IMPACT OF SPACE PLASMA INSTABILITIES ON TEV ASTROPHYSICS AND LIGHT DARK MATTER

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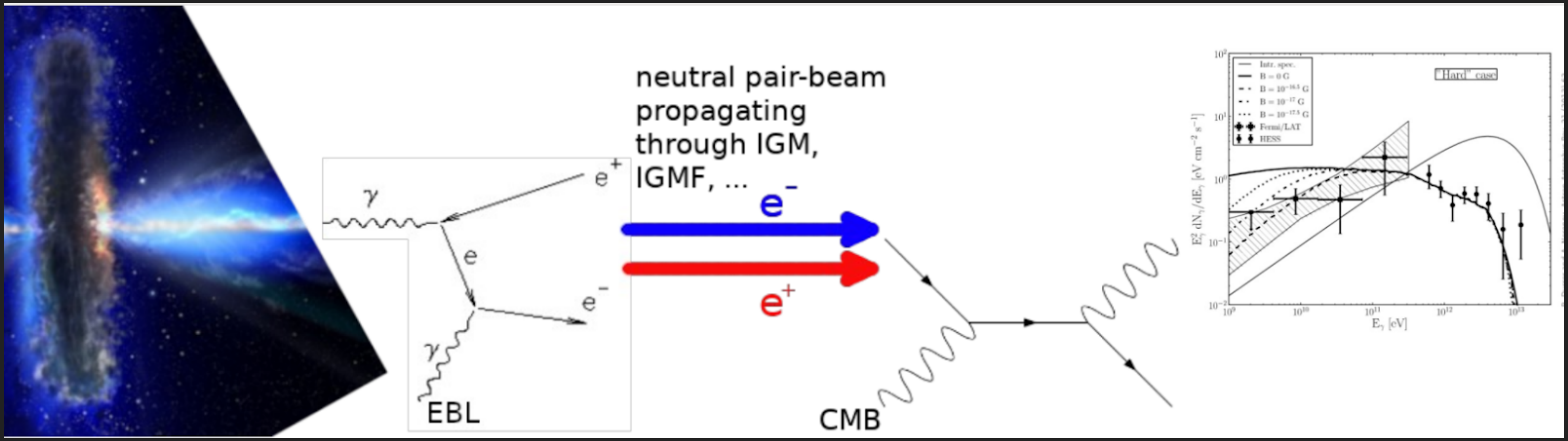
TEV BLAZARS AND SECONDARY GAMMA-RAYS



MISSING CASCADES FROM TEV BLAZARS

- TeV emissions from blazars should be reprocessed into the GeV band through inverse-Compton cooling
- Expected GeV cascade emission suppressed in the 100 GeV-1 TeV band
- Tension seems to be a universal trend in blazars observed with γ-ray telescopes

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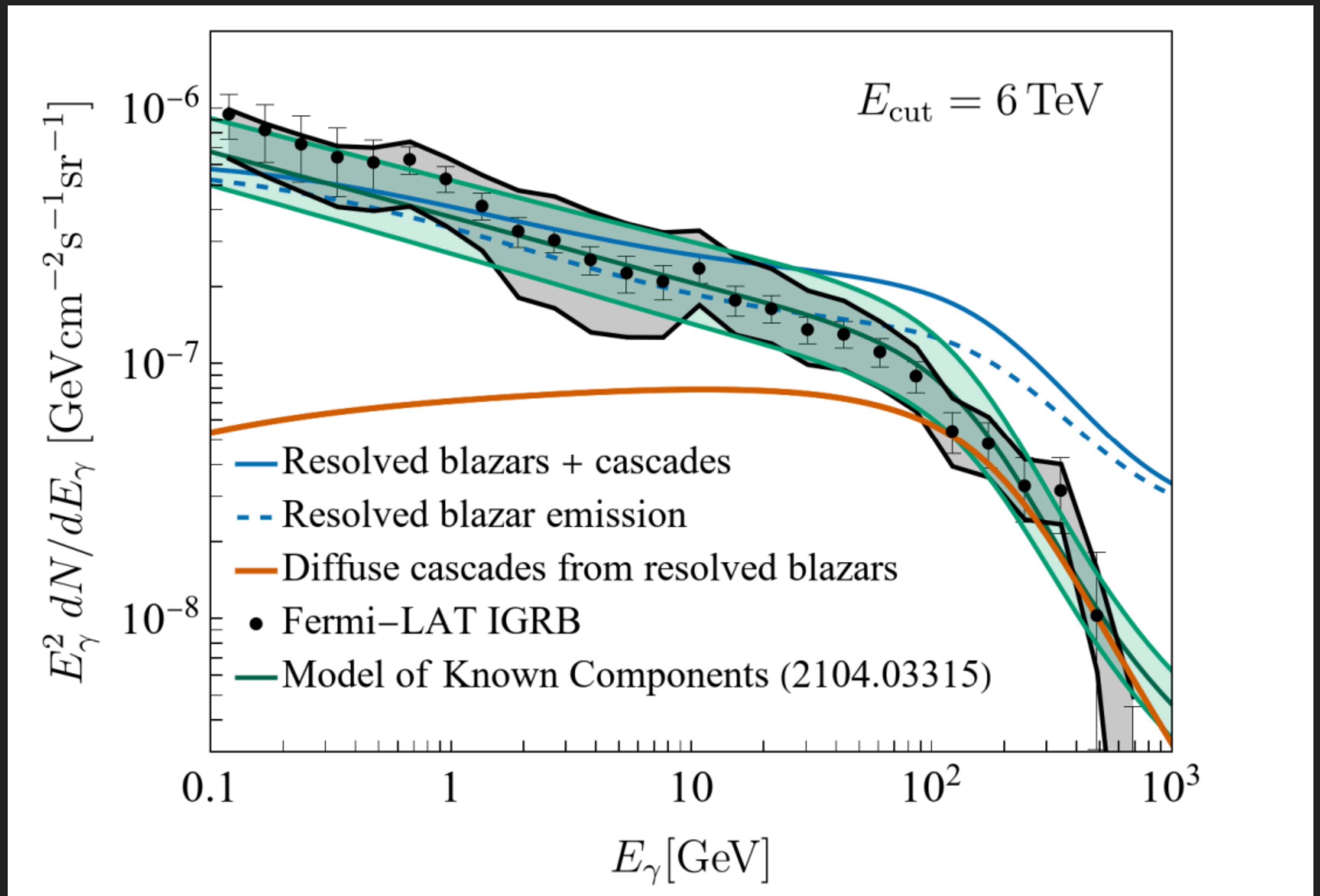
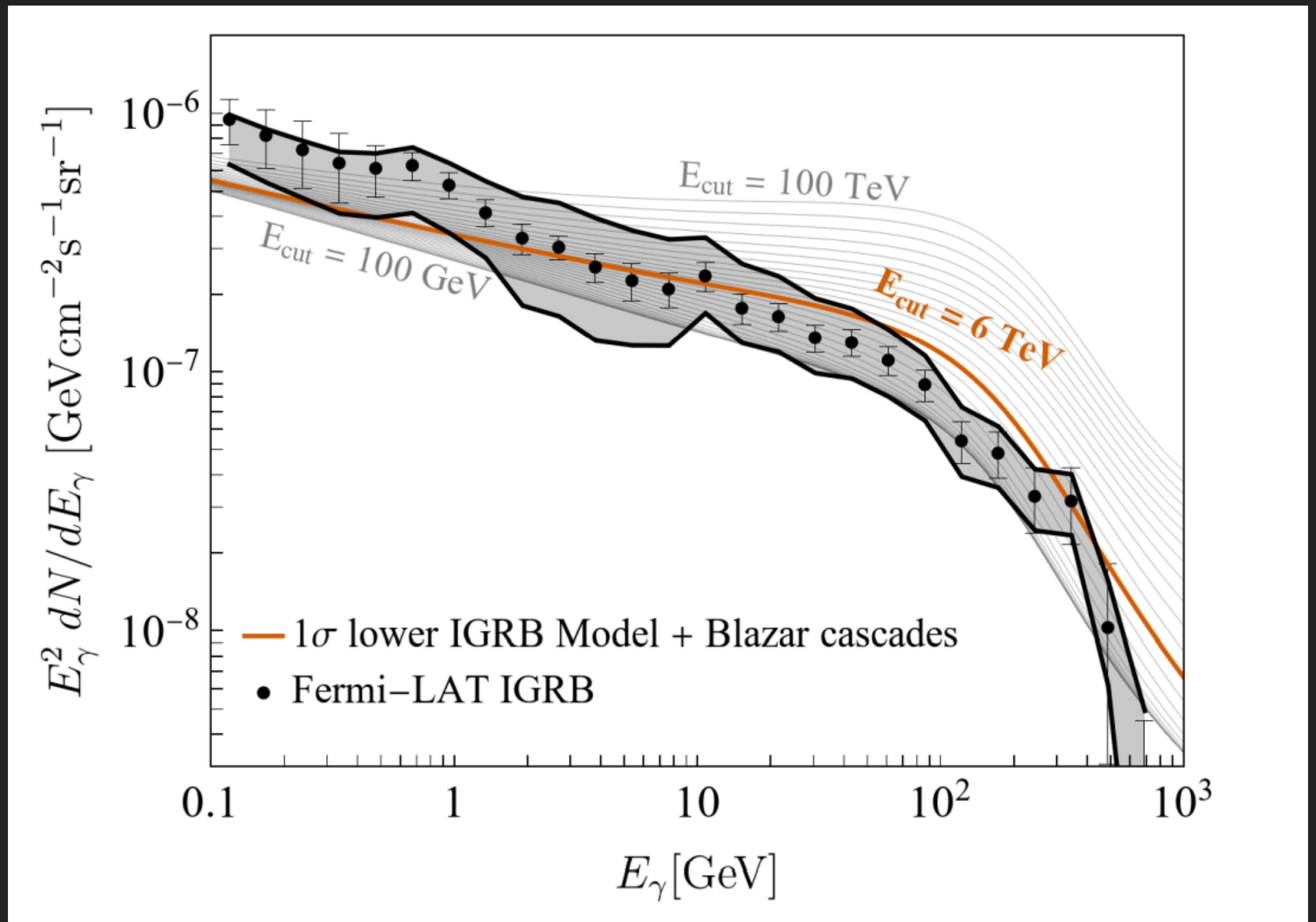
- Collective plasma effects: instability growth, energy loss, beam and plasma heating, nonlinear damping and saturation
- Pair deflections off the intergalactic magnetic field (IGMF): *isotropization* or creation of *pair halo*
- If weak and tangled, IGMF induces *magnetic diffusion* and beam broadening breaking down small-angle approximation

