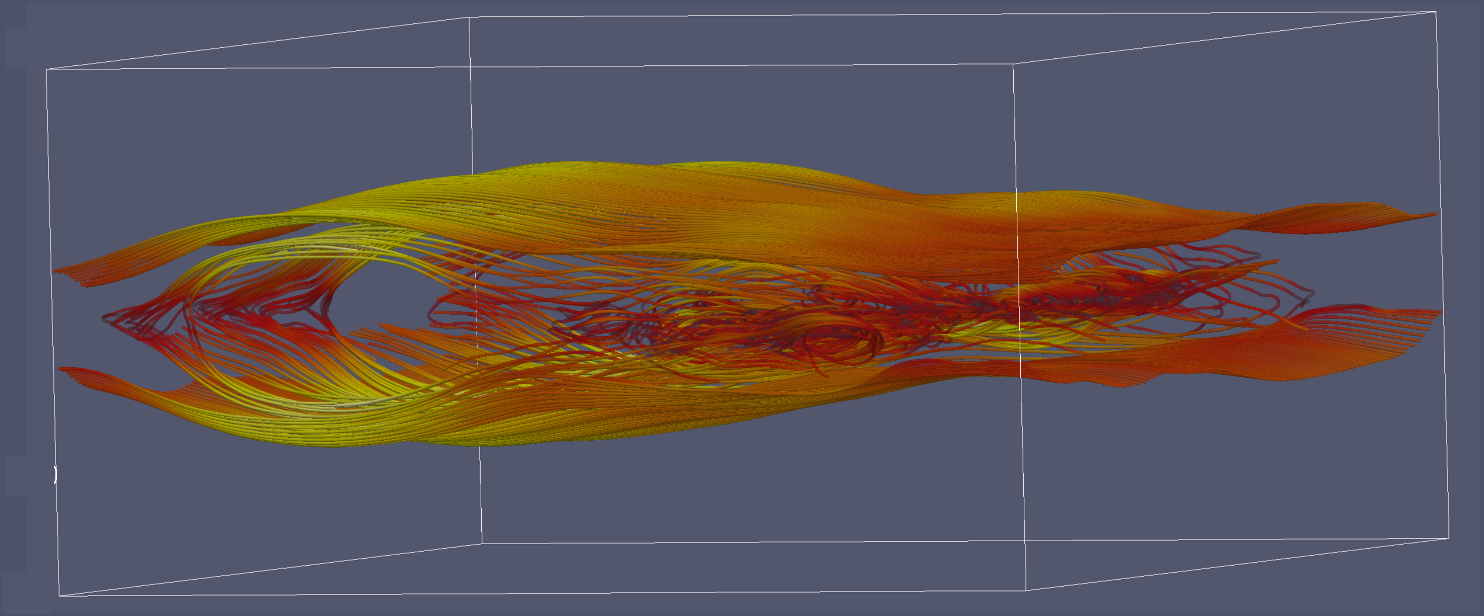
Relativistic Reconnection: radiative and 3D effects

Relativistic reconnection in pair plasma

Using PIC codes:
Zeltron
Tristan-MP



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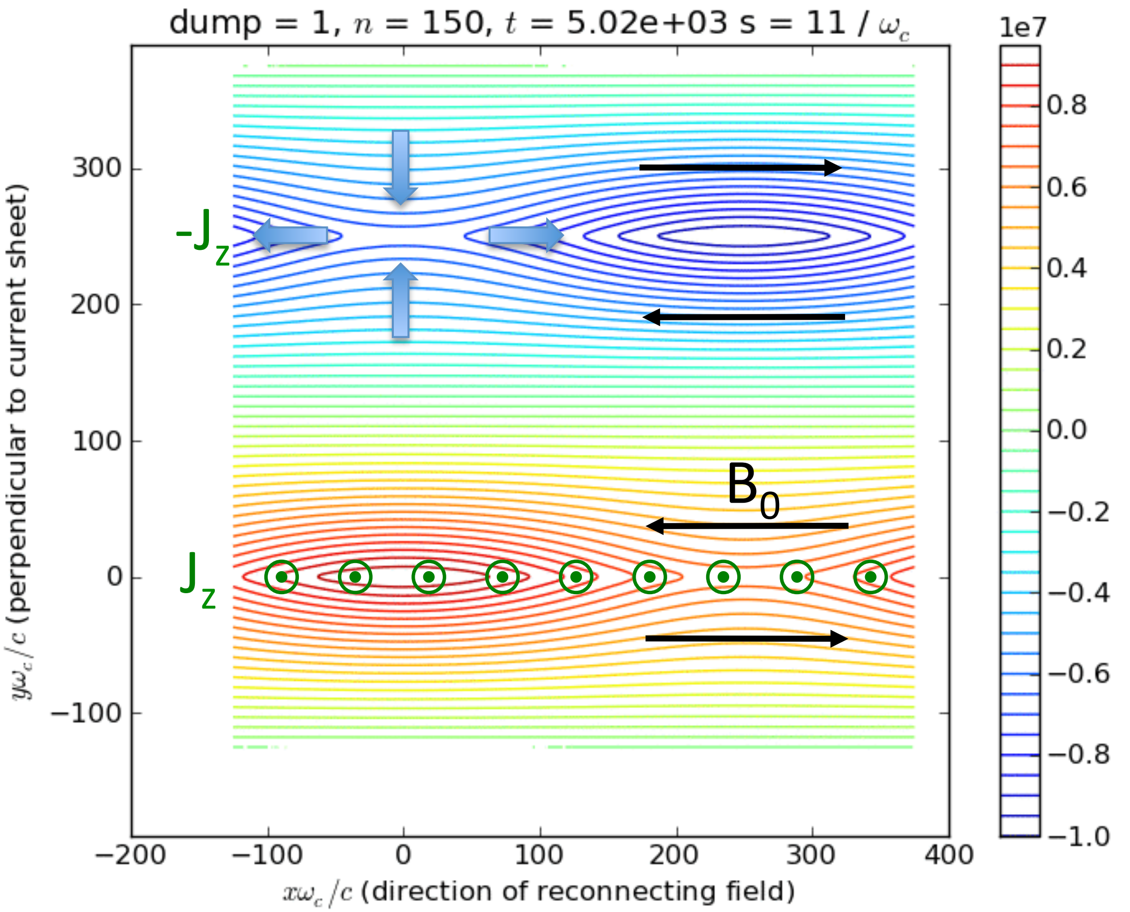
How are
- reconnection dynamics/energetics
- and NTPA

affected by:
- length in the 3rd dimension (z); i.e., 3D-ness
- guide magnetic field
- external inverse Compton cooling

?

Bonus: Code Comparison

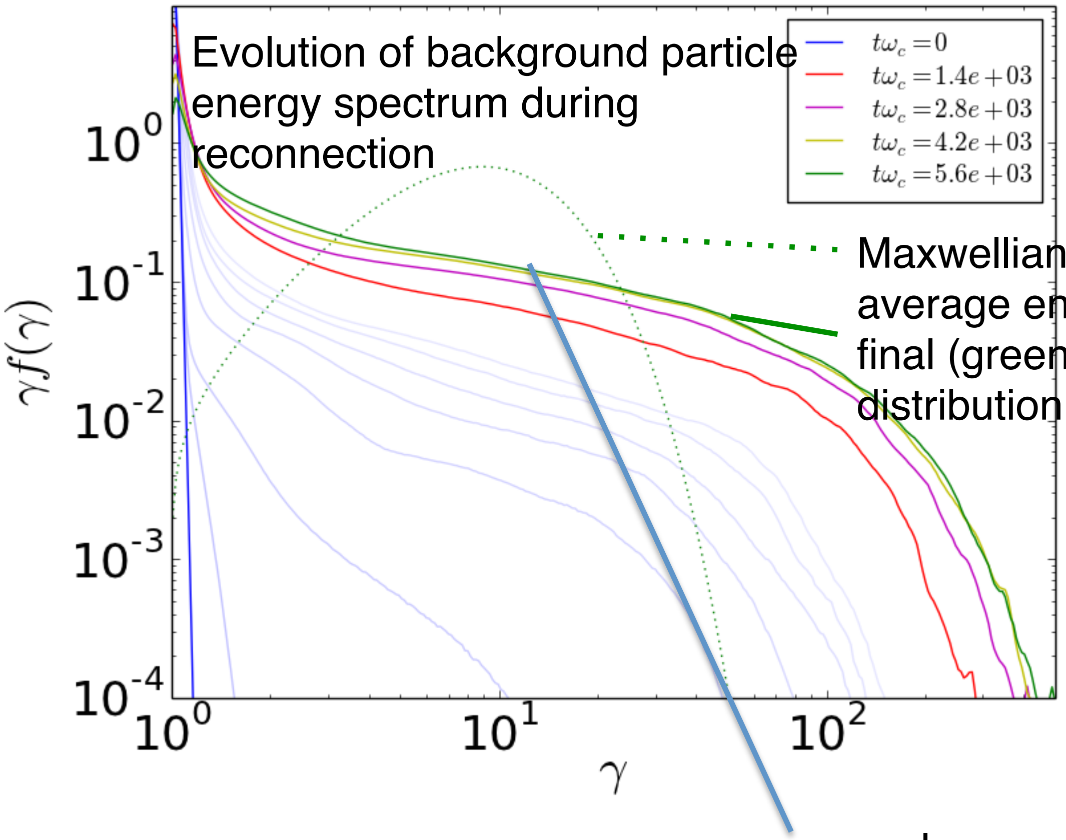
Reconnection’s main job: magnetic field energy -> particle/plasma energy



