Dark Matter and Primordial Black Hole Constraints from Diffuse Galactic Radio Observations

Ding Ran

In collaboration with Zihong Cheng, Yi Liao, Ningqiang Song, Bin Yue and Chi Tian

DM-nu Focus Week
2025.8.22-8.24

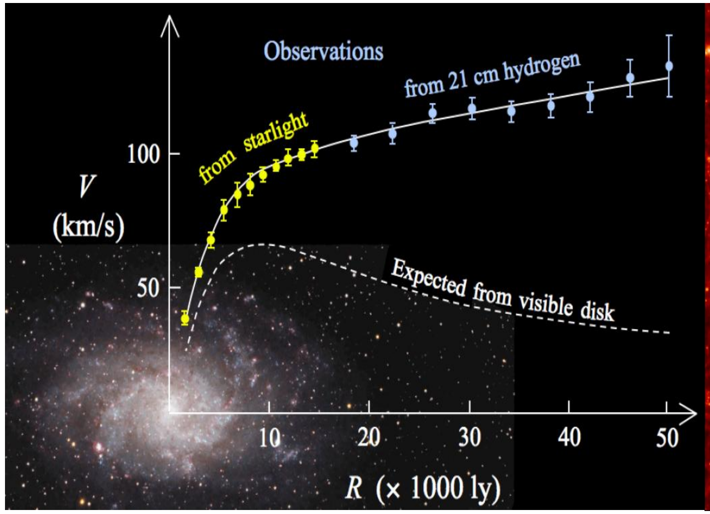
Outline

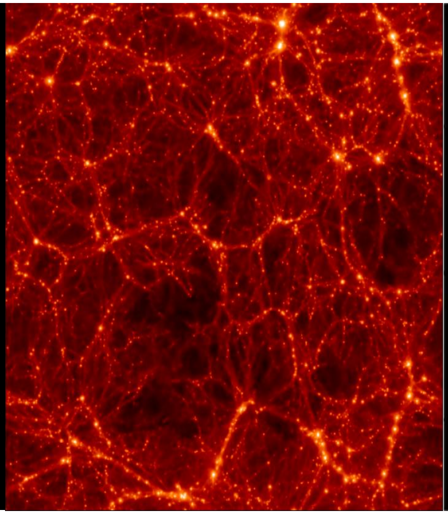
- Introduction
- Dark Matter constraints from diffuse Galactic radio emissions
- PBH constraints from ultra-long wavelength radio observations
- Summary

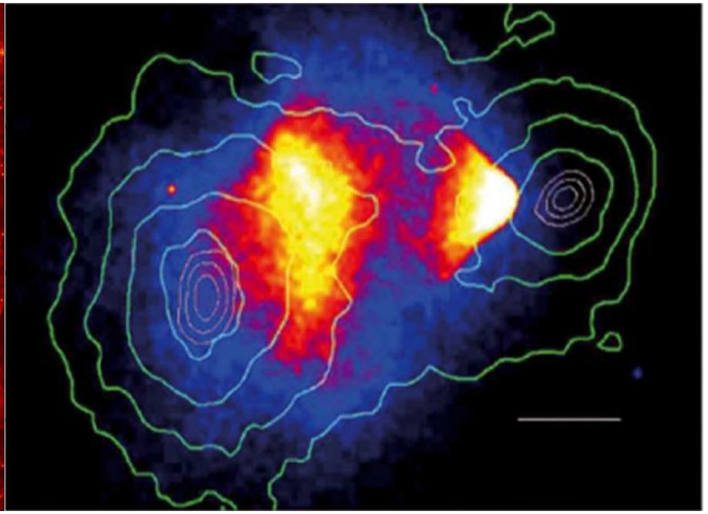
Introduction

Evidences for DM

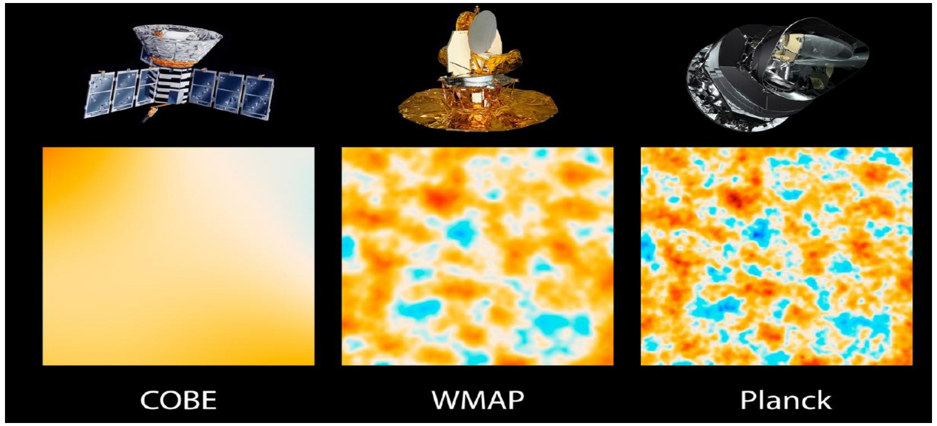
- Rotation curves
- LSS
- Bullet cluster



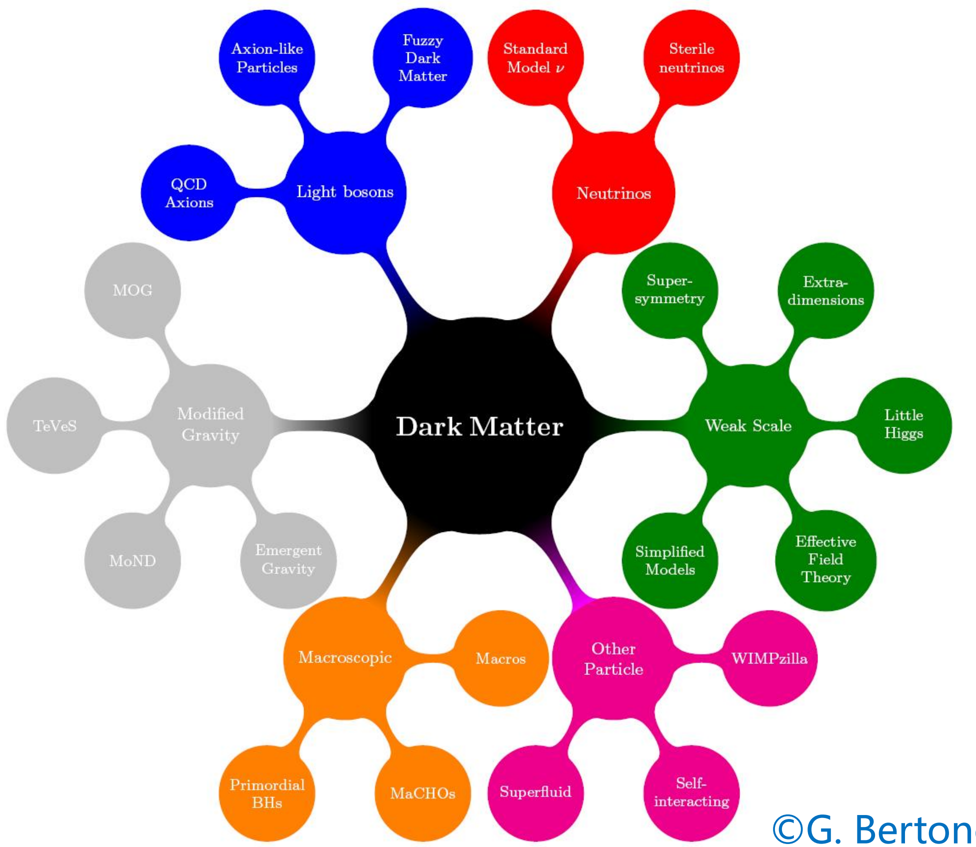




- CMB



● DM candidates



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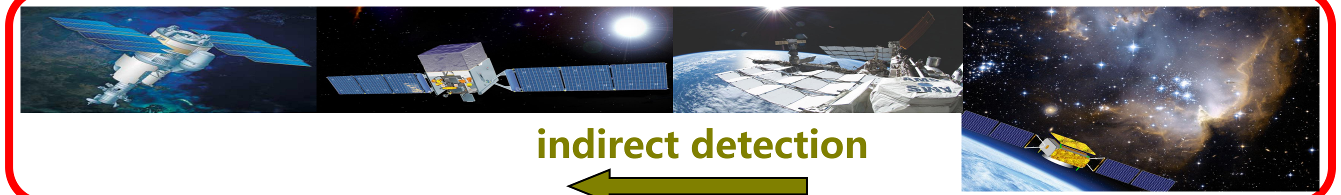
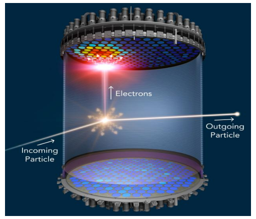
● DM detections

