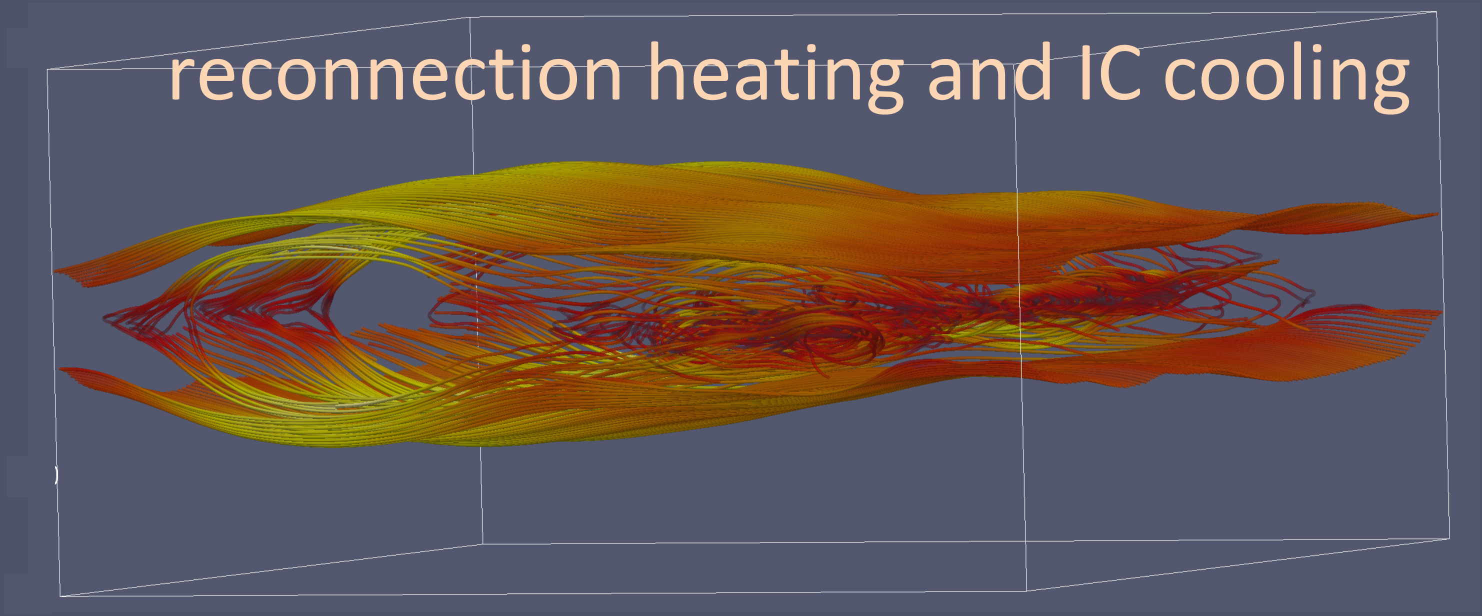
Relativistic Reconnection
reconnection heating and IC cooling



Magnetic reconnection energizes particles;
Energetic particles radiate;
Radiation excites astronomers...

Featuring PIC codes (in omegapsical order)
Zeltron and Vorpal and Tristan-MP

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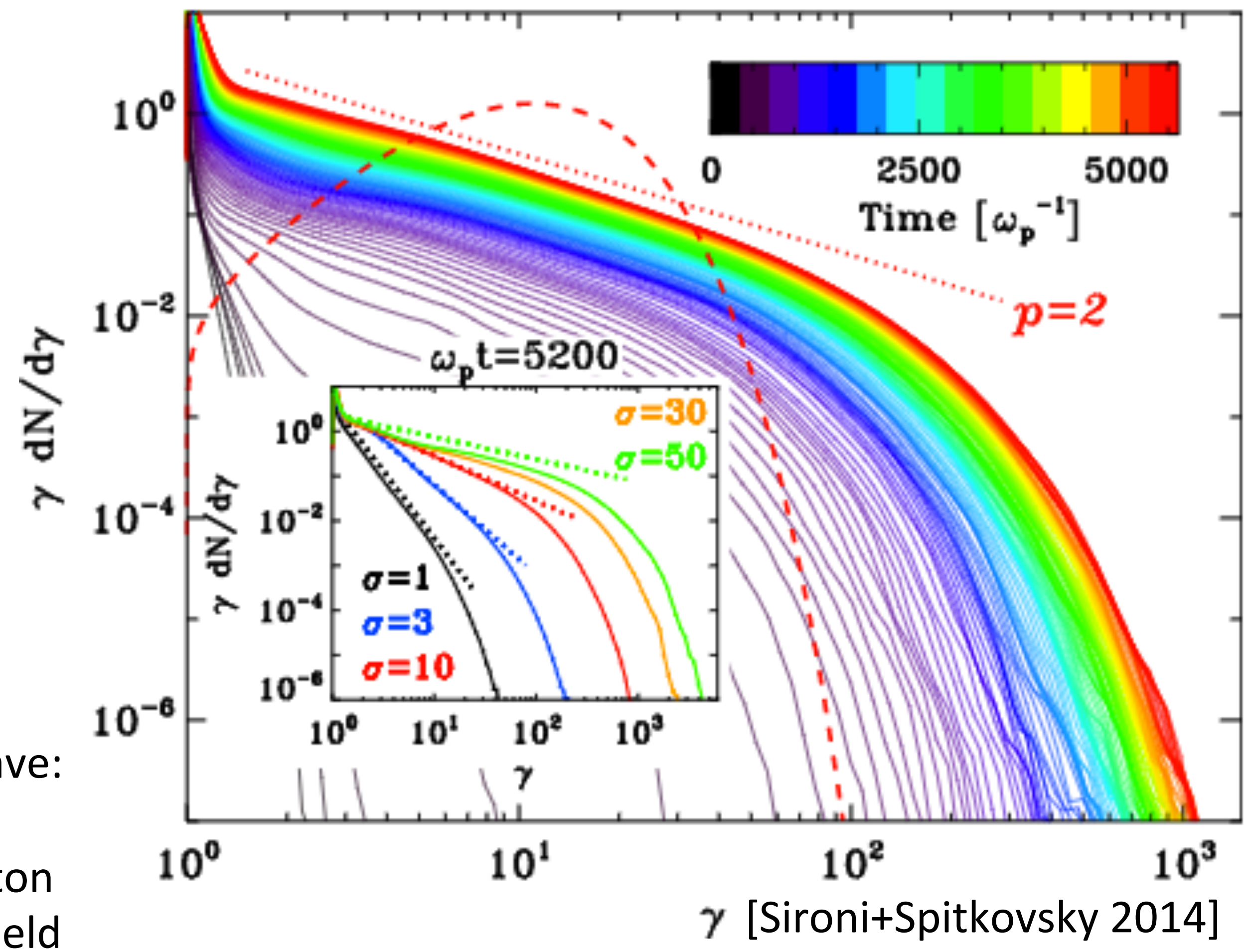
Background: reconnection yields NTPA

Since about 2014 a new generation of PIC simulations has shown really convincing power-law particle distributions from reconnection in:

- 2D
- pair plasma
- zero guide field
- high σ_h
- high σ
- low T_e (cold/nonrel.)
- T_i=T_e



[Sironi+Spitkovsky 2014]

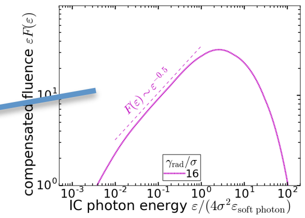
(see also Guo et el 2014, Werner et al 2016...)

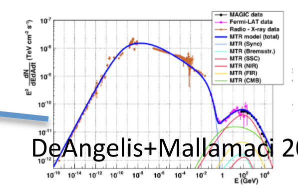
But astrophysical sources have:

- 3D
- pair and/or electron-proton
- some small/large guide field
- maybe σ_h~1 or 10
- high σ is fine
- etc.

The goal of the game

Connect the parameters of reconnection to the corresponding radiation signatures.





DeAngelis+Mallamaci 2018

dimensionality: (e.g., 2D or 3D)

mass ratio: m_i/m_e (e.g., 1 or 1836)

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

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

(ultrarelativistic limit)

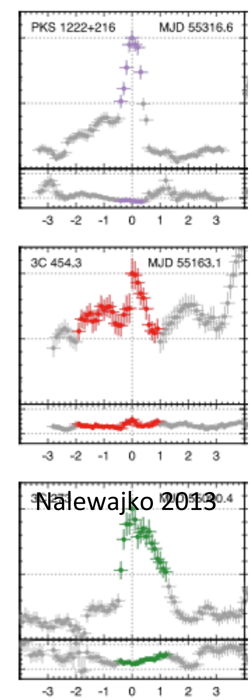
$$\sigma = \frac{B_0^2}{4\pi n_b m_e c^2}$$

