Particle Acceleration
in
astrophysical objects

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Acceleration sites

Astrophysical flows *ideal* (Reynolds number $\gg 1$)
Entropy generation localised at

- Shock fronts/discontinuities (kinetic energy) e.g.,
  - Radio SN, SNR
  - pulsar wind termination shock
  - jet boundary layers
- Current sheets (magnetic energy) e.g.,
  - Solar Corona: movement of foot-points of magnetic loops anchored in photosphere,
  - pulsar winds, jets

Talk contents

- Acceleration at shocks
  - basics
  - outstanding problems
- Current sheets
  - conventional picture
  - relativistic sheets
  - prospects for modelling. . .

Acceleration at shocks

- Kinetic energy dissipated at *collisionless* shock fronts.
- Nonresonant (energetic) particles escape thermalisation
- Energy extracted by (elastic) scattering off long wavelength (magnetic) fluctuations

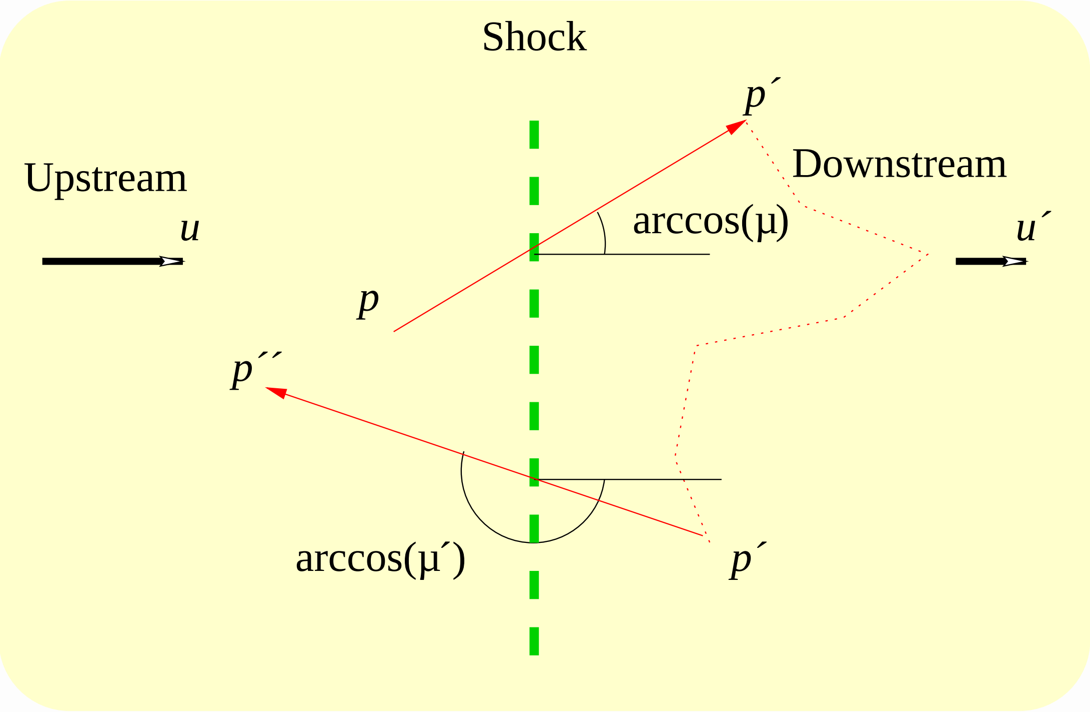
Non-relativistic flows: “diffusive shock acceleration” (DSA)

Krymsky, Bell, Axford et al, Blandford & Ostriker (1977/1978)

Diffusive Shock Acceleration

Scattering by (self-excited) turbulence around shock front

$$\frac{\Delta p}{p} = \frac{\Delta u}{v}(\mu - \mu')$$



Isotropy implies

$$\frac{\langle \Delta p \rangle}{p} = \frac{4\Delta u}{3v}$$

and escape probability downstream $= 4u'/v$

but in relativistic flows, things are different. . .

Nonrelativistic (DSA) vs. Relativistic

pitch-angle diffusion $\Rightarrow$ near-isotropy $\Rightarrow$ spatial diffusion	pitch-angle diffusion, particles in narrow, forward directed cone
solution of PDE in x, p required	solution of PDE in μ, x, p required
small escape probability, small $\langle \Delta p \rangle / p$ per cycle	escape probability ~ 0.5, $\langle \Delta p \rangle / p \sim \Gamma^2$ for first cycle, then ~ 2
power-law of index $s = 3r/(r-1)$, independent of scattering law	Asymptotically, $s = 4.23$, weakly dependent on scattering law

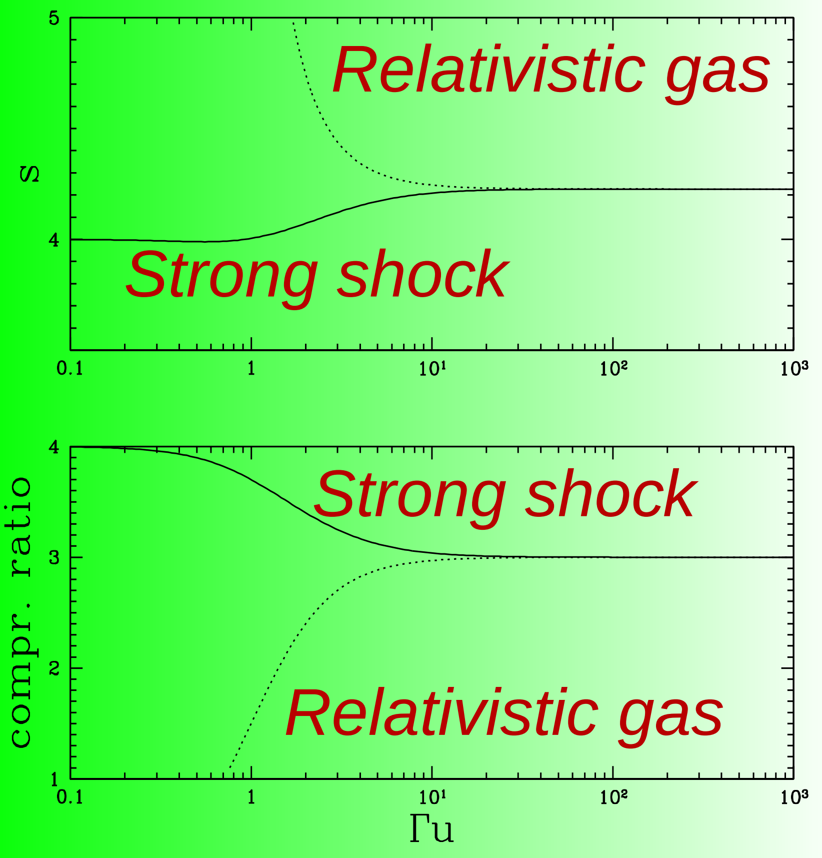
Analytic solution — relativistic shock

Eigenfunction expansion
$\Rightarrow$ angular dependence:

$$\frac{\exp\left(-\frac{1+\mu_{\mathrm{s}}}{1-\mu_{\mathrm{s}}u/c}\right)}{(1-\mu_{\mathrm{s}}u/c)^{s}}$$

As $\Gamma \to \infty$, $s \to 4.23$
Universal index?

