The Case for Particle Acceleration at Ultra-Relativistic Shocks

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GSSI Seminar, Apr 10

Why care about particle acceleration at ultra-relativistic shocks?

Observational Constraints - PWN

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

Pulsars, winds and nebulae

Unique plasma laboratories

$e^{\pm}$ pair winds

Local CR $e^{\pm}$ sources

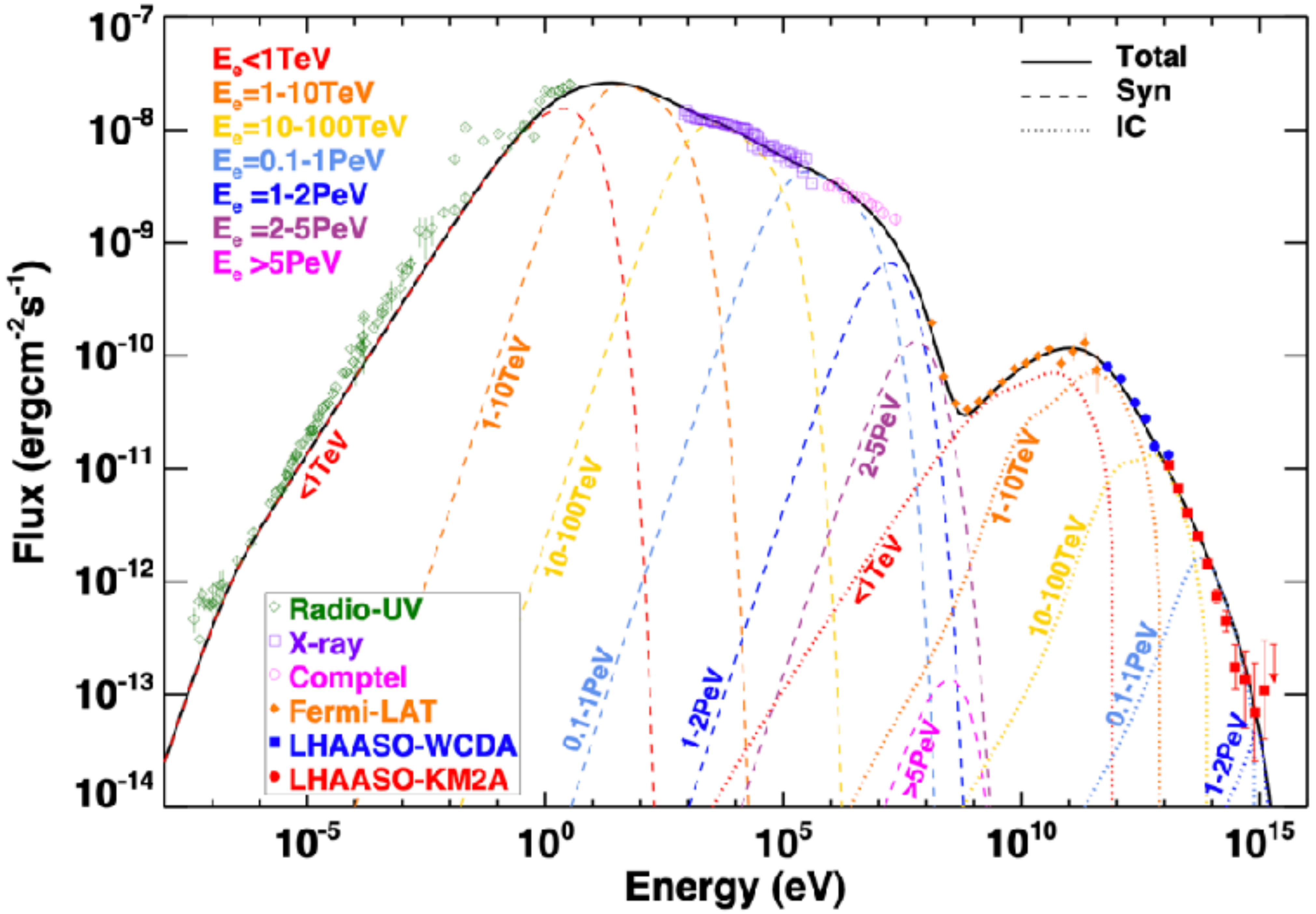
Astrophysical foreground in DM searches

For the Crab Nebula WTS $\Gamma_{\rm sh} \sim 10^3 - 10^6$

Magnetisation $\left(\sigma = \dfrac{\text{Magnetic NRG density}}{\text{Enthalpy density}}\right)$

unknown but probably large

LHAASO collaboration 21



PeV photons = electrons > PeV

An almost perfect accelerator!!

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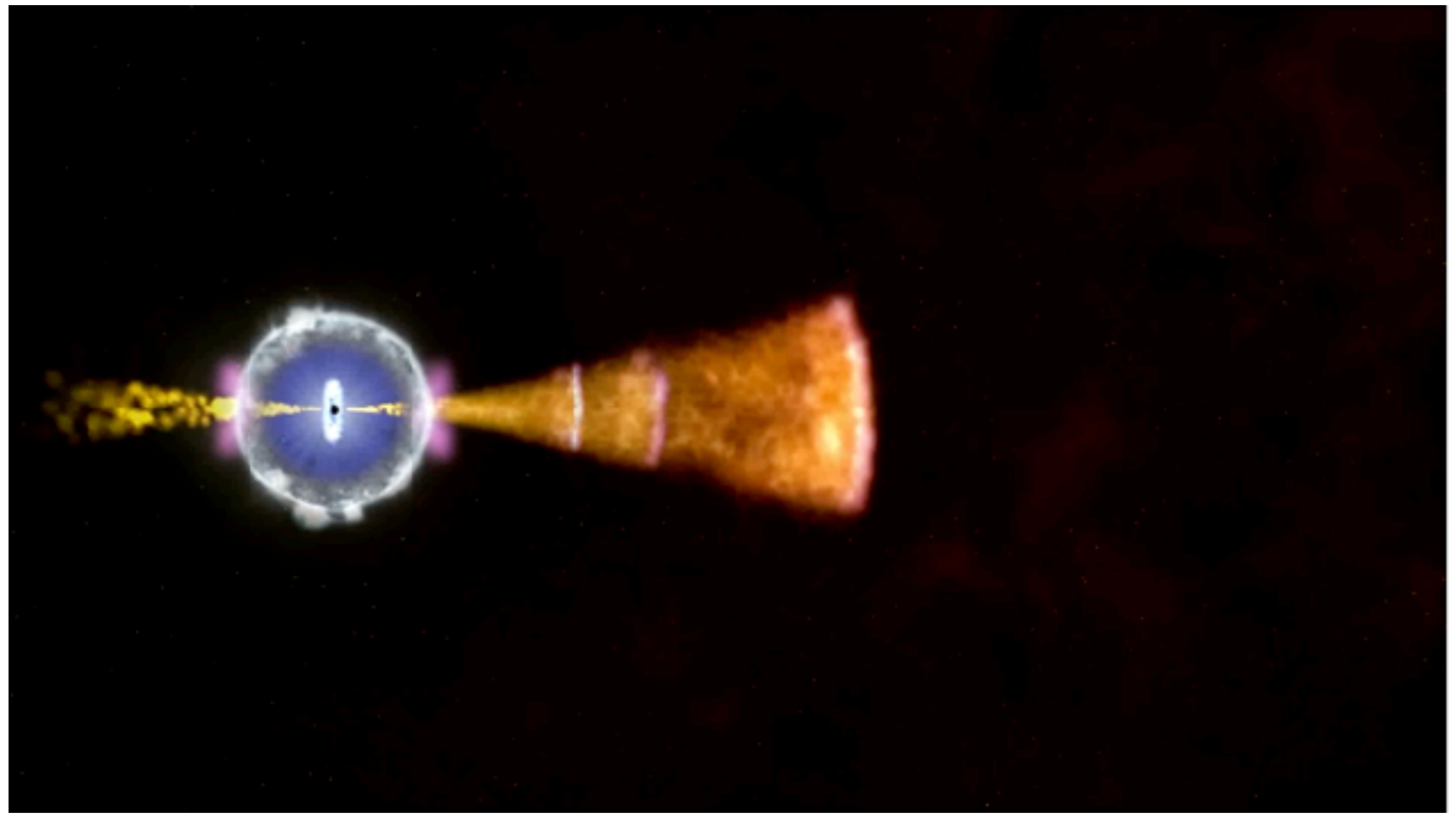
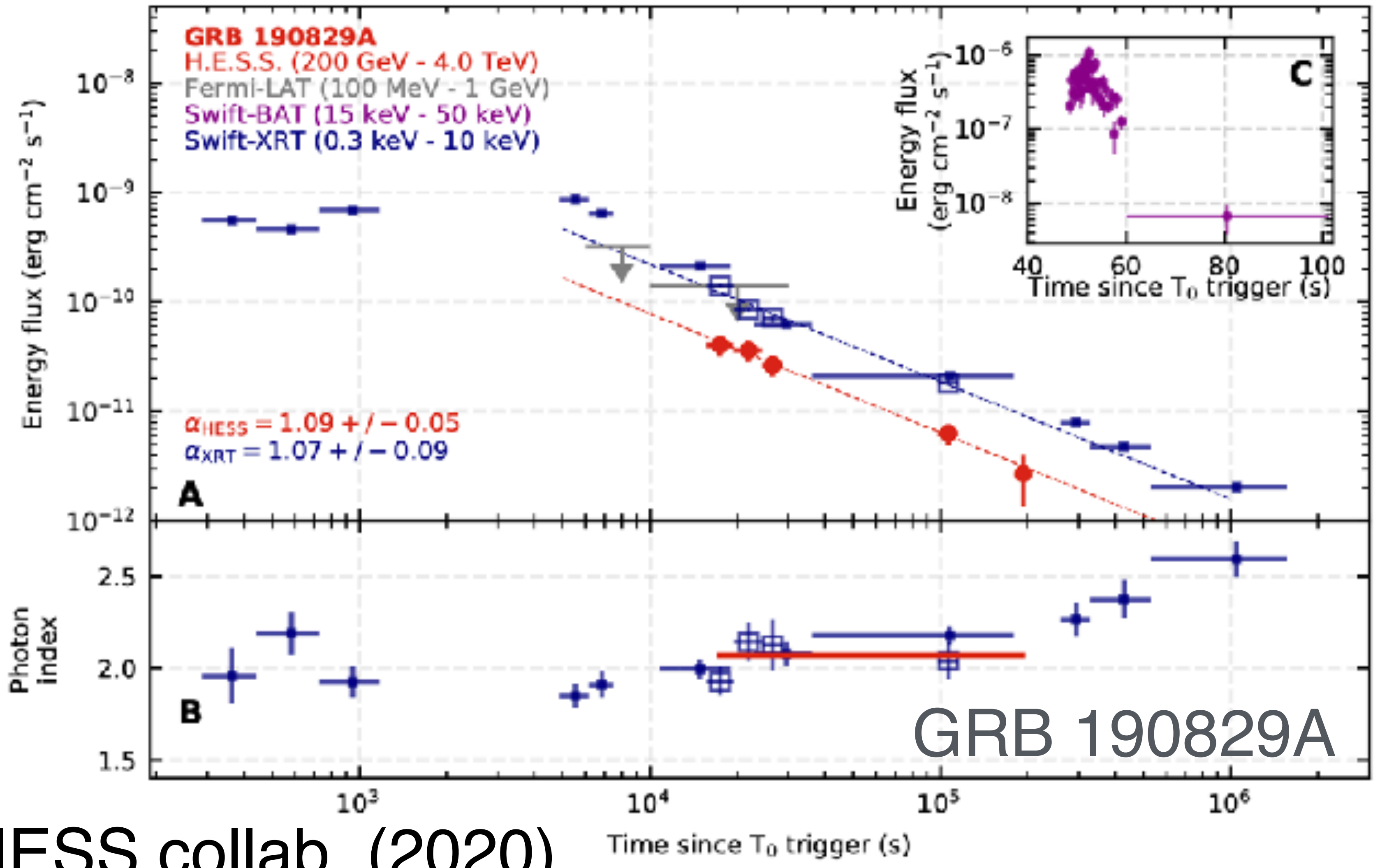
Observational Constraints - GRBs

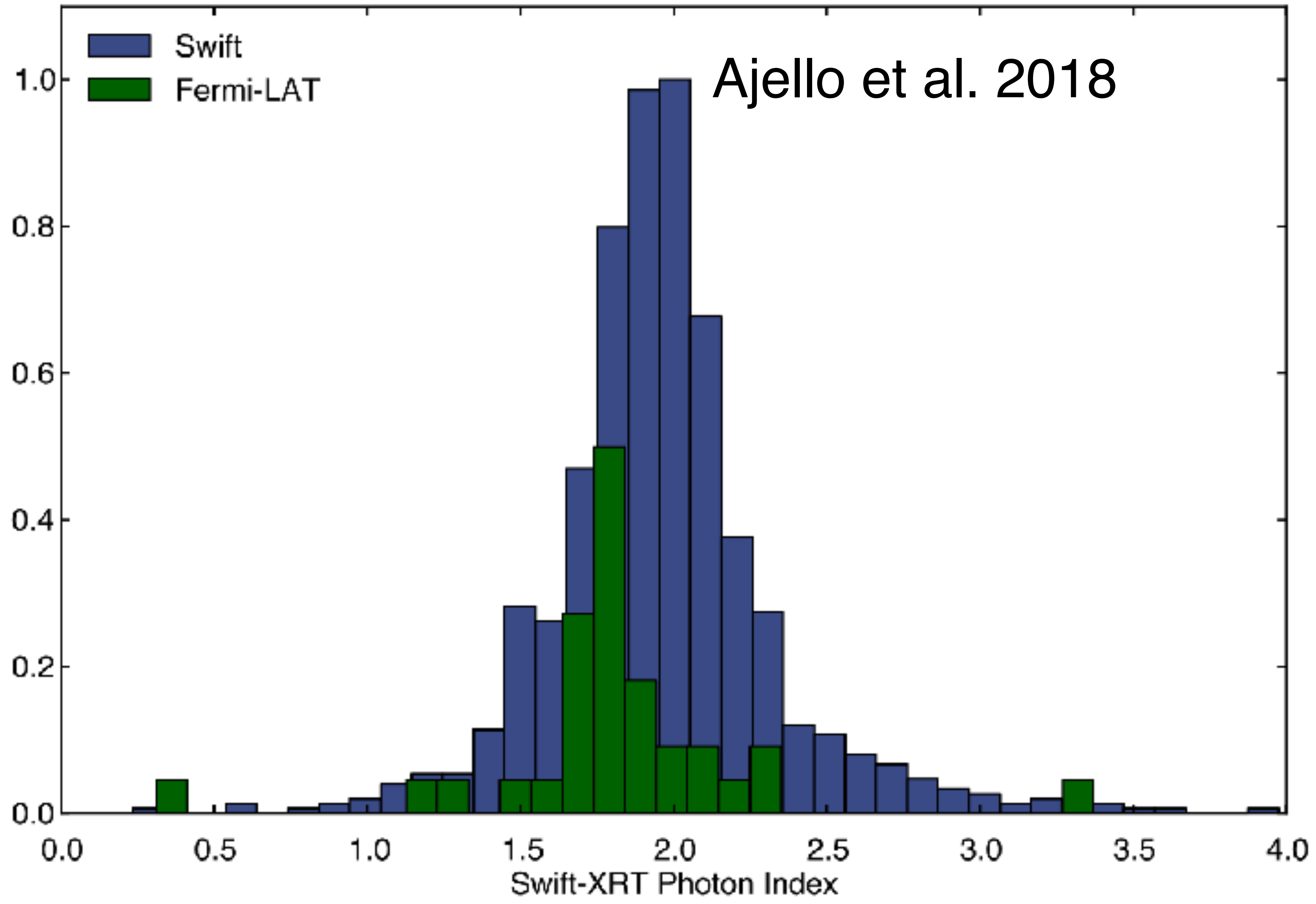


6 GRB afterglows detected to date in VHE domain

Afterglow shock "well defined" (Hydro solution known)



HESS collab. (2020)

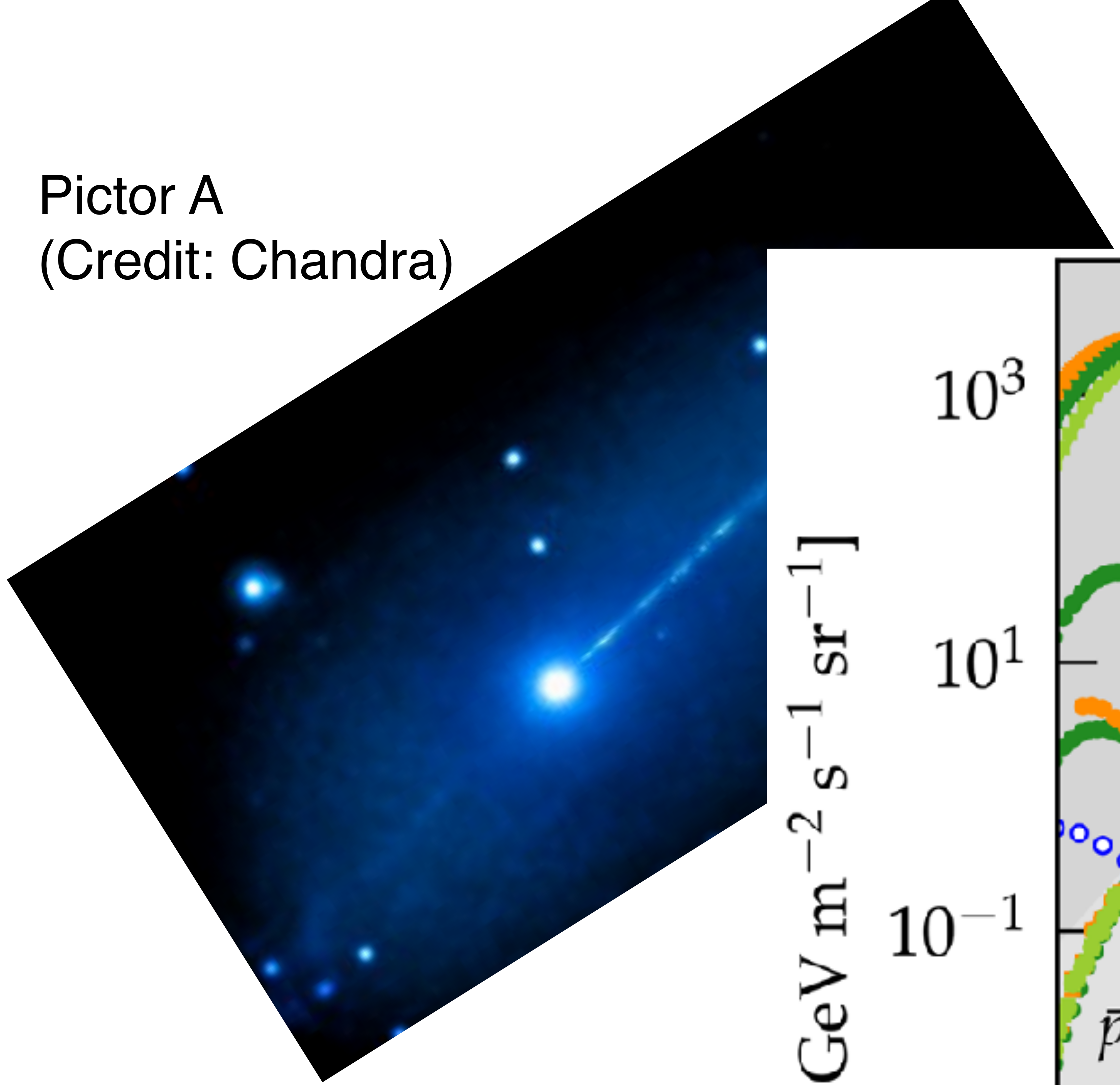


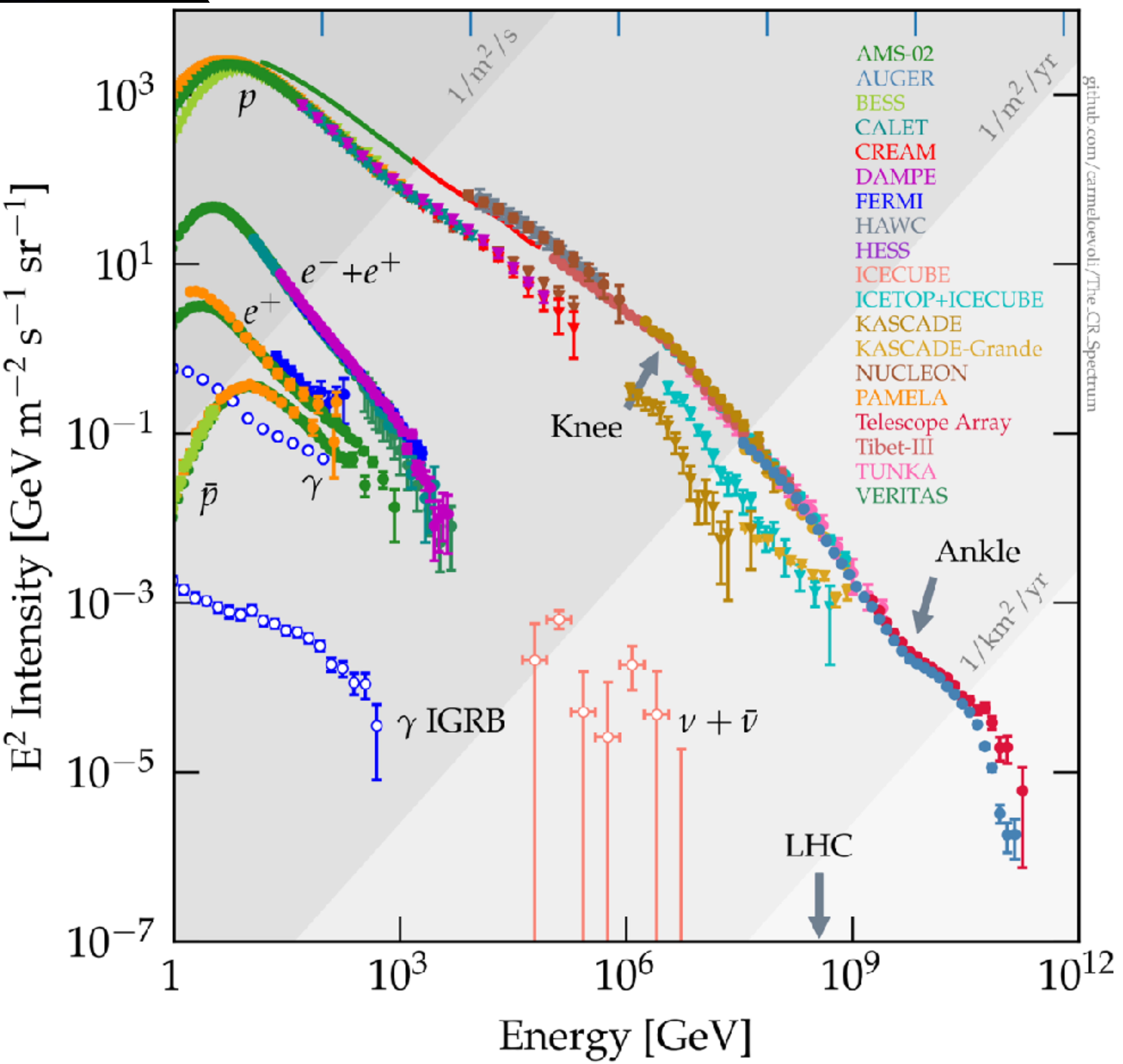
IC collab. (2019)

