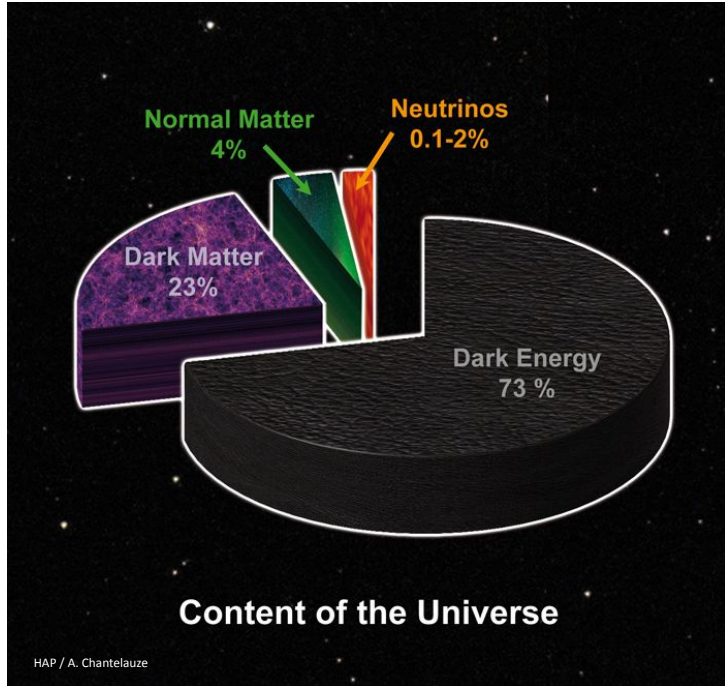


Astrophysical Jets as Laboratories for Light Dark Matter

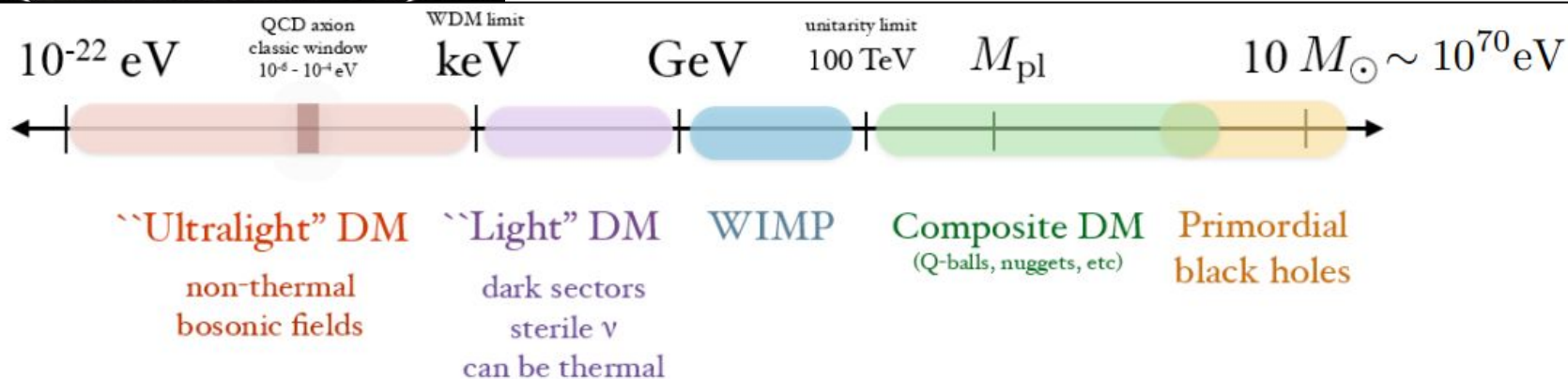
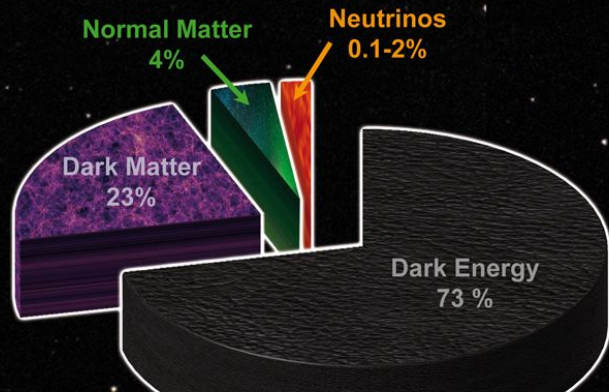
Dimitrios Kantzas
CASS/NYUAD

with
Francesca Calore & Marco Chianese

Indirect Dark Matter Searches

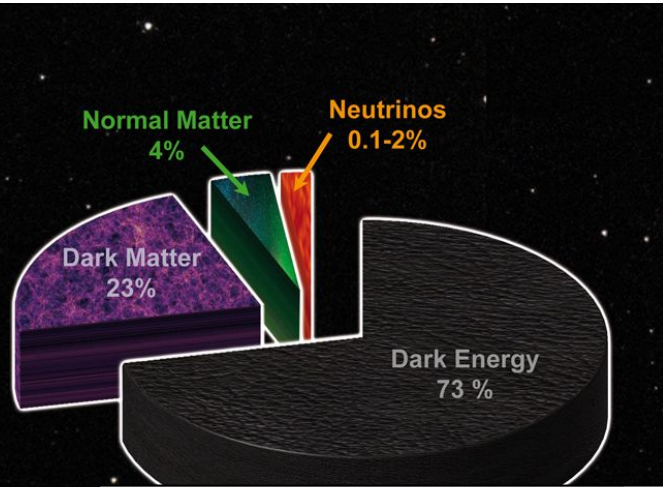


Indirect Dark Matter Searches

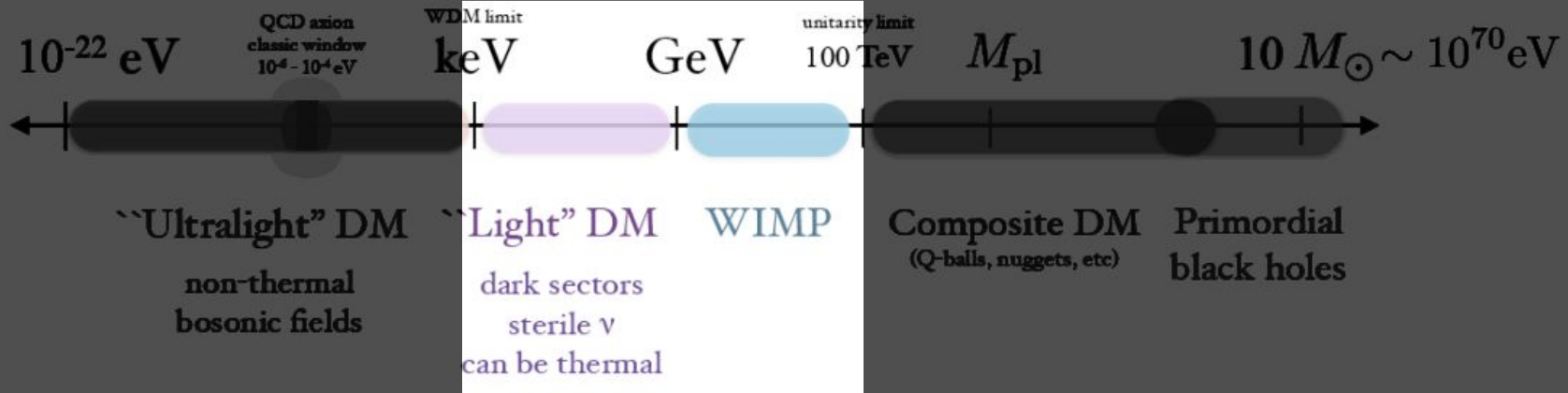
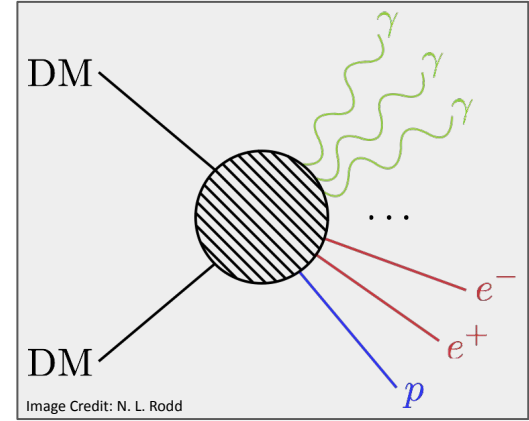


