The Second International Conference on Axion Physics and Experiment

Majoron Dark Matter from Type II Seesaw

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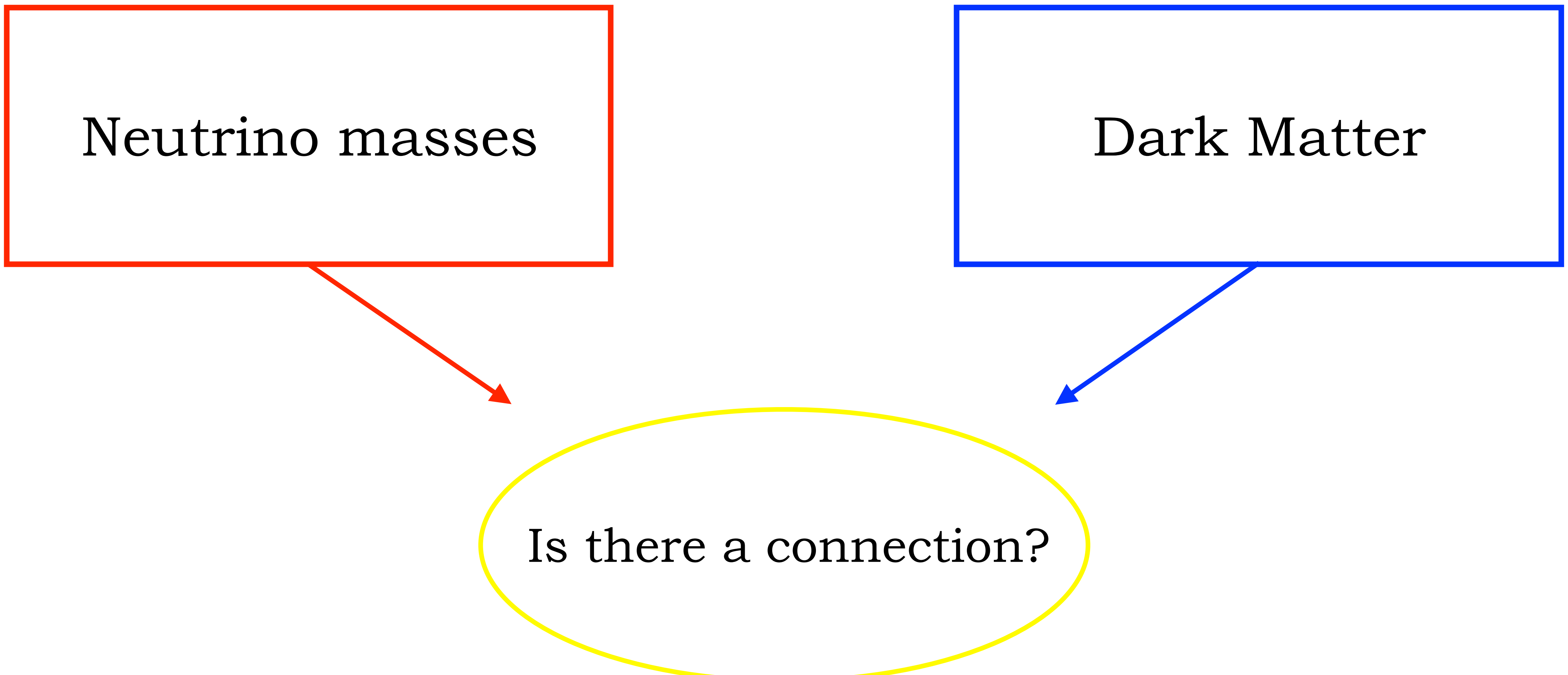
mainly based on C. Biggio, LC, T. Ota, S. Zanchini, arXiv:2304.12527

We know the Standard Model is incomplete.
Observations tell us that, in particular:



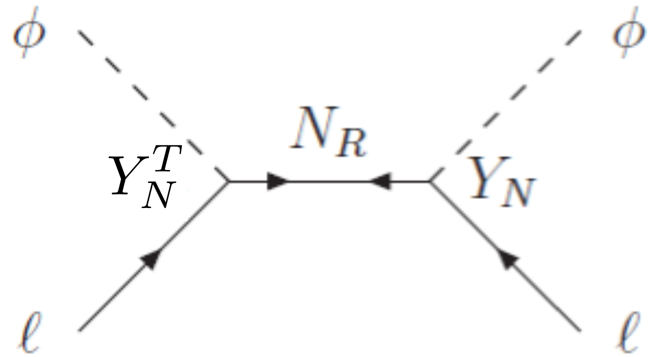
Neutrino masses

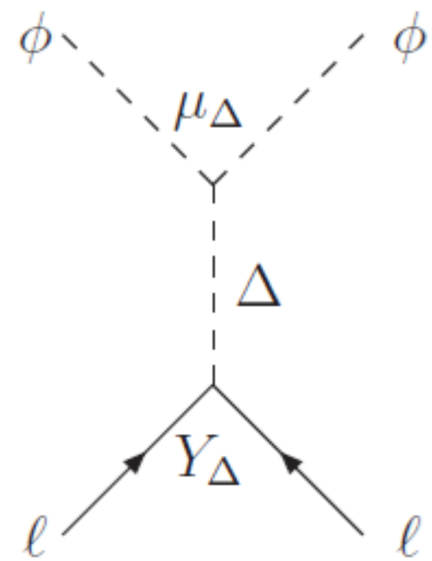
Neutrinos oscillate → we have to add neutrino mass terms to the SM

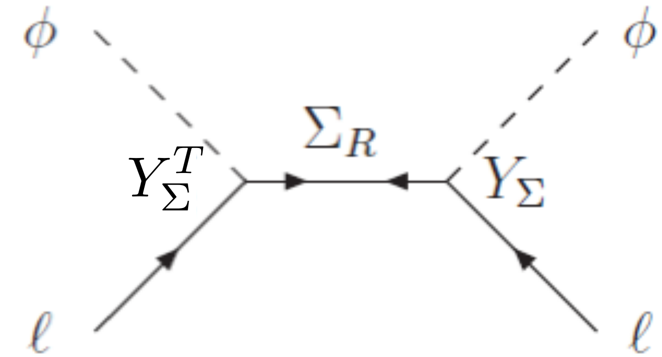
- Dirac: $\mathcal{L} \supset -(Y_\nu)_{ij}\,\overline{\nu}_{R\,i}\,\widetilde{\Phi}^\dagger\,L_{L\,j} + \text{h.c.} \quad \Longrightarrow \quad (m_\nu^D)_{ij} = \frac{v}{\sqrt{2}}(Y_\nu)_{ij}.$
  - At least 2 RH (i.e. sterile) neutrinos are introduced
  - Lepton number (*L*) is conserved
  - *L*-conservation actually needs to be enforced to prevent $M_R \bar{\nu}_R^c \nu_R$
  - Requires $Y_\nu \lesssim 10^{-12}$ (10^7 times smaller than the electron Yukawa)

- Majorana: $\mathcal{L} \supset \frac{C_{ij}}{\Lambda}\left(\overline{L^c_{L\,i}}\,\tau_2\Phi\right)\left(\Phi^T\tau_2 L_{L\,j}\right) + \text{h.c.} \quad \Longrightarrow \quad (m_\nu^M)_{ij} = \frac{C_{ij}v^2}{\Lambda}$ Weinberg '79
  - Effective dimension-5 operator (only one of that order in the SMEFT)
  - $\Delta L = 2 \;\Rightarrow$ Lepton Number Violation
  - Naturally explain smallness of neutrino masses (if $\Lambda \gg v$)
  - Requires an UV completion at Λ (that is, indicates a *new physics* scale)

Three ways of generating the Weinberg operator at the tree level:







Type I

Heavy fermionic singlets (RH neutrinos)

Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic, ...

Type II

Heavy scalar triplet

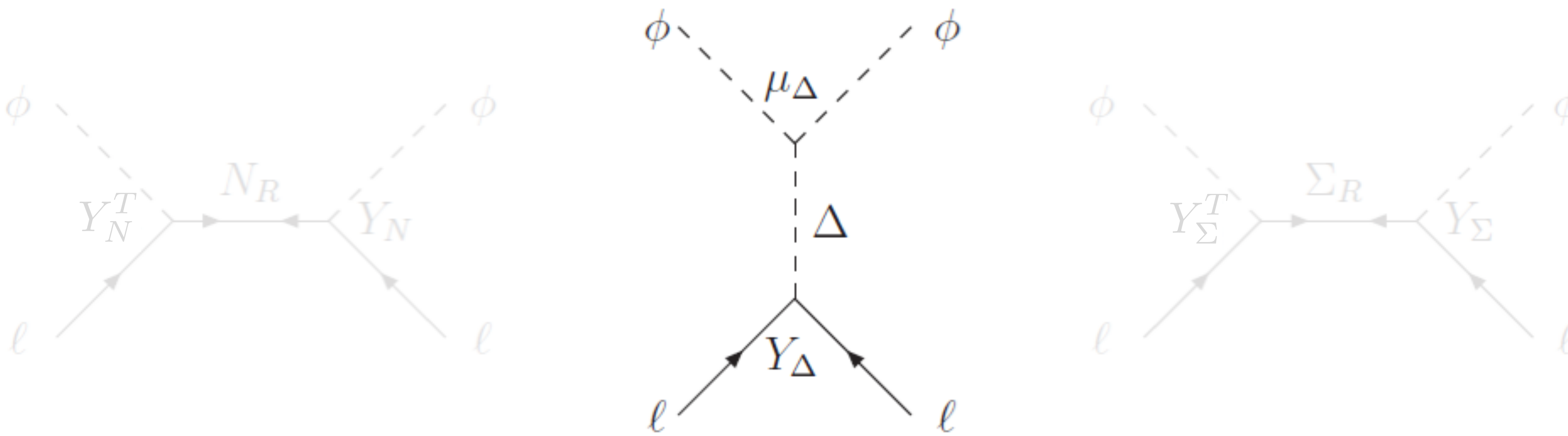
Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle, ...

Type III

Heavy fermionic triplets

Foot, Lew, He, Joshi, Ma, Roy, Hambye et al., Bajc et al., Dorsner, Fileviez-Perez, ...

