Illuminating M87* Inner Shadow with Dark Matter Annihilation

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理论物理前沿与交叉科学研讨会

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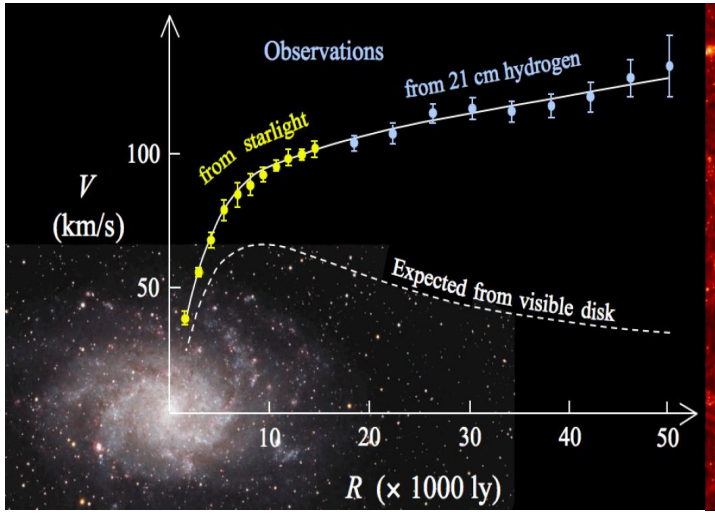
Outline

- Introduction
- Synchrotron emission around SMBH due to DM annihilation
- Constraints from the EHT observations
- Summary