Kirk et al ApJ 542, 235 (2000)



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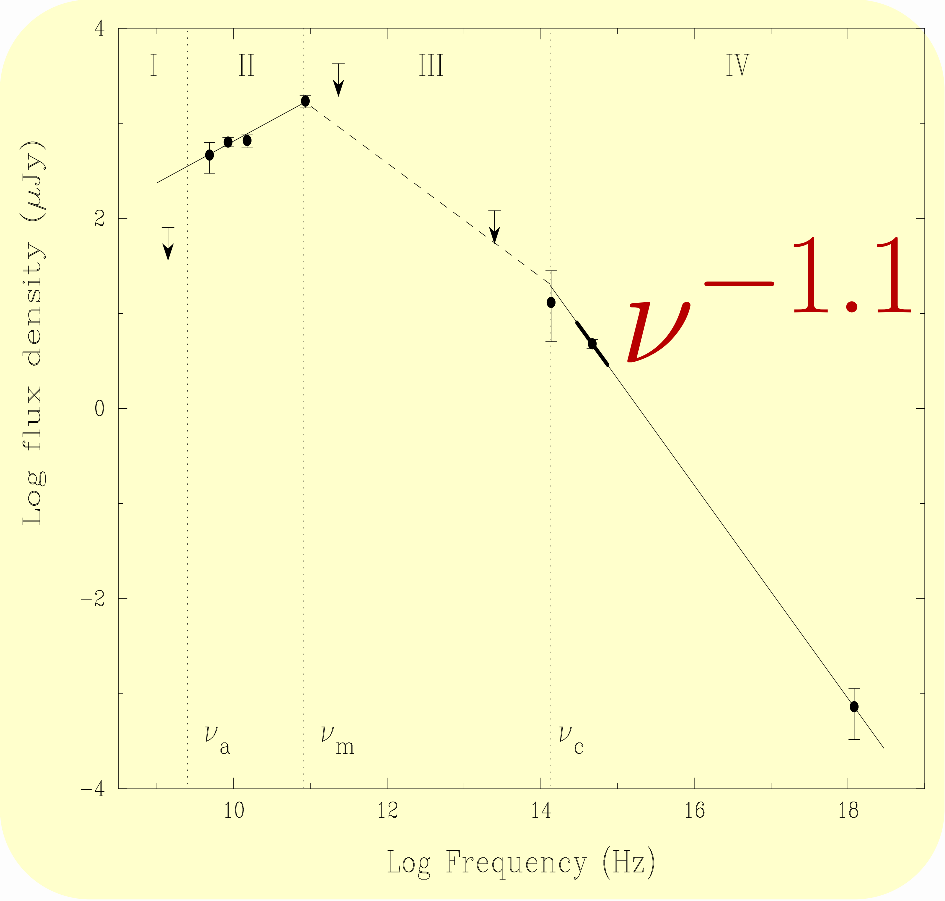
Afterglow observations *Galama et al 1998*



