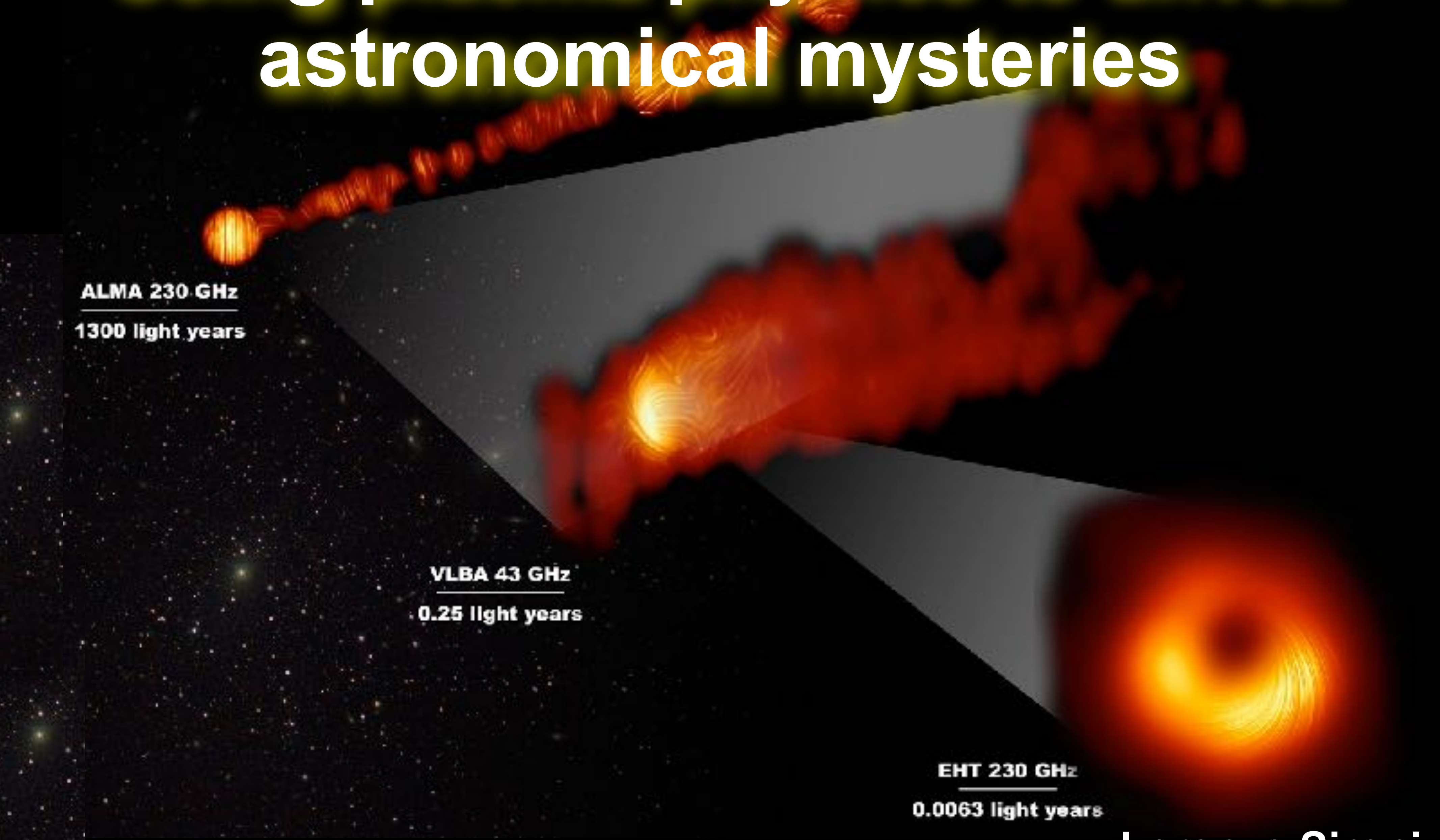
Using plasma physics to unveil astronomical mysteries

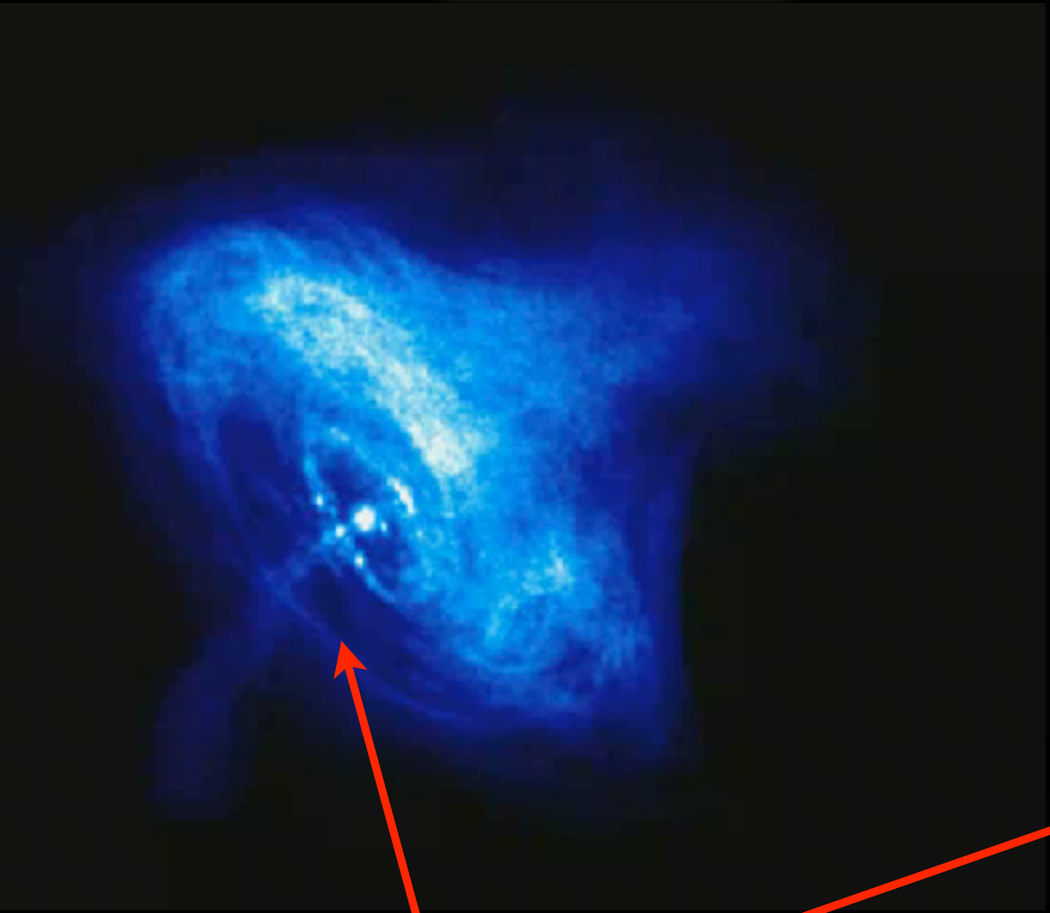


Lorenzo Sironi
Department of Astronomy, Columbia University

NSF/APS-DPP GPAP summer school 2021

The astrophysical “engines”

Crab Nebula



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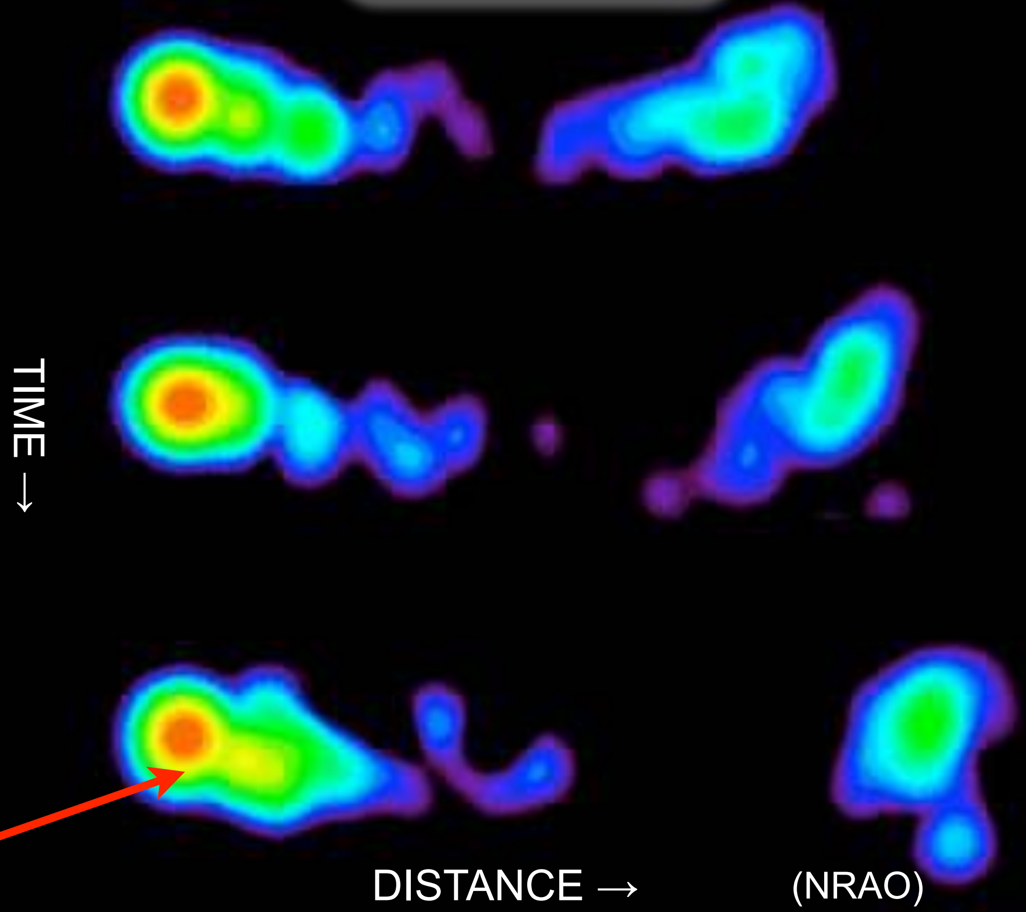


(NRAO)

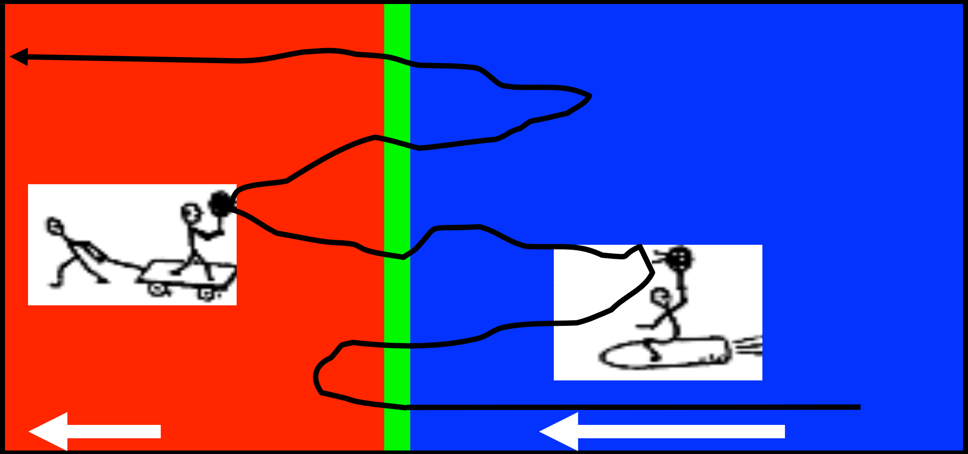
Dissipation Sites: Shocks or Reconnection?

The astrophysical “engines”