The requirement of >TeV electrons brings questions on max energy into focus

Observational Constraints - AGN

Pictor A
(Credit: Chandra)





himmappa et al. '22

$\Gamma_{sh} \sim$ **a few**

X-ray synchrotro
B fields $B \sim 0.1$

1

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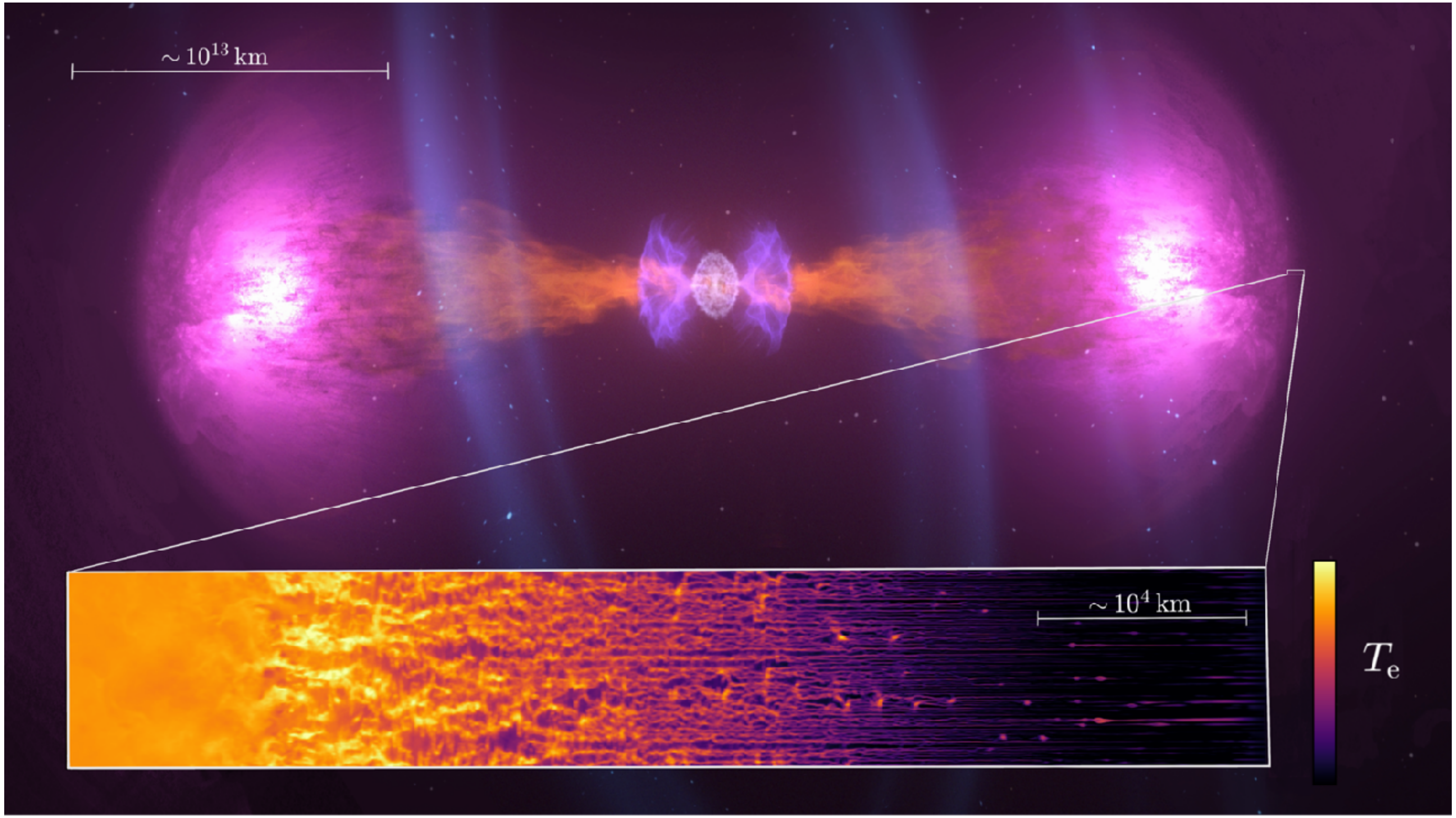
Key Questions

- Do relativistic shocks accelerate at all?
- What determines the maximum energy?
- What determines the shape of non-thermal particle spectrum?

Lessons from kinetic simulations



Credit:
Arno Vanthieghem

Particle in Cell simulations allow us to probe the shock micro-physics
But what can we reliably extract from them for understanding astrophysical systems?

Lessons from non-relativistic shocks

Credit: NASA

Particles accelerate by bouncing repeatedly back and forth across a converging flow (a shock).

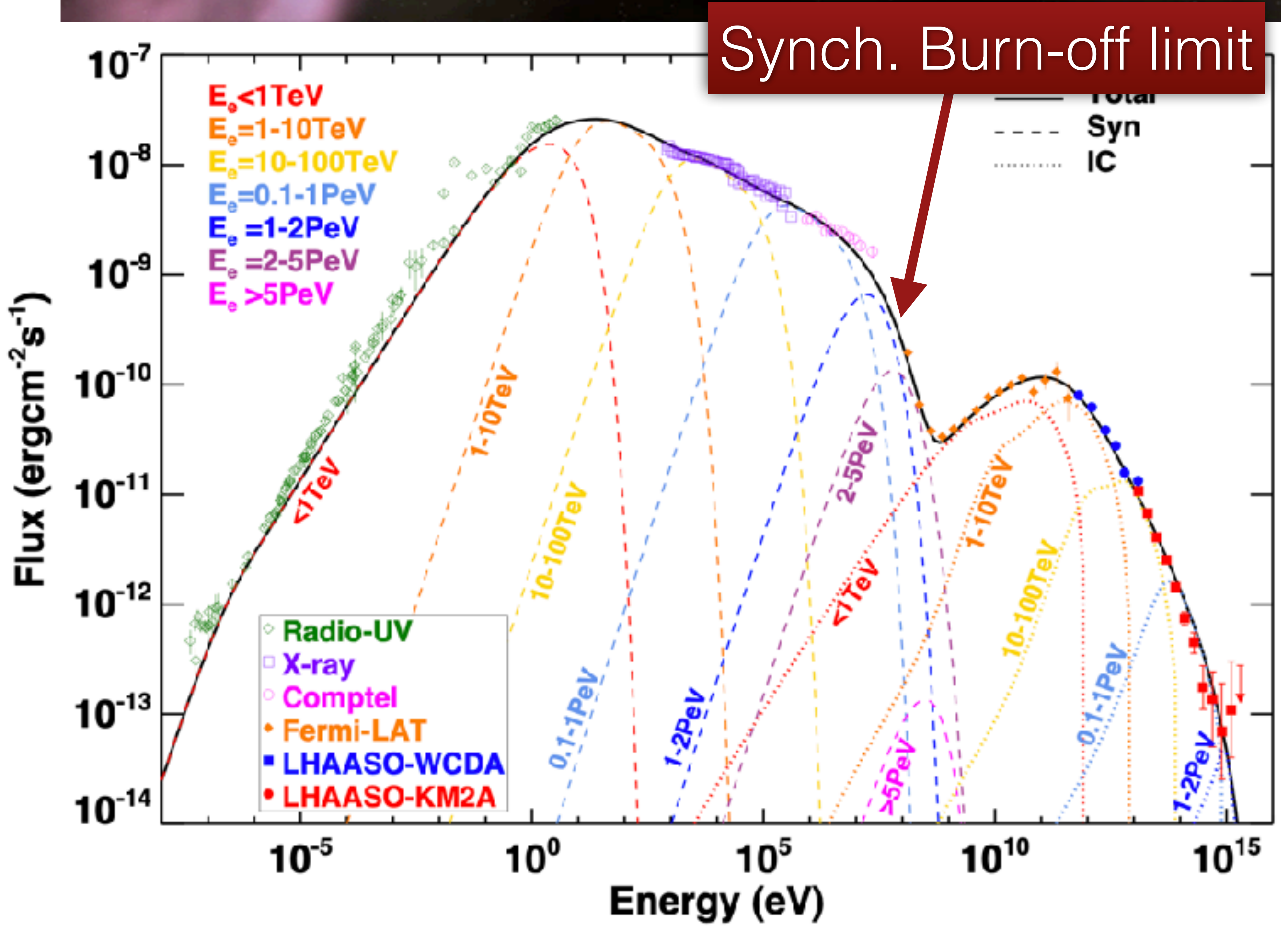
Confinement close to the shock due to scattering on MHD modes. Optimal scenario, diffusion coefficient $D \sim \eta^{-1} r_{\rm gyro} {\rm v} \propto \varepsilon / B$ for relativistic particles.

Can determine an acceleration time $t_{\rm acc} \sim D/u_{\rm sh}^2 \propto \varepsilon/B$

Electrons must compete with cooling $t_{syn} \propto B^{-2}\varepsilon^{-1}$

Equating rates, and inserting into photon energy equation

$$\frac{h\nu_{syn}}{m_e c^2} = 0.44\gamma^2 \frac{B}{B_{\rm crit}} \approx \eta \left(\frac{u}{c}\right)^2 \alpha_f^{-1}$$



Ultra-relativistic (ideal MHD) shocks

Shock Front

Hot thermalised flow

$\beta_2 \approx 1/3$

Cold directed flow

$\Gamma_{sh} \gg 1, \ \beta_1 \approx 1$

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

$$B'_{\perp,2} \approx 3B'_{\perp,1} \qquad B'_{\perp,1} = \Gamma_{sh} B_{\perp,1}$$

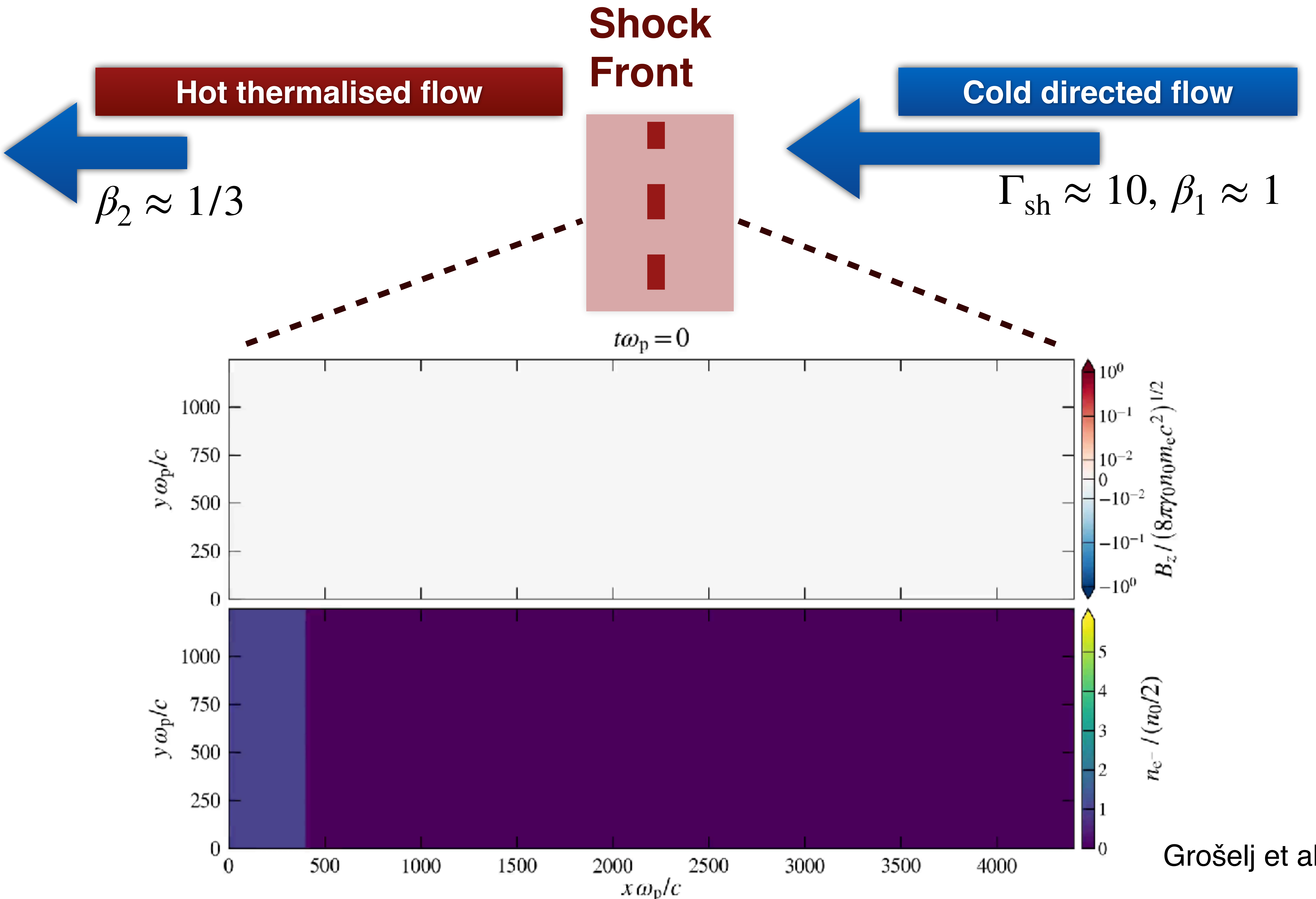
($B_\perp$ out of page)

Assume ideal MHD such that $\boldsymbol{E}' = -\boldsymbol{u} \times \boldsymbol{B}'$

Recall $\Delta\varepsilon = q\int \boldsymbol{E} \cdot \boldsymbol{ds}$

Unless $B_\perp / B_\parallel < \Gamma_{sh}^{-1}$ in far upstream,
In shock frame avg magnetic field is approx. in plane of shock

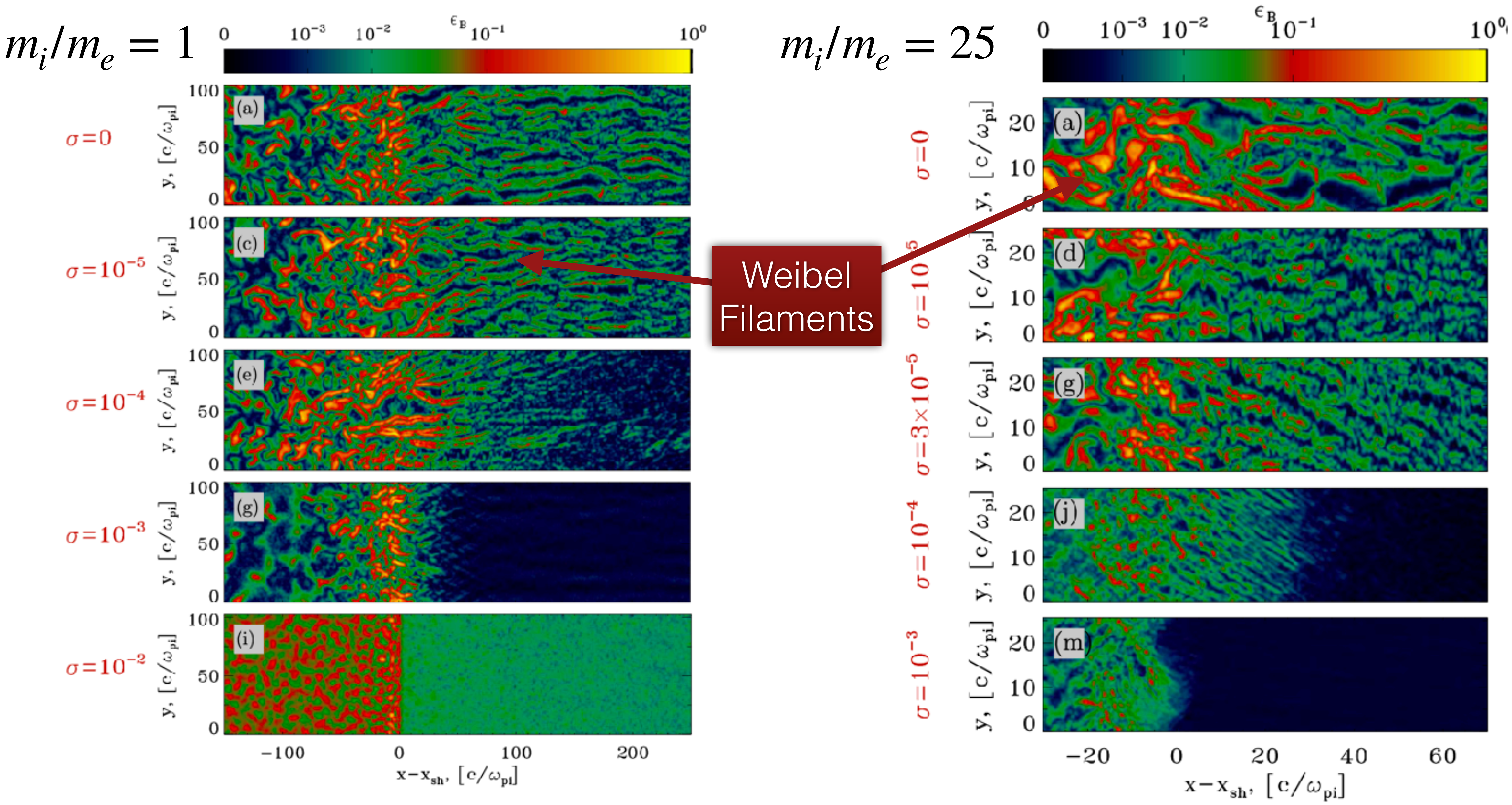
2D unmagnetised ($\sigma = 0$) pair plasma shock simulation



Grošelj et al 2024

Insights from PIC simulations

2D simulations by Sironi, Spitkovsky & Arons 13



Low sigma

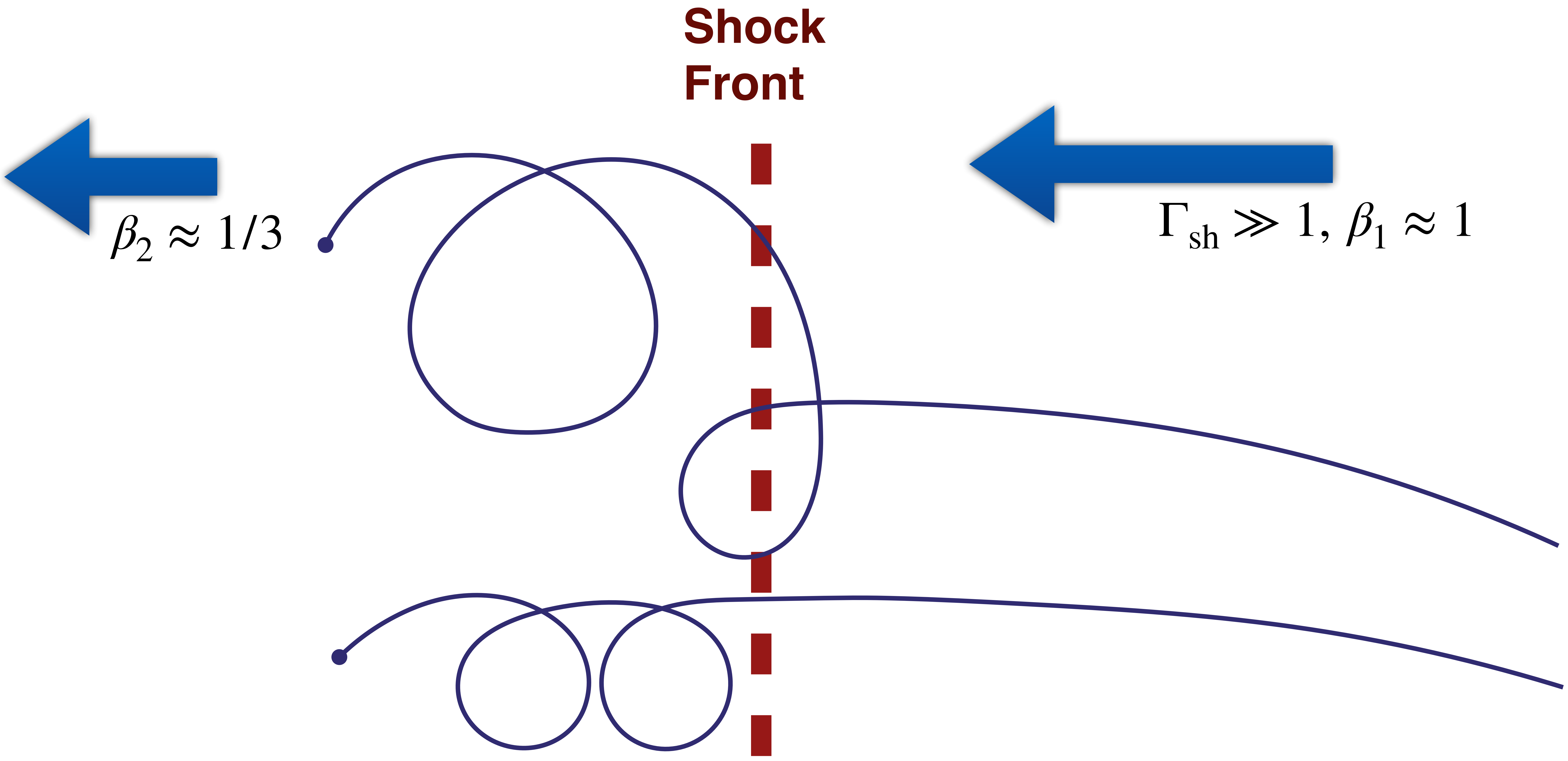
$$\sigma = \frac{\text{Magnetic NRG density}}{\text{Enthalpy density}}$$

$$\approx \frac{B'^2/4\pi}{n'mc^2} = \frac{B^2}{4\pi\Gamma nmc^2}$$

High sigma

Kinetic simulations confirm MHD conditions satisfied on large scales, but with intense fluctuating fields due to Weibel instability for sufficiently weakly magnetised (low σ) shocks.

