Neutrino Portal Composite Dark Matter from a Light Hidden Sector

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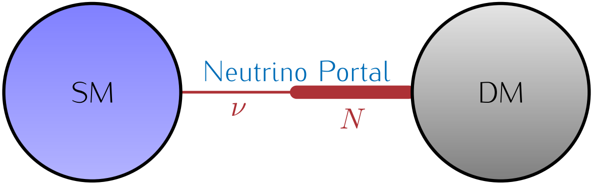
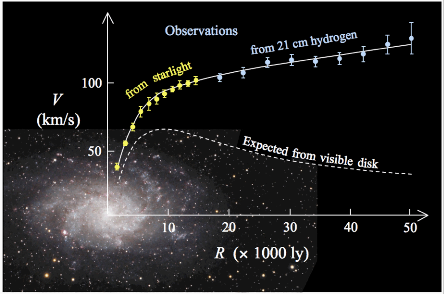
- Two of the most outstanding puzzles of particle physics are
  - Dark matter (DM)
  - SM neutrino masses

- In this talk we discuss a possible connection between these two puzzles, in a framework where DM interacts with the SM through the *neutrino portal*.

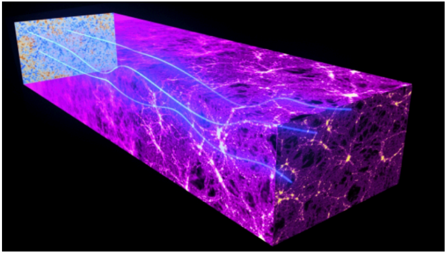


Galatic rotation curves

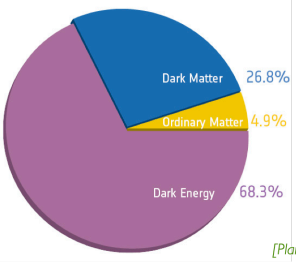


Cluster collisions

Gravitational lensing of CMB



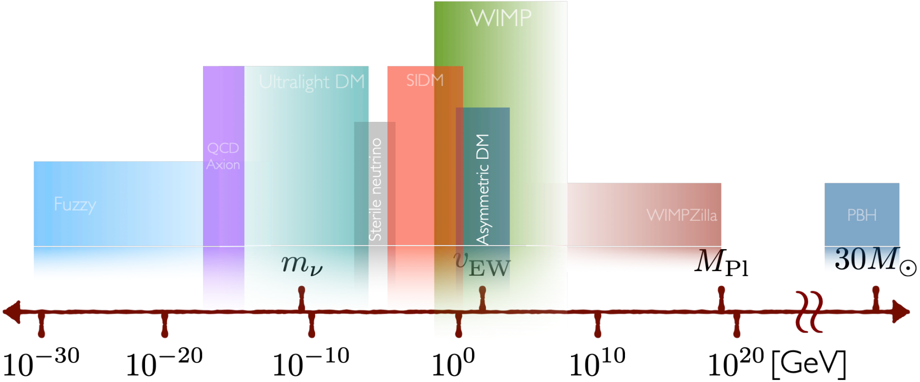
CMB ~ 85% of total matter is DM



[Planck Satellite]

Dark matter candidates

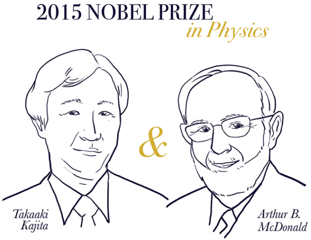
- DM is massive and stable.
- (so far) No evidence of non-gravitational interactions of DM.
- DM can have a wide range of masses and interaction strengths.



- In this talk, we discuss DM in a mass range $\sim$ [1 MeV – 100 GeV] which has strong self-interactions, however interacts weakly with the SM.

