OINDRILA GHOSH

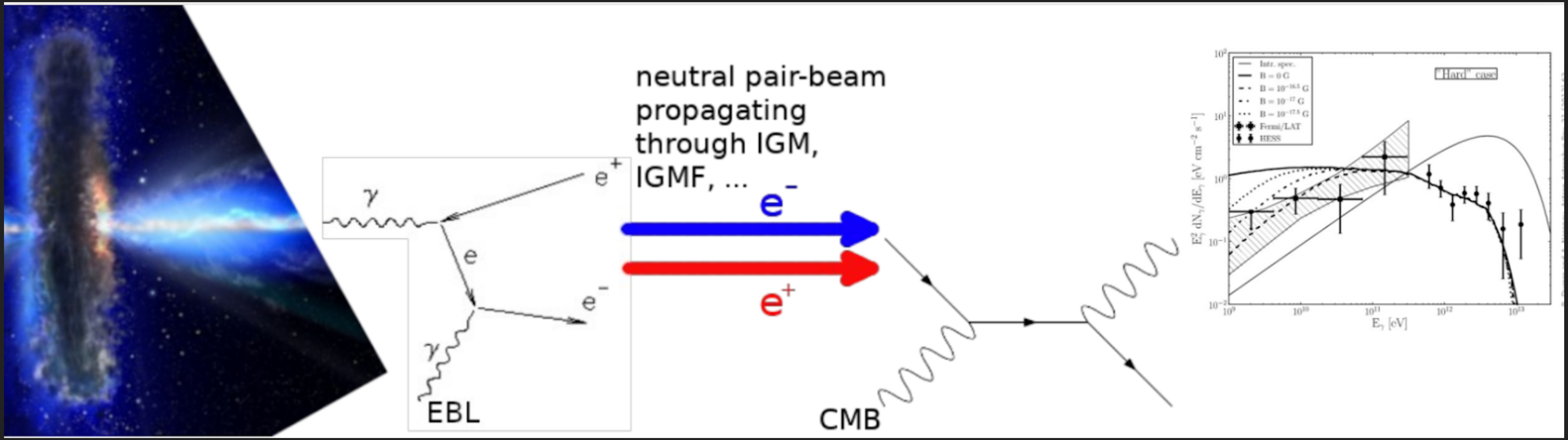
OSKAR KLEIN CENTRE FOR COSMOPARTICLE PHYSICS, STOCKHOLM UNIVERSITY

# FROM BLACK HOLES INTO THE VOIDS: WHAT TEV ASTROPHYSICS TELLS US ABOUT ALPS

18TH PATRAS WORKSHOP | July 3, 2023

# BLAZARS: A QUICK OVERVIEW

- Active galactic nuclei ejecting ultrarelativistic jets onto large cosmological distances
- Characterised by hard power-law spectra extending up to TeV energies, e.g., BL Lacs that peak at high energies



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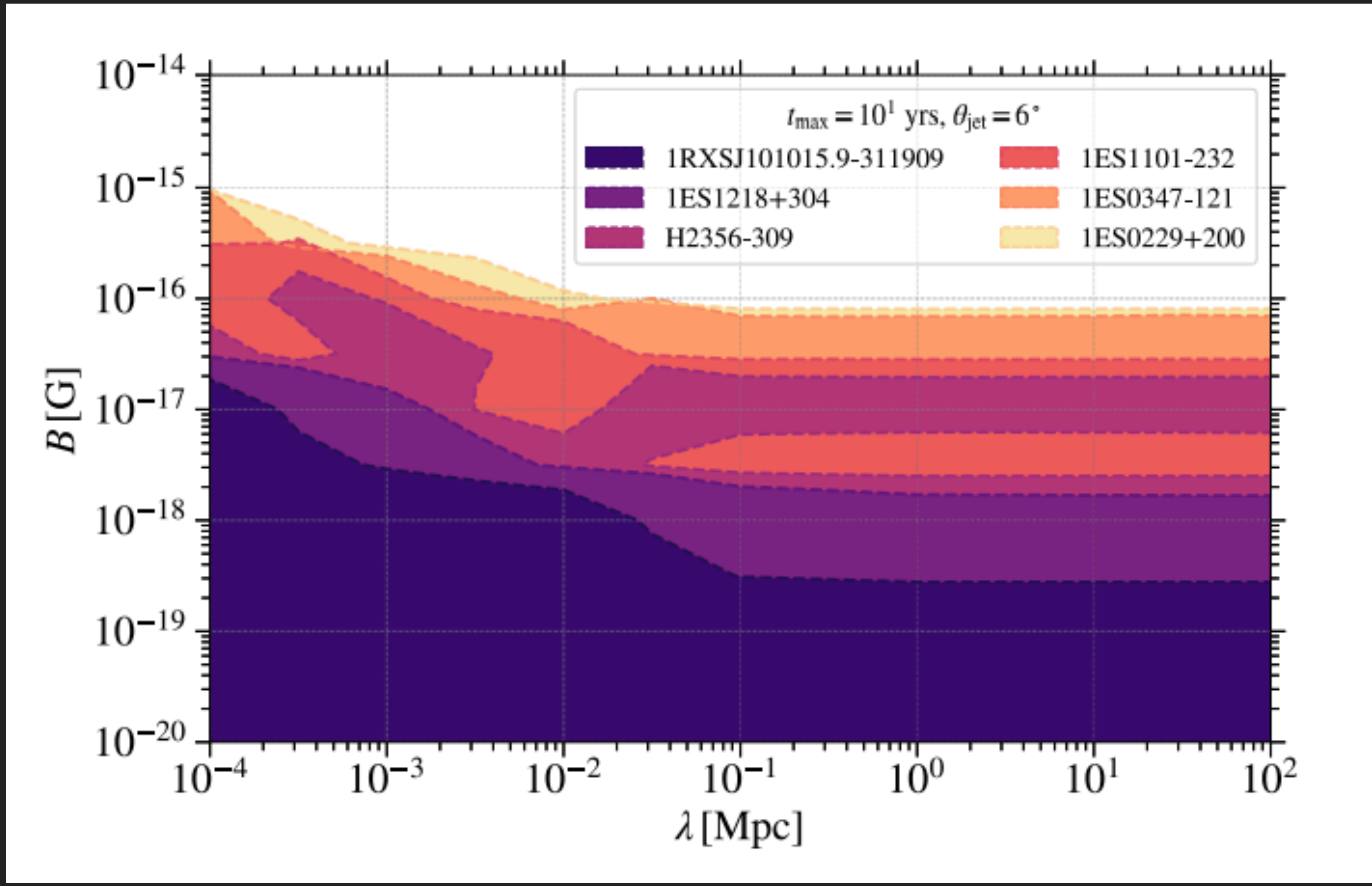
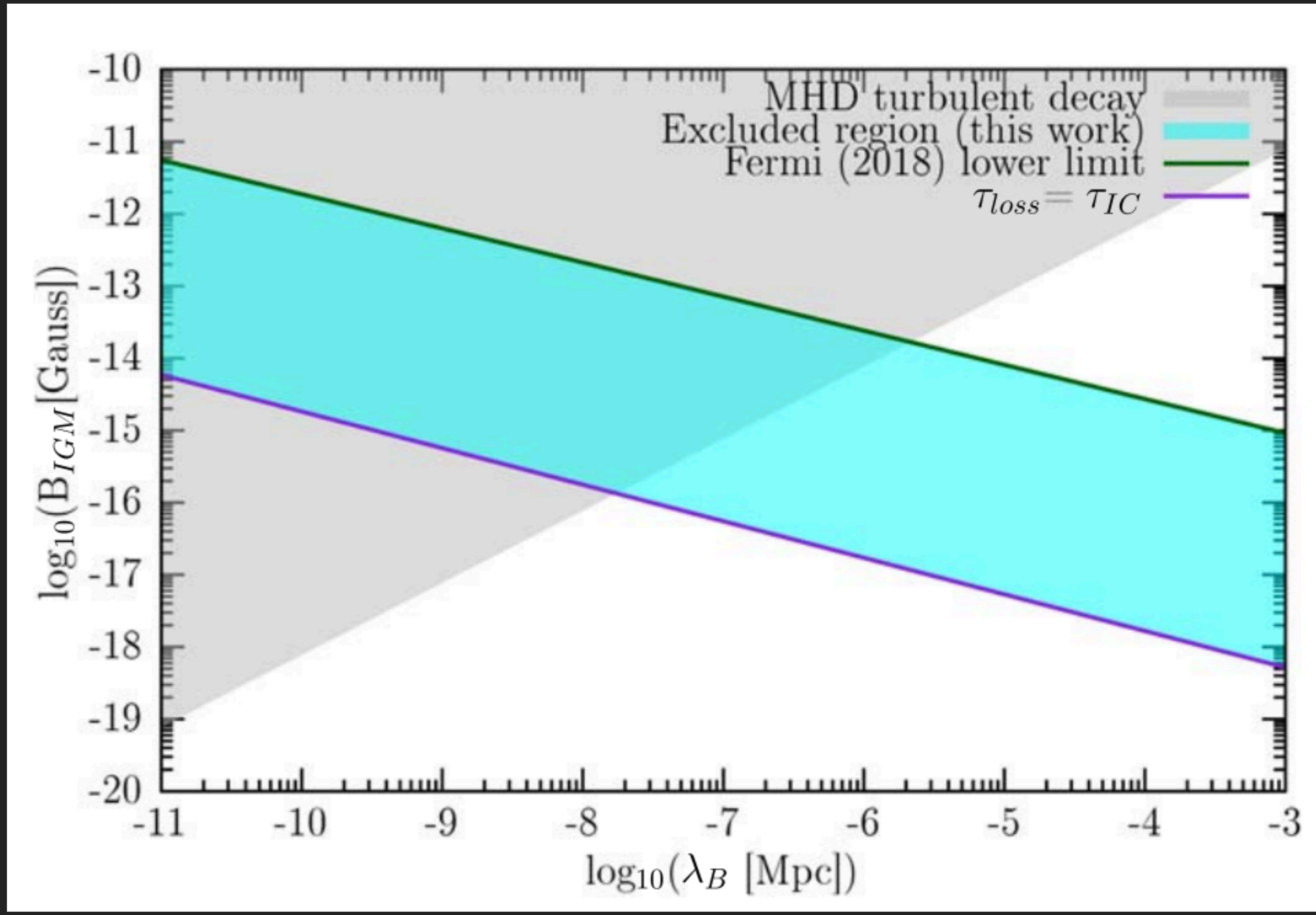
- Collective plasma effects: instability growth, energy loss, beam and plasma heating, nonlinear damping and saturation
- Pair deflections off the intergalactic magnetic field (IGMF): *isotropization* or creation of *pair halo*
- If weak and tangled, IGMF induces *magnetic diffusion* and beam broadening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

# MISSING CASCADE AS A PROBE OF IGMF




Fermi-LAT (2018)