AN EMERGING TENSION IN THE GAMMA-RAY SKY?

- Sharp spectral cutoffs at $\mathcal{O}$(TeV) energies are not observed for local blazars
- Isotropic γ-ray background (IGRB) measurements + non-observation of pair halos together imply IGMF is too feeble to prevent bright γ-ray cascade emission through ICS
- IGRB is dominated by contributions from known sources mAGN, SFG etc.
- Diffuse blazar cascade emission <10%, **in strong tension with blazar models!**

IGRB MEASUREMENTS POINT TOWARDS BEAM-PLASMA INSTABILITIES



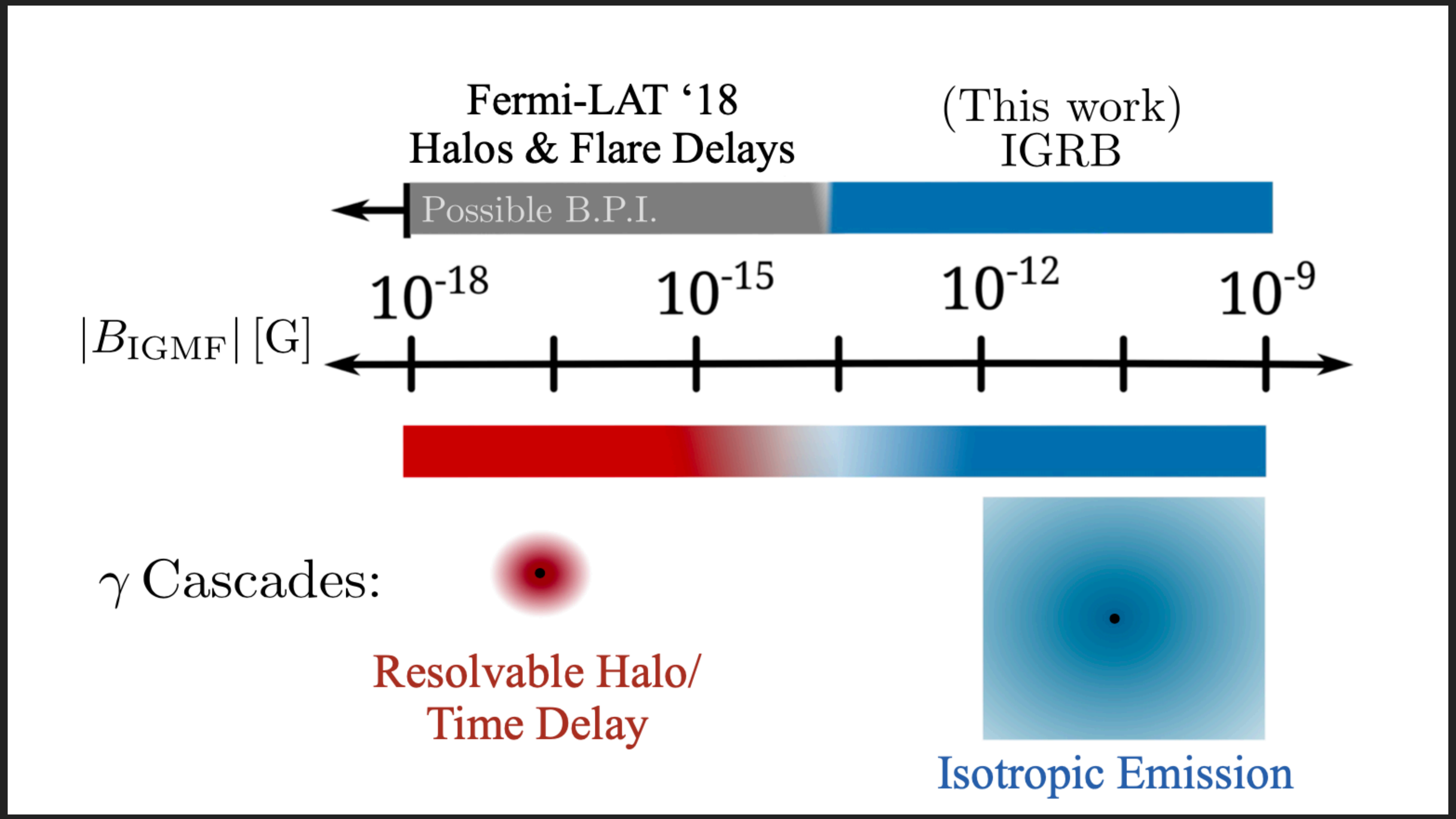


- If intrinsic cutoff $E_{cut} \gtrsim$ 5 TeV, the isotropic cascades + known components exceed the measured IGRB

Blanco, **Ghosh**, Jacobsen, Linden (2023) [arXiv: 2303.01524]

COMPETING EFFECTS OF INSTABILITY GROWTH AND IGMF STRENGTH

- For realistic beam distributions participating in cascade, IGMF stronger than 10^{-14} G required to suppress plasma instabilities
- This introduces a sliding scale in critical IGMF strength ($\lambda_B \sim 1$ kpc) in order to suppress the instabilities