Shocks

Magnetic Reconnection

The Fermi process

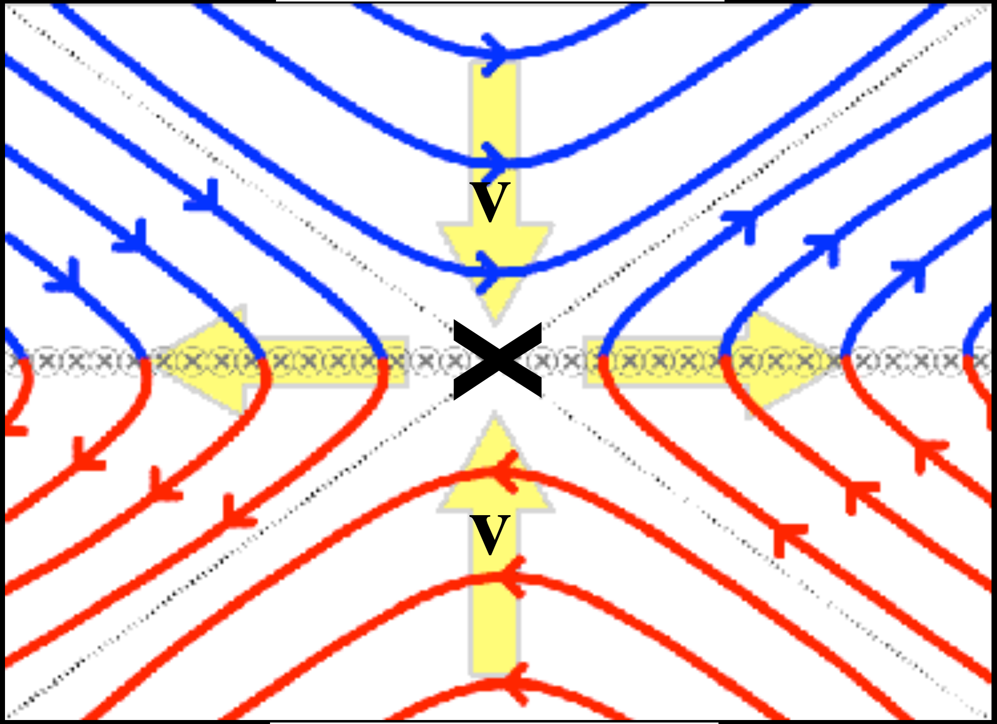


Shock

downstream

upstream

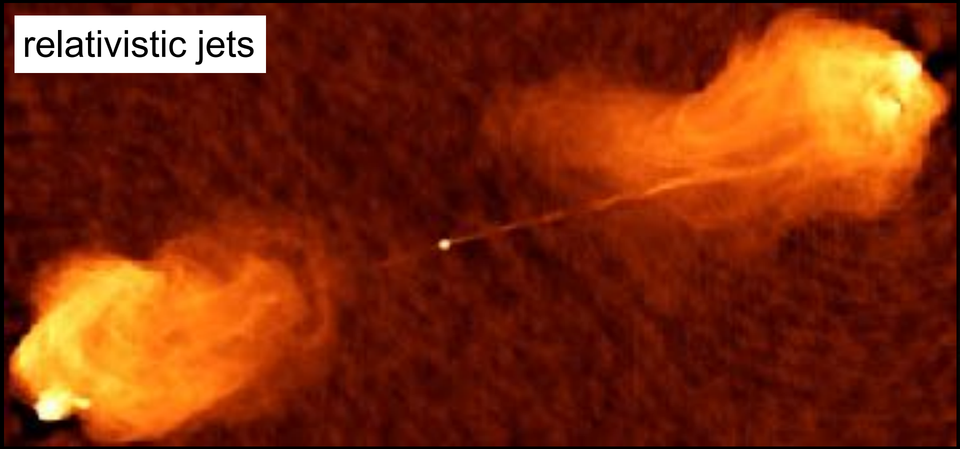
reconnecting field

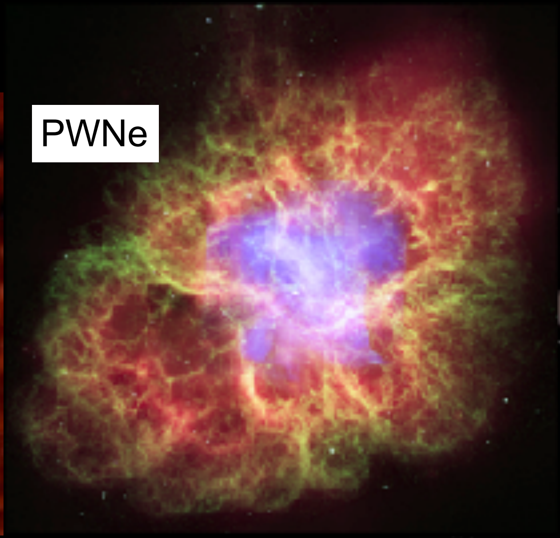


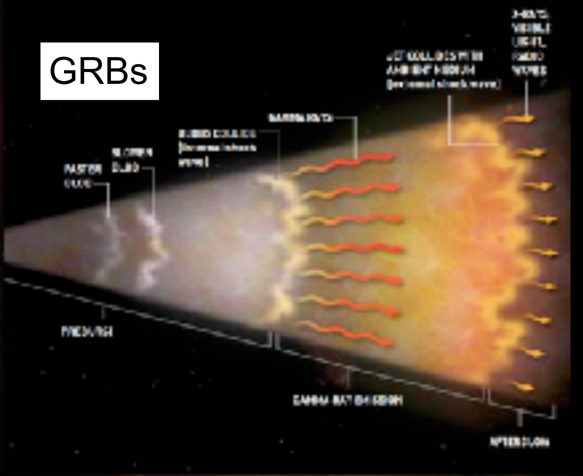
reconnecting field

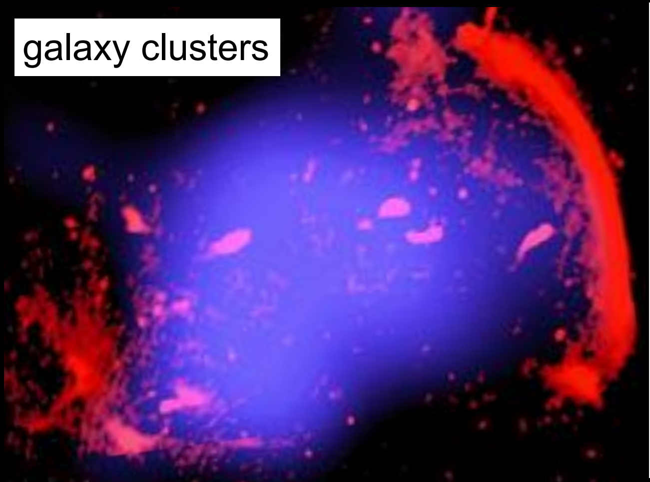
The astrophysical “exhausts”

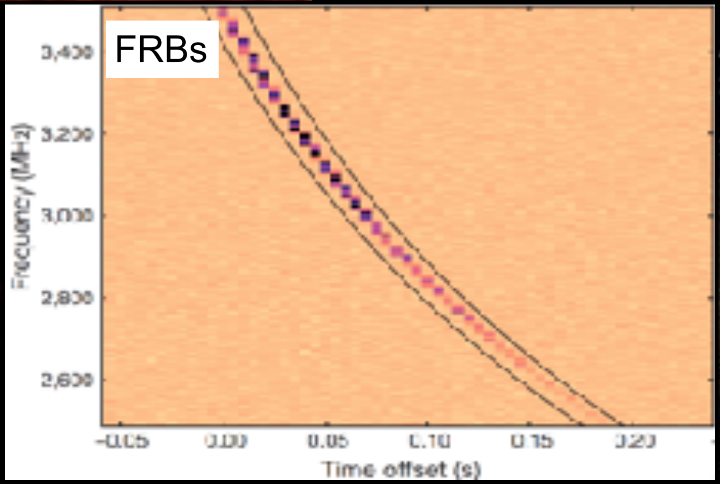
Light and particles from astronomical high-energy sources

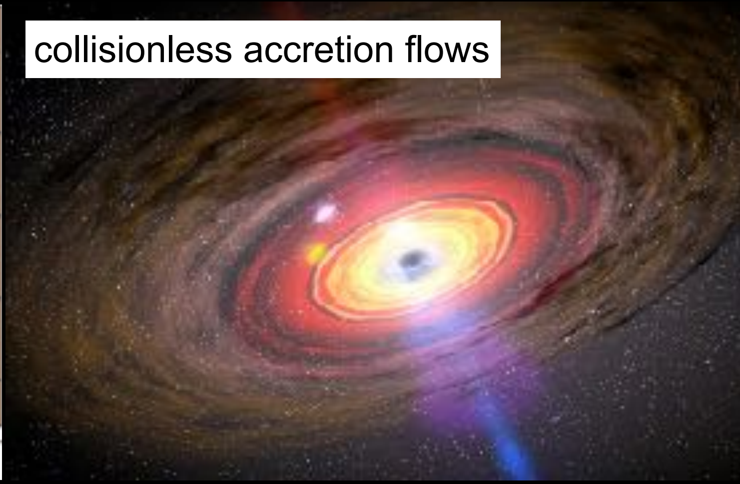

relativistic jets


PWNe

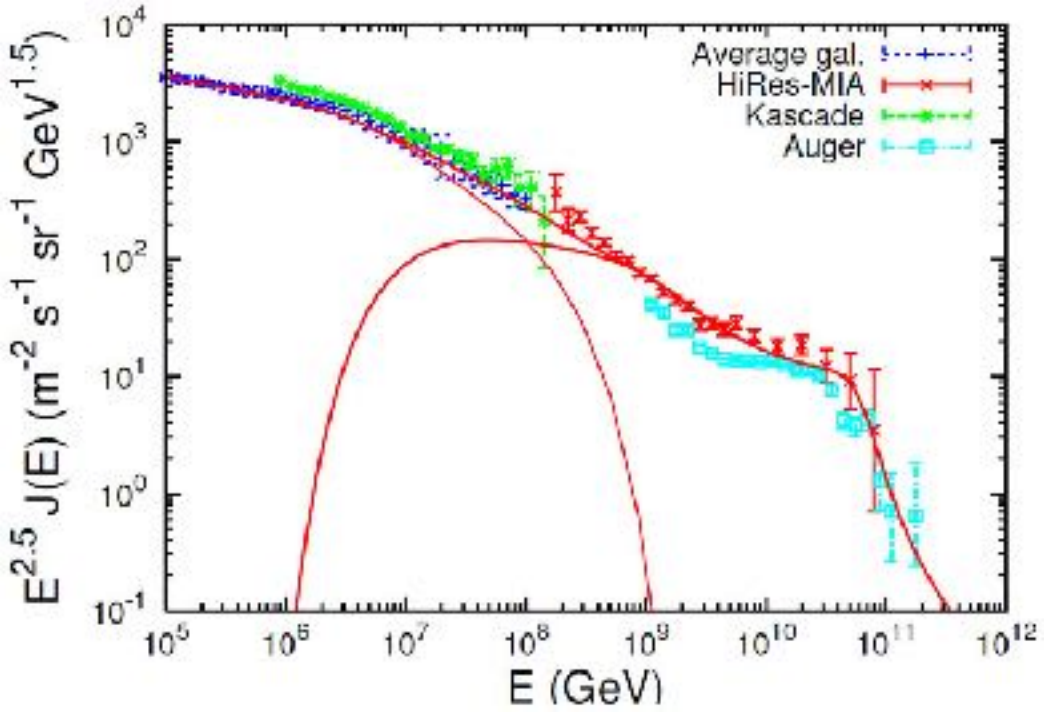

GRBs


galaxy clusters


FRBs


collisionless accretion flows

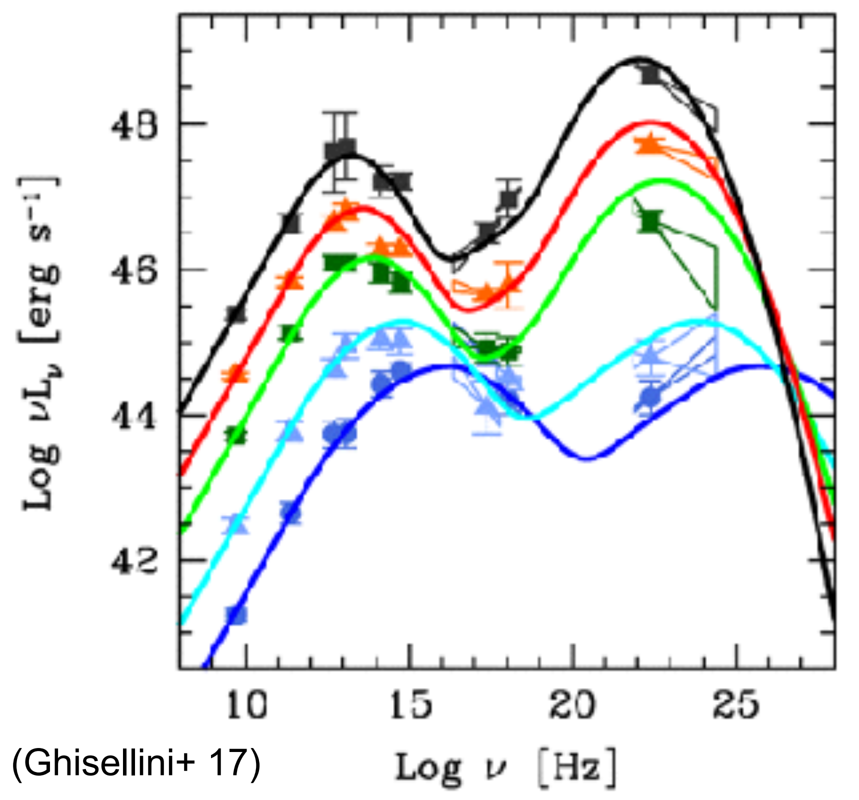
Some astrophysical “exhausts”



Astro high-energy sources can:

- accelerate electrons and protons, including UHECRs (Ultra High Energy Cosmic Rays).

- produce non-thermal photon spectra.



(Ghisellini+ 17)

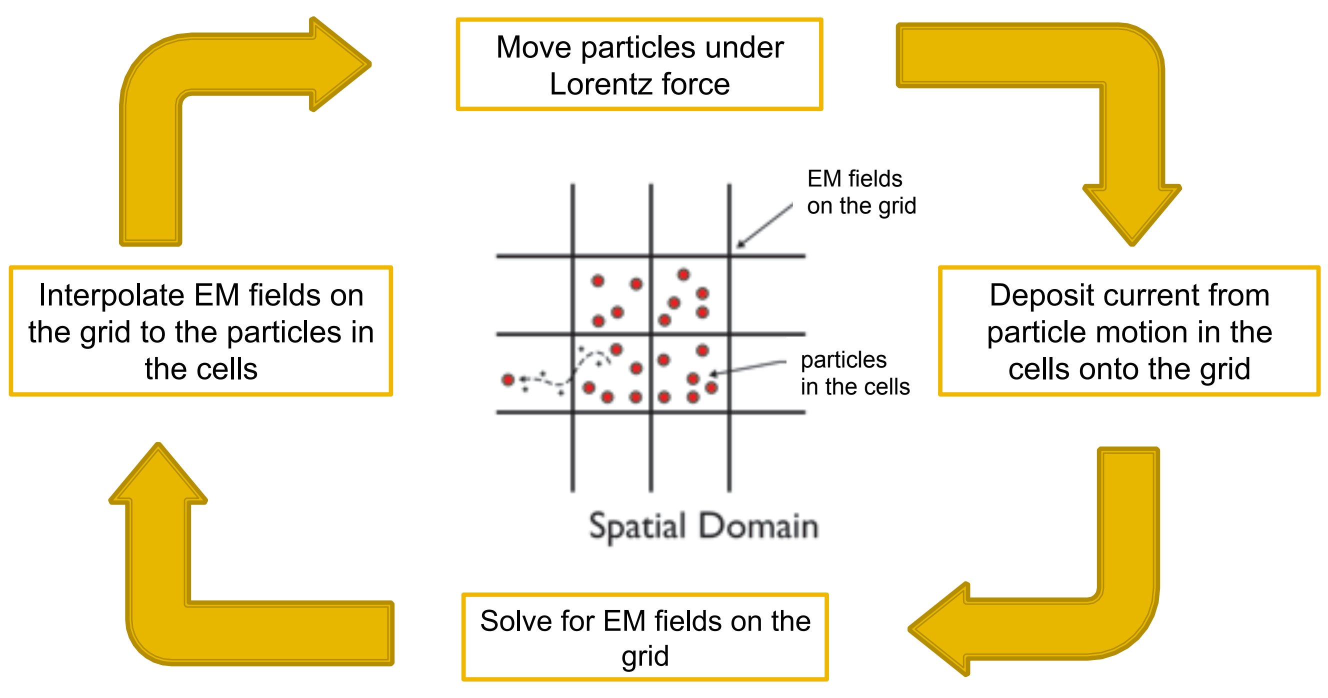
From exhausts to engines

We have no direct probe of the nature of the fuel and of the mechanics of the engine, but we can only observe the exhausts.

Studying the engine: the PIC method

Particle-in-Cell (PIC) method:

It is the most fundamental way of capturing the interplay of charged particles and e.m. fields.


Move particles under Lorentz force

Deposit current from particle motion in the cells onto the grid

Solve for EM fields on the grid

Interpolate EM fields on the grid to the particles in the cells

The computational challenge:

The *microscopic* scales resolved by PIC simulations are much smaller than *astronomical* scales.

Typical length (c/ω_p) and time ($1/\omega_p$) scales are:

$$\frac{c}{\omega_p} \simeq 5.5 \times 10^5 \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{cm} \qquad \frac{1}{\omega_p} \simeq 1.8 \times 10^{-5} \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{s}$$

We need large-scale simulations, state-of-the-art codes and massive computing resources.

