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NuFact 2022

Probing Light Mediators in the Radiative Emission of Neutrino Pair

In Collaboration with:

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(pronouns: He/Him/His)

Pedro S. Pasquini

Shanghai Jiao Tong University

李政道研究所

Tsung-Dao Lee Institute

Neutrino Pair Emission

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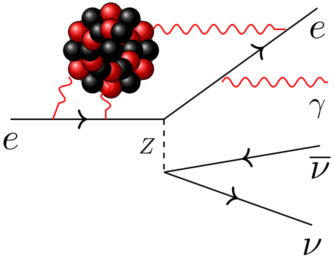

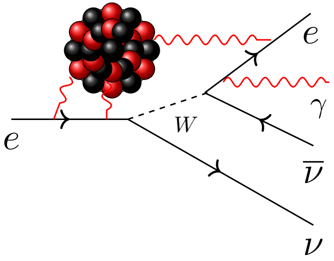

Low E_ν but hard experimentally

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Disadvantages

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- Atomic transition: $\mathcal{O}(1)$ eV
- Can measure the emitted photon
- Can be stimulated and coherently enhanced
- Tests ν physics in a different energy regime

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- Exp. challenge to coherent enhancement
- Very new, still theo. investigation

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- Can be stimulated and coherently enhanced	- Exp. challenge to coherent enhancement
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Benefits are great and can provide interesting results!
m_ν ordering and scale, non-unitary, BSM interactions and maybe neutrino mixing and nature

Neutrino LASER?

Radiative Emission of Neutrino Pair (RENP)

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Usual Laser beam:

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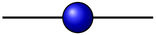
Excited (meta-stable) State ($|e>$)

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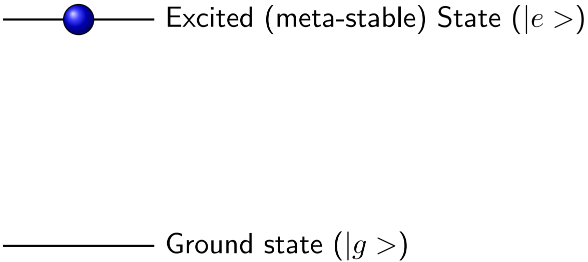

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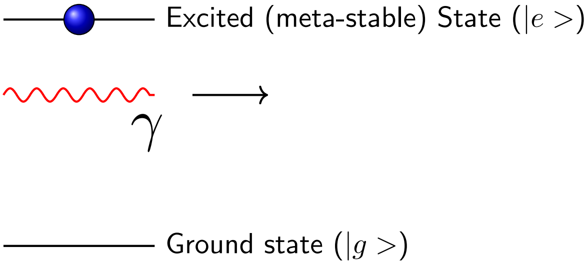

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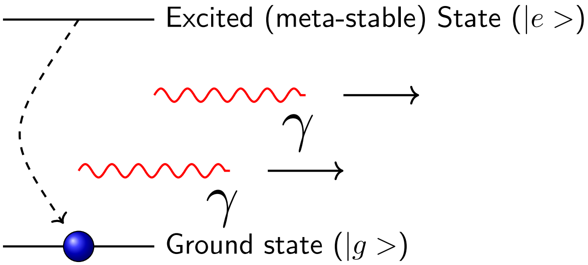

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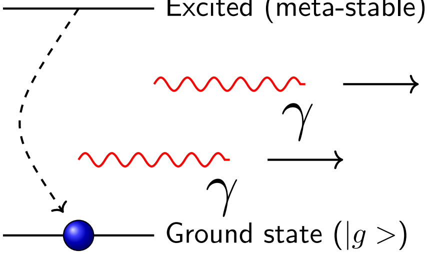

Excited (meta-stable) State ($|e>$)

Ground state ($|g>$)

($E1$, $M1$ transition)

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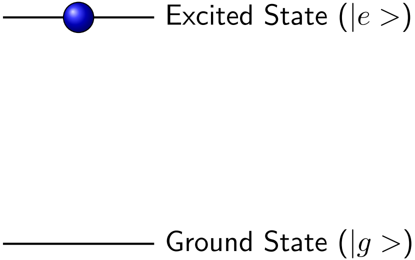

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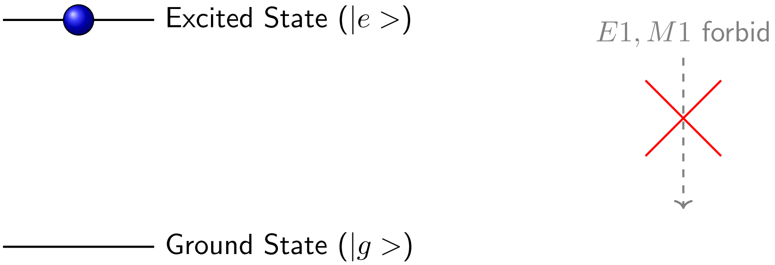

