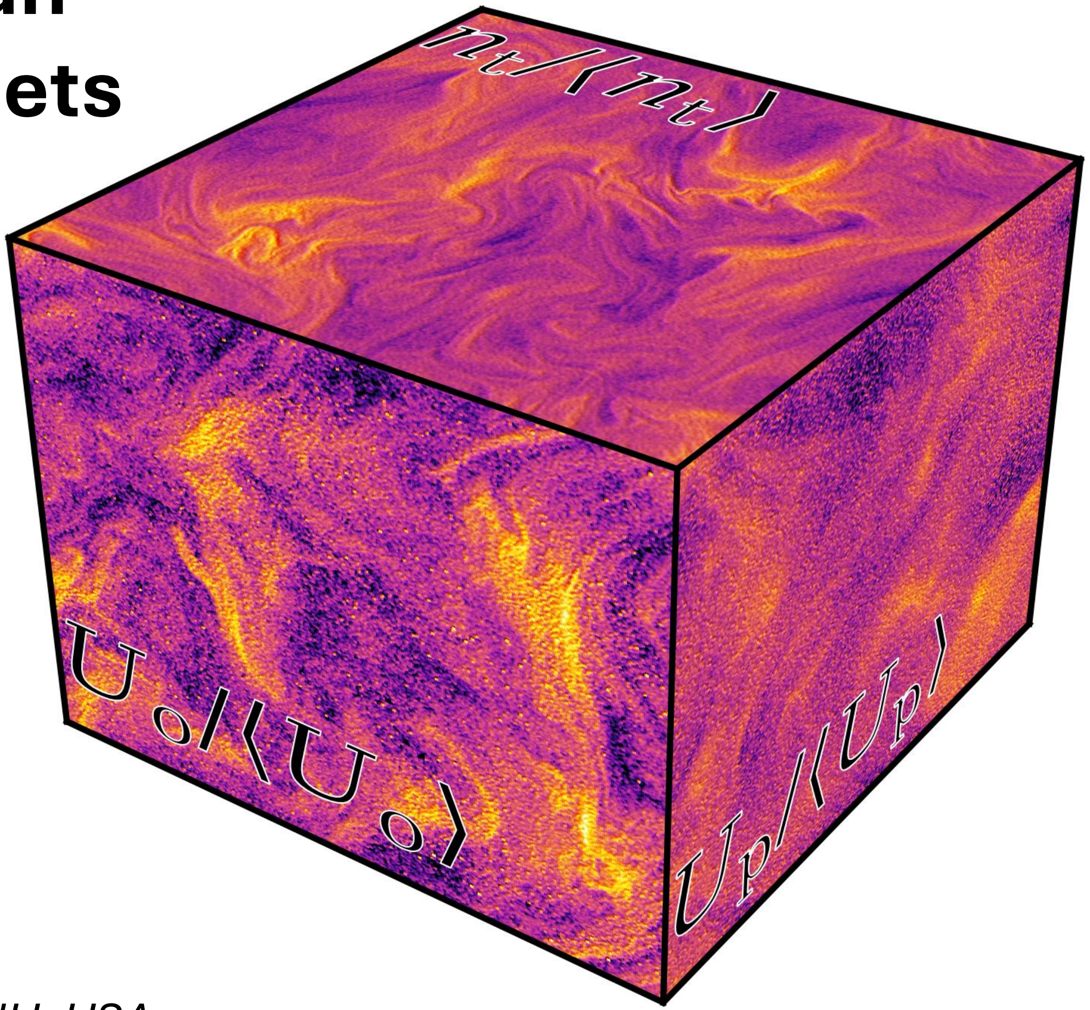
Radiative relativistic turbulence as an *in situ* pair-plasma source in blazar jets

John Mehlhaff[1,2]
with Muni Zhou[3,4] and Vladimir Zhdankin[5]

Submitted. See https://arxiv.org/abs/2504.01072



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[4]*Institute for Advanced Study; Princeton, NJ, USA*
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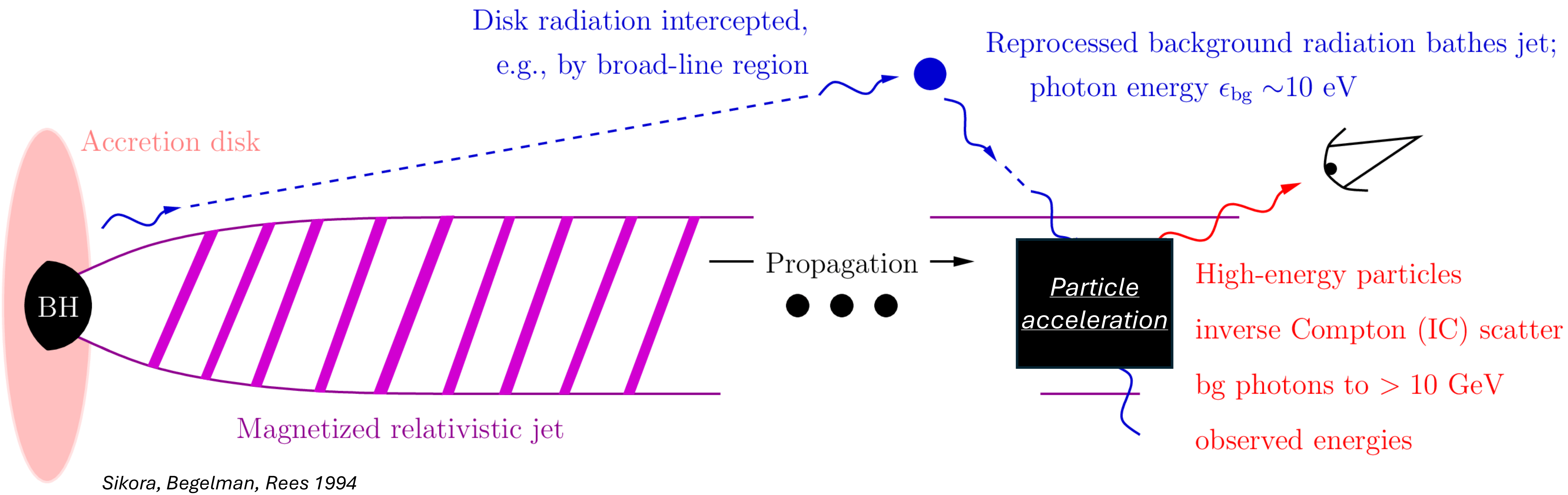
Jet composition and particle acceleration might be linked



Sikora, Begelman, Rees 1994

Observed photon energies hint at pair-production:

- Observed gamma-rays: $\epsilon_\gamma \gtrsim 10$ GeV
- Observed broad emission lines: $\epsilon_{bg} \sim 10$ eV
- ϵ_γ near threshold $\epsilon_{th} = (m_e c^2)^2/\epsilon_{bg} \sim 30$ GeV

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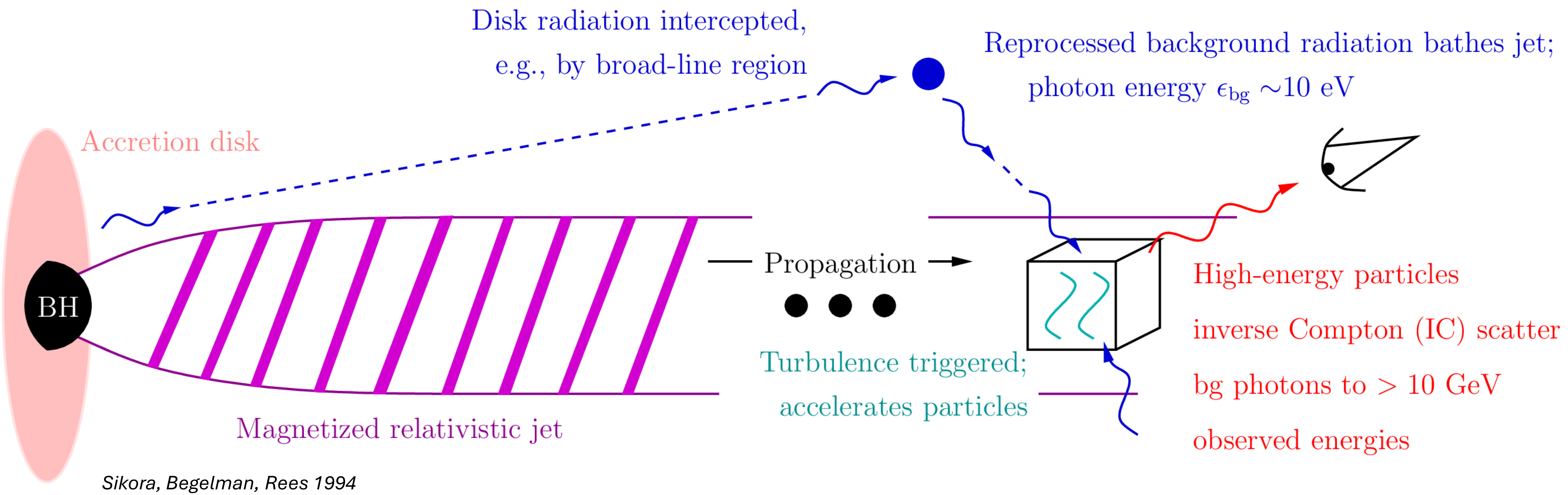

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Need a process to accelerate gamma-ray emitting particles:

- Magnetized turbulence could dissipate magnetic free energy
- (Alternatively, magnetic reconnection: Mehlhaff et al. 2024)

