

Neutrino Portal Dark Matter



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NuTheories: Beyond the 3×3 Paradigm at Current and Near-Future Facilities
University of Pittsburgh, November 4-10, 2018

Based on works with Tao Han, David McKeen, Barmak Shams Es Haghi

- arXiv:1704.08708
- arXiv:1709.07001

Related important works

- Pospelov, Ritz, Voloshin '07
- Bertoni, Ipek, McKeen, Nelson '14
- Schmaltz, Weiner '17

Other works on Neutrino Portal dark matter

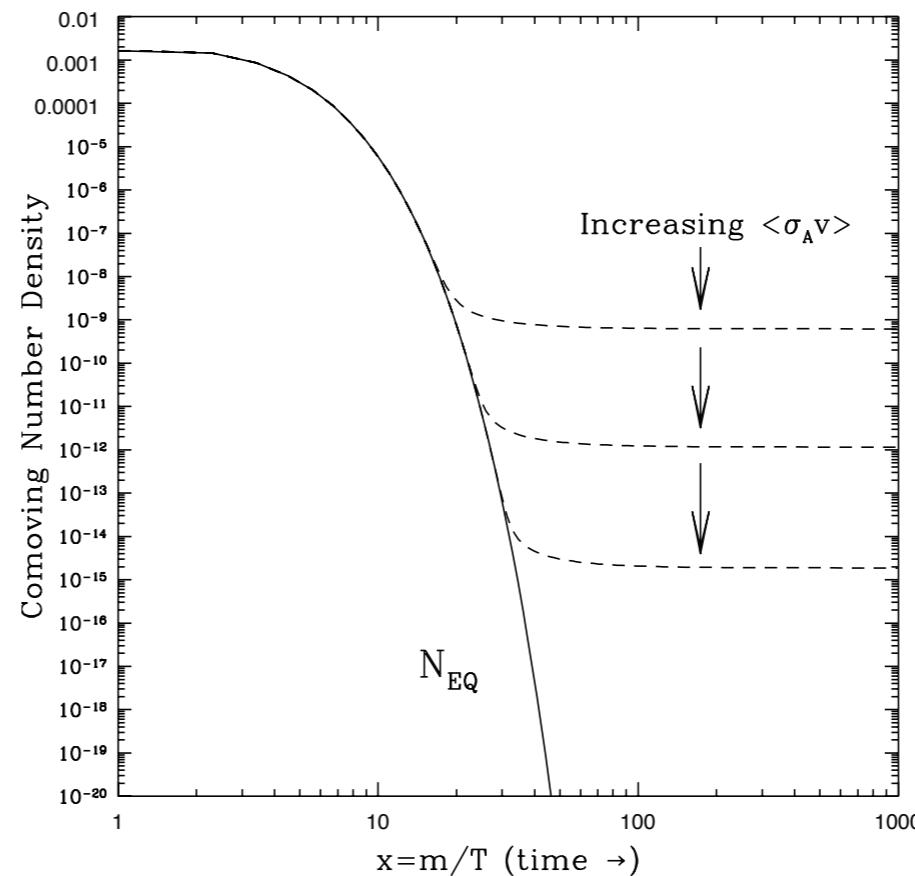
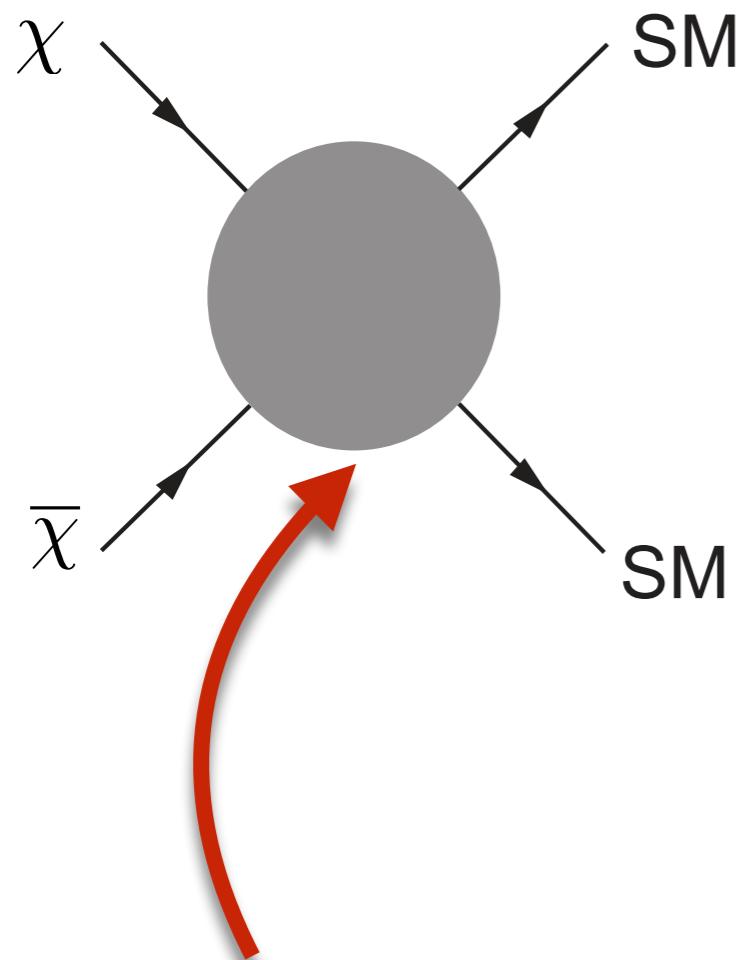
- Falkowski, Juknevich, Shelton '09; Falkowski, Ruderman, Volansky '11; Cherry, Friedland, Shoemaker '14; Gonzalez Macias, Wudka '15+'16; Tang, Zhu '15; Ibarra et. al, 16; Berlin, Hooper, Krnjaic '16; Escudero, Ruis, Sanz '17; Campos et. al. 17

Outline

- Motivation - thermal dark matter
 - WIMPs vs. Light Dark Matter
 - Portals
- Neutrino portal dark matter
 - Minimal Type - I seesaw
 - Approximate lepton number conservation
- Outlook

Thermal Dark Matter

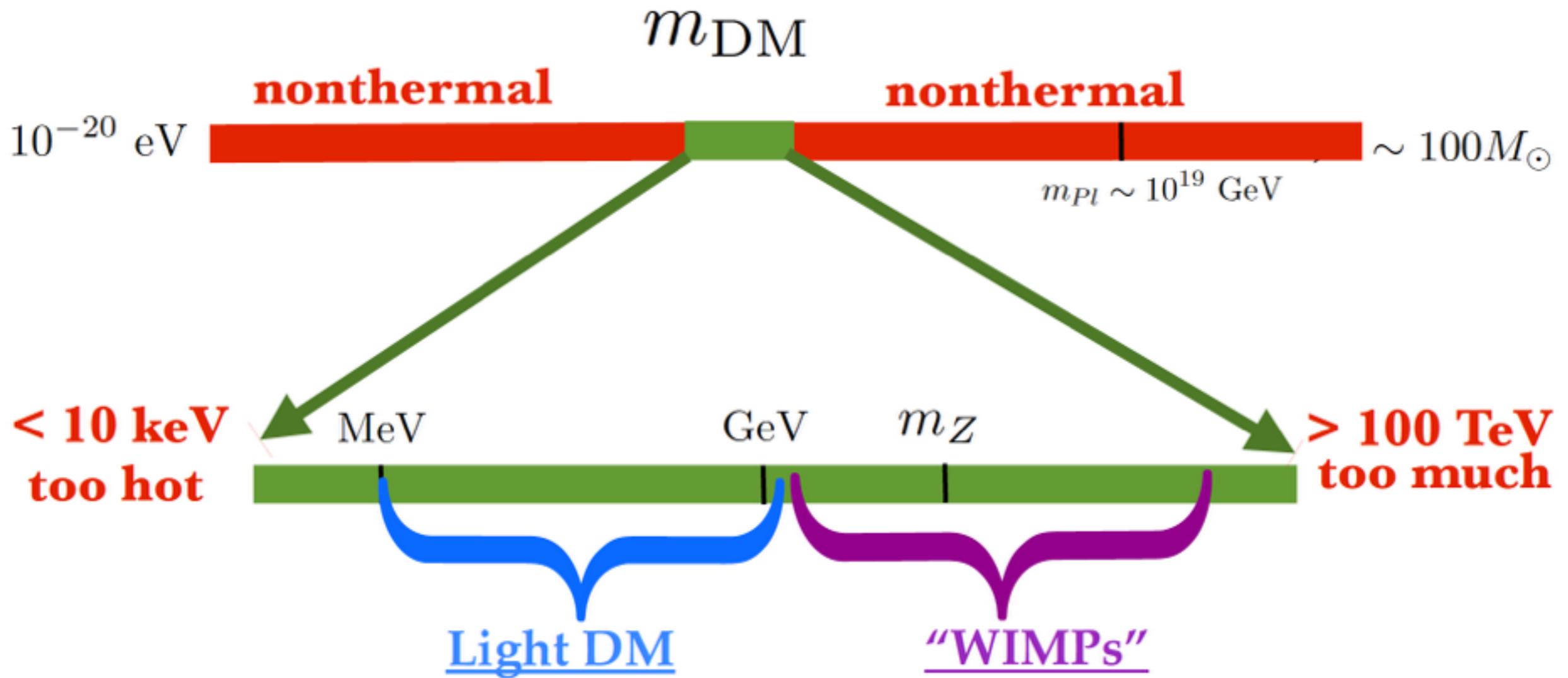
- Search for non-gravitational DM interactions a top priority today
- Such interactions are motivated by a thermal DM cosmology



$$\Omega_\chi \approx 0.1 \left(\frac{p_b}{\langle \sigma v \rangle} \right)$$

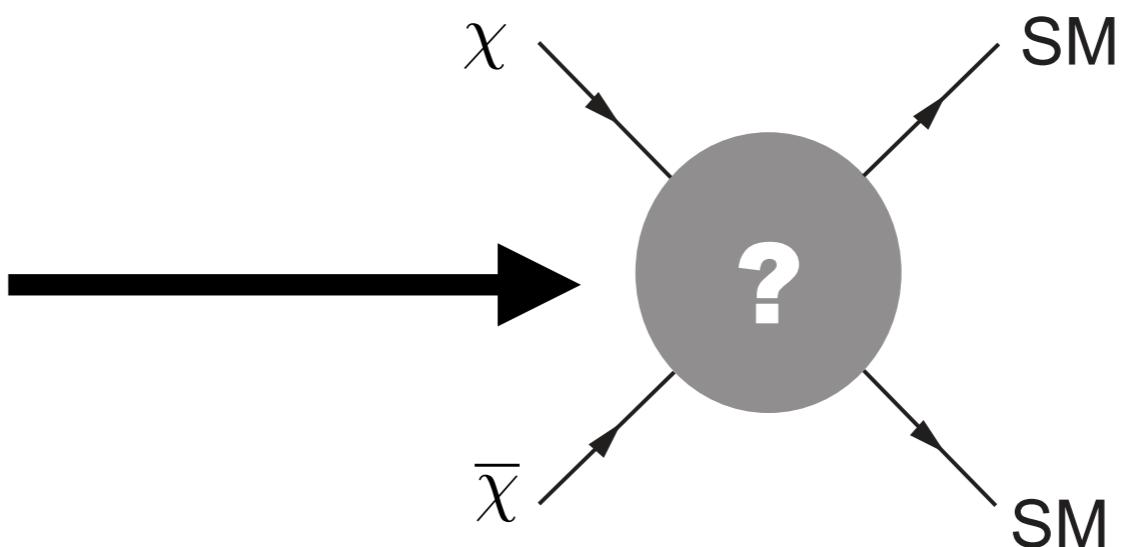
We should explore all viable DM - SM interactions

Thermal Dark Matter Window

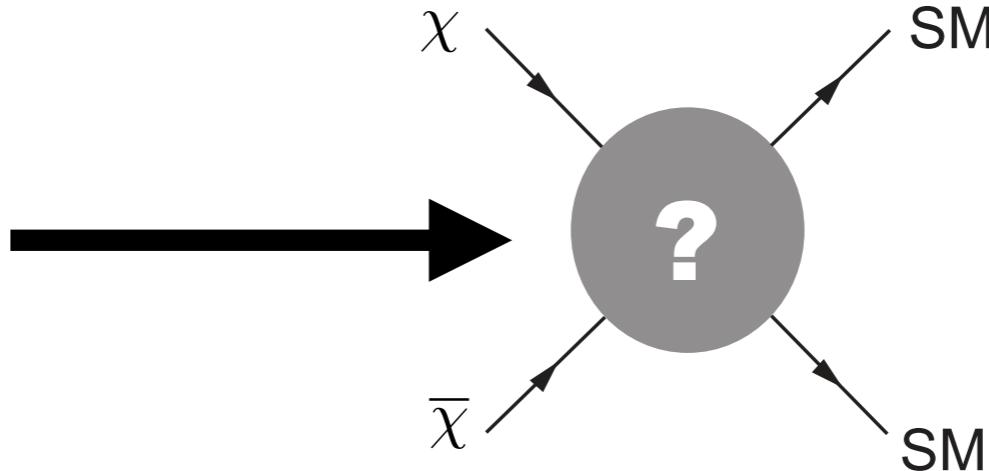


[Figure from G. Krnjaic]

What's here?



