

Cosmic-ray cooling by dark matter in astrophysical jets

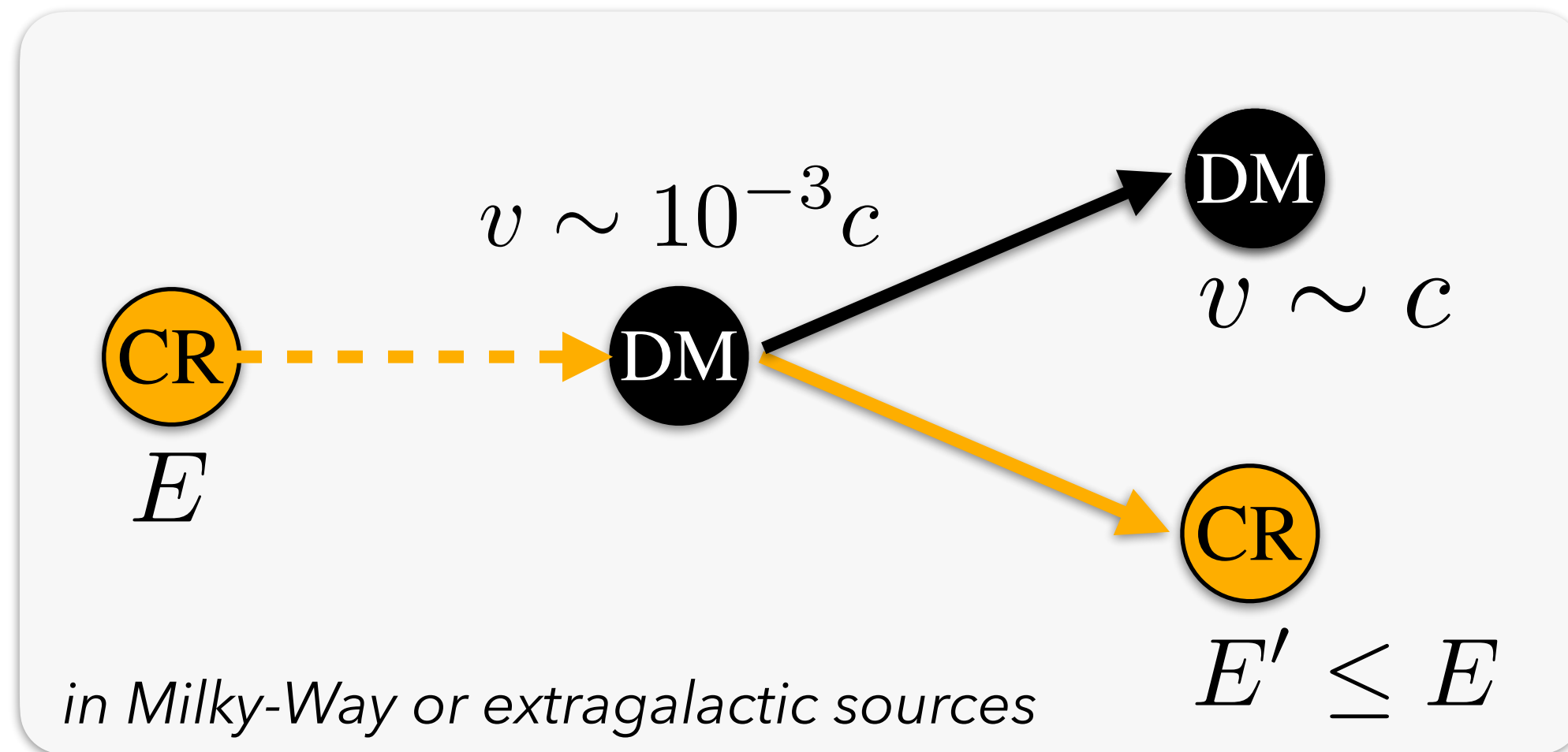
28/01/2026, TAsP meeting, Bologna

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Based on
Dimitrios Kantzas, Francesca Calore, MC,
[arXiv:2509.18850](https://arxiv.org/abs/2509.18850)

DM-CR interactions

A promising way to probe sub-GeV Dark Matter (DM) particles involve their interaction with Cosmic Rays (CRs).



- ◆ **Boosted DM particles:** signatures at direct-detection experiments thanks to higher kinetic energies.

Bringmann & Pospelov PRL'19, Ema+ PRL'19, Alvey+ PRL'19, Bondarenko+ JHEP'20, Wang+ PRL'22, Granelli+ JCAP'22, Cui+ PRL'22, ...

- ◆ **CR cooling mechanism:** modification of the CR transport and the subsequent non-thermal emission.

Gorchtein+ PRD'11, Cappiello+ PRD'19, Herrera & Murase PRD'24, Lu+ RAA'24, Gustafson+ PRD'25, De Marchi+ 2412.07861 & 2506.06416, Mishra+ 2504.03409, Ambrosone+ (with MC) PRL'23

$$\left(\frac{dE}{dt}\right)_{\text{DM-CR}} = \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \int T_{\text{DM}} \frac{d\sigma_{\text{el}}}{dT_{\text{DM}}} dT_{\text{DM}}$$

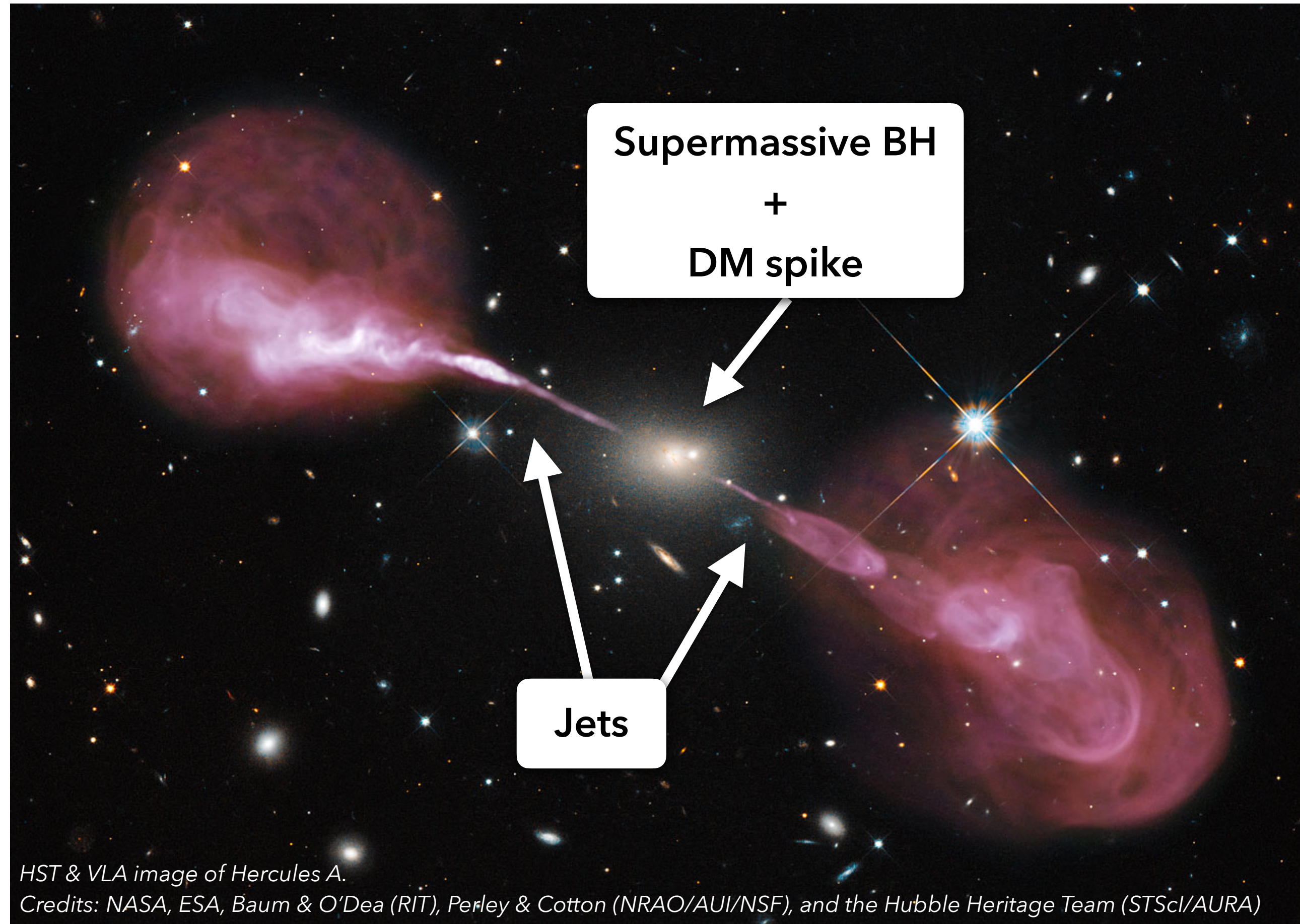
Additional energy-loss process

$$\implies t_{\text{DM-CR}} = \left[-\frac{1}{E} \left(\frac{dE}{dt}\right)_{\text{DM-CR}} \right]^{-1}$$