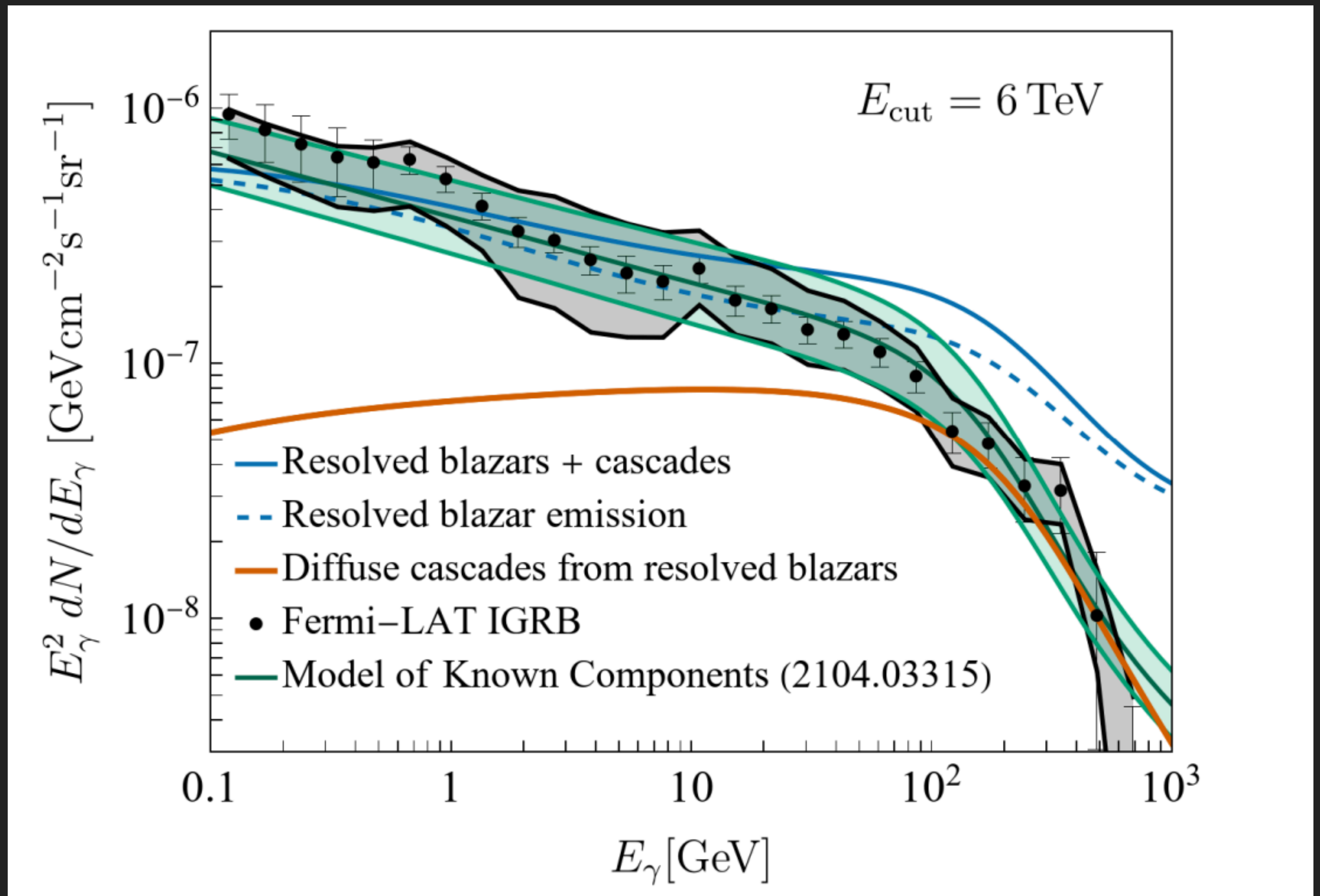


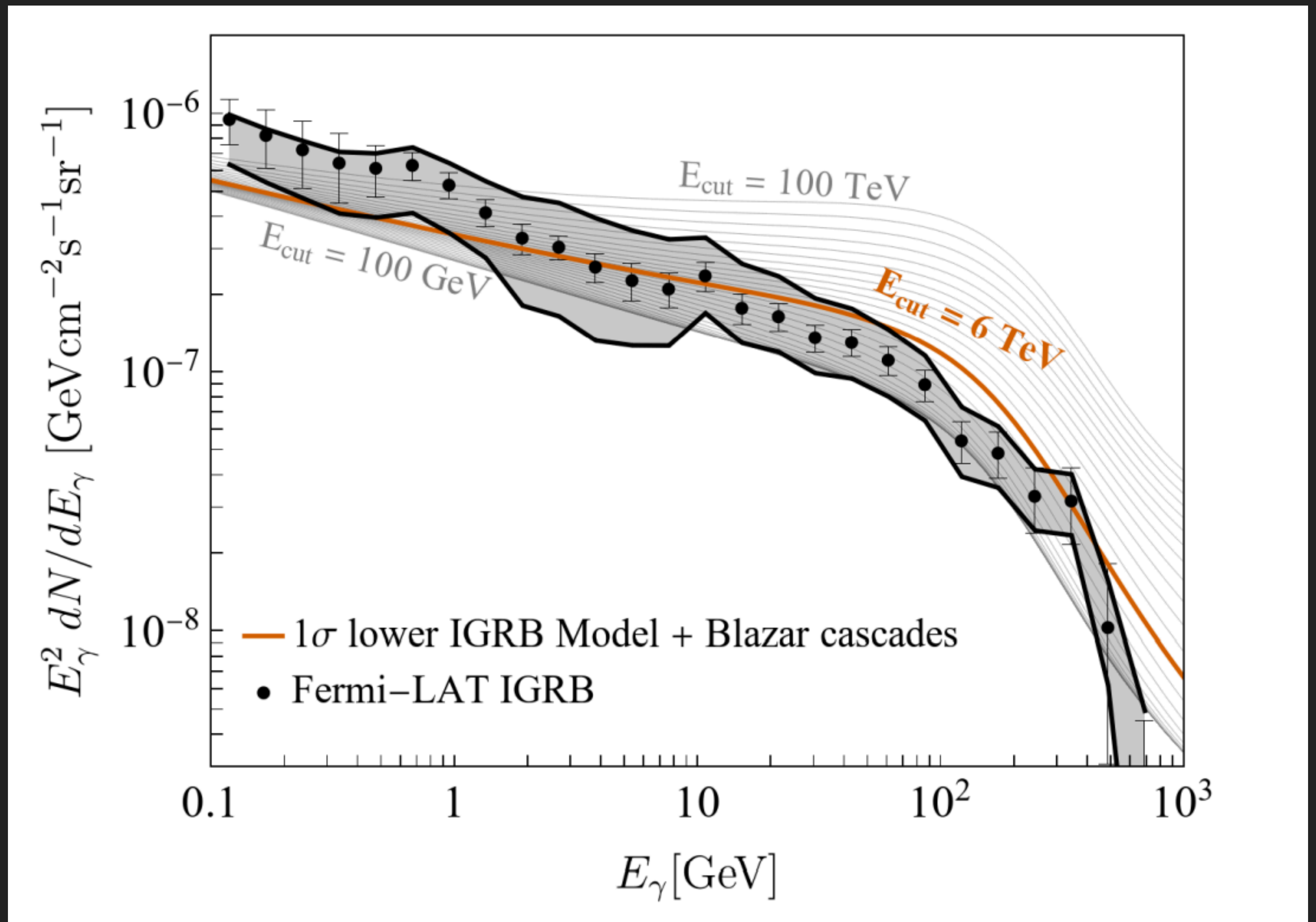

Alawashra & Pohl (2022)

# AN EMERGING TENSION IN THE GAMMA-RAY SKY?

- Sharp spectral cutoffs at $\mathcal{O}$(TeV) energies are not observed for local blazars
- Isotropic $\gamma$-ray background (IGRB) measurements + non-observation of pair halos together imply IGMF is too feeble to prevent bright $\gamma$-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



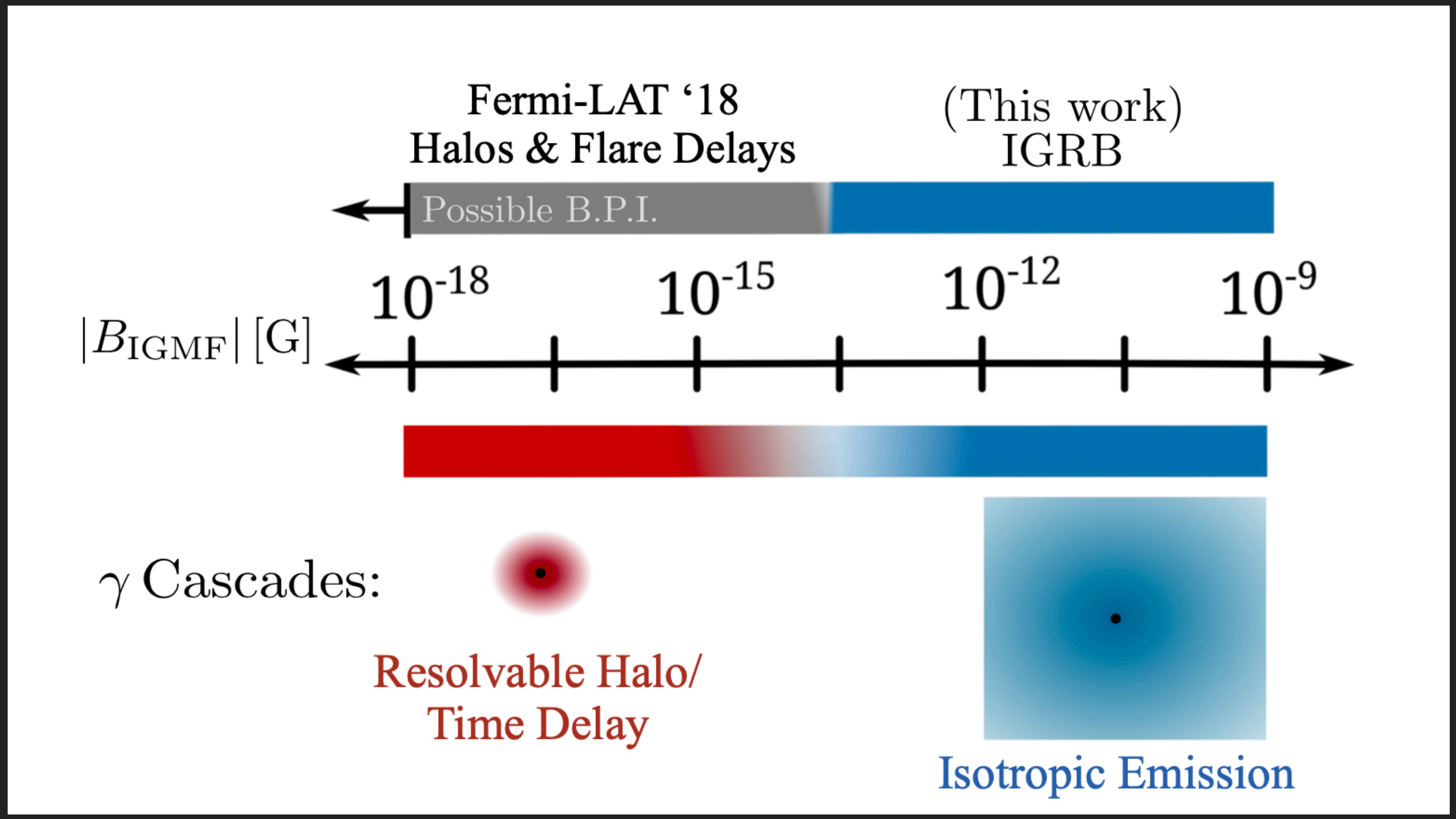




- If intrinsic cutoff $E_{cut} \gtrsim$ 5 TeV, the isotropic cascades + known components exceed the measured IGRB

