Aspects of Sommerfeld Enhancement in the light of Halo gamma-ray excess

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based on arXiv:2512.24662
Collaboration with J. H. Park, M. G. Park and S. C. Park

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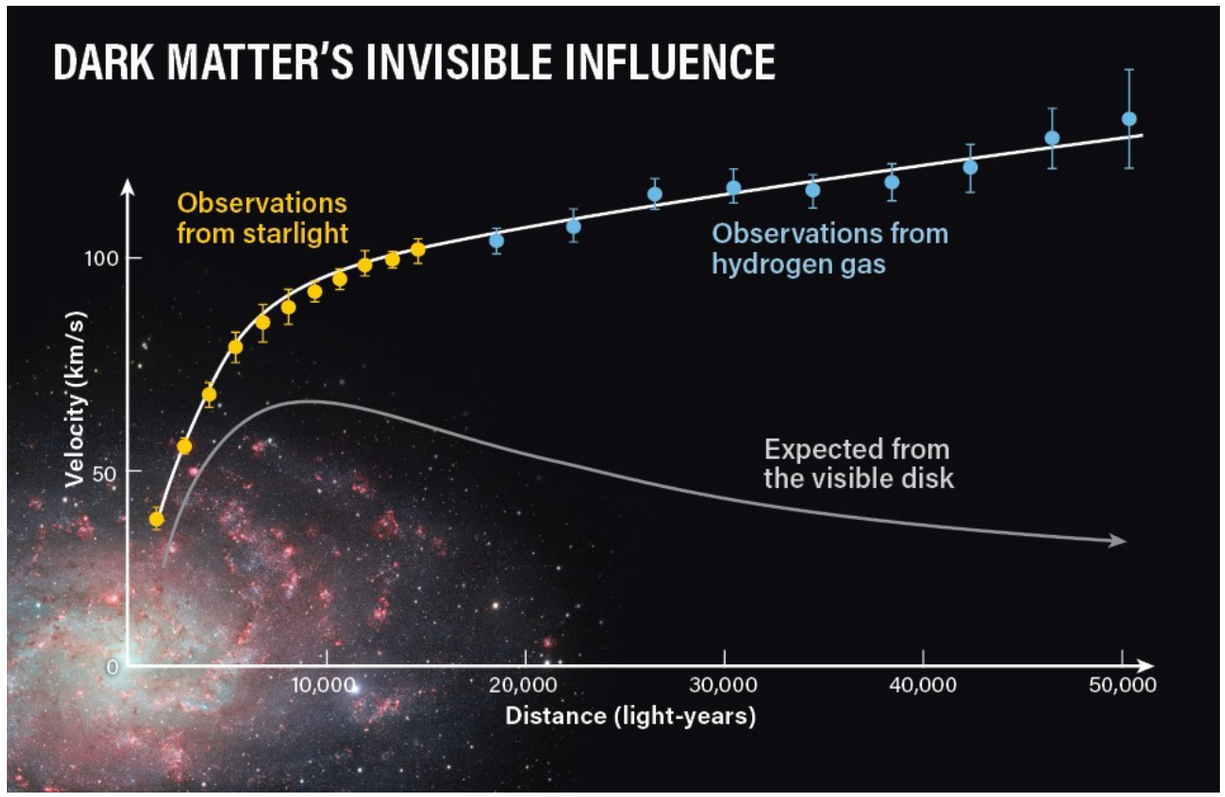
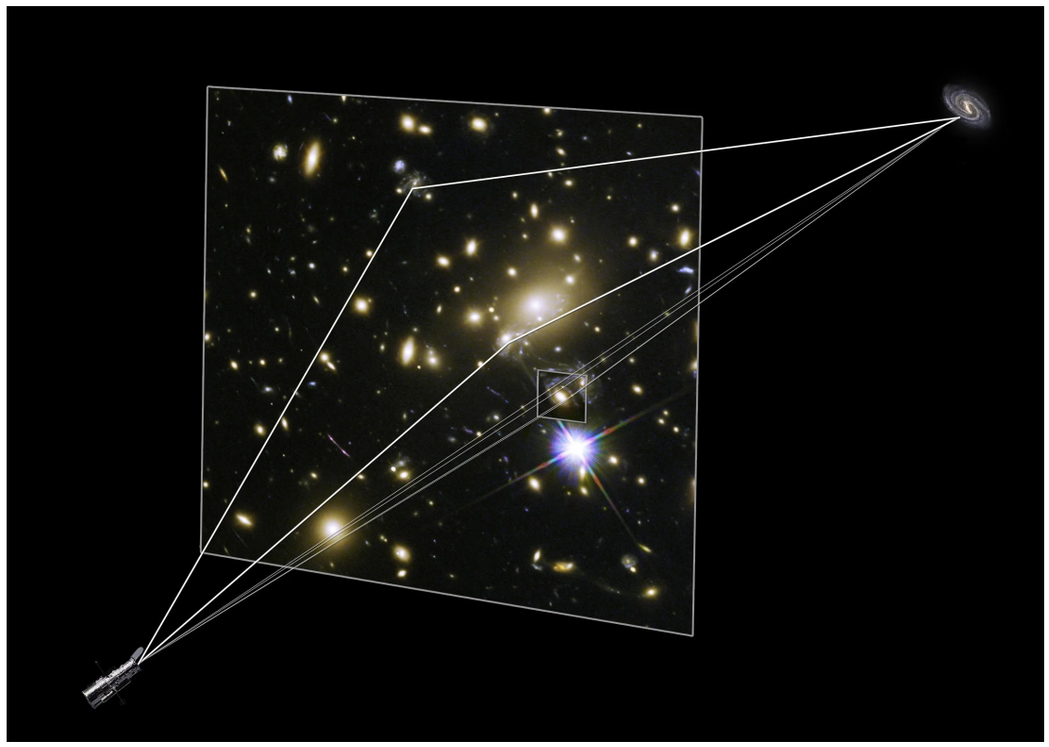
IBS-CTPU Seminar

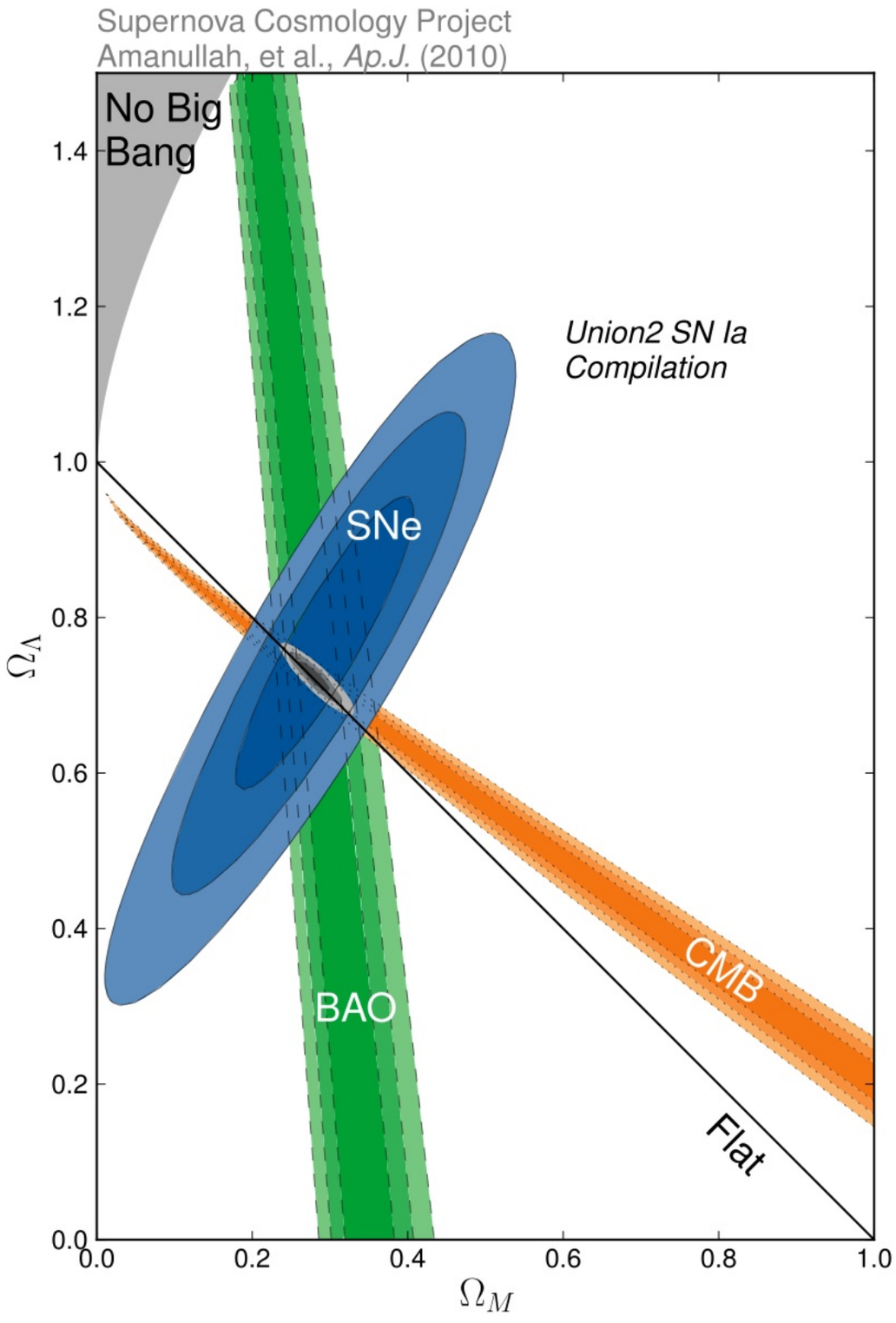
Outline

- Dark Matter and WIMP scenario
- Indirect Search for DM
- Halo-like gamma-ray excess
- p-wave annihilation + Sommerfeld Enhancement
- Results & Constraints
- Conclusion

Why Dark Matter?

