~~The multiwavelength signature of the multizone jets of Mkn 421~~

Indirect dark-matter searches with γ-rays

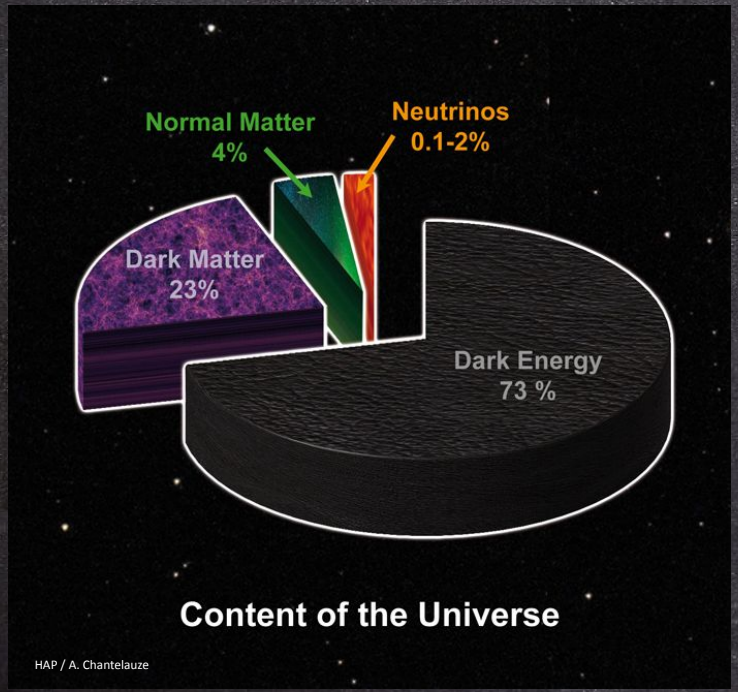
Dimitrios Kantzas
LAPTh/CNRS

with
Francesca Calore, Marco Chianese

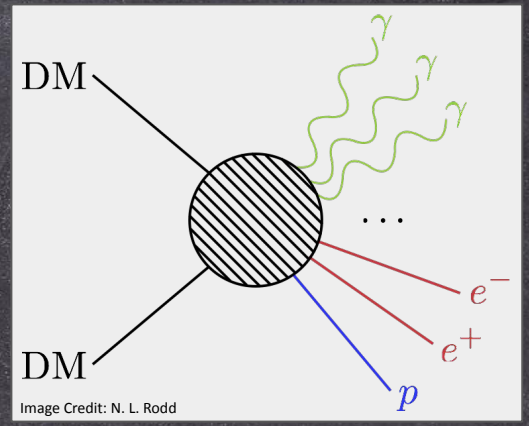
Funded by the European Union

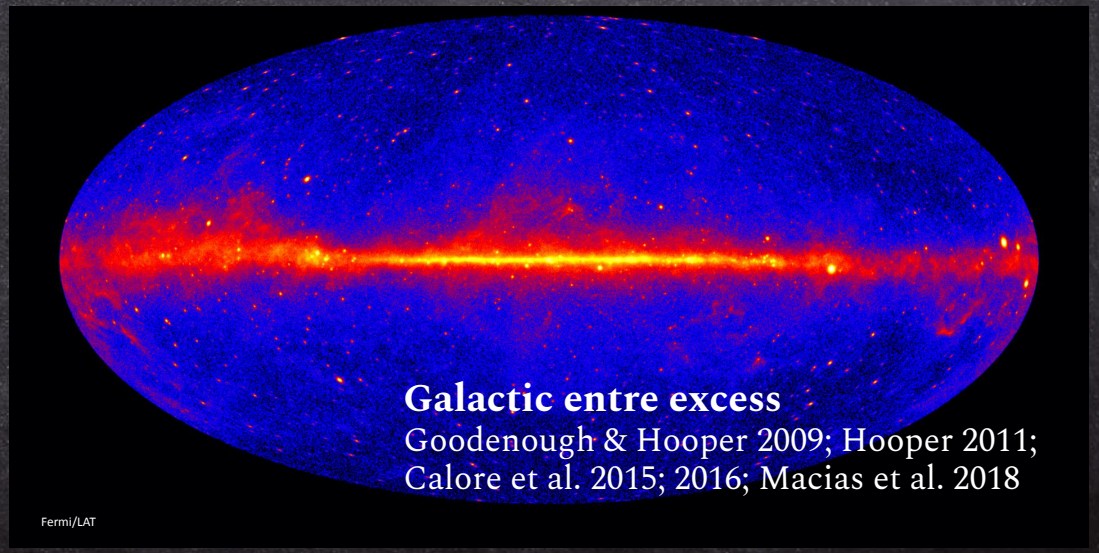
Image Credit: NASA/JPL-Caltech

Indirect dark matter searches

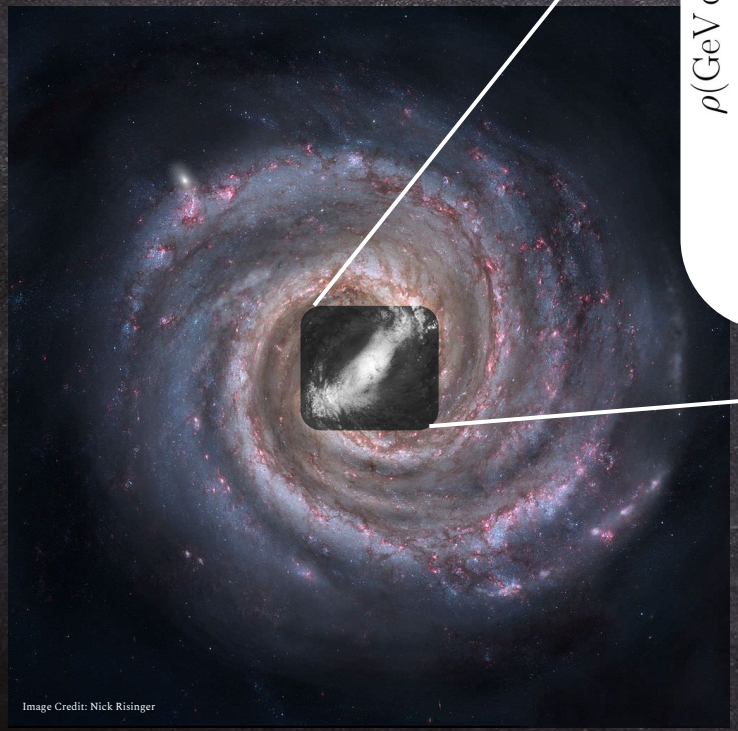


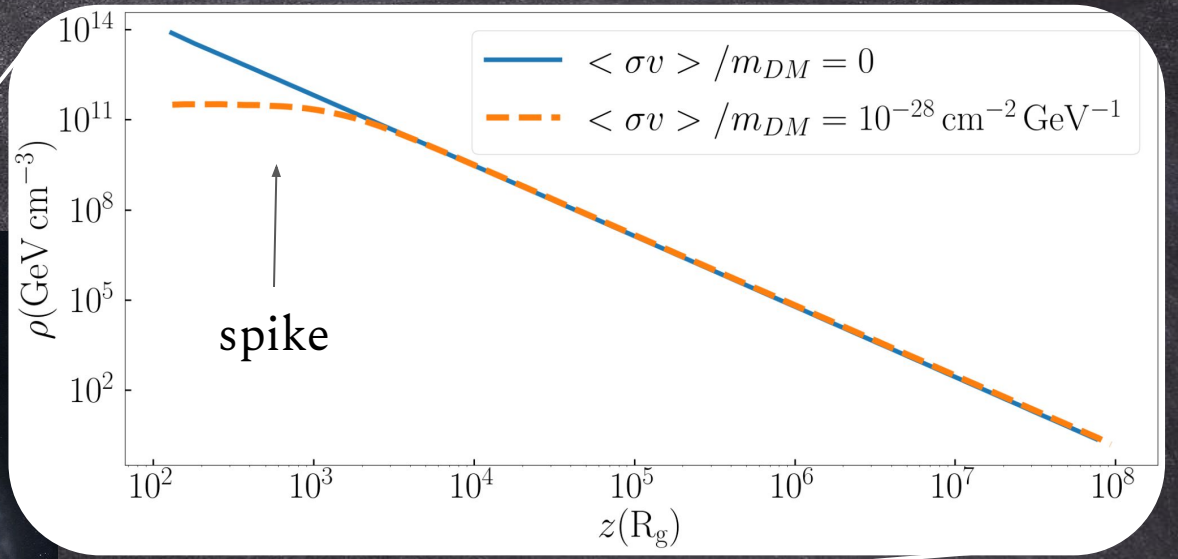
m_{DM} & $\langle\sigma v\rangle$





DM spikes

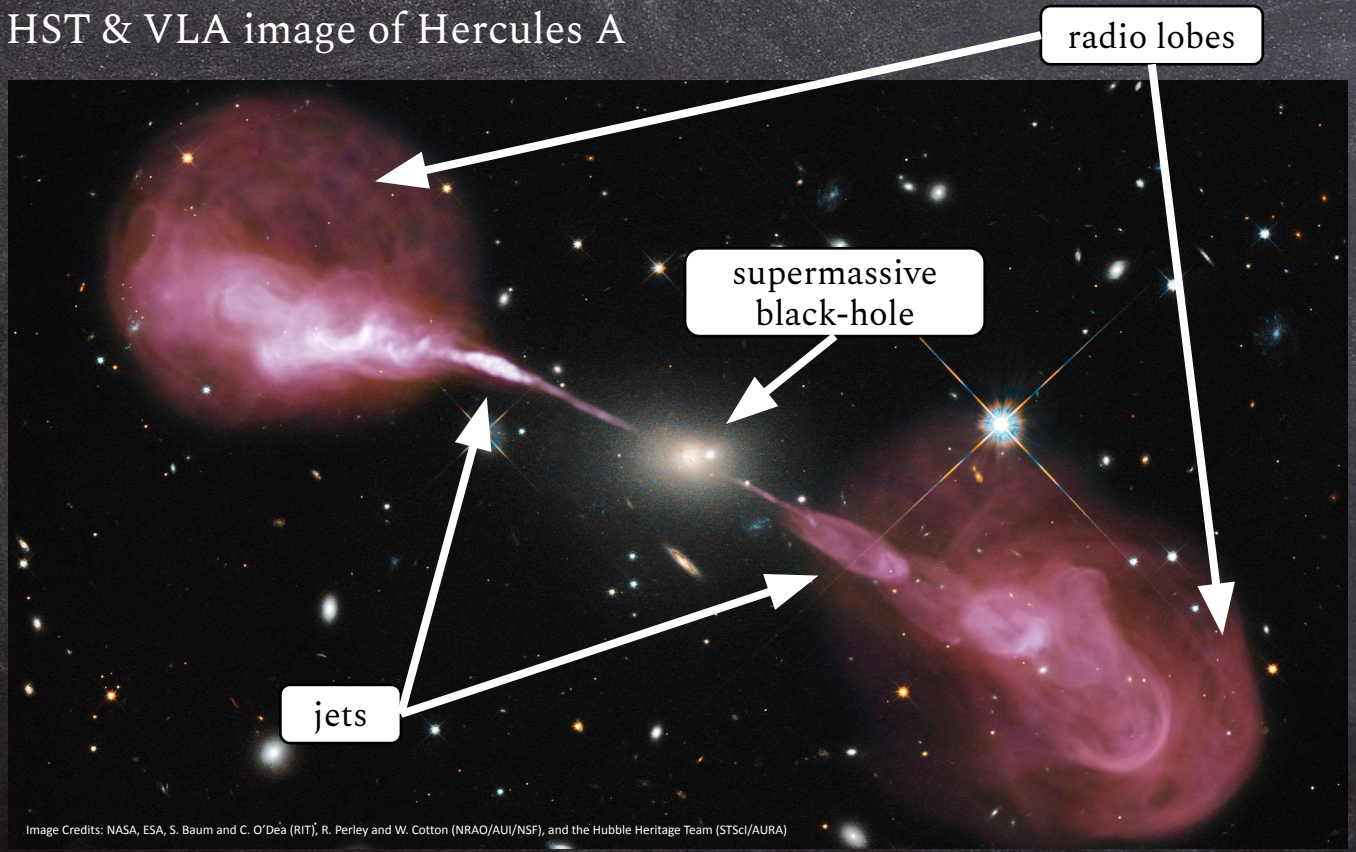




see e.g., Quinlan et a. 1995; Gondolo & Silk 1999; Gorchtein et al. 2010

Active galactic nuclei (AGN)

HST & VLA image of Hercules A

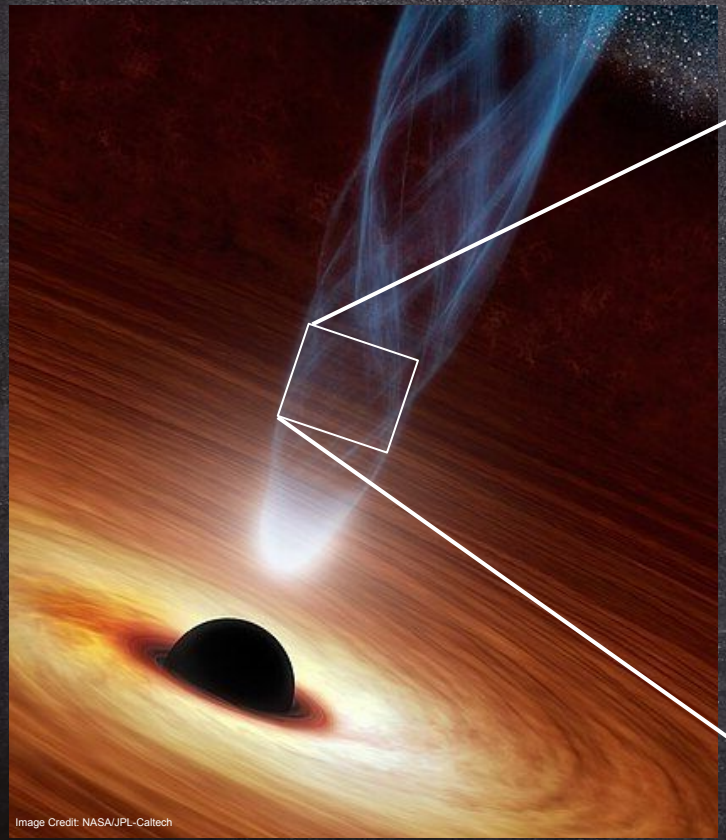


Supermassive BH
- powers jets

Jets
- accelerate CRs

Radio lobes
- feedback

Cosmic ray (CR) acceleration in AGN jets



CR acceleration mechanism!

