Dark Matter and Neutrino Masses from Light Hidden Sector

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Introduction

- Standard Model (SM) of particle physics is the most successful theory of elementary particles and their interactions.
- However, there are several puzzles/observations which are unanswered within the SM.
- Two of the most outstanding puzzles are
  - Dark matter (DM)
  - SM neutrino masses
- Neutrino oscillations have shown that SM neutrinos have tiny but non-zero masses, $m_\nu \lesssim 0.1\,\mathrm{eV}$.
- However, mechanism to generate such tiny neutrino masses is one of the main research topics of BSM physics.

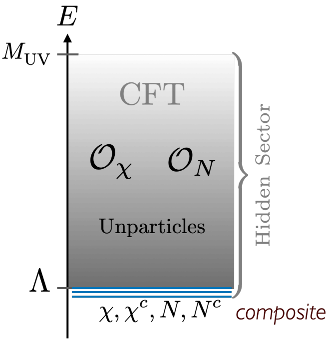
- We propose a new class of models that can account for both the observed abundance of DM and the smallness for neutrino masses.
- We study a class of models in which DM candidates arise as a composites state of a strongly coupled hidden sector.
- Hidden sector is approximately conformal in the UV, and compositeness scale lies at or below the weak scale.
- We construct this framework based on 5D AdS geometry and explore implication for experiments.

A Conformal Hidden Sector

- We consider a hidden sector composed of a strongly coupled conformal field theory (CFT) with a relevant deformation $\mathcal{O}_{\rm def}$,

$$\mathcal{L}_{\rm UV} \supset \mathcal{L}_{\rm CFT} + \lambda_{\rm def}\mathcal{O}_{\rm def}$$

- When the deformation grows large in the infrared, it causes the breaking of the conformal dynamics at a scale $\Lambda \lesssim v_{\rm SM}$.



- Spectrum of hidden sector states includes three composite singlet neutrinos N_i and a composite DM χ along with their Dirac partners N_i^c and χ^c.
- Low energy effective Lagrangian contains ($m_N, m_\chi \sim \Lambda$)

$$\begin{aligned}\mathcal{L}_{\rm IR} \supset\ & i\bar{N}\bar{\sigma}^\mu\partial_\mu N + i\bar{N}^c\bar{\sigma}^\mu\partial_\mu N^c - (m_N N^c N + \text{h.c.}) \\ & + i\bar{\chi}\bar{\sigma}^\mu\partial_\mu\chi + i\bar{\chi}^c\bar{\sigma}^\mu\partial_\mu\chi^c - (m_\chi\chi^c\chi + \text{h.c.})\end{aligned}$$

- SM is assumed to be *elementary*!

Composite Neutrino Portal

- Hidden sector interacts with the SM only through the neutrino portal

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

  - $\mathcal{O}_N$ is a primary fermionic operator with scaling dimension Δ_N
  - $M_{\rm UV}$ is the UV cutoff of the theory and $\hat{\lambda} \sim 1$

- At or below the composite scale Λ, we have $\mathcal{O}_N \to \Lambda^{\Delta_N-3/2} N + \cdots$:

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

- For $\Delta_N \geq 3/2$, the effective coupling λ is hierarchically small for $\Lambda \ll M_{\rm UV}$.

- Naturally small portal coupling λ provides a simple explanation for the both the smallness of the neutrino masses and the observed abundance of DM.

- At Higgs VEV, this term gives mixing between the SM ν and composite N.

Neutrino masses via inverse seesaw mechanism

- We assume that the hidden sector possesses a global symmetry such that $\mathcal{O}_N$, and therefore N, carries charge -1.
- Due to neutrino portal interaction this symmetry can be subsumed into an overall lepton number symmetry, under which N, N^c carry charges -1, $+1$.
- To employ the *inverse seesaw* mechanism we add a lepton number violating deformation,

$$\mathcal{L}_{\mathrm{UV}} \supset -\frac{\hat{\mu}^c}{M_{\mathrm{UV}}^{\Delta_{2N^c}-4}} \mathcal{O}_{2N^c} + \mathrm{h.c.}$$

  where $\hat{\mu}^c$ is dimensionless coupling.
- We assume $\mathcal{O}_{2N^c}$ carries a charge of $+2$ under the global symmetry of the hidden sector, so that this deformation violates lepton number by two units.
- In the low-energy effective theory at scale Λ, this deformation gives,

$$\mathcal{L}_{\mathrm{IR}} \supset -\frac{\mu^c}{2}\left(N^c\right)^2 + \mathrm{h.c.} \qquad \text{with} \qquad \mu^c \sim \hat{\mu}^c \Lambda \left(\frac{\Lambda}{M_{\mathrm{UV}}}\right)^{\Delta_{2N^c-4}}$$

