Dark Matter annihilations from a density spike in Milkyway galaxy

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Based on *Dark Matter spikes around Sgr A* in gamma-rays*

with Shyam Balaji, Filippo Sala, Joe Silk (arXiv : 2303.12107), JCAP 2023

CosmoChart

Horizon 2020, grant agreement No 101002846

European Research Council

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Dark Matter and its probes

Dark Matter

↓

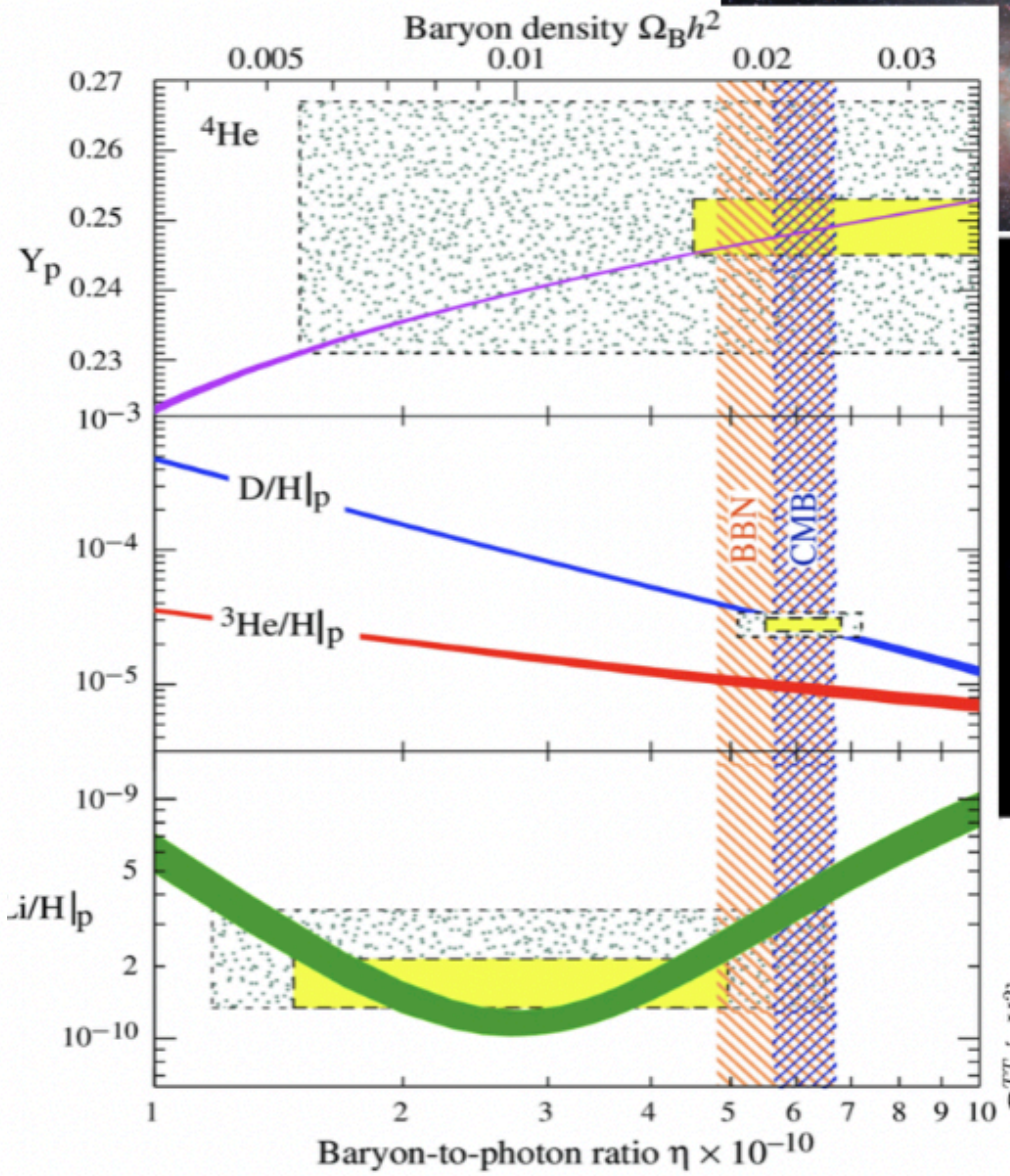
Particle or Modified Gravity

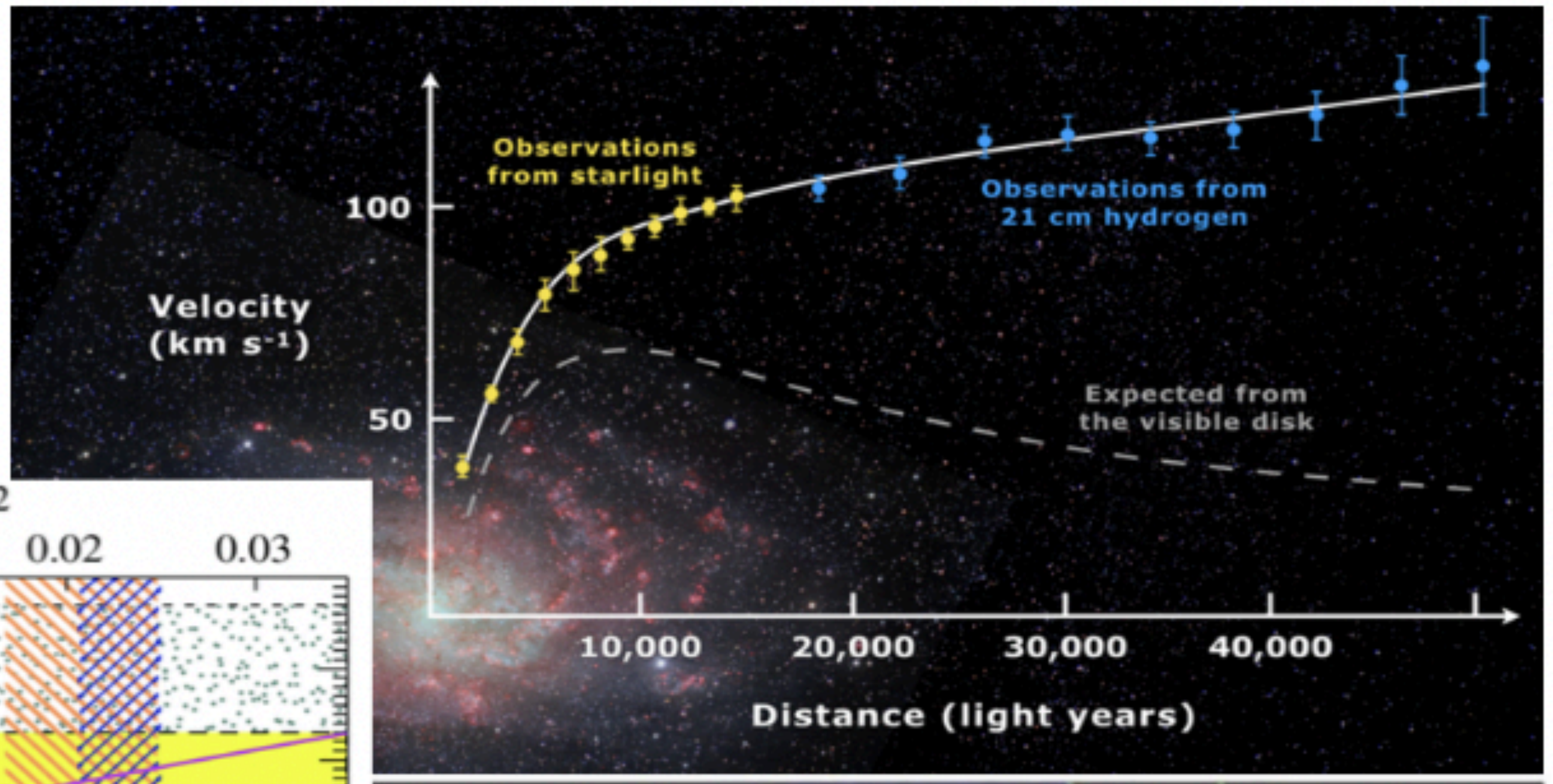
↓

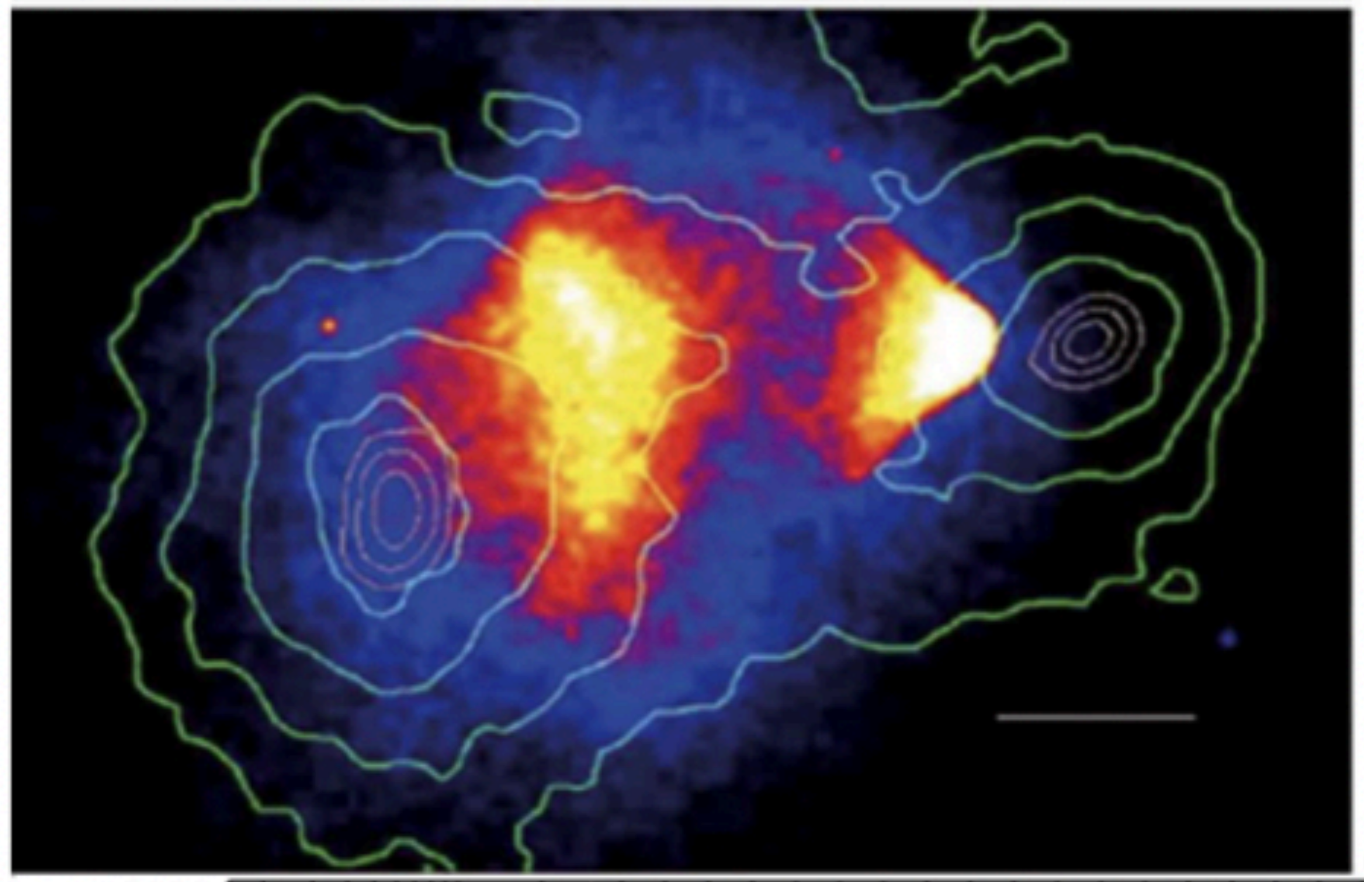
Is it Fermion, Boson? Quantum Nos.?
Does it interact with SM?

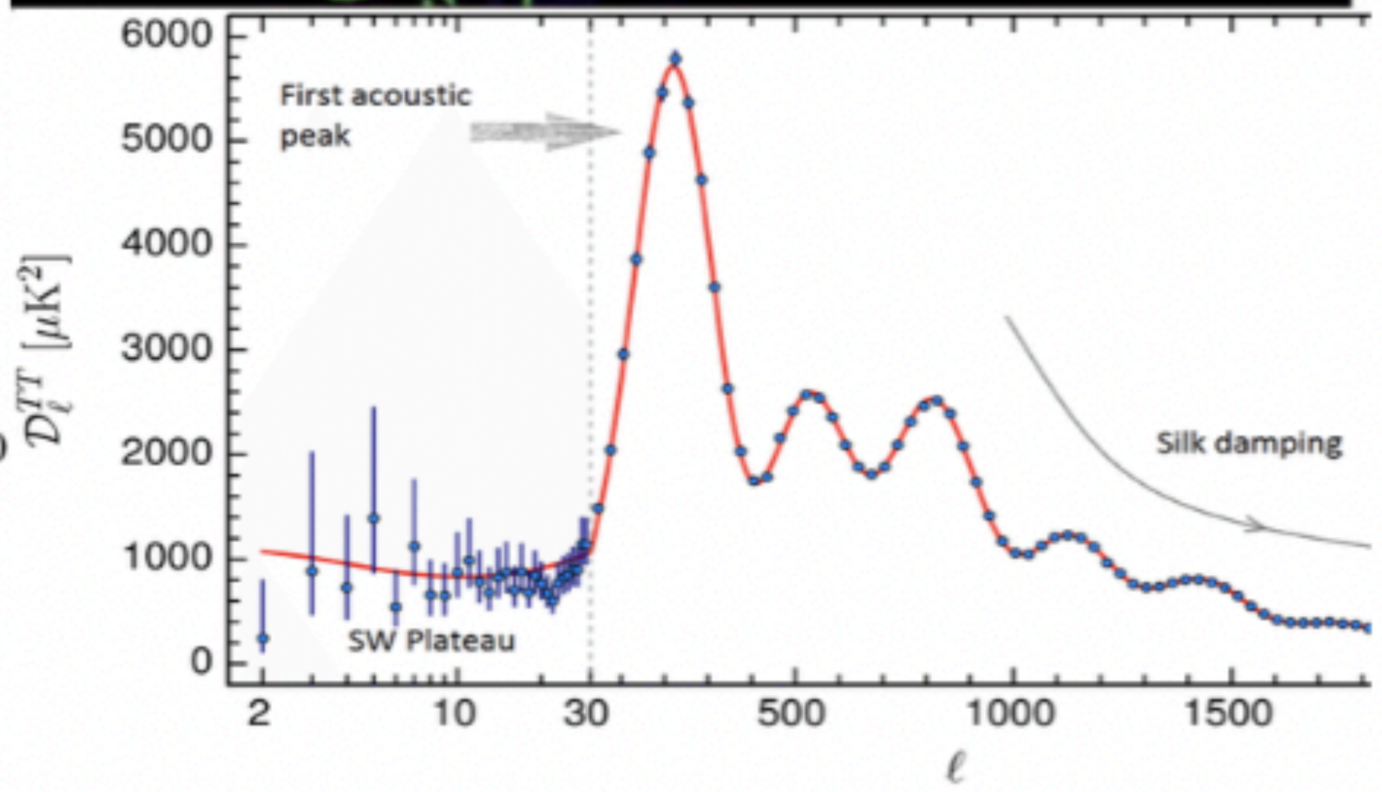
↓

DM Searches:
Astrophysical observations, Colliders signatures
Direct detection experiments etc.

