Impact of cosmic rays on the pair beam instability from TeV blazars

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Yang, Long, Hirata, *Astrophys. J.*, **965**:111 (2024); arXiv:2311.18721
Yang, Long, Hirata, *in prep*

Outline

1. Interaction of TeV gamma rays with the IGM
2. Fate of e^+e^- pair beams
3. MeV cosmic rays: a new ingredient
4. Outlook

Interaction of TeV γ-rays in IGM

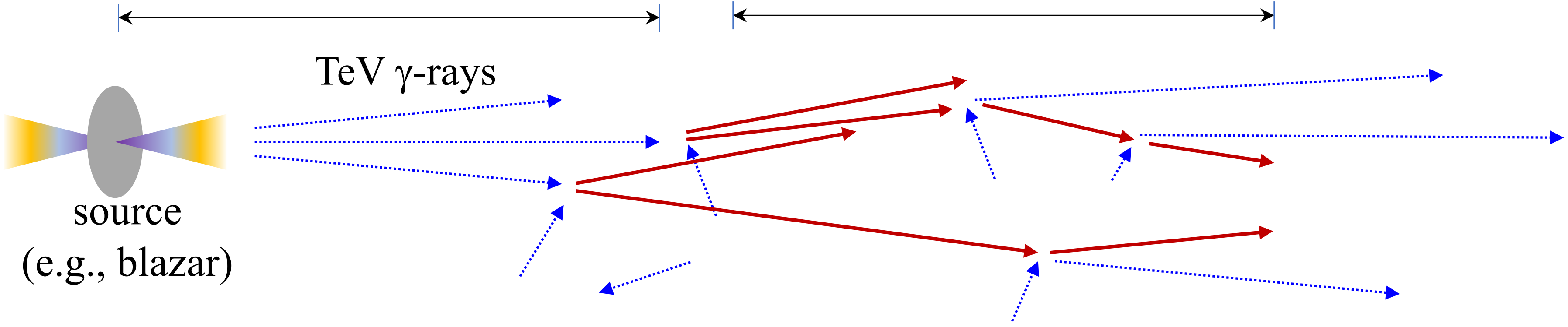
(in the absence of magnetic fields & plasma interactions)

(1) Pair production

$$\gamma_{\mathrm{TeV}} + \gamma_{\mathrm{EBL}} \rightarrow e^{+} + e^{-}$$

(2) Compton cooling

$$e^{\pm} + \gamma_{\mathrm{EBL}} \rightarrow e^{\pm} + \gamma_{\mathrm{IC}}$$



mean free path ~ tens of Mpc
(depends on *E* & *z*)

cooling length ~ 10 kpc
@ z=2 & γ_e=10^6

TeV γ-rays

source
(e.g., blazar)

KEY:
⋯▸ photon
⟶ e^+ or e^-

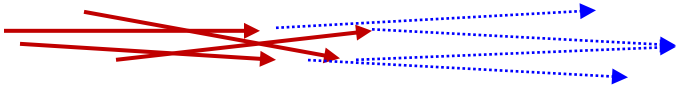
Extragalactic background light (EBL)
~ eV energies
(from starlight)

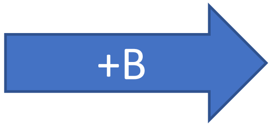
inverse Compton photons
e.g., optical → ~100 GeV

* Not to scale: $e^{\pm}$ are produced, cool, and are replenished over the attenuation length of the TeV beam.

Possible outcomes

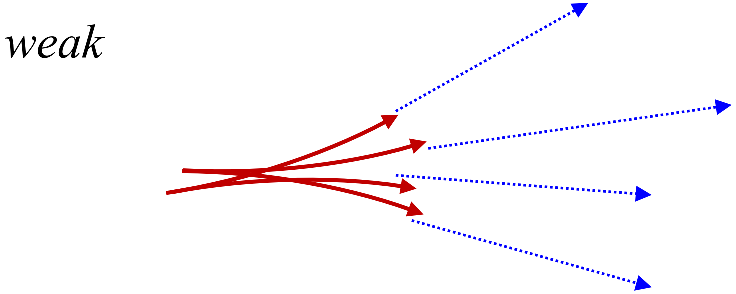
No magnetic field —
forward-beamed
cascade γ-rays

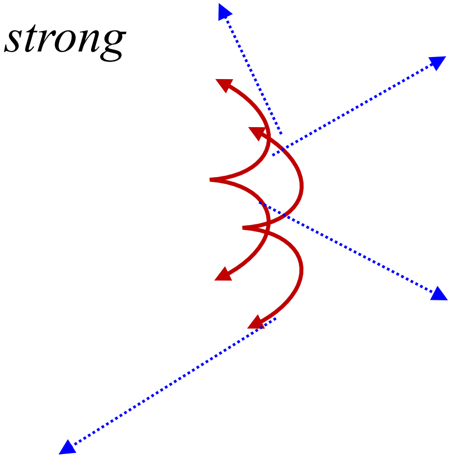




Intergalactic magnetic fields can **broaden** or **isotropize** the cascade γ-rays. Probe of IGMF!