HAP / A. Chantelauze

Indirect Dark Matter Searches



$$m_{\text{DM}} \ \& \ \langle \sigma v \rangle$$



HAP / A. Chantelauze

Dark Matter Halo Radial Profile

Kantzas et al. 2026

$$\rho_{\text{DM}}(r) = \begin{cases} 0 & r < 4R_g \\ \frac{\rho_{\text{sp}}(r)\rho_{\text{core}}}{\rho_{\text{sp}}(r) + \rho_{\text{core}}} & 4R_g \leq r \leq R_{\text{sp}} \\ \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{\gamma-3} & R_{\text{sp}} < r \leq r_{200} \end{cases} \quad (7)$$

$$\rho_{\text{sp}}(r) = \rho_s \left(1 - \frac{4R_g}{r}\right)^3 \left(\frac{R_{\text{sp}}}{r_s}\right)^{-\gamma} \left(\frac{R_{\text{sp}}}{r}\right)^{\gamma_{\text{sp}}}, \quad (8)$$

with slope $\gamma_{\text{sp}} = (9 - 2\gamma)/(4 - \gamma)$ and extension

$$R_{\text{sp}} = \alpha_\gamma r_s \left(\frac{M_{\text{BH}}}{\rho_s \underline{r_s^3}}\right)^{1/(3-\gamma)}, \quad (9)$$

see e.g., Quinlan et al. 1995; Gondolo & Silk 1999;
Gorchtein et al. 2010, Lacroix et al. 2015

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$$M_{\text{halo}} = \frac{4\pi}{3} r_{200}^3 200\rho_{\text{cr}}.$$

from Marasco et al. 2021

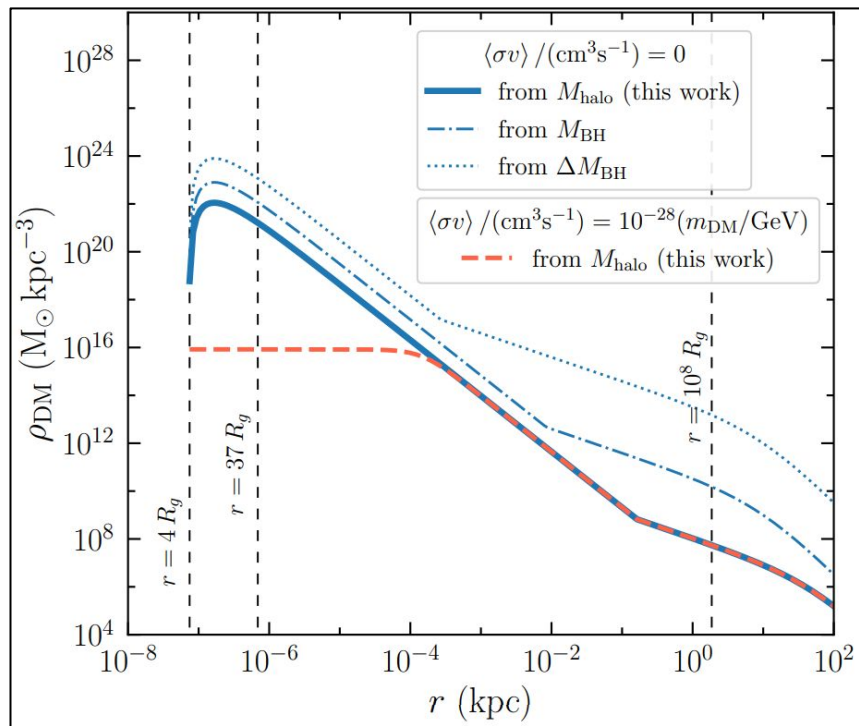
$$\text{and } c_{200} = r_{200}/r_s$$

from Ishiyama et al. 2021 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
$\rho_s/(M_\odot \text{ kpc}^{-3})$	$1.8^{+3.1}_{-1.3} \times 10^6$

for $M_{\text{bh}} = 1.9 \times 10^8 M_\odot$

DM Halo Radial Profile for Markarian 421



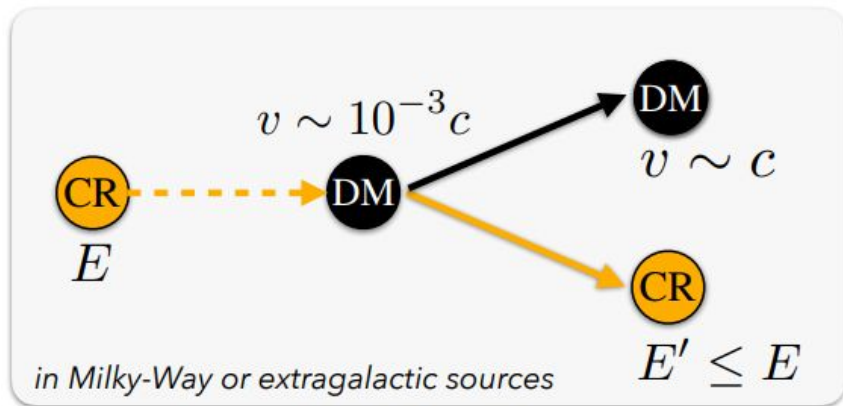
Kantzas et al. 2026

$$\rho_{\text{DM}}(r) = \begin{cases} 0 & r < 4R_g \\ \frac{\rho_{\text{sp}}(r)\rho_{\text{core}}}{\rho_{\text{sp}}(r) + \rho_{\text{core}}} & 4R_g \leq r \leq R_{\text{sp}} \\ \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{\gamma-3} & R_{\text{sp}} < r \leq r_{200} \end{cases} \quad (7)$$

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

Miscalculation of M_{DM} can lead to overestimation of the DM density !

DM-CR Interactions



Bringmann & Pospelov 2019, Ema et al. 2019,
 Alvey et al. 2019, Bondarenko et al. 2020,
 Wang et al. 2022, Granelli et al. 2022, Cui et al. 2022,
 ...

Previous constraints imposing

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

$$t_{\text{DM-e}}(E_e) = \left[-\frac{1}{E_e} \left(\frac{dE_e}{dt} \right)_{\text{DM-e}} \right]^{-1}$$

$$\rightarrow \left(\frac{dE_e}{dt} \right)_{\text{DM-e}} = -\frac{\rho_{\text{DM}}}{m_{\text{DM}}} \int_0^{T_{\text{DM}}^{\text{max}}} T_{\text{DM}} \frac{d\sigma_{\text{el}}}{dT_{\text{DM}}} dT_{\text{DM}}$$

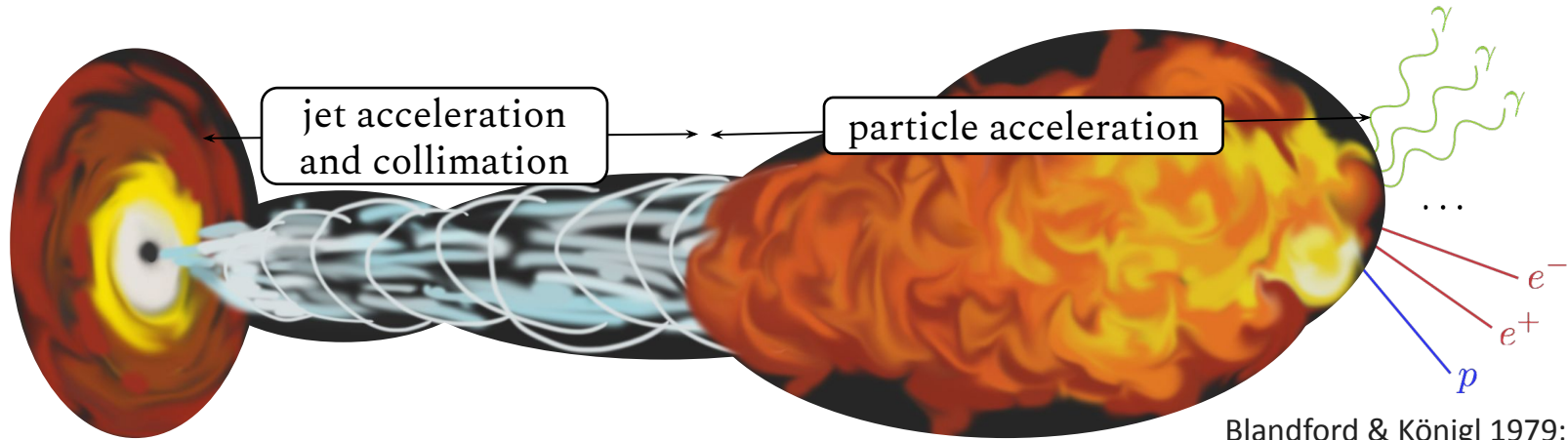
$$\rightarrow \frac{d\sigma_{\text{el}}}{dT_{\text{DM}}} = \frac{\sigma_{\text{DM-e}}}{T_{\text{DM}}^{\text{max}}} \frac{1}{16\mu_{\text{DM-e}}^2 s} (q^2 + 4m_e^2)(q^2 + 4m_{\text{DM}}^2),$$

$$\rightarrow T_{\text{DM}}^{\text{max}} = \frac{2T_e^2 + 4m_e T_e}{m_{\text{DM}}} \left[\left(1 + \frac{m_e}{m_{\text{DM}}} \right)^2 + \frac{2T_e}{m_{\text{DM}}} \right]^{-1}$$

