NEUTRINO AS THE DARK FORCE

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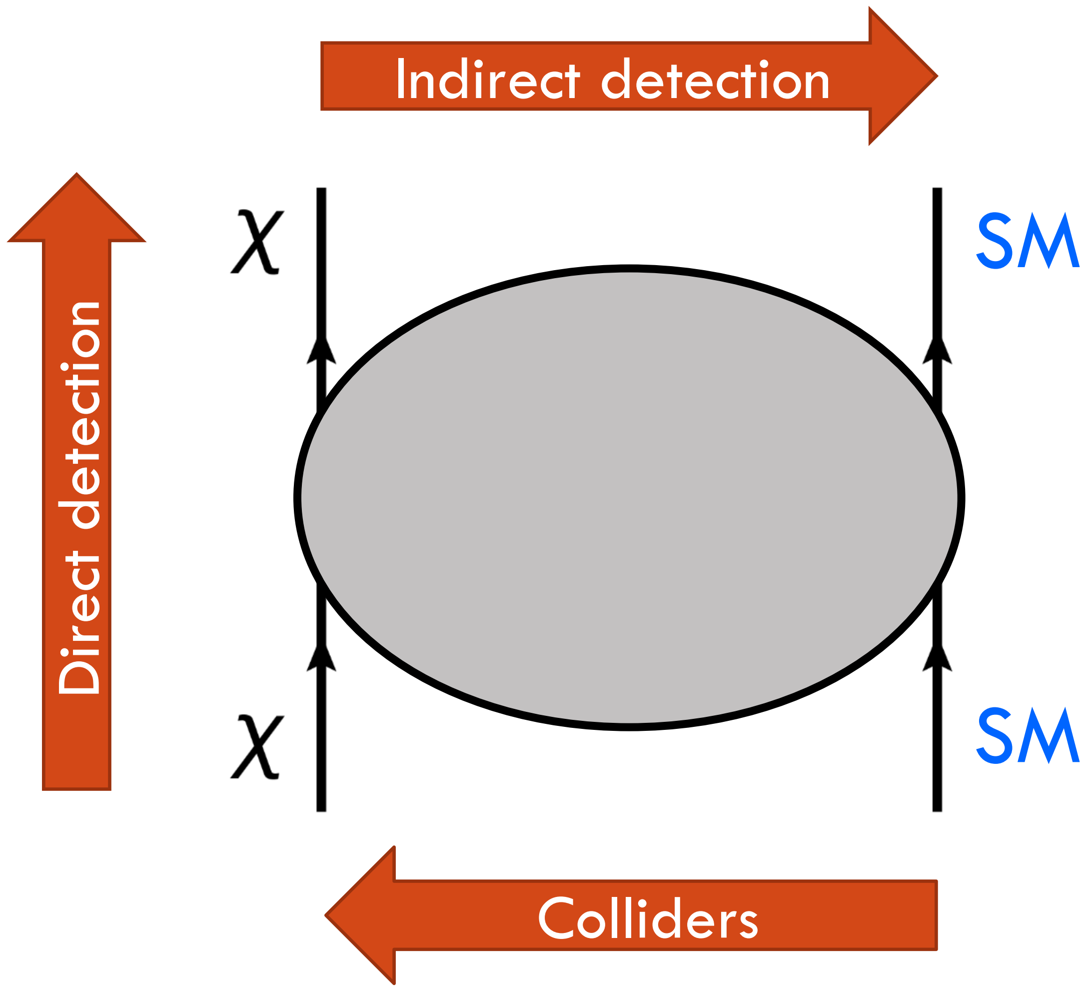
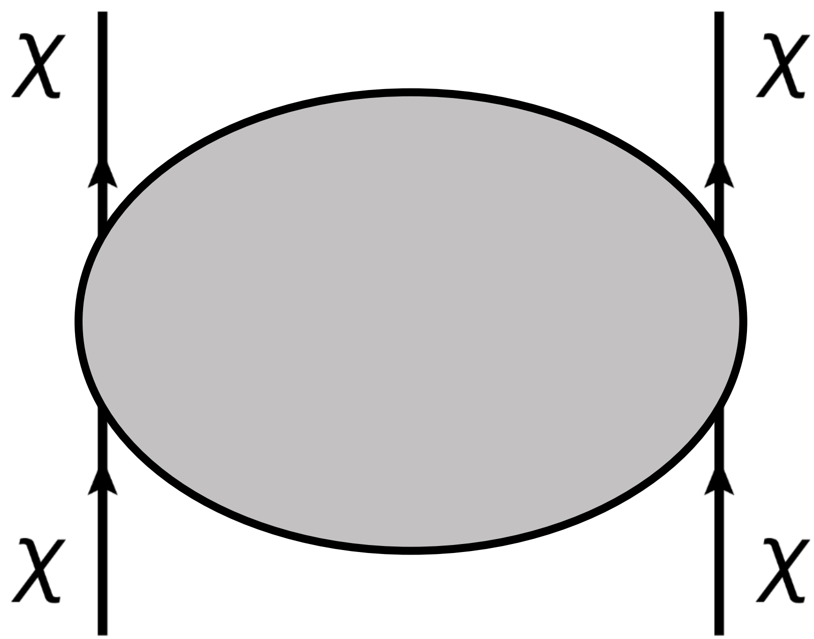
DARK MATTER INTERACTIONS



SELF-INTERACTING DARK MATTER

Dark matter may also have self-interactions.

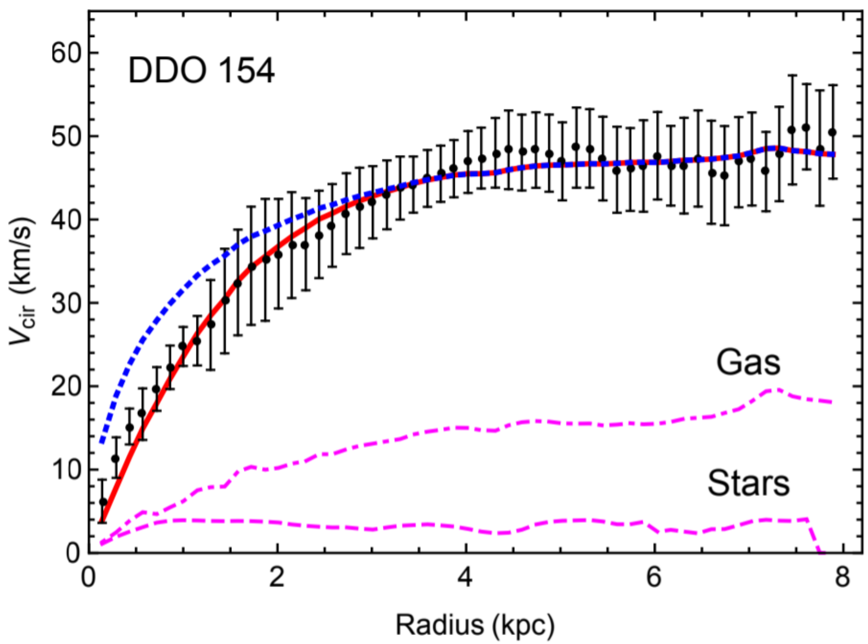
May solve many cosmological structure problems.