Reconnection -> particle energization/NTPA -> radiation

NTPA=Nonthermal Particle Acceleration

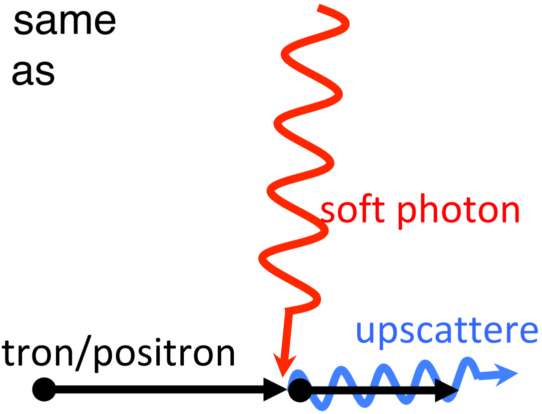
observational diagnostic



Evolution of background particle energy spectrum during reconnection

Maxwellian with same average energy as final (green) distribution.

power-law

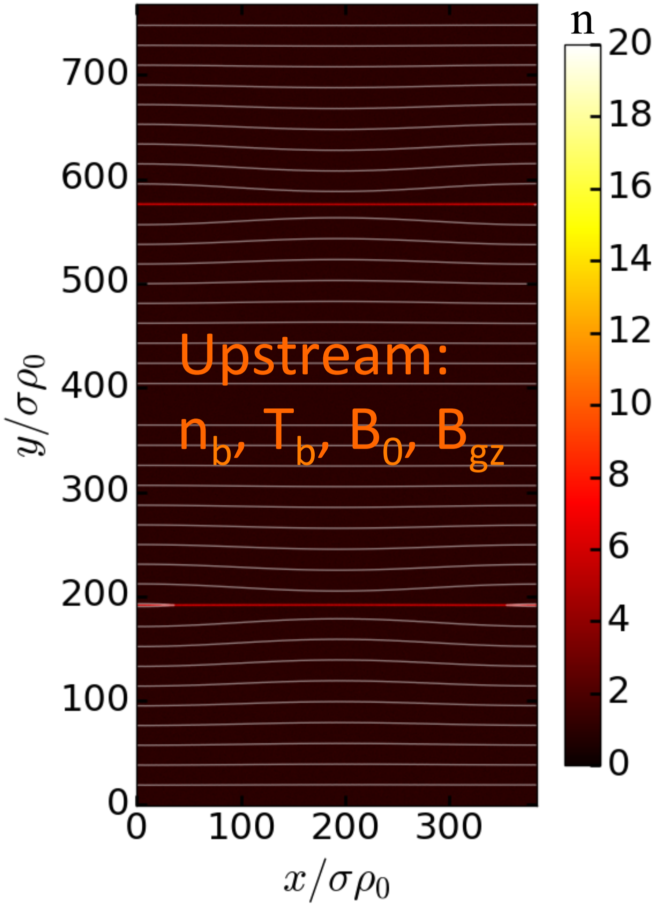


(observable) external inverse Compton (IC) radiation

(The Lorentz factor ϒ is used interchangeably with particle energy ϒmc^2.)

above from 2D simulations (e.g., Sironi&Spitkovsky 2014, Guo et al 2015, Werner et al 2016)

Reconnection parameters



Upstream Parameters: pair plasma
n_b, T_b, B_0, B_{gz} (guide field)

Dimensionless parameters:

$T_b / m_e c^2 >> 1$ (ultrarelativistically-hot)

$$\sigma = \frac{B_0^2}{4\pi n_b m_e c^2} >> \frac{T_b}{m_e c^2}$$ (relativistic reconnection)

$$\sigma_h = \frac{B_0^2}{4\pi h} \approx \frac{B_0^2}{4\pi(4 n_b T_b)} = \boxed{25}, 100$$

relativistic reconnection:
relativistic outflows,
significant energization

B_{gz}/B_0=0, 0.25, 0.5, 1, 2 (guide field)

Later: vary inverse Compton (IC) radiative cooling

nominal length scale:

$$\rho_0 = \frac{m_e c^2}{eB_0}, \rho_c = \sigma\rho_0$$

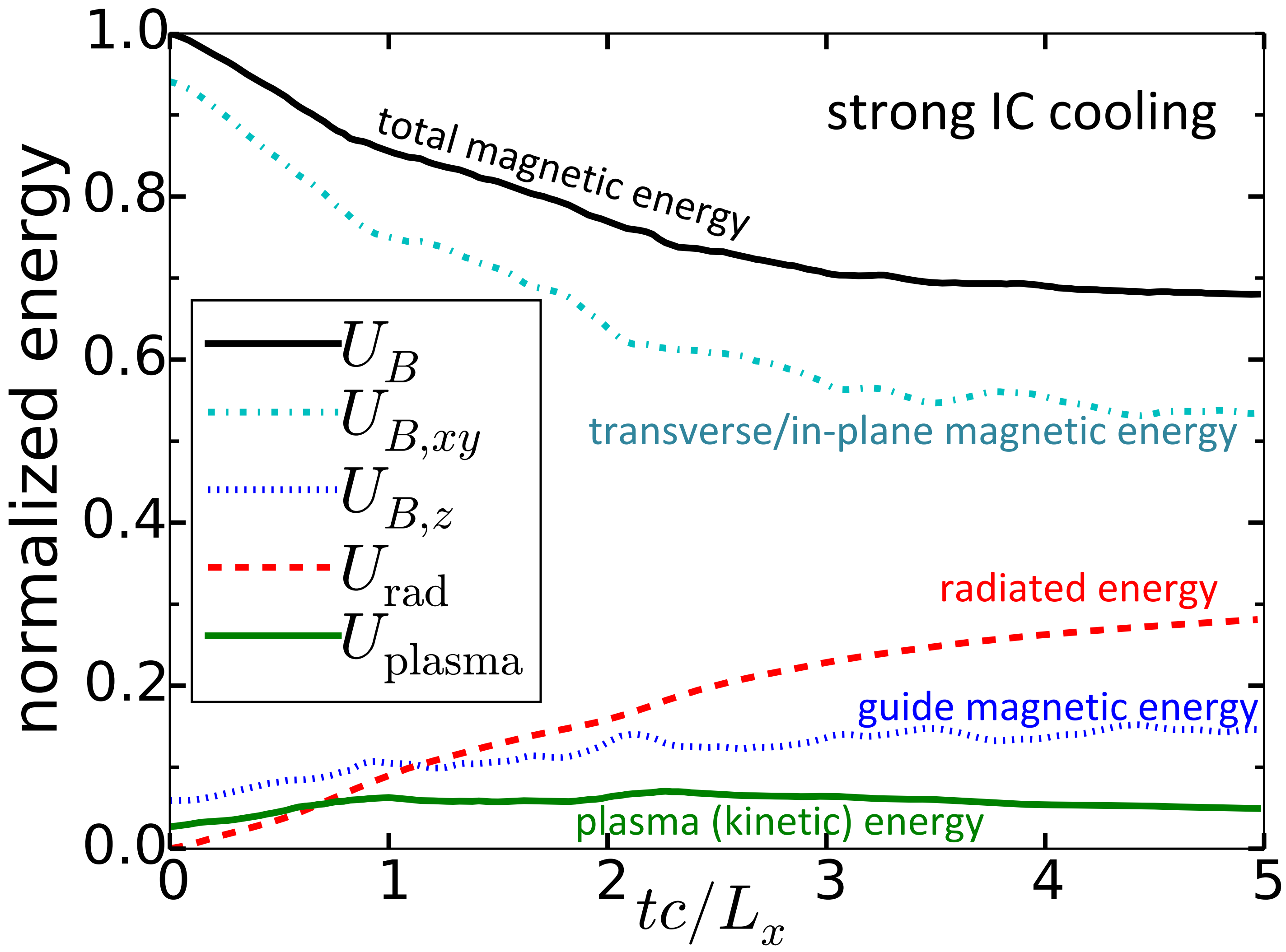
System size: Lx, Ly, Lz

$Lx/\sigma\rho_0$ = 40 (3D) − 320 (2D)
Ly/Lx = 2
Lz/Lx = varying (2D->3D)

How do these parameters affect reconnection?
Specifically:
- energetics
- NTPA

Focus on two “outputs” of reconnection: basic dynamics/energetics, and NTPA

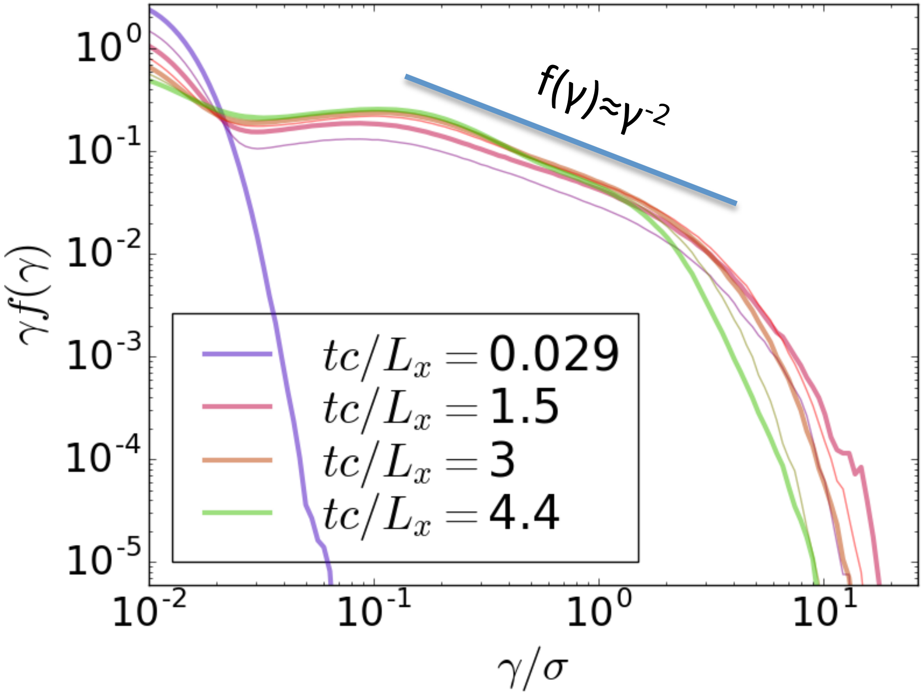
reconnection rate, magnetic energy dissipation, plasmoid formation, etc.