Radiative cooling, e.g., IC or synchrotron: γ_{rad}

Background temperature: $T_b / m_e c^2$

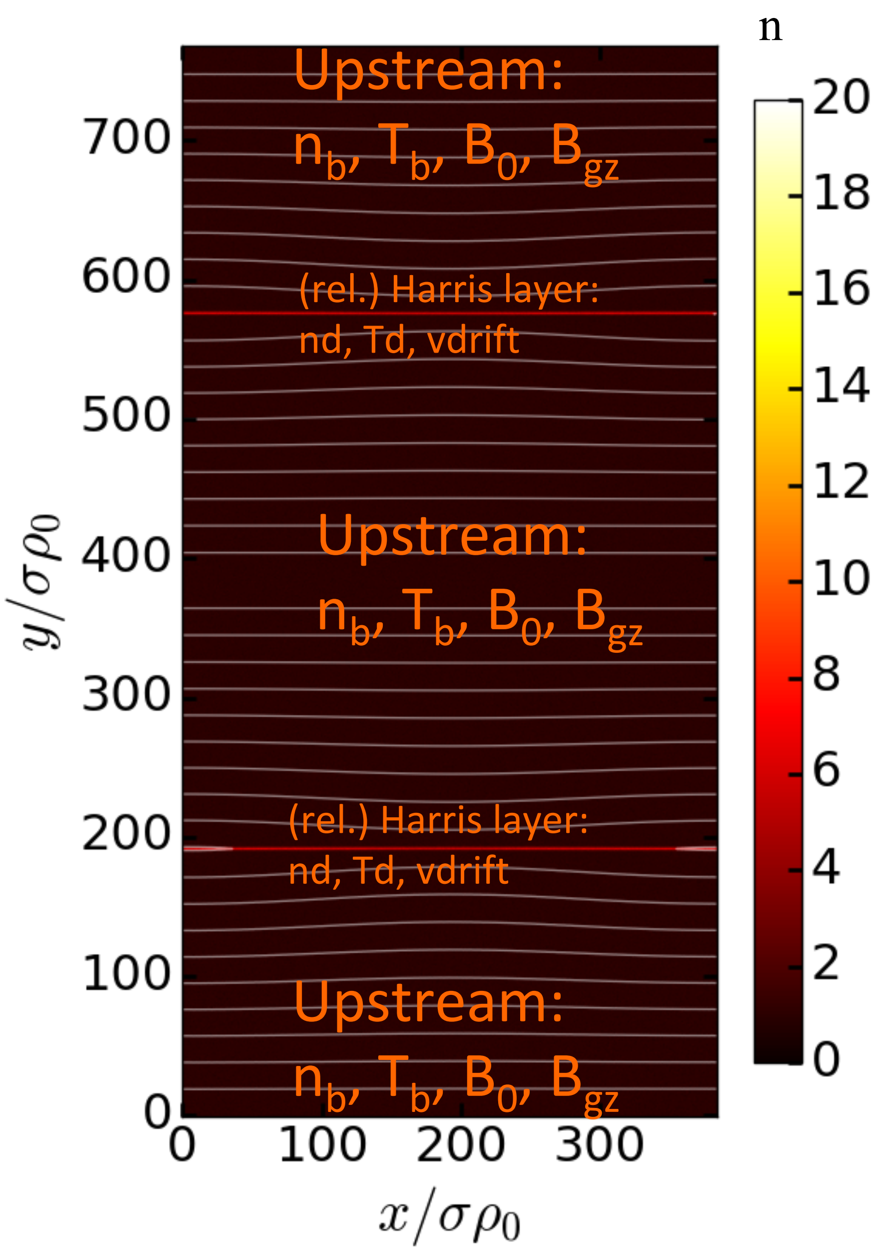
Temperature ratio: T_i/T_e

etc.



Nalewajko 2013

Reconnection simulation setup



Upstream Parameters:

- plasma n_b, T_b
- reversing magnetic field $\pm B_0\mathbf{x}$
- guide field B_{gz}

Plus a Harris layer

- density to balance upstream B_0 pressure
- current J_z to balance dB_x/dy

in double-periodic box

with a small initial magnetic field perturbation.

Nominal length scale:

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

System size: Lx, Ly, and (in 3D) Lz

Formal outline

How do particle (and radiation) spectra vary as we change:

- dimensionality: 2D vs 3D
- guide magnetic field: zero, weak, strong
    - effective magnetization
- mass ratio: positrons vs. protons
    - magnetization
- IC radiaction: weak -> moderately strong
    - radiaction = radiaction reaction (force)

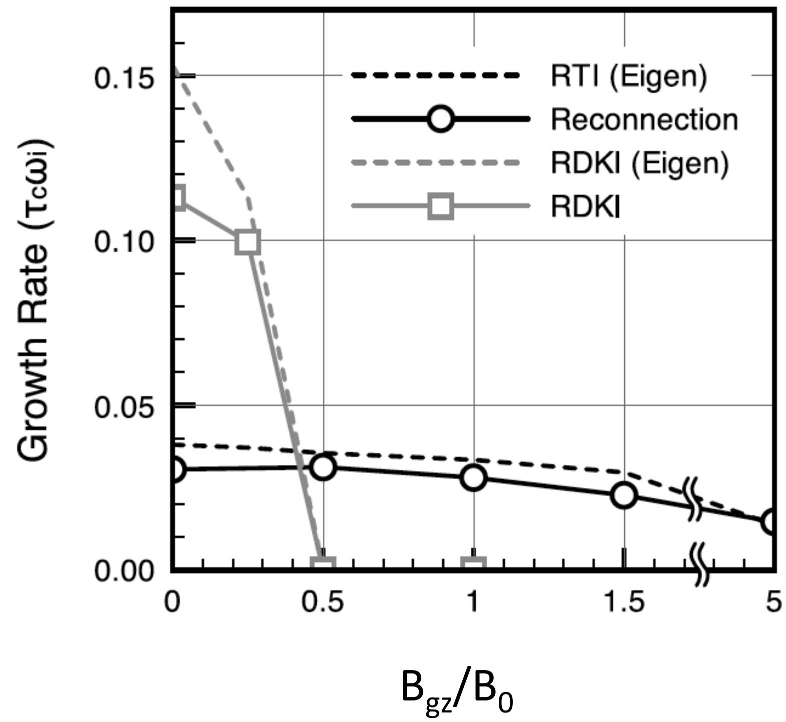
Brief Conclusions

- From 2D, pair, zero guide field, negligible radiaction, we have now explored:
  - 3D pair reconnection (pretty much the same as 2D pair)
  - 2D and 3D with guide field (guide field slows reconnection, steepens NTPA power law)
  - 2D electron-ion (slower ions slow reconnection, steepen electron power law)
  - 2D pair with radiaction (doesn’t slow reconnection, steepens high-energy part of power law)

Why 3D? Isn't 2D good enough? Maybe it is!

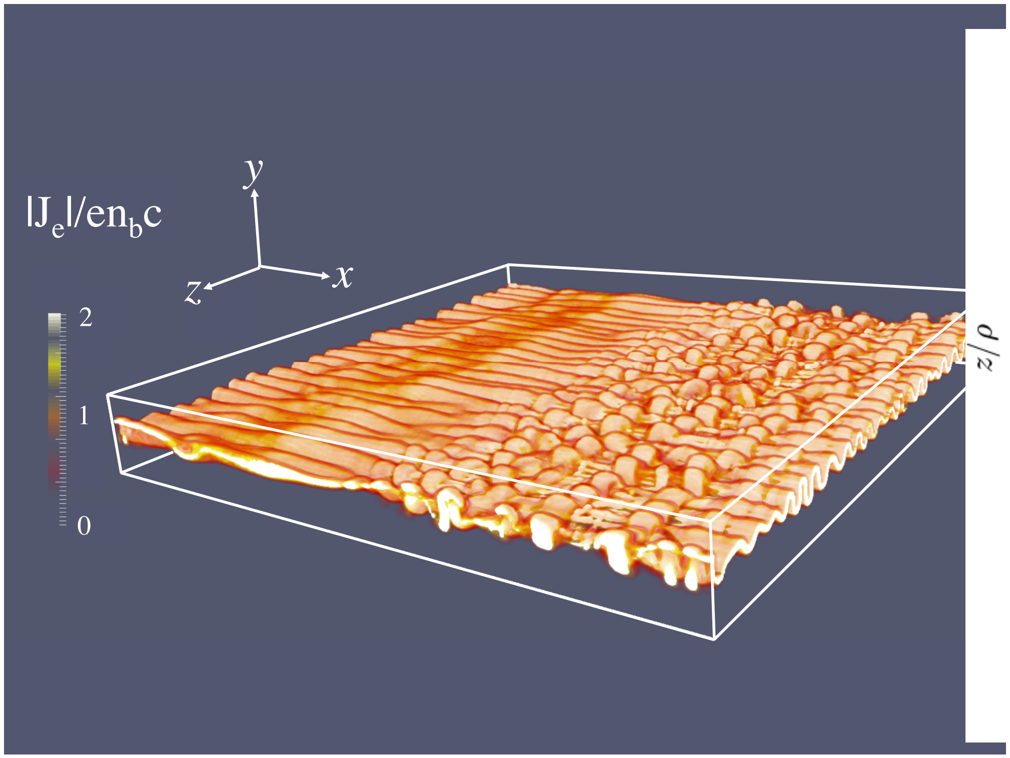
Does the 3D-only relativistic drift-kink instability (RDKI) inhibit particle acceleration?
Guide magnetic field may be important: it inhibits RDKI.

from Zenitani & Hoshino, 2008:

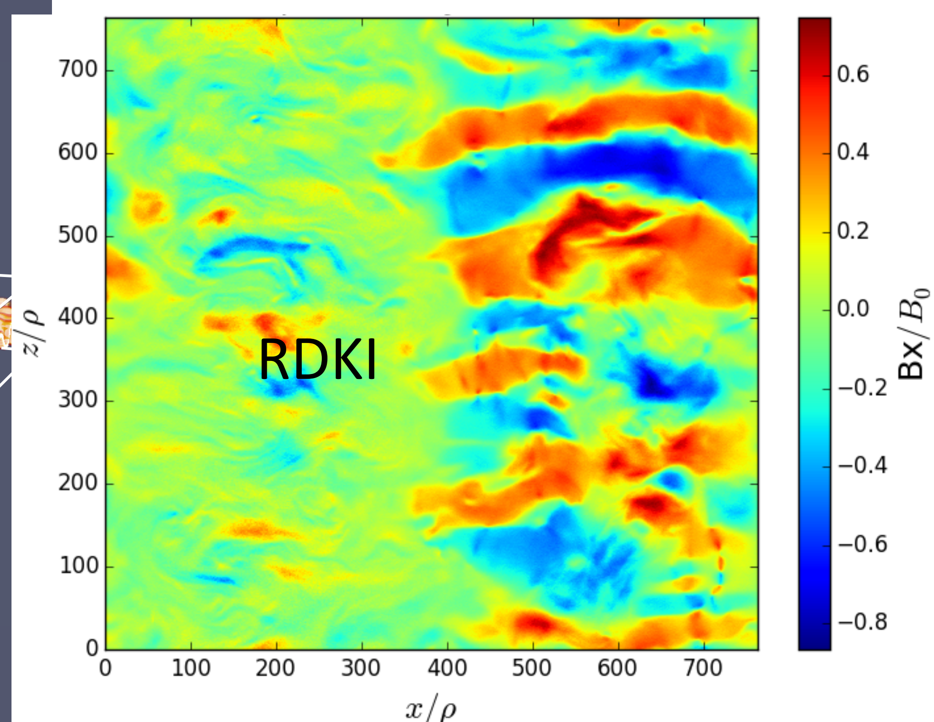


However, more recent simulations (e.g., Sironi & Spitkovsky 2014, Guo et al 2015, Werner & Uzdensky 2017) have suggested that particle acceleration is robust to 3D effects.

