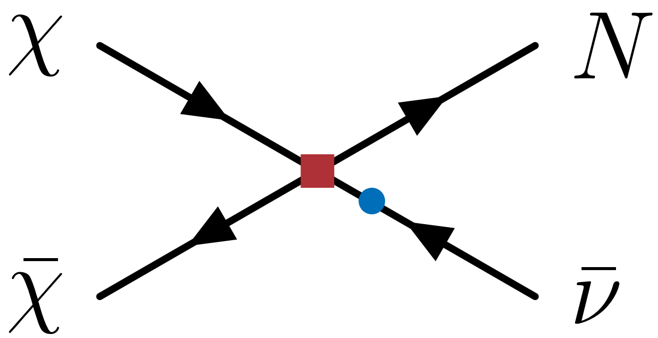
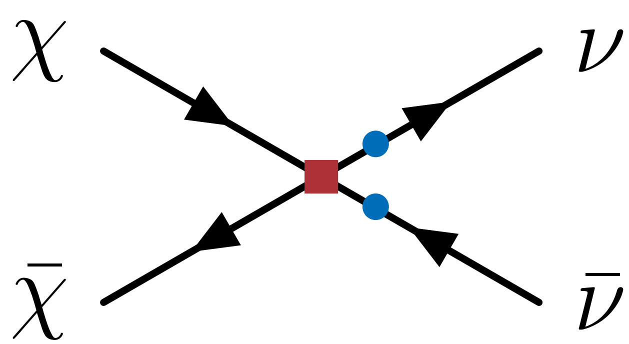
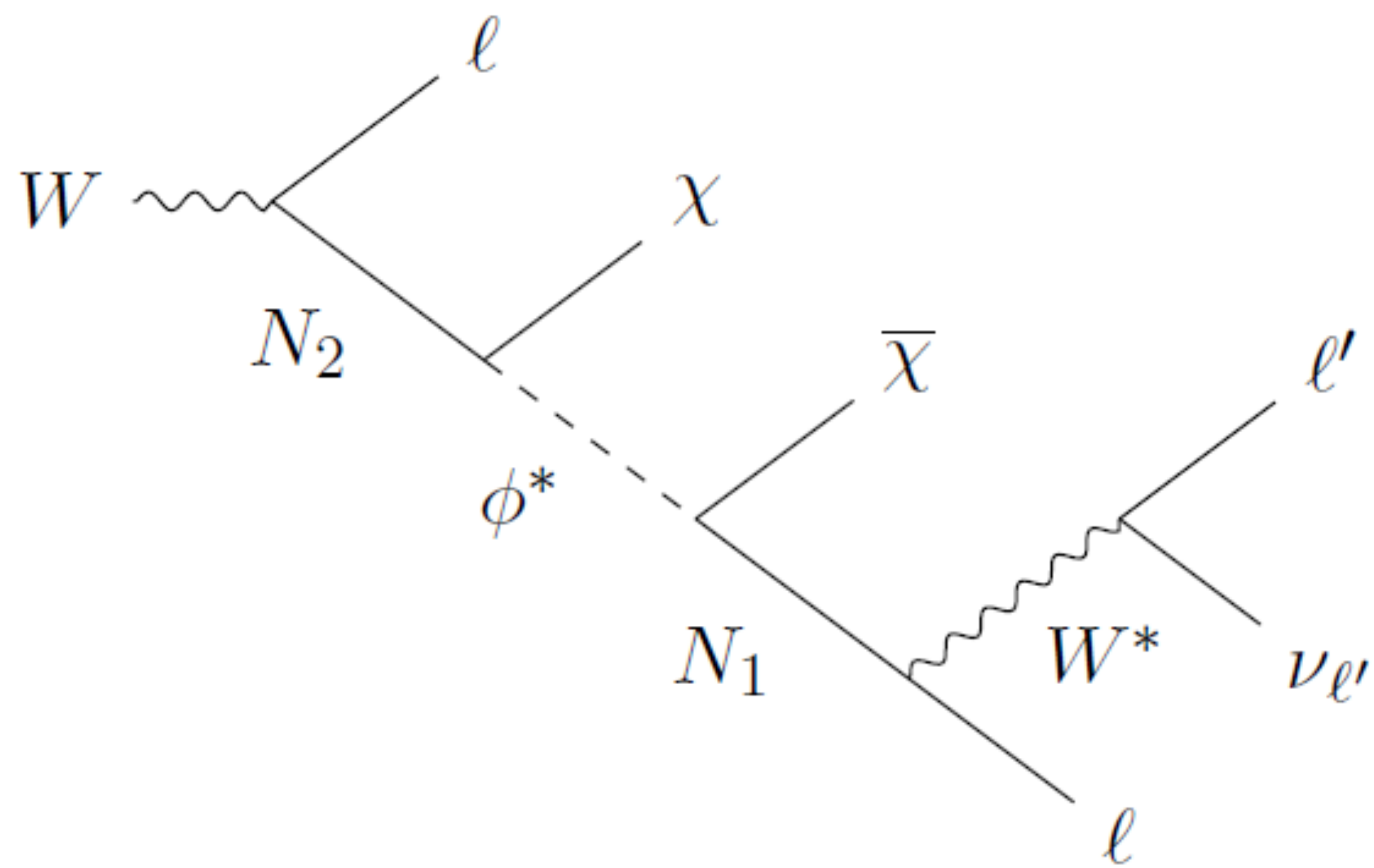
Composite DM via the ν-Portal







The Mitchell Conference on Collider, Dark Matter, and Neutrino Physics 2023

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Hot off the press! [arXiv:2305.09719]

MOTIVATION

Why Portals?

Null results in searches at the LHC, and in direct and indirect DM searches have severely constrained models of new physics.

These constraints mainly stem from attempts to connect the naturalness and DM puzzles, and more broadly having new particles carrying SM gauge charges.

Portals of the form $\mathcal{L} \supset \lambda \mathcal{O}_{\mathrm{SM}} \mathcal{O}_{\mathrm{HS}}$ represent an alternative approach with a broad class of models with qualitatively different constraints.

Through a portal, darkly

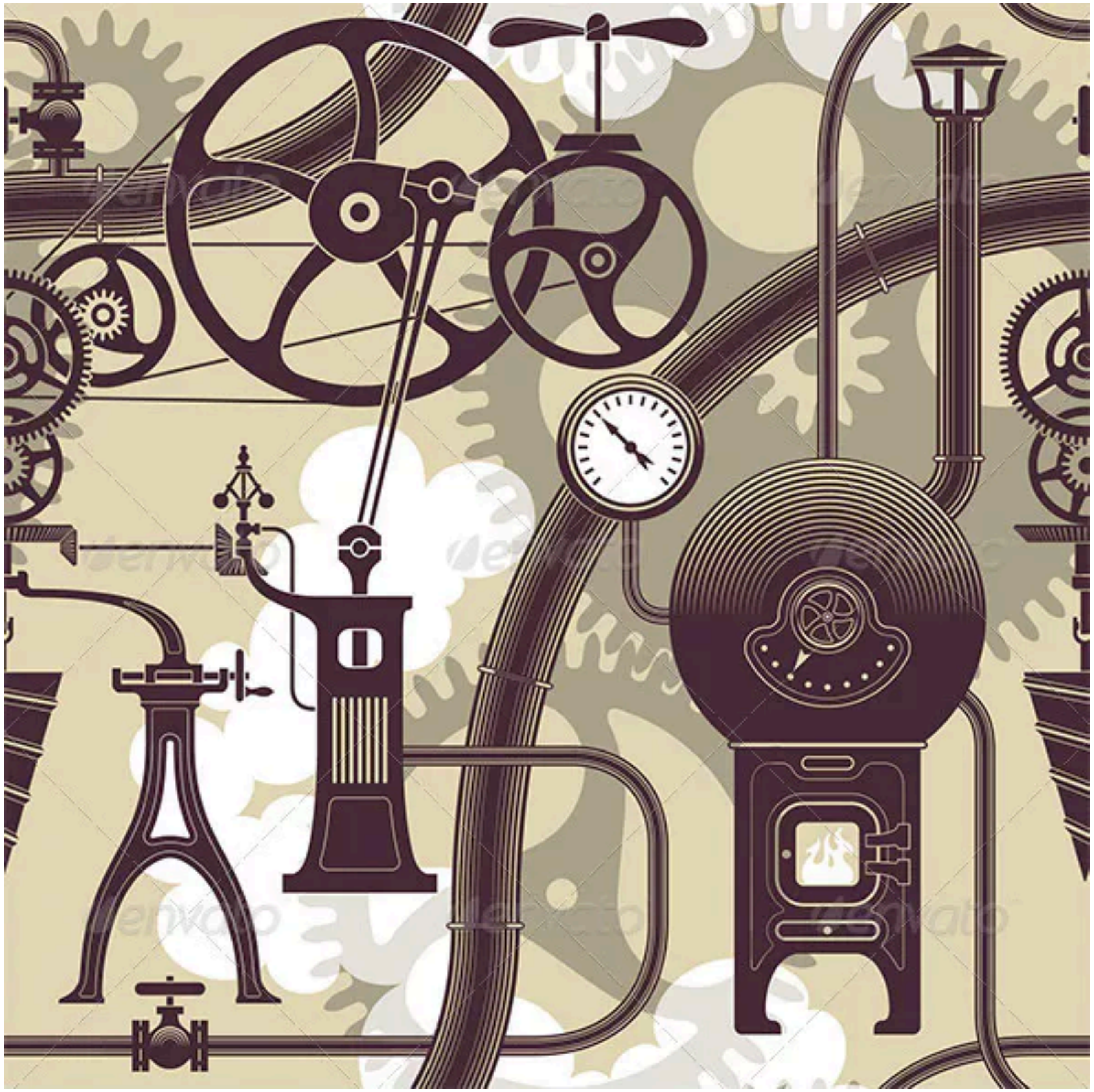
The most interesting portals are the ones where the SM operator has as low a mass dimension as possible, including:

$H^\dagger H$	Higgs portal	$H\ell$	Neutrino portal	$B_{\mu\nu}$	Hypercharge portal

In this talk I will consider the ν-portal and DM belonging to the hidden sector.