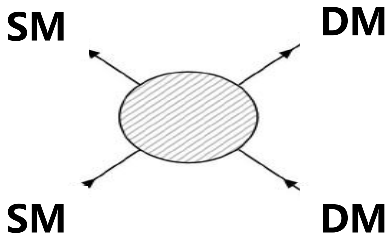
Cosmic-Ray (CR) physics



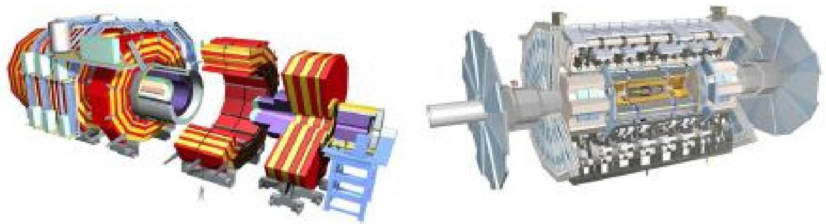
indirect detection

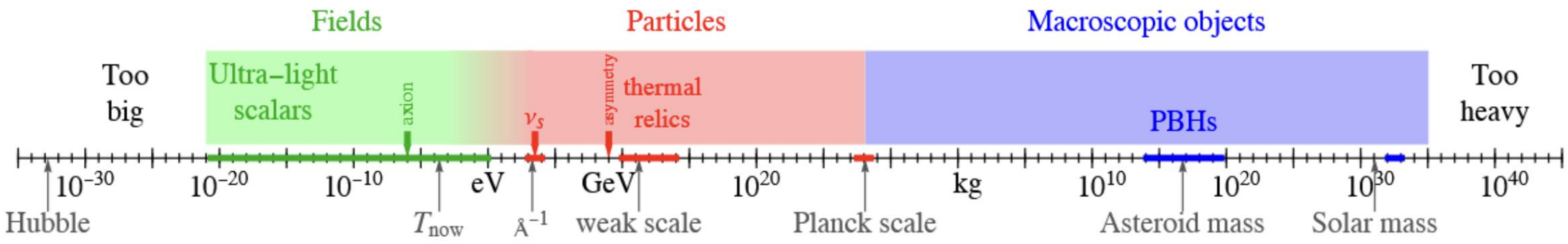
direct detection



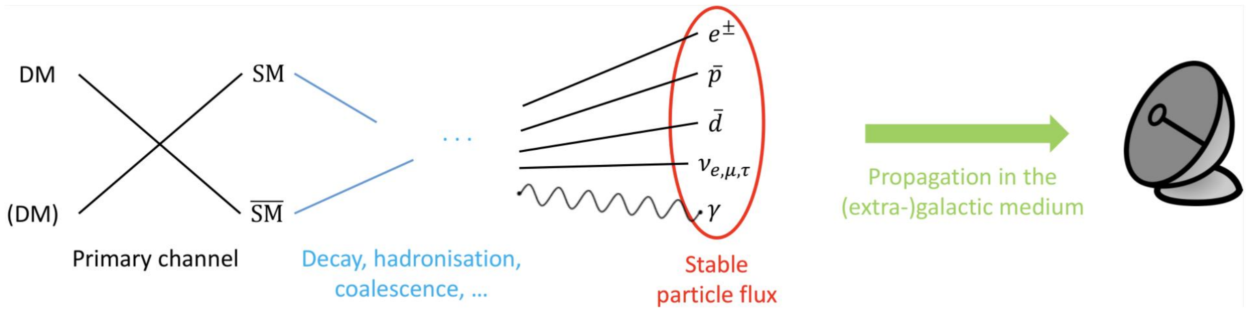


collider detection

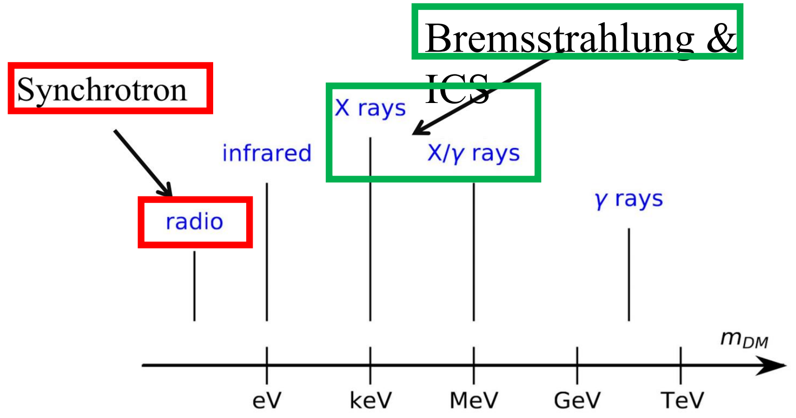


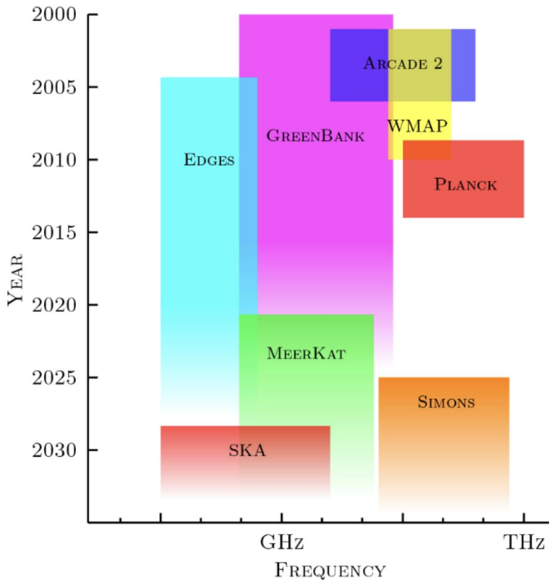


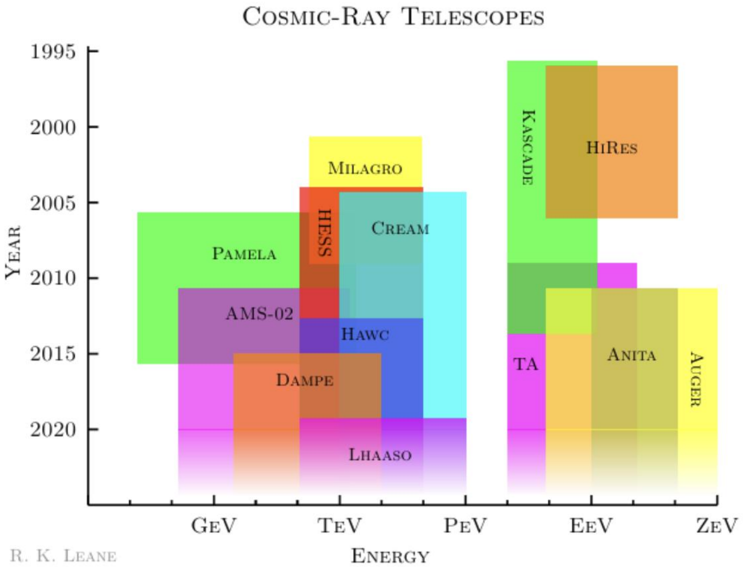
- Indirect detections

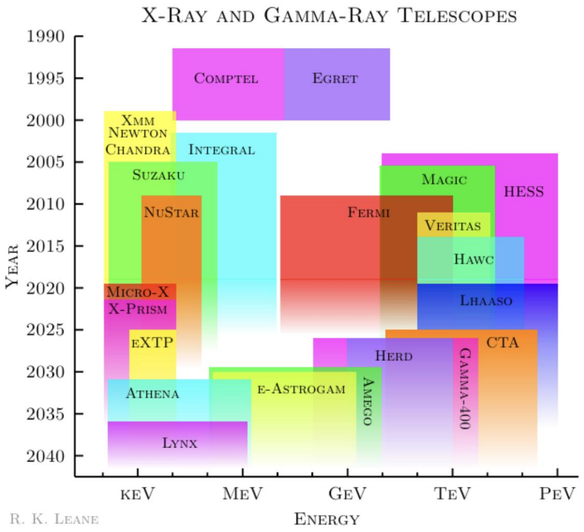


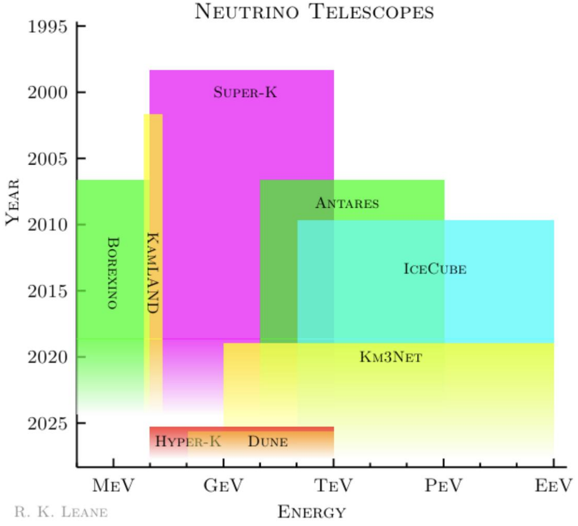
- Multi-frequency observation

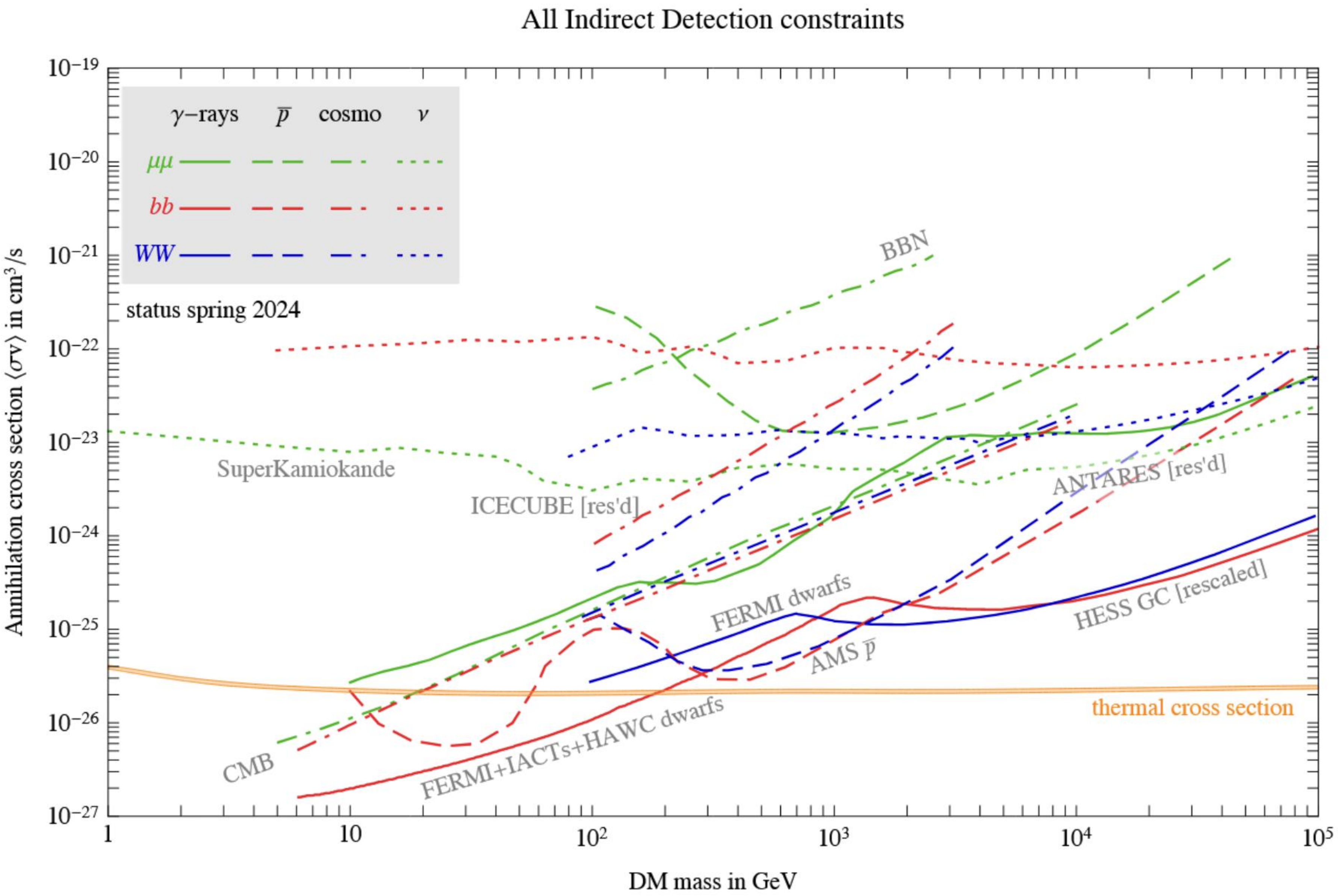








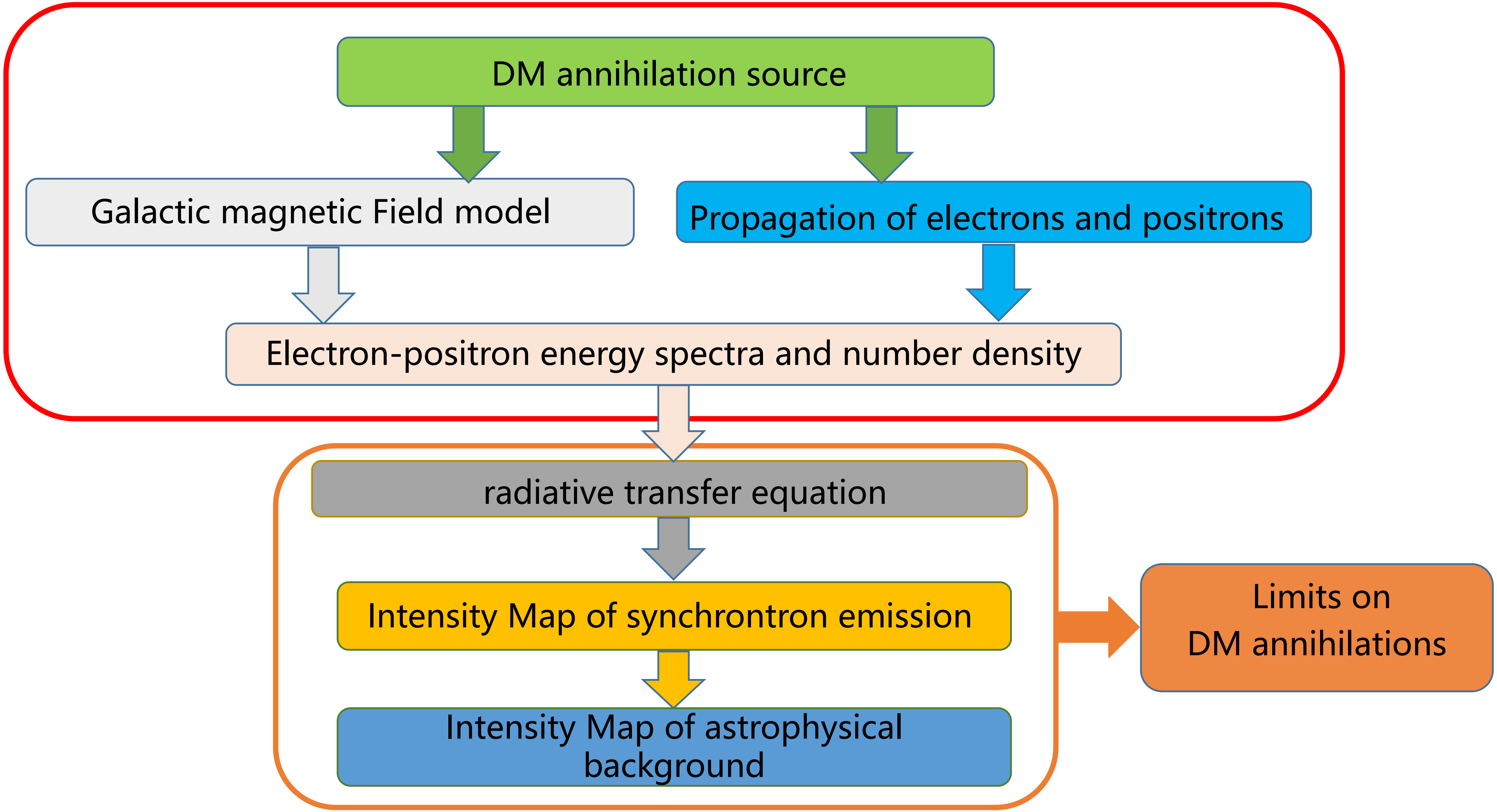




All Indirect Detection constraints
γ−rays
p̄
cosmo
ν
μμ
bb
WW
status spring 2024
BBN
SuperKamiokande
ICECUBE [res'd]
ANTARES [res'd]
FERMI dwarfs
HESS GC [rescaled]
AMS p̄
thermal cross section
CMB
FERMI+IACTs+HAWC dwarfs
Annihilation cross section ⟨σv⟩ in cm³/s
DM mass in GeV

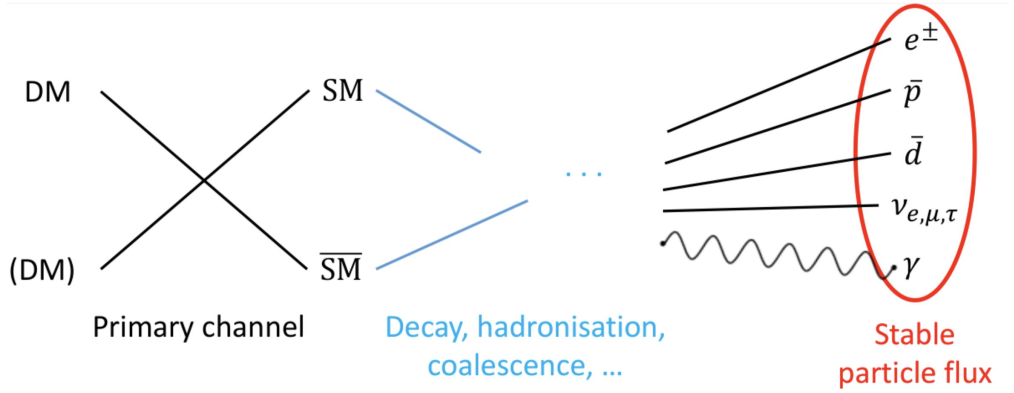
Dark Matter Constraints from Diffuse Galactic Radio emission

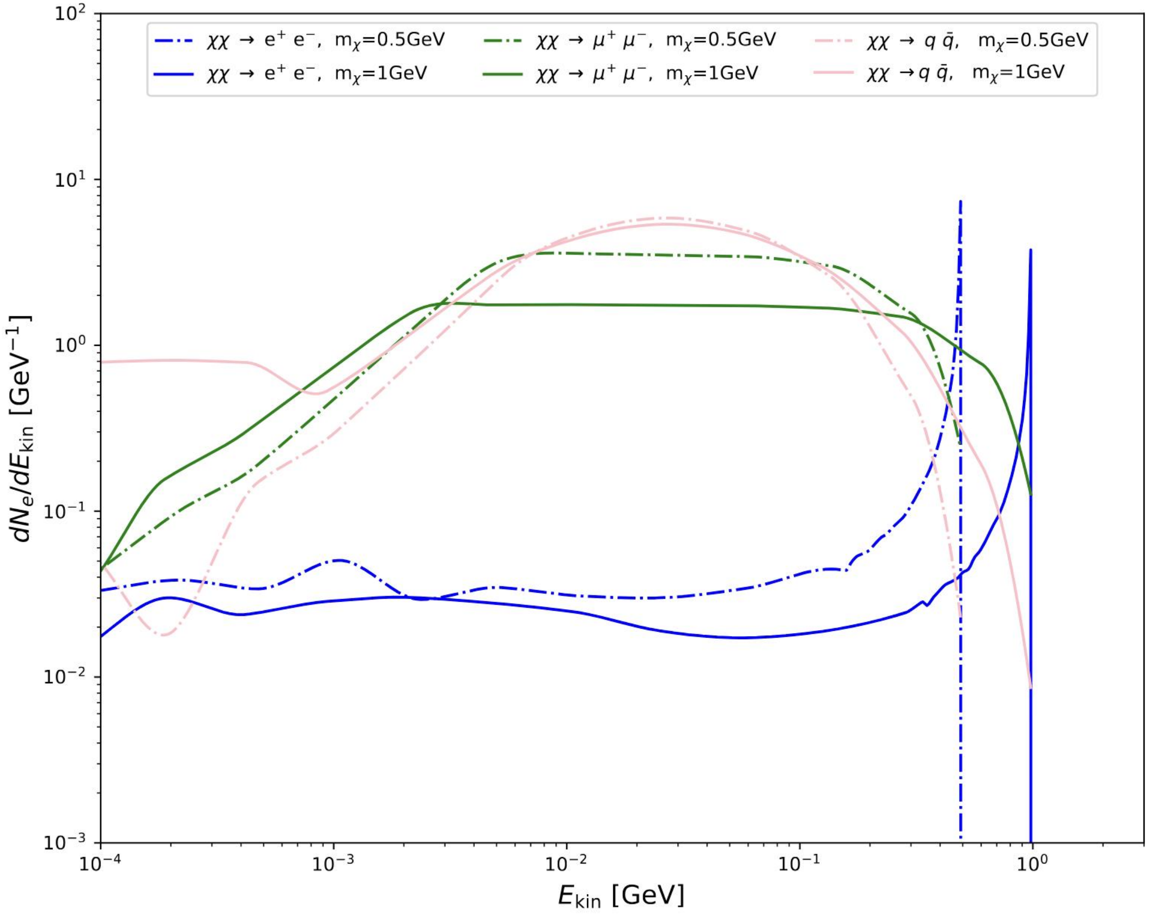
- Synchrotron emission resulted from DM annihilation in Galactic halo



