Instituto de Física Teórica UAM-CSIC

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Multi-TeV Dark Matter density in the inner Milky Way halo: spectral and dynamical constraints

arXiv 2307.06823

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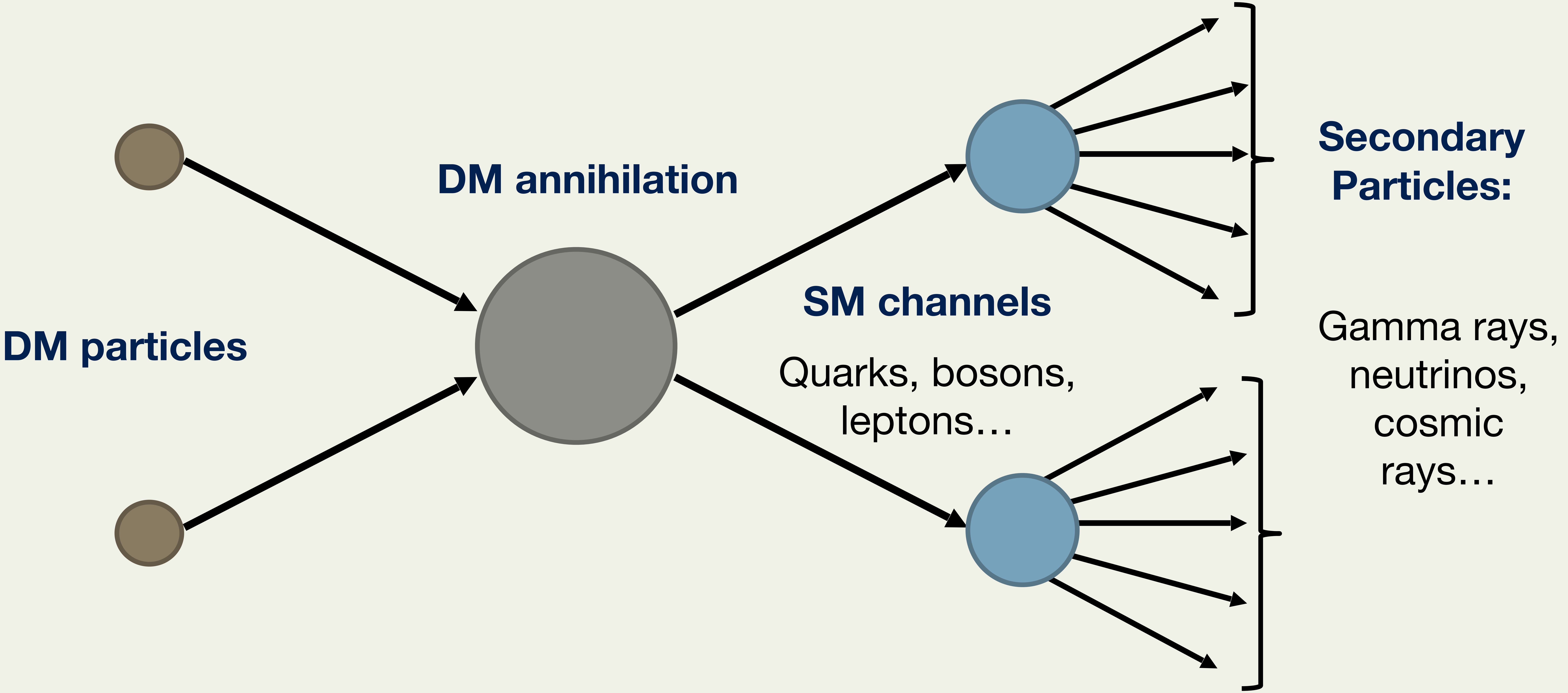
Cosmology 2023 in Miramare - 29 August, 2023

Indirect Detection: WIMPS

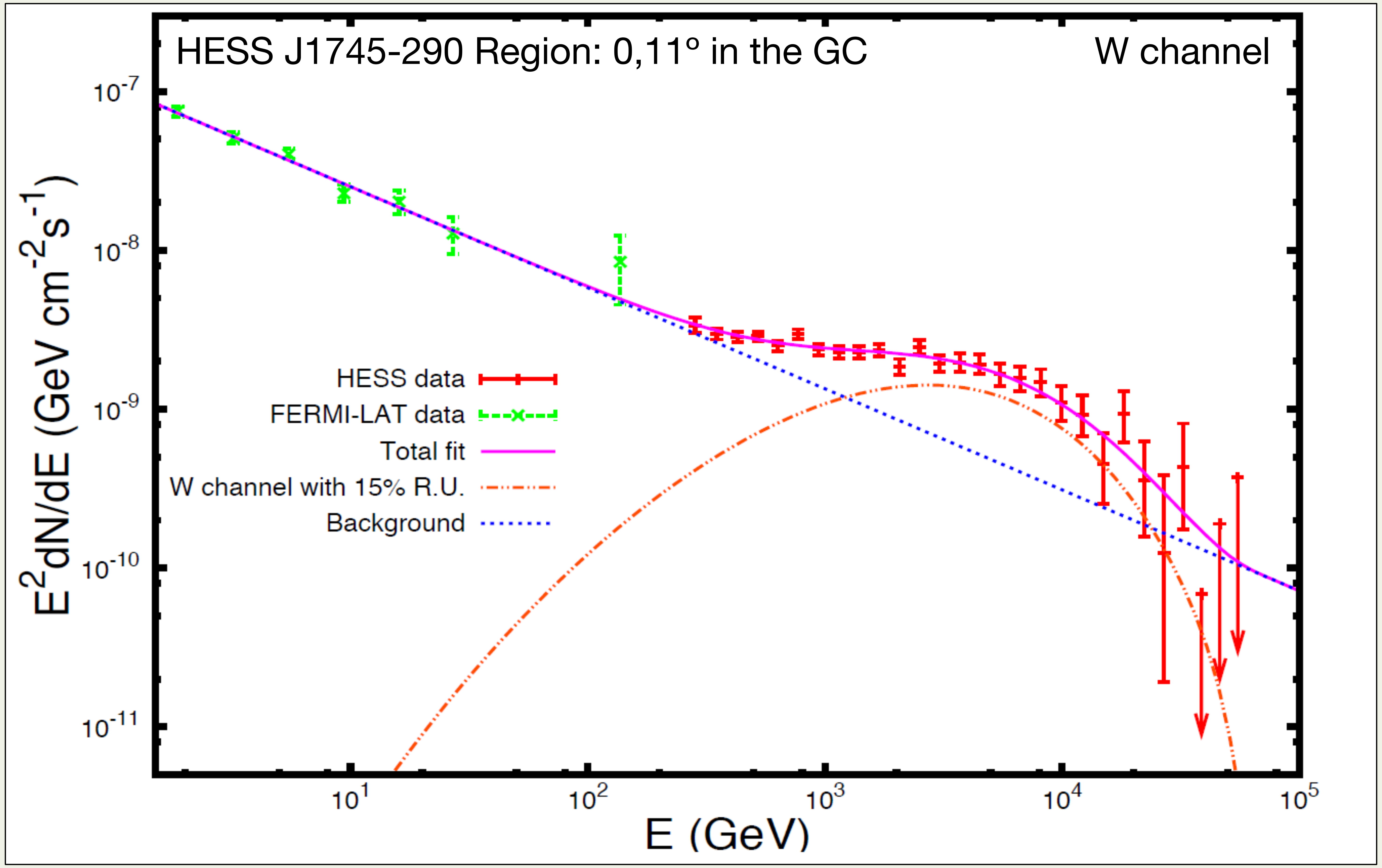
$$\frac{d\Phi_{\rm DM}}{dE} = \sum_{i}^{\rm channels} \frac{\langle\sigma v\rangle_i}{2}\frac{dN_i}{dE}\frac{\Delta\Omega\langle J\rangle_{\Delta\Omega}}{4\pi m_{\rm DM}^2}$$



Motivation: TeV cut-off detected by HESS

Previous works on the DM hypothesis:

- A. V. Belikov et al., Phys.Rev. D (2012): *Study of the gamma-ray spectrum from the Galactic Center in view of multi-TeV dark matter candidates*
- J. A. R. Cembranos et al., JCAP (2013): *Spectral study of the HESS J1745-290 gamma-ray source as a dark matter signal*



Assumptions:

- 2 flux components: DM + Power Law Background
- Thermal relic cross-section

$$\frac{d\Phi_{\rm total}}{dE} = \frac{d\Phi_{\rm DM}}{dE} + \frac{d\Phi_{\rm Back}}{dE}$$

Results:

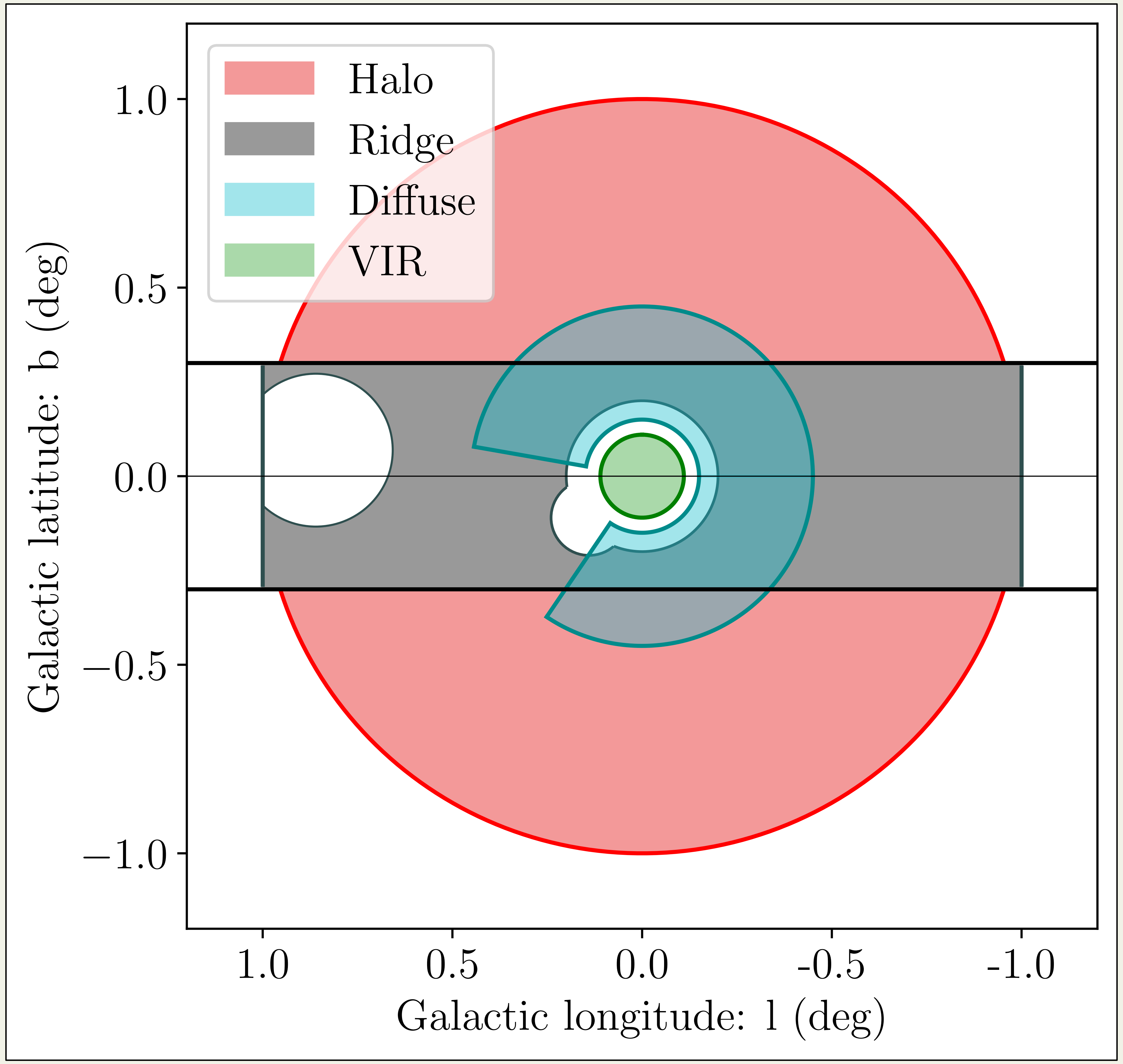
- With this approach, they set constraints on the DM density profile
- Boost factor needed with respect to a NFW profile of $\sim 10^3$
- Possible explanation by an enhancement of the DM density profile?

Outline

- **WIMPS indirect detection with gamma rays**
- **Galactic Centre observed by HESS**
    - 5 Regions Of Interest in the GC
- **Gamma-ray spectral analysis components**
    - 5 regions background model
    - DM density profile
- **Gamma-ray spectral results:**
    - 5 regions J-Factors
- **Constraints on the DM density profile:**
    - Simulations & dynamical observations (external DM profile)
    - S2 star orbit (innermost DM profile)
- **Conclusions**

Galactic Center observed by HESS

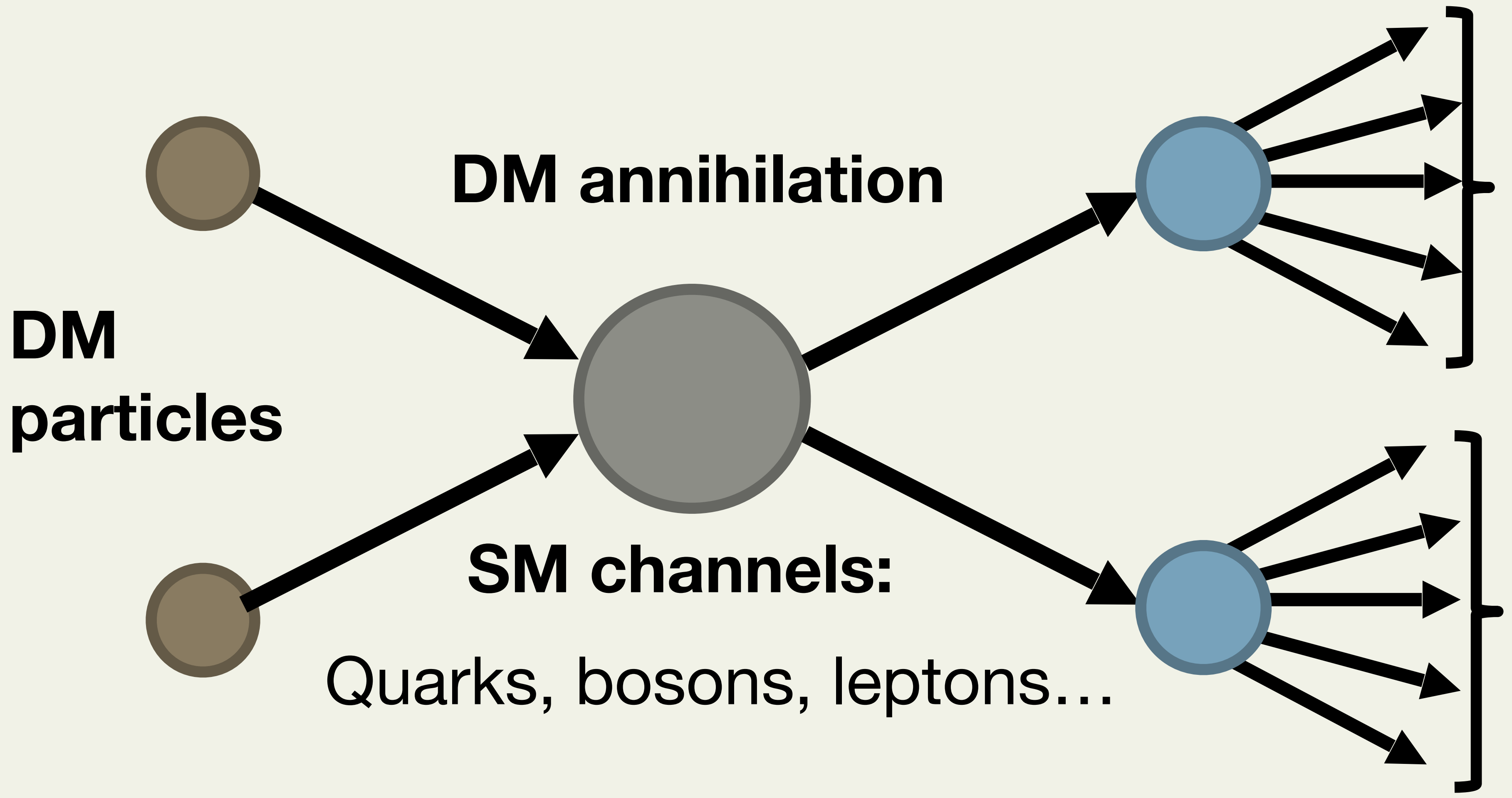
- Very Inner Region (VIR) HESS J1745-290:
  $\theta < 0.11^\circ$
  H.E.S.S. collaboration, Nature (2016)
- HESS Ridge: $|b| < 0.3^\circ, |l| < 1.0^\circ$
  H.E.S.S. collaboration, A&A (2018)
- HESS Diffuse: $0.15^\circ < \theta < 0.45^\circ$
  H.E.S.S. collaboration, Nature (2016)
- HESS Halo: $\theta < 1.0^\circ, |b| > 0.3^\circ$
  H.E.S.S. collaboration, Phys.Rev.Lett. (2011)
  H.E.S.S. collaboration, Phys.Rev.Lett. (2016)
- HESS Inner Galaxy Survey (IGS): $0.5^\circ < \theta < 3.0^\circ$
  H.E.S.S. collaboration, Phys.Rev.Lett. (2022)



This work, J. Zuriaga-Puig et al. arXiv: 2307.06823

Indirect Detection WIMPS: Gamma Rays

DM annihilation produces gamma-rays



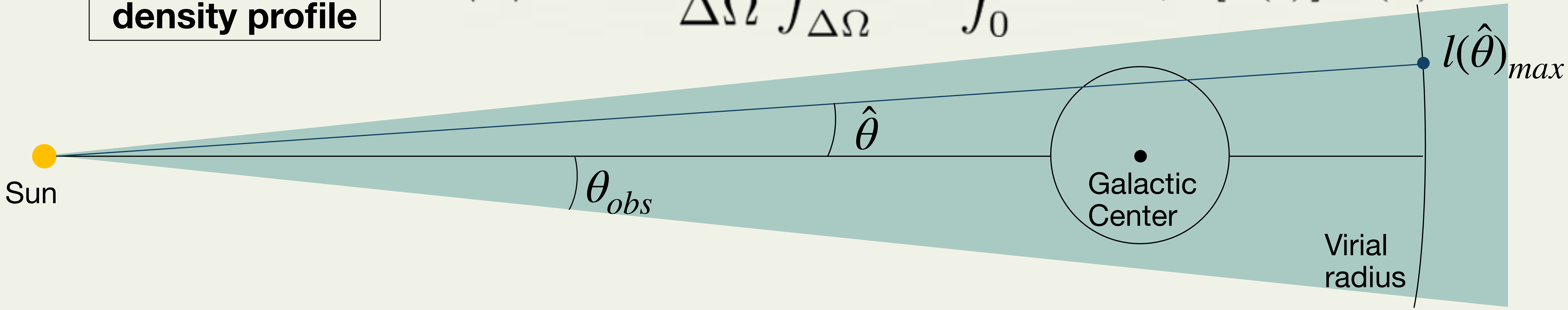
Secondary Particles: Gamma rays, neutrinos, cosmic rays…

$$\frac{d\Phi_{\rm DM}}{dE} = \sum_{i}^{\rm channels} \frac{\langle \sigma v \rangle_i}{2} \frac{dN_i}{dE} \frac{\Delta\Omega \langle J \rangle_{\Delta\Omega}}{4\pi m_{\rm DM}^2}$$

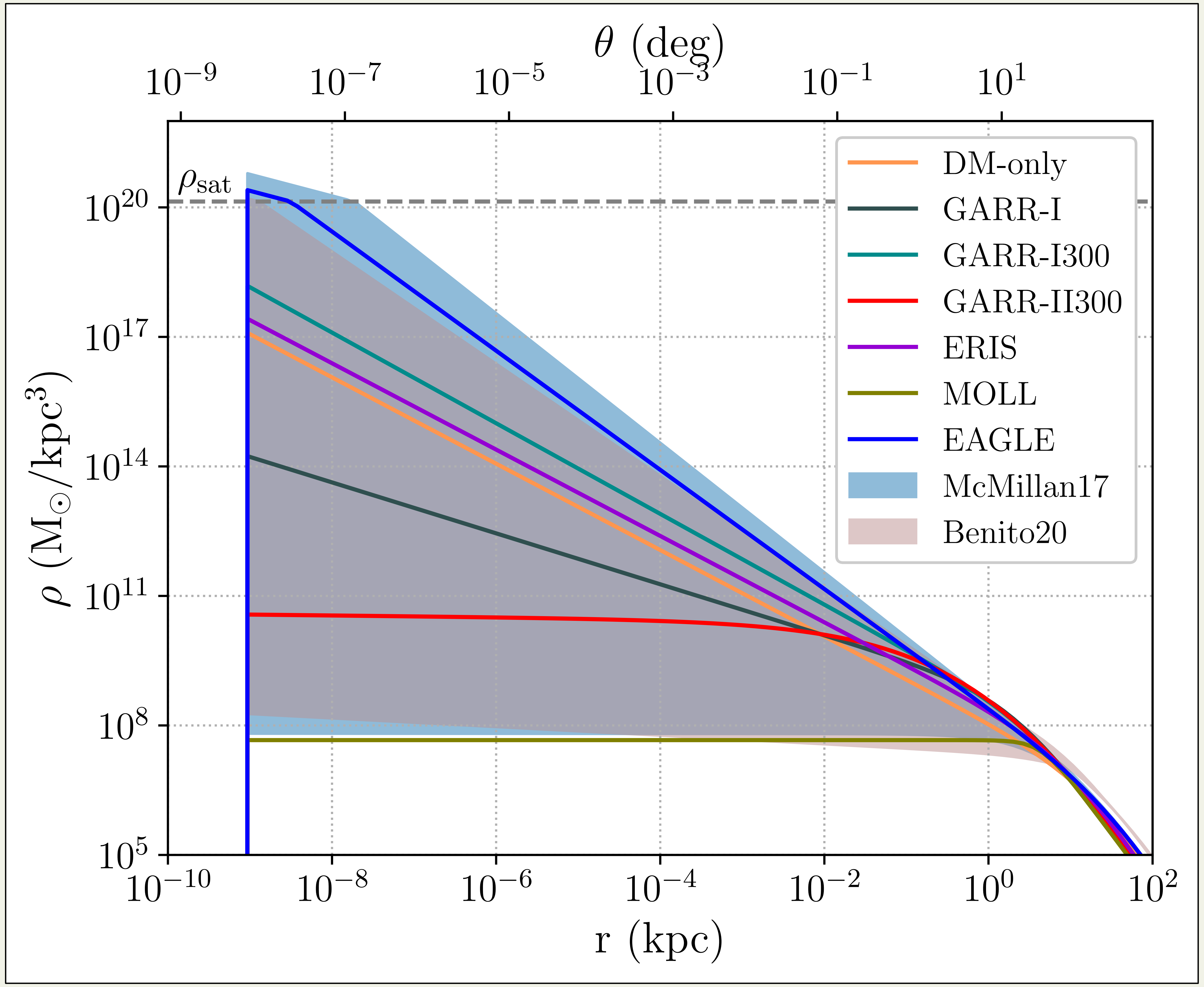
$$\langle \sigma v \rangle = 2.2 \times 10^{-26}\ \text{cm}^3\ \text{s}^{-1}$$

Information about the DM density profile

$$\langle J \rangle_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} {\rm d}\Omega \int_0^{l(\hat\theta)_{\max}} \rho^2[r(l)]\,dl(\hat\theta)$$



Analysis component: DM density profile



This work, J. Zuriaga-Puig et al.

$$\rho_{halo}(r) = \frac{\rho_s}{(\frac{r}{r_s})^{\gamma}(1+(\frac{r}{r_s})^{\alpha})^{\frac{\beta-\gamma}{\alpha}}}$$

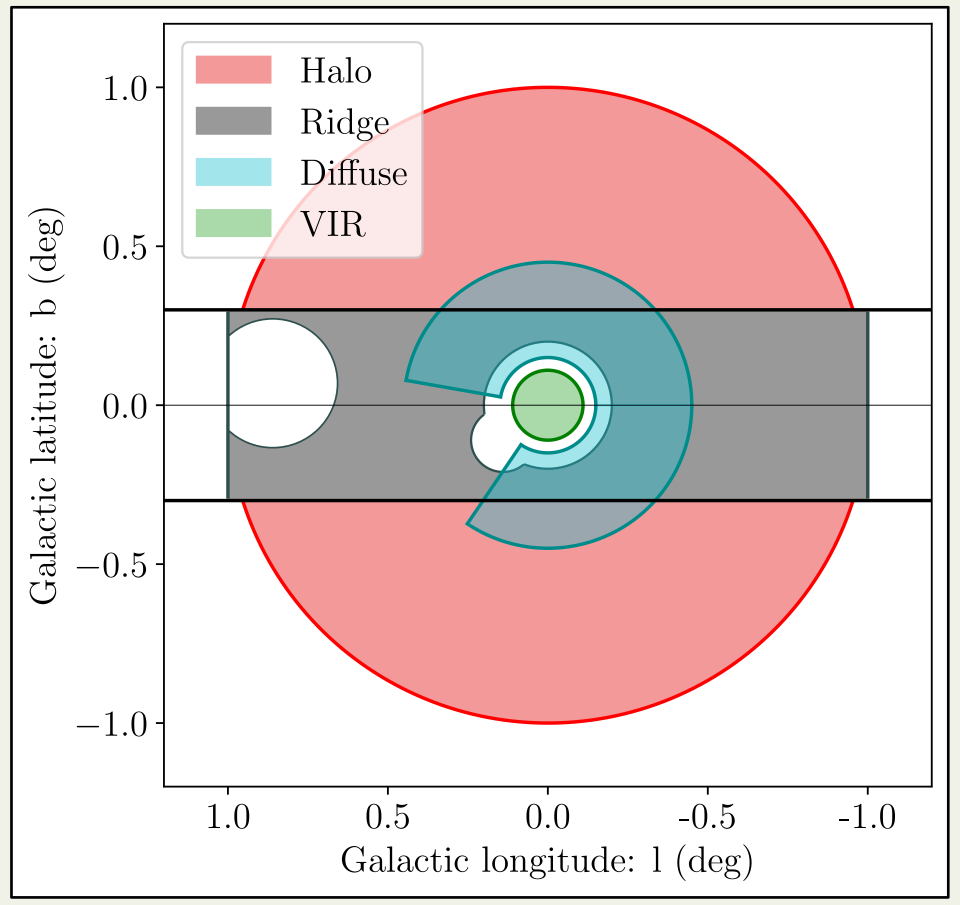
NFW: $(\gamma, \alpha, \beta) = (1,1,3)$

