Non-thermal processes in relativistic outflows

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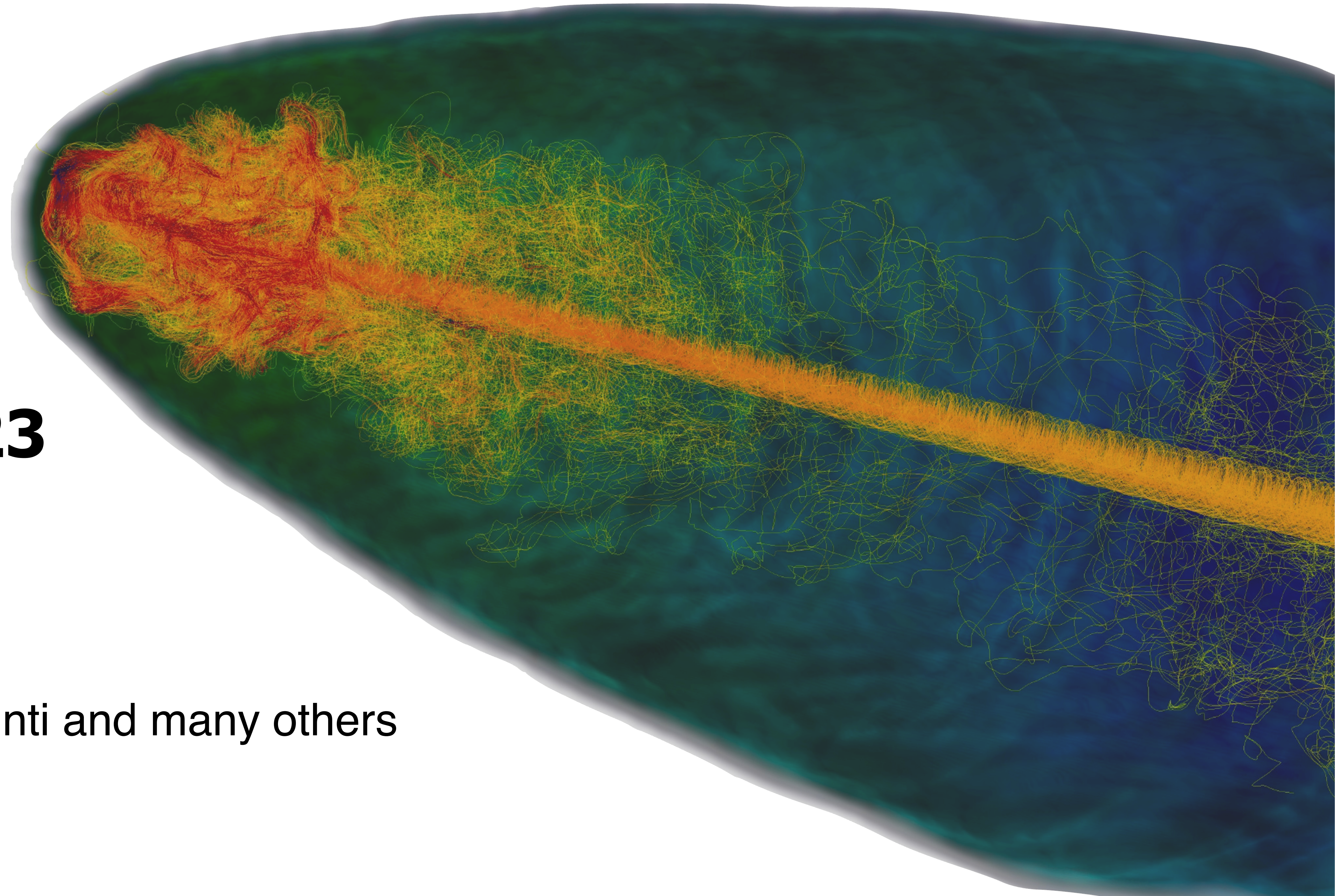
Max-Planck-Insitut für Kernphysik

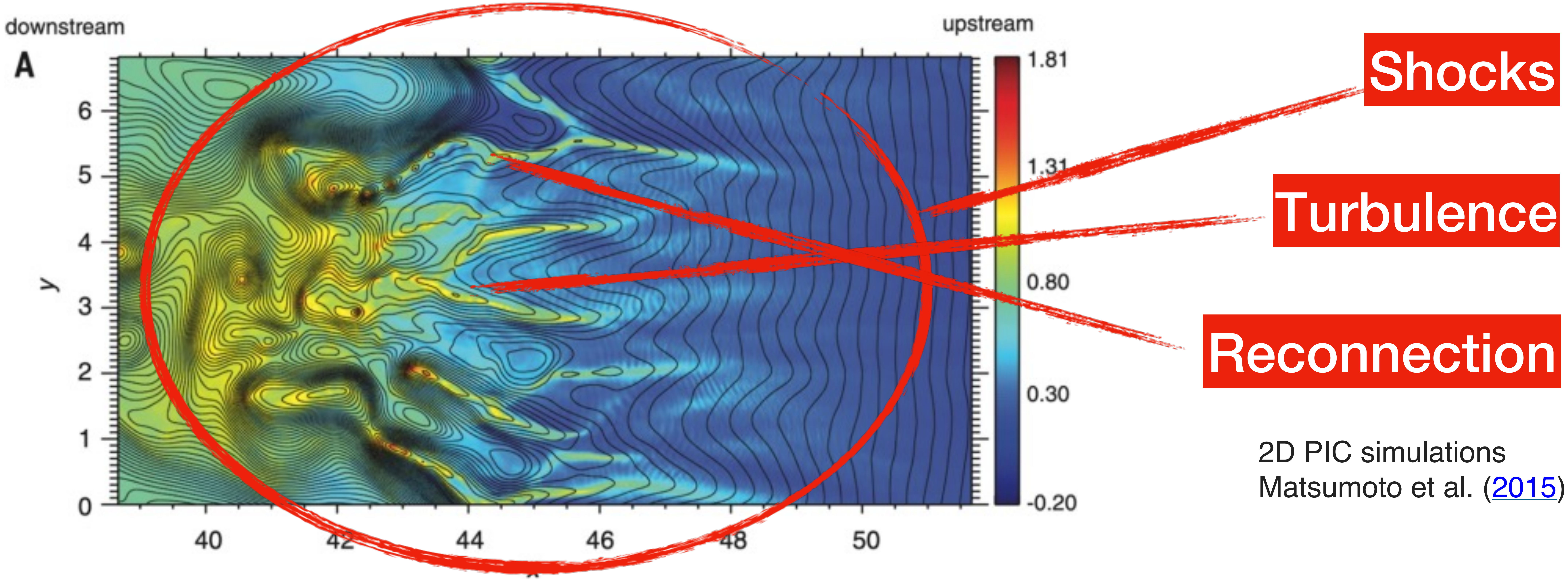
Texas Symposium - Shanghai 2023



With many thanks to ZQ Huang, J Wang, J Kirk, G Giacinti and many others

Why worry about particle acceleration in rel. outflows?

- HE, VHE and now UHE gamma rays are observed from relativistic sources (AGN, GRBs, PWN, TDEs, etc.)
- Plasma conditions not easily accessible to laboratory experiments
- Present a range of sites for energy dissipation -> non-thermal distributions



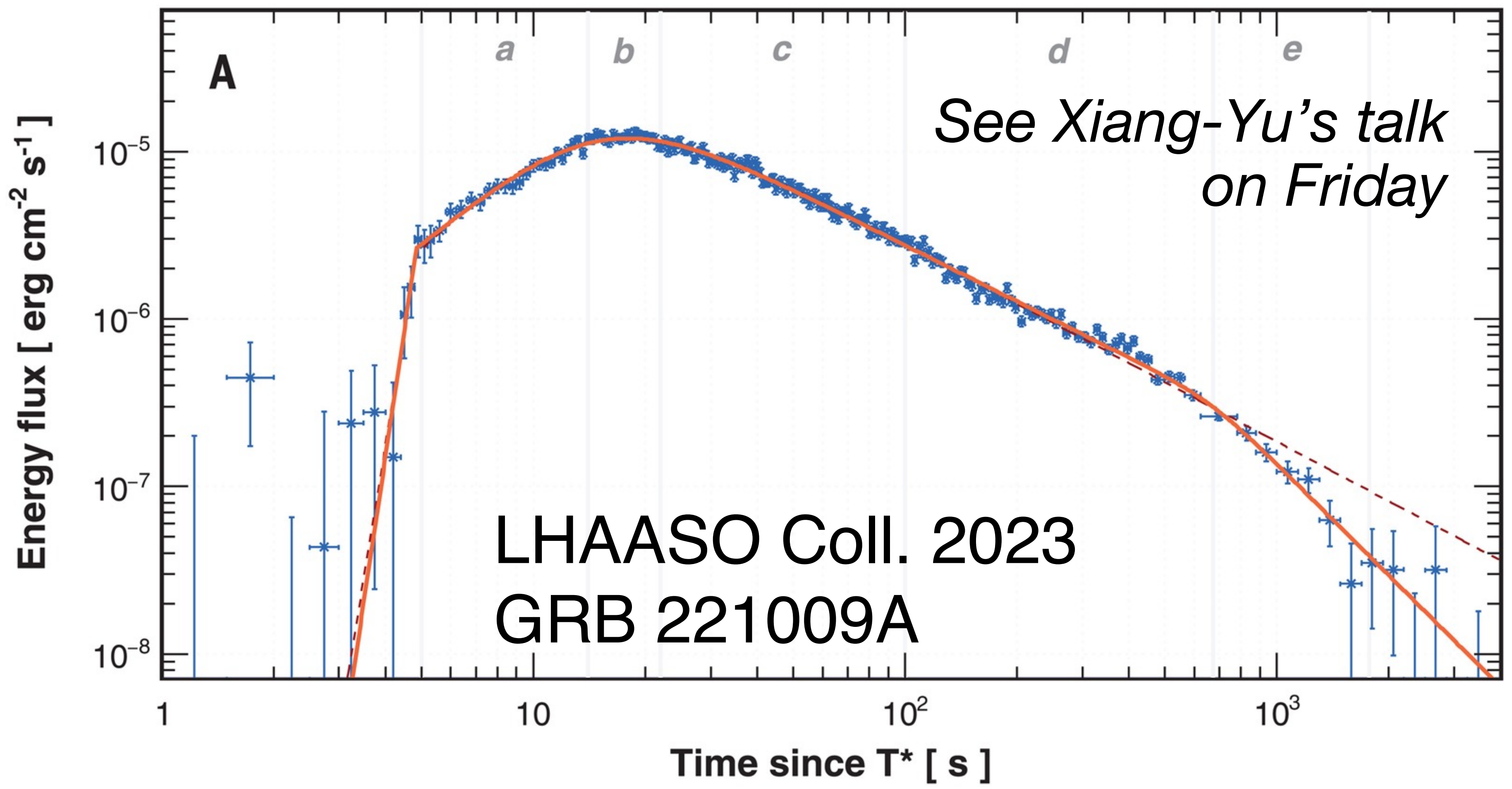
2D PIC simulations
Matsumoto et al. (2015)

Observational drivers - Relativistic Jets

GRBs

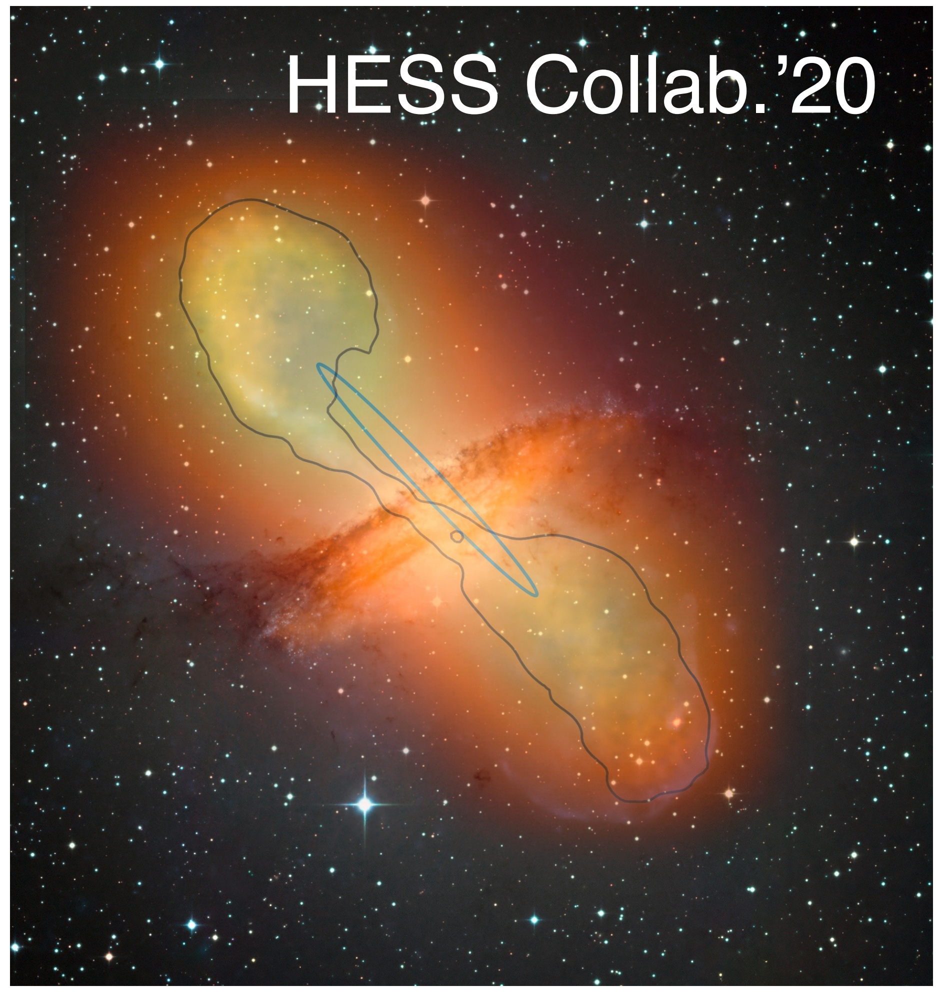
Many GRB afterglows now detected in VHE domain

A combination of internal (magnetised??) and external (unmagnetised) shocks.

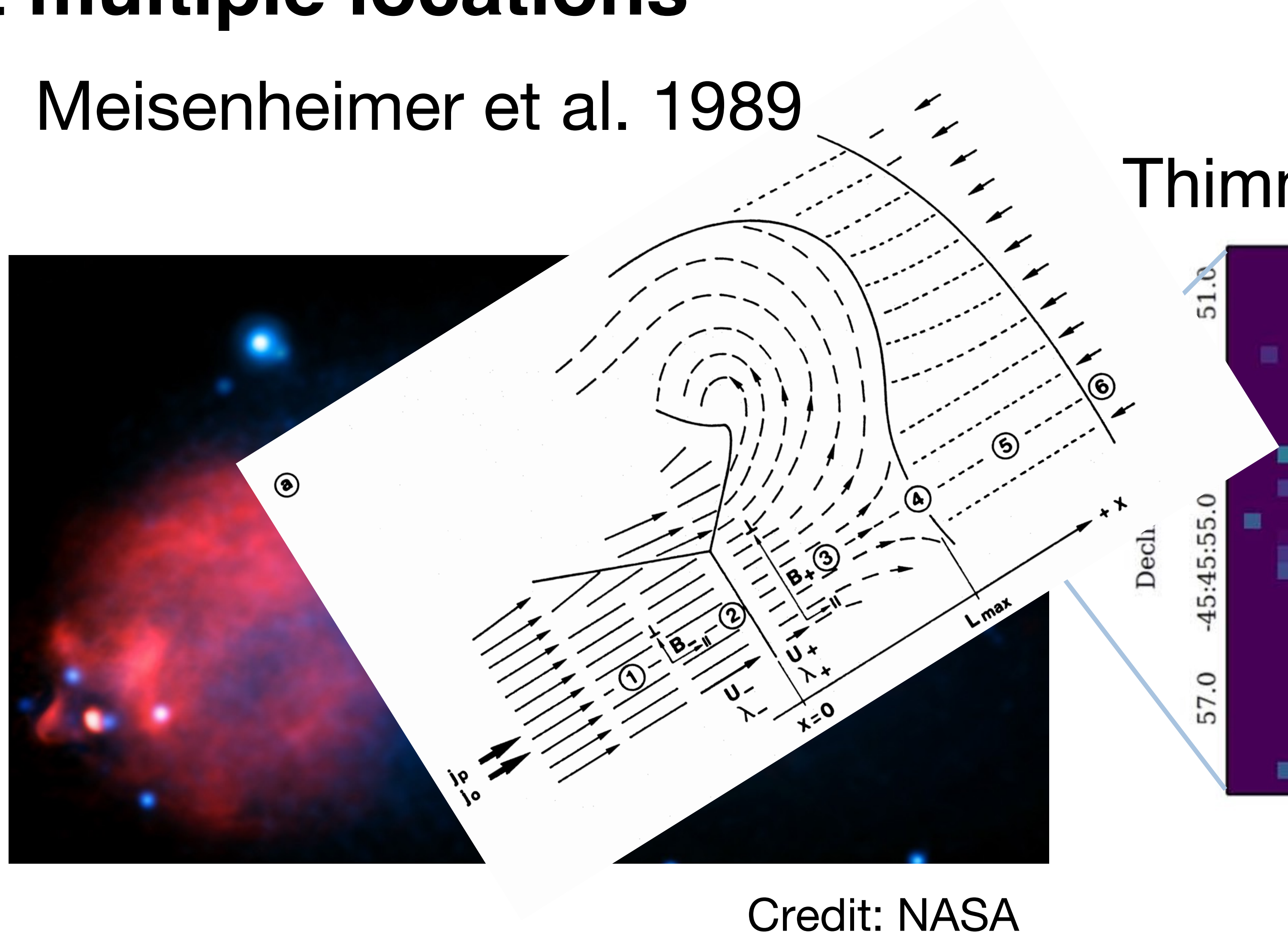


AGN

Extended VHE gamma-ray + synchrotron X-ray observations of AGN indicate effective non-thermal acceleration at multiple locations

