Conformal Dark Sectors

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Happy Birthday Matthias!

Happy 10th Anniversory

Generic framework

- In a generic framework, dark matter (DM) is the lightest stable particle in a dark sector (DS)
- Dark sector interacts with the Standard Model (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 single 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

- The portal interaction is more relevant for the smallest $\Delta_{\mathrm{SM/DS}}$

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- Based on the lowest dimension SM operators $\mathcal{O}_{\mathrm{SM}}$:

$\mathcal{O}_{\mathrm{SM}}$	Δ_{SM}	$\mathcal{O}_{\mathrm{DS}}$	portal
$H^\dagger H$	2	scalar	Higgs portal
$B_{\mu\nu}$	2	tensor	Hypercharge portal
LH	$5/2$	fermion	Neutrino portal
$\vdots$	$\vdots$	$\vdots$	$\vdots$

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- $\mathcal{O}_{\rm DS}$ is completely unknown (spin/Lorentz structure is fixed by $\mathcal{O}_{\rm SM}$)

- DS is a strongly coupled conformal field theory (CFT) below a UV scale $M_{\rm UV}$

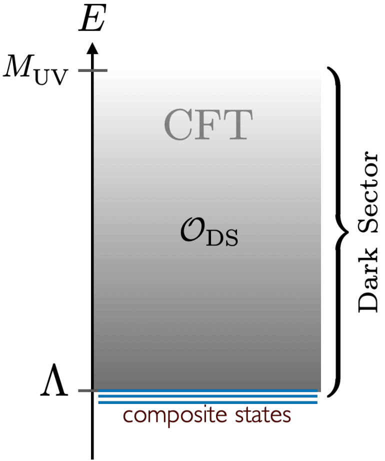
- UV Lagrangian for the dark sector

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

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

- This deformation grows large in the IR, such that it breaks the conformal dynamics at a scale Λ.

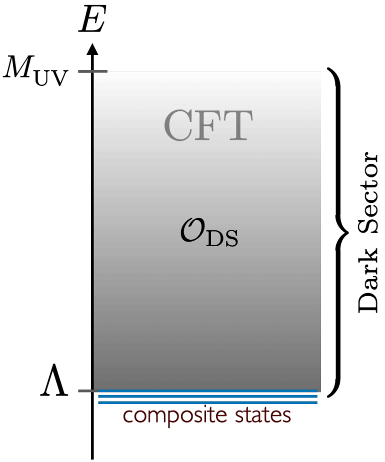
- CFT contains an operator $\mathcal{O}_{\rm DS}$ with scaling dimension $\Delta_{\rm DS}$ that gives composite states at scale Λ.



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 $E \ll \Lambda$, DM is like a *particle*
2. For $E \sim \Lambda$, DM is a *composite state*
3. For $E \gg \Lambda$, DM behaves as *unparticle/continuum states*



- As a concrete realization of this framework, we discuss neutrino portal composite DM with the composite scale $\Lambda \lesssim v_{\rm SM}$.

  [with Z. Chacko, N. Desai, S. Doshi, C. Kilic, S. Najjari, arXiv:2305.nnnn]

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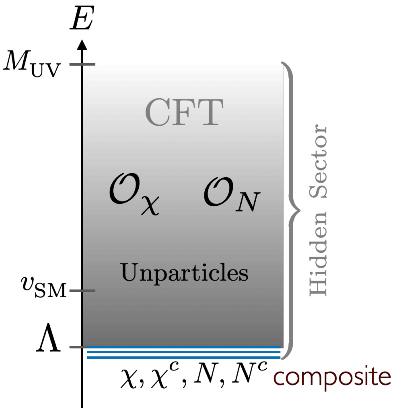
- CFT contains fermionic operators $\mathcal{O}_\chi$ and $\mathcal{O}_N$ with scaling dimensions Δ_χ and Δ_N.
- At scale Λ, DS states includes a composite DM candidate χ and three heavy singlet neutrinos N with $m_\chi, m_N \sim \Lambda$.
- SM particles are elementary.