E_{min}

slope (p)

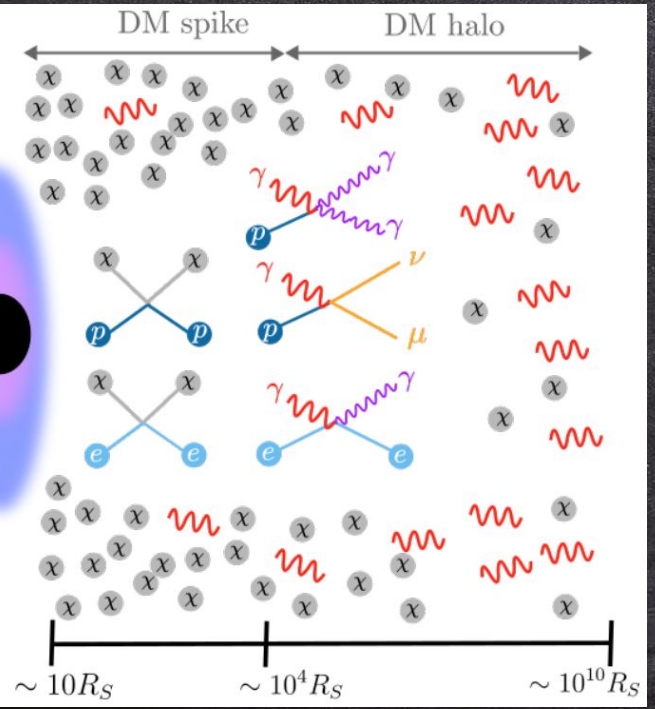
E_{max}

CR density

CR energy

CR cooling due to DM or boosted DM

e.g., Bringmann & Pospelov 2019; Ema et al. 2019;
Cappiello & Beacom 2019; Guo et al. 2020; Wang et al. 2022



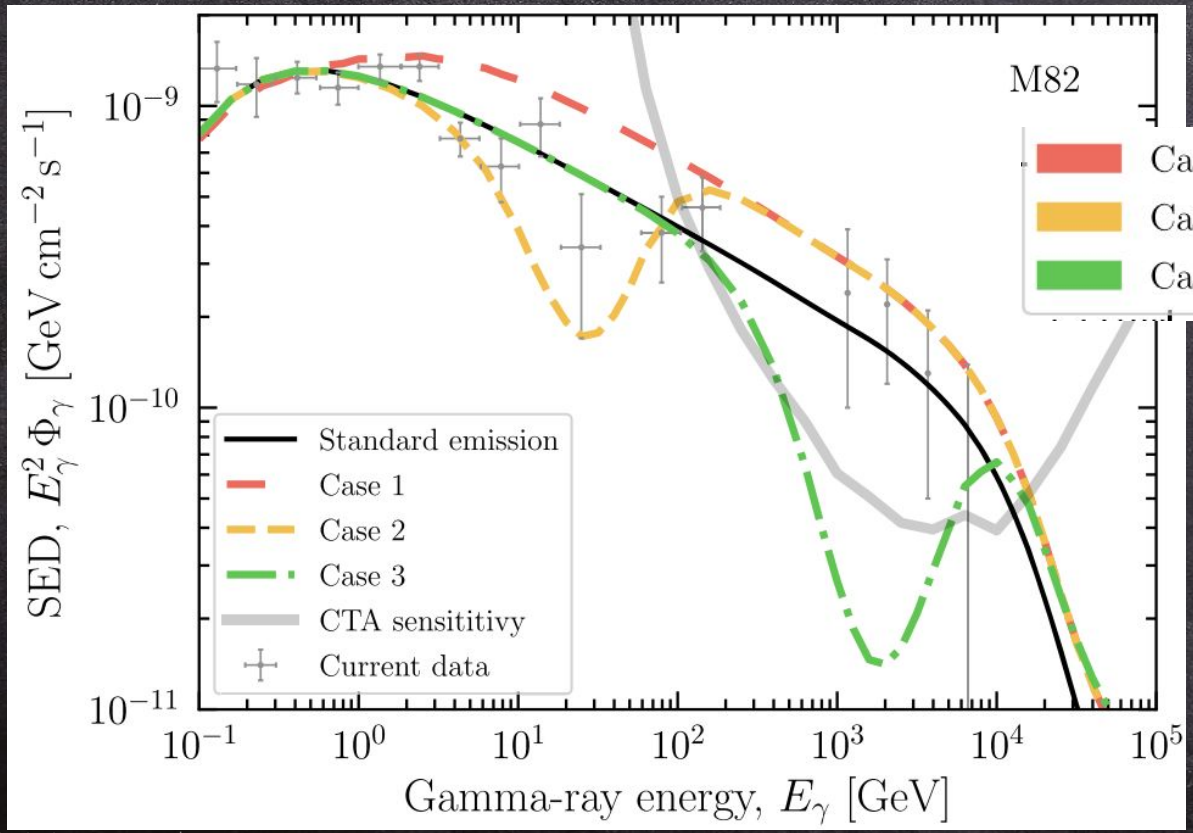
Herrera & Murase, 2024

$\chi + e^-/p^+ \rightarrow \chi + e^-/p^+$ — elastic CR-DM

$\chi + p^+ \rightarrow \chi + p^+ + \ldots +$ **γ-rays** + **neutrinos** — inelastic CR-DM

Effect of inelastic CR-DM on the γ-ray spectrum

Ambrosone et al, 2024



Case 1: $m_\chi = 10^{-1}\,\mathrm{GeV}, \sigma_{\chi p} = 10^{-25}\,\mathrm{cm}^2$

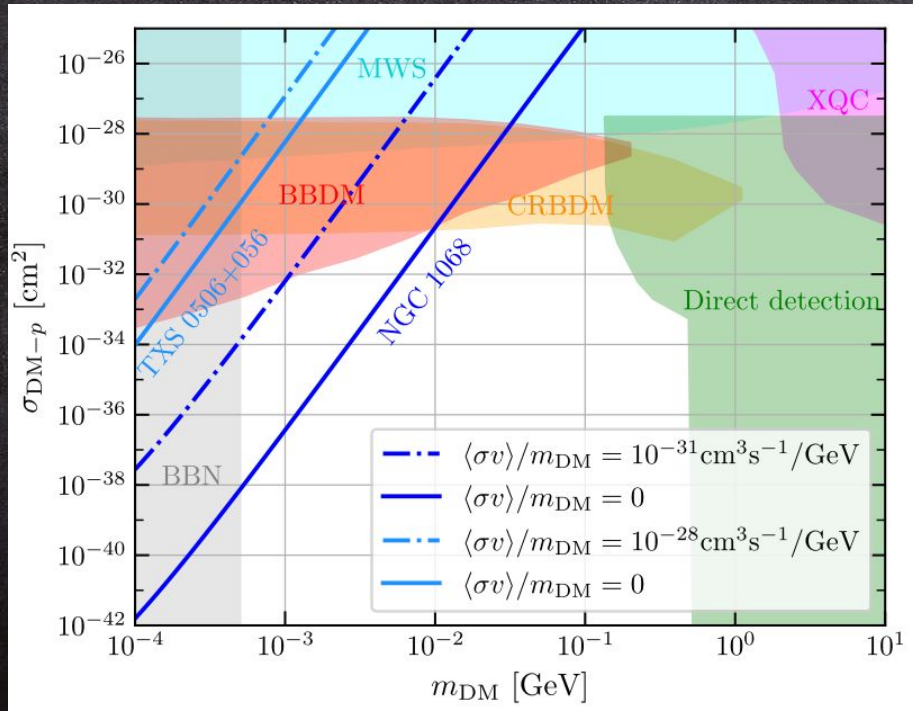
Case 2: $m_\chi = 10^{-3}\,\mathrm{GeV}, \sigma_{\chi p} = 10^{-29}\,\mathrm{cm}^2$

Case 3: $m_\chi = 10^{-5}\,\mathrm{GeV}, \sigma_{\chi p} = 10^{-34}\,\mathrm{cm}^2$