- Electron-positron energy spectra due to DM annihilation

$$q(\vec{r},p) = \frac{1}{4\pi p^2}\frac{\langle\sigma v\rangle\,\rho^2(\vec{r})}{2m_{\rm DM}^2}\sum_i {\rm BR}_i \boxed{\frac{{\rm d}N^{\rm inj}_{e^\pm,i}}{{\rm d}p}(p)}$$

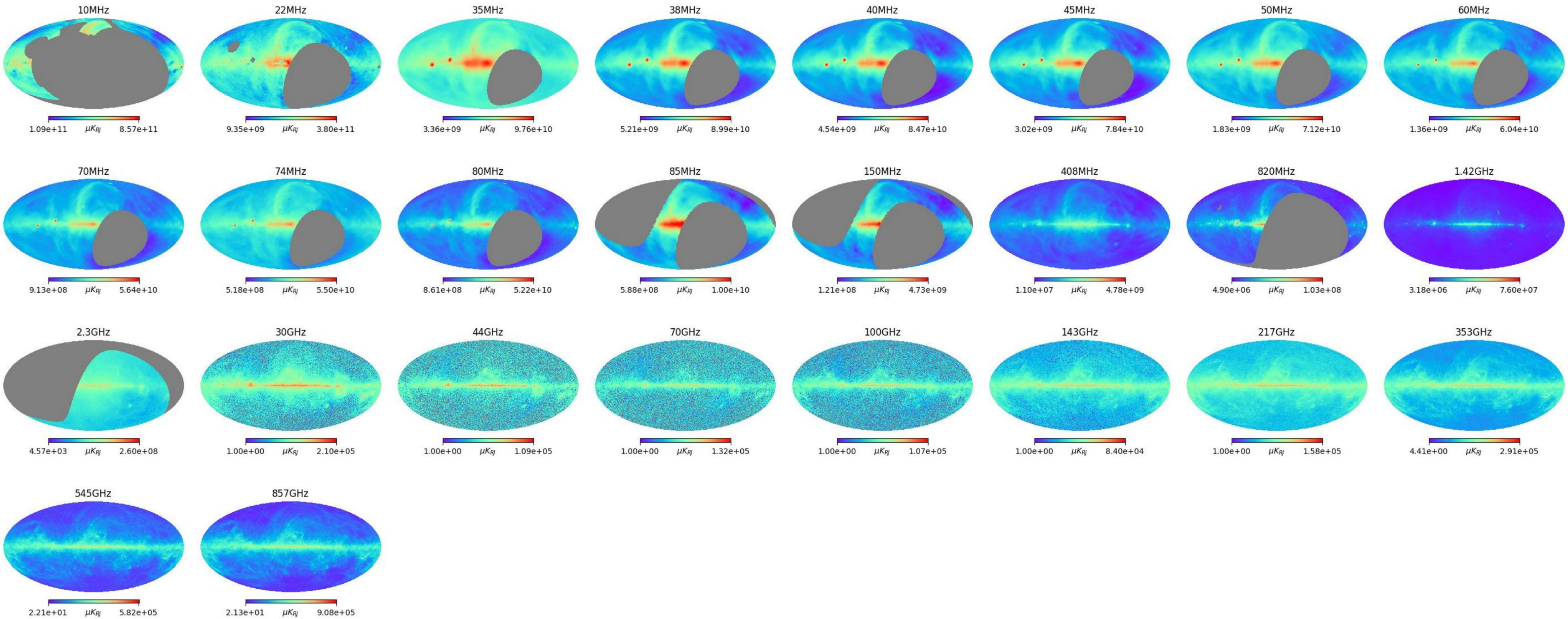




● Galactic rdaio and microwave surveys：10 MHz to 857 GHz

Project/Instrument	ν(GHz)	**Sky coverage**	**Resolution**	**References**
DRAO	0.01	28%	$2.6^\circ \times 1.9^\circ$	Caswell [25]
	0.022	73%	$1.2^\circ \times 1.5^\circ$	Roger et al. [26]
LWA1	0.035 0.038 0.040 0.045 0.050 0.060 0.070 0.074 0.080	82%	$2.0^\circ \sim 4.7^\circ$	Dowell et al. [27]
Parkes	0.085	43%	3.5°	Landecker & Wielebinski [28]
	0.150	43%	2.2°	Landecker & Wielebinski [28]
GER, AUS, ENG	0.408	100%	$56'$	Haslam et al. [29, 30], Remazeilles et al. [31]
Dwingeloo, NLD	0.82	57%	1.2°	Berkhuijsen[32]
Stokert, Villa Elisa	1.42	100%	$36'$	Reich [33], Reich & Reich [34], Reich et al. [35, 36]
S-PASS	2.3	49%	$8.9'$	Carretti et al. [37]
Planck	30 44 70 100 143 217 353 545 857	100%	$32'$ $24'$ $14'$ $10'$ $7'$ $5'$ $5'$ $5'$ $5'$	Planck Collaboration I [38]