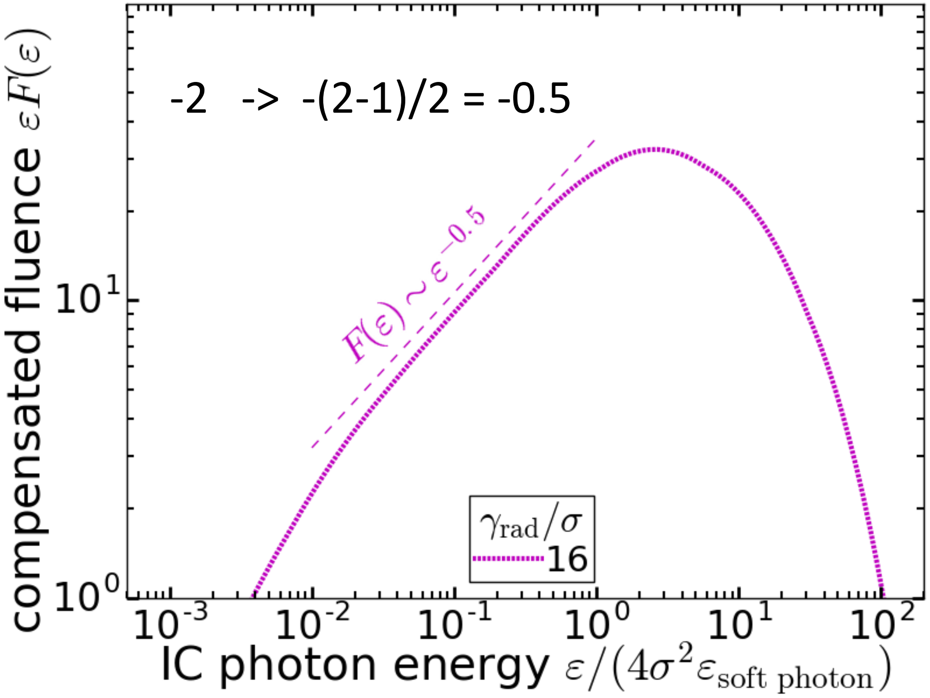
Focus on two outputs of reconnection: basic dynamics/energetics, and NTPA

NTPA:
(shown here, for weak IC cooling)

particle energy spectra


$f(\gamma) \approx \gamma^{-2}$

photon energy spectra


-2 -> -(2-1)/2 = -0.5

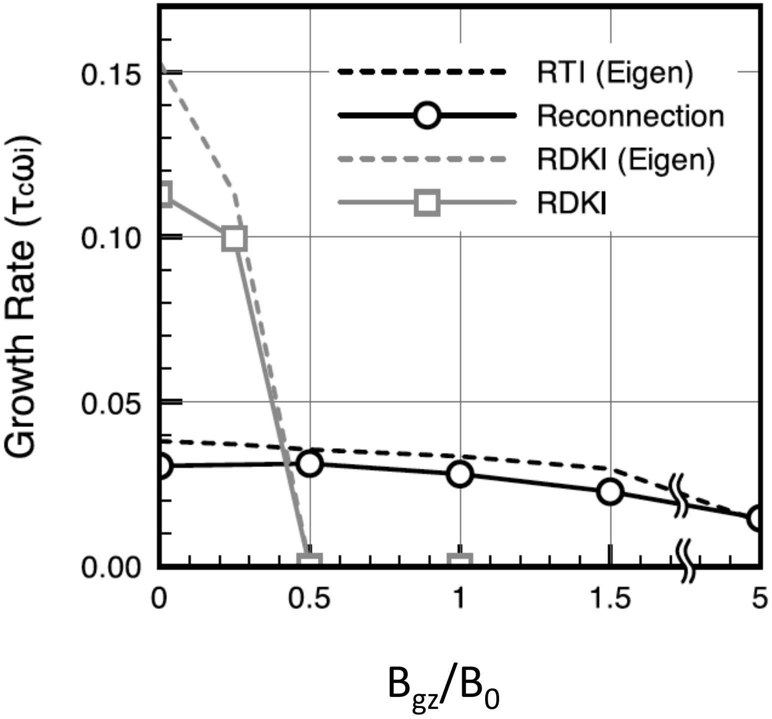
In the following, various input parameters will be varied (B_{gz}, Lz/Lx, IC cooling) with outputs (dissipated magnetic energy and NTPA) shown.

Vary Lz/Lx (3D-ness) and B_{gz}/B_0 and see what happens...

3D effects: does Lz/Lx affect reconnection?

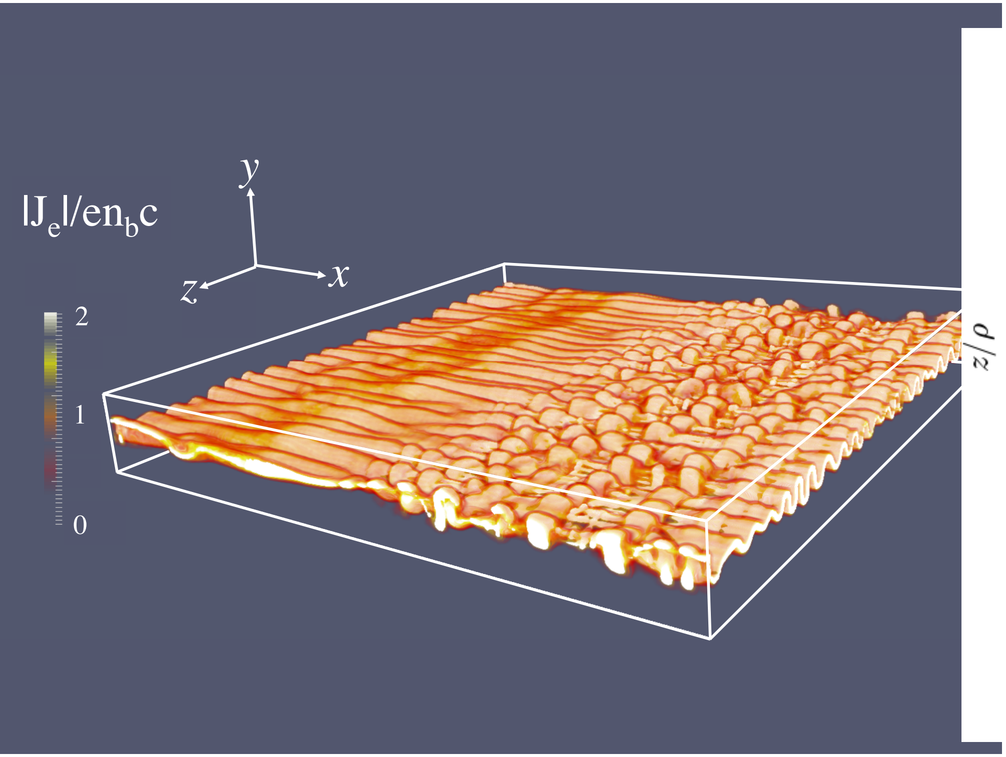
In particular, does the relativistic drift-kink instability (RDKI) inhibit particle acceleration?
Here, guide magnetic field may be important: it inhibits RDKI.

from Zenitani & Hoshino, 2008:

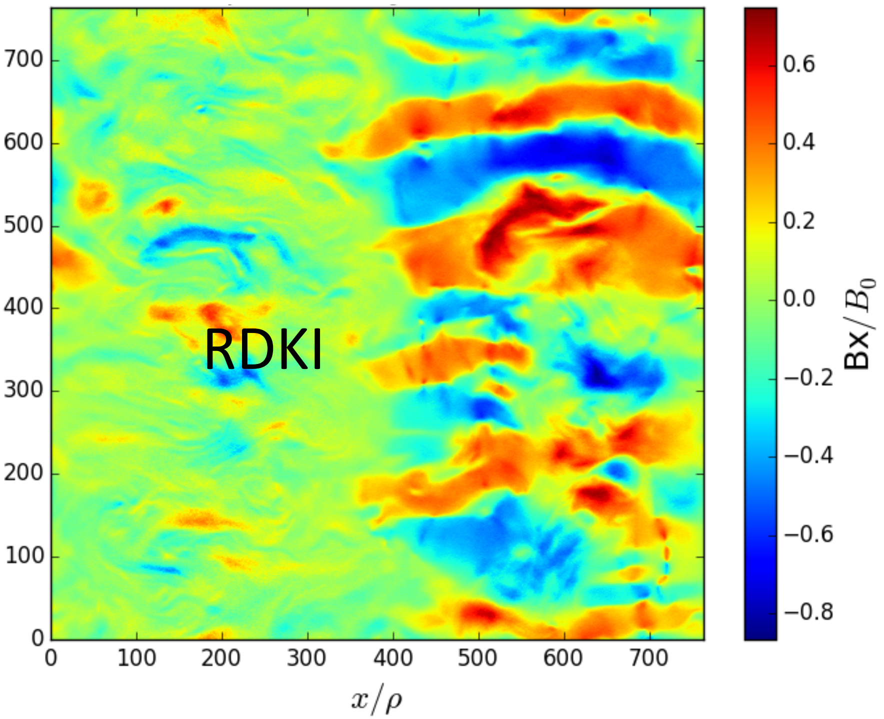


However, more recent simulations (e.g., Sironi & Spitkovsky 2014, Guo et al 2015, Werner & Uzdensky 2017) have suggested that particle acceleration is robust to 3D effects.

