New physics in coherent neutrino scattering

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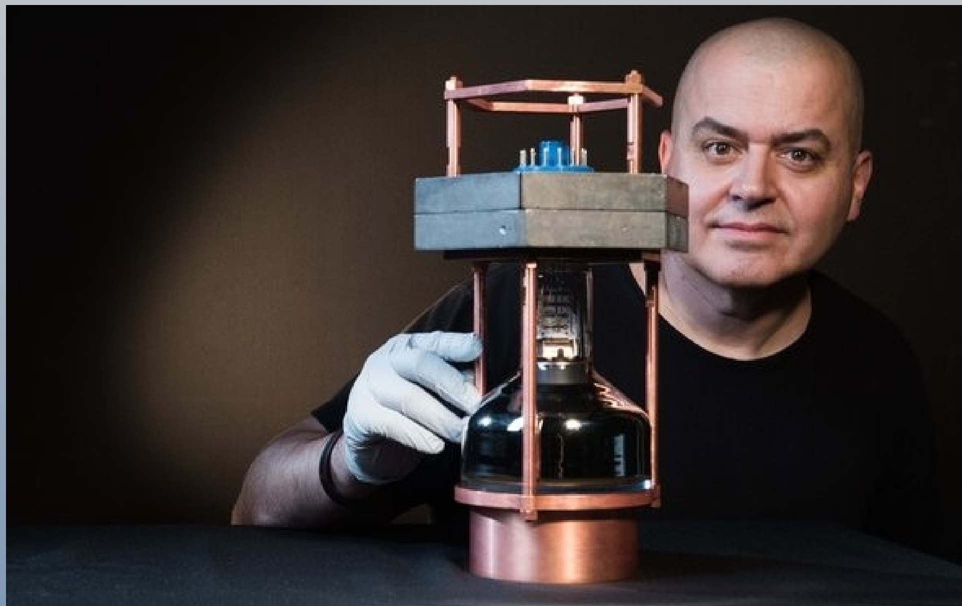
Talk at the NTN workshop on Neutrino Non-Standard Interactions:
https://indico.cern.ch/event/812851/



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1. **Observation of Coherent Elastic Neutrino-Nucleus Scattering**
COHERENT Collaboration (D. Akimov (Moscow, ITEP & Moscow Phys. Eng. Inst.) *et al.*).
Published in **Science 357 (2017) no.6356, 1123-1126**
DOI: 10.1126/science.aao0990
e-Print: **arXiv:1708.01294 [nucl-ex] | PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Interactions.org article; Link to Gizmodo article

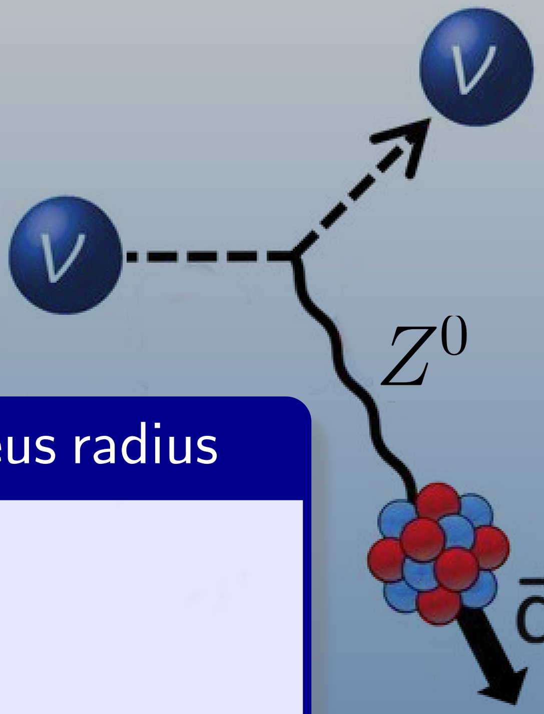
Detailed record - Cited by 129 records 100+

Outline

- Introduction to coherent neutrino scattering
  - What is it? Current status/Future potential
- New physics
  - NSI (Non-Standard Interaction)
  - SPVAT (S: 1, P: γ^5, V: γ^μ, A: $\gamma^\mu\gamma^5$, T: $\sigma^{\mu\nu}$)
  - Light mediators
  - Sterile neutrinos
  - Neutrino magnetic moments
  - Dark matter
- Summary

Coherent Elastic Neutrino-Nucleus Scattering

What is Coherent?



Without Coherency: neutrino wavelength $\ll$ nucleus radius

Sum over cross sections

$$\sigma_{\text{tot}} = \sigma_p + \sigma_p + \cdots + \sigma_n + \sigma_n + \cdots$$

With Coherency: neutrino wavelength $\gg$ nucleus radius

Sum over amplitude, then square

$$i\mathcal{M} = i\mathcal{M}_p + i\mathcal{M}_p + \cdots + i\mathcal{M}_n + i\mathcal{M}_n + \cdots$$

$$\sigma_{\text{tot}} = \left|i\mathcal{M}_p + i\mathcal{M}_p + \cdots + i\mathcal{M}_n + i\mathcal{M}_n + \cdots\right|^2$$

Macroscopic coherence also possible, see E. Akhmedov et al, 1806.10962

Cross section (full coherency)

$$\frac{d\sigma}{dT} = \frac{G_F^2 \left[N - (1 - 4s_W^2)Z\right]^2 M_{\rm nucleus}}{4\pi} \left(1 - \frac{T}{T_{\rm max}}\right)$$

T: recoil energy, $T_{\rm max}$: max recoil, N&Z: neutron&proton numbers.

$$T_{\rm max} = \frac{2E_\nu^2}{M + 2E_\nu}$$

- Weak dependence on Z (proton number)
  - because $1 - 4s_W^2 \approx 0$.
- Large cross section for large N
  - $\frac{d\sigma}{dT} \propto N^2(N+Z)$, $\sigma \propto N^2$
- Although large, difficult to detect, T too low,
  - $T_{\rm max}$ determined by kinetics, 1 MeV neutrino $\Rightarrow$ $T_{\rm max}$ $\approx$0.1 keV
- Modern tech: ultra-low threshold detection
  - thanks to dark matter experiments

Coherency requires: $E_\nu < 50$ MeV.
Two suitable neutrino sources:

SNS

pros: higher $E_\nu \& T$, larger σ, $T_{\rm thre} = \mathcal{O}(10)$ keV enough
cons: $\downarrow T_{\rm thre} \not\Rightarrow \uparrow N_{\rm tot}$, comparatively low ν flux

Reactor neutrino

pros: ν flux high, high statistics if 0.1 keV achieved
cons: needs very low $T_{\rm thre}$, quenching factor unknown

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Example:

100 kg Ge

Threshold: 0.1 keV

1GW nuclear reactor

Distance: 10m

→

Event number:

$7.6 \times 10^6/\text{yr}$

Event number:

$7.6 \times 10^6 / \mathrm{yr}$

- Small, portable detector
- Precise measurement of neutrino interactions and EW parameters
  - E.g. $\sin^2\theta_W = 0.238 \pm 0.0022$ (Lindner, et al, 1612.04150)
- Finding new physics

New physics

- NSI
  - 1804.03660, 1711.09773 , 1711.03521, 1708.04255 , 1708.02899, 1612.04150, 1805.01798, 1812.02778
- SPVAT (S: 1, P: γ^5, V: γ^μ, A: $\gamma^\mu\gamma^5$)
  - 1806.07424, 1711.09773, 1612.04150, 1812.02778
- Sterile neutrinos
  - 1703.00054, 1711.09773, 1511.02834
- Light mediators (scalar, Z', dark photon. . .)
  - 1803.05466, 1803.01224, 1803.00060, 1802.05171, 1711.09773, 1711.04531, 1710.10889, 1612.06350, 1805.01798, 1508.07981, 1810.03626
- Neutrino electromagnetic properties
  - 1510.01684, 1706.02555, 1711.09773, 1805.01798, 1810.05606
- Dark matter
  - 1810.03626

New physics (NSI)

If mediated by a new gauge boson (e.g. Z'), integrated out $\Rightarrow$ NSI.
Alternative: loop-induced NSI (I. Bischer, W. Rodejohann, X.J.X, 1807.08102).