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

# COMPETING EFFECTS OF INSTABILITY GROWTH AND IGMF STRENGTH

- For more realistic beam distributions participating in cascade (e.g., Maxwell-Jüttner), 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



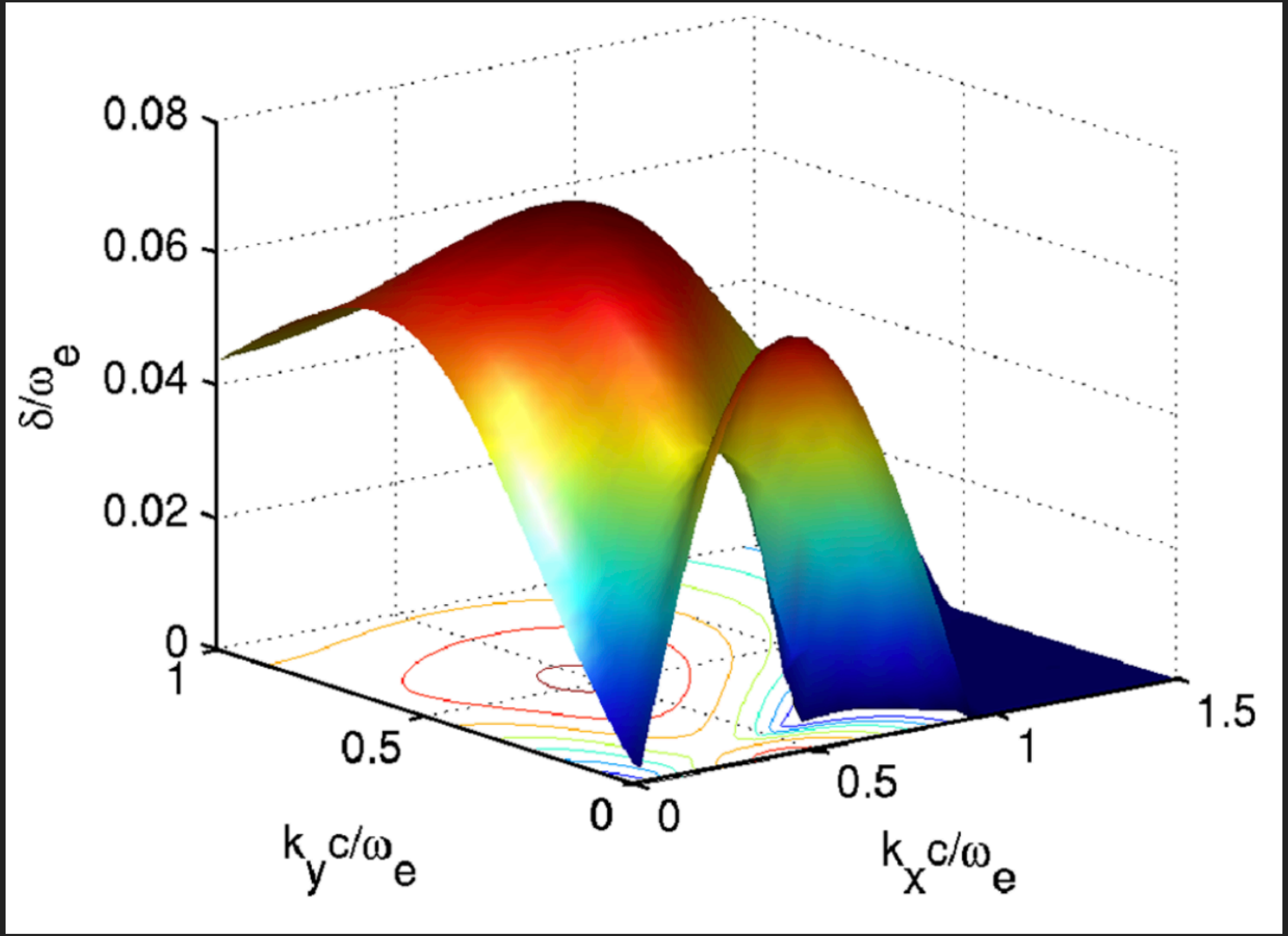

Blanco, **OG**, Jacobsen, Linden (2023) [arXiv: 2303.01524](https://arxiv.org/abs/2303.01524)

# 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 $\omega_p = \sqrt{4\pi n_p e^2 / m_e}$

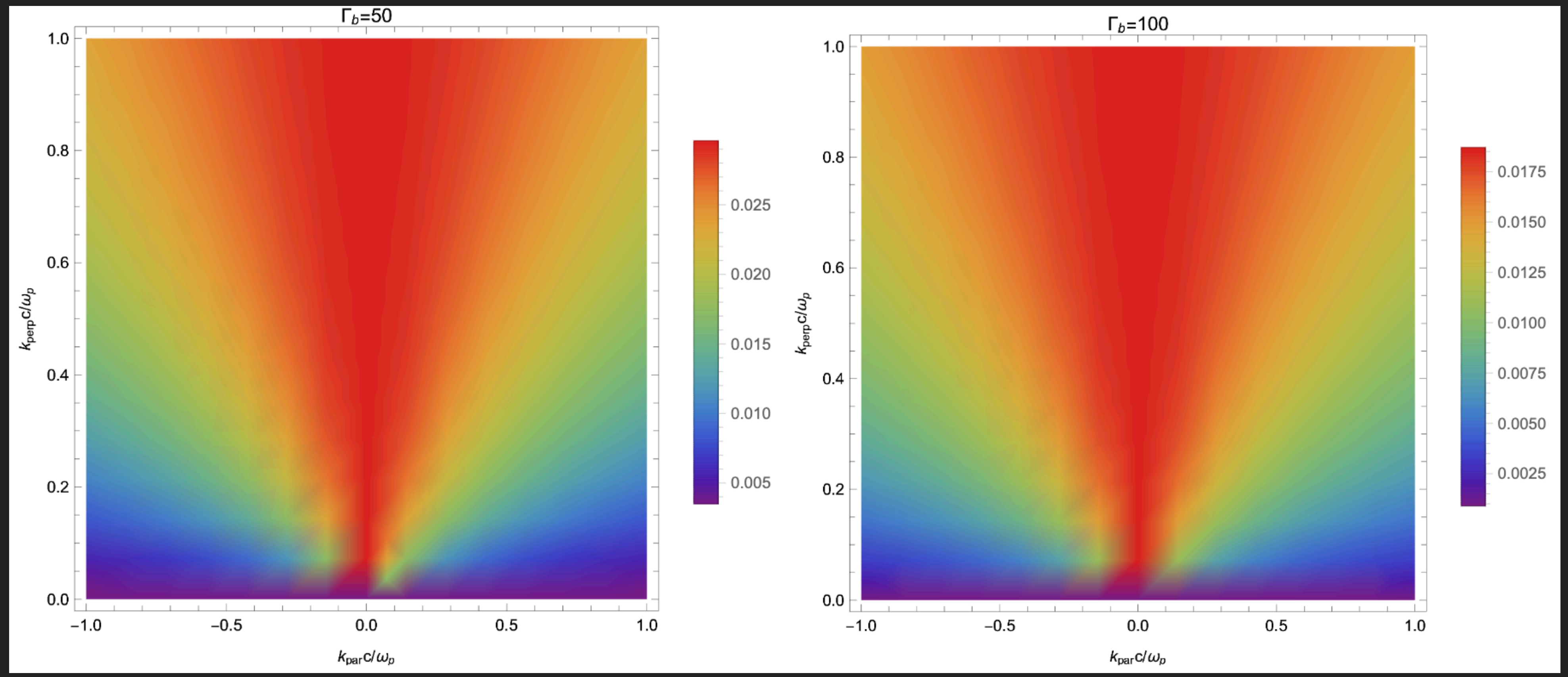
# PLASMA INSTABILITIES

- In electrostatic approximation ($\vec{B} = 0$) as
$$\Lambda(\mathbf{k}, \omega) = 1 - \frac{\omega_p^2}{\omega^2} - \sum_b \frac{4\pi n_b e^2}{k^2} \int d^3p \frac{\mathbf{k}\frac{\partial f_b(\mathbf{p})}{\partial \mathbf{p}}}{\mathbf{kv} - \omega} = 0$$
- Growth rate of unstable modes
$$\mathrm{Im}(\tilde{\omega}) = \omega_p \frac{2\pi e^2}{k^2} \int \mathbf{k} \cdot \frac{\partial f(\mathbf{p})}{\partial \mathbf{p}} \delta\left(\omega_p - \mathbf{k} \cdot \mathbf{v}\right) d^3p$$
- Key parameters: beam Lorentz factor $\gamma_b$, beam temperature $k_B T_b / m_e c^2$, and density contrast $\alpha = n_b / n_p$
- Instability modes: two-stream $\hat{k} \cdot \hat{v} = 1$, filamentation $\hat{k} \cdot \hat{v} = 0$, and oblique $\hat{k} \cdot \hat{v} = \cos\theta_0$