Timescale of DM-CR interactions

Active Galactic Nuclei (AGNs)

AGNs are ideal targets as the DM density is expected to be significantly larger near the Black Hole (BH).



- ◆ When the CR-DM cooling process dominates the CR transport \rightarrow suppression of the γ -ray and ν flux
- ◆ Previous constraints simply according to

$$t_{\text{DM-CR}} \lesssim 0.1 t_{\text{total}}$$

Our innovative methodology

1. More self-consistent DM halo parameters
2. Use of a semi-analytical, multi-zone jet model
3. Assessing the impact of the uncertainties of the dynamical properties of the astrophysical source

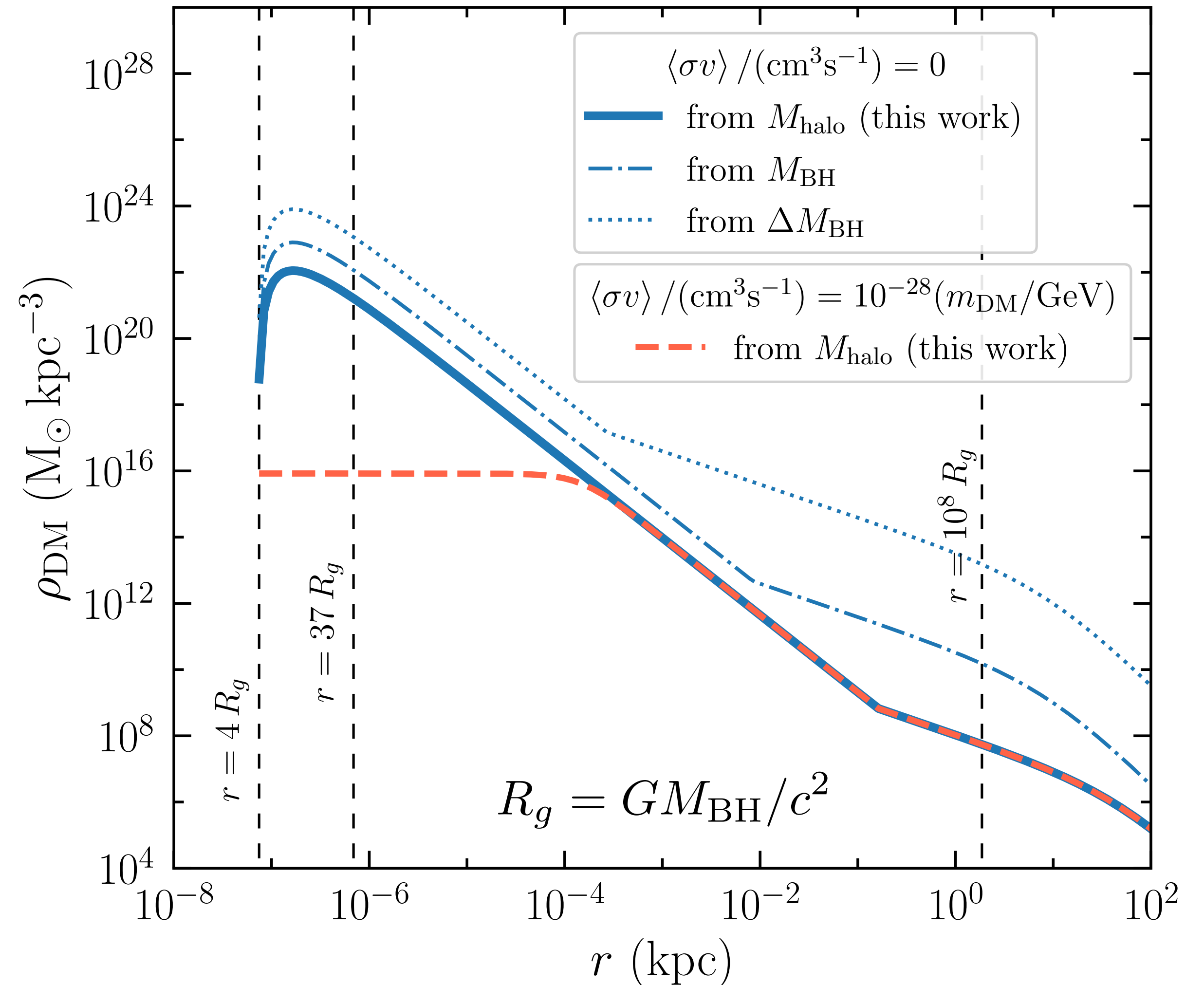
1. Determination of the DM spike parameters

- ◆ Previous works infer the inner DM spike from the BH properties and extrapolate it to larger radii, leading to possible inconsistency!
- ◆ We instead rely on the **measured $M_{\text{BH}} - M_{\text{halo}}$ relation** and on **cosmological simulations**.

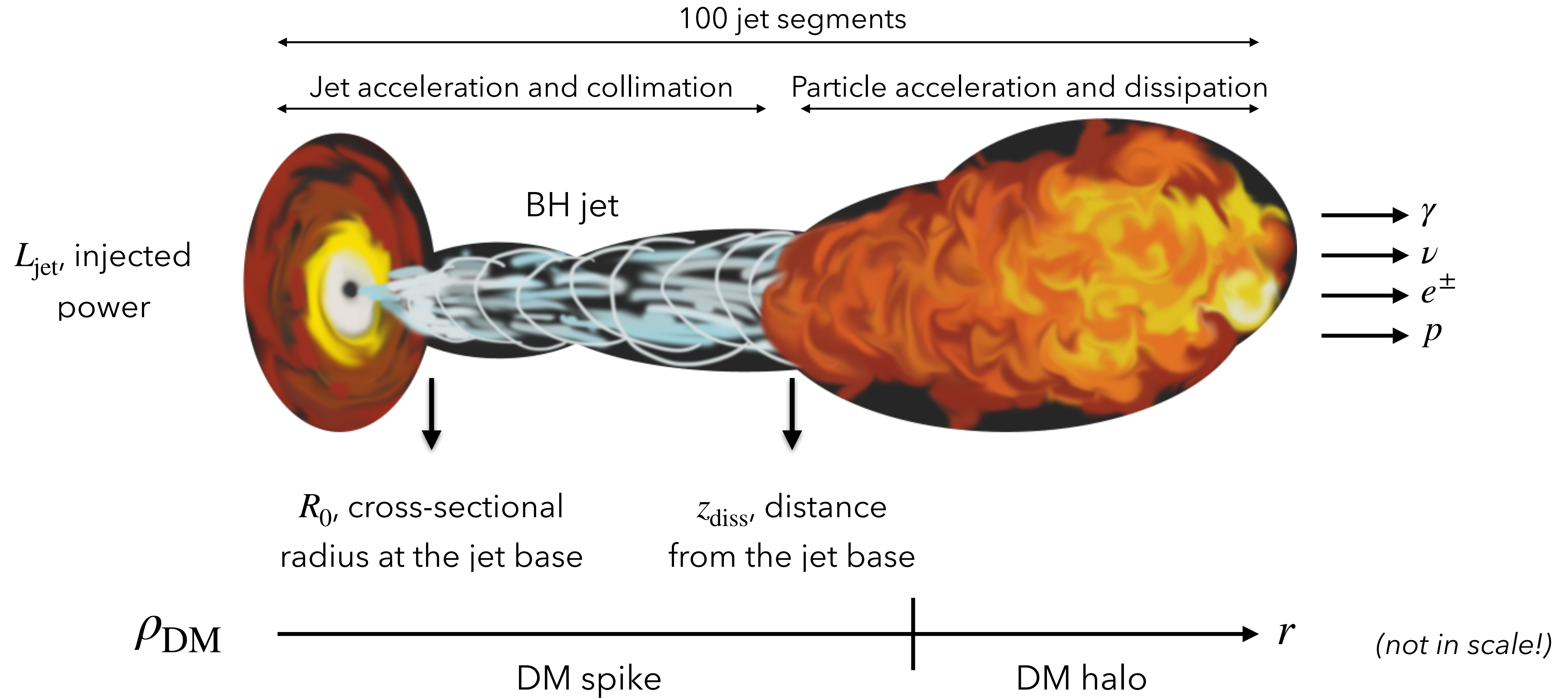
Parameter	Value
$M_{\text{halo}}/M_{\odot}$	$5.7 \pm 3.3 \times 10^{12}$
r_{200}/kpc	377 ± 74
c_{200}	6.21 ± 0.39
r_s/kpc	60.81 ± 12.58
$\rho_s/(M_{\odot} \text{kpc}^{-3})$	$1.8^{+3.1}_{-1.3} \times 10^6$