NSI (Non-Standard Interaction)

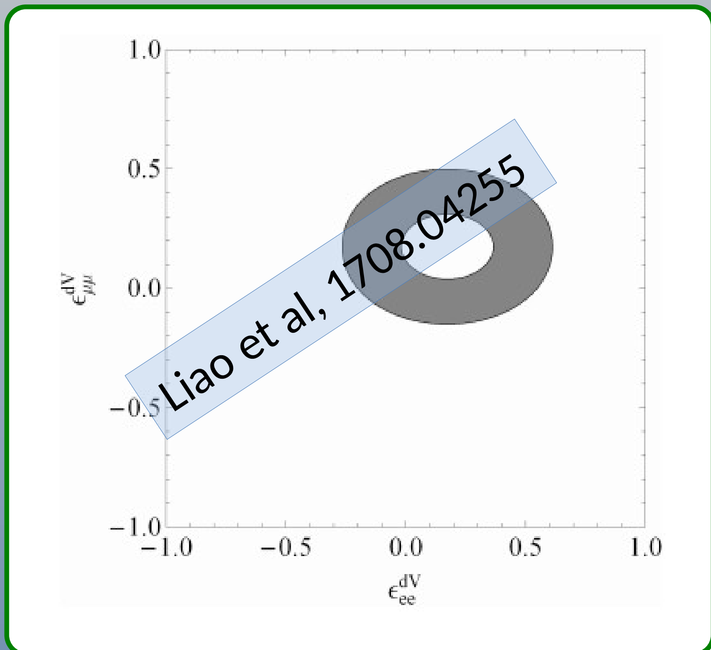
$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \overline{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta \left[\overline{q} \gamma^\mu (\varepsilon^{qV}_{\alpha\beta} + \varepsilon^{qA}_{\alpha\beta} \gamma^5) q \right],$$

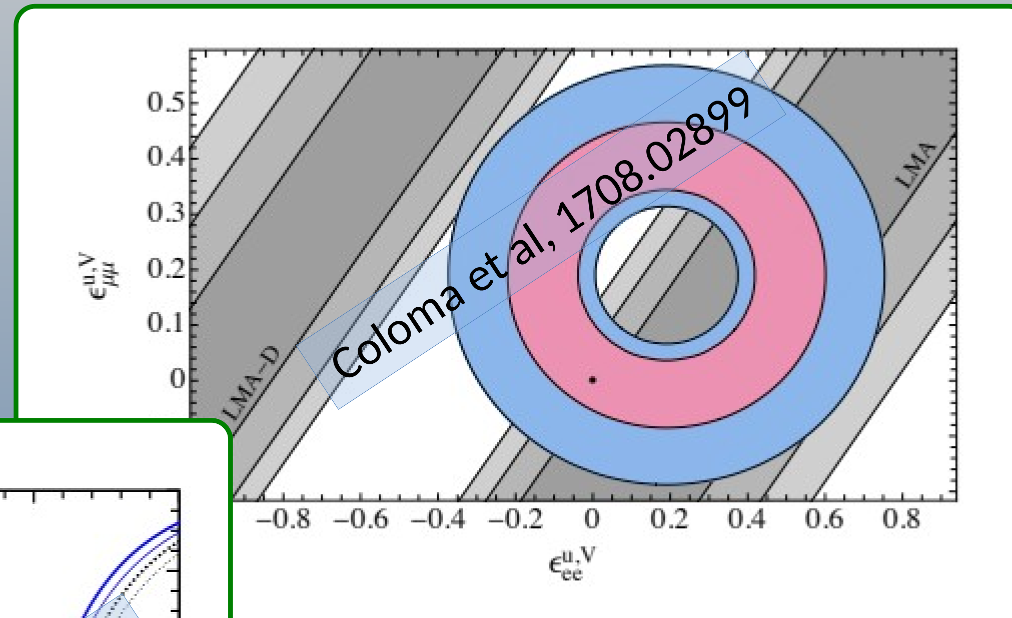
- Lepton Flavor Violation (LFV)
- Still V-A in $\overline{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta$, because only left-handed ν
- the only change in $d\sigma/dT$, Q^2 :$Q^2_{\rm SM} \to Q^2_{\rm NSI}$

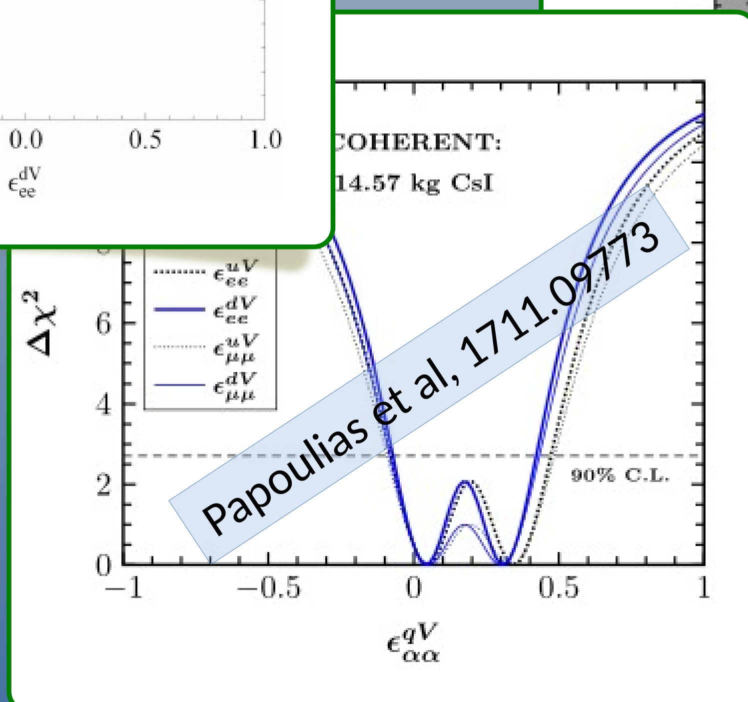
$$\frac{d\sigma}{dT} = \frac{G_F^2 Q^2 M_{\rm nucleus}}{4\pi} \left(1 - \frac{T}{T_{\rm max}}\right)$$

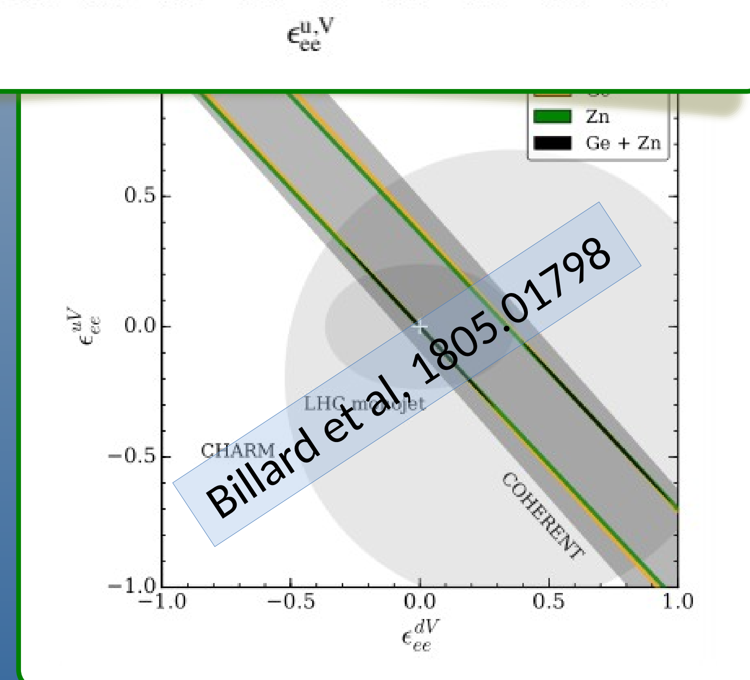
$$Q^2_{\rm NSI} = 4\left[N(\cdots + \varepsilon^{uV}_{ee} + 2\varepsilon^{dV}_{ee}) + Z(\cdots + 2\varepsilon^{uV}_{ee} + \varepsilon^{dV}_{ee})\right]^2 + \cdots$$