Three ways of generating the Weinberg operator at the tree level:



Type I	Type II	Type III
Heavy fermionic singlets (RH neutrinos)	Heavy scalar triplet	Heavy fermionic triplets

Scalar SU(2) triplet (hypercharge Y=1) $\Delta = \begin{pmatrix} \Delta^0 & \Delta^+/\sqrt{2} \\ \Delta^+/\sqrt{2} & \Delta^{++} \end{pmatrix}$

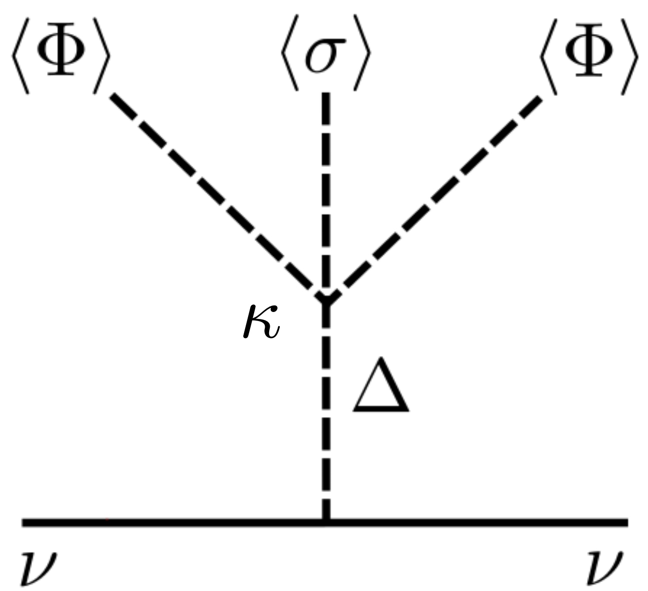
$$\mathcal{L}_{\text{Type II}} \supset (Y_\Delta)_{\alpha\beta}\, \overline{L^c}_\alpha \Delta L_\beta + \mu_\Delta \Phi^\intercal \Delta \Phi + \text{h.c.} \quad \Rightarrow \quad m_\nu = -Y_\Delta \frac{\mu_\Delta v^2}{M_\Delta^2}$$

L-breaking term $[L(\Delta) = -2]$

Type II seesaw with spontaneous L-breaking

What if the lepton number is *spontaneously* broken in type II seesaw, that is, μ_Δ is the vev of an additional scalar singlet σ ?

$$\mathcal{L} \supset (Y_\Delta)_{\alpha\beta}\, \overline{L^c}_\alpha \Delta L_\beta + \kappa\, \sigma\, \Phi^{\mathsf{T}} \Delta \Phi + \text{h.c.}$$



$$\langle \sigma \rangle = \frac{v_1}{\sqrt{2}}, \quad \langle \Phi^0 \rangle = \frac{v_2}{\sqrt{2}} \quad \Longrightarrow \quad v_3 = \frac{1}{2}\kappa \frac{v_1 v_2^2}{M_\Delta^2}$$

$$\langle \Delta^0 \rangle = \frac{v_3}{\sqrt{2}}$$

$$(m_\nu)_{\alpha\beta} = -\sqrt{2}\, (Y_\Delta)_{\alpha\beta}\, v_3 = -\frac{1}{\sqrt{2}}\, (Y_\Delta)_{\alpha\beta}\, \kappa v_1 \frac{v_2^2}{M_\Delta^2}$$

⇒ and the spectrum will include a massless Nambu-Goldstone boson (NGB), the *majoron*,

Choi Santamaria '91
Joshipura Valle '93
Diaz et al. '98
Bonilla Romão Valle '15
...

The states of the three scalar fields mix:

$$\sigma = \frac{1}{\sqrt{2}}\left(v_1 + R_1 + \mathrm{i}I_1\right), \quad \Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(v_2 + R_2 + \mathrm{i}I_2\right) \\ \phi^- \end{pmatrix},$$

$$\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(v_3 + R_3 + \mathrm{i}I_3\right) & \Delta^+/\sqrt{2} \\ \Delta^+/\sqrt{2} & \Delta^{++} \end{pmatrix},$$

$\Rightarrow$

$$H_i = (O_R)_{ia} R_a, \quad A_i = (O_I)_{ia} I_a,$$

$$H_i^\pm = (O_\pm)_{ia} S_a^\pm, \quad H^{\pm\pm} = \Delta^{\pm\pm}.$$

Mass eigenstates:

Majoron!

$$J = A_1, \quad G^0 = A_2, \quad A = A_3, \quad G^\pm = H_1^\pm, \quad H^\pm = H_2^\pm$$

We work in the small mixing regime, consistently with the constraints on the fields' vevs from EWPOs:

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \frac{v_2^2 + 2v_3^2}{v_2^2 + 4v_3^2} = \frac{v_{\rm EW}^2}{v_{\rm EW}^2 + 2v_3^2}$$

$$v_{\rm EW} \equiv \sqrt{v_2^2 + 2v_3^2} \simeq 246\,\mathrm{GeV}$$

$$\rho = 1.0002 \pm 0.0009$$

PDG '22

$\Rightarrow$

$$v_3 < 7\ \mathrm{GeV}$$

$$v_2 \approx v_{\rm EW}$$

A viable model with a *cosmologically stable* majoron requires the hierarchy

$\Rightarrow$ $$v_3 \ll v_2 \ll v_1$$

Under the above assumptions:

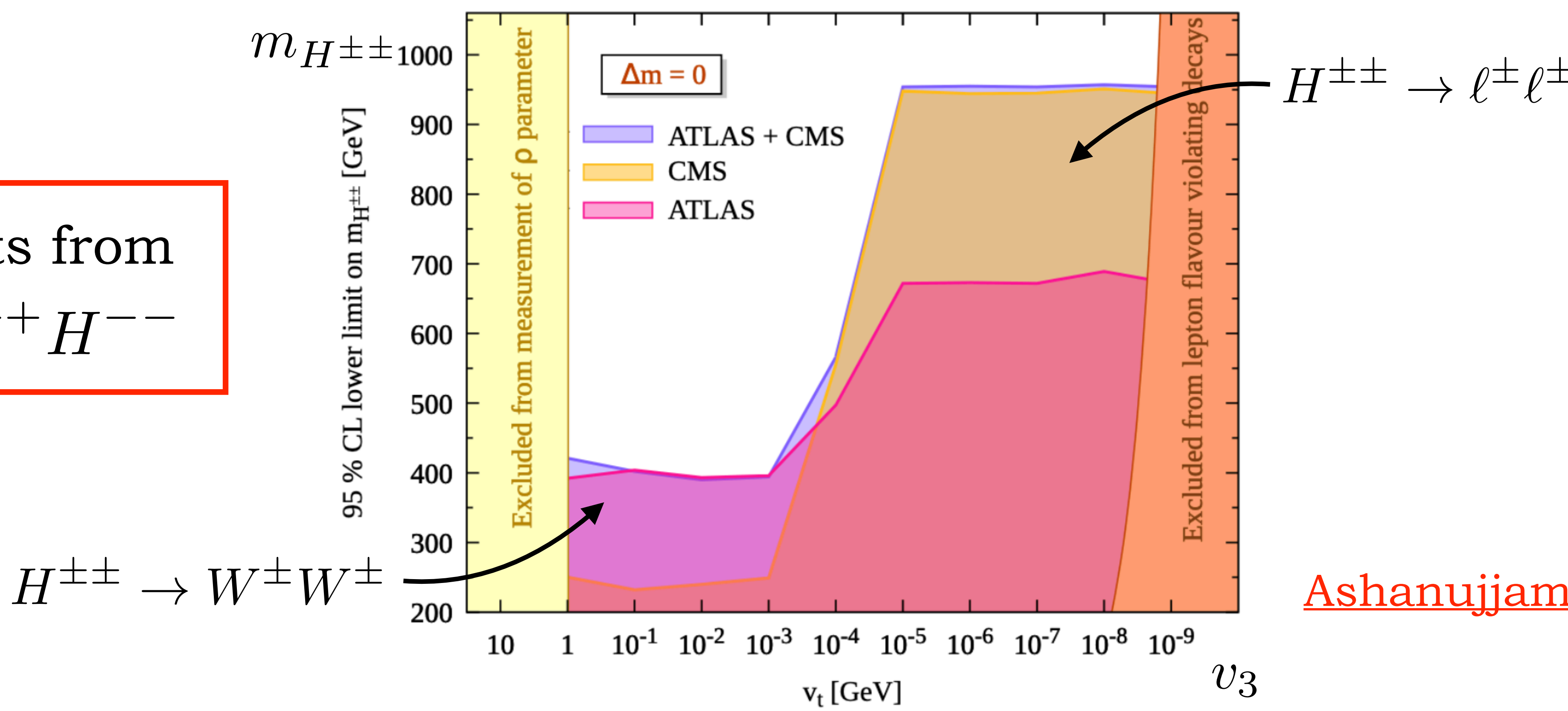
$$M^2_{H_3} \simeq M^2_{H_A} \simeq M^2_{H^\pm} \simeq M^2_{H^{\pm\pm}} \simeq M^2_\Delta \equiv \frac{1}{2}\kappa \frac{v_1 v_2^2}{v_3}$$

We can take $v_1,\ v_3,\ M_\Delta$ as free parameters.

For a given choice of the vevs LHC searches for triplet states than set a *lower bound* on κ (the coupling relevant for majoron DM FI production):

$$\kappa \gtrsim 2.7\cdot 10^{-7}\left[\frac{M_\Delta}{400\,\mathrm{GeV}}\right]^2\left[\frac{v_3}{1\,\mathrm{GeV}}\right]\left[\frac{2\cdot 10^7\,\mathrm{GeV}}{v_1}\right]$$

LHC limits from
$pp \to H^{++}H^{--}$



Ashanujjaman Ghosh '21

Under the above assumptions:

$$M_{H_3}^2 \simeq M_{H_A}^2 \simeq M_{H^\pm}^2 \simeq M_{H^{\pm\pm}}^2 \simeq M_\Delta^2 \equiv \frac{1}{2}\kappa\frac{v_1 v_2^2}{v_3}$$

We can take $v_1,\ v_3,\ M_\Delta$ as free parameters.

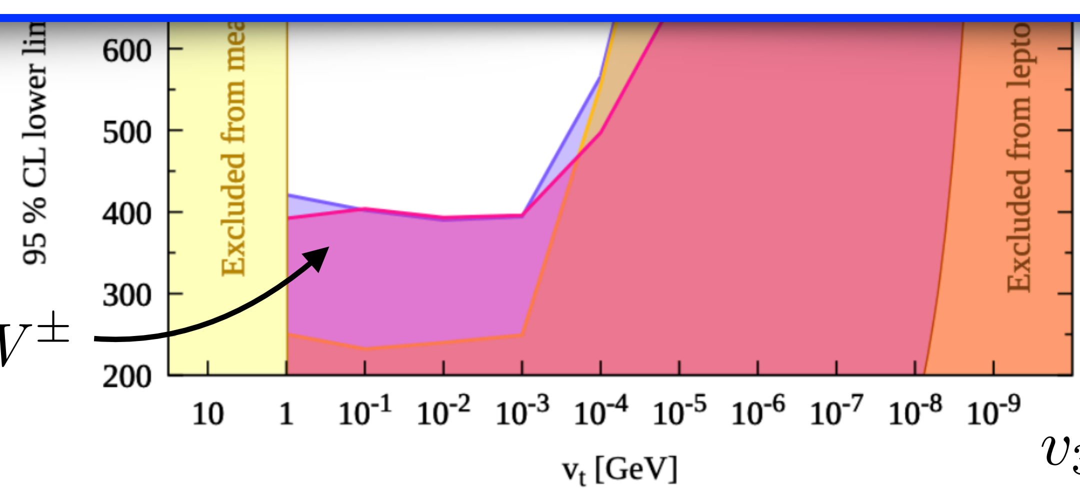
What about the majoron?