- Sky Maps from the Milk Way rdaio and microwave surveys：10 MHz to 857 GHz



- Modeling diffuse Galactic radio emission

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

galprop_v57 PLANCK template model

T.A. Porter, G. Johannesson and I.V. Moskalenko, [2112.12745] 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

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

- 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

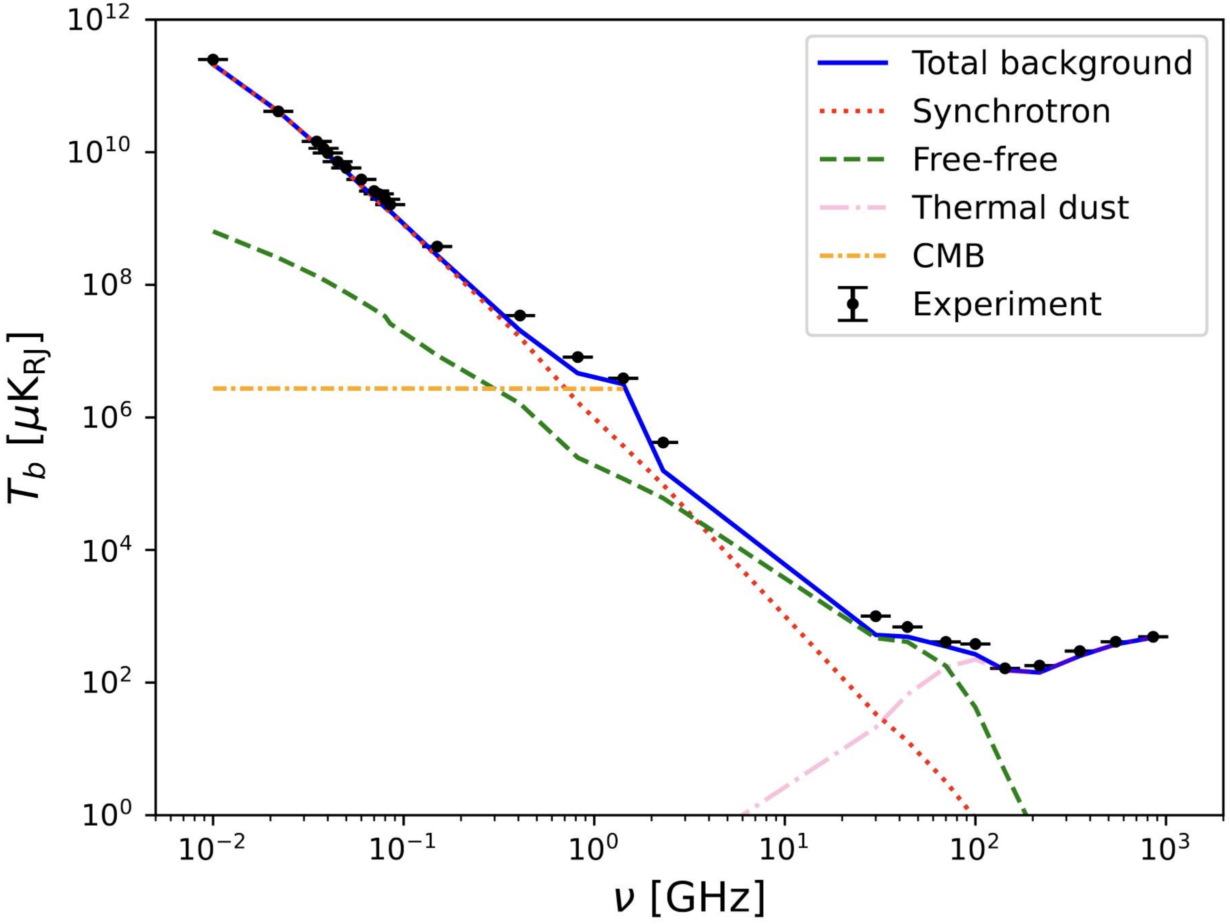
- Galactic Magnetic Field (GMF) model
  - regular component: Psh+11 model
  - random component: Sun model

- Likelihood function

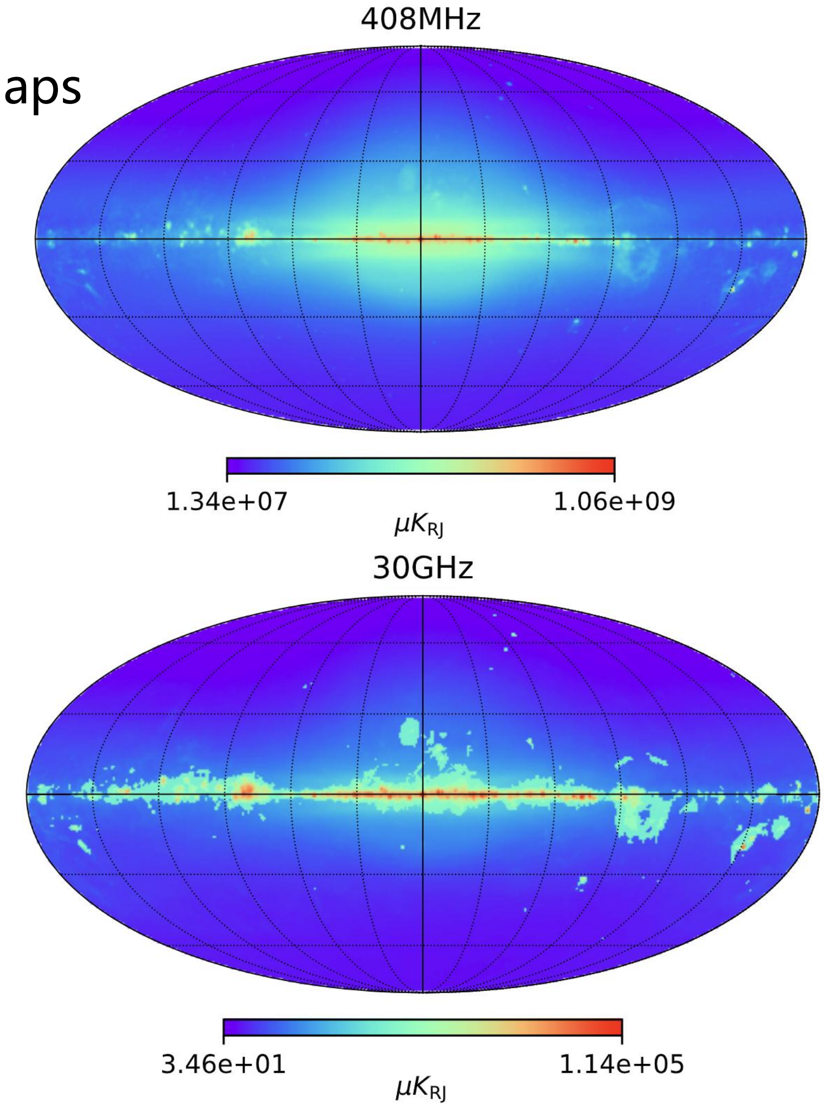
$$L \propto \exp\left\{-\sum_i \frac{(T_i^{\rm model} - T_i^{\rm map})^2}{2{\sigma_i}^2}\right\}$$

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

- Total intensity



- Sky maps



- Intensity from DM annihilation

Propagation equation: $$\boxed{\frac{\partial \psi(\vec{r},p,t)}{\partial t}} = \underbrace{\boxed{q(\vec{r},p,t)}}_{\text{source}} + \underbrace{\boxed{\vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi)}}_{\text{spatial diffusion and convection}} + \underbrace{\boxed{\frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi}}_{\text{reacceleration}} - \underbrace{\boxed{\frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right]}}_{\text{energy loss}}$$

DM injection

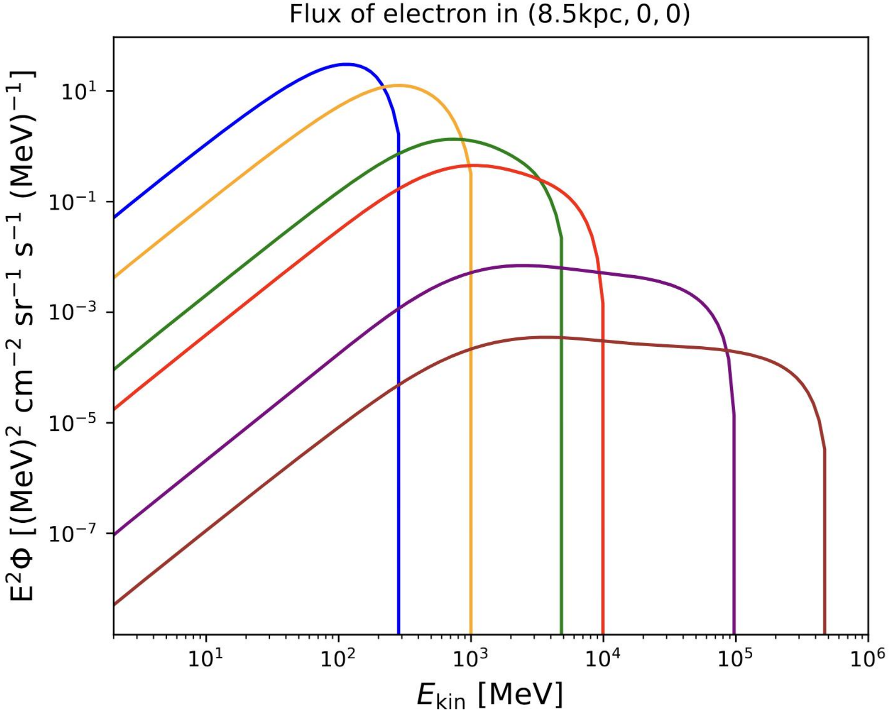
Radiative transfer equation: $$\frac{dI_{\rm syn}(\nu,s)}{ds} = -\underbrace{\boxed{\alpha(\nu,s)}}_{\text{free-free absorption}} I_{\rm syn}(\nu,s) + \frac{j_{\rm syn}(\nu,s)}{4\pi}$$