Profile	γ	α	β	r_s (kpc)	$\rho_\odot$(GeVcm^{-3})
DM-only	1	1	3	21.5	0.28
GARR-I	0.59	1	2.70	2.3	0.35
GARR-I300	1.05	1	2.79	4.6	0.35
GARR-II300	0.02	0.42	3.39	2.5	0.35
ERIS	1	1	3	10.9	0.36
MOLL	8×10^{-9}	2.89	2.54	4.4	0.31
EAGLE	1.38	1	3	31.2	0.35
McMillan17	0-1.5	1	3	6.8-59.9	0.33-0.43
Benito20	0.1-1.3	1	3	7.0-40.0	0.41-0.71

$$\langle J \rangle_{\Delta\Omega} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_0^{l(\hat{\theta})_{\max}} \rho^2[r(l)]dl(\hat{\theta})$$

Analysis component: Background Model DRAGON

- A source of uncertainty is the astrophysical background model: diffuse emission and several point sources
- The diffuse emission is due to the presence of a charged CR sea confined in the galaxy by the turbulent magnetic field
- This sea of CR interact with the interstellar gas and low-energy photons emitting gamma-ray flux up to TeV scale
- Main interactions: synchrotron, bremsstrahlung, Inverse Compton and neutral pion decay
- We use DRAGON & HERMES to model this emission, where the spectral shape is completely defined in each region



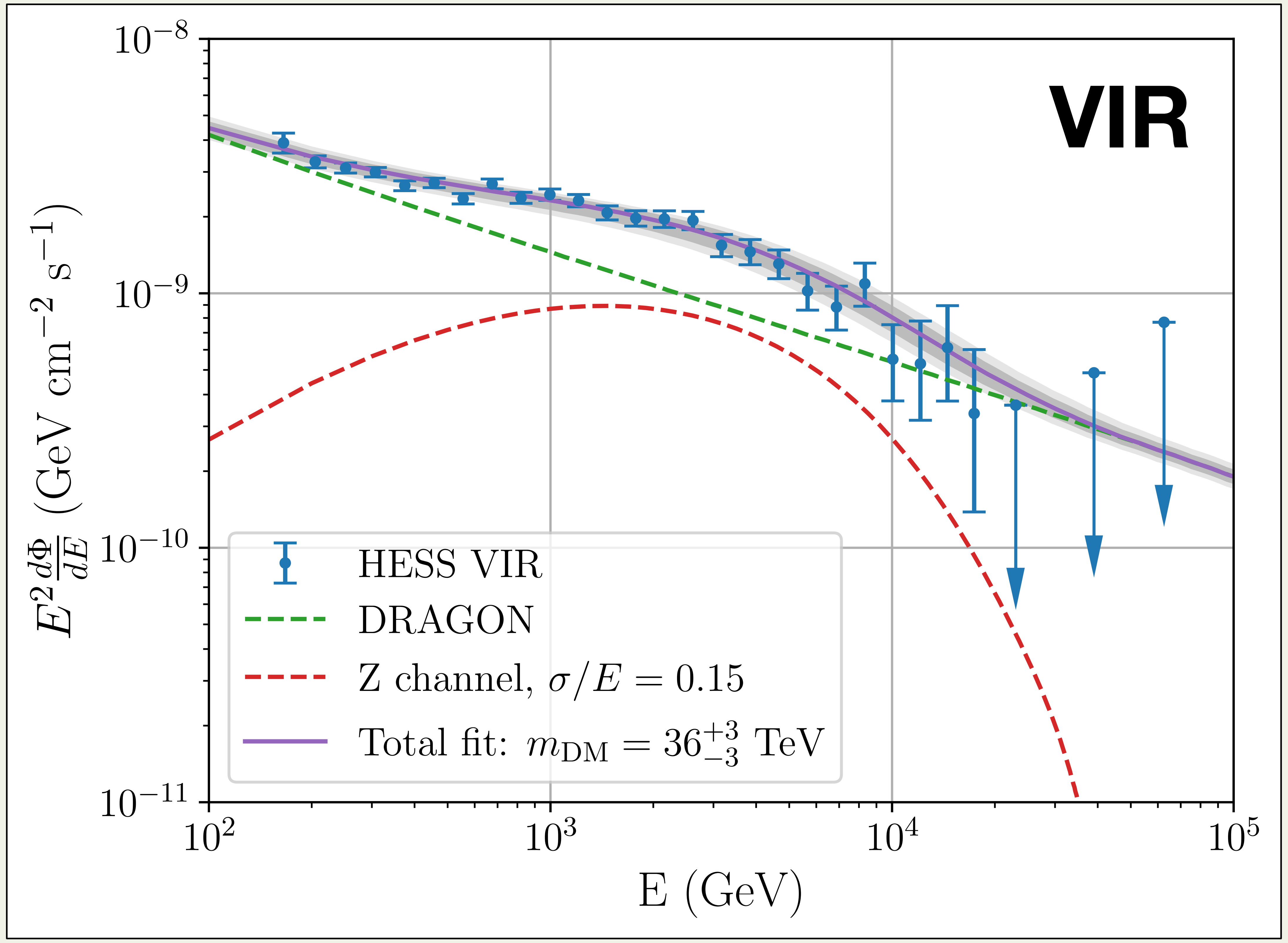
$$\frac{d\Phi_{\text{Bg}}}{dE} = B^2 \frac{d\Phi_{\text{DRAGON}}}{dE}$$

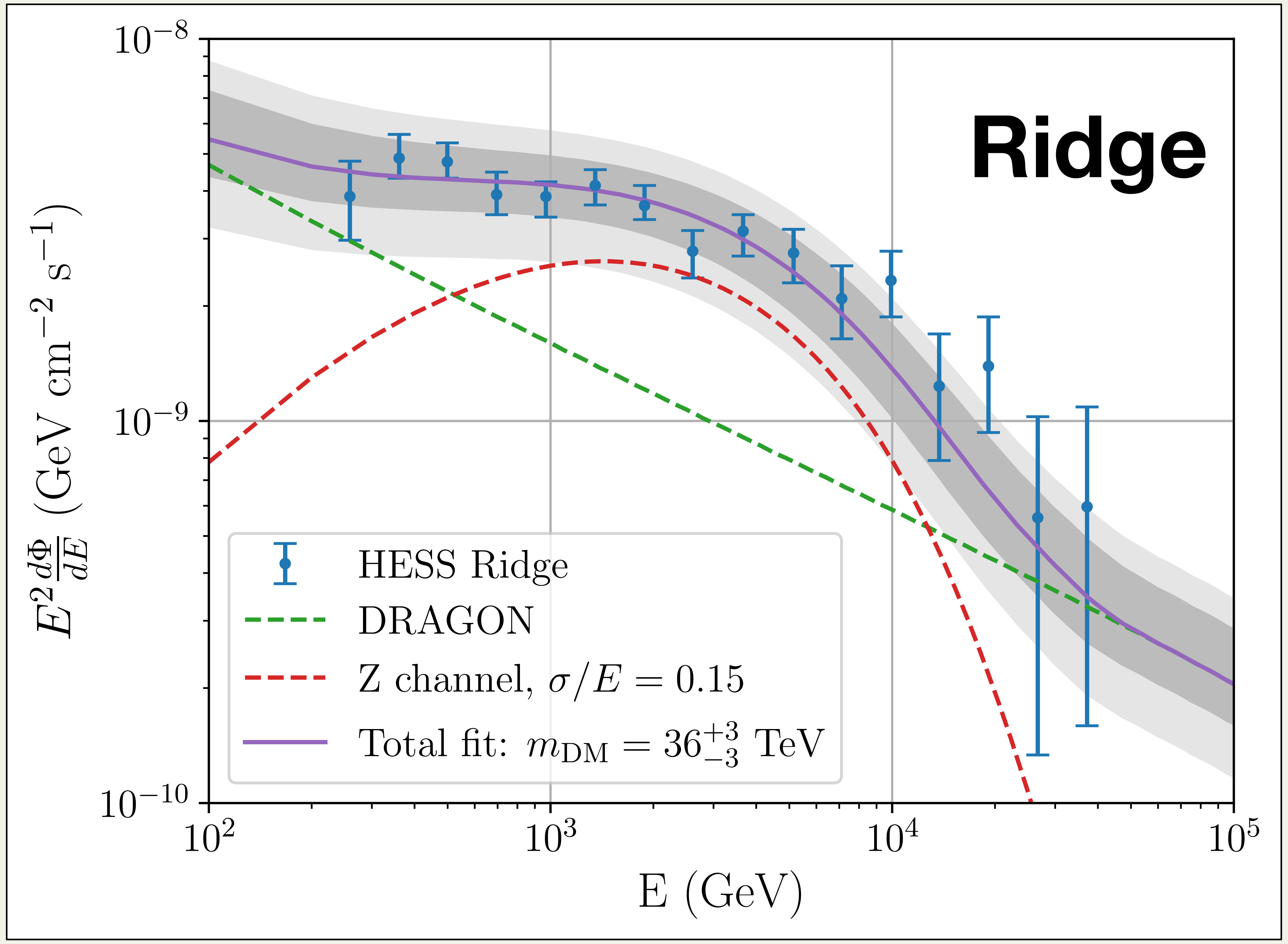
B^2 is an $\mathcal{O}(1)$ normalizing factor left as a free parameter

DRAGON
C. Evoli et al., JCAP (2008)
C. Evoli et al., JCAP (2017)
C. Evoli et al., JCAP (2018)
HERMES
A. Dundovic et al., A&A (2021)

Analysis: VIR & Ridge

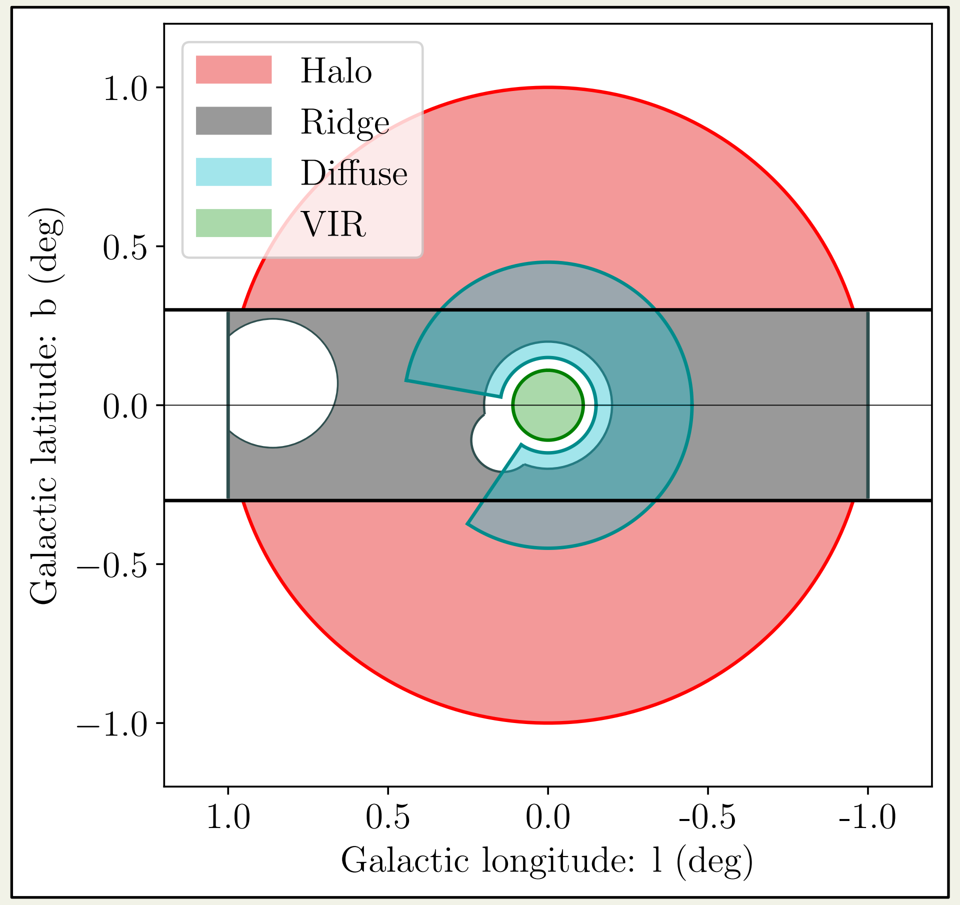
This work, J. Zuriaga-Puig et al.





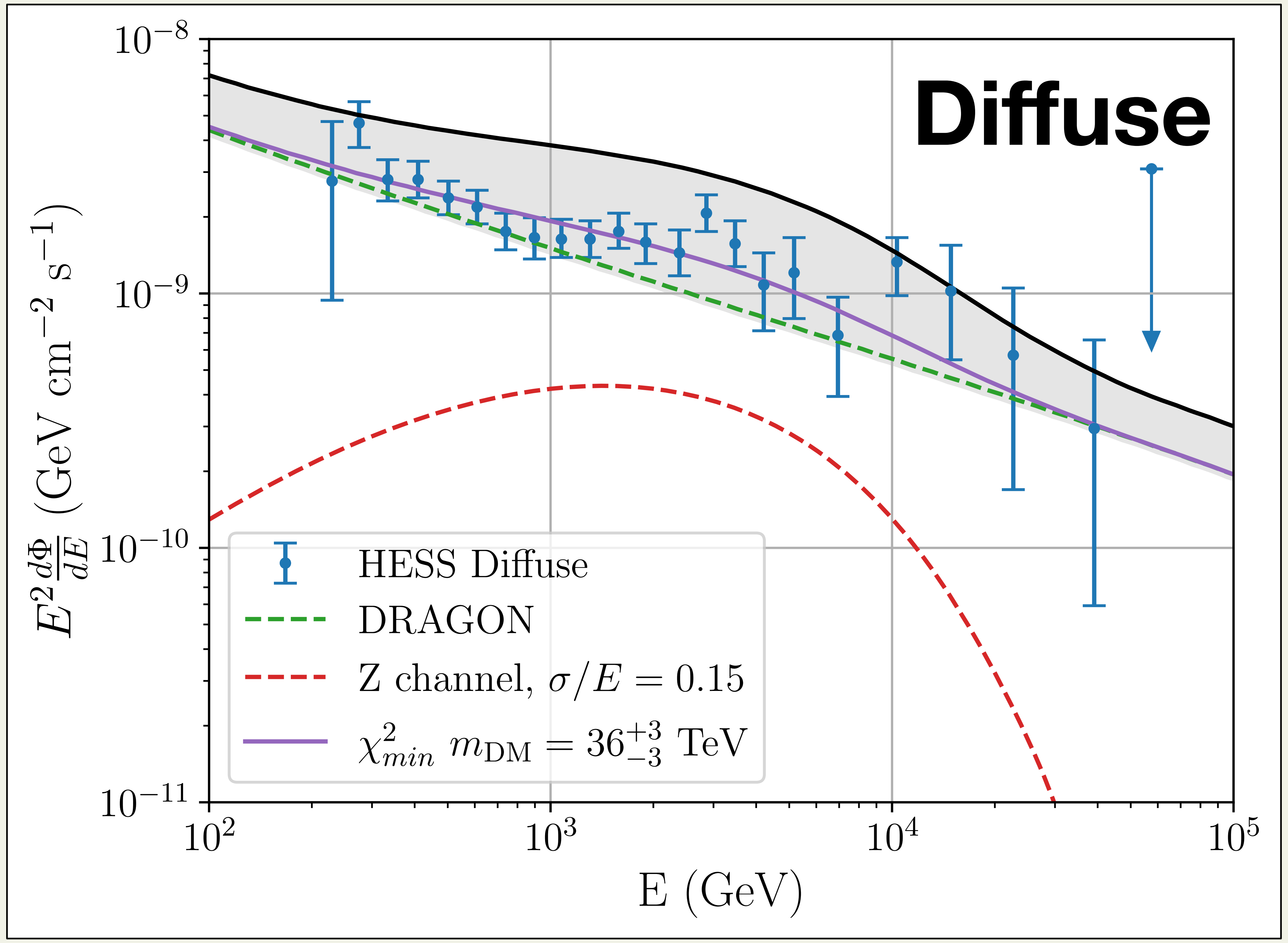
Parameters	VIR	Ridge
$m_{\rm DM}$ (TeV)	36^{+8}_{-6}	–
B^2 (cm^{2}s^{-1})	$7.3^{+0.8}_{-0.7}$	$0.30^{+0.2}_{-0.1}$
$\langle J\rangle_{\Delta\Omega}$ (GeV^{2}cm^{-5})	$2.4^{+0.7}_{-0.7} \times 10^{28}$	$2.5^{+0.8}_{-1.0} \times 10^{27}$
$\langle J\rangle_{\Delta\Omega}/J_{\text{DM-only}}$	1000^{-300}_{+300}	1000^{+300}_{-400}
χ^2 / ddof	0.96	1.01
$\Delta\Omega$ (sr)	1.16×10^{-5}	3.26×10^{-4}

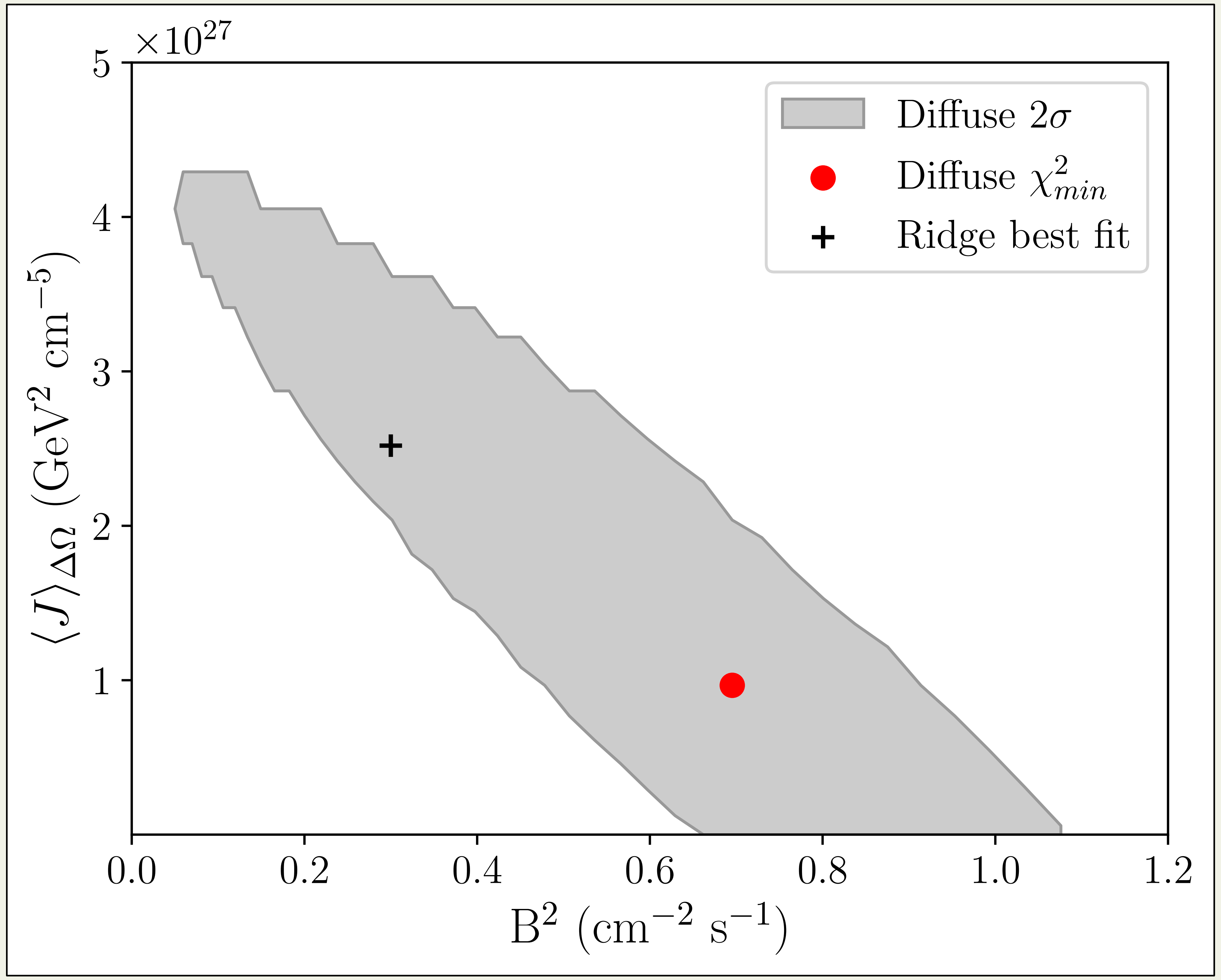
$\langle \sigma v \rangle = 2.2 \times 10^{-26}$ cm^3 s^{-1}



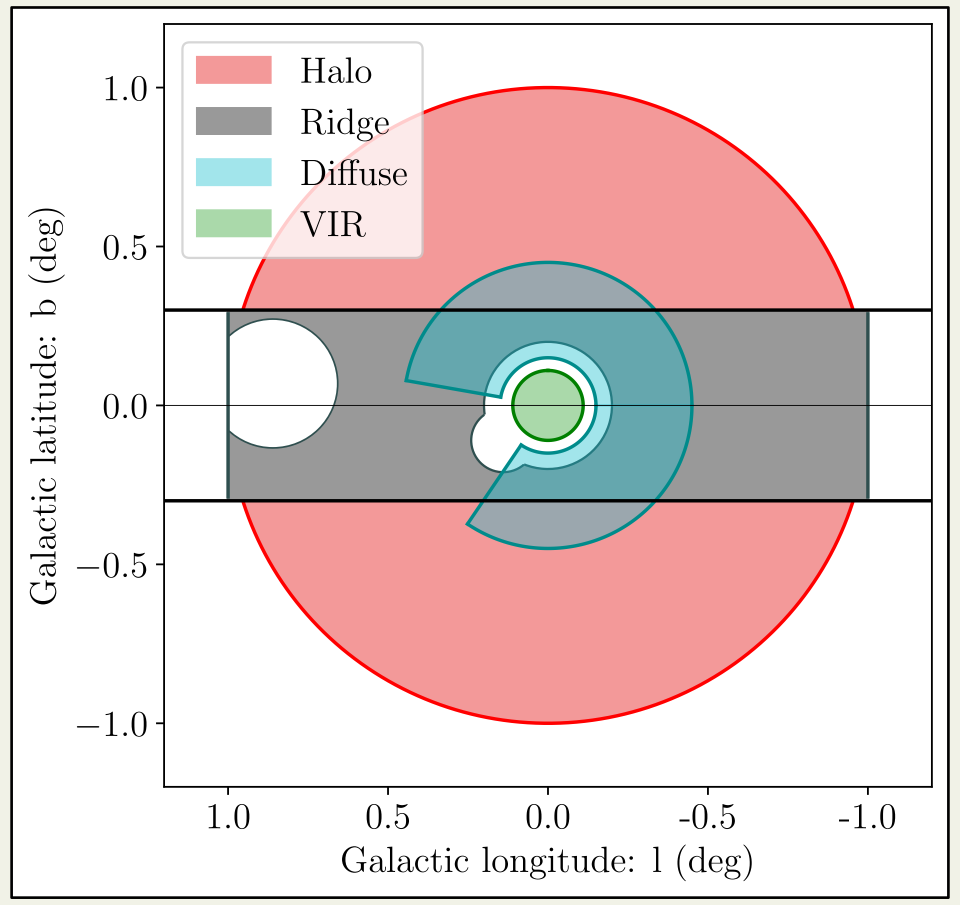
Analysis: Diffuse

This work, J. Zuriaga-Puig et al.