Continuous, constant injection:
for cooled electrons

$$\frac{d \ln F}{d \ln \nu} = -\frac{s-2}{2}$$

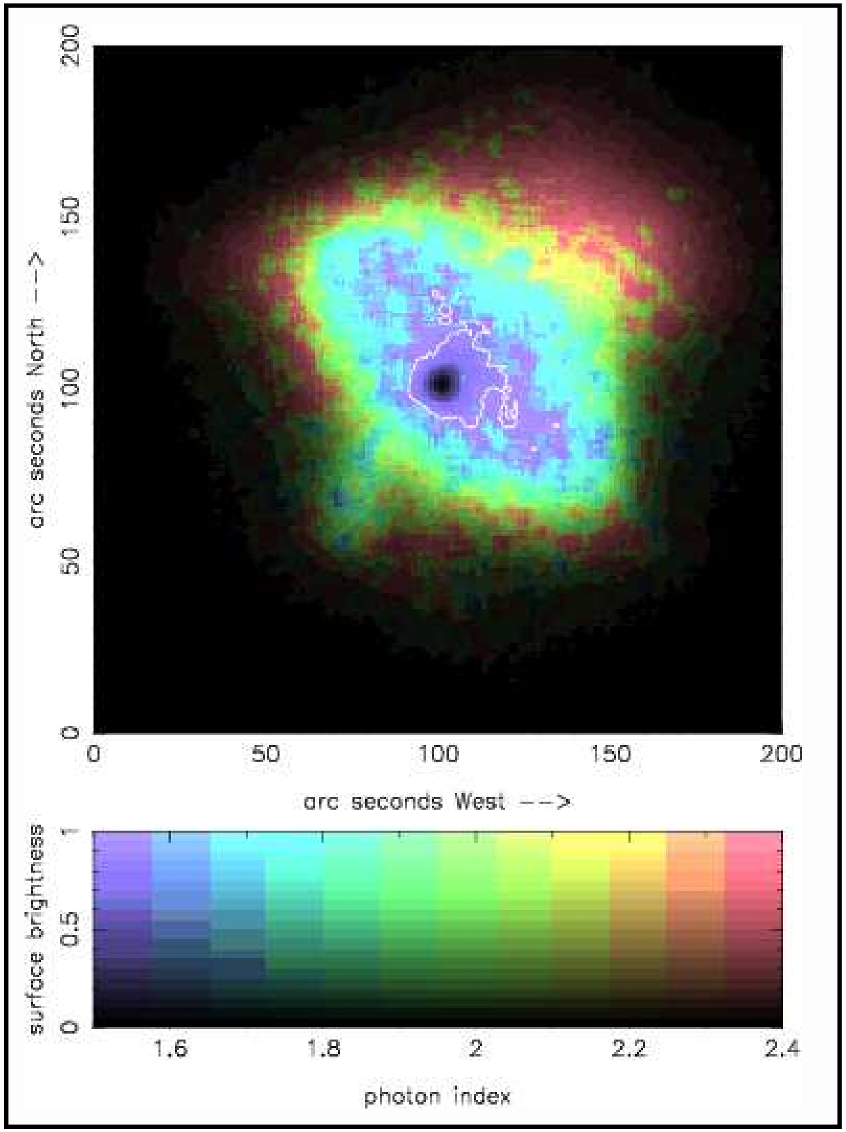
Crab Nebula

XMM-Newton
Willingale et al 2001

$$N(\gamma) \quad \propto \quad \gamma^{2-s}$$

Centre: $s \approx 4.2$

Edge: $s \approx 4.2 + 1$



Shock acceleration — problems

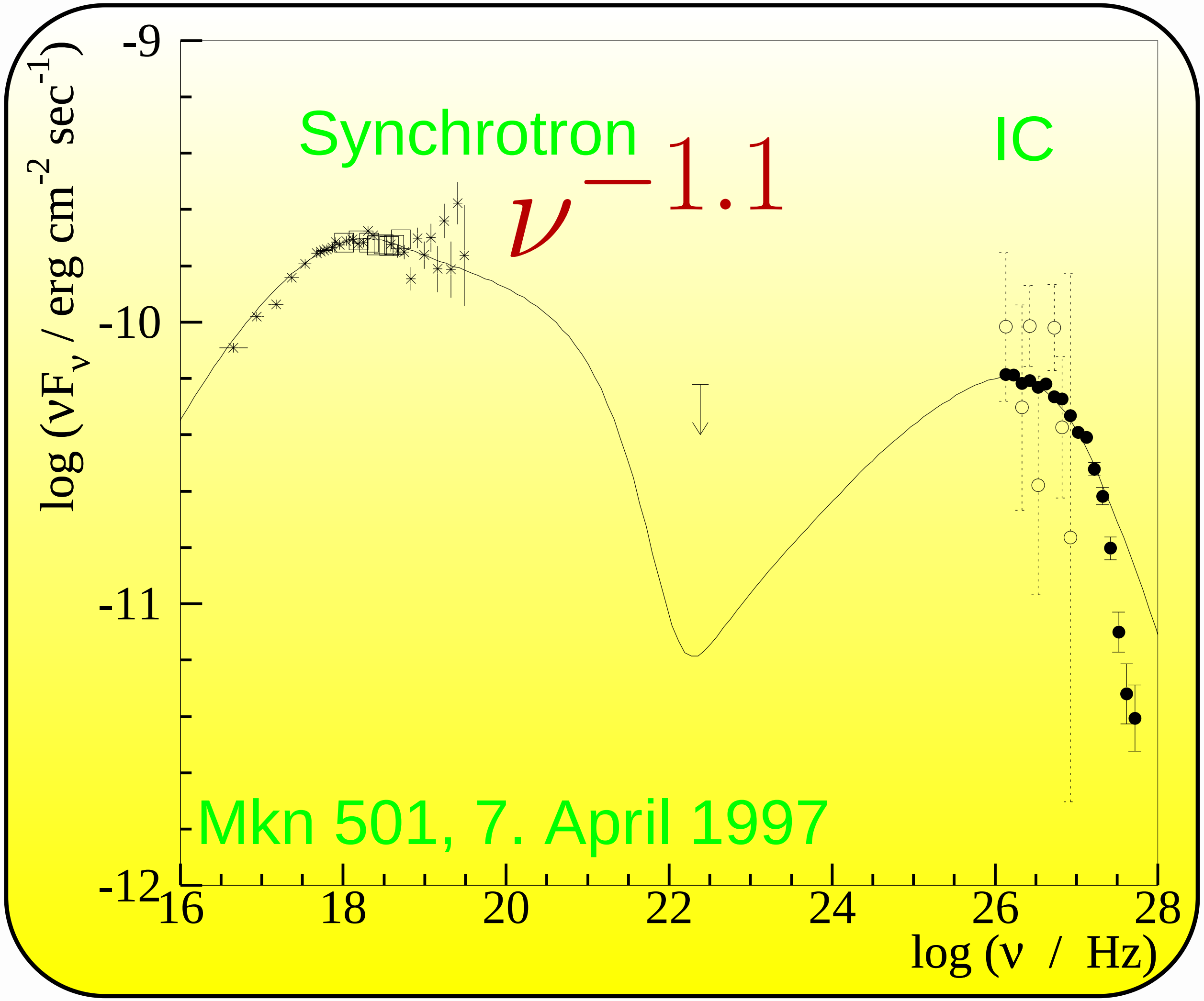
- Magnetic field generation
  - nonlinear evolution of streaming instability in precursor *Bell & Lucek 2001*
  - Weibel instability of postshock plasma

    Medvedev & Loeb 1999, Silva et al 2003
- Injection
  - energization by counterstreaming beam

    McClements 2001, Malkov 1998
  - parallel or perpendicular shocks?

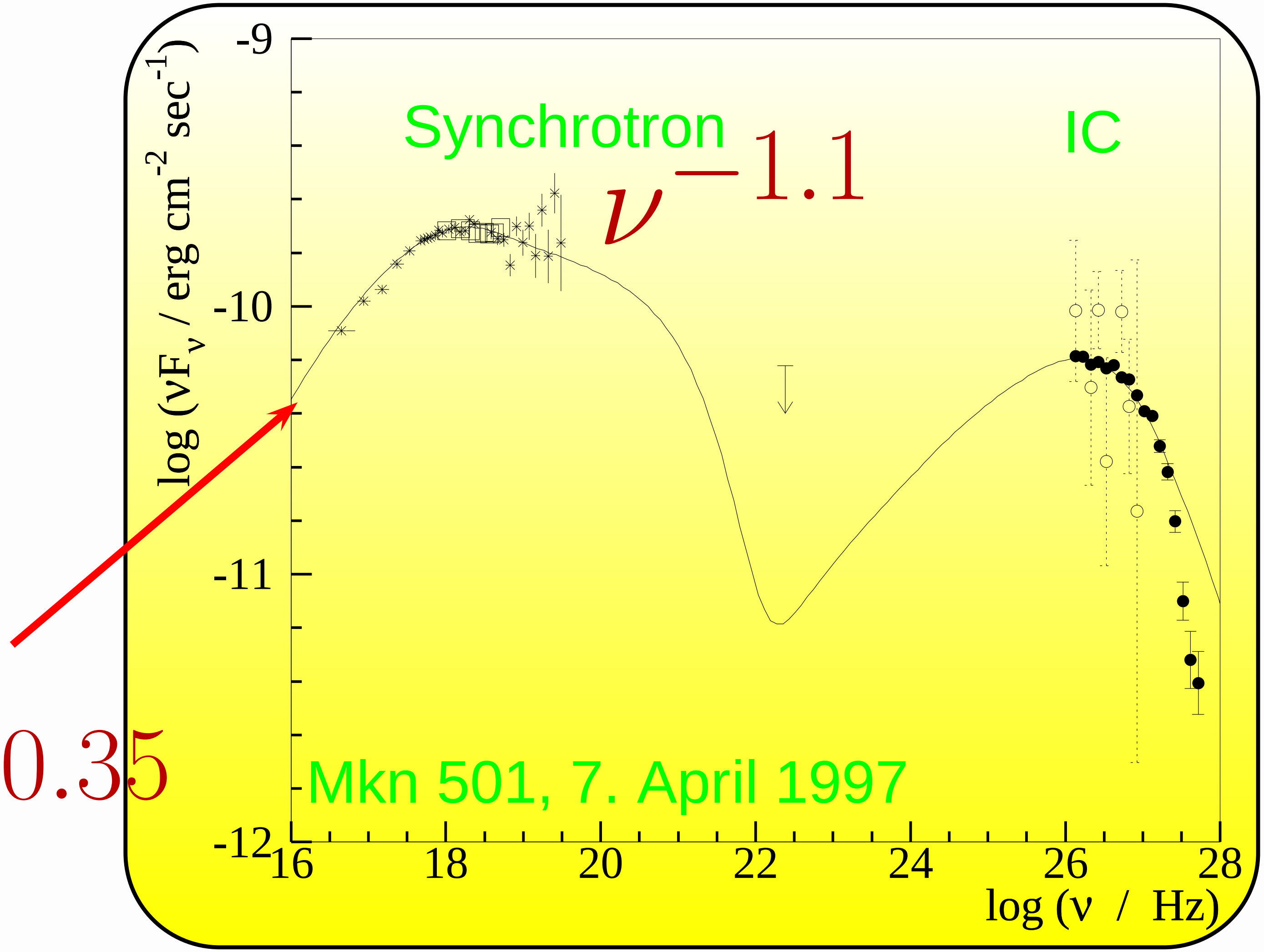
    Fulbright & Reynolds 1990, Völk et al 2003
  - ion/electron coupling *Hoshino et al 1992, Amato et al 2003*
  - dissipation of magnetic energy. . .

