Dark Sector Phenomenology

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VIRGINIA TECH™

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Outline

- Dark Matter could well be a part of a whole new sector. How would we know?

- Non-gravitational phenomenology of DM is dictated by nature of interaction.

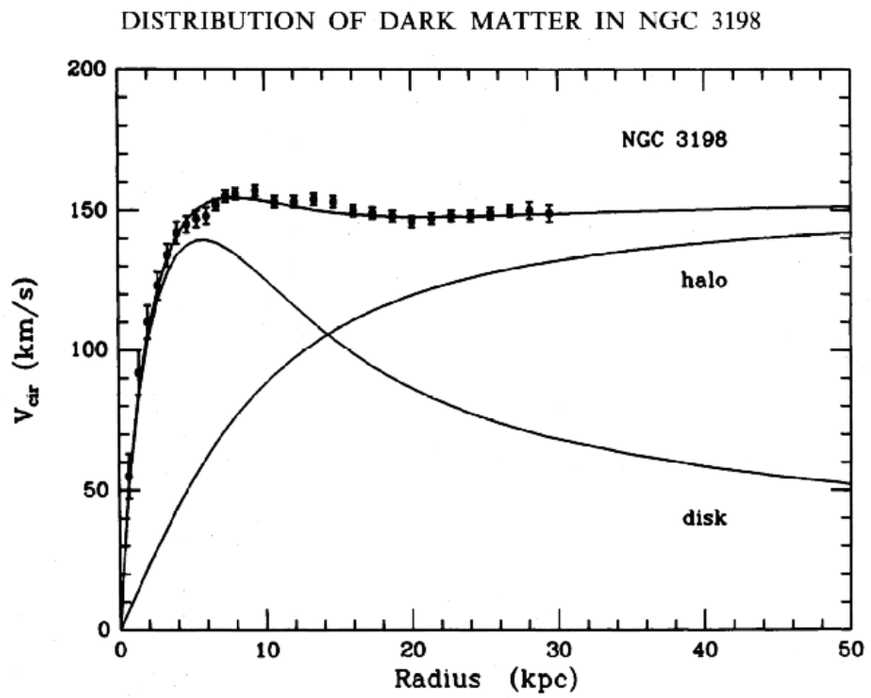
  - **Photon portal:** neutrino experiment searches, direct detection, …

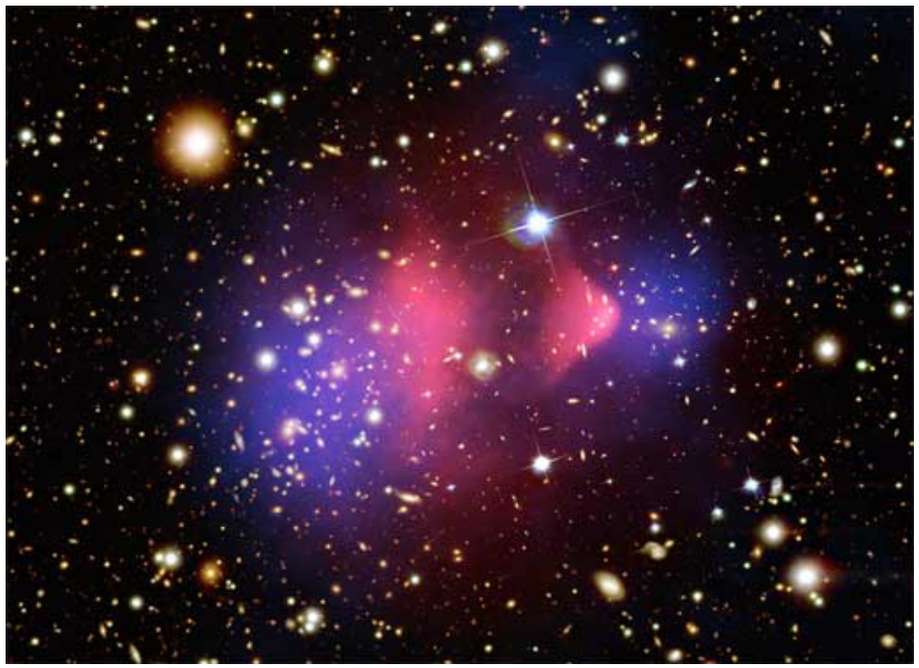
  - **Higgs portal:** rare meson decays, invisible Higgs, direct detection, …

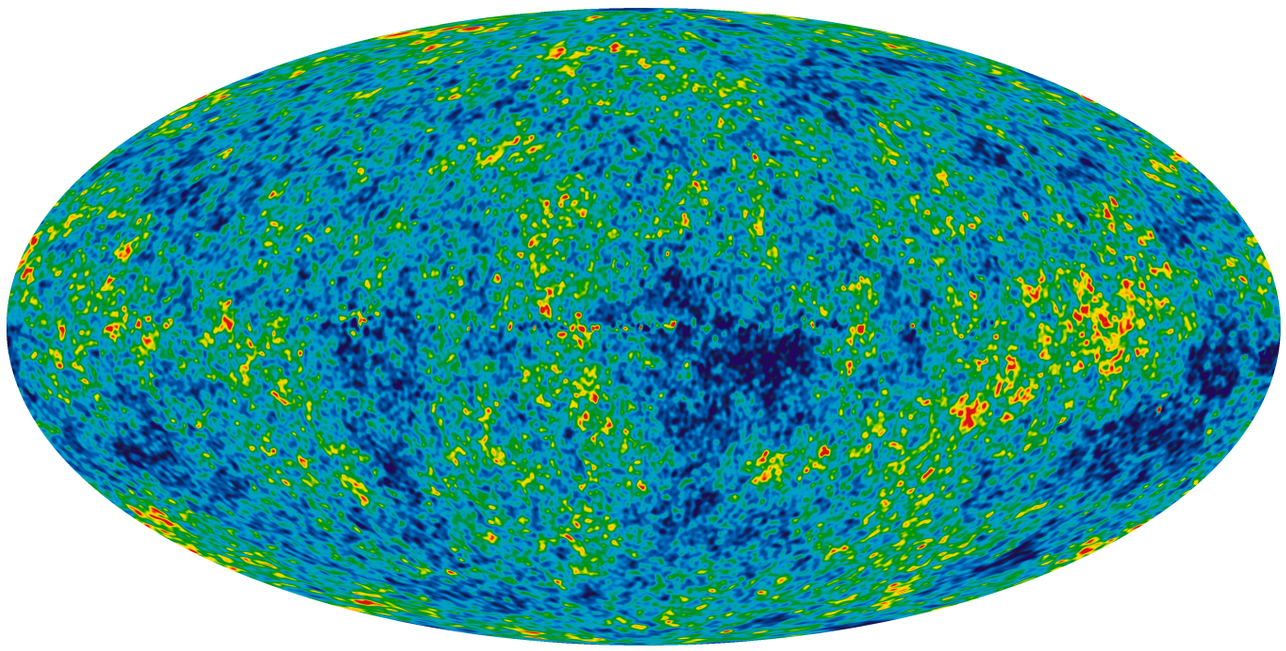
  - **Neutrino portal:** x-rays, neutrino-neutrino scattering, late kinetic decoupling, …

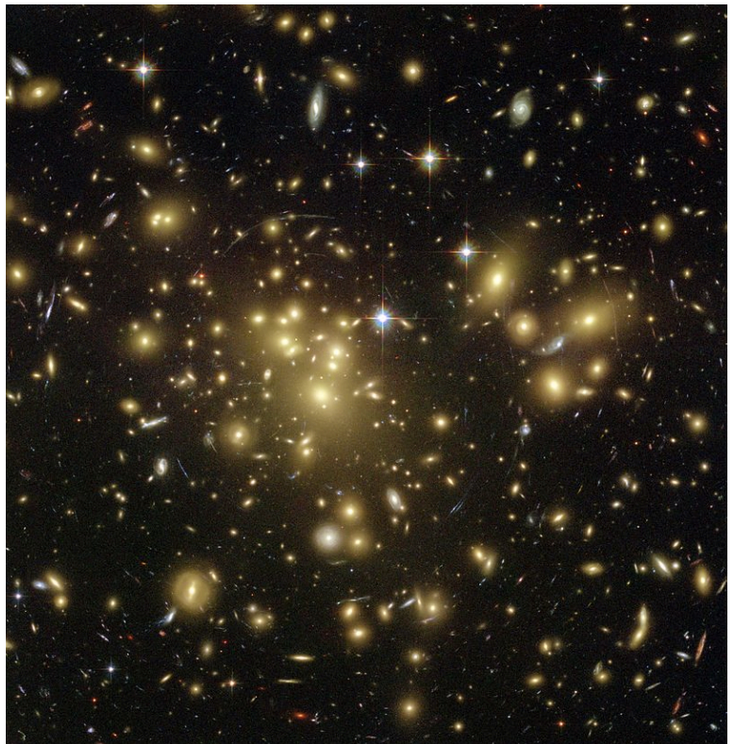
  - **Complementarity of Experimental Probes**

Most of the Universe's Matter is Invisible

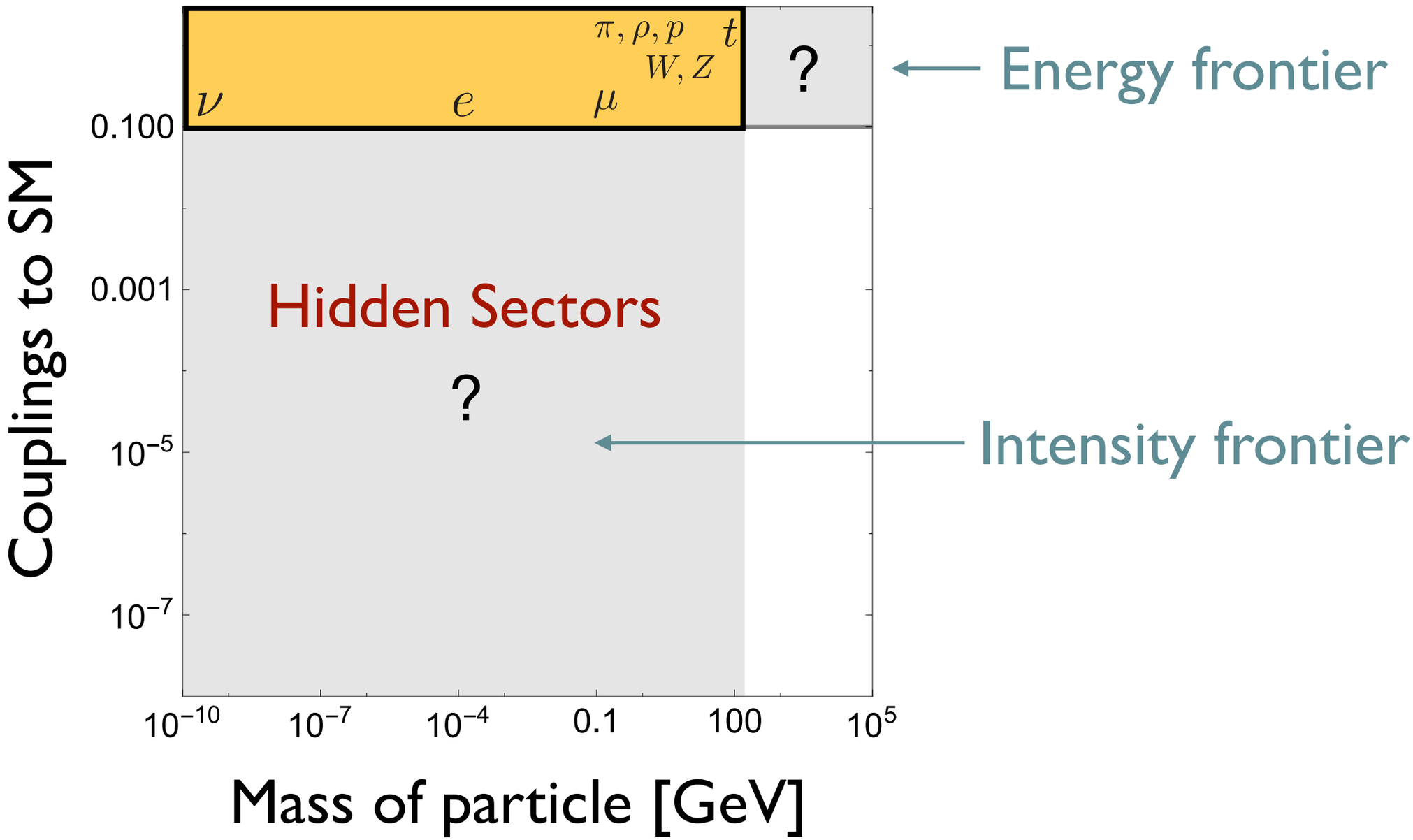






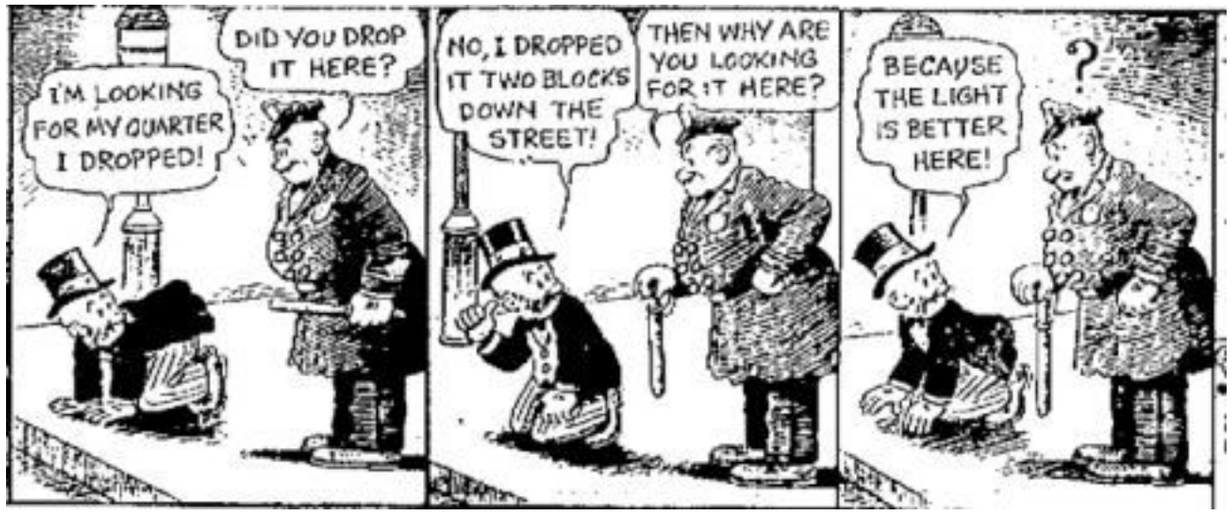


Where is the new physics?



Need a multi-pronged effort to find new physics.

Lampposts and BSM



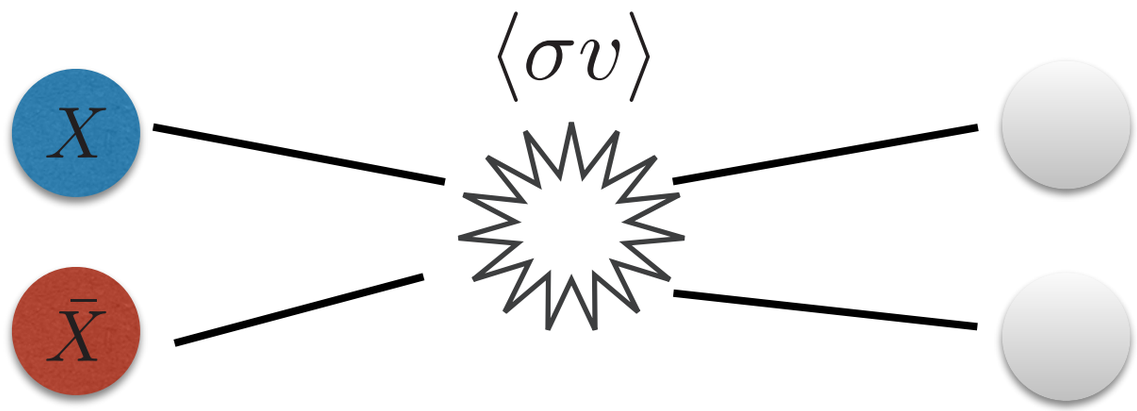
Implications of the lamppost :

1) **We have a lot of lampposts nowadays. Exploit synergies, complementarities.**
2) **Well-motivated & "cheap" new lampposts?**
3) **Might find interesting new physics beyond original intent.**

DM as a Thermal Relic

- The early Universe was a hot/dense place.

DM annihilation



lighter particles

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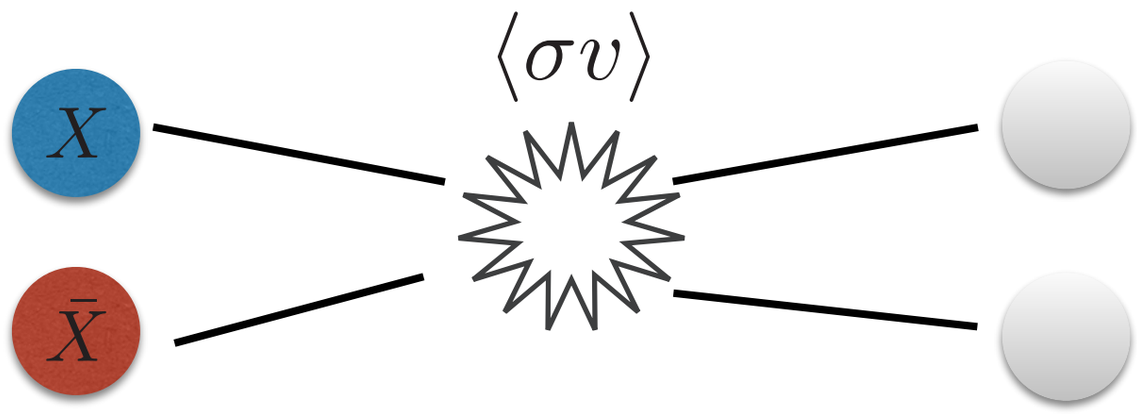

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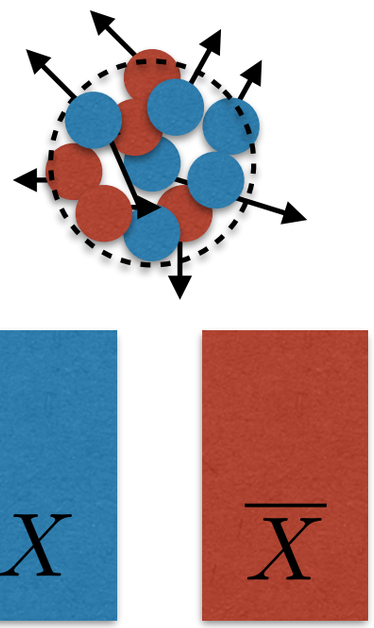

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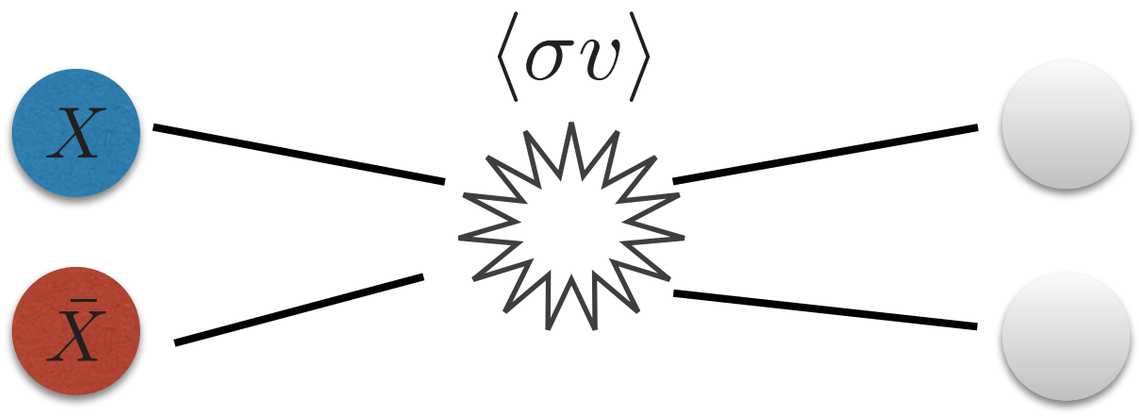

