Nonlinear feedback of the electrostatic instability on the blazar-induced pair beam and GeV cascade

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University of Chicago
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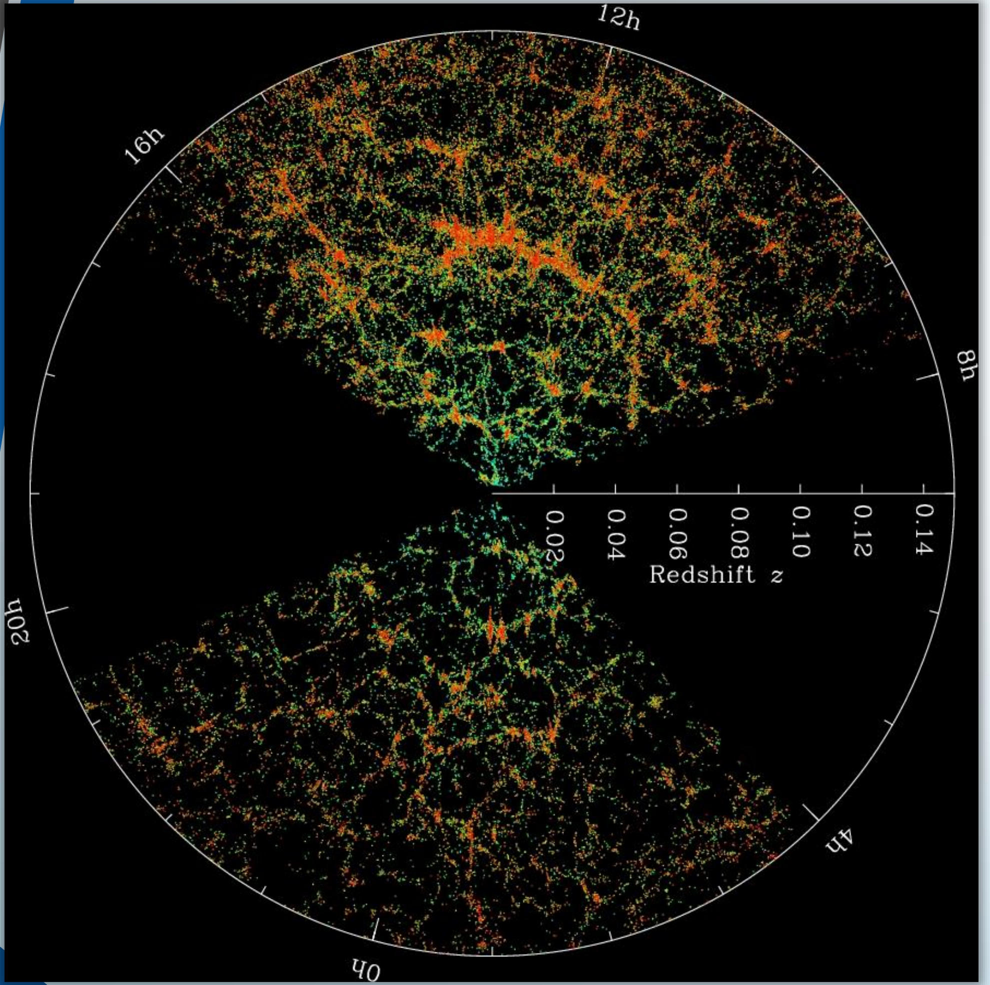
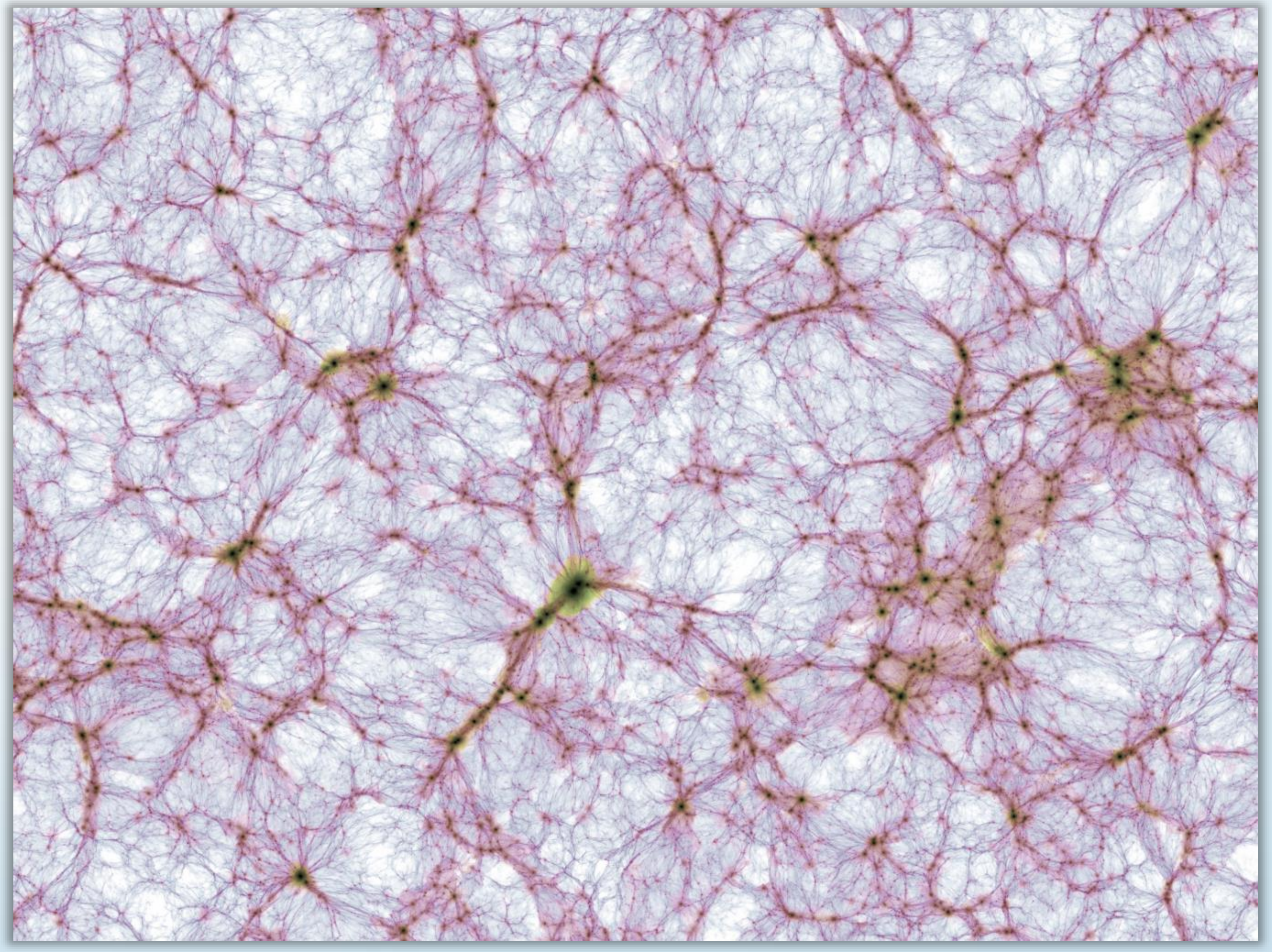
Cosmic Voids



6oo Mpc

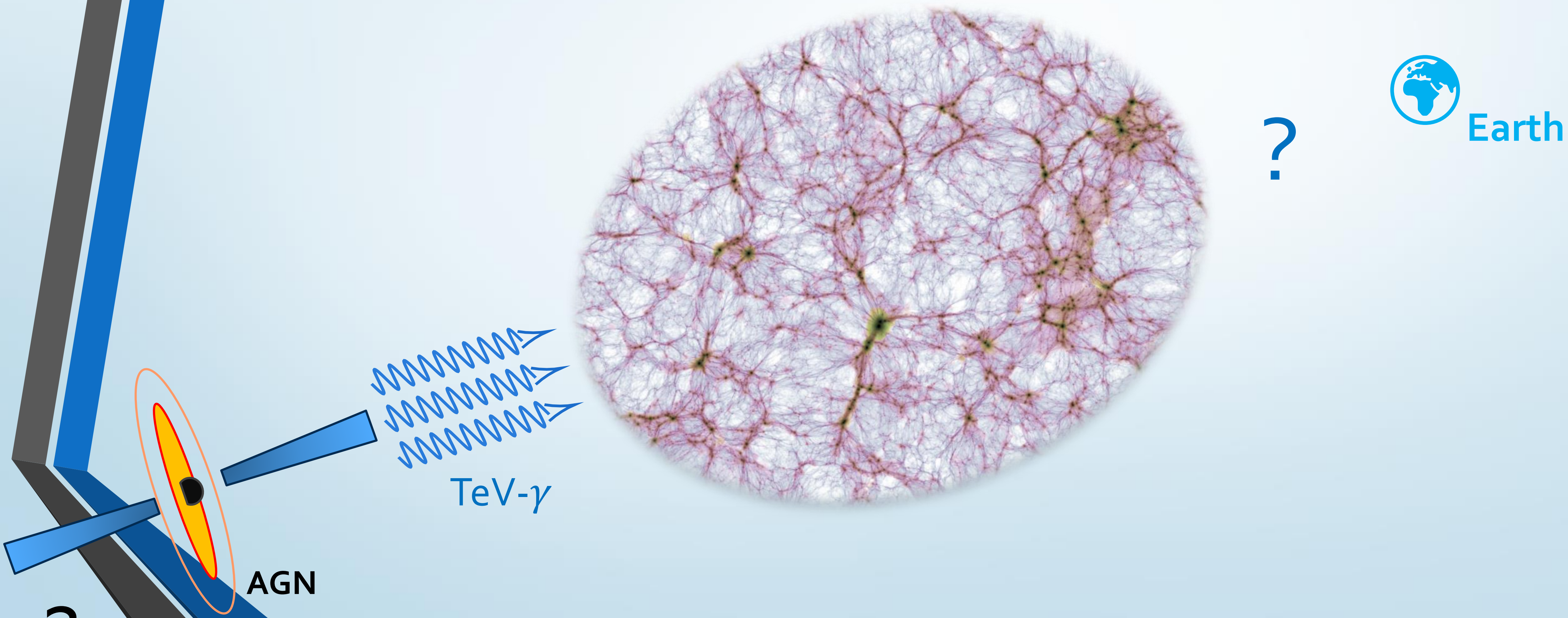
Sloan Digital Sky Survey



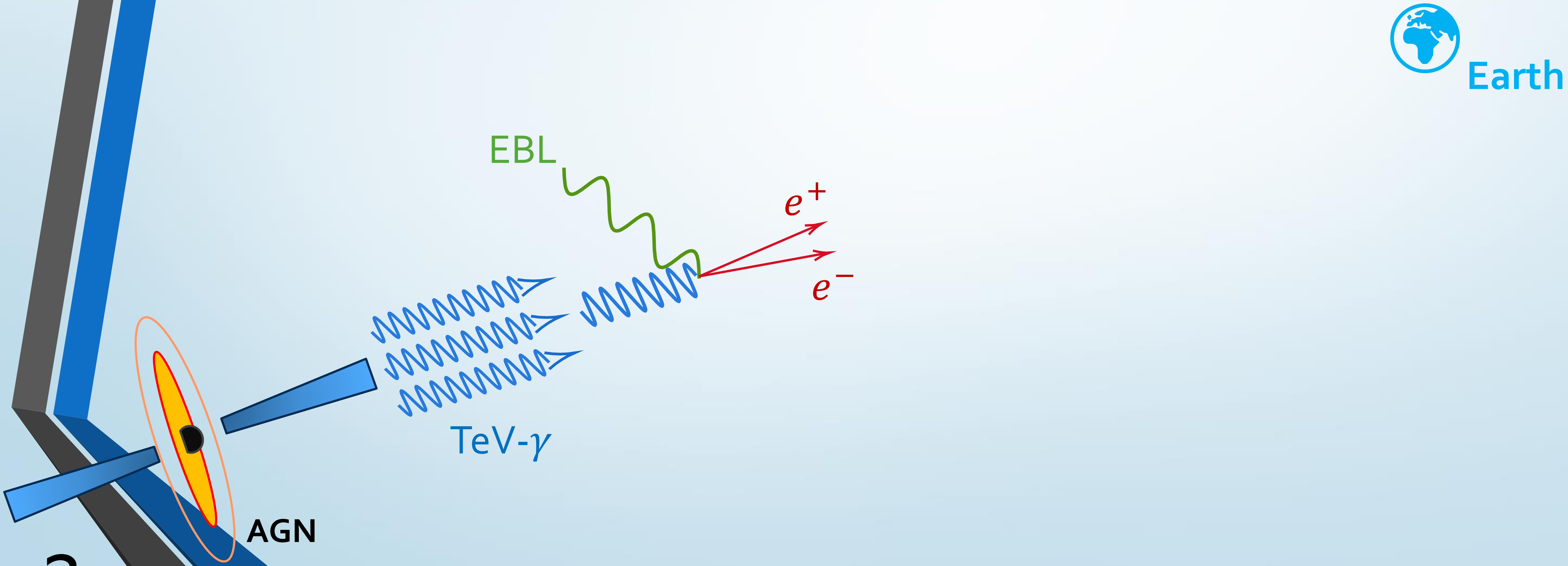
3ooMpcX3ooMpc

TNG300 Simulation

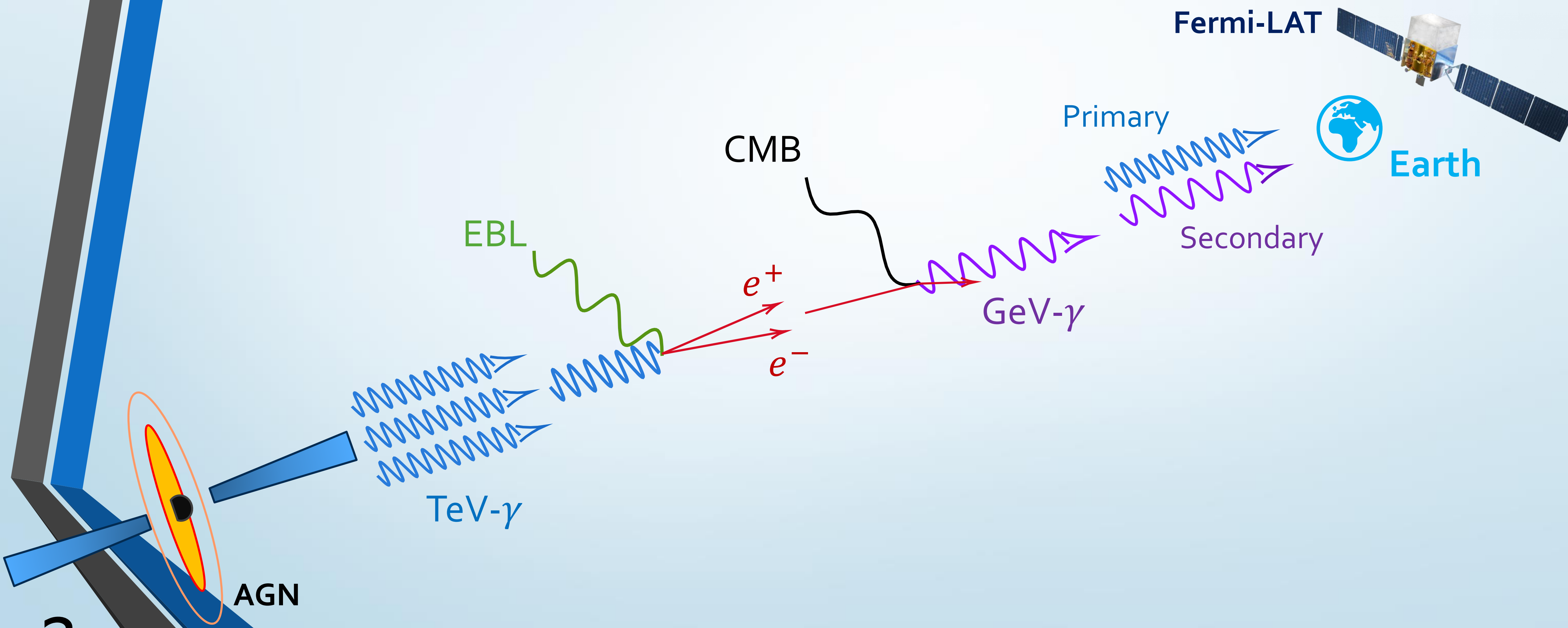
- **Gamma rays from blazars are unique prob of the cosmic voids.**



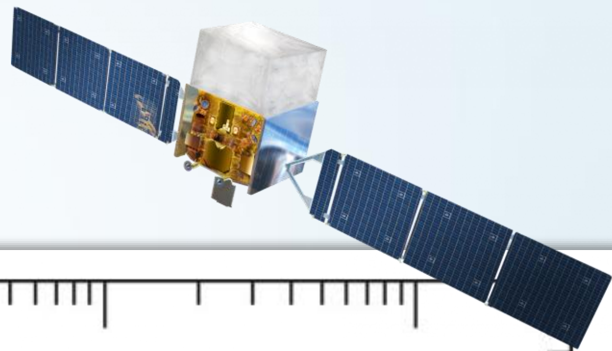
- **TeV gamma-rays attenuate in the cosmic voids giving $e^{\pm}$ pairs.**

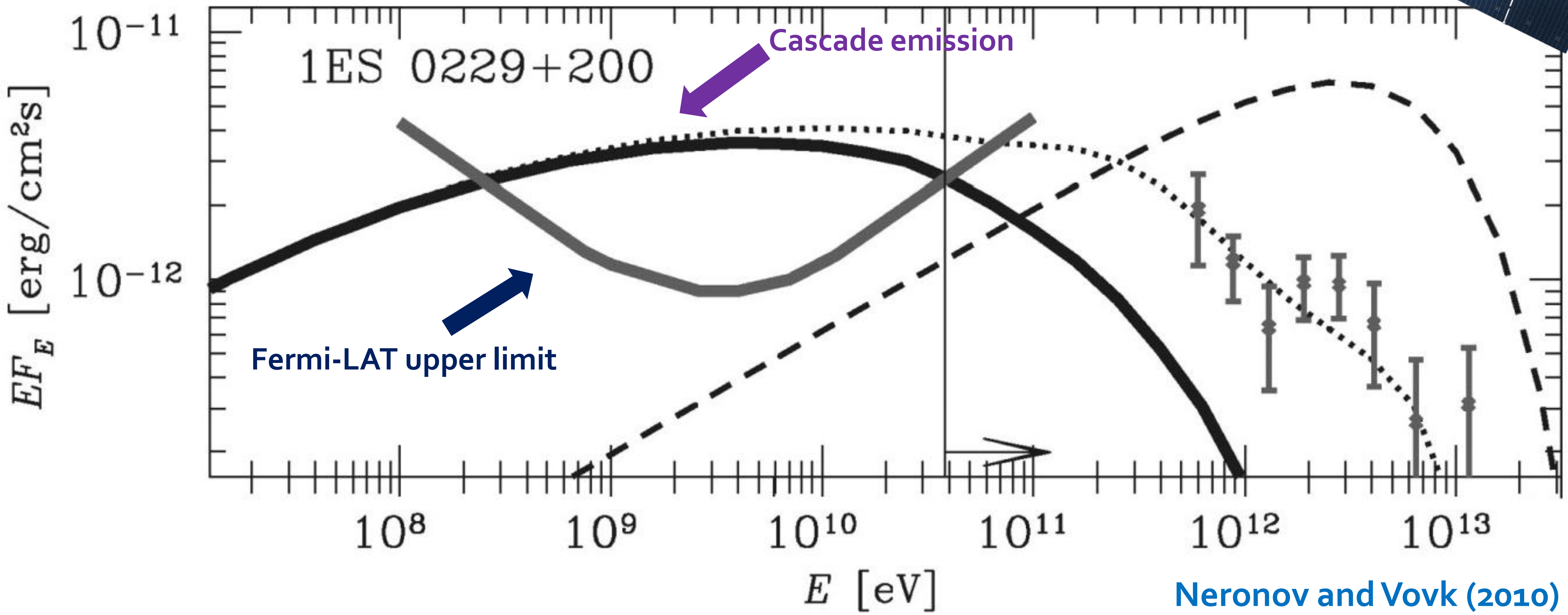


- **The $e^{\pm}$ pairs are expected to produce a detectable GeV cascade.**



The electromagnetic cascade is missing in the observations

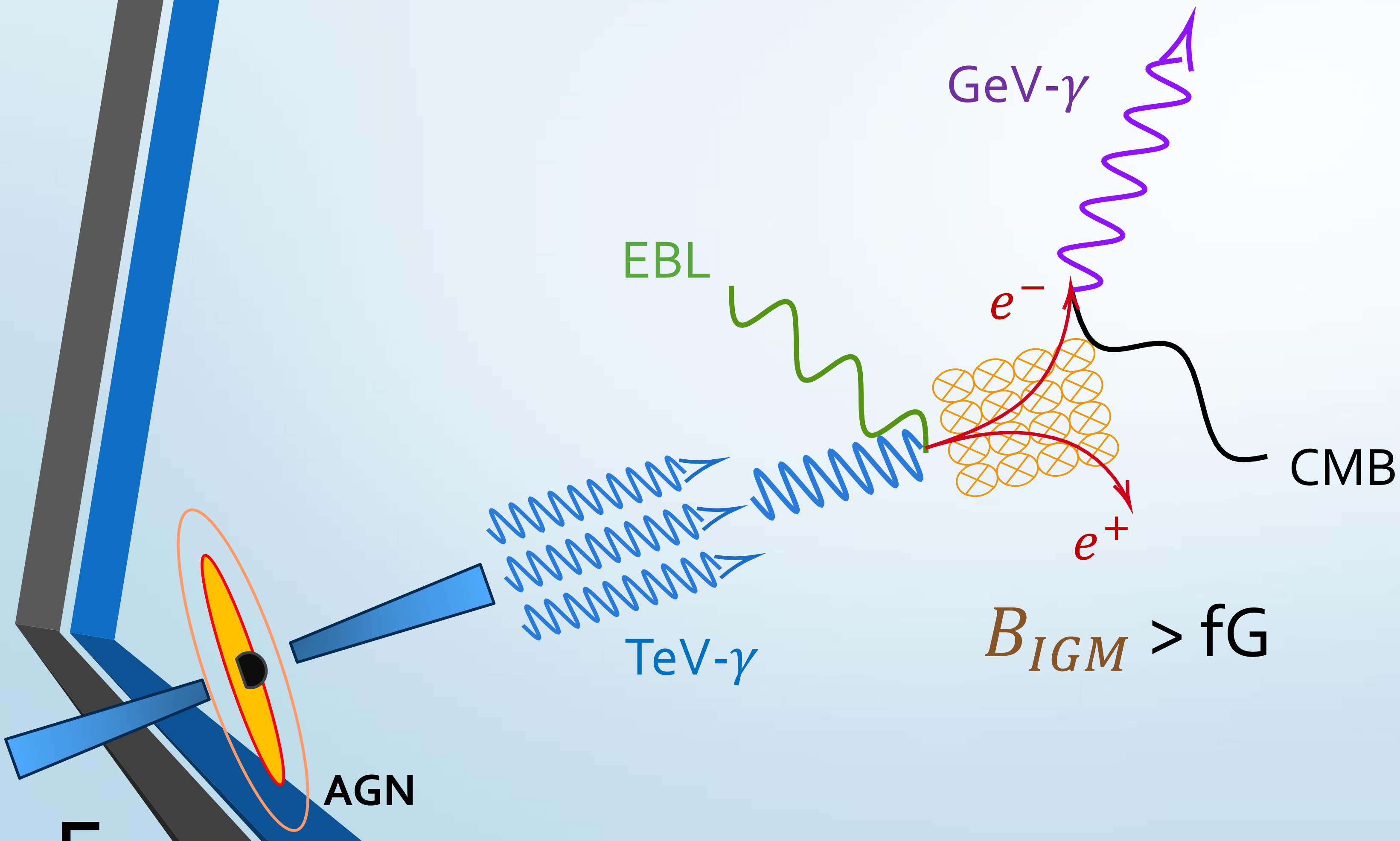


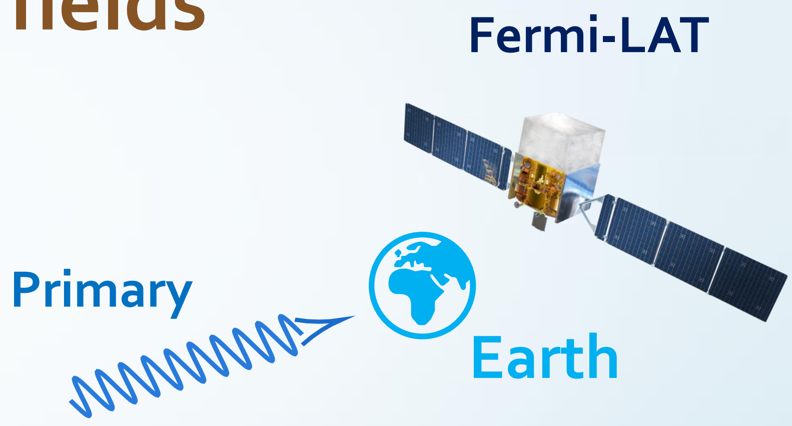


Neronov and Vovk (2010)

First possible solution

Pairs deflected by IGM magnetic fields



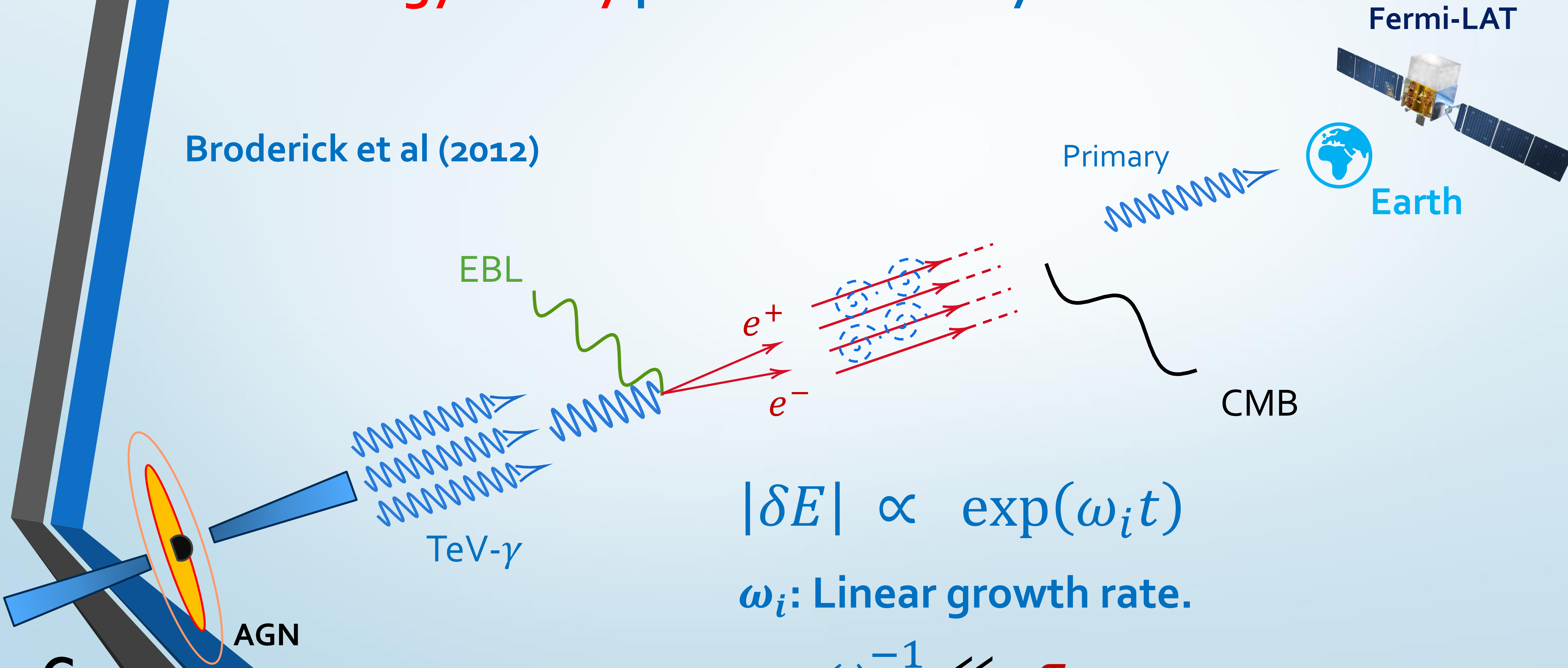


Neronov and Vovk (2010)

