Dark Matter and PBH Constraints from Radio and X-ray Observations

Ding Ran

Yifan Chen, RD, Yuxin Liu, Yosuke Mizuno, Jing Shu, Haiyue Yu and Yanjie Zeng, arXiv:2404.16673

Zihong Cheng, RD, Yi Liao and Chi Tian, arXiv: 2412.xxxxx

第29届 LHC Mini-Workshop

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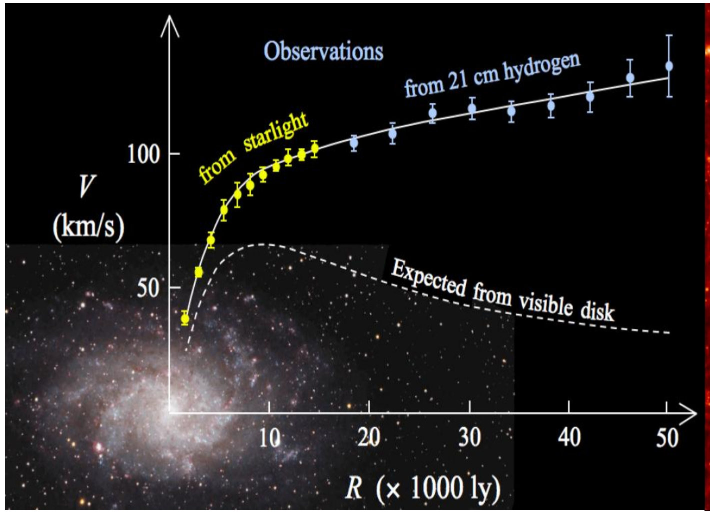
Outline

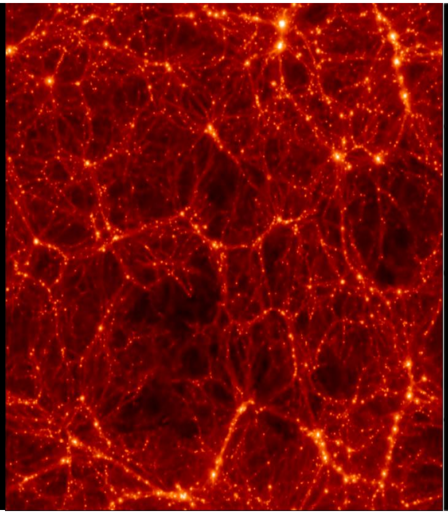
- Introduction
- Illuminating M87* Inner Shadow with DM Annihilation
- DM Constraints from Diffuse Galactic Radio emission
- Limits on Primordial Black Hole as DM with X-ray observations
- Summary

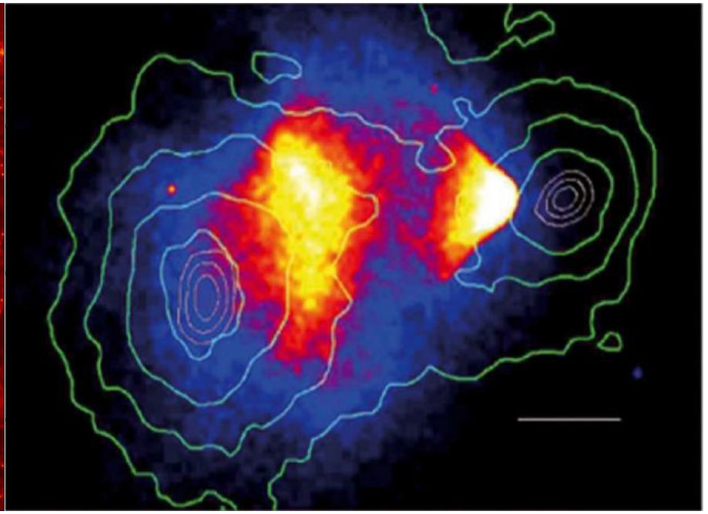
Introduction

Evidences for DM

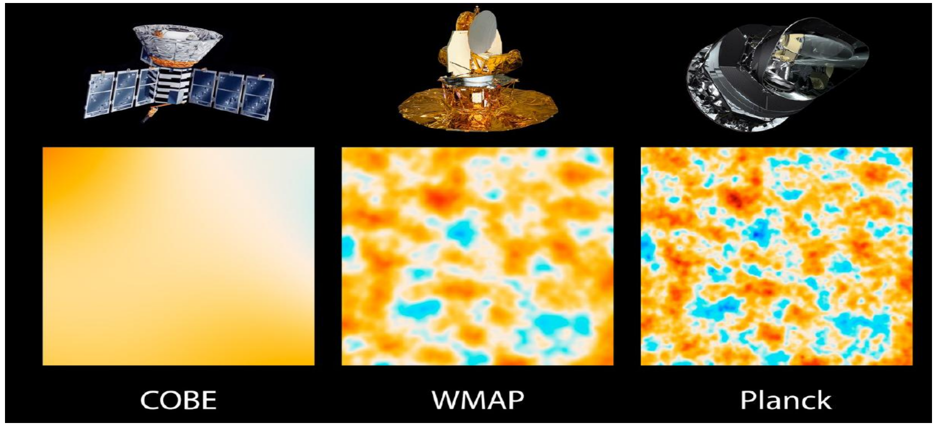
- Rotation curves
- LSS
- Bullet cluster



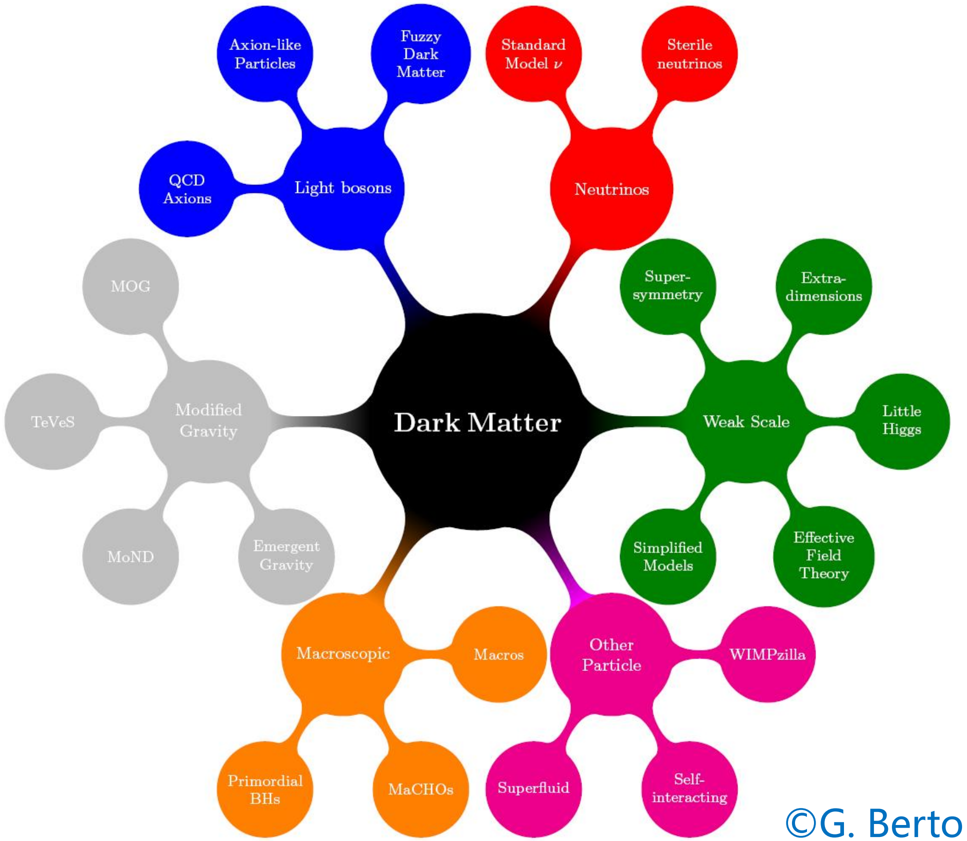




- CMB



● DM candidates



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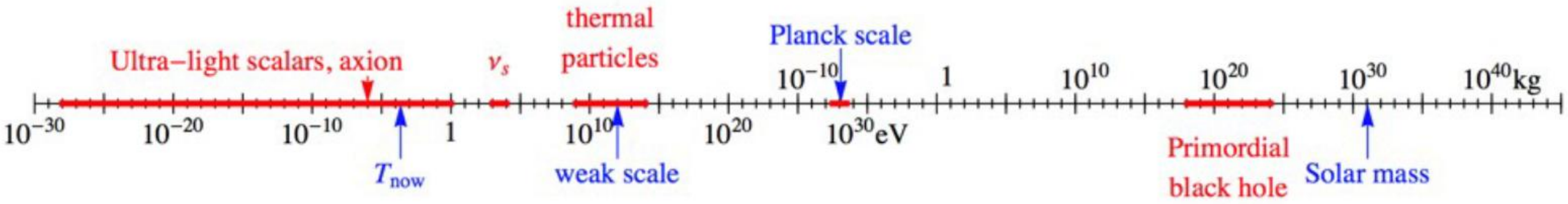
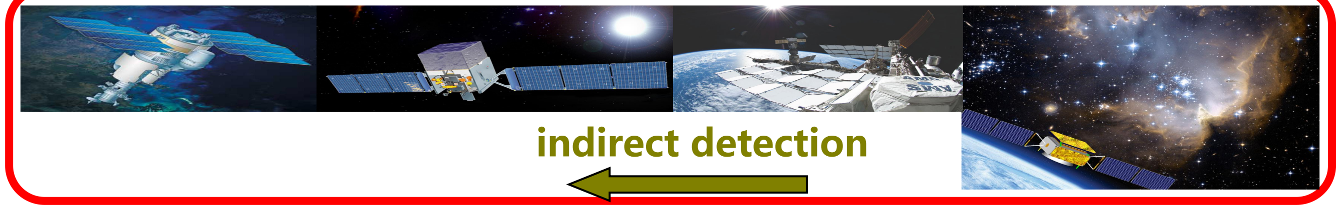