Aharonian et al. 1994; Neronov & Vovk 2010;
Fermi, HESS collaborations; … review by Alves Batista & Saveliev 2021

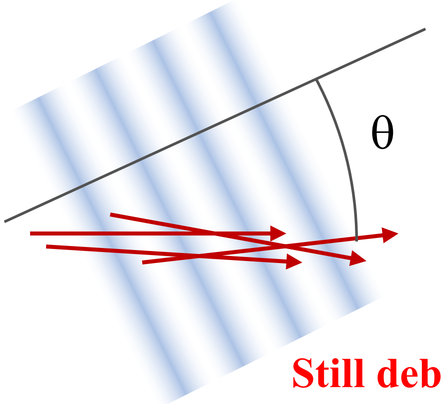




OR

Excitation of plasma oscillations?
(beam-plasma instability)

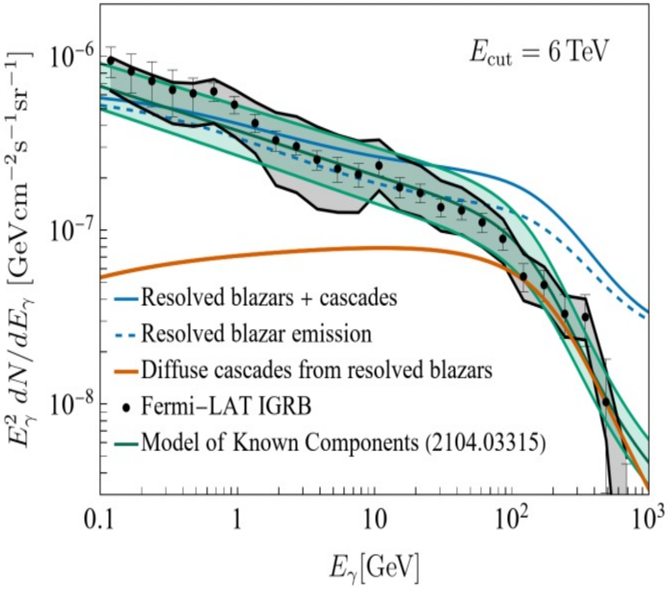
Broderick et al. 2012



Still debated whether this mechanism operates and (if so) what the outcome is.

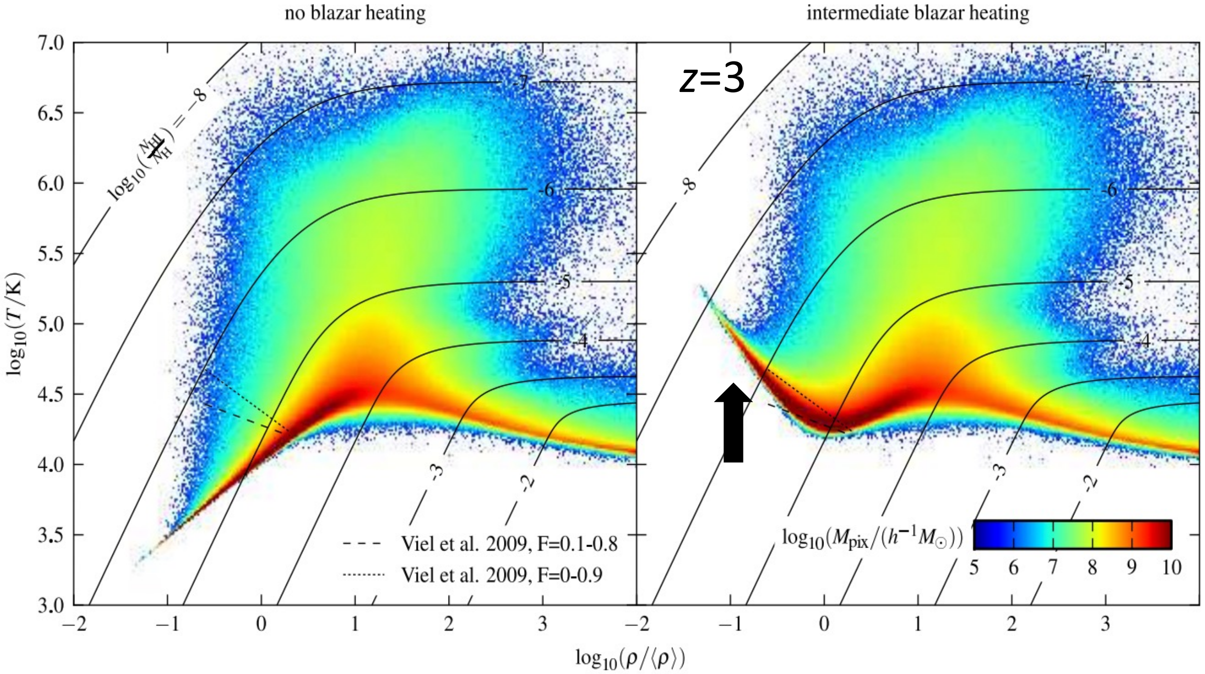
Impact of the plasma instability question

"Missing" cascade photons?
Blanco et al. 2023



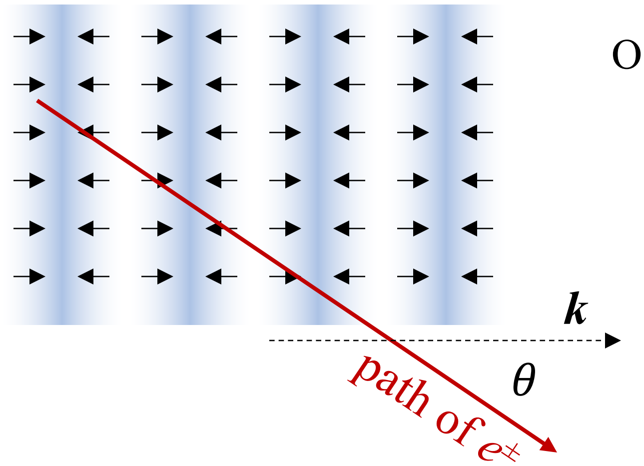
Effect on IGM temperature if beam energy is thermalized.
IGM $T(\rho)$ is a key ingredient for extracting cosmological parameters from Lyman-α forest.