Neutrino masses via inverse seesaw mechanism

- The low-energy effective theory now contains all the ingredients required to realize *inverse seesaw* mechanism,

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

- By integrating out the composite singlet neutrinos N and N^c we obtain the SM neutrinos masses and their mixing with the composite states N,

$$\boxed{m_\nu = \mu^c\left(\frac{\lambda v_{\rm EW}}{m_N}\right)^2} \qquad \boxed{U_{N\ell} \equiv \frac{\lambda v_{\rm EW}}{m_N}}$$

- Smallness of the SM neutrino masses can naturally be explained by either small neutrino mixing λ or small lepton number violating coupling μ^c.
- We require Dirac mass $\lambda v_{\rm EW} \lesssim \Lambda$ and the Majorana mass $\mu^c \lesssim \Lambda$:

$$\frac{m_N}{v_{\rm EW}} \gtrsim \lambda \gtrsim \frac{\sqrt{m_\nu m_N}}{v_{\rm EW}}, \qquad 1 \gtrsim U_{N\ell} \gtrsim \sqrt{\frac{m_\nu}{m_N}}$$

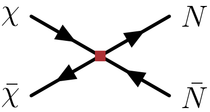
Composite DM through the Neutrino Portal

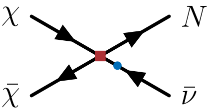
- In our framework, the neutrino portal interaction keeps the hidden sector in equilibrium with the SM in the early universe for $|U_{N\ell}|^2 \gtrsim \sqrt{\Lambda/4\pi M_{\rm Pl}}$.
- Composite nature of the fermions χ, χ^c and N, N^c allows non-renormalizable interactions in the low energy theory at the scale Λ,

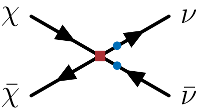
$$\mathcal{L}_{\rm IR} \supset -\frac{y_{\rm eff}^2}{\Lambda^2}\left(\bar{\chi}^c N\right)^2 + \cdots$$

  where $y_{\rm eff} \sim 4\pi$.

- DM abundance is set by the standard thermal freeze-out mechanism.
- The dominant DM annihilation channels to the visible sector are

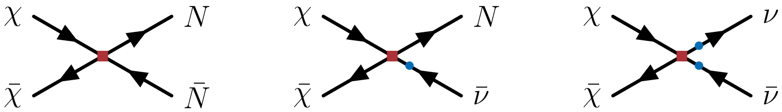






$$\frac{m_\chi}{m_N} \gtrsim 1, \qquad \frac{1}{2} \lesssim \frac{m_\chi}{m_N} < 1, \qquad \frac{m_\chi}{m_N} < \frac{1}{2}$$

DM Relic Abundance



- The thermally averaged DM annihilation cross sections at DM freeze-out, i.e. for $T = T_{\rm fo} \sim m_\chi/20$, are

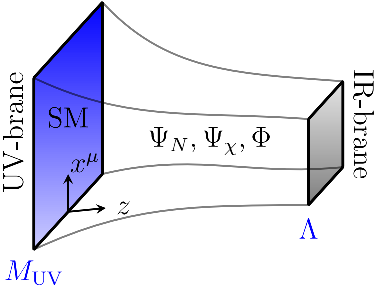
$$\langle \sigma_{\chi\bar{\chi}\to N\bar{N}} v\rangle_{\rm fo} \sim \frac{y_{\rm eff}^4}{32\pi\,\Lambda^2}, \quad \langle \sigma_{\chi\bar{\chi}\to N\bar{\nu}} v\rangle_{\rm fo} \sim \frac{y_{\rm eff}^4\,U_{N\ell}^2}{32\pi\,\Lambda^2}, \quad \langle \sigma_{\chi\bar{\chi}\to \nu\bar{\nu}} v\rangle_{\rm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

- The observed DM relic abundance is produced when $\langle\sigma v\rangle_{\rm fo} \sim 10^{-9}\ \text{GeV}^{-2}$.
- Note $\chi\bar{\chi} \to N\bar{N}$ process leads to DM under-abundance for strong coupling $y_{\rm eff} \sim 4\pi$ and $\Lambda \lesssim \mathcal{O}(100)$ GeV.
- Hence only viable DM production channels are $\chi\bar{\chi} \to N\bar{\nu}$ and $\chi\bar{\chi} \to \nu\bar{\nu}$.