$$M_{\text{halo}} = 4\pi \int_{4R_g}^{r_{200}} r'^2 \rho_{\text{DM}}(r') dr' \quad \text{whole profile}$$

DM spike in Markarian 421



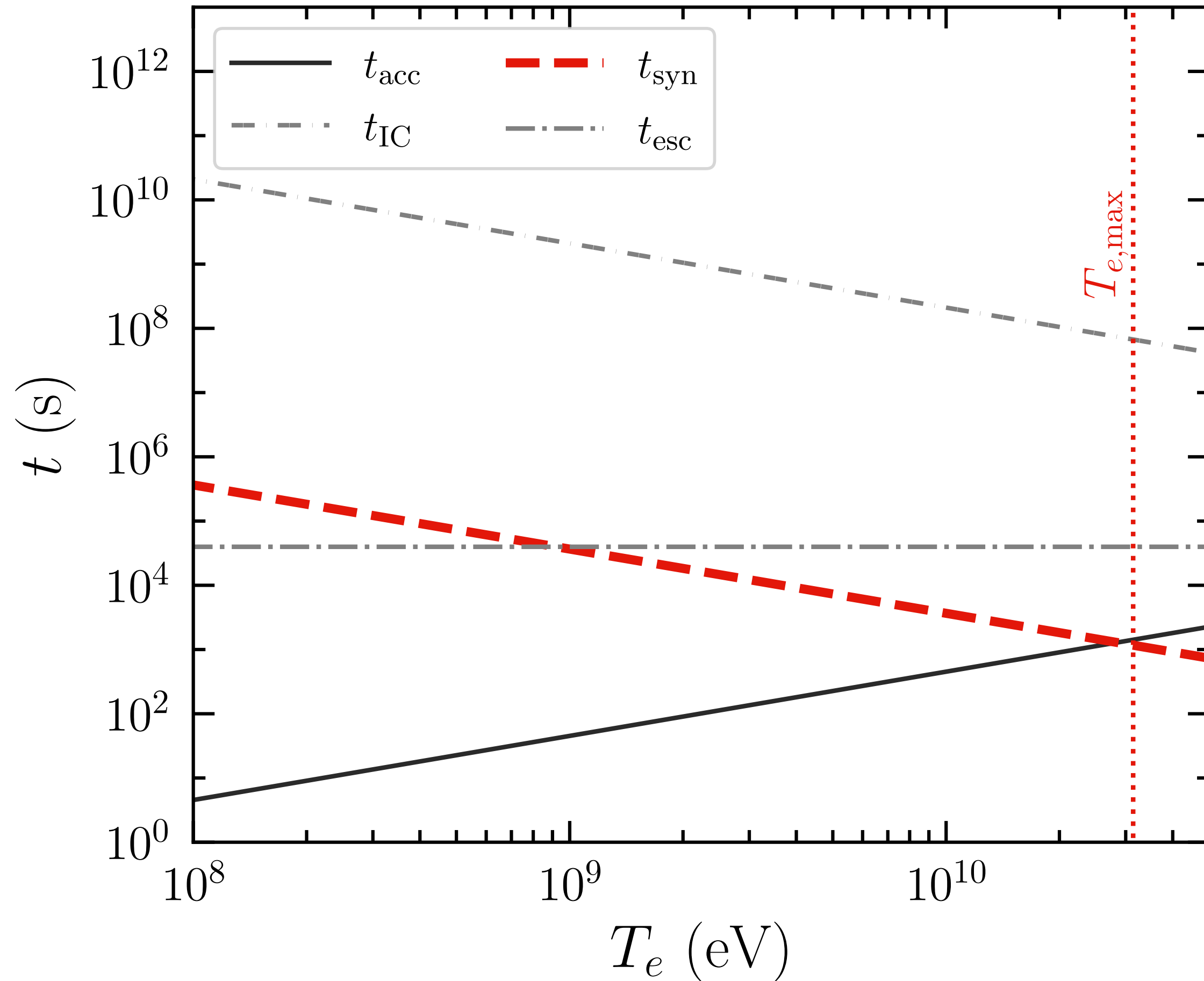
2. The BHJet model: geometry



The jet geometry and the local conditions crucially determine the effects of the DM-CR interactions!

2. The BHJet model: emission from CR electrons

Timescales in the jet segment at z_{diss}



- ◆ In each jet segment, the normalization $Q_0(z)$ of non-thermal electrons from the steady-state transport equation:

$$\frac{n_{\text{nth}}(E_e, z)}{t_{\text{total}}} \simeq Q_0(z) q(E_e)$$



Injected power-law

$$q(E_e) \propto E_e^{-2} \exp(-E_e/E_{e,\text{max}})$$

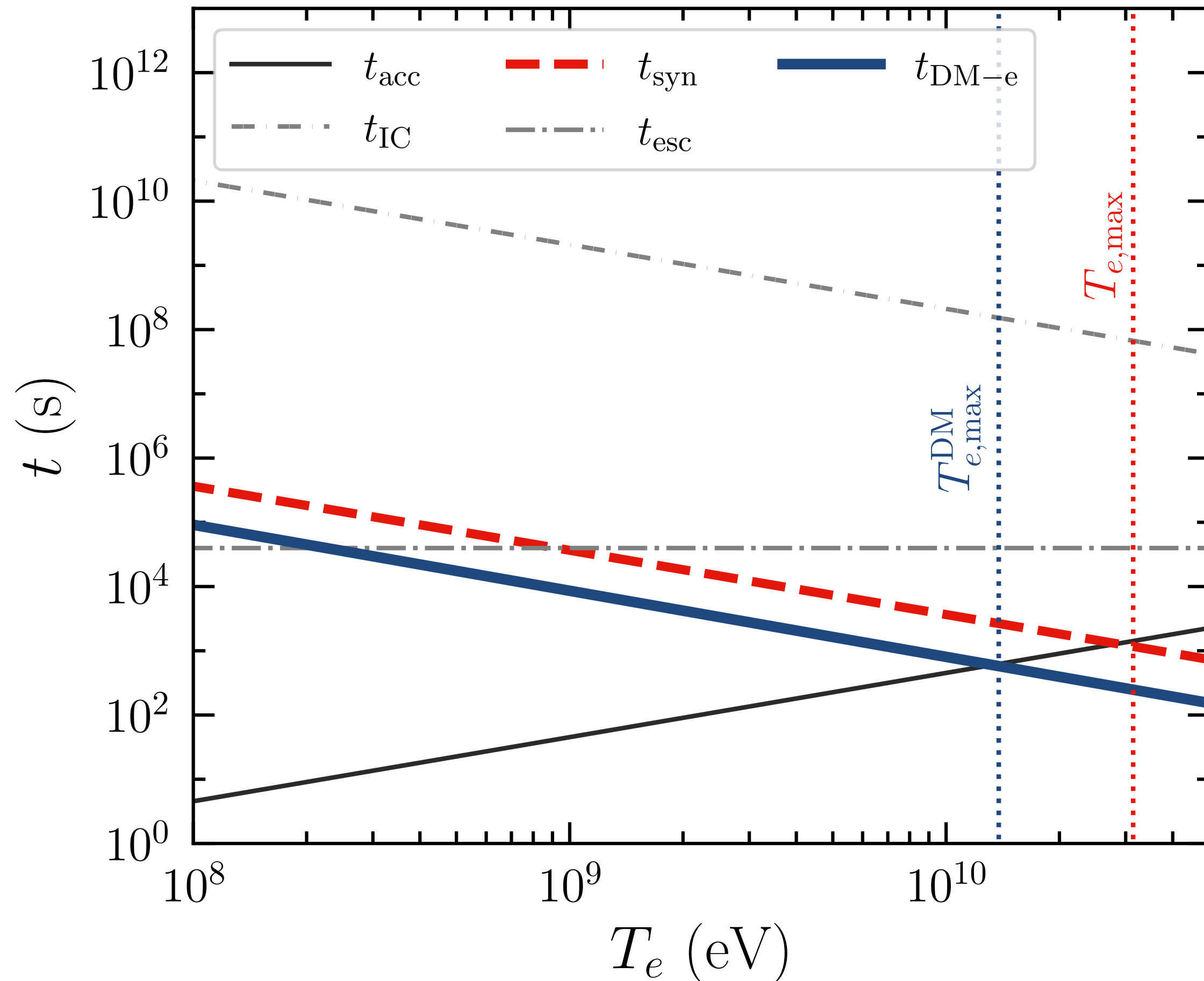
- ◆ Maximum energy $E_{e,\text{max}}$ from the timescale equation:

$$t_{\text{acc}}^{-1}(E_{e,\text{max}}) = t_{\text{syn}}^{-1}(E_{e,\text{max}}) + t_{\text{IC}}^{-1}(E_{e,\text{max}}) + t_{\text{esc}}^{-1}(E_{e,\text{max}})$$

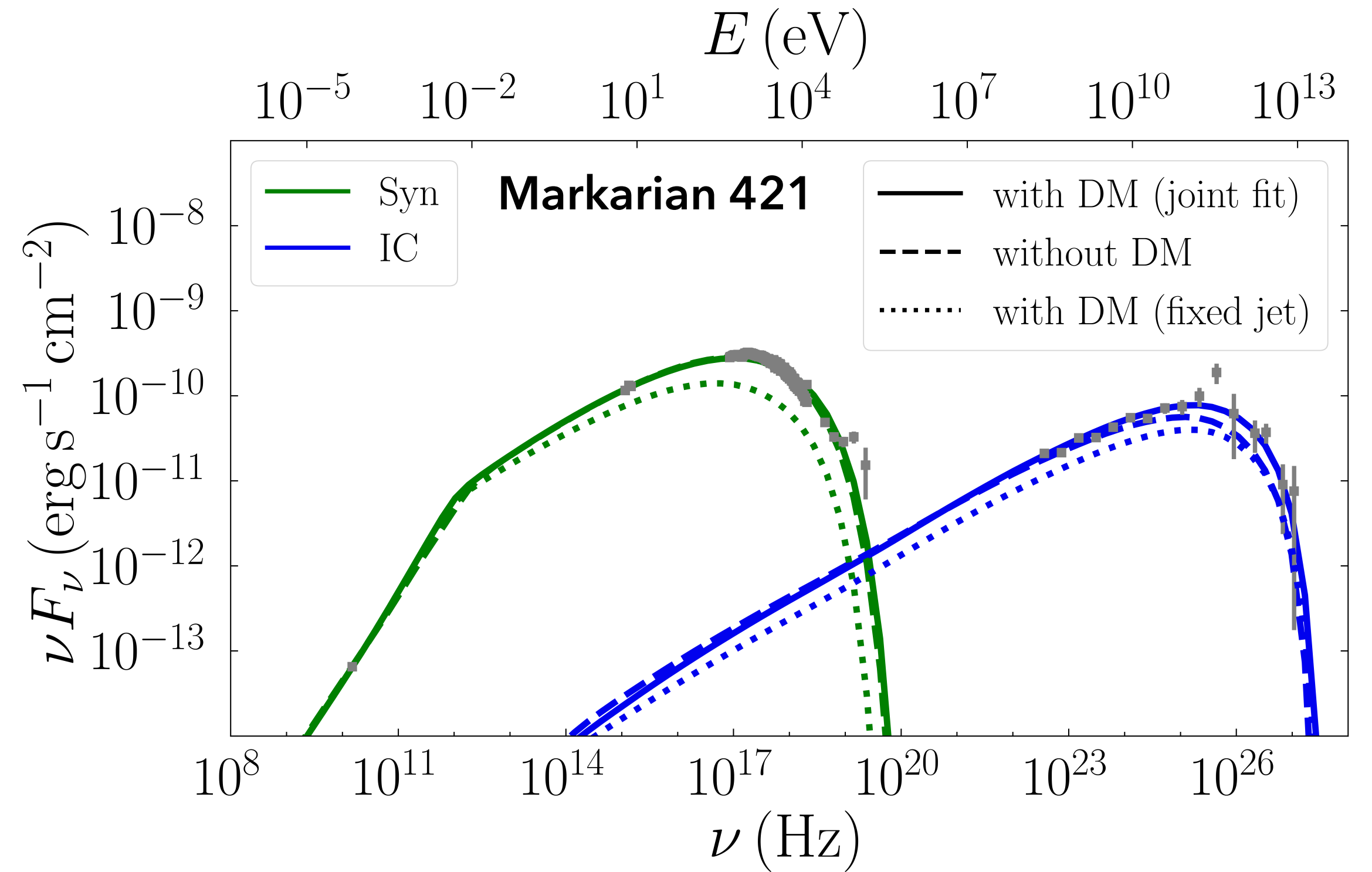
$$\longleftarrow \underbrace{\hspace{15em}}_{t_{\text{total}}^{-1}(E_{e,\text{max}})} \longrightarrow$$

3. Effects of DM-e scatterings

Timescales in the jet segment at z_{diss}



$$t_{\text{acc}}^{-1}(E_{e,\text{max}}) = t_{\text{syn}}^{-1}(E_{e,\text{max}}) + t_{\text{IC}}^{-1}(E_{e,\text{max}}) + t_{\text{esc}}^{-1}(E_{e,\text{max}}) + t_{\text{DM-CR}}^{-1}(E_{e,\text{max}})$$