Homogeneous SSC model



Krawczynski et al (2000)

Homogeneous SSC model

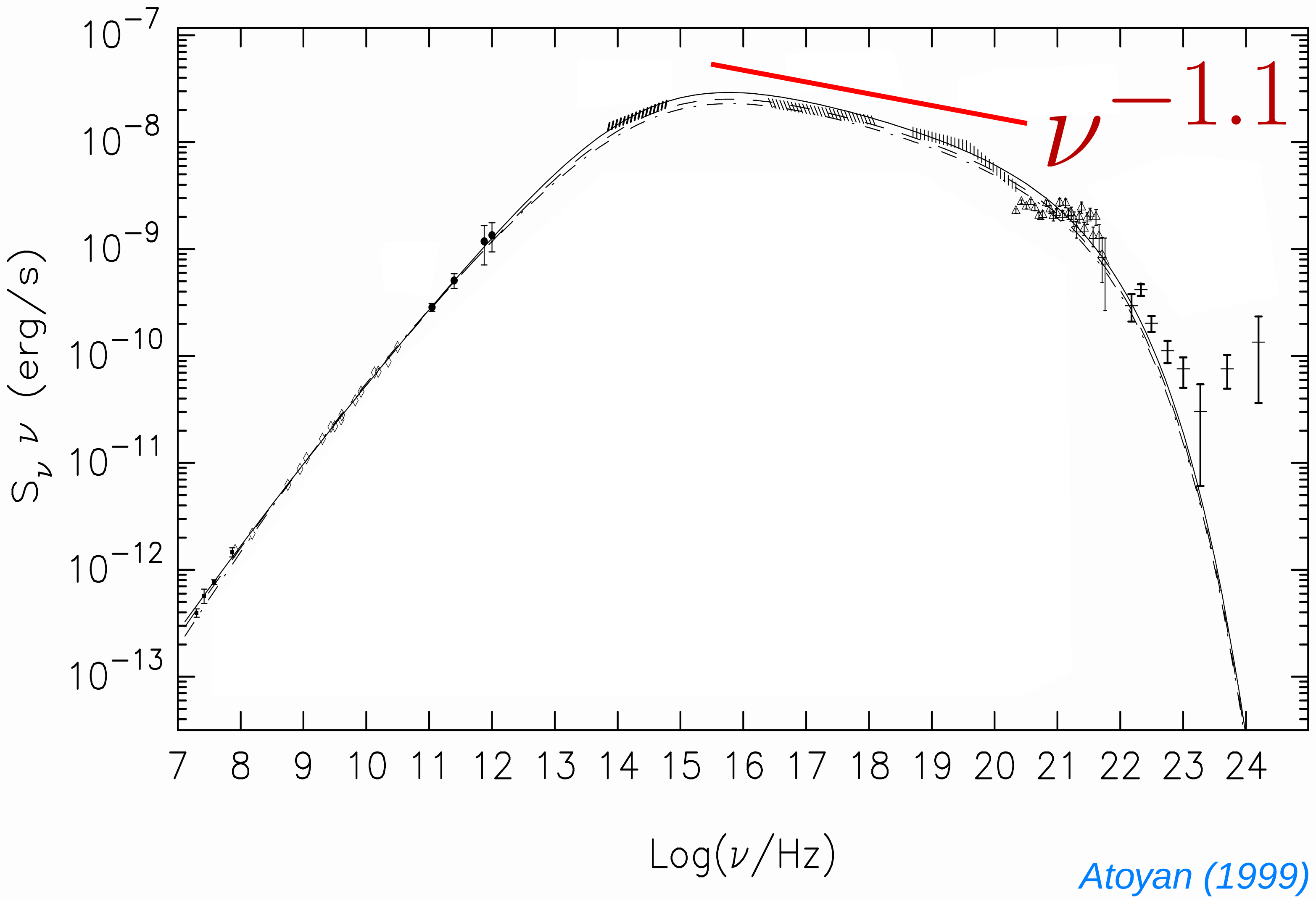


$\nu^{-1.1}$

$\nu^{-0.35}$

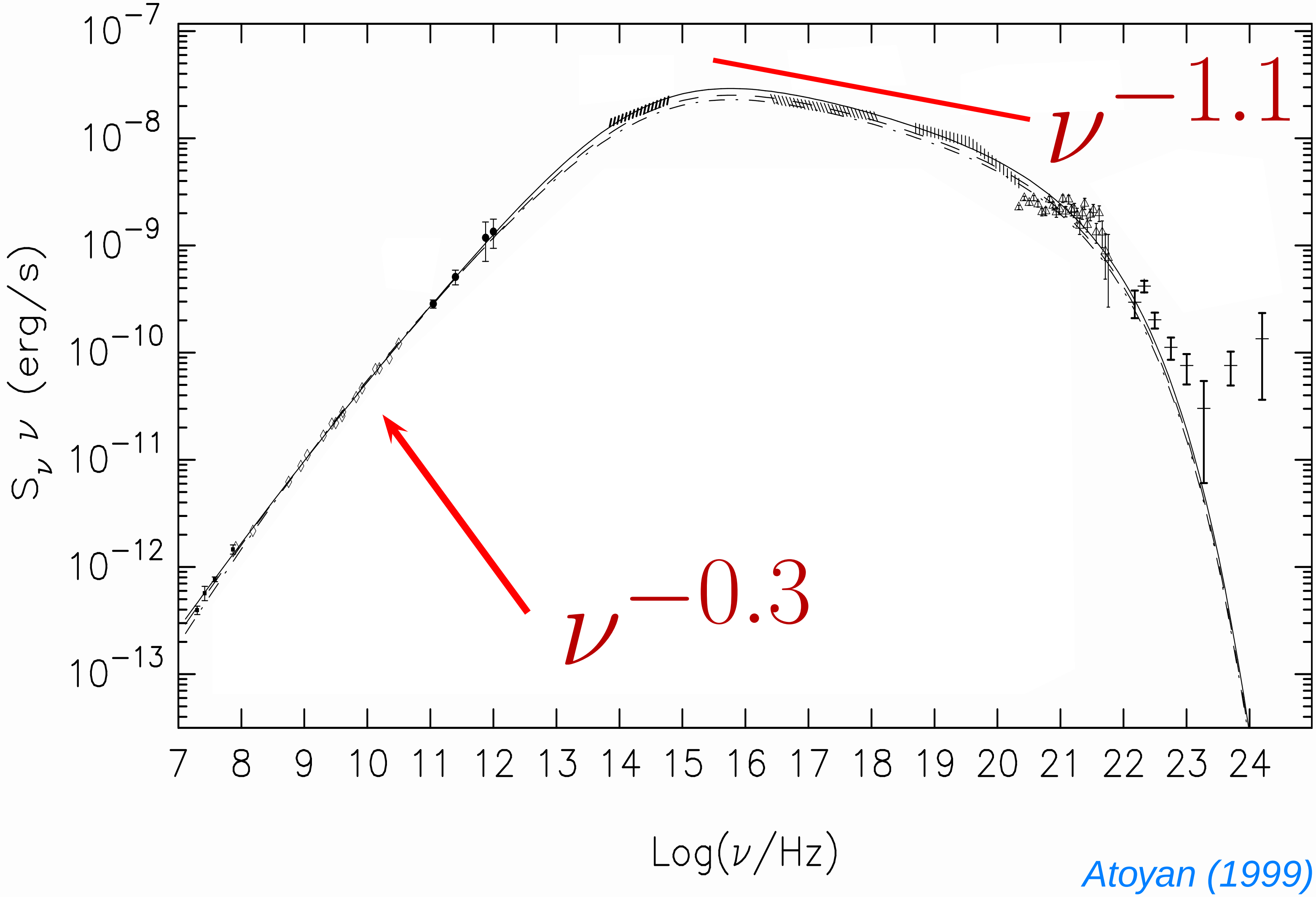
Krawczynski et al (2000)