Kantzas et al. 2026

Semi-analytical, Multi-zone Jet Model

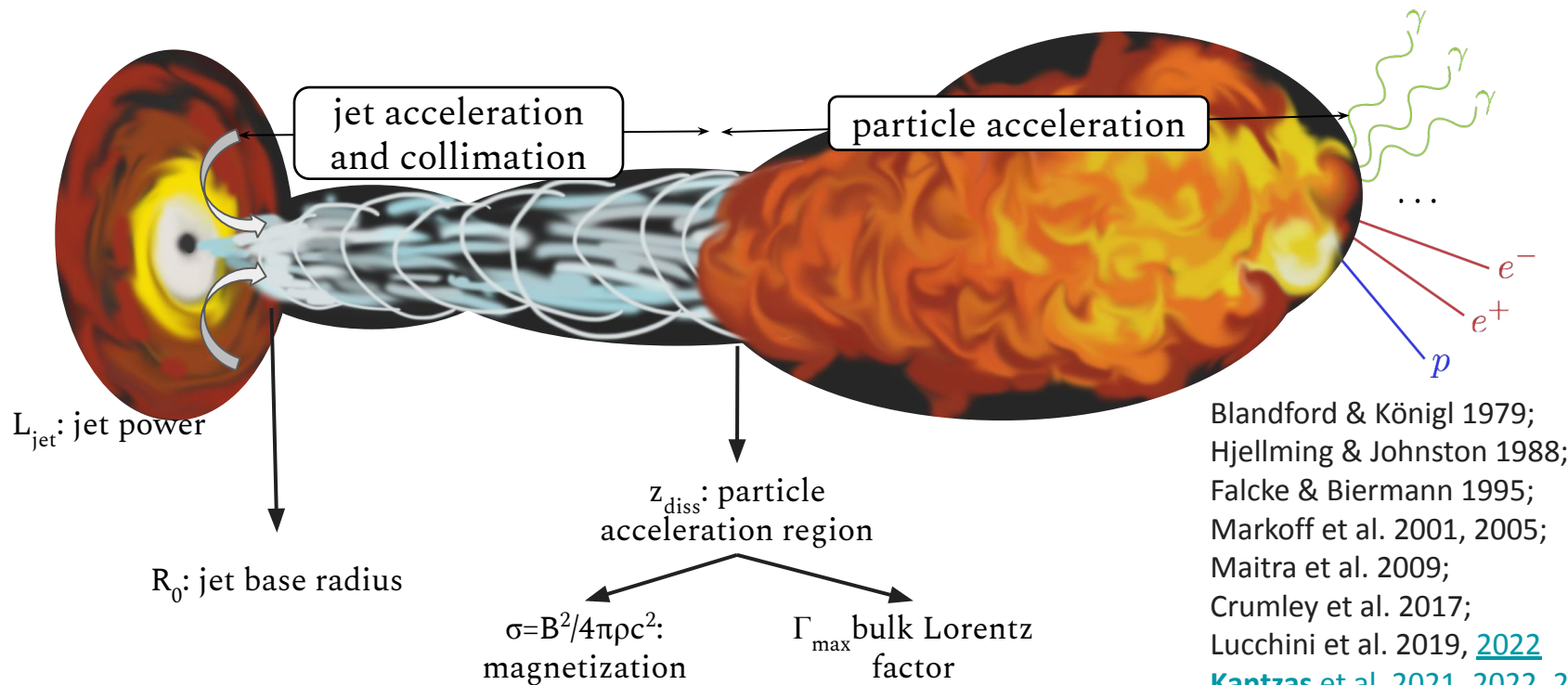
BHJet: a multi-zone model (Lucchini..., [DK](#) et al. 2022)



Blandford & Königl 1979;
Hjellming & Johnston 1988;
Falcke & Biermann 1995;
Markoff et al. 2001, 2005;
Maitra et al. 2009;
Crumley et al. 2017;
Lucchini et al. 2019, [2022](#)
[Kantzas et al. 2021, 2022, 2023a, 2026](#) ⁹

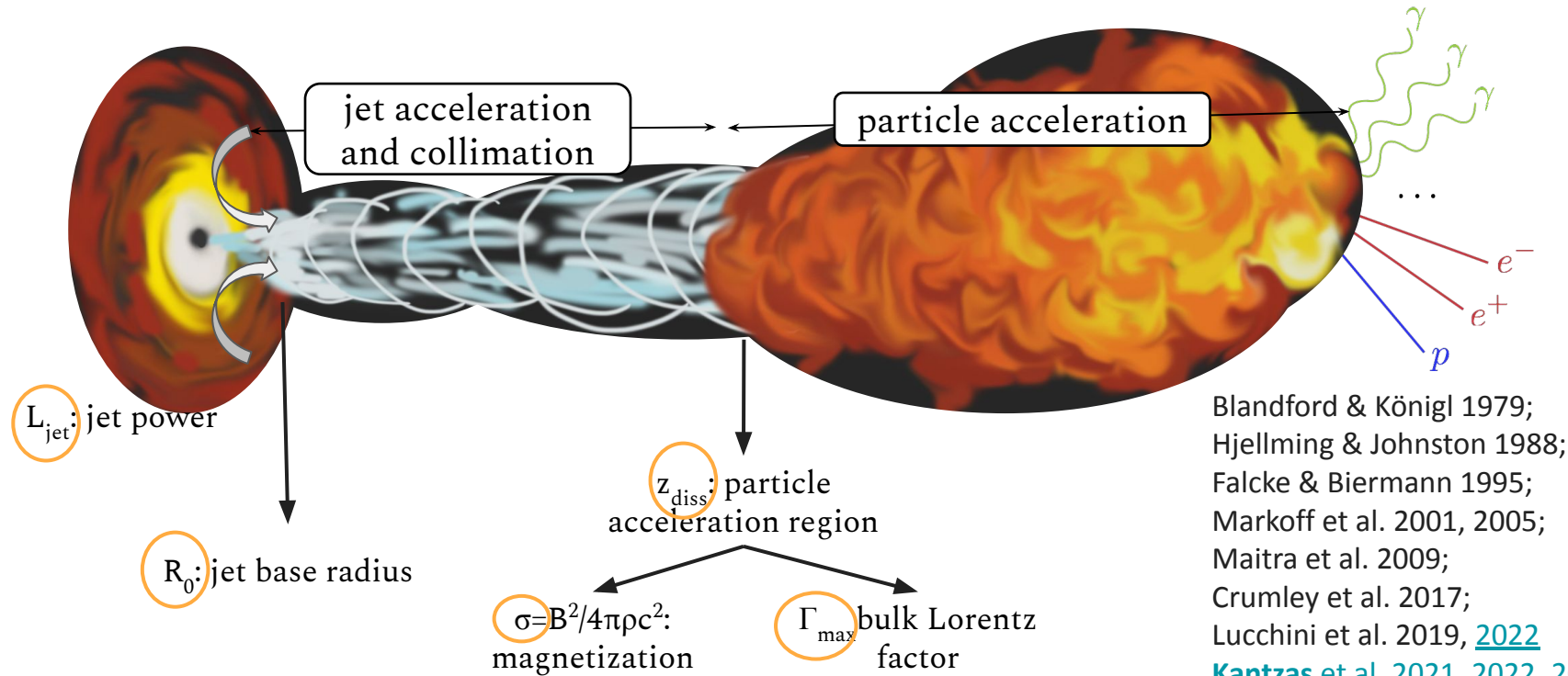
Semi-analytical, Multi-zone Jet Model

BHJet: a multi-zone model (Lucchini..., [DK](#) et al. 2022)



