Connecting Low scale Seesaw for Neutrino Mass and Inelastic sub-GeV Dark Matter with Abelian Gauge Symmetry

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   - Inverse Seesaw with with inelastic DM
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Introduction

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$$\textbf{GOAL :}\ \mathscr{L}_{\textbf{BSM}} = \mathscr{L}_{\textbf{SM}} + \mathscr{L}_{\nu\textbf{mass}} + \mathscr{L}_{\textbf{DM}} + \mathscr{L}_{\dots}$$

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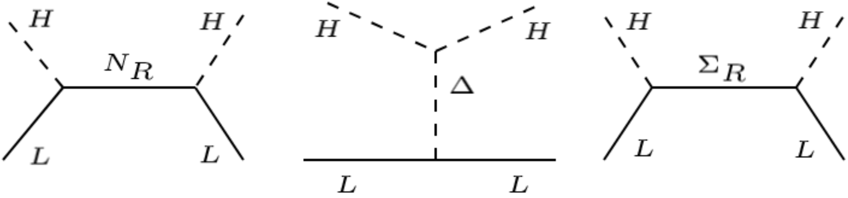

Canonical Seesaw mechanisms

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- Additional discrete symmetries are also incorporated to obtain the desired couplings in the Lagrangian for seesaw realisations.
- A singlet scalar field which effectively gives rise to lepton number violation and hence Majorana light neutrino masses either at tree or radiative level, also splits the dark matter field into two quasi-degenerate particles.

Light Neutrino Mass $\longleftrightarrow$ Inelastic sub-GeV Dark Matter

Inverse Seesaw with Inelastic DM

	N_R	S_R	Φ_1	Φ_2	$\Psi_{L,R}$	η	H_2
$SU(2)_L$	1	1	1	1	1	1	2
$U(1)_X$	1	-1	0	2	-1	-1	1
Z_4	1	i	i	-1	-i	-i	1

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The electroweak symmetry is broken when the Higgs doublets H_1 and H_2 acquire non-zero vevs, while the vevs of Φ_1 and Φ_2 break Z_4 and $U(1)_X$ respectively.

$$\langle H_{1,2} \rangle = v_{1,2}/\sqrt{2}, \ \langle \phi_{1.2} \rangle = u_{1,2}/\sqrt{2}$$

In the basis $n = ((\nu_L)^c, N_R, S_R)^T$, the neutral lepton mass term is

$$-\mathcal{L}_{m_\nu} = \frac{1}{2}\overline{(n)^c}\mathcal{M}_\nu n + h.c.$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M & \mu \end{pmatrix} = \begin{pmatrix} 0 & \frac{y_\nu v_2}{\sqrt{2}} & 0 \\ \frac{y_\nu v_2}{\sqrt{2}} & 0 & \frac{y_{NS} u_1}{\sqrt{2}} \\ 0 & \frac{y_{NS} u_1}{\sqrt{2}} & \frac{y_S u_2}{\sqrt{2}} \end{pmatrix}$$

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$$\begin{aligned} m_\nu &\simeq m_D^T M^{-1} \mu M^{-1} m_D \\ &= (\frac{y_\nu^T v_2}{\sqrt{2}})\frac{1}{M}(\frac{y_S u_2}{\sqrt{2}})\frac{1}{M}(\frac{y_\nu v_2}{\sqrt{2}}) \end{aligned}$$

For $m_D \sim 10$ GeV, $M \sim 1$ TeV and $\mu \sim 1$ keV, we get sub eV neutrino mass.

