Dark Matter annihilations from a density spike in Milkyway galaxy

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Dark Matter and its probes

Dark Matter

↓

Particle or Modified Gravity

↓

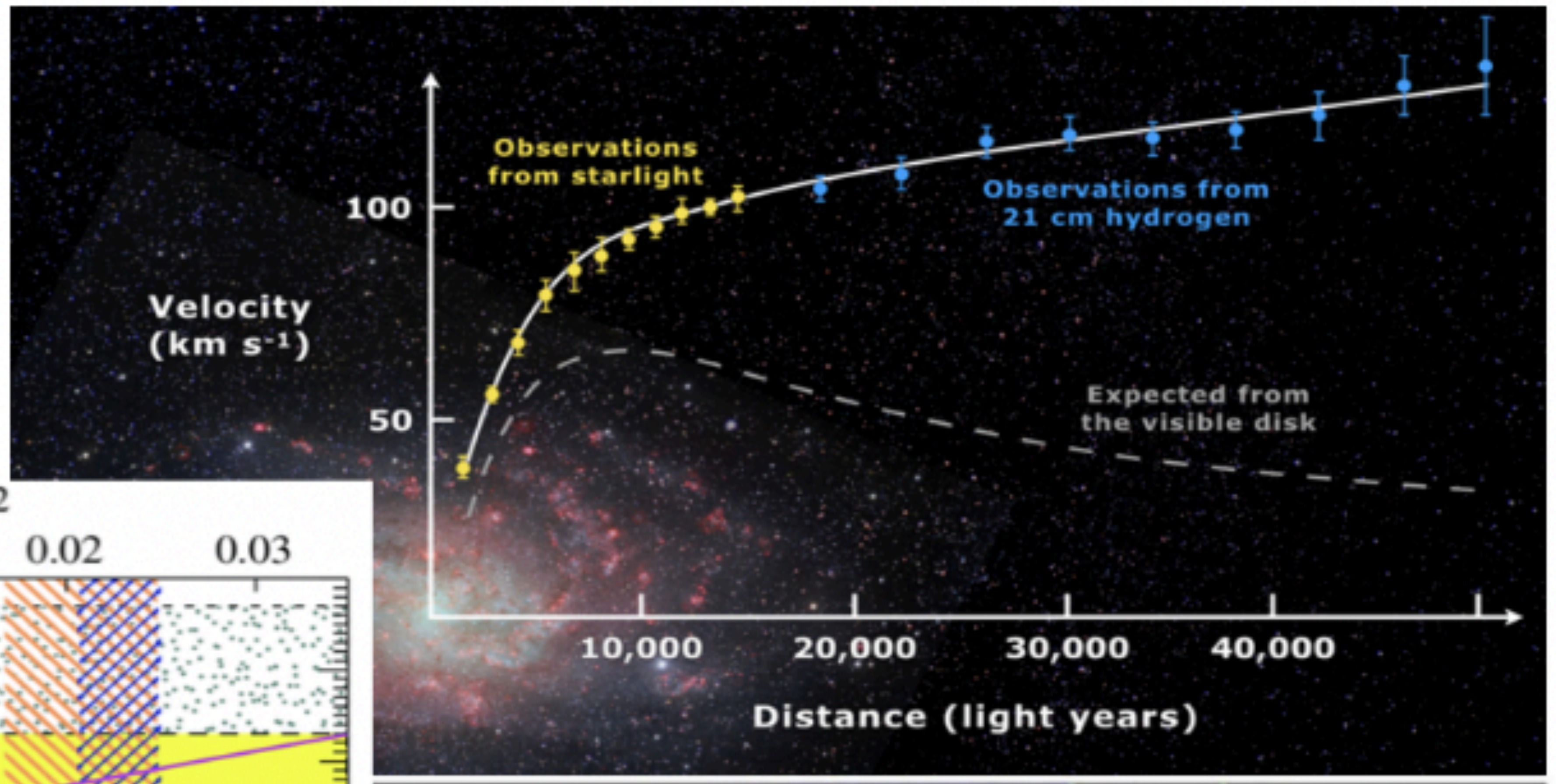
Is it Fermion, Boson? Quantum Nos.?
Does it interact with SM?