Under the same assumptions, it is mostly *singlet-like*

We take its mass m_J as yet another *free parameter*, coming from a small explicit breaking (e.g. from Planck suppressed ops such as $\sim \sigma^5/M_{\rm Pl}$)

[for a different option, m_J arising from explicit breaking due to μ_Δ + scalar mixing see Chao et al. '22 and yesterday's talk by Wei]

$pp \to H^{++}H^{--}$



$H^{\pm\pm} \to W^\pm W^\pm$

v_3

Ashanujjaman Ghosh '21

Type II Majoron couplings

In our limit ($v_3 \ll v_2 \ll v_1$) despite being mostly singlet, the majoron inherits interactions through mixing in the scalar sector:

$$\mathcal{L}_J \supset \; i g^P_{Jff} \, J \, \overline{f} \gamma^5 f - \frac{1}{4} g_{J\gamma\gamma} J \, F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

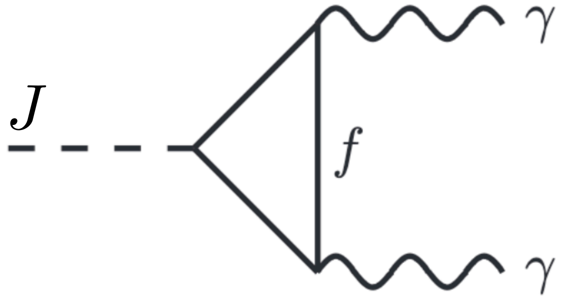
- Couplings to neutrinos (from mixing with the triplet): $g^P_{J\nu_i\nu_i} \simeq -\dfrac{m_{\nu_i}}{2v_1}$

- Couplings to charged fermions (from mixing with the doublet):

$$g^P_{J\ell_\alpha\ell_\alpha} \simeq -m_{\ell_\alpha} \frac{2v_3^2}{v_1 v_2^2}\,, \quad g^P_{Ju_\alpha u_\alpha} \simeq m_{u_\alpha} \frac{2v_3^2}{v_1 v_2^2}\,, \quad g^P_{Jd_\alpha d_\alpha} \simeq -m_{d_\alpha} \frac{2v_3^2}{v_1 v_2^2}$$

flavour conserving (such as the Higgs couplings)!
and $\sim v_3^2/v_2^2$ suppressed

- Couplings to photons from fermion loops: e.g. Bauer Neubert Thamm '17



$$g_{J\gamma\gamma} \simeq \frac{2\alpha}{\pi} \frac{v_3^2}{v_1 v_2^2} \left[\frac{M_J^2}{M_J^2 - m_{\pi^0}^2} - \sum_f Q_f^2 N_c^f B_1(\tau_f) \right] \qquad \tau_f \equiv 4m_f^2/M_J^2$$

L-number *free of EM anomalies* → J decouples from photons for $M_J \ll m_e$
i.e. $B_1(\tau_f) \to 0$ for $\tau_f \to \infty$

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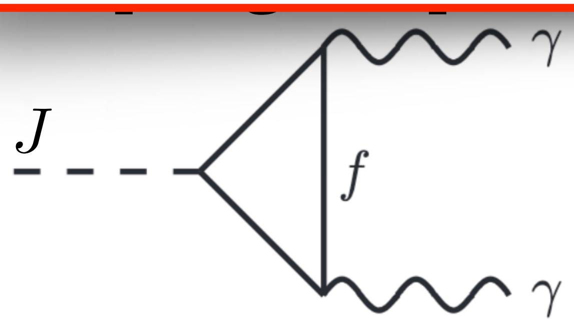
⇨ In the range $M_J \approx 1\,\mathrm{keV} - 100\,\mathrm{MeV}$ (relevant for DM detection), J can decay into photons, neutrinos and (possibly) electrons:

$$\Gamma(J\to\gamma\gamma) = \frac{M_J^3}{64\pi}\left|g_{J\gamma\gamma}\right|^2,$$

$$\Gamma(J\to\nu_i\nu_i) = \frac{M_J}{4\pi}\left|g^P_{J\nu_i\nu_i}\right|^2 \simeq \frac{M_J}{16\pi}\left(\frac{m_{\nu_i}}{v_1}\right)^2,$$

$$\Gamma(J\to e^+e^-) = \frac{M_J}{8\pi}\left|g^P_{Jee}\right|^2\sqrt{1-\frac{4m_e^2}{M_J^2}} \simeq \frac{M_J}{2\pi}\left(\frac{m_e}{v_1}\right)^2\left(\frac{v_3}{v_2}\right)^4\sqrt{1-\frac{4m_e^2}{M_J^2}}\,.$$



$$g_{J\gamma\gamma} \simeq \frac{2\alpha}{\pi}\frac{v_3^2}{v_1 v_2^2}\left[\frac{M_J^2}{M_J^2 - m_{\pi^0}^2} - \sum_f Q_f^2 N_c^f B_1(\tau_f)\right] \qquad \tau_f \equiv 4m_f^2/M_J^2$$

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Majoron DM production: freeze in

Even if our majoron is never in thermal equilibrium with the thermal bath, it can be produced through decays of triplet states via the freeze in mechanism

Hall et al. '09

$$H^\pm \to W^\pm J\,, \quad H_3 \to Z J\,, \quad A \to H_2 J$$

$$\Rightarrow \quad \Omega_J h^2 \simeq 0.12 \left[\frac{110}{g_*(M_\Delta)}\right]^{3/2} \left[\frac{M_J}{10\,\mathrm{keV}}\right] \left[\frac{M_\Delta}{500\,\mathrm{GeV}}\right] \left[\frac{2\cdot 10^9\,\mathrm{GeV}}{v_1}\right]^2 \left[\frac{v_3}{5\,\mathrm{GeV}}\right]^2$$

Caveats and constraints:

- And we need $M_\Delta \lesssim 1$ TeV to keep J out of equilibrium (good news for colliders)
- Lowering v_1, majoron is *overproduced* unless freeze in occurs during an early matter dominated era (low reheating T) such that its abundance is *diluted* by the radiation injected by the decaying matter field (e.g. the inflaton):

Co et al. '15

$$\Omega_J h^2 \simeq 0.12 \left[\frac{90}{g_*(T_R)}\right]^{3/2} \left[\frac{M_J}{10\,\mathrm{keV}}\right] \left[\frac{500\,\mathrm{GeV}}{M_\Delta}\right]^6 \left[\frac{2.7\cdot 10^7\,\mathrm{GeV}}{v_1}\right]^2 \left[\frac{v_3}{5\,\mathrm{GeV}}\right]^2 \left[\frac{T_R}{20\,\mathrm{GeV}}\right]^7$$

- Lower bound on M_J from structure formation (from Lyman-α observations) akin to that for warm DM: $M_J \gtrsim 10$ keV

D'Eramo Lenoci '20

We consider the misalignment mechanism (just as for the QCD axion) with the lepton number broken before inflation

Standard radiation-dominated (RD) era:

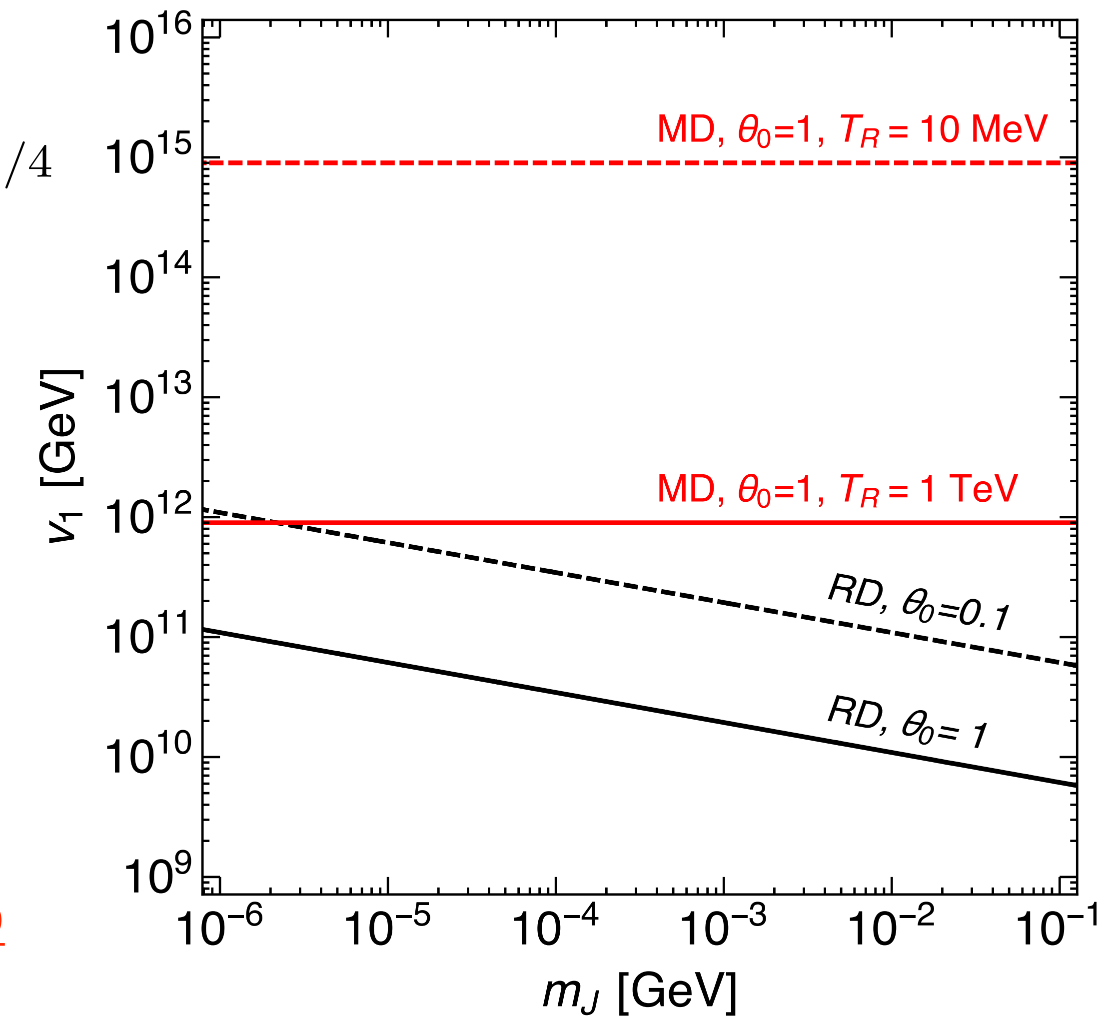
$$\Omega_J h^2 \simeq 0.12 \left[\frac{v_1 \theta_0}{1.9 \cdot 10^{13}\,\mathrm{GeV}}\right]^2 \left[\frac{M_J}{1\,\mu\mathrm{eV}}\right]^{1/2} \left[\frac{90}{g_*(T_{\rm osc})}\right]^{1/4}$$