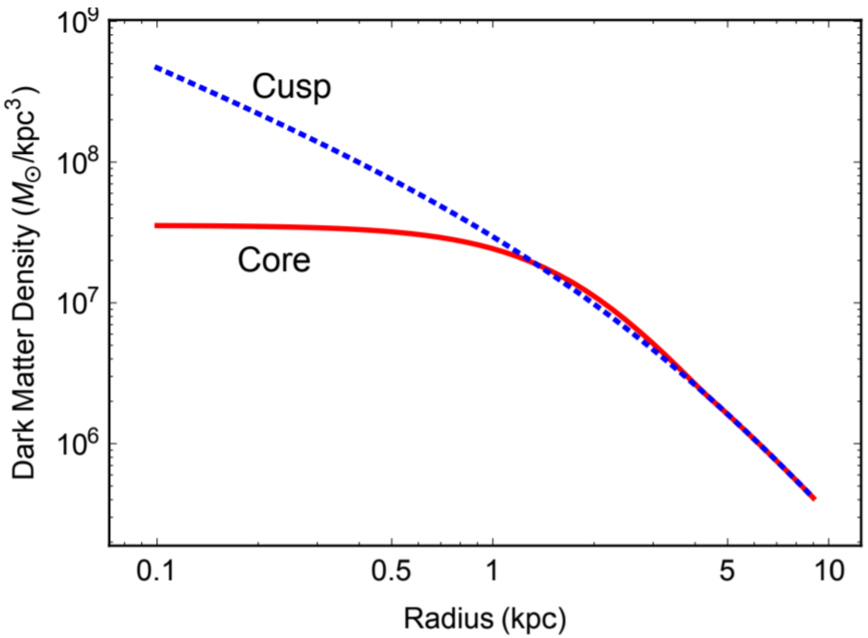


SELF-INTERACTING DARK MATTER

May solve many cosmological structure puzzles:

Core-cusp problem:



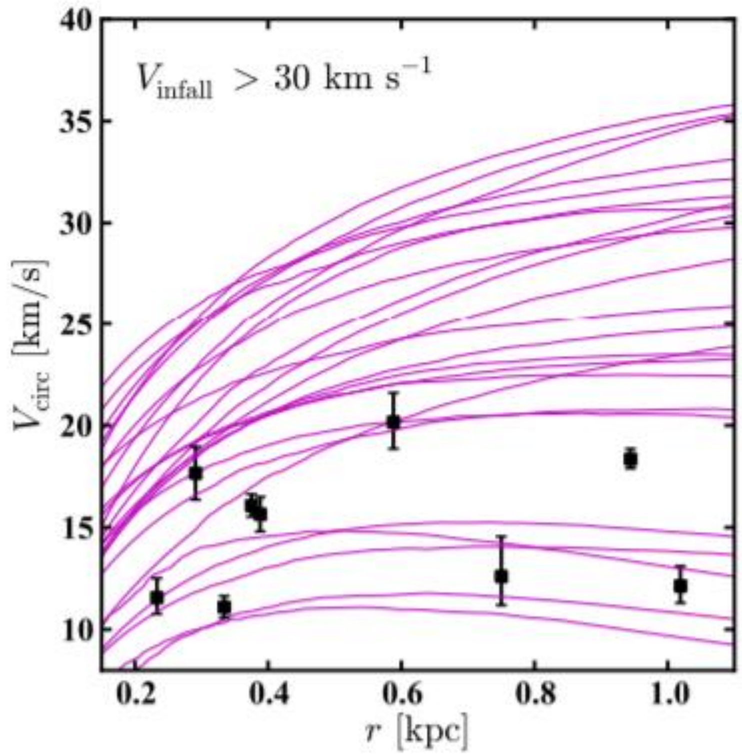


[Tulin, Yu 1705.02358]

SELF-INTERACTING DARK MATTER

May solve many cosmological structure puzzles:

Too big to fail problem:

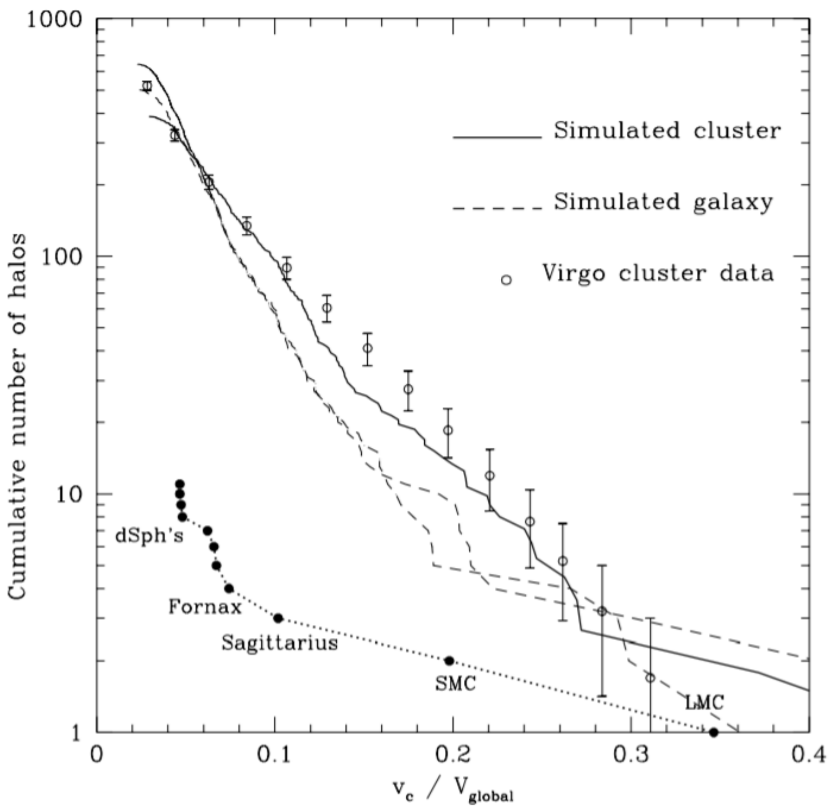


[Tulin, Yu 1705.02358]