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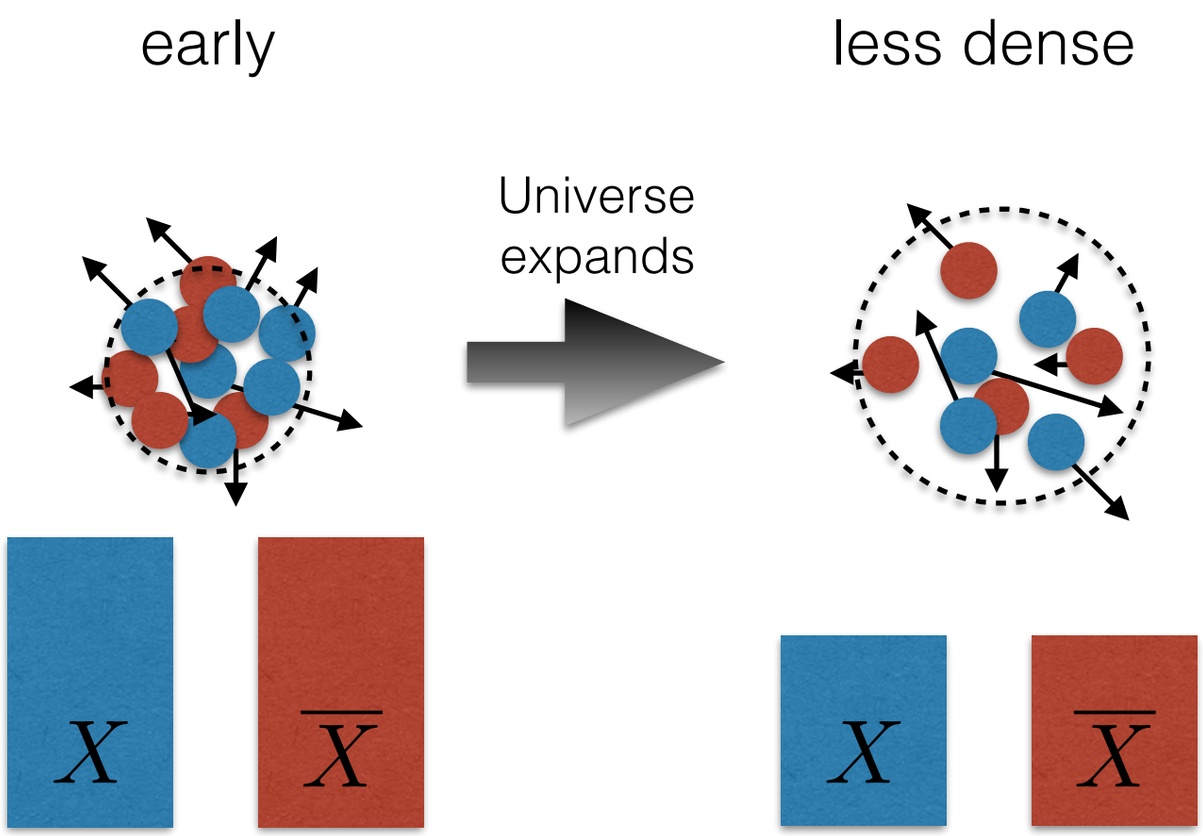

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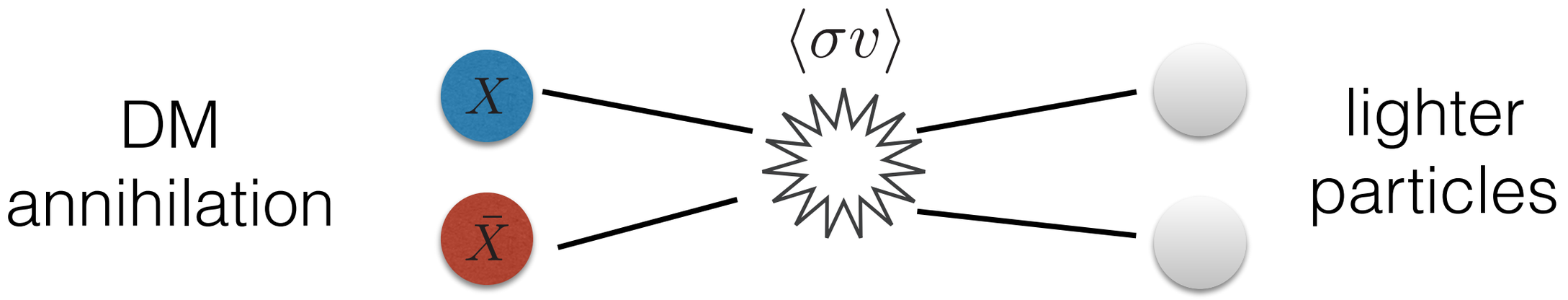

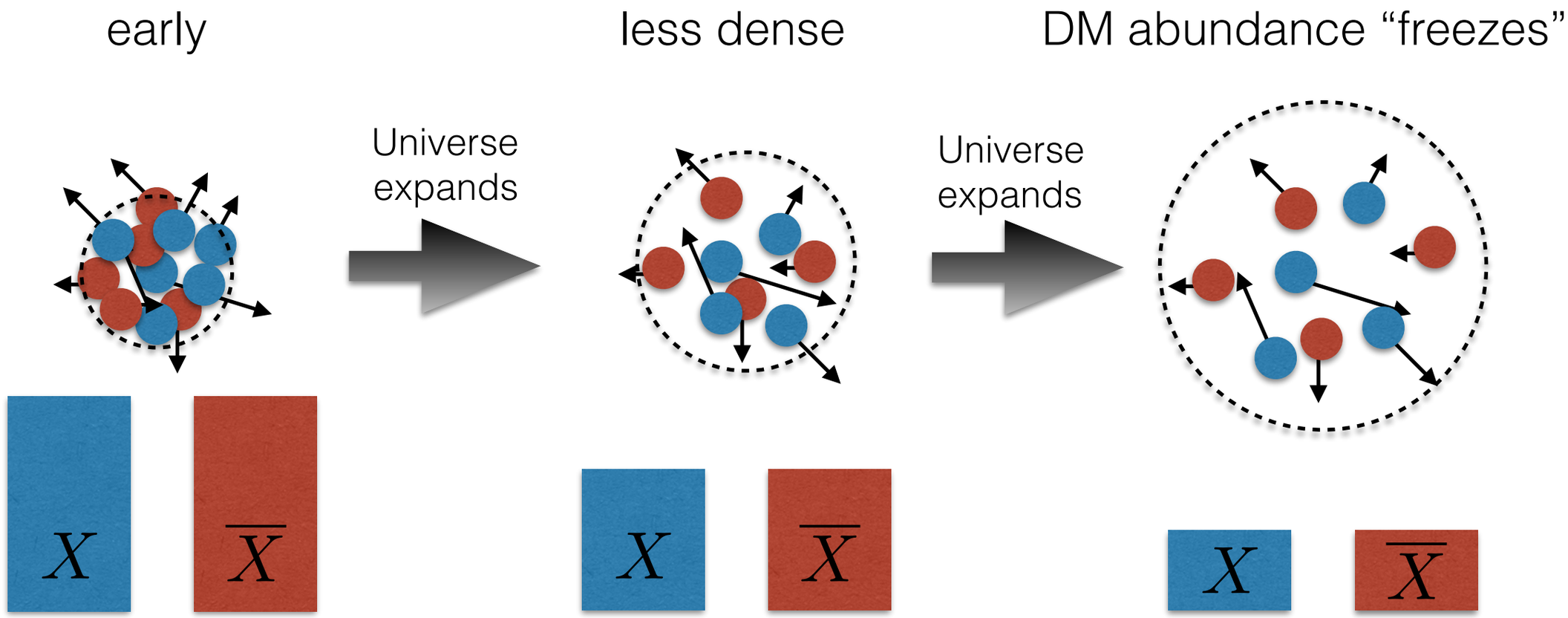

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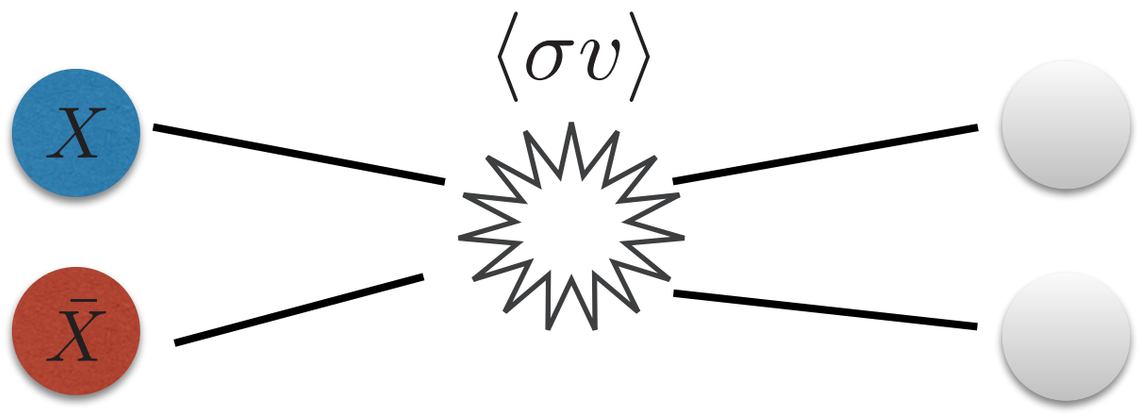

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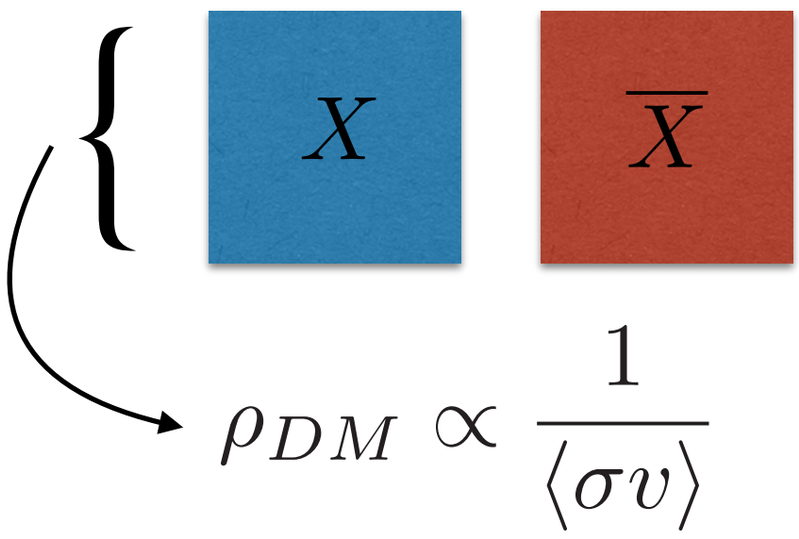
Final “freeze-out” abundance



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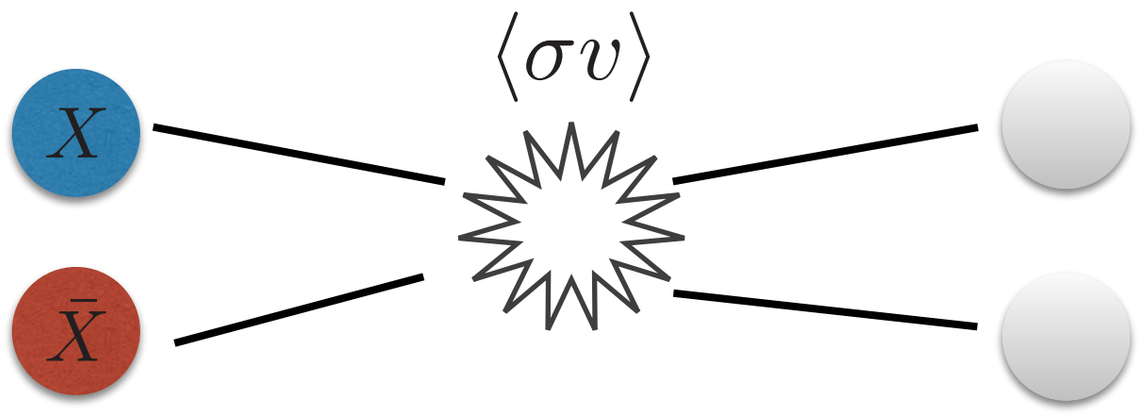

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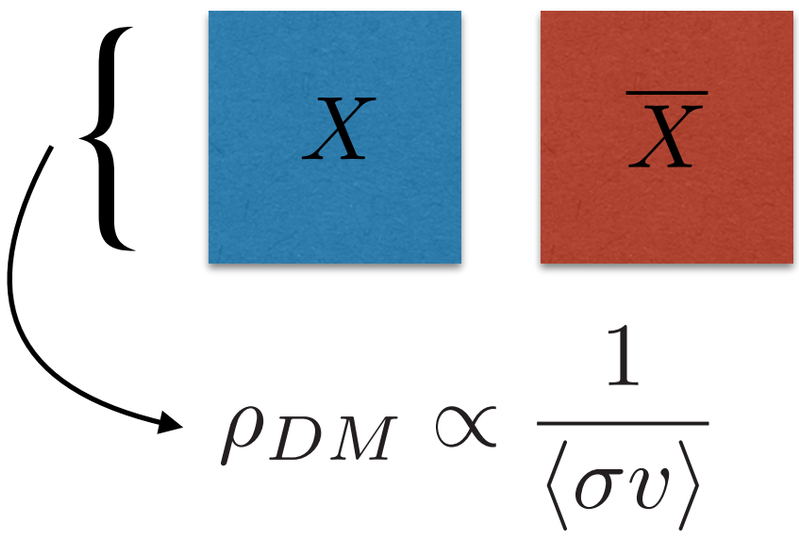

A thermal relic has the observed DM abundance if:

$$\langle \sigma v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

"WIMP miracle"

WIMP = Weakly-Interacting Massive Particle

Elegant, compelling,
but not **unique.**

What about baryons?

- **The amounts of dark and visible matter are comparable:**

$$\Omega_{DM} h^2 = 0.1109 \pm 0.0056$$

$$\Omega_B h^2 = 0.002258^{+0.00057}_{-0.00056}$$

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  - A remarkable coincidence.
  - An anthropic selection effect? [Freivogel (2008)]
  - An indication of an underlying origin.

Asymmetric DM

(Reviews: Petraki, Volkas [1305.4939]; Zurek [1308.0338])

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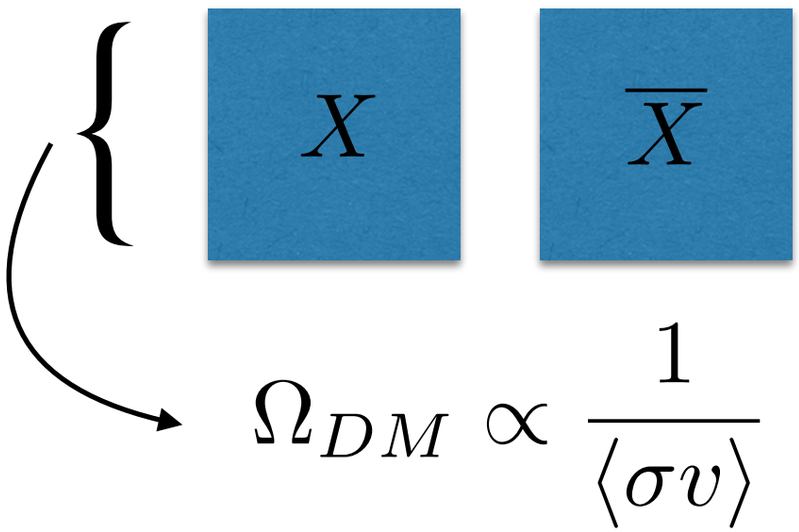

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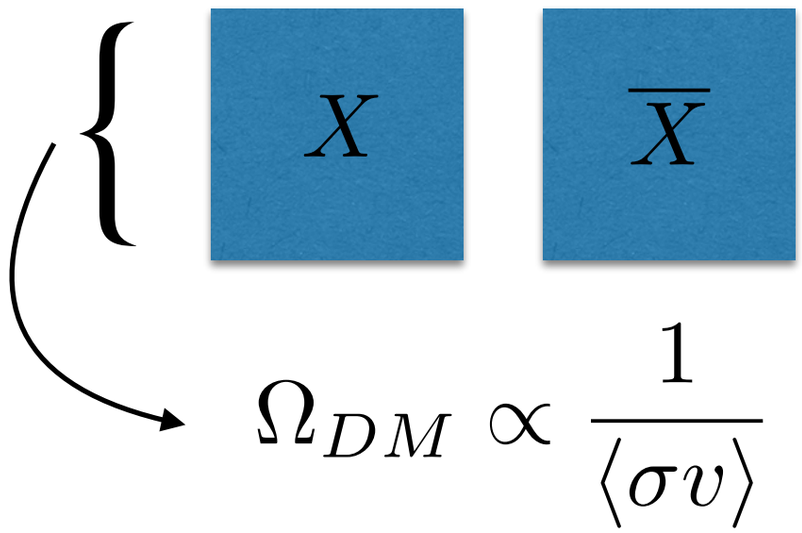

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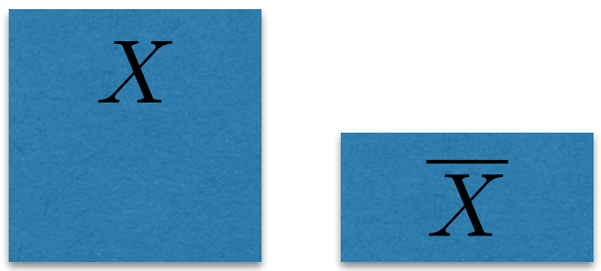

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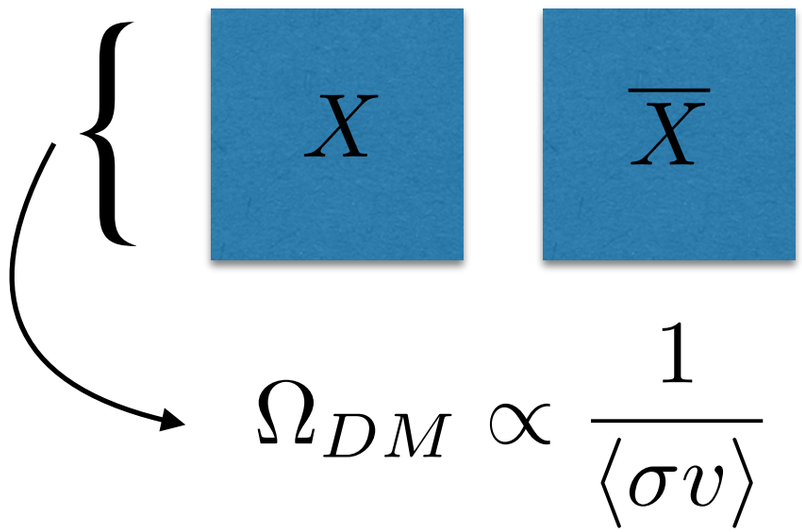

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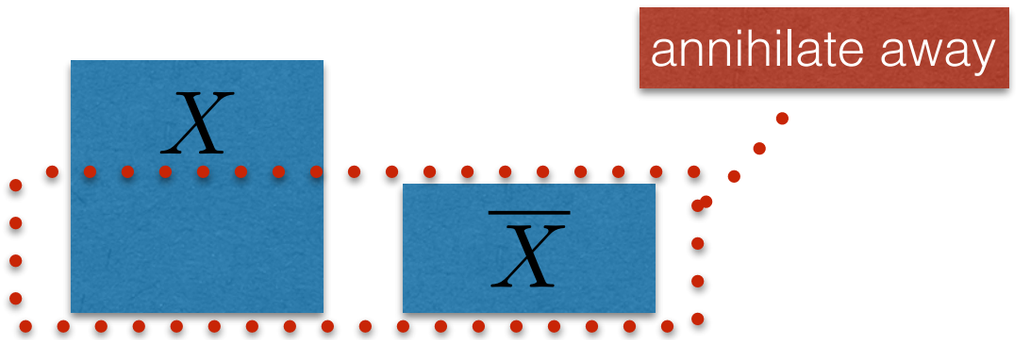

