Light Hidden Sectors, Neutrino Masses and Dark Matter

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with Z. Chacko, N. Desai, S. Doshi, C. Kilic, S. Najjari, arXiv:2305.09719
and with S. Najjari, in preparation

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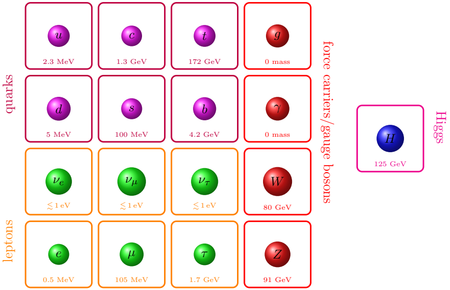
Introduction

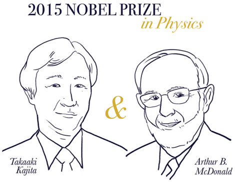
- Standard Model (SM) of particle physics is the most successful theory of elementary particles and their interactions.



- However several outstanding puzzles/observations are unanswered within the SM.
- In this talk I will discuss two such puzzles:
  - SM neutrino masses
  - Dark matter (DM)

Neutrino masses

- In the SM neutrinos are massless, however, neutrino oscillations have shown that they have tiny masses, $m_\nu \sim 0.1\,\mathrm{eV}$.



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

- Neutrino masses can be generated within SM Effective Field Theory via the *Weinberg operator* [Weingberg:1979]

$$\mathcal{L}_5 = -\frac{C_5}{\Lambda}(LH)^2 + \text{h.c.}$$

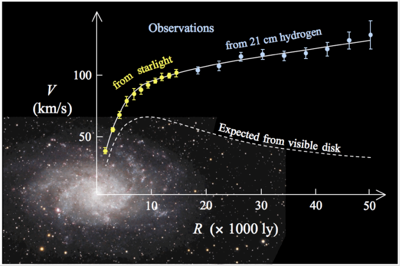
$$\supset -m_\nu \overline{\nu_L^c}\nu_L + \text{h.c.}, \qquad \text{where} \qquad m_\nu = \frac{C_5\, v_{\rm SM}^2}{\Lambda}$$

- $m_\nu \sim 0.1\,\mathrm{eV}$ implies new physics at scale $\Lambda \sim 10^{15}$ GeV for $C_5 \sim 1$.
- In this talk we discuss a scenario where neutrino masses are generated naturally at scale $\Lambda \lesssim v_{\rm SM} \sim O(10^2)$ GeV.

Dark matter evidence

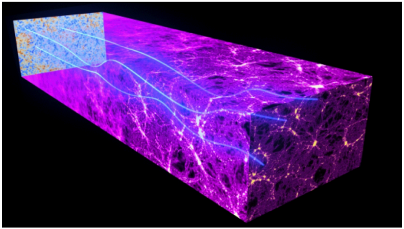
- Evidence for DM is through its gravitational interactions with the SM

Galatic rotation curves

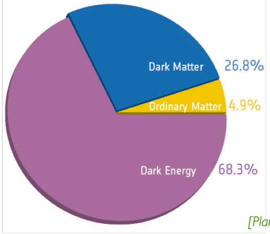


Cluster collisions

Gravitational lensing of CMB

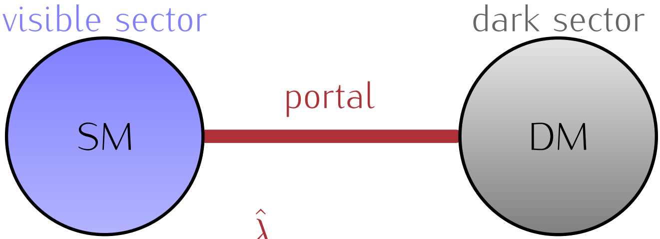


CMB ~ 85% of total matter is DM



[Planck Satellite]

- In a generic framework, DM is the lightest stable particle in a dark sector (DS)
- DS interacts with the SM through a portal



$$\frac{\hat{\lambda}}{M_{\rm UV}^{\Delta_{\rm SM}+\Delta_{\rm DS}-4}}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm DS}$$

- $\mathcal{O}_{\rm SM/DS}$ are the gauge singlet operators with dimension $\Delta_{\rm SM/DS}$
- $M_{\rm UV}$ is the UV scale where portal interaction is generated with $\hat{\lambda}\sim 1$