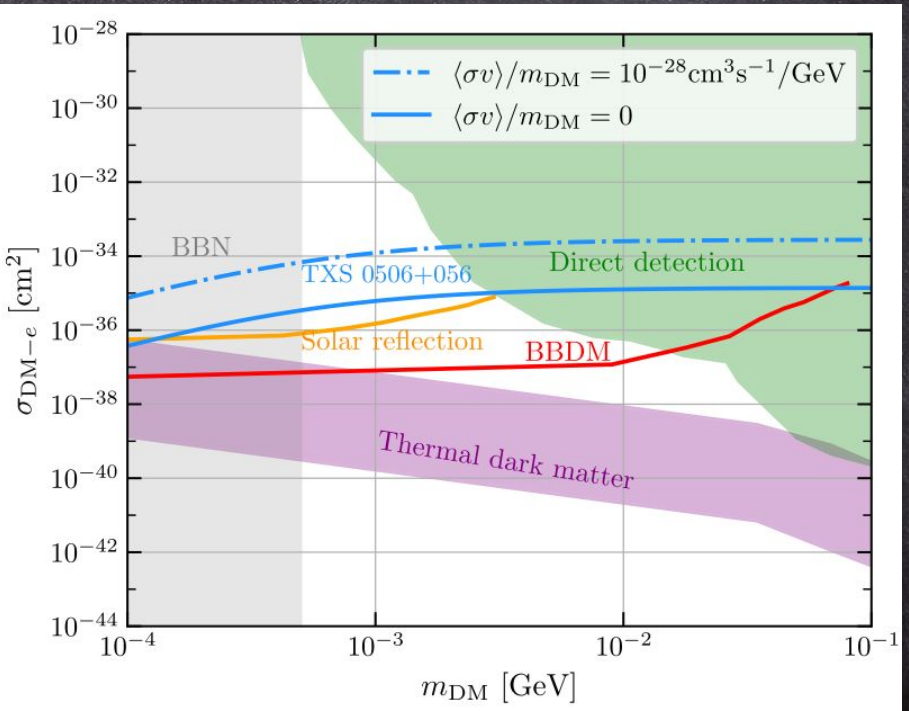
Elastic CR-DM collisions in AGN jets

Herrera & Murase, 2024

CR protons + DM

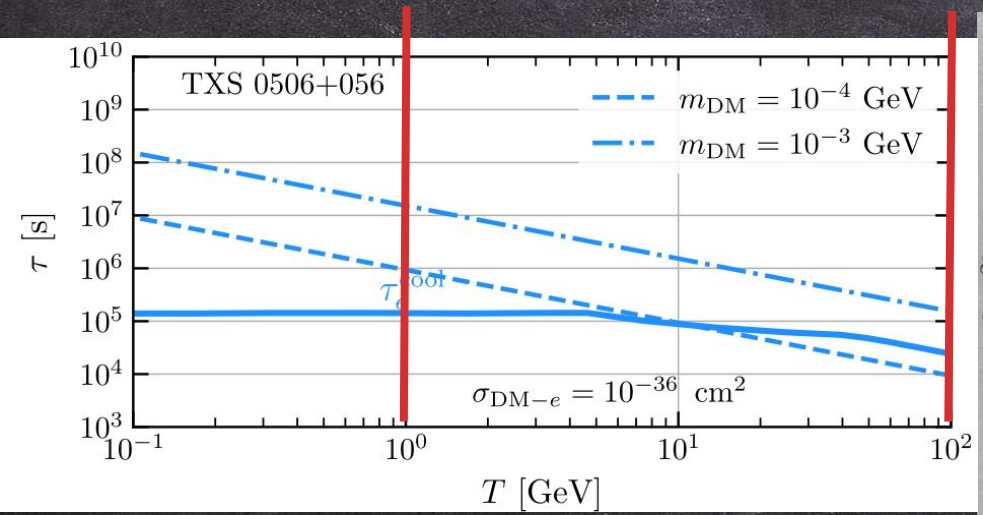


CR electrons + DM



Elastic CR-DM collisions in AGN jets

Herrera & Murase, 2024



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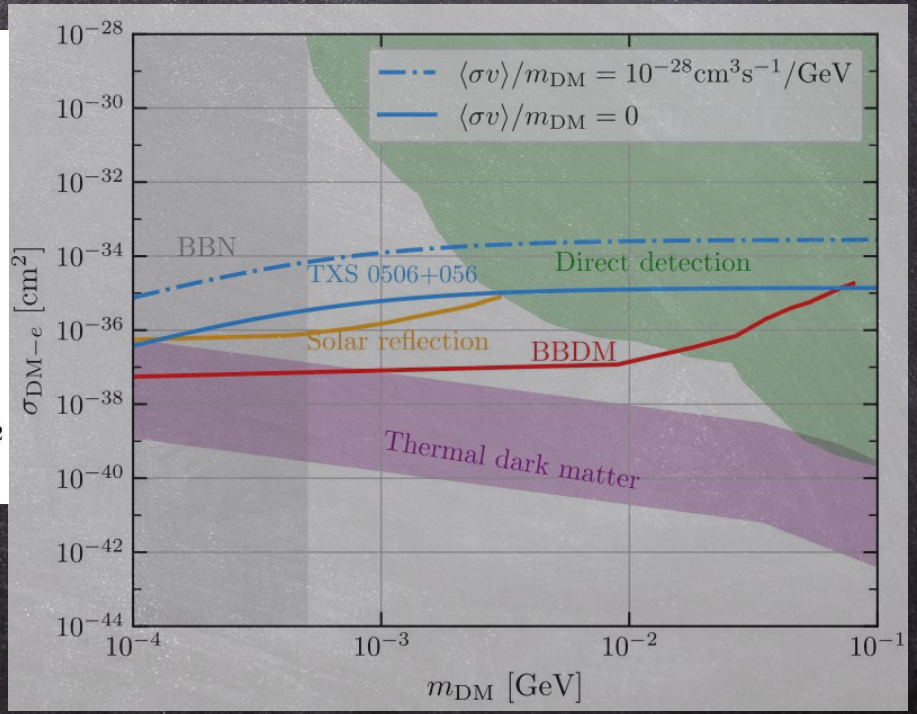
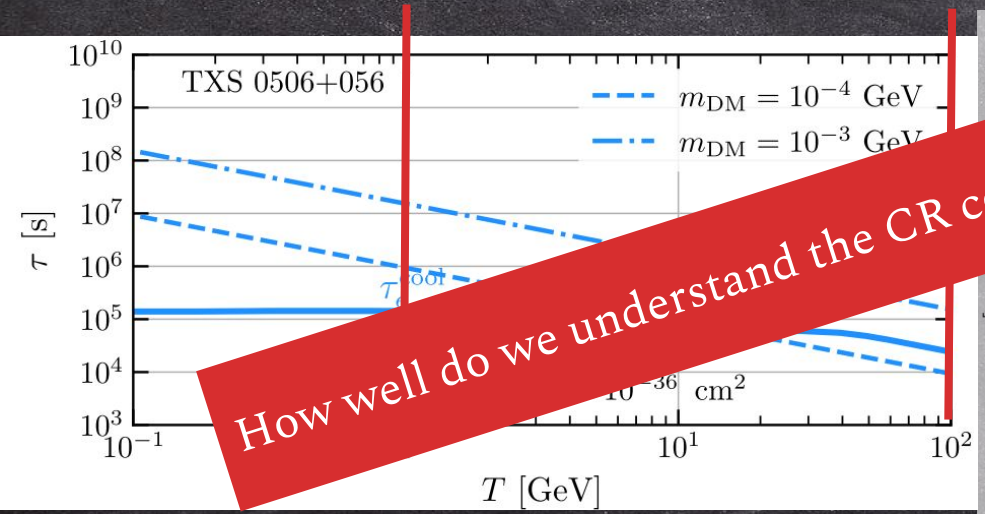


Factor of 10 or less impact on the proton (electron) cooling time scale

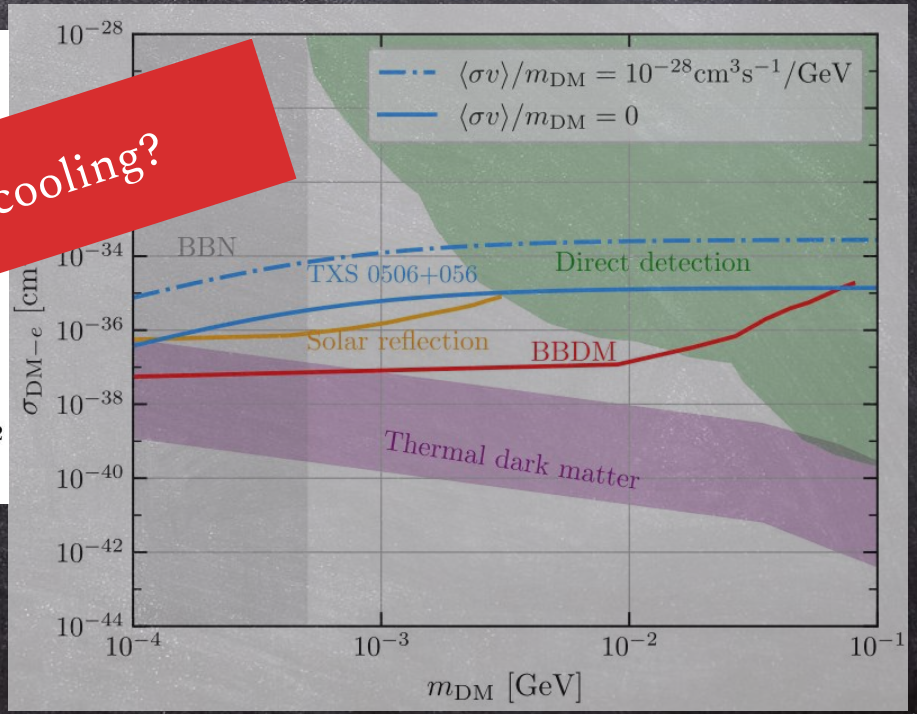
Elastic CR-DM collisions in AGN jets

Herrera & Murase, 2024



How well do we understand the CR cooling?

CR electrons + DM



Factor of 10 or less impact on the proton (electron) cooling time scale

Semi-analytical, multi-zone jet model

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

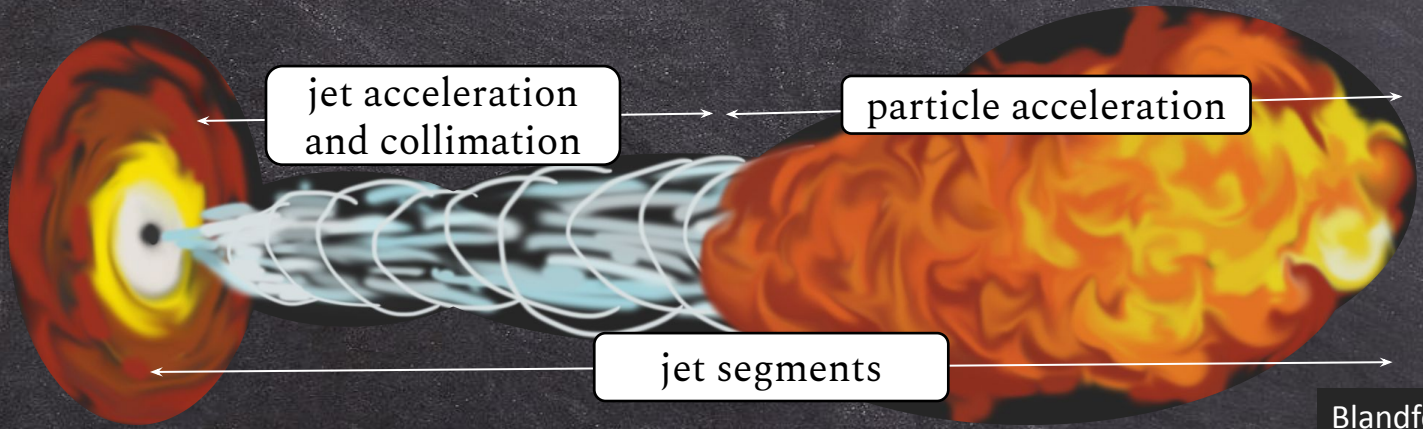
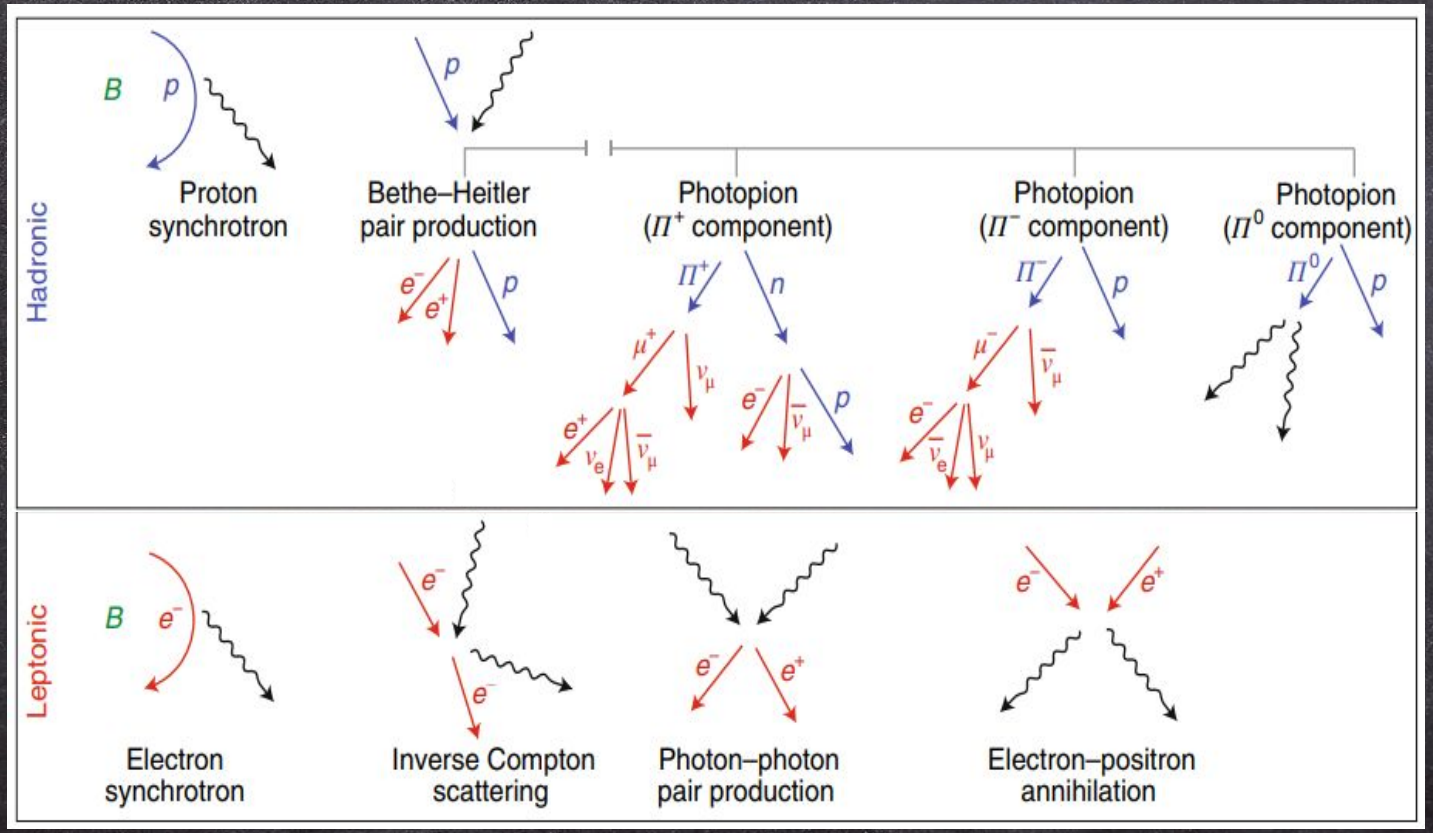


Image Credit: T. Revolta

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

Jet composition and radiative processes



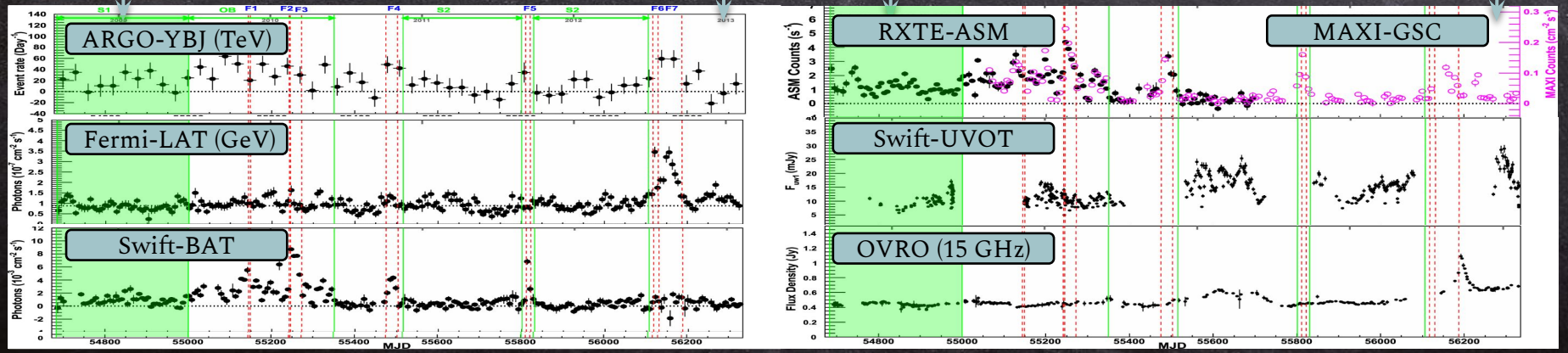
Pian 2019

The study case of Markarian 421

- BL Lac object
- @122Mpc (z=0.0308)
- The 1st extragalactic TeV source (Punch et al. 1992)
- One of the brightest quasars