Simulation by Puchwein et al. 2012



Plasma oscillations & resonance

Electrons displacement along wave vector ***k***



Oscillate at (approximately) plasma frequency

$$\omega_p = \sqrt{\frac{q_e^2 n_{e,\mathrm{th}}}{\varepsilon_0 m_e}}$$

22 Hz @ z=2, mean density

(phase velocity = c at wavelength ~14,000 km)

Particle resonates with a wave if $v\cos\theta \approx \frac{\omega_p}{k}$

$$\boxed{\text{NEED} \quad v \geq \frac{\omega_p}{k}}$$

- Particles moving slightly slower extract energy from the wave (Landau damping)
- Particles moving slightly faster add energy to the wave (excitation)

Isotropic particle distribution leads to net damping:

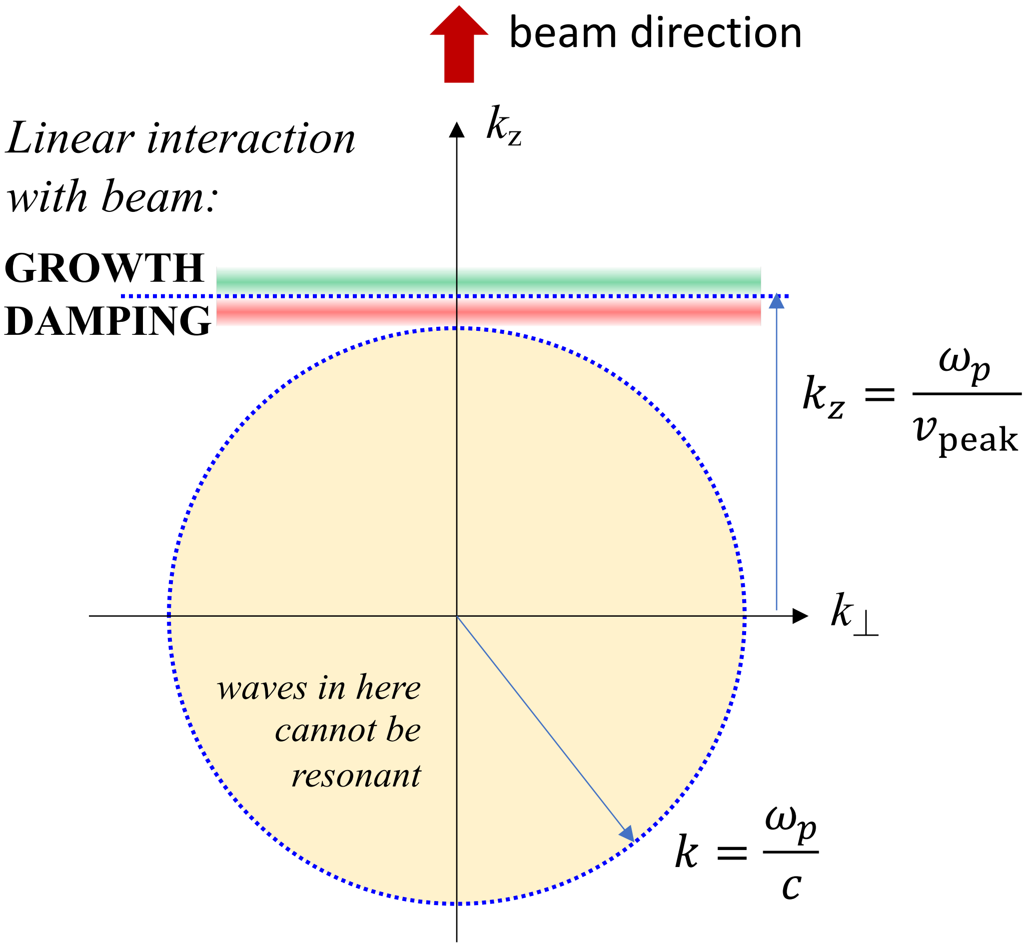
$$t_{\mathrm{damp}}^{-1} = \frac{\pi}{4}\omega_{\mathrm{p}}\left(\frac{\omega_{\mathrm{p}}}{ck}\right)^3 \frac{m_e c^2}{n_{e,\mathrm{th}}}\left\{\frac{E_{\min}+m_e c^2}{\sqrt{E_{\min}(E_{\min}+2m_e c^2)}}N(E_{\min}) + 2\int_{E_{\min}}^{\infty}\frac{N(E)\,dE}{\sqrt{E(E+2m_e c^2)}}\right\}\Theta\left(\frac{ck}{\omega_{\mathrm{p}}}-1\right)$$

$$E_{\min} = m_e c^2\left(\frac{1}{\sqrt{1-\omega_p^2/c^2k^2}}-1\right)$$

(minimum kinetic energy to resonate with wave)