Second possible solution

Energy loss by plasma instability before IC

Broderick et al (2012)

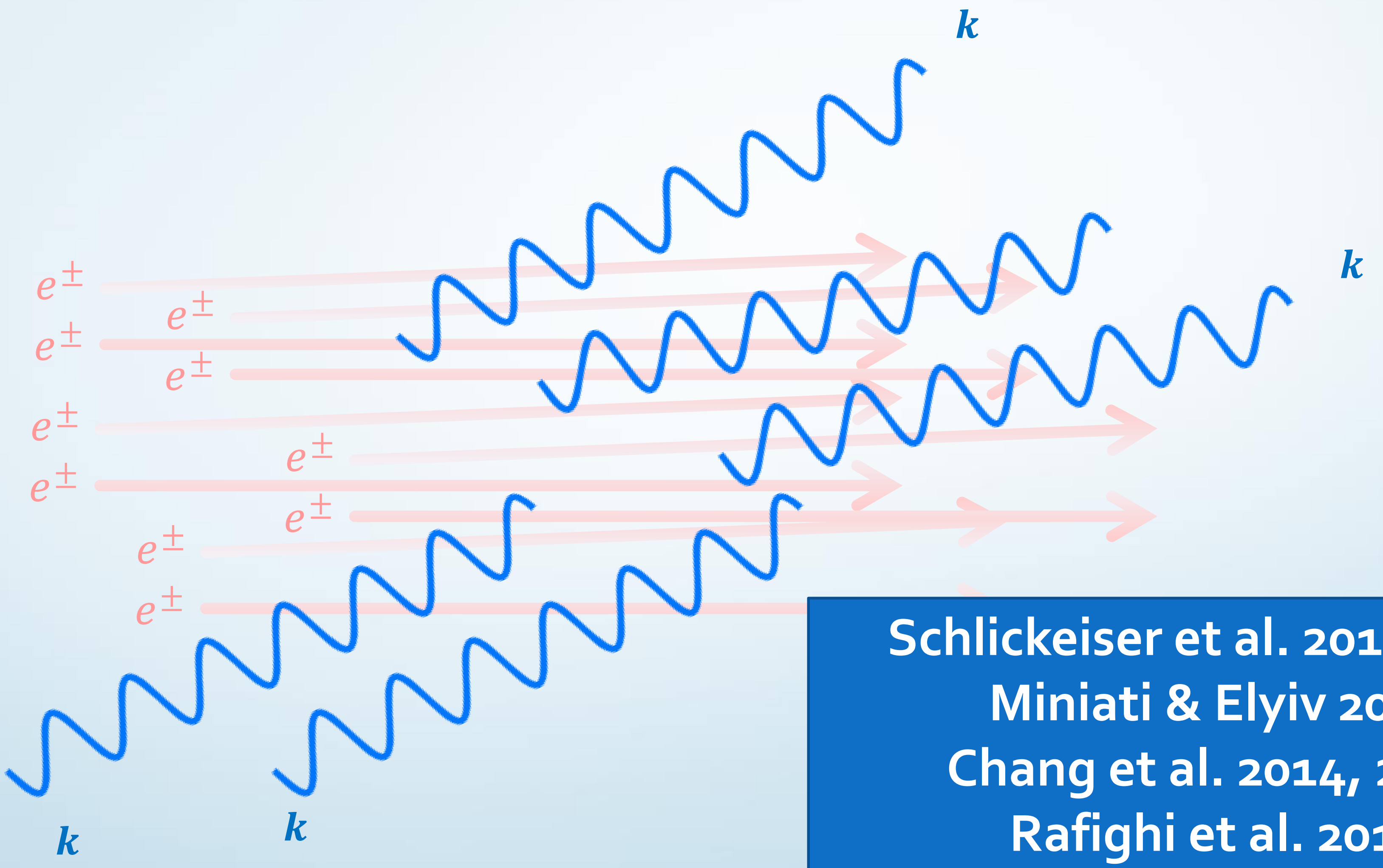


$$|\delta E| \propto \exp(\omega_i t)$$

ω_i: Linear growth rate.

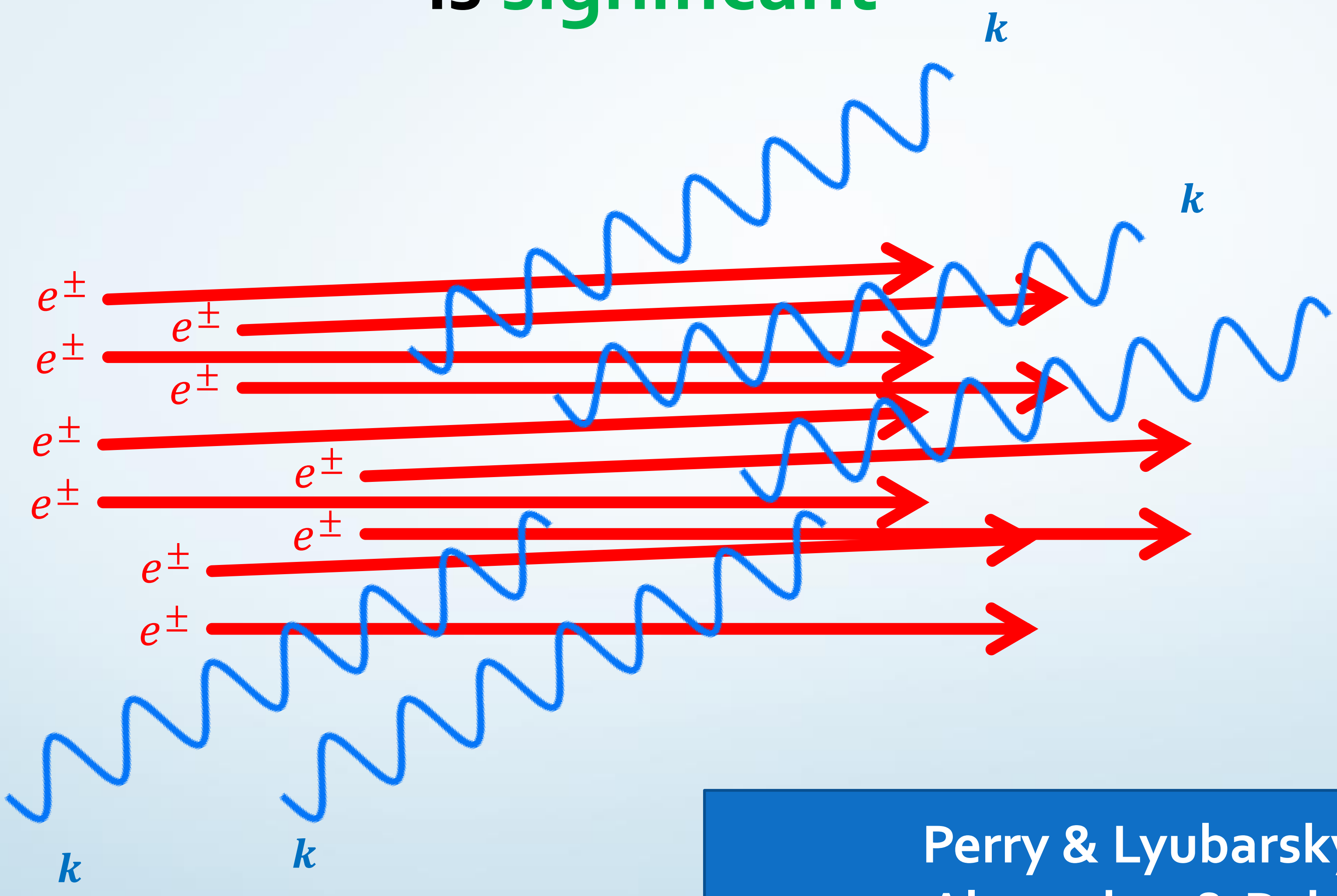
$$\omega_i^{-1} \ll \tau_{\mathrm{IC}}$$

Previous studies focused on the nonlinear saturation of the instability



Schlickeiser et al. 2012, 2013
Miniati & Elyiv 2013
Chang et al. 2014, 2016
Rafighi et al. 2017
Vafin et al. 2018, 2019
Alawashra & Pohl 2022

Feedback of the instability on the pair beam is significant



Perry & Lyubarsky 2021
Alawashra & Pohl 2024
Alawashra, Vovk & Pohl 2024 in perp.

Feedback of the instability on the pair beam

Breizman & Ryutov (1970)

$$\frac{\partial f(p,\theta)}{\partial t} = \frac{1}{p^2\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta p}\frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p D_{p\theta}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)$$

- f: Beam distribution
- D_{ij}: Diffusion coefficients
- W: Wave energy density
- ω_i: Linear growth rate

$$D_{ij}(\boldsymbol{p}) = \pi e^2 \int d^3\boldsymbol{k}\, W(\boldsymbol{k},t)\frac{k_i k_j}{k^2}\delta\left(\boldsymbol{k}\cdot\boldsymbol{v} - \omega_p\right)$$

$$\frac{\partial W(\boldsymbol{k},t)}{\partial t} = 2\left(\omega_i(\boldsymbol{k}) + \omega_c\right) W(\boldsymbol{k},t)$$

$$\omega_i(\boldsymbol{k}) = \omega_p \frac{2\pi^2 n_b e^2}{k^2}\int d^3\boldsymbol{p}\left(\boldsymbol{k}\cdot\frac{\partial f(\boldsymbol{p})}{\partial \boldsymbol{p}}\right)\delta\left(\omega_p - \boldsymbol{k}\cdot\boldsymbol{v}\right)$$

Feedback of the instability on the pair beam

Breizman & Ryutov (1970)

$$\frac{\partial f(p,\theta)}{\partial t} = \frac{1}{p^2\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta p}\frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p D_{p\theta}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)$$

The plasma waves impact the beam

$$\frac{\partial W(\boldsymbol{k},t)}{\partial t} = 2\left(\omega_i(\boldsymbol{k}) + \omega_c\right) W(\boldsymbol{k},t)$$

The beam impacts the plasma waves

Feedback of the instability on the pair beam

$$\frac{\partial f(p,\theta)}{\partial t} = \frac{1}{p^2\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p\theta}\cdots\frac{\partial f}{\partial p}\Big) + \frac{1}{p^2}\cdots\frac{\partial f}{\partial\theta}\Big) + \frac{1}{p^2}\cdots\frac{\partial f}{\partial p}\Big)$$

Perry & Lyubarsky (2021)
MNRAS 503 2
Alawashra & Pohl (2024)
ApJ 964 82

The significant feedback is the beam widening $\theta\theta$.

Feedback of the instability on the pair beam

$$\frac{\partial f(p,\theta)}{\partial t} = \frac{1}{p^2\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p\theta}\cdots\frac{\partial f}{\partial p}\Big) + \frac{1}{p^2}\cdots\frac{\partial f}{\partial\theta}\Big) + \frac{1}{p^2}\cdots\frac{\partial f}{\partial p}\Big)$$

Perry & Lyubarsky (2021)
MNRAS 503 2
Alawashra & Pohl (2024)
ApJ 964 82

The significant feedback is the beam widening $\theta\theta$.

The beam widens by certain factors, suppressing the instability energy loss of the beam.

Energy loss by the instability ~ 1%

What is the Impact of the Instability widening on the GeV cascade?

Alawashra, Vovk & Pohl (2024) In perp.

Limitations of the initial beam distribution

- **Study of Perry & Lyubarsky (2021) :**

  - Simplified 1D beam distribution.

$$g(\theta) = \int_0^\infty dp\, p\, f(p,\theta) \approx \exp(-0.2(\gamma\theta)^5)\,, \qquad \gamma = 10^6$$

- **Study of Alawashra & Pohl (2024) :**

  - Realistic 2D beam distribution at distance 50 Mpc from fiducial blazar.
  - Include the continuous production of the pairs.

Beams induced by the blazar 1ES 0229+200

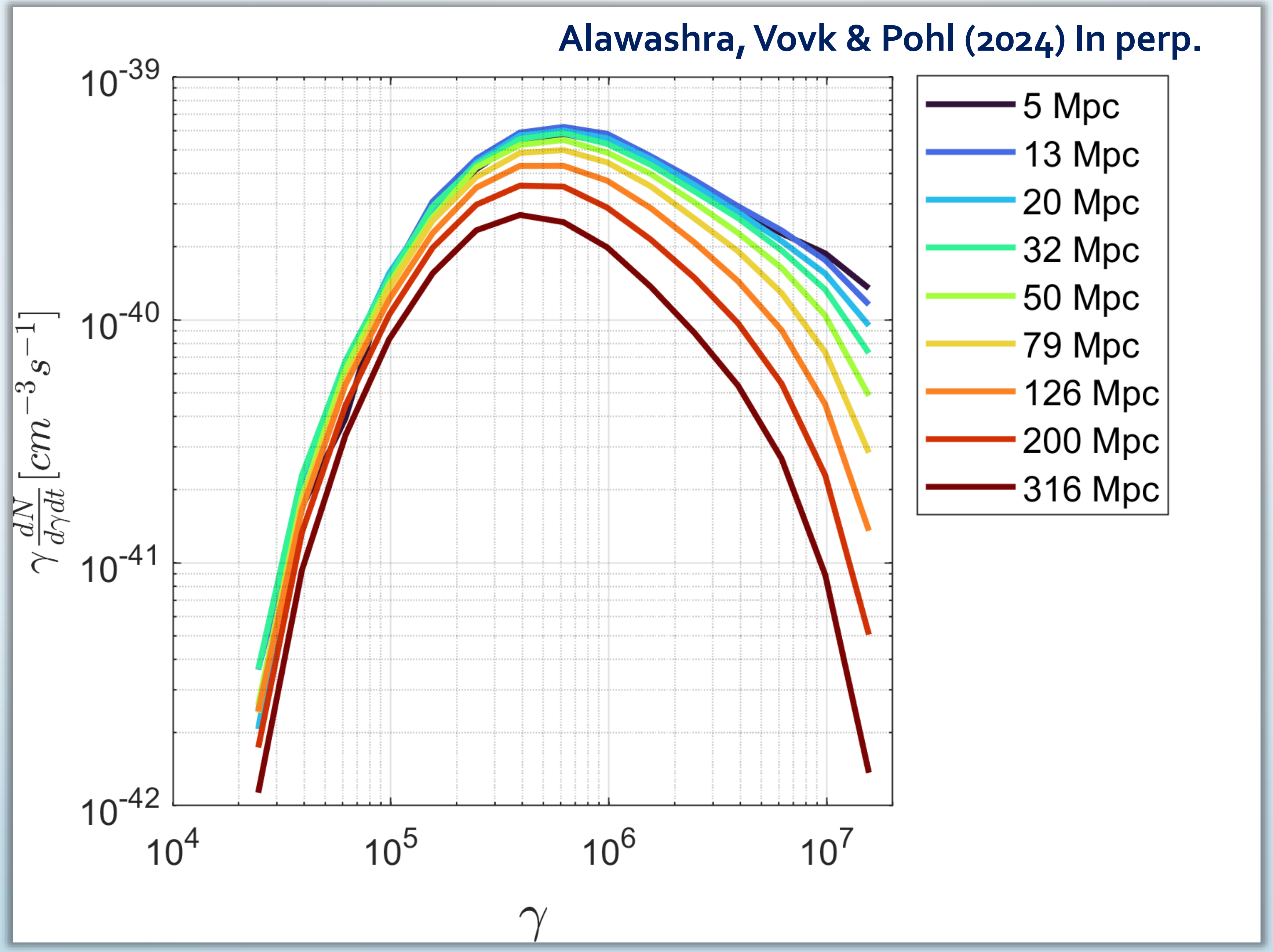
Alawashra, Vovk & Pohl (2024) In perp.

- Consider 1ES 0229+200 like gamma ray source:

$$F\left(E_\gamma, z=0\right) = 2.6 \, * 10^{-10} \left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{-1.7} \exp\left(-\frac{E_\gamma}{10\ \mathrm{TeV}}\right) \frac{\mathrm{ph.}}{\mathrm{cm^2 s\ GeV}}$$

- Using the Monte Carol code (CRpropa), we calculated the beams injection rates, Q_{ee}, at different distances in the IGM.

1ES 0229+200 induced beam production rates



Normalized to the Earth distance

Simulation of the instability broadening of 1ES 0229+200 induced beams

Pair Beam:

$$\frac{\partial f(p,\theta)}{\partial t} = \frac{1}{p^2\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(-\dot{p}_{IC}p^2 f\right) + Q_{ee}$$

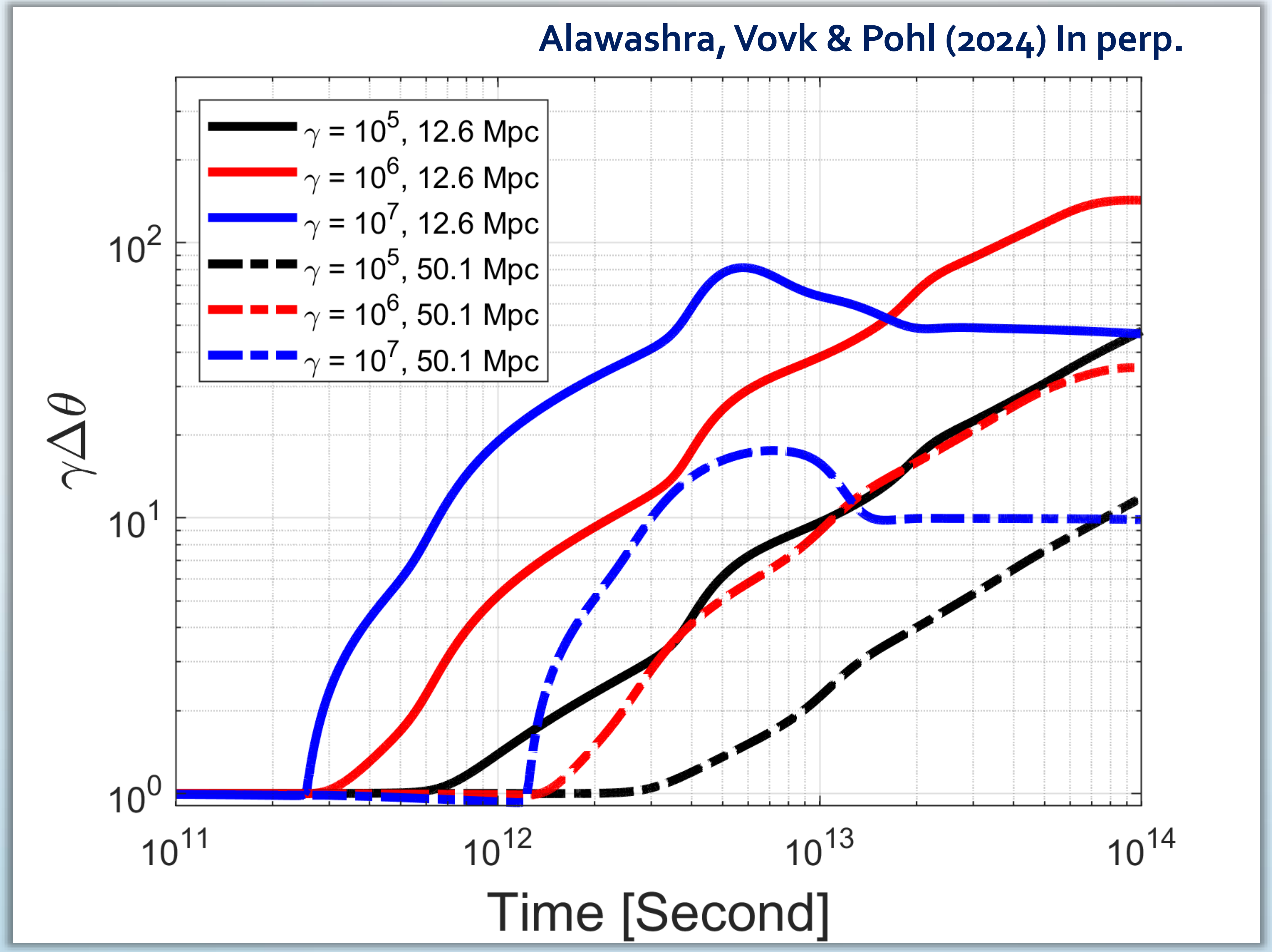
Plasma waves:

$$\frac{\partial W(\boldsymbol{k},t)}{\partial t} = 2\left(\omega_i(\boldsymbol{k}) + \omega_c\right) W(\boldsymbol{k},t)$$

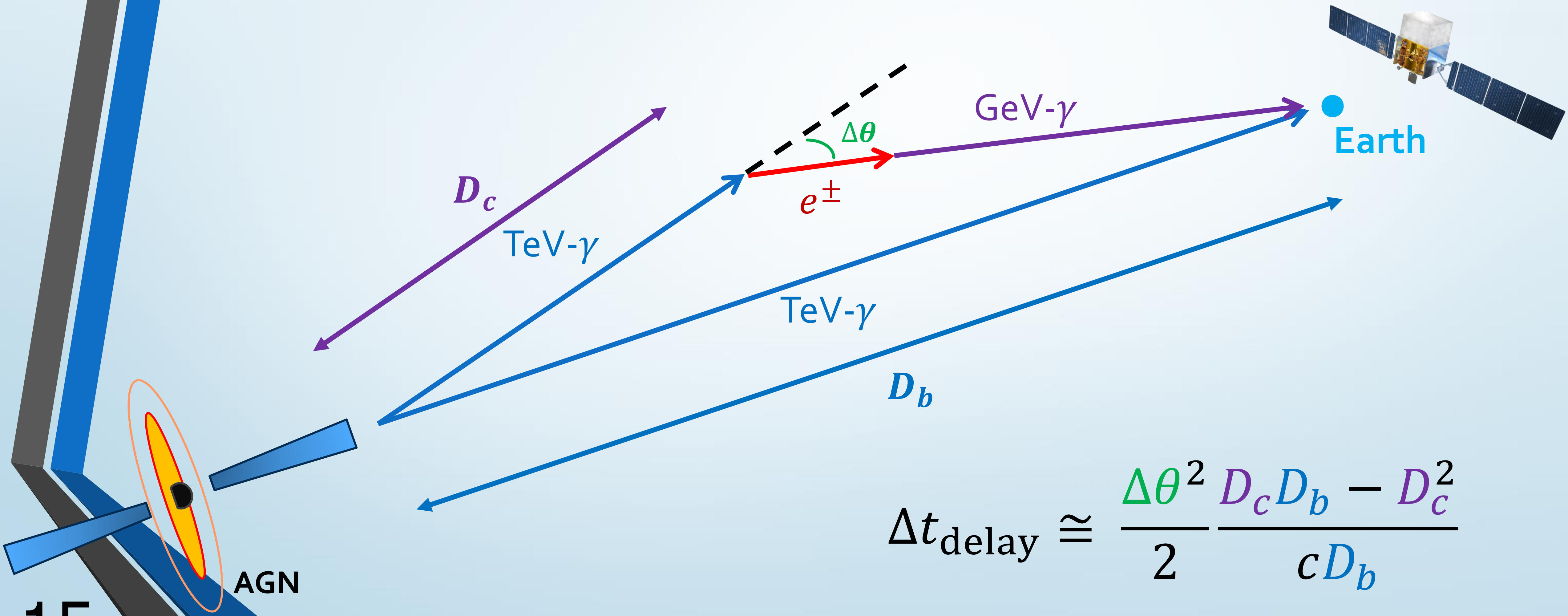
Q_{ee} : Continuous production of new pairs.

Pairs cooling: $\dot{p}_{IC} = -\frac{4}{3}\sigma_T u_{CMB}\gamma^2$

Beams broadening due to the instability



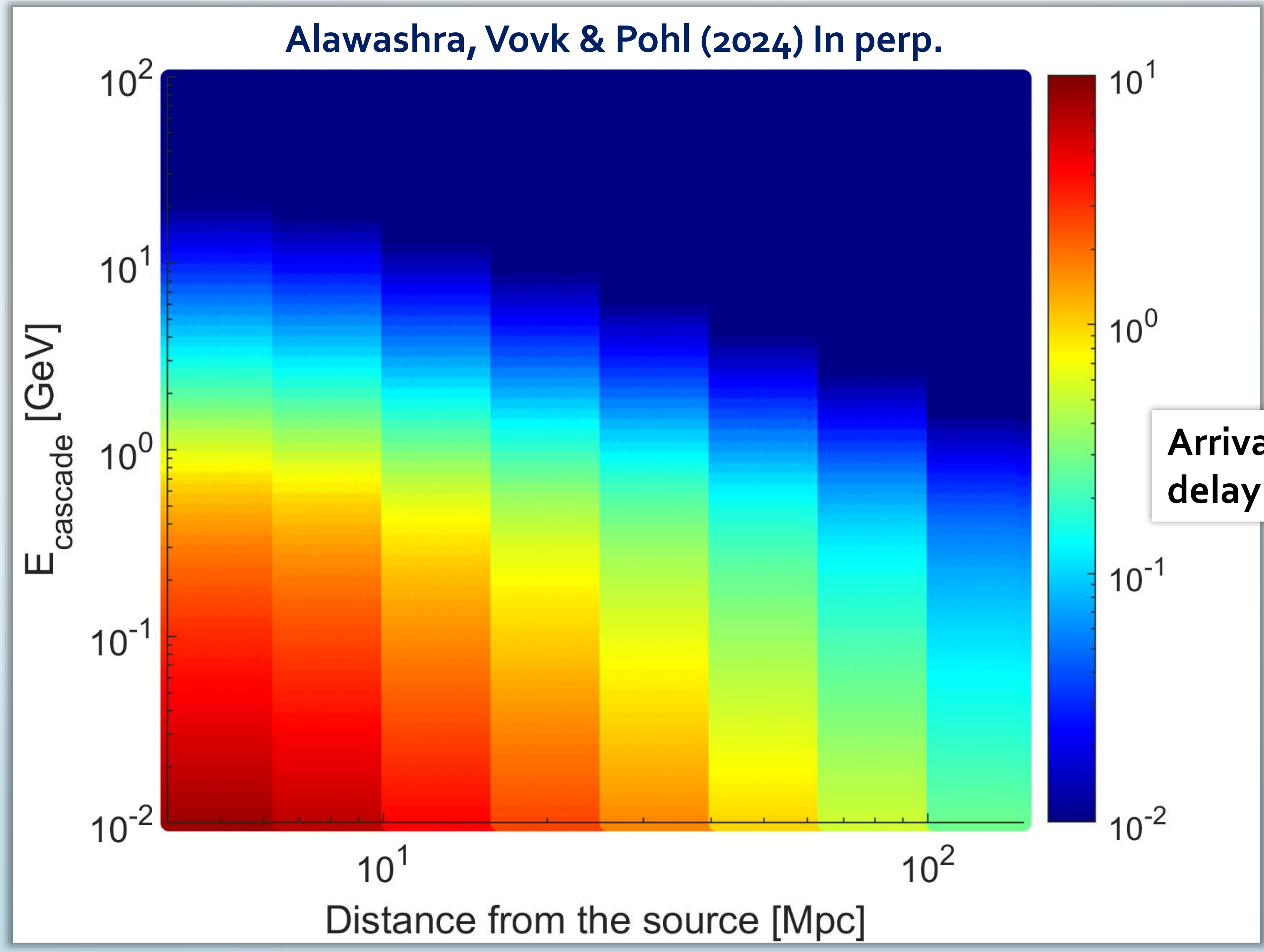
Cascade arrival time delay due to the instability broadening



$$\Delta t_{\rm delay} \cong \frac{\Delta\theta^2}{2}\frac{D_c D_b - D_c^2}{c D_b}$$