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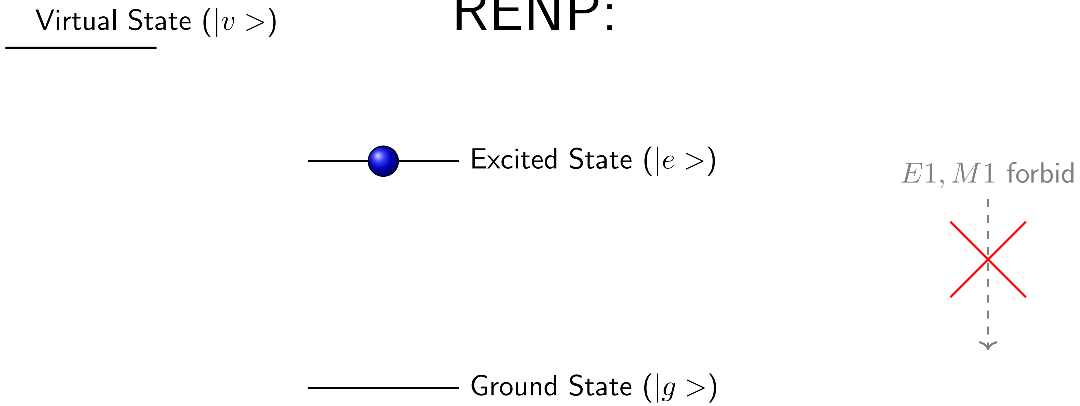

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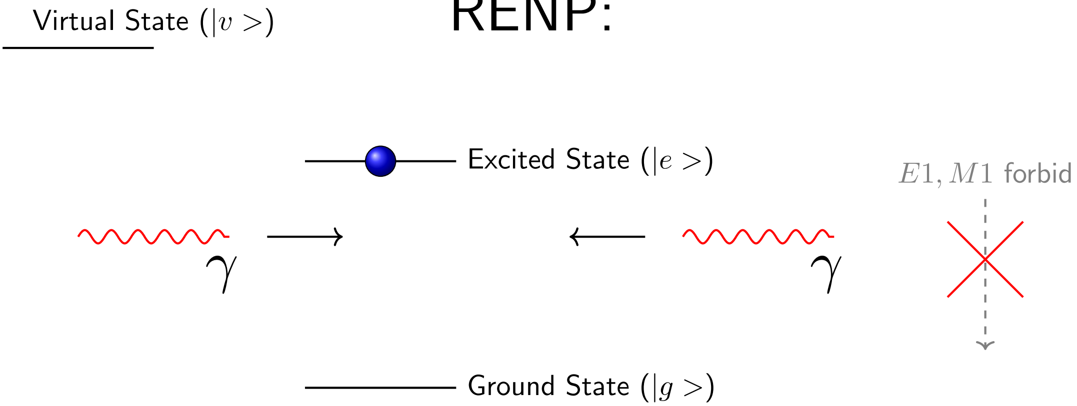

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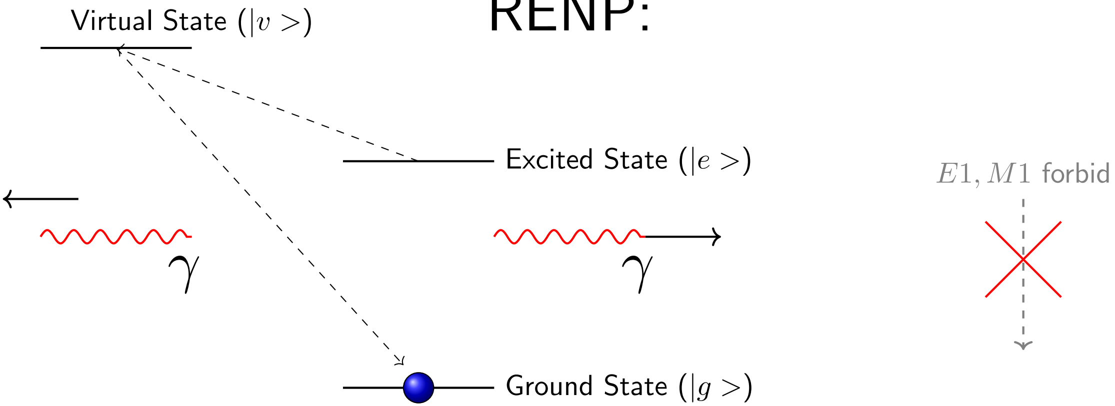

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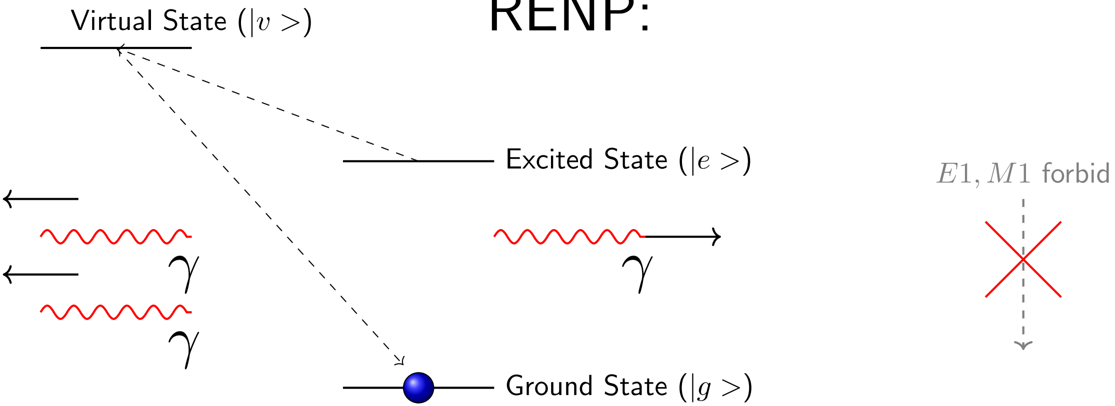