Trajectories at (perpendicular) relativistic shocks

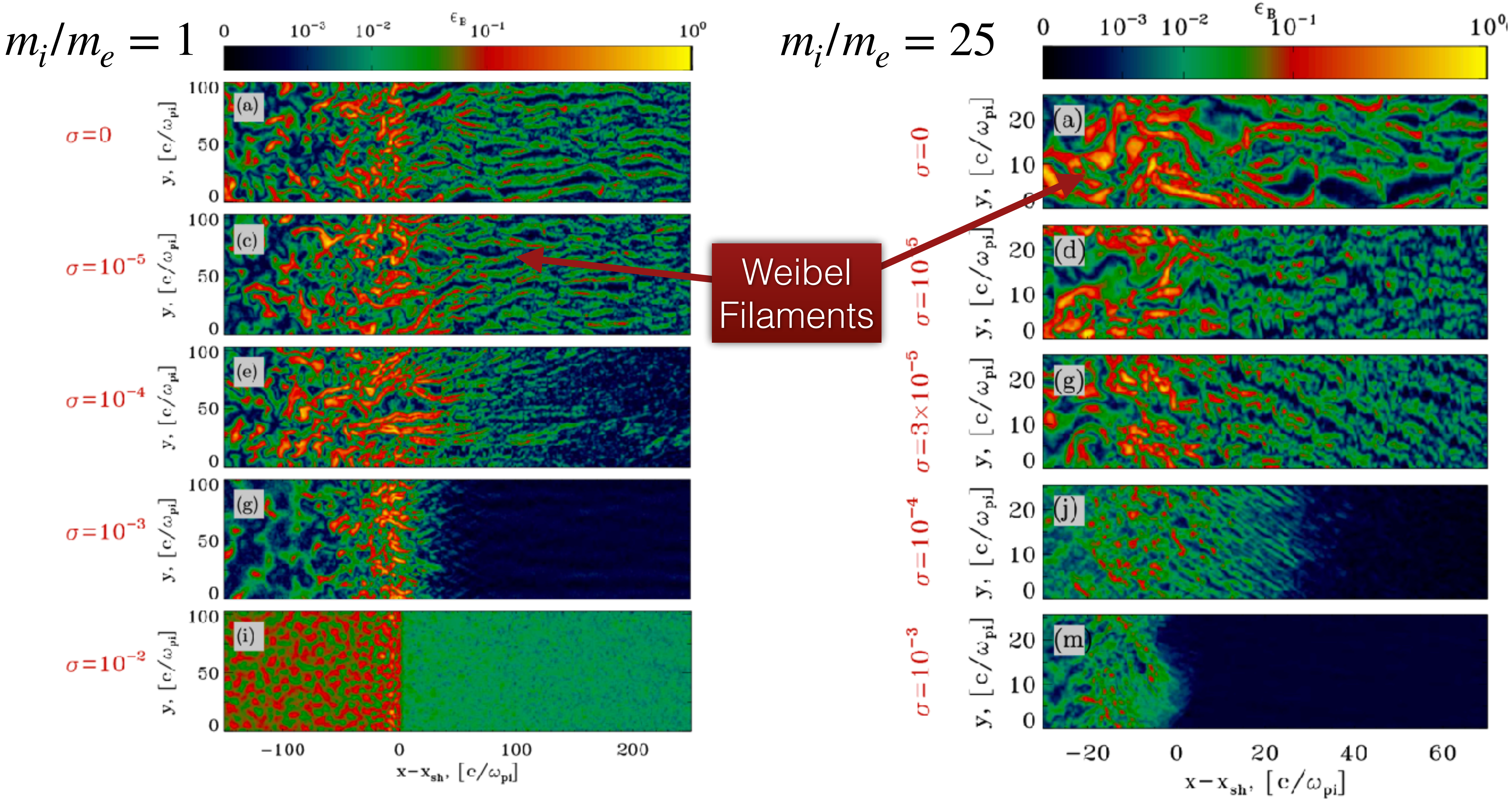


W/o scattering particles are limited to ≤ 3 crossings (Begelman & Kirk '90)

We need an effective scattering/thermalisation process.

Insights from PIC simulations

2D simulations by Sironi, Spitkovsky & Arons 13



Low sigma

$$\sigma = \frac{\text{Magnetic NRG density}}{\text{Enthalpy density}}$$

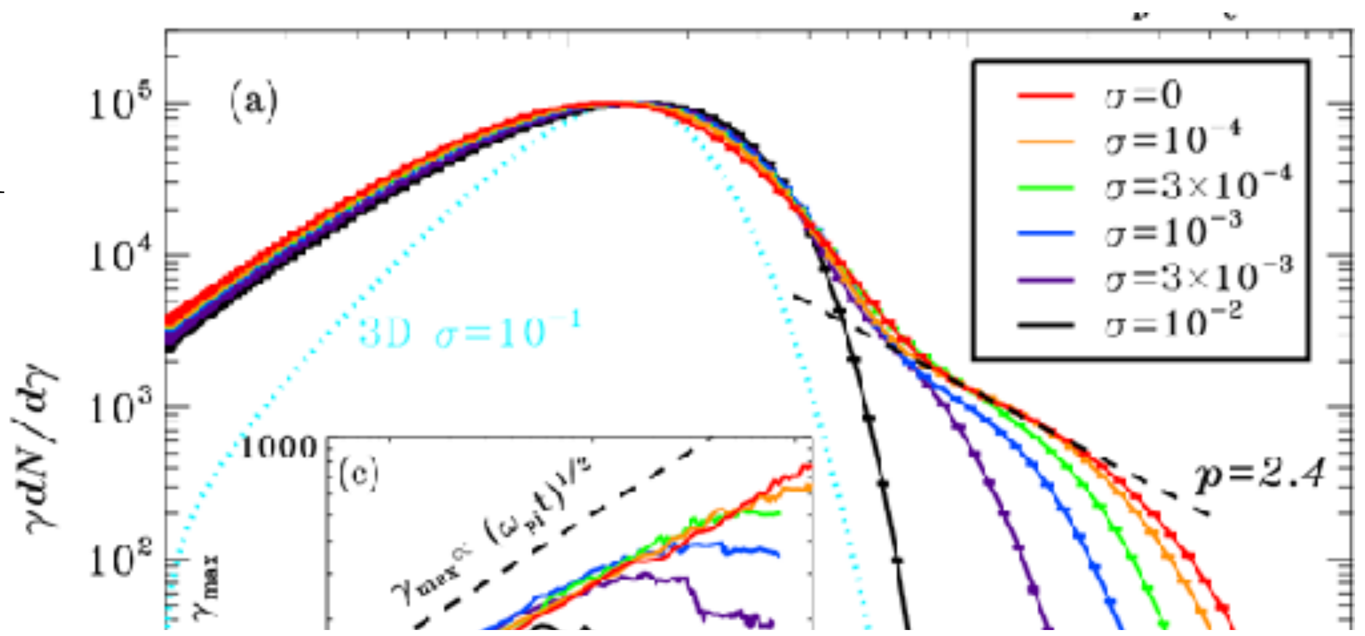
$$\approx \frac{B'^2/4\pi}{n'mc^2} = \frac{B^2}{4\pi\Gamma nmc^2}$$

High sigma

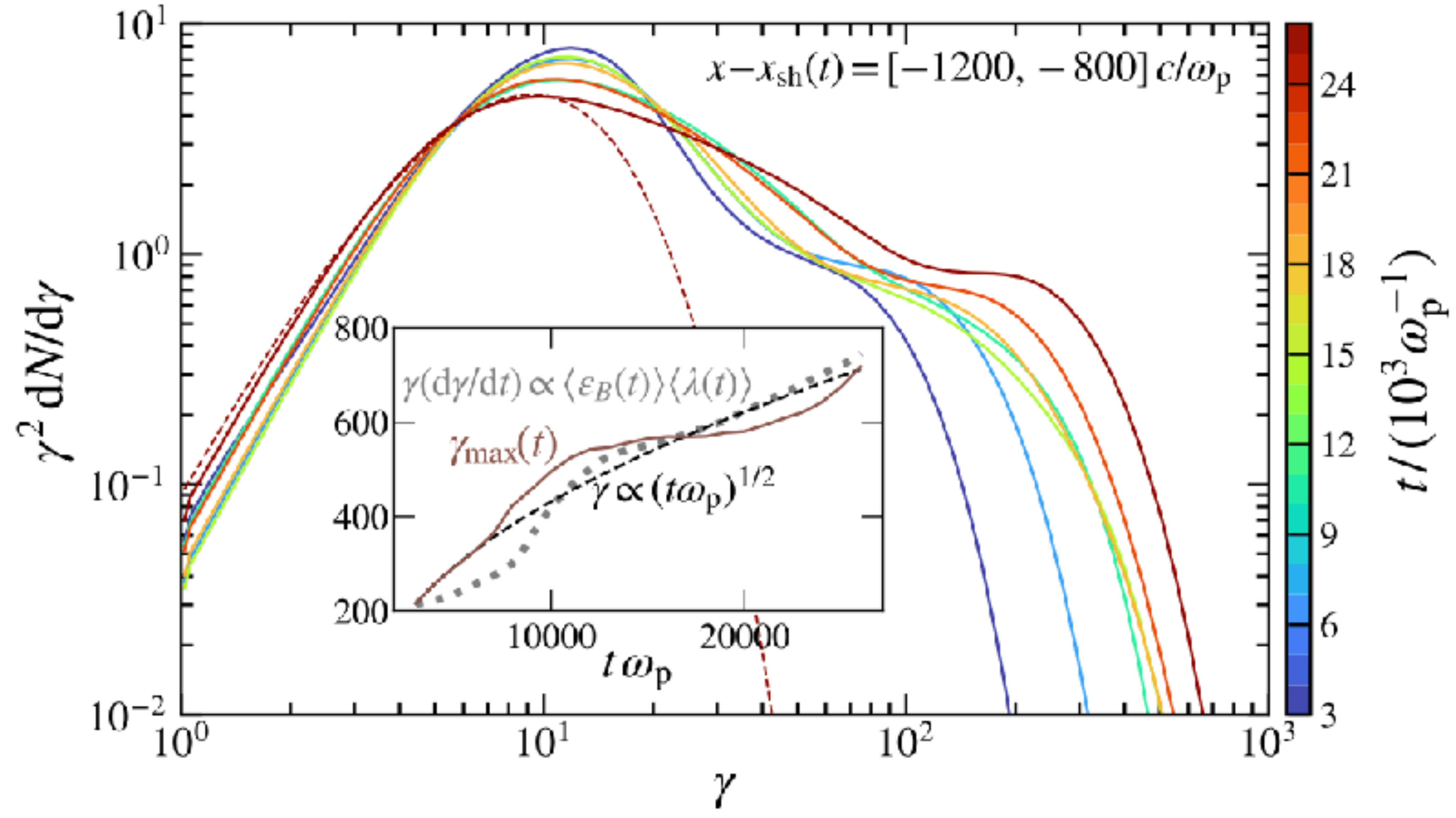
Weakly magnetised shocks are “turbulent”. Is it enough to allow multiple shock cycles?

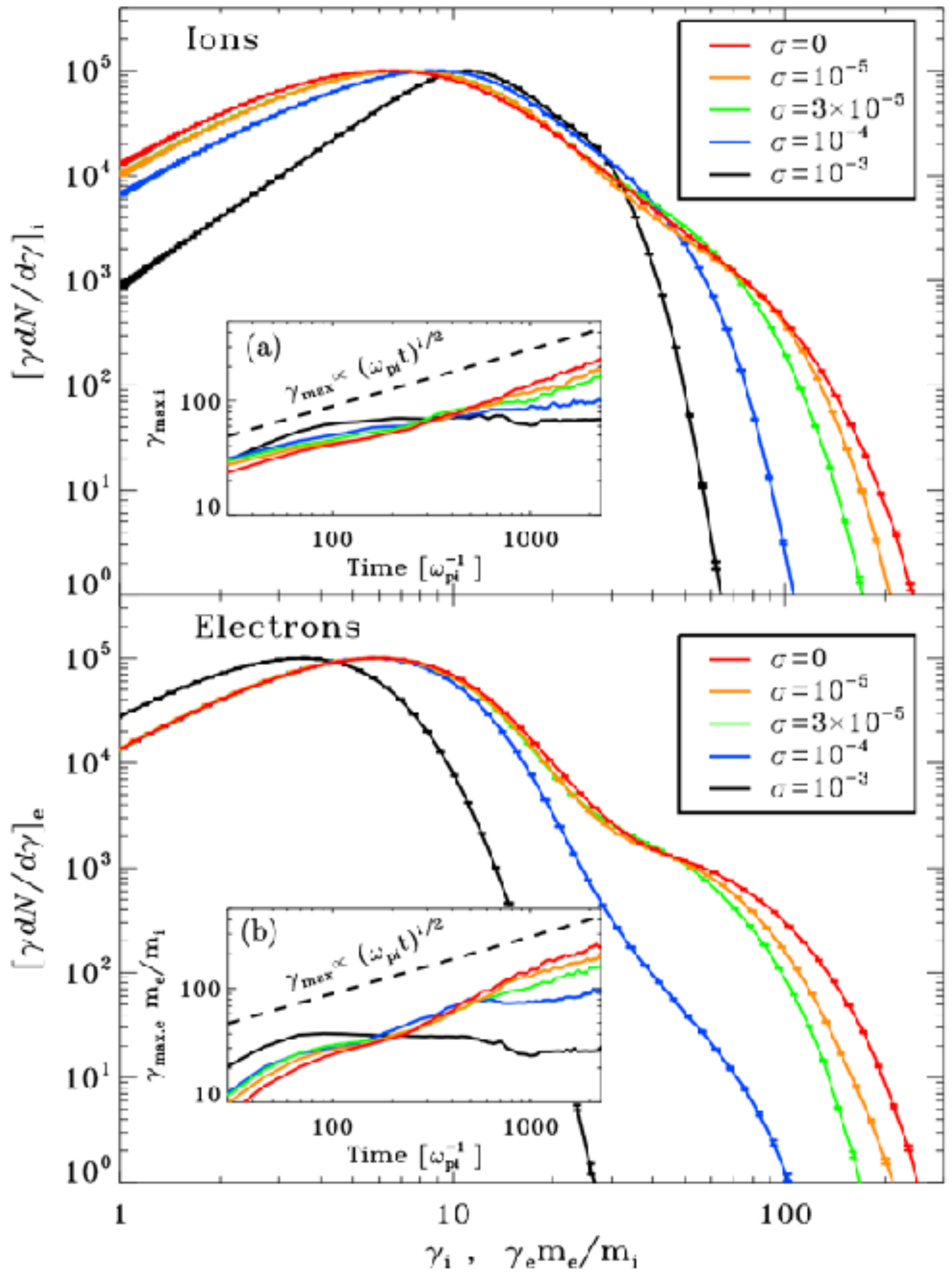
Fermi acceleration in PIC simulations?

$m_i/m_e = 1$



Grošelj et al. 24





$m_i/m_e = 25$

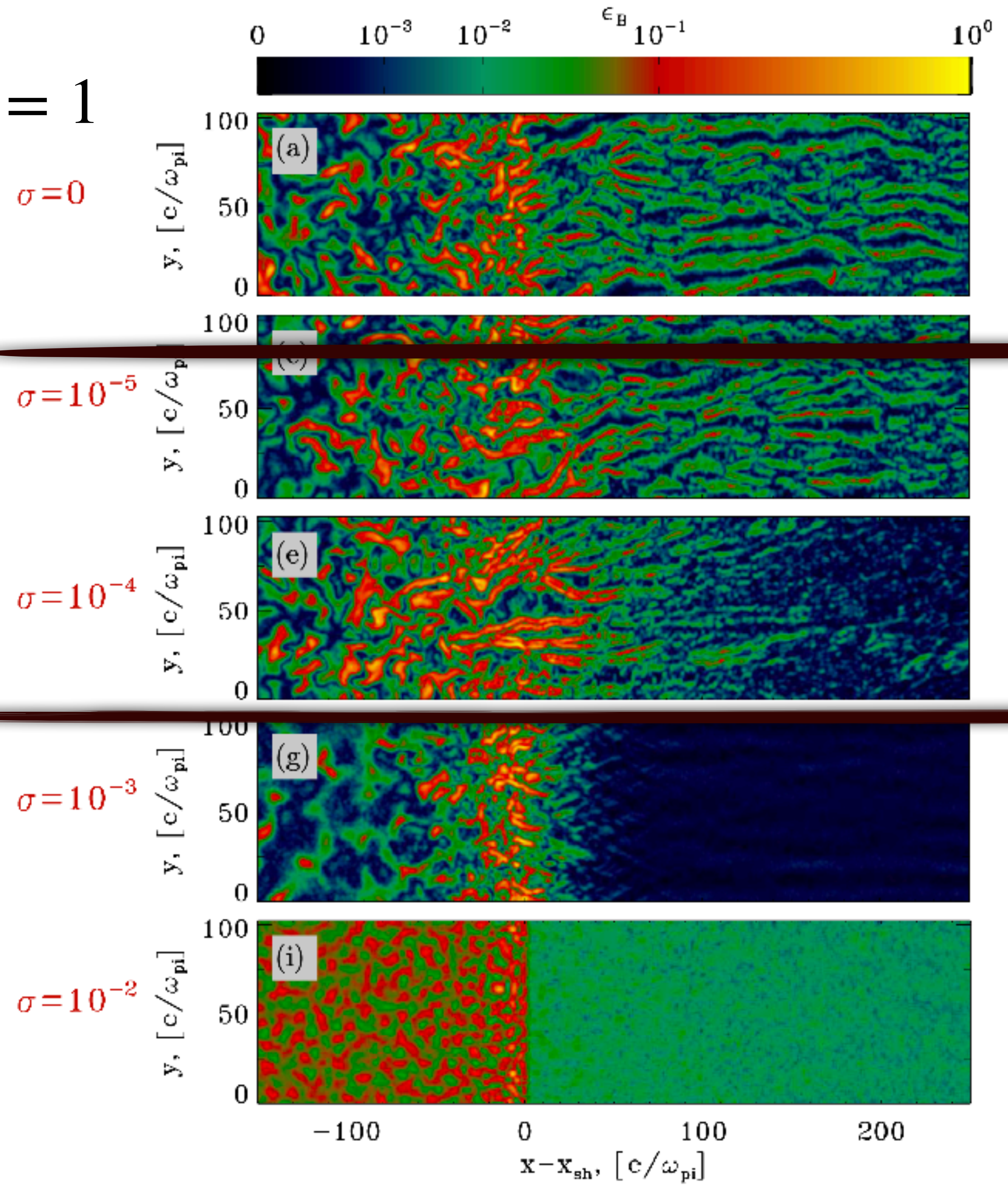
2D simulations by Sironi et al. 13

Bulk of particles are thermalised, but for $\sigma < \approx 10^{-3.5}$, non-thermal spectra emerges.