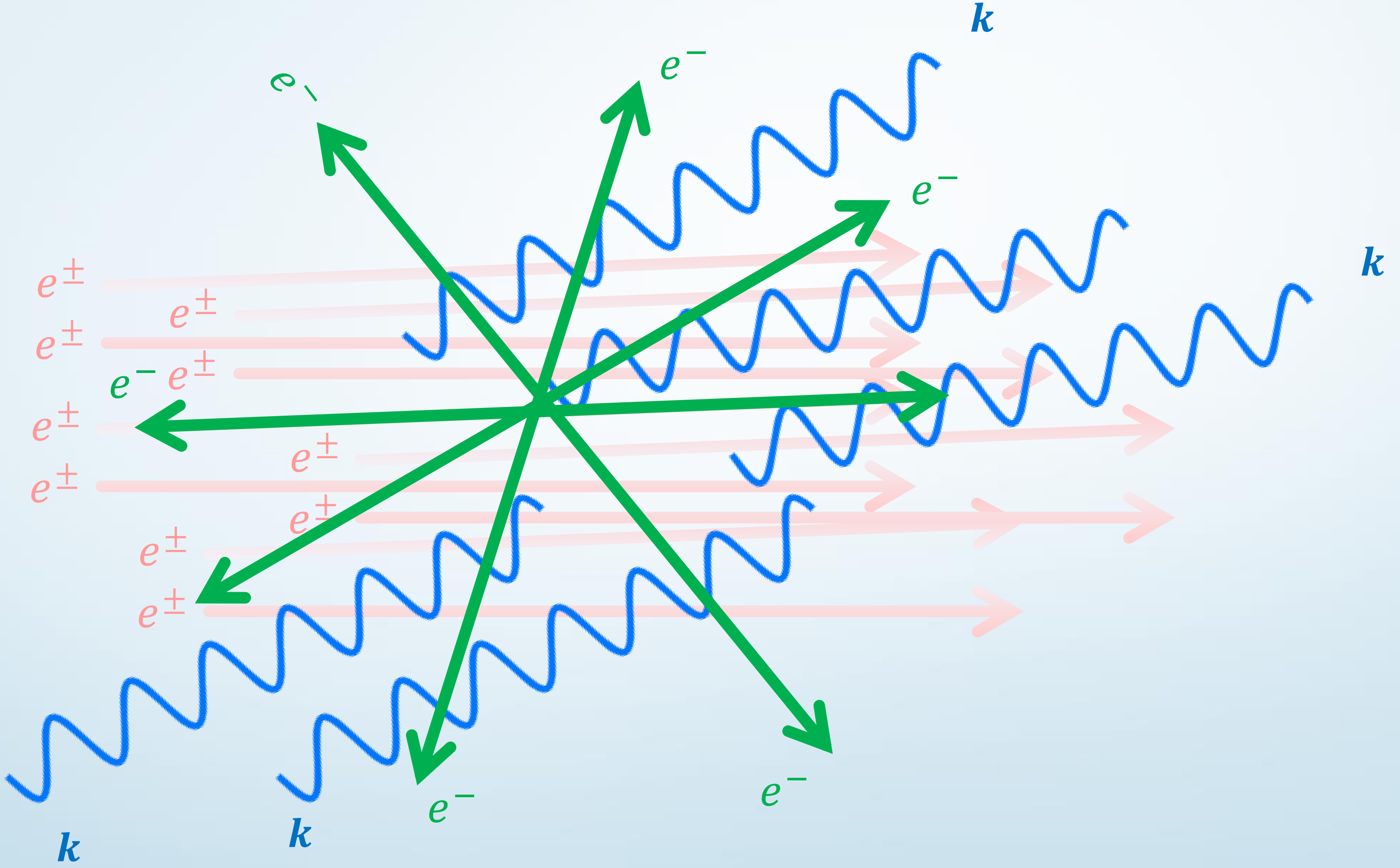
Cascade delay due to the instability broadening

Fermi-LAT Energy Range



Arrival time delay [years]

Compton-included cosmic rays could Landau damp the instability



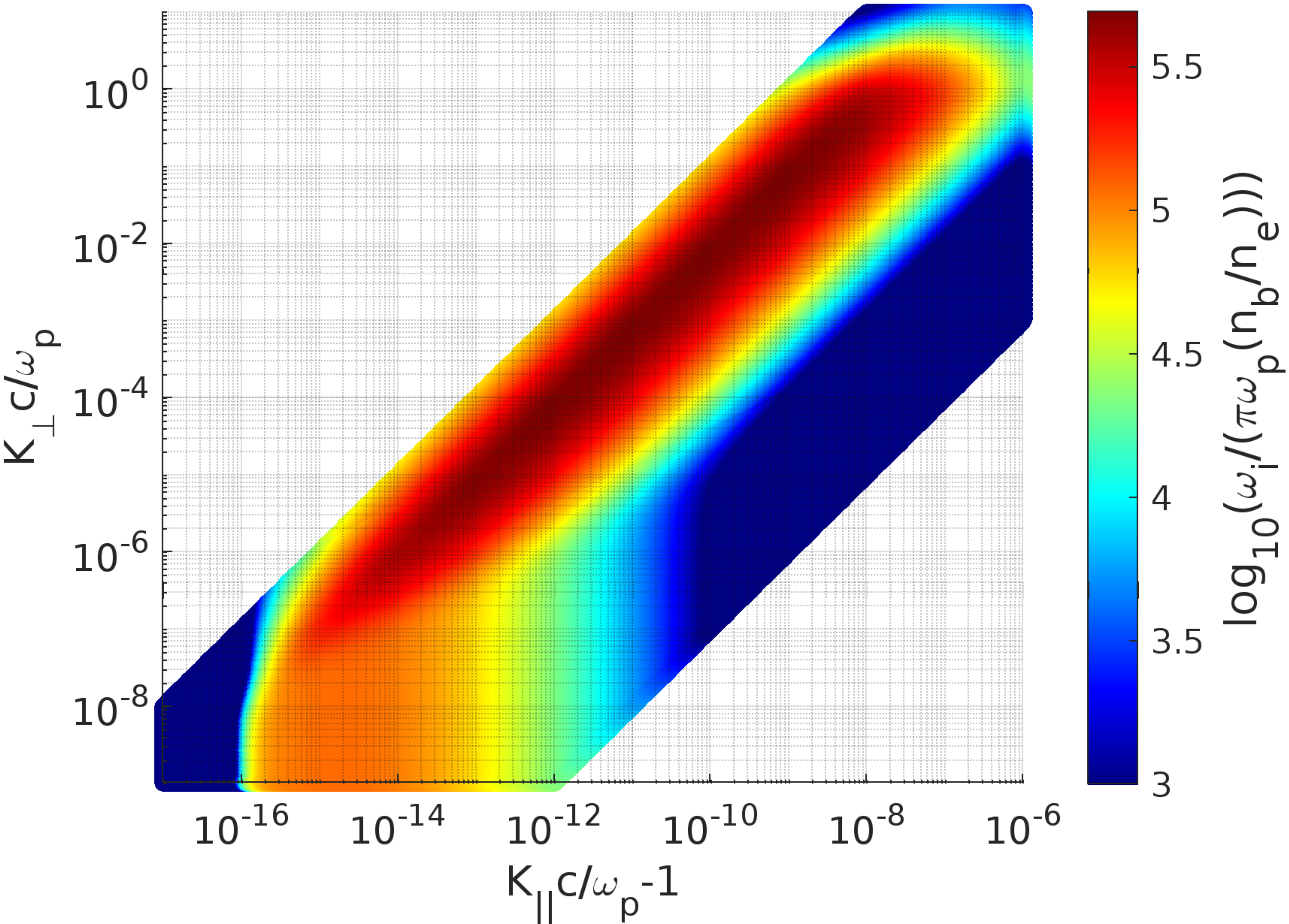
Yang, Long & Hirata (2024) ApJ 965 111

Conclusions

- Beam broadening is the dominant instability feedback.
- New confined Steady-state of the beams due to the balance between continues pairs production, inverse Compton cooling and instability diffusion.
- Time delay of the cascade arrival due to the instability diffusion is NEGLIGIBLE.

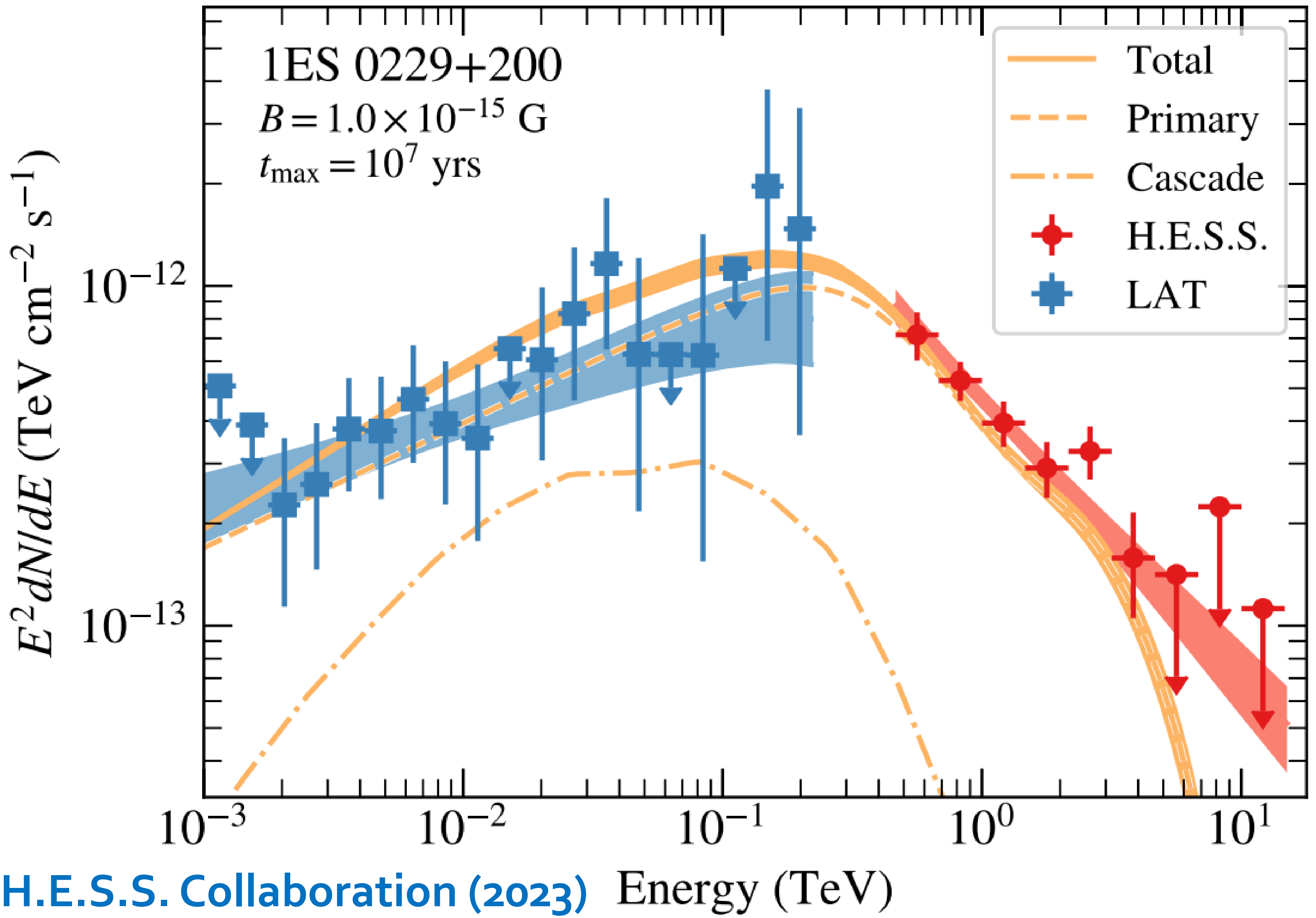
Thank you

Back up slides



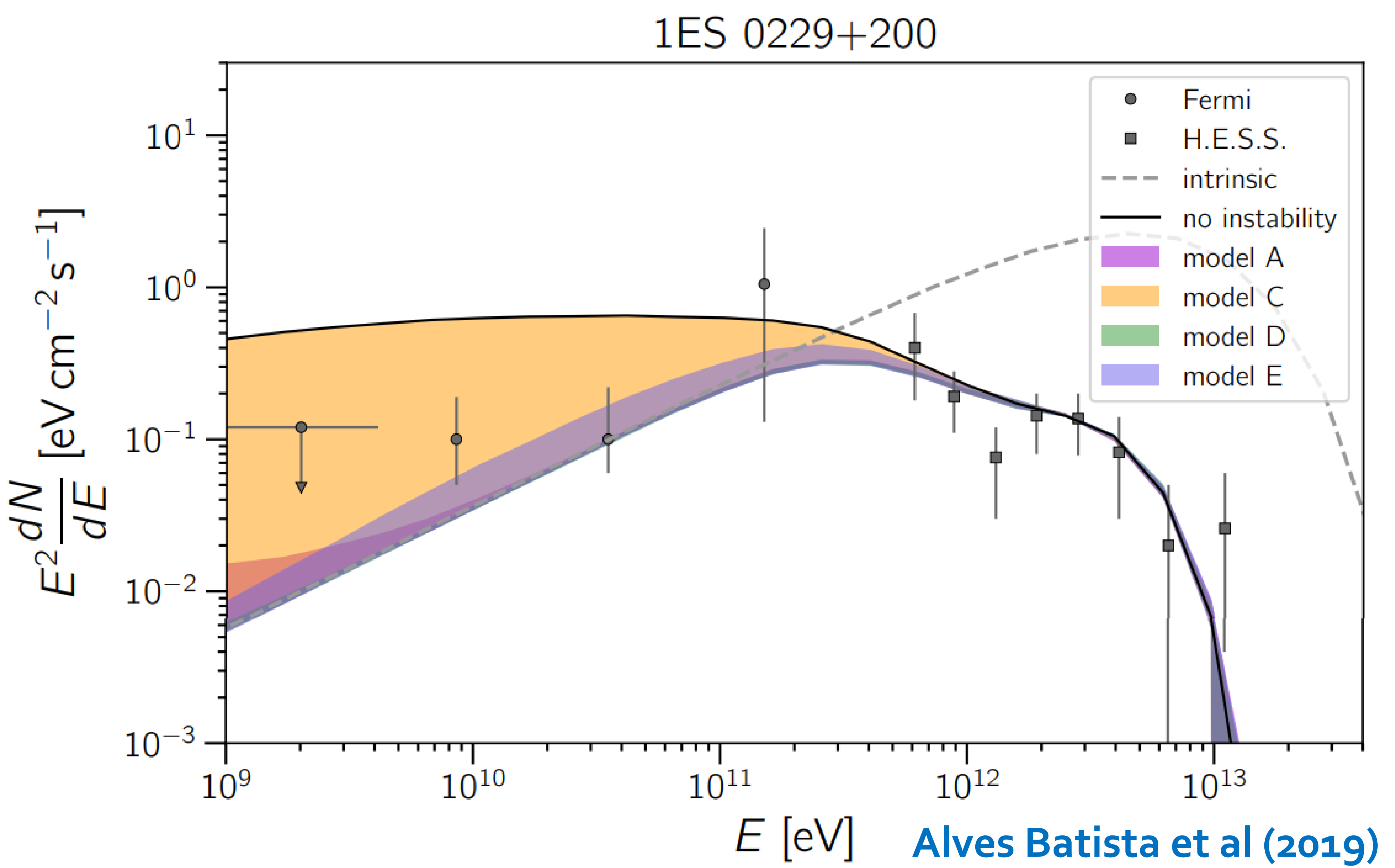
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$K_{\perp}c/\omega_p$
10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6}
$K_{||}c/\omega_p$-1
5.5
5
4.5
4
3.5
3
$\log_{10}(\omega_i/(\pi\omega_p(n_b/n_e)))$

Suppression of the cascade emission by IGMFs



H.E.S.S. Collaboration (2023)

Suppression of the cascade by instability energy loss



Alves Batista et al (2019)

Second study

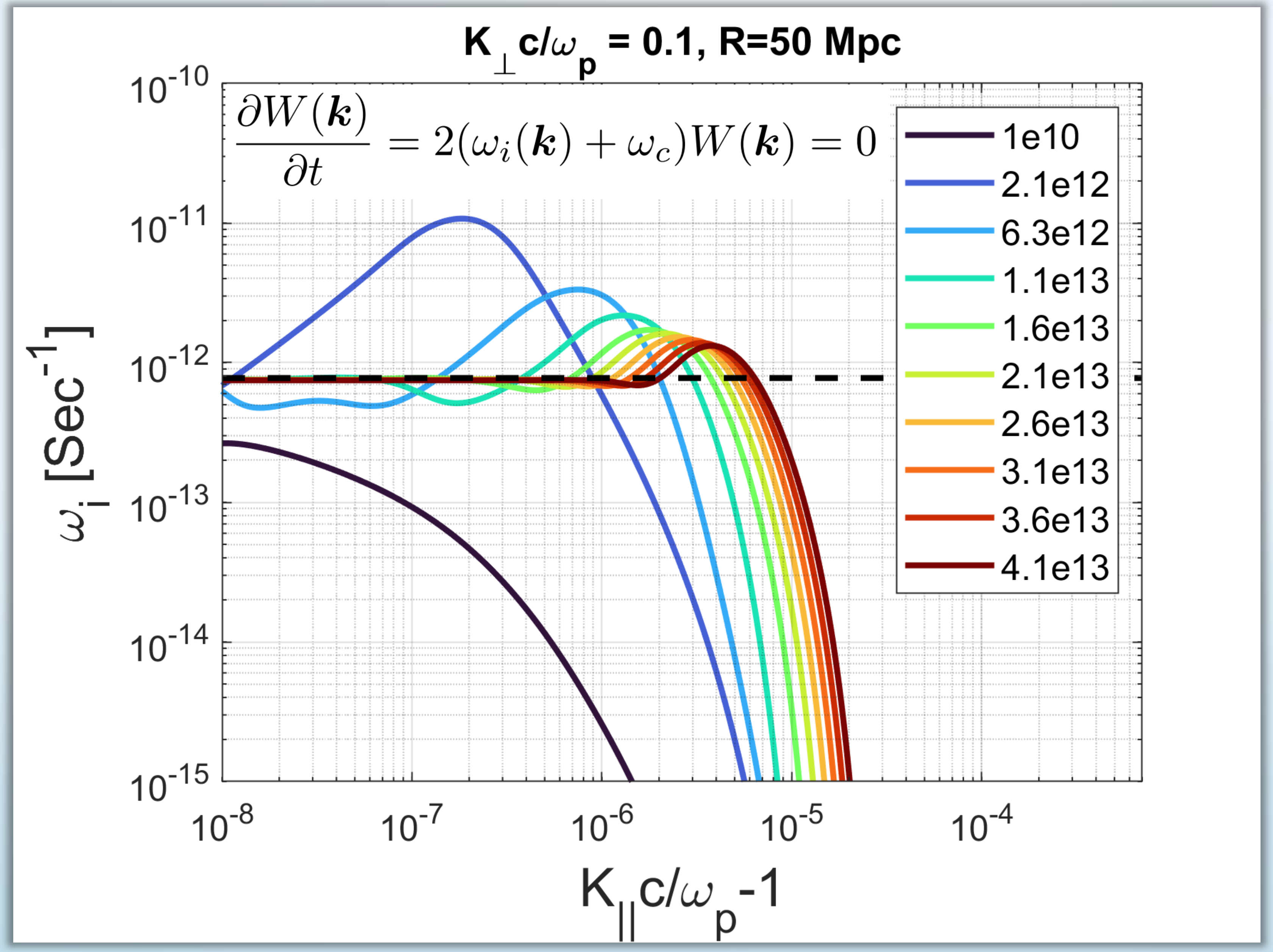
Alawashra, Vovk and Pohl (2024) In perp.

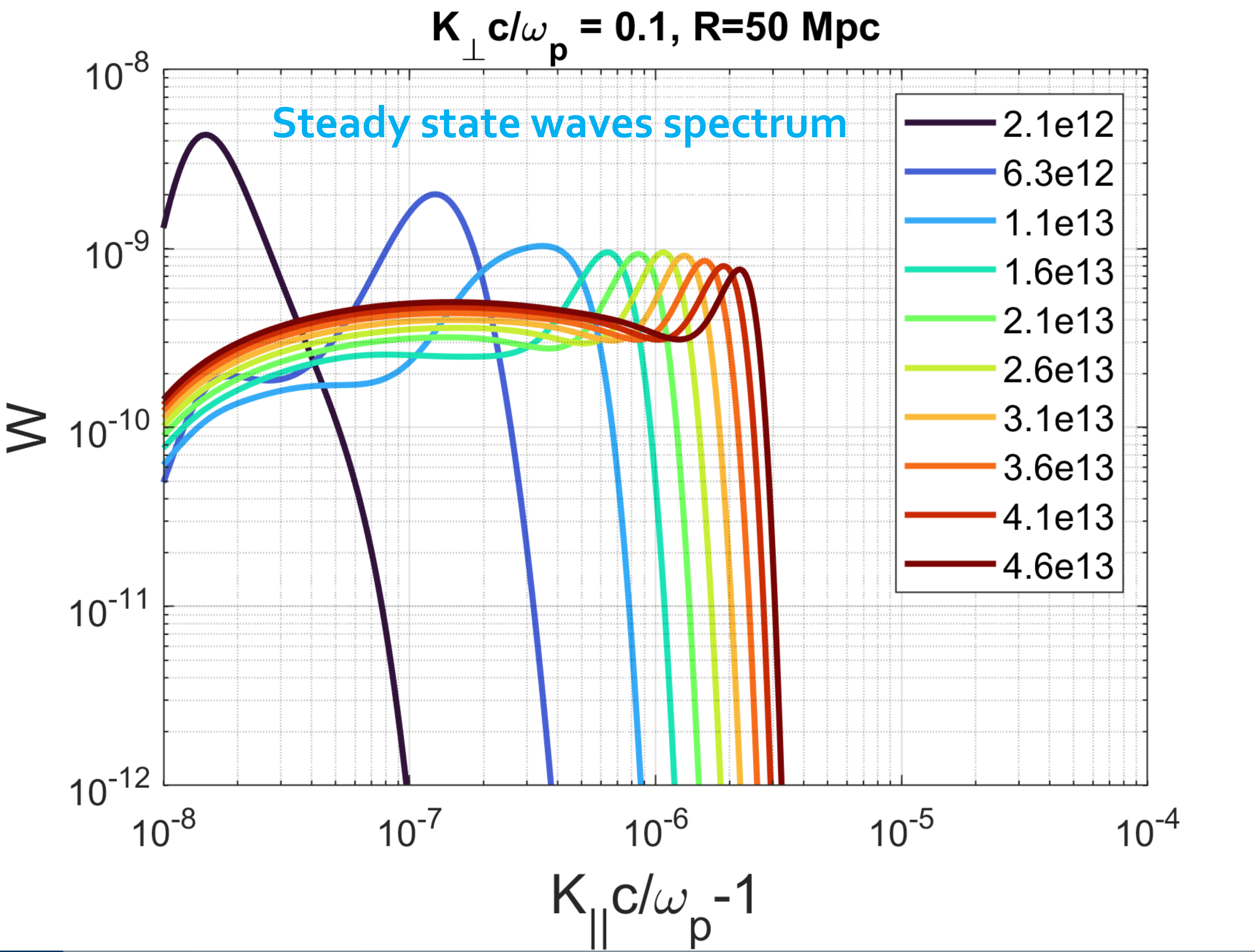
Beams induced by the blazar 1ES 0229+200

- The cascade gets emitted at scales of more than tenths of Mpc in the intergalactic medium while the instability operates at scales of kpc and less.

- We can take the cosmological scale information about the beams from Monte Carlo simulations of the blazar beams as an input into the beam-plasma Fokker-Planck diffusion simulation.

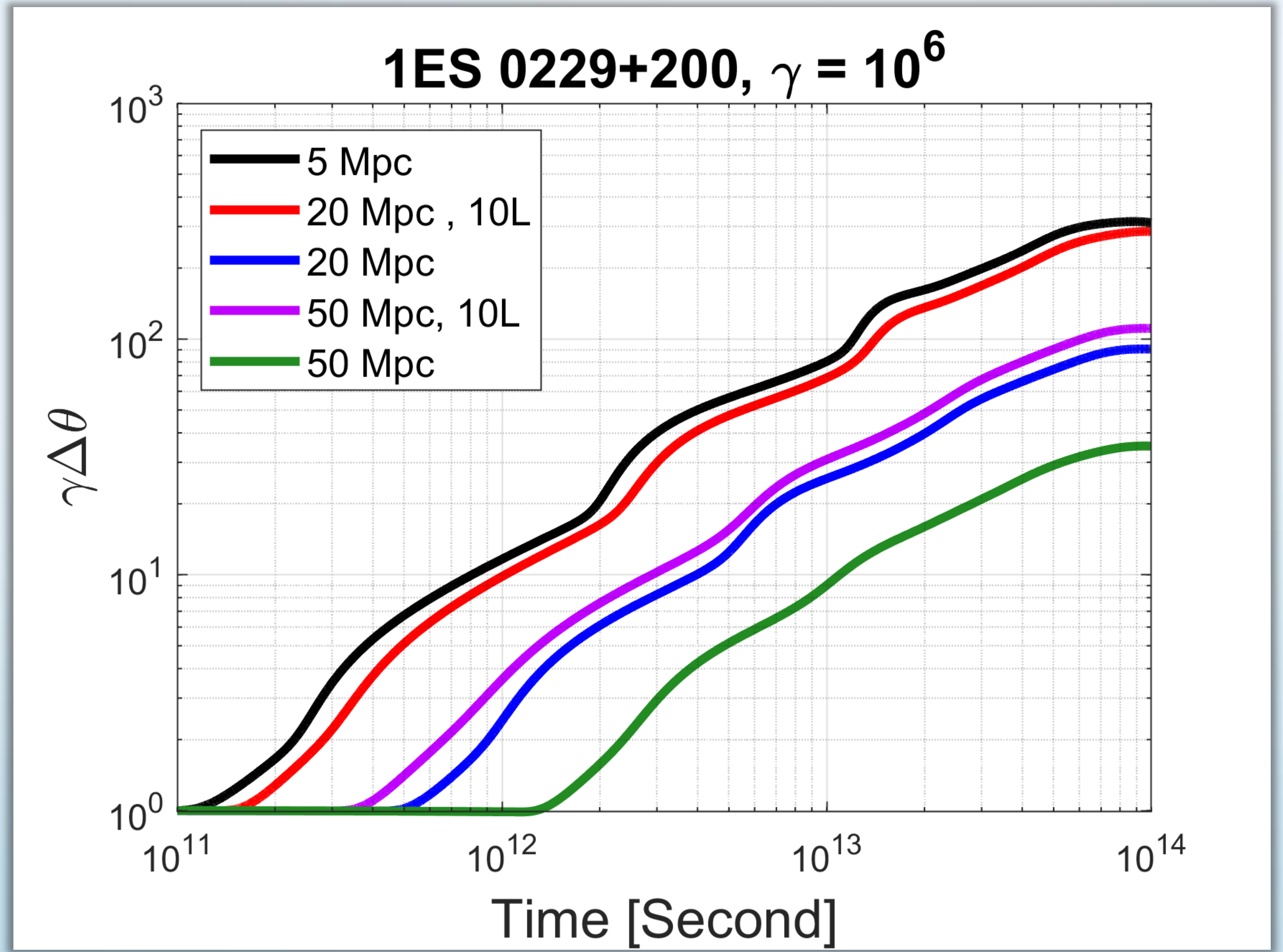
The linear growth rate balances the damping rate