New physics (NSI)





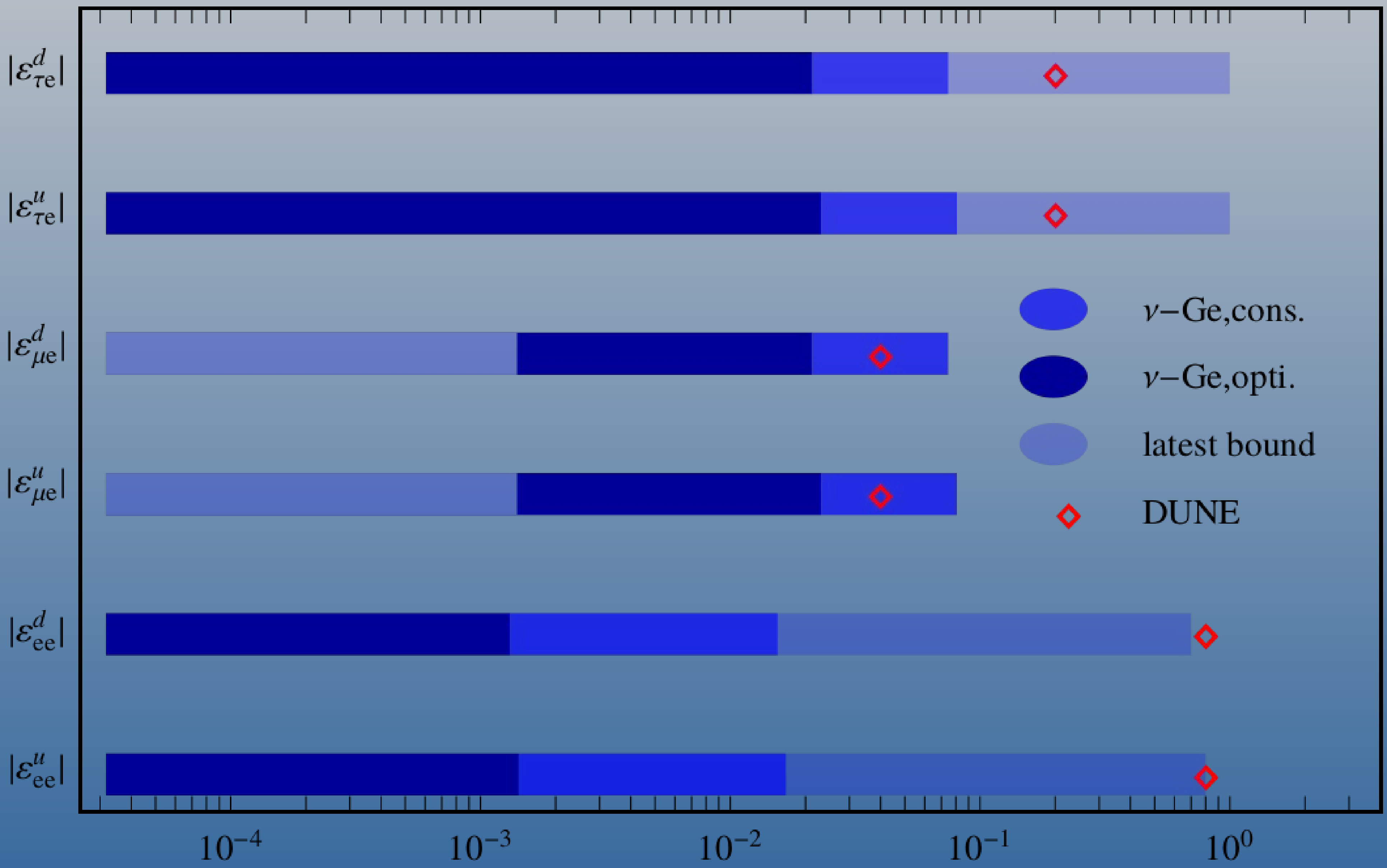




Degeneracy:
because what
we can measure is just Q^2

$$Q^2_{\rm NSI} = 4\left[N(\cdots + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) + Z(\cdots + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV})\right]^2 + \cdots$$

New physics (NSI)



M. Lindner, W. Rodejohann, X.J.X, 1612.04150.

New physics (SPVAT)

If mediated by any kinds of forces, integrated out ⇒ SPVAT.

SPVAT (Scalar, Pseudo-S, Vector, Axial-V, Tensor

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \overline{\nu}\Gamma^a\nu \left[\overline{\psi}\Gamma^a(C_a + D_a i\gamma^5)\psi\right],$$

$$\Gamma^a = \{1,\, i\gamma^5,\, \gamma^\mu,\, \gamma^\mu\gamma^5,\, \sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu]\}.$$

- Scalar (Pseudo-S) mediator ⇒ 1 $(i\gamma^5)$
- Charged scalar (Pseudo-S) mediator ⇒ 1 $(i\gamma^5)+\sigma^{\mu\nu}$
- Vector (Axial-V) mediator ⇒ $\gamma^\mu, \gamma^\mu\gamma^5$
- contains all possible Lorentz-invariant interactions
- involves ν_R. Light ν_R signal implies: ν is Dirac, not Majorana.

W. Rodejohann, X.J.X, C. Yaguna, 1702.05721.

New physics (SPVAT)

SM cross section:

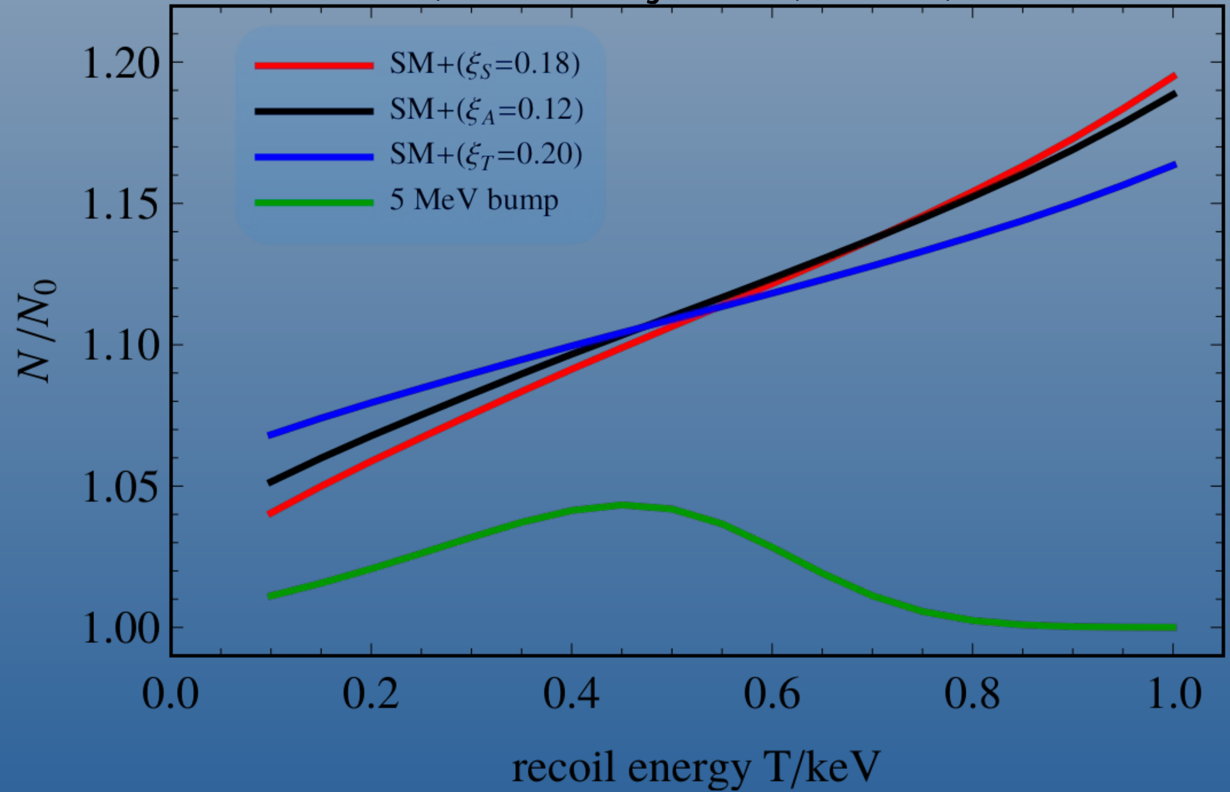
$$\frac{d\sigma}{dT} = \frac{G_F^2 Q^2 M}{4\pi}\left(1 - \frac{T}{T_{\max}}\right)$$