Crab Nebula



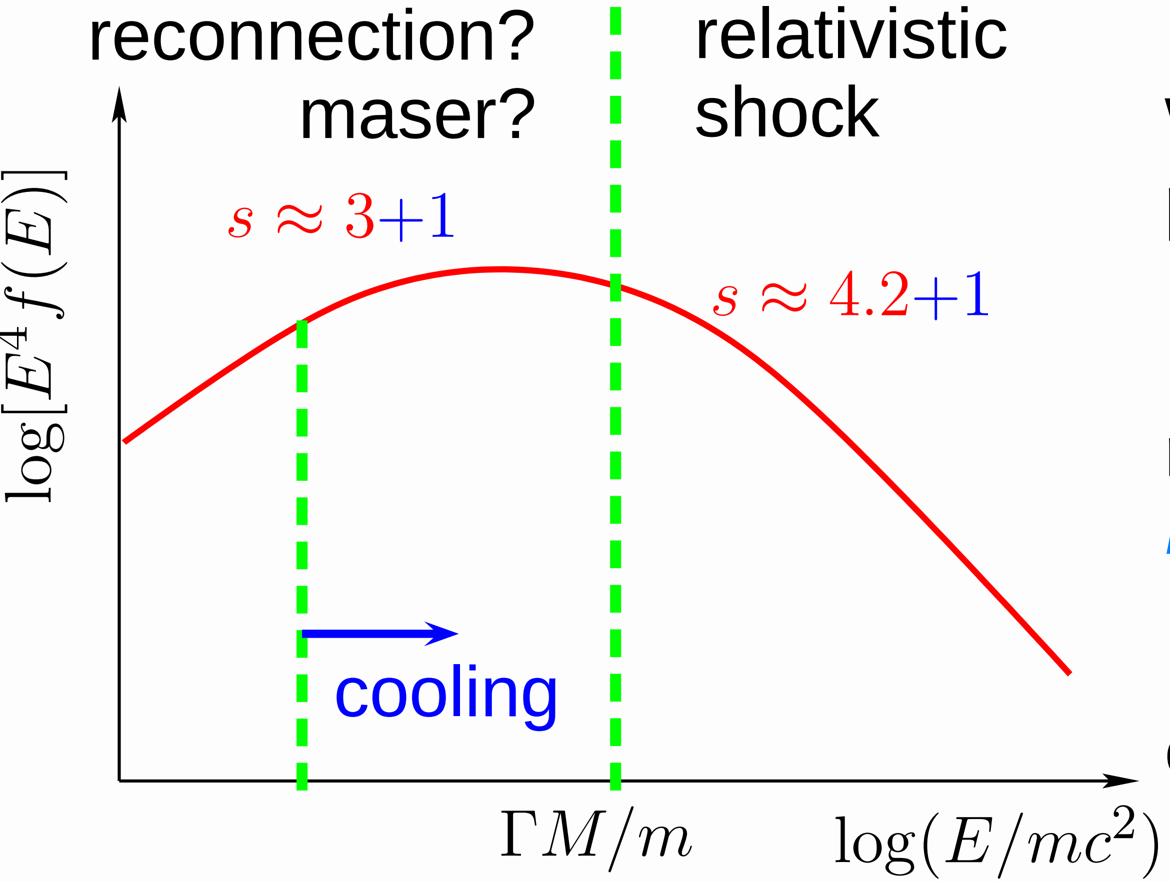
Atoyan (1999)

Crab Nebula



Atoyan (1999)

Injection problem?