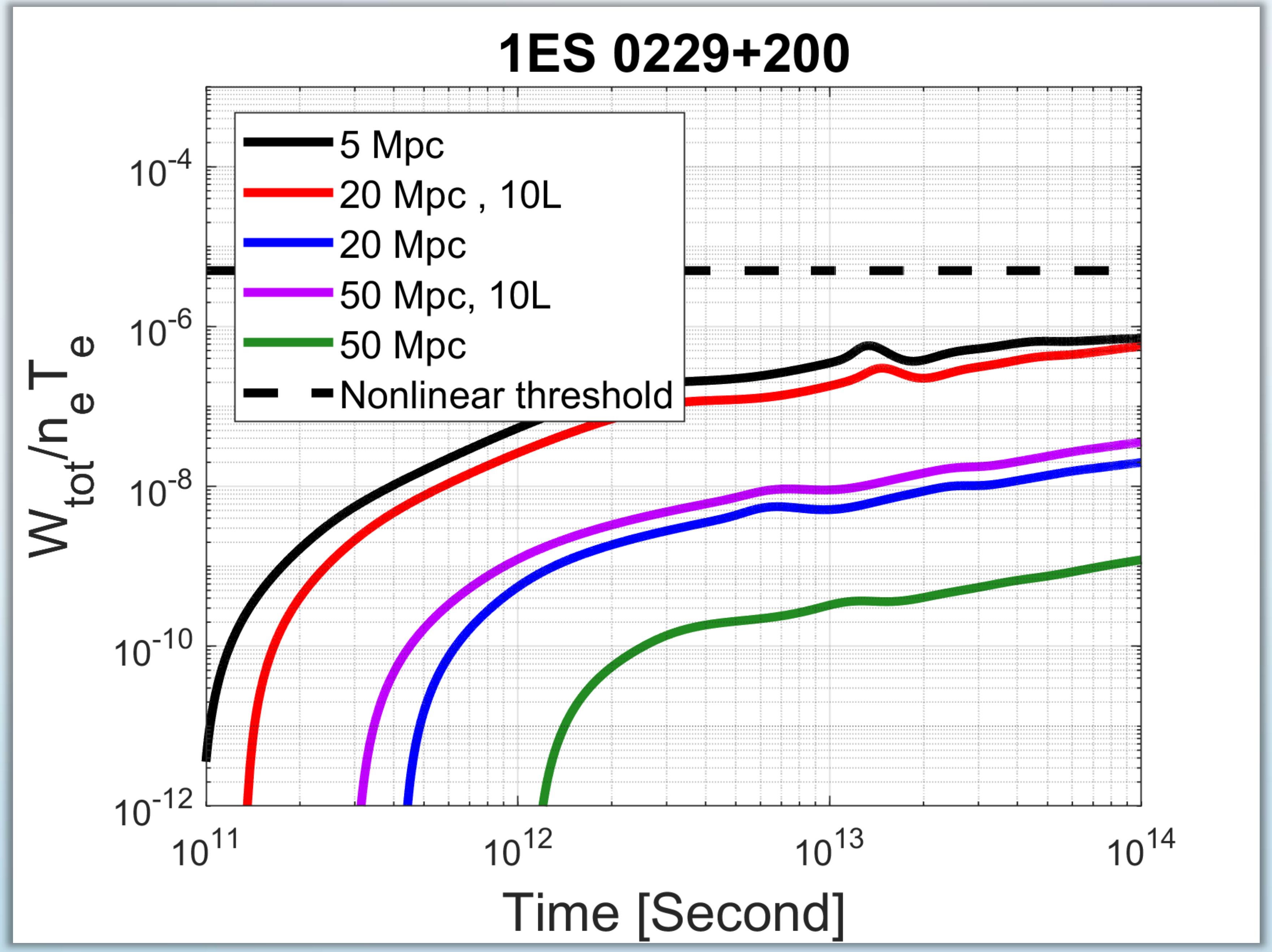


$K_\perp c/\omega_p$ = 0.1, R=50 Mpc
Steady state waves spectrum
W
$K_{||}c/\omega_p$-1
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
2.1e12
6.3e12
1.1e13
1.6e13
2.1e13
2.6e13
3.1e13
3.6e13
4.1e13
4.6e13

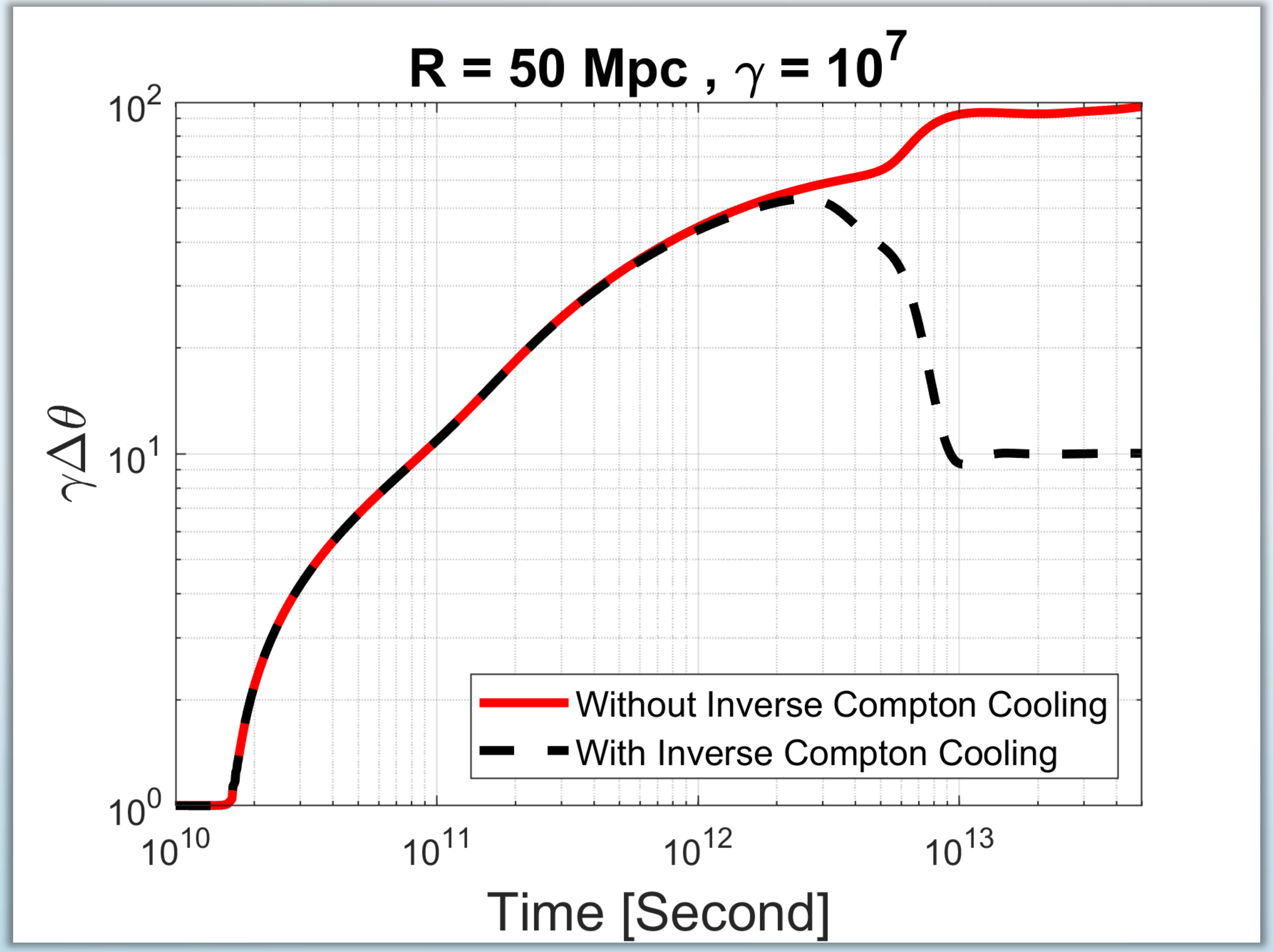
Distance and Luminosity dependence

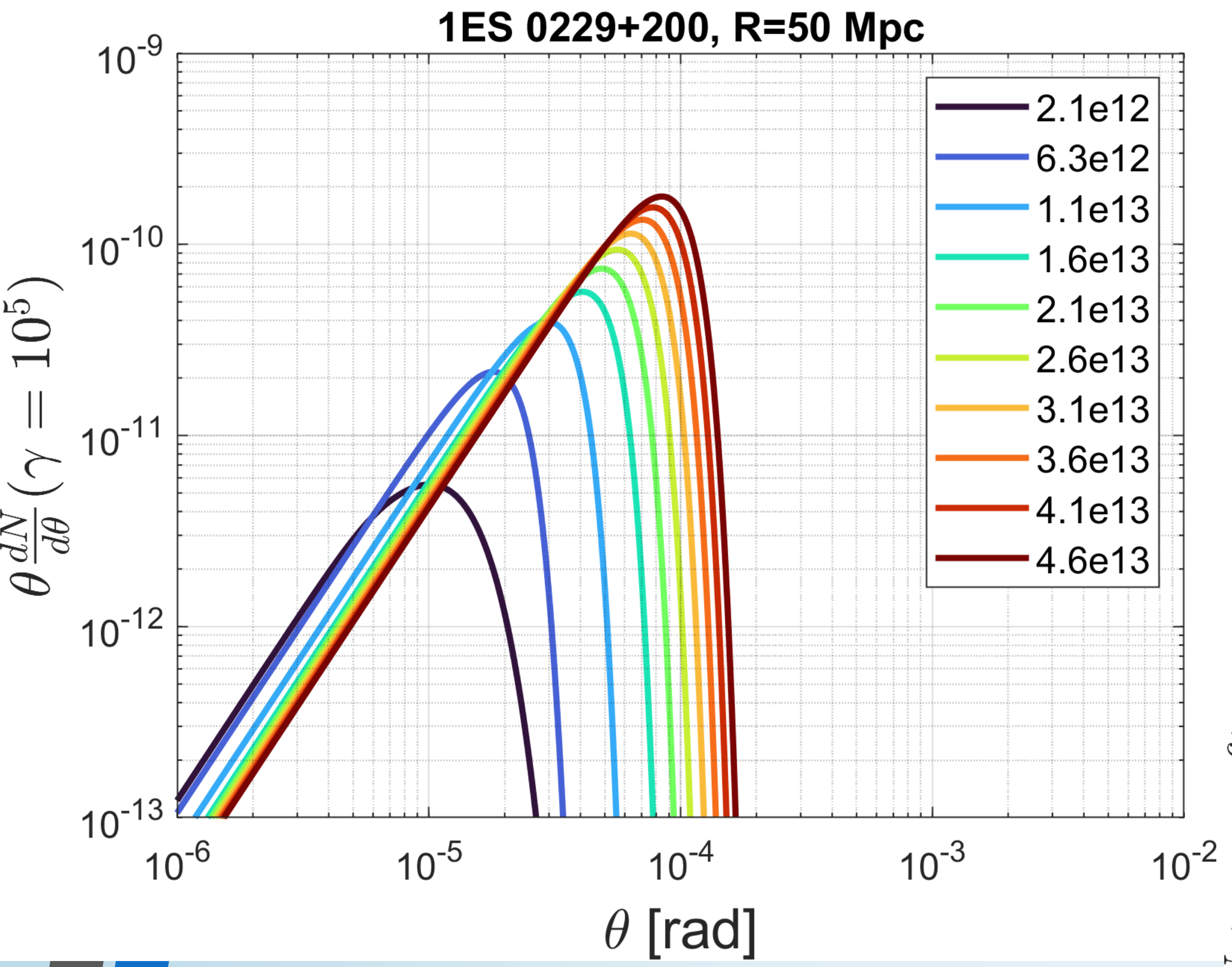


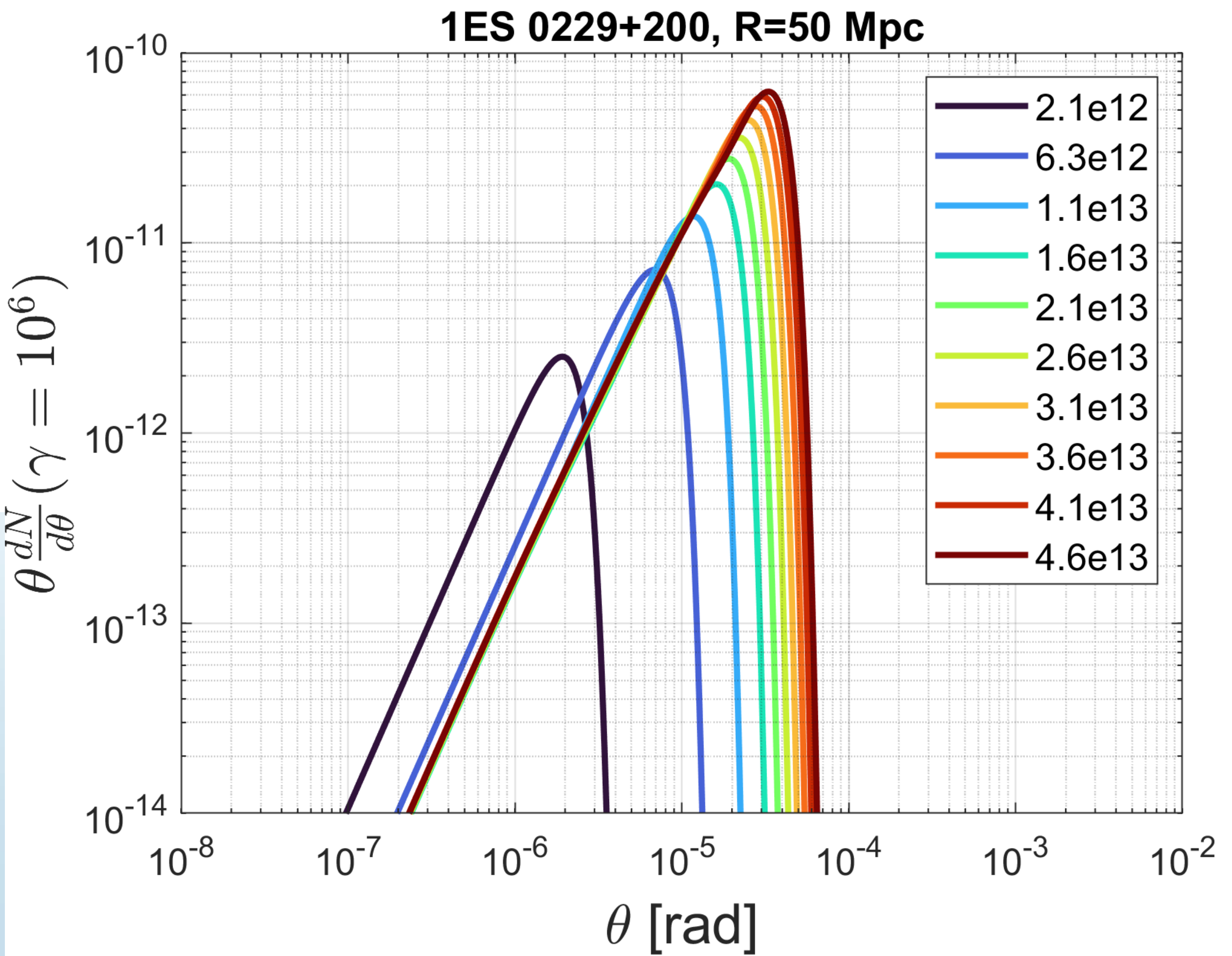
Instability saturation



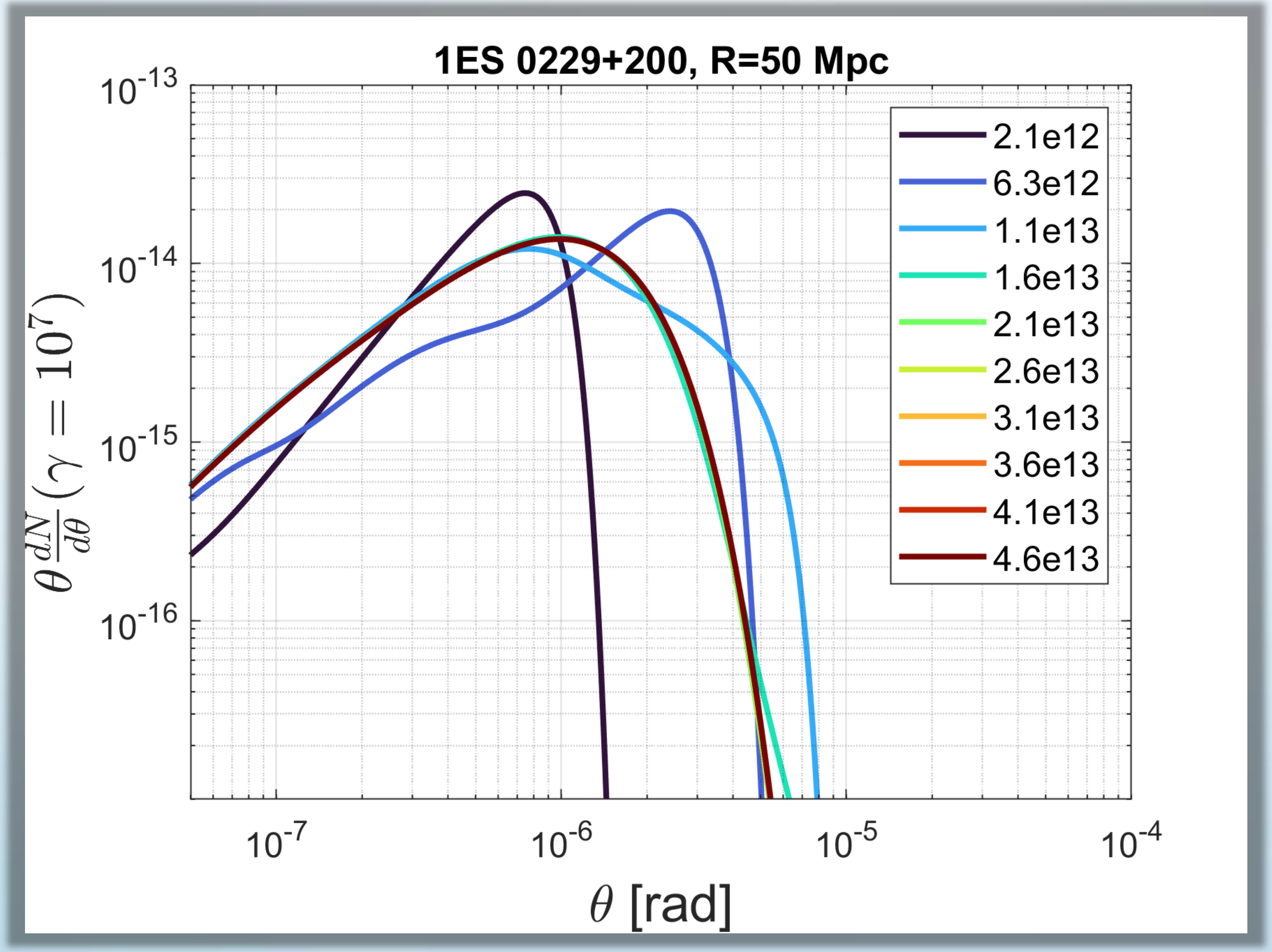
Effect of Inverse Compton Cooling




1ES 0229+200, R=50 Mpc
$\theta \frac{dN}{d\theta}(\gamma = 10^5)$
θ [rad]
2.1e12
6.3e12
1.1e13
1.6e13
2.1e13
2.6e13
3.1e13
3.6e13
4.1e13
4.6e13


1ES 0229+200, R=50 Mpc
$\theta \frac{dN}{d\theta}(\gamma = 10^6)$
θ [rad]
2.1e12
6.3e12
1.1e13
1.6e13
2.1e13
2.6e13
3.1e13
3.6e13
4.1e13
4.6e13

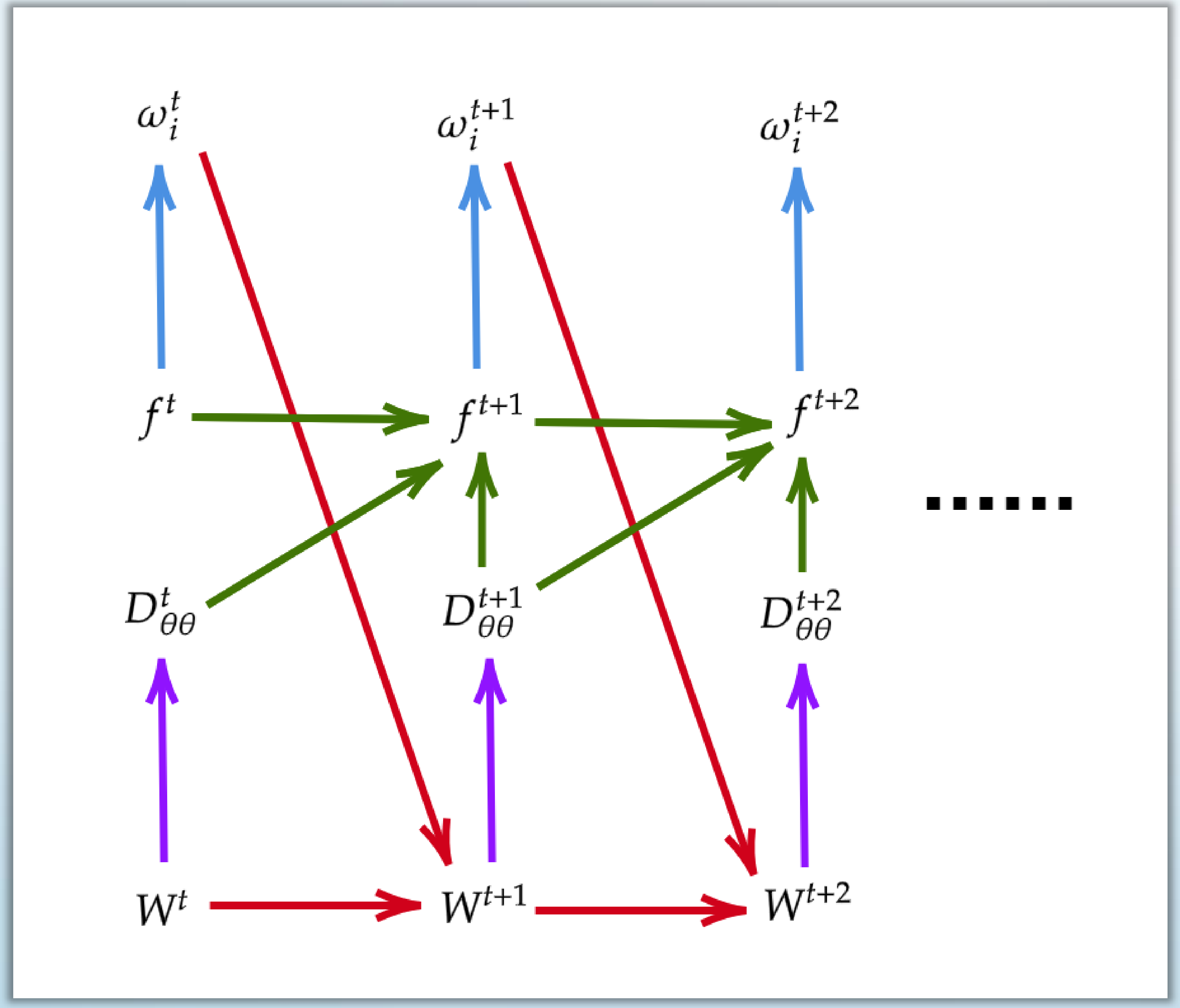
Confined steady state



First study

Alawashra and Pohl (2024) *ApJ 964 82*

Simulation steps



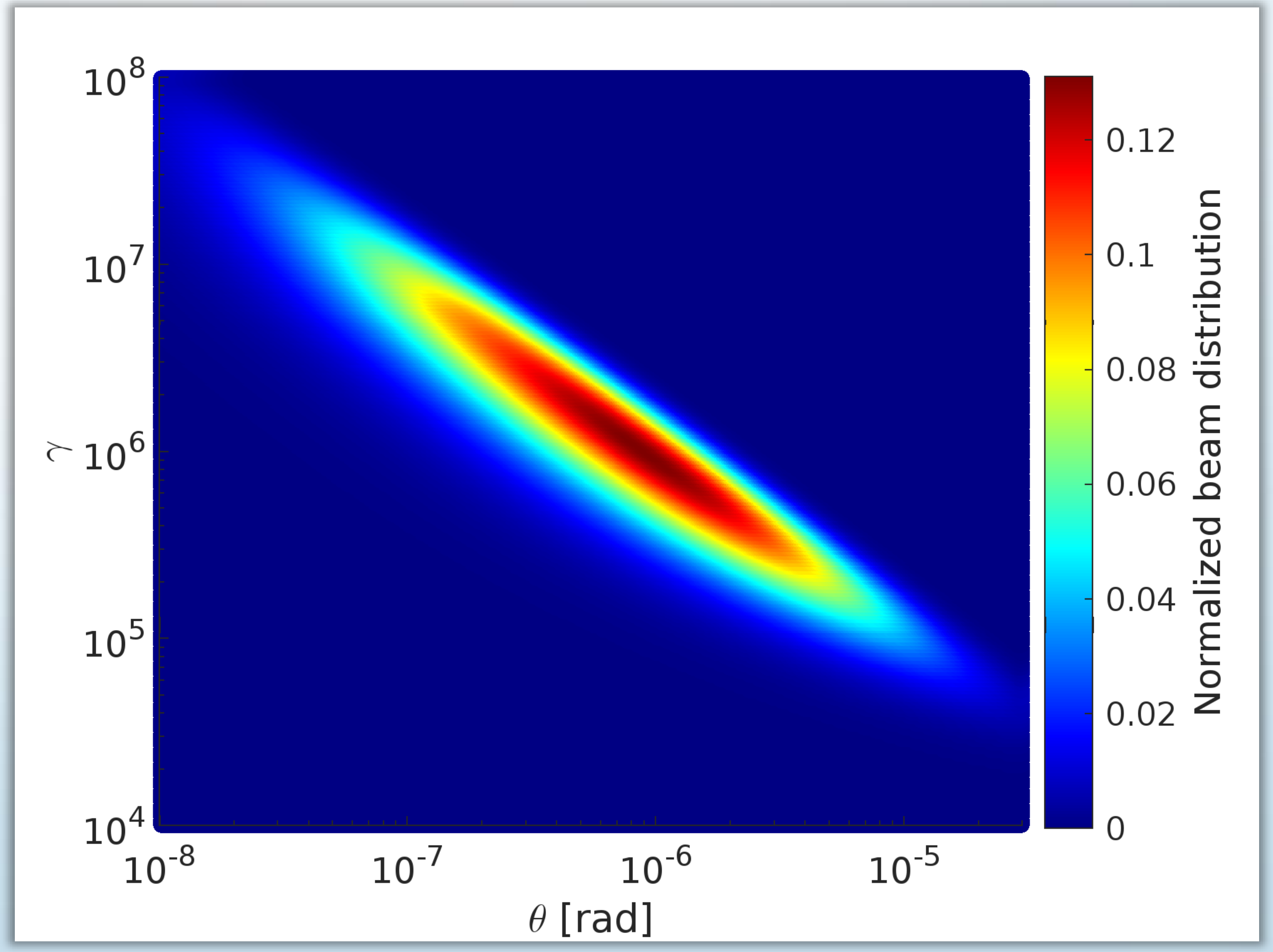
The realistic initial beam distribution

- **Consider the fiducial BL Lac source (Vafin et al 2018):**

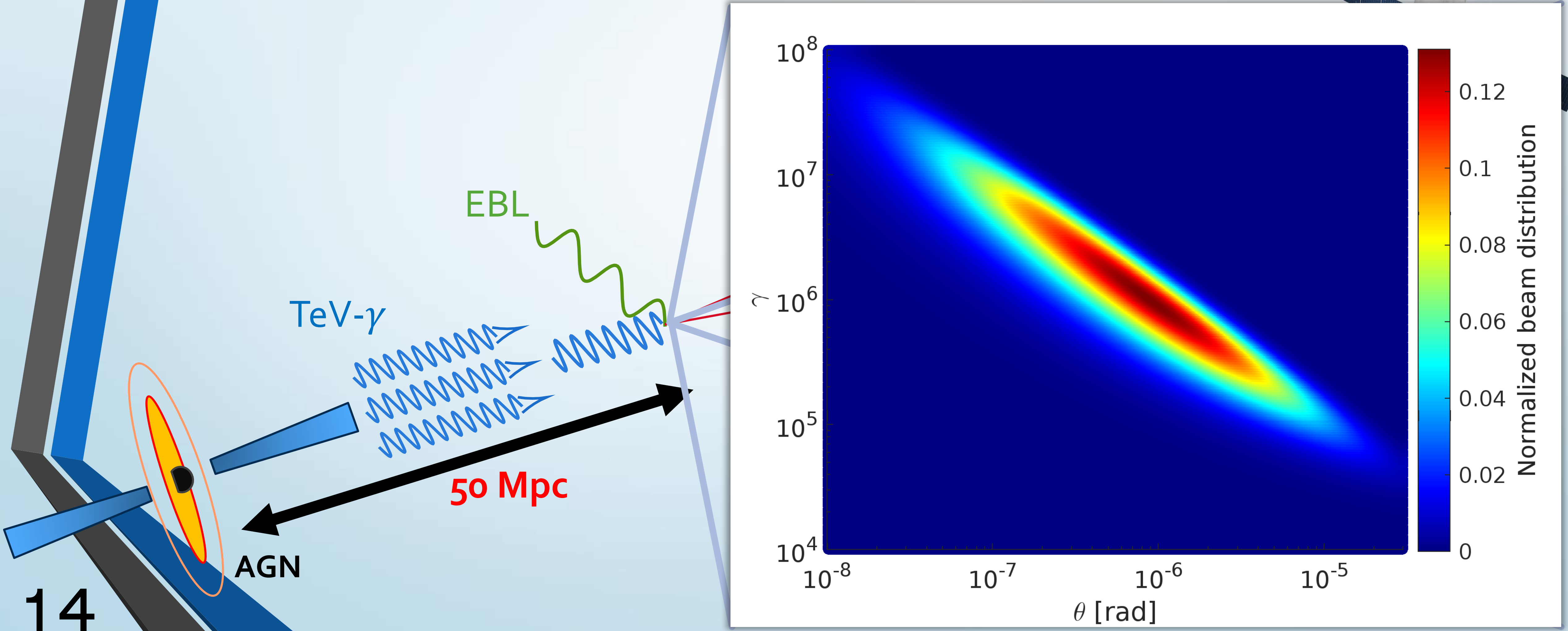
$$F(E_\gamma, z=0) = 10^{-9}\left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{-1.8}\Theta(50\ \mathrm{TeV} - E_\gamma)\ \frac{\mathrm{ph.}}{\mathrm{cm^2 s\ GeV}}$$

