Boosted Dark Photons:

Looking for Light Dark Matter with Dark Light

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IN COLLABORATION WITH VARUN MATHUR (VT), IAN SHOEMAKER (VT), AND MICHAEL GRAESSER (LANL)

Our Model – Fermionic Dark Matter with a Dark Photon Mediator

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$$\mathcal{L} \supset \bar{\chi}\left(i\partial_\mu\gamma^\mu - m_\chi\right)\chi$$

Dark Matter (DM)
Kinematics

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$$\mathcal{L} \supset \bar{\chi}\left(i\partial_\mu\gamma^\mu - m_\chi\right)\chi \ - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^\mu A'_\mu$$

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Dark Photon (DP) Kinematics

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DM-DP Interactions

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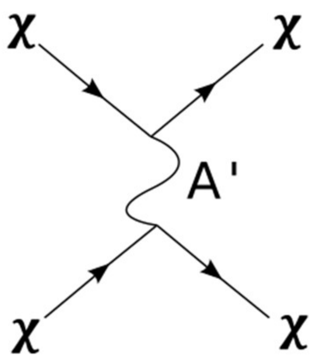

Time

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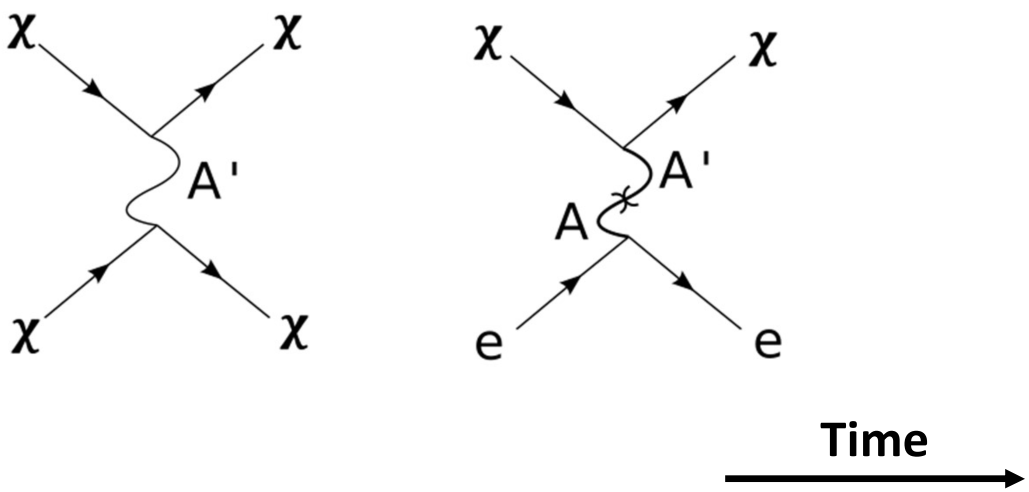

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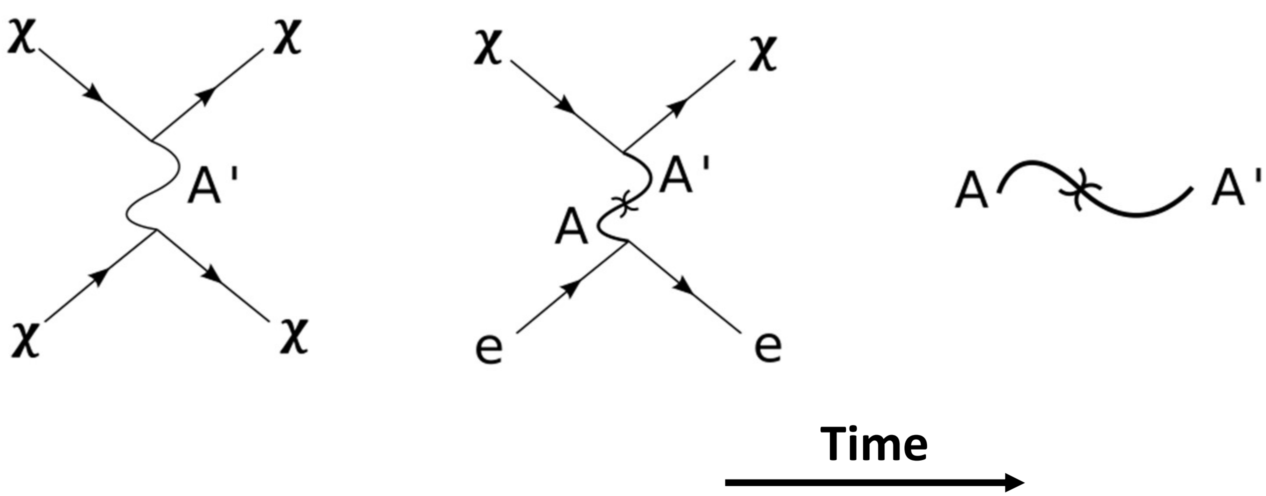

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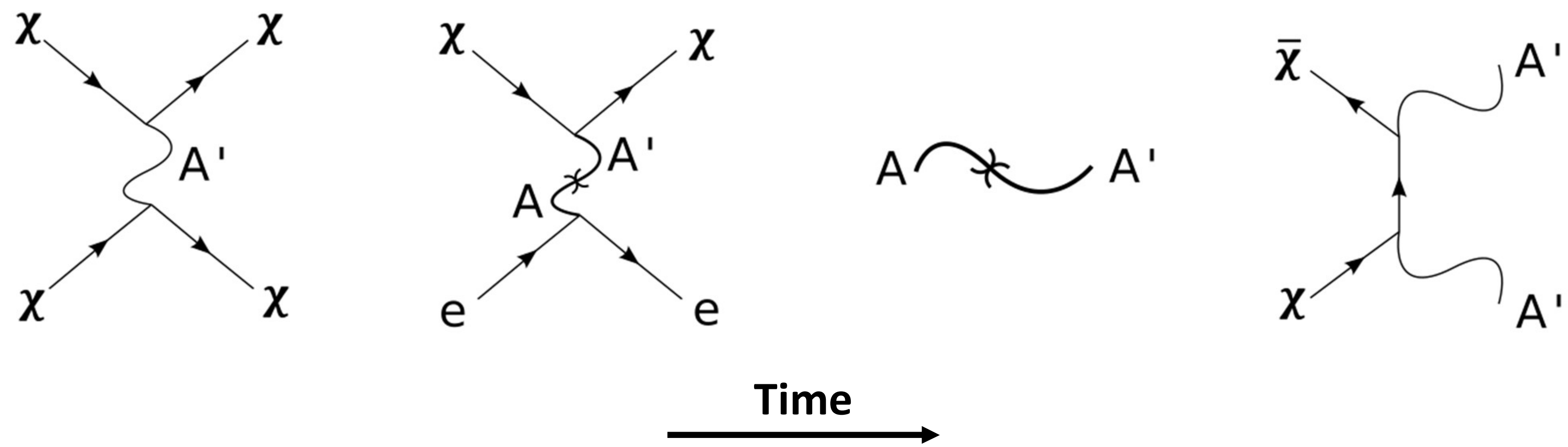