Composite Neutrino Portal

- In the UV, DS interacts with the SM only through the neutrino portal

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

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

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

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- 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 both the smallness of the neutrino masses and the DM abundance.

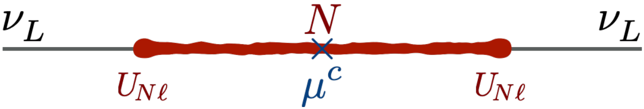
Neutrino masses

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

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

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

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



- Smallness of the SM neutrino masses can 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 involve non-renormalizable interactions 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 $y_{\rm eff} \sim 4\pi/\mathcal{N}$ in Large-$\mathcal{N}$ limit.

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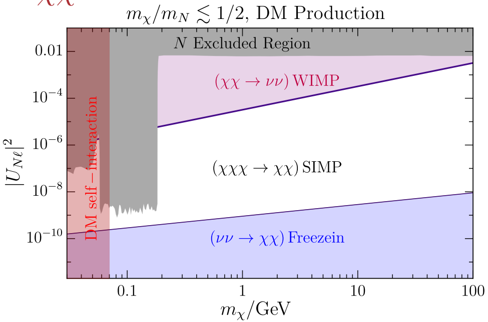
- Thermal equilibrium between the DS and SM is achieved for portal coupling

$$\lambda \gtrsim \frac{\Lambda}{v_{\rm EW}}\left(\frac{\Lambda}{4\pi M_{\rm Pl}}\right)^{1/4}, \qquad |U_{N\ell}|^2 > \sqrt{\frac{\Lambda}{4\pi M_{\rm Pl}}}$$

- DM can be produced in three different ways:

1. Standard $2 \to 2$ freeze-out (WIMP): $\chi\chi \to NN, N\nu, \nu\nu$
2. Dark $3 \to 2$ freeze-out (SIMP): $\chi\chi\chi \to \chi\chi$
3. Freeze-in: $\nu\nu \to \chi\chi$



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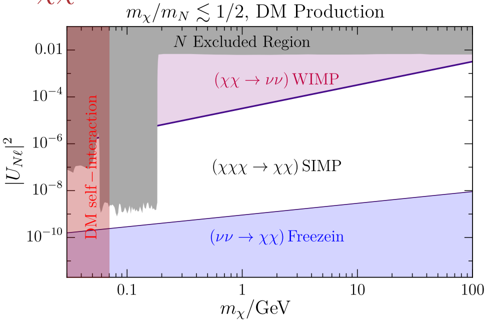
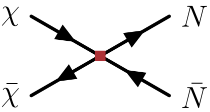


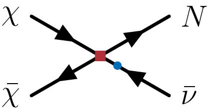
- In the following, I will discuss the WIMP-like standard $(2 \to 2)$ freeze-out for $\chi\chi \to NN, N\nu, \nu\nu$

DM Relic Abundance

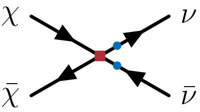
- The dominant DM annihilation channels to the visible sector are



$$\frac{m_\chi}{m_N} \gtrsim 1,$$



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



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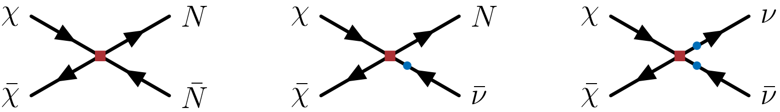

$$\frac{m_\chi}{m_N} \gtrsim 1, \qquad \frac{1}{2} \lesssim \frac{m_\chi}{m_N} < 1, \qquad \frac{m_\chi}{m_N} < \frac{1}{2}$$