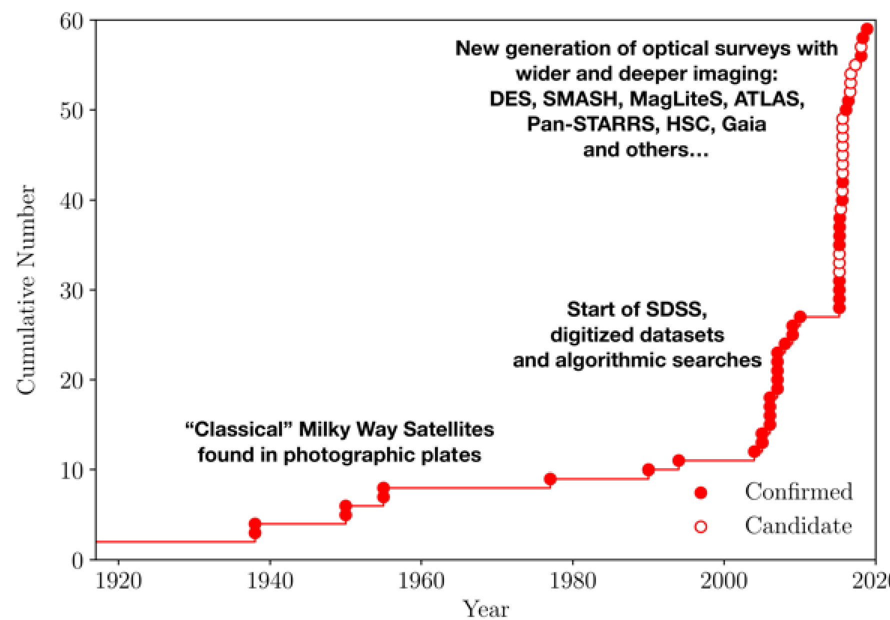
SELF-INTERACTING DARK MATTER

May solve many cosmological structure puzzles:

Missing satellite problem:



[Tulin, Yu 1705.02358]

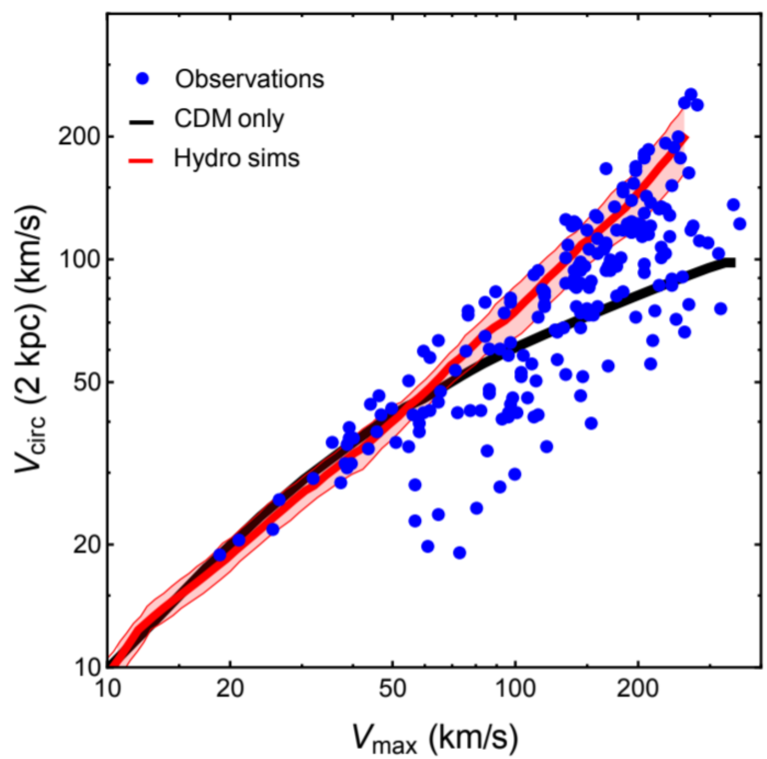


[Dark Energy Survey]

SELF-INTERACTING DARK MATTER

May solve many cosmological structure puzzles:

Diversity problem:



[Tulin, Yu 1705.02358]

SELF-INTERACTING DARK MATTER

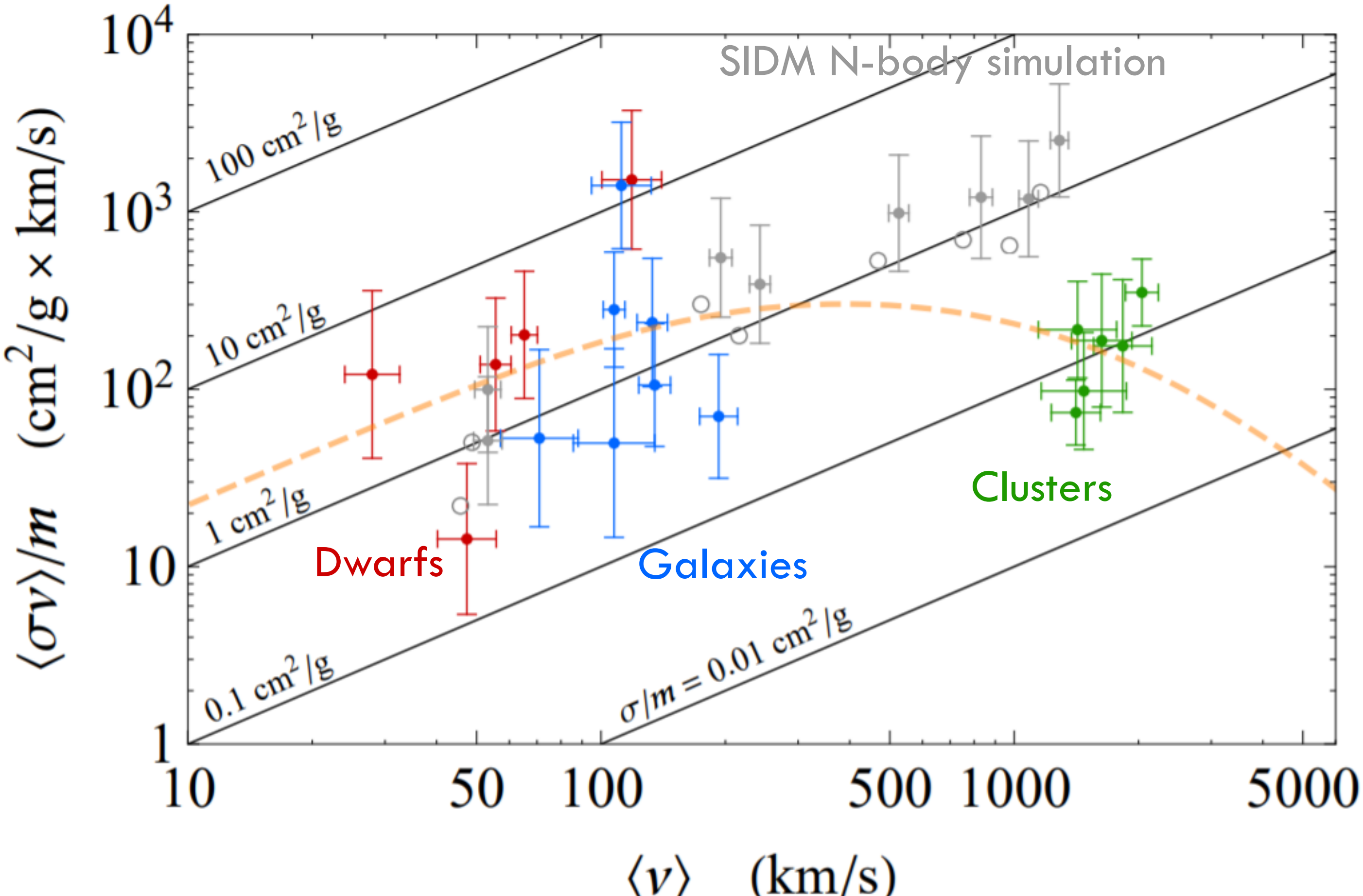
SIDM may solve many cosmological structure puzzles.