Despite significant RDKI, 2D and 3D reconnection have similar reconnection rates and NTPA.



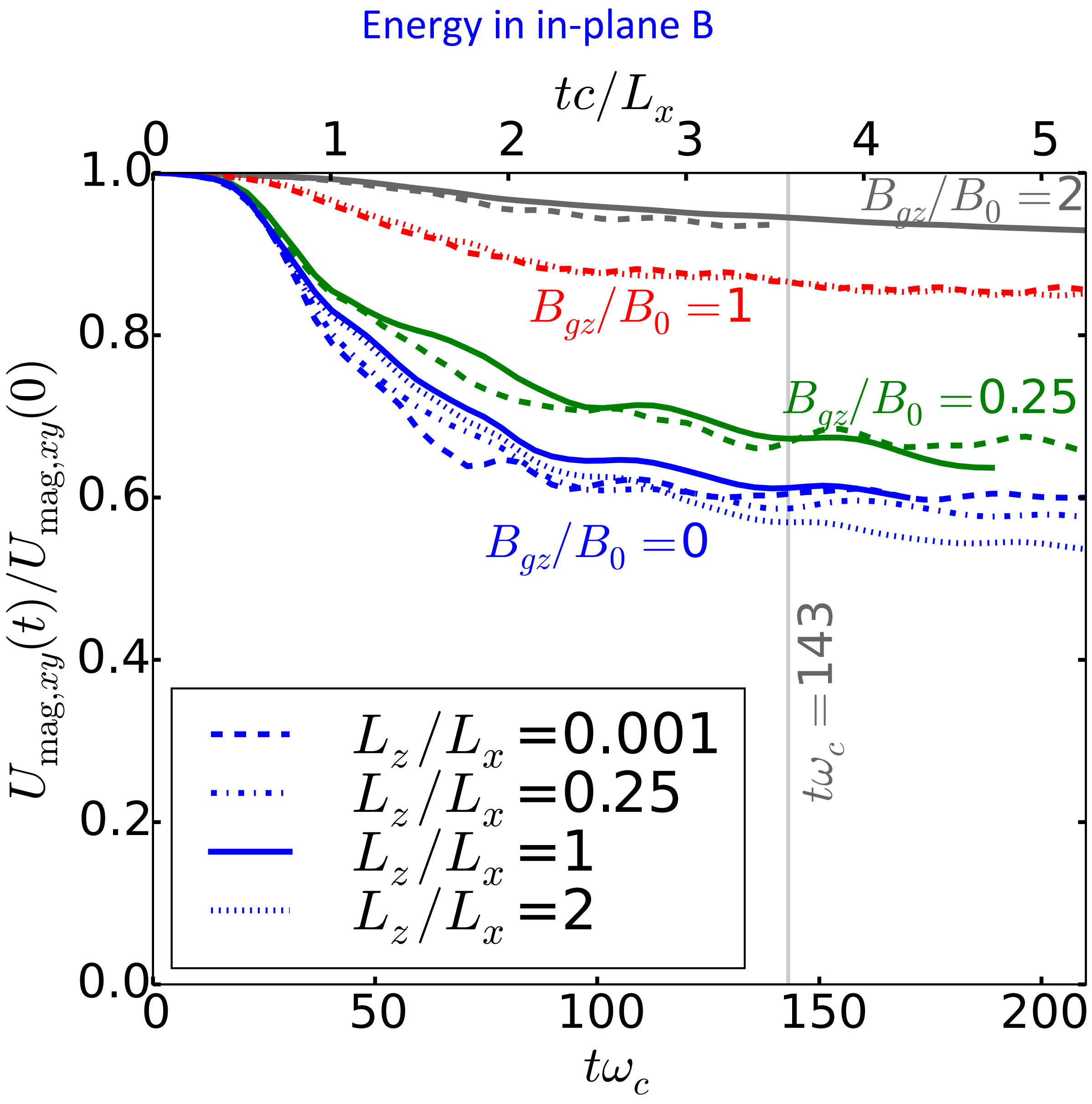
B_x in the x-z reconnection midplane



3D, $L_z=L_x$, $B_z=0$

3D current sheet evolution

Energetics of 2D and 3D reconnection are similar regardless of guide field (for later: guide field has a significant effect)

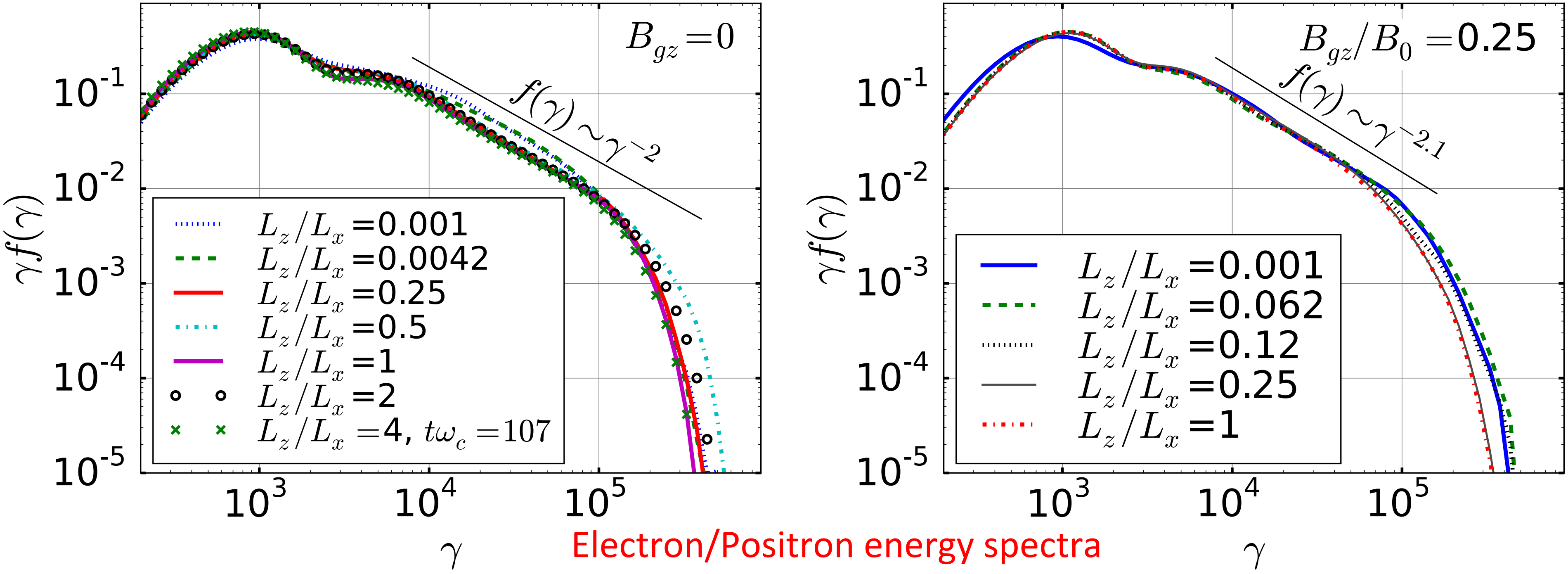


$\sigma_h=25$

And 2D and 3D particle spectra are similar!

Nonthermal acceleration remains robust from 2D to 3D!
Also, a little guide field B_{gz} hardly disturbs acceleration.

$L_x=40\sigma\rho_0$
$L_y=80\sigma\rho_0$



Electron/Positron energy spectra

$\sigma_h=25$

Compressing plasmoids

n/n_b

During reconnection, the in-plane magnetic field compresses plasmoids.

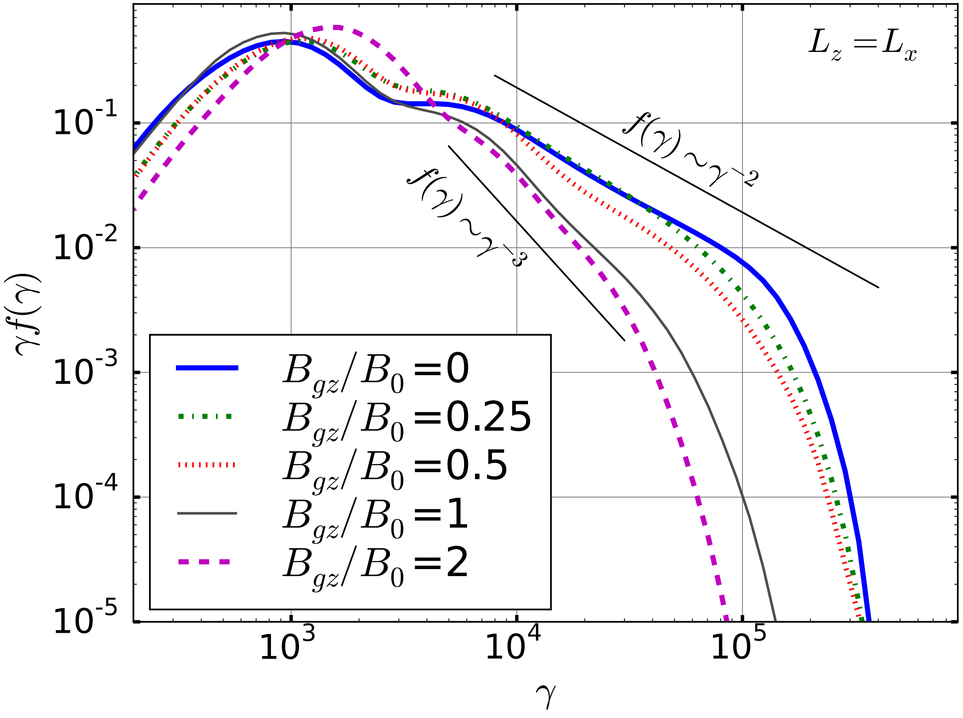
When there’s a guide field, that guide field rests compression. This slows reconnection and inhibits particle acceleration.