What's here?



“WIMP” regime: $1 \text{ GeV} \lesssim m_\chi \lesssim 100 \text{ TeV}$

- Weak interaction, Higgs portal, BSM mediator (Z' , sfermion, etc.),...
-

Light DM regime: $m_\chi \lesssim 1 \text{ GeV}$

- Lee-Weinberg bound; suggests new light mediator [Boehm, Fayet]
 - Renormalizable Portals
 - Gauge anomaly-free SM symmetry ($B - L, L_\mu - L_\tau, \dots$)
 - Gauge anomalous symmetry, couple light scalar via higher dimension operators (e.g., axion portal), ...

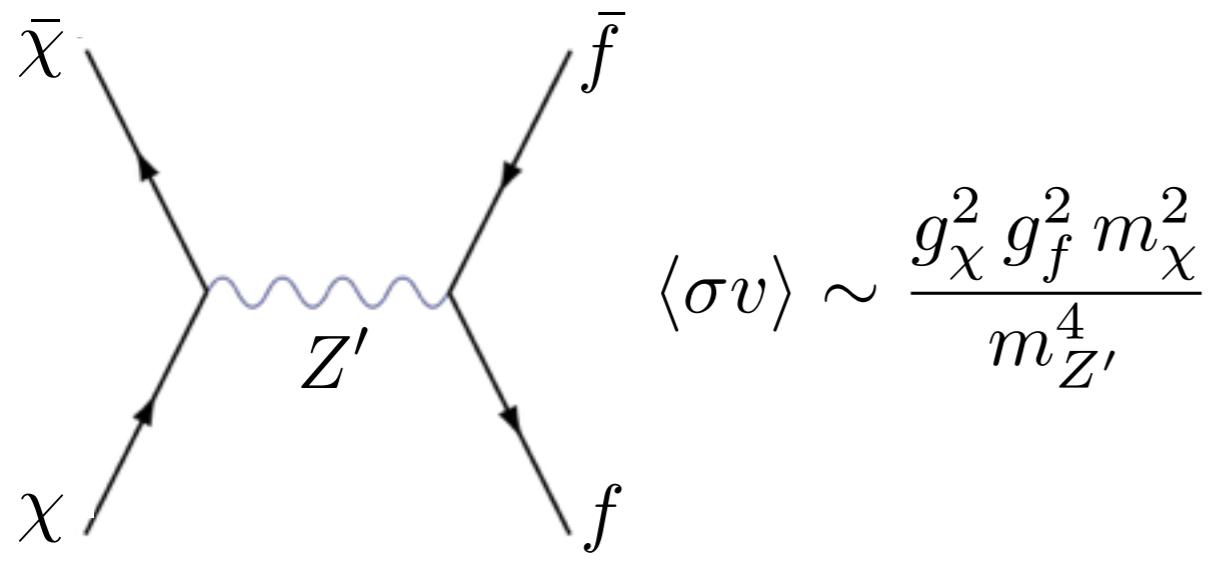
Direct vs. Secluded Annihilation

[Pospelov, Ritz, Voloshin]

Consider generic Z' mediator: $\mathcal{L} \supset g_\chi Z'_\mu \bar{\chi} \Gamma^\mu \chi + g_f Z'_\mu \bar{f} \Gamma^\mu f$

Two characteristic regimes:

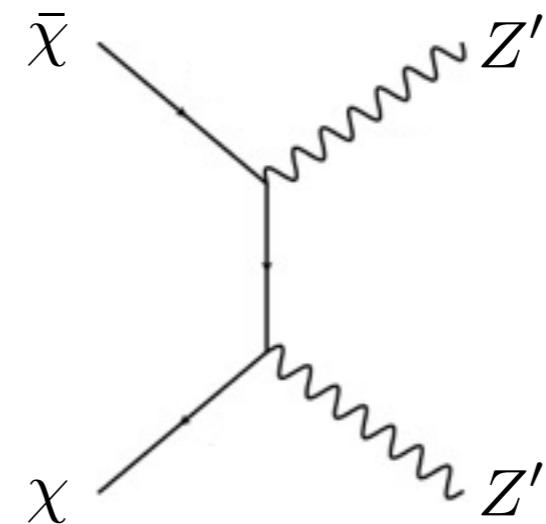
1. Direct annihilation: $m_\chi < m_{Z'}$



$$\langle \sigma v \rangle \sim \frac{g_\chi^2 g_f^2 m_\chi^2}{m_{Z'}^4}$$

Requires sizable portal coupling
to deplete DM abundance

2. “Secluded annihilation: $m_\chi > m_{Z'}$



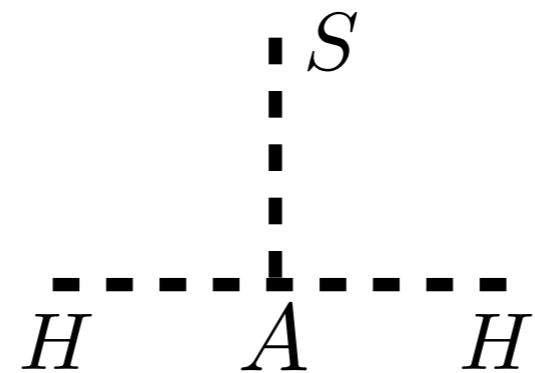
$$\langle \sigma v \rangle \sim \frac{g_\chi^4}{8\pi m_\chi^2}$$

