Beaming of particles and synchrotron radiation in relativistic magnetic reconnection at high magnetizations

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Relativistic reconnection

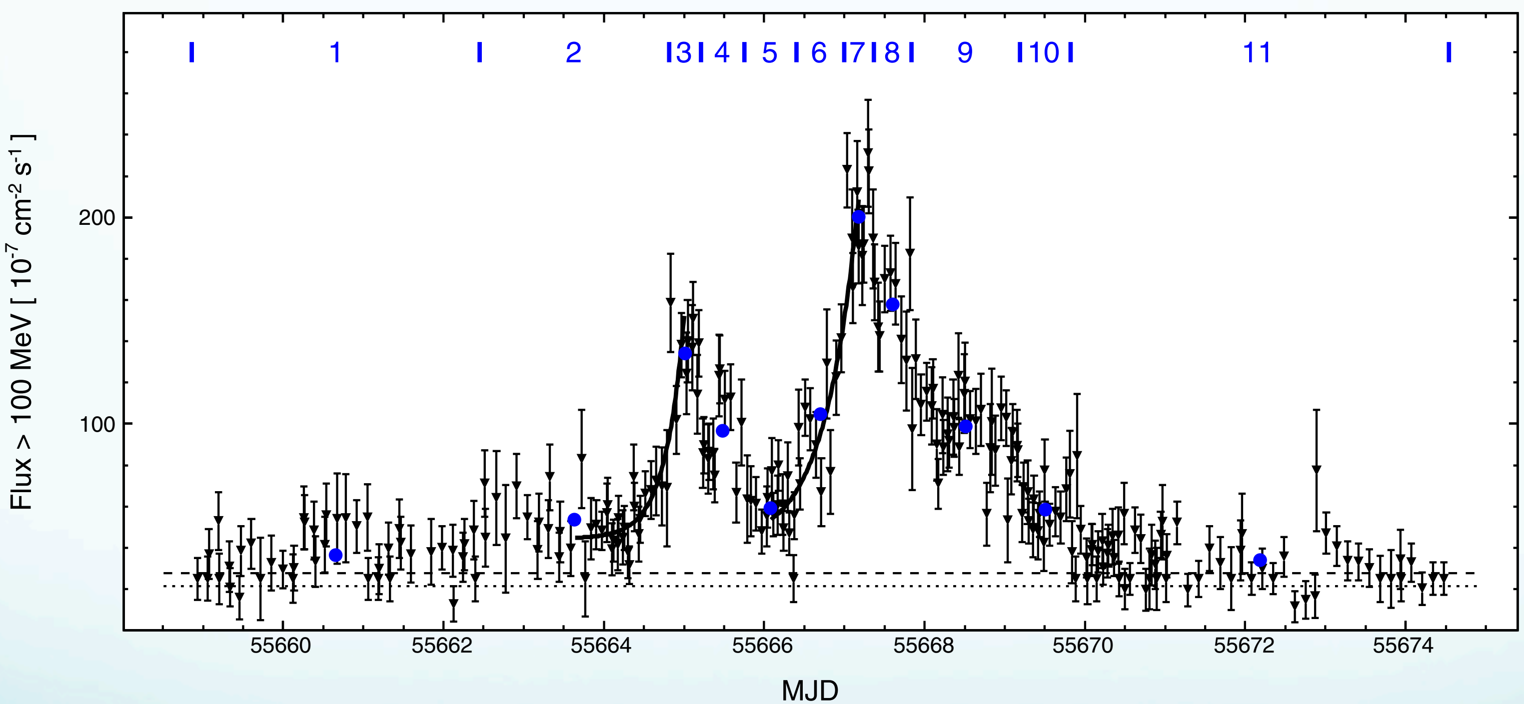
- Relativistic magnetic reconnection magnetic field energy is significantly larger than the total particle enthalpy

$$\sigma = \frac{B^2}{8\pi(\rho + P)c^2} \gg 1$$

- Many possible applications in astrophysics
  - Gamma ray bursts (if magnetically dominated) (Narayan & Kumar 2009)
  - Active galactic nucleus jets (same) (Giannios et al 2008, Narayan & Piran 2012)
  - Accretion disks (discussed by Prof. Hoshino)
  - Pulsar Wind Nebulae (Crab flare) (Uzdensky et al 2011, Cerutti et al 2012 ,2013, 2014)
- Only observational constraint is observed radiation