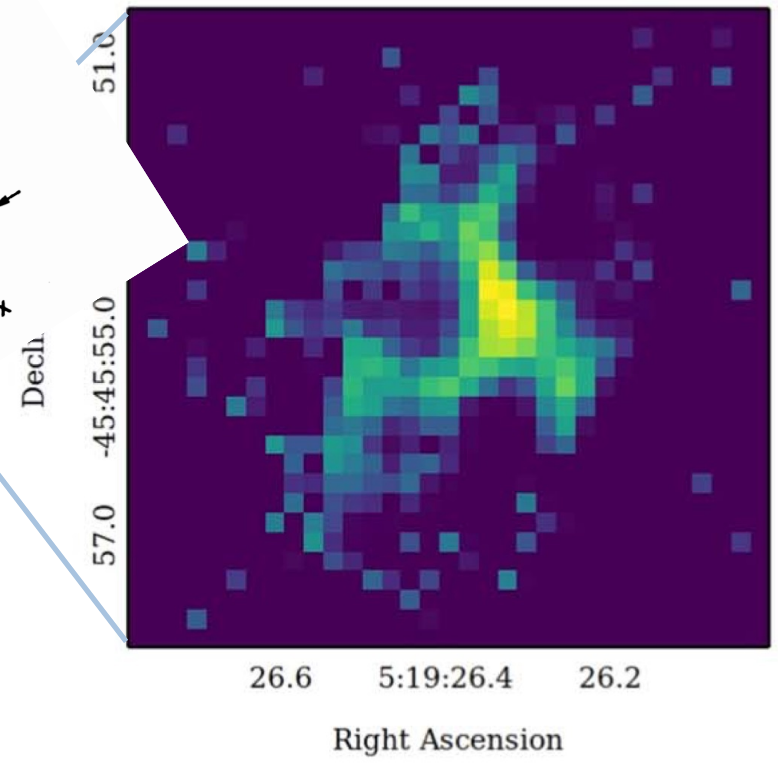


Meisenheimer et al. 1989



Credit: NASA

Thimmappa et al. '22



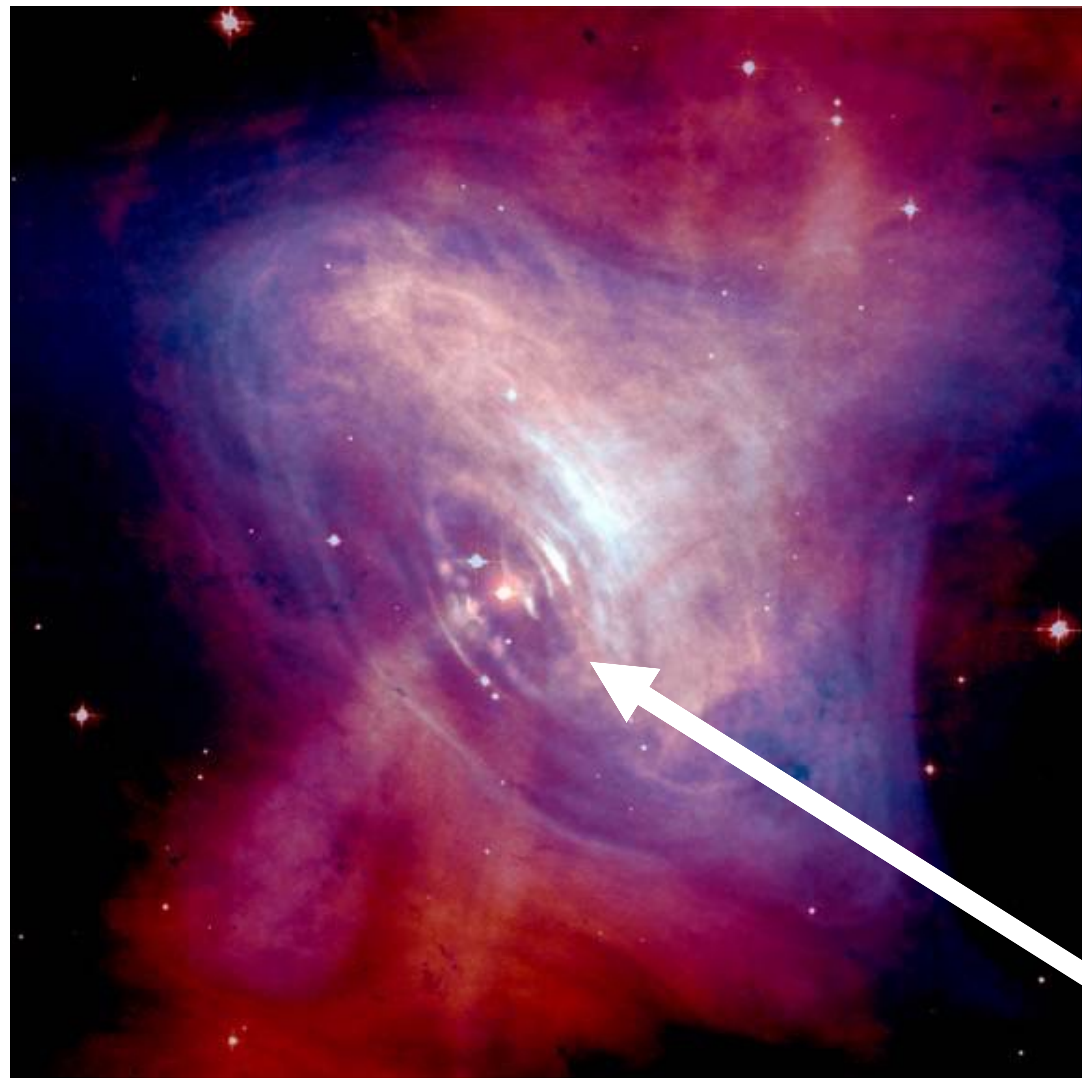
Magnetisation

$$\sigma = \frac{\mathrm{PoyntingFlux}}{\mathrm{EnthalpyFlux}}$$

Magnetic fields play an essential role in jet launching, collimation and acceleration.

Necessity for >>TeV electrons brings questions on the maximum energy + spectrum into focus

Observational Constraints - PWN



$r_{\rm sh} \approx 10^{17}$ cm

Pulsars, winds and nebulae

Unique plasma laboratories:

$e^{\pm}$ pair winds (possibly with some ions)

Local CR $e^{\pm}$ sources

Astrophysical foreground in DM searches

For the Crab Nebula WTS

$\Gamma_{\rm sh} \sim 10^2 - 10^4$

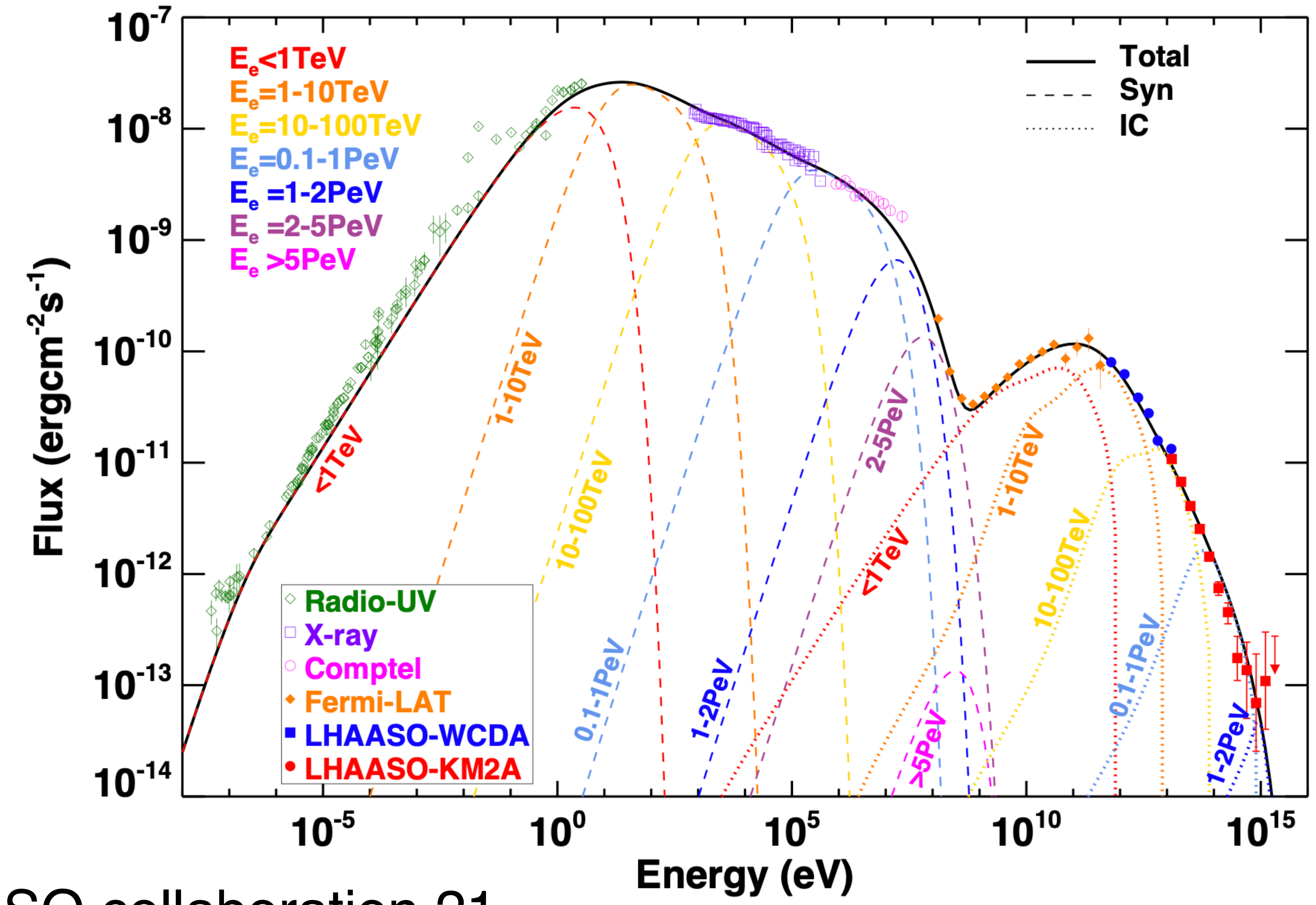
Magnetisation unknown but large at light cylinder

PeV photons = electrons > PeV

An almost perfect accelerator!!

Crab is not unique in this aspect

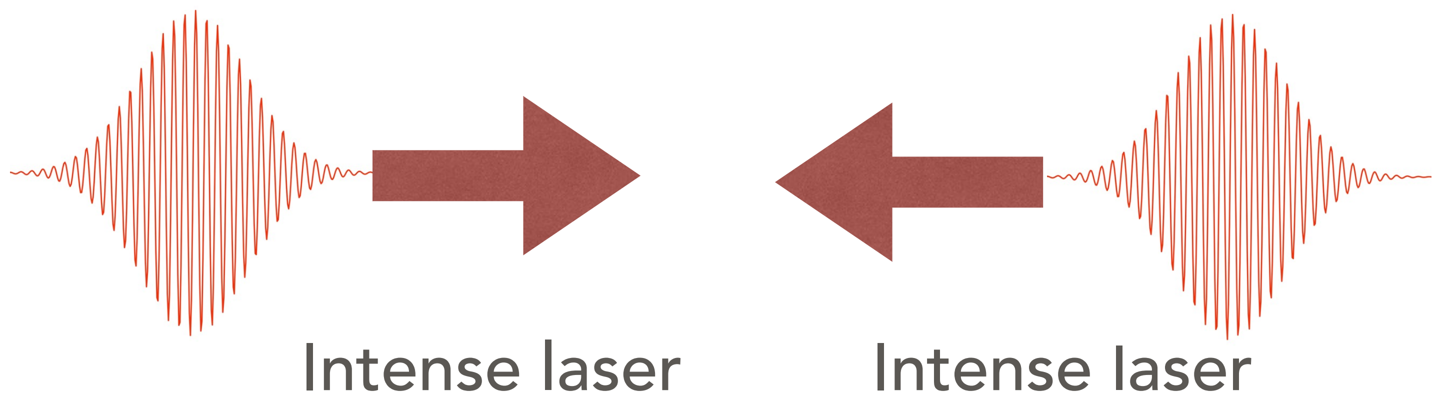
(J. Hinton's talk earlier today)