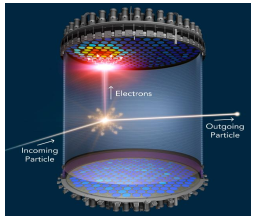
● DM detections

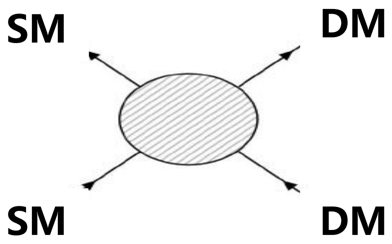
Cosmic-Ray (CR) physics



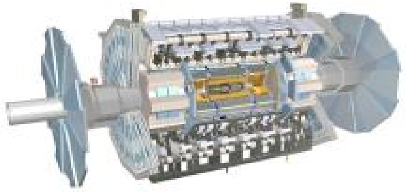
indirect detection

direct detection

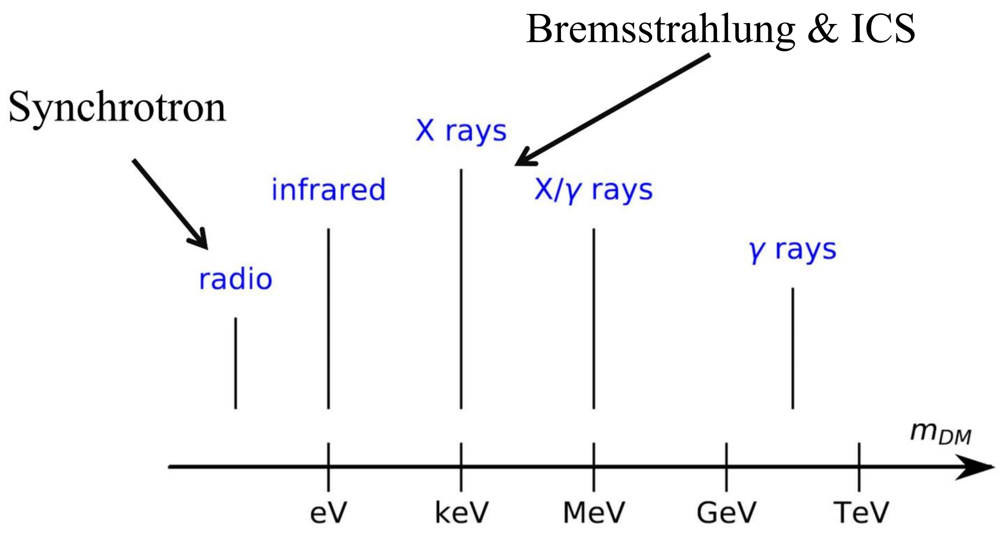




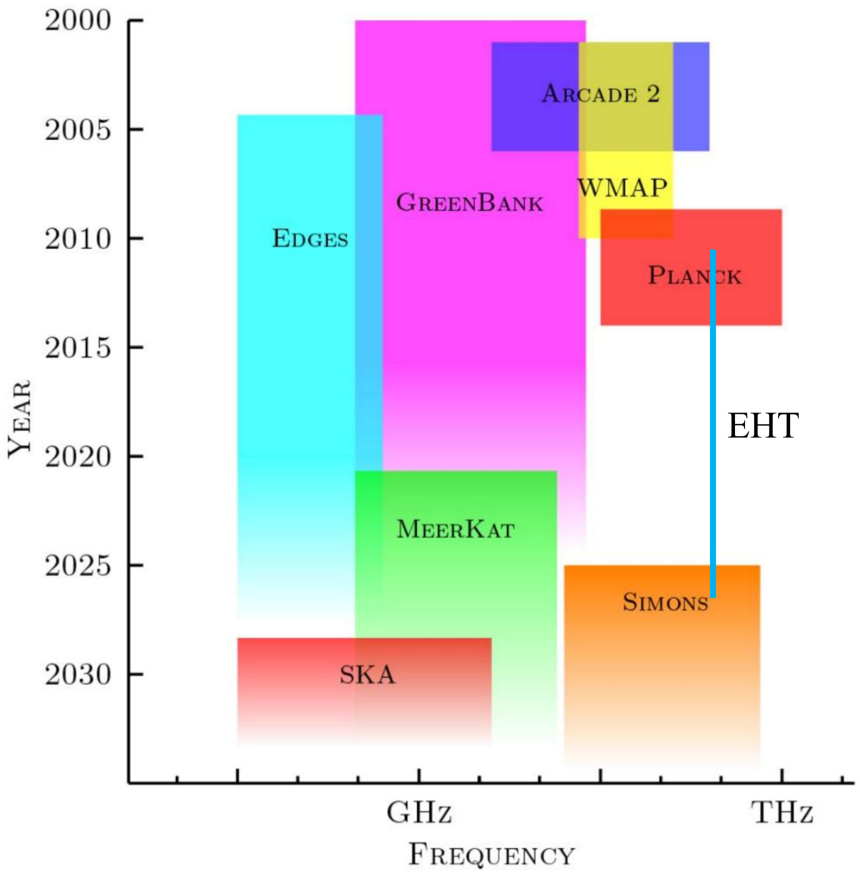
collider detection



- Multi-frequency observations



- Current and future radio and microwave observations



2006.00513

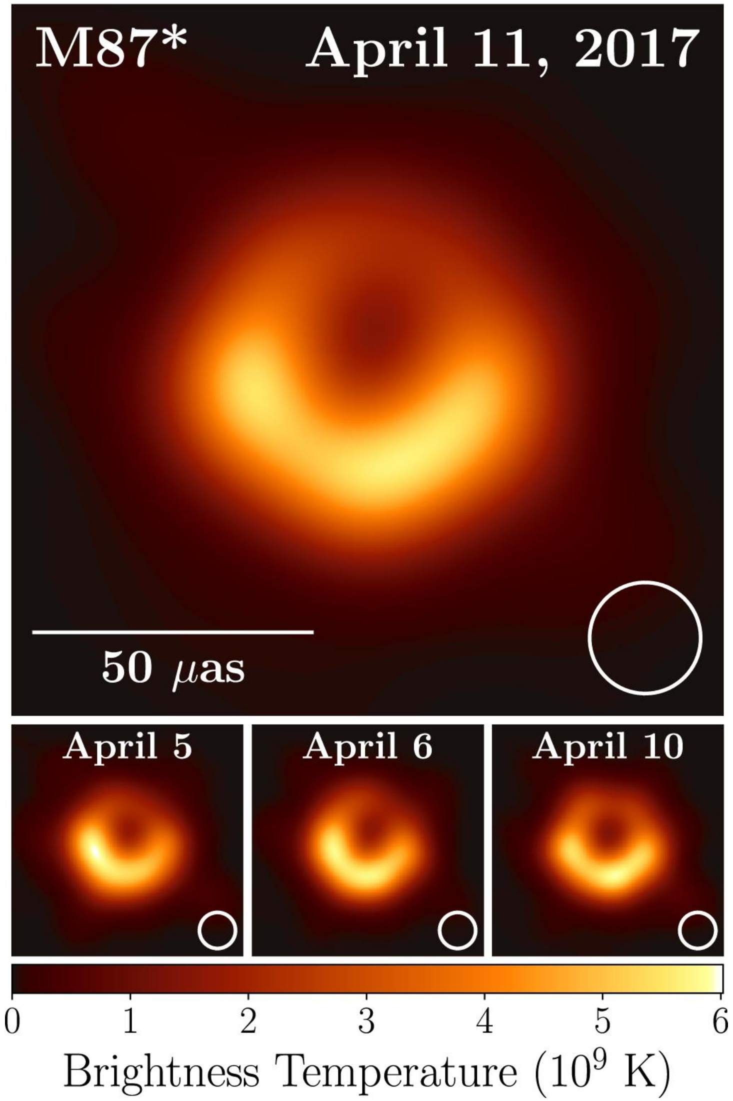
Illuminating M87* Inner Shadow with DM Annihilation

● The Event Horizon Telescope (EHT) project

- EHT collaboration: an internationalcollaboration capturing images of black holes using a virtual Earth-sized telescope based on VLBI (Very Long Baseline Interferometry) Technology.
- Primary Observing Targets:
  - Sgr A*: the SMBH at the center of the Milky Way.
  - M87*: the SMBH living at M87 center (a giant elliptical galaxy in the constellation Virgo).
- The resolution achievable on Sgr A* with current and future EHT baselines.

Baseline	Resolution at 230 GHz	Resolution at 345 GHz
LMT - SMT	140 μas/ 14 R_{Sch}	93 μas/ 9.3 R_{Sch}
Hawaii - SMT	58 μas/ 5.8 R_{Sch}	39 μas/ 3.9 R_{Sch}
Hawaii - ALMA	28 μas/ 2.8 R_{Sch}	19 μas/ 1.9 R_{Sch}
Plateau de Bure - South Pole	23 μas/ 2.3 R_{Sch}	15 μas/ 1.5 R_{Sch}

- First image of a SMBH: M87*



DM spike scenario

- Adiabatic growth of SMBH will significantly enhance the DM density and form a spiky 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)