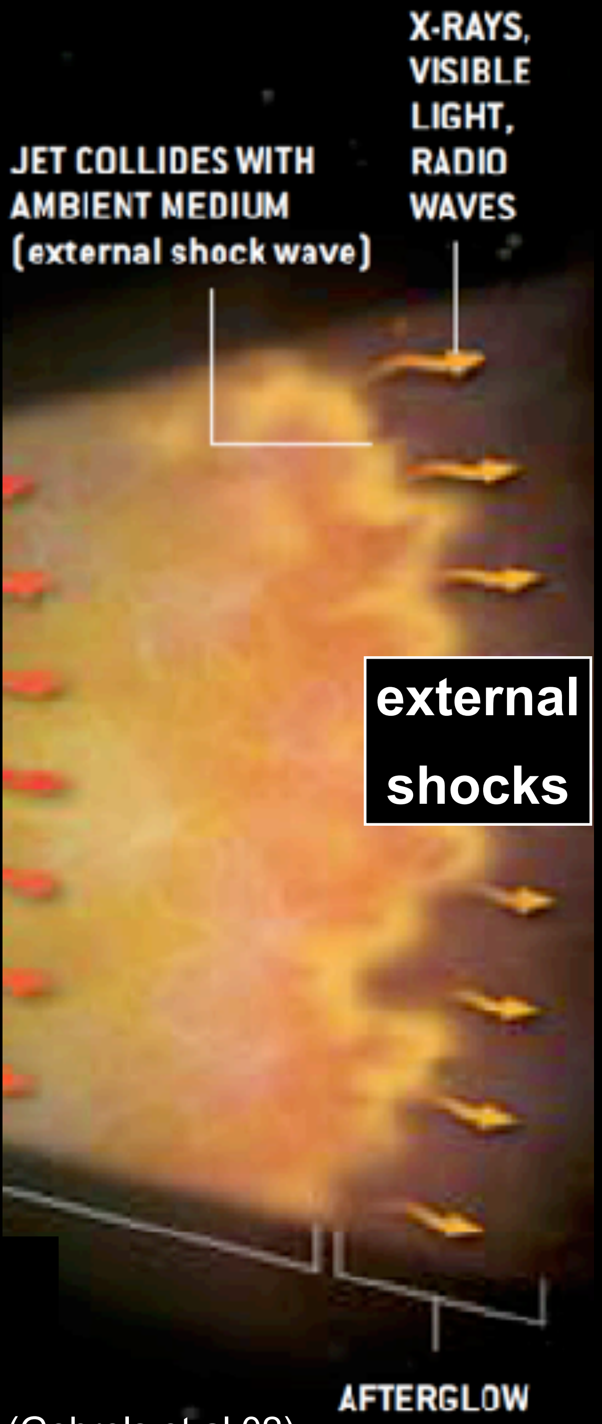
Mystery #1: neutron star mergers

(Gehrels et al 02)

Open questions

- How to make magnetic fields from scratch?
- How to accelerate particles to very high energies?

Relativistic shocks



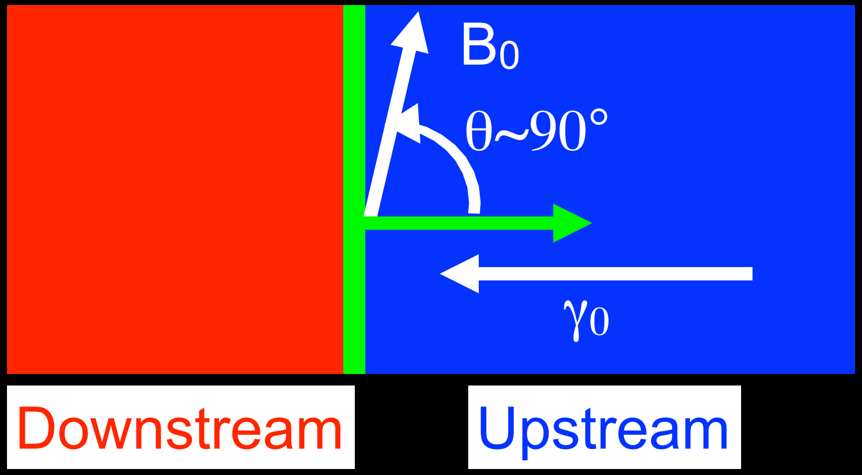
(Gehrels et al 02)

Gamma-ray burst external shocks:

- γ_0~a few hundreds
- weakly magnetized: $\sigma \sim 10^{-9}$

$$\boxed{\sigma = \frac{B_0^2}{4\pi\gamma_0 n_0 m_p c^2}}$$

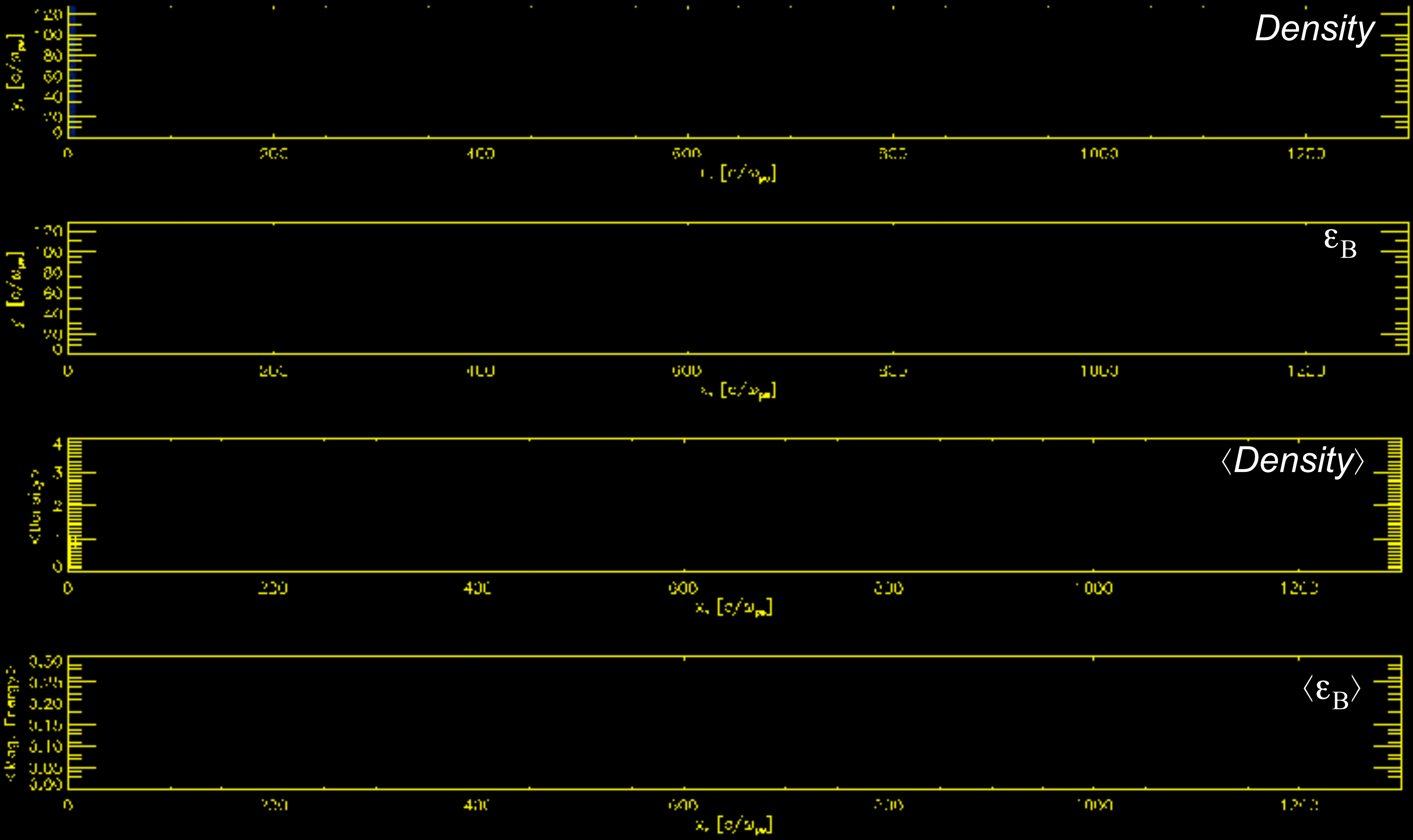
- quasi-perpendicular shocks



Weakly magnetized shocks

Mediated by the Weibel instability, that generates small-scale sub-equipartition magnetic fields.

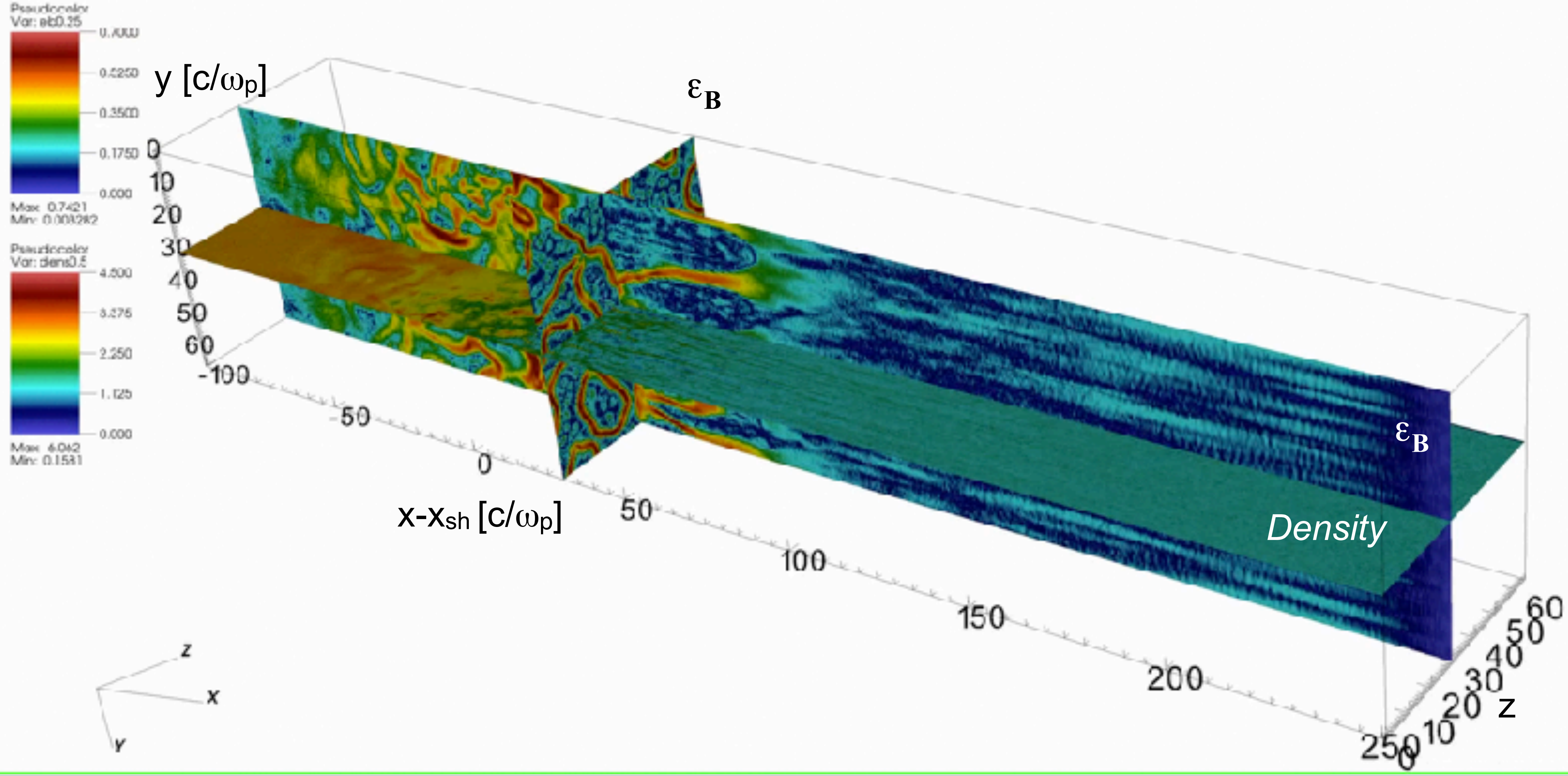
2D PIC simulation of $\sigma=0$ $\gamma_0=15$ e^--e^+ shock



Low-σ shocks are filamentary

Mediated by the Weibel instability, that generates
small-scale sub-equipartition magnetic fields.

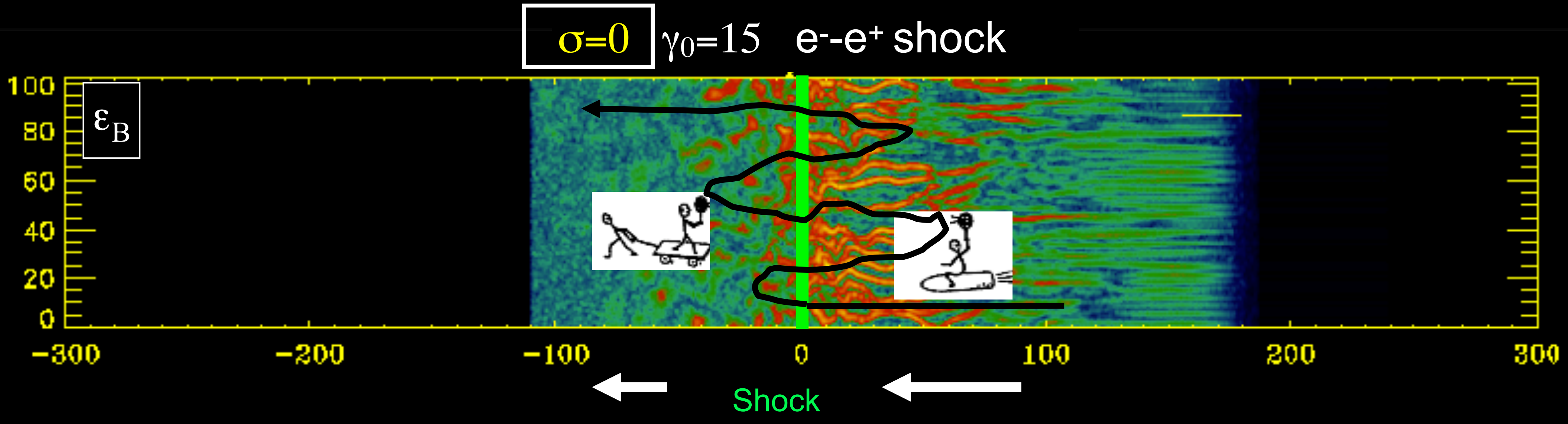
$\sigma=0 \quad \gamma_0=15$ e^--e^+ shock



(LS et al. 13)

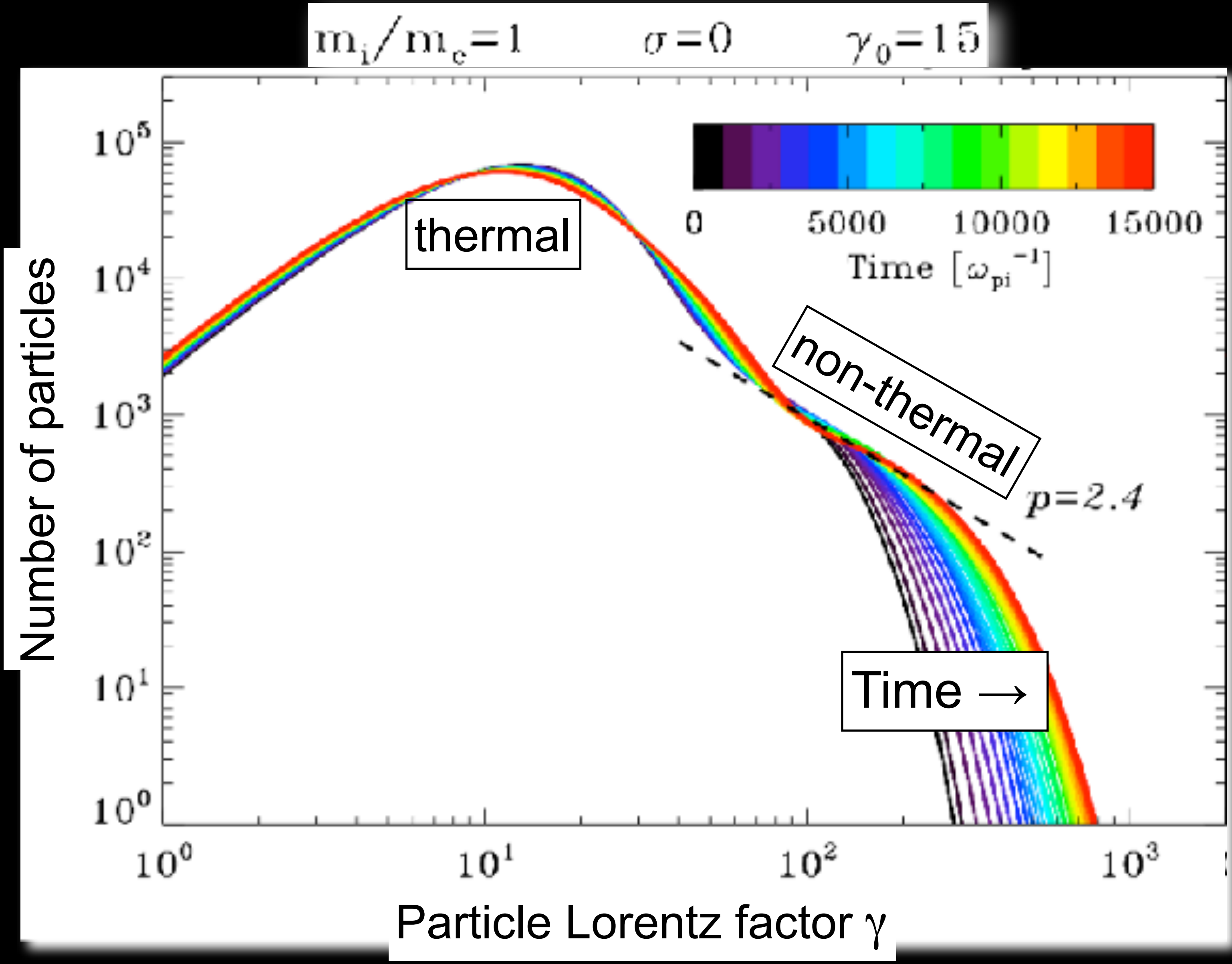
The Fermi process in low-σ shocks

Particle acceleration via the Fermi process in self-generated turbulence, for initially unmagnetized (i.e., $\sigma=0$) or weakly magnetized flows.