Weakly coupled examples for this setup have been explored. Let us focus on generic features of strongly coupled models.

MODEL DETAILS



The Singlet Neutrino: N

Consider a strongly coupled CFT with an IR deformation (IR scale Λ, UV cutoff M_{UV}), and the portal operator

$$\mathcal{L}_{\rm UV} \supset -\frac{\hat{\lambda}}{M_{\rm UV}^{\Delta_{\widehat{N}}-3/2}} \bar{L}\widetilde{H}\widehat{\mathcal{O}}_N + \text{h.c.}$$

we consider $3/2 \leq \Delta_{\widehat{N}} \leq 5/2$

In the IR, let N be the degree of freedom corresponding to this operator:

$$\mathcal{L}_{\rm IR} \supset i\bar{N}\gamma^\mu\partial_\mu N - m_N\bar{N}N - \lambda\,\bar{L}\widetilde{H}N_R + \text{h.c.}$$

Where the portal coupling is naturally small.

$$\lambda \sim \hat{\lambda}\left(\frac{\Lambda}{M_{\rm UV}}\right)^{\Delta_{\widehat{N}}-3/2}$$

This is similar to Chacko, Fox, Harnik, Liu (2020)
See also: Zhen Liu's talk from yesterday.

The Dark Matter: χ

The hidden sector contains states that are odd under a Z_2 symmetry. Of these, let χ be the lightest, and therefore stable.

$$\mathcal{L}_{\rm IR} \supset i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_\chi\bar{\chi}\chi$$

Generically, we expect interactions

$$-\frac{\kappa_\chi}{\Lambda^2}\left(\bar{\chi}\gamma^\mu\chi\right)^2 \qquad \text{and} \qquad -\frac{\tilde{\kappa}}{\Lambda^2}(\bar{\chi}N)(\bar{N}\chi)$$

where both couplings are of order $16\pi^2$.

The former gives rise to DM self interactions and the latter is crucial for setting the relic abundance.

Neutrino masses

N can be assigned lepton number, need to break it to generate neutrino masses. This can be done with:

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

This turns into a Majorana mass for N in the IR of order

$$\hat{\mu}\Lambda\left(\frac{\Lambda}{M_{\rm UV}}\right)^{\Delta_{2N}-4}$$

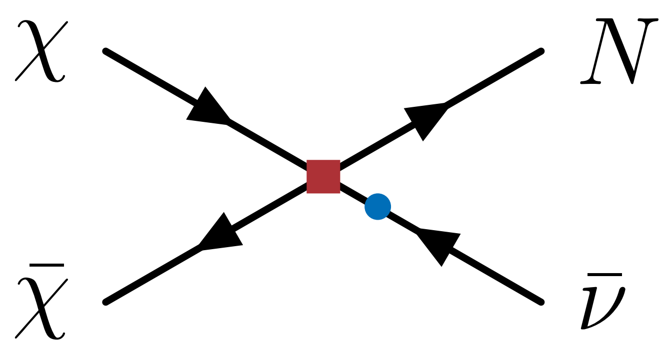
Via the inverse seesaw mechanism, ν-masses are generated.

$$m_\nu \sim \mu\left(\frac{\lambda v_{\rm EW}}{m_N}\right)^2$$ with a mixing angle $$U_{N\ell} \equiv \frac{\lambda v_{\rm EW}}{m_N}$$

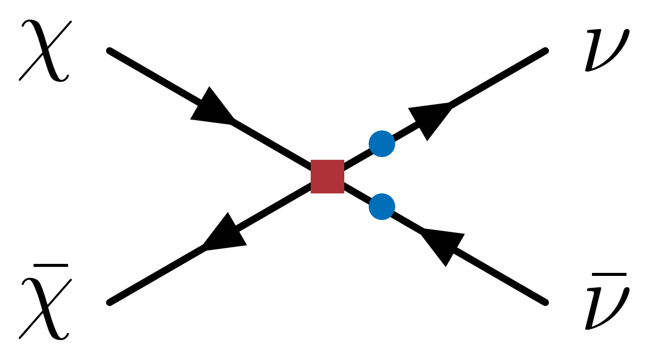
Relic Abundance

ν-portal keeps the hidden sector in thermal equilibrium with the SM down to T~Λ for the entire parameter region of interest.

χ is a thermal relic. Dominant annihilation channel is Nν when $0.5 \lesssim m_\chi/m_N \lesssim 0.8$. σ scales like $|U|^2$ (10^{-8} favored).



Annihilation channel is $\nu\nu$ when $m_\chi/m_N < 0.5$ σ scales like $|U|^4$ (10^{-4} favored).



Going beyond 4π's

In order to make more quantitative predictions, we can construct a holographic model of the hidden sector in a warped 5D setup.

Elevate all hidden sector fields to 4-component fermions.

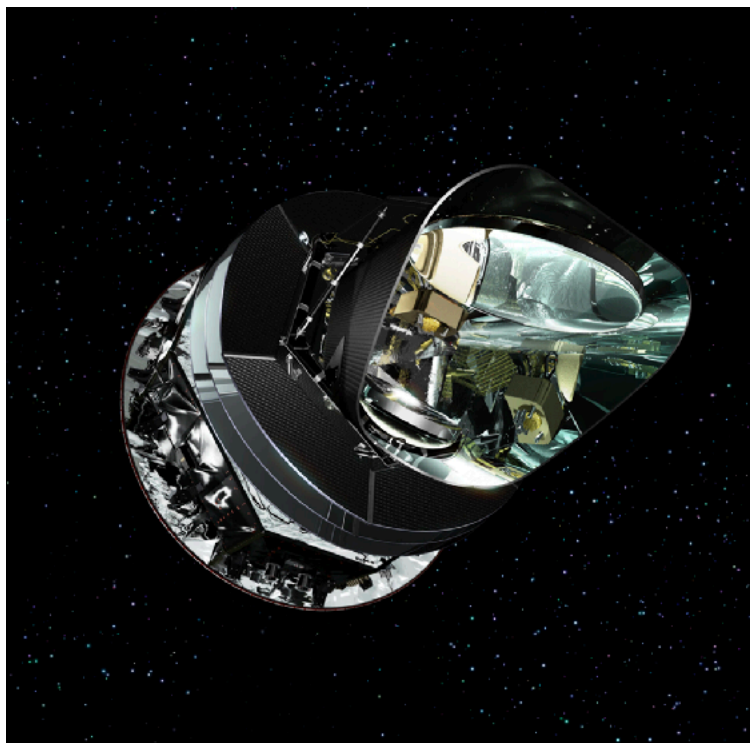
Focus only on low-lying KK modes from here on.

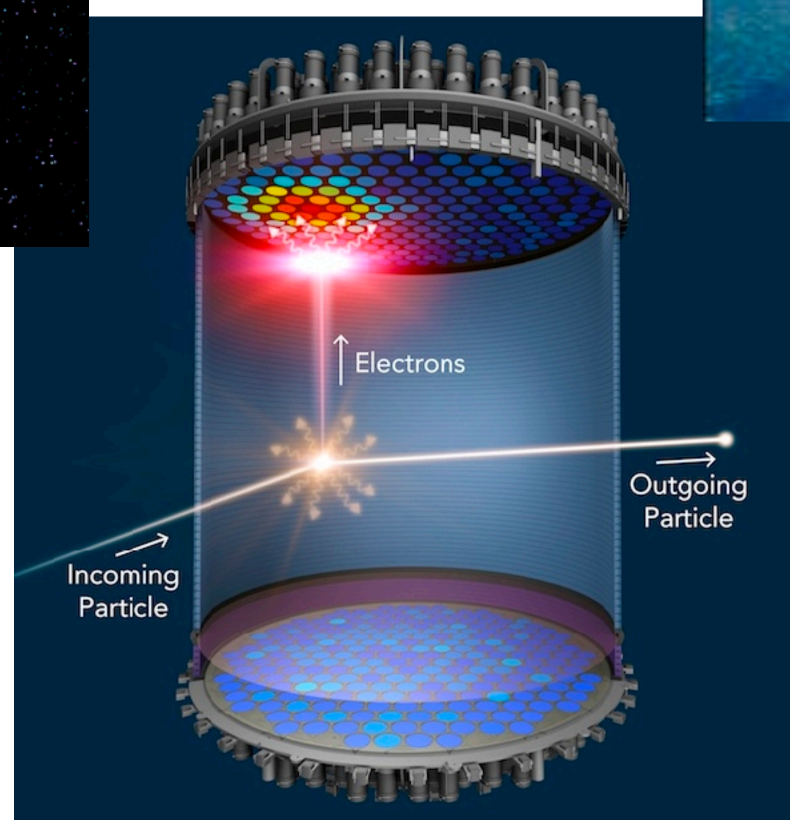
IR Brane (Λ):
Dirac mass terms
for N, χ

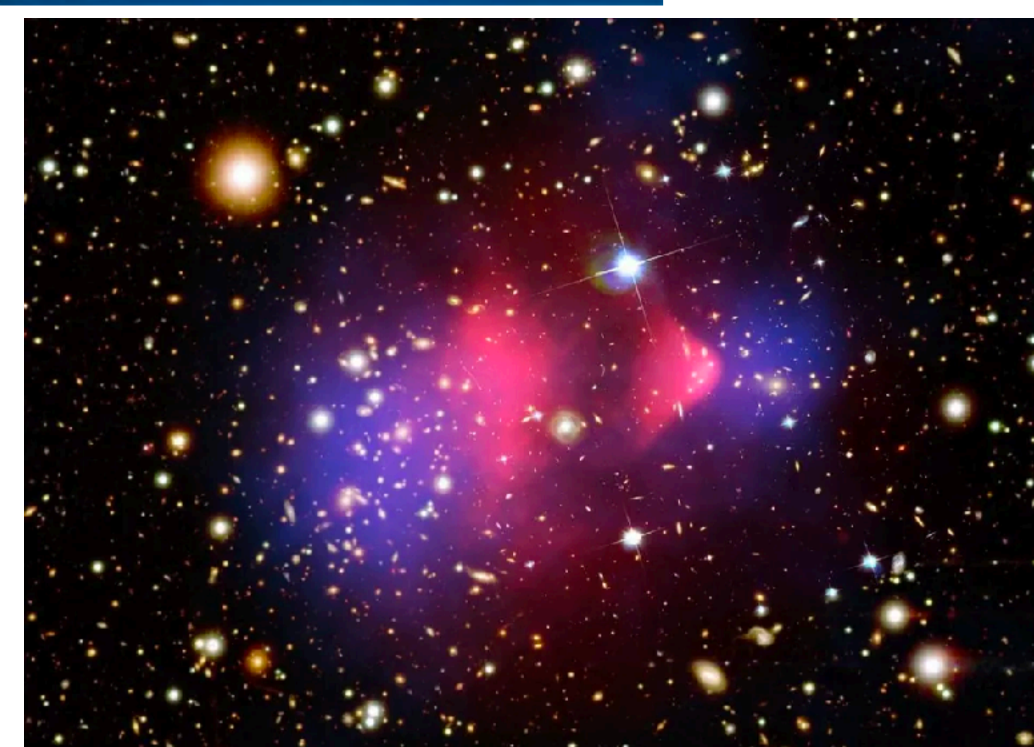
Bulk:
Mediator ϕ
N$\phi\chi$ interaction