Beam-plasma instability

Wave modes in Fourier space



beam direction

Linear interaction with beam:

GROWTH

DAMPING

k_z

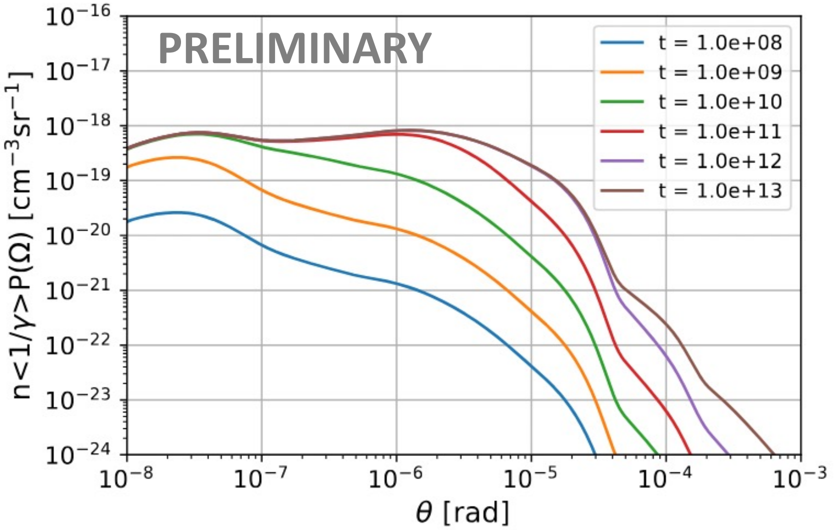
$k_\perp$

$$k_z = \frac{\omega_p}{v_{\rm peak}}$$

waves in here cannot be resonant

$$k = \frac{\omega_p}{c}$$

Development of angular beam profile (including pair production source, Compton & Molière broadening; no plasma instability or B-field)
Yang et al. in prep



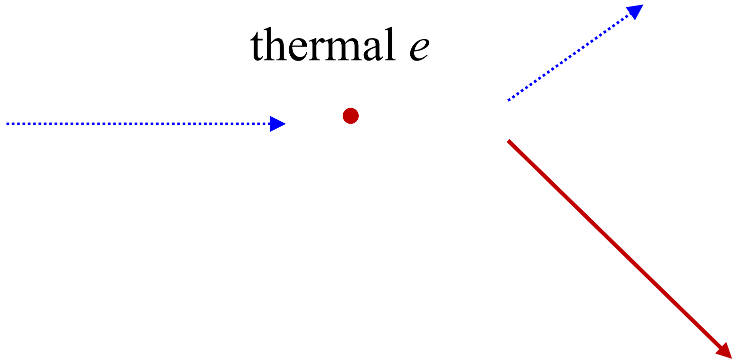
z=2, mean density IGM,
10 Mpc from fiducial blazar
(Mrk421-like spectrum: Albert et al. 2020)

Beam is dilute, growth timescales are long

==> $t_{\rm grow} \sim 10^{10}$ s

New ingredient: cosmic rays

- Thermal electrons cannot resonate with these waves (too slow).
- But what about cosmic rays?
- Even “pristine” unshocked regions of the IGM must have electron cosmic rays because they are illuminated by the ~MeV γ-ray background.