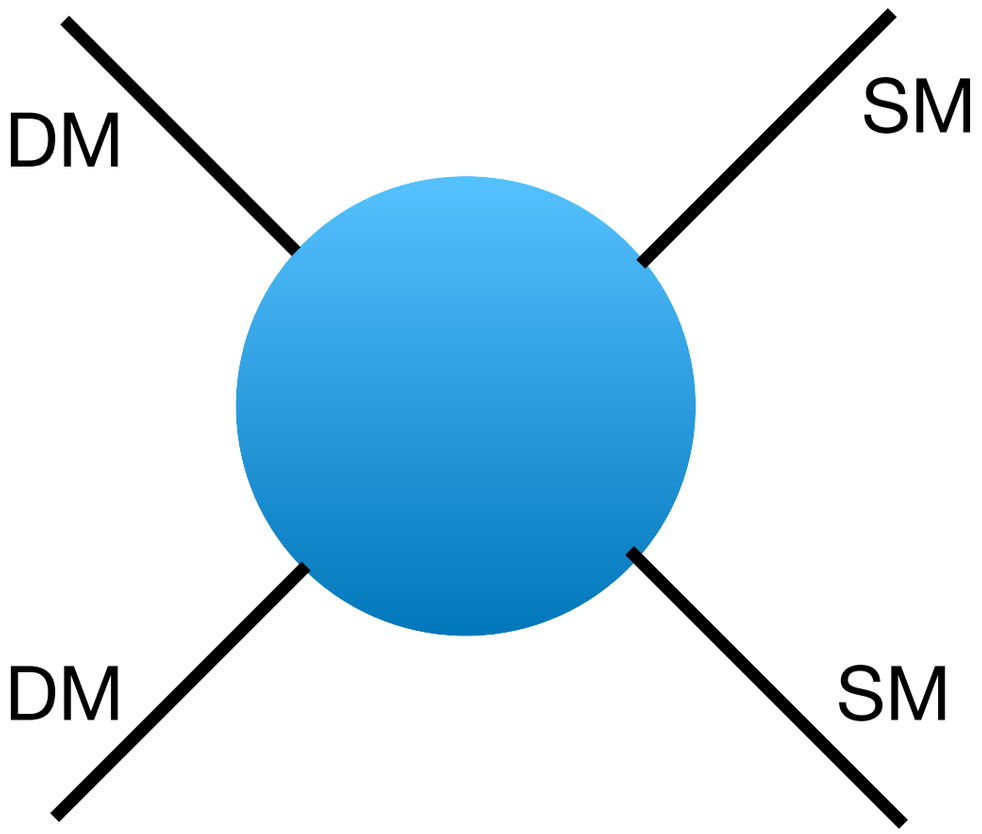


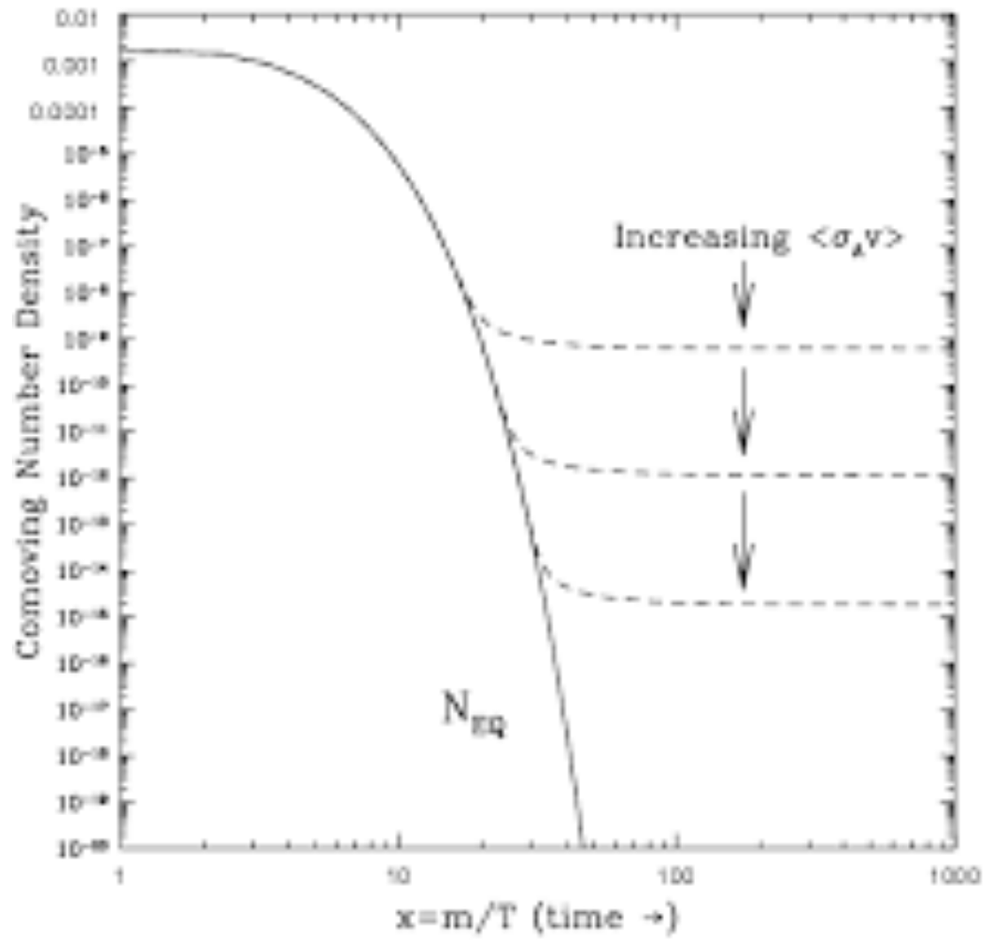




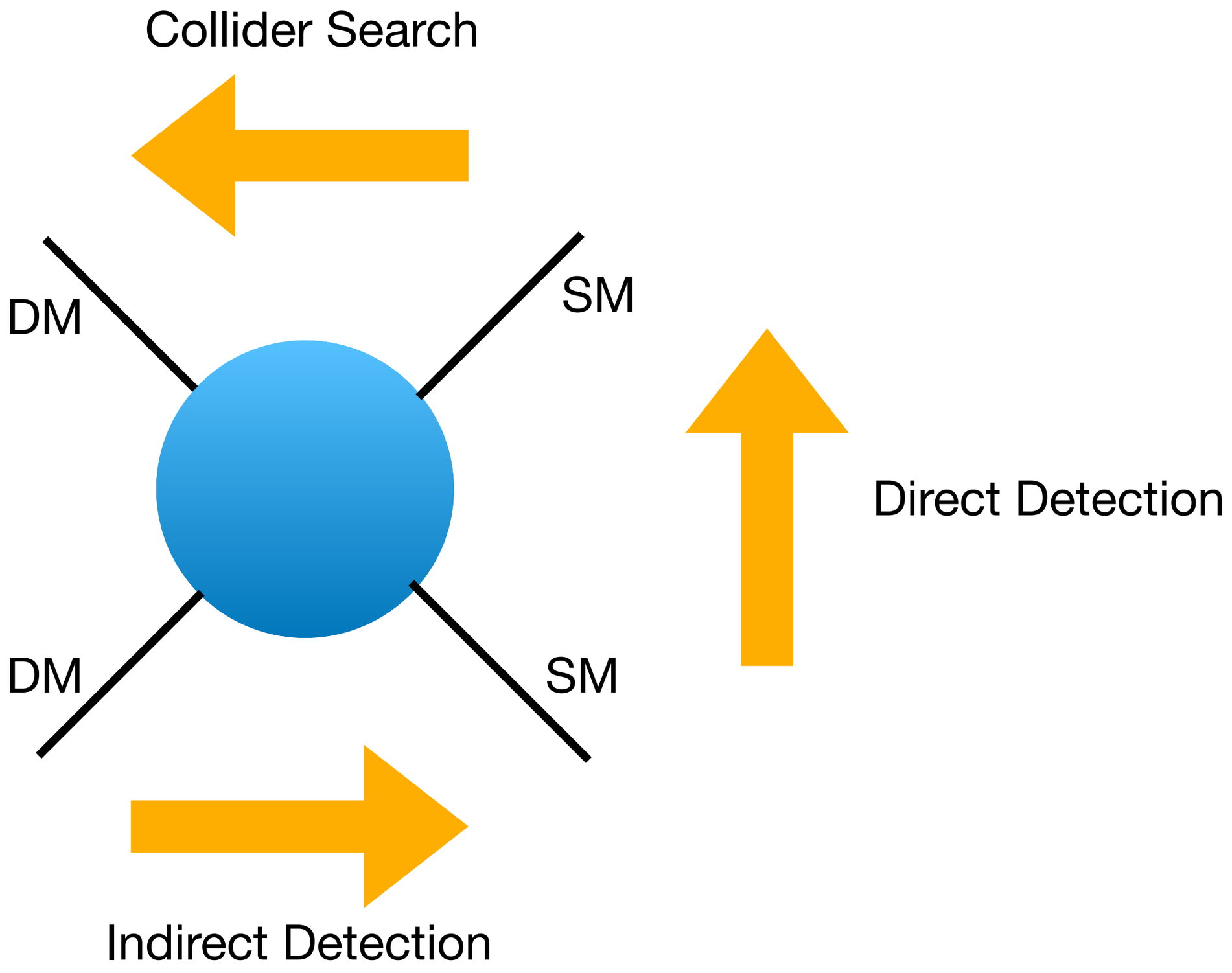
WIMP scenario

- SM and DM sector are in thermal equalibrium in Early Universe
- Expansion of the Universe makes the departure from the equilibrium (i.e. Freeze-out)
- The amount of relic abundance is related to the annihilation cross section at Freeze-out





Search for WIMP DM



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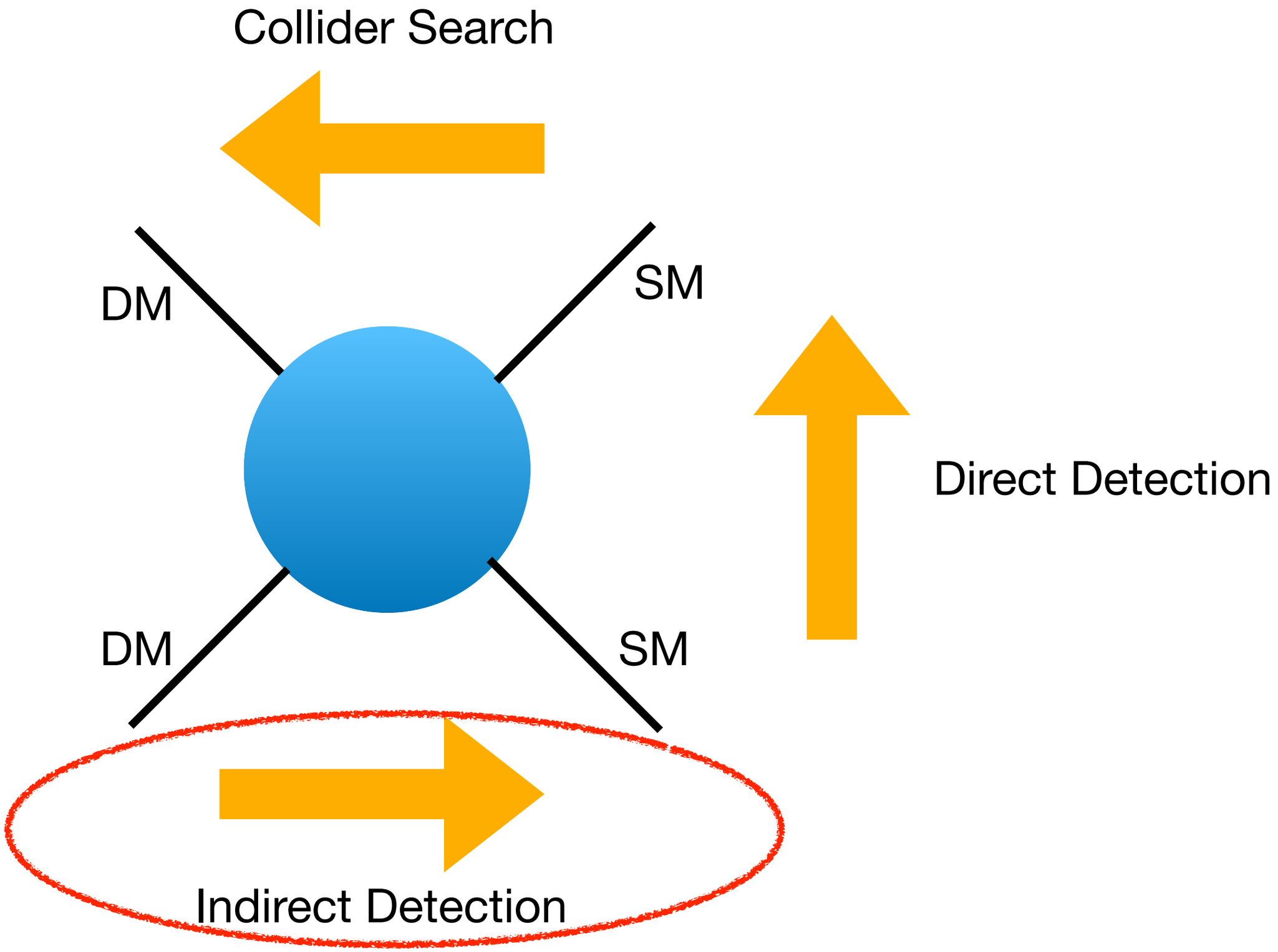
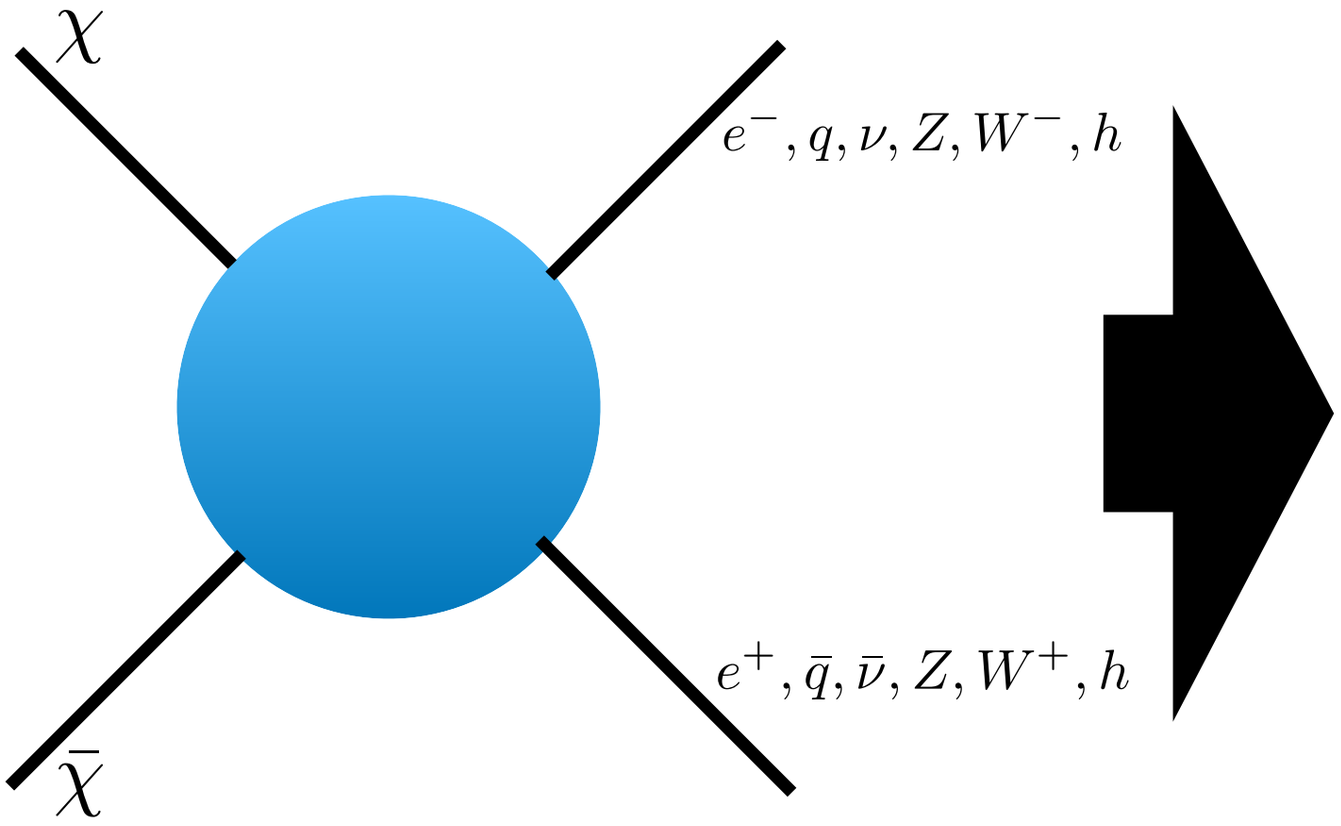
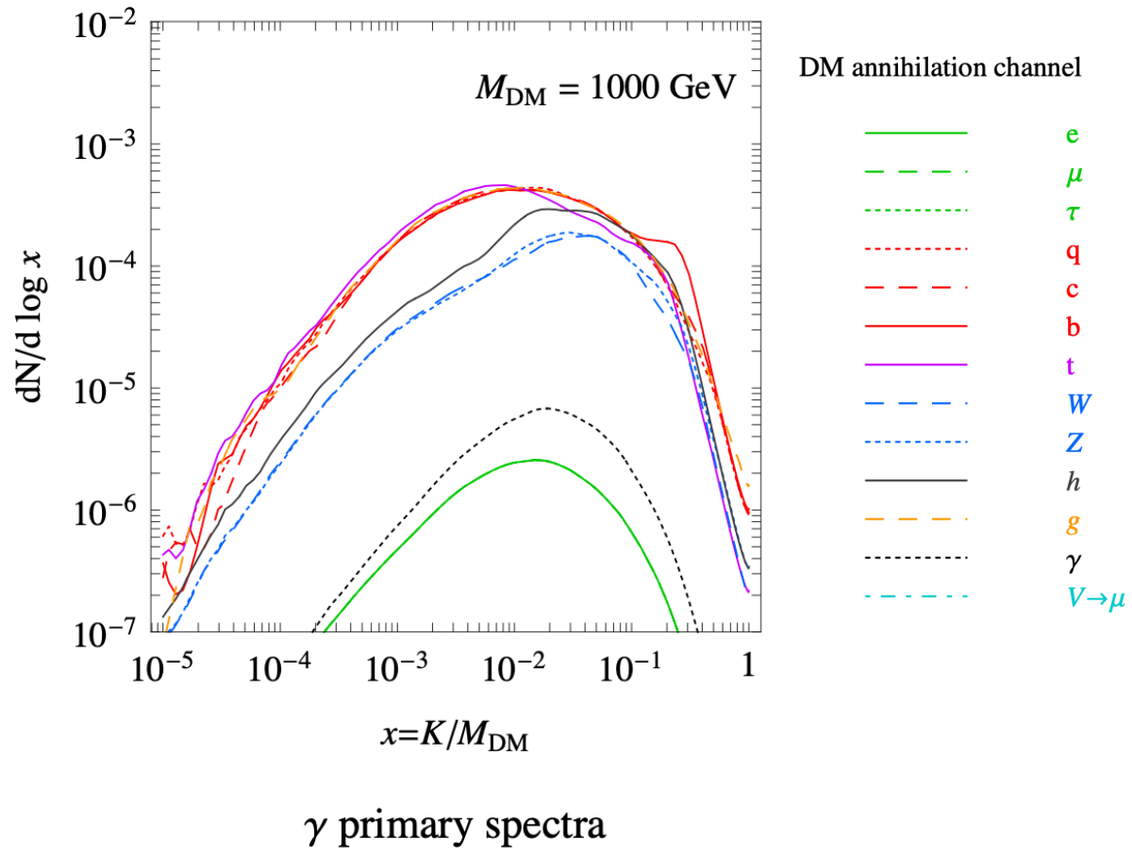


Indirect Search for WIMP

- Annihilation and/or Decay of Dark Matter produces energetic astrophysical signals, e.g. gamma-ray, cosmic-rays, neutrinos.