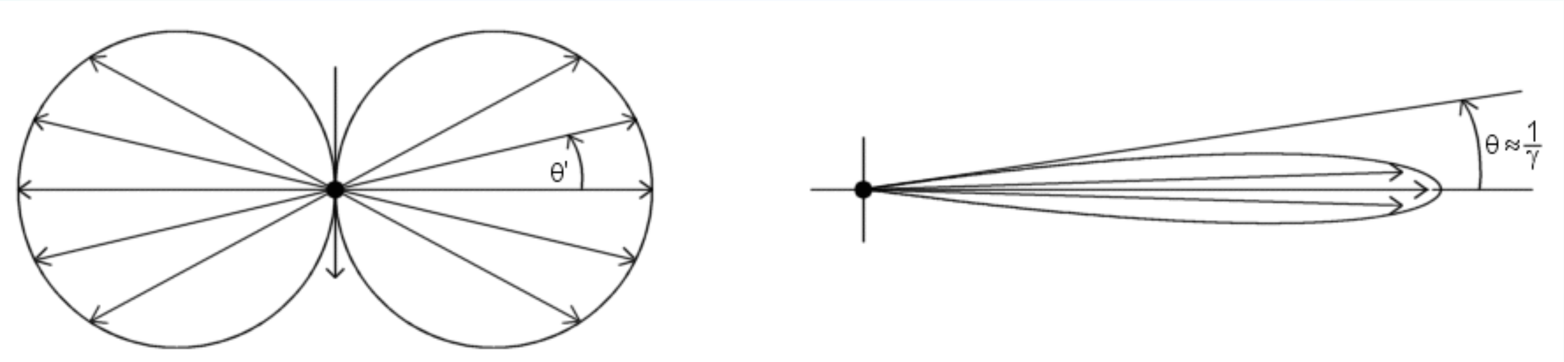
Fast Variability in these sources

(Buehler et al 2012)



Variability is present on timescales of ~2 hours!

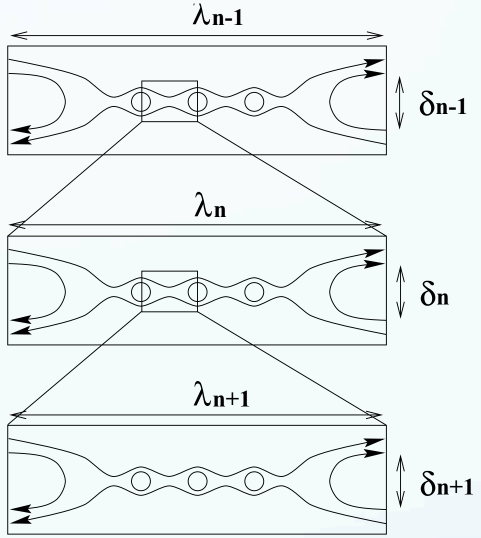
Relativistic Beaming



- Radiation emitted by ultrarelativistic particles is beamed in a cone with an an opening angle $1/\gamma$
  - Measured intensity is enhanced if the observer is located inside the common cone of many particles
- Beamed radiation can be highly variable
  - Each pulse is one reconnection event that moves across our line of sight
- Acceleration in reconnection is directional, so it may produce beamed particles and radiation

Cooling regimes and their effect on beaming

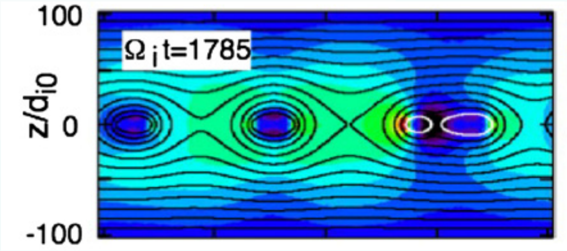
- Fast cooling – particles radiate as soon as they leave the acceleration region
- Slow cooling – particles radiate after reconnection is complete
- Intermediate cooling/fractal reconnection (e.g. Shibata and Tanuma 2001)
  - Our target
- Previous work by Cerutti et al. (2012, 2013, 2014) calculates beaming for fast cooling case (including radiation reaction)
  - Particles beamed within 2-4% of total solid angle
- What about the slow and intermediate cases?