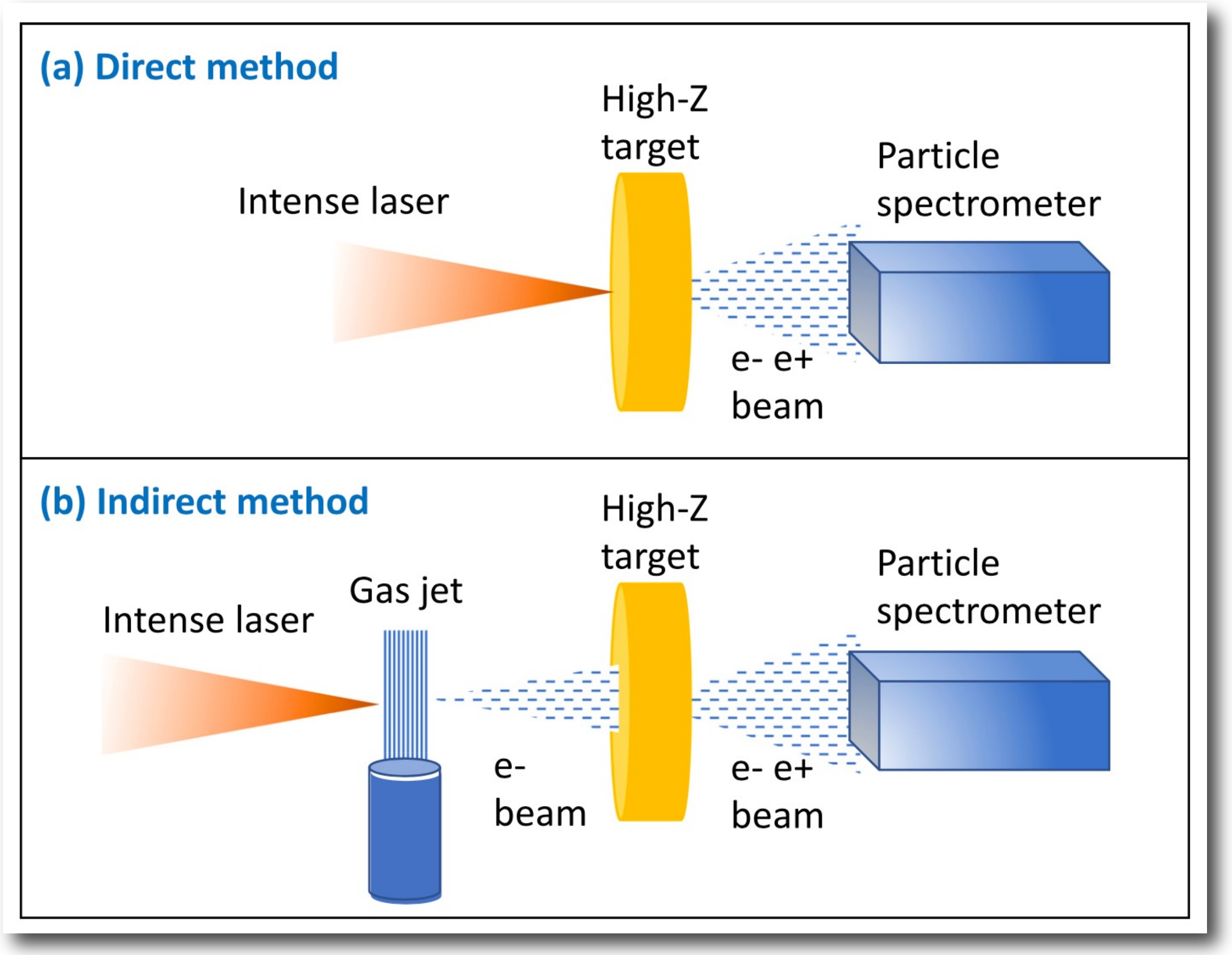
LHAASO collaboration 21

Producing pair-plasmas in the lab

Breit-Wheeler method



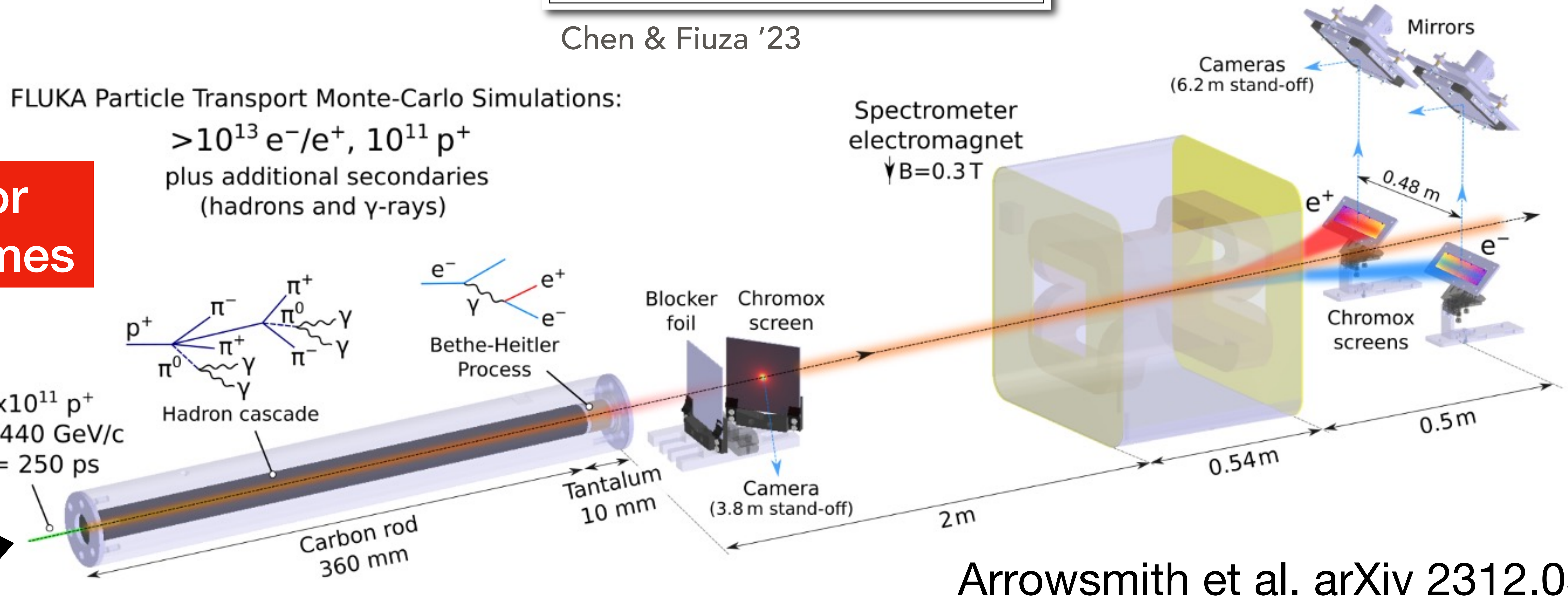
Kirk & Bell '09



Chen & Fiuza '23

Laser based schemes

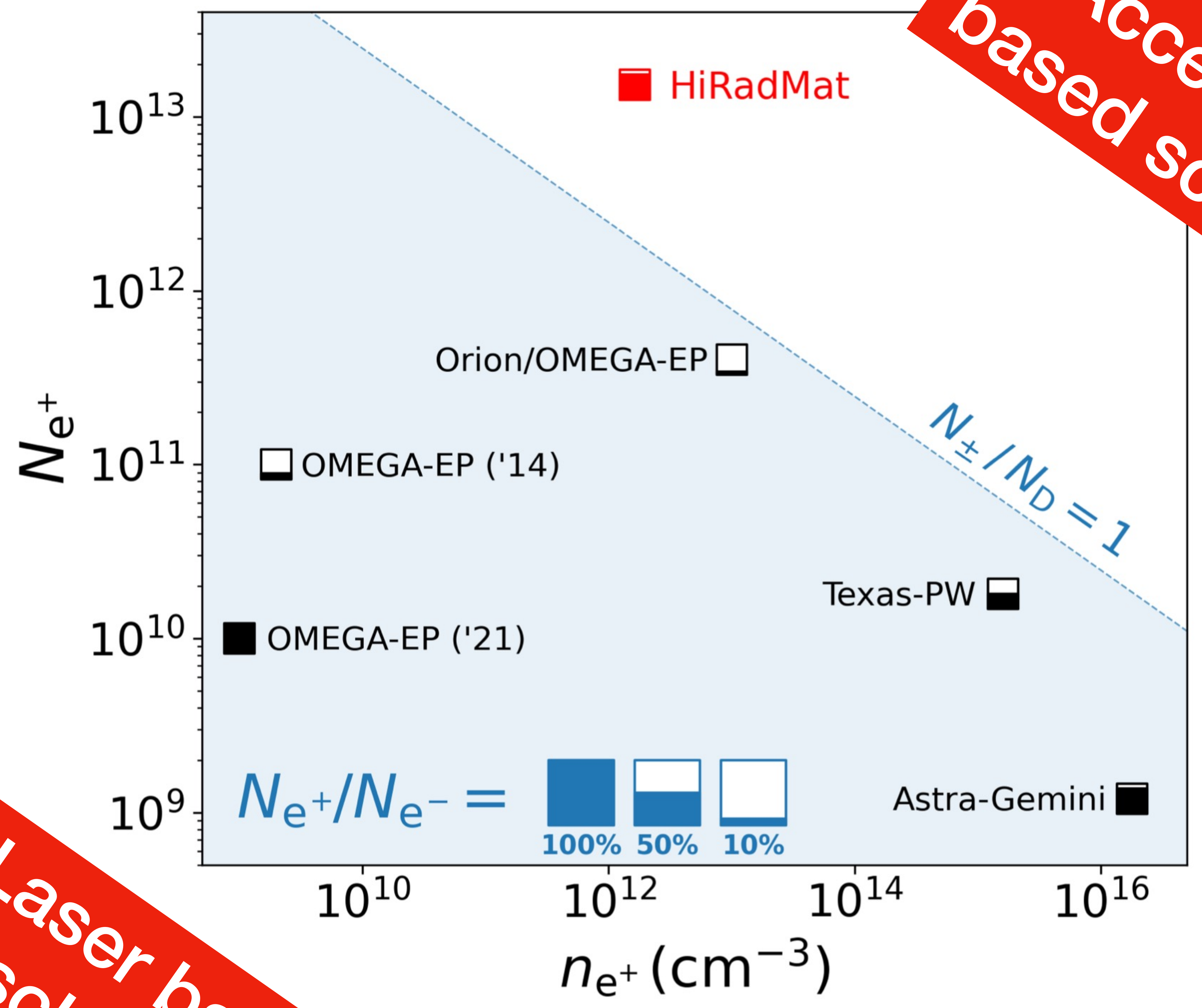
Accelerator based schemes



Cern p^+ beam

Arrowsmith et al. arXiv 2312.05244

Producing pair-plasmas in the lab

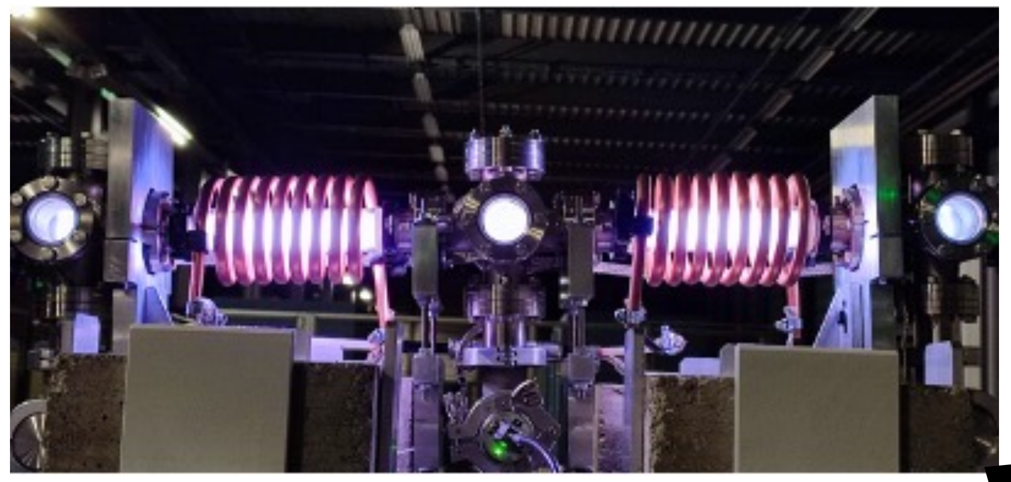


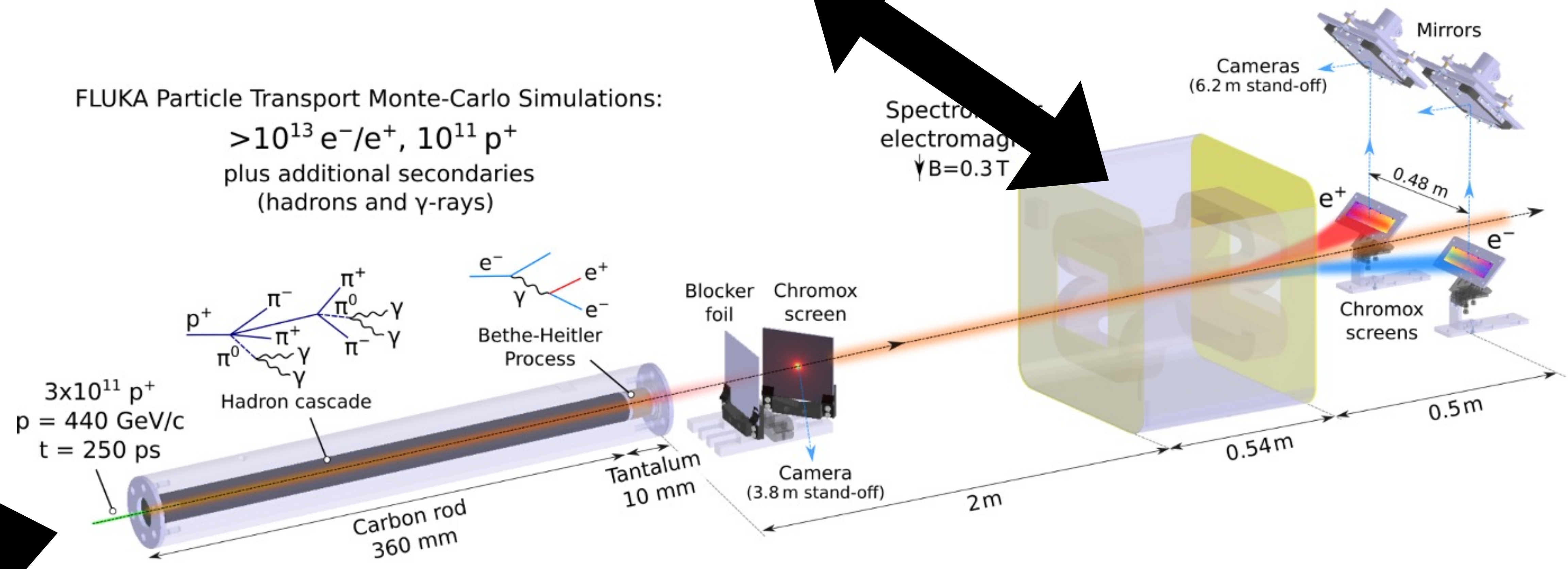
Accelerator based schemes

Laser based schemes

Pair plasmas in the lab at last.

First test of relativistic pair beam in a plasma
Arrowsmith APS DPP 23





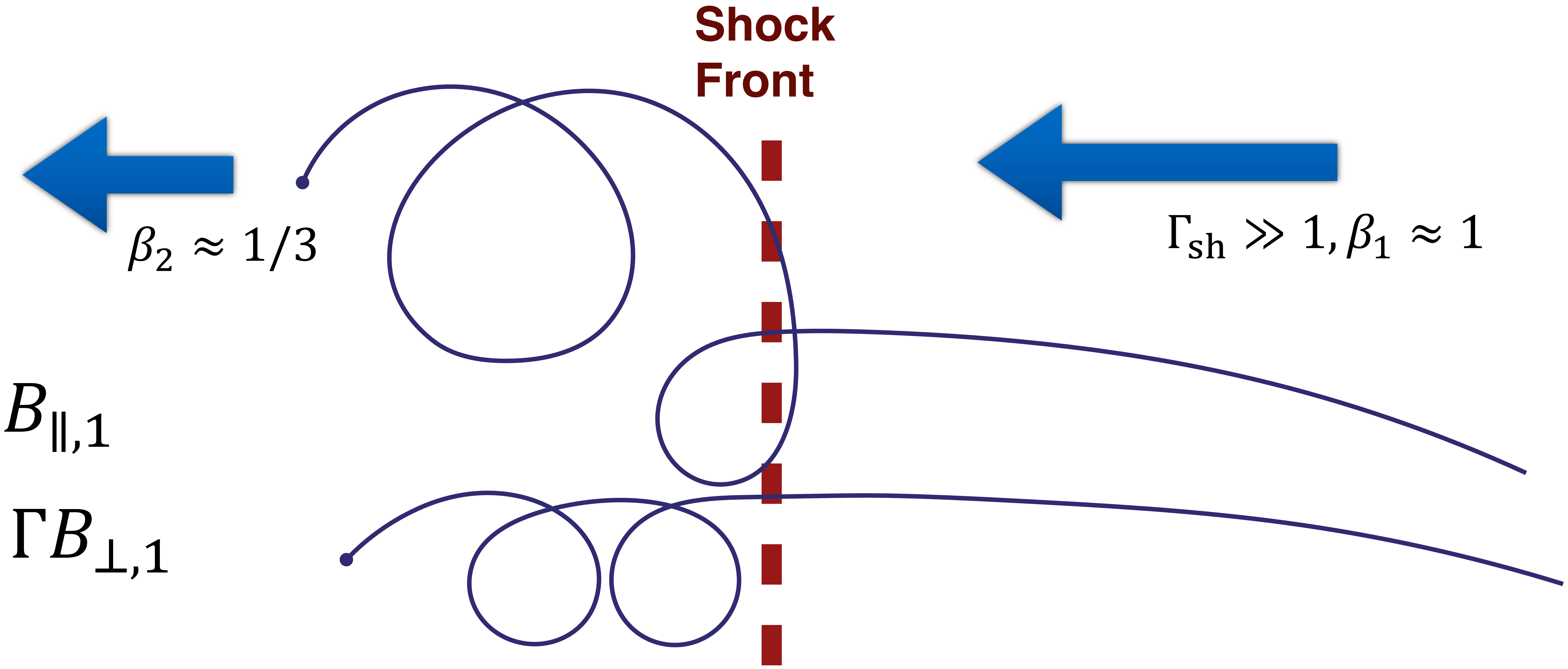
Cern p^+ beam

Arrowsmith et al. arXiv 2312.05244

Back to business - key questions

- Do relativistic shocks accelerate at all?
- What determines the maximum energy?
- What determines the shape of non-thermal particle spectrum?
- Can we predict radiative signatures (breaks, cut-offs, etc.)?