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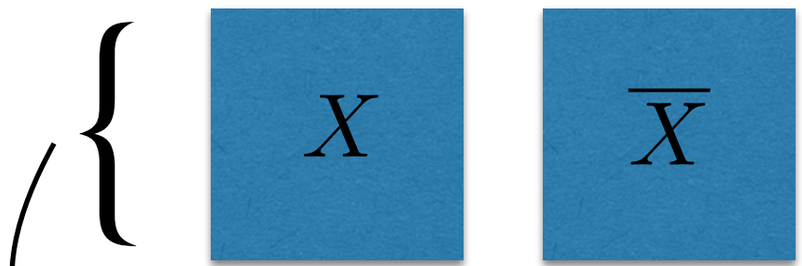
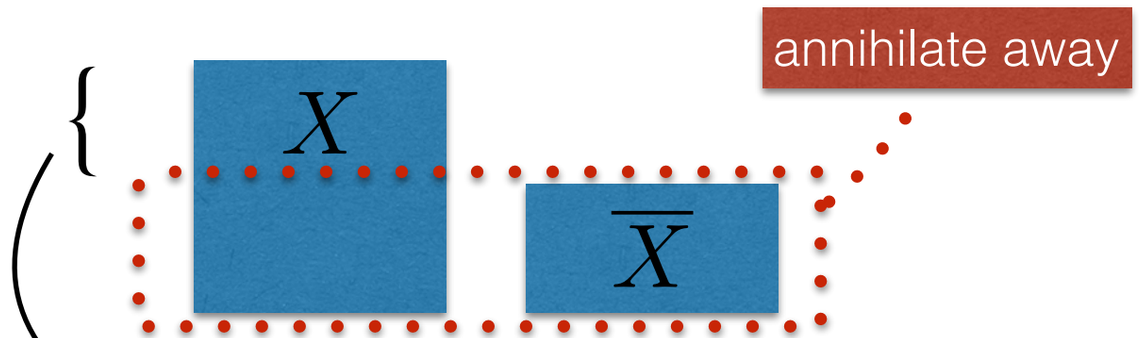


$$\Omega_{DM} \propto \frac{1}{\langle \sigma v \rangle}$$

asymmetric DM



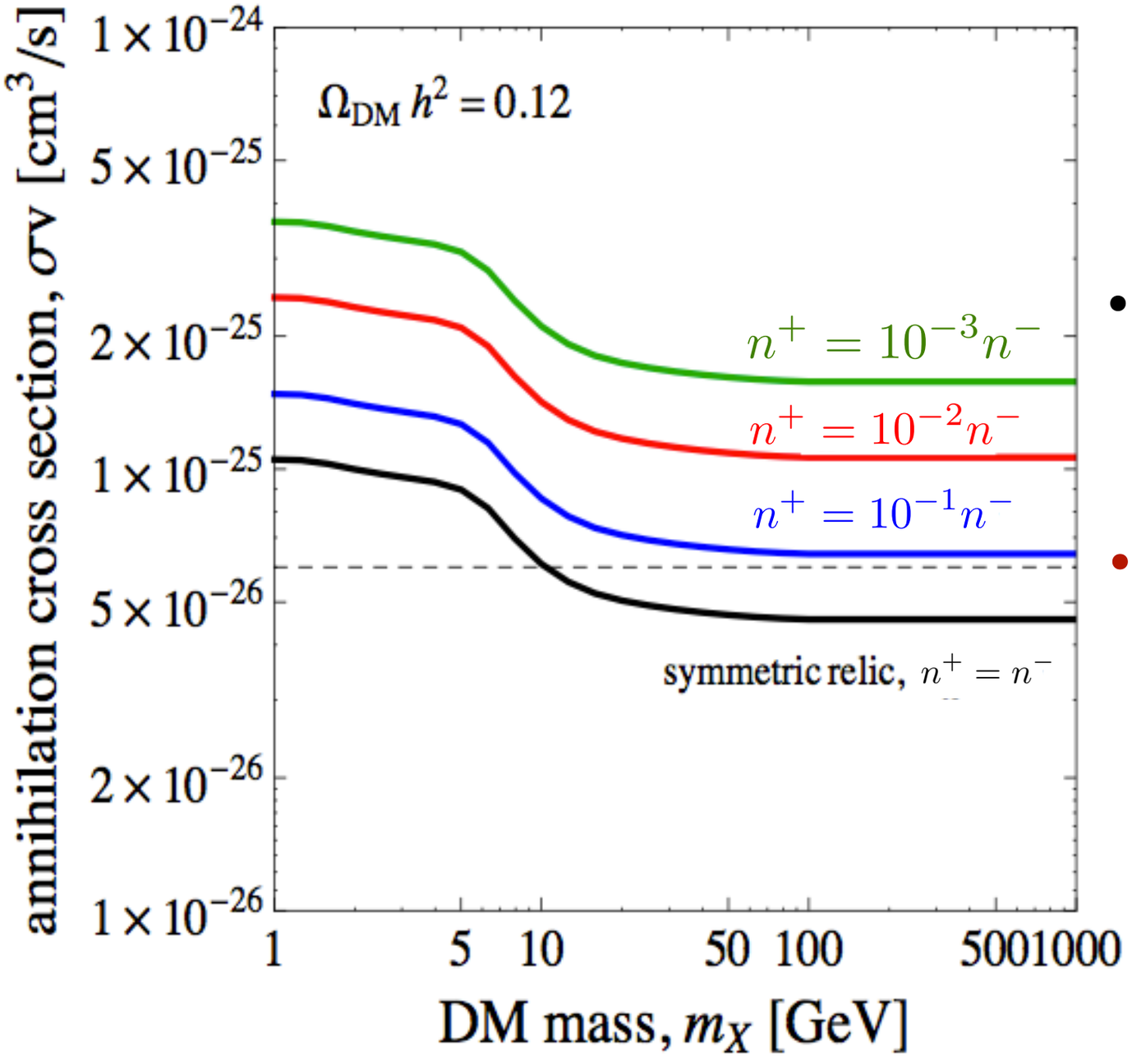
$$\Omega_{DM} \propto \text{excess}$$

ADM "Miracle" Cross Sections

Michael Graesser, **IMS**, and Luca Vecchi, JHEP 1110 (2011) 110.

Lin, Yu, Zurek, Phys.Rev. D85 (2012) 063503 .

Nicole Bell, Shunsaku Horiuchi, **IMS**, *Phys.Rev.* D91 (2015) 2, 023505.



- **Size of cross section, will yield different anti-particle abundances.**
- **Cross sections needed are larger than the symmetric case.**

Questions:
1. How does the requisite annihilation occur?
2. How do we test it?

Light DM via Light Mediators

[Lee, Weinberg (1977)]

- Suppose we like **sub-GeV** DM but also like Occam, and want to just use the **SM weak force** to yield the relic abundance of DM.

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- To regimes for annihilation:

$$\langle \sigma v \rangle \sim \frac{g^4 m_X^2}{m_W^4}$$

[light DM, (<<W mass)]

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[heavy DM]

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Fails for sub-GeV DM.

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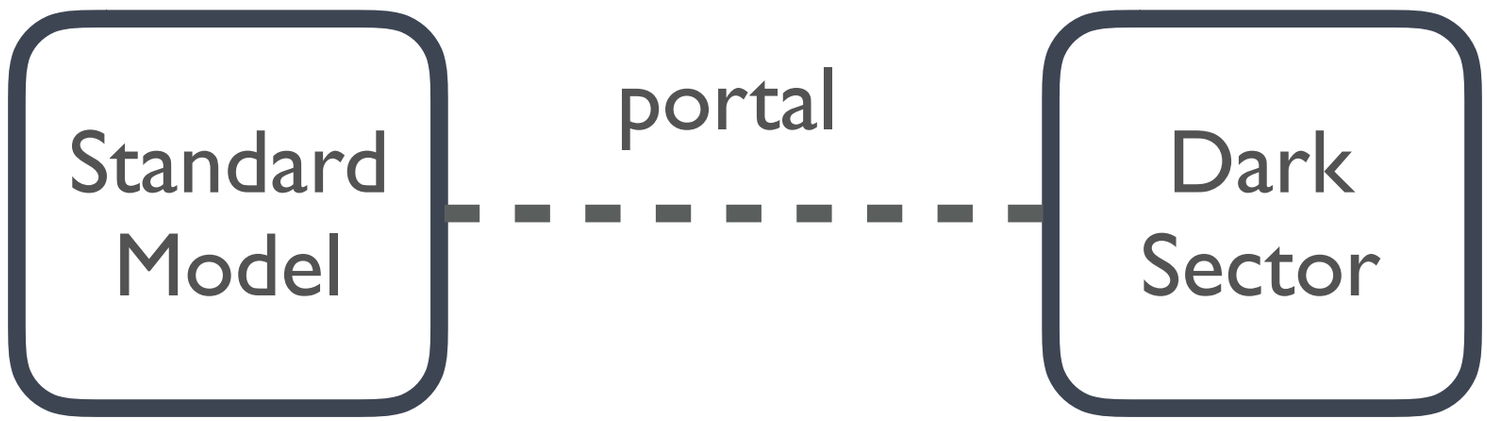
Simple escape route for sufficient annihilation: light DM is non-Occam!
Comes with a light mediator to facilitate annihilation.

[Boehm, Fayet (2003)]

Dark Sectors

Dark (Hidden) ((Secluded)) Sector Models

[Batell, Pospelov, Ritz (2009)]



A dark world hiding alongside our world only connected through a “portal” interaction (and gravity).

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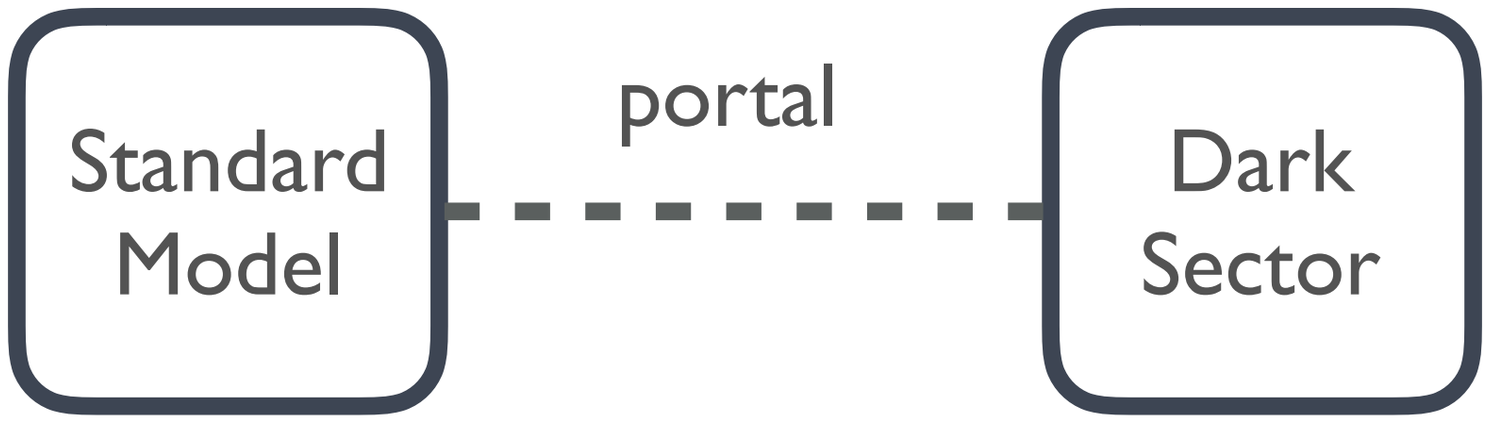
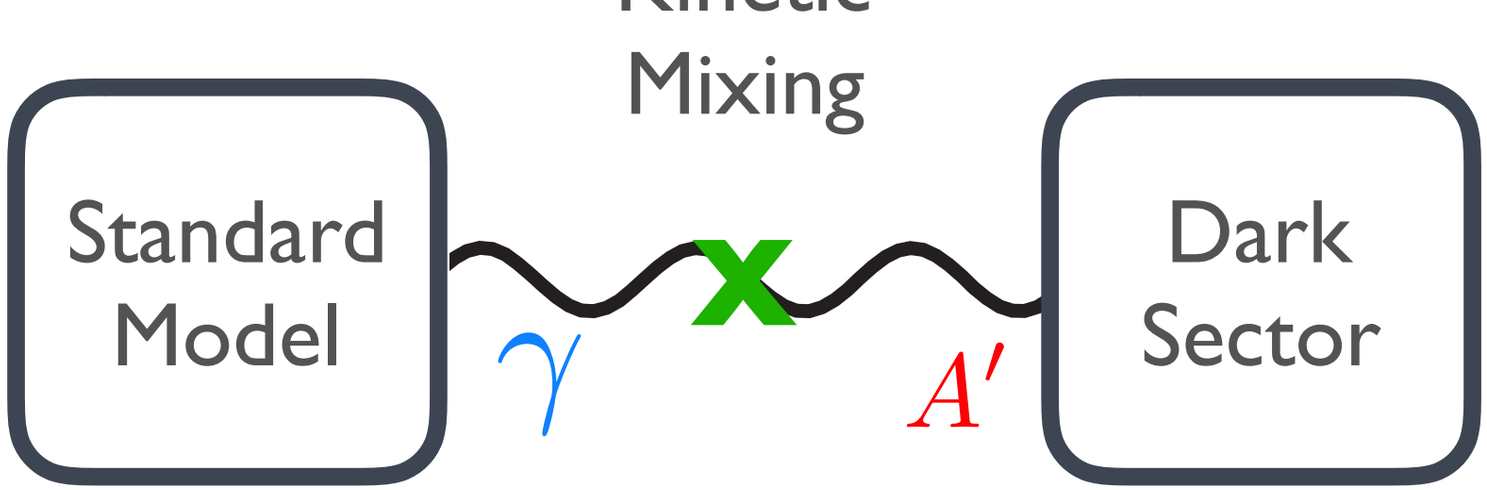


$$\mathscr{L}_{\text{portal}} = \begin{cases} \epsilon F_{\mu\nu} F_h'^{\mu\nu} & \text{(photon portal)} \\ h|H^2||H_h^2| & \text{(Higgs portal)} \\ y(LH)N & \text{(neutrino portal)}, \end{cases}$$

Only 3 renormalizable portals!

Part 1

Photon Portal



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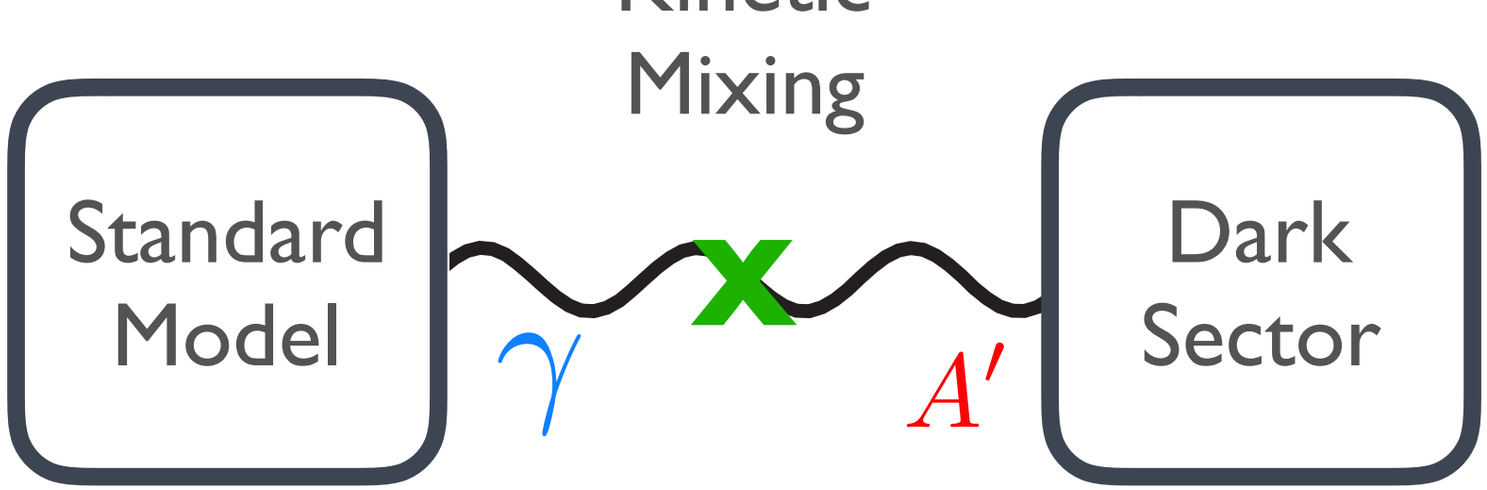

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Photon Portal DM

[Holdom 1986; Batell, Pospelov, Ritz, 0906.5614]

$$\mathcal{L}_{V,\chi} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 + \epsilon V_{\mu\nu} F^{\mu\nu} + \dots$$

$$D_\mu = \partial_\mu - i g_D V_\mu \ , \quad g_D = \sqrt{4\pi\alpha_D}$$

4 parameters: $m_\chi,\ m_V,\ \epsilon,\ \alpha_D$

- **For scalar DM, annihilation to SM particles is velocity-dependent (p-wave).**

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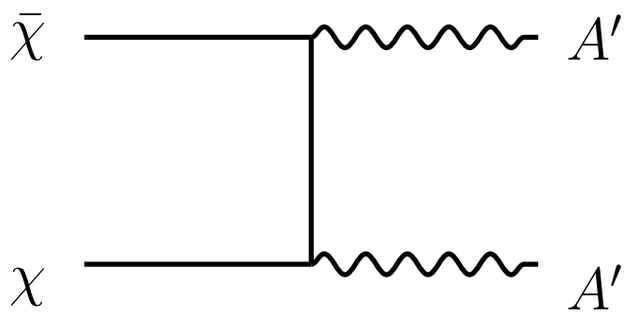
- **Simple modification with Fermion DM works if Asymmetric (i.e. antiparticles << particles).**

Thermal Relic Targets

$\sigma v \propto \alpha_D^2$

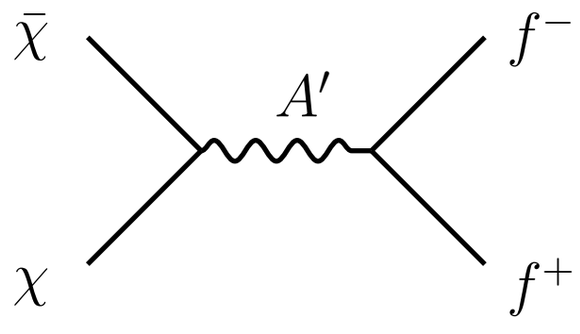


Secluded annihilation

$m_\chi > m_{A'}$

A' visibly decays

$\sigma v \propto \epsilon^2 \alpha_D$



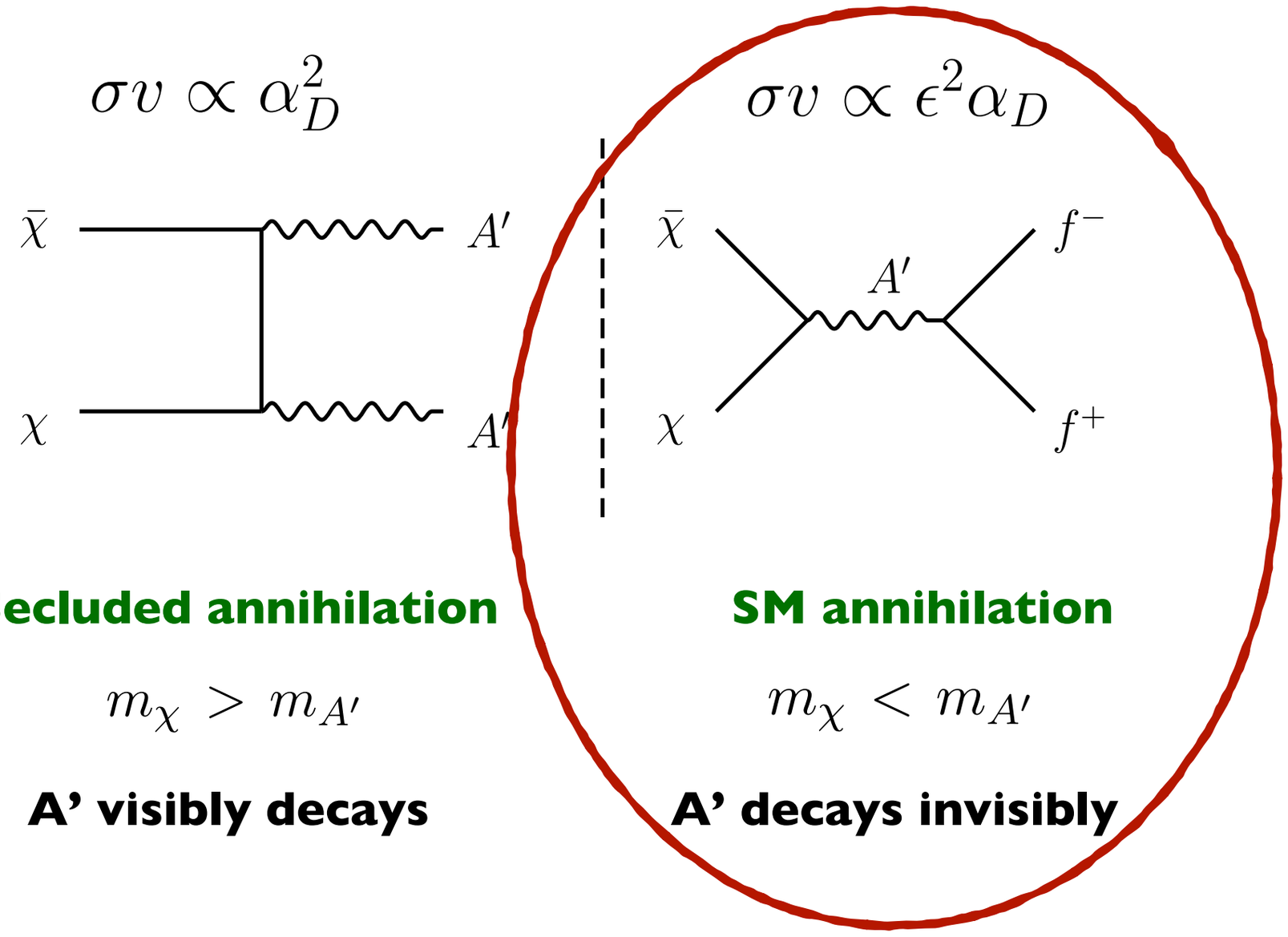
SM annihilation

$m_\chi < m_{A'}$

A' decays invisibly

$$\sigma v(\chi\chi \to A'^* \to f f) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2} \quad , \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