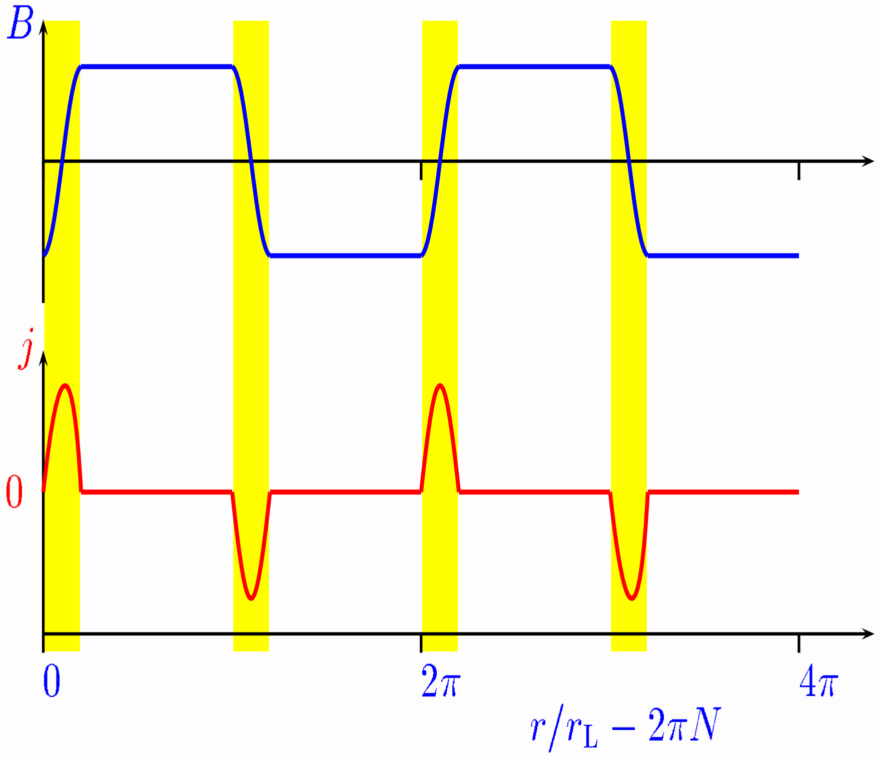


Width ≈ gyro radius of particles carrying the energy

Lower energy: ion/positron resonance
Hoshino et al 1992

Higher energy: shock effectively thin

Current sheets



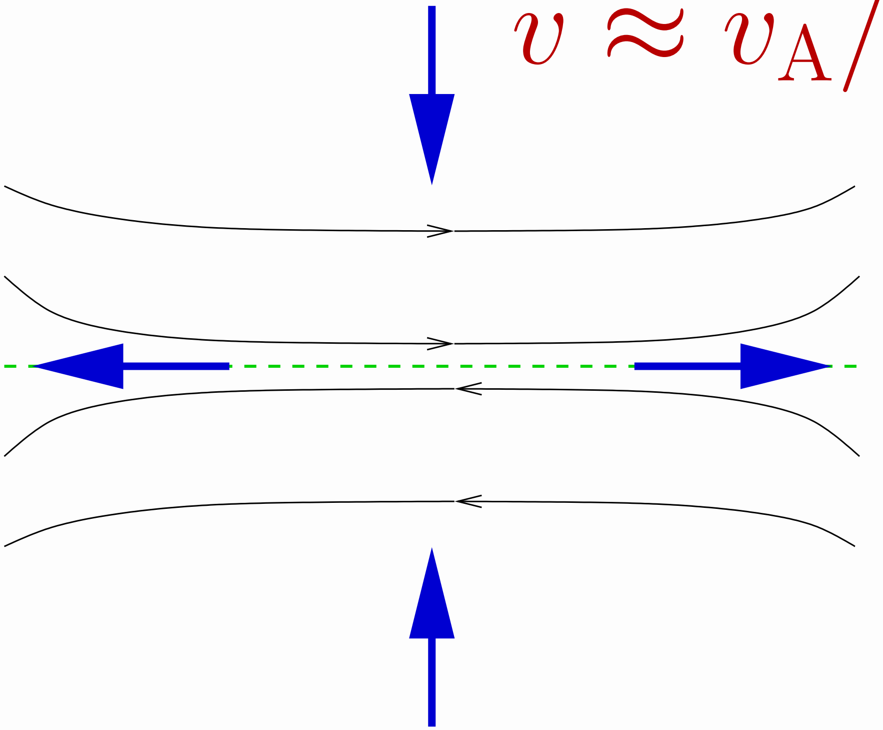
Magnetic pressure balanced by hot plasma in sheet.

Key question:

What controls the dissipation rate?

Sweet-Parker reconnection

Nonrelativistic, 2D picture



$$v \approx v_{\mathrm{A}}/R^{1/2}$$

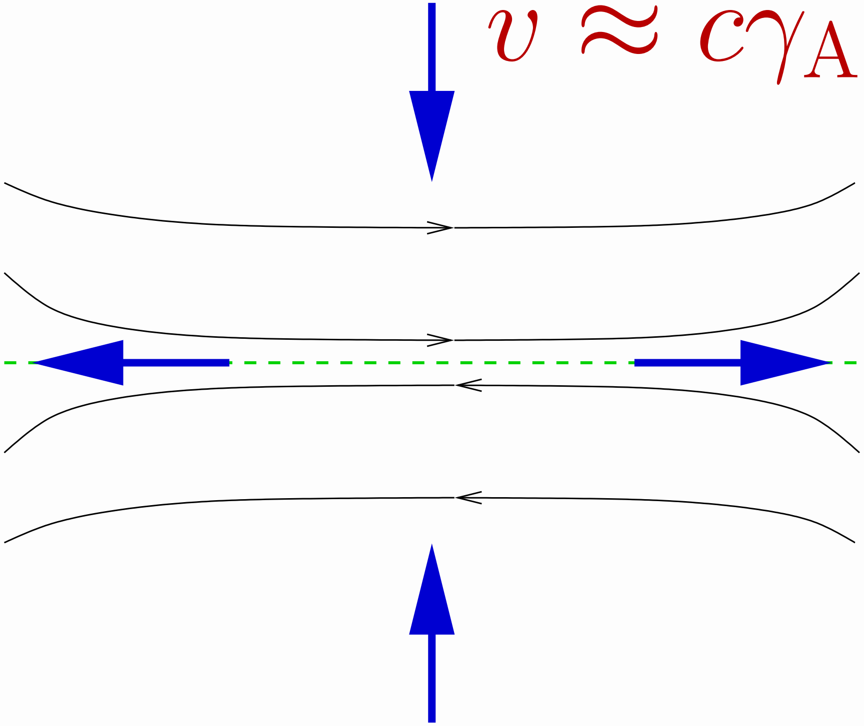
$$v \approx v_{\mathrm{A}}$$

Plasma ejected at approximately Alfvén speed.

Dissipation rate controlled by boundary conditions (R)

Resistive relativistic reconnection

Lyutikov & Uzdensky 2003



$$v \approx c\gamma_{\mathrm{A}}/R^{1/2}$$

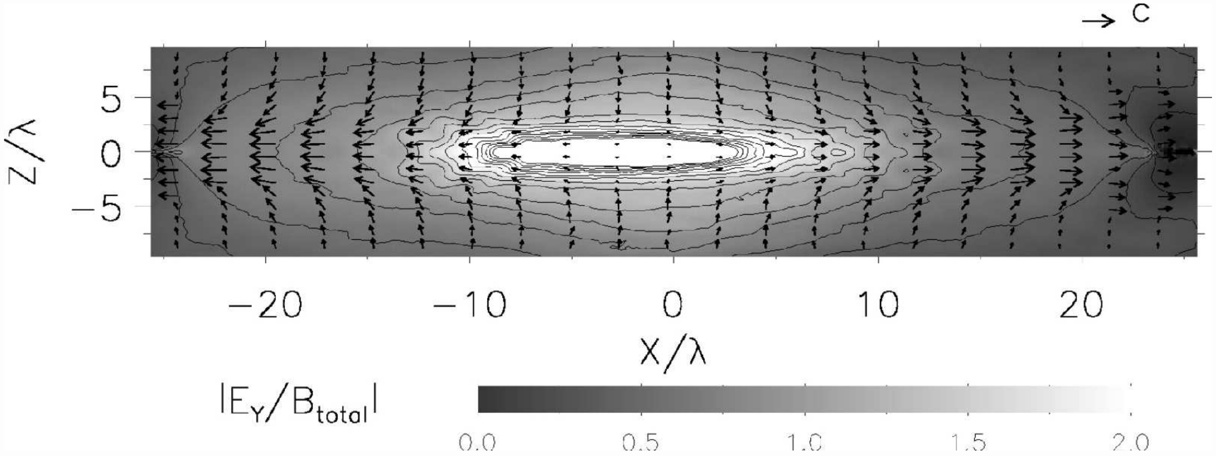
$$\gamma \approx \gamma_{\mathrm{A}}^2$$

Magnetization parameter $\sigma = B^2/(4\pi w) \approx \gamma_{\mathrm{A}}^2 \gg 1$
Nonrelativistic inflow for $\sigma \ll R$.