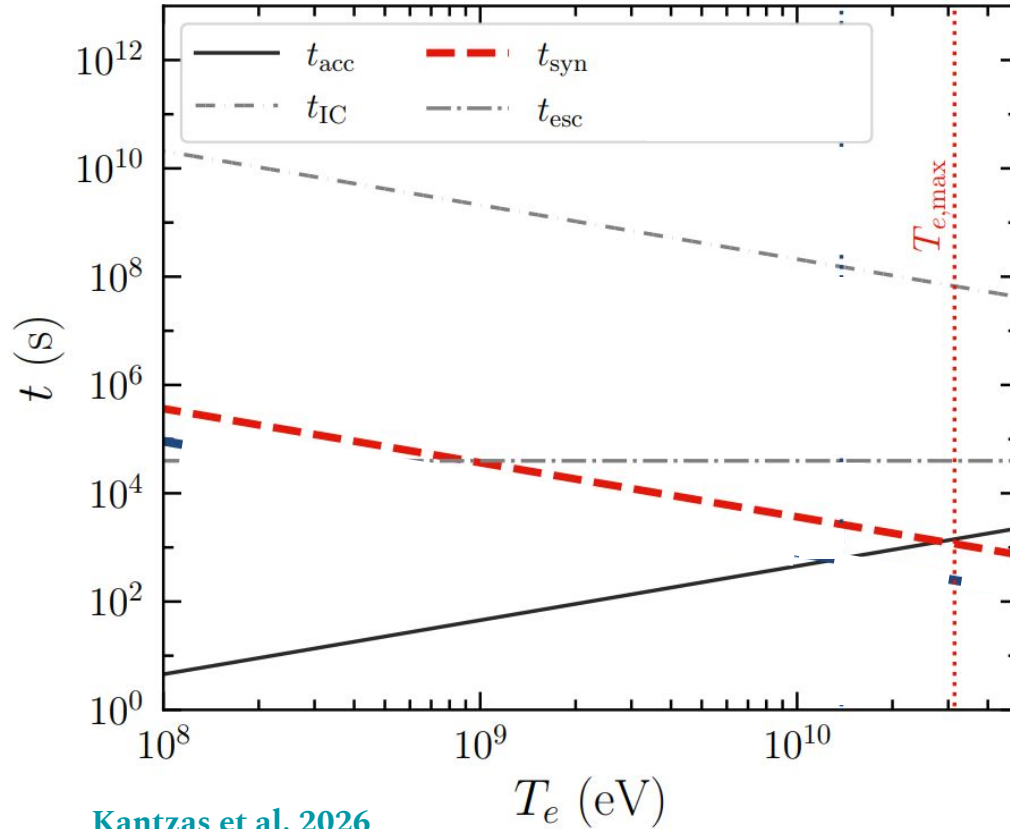
Semi-analytical, Multi-zone Jet Model

BHJet: a multi-zone model (Lucchini..., [DK](#) et al. 2022)



Blandford & Königl 1979;
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Crumley et al. 2017;
Lucchini et al. 2019, [2022](#)
[Kantzas et al. 2021, 2022, 2023a, 2026](#)¹¹

Nonthermal Particle Acceleration

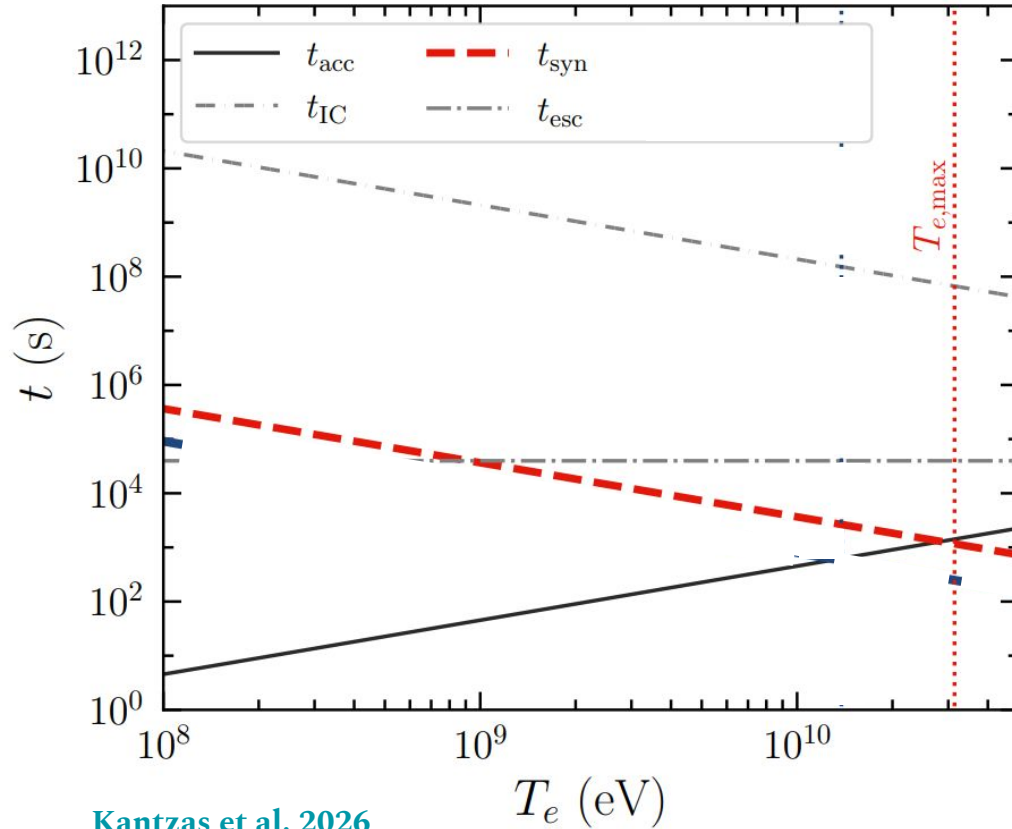


Kantzas et al. 2026

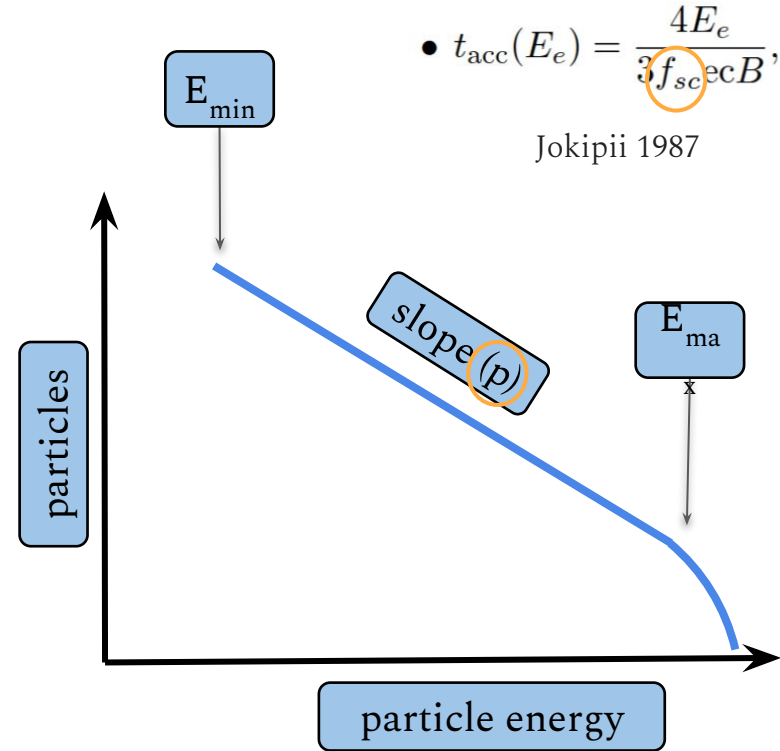
$$\bullet t_{\text{acc}}(E_e) = \frac{4E_e}{3f_{\text{sc}}ecB},$$