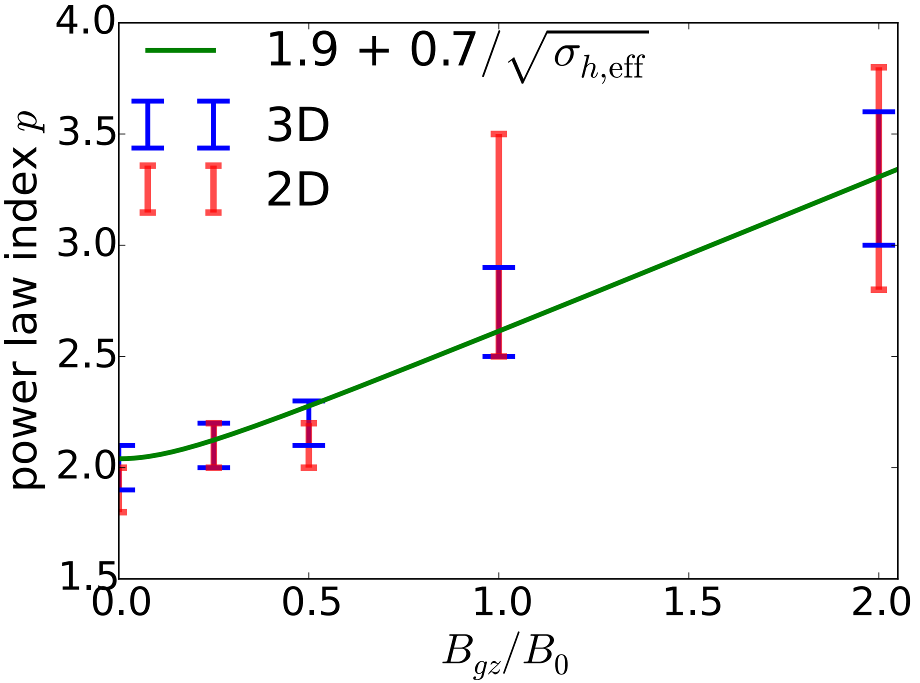
Guide field not only slows reconnection rate, but steepens the NTPA power law.

Guide field slows reconnection, dissipates less magnetic energy (guide field resists compression).

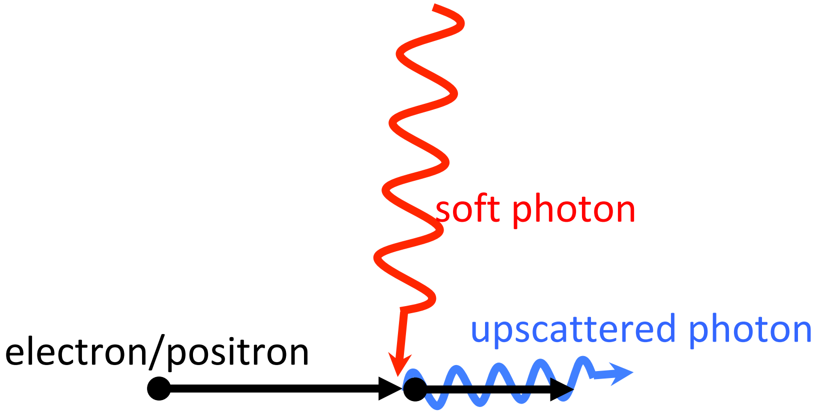
σ_h=25

$$\sigma_{h,eff} = \frac{B_0^2/4\pi}{h_{particle} + B_z^2/4\pi}$$





Reconnection in a bath of soft (low-energy) photons



external inverse Compton (IC) radiation

High energy electrons (or positrons) scatter of photons, emitting high energy photons, and experiences radiation reaction (radiaction) force.

If U_{ph} is the photon energy density, then the power loss, for an electron with $\gamma m_e c^2$ is:

$$P_{rad} = \frac{4}{3}\sigma_T c U_{ph}\gamma^2$$

Power gain (accel.) in the reconnection electric field $E=0.1B_0$:

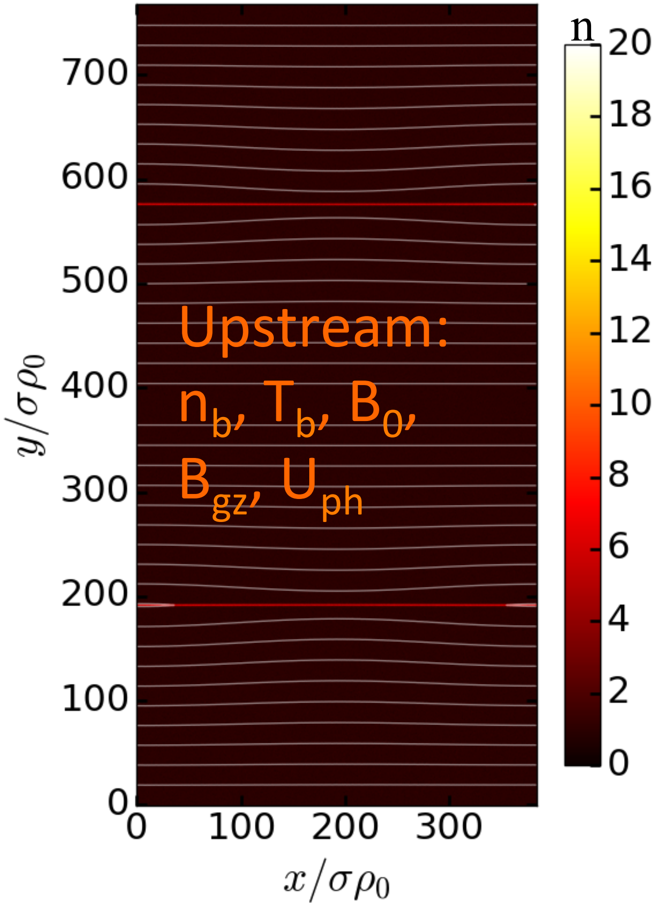
$$P_{acc} = (0.1)eB_0 c$$

These 2 forces (powers) balance for $\gamma=\gamma_{rad}$:

$$\gamma_{rad} = \sqrt{\frac{3(0.1)eB_0}{4\sigma_T U_{ph}}}$$

Particles can't gain much more energy than this.

Reconnection setup with photon bath



Upstream Parameters: pair plasma
n_b, T_b, B_0, B_{gz} (guide field),
U_{ph} (soft radiation bath energy density)

Dimensionless parameters:

$T_b / m_e c^2 >> 1$ (ultrarelativistically-hot)

$$\sigma = \frac{B_0^2}{4\pi n_b m_e c^2} >> \frac{T_b}{m_e c^2}$$ (relativistic reconnection)

$$\sigma_h = \frac{B_0^2}{4\pi h} \approx \frac{B_0^2}{4\pi(4n_b T_b)} = 25, \boxed{100}$$

relativistic reconnection:
relativistic outflows,
significant energization

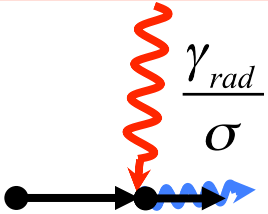
B_{gz}/B_0=0, 0.25, 0.5, 1, 2

nominal reconnection rate

nominal length scale:

$$\rho_0 = \frac{m_e c^2}{eB_0}, \rho_c = \sigma\rho_0$$

System size: Lx, Ly, Lz



$$\frac{\gamma_{rad}}{\sigma} = \frac{1}{\sigma}\sqrt{\frac{3(0.1)eB_0}{4\sigma_T U_{ph}}}$$

$\gamma_{rad} m_e c^2$ is the energy at which acceleration by reconnection E equals deceleration by IC radiation reaction.

$Lx/\sigma\rho_0$ = 40 (3D) – 320 (2D)
Ly/Lx = 2
Lz/Lx = varying (2D->3D)

How do these parameters affect reconnection?