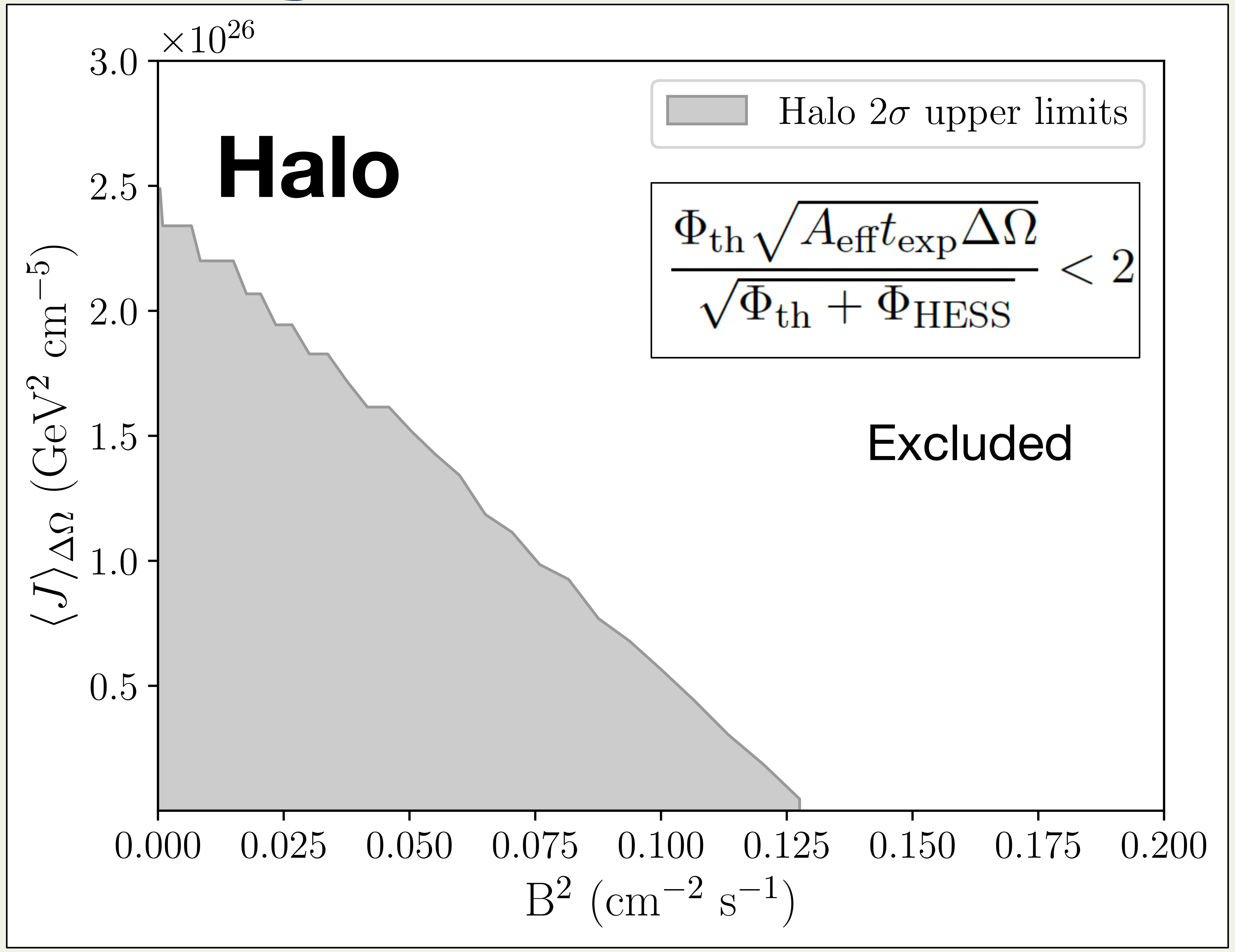




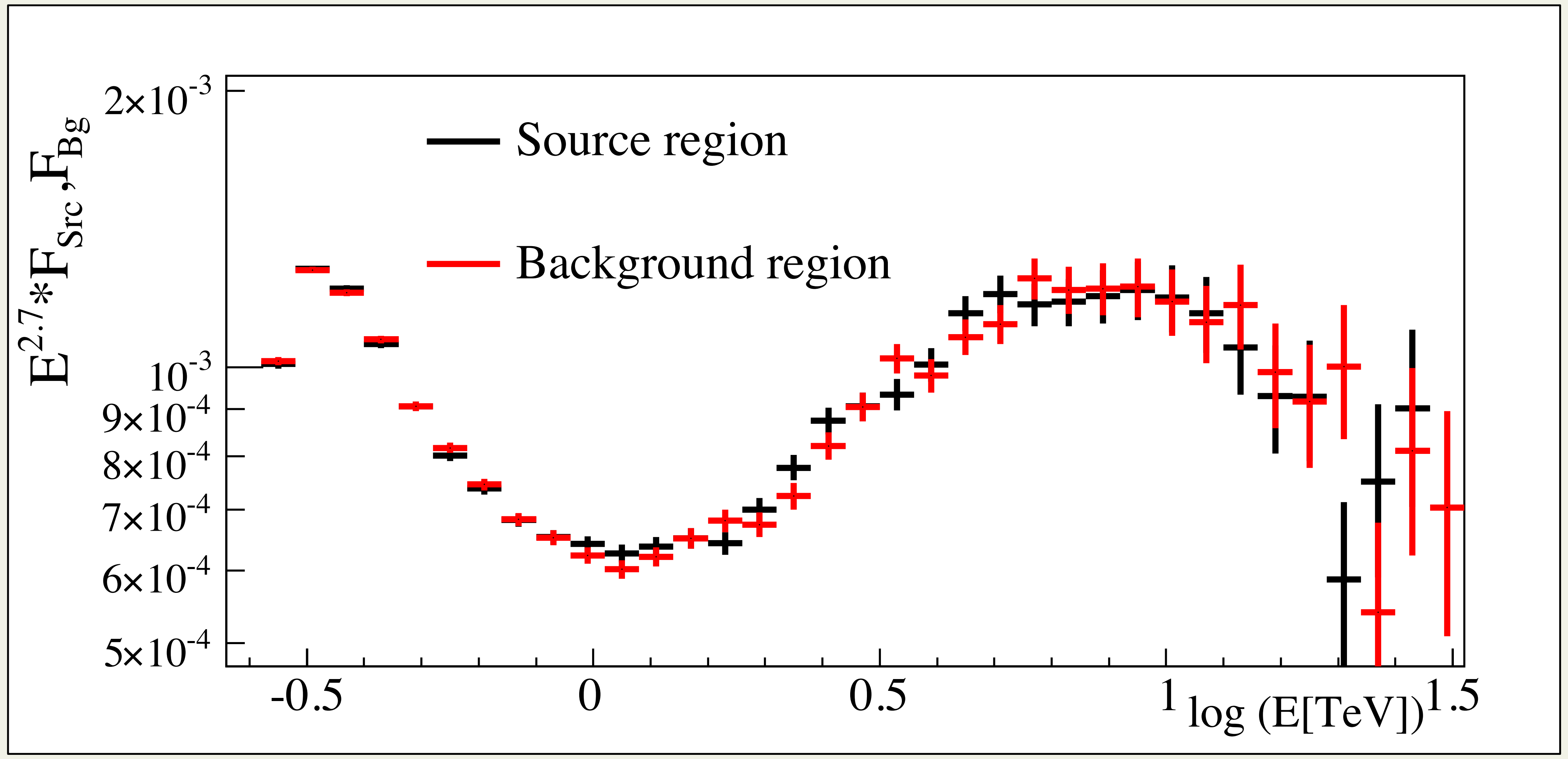
Parameters	VIR	Ridge	Diffuse
$m_{\rm DM}$ (TeV)	36^{+8}_{-6}	–	–
B^2 (cm^{2}s^{-1})	$7.3^{+0.8}_{-0.7}$	$0.30^{+0.2}_{-0.1}$	$0.7^{+0.3}_{-0.6}$
$\langle J \rangle_{\Delta\Omega}$ (GeV^{2}cm^{-5})	$2.4^{+0.7}_{-0.7} \times 10^{28}$	$2.5^{+0.8}_{-1.0} \times 10^{27}$	$9.7^{+33.0}_{-9.7} \times 10^{26}$
$\langle J \rangle_{\Delta\Omega}/J_{\rm DM\text{-}only}$	1000^{-300}_{+300}	1000^{+300}_{-400}	200^{+800}_{-200}
χ^2 / ddof	0.96	1.01	0.89
$\Delta\Omega$ (sr)	1.16×10^{-5}	3.26×10^{-4}	1.41×10^{-4}



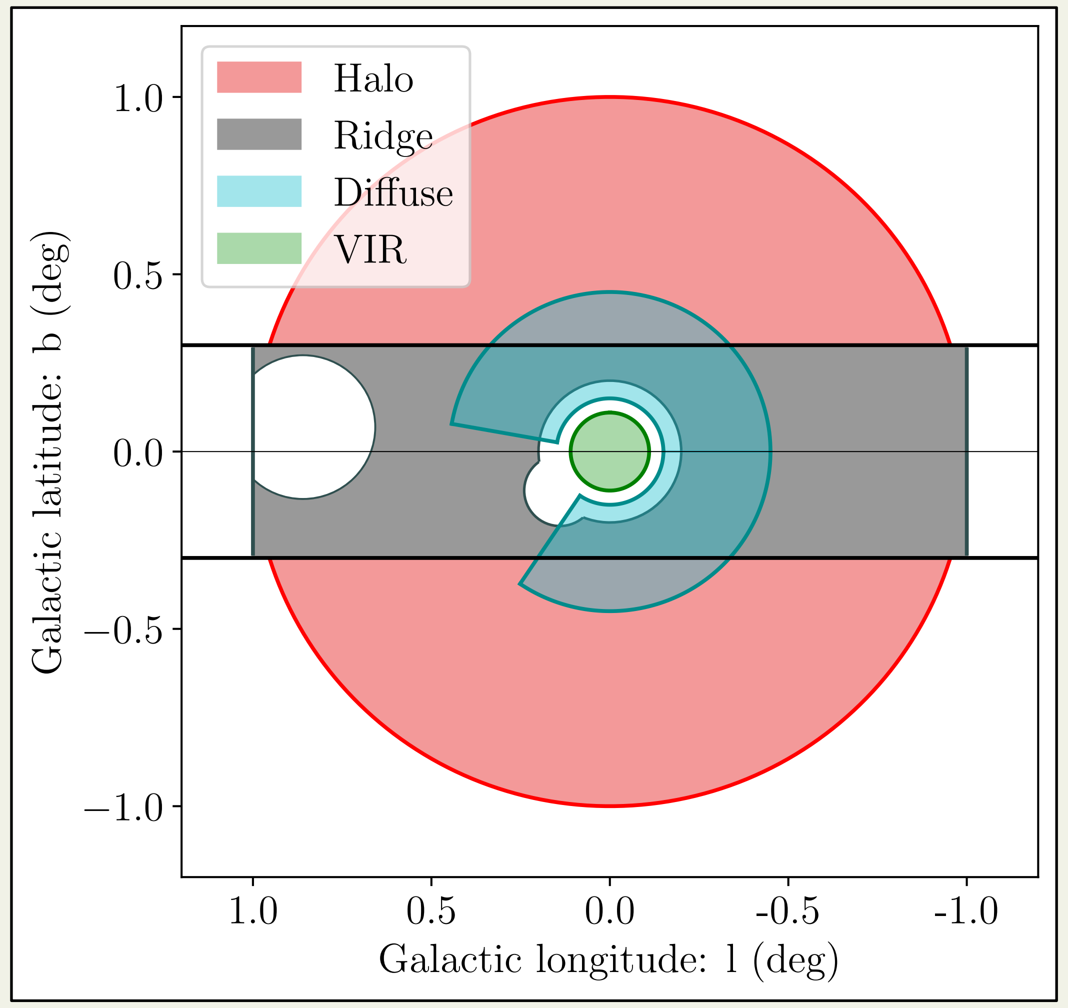
Analysis: Halo



Parameters	Halo	IGS
$m_{\rm DM}$ (TeV)	–	–
$B^2_{\rm UL}$ $({\rm cm}^2{\rm s}^{-1})$	0.13	0.02
$\langle J \rangle^{\rm UL}_{\Delta\Omega}$ $({\rm GeV}^2{\rm cm}^{-5})$	2.5×10^{26}	1.7×10^{25}
$\Delta\Omega$ (sr)	5.97×10^{-4}	6.38×10^{-3}



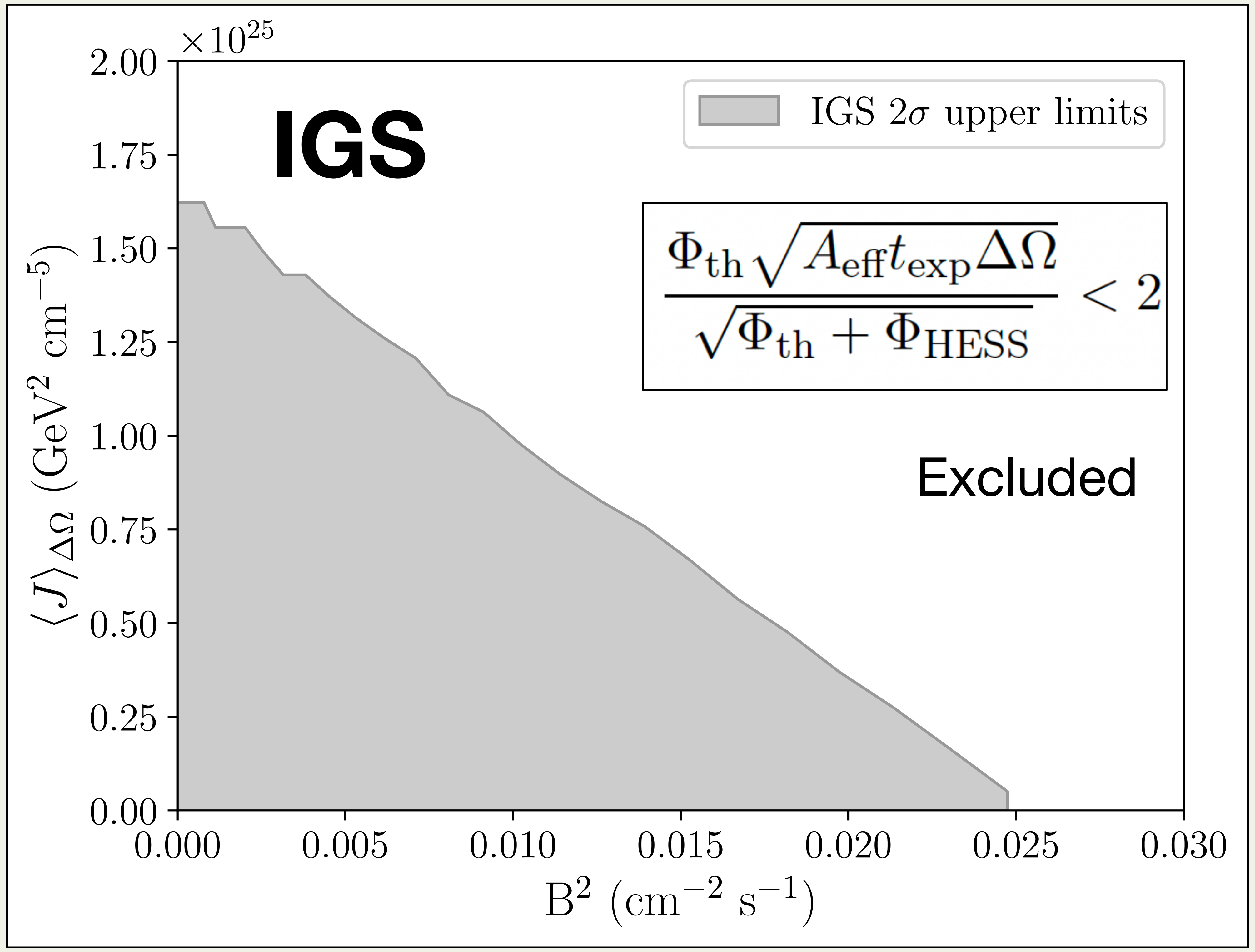
H.E.S.S. collaboration, Phys.Rev.Lett. (2011)

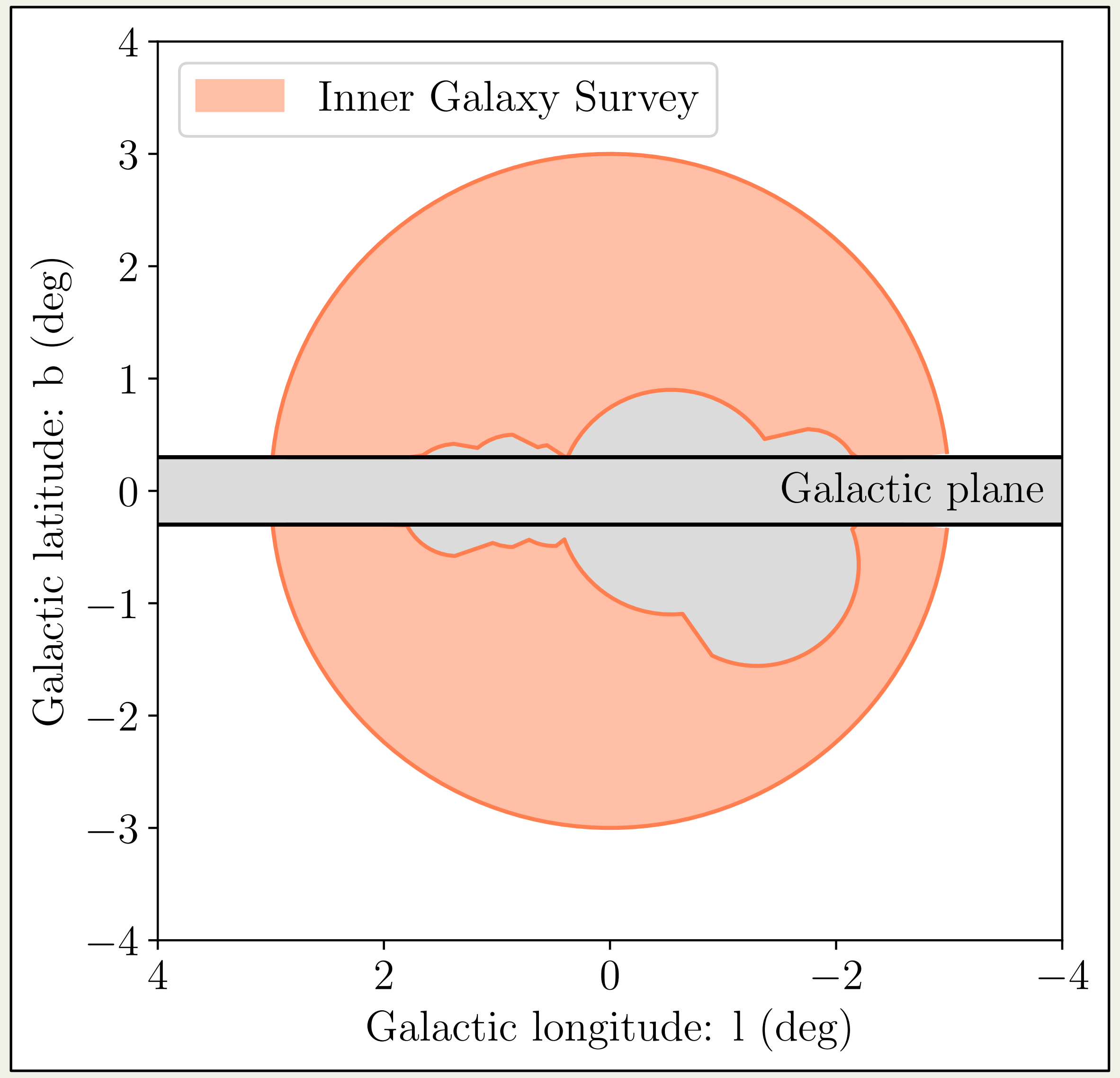


$\langle \sigma v \rangle = 2.2 \times 10^{-26}$ cm^3 s^{-1}

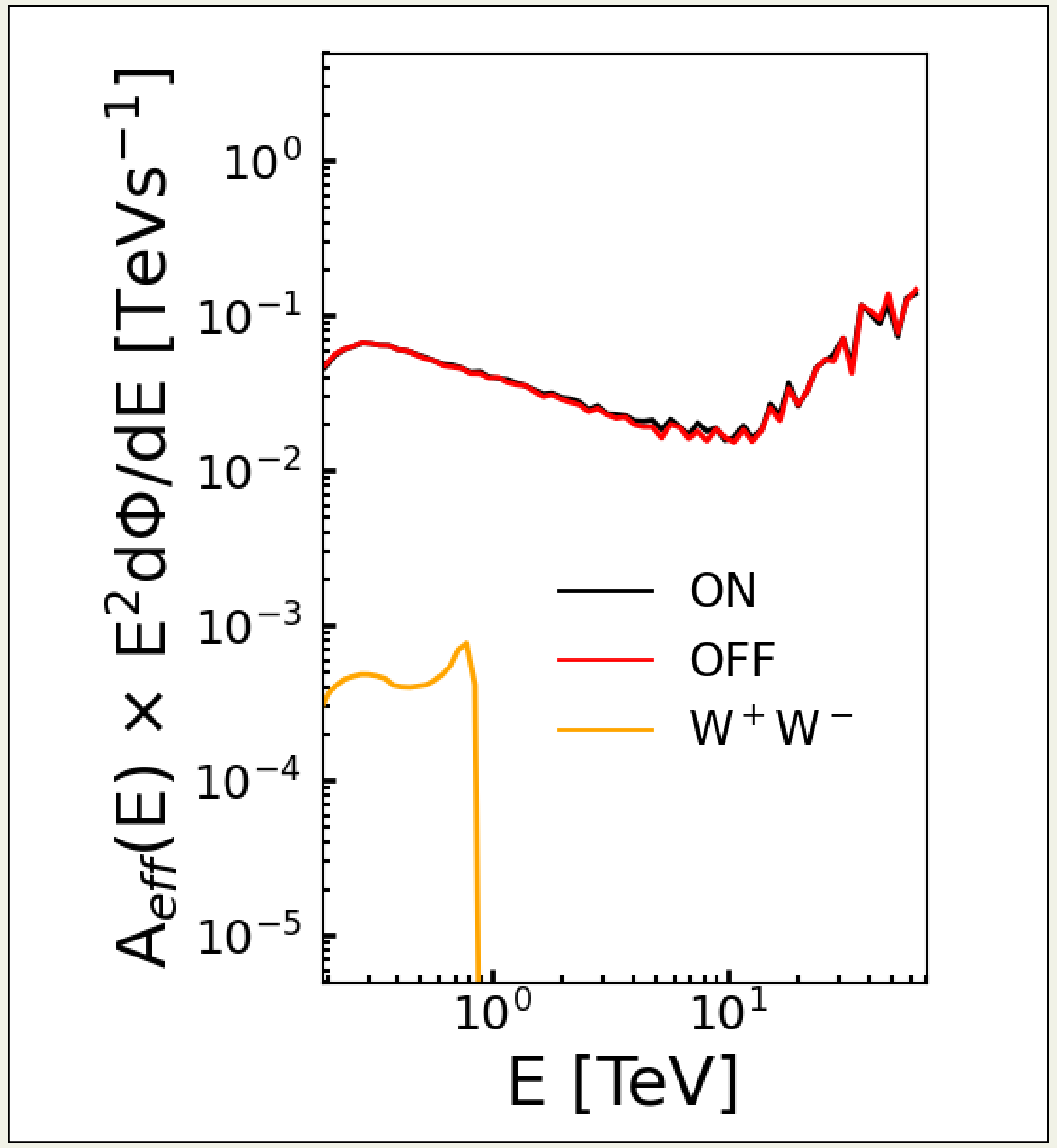
This work, J. Zuriaga-Puig et al.

Analysis: IGS





This work, J. Zuriaga-Puig et al.