Requires only minuscule portal coupling
to maintain kinetic equilibrium

Direct annihilation is more predictive, more easily testable

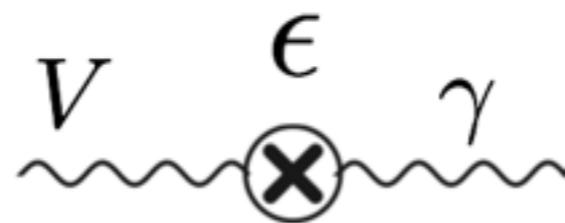
Portals

$$AH^\dagger HS$$



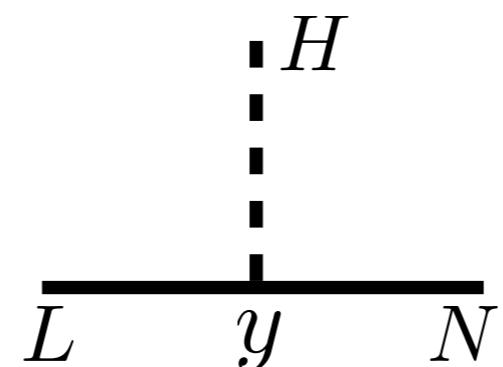
Higgs Portal

$$\frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu}$$



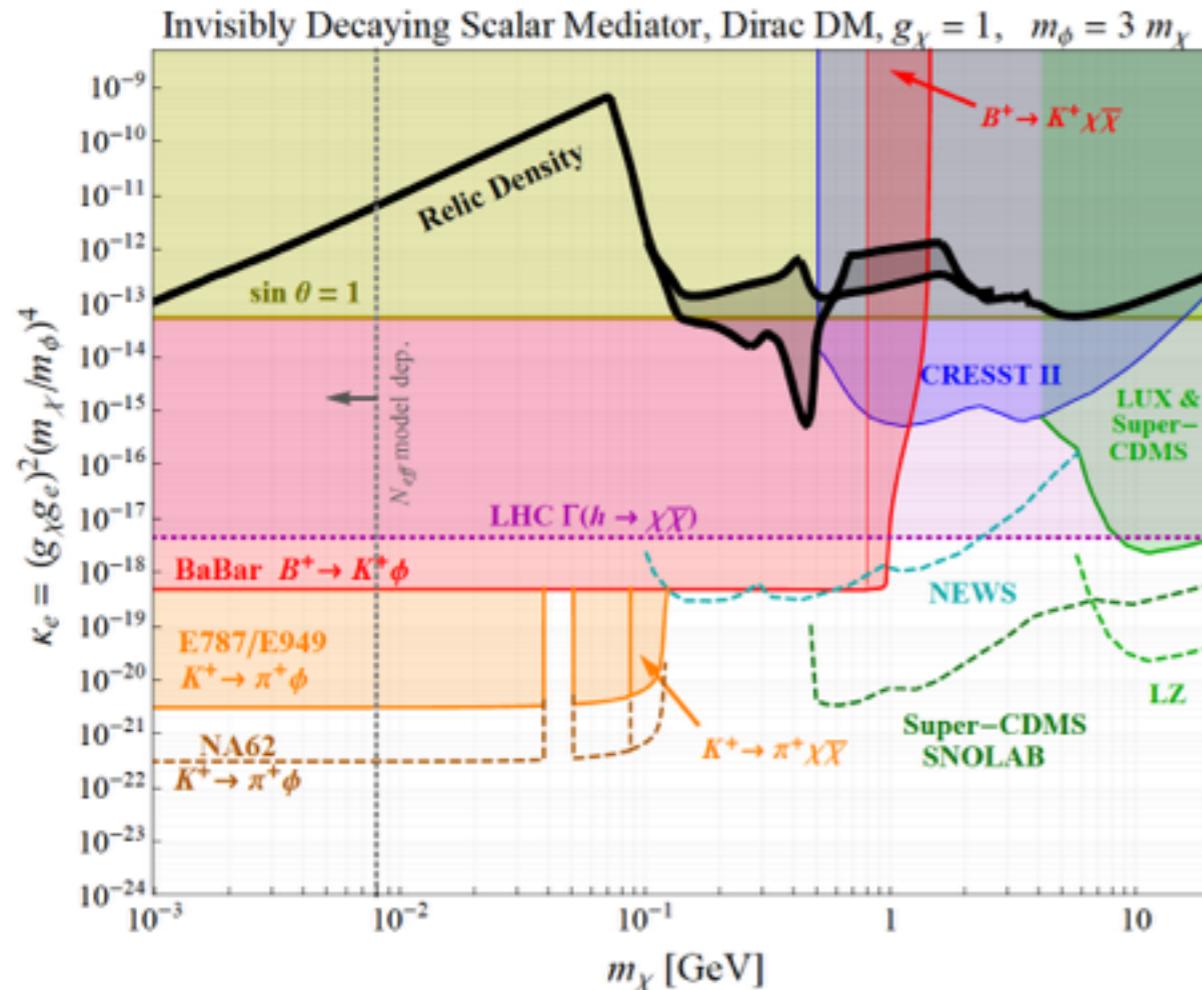
Vector Portal

$$yLHN$$



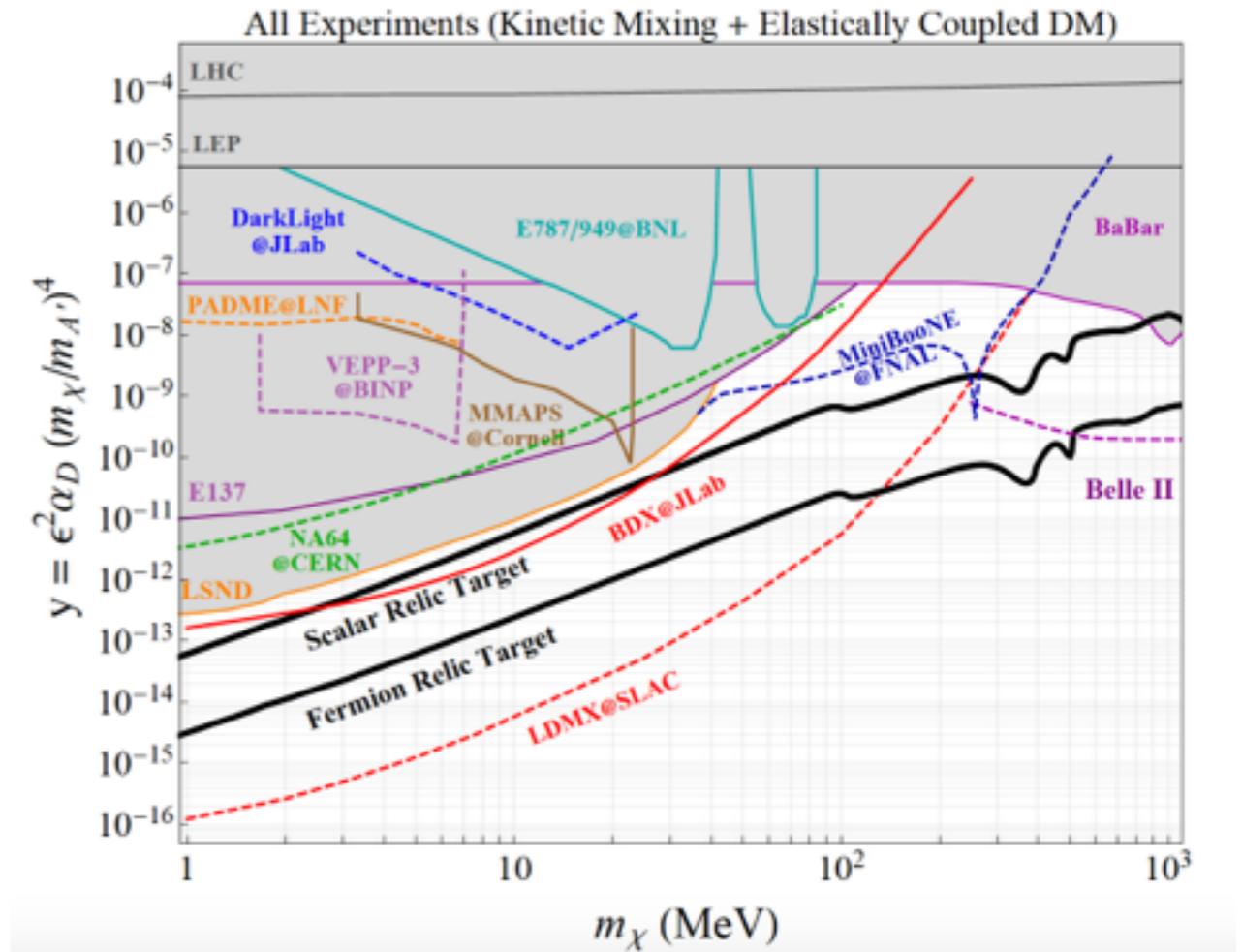
Neutrino portal

Higgs Portal



[Krnjaic]

Vector Portal



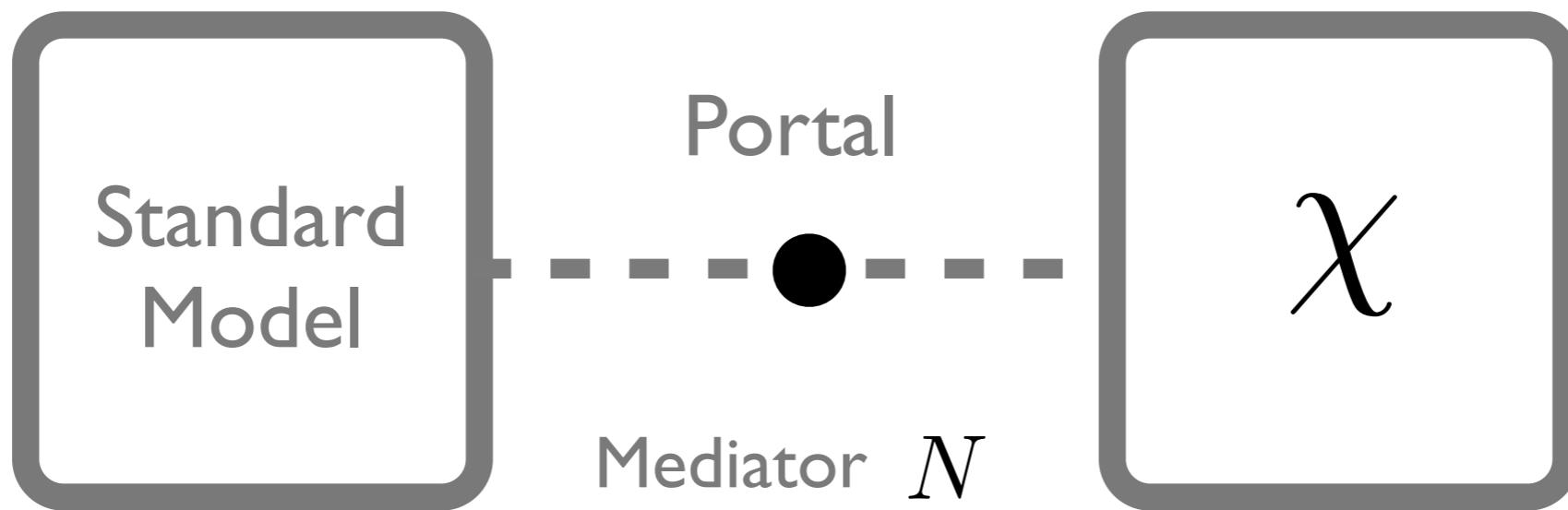
[U.S. Cosmic Visions, 1707.04591]

Higgs portal strongly constrained

Vector portal will be tested

What about the Neutrino portal option?

Neutrino Portal Dark Matter

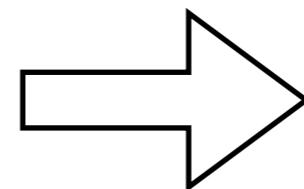
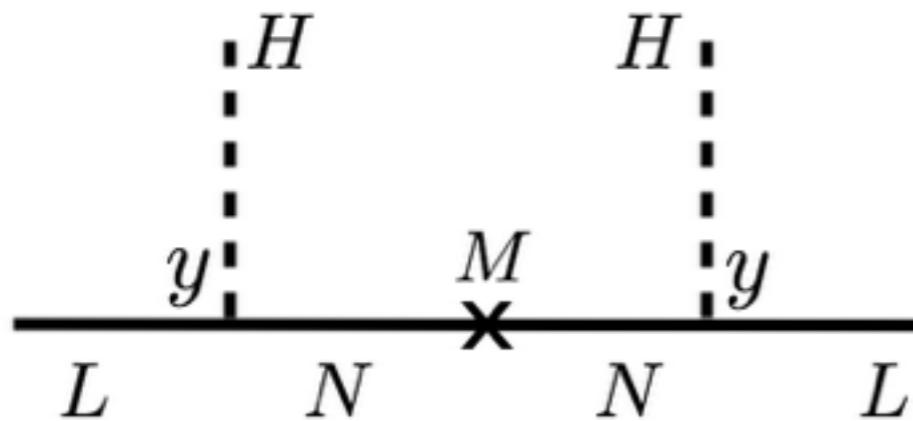


$$yLHN + \lambda N\chi\phi + \text{h.c.}$$

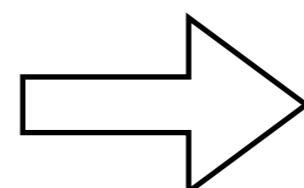
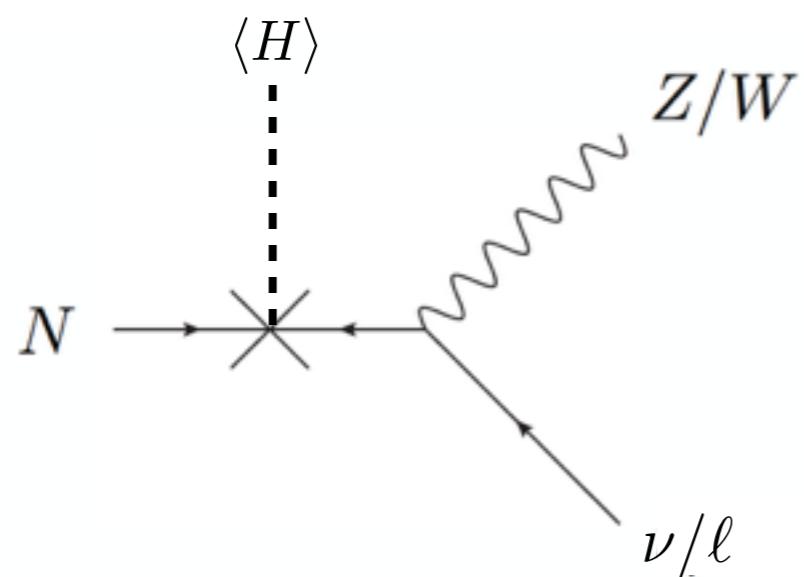
Seesaw Mechanism

Minkowski; Yanagida; Mohapatra, Senjanovic;
Gell-Mann, Ramond, Slansky; Schechter, Valle

$$yLHN + \frac{1}{2}MN^2 + \text{h.c.}$$



$$m_\nu \sim \frac{y^2 v^2}{M}$$



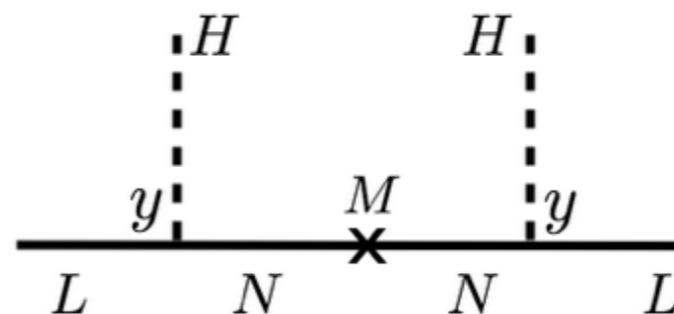
$$U \frac{g}{\sqrt{2}} W_\mu^- \ell^\dagger \bar{\sigma}^\mu N + \text{h.c.} + \dots$$

$$U \sim \frac{yv}{M} \sim \sqrt{\frac{m_\nu}{M}} \sim 10^{-5} \times \left(\frac{m_\nu}{0.05 \text{ eV}} \right)^{1/2} \left(\frac{\text{GeV}}{M} \right)^{1/2}$$

Minimal model based on Type-I seesaw

$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \left[\frac{1}{2}m_N NN + \frac{1}{2}m_\chi \chi \chi + y L H N + \lambda N \phi \chi + \text{h.c.} \right]$$