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



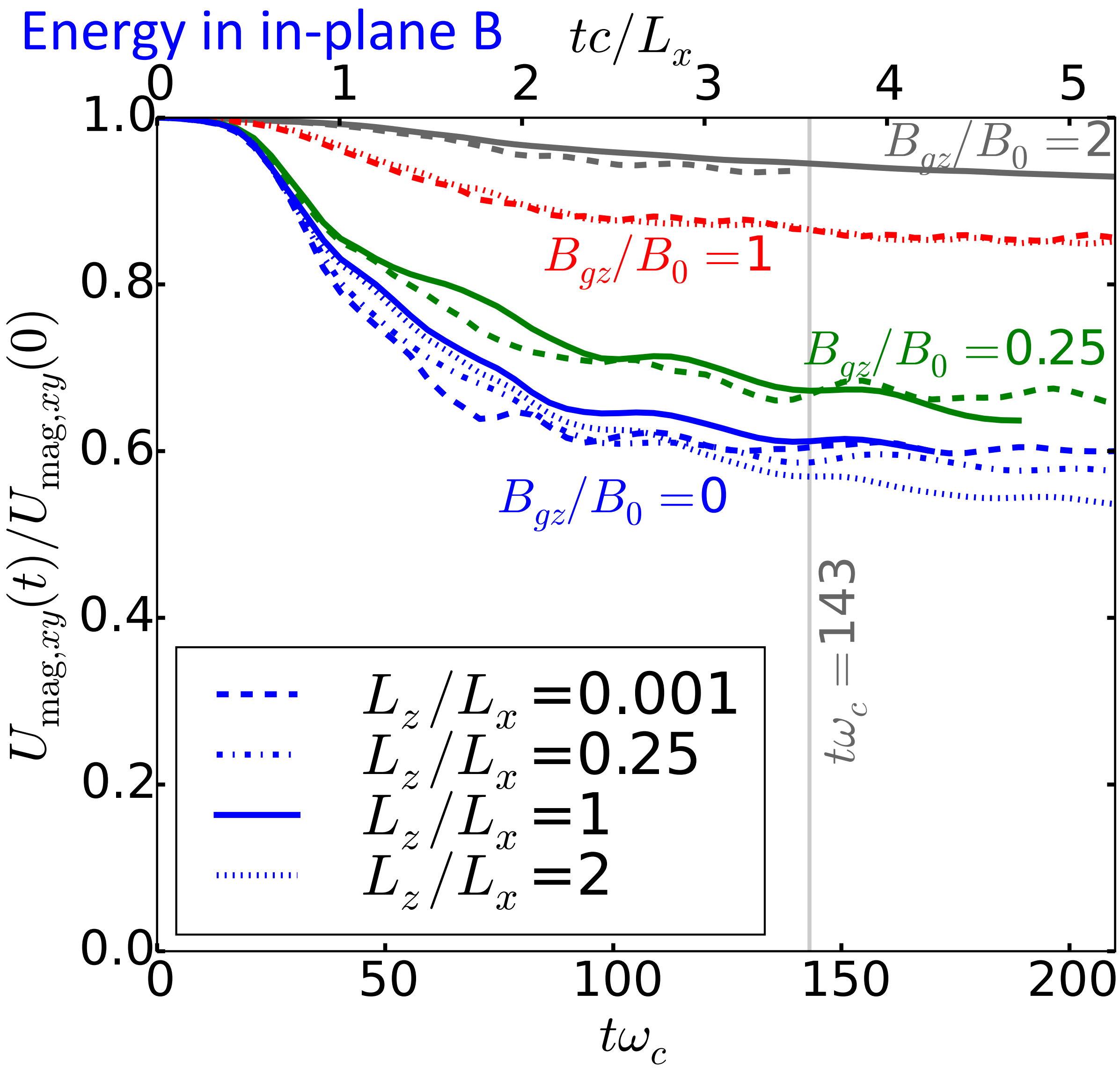
B_x in the x-z reconnection midplane



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)
Here L_z is the length in the 3rd dimension.



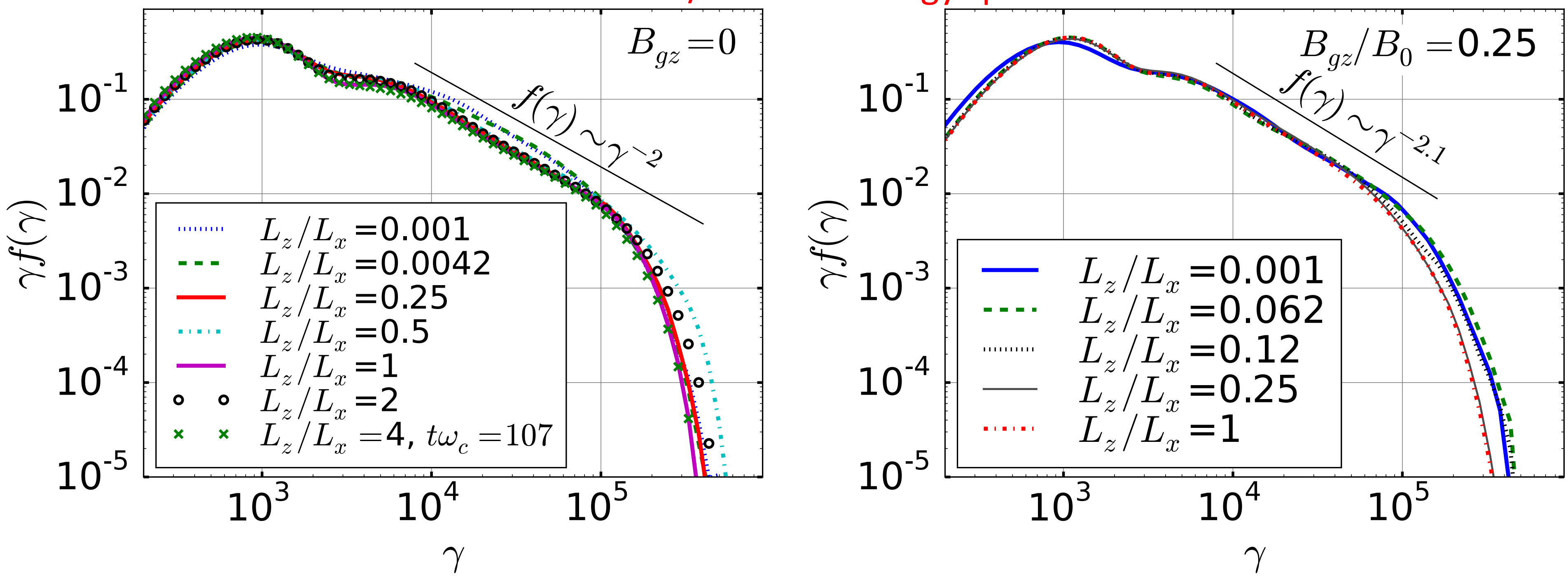
2D-3D
m_i/m_e=1
B_{gz}/B_0=0-1
σ_h=25
σ>>1
T_e/m_ec^2 >>1
$T_i=T_e$
$\gamma_{rad}=\infty$

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=40σρ_0
L_y=80σρ_0

Electron/Positron energy spectra



2D-3D
m_i/m_e=1
B_{gz}/B_0=0 - 0.25
σ_h=25
σ>>1
T_e/m_ec^2 >>1
T_i=T_e
γ_{rad}=∞

Compressing plasmoids

n/n_b

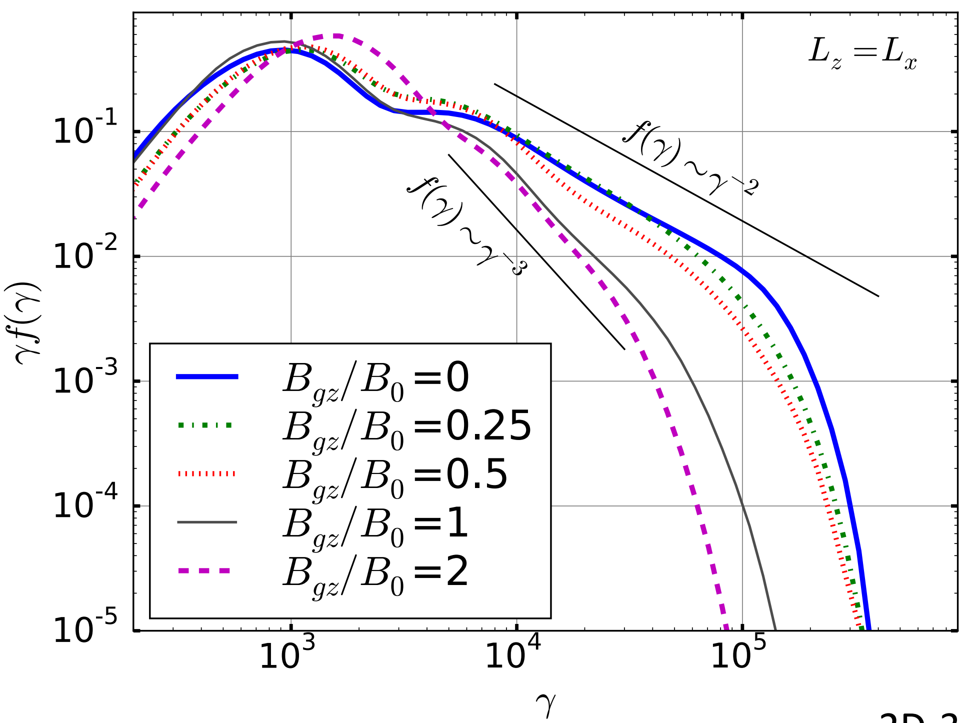
During reconnection, the in-plane magnetic field compresses plasmoids.