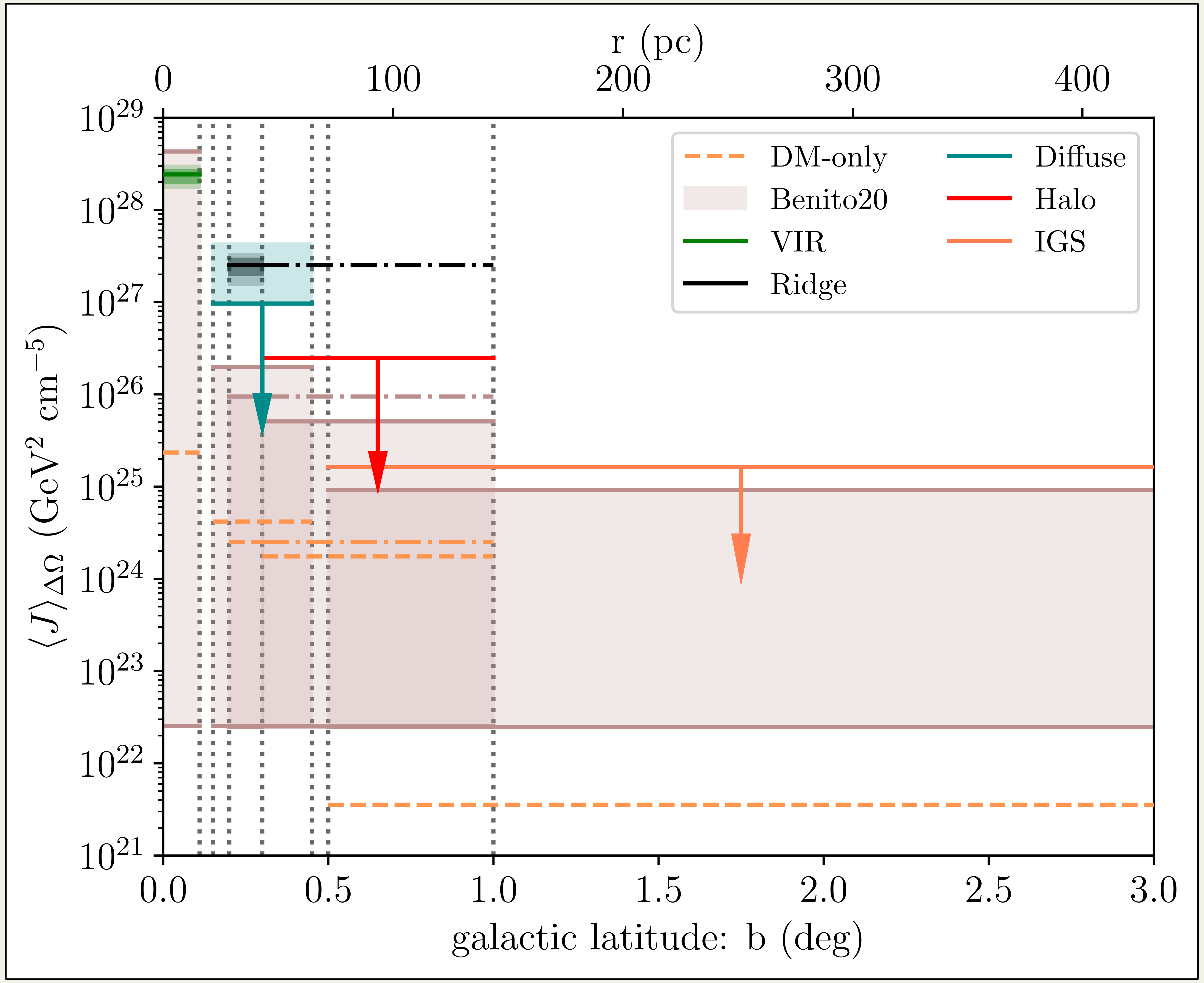
H.E.S.S. collaboration, Phys.Rev.Lett. (2022)

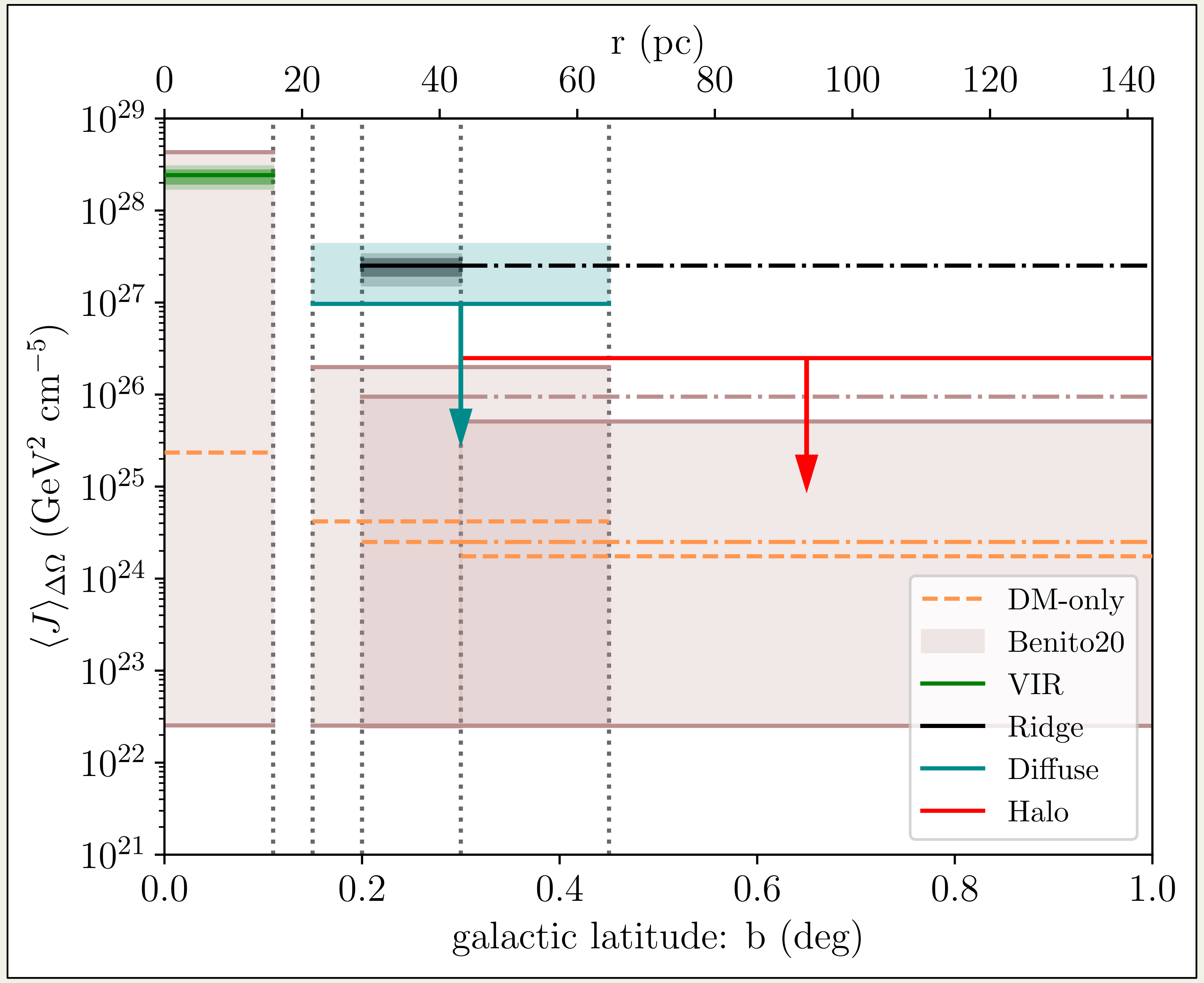
Parameters	Halo	IGS
m_{DM} (TeV)	–	–
B^2_{UL} (cm^{2}s^{-1})	0.13	0.02
$\langle J \rangle^{UL}_{\Delta\Omega}$ (GeV^{2}cm^{-5})	2.5×10^{26}	1.7×10^{25}
$\Delta\Omega$ (sr)	5.97×10^{-4}	6.38×10^{-3}

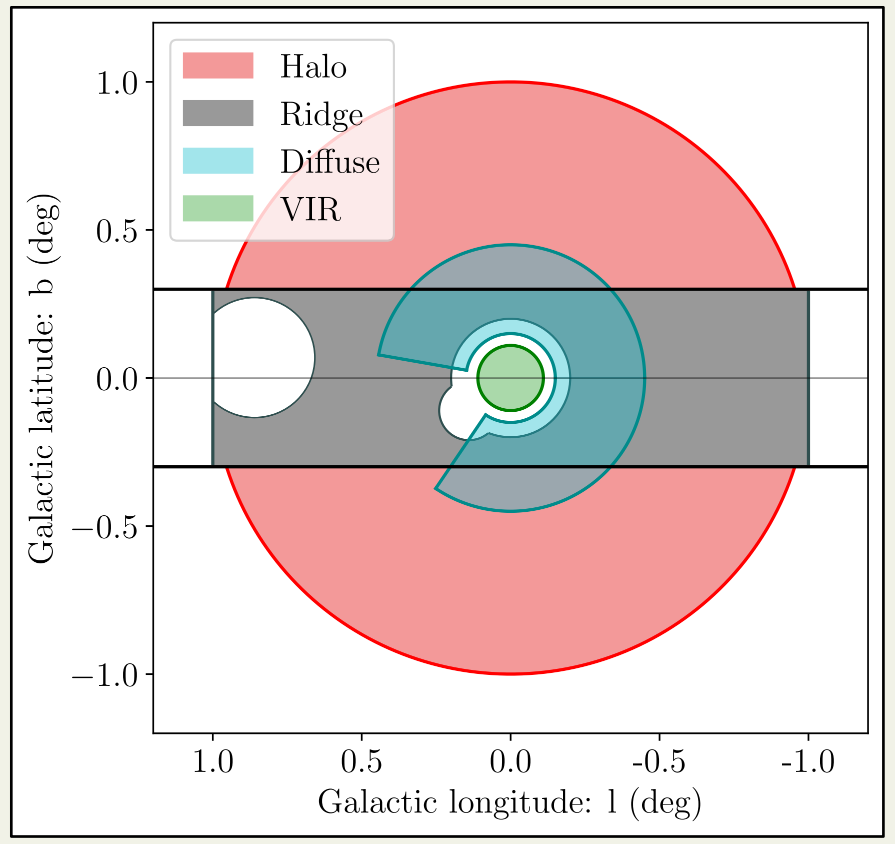
$$\langle \sigma v \rangle = 2.2 \times 10^{-26}\ \text{cm}^3\ \text{s}^{-1}$$

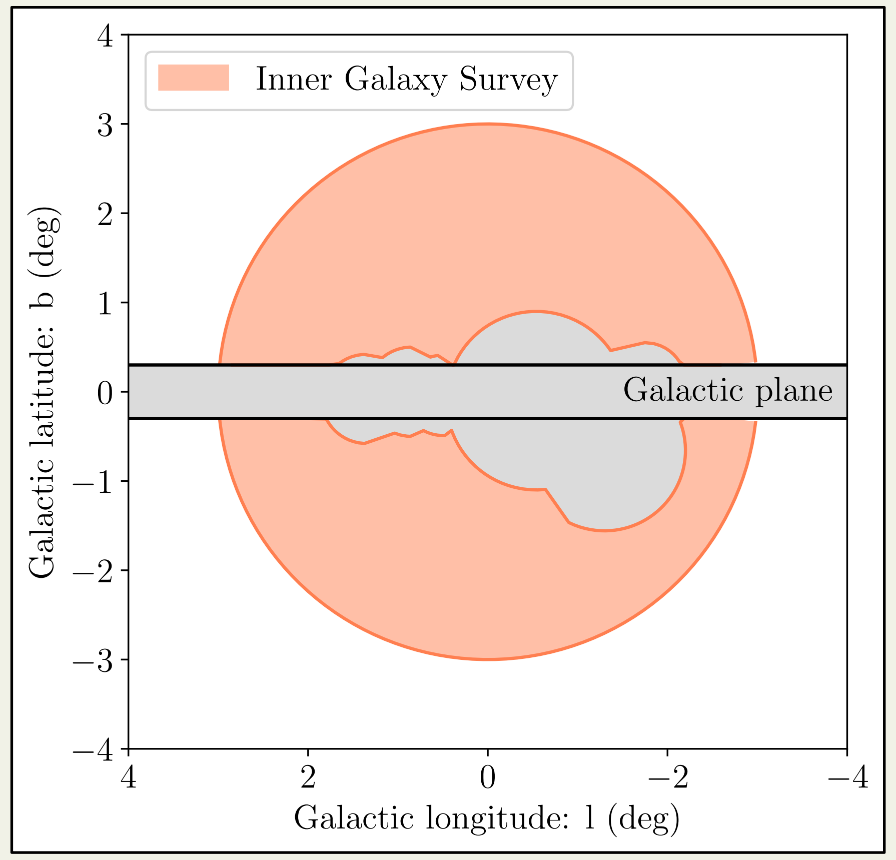
Spectral analysis results: J-Factors

This work, J. Zuriaga-Puig et al.









$$\langle J \rangle_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \mathrm{d}\Omega \int_0^{l(\hat{\theta})_{\max}} \rho^2[r(l)] dl(\hat{\theta})$$

Outline

- **WIMPS indirect detection with gamma rays**
- **Galactic Centre observed by HESS**
  - 5 Regions Of Interest in the GC
- **Gamma-ray spectral analysis components**
  - 5 regions background model
  - DM density profile
- **Gamma-ray spectral results:**
  - 5 regions J-Factors
- **Constraints of the DM density profile:**
  - Simulations & dynamical observations (external DM profile)
  - S2 star orbit (innermost DM profile)
- **Conclusions**

DM Density Profile

- We need DM density profiles well described in order to compute the J-Factors
- We will use different models coming from simulations and observations
- Given the uncertainties in the GC: we use a wide range of models

$$\rho_{halo}(r) = \frac{\rho_s}{(\frac{r}{r_s})^{\gamma}(1+(\frac{r}{r_s})^{\alpha})^{\frac{\beta-\gamma}{\alpha}}}$$

NFW: $(\gamma, \alpha, \beta) = (1,1,3)$

Profile	γ	α	β	r_s (kpc)	$\rho_\odot(\mathrm{GeV cm^{-3}})$
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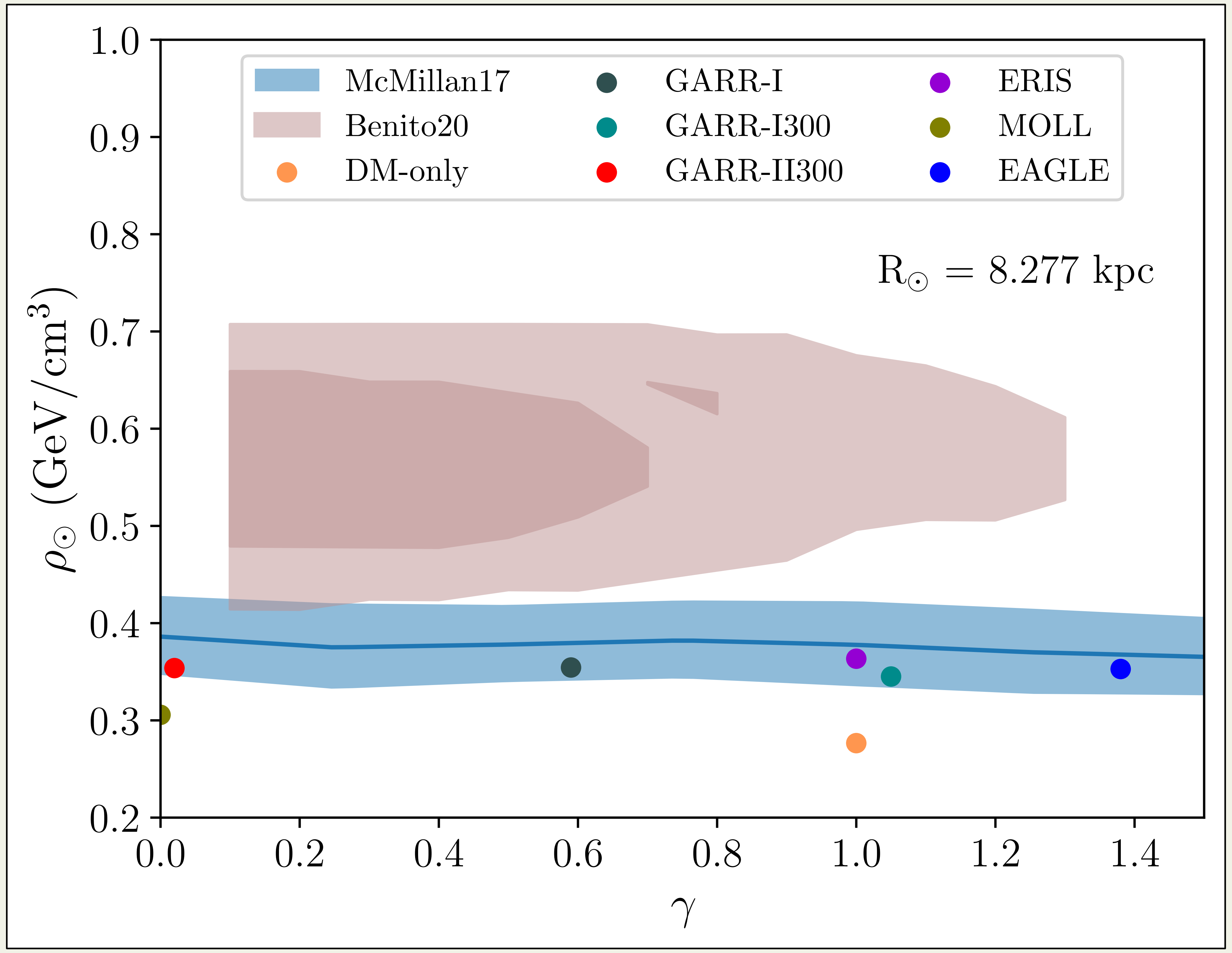
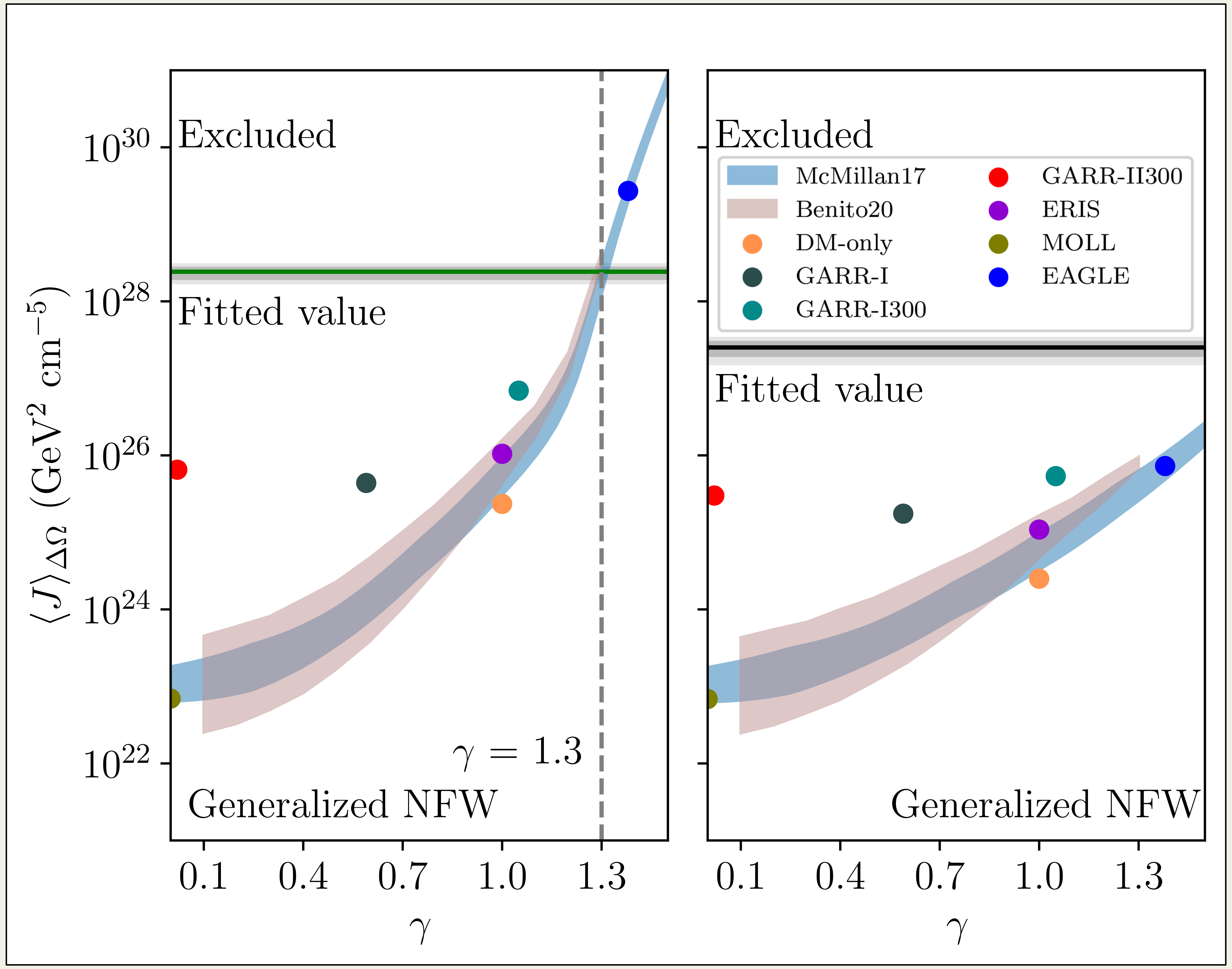


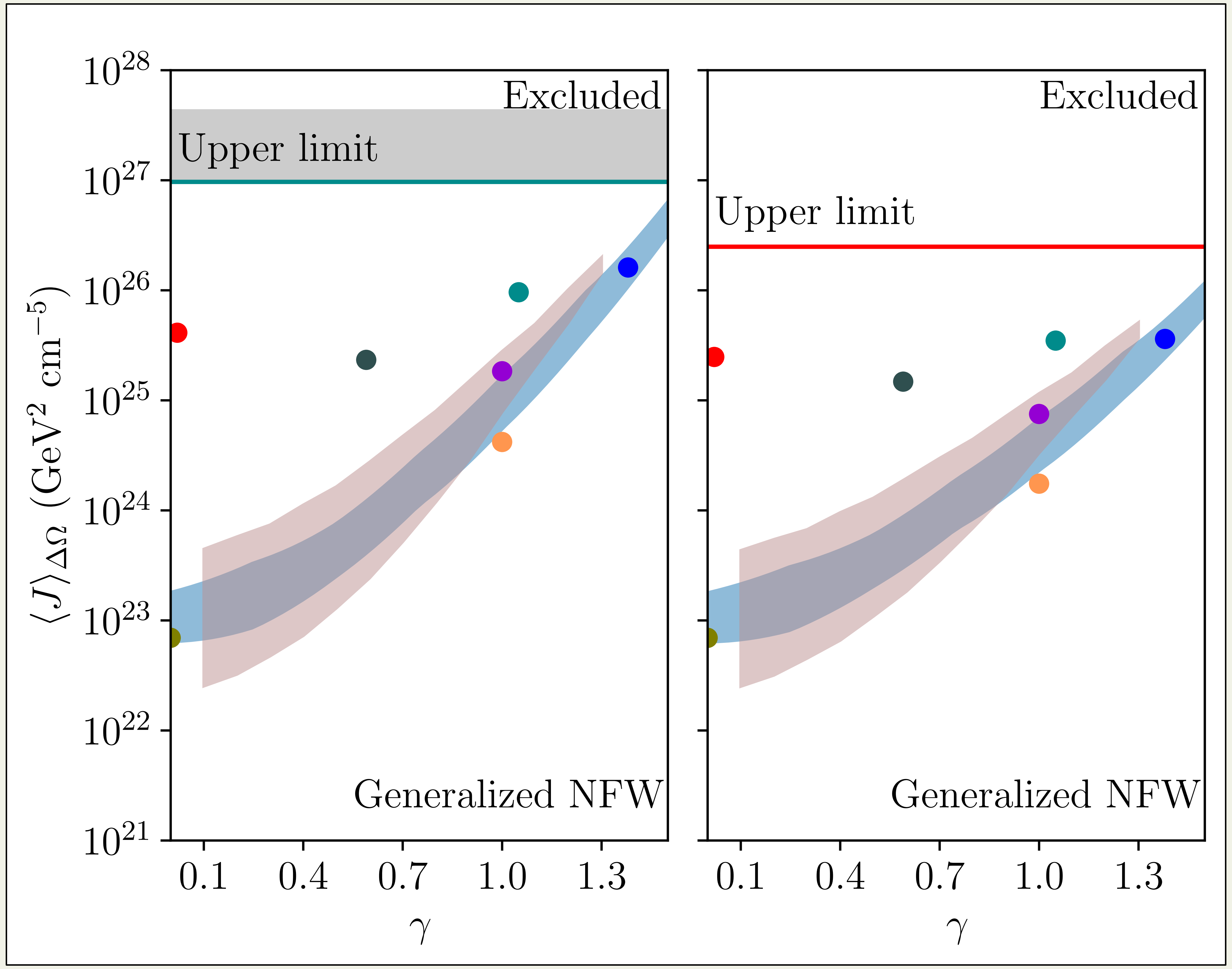
This work, J. Zuriaga-Puig et al.

Generalized NFW

This work, J. Zuriaga-Puig et al.



VIR **Ridge**

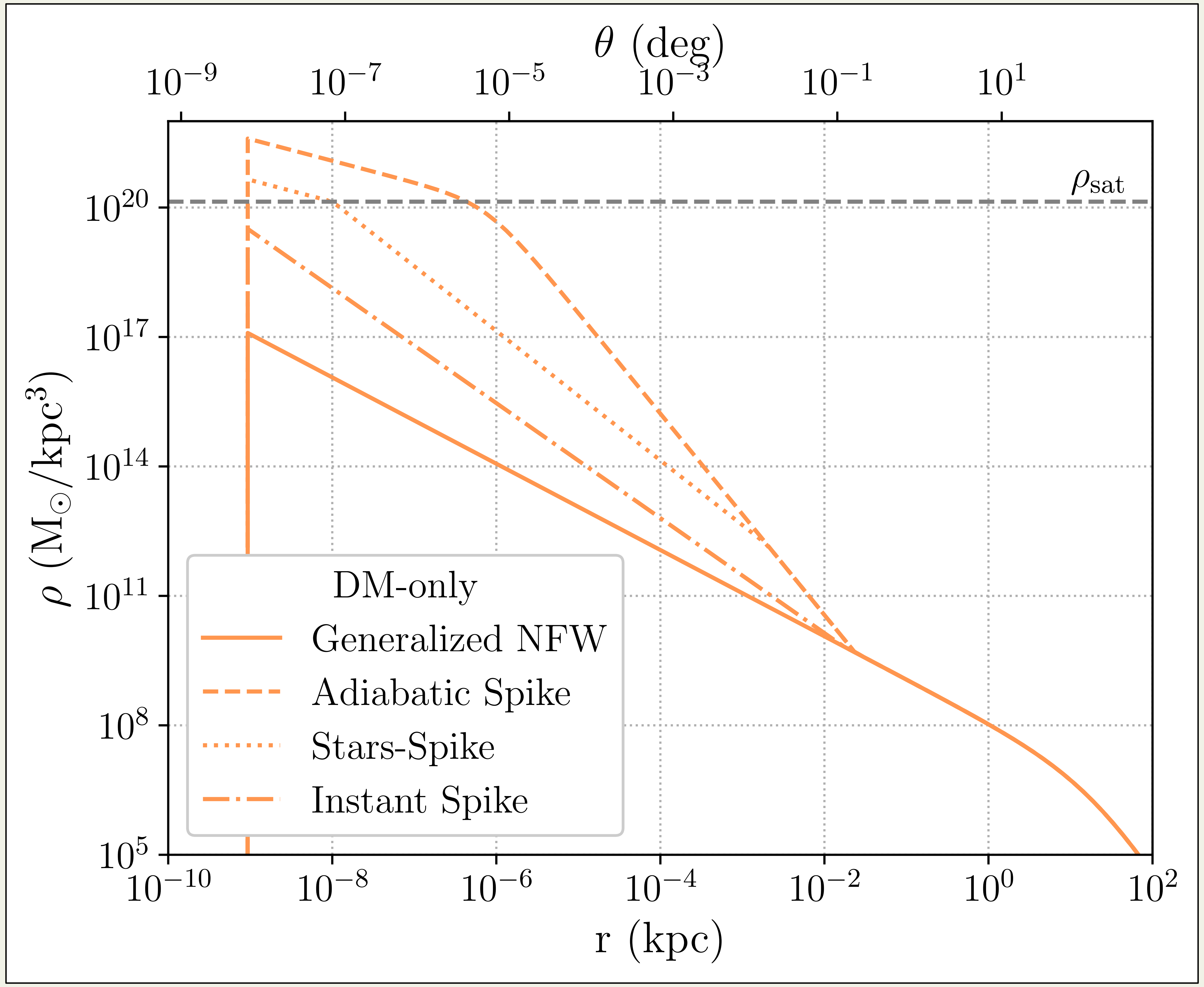


Diffuse **Halo**

- Extrapolation of the external profile to the inner region

$$\rho_{halo}(r) = \frac{\rho_s}{(\frac{r}{r_s})^\gamma (1 + (\frac{r}{r_s})^\alpha)^{\frac{\beta-\gamma}{\alpha}}}$$

Inner DM spike?