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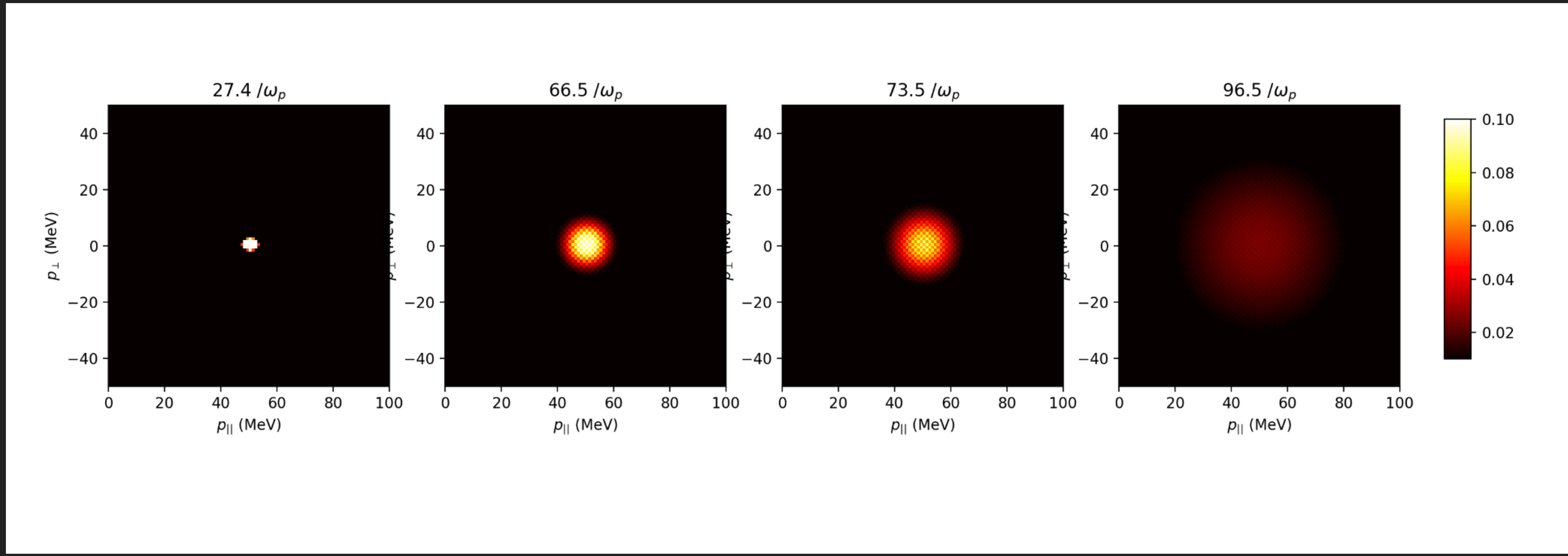
COLLECTIVE PLASMA EFFECTS: GROWTH OF UNSTABLE MODES

- Instabilities occur when the Langmuir waves undergo Cherenkov resonance $\omega = \vec{k} \cdot \vec{v}$
- Such excitations in the beam transfer energy through the resonant window
- Spectral energy density in the background of intergalactic medium (IGM) grows as $W(k) = W_0 \int_0^\tau e^{2\,\mathrm{Im}(\tilde{\omega})\,t} dt$ through instability losses of the beam
- Dynamics and evolution of the beam-plasma interaction is set by characteristic length scales related to the background plasma frequency $\omega_p = \sqrt{4\pi n_p e^2 / m_e}$

ENERGY LOSS (PLASMA HEATING) AND BEAM RELAXATION (SELF-HEATING)



- Evolution of beam-plasma system is diffusive-dissipative described best with a Fokker-Planck equation

$$\frac{\partial}{\partial t} f(\mathbf{p}, t) = -\frac{\partial}{\partial \mathbf{p}}[v(\mathbf{p}, t) f(\mathbf{p}, t)] + \frac{\partial}{\partial \mathbf{p}}\left[D(\mathbf{p}, k, t)\frac{\partial}{\partial \mathbf{p}} f(\mathbf{p}, t)\right]$$

- Consistent with results from particle-in-cell simulations for a laboratory astrophysics experiment

Beck, **Ghosh**, Grüner, Pohl, Schroeder, Sigl, Stark, Zeitler 2023 arXiv: 2306.16839

BLAZAR HEATING: A MODIFIED THERMAL HISTORY

- IGM heating due to a single blazar
  $$\dot{q} = \int dE \frac{\Theta(E)}{D_{\rm pp}(E,z)} f\left(F_E, E, z\right) F_E$$
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- Average heating due to a population of blazars

$$\dot{Q} = \int dV d\log_{10} L d\alpha' d\Omega \tilde{\phi}_B(z; L, \alpha', \Omega) \frac{\Omega}{2\pi} \dot{q}$$

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(Broderick et al., 2012)

- Incorporating other heating mechanisms
$$\dot{Q}_{\rm canon} = \dot{Q}_{\rm H-I,photo} + \dot{Q}_{\rm He-I,photo} + \dot{Q}_{\rm He-II,photo} + \dot{Q}_{\rm H-II,rec} + \dot{Q}_{\rm He-III,rec} + \dot{Q}_{\rm Compton} + \dot{Q}_{\rm free-free}$$

- Total uniform volumetric heating rate $\dot{Q} = \dot{Q}_{\rm canon} + \dot{Q}_{\rm B}$

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- Casting temperature-density-redshift relation during $2 < z < 3.5$ as
  $$T = T_0 \Delta^{\gamma(z)'-1}$$

BLAZAR HEATING: A MODIFIED THERMAL HISTORY

- Effective redshift-dependence of volumetric heating from fitting 40 blazars

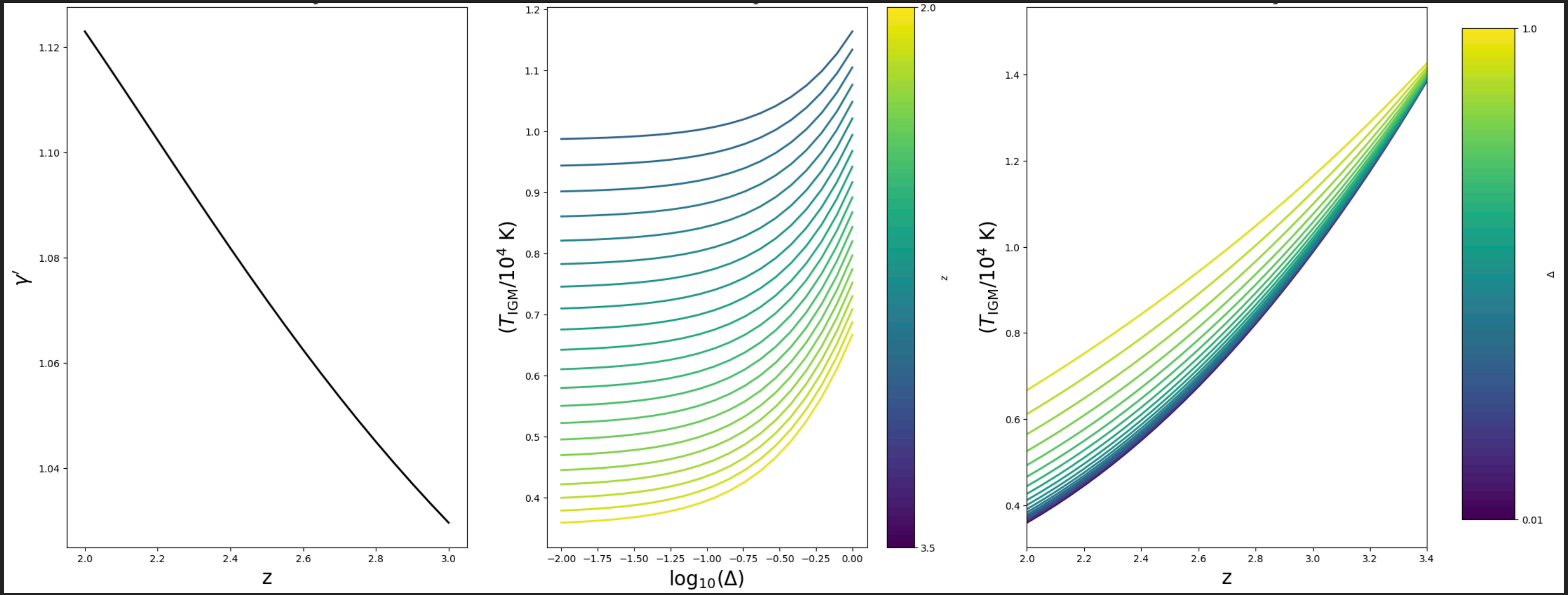
$$\log_{10}\left(\frac{\dot{Q}_{\rm B}/n_{\rm bary}}{1{\rm eVGyr}^{-1}}\right) = 0.0315(1+z)^3 - 0.512(1+z)^2 + 2.27(1+z) - \log_{10}\dot{Q}_{\rm mod}$$

(Chang *et al*, 2011)