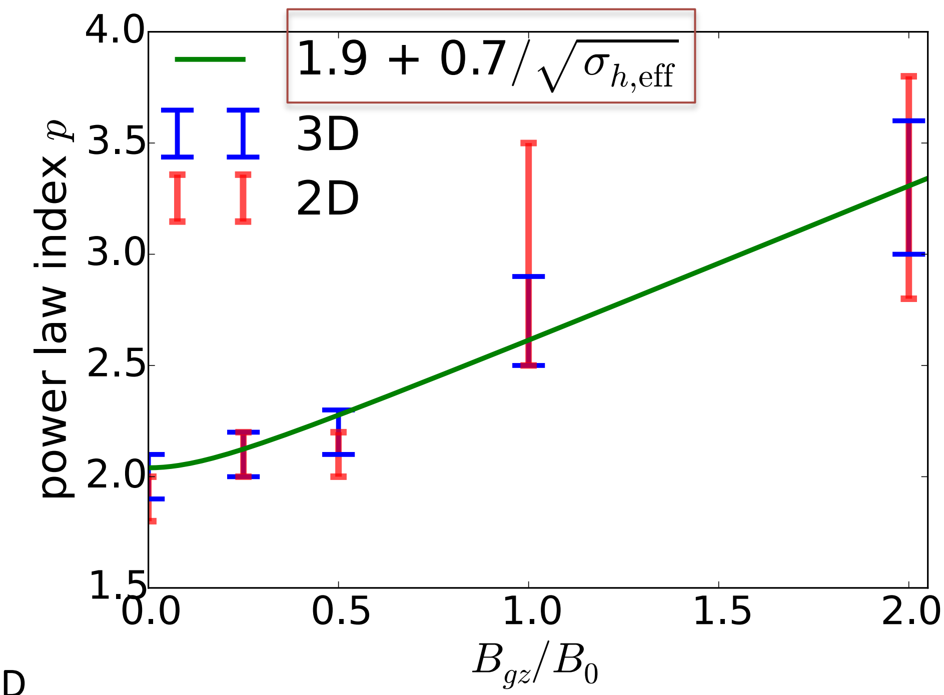
When there's a guide field, that guide field resists compression and slows reconnection (reduced v_A, reduced $E/B_0 \sim 0.1\ v_A/c$).

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

Including the guide field enthalpy into an effective σ_h accounts for compression of guide field.

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

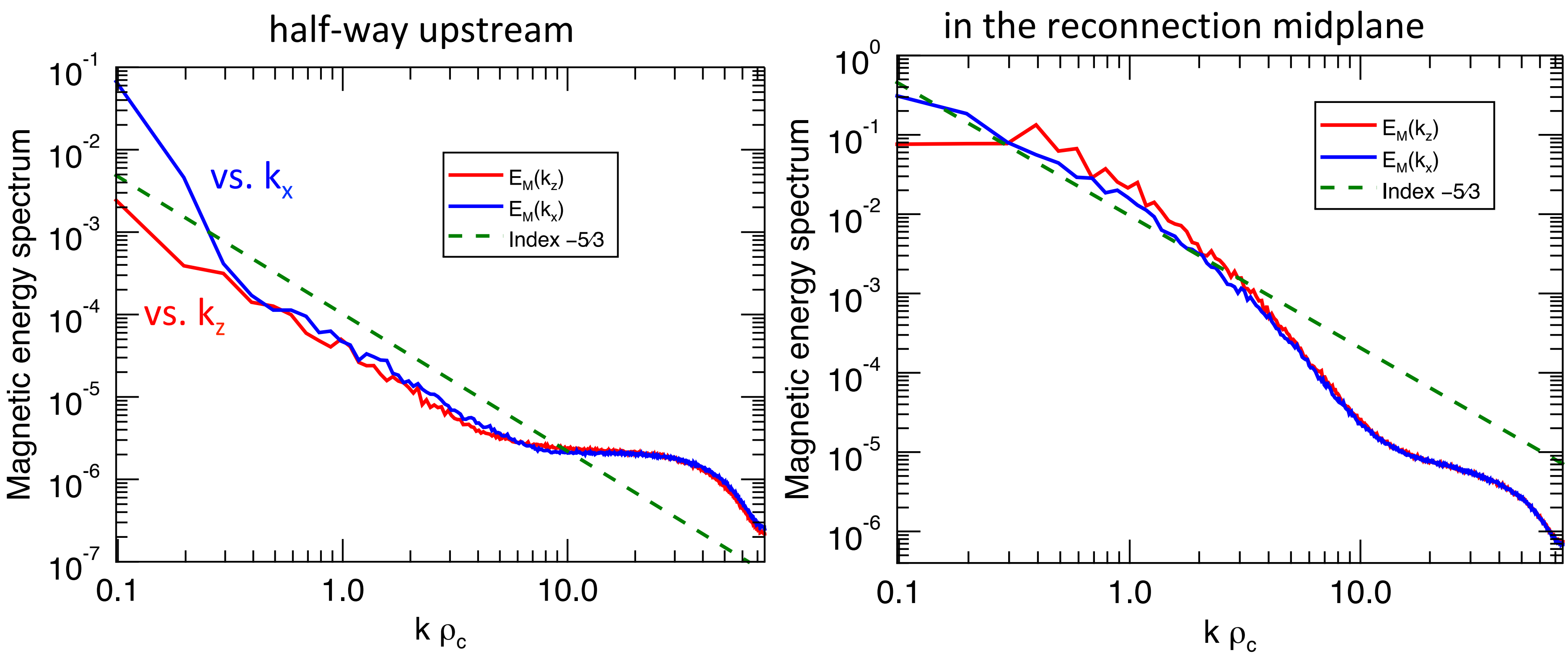




2D-3D
$m_i/m_e=1$
$B_{gz}/B_0=0 - 2$
$\sigma_h=25$
$\sigma>>1$
$T_e/m_ec^2 >>1$
$T_i=T_e$
$\gamma_{rad}=\infty$

3D aside: spatial fluctuations -> turbulence?

Power spectrum of magnetic field (3D, $L_z=L_x$, $B_z=0$)



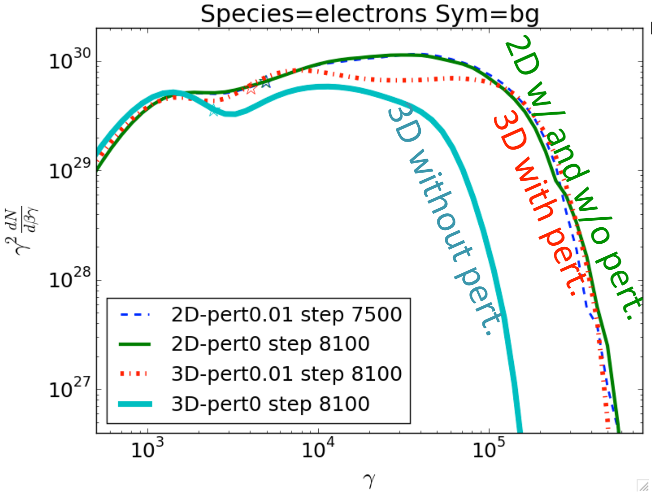
x is the direction of B_0 reconnecting magnetic field;

z is the initial current direction

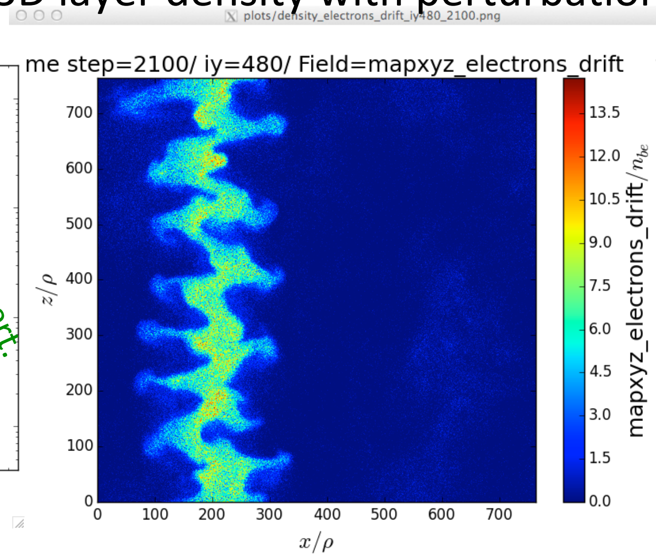
3D aside: Effect of initial perturbation in 3D (and 2D)

Density of initial Harris layer particles in the middle of the current sheet.