Portals

$$\boxed{\mathcal{L}_{\rm portal} = -\frac{\hat{\lambda}}{M_{\rm UV}^{\Delta_{\rm SM}+\Delta_{\rm DS}-4}} \mathcal{O}_{\rm SM}\mathcal{O}_{\rm DS}}$$

- $\mathcal{O}_{\rm SM}$ can be constructed from the SM fields for $\Delta_{\rm SM} \geq 2$
- $\mathcal{O}_{\rm DS}$ is completely unknown up to spin/Lorentz structure (set by $\mathcal{O}_{\rm SM}$)
- $\Delta_{\rm DS}$ can have any values above the unitarity constraint

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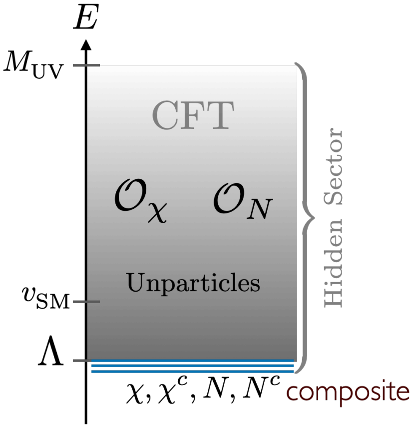
$\mathcal{O}_{\rm SM}$	$\Delta_{\rm SM}$	$\mathcal{O}_{\rm DS}$	$\Delta_{\rm DS}$	portal
$H^\dagger H$	2	scalar	≥ 1	Higgs portal
$B_{\mu\nu}$	2	tensor	≥ 2	Hypercharge portal
LH	$\frac{5}{2}$	fermion	$\geq \frac{3}{2}$	Neutrino portal
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

- In this talk, we consider DS which is strongly coupled conformal field theory (CFT) below M_{UV}. [Ahmed,Chacko,Desai,Doshi,Kilic,Najjari:2305.09719]
- We assume conformal symmetry is broken at IR scale $\Lambda \lesssim v_{\mathrm{SM}}$.

- Above scale Λ, DS has fermionic operators $\mathcal{O}_\chi$ and $\mathcal{O}_N$ with scaling dimensions Δ_χ and Δ_N.
- At scale Λ, DS confines due to strong dynamics and leads to composite states including DM χ and singlet neutrino N with masses $m_\chi, m_N \sim \Lambda$.
- All SM particles are elementary.



DM from Conformal Dark Sector

- DM χ is the lightest stable composite state
- Natural expectation is $m_\chi \sim \Lambda$ (exception if DM is pseudo-Goldstone)

- DM has strong self-interactions
- DM signals depend on the energy scale

1. For $E \gg \Lambda$, DM behaves as *unparticle/continuum states*

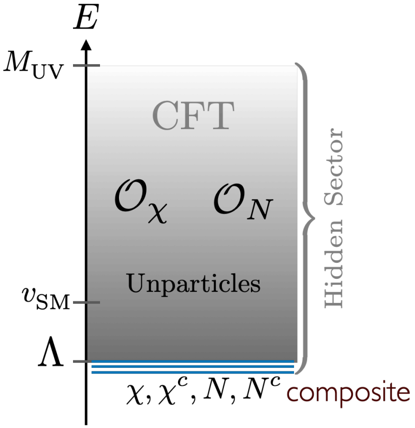
   (collider signals)

2. For $E \sim \Lambda$, DM is a *composite state*

   (DM production)

3. For $E \ll \Lambda$, DM behaves as a *particle state*

   (direct/indirect detection)



Composite Neutrino Portal

- In the UV, DS–SM interaction through the neutrino portal

$$\boxed{\mathcal{L}_{\rm UV} \supset -\frac{\hat{\lambda}}{M_{\rm UV}^{\Delta_N - 3/2}} L H \mathcal{O}_N + \text{h.c.} \qquad \text{with} \qquad \hat{\lambda} \sim 1}$$

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- At the composite scale Λ, we can write $\mathcal{O}_N \sim \Lambda^{\Delta_N - 3/2} N + \cdots$ and portal interaction becomes

$$\boxed{\mathcal{L}_{\rm IR} \supset -\lambda\, L H N + \text{h.c.} \quad \text{with} \quad \lambda \sim \hat{\lambda} \left(\frac{\Lambda}{M_{\rm UV}} \right)^{\Delta_N - 3/2}}$$

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- Note, for $\Delta_N > 3/2$, we get naturally small effective portal coupling $\lambda \ll 1$ for $\Lambda \ll M_{\rm UV}$.

- Small effective portal coupling λ provides a simple explanation for both the smallness of the neutrino masses and the DM abundance.