- Seesaw mechanism generates small masses for light neutrinos



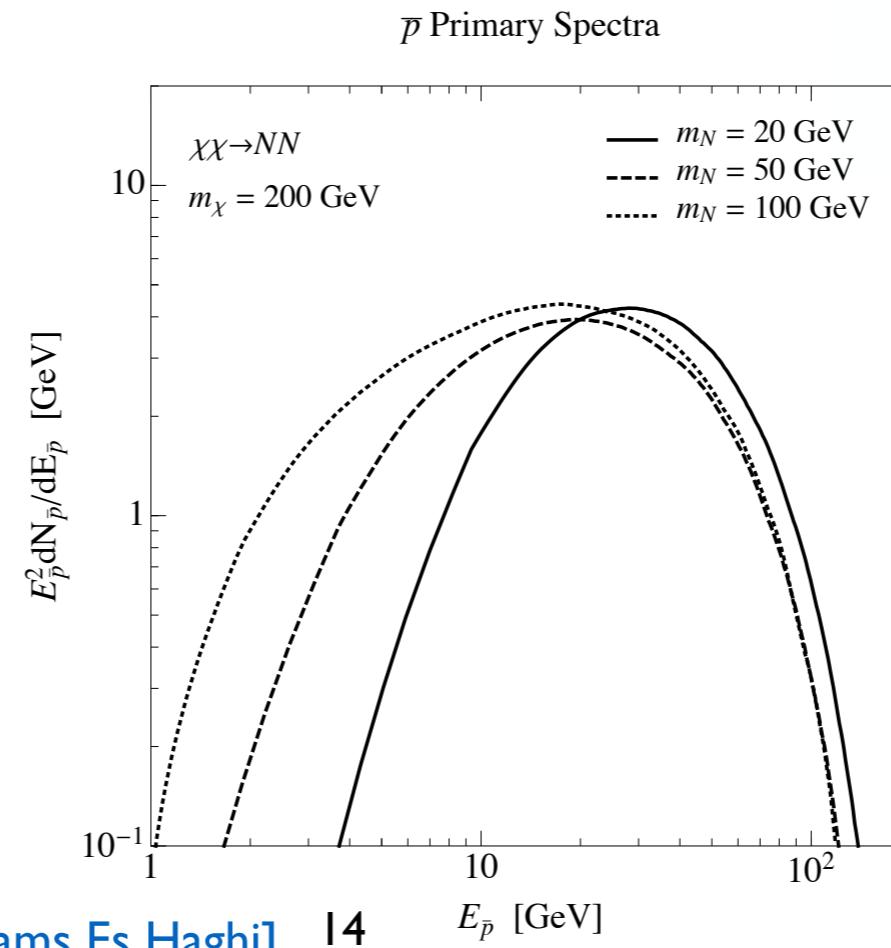
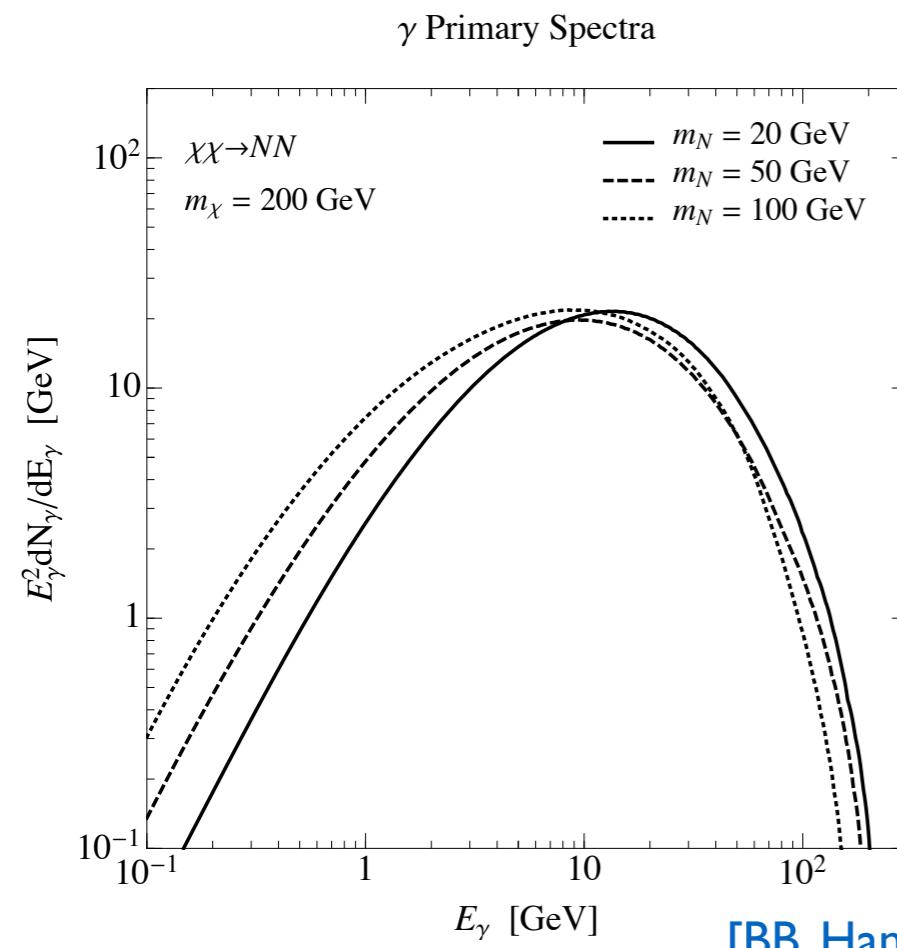
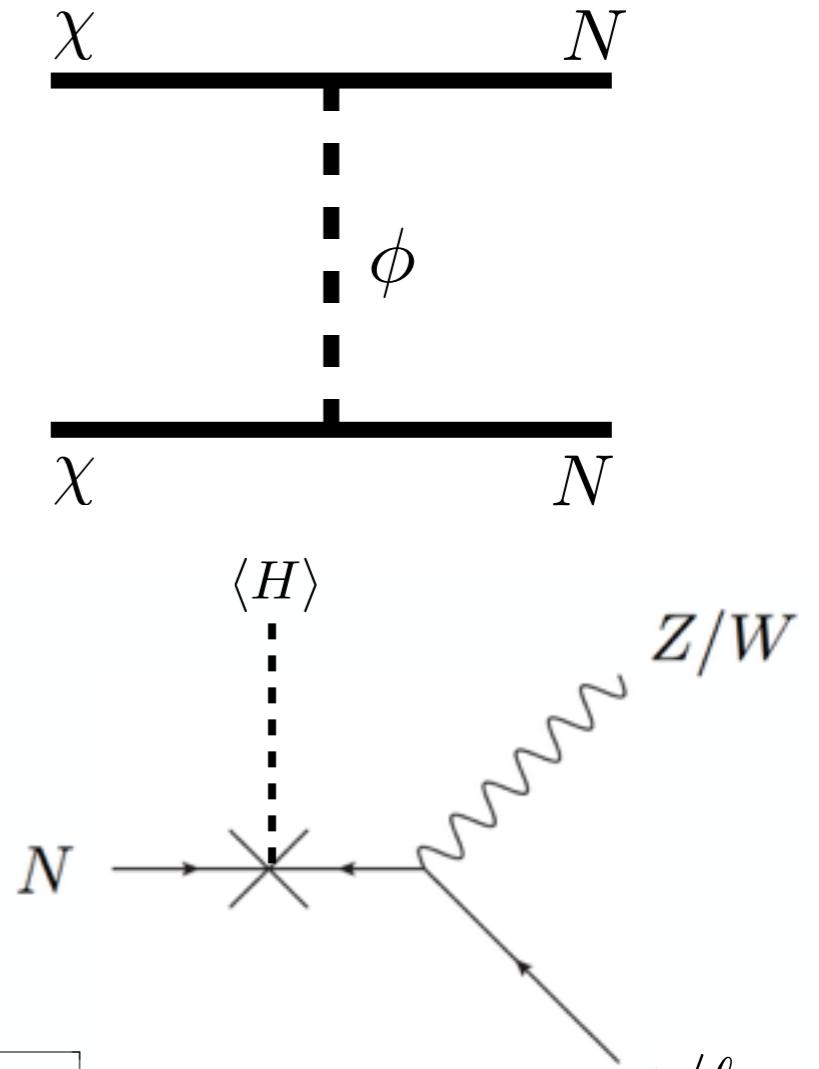
$$m_\nu \sim \frac{y^2 v^2}{2m_N}$$

- For masses in the thermal window, neutrino Yukawa coupling is naively tiny $y \simeq 10^{-6} (m_N/v)^{1/2}$
- Direct annihilation to light neutrinos is inefficient, and direct detection, accelerator tests of this scenario are challenging
- Secluded annihilation is still viable; indirect detection offers a probe

Secluded Annihilation

$$m_\chi > m_N$$

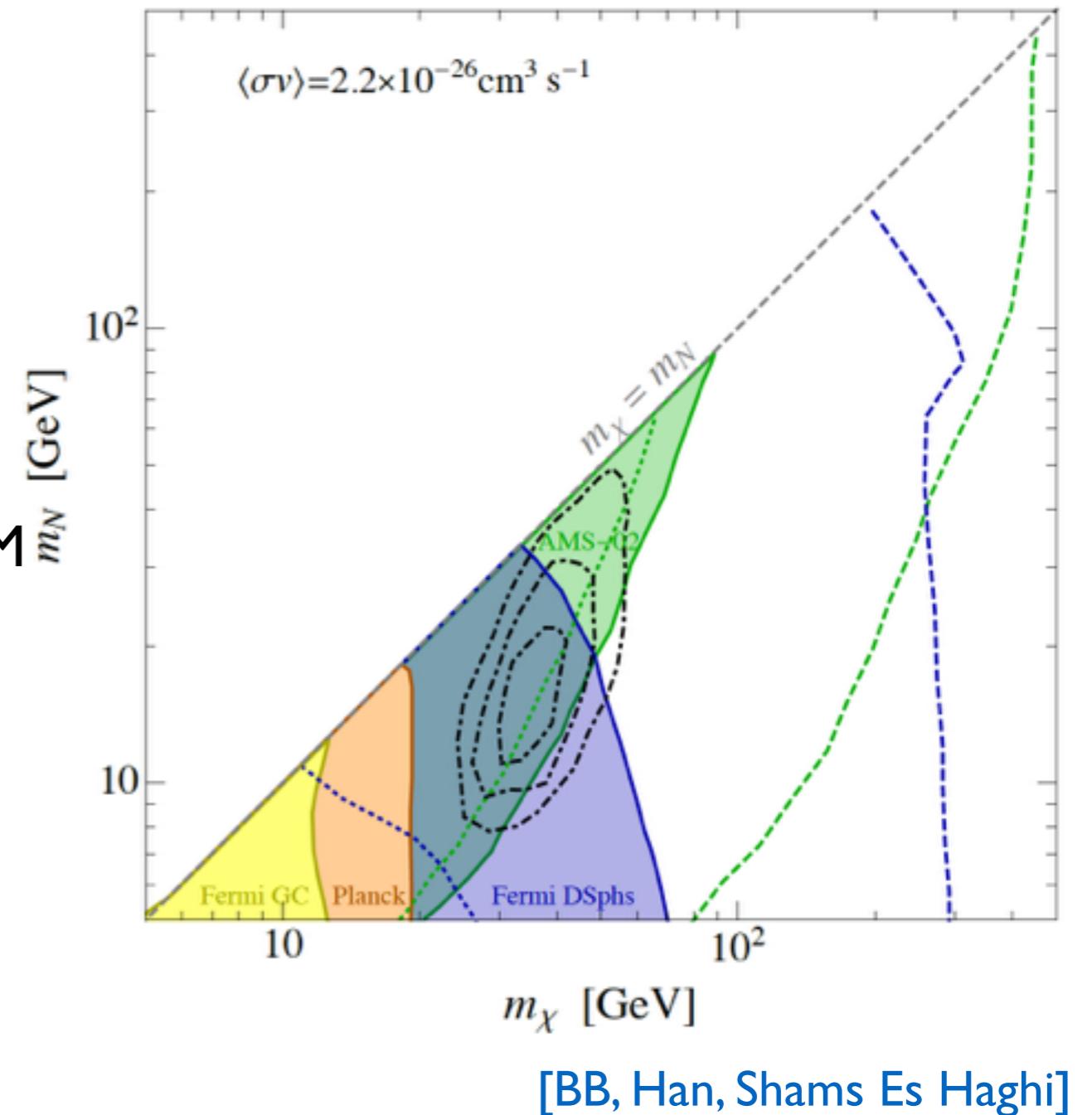
- Annihilation $\chi\chi \rightarrow NN$ is efficient
- Indirect detection: gamma-rays, antiprotons from DM annihilation, distortion of CMB anisotropies
- Can be probed by Fermi, AMS-02, Planck, ...