UV Brane (M_{UV}):
SM, portal coupling
Lepton # violation

NON-COLLIDER PROBES





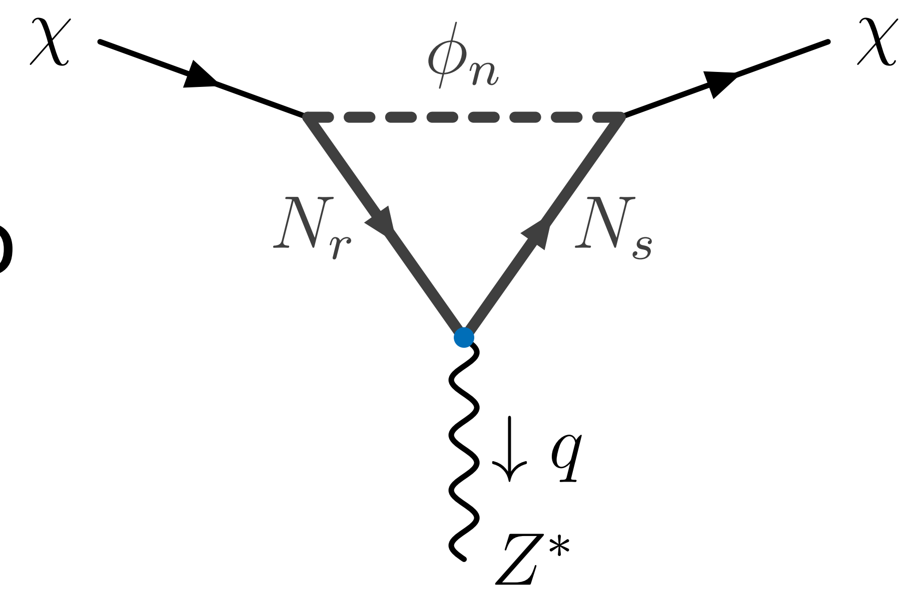


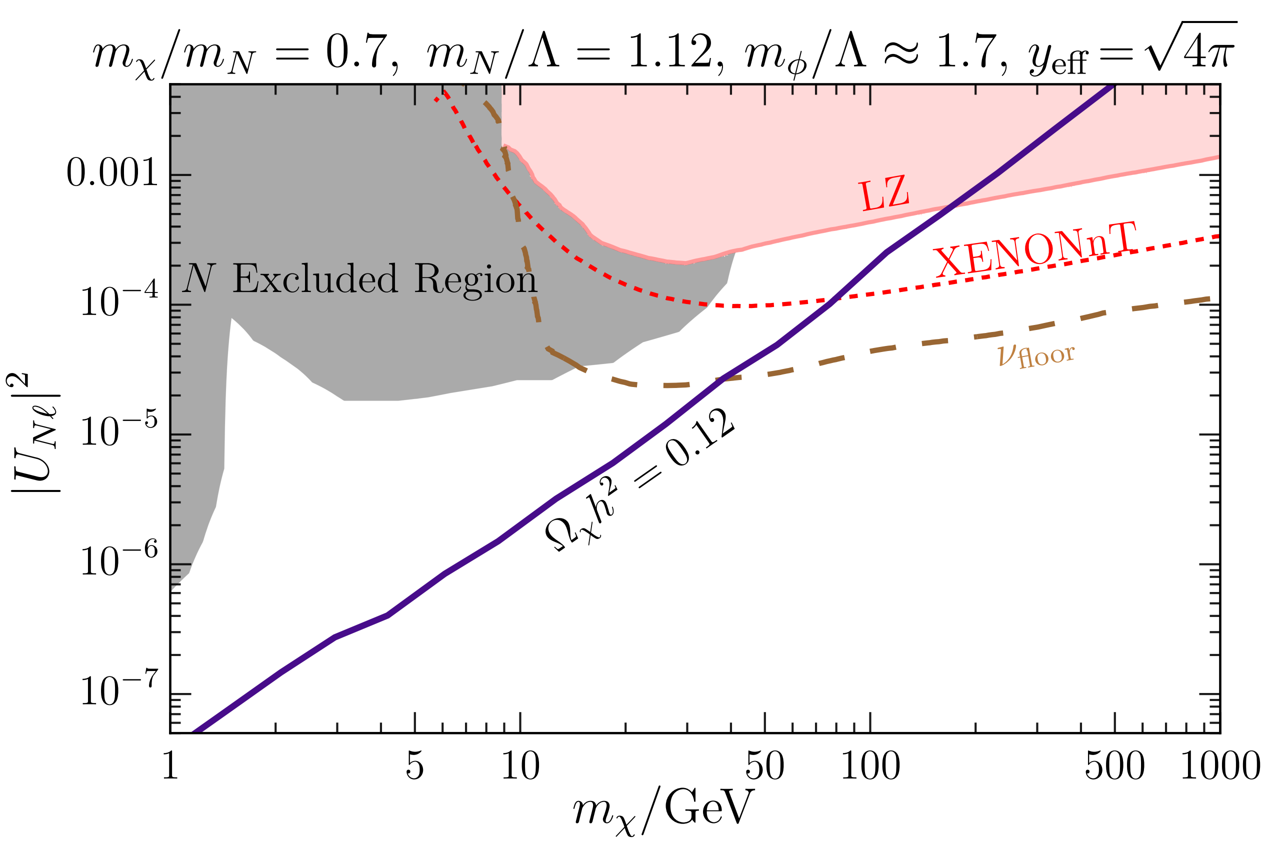
Direct Detection

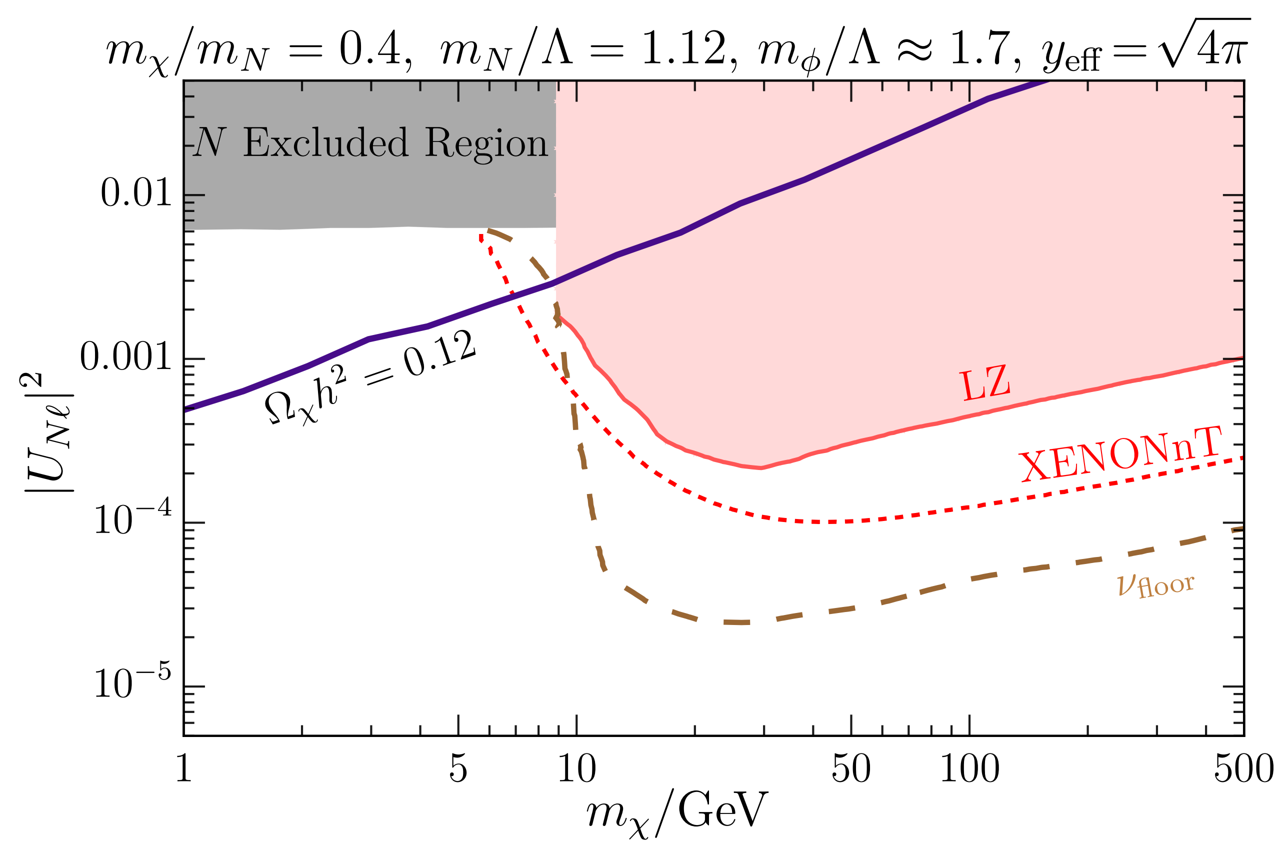
Leading contribution shown.