- The holographic model is realized in a 5D anti-de Sitter (AdS) space

$$\boxed{ds^2 = \left(\frac{R}{z}\right)^2 \eta_{MN}\, dx^M dx^N}$$

where $x^M = (x^\mu, z)$ and $R \le z \le R'$.



- The two branes correspond to the UV and IR scales, $M_{\rm UV} \equiv 1/R$ and $\Lambda \equiv 1/R'$.
- The SM is localized at the UV brane which corresponds to the elementary states in the 4D dual picture.
- New composite states corresponding the strongly coupled hidden sector are in the bulk and at the IR-brane.

Holographic realization

- Interaction between 5D neutrinos with the SM is

$$S_{\rm UV} \supset \int d^4x \int dz \left(\frac{R}{z}\right)^4 \delta(z-R)\sqrt{R}\,\hat{\lambda}\,LH\,\Psi_N(x,z)$$

- After choosing appropriate boundary conditions and KK-decomposing the bulk fields, 4D effective theory contains KK towers of singlet neutrinos N_n, N_n^c, fermion DM χ_n, χ_n^c, as well as the singlet scalar ϕ_n modes.

- Neutrino portal interaction is

$$S_{\rm UV} \supset \int d^4x \sum_n \lambda_n\,LH\,N_n(x)$$

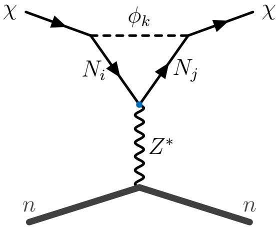
where λ_n contains the bulk neutrino $\Psi_N(x,R)$ wave-function.

- DM and singlet neutrino interact through Yukawa term.

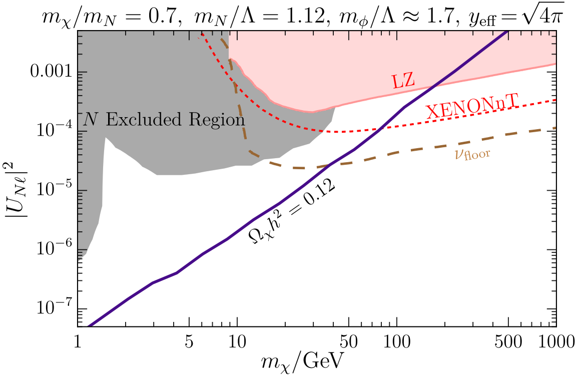
$$S_{\rm bulk} \supset \int d^4x \int dz \sqrt{g}\,\hat{y}\sqrt{24\pi^3 R}\,\bar{\Psi}_\chi^c \Psi_N\,\Phi = \int d^4x \sum_{n,p,q} y_{npq}\,\bar{\chi}_n^c N_p \phi_q$$

- Holographic model reproduces our 4D CFT results.

- Signature in direct and indirect detection
  - direct detection: XENONnt/LZ experiments
  - indirect detection: precision observation of CMB, search for gamma rays, signal for neutrino-line
- Lepton flavour violating
  - $\mu \to e(\gamma)$
- Collider searches: LHC
- Reach of future experiments
  - XENONnt
  - Hyper-Kamiokande and DUNE (sensitivity to neutrino-line)
  - MATHUSLA



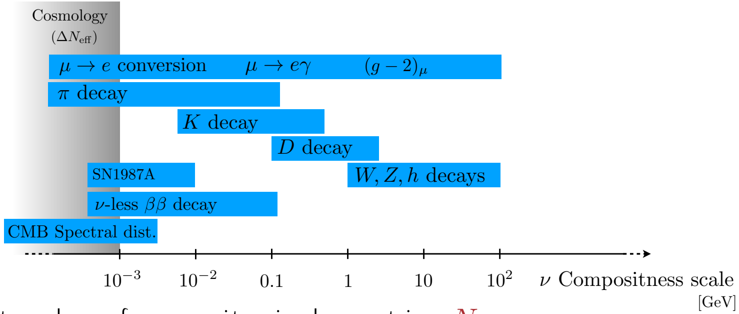
- Dominant contribution to DM–Nucleon arises from Z-boson exchange.
- Spin-independent DM–Nucleon cross-section is: $\boxed{\sigma_{\chi n} \sim \frac{g^4\, y_{\rm eff}^4\, U_{N\ell}^4}{\pi(4\pi)^4}\frac{\mu_{\chi n}^2}{m_Z^4}}$



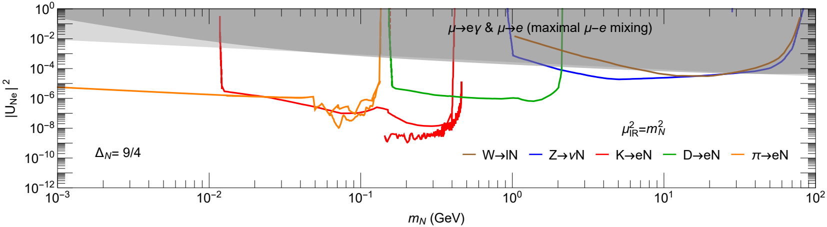
Composite neutrino signals

- There are various probes of neutrino compositeness scales Λ.

