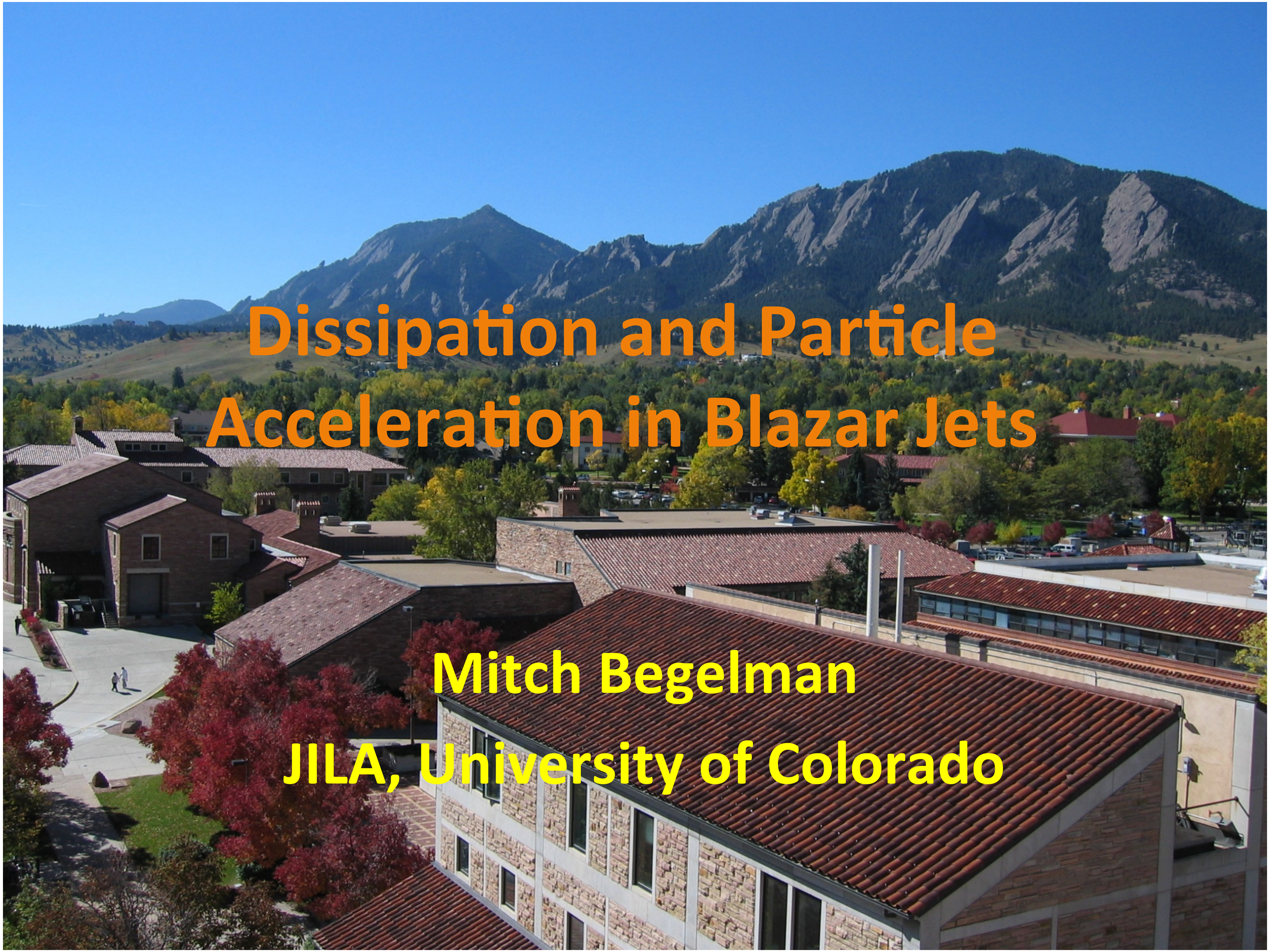


Dissipation and Particle Acceleration in Blazar Jets

Mitch Begelman

JILA, University of Colorado

Why do blazar jets shine?

Why/how/where does (some) jet energy get converted into (nonthermal) particle pressure?

After all, magnetic acceleration is not intrinsically a dissipative process…

MAGNETIC ACCELERATION

Target: $\boxed{?}_{\boxed{?}}=L_j/\dot{M}_j c^2$

- Stage 1: Magnetocentrifugal: launching the jet
  - Brings jet to Alfvén point (R_A – basically the light cylinder) and $\boxed{?}_{\boxed{?}}{}^{1/3}$
  - Insensitive to streamline shape (“split monopole” model)
  - Rotational energy converted to Poynting flux
- Stage 2: Magnetic nozzle: main acceleration stage
  - Boosts $\boxed{?}$ using magnetic pressure
  - Brings jet through fast magnetosonic point and to ~ $\boxed{?}_{\boxed{?}}/2$
  - Converts Poynting flux to kinetic energy, but …
  - ~Half energy still in Poynting flux
- Stage 3: Coasting:
  - Near cancellation of forces $\boxed{?}$ further acceleration by magnetic forces (sub)logarithmic
  - Only this stage *needs* gas pressure (dissipation) to extract the last half of the energy

Relativistic acceleration is gradual (outside R_A)

- Inside R_A energy “passes through” field lines; outside R_A energy is carried by flow
- But energy has <u>inertia</u>: $(E = Mc^2)$

in relativistic version of $a = \dfrac{F}{M}$

both numerator and denominator $\boxed{?}$ energy content

in hydrodynamic limit,

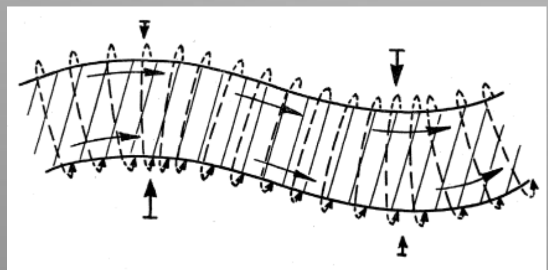
$$\Gamma \propto (ext.\ pressure)^{-1/4}$$

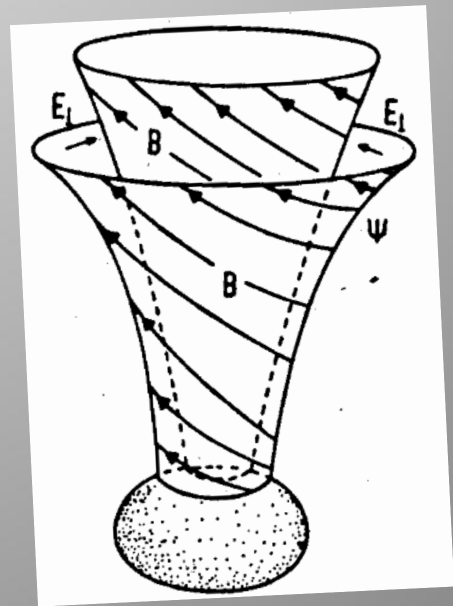
SOURCES OF DISSIPATION

- Boundary conditions
  - Unsteady conditions at base of jet (disk connection)
  - Recollimation shocks
  - Jostle sides of jet (turbulent cocoon, intercept clouds)
  - Both are externally induced: tap unknown fraction of jet energy
- Surface/global instabilities
  - Kelvin-Helmholtz: suppressed as ? becomes large
  - Current-driven instabilities (kink)
    - Suppressed by poloidal field
    - Tend to wiggle whole jet
- Internal instabilities
  - Internal shear
  - Current-driven – not effective when jet too close to force-free
    - Need pre-existing dissipation (see above) to "prime pump"

CURRENT-DRIVEN INSTABILITIES

- Jets are basically moving screw-pinches
  - Helical current wound around z
  - Ubiquitous unstable configuration in plasma physics *(Kruskal & Schwarzschild 1954)*
- Competing effects:
  - Toroidal $B_{?}$ is destabilizing
  - Poloidal B_p is stabilizing
  - Gas pressure can enhance destabilizing effect of $B_{?}$ *(MCB '98)*
- Conclude:
  - m=1 (kink) most unstable
  - catalyzed by particle pressure



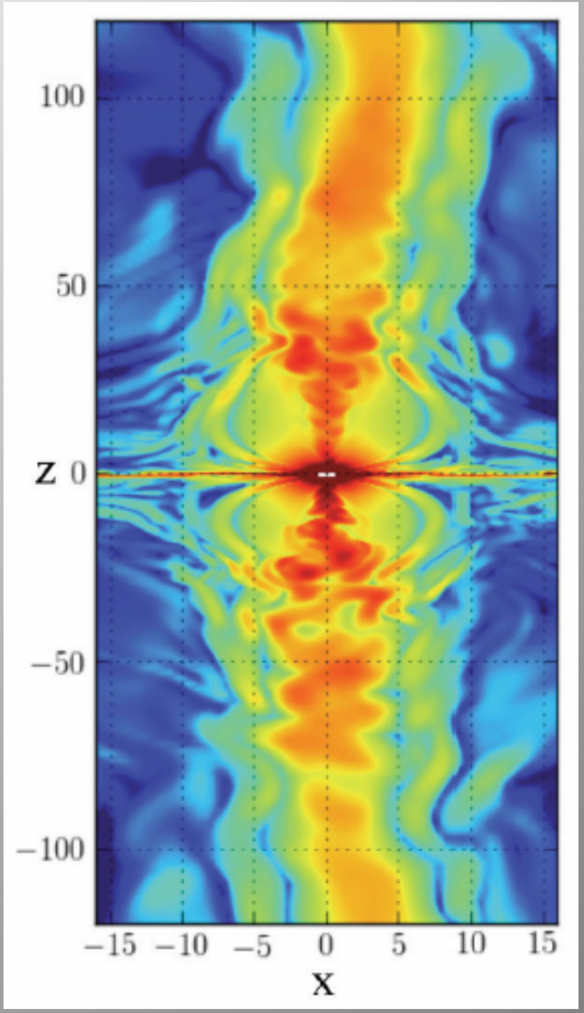


CURRENT-DRIVEN INSTABILITIES

- Purely magnetic (force free) jets unstable if …
  - Poloidal field not too strong
  - Jet boundaries are "soft" (jet not too fast)

- Force-free jets enclosed in rigid walls are stable

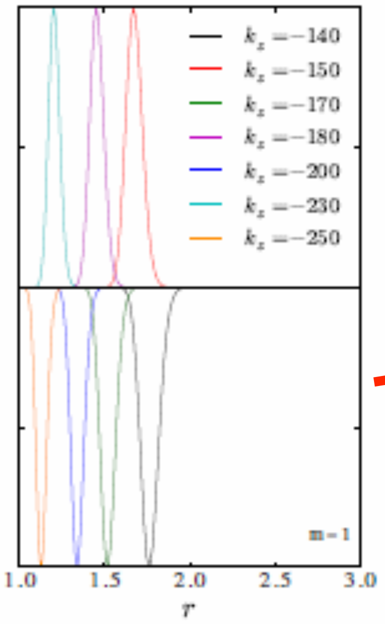
- Conclude:
  - Best place to build up significant gas pressure is early in the acceleration process
  - Otherwise jet can be "stuck" with large Poynting flux over long distances