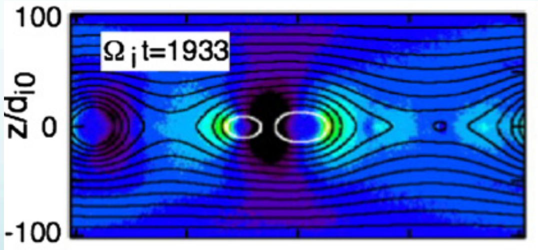
The effects of high σ on reconnection

- For low $\sigma \sim 10$, $v_{in}/c \sim 0.05$-0.2
  (e.g. Sironi & Spitkovsky 2014, Guo et al 2014, Liu et al 2015)
  - Similar to nonrelativistic reconnection
- Recent simulations by Bessho and Bhattacharjee (2012) find reconnection rates of ~1 for high σ
  - Also, big differences in current sheet structures >>>>>
- More recent calculations (Liu et al 2015) confirm that local reconnection rates increase with σ

High σ



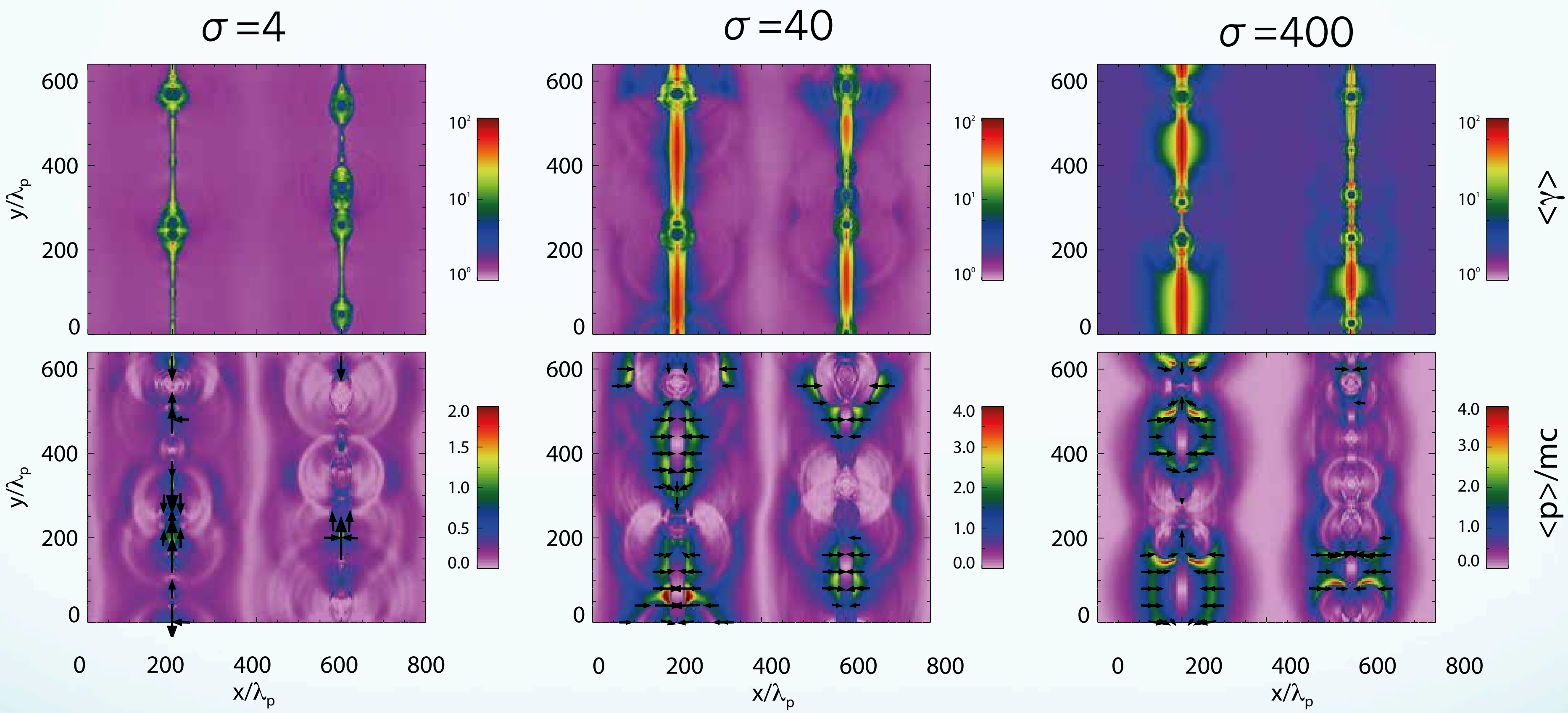
Lower σ



2D PIC simulations

- Use Tristan-MP particle-in-cell code (Spitkovsky 2008) with current density filtering algorithm that reduces particle noise
  - Use 16 particles per cell (similar results for up to 50 particles per cell)
  - Skin depth is set to $\lambda_p=8\Delta$ (similar results for up to 20Δ)
- Simulation setup:
  - Pair plasma
  - Use Harris current sheet with sheet width $\delta=3\lambda_p$
  - 2D simulations with $L_x \times L_y=800\lambda_p \times 640\lambda_p$ ($6400\Delta \times 5120\Delta$)
  - Periodic boundary conditions
- Set background magnetizations of $\sigma=4$, 40, and 400