2009 2013 2009 2013

Bartoli et al. 2016



2 jet cases for Mkn 421

Pencil jet: slim and powerful

jet power: **0.08 Edd**

radius: **10 R_g**

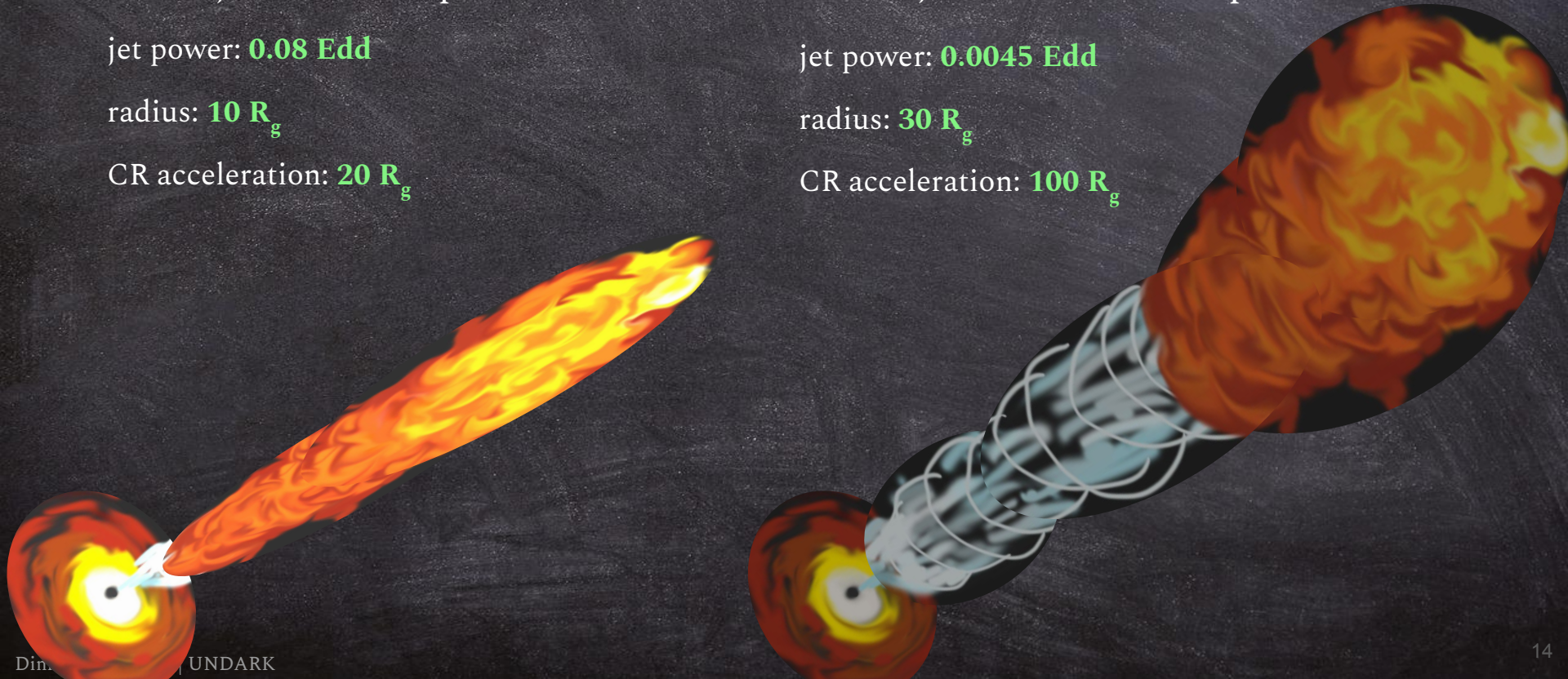
CR acceleration: **20 R_g**

Brush jet: thick and less powerful

jet power: **0.0045 Edd**

radius: **30 R_g**

CR acceleration: **100 R_g**



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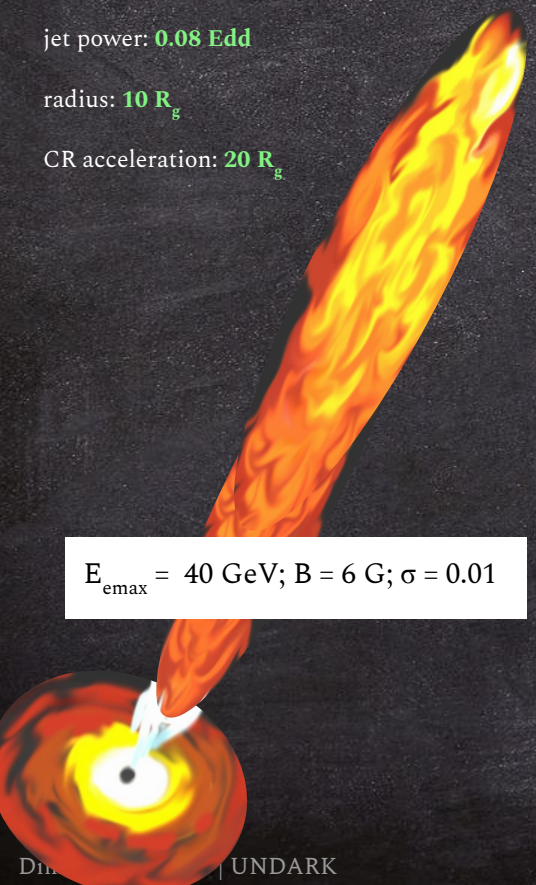
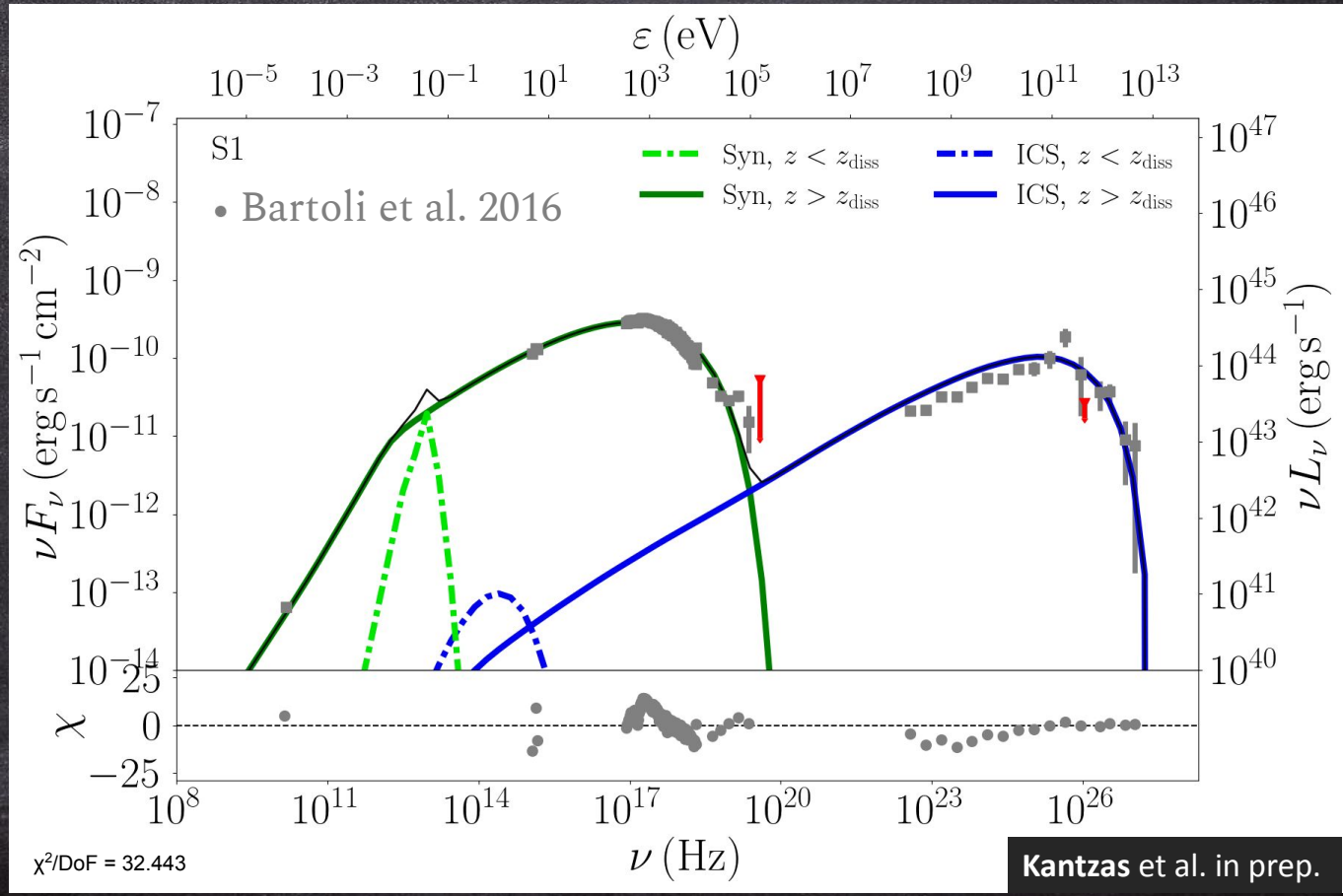


E_{emax} = 40 GeV; B = 6 G; σ = 0.01



Kantzas et al. in prep.