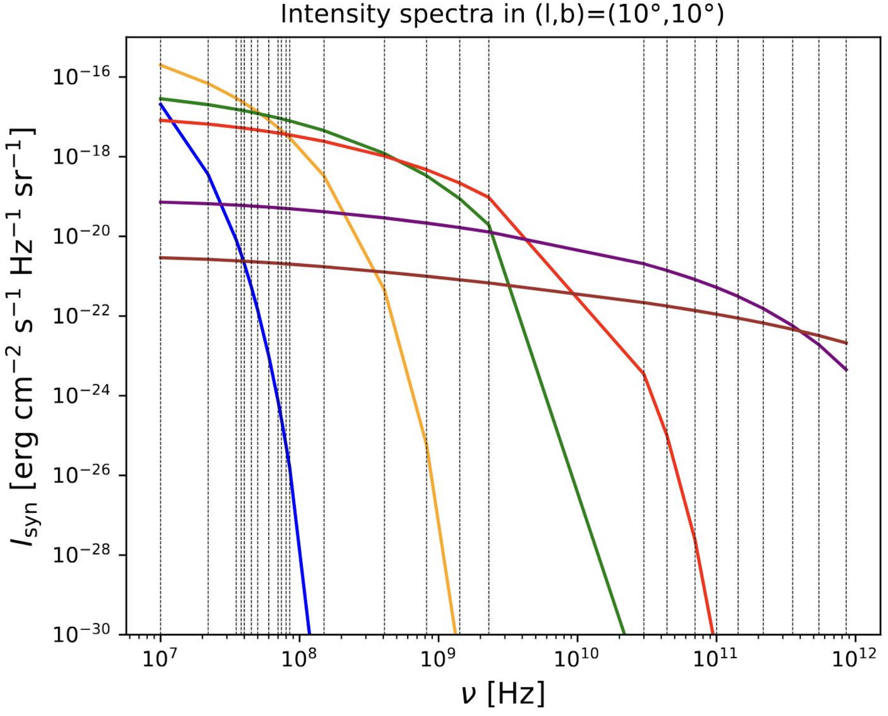
$$j_{\rm syn}(\boldsymbol{r},\nu) = \frac{4\pi}{c}\int {\rm d}E\,\Phi_e(\boldsymbol{r},E)\,\mathcal{P}(\boldsymbol{r},E,\nu)$$

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

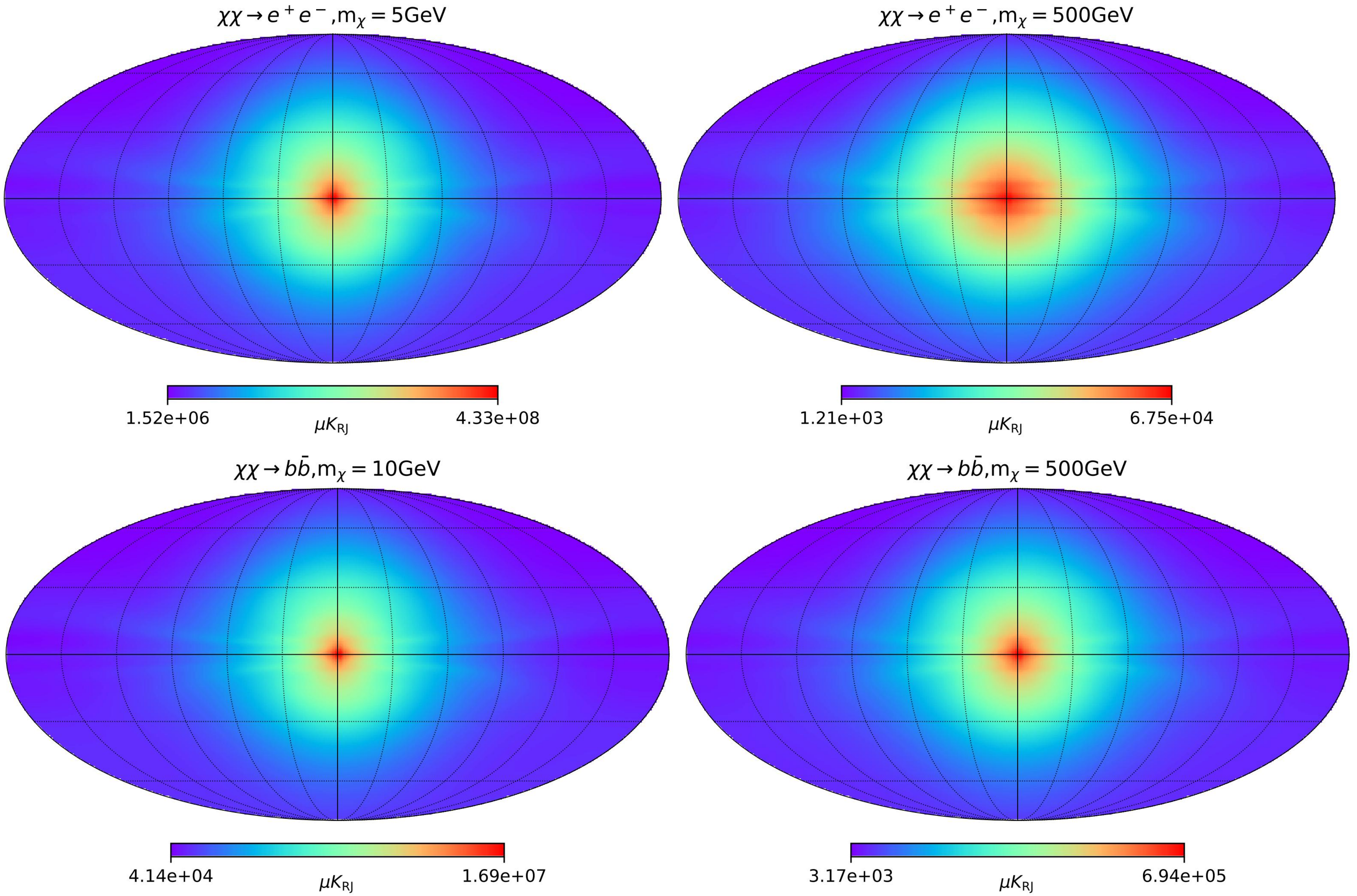
$$\langle\sigma v\rangle = 3\times10^{-26}{\rm cm}^3/{\rm s}$$

$$\chi\chi\to\mu^+\mu^-$$

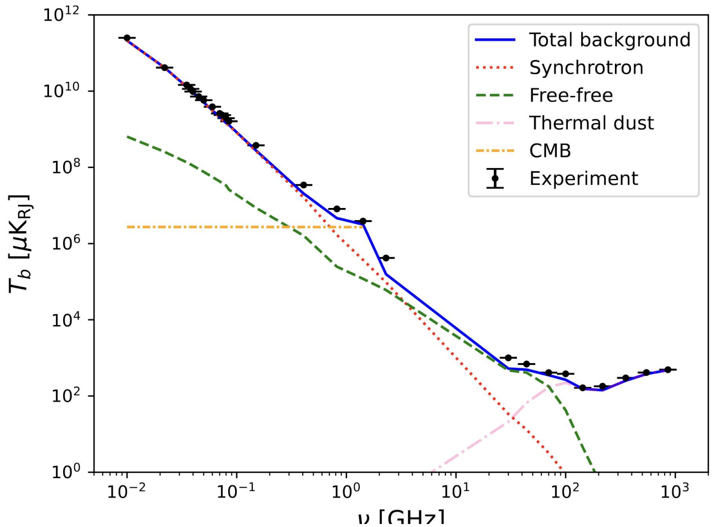




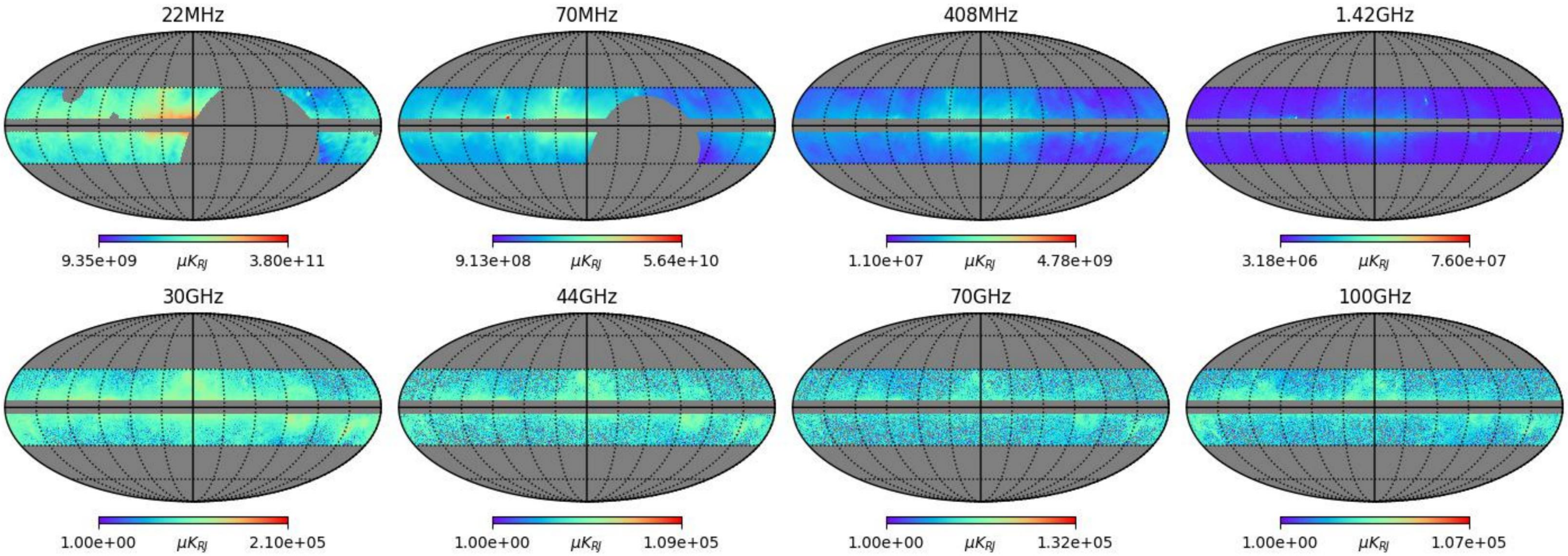
• Intensity skymap from DM annihilation at 408 MHz