DM w/ Boosted DP - Schematic

When $m_\chi \gg m_{A'}$, the DPs from annihilation act as Long-Lived Particles with galactic scale decay lengths. The dark photon flux is:

$$\Phi_{A'} = \frac{1}{4\pi} \frac{< \sigma_{ann} v >}{2\, m_\chi^2} \int d\Omega \int_{LOS} \rho_\chi^2 \, dx$$

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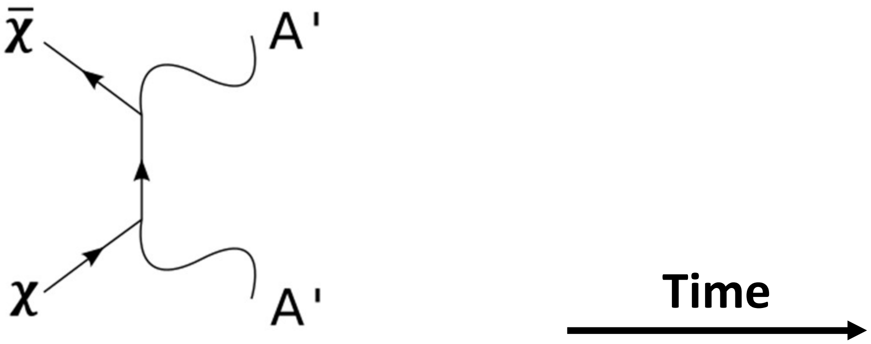
Milky Way Halo



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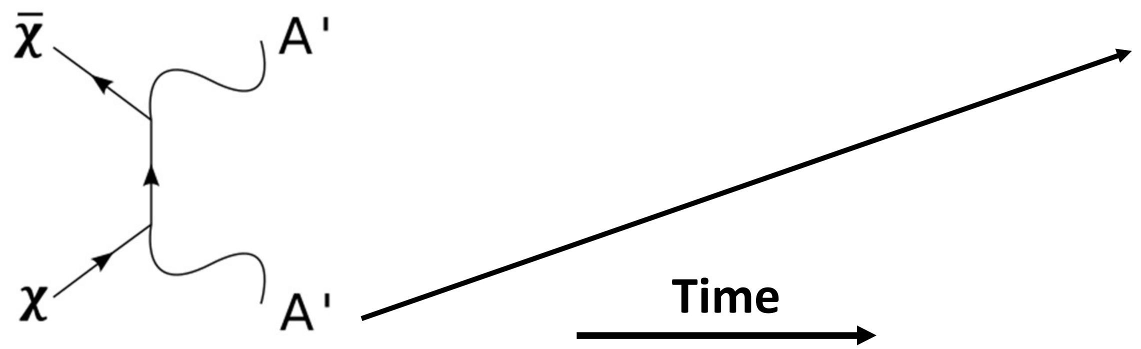

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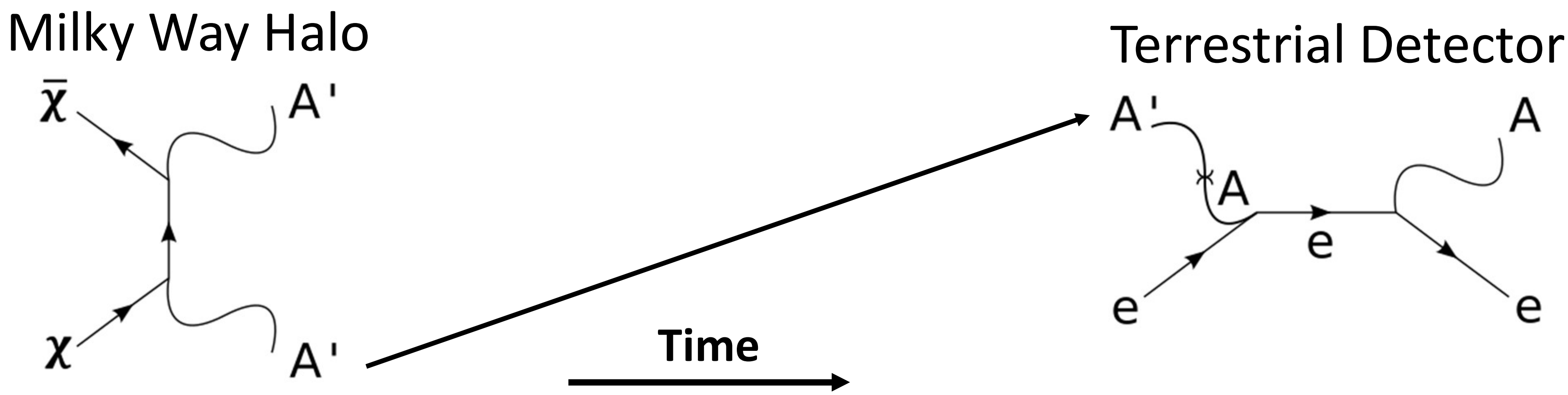

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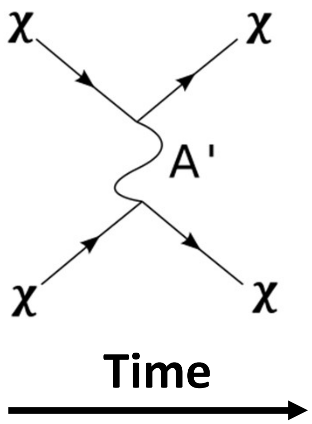
Existing Constraints : DM-DM Scattering



DM – DM scattering constrained by Bullet Cluster observations and the ellipticity of galactic DM halos [1].

