Sommerfeld enhancement in the light of halo gamma-ray excess

Yongsoo Jho

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

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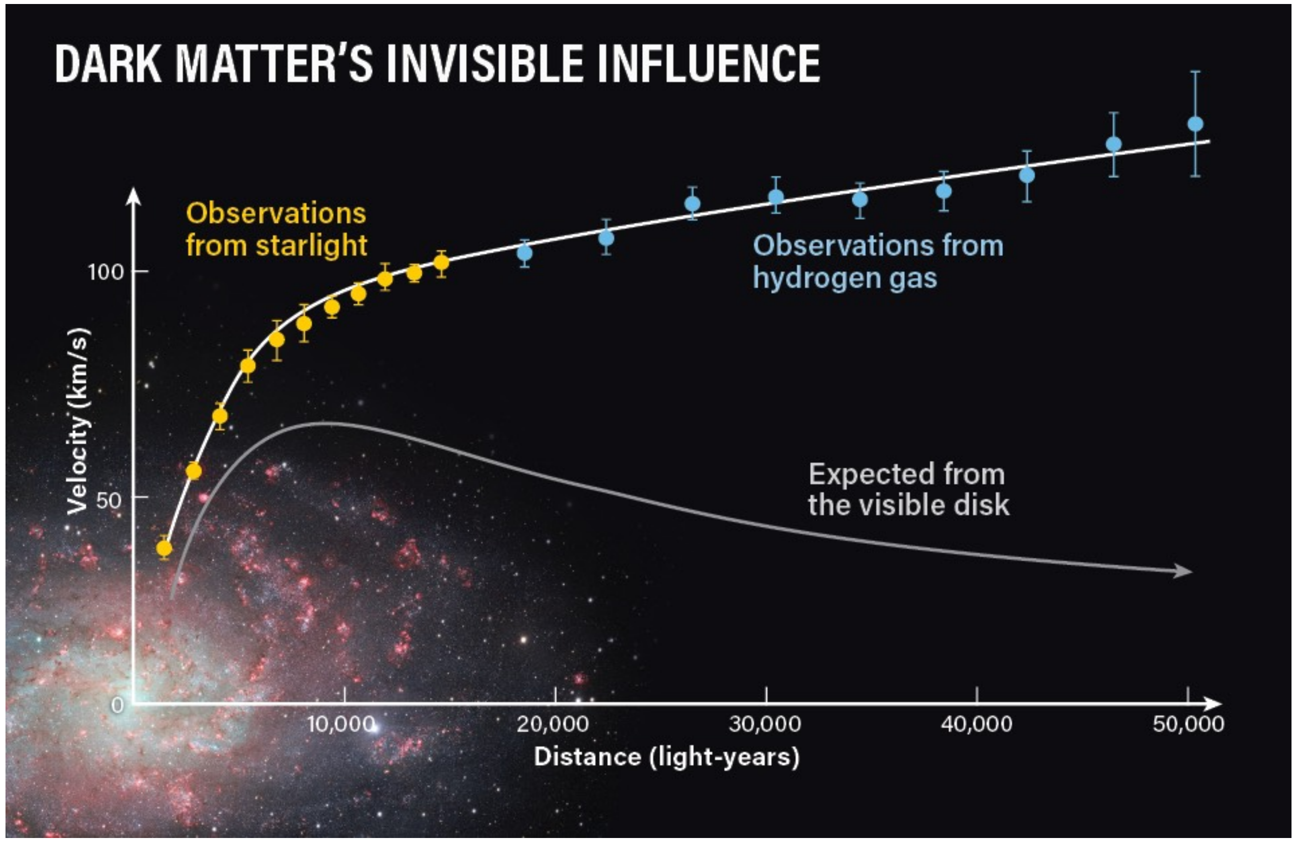
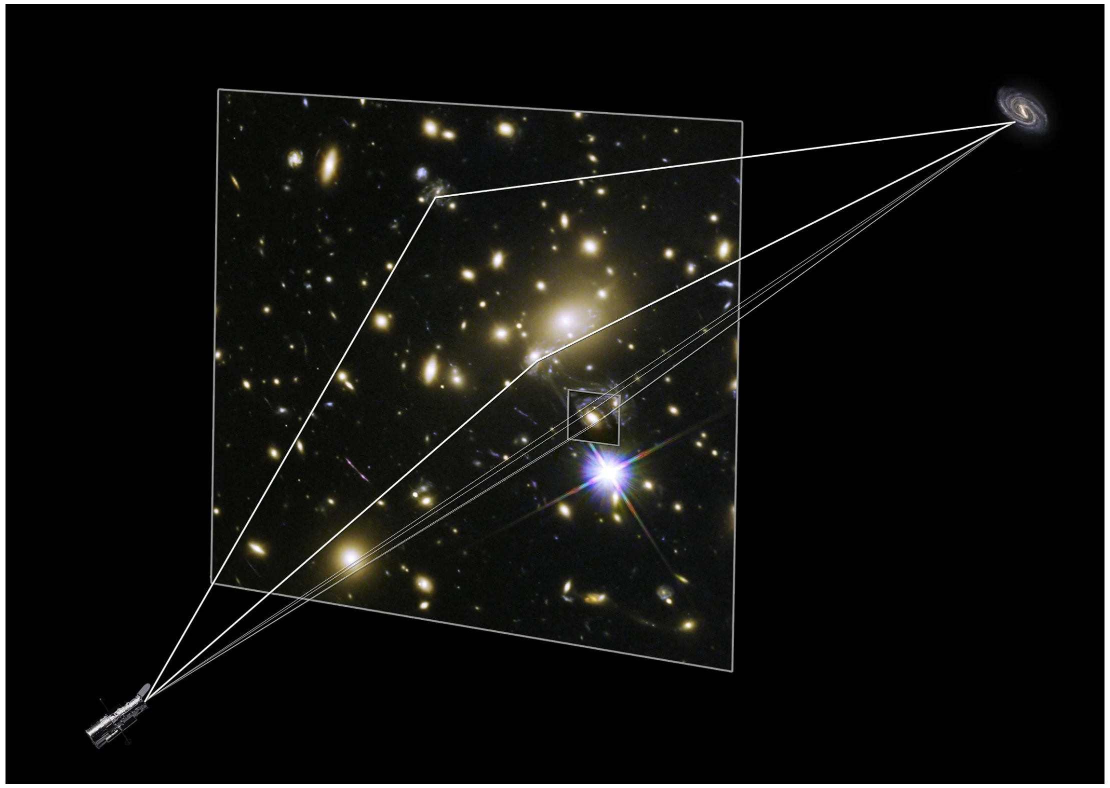
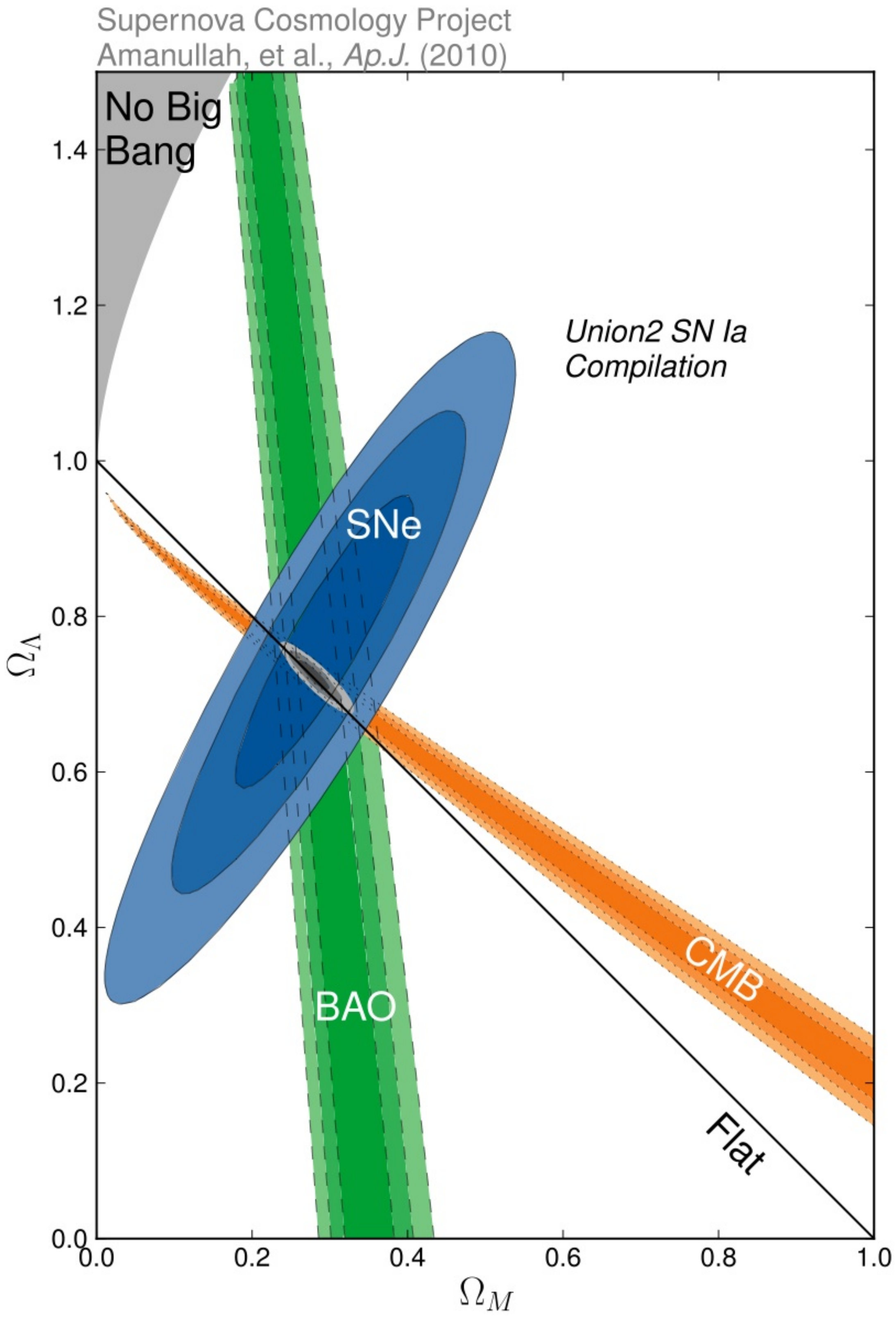
Outline

- 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?







Observational anomalies in DM Indirect detection

- Various observational anomalies in Indirect Detections still exist, showing a clear statistical deviation from any background models, and their sources are not identified yet.

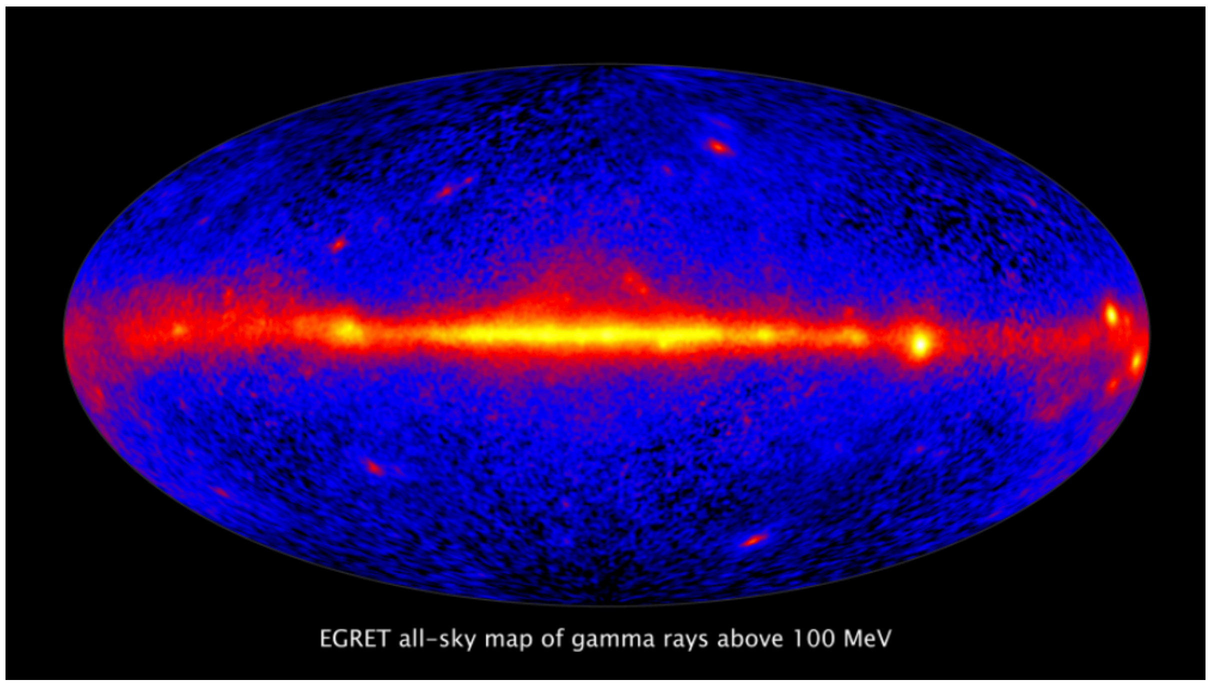
  - O(1) GeV Galactic Center gamma-ray Excess
  - 1-2 TeV AMS-02 positron excess
  - 511 keV line excess
  - and more.