(LS et al 13)

GRB shocks accelerate non-thermal particles



(LS et al. 13, Martins et al. 09, Haugbolle 10)

Conclusions are the same in 2D and 3D, for electron-positron and electron-ion plasmas

Mystery #1 solved !?

- How to make magnetic fields from scratch?

via the Weibel instability.

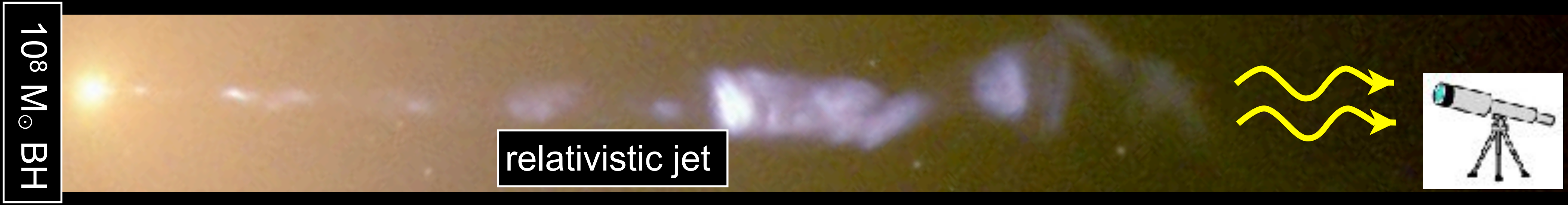
But what is the long-term evolution of the post-shock field?

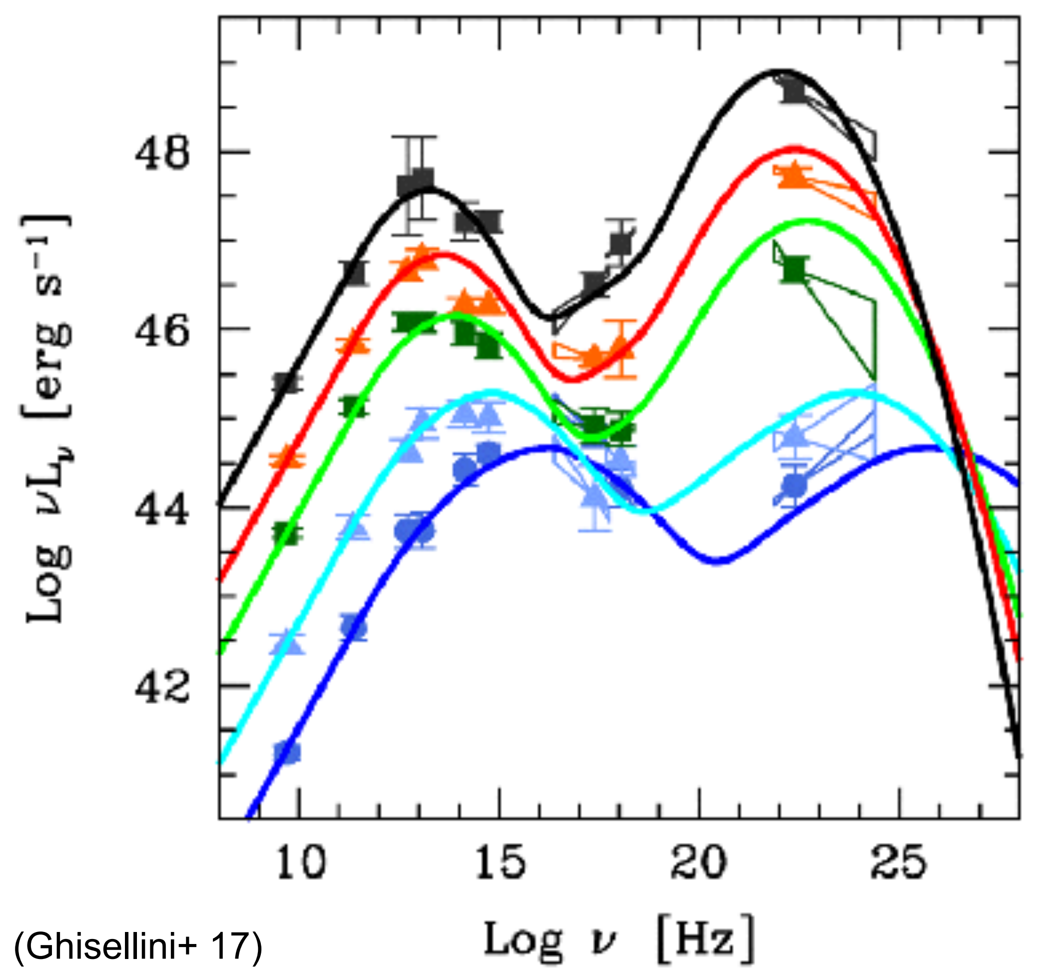
- How to accelerate particles to very high energies?

via the Fermi process at shocks.

Mystery #2: blazars

Blazars: jets from Active Galactic Nuclei pointing along our line of sight





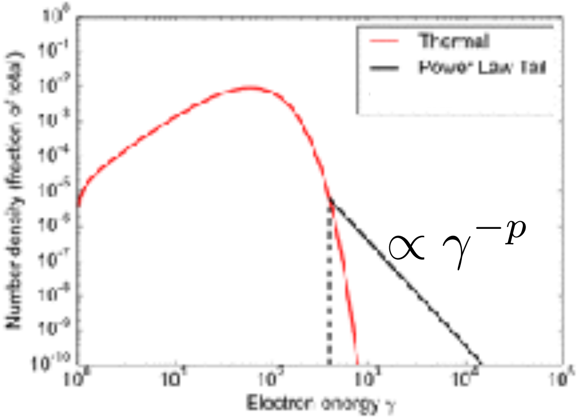
(Ghisellini+ 17)

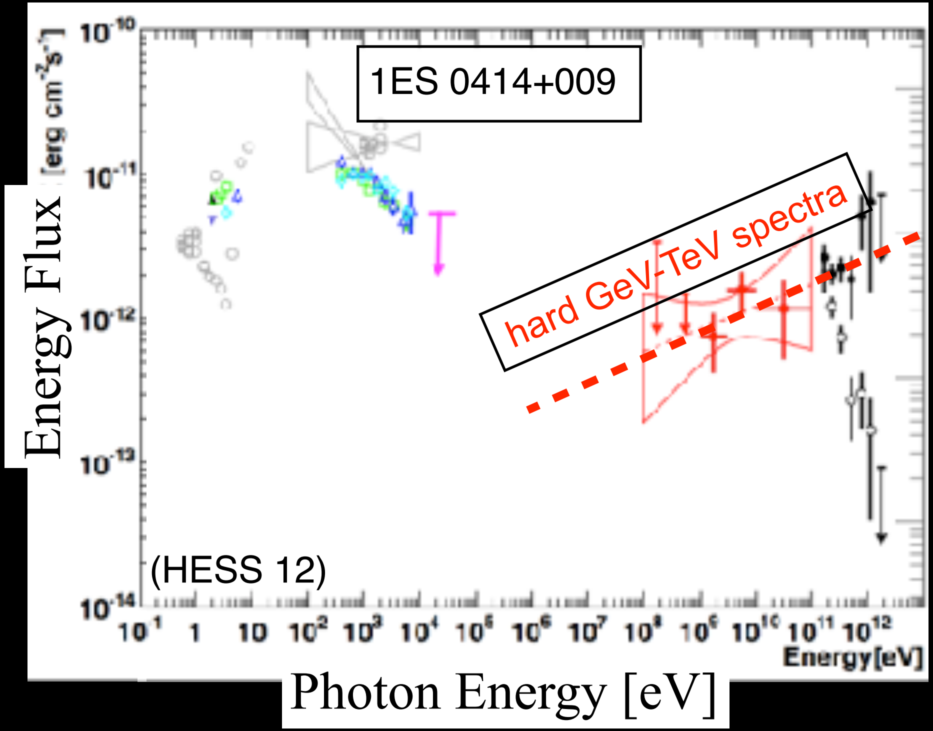
- broadband spectrum, from radio to γ-rays (and even TeV energies)
- low-energy synchrotron + high-energy inverse Compton (IC)

Powerful, hard and fast emission

(A) extended power-law spectra of the emitting particles, often with hard slope

$$\frac{dn}{d\gamma} \propto \gamma^{-p} \qquad p \lesssim 2$$





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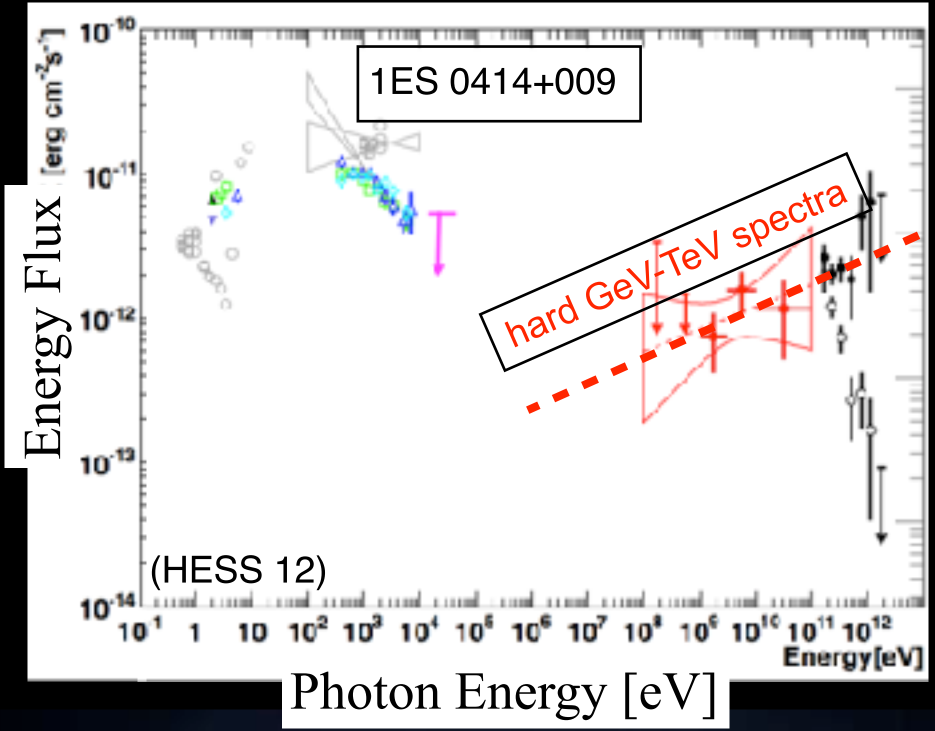
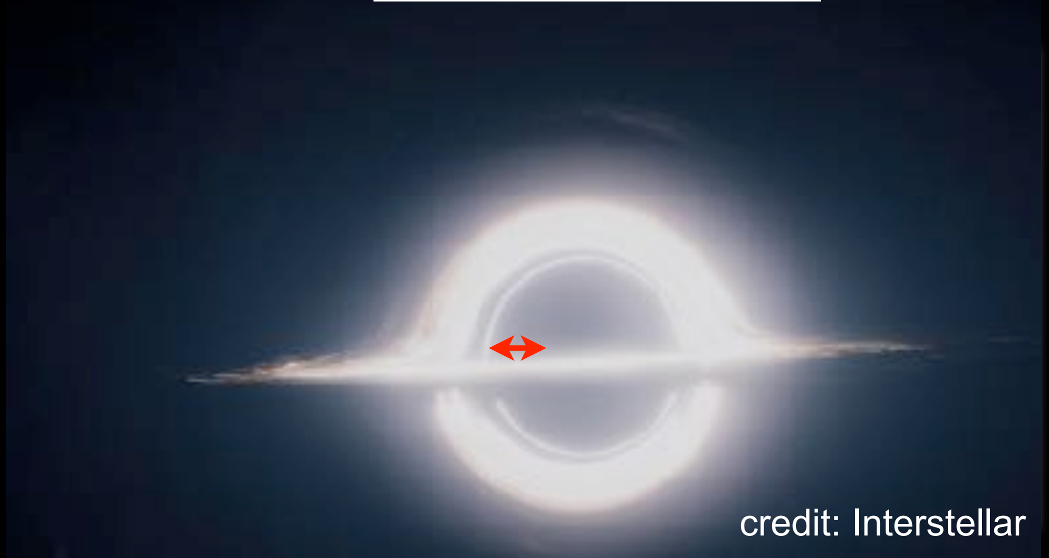


(B) fast time variability

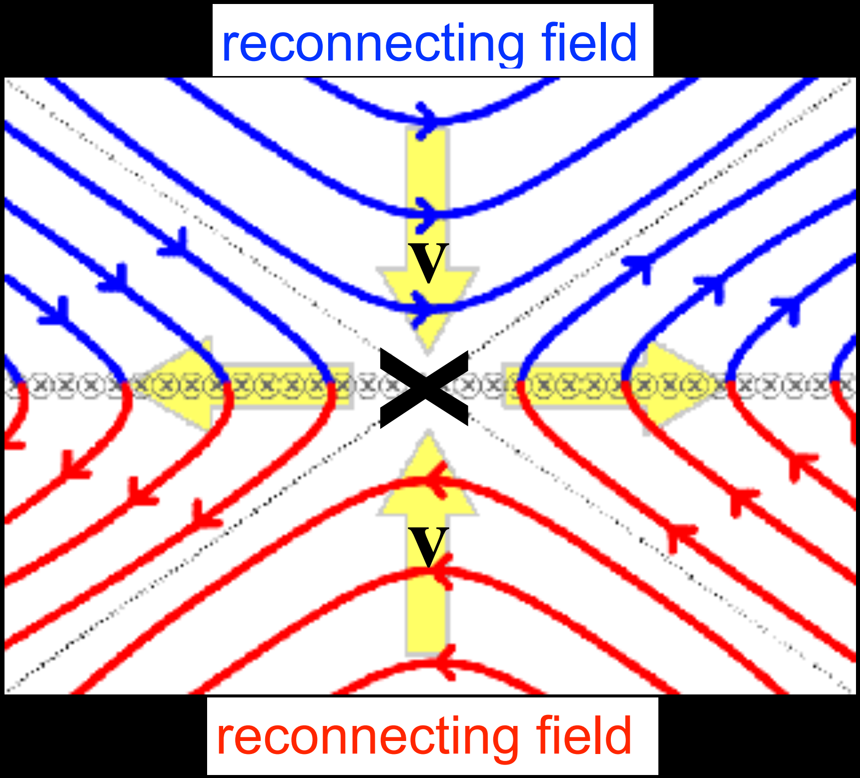


credit: Interstellar

Open questions

- How to accelerate particles in jets?
- How to produce ultra-fast time variability?