SM neutrino masses

- Neutrino oscillations have shown that SM neutrinos have tiny but non-zero masses, $m_\nu \sim 0.1\,\mathrm{eV}$.
- Neutrino masses can be generated within SM effective field theory via the *Weinberg operator* [Weingberg: PRL'1979]



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

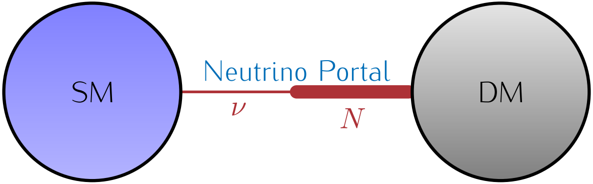
$$\mathcal{L}_5 = -\frac{C_5}{\Lambda}(LH)^2 + \text{h.c.}$$

$$\supset -m_\nu \overline{\nu^c}\nu + \text{h.c.},$$

$$\boxed{m_\nu = \frac{C_5\, v_{\rm SM}^2}{\Lambda}}$$

- To get $m_\nu \sim 0.1\,\mathrm{eV}$ one requires $\Lambda \sim C_5 \times 10^{15}$ GeV.
- In the "seesaw mechanism" the right-handed neutrino masses are $M_N \sim \Lambda$.
- However, in this talk we discuss SM neutrinos mass generation through the "inverse seesaw mechanism" where $M_N \sim [1\text{ MeV} - 100\text{ GeV}]$.

Outline



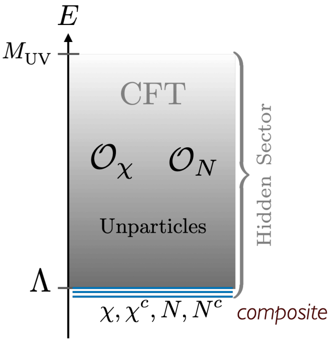
- A framework for a strongly interacting light hidden sector involving the composite DM and singlet neutrinos
- Generation of SM neutrino masses
- DM freeze-out via the neutrino portal
- Phenomenology
- Holographic realization
- Conclusions

- We consider a hidden sector composed of a strongly coupled conformal field theory (CFT) below a cutoff scale $M_{\rm UV}$,

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

where $\mathcal{O}_{\rm def}$ a relevant deformation operator with coupling $\lambda_{\rm def}$.

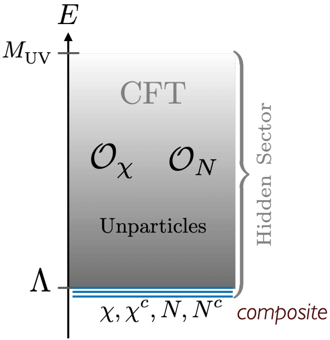
- The deformation grows large in the infrared, such that it breaks the conformal dynamics at a scale $\Lambda \lesssim v_{\rm SM}$.



- CFT contains fermionic operators $\mathcal{O}_\chi$ and $\mathcal{O}_N$ with scaling dimensions Δ_χ and Δ_N.

- At the CFT breaking scale Λ, spectrum of hidden sector states includes a composite DM candidate χ and three heavy singlet neutrinos N with masses of the order Λ, i.e. $m_\chi, m_N \sim \Lambda$.

- For $E > \Lambda$ the hidden sector states behave as *Unparticles*.



- SM particles are assumed to be "elementary"!

- For $E \lesssim \Lambda$ the low-energy effective Lagrangian contains

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

Composite Neutrino Portal

- Hidden sector interacts with the SM only through the neutrino portal in the UV theory

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

where $\hat{\lambda} \sim 1$.

- At or below the conformal breaking scale Λ, the portal interaction is

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

- For $3/2 \leq \Delta_N \leq 5/2$, the coupling $\lambda \ll 1$ 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.

- 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 in the UV theory through a scalar operator $\mathcal{O}_{2N^c}$

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

  where $\Delta_{2N^c} \geq 1$ is scaling dimension of $\mathcal{O}_{2N^c}$ and $\hat{\mu}^c$ is a small parameter.
- 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,

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

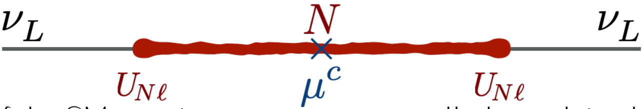
Neutrino masses via inverse seesaw mechanism

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

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

- Due to the portal interaction, in the low-energy theory, we obtain the SM neutrinos masses and their mixing with the composite states N:

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

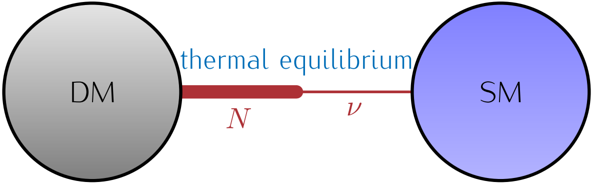


- Smallness of the SM neutrino masses can naturally be explained by either small neutrino mixing λ or small lepton number violating coupling μ^c.
- Requiring Dirac mass $\lambda v_{\rm EW} \lesssim \Lambda$ and Majorana mass $\mu^c \lesssim \Lambda$ gives

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

Composite DM through the Neutrino Portal

- In our framework DM abundance is set by the standard thermal freeze-out mechanism.



- Condition for thermal equilibrium of the tho sectors imply

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

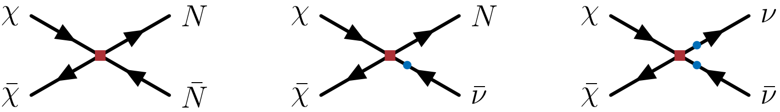
- In a strongly coupled theory the composite DM χ and singlet neutrino N involve non-renormalizable interactions in the low-energy theory, i.e.

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

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

DM Relic Abundance

- The dominant DM annihilation channels to the visible sector are



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

- The thermally averaged DM annihilation cross sections at DM freeze-out, i.e. for $T = T_{\rm fo} \sim m_\chi/10$, are

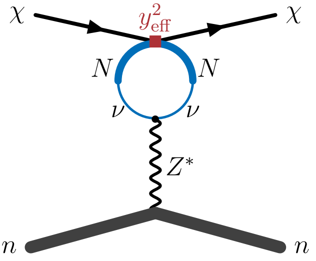
$$\langle \sigma_{\chi\bar{\chi}\to N\bar{N}} v\rangle_{\rm fo} \sim \frac{y_{\rm eff}^4}{40\pi\,\Lambda^2}, \quad \langle \sigma_{\chi\bar{\chi}\to N\bar{\nu}} v\rangle_{\rm fo} \sim \frac{y_{\rm eff}^4\, U_{N\ell}^2}{40\pi\,\Lambda^2}, \quad \langle \sigma_{\chi\bar{\chi}\to \nu\bar{\nu}} v\rangle_{\rm fo} \sim \frac{y_{\rm eff}^4\, U_{N\ell}^4}{40\pi\,\Lambda^2}$$

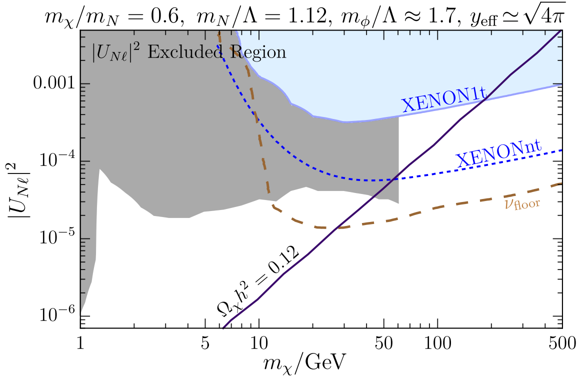
- The observed DM relic abundance is produced when $\langle \sigma v\rangle_{\rm fo} \sim 10^{-8}$ GeV^{-2}.

- Note $\chi\bar{\chi} \to N\bar{N}$ channel leads to DM under-abundance due to strong coupling $y_{\rm eff} \sim 4\pi$ for $\Lambda \lesssim \mathcal{O}(100)$ GeV.

- Hence only viable DM production channels are $\chi\bar{\chi} \to N\bar{\nu}$ and $\chi\bar{\chi} \to \nu\bar{\nu}$.