The trouble with relativistic shocks



$$B'_{\parallel,2} = B_{\parallel,1}$$

$$B'_{\perp,2} \sim \Gamma B_{\perp,1}$$

An un-scattered particle is limited to ≤ 3 crossings (Begelman & Kirk ’90)

Strong scattering needed to overcome the $\mathbf{E}\times\mathbf{B}$ drift which acts to transport particles downstream at $\approx c/3$

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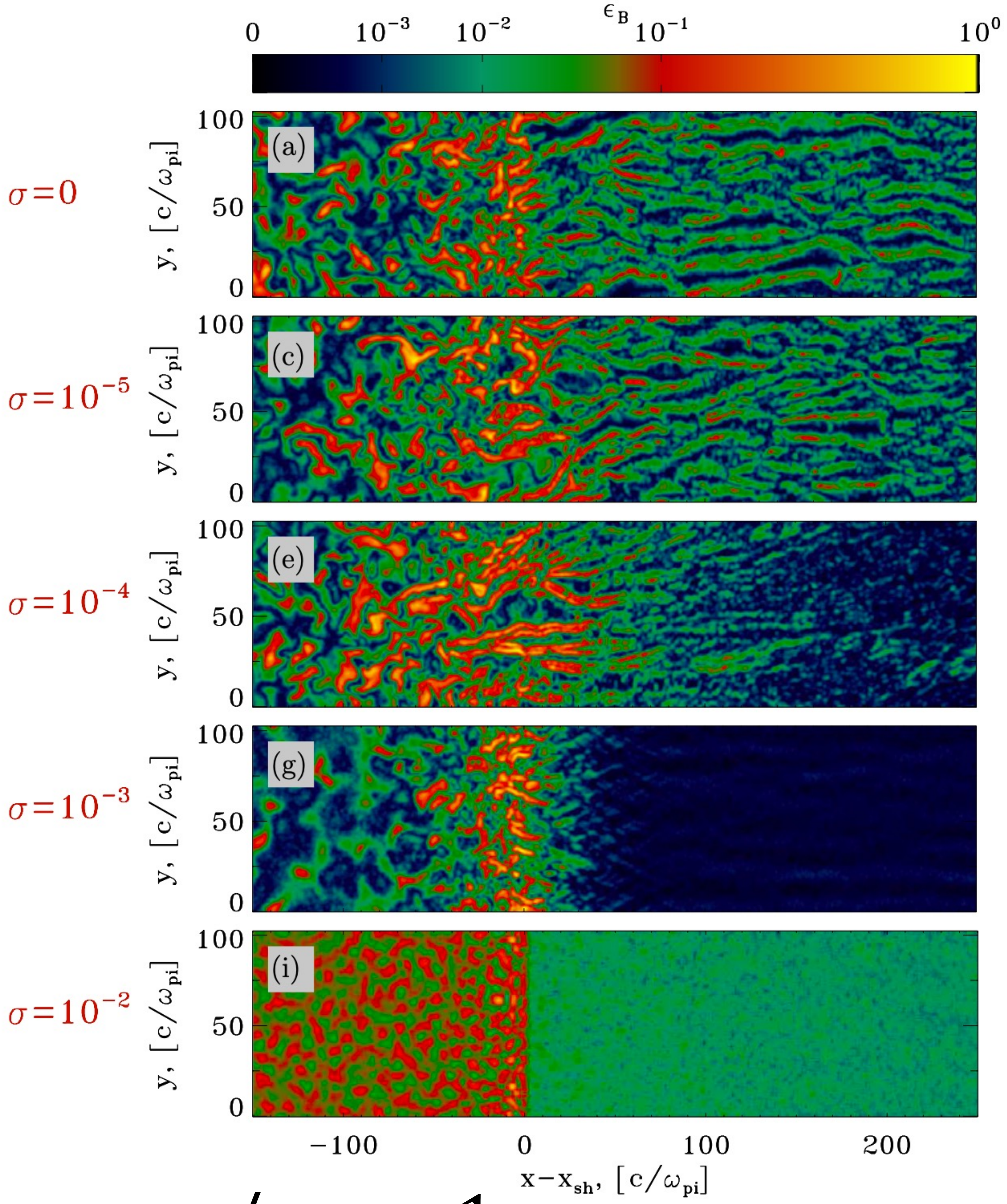
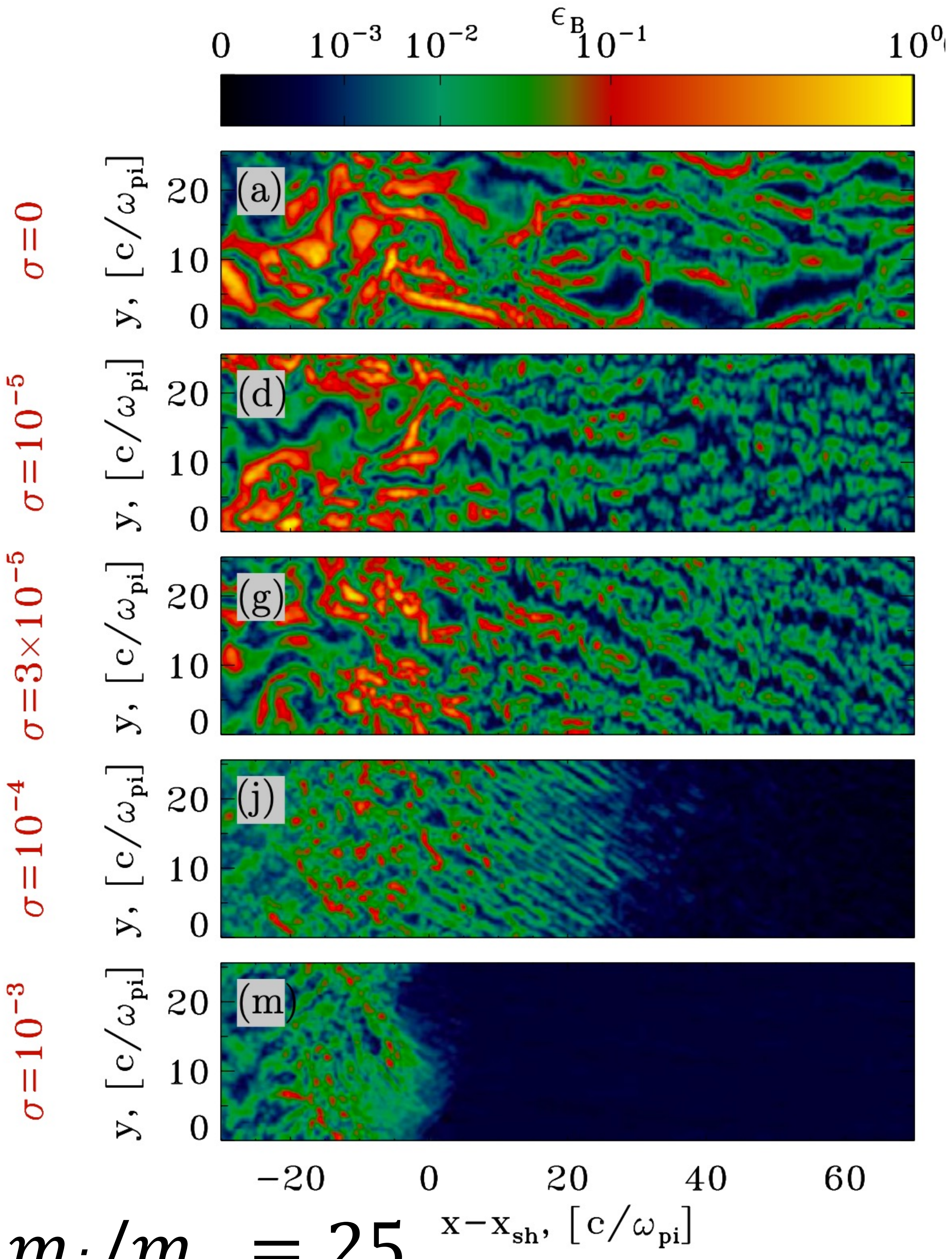
Insights from PIC simulations

2D quasi-perp sims (Sironi, Spitkovsky & Arons '13)

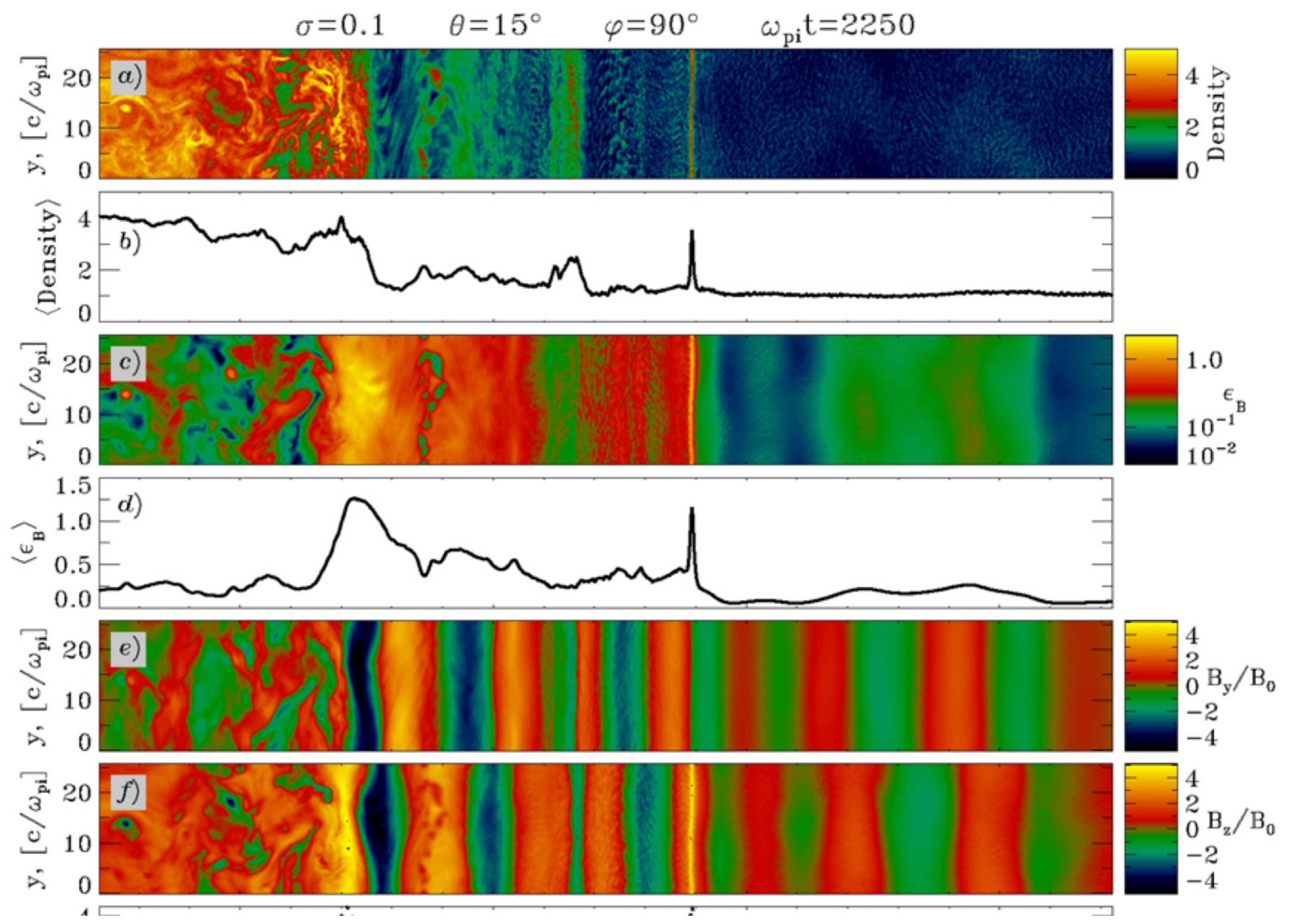


$m_i/m_e = 1$



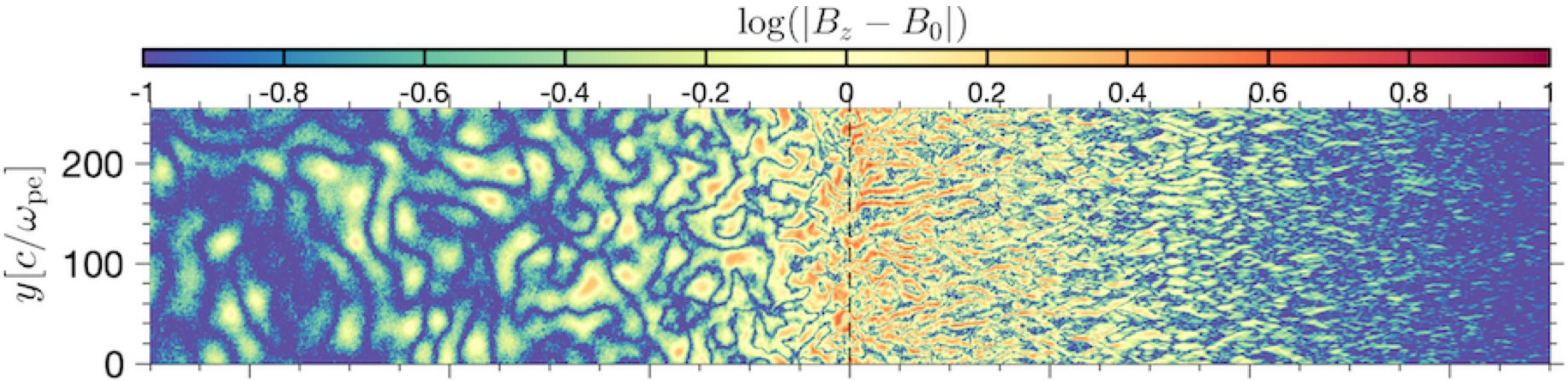
$m_i/m_e = 25$

2D quasi-pll sims (Sironi & Spitkovsky '11)



For weakly magnetised **or** subluminal shocks, particles can behave as though **unmagnetised.**

Limitations of the weakly magnetised shock model



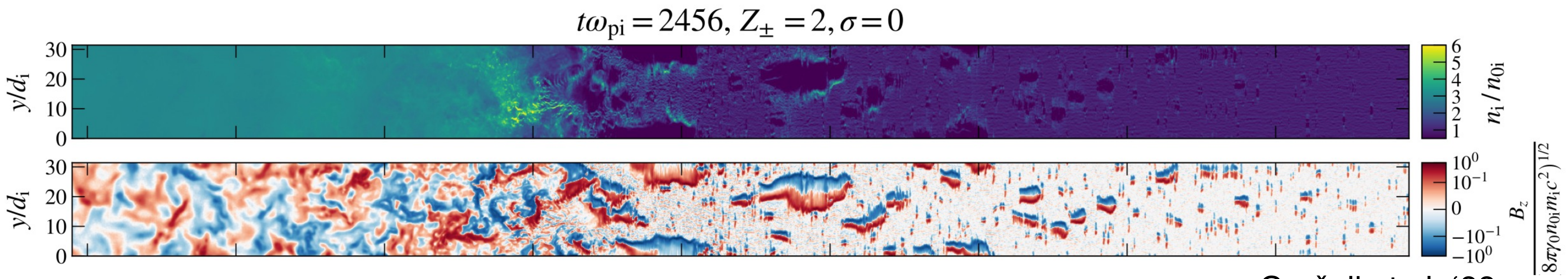
Plotnikov et al, '18

- Scattering is non-resonant (frequent small-angle deflections)⇒ $t_{sc} \propto \gamma^2$
- Acceleration is **slow**

  $t_{acc} \approx \Delta t_- + \Delta t_+ \sim \gamma^2$ **if** scattering dominates. (Kirk & BR '10)

  Synchrotron emission falls short of burn-off limit (see also Derishev '07).
- At some point becomes cooling limited ($t_{cool} \propto \gamma^{-1}|B|^{-2}$) or magnetised ($t_{gyro} \propto \gamma/\langle B \rangle$)
- For typical GRB conditions, the latter is more constraining possibly in **tension** with TeV detection of late GRB afterglows (Huang et al. 22).

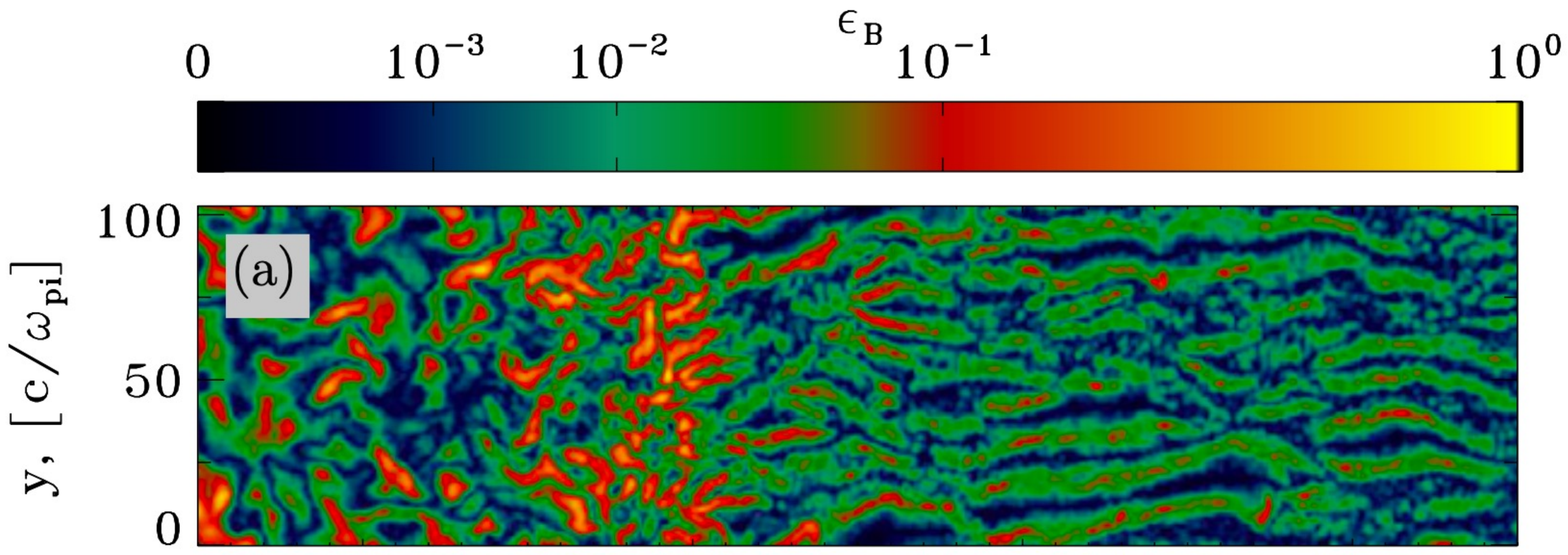
Ways out



Grošelj et al. '22

1. Quasi-parallel shocks — unlikely in all cases (but not impossible)
2. If magnetic structures grow to larger size
    - Bigger simulation box seems to suggest this is possible (D. Groselj private comm.)
    - CR driven Rayleigh-Taylor instability likely requires 3D simulations (BR & Bell '14)