SPVAT cross section:

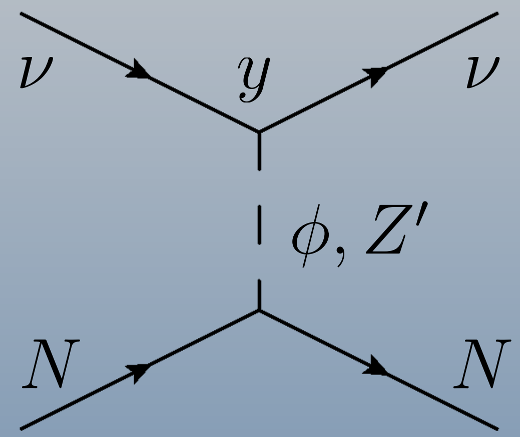
$$\frac{d\sigma}{dT} = \frac{G_F^2 Q^2 M}{4\pi}\left(\boxed{\cdots} \times 1 - \boxed{\cdots} \times \frac{T}{T_{\max}}\right)$$

M. Lindner, W. Rodejohann, X.J.X, 1612.04150

$\Rightarrow$ distortion of spectrum.



Light mediator (scalar, Z', dark photon, etc.)



SM cross section:

$$\frac{d\sigma}{dT} = \frac{G_F^2 Q^2 M}{4\pi}\left(1 - \frac{T}{T_{\max}}\right)$$

Light mediator:

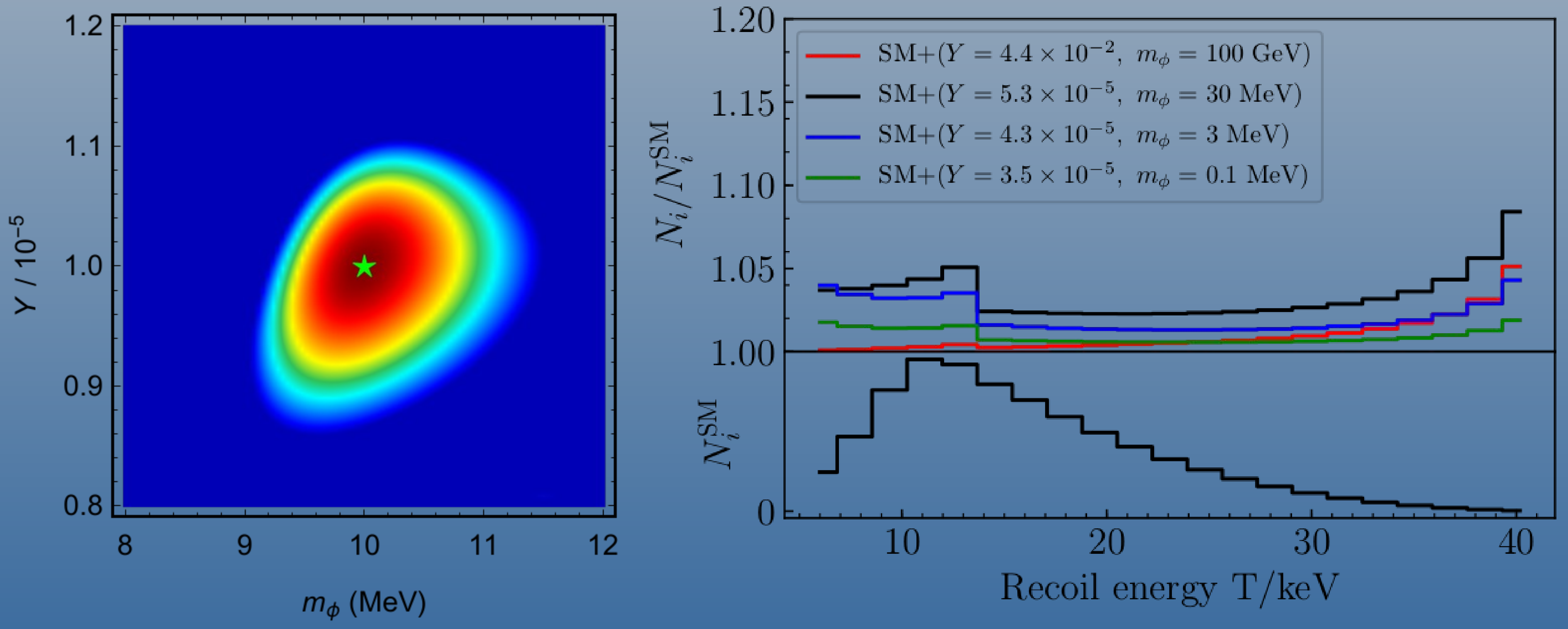
$$\frac{d\sigma}{dT} = \frac{y^4 M}{4\pi\underbrace{(2MT + m_\phi^2)^2}}\underbrace{\left(\boxed{\cdots} \times 1 - \boxed{\cdots} \times \frac{T}{T_{\max}}\right)}$$

(i) effect of mediator mass (ii) effect of mediator spin

$\Rightarrow$ distortion of spectrum due to (i) and (ii).

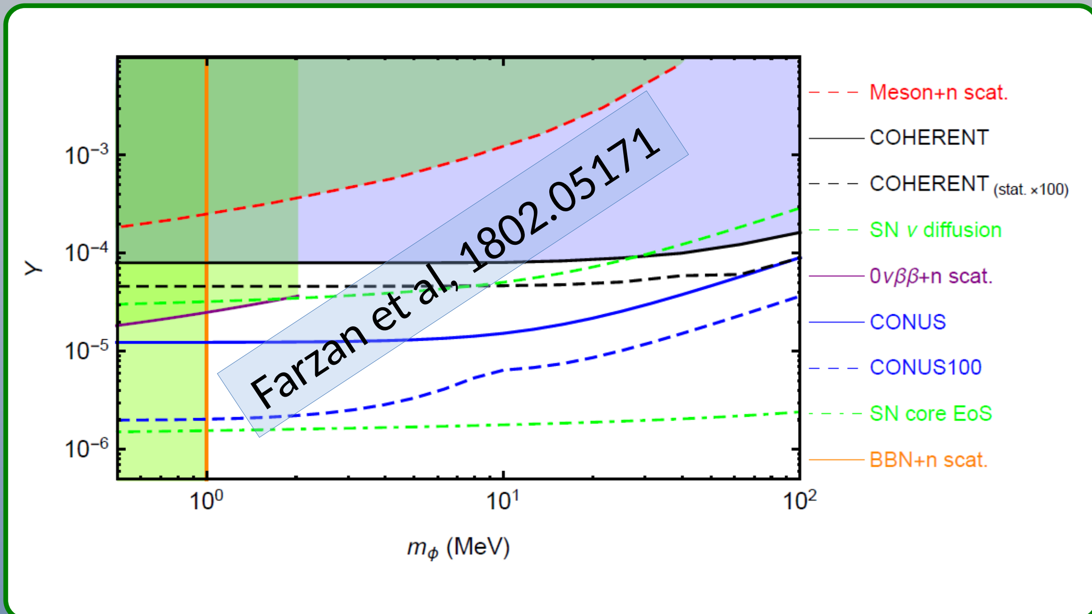
Light mediator (scalar, Z', dark photon, etc.)