- At the freeze-out temperatures $T \sim m_\chi/10$,

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

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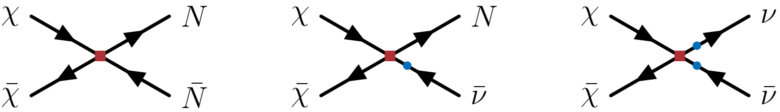

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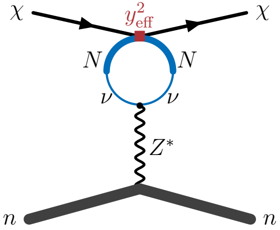
- DM abundance requires $\langle \sigma v \rangle \sim 10^{-8}$ GeV^{-2}.
- Note $\chi\bar{\chi} \to N\bar{N}$ channel leads to DM under-abundance due to strong coupling $y_{\text{eff}} \sim 4\pi$ for $\Lambda \lesssim \mathcal{O}(100)$ GeV.
- Hence viable DM production channels are: $\chi\bar{\chi} \to N\bar{\nu}$ and $\chi\bar{\chi} \to \nu\bar{\nu}$.

DM direct detection

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



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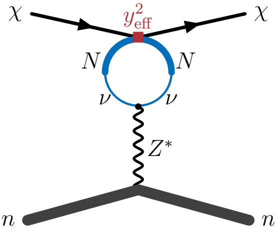

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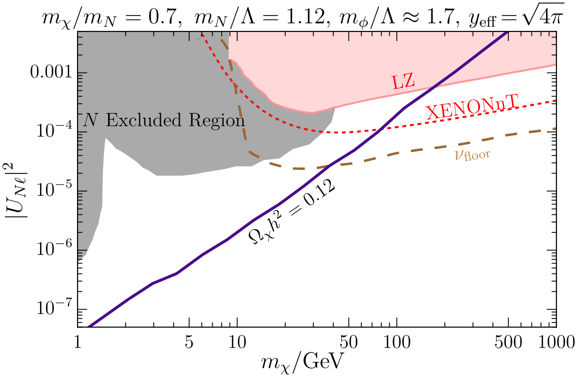

DM indirect detection

- For $\chi\bar{\chi} \to N\bar{\nu}$, the final state N decays to visible end-products electrons, photons etc.
  - Planck CMB data excludes $m_\chi \lesssim 1$ GeV at 95% C.L.
  - Gamma-rays data from the Galactic Center (GC) and Dwarf Spheroidal Satellite (dSphs) galaxies excludes $m_\chi \in [1 - 20]$ GeV.

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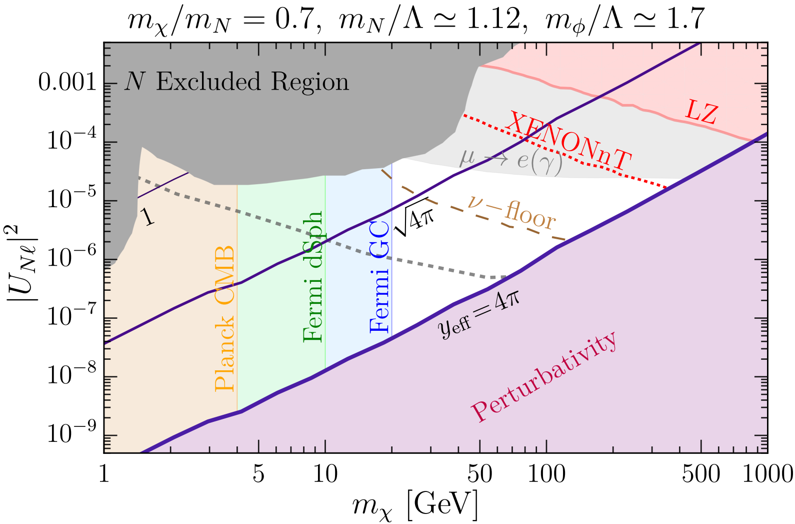
- $\chi\bar{\chi} \to N\bar{\nu}$ or $\chi\bar{\chi} \to \nu\bar{\nu}$ annihilation channels give rise to monochromatic neutrinos in the final state.
  - Possibility of observing neutrino-line signals.
  - Future experiments HyperK and DUNE will have the required sensitivity.