- Degree of blazar heating $p = \log_{10}\dot{Q}_{\rm mod}$

BLAZAR HEATING: A MODIFIED THERMAL HISTORY

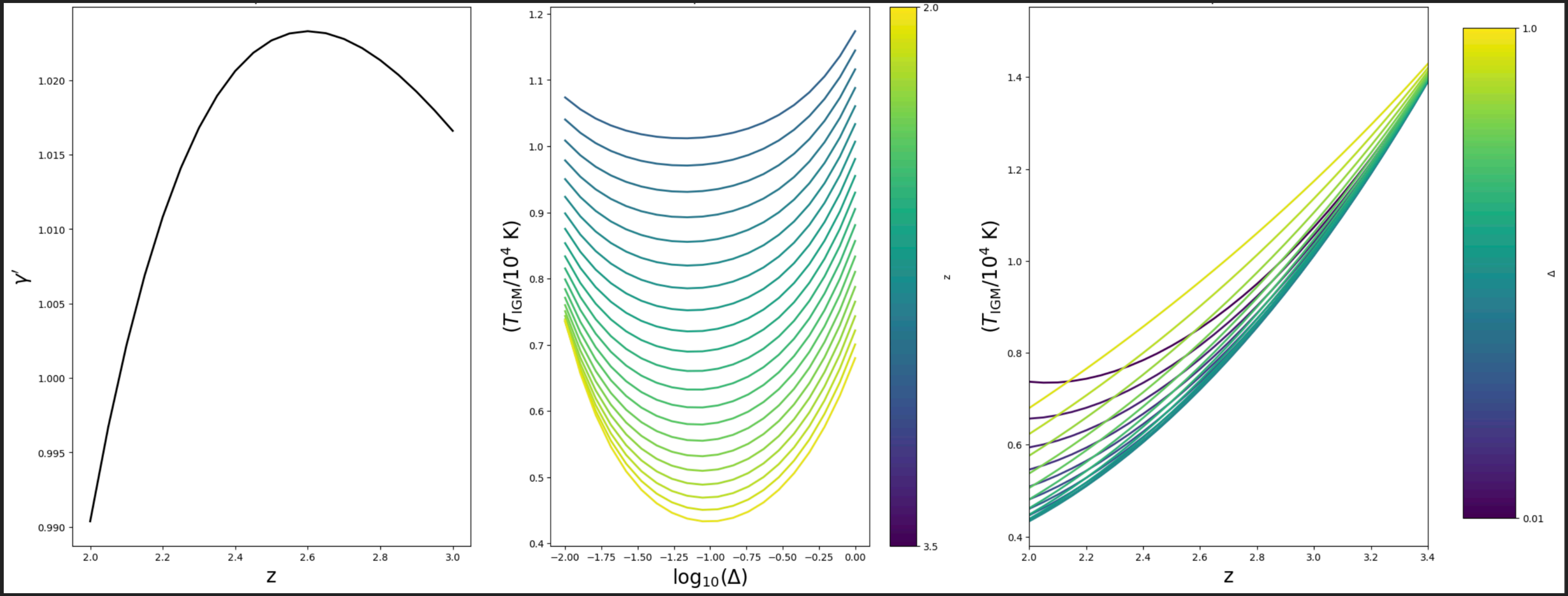
Ghosh & Bhattacharyya 2309.05421



Redshift evolution of index, temperature-density and temperature-redshift relation without blazar heating

BLAZAR HEATING: A MODIFIED THERMAL HISTORY

Ghosh & Bhattacharyya 2309.05421



Redshift evolution of index, temperature-density and temperature-redshift relation for low global blazar heating

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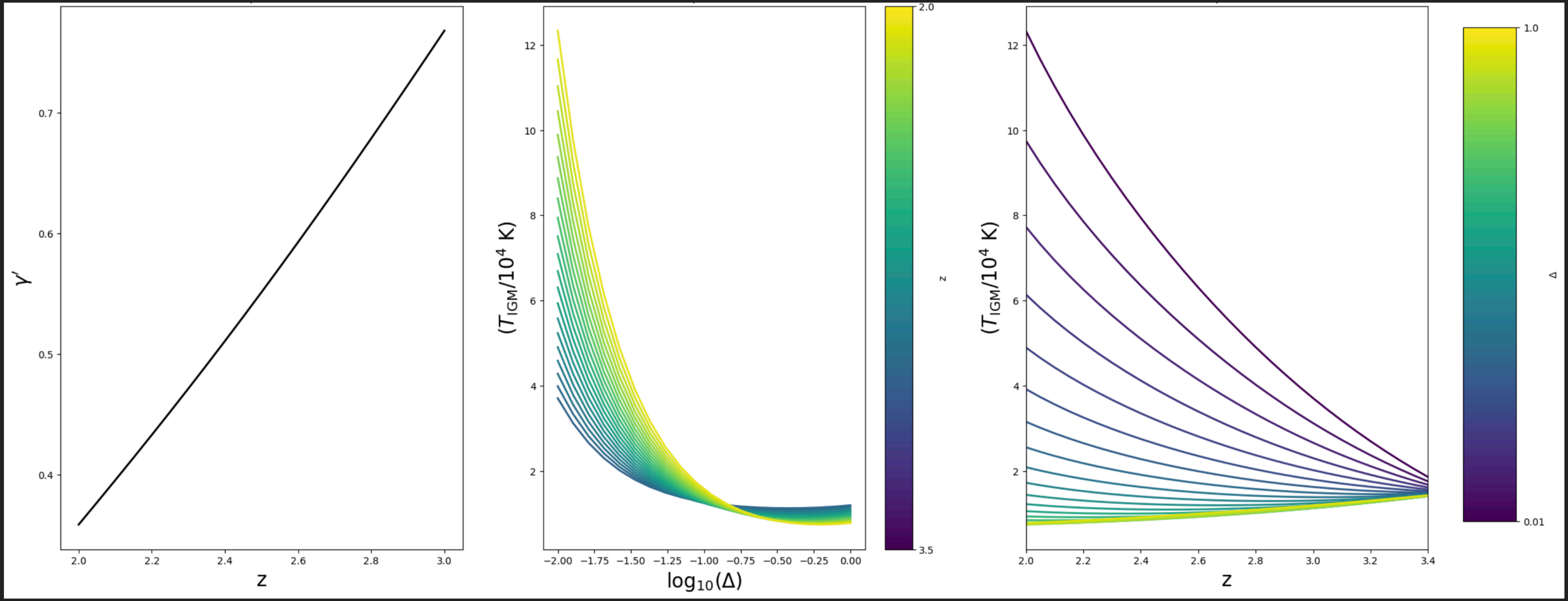

Redshift evolution of index, temperature-density and temperature-redshift relation for moderate global blazar heating