This work, J. Zuriaga-Puig et al.

Profile	γ_{sp}	R_{sp} (pc)	γ_{inst}	R_{inst} (pc)
DM-only	2.33	23.5	1.33	16.9
GARR-I	2.29	16.1	1.23	13.2
GARR-I300	2.34	10.2	1.35	8.0
GARR-II300	2.25	2.8	1.14	19.0
ERIS	2.33	16.2	1.33	11.6
MOLL	2.25	0.03	1.12	88.0
EAGLE	2.38	6.8	1.48	72.6
McMillan17	2.25 - 2.40	3.8 - 47.6	1.12 - 1.41	80.5 - 11.7*
Benito20	2.26 - 2.37	6.9 - 61.3	1.14 - 1.44	98.4 - 10.1*

In order to define the inner profile, we can take different approaches:

- Generalized NFW (no modification of the profile)
- Adiabatic Spike from the BH

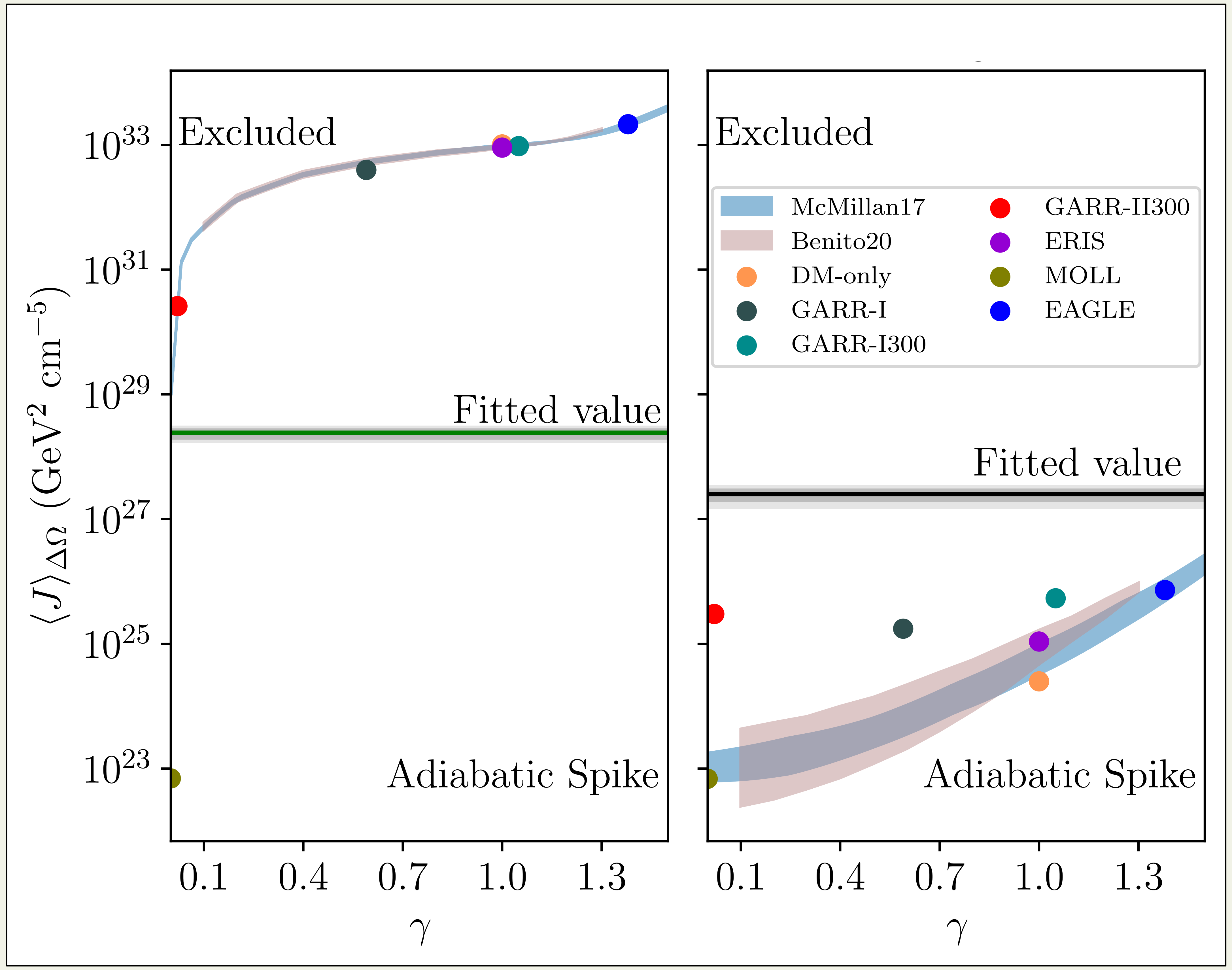
  Gondolo & Silk Phys.Rev.Lett. (1999)
  L.Sadeghian et al. Phys.Rev. D (2013)
- Adiabatic Spike + Stars interactions

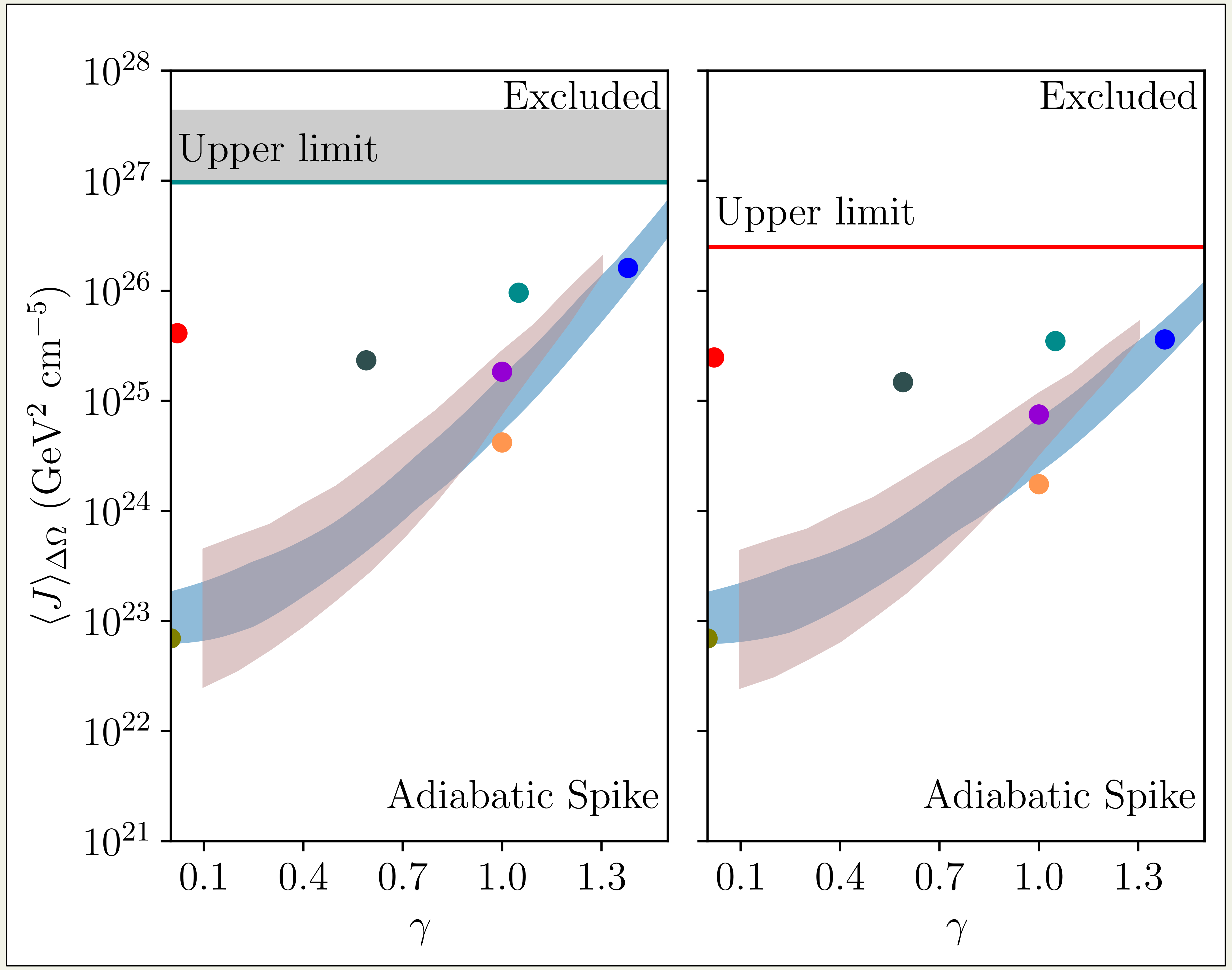
  E. Vasiliev et al. Phys.Rev. D (2008)
  G. Bertone et al. Modern Phys. Letters (2005)
- Extreme case of the Instant Spike

  P. Ullio et al. Phys.Rev. D (2001)

Adiabatic spike

This work, J. Zuriaga-Puig et al.





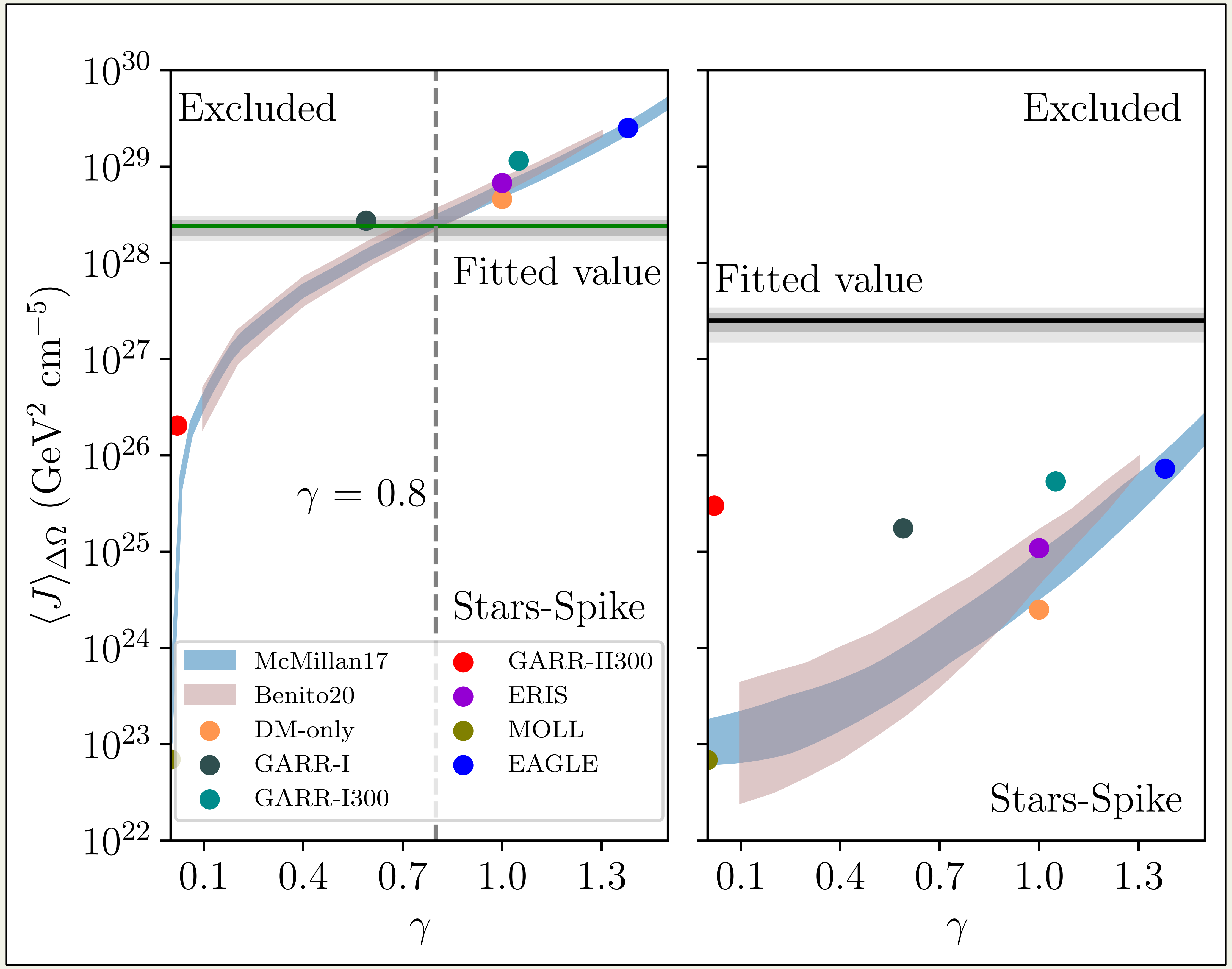
VIR **Ridge** **Diffuse** **Halo**

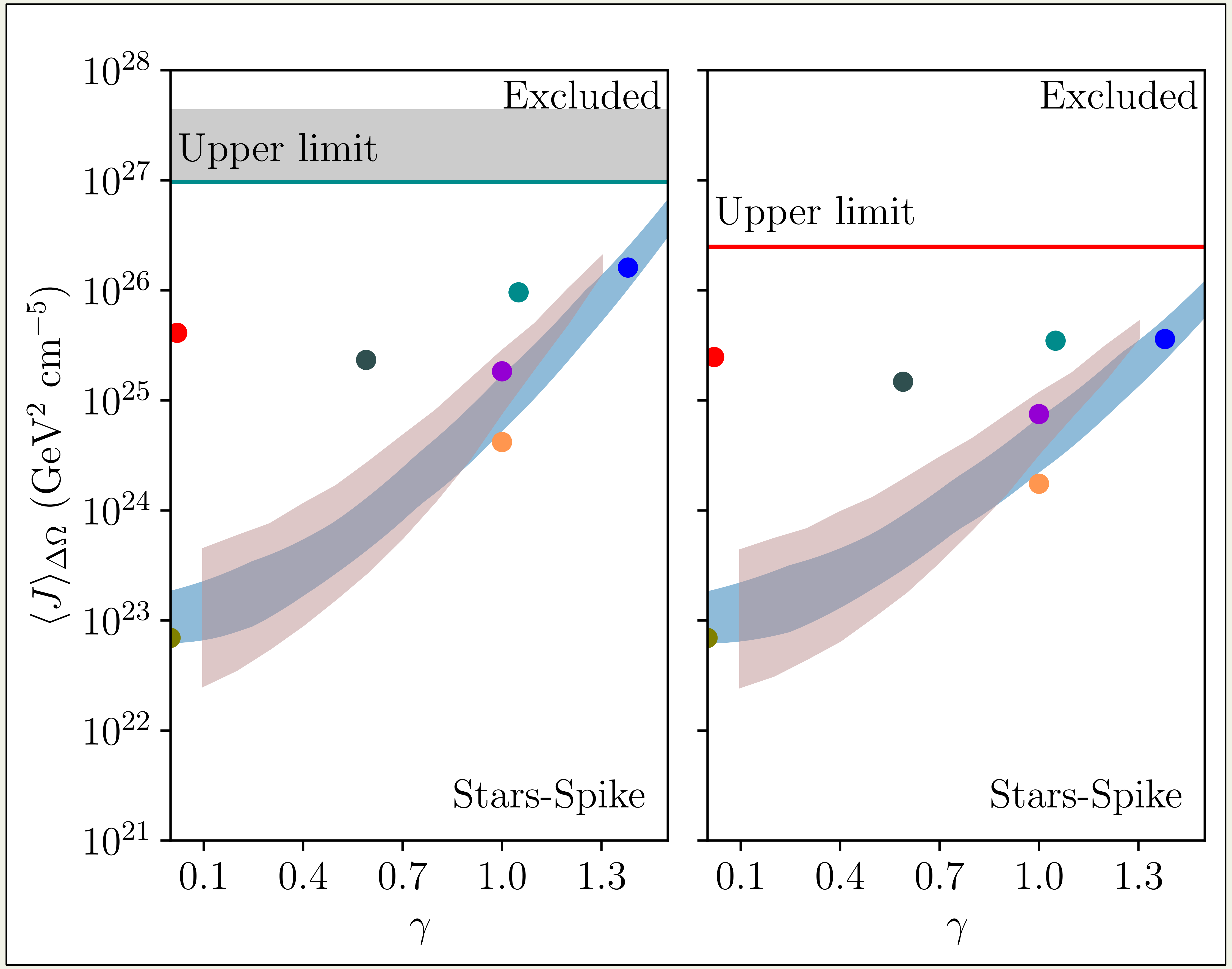
Assuming:

- Adiabatic growth of the SMBH Sgr. A*
- Central position of Sgr. A* during its formation
- No major mergers during the last t_{BH} = 10 Gyr

Spike-stars

This work, J. Zuriaga-Puig et al.



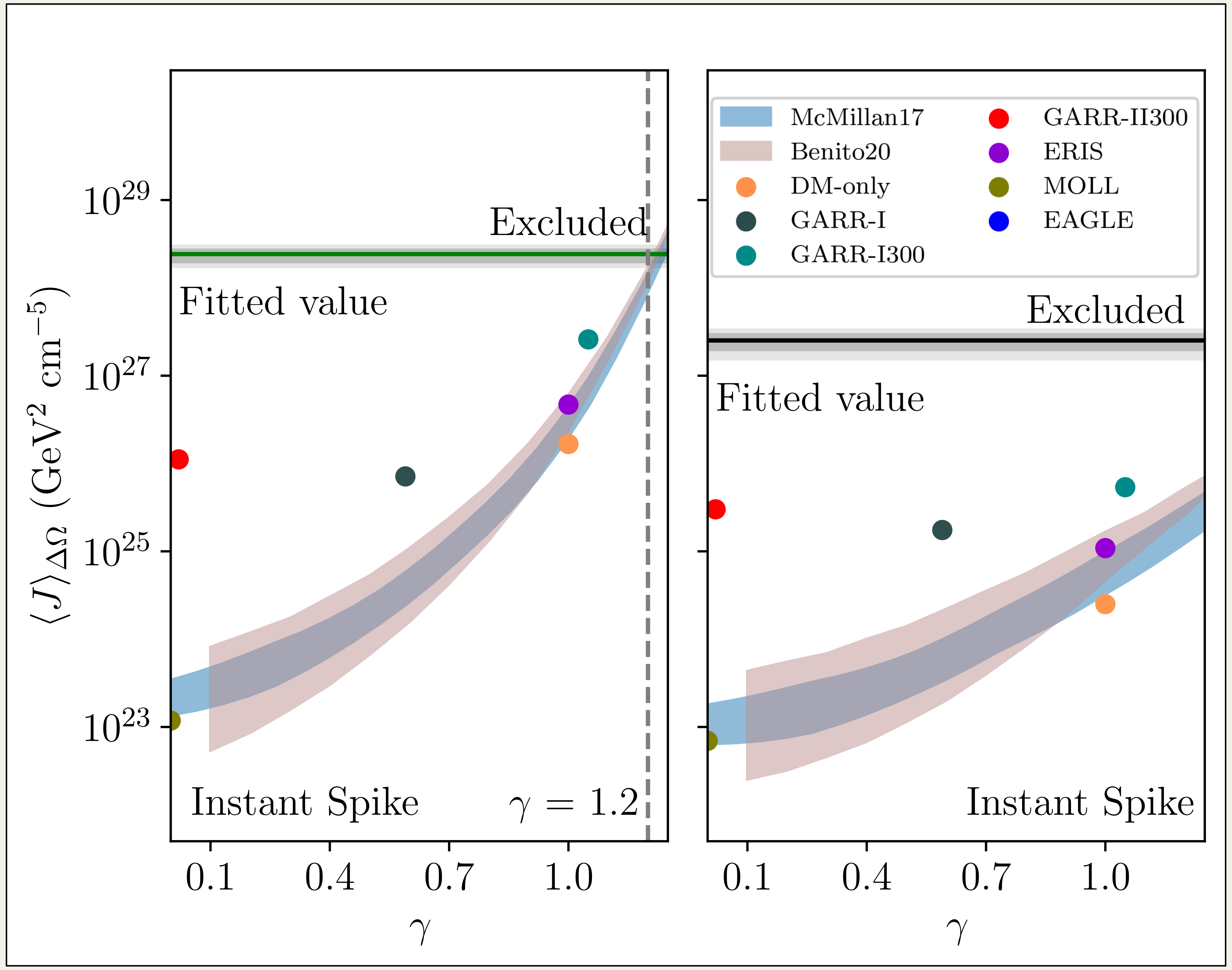


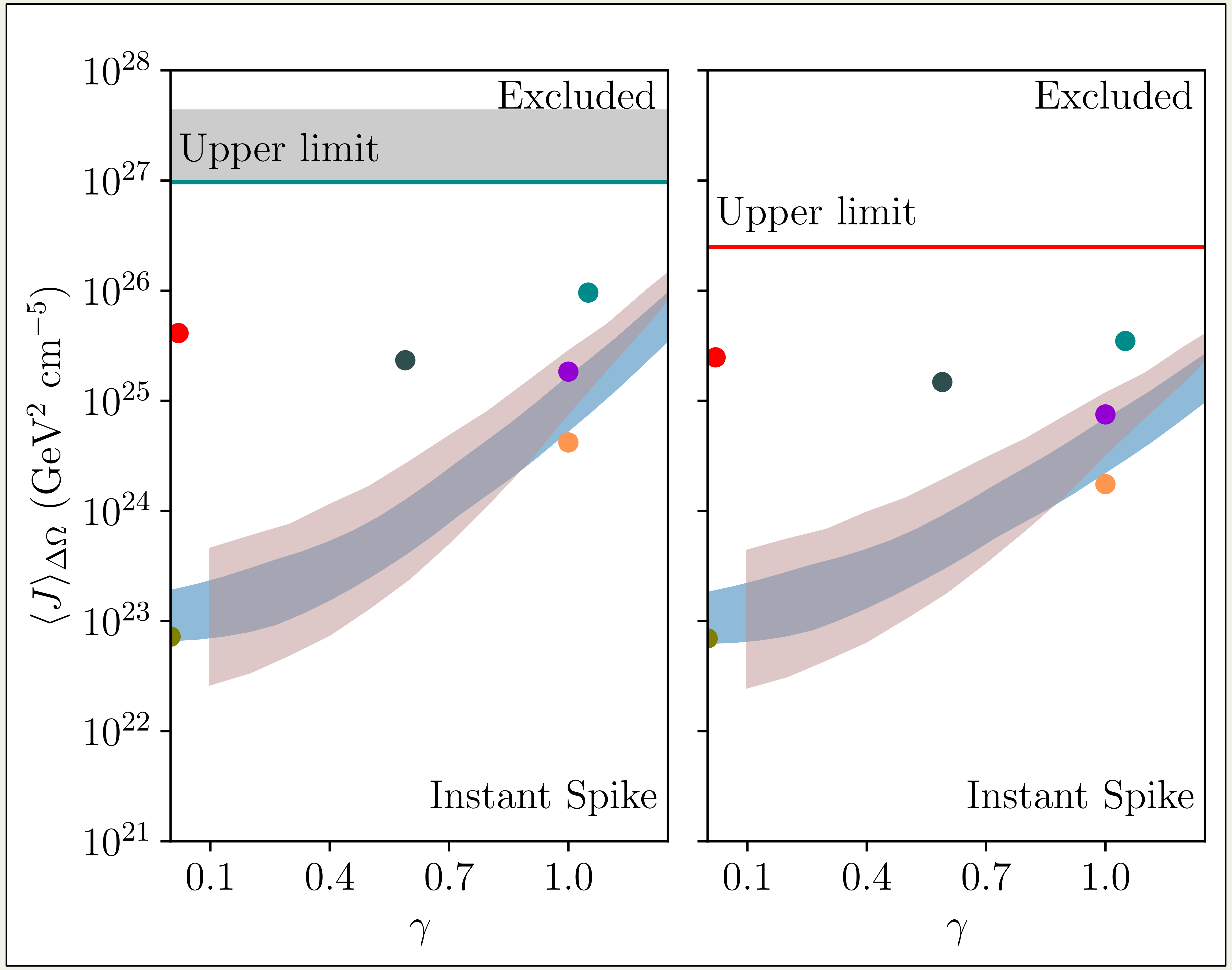
VIR **Ridge** **Diffuse** **Halo**

Assuming:
- Adiabatic spike
- Scattering of DM particles off stars → Flattening of the spike
- Heating of DM particles

Instant spike

This work, J. Zuriaga-Puig et al.