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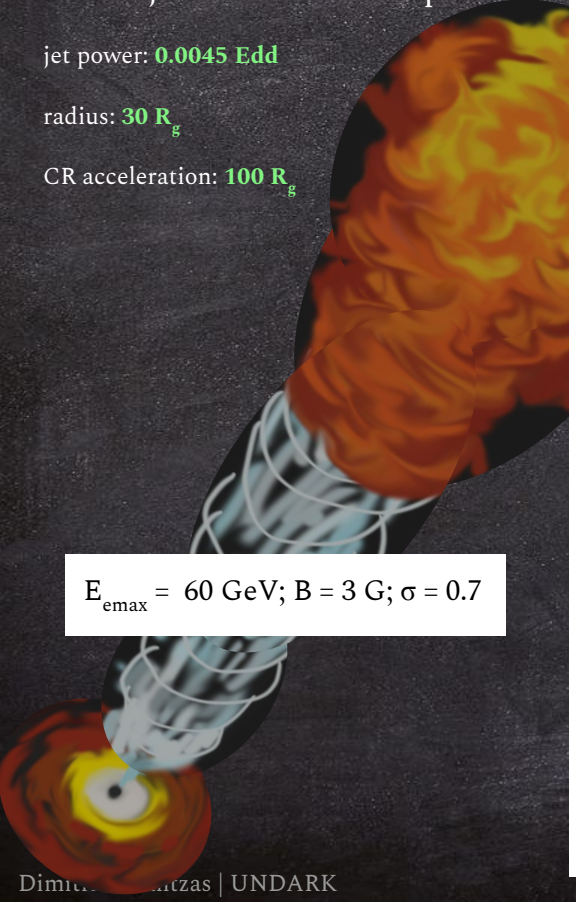
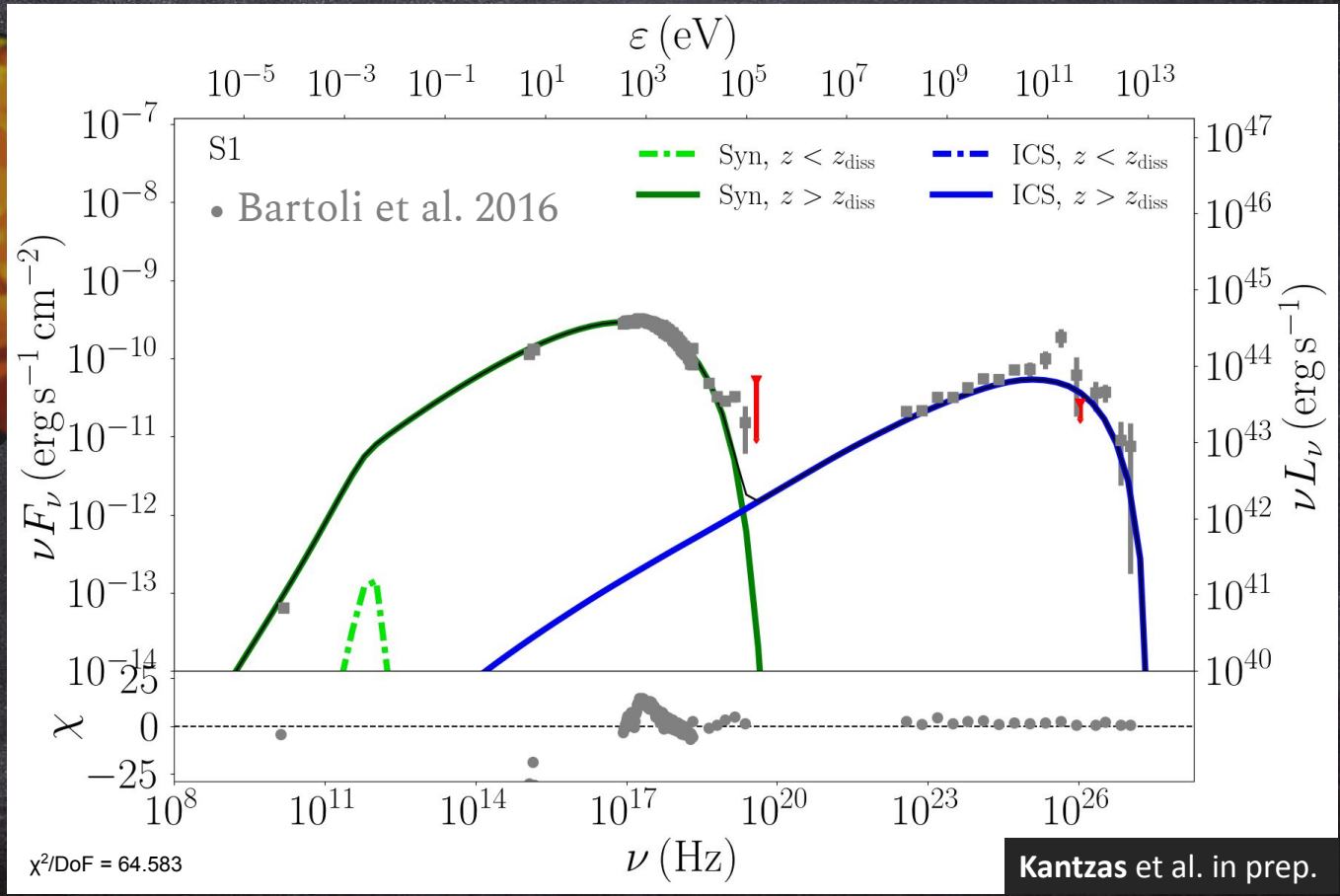
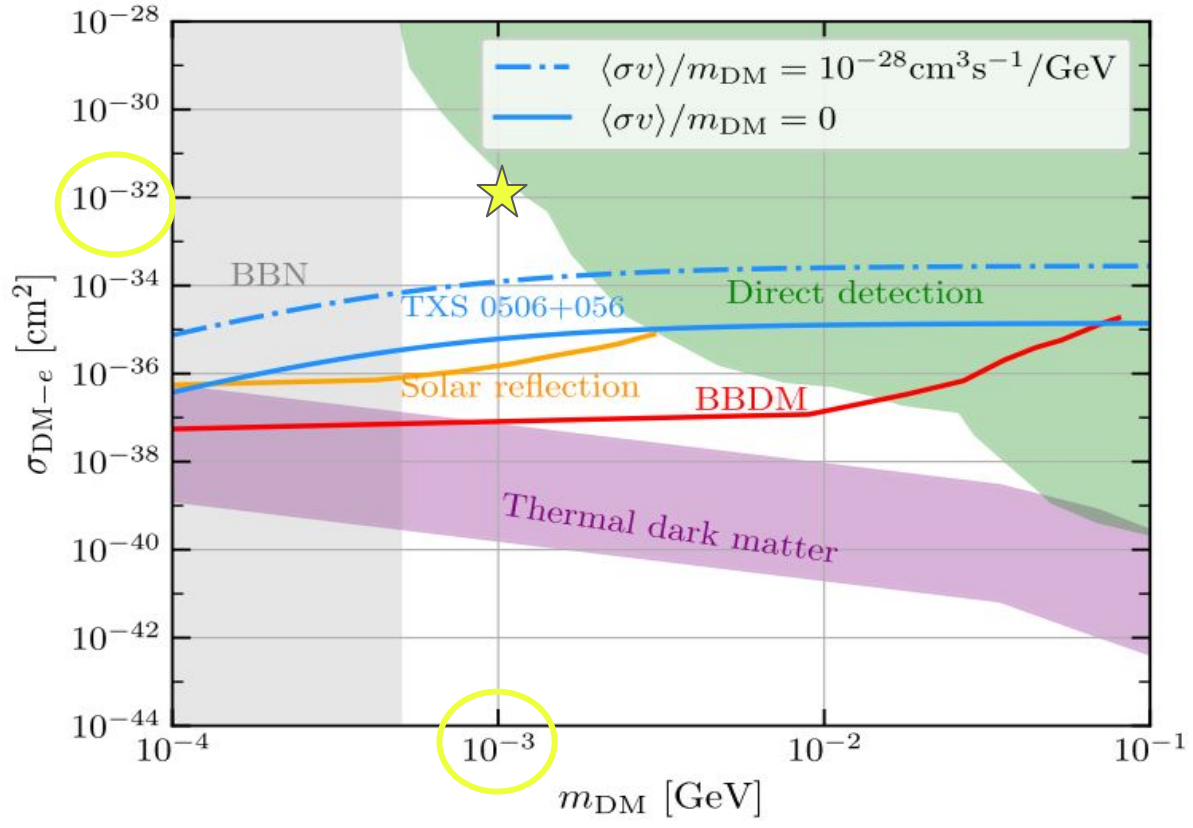


E_{emax} = 60 GeV; B = 3 G; σ = 0.7



Kantzas et al. in prep.

The MW spectrum of Mkn 421 with DM



Herrera & Murase, 2024

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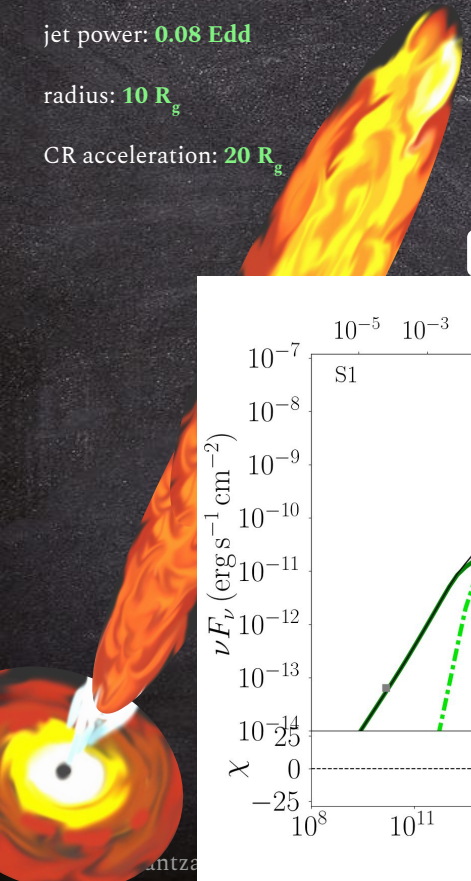
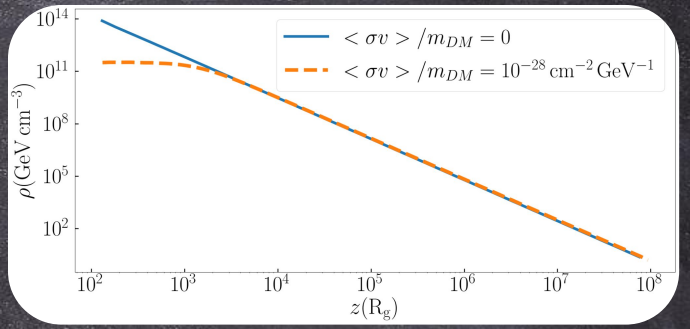
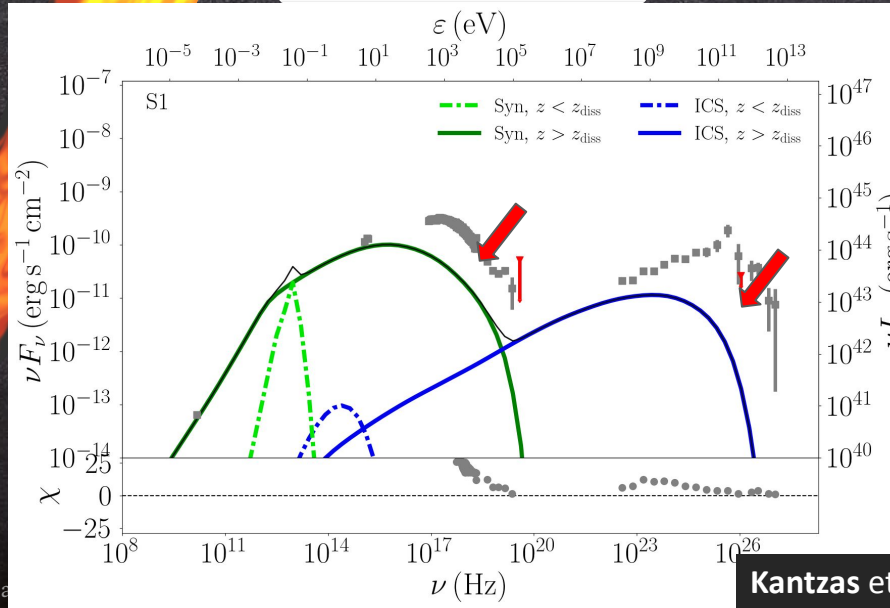




$< \sigma v > /m_{DM} = 10^{-28}\,\mathrm{cm}^{-2}\,\mathrm{GeV}^{-1}$



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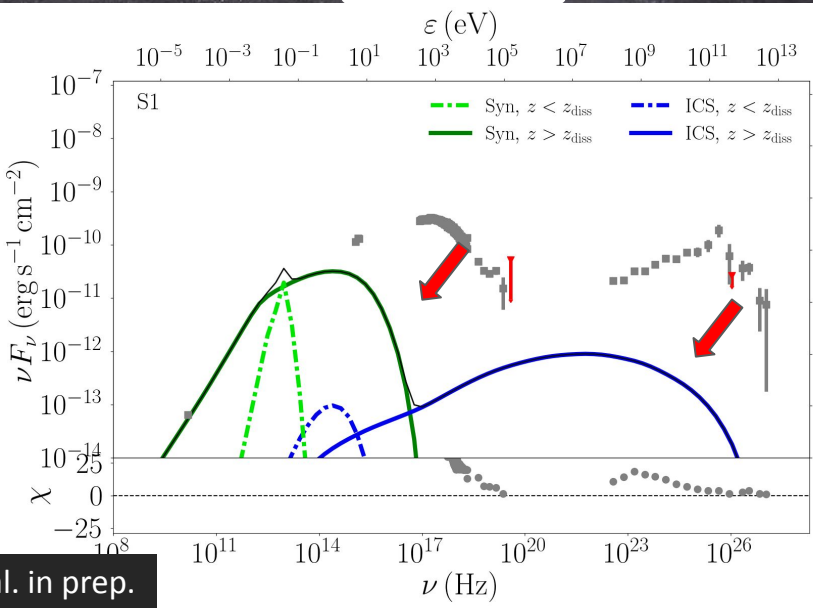

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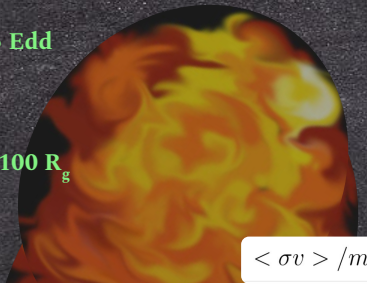

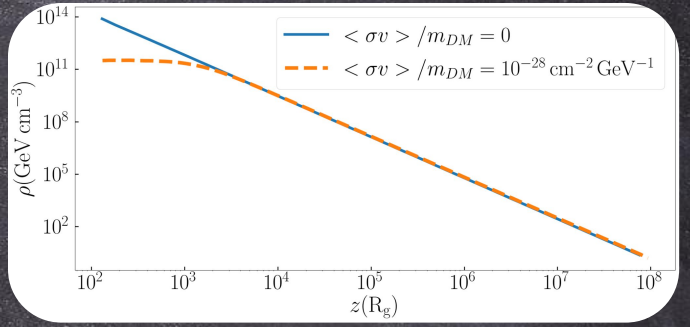

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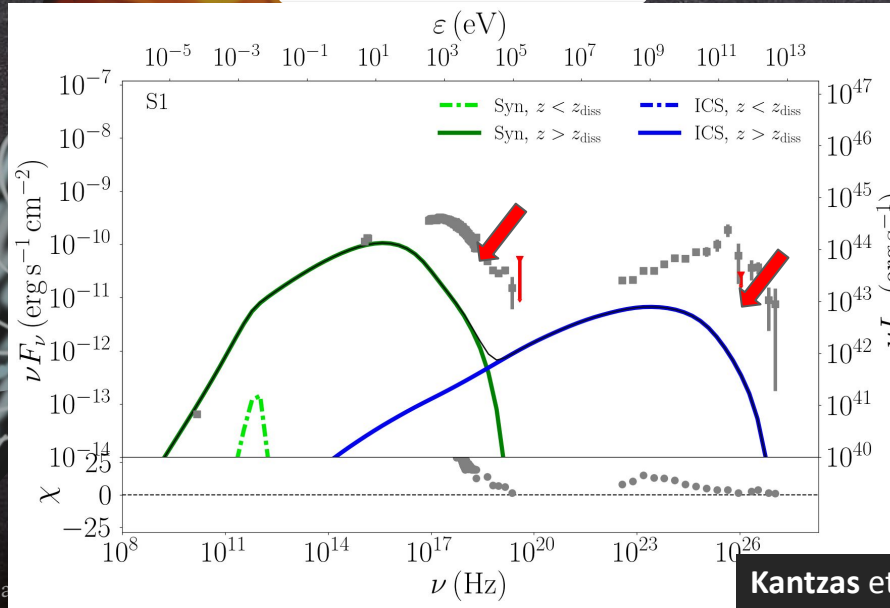

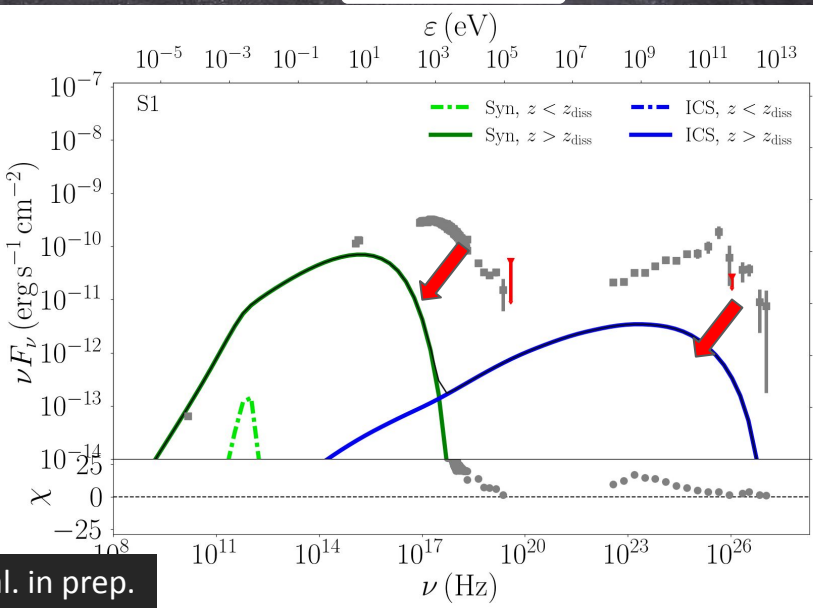

Kantzas et al. in prep.