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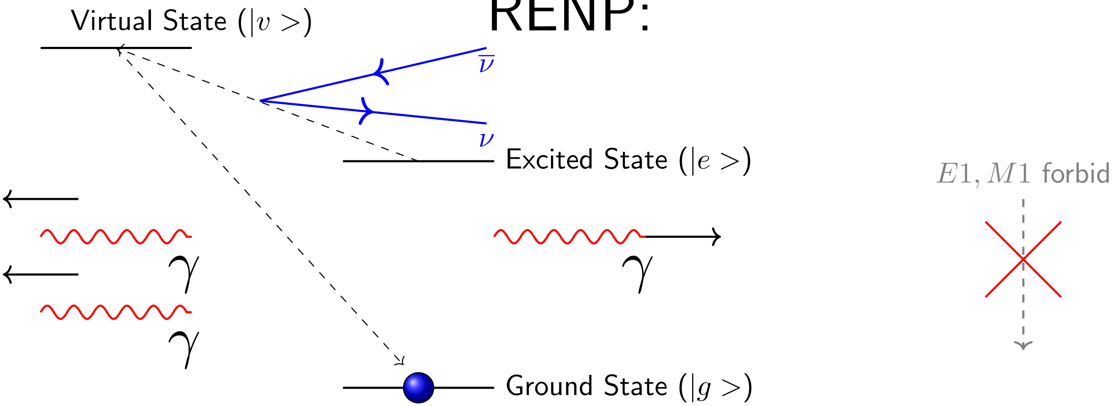
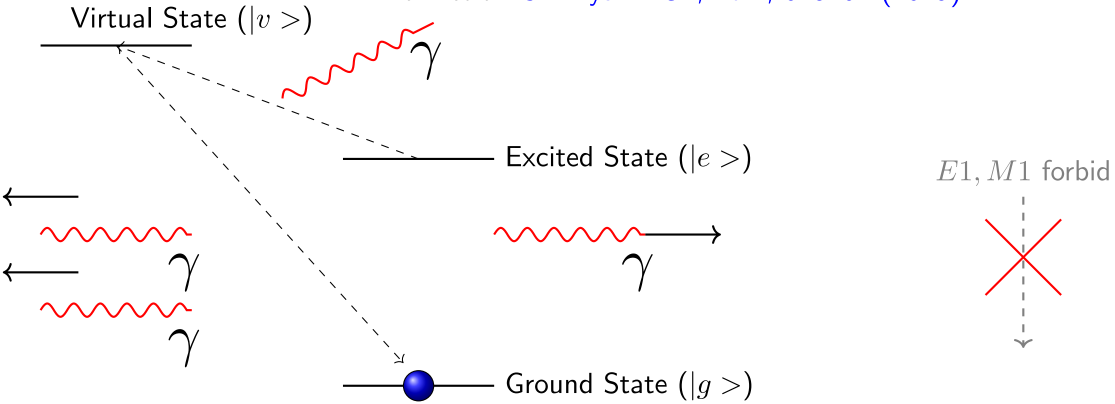


$E1 \times M1$ transition

"Coherent two-photon emission from hydrogen molecules excited by counter-propagating laser pulses,"

T. Hiraki et al. J. Phys. B **52**, no.4, 045401 (2019)



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Current technology (probably) allows $\mathcal{O}(10)$ events/days of exposure

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The $\#$ of photons from de transition depends on ω.

Two important information: $I \equiv I(\omega)$ and $\omega_{ij}^{\max}$

Threshold contain mass information

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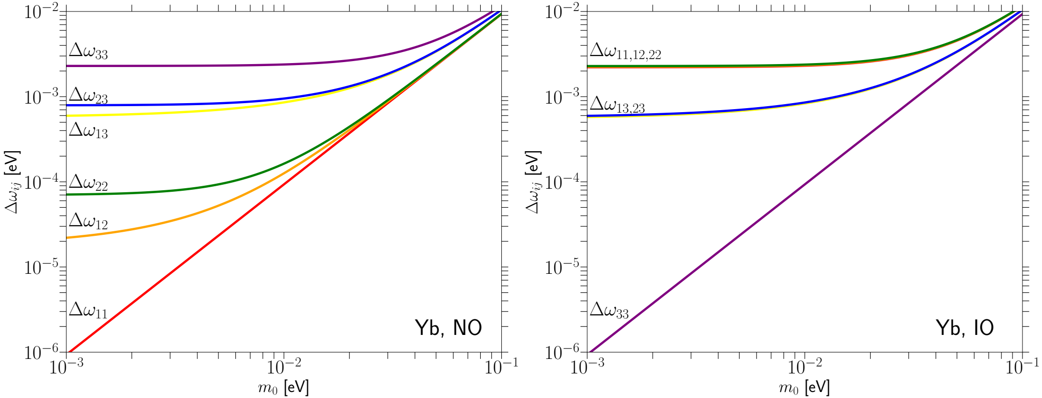
There is a total of 6 thresholds related to all combinations of m_i, m_j, $i, j = 1, 2, 3$.