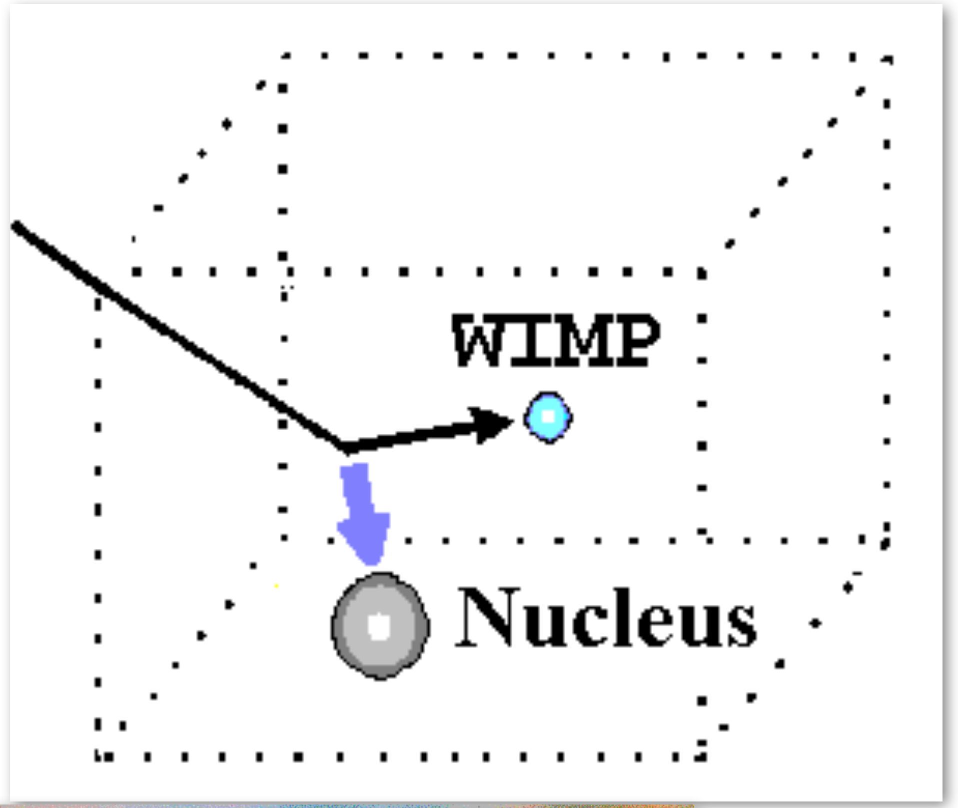


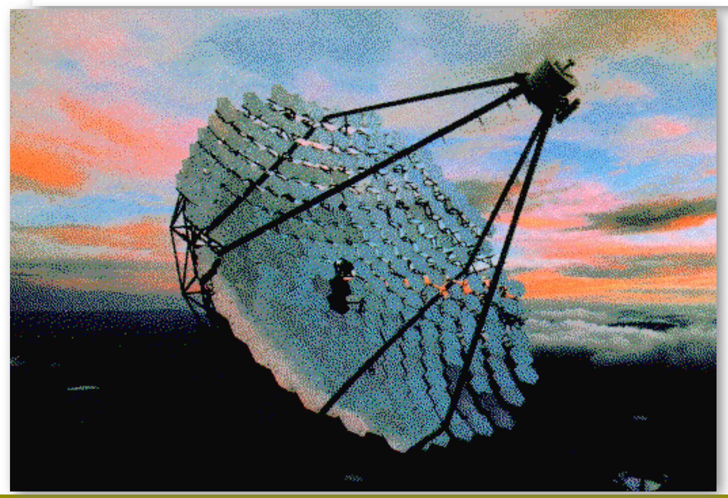






astro-ph/0601514v2,wikipedia,1612.05036





Advantages of Gamma-Rays:

- Propagate undeflected (point sources possible, angular information)
- Propagate without energy loss (spectral information)
- Rapid development in both space (FermiLAT) and ground-based (HESS, MAGIC, VERITAS) technologies

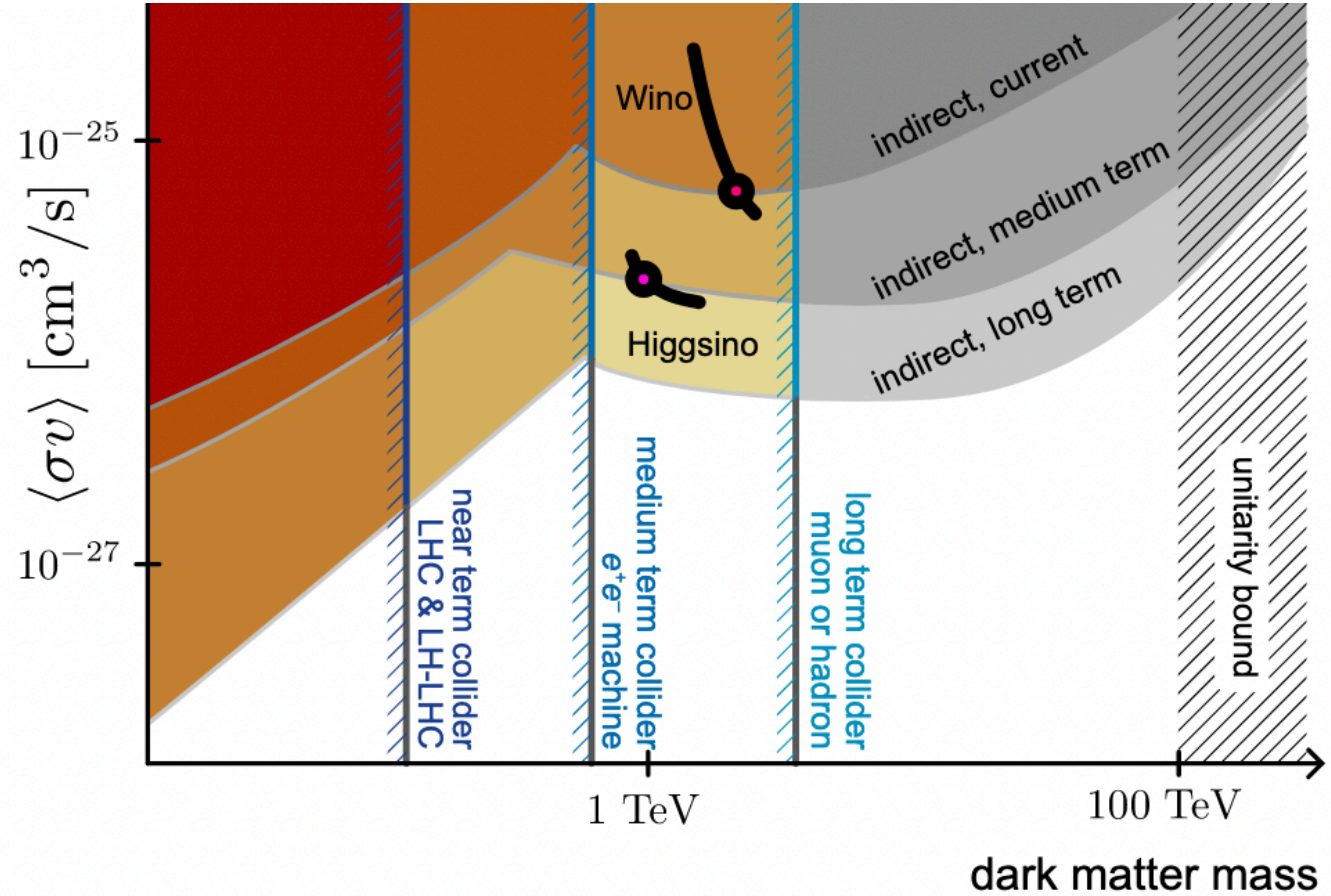
Direct Detection

Momentum transfer to detector through elastic scattering

Indirect Detection

Simulations predict that the GC contains very high densities of dark matter (and high annihilation rates)

Observation of annihilation products (γ, ν, e+, p, etc.)



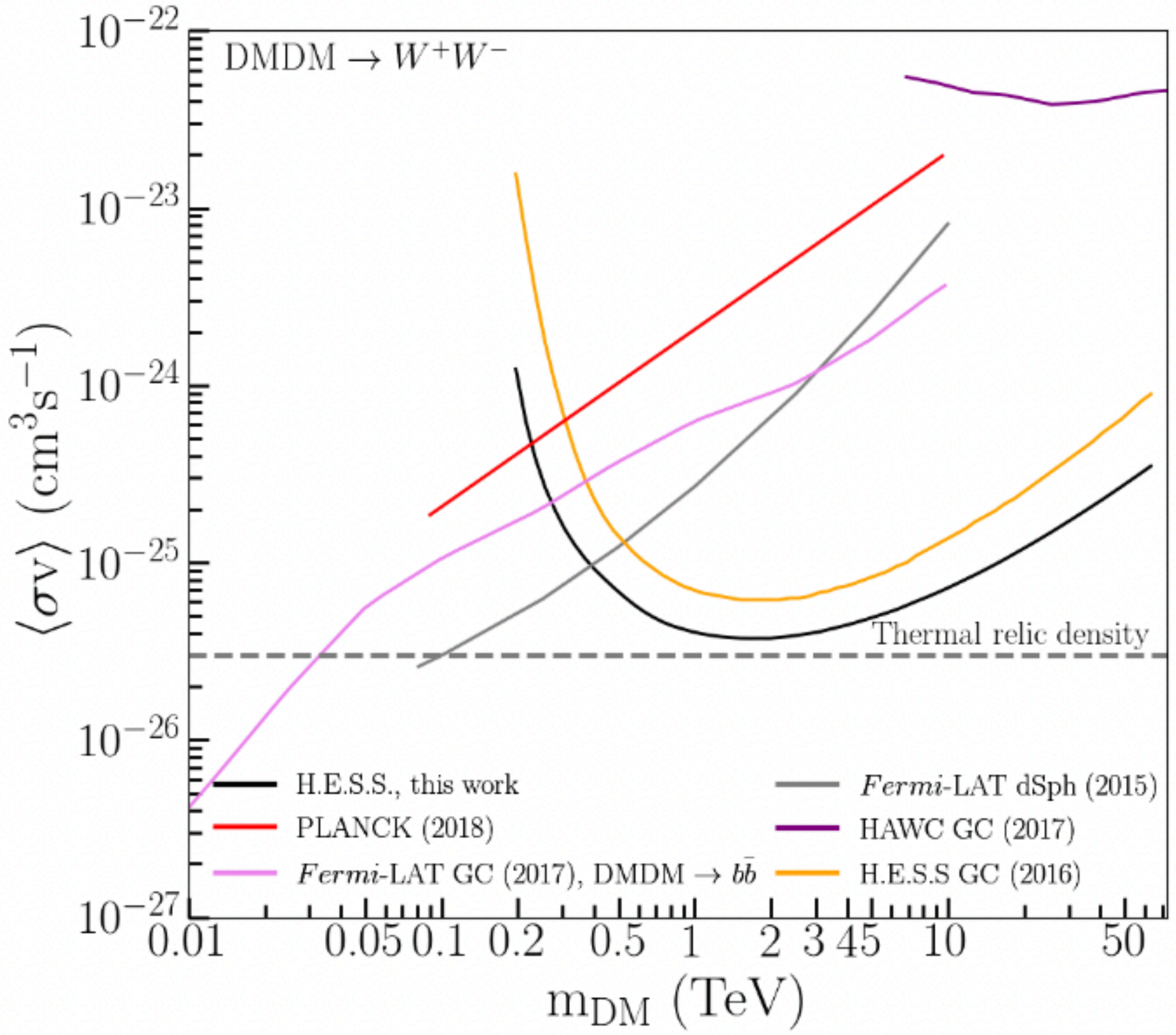
Snowmass 2021 Dark Matter Complementarity Report