Primary production

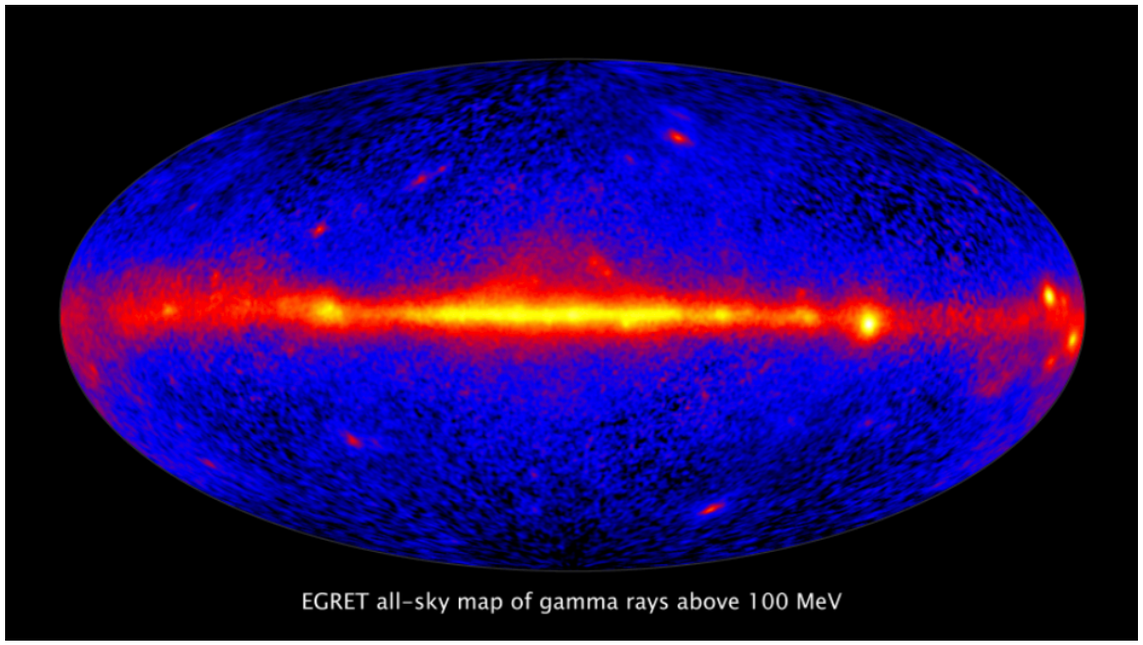


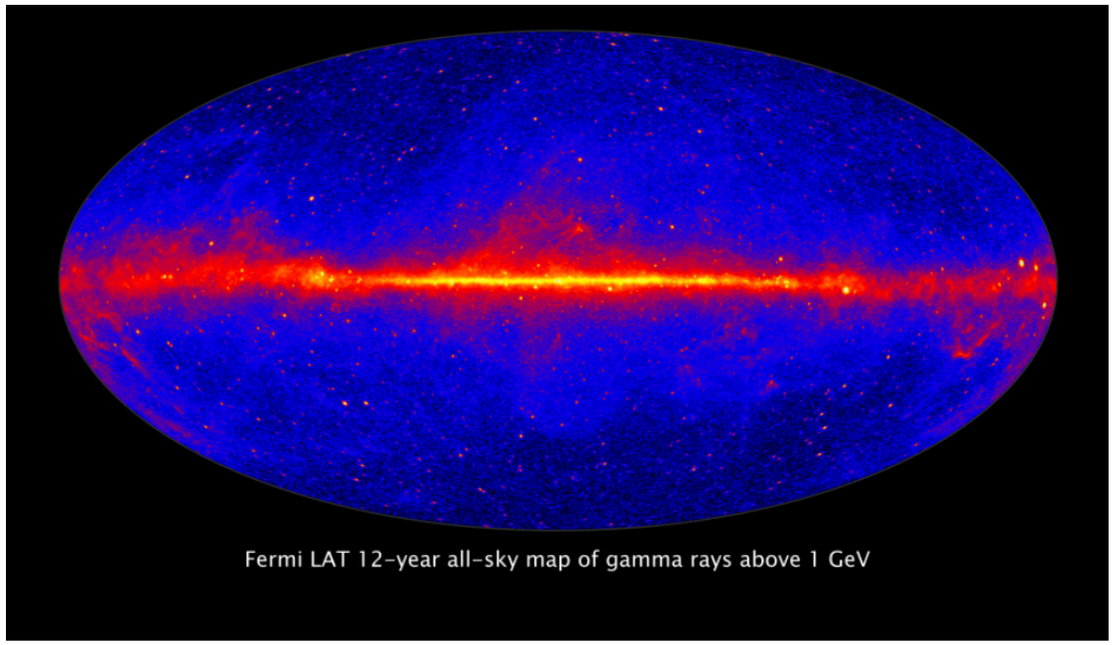
γ primary spectra

Secondary production $\gamma, e^+, \bar{p}, \bar{d}, \nu$

FermiLAT data in Gamma-ray sky

- FermiLAT provides gamma-ray map with a ~ 15-years of data set in a wide range of Galactic coordinates.

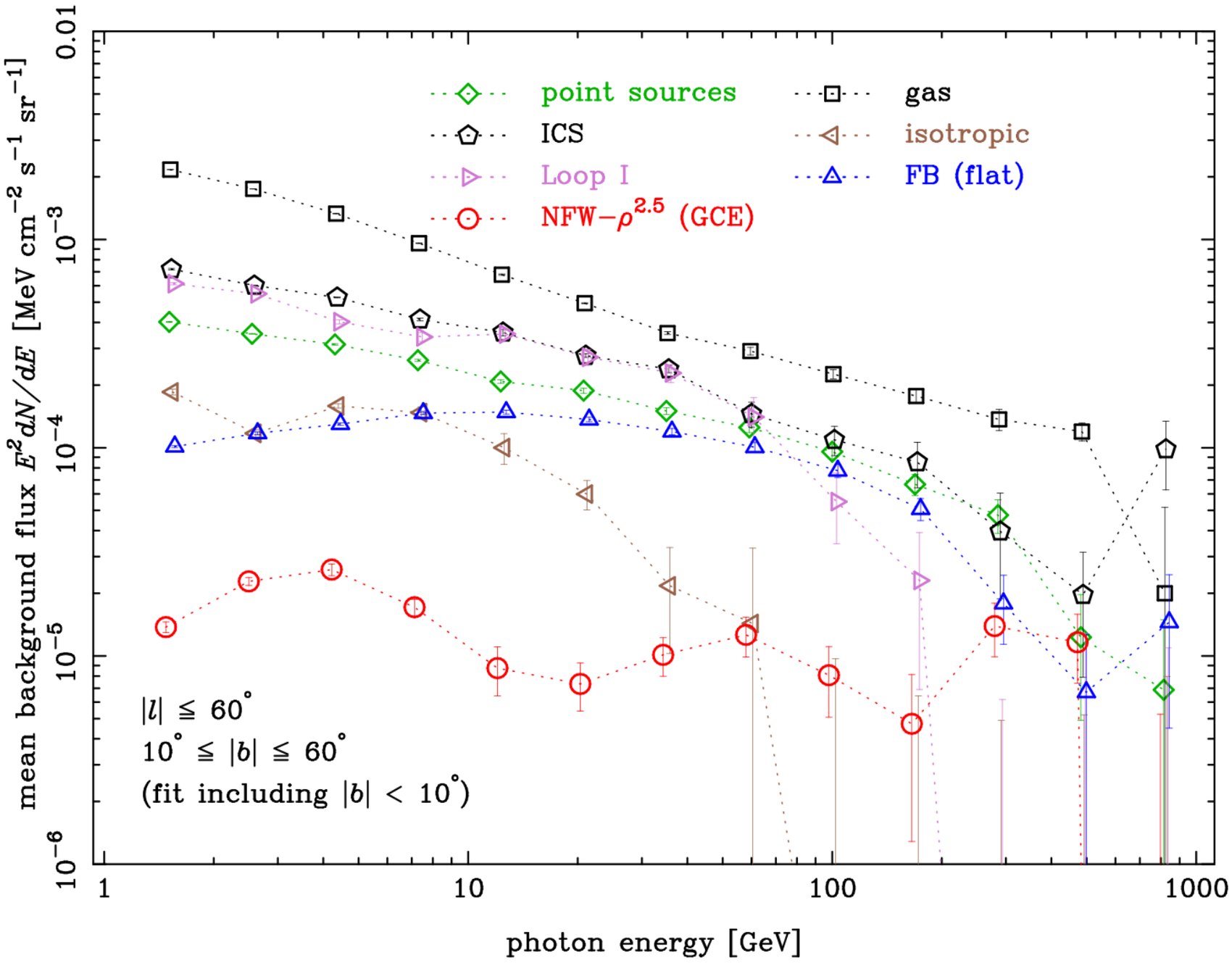




- Backgrounds of gamma-rays are usually dominated by
  - Galactic Diffusion Emission induced by cosmic-ray interacting with the interstellar medium (ISM), inverse compton scattering and bremsstrahlung.
  - Isotropic Diffuse gamma-rays
  - Point sources (Pulsar, SNR, etc.)

Halo-like excess in 15-years data of FermiLAT

- Totani recently presented an analysis for halo-like gamma-ray excess in the 15-years data set of FermiLAT observation



Totani (25')

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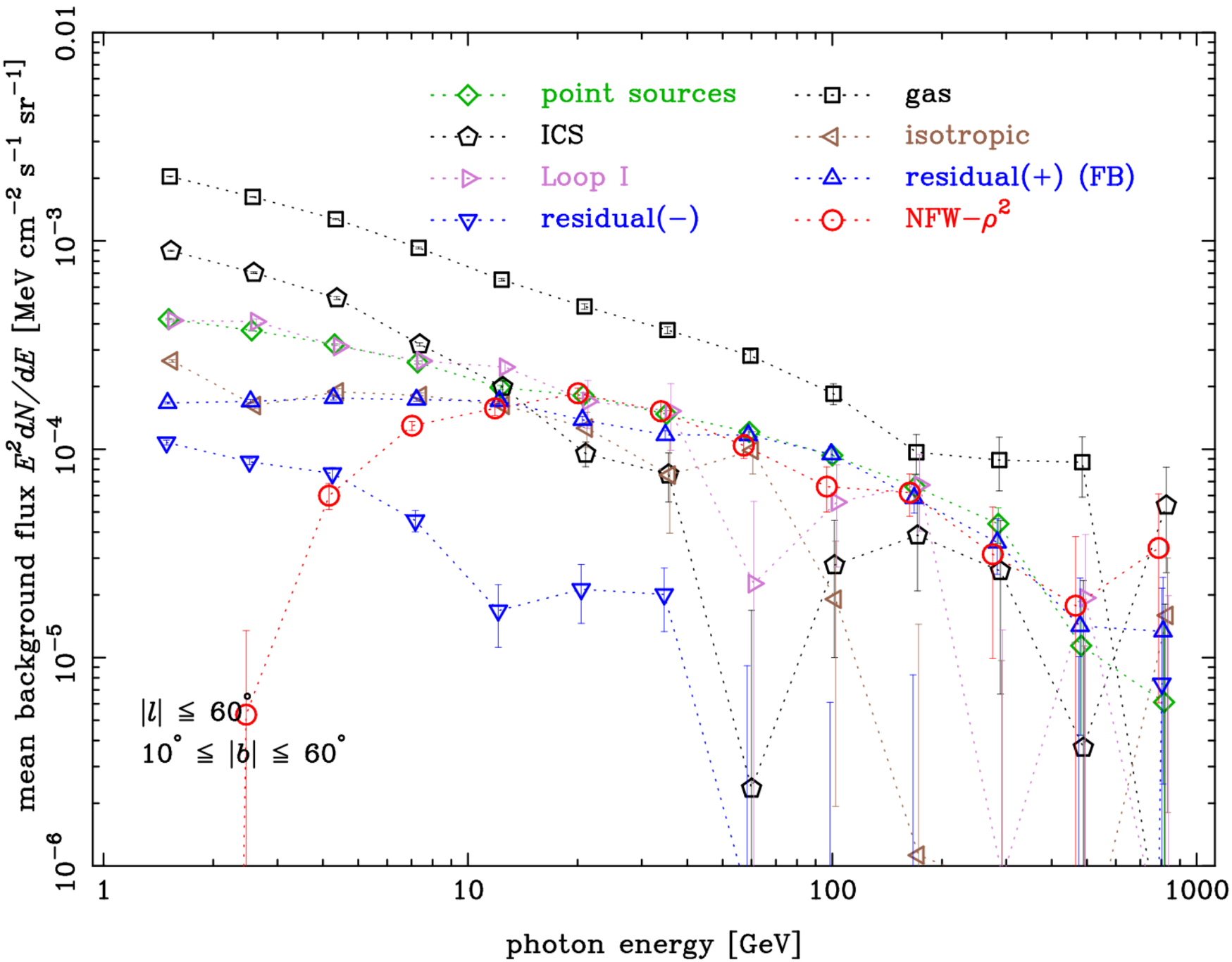

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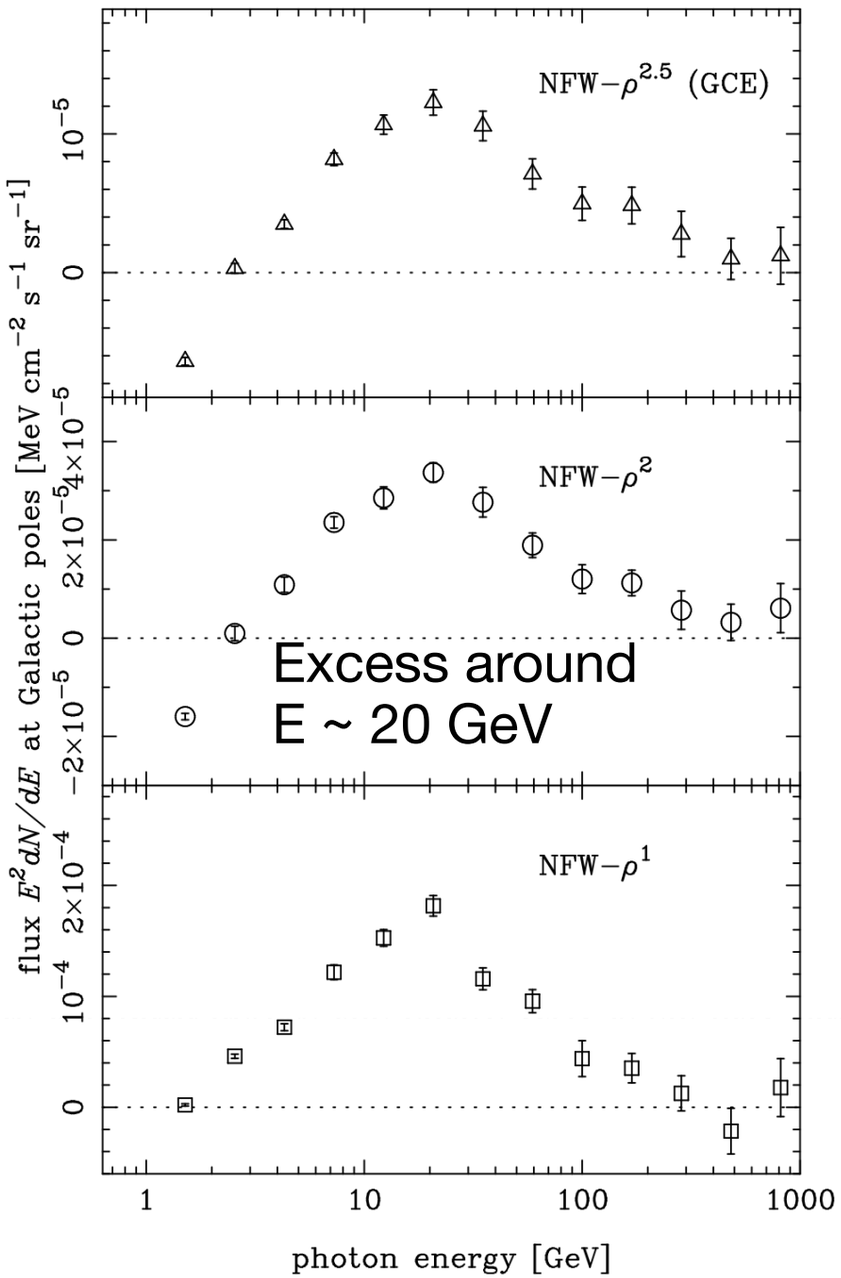