Some or all puzzles may or may not be explained by baryonic physics.
[Read, Gilmore astro-ph/0409565; Mashchenko, Wadsley, Couchman 0711.4803; Governato et al 1202.0554; Sawala et al 1511.01098; Wetzel et al 1602.05957; Fattahi et al 1607.06479]

Presents an interesting motivation for model building.

SELF-INTERACTING DARK MATTER

Favored cross sections:



[Kaplinghat, Tulin, Yu 1508.03339]

SELF-INTERACTING DARK MATTER

Interaction strength bounded by Bullet Cluster

$$\sigma/m \lesssim 1 \text{ cm}^2/\text{g for } v \sim 4000 \text{ km/s}$$

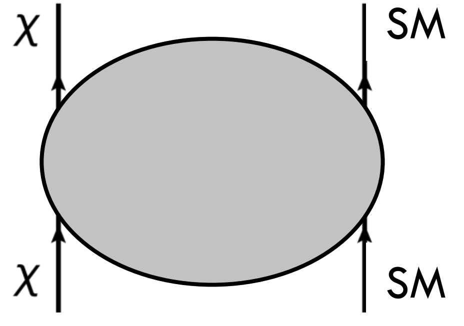
(http://apod.nasa.gov/apod/ap060824.html)

DARK MATTER INTERACTIONS

How might SIDM interact?

For its interactions to the Standard Model, there are 3 portals:

1. Higgs portal
2. Photon portal
3. Neutrino portal



First 2 involve adding a new light degree of freedom to mediate the DM-DM scattering. [Kaplinghat, Tulin, Yu 1310.7945]

Our work: neutrino portal allows neutrinos to mediate SIDM interactions.

NEUTRINO PORTAL

The neutrino portal effective Lagrangian:

$$\mathcal{L}_{\text{int}} = \frac{(\bar{L}_\alpha H)(\chi\phi)}{\Lambda_\alpha} + \text{h.c.}$$

$$\{\alpha = e, \mu, \tau\}$$

Where χ (fermion) and ϕ (scalar) are protected by global $U(1)$ or Z_2 symmetry, so lighter one (taken χ) is stable DM.

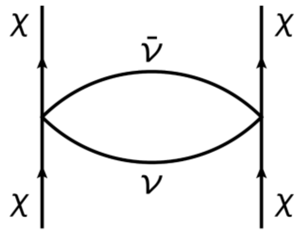
After electroweak symmetry breaking

$$\mathcal{L}_{\text{int}} = y_\alpha \bar{\nu}_\alpha \chi \phi + \text{h.c.}$$

Integrating out ϕ

$$\mathcal{L}_{\text{int}} \simeq \frac{|y_\alpha|^2}{2(m_\phi^2 - m_\chi^2)} (\bar{\chi}\gamma^\mu \mathbb{P}_R \chi)(\bar{\nu}_\alpha \gamma_\mu \mathbb{P}_L \nu_\alpha)$$

SIDM INTERACTION



$$\mathcal{L}_{\rm int} \simeq \frac{|y_\alpha|^2}{2(m_\phi^2 - m_\chi^2)}(\bar{\chi}\gamma^\mu \mathbb{P}_R \chi)(\bar{\nu}_\alpha \gamma_\mu \mathbb{P}_L \nu_\alpha)$$

Matrix element:

$$i\mathcal{M}(t) = \frac{-i|y_\alpha|^4}{24\pi^2(m_\phi^2 - m_\chi^2)^2}\left(\frac{1}{\epsilon} + \log\frac{\mu^2}{-t} + \frac{5}{3}\right)t$$

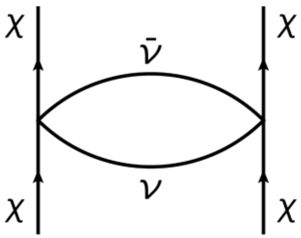
Long-range potential:

$$V(r) = \int \frac{d^3q}{(2\pi)^3}\frac{-1}{2\pi i}e^{-i\mathbf{q}\cdot\mathbf{r}}\int_0^\infty dt' \frac{\mathrm{disc}\mathcal{M}(t')}{t' - q^2}$$
$$= \frac{|y_\alpha|^4}{128\pi^3(m_\phi^2 - m_\chi^2)^2 r^5} ,$$

$1/r^5$ potential first pointed out in [Feinberg, Sucher '68] and studied in the SM. [Hsu, Sikivie hep-ph/921130; Stadnick 1711.03700; Thien, Krause 1901.05345; Ghosh, Grossman, Tangarife 1912.09444; Segarra, Bernabeu 2001.05900; Constantino, Fichet 2003.11032; Bolton, Deppisch, Hati 2004.08328]

Never been studied for the dark sector.

NEUTRINO-MEDIATED FORCE



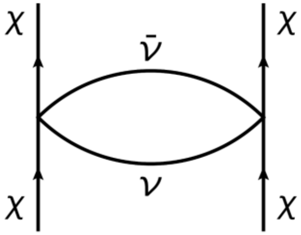
$$V(r) = \frac{|y_\alpha|^4}{128\pi^3(m_\phi^2 - m_\chi^2)^2 r^5} \ ,$$

$V(r)$ breaks down at small and large separations:

- Small separations $r \lesssim m_\phi^{-1}$ are unlikely for non-relativistic energies because the potential is repulsive [assumes asymmetric DM].
- Large separations $r \gtrsim m_\nu^{-1}$ has negligible potential energy compared to DM kinetic energy.

To good approximation, we can neglect these regimes.

NEUTRINO-MEDIATED FORCE



Leading S-wave term of the partial wave expansion, worked out analytically [Del Giudice, Galzenati '65]

$$\tan\delta_0 = \frac{3^{-2/3}\Gamma(-1/3)}{\Gamma(1/3)} f^{5/3} + \mathcal{O}(f^5) \; ,$$

$$f = k^{3/5}\left[\frac{\mu_{\chi\chi}|y_\alpha|^4}{64\pi^3(m_\phi^2 - m_\chi^2)^2}\right]^{1/5} \; ,$$

$$\left\{\mu_{\chi\chi} = m_\chi/2\right\}$$

Resulting cross section

$$\sigma_{\chi\chi\to\chi\chi} \simeq \frac{4\pi}{k^2}\sin^2\delta_0 \simeq 0.027\left[\frac{m_\chi|y_\alpha|^4}{(m_\phi^2 - m_\chi^2)^2}\right]^{2/3}$$

$\sigma/m \sim 6\, y_\alpha^{8/3}\,(10\ \mathrm{MeV}/m)^{-3}$ cm^2/g, velocity-independent!