IC scattering doesn't affect basic reconnection dynamics very much

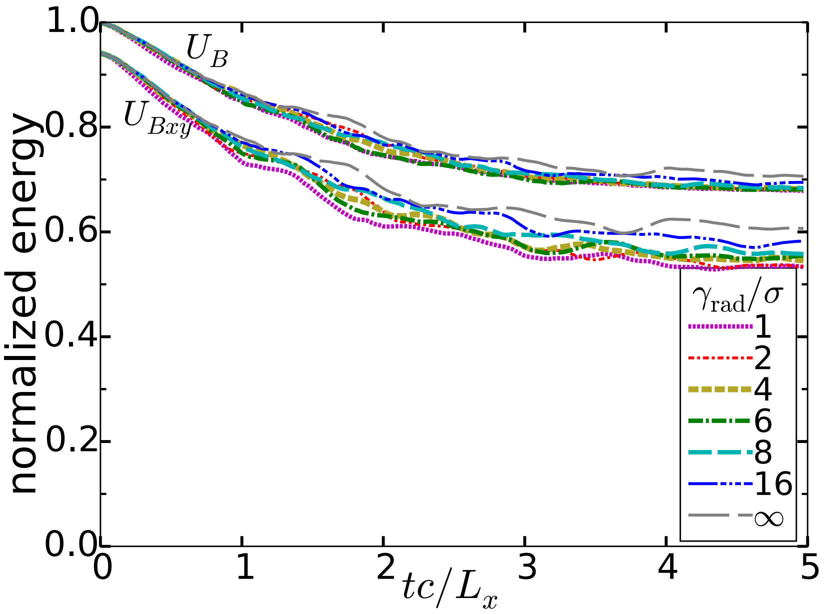
$\gamma_{rad}=\infty$ (no cooling)

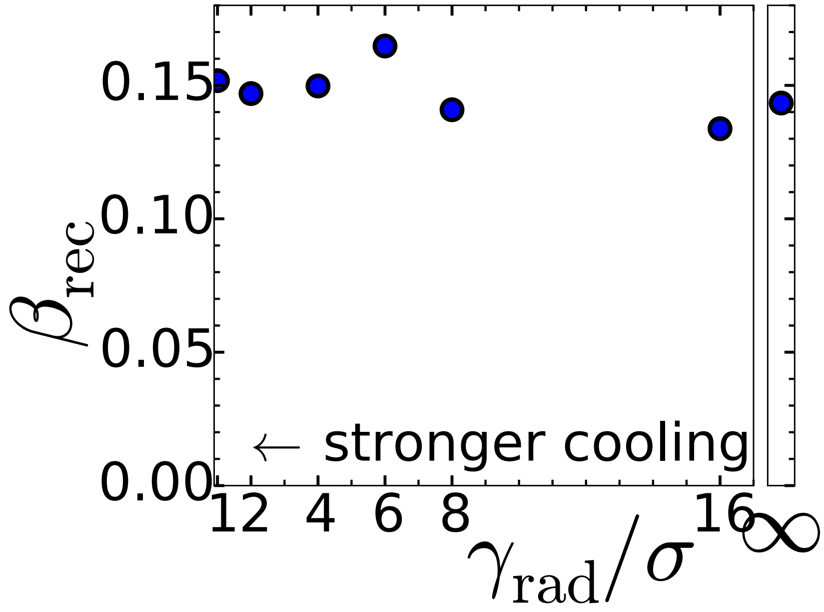
$\gamma_{rad}=2\sigma$ (strong cooling)

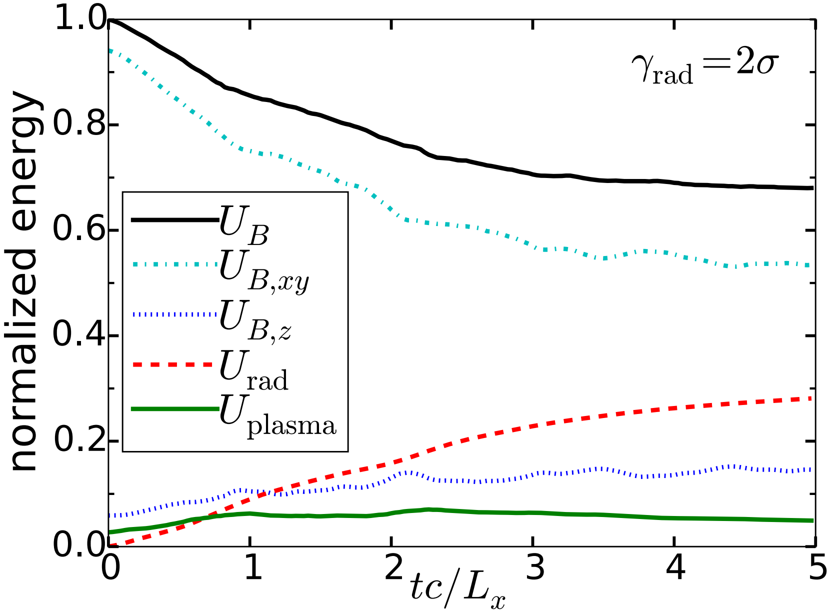
color=plasma density (normalized to n_b)

IC cooling has little effect on magnetic energy dissipation, reconnection rate

$\sigma_h=100$, $B_{gz}=B_0/4$



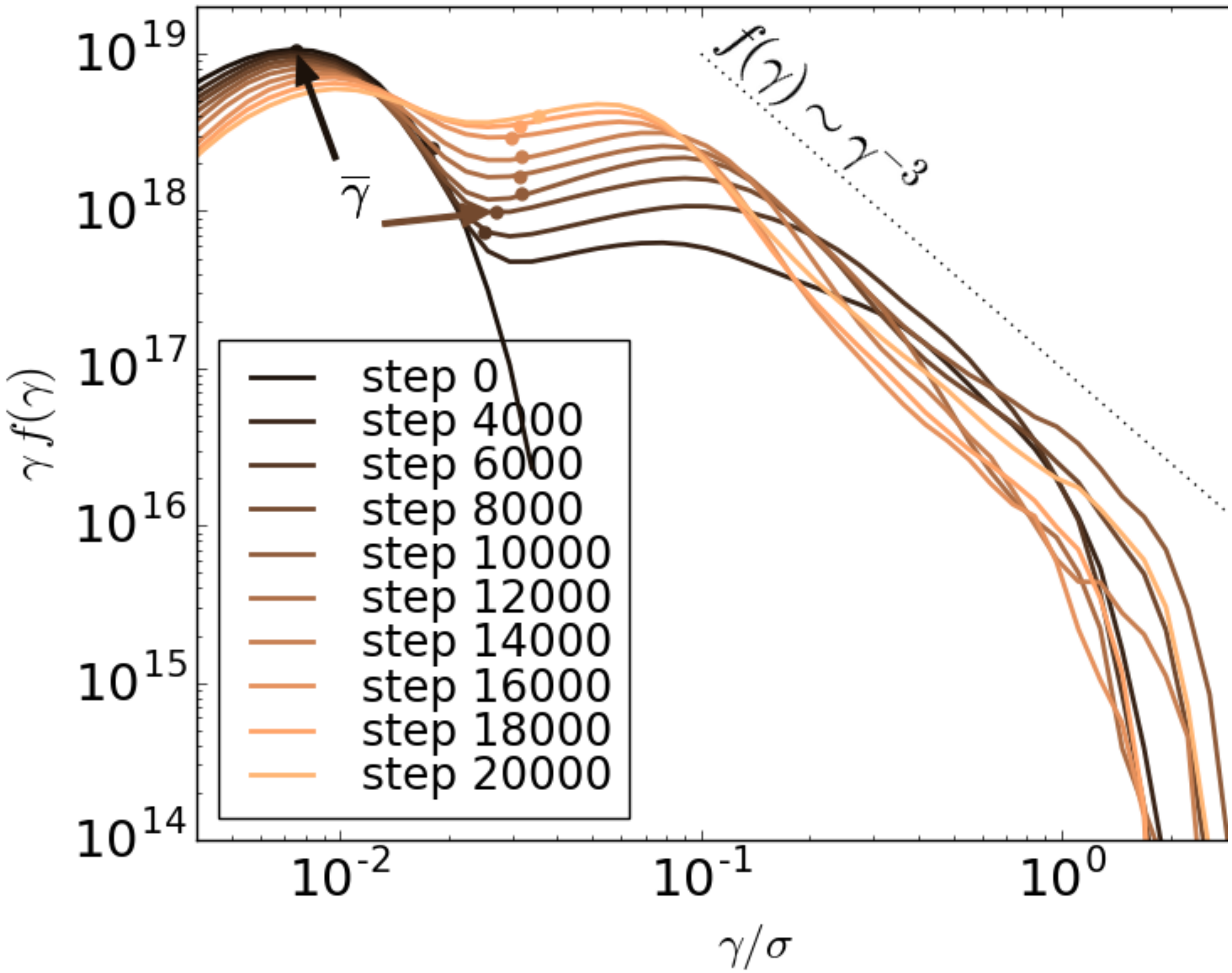




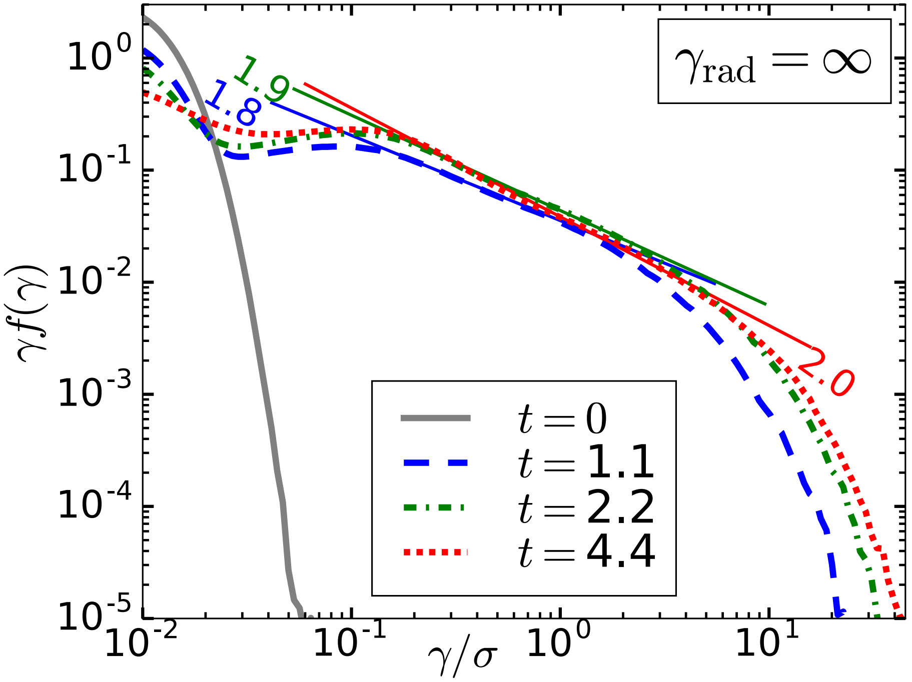
Strong cooling doesn't alter the amount of magnetic energy transferred to particles...but strong cooling means particles promptly radiate that energy.