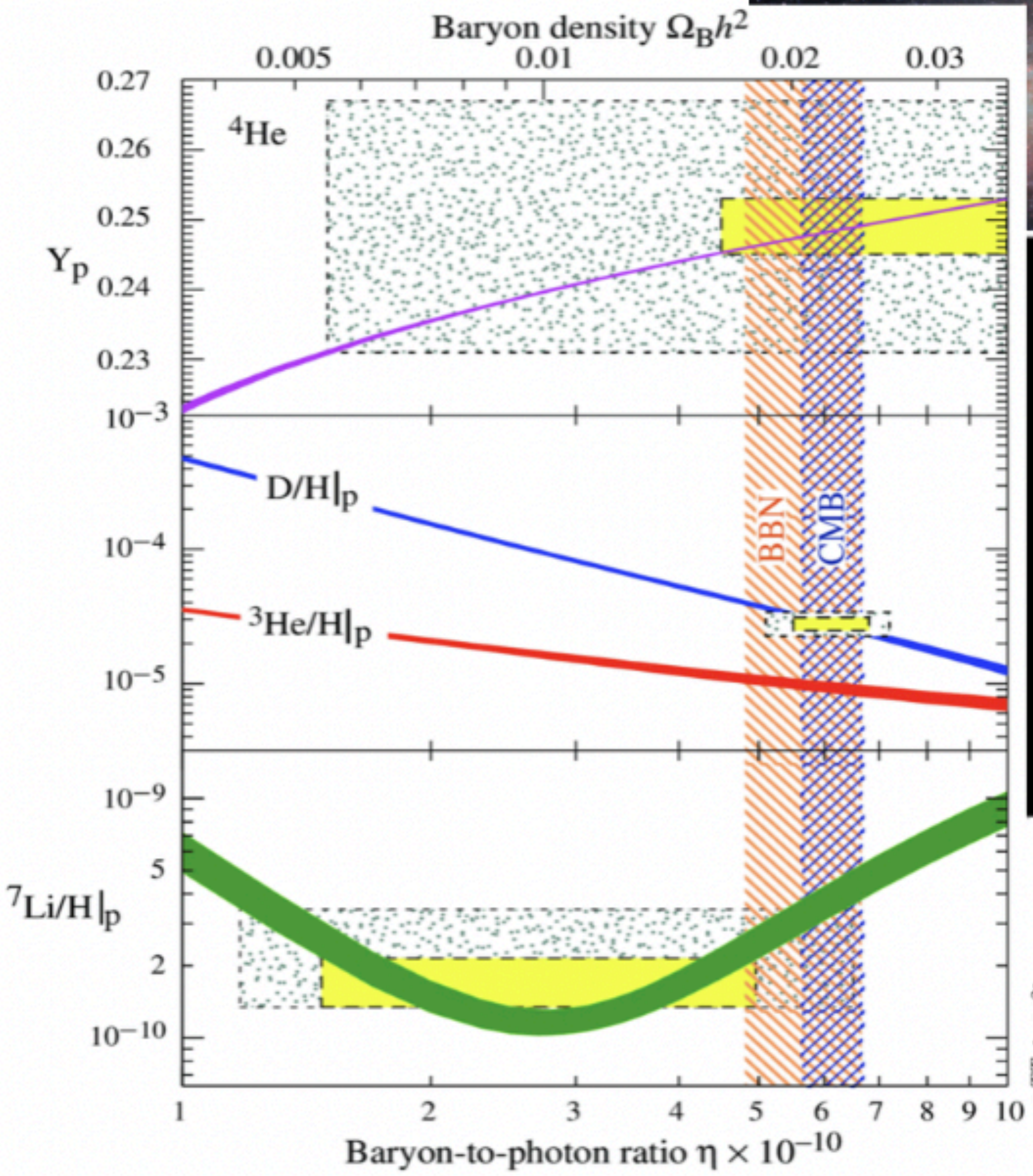
↓

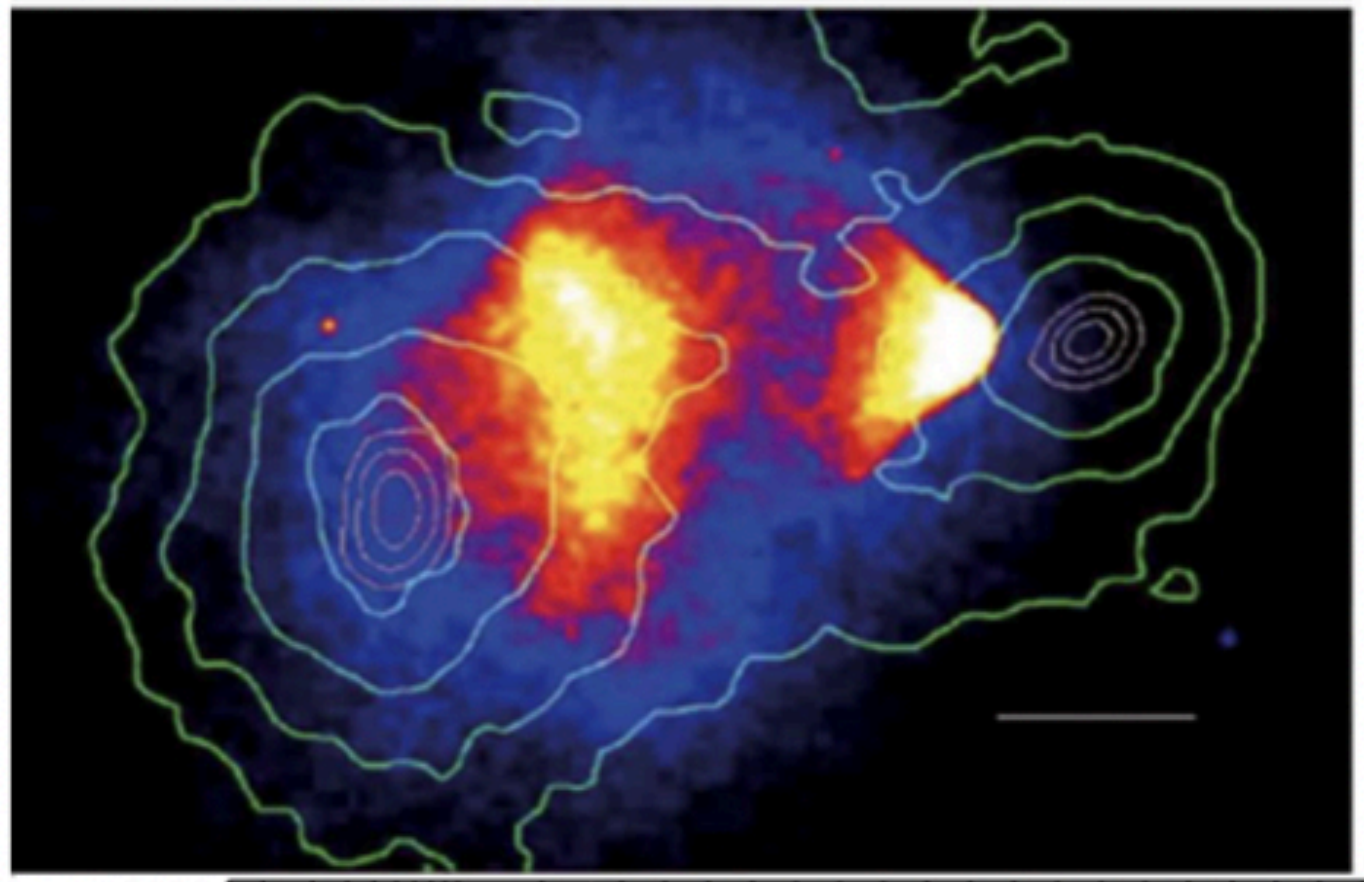
DM Searches:
Astrophysical observations, Colliders signatures
Direct detection experiments etc.