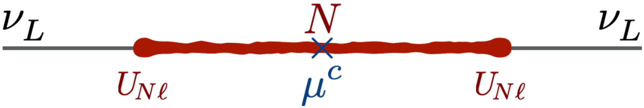
Neutrino masses

- Neutrino masses are generated via the *inverse seesaw* mechanism,
[see also Chacko,Fox,Harnik,Liu:2012.01443]

$$\mathcal{L}_{\rm IR} \supset -\left[m_N N^c N + \frac{\mu^c}{2} \left(N^c\right)^2 + \lambda L H N + \text{h.c.} \right]$$

- SM neutrinos acquire masses and mixings with the composite states N as,

$$\boxed{m_\nu \simeq \mu^c \left|U_{N\ell}\right|^2 \qquad \text{with} \qquad U_{N\ell} \equiv \frac{\lambda v_{\rm EW}}{m_N}}$$



- Smallness of the SM neutrino masses can be explained by either small neutrino mixing λ or small lepton number violating coupling μ^c.

Composite DM via Neutrino Portal

- In a strongly coupled theory composite DM χ and singlet neutrino N have non-renormalizable interactions at the scale Λ,

$$\boxed{\mathcal{L}_{\rm IR} \supset -\frac{y_{\rm eff}^2}{\Lambda^2}\left(\bar{\chi}^c N\right)^2 + \cdots}$$

where $y_{\rm eff} \sim 4\pi/\mathcal{N}$ in Large-$\mathcal{N}$ limit.

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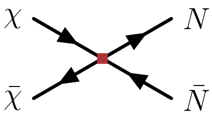
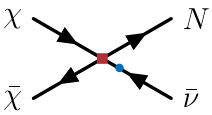
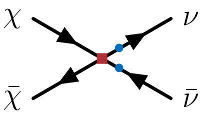
- Condition for thermal equilibrium between the DS and SM is

$$|U_{N\ell}|^2 \gtrsim \sqrt{\frac{\Lambda}{4\pi M_{\rm Pl}}}$$

- DM annihilation through $2 \to 2$ freeze-out







$m_\chi \gtrsim m_N,$

$\frac{m_N}{2} \lesssim m_\chi < m_N,$

$m_\chi < \frac{m_N}{2}$

DM Relic Abundance

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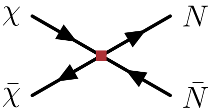

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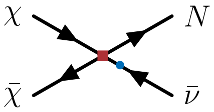

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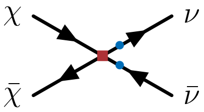

$m_\chi < \frac{m_N}{2}$

- Thermal averaged cross-section at freeze-out temperature $T \sim m_\chi/20$

$$\langle \sigma_{\chi\bar{\chi}\to N\bar{N}} v \rangle \sim \frac{y_{\rm eff}^4}{32\pi\,\Lambda^2}, \qquad \langle \sigma_{\chi\bar{\chi}\to N\bar{\nu}} v \rangle \sim \frac{y_{\rm eff}^4\, U_{N\ell}^2}{32\pi\,\Lambda^2}, \qquad \langle \sigma_{\chi\bar{\chi}\to \nu\bar{\nu}} v \rangle \sim \frac{y_{\rm eff}^4\, U_{N\ell}^4}{32\pi\,\Lambda^2}$$

- Observed DM abundance requires $\langle \sigma v \rangle \sim 10^{-9}\ \mathrm{GeV}^{-2}$.

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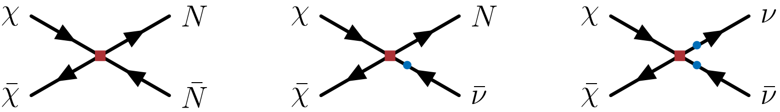

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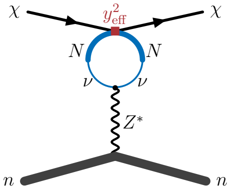
- Observed DM abundance requires $\langle \sigma v\rangle \sim 10^{-9}\ \text{GeV}^{-2}$.
- For $\Lambda \lesssim v_{\rm EW}$, DM annihilation $\chi\bar{\chi} \to N\bar{N}$ leads to under-abundance due to strong coupling $y_{\rm eff} \sim 4\pi$.
- Hence viable DM production channels are: $\chi\bar{\chi} \to N\bar{\nu}$ and $\chi\bar{\chi} \to \nu\bar{\nu}$.