Additional regimes with relativistic inflow possible…

Collisionless relativistic reconnection

Zenitani & Hoshino (2001): Relativistic PIC simulations, $\sigma \approx 1$



Collisionless relativistic reconnection

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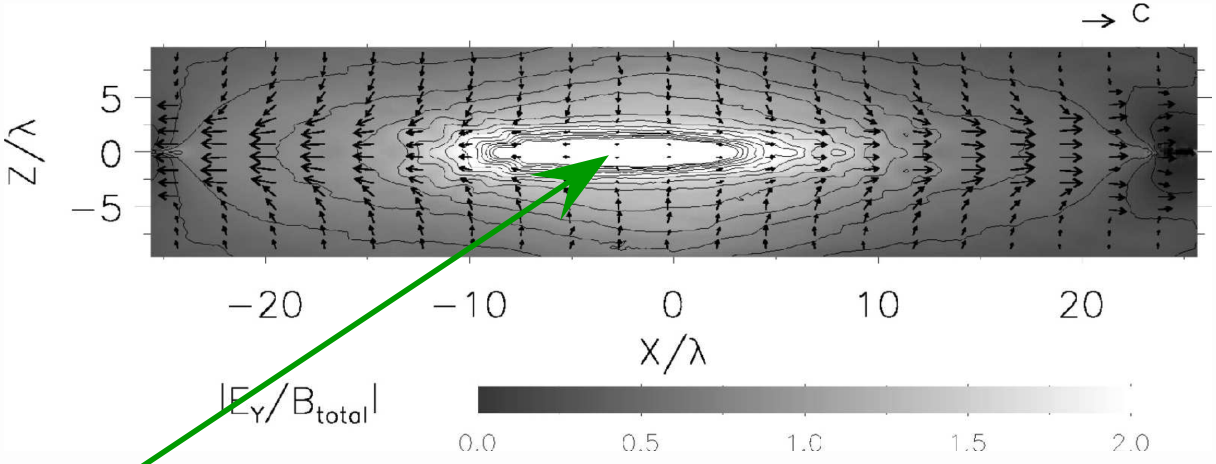
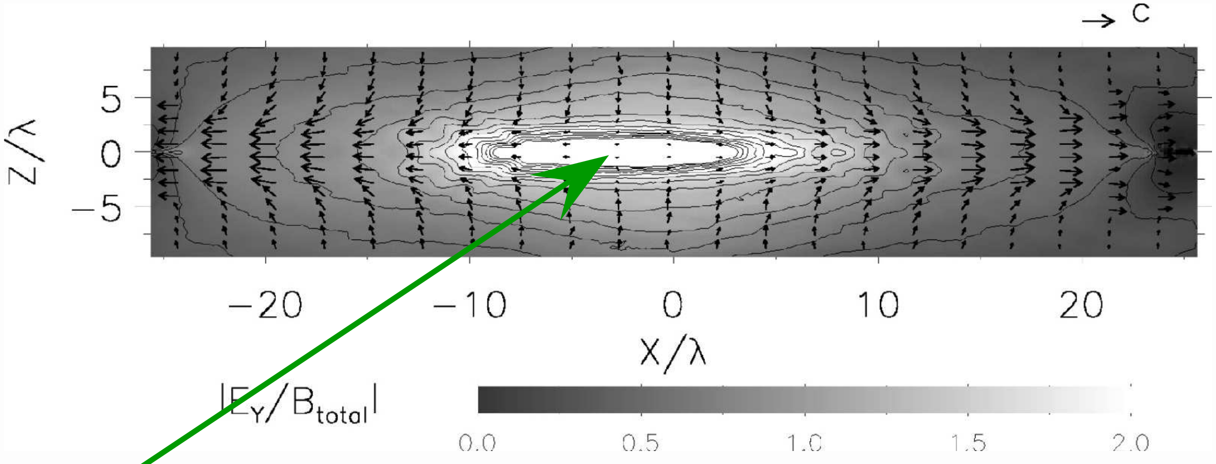


