Dark matter constraints from the observations of synchrotron emission

Ding Ran

Yuan Guan-Wen et al. arXiv:2106.05901
Yifan Chen et al. in preparation.

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1–4 Jun 2023

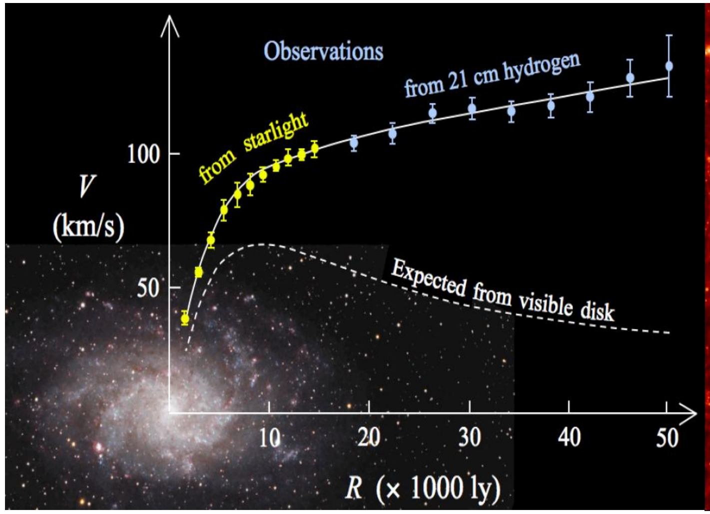
Outline

- Introduction to DM spike model
- Synchrotron emission around SMBH due to DM annihilation
- Results & Discussion