- DM–nucleon cross-section arises from Z-boson exchange



$$\sigma_{\chi n}^{\text{SI}} \sim \frac{g^4\, y_{\text{eff}}^4\, U_{N\ell}^4}{\pi(4\pi)^4} \frac{\mu_{\chi n}^2}{m_Z^4}$$

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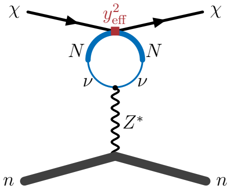
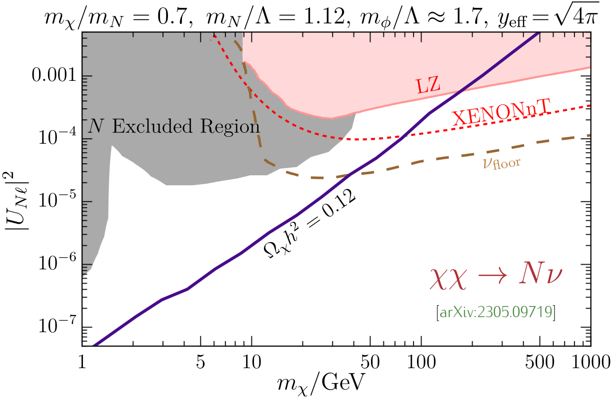
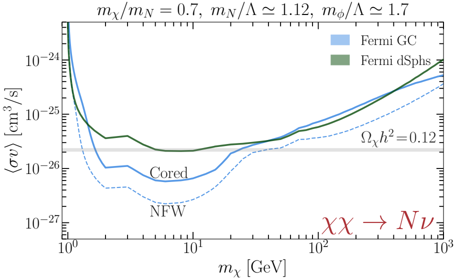
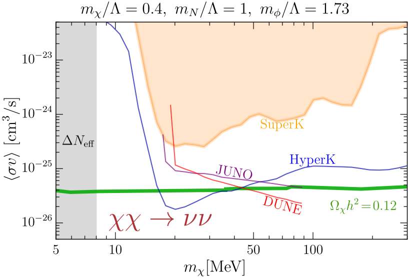




DM INDIRECT DETECTION

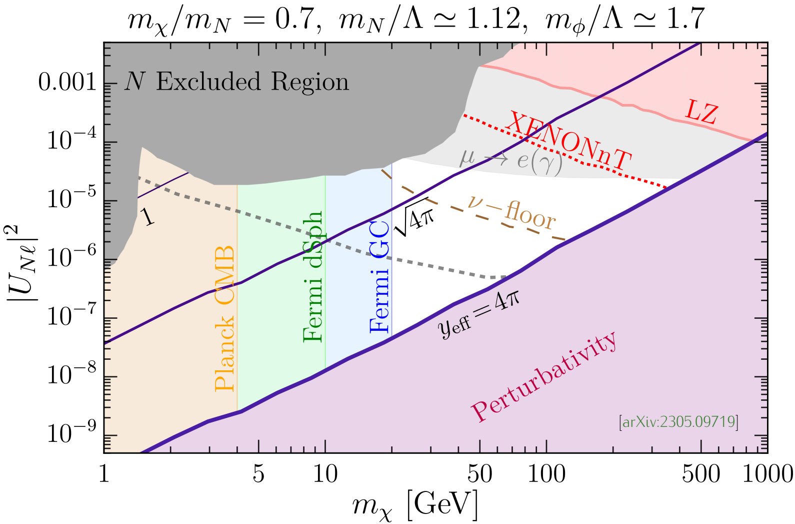
- DM annihilation $\chi\bar{\chi} \to N\bar{\nu}$ produce visible stuff (electrons, photons etc.) through N decays to the SM
- Planck CMB data excludes $m_\chi \lesssim 1$ GeV at 95% C.L.
- Gamma-rays data excludes $m_\chi \in [1-20]$ GeV at 95% C.L.