[1] Prateek Agrawal, Francis-Yan Cyr-Racine, Lisa Randall, and Jakub Scholtz, "Make dark matter charged again," Journal of Cosmology and Astroparticle Physics 2017, 022 (2017).

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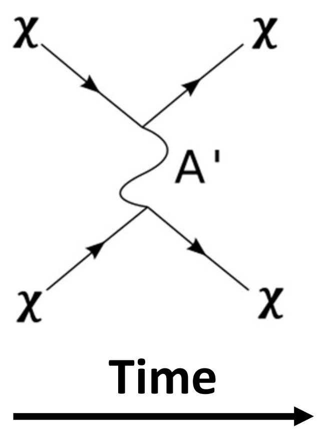

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How to evade these bounds:
Let χ make up ~10% of the total dark matter density. These gravitational observations can have sizable uncertainties.

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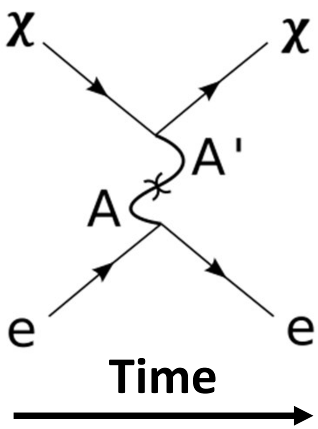
Existing Constraints : DM-SM Scattering



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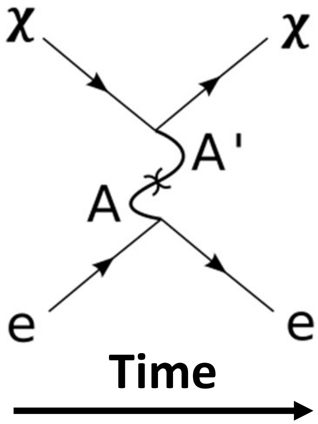

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How to evade these bounds:

Let $m_\chi \lesssim \mathrm{MeV}$. Below this mass, galactic dark matter lacks the energy necessary to produce visible signals in detectors.

For CMB constraints, we need the cross-section to be small.

[2]Sensei Collaboration, "Direct-detection results on sub-gev dark matter from a new skipper CCD", Phys. Rev. Lett. 125, 171802 (2020).
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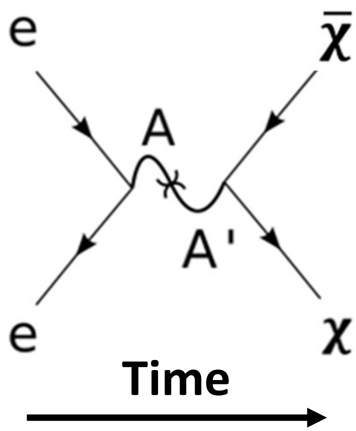
Existing Constraints : DM Stellar Cooling



[5] S. Davidson, S. Hannestad, and G. Raffelt, JHEP 05, 003 (2000), arXiv:hep-ph/0001179.

If $m_\chi < T_{\text{core}}$ in stars, then electromagnetic currents can produce χ which will escape and lead to over-cooling [5]

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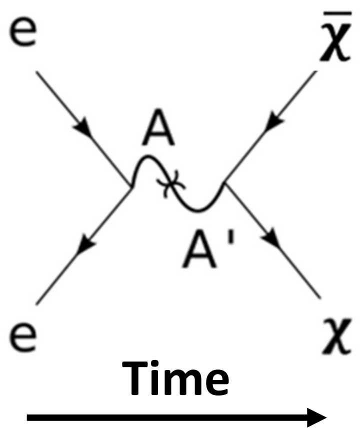


If $m_\chi < T_{\text{core}}$ in stars, then electromagnetic currents can produce χ which will escape and lead to over-cooling [5]

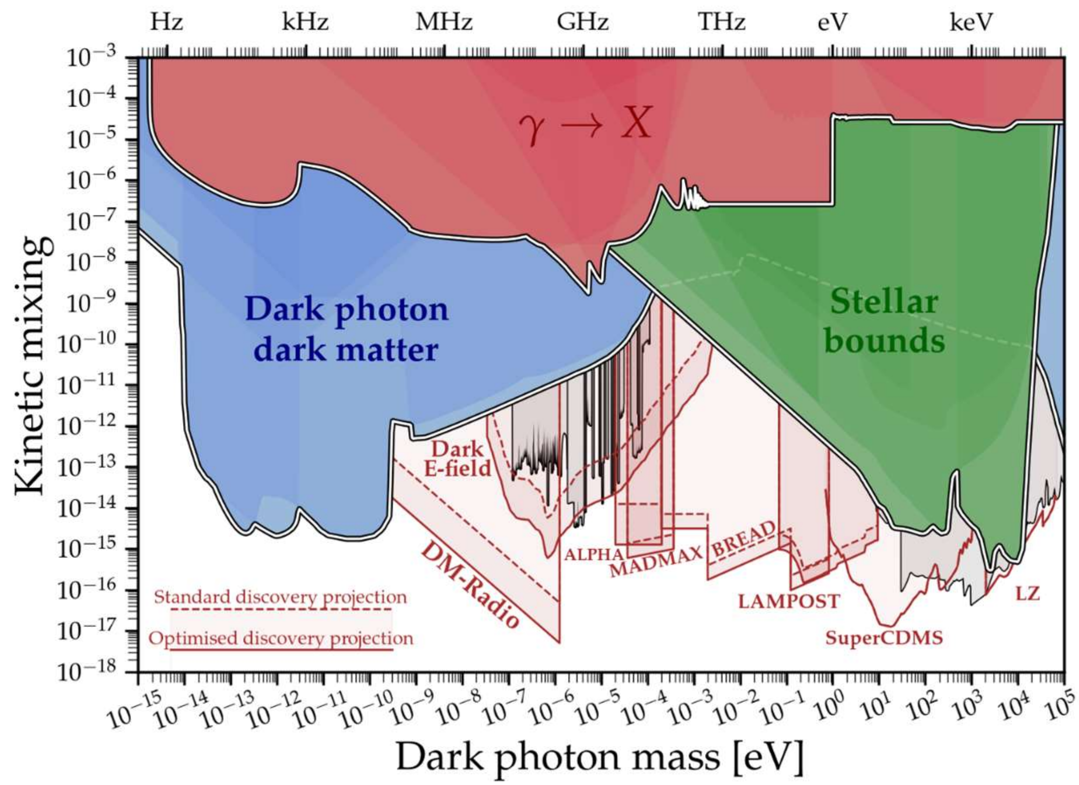
How to evade these bounds:
Let $m_\chi \gg T_{\text{core}}$ $(\mathcal{O}(10)\text{keV})$ so emission is kinematically forbitten
OR
Let $g_D\epsilon$ be small so χ has little coupling to EM currents.