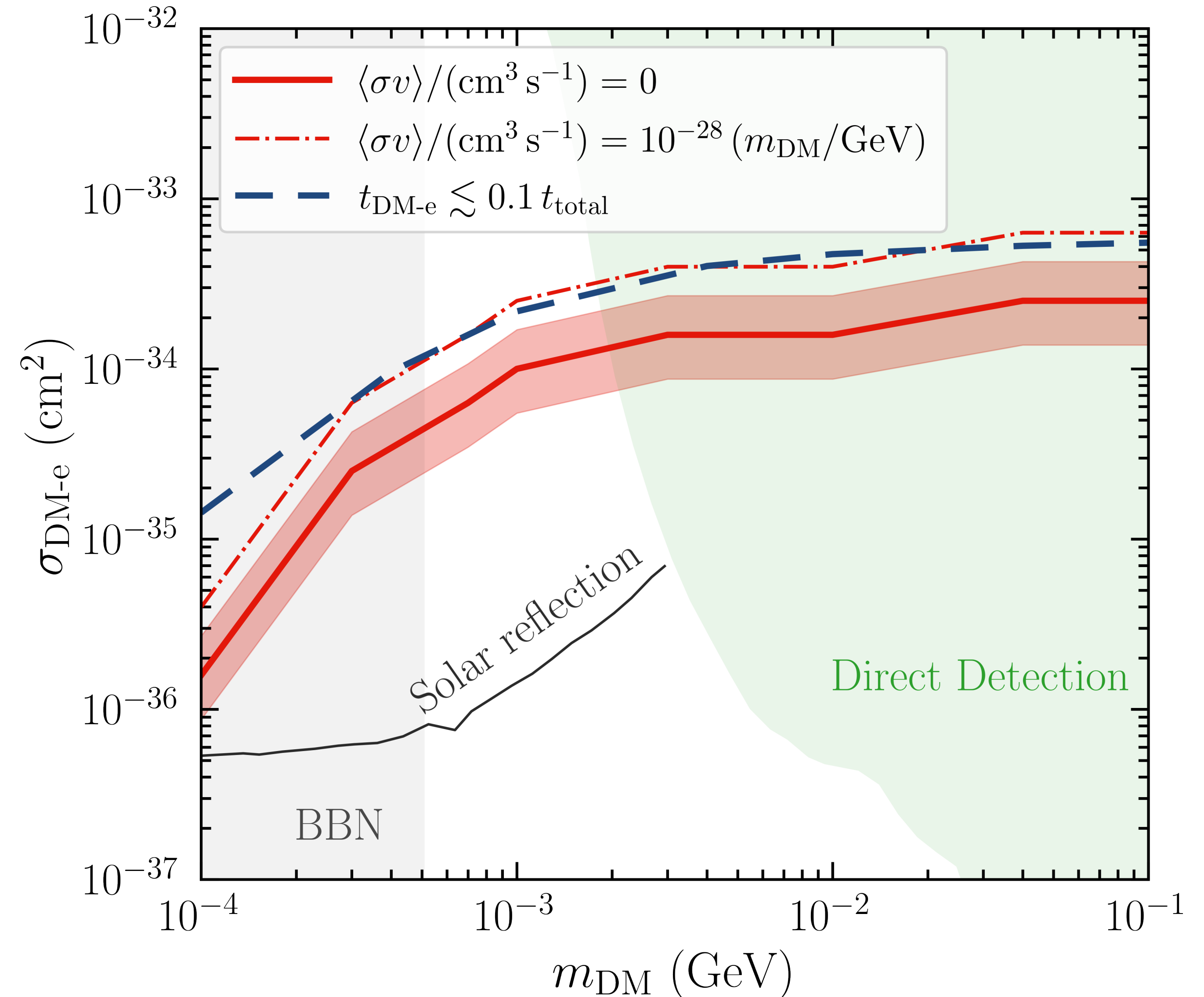
- ◆ Lower maximum energy $E_{e,\text{max}}$ of the electrons (cooling).
- ◆ However, the photon flux can be still compatible with data.

→ Fixing the jet parameters leads to too optimistic constraints!

Results and conclusions

Kantzas, Calore, MC, [arXiv:2509.18850](https://arxiv.org/abs/2509.18850)

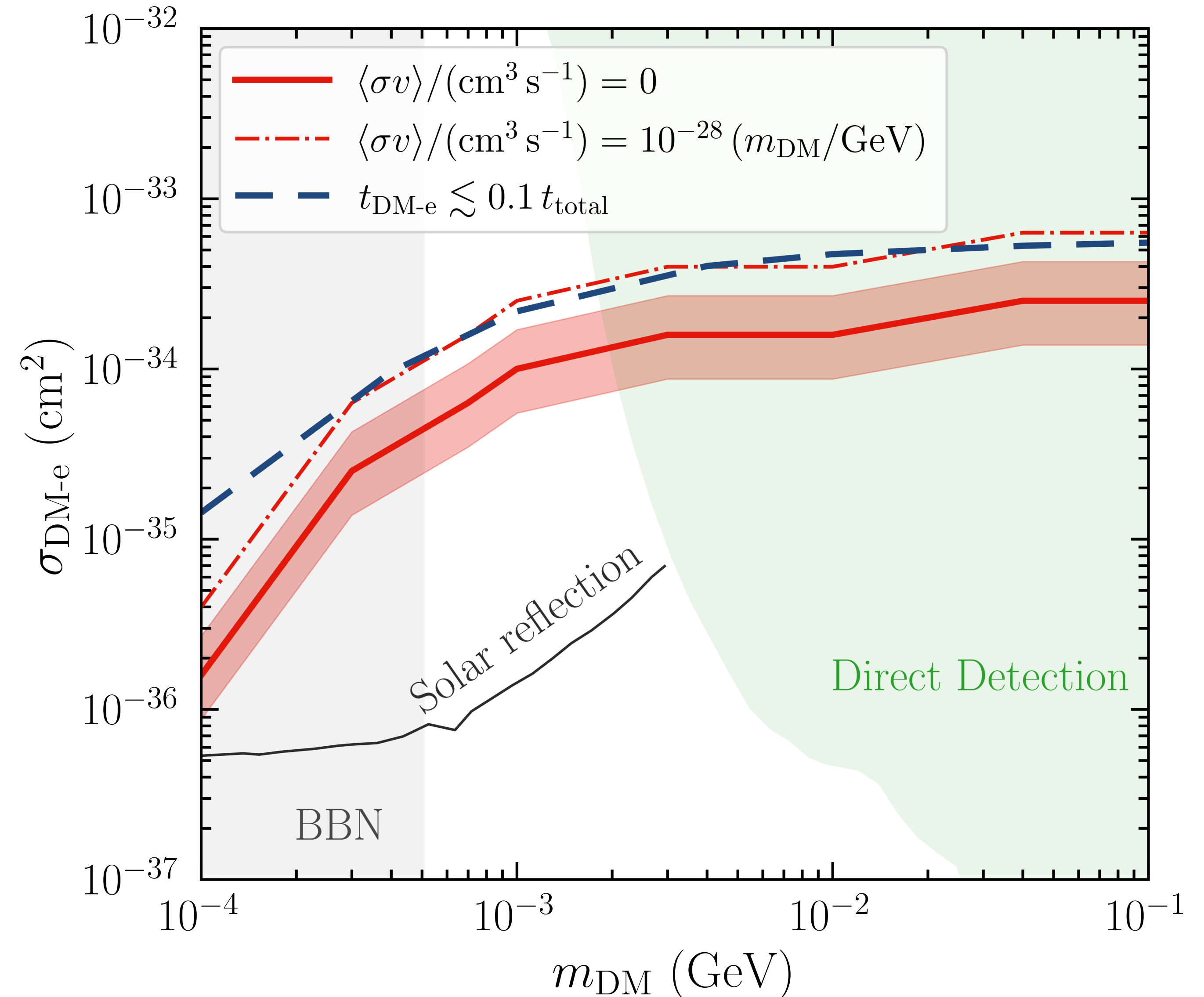
- ◆ Upper limits at 5σ CL on the DM parameter space derived through a joint fit of the jet dynamics and the DM-e interactions
- ◆ Stronger results from the “timescale approach”
- ◆ More self-consistent bounds:
 1. Global DM halo parameters
 2. Accurate astrophysical jet modelling
 3. Inclusion of astrophysical uncertainties
- ◆ Future perspectives: analyzing other sources and different DM-CR interactions!