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



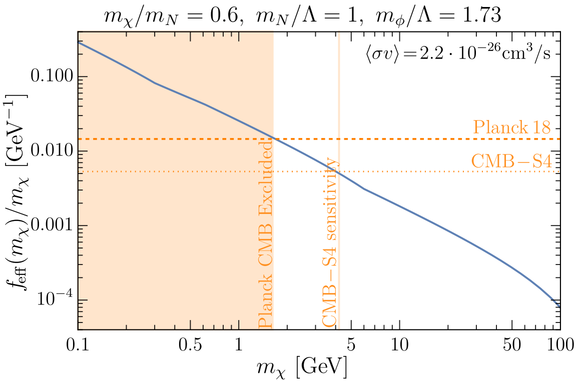


- For $\chi\bar{\chi} \to N\bar{\nu}$ channel, the final state N decays to visible end-products such as electrons, photons etc., which can alter the CMB measurements.

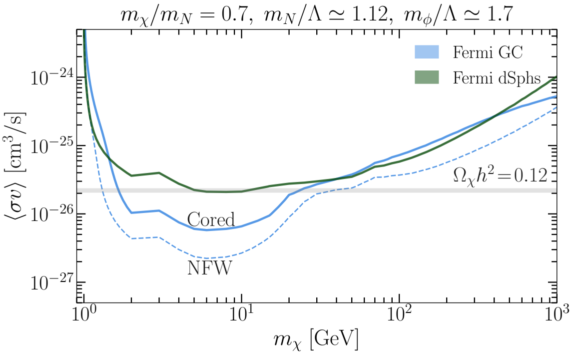
- CMB data from Planck collaboration constraints at 95% C.L. on

$$f_{\rm eff}(m_\chi)\frac{\langle\sigma v\rangle}{m_\chi} < 3.2\times 10^{-28}\,{\rm cm}^3\,{\rm s}^{-1}\ {\rm GeV}^{-1}$$

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

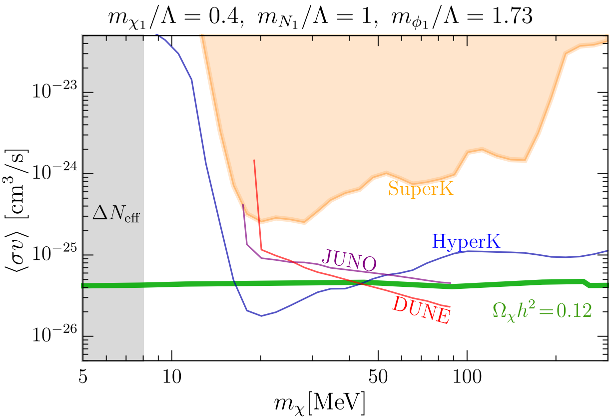


- For $\chi\bar{\chi} \to N\bar{\nu}$ channel, the final state N decays also lead to gamma ray signals.
- Fermi-LAT data from the Galactic Center (GC) and Dwarf Spheroidal Satellite (dSphs) galaxies puts constraints on our model parameters



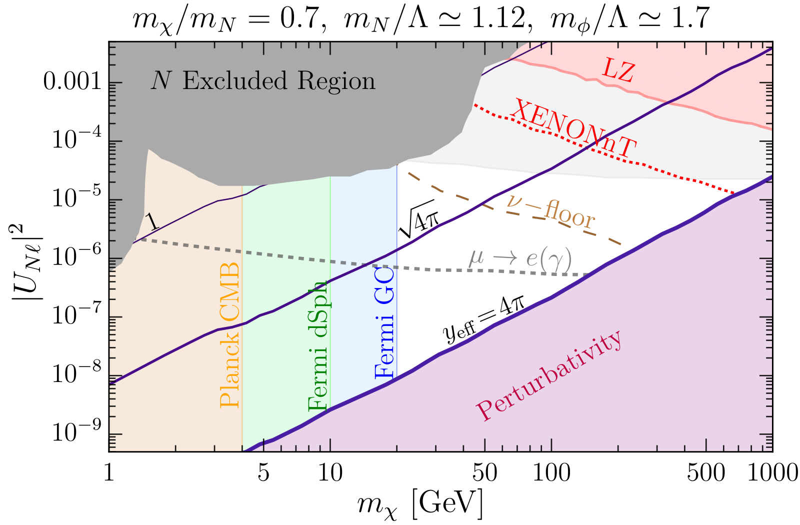
- The dominant annihilation channel $\chi\bar{\chi} \to N\bar{\nu}$ or $\chi\bar{\chi} \to \nu\bar{\nu}$, gives rise to monochromatic neutrinos in the final state.