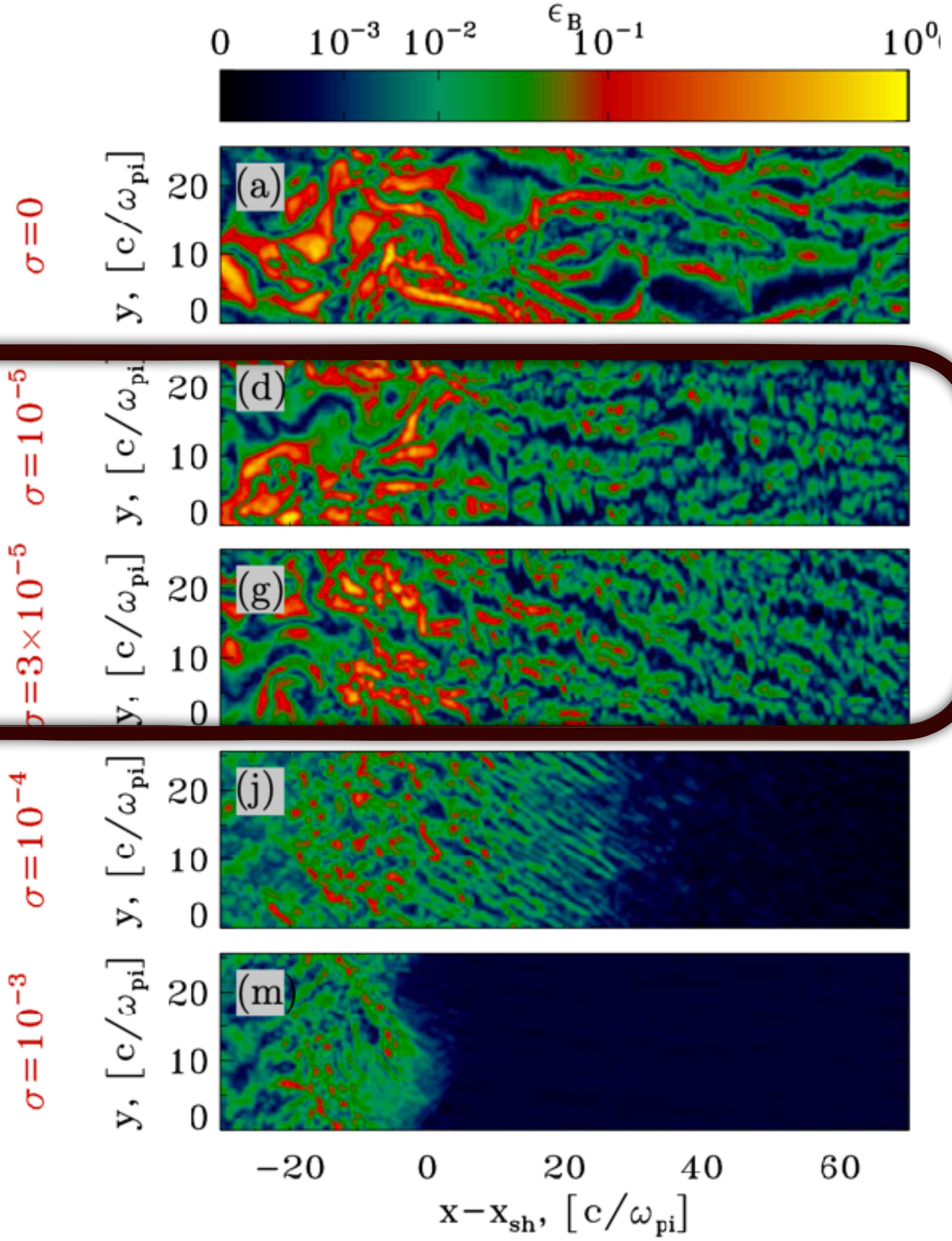
Note $\gamma_{max} \propto \sqrt{t}$, Spectrum $dN/d\gamma \propto \gamma^{-(2-2.4)}$

Insights from PIC simulations

$m_i/m_e = 1$



$m_i/m_e = 25$

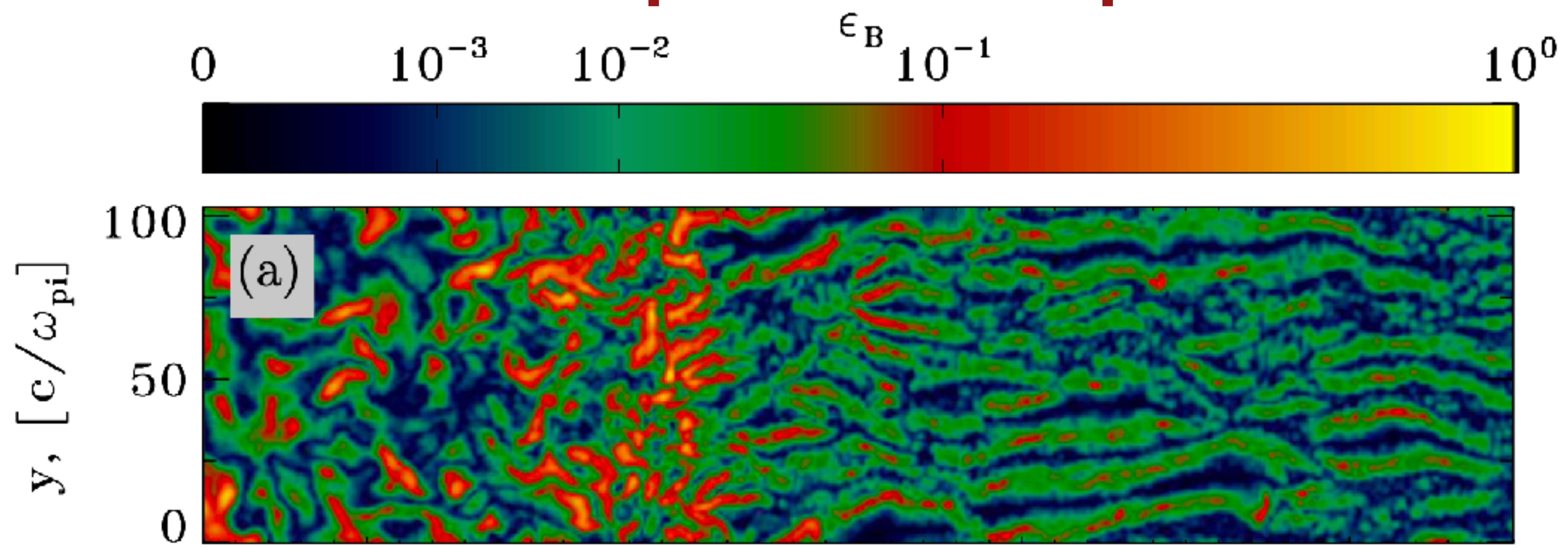


2D simulations by Sironi et al. 13

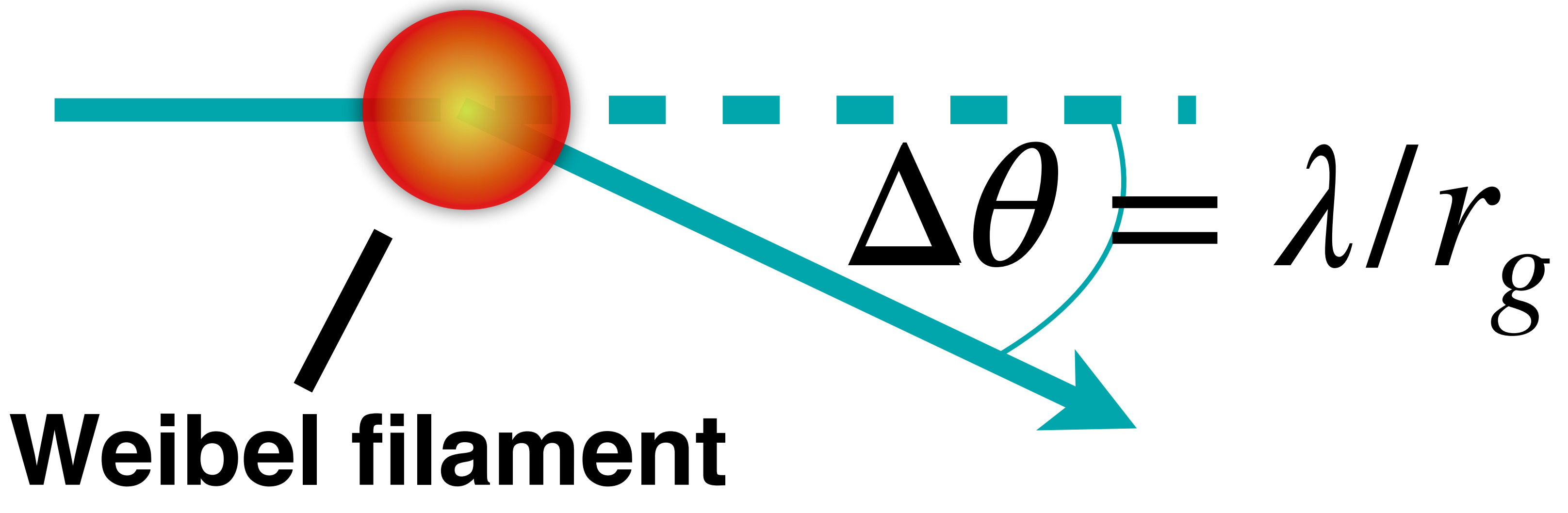
Focus on “weakly magnetised” shocks $0 < \sigma \ll 10^{-3}$.
What can say about maximum energy?

Scattering on Weibel filaments

Characteristic strength $\epsilon_B \sim 0.01 - 0.1$



Characteristic scale: $\lambda \sim 10\ c/\omega_{pp}$



Electron "strength" parameter:

$$a = \frac{e\delta B\lambda}{m_e c^2} = \gamma_e \Delta\theta$$

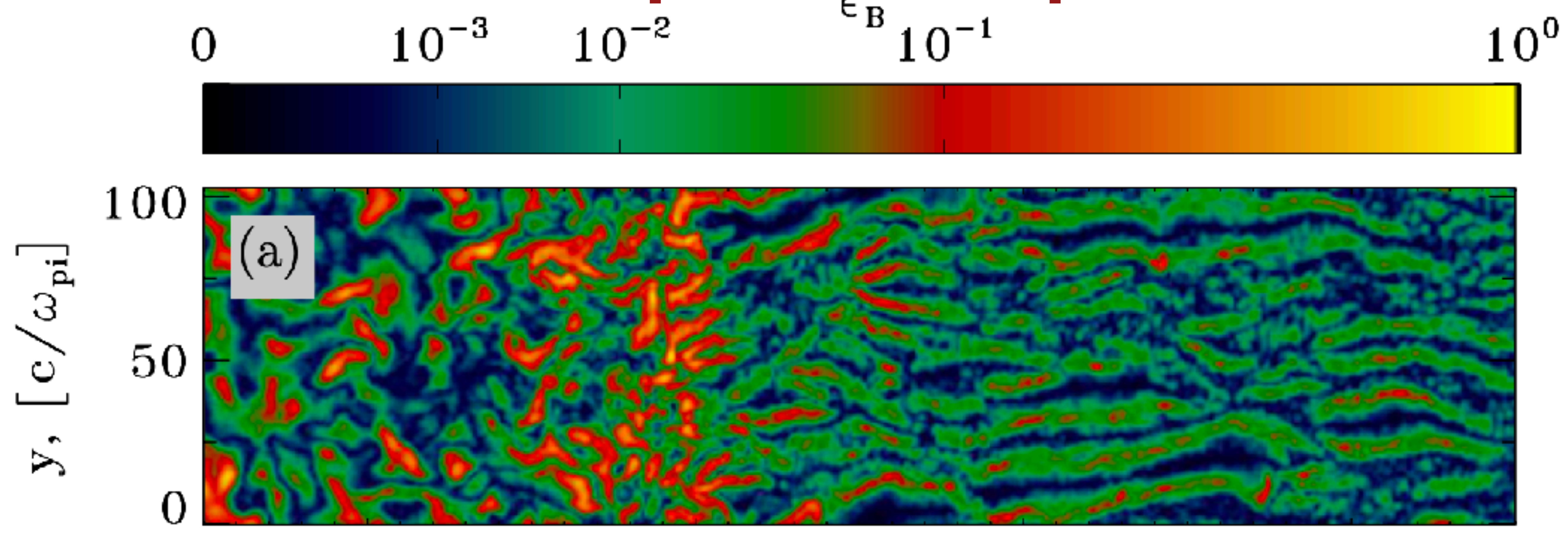
Numerically:

$$a = (\Gamma\bar{\gamma}\epsilon_B)^{1/2}\frac{m_p}{m_e}\frac{\lambda}{c/\omega_{pp}} \gg 1$$

Note, $a \gg 1$ is necessary for synchrotron approx.

Scattering on Weibel filaments

Characteristic strength $\epsilon_B \sim 0.01 - 0.1$



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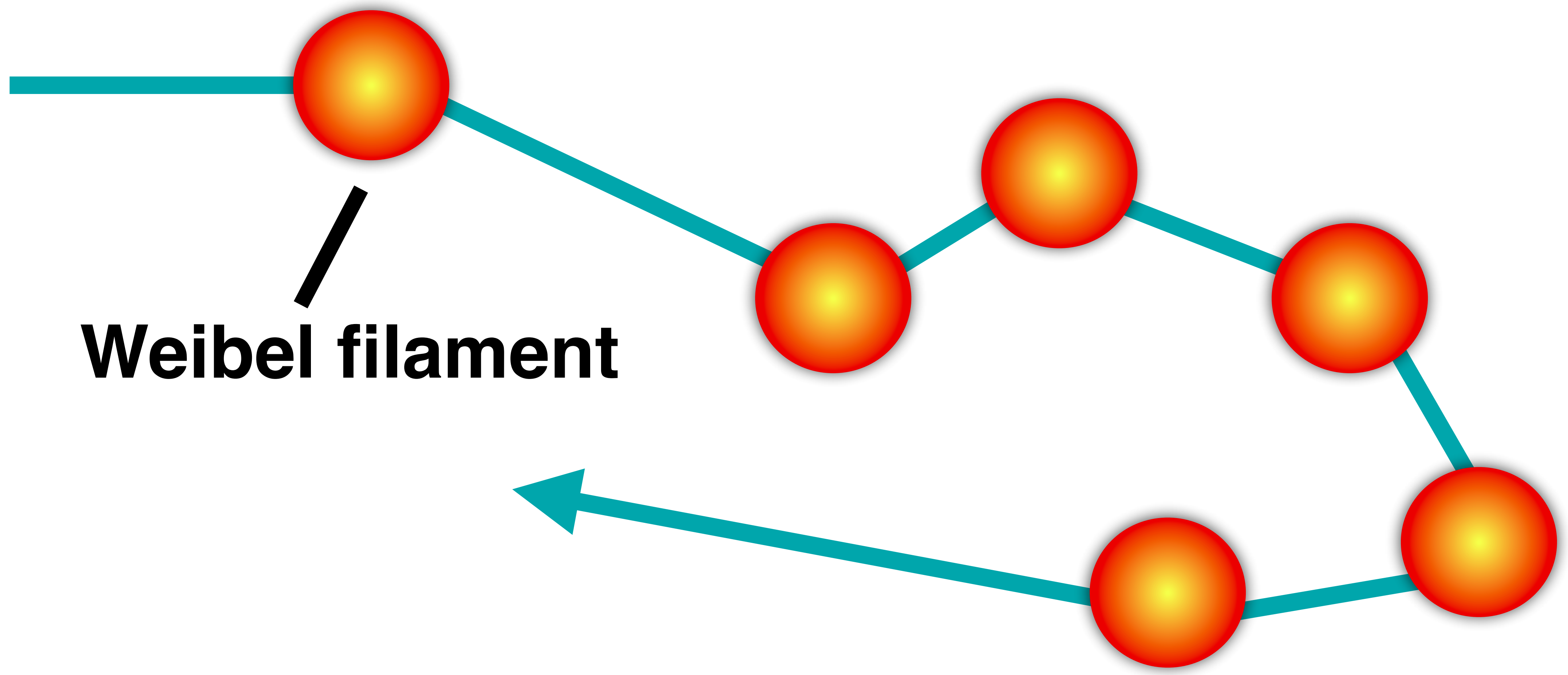


(Dramatisation)

Particle diffuses **in angle**: $D_\theta = \frac{\langle \Delta\theta^2 \rangle}{2\Delta t} \approx \frac{a^2}{\gamma^2}\frac{c}{\langle\lambda\rangle}$

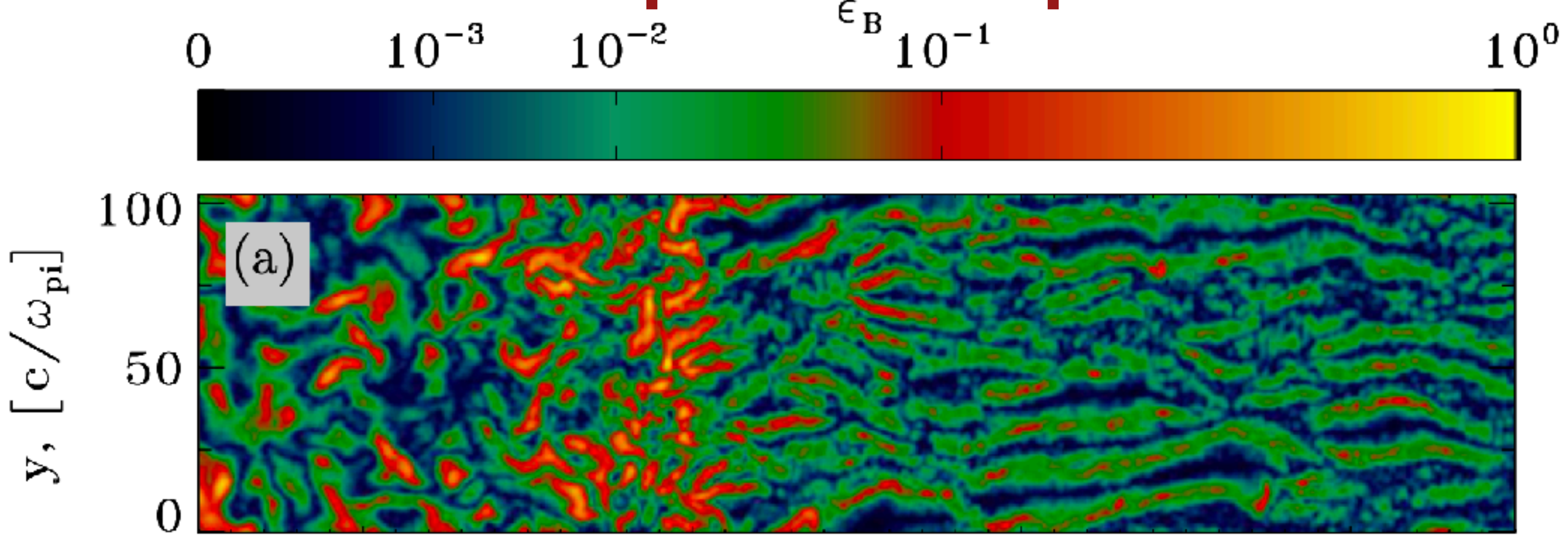
Thus isotropisation time: $t_{sc} = \nu_{sc}^{-1} \approx D_\theta^{-1} \propto \gamma^2$

For relativistic shocks, $t_{acc} \approx t_{sc}$, i.e $t_{acc} \propto \gamma^2$

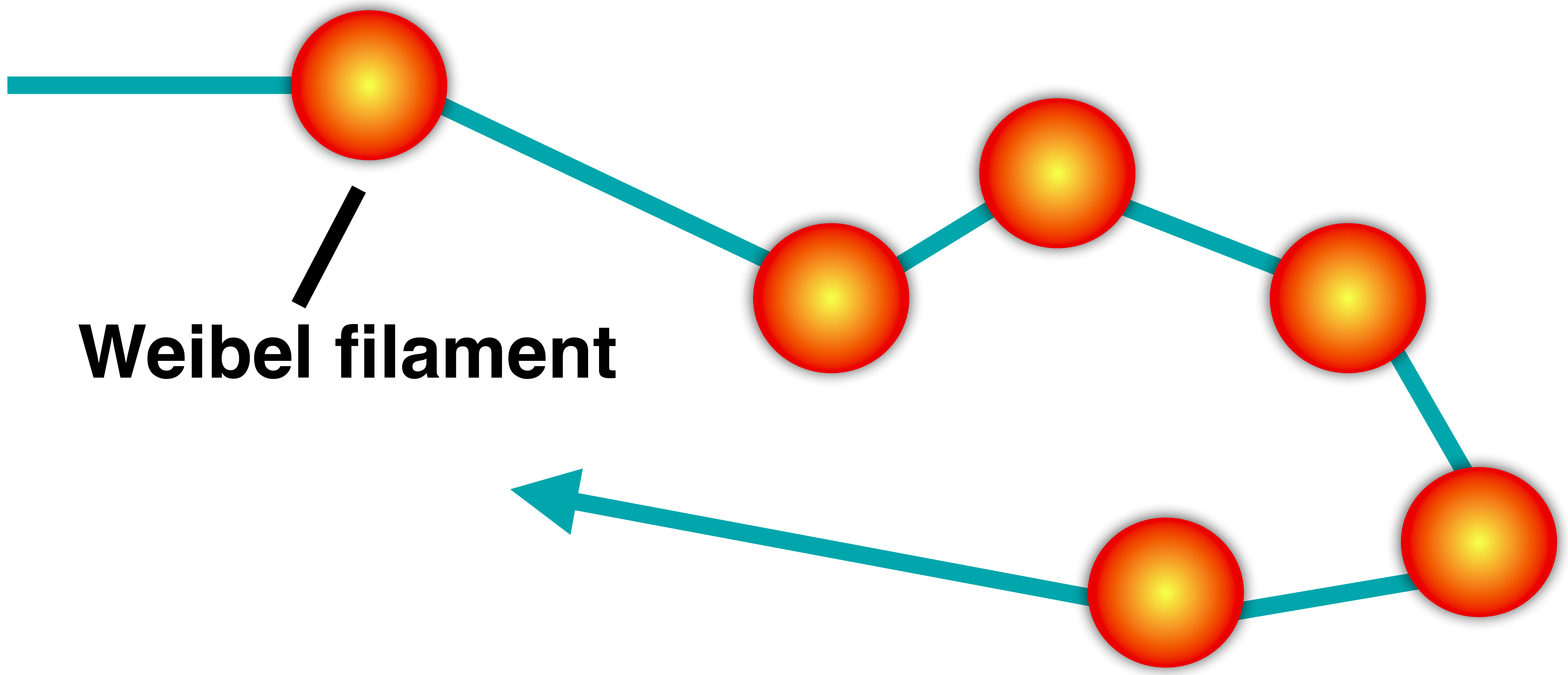
Or….. $\gamma_{max} \propto \sqrt{t}$ as seen in simulations