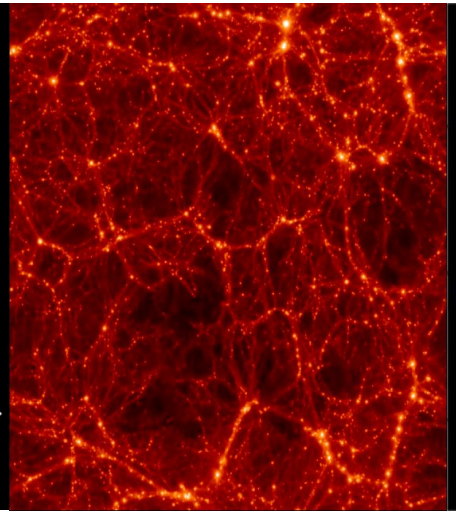
Introduction

Evidences for DM

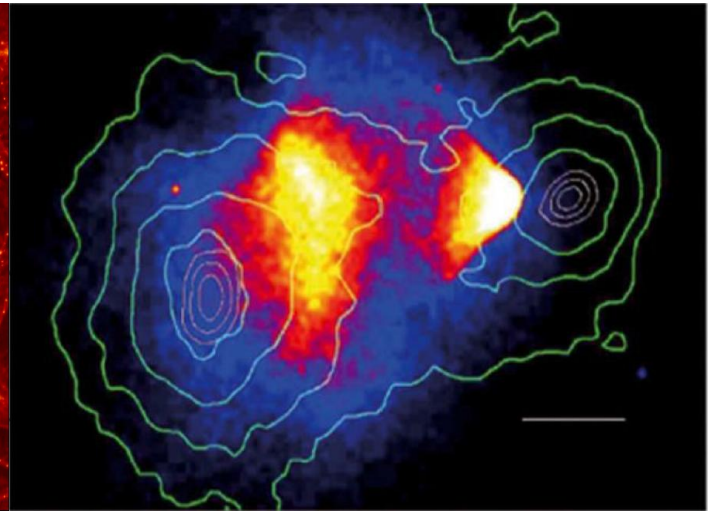
- Rotation curves



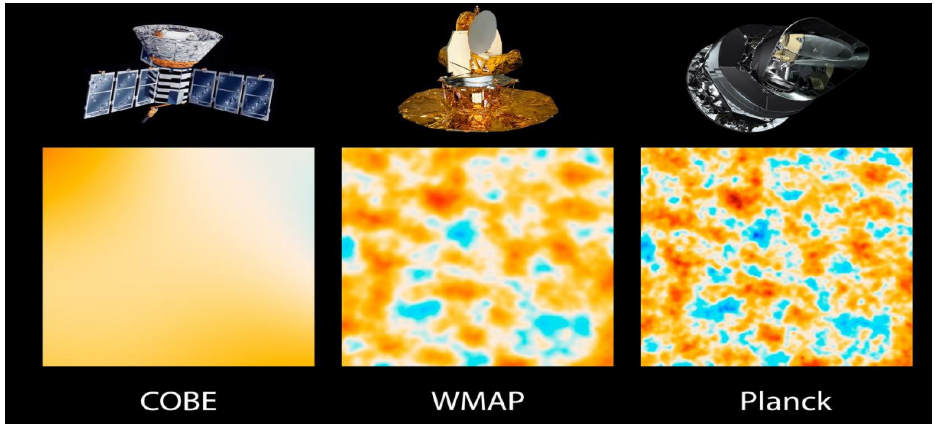
- LSS



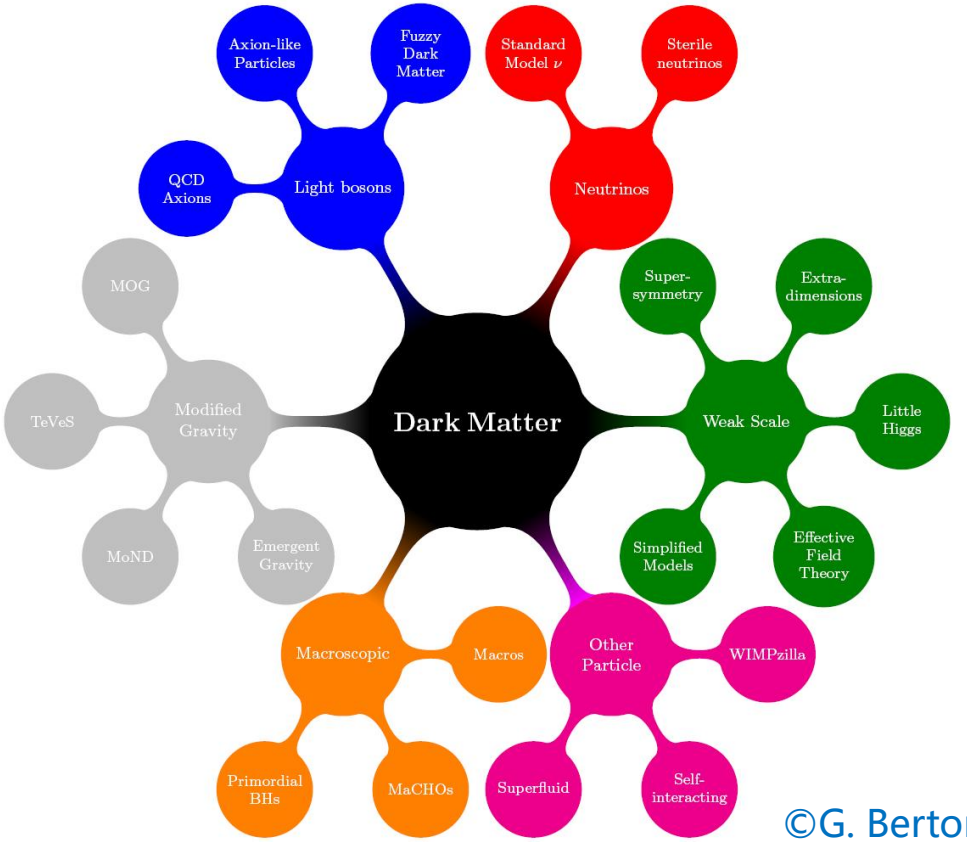
- Bullet cluster



- CMB



●DM candidates



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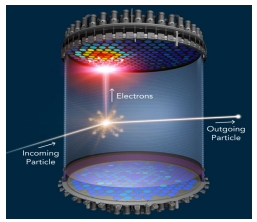
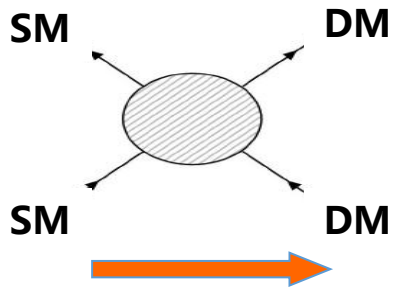
● DM detections