Ways out



3. Particles become magnetised on **one** side of the shock (Huang et al ’23)

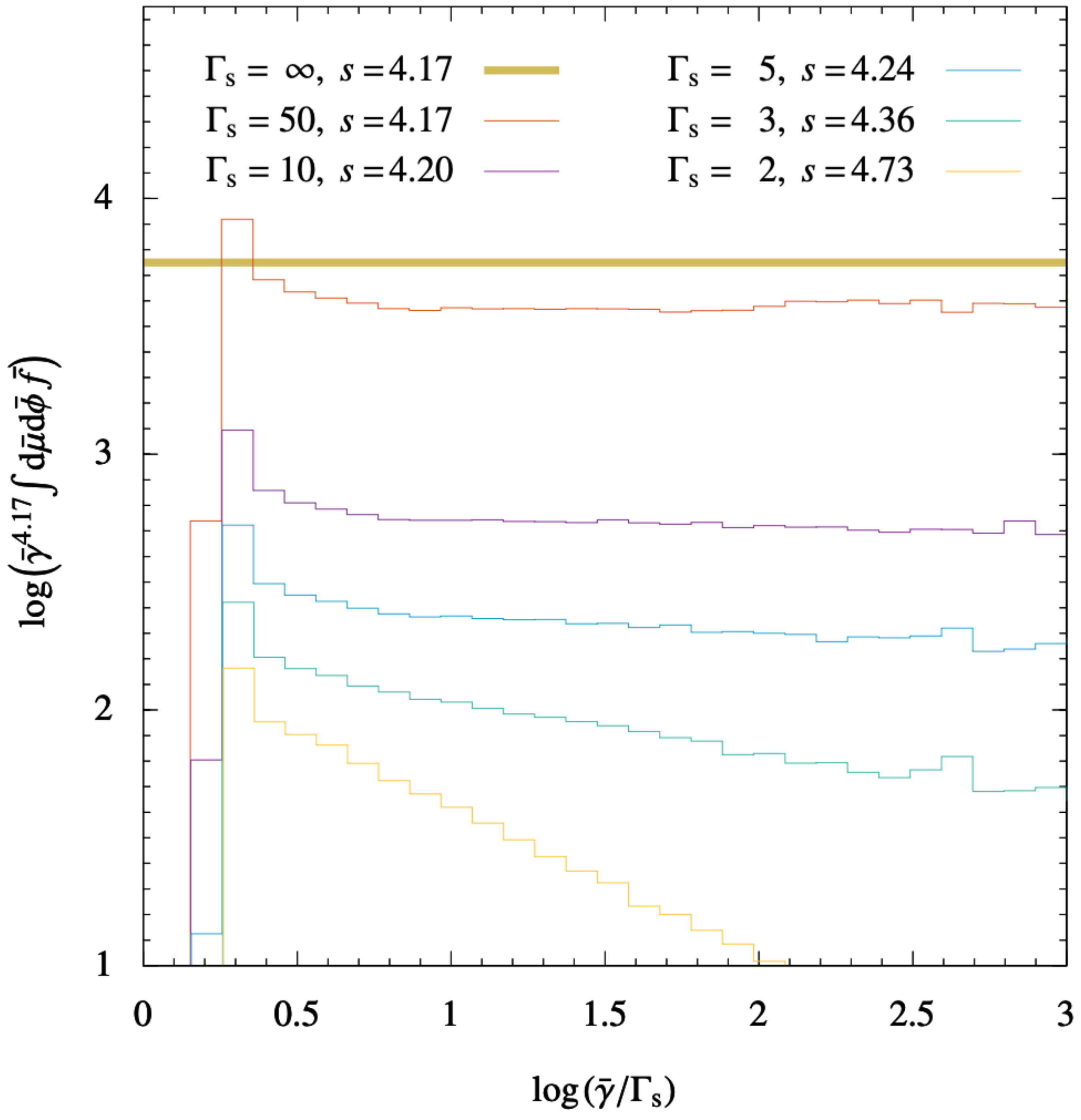
$$t_{\mathrm{acc}} \approx \Delta t_- + \Delta t_+ \sim \gamma$$

- This only gets you so far (upstream loses out unless particles sample damped zone downstream)
- Contrary to earlier claims by myself and others, conditions + instabilities driven upstream is equally if not more important.

Predicted (test) particle spectrum

Kirk et al. 2000: parallel shock - scattering dominates up & downstream $dN/d\gamma \propto \gamma^{-2.22}$

Achterberg et al 2001: scattering downstream, regular deflection upstream $dN/d\gamma \propto \gamma^{-2.2\pm0.1}$

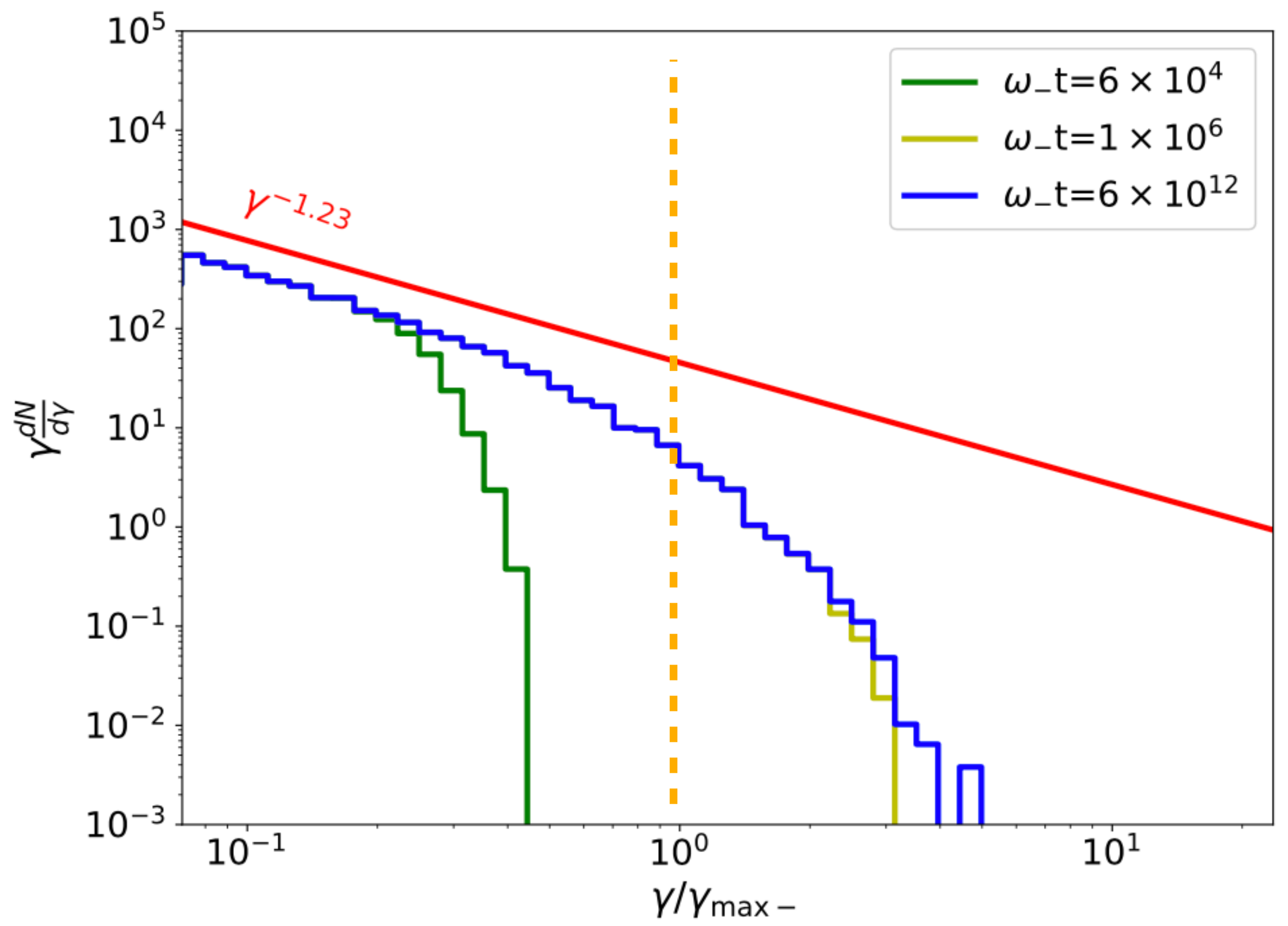


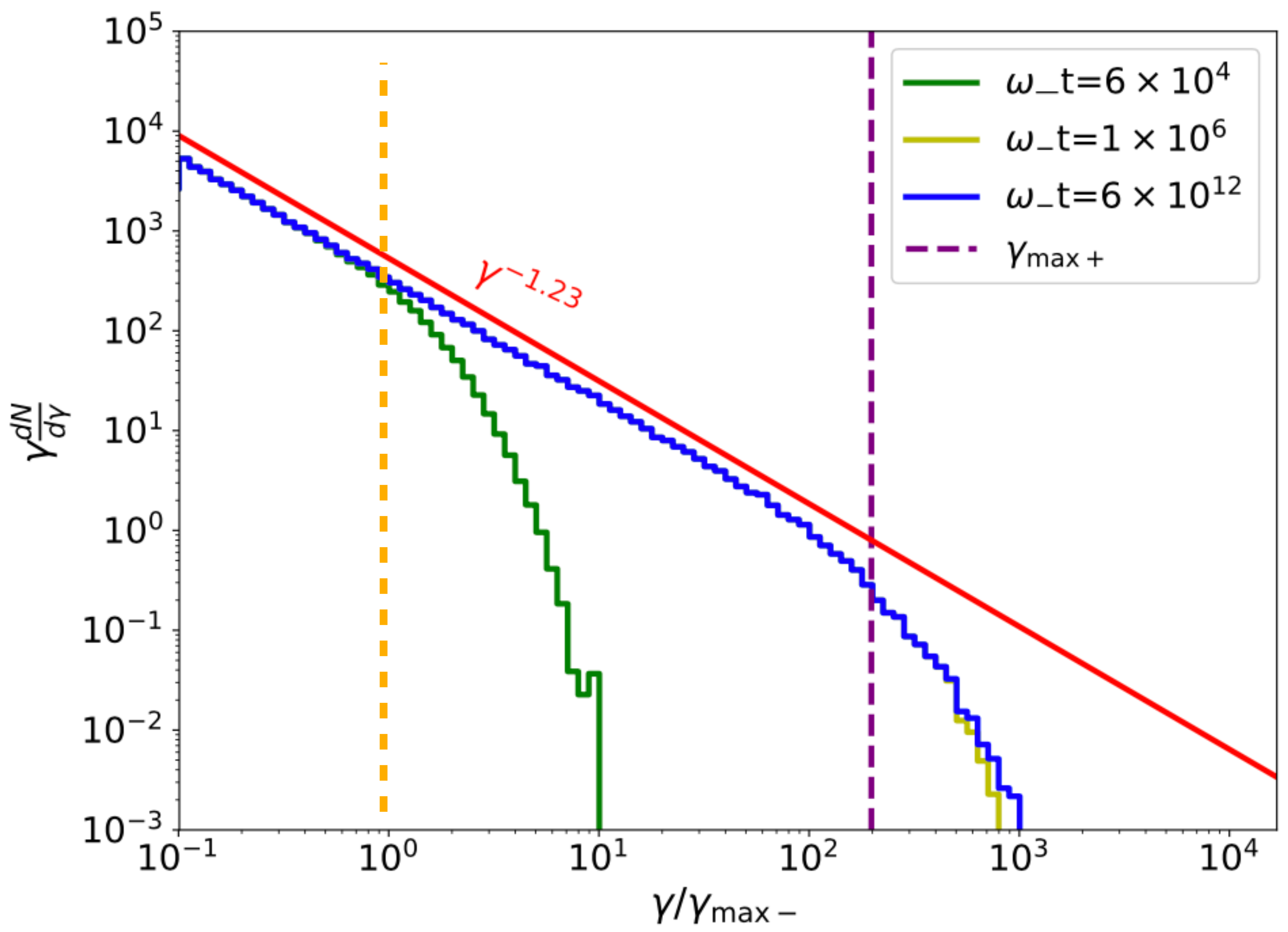
Kirk et al. 2023:

Scattering upstream, regular deflection downst. $dN/d\gamma \propto \gamma^{-2.17}$

(Only slightly harder then parallel case)

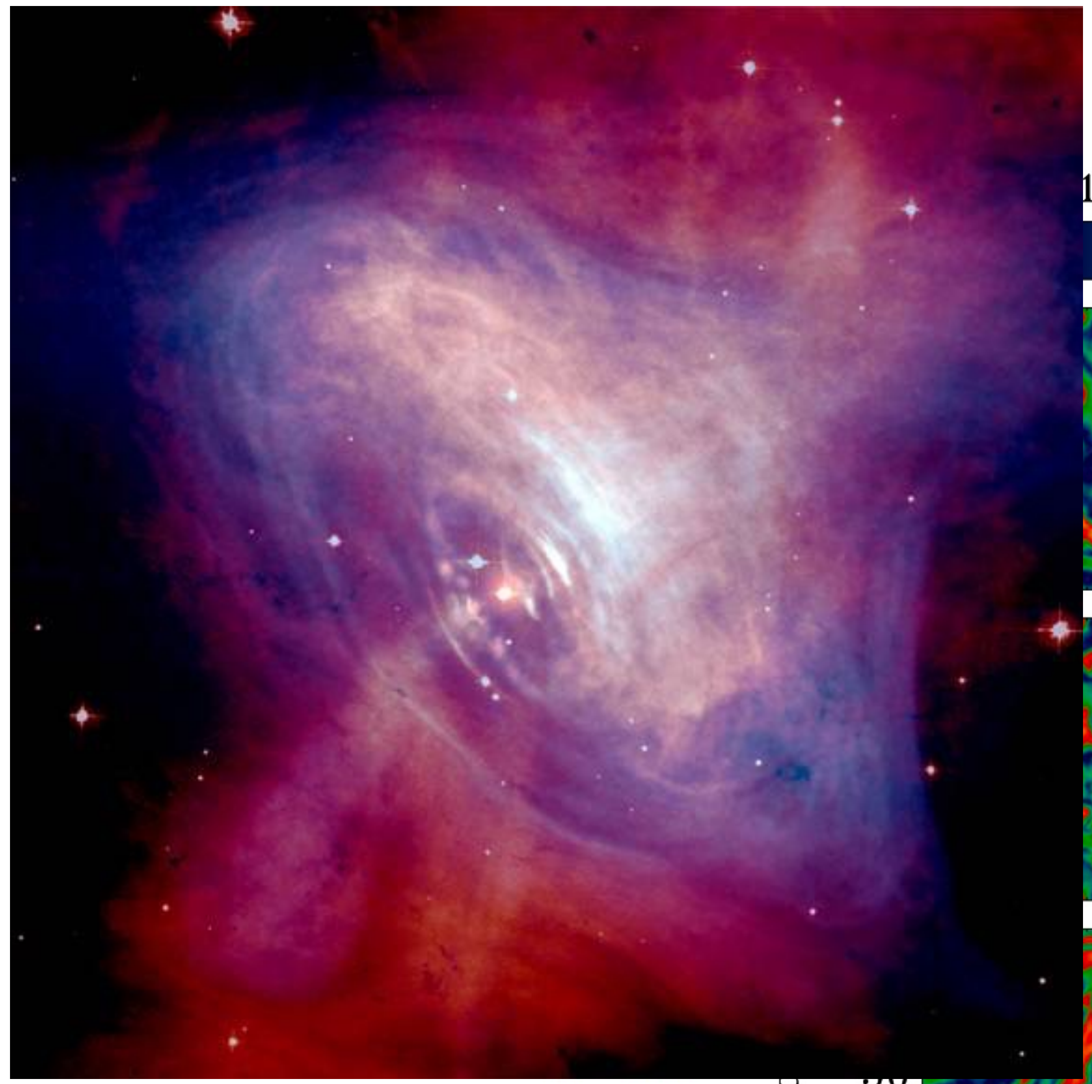
Huang et al .23, scattering + regular field everywhere, no losses

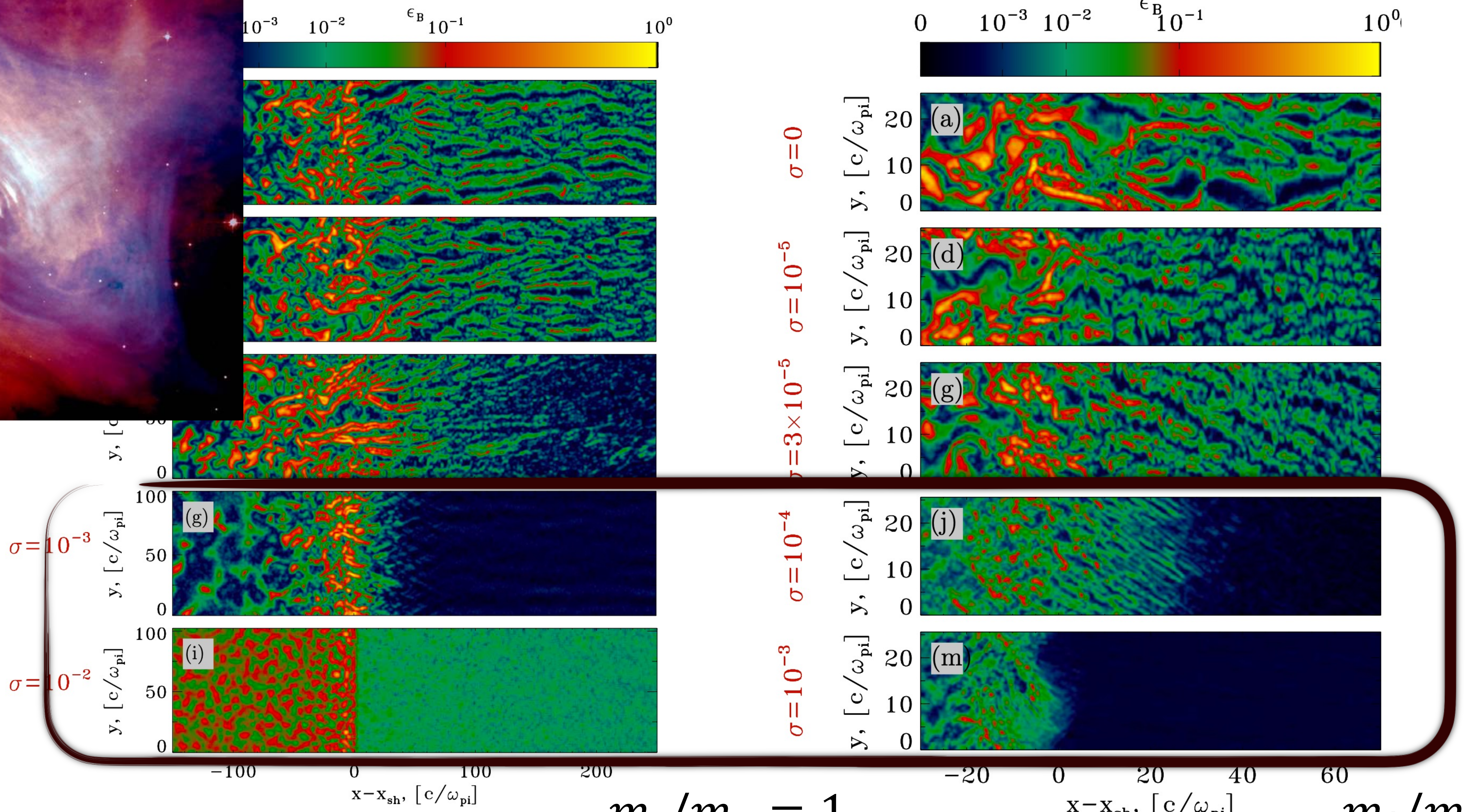




Acceleration saturates when magnetised both upstream AND downstream

What about magnetised perpendicular shocks?