Turbulence could couple to radiation and pair production

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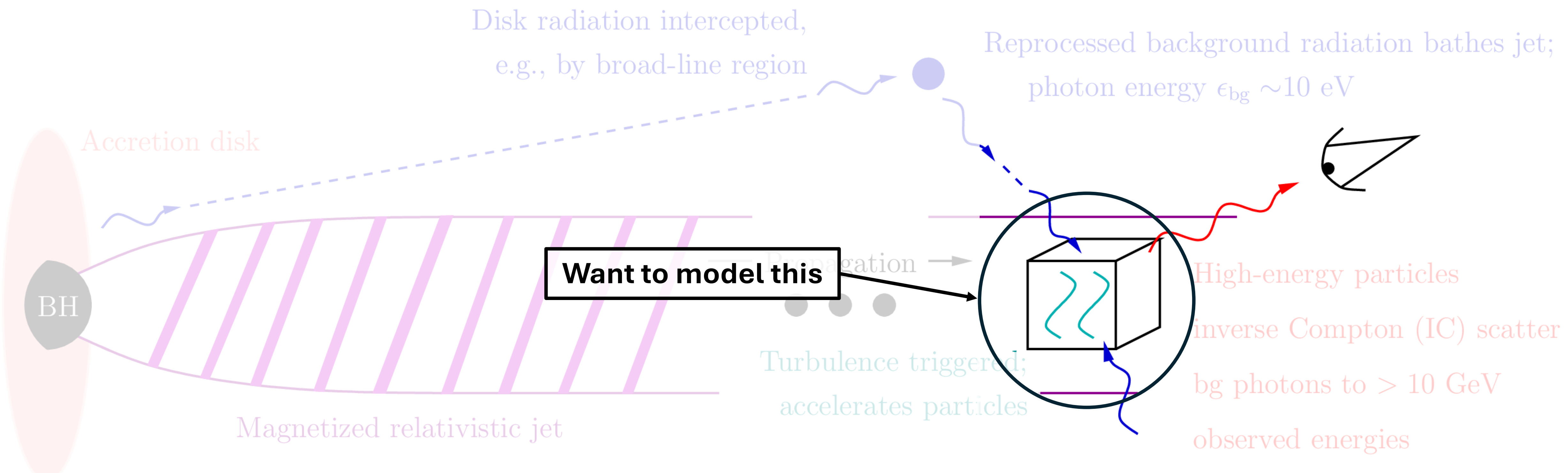

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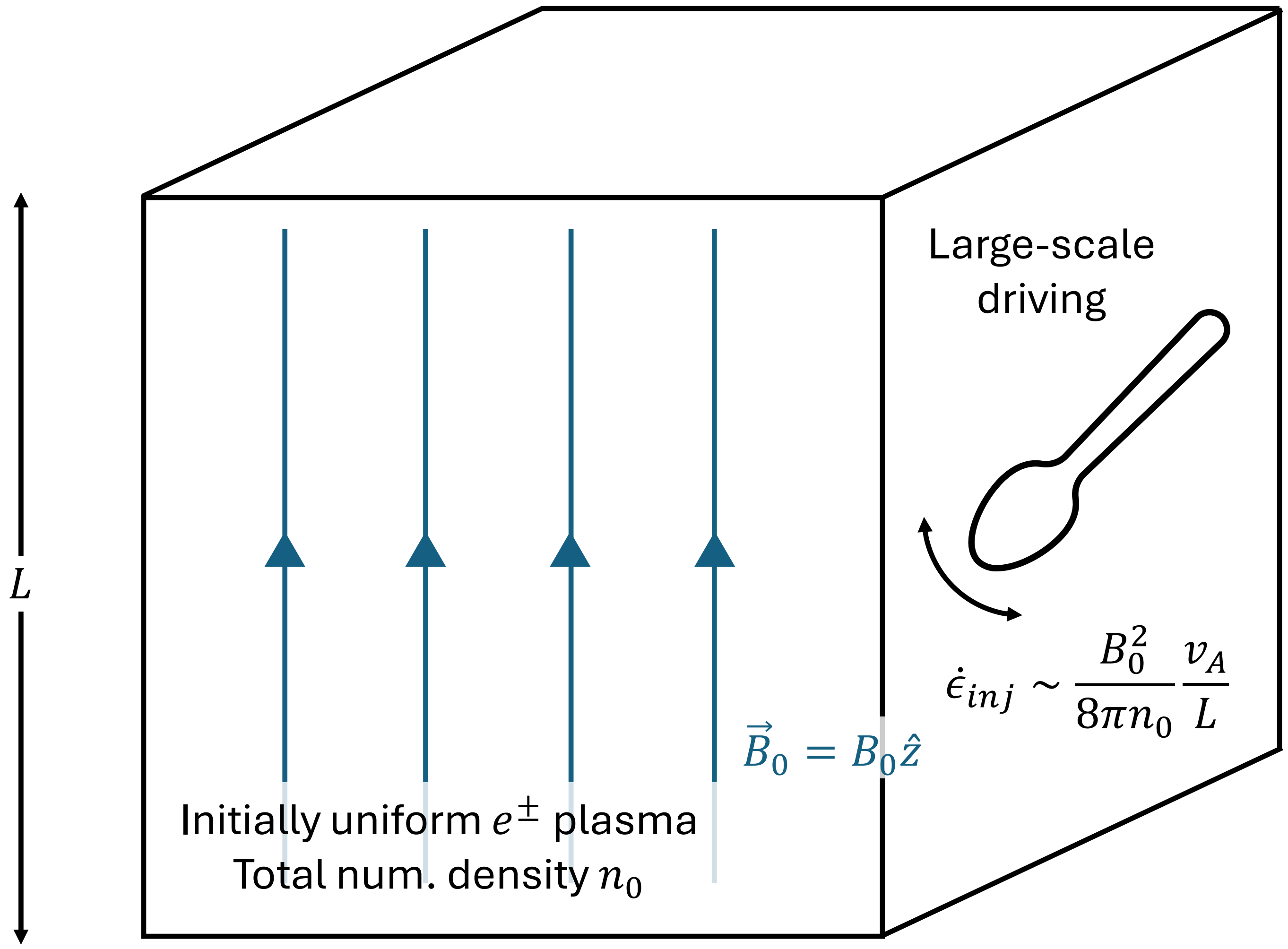
A minimum local model

Standard turbulence setup

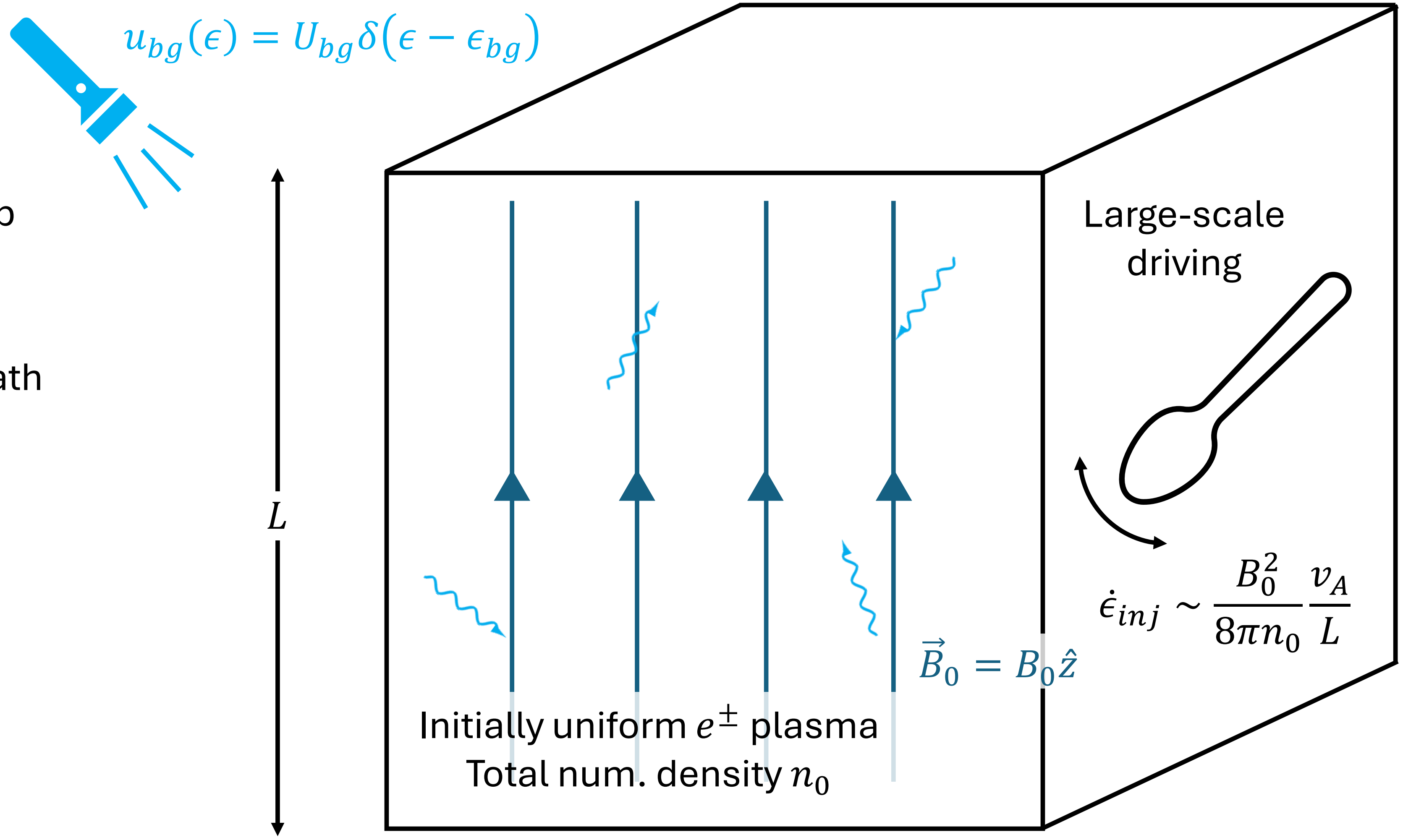


A minimum local model

Standard turbulence setup

+

Interaction with radiation bath



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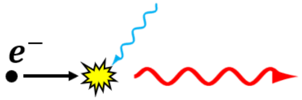
Interaction with radiation bath