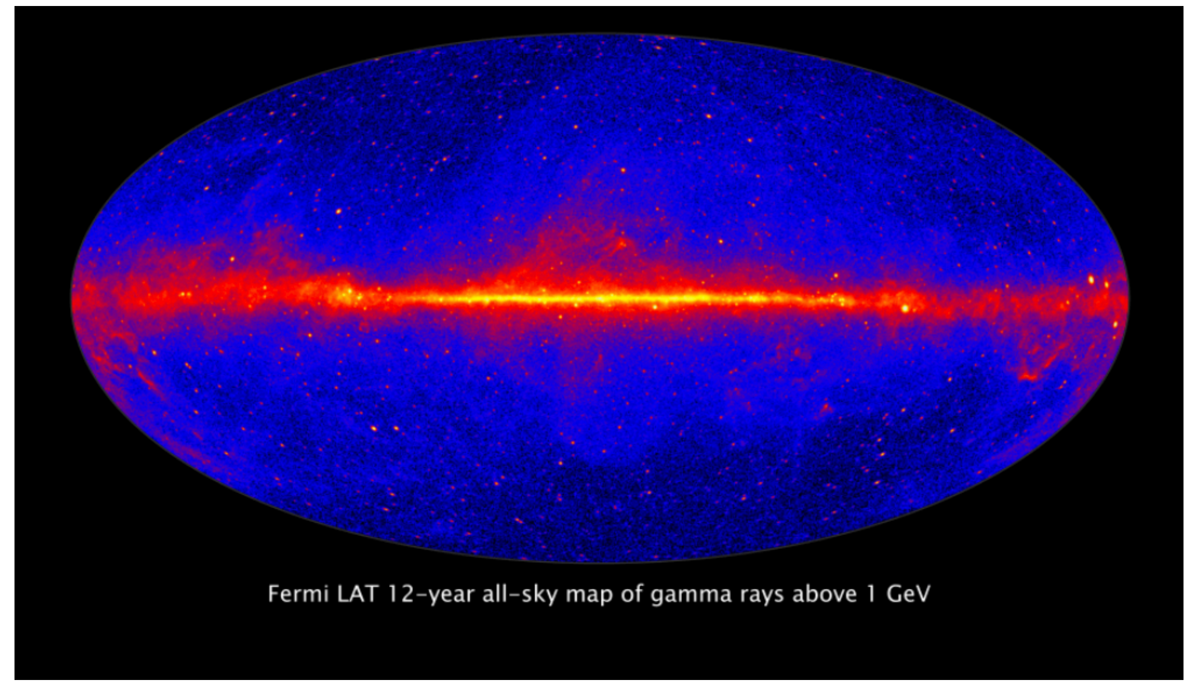
- Recently, an additional analysis of 15-year FermiLAT data for Milky Way Halo region has been reported, showing an excess of gamma-rays around 20 GeV.

- **Q: Can we have thermal dark matter scenarios to explain these anomalies, satisfying all important constraints? (dwarf shperoidal galaxies, anti-proton bounds, and so on.)**

FermiLAT data in Gamma-ray sky

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

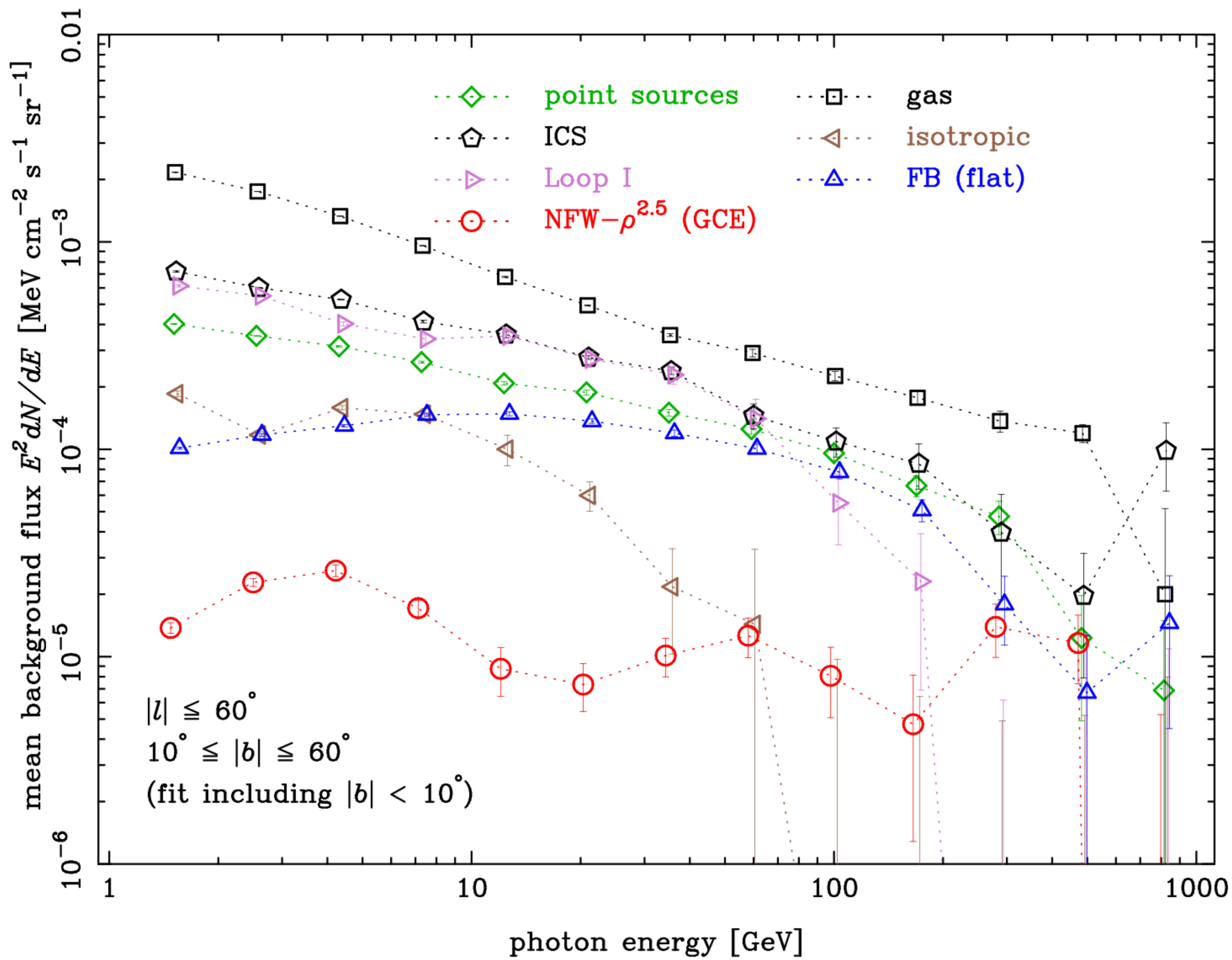




- Backgrounds of gamma-rays are usually dominated by
  - Galactic Diffusion Emission induced by cosmic-ray interacting with the interstellar medium (ISM), inverse compton scattering and bremsstrahlung.
  - Isotropic Diffuse gamma-rays
  - Point sources (Pulsar, SNR, etc.)

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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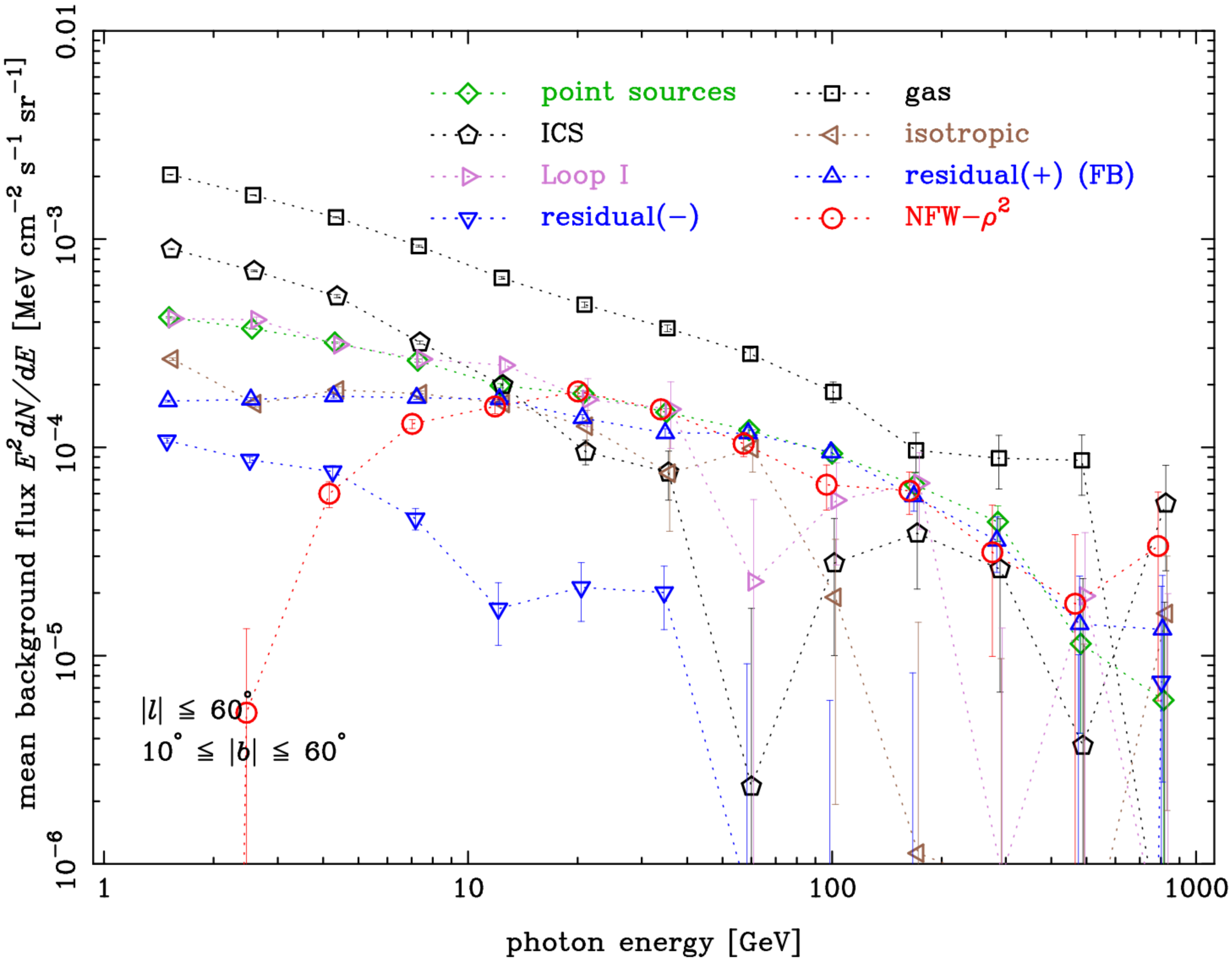

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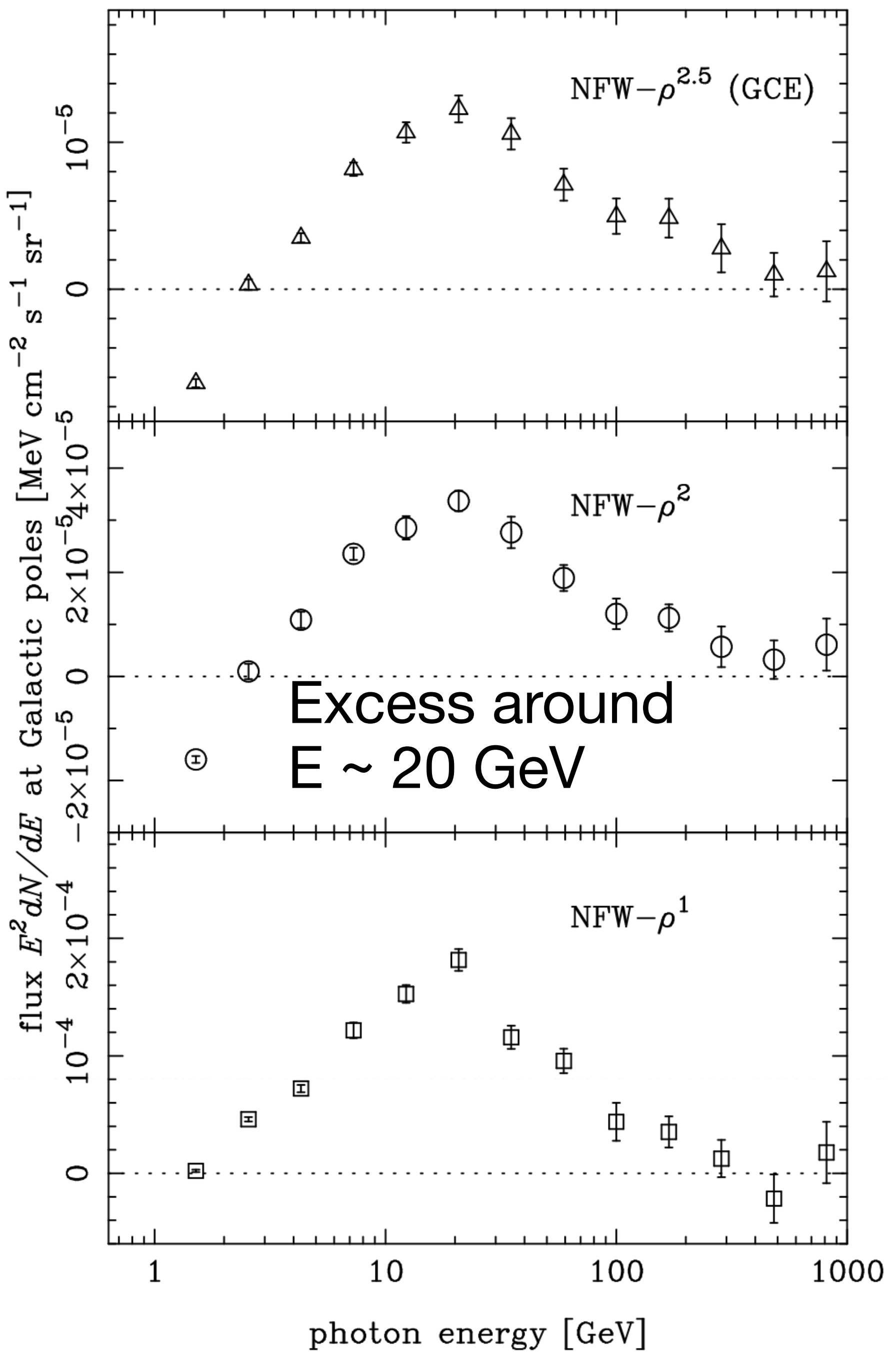