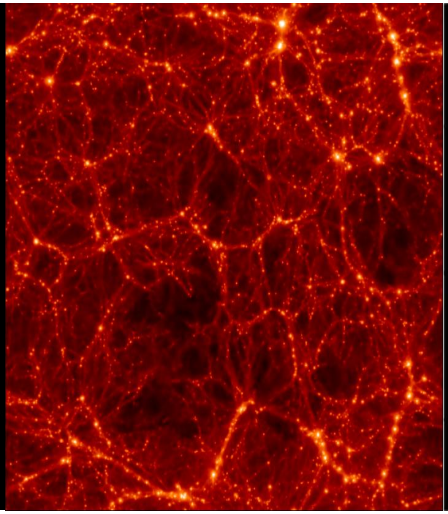
Introduction to DM spike model

Evidences for DM

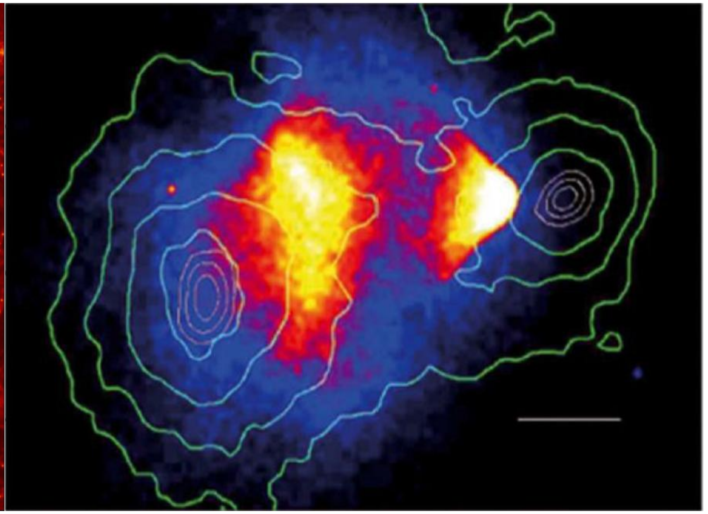
- Rotation curves



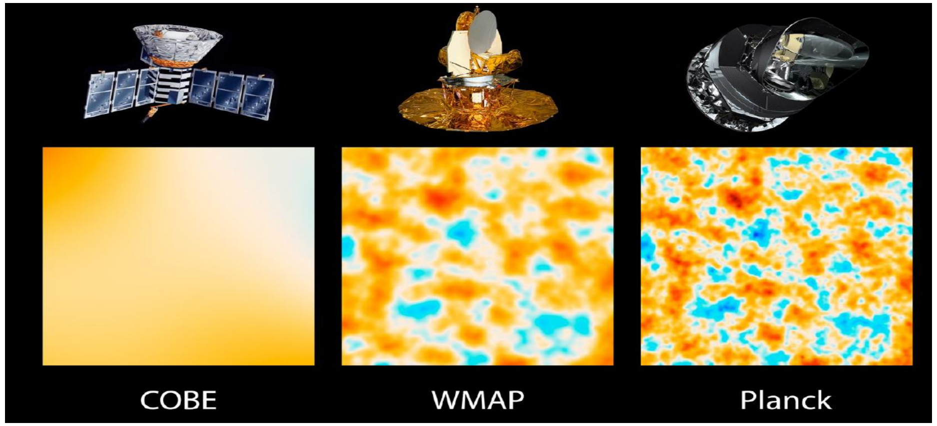
- LSS



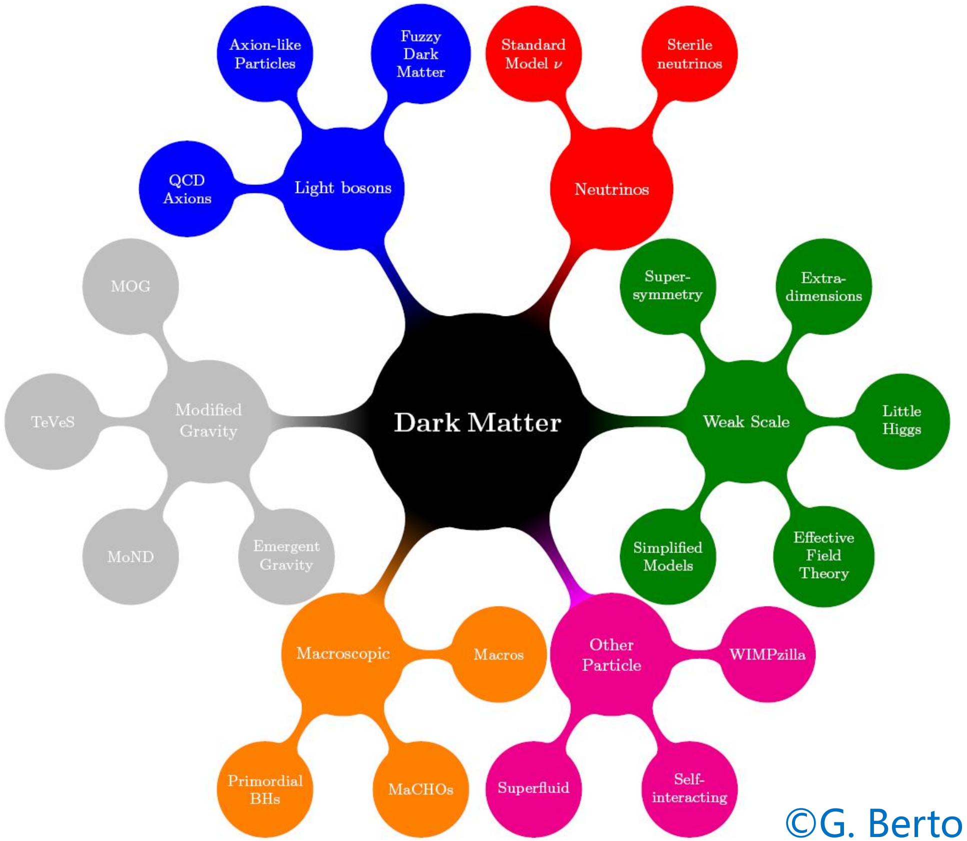
- Bullet cluster



- CMB



- DM candidates



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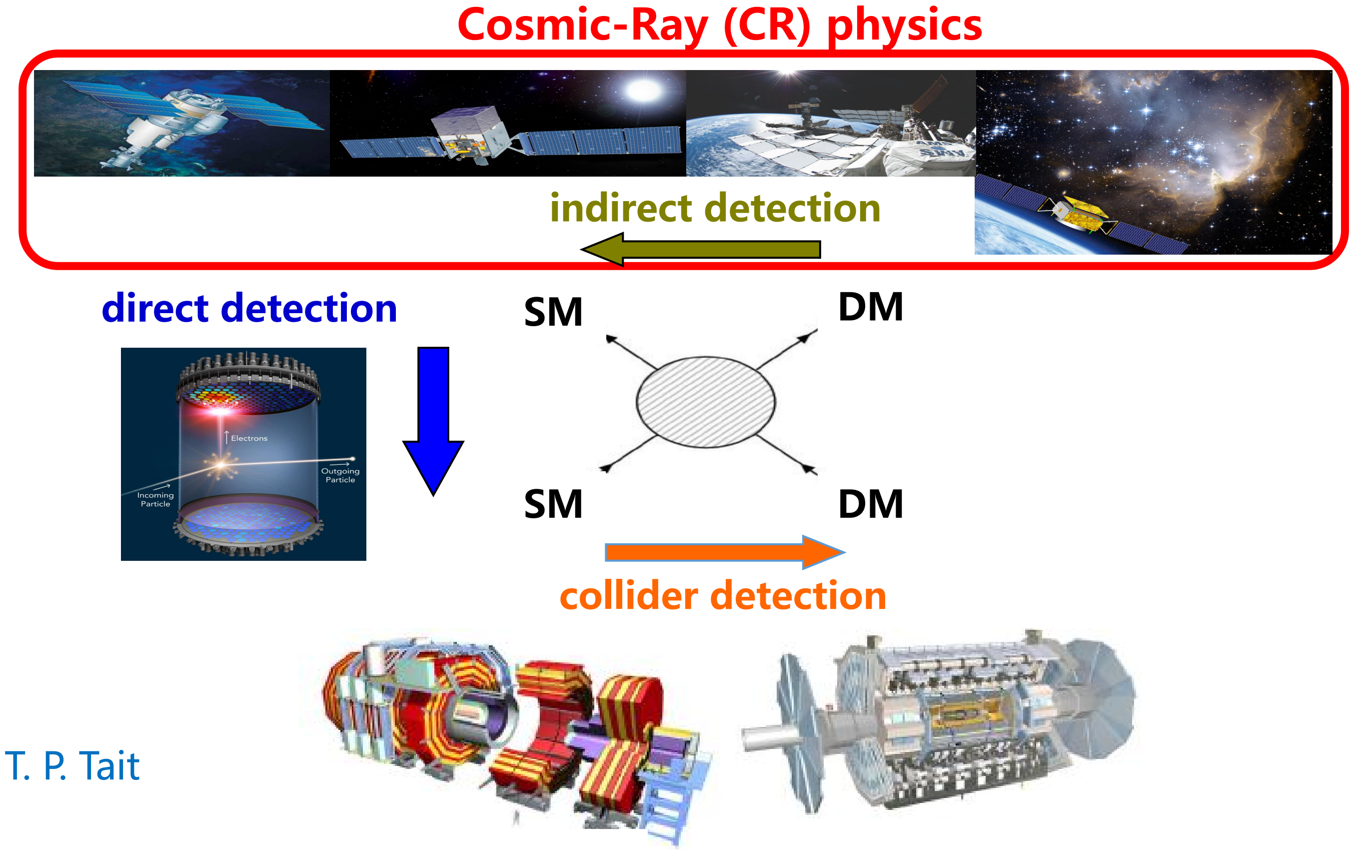
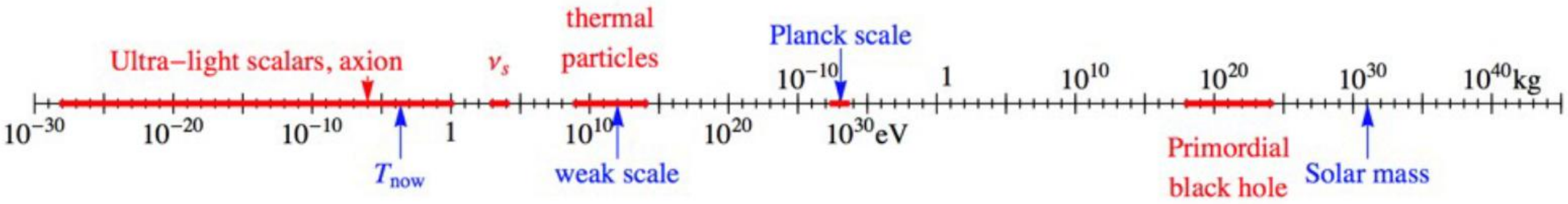
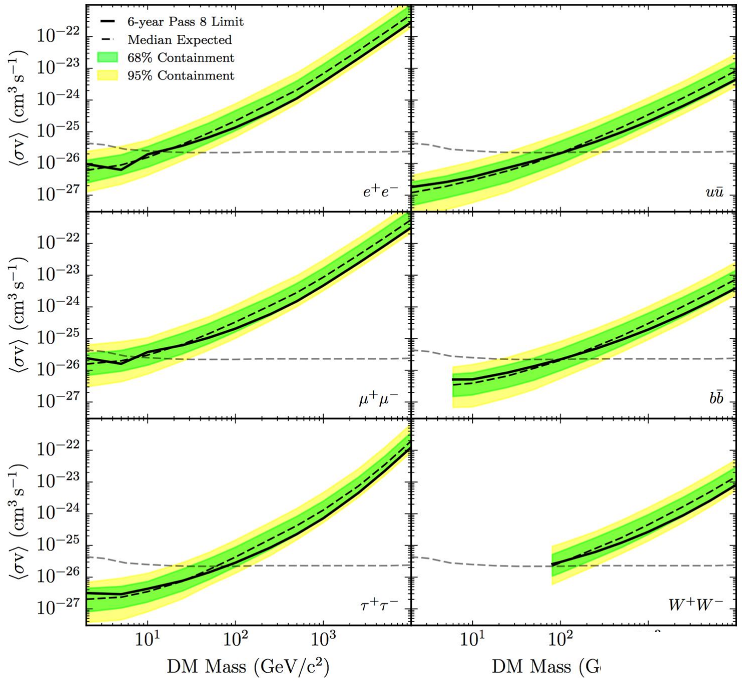
- WIMP detections