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The relevant Lagrangian can be written as:

$$\mathcal{L}_{\mathrm{DM}} = i\overline{\Psi}\gamma^{\mu} D_{\mu}\Psi - M(\overline{\Psi_L}\Psi_R + \overline{\Psi_R}\Psi_L) - y_L\Phi_2\overline{(\Psi_L)^c}\Psi_L - y_R\Phi_2\overline{(\Psi_R)^c}\Psi_R + \frac{\epsilon}{2}B^{\alpha\beta}Y_{\alpha\beta} + \mathrm{h.c.}$$

$D_{\mu} = \partial_{\mu} + ig' Z'_{\mu}$
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- Φ_2 generates Majorana masses for fermion DM: $m_L = y_L u_2/\sqrt{2}$ and $m_R = y_R u_2/\sqrt{2}$

- Dirac fermion $\Psi = \Psi_L + \Psi_R$ splits into two pseudo-Dirac states ψ_1 and ψ_2 with masses $M_1 = M - m_+$ and $M_2 = M + m_+$, where $m_\pm = m_L \pm m_R/2$.

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Lagrangian in terms of physical mass eigenstates

$$\begin{aligned}\mathcal{L}_{\rm DM} =& \frac{1}{2}\overline{\psi_1} i\gamma^\mu \psi_1 + \frac{1}{2}\overline{\psi_2} i\gamma^\mu \psi_2 - \frac{1}{2}M_1\overline{\psi_1}\psi_1 - \frac{1}{2}M_2\overline{\psi_2}\psi_2 \\ &+ ig' Z'_\mu \psi_1\gamma^\mu\psi_2 + \frac{1}{2}g' Z'_\mu(\frac{m_-}{M})(\overline{\psi_2}\gamma^\mu\gamma^5\psi_2 - \overline{\psi_1}\gamma^\mu\gamma^5\psi_1) \\ &+ \frac{1}{2}(y_L\cos^2\theta - y_R\sin^2\theta)\overline{\psi_1}\psi_1\phi_2 \\ &+ \frac{1}{2}(y_R\cos^2\theta - y_L\sin^2\theta)\overline{\psi_2}\psi_2\phi_2 + \frac{\epsilon}{2}B^{\alpha\beta}Y_{\alpha\beta}\,,\end{aligned}$$

- where $\sin\theta \approx m_-/M$. The mass splitting between the two mass eigenstates is given by $\Delta m = M_2 - M_1 = 2m_+ = (y_L + y_R)\frac{u_2}{\sqrt{2}}$

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- We parametrise the scalar singlet DM field η as:

$$\eta = \frac{\eta_1 + i\eta_2}{\sqrt{2}}\,.$$

- $\langle \Phi_2 \rangle$ not only gives mass to Z' gauge boson: $M_{Z'}^2 = g'^2(4u_2^2)$, but also creates a mass splitting between η_1 and η_2

$$-\mathcal{L}_{\rm DM} \supseteq (\frac{1}{2} m_\eta^2 - \frac{\mu_\phi u_2}{\sqrt{2}})\eta_1^2 + (\frac{1}{2} m_\eta^2 + \frac{\mu_\phi u_2}{\sqrt{2}})\eta_2^2\,.$$

- Thus the mass splitting between the two states η_1 and η_2 is given by $\Delta M_\eta^2 = m_{\eta_2}^2 - m_{\eta_1}^2 = \sqrt{2}\mu_\phi u_2$.
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- Because of the kinetic mixing between the $U(1)_X$ gauge boson Z' and the SM Z boson, these DM particles can interact with the SM particles which is evident from the following Lagrangian:

$$\mathcal{L} \supseteq g' Z'^\mu (\eta_1 \partial_\mu \eta_2 - \eta_2 \partial_\mu \eta_1) + \frac{\epsilon}{2} B^{\alpha\beta} Y_{\alpha\beta}$$

Type-II Seesaw with inelastic DM

	L	e_R	Δ_L	Φ_1	Φ_2	$\Psi_{L,R}$	η
$U(1)_X$	0	0	0	0	2	-1	-1
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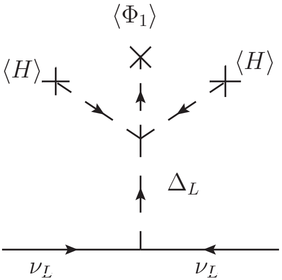