IC cooling changes particle spectra significantly: noisy, steeper

σ_h=100, B_{gz}=B_0/4



IC cooling changes particle spectra significantly

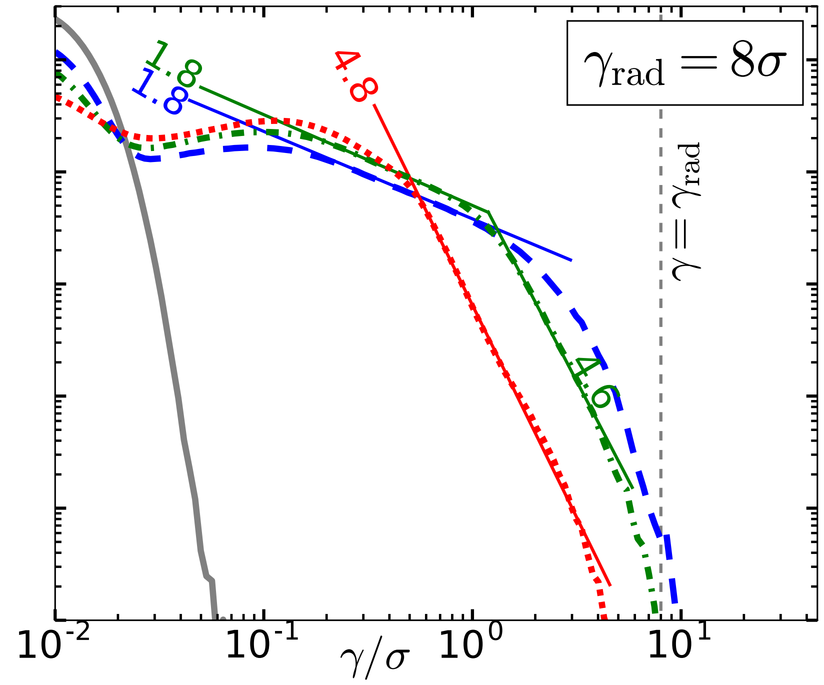


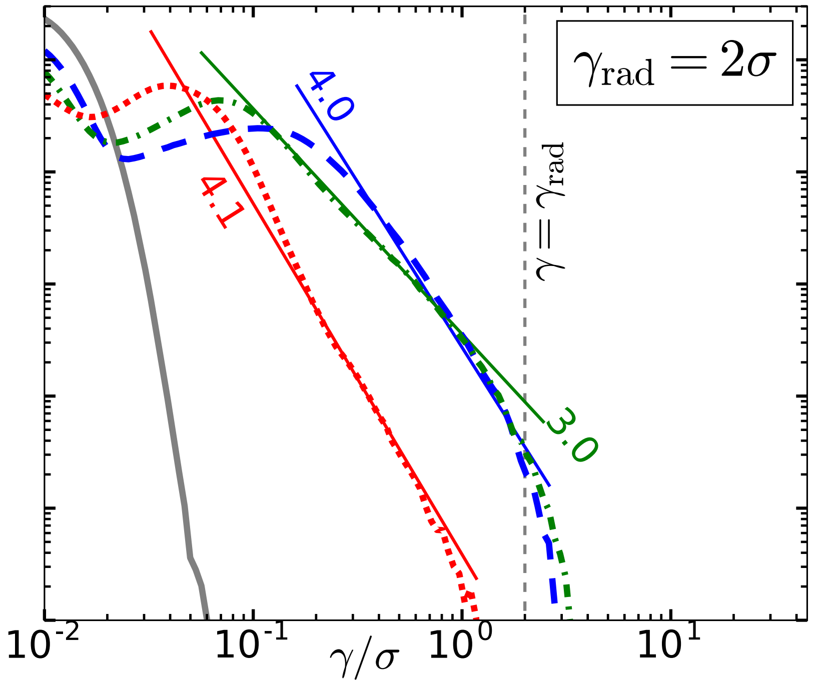
Weak cooling: usual hard power law

Strong cooling: variable steep power law

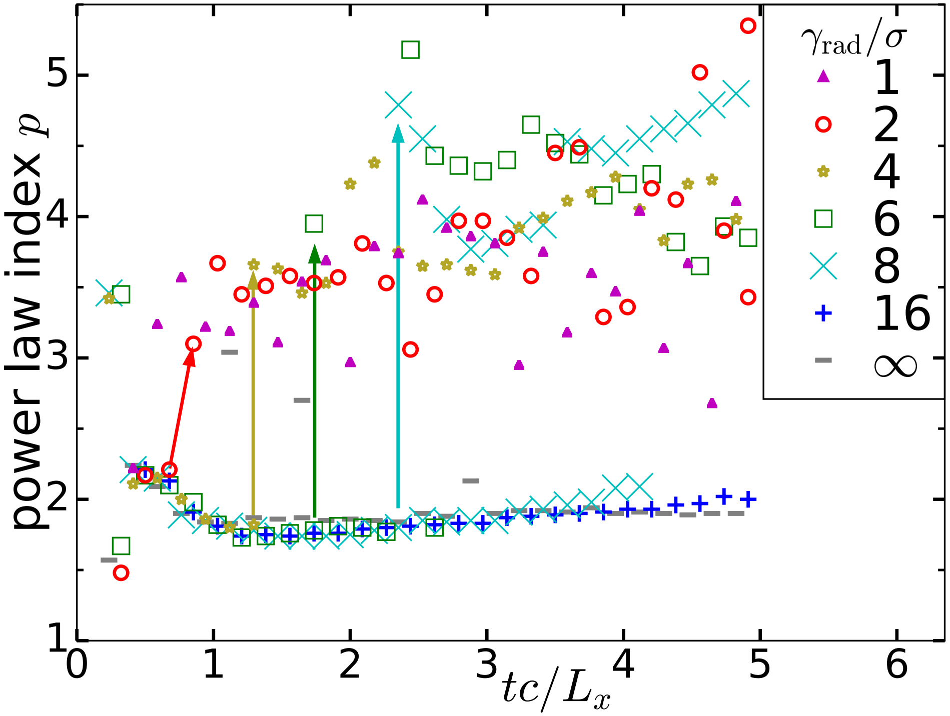
Intermediate: both power laws

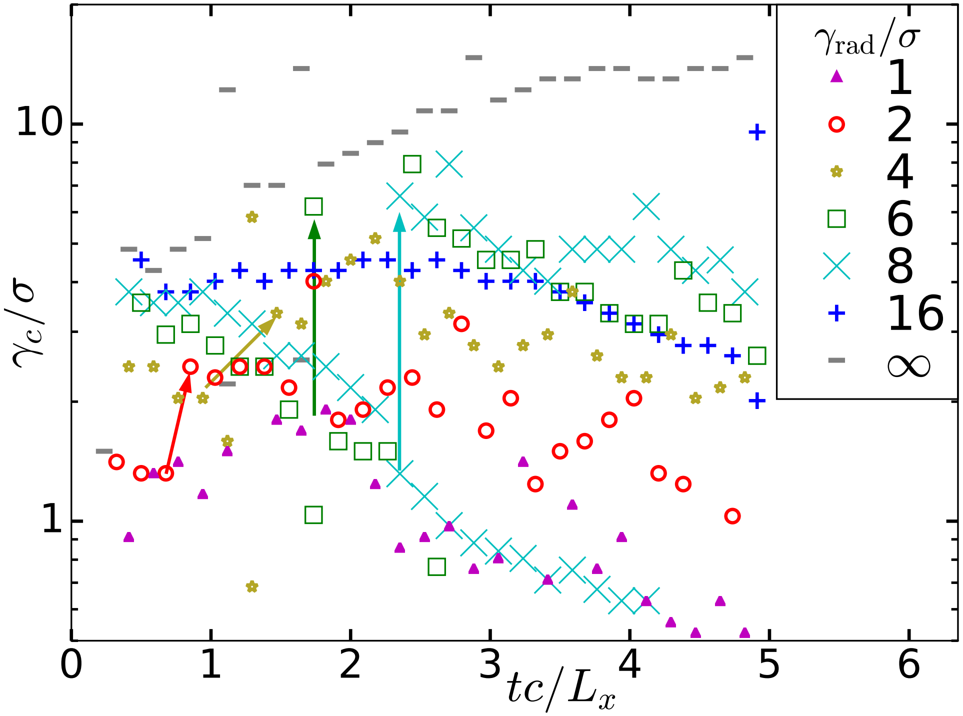
σ_h=100, B_{gz}=B_0/4





Time-dependence of power laws shows both powers laws present (mostly); steep power law is highly variable