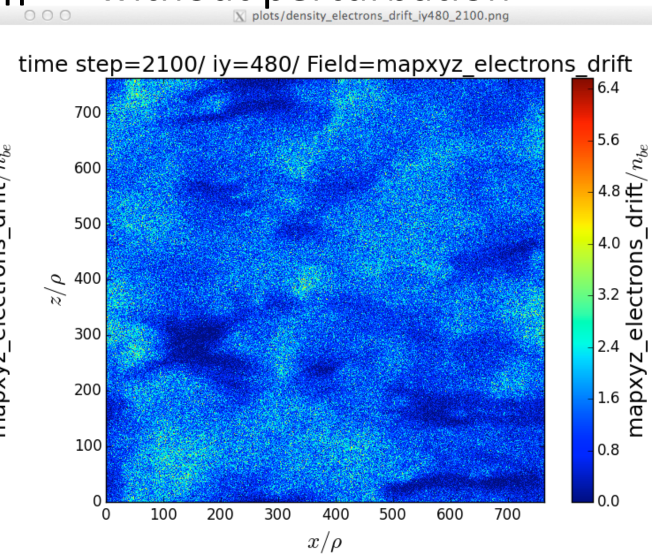
particle spectra



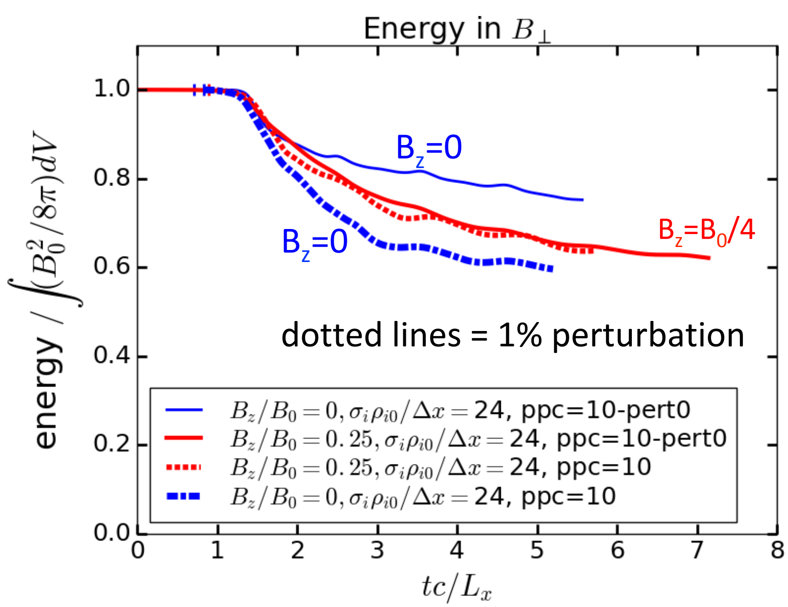
3D layer density with perturbation

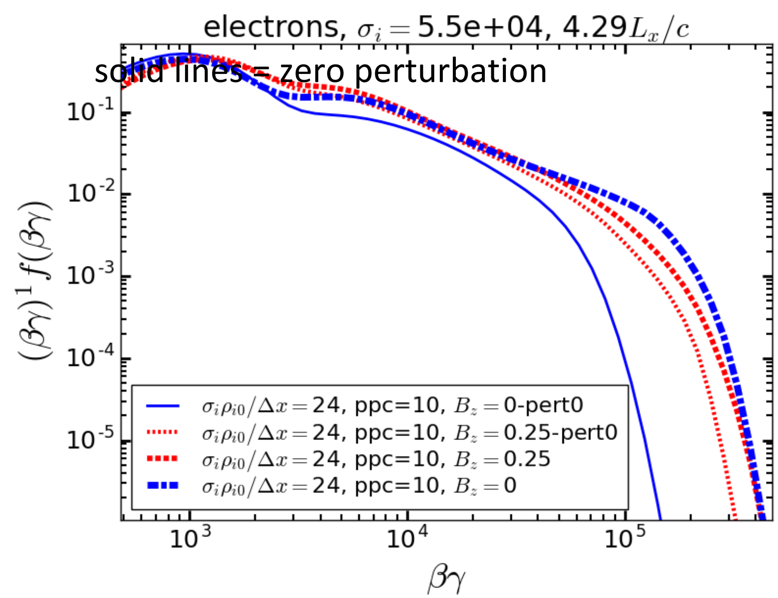


without perturbation



If you add a little guide field, perturbation doesn’t matter.





Electron – **Proton**: m_i/m_e=1836
(We use the real mass ratio!)

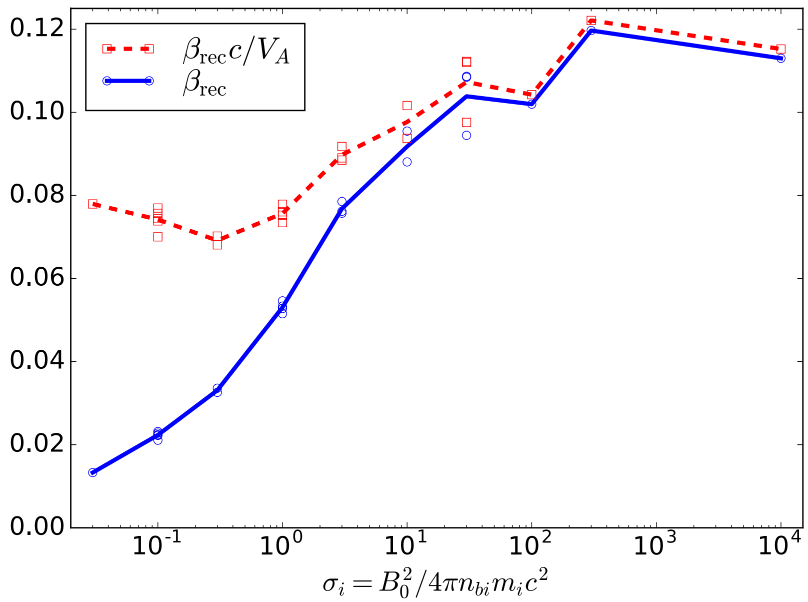
(Why is this possible? In the ultrarelativistic [but nonradiative] limit, ions and positrons have the identical motion. As ions become less relativistic, the scale separation between electrons and ions increases, and simulation becomes more difficult.)

$$\sigma_i = \frac{B_0^2}{4\pi n_b m_i c^2}$$

= (roughly) average magnetic energy per ion, normalized by ion rest mass energy.

$\sigma_i >> 1$ -> ultrarelativistic
$1/1836 < \sigma_i < 1$ -> **semirelativistic** (electrons are relativistic, ions are sub-rel.)
$\sigma_i << 1/1836$ -> nonrelativistic

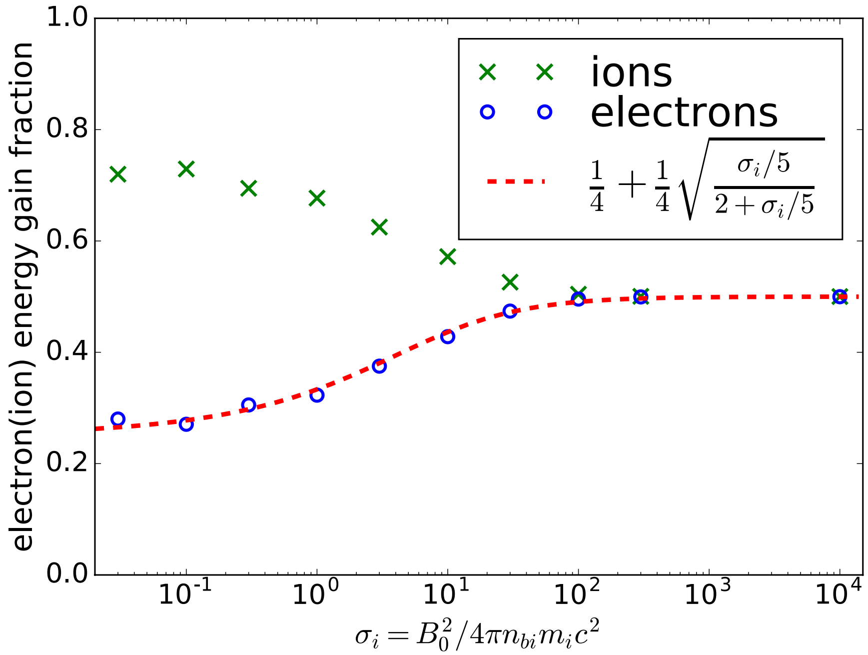
Semirelativistic electron/ion reconnection energetics: ions are slow energy hogs



σ_i

The absolute reconnection rate slows as ions become more iony, but so does v_A;

the normalized reconnection rate stays around 0.1 (within 20 or 30%).