Note: Born approximation does not give the correct result, predicting $\sigma \propto y^8$ instead of $y^{8/3}$.

MISSING SATELLITE PROBLEM

For large y_α, DM-neutrino interactions may remain in kinetic equilibrium down to low temperatures.

$$T_{\rm d} = 1.6 \text{ keV} \left(\frac{g_{\rm eff}(T_{\rm d})}{3.36}\right)^{1/8} \left(\frac{m_\chi}{20 \text{ MeV}}\right)^{1/4} \left(\frac{\sqrt{m_\phi^2 - m_\chi^2}}{35 \text{ MeV}}\right) \left(\frac{|y_\alpha|}{0.3}\right)^{-1}$$

Leads to collisional damping of acoustic oscillations in the DM density power spectrum.

The lower cutoff mass for small scale structures is then $\sim \rho\, H^{-3}(T_d)$:

$$M_{\rm cut} \simeq 10^8 M_\odot \left[\frac{|y_\alpha|}{0.3}\right]^3 \left[\frac{20\,\text{MeV}}{m_\chi}\right]^{\frac{3}{4}} \left[\frac{26\,\text{MeV}}{\sqrt{m_\phi^2 - m_\chi^2}}\right]^3$$

[Bertoni, Ipek, McKeen, Nelson 1412.3113]

COSMOLOGY CONSTRAINTS

Related constraint from Lyman-α on DM-neutrino scattering [Wilkensen, Boehm, Lesgourgues 1401.7597]:

$$\sigma_{\rm el}/m_\chi < 10^{-36}\,{\rm cm}^2/{\rm MeV}$$

The DM cannot be too light. Otherwise, it contributes to the dark radiation degrees of freedom during BBN. From Planck (combined with H_0 from Reiss et al)

$$\Delta N_{\rm eff} < 0.5$$

PARTICLE DECAY CONSTRAINTS

The dark sector particles will appear as missing energy in colliders.

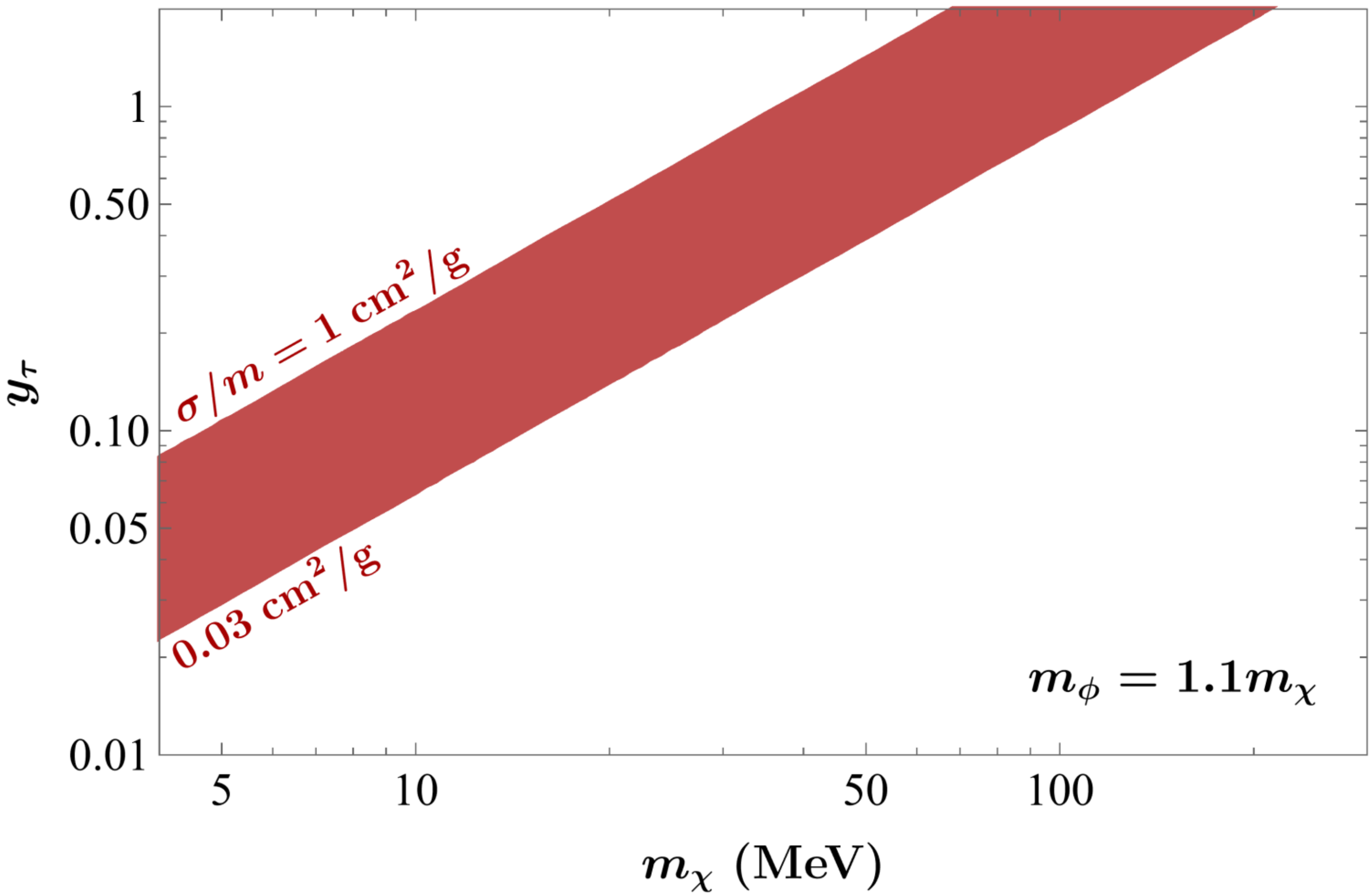
Can set limits on branching ratios from these channels:

- $Z \to \text{invis } (\bar{\nu}_\alpha \chi \phi + h.c.)$
- $h \to \text{invis } (\bar{\nu}_\alpha \chi \phi + h.c.)$
- $\tau \to \mu + \text{invis } (\bar{\nu}_\mu \chi \phi)$
- Charged meson decays $K \to \mu + \text{invis}; \pi \to \ell + \text{invis}$

The meson decays set much more stringent bounds on y_e and y_μ, excluding large enough SIDM cross section to solve small scale structure problems.