Thermal Relic Targets



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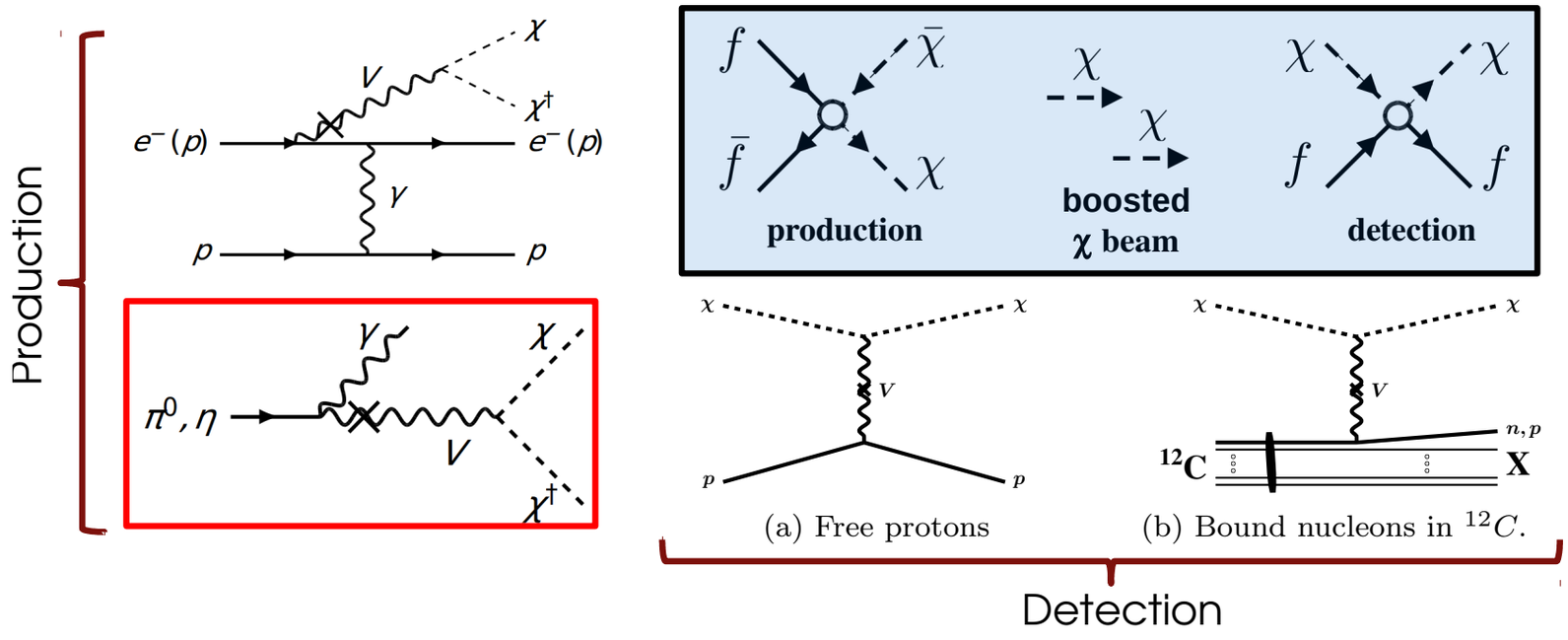
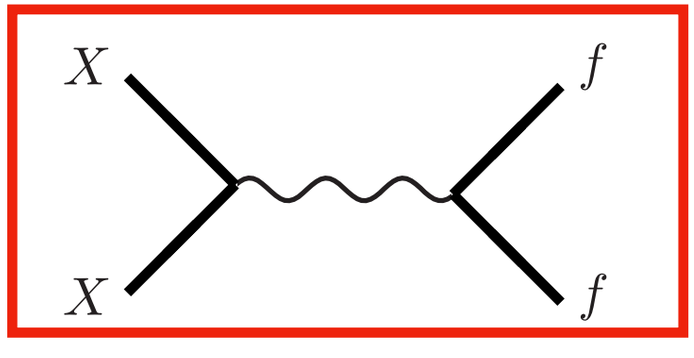
A Light DM Beam @ A Nu Experiment

[Batell, Pospelov, Ritz, 0906.5614, MiniBooNE 1702.02688]



Total event rate~ (branching)x(DM-N cross section) : $\sim \epsilon^4 \alpha_D$

Main assumption, light mediator can decay to DM: $m_V > 2m_\chi$

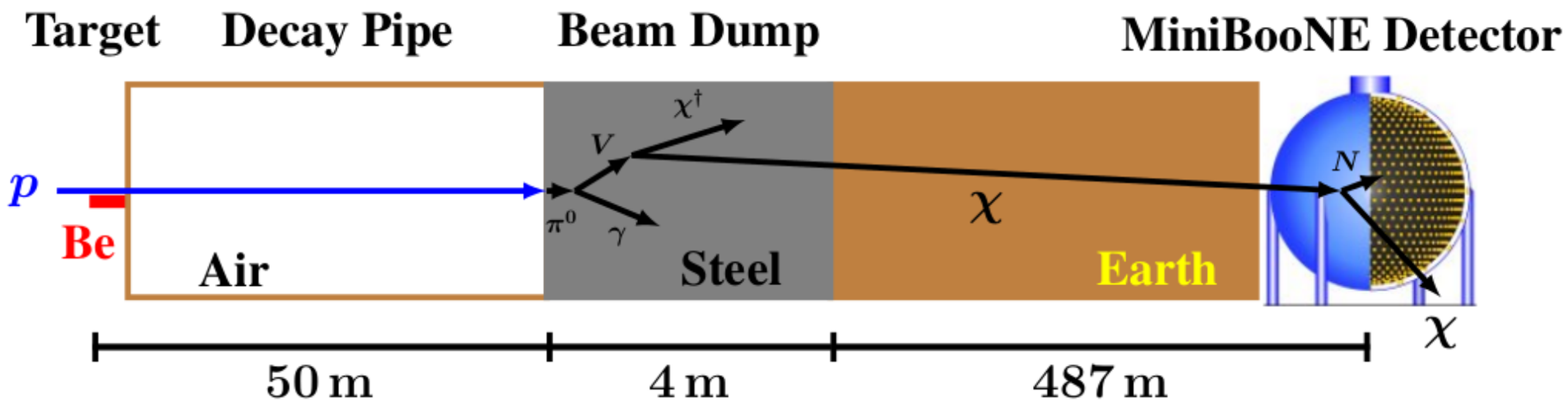


DM annihilation rate: $\sim \epsilon^2 \alpha_D$

A Light DM Beam

[1702.02688]

MiniBooNE in "off-target" mode

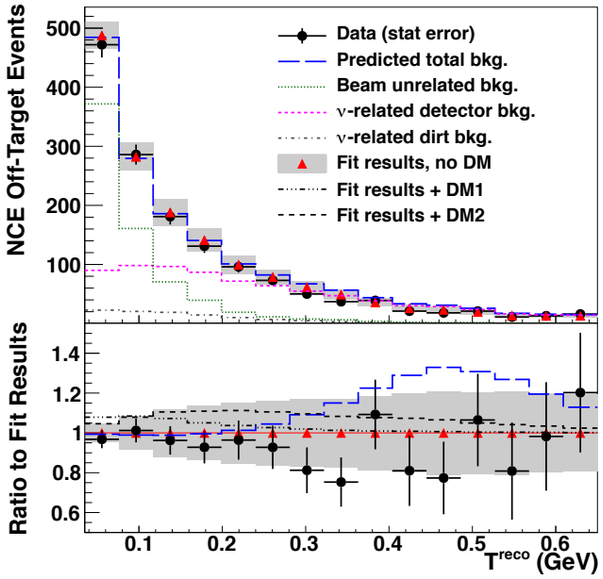


- **Rather than reanalyze old data, this was first dedicated search of this type! No longer need to trust theorists.**

- **Instead of impacting the Beryillium target, the 8 GeV protons are steered off-target to steel target.**
  -> Greatly suppresses nu's from in-flight meson decay

MiniBooNE DM results

[1702.02688]



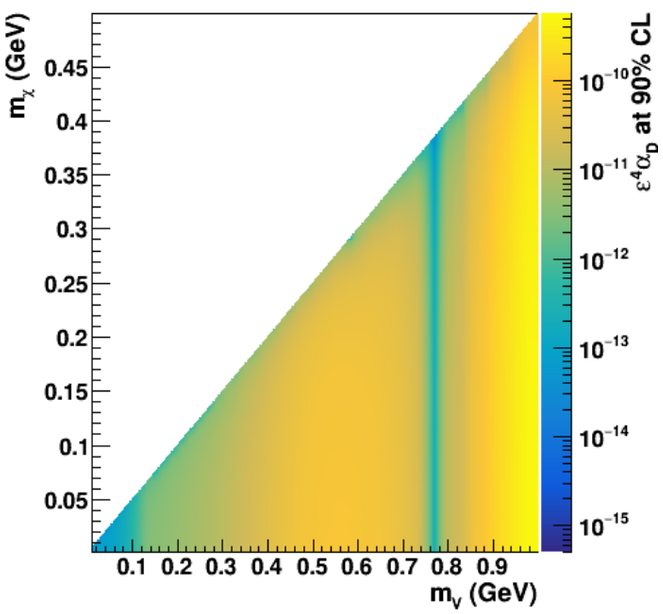


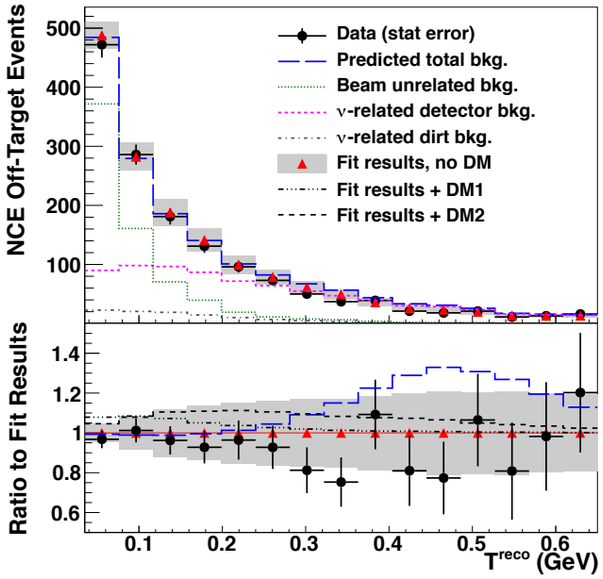
TABLE I. Number of selected data events with predicted backgrounds.

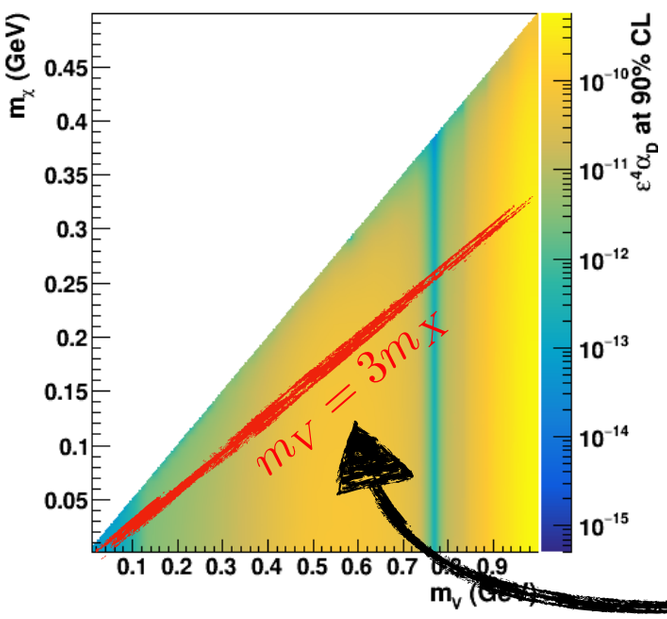
background source	events
beam-unrelated **(cosmic)**	697 ± 11
beam-related, detector **(CCQE)**	775 ±454
beam-related, dirt **(nu induced neutrons)**	107 ± 81
total estimated background	1579 ±529
constrained-fit background	1548 ±198
data events	1465 ± 38

- **Data consistent with bkg. only**
- **Systematics dominated.**

MiniBooNE DM results

[1702.02688]





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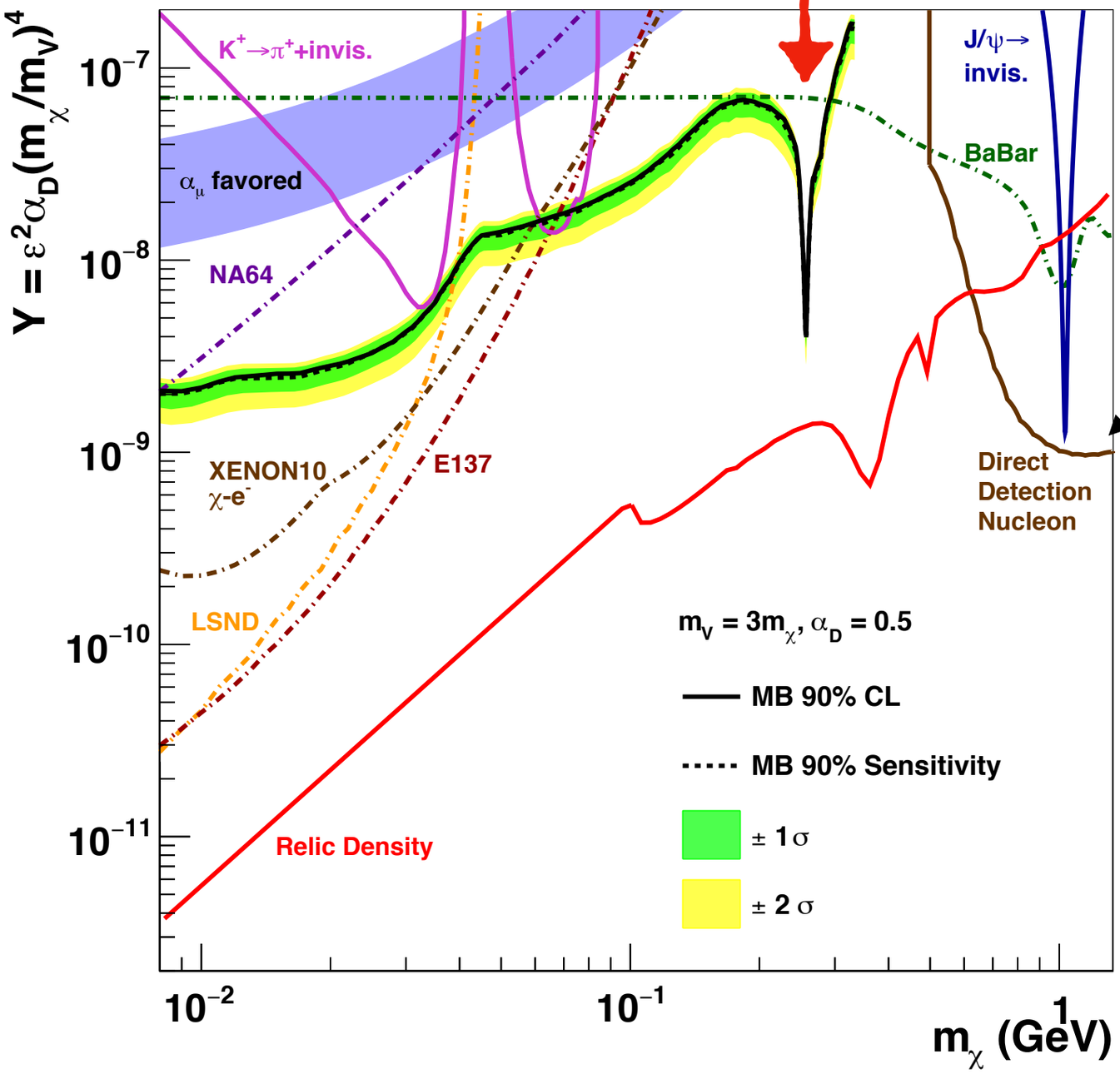
Take a slice of parameter space to compare to other searches.

Dark Matter Search in a Proton Beam Dump with MiniBooNE

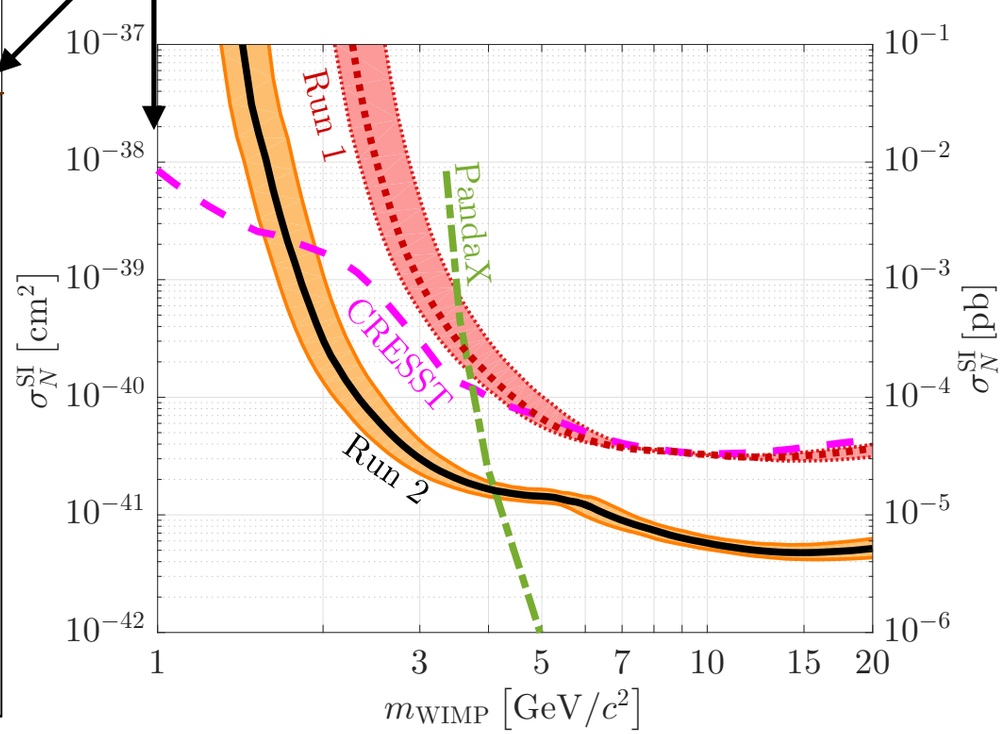
ρ, ω

[1702.02688]



Success at extending cross section bounds to sub-GeV regime.