- 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.

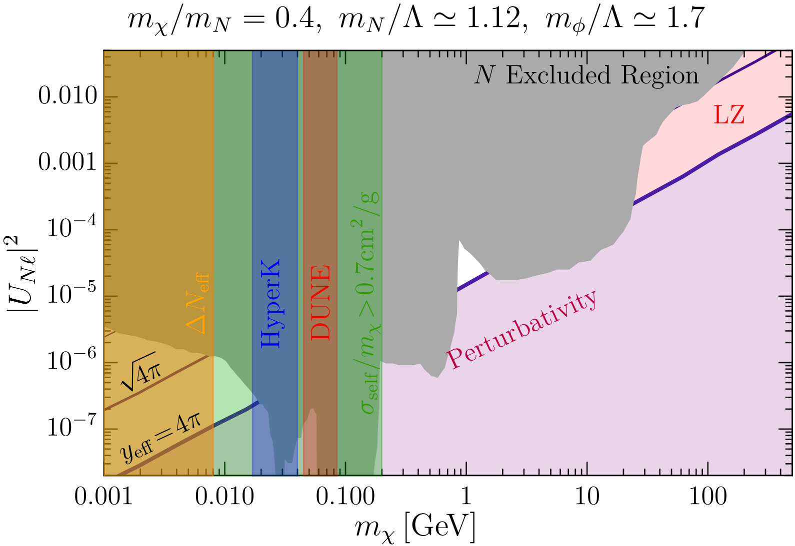


Composite DM phenomenology

- 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 $\chi\bar{\chi} \to N\bar{\nu}$.

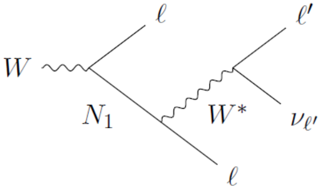


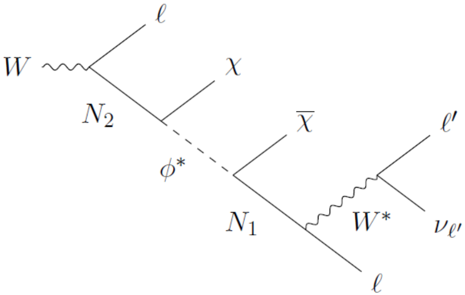
- Summary for a benchmark in the DM mass range $m_\chi/m_N \lesssim 1/2$ where the dominant DM annihilation channel is $\chi\bar{\chi} \to \nu\bar{\nu}$.



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

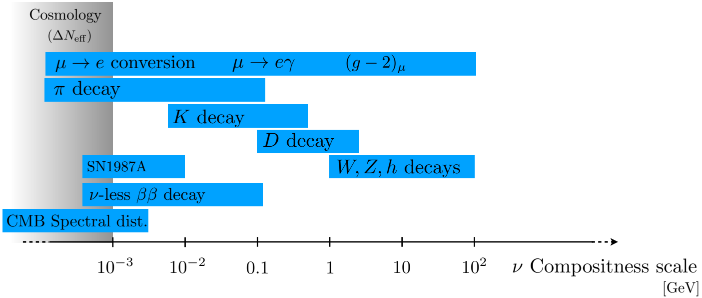




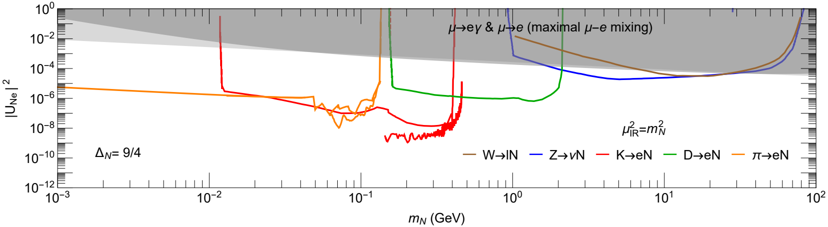
- Searches for N are broadly divided based on whether N decays promptly in colliders, displaced, or is long-lived.