Jokipii 1987

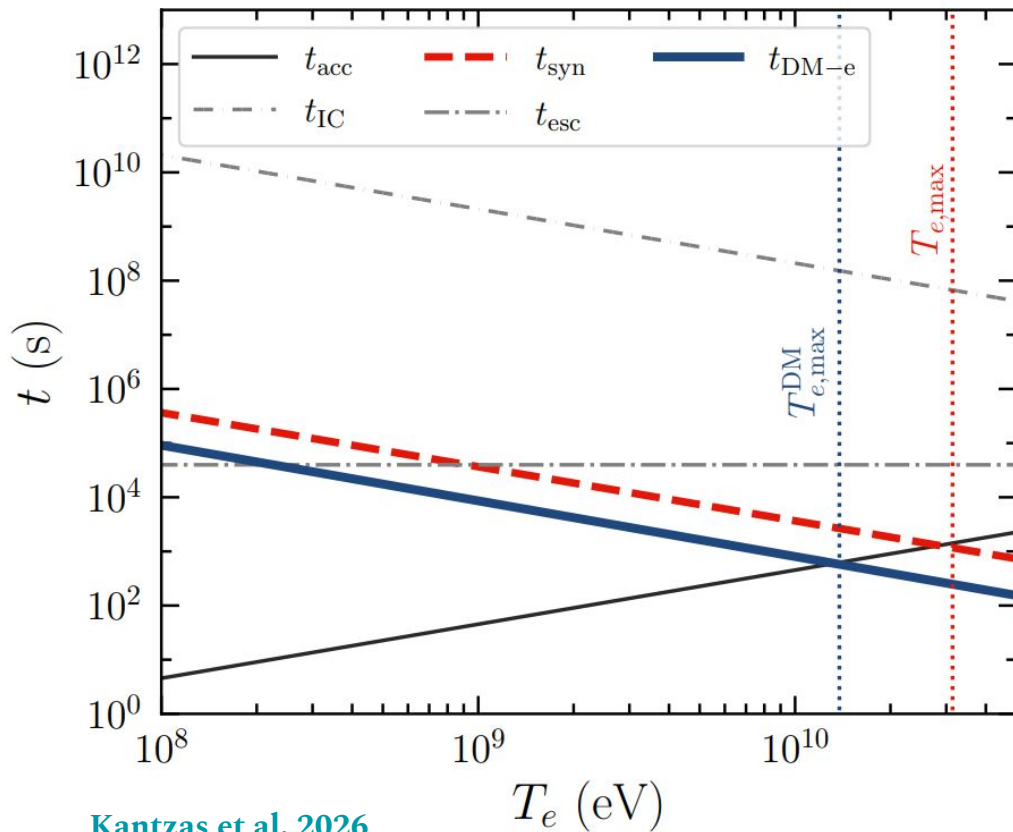
Nonthermal Particle Acceleration



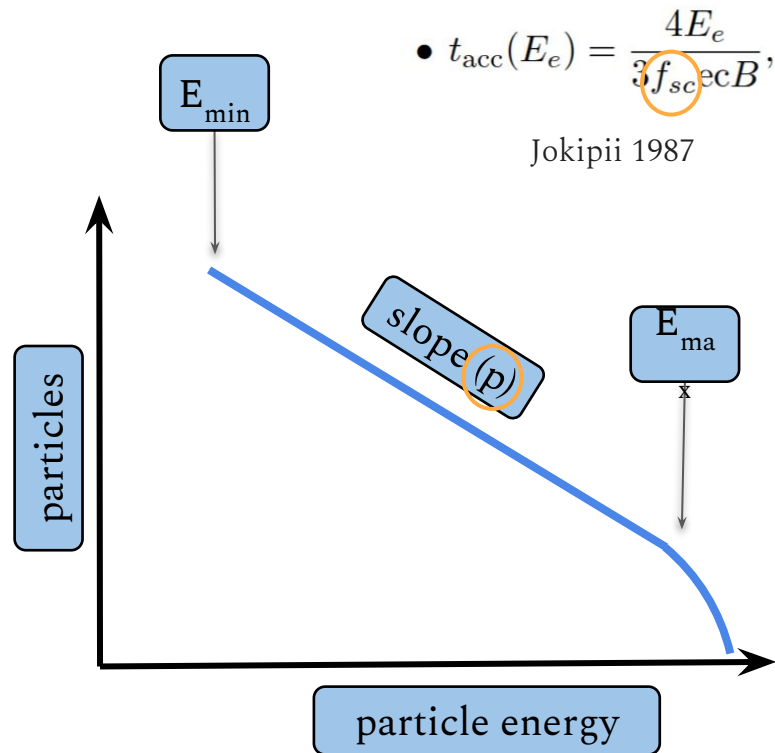
Kantzas et al. 2026



Nonthermal Particle Acceleration



Kantzas et al. 2026

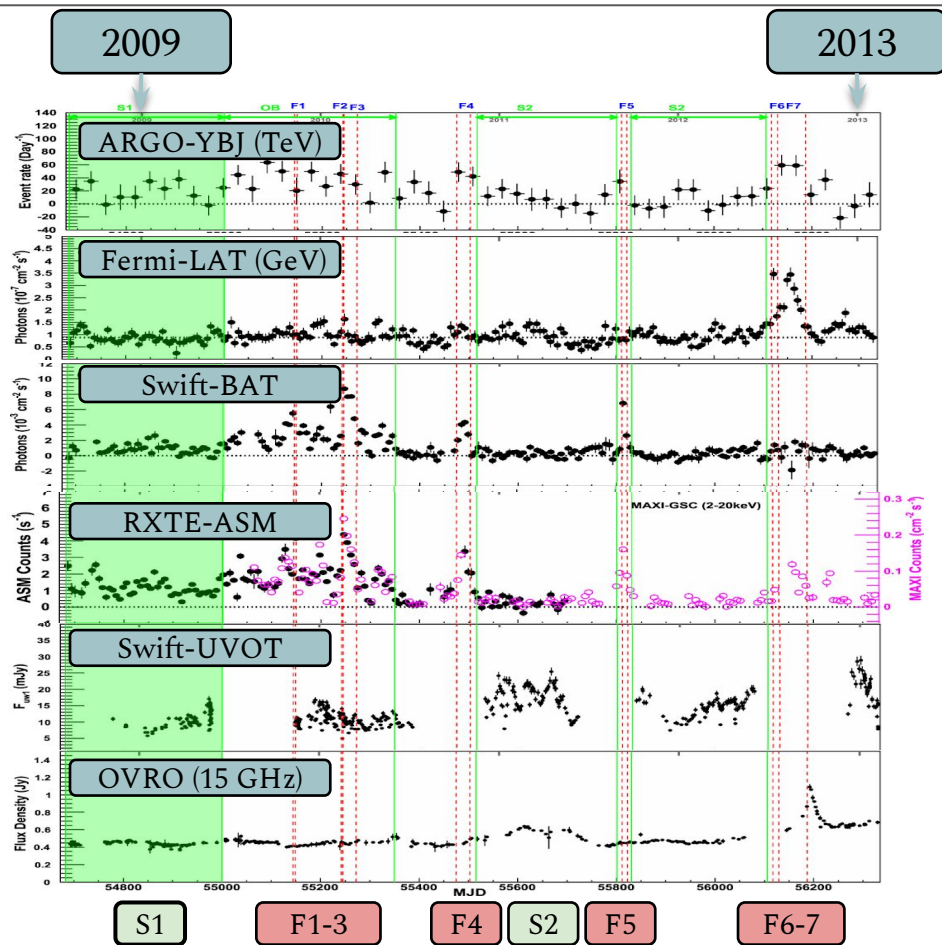


Application to Markarian 421 with and without DM

Kantzas et al. 2026 & Kantzas et al. in prep

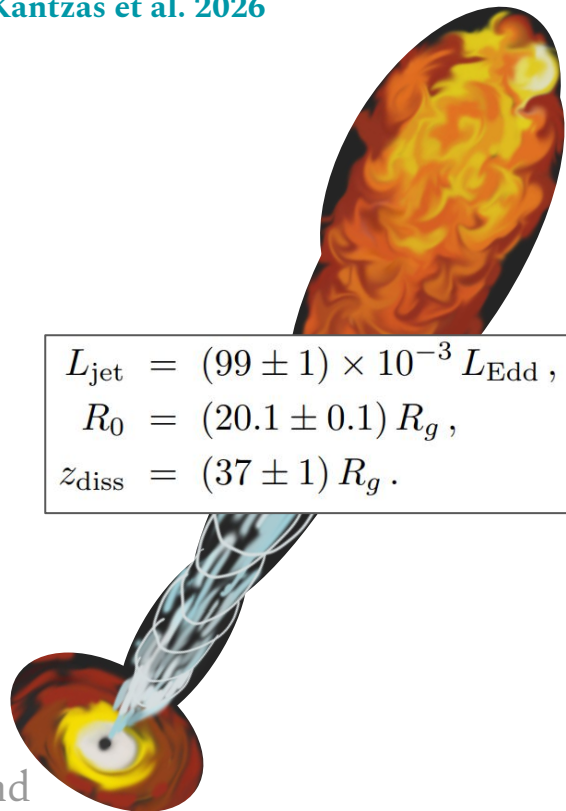
Markarian 421

Bartoli et al. 2016

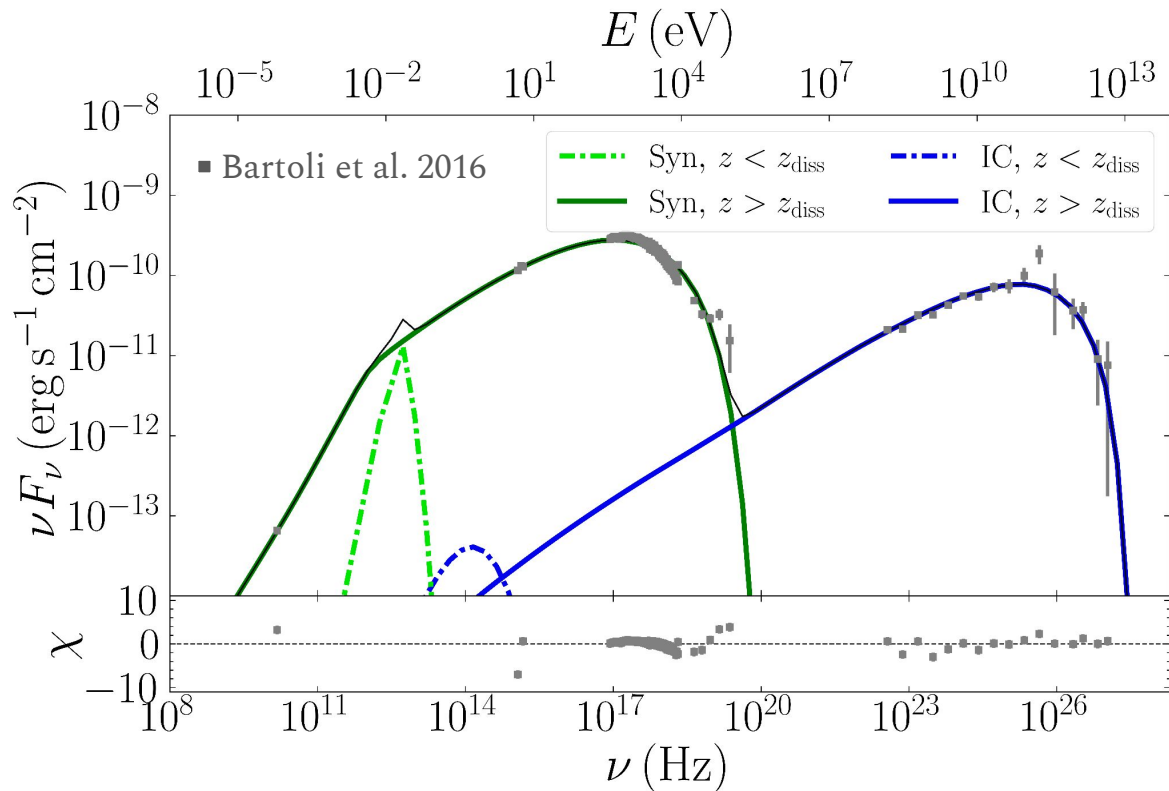


Markarian 421 Spectrum WITHOUT DM

Kantzas et al. 2026



and $\sigma=0.02, \Gamma_{\text{max}}=25, f_{\text{sc}}=10^{-6},$ and $p=2$