Spectra display mild dependence on sterile neutrino masses

Indirect detection constraints & prospects

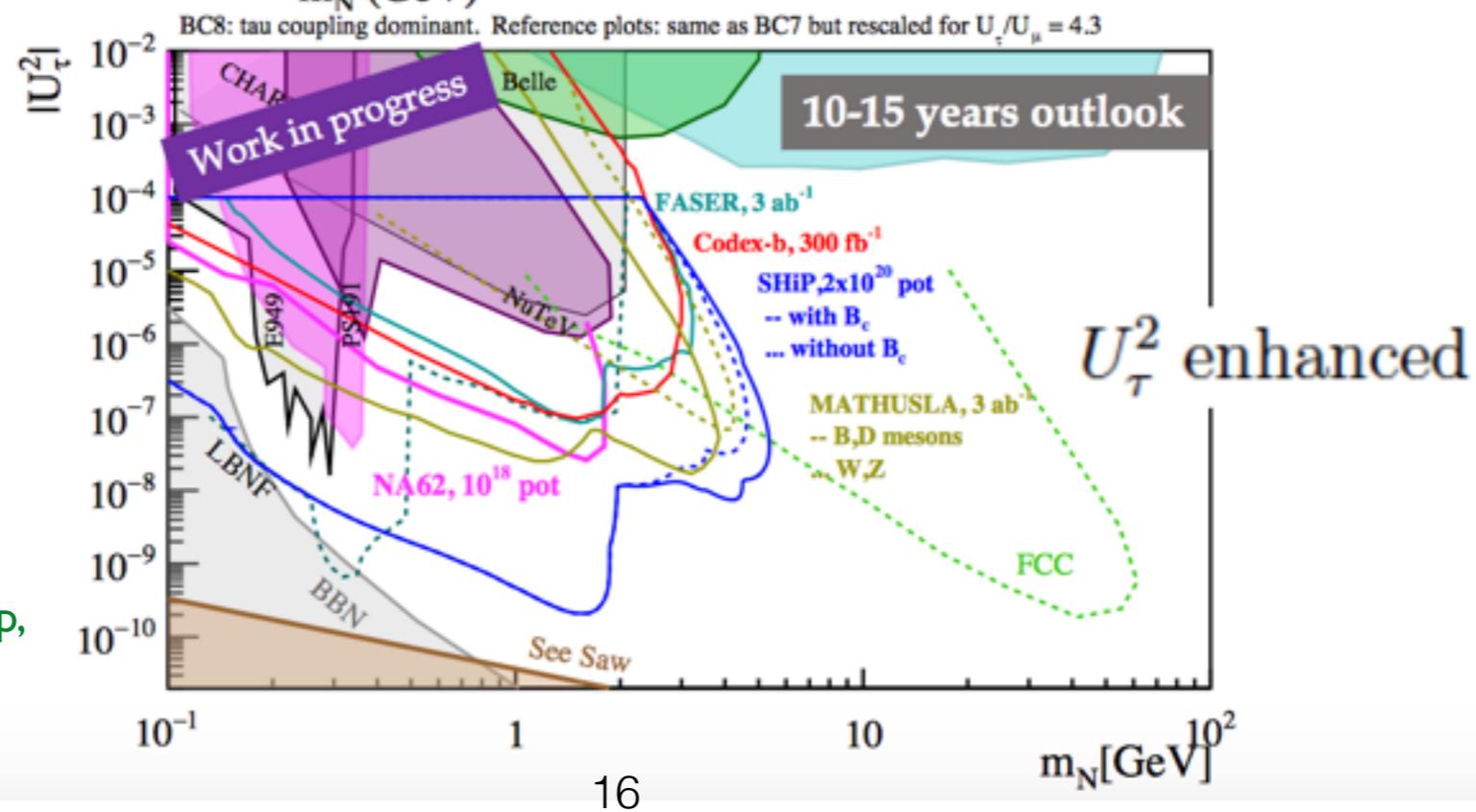
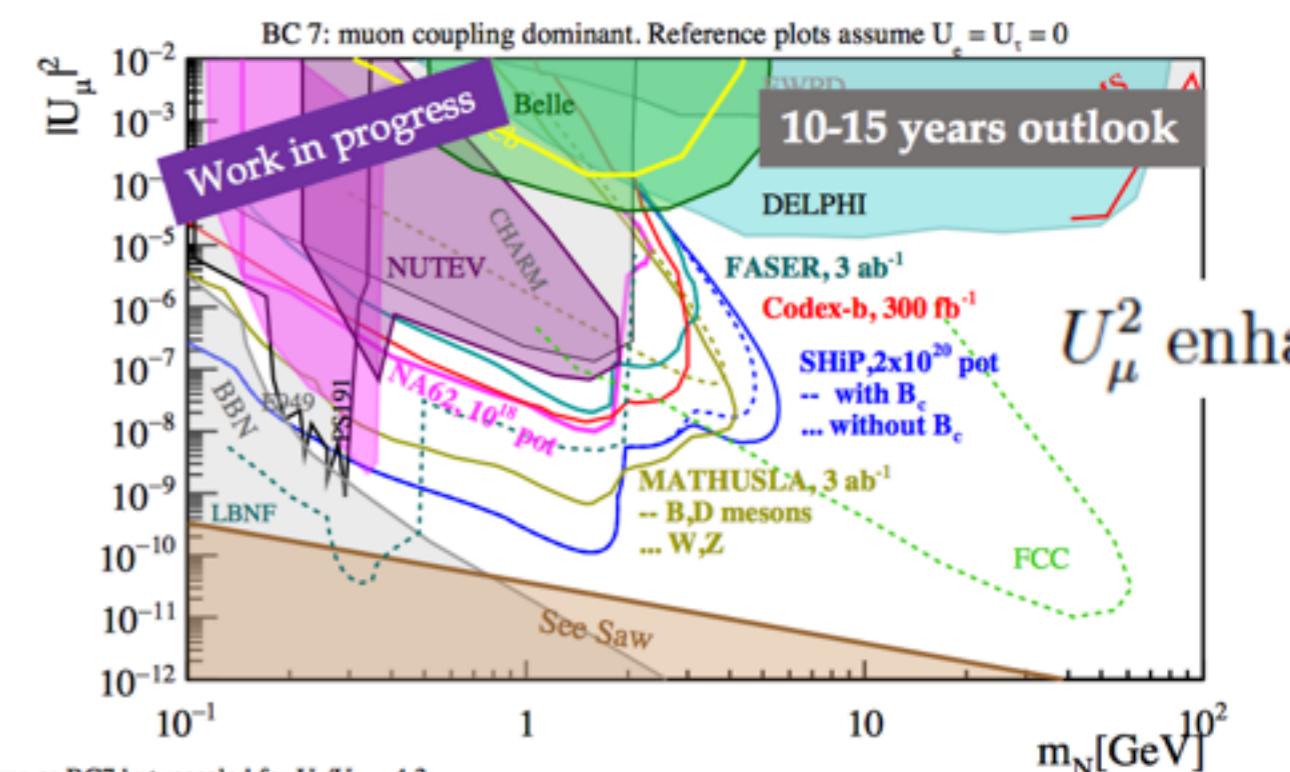
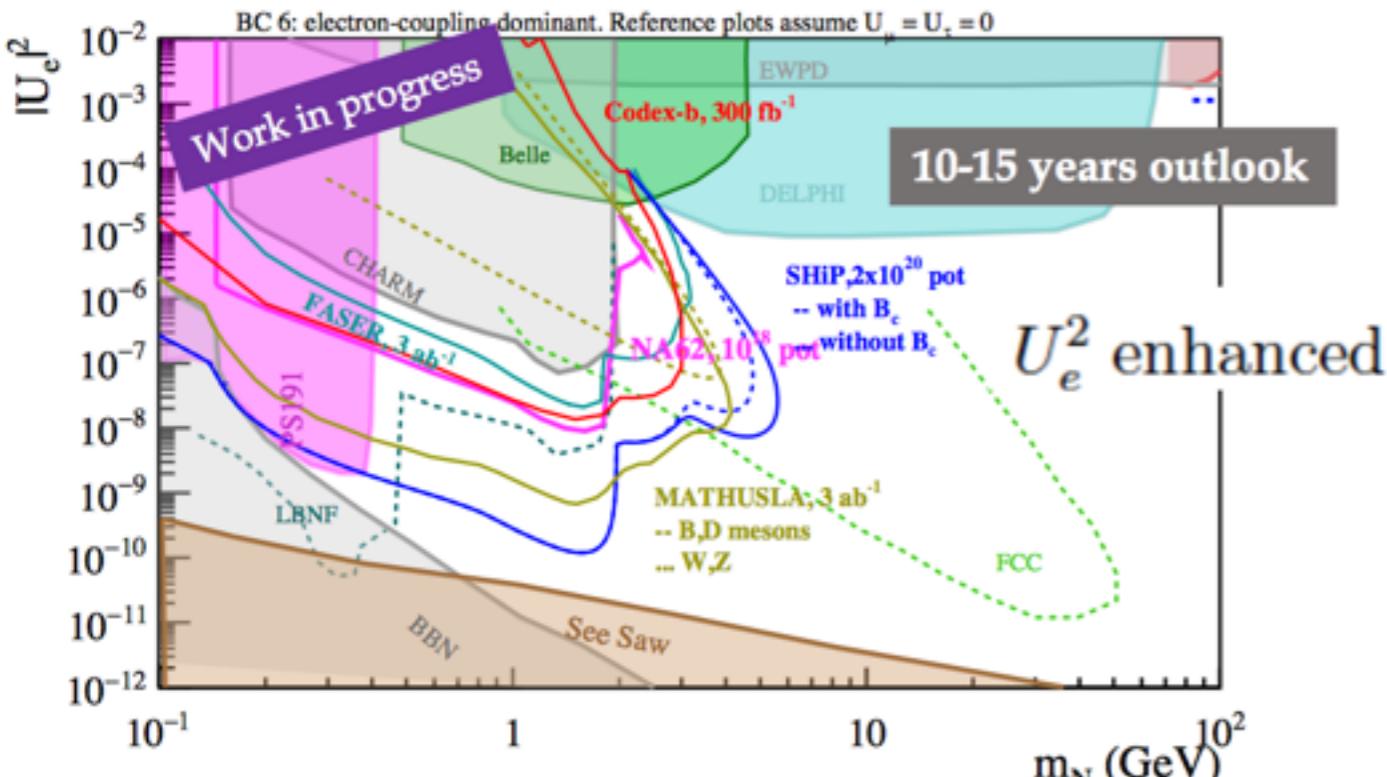
- Fermi dSphs, AMS-02 antiprotons probe thermal DM below ~ 60 GeV
- GeV excess interpretation is in tension with these constraints
- H.E.S.S. also has sensitivity to heavier DM m_N
- Fermi dSphs should eventually have sensitivity to $m_\chi \gtrsim 100$ GeV
- CTA will be able to probe TeV-mass DM



For related
studies, see also
15

Tang, Zhu
Ibarra, Lopez-Gehler, Molinaro, Pato
Campos, Queiroz, Yaguna, Weniger

Direct searches for “visible” sterile neutrino



Talk by Gaia Lanfranchi
Physics Beyond Colliders Workshop,
June 2018

Dirac Neutrino Portal

[Bertoni, Ipek, Nelson, McKeen]
[BB, Han, McKeen, Shams Es Haghi]

$$\begin{aligned}-\mathcal{L} \supset & m_\phi^2 |\phi|^2 + m_\chi \bar{\chi}\chi + m_N \bar{N}N \\ & + \left[\lambda_\ell \bar{L}_\ell \hat{H} N_R + \phi \bar{\chi} (y_L N_L + y_R N_R) + \text{h.c.} \right]\end{aligned}$$

- Approximate lepton number symmetry allows for light SM neutrinos even if the Yukawa coupling λ_ℓ (and active sterile mixing) is large

$$\nu_4 = \begin{pmatrix} U_{N4}^* N_L + \sum_\ell U_{\ell 4}^* \nu_{\ell L} \\ N_R \end{pmatrix} \quad U_{\ell 4} = \frac{\lambda_\ell v}{m_4}, \quad |U_{N4}| = \frac{m_N}{m_4} = \sqrt{1 - \sum_\ell |U_{\ell 4}|^2}.$$