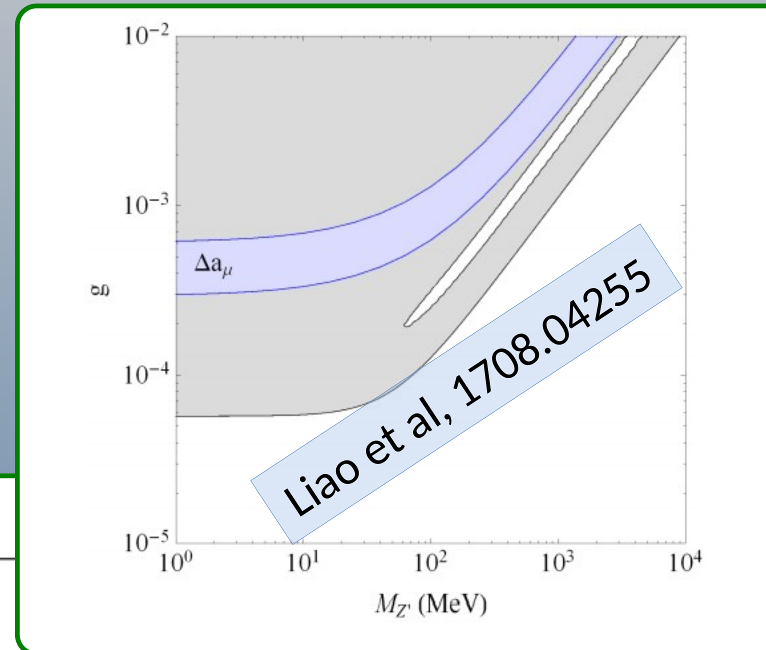
Distortion of spectrum $\Rightarrow$ distinct signal
$\Rightarrow$ to reconstruct the mediator mass & coupling

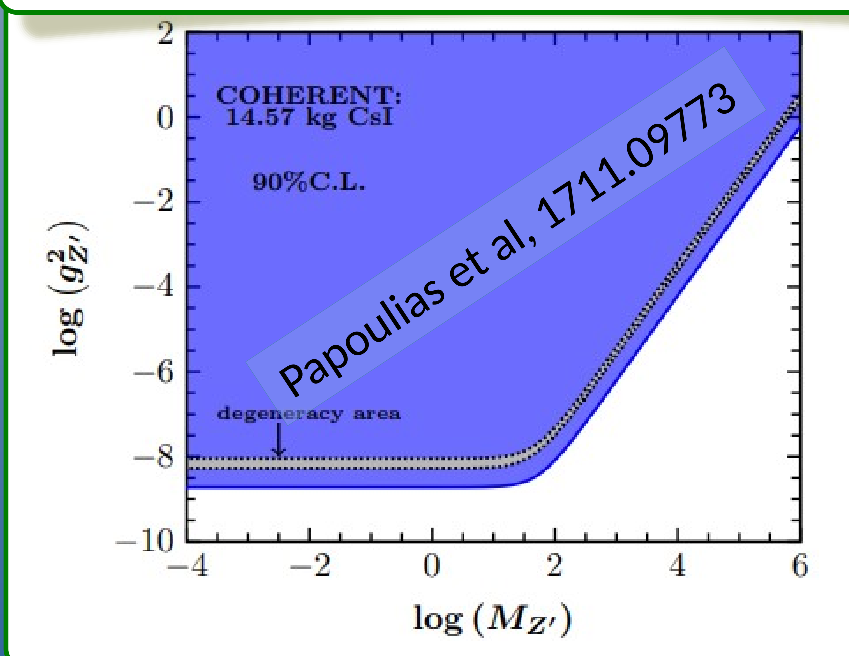


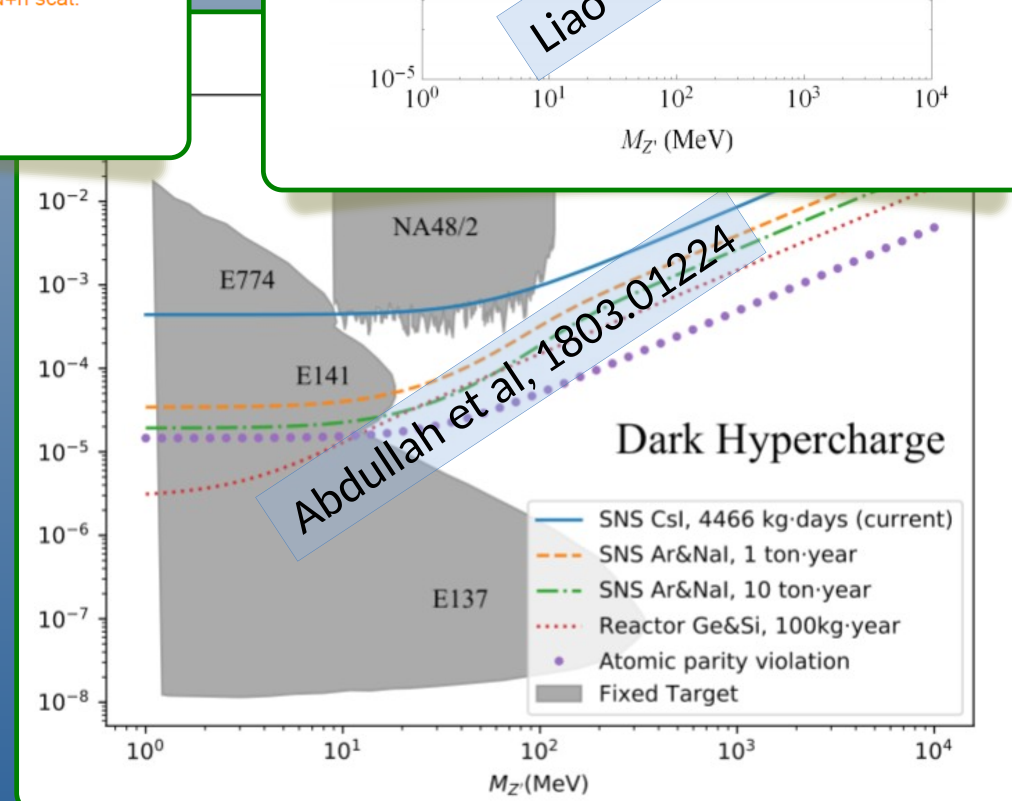
Farzan, Lindner, Rodejohann, X.J.X, 1802.05171

Light mediator (scalar, Z', dark photon, etc.)