Cosmic-Ray (CR) physics

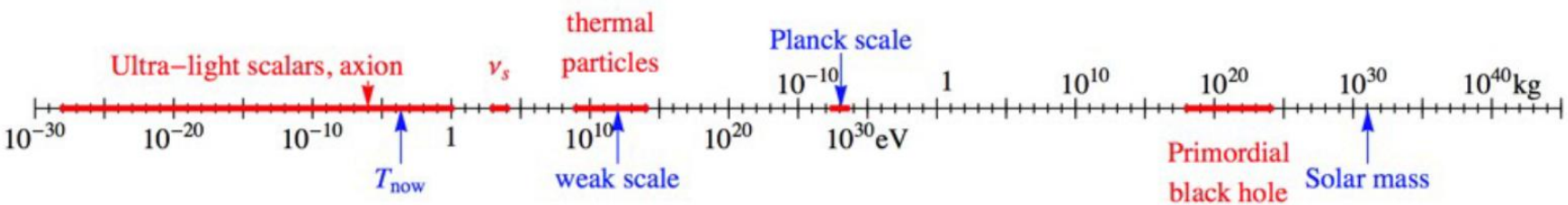
indirect detection

direct detection



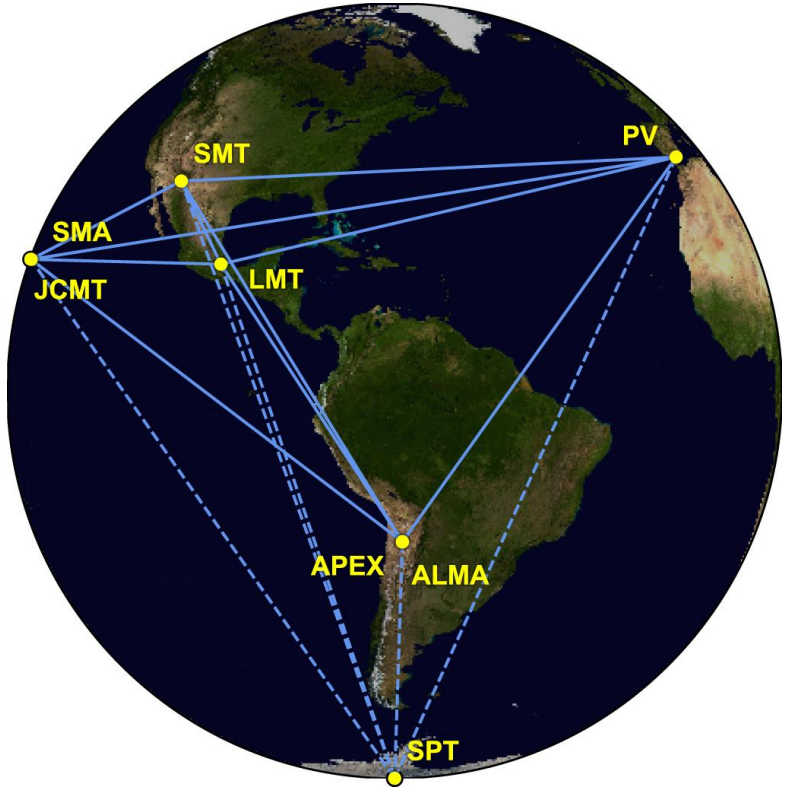


collider detection



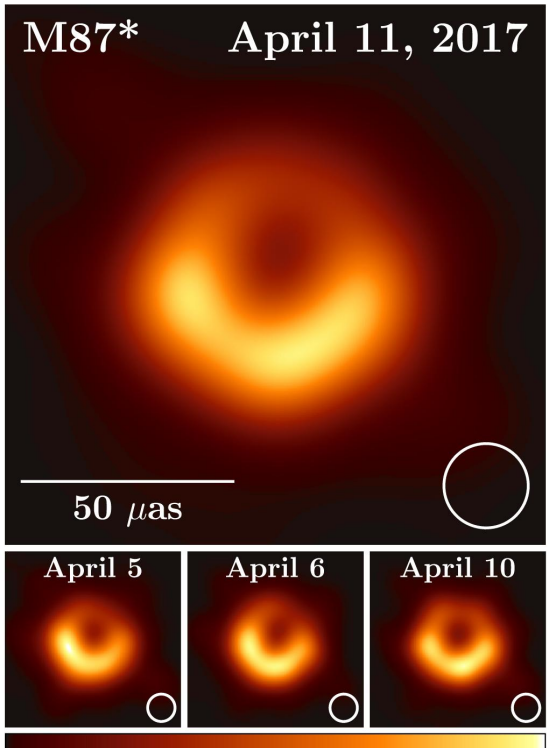
The Event Horizon Telescope (EHT) project

- VLBI: Very Long Baseline Interferometry, an Earth-sized interferometer.
- EHT collaboration: focus on improving the capability of VLBI at short wavelengths.



- First image of a SMBH

EHT collaboration, Astrophys. J. Lett. 875 (2019) L1, [1906.11238]



Symbol	Value	Property
M	$6.2 \times 10^9\ M_\odot$	Compact object mass
D	16.9 Mpc	Compact object distance
$\nu_{\mathrm{obs},0}$	230 GHz	Observing frequency

- Synchrotron emission due to DM annihilations can be stringently constrainted!

DM spike model

- Adiabatic growth of SMBH will significantly enhance the DM density and form a spike structure.

P. Dehnen, MNRAS 265,250-256 (1993)

G.D. Quinlan, Hernquist, S.sigurdsson , APJ 440;554-564250-256 (1995)

P. Gondolo & J. Silk,PRL 83(1999) 1719{1722, [astro-ph/9906391]

O. Y. Gnedin & J. R. Primack, PRL 93 (2004) 061302, [astro-ph/0308385]

P. Ullio, H. Zhao & M. Kamionkowski, PRD 64 (2001) 043504, [astro-ph/0101481]

R. Aloisio, P. Blasi & A. V. Olinto, JCAP 05 (2004) 007, [astro-ph/0402588]

T. Lacroix, M. Karami, A. E. Broderick, J. Silk & C. Boehm, PRD 96 (2017) 063008,[1611.01961]

- Scaling relation arguments G.D. Quinlan, Hernquist, S.sigurdsson , APJ 440;554-564250-256 (1995)

Assume a power-low initial density profile $\rho_i \sim r^{-\gamma}$

Conservation of mass

$$\rho_i r_i^2 dr_i = \rho_f r_f^2 dr_f \Rightarrow r_i^{3-\gamma} \sim r_f^{3-\gamma_{\rm sp}}$$

Conservation of angular momentum

$$r_i M_i(r) \simeq r_f M_{\rm BH} \Rightarrow r_i^{4-\gamma} \sim r_f$$

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

- General phase space arguments

Differential energy distribution $N(E) = g(E)f(E)$

Density of state

$$g_i(E_i) \sim \int_0^{\Phi_i^{-1}(E_i)} dr r^2 \sqrt{\Phi_i(r) - E_i} \sim E_i^{(8-\gamma)/2(2-\gamma)}$$

Distribution function

$$f_i(E_i) \sim [\Phi(0)_i - E_i]^{-n}$$

Invariance of radial action

$$E_i \sim E_f^{-(2-\gamma)/(4-\gamma)} \sim r^{(2-\gamma)/(4-\gamma)}$$

G.D. Quinlan, Hernquist, S.sigurdsson , APJ 440;554-564250-256 (1995)

$$\rho_f(r) \sim r^{-2} N_f(E_f) \left(\frac{dE_f}{dr}\right) \sim r^{-4} N_i(E_i) \left(\frac{dE_i}{dE_f}\right) \sim r^{-\gamma_{sp}}$$

with $\gamma_{sp} = \frac{3}{2} + n\left(\frac{2-\gamma}{4-\gamma}\right)$

- Final density profile is determined by exact form of distubution function

Conservation of mss

$$f(E) = \frac{1}{\sqrt{8}\pi^2}\left[\int_E^0 \frac{d^2\rho}{d\Phi^2}\frac{d\Phi}{\sqrt{\Phi - E}} - \frac{(d\rho/d\Phi)_{\Phi=0}}{\sqrt{-E}}\right]$$

$$f(E) = \frac{(3-\gamma)M}{2\left(2\pi^2 GMa\right)^{3/2}} \int_0^E \frac{(1-y)^2\left[\gamma + 2y + (4-\gamma)y^2\right]}{y^{4-\gamma}\sqrt{E-\Phi}} \mathrm{d}\Phi \propto \begin{cases} [\Phi(0) - E]^{-1} & \gamma = 0 \\ [\Phi(0) - E]^{-(6-\gamma)/2(2-\gamma)} & 0 < \gamma < 2 \\ \mathrm{e}^{2E} & \gamma = 2 \\ E^{(6-\gamma)/2(\gamma-2)} & 2 < \gamma < 3 \end{cases}$$