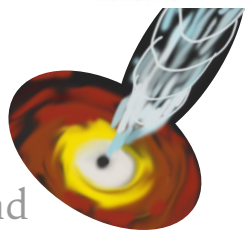
Markarian 421 Spectrum WITH DM

Kantzas et al. 2026



$$\begin{aligned} L_{\text{jet}} &= (99 \pm 1) \times 10^{-3} L_{\text{Edd}}, \\ R_0 &= (20.1 \pm 0.1) R_g, \\ z_{\text{diss}} &= (37 \pm 1) R_g. \end{aligned}$$

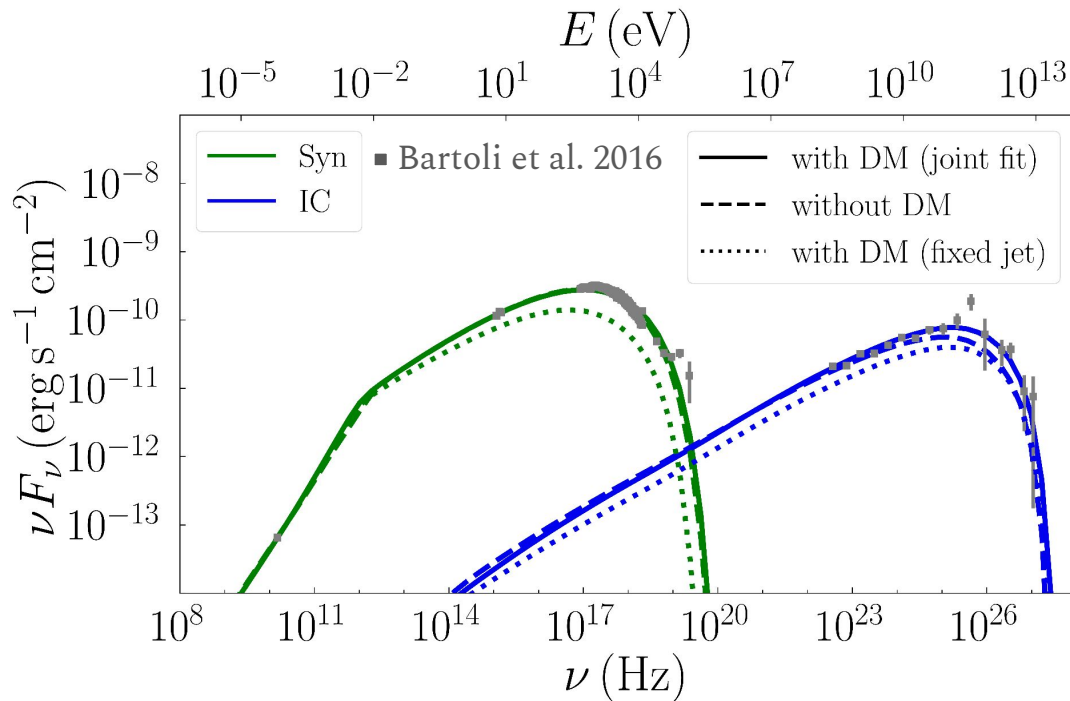
$$\sigma_{\text{DM-e}} = 1.58 \times 10^{-34} \text{ cm}^2$$



and

$$\sigma=0.02, \Gamma_{\text{max}}=25, f_{\text{sc}}=10^{-6}, \text{ and } p=2$$

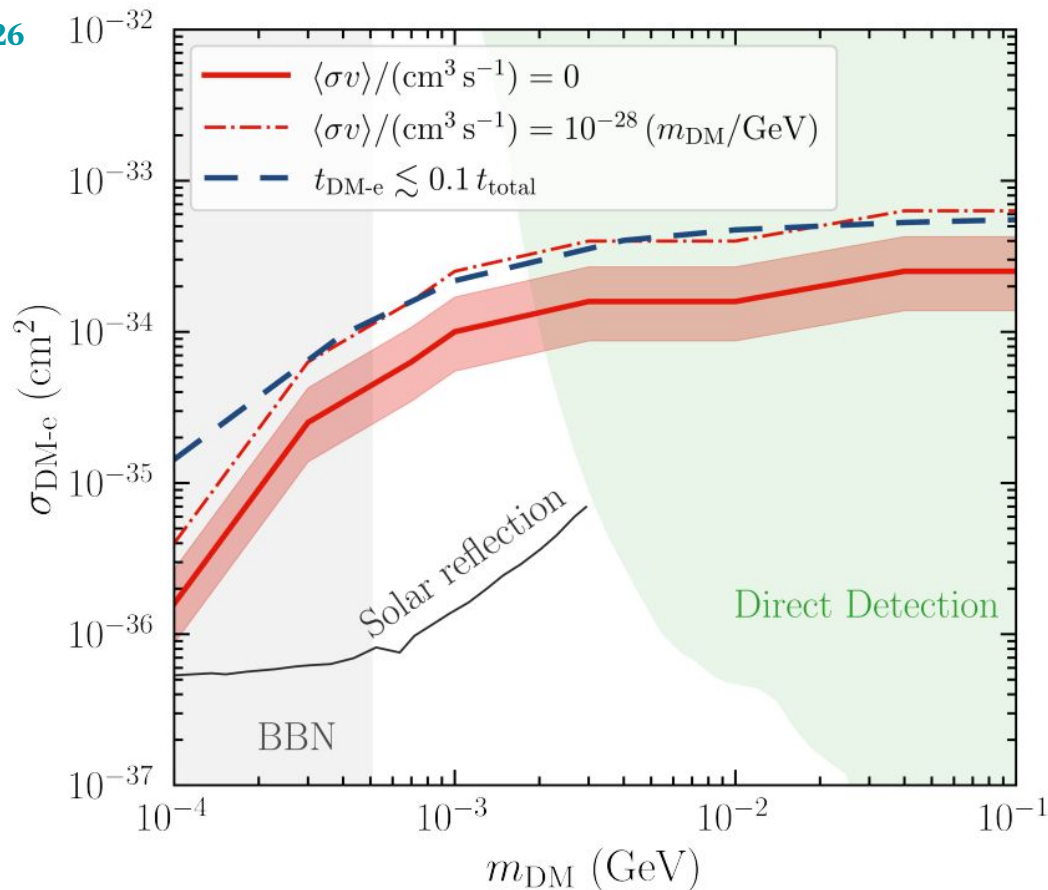
fixed: $m_{\text{DM}} = 1 \text{ MeV}$ and $\sigma_{\text{DM-e}} = 10^{-34} \text{ cm}^2$ ❌



Fixing the jet parameters leads to too optimistic results !