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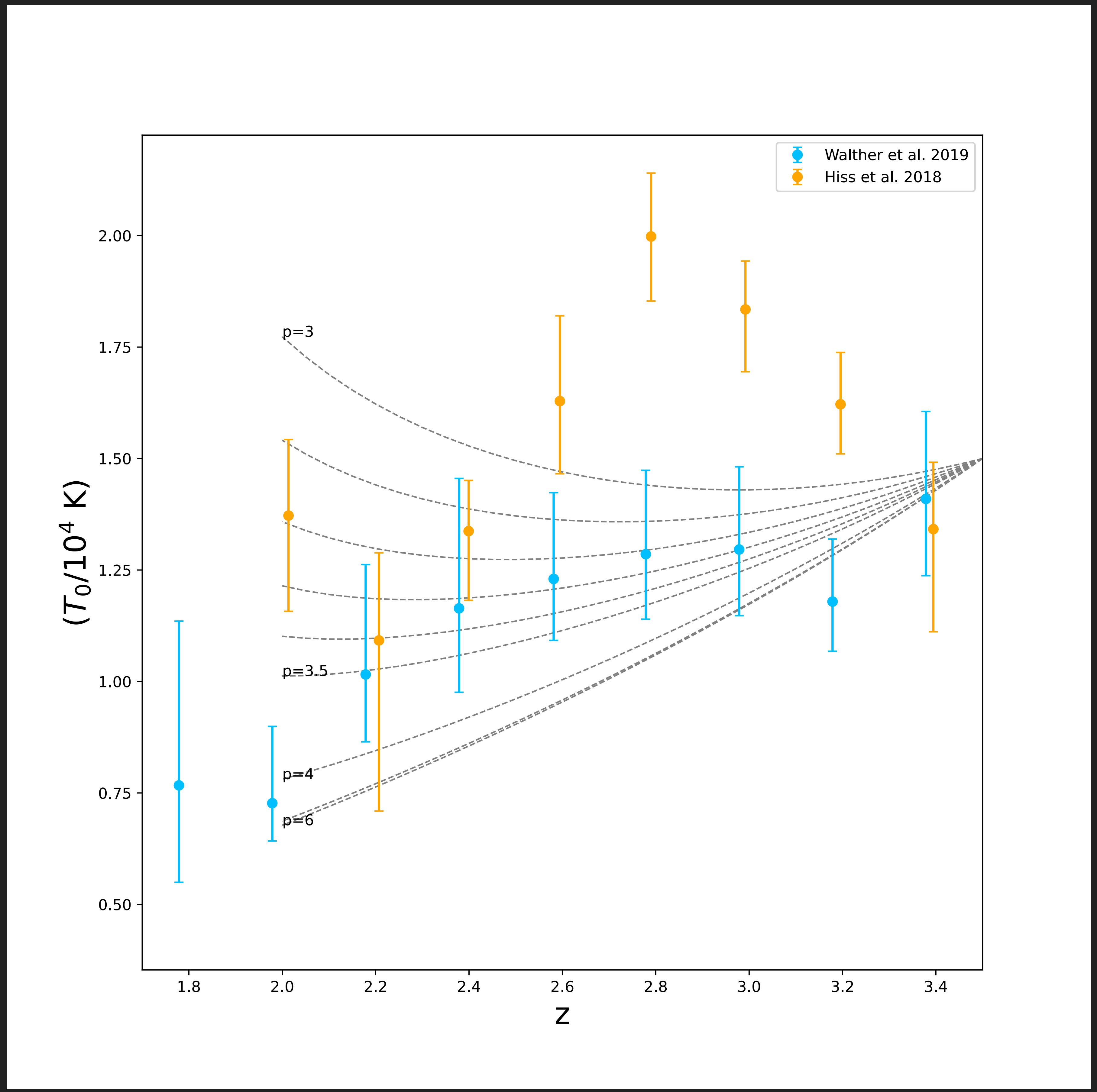
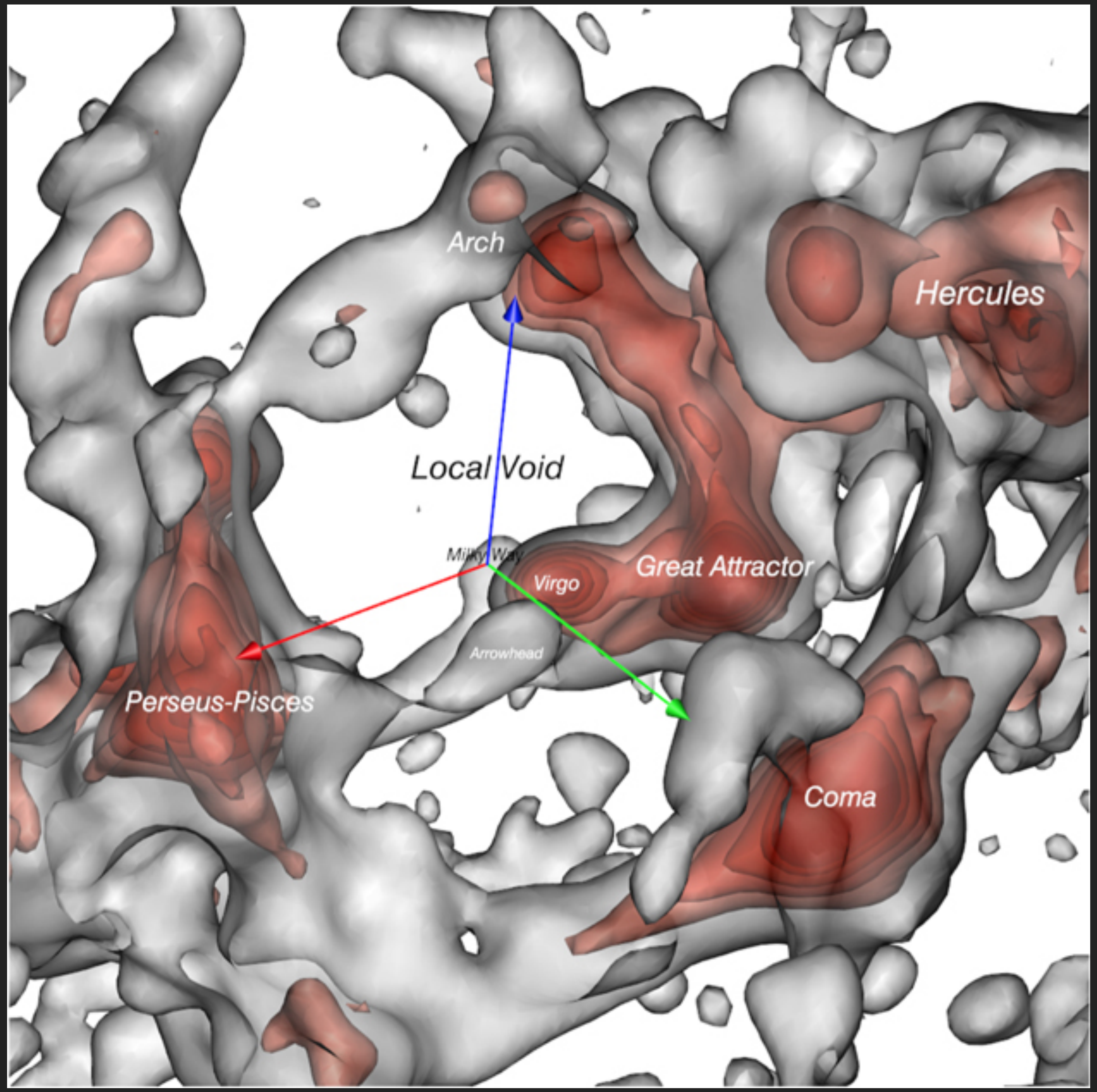


- End of reionization set at z=3.5
- Lyman-α bounds indicate IGM temperature at mean density favours intermediate to low levels of blazar heating
- Main source of uncertainty stems from HeII reionization models

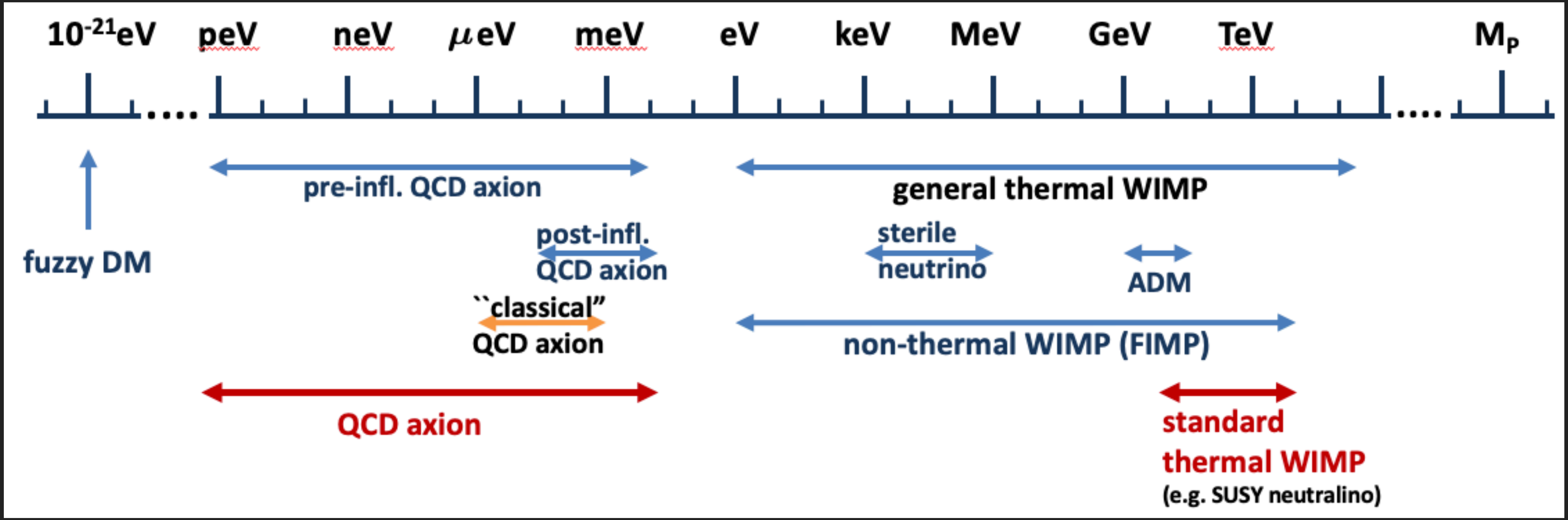
BLAZAR HEATING: A MODIFIED THERMAL HISTORY

- Void dwarfs are relatively isolated, with less rich merger and accretion history
- Worthwhile to explore cosmologies with various degrees of blazar heating
- Implications for light dark matter candidates such as axion-like particles



R. Brent Tully *et al* 2019 *ApJ* **880** 24

AXION-LIKE PARTICLES (ALPS) AS DARK MATTER



LIGHT ALPS AS A SOLUTION TO SMALL-SCALE ANOMALIES

- Cusp-vs.core problem
- Missing satellites problem
- Too-big-to-fail problem
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- This introduces an axionic Jeans scale $k_{J,a} = \left(16\pi G\bar{\rho}\right)^{1/4} m_a^{1/2}$, with $\bar{\rho} = \rho_0 a^3$