Inverse Compton (IC) scattering



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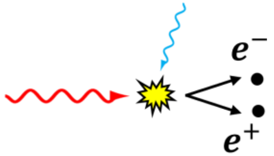
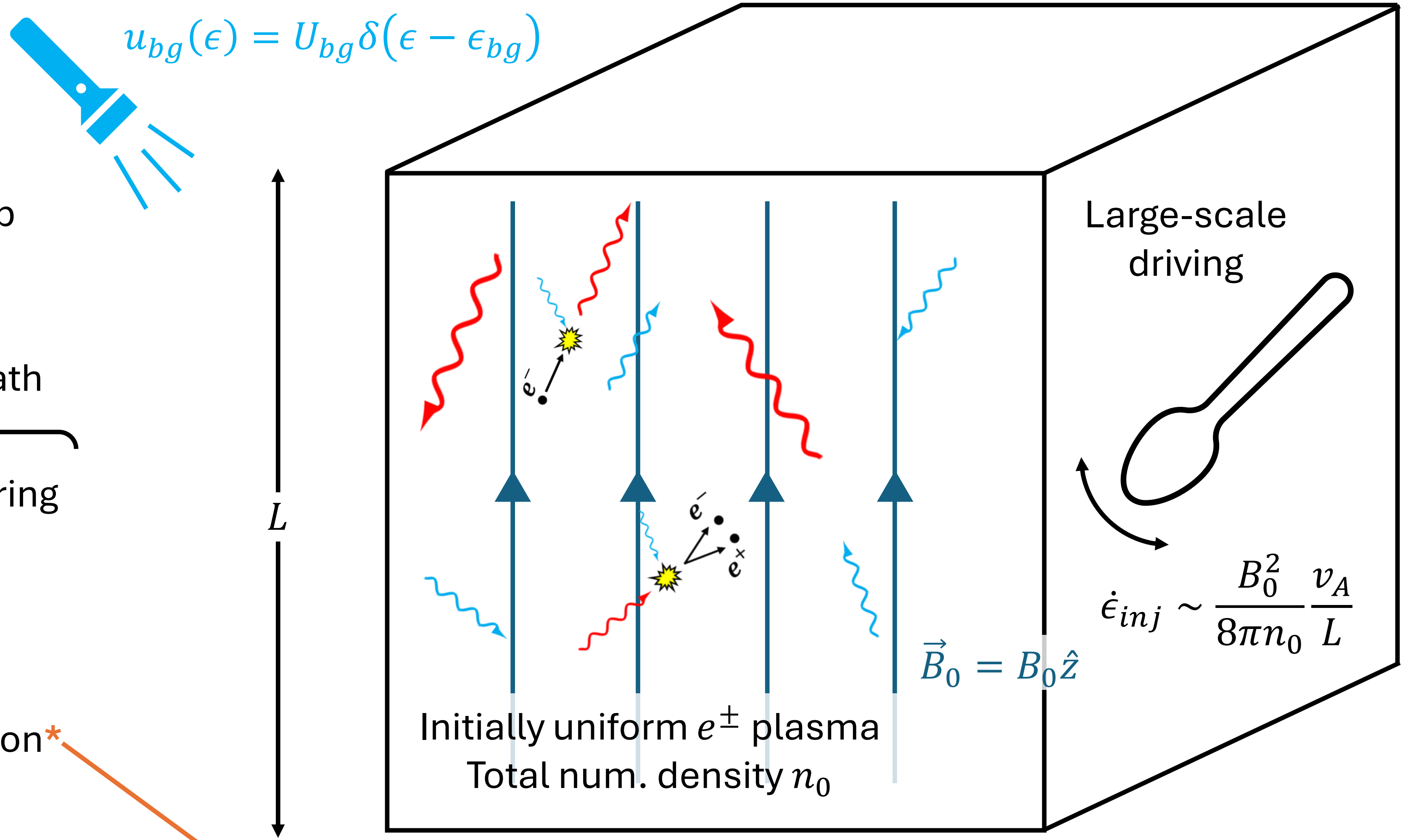
Photon-photon pair production*





*Requires particles to reach a critical Lorentz factor $\gamma_{KN} \equiv m_e c^2/4\epsilon_{ph}$

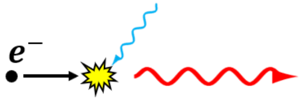
Warm-up: Case when all particles have $\gamma \ll \gamma_{KN}$

Standard turbulence setup

+

$\underbrace{\text{Interaction with radiation bath}}$

Inverse Compton (IC) scattering



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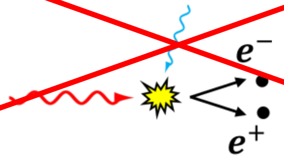

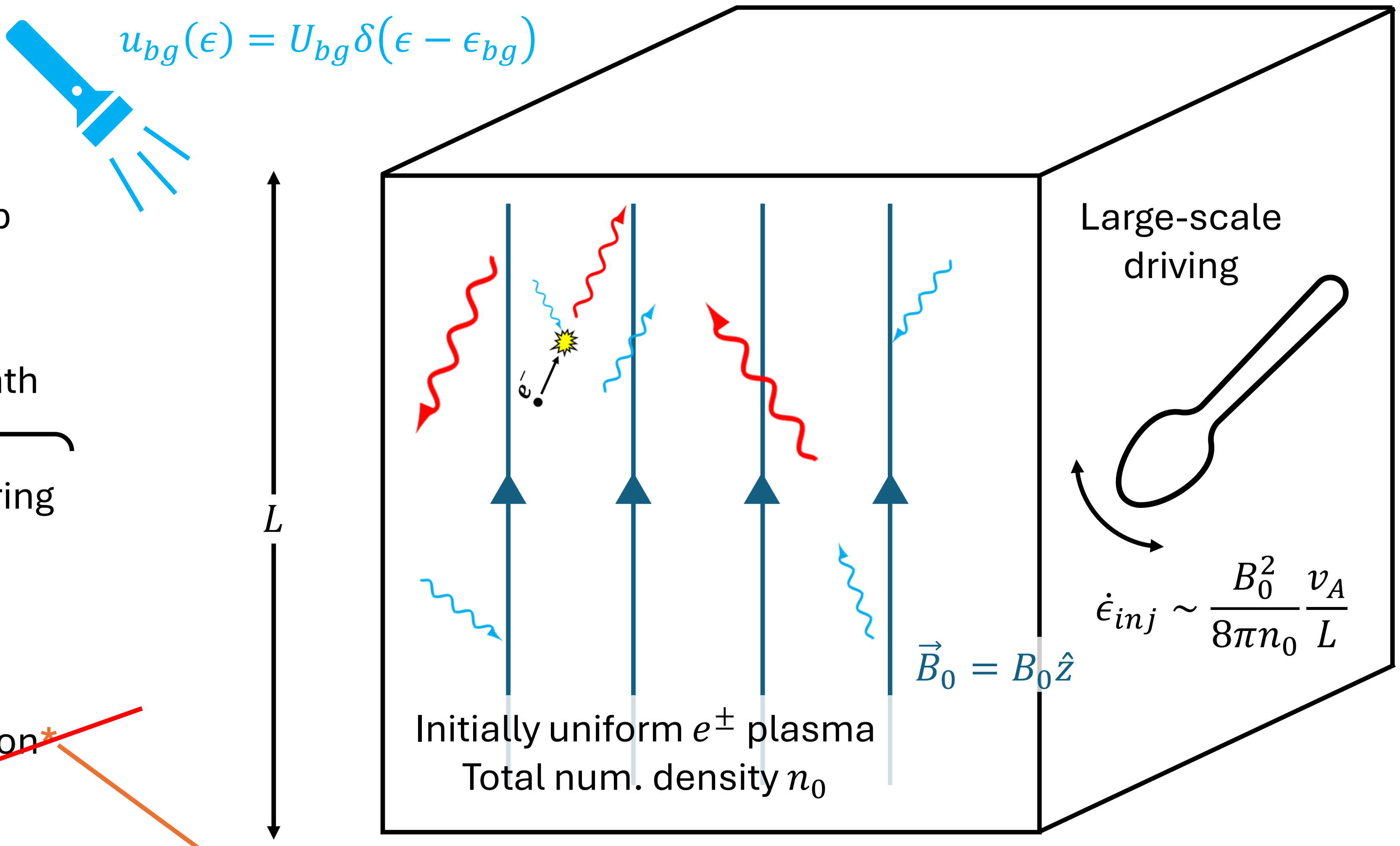

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Warm-up: $\gamma \ll \gamma_{KN}$ yields a thermal equilibrium

Standard turbulence setup

$$\left(\dot{\epsilon}_{inj} \sim \frac{B_0^2}{8\pi n_0} \frac{v_A}{L} \right)$$

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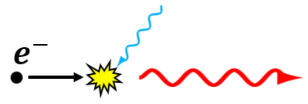
Interaction with radiation bath