Scattering on Weibel filaments

Characteristic strength $\epsilon_B \sim 0.01 - 0.1$



Characteristic scale: $\lambda \sim 10\ c/\omega_{pp}$



(Dramatisation)

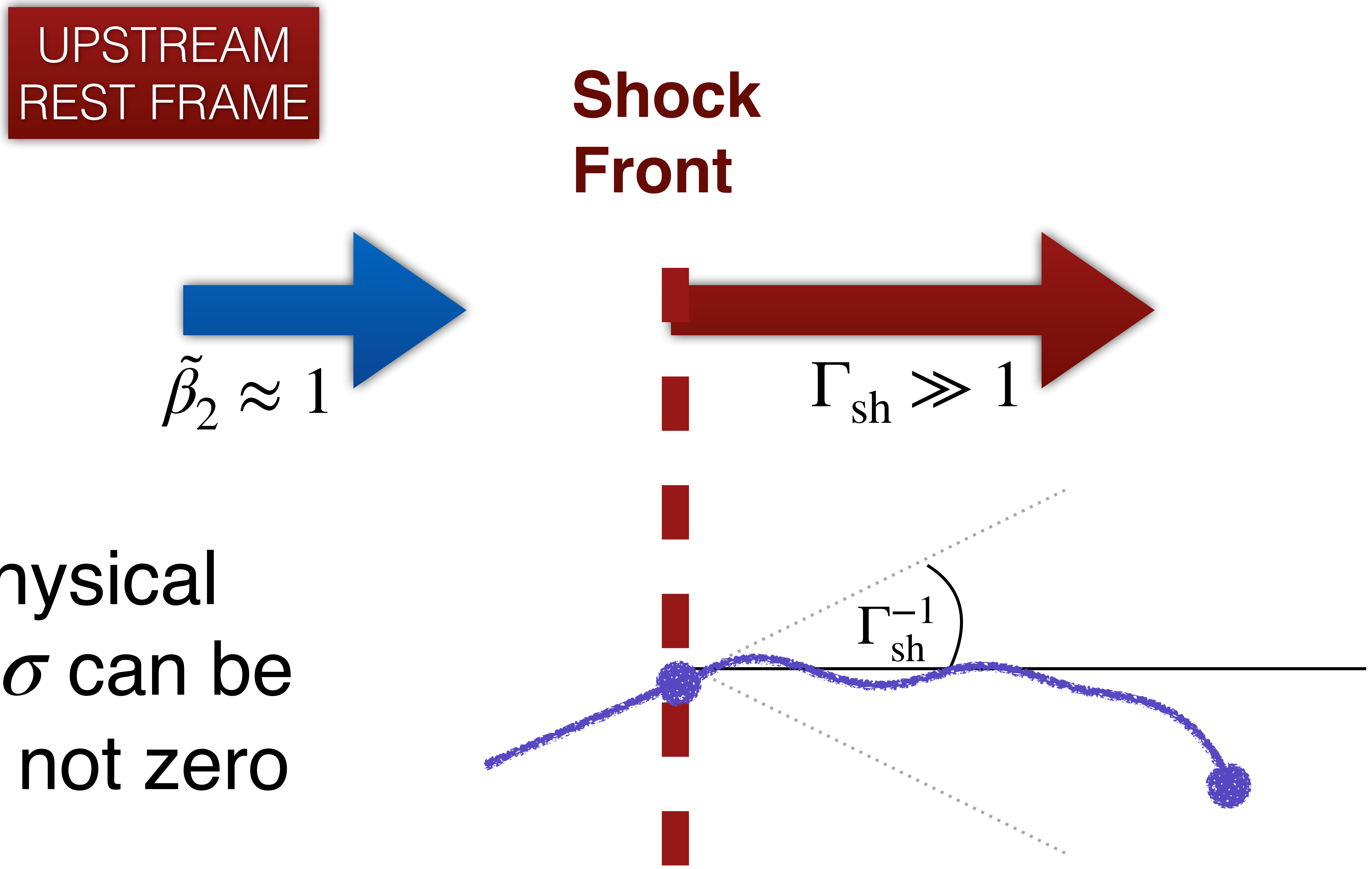
Note, it takes $N_{sc} \approx \alpha^2/\langle \Delta\theta^2 \rangle$ scatterings to diffuse through an angle α

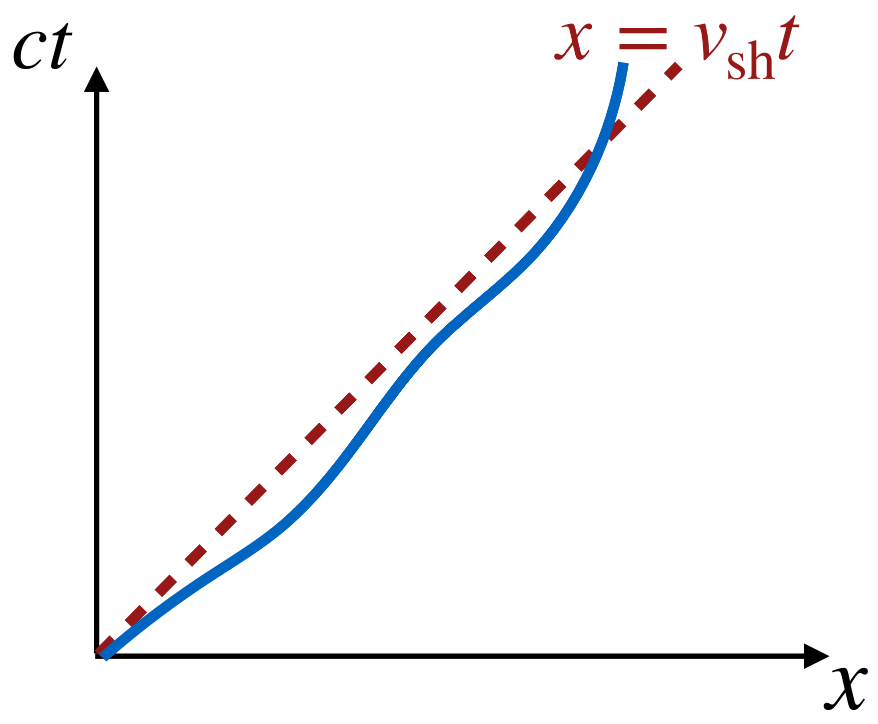
In each scattering, an electron would radiate an amount $\Delta\gamma/\gamma \propto a^2\gamma/\lambda$

Electrons do NOT reach synchrotron burn-off limit

But, it turns out something else can be EVEN more limiting

Particle acceleration at Ultra-rel. shocks





In astrophysical sources, σ can be small but not zero

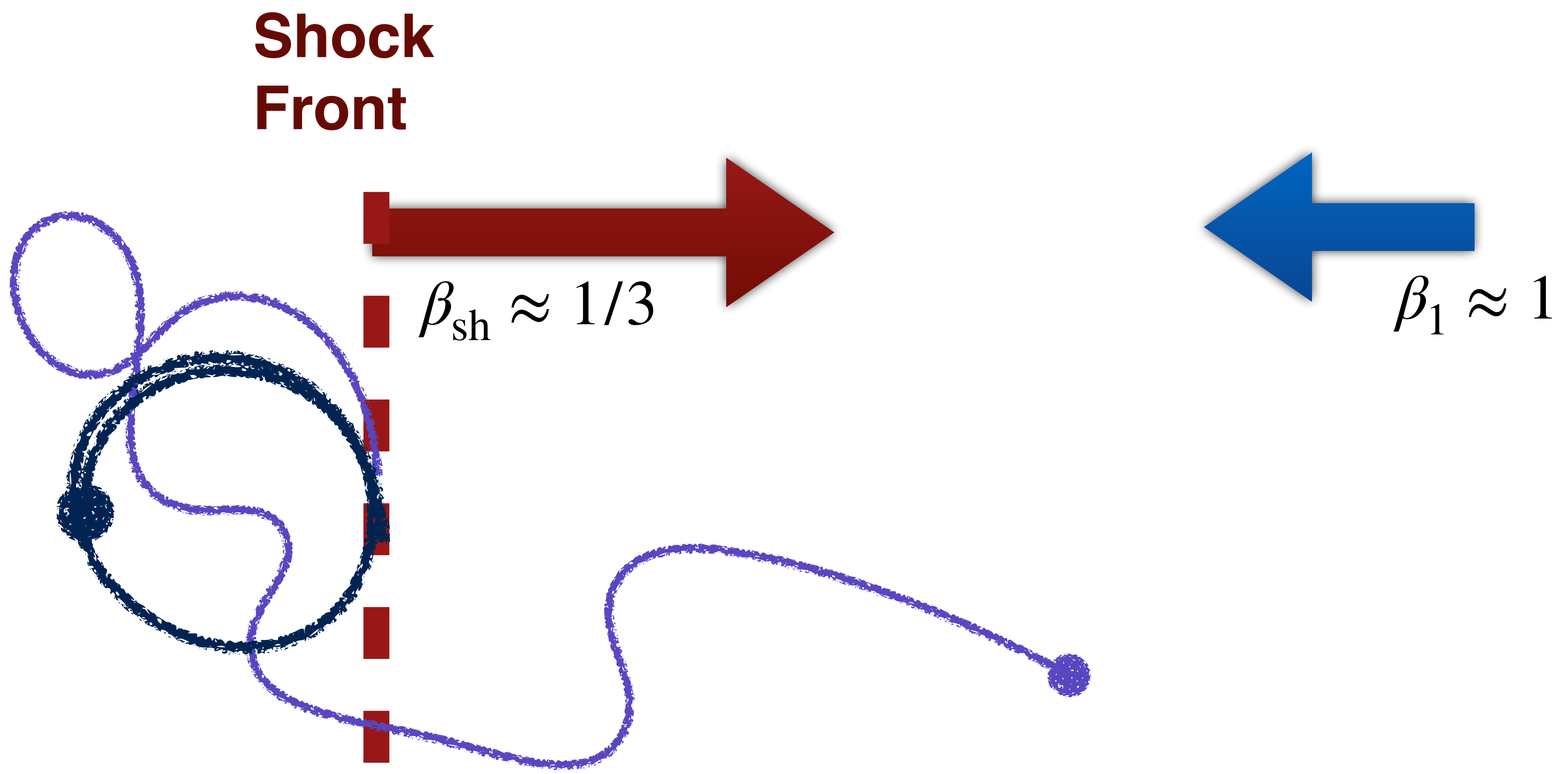
Any particle overtaking shock has $\mu > \beta_{sh}$ $(\theta < \Gamma_{sh}^{-1})$
Seen from upstream frame, particle doesn't get far.

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

Particle acceleration at Ultra-rel. shocks

DOWNSTREAM
REST FRAME

In DSF: any particle overtaken by shock
$\bar{\mu} < \beta_2 \approx 1/3$



If $\nu_{sc} < \Omega_{gyro}$ -> Game Over??

If $\nu_{sc} > \Omega_{gyro}$ -> Particle can diffuse back to shock

Question: is it more important for scattering to dominate ($\nu_{sc} > \Omega_{gyro}$) upstream or downstream?

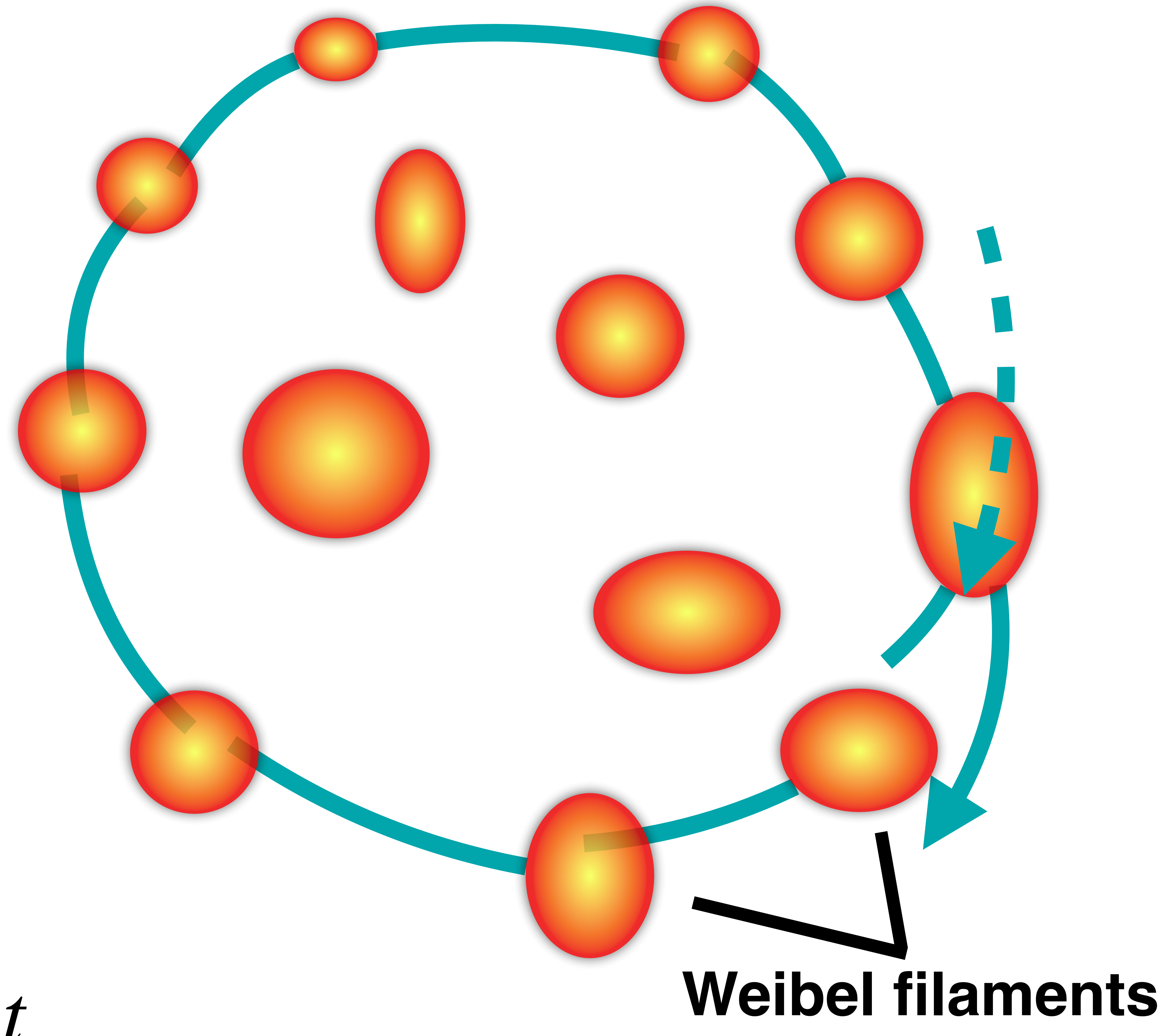
Magnetised Limit on Maximum Energy

Scattering on Weibel filaments

$$t_{\mathrm{sc}} \propto \gamma^2$$

$$t_{\mathrm{gyro}} \propto \gamma$$

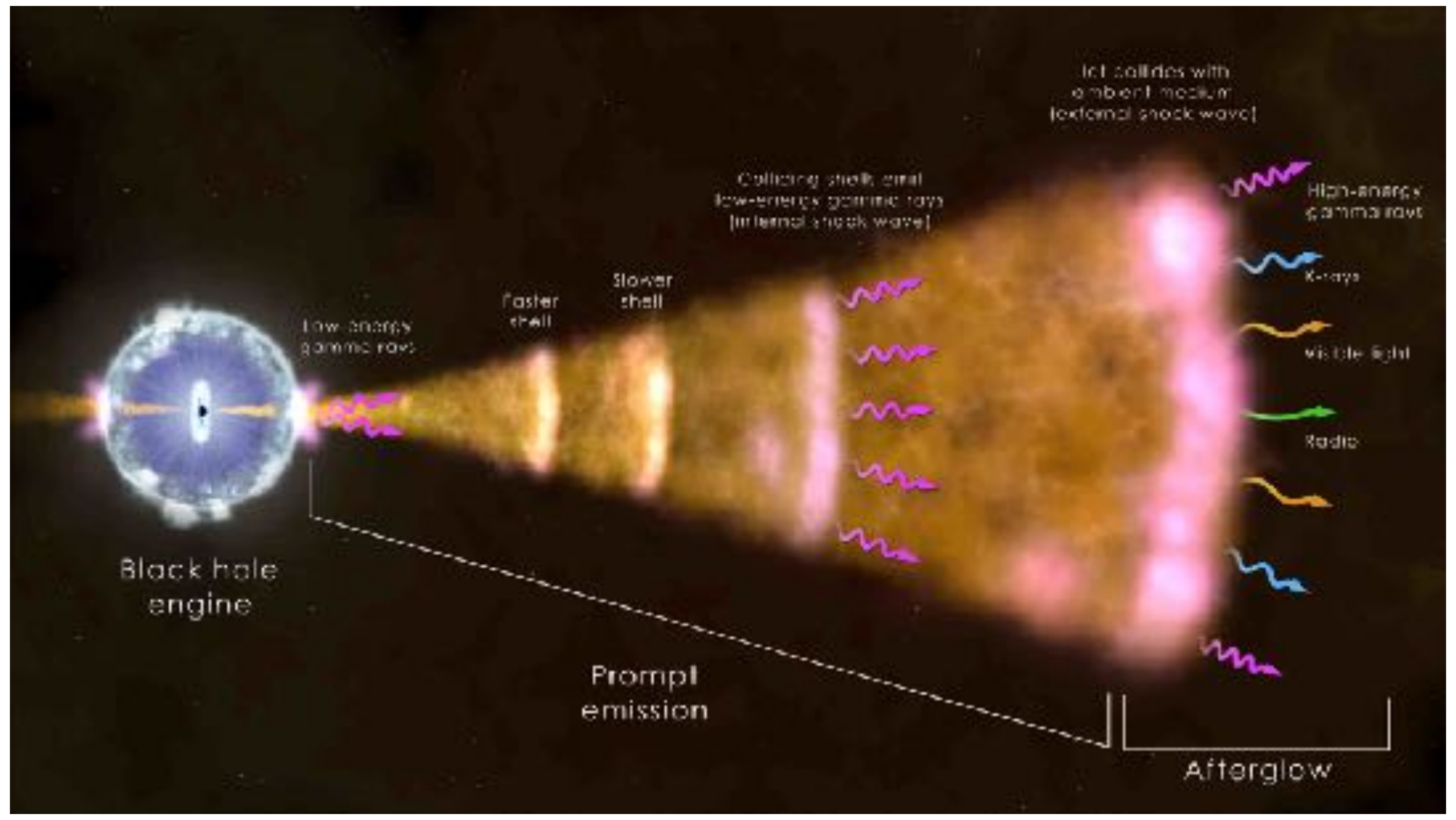
(Measured in average field)



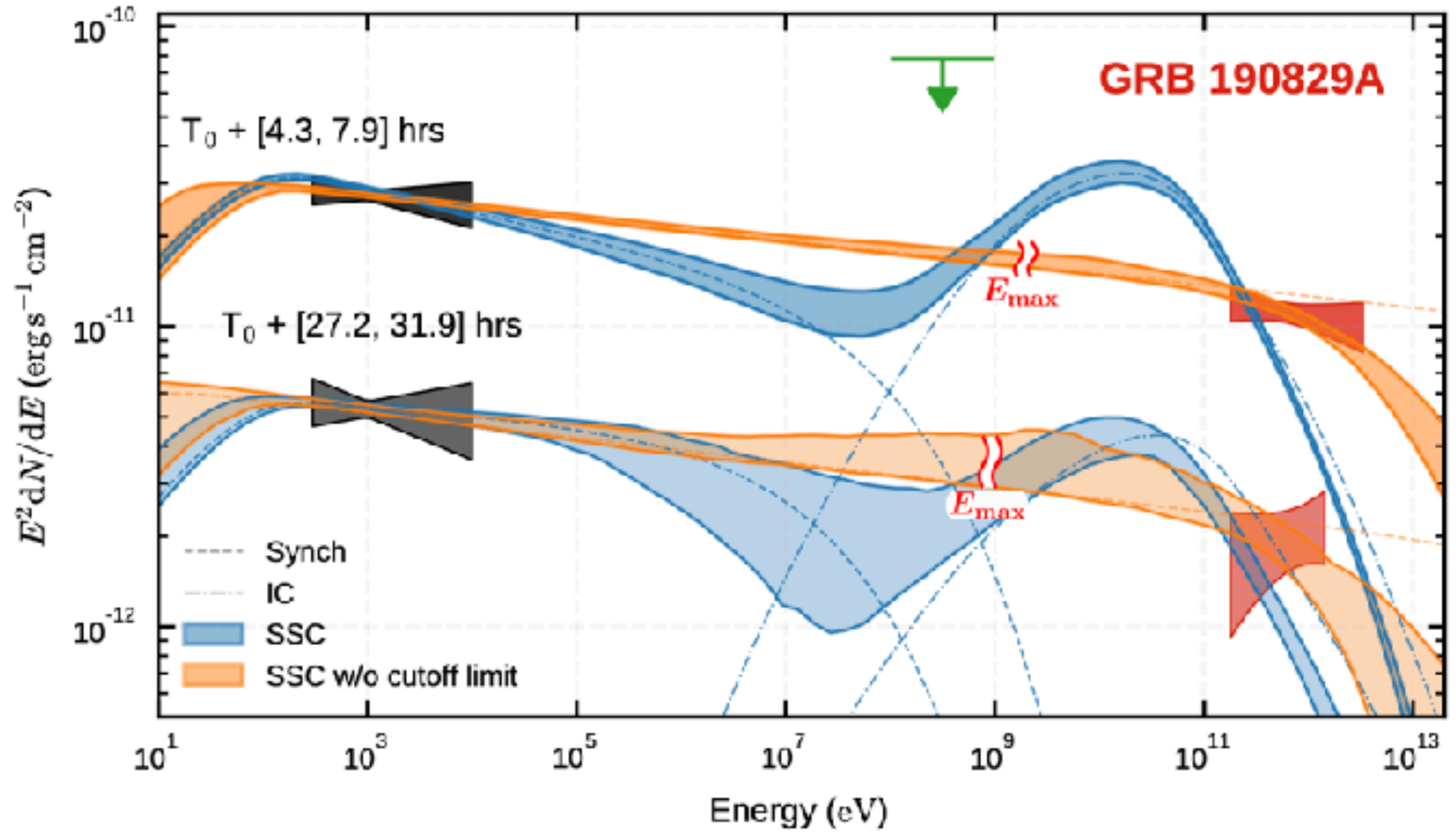
Suggests a critical energy when $t_{\mathrm{sc}} = t_{\mathrm{gyro}}$