P. Dehnen, MNRAS 265,250-256 (1993)

$$y = y(\Phi) = \begin{cases} [1 - (2-\gamma)\Phi]^{1/(2-\gamma)} & \gamma \neq 2 \\ \mathrm{e}^{-\Phi} & \gamma = 2 \end{cases}$$

- Approximate distribution function for NFW profile

$$f(\varepsilon) = \frac{3M_{\rm BH}}{2(2\pi)^3 \left(r_0 G M_{\rm BH}\right)^{3/2}} \hat{f}(\hat{\varepsilon})$$

$$\hat{\varepsilon} = -\frac{2r_0}{GM_{\rm BH}} E$$

- DM spike profile with annihilation

$$\rho(\vec{r}) = \begin{cases} 0 & r < r_{\rm crit}(\theta, a_J)\,, \\ \rho_{\rm sat} \equiv m_{\rm DM}/(\langle\sigma v\rangle\, t_{\rm BH}) & r_{\rm crit}(\theta, a_J) \le r < r_{\rm sat} \\ \rho_{\rm sp}(r) \equiv \rho_0 \left(r/r_0\right)^{-\gamma_{\rm sp}} & r_{\rm sat} \le r < r_{\rm sp}\,, \\ \rho_{\rm halo}(r) = \rho_0 (r_{\rm sp}/r_0)^{-\gamma_{\rm sp}} (r/r_{\rm sp})^{-1} & r \ge r_{\rm sp}\,. \end{cases}$$

- Final DM density profile

$$\rho_{\rm sp}(r) = \frac{4\pi}{r^2} \int_{\Phi_f}^{0} {\rm d}E \int_{L_{\rm min}}^{L_{\rm max}} L\,{\rm d}L \frac{f\left(E^i\left(E^f, L\right), L\right)}{\sqrt{2E - 2\Phi(r) - L^2/r^2}}$$

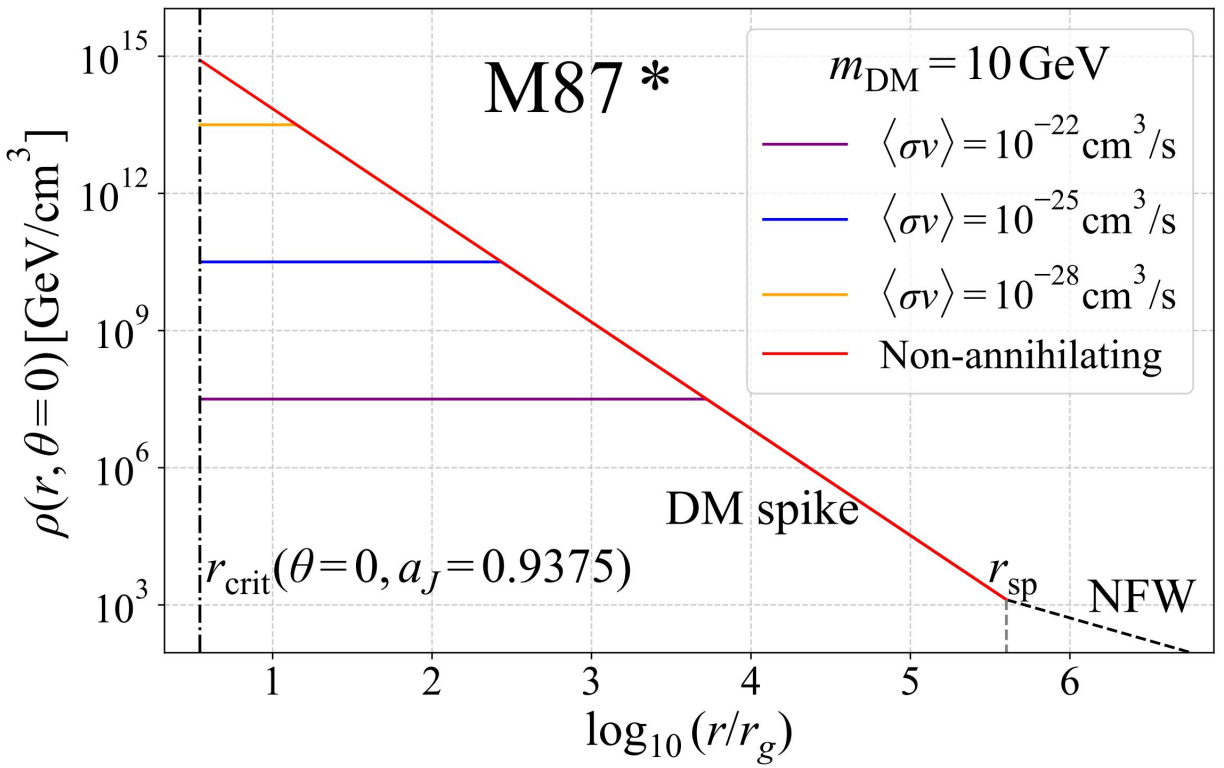
- Approximate power-low model

P. Gondolo & J. Silk,PRL 83(1999)

$$\rho_{\rm sp}(r) = \rho_r g_\gamma(r) \left(\frac{R_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