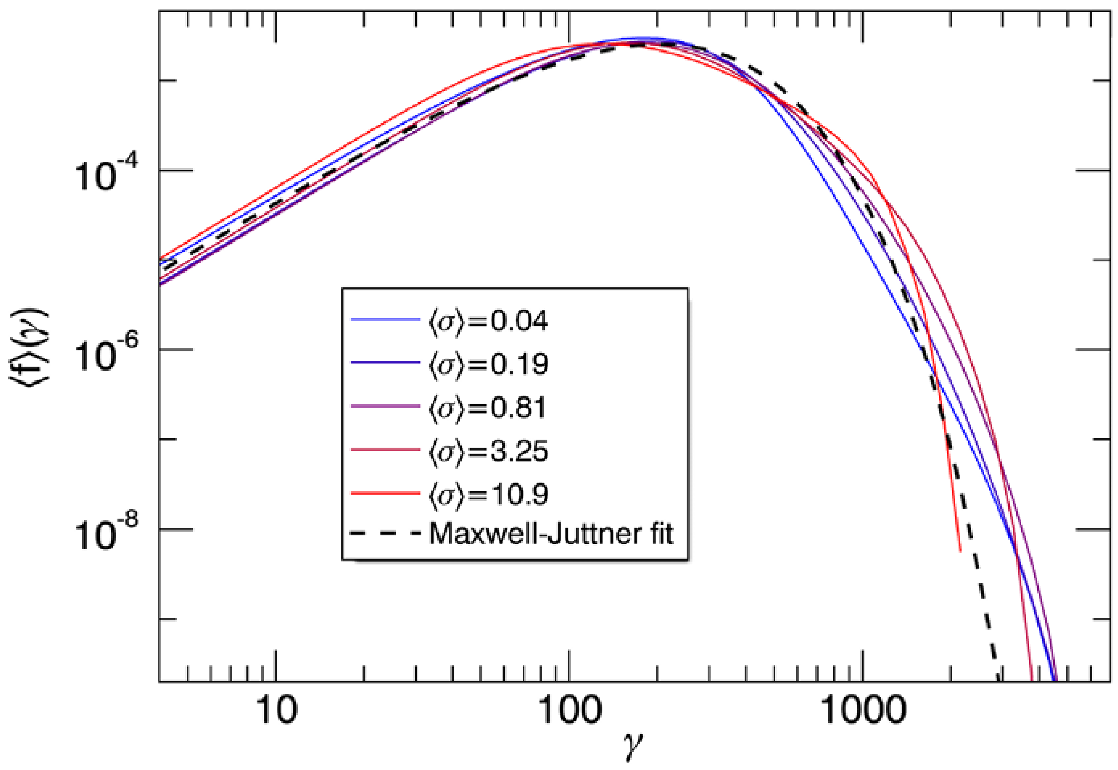
Inverse Compton (IC) scattering



$$\dot{\epsilon}_{rad} = \frac{4}{3} \sigma_T c \langle \gamma^2 \rangle U_{bg}$$

Condition $\dot{\epsilon}_{rad} = \dot{\epsilon}_{inj}$ gives **stable thermal equilibrium**
temperature $kT_{ss}/mc^2 = \theta_{ss}(\sigma, U_{bg})$
where $\sigma \equiv B_0^2/16\pi\theta_{ss} n_0 m_e c^2$

Zhdankin et al. 2020



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$$\dot{\epsilon}_{rad} = \frac{4}{3}\sigma_T c\langle\gamma^2\rangle U_{bg}$$

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<u>Steps:</u>

- Require $\dot{\epsilon}_{inj} = \dot{\epsilon}_{rad}$
- Use $\langle\gamma^2\rangle = 12\theta_{ss}^2$ and $\frac{v_A}{c} = \sqrt{\frac{\sigma}{1+\sigma}}$
- where $\sigma \equiv B_0^2/16\pi\theta_{ss}n_0 m_e c^2$
- Can write:

$$\theta_{ss} = \frac{1}{6}\sqrt{\frac{\sigma^3}{1+\sigma}}\underbrace{\left(\frac{3m_e c^2}{4\sigma_T U_{bg} L}\right)}_{\gamma_{cool}} = \frac{1}{6}\sqrt{\frac{\sigma^3}{1+\sigma}}\gamma_{cool}$$

For $\gamma > \gamma_{KN}$, expect pair-mediated thermalization

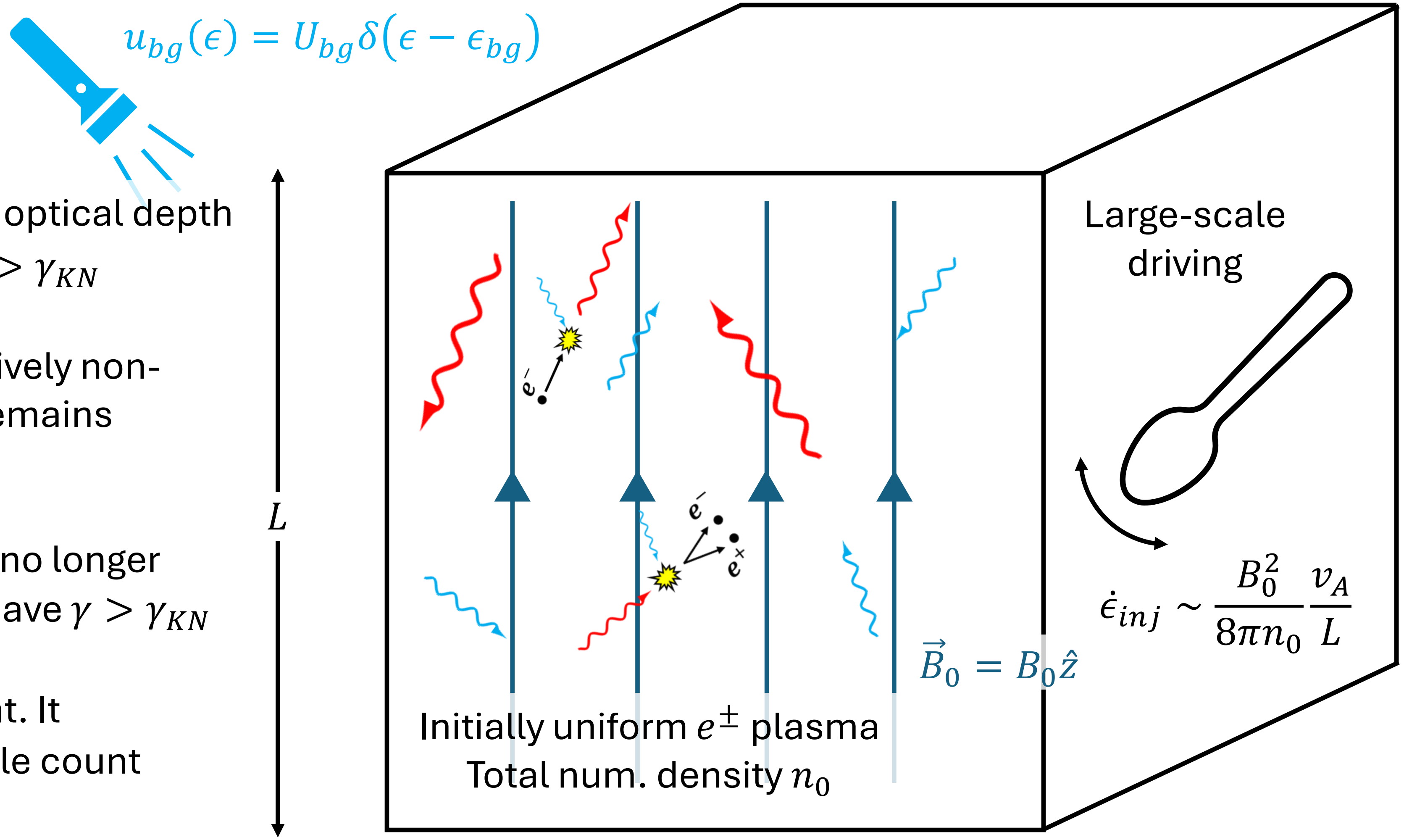
Suppose gamma-ray absorption optical depth $\tau_{\gamma\gamma} \gg 1$ and initially $\theta_{ss}(\sigma, U_{bg}) > \gamma_{KN}$

Particles with $\gamma > \gamma_{KN}$ are effectively non-radiative: their radiated energy remains trapped in the system

Unless something changes, can no longer match $\dot{\epsilon}_{rad}$ and $\dot{\epsilon}_{inj}$ if particles have $\gamma > \gamma_{KN}$