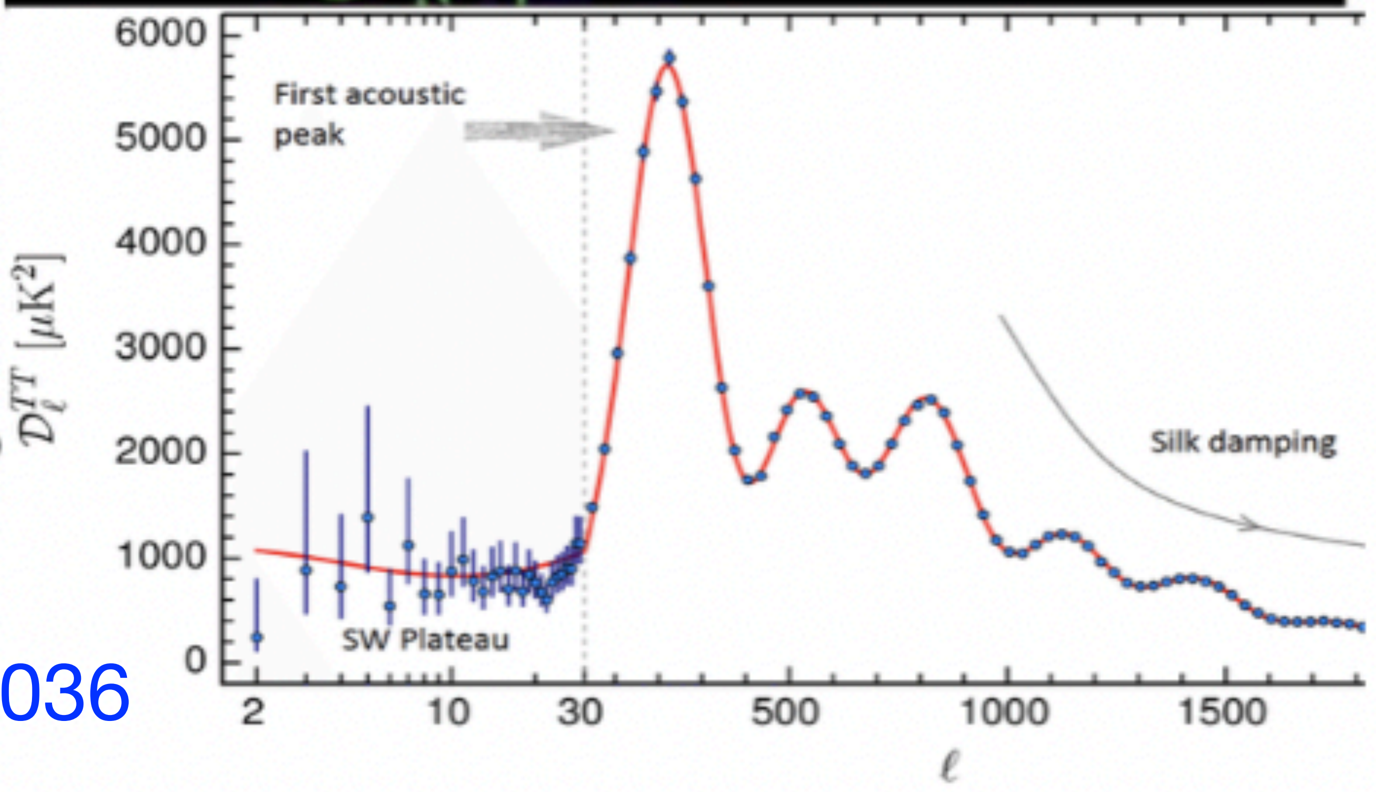
Standard Model Inconsistencies

Tiny neutrino masses, Anomalous magnetic moment of the Muon, Baryon asymmetry, Hierarchy problem, strong CP problem - Dark Matter candidate