Suppressed by loop factor as well as two mixing angles.

KK modes of N also contribute.

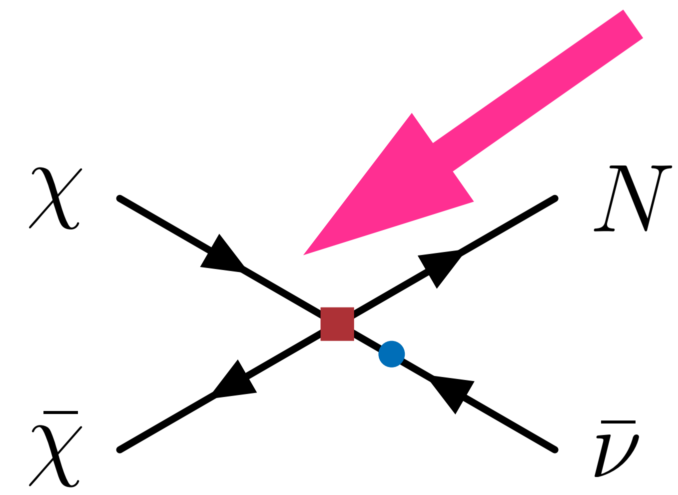




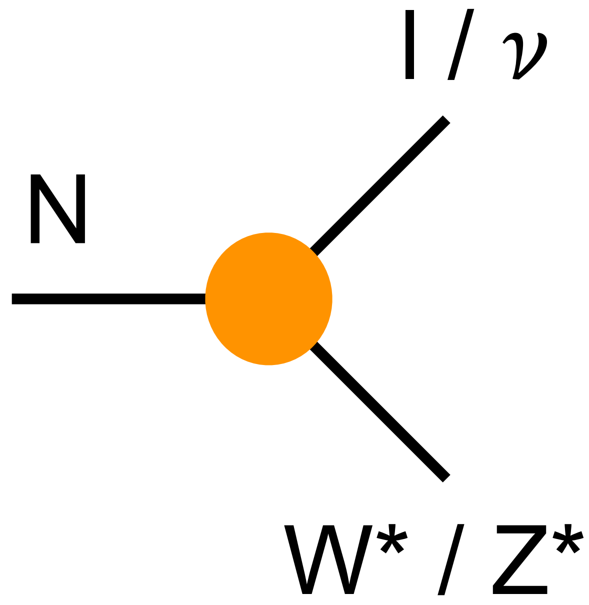


Interlude - N decays

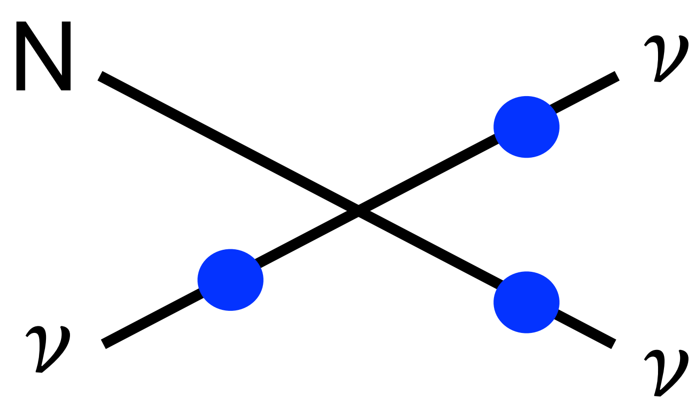
When $m_N > 2m_\chi$ then N can decay to $\chi\chi\nu$ via strong hidden sector interactions and one mixing angle.



Any competing visible decay has to go through the portal so these also include a mixing angle, as well as other suppression factors such as G_F. So in this regime the N decays invisibly.



When $m_N < 2m_\chi$ then the invisible decay is kinematically closed. There is still a 3ν channel, but it is suppressed by additional mixing angles, so visible decays can compete, except when U~O(1).

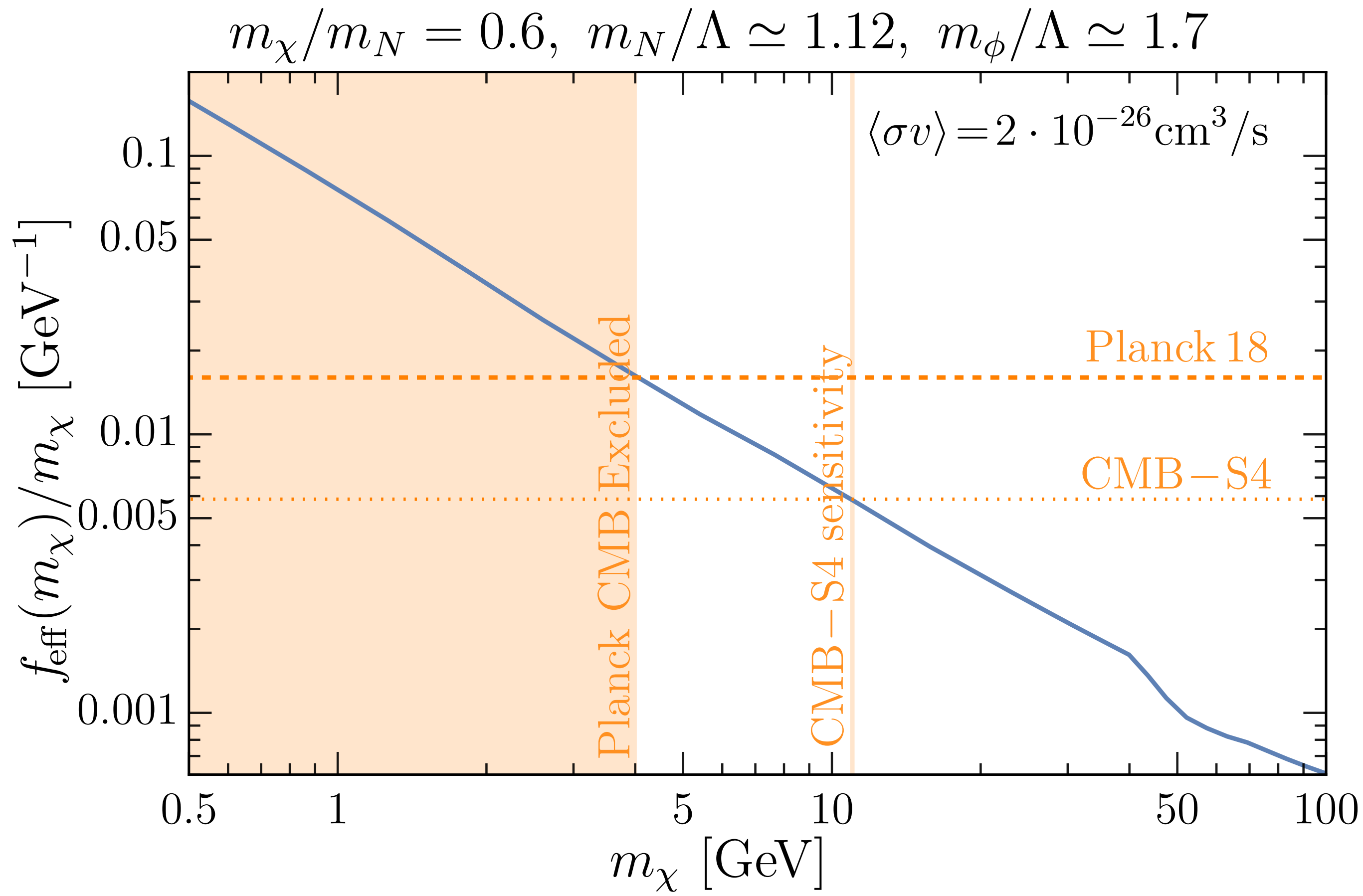


Indirect detection-CMB

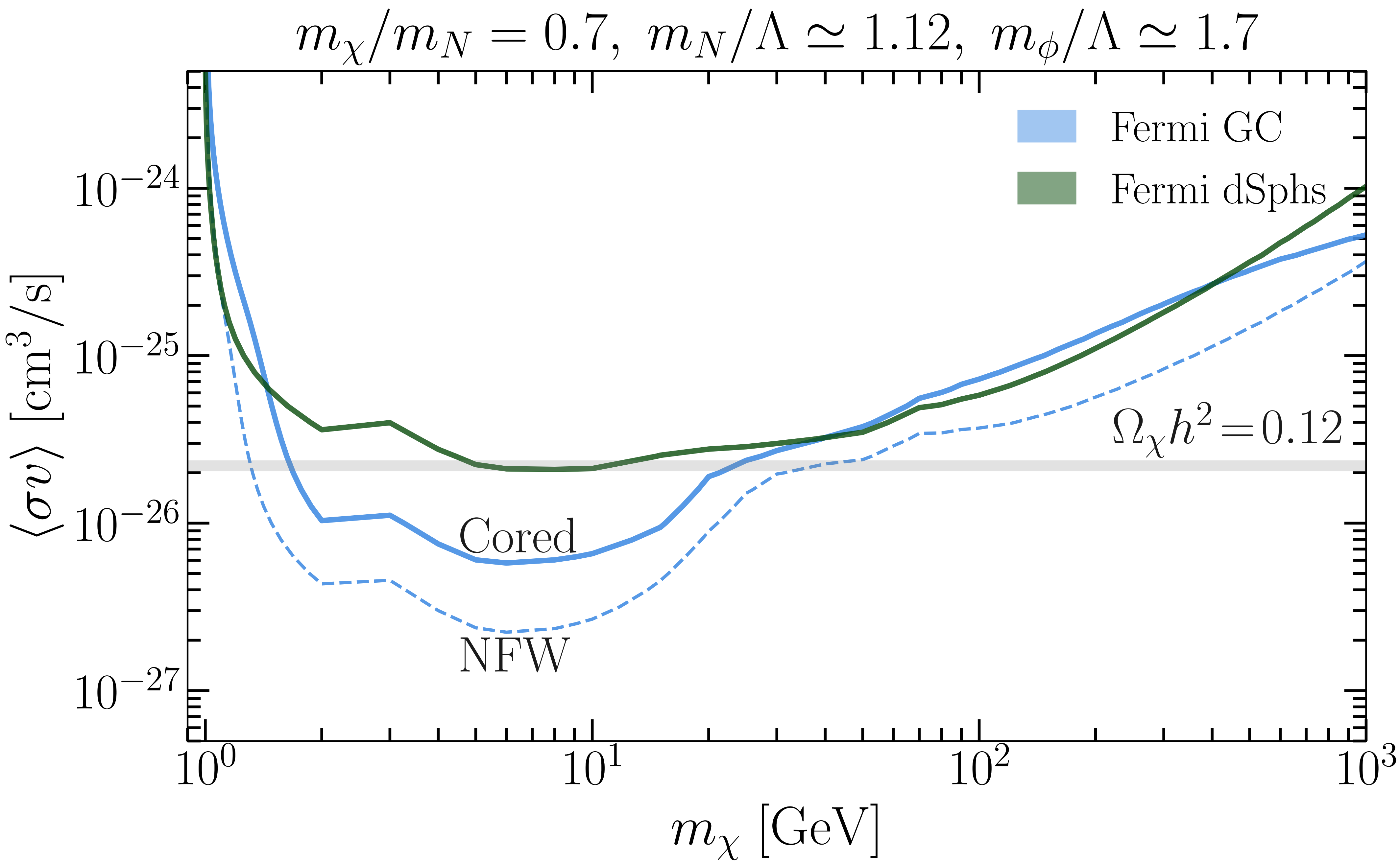
When $m_N < 2m_\chi$ then the $N\nu$ annihilation channel is open, and the N decays visibly, producing electrons, positrons and photons. These give indirect detection signatures.