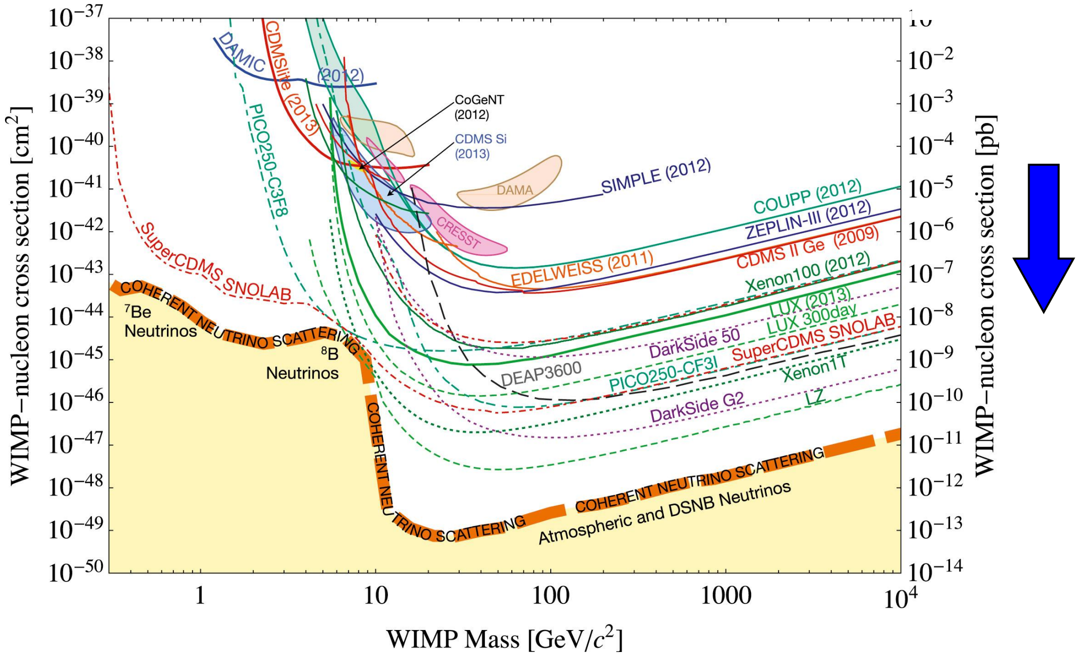
- WIMP Liimits

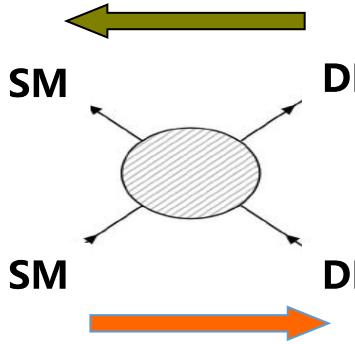


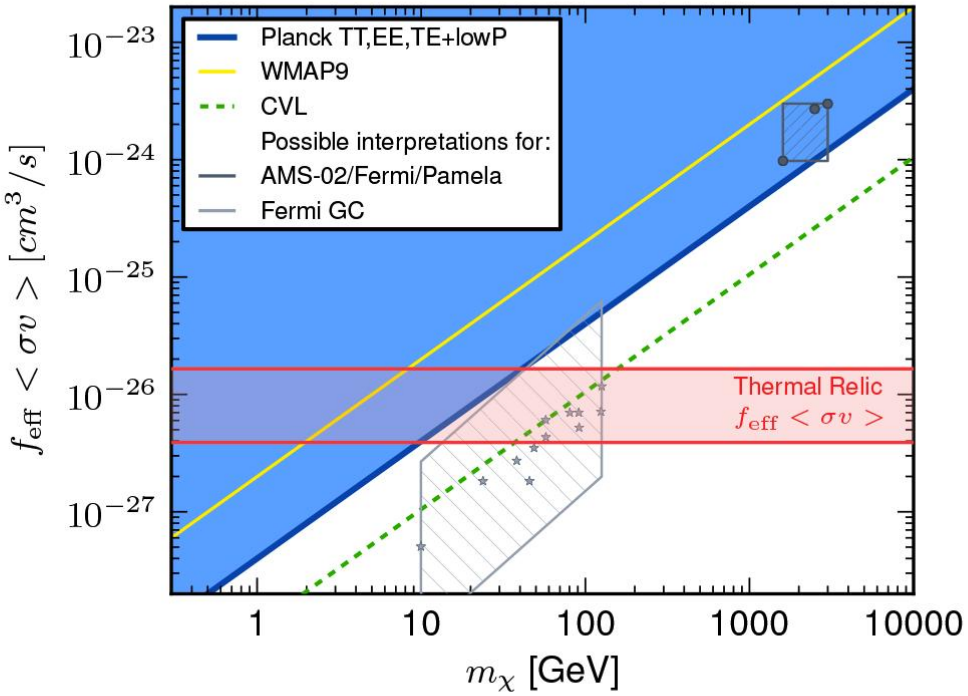
Indirect detection

Direct detection

CMB energy injection







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

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

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

- General phase space arguments

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

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

Density of state

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

Distribution function

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

Invariance of radial action

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

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

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

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

Conservation of mss

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

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

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

- Approximate analytical distribution function for NFW profile

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

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

$$\hat{f}(\hat{\varepsilon}) = \frac{1}{7\cdot 2^{11/2}(8-\hat{\varepsilon})(1-\hat{\varepsilon})^2}\left[252\frac{8+\hat{\varepsilon}}{\sqrt{2(1-\hat{\varepsilon})}}\arcsin\sqrt{\hat{\varepsilon}} + P_1(\hat{\varepsilon})\sqrt{\frac{\hat{\varepsilon}}{2}} + P_2(\hat{\varepsilon})E_1\left(-\frac{\hat{\varepsilon}}{8}\right) + P_3(\hat{\varepsilon})K\left(-\frac{\hat{\varepsilon}}{8}\right) + 189(8+\hat{\varepsilon})\prod\left(\hat{\varepsilon}, -\frac{\hat{\varepsilon}}{8}\right)\right]$$