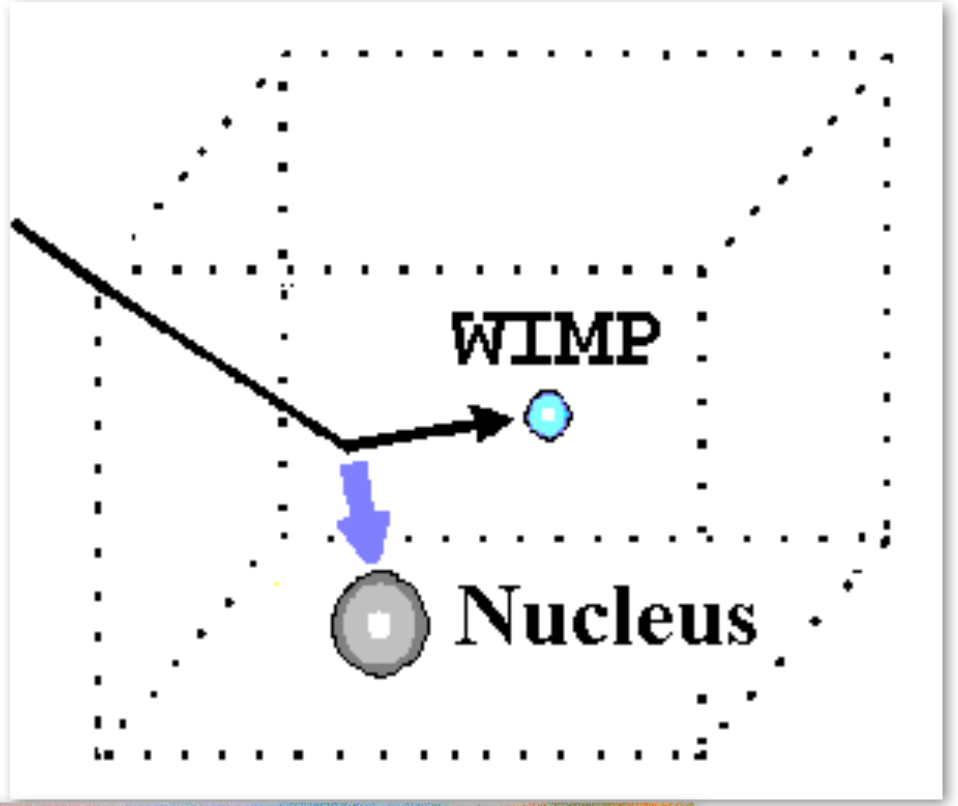


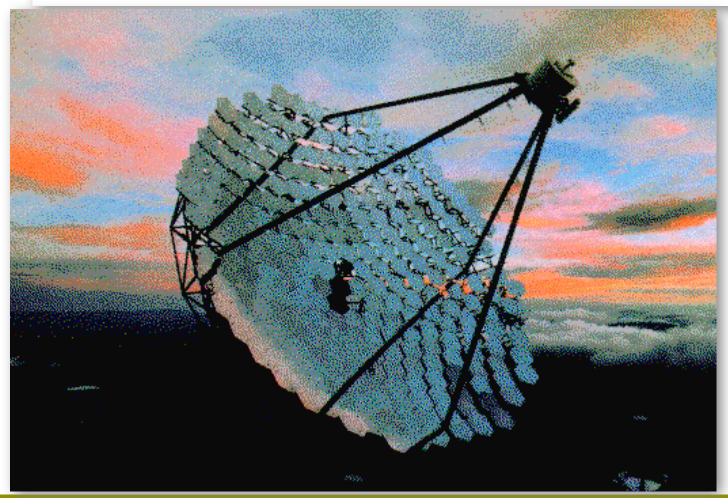






astro-ph/0601514v2,wikipedia,1612.05036





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

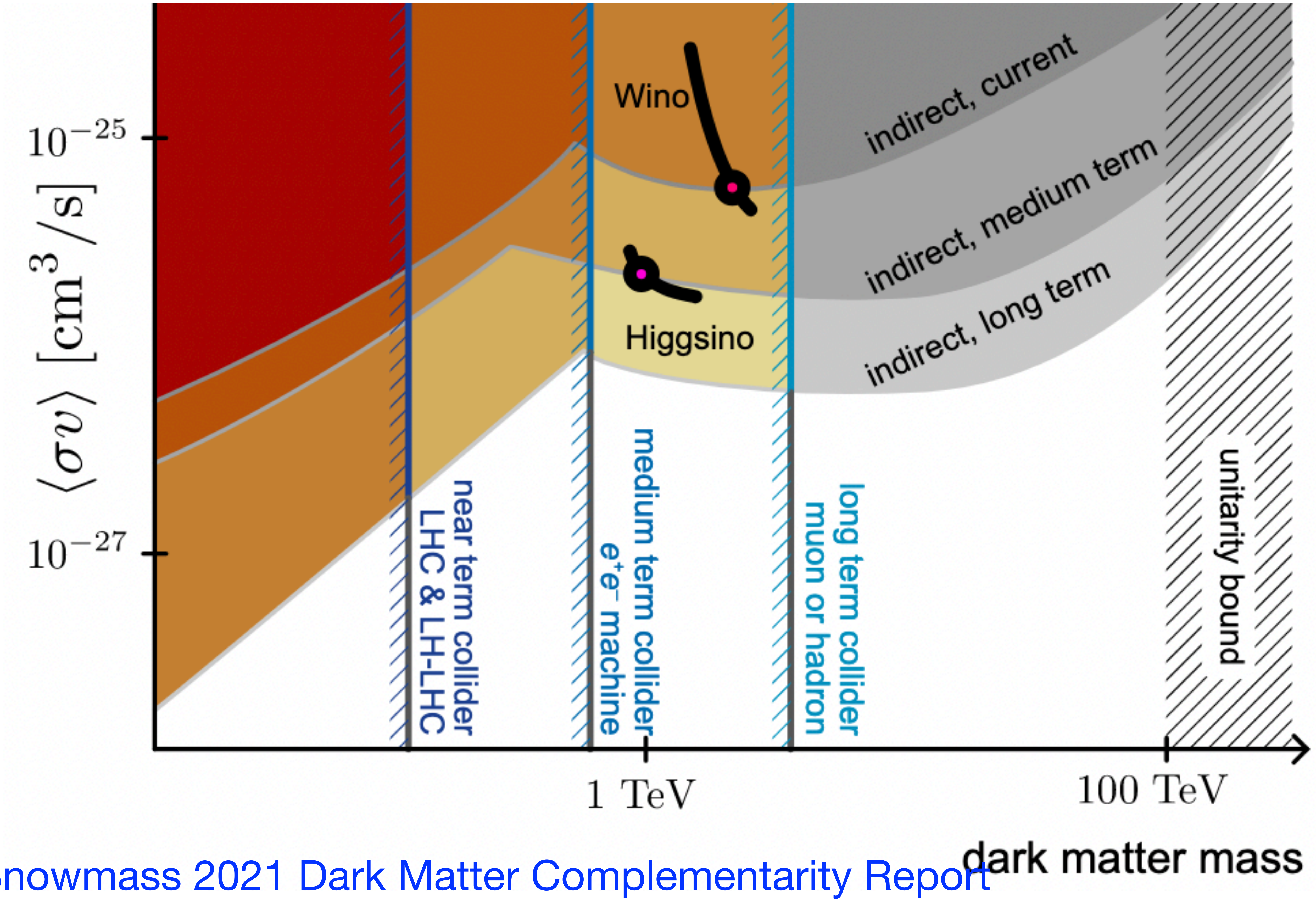
Direct Detection

Momentum transfer to detector through elastic scattering

Indirect Detection

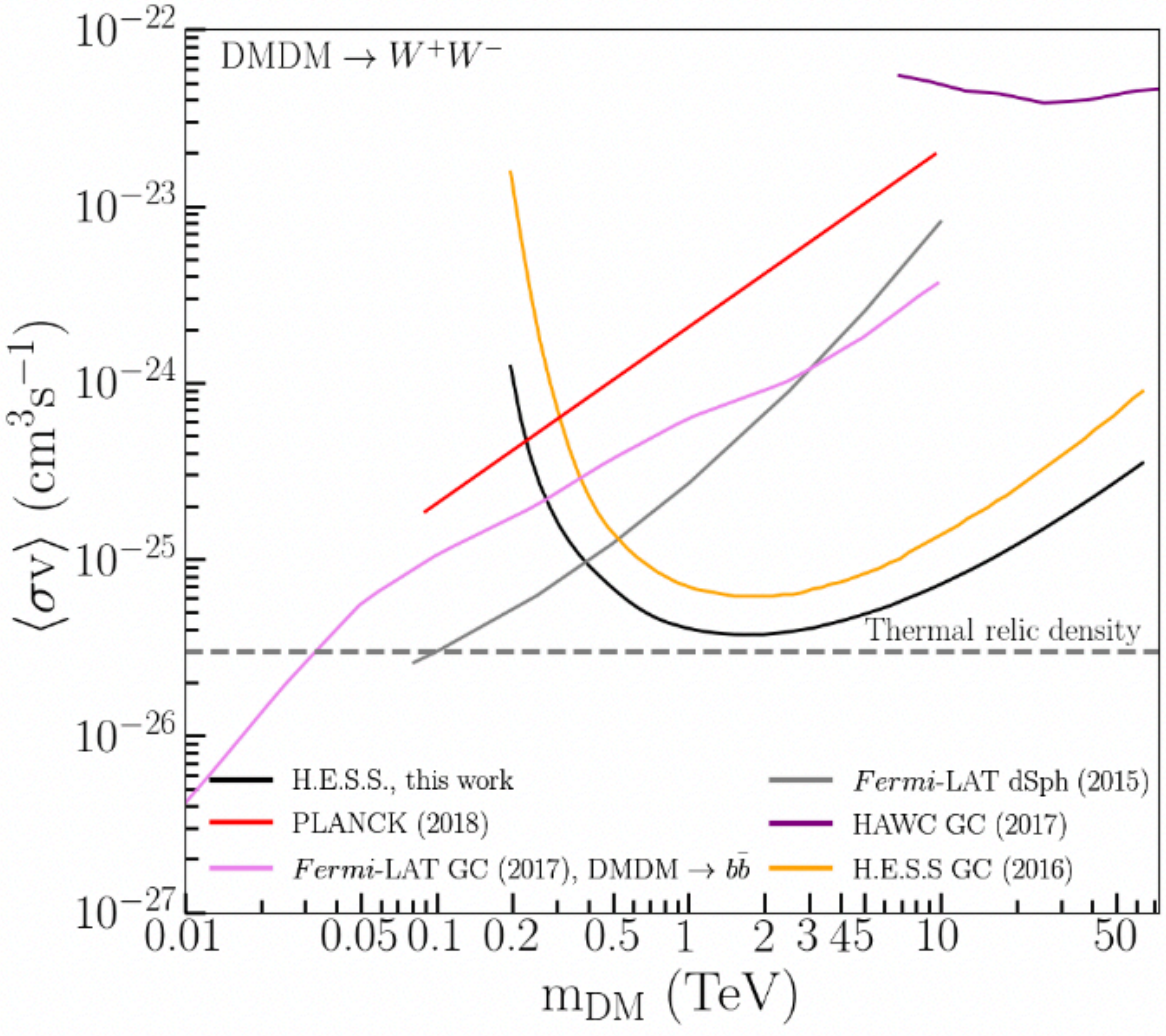
Simulations predict that the GC contains very high densities of dark matter (and high annihilation rates)