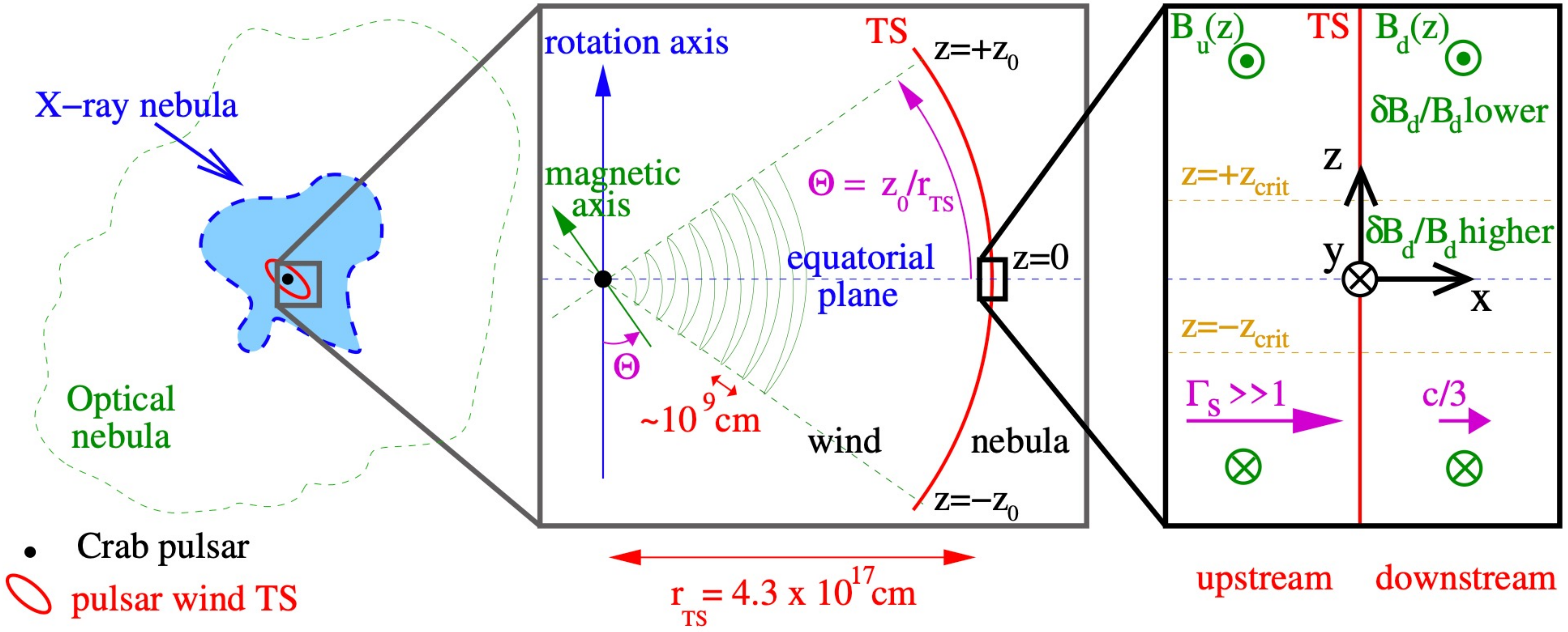




$m_i/m_e = 1$ $m_i/m_e = 25$

We assumed that injection looked after itself, but regular field suppresses injection

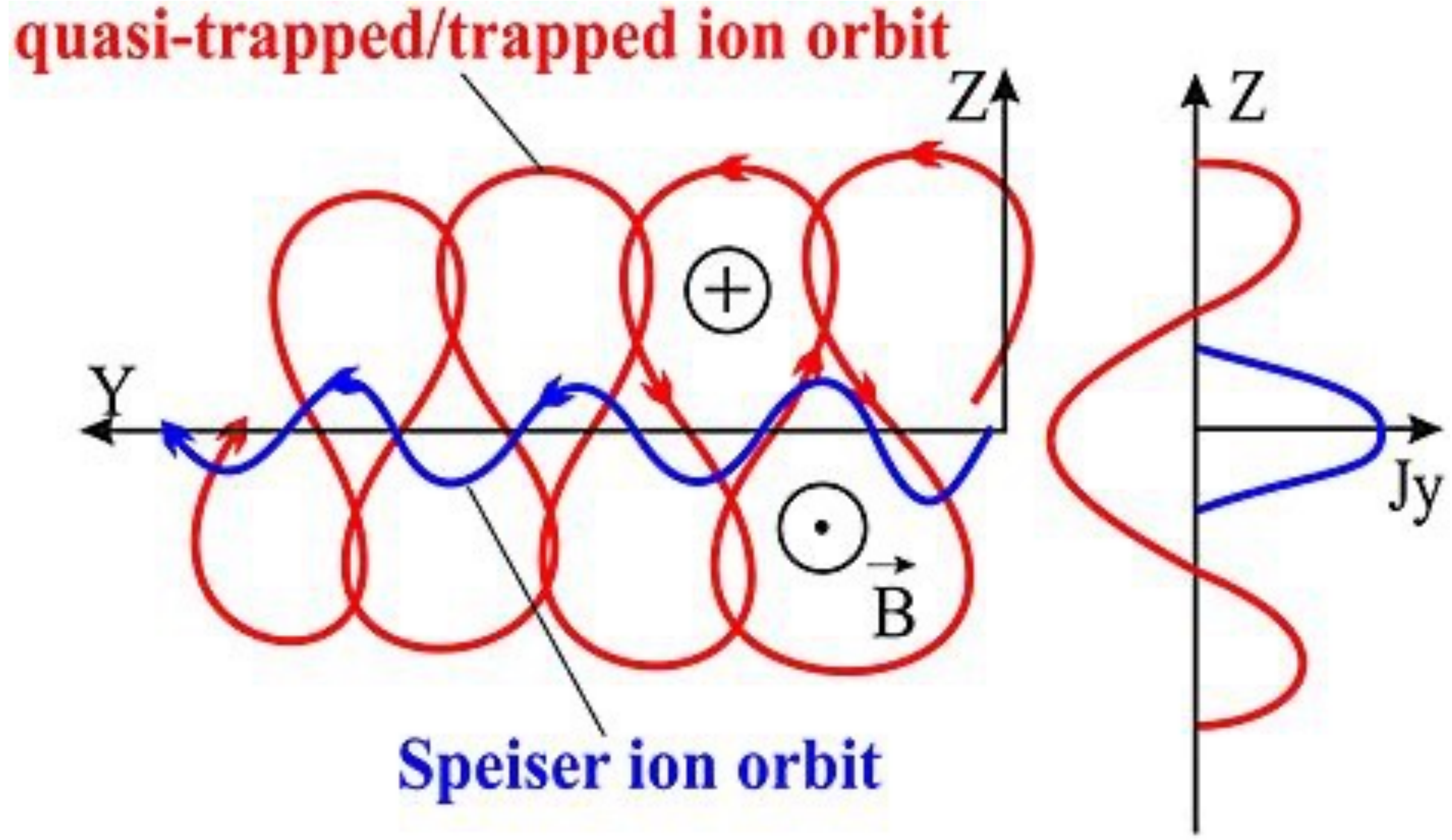
The impact of global field topology



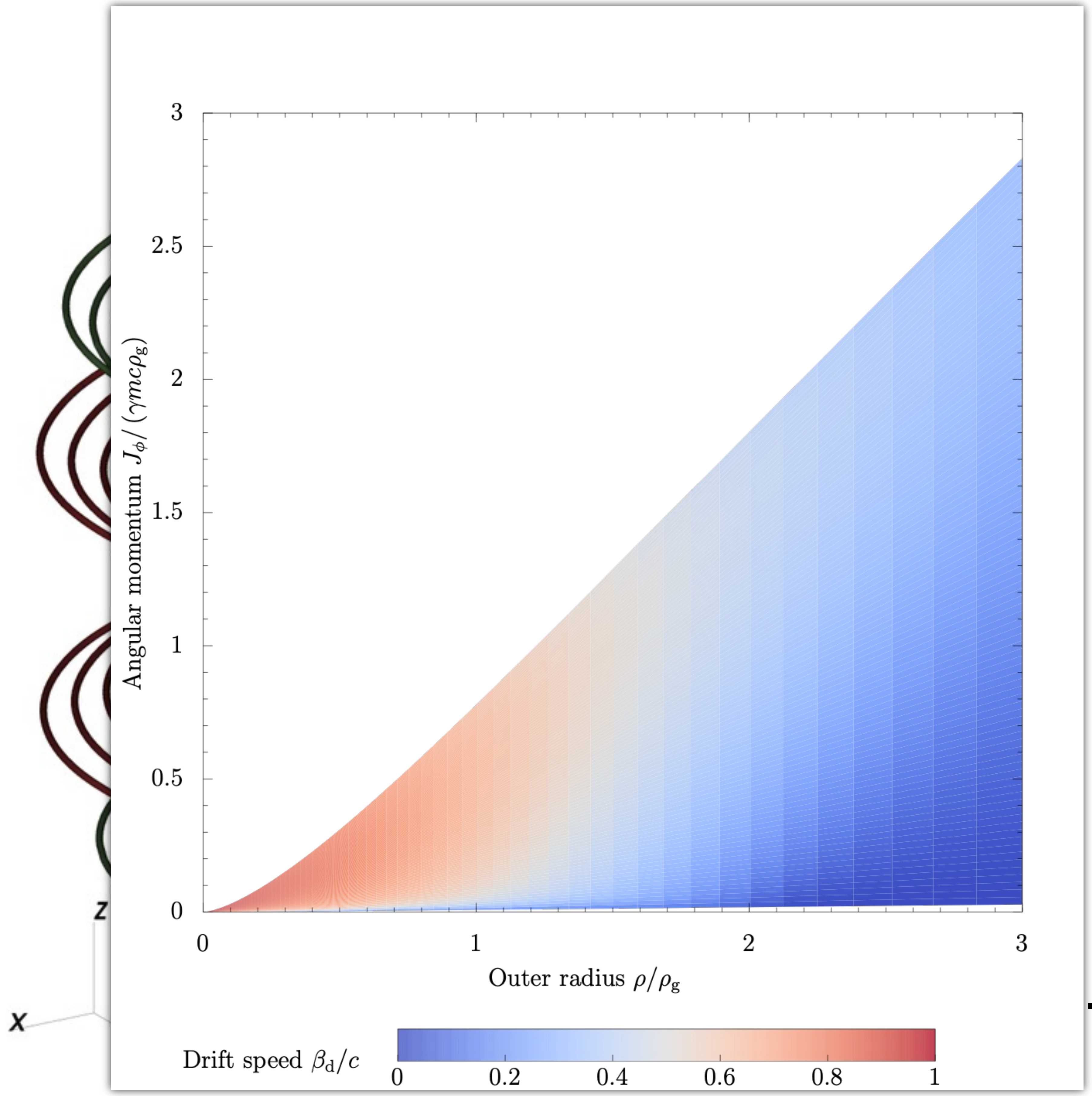
Giacinti & Kirk (2018)

Fermi acceleration at termination shock facilitated by Speiser orbits in ds returning particles to shock (note charge dep.).

Can account for PeV γ-ray production seen in Crab PWN by LHAASO (Giacinti, BR & Kirk, ICRC 21)
See Gwenael's talk on Friday



Shocks in cylindrical field jets



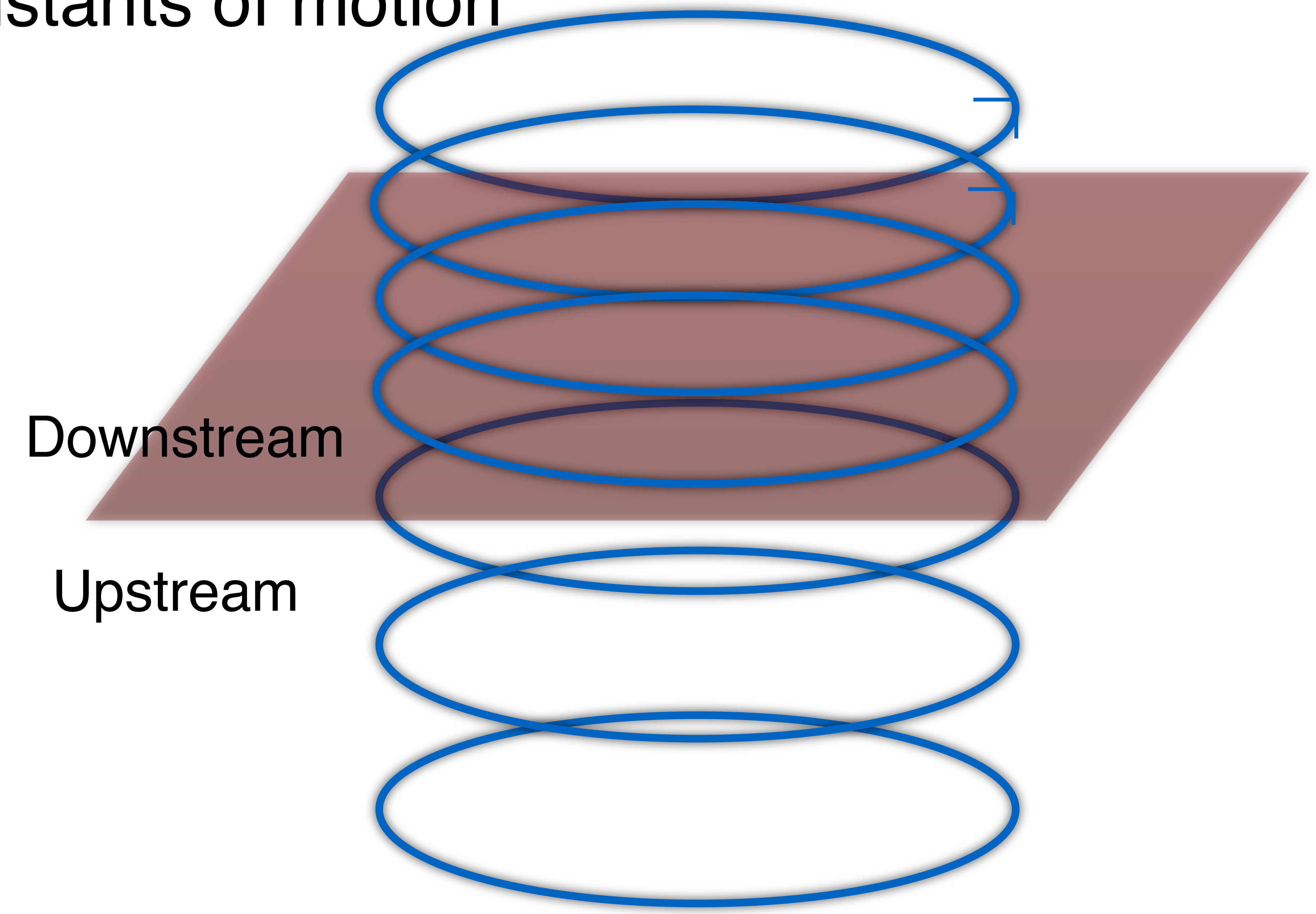
. ‘11

Consider simplest case scatter free trajectory in axially symmetric static magnetic field

Far from axis, we approximate (this diverges as $\rho \to 0$)

$$\mathbf{A} = -B_0 \rho \hat{\mathbf{z}} \Longrightarrow \mathbf{B} = B_0 \hat{\phi}$$

Lagrangian indep. of z, ϕ and $E = 0$,
$\gamma, P_z and P_\phi$ are constants of motion