Early matter domination (MD):

$$\Omega_J h^2 \simeq 0.12 \left[\frac{v_1 \theta_0}{9 \cdot 10^{14}\,\mathrm{GeV}}\right]^2 \left[\frac{T_R}{10\,\mathrm{MeV}}\right]$$

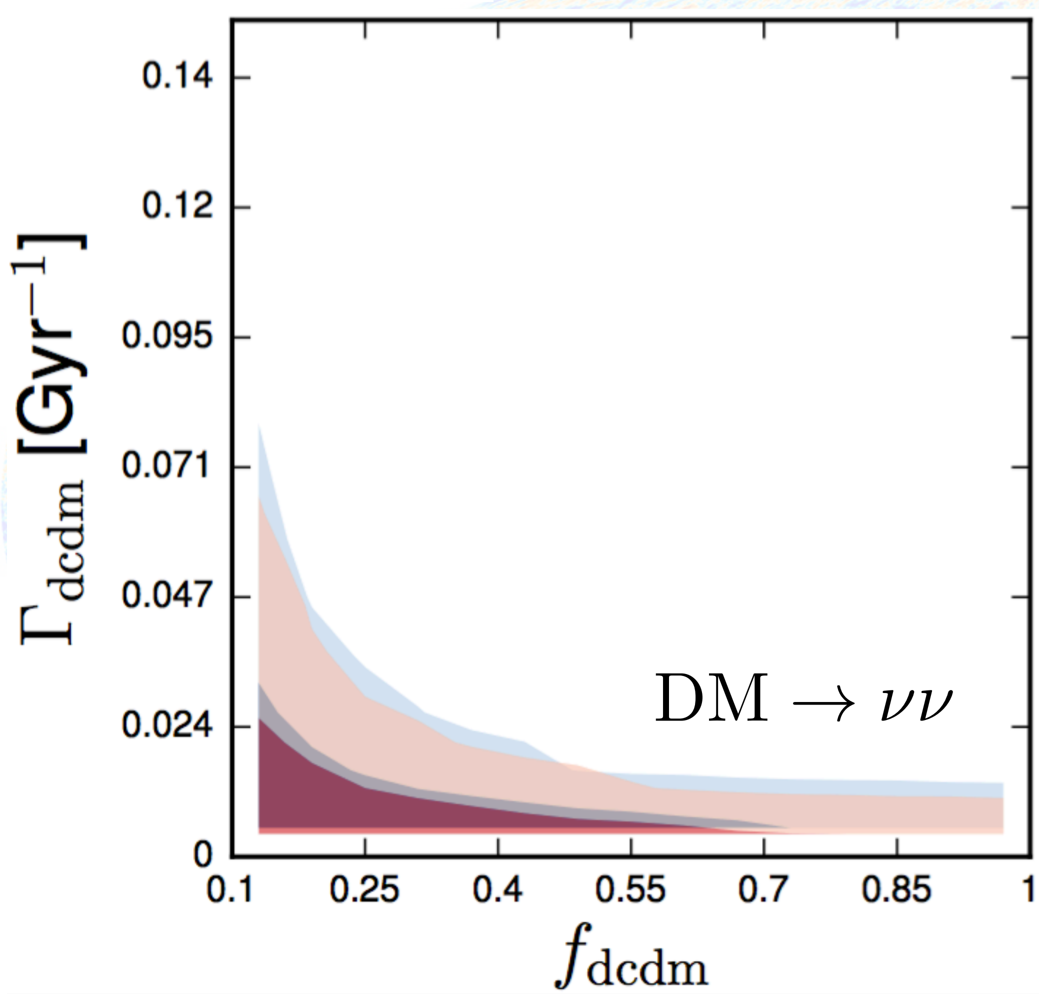
e.g. Blinov et al. '19

$\Omega_J h^2$=0.12 from misalignment

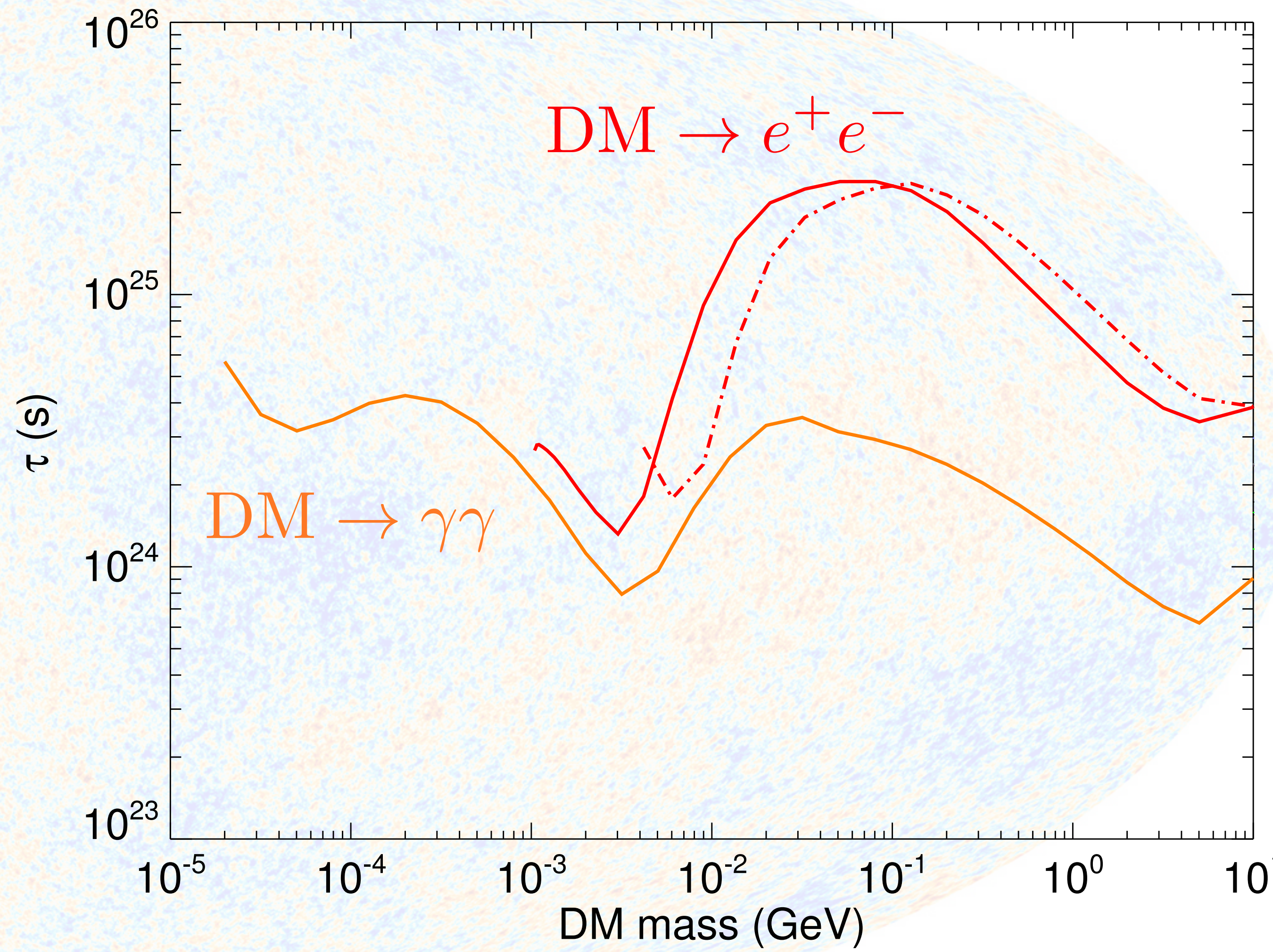


For $v_1 \lesssim 10^{10}$ GeV DM is underproduced (unless other mechanisms are are work)

Energy injection from particles decaying after recombination modifies thermal history and ionisation of the universe affecting the CMB:



Poulin et al. '16

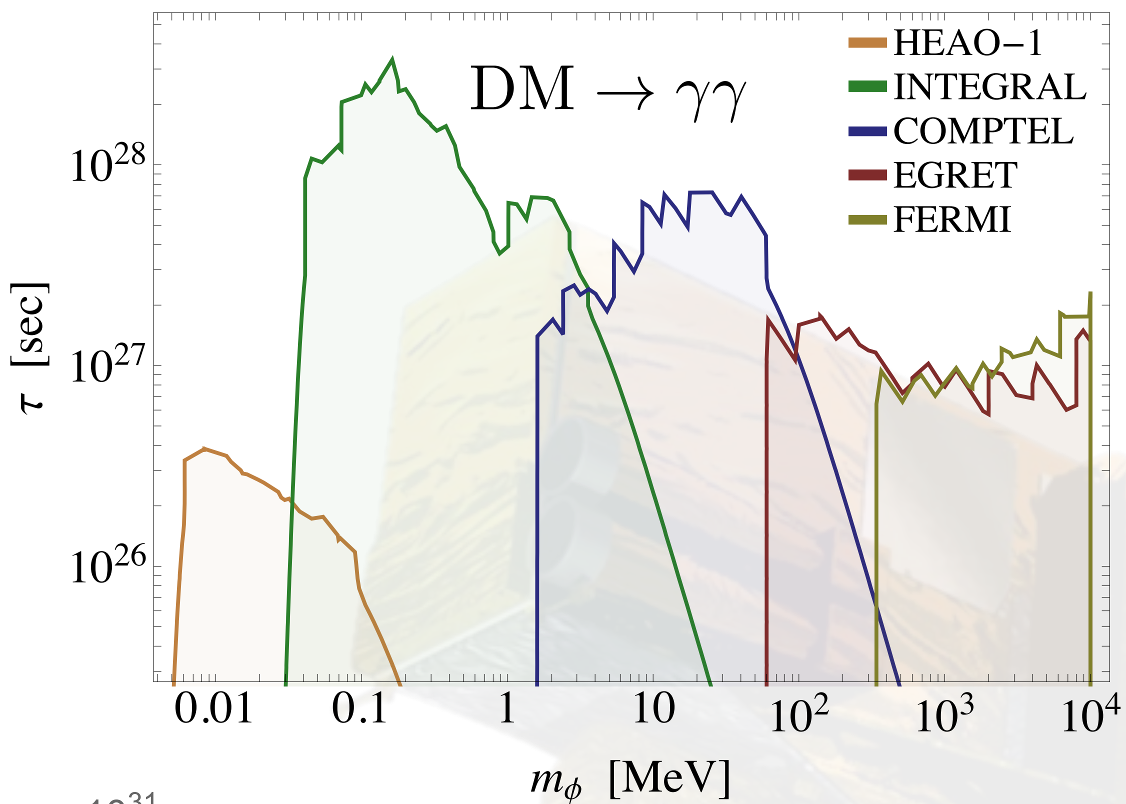


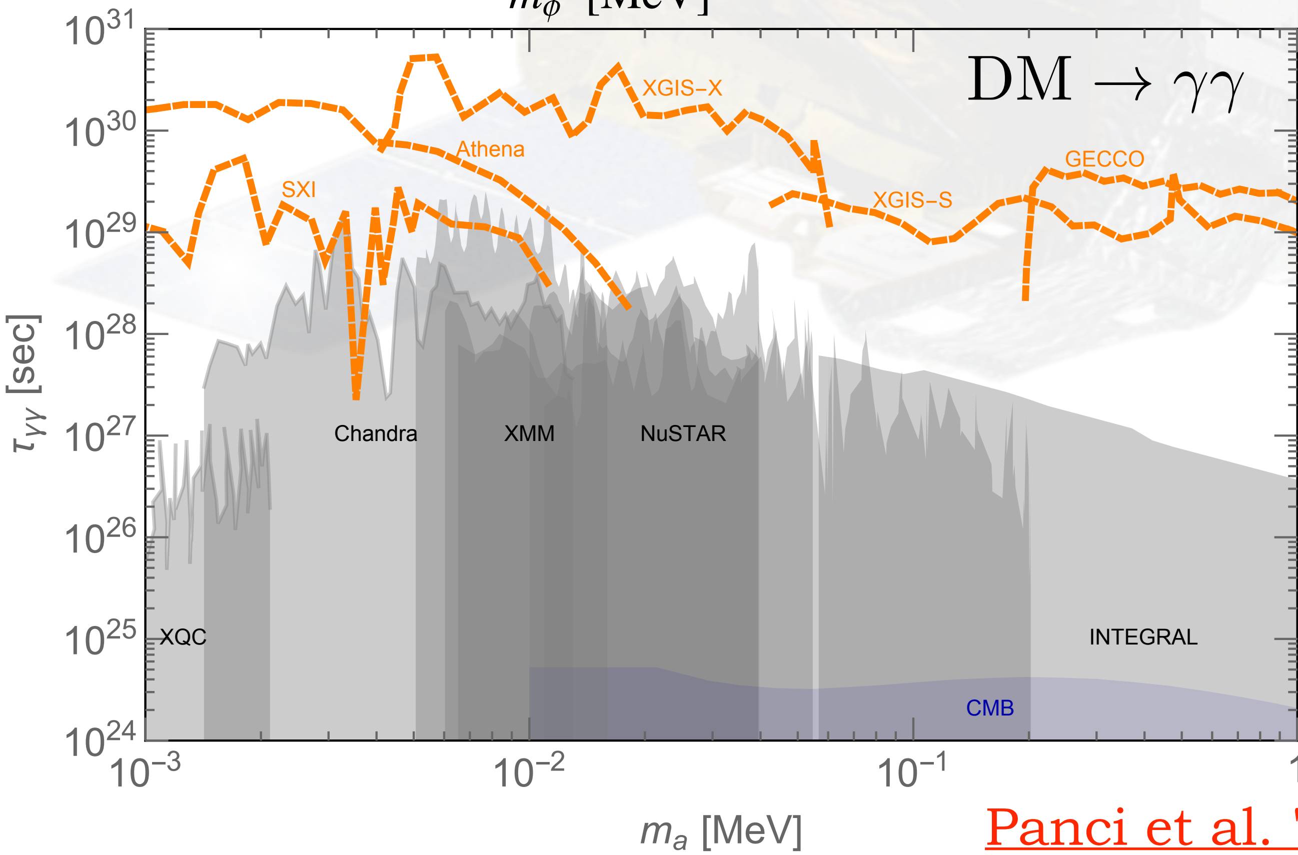
Slayter Wu '16

$$\tau_{\nu\nu} \equiv 1/\Gamma(J \to \nu\nu) > 63\,\text{Gyr} \approx 2 \times 10^{18}\ \text{s} \qquad \tau_{\gamma\gamma/ee} \equiv 1/\Gamma(J \to \gamma\gamma/e^+e^-) > 10^{24} - 10^{25}\ \text{s}$$

Bounds on decaying DM: indirect searches

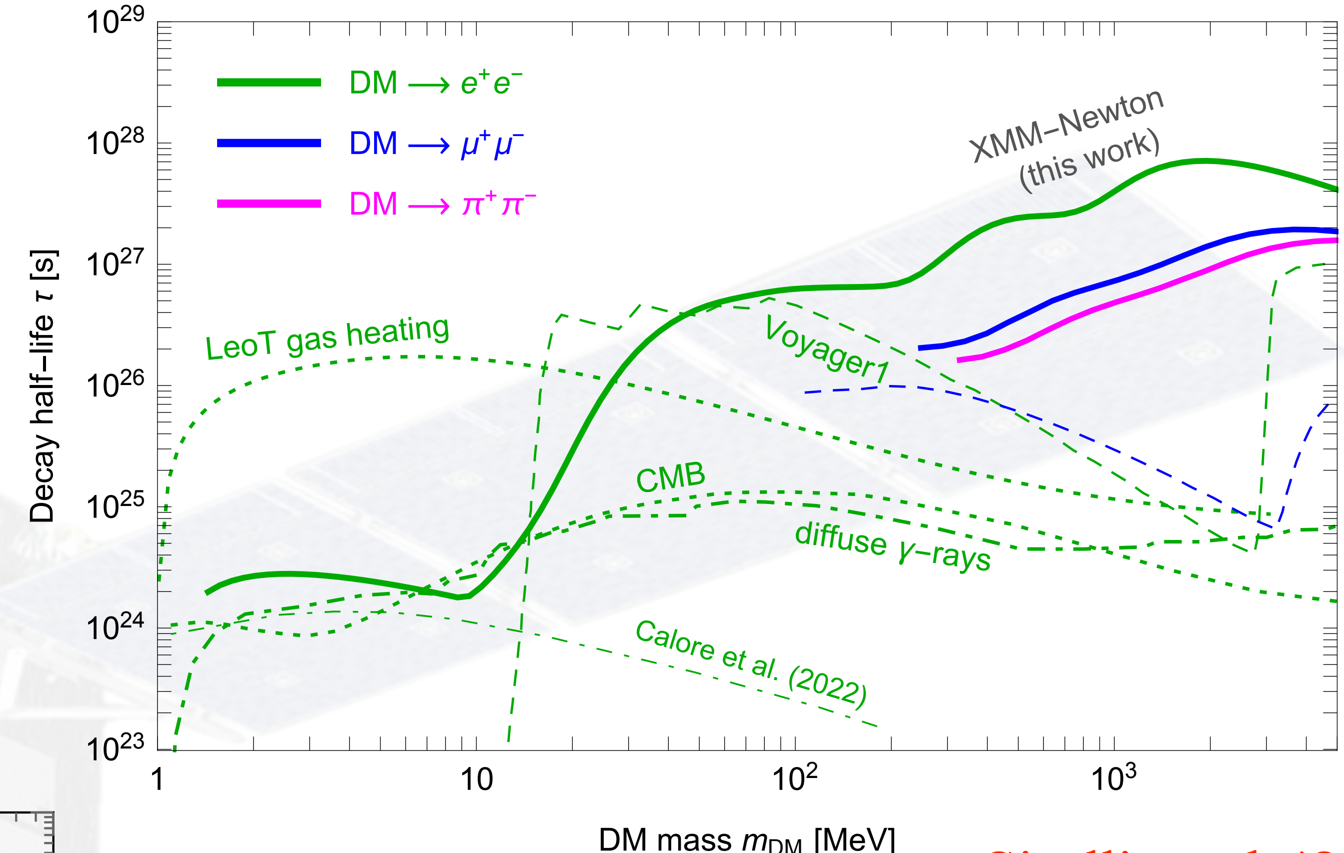
Diffuse X/γ-rays: Essig et al. '13





Panci et al. '22

Diffuse X-rays from e-γ scattering:

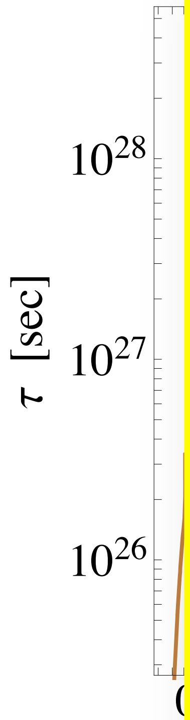


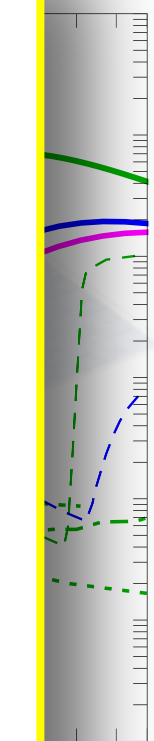
Cirelli et al. '23

$$\mathcal{O}(\mathrm{keV}) \lesssim m_J \lesssim \mathcal{O}(\mathrm{GeV}):$$
$$\tau_{\gamma\gamma} > 10^{26} - 10^{29}\ \mathrm{s}$$
$$\mathcal{O}(\mathrm{MeV}) \lesssim m_J \lesssim \mathcal{O}(\mathrm{GeV}):$$
$$\tau_{ee} > 10^{24} - 10^{28}\ \mathrm{s}$$

Bounds on decaying DM: indirect searches

Diffu… …ing:





…al. '23

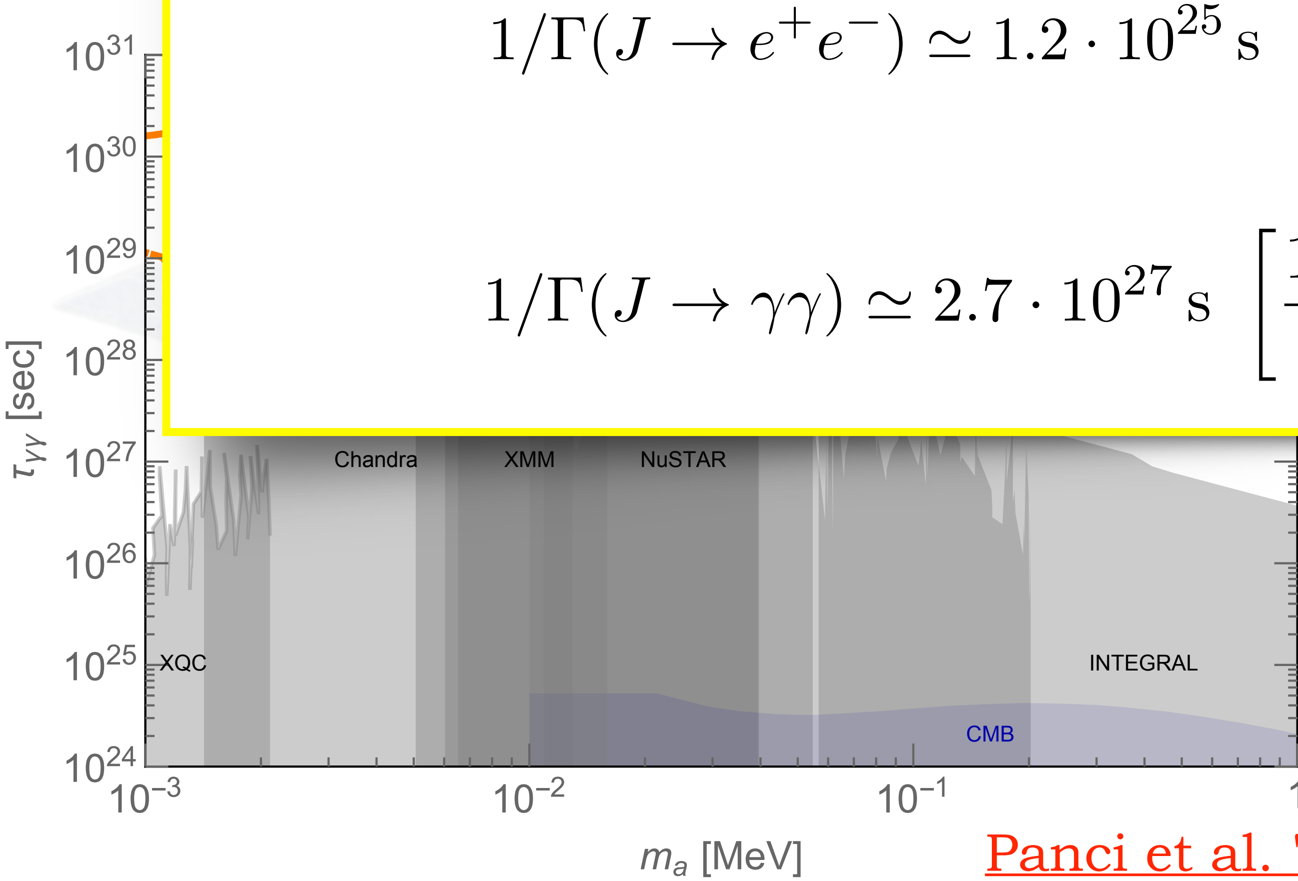
Let's compare this with the model's predictions:

$$g^P_{J\nu_i\nu_i} \simeq -\frac{m_{\nu_i}}{2v_1} \qquad g^P_{J\ell_\alpha\ell_\alpha} \simeq -m_{\ell_\alpha}\frac{2v_3^2}{v_1 v_2^2} \qquad g_{J\gamma\gamma} \simeq \frac{2\alpha}{\pi}\frac{v_3^2}{v_1 v_2^2}\left[\frac{M_J^2}{M_J^2 - m_{\pi^0}^2} - \sum_f Q_f^2 N_c^f B_1(\tau_f)\right]$$

$$1/\Gamma(J \to \nu\nu) \simeq 15\,\mathrm{Gyr}\left[\frac{0.01\,\mathrm{eV}^2}{\sum_i m_{\nu_i}^2}\right]\left[\frac{10\,\mathrm{keV}}{M_J}\right]\left[\frac{v_1}{3.8\cdot 10^7\,\mathrm{GeV}}\right]^2$$

$$1/\Gamma(J \to e^+e^-) \simeq 1.2\cdot 10^{25}\,\mathrm{s}\left[\frac{5\,\mathrm{MeV}}{M_J}\right]\left[\frac{1\,\mathrm{GeV}}{v_3}\right]^4\left[\frac{v_1}{10^{15}\,\mathrm{GeV}}\right]^2$$

$$1/\Gamma(J \to \gamma\gamma) \simeq 2.7\cdot 10^{27}\,\mathrm{s}\left[\frac{1\,\mathrm{MeV}}{M_J}\right]\left[\frac{1\,\mathrm{GeV}}{v_3}\right]^4\left[\frac{v_1}{10^{13}\,\mathrm{GeV}}\right]^2$$



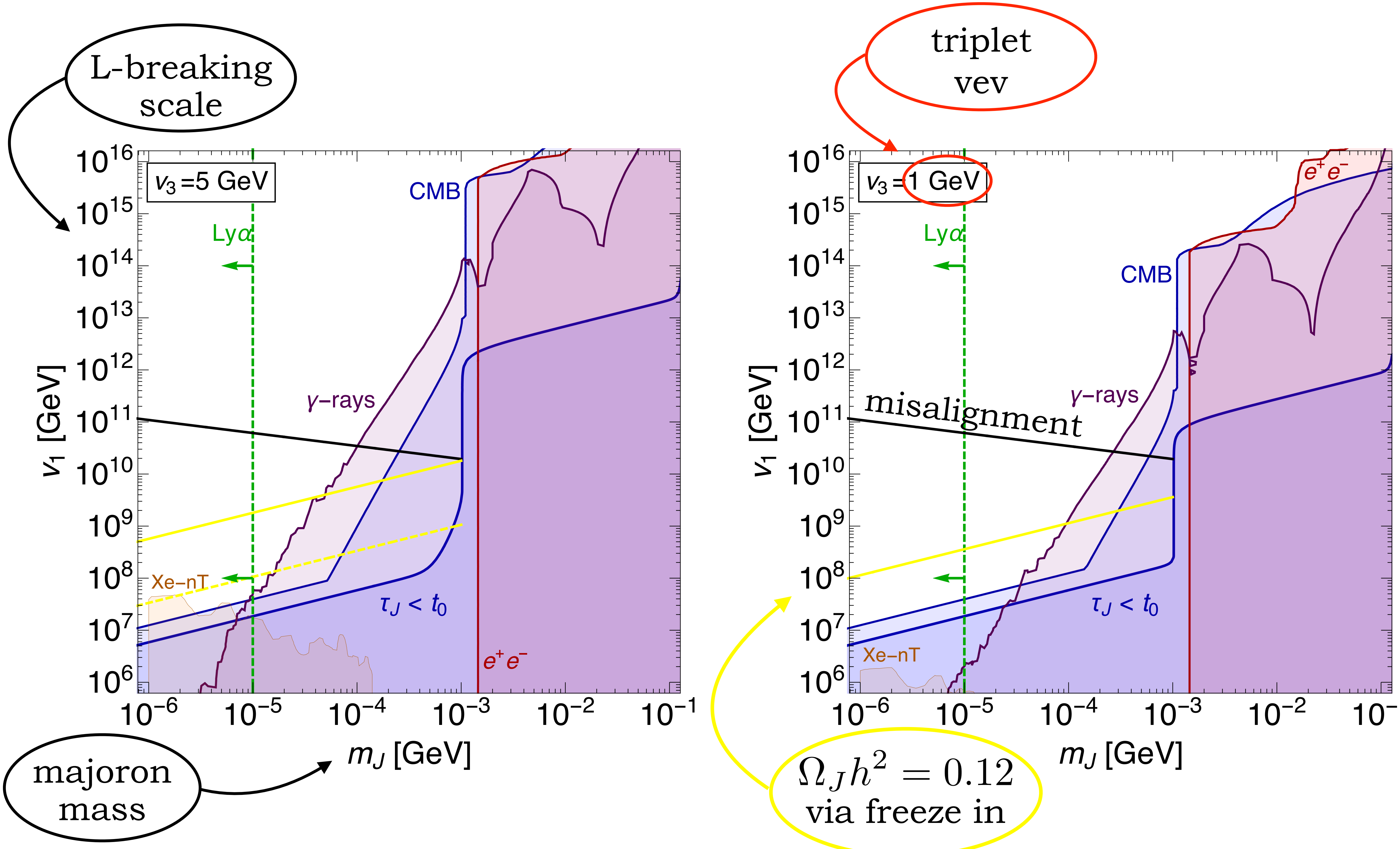
Panci et al. '22

$\tau_{\gamma\gamma} > 10^{26} - 10^{29}$ s

$\mathcal{O}(\mathrm{MeV}) \lesssim m_J \lesssim \mathcal{O}(\mathrm{GeV})$:

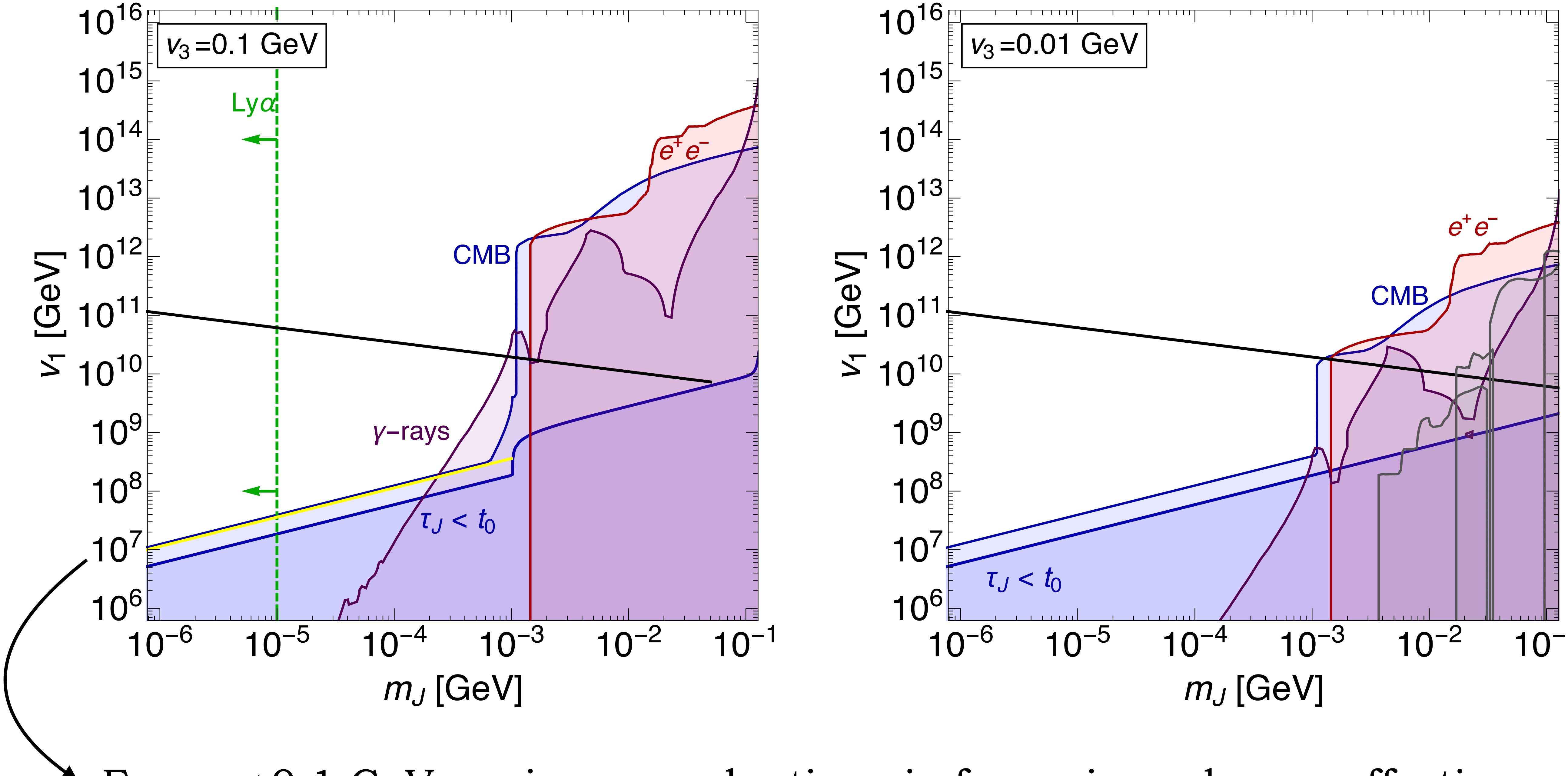
$\tau_{ee} > 10^{24} - 10^{28}$ s

Bounds on type-II majoron DM



⇨ Lyman-α + DM abundance $\Rightarrow$ $v_1 \gtrsim 10^7$ GeV

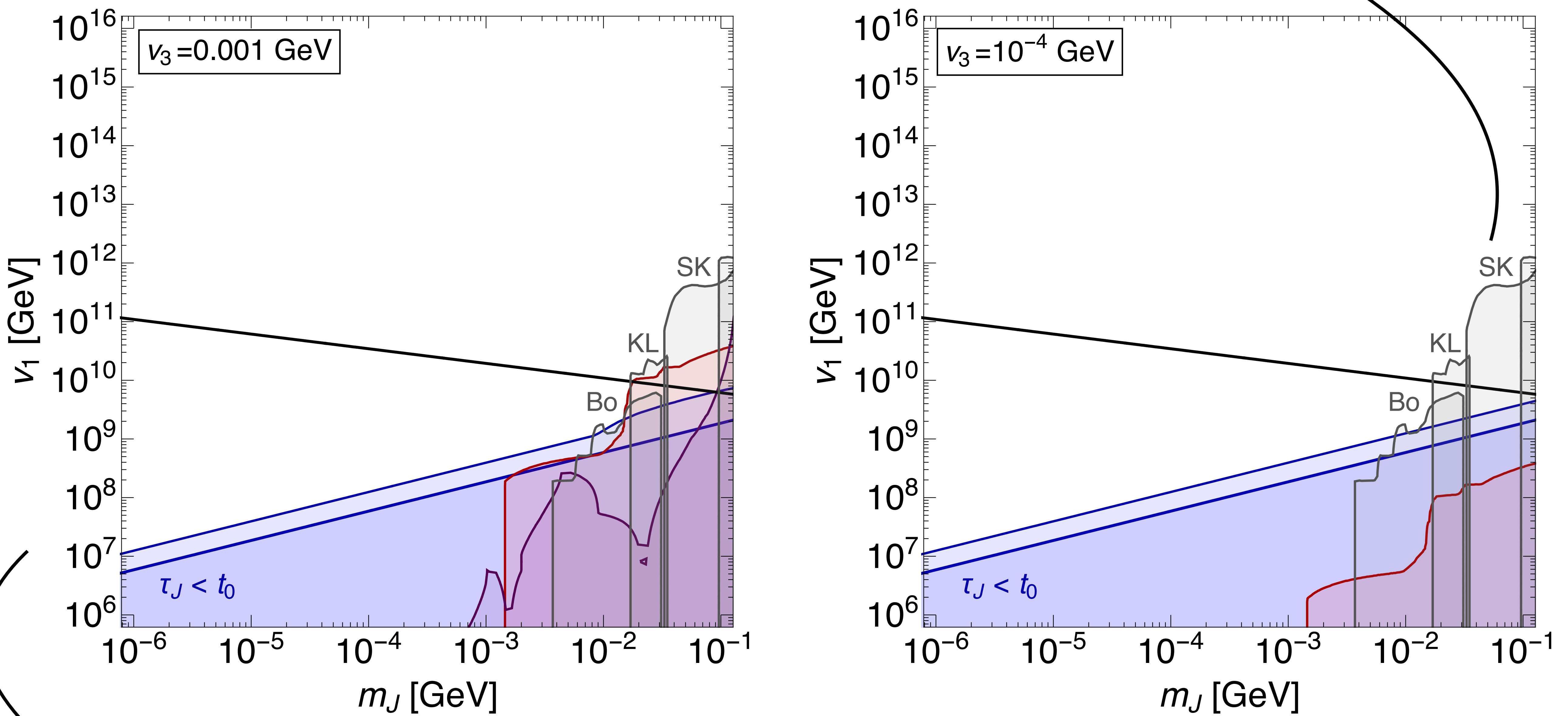
Bounds on type-II majoron DM



For $v_3 \lesssim 0.1$ GeV, majoron production via freeze in no longer effective

Bounds on type-II majoron DM

Bounds on $J \to \nu\nu$ from Borexino (Bo), KamLAND (KL), Super-Kamiokande (SK) Garcia-Cely Heeck '17



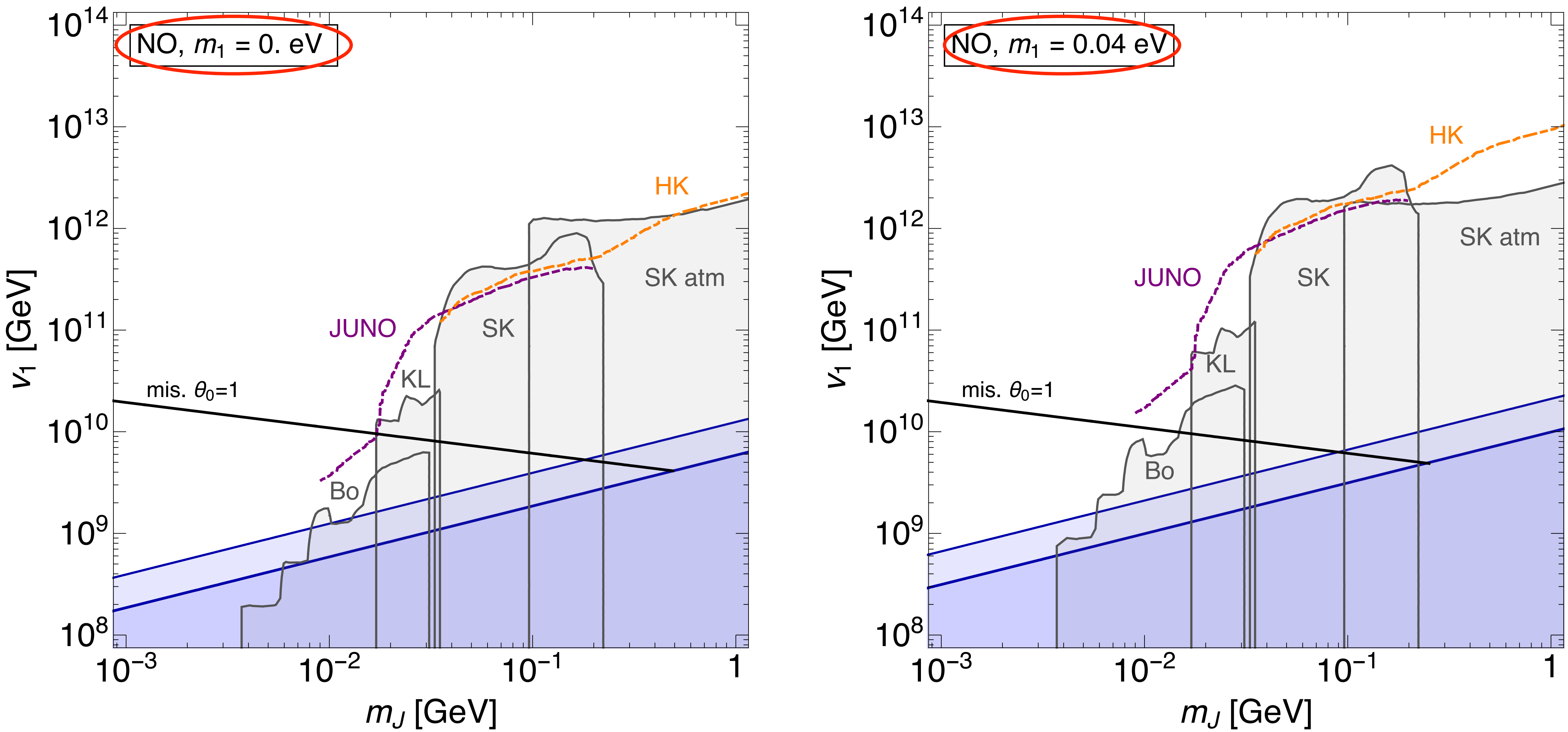
For $v_3 \lesssim 10^{-3}$ GeV, majoron phenomenology is dominated by its couplings with neutrinos (other interactions suppressed as $\sim v_3^2/v_2^2$)

Prospects: neutrino lines

Sensitivity to neutrino lines of experiments such as JUNO and Hyper-Kamiokande (Argüelles et al. '22) depends on neutrino parameters:

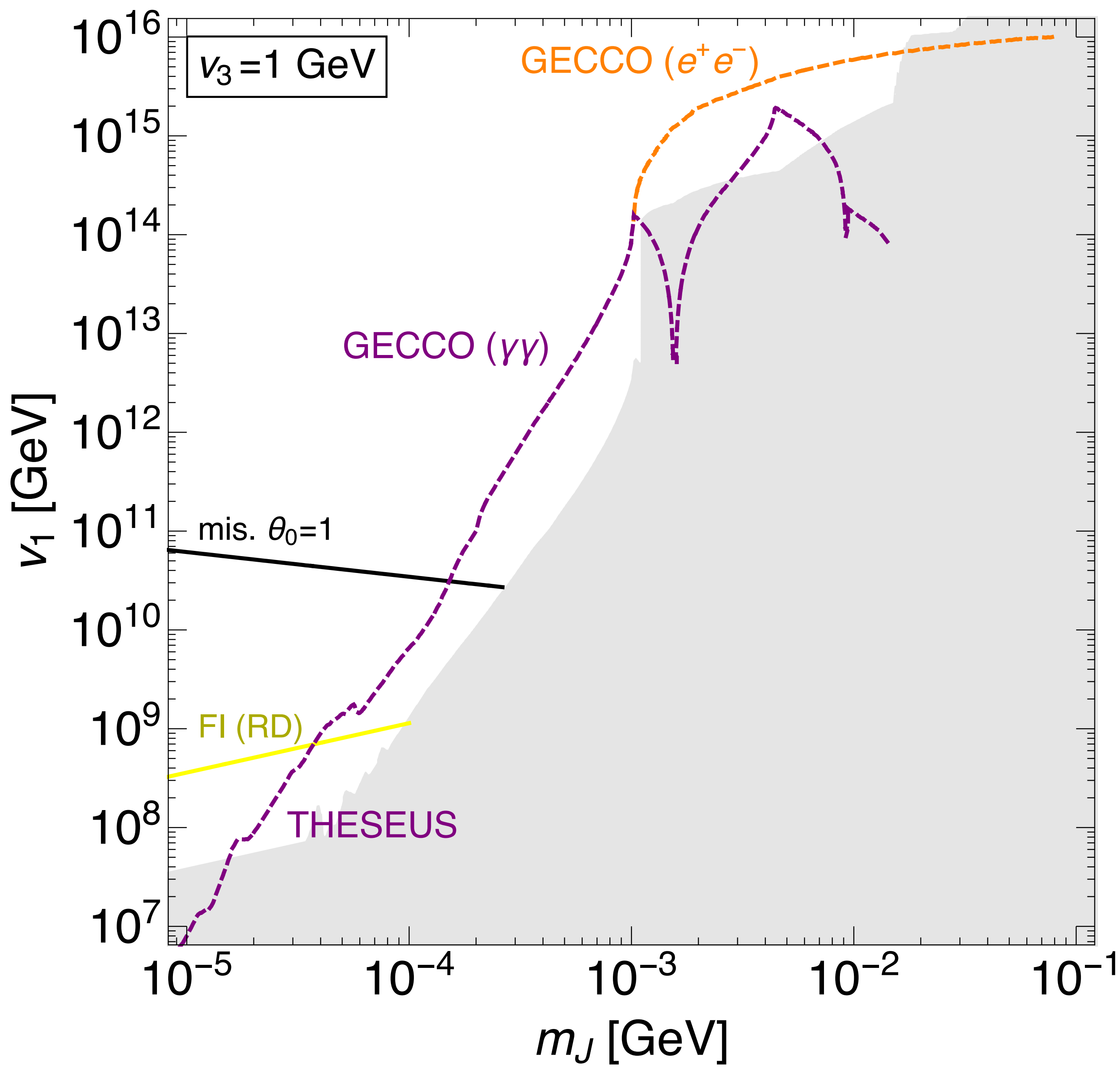
Garcia-Cely Heeck '17

flavour composition of the flux $\propto \dfrac{\sum_i m_{\nu_i}^2 |U_{\ell i}|^2}{\sum_i m_{\nu_i}^2} \Gamma(J \to \nu\nu)$