- **The yielded beam distribution at 50 Mpc from the blazar:**

$$n_b = 3\times 10^{-22}\ \mathrm{cm}^{-3}$$



- **The realistic beam distribution at 50 Mpc from blazar (Vafin et al (2018))**



2D simulation of the widening feedback

Beam and IGM parameters

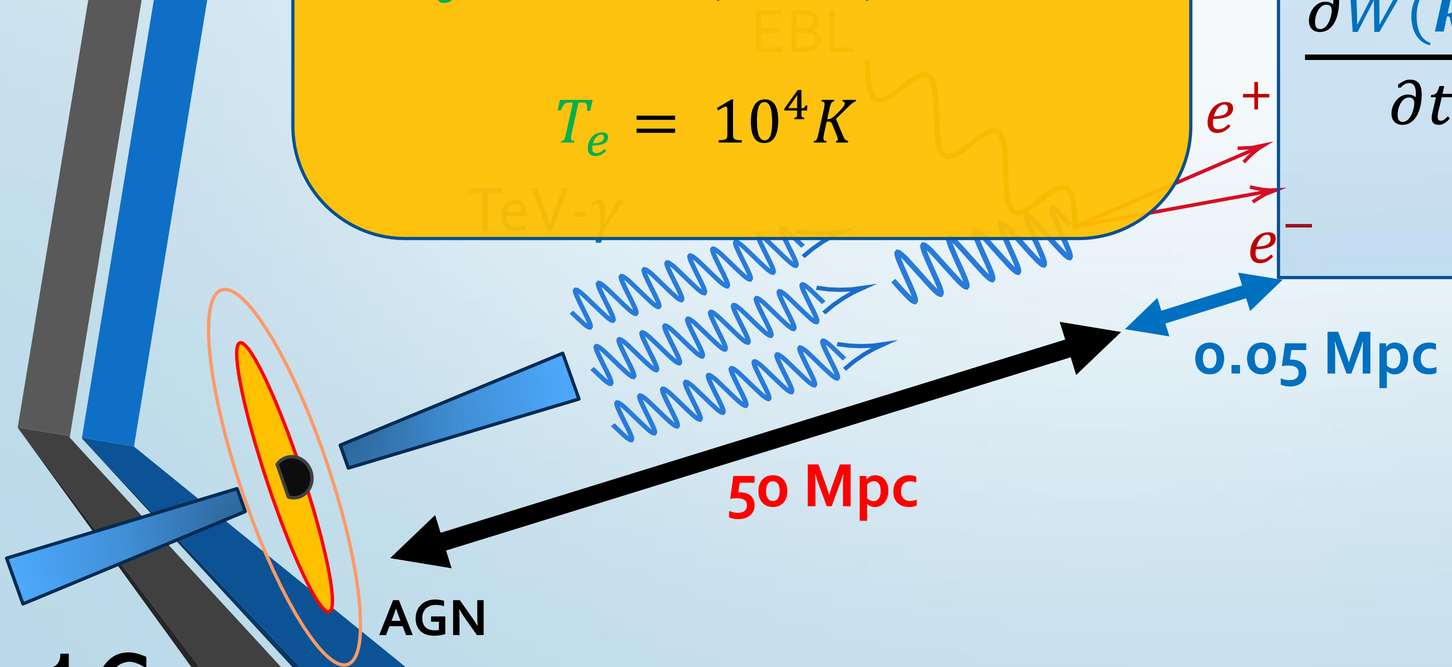
$n_b = 3 \times 10^{-22}\ \mathrm{cm}^{-3}$

$n_e = 10^{-7}\,(1+z)^3\,\mathrm{cm}^{-3}$

$T_e = 10^4 K$

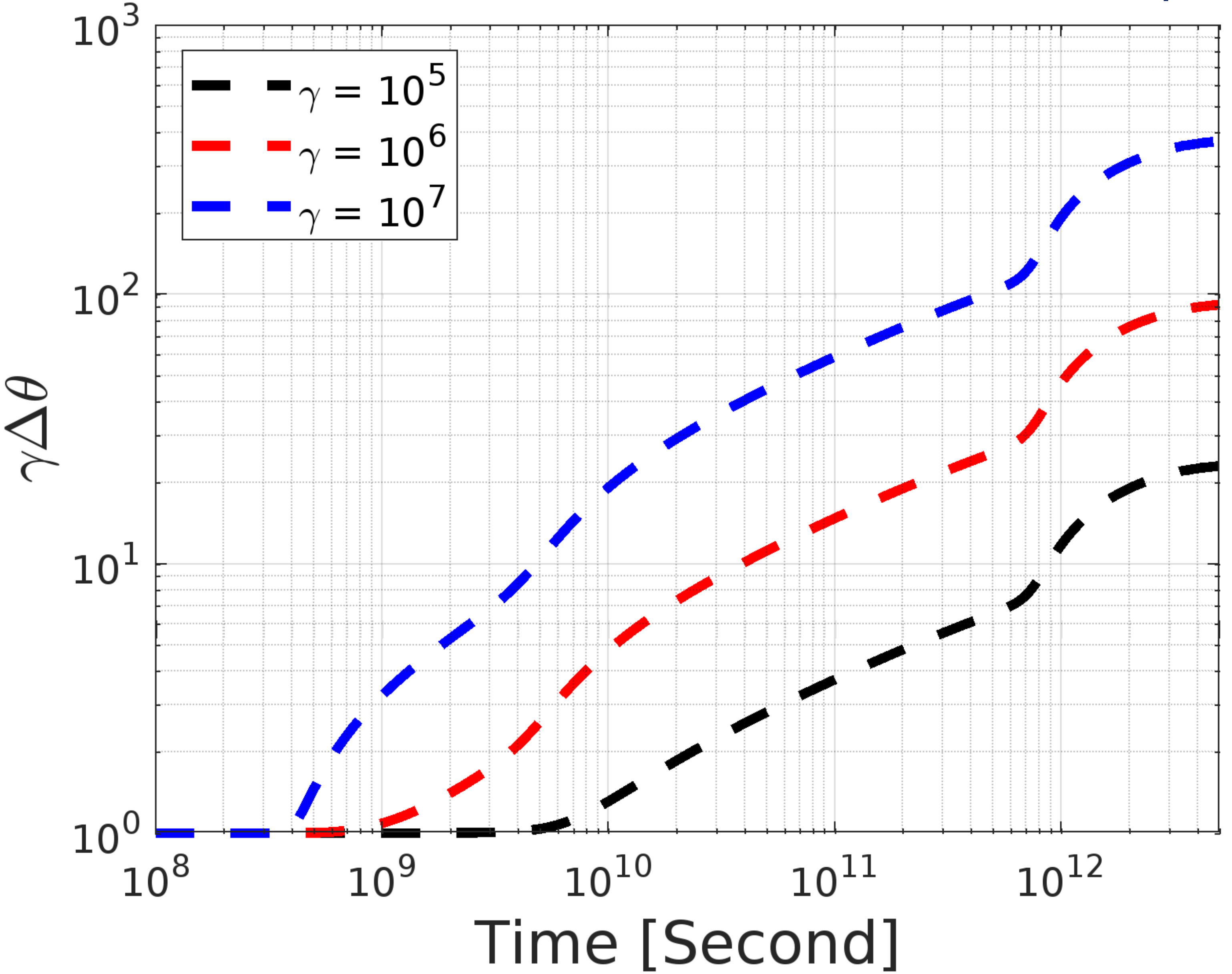
$$\frac{\partial f(p,\theta)}{\partial t} = \frac{1}{p^2\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right)$$

$$\frac{\partial W(\boldsymbol{k},t)}{\partial t} = 2\left(\omega_i(\boldsymbol{k}) + \omega_c\right) W(\boldsymbol{k},t)$$



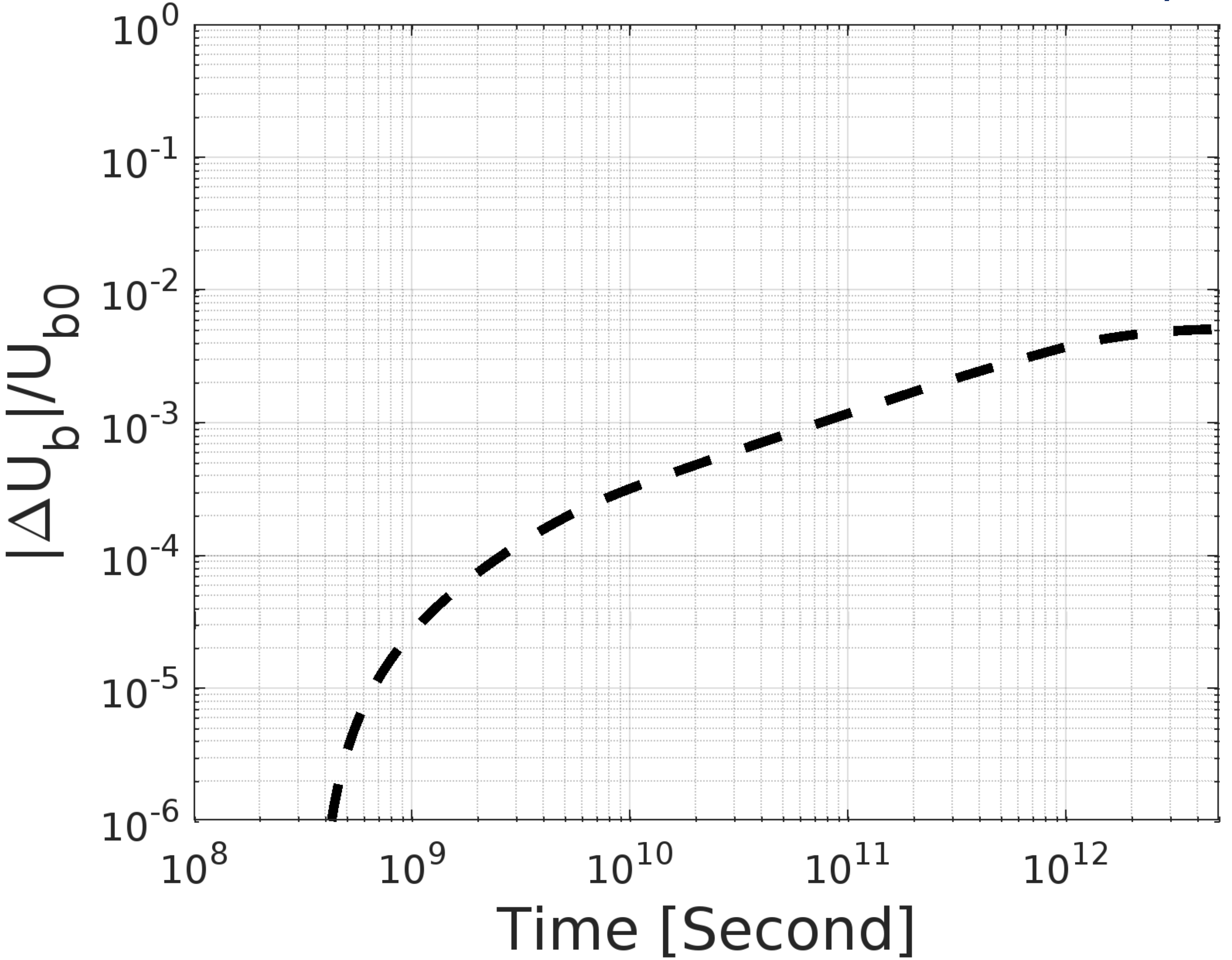
Significant widening of the beam

Alawashra and Pohl (2024) *ApJ 964 82*



Beam energy loss is subdominant

Alawashra and Pohl (2024) *ApJ 964 82*



Simulation of the beam-plasma system

Alawashra and Pohl (2024) *ApJ 964 82*

$$\frac{\partial f(p,\theta)}{\partial t} = \frac{1}{p^2\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right) + Q_{ee}$$

$$\frac{\partial W(\boldsymbol{k},t)}{\partial t} = 2\left(\omega_i(\boldsymbol{k}) + \omega_c\right) W(\boldsymbol{k},t)$$

Q_{ee} **: Continuous production of new pair due to the gamma-rays annihilation with EBL (Vafin et. al (2018))**

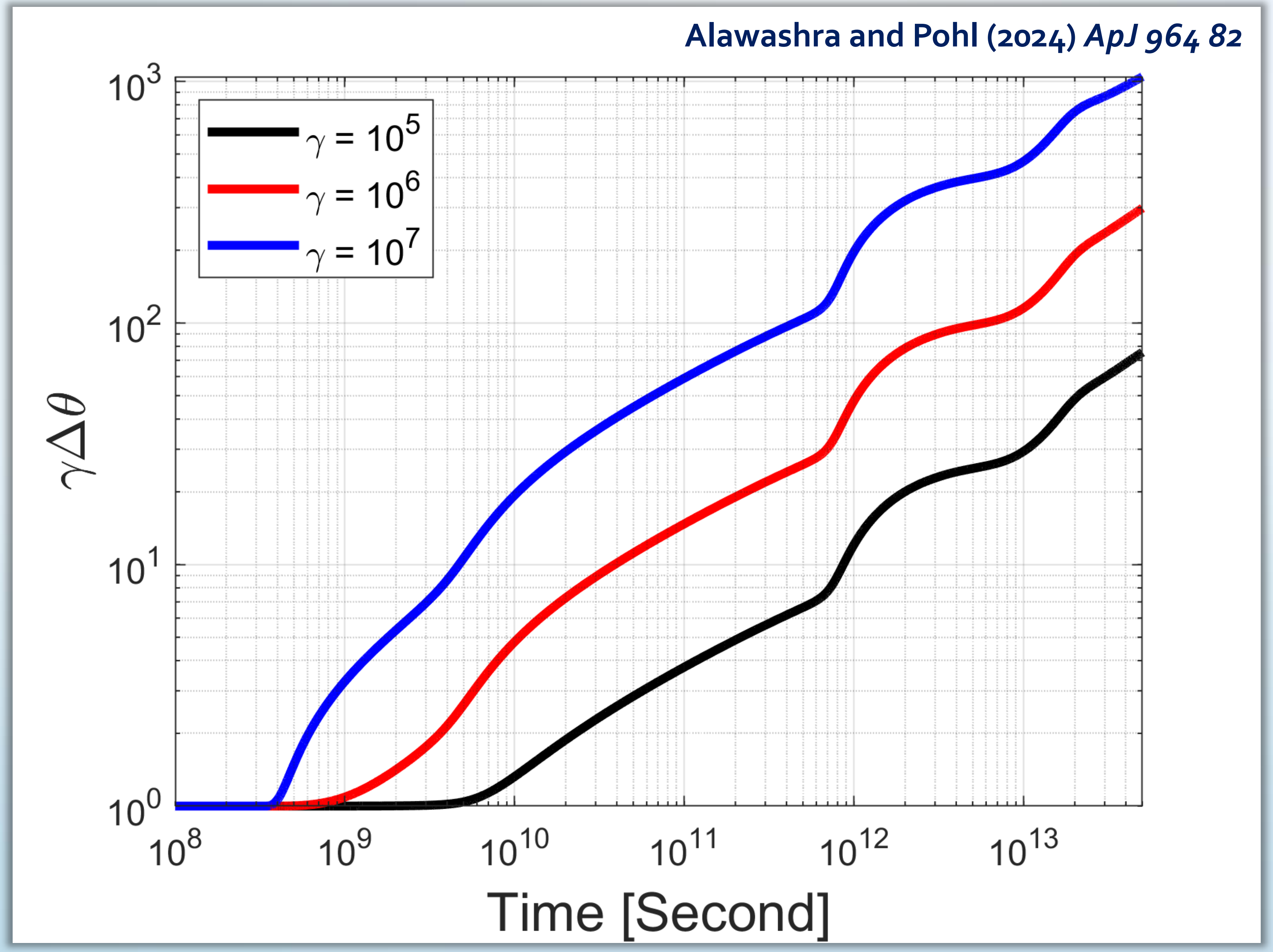
Beam and IGM plasma parameters:

$$n_b = 3 \times 10^{-22}\ \text{cm}^{-3}$$

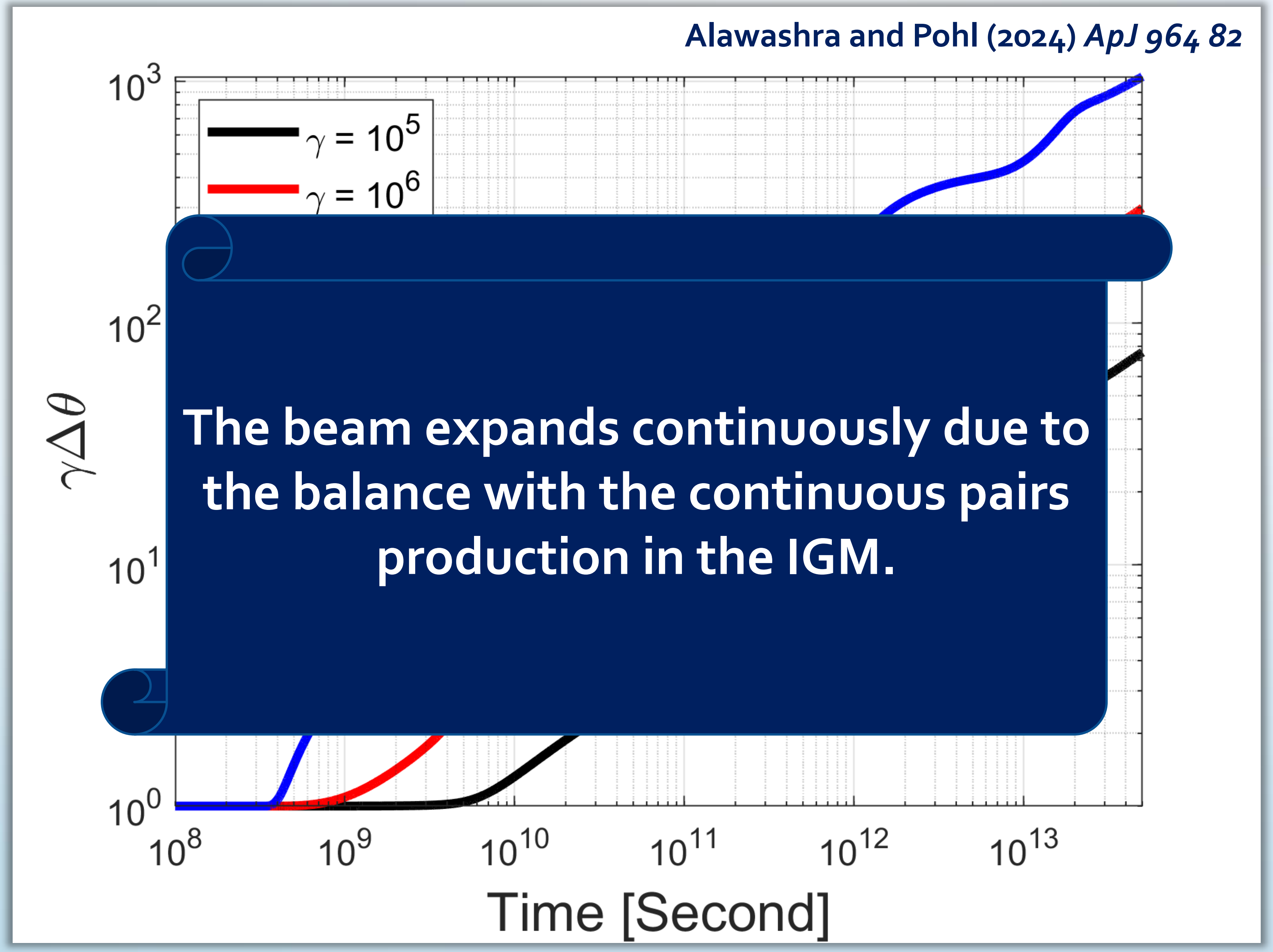
$$n_e = 10^{-7}\,(1+z)^3\text{cm}^{-3}$$

$$T_e = 10^4 K$$

Expansion of the beam due to the instability



Expansion of the beam due to the instability



The beam expands continuously due to the balance with the continuous pairs production in the IGM.

Adding Inverse-Compton cooling

$$\frac{\partial f(p,\theta)}{\partial t} = \frac{1}{p^2\theta}\frac{\partial}{\partial\theta}\left(\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(-\dot{p}_{IC}p^2 f\right) + Q_{ee}$$

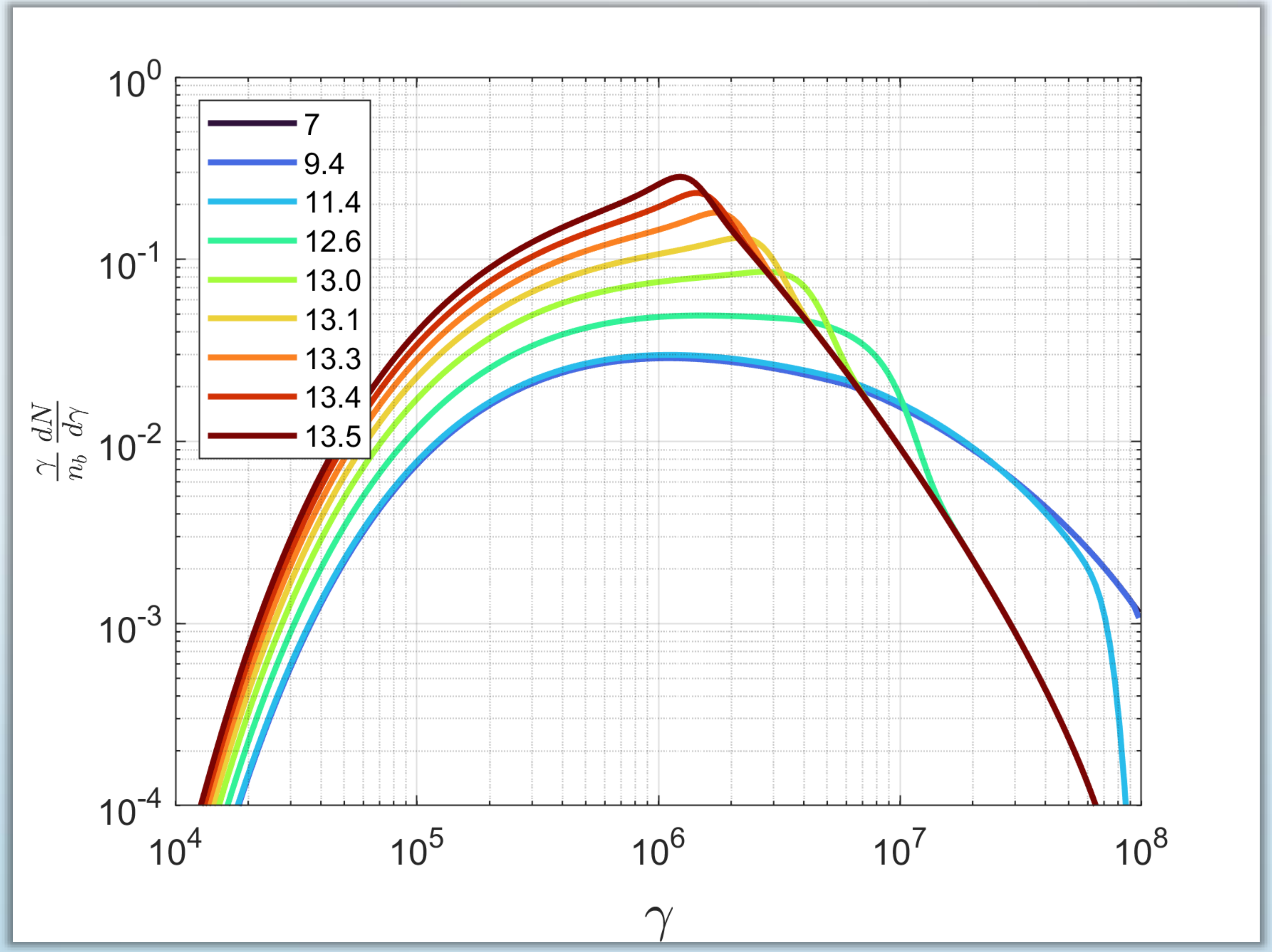
The IC cooling is only relevant for particle momentum

$$\dot{p}_{IC} = -\frac{4}{3}\sigma_T u_{CMB}\gamma^2$$

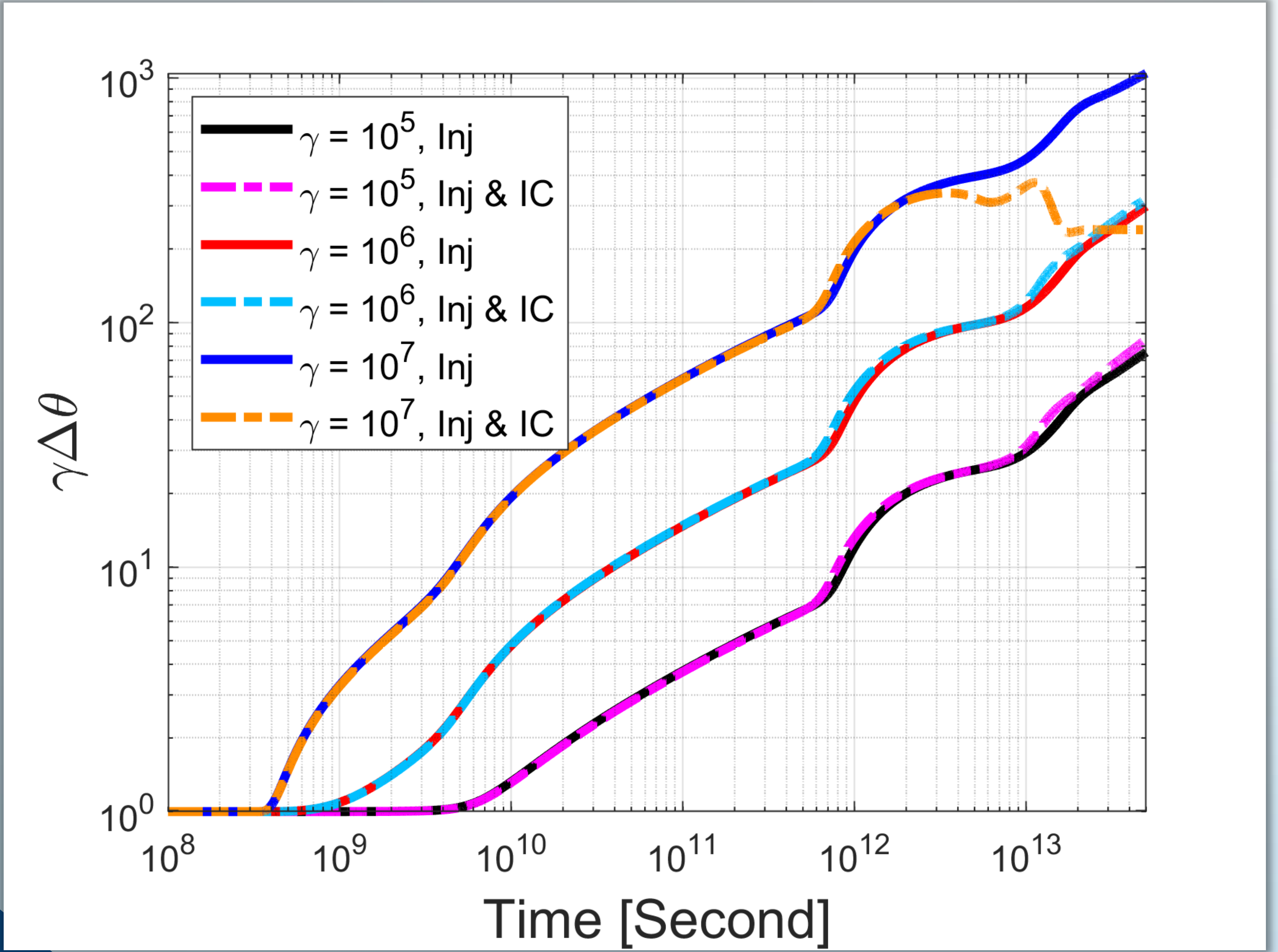
We use the linear evolution of the plasma waves

$$\frac{\partial W(\boldsymbol{k},t)}{\partial t} = 2\left(\omega_i(\boldsymbol{k}) + \omega_c\right) W(\boldsymbol{k},t)$$