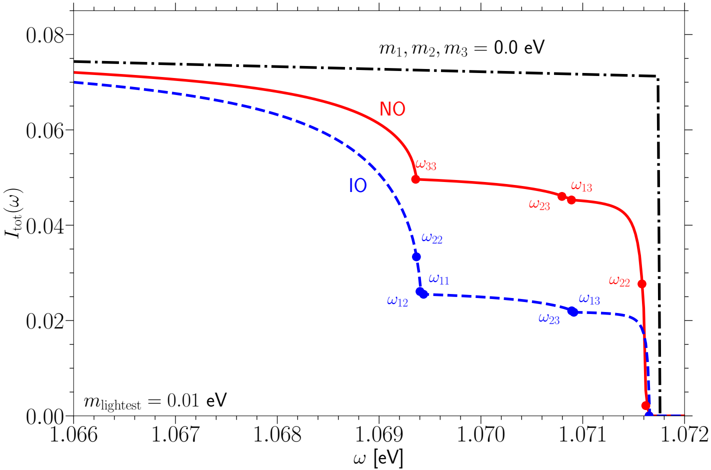
Threshold contain mass information

$$\Delta\omega_{ij} = \frac{(m_i+m_j)^2}{2\Delta E}$$



$\Delta\omega \sim \mathcal{O}(10^{-5})$ eV

Mass and hierarchy is observable!



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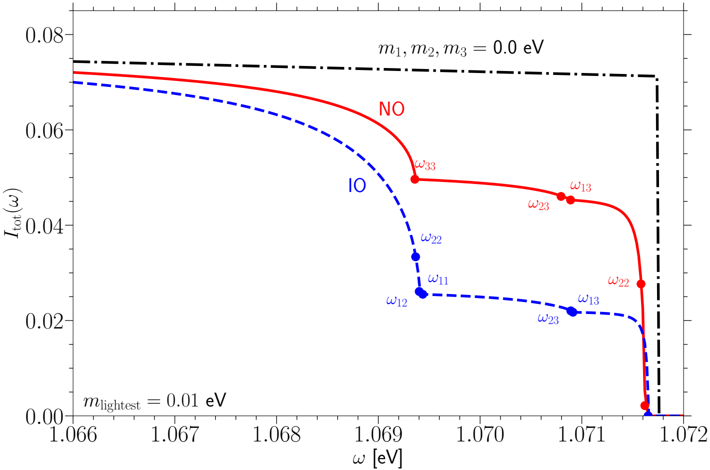

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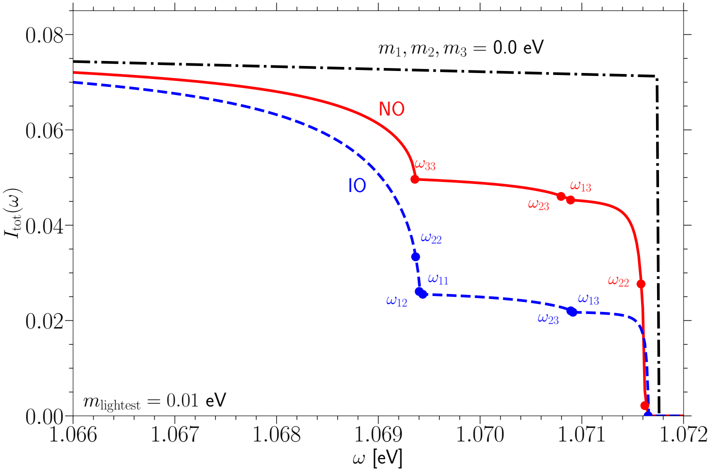

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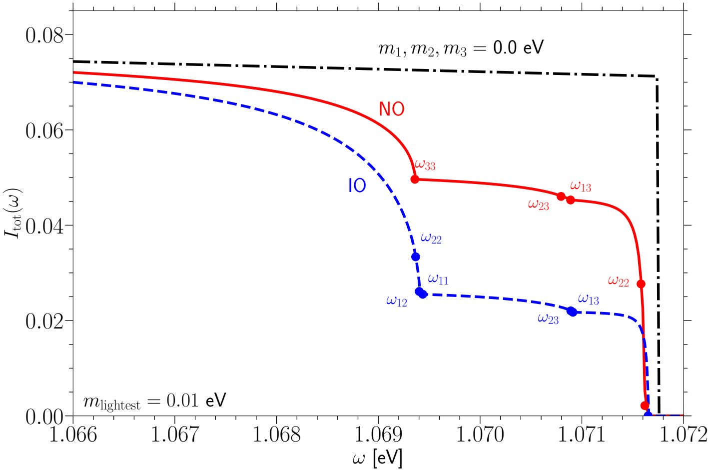

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- Size gives mass hierarchy

Under reasonable assumptions:

3σ for $m_{\rm lightest}$ and mass ordering

N. Song, R. B. Garcia et.al.
Phys. Rev. D **93**, no.1, 013020 (2016)

We can go further: BSM physics

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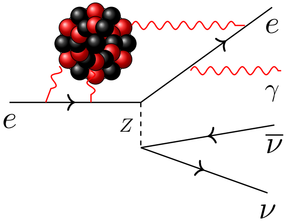