Thus, laboratory + SIDM constraints require $y_\tau \gg y_e, y_\mu$

PARAMETER SPACE



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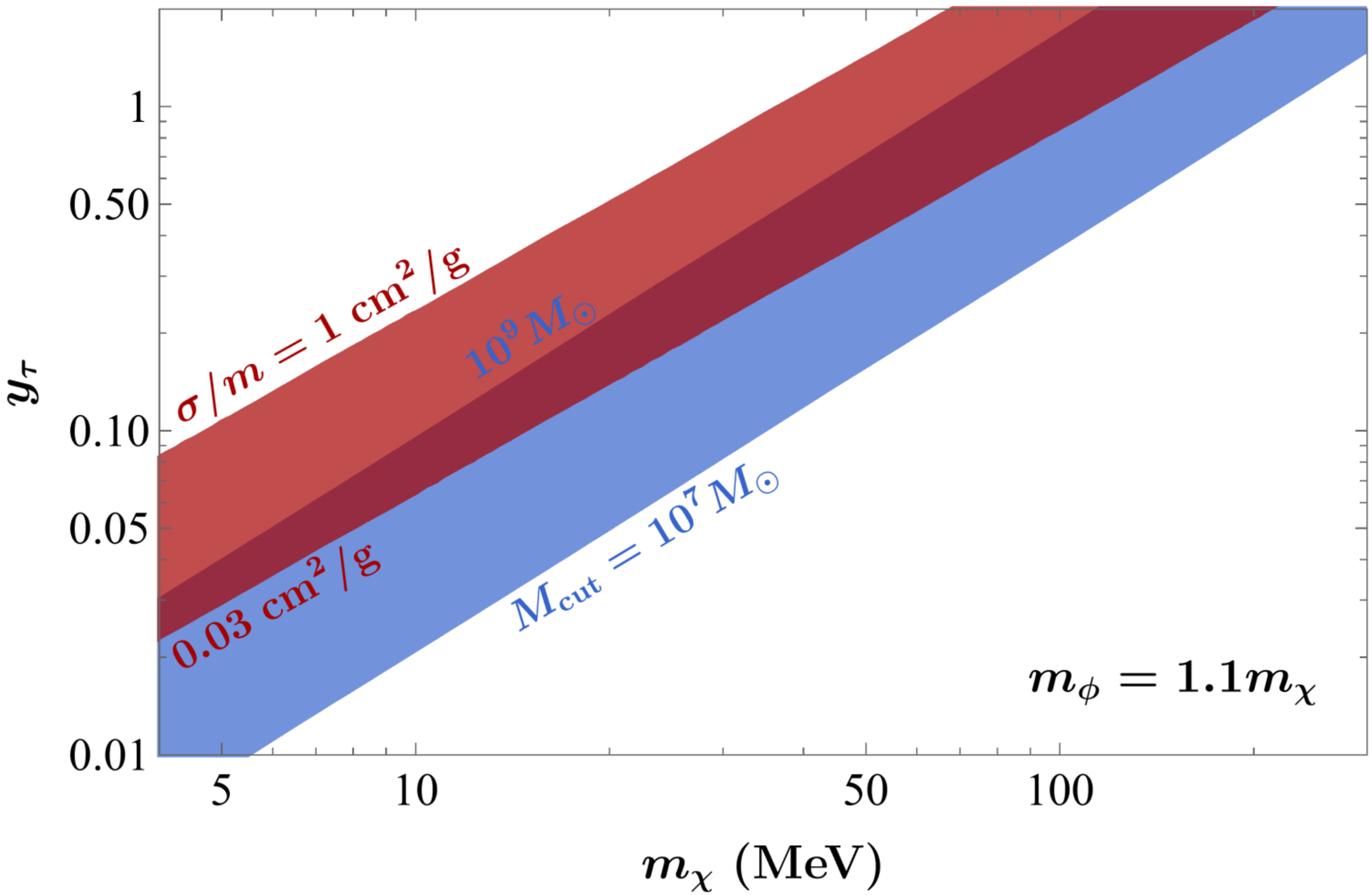

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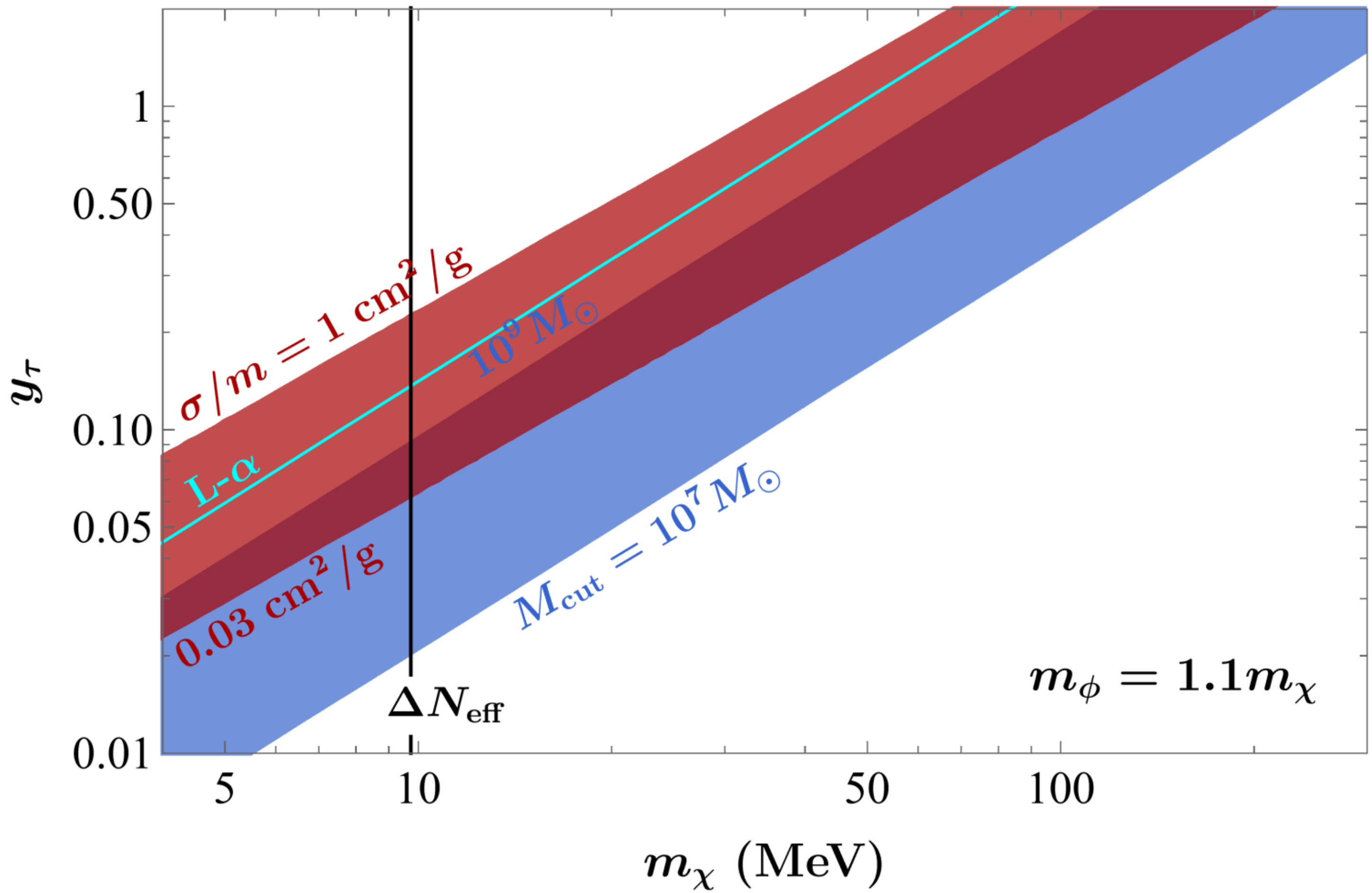