complete elliptic integrals

- Final DM density profile

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

- Approximate power-low model

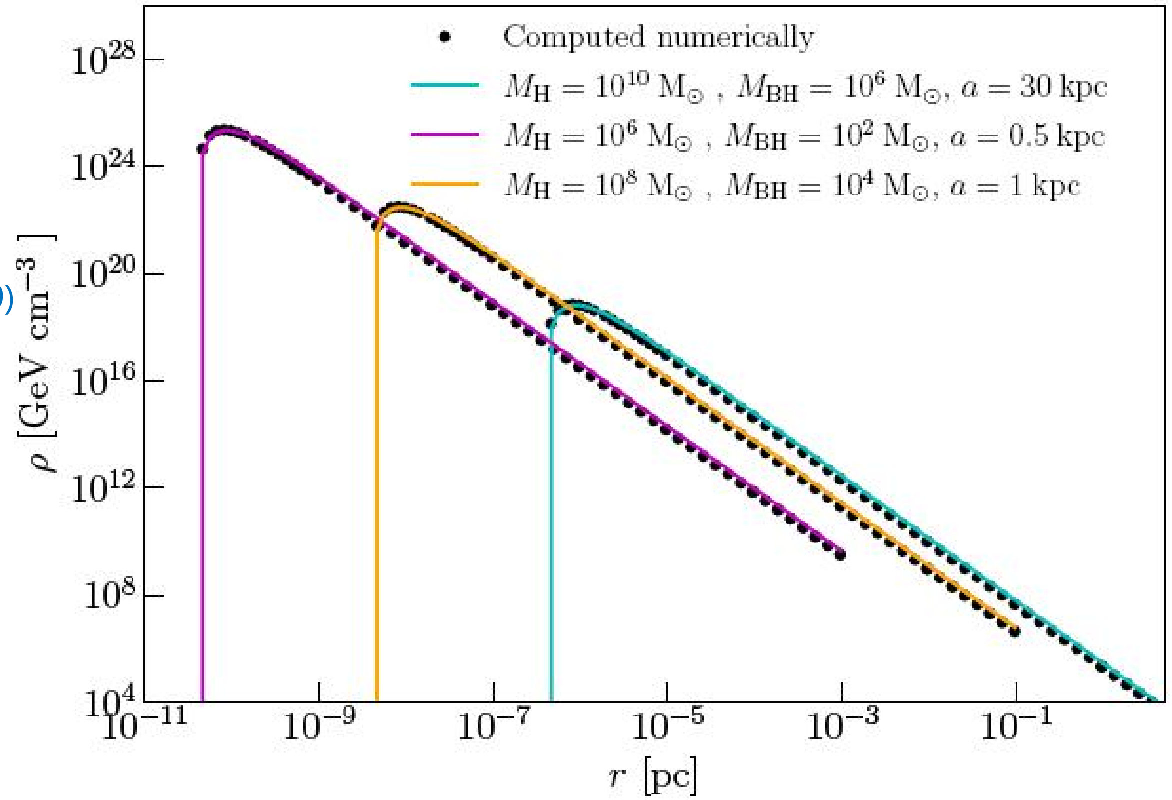
P. Gondolo & J. Silk,PRL 83(1999)

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

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

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

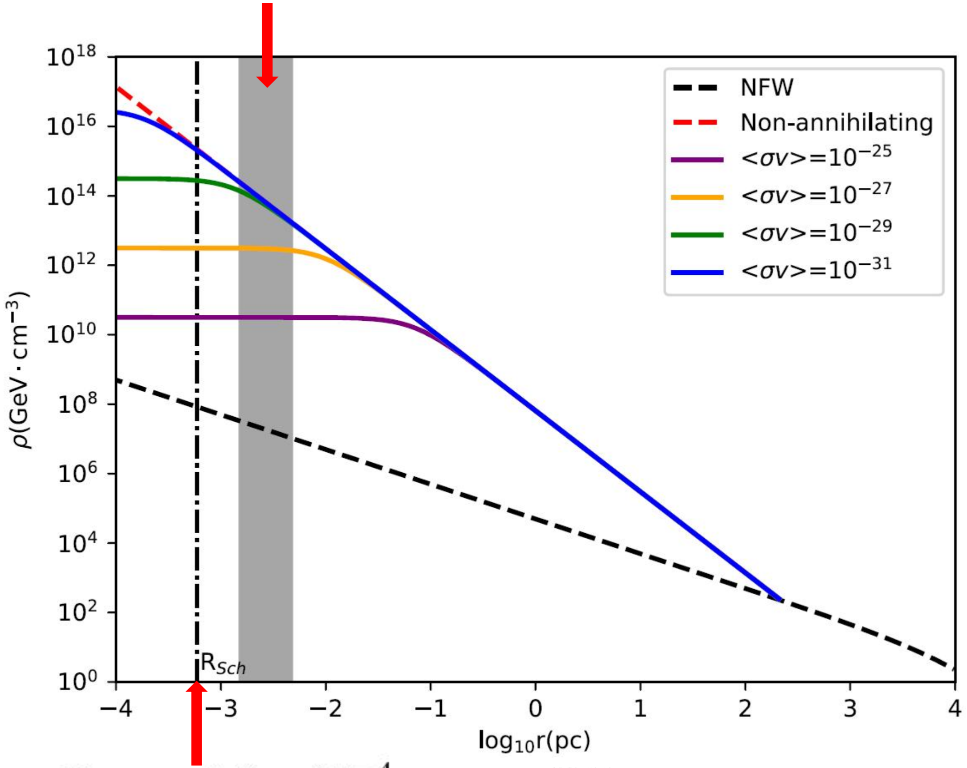
- Comparison of full numerical and pproximate power-low