join here

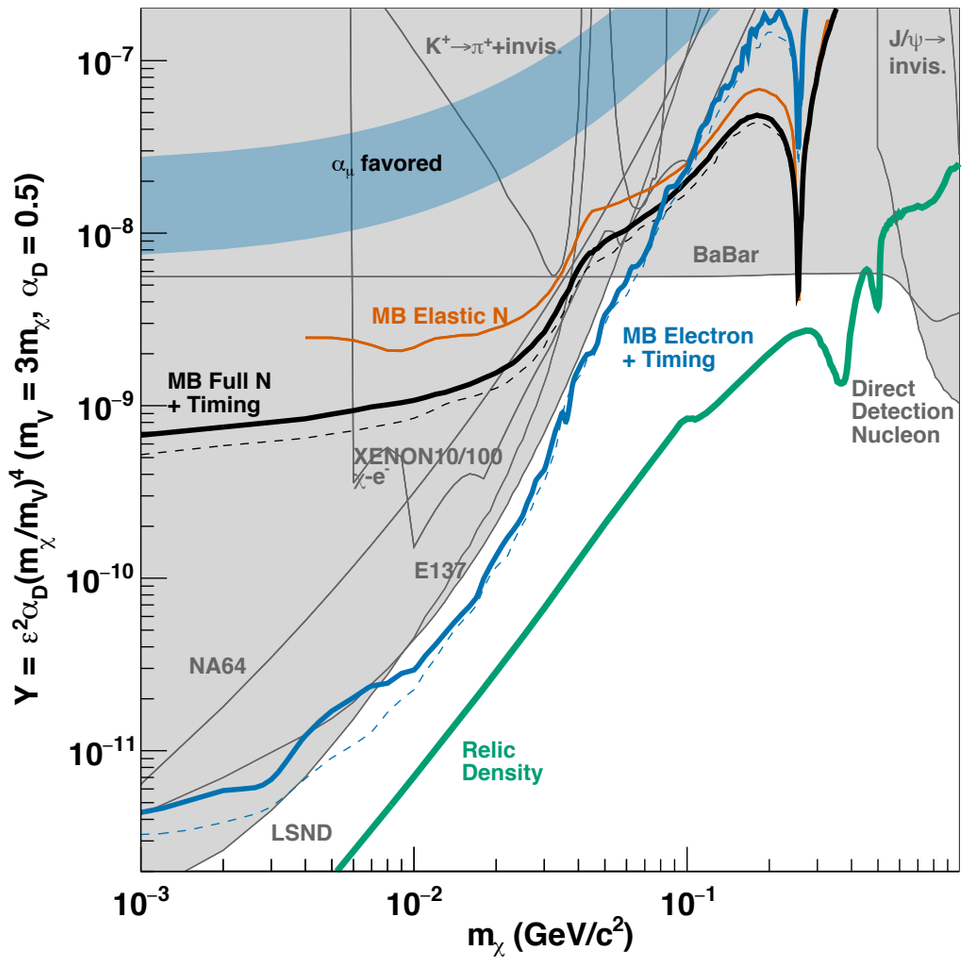


Recent updates

Improvements including electron scattering, timing information

1807.06137

Same canonical mass ratio + dark coupling



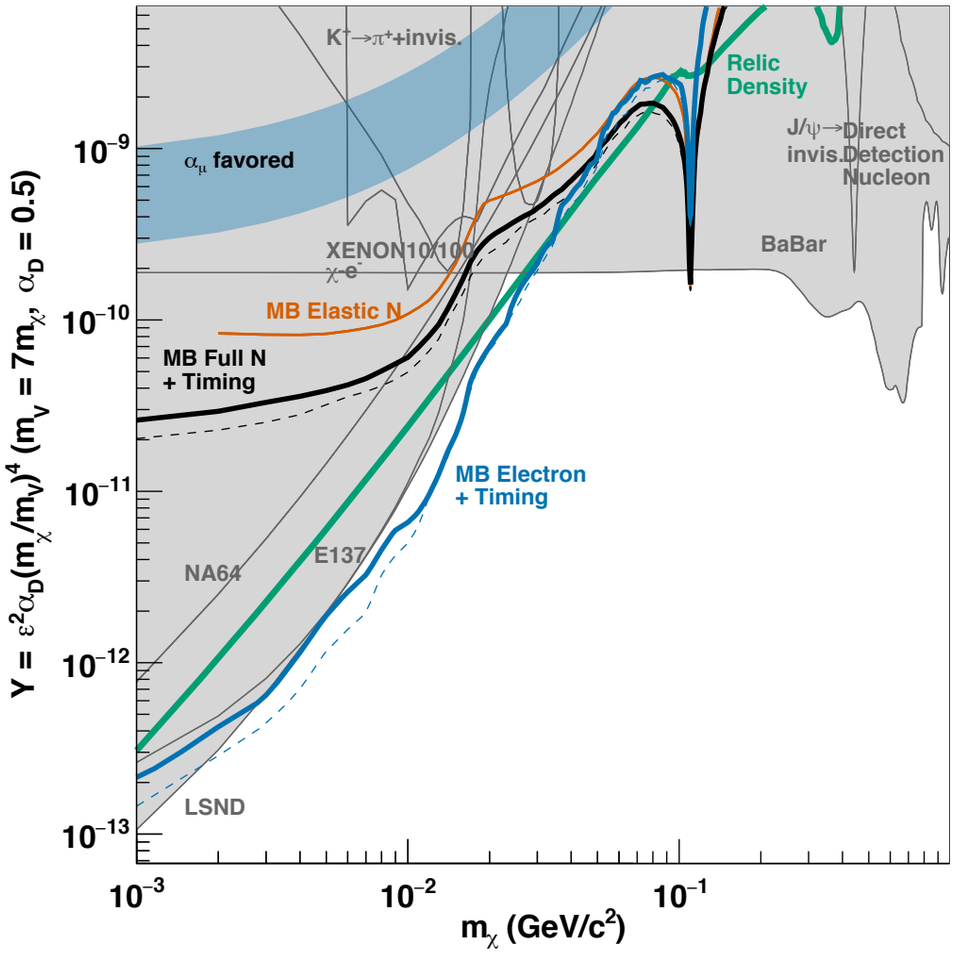
$$\sigma v(\chi\chi \to A'^* \to f f) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2} \quad , \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

Recent updates

Improvements including electron scattering, timing information

1807.06137

Larger mediator masses Excluded



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Variations

- Similar bounds from NOvA [deNiverville,Frugiuele (2018)], and COHERENT [Ge, IMS (2017)], and future bounds from DUNE-PRISM [De Romeri, Kelly, Machado (2019)].

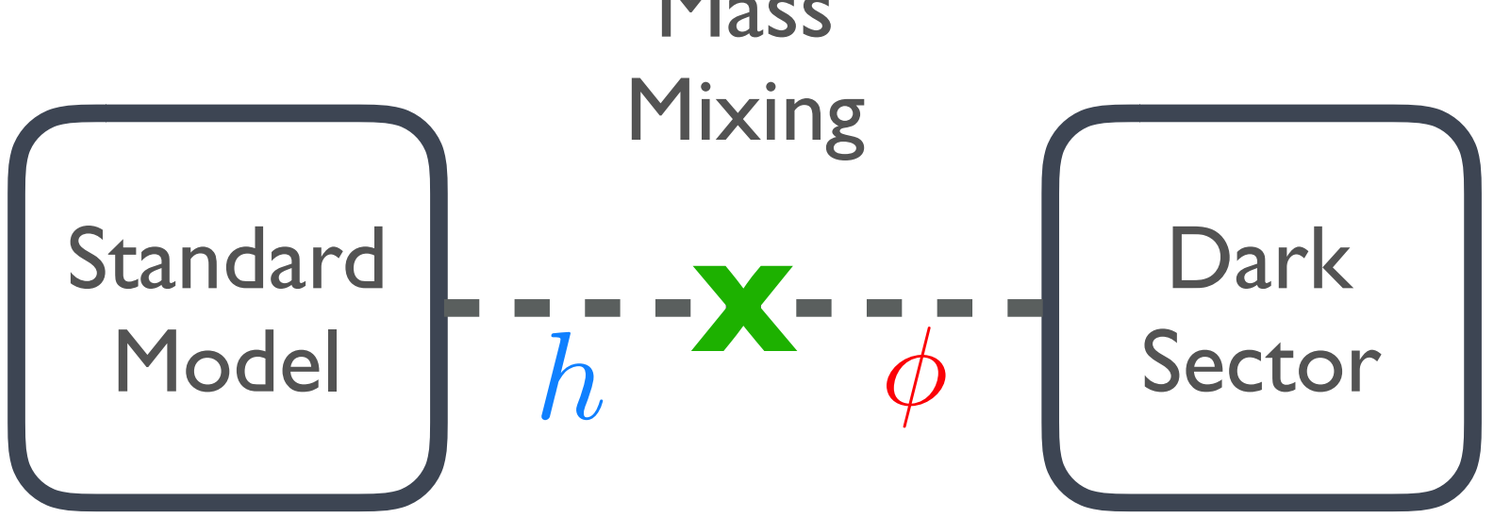
- Dark Tridents in argon detectors [de Gouvea, Fox, Harnik, Kelly, Zhang (2018)].

- Future Missing energy searches [LDMX].

- Also look for other models, e.g. leptophobic vector mediators [Dobrescu, Frugiuele (2014)], [Batell, deNiverville, McKeen, Pospelov (2014)], [Coloma, Dobrescu, Frugiuele, Harnik (2015)], [Frugiuele (2017)], [deNiverville, Chen, Pospelov, Ritz (2017)].

Part 2

Higgs Portal

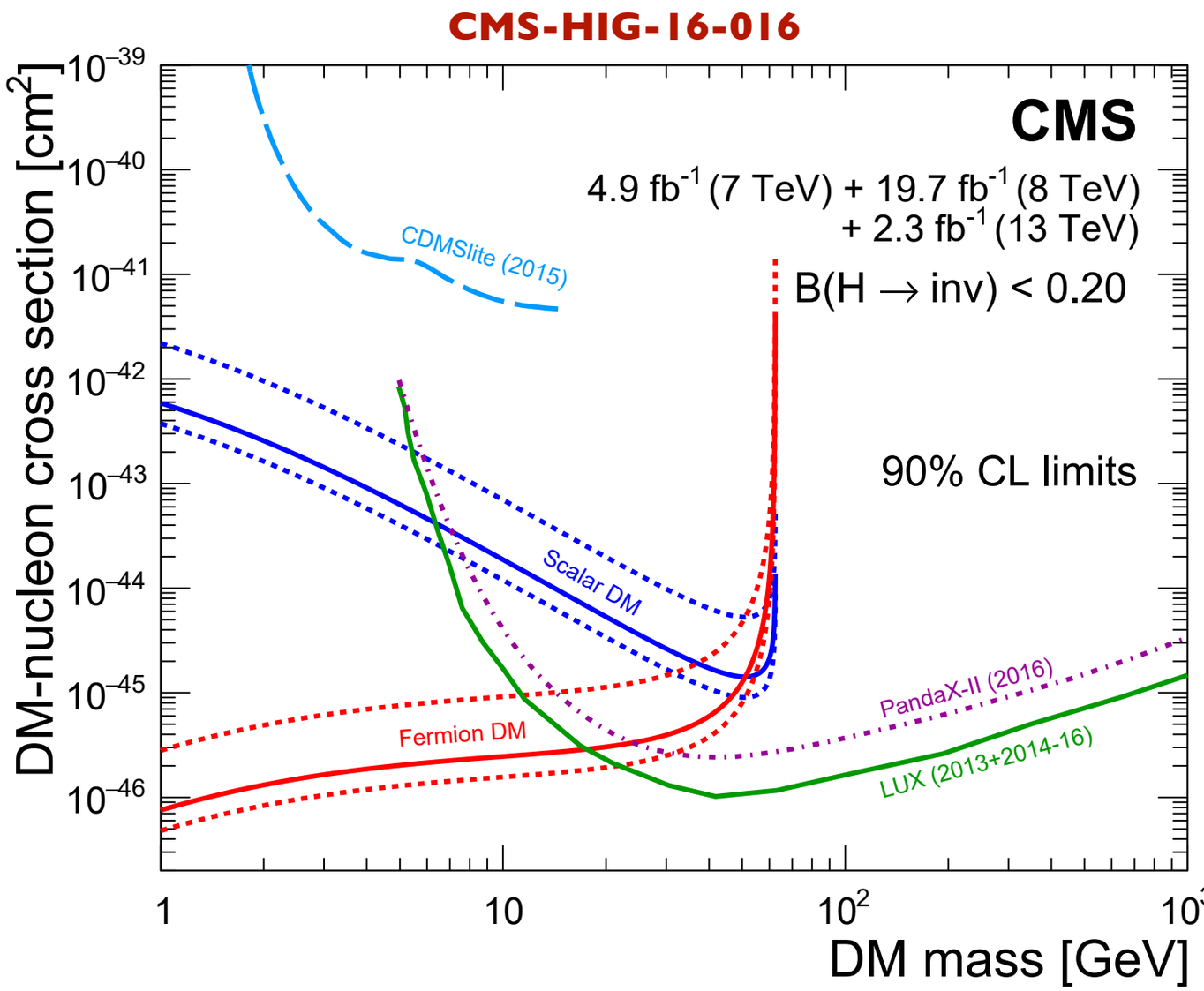


SM Coupling scales with SM particle mass.

Invisible Higgs Constraints

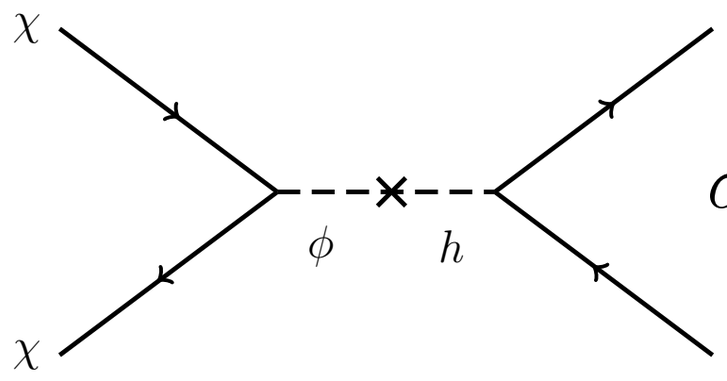
Combination of VBF, ZH and ggH results at 7, 8 and 13 TeV.

Applies to models where 2(DM mass) < Higgs mass.



Higgs Portal at Low Masses

Focus on direct SM annihilation



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$$(m_\phi > m_\chi)$$

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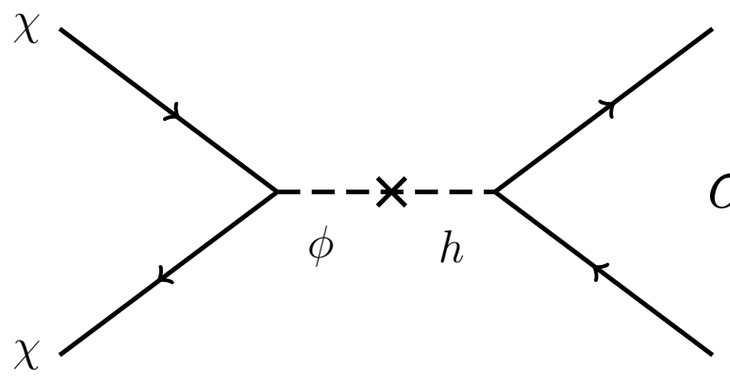

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P-wave annihilation allowed by CMB

$$\sigma v_{\text{rel.}}(\chi\chi \to f\bar{f}) = \frac{g_\chi^2 g_f^2 m_\chi^2 v_{\text{rel.}}^2}{8\pi(m_\phi^2 - 4m_\chi^2)^2} \propto g_\chi^2 g_f^2 \left(\frac{m_\chi}{m_\phi}\right)^4 \frac{1}{m_\chi^2}$$

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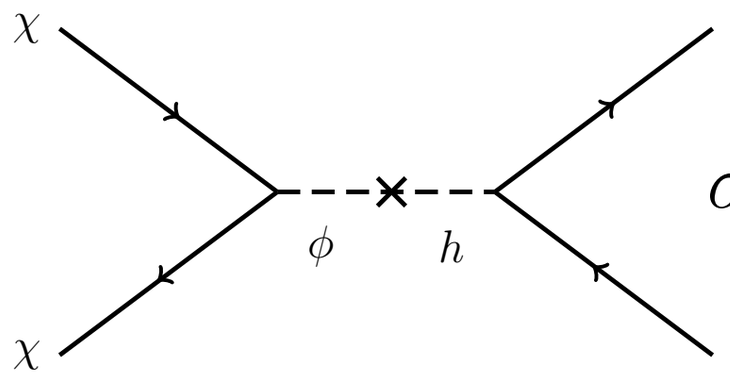

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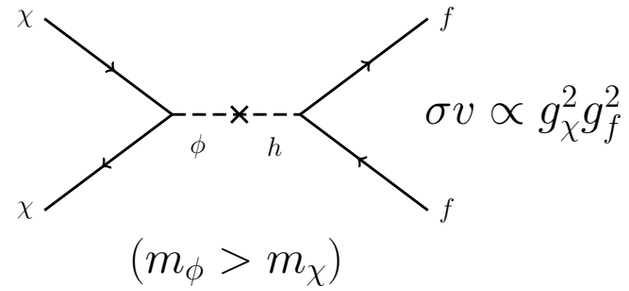
SM fermion coupling controlled by mass + Higgs-φ mixing

$$\kappa_f \equiv g_\chi^2 g_f^2 \left(\frac{m_\chi}{m_\phi}\right)^4 = g_\chi^2 \left(\frac{m_f}{v}\sin\theta\right)^2 \left(\frac{m_\chi}{m_\phi}\right)^4$$

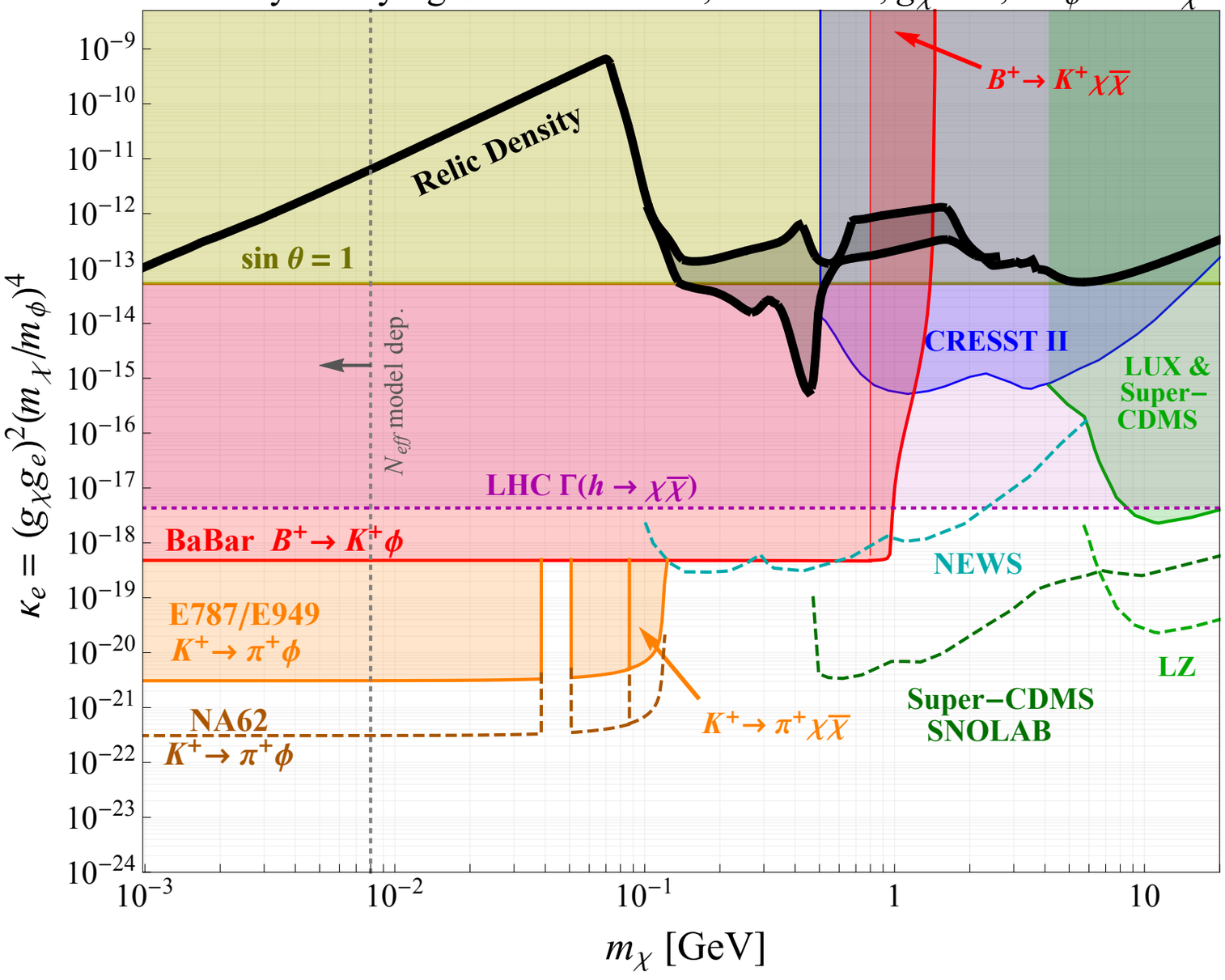
Higgs Portal DM



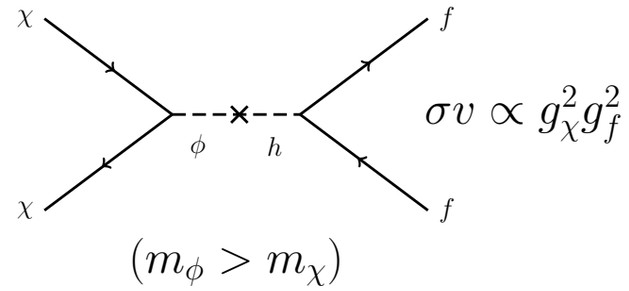
Interplay of Cosmic, Intensity and Energy frontiers

Krnjaic, 1512.04119

Invisibly Decaying Scalar Mediator, Dirac DM, $g_\chi = 1$, $m_\phi = 3\, m_\chi$