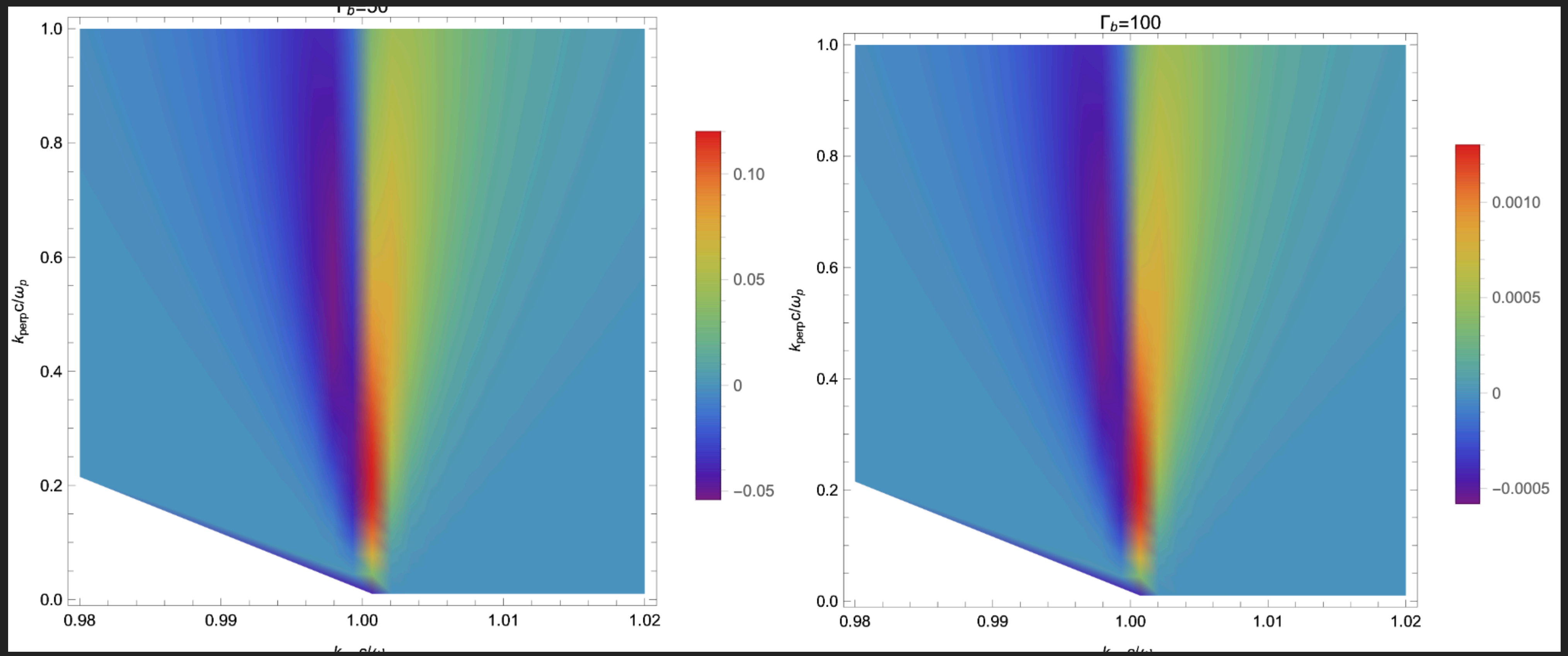



Bret et al. (2010)

# LINEAR THEORY



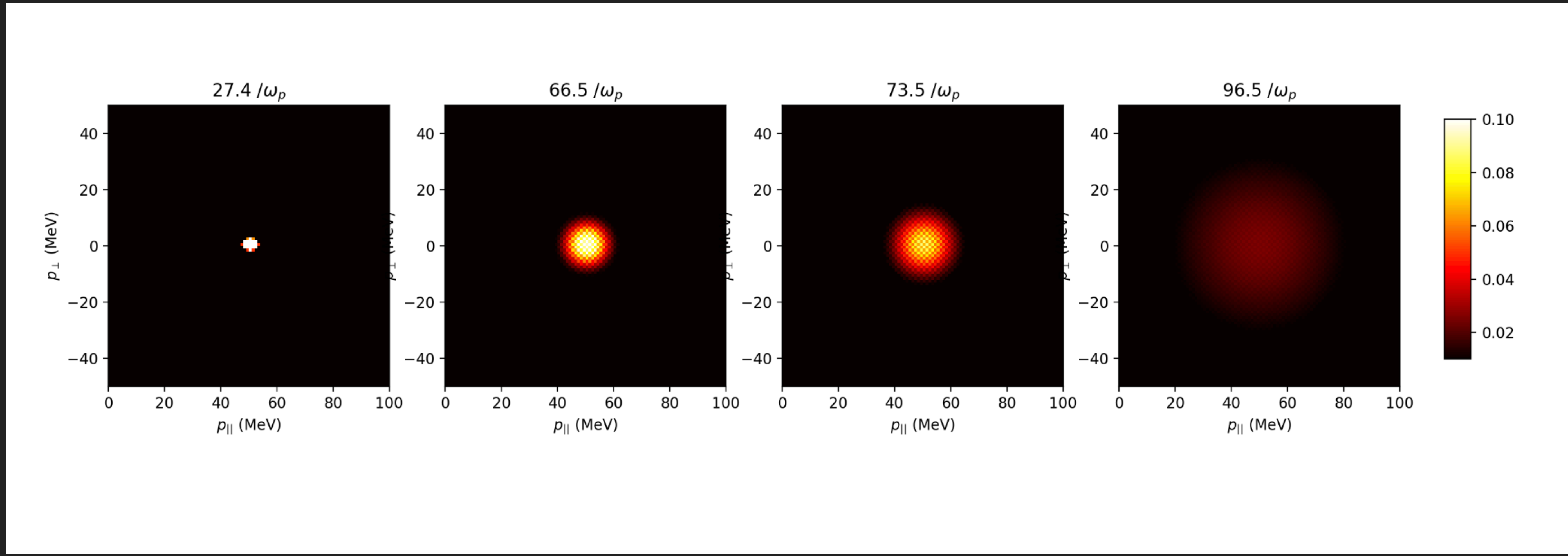

Reactive growth map ($\alpha = n_b/n_e = 10^{-3}$)




Kinetic growth map ($\alpha = n_b/n_e = 10^{-3}$)

- For monochromatic beams, $|\boldsymbol{k} \cdot \boldsymbol{\Delta}\mathbf{v}| < \mathrm{Im}(\tilde{\omega})$
- For beams with transverse momentum width, growth occurs in the so-called kinetic regime

# BEAM RELAXATION AND SELF-HEATING



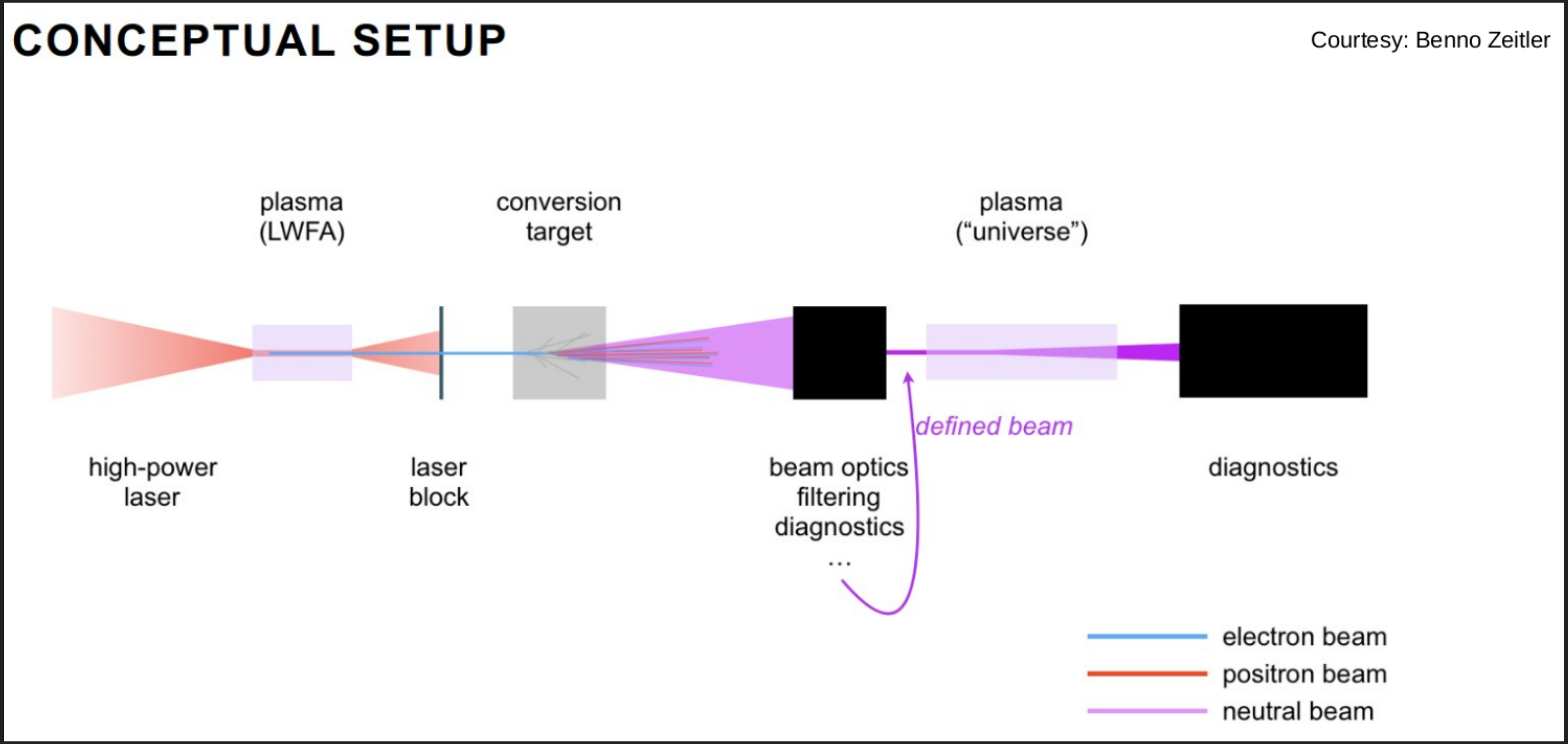

- Evolution of beam-plasma system is diffusive-dissipative described best with a Fokker-Planck equation

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

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

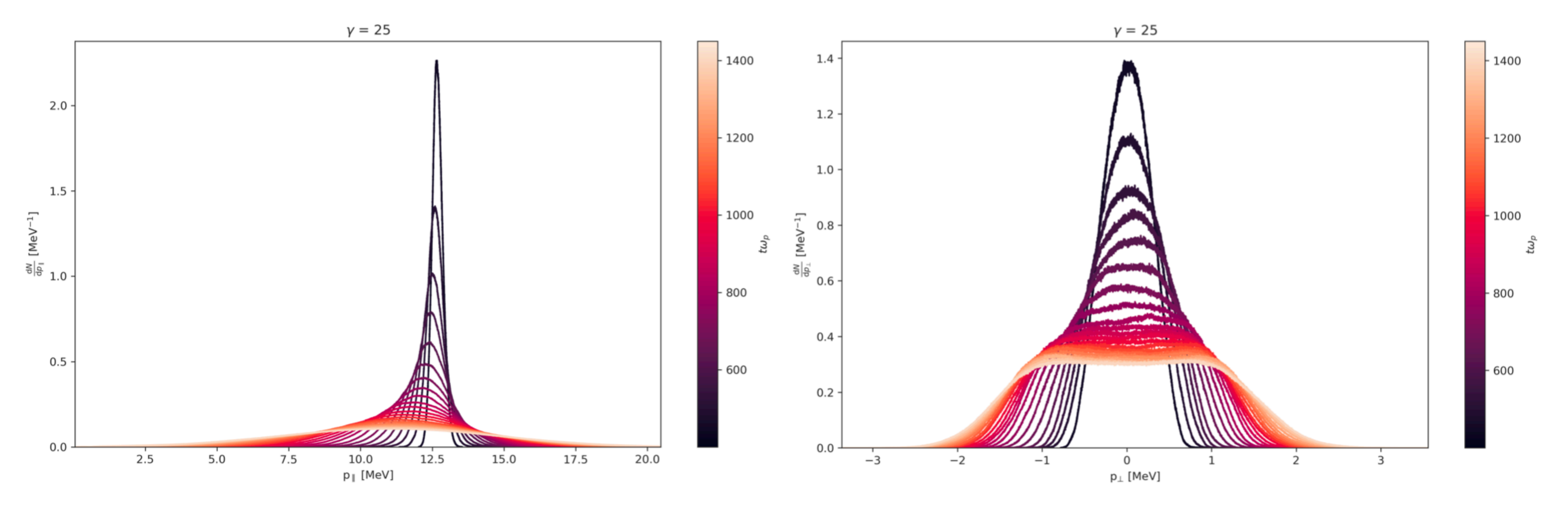
Beck, **OG**, Grüner, Pohl, Schroeder, Sigl, Stark, Zeitler 2023 arXiv: 2306.16839