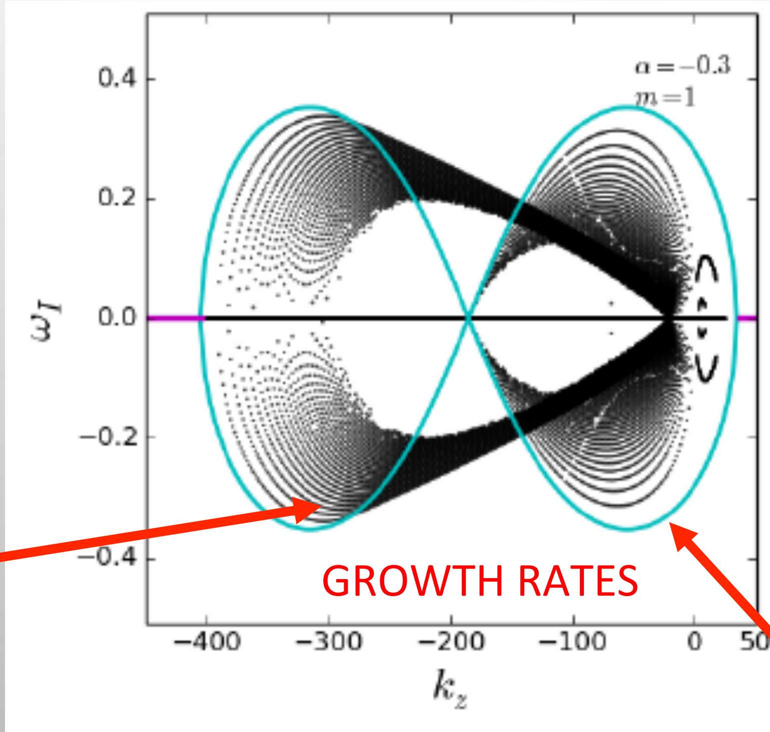


Plot of current density:
Bromberg & Tchekhovskoy 2016

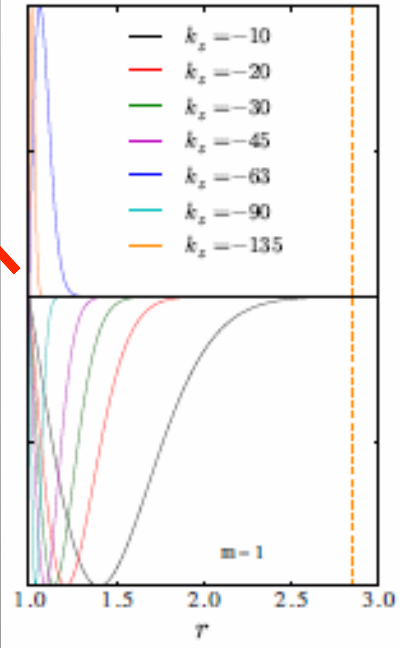
LOCALIZED INTERNAL INSTABILITIES

Non-resonant modes



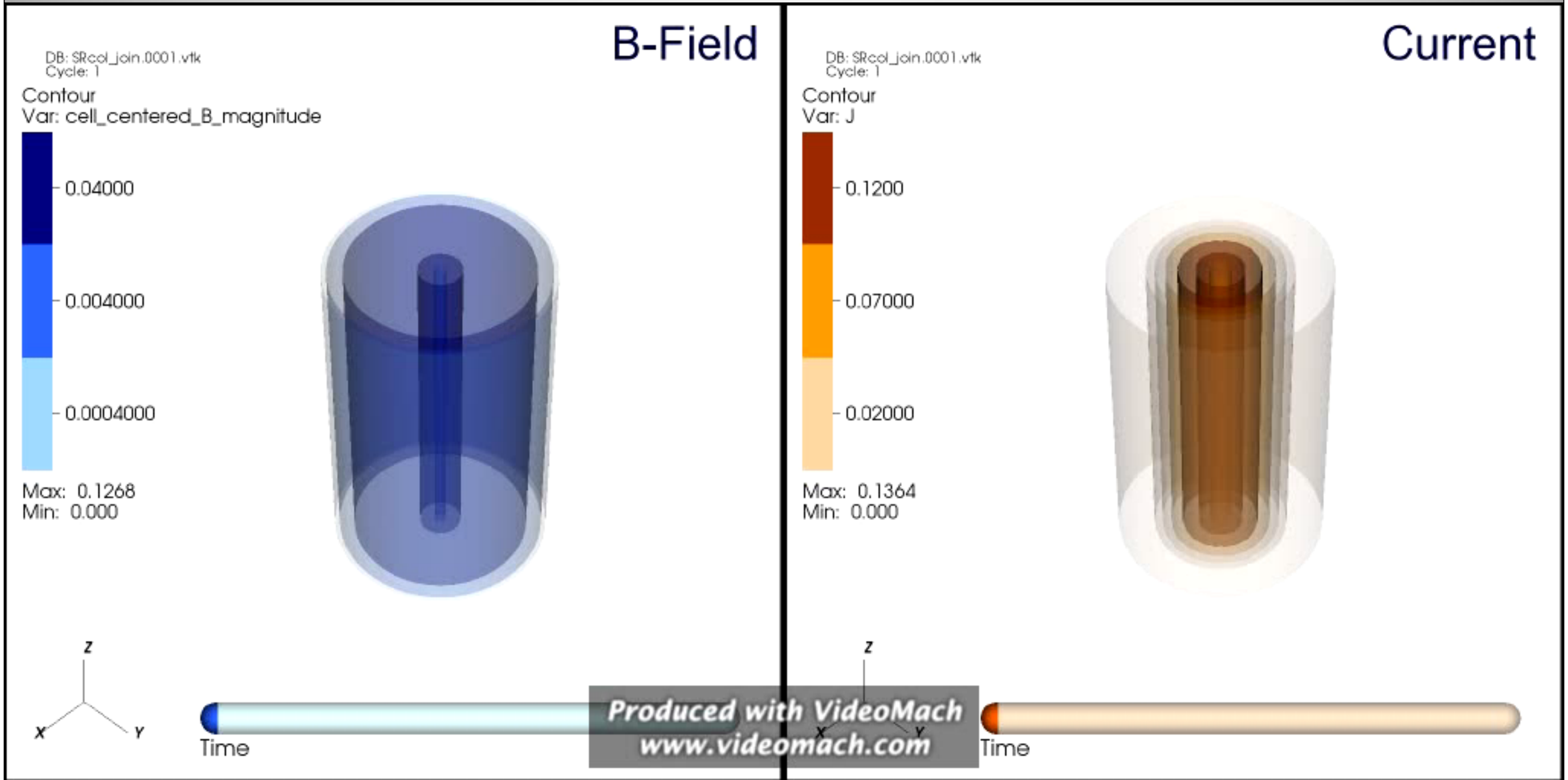


Resonant modes



- Present when gas pressure balances toroidal field *(MCB '98)*
- Global eigenfunction analysis confirms modes confined to annulus *(Das & MCB '18)*

Nonlinear state: turbulence, current sheets ? dissipation



Pinch balanced by gas pressure: $?_{min}$=0.3

Special relativistic MHD (Athena) simulations – O'Neill et al. 2012

How does the dissipation takes place?

First-order Fermi acceleration at shocks

- The astrophysical “standard” for ~40 years
  - Roughly the right index (for strong shocks)
  - Efficient
  - Simultaneously explain synchrotron spectra and cosmic rays

But shock acceleration doesn't work well for:

Highly magnetized flows $\boxed{?}$ shocks weak

OR

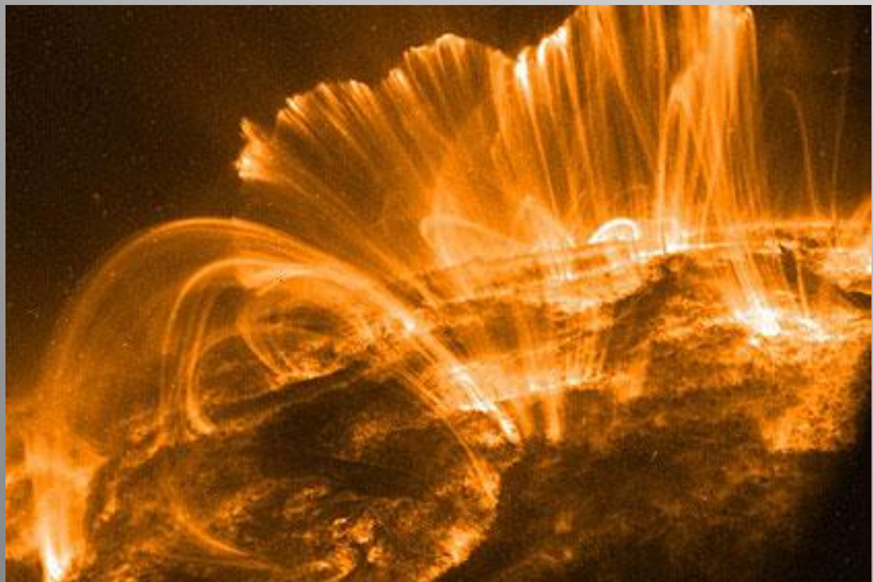
Highly relativistic flows $\boxed{?}$ diffusion model (multiple shock crossings) fails

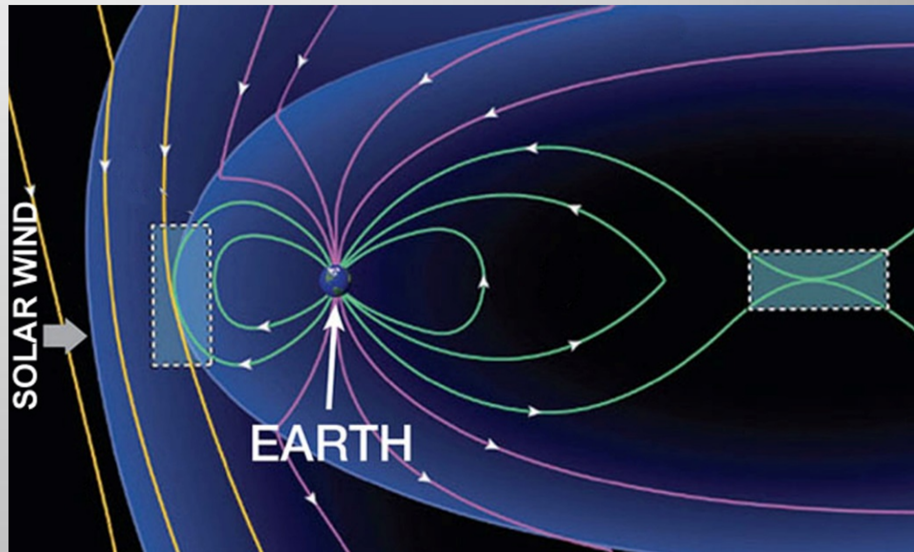
BLAZARS FAIL BOTH TESTS

(Sironi et al. 2015)