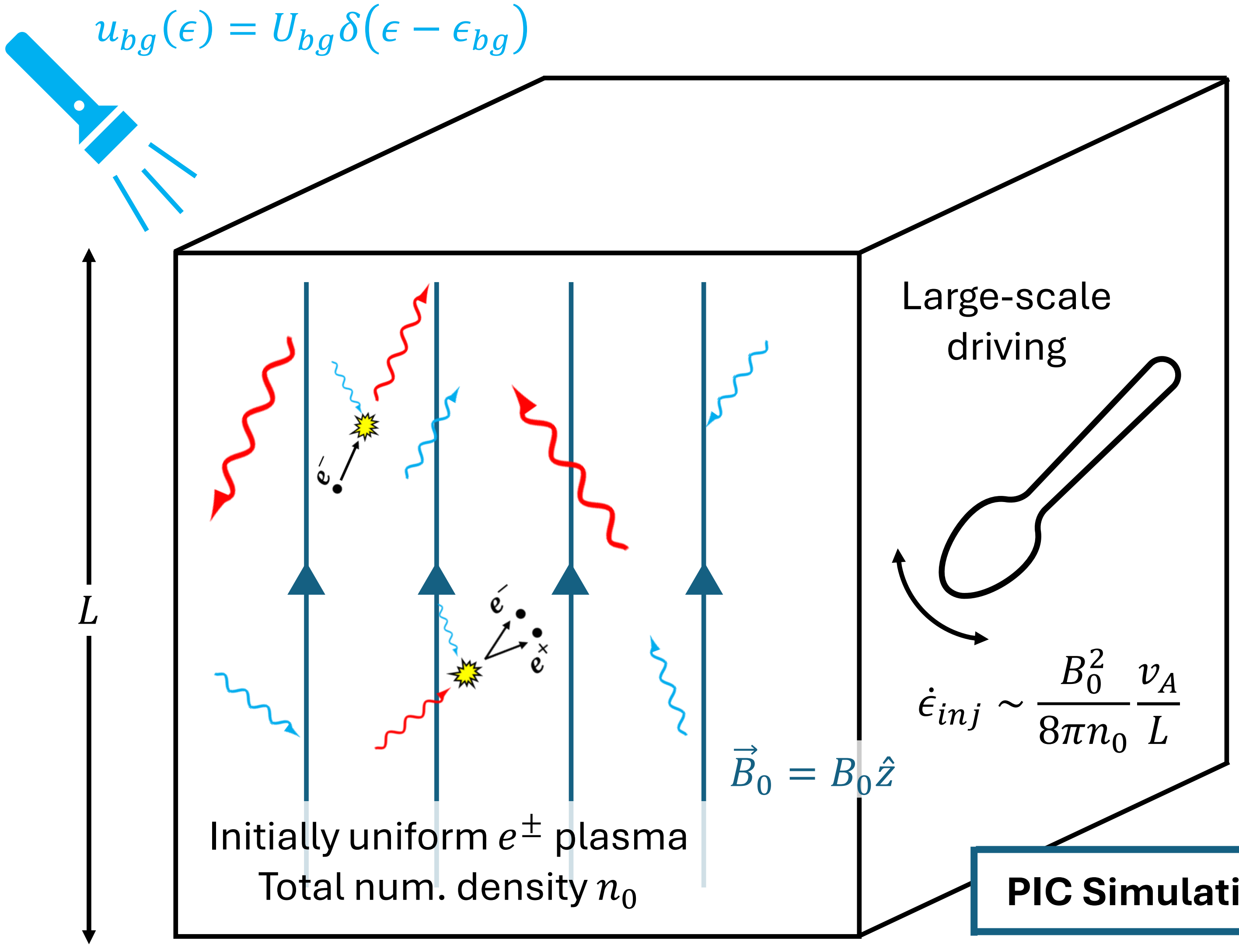
EXCEPT $\dot{\epsilon}_{inj}$ is no longer constant. It decreases with increasing particle count

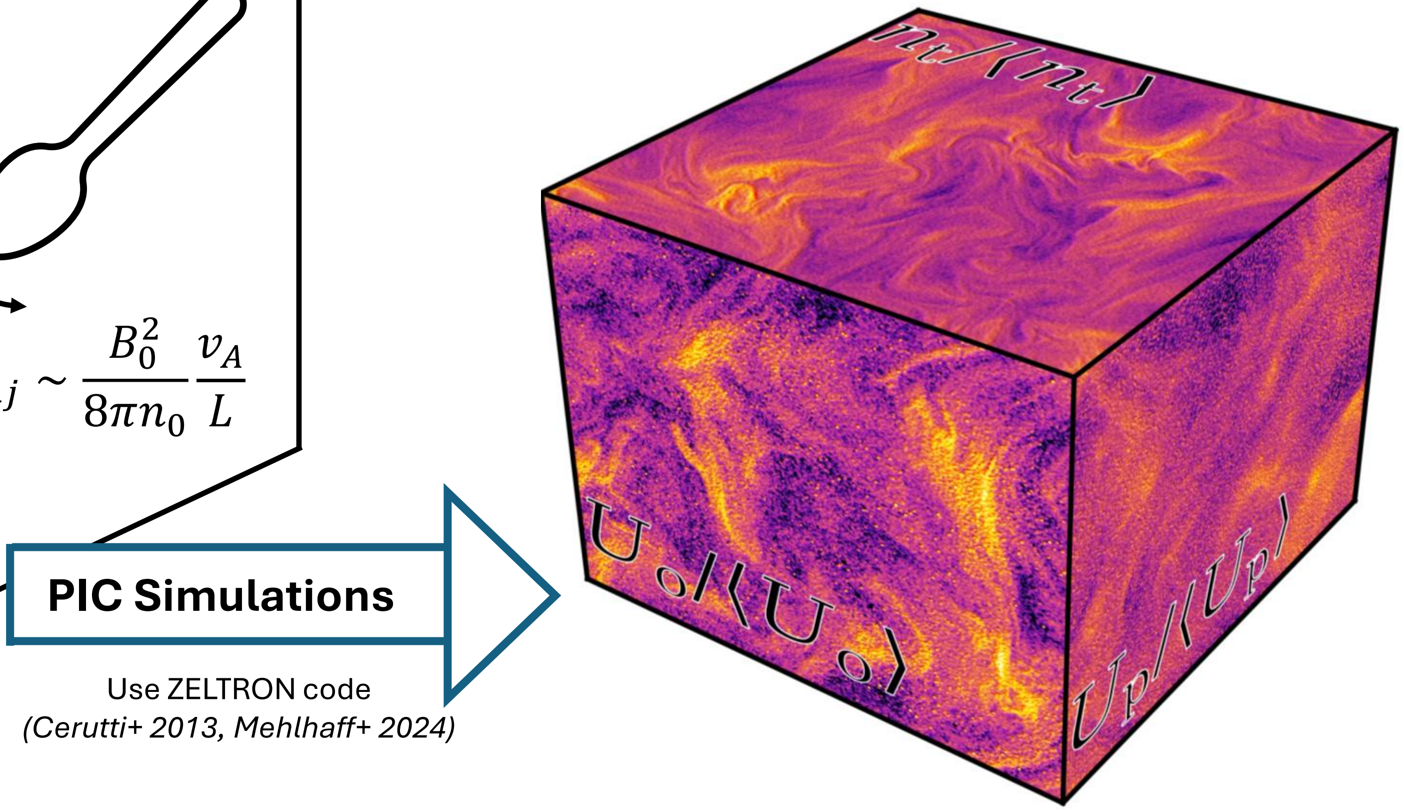
System may regulate $\dot{\epsilon}_{inj}$ through pair production to push particles back to $\gamma < \gamma_{KN}$, **restoring thermal equilibrium from before!**



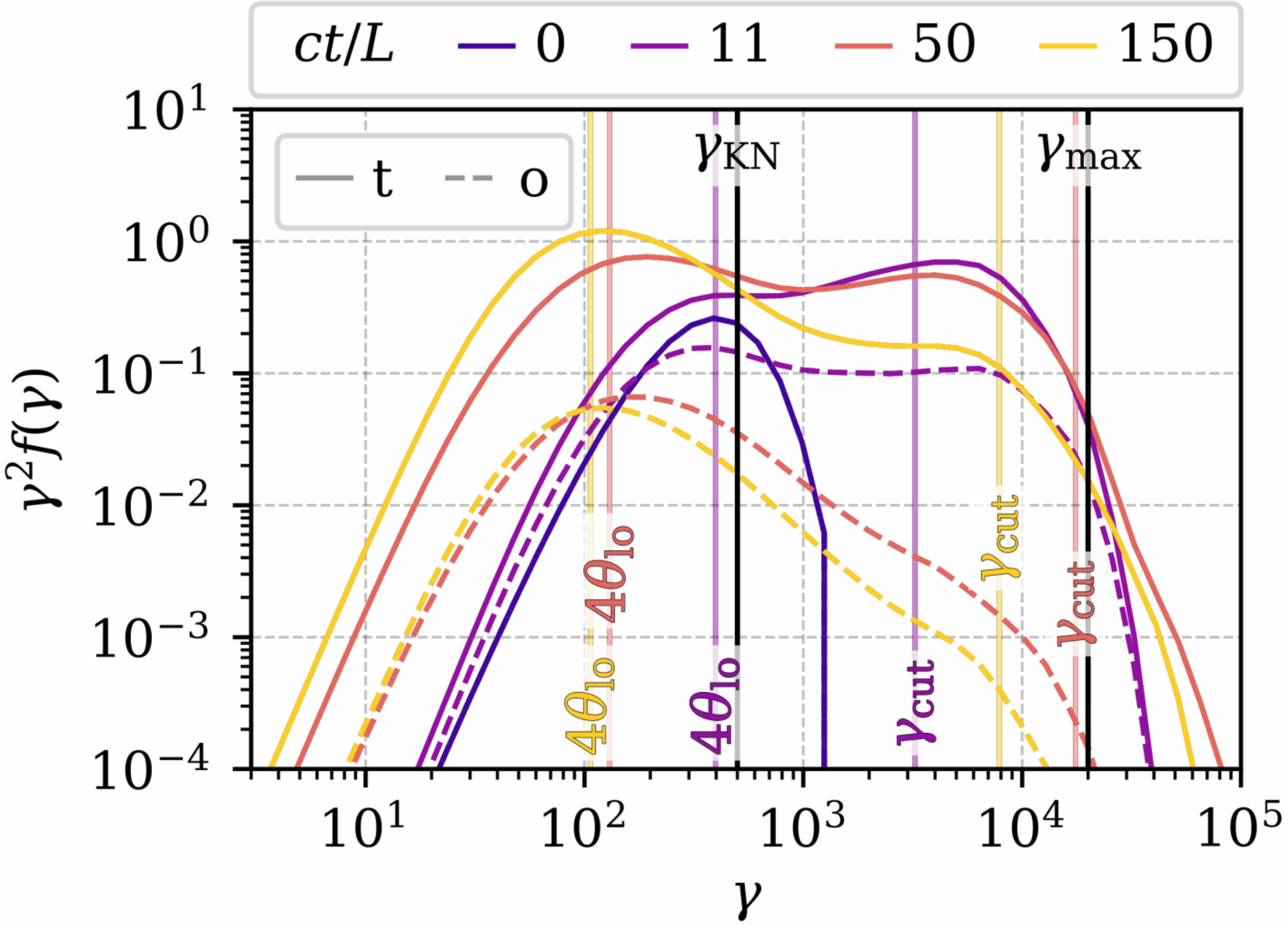
Numerical experiments to test thermalization hypothesis