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RESOLVES MANY OF THE ISSUES WITH ΛCDM COSMOLOGY IN SMALL SCALES

BLAZAR HEATING: A MODIFIED THERMAL HISTORY

Ghosh & Bhattacharyya [2309.05421](https://doi.org/10.22323/1.444.1448)

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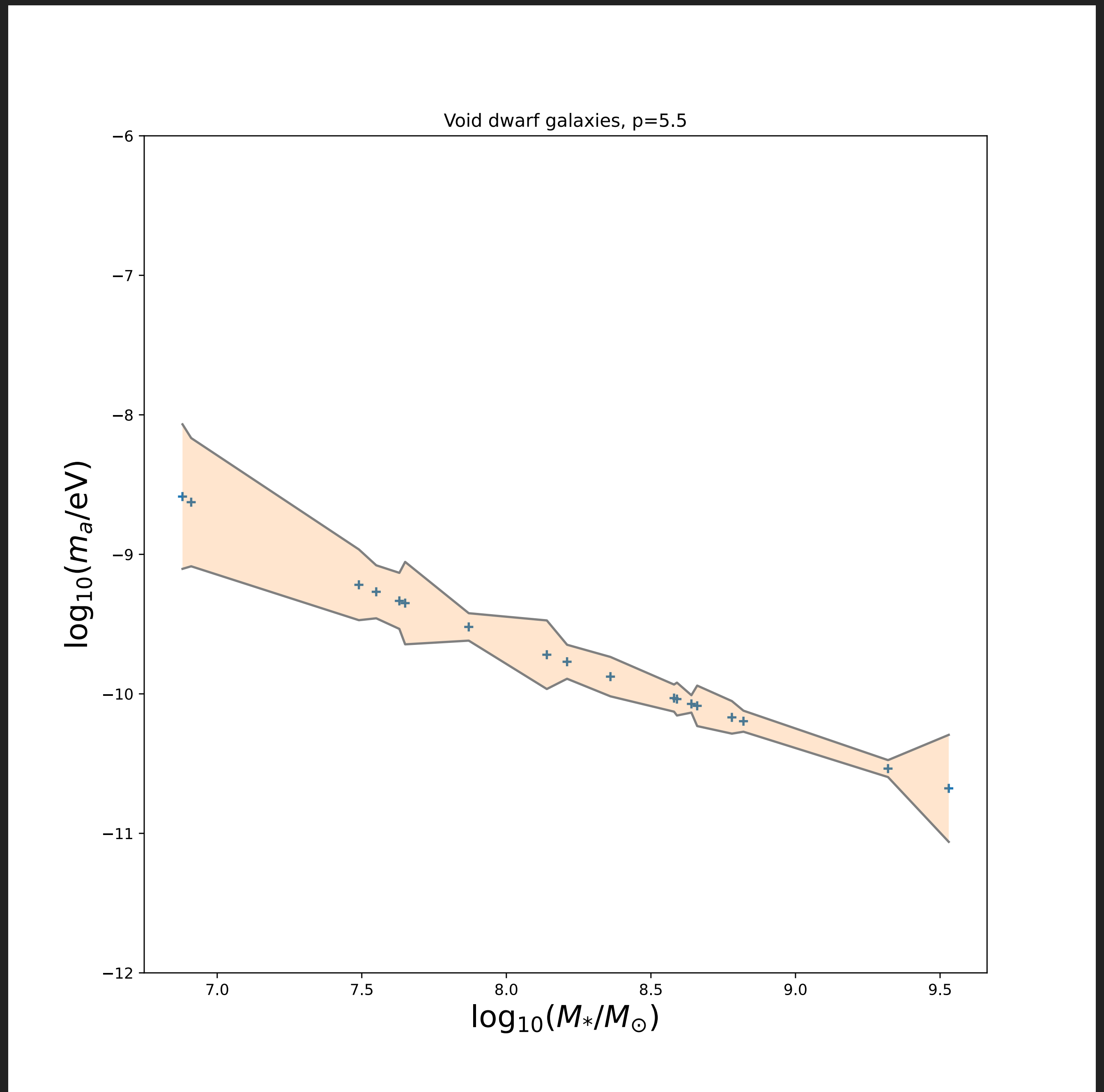

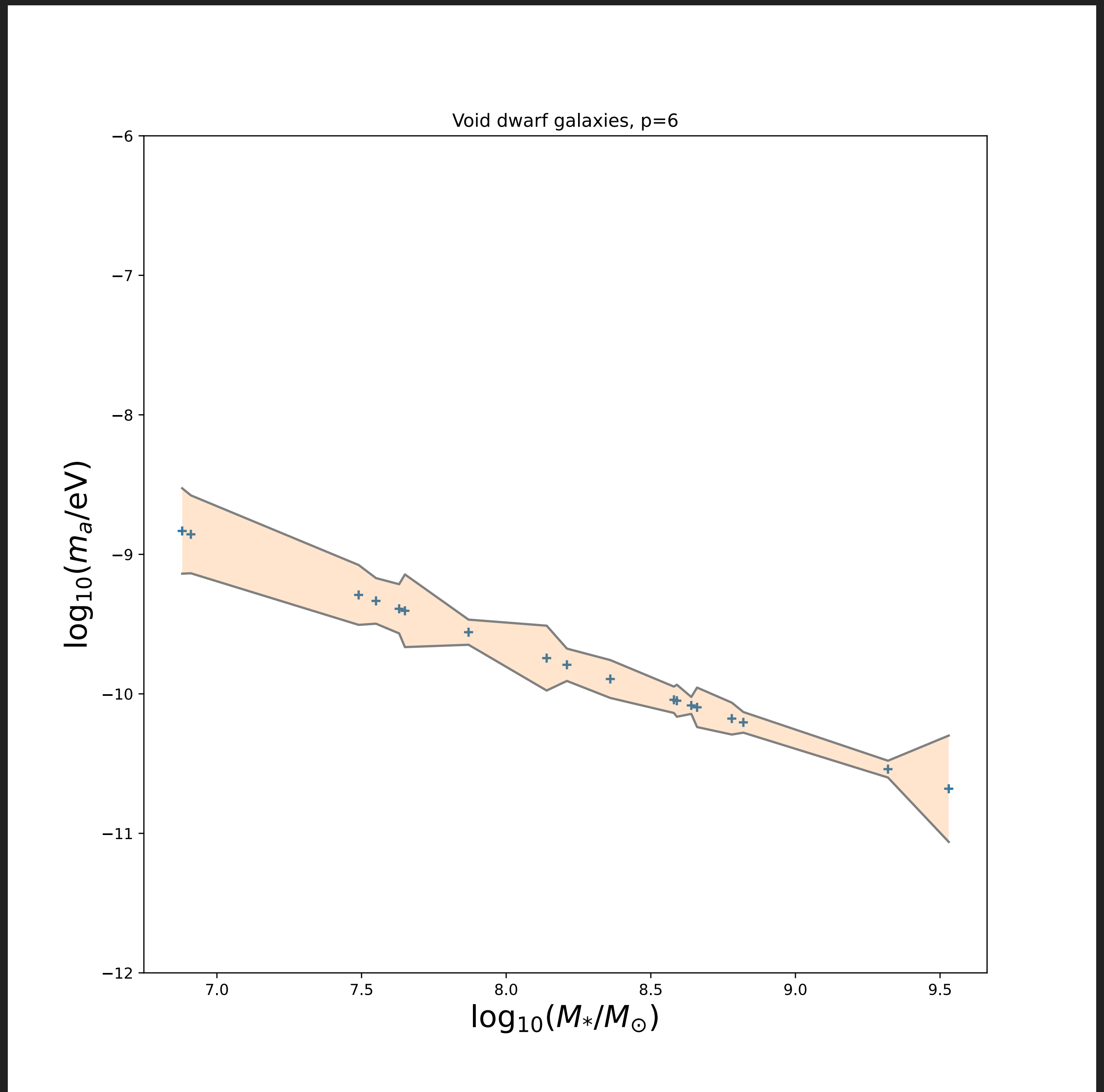

- Characteristic masses of void dwarfs based stellar kinematics data from KCWI (de Los Reyes *et al*, 2023) translates to ALP masses of $m_a \sim 10^{-10.5} - 10^{-8.5}$ eV in presence of blazar heating (shown for p = 5.5 and p =6)