Sensitive to majorons with $M_J \gtrsim$10 MeV

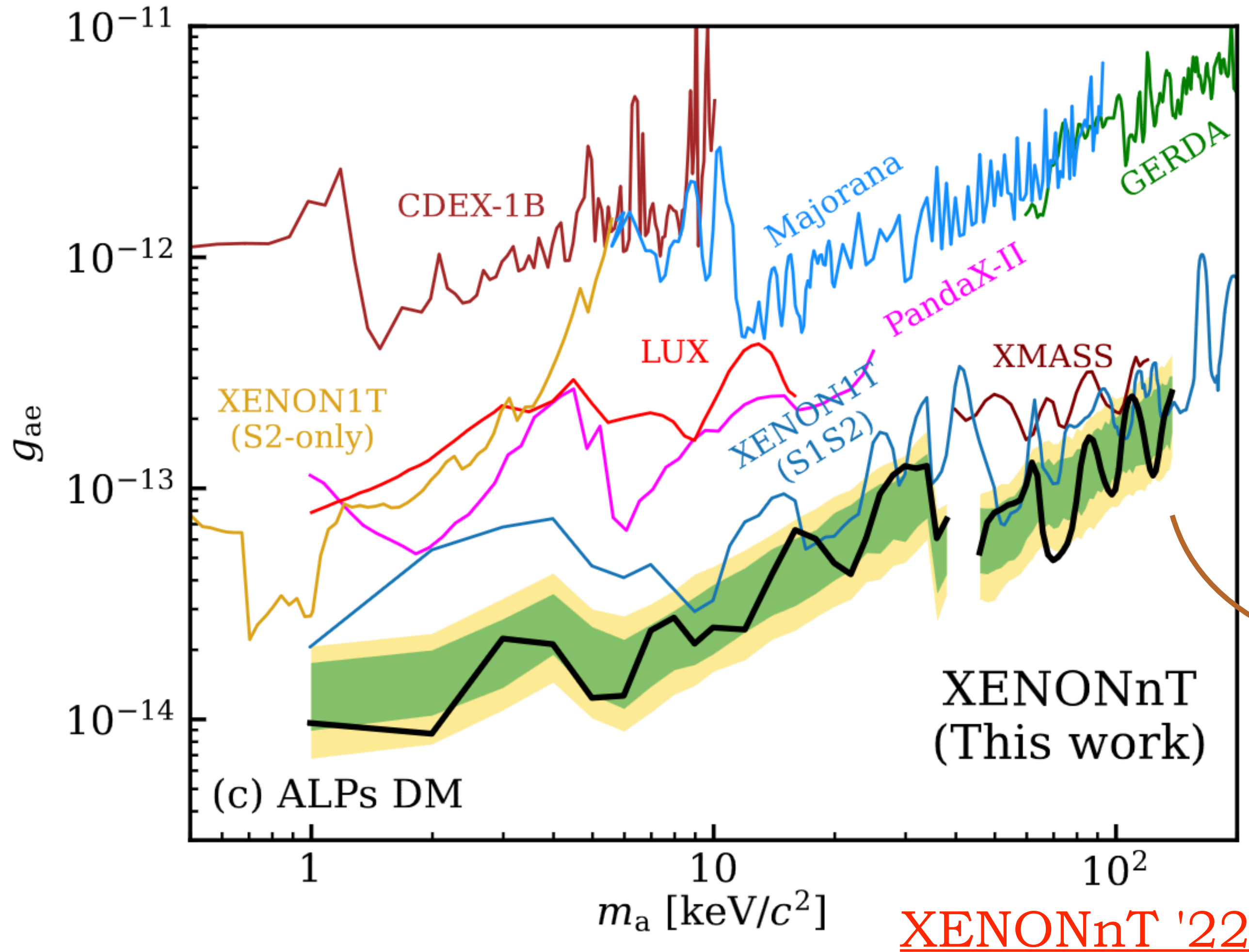
For $v_3 \gtrsim 10^{-3}$ GeV, $J \to \gamma\gamma$ / $J \to ee$ can give observables signals at future X-ray and soft γ-ray probes (such as GECCO) for M_J as low as ~10 keV



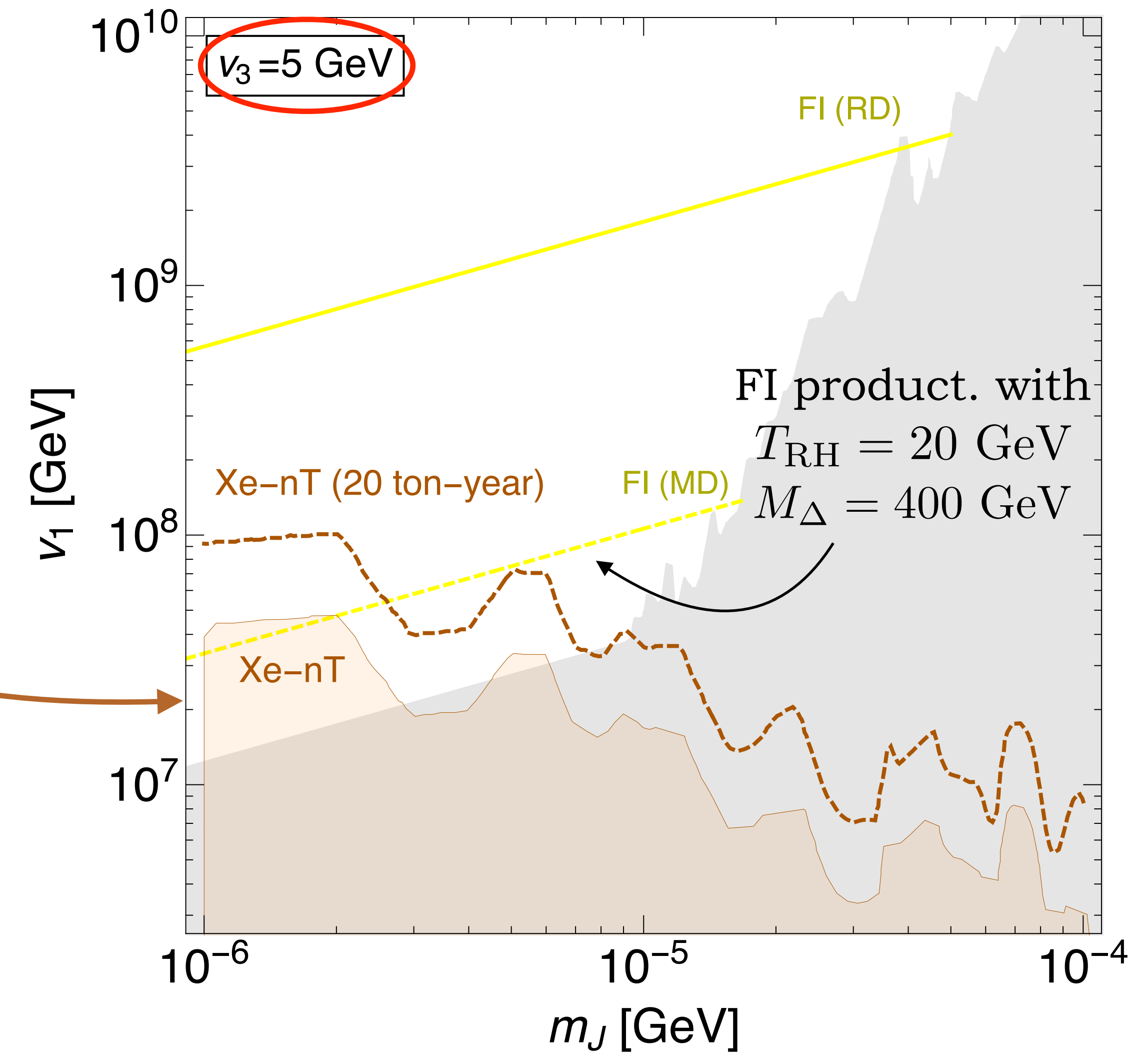
Prospects: direct detection

Searches for DM-electron recoils at direct detection experiments can test the majoron-electron coupling (for $v_3 = O(1)$ GeV):

$$|g^P_{Jee}| \simeq \frac{2 m_e v_3^2}{v_1 v_2^2} \simeq 1.7 \cdot 10^{-15} \left[\frac{10^7\,\text{GeV}}{v_1}\right] \left[\frac{v_3}{1\,\text{GeV}}\right]^2$$



XENONnT '22



Corner of the parameter space direct detection exps are sensitive to:

$$v_1 \approx 10^7 - 10^8\ \text{GeV},\ 1\,\text{keV} \lesssim M_J \lesssim 10\,\text{keV},\ v_3 > 1\ \text{GeV}$$

where J can be produced via freeze-in (with a low T_{RH})

Summary

Type II seesaw is perhaps the most economical model to address the origin of neutrino masses

If the lepton number is spontaneously broken by the vev of an additional scalar the resulting pNGB (the type II majoron) is a good DM candidate

Majoron production in the early universe can account for 100% of the observed DM either by the freeze in or the misalignment mechanism

Depending on the majoron mass, the production mechanism and the vev of the triplet, all three decay modes (e^+e^-, $\gamma\gamma$, $\nu\nu$) can yield signals at future indirect DM searches

In a corner of the parameter space, detection of majoron DM is possible through electron recoil at running and future direct detection experiments

谢谢大家!

Thank you!

Additional slides

Majoron DM production: freeze in