- 512^3 box size
- Initial temperature $\theta_0 = kT_0/m_e c^2 = 100$
- Magnetization $\sigma_0 = B_0^2/16\pi n_0 \theta_0 m_e c^2 = 2.5$
- Fluctuations driven to $\delta\vec{B}^2 \sim \vec{B}_0^2$
- ϵ_{bg} set so that $\gamma_{KN} = m_e c^2/4\epsilon_{bg} = 500$
- U_{bg} set so that $\theta_{ss}(U_{bg}, \sigma_0) = \theta_0 = 100$





PIC simulations demonstrate pair-regulated thermalization



- $\gamma_{max} = eB_0L/m_ec^2 = 2 \times 10^4$
- θ_{lo} = temperature of low-energy hump
- t = total (original+produced) particles
- o = original particles only

Stages:

1. Nonthermal particle acceleration ($ct/L = 11$) to $\gamma > \gamma_{KN}$
2. Newborn pairs accumulate, impeding further energy injection
3. Particle energy distribution cools down; low-energy "thermal hump" develops at $\gamma < \gamma_{KN}$ ($ct/L = 50$)
4. Eventually ($ct/L = 150$), high-energy nonthermal tail dies away, leaving low-energy thermal distribution

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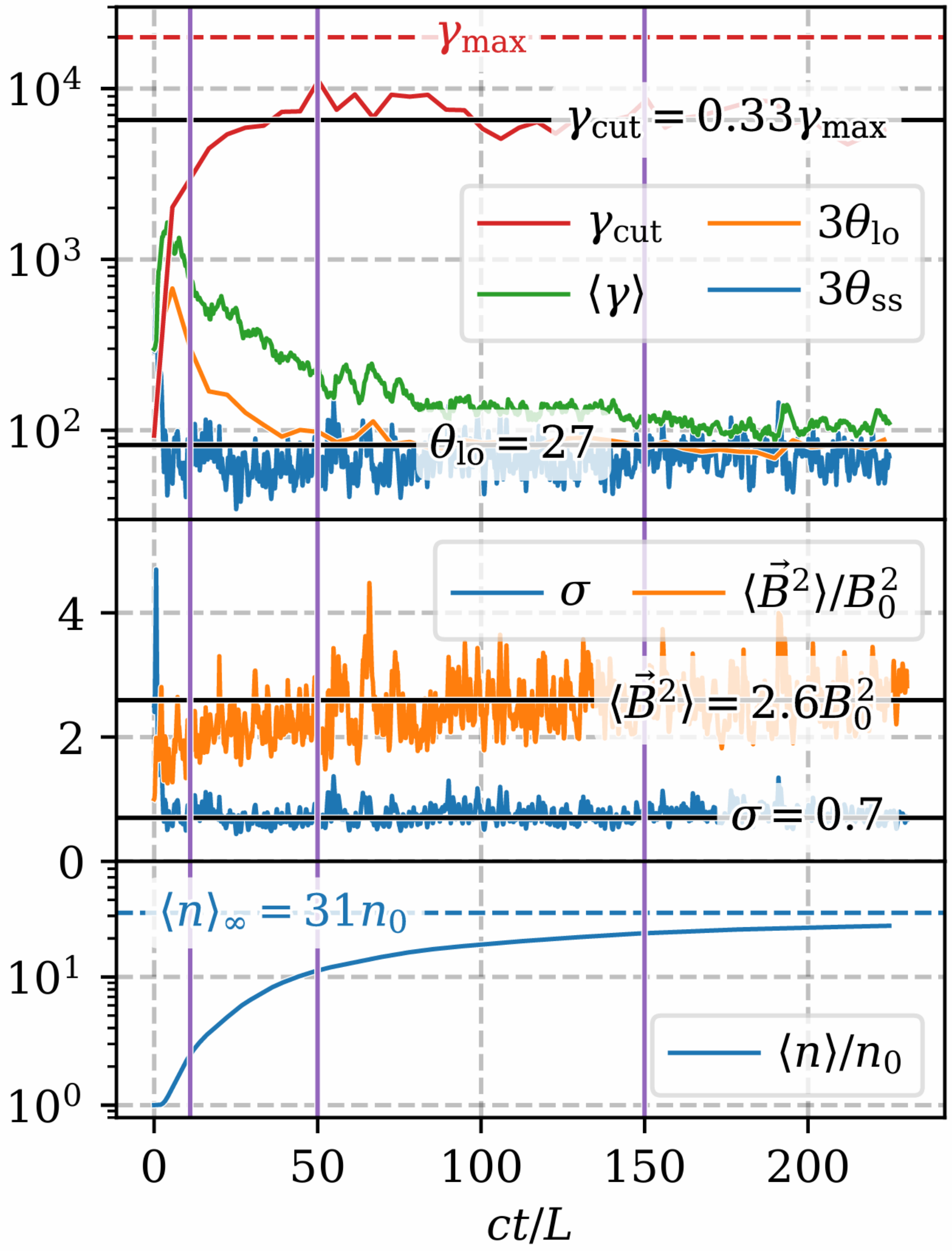

Convergence of macroscopic quantities

Stages:

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- $\theta_{ss}(\sigma) \equiv$ expected equilibrium temp. based on current σ
- $\sigma \equiv 3\langle\vec{B}^2\rangle/16\pi\langle\gamma\rangle\langle n\rangle m_e c^2$
- $\langle n\rangle_\infty = \langle\vec{B}^2\rangle/16\pi\theta_{lo}\sigma m_e c^2$
- $\theta_{lo} \equiv$ temperature of low-energy hump

Outlook so far

PIC validates pair-thermalization hypothesis.

But a quantitative understanding is still lacking.

Want to predict final state: σ_f, θ_f, and n_f/n_0

Need thorough exploration of parameter space.

PIC is too expensive.

Idea: use a Fokker-Planck approach? →

Why Fokker-Planck?

Validated in the non-radiative case by recent PIC simulations (Wong et al. 2020, 2025).

Works for IC cooling when $\gamma < \gamma_{KN}$ (Zhdankin et al. 2020). Why not the more general case?

Can simulate in just 1D energy space! CHEAPER

Approach: simulate the time evolution of

$$\partial_t f = \partial_\gamma\left[D(\gamma)\partial_\gamma f\right] - \partial_\gamma\left[\left(2D(\gamma)/\gamma + A(\gamma)\right)f\right]$$
$$+ \text{IC radiation} + \text{pair production}$$

where $D(\gamma) = \gamma^2/t_{acc}$ and $A(\gamma) = 0$. Model feedback of pair production by making $t_{acc}(\langle\gamma\rangle, \langle n\rangle/n_0)$

Conclusions from PIC and Fokker-Planck models

`if:`

$$\theta_{ss,0} = \frac{1}{6}\sqrt{\frac{\sigma_0^3}{1+\sigma_0}}\gamma_{cool} \gtrsim \gamma_{KN}$$

`then:`

Conclusions from PIC and Fokker-Planck models

if:

$$\theta_{ss,0} = \frac{1}{6}\sqrt{\frac{\sigma_0^3}{1+\sigma_0}}\gamma_{cool} \gtrsim \gamma_{KN}$$

then:

1. $\theta_f \sim \gamma_{KN}/20$

Conclusions from PIC and Fokker-Planck models

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`then:`

1. $\theta_f \sim \gamma_{KN}/20$
2. $\sqrt{\sigma_f^3/(1+\sigma_f)} \sim \tau_{\gamma\gamma}$ $\longleftarrow$ $\left(\text{because} \quad \frac{\gamma_{KN}}{20} \sim \theta_{ss,f} = \frac{1}{6}\sqrt{\frac{\sigma_f^3}{1+\sigma_f}}\gamma_{cool} \Rightarrow \sqrt{\frac{\sigma_f^3}{1+\sigma_f}} \sim \frac{\gamma_{KN}}{\gamma_{cool}} \sim \frac{U_{bg}\sigma_T L}{\epsilon_{bg}} \sim \tau_{\gamma\gamma}\right)$

Conclusions from PIC and Fokker-Planck models

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if:
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3. $t_{conv} \sim 70\lambda_{mfp}/c$

Conclusions from PIC and Fokker-Planck models

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$$\theta_{ss,0} = \frac{1}{6}\sqrt{\frac{\sigma_0^3}{1+\sigma_0}}\gamma_{cool} \gtrsim \gamma_{KN}$$