Indirect Searches

$$\frac{d\Phi}{dE_\gamma} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} J$$

Spectrum

Amount of Dark Matter



Thermal relic cross-section for WIMPs : $3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

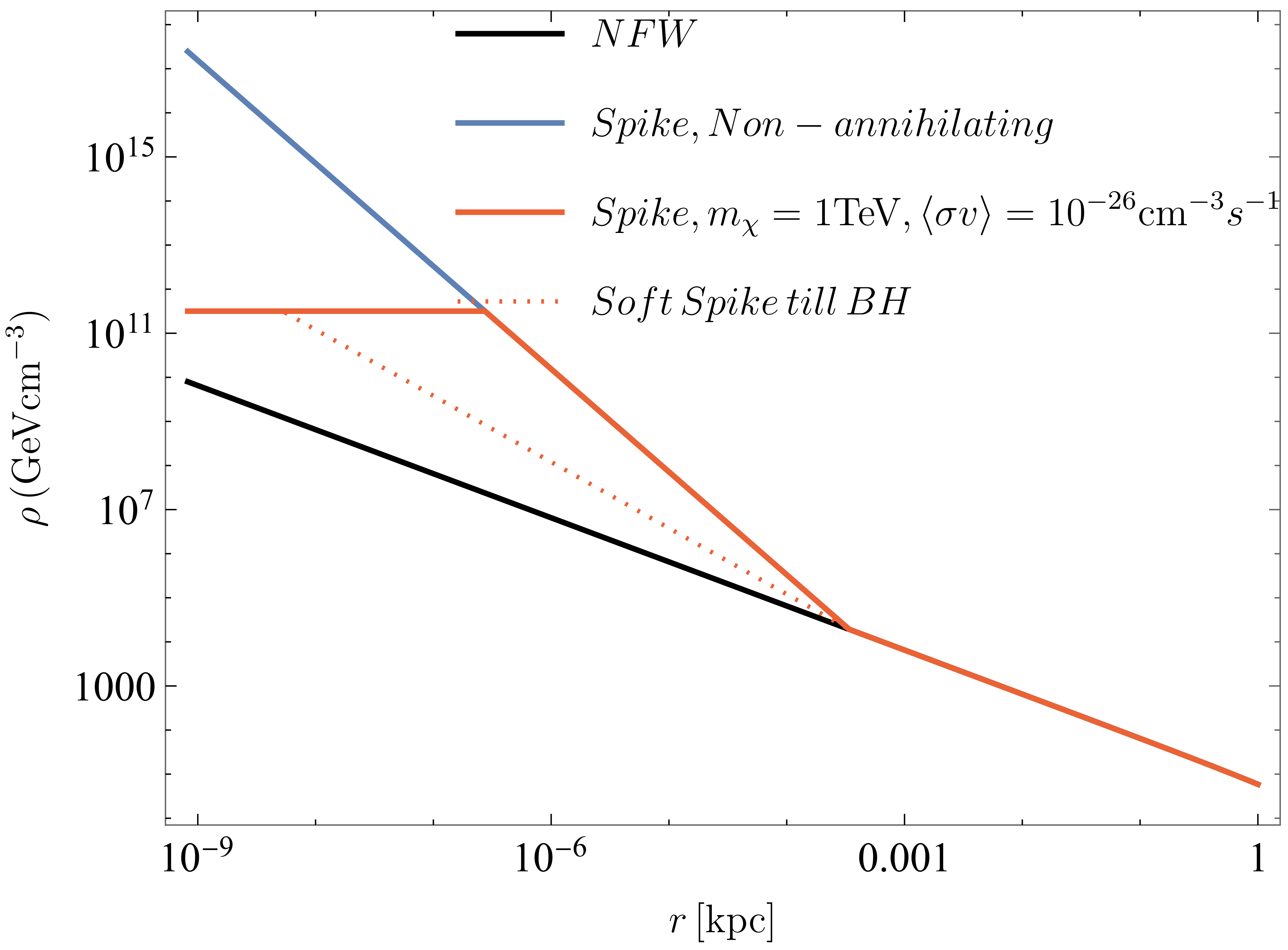
H.E.S.S Collaboration: arXiv: 2207.10471, PRL

DM Spikes

- The inner volume of the MilkyWay is one of the most promising targets for the indirect detection of DM.
- Slow growth of Supermassive Black Hole at the center of a galaxy

$\implies \rho(r) \propto r^{-7/3}$ i.e overdensity of DM at center

DM spikes can lead to strong annihilation signals.



Gondolo & Silk 1999, Ullio Zhao & Kamionkowski 2001

Rough understanding of formation of spike

Initial Condition:

- $\rho_i(r) \propto r^{-\gamma}$, the initial distribution of DM particles in Circular orbits.
- BH grows adiabatically at the center, that is, on a much longer timescale than the dynamical timescale.

Final result:

$\rho_f(r) \propto r^{-\gamma_{sp}}$

The slow process of accretion onto BH induces no torque on the DM particles, so that the angular momentum of each particle is conserved.

$$r_{\mathrm{i}} M_{\mathrm{i}}(r_{\mathrm{i}}) = r_{\mathrm{f}} M_{\mathrm{f}}(r_{\mathrm{f}}).$$

Additionally, conservation of the DM mass $M_{\mathrm{i}}^{\mathrm{DM}}(r_{\mathrm{i}}) = M_{\mathrm{f}}^{\mathrm{DM}}(r_{\mathrm{f}})$ can be expressed as

$$\int_0^{r_{\mathrm{i}}} \rho_{\mathrm{i}}(r) r^2 \, \mathrm{d}r = \int_0^{r_{\mathrm{f}}} \rho_{\mathrm{f}}(r) r^2 \, \mathrm{d}r,$$

$$r_{\mathrm{i}}^{3-\gamma} \propto r_{\mathrm{f}}^{3-\gamma_{\mathrm{sp}}}$$

Initially, $M_i(r_i) \approx M_i^{\mathrm{DM}} \propto r_i^{3-\gamma}$ and Finally $M_f(r_f) \approx M_{\mathrm{BH}}$

$$\therefore \quad r_i^{4-\gamma} \propto r_f$$

$$\gamma_{\mathrm{sp}} = \frac{9 - 2\gamma}{4 - \gamma}$$

DM - spike profile

$$\rho(r) = \begin{cases} 0 & r < 2R_s \\ \rho_{\rm sat} & 2R_S \leq r < R_{\rm sat} \\ \rho_{\rm halo}(R_{\rm sp}) \left(\dfrac{r}{R_{\rm sp}}\right)^{-\gamma_{\rm sp}(\gamma_c)} & R_{\rm sat} \leq r < R_{\rm sp} \\ \rho_{\rm halo}(r, \gamma_c) & r \geq R_{\rm sp} \end{cases}$$

where $\rho_{\rm sat} = \dfrac{m_\chi}{\langle \sigma v \rangle t_{\rm BH}}$, R_{sp} is radial extension of spike and R_s is Schwarzchild radius.

Numerical studies suggest that the spike begins to grow inside the gravitational influence radius, $r_h = GM_{\rm BH}/v_o^2$, where the gravitational potential energy due to the BH is equal to the typical kinetic energy of a DM particle in the halo $\therefore R_{\rm sp} \leq r_h$.

DM in Halo

Peaked profile

$$\rho_{\text{halo}}^{\text{NFW}}(r) = \rho_s \left(\frac{r}{r_s}\right)^{-1} \left(1 + \frac{r}{r_s}\right)^{-2}$$

Slope of spike depends on halo profile close to BH.