The cooling timescales

$< \sigma v > / m_{DM} = 10^{-28}\,\mathrm{cm}^{-2}\,\mathrm{GeV}^{-1}$

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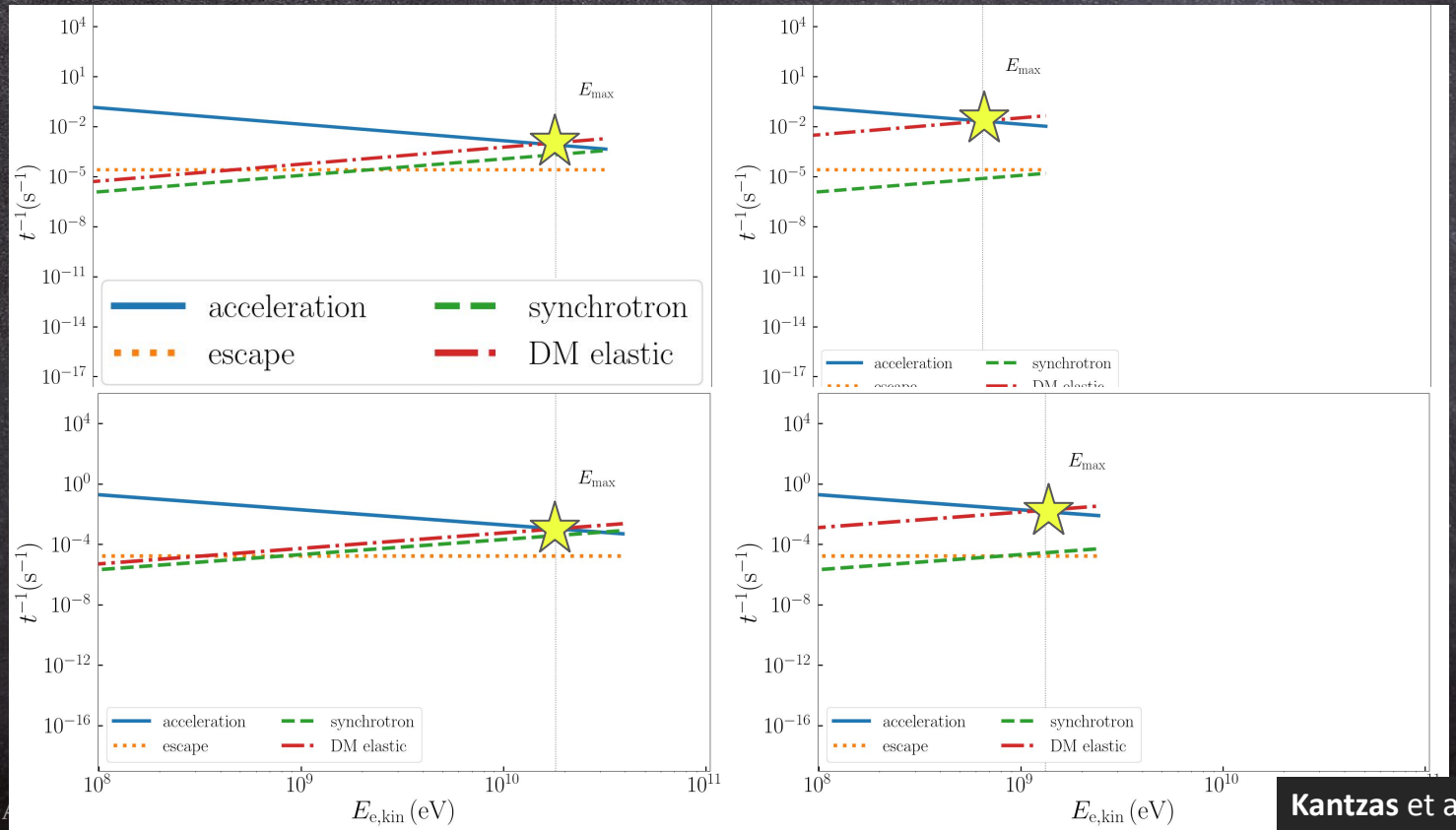


Kantzas et al. in prep.

Conclusions

- CRs may cool due to CR-DM collisions
- CR-DM may produce secondary particles via inelastic collisions
- We cannot draw conclusions on the DM nature unless we better constrain jet physics !
- More physical-driven jet models are required !! ⟶
- DMJet in prep

Find BHJet here

Extra material

A multi

How to mo

The kinetic equation approach

Protons:

$$\frac{\partial n_{\rm p}}{\partial t} + L_{\rm p}^{\rm BH} + L_{\rm p}^{\rm photopion} + L_{p}^{\rm psyn} + L_{p}^{pp} + \frac{n_{\rm p}}{t_{\rm p,esc}} = Q_{\rm p}^{\rm inj} + Q_{\rm p}^{\rm photopion}$$

Electrons:

$$\frac{\partial n_{\rm e}}{\partial t} + L_{\rm e}^{\rm syn} + L_{\rm e}^{\rm ics} + L_{\rm e}^{\rm ann} + L_{\rm e}^{\rm tpp} + \frac{n_{\rm e}}{t_{\rm e,esc}} = Q_{\rm e}^{\rm ext} + Q_{\rm e}^{\rm BH} + Q_{\rm e}^{\gamma\gamma} + Q_{\rm e}^{\rm photopion} + Q_{\rm e}^{\rm tpp} + Q_{e}^{pp}$$

Photons:

$$\frac{\partial n_{\gamma}}{\partial t} + \frac{n_{\gamma}}{t_{\gamma,\rm esc}} + L_{\gamma}^{\gamma\gamma} + L_{\gamma}^{\rm ssa} = Q_{\gamma}^{\rm syn} + Q_{\gamma}^{\rm psyn} + Q_{\gamma}^{\rm ics} + Q_{\gamma}^{\rm ann} + Q_{\gamma}^{\rm photopion} + Q_{\gamma}^{pp}$$

Neutrinos:

$$\frac{\partial n_{\nu}}{\partial t} + \frac{n_{\nu}}{t_{\rm esc}} = Q_{\nu}^{\rm photopion} + Q_{\nu}^{pp}$$

Neutrons:

$$\frac{\partial n_{n}}{\partial t} + L_{n}^{\rm photopion} + \frac{n_{n}}{t_{\rm esc}} = Q_{n}^{\rm photopion} + Q_{n}^{pp}$$

injection		
pp	Bethe-Heitler	
ssa	proton synchrotron	
γγ	synchrotron	
photopion	annihilation	triplet pair production

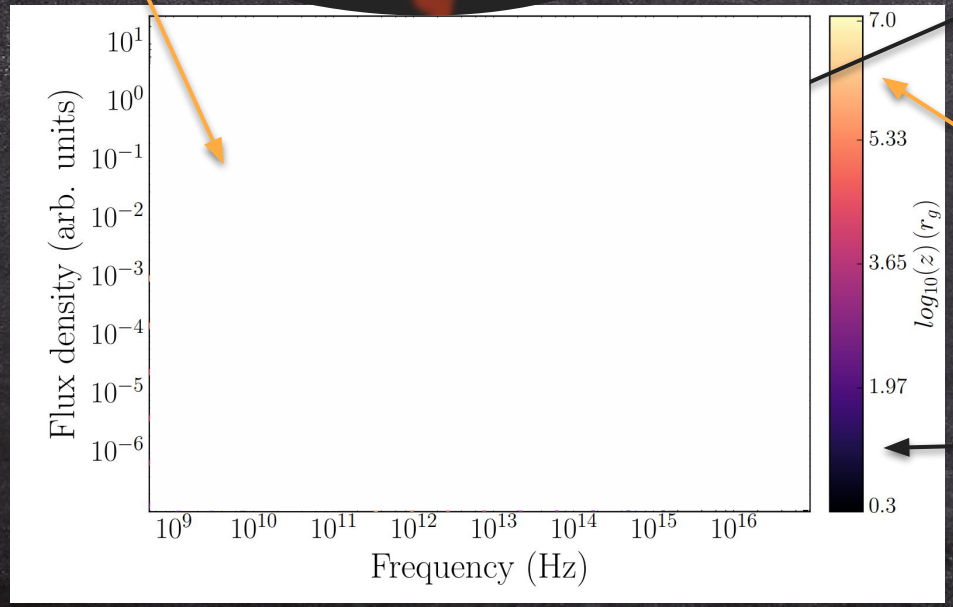
ction

$E, t, z)$

et al. 2017;
et al. 2019, 2022
et al. 21, 22, 23a

Image Credit: T. Revolta

The multi-wavelength emission

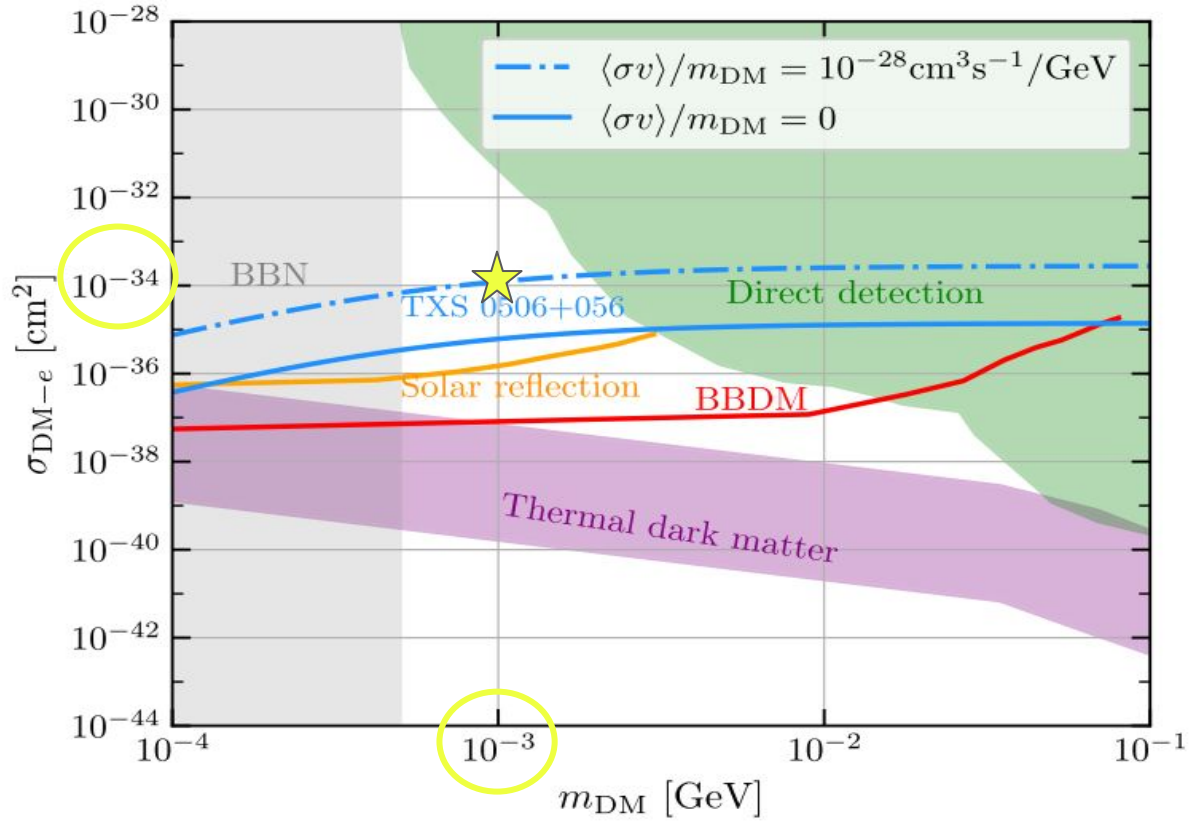


10^7 r_g

~few r_g ($1r_g \simeq 1.5\text{km}\ M_{bh}/M_\odot$)

Lucchini..., DK et al. 2022

The MW spectrum of Mkn 421 with DM (2)



Herrera & Murase, 2024

Pencil jet: the MW spectrum of Mkn 421 with DM (2)