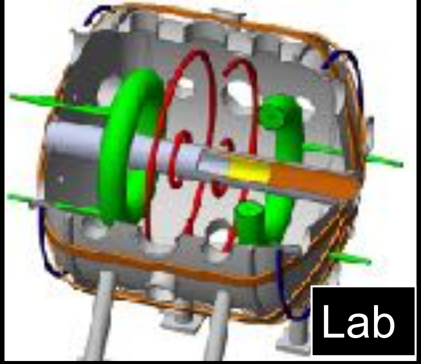
The mechanism: magnetic reconnection?



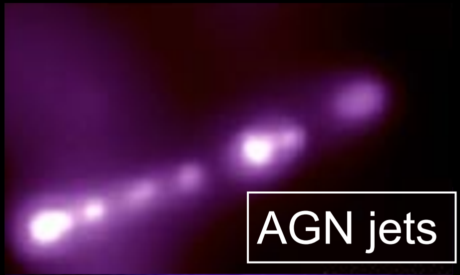
$$\sigma = \frac{B_0^2}{4\pi \rho c^2}$$

σ«1

σ»1


Lab


MMS


AGN jets


Crab Nebula

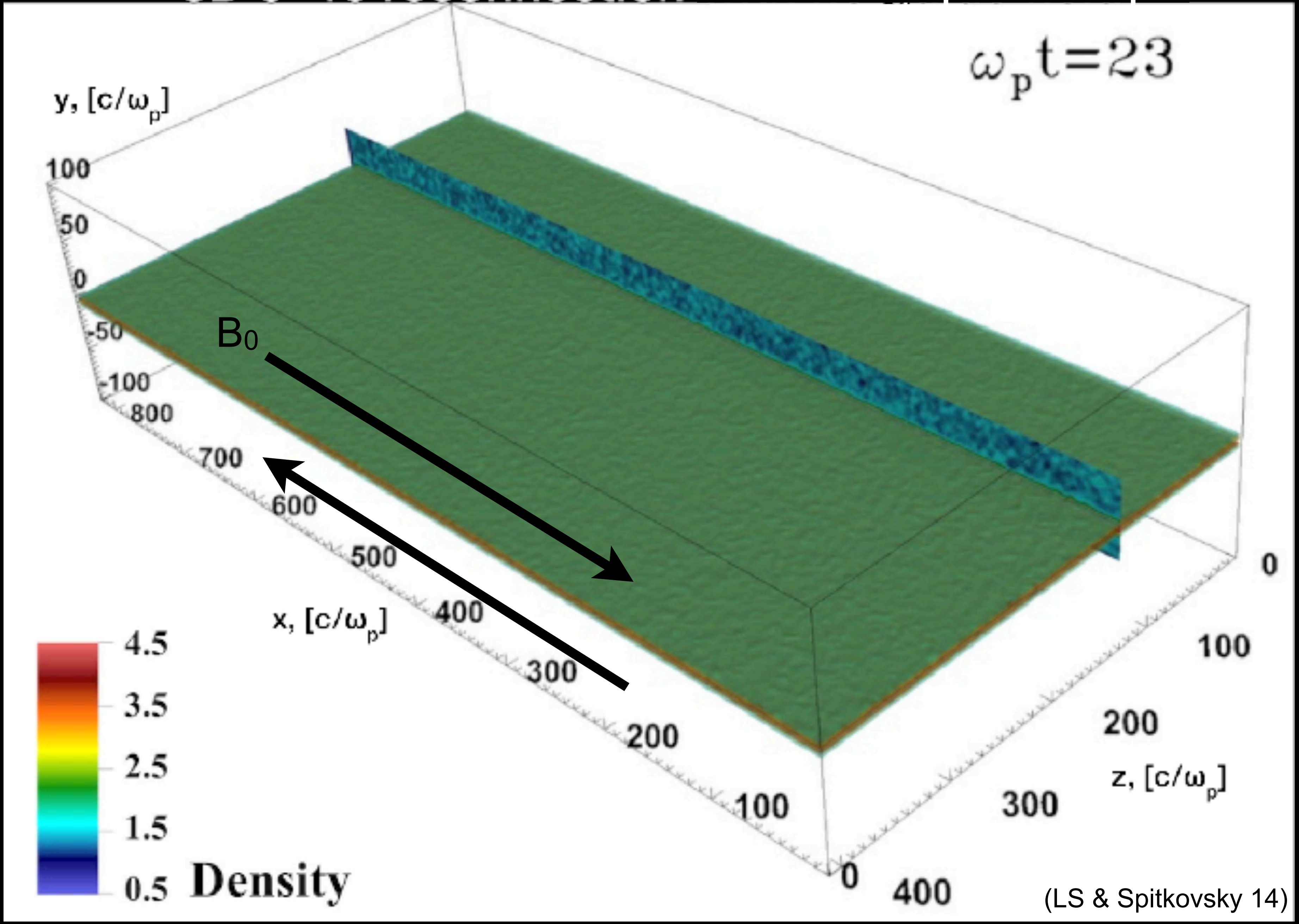
Relativistic Reconnection

$$\sigma = \frac{B_0^2}{4\pi \rho c^2} \gg 1$$

$$v_A \sim c$$

High-energy astro sources are our best “laboratories” of relativistic reconnection

3D σ=10 reconnection in electron-positron plasma

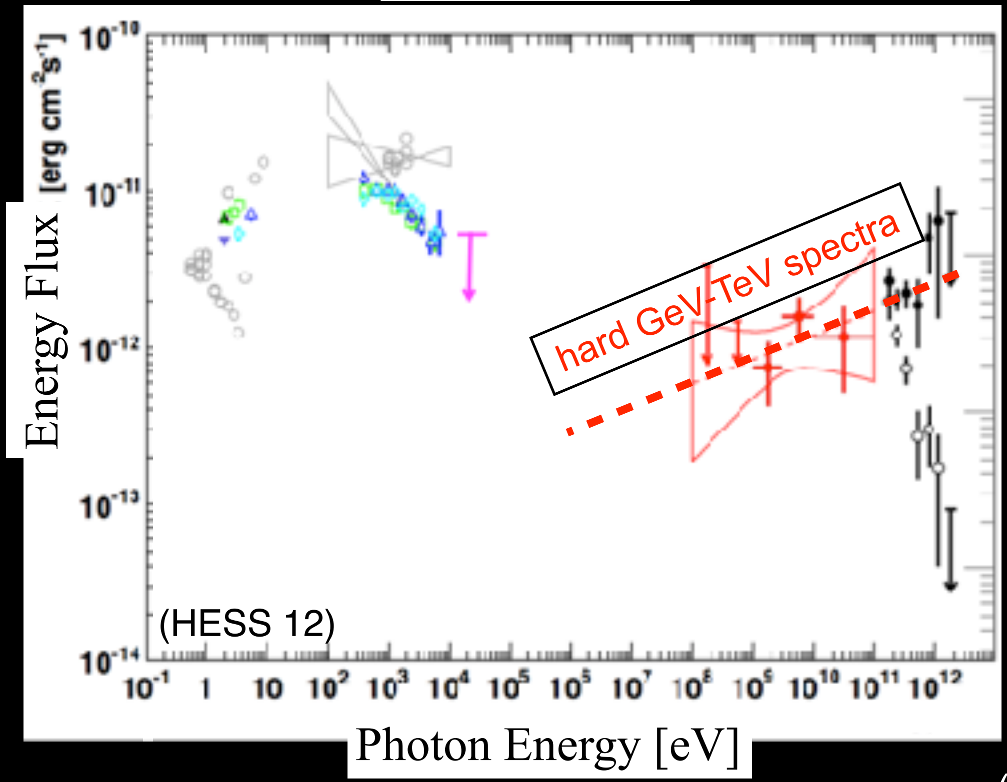


(LS & Spitkovsky 14)

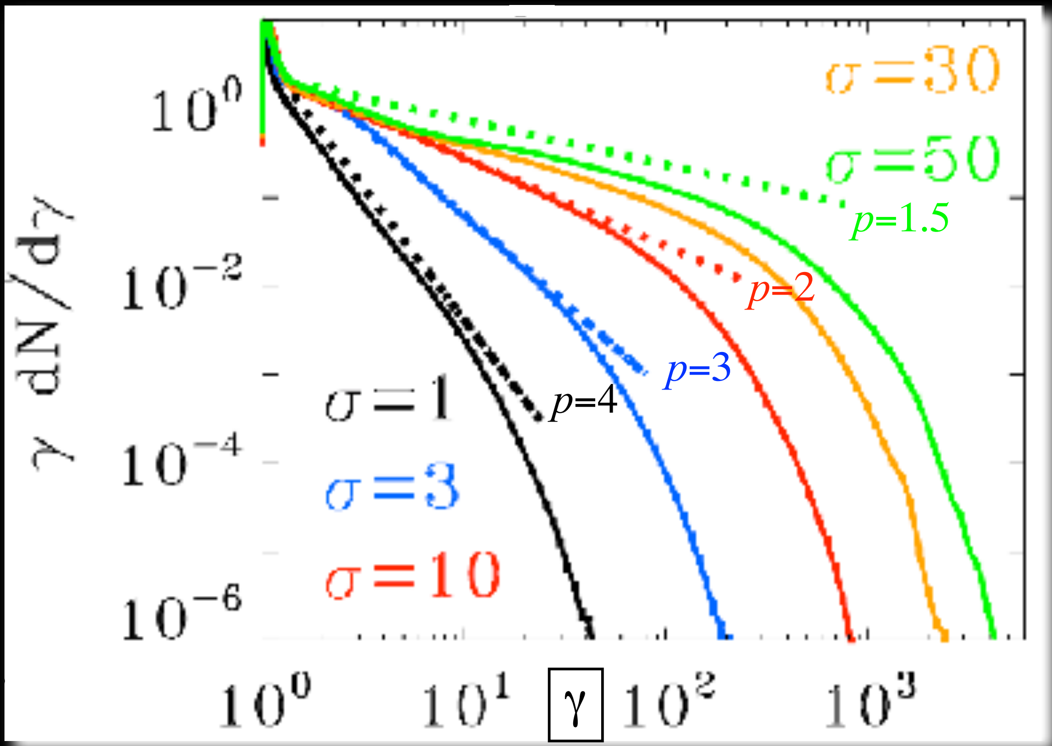
The reconnection layer breaks into a chain of <u>magnetic islands / plasmoids</u>

(A) Extended non-thermal spectra

1ES 0414+009



2D electron-positron



(LS & Spitkovsky 14, see also Melzani+14, Guo+14,15, Werner+16)

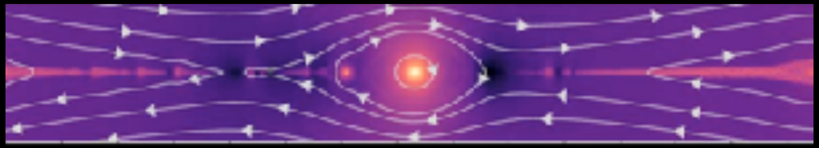
- power-law spectra of the emitting particles, often with hard slope

$$\frac{dn}{d\gamma} \propto \gamma^{-p} \qquad p \lesssim 2$$

✓ Reconnection produces power laws of accelerated particles, with hard slopes ($p \lesssim 2$) for high magnetizations ($\sigma \gtrsim 10$).

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

The highest energy particles



- In 2D, particles are trapped in plasmoids and they gain energy slowly, $\gamma \propto t^{1/2}$

The highest energy particles

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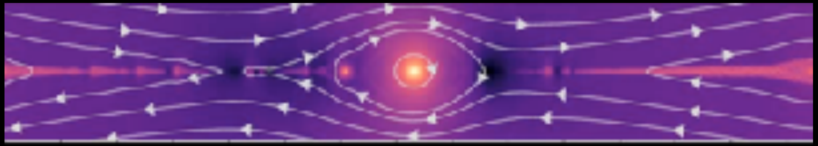
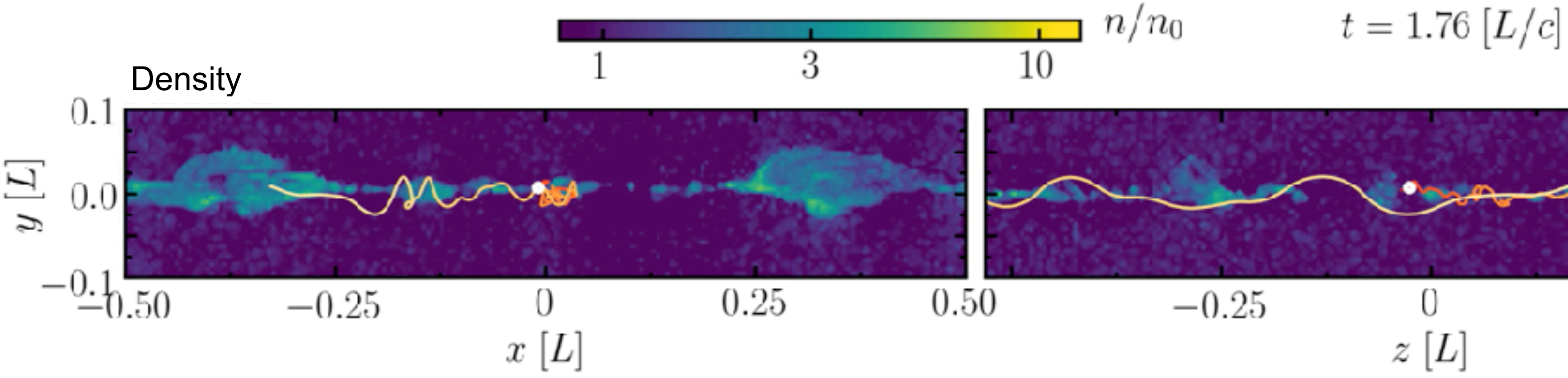