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

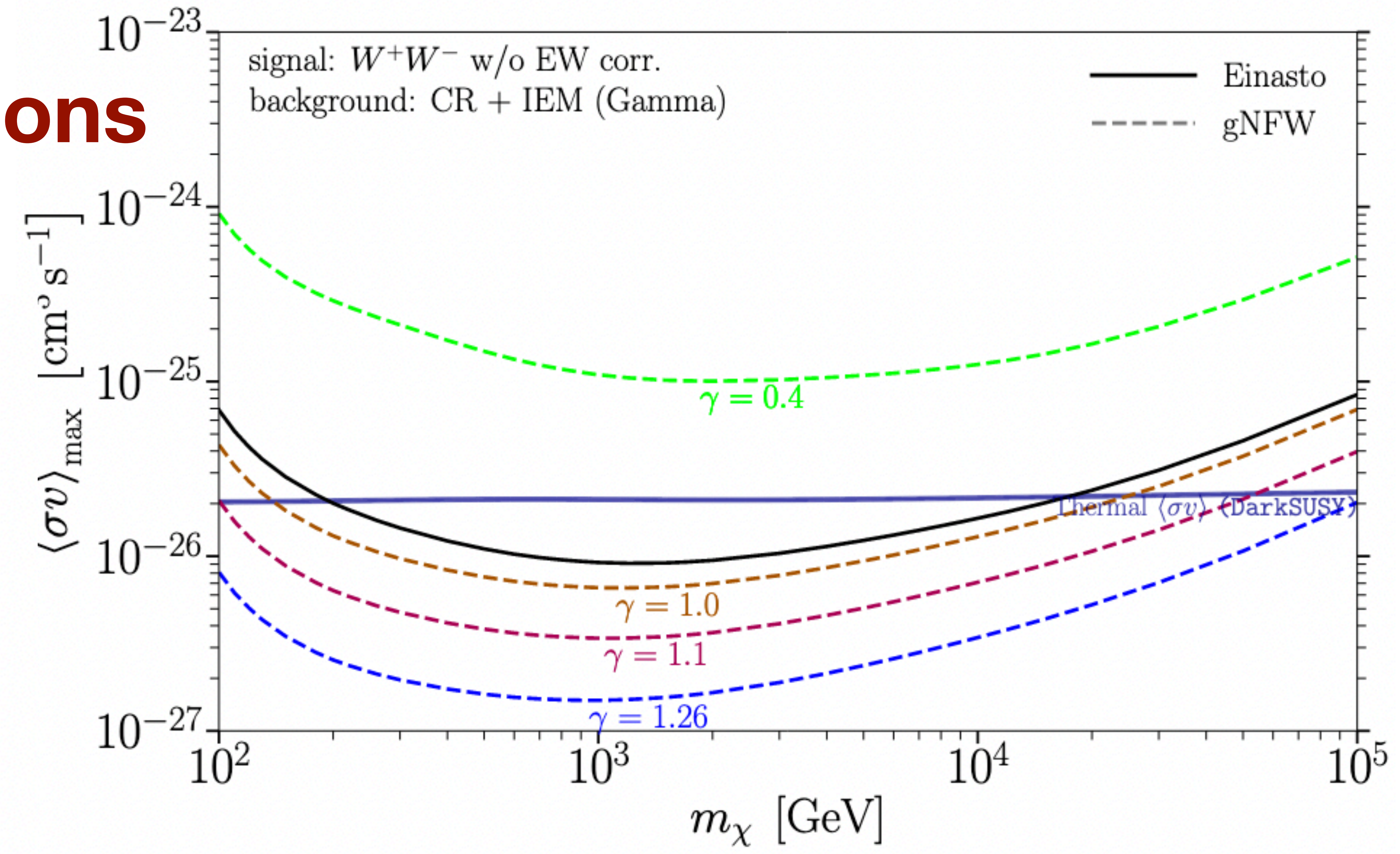


Snowmass 2021 Dark Matter Complementarity Report

Existing limits and projections on DM annihilations



arXiv: 2207.10471 (HESS collaboration)



arXiv: 2007.16129 (CTA consortium)

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

$$\rho(r, \gamma_c) = \begin{cases} \rho_s \left(\frac{r_c}{r_s}\right)^{-\gamma_c} \left(1 + \frac{r_c}{r_s}\right)^{\gamma_c - 3} & r < r_c \\ \rho_s \left(\frac{r}{r_s}\right)^{-1} \left(1 + \frac{r}{r_s}\right)^{-2} & r \geq r_c \end{cases}$$

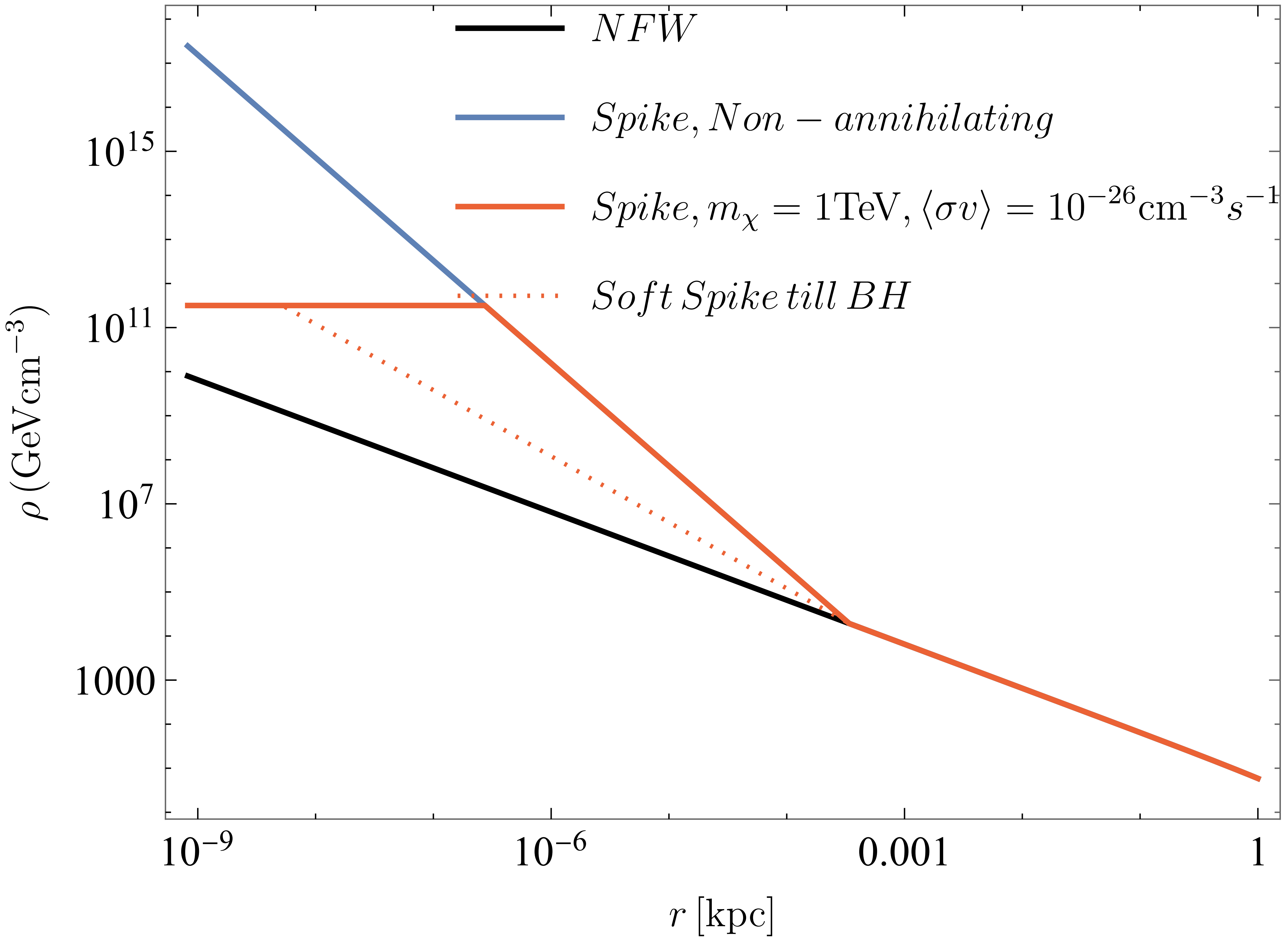
DM Spikes and Indirect Detection

- Indirect detection promising avenue to look for DM particles.
- 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

Gondolo & Silk 1999

- DM spikes can lead to strong annihilation signals.