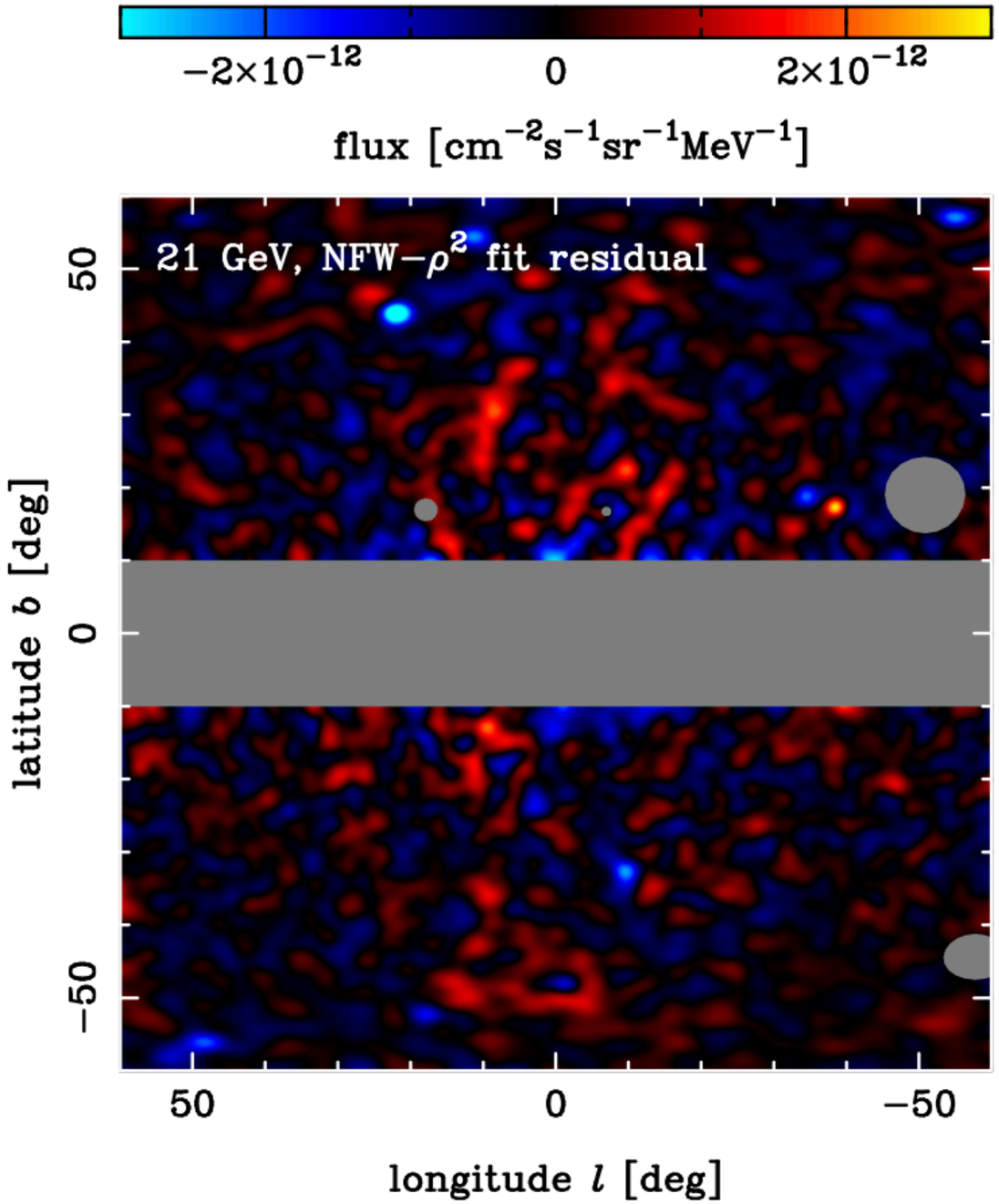

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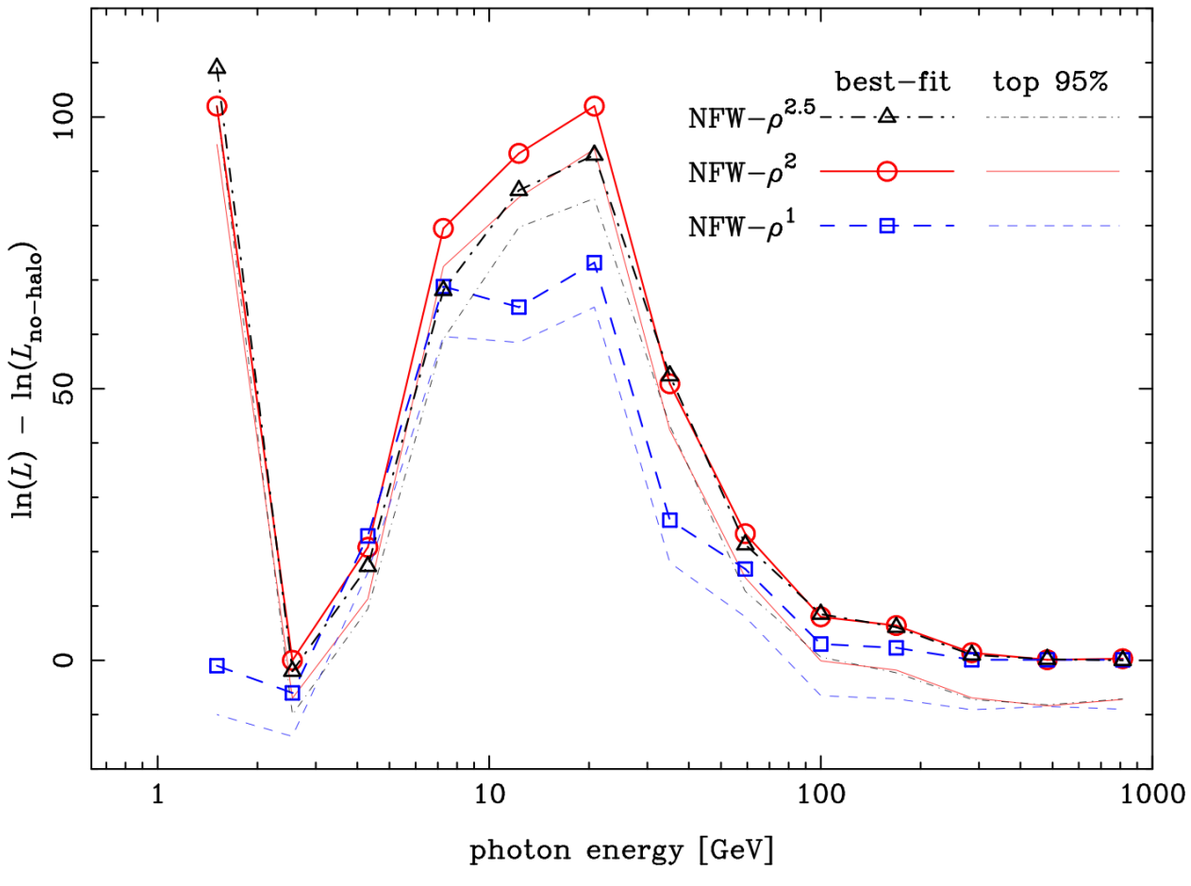
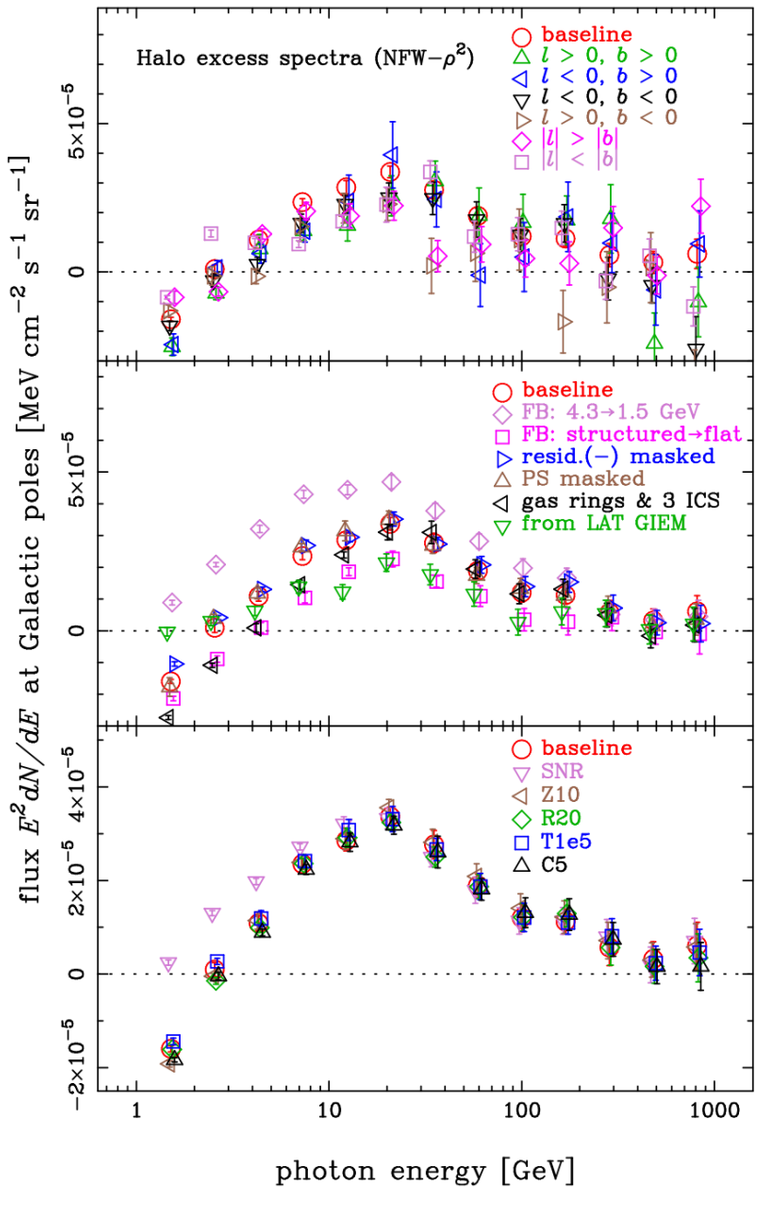


Both annihilation-like and decay-like fit show meaningful statistical significances

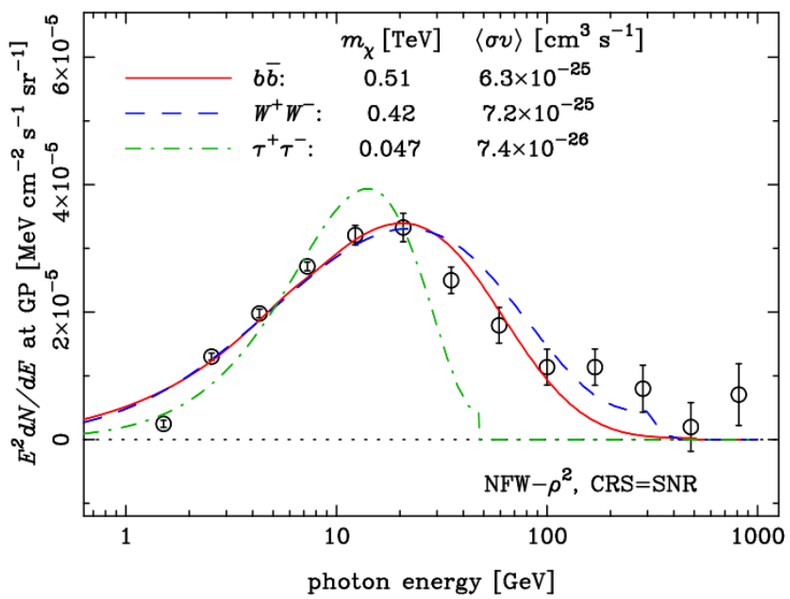


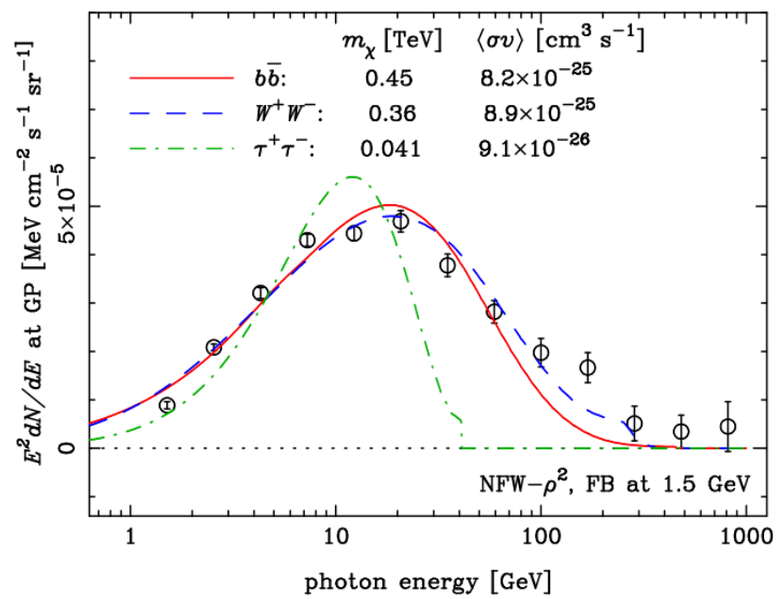
Totani (25')

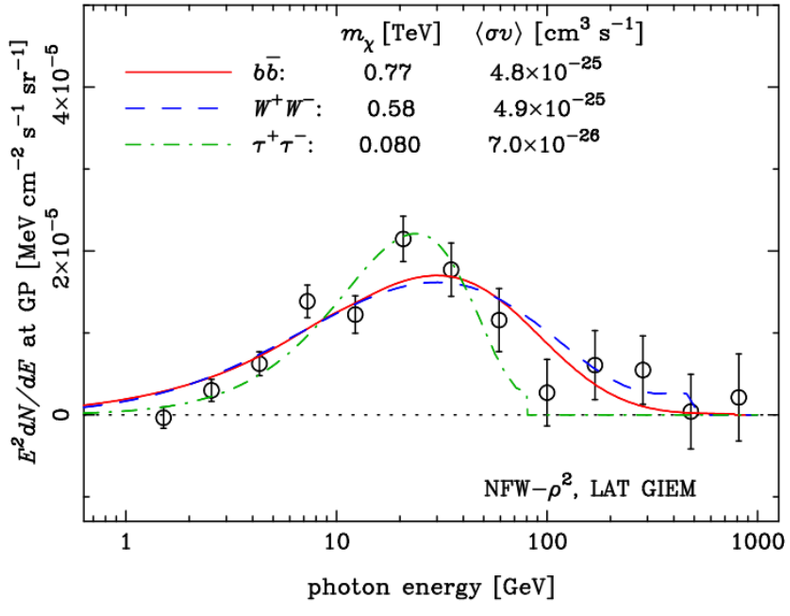
Excess around E ~ 20 GeV is shown in both GALPROP and Fermi-provided GIEM models.

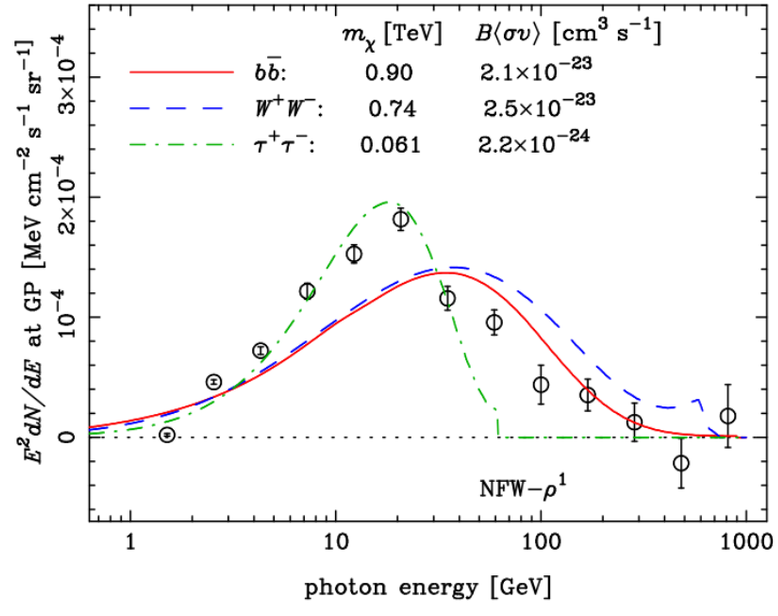
Halo-like excess in 15-years data of FermiLAT

- DM interpretation









$b\bar{b}, W^+W^-$ preferred

$$m_\chi = 500 - 800 \text{ GeV}$$

$$\langle\sigma v\rangle = (5-8)\times10^{-25}\text{cm}^3/s$$

Totani (25')

Does Standard WIMP scenarios can explain the excess?

$$\langle \sigma v \rangle_{FO} = 3 \times 10^{-26} \mathrm{cm}^3/s$$

- Annihilation cross section is large $\langle \sigma v \rangle = (5-8) \times 10^{-25} \mathrm{cm}^3/s$
- Strong constraints from dwarf spheroidal galaxies
- A vanilla scenario with s-wave annihilation is problematic
- What scenarios will be available?