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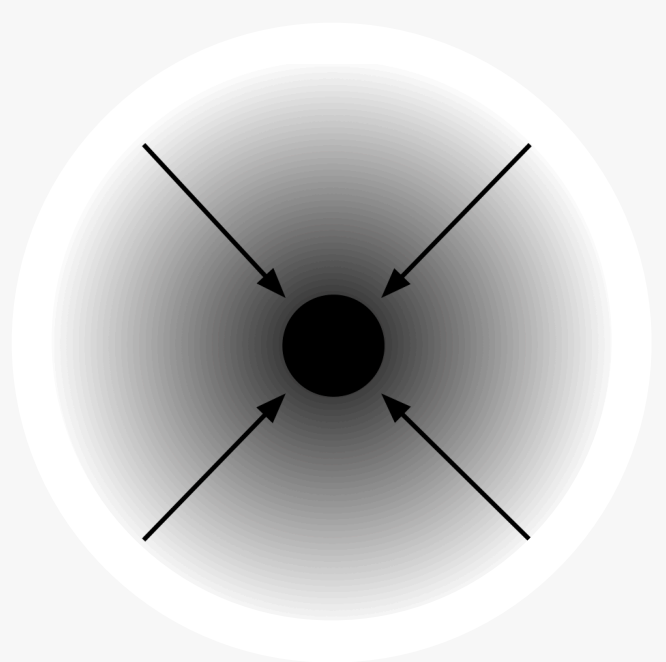
Thank you for your attention

SUPPLEMENTAL MATERIAL

The DM spike profile

The adiabatic growth of a black hole in the central region of a DM halo gives rise to a very dense spike.

DM halo at redshift $z \gg 0$

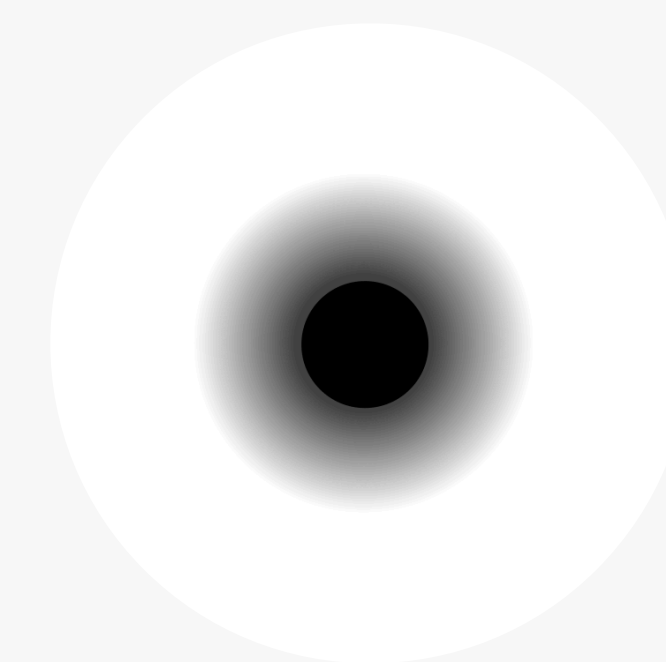


$$\rho_{\text{in}}(r) = \rho_s \left(\frac{r}{r_s} \right)^{-\gamma}$$

($\gamma = 1$ for NFW)



DM spike at redshift $z = 0$



$$\rho_{\text{sp}}(r) = \rho_R \left(\frac{r}{R_{\text{sp}}} \right)^{-\gamma_{\text{sp}}}$$

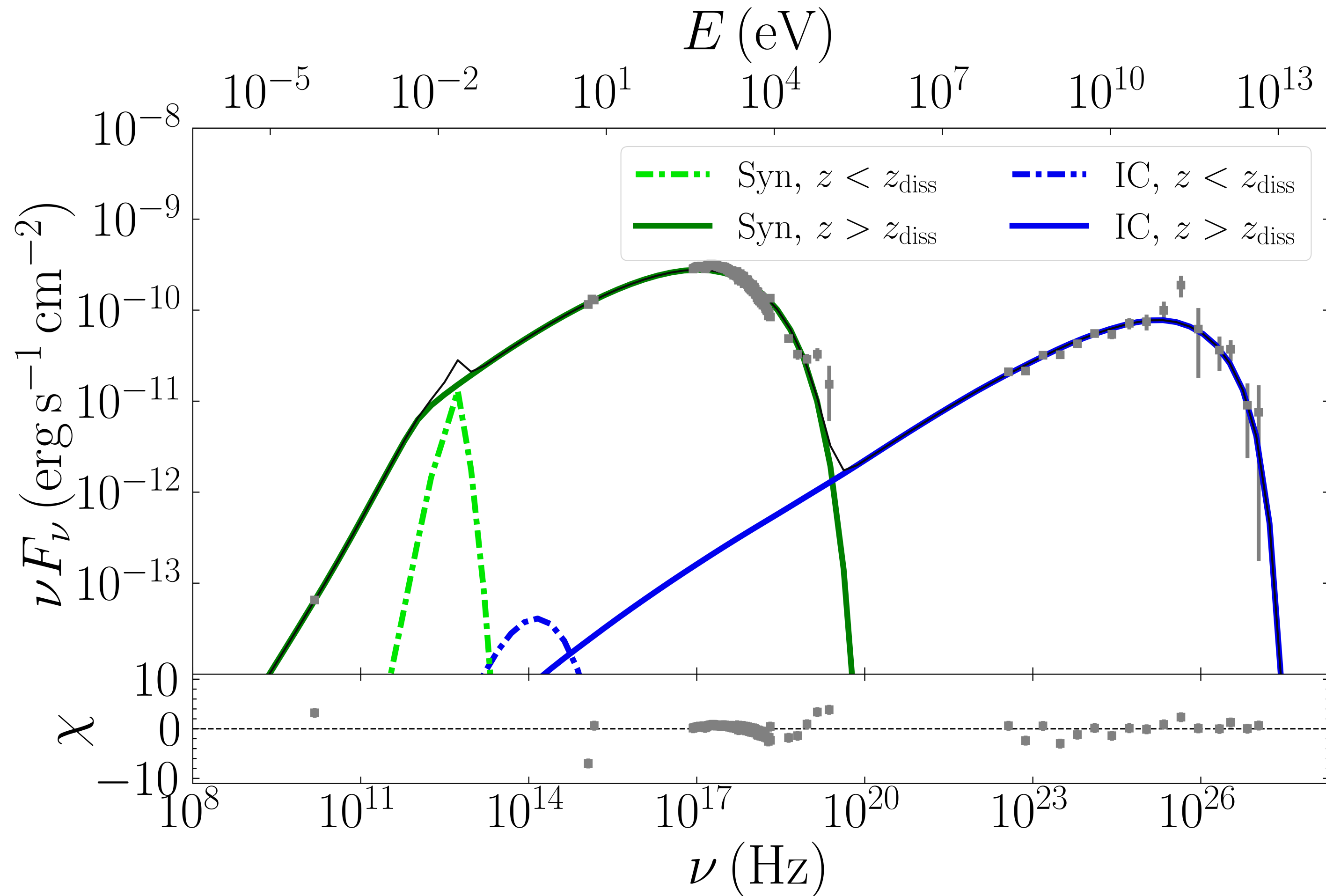
$$\gamma_{\text{sp}} = \frac{9 - 2\gamma}{4 - \gamma}$$

$$\Rightarrow \rho_{\text{DM}}(r) = \begin{cases} 0 & r < 4R_g \\ \frac{\rho_{\text{sp}}(r)\rho_{\text{core}}}{\rho_{\text{sp}}(r) + \rho_{\text{core}}} & 4R_g \leq r \leq R_{\text{sp}} \\ \rho_s \left(\frac{r}{r_s} \right)^{-\gamma} \left(1 + \frac{r}{r_s} \right)^{\gamma-3} & R_{\text{sp}} < r \leq r_{200} \end{cases}$$

Free halo parameters
normalization ρ_s and scale radius r_s

Core density due to DM self-annihilation: $\rho_{\text{core}} \propto 1/\langle\sigma v\rangle$

Markarian 421: astrophysical emission



- ◆ Multi-wavelength data of Markarian 421 from the steady state are compatible with a **pure leptonic emission**.