Constraints on DM-e scattering

Kantzas et al. 2026

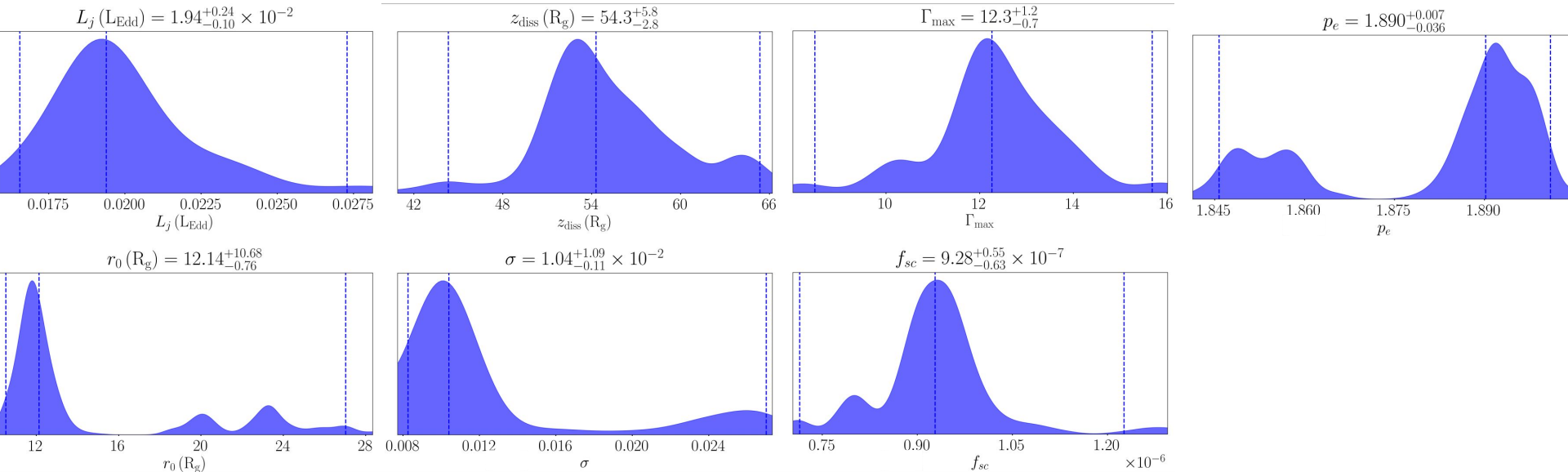


$$\Delta\chi^2 = \chi^2(\theta_{\text{astro}}, \sigma_{\text{DM-e}}; m_{\text{DM}}) - \chi^2(\theta_{\text{astro}}, 0; m_{\text{DM}})$$

Towards joint fits ...

Improving the Best Fits of Markarian 421 – S1

Kantzas et al. in prep

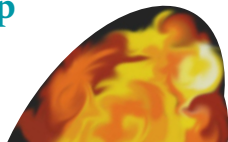


vs

$$\begin{aligned}
 L_{\text{jet}} &= (99 \pm 1) \times 10^{-3} L_{\text{Edd}} , \\
 R_0 &= (20.1 \pm 0.1) R_g , \\
 z_{\text{diss}} &= (37 \pm 1) R_g .
 \end{aligned}$$

Spectrum WITHOUT DM – S1

Kantzas et al. in prep



$$L_j(L_{\text{Edd}}) = (1.94^{+0.24}_{-0.10}) \times 10^{-2}$$

$$r_0(R_g) = 12.14^{+10.68}_{-0.76}$$

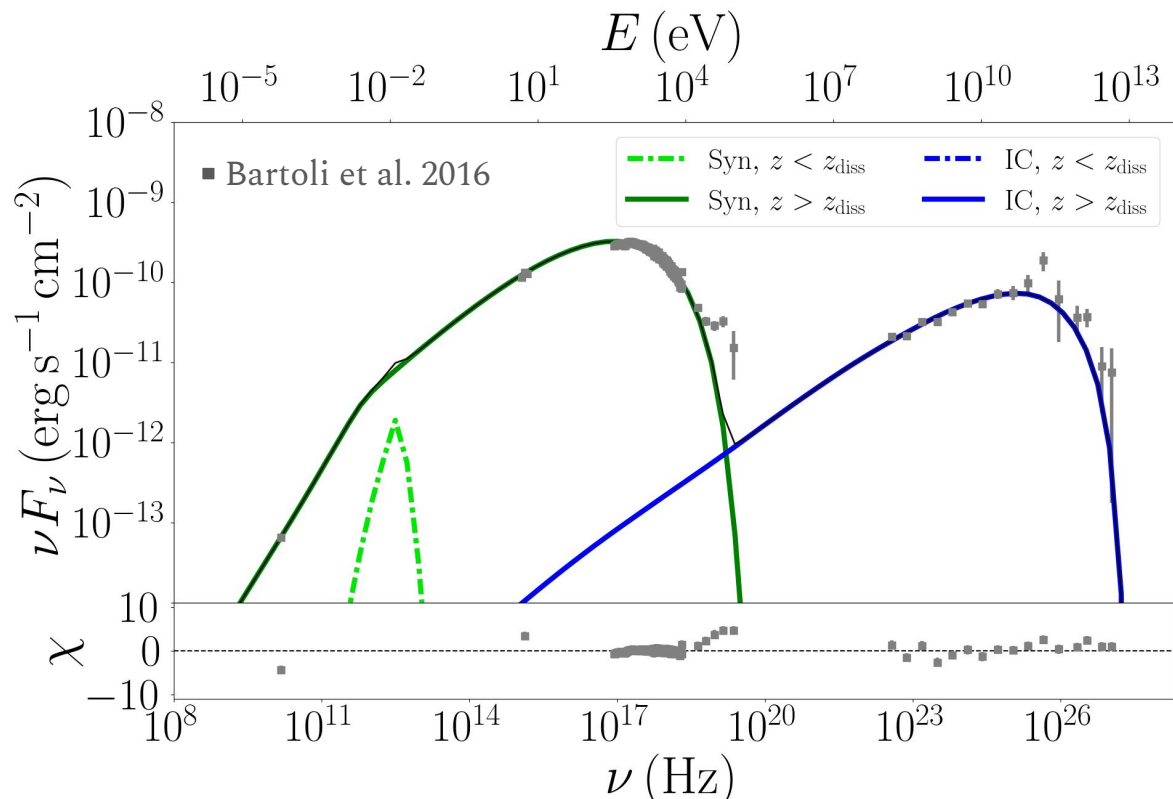
$$z_{\text{diss}}(R_g) = 54.3^{+5.8}_{-2.8}$$

$$\sigma = (1.04^{+1.09}_{-0.11}) \times 10^{-2}$$

$$\Gamma_{\text{max}} = 12.3^{+1.2}_{-0.7}$$

$$f_{\text{sc}} = (9.28^{+0.55}_{-0.63}) \times 10^{-7}$$

$$p_e = 1.890^{+0.007}_{-0.036}$$



Spectrum WITHOUT DM – S2

Kantzas et al. in prep



$$L_j(L_{\text{Edd}}) = (6.76^{+0.23}_{-0.24}) \times 10^{-2}$$

$$r_0(R_g) = 5.38^{+0.13}_{-0.22}$$

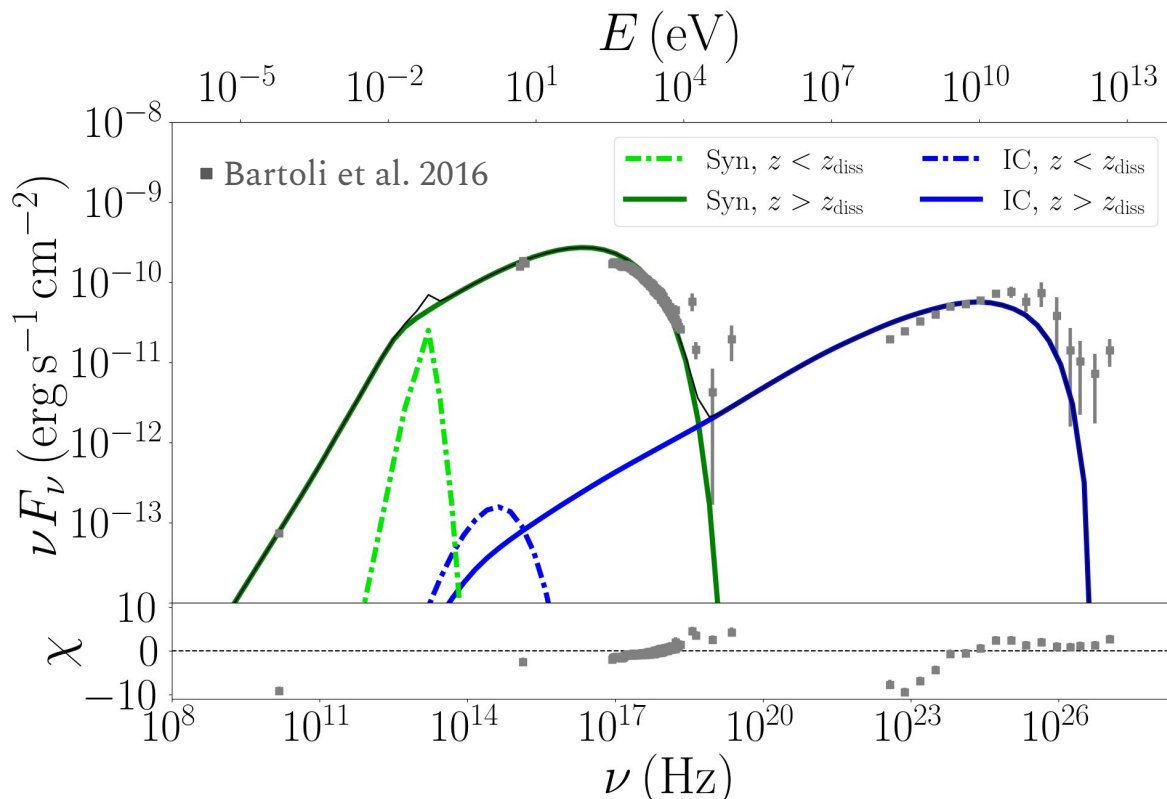
$$z_{\text{diss}}(R_g) = 13.5^{+0.9}_{-1.4}$$