THE ALTERNATIVE: RECONNECTION

Key element in space and solar physics for decades…





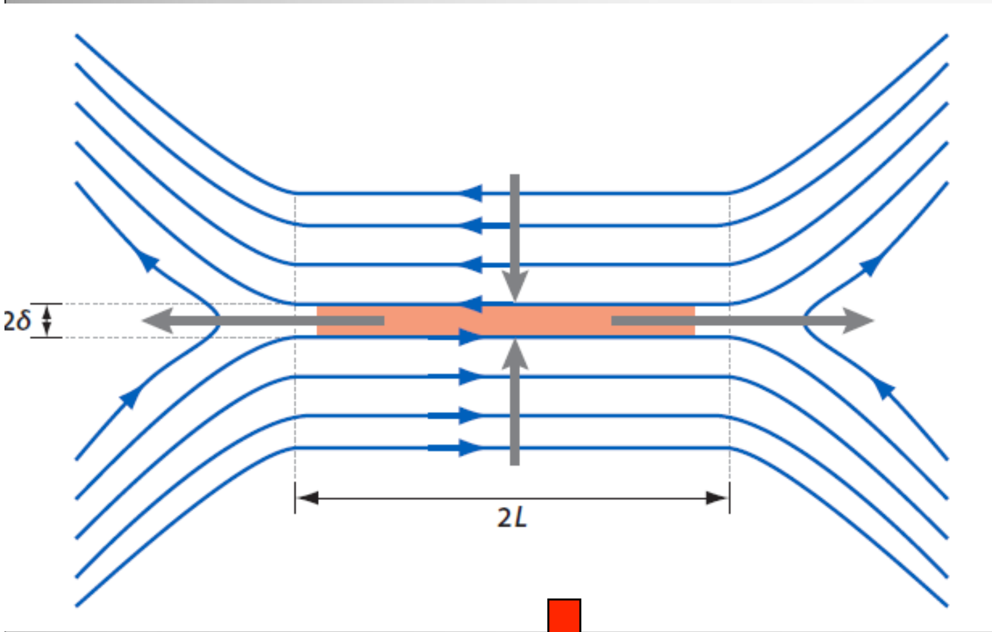
… astrophysics lags behind in applying it

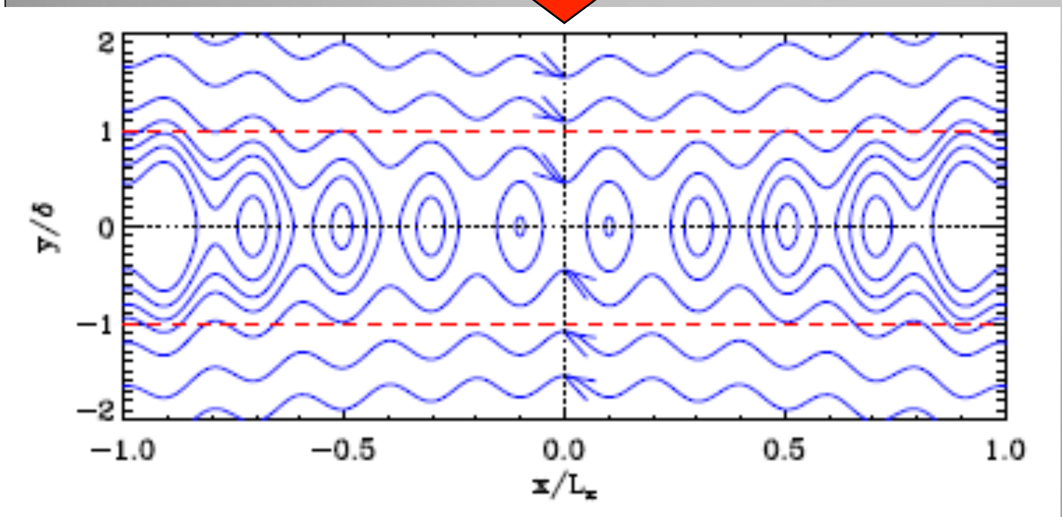
Why?

- Difficult to calculate
- Resistive models too slow
- Nonthermal particle acceleration inefficient at non-relativistic (Solar System) energies, particle heating instead

Picture is very different for relativistic plasmas

TEARING MODE INSTABILITY

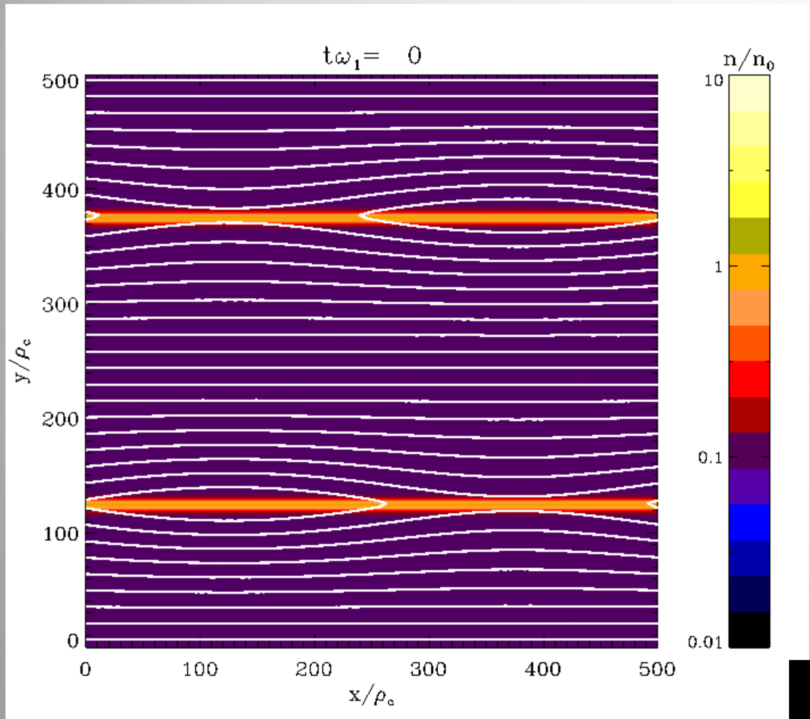




- Tears up current sheet into filaments
- Creates magnetic "islands" (plasmoids)
- Speeds up collisional & collisionless reconnection

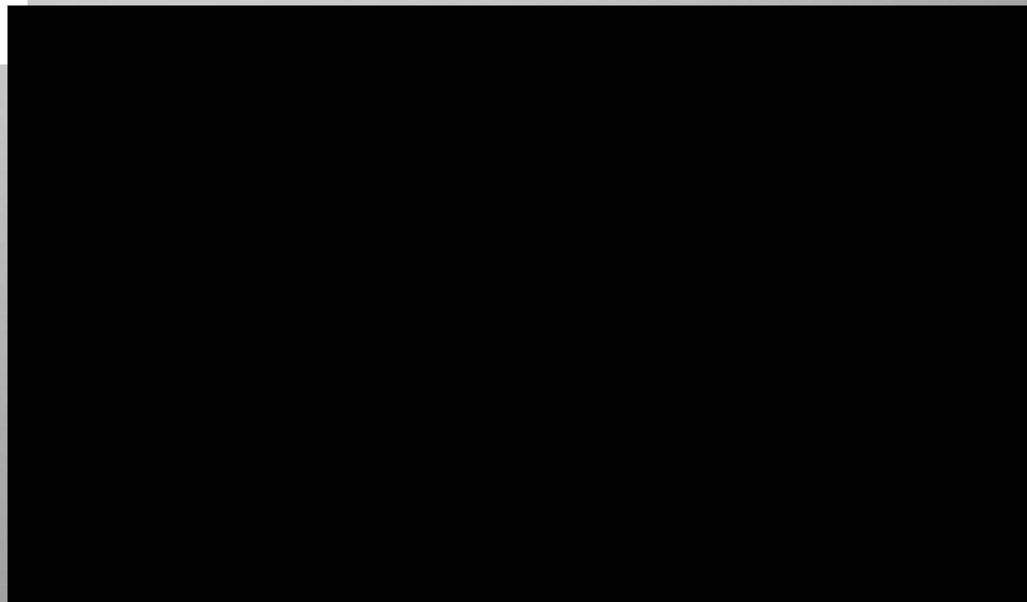
ALL RECONNECTION IS FAST ($\boxed{?}$0.1 v_A)

PARTICLE IN CELL SIMULATION – 2D



(Cerutti et al. 2013)

PARTICLE IN CELL SIMULATION – 3D w/guide field



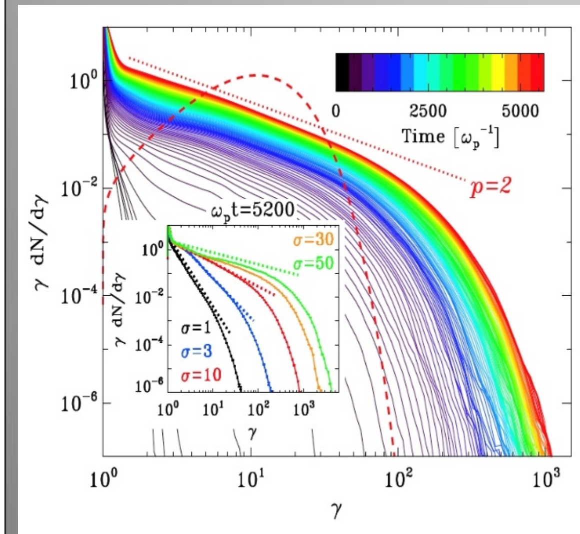
(Cerutti et al. 2014)