In contrast, when $m_N > 2m_\chi$ then the annihilation channel is $\nu\nu$ and there are no indirect detection signatures except possibly a ν-line.

For light DM with $m_N < 2m_\chi$, there are constraints from the CMB.



Indirect detection - gamma rays



The strongest constraints come from the Galactic Center, using the NFW density profile.

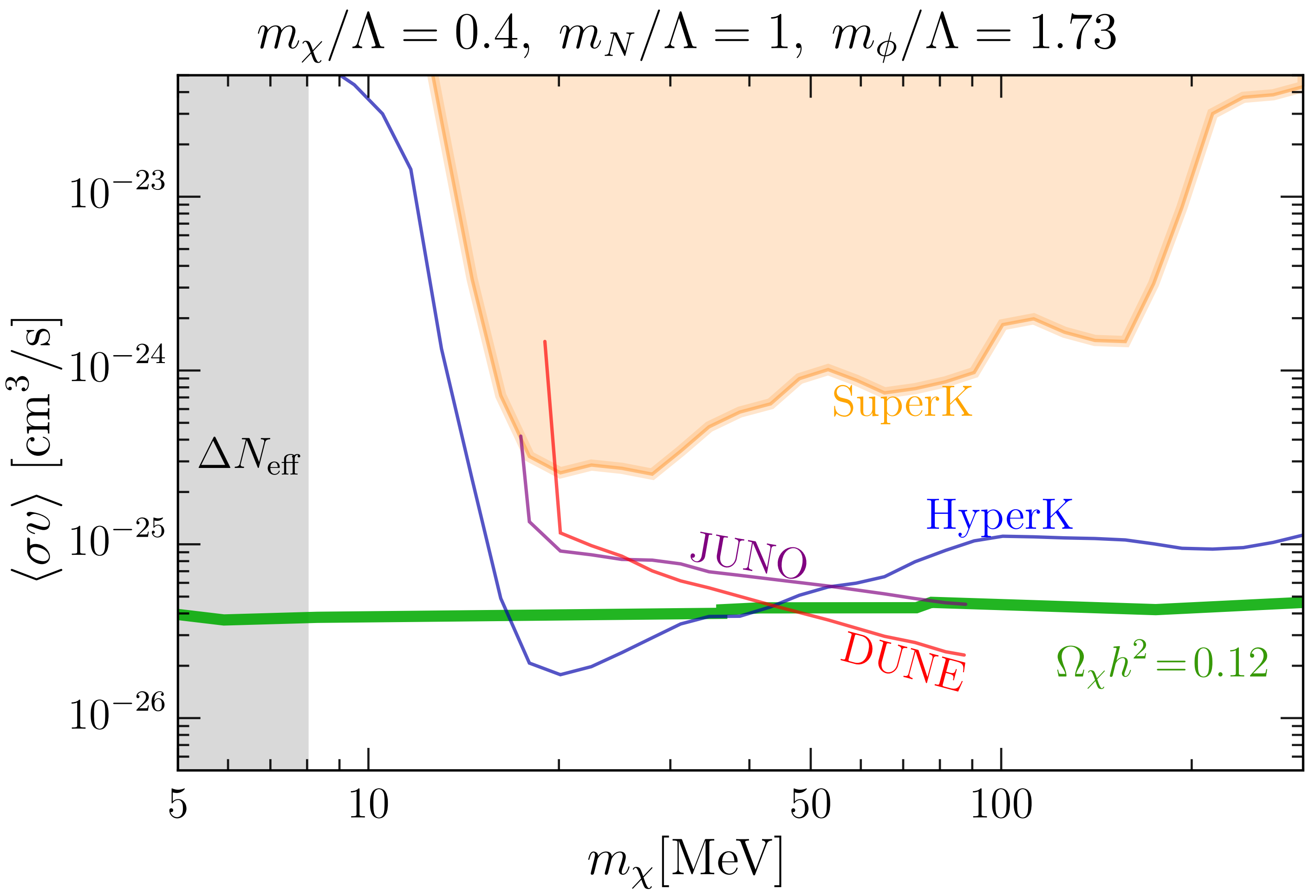
Neutrino-line signal

Both the Nν and $\nu\nu$ annihilation channels produce monoenergetic neutrinos.

There are bounds from existing searches, as well as projections for future experiments. In order to get sufficient flux, light DM masses are preferred.

For the Nν channel, a line signal would be in conflict with CMB bounds.

For the $\nu\nu$ channel, there is conflict with beam dump searches.



Other non-collider constraints

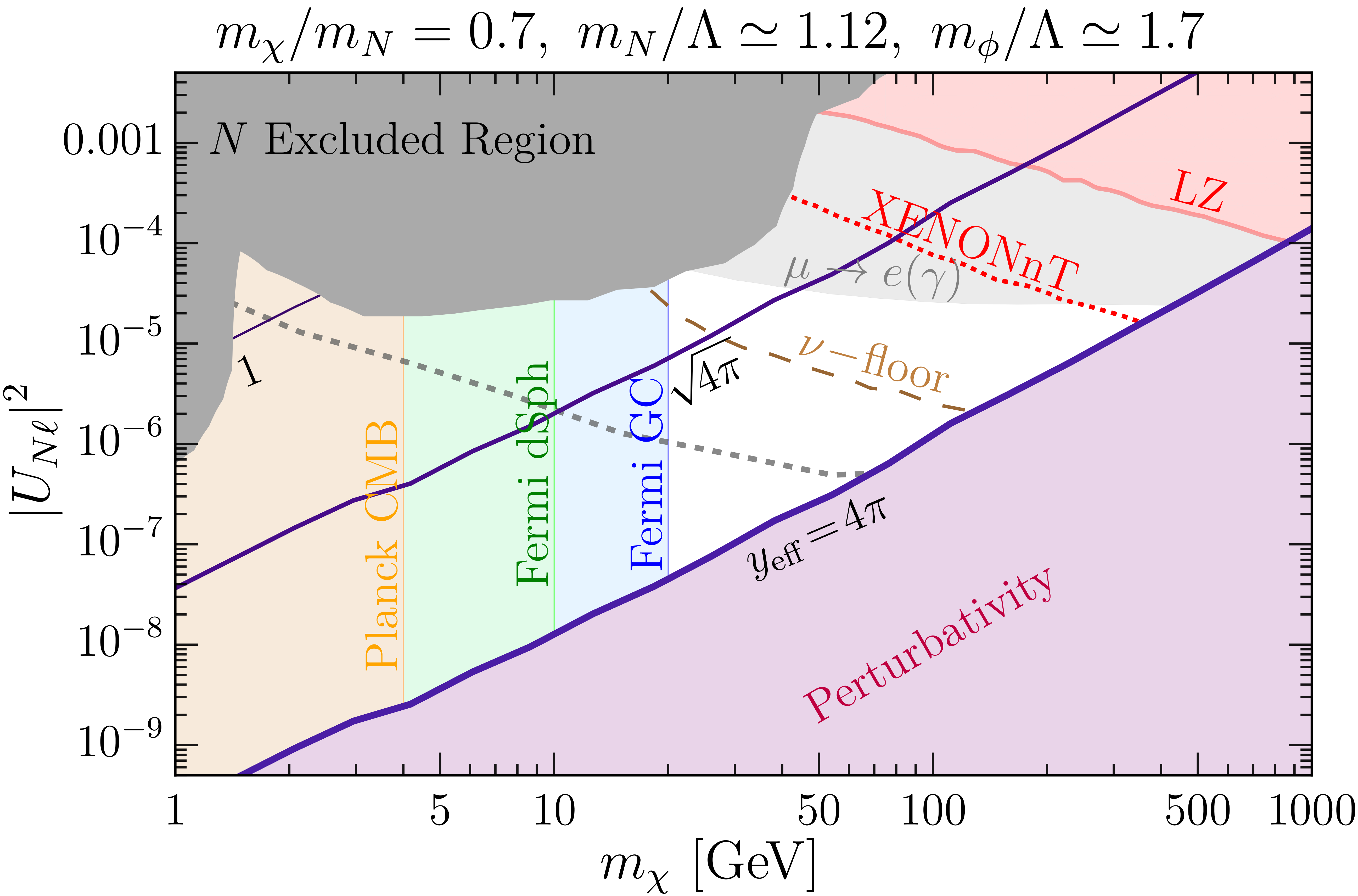
- Terms such as $-\frac{\kappa_\chi}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)^2$ give rise to DM self interactions.