Spike with DM annihilation

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

EHT observational areas



$R_{\rm Sch} = 5.9 \times 10^{-4}$ pc $\longrightarrow$ $7.3\ \mu$as

- DM spike profile with annihilation

$$\rho_\chi(r) = \begin{cases} 0 & r < R_{\rm Sch}, \\ \frac{\rho_{\rm sp}(r)\rho_{\rm sat}}{\rho_{\rm sp}(r)+\rho_{\rm sat}} & R_{\rm Sch} \le r < R_{\rm sp}, \\ \rho_{\rm NFW}(r) & r \ge R_{\rm sp}. \end{cases}$$

spike radius

$R_{\rm sp} \simeq 220$ pc

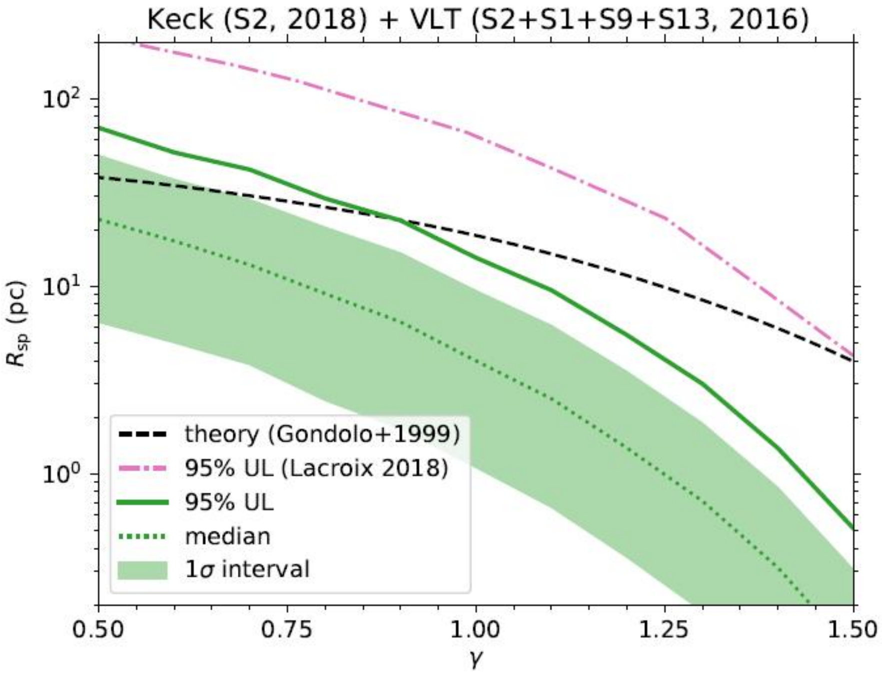
- Saturate DM density

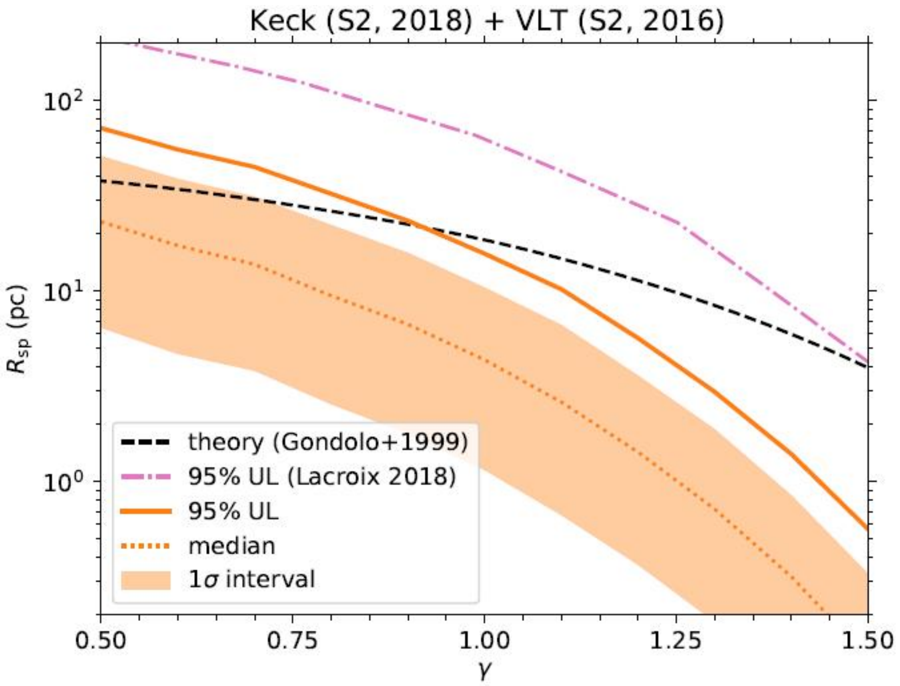
$$\rho_{\rm sat} = m_\chi / \langle \sigma v \rangle t_{\rm BH}$$

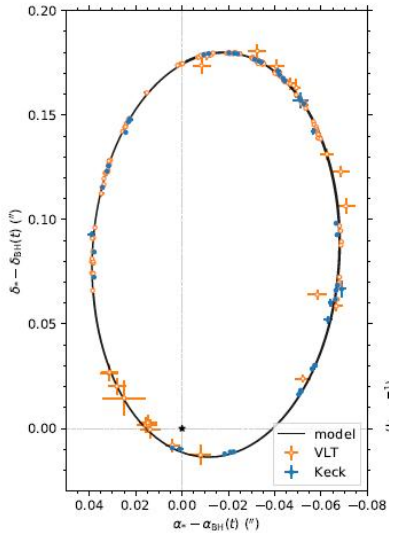
$\longrightarrow$ age of SMBH $t_{\rm BH} = 10^9$ yr

- Constraints DM spike at the GC from stellar orbits

Z-Q Shen et al.,2303.09284 [astro-ph]