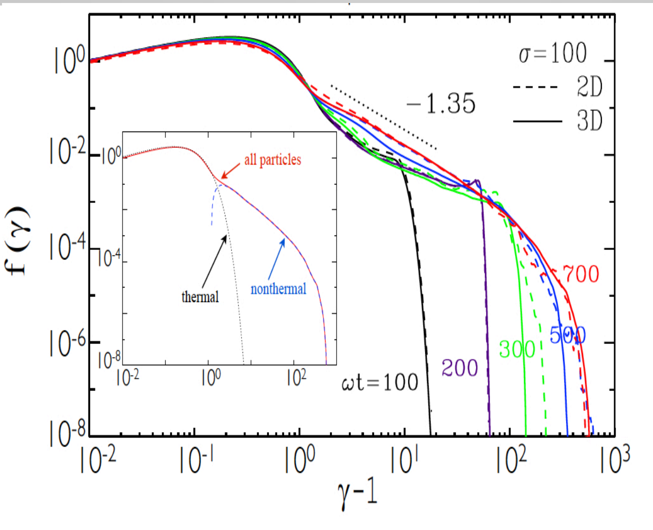
Particle Acceleration

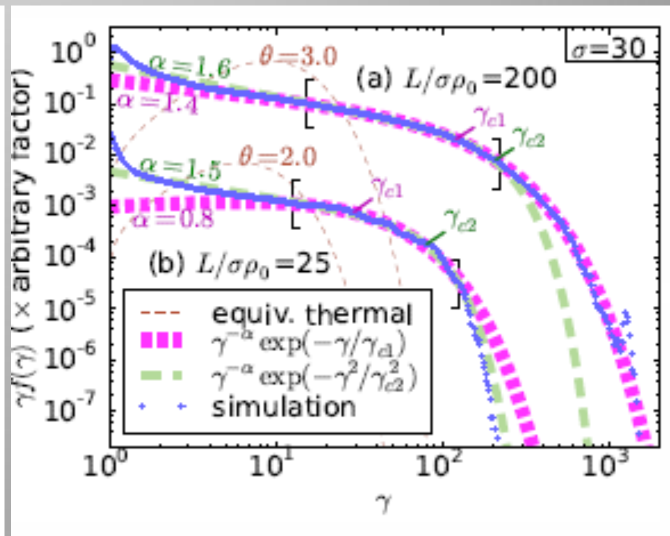
- Electron energy distributions develop power-law tail
- Index depends on "magnetization"

$$\sigma = \frac{B^2}{4\pi n \bar{\gamma} m c^2}$$

- Groups using different codes agree







Sironi et al. – Princeton, CfA, Columbia

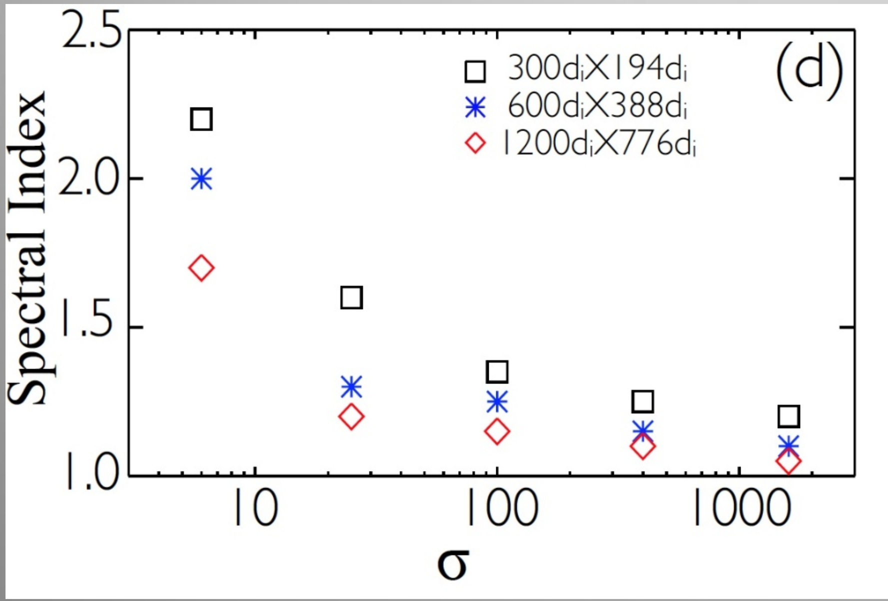
Guo et al. – Los Alamos

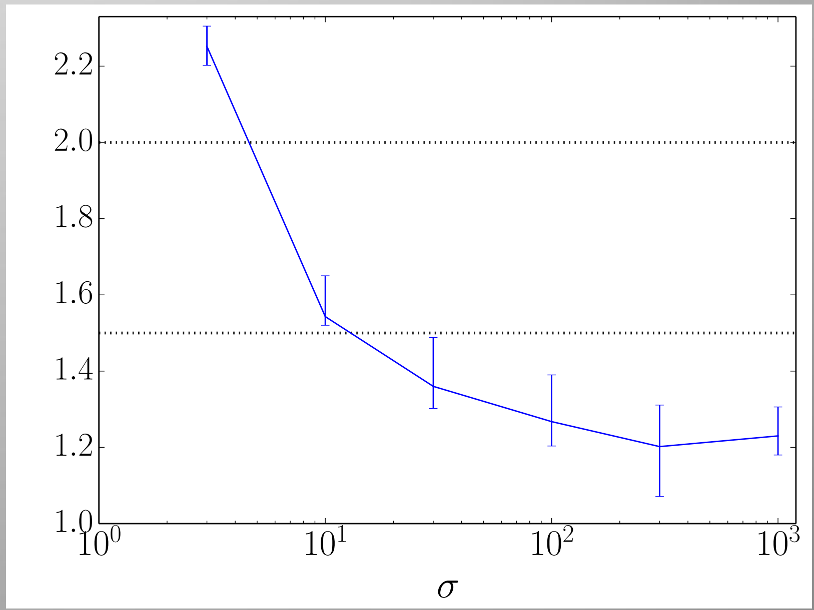
Werner et al. – Colorado

Power-law index (pair plasma)

- Flatter spectrum for larger $\sigma = \dfrac{B^2}{4\pi n\bar{\gamma}mc^2}$

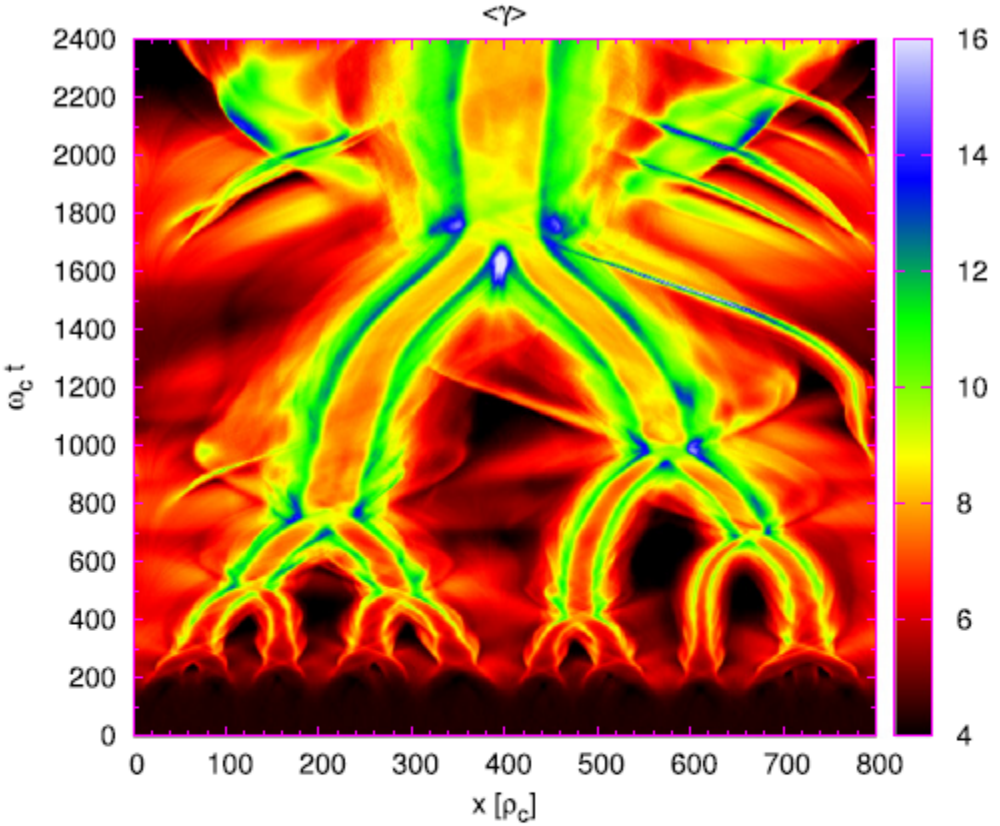
$f(\gamma) \sim \gamma^{-p}$





Guo et al. –
Los Alamos

Werner et al. –
Colorado



Particle energies: most energetic particles found around edges of plasmoids

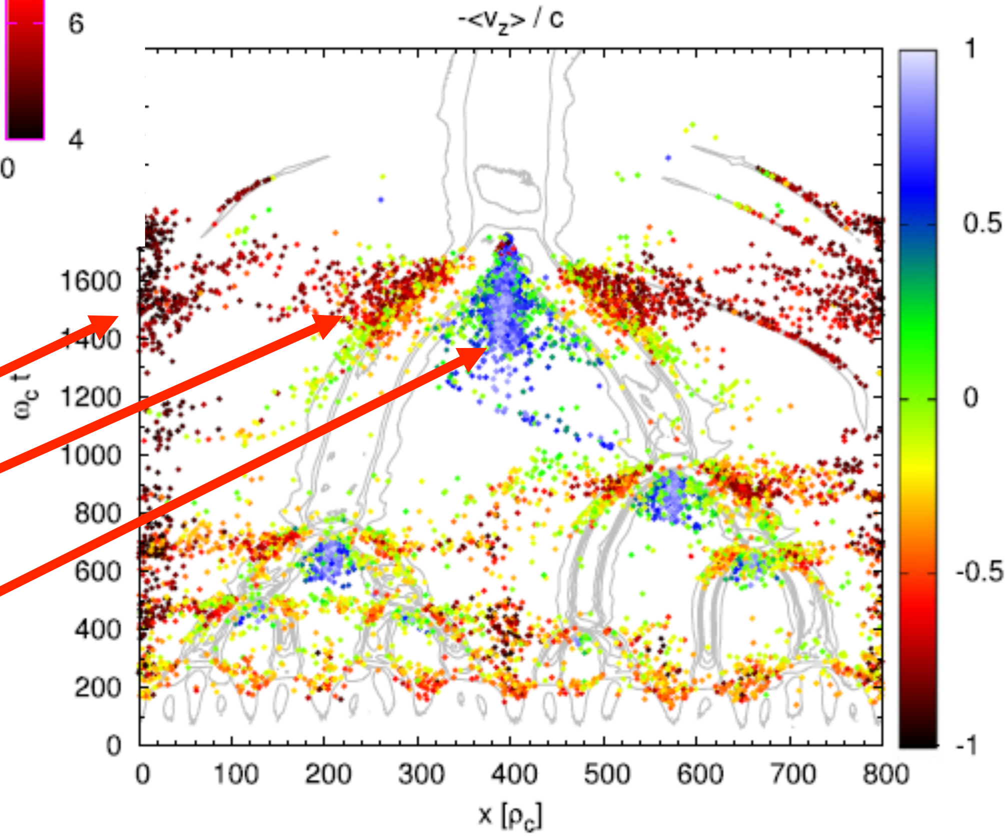
Particle acceleration sites:

• between separating plasmoids

• trailing and penetrating merging plasmoids

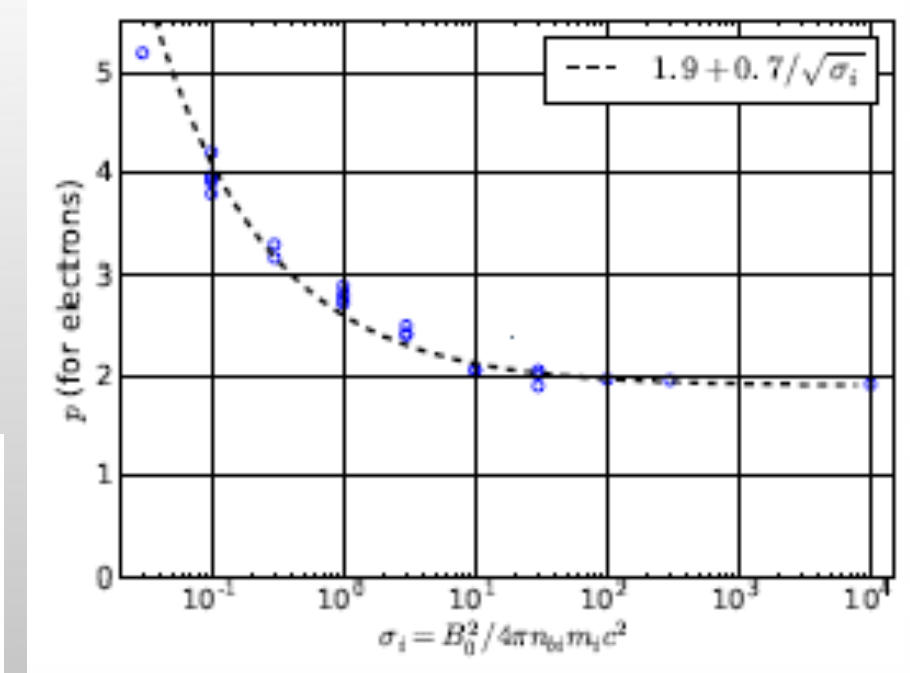
• between merging plasmoids

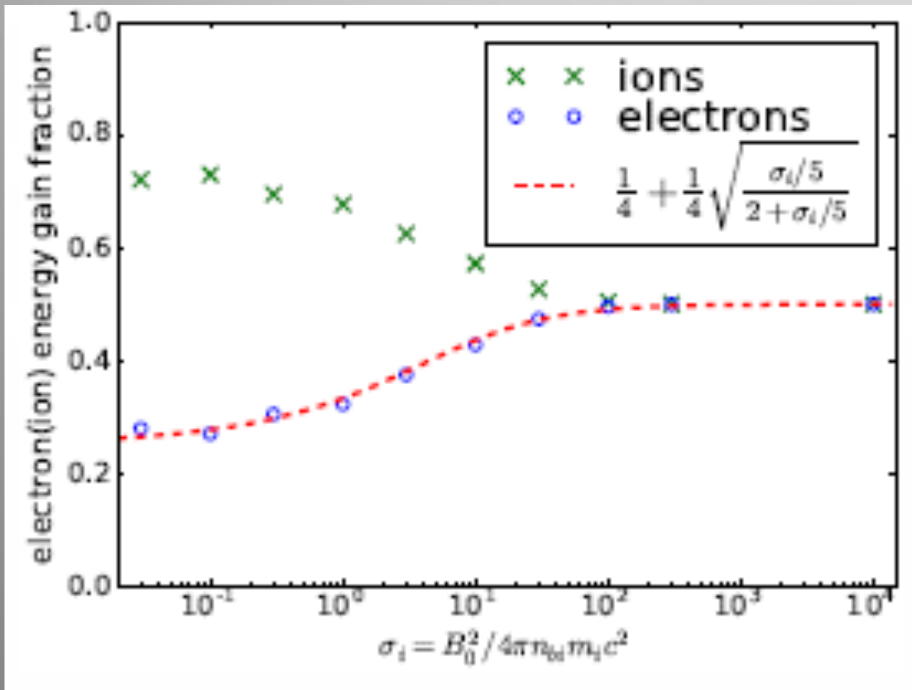
(Nalewajko et al. 2015)



Electron-ion reconnection:

- Electron power-laws – similar dependence on $\boxed{?}$

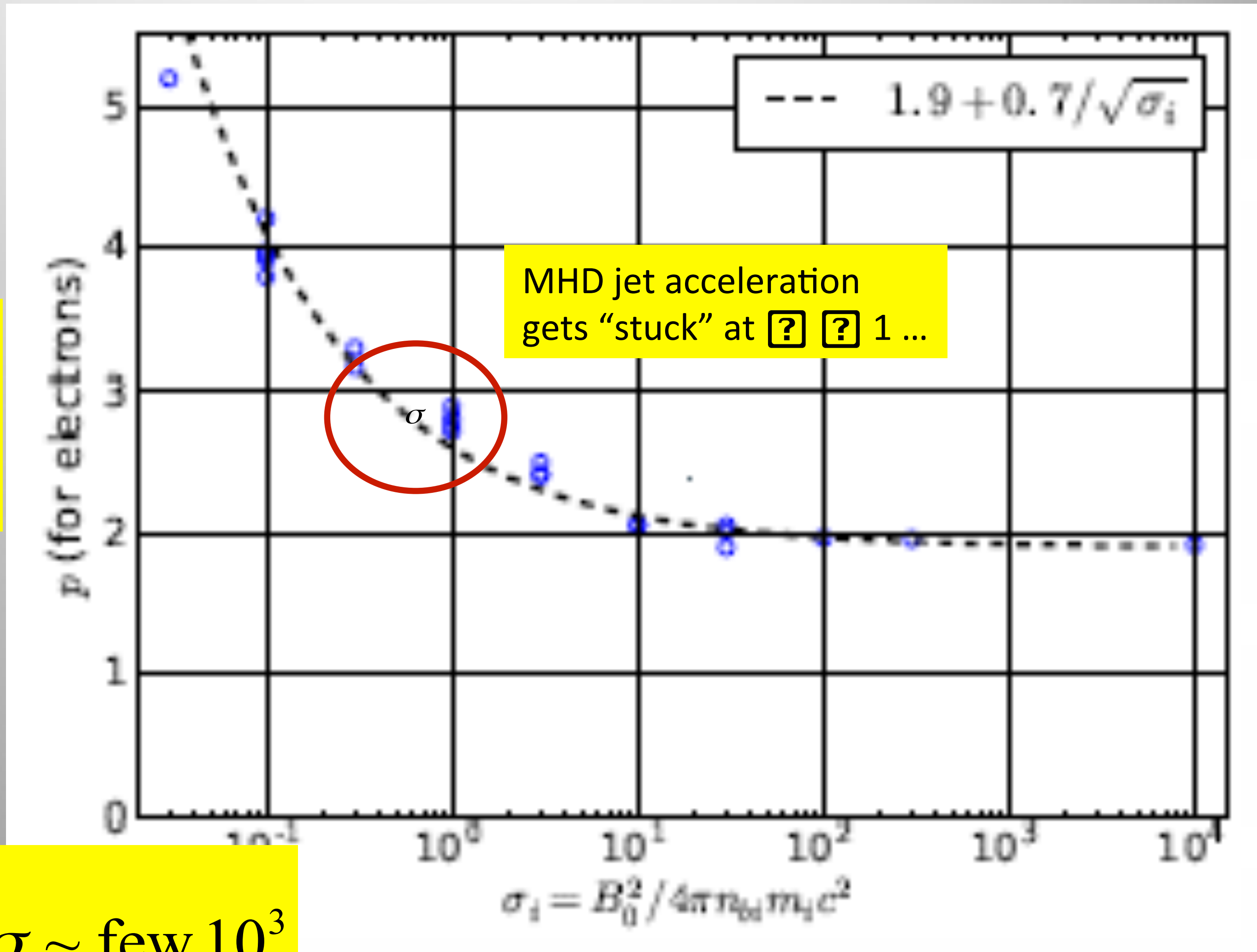




- e-i energy partition also depends on $\boxed{?}$

(Werner et al. 2018)

The "sweet spot" for relativistic jets?



MHD jet acceleration gets "stuck" at ? ? 1 …

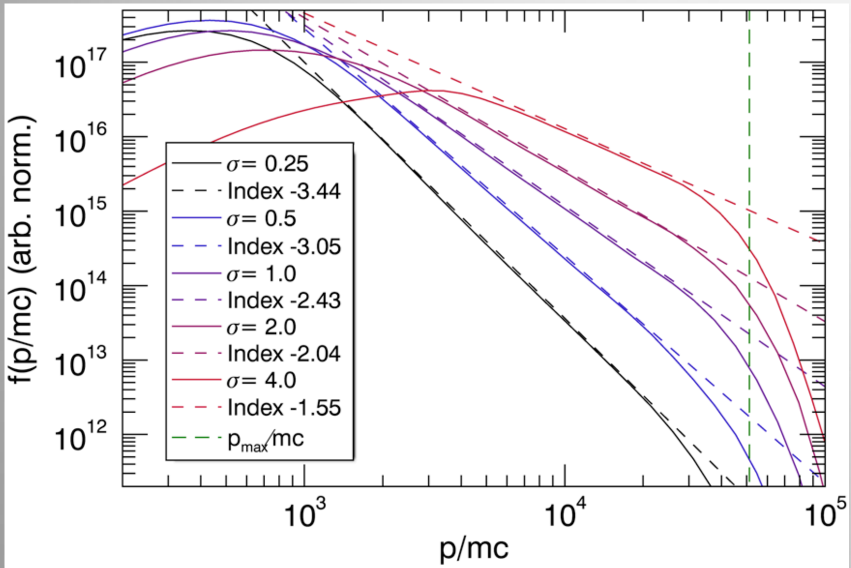
… predicting roughly the correct observed spectral index

$$\gamma_{\rm cutoff} \approx 4\left(\frac{m_i}{m_e}\right)\sigma \sim \text{few } 10^3$$

(Werner et al. 2018)