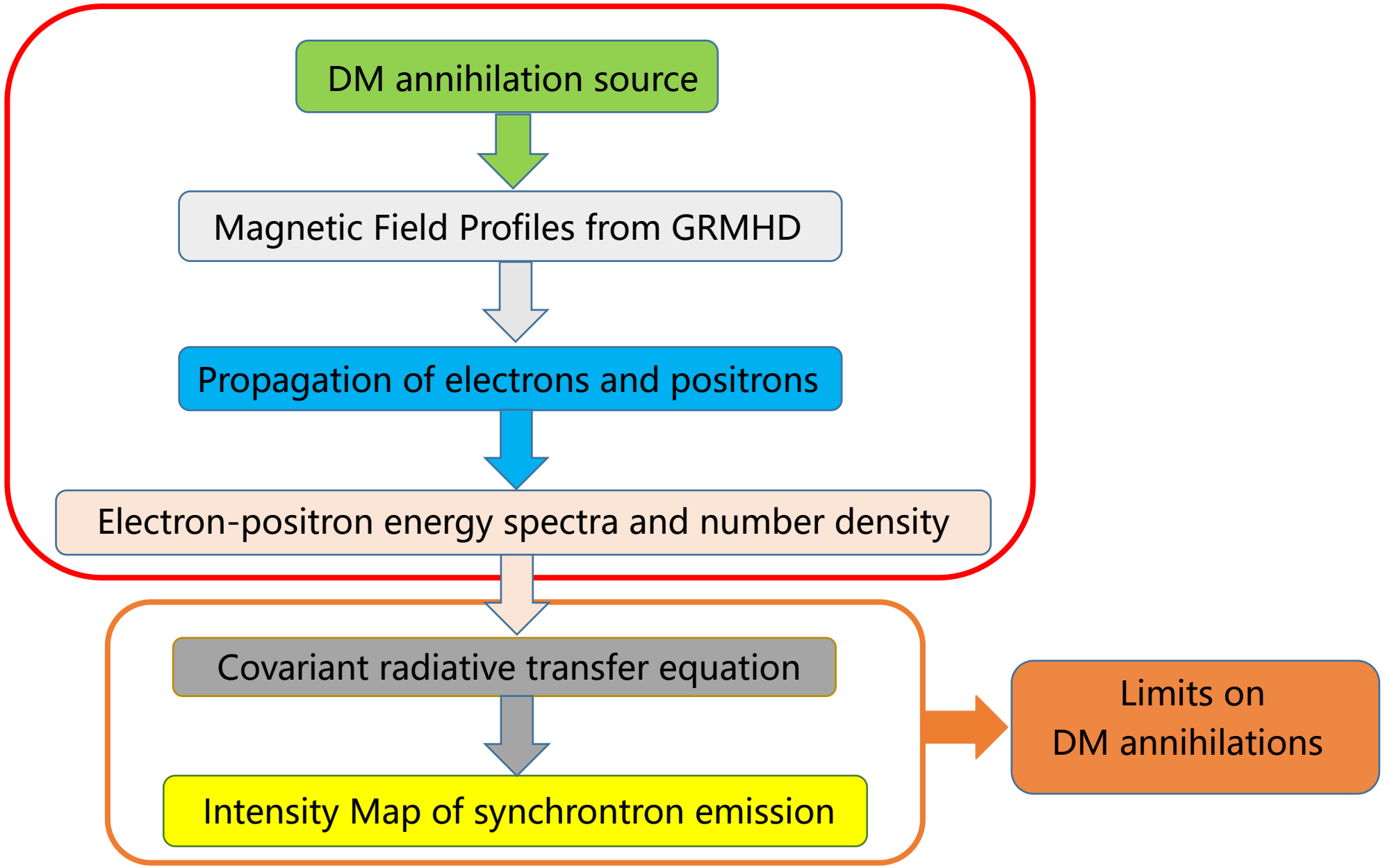
$$\rho_r = \rho_0 \left(\frac{R_{\rm sp}}{r_0}\right)^{-\gamma}, \quad R_{\rm sp} = \alpha_\gamma r_0 \left(\frac{M_{\rm BH}}{\rho_0 r_0^3}\right)^{1/(3-\gamma)}$$

$$g_\gamma(r) = \left(1 - \frac{2R_s}{r}\right)^3, \quad \gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma}$$