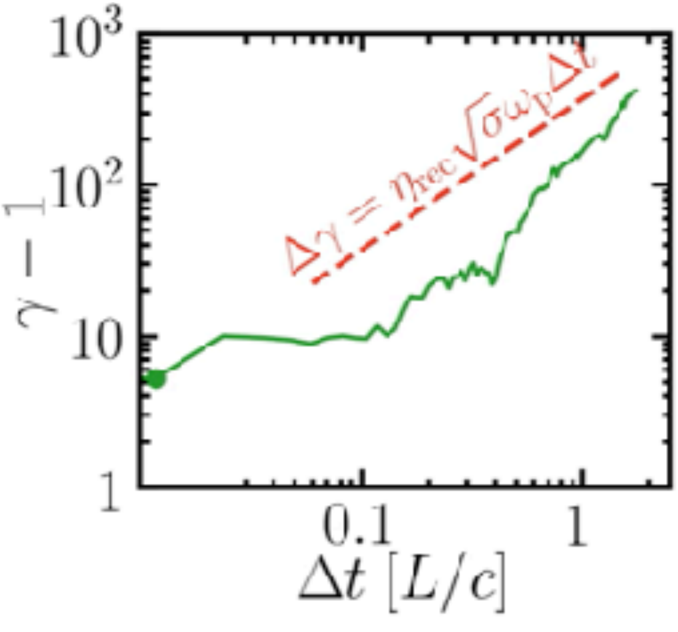
Density

L=box length

(Zhang, LS, Giannios, in prep)

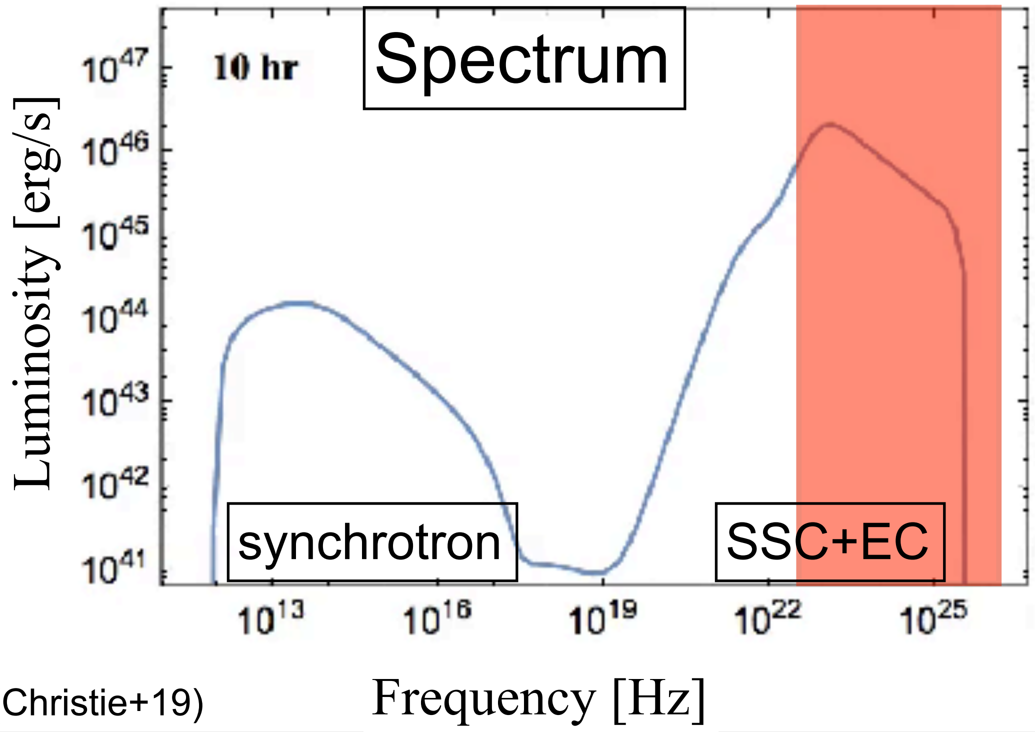
- In 3D, a few lucky particles escape from plasmoids.
- After escaping, they wiggle around the layer and accelerate linearly in time, $\gamma \propto t$.

- In powerful AGNs, ions can be accelerated up to UHECR energies.

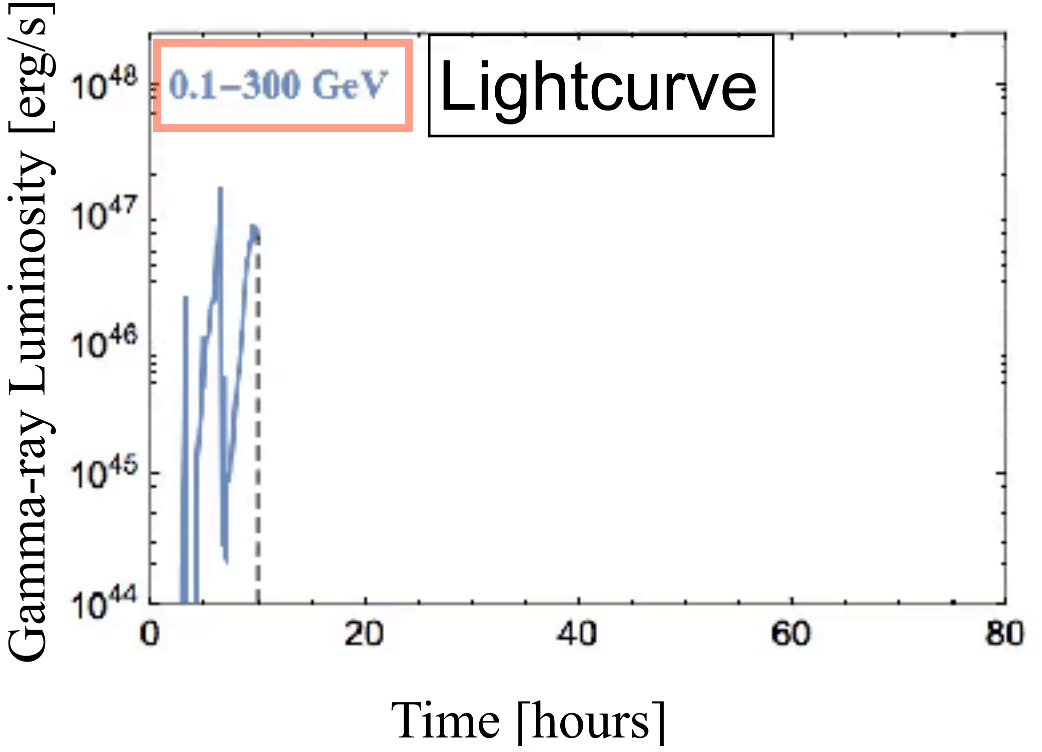


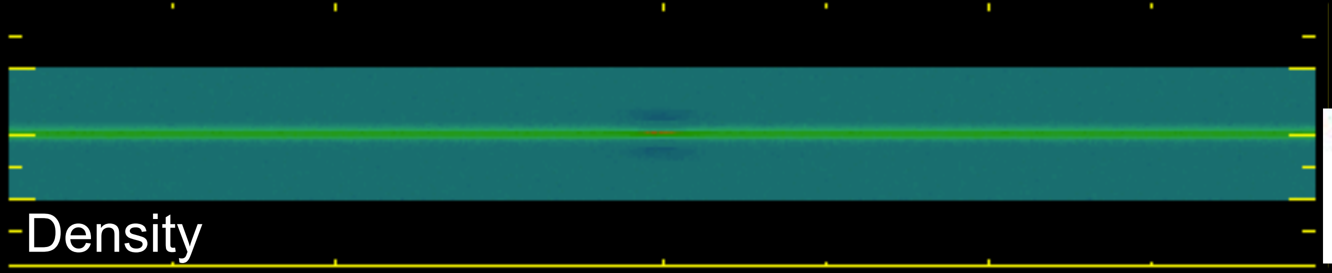
(B) Fast and powerful flares

Magnetic reconnection in jets can power the observed high-energy emission.

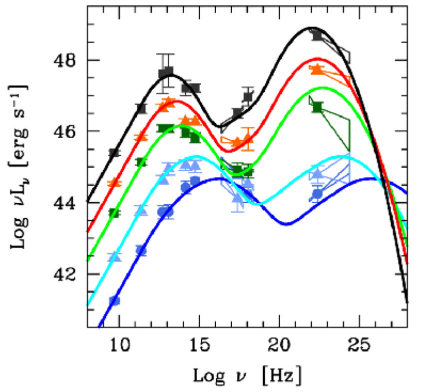


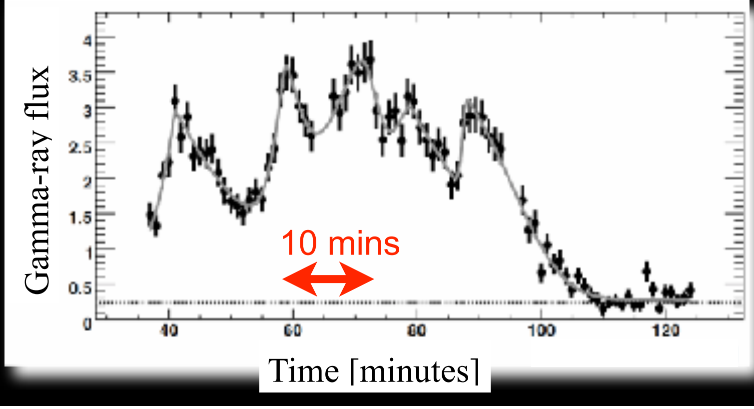
(Christie+19)

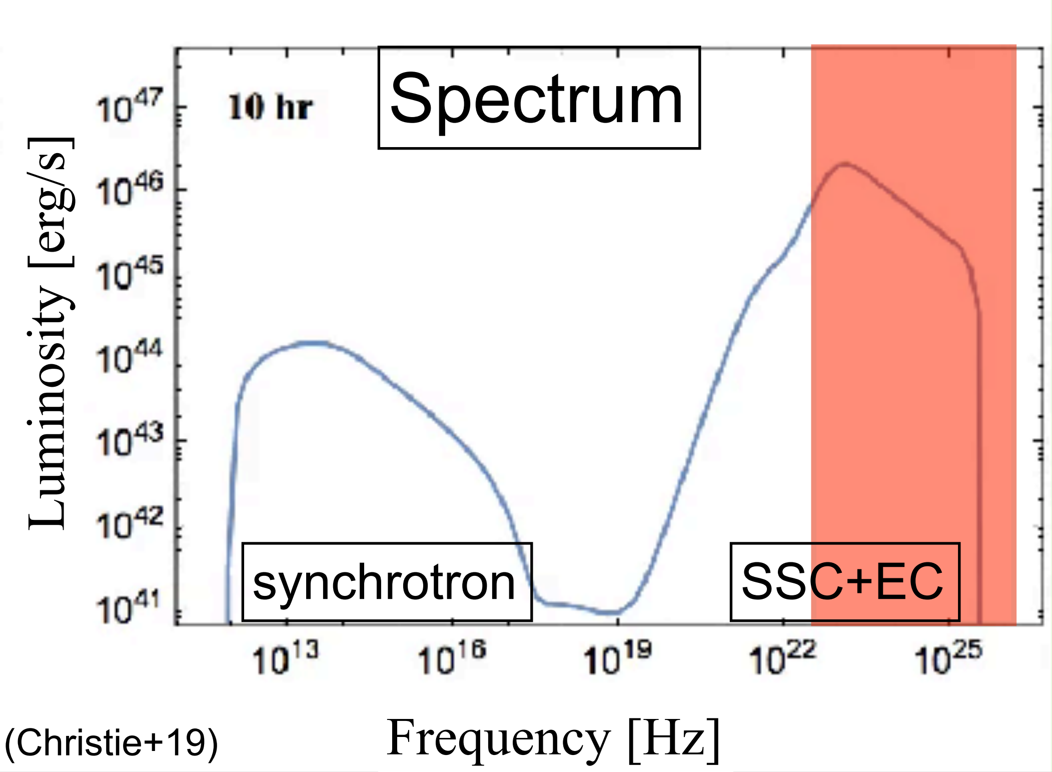




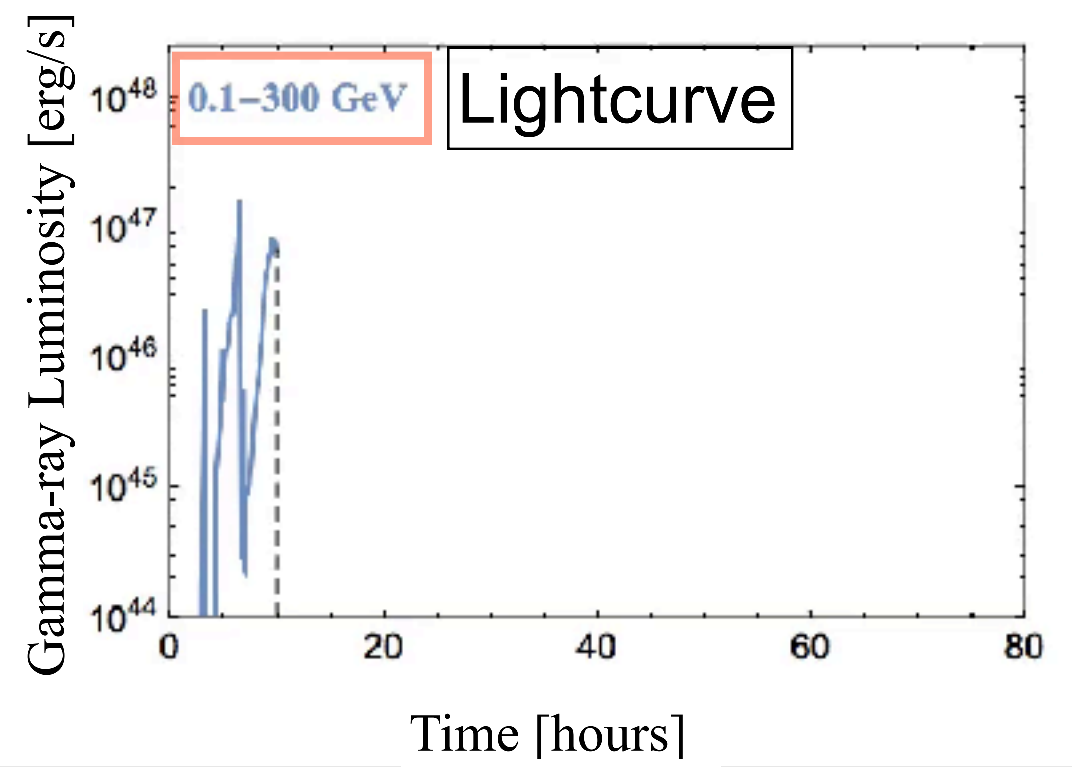
(B) Fast and powerful flares

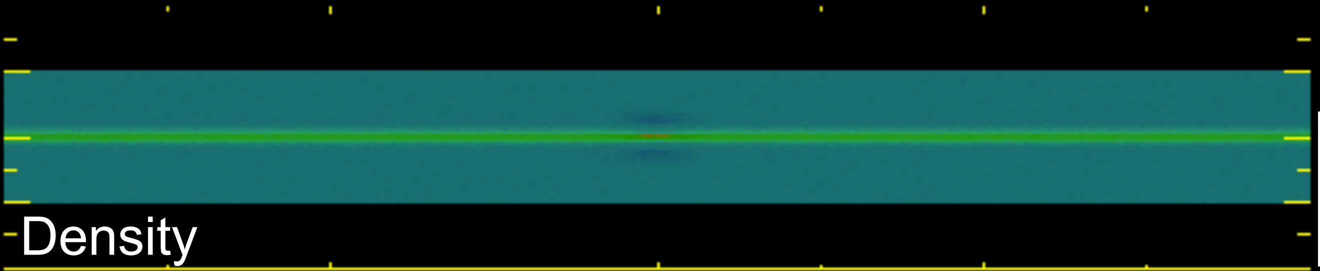






(Christie+19)





Fast time variability

The Doppler effect

https://www.youtube.com/watch?v=h4OnBYrbCjY

Plasmoids moving toward the observer lead (via Doppler effect) to high frequencies, so short timescales

Mystery #2 solved !?