Driven Kinetic Turbulence in Relativistic Pair Plasma

Non-thermal power-law energy distribution



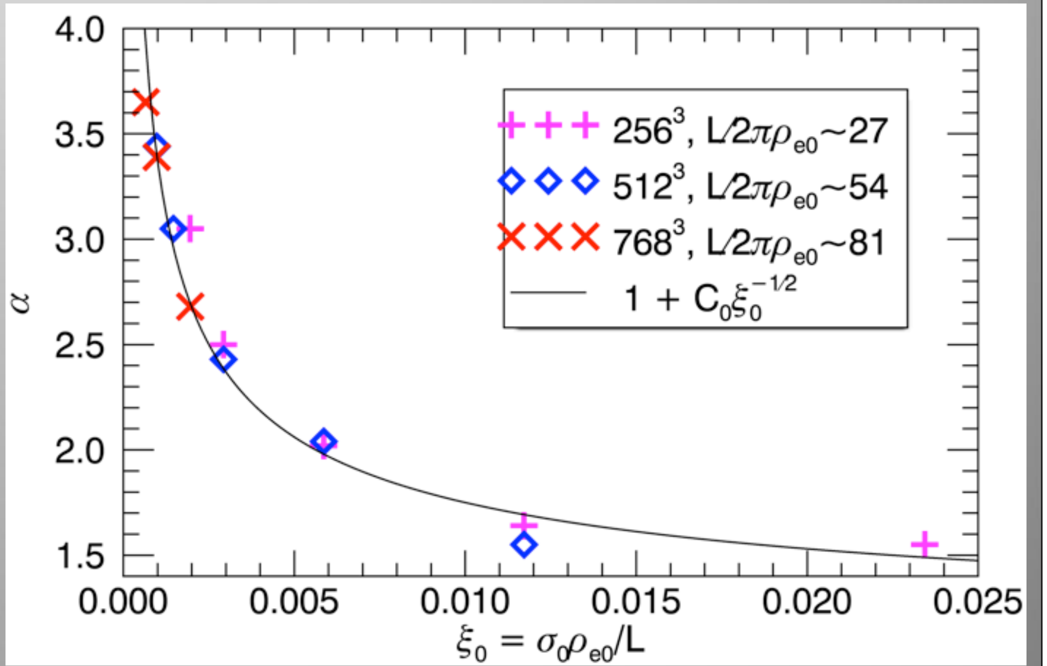
- Empirical fit:

$$\alpha \sim 1 + C_0(\sigma \rho_e / L)^{-1/2}$$

$$C_0 \approx 0.075$$

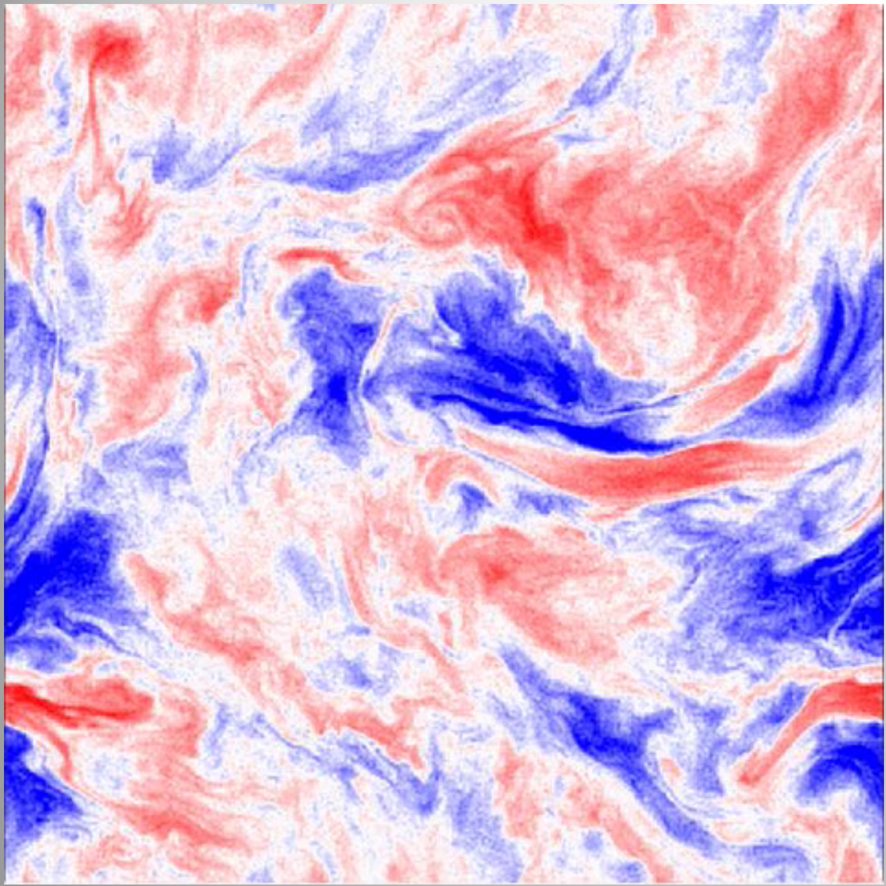
THIS JUST IN: no size dependence – models converge (arXiv:1805.08754)

Hardens with increasing ?



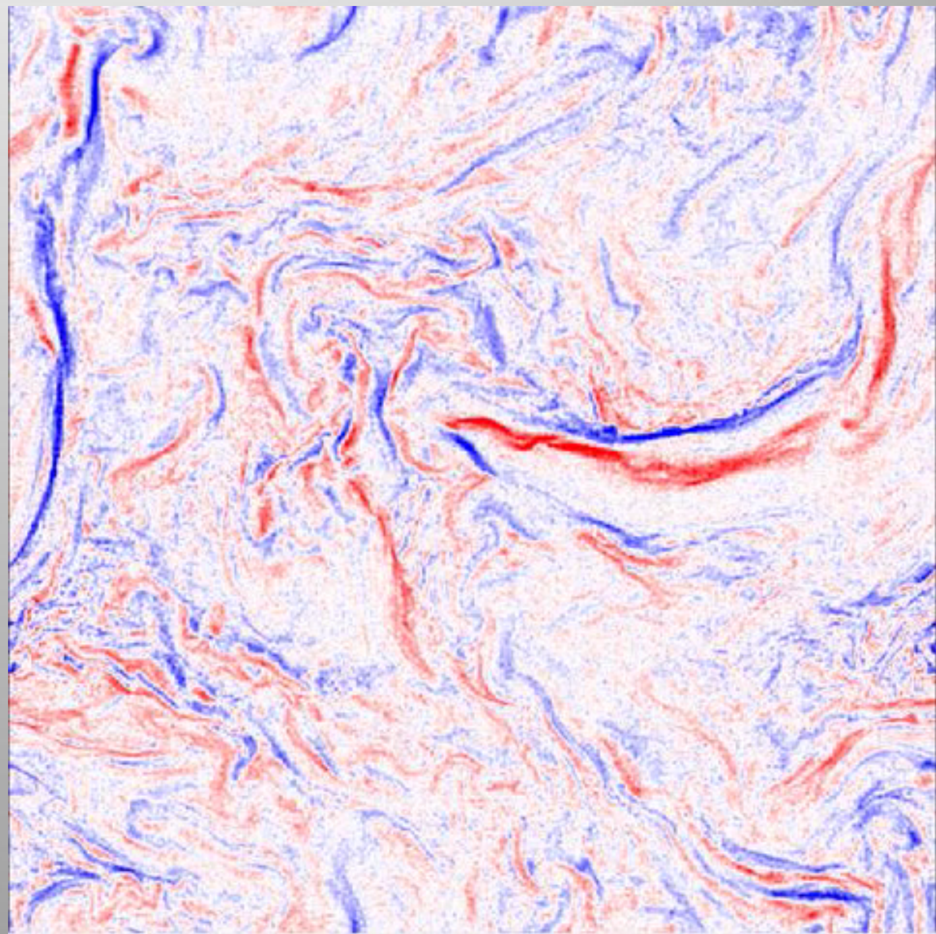
*Zhdankin, Werner, Uzdensky, & Begelman (PRL **118**, 055103 2017)*

768^3 TURBULENCE SNAPSHOT FLY-THROUGH



DENSITY

CURRENT

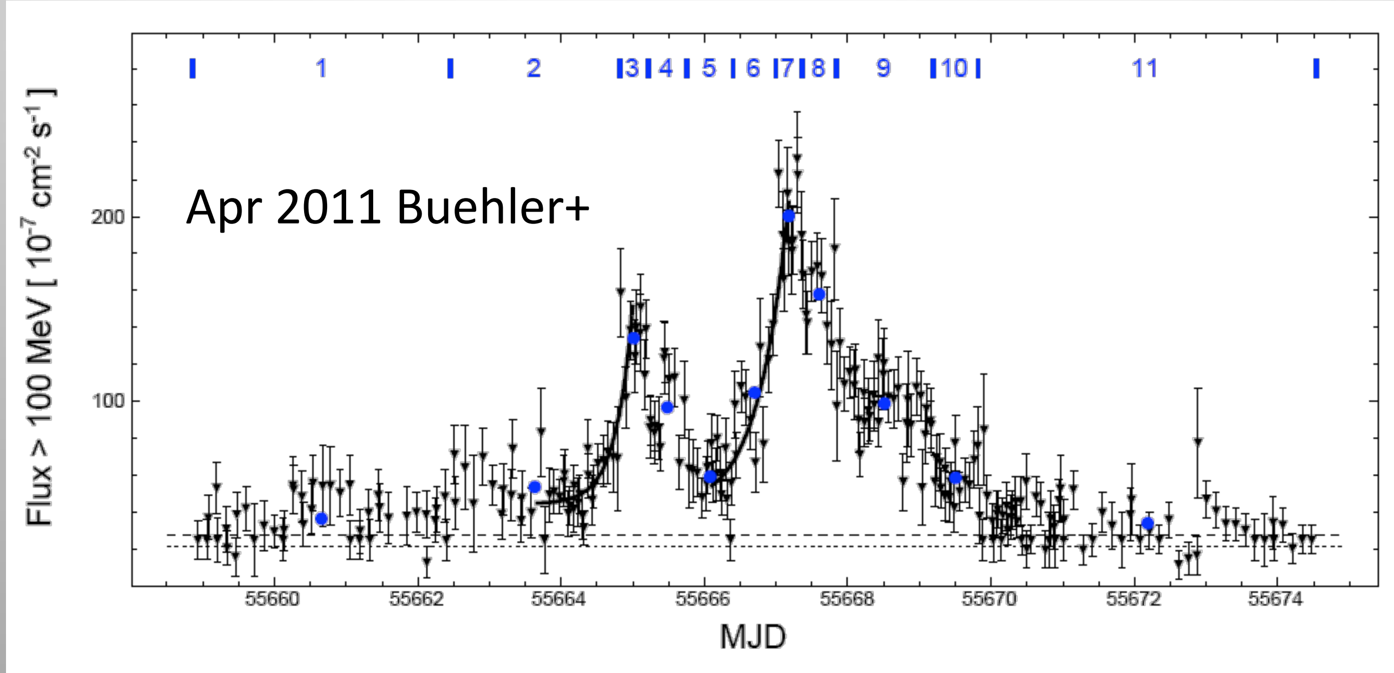


(Zhdankin et al. 2018)

?-ray flares

Is a separate (linear accelerator) mechanism also operating?