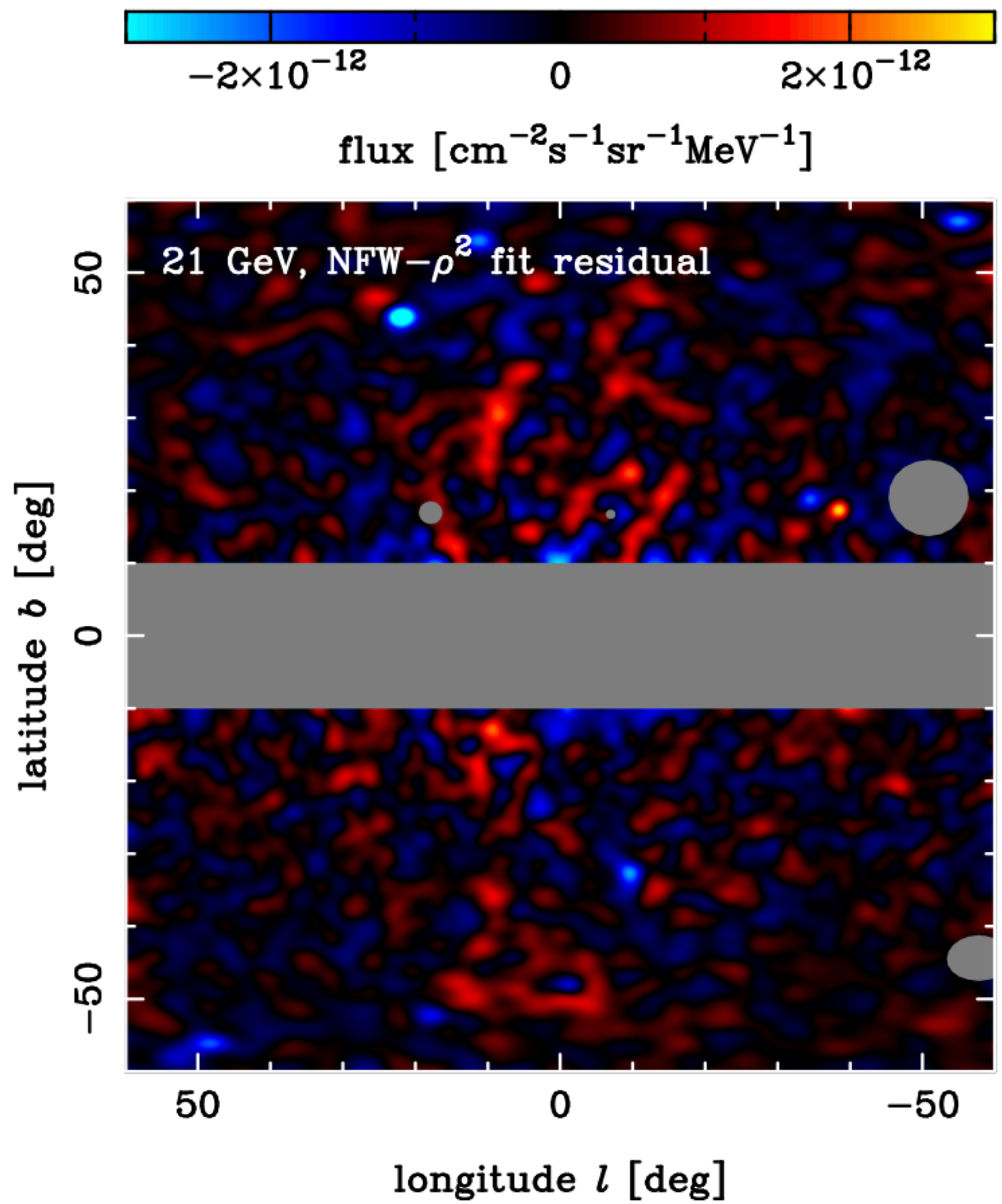

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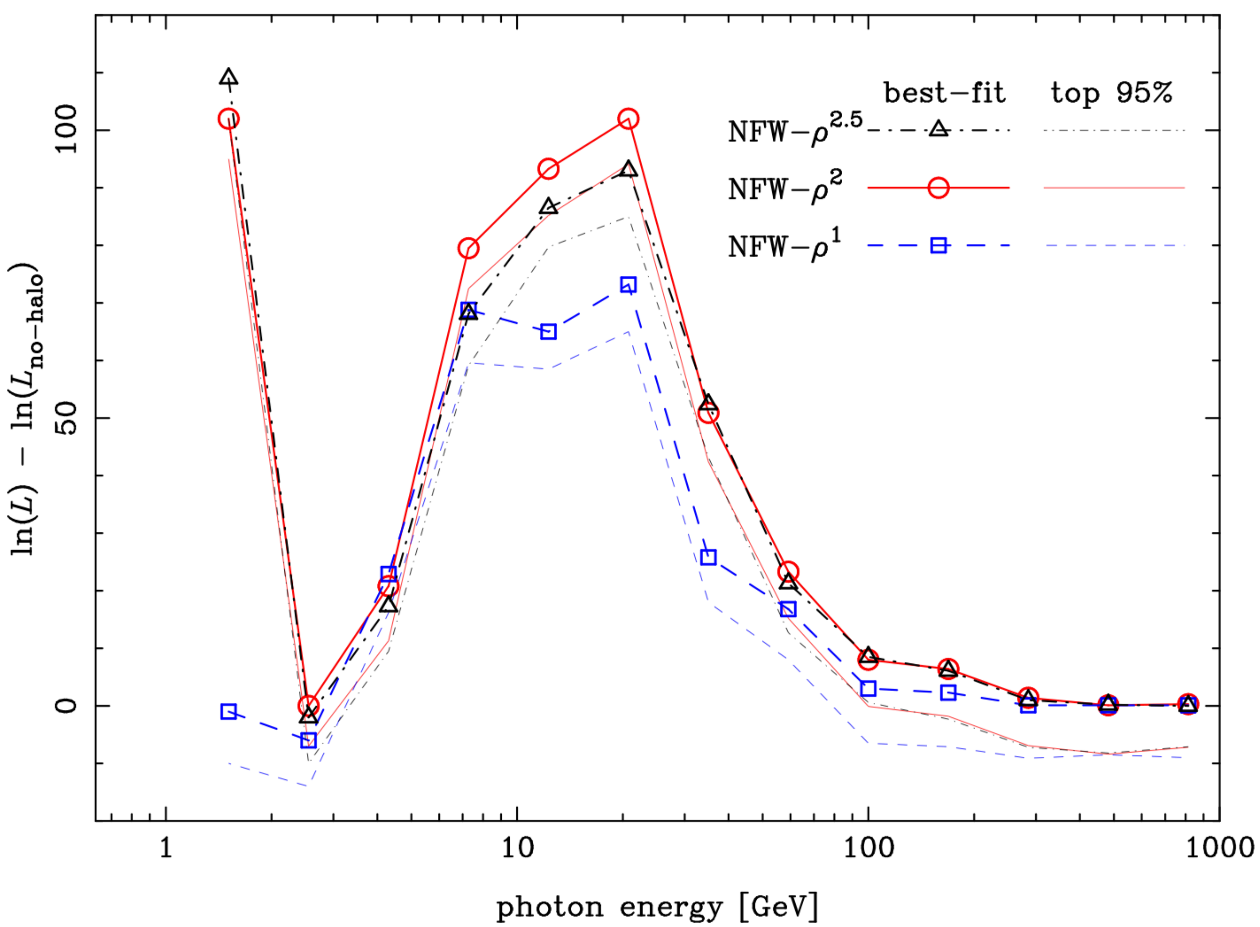
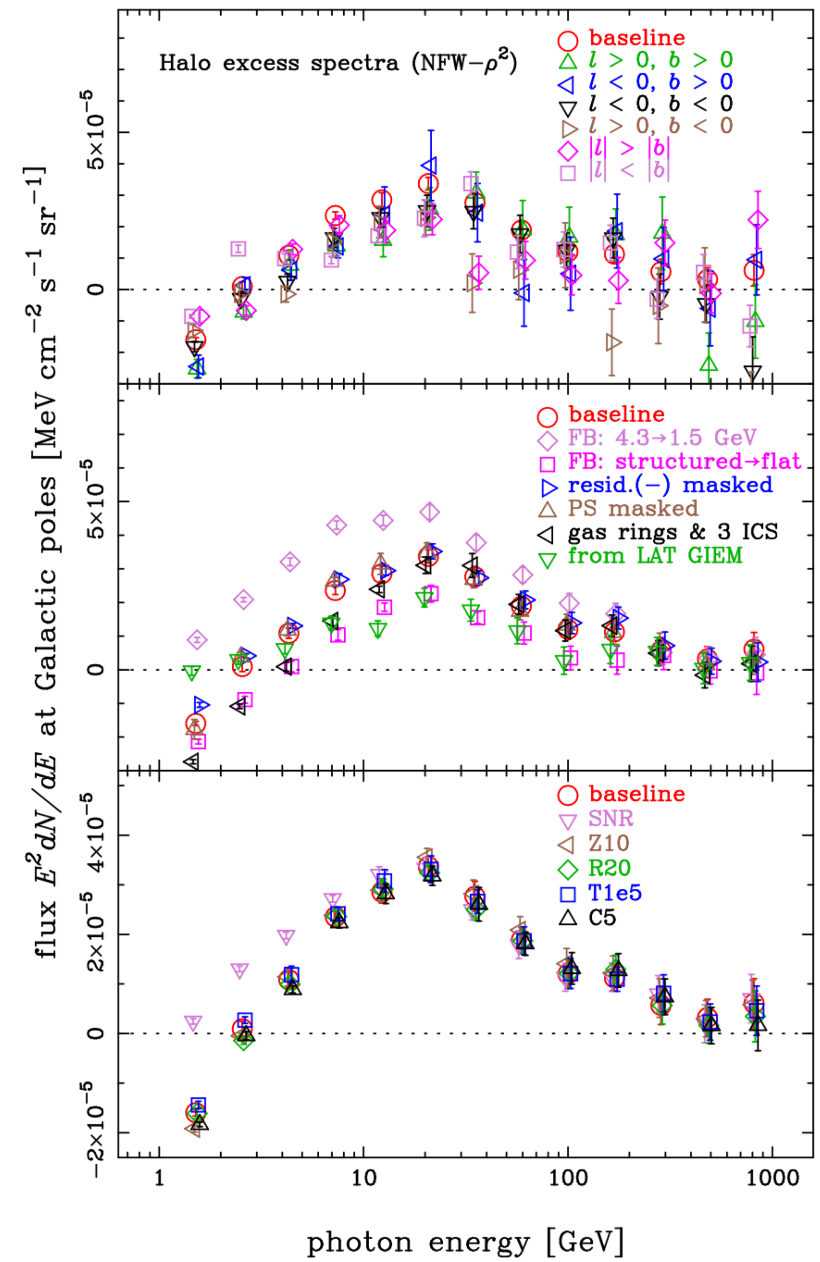


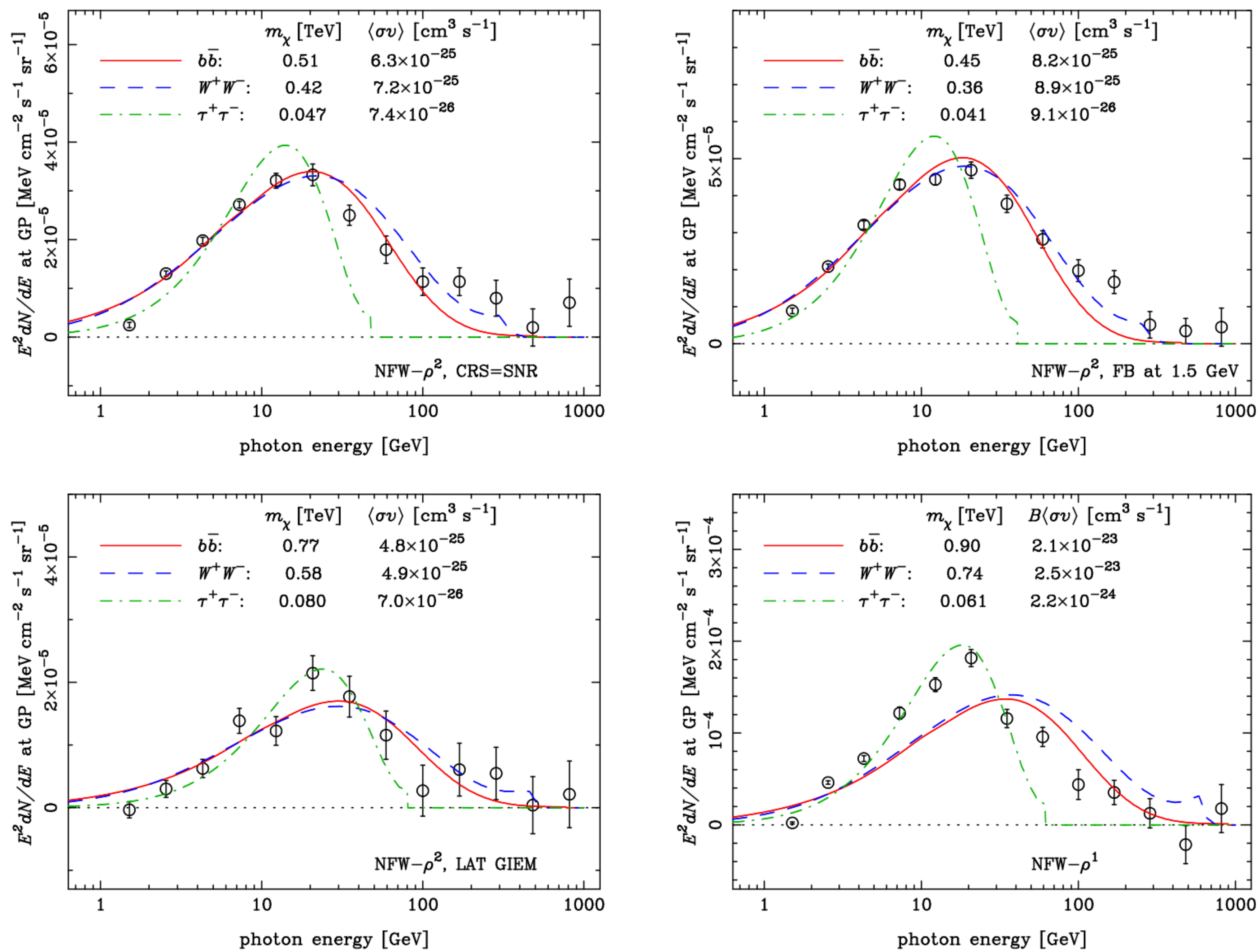
Both annihilation-like and decay-like fit show meaningful statistical significances



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

Halo-like excess in 15-years data of FermiLAT

- DM interpretation



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

are main channels discussed.