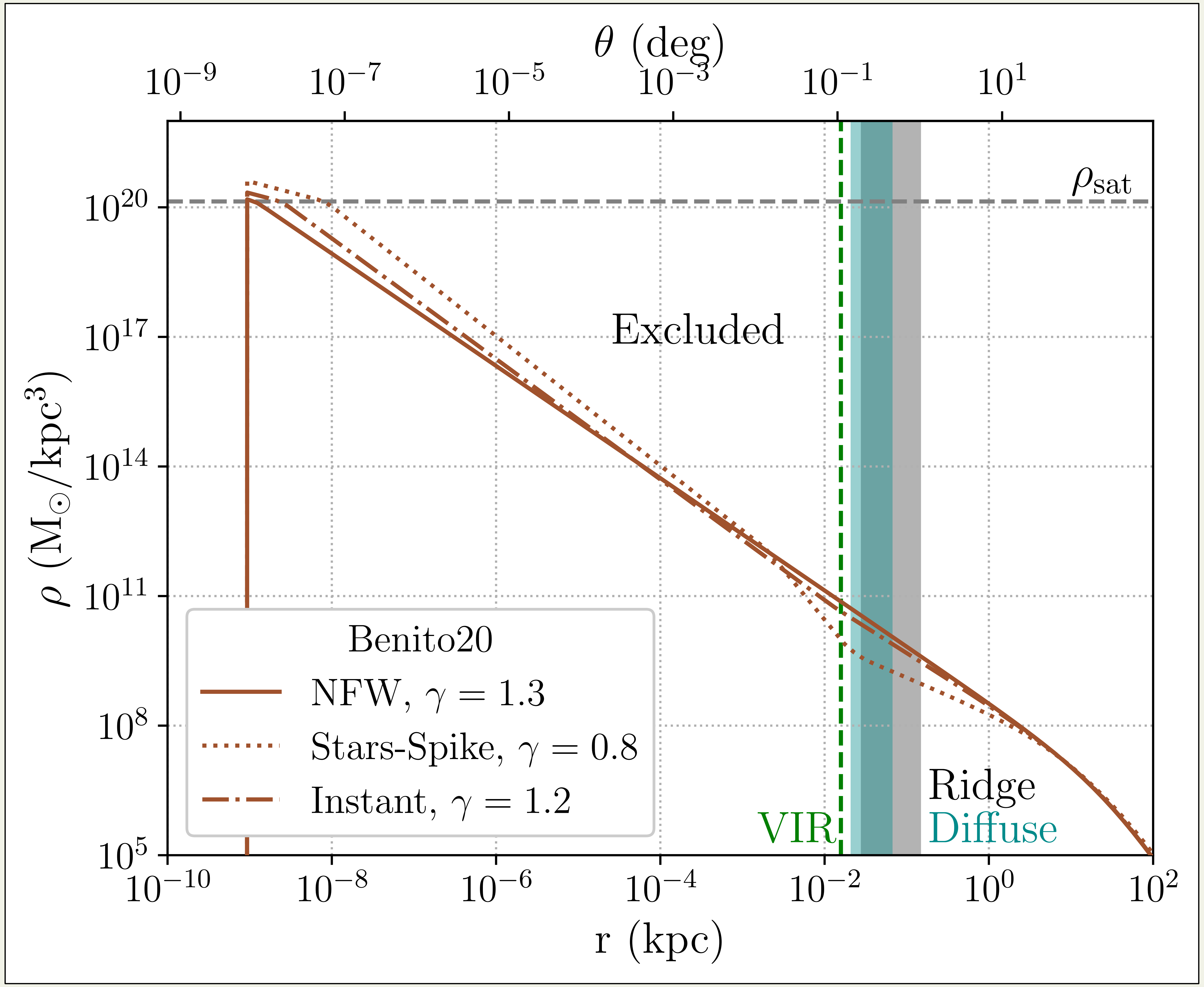


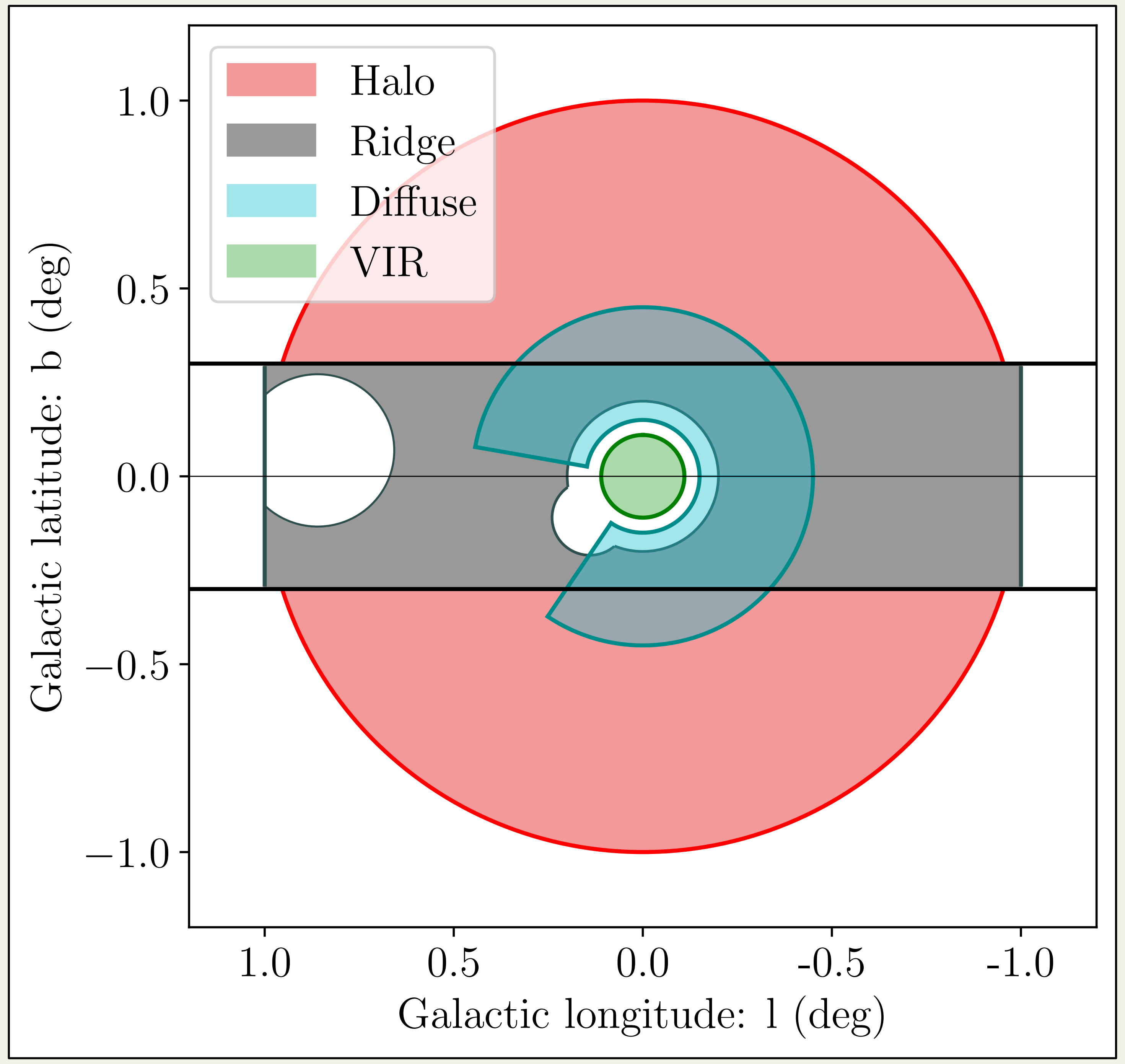


VIR **Ridge** **Diffuse** **Halo**

Assuming:
- Extreme case of instantaneous formation of the SMBH Sgr. A*

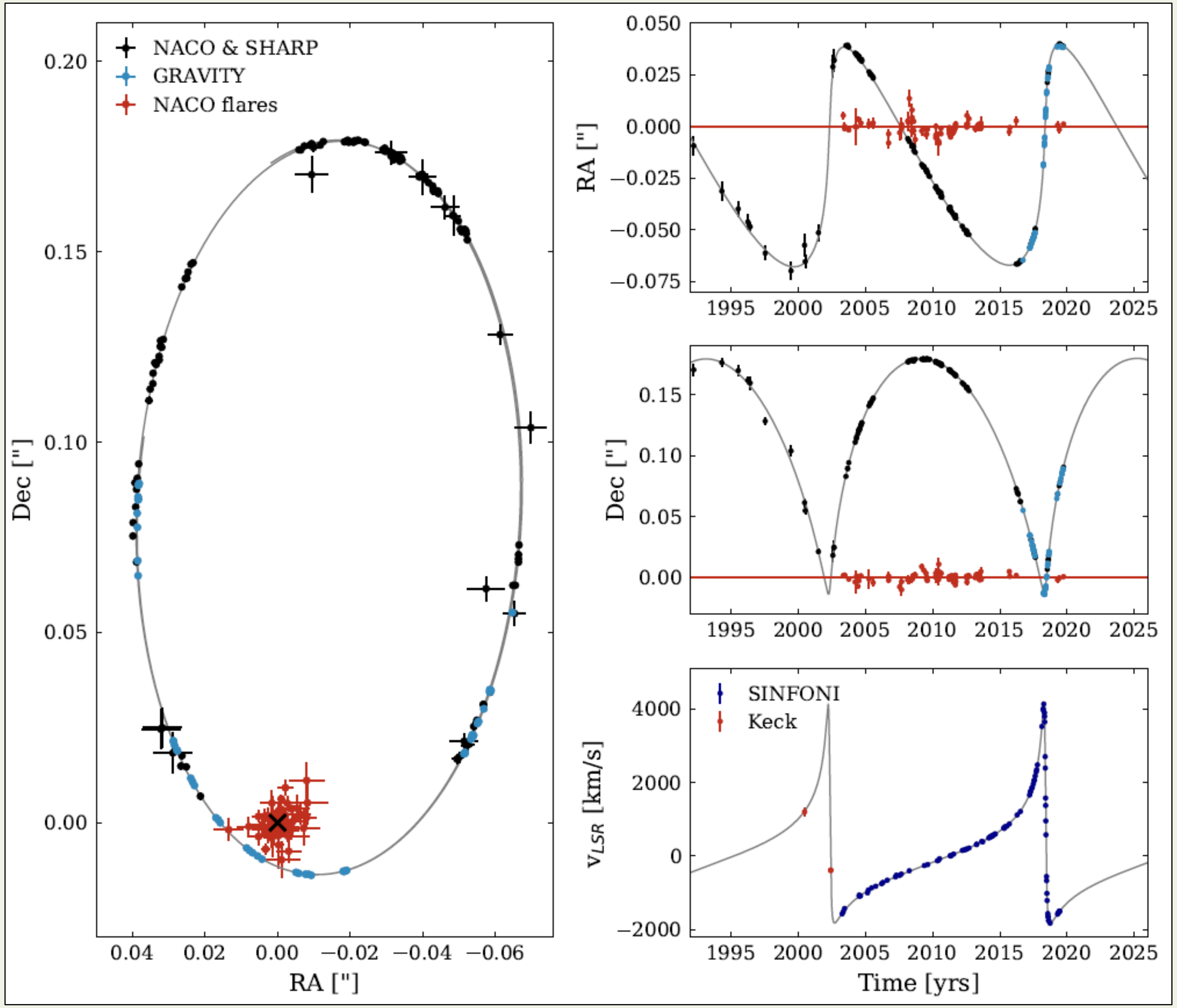
Best Profiles





- Best profiles obtained in each case
- Excluded region: the computed J-factors are greater than the fitted values

S2 star: Dynamical constraints



From the S2 orbit, we can set constraints on the extended mass within the orbit

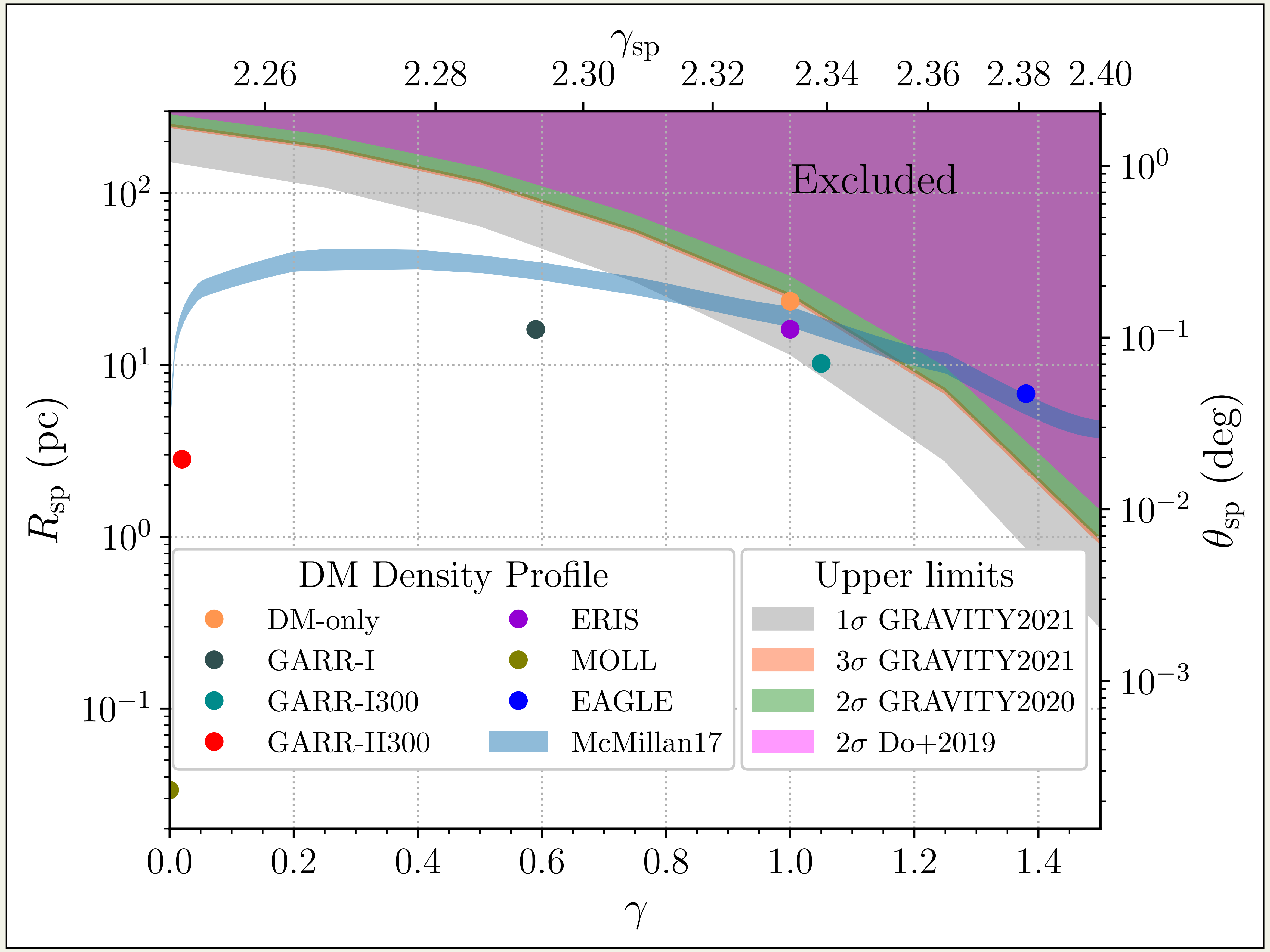
This analysis is independent on a particular DM theory or assumptions

GRAVITY Collaboration, A&A (2020)

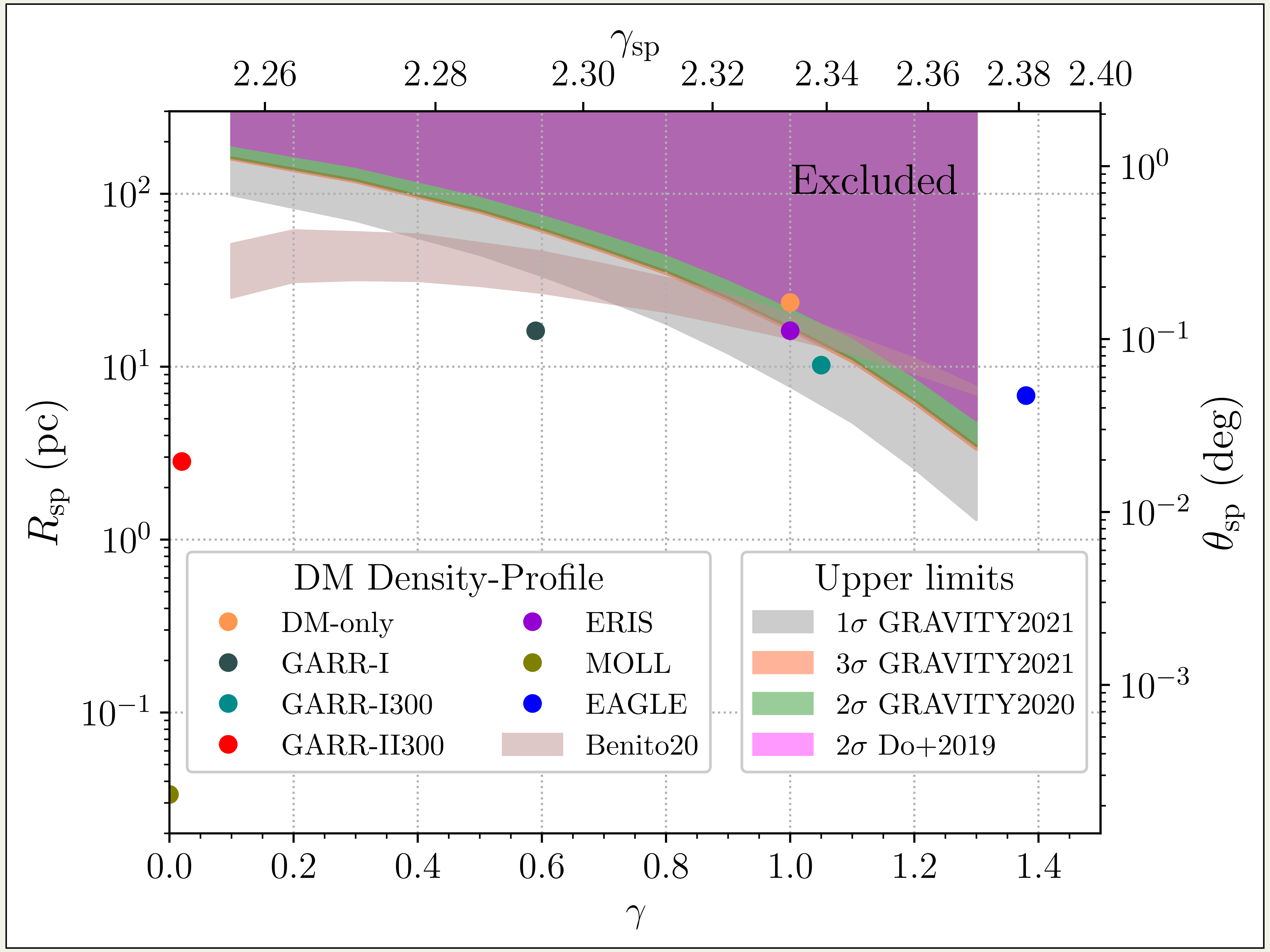
Dynamical constraints: S2 Star orbit

Adiabatic spike constraints

Update of T. Lacroix, A&A (2018)

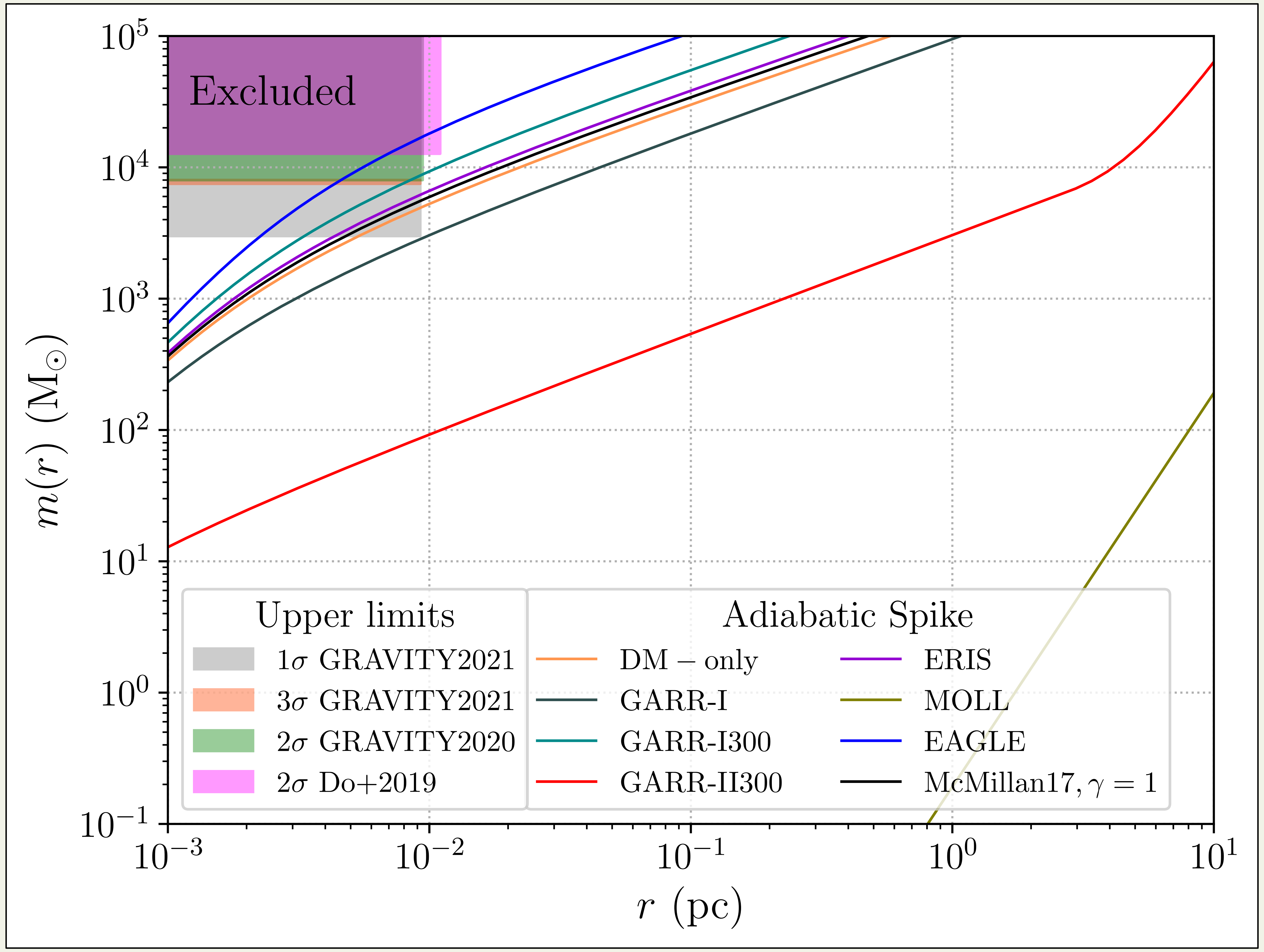


This work, J. Zuriaga-Puig et al.

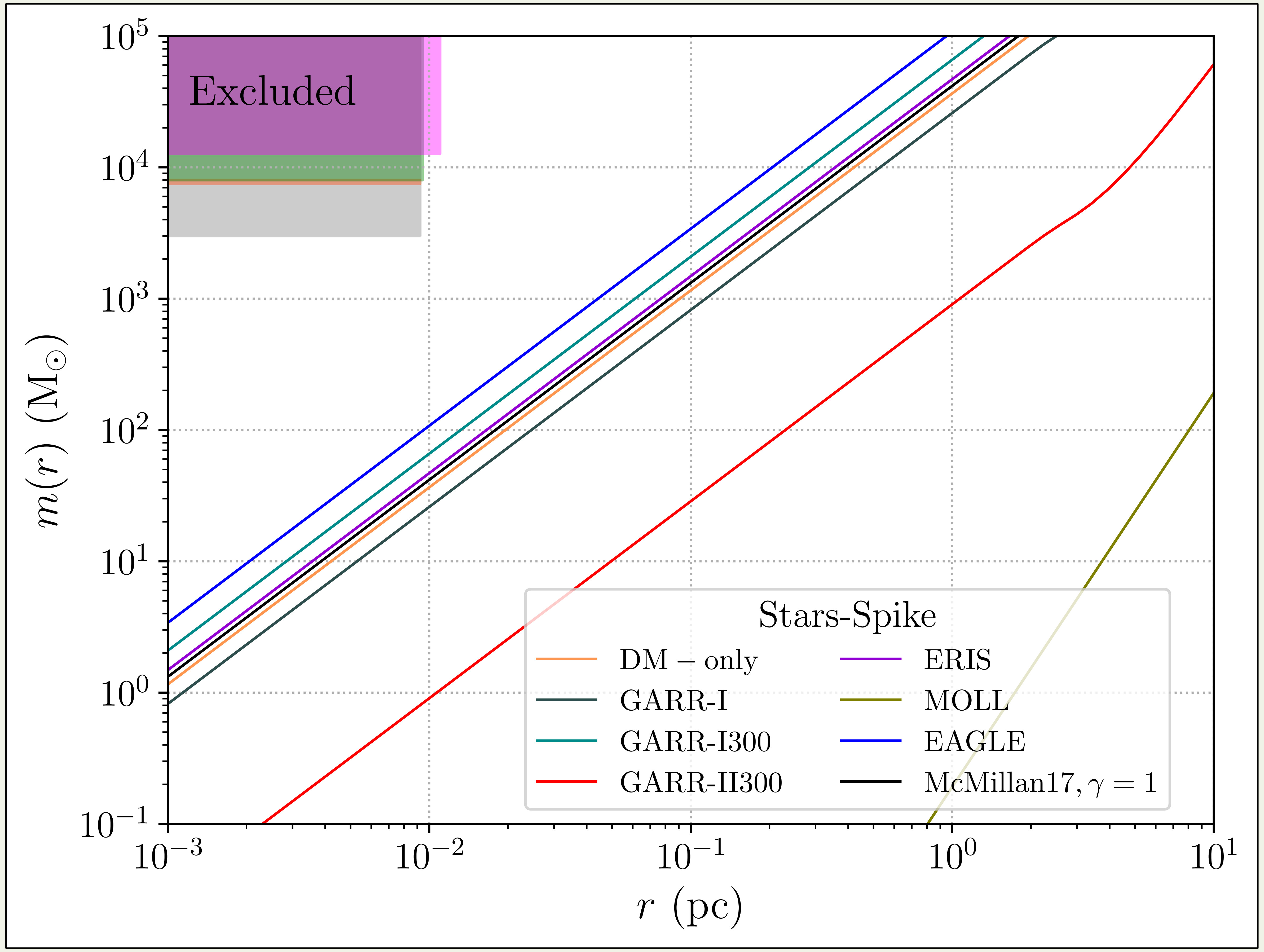


Dynamical constraints: enclosed mass

Adiabatic spike



Stars-spike

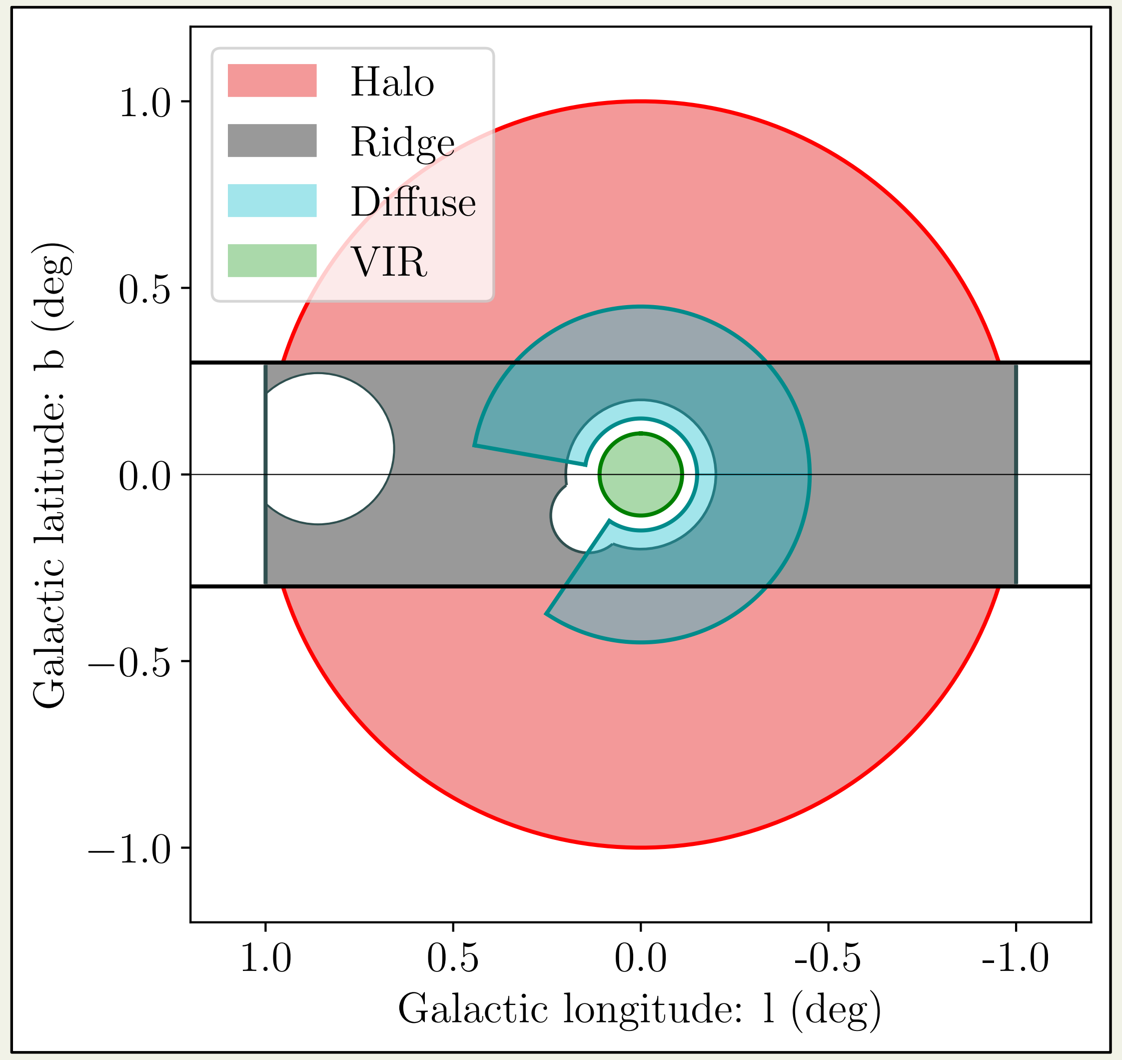


This work, J. Zuriaga-Puig et al.