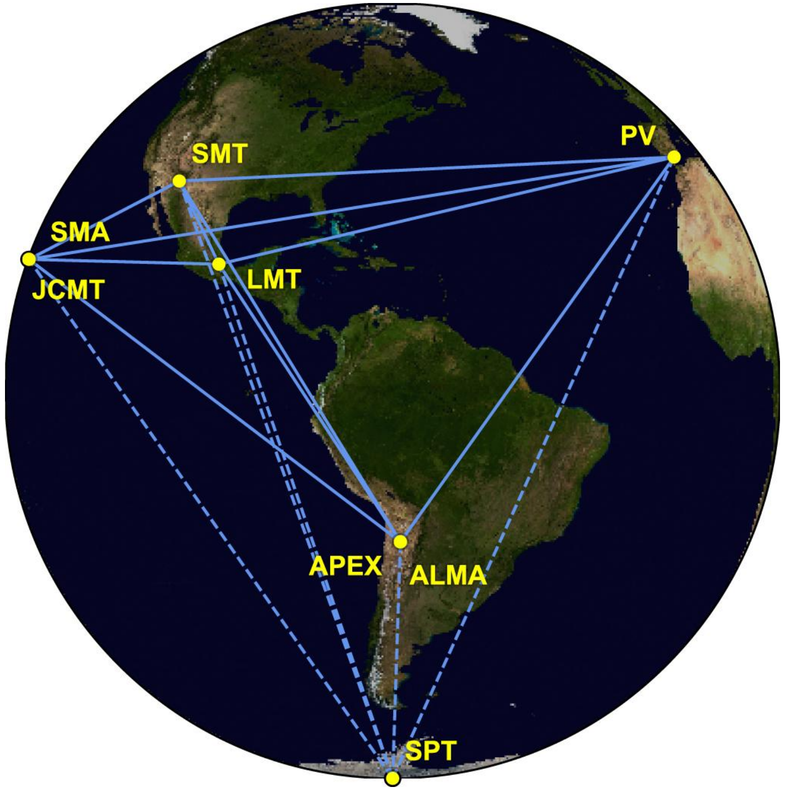






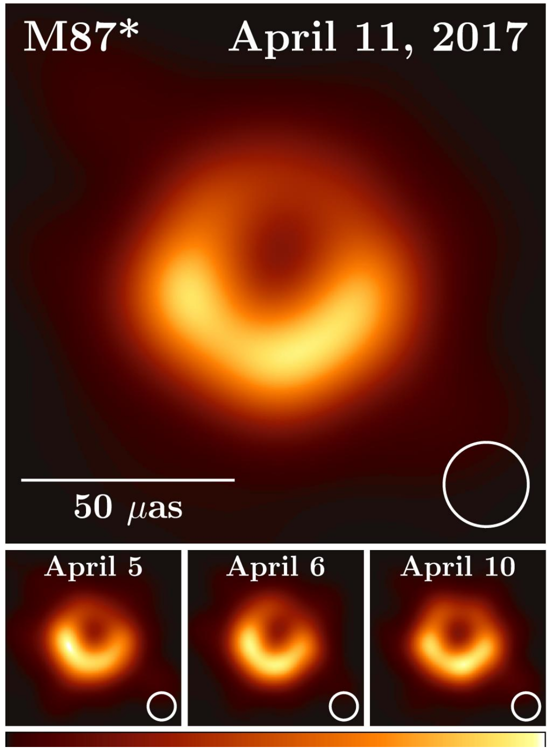
The EHT project

- 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 WIMP annihilations can be stringently constrainted!

Calculation framework

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]

$$S_{\rm syn}(\nu) = \int d\Omega_{\rm obs} \int_{l.o.s} dI_{\rm syn}(\nu)$$

Specific intensity: radiative transfer equation

$$\frac{dI_{\rm syn}(\nu,s)}{ds} = -\alpha(\nu,s) I_{\rm syn}(\nu,s) + \frac{j_{\rm syn}(\nu,s)}{4\pi}$$

relativistic Doppler effect and gravitational redshift

$$I_{\rm obs}(\nu_{\rm obs}) = \left(\frac{\nu_{\rm obs}}{\nu_{\rm em}}\right)^3 I_{\rm em}(\nu_{\rm em}) = g^3 I_{\rm em}(\nu_{\rm em})$$

emissivity

$$j_{\rm syn}(\nu,r) = 2\int_{m_e}^{M_\chi} dE \langle P_{\rm syn}\rangle(\nu,E_e,B) n_e(r,E_e)$$

power of synchrotron emission

$$P_{\rm syn}(\nu,E_e,B,\theta_p) = \frac{\sqrt{3}e^3 B \sin\theta_p}{m_e c^2} F(\nu/\nu_c)$$

$B \sim 1 - 30$ G

electron and positron energy spectrum

$$n_e(r,E) = \frac{4\pi p^2}{c} f_e(r,p)$$

outside accretion radius : propagation equation

$$-\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D \frac{\partial f_e}{\partial r}\right] + v\frac{\partial f_e}{\partial r} - \frac{1}{3r^2}\frac{\partial}{\partial r}(r^2 v)\, p\frac{\partial f_e}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}(\dot{p}p^2 f_e) = q(r,p)$$

source function

$$q(r,p) = \frac{c}{4\pi p^2} Q(r,E) = \frac{c}{4\pi p^2}\frac{\langle\sigma v\rangle \rho_\chi^2(r)}{2m_\chi^2}\sum_i {\rm BR}_i \frac{dN_{e^\pm}^{\rm inj}}{dE}(E)$$

annihilation rate

injection spectrum

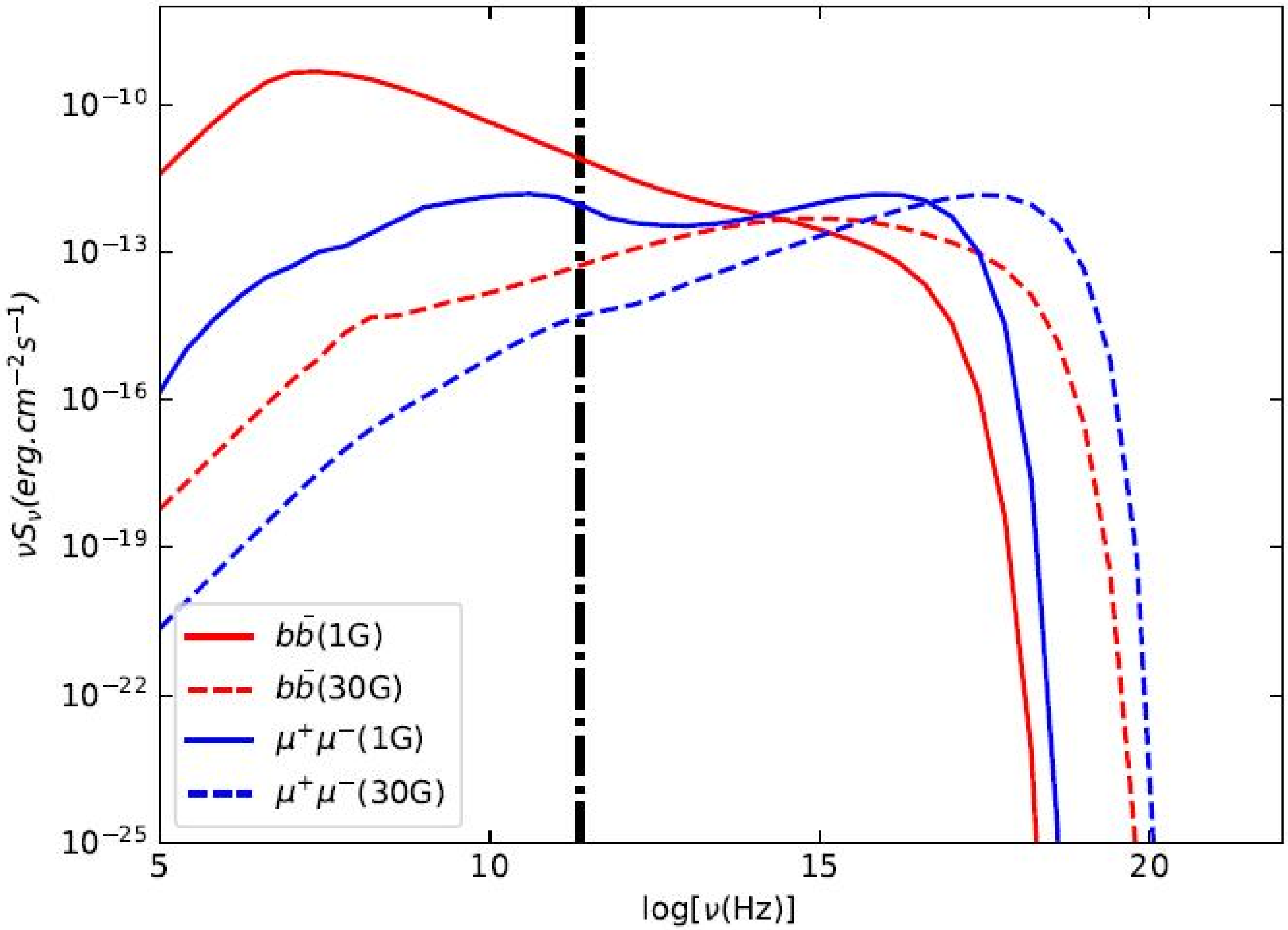
inside accretion radius: integral analytic solution