[5] S. Davidson, S. Hannestad, and G. Raffelt, JHEP 05, 003 (2000), arXiv:hep-ph/0001179.

Existing Constraints : DP Mixing

For DPs that mix with SM photons, this can lead to DPs free-streaming out of the Sun (and other stars). Stellar cooling observations and direct detection constrains these models.

Constraints weaken when $m_{A'} < \omega_p$ (the plasma mass)



[6] Andrea Caputo, Ciaran A. J. O'Hare, Alexander J. Millar, and Edoardo Vitagliano, "Dark photon limits: a cookbook," (2021), arXiv:2105.04565 [hep-ph].

Dark Photon In-Medium Effects

In matter, dielectric properties lead to a modified photon propagator via a polarization tensor Π [7].

For transversely polarized photons in an isotropic, non-magnetic medium, we relate this polarization tensor to the index of refraction

$$\Pi_T = \omega^2(1 - n_{ref}^2)$$

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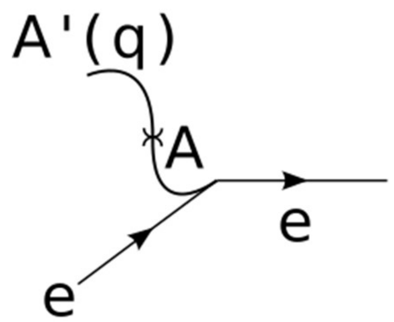

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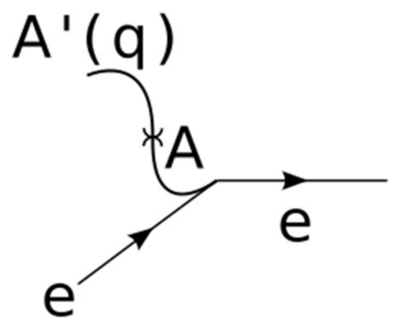

$$\sim \epsilon q^2 * \frac{1}{q^2 - \Pi}$$

Mixing

Photon Propagator

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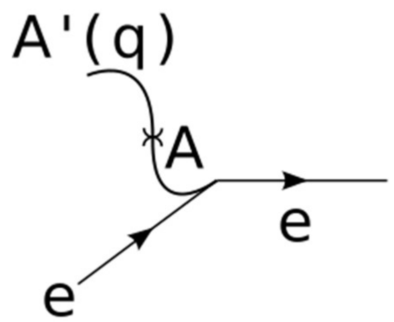

On-shell condition

$$q^2 = m_{A'}^2$$

$$\sim \epsilon q^2 * \frac{1}{q^2 - \Pi}$$

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For transversely polarized photons in an isotropic, non-magnetic medium, we relate this polarization tensor to the index of refraction

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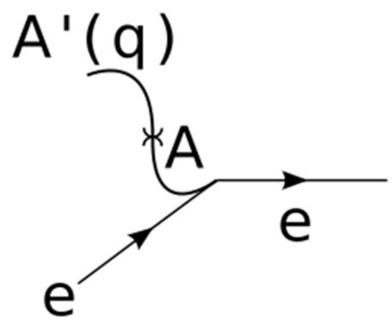