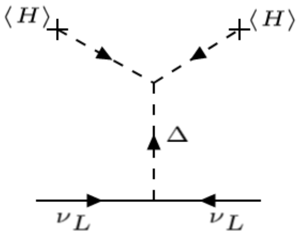

Figure: Type II Seesaw

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$$V = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_\Delta^2 \mathrm{Tr}[\Delta_L^\dagger \Delta_L] + \lambda_\Delta \mathrm{Tr}[\Delta_L^\dagger \Delta_L]^2 + (\lambda_1 \Phi_1 H^T \Delta_L H + \mathrm{h.c.}) + V_{\mathrm{DM}}$$

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$$V_{\text{DM}} = (\lambda_2 \Phi_1 \Phi_2 \eta \eta + \text{h.c.})$$

- Type II seesaw contribution to light neutrino masses arise after the neutral component of scalar triplet acquires an induced vev as

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- Here, the trilinear term is dynamically generated $\mu = \lambda_1 \langle \Phi_1 \rangle$ via vev of the scalar Φ_1.
- Φ_1 vev is not involved in $U(1)_X$ gauge symmetry breaking. $\Longrightarrow$ can be even lower than the electroweak scale.

- Thus, depending upon $\lambda_1\langle\Phi_1\rangle \ll \mu_\Delta$ (which can be achieved by suitable tuning of λ_1 and Φ_1 vev), one can bring down the scale of type II seesaw μ_Δ to a much lower scale.

- For scalar singlet DM $\eta = (\eta_1 + i\eta_2)/\sqrt{2}$, the mass splitting is $\Delta M_\eta^2 = m_{\eta_2}^2 - m_{\eta_1}^2 = \lambda_2\langle\Phi_1\rangle\langle\Phi_2\rangle$. A tiny mass splitting can be generated by suitable tuning of λ_2 and $\langle\Phi_1\rangle$.

- For fermion DM, then also one can split the Dirac fermion DM into pseudo-Dirac components by virtue of the dimension five term in the above Yukawa Lagrangian.

Radiative Seesaw with inelastic DM

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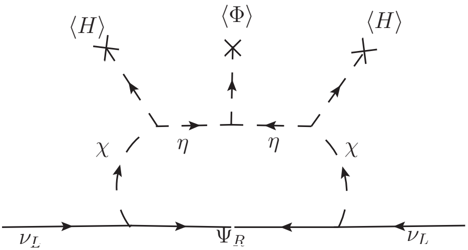

Figure: Radiative seesaw origin of light neutrino masses

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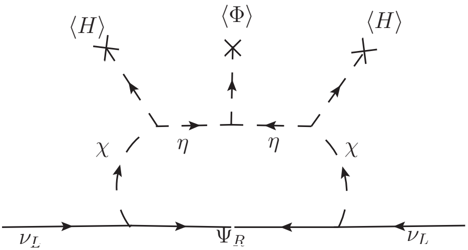

Figure: Radiative seesaw origin of light neutrino masses

	η	Φ	$\Psi_{L,R}$	χ
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Table: New particles and their quantum numbers under the imposed symmetry for radiative seesaw model.

$$-\mathcal{L} \supset M\bar{\Psi}\Psi + \left(Y_\nu \bar{L}\tilde{\chi}\Psi_R + Y_L \Phi^\dagger \overline{(\Psi_L)^c}\Psi_L + Y_R \Phi^\dagger \overline{(\Psi_R)^c}\Psi_R + \text{h.c.} \right)$$

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$$V \supset m_\eta^2 \eta^\dagger \eta + m_\chi^2 \chi^\dagger \chi + (\mu_1 \chi^\dagger H \eta + \mu_2 \eta\eta\Phi^\dagger + \mathrm{h.c.})$$

- The $U(1)_X$ symmetry is broken by nonzero vev of Φ to a remnant Z_2 symmetry under which $\Psi_{L,R}, \eta, \chi$ are odd while all other fields are even as a result the lightest among $\Psi_{L,R}$, η and χ can gives rise to a viable DM candidate.