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

$$\langle\sigma v\rangle = (5-8)\times 10^{-25}\text{cm}^3/s$$

Totani (25')

Do Standard WIMP scenarios 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

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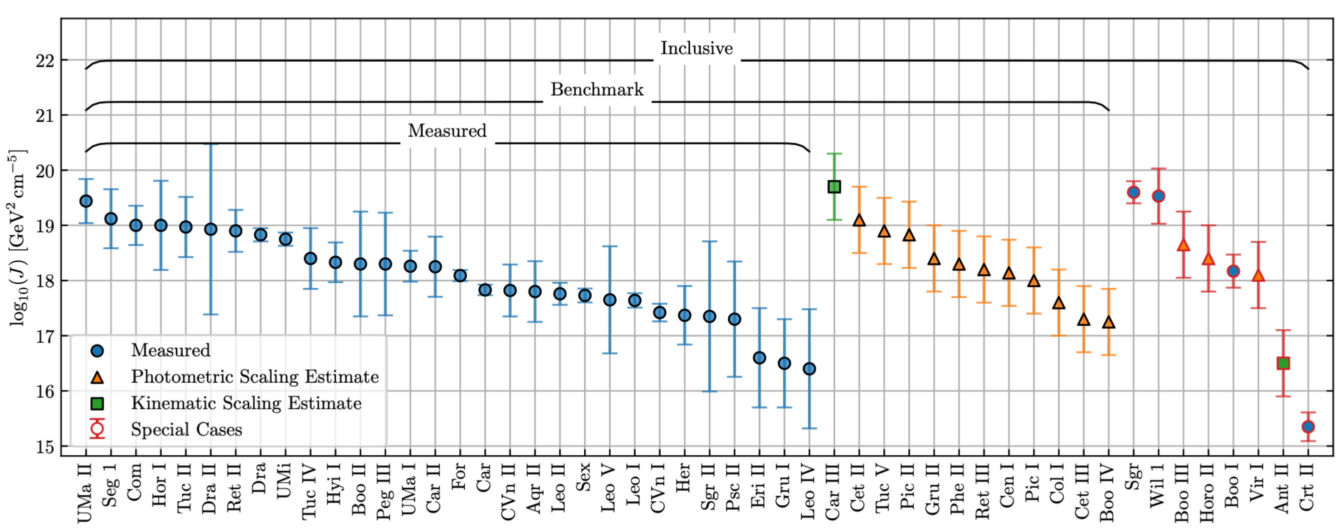

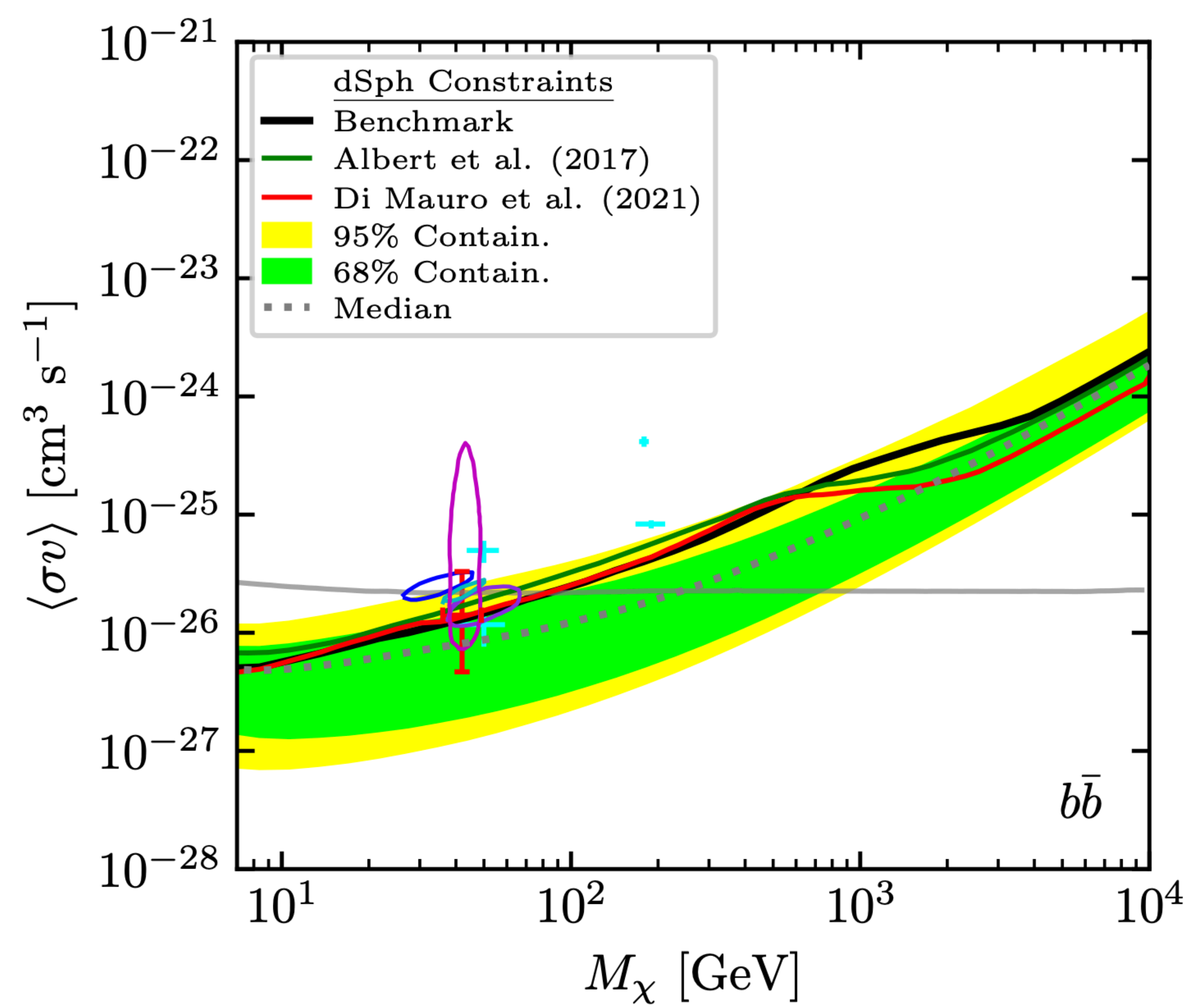

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- Strong constraints from dwarf spheroidal galaxies
- **Minimal scenarios with s-wave annihilation is problematic**
- What cases will be available?

Model

- Effective Lagrangian

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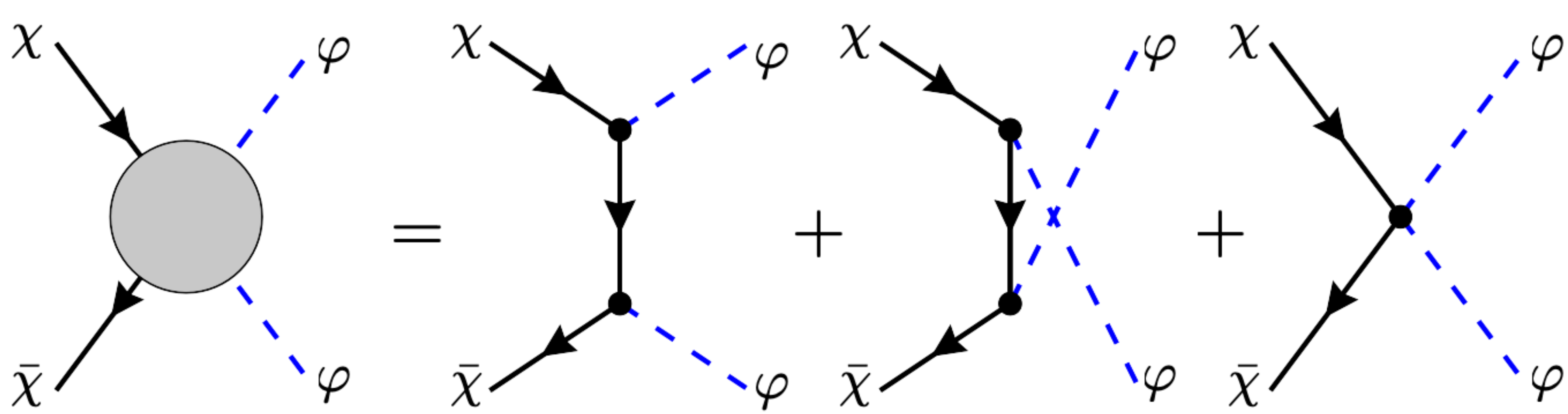
$$\mathcal{L}_{eff} \supset m_\chi e^{-\varphi/f}\bar{\chi}\chi \sim -m_\chi \frac{\varphi}{f}\bar{\chi}\chi + m_\chi \frac{\varphi^2}{2f^2}\bar{\chi}\chi + \mathcal{O}(f^{-3})$$

A dilaton-like DM-mediator interaction

SM coupling from e.g. 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 interaction(s), 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.

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

Sommerfeld Enhancement

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

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

- 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

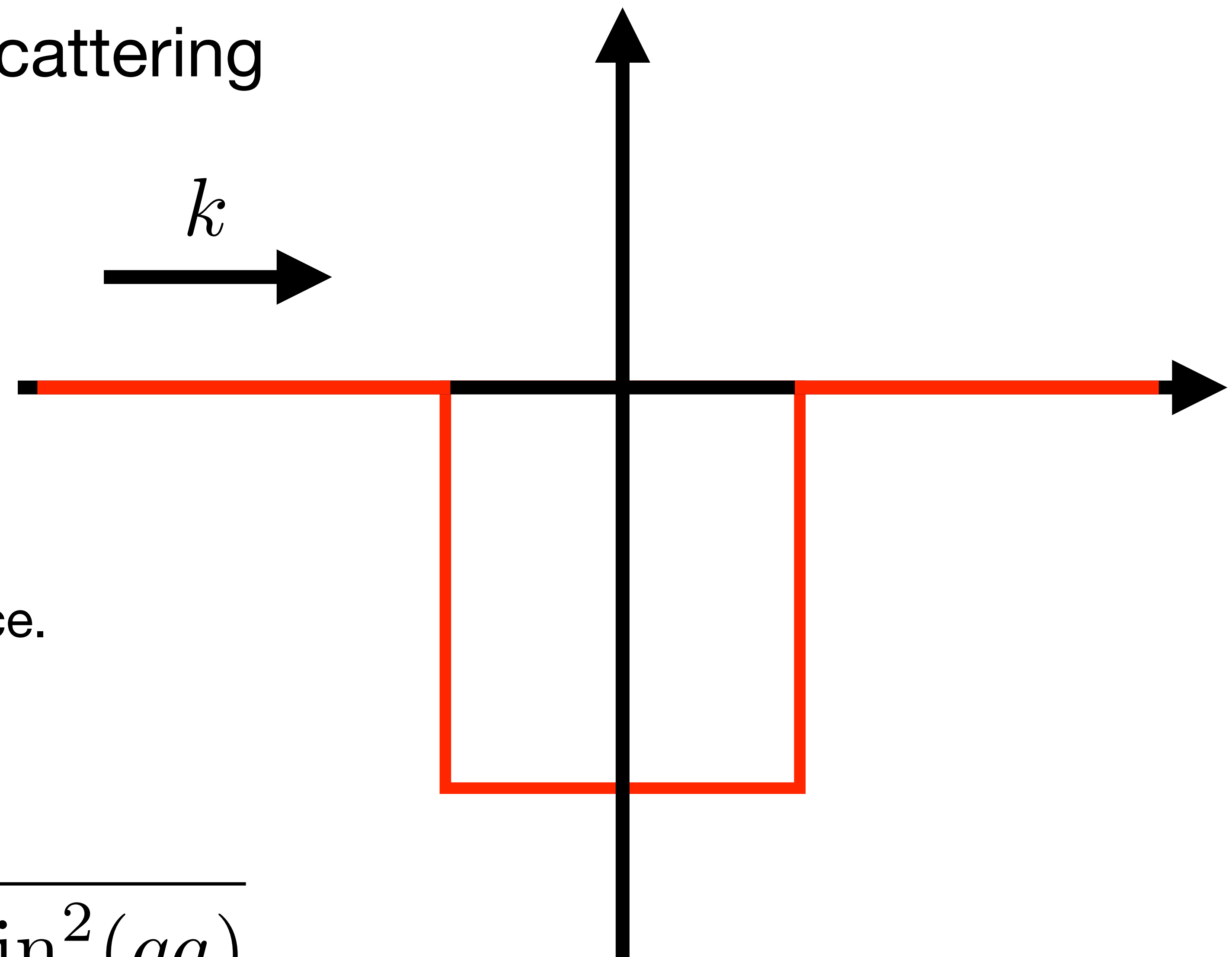
- 1-D analogy of resonant scattering

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

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.



