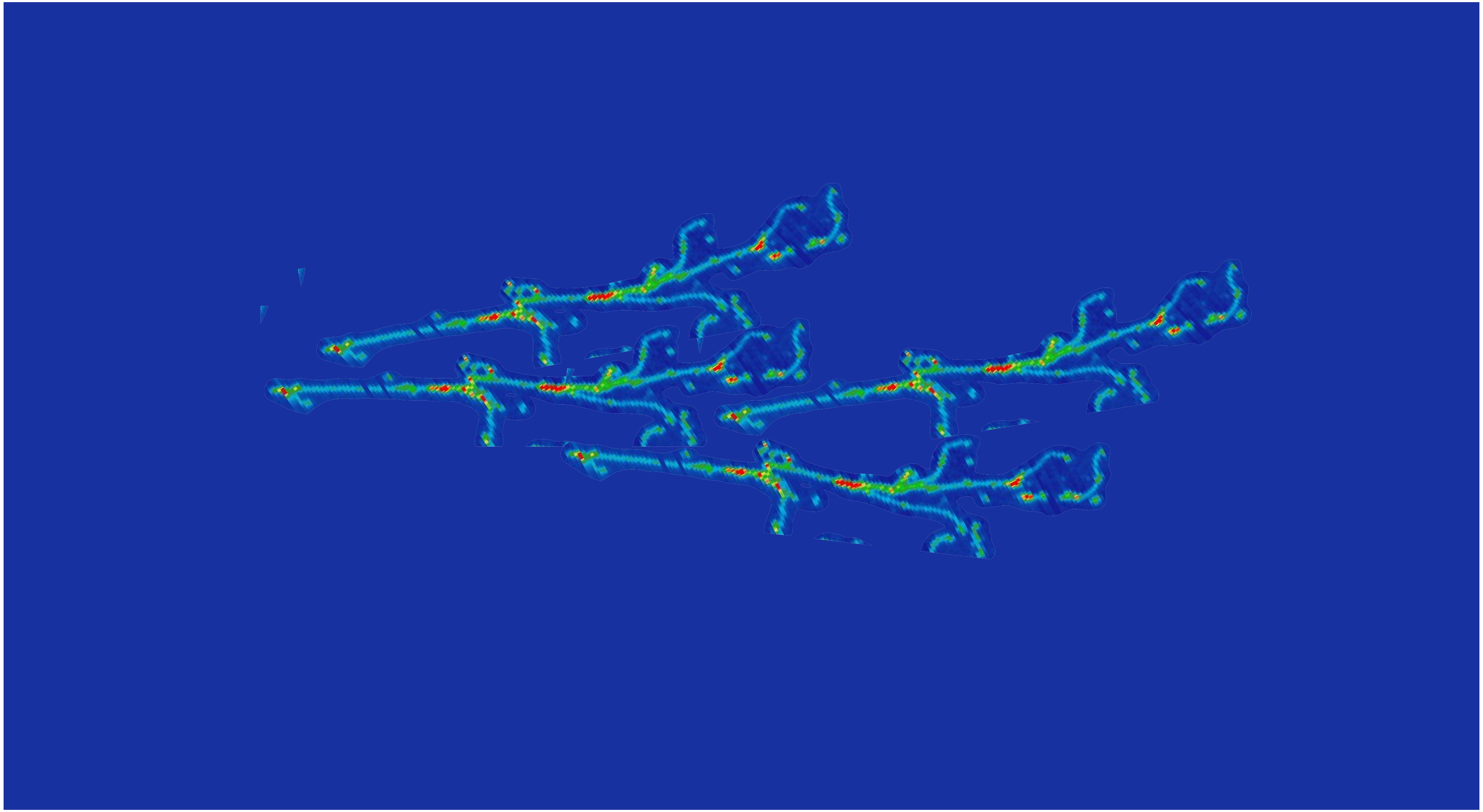

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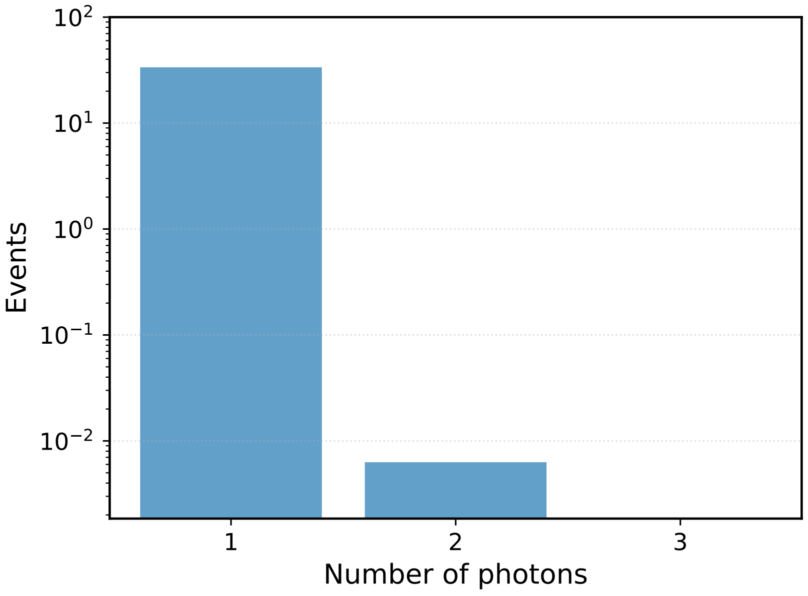