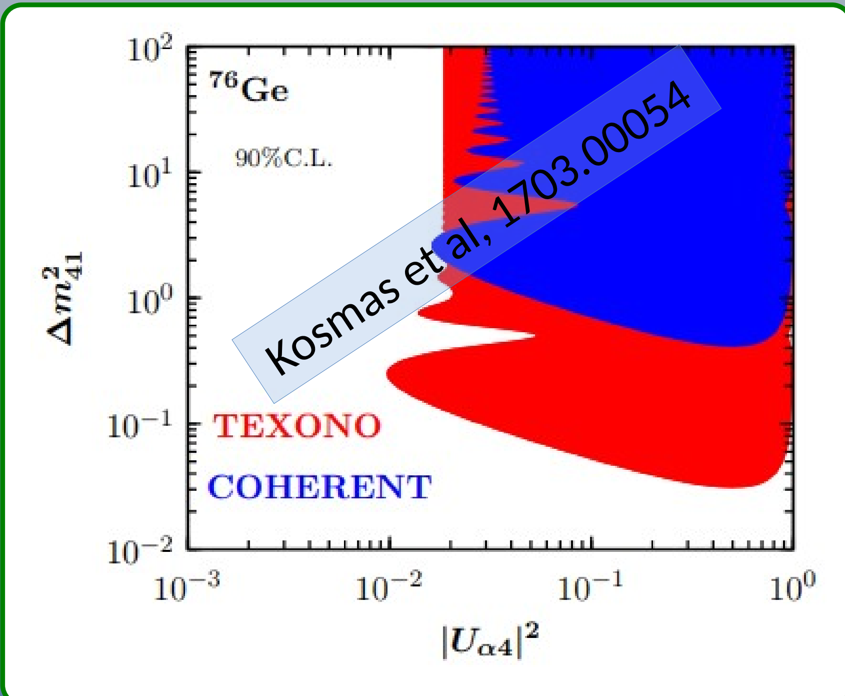


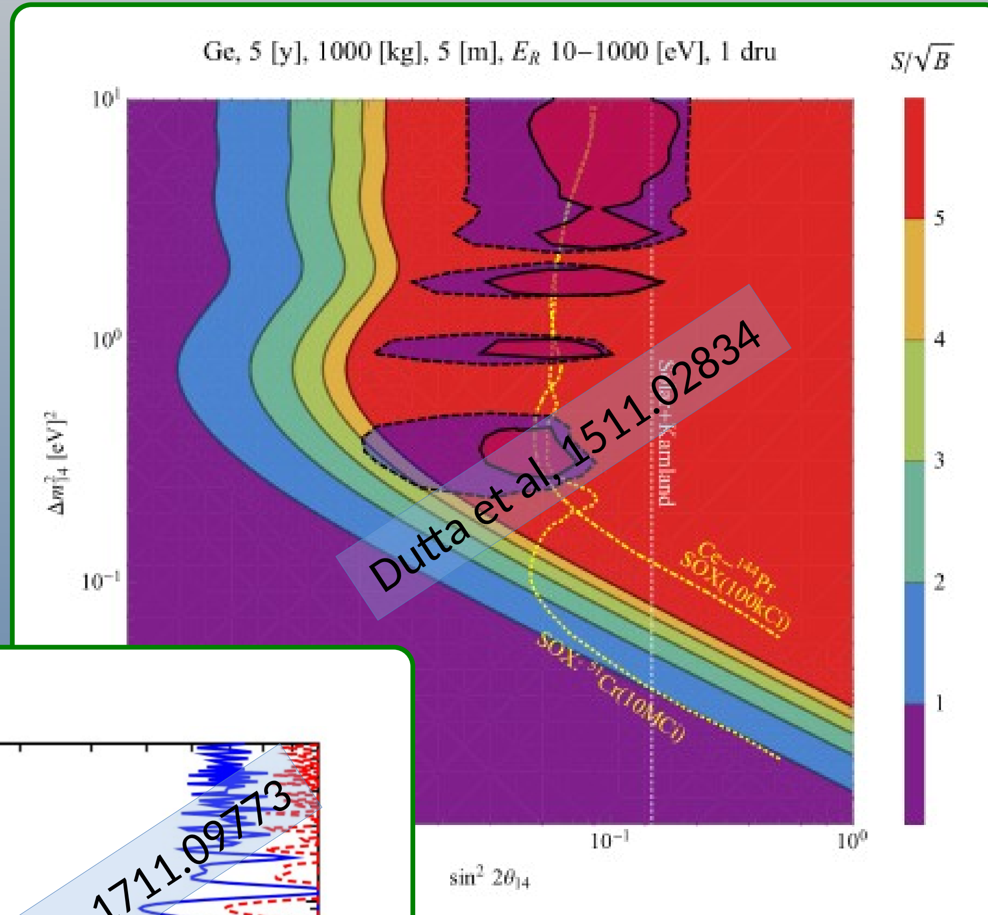


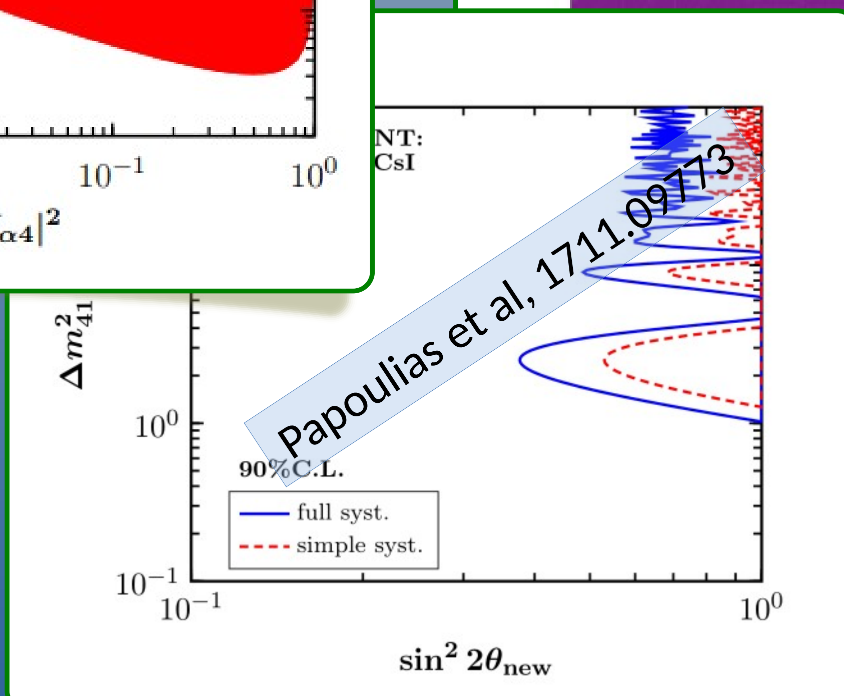


Sterile neutrinos

$$P_{ee} = 1 - \sin^2 2\theta_{14} \sin^2 \left(\frac{\Delta m^2_{41} L}{4E_\nu} \right)$$