- There are various direct and indirect probes of composite neutrino N.

[Chacko,Fox,Harnik,Liu:2012.01443]

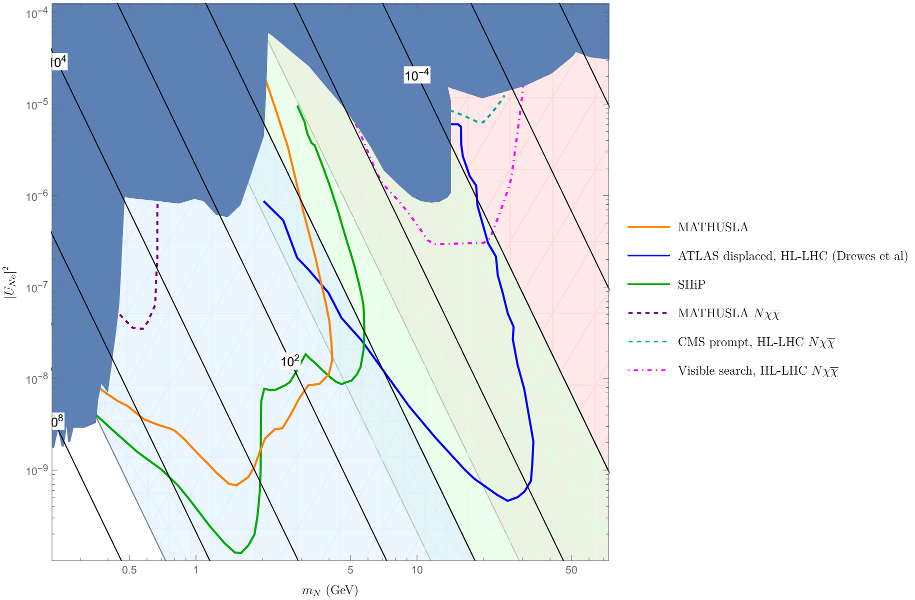


- Constraint on neutrino mixing due to composite neutrino N searches.



Collider signals of composite DM and neutrino

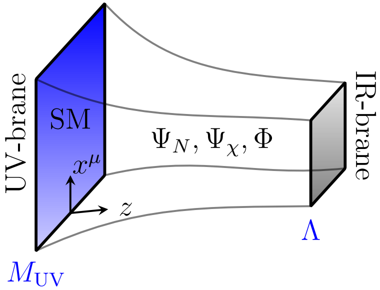
Contours of the N lifetime (in meters) with prompt (red), displaced (green) and long-lived (blue) shaded regions



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

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

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 Kaluza-Klein (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

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

where λ_n contains the bulk neutrino $\Psi_N(x,R)$ wave-function.
- DM and singlet neutrino interact through Yukawa term.

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

Holographic model with lightest KK-modes reproduces our 4D CFT results

4D strongly coupled CFT		5D weakly coupled gravity theory
Energy scale μ	$\Longleftrightarrow$	Extra dimensional space $z = 1/\mu$
UV cutoff scale $M_{\rm UV}$	$\Longleftrightarrow$	UV brane location $R = 1/M_{\rm UV}$
CFT breaking scale Λ	$\Longleftrightarrow$	IR brane location $R' = 1/\Lambda$
CFT operators $\mathcal{O}(x)$	$\Longleftrightarrow$	Bulk fields $\Psi(x, z)$
Scaling dimensions $\Delta_{\mathcal{O}}$	$\Longleftrightarrow$	Bulk mass parameter $c_\Psi = \Delta_{\mathcal{O}} - 2$
Low-energy comp. states χ, N	$\Longleftrightarrow$	Lowest KK modes χ_1, N_1
High-energy states, *Unparticles*	$\Longleftrightarrow$	Tower of KK modes, $n > 1$
Elementary states, e.g. SM	$\Longleftrightarrow$	UV brane localized fields

Phenomenological analysis is performed in the holographic 5D picture!

- 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, with composite hidden sector states playing the role of the singlet neutrinos.
- 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 direct/indirect detection experiments as well as in colliders/beam-dump facilities in the near future.