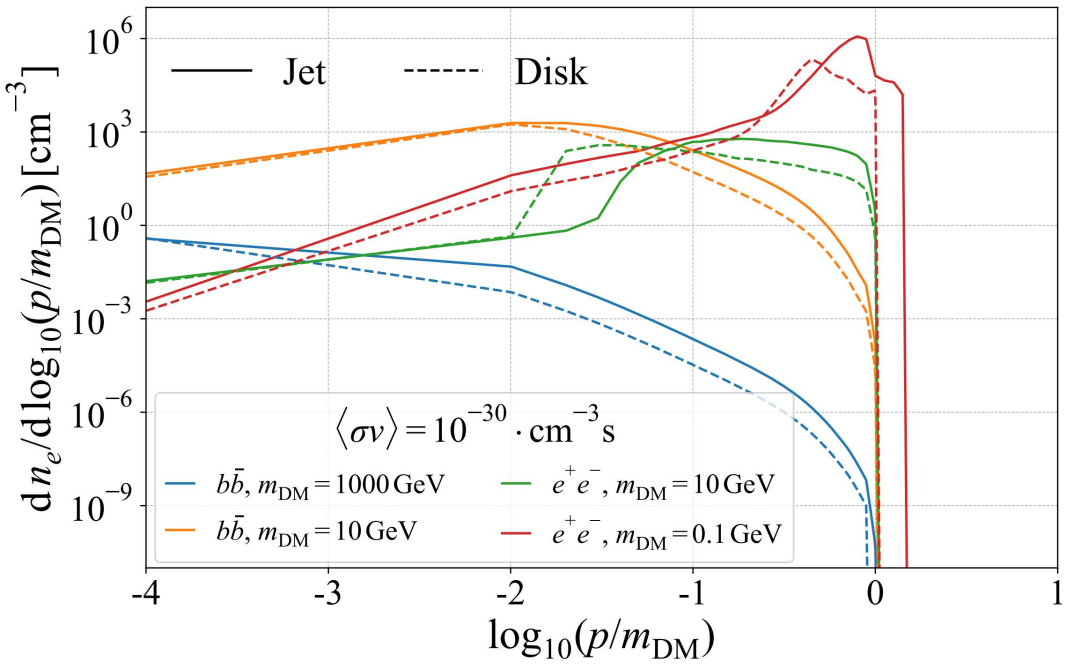


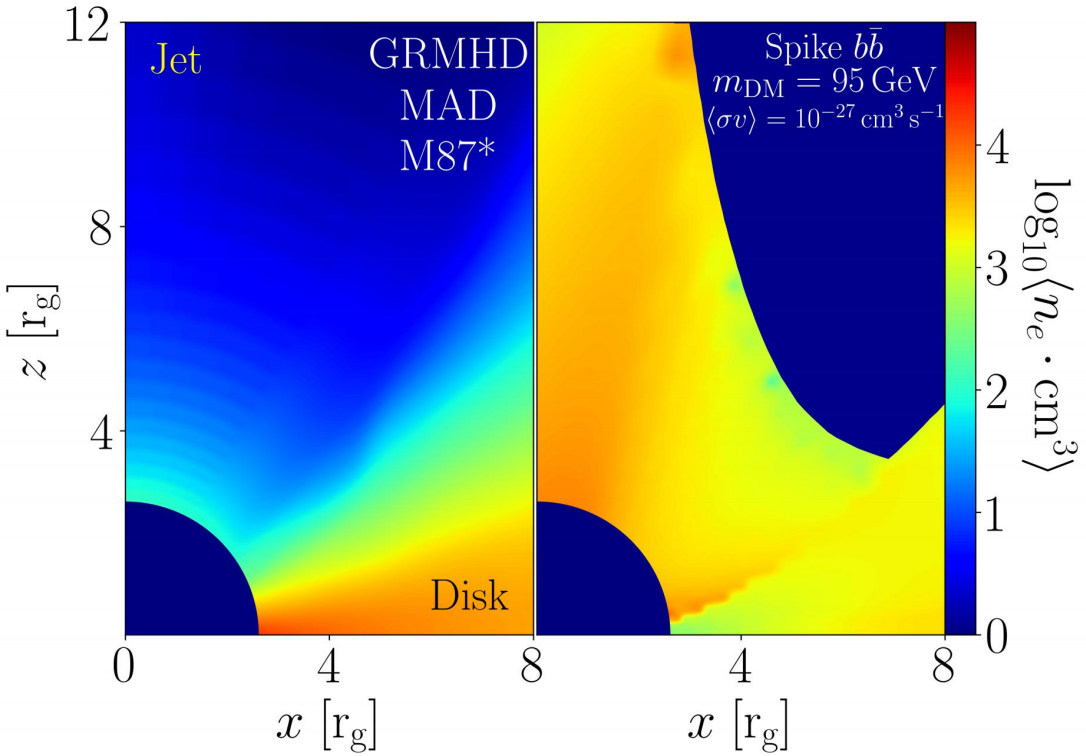
Synchrotron emission around SMBH due to DM annihilation