- Studies incorporating the affect of baryonic matter into N-body simulations found that the DM density distribution at small radii is a constant-density “core”.

Self interactions of DM can alter the profile.

Core profile

$$\rho_{\text{halo}}^{\text{cored}}(r, \gamma_c) = \begin{cases} \rho_{\text{halo}}^{\text{NFW}}(r_c) \left(\frac{r}{r_c}\right)^{-\gamma_c} & r < r_c \\ \rho_{\text{halo}}^{\text{NFW}}(r) & r \geq r_c \end{cases}$$

$$r_c = 1kpc, \quad 0 \leq \gamma_c \leq 1.$$

DM in spike

Gondolo Silk profile

$$\gamma_{\rm sp}(\gamma > 0) = \frac{9 - 2\gamma}{4 - \gamma}$$

$$2.4 \geq \gamma_{\rm sp} > 2.25 \text{ for } 1.5 \geq \gamma > 0$$

$$\gamma_{sp}(\gamma = 0) = 1.5$$

A conservative approach: if core profile is recent, spike would be more prominent.

Gondolo & Silk 1999, Ullio Zhao & Kamionkowski 2001

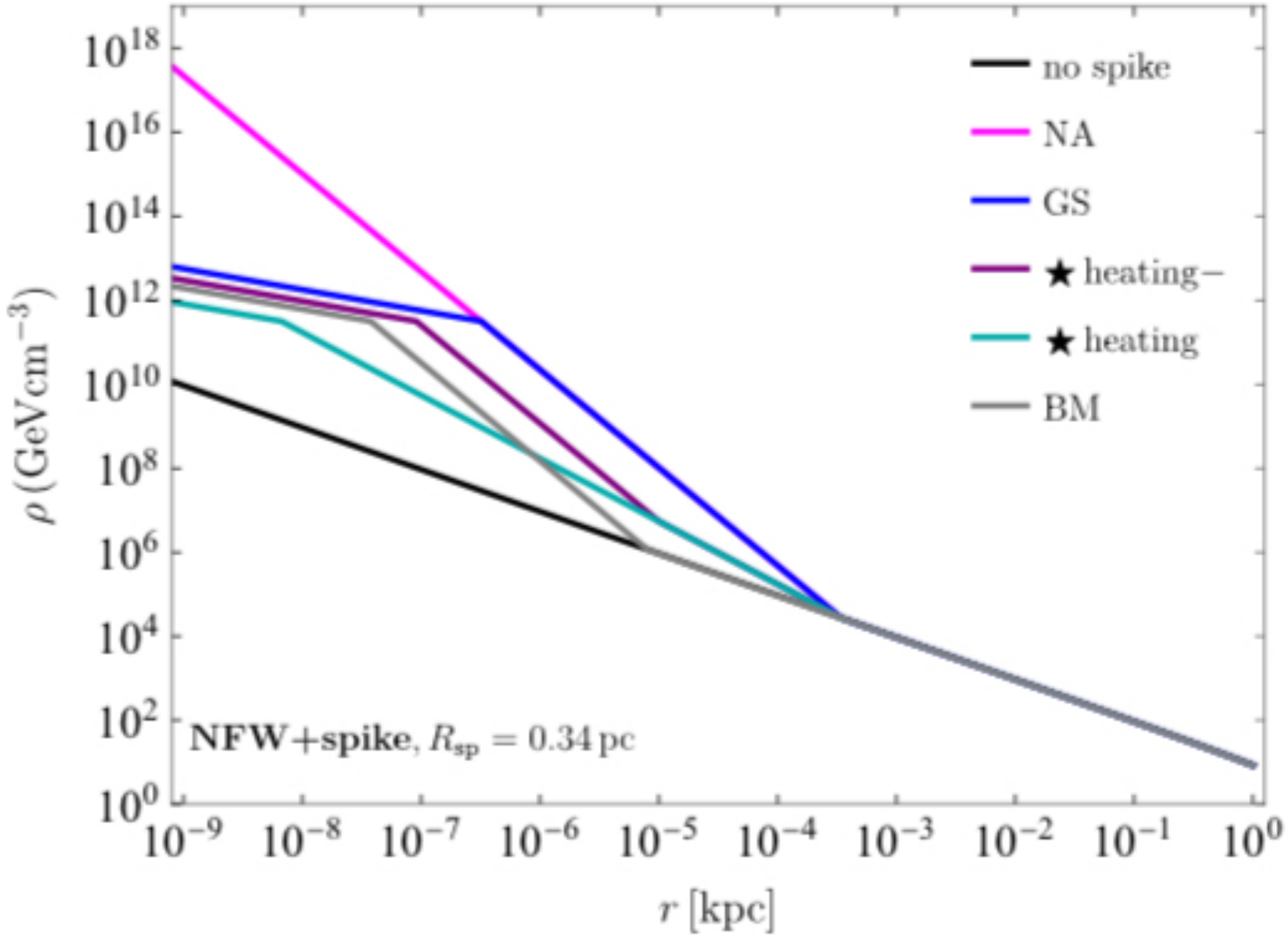
Stellar heating

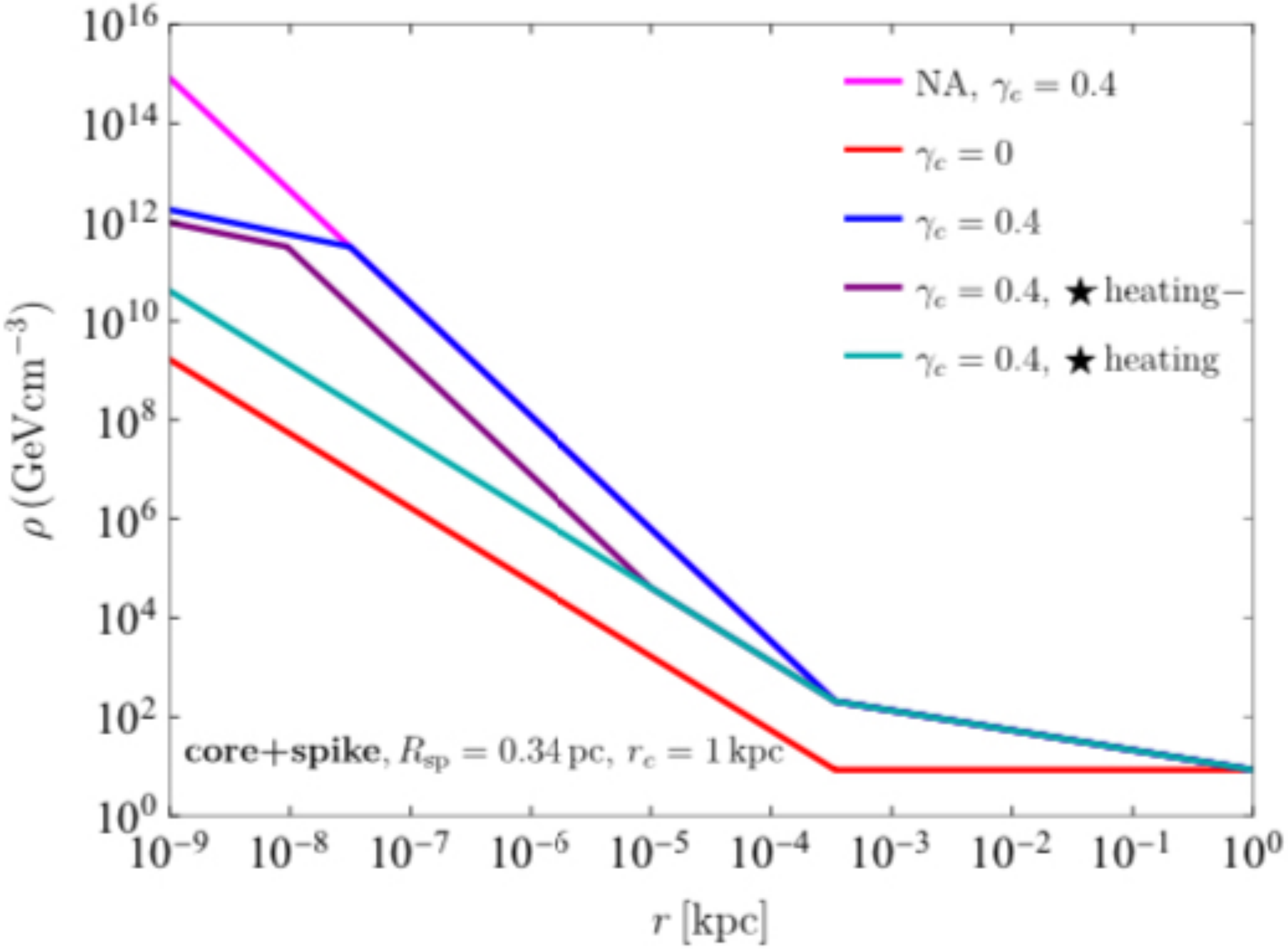
Even if spike is formed, the DM spike may be significantly softened due to DM particle scattering by stars and capture in the SMBH, resulting in a equilibrium spike solution as low as $\gamma_{\rm sp} = 1.5$.