Maximum electron energy is minimum of cooling limited and magnetisation limited value (see Huang et al. ’22 for equations)

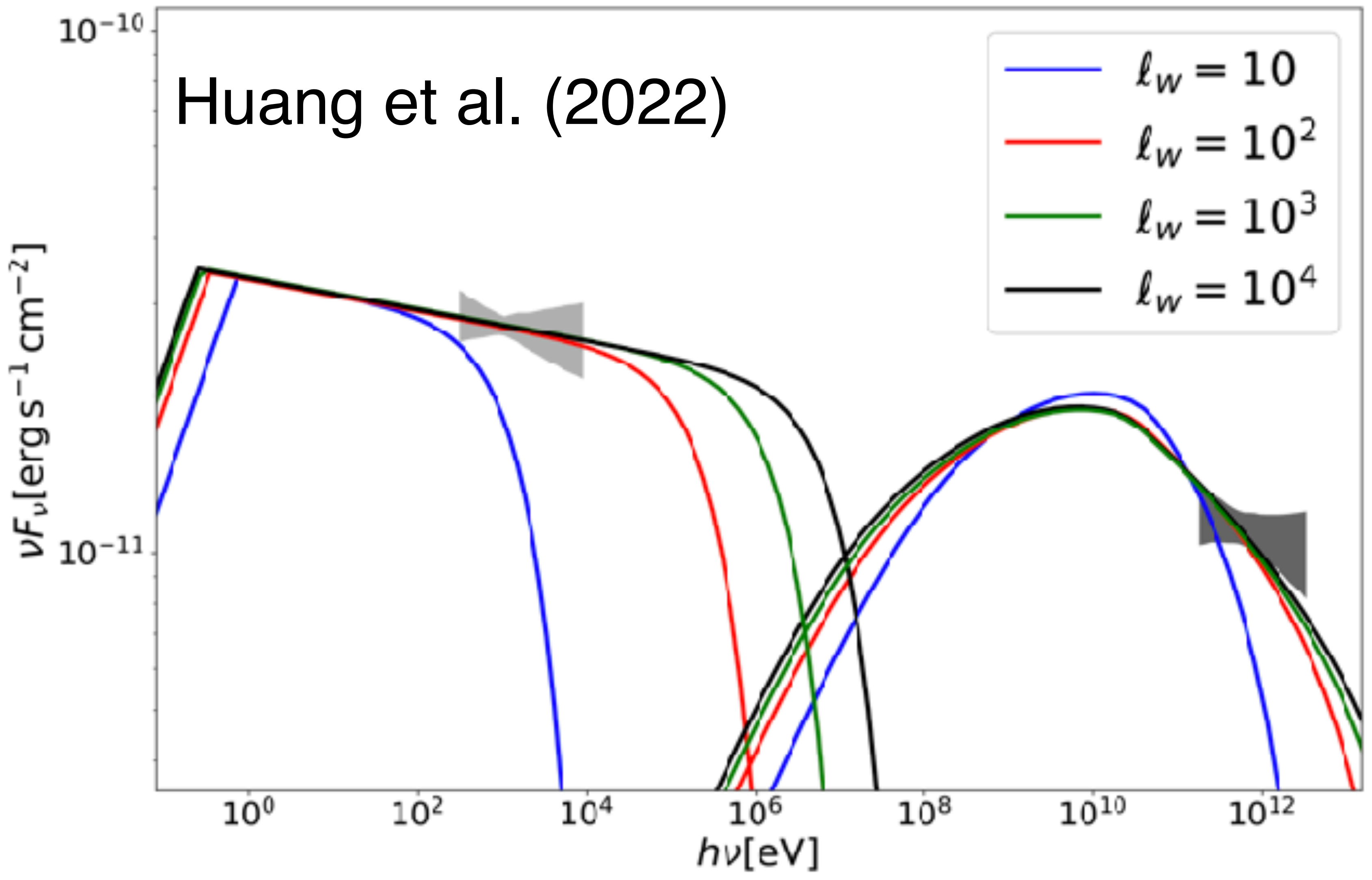
Application: GRB 190829A Afterglow



HESS Collaboration 2020



Standard GRB afterglow models are surprisingly easy, since the hydrodynamic solution is “known” (Blandford & McKee ’76)



$$\lambda = \ell_{\rm w} \frac{c}{\omega_{\rm p}}$$

Environmental parameters:
Explosion energy, external density
(free params)

Shock Parameters:
ϵ_B & ϵ_e (PIC)
Power-law index (PIC?)
Maximum electron energy

PIC sims indicate
$\ell_{\rm w} = 10 - 20$

Do we have a complete picture yet?

- Are particles only accelerated at weakly magnetised shocks?
  - If Yes, then we have to provide a robust alternative for other sources
- Is the maximum synchrotron energy always << burn-off limit (cooling time= gyro time : $h\nu/m_e c^2 \approx \alpha_f^{-1}$)
  - If Yes, then why haven't we seen the cut-offs yet?
- Are we missing some important details?
  - Yes.

Return to Bohm - the limiting cases

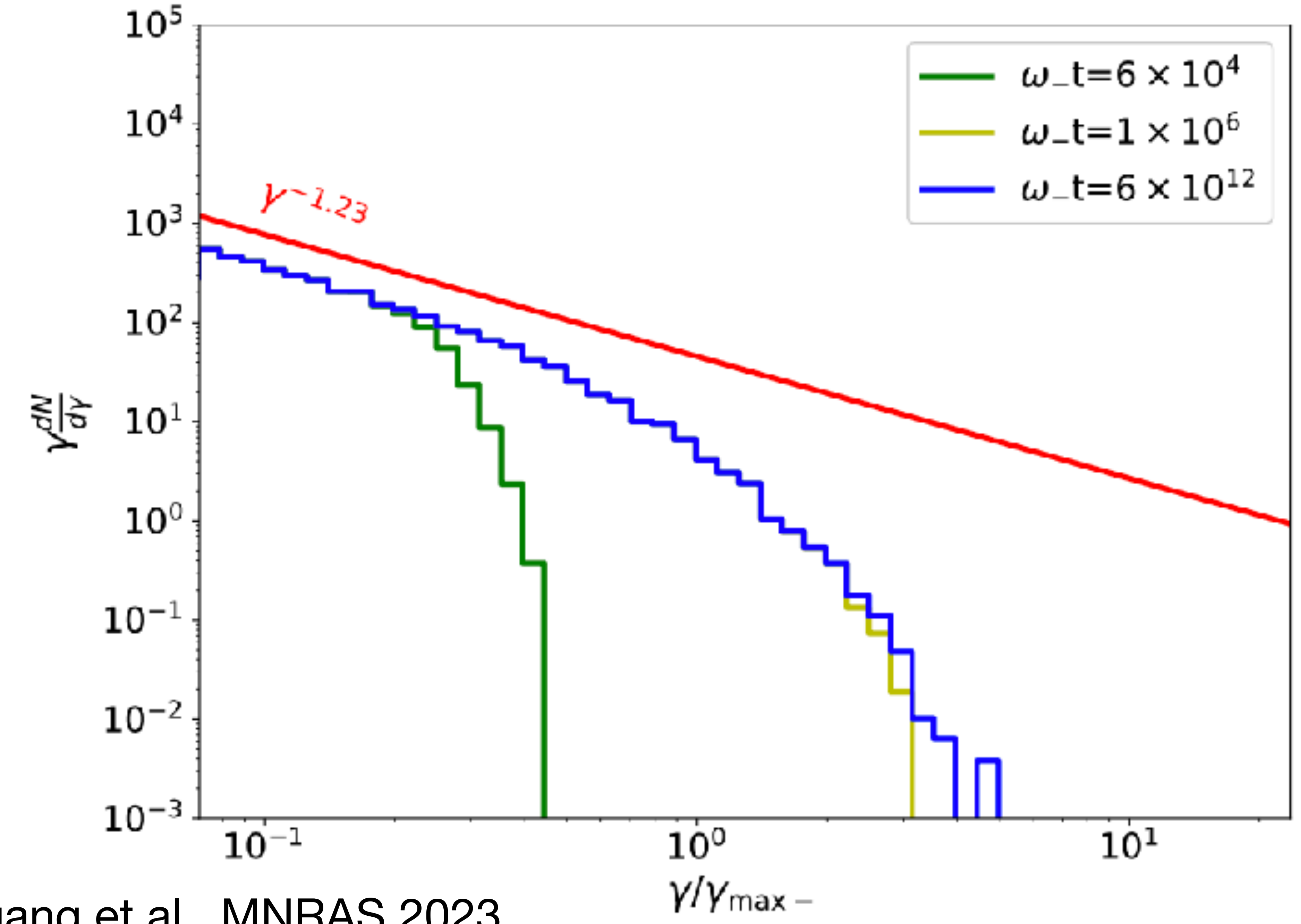
Let's introduce some notation (with apologies) :

$\nu_\pm = \nu_{0\pm}\gamma^{-2}$ are upstream (+) /downstream (-) scattering rates measured *locally.*

$\omega_- = \gamma\Omega_{\rm gyro} = eB_-/mc$

Measuring all quantities in downstream observer's frame:

Residence Times	Scattering Dominates	Deflection dominates	Cross over
Upstream	$\Delta t_+ = \gamma^2/(\Gamma_{\rm sh}\nu_{0+})$	$\Delta t_+ = 2\sqrt{2}\gamma/\omega_-$	$\gamma_{\rm max,+} = 2\sqrt{2}\Gamma_{\rm sh}\nu_{0+}/\omega_-$
Downstream	$\Delta t_- = \gamma^2/\nu_{0-}$	$\Delta t_- = \gamma/\omega_-$	$\gamma_{\rm max,-} = \nu_{0-}/\omega_-$



Huang et al., MNRAS 2023

Lets assume $\gamma_{\rm max,+} < \gamma < \gamma_{\rm max,-}$

$$\frac{\Delta t_+}{\Delta t_-} = \frac{2\sqrt{2}\gamma_{\rm max,-}}{\gamma} > 1$$

Fermi cycle dominated by upstream residence time, $\gamma_{\rm max} \propto t$

Saturates at $\gamma_{\rm max,-}$

Return to Bohm - the limiting cases

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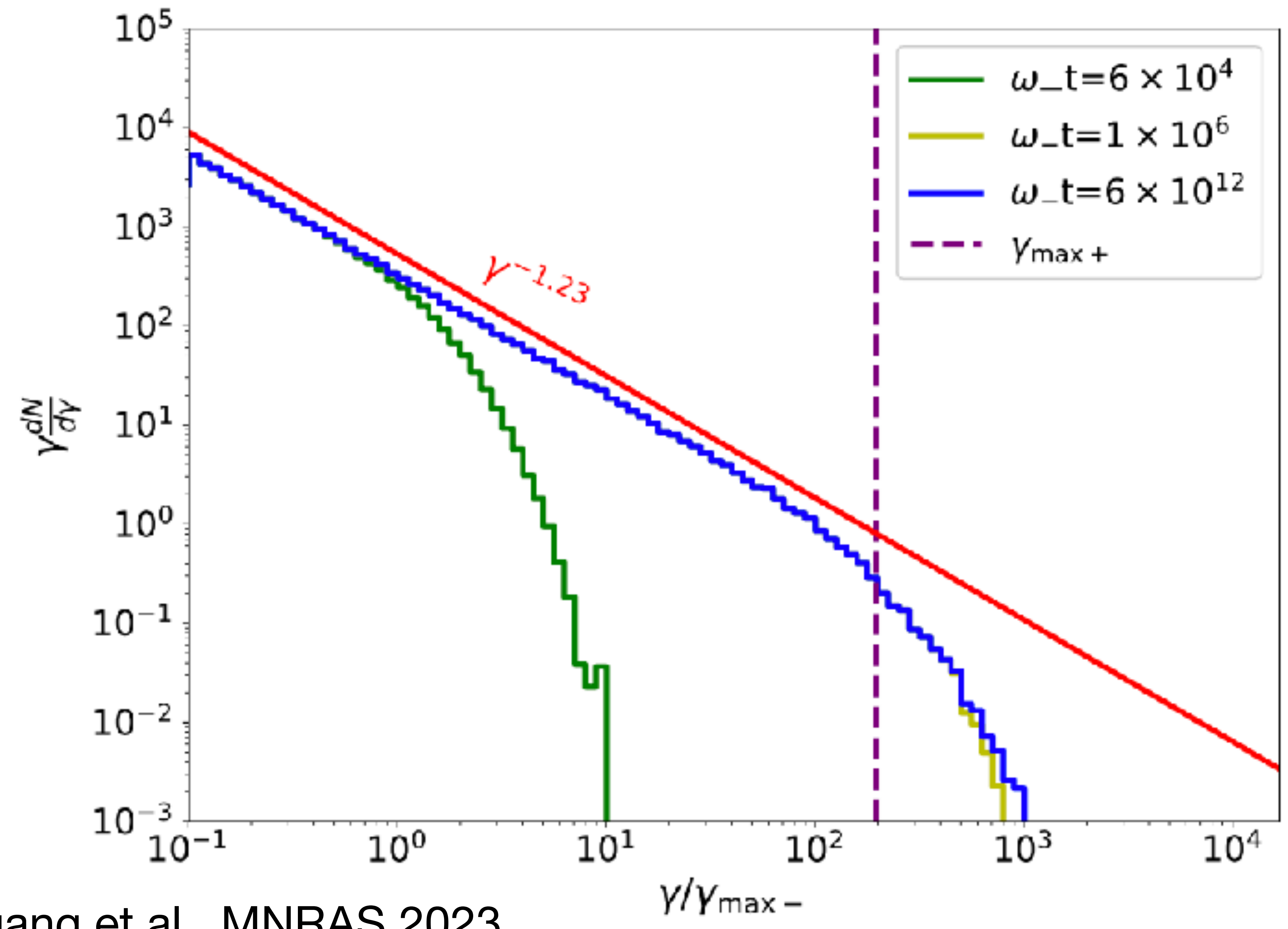
$\omega_{-} = \gamma\Omega_{\text{gyro}} = eB_{-}/mc$

Measuring all quantities in downstream observer's frame:

Residence Times	Scattering Dominates	Deflection dominates	Cross over
Upstream	$\Delta t_{+} = \gamma^2/(\Gamma_{\text{sh}}\nu_{0+})$	$\Delta t_{+} = 2\sqrt{2}\gamma/\omega_{-}$	$\gamma_{\text{max},+} = 2\sqrt{2}\Gamma_{\text{sh}}\nu_{0+}/\omega_{-}$
Downstream	$\Delta t_{-} = \gamma^2/\nu_{0-}$	$\Delta t_{-} = \gamma/\omega_{-}$	$\gamma_{\text{max},-} = \nu_{0-}/\omega_{-}$



Huang et al., MNRAS 2023

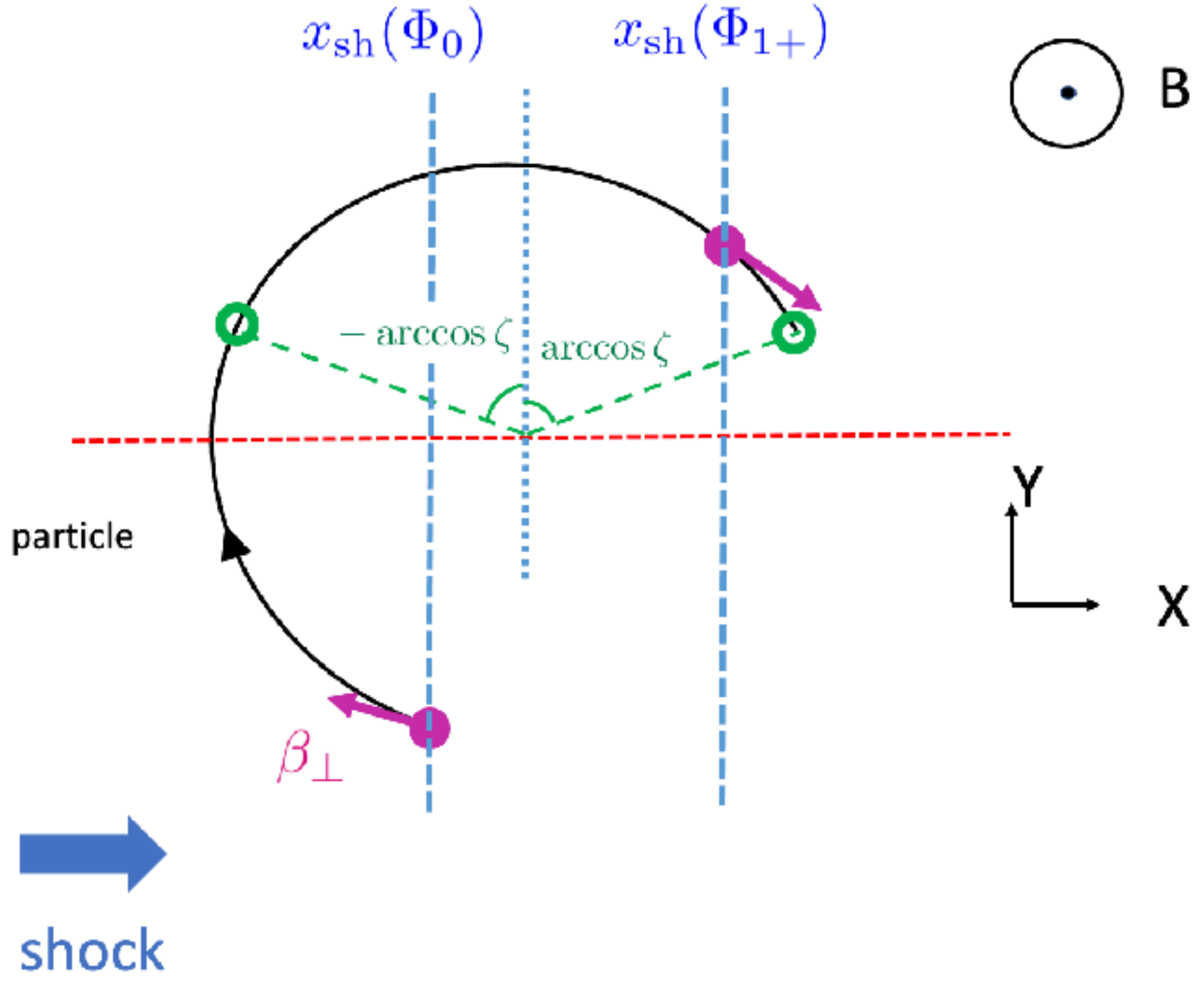
Opposite case, $\gamma_{\text{max},-} < \gamma < \gamma_{\text{max},+}$

$$\frac{\Delta t_{+}}{\Delta t_{-}} = \frac{2\sqrt{2}\gamma}{\gamma_{\text{max},+}} < 1$$

Fermi cycle dominated by downstream residence time, $\gamma_{\text{max}} \propto t$