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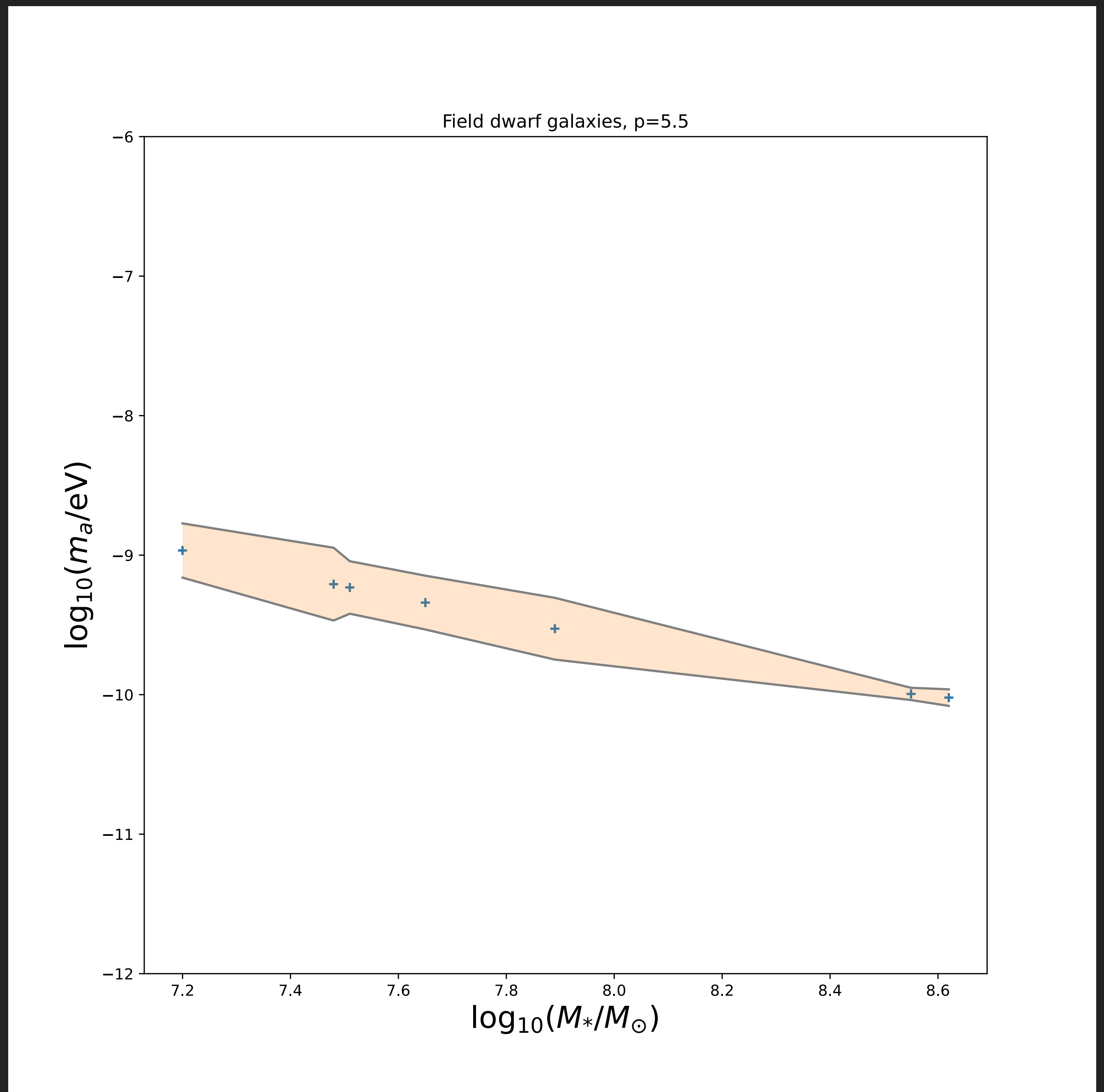

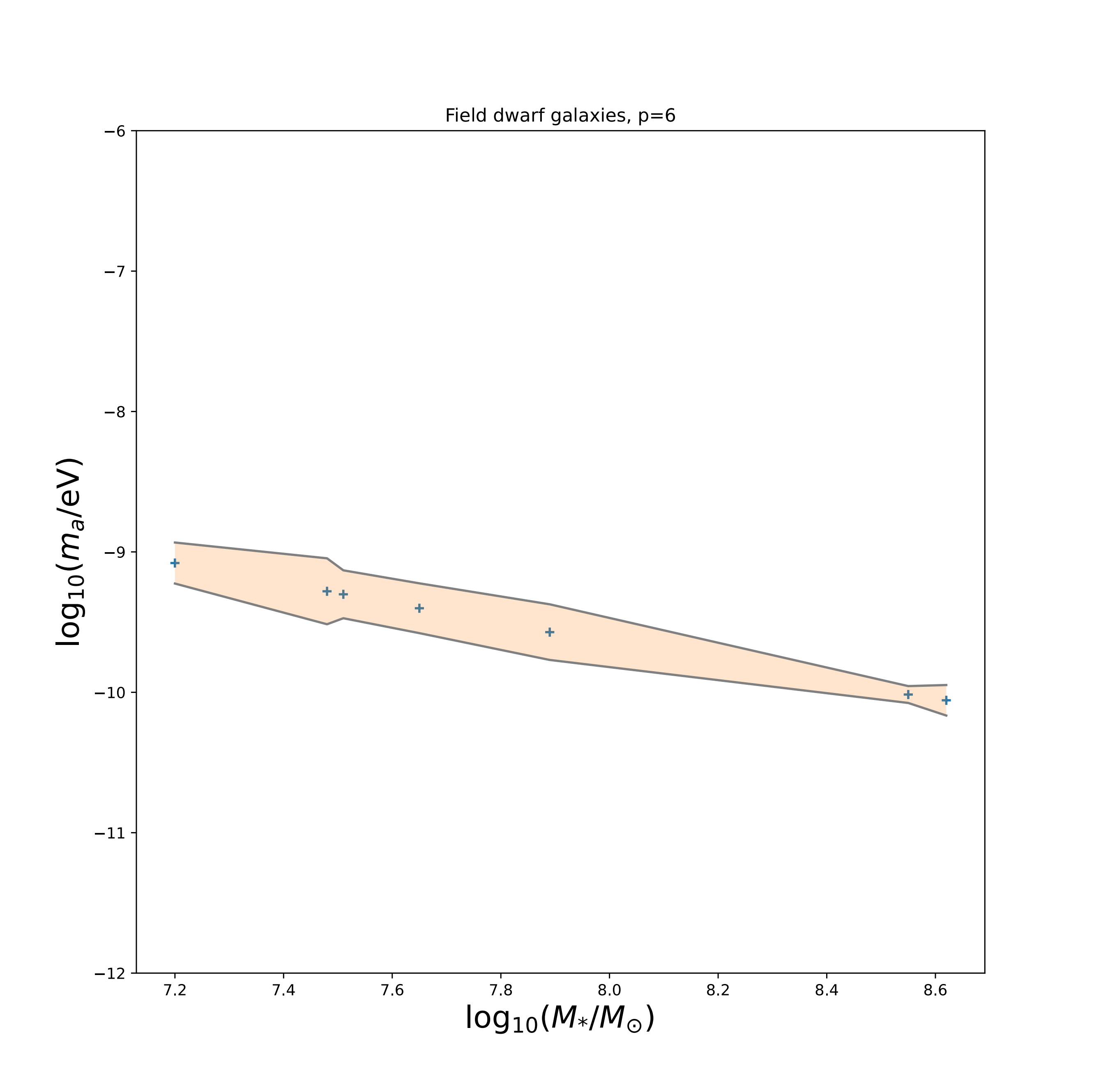

- Characteristic masses of field dwarfs based stellar kinematics data from KCWI (de Los Reyes *et al*, 2023) translates to ALP masses of $m_a \sim 10^{-10} - 10^{-9}$ eV in presence of blazar heating (shown for p = 5.5 and p =6)

KEY TAKEAWAYS

- GeV-TeV tension combined with absence of pair halo and IGRB excess in the gamma-ray sky point towards collective plasma effects
- While propagating through plasma, pair beams suffer from virulent instabilities, however only accessible through a narrow resonance window
- In absence of significant inhomogeneities in the IGM, instability losses heat the intergalactic medium, altering thermal histories locally
- Strongly supported by Lyman-α observations, this raises the entropy floor and modifies the filtering scale
- In presence of blazar heating, recent void and field dwarf measurements translate to a favoured axion mass range of $m_a \sim 10^{-10.5} - 10^{-8.5}$ eV and $m_a \sim 10^{-10} - 10^{-9}$ eV respectively

Thank you!