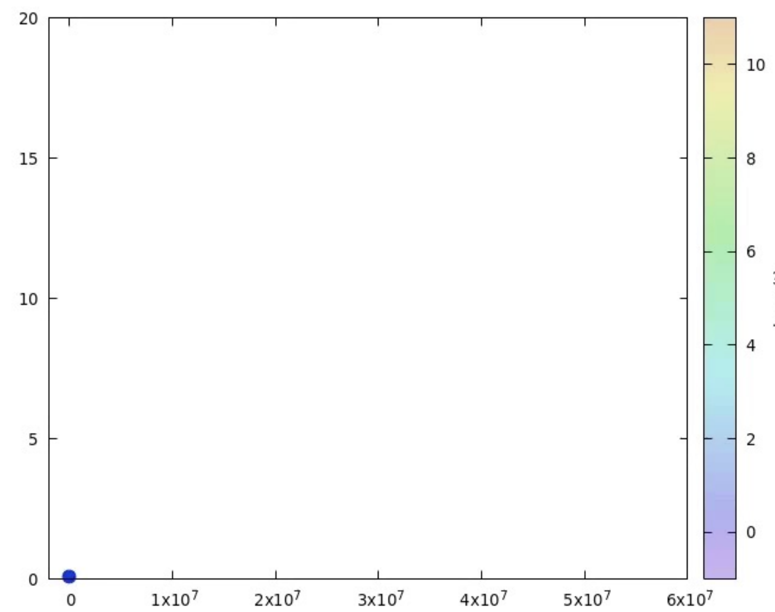
$$\frac{P_z}{\gamma m c} = \frac{v_z}{c} + \frac{\rho}{\rho_{g,0}} = const$$ where $\rho_{g,0} = \dfrac{\gamma m c^2}{q B_0}$,

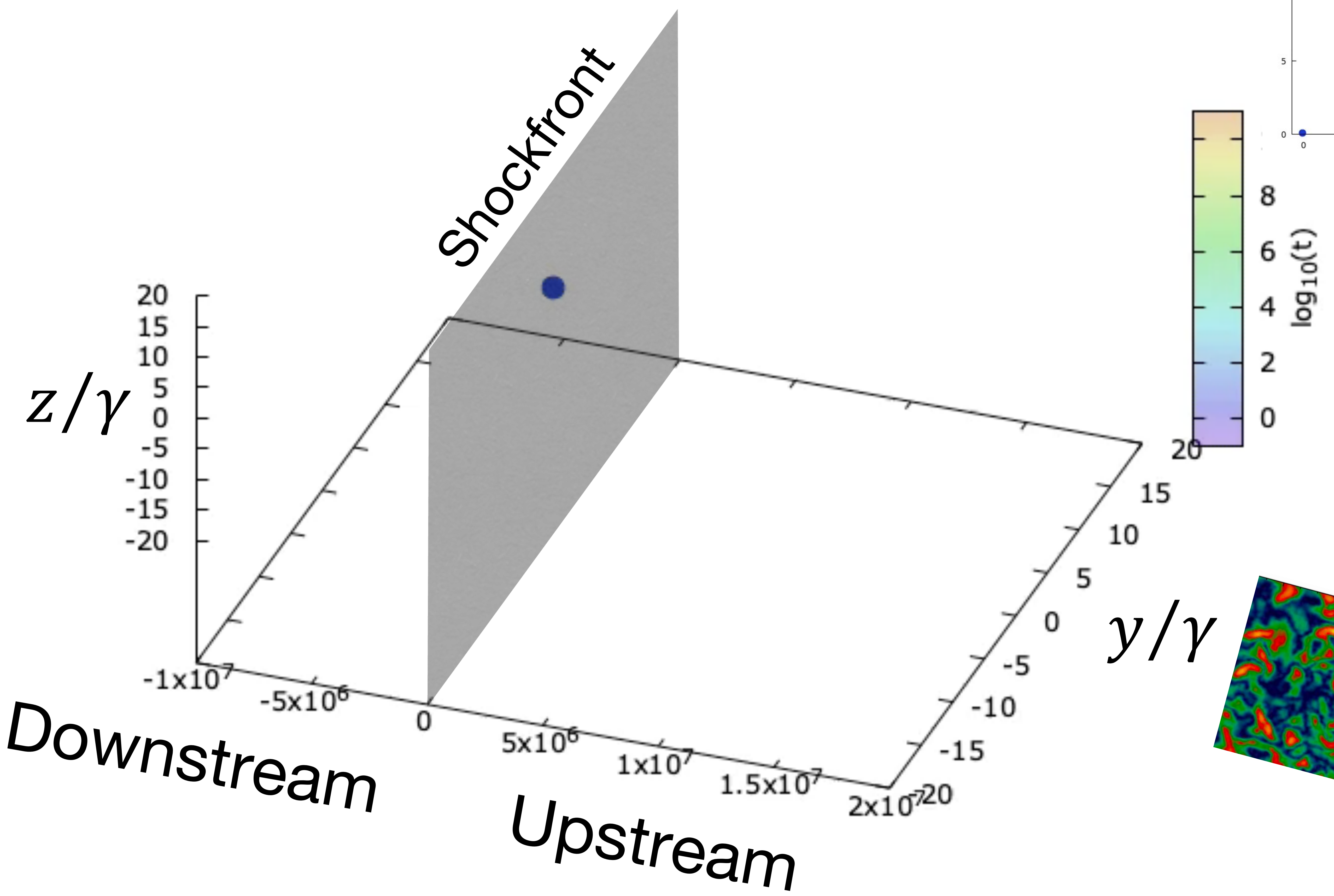
If $\rho < \rho_{g,0}$, **curvature** drifts approach c (direction determined by sign of qB_0)

Shocks in cylindrical field jets

Monte Carlo simulations of particle accelerated at ultra-relativistic shock. Assumes:

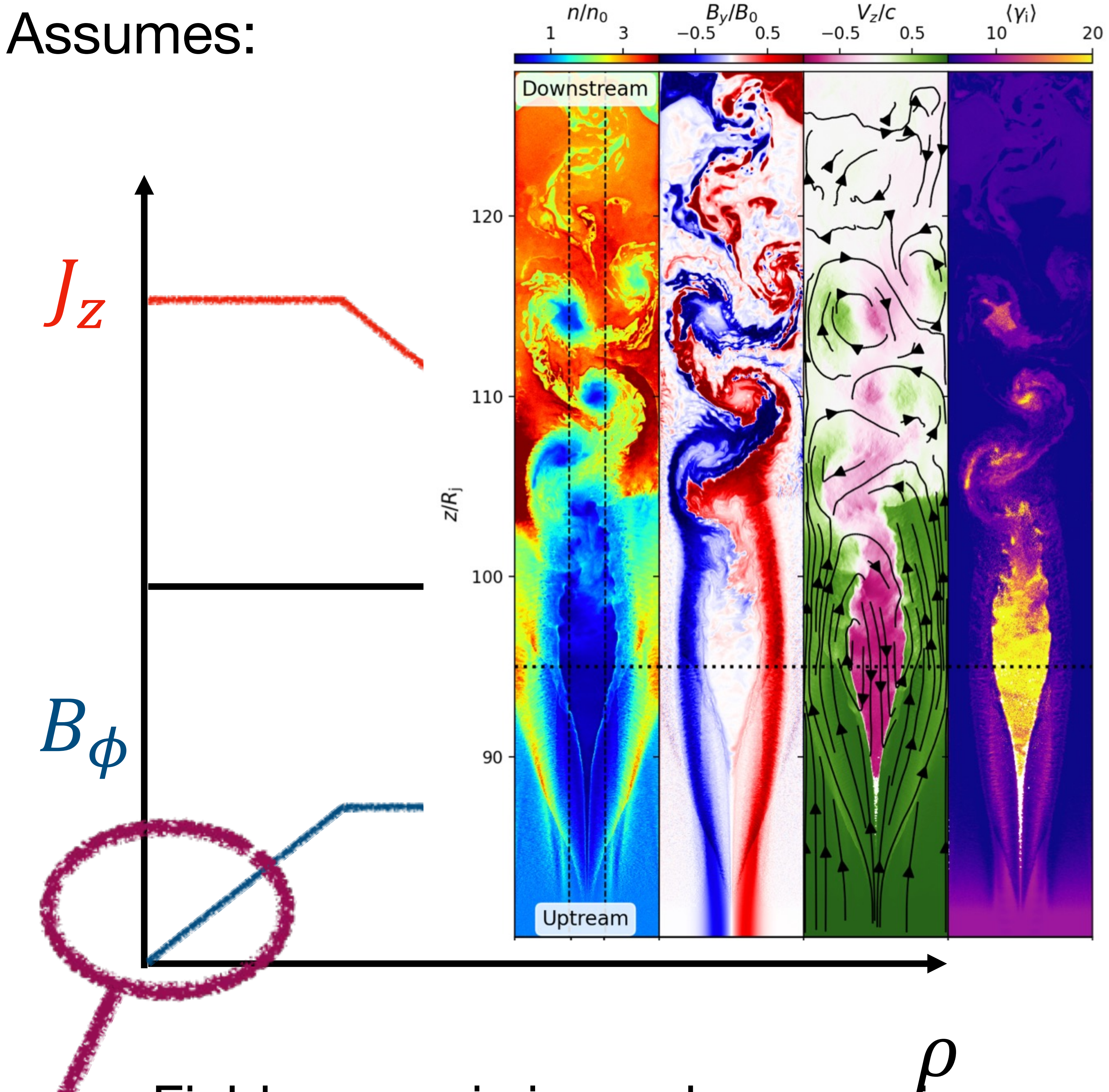
- Non-resonant scattering $\nu_{sc} \propto \gamma^{-2}$ (no large scale turbulence in jet)
- Axially symmetric cylindrical jet
- Free escape boundary at radius $\rho = \rho_{\max}$

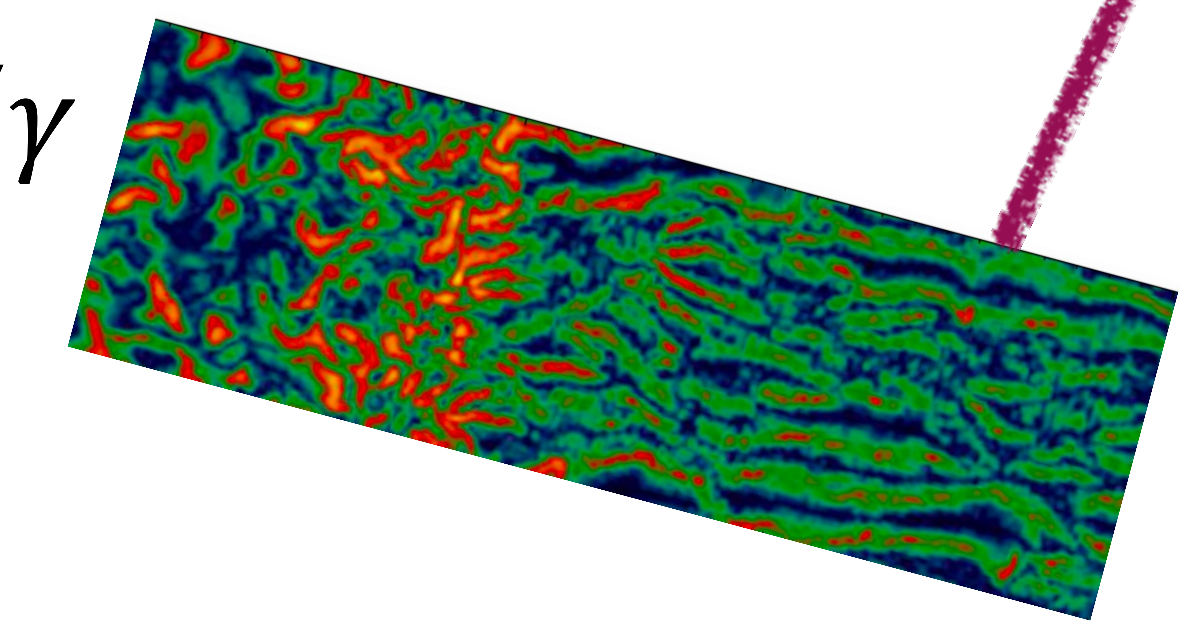




Huang et al., MNRAS 2023

Cerruti & Giacinti '23





Field near axis is weak or quasi-parallel

PIC simulations show such shocks are (in principle) efficient accelerators

(See G. Giacinti's talk on Friday)

Monte-Carlo simulations

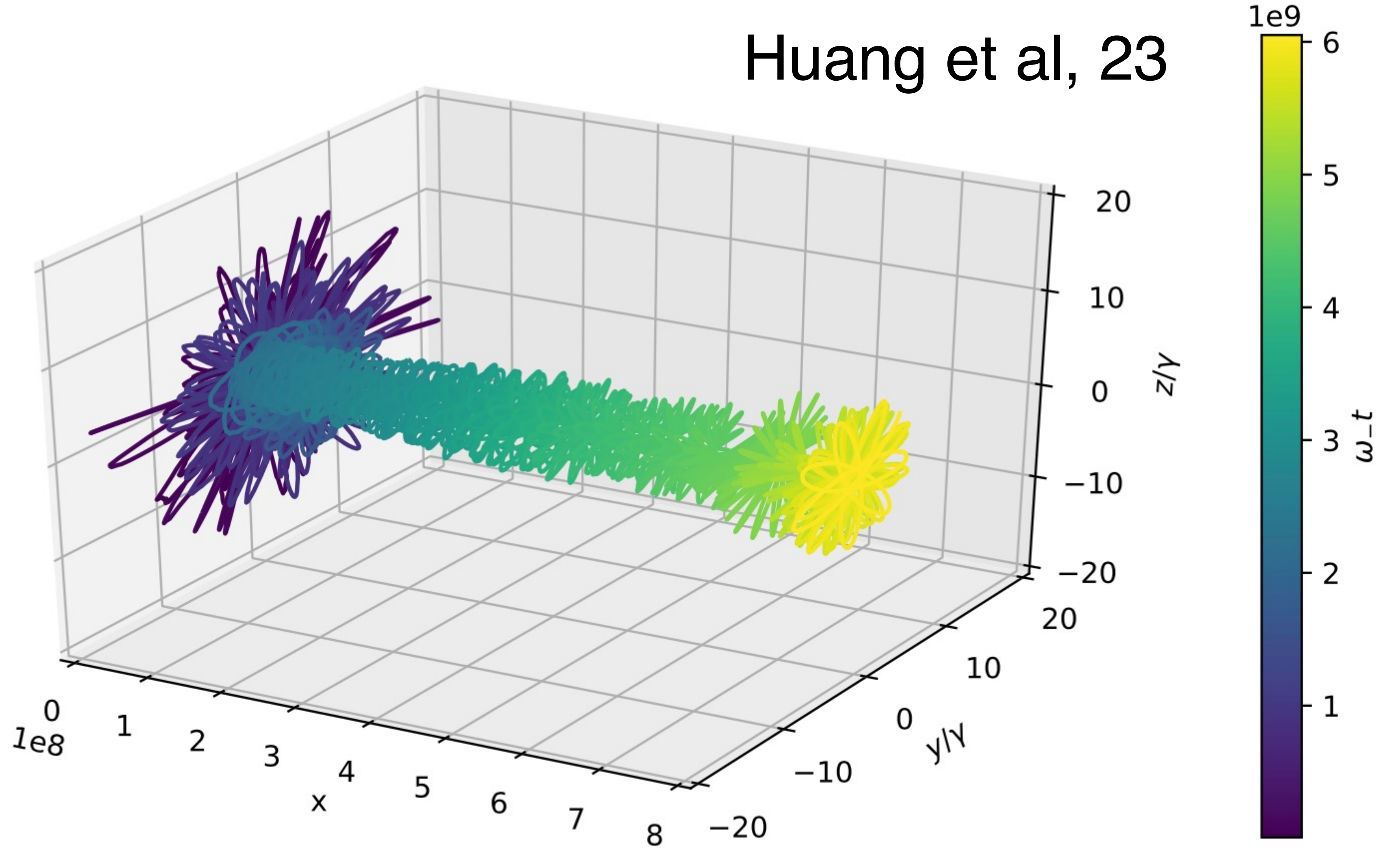
Because scattering is weak (an assumption), particles close to axis stay there.