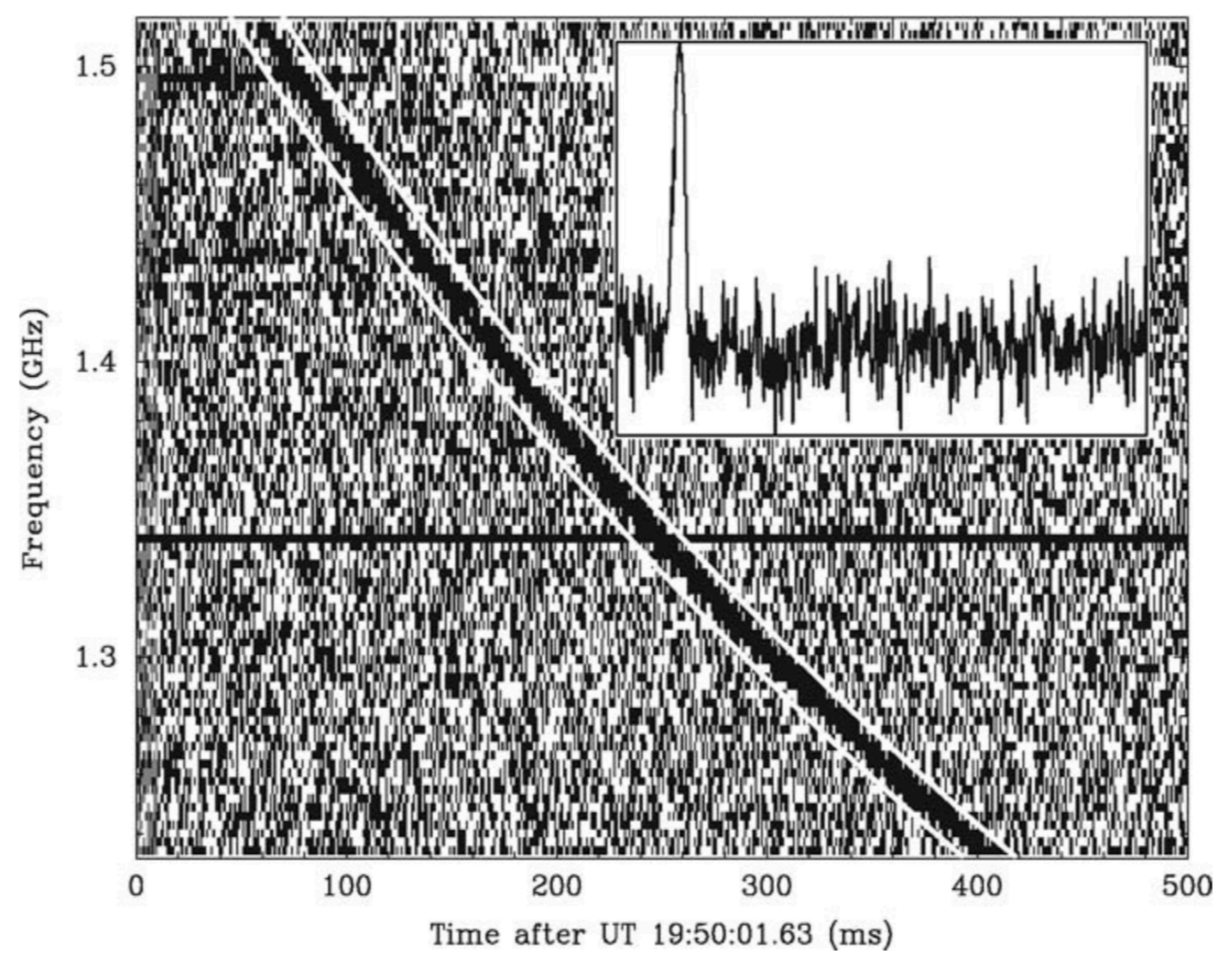
- How to accelerate particles in jets?

via magnetic reconnection.

- How to produce ultra-fast time variability?

with fast reconnection plasmoids moving toward the observer.

Mystery #3: FRBs



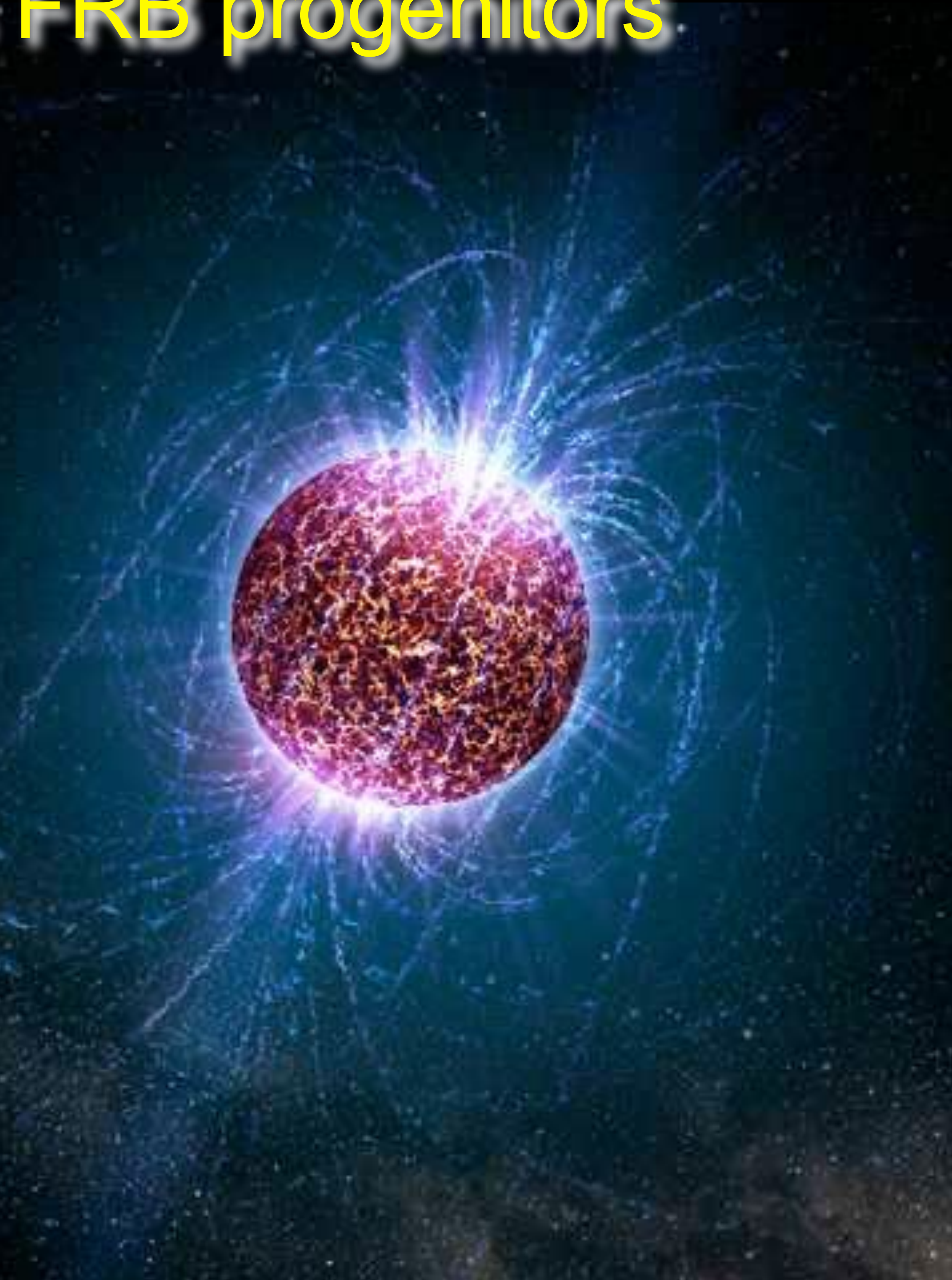
Lorimer et al. (2007)

Magnetars as FRB progenitors

Circumstantial evidence:

- Fast (~ms) duration requires a compact source.
- Magnetic energy of a young magnetar is sufficient to power FRBs.

recently confirmed by the discovery of an FRB from a Galactic magnetar!

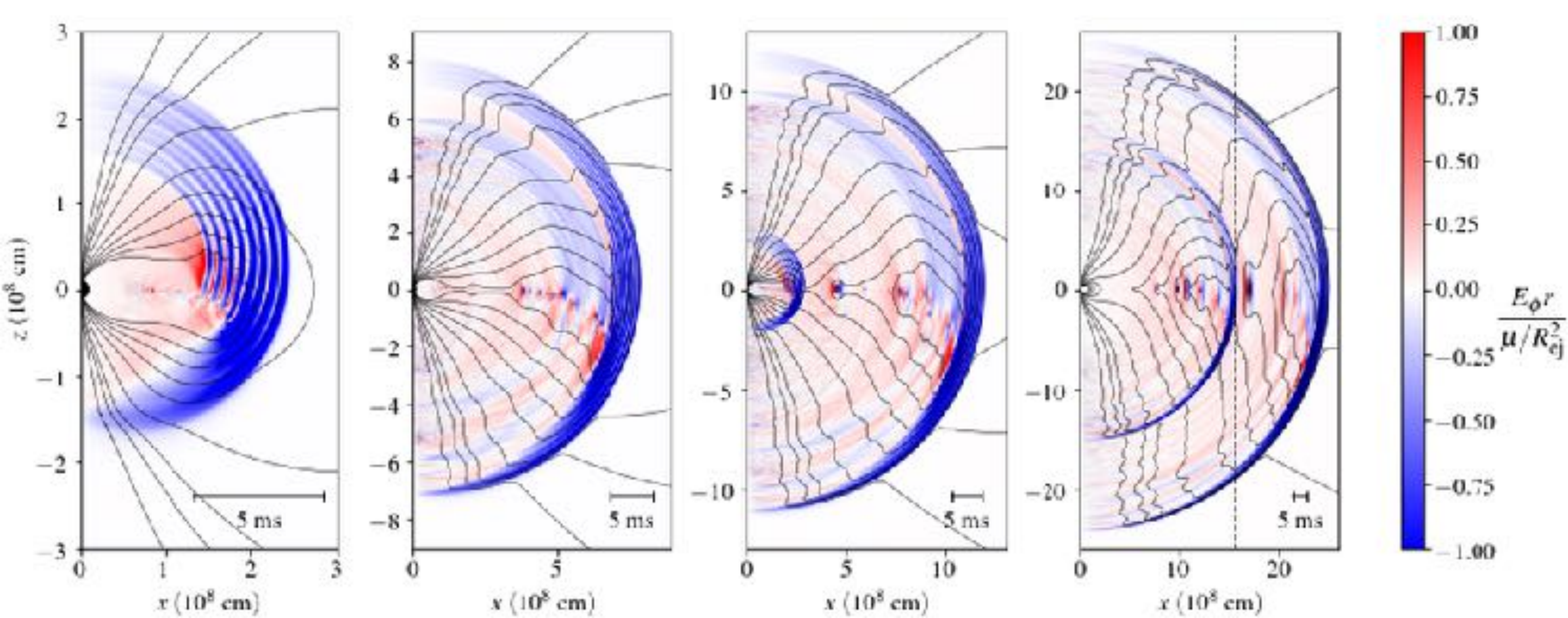


Open questions

- What causes the FRB emission?

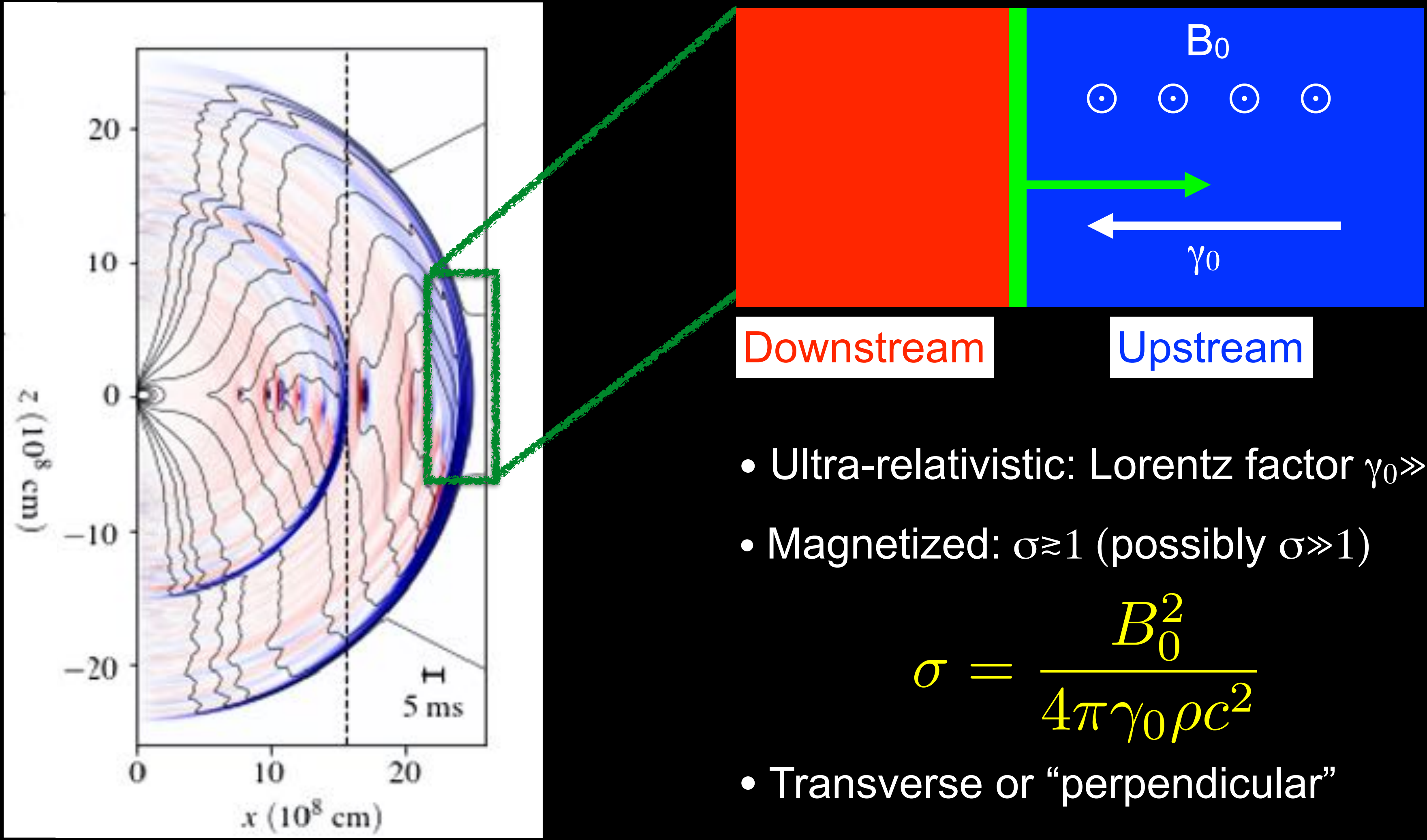
FRBs from magnetars

- Energy may be released by a “magnetar quake”, launching Alfven waves
- Alfven waves become nonlinear, driving magnetic reconnection and shocks



(Yuan+ 20)

Relativistic shocks from magnetar flares



(Yuan+ 20)

- Ultra-relativistic: Lorentz factor $\gamma_0 \gg 1$
- Magnetized: $\sigma \gtrsim 1$ (possibly $\sigma \gg 1$)

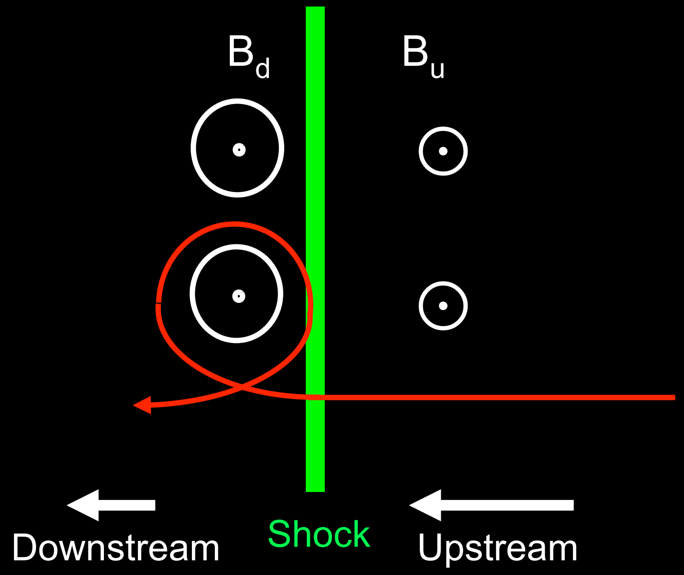
$$\sigma = \frac{B_0^2}{4\pi\gamma_0\rho c^2}$$

- Transverse or “perpendicular”
- Pre-shock medium:
  - magnetar e^-e^+ wind, or
  - $e^-e^+p^+$ shell ejected in a prior flare

The synchrotron maser

The synchrotron maser:

(1) Electrons and positrons gyrate *coherently* in the shock field.