Resonance effect in Sommerfeld Enhancement

- Hulthen Potential in 3D, s-wave (l=0)

$$-\frac{1}{m_\chi}\frac{d^2\phi}{dr^2} + V_H(r)\phi = \frac{m_\chi v^2}{4}\phi \qquad V_H(r) = -\frac{\alpha m_* e^{-m_* r}}{1-e^{-m_* r}}$$

$$\epsilon_v = v/\alpha$$

$$\epsilon_\phi = \frac{m_\phi}{\alpha m_\chi}$$

$$S = \frac{\pi}{\epsilon_v}\frac{\sinh\left(\frac{2\pi\epsilon_v}{\pi^2\epsilon_\phi/6}\right)}{\cosh\left(\frac{2\pi\epsilon_v}{\pi^2\epsilon_\phi/6}\right) - \cos\left(2\pi\sqrt{\frac{6}{\pi^2\epsilon_\phi} - \left(\frac{\epsilon_v}{\pi^2\epsilon_\phi/6}\right)^2}\right)}$$

At the resonances, i.e. $\sqrt{\frac{6}{\pi^2\epsilon_\phi}} = n \quad (n = 1, 2, 3, \dots)$

SE factor diverges in small velocity limit $v \to 0 \ (\epsilon_v \to 0)$

Resonance effect in Sommerfeld Enhancement

- Hulthen Potential in 3D, s-wave (l=0)

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$$a = \frac{v}{2\pi\alpha\epsilon_\phi} \sim \frac{v m_\chi}{m_\phi}$$

$$c = \frac{6\alpha m_\chi}{\pi^2 m_\phi}$$

Let's take i) small v limit & ii) small deviatiion from a resonance

i) $v \ll 1 \; (a \ll 1)$ ➡ $\cosh(2\pi a) \approx 1 + \frac{(2\pi a)^2}{2} = 1 + 2\pi^2 a^2$

ii) $c \approx n^2$ ➡ $c = (n+\delta)^2 \approx n^2 + 2n\delta$

$$\cos(2\pi\sqrt{c}) = \cos(2\pi(n+\delta)) = \cos(2\pi n + 2\pi\delta) = \cos(2\pi\delta) \approx 1 - \frac{(2\pi\delta)^2}{2} = 1 - 2\pi^2\delta^2$$

$$D \approx (1 + 2\pi^2 a^2) - (1 - 2\pi^2\delta^2) = 2\pi^2(a^2 + \delta^2)$$

➡ $$S \propto \frac{1}{a^2 + \delta^2}$$

$$\delta \propto \Delta\alpha \equiv \alpha_{\text{eff}} - \alpha_{\text{crit.}}$$

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- 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.
- 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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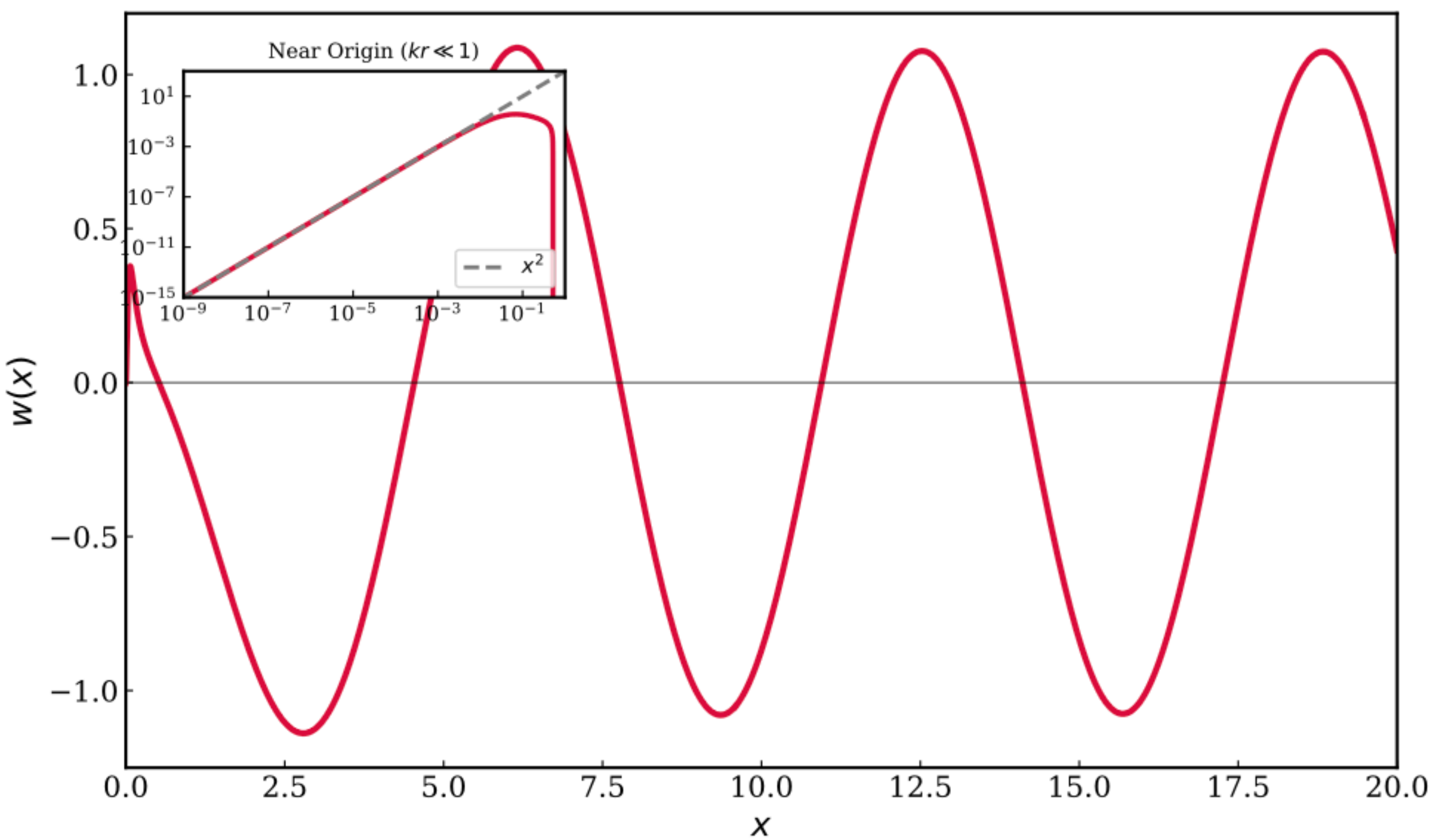
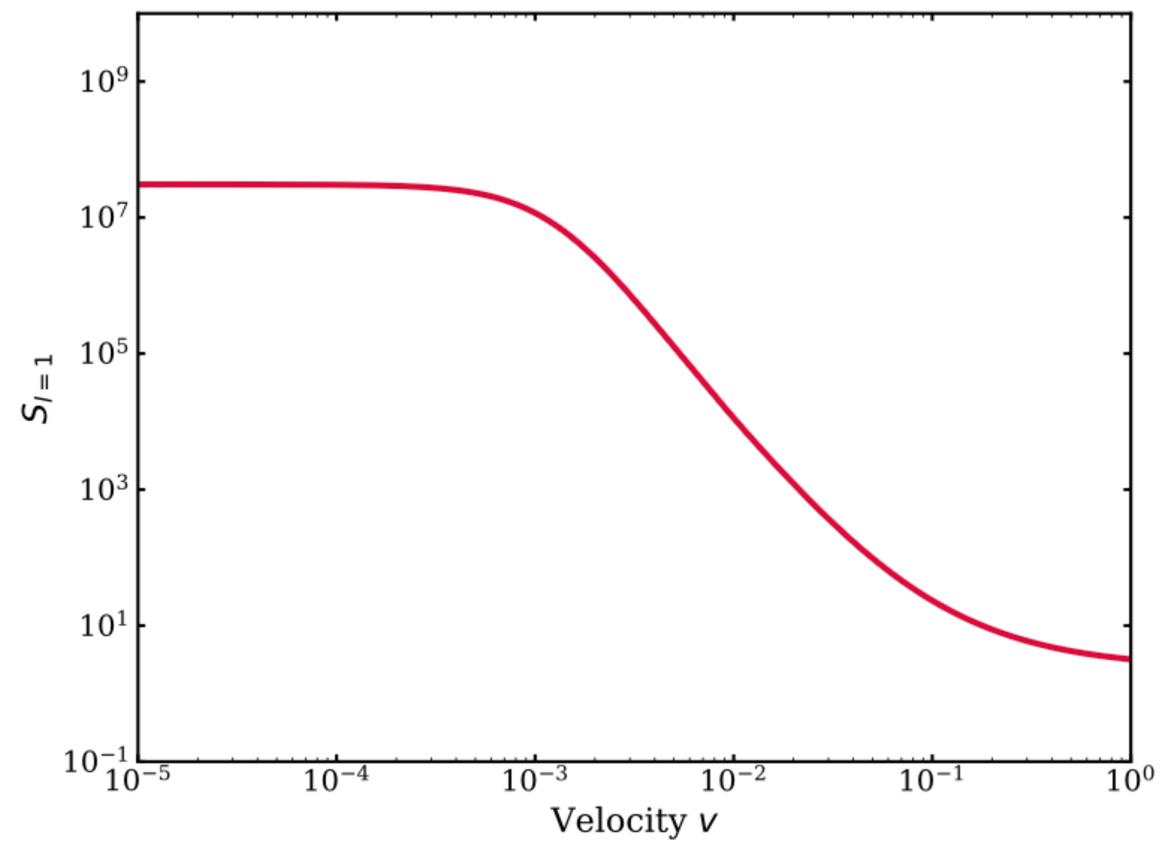
(2512.24662)

- Numerical solution of radial Schrodinger equation



Radial wavefunction



Enhancement factor

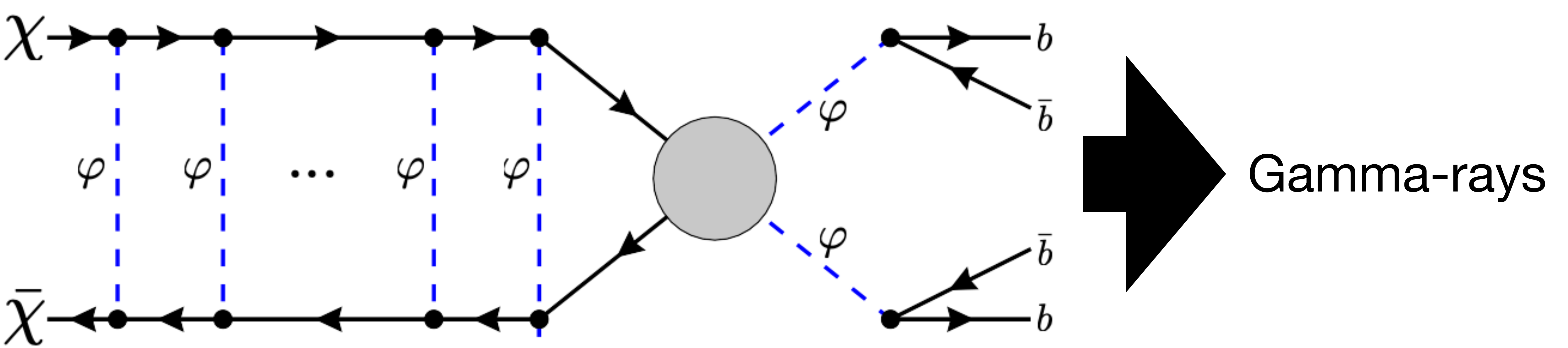
$$u''_{l,k}(r) + \left[k^2 - \frac{l(l+1)}{r^2} + m_\chi \alpha \, \frac{e^{-m_\varphi r}}{r}\right] u_{l,k}(r) = 0.$$

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

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

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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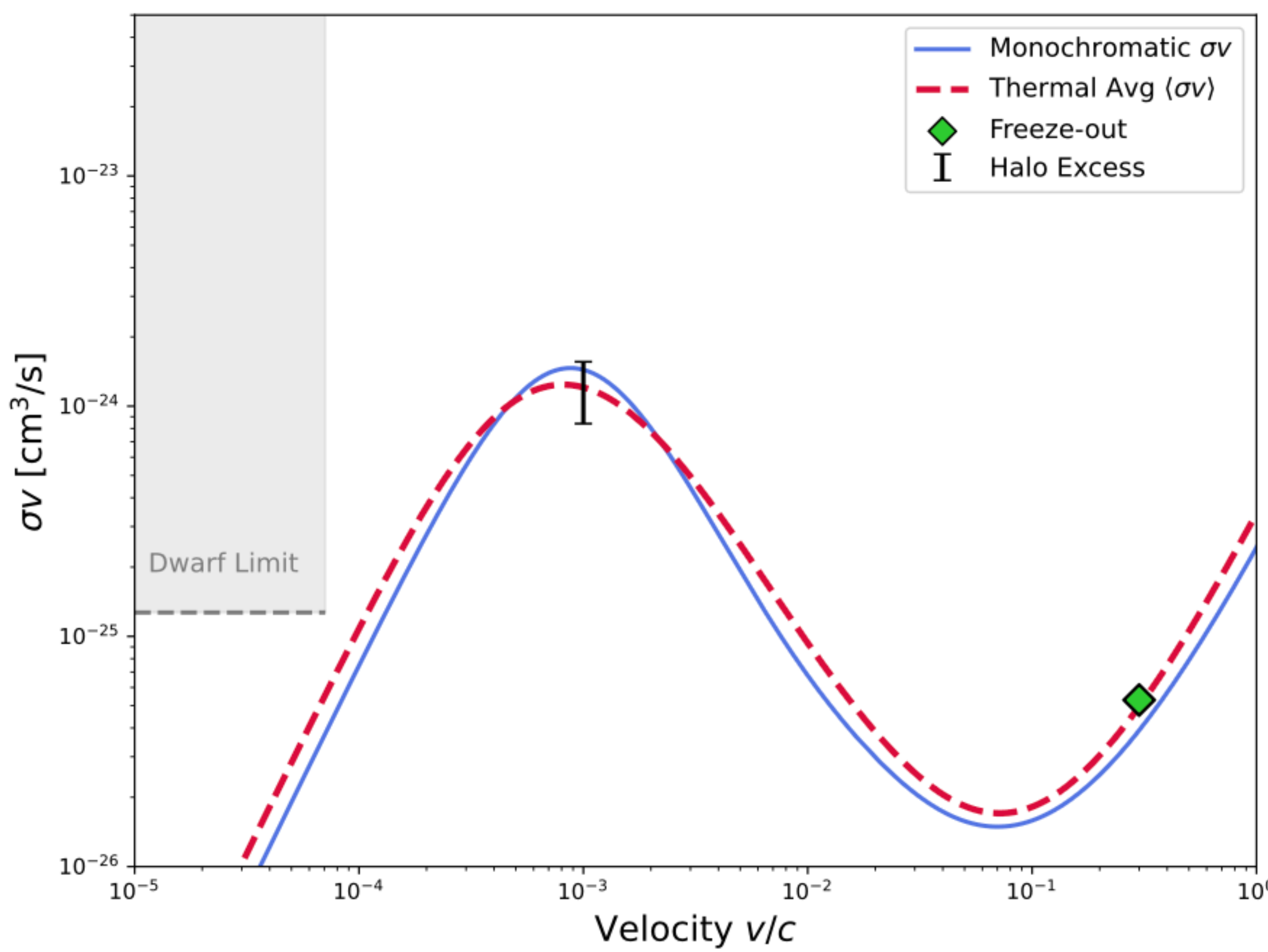