If drift →DS, particles drift downstream once magnetised

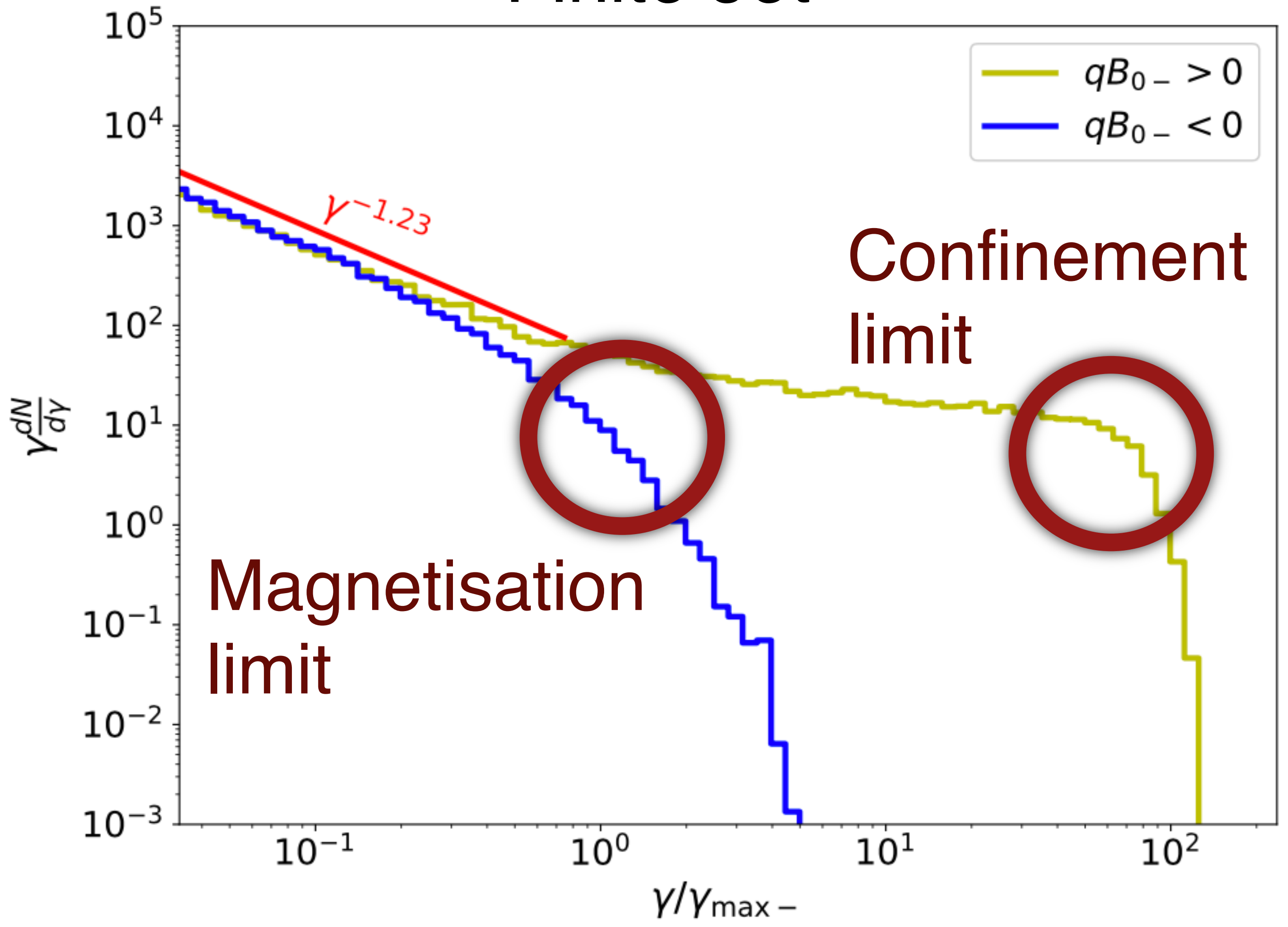
If drift → US, **particles accelerated to radiation reaction/confinement limit**

Ess. escape free (because scattering is weak), spectrum $\sim E^{-1}$

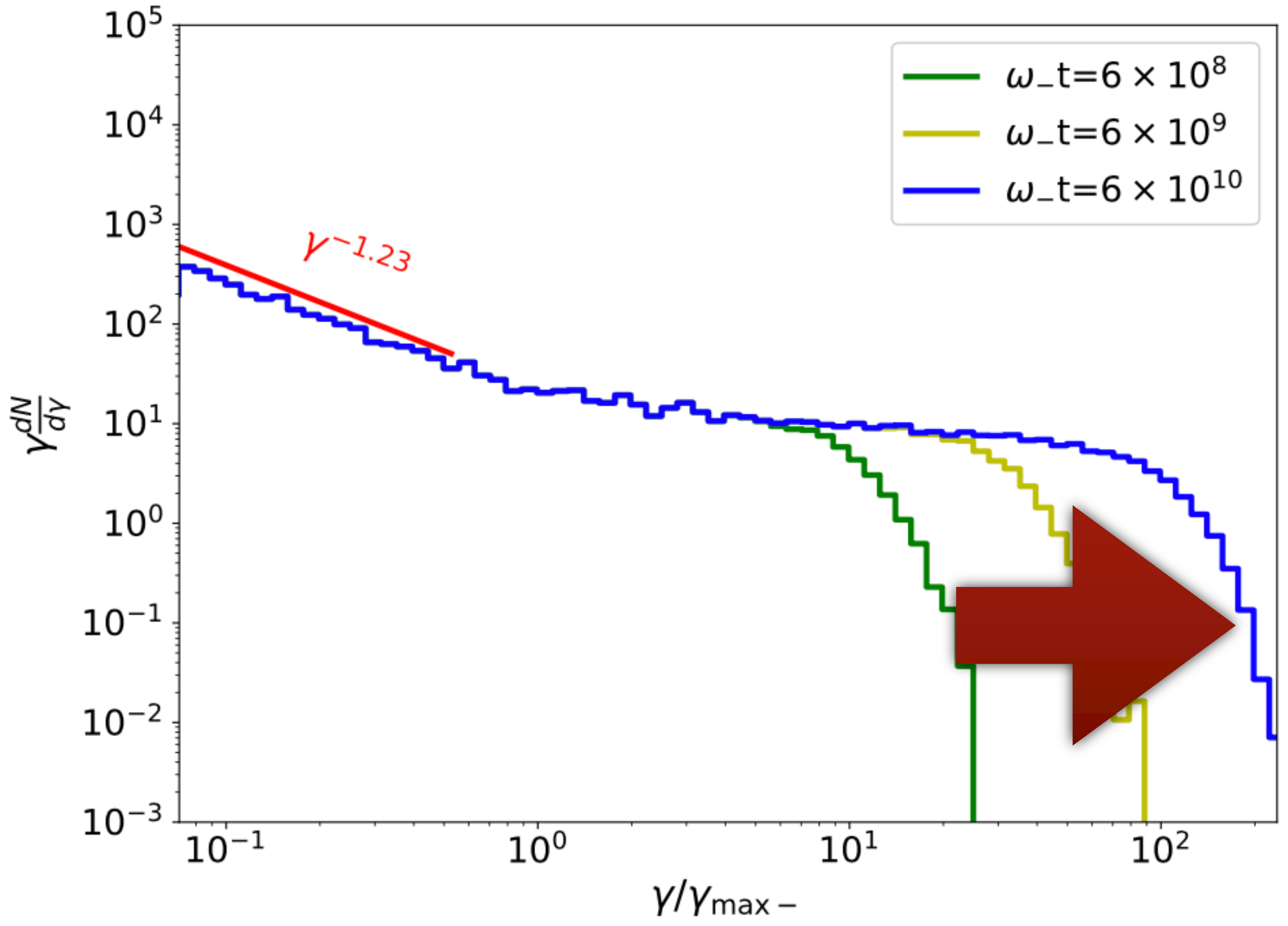
Huang et al, 23



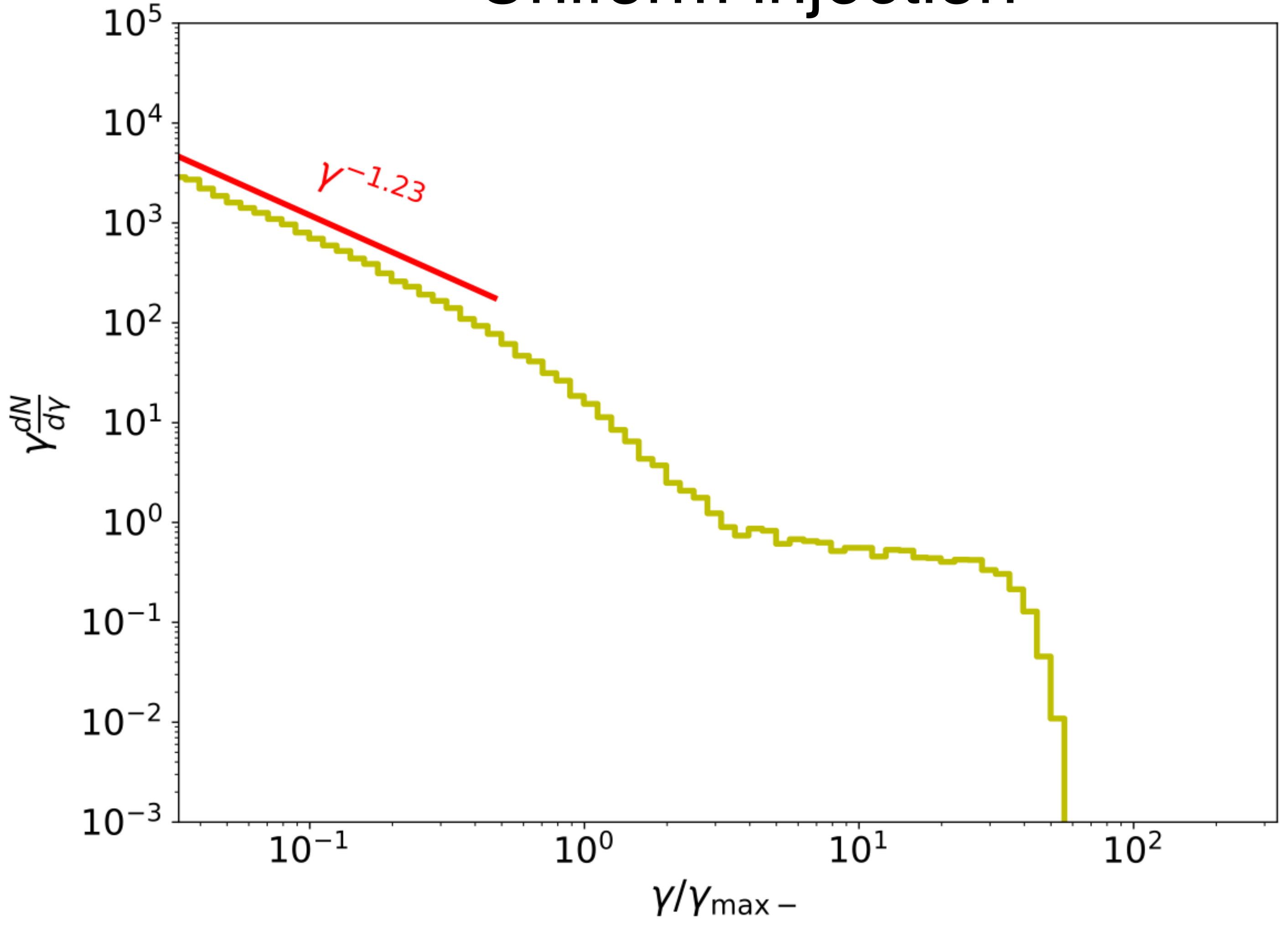
Finite Jet



Infinite Jet



Uniform injection

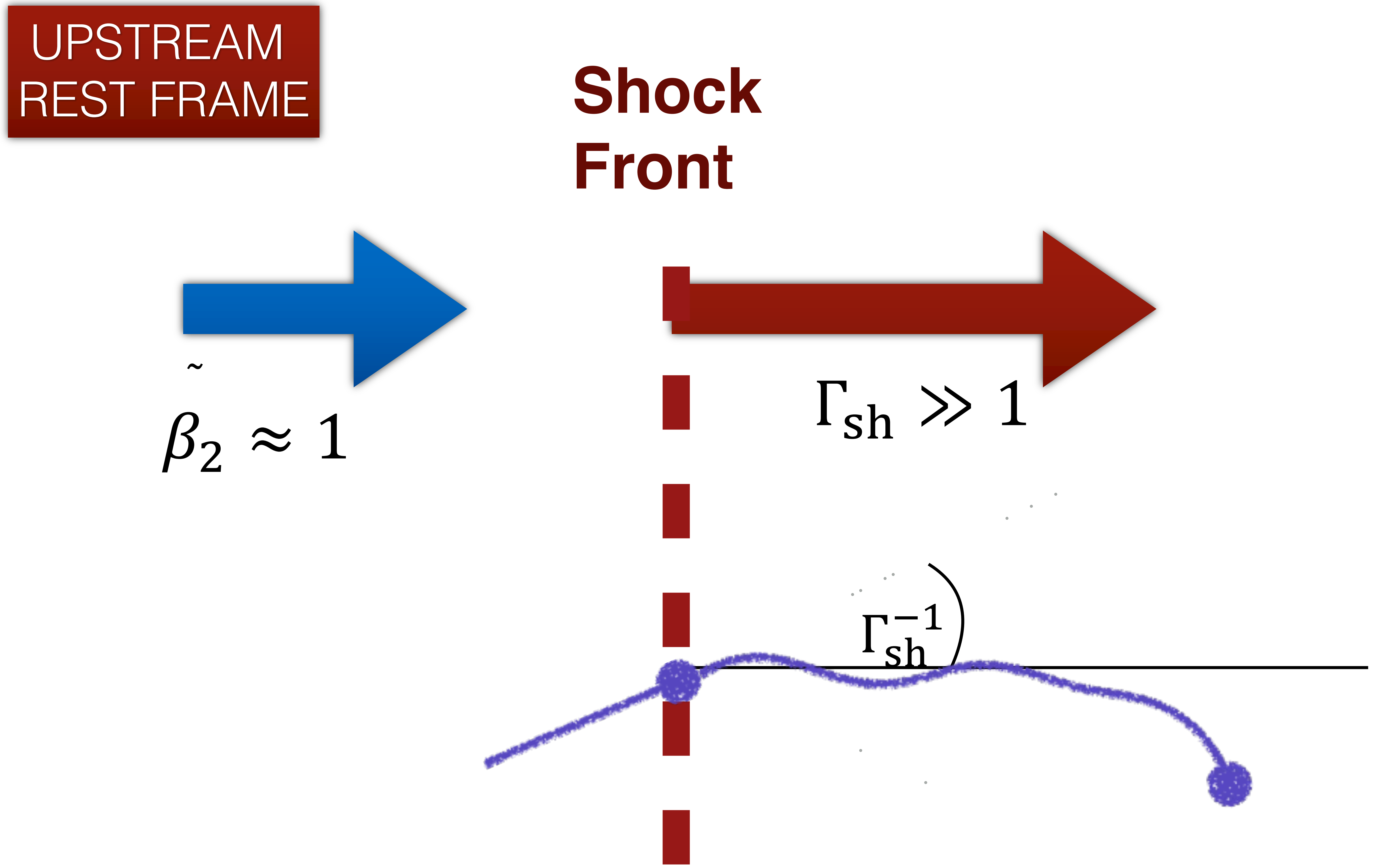


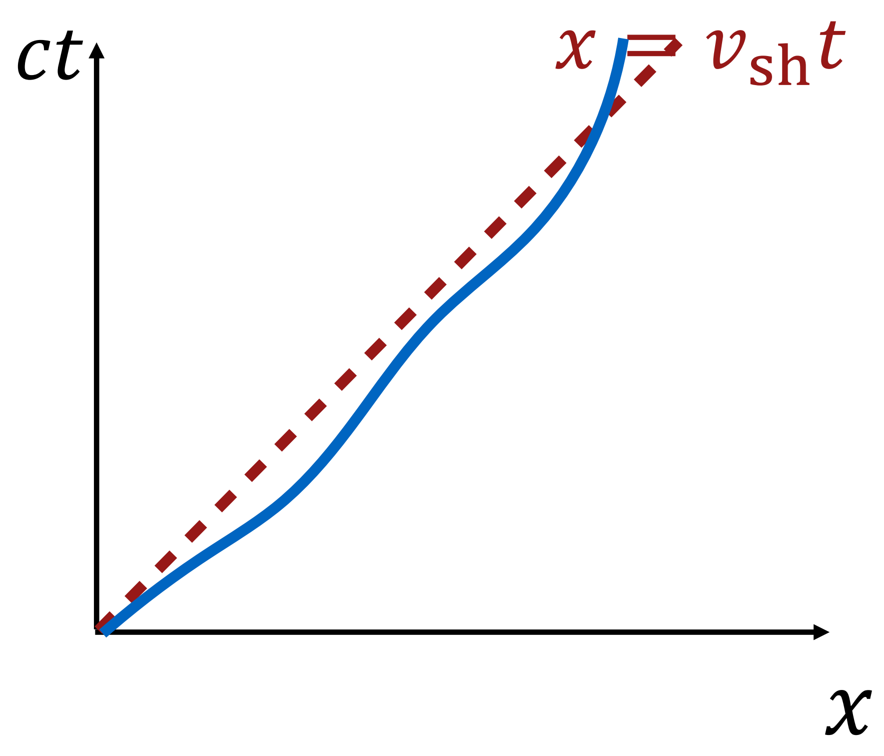
Conclusions

- PIC Simulations provide a reliable basis to address the so-called injection problem for relativistic shocks
- Scattering on small scale structures implies acceleration is “slow” (compared to the hypothetical maximum). This limitation is not unique to shock acceleration.
- Upstream conditions more important than previously thought
- Robust prediction of $dN/dE \propto E^{-2.2}$ for most cases (possibility of spectral breaks)
- Global magnetic field topology enforces energetic particle currents that ensure efficient particle acceleration ($\nabla \cdot \mathbf{j} = \nabla \cdot \nabla \times \mathbf{B} = 0$).
- Helical field structures may be common (Parker spiral, hourglass structures in binaries, launched jets). A self-consistent (multi-scale) picture is required.
- (Maybe laboratory experiments can help?)

Thank you

Does this make sense?





Any particle overtaking shock has $\mu > \beta_{sh}$ ($\theta < \Gamma_{sh}^{-1}$)
Seen from upstream frame, particle doesn't get far

The larger Γ_{sh}, the easier to scatter out of loss cone