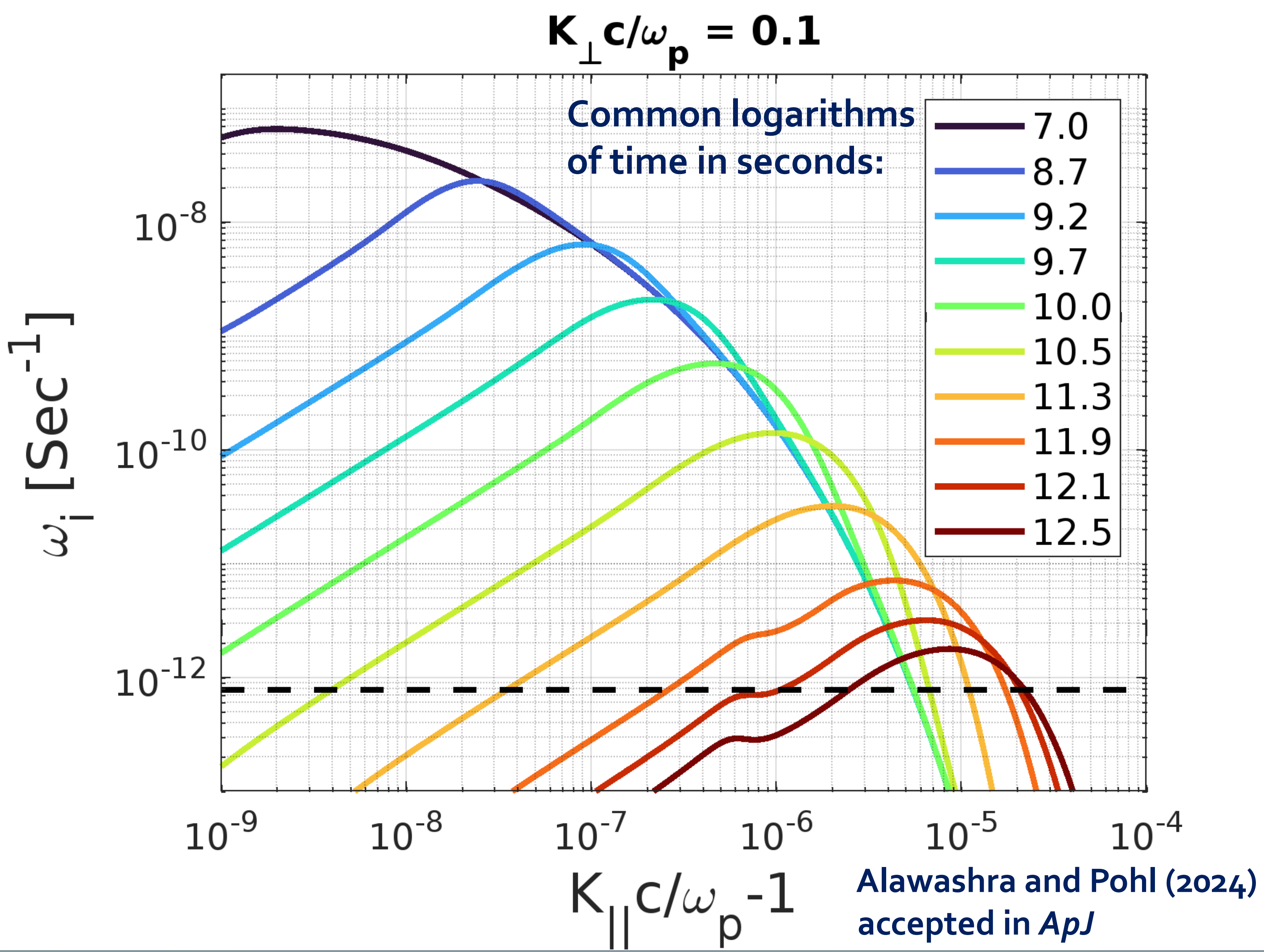
Momentum beam distribution evolution



Confined steady state after IC cooling time

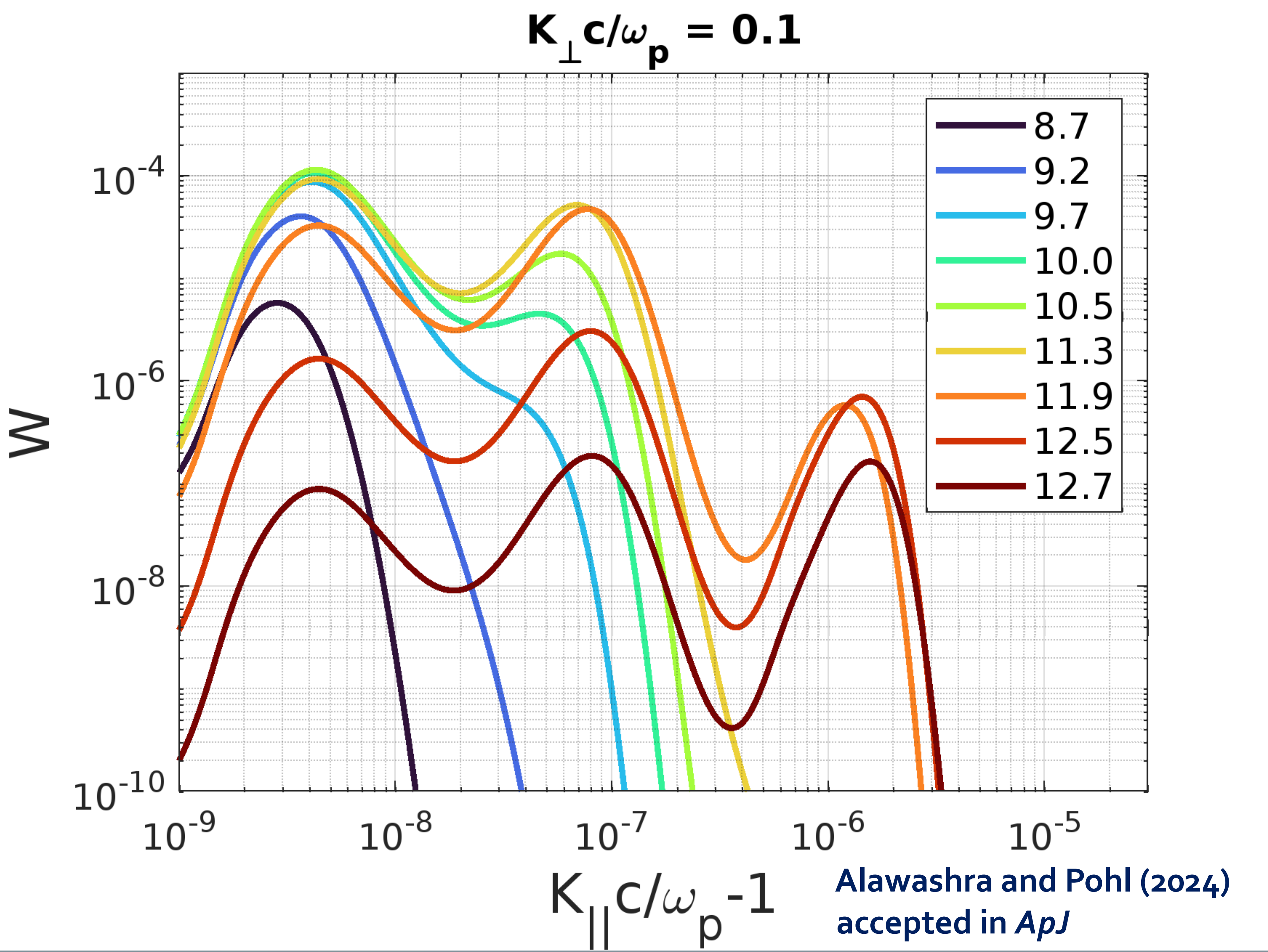


The instability is suppressed by the widening



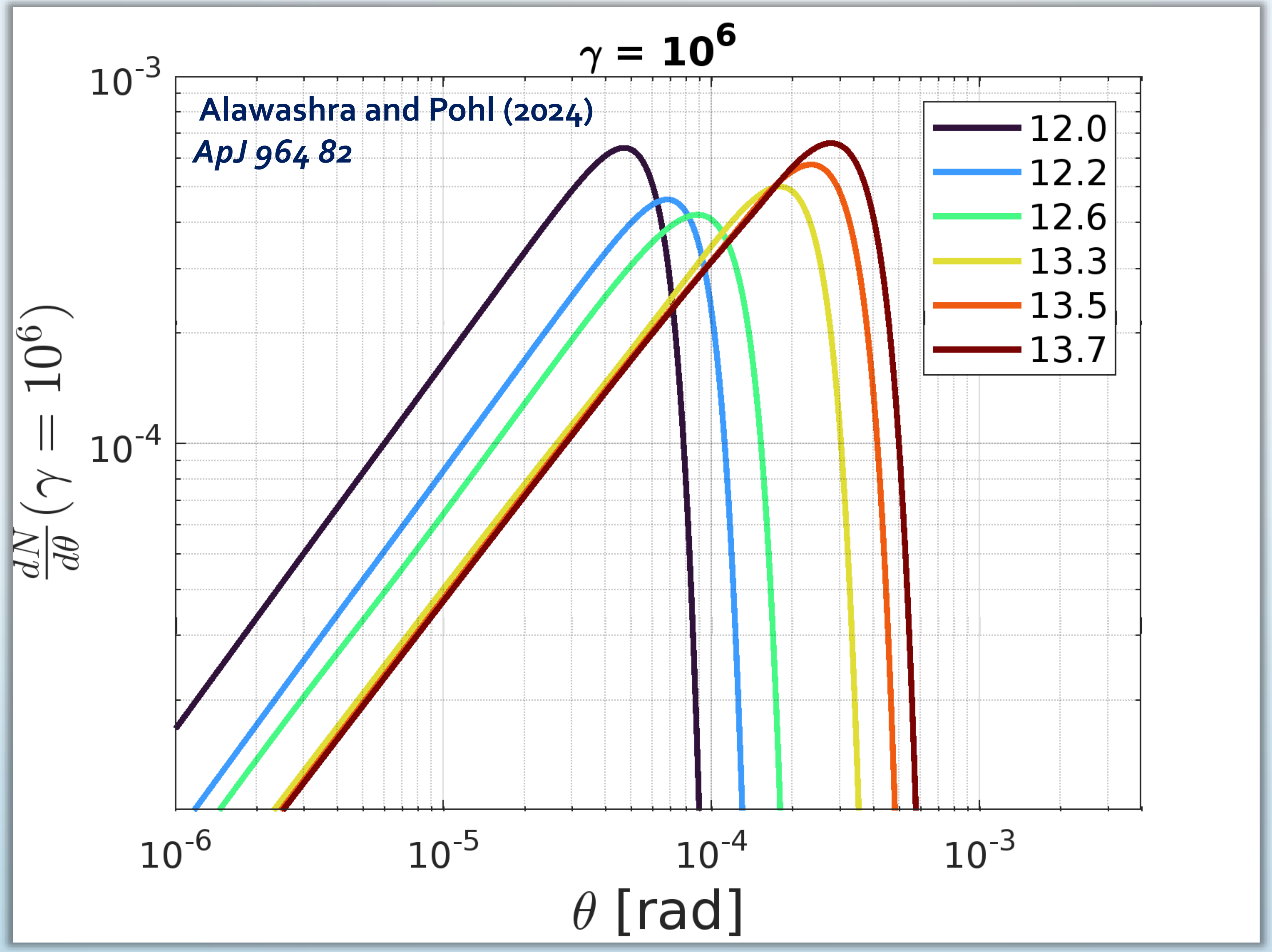
Alawashra and Pohl (2024) accepted in *ApJ*

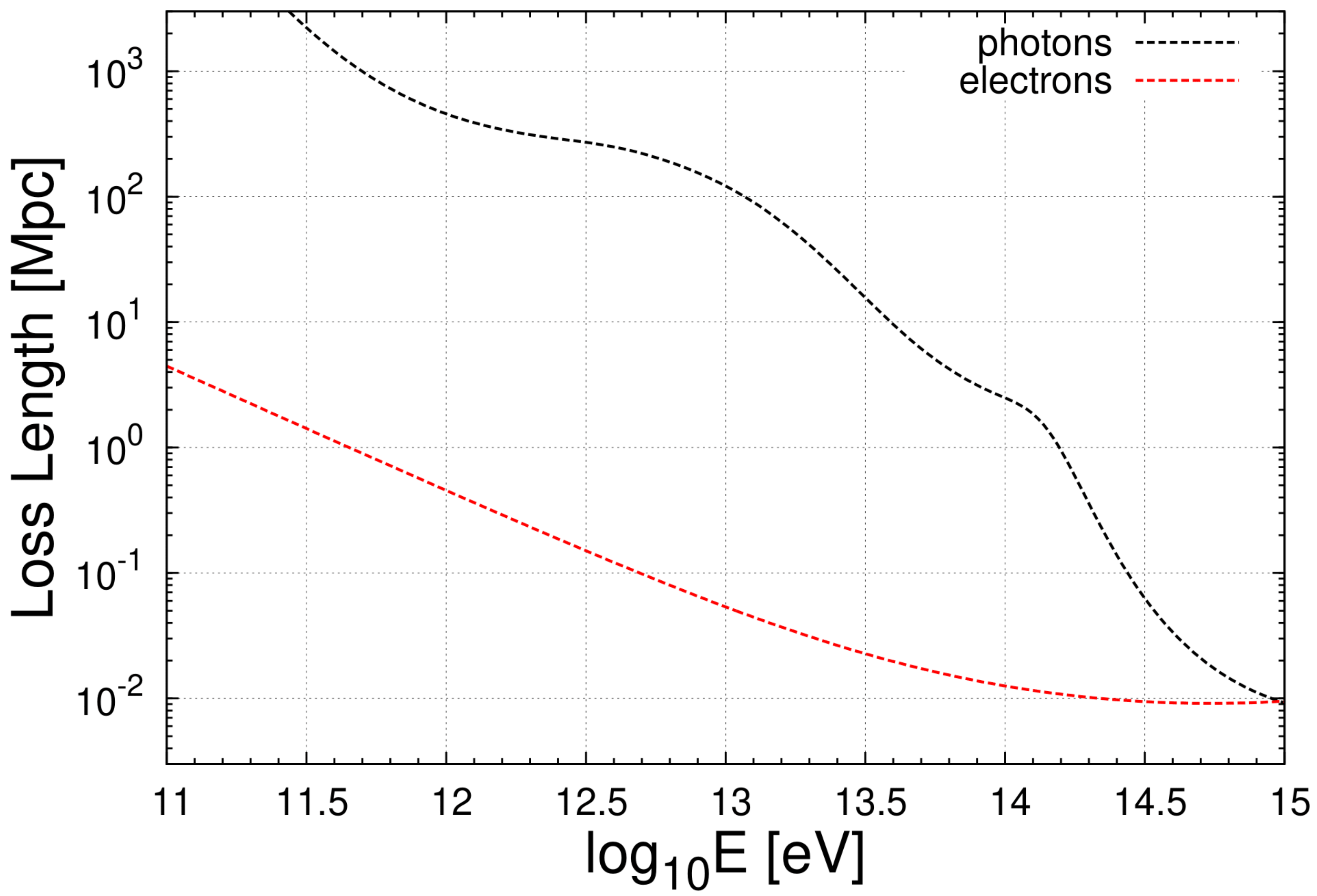
Unstable wave spectrum evolution



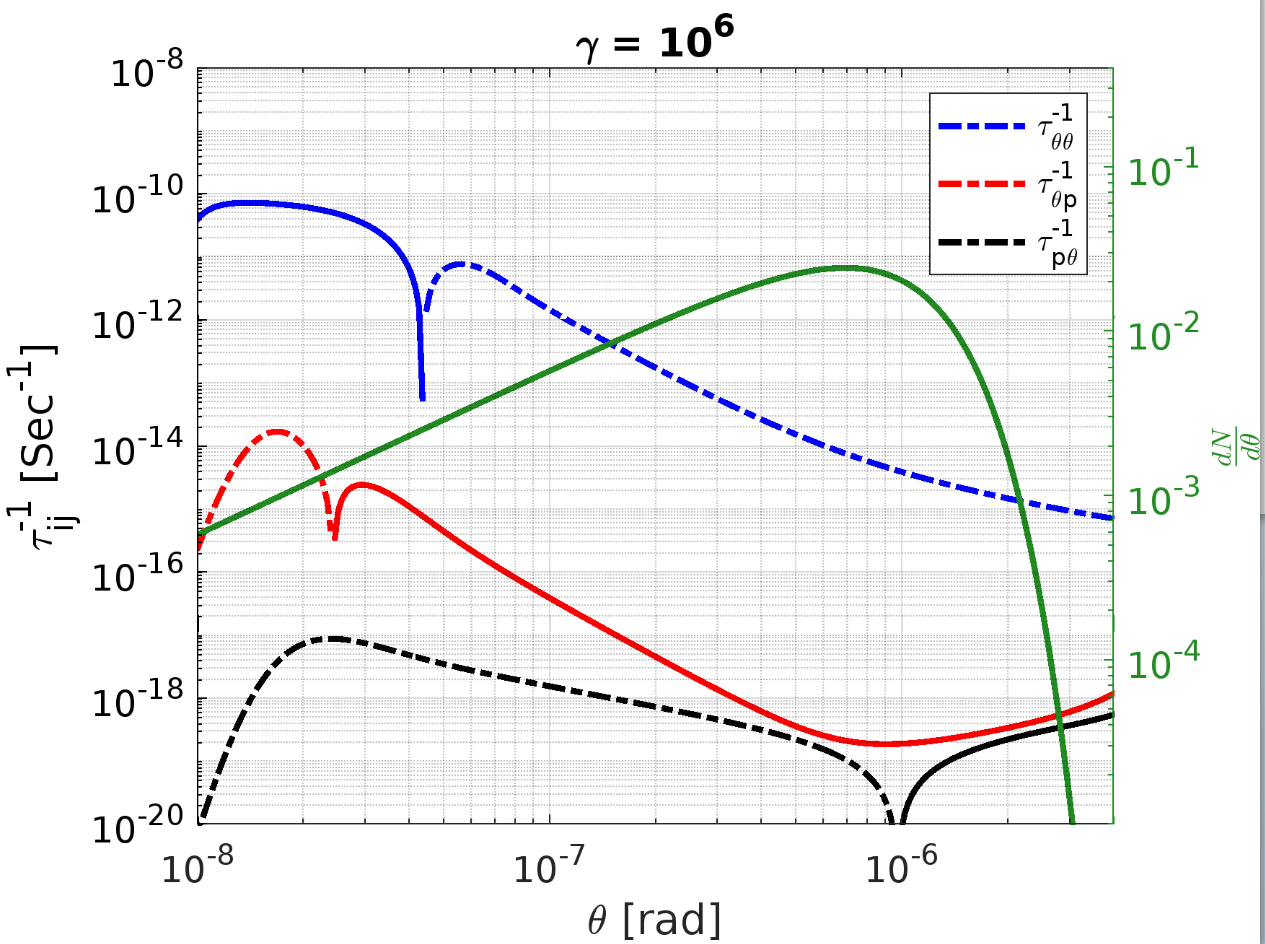
Alawashra and Pohl (2024) accepted in *ApJ*

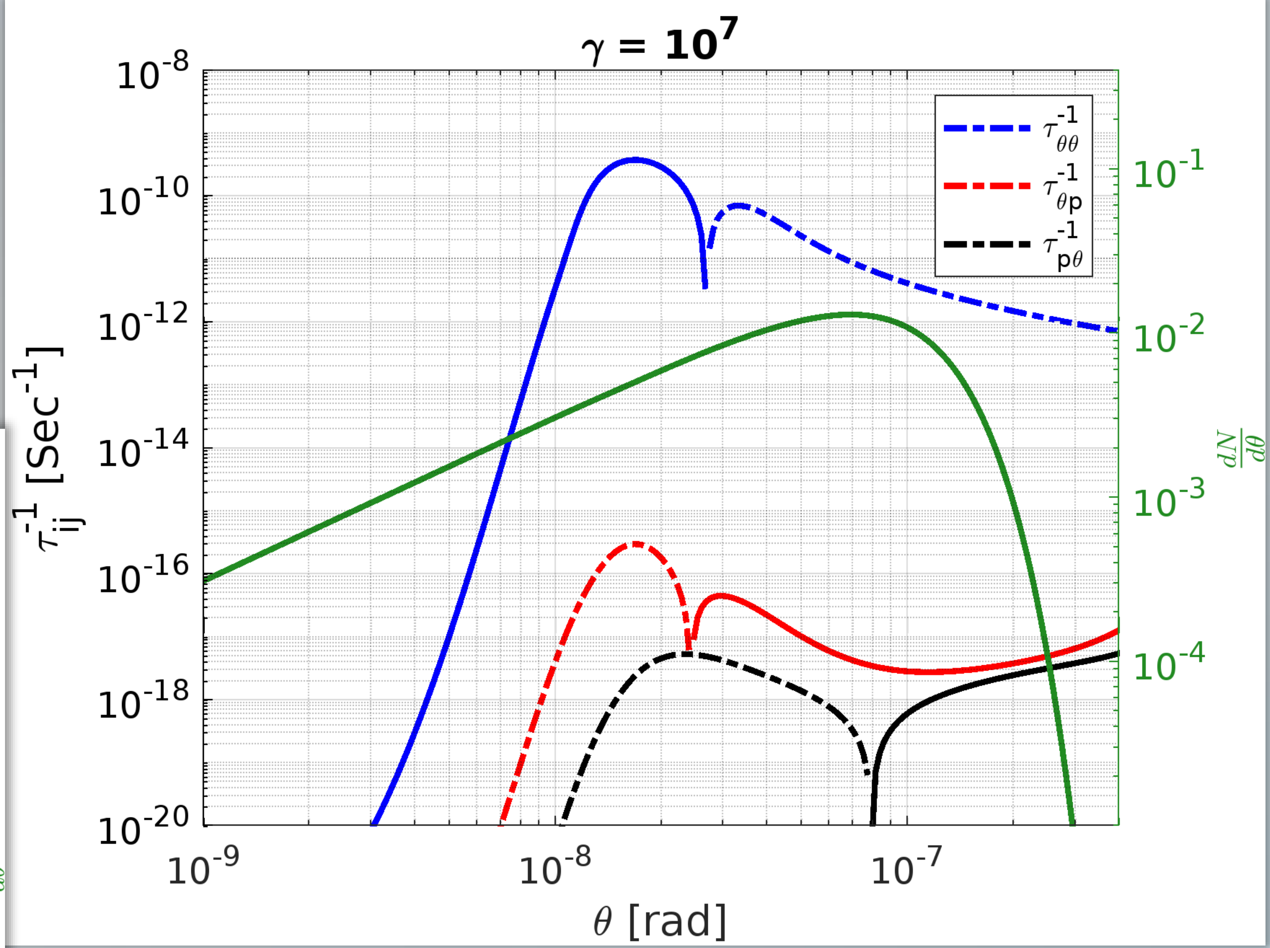
The beam keeps widening

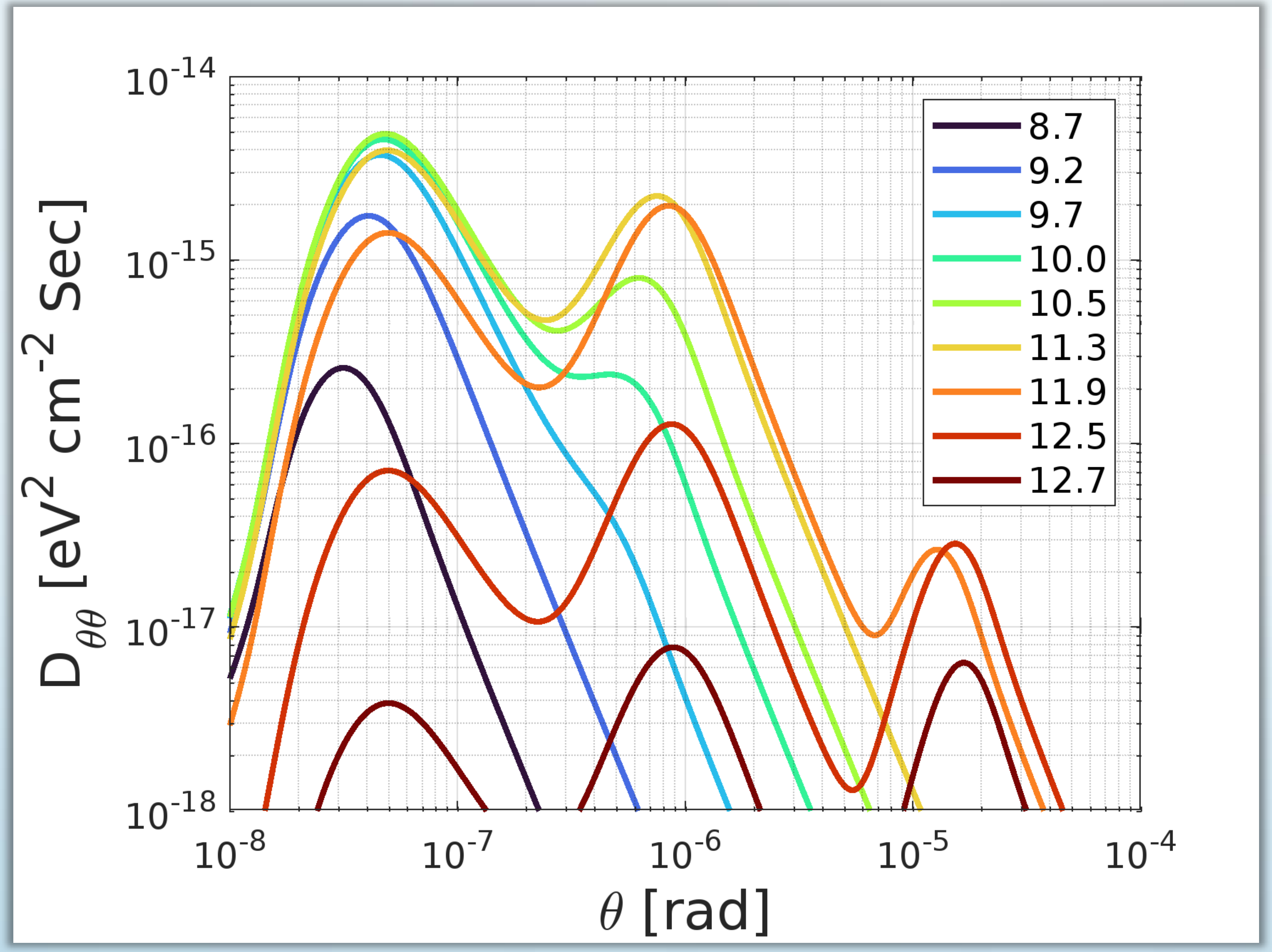




Andrew Taylor (private communication)