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



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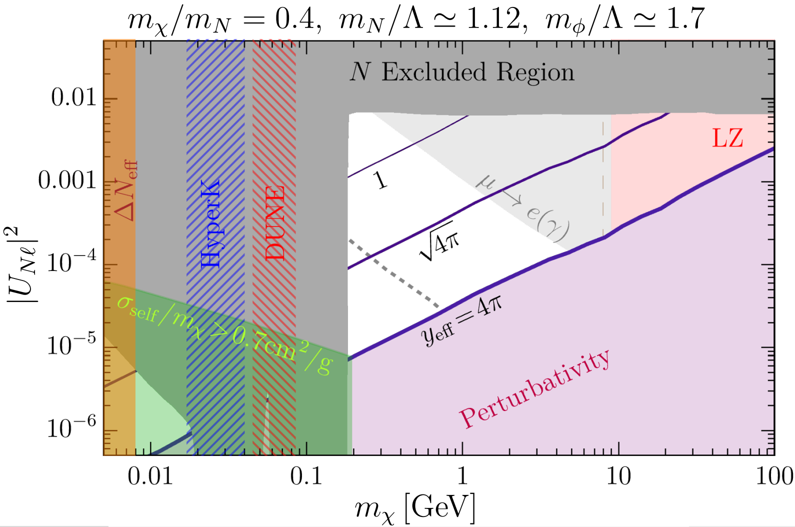
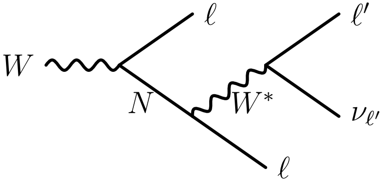
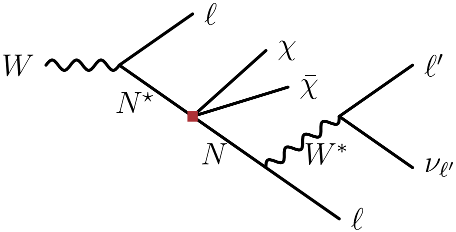


Collider phenomenology

- 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.