thermal *e*

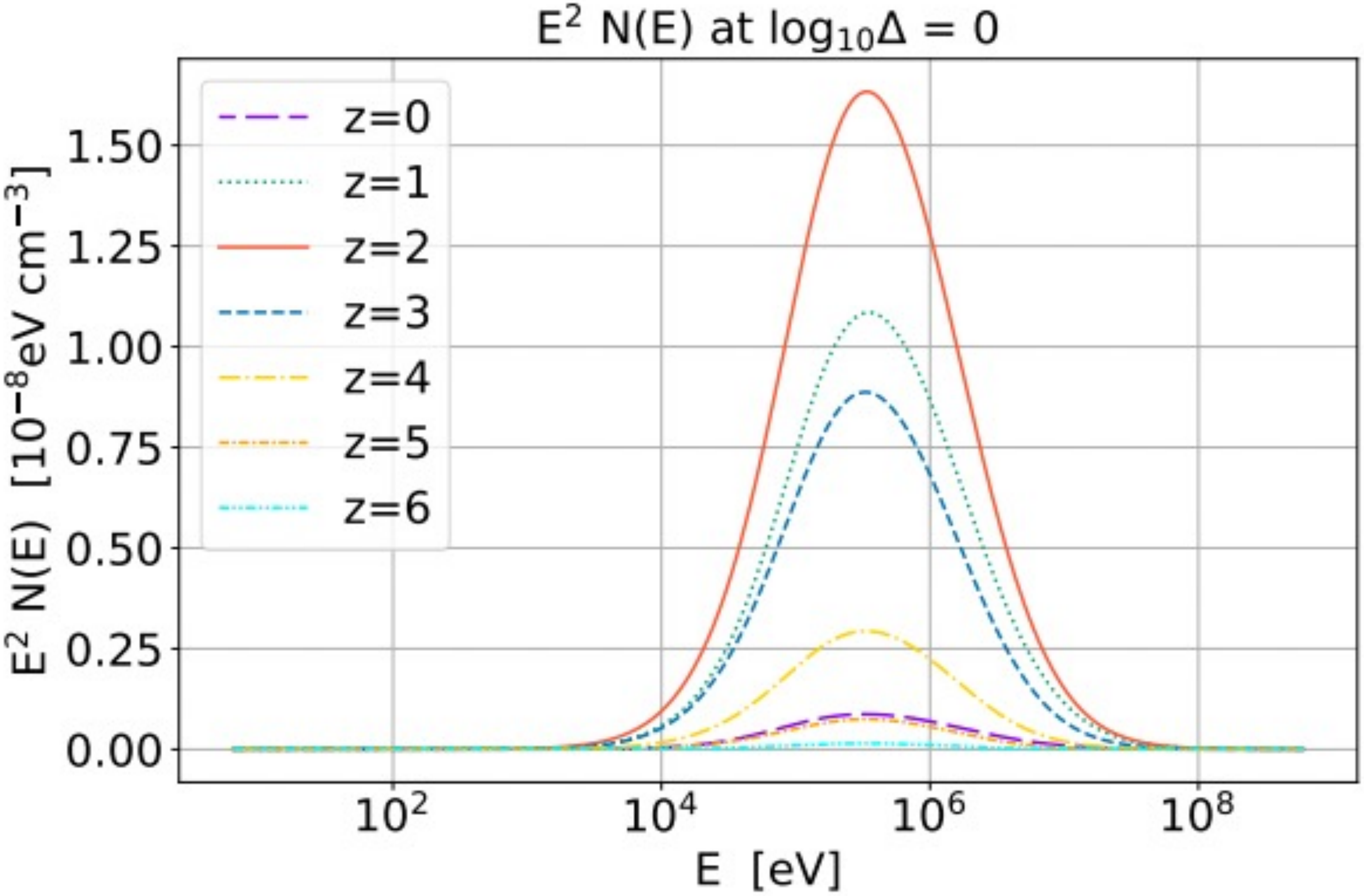
$$\boxed{\gamma + e^-_{\rm th} \to \gamma + e^-_{\rm CR}}$$

scattered electron
at IGM densities, the energy
loss timescale can be > age of Universe

- Source of heating in low-*z* IGM (Madau & Efstathiou 1999)
- Electron CR contribute up to ~2% of pressure at z=0, and modify plasma properties (Yang, Long, Hirata 2024)

Evolution of Compton-induced cosmic ray spectrum at mean density

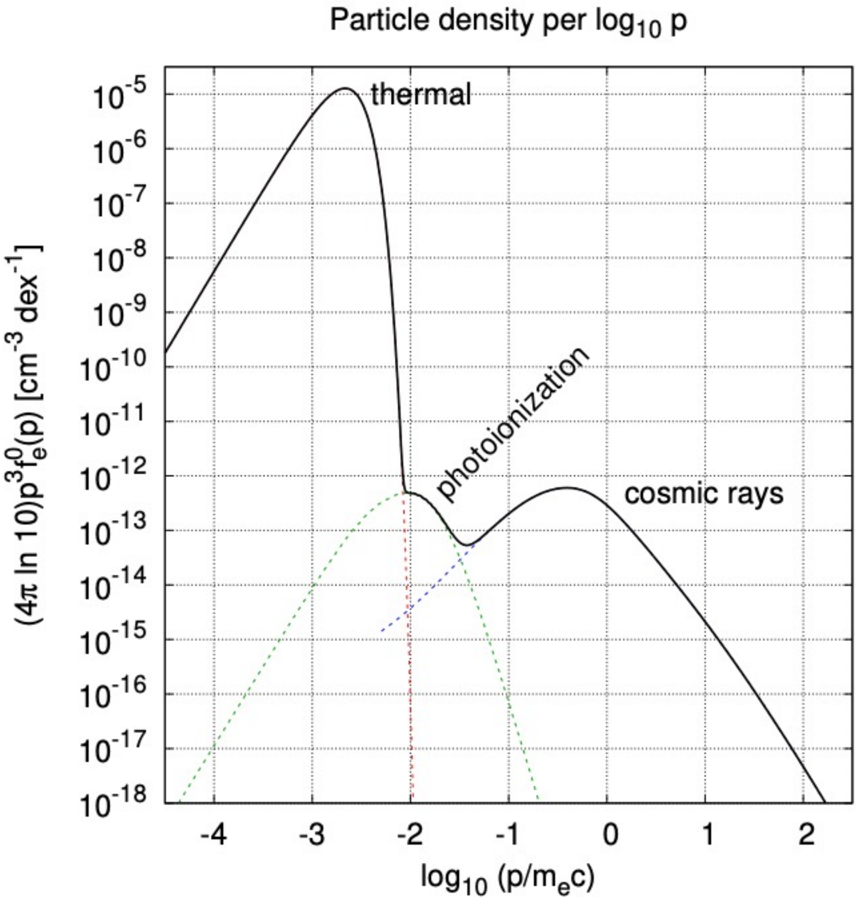
(using Khaire & Srianand EBL model)