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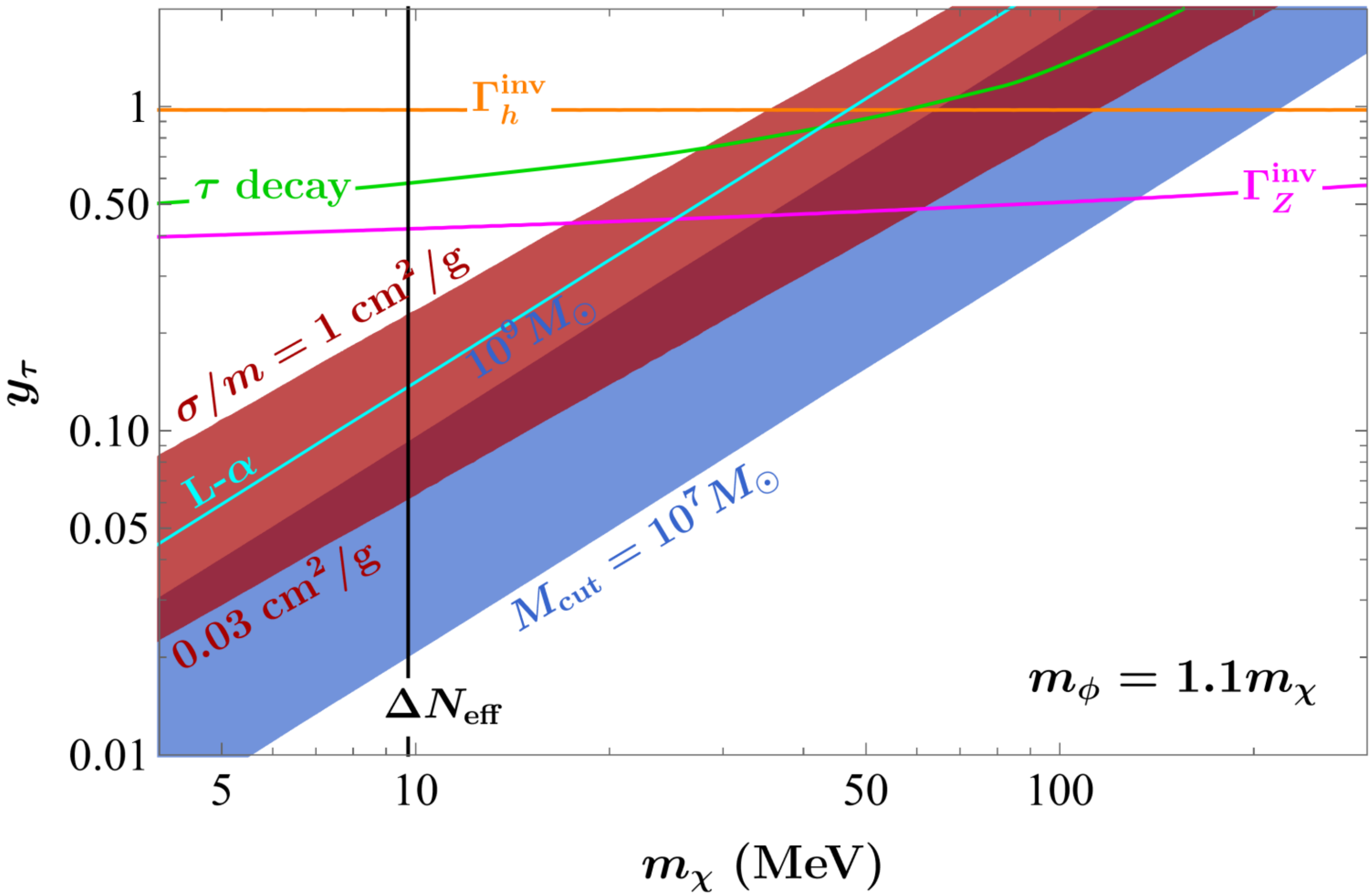
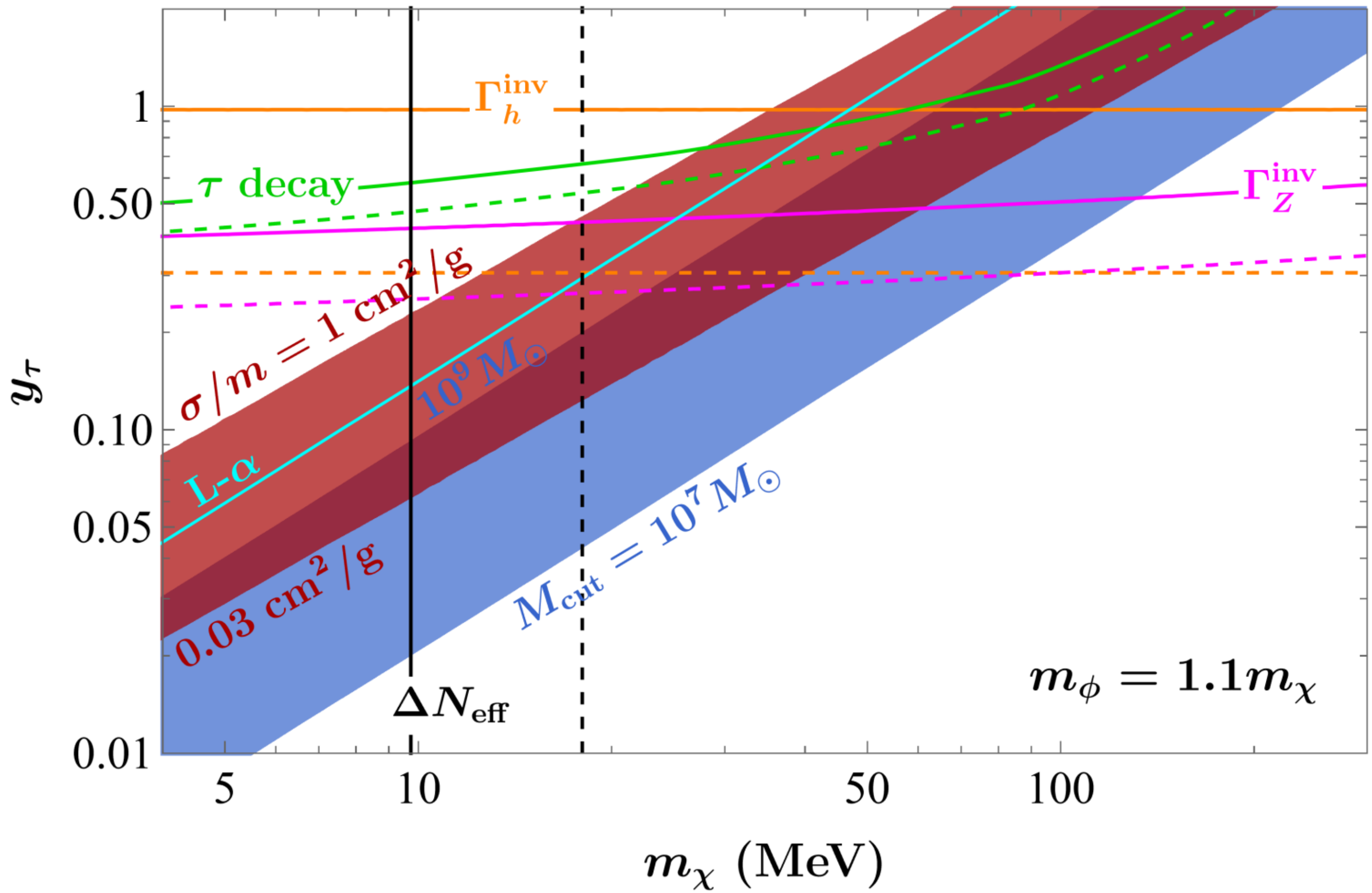