# EXPLORING GEV-TEV TENSION WITH LABORATORY ASTROPHYSICS



# INSTABILITY LOSSES AND BEAM RELAXATION

- In absence of magnetic field, we observe broadening in the energy width of the beam both in the parallel and transverse direction

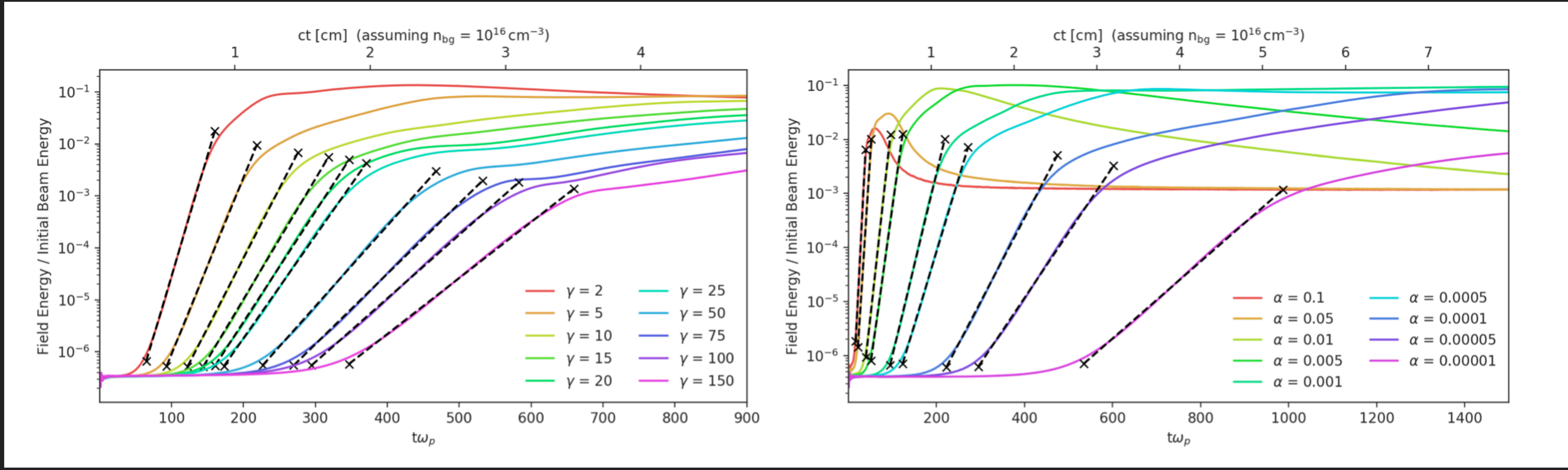



PIC evolution of a pair beam distribution for a laboratory beam-plasma system

Beck, **OG**, Grüner, Pohl, Schroeder, Sigl, Stark, Zeitler 2023 [arXiv: 2306.16839]

# LESSONS FROM LABORATORY ASTROPHYSICS & PIC SIMULATION

- The extent of energy loss of pair beams is sensitive to $\gamma_b(\sim 10^6)$, $\alpha(\sim 10^{-15})$ for TeV blazar beams




Evolution of energy transfer from the pair beam into the background plasma

Beck, **OG**, Grüner, Pohl, Schroeder, Sigl, Stark, Zeitler (2023) arXiv: 2306.16839

# ENERGY LOSS AND IGM HEATING

- Energy loss due to instabilities depend on growth rate
$$W(k) = W_0 \int_0^\tau \exp[2\ \mathrm{Im}(\tilde{\omega})\ dt]$$
- Characteristic instability timescale $\tau \sim 1/\mathrm{Im}(\tilde{\omega})$
- Initial spectral energy density $W_0$ is determined by thermal fluctuations in the IGM plasma, $\sim \mathcal{O}(\mathrm{keV})$
- Maximum energy loss occurs for the oblique growth for near-monochromatic injection $\mathrm{Im}(\tilde{\omega}) \propto (\frac{\alpha}{\gamma_b})^{1/3}$

# BLAZAR HEATING: A MODIFIED THERMAL HISTORY

Parameterization of instability losses w.r.t. ICS

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**Parameterization of instability losses w.r.t. ICS**

- Contribution of plasma instabilities

$$f\left(F_E, E, z\right) = 1 - f_{\mathrm{IC}} = \frac{\Gamma_{\mathrm{plasma}}}{\Gamma_{\mathrm{IC}} + \Gamma_{\mathrm{plasma}}}$$

- ICS rate

$$\Gamma_{\mathrm{IC}} = \frac{4\sigma_{\mathrm{T}} u_{\mathrm{CMB}}}{3 m_e c}\gamma_b \simeq 1.4 \times 10^{-20} (1+z)^4 \gamma_b \mathrm{s}^{-1}$$

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**Properties of the gamma-ray emission**

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**Properties of the gamma-ray emission**

- VHEGR flux $F_E = EdN/dE \propto E^{1-\beta}$
- Redshift dependence of the mean free path is characterised by star formation history (through EBL)

$$D_{\mathrm{pp}}(E, z) = 35 \left(\frac{E}{1\mathrm{TeV}}\right)^{-1} \left(\frac{1+z}{2}\right)^{-\zeta} \mathrm{Mpc}$$

# BLAZAR HEATING: A MODIFIED THERMAL HISTORY

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

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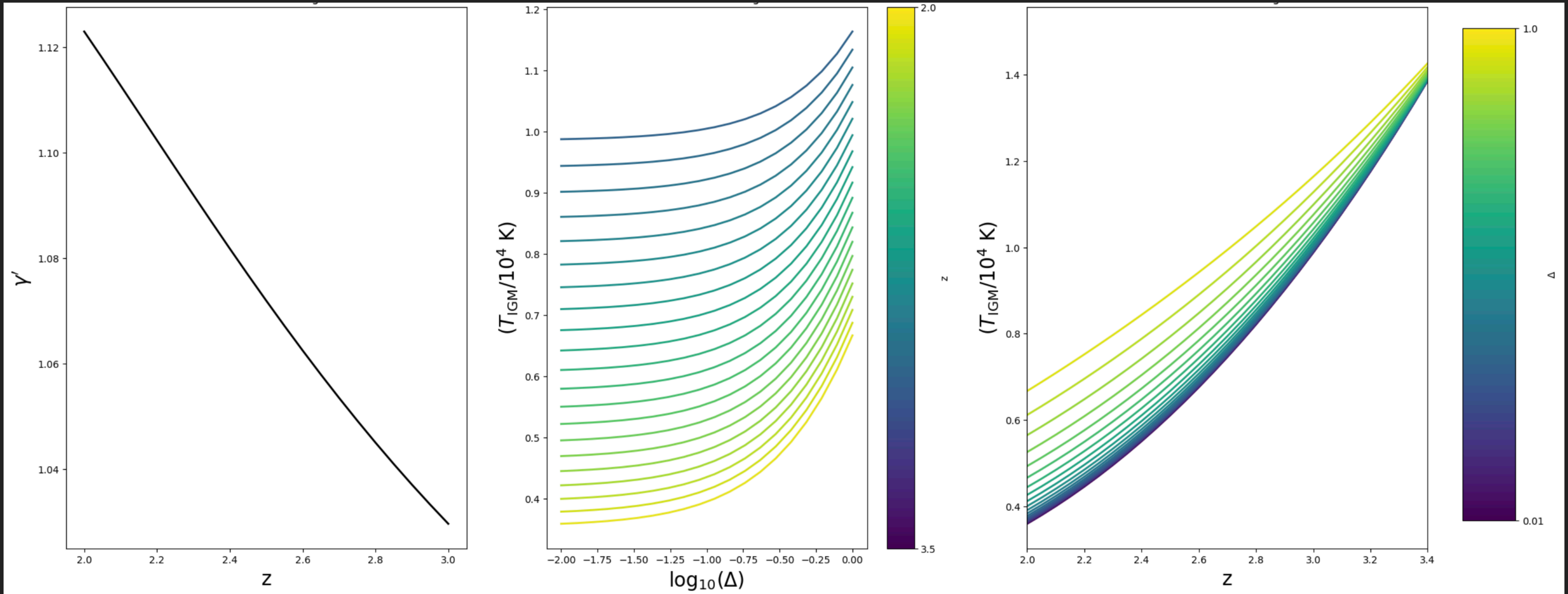
- Casting temperature-density-redshift relation during $2 < z < 3.5$ as
$$T = T_0 \Delta^{\gamma(z)'-1}$$