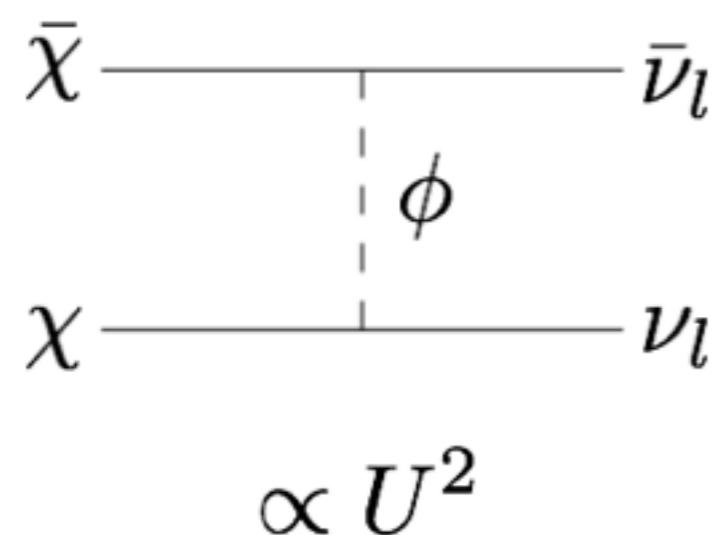
- Large mixing allows for a sizable DM - SM neutrino coupling

$$\begin{aligned}y_L \phi \bar{\chi}_R N_L + \text{h.c.} \\ \rightarrow y_L |U_{N4}| \phi \bar{\chi}_R \nu_{4L} - y_L \sqrt{1 - |U_{N4}|^2} \phi \bar{\chi}_R \nu_{lL} + \text{h.c.}\end{aligned}$$

- Important implications for cosmology and phenomenology

Direct annihilation to light SM neutrinos

$$m_\chi < m_N$$



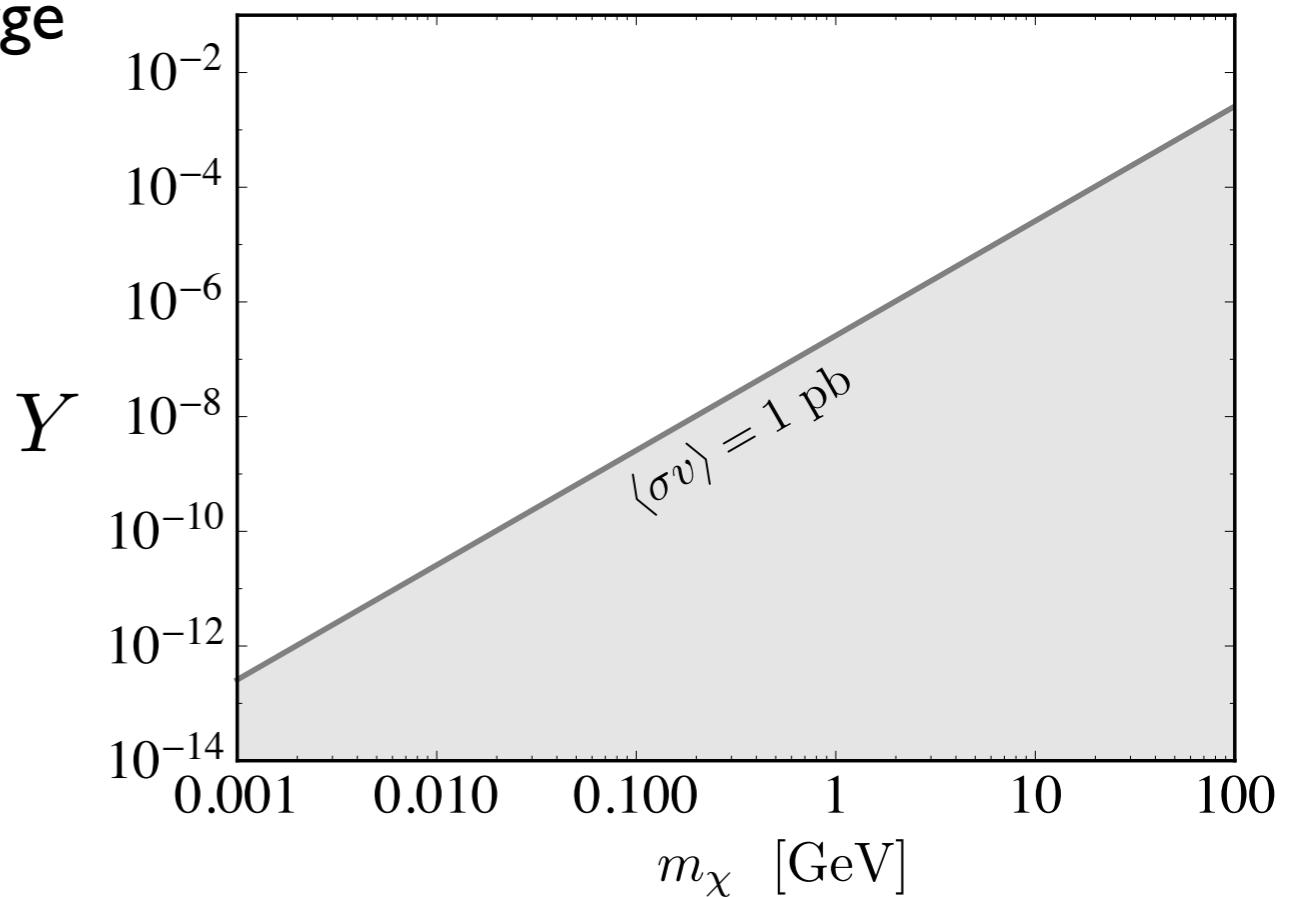
$$\begin{aligned} \langle\sigma v\rangle &= \frac{y_L^4}{32\pi} \left(\sum_{\ell} |U_{\ell 4}|^2 \right)^2 \frac{m_\chi^2}{m_\phi^4} \left(1 + \frac{m_\chi^2}{m_\phi^2} \right)^{-2} \\ &\simeq 1 \text{ pb} \left(\frac{y_L \sqrt{\sum_{\ell} |U_{\ell 4}|^2}}{0.2} \right)^4 \left(\frac{10 \text{ GeV}}{m_\chi} \right)^2 \left(\frac{3}{m_\phi/m_\chi} \right)^4, \end{aligned}$$

- DM may be a thermal relic if mixing is large
- Thermal target in $m_\chi - Y$ plane:

$$Y \equiv y_L^4 \left(\sum_i |U_{i4}|^2 \right)^2 \frac{m_\chi^4}{m_\phi^4}$$

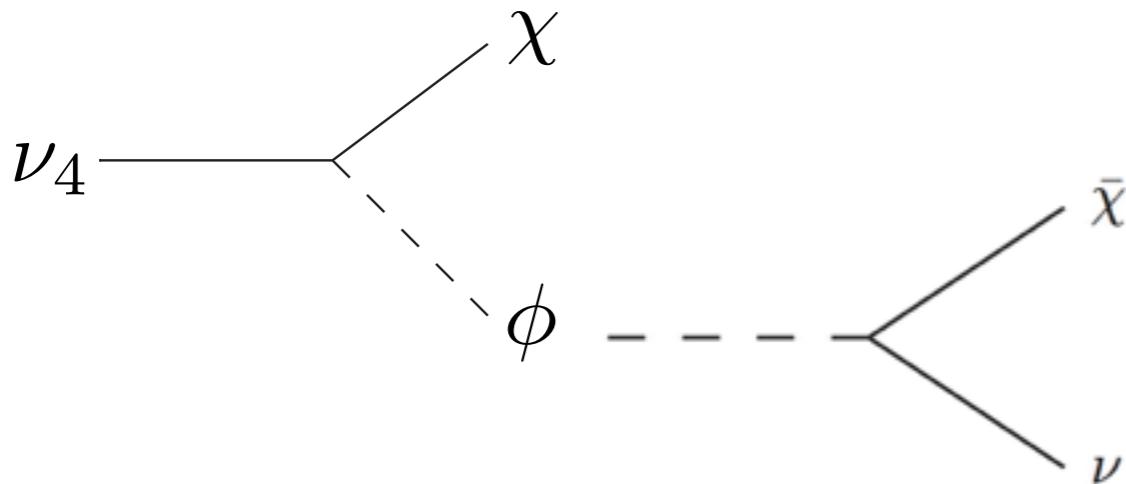
$$\langle\sigma v\rangle \simeq \frac{Y}{32\pi m_\chi^2}$$

- CMB + other indirect constraints evaded



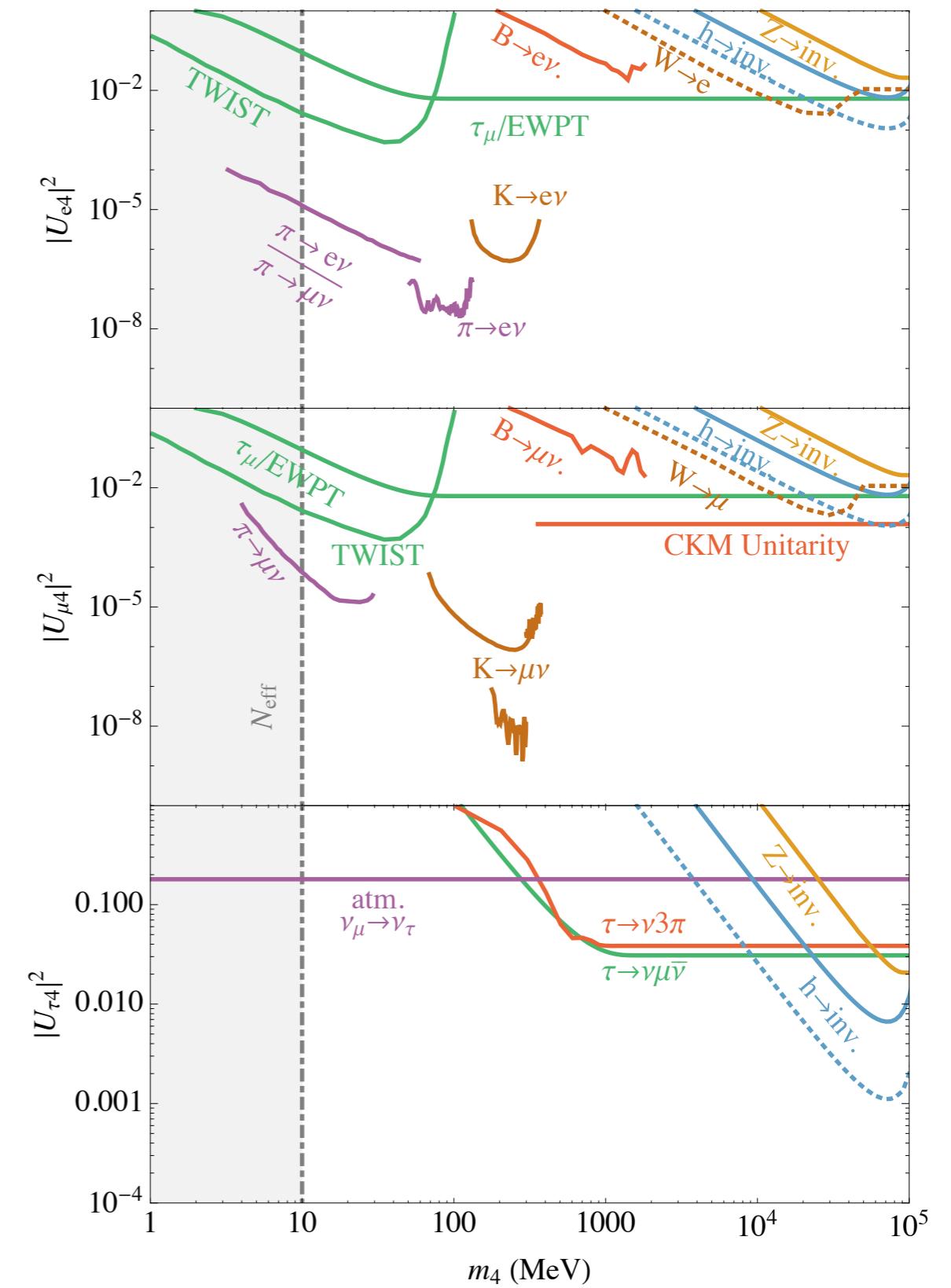
“Invisible” Sterile Neutrino

$$m_N > m_\phi, m_\chi$$



Phenomenology

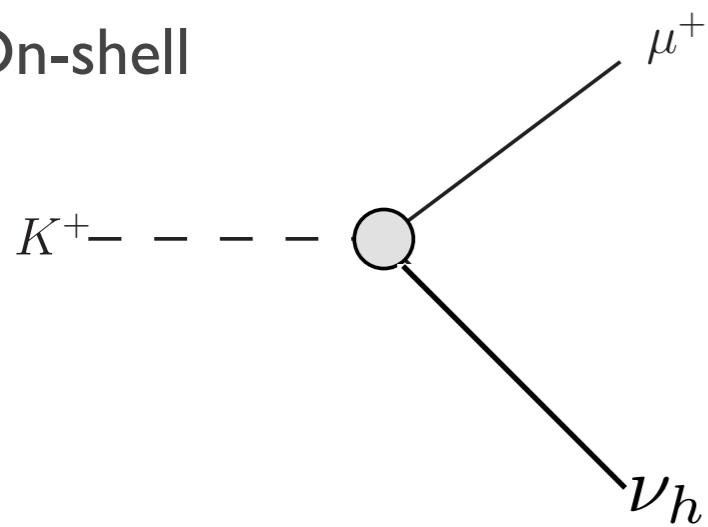
- Fermi constant (muon lifetime); PMNS non-unitarity; EW precision; CKM unitarity
- Muon, tau, Meson decays (peak searches); lepton universality tests;
- Invisible Z, Higgs decays; Drell-Yan (W decays)
- Atmospheric oscillations (relevant for ν_τ)