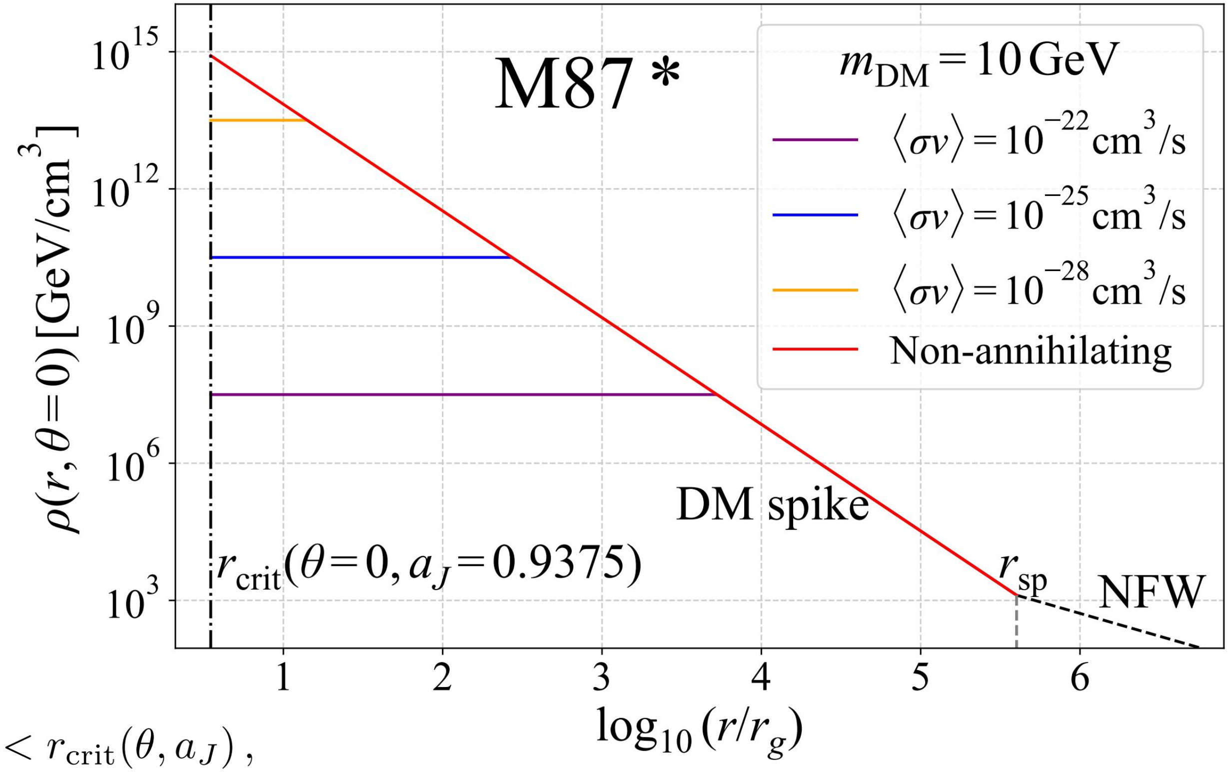
- Approximate power-low model

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

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

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

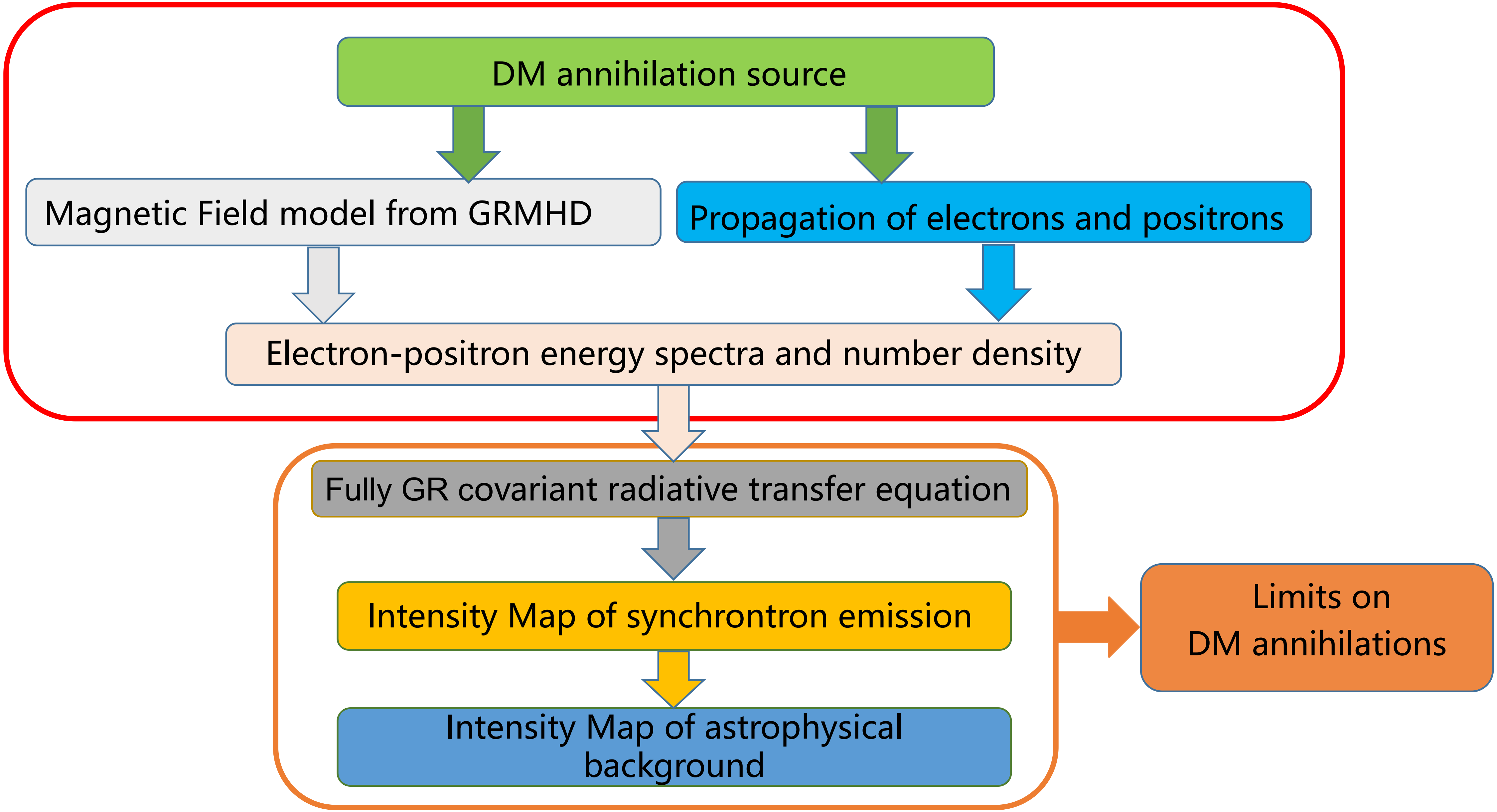
$$g_\gamma(r) = \left(1 - \frac{2R_s}{r}\right)^3, \quad \gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma}$$



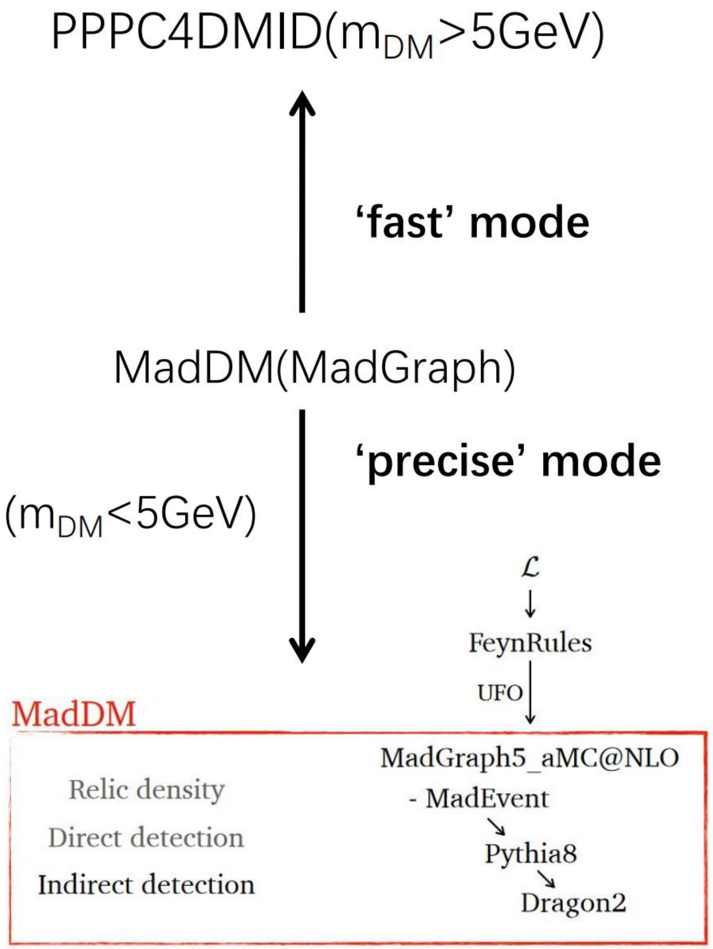
- DM spike profile with annihilation

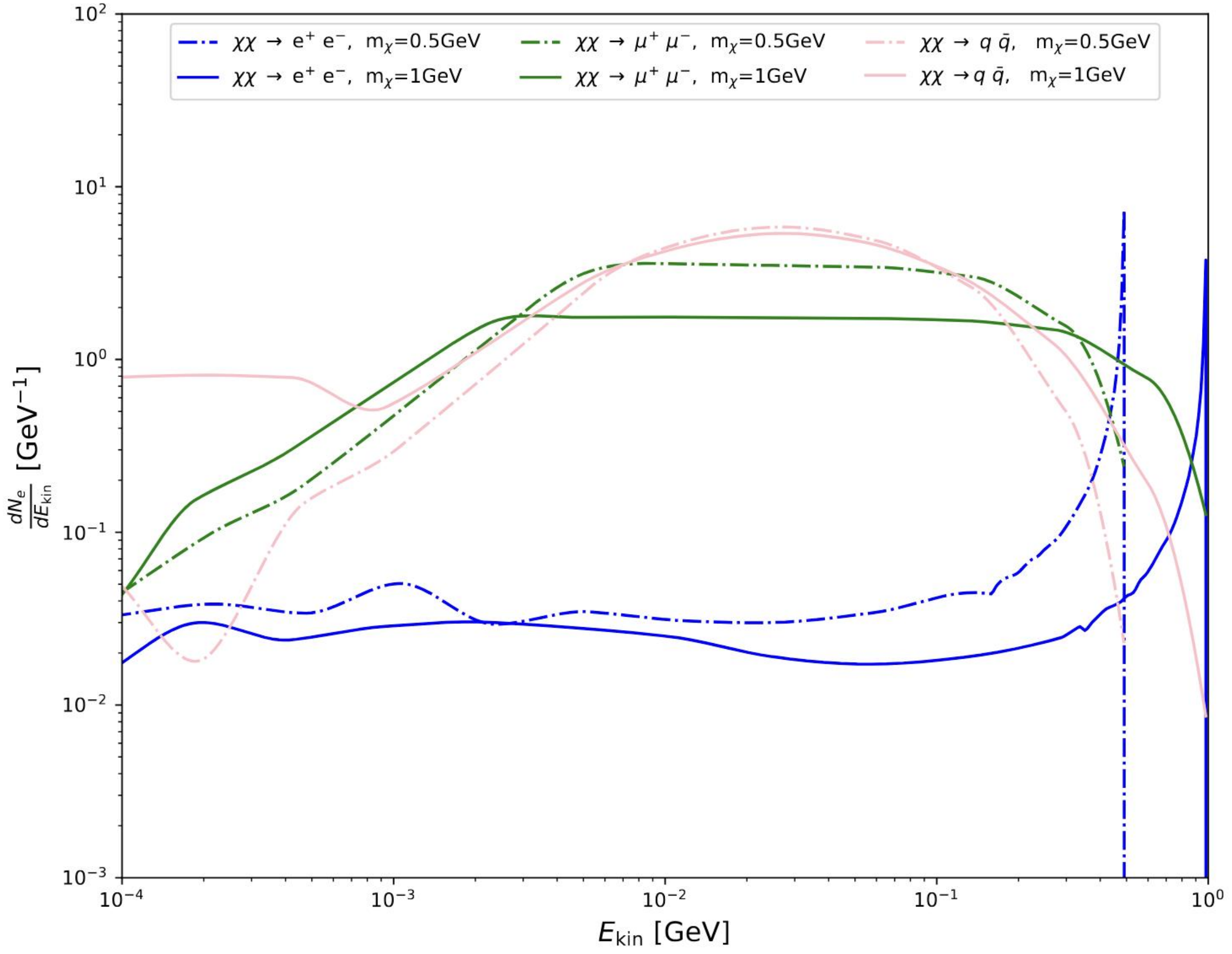
$$\rho(\vec{r}) = \begin{cases} 0 & r < r_{\rm crit}(\theta, a_J)\,, \\ \rho_{\rm sat} \equiv m_{\rm DM}/(\langle\sigma v\rangle\, t_{\rm BH}) & r_{\rm crit}(\theta, a_J) \le r < r_{\rm sat} \\ \rho_{\rm sp}(r) \equiv \rho_0\,(r/r_0)^{-\gamma_{\rm sp}} & r_{\rm sat} \le r < r_{\rm sp}\,, \\ \rho_{\rm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