$$f_e(r,p) = \int_r^{r_{\rm acc}} \frac{Q_i(R_{\rm inj},p_{\rm inj})}{v(R_{\rm inj})}\left(\frac{R_{\rm inj}}{R_{\rm Sch}}\right)^{\frac{5}{2}}\left(\frac{p_{\rm inj}}{p}\right)^4 {\rm d}R_{\rm inj}$$

injection momentum

$$p_{\rm inj}(R_{\rm inj};r,p) = p\left[\frac{k_0 R_{\rm Sch}^{-\frac{1}{2}}}{c} R_{\rm inj}^{\frac{3}{2}} p \left(\frac{r}{R_{\rm inj}} - 1\right) + \left(\frac{R_{\rm inj}}{r}\right)^{\frac{1}{2}}\right]^{-1}$$

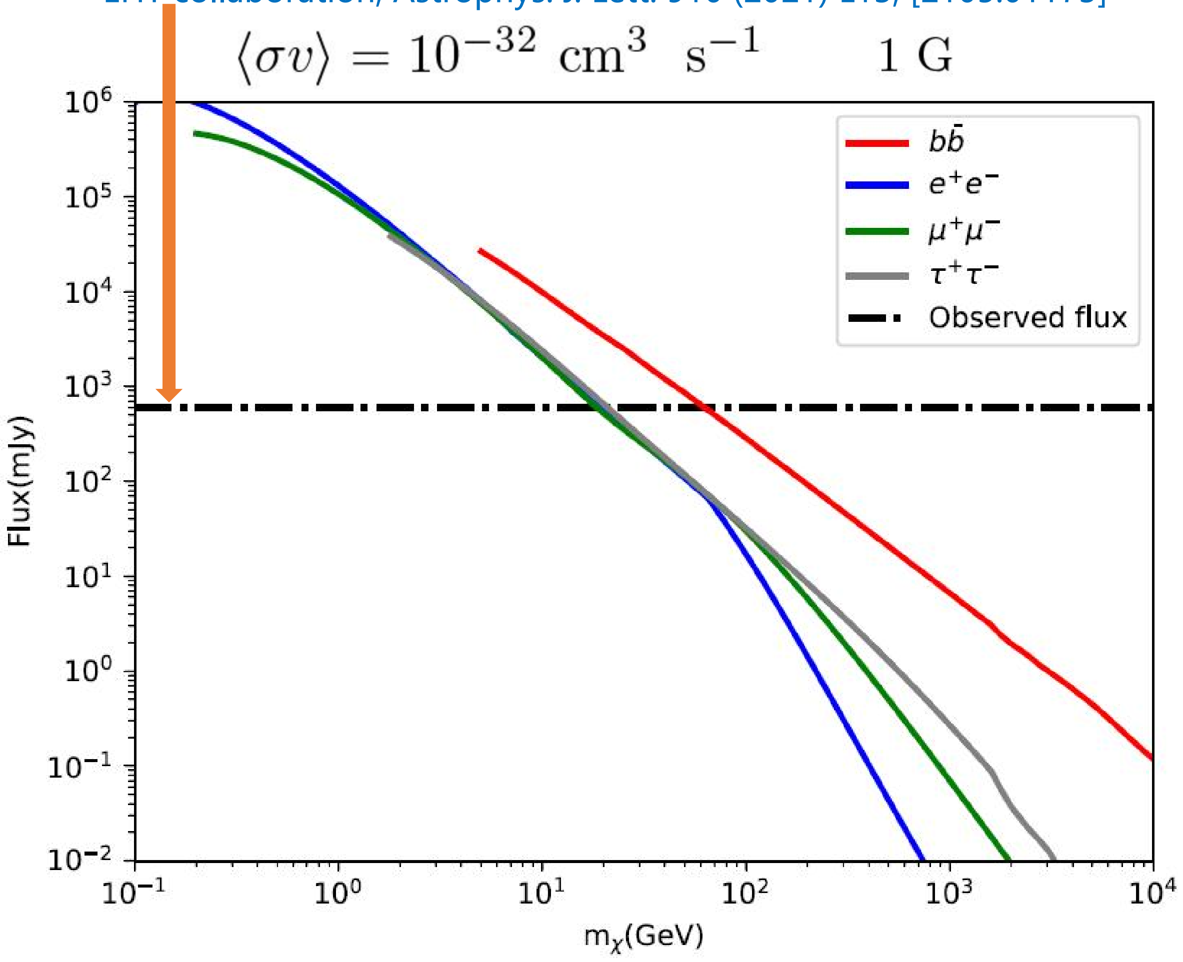
- Spectra of synchrotron emission from DM annihilation