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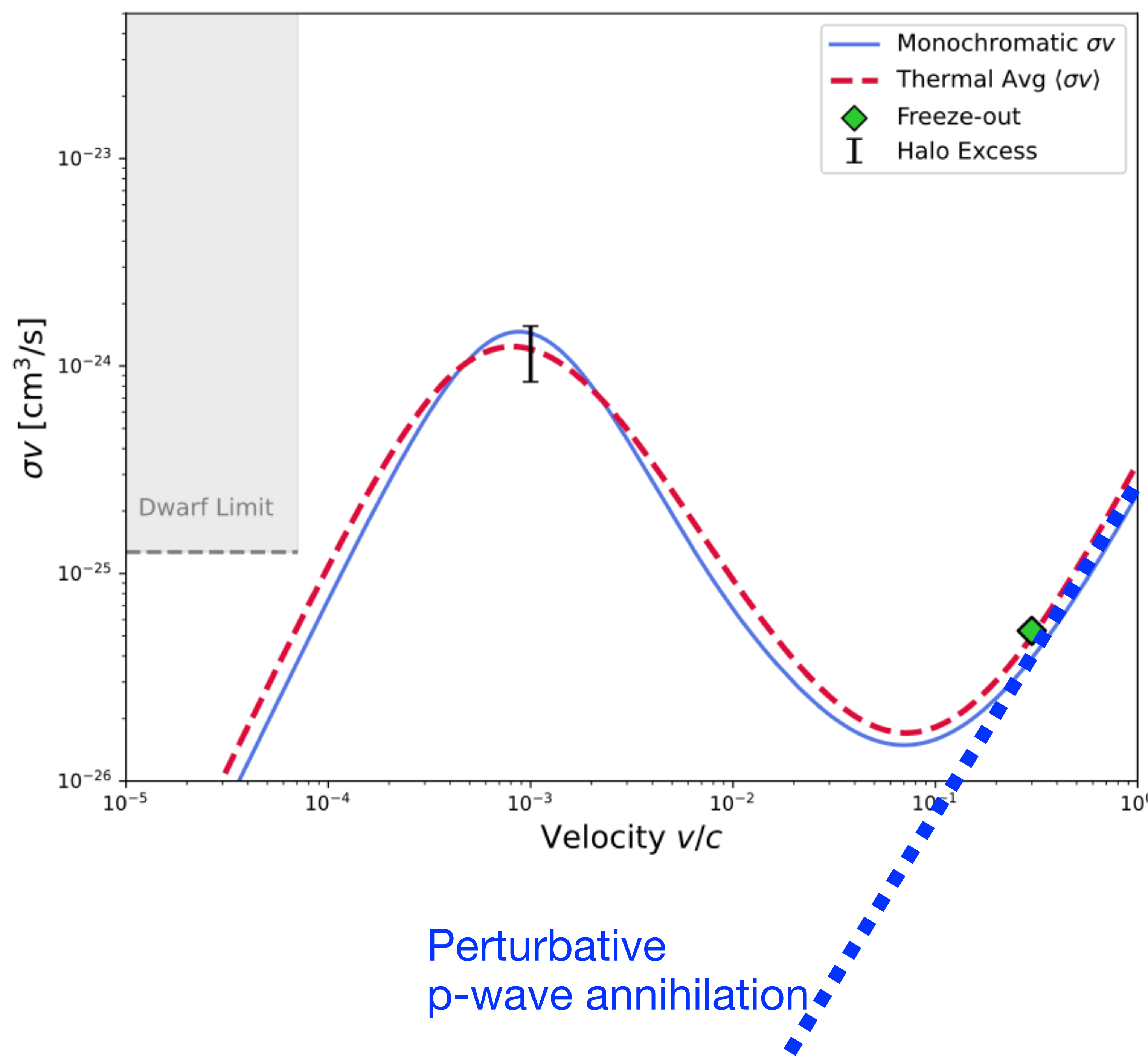

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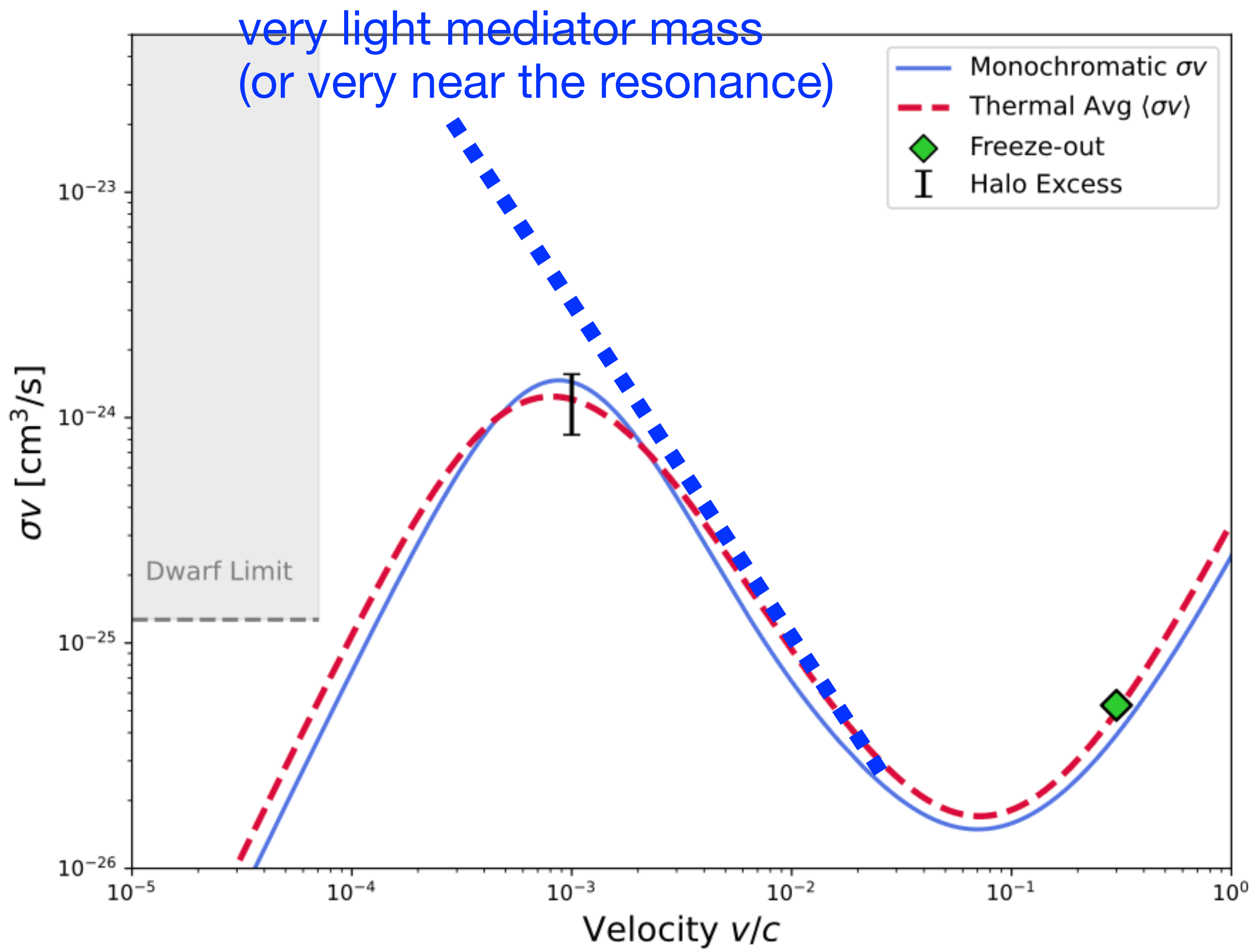

Annihilation cross section

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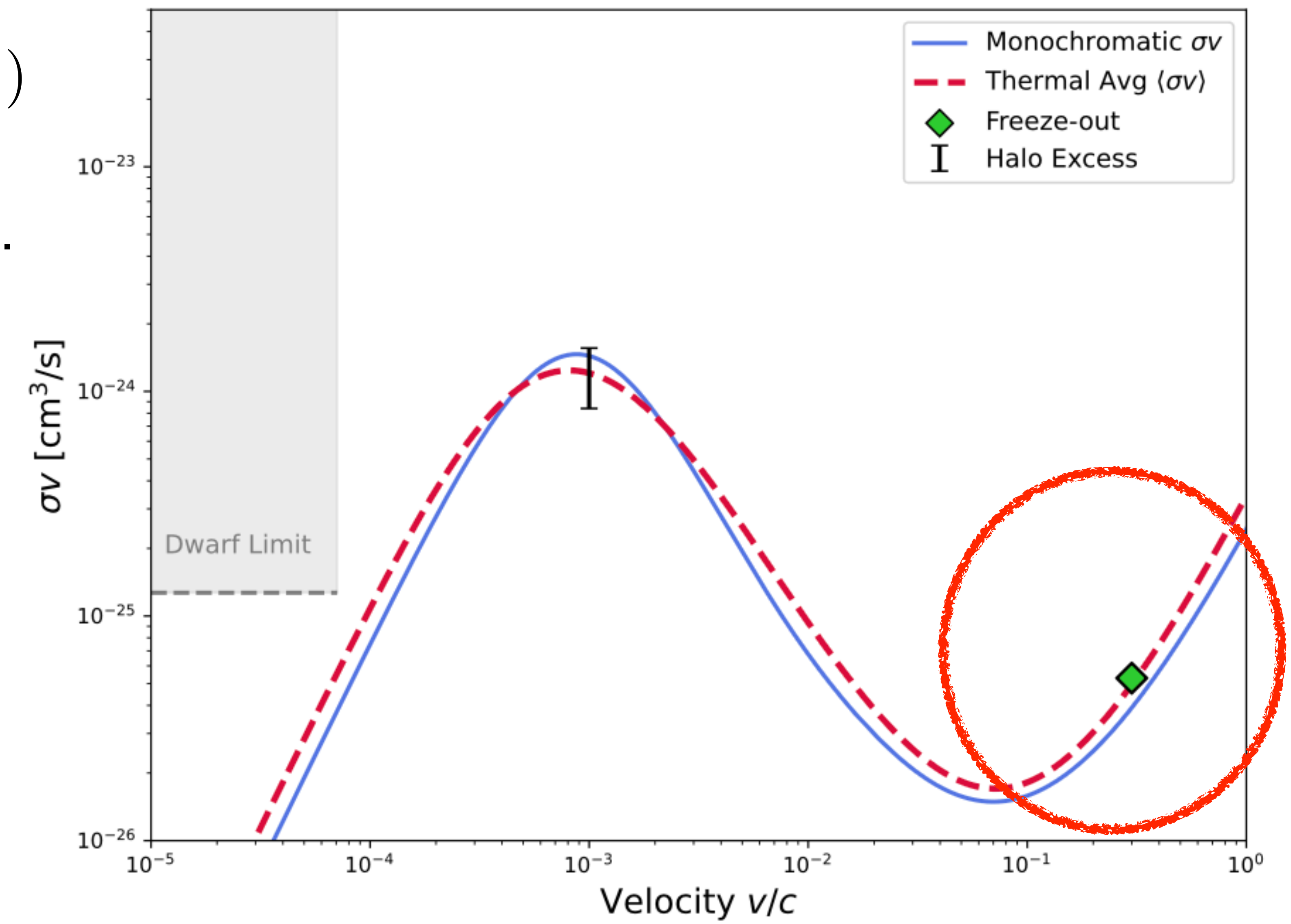
- There are three main regimes:

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

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



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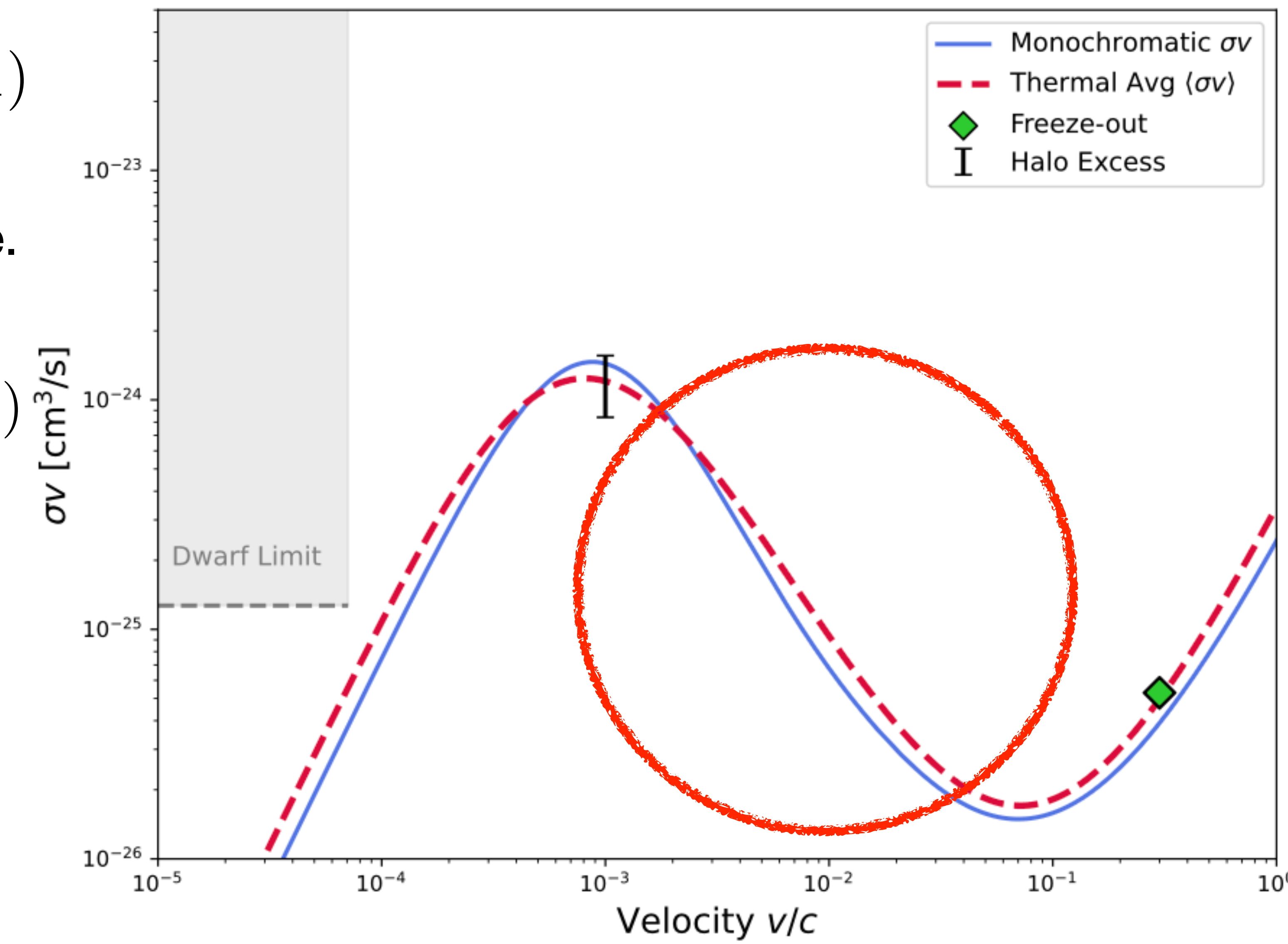
2. Sommerfeld Regime $(\Delta\alpha < v < \alpha)$