Bartoli+ ApJ 2016

- ◆ 3D parameter space with uniform priors:

$$L_{\text{jet}} \in [10^{-2} L_{\text{Edd}}, 1.25 L_{\text{Edd}}]$$

$$R_0 \in [2R_g, 30R_g]$$

$$z_{\text{diss}} \in [2R_g, 55R_g]$$

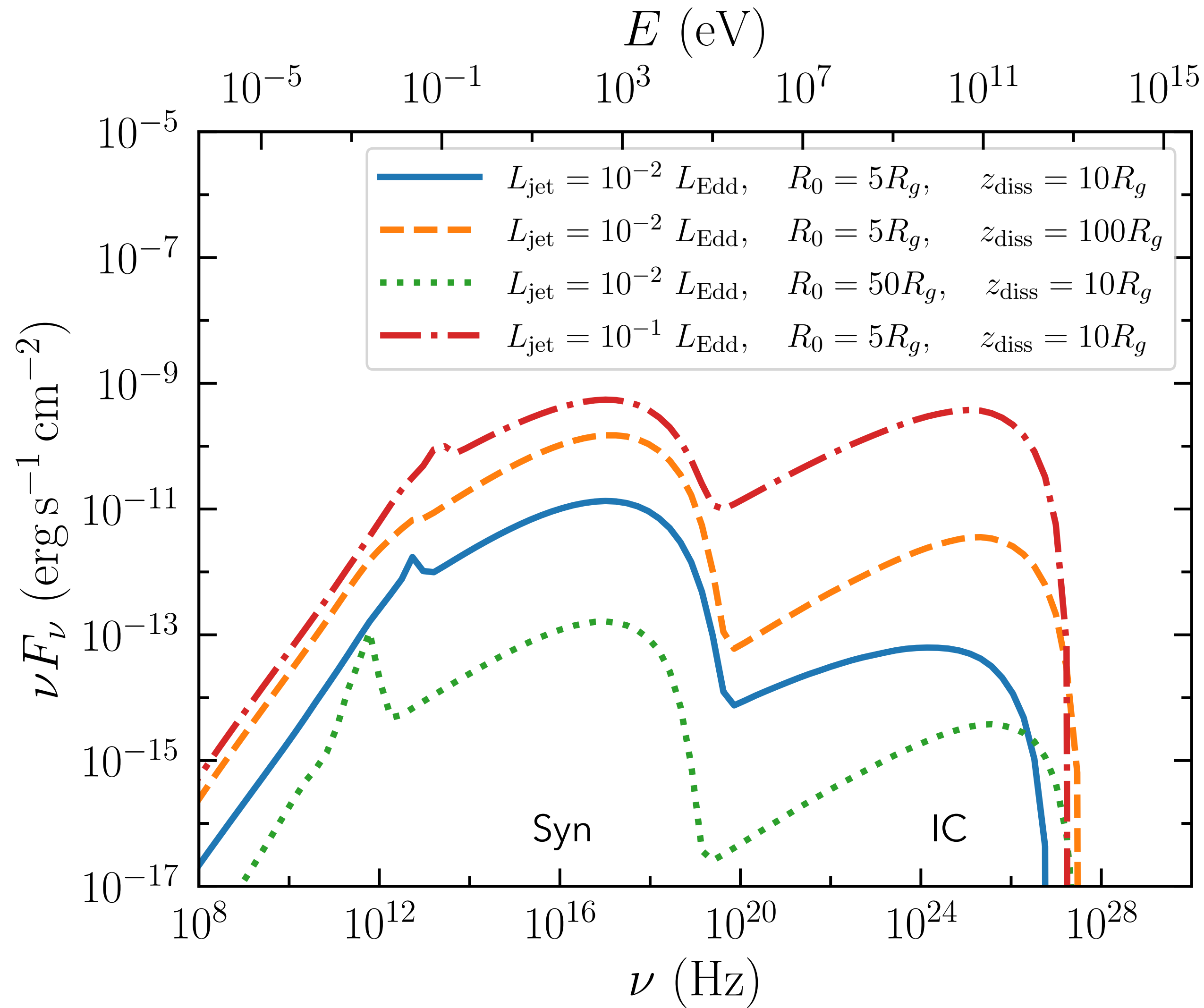
- ◆ Best-fit parameters:

$$L_{\text{jet}} = (0.099 \pm 0.001) L_{\text{Edd}}$$

$$R_0 = (20.1 \pm 0.1) R_g$$

$$z_{\text{diss}} = (37 \pm 1) R_g$$

Three main parameters



Synchrotron-Self-Compton spectrum

- ◆ **More distant dissipation region from BH z_{diss}** : higher magnetic energy density, and so higher synchrotron luminosity.
- ◆ **Larger jet base R_0** : larger size of the dissipation region, lower magnetic energy density, and so lower synchrotron luminosity.
- ◆ **Higher jet power L_{jet}** : increasing the total non-thermal emission.

More about DM halo parameters

Kantzas, Calore, MC, [arXiv:2509.18850](https://arxiv.org/abs/2509.18850)

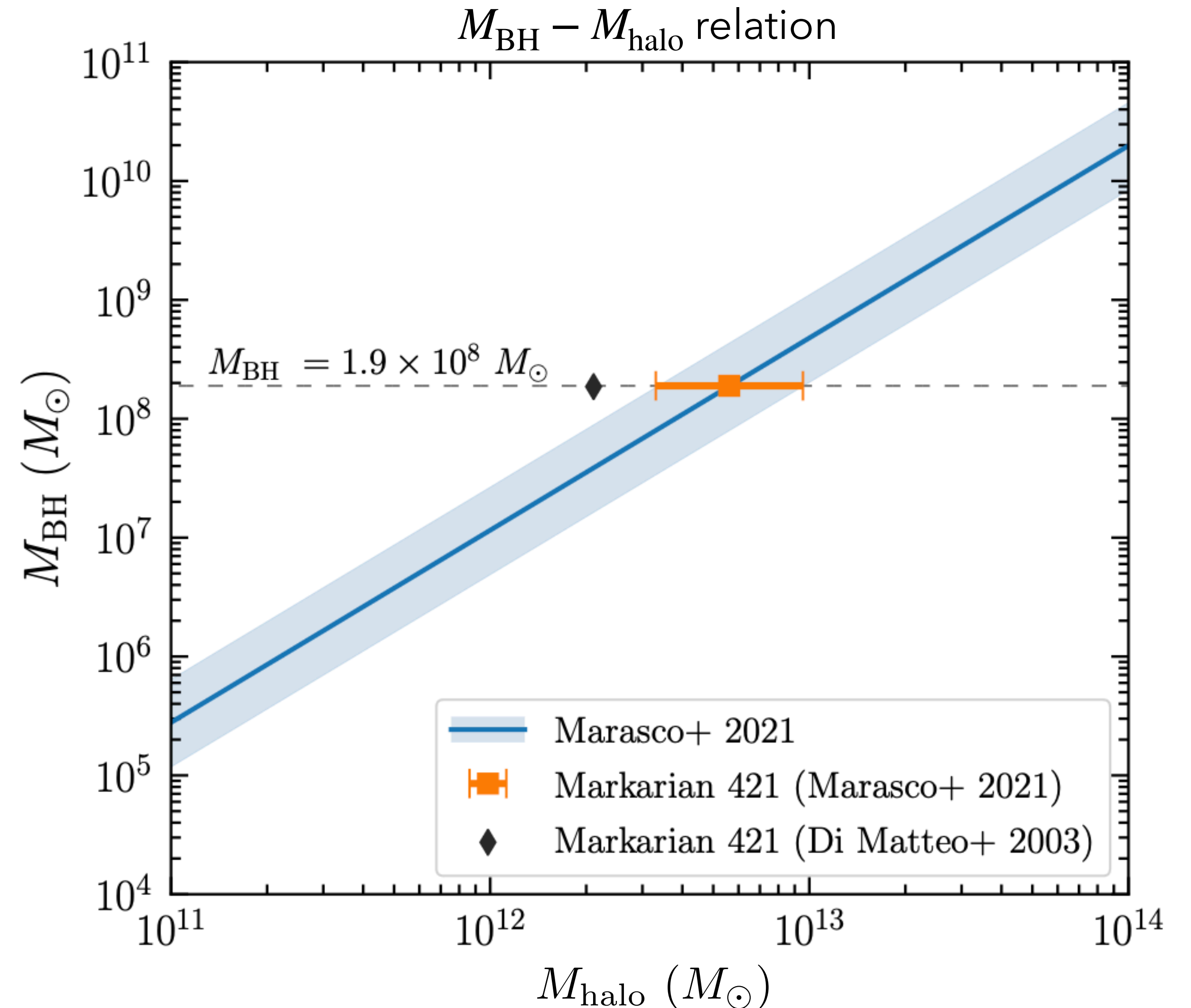
$$\rho_{\text{DM}}(r) = \begin{cases} 0 & r < 4R_g \\ \frac{\rho_{\text{sp}}(r)\rho_{\text{core}}}{\rho_{\text{sp}}(r) + \rho_{\text{core}}} & 4R_g \leq r \leq R_{\text{sp}} \\ \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{\gamma-3} & R_{\text{sp}} < r \leq r_{200} \end{cases}$$