$$\sim \epsilon q^2 * \frac{1}{q^2 - \Pi}$$

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$$q^2 = m_{A'}^2$$

$$\epsilon_{\text{eff}} \sim \frac{\epsilon\, m_{A'}^2}{m_{A'}^2 - \Pi}$$

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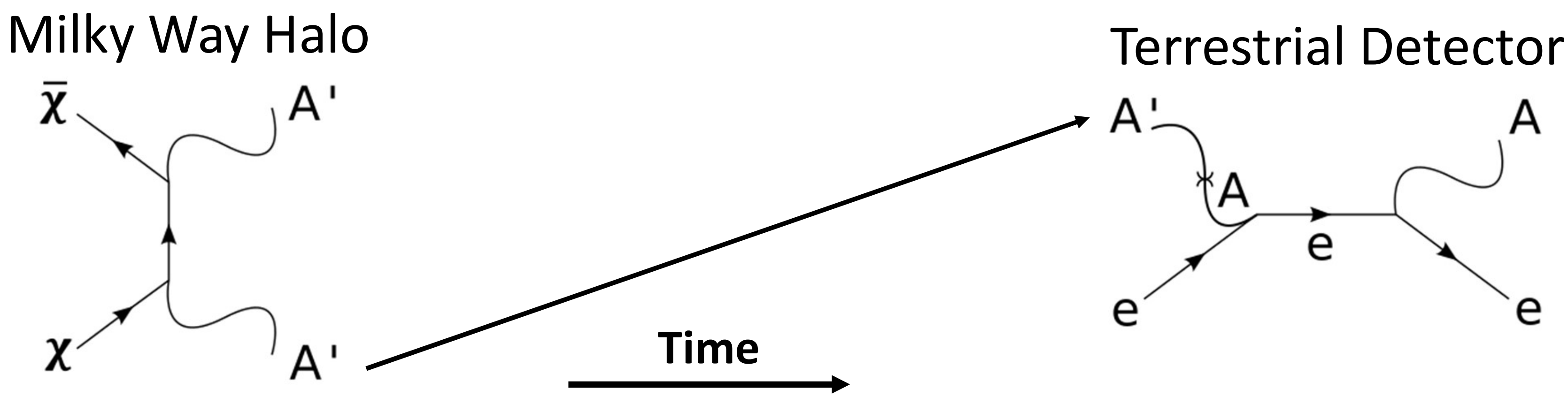
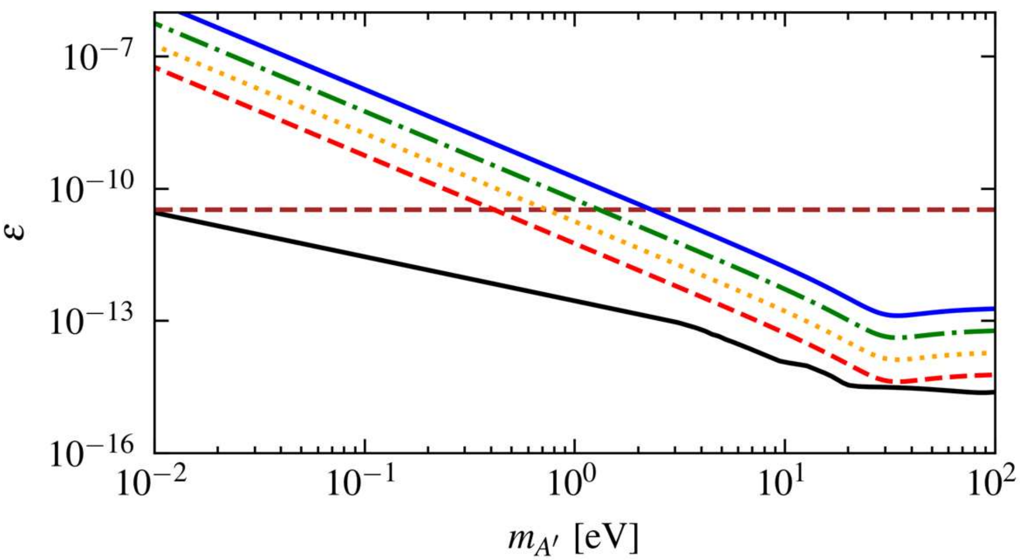
Results