- Calculation framework

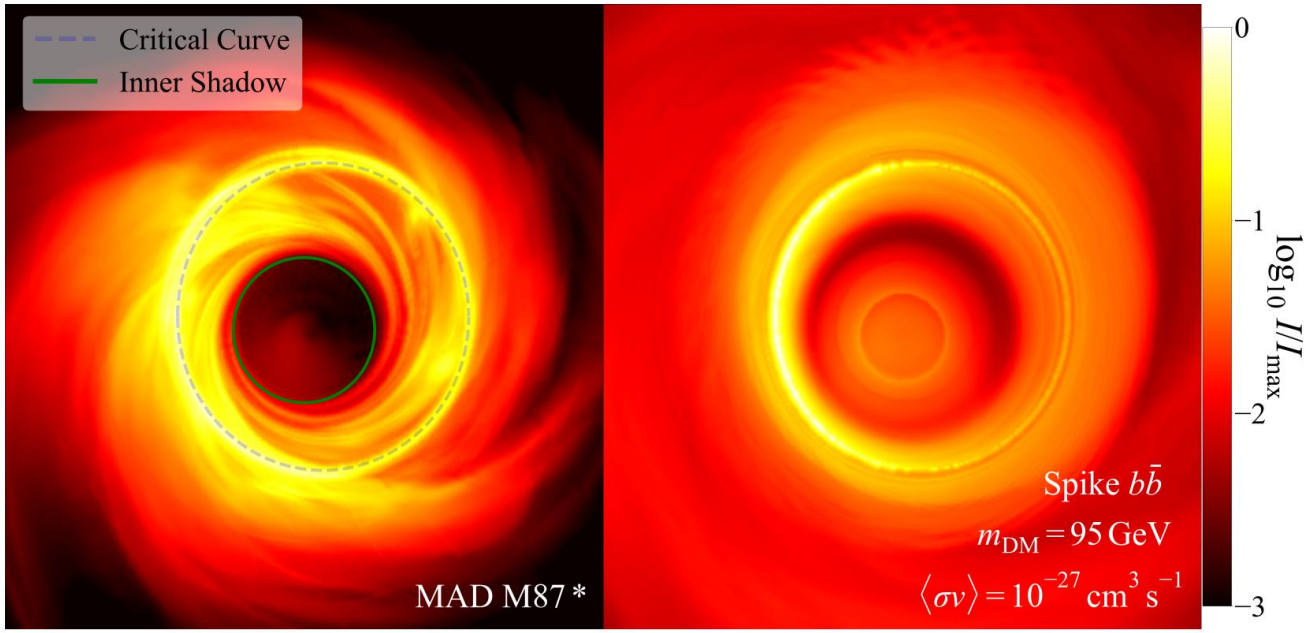


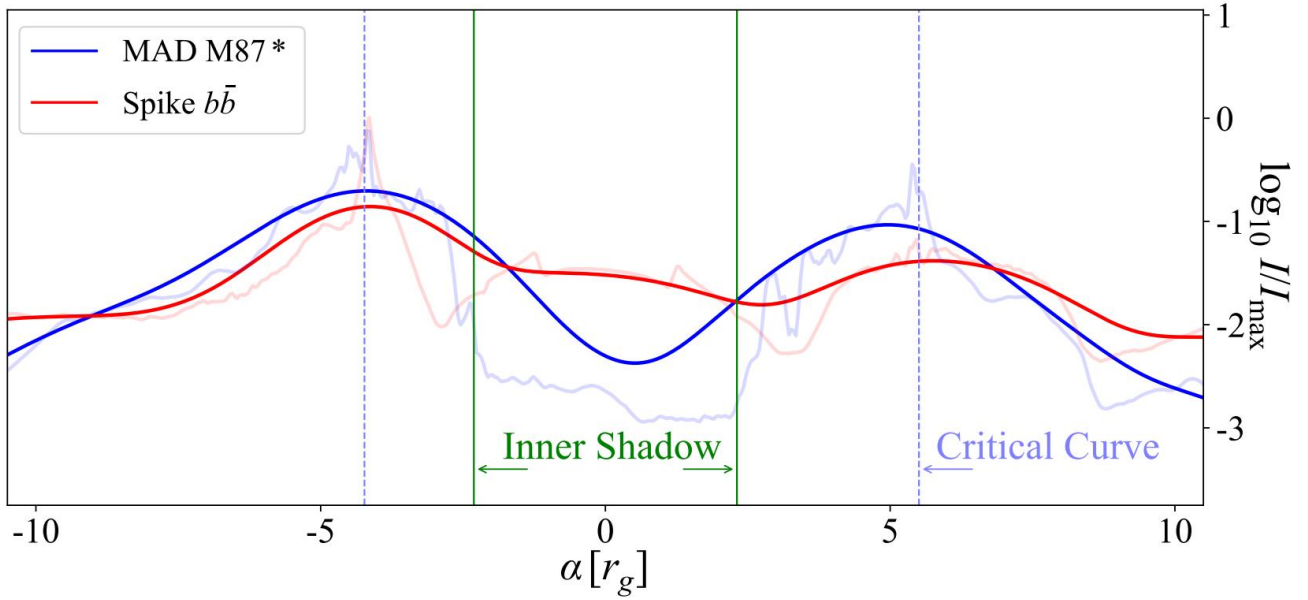
Electron-positron energy spectra and number density