# BLAZAR HEATING: A MODIFIED THERMAL HISTORY

**OG** & Bhattacharyya *(in preparation)*




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

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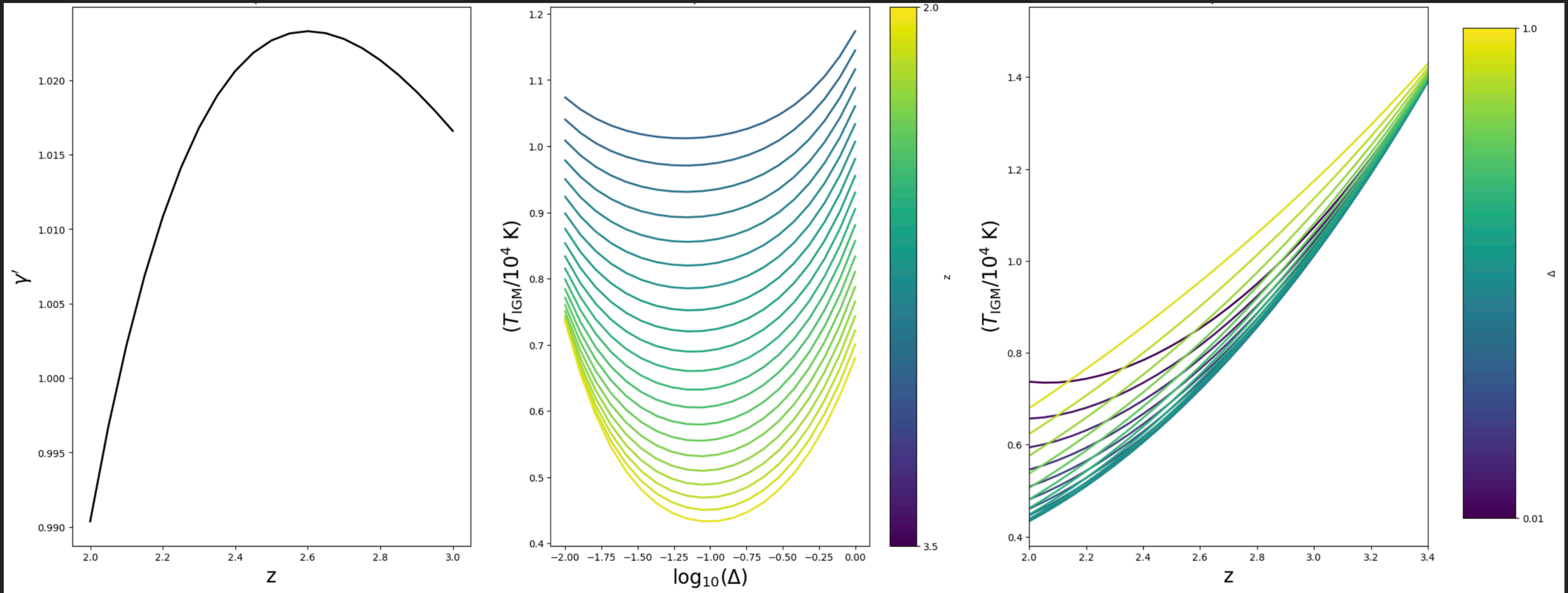
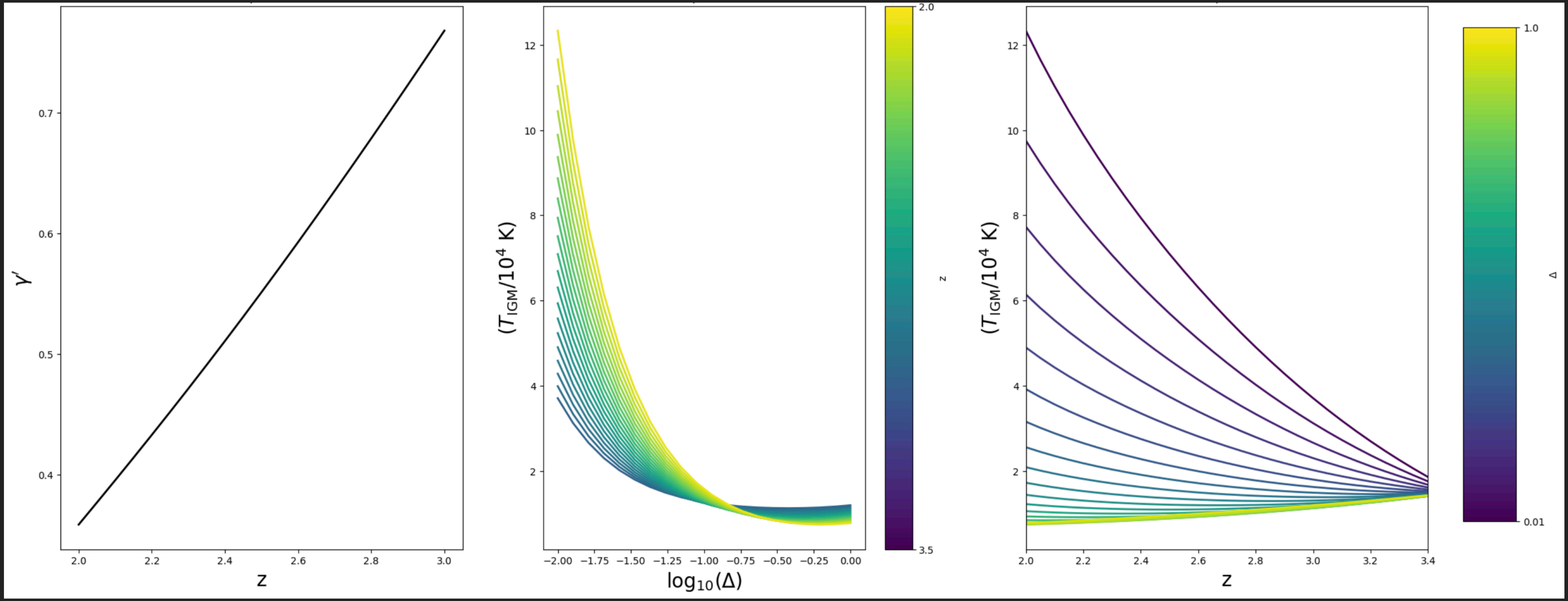



Redshift evolution of index, temperature-density and temperature-redshift relation for low global blazar heating

# BLAZAR HEATING: A MODIFIED THERMAL HISTORY

**OG** & Bhattacharyya *(in preparation)*




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

# BLAZAR HEATING: A MODIFIED THERMAL HISTORY

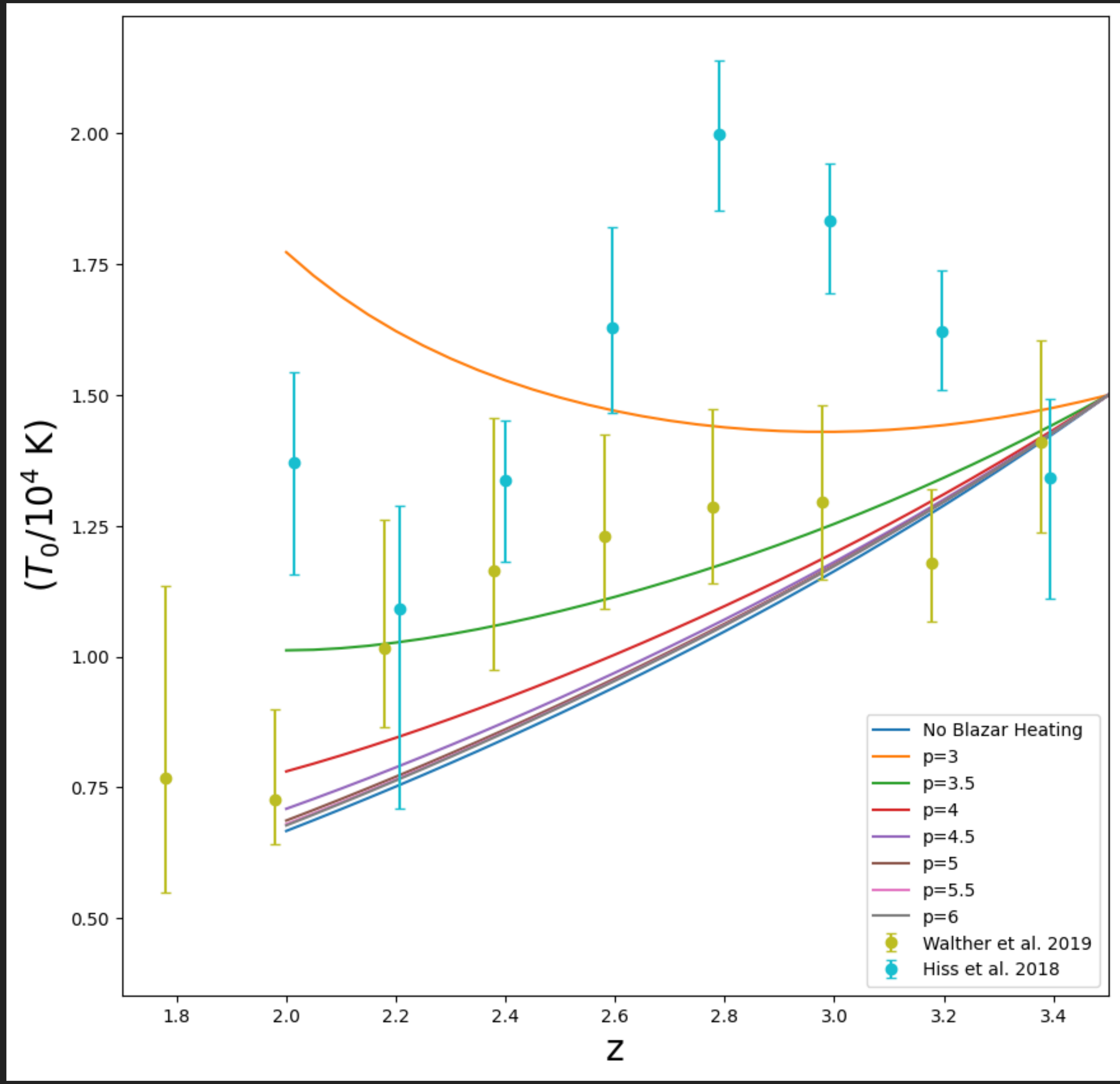
- Blazar-heating inverts the temperature-density relation
- This leads to an elevated entropy floor, raising the filtering mass
- Effective redshift-dependence of volumetric heating from fitting 40 blazars

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

(Chang *et al*, 2011)