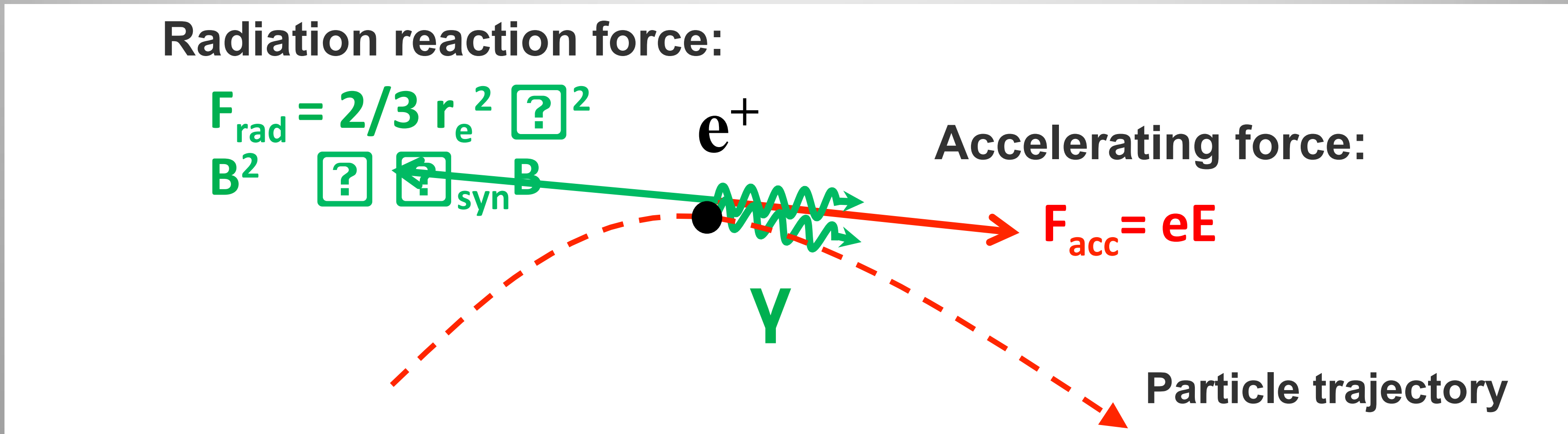
The Crab Provides Clues



-

- Duration ~ 1 day ? c ? ~ 3 x 10^{15} cm
- Photon energy > 100 MeV ? PeV electrons
- Not power-law: fit by monoenergetic spectrum
- Isotropic flare energy: E ~ 4 x 10^{40} erg

Synchrotron emission >100 MeV challenges particle acceleration models

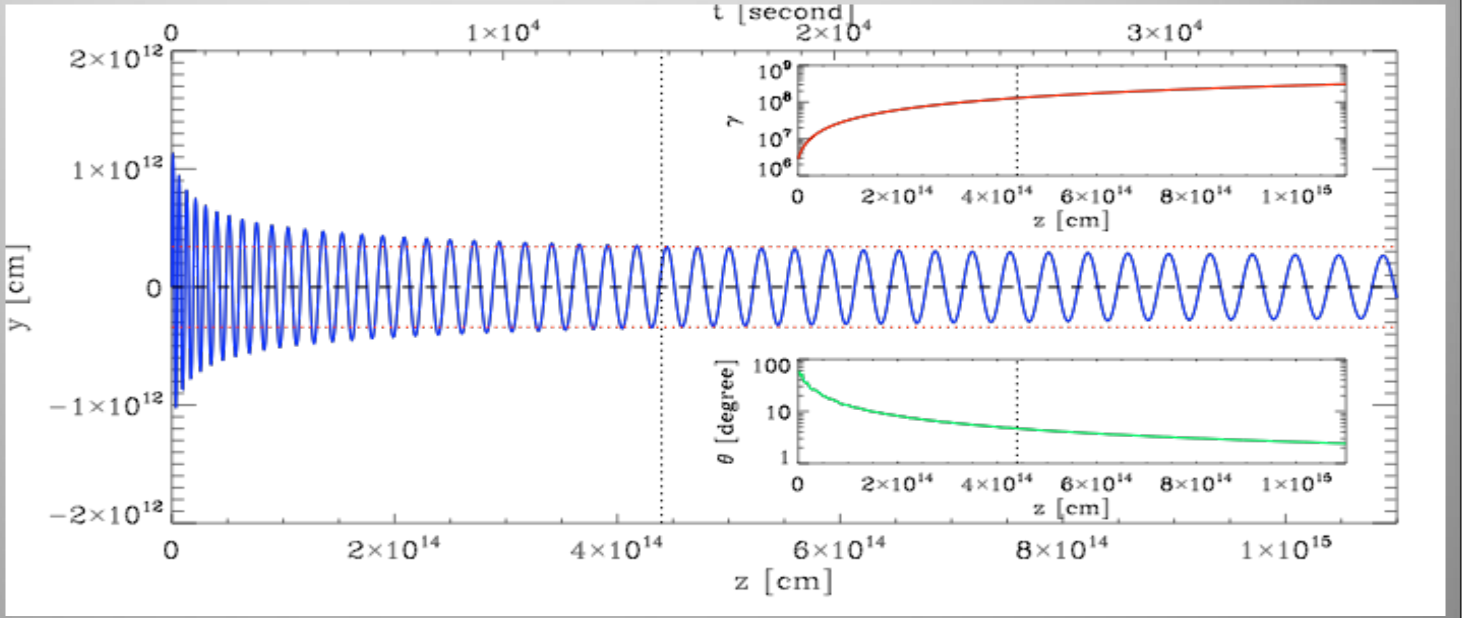


Under ideal MHD conditions: E<B ? ε_{max}< 160 MeV

(Guilbert+1983, de Jager+1996, Uzdensky+2011)

Speiser Orbits

- Most energetic particles: gyroradius > current sheet thickness
  - B- field field reverses during gyro-orbit
  - accelerated by E_z in z-direction [?] orbit stretched
  - particles become confined to current sheet
- Orbits focus towards midplane

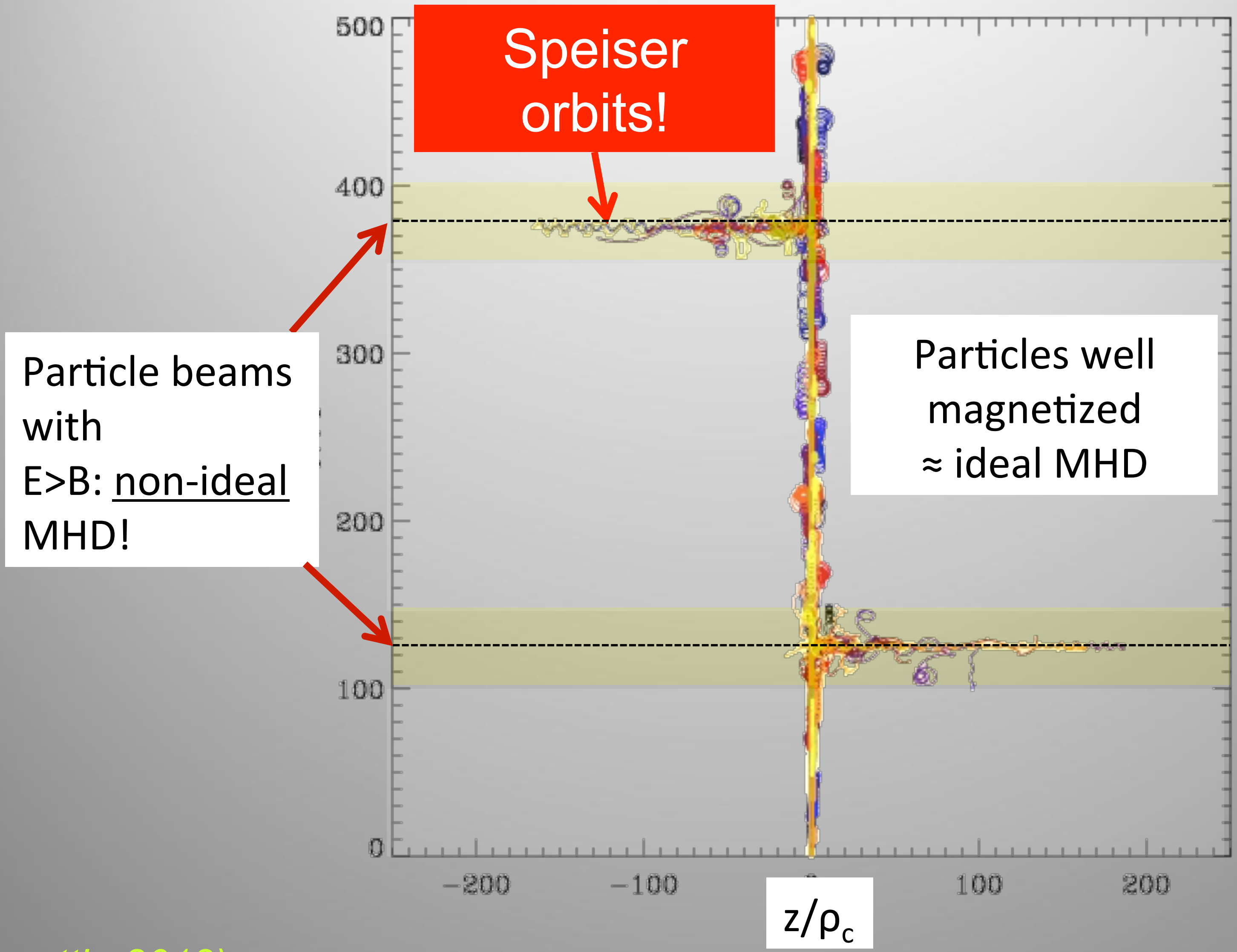


- Midplane B is small and radiation reaction is reduced
- Particles reach higher energies and emit photons with $\varepsilon > \varepsilon_{max}$

(Non-rel: Speiser 1965; Rel: Kirk 04, Uzdensky+ 2011)

Evidence for relativistic Speiser orbits

Sample of 150 particle orbits



(Cerutti+ 2013)

“Kinetic beaming”