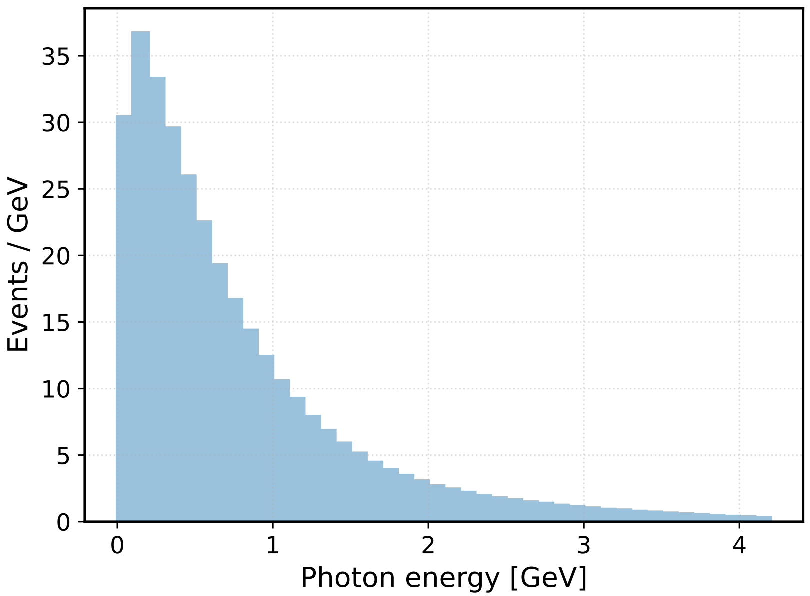

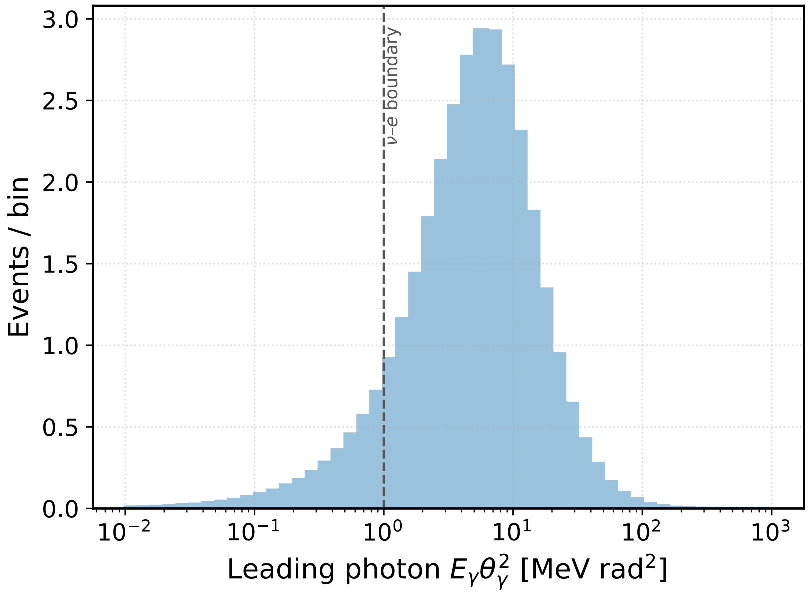

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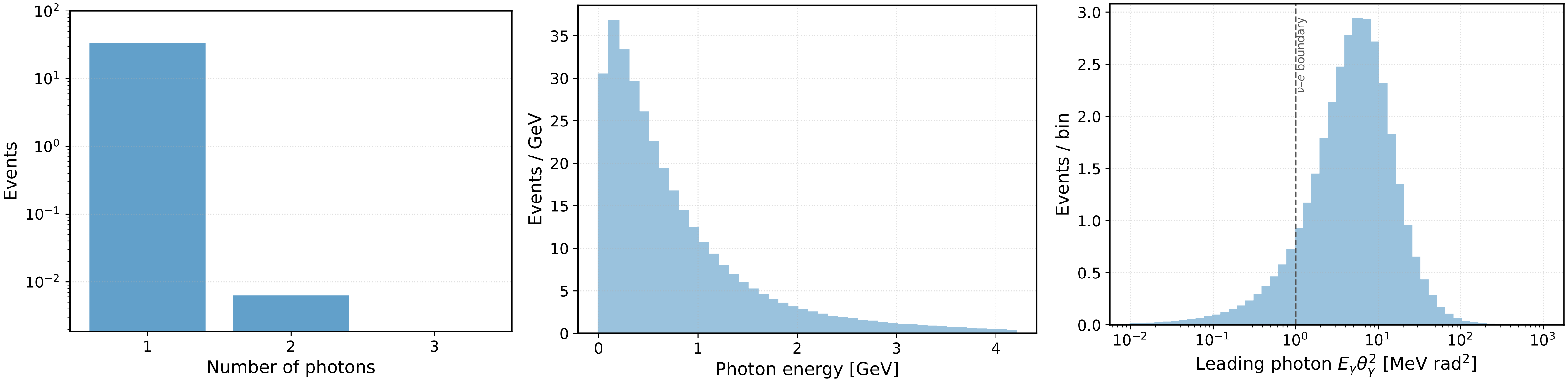