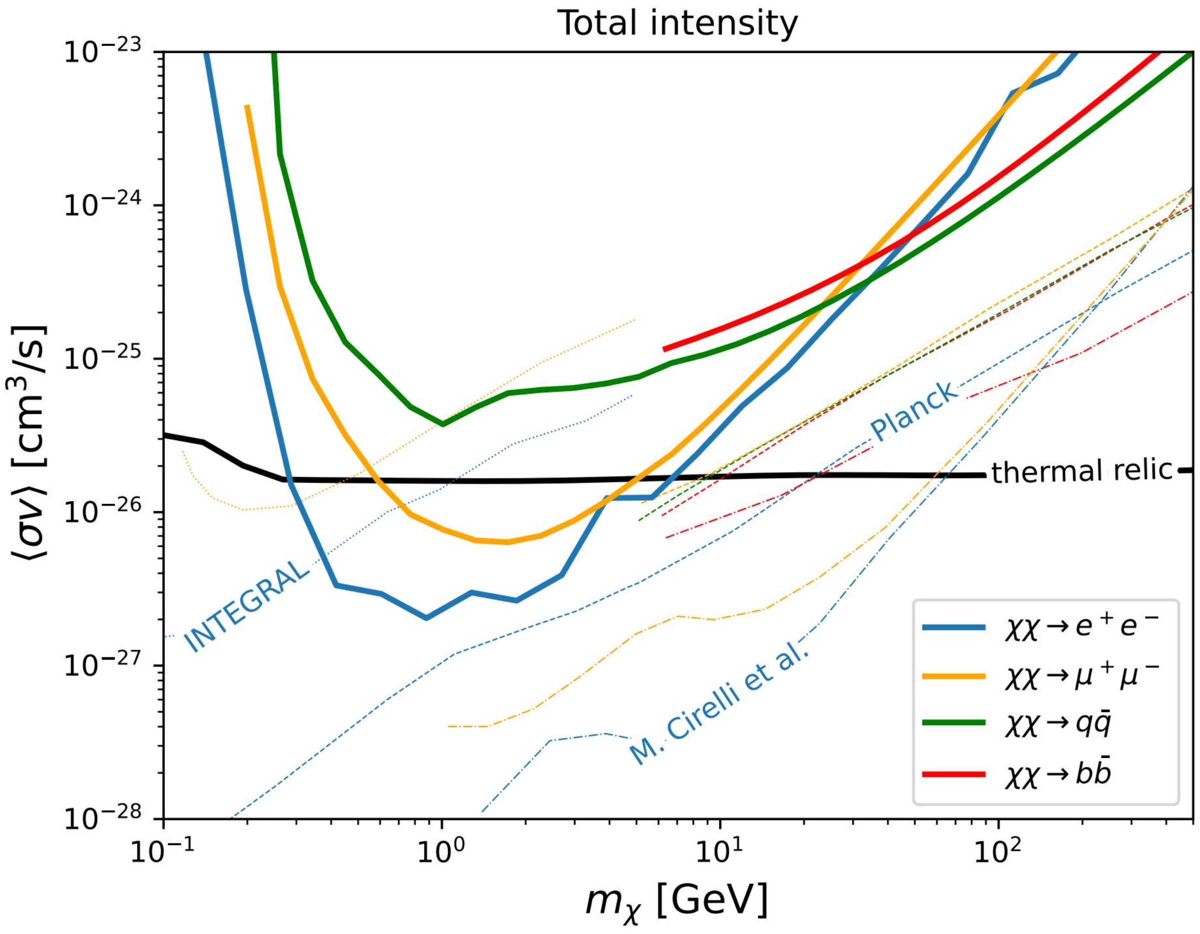
- Constraints from the total intensity



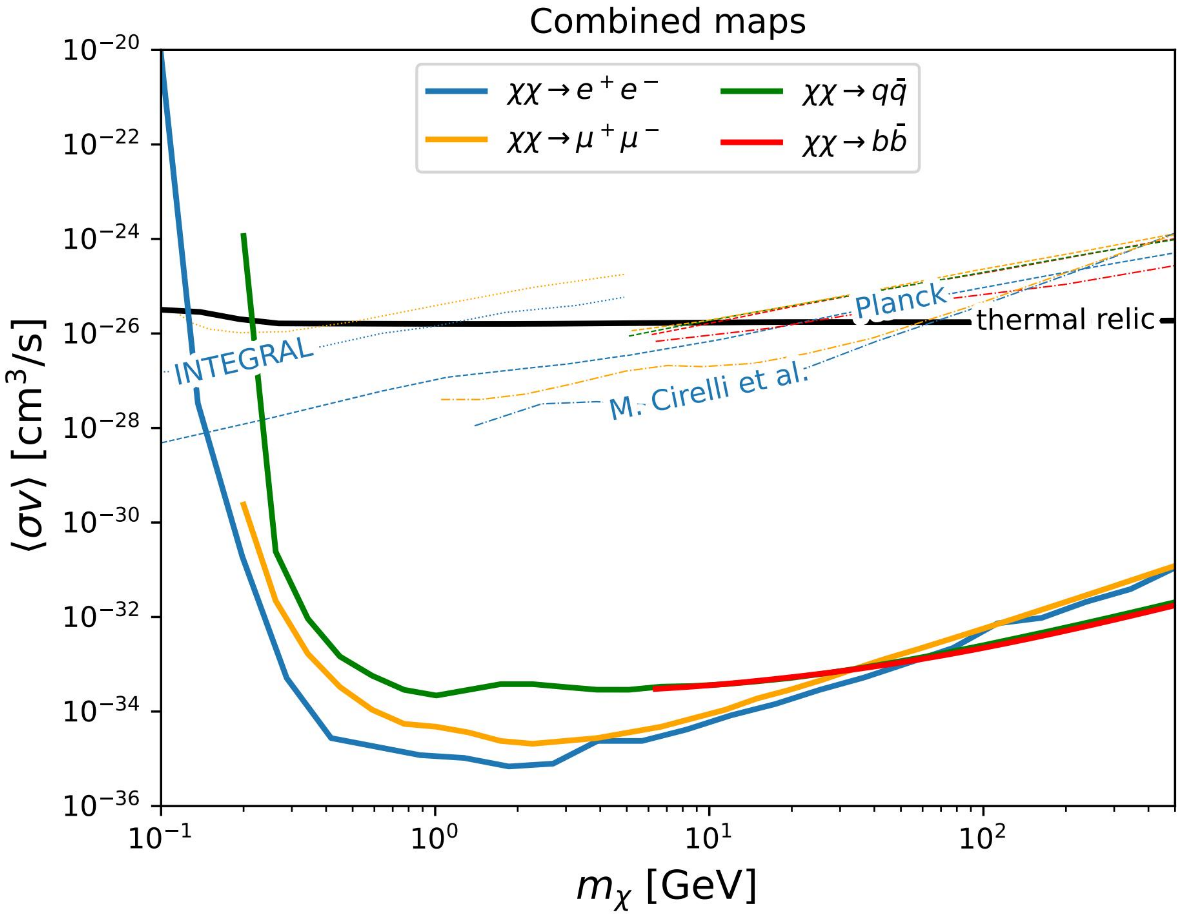
- Constraints from combined sky maps



- Constraints from the total intensity



- Constraints from combined sky maps

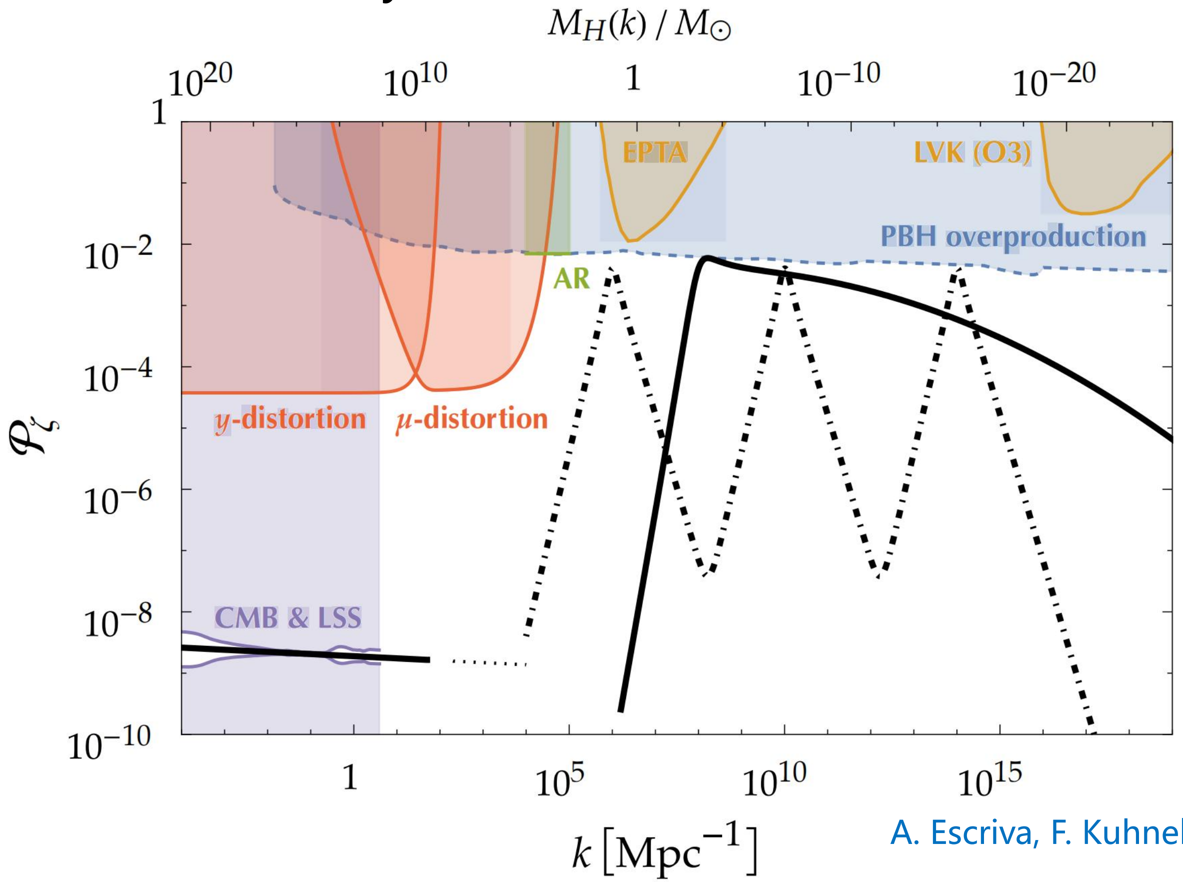


Limits on Primordial Black Hole with MHz radio observations

PBH as a DM candidate

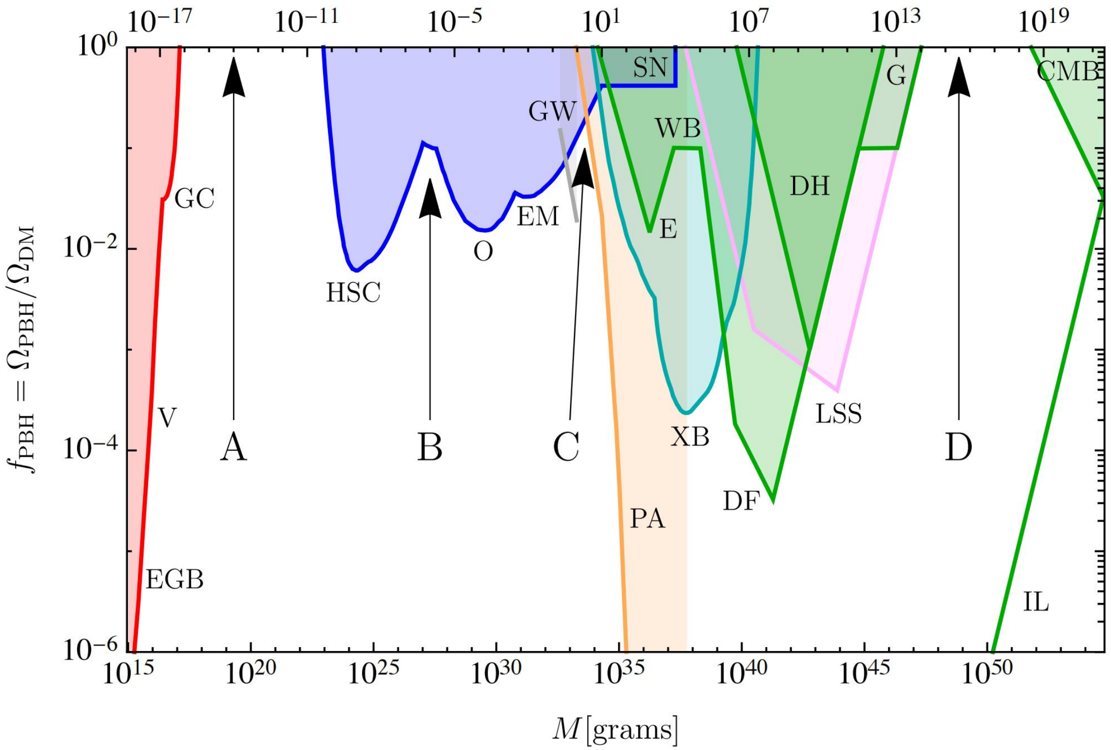
- Production mechanism of PBH