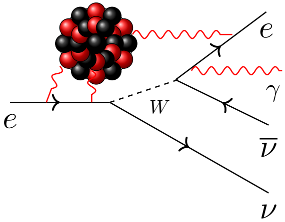

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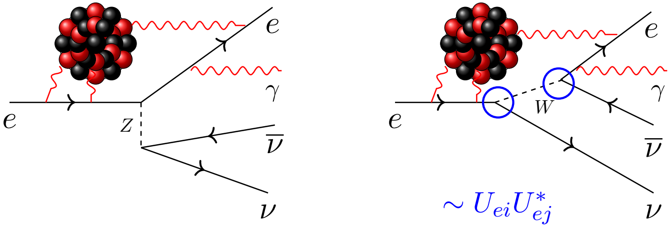

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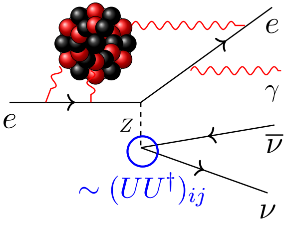

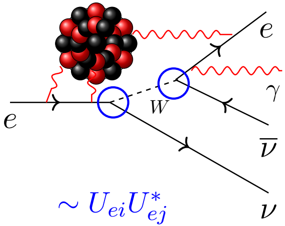

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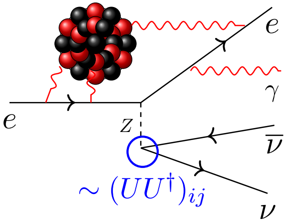

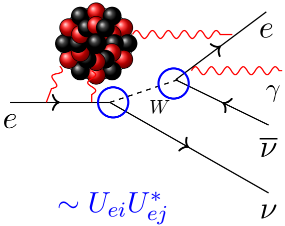

$$I(\omega) = \sum_{ij} \frac{\Delta_{ij}(\omega)}{(E_{vg} - \omega)^2} \Theta(\omega - \omega_{ij}^{\max}) \left[|a_{ij}|^2 I_{ij}^{(D)} - \delta_M \mathrm{Re}[a_{ij}^2] m_i m_j \right]$$

$$a_{ij} = U_{ei}U^*_{ej} + \frac{1}{2}(UU^\dagger)_{ij}$$

Require a large number of events...

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- Information on mixing angles

- Non-unitarity of U

- Even majorana phases

See: N. Song etal Phys. Rev. D **93**, no.1, 013020 (2016) and G. Y. Huang et al. Int. J. Mod. Phys. A **35**, no.01, 2050004 (2020)

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Caveat: Needs larger number of events ($\sim 10^3$ or larger).
But current technology $\mathcal{O}(10)$ $\Rightarrow$ needs technological improvement

Possible to probe new interactions too!

BSM Interactions

S.-F. Ge & Pedro, Pasquini Eur.Phys.J.C 82 (2022) 3, 208

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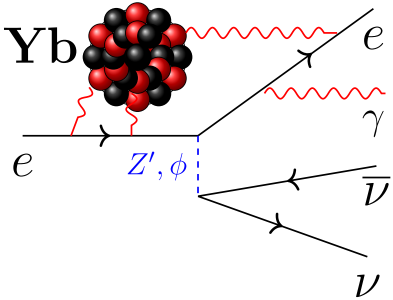

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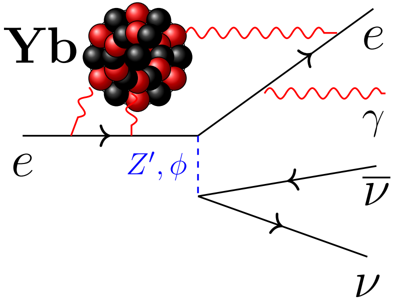

$$\mathcal{L}_V = g^e \bar{e}\gamma^\mu\gamma_5 e Z'_\mu + \bar{\nu}_i\gamma^\mu(g^\nu_{L,ij}P_L + g^\nu_{R,ij}P_R)\nu_j Z'_\mu.$$

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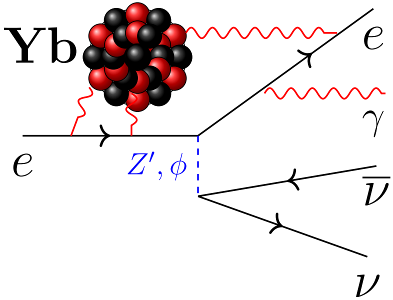

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$$\mathcal{L}_S = i y^e_P \bar{e}\gamma_5 e\phi + \bar{\nu}_i (y^\nu_{S,ij} + i\gamma_5 y^\nu_{P,ij})\nu_j \phi + h.c.,$$

Specially good for light mediators

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- Also, light mediators, the effect (and bounds) will be enhanced, specially for m_ϕ^2 around the eV scale: $\frac{m_W^2}{q^2 - m_{\phi,Z'}^2} \sim 10^{21}$