Pencil jet: slim and powerful

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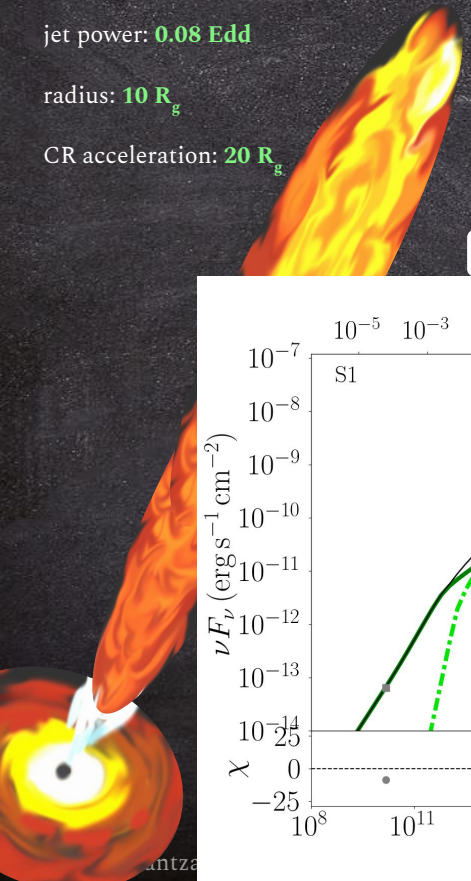

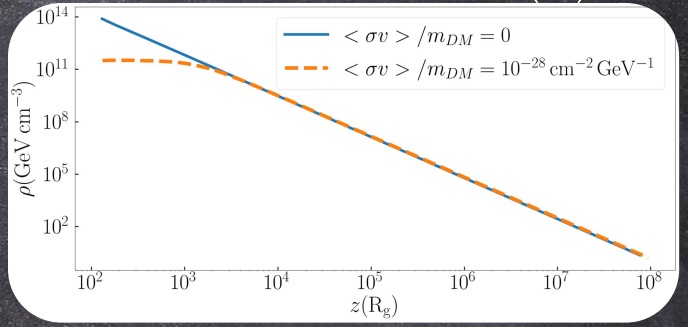

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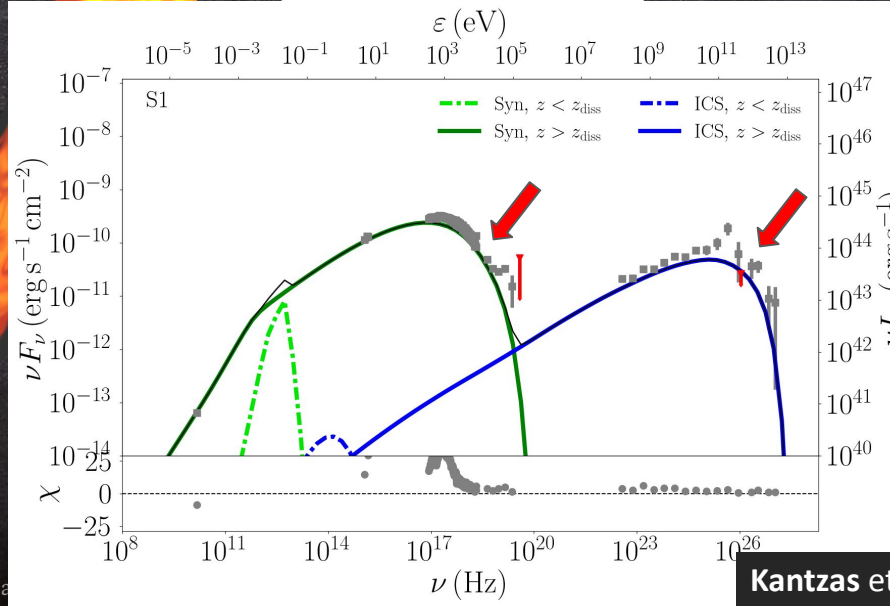

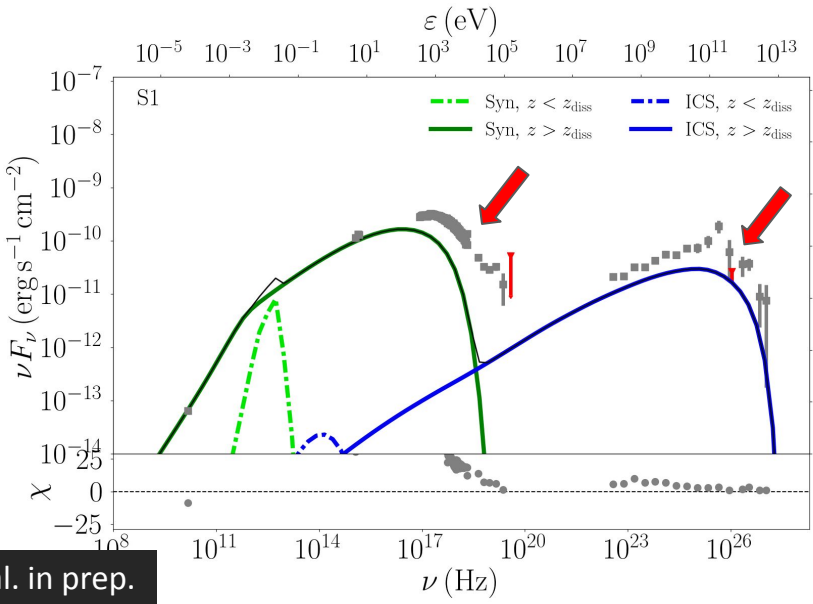

Kantzas et al. in prep.

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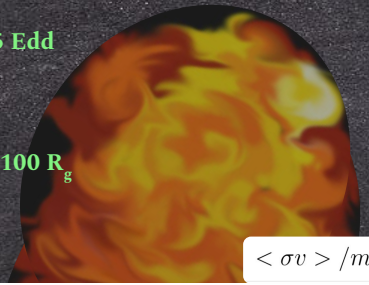

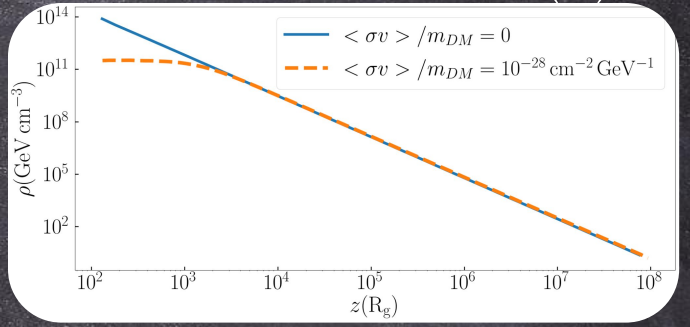

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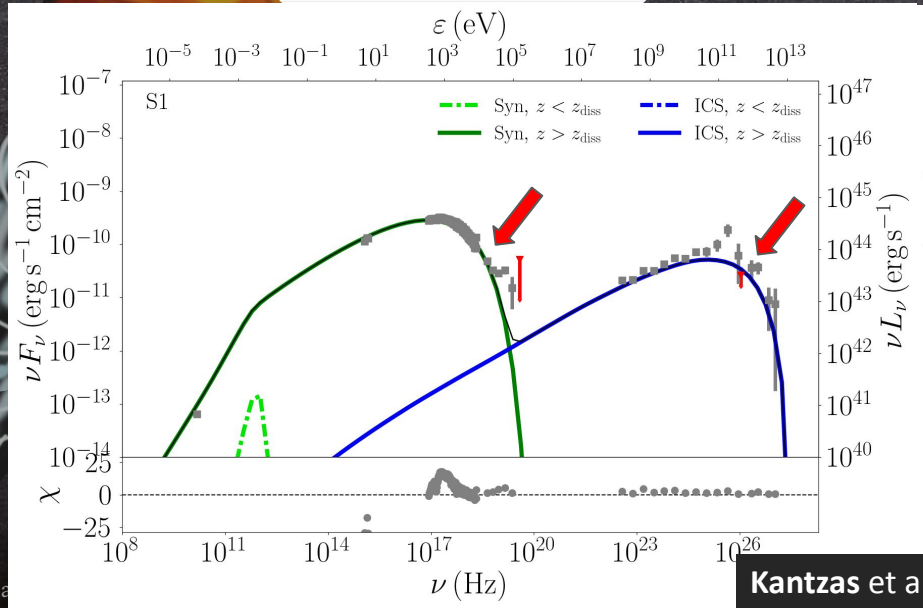

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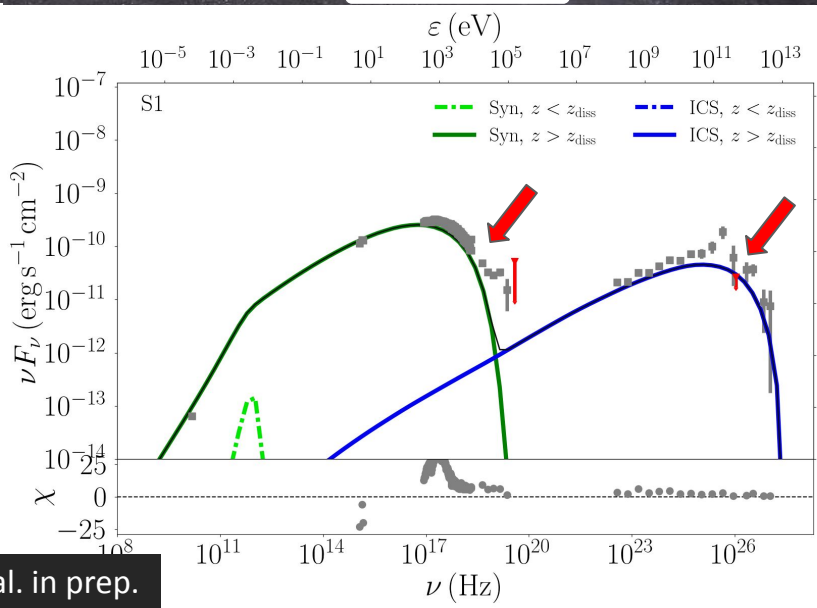

Kantzas et al. in prep.

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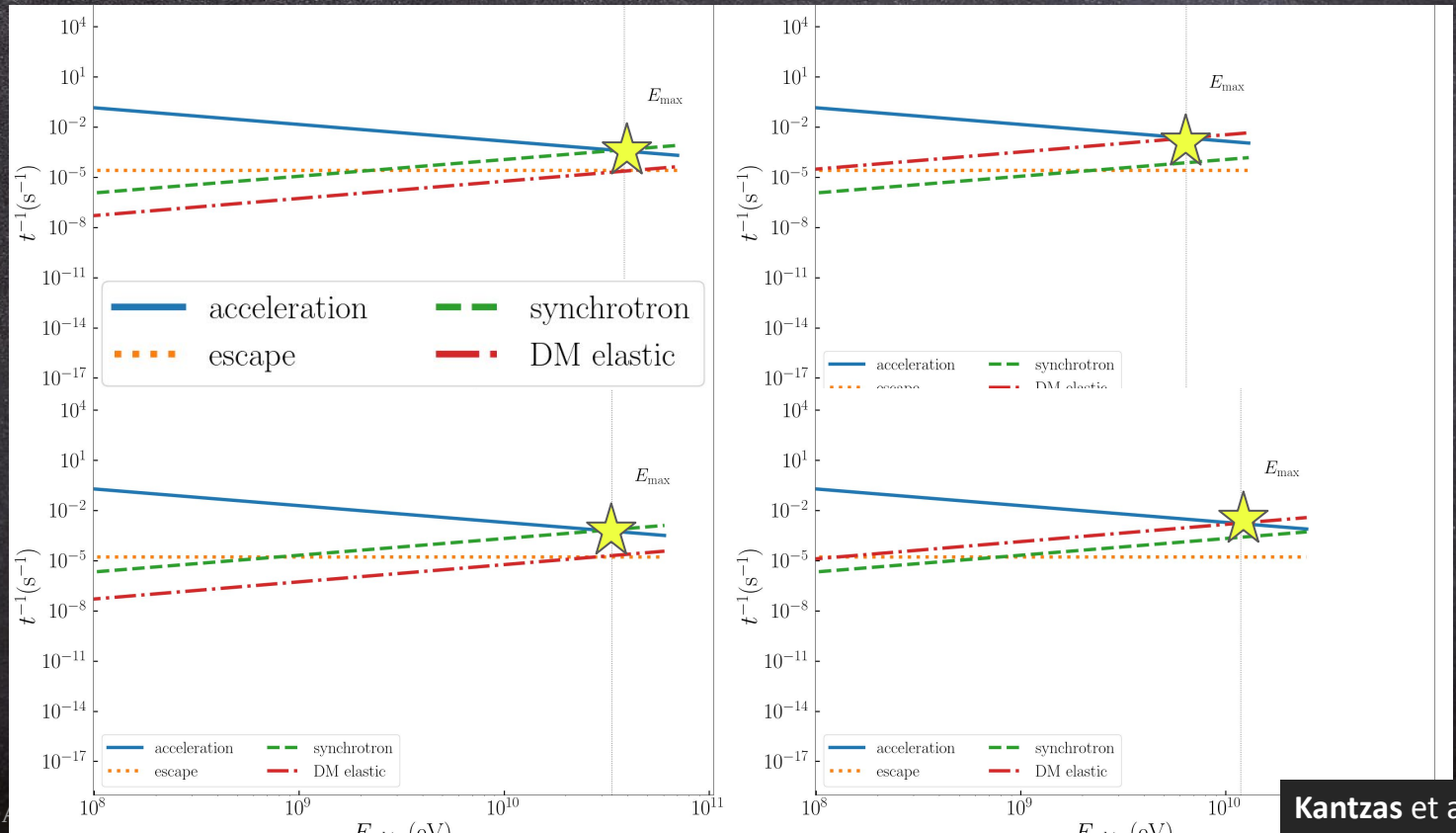
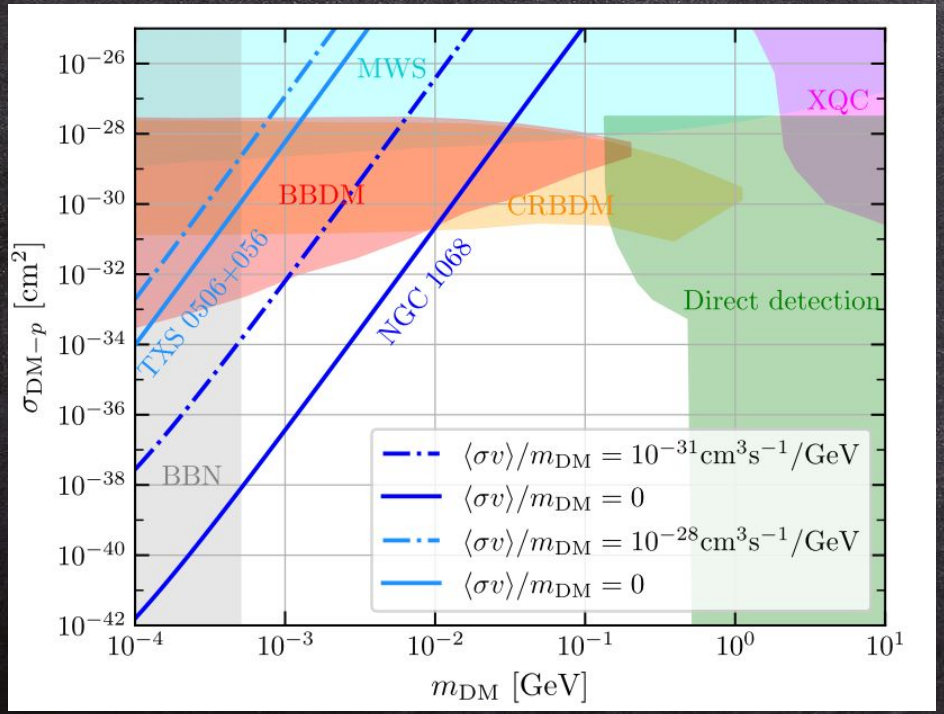