Large curvature perturbations generated at small scale in the early Universe



- 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

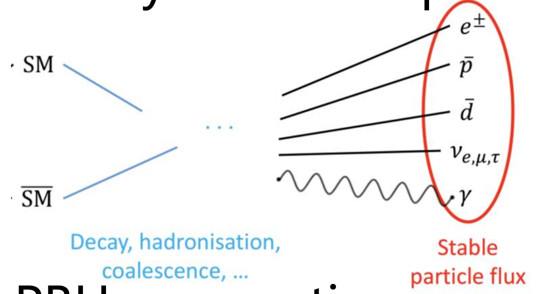
- Temperature

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

- Primary emission spectrum

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

Secondary emission spectrum



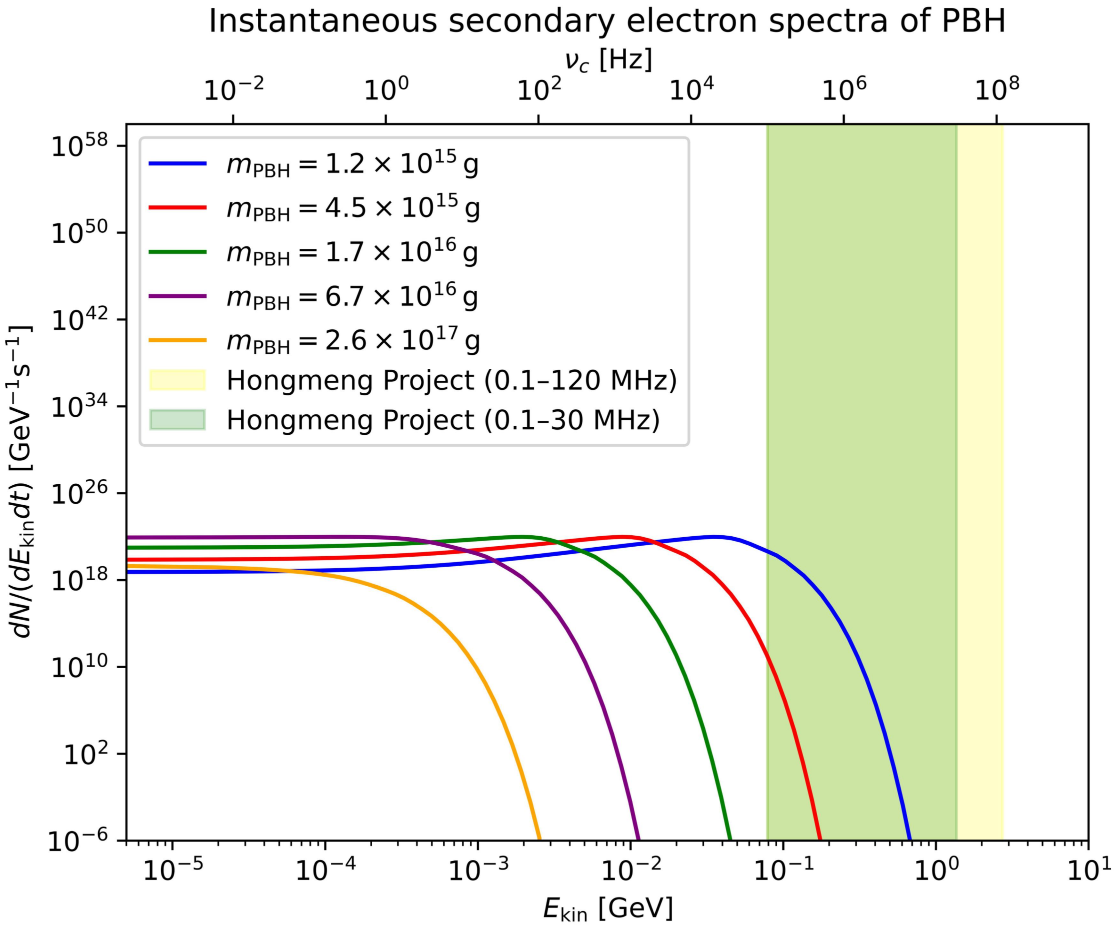
BlackHawk

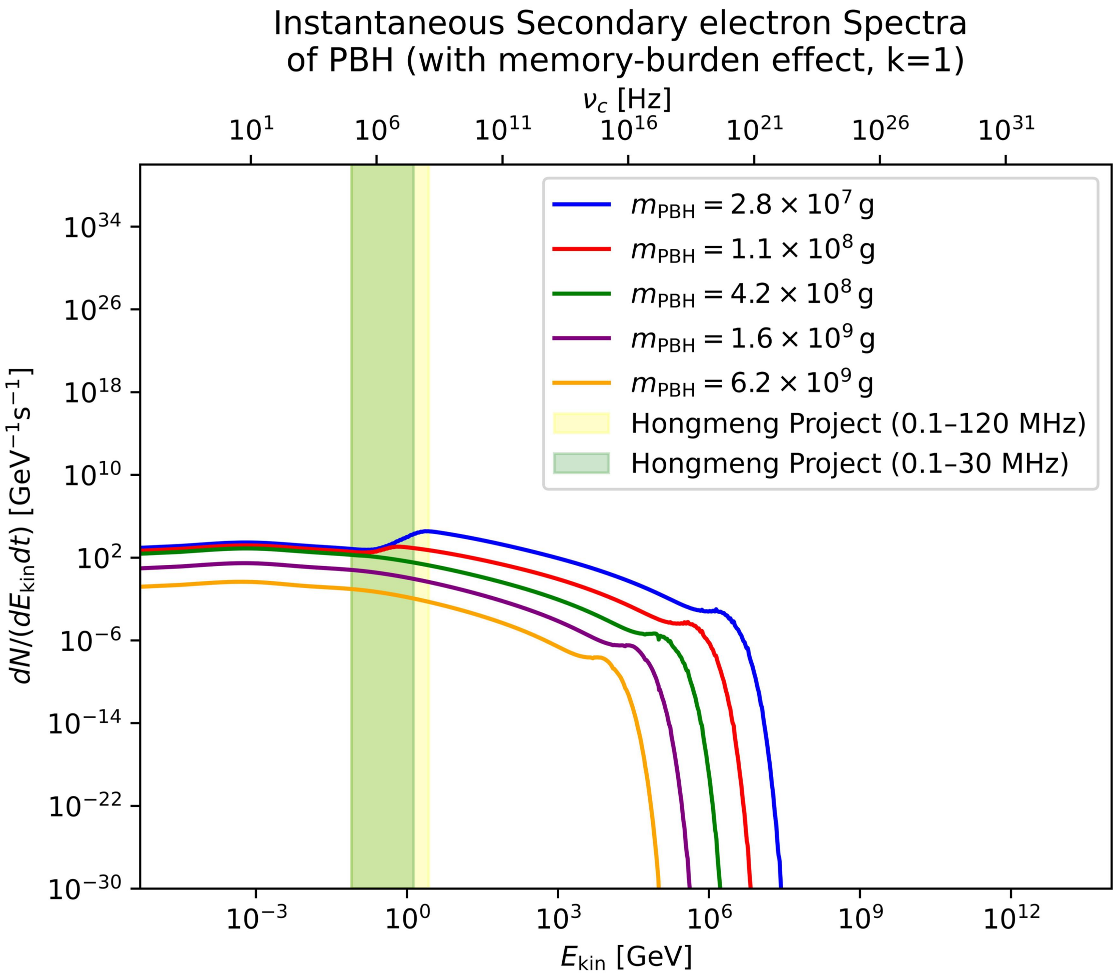
- Number of electron-positron injected by PBH evaporation