Our model

- Effective Lagrangian

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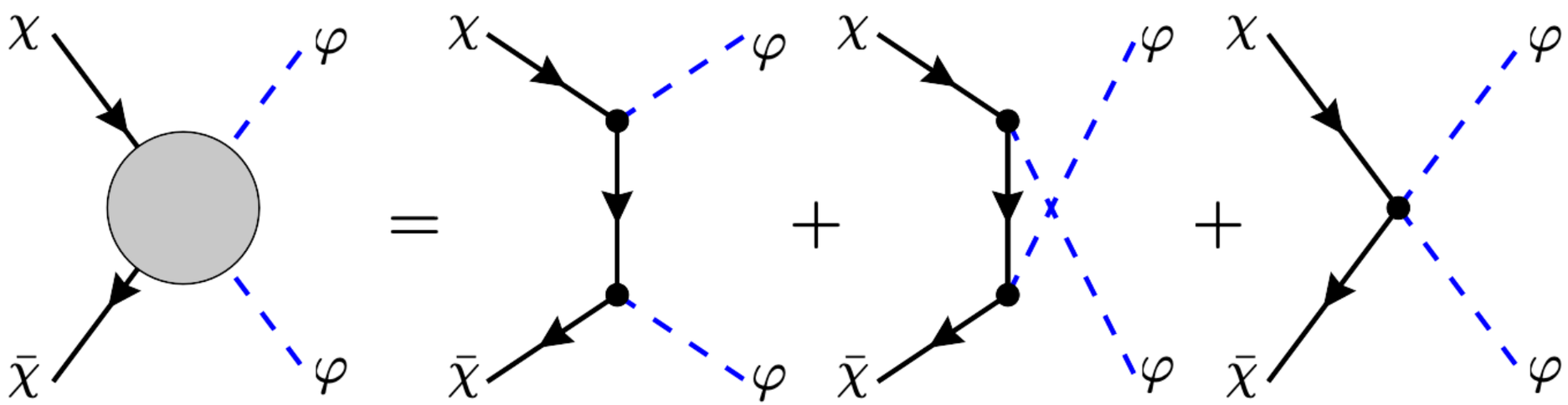
$$\mathcal{L}_{eff} \supset m_\chi e^{-\varphi/f}\bar{\chi}\chi \sim -m_\chi \frac{\varphi}{f}\bar{\chi}\chi + m_\chi \frac{\varphi^2}{2f^2}\bar{\chi}\chi + \mathcal{O}(f^{-3})$$

A dilaton-like DM-mediator interaction

SM coupling from Higgs-mediator mixing

$$\mathcal{L}_{eff} \supset y_b \sin\theta \varphi \bar{b} b$$

φ : a CP-even scalar



The (perturbative) annihilation cross section is p-wave $\langle\sigma v\rangle_{\chi\chi\to\varphi\varphi} = bv^2 + \mathcal{O}(v^4)$

Sommerfeld Enhancement

- The Sommerfeld Enhancement is a non-perturbative phenomena increasing the amplitude of some processes in the presence of long-range interactions, originated by the amplification of the wave function around the interaction point.

- For arbitrary partial waves with angular momentum l, the enhancement (the ratio total cross section/perturbative cross section) is given by

$$S_l = \left| \frac{(2l+1)!!}{|p|^l l!} \frac{\partial^l R}{\partial r^l} \Big|_{r=0} \right|^2$$

- In our model, a light scalar mediator induces a Yukawa potential which is responsible for Sommerfeld Enhancement.

$$V_{Yuk.}(r) = \alpha_{eff} \frac{e^{-m_\varphi r}}{r} \qquad \alpha_{eff} = \frac{m_\chi^2}{4\pi f^2}$$

Sommerfeld Enhancement

- The Sommerfeld Enhancement factor in the Coulomb limit is typically given by

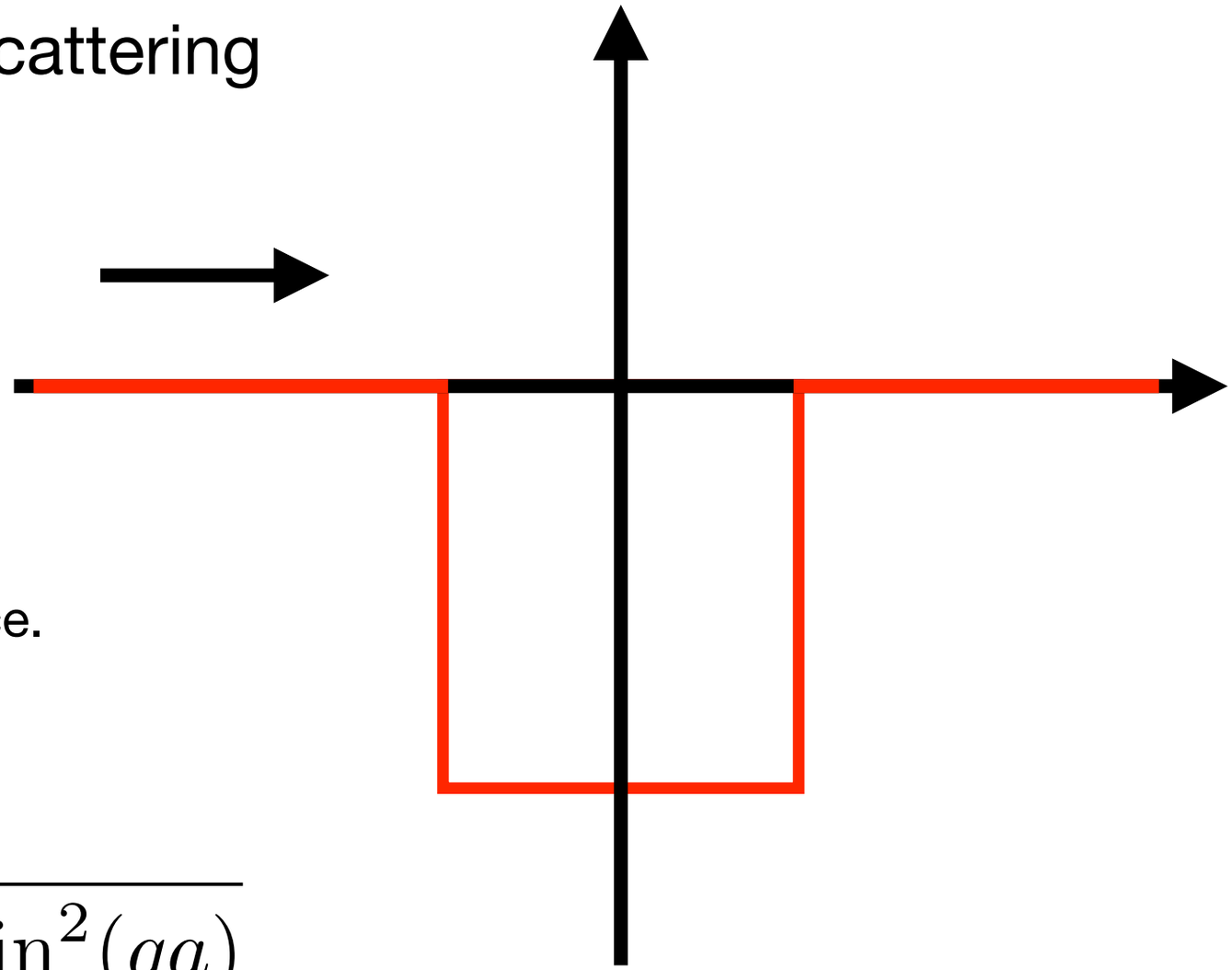
$$S_l \sim \left(\frac{\alpha\pi}{v}\right)^2 \qquad \langle\sigma v\rangle = S_l \cdot \langle\sigma v\rangle_{(pert.)} \sim 1/v$$

- Usually, this effect is saturated around $v \sim m_\varphi/m_\chi$
- However, near the resonance of zero-energy quasi-bound state, the effect is significant down to further low velocities.

Resonant scattering in Sommerfeld Enhancement

- 1-D analogy of resonant scattering

$$\sqrt{\frac{2mV_0}{\hbar^2}}a \equiv qa = n\pi$$



The strength of interaction (potential) determines the condition of resonance.

$$|\psi_{in}|^2 \sim \frac{1}{\cos^2(qa) + \frac{q^2}{k^2}\sin^2(qa)}$$

Near the resonance, the amplification of the wave function is further enhanced.

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- For the Yukawa potential, the zero-E resonance occurs around $\alpha_{\rm crit.} \sim 9.08 m_\varphi/m_\chi$
- Near the resonance, the saturation velocity is given at the order of the amount of off-resonance $\Delta\alpha = \alpha - \alpha_{crit.}$

Sommerfeld Enhancement

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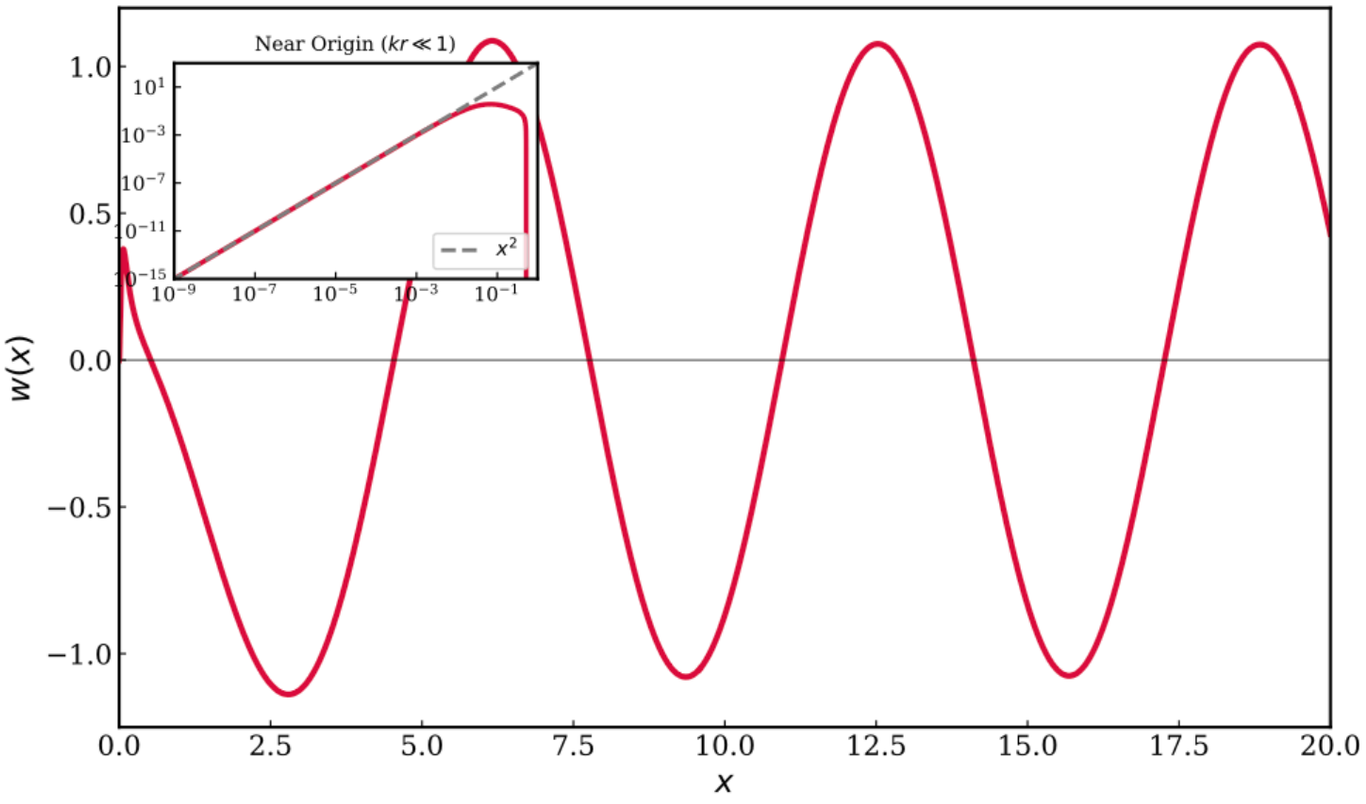
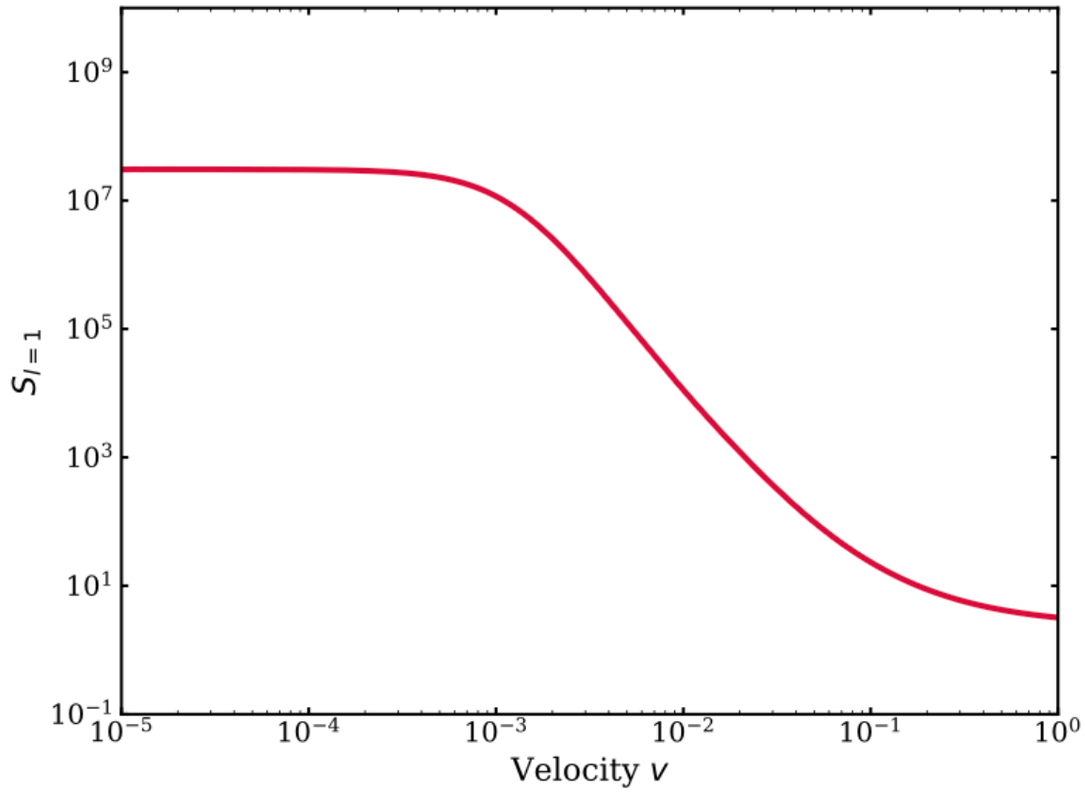
- Numerical solution of radial Schrodinger equation



Radial wavefunction



Enhancement factor

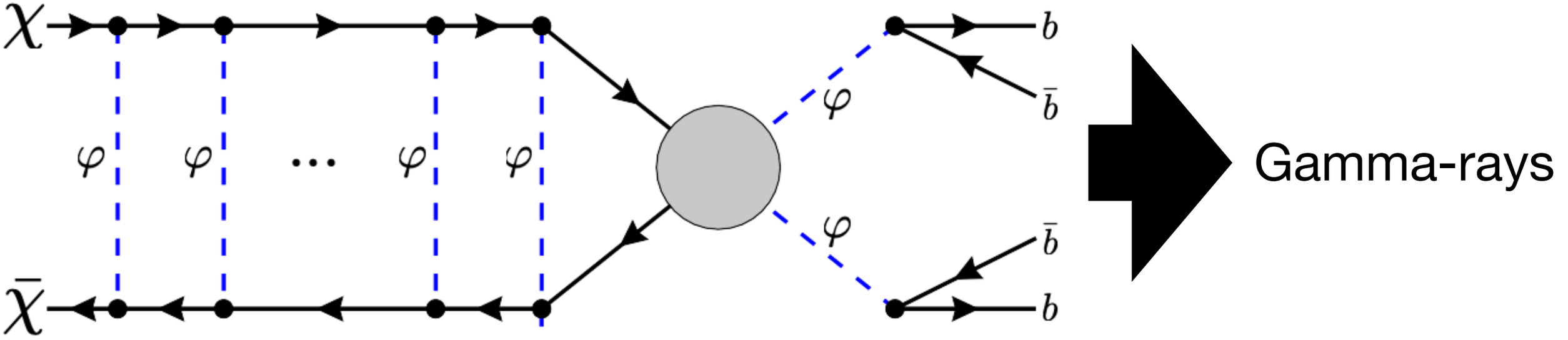
$$u''_{l,k}(r) + \left[k^2 - \frac{l(l+1)}{r^2} + m_\chi \alpha \frac{e^{-m_\varphi r}}{r}\right] u_{l,k}(r) = 0.$$

$$u_{l,k}(r) \equiv r\, R_{l,k}(r)$$

$$\Delta\alpha = \alpha - \alpha_{crit.} \sim 10^{-3} \sim v_{sat.}$$

Signal process

- The resulting annihilation process will make two pair of quarks in the final states with an increased cross section.