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$$(m_\nu)_{ij} \simeq \frac{\mu_1^2 v^2 \mu_2 v_\phi}{(4\sqrt{2})16\pi^2} \frac{(Y_\nu)_{ik}(M)_k(Y_\nu^T)_{kj}}{m_\chi^6} I_\nu(r_\chi, r_k)$$

- The parameters r_i are defined as $r_\chi = m_\chi^2/M_\eta^2, r_k = M_k^2/M_\eta^2$

$$I_\nu(r_1, r_2) = \frac{1 + r_1 - 2r_2}{2(1-r_1)^2(1-r_2)(r_1-r_2)} - \frac{1}{2(1-r_1)^3(r_1-r_2)^2}\left[r_2 + r_1(r_2 - 2r_1)\ln r_1 + (1-r_1)^3 r_2 \ln r_2\right].$$

- Non-zero μ_2 implies non-zero mass splitting between scalar and pseudoscalar components of η. That is, $m_{\eta_2}^2 - m_{\eta_1}^2 = \sqrt{2}\mu_2 v_\phi$.

$$(m_\nu)_{ij} \simeq \frac{\mu_1^2 v^2 (m_{\eta_2}^2 - m_{\eta_1}^2)}{(8\sqrt{2})16\pi^2} \frac{(Y_\nu)_{ik}(M)_k(Y_\nu^T)_{kj}}{m_\chi^6} I_\nu(r_\chi, r_k)$$

- Can have Fermion as well as Scalar inelastic DM in the model.
- Mass splitting gets directly related to the light neutrino mass due to the involvement of DM fields in the neutrino mass loop.

Inelastic sub-GeV Dark Matter

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- $U(1)_X$ extension which can simultaneously accommodate non-zero neutrino mass and inelastic dark matter, comprising of two quasi-degenerate components χ_1 and χ_2 with masses M_1 and M_2 respectively.

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- The inelastic sub-GeV DM is appealing in the light of recent from XENON1T as the inelastic down scattering of a sub-GeV scale DM with the electrons in Xenon atoms provides a viable explanation for XENON1T excess of electron recoil events near 1-3 keV energy.

Inelastic Fermion DM

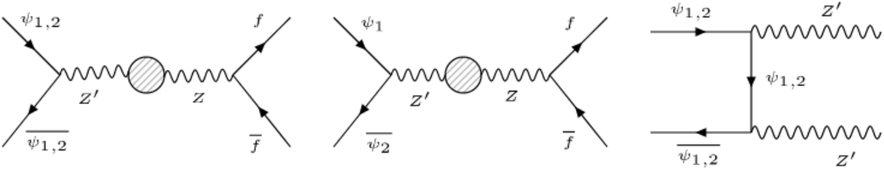
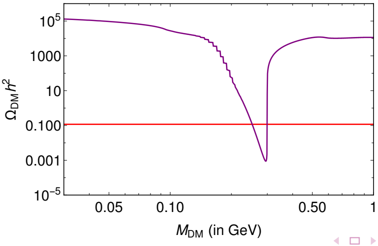


Figure: Dominant channels for relic abundance of fermionic DM



Inelastic Scalar DM

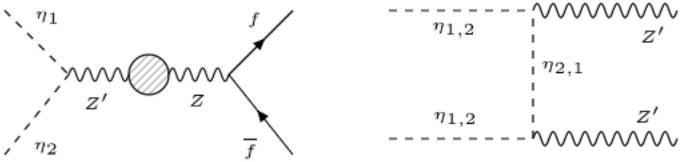
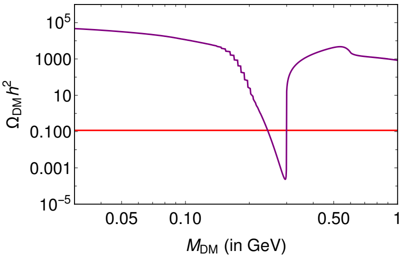


Figure: Dominant channels for relic abundance of scalar DM



XENON1T Electron Recoil Excess

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Recent results from XENON1T collaboration

"Observation of Excess Electronic Recoil Events in XENON1T"

[arXiv: 2006.09721[hep-ex]]