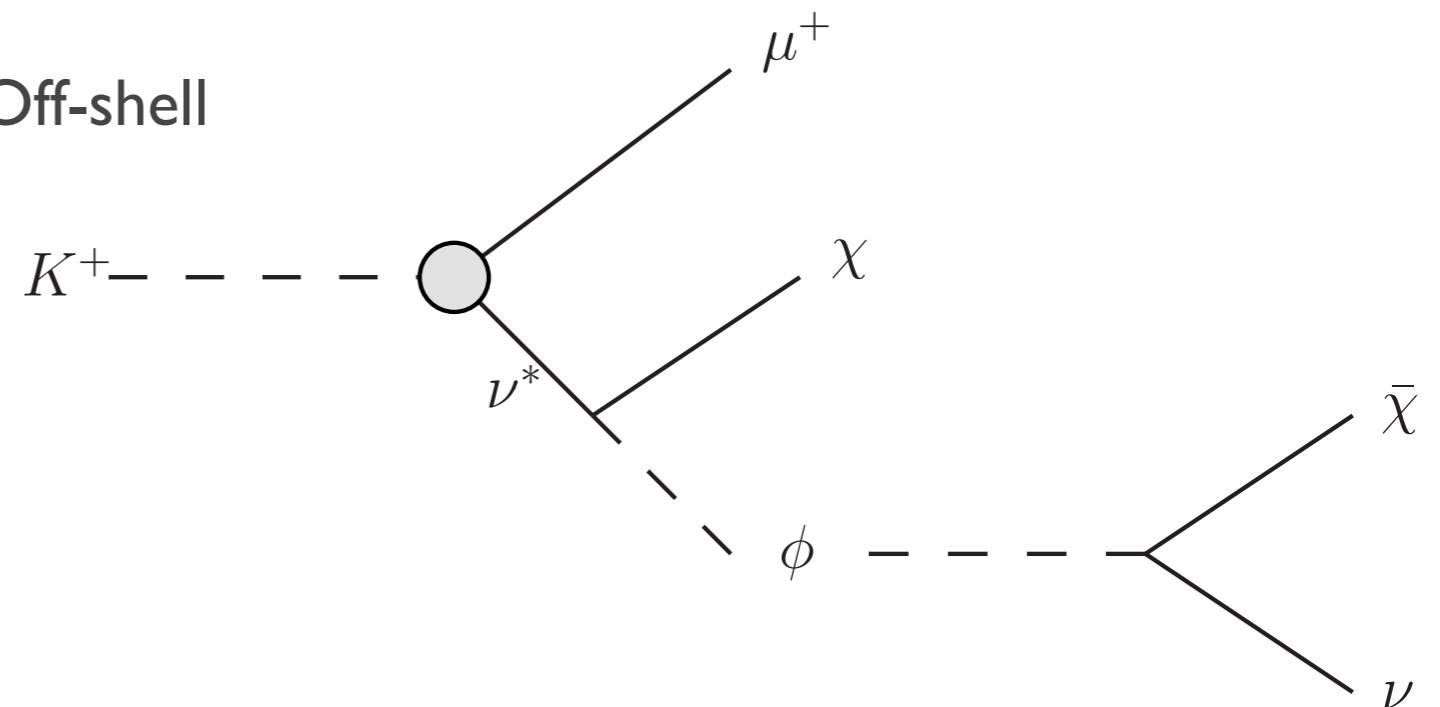
[Bertoni, Ipek, DM, & Nelson]
 [BB, Han, McKeen, Shams Es Haghi]
 [De Gouvea, Kobach]

Meson decays

On-shell

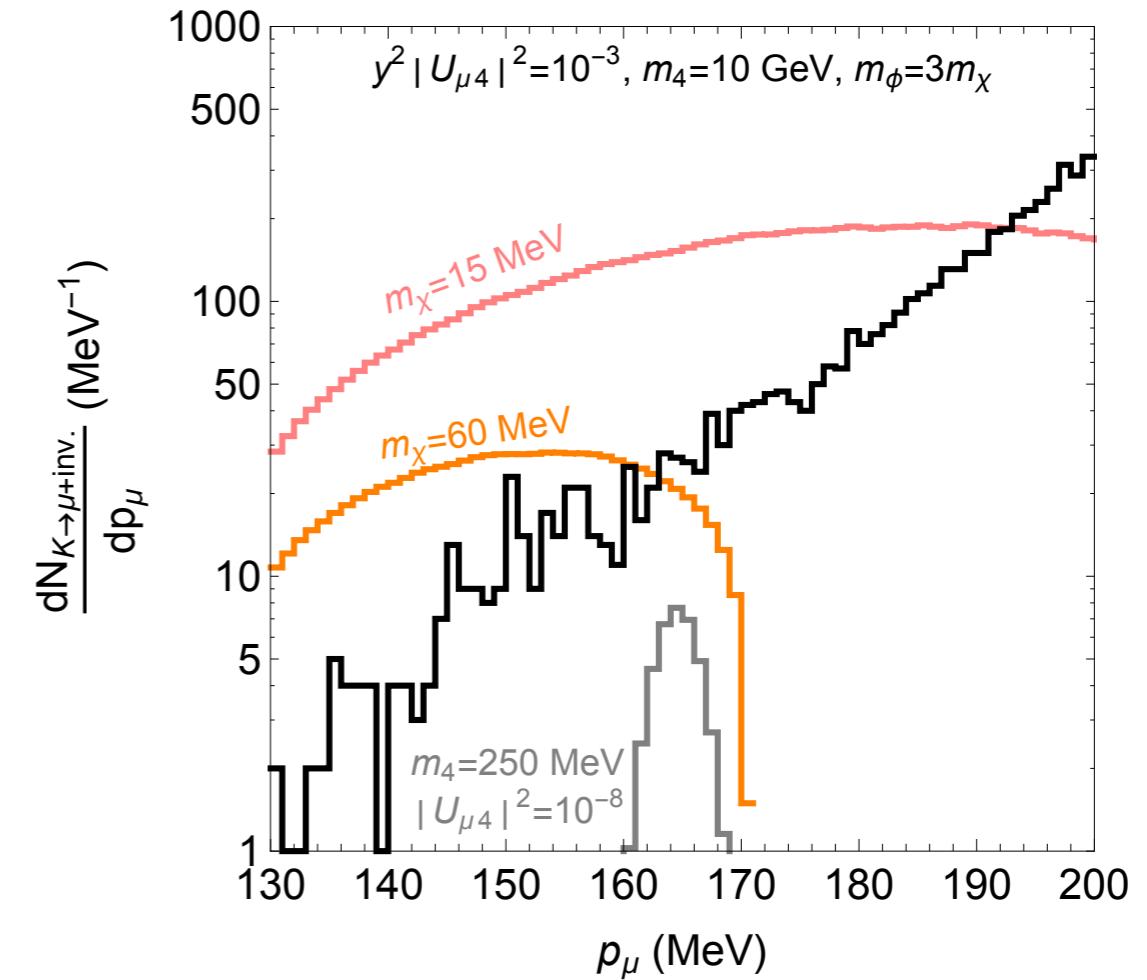


Off-shell



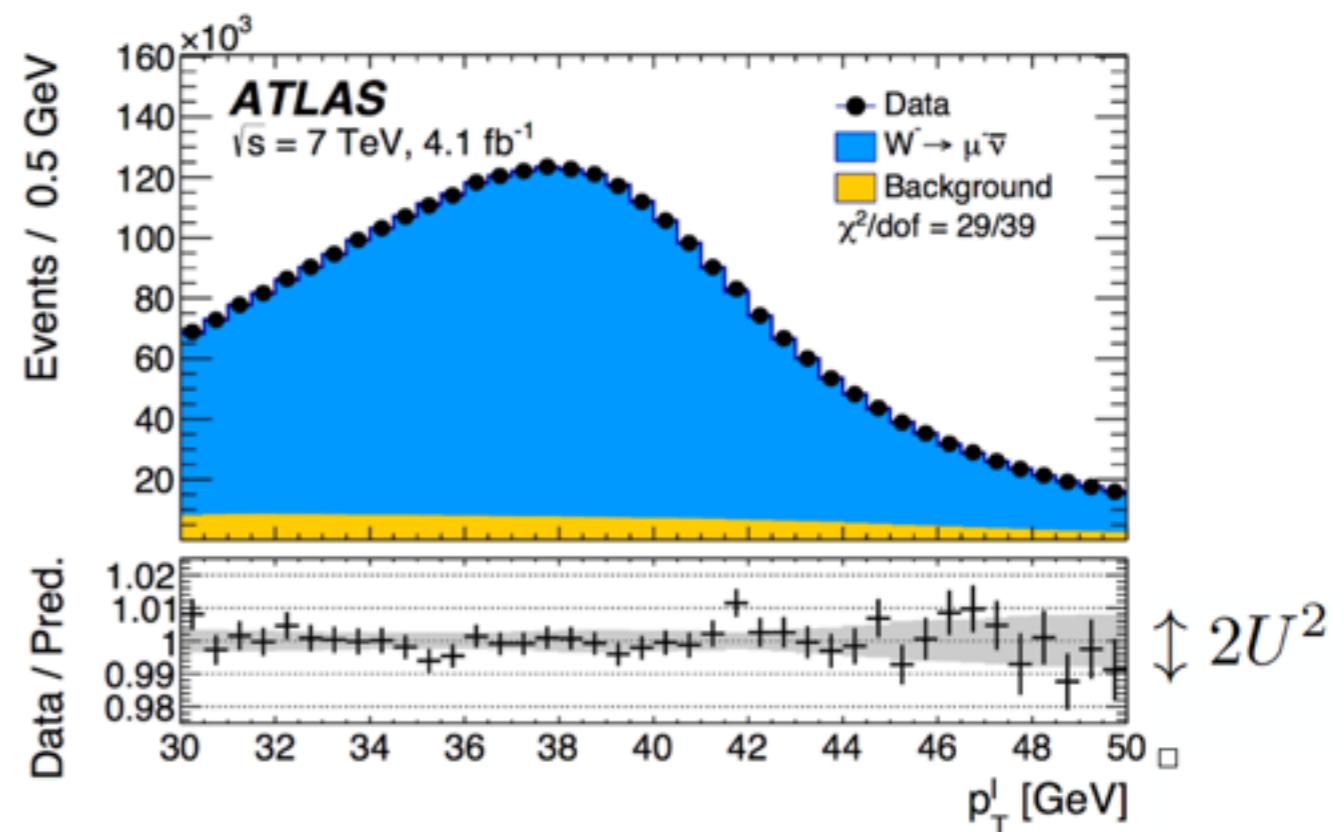
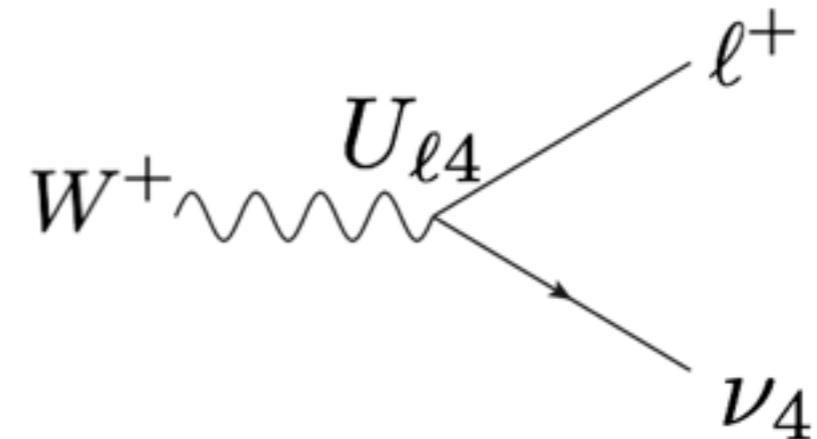
E949: 10^{12} kaons