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BACKUP: MAGNETIC DIFFUSION LEADS TO PAIR BEAM BROADENING

- For a 2D Gaussian pair beam distribution at injection

$$f_{b,\theta}(\theta, p) = \frac{1}{\pi \Delta\theta^2} \exp\left\{-\left(\frac{\theta}{\Delta\theta}\right)^2\right\}, \quad 0 \leq \theta \leq \pi$$

- Magnetic diffusion in the beam due to weak tangled IGMF

$$\Delta\theta = \frac{m_e c}{p} \sqrt{1 + \frac{2}{3}\lambda_B \lambda_{\rm IC} \left(\frac{eB_{\rm IGM}}{m_e c}\right)^2}$$

Alawashra & Pohl, 2022

BACKUP SLIDES: REACTIVE GROWTH RATE

- For cold beams propagating through cold plasma growth is reactive
- Hydrodynamic calculation yields

$$\mathrm{Im}(\tilde{\omega})_r = \frac{\sqrt{3}}{2^{4/3}}\omega_p \left(\frac{n_b}{\gamma_b n_p}\right)^{1/3} \left[\left(\frac{k_\perp}{k}\right)^2 + \frac{1}{\gamma_b^2}\left(\frac{k_\parallel}{k}\right)^2\right]^{1/3}$$

BACKUP: MOMENTUM DIFFUSION IN COSMIC PAIR BEAMS

- Prompt flux $\frac{d^2N_\gamma}{dE_\gamma dt} = \frac{(\alpha-1)L_{\gamma,iso}(t)}{4\pi D_L^2 E_{\gamma,pk}^2}\left(\frac{E_\gamma}{E_{\gamma,pk}}\right)^{-\alpha}, \quad \left(E_{\gamma,pk} < E_\gamma < E_{\text{cut}}\right)$

- Luminosity distance $D_\text{L}(z) = \frac{(1+z)}{H_0}\int_0^z dz' \left[\Omega_r(1+z')^4 + \Omega_m(1+z')^3 + \Omega_\Lambda\right]^{-1/2}$

BACKUP: MOMENTUM DIFFUSION IN COSMIC PAIR BEAMS

- Delayed emission due to pair deflection, ICS and momentum diffusion

$$\frac{d^2N_{\text{delayed}}}{dt_{\text{obs}}\,dE_\gamma} = \int d\gamma_e \frac{dN_e}{d\gamma_e}\frac{3\sigma_T}{4\gamma_e^2}\frac{d\langle r\rangle}{dt_{\text{obs}}}\int d\epsilon_{\gamma,\mathrm{CMB}}\, n_{\mathrm{CMB}}\left(\epsilon_{\gamma,\mathrm{CMB}}\right)\frac{f(x)}{\epsilon_{\gamma,\mathrm{CMB}}}$$

- However $\left\langle \theta^2_{\mathrm{broad}}(\theta)\right\rangle \ll \left\langle \theta^2_{\mathrm{IC}}(\theta)\right\rangle$, momentum diffusion is not significant for astrophysical pair beams

BACKUP: MOMENTUM DIFFUSION IN COSMIC PAIR BEAMS

- Pairs at production travels to the observer at a speed of

$$\frac{d\langle r\rangle}{dt_{\mathrm{obs}}} = \frac{2c}{(1+z)\left[\theta^2 + \Theta^2/3\right]}$$

- Relevant quantity: IC mean free path $\ell_{\mathrm{ICS}} = \frac{1}{\sigma_{\mathrm{T}} n_{\mathrm{CMB}}} \approx 10\ \mathrm{kpc}\ (1+z)^{-3}$

BACKUP: BLAZAR HEATING: A MODIFIED THERMAL HISTORY

- Taking into account pressure dilution owing to Hubble expansion, a filtering scale $\lambda_F = 2\pi a/k_F$ can be applied

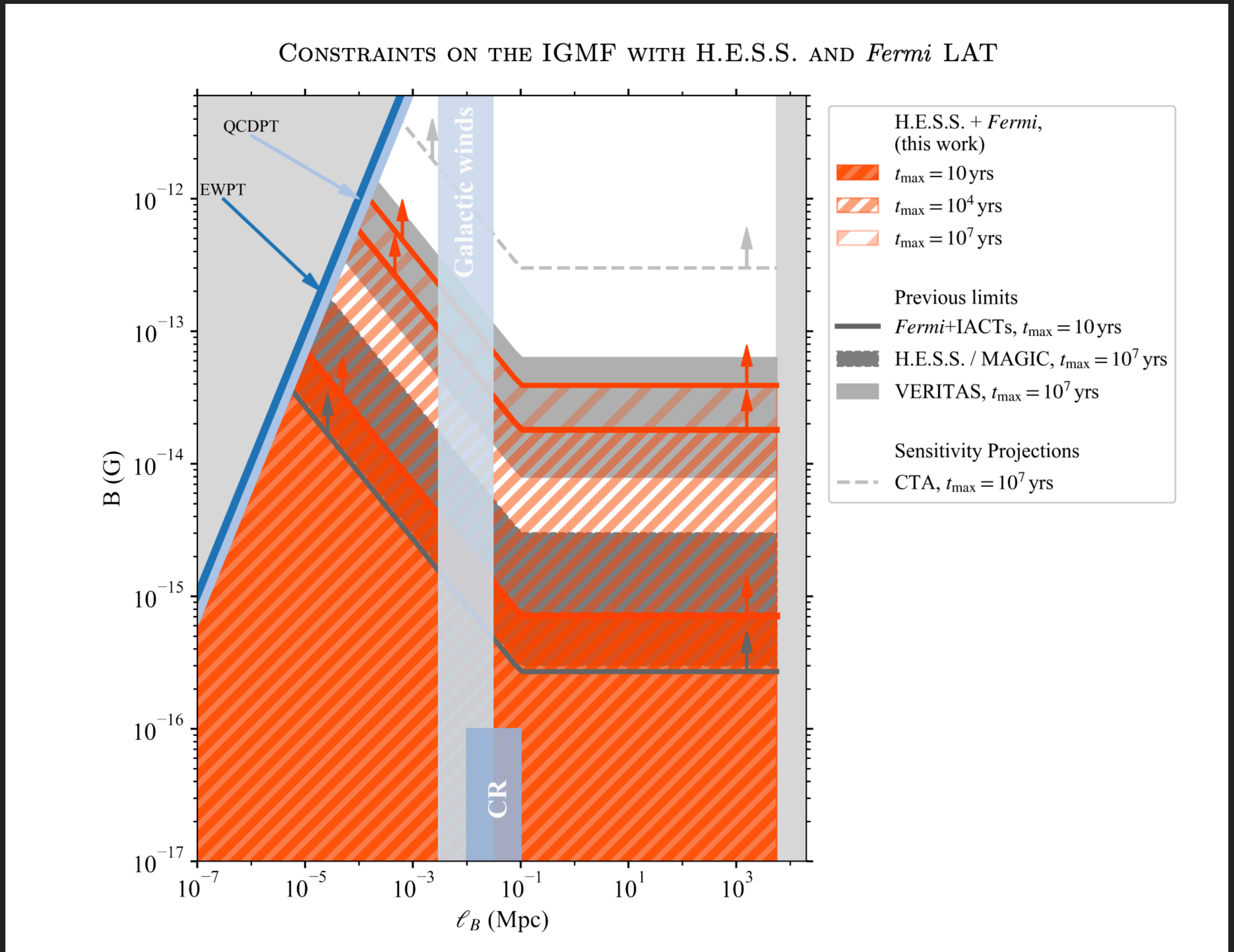
- Generally, $$\frac{1}{k_F^2(t)} = \frac{1}{D_+(t)} \int_0^t dt' a^2(t') \frac{\ddot{D}_+(t') + 2H(t')\dot{D}_+(t')}{k_J^2(t')} \int_{t'}^{t} \frac{dt''}{a^2(t'')}$$

- Corresponding filtering mass $M_F = \frac{4}{3}\pi\bar{\rho}\lambda_F^3$

BACKUP: INHOMOGENEITIES IN IGM

- When beam opening angle $\theta_0 \sim 1/\mu\Lambda$, instability is weak as resonant modes are confined within narrow Δk
- Λ is the plasma parameter, and in longitudinal direction $\mu_{||} = \dfrac{c}{\omega_p L_{||}} \dfrac{\gamma_b}{\alpha}$

BACKUP: FERMI-LAT + H.E.S.S. COMBINED ANALYSIS, LIMITS ON IGMF



Fermi-LAT Collaboration, 2023