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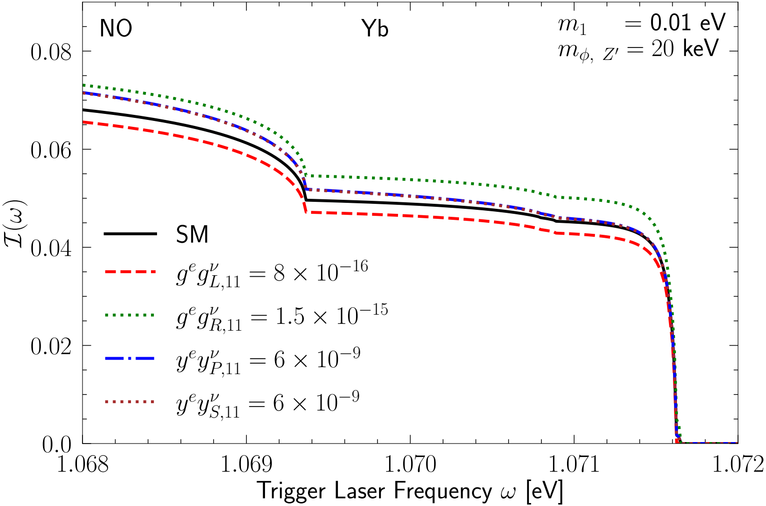
- The media

$$\frac{1}{q^2 - M^2}$$

- SM $M = l$

- Also, light ... or m_ϕ^2

around the e



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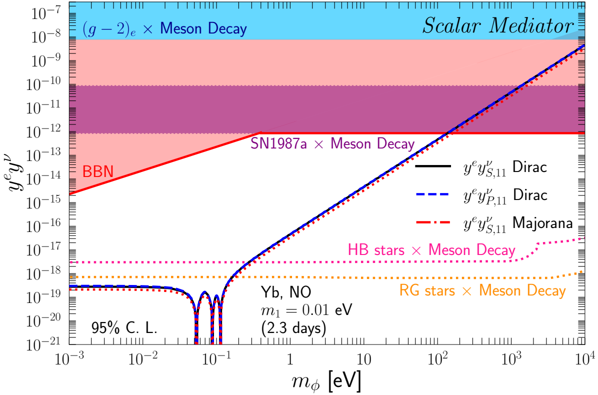

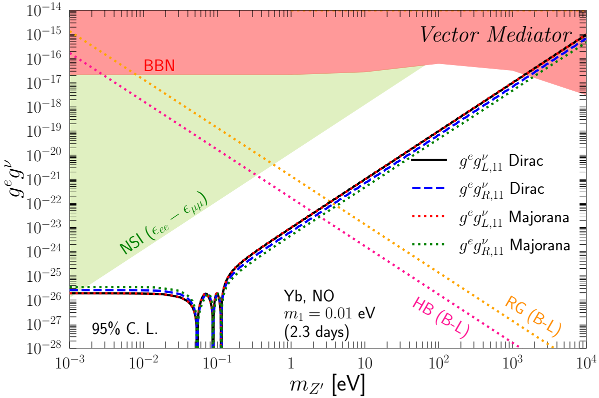

See S.-F. Ge & Pedro Pasquini Eur.Phys.J.C 82 (2022) 3, 208

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Another Possibility: The standard model has a massless mediator, the photon!

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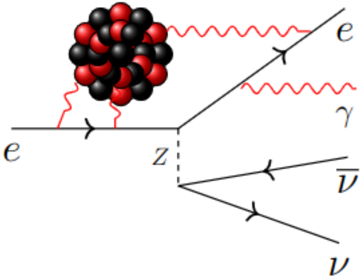
Still too small, but BSM physics can make $\mu_\nu, \epsilon_\nu \sim 10^{-11} \mu_B$

Photon as mediator for RENP



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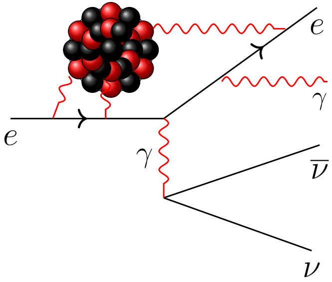
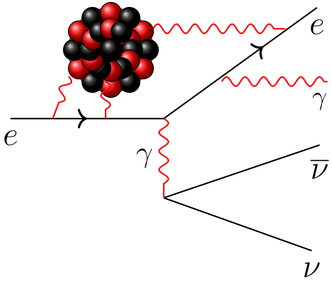
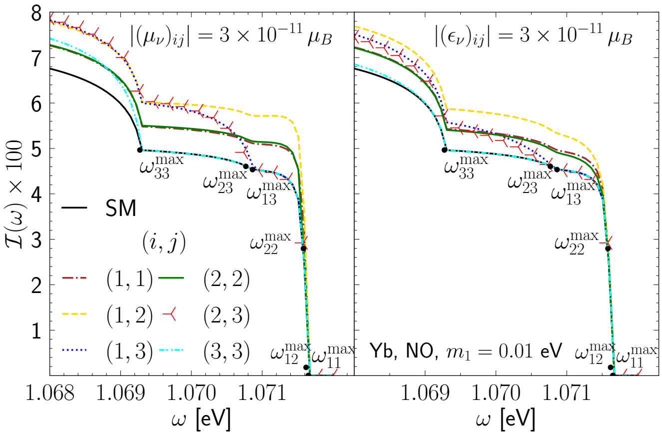
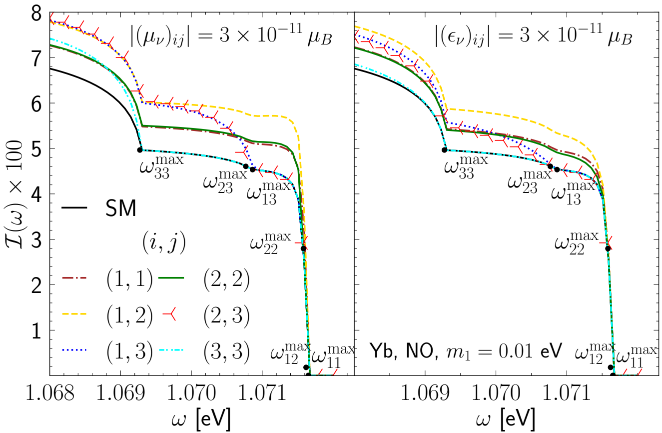