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

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 $M_f(r_f) \approx M_{\mathrm{BH}}$

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

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

Ideal DM spike profile

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

where $\rho_{\text{sat}} = \dfrac{m_\chi}{\langle \sigma v \rangle t_{\text{BH}}}$, $\gamma_{\text{sp}} = \dfrac{9-2\gamma}{4-\gamma}$ and R_s is Schwarzchild radius.

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

Caveats and counter-studies

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

- If the growth of BH is too fast, $\rho(r) \propto r^{-4/3}$.
- Mergers between halos containing SMBH can destroy spikes, $\rho(r) \propto r^{-1/2}$.
- DM scattering off stars can smooth down the spike to $\rho(r) \propto r^{-3/2}$.

- DM self-interactions can enhance the spike.
- Dissipative infall of baryons at the center of a galaxy can be modeled as an adiabatic contraction process and has been shown to enhance the DM density

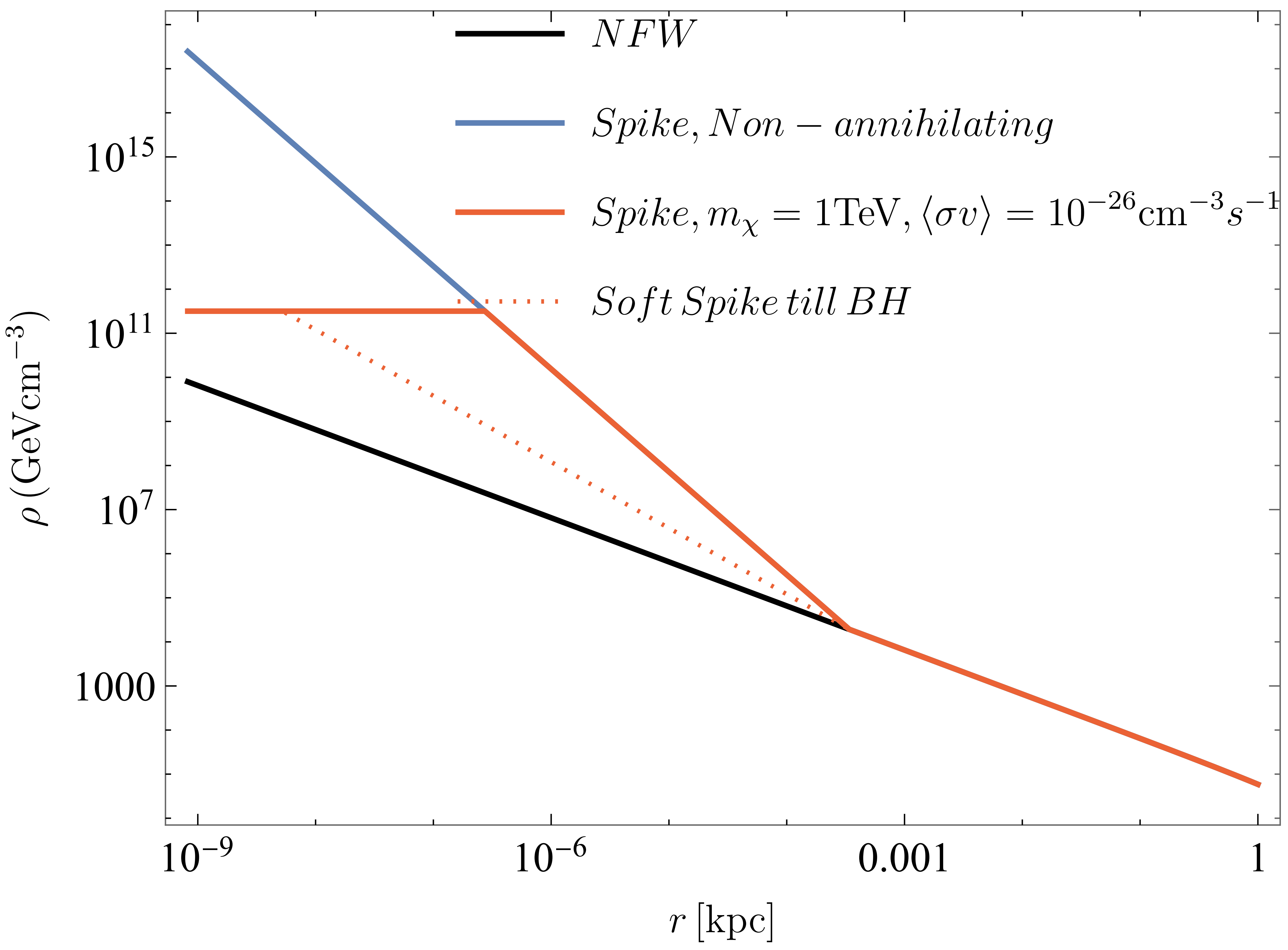
Realistic DM Spike profile

Spike with Cored profile

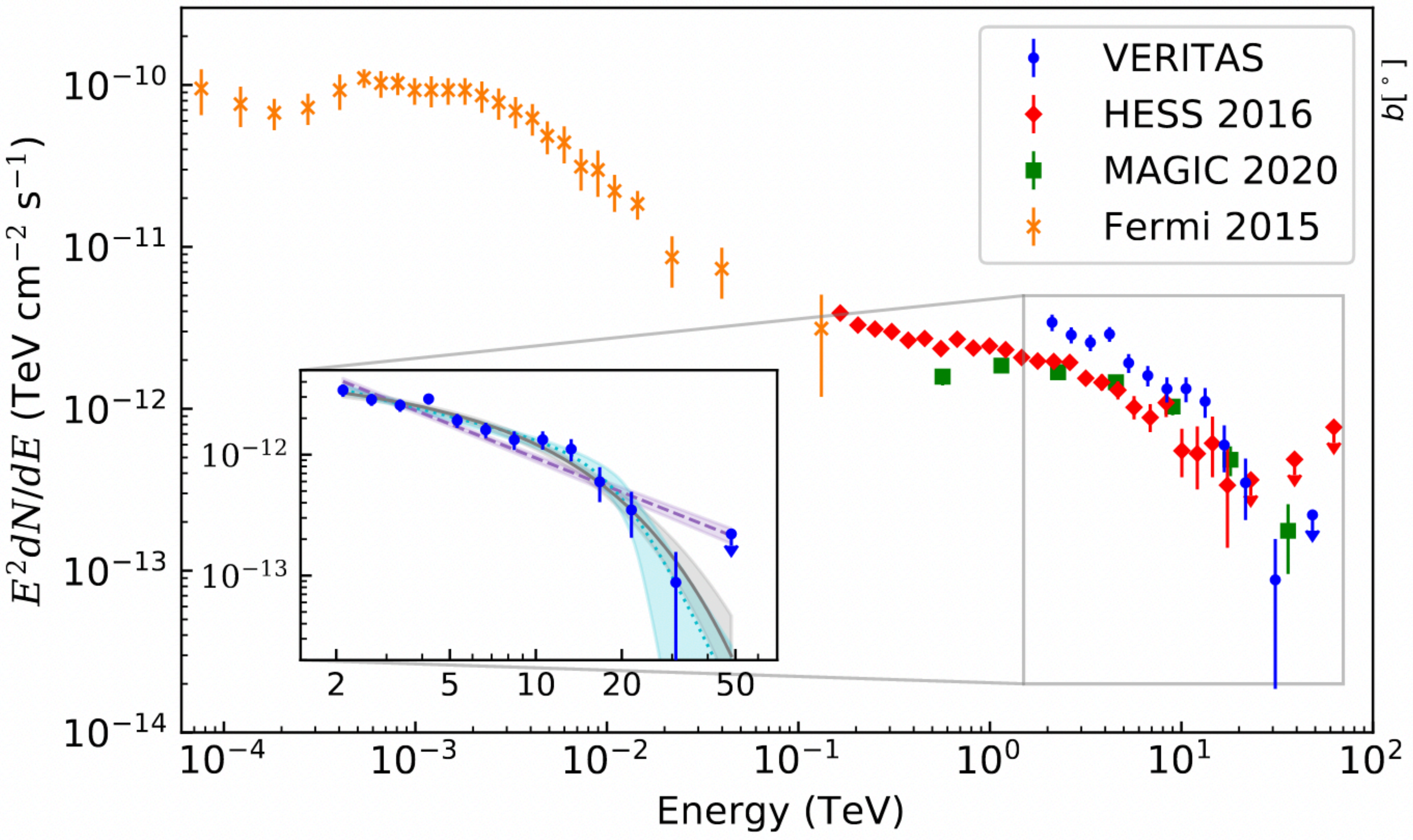
Many observations favor a cored profile. Studies incorporating the affect of baryonic matter into N-body simulations found that the DM density distribution at small radii is a constant-density “core”.

Soft Spike

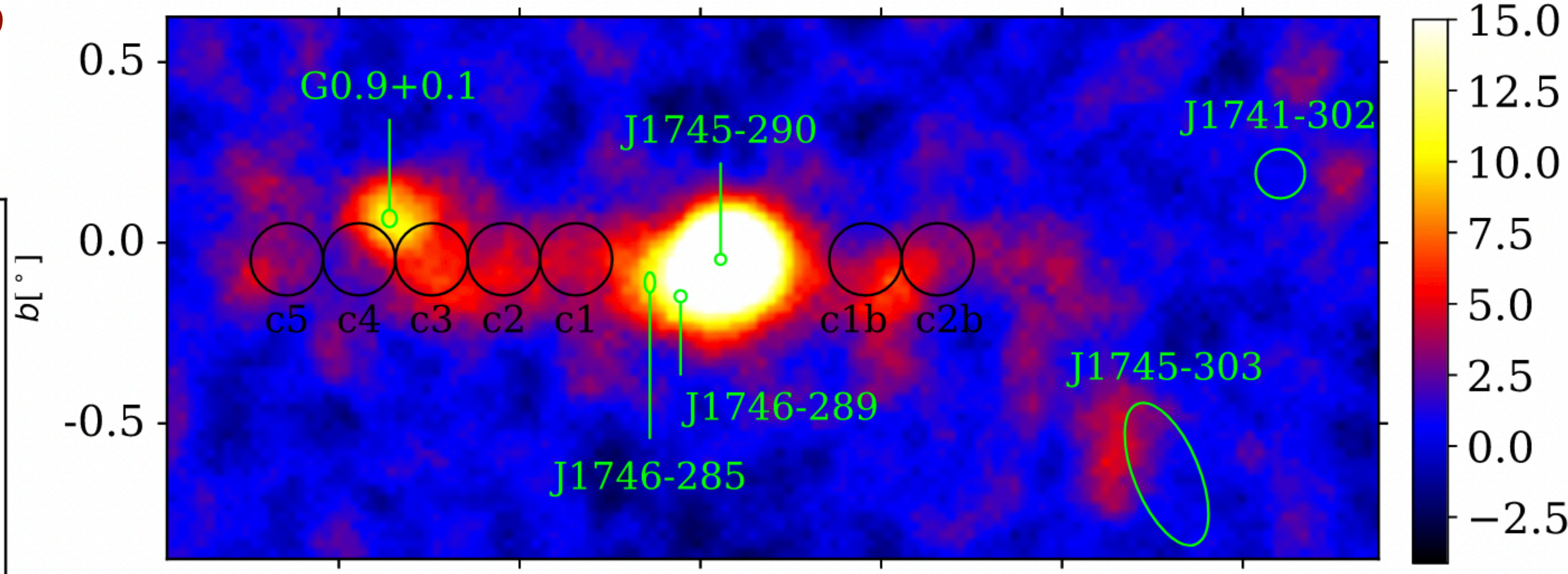
Even if spike is formed, the DM spike may be significantly softened due to DM particle scattering by stars and capture in the SMBH, resulting in a equilibrium spike solution as low as $\gamma_{sp} = 1.5$.