[Chacko,Fox,Harnik,Liu:2012.01443]



- Direct probes of composite single neutrino N.



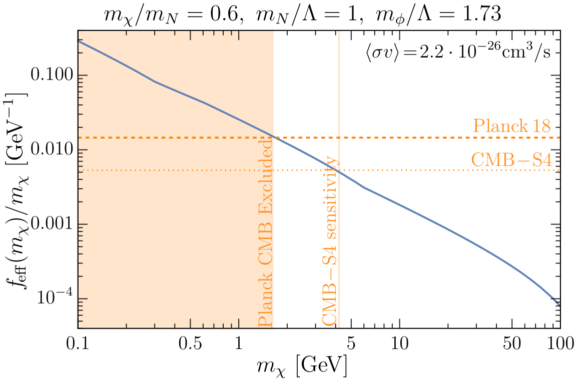
DM indirect detection: CMB constraint

- For $\chi\bar{\chi} \to N\bar{\nu}$ channel, the final state N decays to visible end products such as electrons, photons etc., which could alter the CMB measurements.

- From the CMB data Planck collaboration constraints at 95% C.L. on

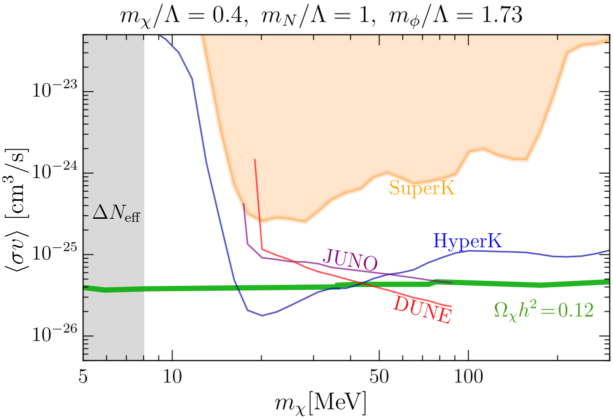
$$f_{\rm eff}(m_\chi)\frac{\langle\sigma v\rangle}{m_\chi} < 3.2\times10^{-28}\,{\rm cm}^3\,{\rm s}^{-1}\,{\rm GeV}^{-1}$$

$f_{\rm eff}(m_\chi)$ is the effective fraction of energy transferred to the IGM.

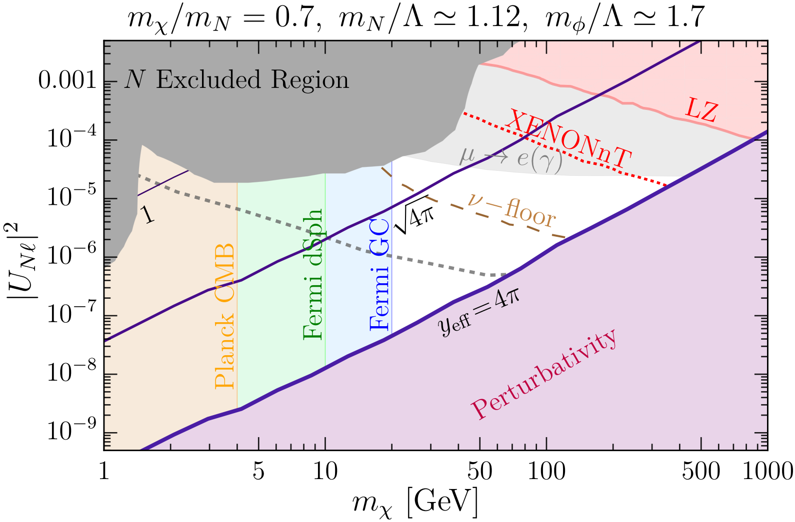


DM indirect detection: Neutrino-line signals

- The dominant annihilation channel $\chi\bar{\chi} \to N\bar{\nu}$ or $\chi\bar{\chi} \to \nu\bar{\nu}$, gives rise to monochromatic neutrinos in the final state.
- In dense DM matter environments e.g. the centre of our Milky Way galaxy such DM annihilations could lead to the possibility of observing neutrino-line signals in neutrino detection experiments.