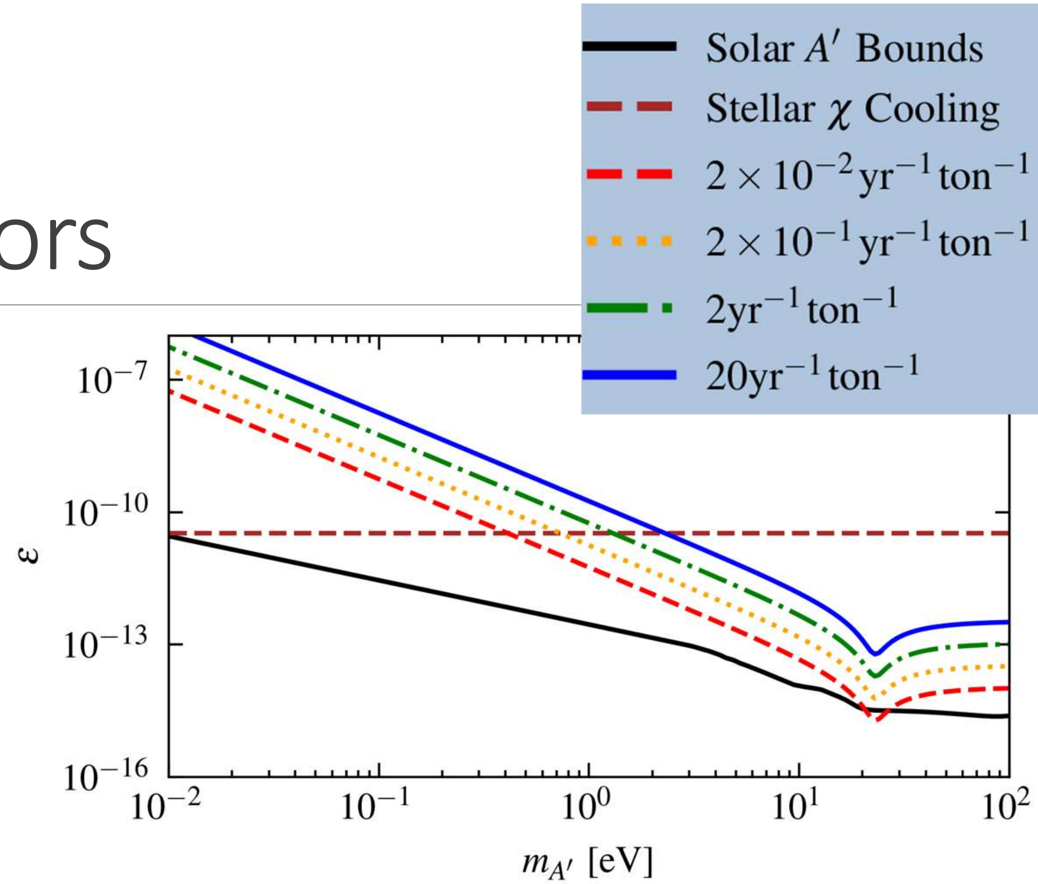


$f_i = 10\%$ $m_\chi \sim 1\text{keV}$ g_D to optimize flux

Results –Liquid Xenon/Argon Detectors



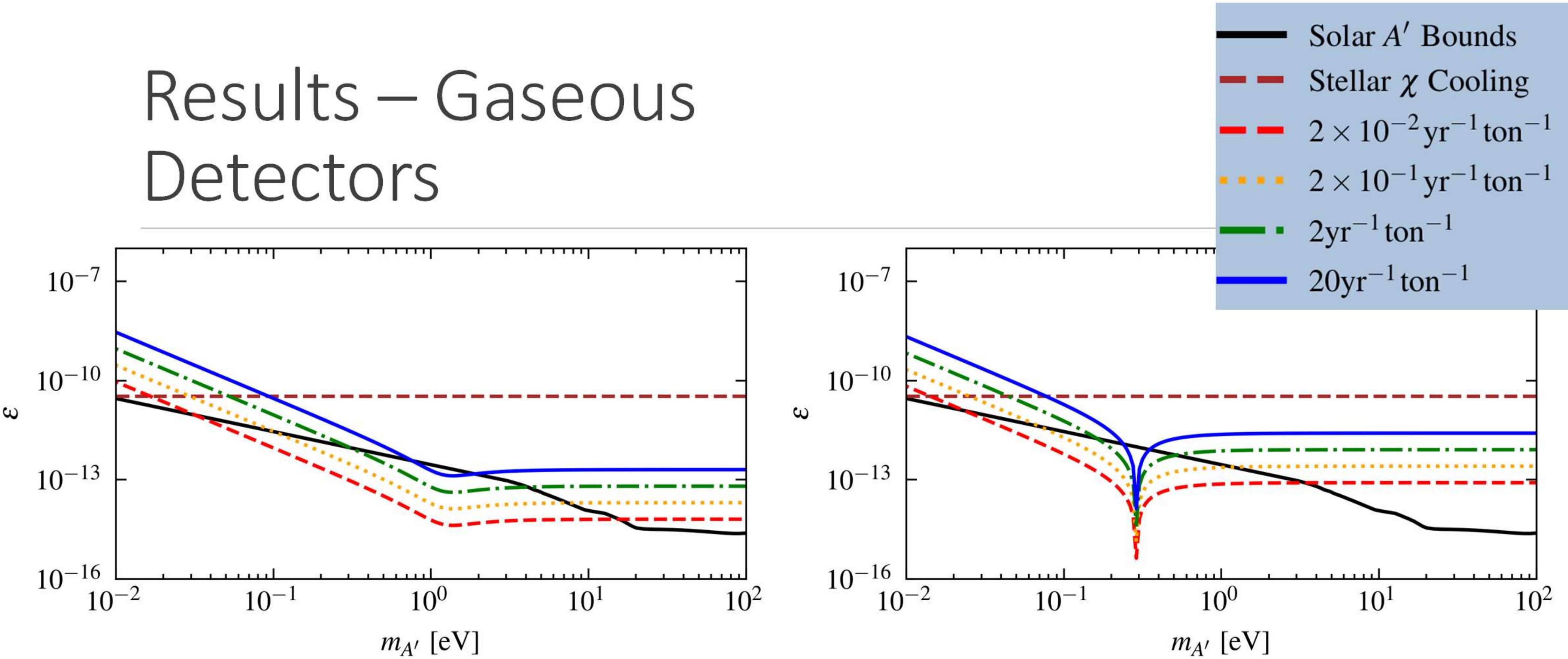
Liquid Xenon



Liquid Argon

$f_i = 0.1\,; m_\chi = 1$ keV

Results – Gaseous Detectors

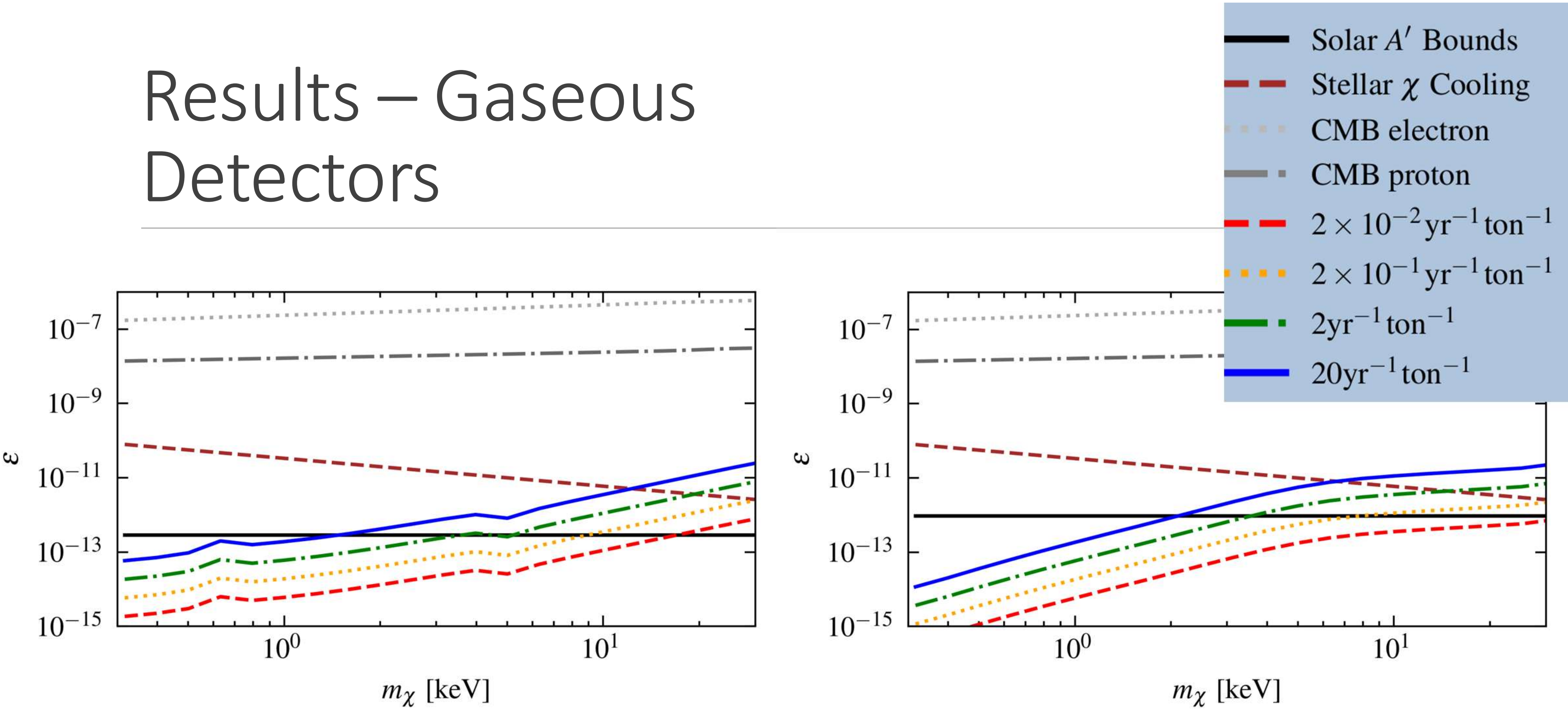


Xenon $\rho = 5 \text{ kg m}^{-3}$

Helium $\rho = 0.2 \text{ kg m}^{-3}$

$f_i = 0.1 \,; m_\chi = 1 \text{ keV}$

Results – Gaseous Detectors



Xenon $\rho = 5 \ \mathrm{kg\,m^{-3}}$, $m_{A'} = 1\mathrm{eV}$

$f_i = 0.1$

Helium $\rho = 0.2 \ \mathrm{kg\,m^{-3}}$, $m_{A'} = 0.3\mathrm{eV}$

Conclusion

Here, we explore the indirect detection of keV dark matter annihilating into dark photons with an optimized annihilation cross section.

Future detectors can search for this signal if they have the following properties

- Large Volumes and Low Densities