Results from middle of simulation



- X-points and outskirts of islands contain the highest-energy particles – consistent with results of Prof. Hoshino!
- Fast inflows and thick current sheets found for σ =40, 400
- Does this mean that energy transfer depends drastically on σ ?

Global definition of reconnection rate

- For relativistic reconnection, maximum possible kinetic energy gain is

$$\frac{d\mathcal{E}_{\mathrm{K,max}}}{dt} = 4cL_y\frac{B_0^2}{8\pi}$$

- So we can define the reconnection rate as

$$r_{\mathrm{rec}} = \frac{d\mathcal{E}_{\mathrm{K}}}{d\tau}\frac{1}{4\mathcal{E}_{\mathrm{B,0}}} \qquad \tau = \frac{L_x}{c}t$$

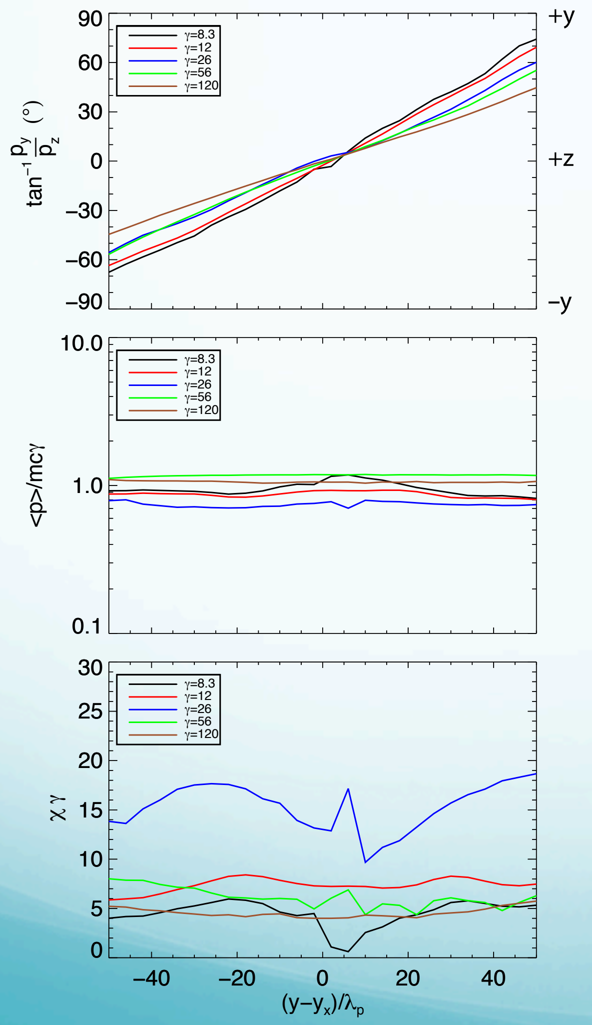
- Definition is extremely easy to use for periodic boundary conditions, but difficult for observations
- r_{rec}=0.15, 0.20, and 0.17 for σ=4,40, and 400

No dependence on σ!

Measuring beaming

- Beaming of particles and radiation also doesn't depend significantly on σ
  - Remaining results are from the simulation with σ =40
- We calculate beaming for particles in an X-point and an island in various energy bins
- $<p>/mc\gamma$ measures how focused the particles are towards the direction of bulk motion
- $\chi\gamma$ measures the spread (1 s.d.) of the particles relative to the minimum spread of radiation $(1/\gamma)$