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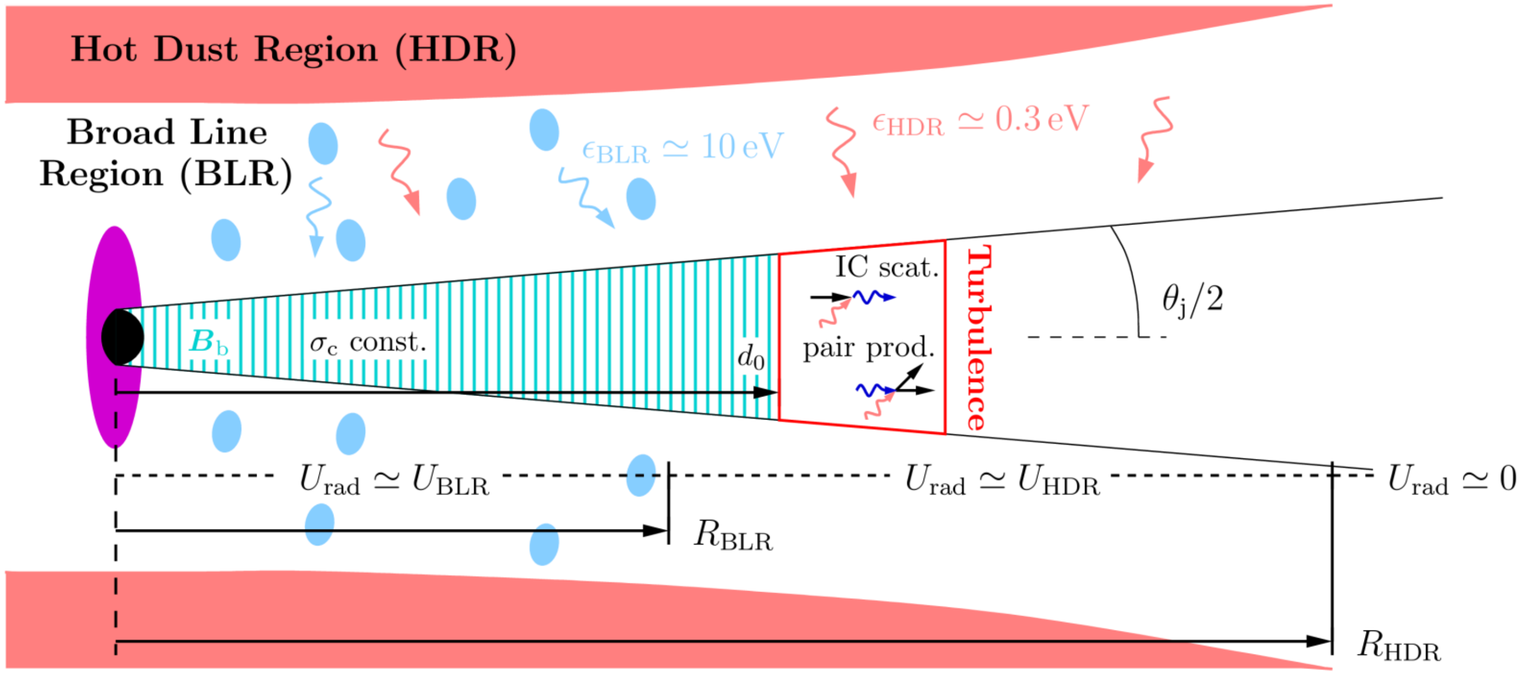
$\longleftarrow$ because $\frac{\gamma_{KN}}{20} \sim \theta_{ss,f} = \frac{1}{6}\sqrt{\frac{\sigma_f^3}{1+\sigma_f}}\gamma_{cool} \Rightarrow \sqrt{\frac{\sigma_f^3}{1+\sigma_f}} \sim \frac{\gamma_{KN}}{\gamma_{cool}} \sim \frac{U_{bg}\sigma_T L}{\epsilon_{bg}} \sim \tau_{\gamma\gamma}$

Plasma = radiation

Radiative turbulence as an *in situ* pair source in blazar jets



Use:

1. $\theta'_f \sim \gamma'_{KN}/20$
2. $\sqrt{\sigma_f'^3/(1+\sigma'_f)} \sim \tau'_{\gamma\gamma}$
3. $t'_{conv} \sim 70\lambda'_{mfp}/c$

Assume:

- Turbulence triggered at d_0 from BH
- Couples to BLR ($d_0 < R_{BLR}$) or HDR ($R_{BLR} < d_0 < R_{HDR}$) photons
- Bulk Lorentz factor Γ_j (e.g., $\gamma'_{KN} = \gamma_{KN}/\Gamma_j$)

What is the turbulence-powered pair yield, n_f/n_0?

- Parameterize n_0 via: $\sigma'_c = B_0'^2/4\pi n'_0 m_e c^2 = \sigma_c/\Gamma_j$
- Parameterize n_f via: $\sigma'_f = B_f'^2/16\pi n'_f \theta'_f m_e c^2$
- Conclude:

Helpful info (Mehlhaff+ 2021):

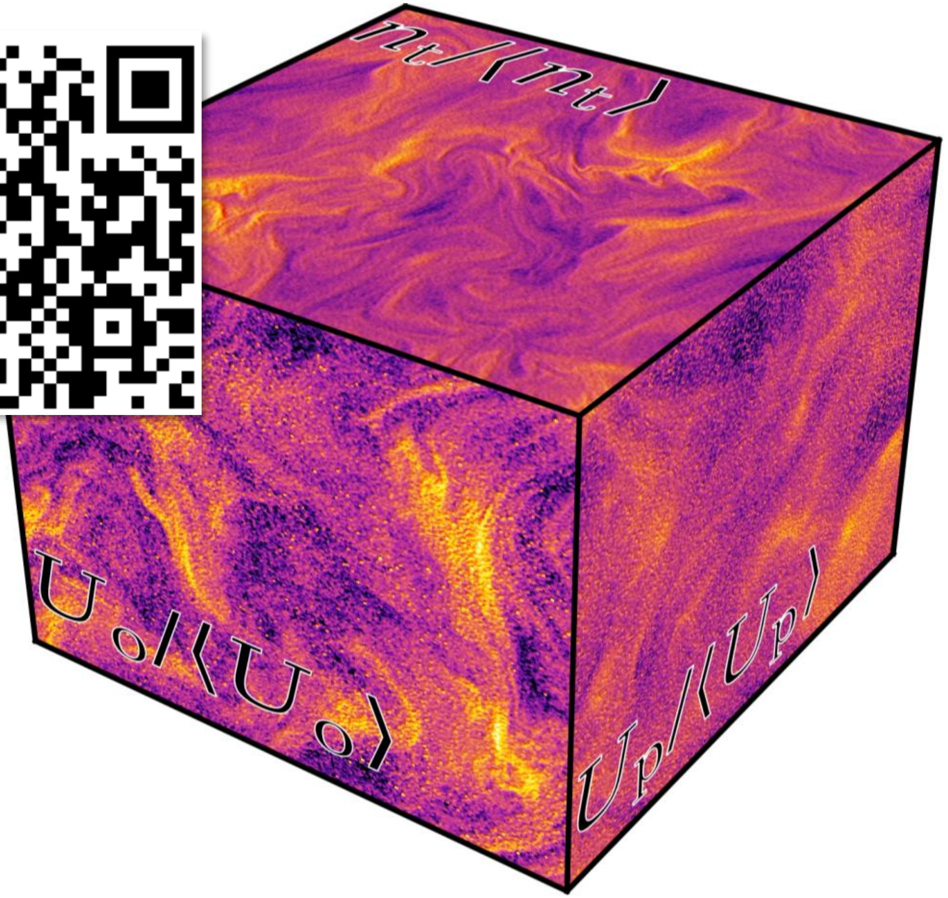
- $\tau'_{BLR} \sim 3 \Rightarrow \sigma'_{f,BLR} \simeq 2$
- $\tau'_{HDR} \sim 20 \Rightarrow \sigma'_{f,HDR} \simeq 20$
- $\gamma_{KN,BLR} \sim 1\times10^4$; $\gamma_{KN,HDR} \sim 4\times10^5$

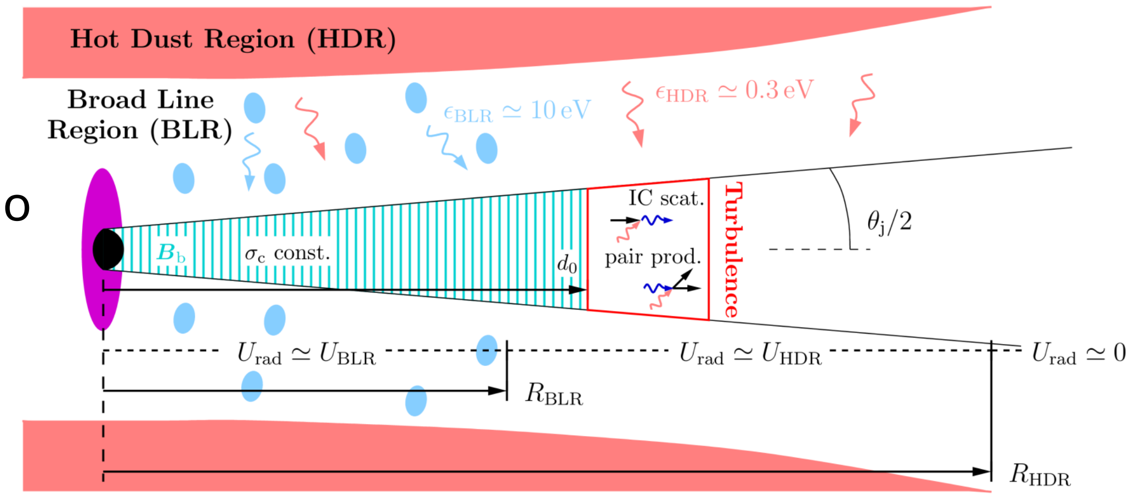
$$\boxed{\frac{n_f}{n_0} = \frac{n'_f}{n'_0} = \underbrace{\left(\frac{B_f'^2}{B_0'^2}\right)}_{\simeq 1}\left(\frac{\sigma'_c}{4\theta'_f}\right)\left(\frac{1}{\sigma'_f}\right) \simeq \left(\frac{\sigma'_c}{4\theta'_f}\right)\left(\frac{1}{\sigma'_f}\right) \simeq \left(\frac{5\sigma_c}{\gamma_{KN}}\right)\left(\frac{1}{\sigma'_f}\right) \sim \begin{cases}\sigma_c/10^4, BLR \\ \sigma_c/10^6, HDR\end{cases}}$$

For M87*, magnetospheric models (Kimura+ 2022, Chen+ 2023, Hakobyan+ 2023) predict $\sigma_c \in [10^4, 10^8]$ at jet base

Conclusions

- Studied relativistic turbulence coupled to an external radiation bath, as in blazar jets
- Predicted and confirmed (via PIC simulations) pair-thermalization mechanism
- Explored parameter space using Fokker-Planck modeling, benchmarked by PIC
- Worked out final thermal temperature $\theta_f \sim \gamma_{KN}/20$, final (hot) magnetization obeying $\sqrt{\sigma_f^3/(1+\sigma_f)} \sim \tau_{\gamma\gamma}$, and thermalization time $t_{conv} \sim 70\lambda_{mfp}/c$
- Plasma forgets its initial state; radiation tells it what to do
- ***Radiative turbulence may be an in situ pair source in blazar jets (particle acceleration ↔ composition)***