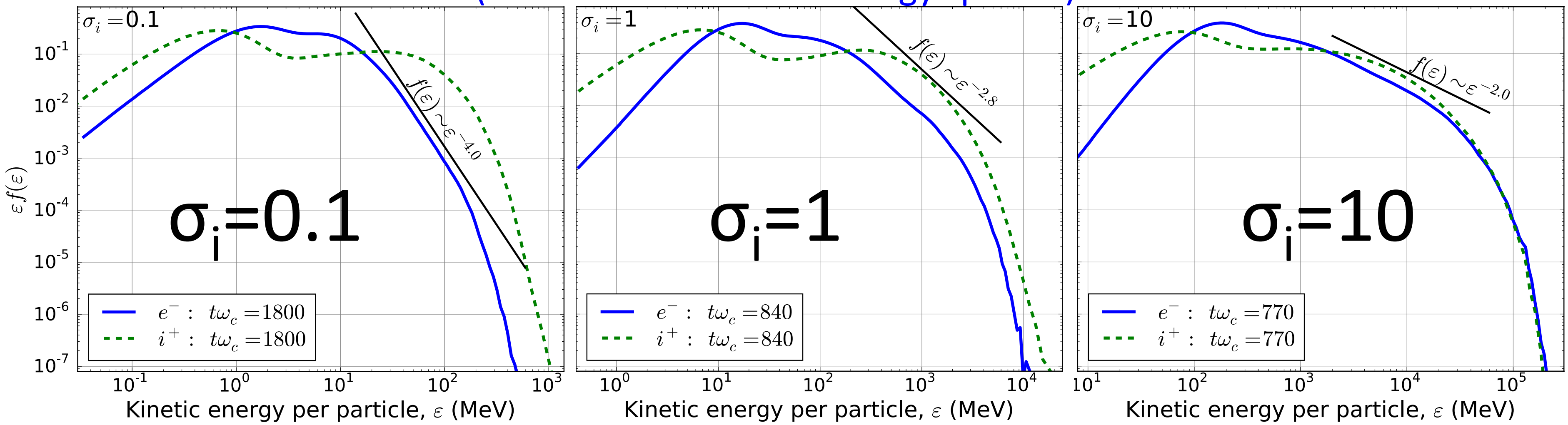
σ_i

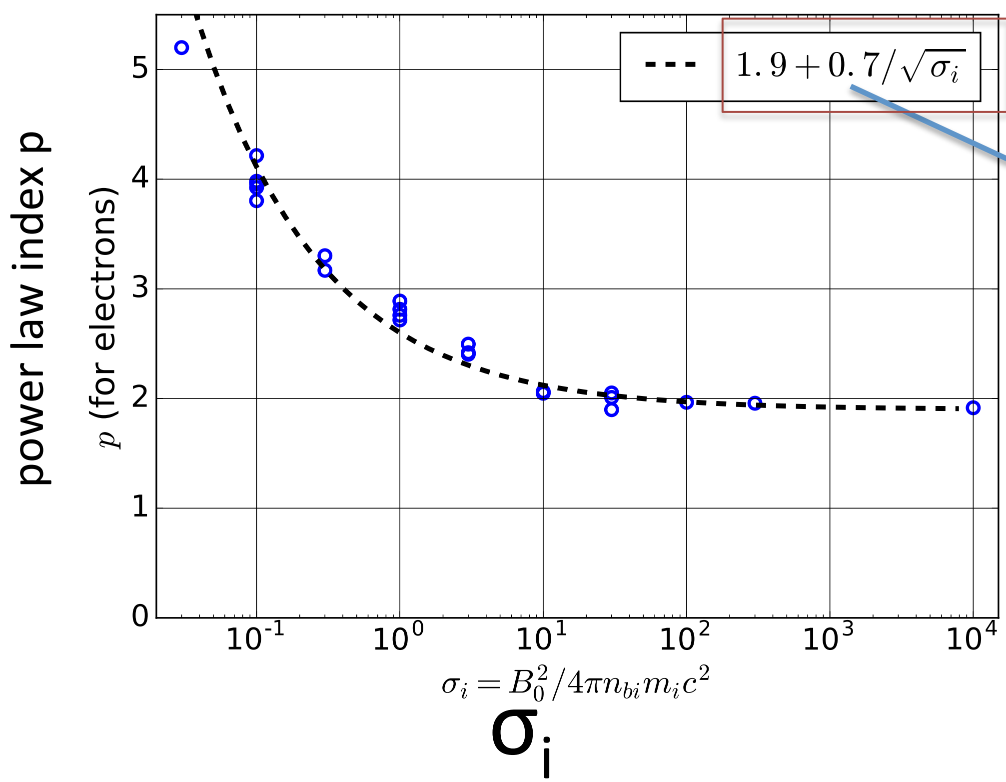
Ions gain more energy than electrons....

2D
m_i/m_e=1836
B_{gz}/B_0=0
σ_i=0.03 − 10000
T_e/m_ec^2 = $1836\sigma_i/200$
T_i=T_e
γ_{rad}=∞

Our most important semirelativistic electron/ion NPTA results

(blue lines = electron energy spectra)





resembles guide-field dependence

2D

m_i/m_e=1836

B_{gz}/B_0=0

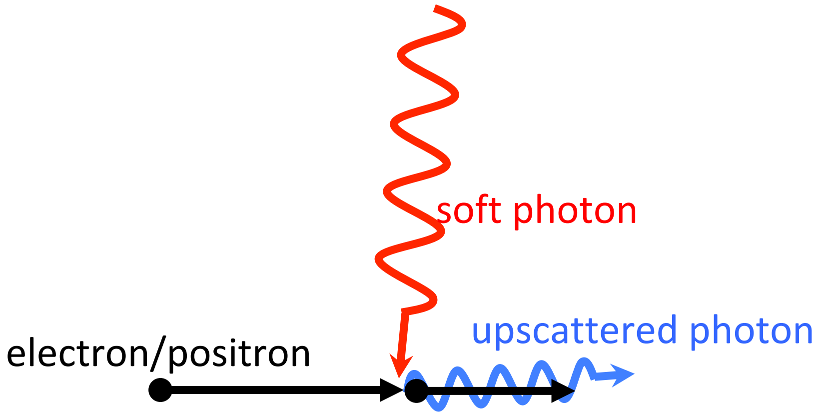
σ_i=0.03 – 10000

$T_e/m_ec^2 = 1836\sigma_i/200$

T_i=T_e

$\gamma_{rad}=\infty$

Finally, (ultrarelativistic pair) reconnection with IC radiaction



external inverse Compton (IC) radiation

2D
$m_i/m_e=1$
$B_{gz}/B_0=0.25$
$\sigma_h=100$
$\sigma>>1$
$T_e/m_ec^2 >>1$
$T_i=T_e$
$\gamma_{rad}<\infty$

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 $E=0.1B_0$:

$$P_{acc} = (0.1)eB_0c$$

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.

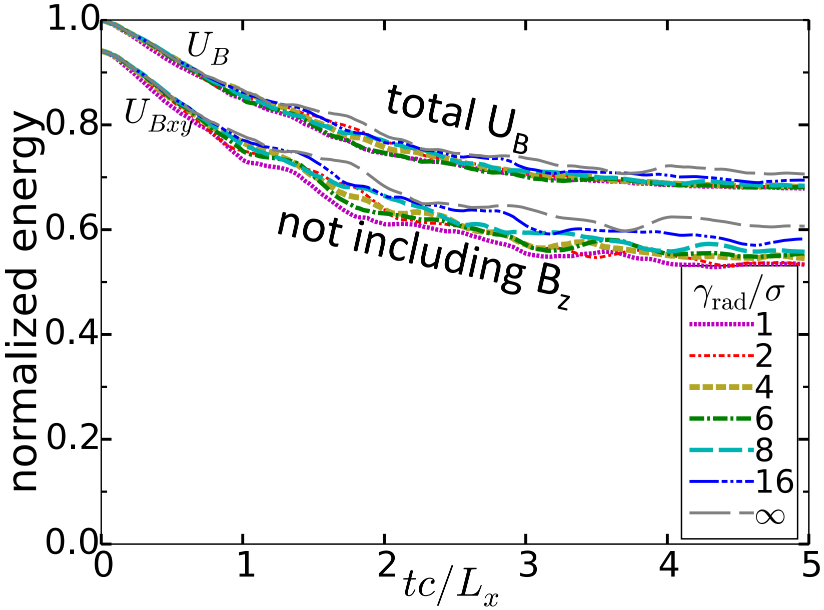
IC scattering doesn't affect basic reconnection dynamics very much

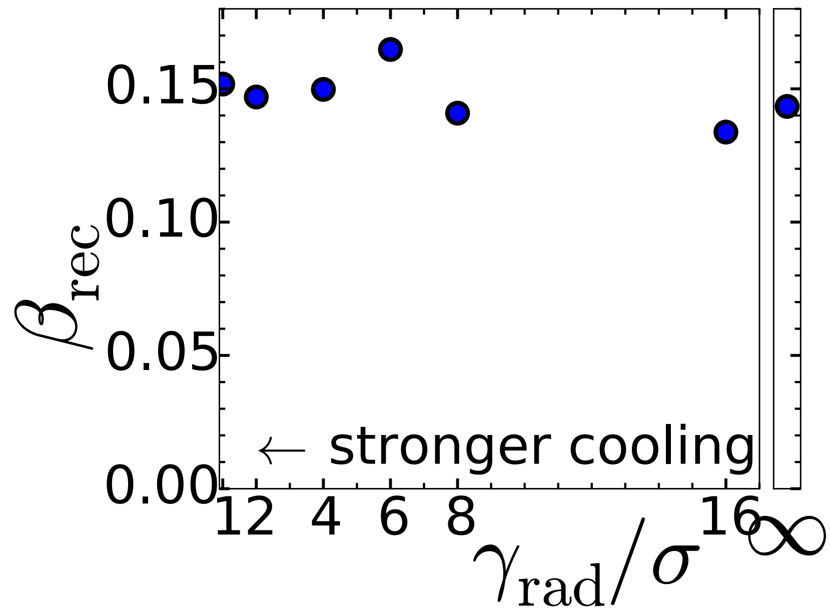
$\gamma_{rad}=\infty$ (no cooling) $\gamma_{rad}=2\sigma$ (strong cooling)

color=plasma density (normalized to n_b)