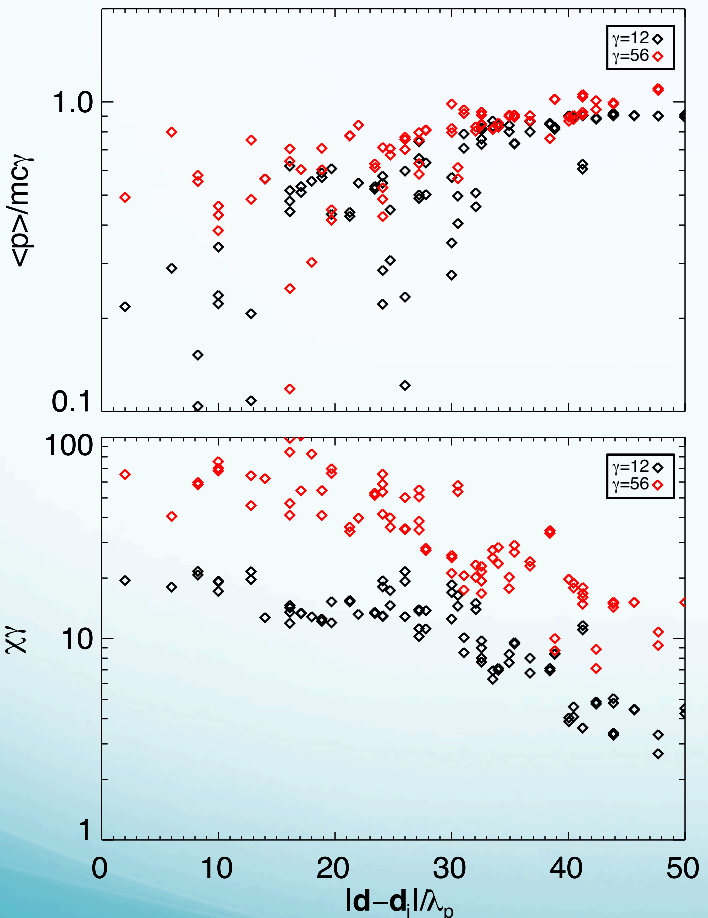
X-point particles

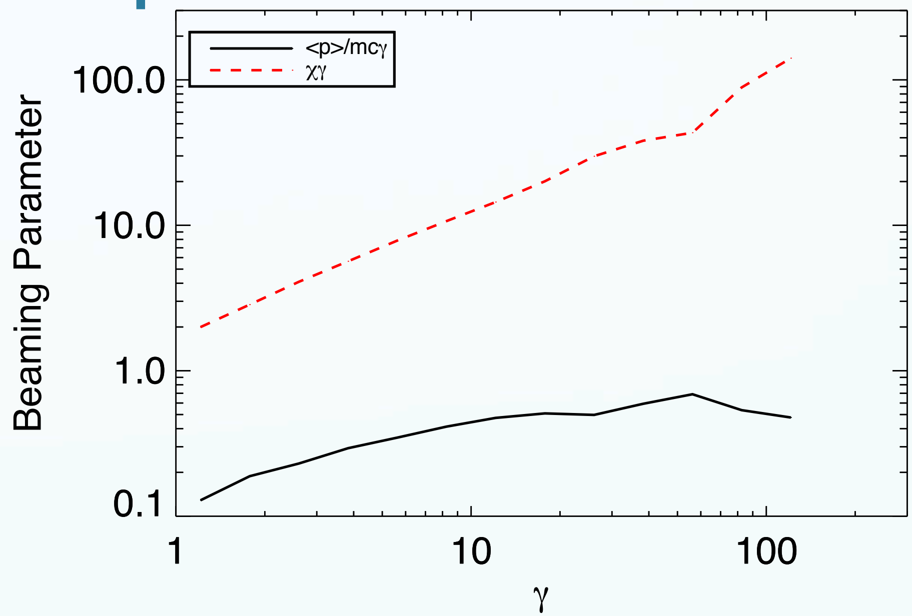


Distance from X-point center

- Particles at all values of γ in the X-line are locally highly beamed
- Direction of beaming changes linearly with distance from the center of the X-point