Constraints on the cross section (bullet cluster) translate to

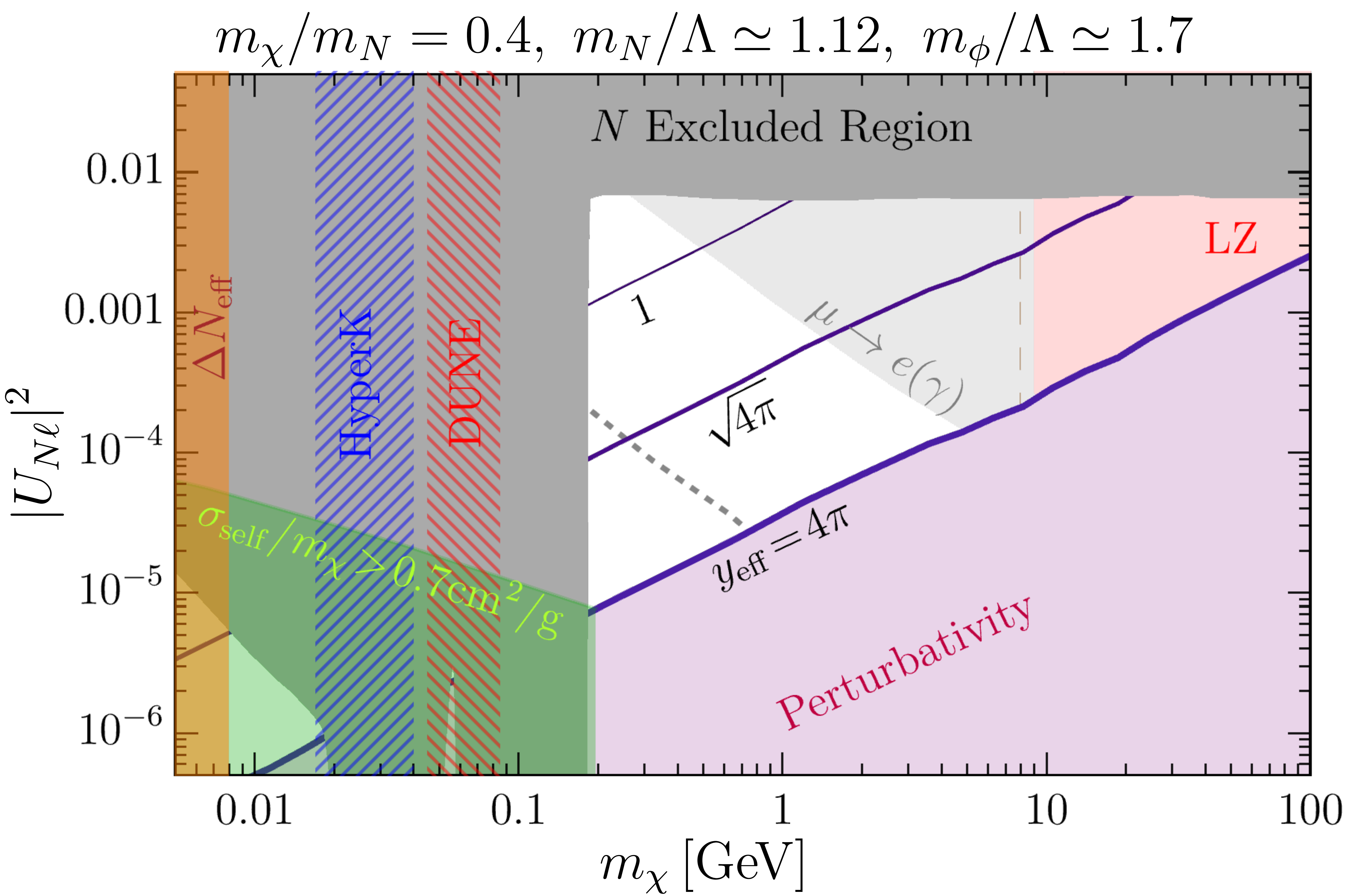
$$m_\chi \gtrsim \frac{2}{3}\left(\frac{\kappa_\chi}{16\pi^2}\right)^{2/3}\left(\frac{m_\chi}{\Lambda}\right)^{4/3}\ \mathrm{GeV}$$

- So far we assumed a flavor diagonal portal coupling. However, off-diagonal couplings would give rise to processes such as $\mu \to e\gamma$. Existing constraints are already strong, and they will further improve.

Summary of non-collider constraints



Summary of non-collider constraints



COLLIDER PHENOMENOLOGY

Collider overview

Production always through ν-portal.

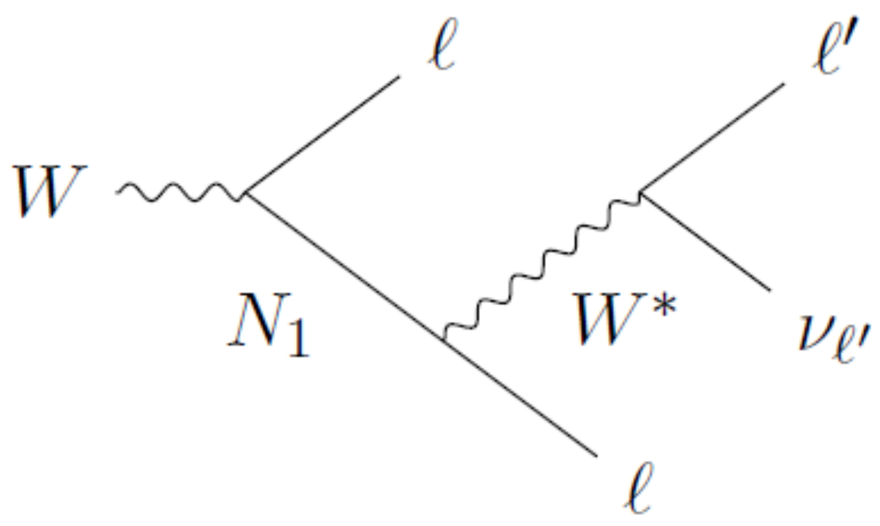
N or its KK modes produced first. Depending on mass, dominant source is heavy meson decays or Drell-Yan.

N behaves as a Heavy Neutral Lepton

χ can be produced along with N (from N_2 decays etc.)

Need visible N decays. Take $m_\chi > M_N/2$

Relax relic abundance constraint for exploring collider signatures (χ might be only subcomponent of DM).



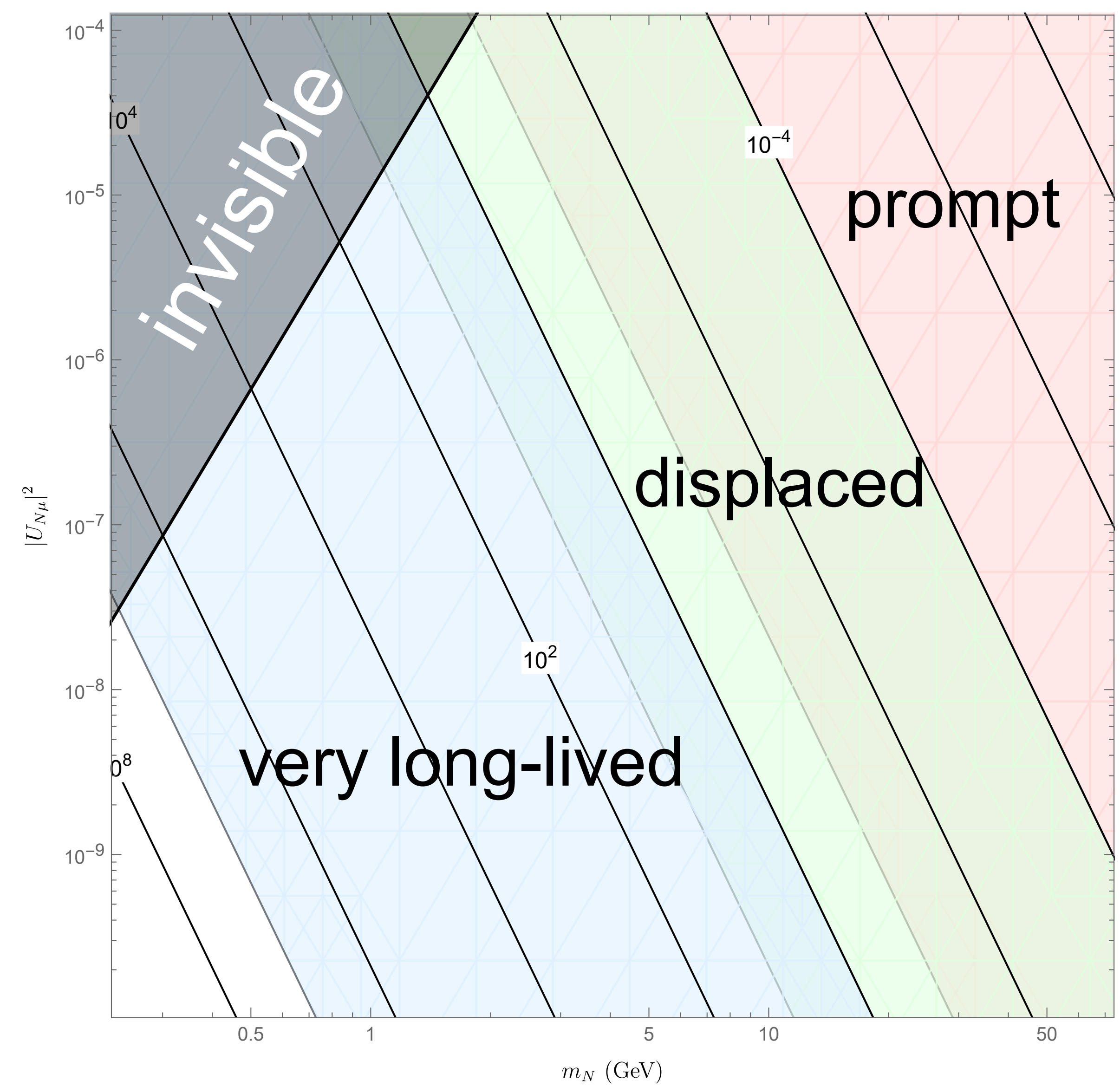
since N is pseudo-Dirac, we can select charge/flavor combinations incompatible with a Z

Status of HNL searches

Depending on the N mass and the mixing angle, a wide range of N lifetimes are possible.