● Synchrotron emission around SMBH due to DM annihilation

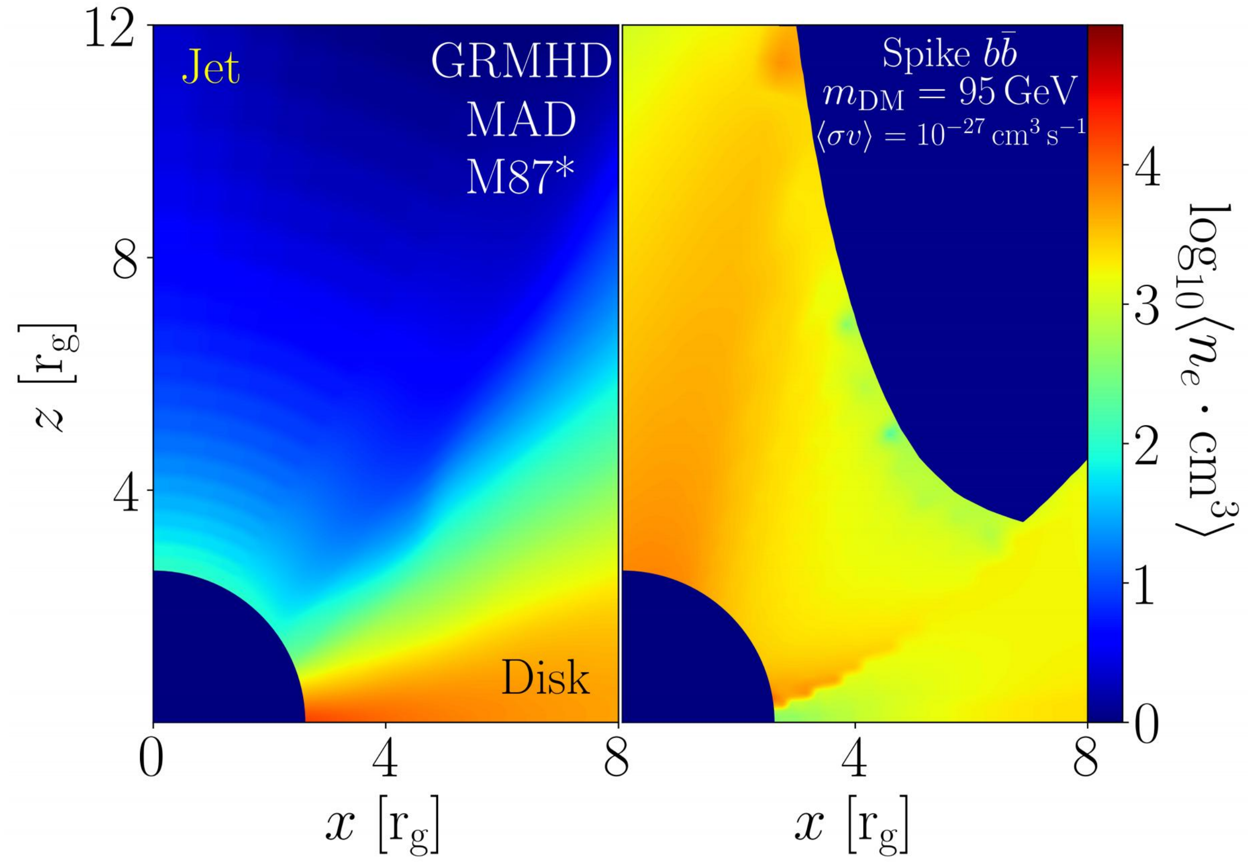


DM annihilation energy spectra

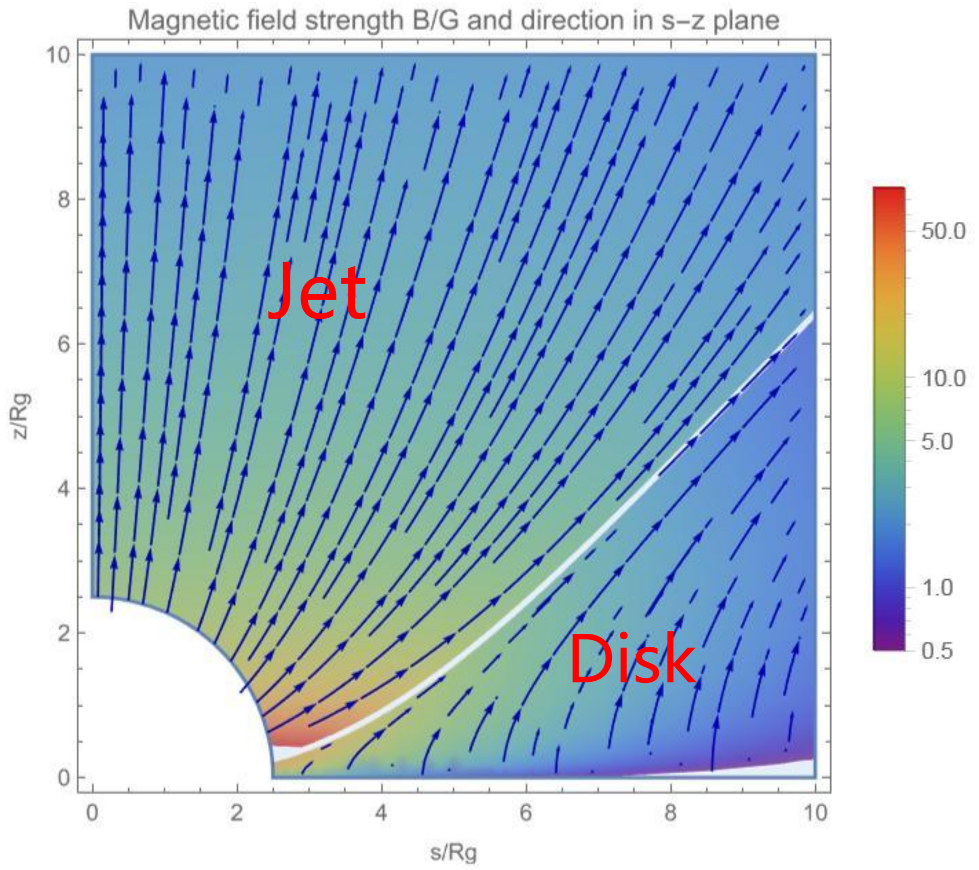




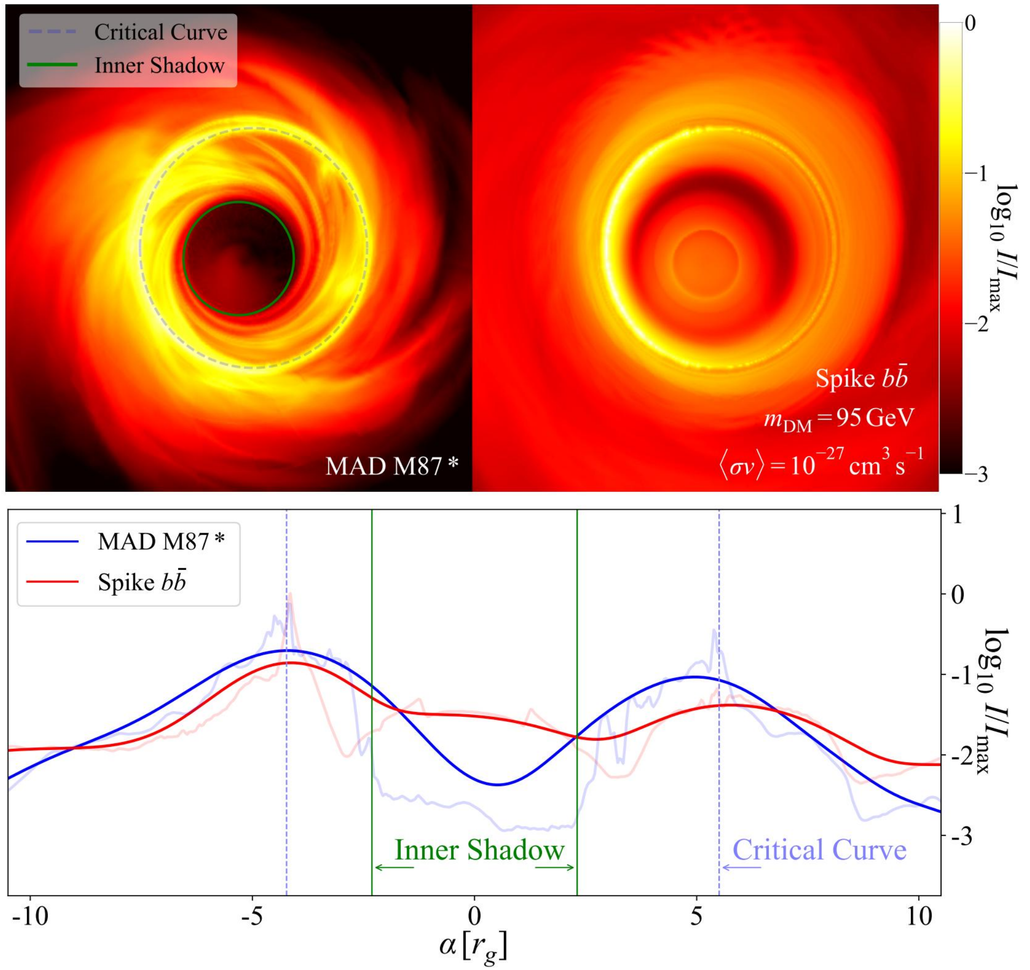
- Electron-positron energy spectra and number density