PARAMETER SPACE

<u>Future</u>:
h: HL-LHC
Z: Giga-Z lepton collider
τ: Belle II
ΔN_{eff}: CMB-S4



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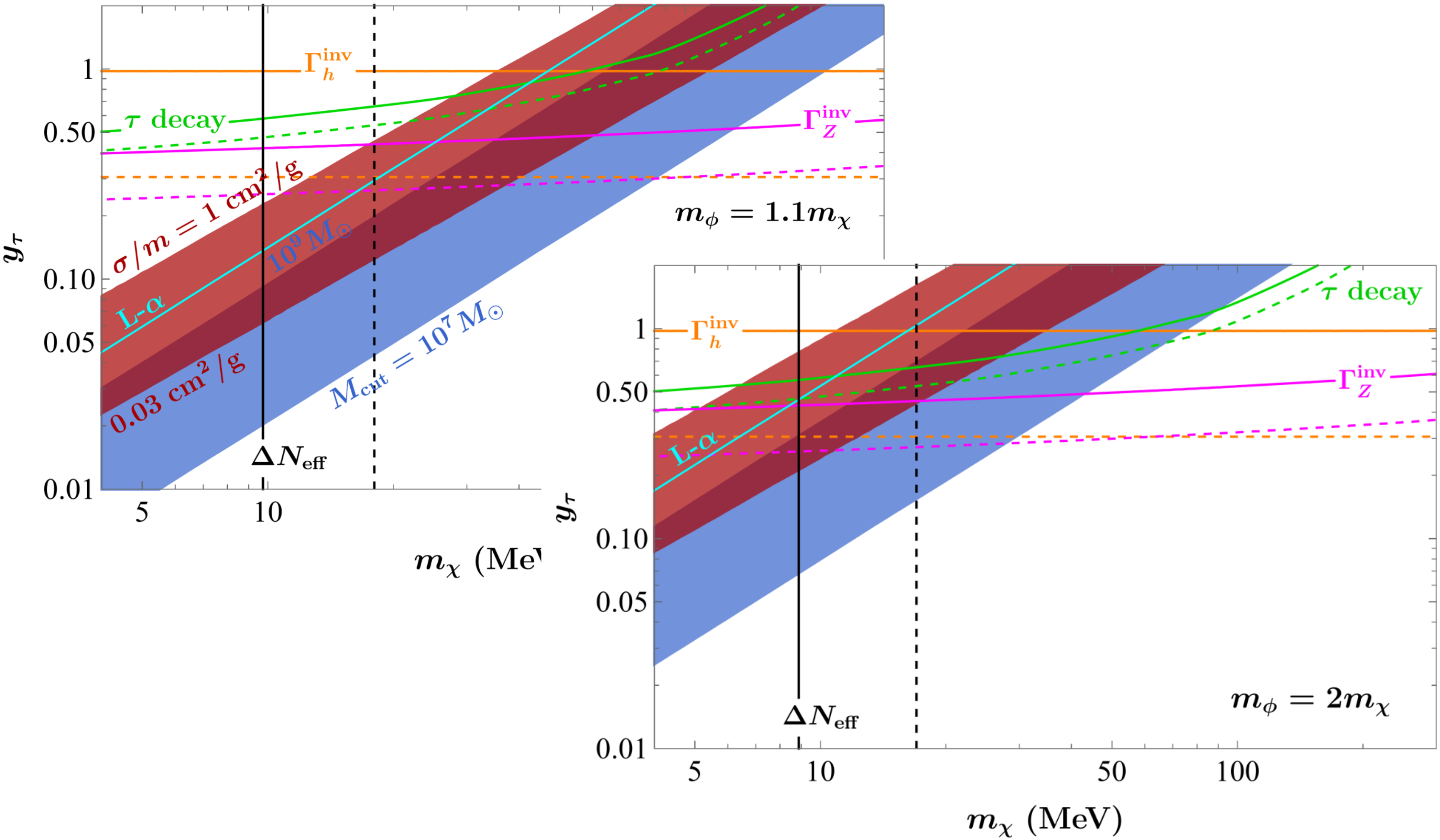

OTHER POSSIBILITIES

- We took χ to be asymmetric so that the interactions would be repulsive.
  However, the neutrinos mediate an attractive force between χ and $\bar{\chi}$.
  Requires detailed study of short-distance physics for consideration of the symmetric case.

- We kept ϕ mass large enough to integrate out.
  If it is smaller, χ could upscatter into ϕ via inelastic collisions.
  ϕ could then decay back to $\chi + \nu$, leading to dissipative DM.

- If ϕ and χ are completely degenerate, get a velocity-dependent momentum-transfer cross section at tree level:

$$\sigma_{\chi\phi\to\chi\phi} \simeq |y_\alpha|^4/(32\pi m_\chi^2 v^2) \quad \text{for} \quad m_\chi v \gg m_\nu$$

  But, need to do full calculation of non-perturbative multiple neutrino exchange.

SUMMARY

- SIDM can be **mediated by the SM neutrino.**
  No new light mediators required.

- Such neutrino-mediated SIDM is a natural possibility in the **neutrino portal** framework.

- The SIDM cross section is **velocity-independent.**
  Potentially falsifiable as a unified small-scale structure solution with better measurements and simulations.
  (Even in that case, could solve some problems.)

- Overlap with neutrino-DM interacting solution to missing satellite problem.

- Its guarantee coupling to the SM makes it **highly testable** by precision cosmology and SM particle decay measurements.