Annihilation cross section

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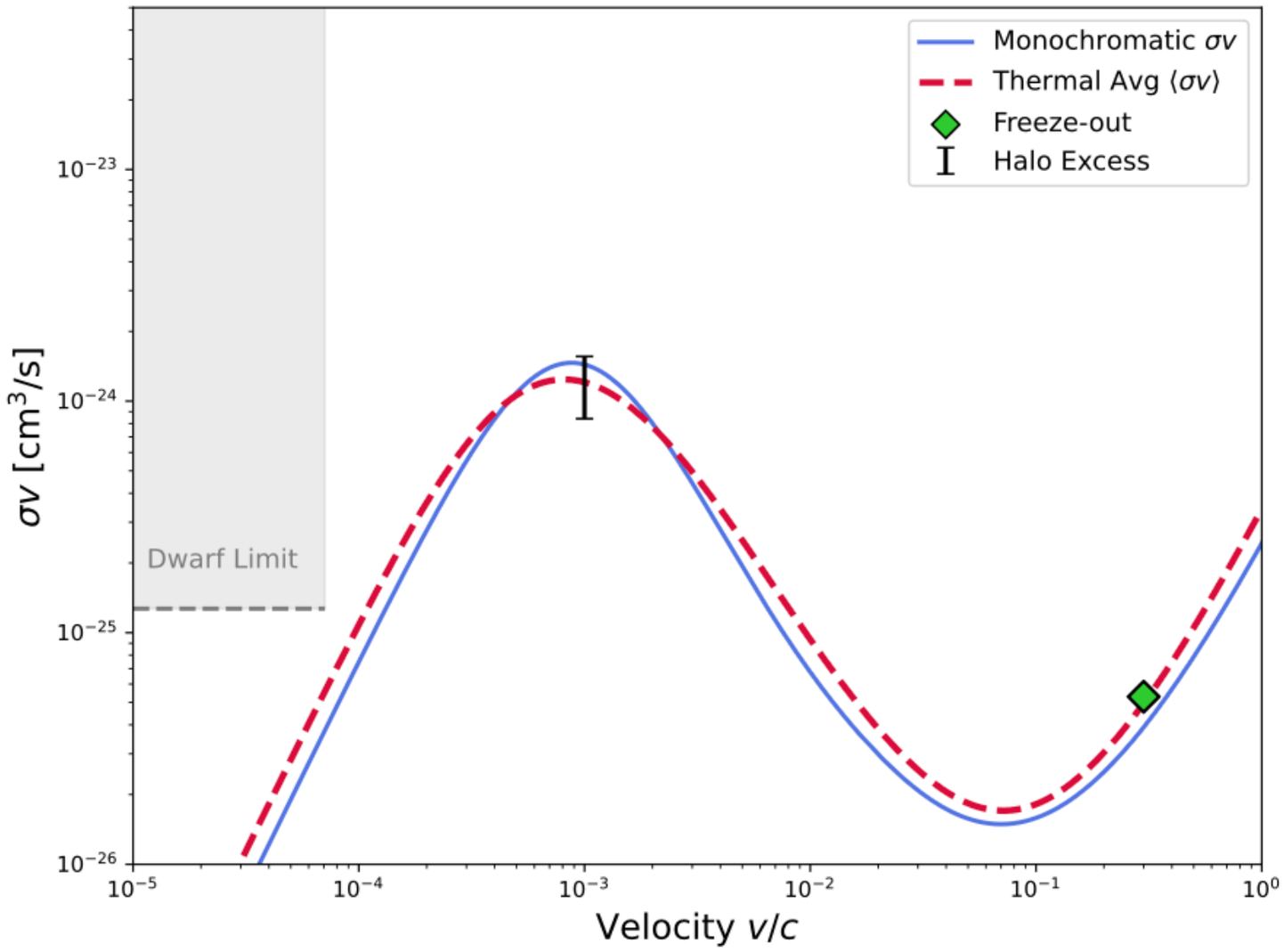

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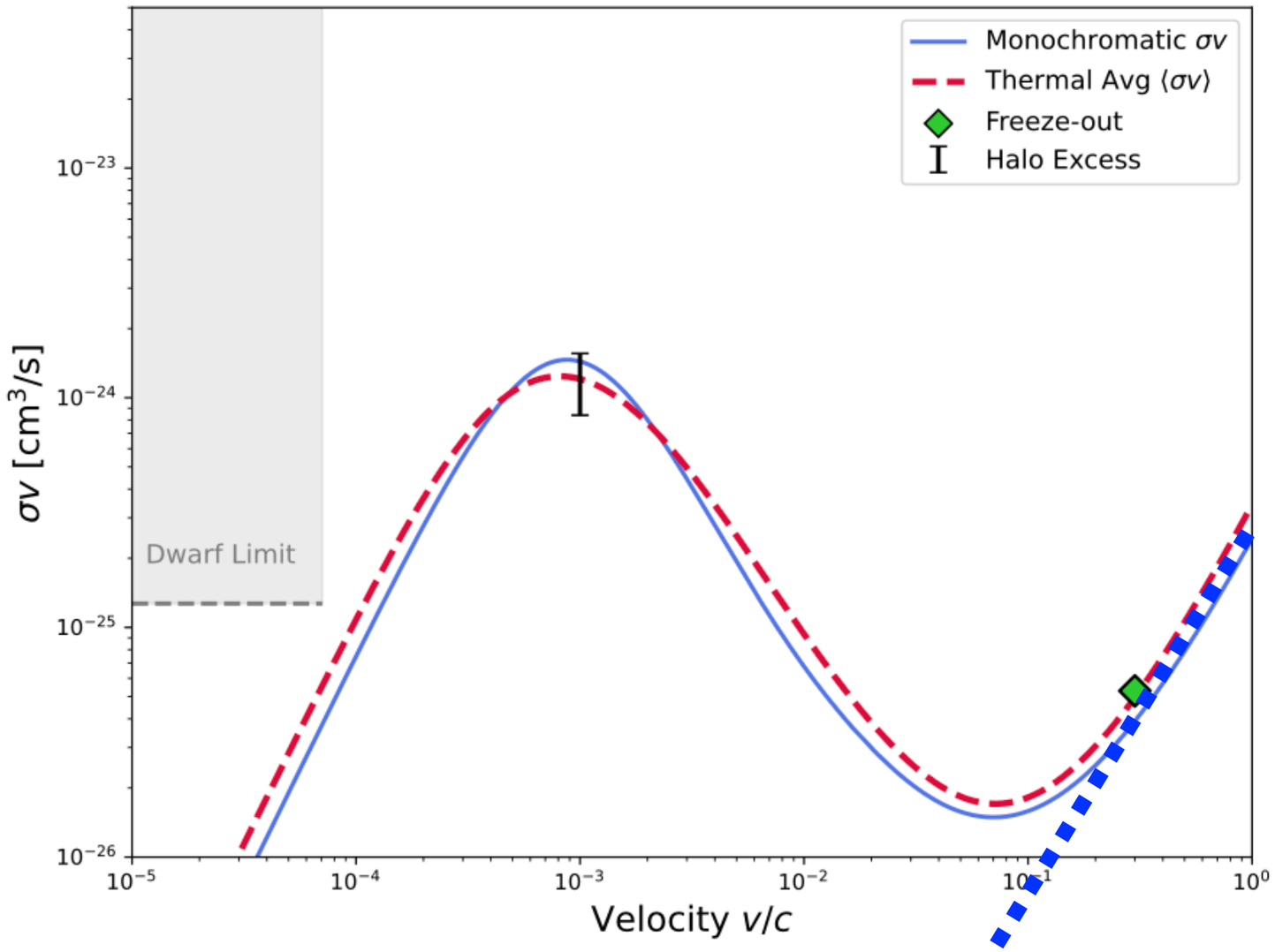

Perturbative
p-wave annihilation

Annihilation cross section

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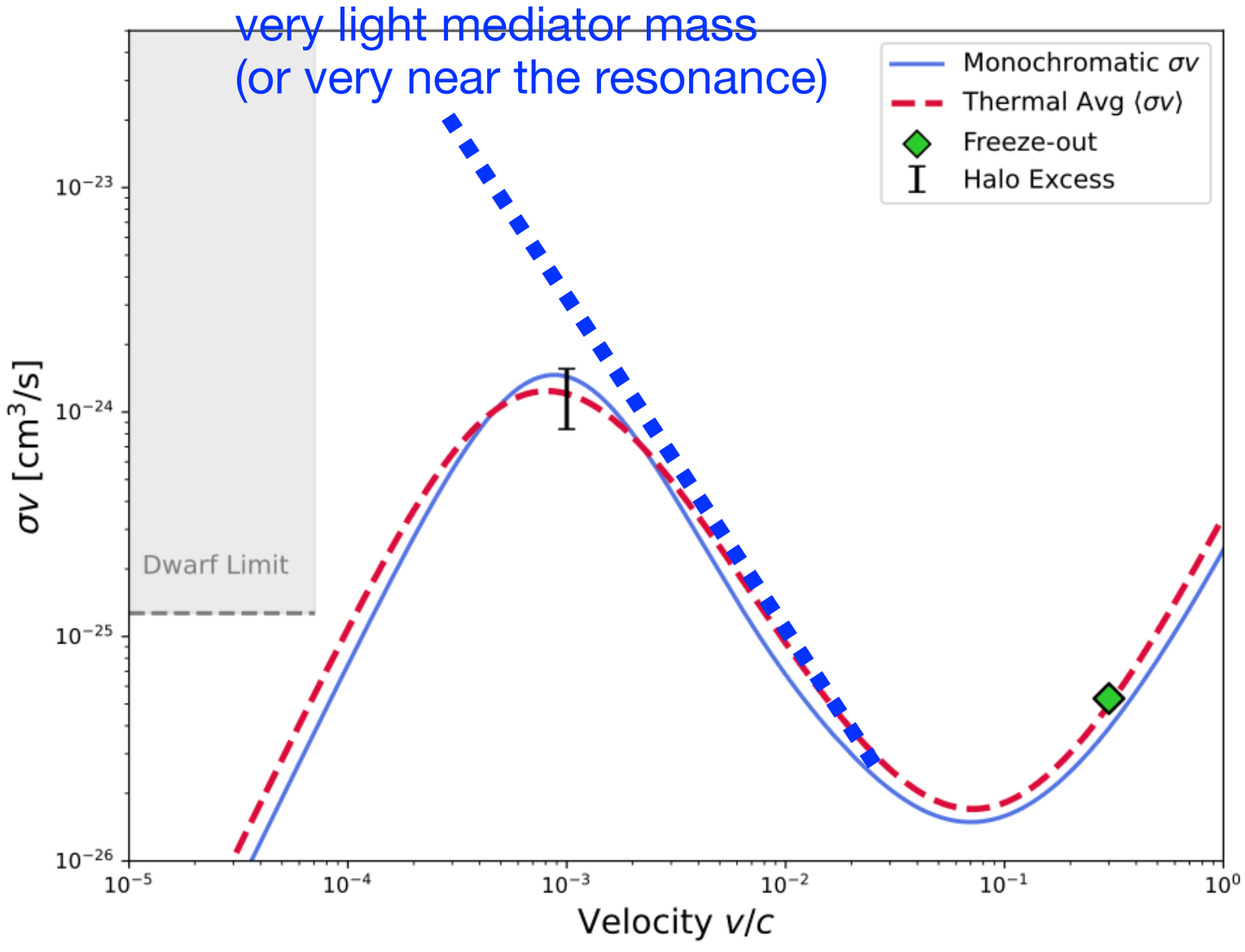

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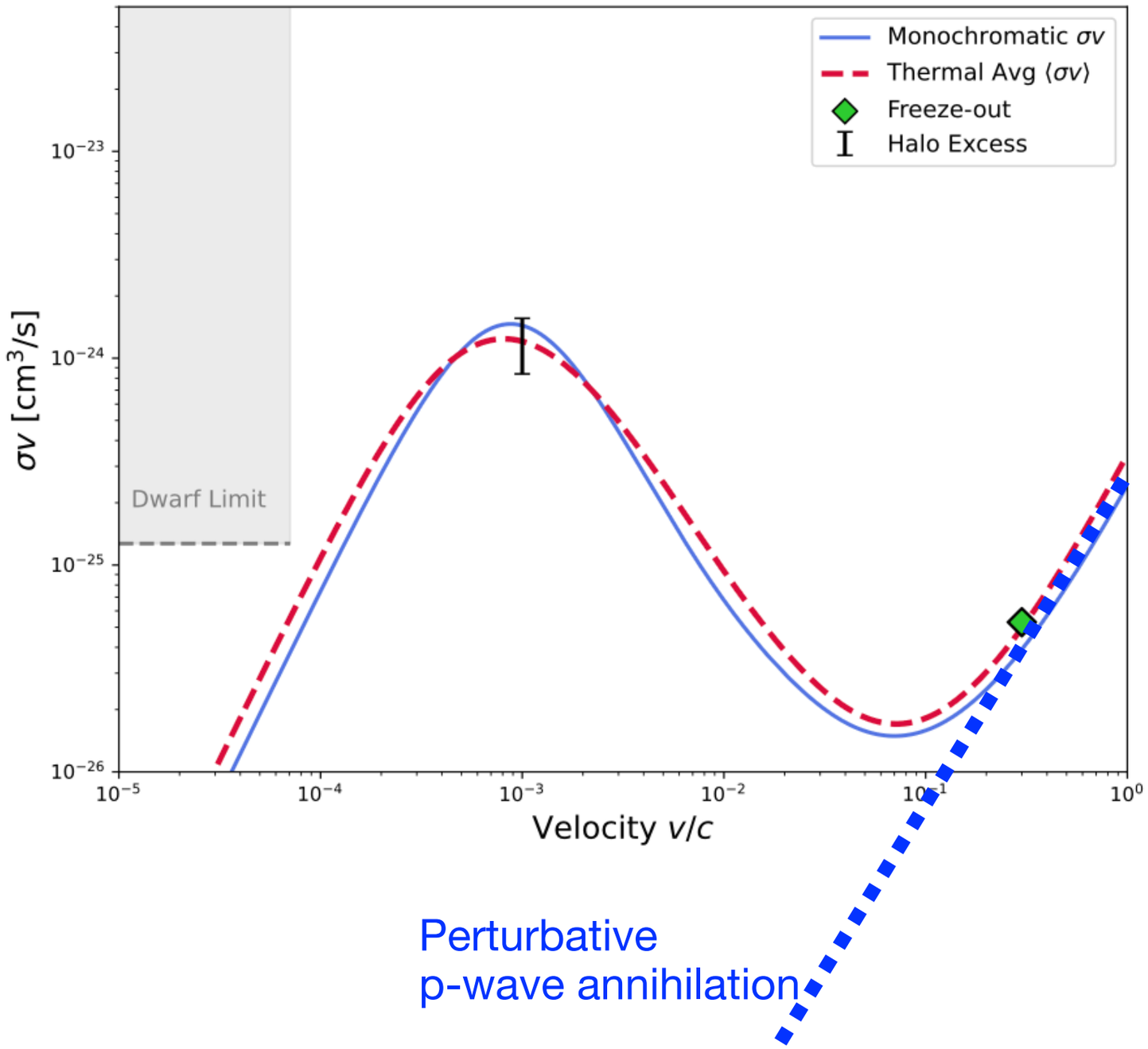

Annihilation cross section

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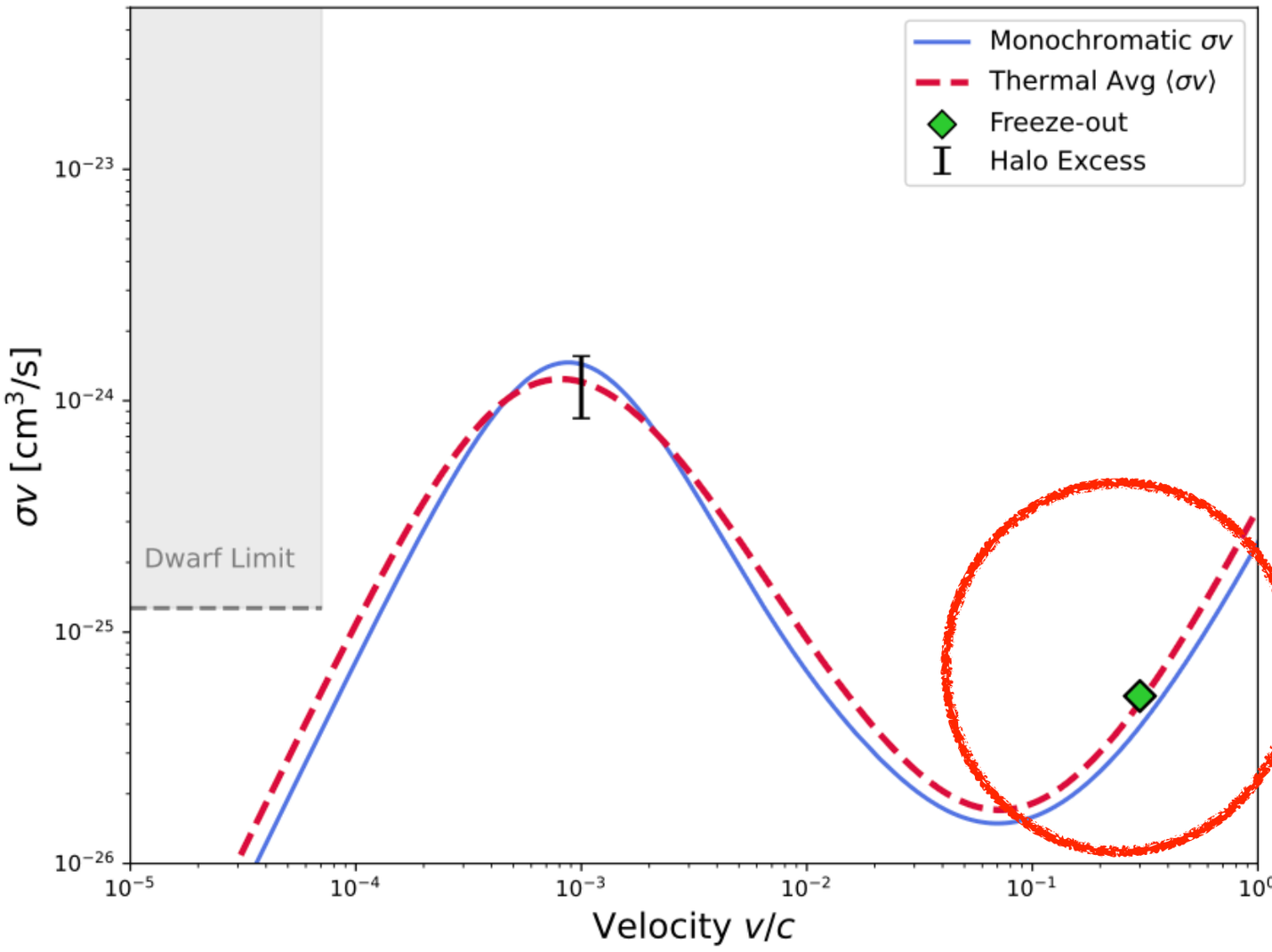
- There are three main regimes:

1. Perturbative Regime $(\alpha < v < 1)$

Non-perturbative effect is negligible and
the perturbative piece is only relevant one.