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



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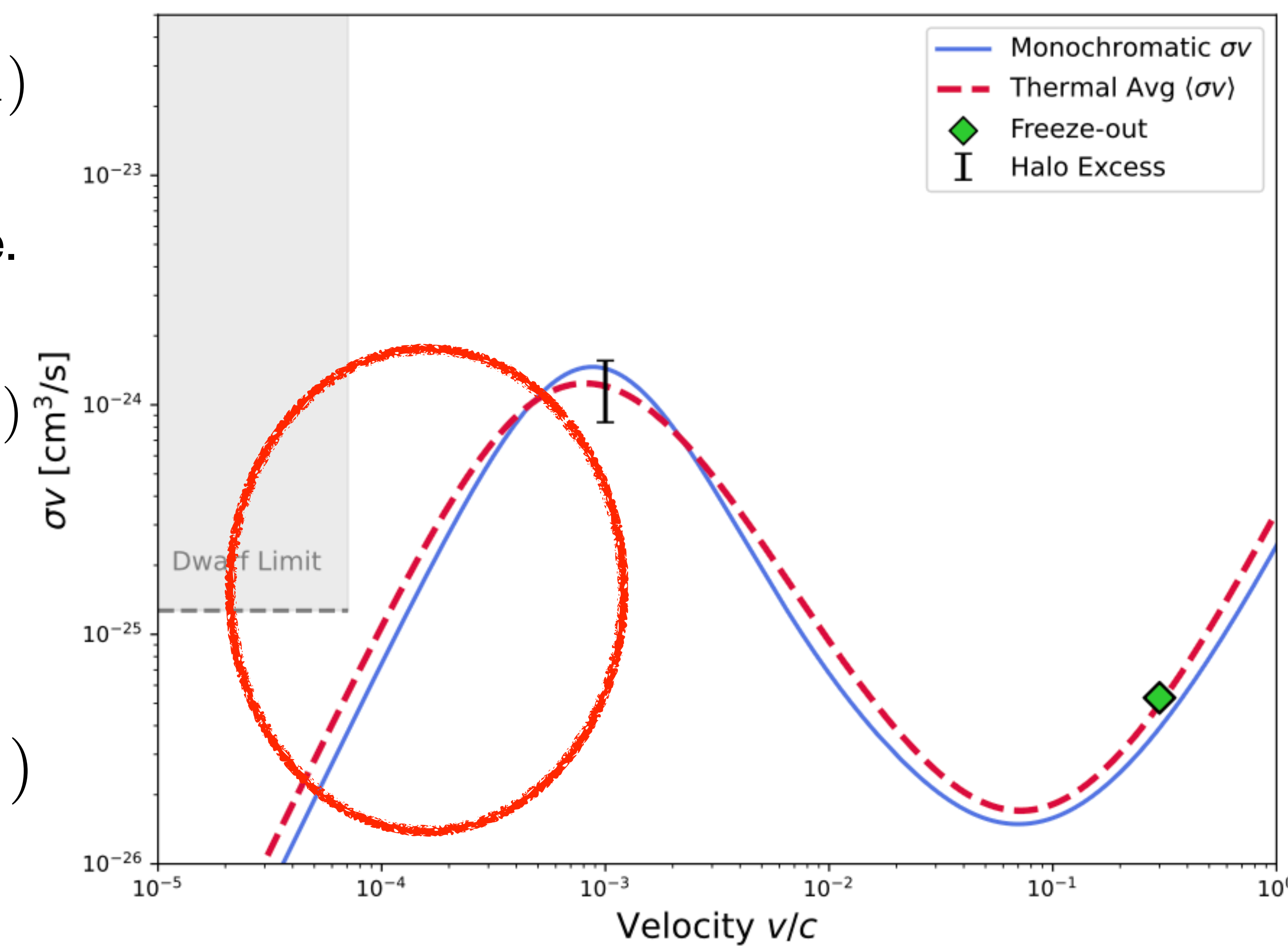
The Sommerfeld Enhancement becomes efficient and the cross section scales as ~1/v

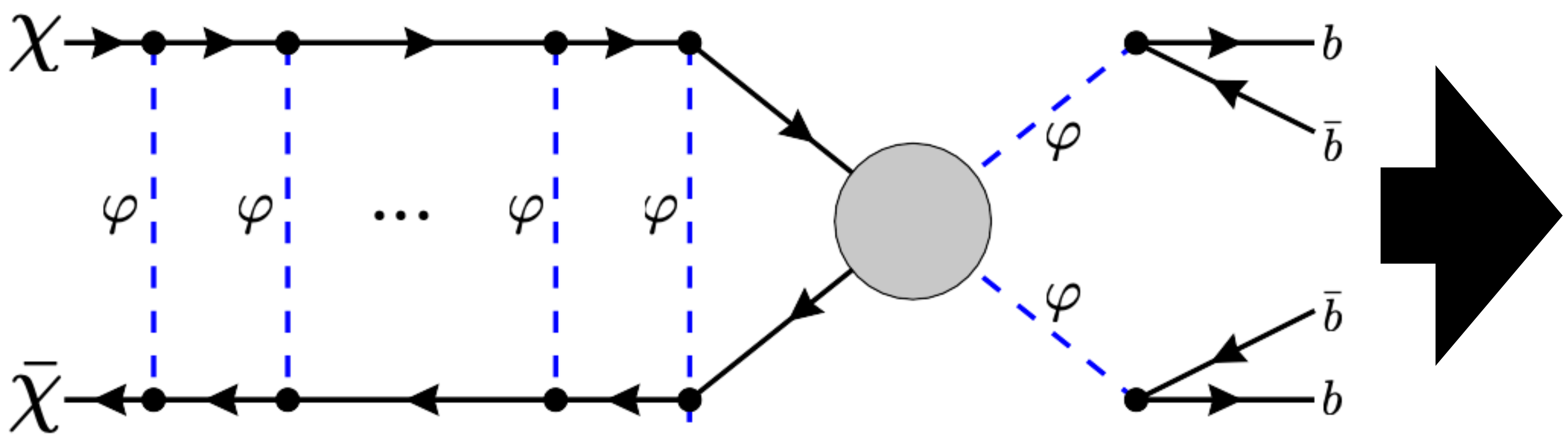
$$3.\ \text{Saturation Regime}\ (v < v_{sat.})$$

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.