Conclusions

Gamma Rays:

- Fitted value TeV WIMP: $m_{DM} = 36^{+8}_{-6}$ TeV with $\langle \sigma v \rangle = 2.2 \times 10^{-26}$ cm^3 s^{-1}
- Conservative approach: we can exclude all the profiles with a J-Factor greater than the fitted values
- Diffuse region: If a DM spike exists in the GC, it is required to have angular dimensions $\theta_{spike} \lesssim \theta_{Diff} = (0.15^{\circ}, 0.45^{\circ})$ Future analysis is required



Final constraints:

Profile	VIR	Ridge	Diffuse	S2-star
Gen. NFW	Excluded $\gamma \gtrsim 1.36 \pm 0.02$	Allowed	Allowed	Allowed
Adiabatic	Excluded	Allowed	Allowed	Excluded $\gamma \gtrsim 0.6 \pm 0.2$
Star-spike	Excluded $\gamma \gtrsim 0.76^{+0.04}_{-0.07}$	Allowed	Allowed	Allowed
Instant	Excluded $\gamma \gtrsim 1.21^{+0.02}_{-0.01}$	Allowed	Allowed	Allowed

Thank you for your time!

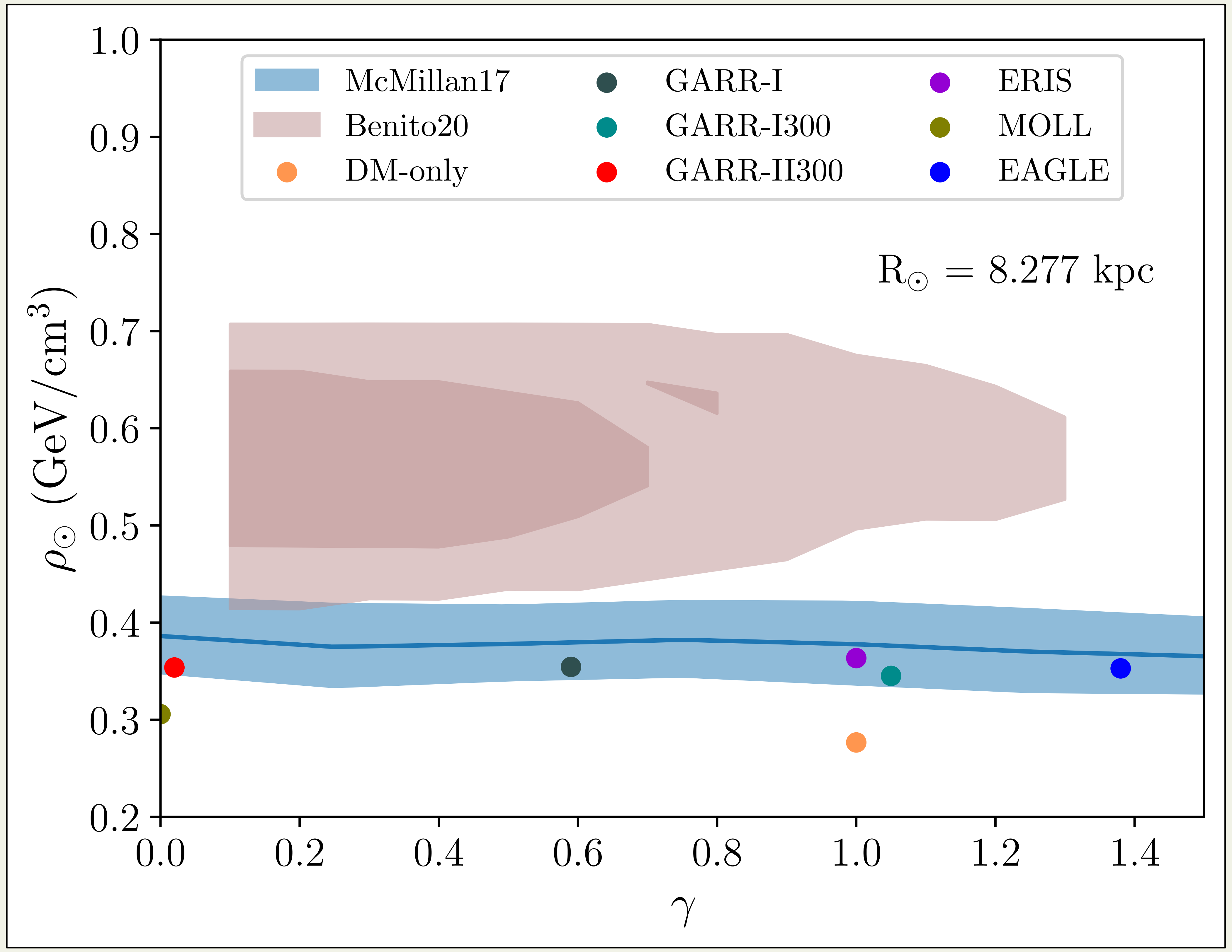
McMillan17 & Benito20

McMillan17 [MNRAS(2017)]

- Modeling of the bulge, the stellar disc, the gas disc and the DM halo
- Object of observation: maser sources, associated with high-mass star forming regions (HMSFR)
- HMSFR are expected to be in circular orbits

Benito20 [Physics of the Dark Universe (2021) 2009.13523_v3]

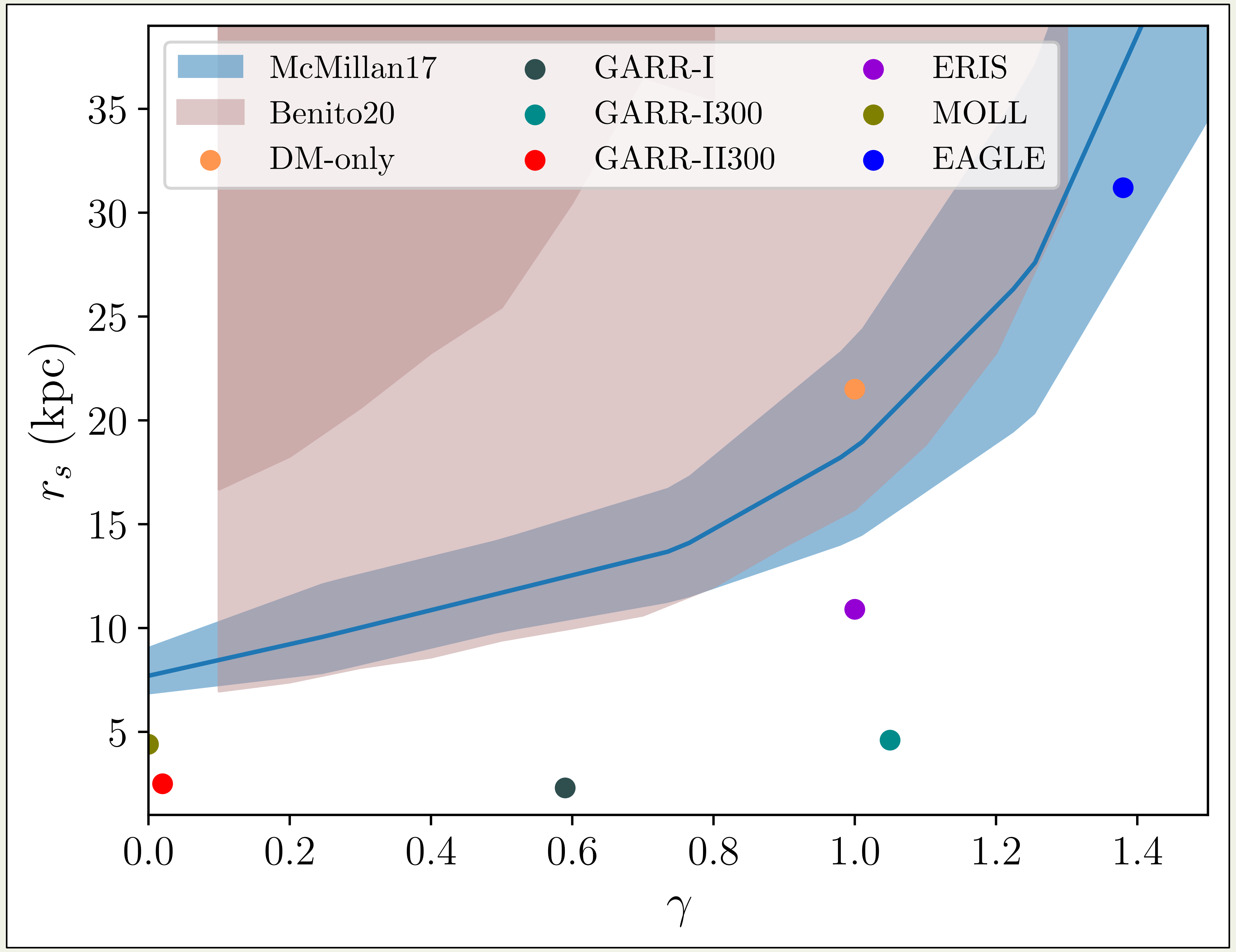
- Modeling of the bulge, the stellar disc, the gas disc and the DM halo
- Rotation curve analysis: kinematics of gas, masers and stars

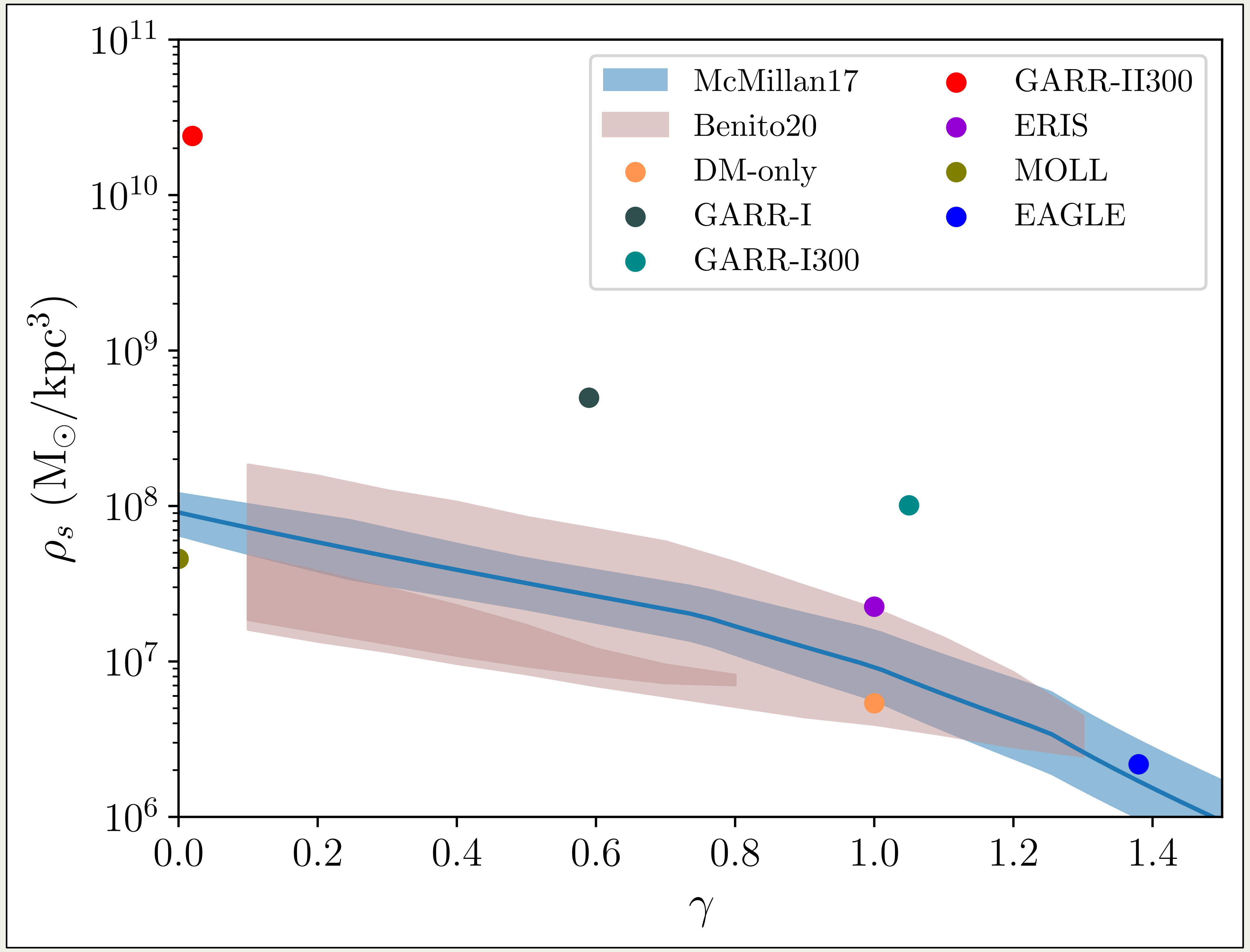


Parameters of the DM Density Profile

$$\rho_{halo}(r) = \frac{\rho_s}{(\frac{r}{r_s})^\gamma (1 + (\frac{r}{r_s})^\alpha)^{\frac{\beta-\gamma}{\alpha}}}$$

NFW: $(\gamma, \alpha, \beta) = (1,1,3)$





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NFW: $(\gamma, \alpha, \beta) = (1,1,3)$

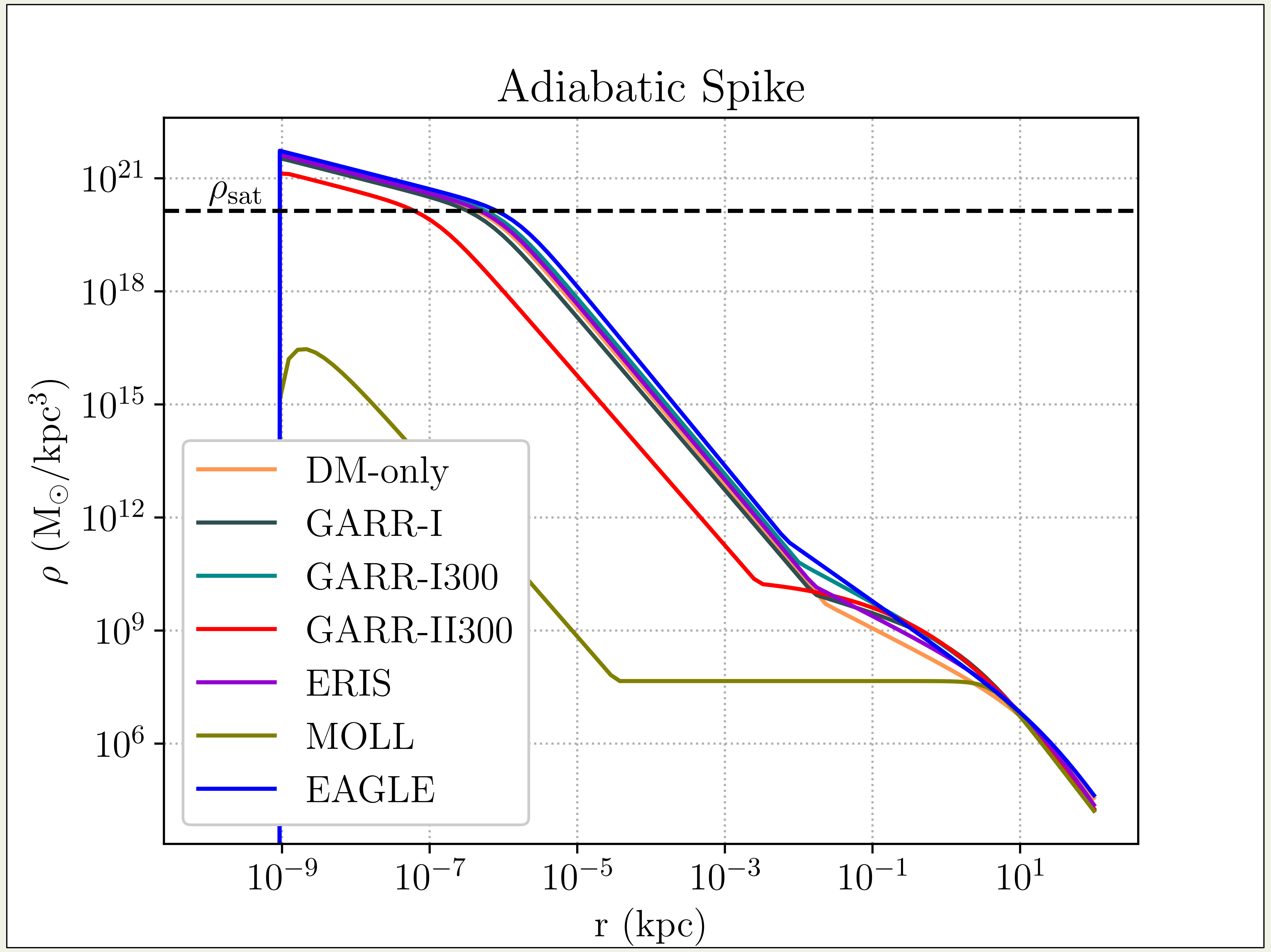
Profile	γ	$\gamma_{\rm sp}$	$R_{\rm sp}$ (pc)	$\theta_{\rm sp}$ (deg)	$\gamma_{\rm inst}$	$R_{\rm inst}$ (pc)	$\theta_{\rm inst}$ (deg)
DM-only	1	2.33	23.5	0.17	1.33	16.9	0.12
GARR-I	0.59	2.29	16.1	0.11	1.23	13.2	0.09
GARR-I300	1.05	2.34	10.2	0.07	1.35	8.0	0.06
GARR-II300	0.02	2.25	2.8	0.02	1.14	19.0	0.13
ERIS	1	2.33	16.2	0.1	1.33	11.6	0.08
MOLL	8×10^{-9}	2.25	0.03	0.0002	1.12	88.0	0.62
EAGLE	1.38	2.38	6.8	0.05	1.48	72.6	0.51
McMillan17	0 - 1.5	2.25 - 2.40	3.8 - 47.6	0.03 - 0.33	1.12 - 1.41	80.5 - 11.7*	0.56 - 0.08*
Benito20	0.1 - 1.3	2.26 - 2.37	6.9 - 61.3	0.05 - 0.43	1.14 - 1.44	98.4 - 10.1*	0.70 - 0.07*

Adiabatic spike

Gondolo & Silk Phys.Rev.Lett. (1999)
L.Sadeghian et al. Phys.Rev. D (2013)

Assuming:

- Adiabatic growth of the SMBH Sgr. A*
- Central position of Sgr. A* during its formation
- No major mergers during the last t_{BH} = 10 Gyr



- Central slope (non circular orbits of the DM particles):

$$\rho_{sat}(r) = m_{DM}/(t_{BH}\langle\sigma v\rangle)(\frac{r}{R_{sat}})^{-1/2}$$

- Spike ($\gamma_{sp} \sim 2{,}25 - 2{,}5$):

$$\rho_{sp(r)} = \rho_{sp}(1 - 2\frac{R_S}{r})^3(\frac{r}{R_{sp}})^{-\gamma_{sp}}$$

- External profile:

$$\rho_{halo}(r) = \frac{\rho_s}{(\frac{r}{r_s})^{\gamma}(1 + (\frac{r}{r_s})^{\alpha})^{\frac{\beta-\gamma}{\alpha}}}$$

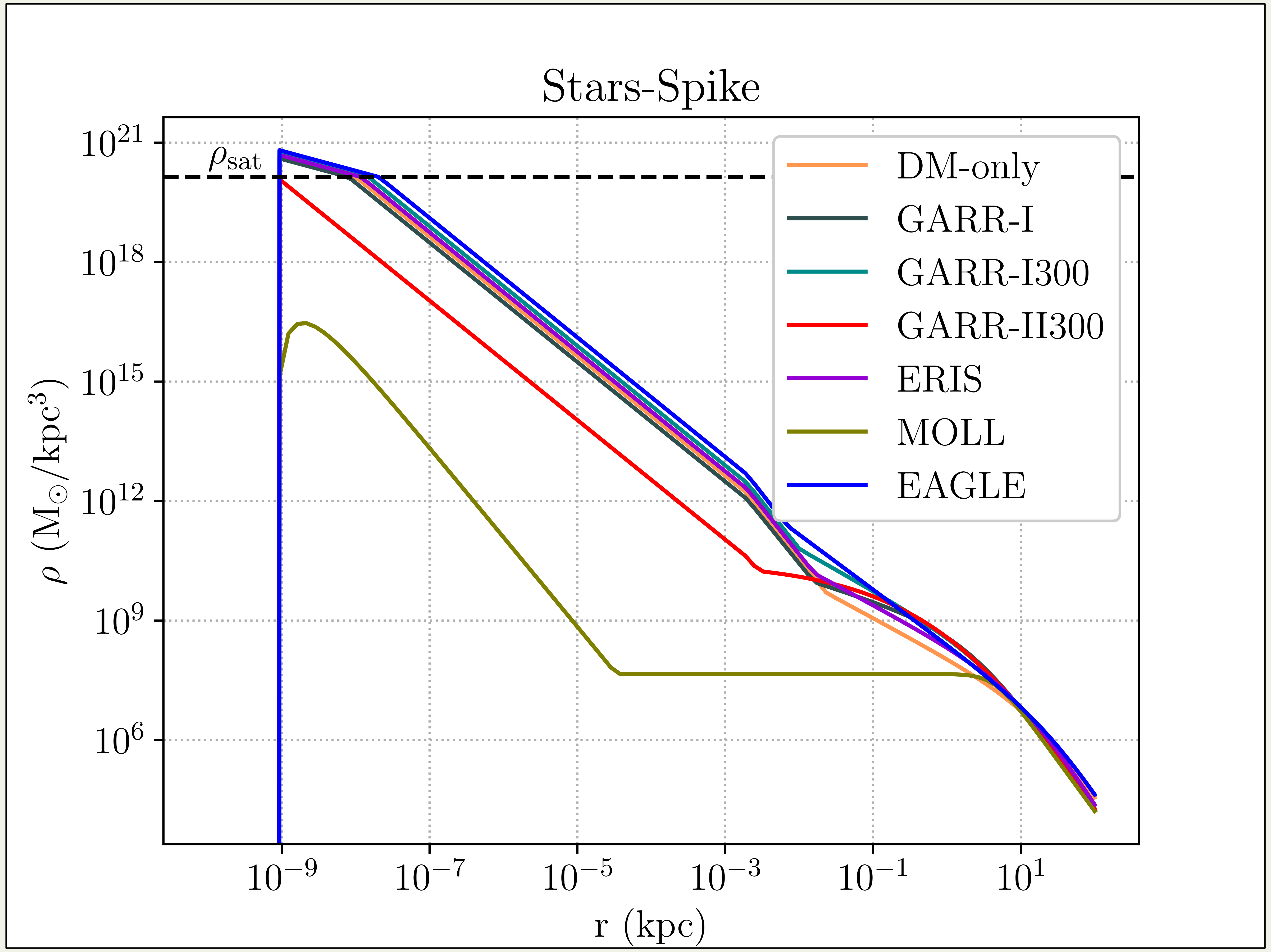
Stars-spike

E. Vasiliev et al. Phys.Rev. D (2008)
G. Bertone et al. Modern Phys. Letters (2005)

Assuming:

- Adiabatic spike
- Scattering + heating of DM particles off stars

This results on the flattening of the spike to $\gamma_{star} = 1.5$ at $r < 2$ pc



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- Spike ($\gamma_{sp} \sim 2{,}25 - 2{,}5$):

$$\rho_{sp(r)} = \rho_{sp}(1 - 2\frac{R_S}{r})^3(\frac{r}{R_{sp}})^{-\gamma_{sp}}$$

- External profile:

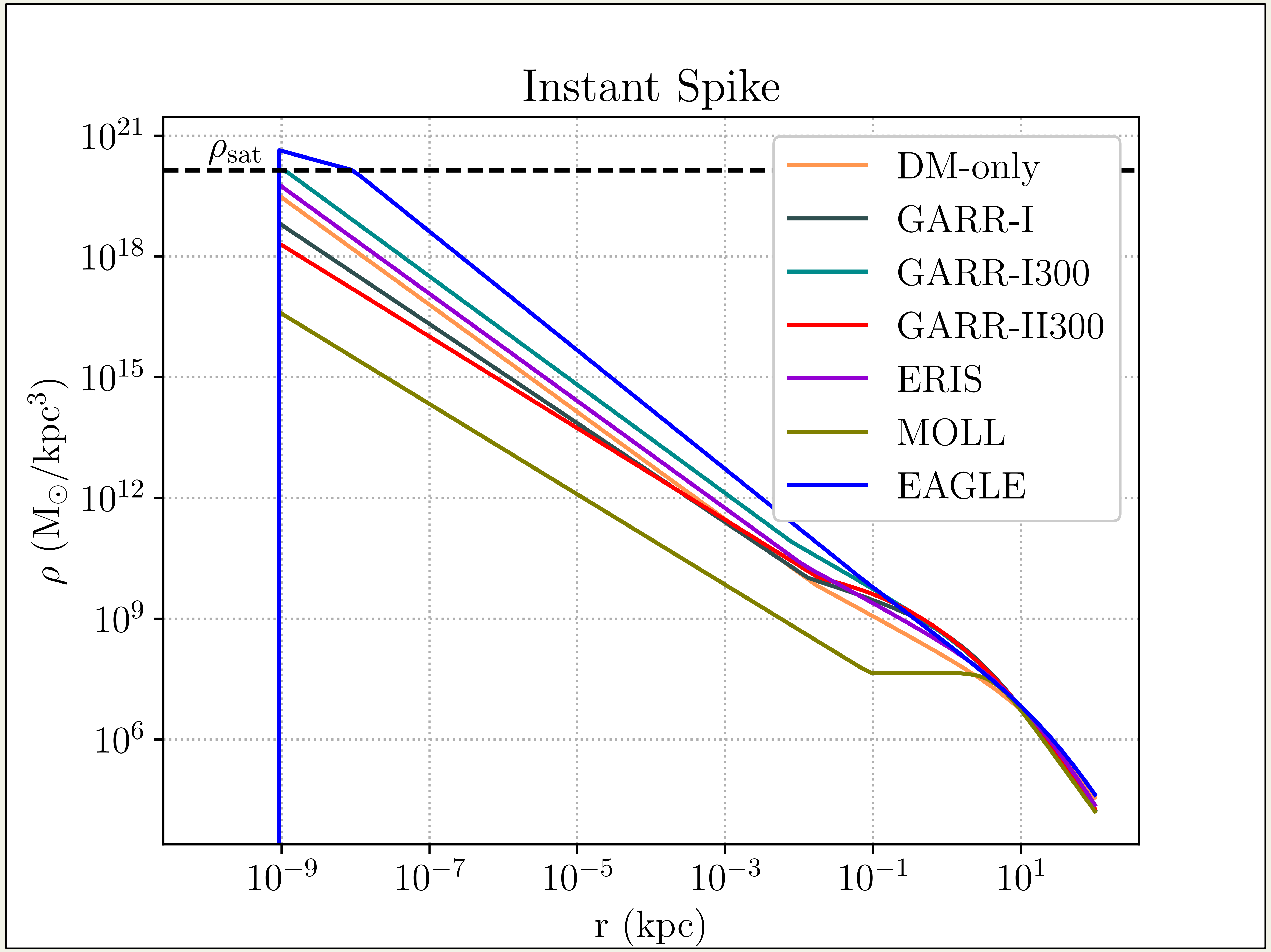
$$\rho_{halo}(r) = \frac{\rho_s}{(\frac{r}{r_s})^\gamma(1 + (\frac{r}{r_s})^\alpha)^{\frac{\beta-\gamma}{\alpha}}}$$

Instant spike

P. Ullio et al. Phys.Rev. D (2001)

Assuming:

- Extreme case of the instantaneous growth of Sgr. A*



- Central slope (non circular orbits of the DM particles):

$$\rho_{sat}(r) = m_{DM}/(t_{BH}\langle\sigma v\rangle)(\frac{r}{R_{sat}})^{-1/2}$$

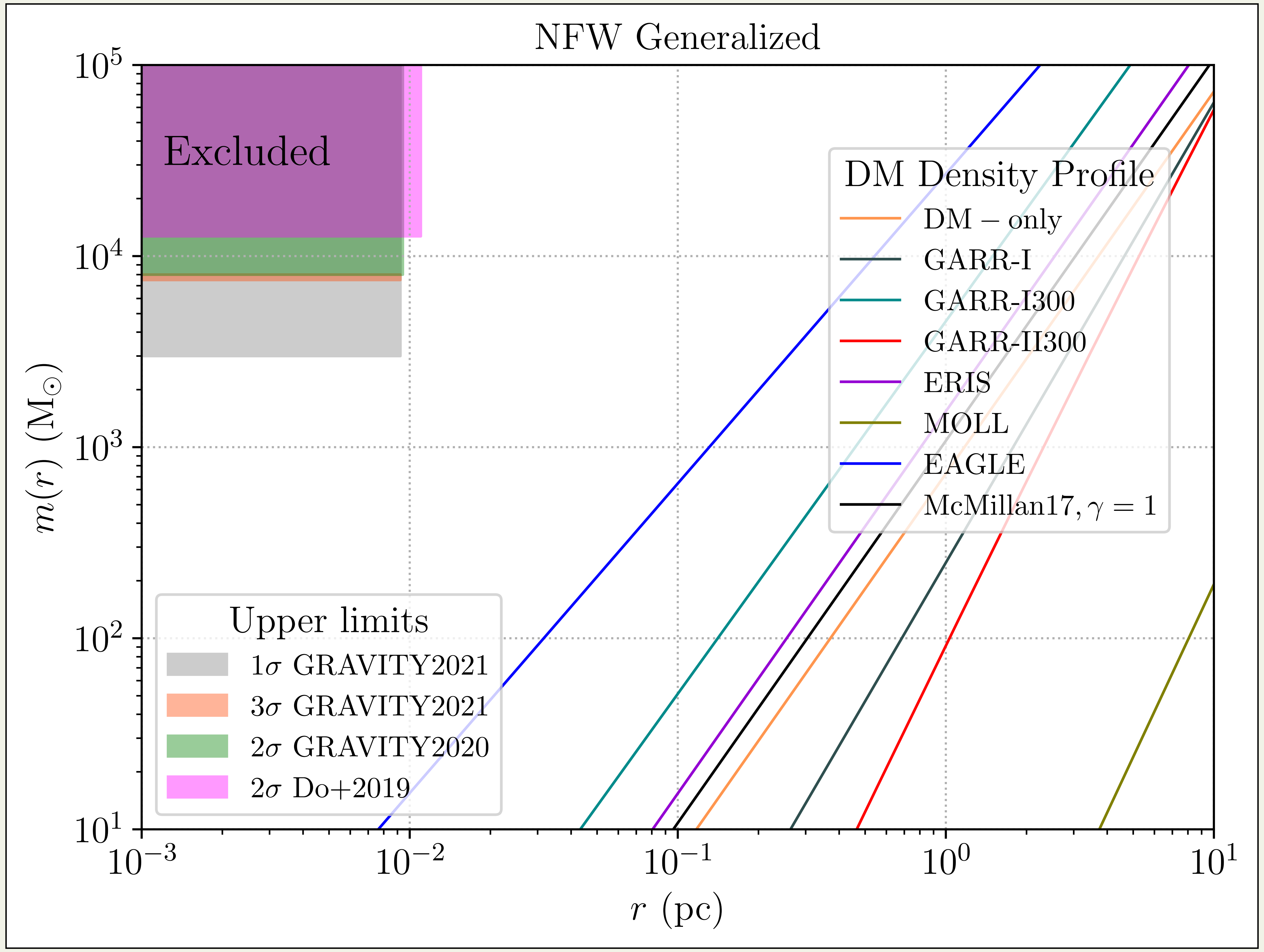
- Instantaneous spike ($\gamma_{ints} \sim 4/3$, $R_{inst} \sim 10 - 90$ pc):

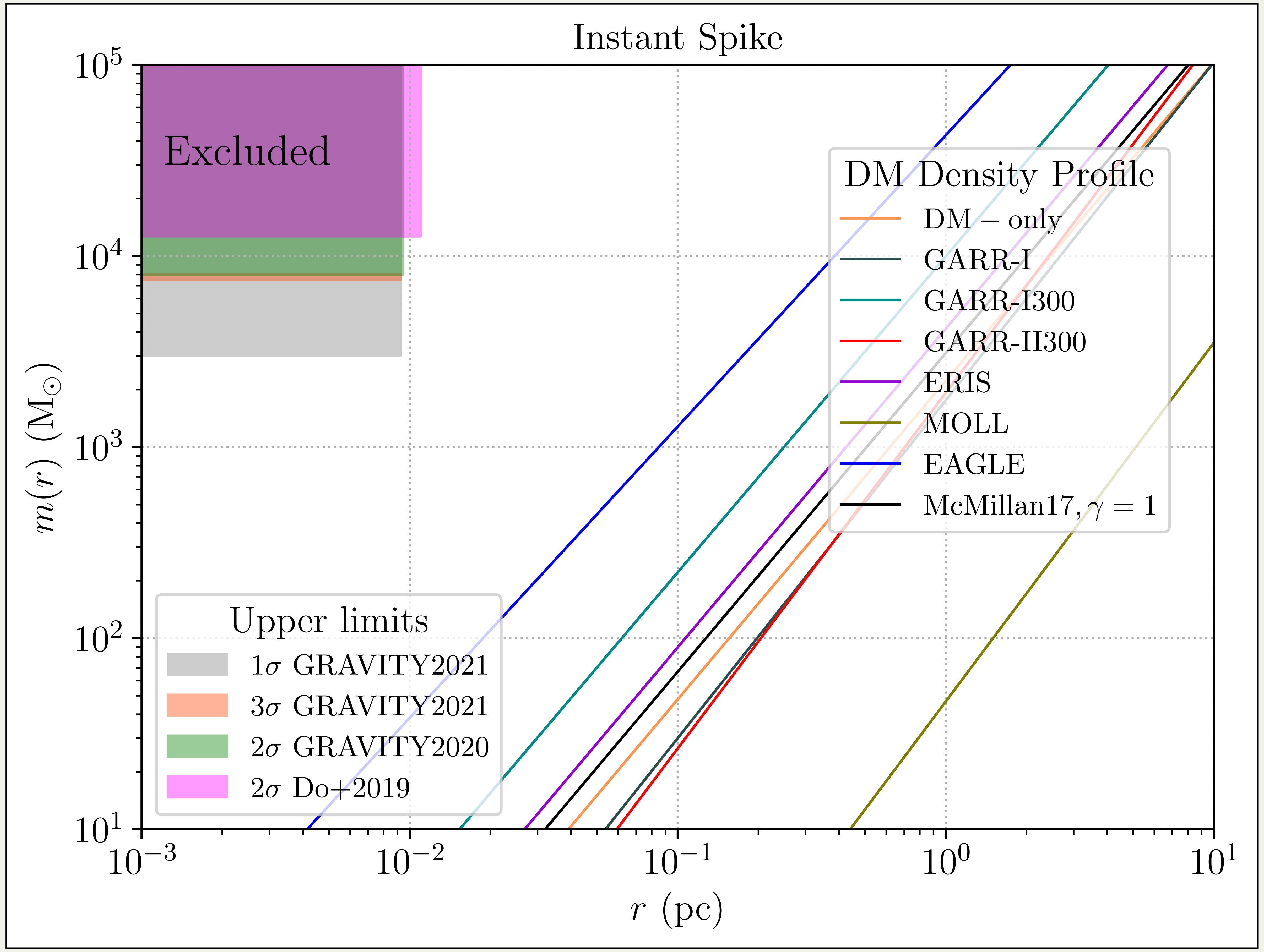
$$\rho_{inst}(r) = \rho_{halo}(R_{inst})(\frac{r}{R_{inst}})^{-\gamma_{inst}}$$

- External profile:

$$\rho_{halo}(r) = \frac{\rho_s}{(\frac{r}{r_s})^{\gamma}(1+(\frac{r}{r_s})^{\alpha})^{\frac{\beta-\gamma}{\alpha}}}$$

More dynamical constraints





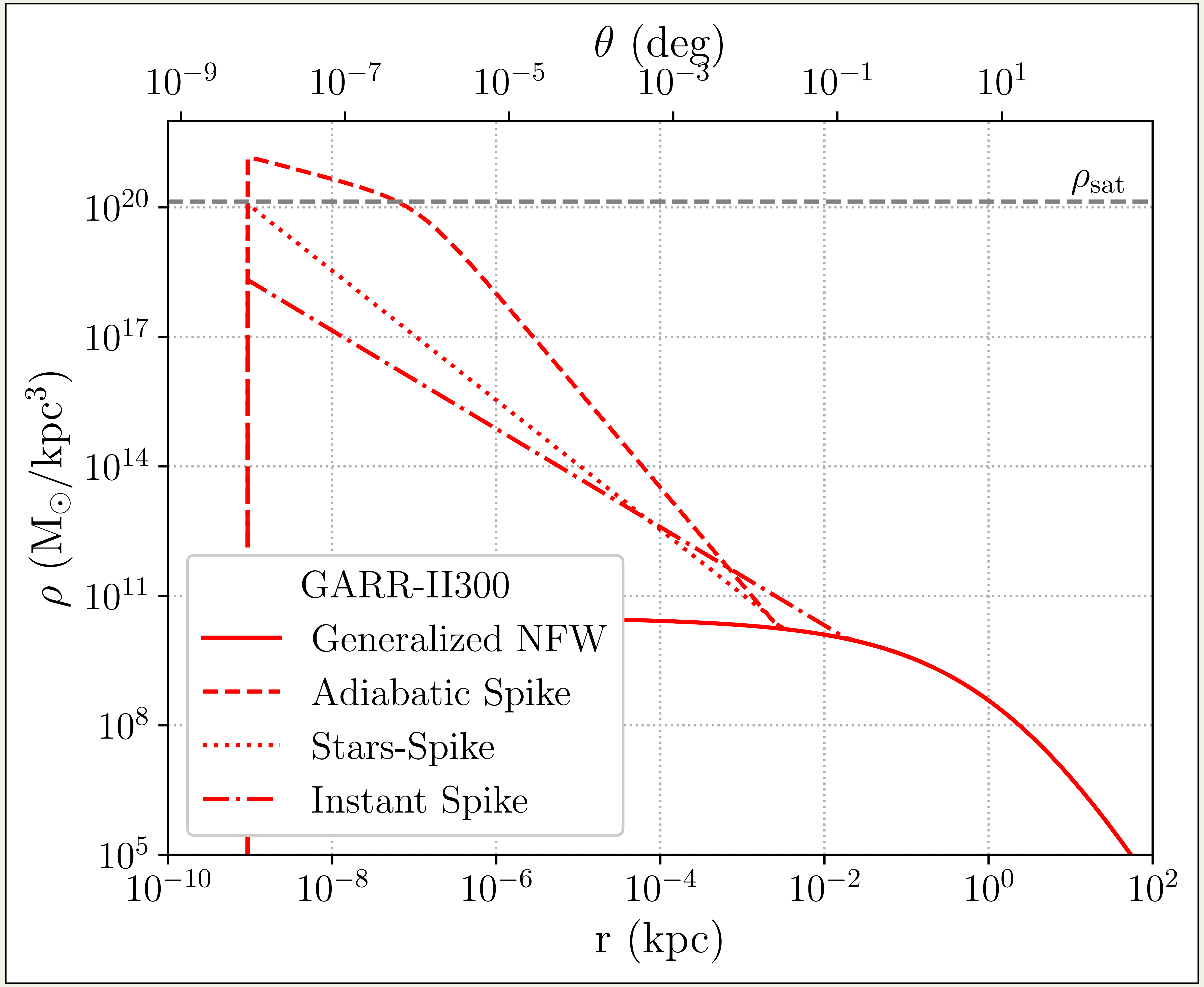
DRAGON model

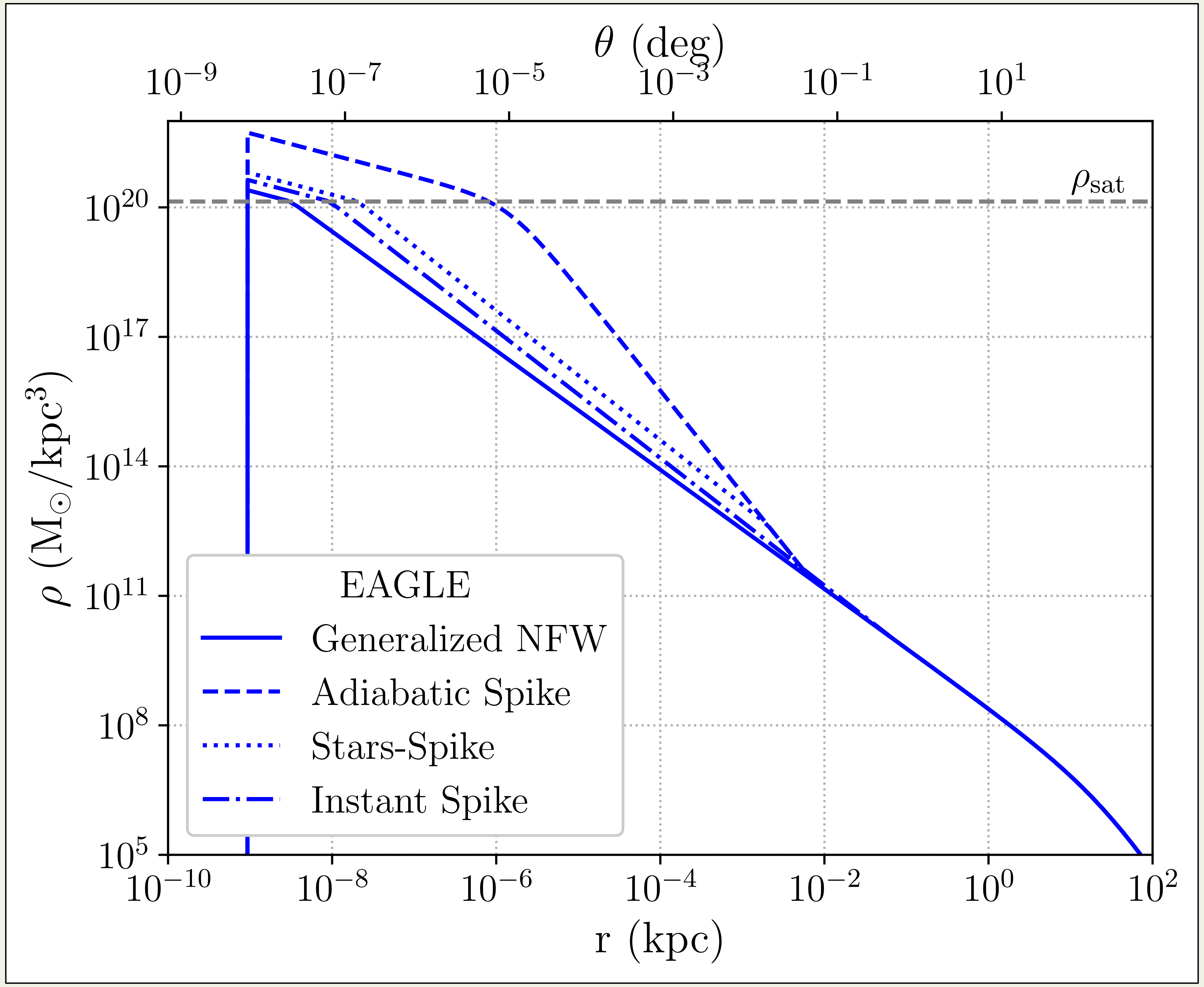
$$\frac{d\Phi_{\mathrm{Bg}}}{dE} = B^2 \frac{d\Phi_{\mathrm{DRAGON}}}{dE}$$

B^2 is an $\mathcal{O}(1)$ normalizing factor left as a free parameter

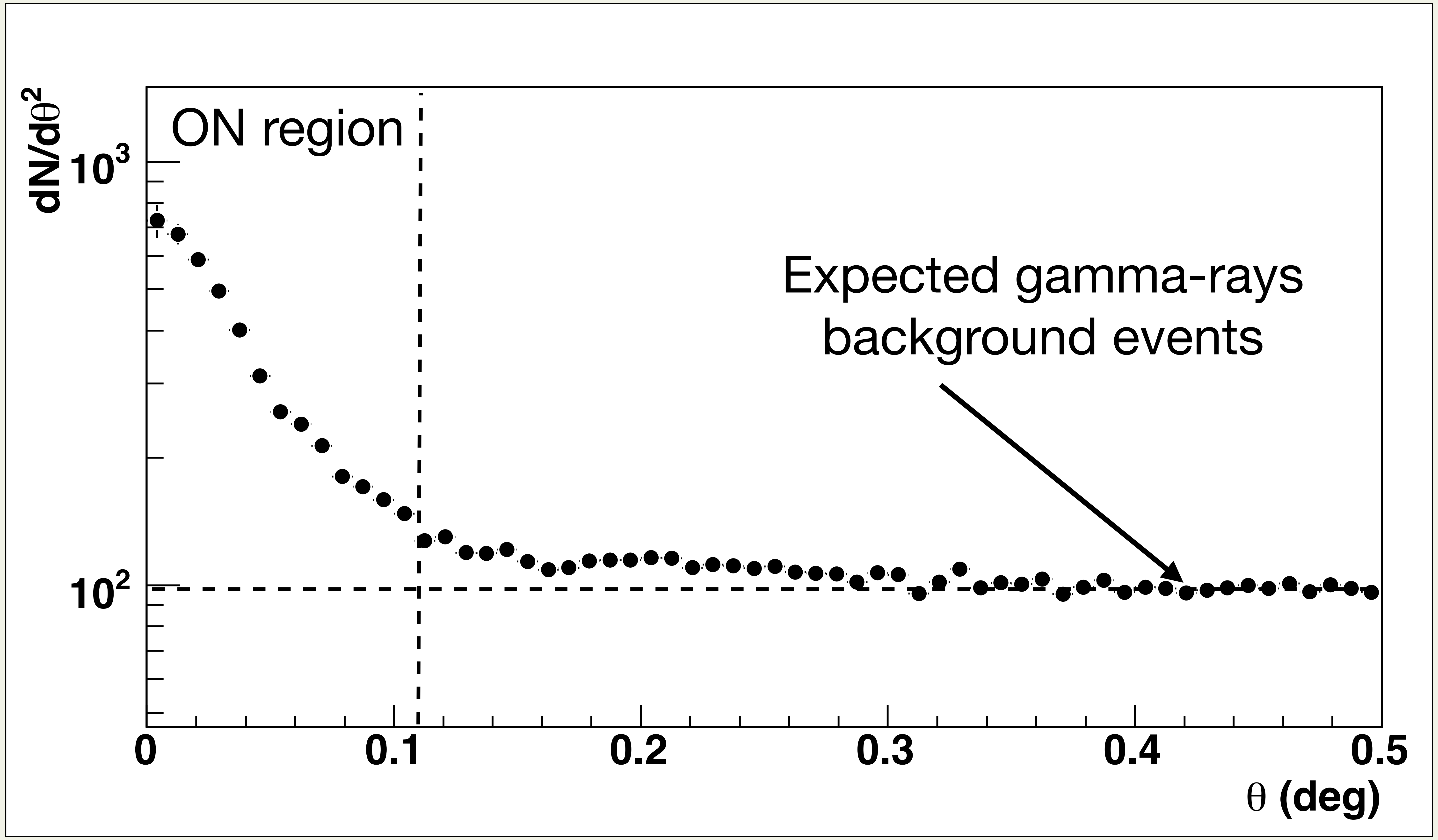
- The reason of this renormalization is due to the poor knowledge of the conversion factor between the CO emissivity and the molecular gas column density (see L. Tibaldo et al., Universe (2021) for a review)
- This factor scales linearly with the diffuse emission, hence we leave B as a free parameter
- The spectral shape is given by DRAGON, and we have computed the flux in each region

DM density profiles examples





VIR HESS J1745-290



HESS collaboration, A&A (2009)

Expected gamma-rays background events computed as an ON-OFF analysis

Comparison with other observations