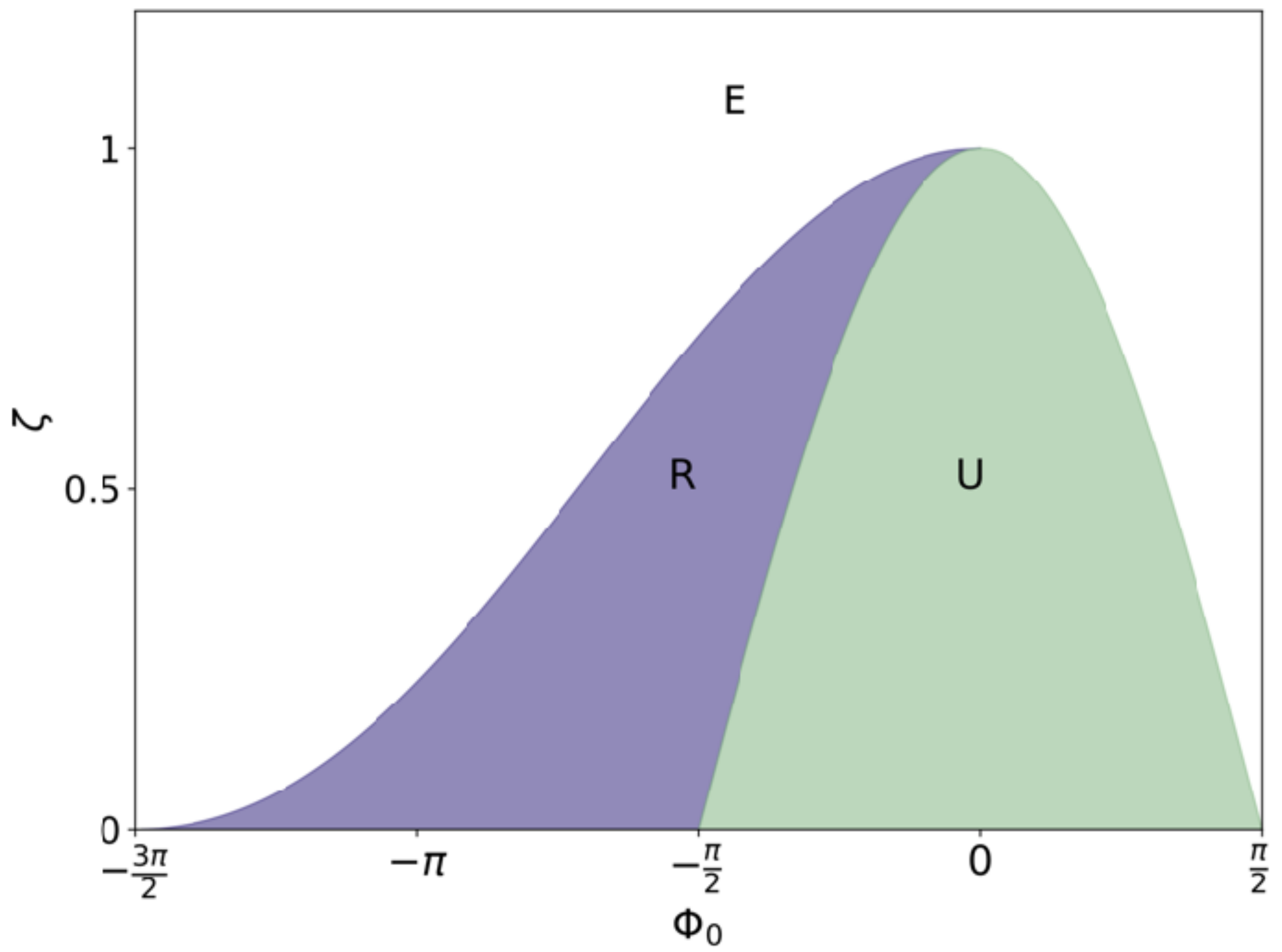
Saturates at $\gamma_{\text{max},+}$

Return to Bohm - the limiting cases



Consider the extreme case of pure scattering upstream , no scattering ds

$\zeta = \beta_2/\beta_\perp$ where recall $\beta_2 \approx 1/3$ is shock velocity seen from downstream



If pitch angle diffusion operates upstream (which it must in $\Gamma_{\rm sh} \to \infty$ limit) return probability is high

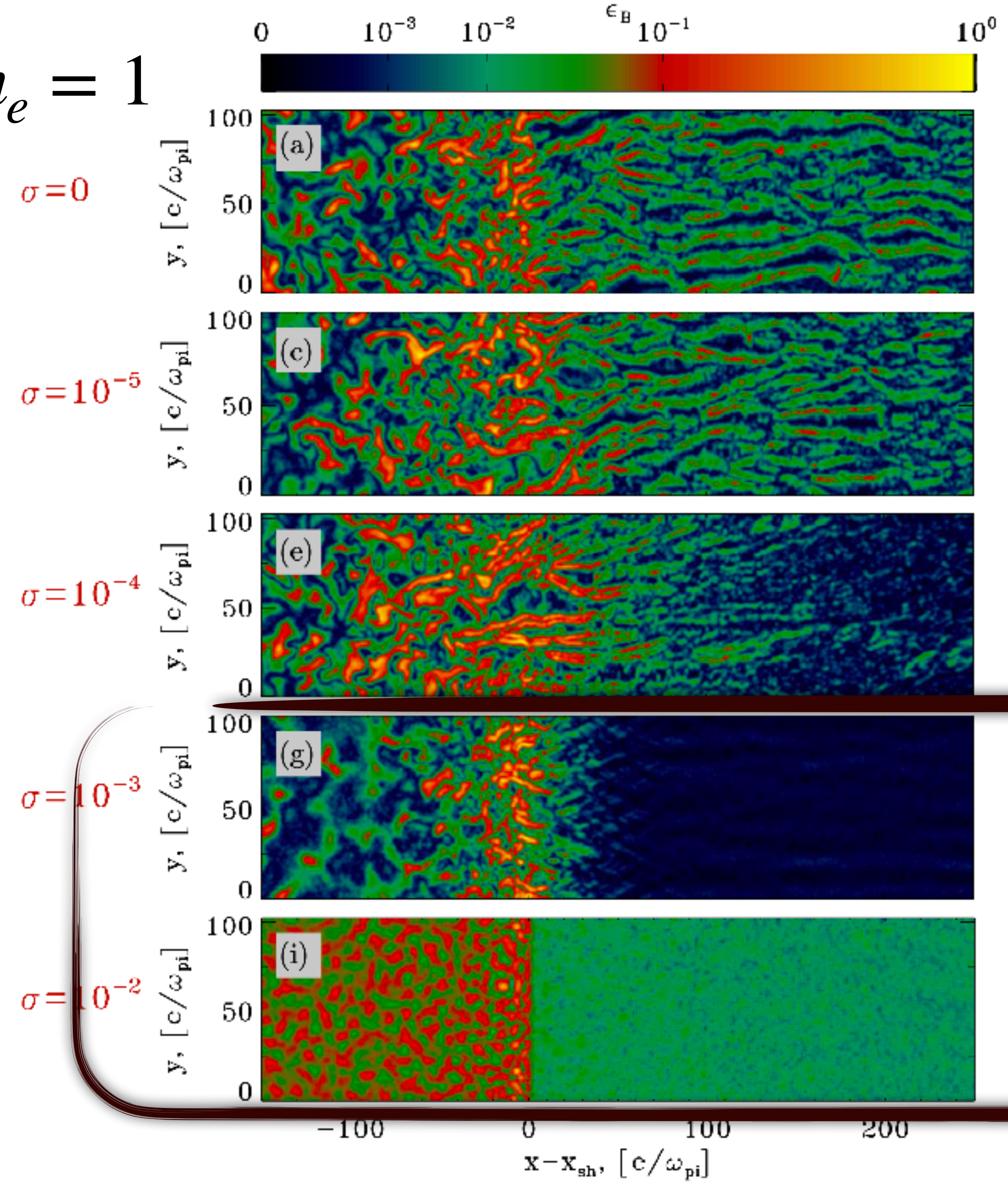
Kirk, BR & Huang, '23

Details of plasma physics in Shock *precursor* critical

Is there more to the high σ PIC simulations?

2D simulations by Sironi, Spitkovsky & Arons 13

$m_i/m_e = 1$



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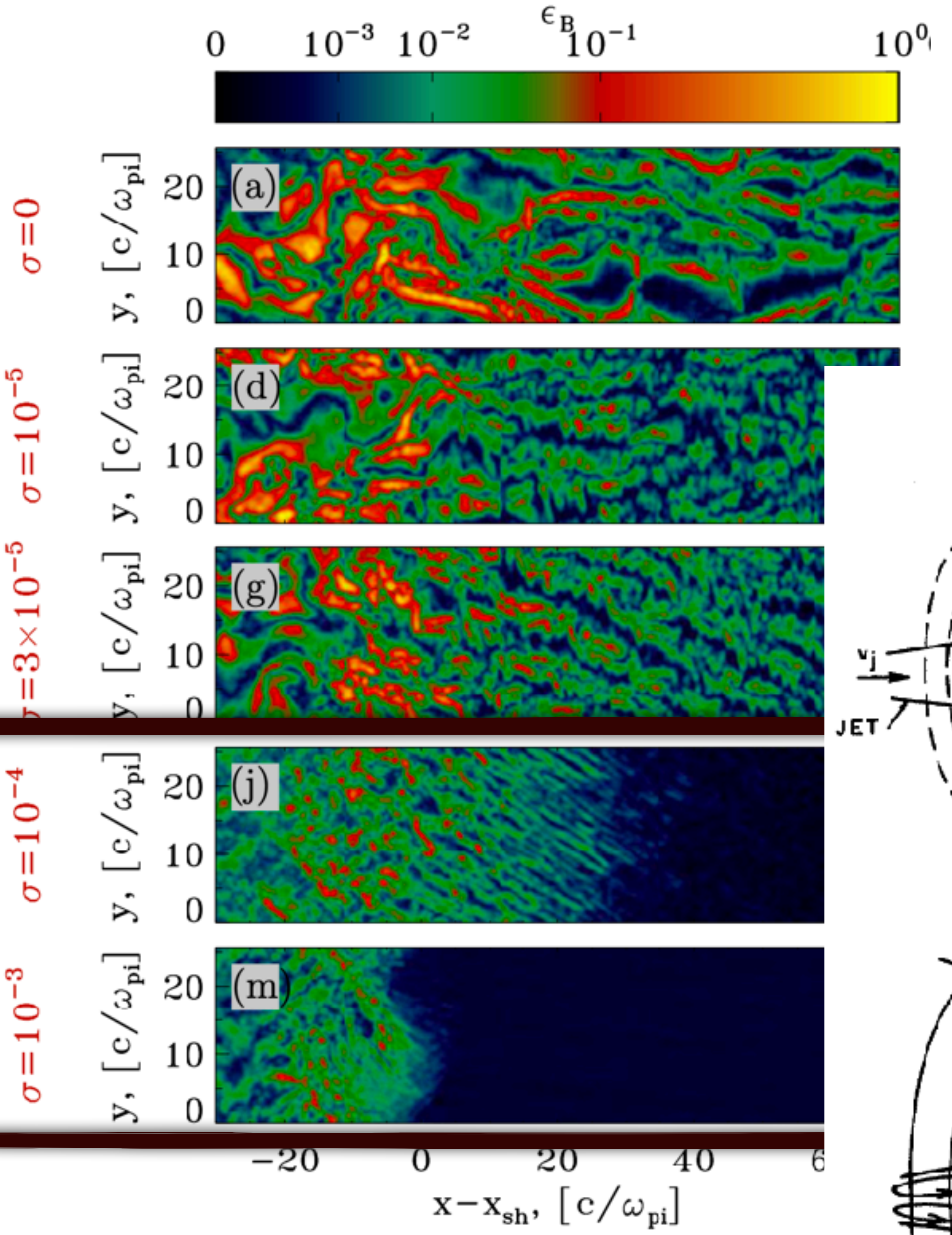
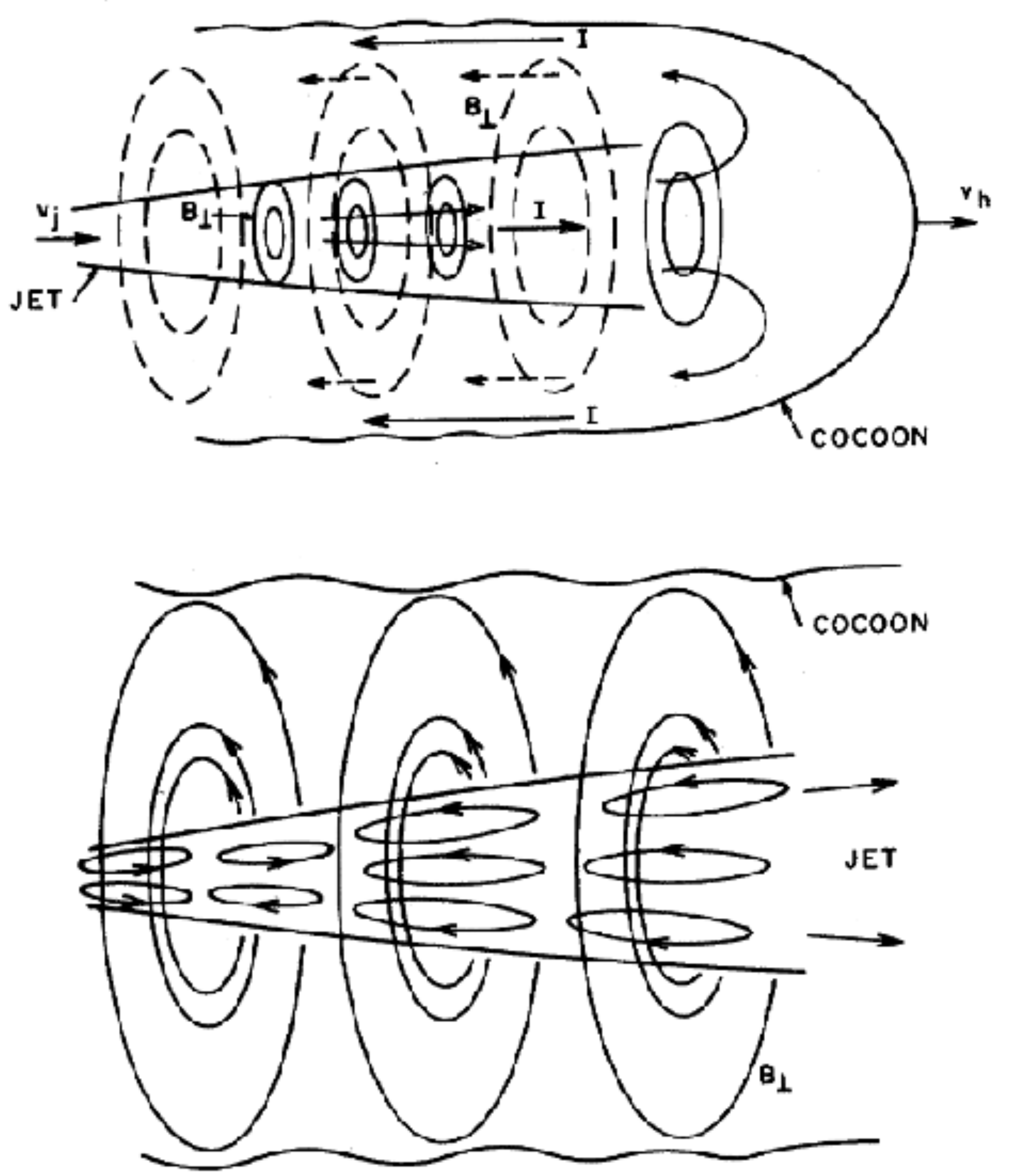
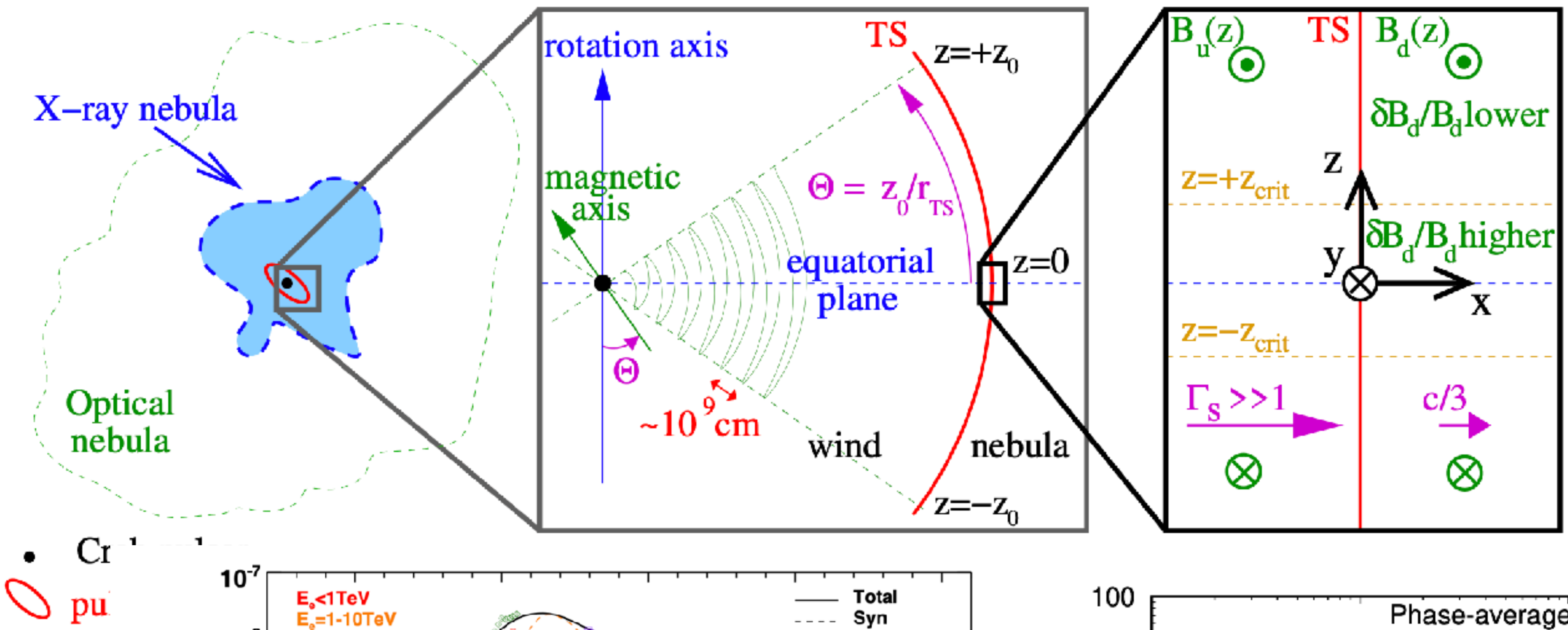


Begelman, Blandford, and Rees:



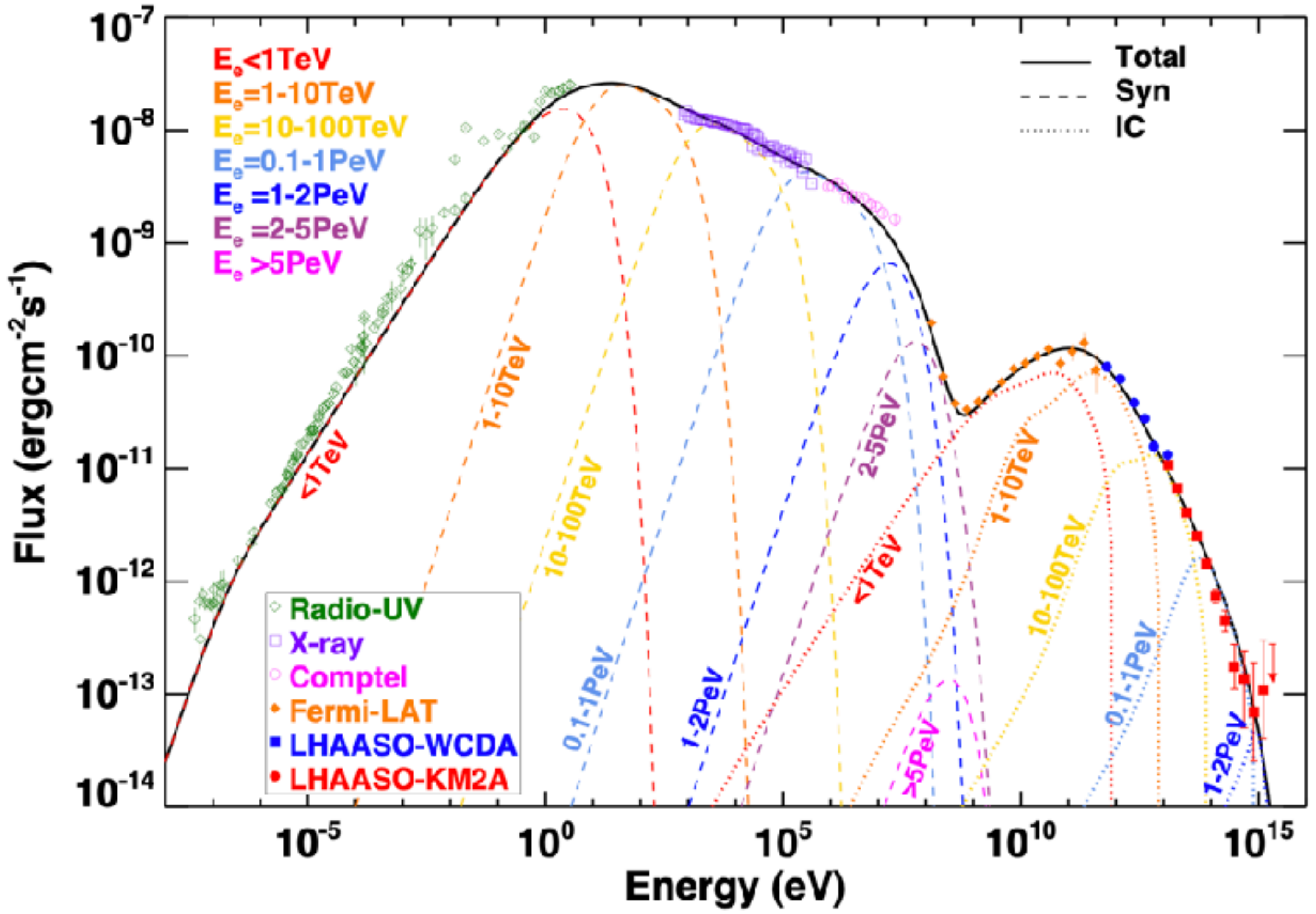
Any hope for these shocks?