$$\sigma = (6.77^{+1.57}_{-0.80}) \times 10^{-2}$$

$$\Gamma_{\text{max}} = 29.9^{+0.0}_{-0.1}$$

$$f_{\text{sc}} = (1.82^{+0.01}_{-0.02}) \times 10^{-7}$$

$$p_e = 2.000^{+0.003}_{-0.003}$$



Interpretation of New Results



S1

F1-4

S2

$$L_j(L_{\text{Edd}}) = (1.94^{+0.24}_{-0.10}) \times 10^{-2}$$

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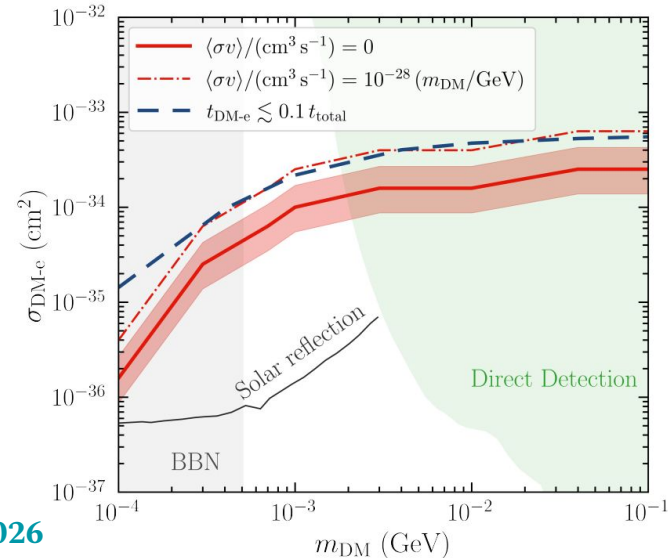
$$p_e = 2.000^{+0.003}_{-0.003}$$



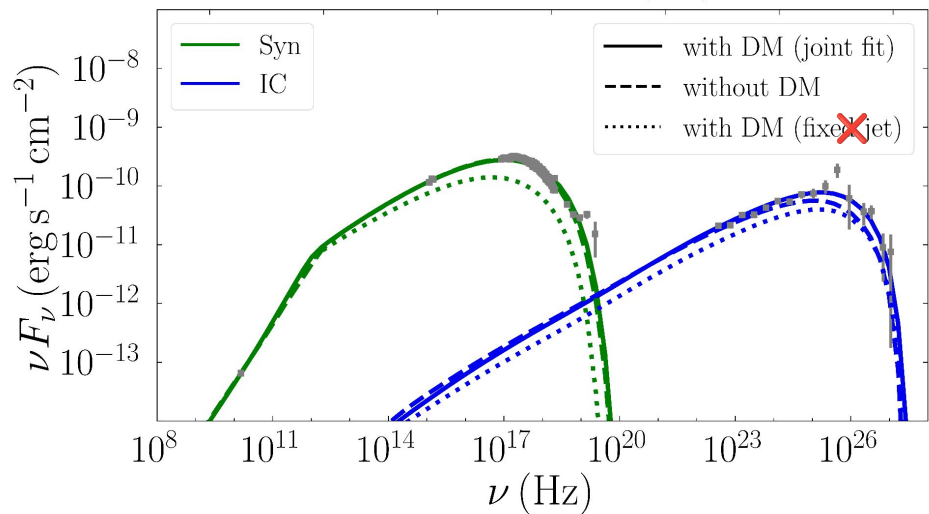
Kantzas et al. in prep

Take home message

- ❑ Self-consistent DM halo profile
- ❑ Combination of DM with more physical jet model (BHJet)
- ❑ Assessing the impact of uncertainties of the dynamical properties
- ❑ More robust results compared to “timescale approach” and fixed jet
- ❑ Further analysis of multiple states in prep



Kantzas et al. 2026



Extra Material

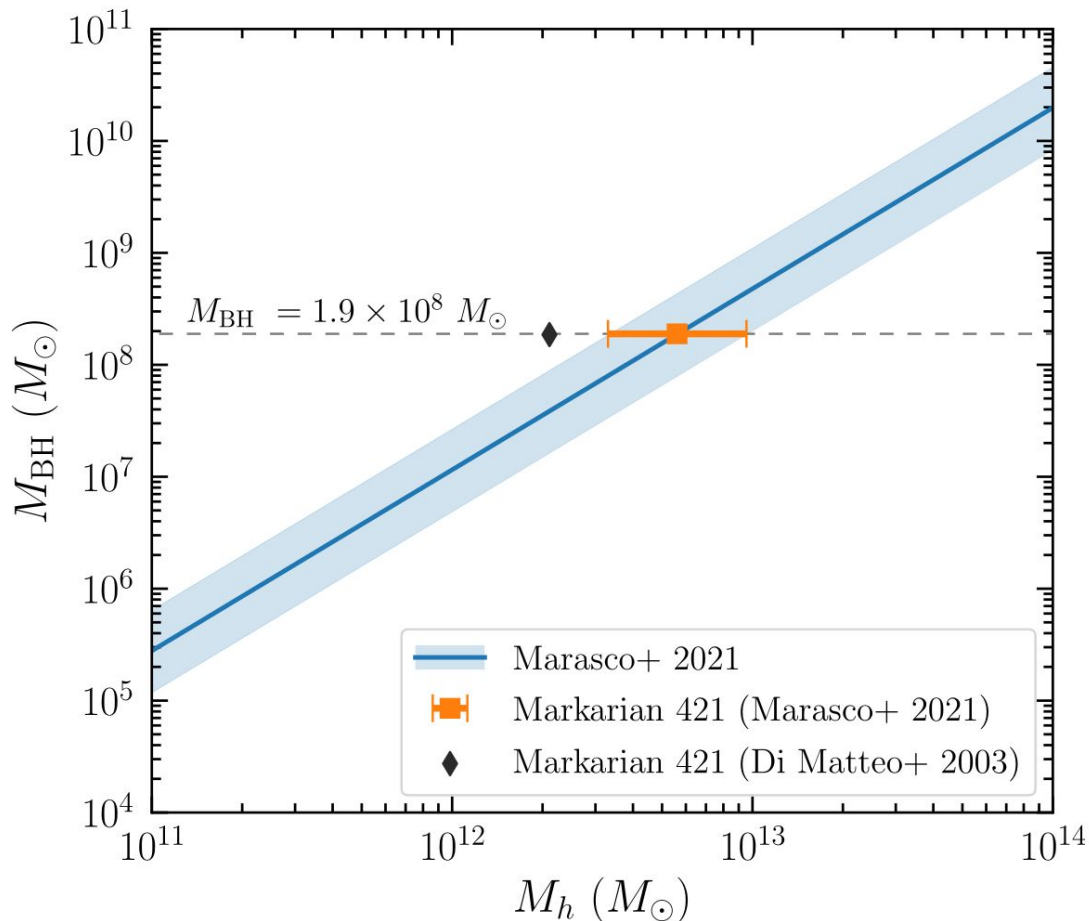
More about DM Halo

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

Kantzas et al. 2026

Previous works

$$\int_{R_S}^{10^5 R_S} 4\pi r^2 \rho(r) dr = \Delta M_{\text{BH}},$$



Elastic CR-DM Collisions in Other Sources