Higgs Portal DM



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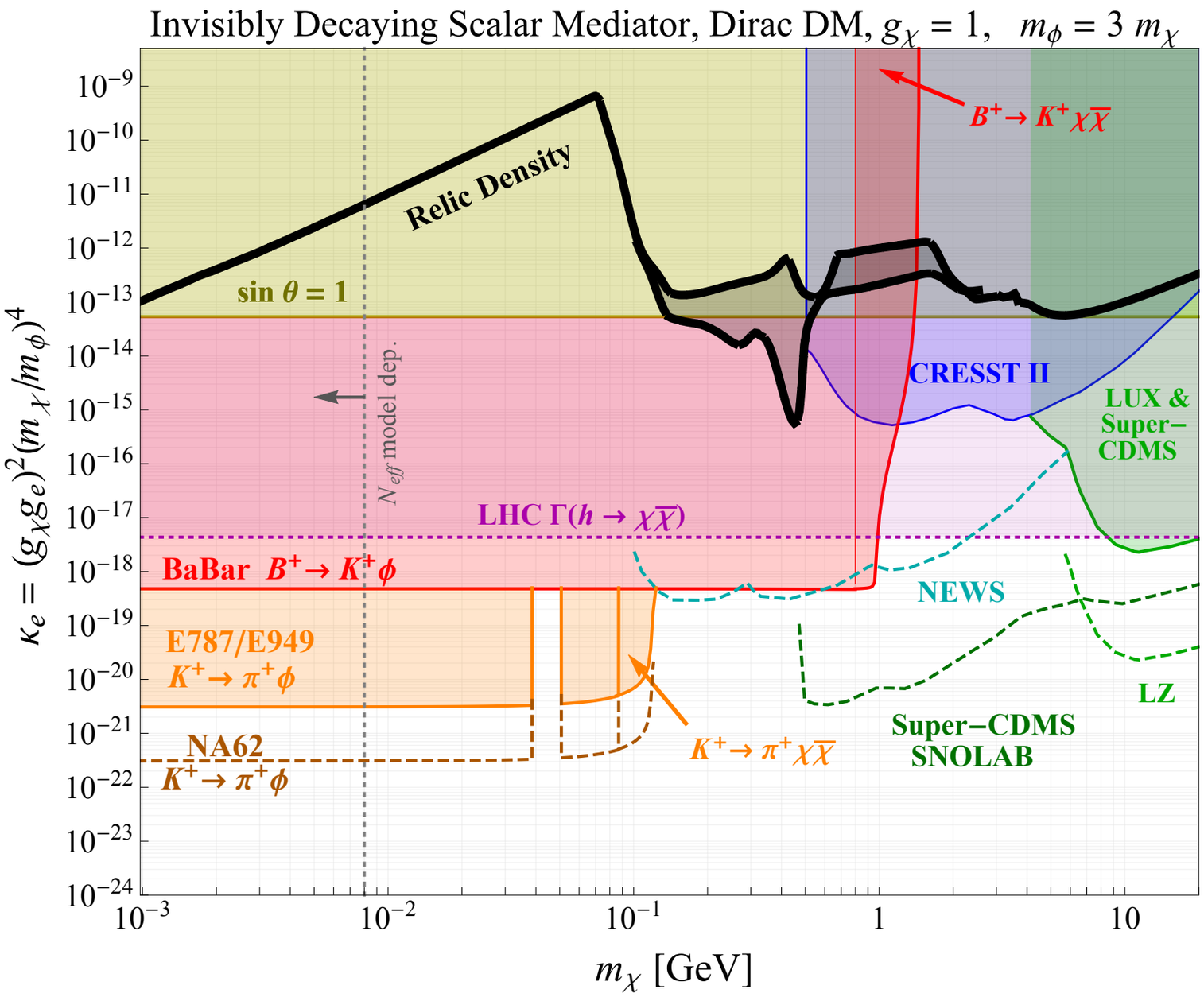
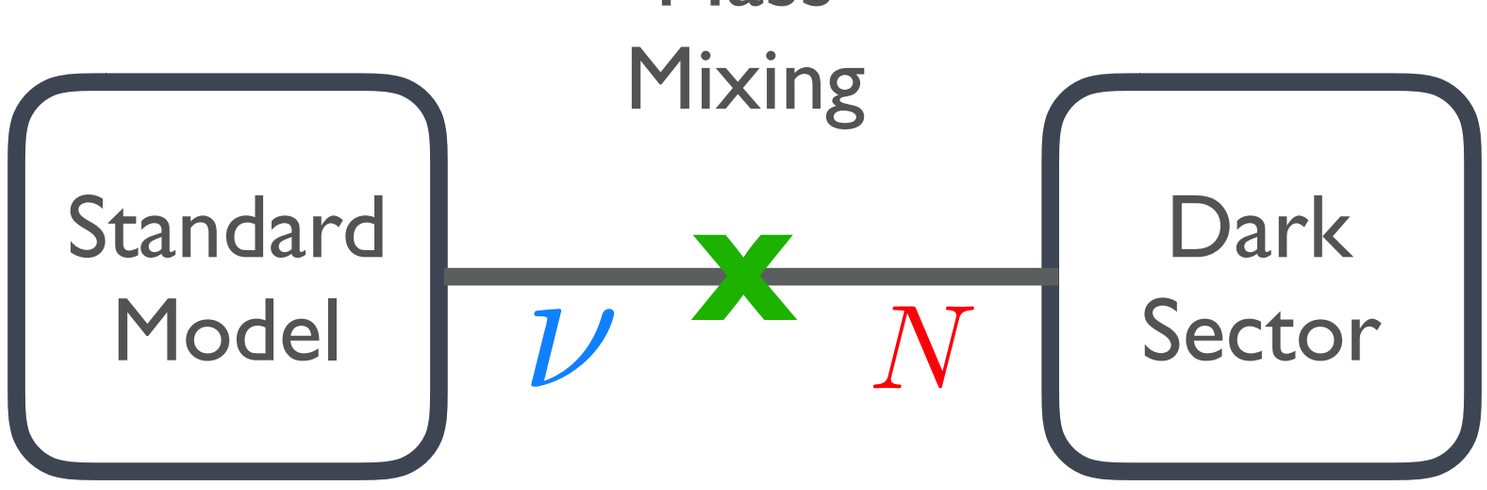


More on Higgs portal DM from Anastasiia Filimonova in parallel.

Part 3

Neutrino Portal



Loosely speaking, any dark sector models with neutrino mixing being key portal.

Neutrino Portal DM

- New fermion singlets are DM = sterile neutrino DM [Dodelson-Widrow (1993)].

- New fermion singlets are not DM, but act as messenger between SM and dark sector.

    - Small-scale structure modifications from late DM kinetic decoupling. [Dasgupta, Kopp (2015); Cherry, Friedland, IMS (2014); Ipek, McKeen, Nelson (2015); Batell, Han, McKeen, Haghi (2017)].

    - Neutrino scattering @ IceCube [Cherry, Friedland, IMS (2014,2016)].

    - Modified neutrino oscillations from ambient DM [Capozzi, IMS, Vecchi (2017); Brdar, Kopp, Liu, Prass, Wang (2017); Krnjaic, Machado, Necib (2017); Capozzi, IMS, Vecchi (2018)].

    - Local DM sources the neutrino mass [Davoudiasl, Mohlabeng, Sullivan (2018)].

Neutrino masses + DM

$$\{\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \dots, \nu_{s,N}\}$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a}\left(i\partial_\mu\gamma^\mu\right)\nu_{s,a} - y_{\alpha a} H\,\bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2}\,\bar{\nu}^c_{s,a}\nu_{s,b} + h.c.\,,$$

where H is the Higgs boson and L_α ($\alpha = e, \mu, \tau$) are the lepton doublets. The mass matrix:

$$M = \begin{pmatrix} 0 & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{pmatrix}$$

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- **Don't know the number of N's!**
- **Need at least two of them for atm/sol mass splittings N =2.**

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If you want Nu osc. + DM need at least N=3.

DM from Neutrino Scattering

Dodelson, Widrow (1993)

Oscillations + Collisions in expanding Universe:

$$\left(\frac{\partial}{\partial t} - HE\frac{\partial}{\partial E}\right) f_S(E,t) = \left[\frac{1}{2}\sin^2(2\theta_M(E,t))\ \Gamma(E,t)\right] f_A(E,t)$$

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Mechanism gives correct DM abundance if:

$$\rightarrow \sin^2(2\theta) \simeq 9\times 10^{-10} \left(\frac{g_*(T=100\ \mathrm{MeV})}{20}\right)^{1/2} \left(\frac{10\ \mathrm{keV}}{m_s}\right)^2$$

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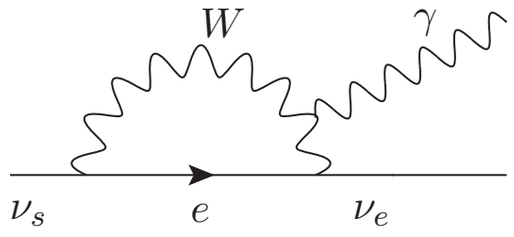
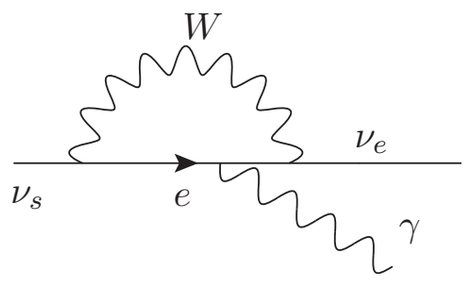
Peak production occurs when "collision rate" = "oscillation rate":

$$T_{\max} \simeq (m_s/G_F)^{1/3} \simeq 200\ \mathrm{MeV} \left(\frac{m_s}{\mathrm{keV}}\right)^{1/3}$$

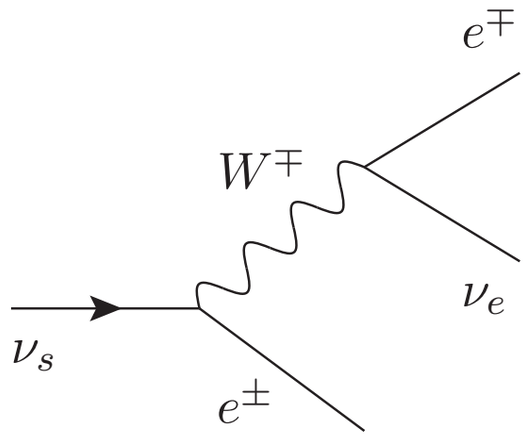
How do you detect it?

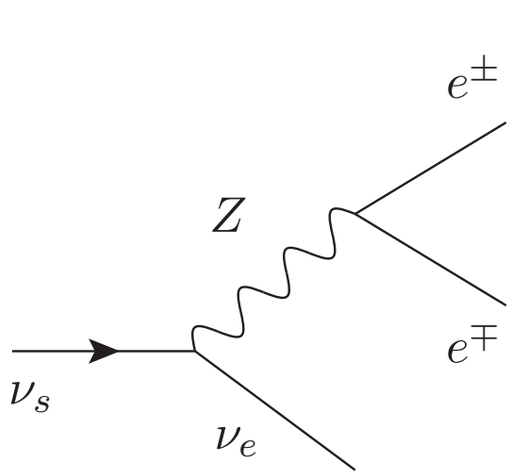
Sterile Neutrino DM is unstable





X-ray lines!





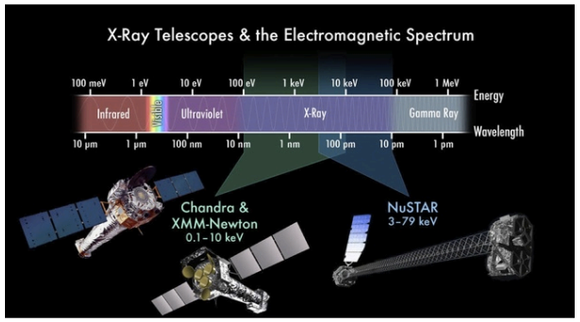
gamma spectrum

Sanity check: Stable on universe lifetime scales.

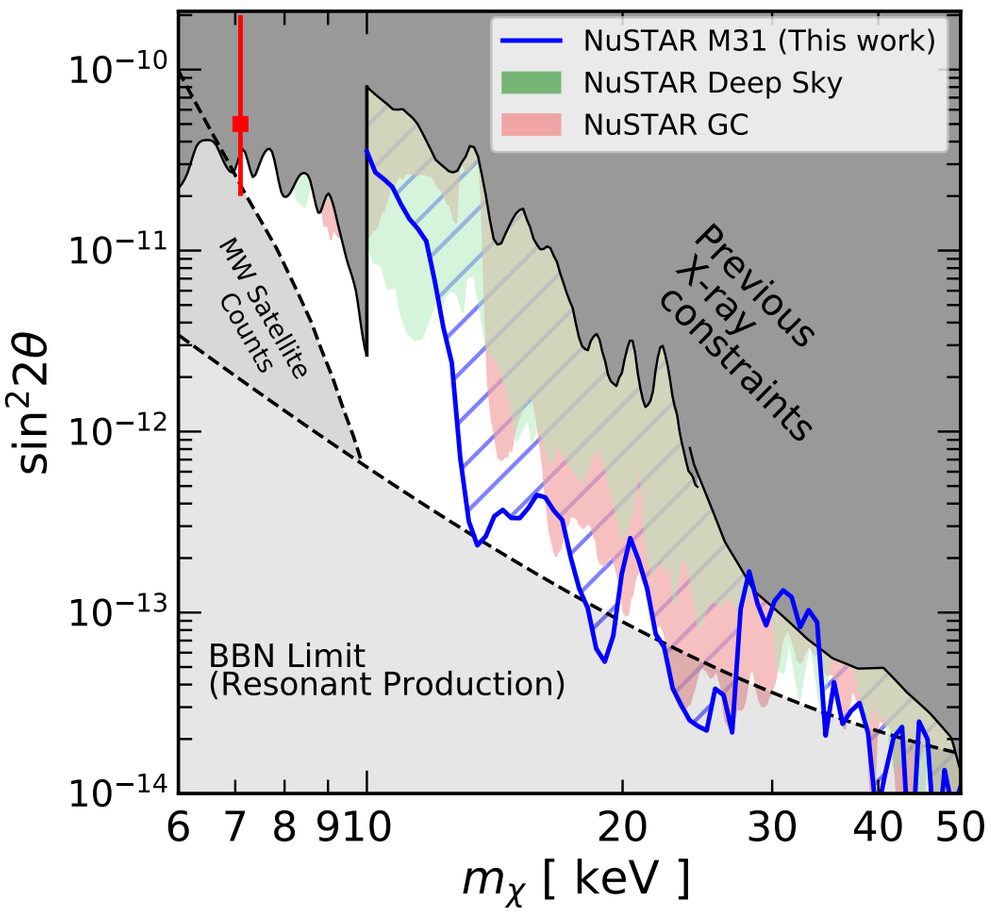
$$\Gamma \sim \sin^2 2\theta G_F^2 m_s^5 \qquad \Rightarrow \sin^2 2\theta \lesssim 0.06 \left(\frac{10\ \mathrm{keV}}{m_s}\right)^5$$

Dodelson-Widrow doesn't work for DM above ~700 keV masses.

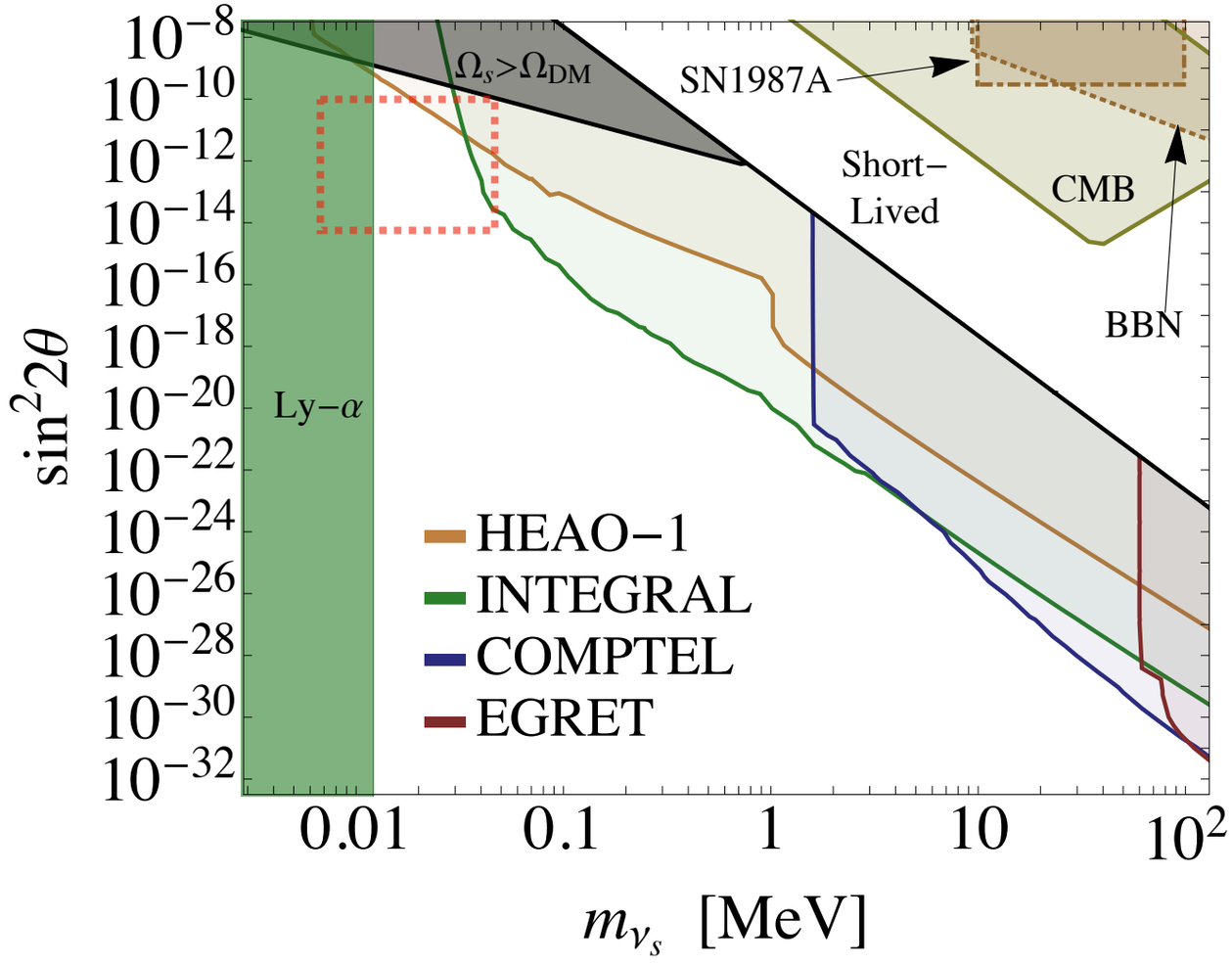
X-ray limits are strong



Ng et al, [1901.01262]



Essig et al, [1309.4091]



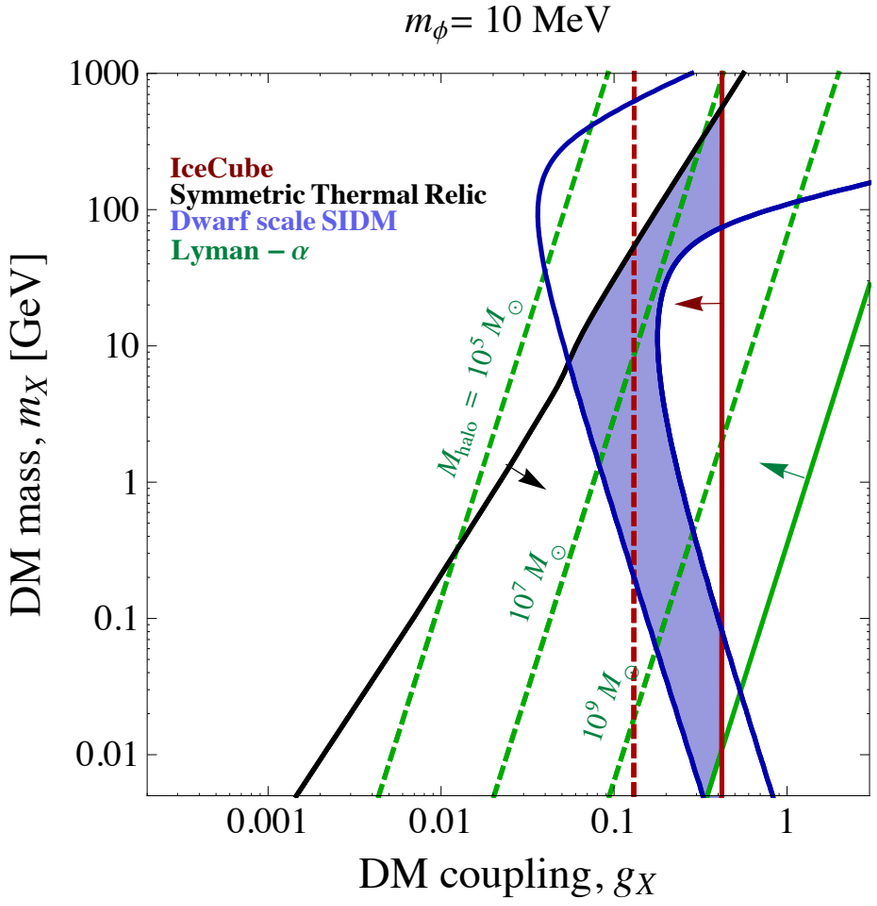
Strongly **excludes minimal DM production mode.**