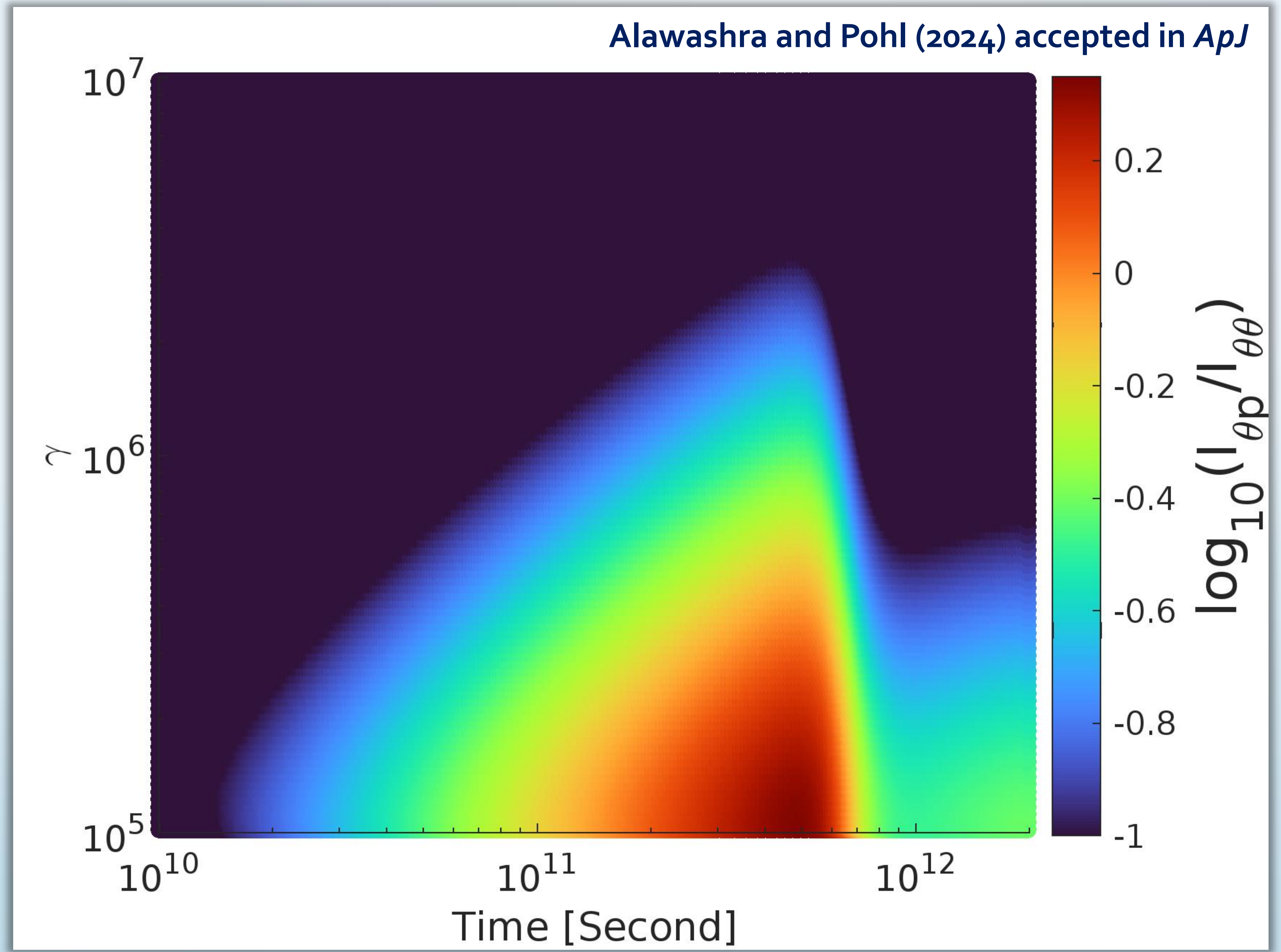

γ = 10^6
10^-8
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-1
10^-2
10^-3
10^-4
10^-8
10^-7
10^-6
θ [rad]
τ^-1_ij [Sec^-1]
dN/dθ
τ^-1_θθ
τ^-1_θp
τ^-1_pθ

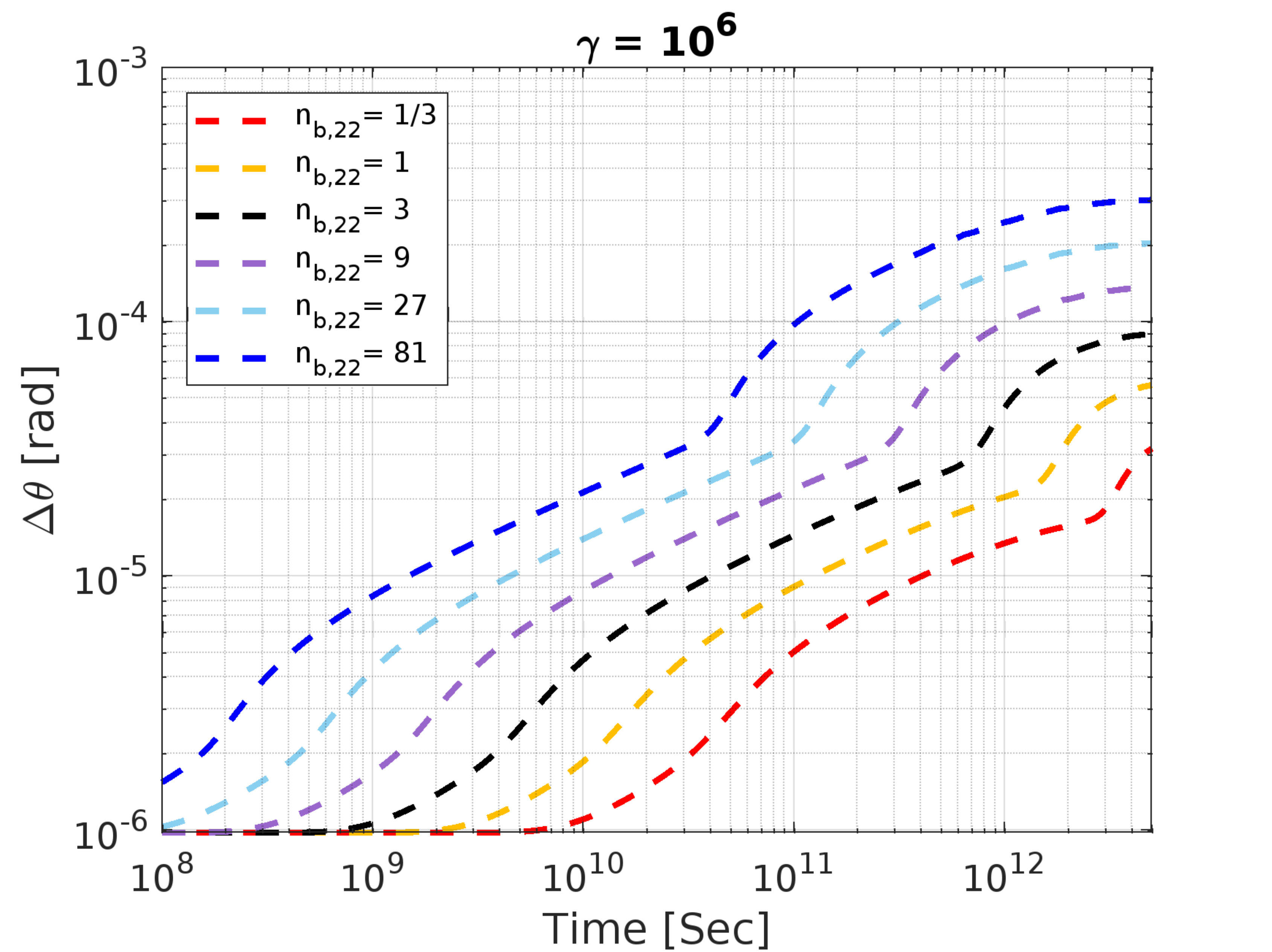

γ = 10^7
10^-8
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-1
10^-2
10^-3
10^-4
10^-9
10^-8
10^-7
θ [rad]
τ^-1_ij [Sec^-1]
dN/dθ
τ^-1_θθ
τ^-1_θp
τ^-1_pθ



10^-14
10^-15
10^-16
10^-17
10^-18
D_θθ [eV^2 cm^-2 Sec]
10^-8
10^-7
10^-6
10^-5
10^-4
θ [rad]
8.7
9.2
9.7
10.0
10.5
11.3
11.9
12.5
12.7

Relevant for pairs with Lorentz factors less than 10^6

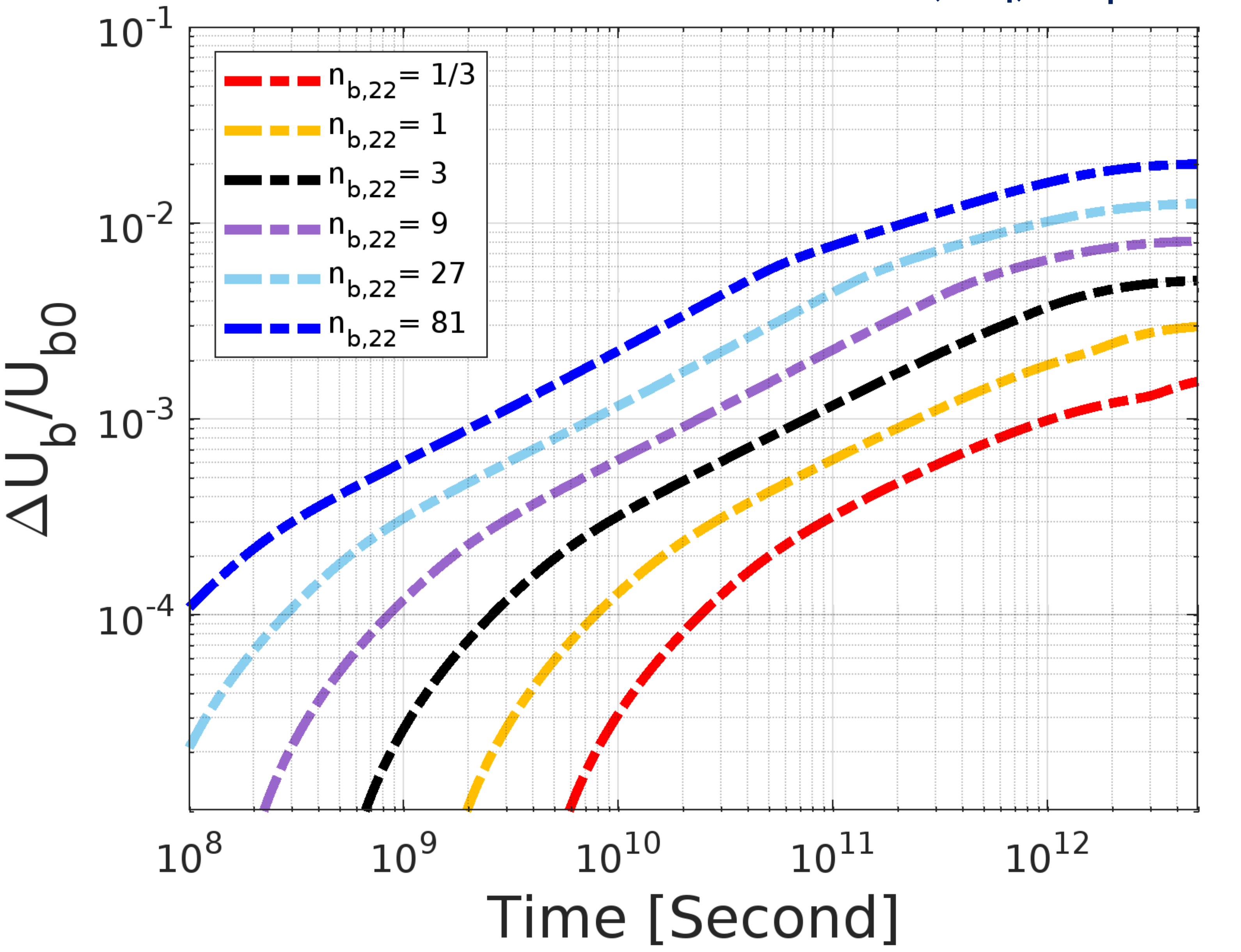




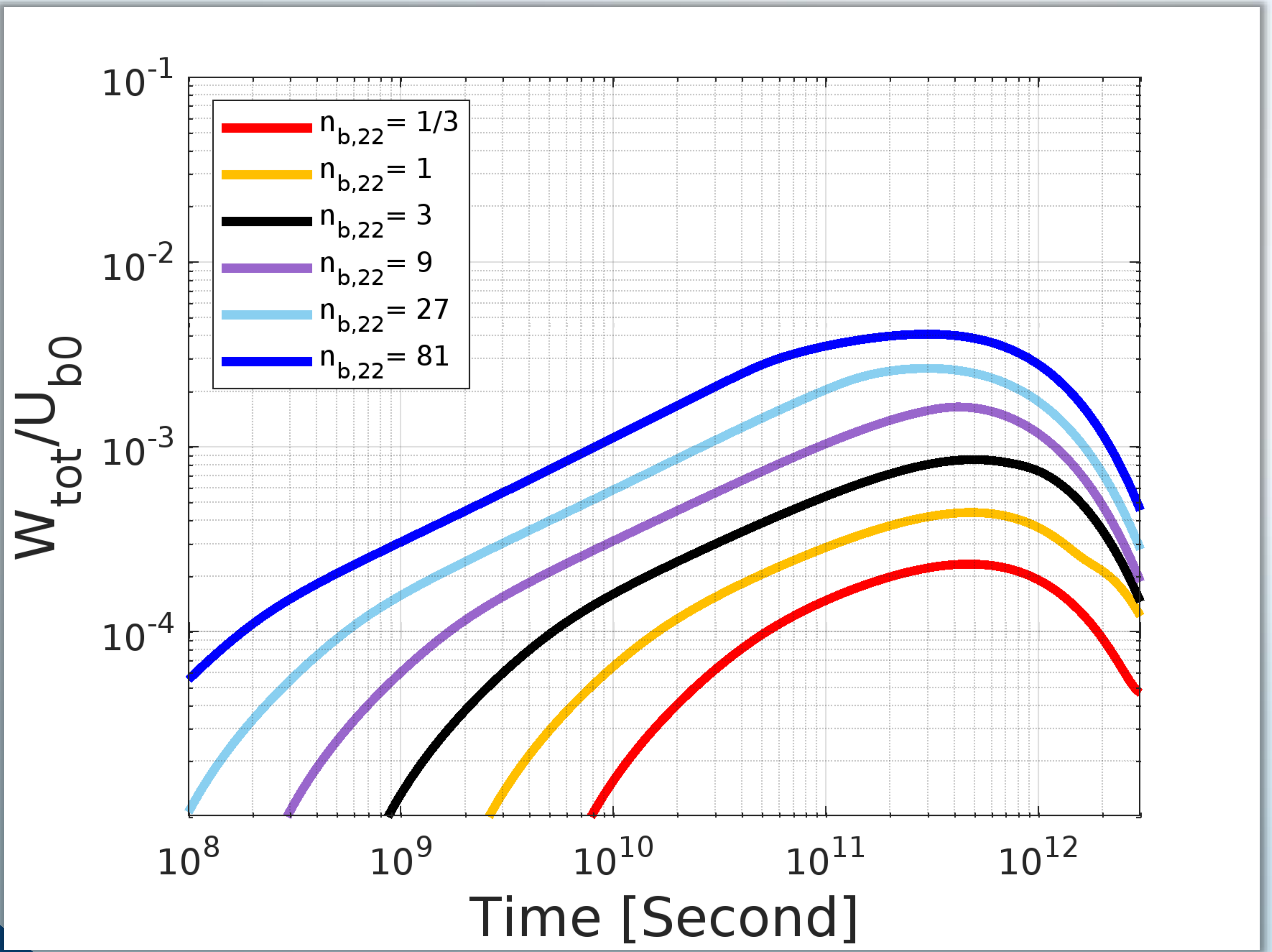
γ = 10^6
$n_{b,22}$= 1/3
$n_{b,22}$= 1
$n_{b,22}$= 3
$n_{b,22}$= 9
$n_{b,22}$= 27
$n_{b,22}$= 81
Δθ [rad]
Time [Sec]
10^-3
10^-4
10^-5
10^-6
10^8
10^9
10^10
10^11
10^12

Small energy loss even for higher densities

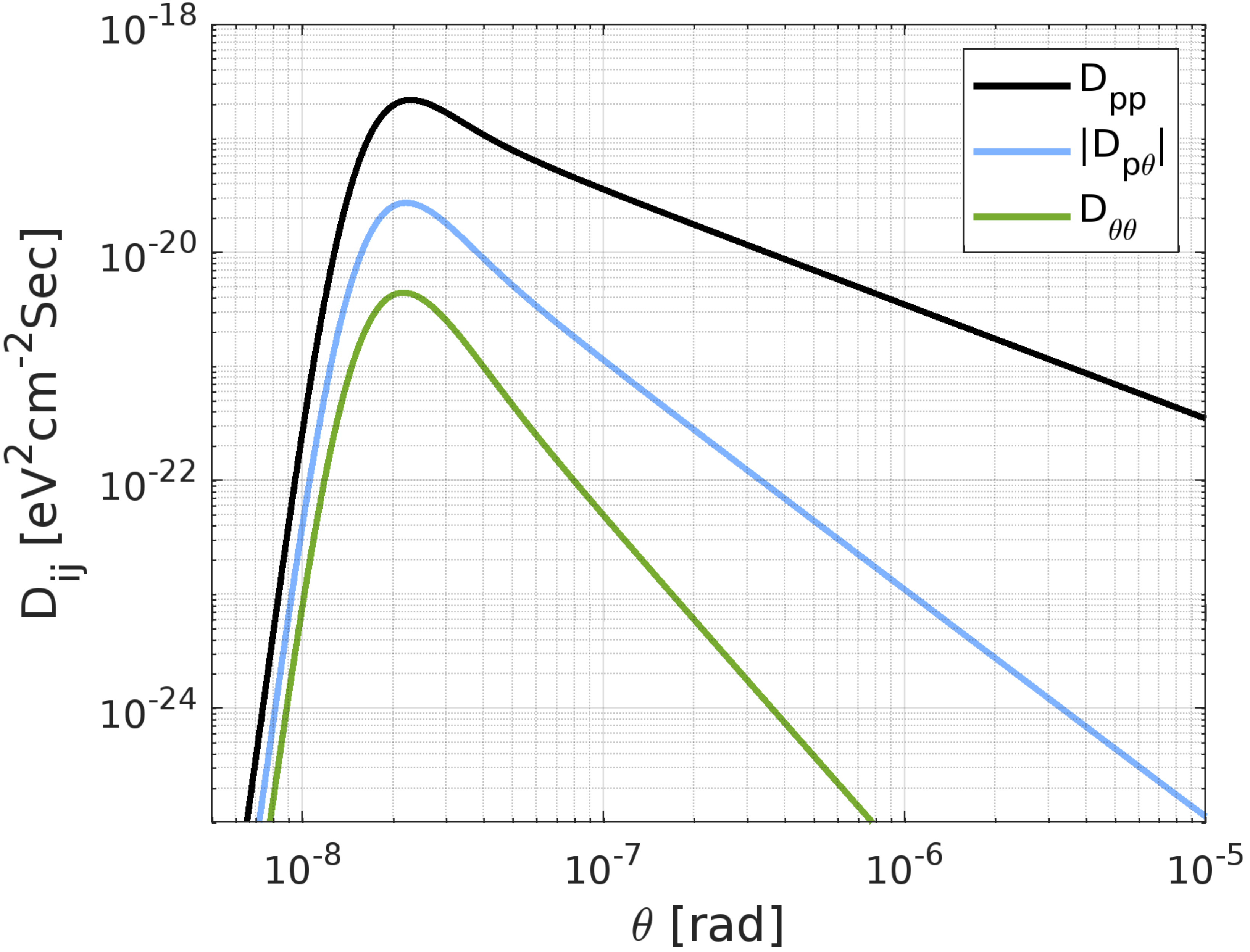
Alawashra and Pohl (2024) accepted in *ApJ*



$$\begin{aligned}\frac{dU_b}{dt}(t) &= -2\frac{dW_{\text{tot}}}{dt}(t) \\ &= -8\pi \int dk_\perp k_\perp \int dk_{||} W(k_\perp, k_{||}, t)\,\omega_i(k_\perp, k_{||}, t),\end{aligned} \tag{5.38}$$

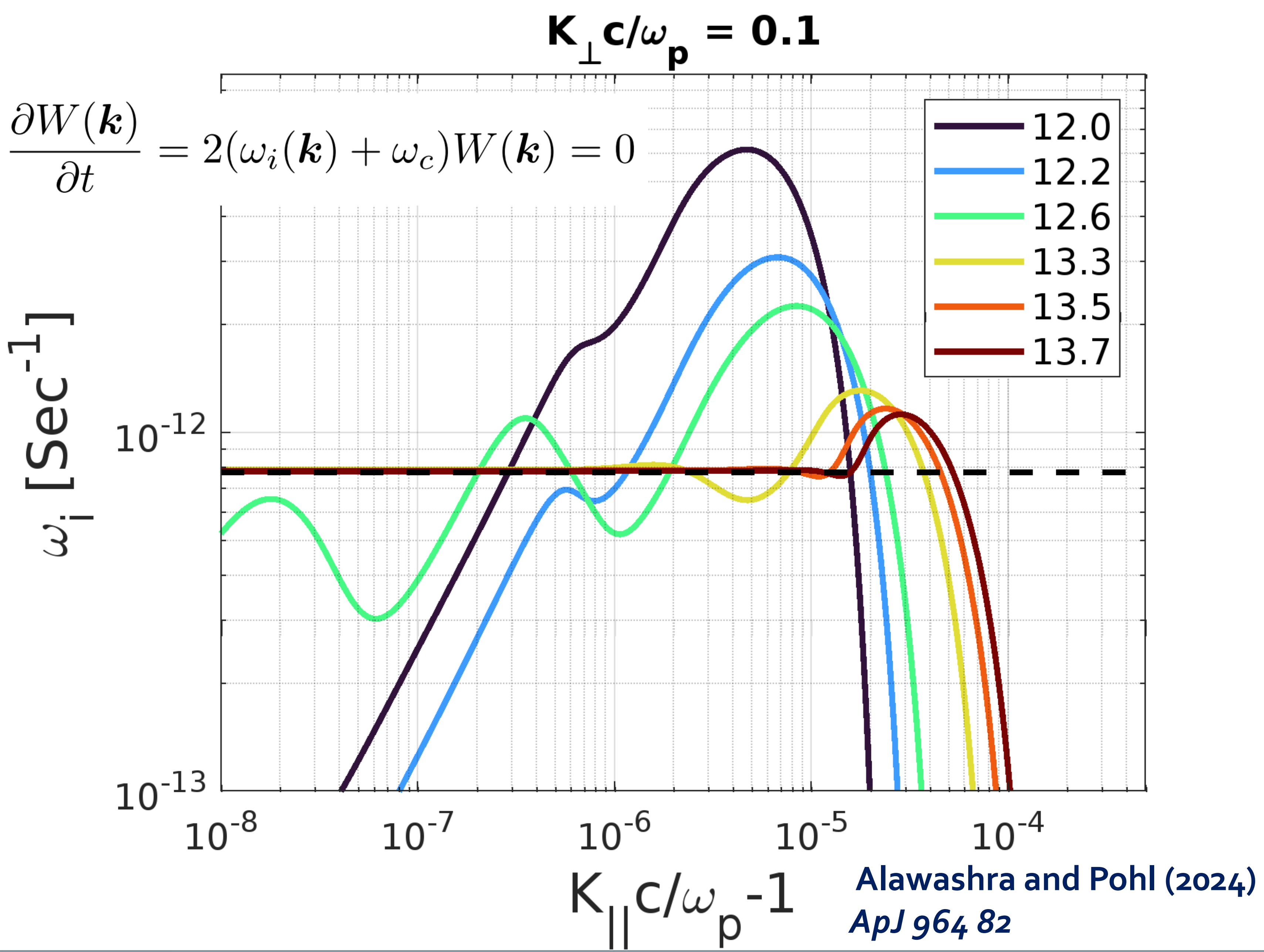


$n_{b,22}$= 1/3
$n_{b,22}$= 1
$n_{b,22}$= 3
$n_{b,22}$= 9
$n_{b,22}$= 27
$n_{b,22}$= 81
10^{-1}
10^{-2}
10^{-3}
10^{-4}
W_{tot}/U_{b0}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
Time [Second]

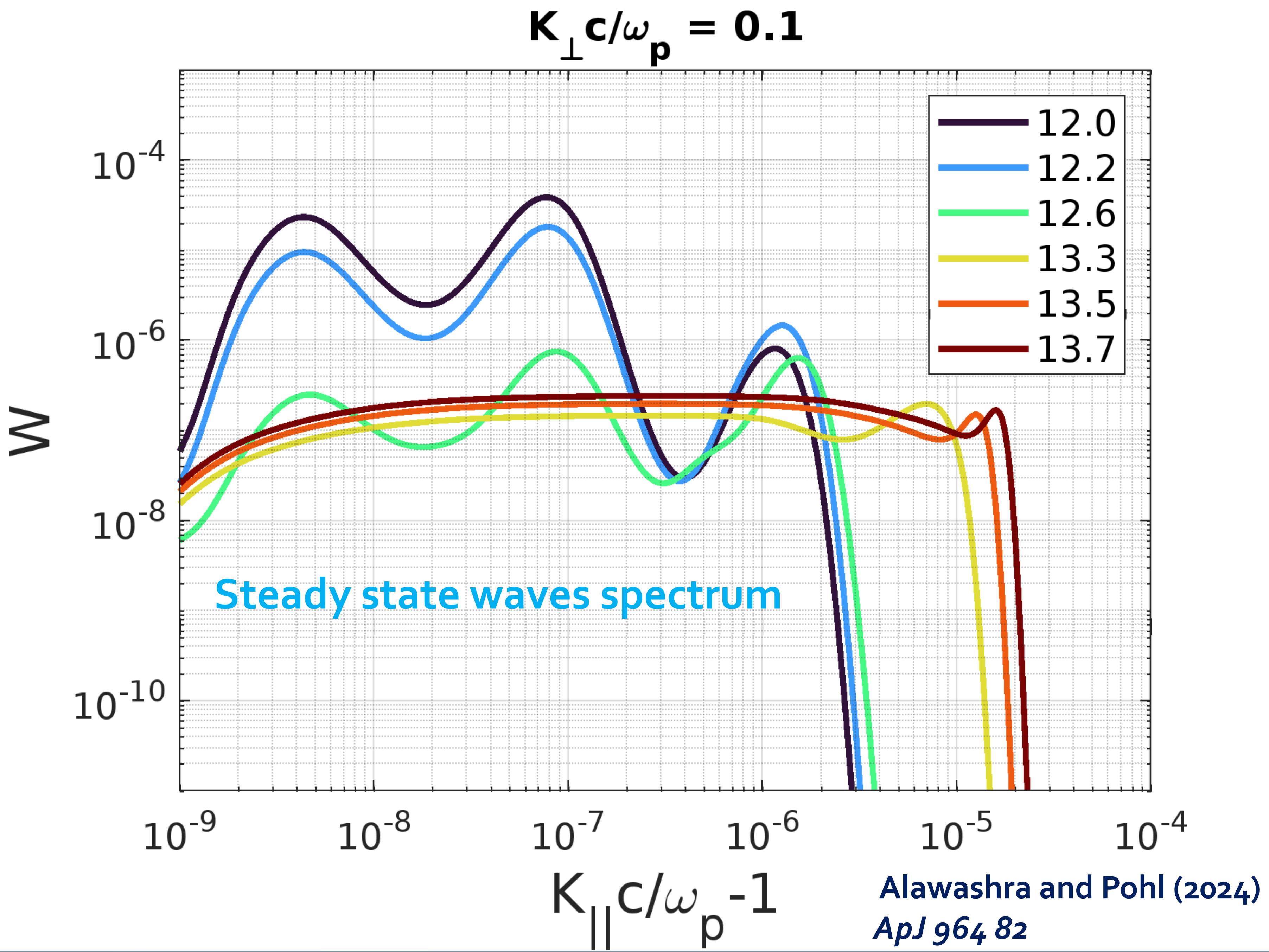


10-18
10-20
10-22
10-24
D_ij [eV²cm⁻²Sec]
10-8
10-7
10-6
10-5
θ [rad]
D_pp
|D_pθ|
D_θθ