Data used in analysis



arXiv: 2104.12735

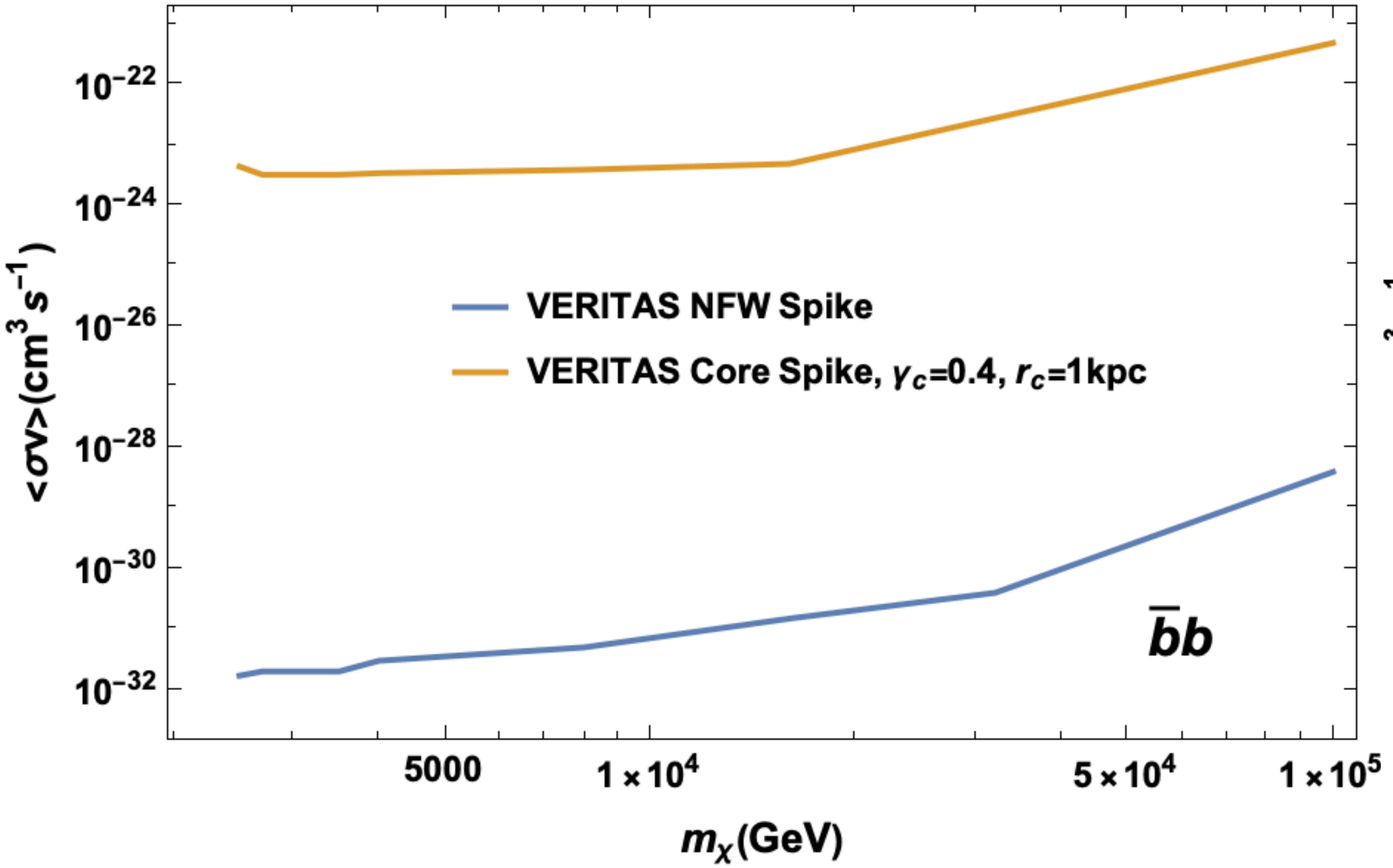


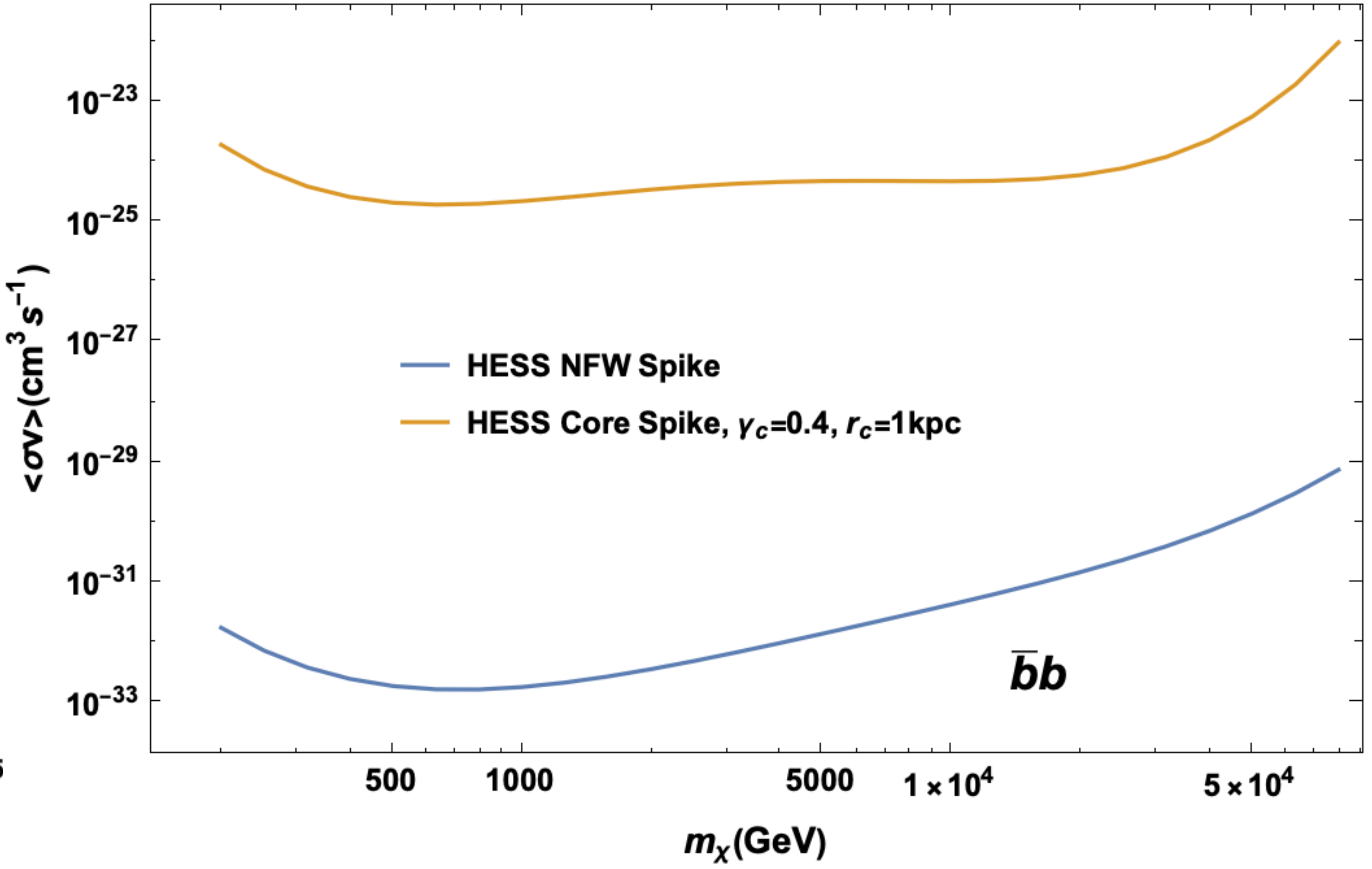
The spectrum of the central source is extracted from a circular region of radius 0.1° centered on Sgr A* (SuperMassive Black Hole of MilkyWay).

Upper limits from VERITAS, H.E.S.S.

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

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





Conclusion

- Strong motivation to study DM spikes in more detail.
- Extremely stringent constraints on that exclude s-wave DM up to 100 TeV from H.E.S.S observations of Galactic Center.
- But requirement is spike effectively formed and not destroyed.
- 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.
- Study with neutrinos from such annihilations is also being done.