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

Magnetic energy vs time

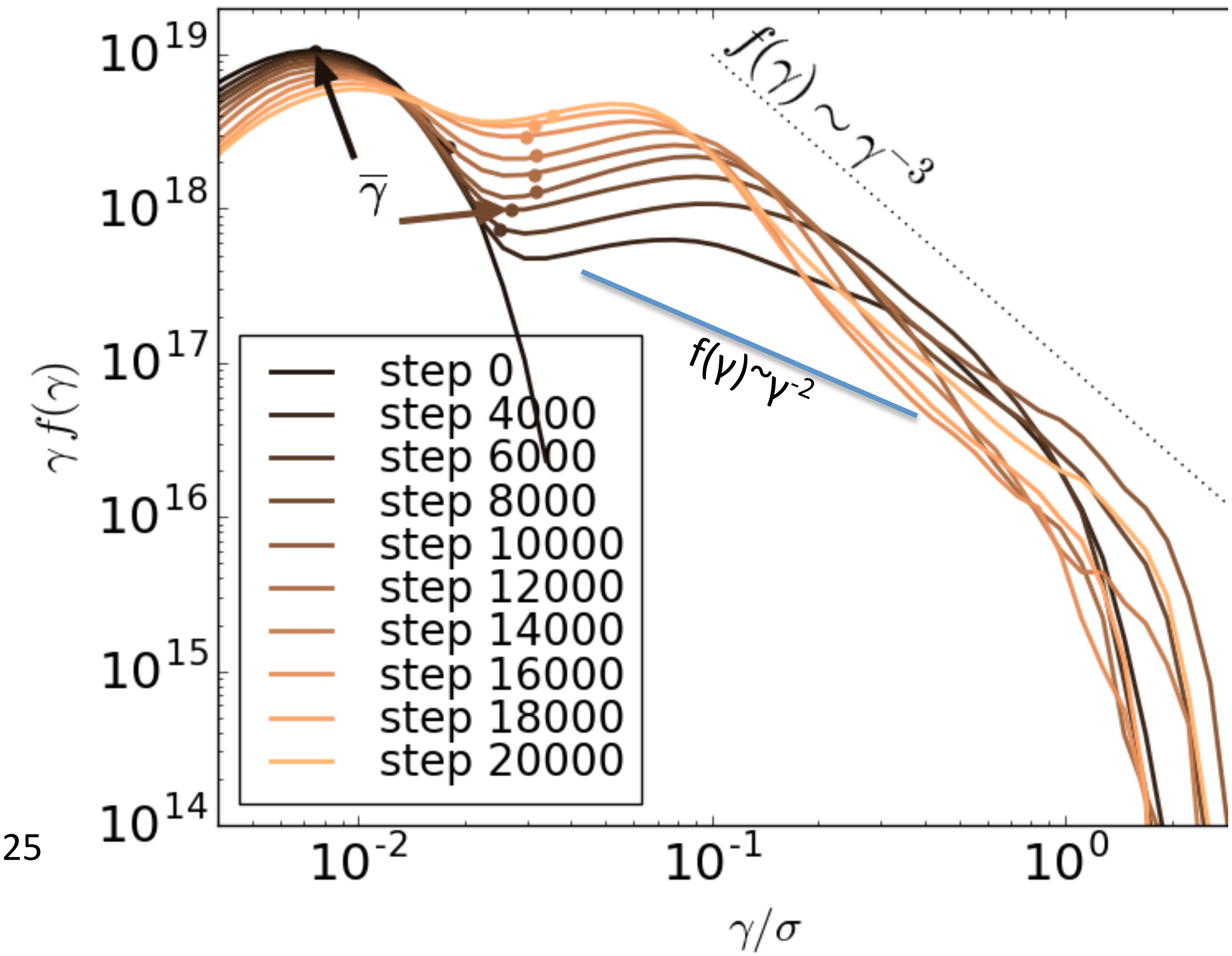




2D
$m_i/m_e=1$
$B_{gz}/B_0=0.25$
$\sigma_h=100$
$\sigma>>1$
$T_e/m_ec^2 >>1$
$T_i=T_e$
$\gamma_{rad}/\sigma=1$ to ∞

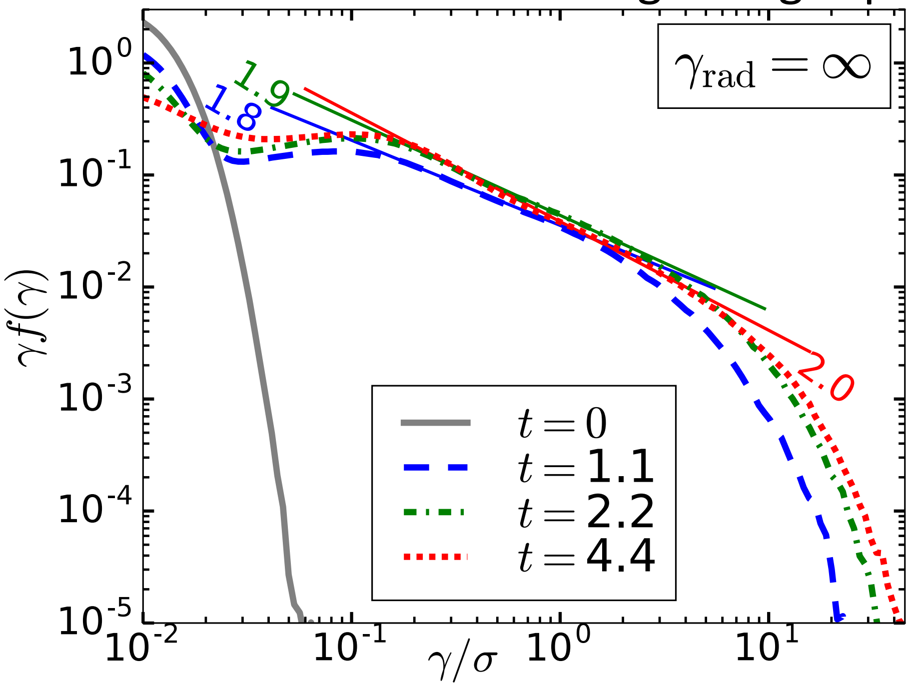
Strong cooling doesn't alter the amount of magnetic energy transferred to particles...but strong cooling means particles promptly radiate that energy.

IC cooling changes particle spectra significantly: noisy, steeper



2D
$m_i/m_e=1$
$B_{gz}/B_0=0.25$
$\sigma_h=100$
$\sigma>>1$
$T_e/m_ec^2>>1$
$T_i=T_e$
$\gamma_{rad}/\sigma=2$

IC cooling changes particle spectra significantly



Weak cooling: usual hard power law

Strong cooling: variable steep power law

Intermediate: both power laws

2D

m_i/m_e=1

B_{gz}/B_0=0.25

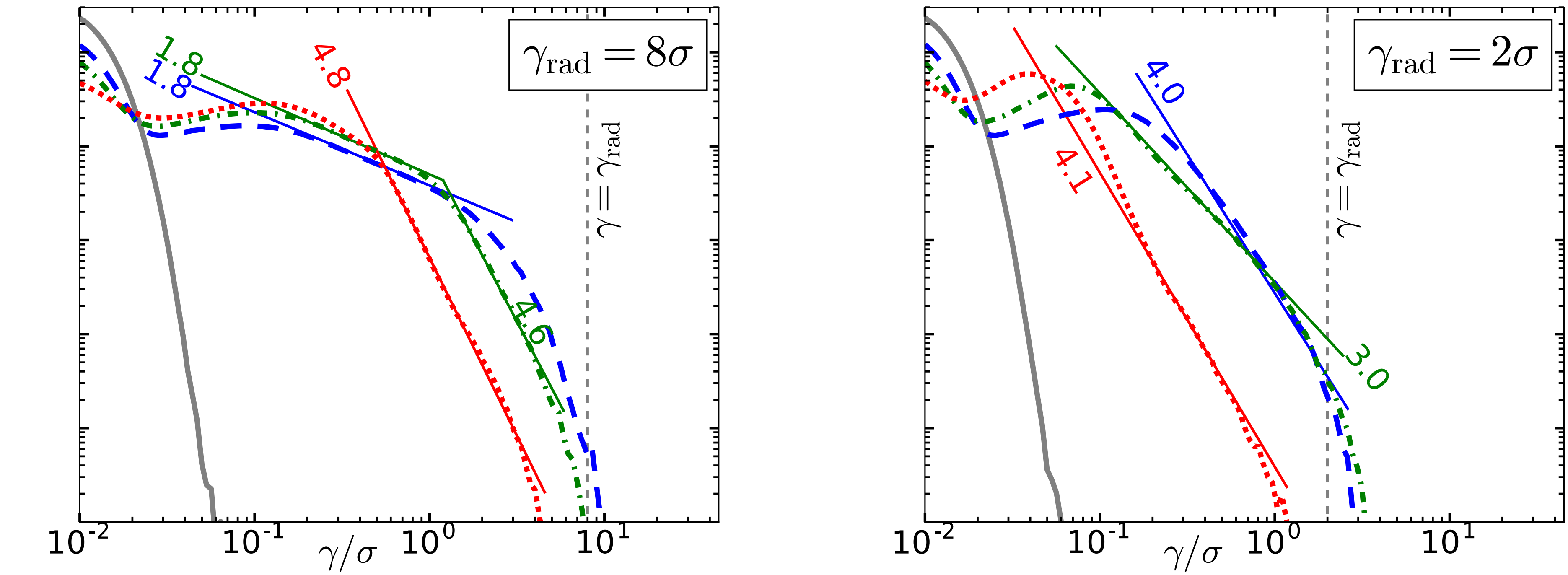
σ_h=100

σ>>1

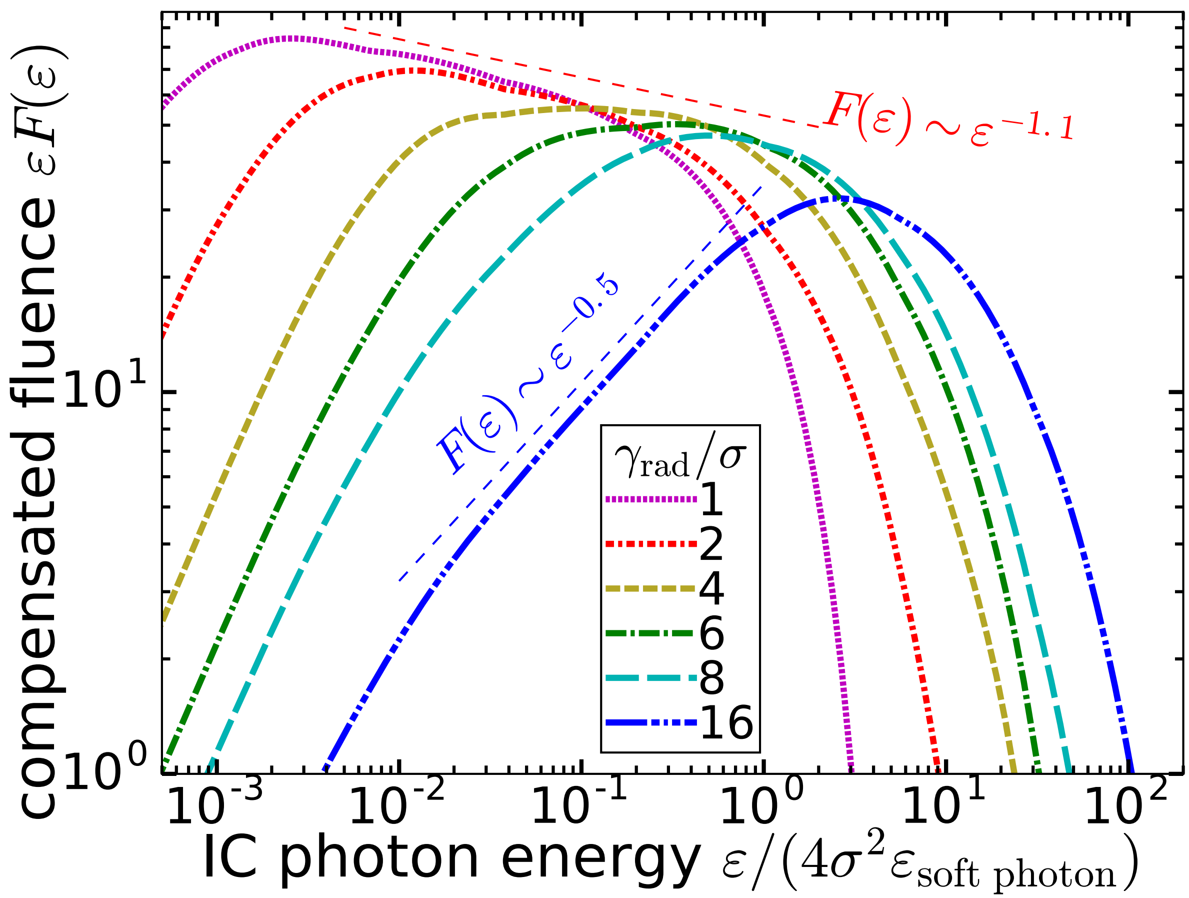
T_e/m_ec^2 >>1

T_i=T_e

γ_{rad}/σ=2, 8, ∞



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)