  - Gaseous detectors have less suppression from in-medium effects
- Low Energy Thresholds and Good Energy Resolution
  - The signal will be a mono-energetic peak at m_χ
  - Smaller m_χ means more signal
- Good Spatial Resolution
  - Dark photons can interact anywhere within the detector, while most x-ray background will be on the detector edges

Thank You!

arXiv: 2402.00941
Phys. Rev. D 109, 095015
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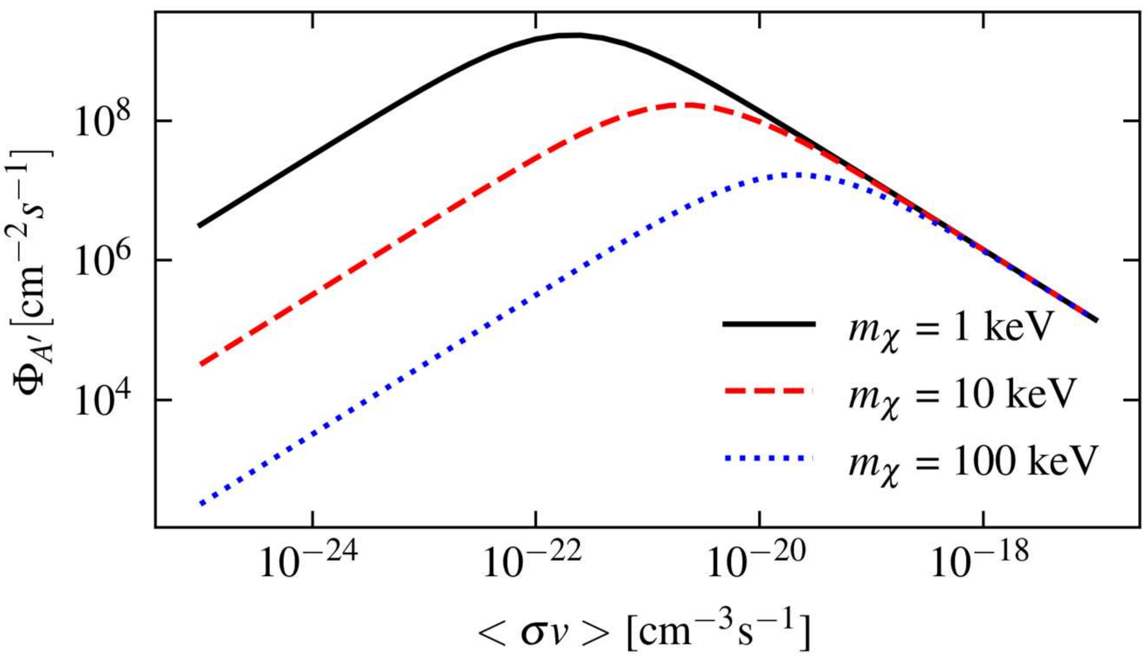
Bonus Slide - χ Distribution And DP Flux

We let the χ distribution follow an NFW profile with a time-dependent scaling.

$$\rho_\chi(r,t) = f(t) \times \rho_{\mathrm{NFW}}(r)$$

After picking a value of $f_i = f(t=0)$, we can then time-evolve the distribution due to annihilations. Given our choice of m_χ and $< \sigma\, v >$, we can then compute the flux of dark photons at Earth.