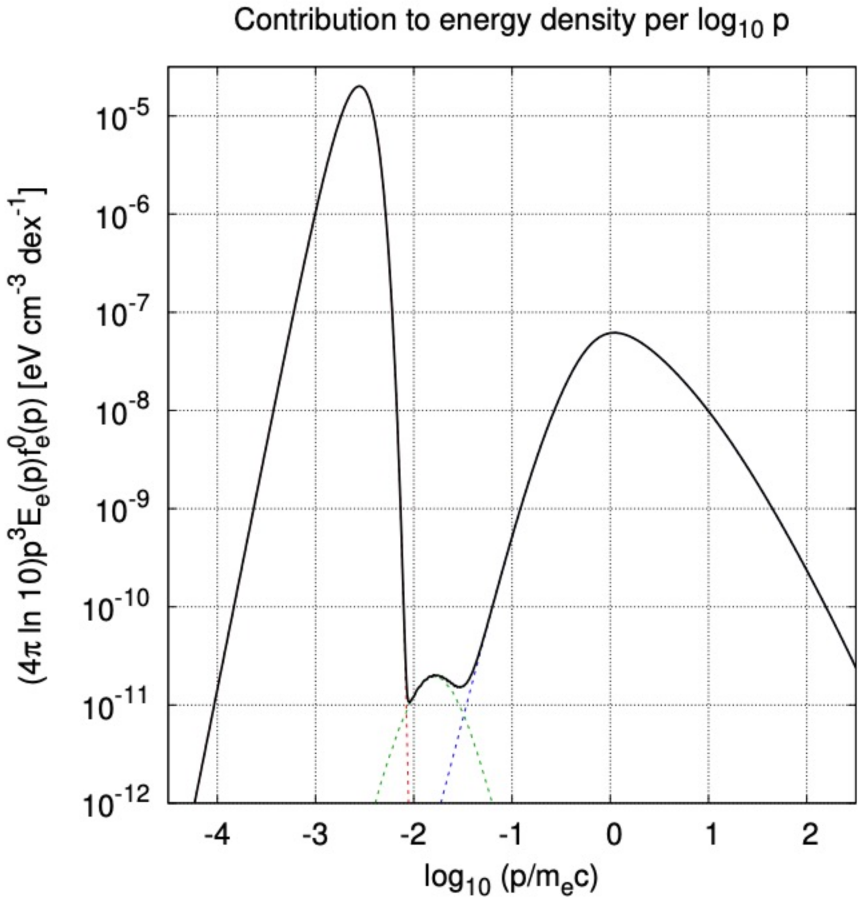


Yang, Long, Hirata 2024

Synthesis model of the electron spectrum in “pristine” IGM

z=2, mean density

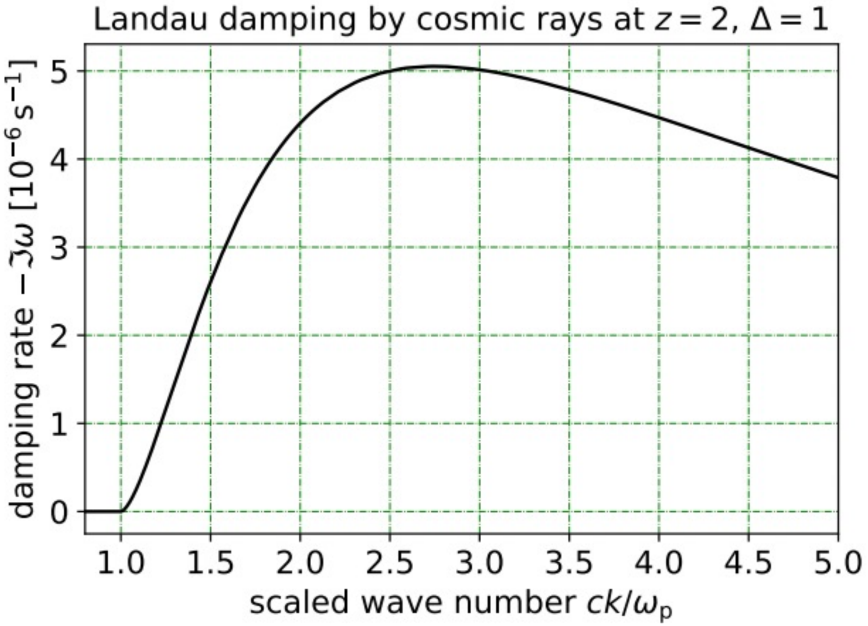

Particle density per $\log_{10}$ p

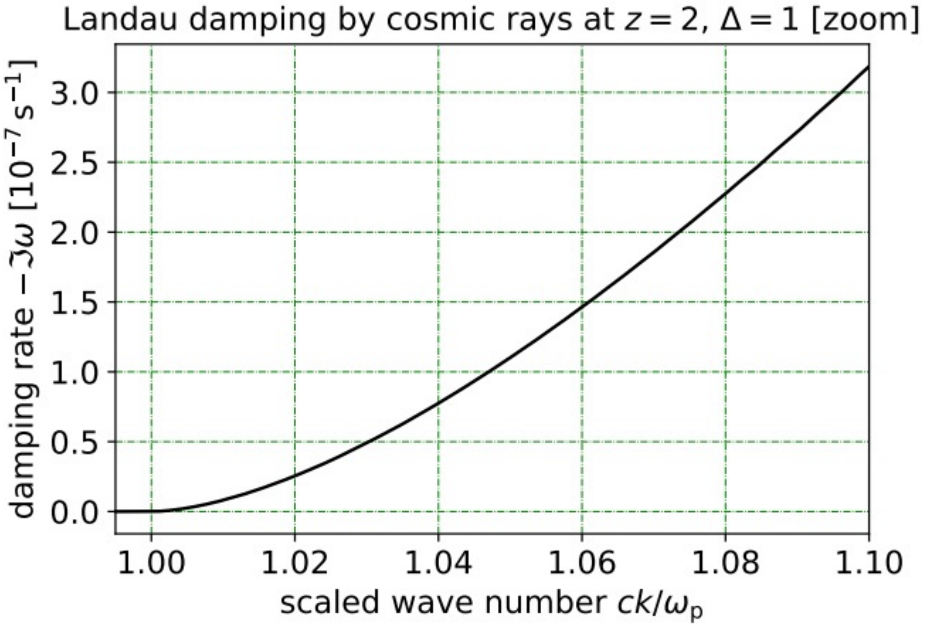

Contribution to energy density per $\log_{10}$ p

Yang, Long, Hirata 2024

Linear damping of plasma oscillations by the electron CRs