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

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

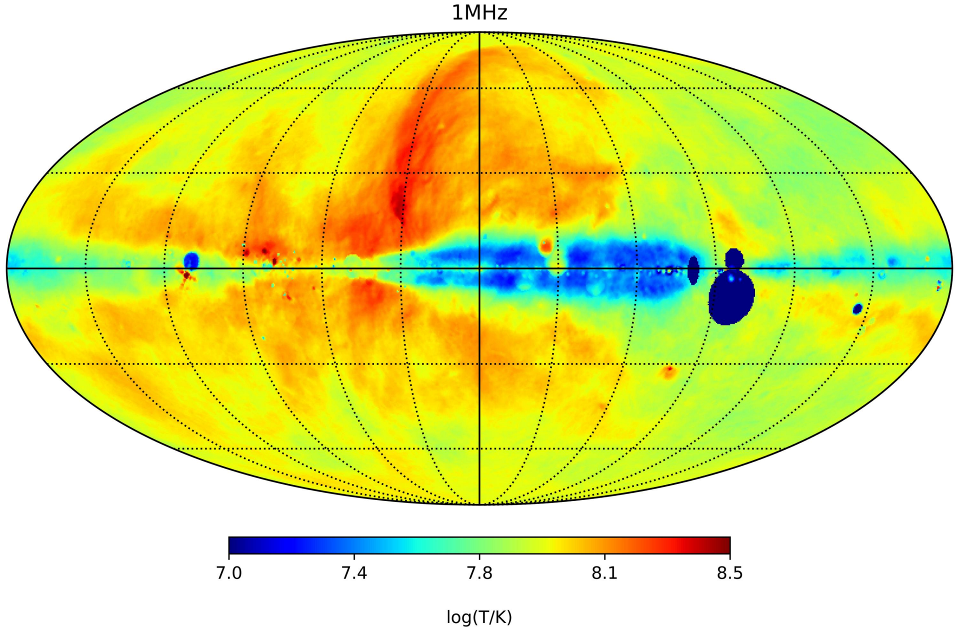
PBH energy spectra

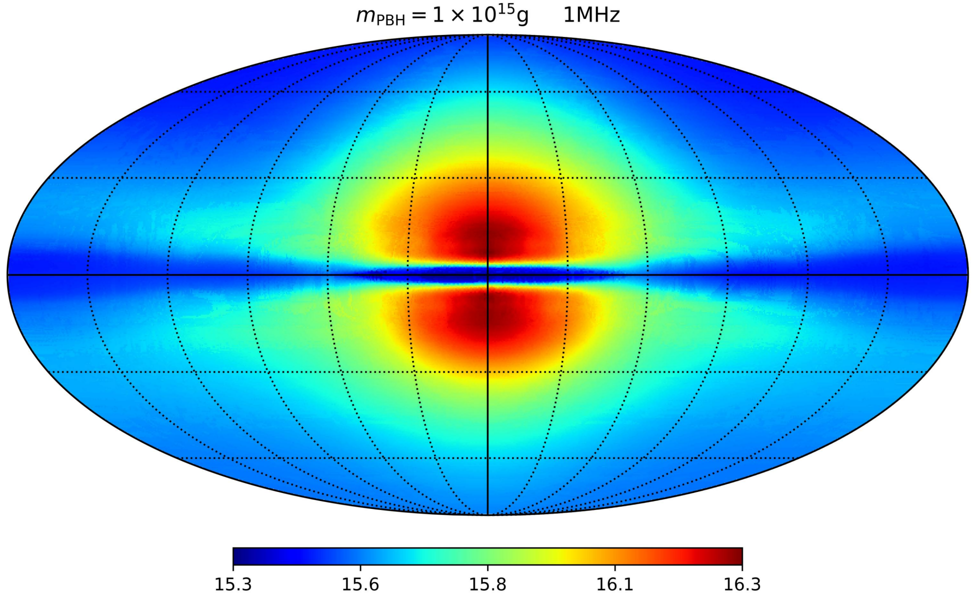


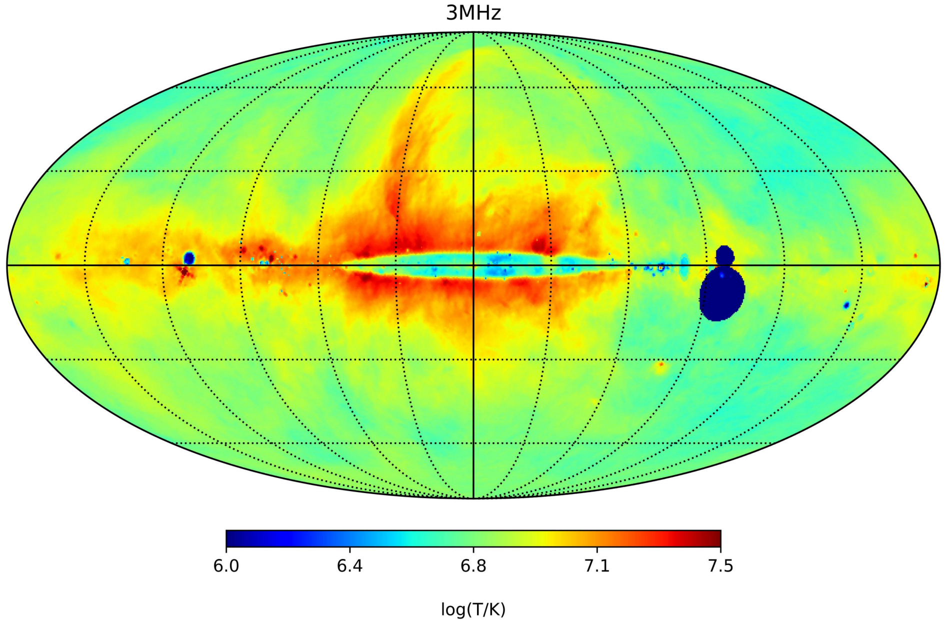


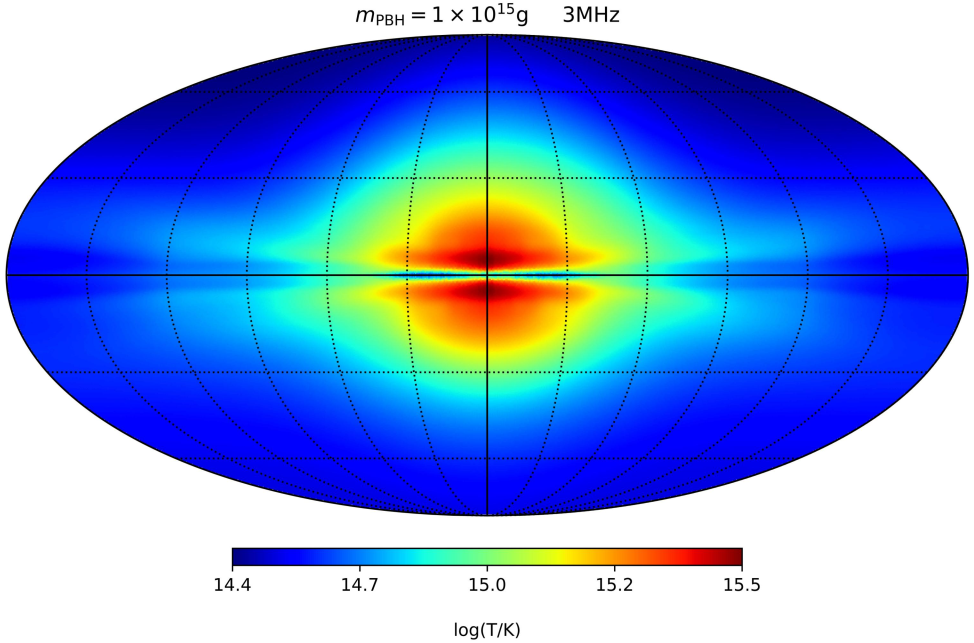
$$\nu_c = \frac{3e}{4\pi m_e c} B \gamma_e^2 \simeq (16\text{MHz}) \left(\frac{B}{\mu\text{G}}\right) \left(\frac{E_e}{\text{GeV}}\right)^2$$

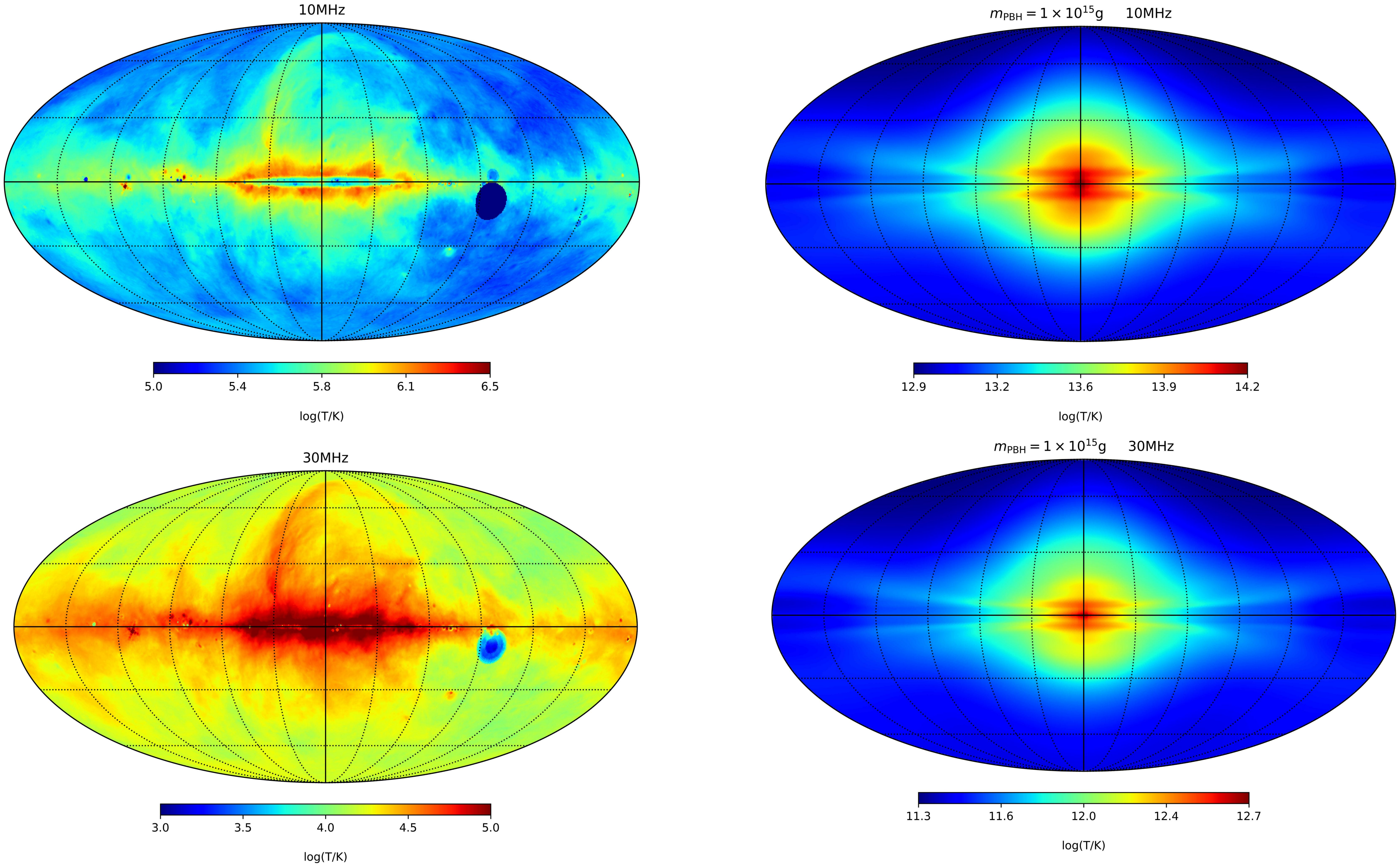
Preliminary results

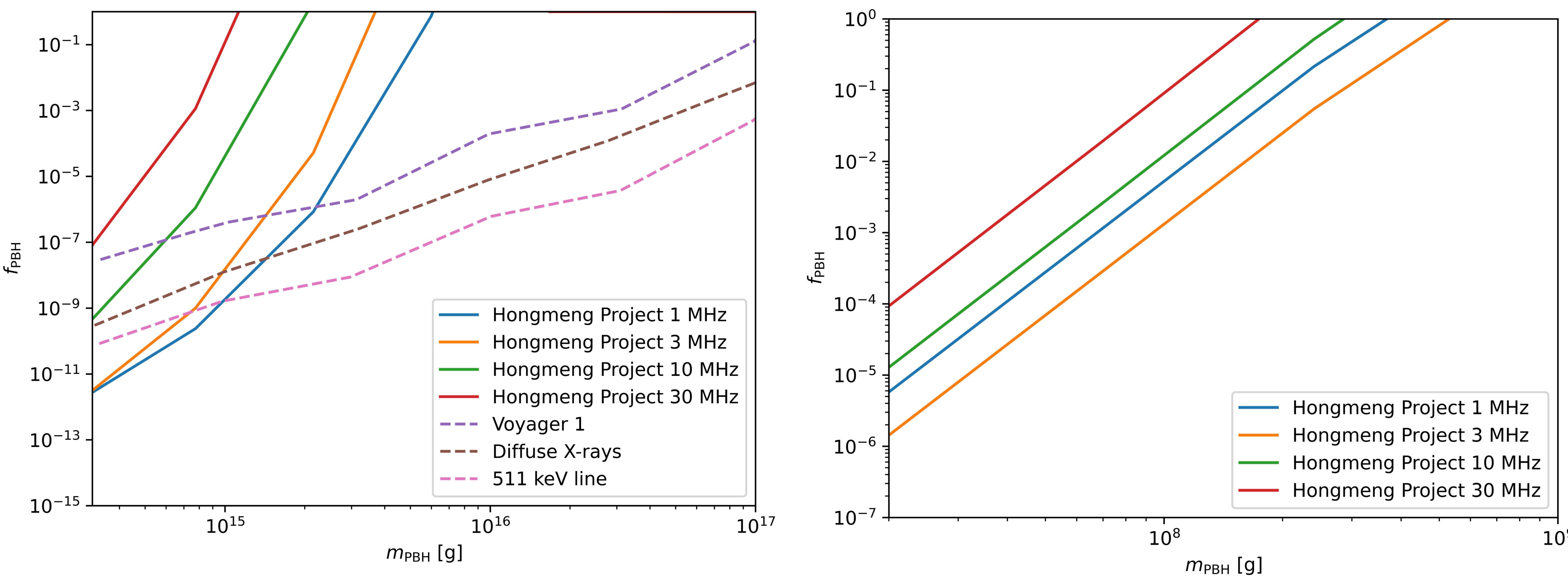









10MHz
5.0
5.4
5.8
6.1
6.5
log(T/K)
$m_{\rm PBH} = 1 \times 10^{15}$g 10MHz
12.9
13.2
13.6
13.9
14.2
log(T/K)
30MHz
3.0
3.5
4.0
4.5
5.0
log(T/K)
$m_{\rm PBH} = 1 \times 10^{15}$g 30MHz
11.3
11.6
12.0
12.4
12.7
log(T/K)



$f_{\rm PBH}$
$m_{\rm PBH}$ [g]
Hongmeng Project 1 MHz
Hongmeng Project 3 MHz
Hongmeng Project 10 MHz
Hongmeng Project 30 MHz
Voyager 1
Diffuse X-rays
511 keV line
$f_{\rm PBH}$
$m_{\rm PBH}$ [g]
Hongmeng Project 1 MHz
Hongmeng Project 3 MHz
Hongmeng Project 10 MHz
Hongmeng Project 30 MHz

Summary

- We present the sophisticated calculation of synchrotron emission resulting from DM annihilation within the Galactic halo, which can be strongly constrained by the rdaio and microwave surveys of the Mike Way.

- For Mike Way rdaio constraints, we impose constraints for both total intensity and morphology of individual sky maps, by using galprop cosmic-ray propagation code, coupled with a best-fit foreground model. This approach substantially refined the existing limits.

Thanks for your attention