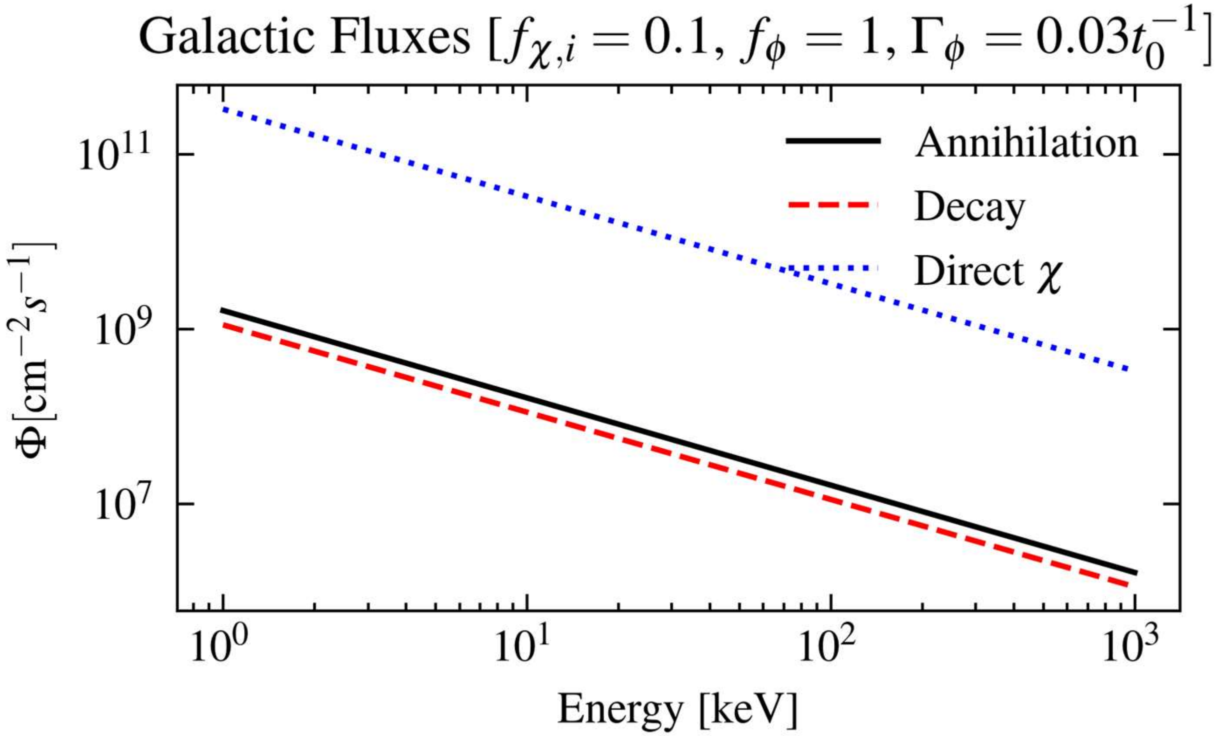


Bonus Slide – Decaying Dark Matter

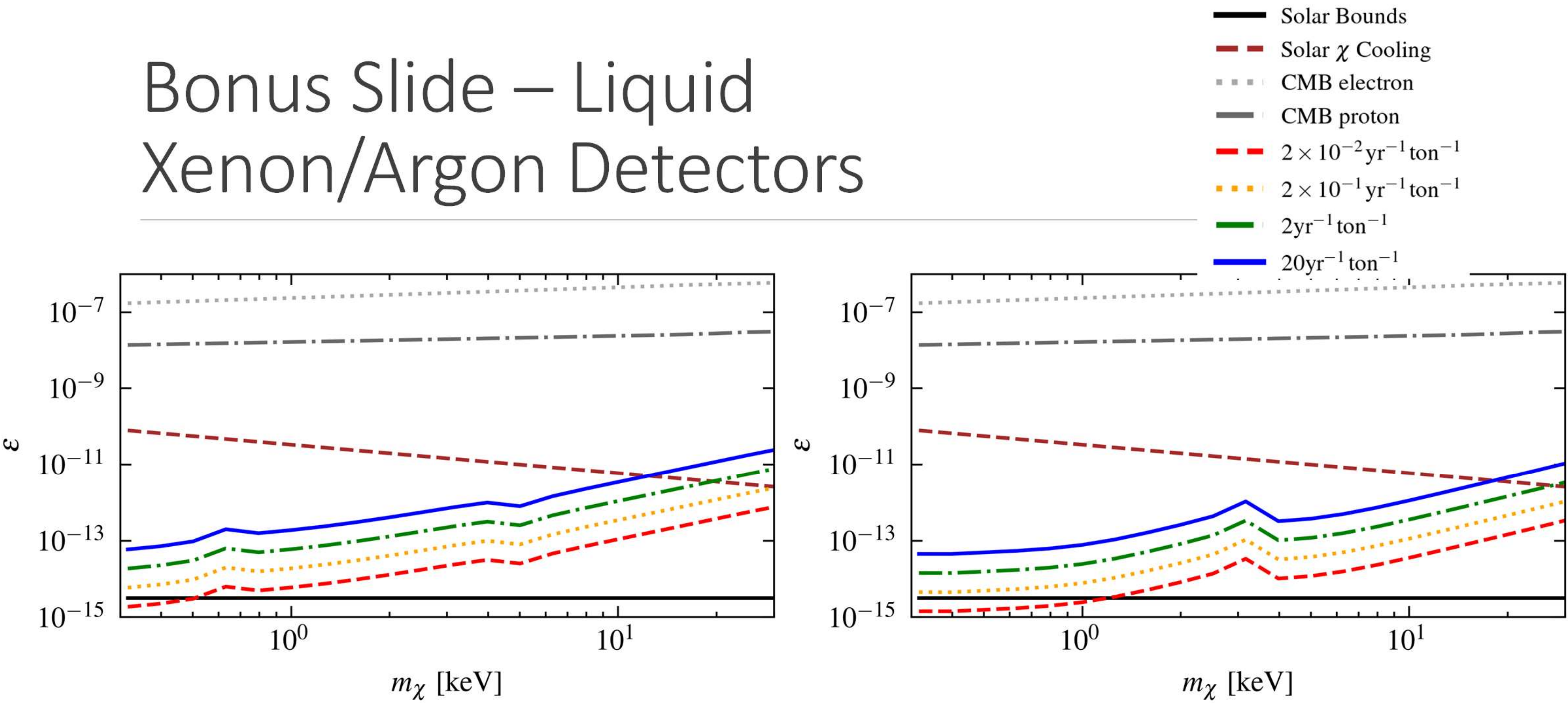
An alternative model dark matter model could be a scalar ϕ which decays into DPs

$$\phi \rightarrow A'A'$$

This could produce a flux of similar magnitude to the annihilating case.



Bonus Slide – Liquid Xenon/Argon Detectors



Liquid Xenon

Liquid Argon

$f_i = 0.1 \, ; m_{A'} = 25$ eV