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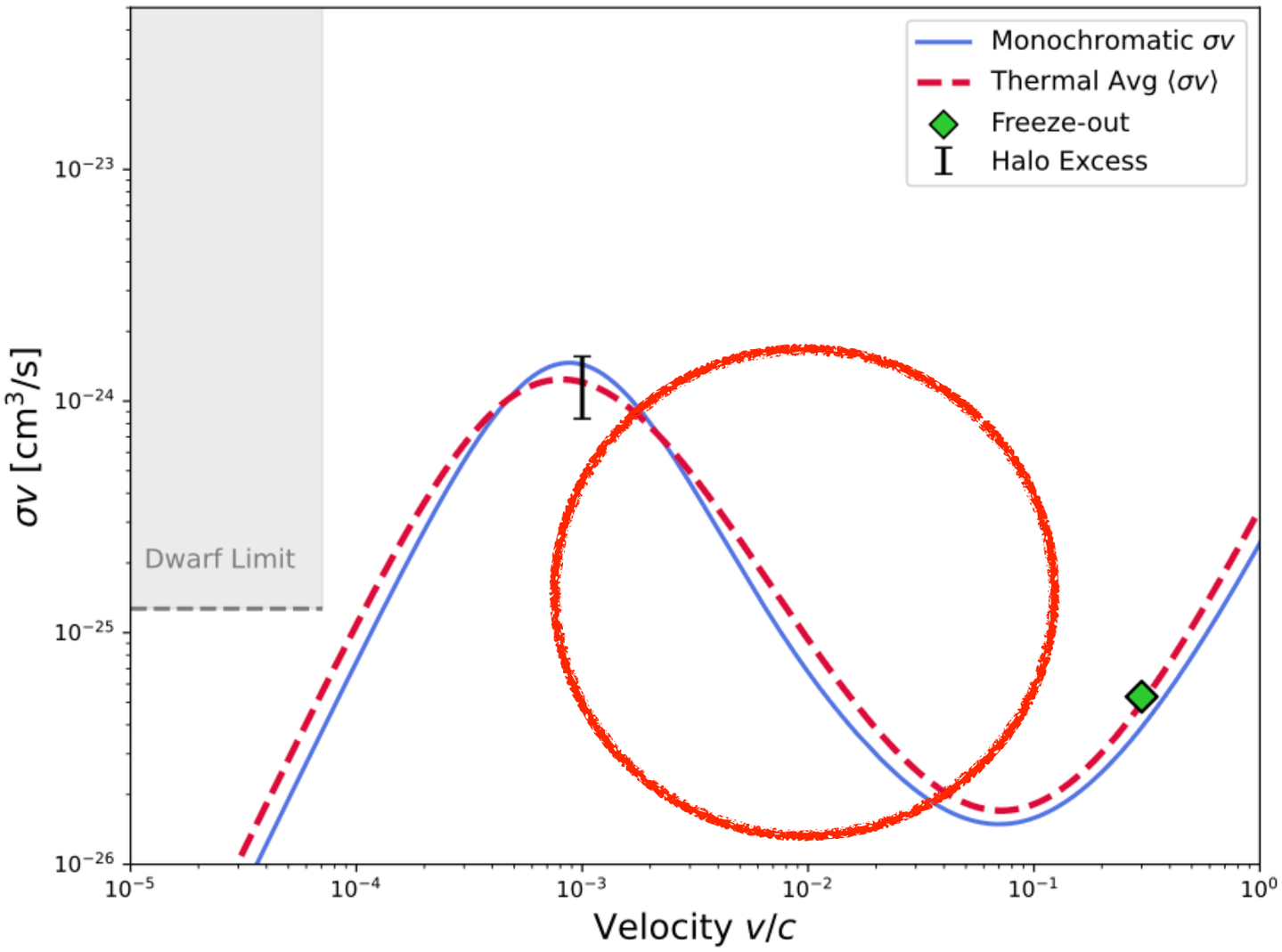
The Sommerfeld Enhancement becomes efficient and the cross section scales as ~1/v



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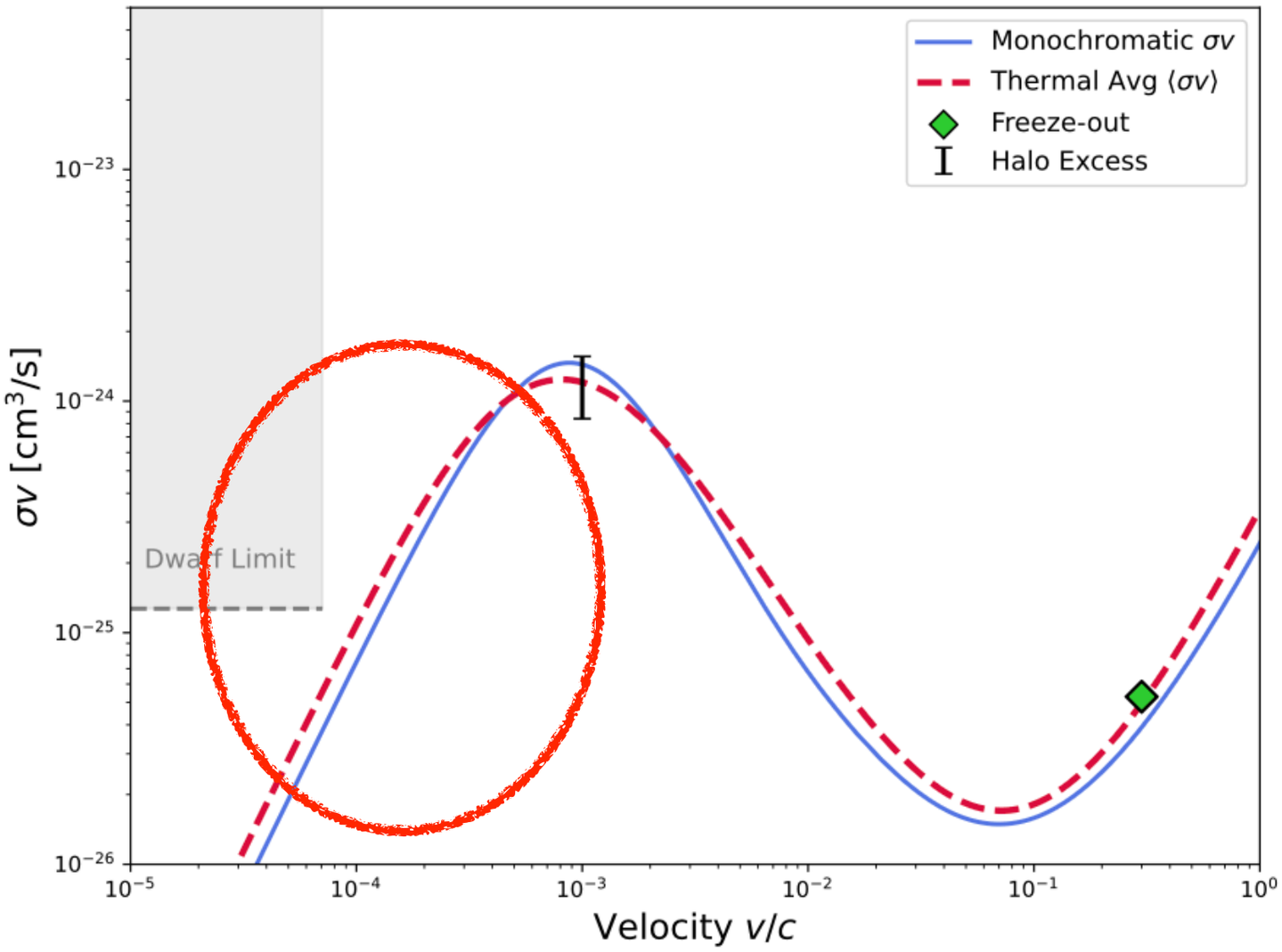
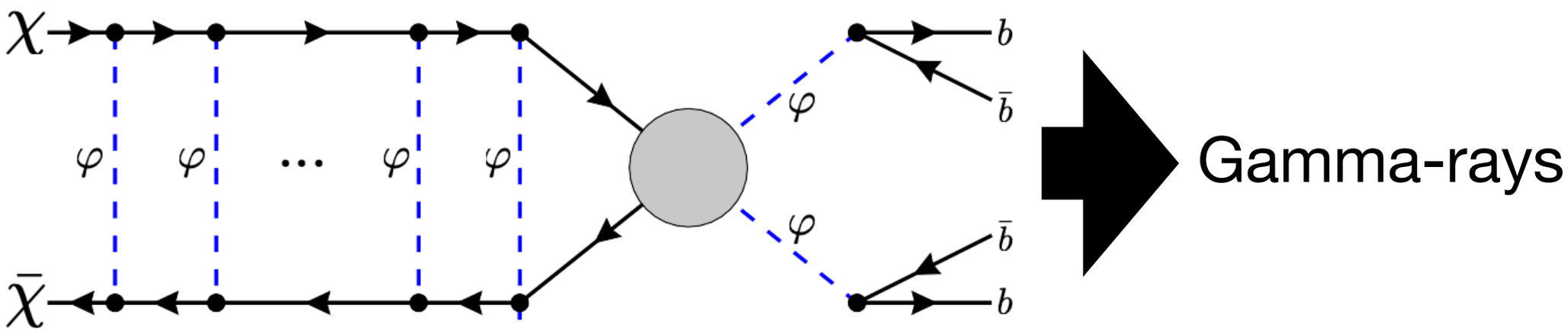
3. Saturation Regime $(v < v_{sat.})$

Sommerfeld Factor is saturated, and the cross section recovers its perturbative behavior ($\langle\sigma v\rangle \propto v^2$).
The constraints from dwarf galaies can be naturally avoid.

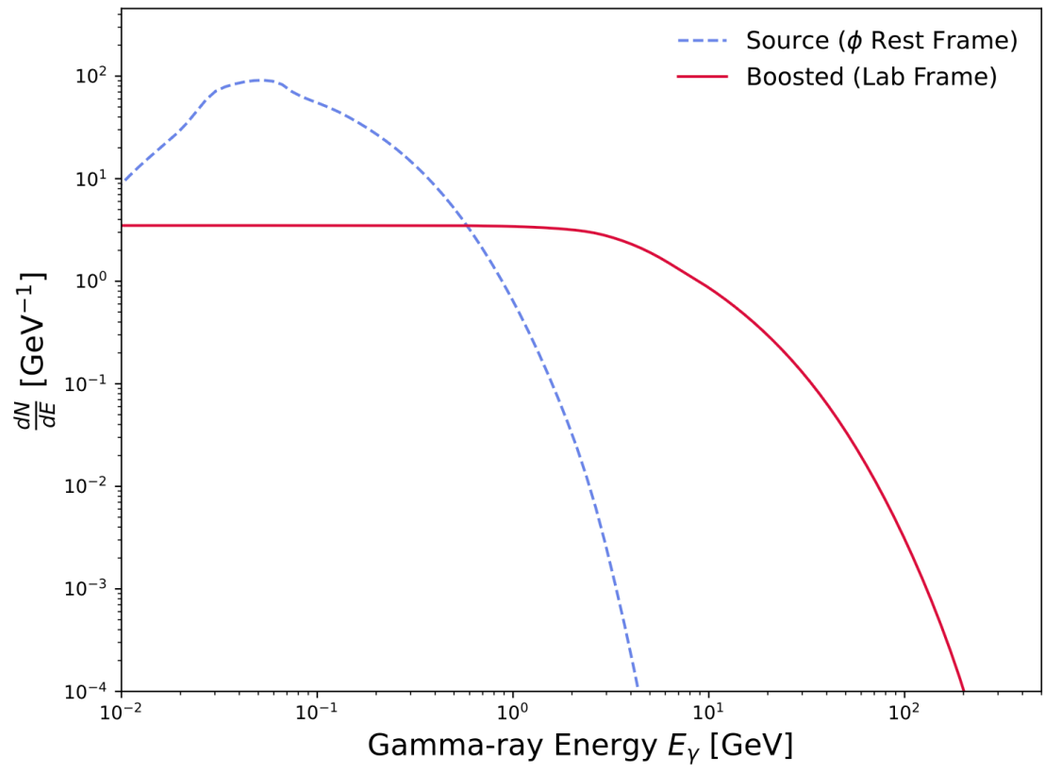


Gamma-ray signal spectrum

- In our model, the scalar mediators in the final state are highly boosted with a factor $\gamma \sim m_\chi / m_\varphi$