e
e
γ
γ
$\overline{\nu}$
ν


$|(\mu_\nu)_{ij}| = 3 \times 10^{-11}\ \mu_B$
$|(\epsilon_\nu)_{ij}| = 3 \times 10^{-11}\ \mu_B$
$\mathcal{I}(\omega) \times 100$
ω [eV]
SM
(i, j)
(1, 1)
(2, 2)
(1, 2)
(2, 3)
(1, 3)
(3, 3)
Yb, NO, $m_1 = 0.01$ eV
$\omega_{33}^{\max}$
$\omega_{23}^{\max}$
$\omega_{13}^{\max}$
$\omega_{22}^{\max}$
$\omega_{12}^{\max}$
$\omega_{11}^{\max}$

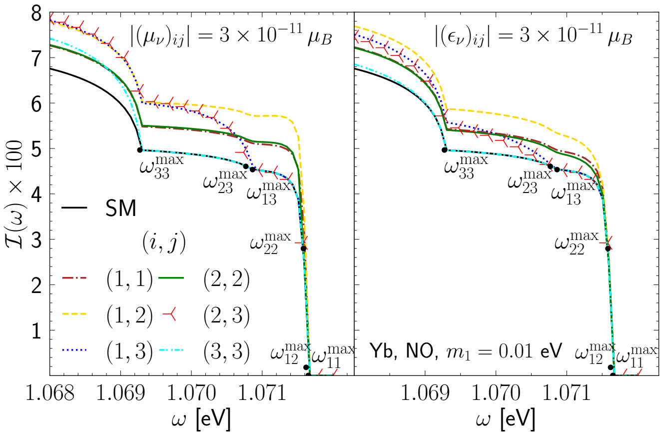
Photon as mediator for RENP

Notice



Notice

(1) Shape is different for μ_ν and ϵ_ν



Notice

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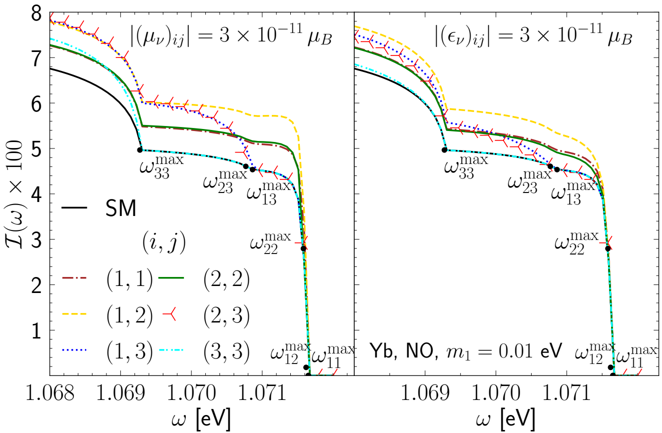
(2) ij contribution starts when $\omega < \omega_{ij}^{\max}$



Separate magnetic from electric dipoles

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$(\nu + e \to \nu + e)$

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D. A. Sierra et al.

Phys.Rev.D 105 (2022) 3, 035027

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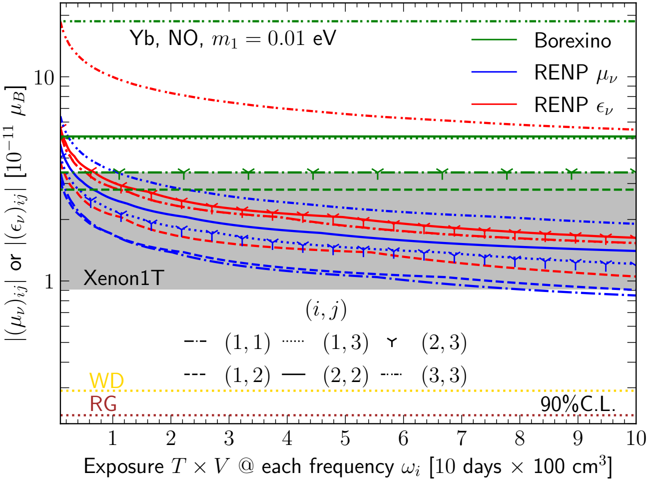
Large system. uncertanties

R. J. Stancliffe et al.

A&A 586, A119 (2016)

Good Sensitivity!



Summary

- Radiative emission of neutrino pair (RENP) is a novel and interesting idea.

- The RENP can obtain the neutrino mass scale and look for new physics.

- The low energy q^2 of RENP makes it specially powerful probe of light mediator.