single N production

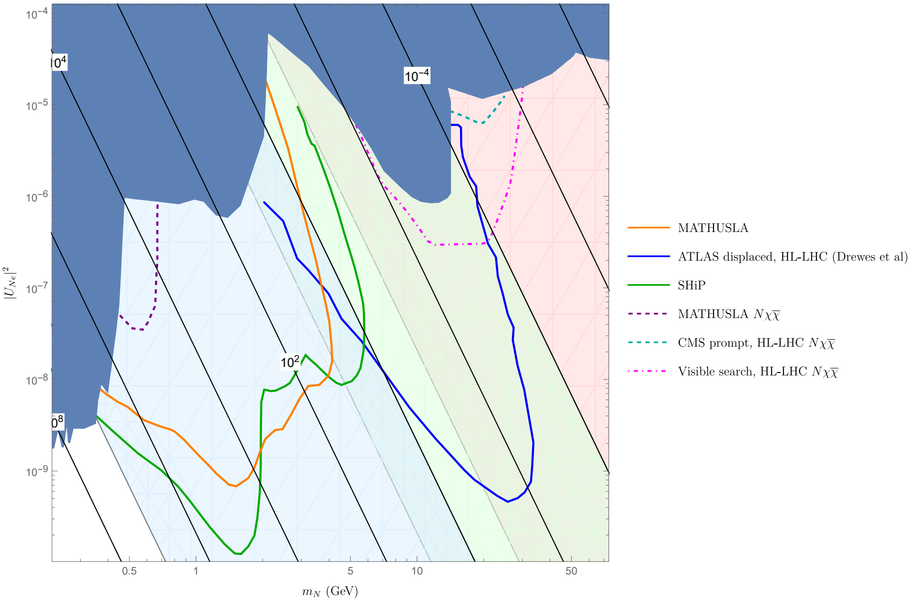


$N\chi\bar{\chi}$ production

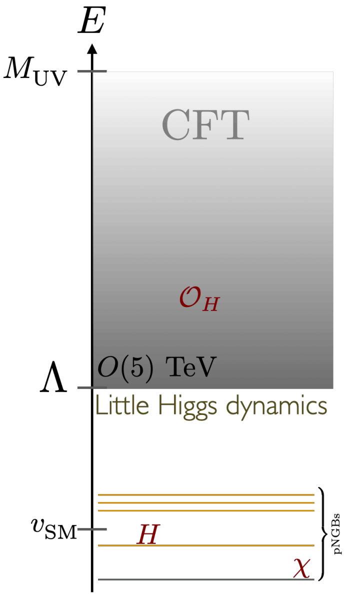
- Searches for N are broadly divided based on whether N decays promptly, displaced or long-lived.

Collider signals

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



- A solution to the hierarchy problem from a conformal theory
  [with M. Lindner, P. Saake; arXiv:2305.nnnn]
- Conformal symmetry is broken at scale $\Lambda \sim O(5)$ TeV by fermion condensate.
- Breaking of conformal symmetry leads to spontaneous breaking of a global symmetry.
- Higgs and partners emerge as pseudo-Nambu-Goldstone bosons (pNGBs).
- Little hierarchy between $v_{\rm SM}$ and Λ is explained by Little Higgs dynamics.
- The lightest stable neutral composite scalar can be a DM candidate.



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.
- DM relic abundance is set by annihilation into neutrinos.
- This scenario can lead to signals in DM direct/indirect detection experiments as well as in colliders/beam-dump facilities.
- Higgs boson emerging as a pNGB from a conformal sector can explain the SM hierarchy problem up to UV scale.

Long-Live MITP!

&

Long-Live Matthias!

- 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 leads to 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 $\mathcal{O}_{2N^c}$

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

  $\Delta_{2N^c} \geq 1$ is scaling dimension of $\mathcal{O}_{2N^c}$ and $\hat{\mu}^c$ is a small parameter.
- $\mathcal{O}_{2N^c}$ carries a charge of $+2$ under the hidden sector's global symmetry, so this deformation violates lepton number by two units.
- In the low-energy effective theory at scale Λ, this deformation gives,

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

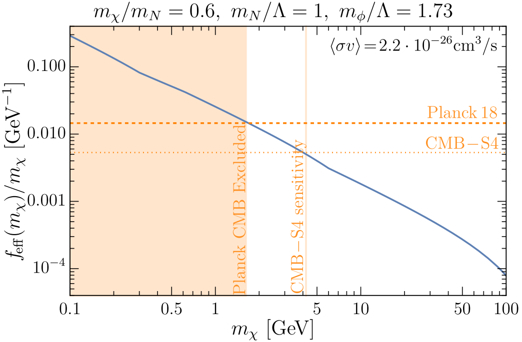
Indirect detection: CMB constraint

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

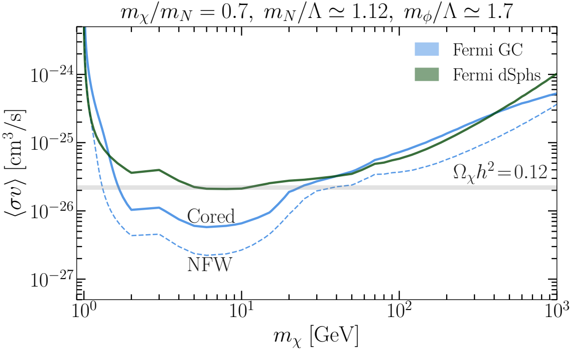
- CMB data from Planck collaboration constraints at 95% C.L. on