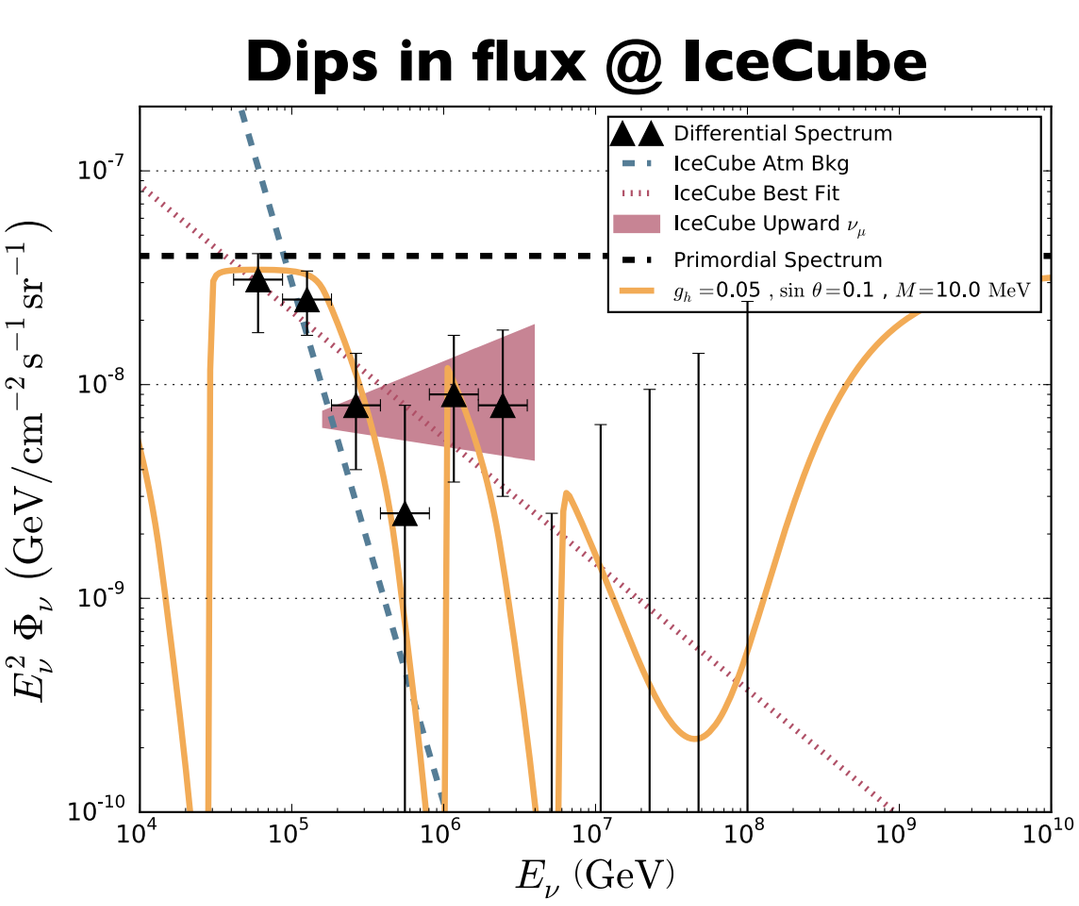
Sterile Neutrinos in a Dark Sector

Cherry, Friedland, IMS [1411.1071], Cherry, Friedland, IMS [1605.06506]

$$\Delta\mathscr{L}_\phi = g_\nu \bar{\nu}_s \gamma_\mu \nu_s \phi^\mu + g_X \bar{X} \gamma_\mu X \phi^\mu \qquad \Delta\mathscr{L}_M = y_\alpha \frac{(L_\alpha H)(h_X \nu_s)}{\Lambda}$$

- Charging sterile neutrinos under a new U(1) can reconcile eV sterile neutrinos with cosmology.
- Same boson mediates DM self interactions, and neutrino self-interactions.





Conclusions

- Dark Matter may be a part of a whole new sector of particles and interactions.
- Cast a wide net: re-use existing data, propose new analyses, new searches, new experiments.
    - We need to simultaneously expand the theoretical terrain and to widen the experimental search strategies if we are going to uncover the New Standard Model.

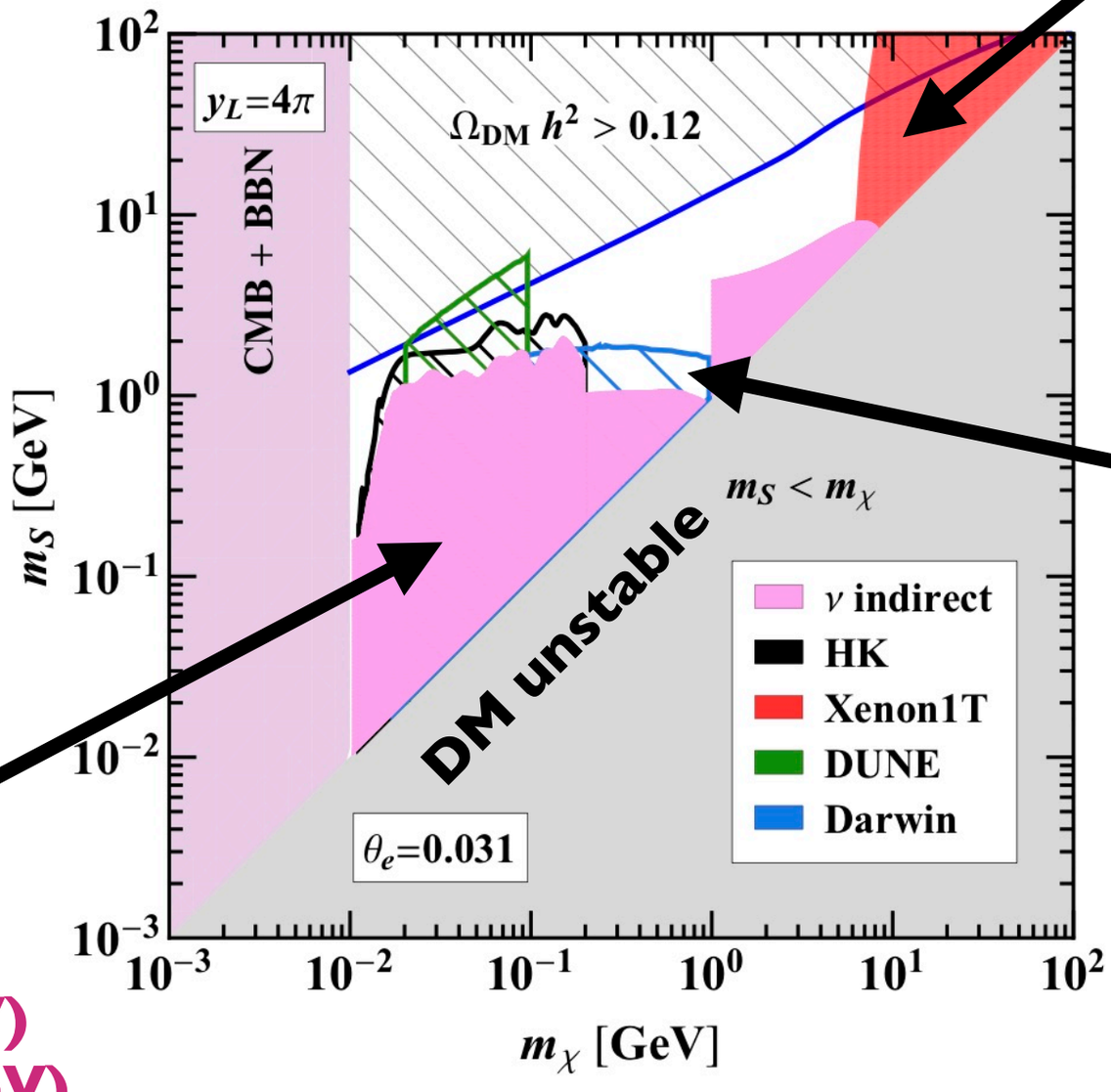
Scalar Mediated Neutrino Portal

DUNE:
3000 days
46.4 kton.

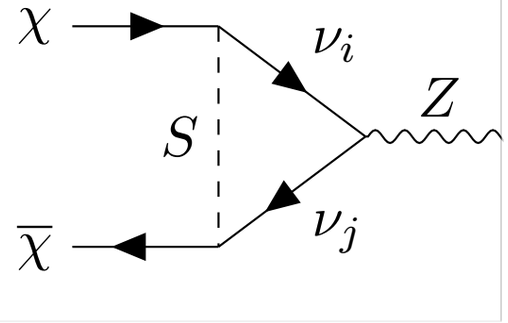
$\bar{X}X \to \nu\nu$

Klop, Ando [1809.00671]

Blennow, et al. [1903.00006]



XENONIT



DARWIN
(Xe @ 200t-yr)

Nu Indirect:
Borexino (2-17 MeV)
+Super-K (10-200 MeV)
+ Atmospheric nu bkg.
(100 MeV-100 TeV)

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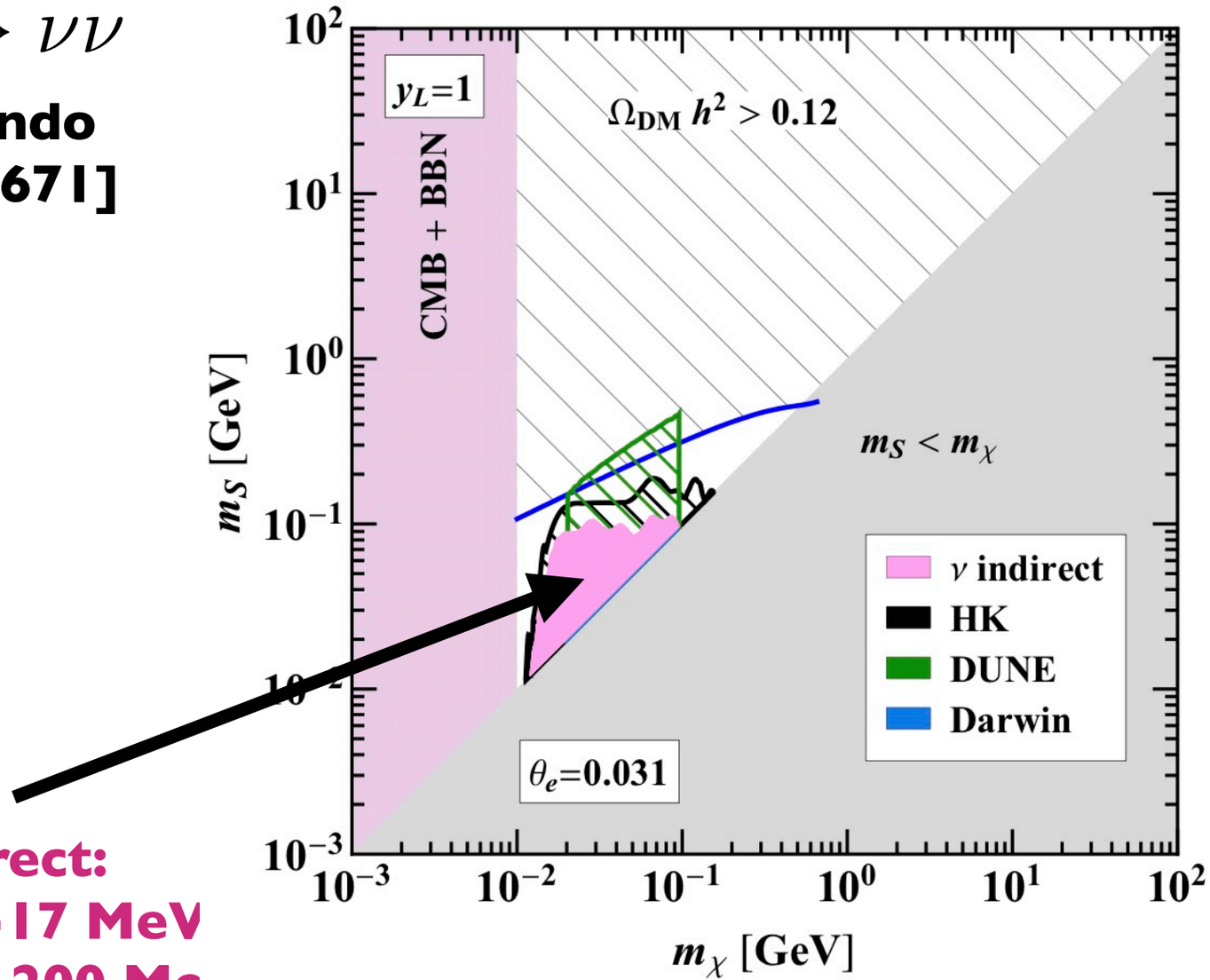

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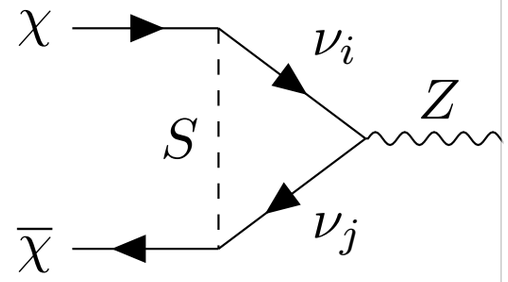
(100 MeV-100 TeV)

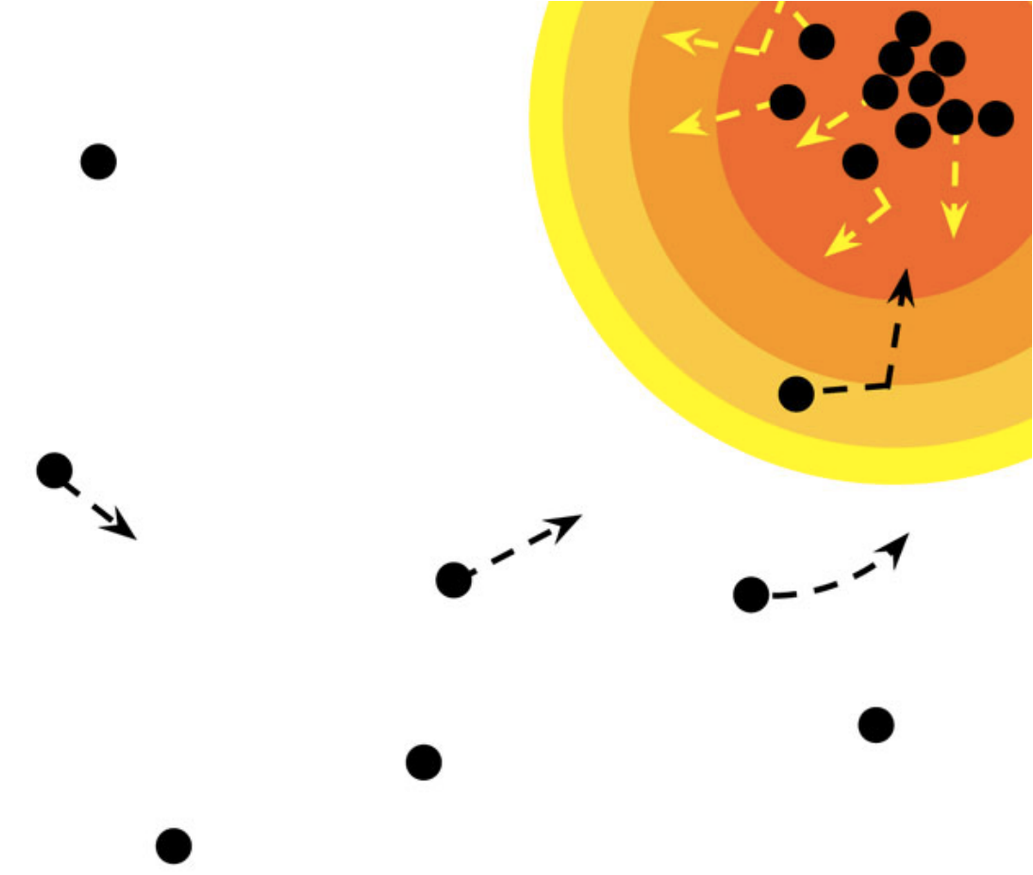
XENONIT



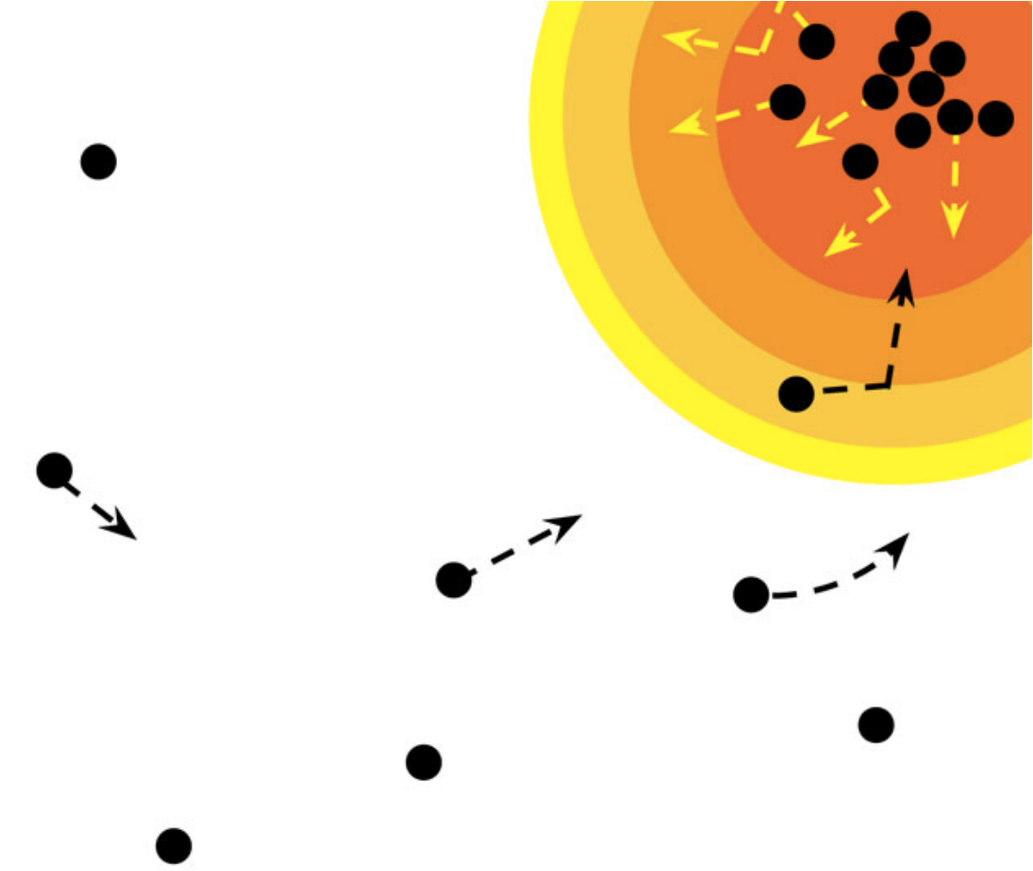
DARWIN
(Xe @ 200t-yr)

DM in the Sun

- Standard WIMPs accumulate, start annihilating. Searches for high-E neutrinos from solar core.