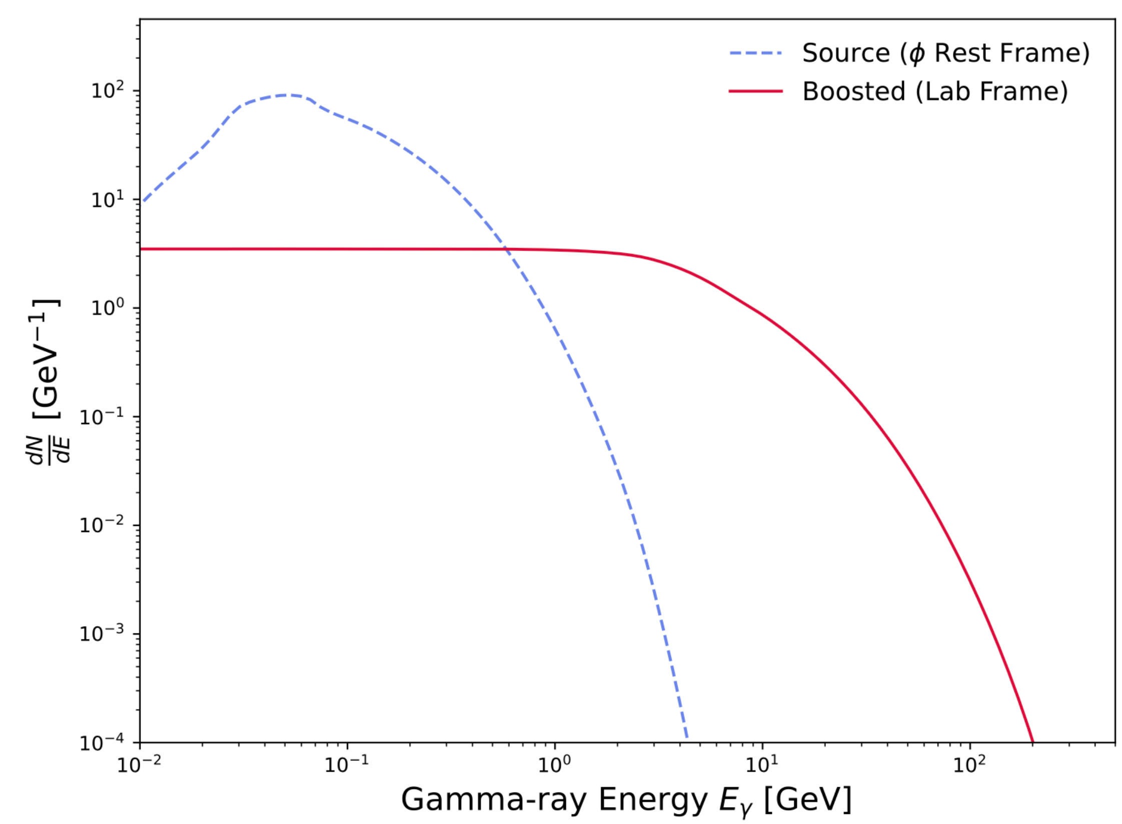


Gamma-ray signal spectrum

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

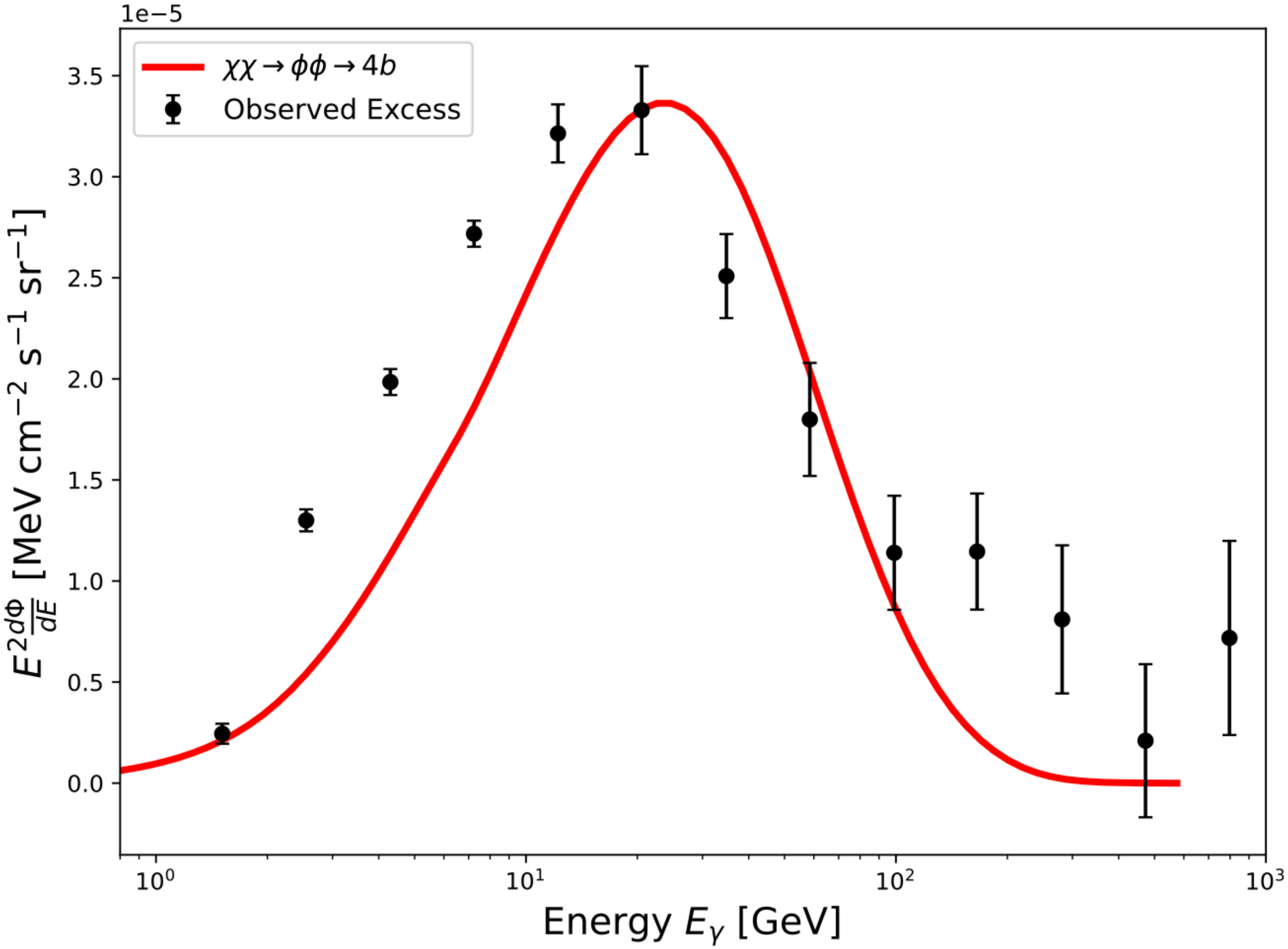


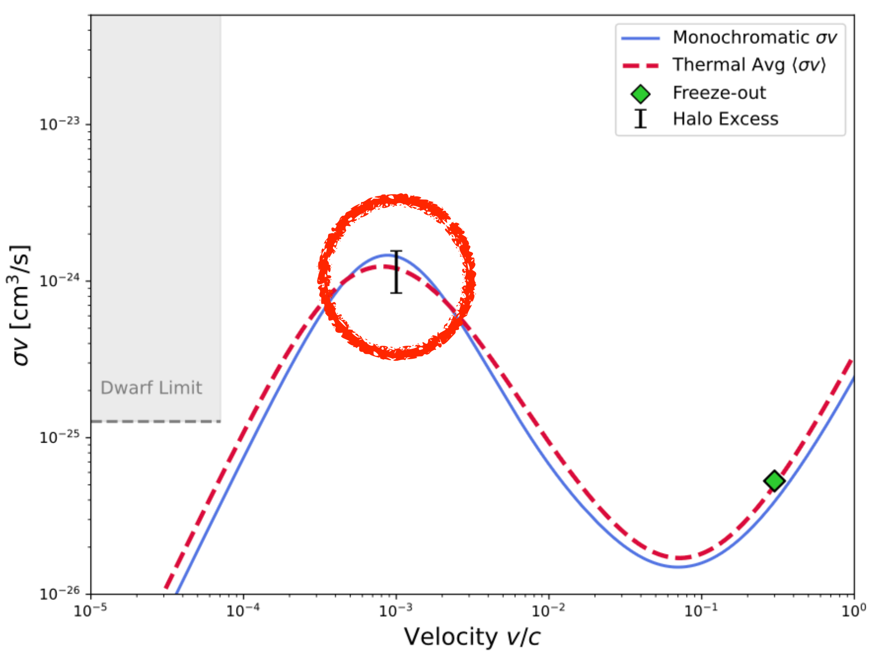
- After considering the Lorentz boost effect, the spectrum becomes flat and box-like.



Gamma-ray signal spectrum

- Signal spectrum with benchmark parameters





$$m_\chi = 575 \text{ GeV}$$

$$m_\varphi = 11.6 \text{ GeV}$$

$$\alpha = 0.183$$

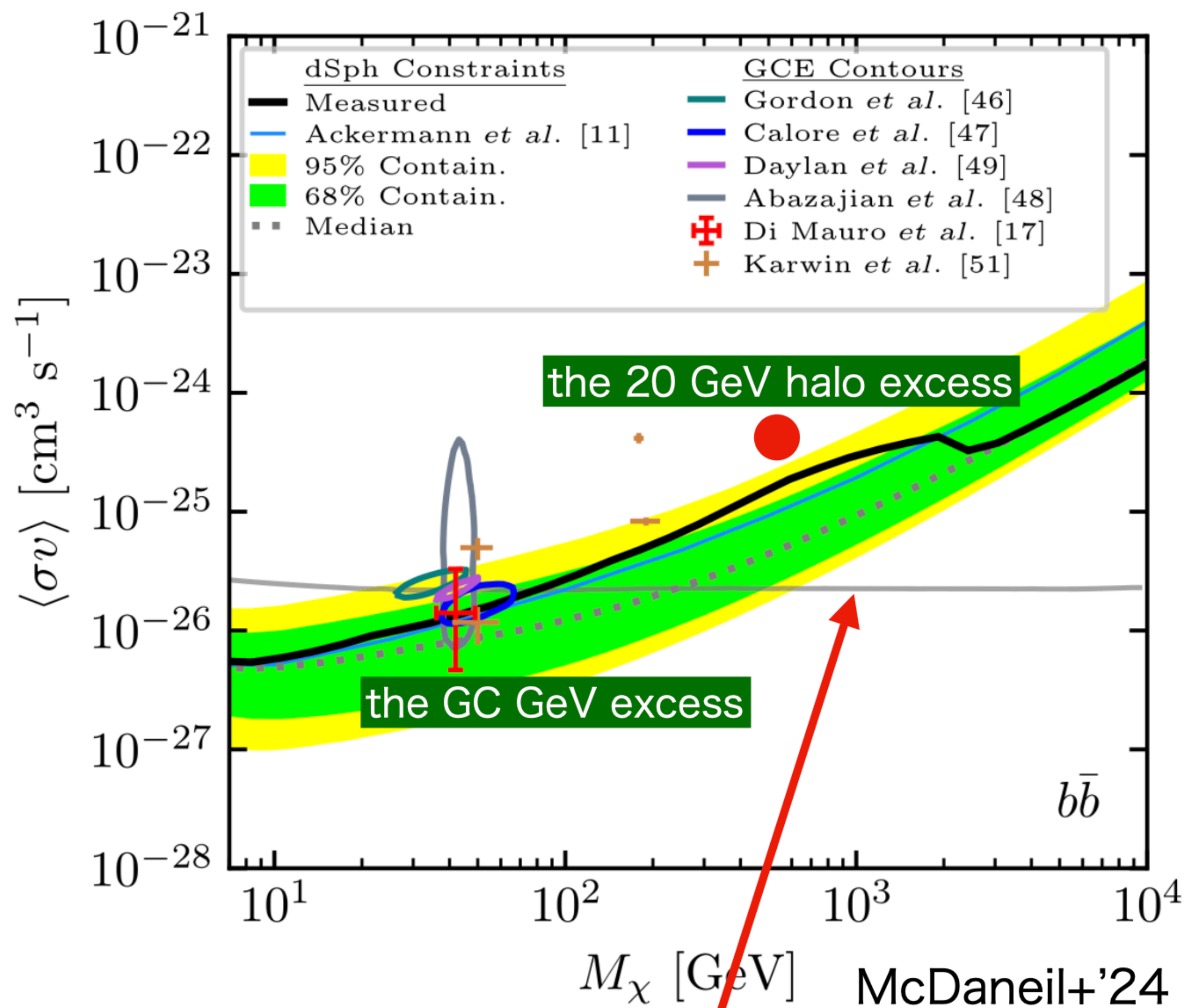
Other Constraints & Future prospects

- 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.

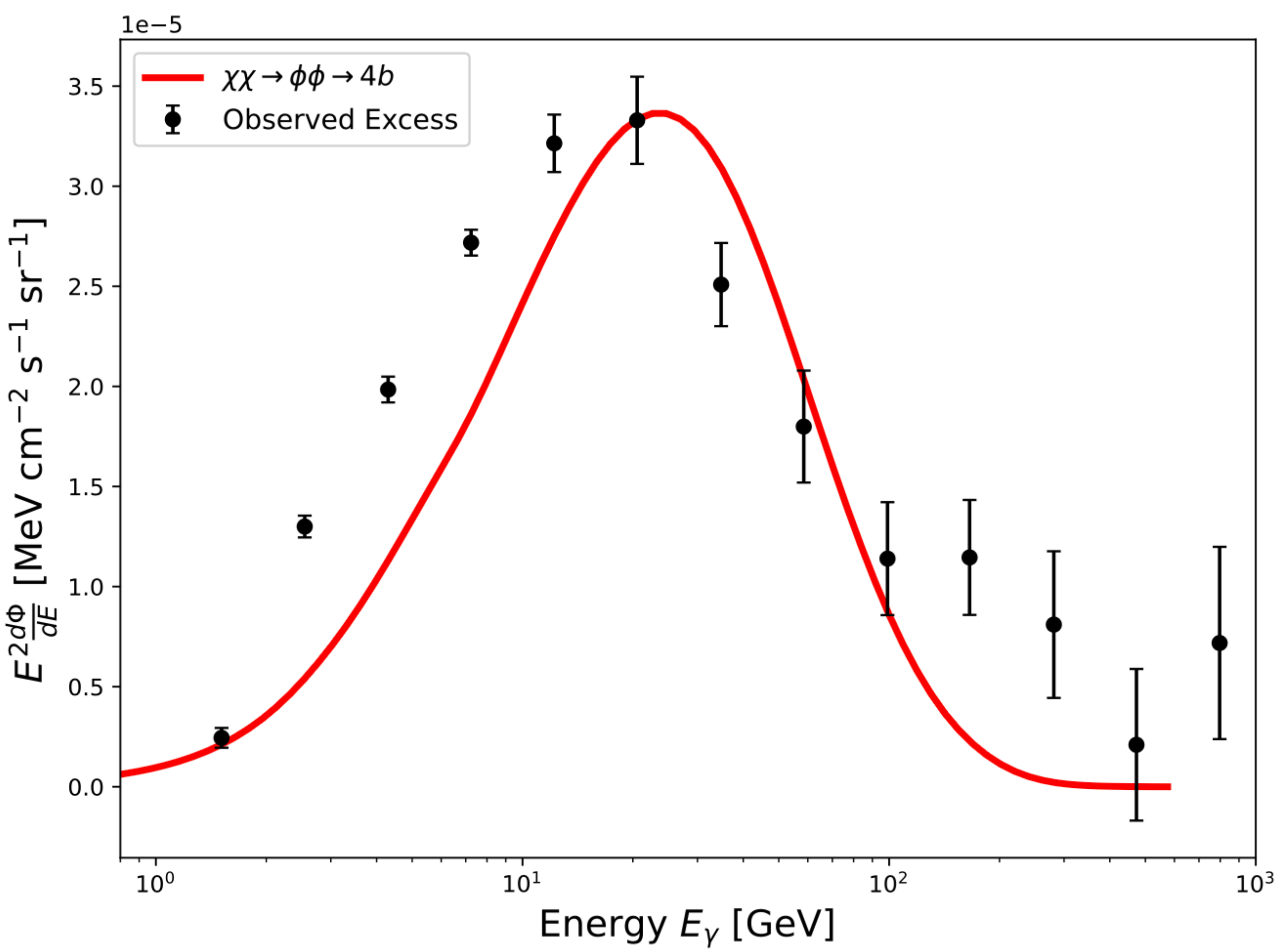
  - How about GCE? or other anomalies?

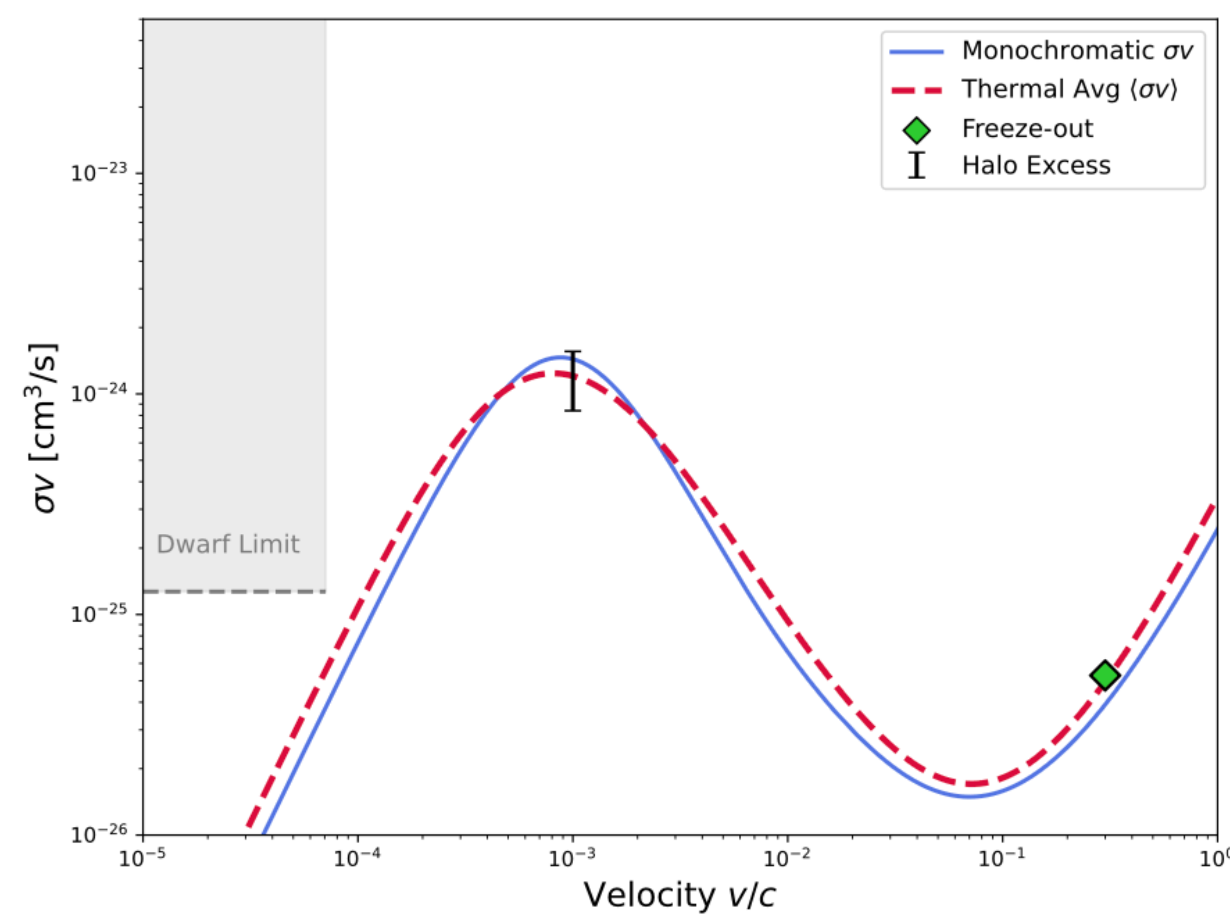


Thermal Freeze-out xsec.

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 for your attention

Anti-proton bounds

[2401.10329]