Island particles



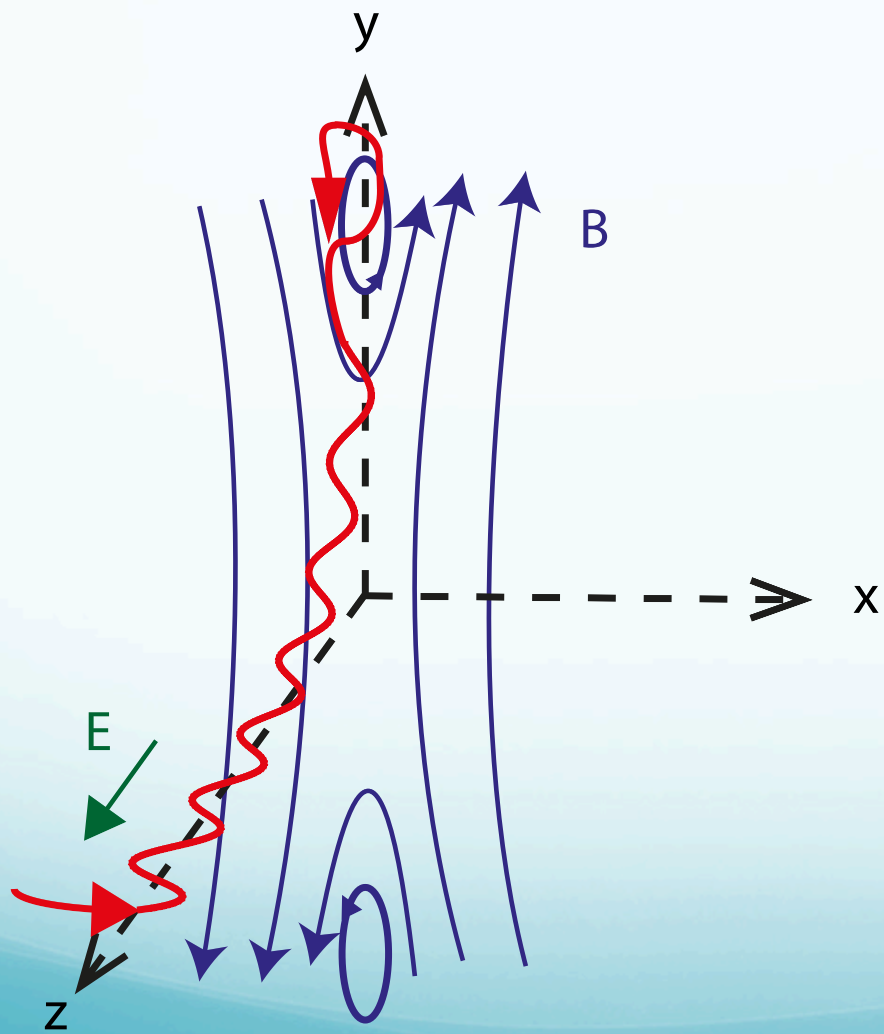


Particles are more beamed near the edges of the island

On average, no beaming in islands

Distance from island center

Schematic motion of an electron



- Particle enters X-point, and is accelerated by electric field (most acceleration takes place here)
- Deflected towards the magnetic island by the reconnected field
- Then it is isotropized in the island

Synchrotron Radiation Calculations

- Calculate effective magnetic field from the curvature of particle trajectories (Wallin et al 2015)