DM in the Sun



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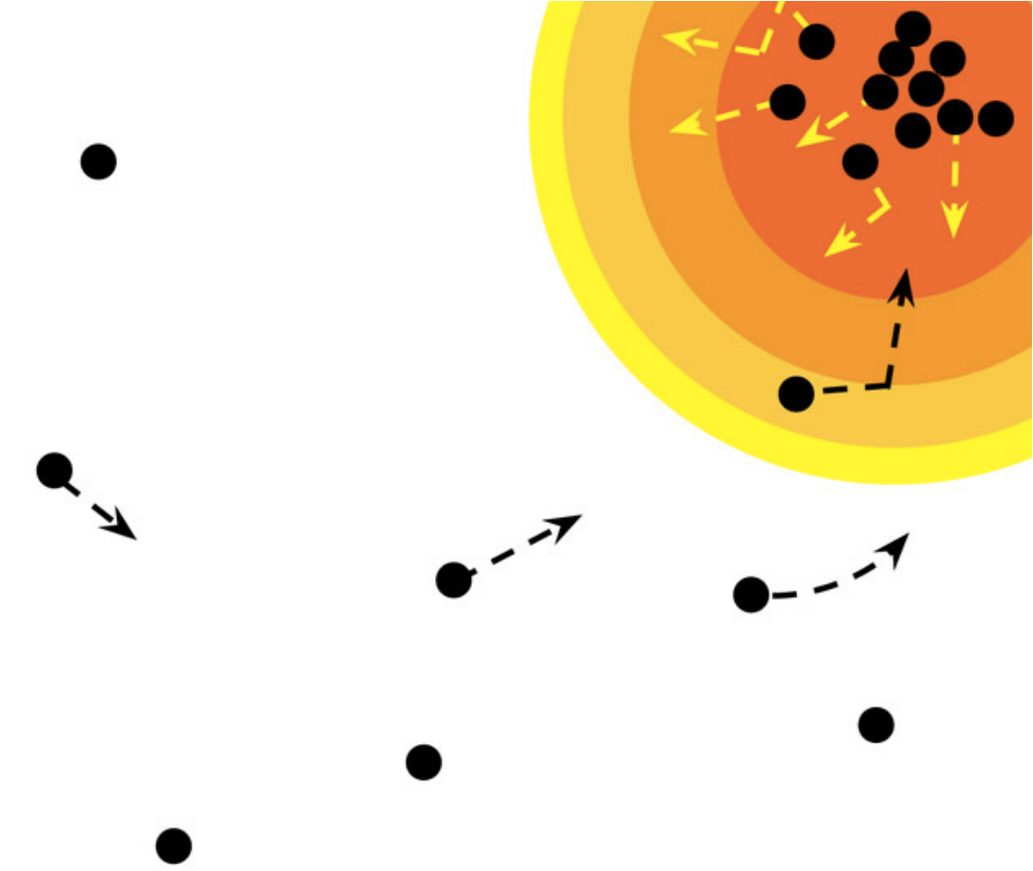

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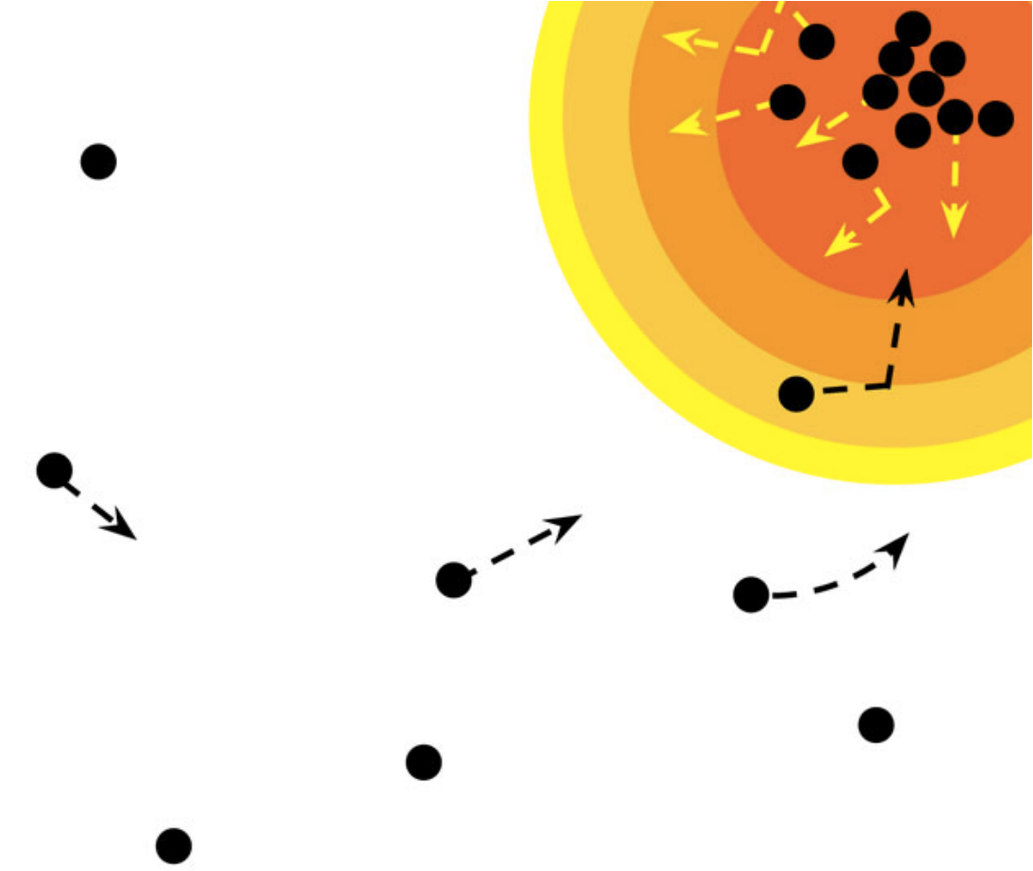

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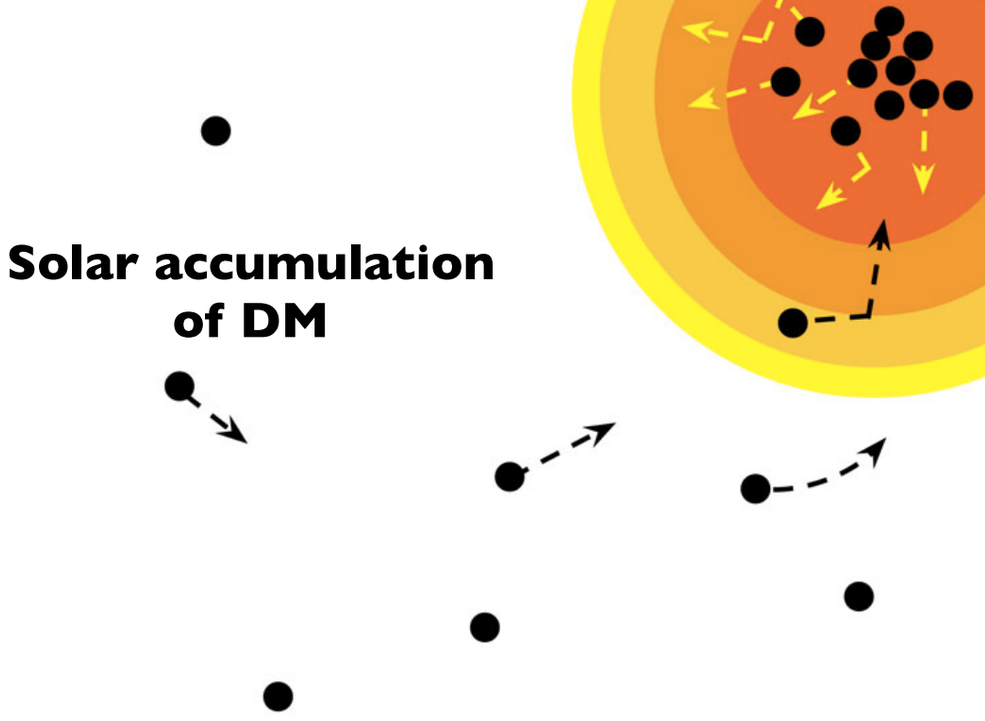
    - => Can look for a modified matter potential for solar neutrinos.

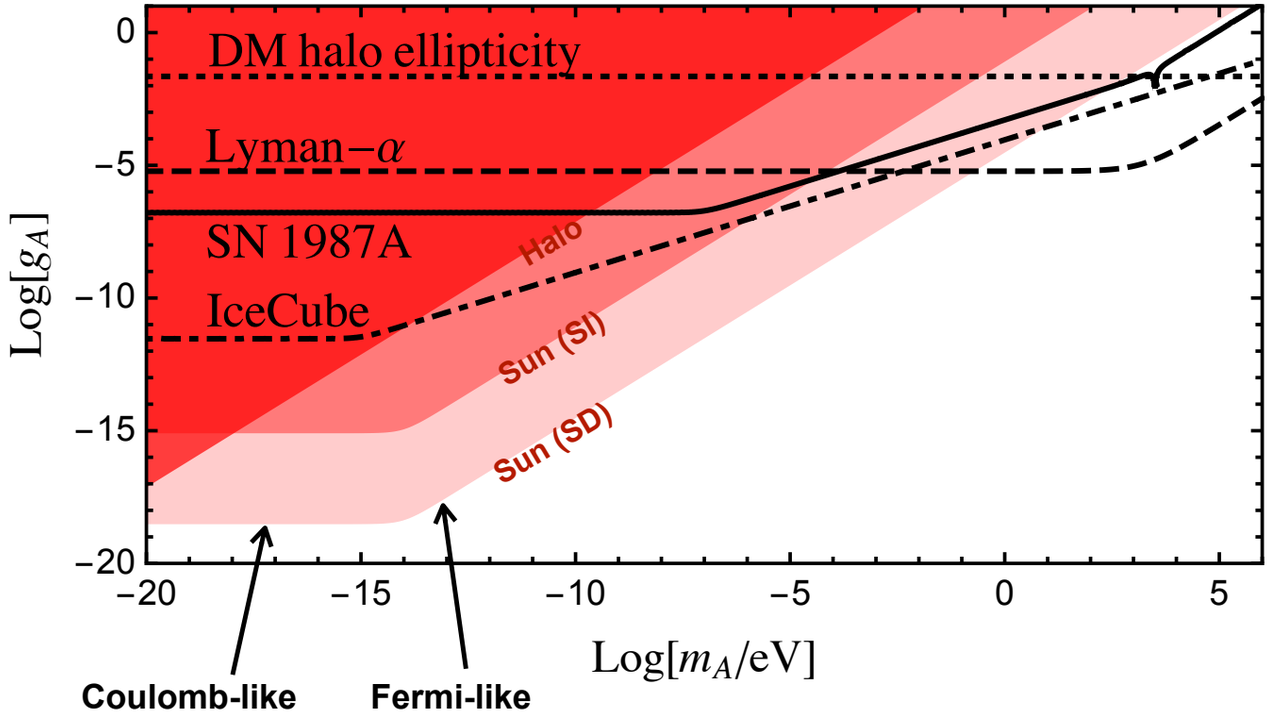
Probing DM-Neutrino Interactions

$$\mathcal{L} \supset g\bar{X}\gamma_\mu X A^\mu + g\bar{\nu}\gamma_\mu \nu A^\mu$$

DM impact on oscillations



Capozzi, **IMS**, Vecchi (2017)



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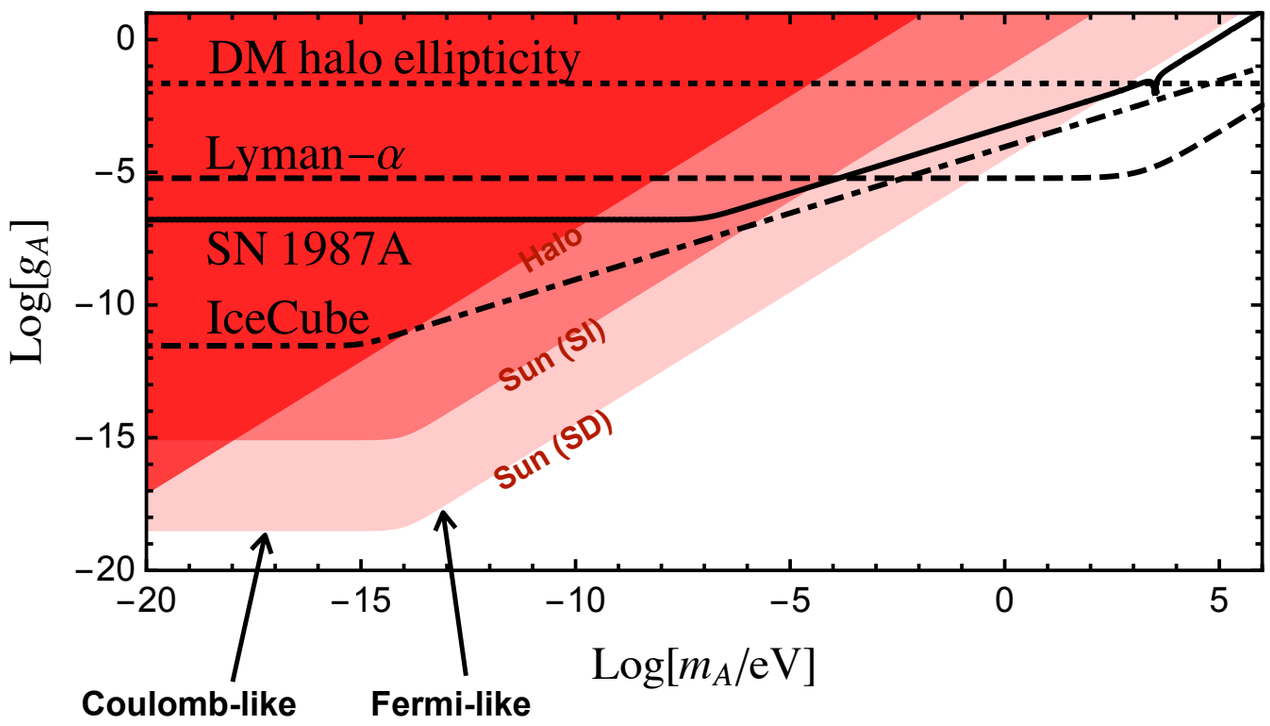
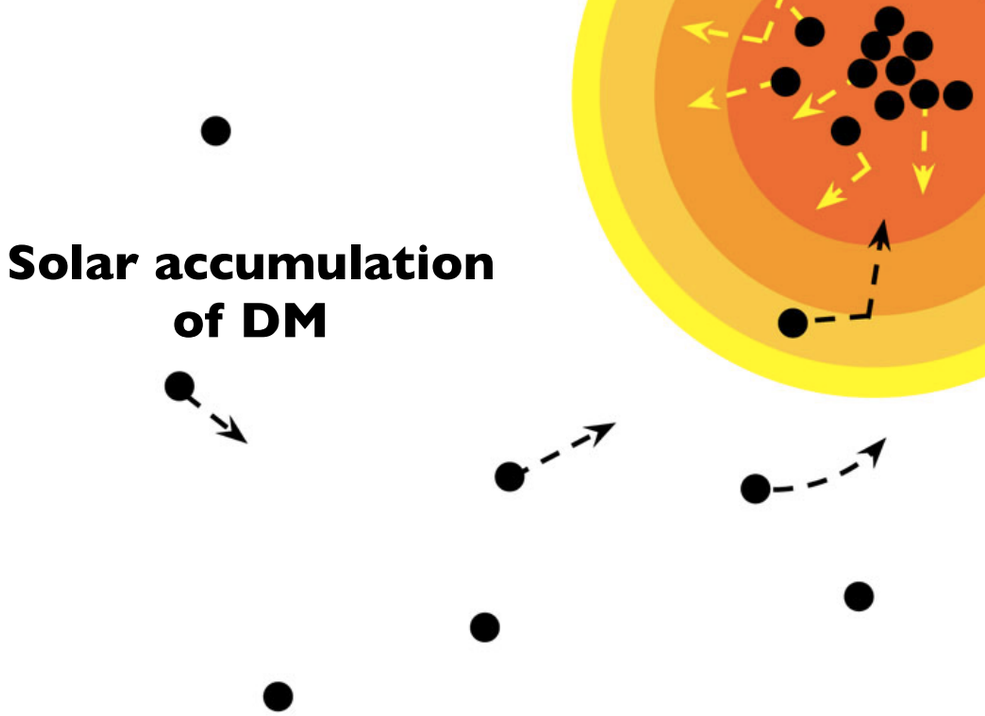
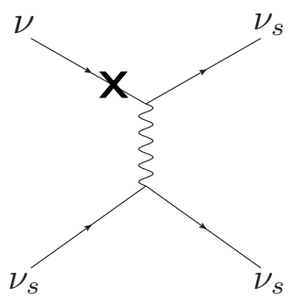
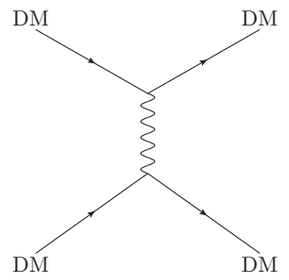




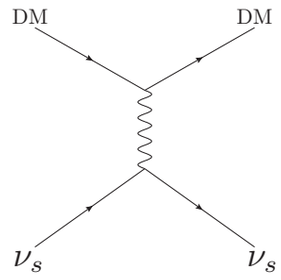
IceCube/ SN1987A



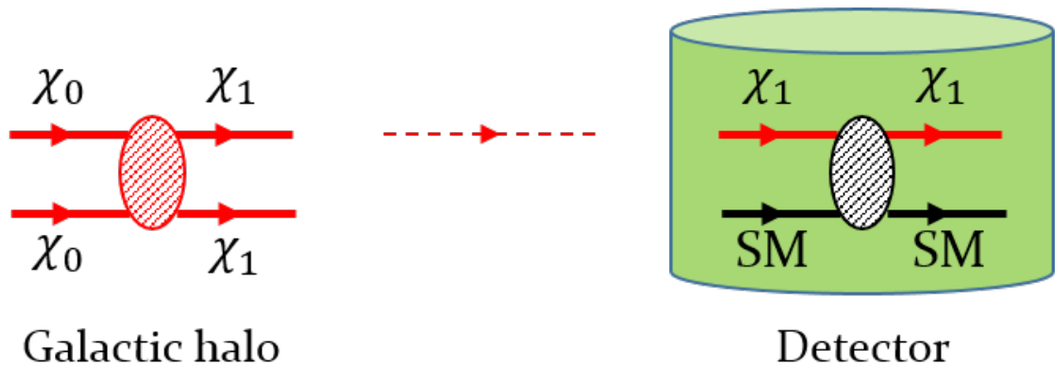
DM Self-Interactions



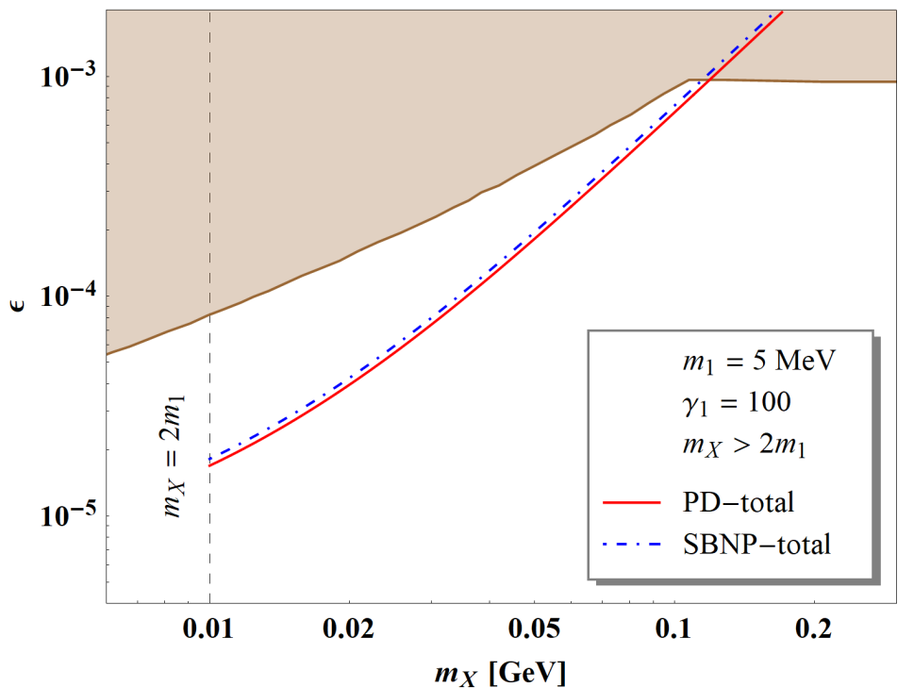
Lyman-alpha



Boosted DM at Neutrino Detectors



Decays Invisibly



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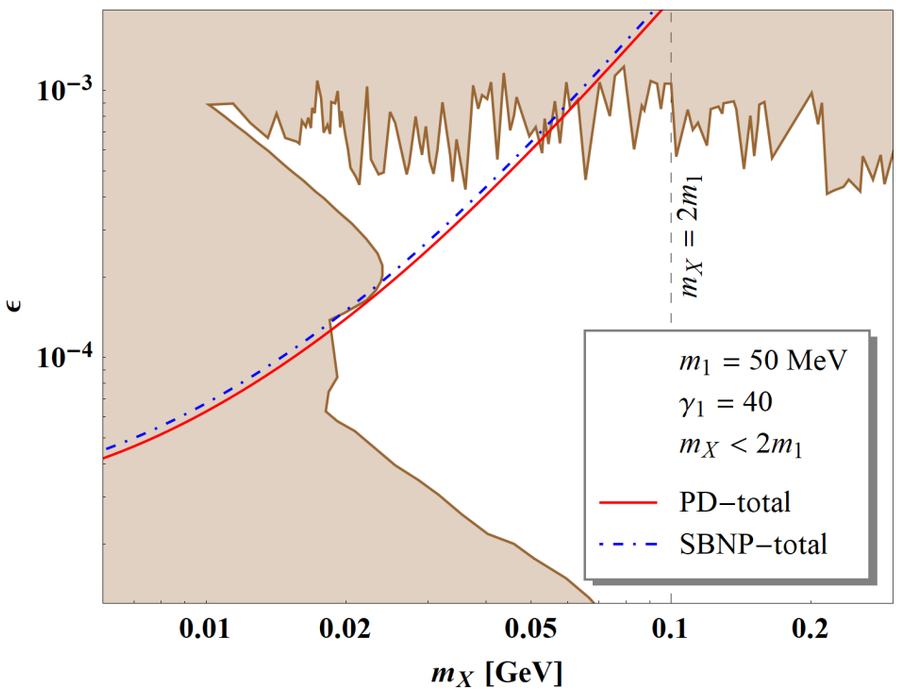

Kim et al. [1804.07302]