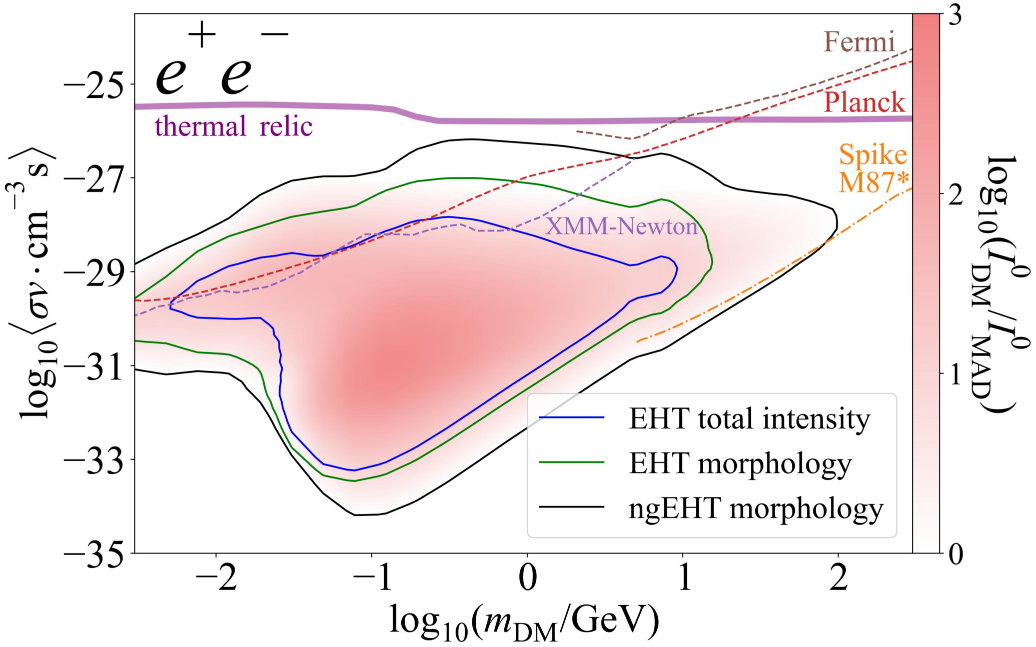
- Magnetic field model Based on GRMHD simulations

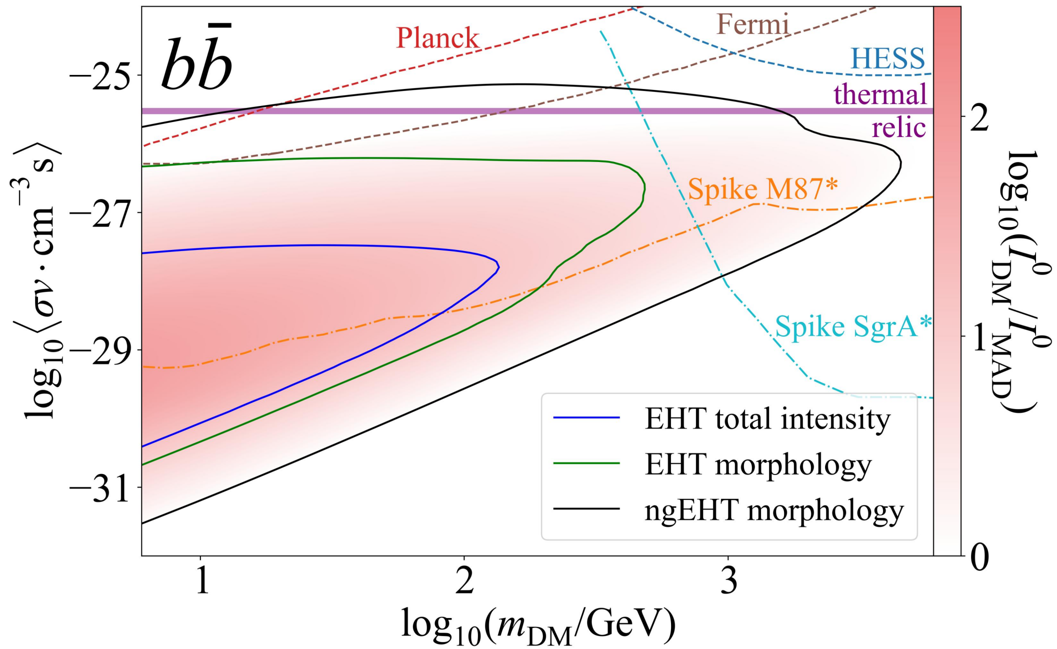


- Intensity Map of synchrontron emission



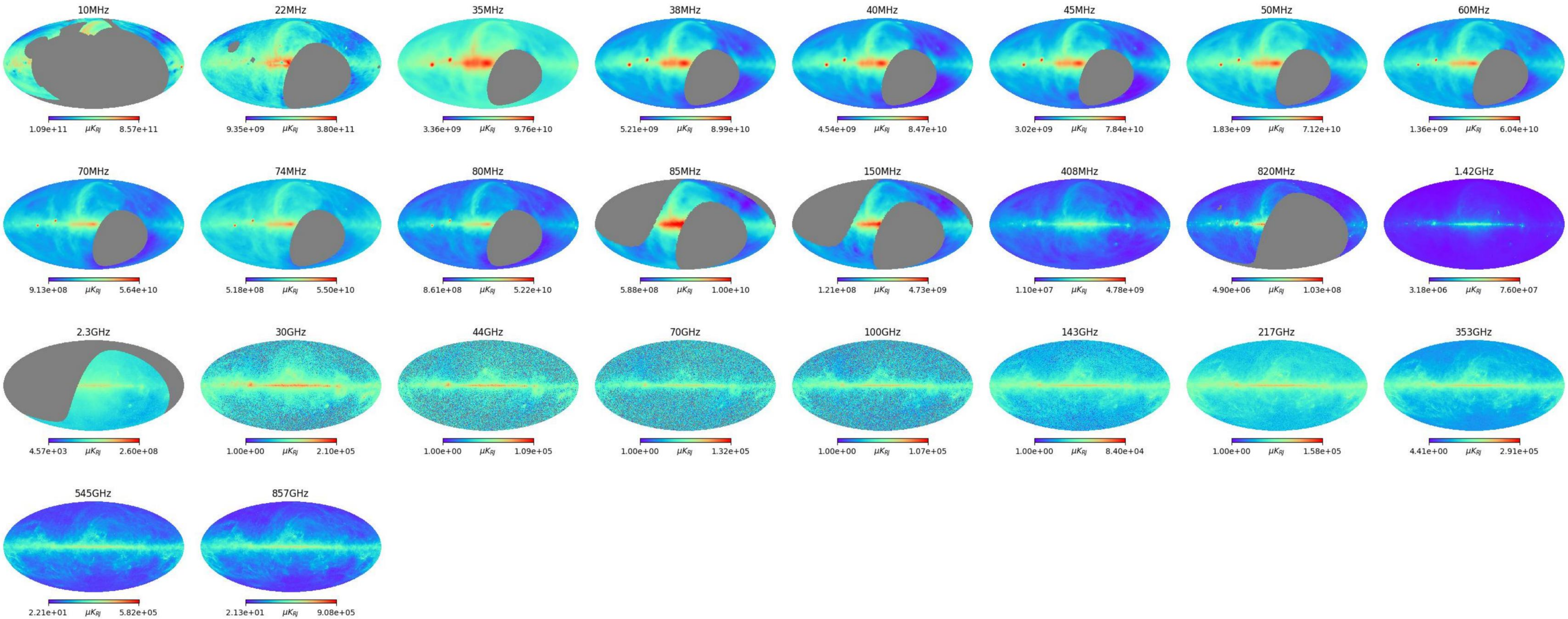
- Limits on DM annihilation cross sections





DM Constraints from Diffuse Galactic Radio emission

Sky Maps from observation: 10 MHz to 857 GHz



- Modeling diffuse Galactic radio emission

Astrophysical emission components: Synchrotron + CMB + Free–free emission + Thermal dust

Synchrotron: galprop_v57 — T.A. Porter, G. Johannesson and I.V. Moskalenko, [2112.12745]

Free–free emission + Thermal dust: PLANCK template model — PLANCK collaboration, PAstron. Astrophys. [1502.01588]

Component	Free Parameters and Priors	Brightness Temperature, $T_b(\nu)$ [μK_{RJ}]	Additional Information
CMB		$T_b^{\mathrm{CMB}}(\nu) = 10^6 \frac{c^2 I(\nu,T)}{2\nu^2 k_B}$	$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp[h\nu/(k_B T_{\mathrm{CMB}})]-1}$ $T_{\mathrm{CMB}} = 2.7255K$
Free-Free	$\log \mathrm{EM} \sim U(-\infty,\infty)$ $T_e \sim \mathcal{N}(7000\mathrm{K},\ 500\mathrm{K})$	$T_b^{\mathrm{ff}}(\nu) = 10^6 T_e(1-e^{-\tau})$	$\tau = 0.05468 T_e^{-3/2}\nu_9^{-2}\mathrm{EM}\cdot g_{\mathrm{ff}}$ $g_{\mathrm{ff}} = \log\left\{\exp\left[5.960 - \sqrt{3}/\pi \log(\nu_9 T_4^{-3/2})\right] + e\right\}$ $T_4 = T_e/(10^4\mathrm{K}),\quad \nu_9 = \nu/(10^9\mathrm{Hz})$
Thermal Dust	$A_d > 0$ $\beta_d \sim \mathcal{N}(1.55,\ 0.1)$ $T_d \sim \mathcal{N}(23\mathrm{K},\ 3\mathrm{K})$	$T_b^{\mathrm{dust}}(\nu) = A_d\left(\frac{\nu}{\nu_0}\right)^{\beta_d+1}\frac{\exp(\gamma\nu_0)-1}{\exp(\gamma\nu)-1}$	$\nu_0 = 545\mathrm{GHz}$

$$T_b^{\mathrm{syn}}(\nu) = \frac{c^2 I_{\mathrm{syn}}(\nu)}{2\nu^2 k_B}$$

- Propagation model

Astrophysical injection

$$\frac{\partial\psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right]$$

- Propagation parameters

parameters	$D_{0,xx}[10^{28}\mathrm{cm}^2\mathrm{s}^{-1}]$	D_R [MV]	D_{br} [MV]	δ_1
values	4.161	4.0e3	4.3e30	0.35271

parameters	δ_2	η	diff_ reacc (for galprop)	V_{Alf} [km s^{-1}]
values	0.404	1.0	-1	15.32