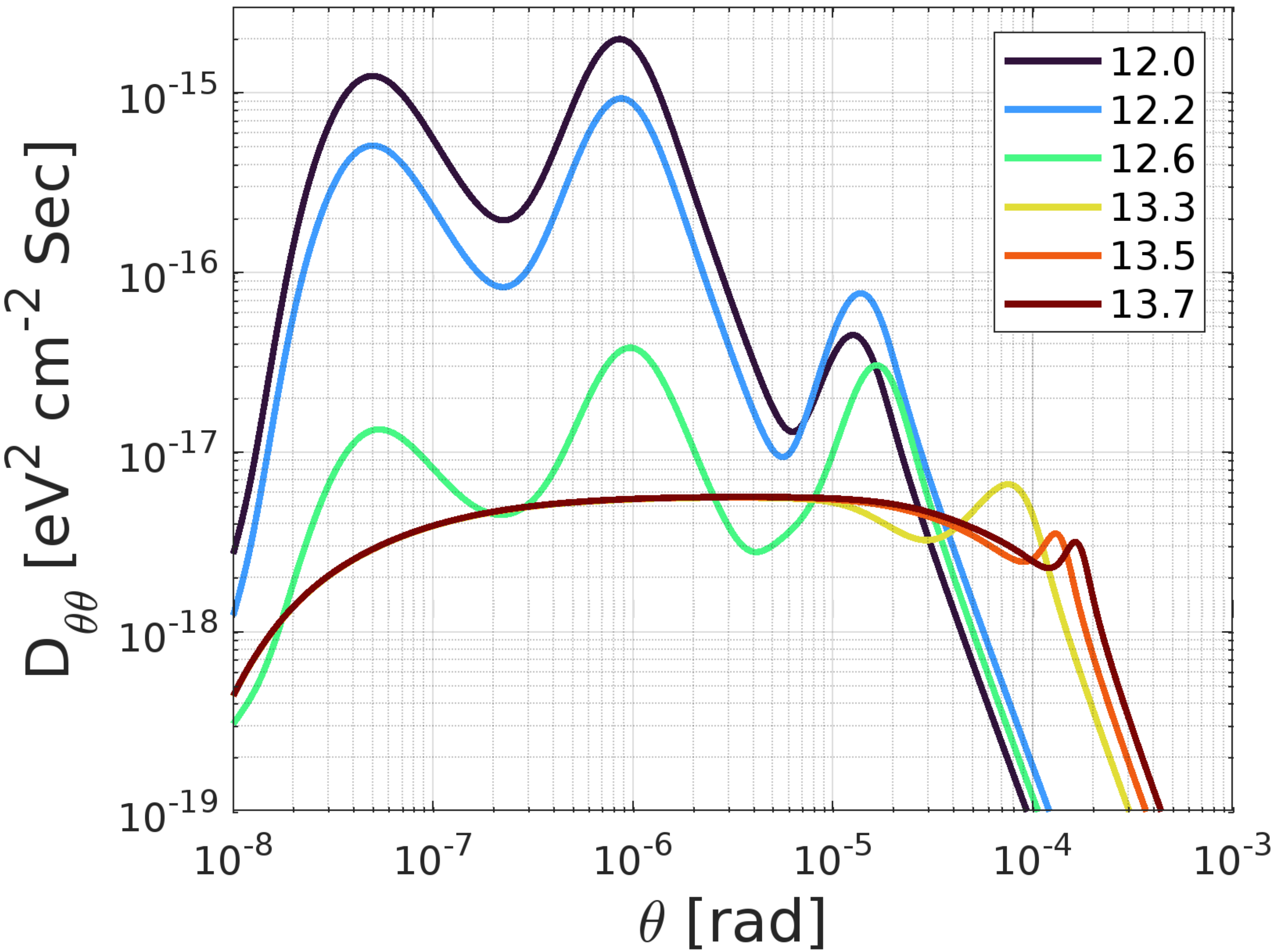
The linear growth rate balances the damping rate



Alawashra and Pohl (2024)
ApJ 964 82

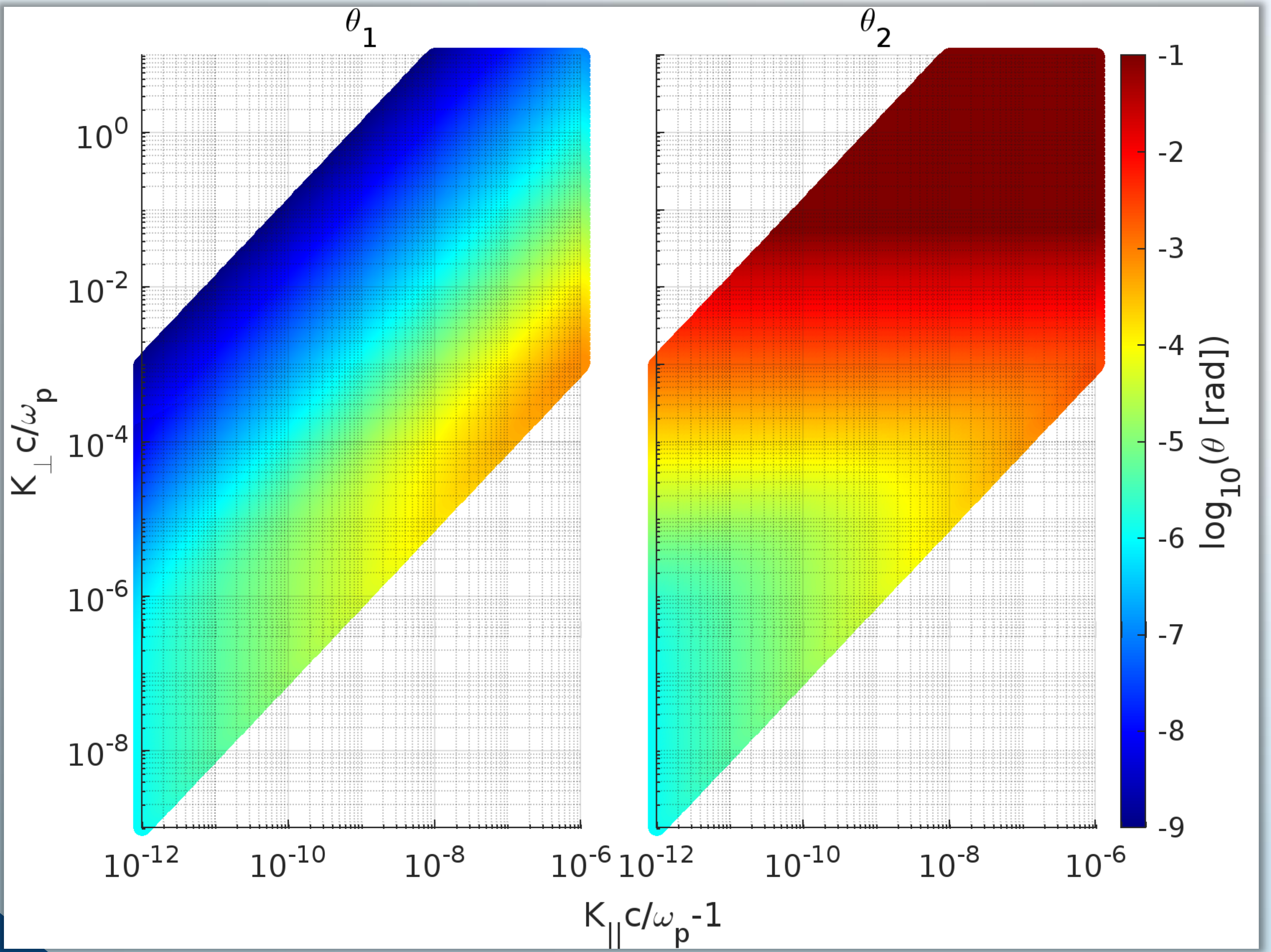


Alawashra and Pohl (2024)
ApJ 964 82

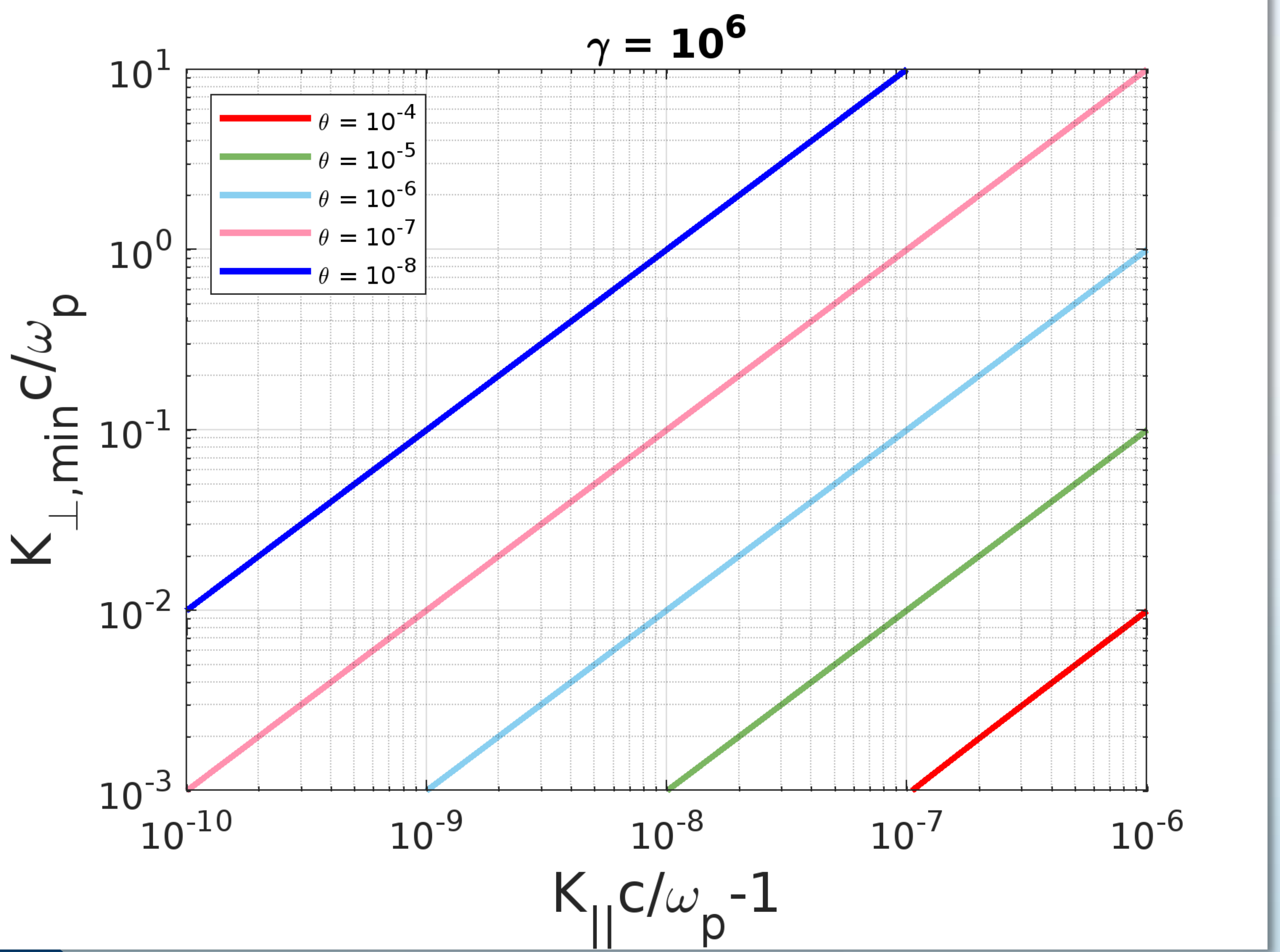


$D_{\theta\theta}$ [eV^2 cm^{-2} Sec]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
θ [rad]
12.0
12.2
12.6
13.3
13.5
13.7

Resonance

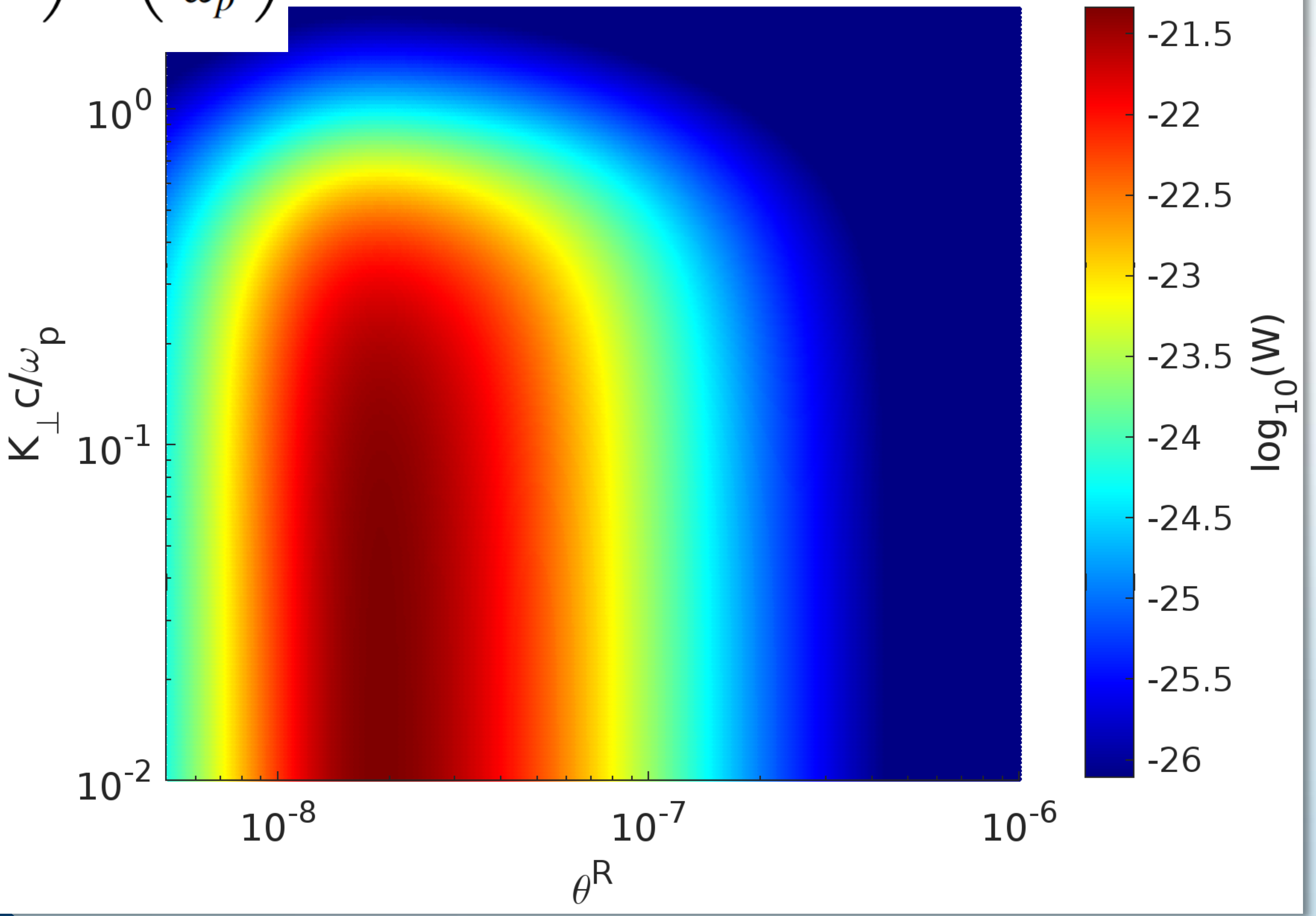


θ_1
θ_2
$K_\perp c/\omega_p$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
$K_{||} c/\omega_p$-1
$\log_{10}(\theta$ [rad])
-1
-2
-3
-4
-5
-6
-7
-8
-9



γ = 10^6
θ = 10^-4
θ = 10^-5
θ = 10^-6
θ = 10^-7
θ = 10^-8
10^1
10^0
10^-1
10^-2
10^-3
10^-10
10^-9
10^-8
10^-7
10^-6
K⊥,min c/ωp
K|| c/ωp -1

$$\theta^R = \left(\frac{ck_{||}}{\omega_p} - 1\right) / \left(\frac{ck_{\perp}}{\omega_p}\right)$$



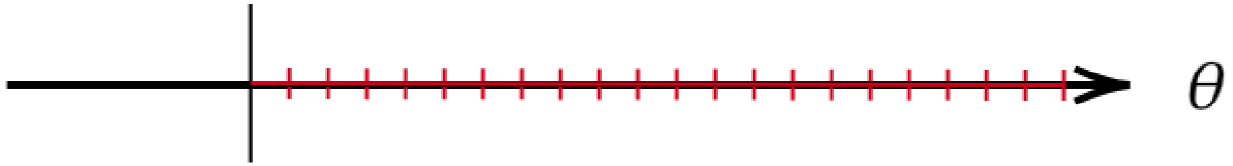
For $\frac{ck_\perp}{\omega_p} > 10^{-2}$, $\gamma > 10^3$ and $\theta < 10^{-3}$

The resonance condion: $\frac{ck_{||}}{\omega_p} - 1 = \frac{ck_\perp}{\omega_p}\theta$

Let's look at the case of fixed $\frac{ck_\perp}{\omega_p}$

For plasma waves with $\frac{ck_{||}}{\omega_p} - 1$

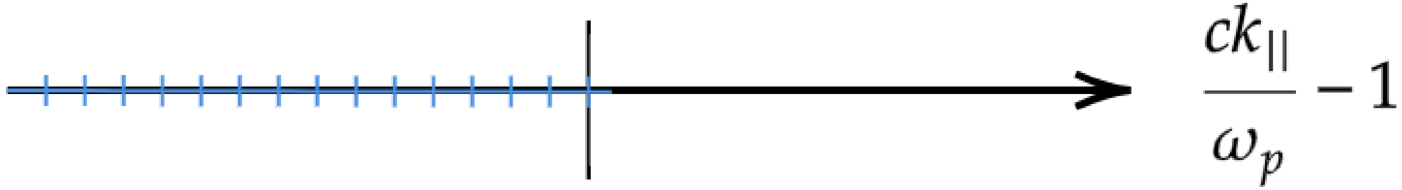
The resonance of the beam is



$$\theta_{R,min} = \frac{\frac{ck_{||}}{\omega_p} - 1}{\frac{ck_{\perp}}{\omega_p}}$$

For beam angles with θ

The resonance of the waves is



$$\left(\frac{ck_{||}}{\omega_p} - 1\right)_{R,max} = \theta \frac{ck_{\perp}}{\omega_p}$$

Are the two solutions independent of each other?

NO, IGMFs impact on the instability.

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IGMFs impact the instability

- Weak IGMFs with small correlation lengths, $\lambda_B \ll \lambda_e$, deflect the beam stochastically

$$\Delta\theta = \frac{1}{\gamma}\sqrt{1 + \frac{2}{3}\lambda_e\lambda_B\left(\frac{eB_{IGM}}{m_e c}\right)^2}$$

- IGMFs widening of the beam impacts the instability growth:

$$\omega_i \propto \frac{1}{\Delta\theta^2}$$

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Instability suppression by the IGMFs

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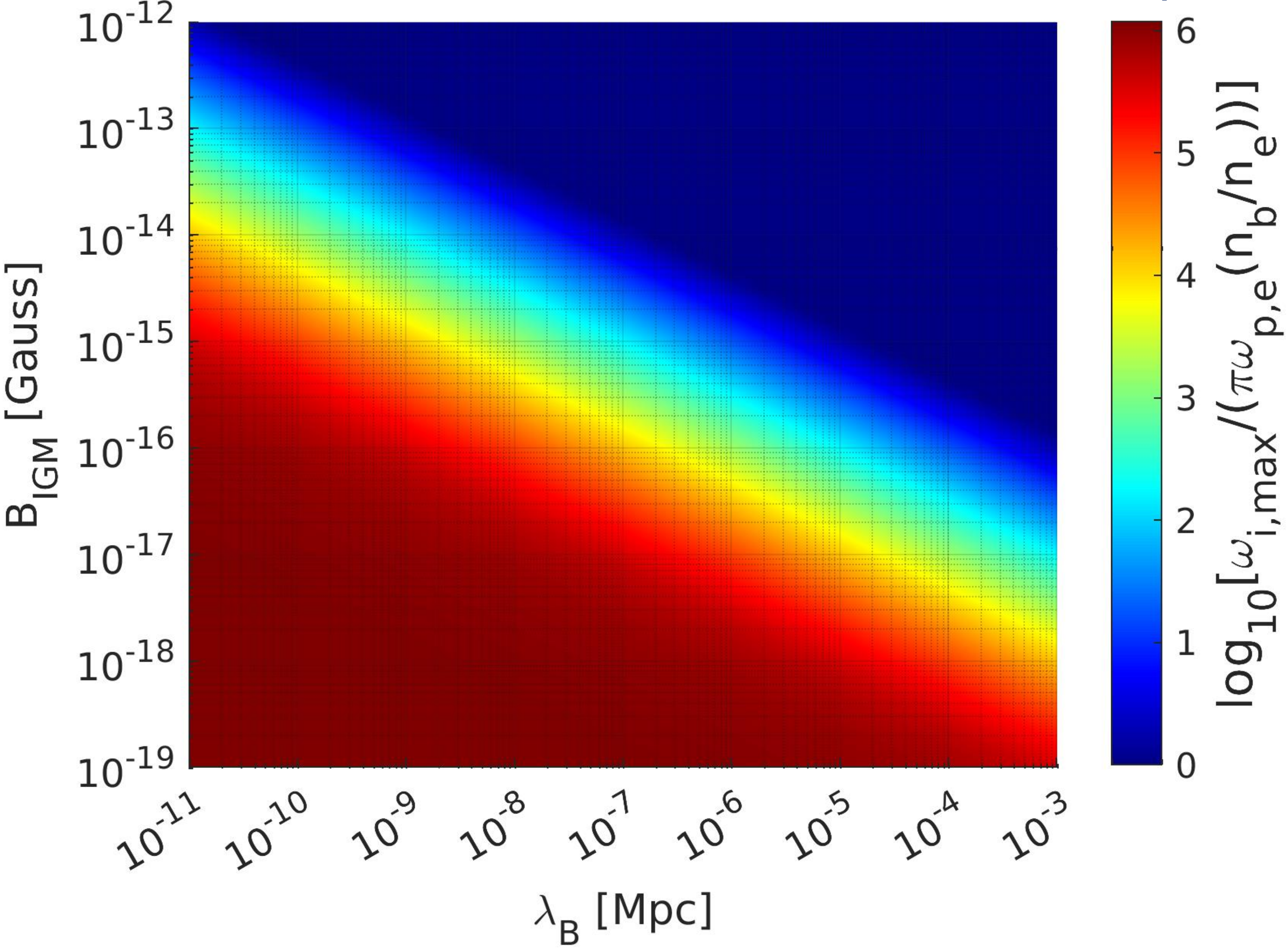


IGMFs impact the instability

- **Assume certain non-linear saturation of the waves**

$$\tau_{\mathrm{loss}}^{-1} = 2\ \delta\ \omega_{i,\mathrm{max}}$$

$$\delta = W_{\mathrm{tot}}/U_{\mathrm{beam}}$$

We consider the one found in Vafin et al. (2018)

$$\tau_{\mathrm{loss}}/\tau_{\mathrm{IC}} = 0.026$$

IGMFs impact the instability

- Assume certain non-linear saturation of the waves

$$\tau_{\text{loss}}^{-1} = 2\ \delta\ \omega_{i,\max}$$

$$\delta = W_{\text{tot}}/U_{\text{beam}}$$

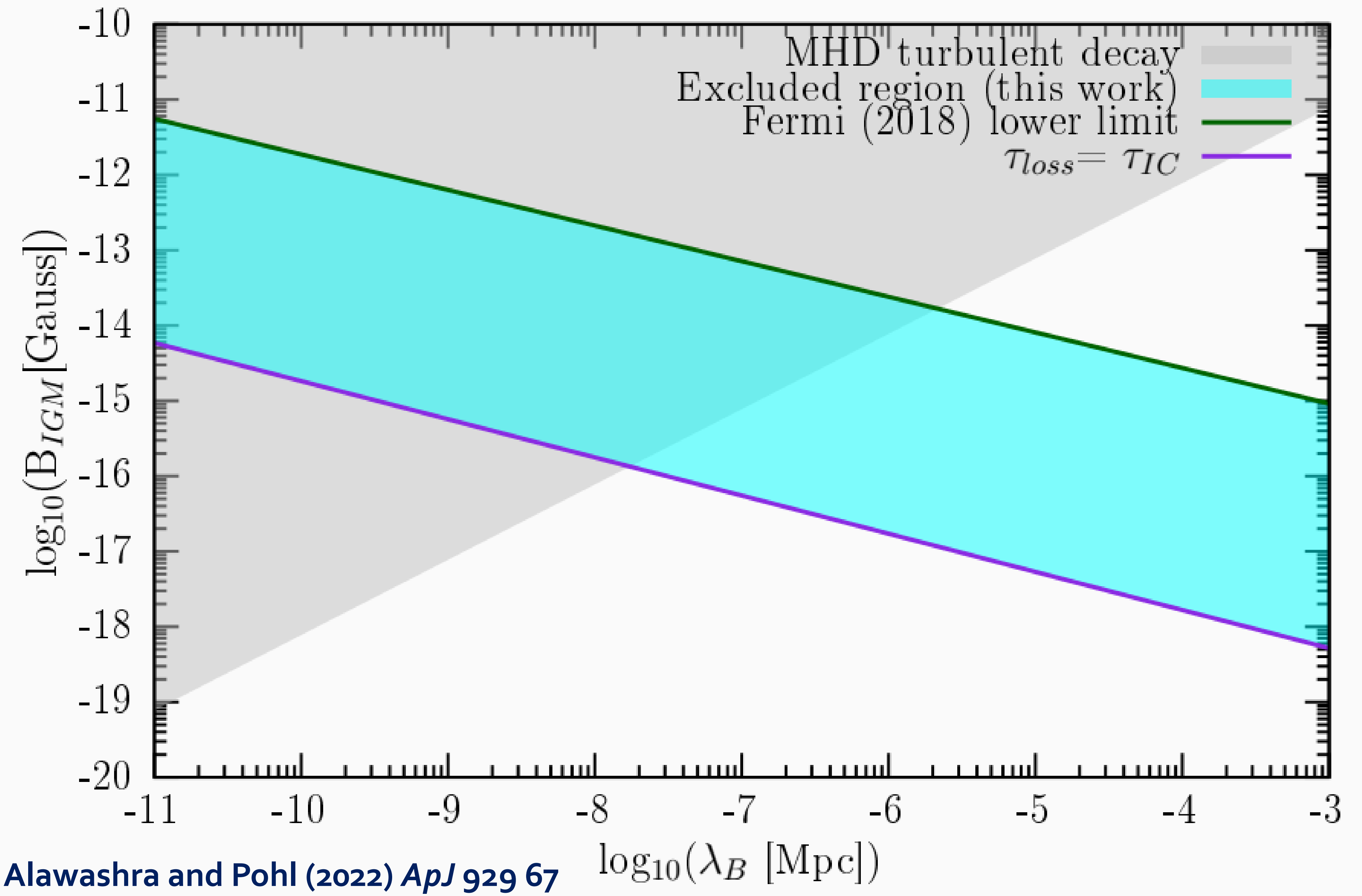
We consider the one found in Vafin et al. (2018)

$$\tau_{\text{loss}}/\tau_{\text{IC}} = 0.026$$

- The instability is suppressed by the IGMFs when

$$\tau_{\text{loss}} = \tau_{\text{IC}}$$

Instability suppression by the IGMFs



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