z=2, mean density





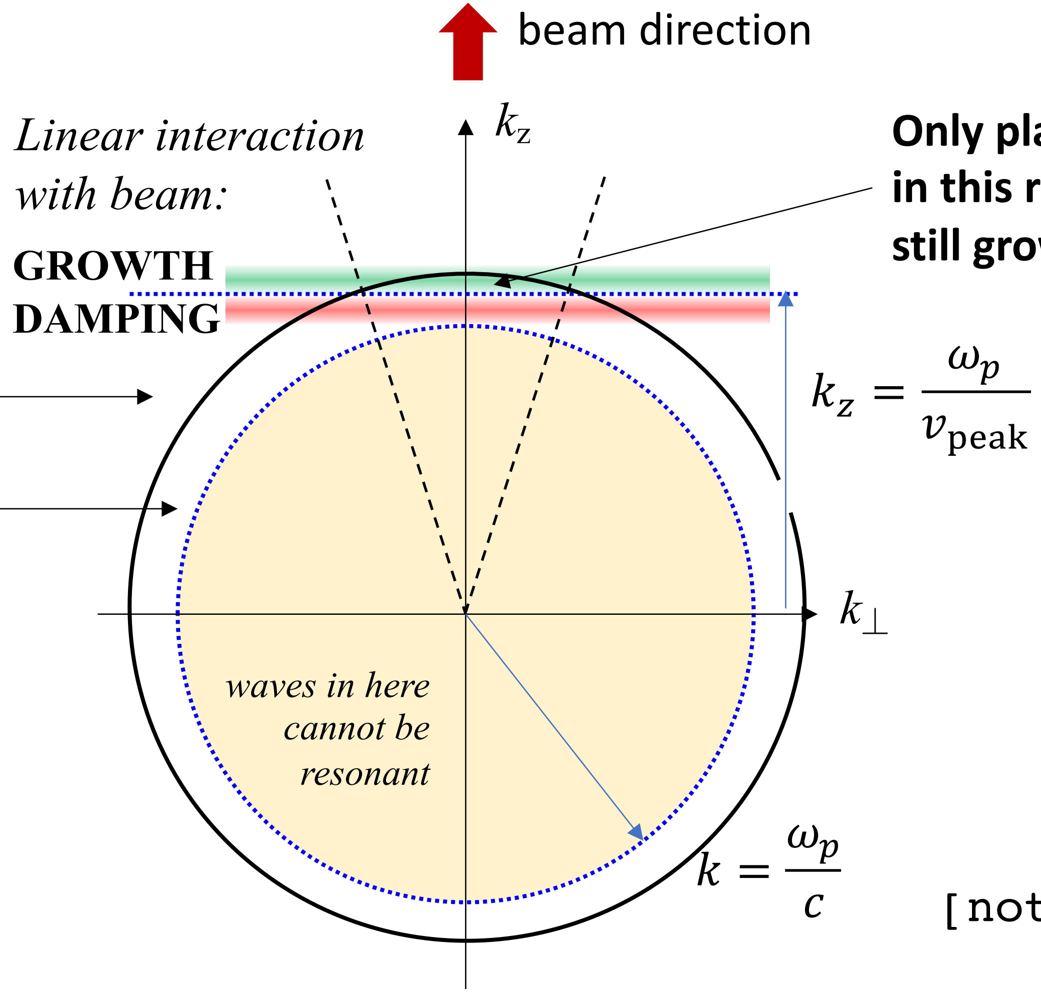
Yang, Long, Hirata 2024

Note extremely rapid timescale: $t_{\mathrm{damp}} \sim 10^6$—$10^7$ s

… except at k very close to ω_p/c.

Implications for beam-plasma system

Wave modes in Fourier space



beam direction

k_z

Linear interaction with beam:

GROWTH

DAMPING

Only plasma oscillations in this region can still grow.