- Galactic Magnetic Field (GMF) model

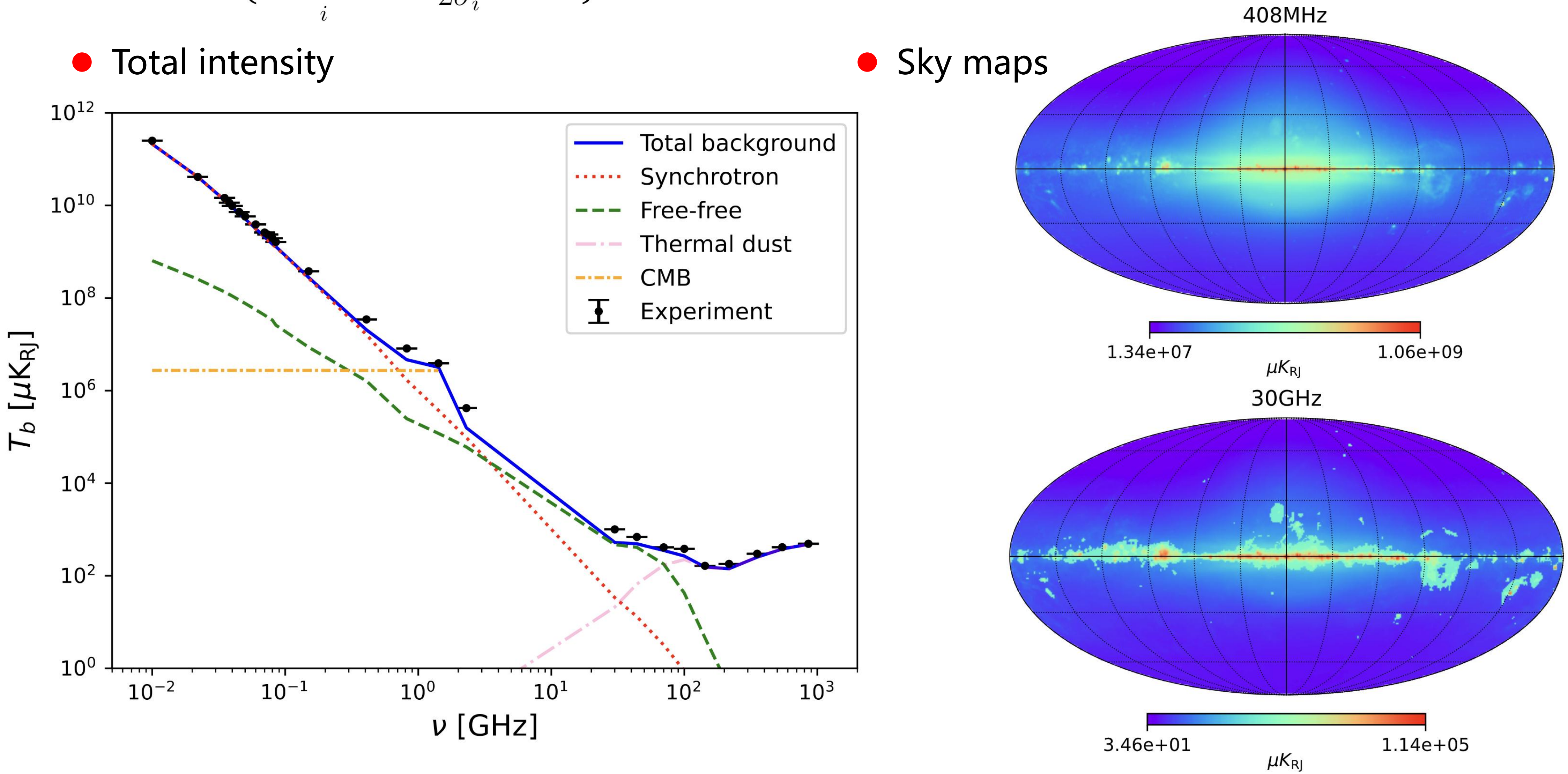
- Likelihood function

$$L \propto \exp\left\{ -\sum_i \frac{(T_i^{\rm model} - T_i^{\rm map})^2}{2{\sigma_i}^2} \right\}$$

$$T_{b,i}^{\rm model}(\nu) = N_1\, T_{b,i}^{\rm syn}(\nu) + T_{b,i}^{\rm CMB}(\nu) + N_2 \left[T_{b,i}^{\rm ff}(\nu) + T_{b,i}^{\rm dust}(\nu) \right]$$

- Total intensity

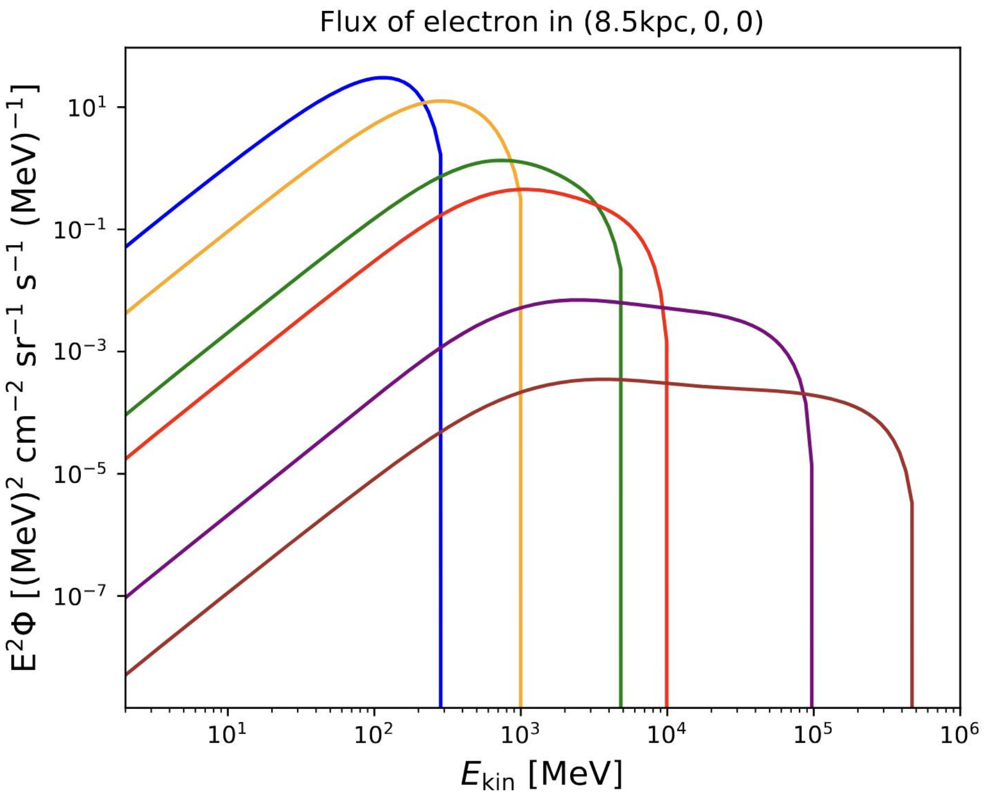
- Sky maps

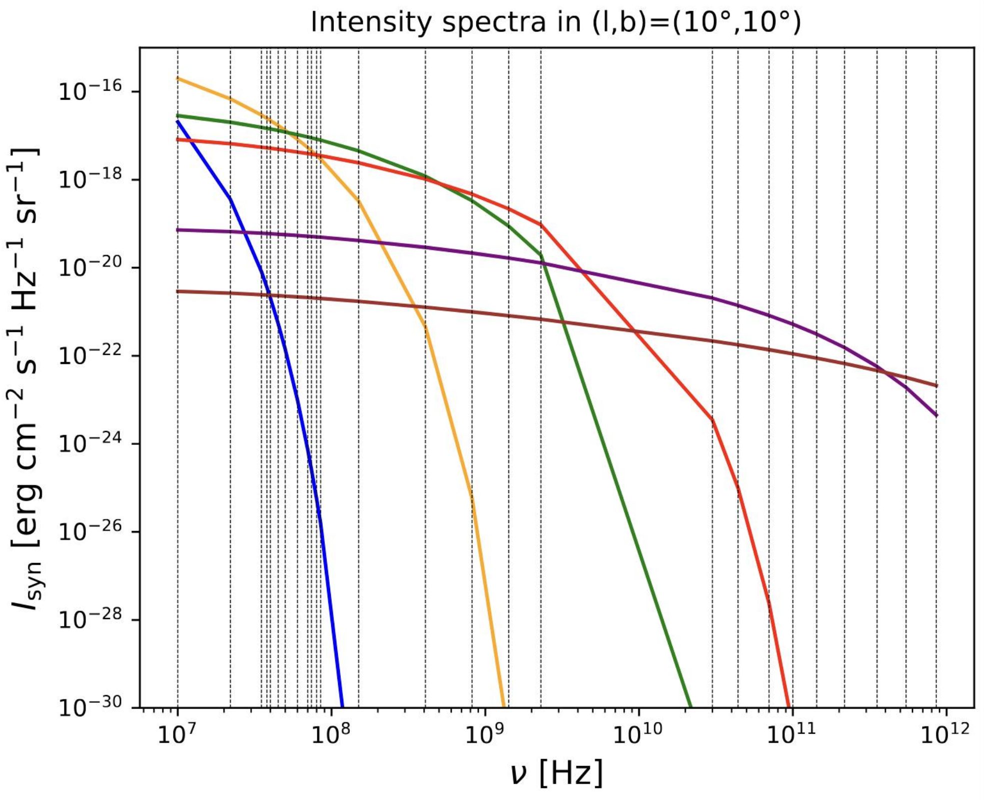


- Intensity from DM annihilation

$$\frac{\partial\psi(\vec{r},p,t)}{\partial t}=q(\vec{r},p,t)+\vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi-\vec{V}\psi)+\frac{\partial}{\partial p}p^2D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi-\frac{\partial}{\partial p}\left[\dot{p}\psi-\frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right]$$

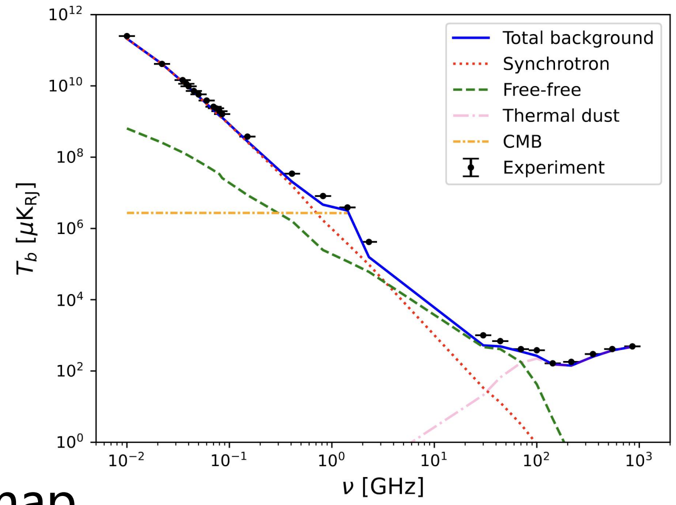
$$T_b^{\rm syn}(\nu)=\frac{c^2I_{\rm syn}(\nu)}{2\nu^2k_B}$$