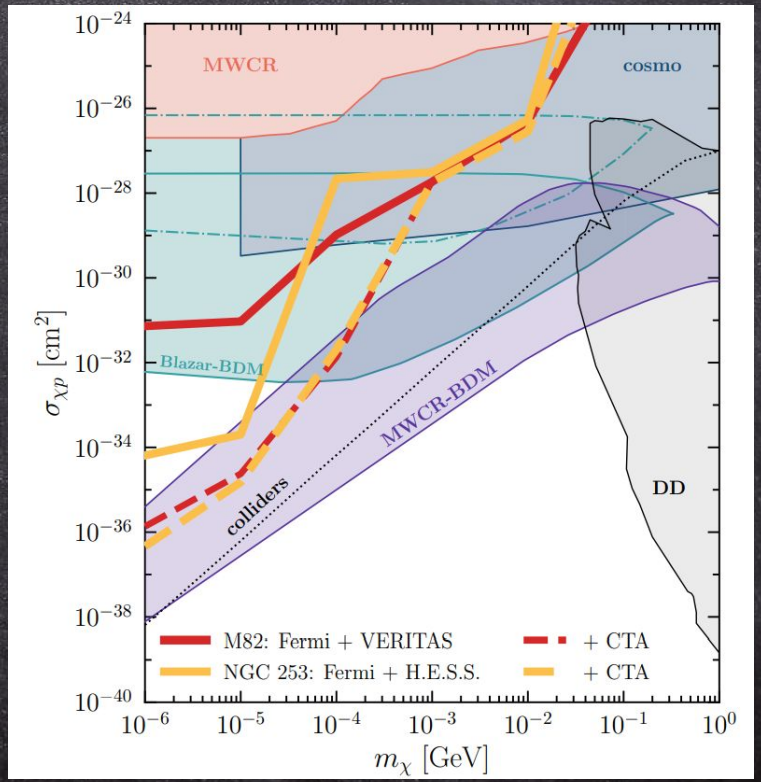
Kantzas et al. in prep.

Constraints from CR-DM collisions

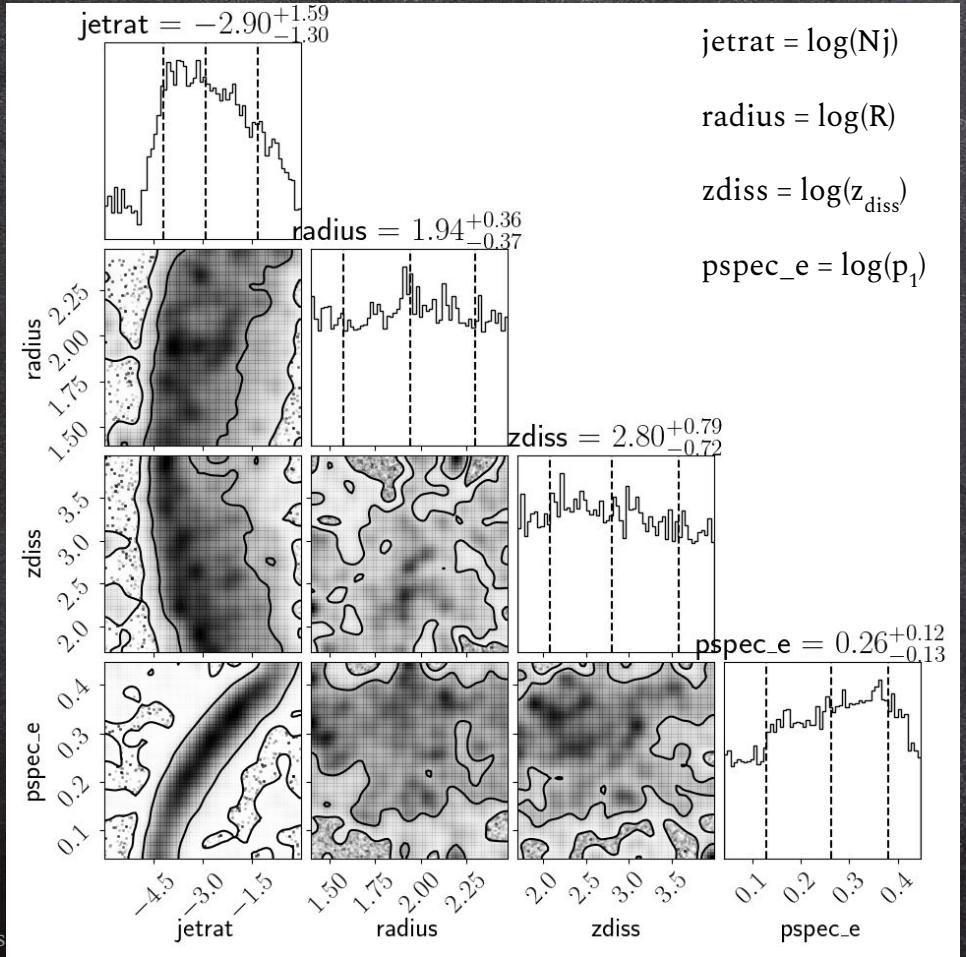
Herrera & Murase, 2024



Ambrosone et al. 2023



Best-fit (?) of the Steady state with BHJet



jetrat = log(Nj)

radius = log(R)

zdiss = $\log(z_{diss})$

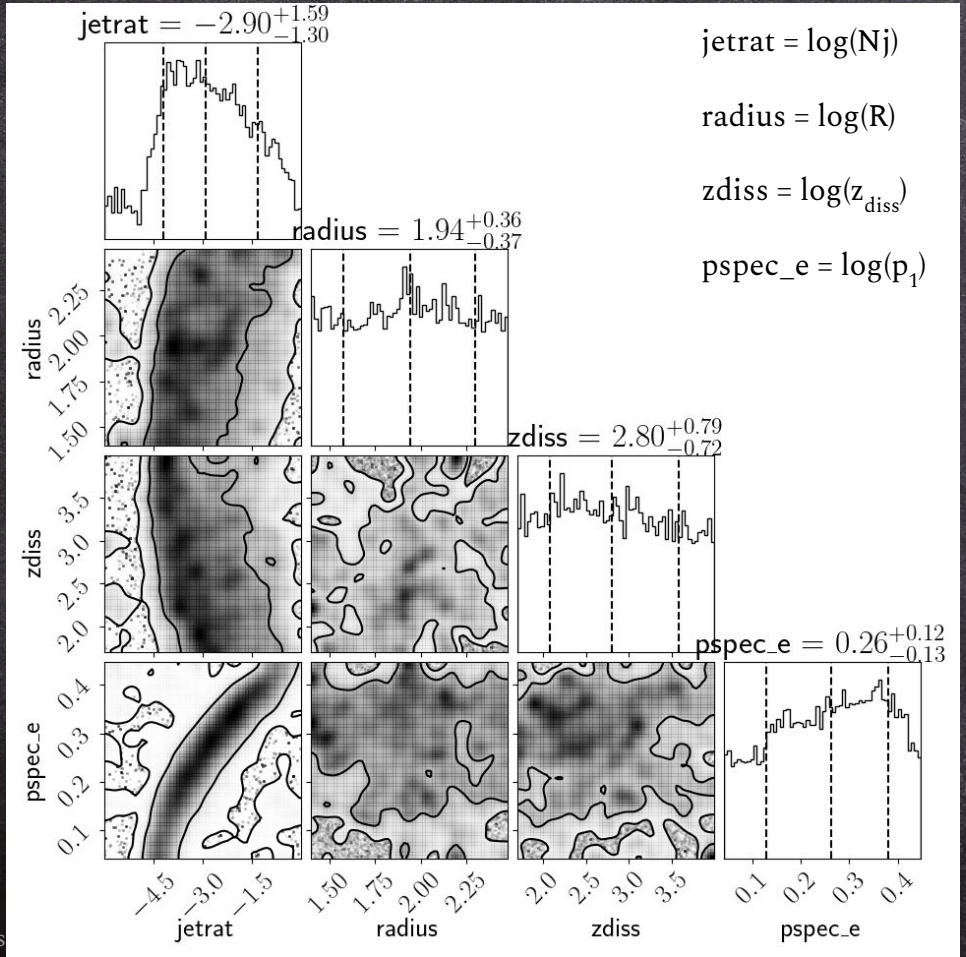
pspec_e = $\log(p_1)$

preliminary

parameter	value
p_1	1.83
E_{break} (GeV)	155
δ	42
B (G)	0.4
u_e/u_B	7.4
R (r_g)	36
z_{diss} (r_g)	435
N_j (L_{Edd})	0.0007

Kantzas et al. in prep

Best-fit (?) of the Steady state with BHJet



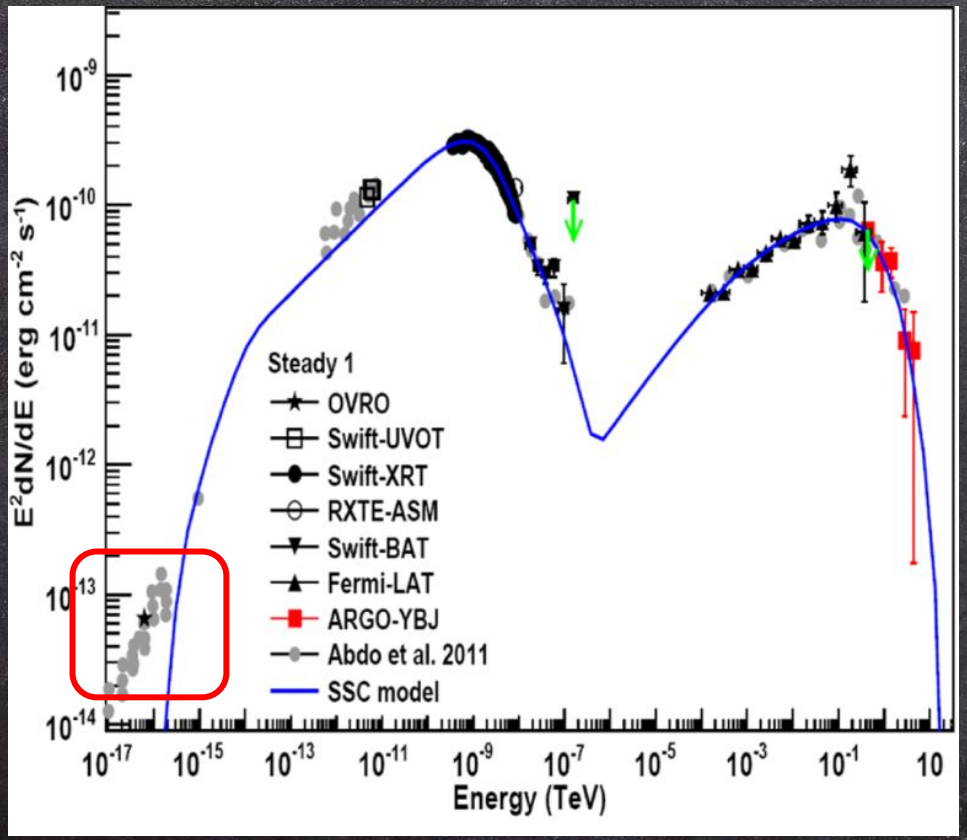
16500 iterations with 48 walkers

↓

autocorrelation time:

[421 232 252 293]

The Steady state



parameter	value
p_1	2.3
p_2	4.7
E_{break} (GeV)	100
δ	38
B (G)	0.048
u_e/u_B	70.6
R (r_g)	2

Bartoli et al. 2016