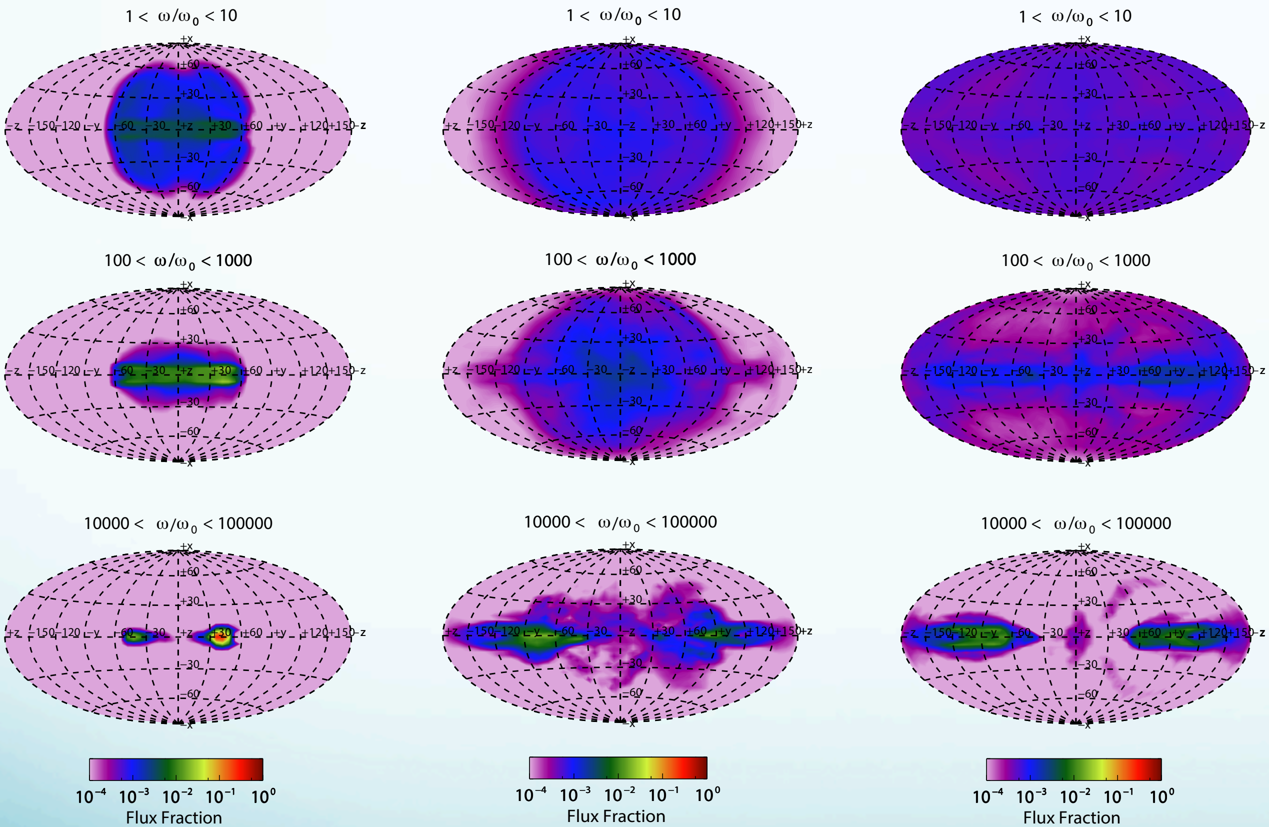
$$B_{\text{eff}} = \frac{mc\gamma}{q} \frac{\sqrt{p^2 F_L^2 - (\mathbf{p} \cdot \mathbf{F}_L)^2}}{p^2}$$

- Use synchrotron formula to calculate radiation

$$\frac{dF_\omega}{d\omega} = \frac{\sqrt{3} q^3 B_{\text{eff}}}{2\pi mc^2} F\left(\frac{\omega}{\omega_c}\right) \qquad \omega_c = \frac{3qB_{\text{eff}}\gamma^2}{2mc}$$

- Assume radiation from each particle is beamed within $1/\gamma$ to calculate directional distribution
- This is a calculation based on the current particle location (fractal reconnection regime)