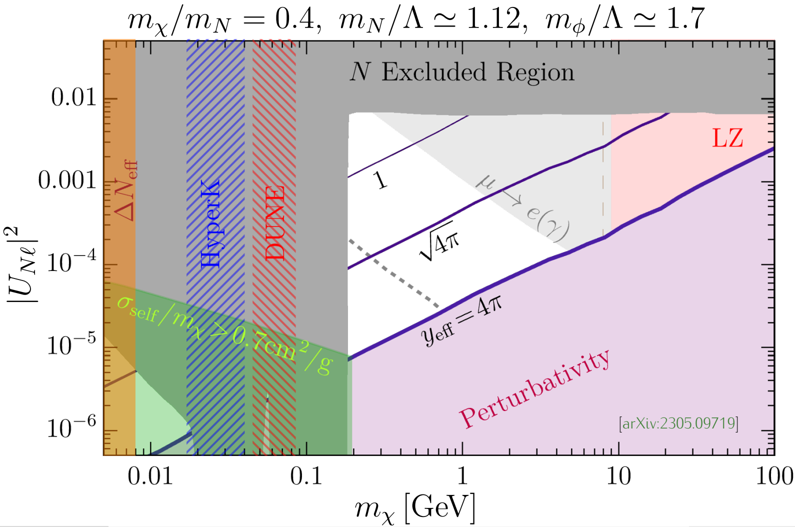


- DM annihilation $\chi\bar{\chi} \to N\bar{\nu}$ and $\chi\bar{\chi} \to \nu\bar{\nu}$ give neutrino-line signals
- Future experiments HyperK/DUNE will probe $m_\chi \in [20-100]$ MeV

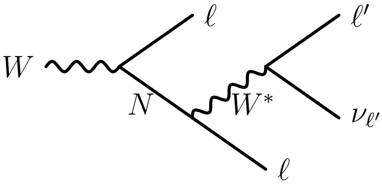
- Summary for a benchmark in the DM mass range $1/2 \lesssim m_\chi/m_N \lesssim 1$ where the dominant DM annihilation channel is $\chi\bar{\chi} \to N\bar{\nu}$.



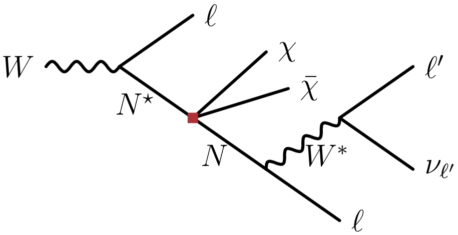
- Summary for a benchmark in the DM mass range $m_\chi/m_N \lesssim 1/2$ where the dominant DM annihilation channel is $\chi\bar{\chi} \to \nu\bar{\nu}$.



- At colliders and beam-dump experiments, DM can be pair-produced in association with one or more composite singlet neutrinos.
- To discover the DM, it is therefore necessary to first discover the composite singlet neutrinos N.



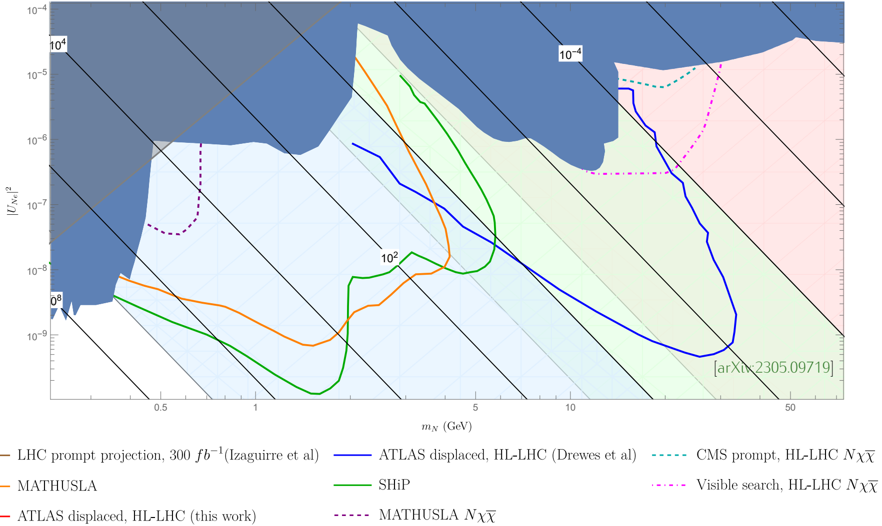
single N production



$N\chi\bar{\chi}$ production

- Searches for N are broadly divided based on whether N decays promptly, displaced or long-lived.

- Summary of collider signals; N lifetime contours (in meters) with prompt (red), displaced (green) and long-lived (blue) shaded regions



Conclusions

- We presented a class of models in which DM is a composite state of a strongly coupled conformal hidden sector.
- In our example we consider the neutrino portal interactions between the SM and DS.
- Small SM neutrino masses are naturally obtained due to conformal dynamics.
- Composite DM relic abundance is set by annihilation into neutrinos.
- This scenario can lead to signals in DM direct/indirect detection experiments and colliders/beam-dump facilities.
- A holographic realization of this framework is studied based on 5D AdS geometry. [arXiv:2305.09719]