Gnedin & Primack, 2004

Less Stellar heating

DM spike follows GS profile for $r < 0.01pc$ and $\gamma_{\rm sp} = 1.5$ for larger radius.
Because of paucity of stars in the inner miliparsec region.





GS : Gondolo - Silk profile ($\gamma_{sp} = 7/3$)

★ Heating : stellar heating ($\gamma_{sp} = 1.5$)

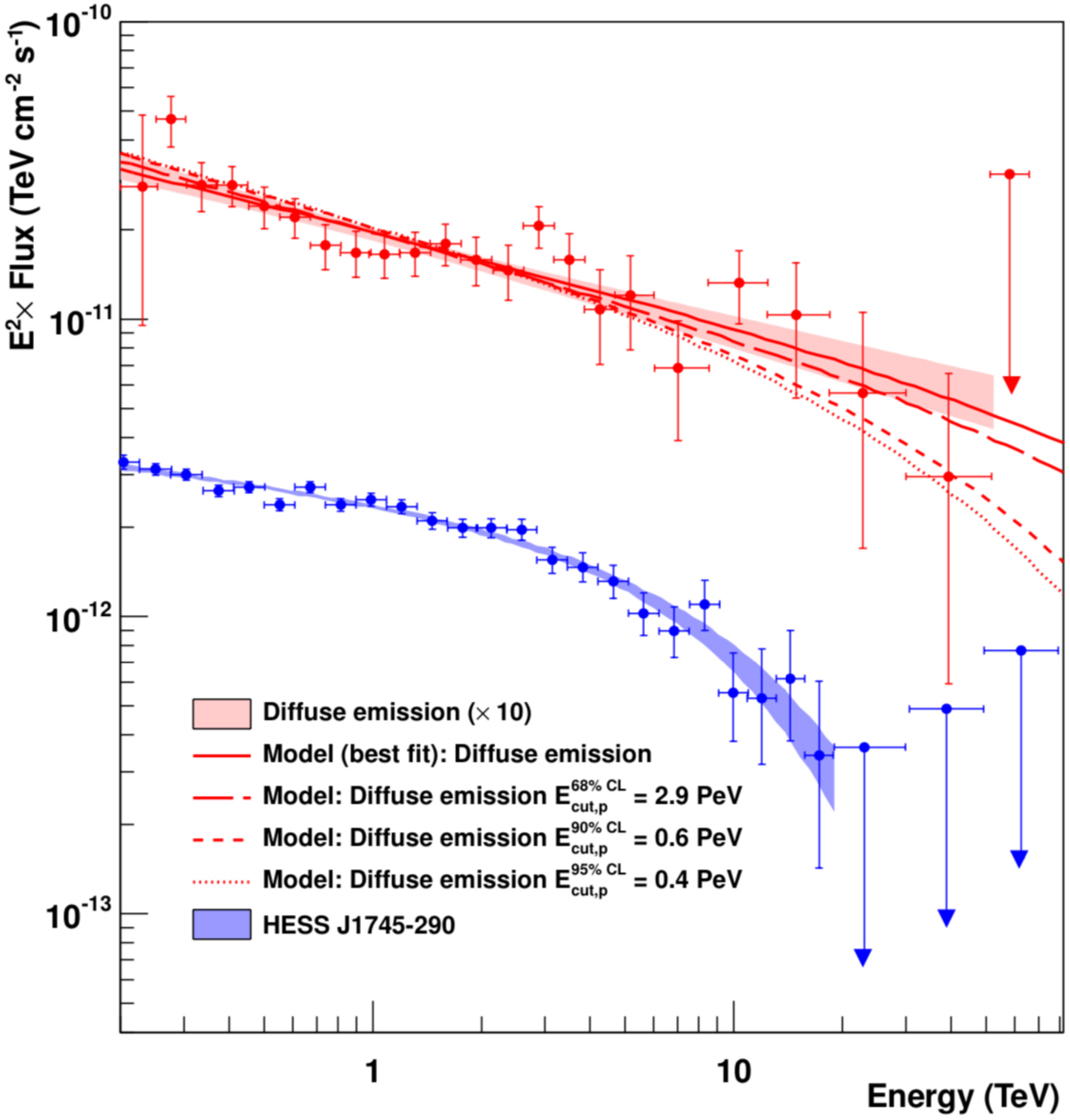
★ Heating - : less stellar heating ($\gamma_{sp} = 1.5$; r > 0.01 pc)