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

# BLAZAR HEATING: A MODIFIED THERMAL HISTORY

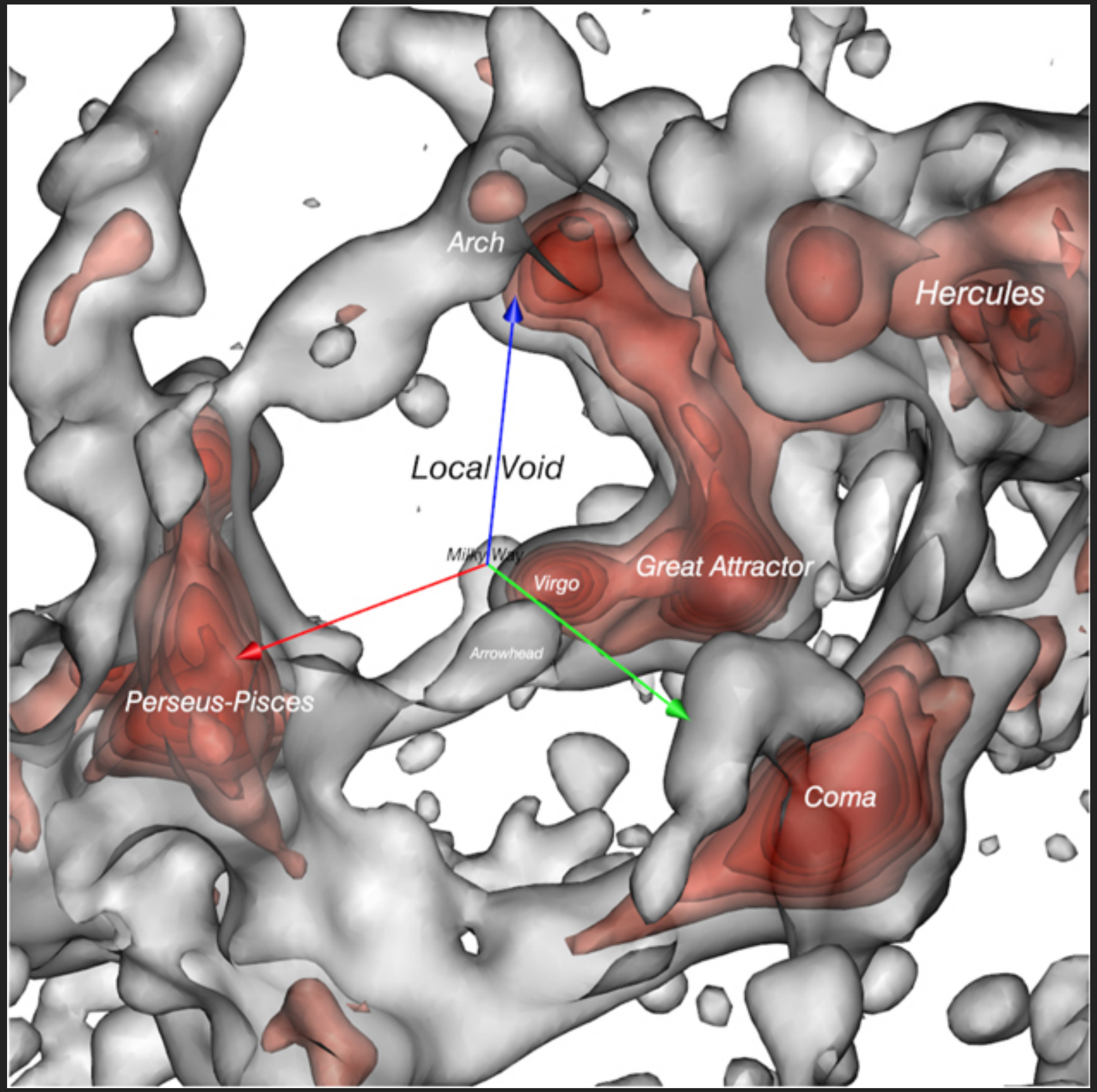



- Reionization ends at z=3.5
- Lyman-$\alpha$ bounds indicate IGM temperature at mean density favours intermediate to low levels of blazar heating
- Main source of uncertainty stems from HeII reionization models

**OG** & Bhattacharyya *(in preparation)*

# BLAZAR HEATING: A MODIFIED THERMAL HISTORY

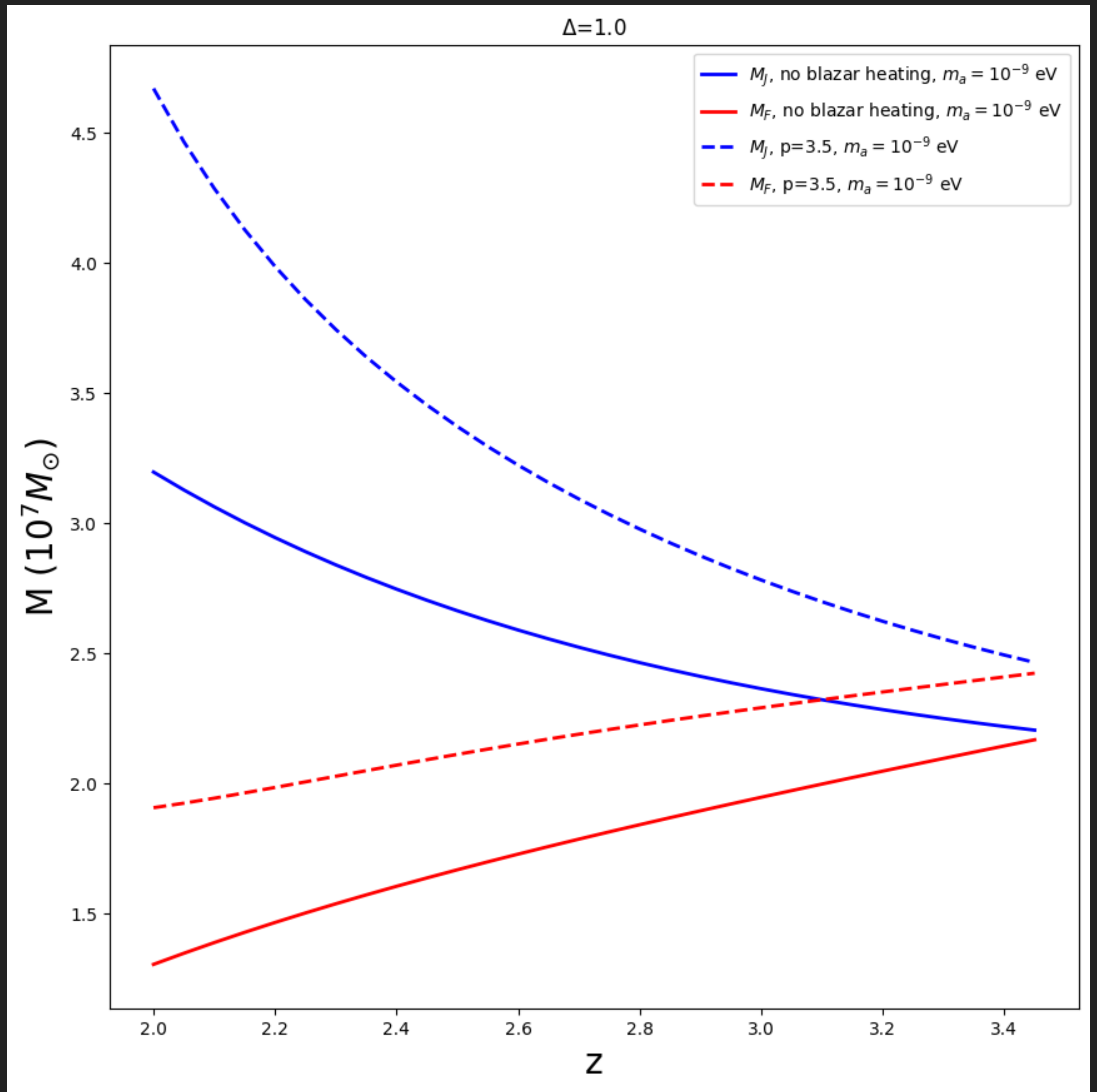
- Void dwarfs are relatively isolated, with less rich merger and accretion history
- Worthwhile to explore cosmologies with various degrees of blazar heating
- Implications for light dark matter candidates such as axion-like particles

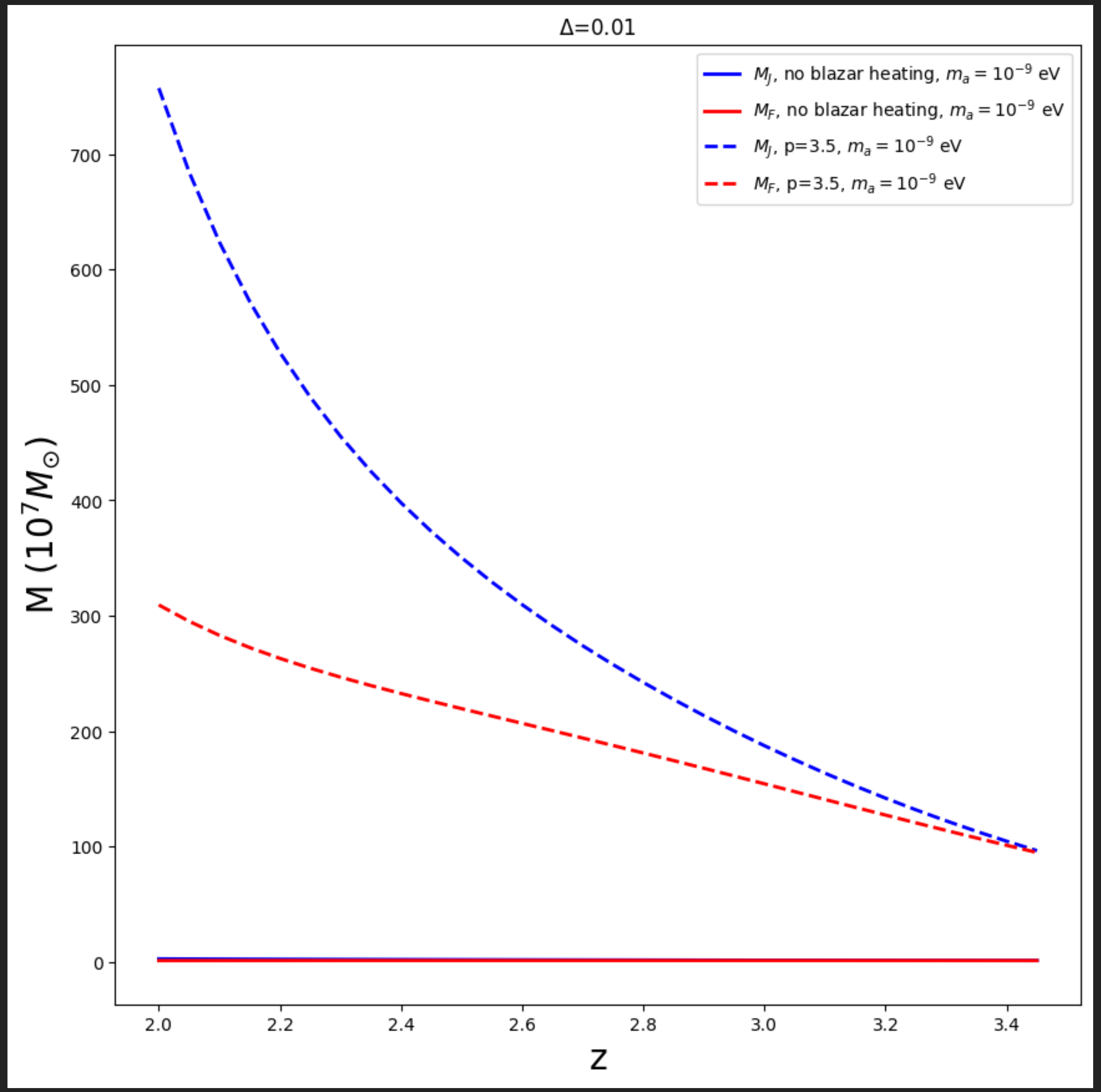



R. Brent Tully *et al* 2019 *ApJ* **880** 24

# BLAZAR HEATING: A MODIFIED THERMAL HISTORY

- Impact of global blazar heating is most prominent in underdense regions
- Blazar heating in the voids leads to modification the filtering masses
- Redshift dependence shows the impact is stronger at late times