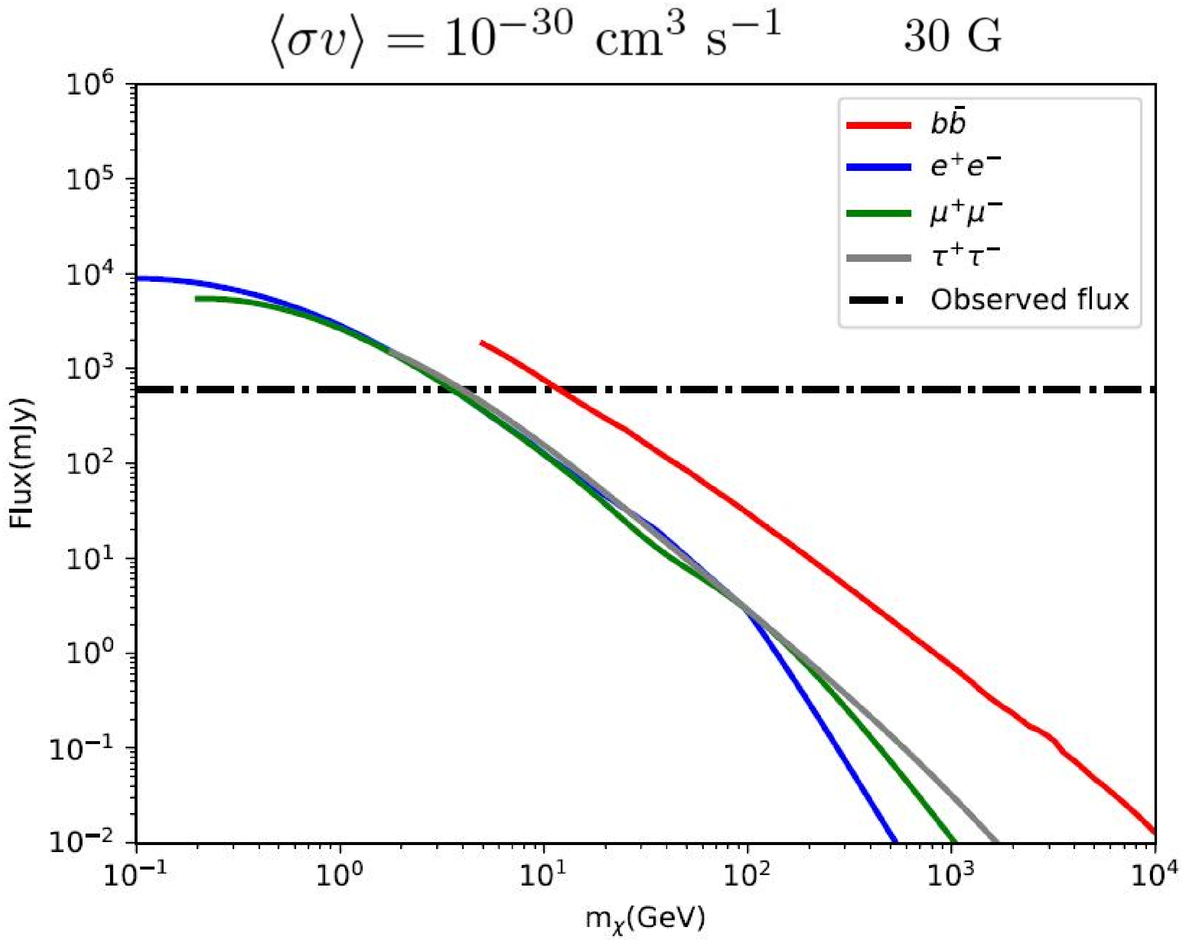


● Bnechmark flux for four annihilation channels

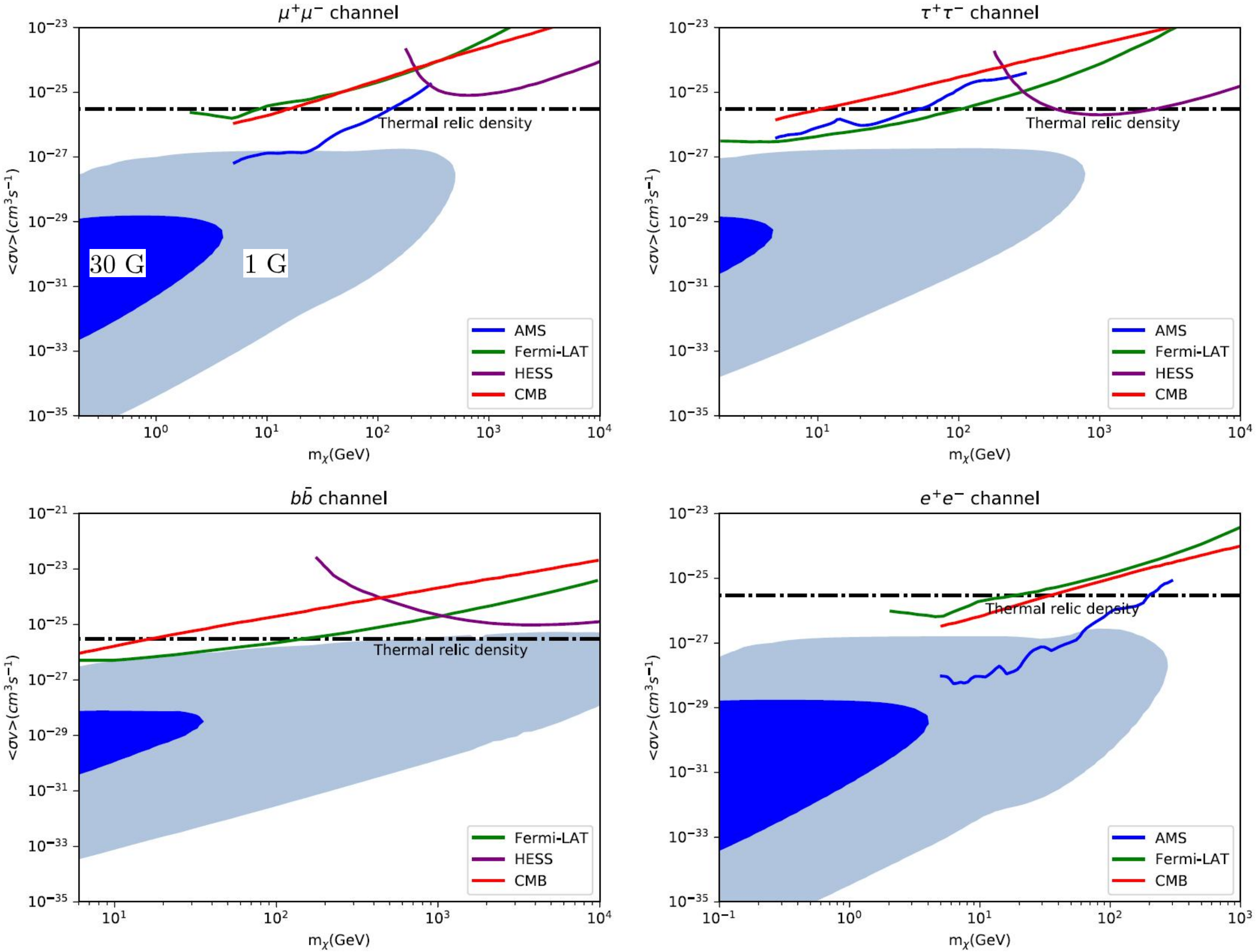
EHT collaboration, Astrophys. J. Lett. 910 (2021) L12,[2105.01169]

EHT collaboration, Astrophys. J. Lett. 910 (2021) L13, [2105.01173]





Limits on WIMP annihilation cross sections



Future work for improvement

Yifan Chen et al. in preparation

- Realistic magnetic field model from GRMHD
- Characteristic electron trajectory configuration captured by the magnetic lines
- GR effect on electron injection momentum
- The effect of the accretion disk

Thanks for your attention