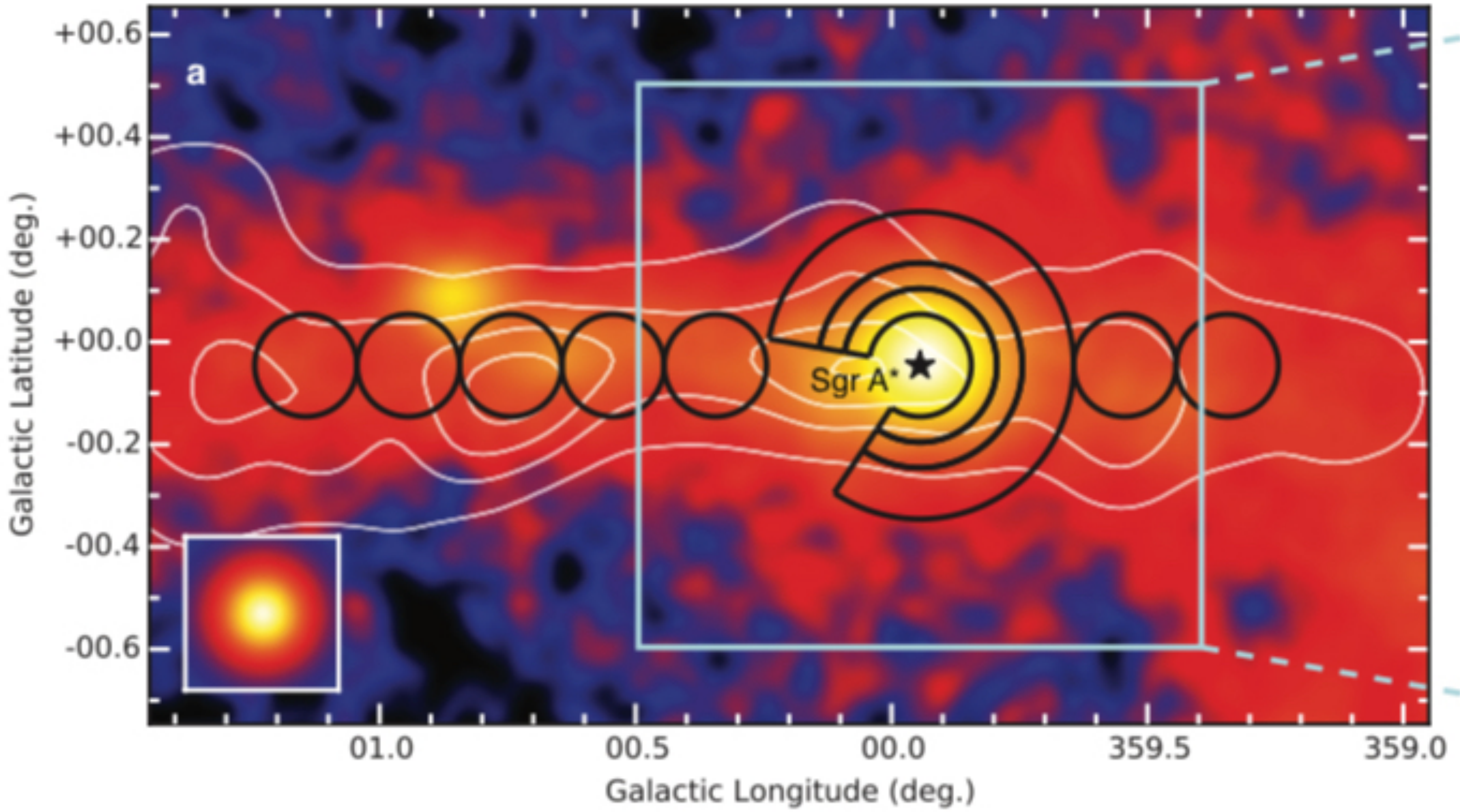
BM : Bertone Merritt

$$R_{sp}(t) = R_{sp}(0)e^{-\tau/2(\gamma_{sp}-\gamma)}$$

arXiv:2303.12107
Balaji, Sachdeva, Sala, Silk

Data used in analysis





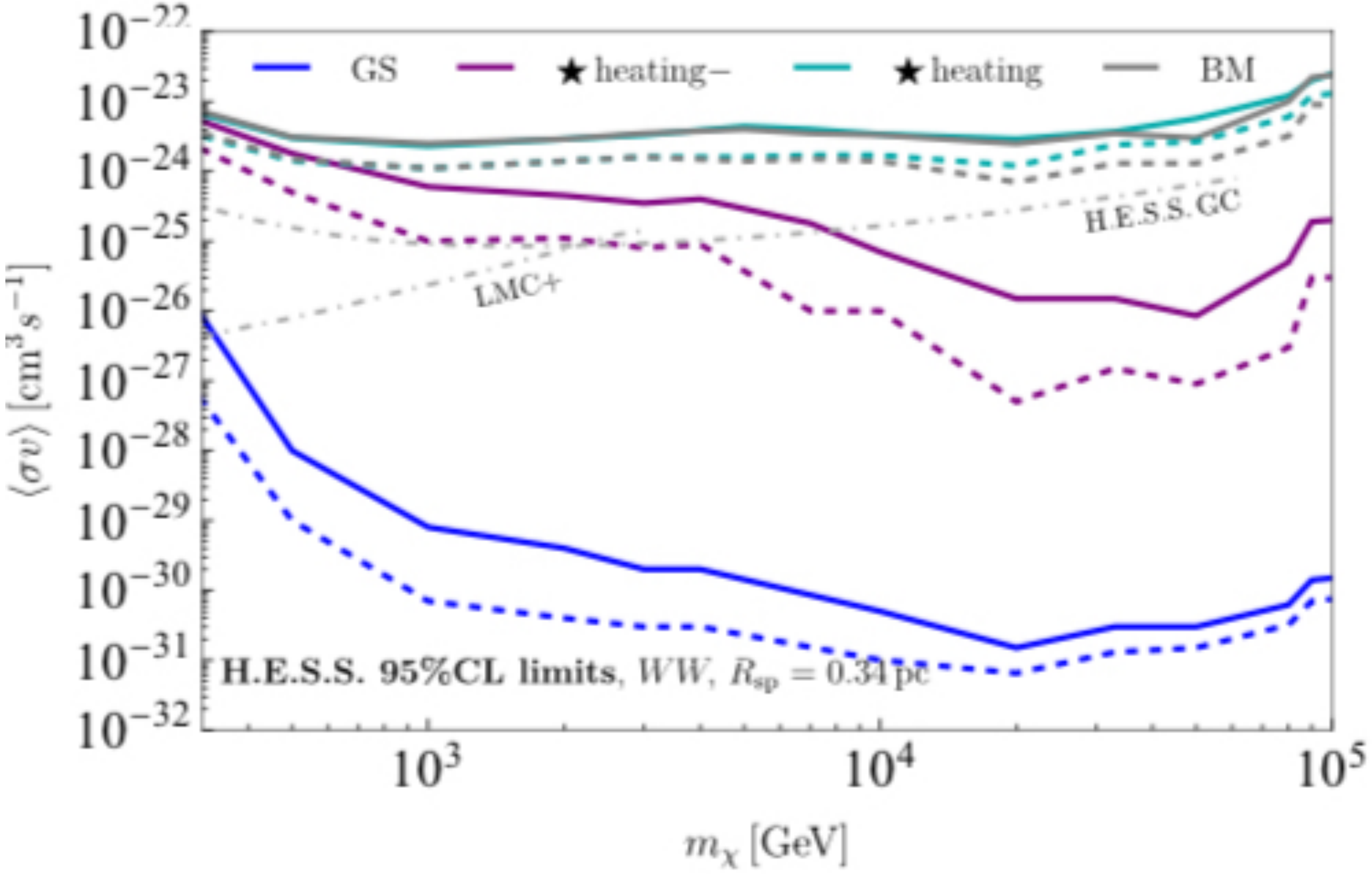
The spectrum of the central source is extracted from a circular region of radius 0.1° centered on Sgr A* (SuperMassive Black Hole of MilkyWay).

H.E.S.S Collaboration: arXiv 1603.07730, Nature

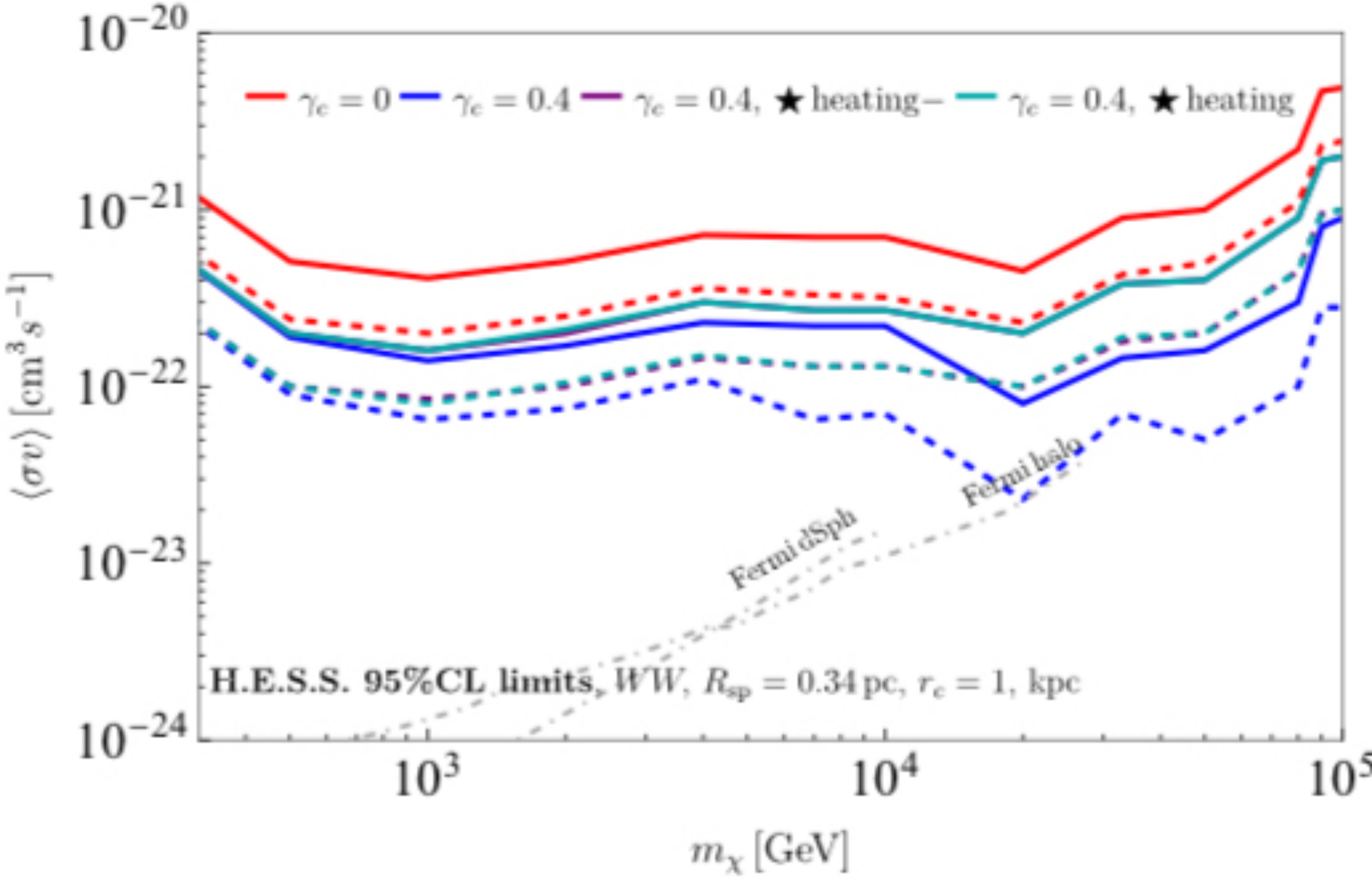
Upper limits from H.E.S.S.

Requirement that DM-induced signal do not overshoot the data.

$$M_{SgrA*} = 4.3 \times 10^6 M_\odot \qquad t_{BH} = 10^{10} \text{yrs}$$



NFW + spike



Core + spike arXiv:2303.12107

Balaji, Sachdeva, Sala, Silk

Caveats and counter-studies

Existence of DM spikes is however debated because of dynamical effects.

- If the BH sits away from center, spike would be less prominent. Spike with core profile is mostly immune to this

Ullio Zhao & Kamionkowski 2001

- Mergers between halos containing SMBH can destroy spikes. But GAIA data suggests last merger happened billion years ago leading to regeneration of spike if destroyed.

arXiv: 2211.01006, MNRAS

Observations of spikes so far!

- The monitoring of the orbits of the S stars within 1 arcsec of the central BH, can provide a unique window on the DM distribution at the Galactic Centre (GC) in the inner region of the MW.