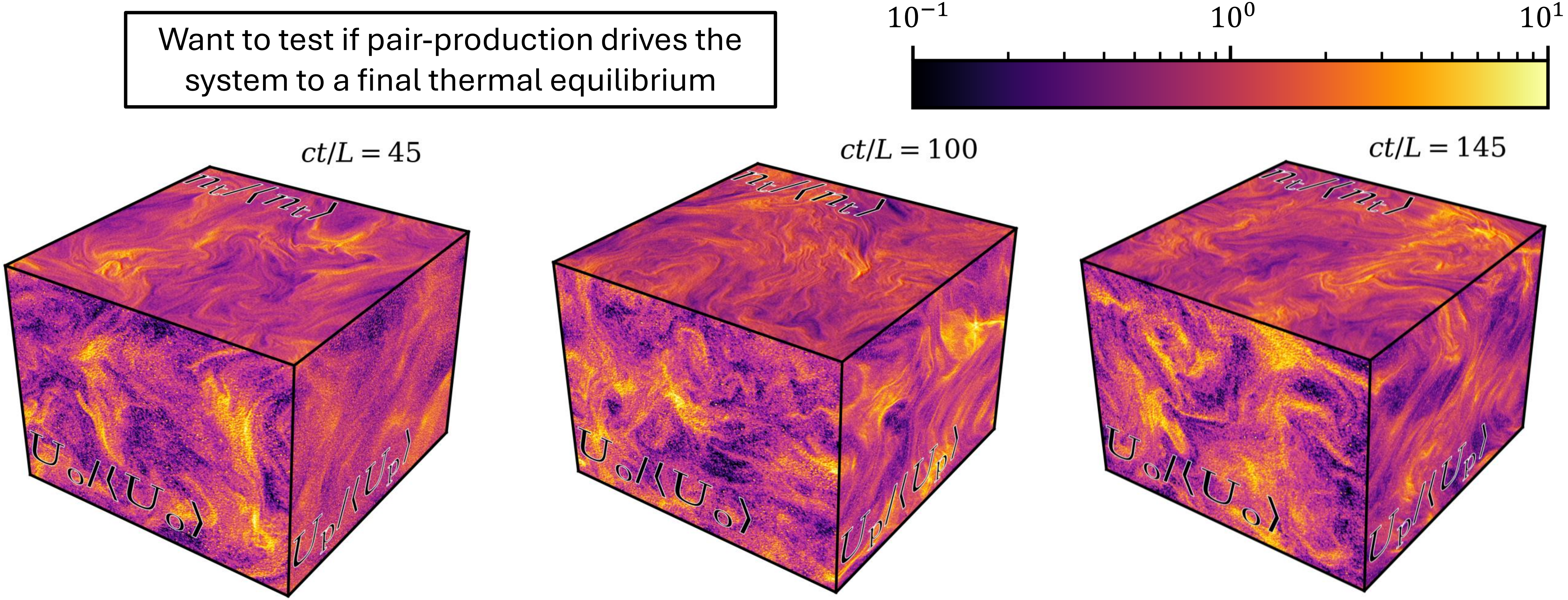


Backup Slides

Some notes about the simulations

- 512^3 cells; initially **2** particles per cell
- Box length $L = 64\lambda_0$ where λ_0 is initial plasma Debye length: $\Delta x = \lambda_0/8$
  - Have to "catch" final Debye length λ_f: need $\Delta x \leq \lambda_f$
- Initially thermal (Maxwell-Jüttner) particle energy distribution $f \propto \gamma^2 \exp(-\gamma/\theta_0)$
- Initial temperature = initial θ_{ss} = 100; $\gamma_{cr} = 500$

Want to test if pair-production drives the system to a final thermal equilibrium



Allowing $\gamma > \gamma_{KN}$ breaks equilibrium, even without pair production

Condition $\dot{\epsilon}_{rad} = \dot{\epsilon}_{inj}$ now difficult to achieve

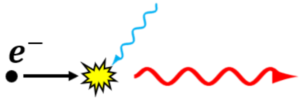
Standard turbulence setup

$$\dot{\epsilon}_{inj} \sim \frac{B_0^2}{8\pi n_0} \frac{v_A}{L}$$

+

Interaction with radiation bath

Inverse Compton (IC) scattering



$$\dot{\epsilon}_{rad} \propto \langle \gamma^2 \rangle \rightarrow \dot{\epsilon}_{rad} \propto \langle \gamma^2 f_{KN}(\gamma/\gamma_{KN}) \rangle$$

where $f_{KN}(x) \simeq 1/(1+x)^{3/2}$

Allowing $\gamma > \gamma_{KN}$ breaks equilibrium, even without pair production

Condition $\dot{\epsilon}_{rad} = \dot{\epsilon}_{inj}$ now *impossible* to achieve

Standard turbulence setup

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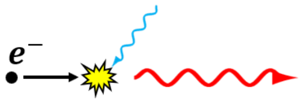
$$\underbrace{\text{Interaction with radiation bath}}_{\text{Inverse Compton (IC) scattering}}$$



$$\dot{\epsilon}_{rad} \propto \langle \gamma^2 \rangle \rightarrow \dot{\epsilon}_{rad} \propto \langle \gamma^2 f_{KN}(\gamma/\gamma_{KN}) \rangle$$

where $f_{KN}(x) \simeq 1/(1+x)^{3/2}$

Fokker-Planck forbids $\dot{\epsilon}_{rad} = \dot{\epsilon}_{inj}$

Consider the same Fokker-Planck equation from before:

$$\partial_t f = \partial_\gamma[D(\gamma)\partial_\gamma f] - \partial_\gamma[(2D(\gamma)/\gamma + A(\gamma))f]$$

with $D \propto \gamma^2$ and $A = A_{IC} \propto \gamma^2 f_{KN}(\gamma/\gamma_{KN})$.

Solve new steady state, $\frac{d}{d\gamma}\ln\left(\frac{f}{\gamma^2}\right) = \frac{A}{D} = f_{KN}$:

$$\Rightarrow f(\gamma) \propto \gamma^2 \exp\left(const./\sqrt{1+\gamma/\gamma_{KN}}\right)$$

Not normalizable. $\dot{\epsilon}_{rad}$ can no longer keep up with $\dot{\epsilon}_{inj}$!

Allowing $\gamma > \gamma_{KN}$ breaks equilibrium, even without pair production

...but pair production doesn't help

Condition $\dot{\epsilon}_{rad} = \dot{\epsilon}_{inj}$ now *impossible* to achieve

Standard turbulence setup

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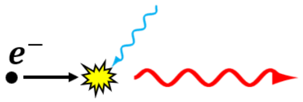

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where $f_{KN}(x) \simeq 1/(1+x)^{3/2}$

With pair production:

Particles with $\gamma > \gamma_{KN}$ are effectively less radiative. Their radiated energy remains trapped in the system (producing pairs)

The collective radiative efficiency is **strictly diminished**, even for $\tau_{\gamma\gamma} < 1$

The particle number keeps growing

How can equilibrium be reached?

The PIC loop

Update particle $(\vec{x}, \vec{p})$ from $(\vec{E}, \vec{B})$;
+ apply continuous cooling:

$$\vec{F} = q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right) + \vec{f}_{\rm rad};$$

Advance photon positions

Calculate discrete photon emission
+ apply discrete cooling;
Calculate pair production

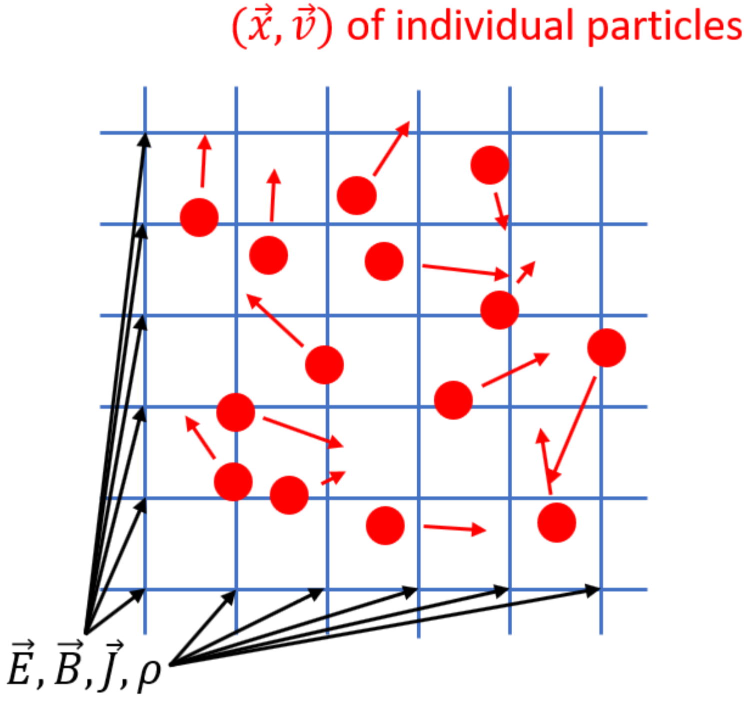
Δt

Compute ρ and $\vec{J}$
from $(\vec{x}, \vec{v})$ of particles

Advance $(\vec{E}, \vec{B})$:

$$\partial_t \vec{B} = -c\vec{\nabla} \times \vec{E}$$

$$\partial_t \vec{E} = c\vec{\nabla} \times \vec{B} - 4\pi \vec{J}$$



Using Zeltron (Cerutti et al. 2013)