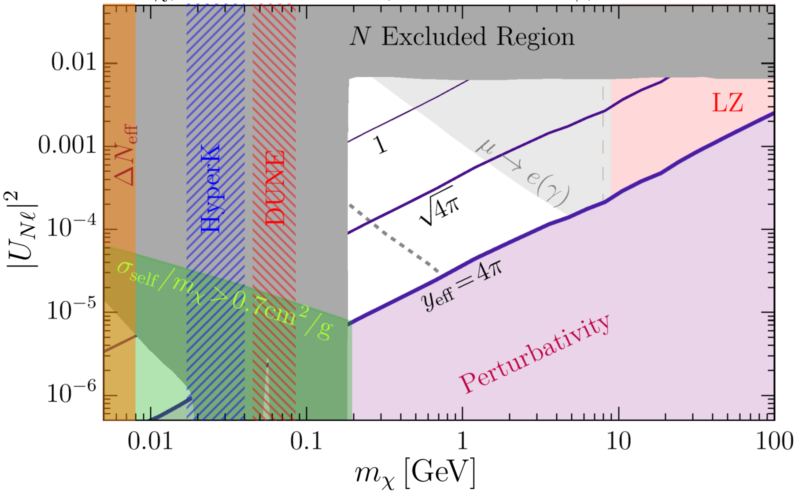


- Summary for a benchmark in the DM mass range $1/2 \lesssim m_\chi/m_N \lesssim 1$ where the dominant DM annihilation channel is $\chi\bar{\chi} \to N\bar{\nu}$.



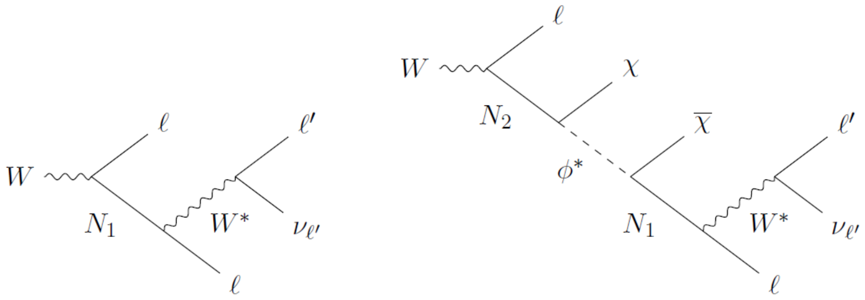
- Summary for a benchmark in the DM mass range $m_\chi/m_N \lesssim 1/2$ where the dominant DM annihilation channel is $\chi\bar{\chi} \to \nu\bar{\nu}$.

$$m_\chi/m_N = 0.4,\ m_N/\Lambda \simeq 1.12,\ m_\phi/\Lambda \simeq 1.7$$



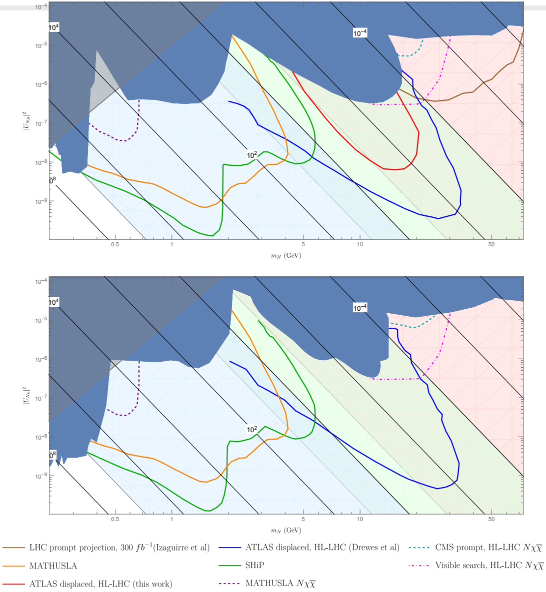
Collider phenomenology

- 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.
- Collider signal processes of interest for this work are



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

Collider signals of composite DM and neutrino



Summary

- We presented a class of models in which DM is a composite state of a strongly coupled hidden sector which interacts with the SM through the neutrino portal.
- DM relic abundance is set by annihilation into neutrinos.
- The neutrino portal also leads to the generation of SM neutrino masses through the *inverse seesaw* mechanism.
- We focused on the scenario in which the hidden sector is conformal in the ultraviolet, and the compositeness scale lies at or below the weak scale.
- A holographic realization of this framework is studied based on 5D AdS geometry.
- This scenario can lead to signals in DM detection experiments as well as in colliders in the near future.