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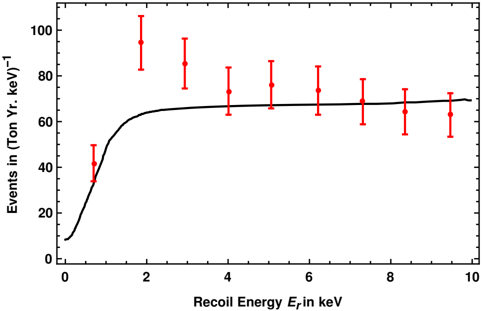
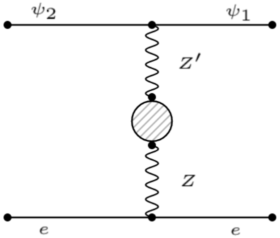
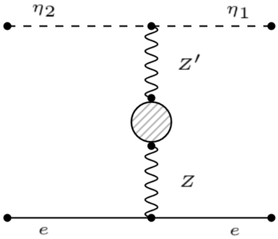


Many possible interpretations : Solar Axions, Neutrino magnetic moment, Beta decay from Tritium and New Physics(DM and other).

- We consider the down-scattering of heavier DM component $\chi_2 e \to \chi_1 e$ as the process responsible for XENON1T excess of electron recoil events near 1-3 keV energy.





- For a fixed DM velocity v,the differential cross section is given by

$$\frac{d\sigma v}{dE_r} = \frac{\sigma_e}{2m_e v} \int_{q-}^{q+} a_0^2 q dq |F(q)|^2 K(E_r, q) \tag{1}$$

$K(E_r, q)$ Atomic excitation factor, and σ_e is the free electron cross section.

We assume the DM form factor to be unity.

- The limits of integration in Eq. (1) are determined depending on the relative values of E_r and $\delta = M_2 - M_1$.
- For $E_r \geq \delta$

$$q_{\pm} = M_2 v \pm \sqrt{M_2^2 v^2 - 2M_2(E_r - \delta)} \quad (2)$$

And for $E_r \leq \delta$

$$q_{\pm} = \sqrt{M_2^2 v^2 - 2M_2(E_r - \delta)} \pm M_2 v \quad (3)$$

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- The differential event rate for the inelastic DM scattering with electrons in xenon is given by

$$\frac{dR}{dE_r} = n_T n_{\chi_2} \frac{d\sigma v}{dE_r} \quad (4)$$

where $n_T = 4 \times 10^{27}\ \mathrm{Ton}^{-1}$ = number density of xenon atoms. n_{χ_2}= number density of the dark matter $\chi_2 = n_{\chi_2} \approx n_{\chi_1} \approx n_{\mathrm{DM}}/2$.

Inelastic DM-Electron scattering at XENON1T

Features of inelastic scattering

Inelastic DM-Electron scattering at XENON1T

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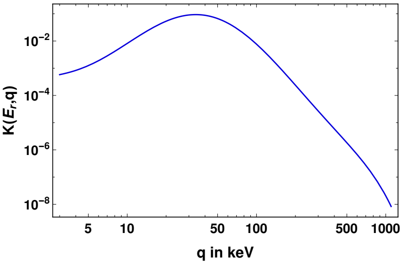
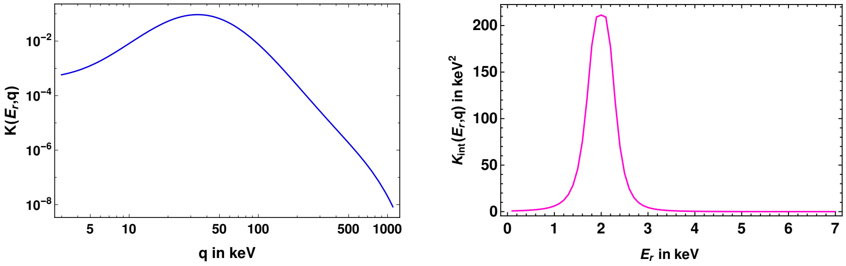
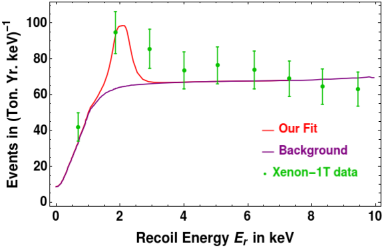


Features of inelastic scattering



Left:Dependence of Atomic excitation factor on momentum transferred. Right: The atomic excitation factor, after the q integration, is plotted as a function of the transferred recoil energy E_r.