Acceleration Region with $E > B$

Collisionless relativistic reconnection

Zenitani & Hoshino (2001): Relativistic PIC simulations, $\sigma \approx 1$

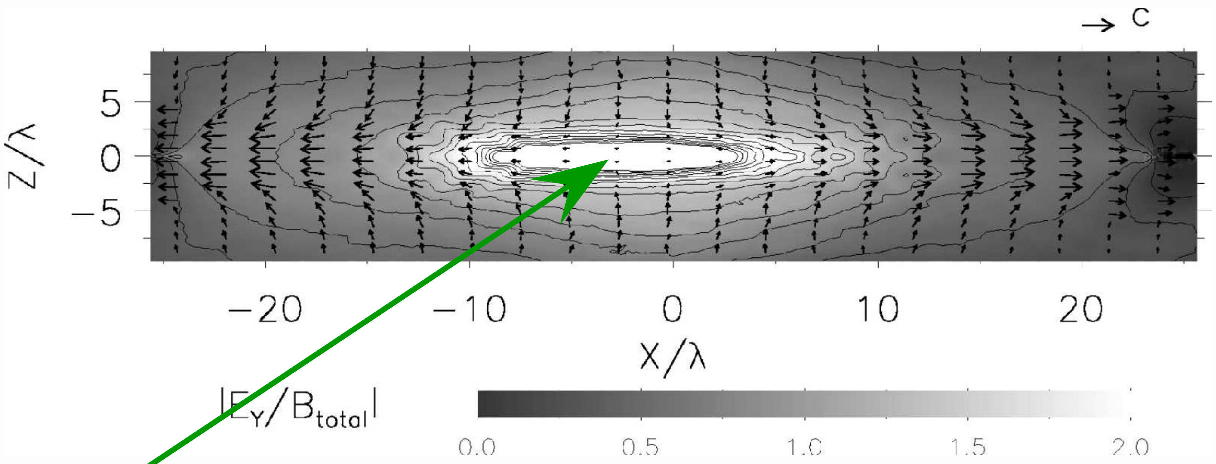


Acceleration Region with $E > B$

Particle ejection by gyration in B_z-field *Speiser 1965*

Collisionless relativistic reconnection

Zenitani & Hoshino (2001): Relativistic PIC simulations, $\sigma \approx 1$



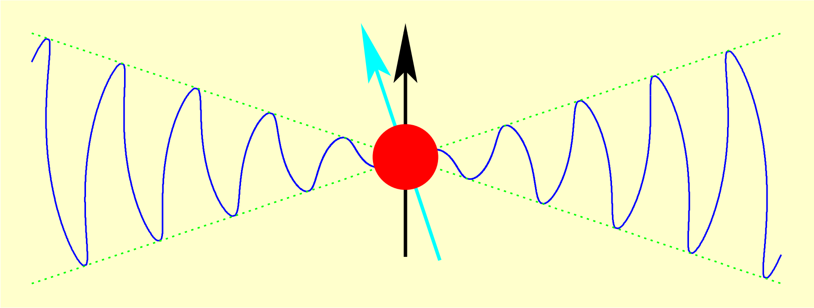
Acceleration Region with $E > B$

Particle ejection by gyration in B_z-field *Speiser 1965*

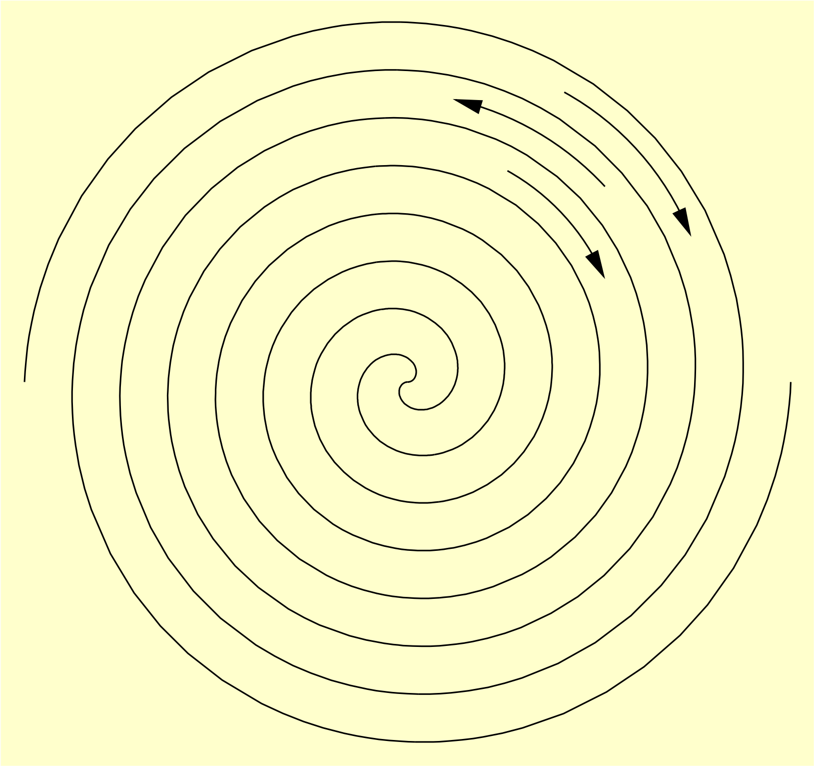
Escape rate $eB_z/\gamma mc \Rightarrow d\ln N/d\ln\gamma = -2B_z/E \approx -1$

Striped wind I

Oblique, split-monopole solution *Bogovalov 1999*



Meridional plane



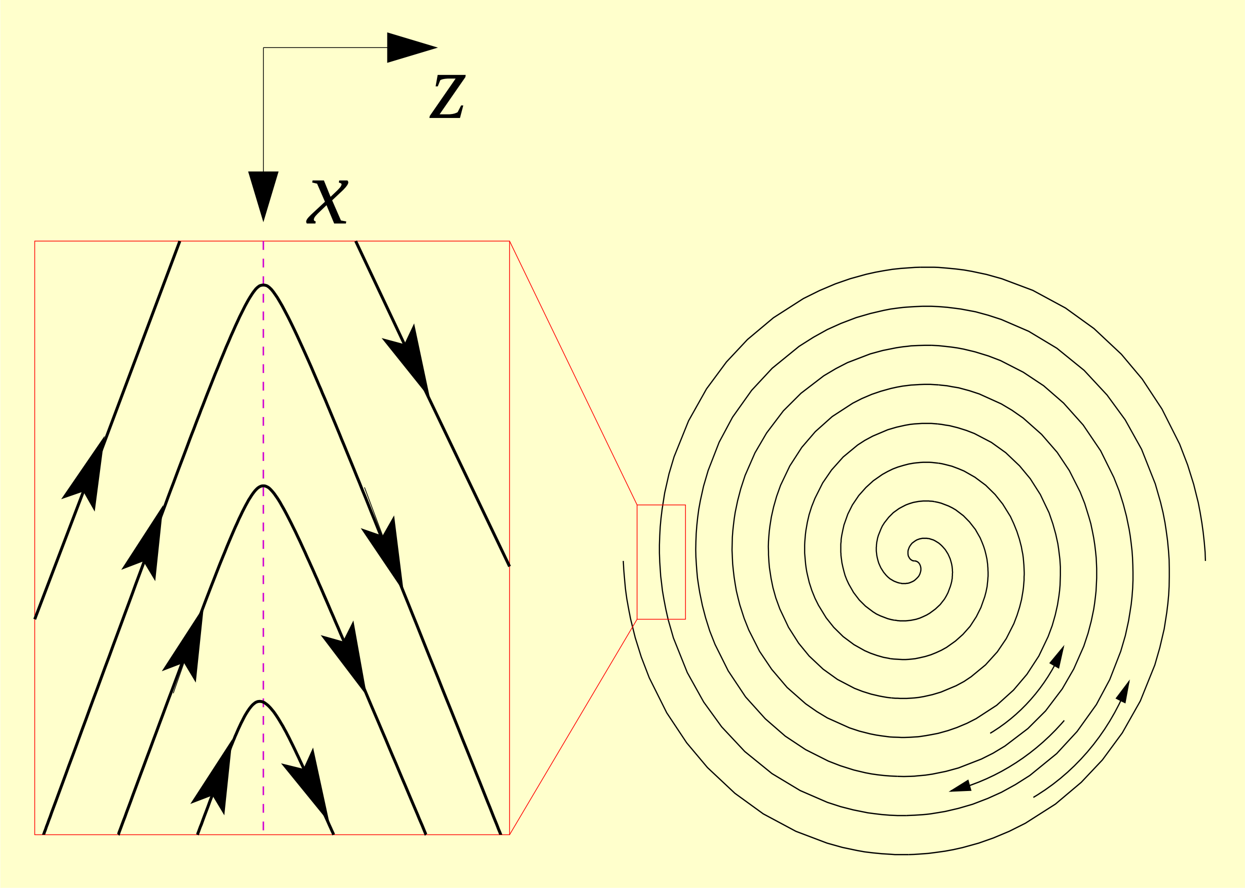
Equatorial plane

The *striped wind* *Coroniti 1990*

Reconnection inside termination shock?

Lyubarsky & Kirk 2001, Kirk & Skjæraasen 2003, Lyubarsky 2003

Striped wind II



Stationarity $\Rightarrow$ superluminal “drift” speed

B_z cannot eject particles $\Rightarrow$ finite length in y direction

Maximum energy I

Standard estimate *Alfvén (1968); Vasyliunas (1980)*

Rate at which particles enter sheet:

$$\dot{N} \quad = \quad 2nc\Delta x\Delta y\frac{\vec{E}\wedge\vec{B}}{B^2}$$

Ampère’s law in comoving frame:

$$\begin{aligned}\left(\frac{c}{4\pi}\right)2B\Delta x &= I \\ &> e\dot{N} \\ \Rightarrow \qquad & \boxed{\frac{eE\Delta y}{mc^2} = \gamma_{\rm max} < \frac{B^2}{4\pi nmc^2}}\end{aligned}$$

Maximum energy II

In terms of the magnetization parameter

$$\sigma = \frac{B^2}{4\pi w}$$

The maximum Lorentz factor is

$$\gamma_{\max} = 2\sigma,$$

in a cold electron-positron plasma and

$$\gamma_{\max} \approx \sigma \qquad \text{for protons}$$

$$\gamma_{\max} \approx \sigma M/m \qquad \text{for electrons,}$$

in a cold electron proton plasma.

Summary

- Basics of acceleration at nonrelativistic and relativistic shocks well-understood
- Some stubborn problems — injection and magnetic field generation
- Basics of reconnection complicated
- Relativistic generalization of Sweet-Parker → hard spectra
- Generic topology may be different, but estimates of maximum energy possible