- μ_ν and ϵ_ν can be thoroughly explored

Founding Support:

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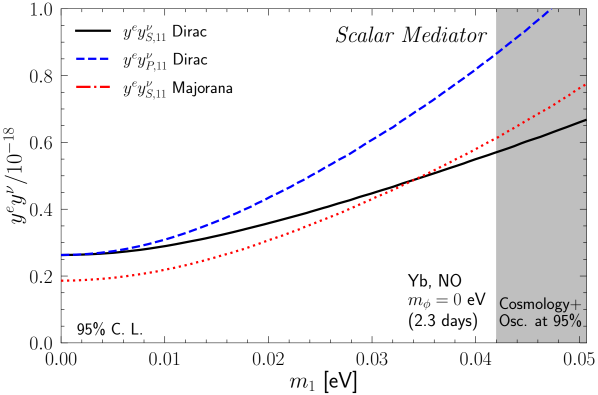
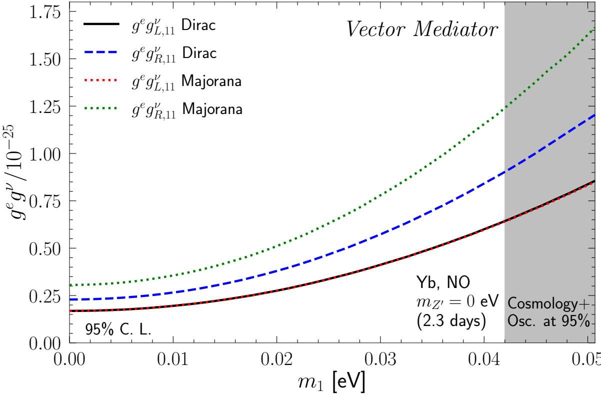
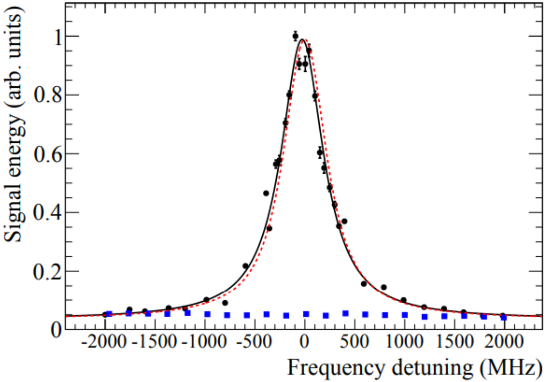
Backup Slides

Backup slides







Source: T. Hiraki et al. J. Phys. B **52**, no.4, 045401 (2019)

Backup slides

$$\mathcal{I}_{Z'} = \sum_{ij} \frac{\Delta_{ij}(\omega)}{(E_{vg}-\omega)^2}\Theta(\omega-\omega_{ij}^{\max})\left[\left(|a_{ij}^L|^2+|a_{ij}^R|^2-2\delta_M \mathrm{Re}[a_{ij}^L a_{ij}^R]\right)I_{ij}^{(D)} + \left(\delta_M \mathrm{Re}\left[(a_{ij}^L)^2+(a_{ij}^R)^2\right]-2\mathrm{Re}\left[a_{ij}^{L*}a_{ij}^R\right]\right)\right.$$

$$\mathcal{I}_{\phi} = \sum_{ij} \frac{\Delta_{ij}(\omega)}{(E_{vg}-\omega)^2}\Theta(\omega-\omega_{ij}^{\max})\left[I_{ij}^{\mathrm{SM}}(\omega)+\delta I_{ij}(\omega)\right]$$

$$\delta I_{ij} = \frac{|y^e|^2\omega^2}{m_e^2 G_\mathrm{F}^2}\frac{\left[|y_{S,ij}^\nu|^2+(1-\delta_M)|y_{P,ij}^\nu|^2\right]E_{eg}(E_{eg}-2\omega)-|y_{S,ij}^\nu|^2(m_i+m_j)^2-(1-\delta_M)|y_{P,ij}^\nu|^2(m_i-m_j)^2}{24[E_{eg}(E_{eg}-2\omega)-m_\phi^2]^2} \tag{29}$$

$$+\frac{y^e\omega^2}{6\sqrt{2}G_F}\left\{\frac{\mathrm{Re}\left[a_{ij}y_{S,ij}^\nu\right](m_i-m_j)\left[1-\frac{(m_i+m_j)^2}{E_{eg}(E_{eg}-2\omega)}\right]}{m_e[E_{eg}(E_{eg}-2\omega)-m_\phi^2]}-(1-\delta_M)\frac{\mathrm{Im}\left[a_{ij}y_{P,ij}^\nu\right](m_i+m_j)\left[1-\frac{(m_i-m_j)^2}{E_{eg}(E_{eg}-2\omega)}\right]}{m_e[E_{eg}(E_{eg}-2\omega)-m_\phi^2]}\right\}.$$

Coupling	$\mathcal{L}_{\text{new}}$	Non-Relativistic Transition	Type
scalar	$y_S^e \bar{e} e$	$\langle f \| i \rangle$	E1
pseudo-scalar	$i y_P^e \bar{e} \gamma_5 e$	$\frac{\mathbf{q}}{2m_e} \cdot \langle f \| \boldsymbol{\sigma} \| i \rangle$	M1
vector	$g_V^e \bar{e} \gamma^\mu e$	$(\langle f \| i \rangle, \frac{\mathbf{q}}{2m_e} \cdot \langle f \| \boldsymbol{\sigma} \boldsymbol{\sigma} \| i \rangle)$	E1
axial-vector	$g_A^e \bar{e} \gamma^\mu \gamma_\mu e$	$(\frac{\mathbf{q}}{2m_e} \cdot \langle f \| \boldsymbol{\sigma} \| i \rangle, \langle f \| \boldsymbol{\sigma} \| i \rangle)$	M1