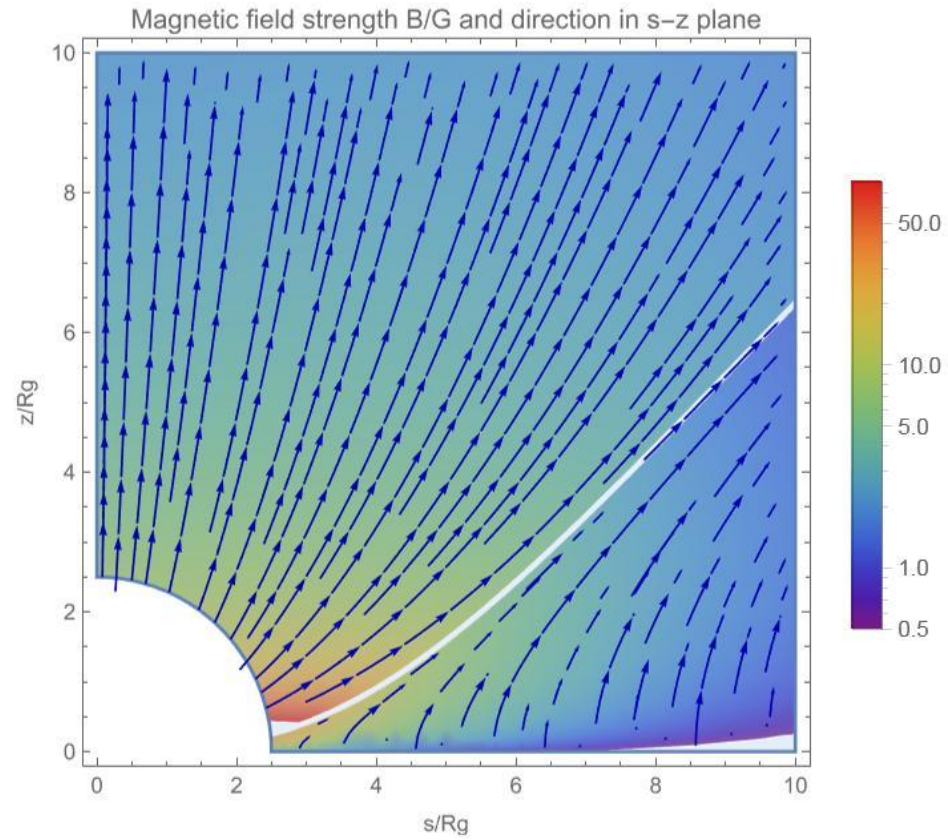




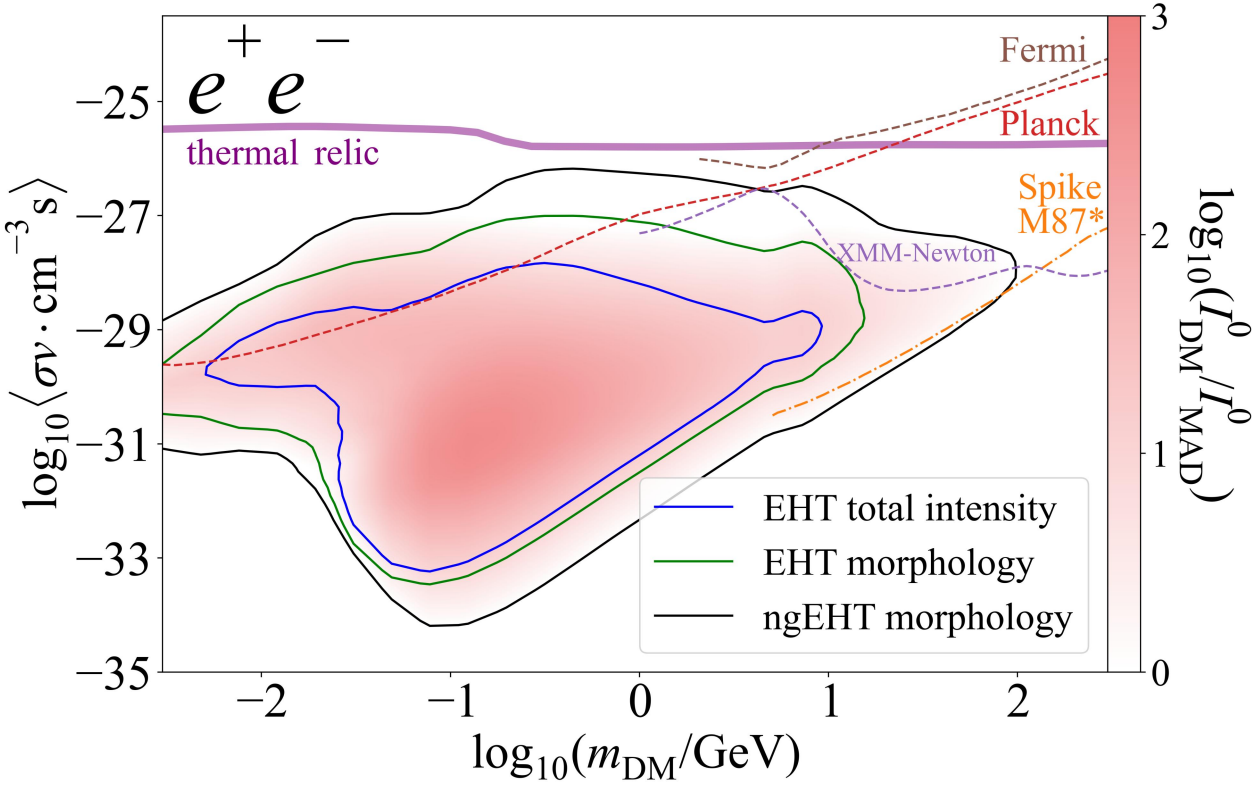
Intensity Map of synchrontron emission

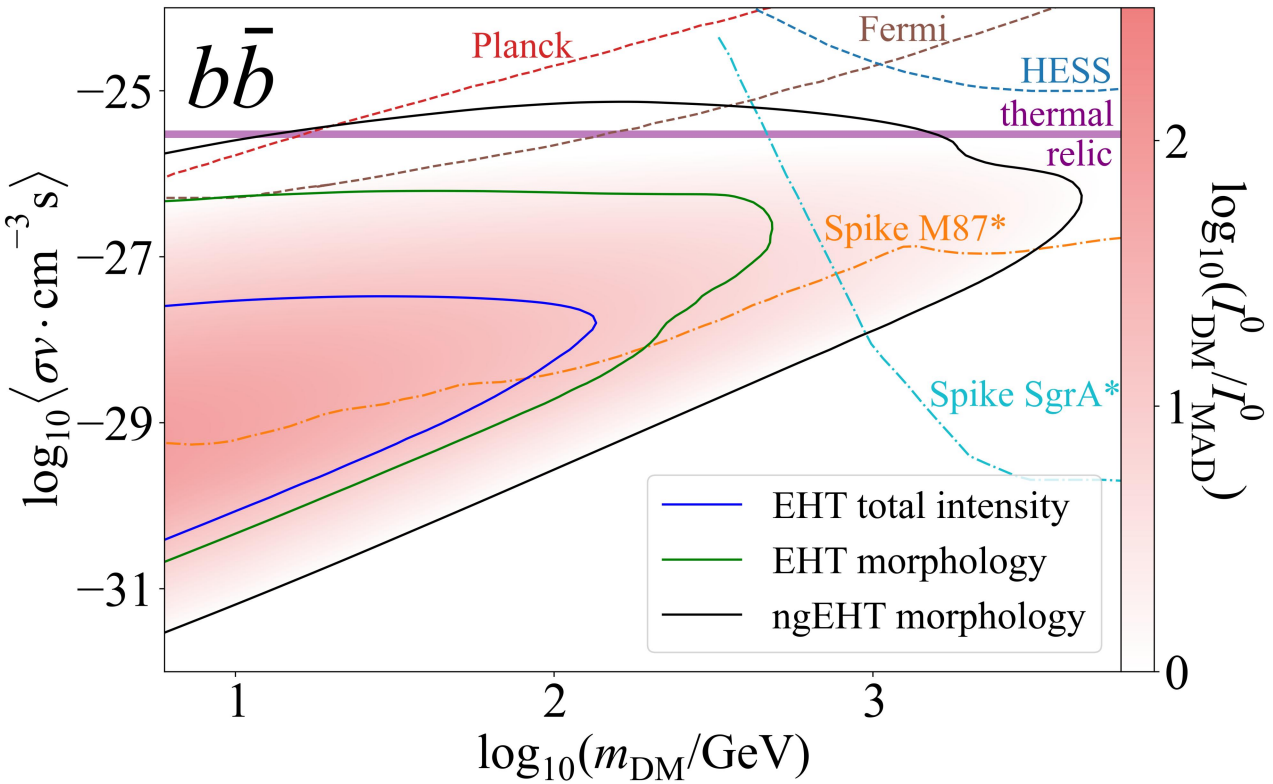






- Limits on DM annihilation cross sections





Summary

- Realistic magnetic field profles from GRMHD Simulation
- Characteristic electron-positron trajectory configurations captured by the magnetic lines
- Fully GR convariant radiative transfer and Intensity Map
- The effect of the accretion disk

Thanks for your attention