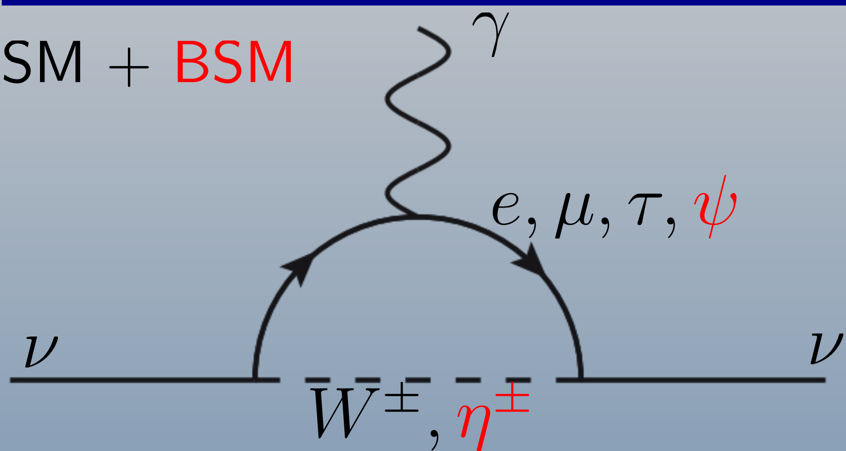






Neutrino magnetic moments

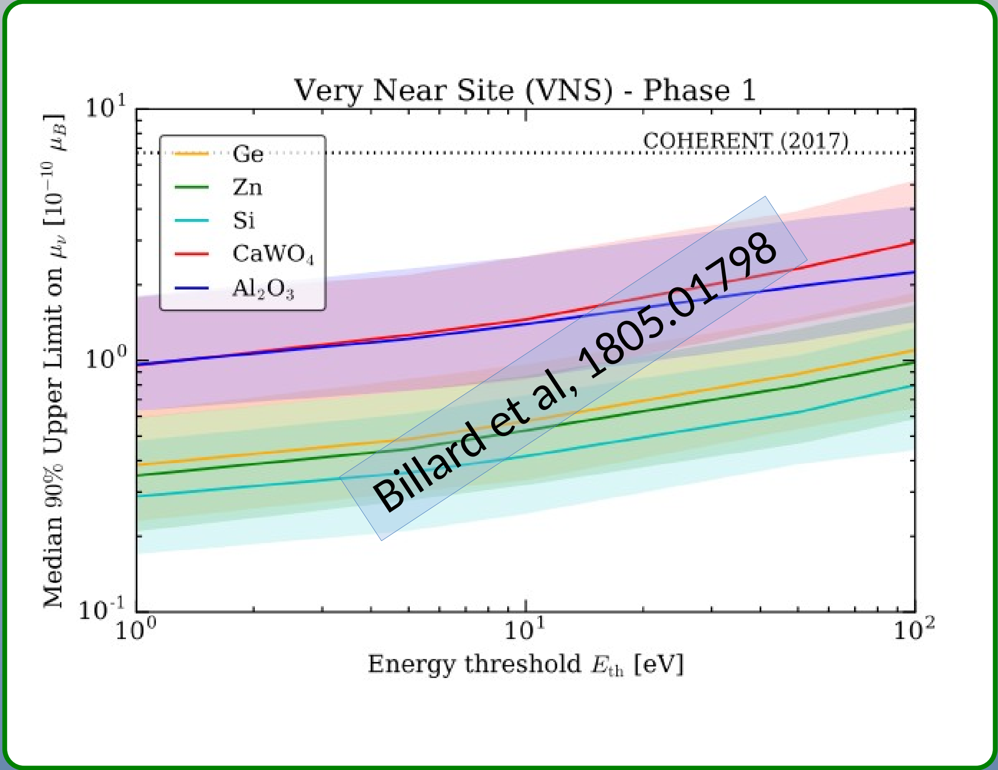
SM + BSM

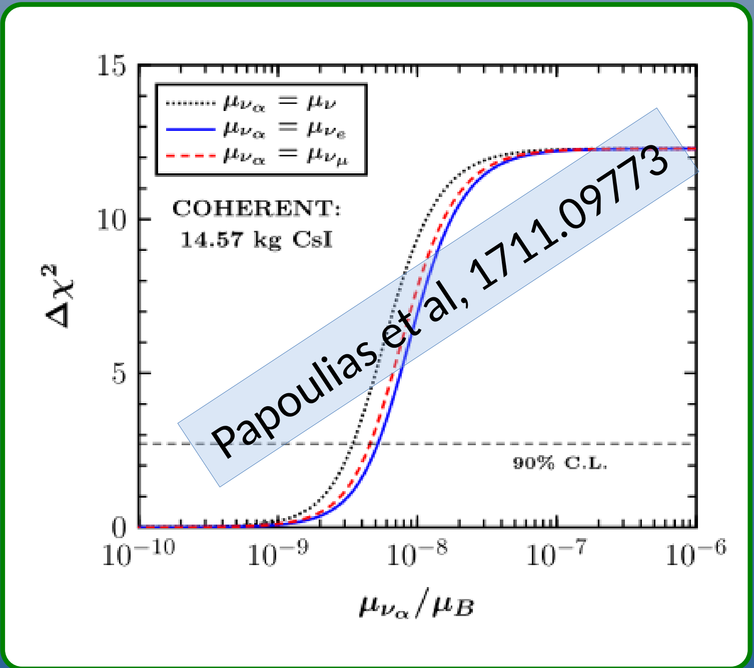


SM : $\mu_\nu \sim 10^{-20}\mu_B$

chirality flipping $\Rightarrow$ $\mu_\nu \uparrow$ to $10^{-9}\mu_B$

[X.J.X, 1901.00482]

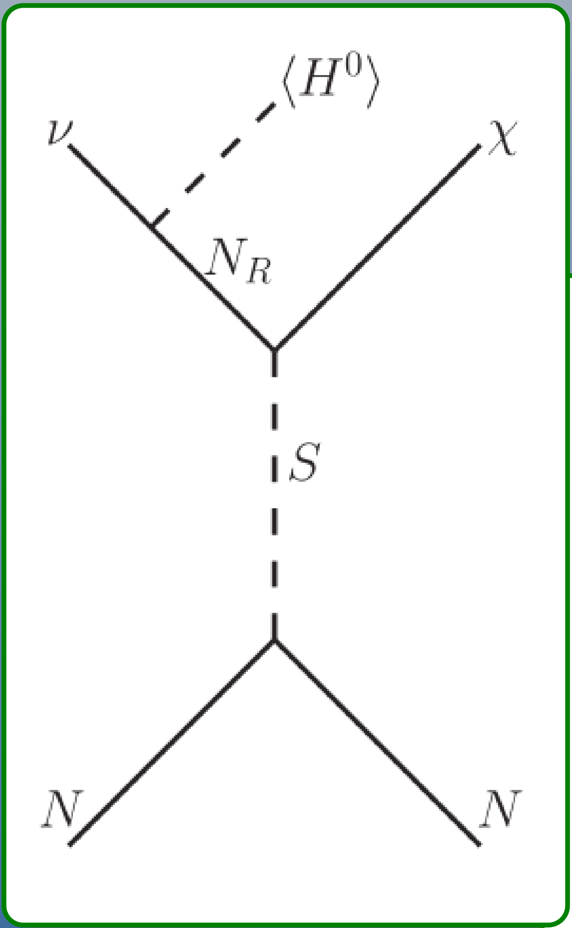




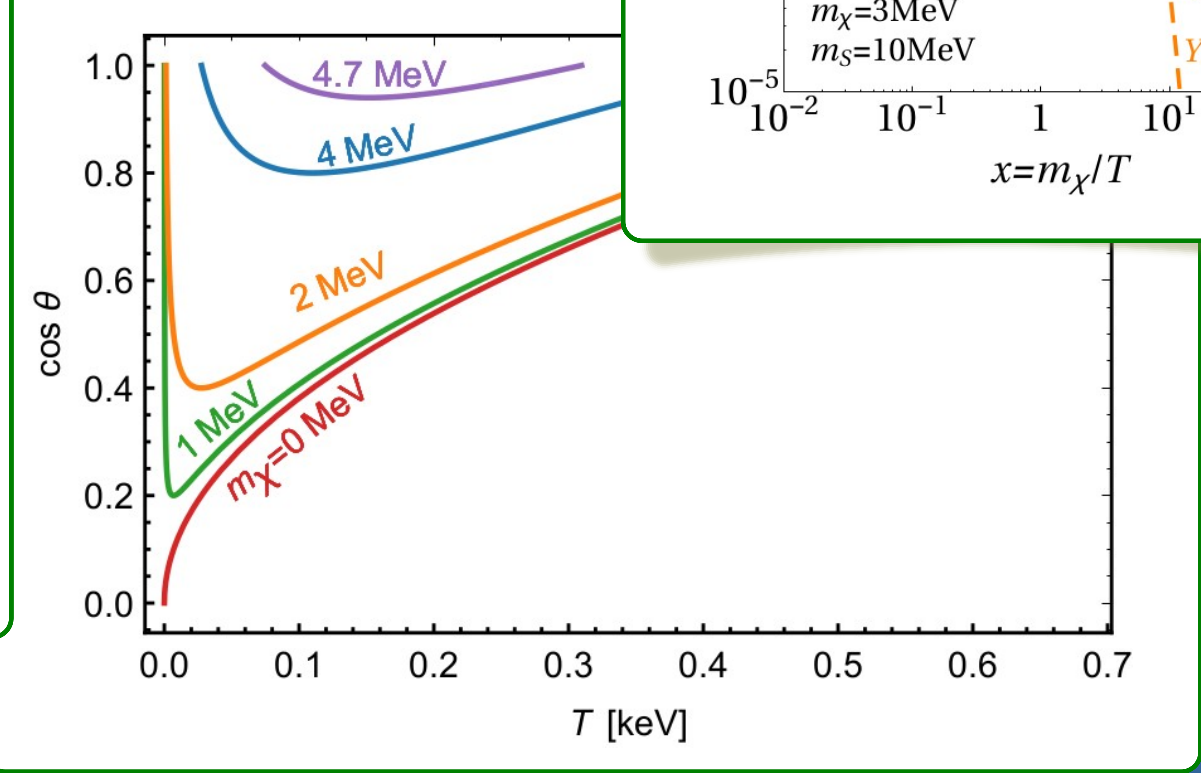
- $\nu + e$ scattering is better:
  GEMMA: $\mu_\nu < 10^-11\mu_B$
- Also constraint on charge radius:
  $-8 \times 10^{-32} < \langle r^2 \rangle < 11 \times 10^{-32}\text{cm}^2$
  [M. Cadeddu, et al, 1810.05606]