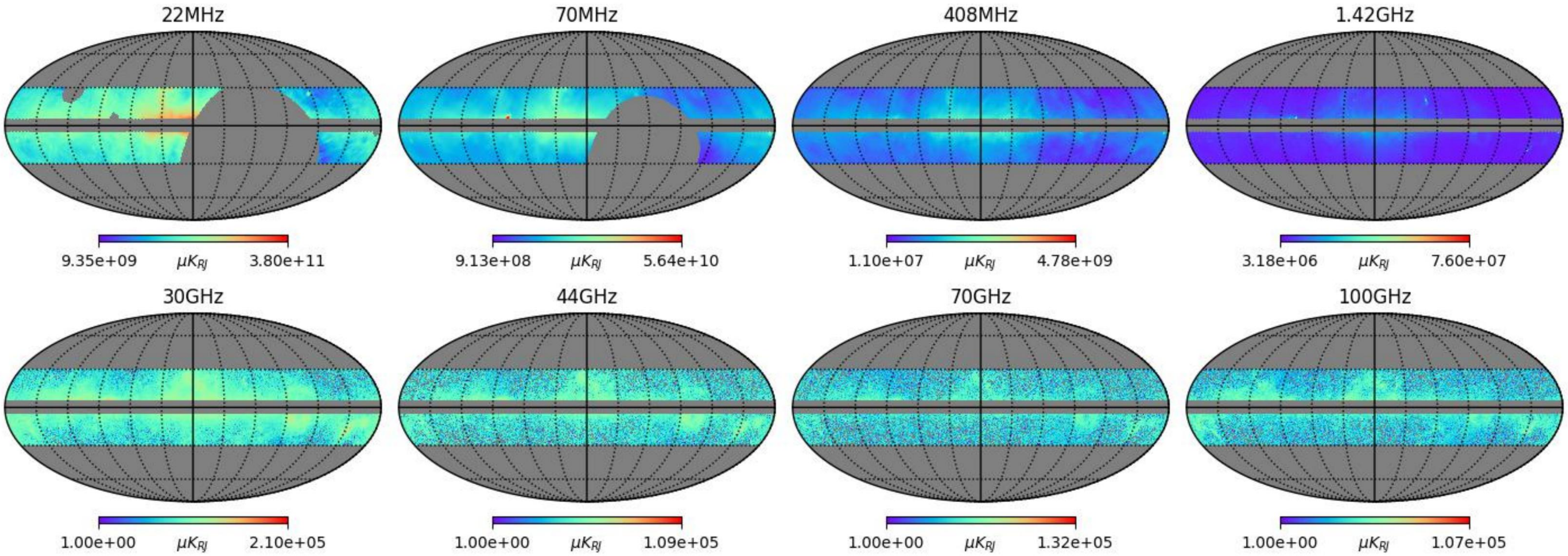


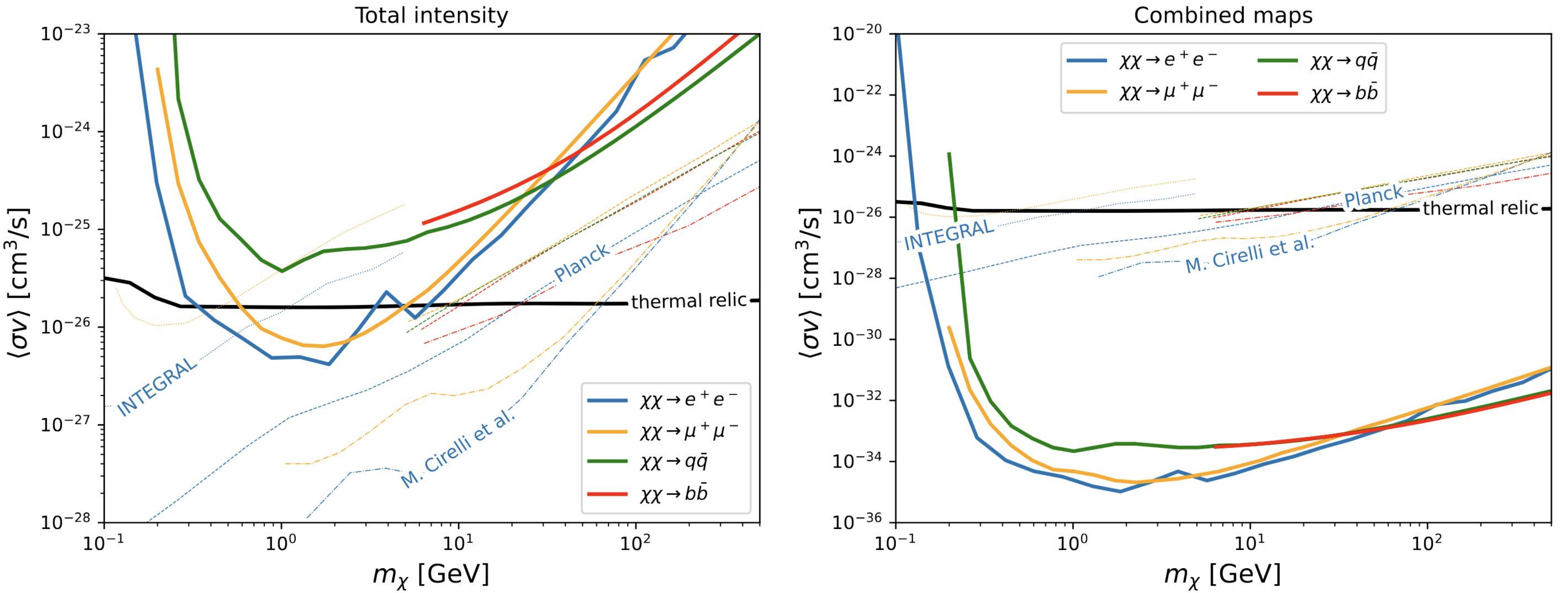
$$\langle\sigma v\rangle=3\times10^{-26}{\rm cm}^3/{\rm s}\qquad \chi\chi\rightarrow\mu^+\mu^-$$

- Constraints from the total intensity



- Constraints from combined individual sky map





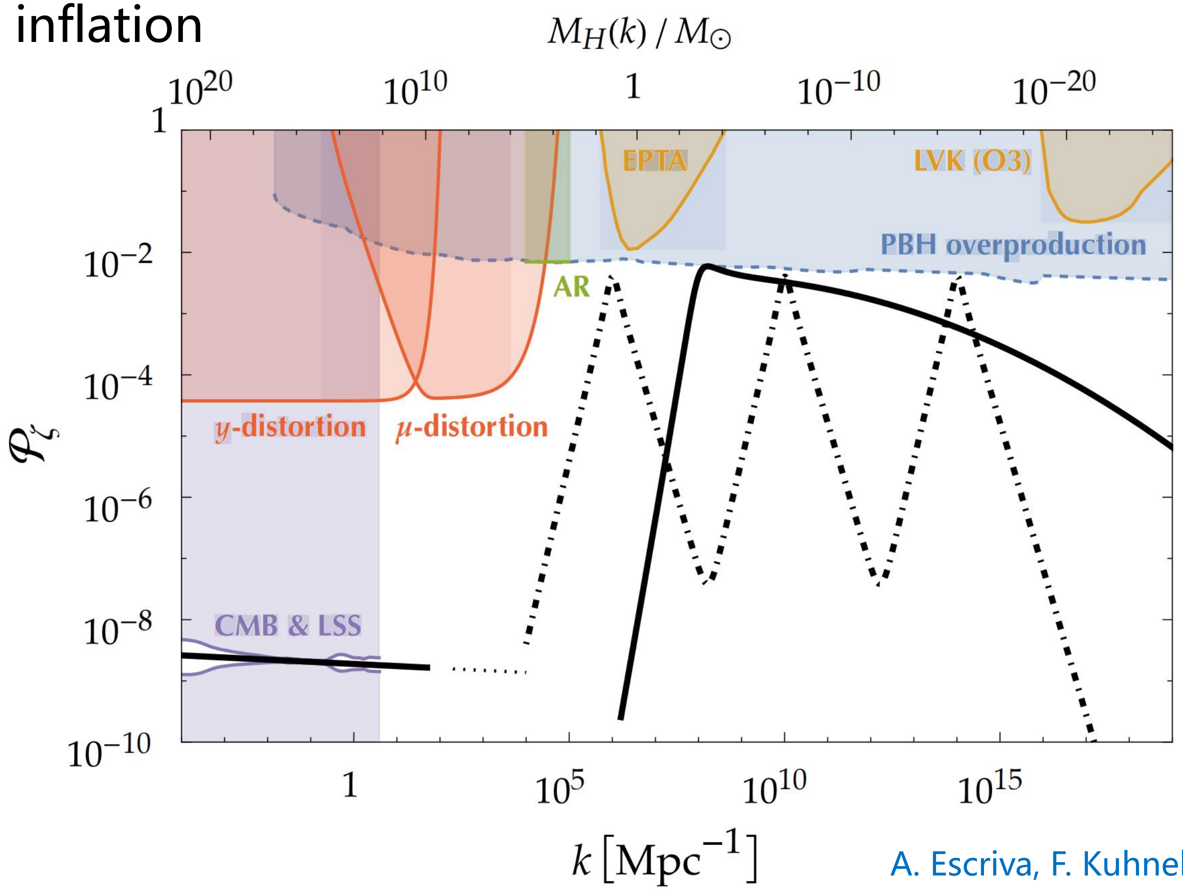
Total intensity
Combined maps
$\langle \sigma v \rangle$ [cm^3/s]
m_χ [GeV]
$\chi\chi \to e^+e^-$
$\chi\chi \to \mu^+\mu^-$
$\chi\chi \to q\bar{q}$
$\chi\chi \to b\bar{b}$
thermal relic
Planck
INTEGRAL
M. Cirelli et al.