- Beaming of radiation due to the strong energy-dependent particle anisotropy

- Distinct signature from Doppler beaming = energy-independent boosting

Energy-dependent synchrotron anisotropy

(Aitoff projection, $t = 397\ \omega_c^{-1}$)

$\Omega_{50\%}/4\pi = 0.35$

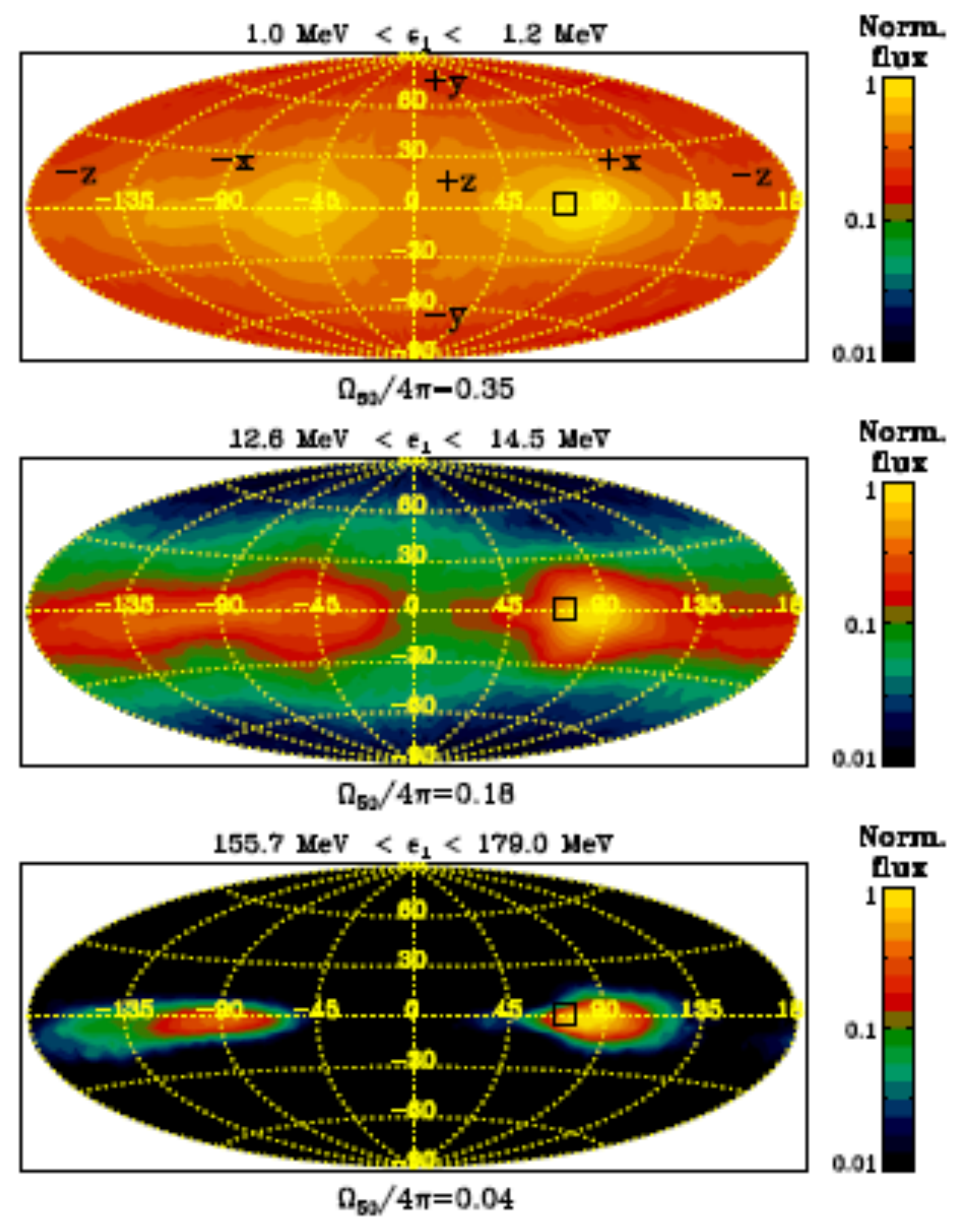
$\Omega_{50\%}/4\pi = 0.18$

$\Omega_{50\%}/4\pi = 0.04$

Solid angle containing 50% flux:

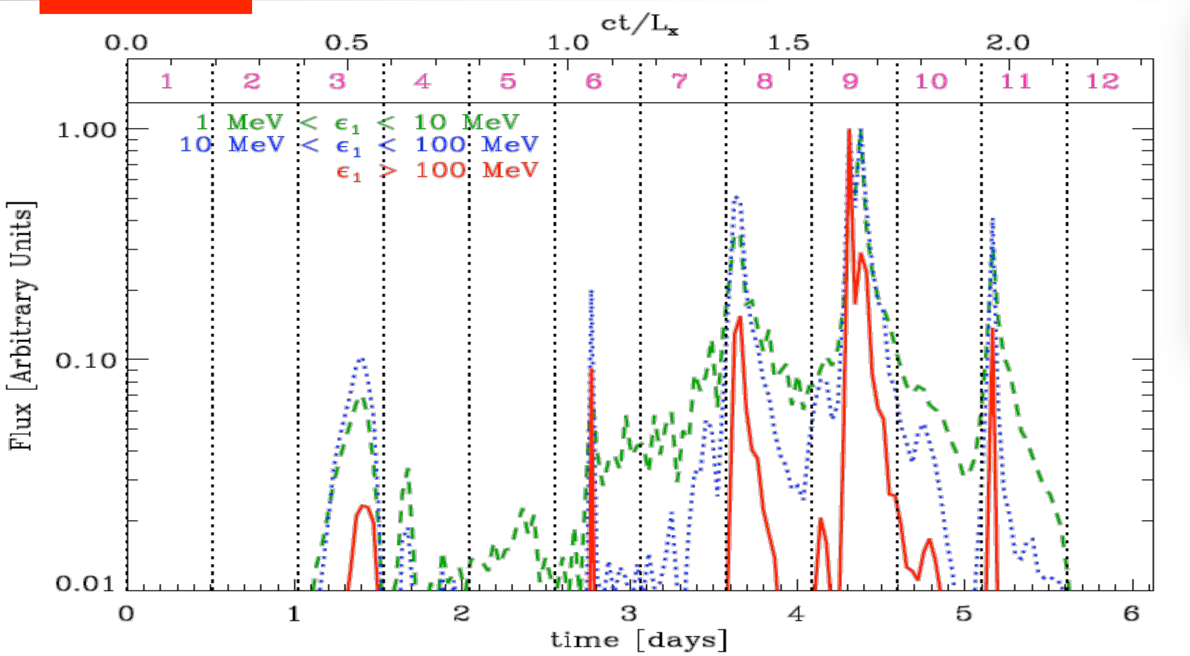
Variability from narrow beams swinging past observer

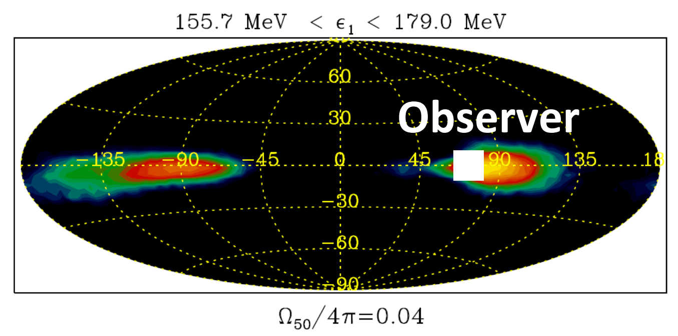
(Cerutti+ 2013)



Expected lightcurves – (Crab model)

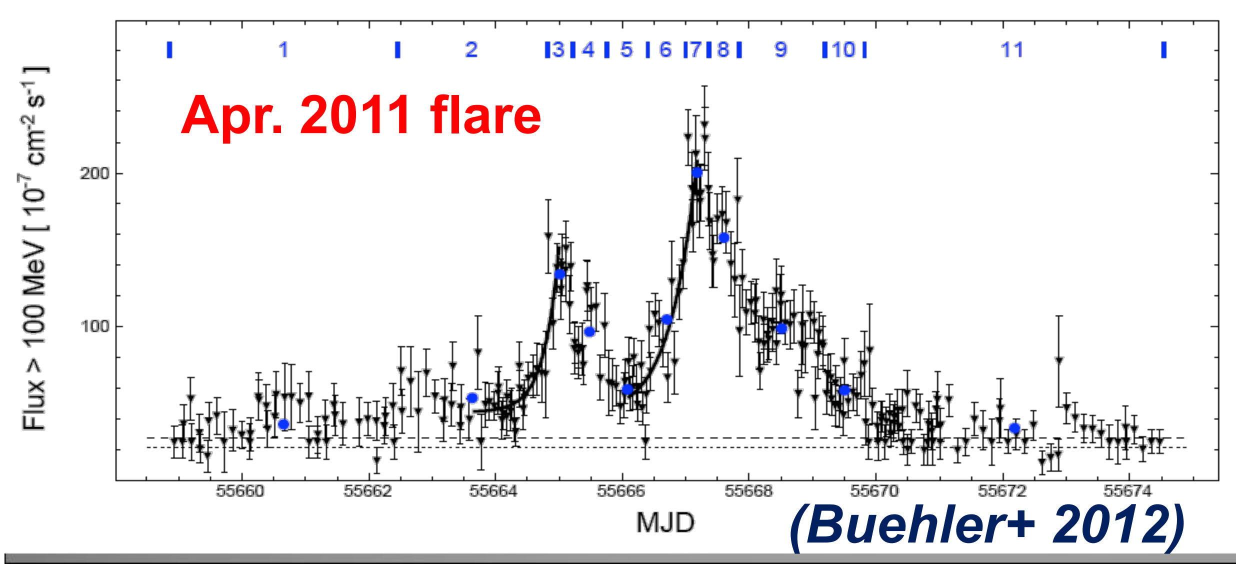
MODEL





Predicted ultra-short time variability < 6 hours due to particle bunching and anisotropy

OBSERVATIONS



Observed ultra-short time variability < 8 hours

SUMMARY…

- EM acceleration of relativistic jets can lead to conditions conducive to particle heating/acceleration
- Occurs at a moderate to high magnetization $\boxed{?}$
  - Disfavors shock acceleration
  - Favors reconnection in discrete current sheets or turbulence
- Large PIC simulations reveal robust phenomenology
  - Power-law indices: similar dependence on $\boxed{?}$ for reconnection/turbulence in pair/electron-ion plasma
  - High energy cutoffs
  - observed spectra consistent with $\boxed{?}$ ~ 1 (natural regulation?)
- Separate "linear accelerator" mechanism predicted by reconnection theory could explain hard $\boxed{?}$-ray flares