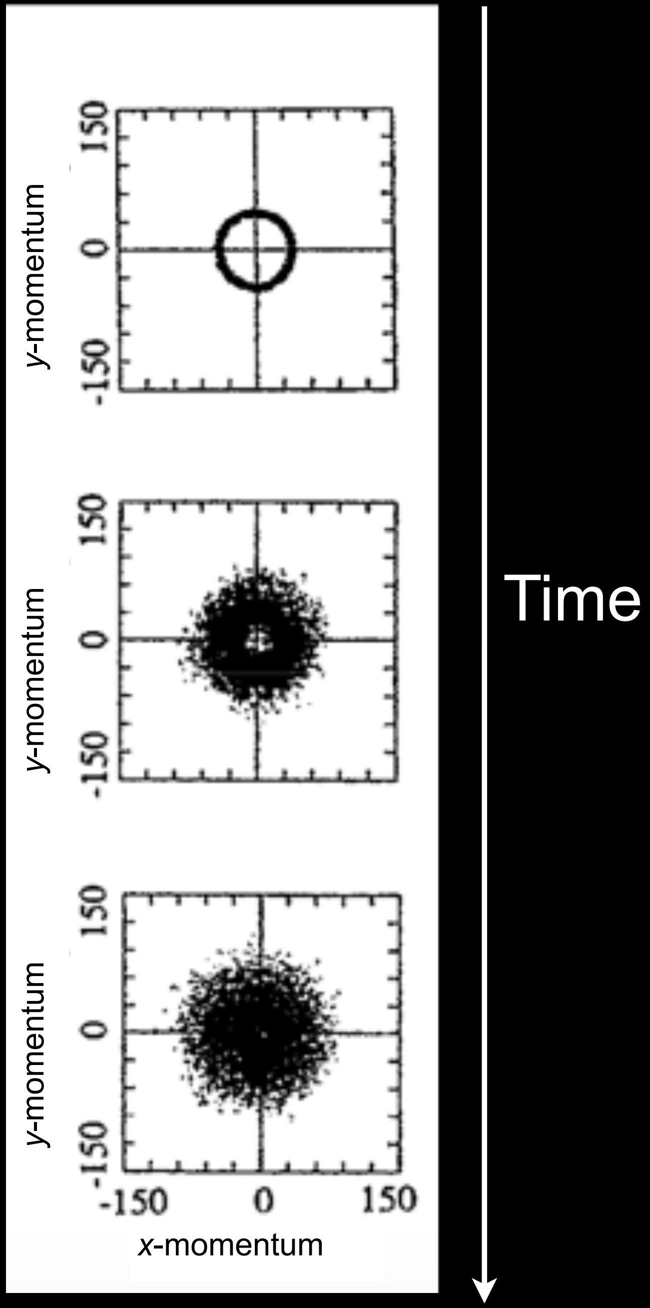
The synchrotron maser

The synchrotron maser:

(1) Electrons and positrons gyrate *coherently* in the shock field.

(2) Shocked particles form an unstable "ring" distribution in momentum space.

The population inversion is constantly replenished.



(Hoshino & Arons 91)

The synchrotron maser

The synchrotron maser:

(1) Electrons and positrons gyrate *coherently* in the shock field.

(2) Shocked particles form an unstable “ring” distribution in momentum space.

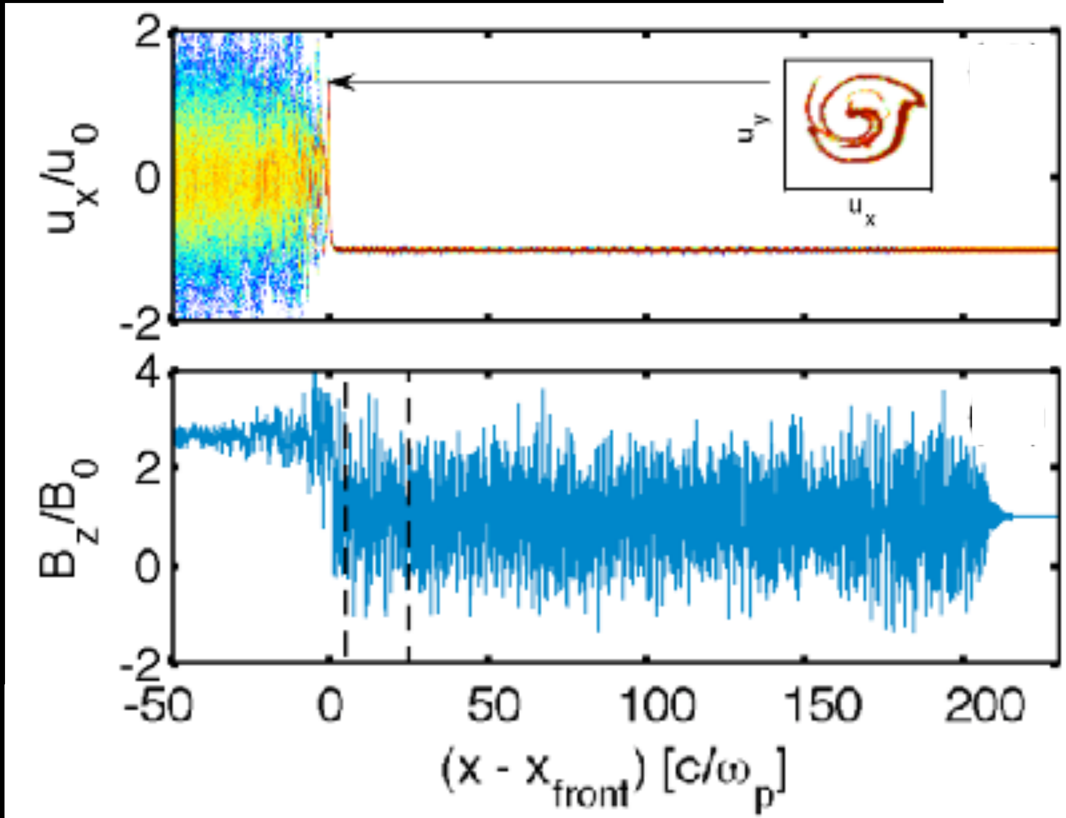
The population inversion is constantly replenished.

(3) Collapse of the unstable ring results in the emission of e.m. “precursor” waves.

→ FRBs [?] from first principles!

$\sigma=0.3$; $\gamma_0=10$; e^--e^+

1D

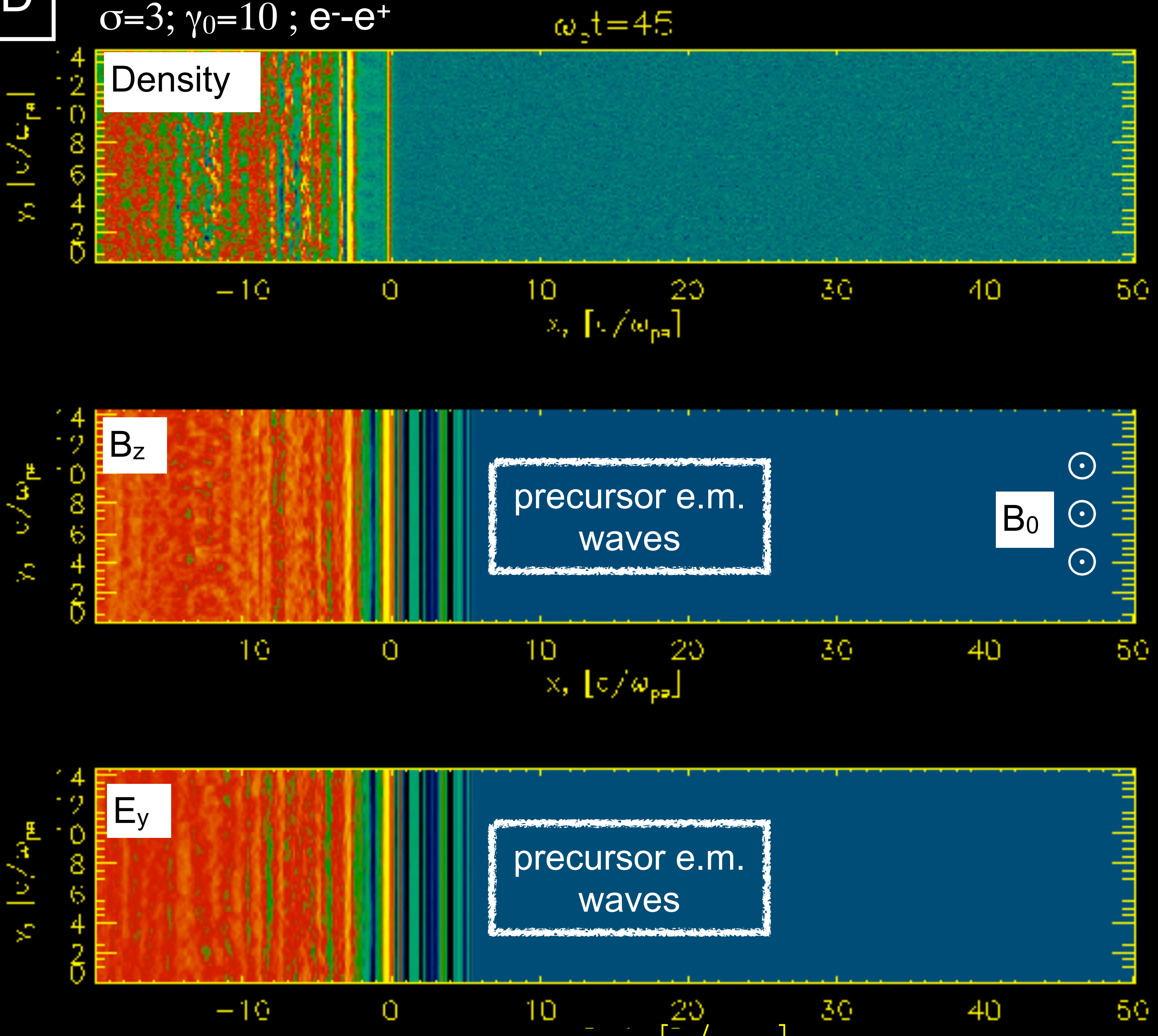


(Plotnikov & LS 19)

Shock-powered coherent emission

2D

$\sigma=3; \gamma_0=10$; e⁻-e⁺



precursor e.m. waves

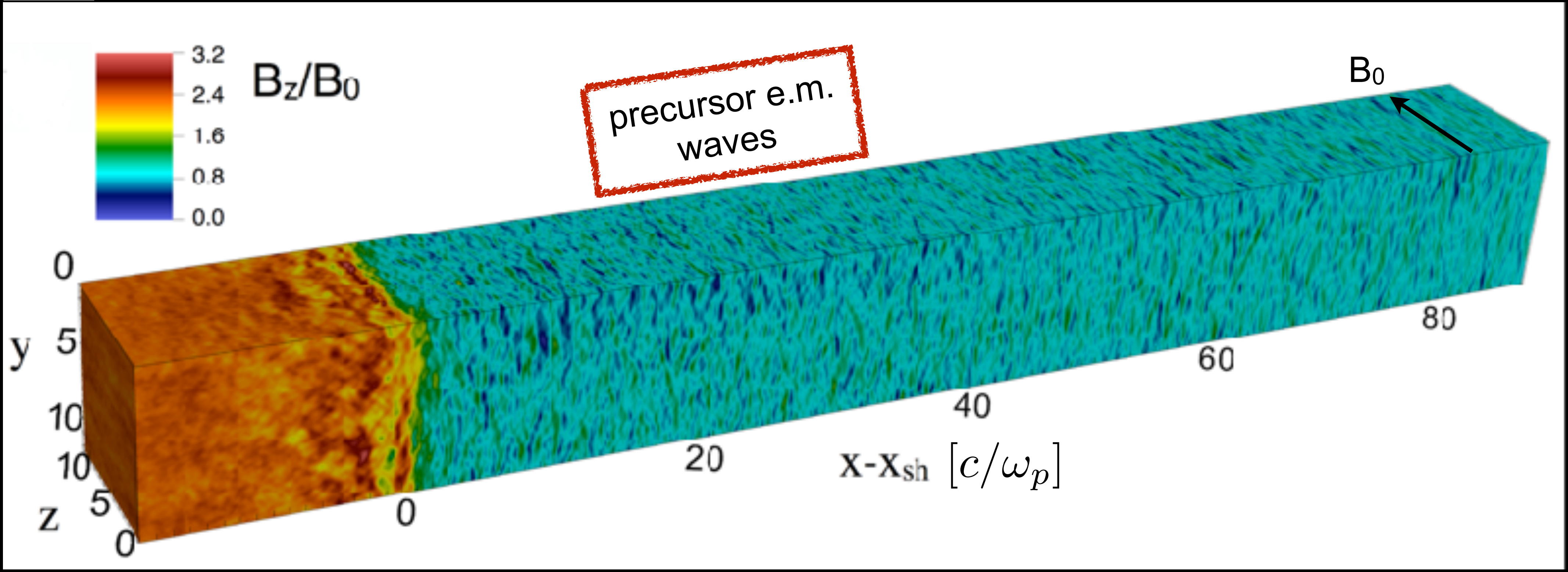
precursor e.m. waves

(Babul & LS 20)

Shock-powered coherent emission

3D

$\sigma=0.6; \gamma_0=10$; e⁻-e⁺



(Nattila, LS+ 21, in prep)

→ Synchrotron maser emission is robust in 1D, 2D, 3D

PIC simulations allow to assess from first principles:

(1) Efficiency

(2) Spectrum

(3) Beaming

(4) Polarization

Mystery #3 solved?

Stay tuned!