Fit to XENON1T data with inelastic DM in our model

- Relevant Parameters used :$\Delta m = 2$ keV , $m_{\chi_2} = 0.3$ GeV, $v \approx 5 \times 10^{-3}$, $g_x = 7 \times 10^{-4}$, $M_{Z'} = 0.6$ GeV, $\epsilon = 5 \times 10^{-3}$ which corresponds cross section $\sigma_e = 1.78 \times 10^{-17}\ \mathrm{GeV}^{-2}$.

Summary for Inelastic Fermionic DM

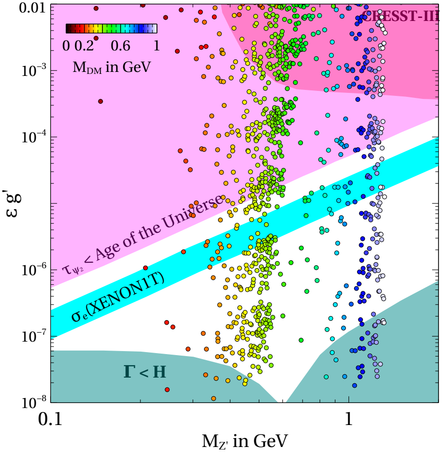


Figure: Summary plot for fermionic inelastic DM showing the final parameter space from various relevant constraints.

Summary for Inelastic Scalar DM

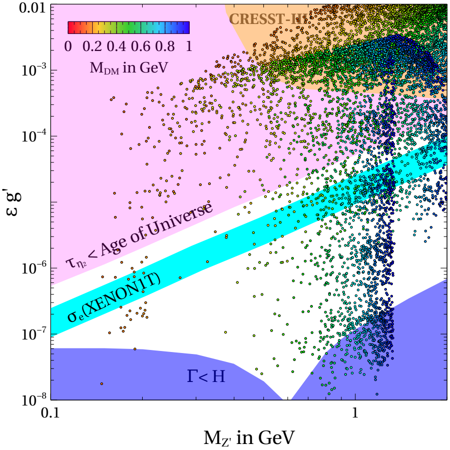
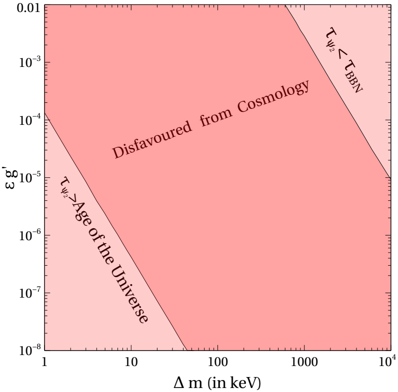
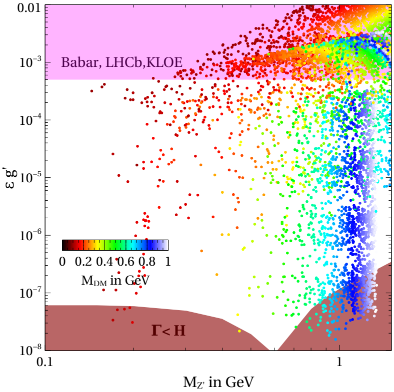


Figure: Summary plot for inelastic scalar DM showing the final parameter space from various relevant constraints.

Summary





Left: DM mass splitting versus $U(1)_X$ portal coupling showing the bounds on lifetime on heavier DM component.

Right: Summary plot for fermion DM with mass splitting of 1 MeV with next to lightest dark sector particle.


Thank You