NA62 will collect ~ 1 order
of magnitude more Kaons



W boson decays

- W boson may decay to heavy neutrino, which subsequently decays invisibly
- Distortion of kinematics that is sensitive to mass of heavy neutrino
- Heavy neutrinos produced in on-shell decays would appear as a kink in lepton pT
- Lepton pT in Drell-Yan are well-studied; used for W boson mass measurement



Small scale structure

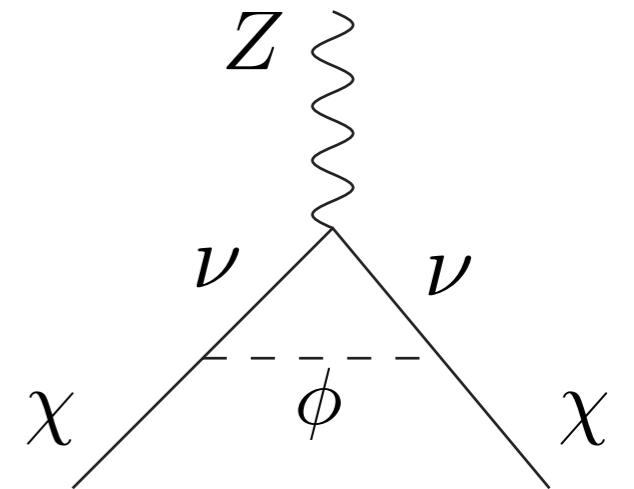
[Boehm, Fayet, Schaeffer]
[Shoemaker; Cherry, Shoemaker, Friedland]
[Bertoni, Ipek, McKeen, Nelson]

- Strong DM - neutrino scattering can delay DM kinetic decoupling
- Pressure due to DM-neutrino coupling resists gravitational collapse (analogous to coupled photon-baryon plasma)
- Formation of structures smaller than horizon size at DM kinetic decoupling are suppressed
- Smallest structures observed via gravitational lensing have masses of order 10^8 solar masses
- Late kinetic decoupling leads to a lower bound on mass of gravitationally bound objects

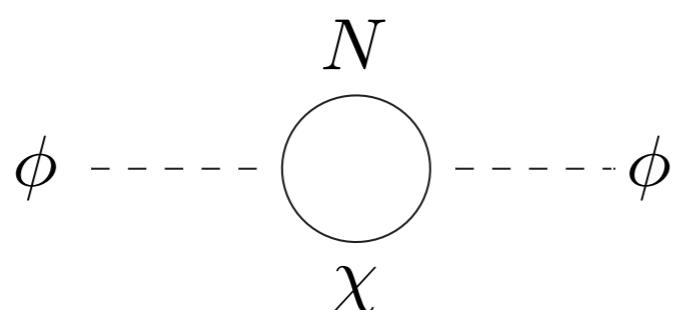
$$M > M_{\text{cutoff}} = 10^8 M_{\text{solar}} \left(\frac{T_d}{\text{keV}} \right)^{-3}$$

Direct Detection

- DM acquires coupling to the Z boson at one loop;
Probes DM heavier than few GeV
- Constraints can be weakened if DM split; other probes
are complementary



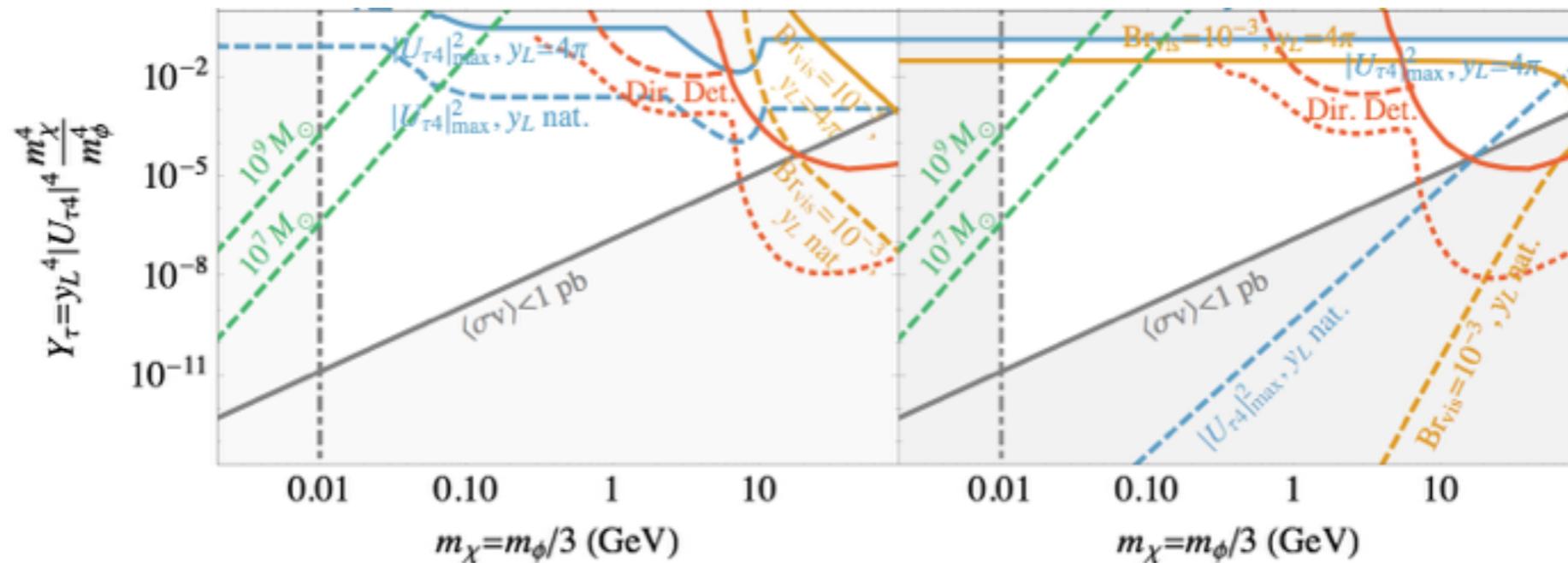
Naturalness of light scalar



$$\delta m_\phi^2 \sim \frac{y^2}{16\pi^2} m_N^2$$

- Naturalness “constraint” is complementary to invisible neutrino constraints

Testing the thermal target



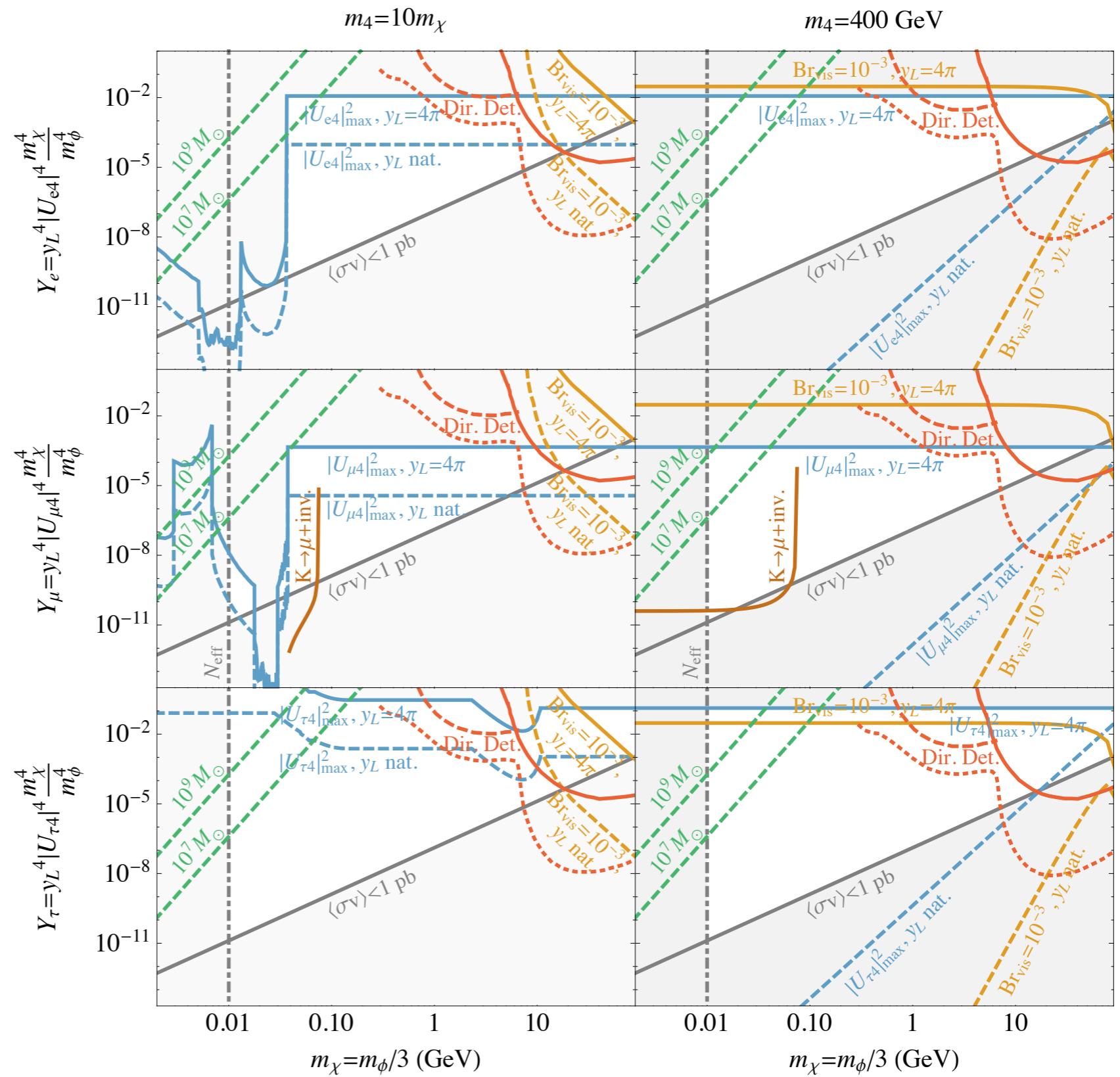
- On or above grey line, DM can be a thermal relic - probe this region
- Direct detection, structure constraints scale in the same way $\langle \sigma v \rangle$
- Constraints from invisibly decaying sterile neutrinos limit mixing angle vs. N mass.
To place conservative constraints:
 - Saturate experimental bound on the mixing angle
 - Take coupling y_L close to non-perturbative values
 - Maximize the ratio m_χ/m_ϕ
- Left plot - N taken light so as to mitigate the naturalness ‘‘constraint’’
- Right plot - N taken heavy so as to mitigate the experimental constraints

Thermal target

$$Y \equiv y_L^4 \left(\sum_i |U_{i4}|^2 \right)^2 \frac{m_\chi^4}{m_\phi^4}$$

$$\langle \sigma v \rangle \simeq \frac{Y}{32\pi m_\chi^2}$$

- Represent conservative constraints on the thermal hypothesis
- New ideas to probe remaining open parameter space are welcome!



Outlook

- Thermal dark matter implies coupling between DM and SM; requires new mediators, interactions for masses below \sim GeV
- Neutrino portal is a well-motivated, but less explored option
- Secluded annihilation is difficult to probe in general; indirect detection offers a handle
- Approximate lepton number symmetry allows for viable direct annihilation. This scenario is predictive, but we still need new ideas to probe the remaining parameter space.

Thanks to Josh, Cindy, Dorival, Tao, Ahmed, Donna,
Richard, and Cédric for organizing a wonderful workshop

Thanks to the Department of Energy and the Neutrino
Theory Network for generous support!

Thanks to all of you for the excellent talks and
stimulating discussion!

**Phenomenology 2019 Symposium
will be held May 6-8, 2019
at the University of Pittsburgh**

We hope to see all of you at PHENO!