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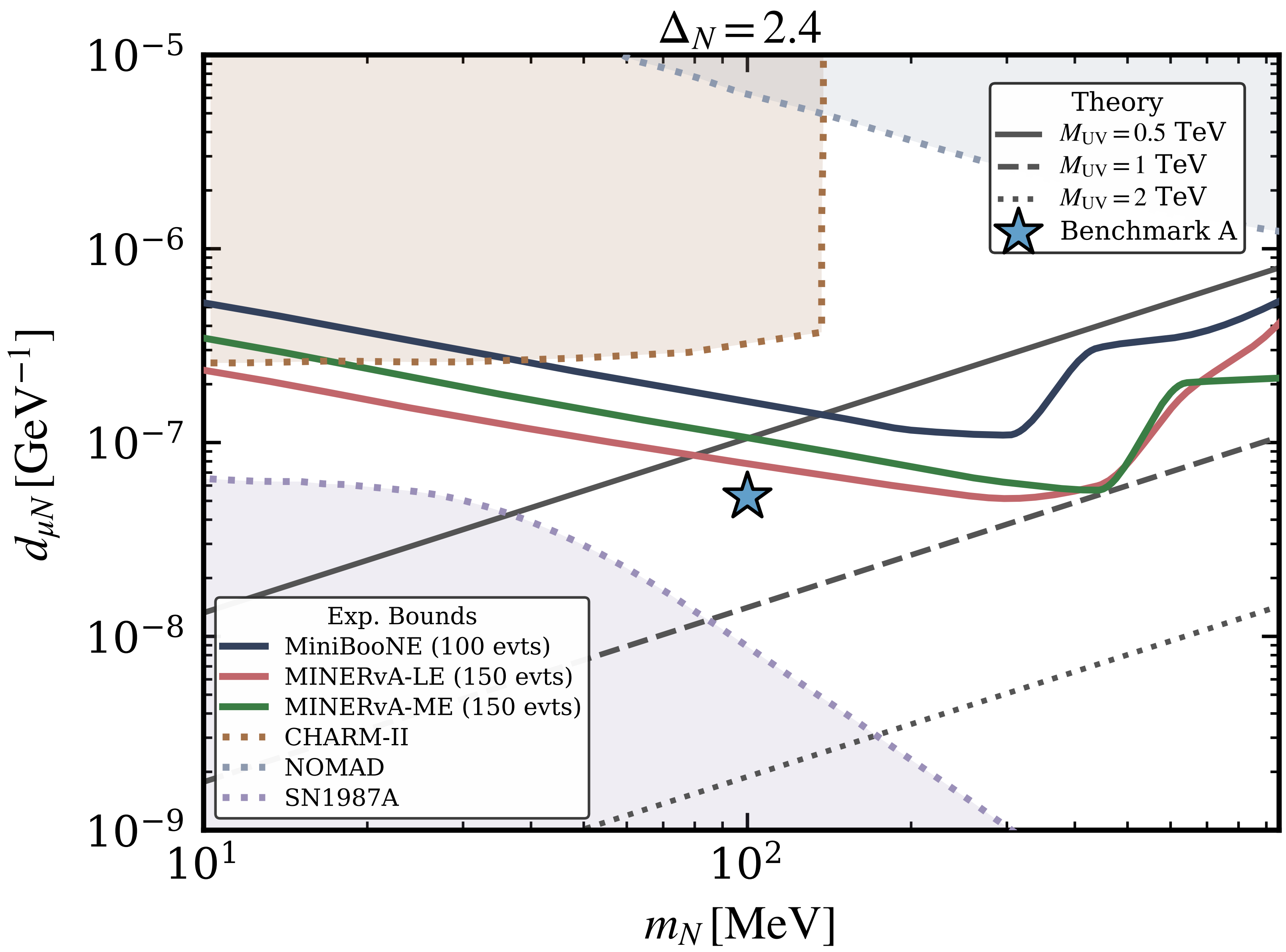
Neutrino Masses and New Physics



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Conclusions

Neutrino experiments can probe exciting new physics

It requires creativity to extract the most out of experiments

Detectable BSM could live in a very wide range of scales,
strongly (but secluded) or weakly coupled

Liquid argon time projection chambers like DUNE or the Short Baseline Neutrino detectors offer a new window to new physics in the neutrino sector