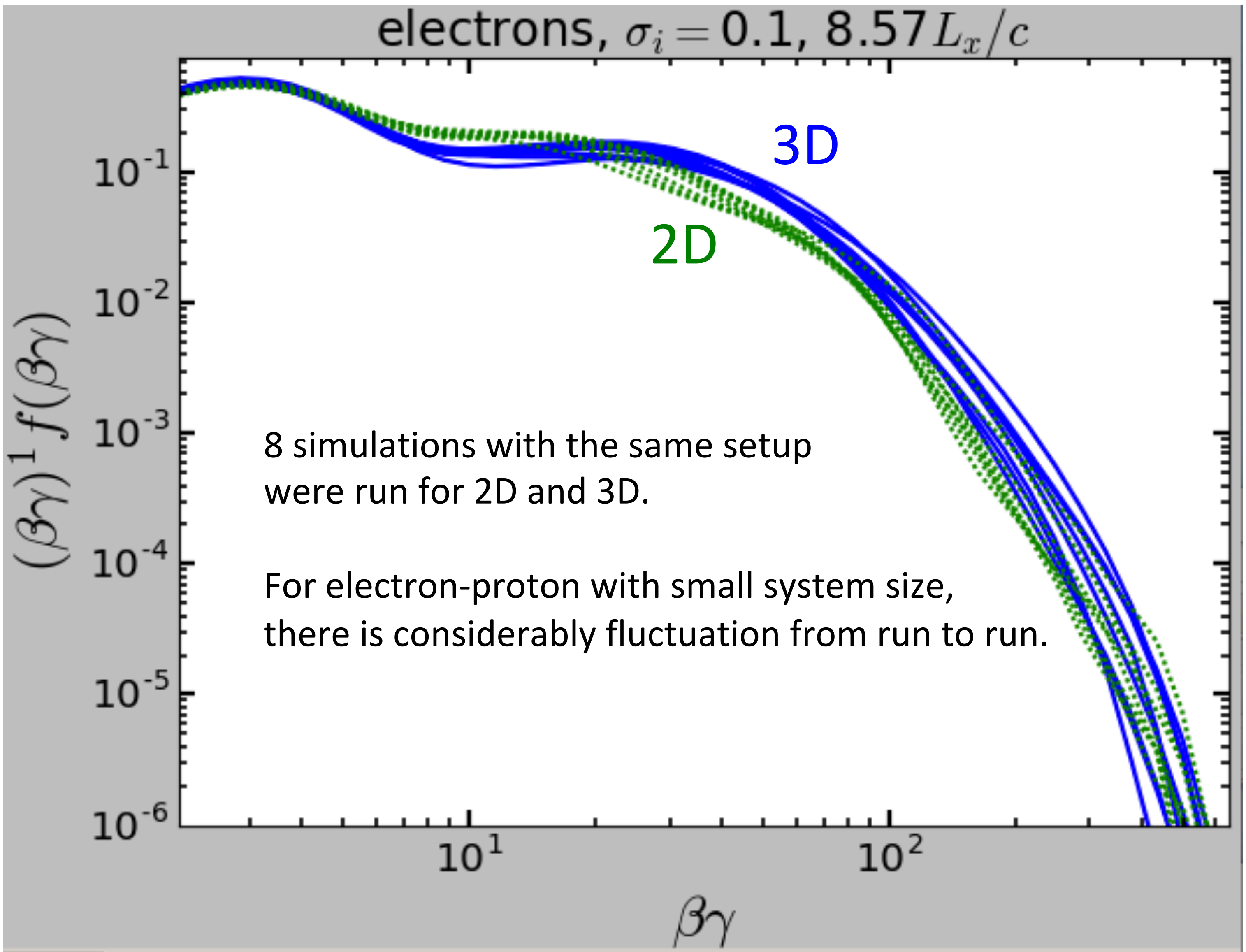
Steep slope p_s=3-5 -> alpha = 1-3

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.

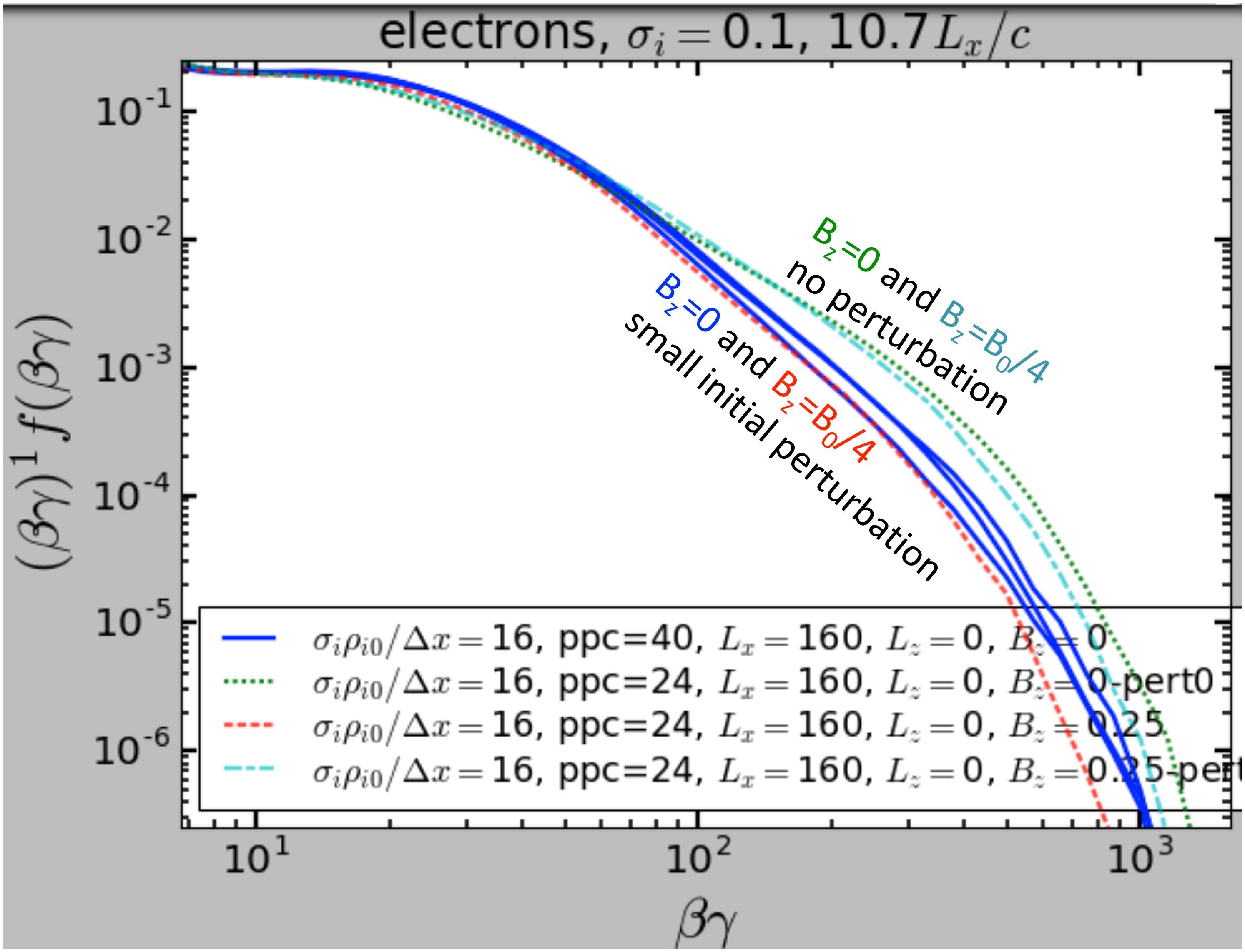
Moving on: 3D electron-proton reconnection differs slightly from 2D



2-3D
m_i/m_e=1836
B_{gz}/B_0=0
σ_i=0.1
T_e/m_ec^2 =1836σ_i/200
T_i=T_e
γ_{rad}/σ=∞

But: for electron-proton reconnection, the perturbation may be significant

Unlike the 2D ultrarelativistic (pair) case, where a small guide field has a small effect and the initial perturbation has no effect, in semirelativistic electron-proton reconnection, the perturbation has a significant effect (e.g., on electron power-law slope).



2-3D
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B_{gz}/B_0=0 – 0.25
σ_i=0.1
T_e/m_ec^2 =1836σ_i/200
T_i=T_e
γ_{rad}/σ=∞

Brief Conclusions

- From 2D, pair, zero guide field, negligible radiaction, we have now explored:
  - 3D pair reconnection (pretty much the same as 2D pair)
  - 2D and 3D with guide field (guide field slows reconnection, steepens NTPA power law)
  - 2D electron-ion (slower ions slow reconnection, steepen electron power law)
  - 2D pair with radiaction (doesn’t slow reconnection, steepens high-energy part of power law)