- Recent study by GRAVITY collaboration constrains extended mass component inside the S2 apocenter to be less than $3000 M_{\circ}$ which constrain spike's size less than 10 pc.

GRAVITY Collaboration : 2212.05664, A&A

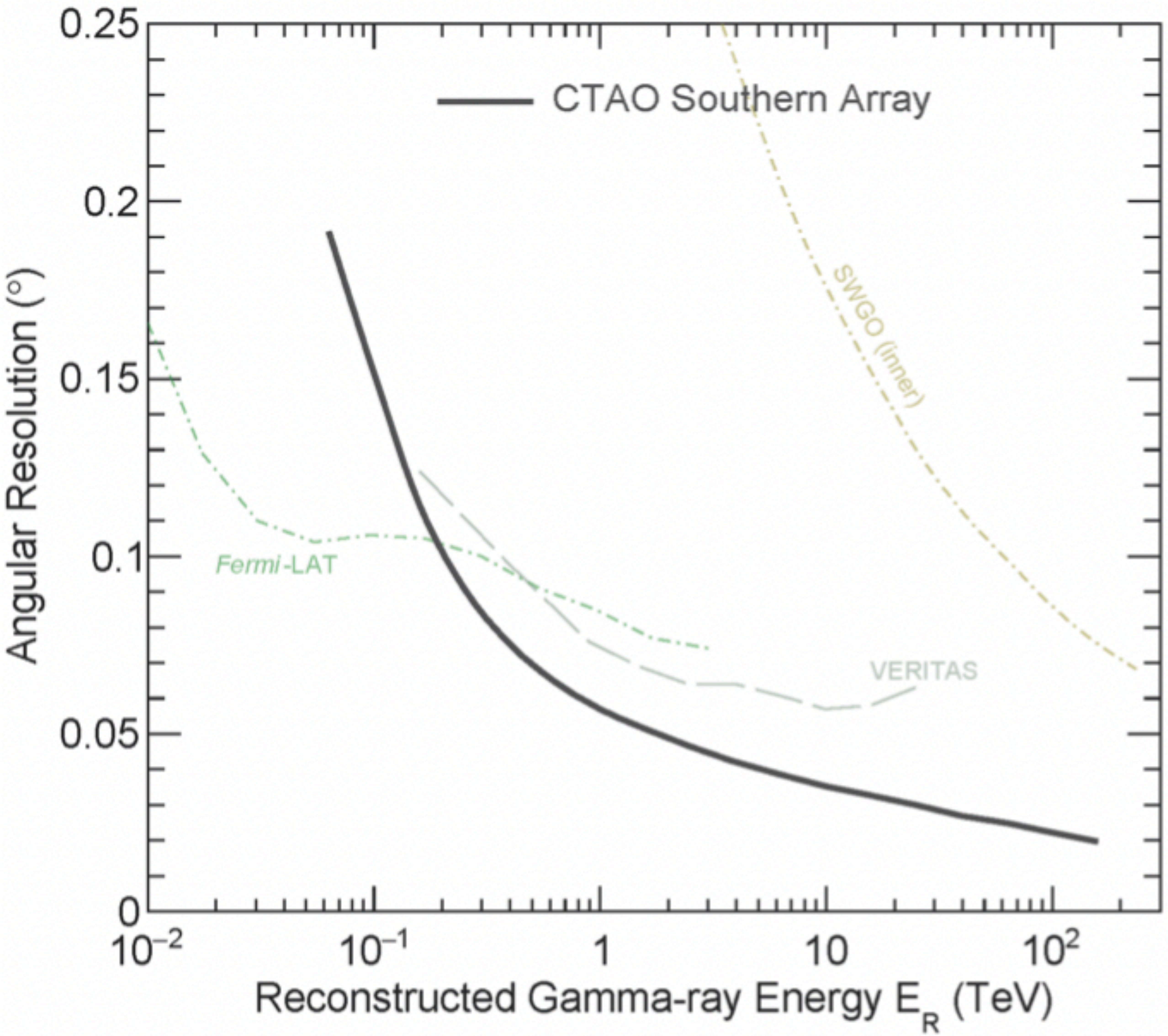
- Chan and Lee, 2022 reports existence of spikes around two stellar mass BHs.

arXiv: 2212.05664, ApJL

There is no conclusive evidence in favour or against such spikes. This is primarily due to the small size of the regions involved.

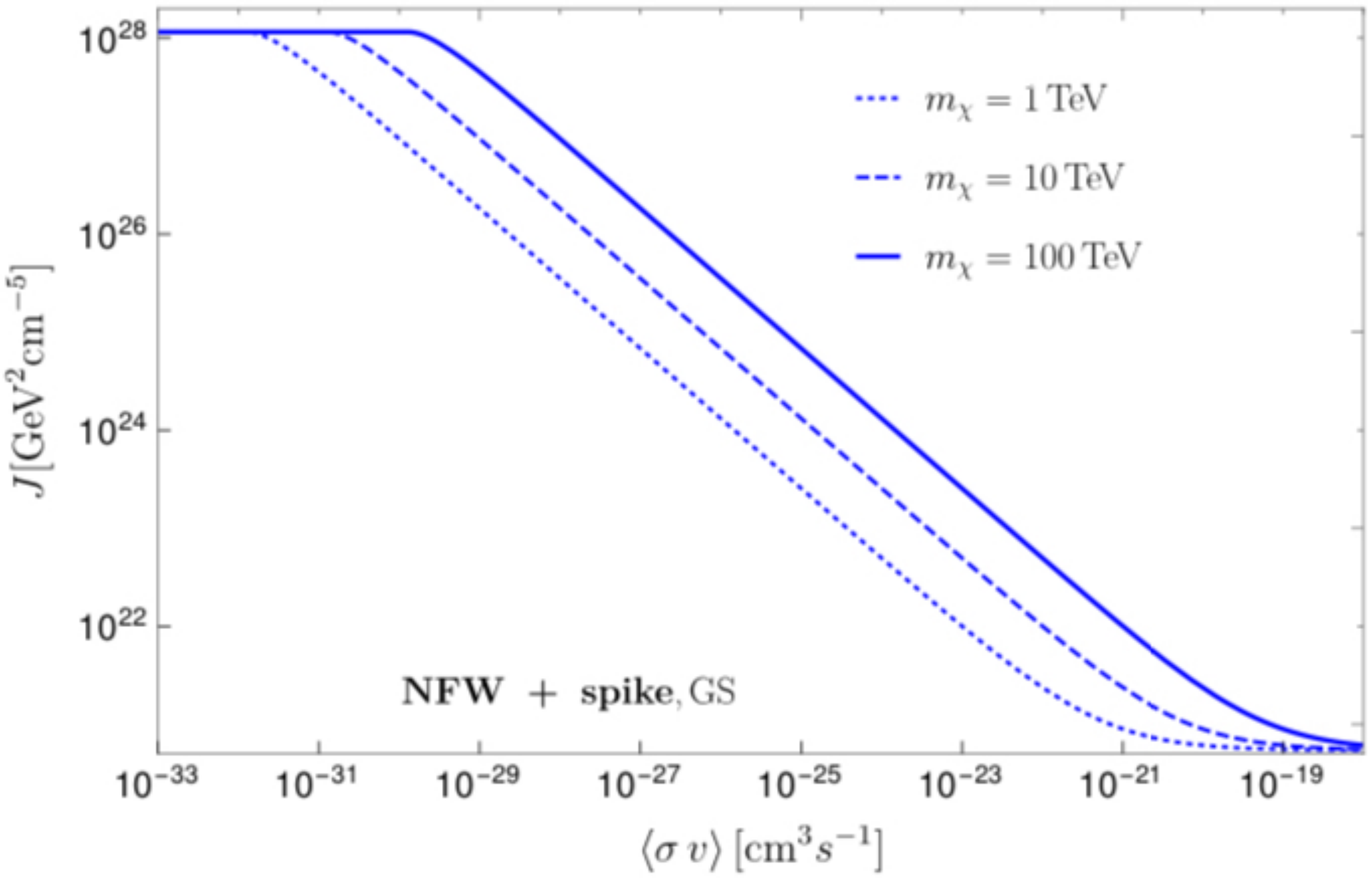
Conclusion

- Strong motivation to study DM spikes in more detail.
- Obtained constraints on s-wave DM up to 100 TeV from H.E.S.S observations of Galactic Center.
- Detection of a DM spike with $\rho(r) \propto r^{-\gamma}$ where $\gamma \geq 2$ in milky way is promising.
- Especially with upcoming observations of Galactic center from (Cherenkov Telescope Array) CTA because they will have better angular resolution to resolve DM spike encompassing inner 0.34 pc of Galactic Center.



J factor

$$\frac{d\Phi}{dE_\gamma} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} J$$



For spikes, J factor depends on DM parameter space and limits are not linearly proportional to J factor.

arXiv:2303.12107
Balaji, Sachdeva, Sala, Silk