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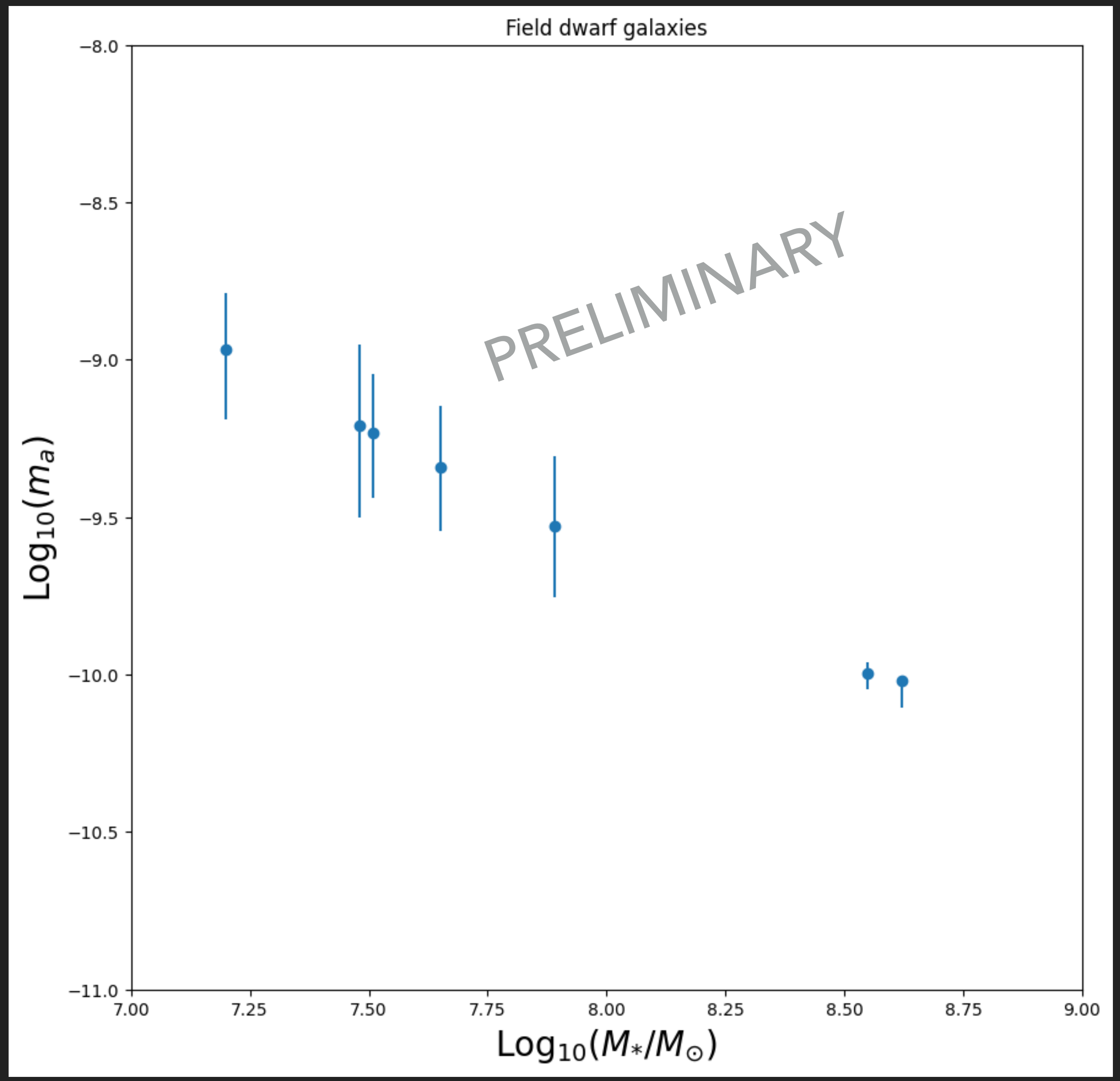
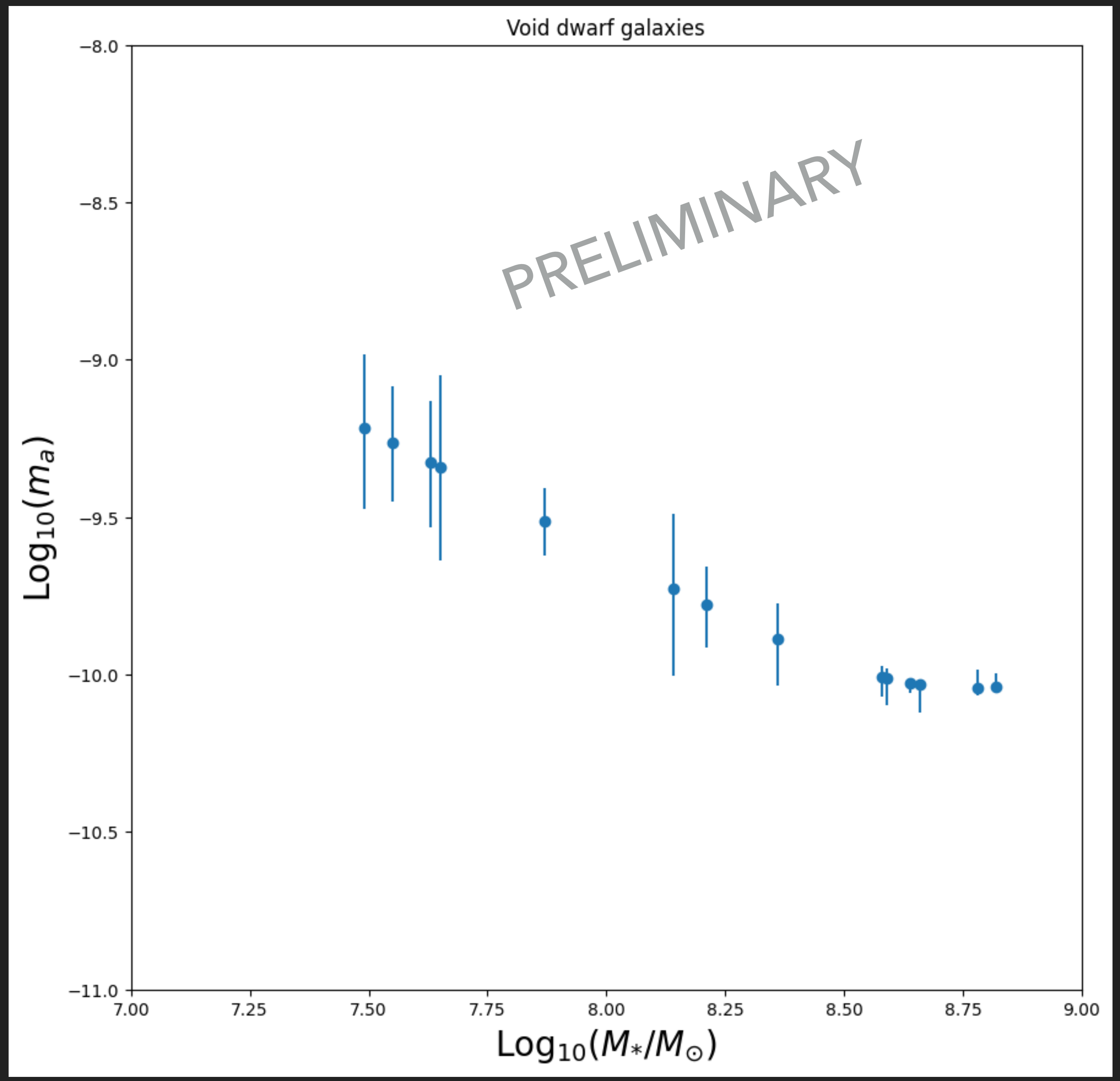



- A comparison between of field and void dwarfs based stellar kinematics data from KCWI (de Los Reyes *et al*, 2023) translates to ALP masses of $m_a \sim 10^{-10} - 10^{-9}$ eV in presence of blazar heating (shown for p = 3.5)

**OG** & Bhattacharyya *(in preparation)*

# KEY TAKEAWAYS

- GeV-TeV tension combined with absence of pair halo and IGRB measurements 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
- Momentum diffusion in the beam can suppress instabilities thus energy drain is slower and not as efficient, magnetic diffusion more important for TeV blazar beams
- In absence of significant inhomogeneities in the IGM, instability losses heat the intergalactic medium, altering thermal histories locally
- Strongly supported by Lyman-$\alpha$ 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 $m_a \sim 10^{-10} - 10^{-9}$ eV

# Thank you!

oindrila.ghosh@fysik.su.se

# 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

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

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

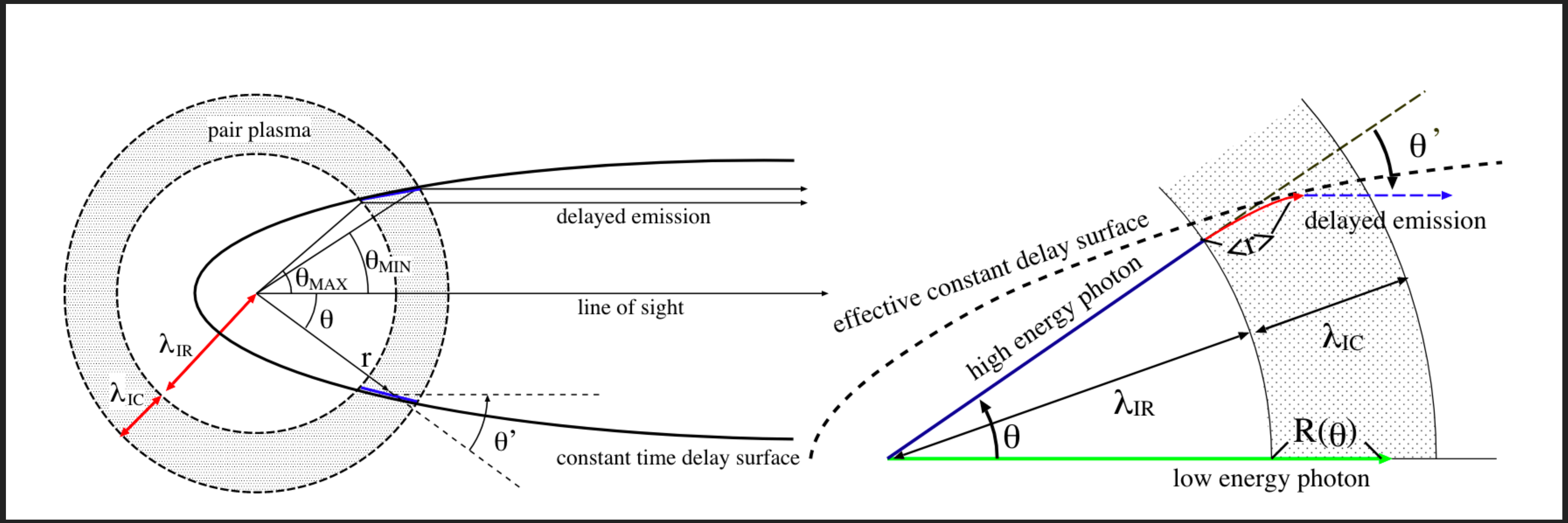
# BACKUP: MOMENTUM DIFFUSION IN COSMIC PAIR BEAMS

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

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

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

# BACKUP: MOMENTUM DIFFUSION IN COSMIC PAIR BEAMS




- Delayed gamma-ray flux

$$\frac{d^2N_{\text{delayed}}}{dtdE_\gamma} = \int d\gamma_e \frac{dN_e}{d\gamma_e}\frac{d^2N_{IC}}{dtdE_\gamma}$$

- Taking into account ICS, this can be written as

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

Ichiki & Inoue, 2007

# BACKUP: MOMENTUM DIFFUSION IN COSMIC PAIR BEAMS

- Pairs at production travels to the observer at a speed of
$$\frac{d\langle r\rangle}{dt_{\rm obs}} = \frac{2c}{(1+z)\left[\theta^2 + \Theta^2/3\right]}$$

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

# 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 $\Delta k$
- $\Lambda$ 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