Limits on Primordial Black Hole as DM with X-ray observations

- PBH as a DM candidate

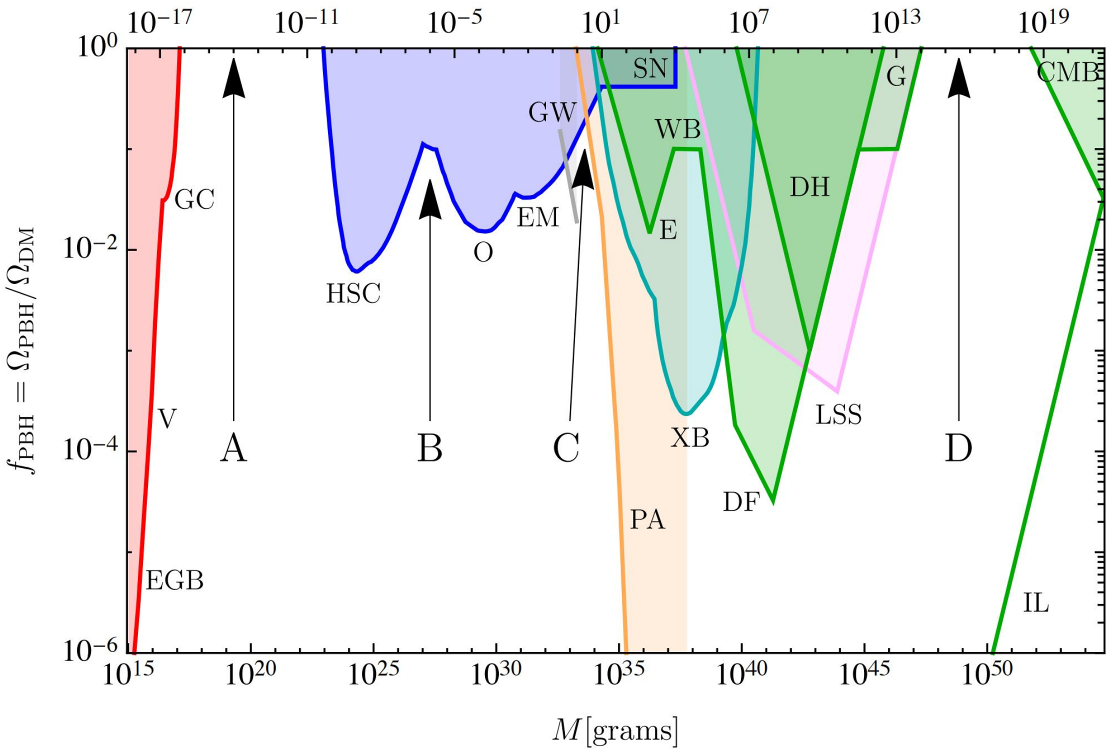
- Production mechanism of PBH

Large curvature perturbations generated during inflation



- Constraints on the PBH DM for a monochromatic mass function

Constraints: evaporation, lensing dynamical, accretion, CMB, GW, primordial perturbations



A. Escriva, F. Kuhnel and Y. Tada, [2211.05767]

PBH Hawking evaporation

- Temperature

$$T_{\rm BH} = \frac{M_P^2}{8\pi M_{\rm BH}}$$

- Primary emission spectrum

$$\frac{d^2N_i}{dtdE_i} = \frac{1}{2\pi}\sum_{\rm d.o.f.}\frac{\Gamma_i(E_i, M, a^\star)}{e^{E_i'/T} \pm 1}$$

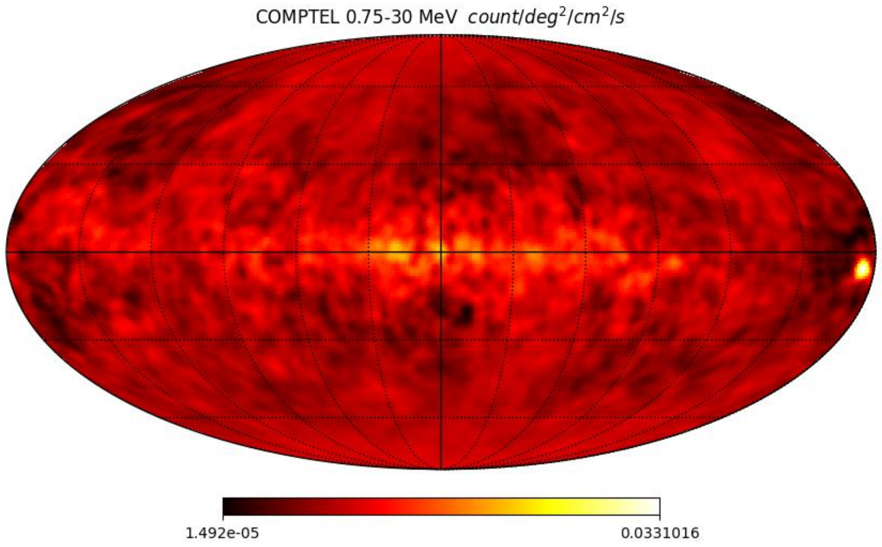
BlackHawk + hazama

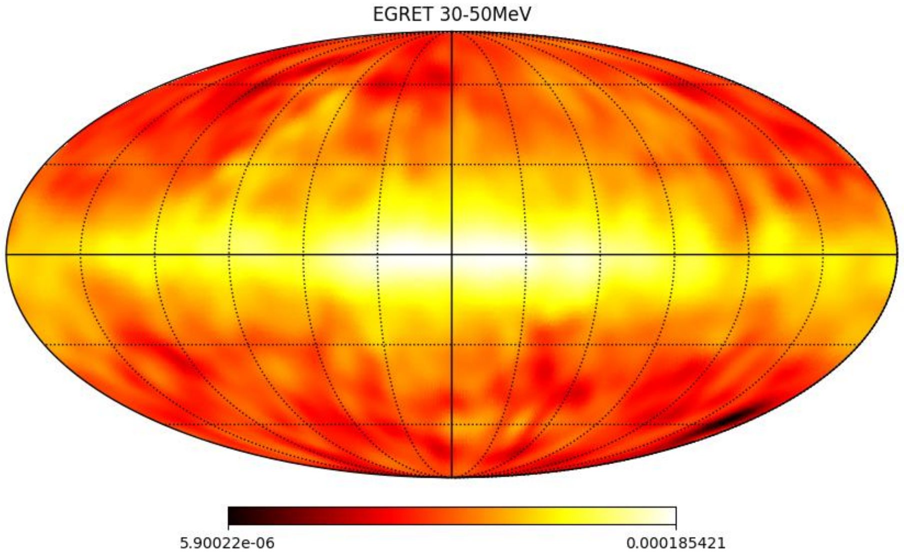
- Number of electron-positron injected by PBHs evaporation

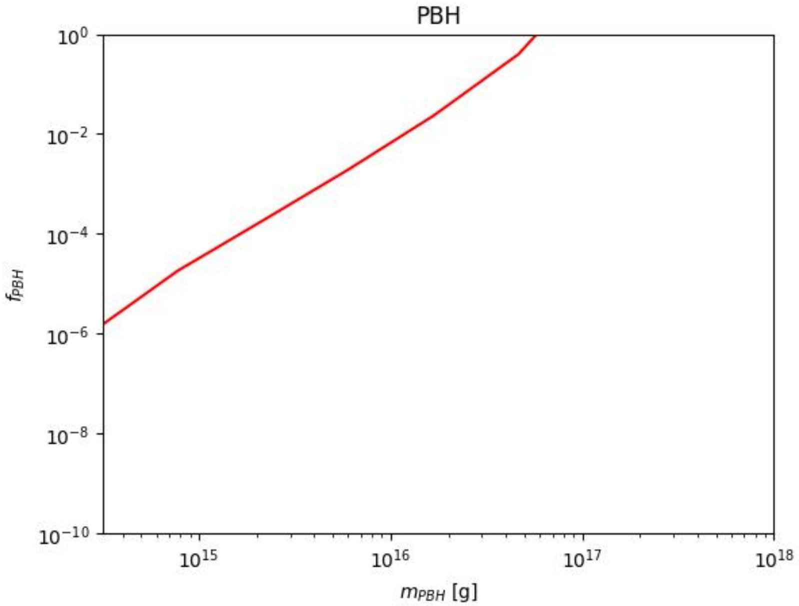
$$Q_e(E_e, \vec{x}) = f_{\rm PBH}\rho_{\rm DM}(\vec{x})\int_{M_{\rm min}}^{\infty}\frac{dM}{M}\frac{dN_{\rm PBH}}{dM}\frac{d^2N_e}{dtdE_e}$$

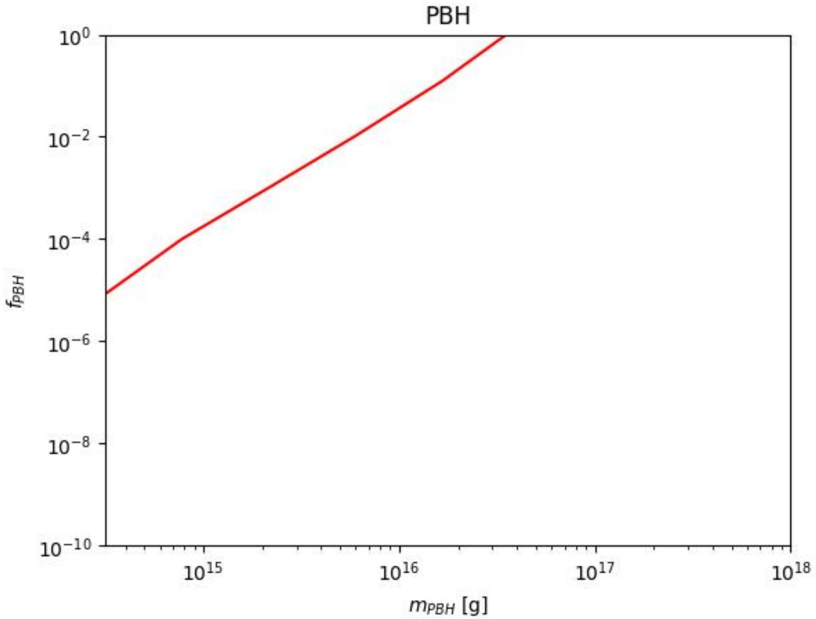
$$\frac{\partial\psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right]$$

Preliminary results









Summary

- We present the advanced calculations of DM annihilation near SMBH M87*.
- We developed a comprehensive framework to calculate electron-positron propagation under strong gravity and magnetic fields, based on GRMHD simulations that are best-fit to current intensity and polarimetric observations of the SMBH.
- Our study shows a possible way for DM searches through the morphology of BH images, including significant exclusion results based on current and projected EHT observations.
- These results provide immediate relevance and significance, showcasing the ability of existing EHT data to contribute to DM studies.

Thanks for your attention

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