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

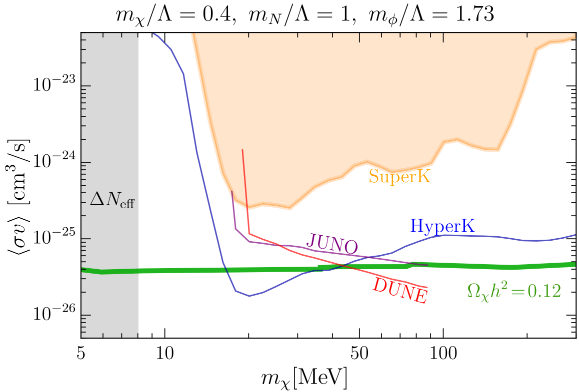
$f_{\rm eff}(m_\chi)$ is the effective fraction of energy transferred to the IGM.



- 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 center of our Milky Way galaxy such DM annihilations could lead to the possibility of observing neutrino-line signals in neutrino detection experiments.

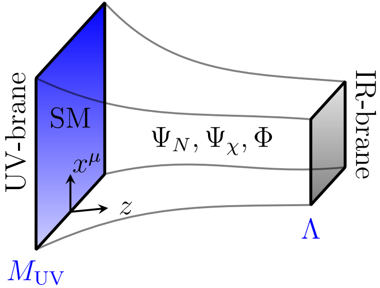


Holographic realization

- 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 $R \leq z \leq R'$.



- 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 to 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.

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

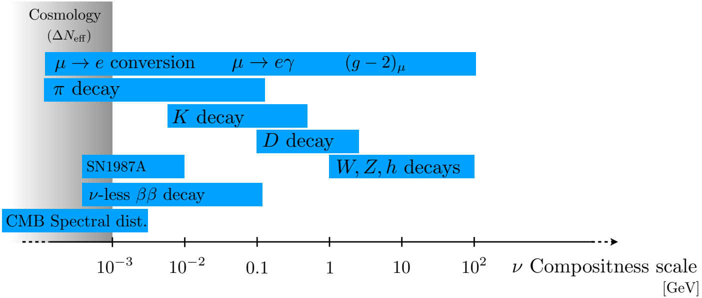
- $\boxed{\text{Holographic model reproduces our 4D CFT result}}$

AdS/CFT dictionary

4D strongly coupled CFT		5D weakly coupled theory
Energy scale μ	$\Longleftrightarrow$	5D 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 $c_\Psi = \Delta_{\mathcal{O}} - 2$
Composite states χ, N	$\Longleftrightarrow$	Lowest KK modes χ_1, N_1
Unparticles/continuum states	$\Longleftrightarrow$	Tower of KK modes, $n > 1$
Elementary states, e.g. SM	$\Longleftrightarrow$	UV brane localized fields

Composite neutrino signals

- There are various direct and indirect probes of composite neutrino N.
[Chacko,Fox,Harnik,Liu:2012.01443]



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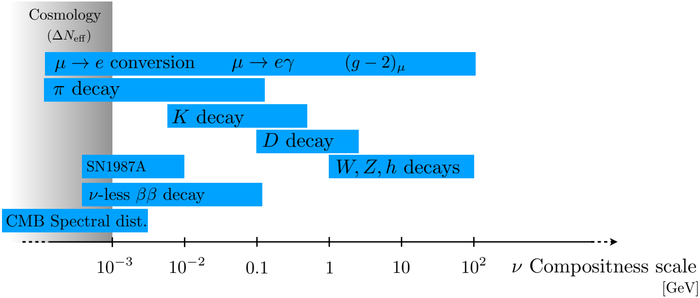

- Constraint on neutrino mixing due to composite neutrino N searches.