- ◆ Derivations of the profile normalization (arbitrary scale radius $r_s \simeq 10$ kpc) found in literature from M_{BH} or ΔM_{BH} :

$$4\pi \int_{4R_g}^{10^5 R_g} r' \rho_{\text{DM}}(r') dr' \simeq M_{\text{BH}} \text{ (or } \Delta M_{\text{BH}})$$

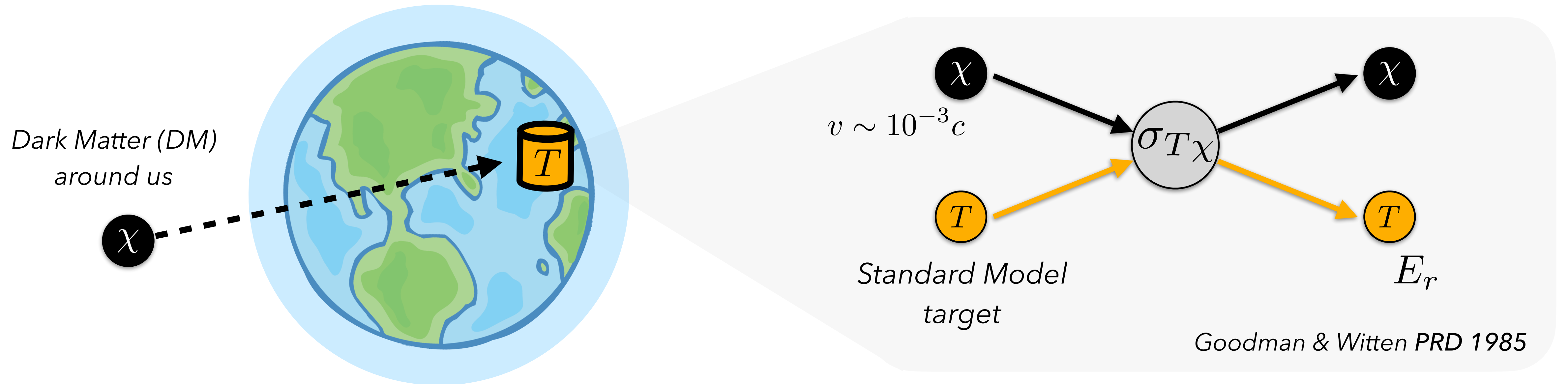
- ◆ Our derivation with $r_s = r_{200}/c_{200}(M_{\text{halo}})$ from cosmo simul.:

$$M_{\text{halo}} = 4\pi \int_{4R_g}^{r_{200}} r'^2 \rho_{\text{DM}}(r') dr'$$



Direct detection experiments

They search for the nuclear recoil energy E_r caused by the possible scatterings with DM particles.



- ◆ DM might interact with p, n , and e^- typically bound to stable nuclei
- ◆ Sensitive to DM masses $m_\chi \gtrsim \text{GeV}$

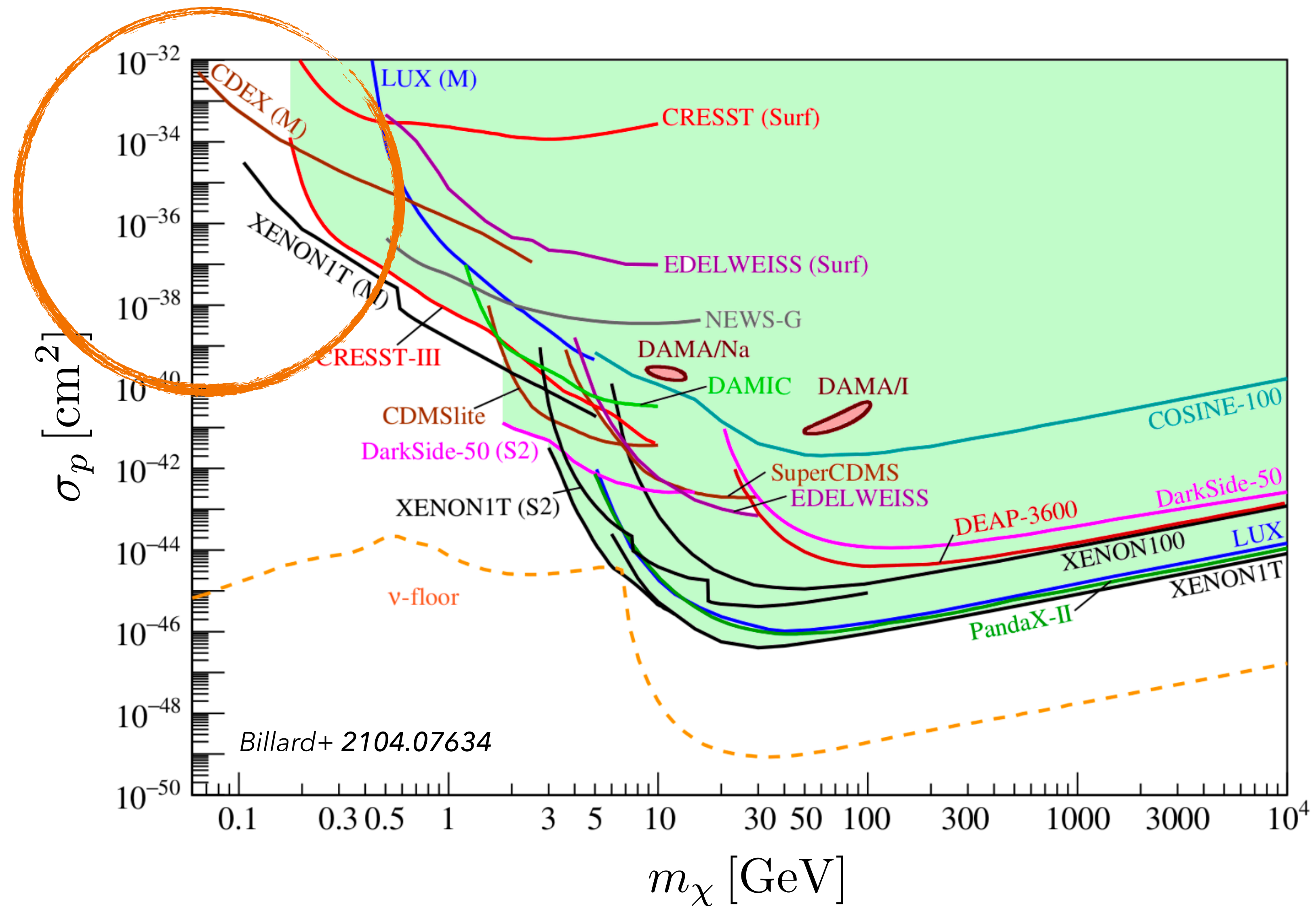
- ◆ Counting experiments for which:

$$N = T_{\text{obs}} \int_0^{E_r^{\text{max}}} dE_r \eta(E_r) \frac{dR}{dE_r}$$

Differential event rate

Detector efficiency $E_r \gtrsim \text{keV}$

Direct detection constraints



Light DM is almost directly unexplored: new probes are required!