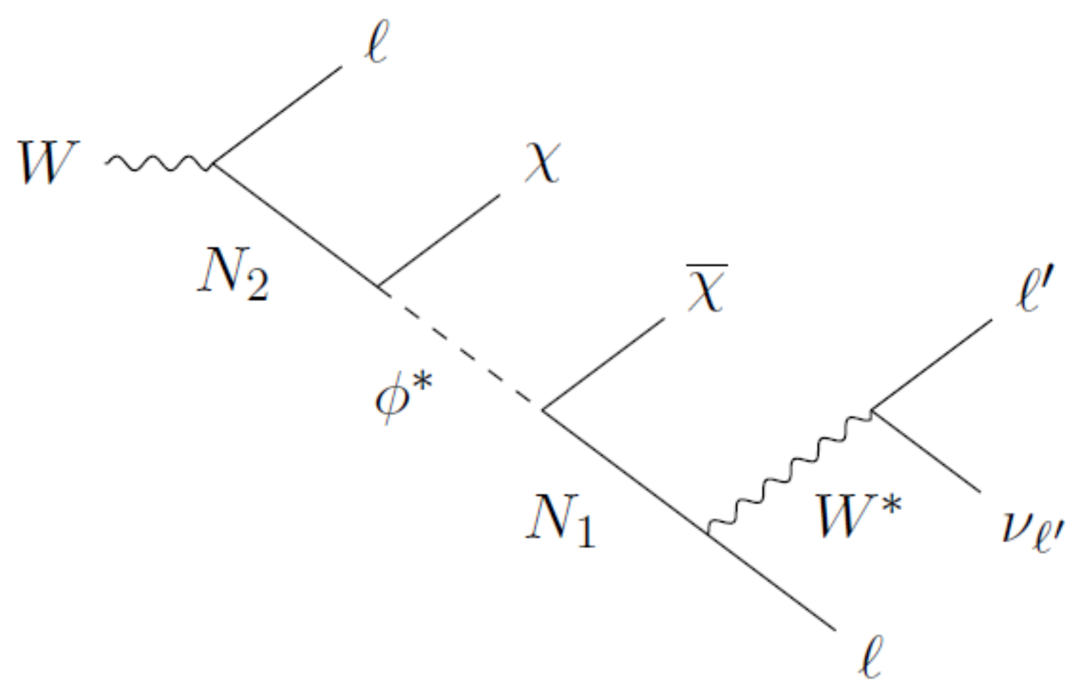
We use Monte Carlo methods to reproduce existing analyses in the three lifetime regions. This serves as calibration for the later part of our analysis.

We also incorporate projections at increased luminosity into our results.



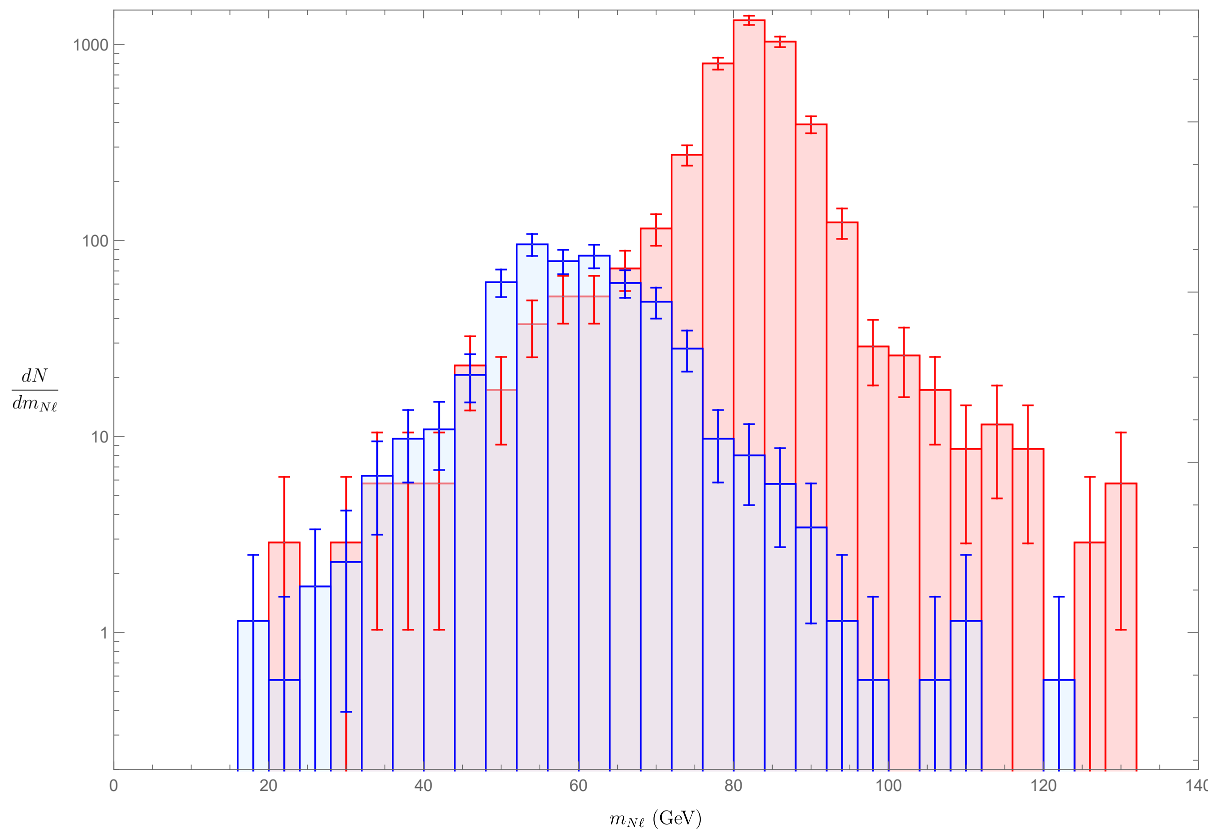
Going beyond HNL searches

DM can be produced along with N, but discovery is challenging.



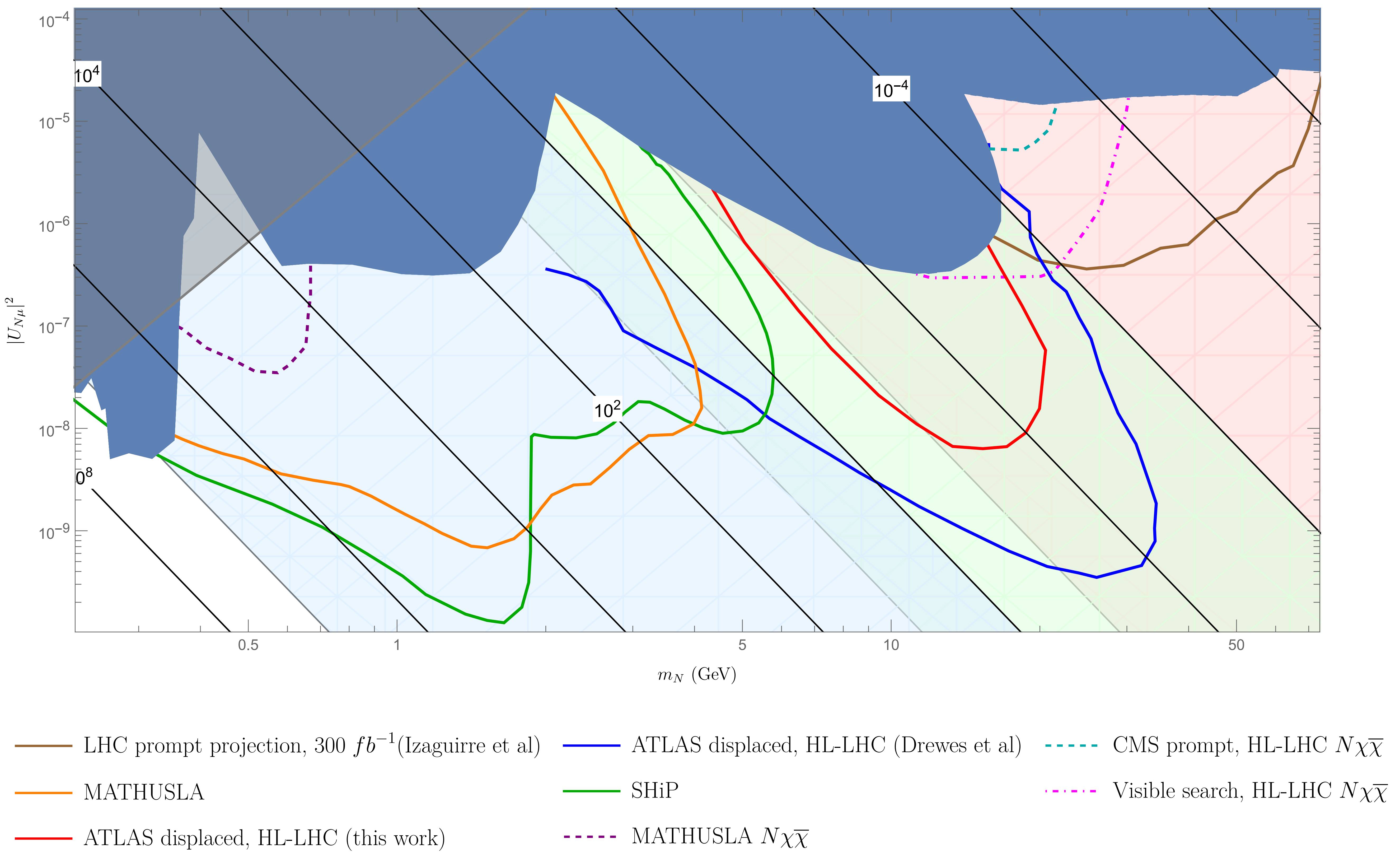
Suppose that N is first discovered in a traditional HNL channel, and then a search is performed in the visible channel to measure m_N.