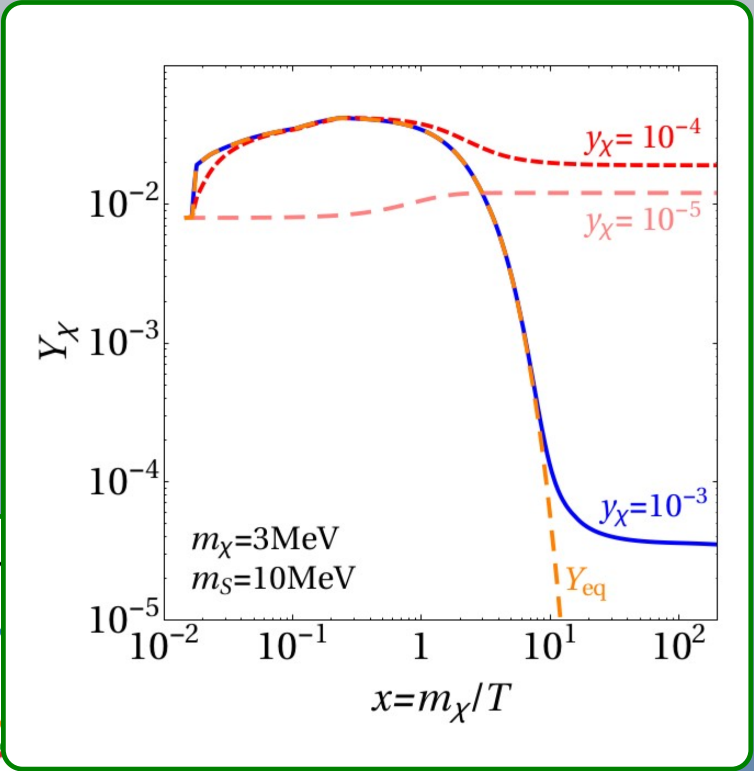
Dark matter

BSM particles could appear in the final states.
Invisible ⇒ Dark matter?



V. Brdar, W. Rodejohann, X.J.X, 1810.03626





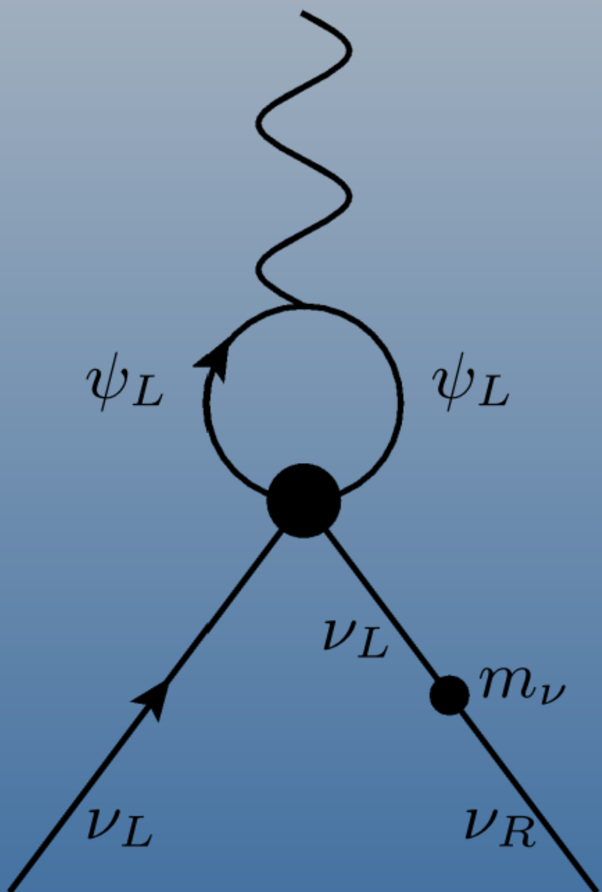
Summary

- Coherent neutrino scattering $\Rightarrow$ a new chanel to probe SM & BSM neutrino interactions;
- Recent experiments $\Rightarrow$ constraints on NSI, SPVAT, sterile neutrinos, light mediators, neutrino magnetic moments;
- Future reactor-based experiments $\Rightarrow$ very high statistics $\Rightarrow$ more neutrino-related new physics.

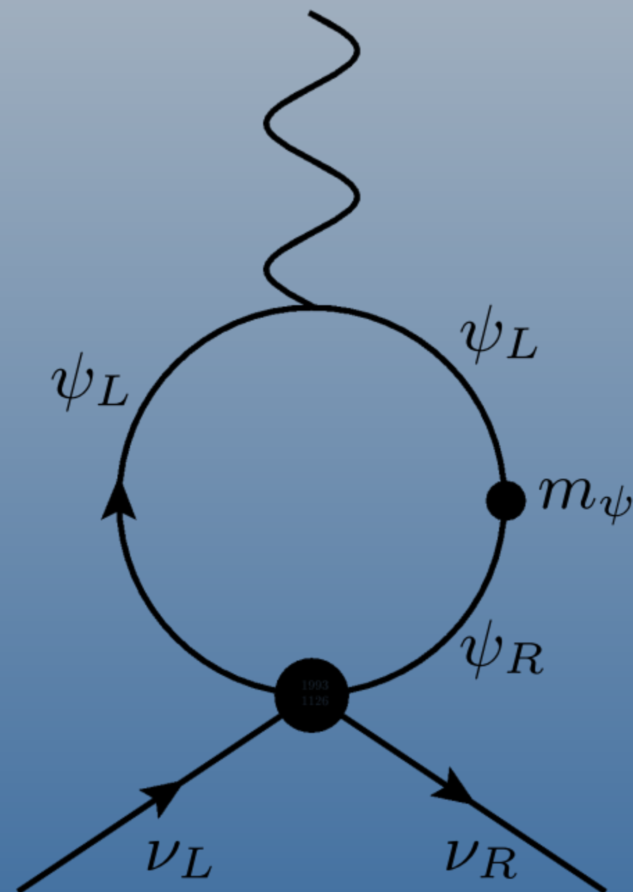
Backup

Backup

Chirality flipping and neutrino magnetic moment



(a): $\boldsymbol{\mu}_\nu \propto m_\nu$



(b): $\boldsymbol{\mu}_\nu \propto m_\psi$