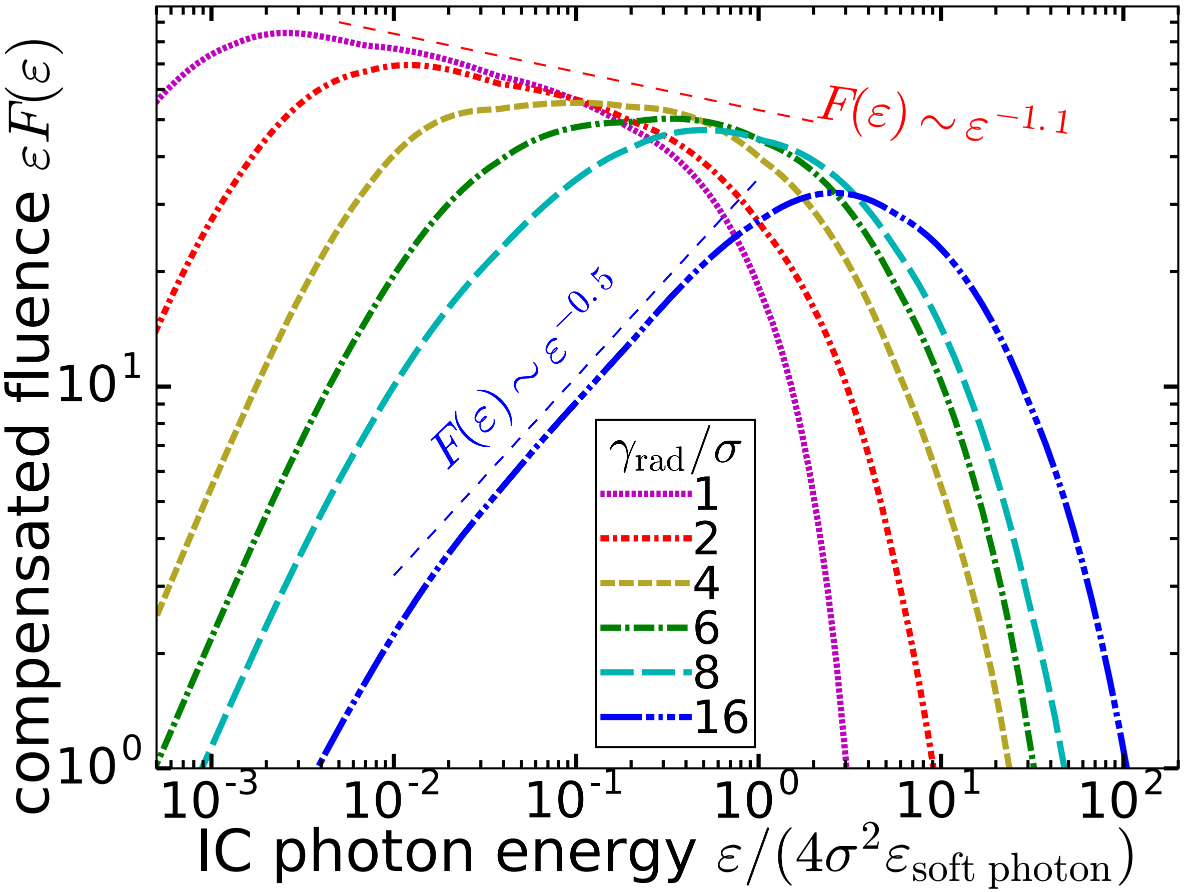
Regardless of IC cooling, (plasmoid-dominated) reconnection is bursty process with discrete acceleration episodes that yield NTPA spectra with a hard slope (p_h=1.9 in this case).

Cooling occurs between episodes, steepening the slope. Depending on episodes of acceleration and cooling, the steep slope p_s falls between 3 and 5.

Continuous acceleration/cooling would yield $p_{s,min}$=p_h+1 = 3...but additional cooling results in higher p_s.

σ_h=100, B_{gz}=B_0/4

Time-integrated IC photon spectra



Photon power law index alpha = (p-1)/2.

Hard slope p_h=1.9 -> alpha = 0.45 (measured 0.5)

Steep slope p_s=3-5 -> alpha = 1-3

however: a harder slope means more IC emission,

so alpha should be dominated by the hardest $p_{s,min}$=3 -> alpha= 1 (measured 1.1)

In this particular case (ultrarelativistic pair plasma, sigma_h=100, B_gz=B_0/4), adding a soft photon bath changes index from alpha=0.5 to alpha=1.1.

Simulation comparison: TRISTAN-MP and Zeltron

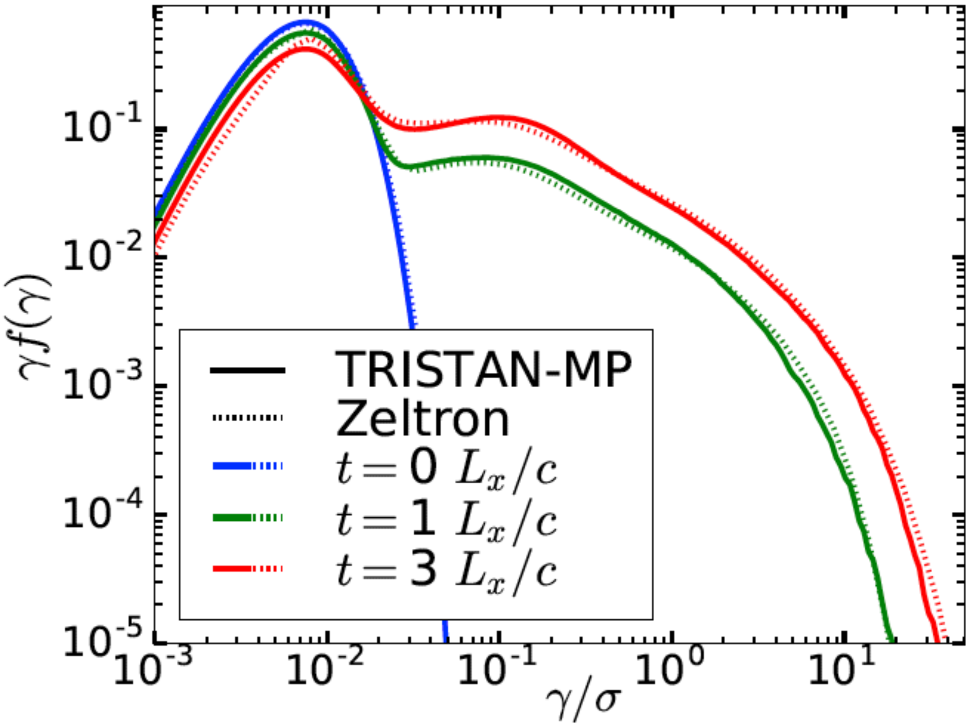
Both codes implement same fundamental algorithms: explicit EM-PIC with minor variants.

Both (as of this year) use charge-conserving current deposition (div E = rho is automatically maintained to high precision), though different variants.

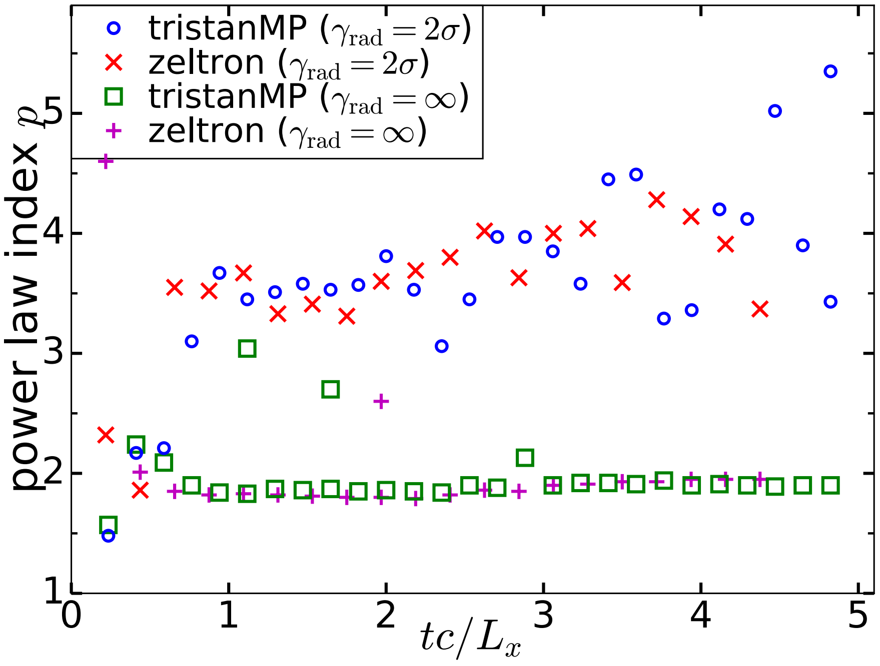
Both codes implement IC radiation reaction force (in somewhat different ways).

The implementations are entirely independent. Do they agree? Yes; very well.

Particle spectra (no IC cooling)



Spectra power law indices



Conclusions

- 3Dness (Lz/L x) has little effect − despite significant RDKI − on reconnection rate and NTPA
- Guide field slows reconnection and inhibits NTPA
  - magnitude of effect depends on guide field enthalpy vs. particle enthalpy
    - if guide field enthalpy is large, the guide field resists compression and slows reconnection
    - if guide field enthalpy is small (compared to particle enthalpy), not much effect
- IC cooling (drag due to radiation reaction) has little effect on reconnection rate
- IC cooling significantly affects NTPA
  - Particle spectrum forms a broken power law, with
    - a hard slope p_h (independent of IC cooling strength)
    - a highly-variable steep slope p_s, with $p_s > p_h + 1$ (also independent of cooling)
      - $p_s=p_h+1$ would mean continous acceleration and cooling
      - $p_s > p_h+1$ for episodes of acceleration followed by further cooling
    - a break that decreases in energy as cooling strength increases
  - For very weak cooling, the break is above the reconnection-high-energy-cutoff and only the hard power law appears;
  - for intermediate cooling, both power laws are visible;
  - for strong cooling, the hard power law appears only at the very beginning before being overwhelmed by the steep power law
- The IC radiation spectrum varies with the particle spectrum.
  - For weak cooling, p_h=1.9 -> alpha=0.5
  - For strong cooling, p_s varies, $p_s >= 3=p_h+1$, but the hardest component dominates so the photon spectrum corresponds roughly to p_s=3, or alpha=1 (measured 1.1).