Modes out here are strongly damped

Modes here survive

$$k_z = \frac{\omega_p}{v_{\text{peak}}}$$

$k_\perp$

waves in here cannot be resonant

$$k = \frac{\omega_p}{c}$$

`[not to scale]`

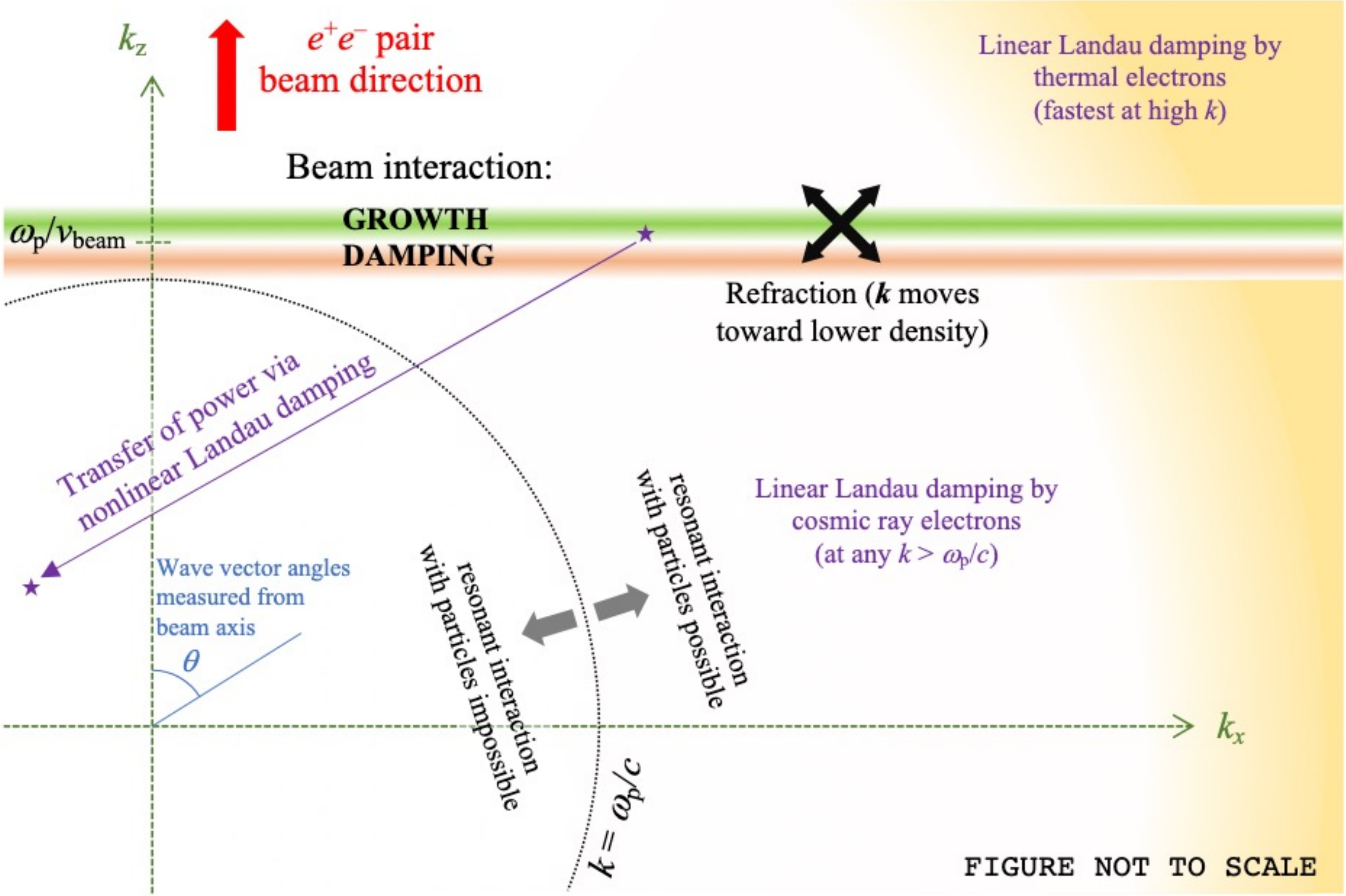
So what happens?

- We're still working on that, because it depends on the non-linear development of the instability.
- On the one hand, **most of the wave vector space for the beam-plasma instability is turned off**.
  - These "high θ" modes are the most robust against other forms of suppression (non-linear Landau damping, density gradients refracting waves out of the growth region).*
- But the "high θ" modes are also the ones responsible for angular broadening of the beam.[+]
  - Growth rate of the instability scales as 1/(angular width)^2, so "turning off" these modes could allow the low θ modes to keep growing.

* See objections to the beam-plasma instability, e.g., Minianti & Elyiv (2013), Sironi & Giannios (2014), and response in Chang et al. (2014), Shalaby et al. (2018), etc.

[+] See quasilinear theory studies, e.g., Alawashra & Pohl (2024)

It’s a complex system, so stay tuned!
Thank you!



k_z

e^+e^- pair beam direction

Linear Landau damping by thermal electrons (fastest at high k)

Beam interaction:

GROWTH

DAMPING

ω_p/v_{beam}

Refraction ($\boldsymbol{k}$ moves toward lower density)

Transfer of power via nonlinear Landau damping

Linear Landau damping by cosmic ray electrons (at any $k > \omega_p/c$)

Wave vector angles measured from beam axis

θ

resonant interaction with particles impossible

resonant interaction with particles possible

$k = \omega_p/c$

k_x

FIGURE NOT TO SCALE