Aitoff projections of radiation in all three cases



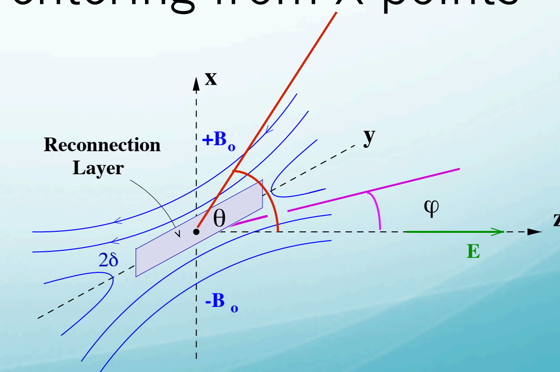
X-line
Fast cooling

Island
Slow Cooling

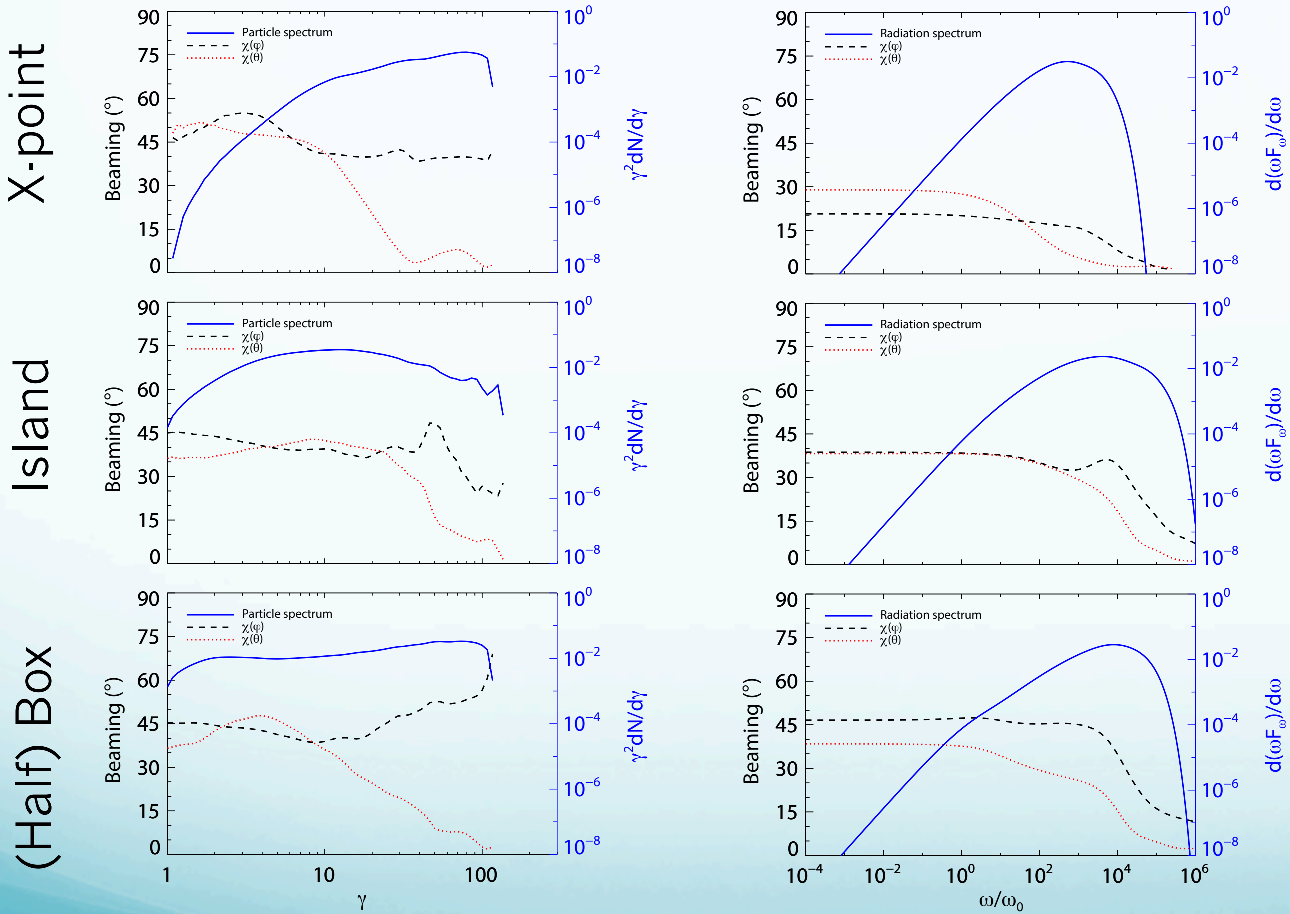
(Half) Box
Fractal
Reconnection

X-point and box radiation is focused toward equator (ϑ=0) at high energies

Radiation from islands not beamed at all except at highest energies - particles entering from X-points



Quantitative Beaming of Particles and Radiation



High-Energy Radiation

$\chi(\theta) = 3^\circ,\ \chi(\phi) = 11^\circ$

$\Omega/4\pi \sim 0.005$

$\chi(\theta) = 7^\circ,\ \chi(\phi) = 22^\circ$

$\Omega/4\pi \sim 0.025$

$\chi(\theta) = 4^\circ,\ \chi(\phi) = 16^\circ$

$\Omega/4\pi \sim 0.01$

Conclusion

- The global reconnection rate has no dependence on magnetization despite the increase in locally measured reconnection rates
- Particles in X-points are strongly beamed, but the direction of beaming changes with location
- Particles in islands are moderately beamed at the edges, unbeamed at the center
  - Particles entering the island from the X-points are beamed
- The high-energy radiation in all three regimes of cooling are beamed within ~0.5-2.5% of the sky
  - Consistent with previous results by Cerutti et al (2012,2013,2014)
  - But! Slow cooling may result in no beaming if hot outflows from X-points cease at late times

Connection with space physics

- Global and energy-based reconnection rate calculations needed for astrophysics
  - Local measurements of inflow velocities or electric fields may not accurately measure energy transfer
  - $E \cdot J$ measurement can probe energy transfer directly
  - Can global measurements be made for observations?
- The large-scale physics of reconnection affects whether it can explain high-energy, variable sources
  - Does fractal reconnection occur on large scales?
  - How intermittent is reconnection, and what is the “true” reconnection rate
  - If not, do outflows from reconnection regions contribute to beaming at late times?