Now the kinematics in the visible N channel can be used to separate the added signal component.

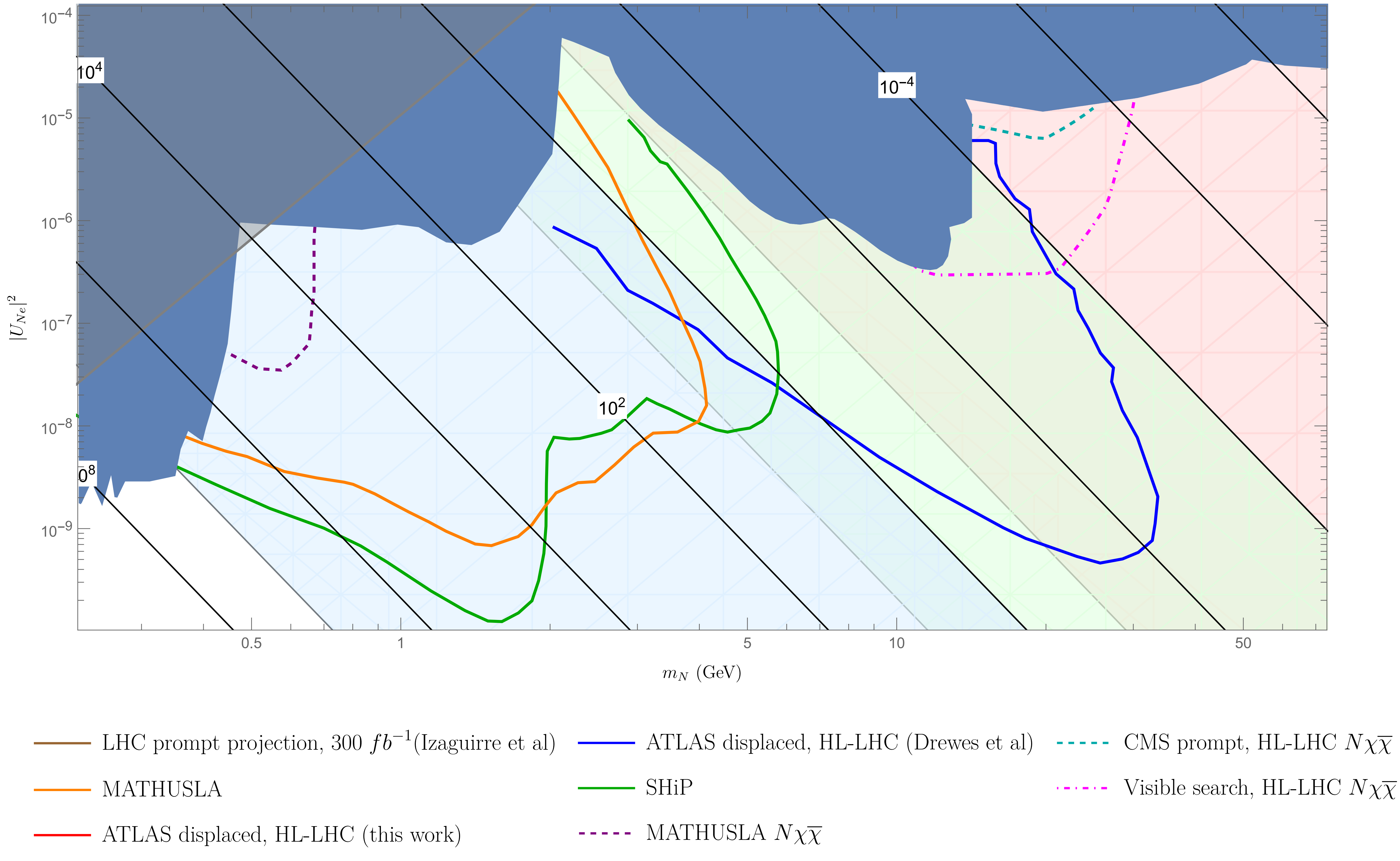


Standard channels will also have sensitivity with well-chosen kinematic cuts (MET, m_{3l}) or a long-lived particle facility like MATHUSLA.

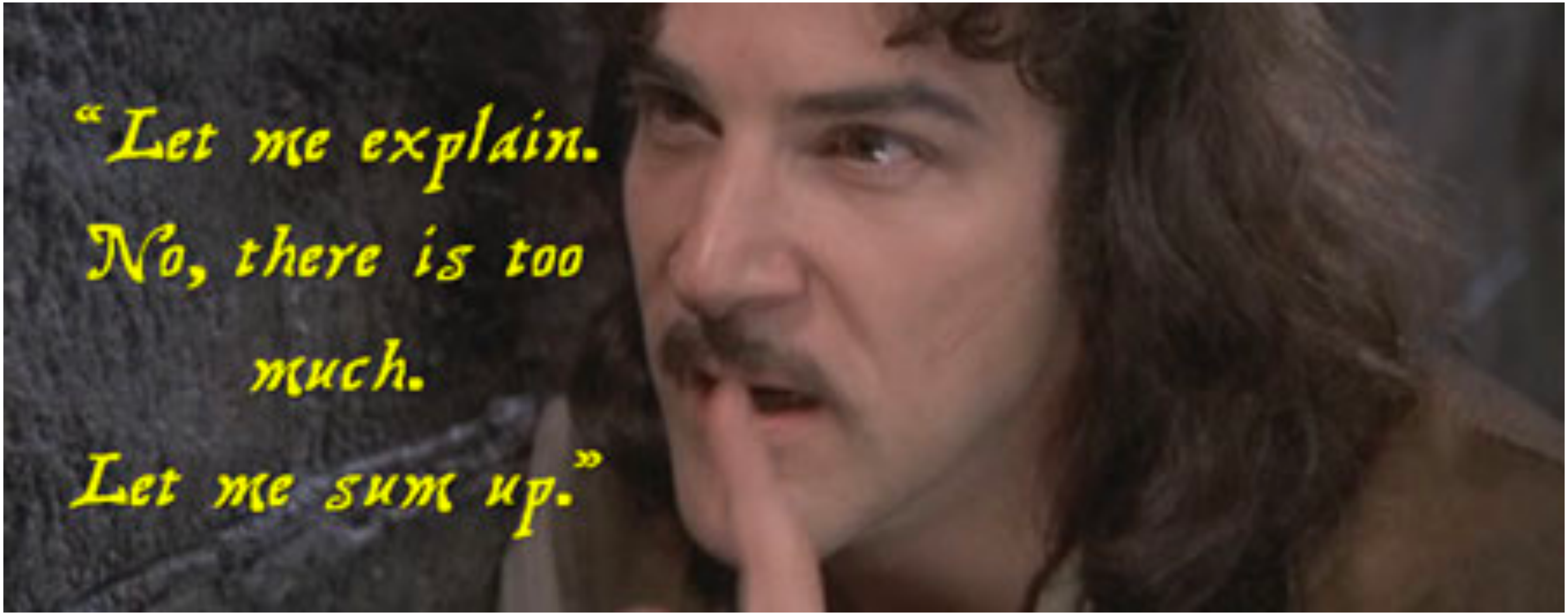
Collider summary



Collider summary



SUMMARY



We have explored the possibility of a strongly coupled hidden sector coupled to the SM via a ν-portal.

The state directly accessed by the portal is a composite singlet neutrino, and small SM neutrino masses can arise naturally via the inverse seesaw mechanism.

The DM can be a composite state in the hidden sector, kept stable by a Z_2 symmetry. The relic abundance is set by thermal freezeout.

The phenomenology is different for m_χ/m_N being above or below 0.5.

For the former case, indirect detection, colliders and lepton flavor violation searches can probe most of the parameter space.

The latter case is more challenging due to invisible N decays, but rare meson decay searches, DM self interactions and ΔN rule out low masses, with LFV providing sensitivity at larger masses.

HNL searches at the LHC are expanding the reach for N. If N can be observed in a visible channel, then there may be sensitivity for the DM production as well.

ADDITIONAL INFORMATION

Consistency condition for ν-masses

Both the Dirac and Majorana masses for N need to be smaller than the compositeness scale.

$$\frac{\sqrt{m_\nu m_N}}{v_{\rm EW}} \lesssim \lambda \lesssim \frac{m_N}{v_{\rm EW}}$$

Or in terms of the mixing angle:

$$\sqrt{\frac{m_\nu}{m_N}} \lesssim U_{N\ell} \lesssim 1$$

Further details on the 5D model

Fermionic field content:

$$\Psi_N = \begin{pmatrix} N_L \\ N'_R \end{pmatrix}, \qquad \widehat{\Psi}_N = \begin{pmatrix} N'_L \\ N_R \end{pmatrix}, \qquad \Psi_\chi = \begin{pmatrix} \chi_L \\ \chi'_R \end{pmatrix}, \qquad \widehat{\Psi}_\chi = \begin{pmatrix} \chi'_L \\ \chi_R \end{pmatrix}.$$

Boundary conditions: Primed fields and mediator vanish on the UV brane, unprimed fields vanish on the IR brane.

$$S_{\rm UV} \supset \int d^4x \int dz \left(\frac{R}{z}\right)^4 \delta(z-R)\,\hat{\lambda}\,\sqrt{R}\,\bar{L}\widetilde{H}\,N_R + \int d^4x \int dz \left(\frac{R}{z}\right)^4 \delta\left(z-R\right)\,\hat{\mu}\,N_L N_L + \text{h.c.}$$

$$S_{\rm IR} \supset \int d^4x \int dz \left(\frac{R}{z}\right)^4 \delta\left(z-R'\right)\,\kappa_\psi\left(\bar{\psi}_L\psi_R + \bar{\psi}'_L\psi'_R + \text{h.c.}\right)$$

$$S_{\rm bulk} \supset \int d^4x \int dz \sqrt{g}\left\{g^{MN}\partial_M\Phi\partial_N\Phi^* - \frac{a^2}{R^2}|\Phi|^2 + \left(\hat{y}\,\sqrt{R}\,\Phi\bar{\Psi}_\chi\widehat{\Psi}_N + \text{h.c.}\right)\right\}$$