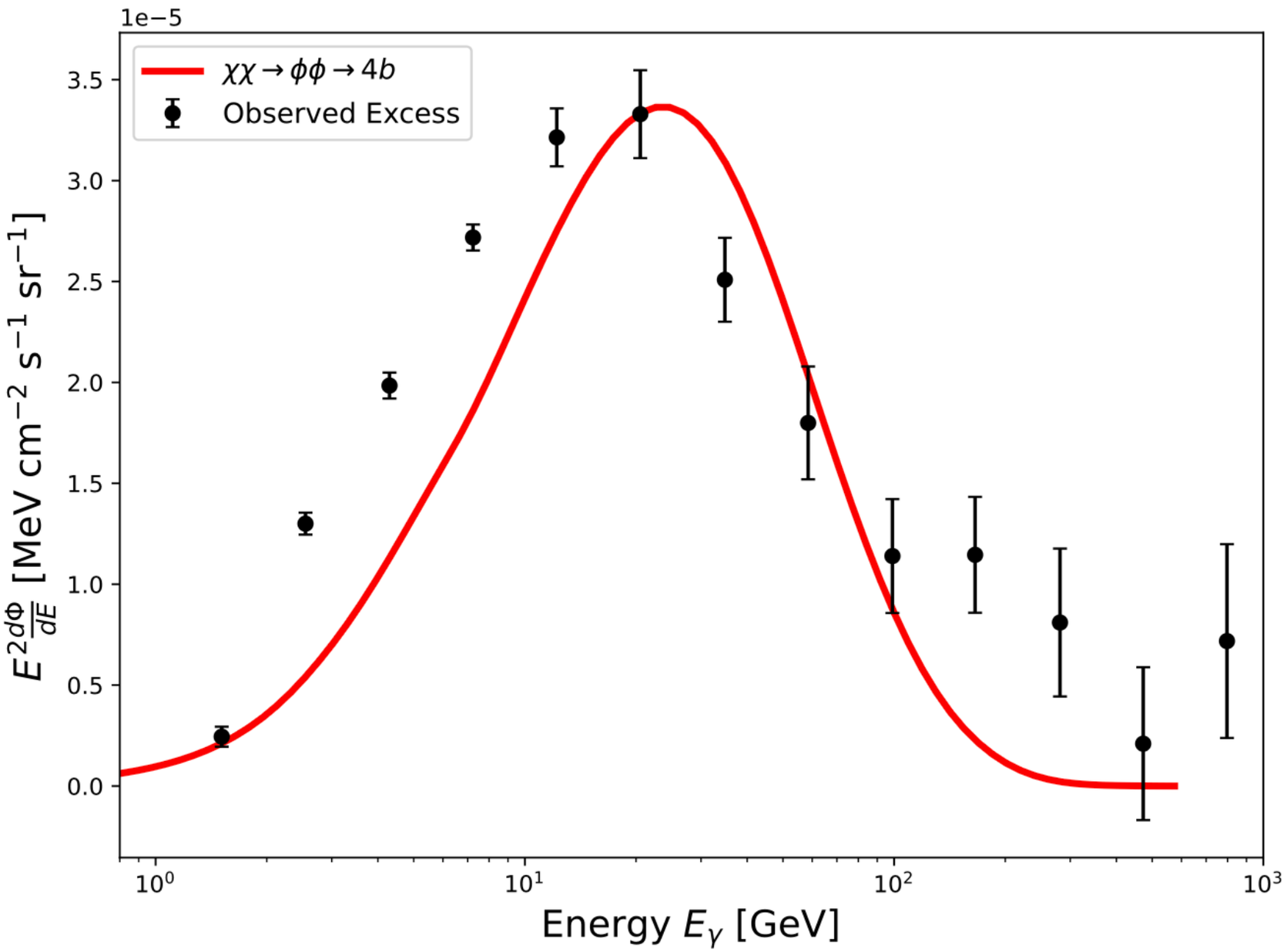


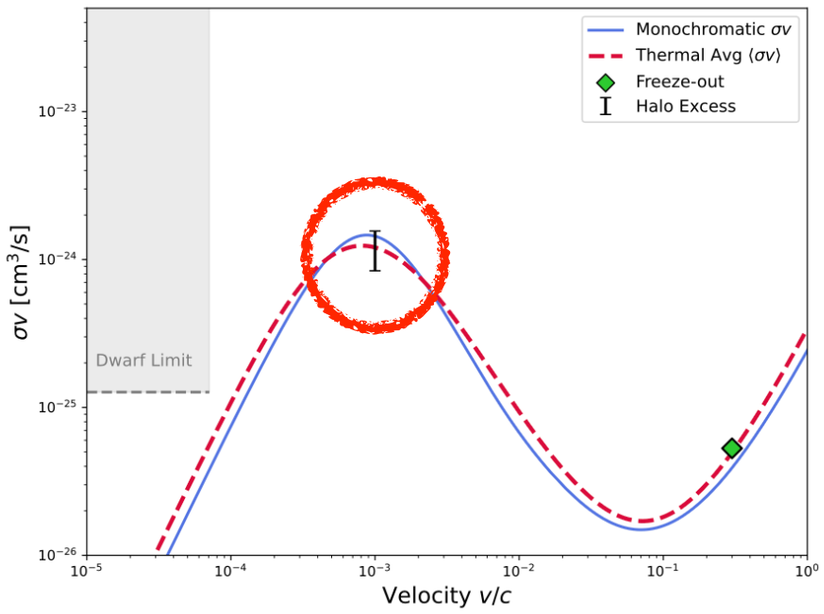
- After considering the Lorentz boost effect, the spectrum becomes flat and box-like.



Gamma-ray signal spectrum

- Signal spectrum with benchmark parameters





$$m_\chi = 575 \text{ GeV}$$
$$m_\varphi = 11.6 \text{ GeV}$$
$$\alpha = 0.183$$

Other Constraints & Future prospects

- For our benchmark parameters, the most relevant constraints come from i) the direct detection, ii) Thermal equilibrium condition. Available mixing between SM Higgs and the scalar mediator should be in the range $10^{-7} < \theta < 10^{-5}$

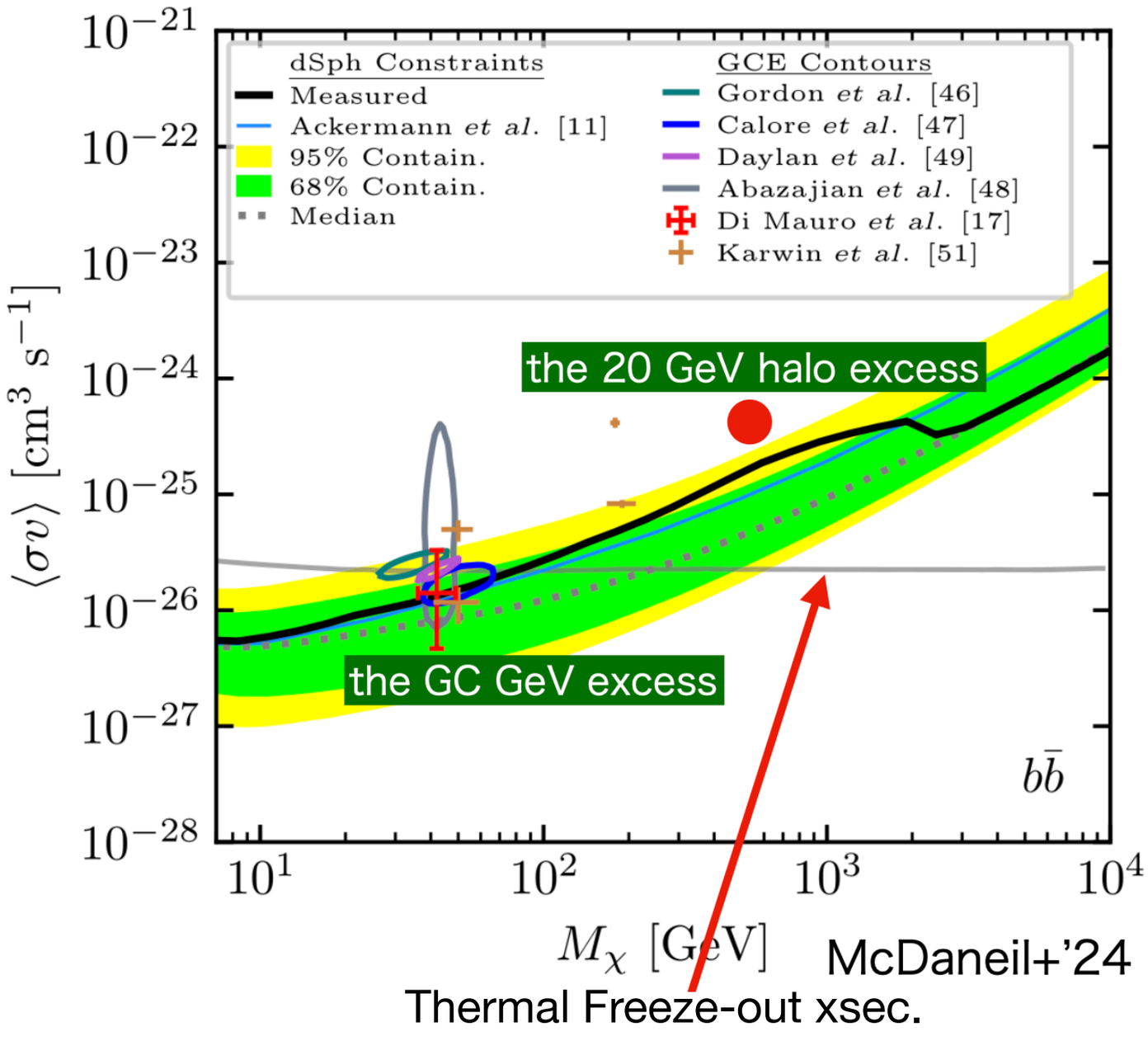
- Interestingly, searching for the light scalar with a O(10) GeV mass coupled to SM sector can be promising in future long-lived particle searches at terrestrial experiments, such as MATHUSLA, SHiP. FASER

- Antiproton bound from AMS-02 data will be a strong constraints on some WIMP scenarios. In our case, the mass of mediator is very low, and the production of secondary nucleon is very suppressed, and the spectrum becomes much soften and reduced.

- This p-wave + Sommerfeld Enhancement scenario might be naturally compatible with i) various Milky-Way gamma-ray and/or cosmic-ray anomalies, ii) dwarf galaxy constraints at much low velocities in general.

Other Constraints & Future prospects

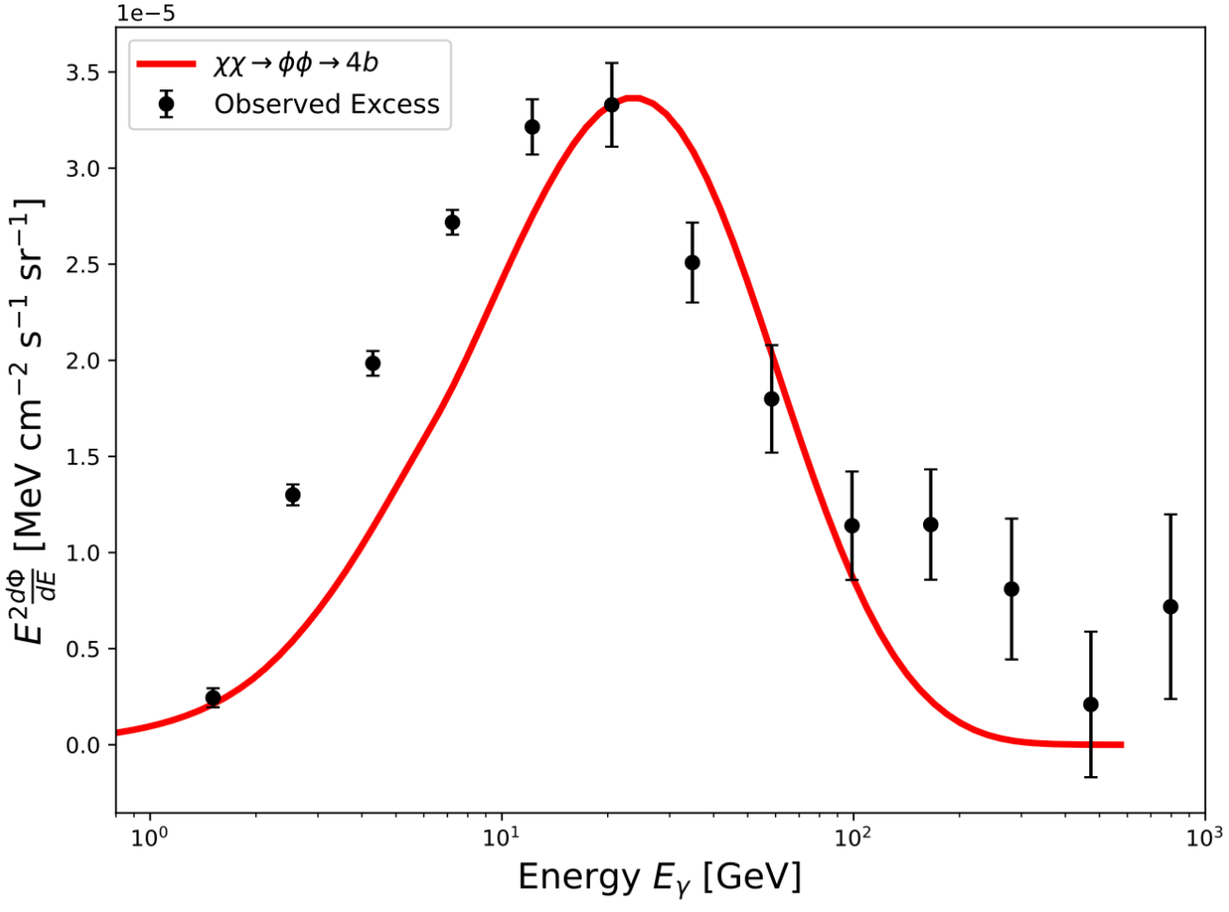
- This p-wave + Sommerfeld Enhancement scenario might be naturally compatible with i) various Milky-Way gamma-ray and/or cosmic-ray anomalies, ii) dwarf galaxy constraints at much low velocities in general.
  - How about GCE? or other anomalies?

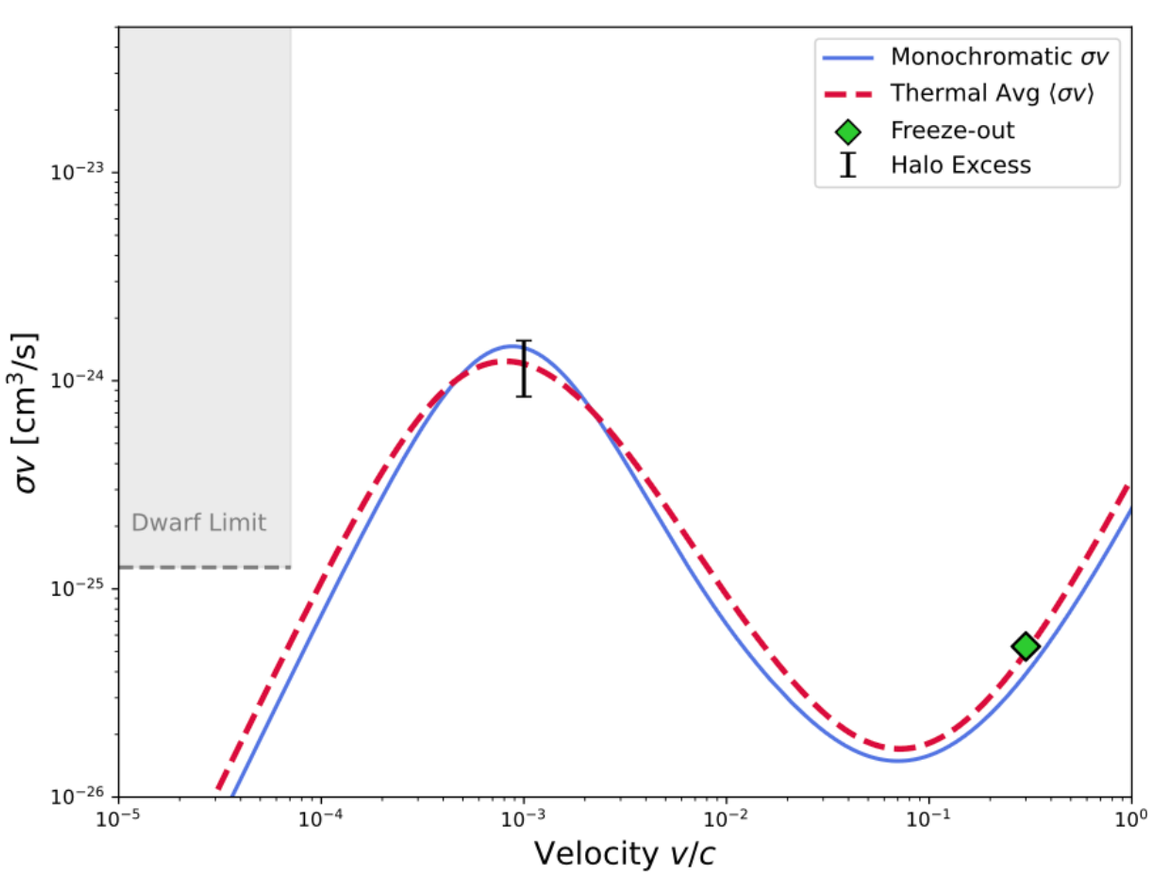


Summary

- Regarding 15-years data set of FermiLAT, Totani recently provided an analysis on Halo-like excess of gamma-rays around 20 GeV.

- A minimal model of Dark Matter with a CP-even scalar mediator successfully explains i) freeze-out annihilation cross section, ii) Halo-excess and iii) the dwarf galaxy constraints.





Thank you

backup slides