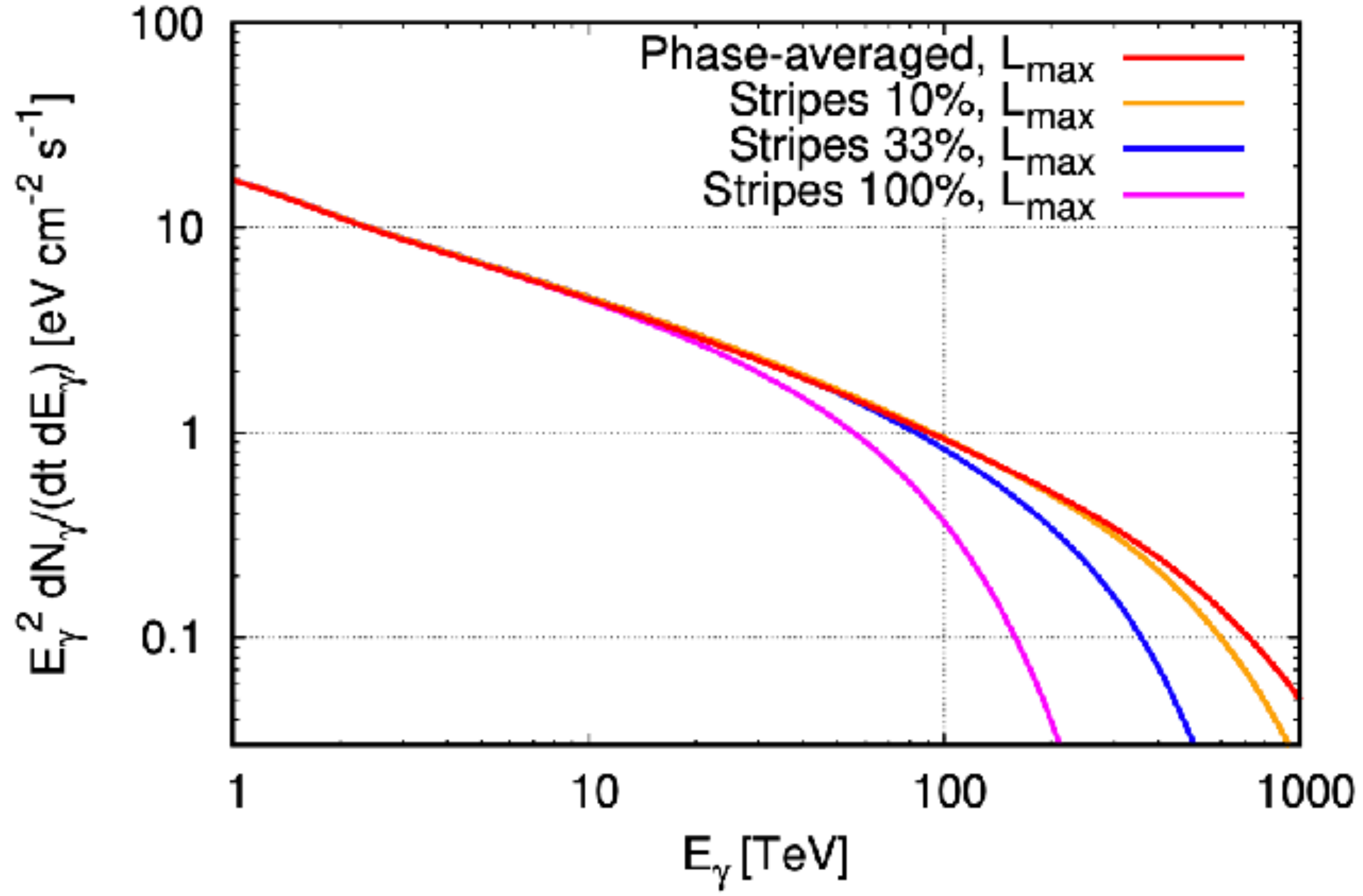
The impact of structured fields



Giacinti & Kirk (2018)

Fermi accele
facilitated by
particles to s





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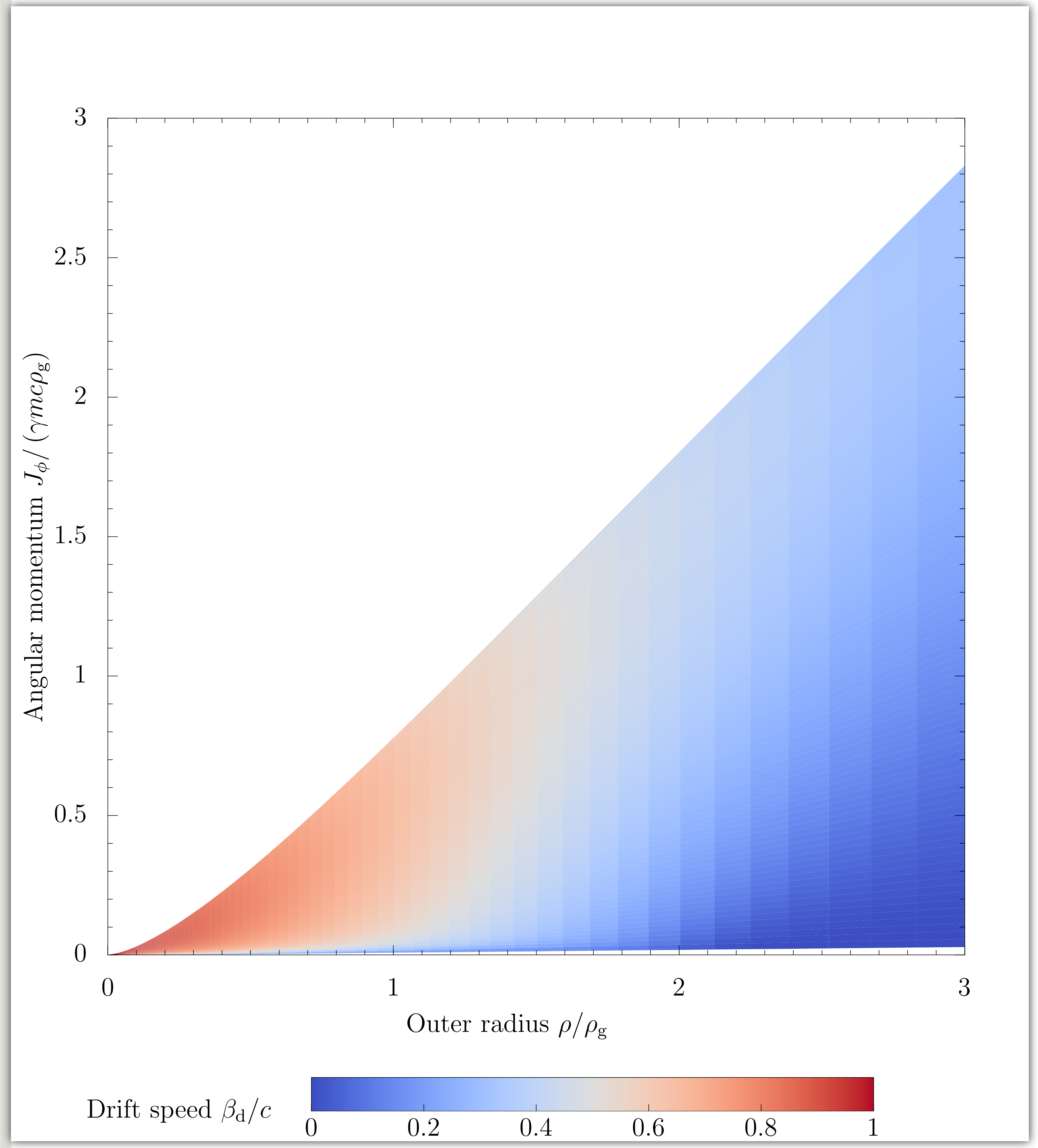
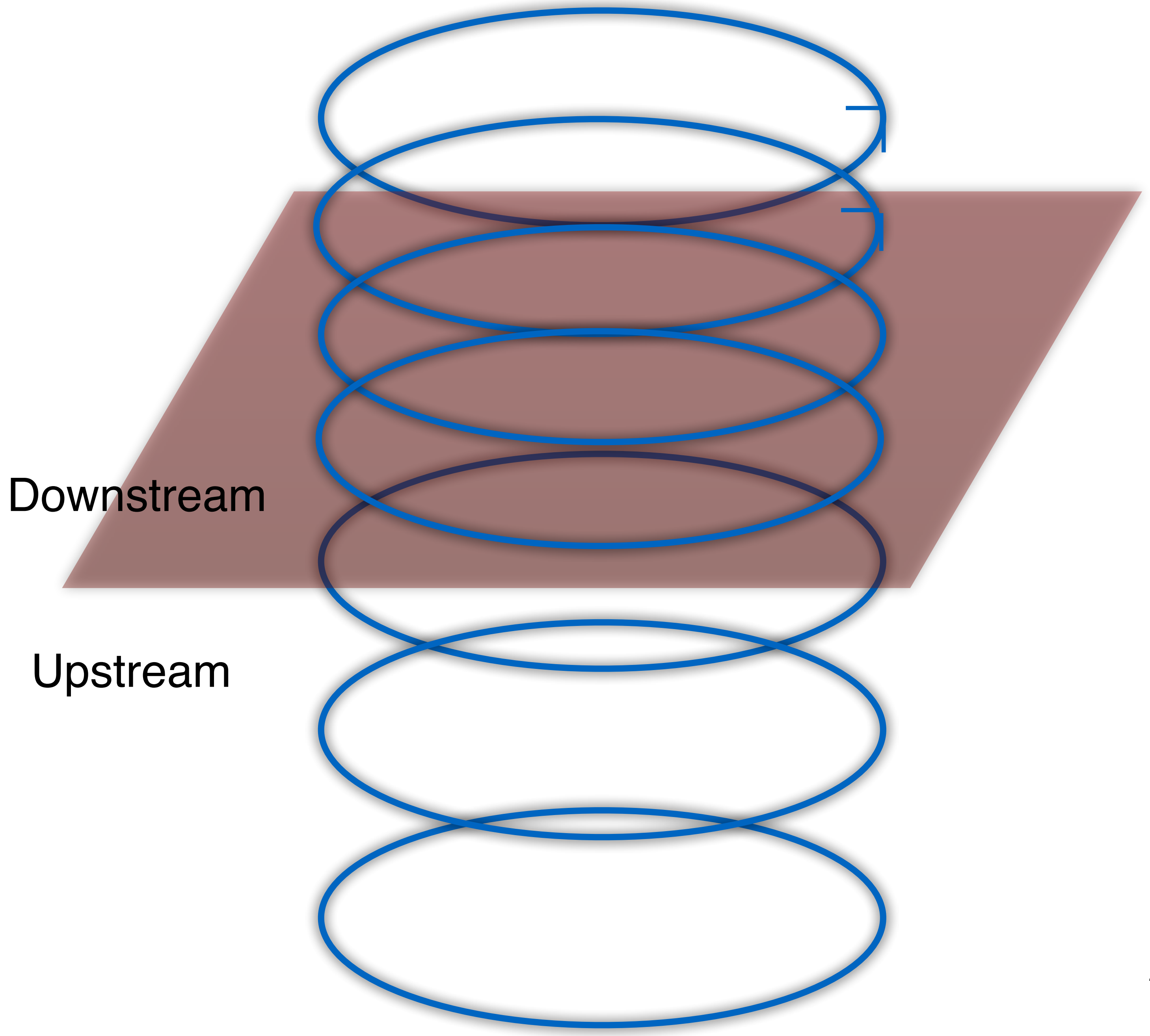
Shocks in current carrying jets





Consider a scatter free trajectory

Far from axis, we approximate
$\mathbf{A} = -B_0 \rho\ \hat{\mathbf{z}}$
and $\mathbf{B} = \nabla \times \mathbf{A} \ \Rightarrow\ \mathbf{B} = B_0 \hat{\phi}$

$(\, \mathbf{j} \propto \nabla \times \mathbf{B} \ \Rightarrow\ j_z \propto 1/\rho\,)$

γ, P_z and P_ϕ are constants of motion

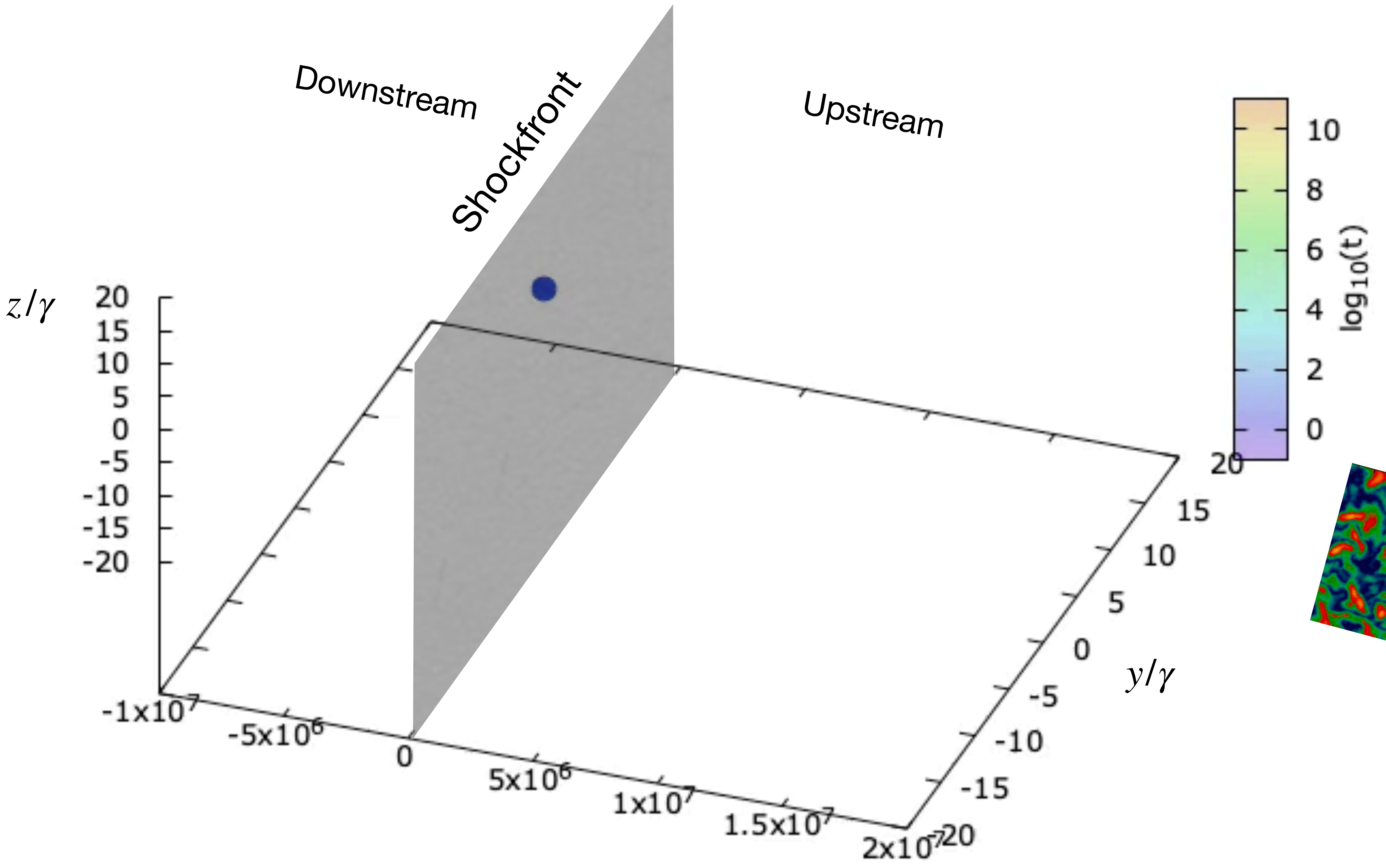
$$\frac{P_z}{\gamma m c} = v_z - \frac{\rho}{\rho_{g,0}} = \text{const} \quad \text{where } \rho_{g,0} = \frac{\gamma m c^2}{q B_0},$$

If $\rho < \rho_{g,0}$ particles can have relativistic **curvature** drifts (depending on sign of qB_0)
Speiser orbits (particles crossing the $\rho = 0$ axis, do not appear to be important

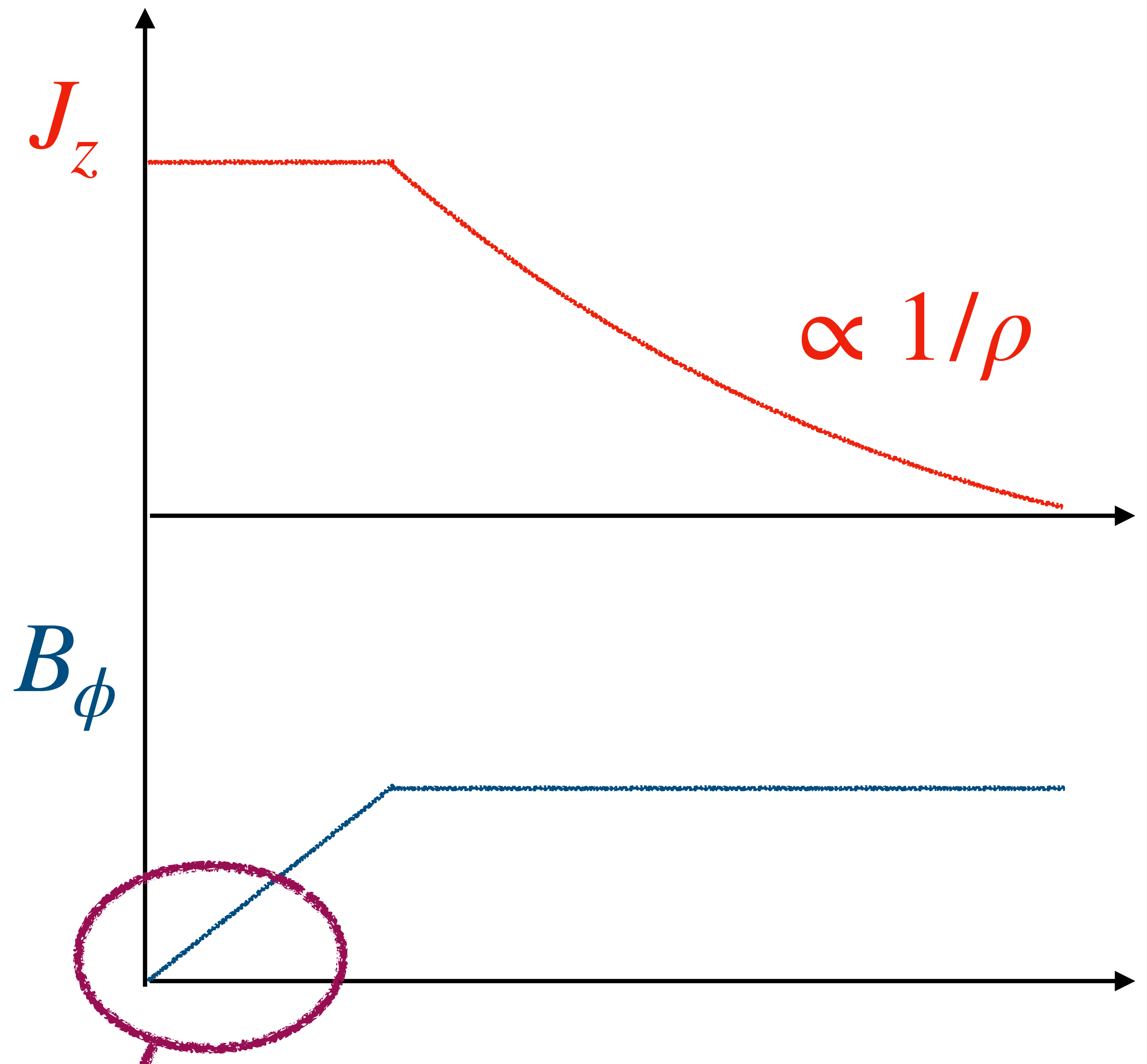
Confirmation by Monte-Carlo simulations

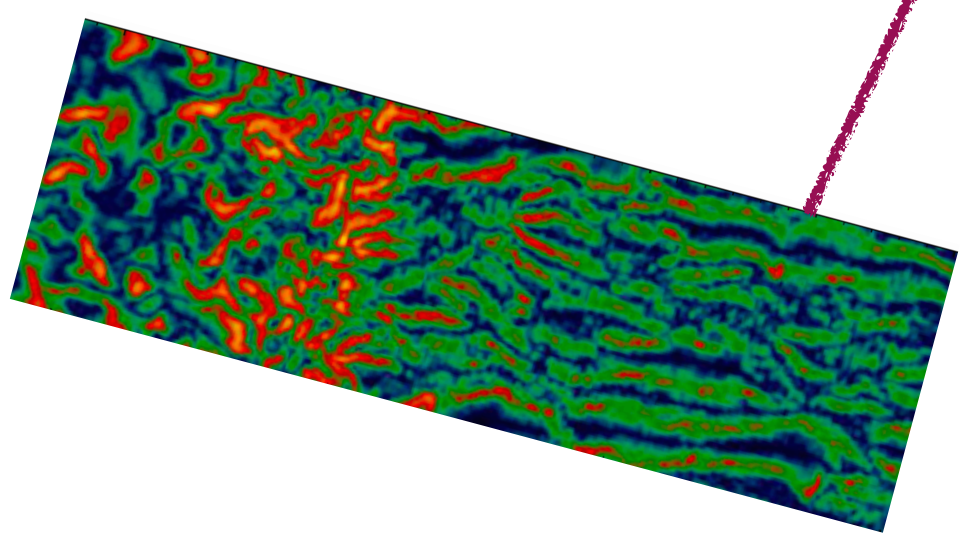
Monte Carlo simulations of particle accelerated at ultra-relativistic shock.
Assumes:

- 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





Field near axis is weak or quasi-parallel

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

Conclusions of Monte-Carlo Simulations

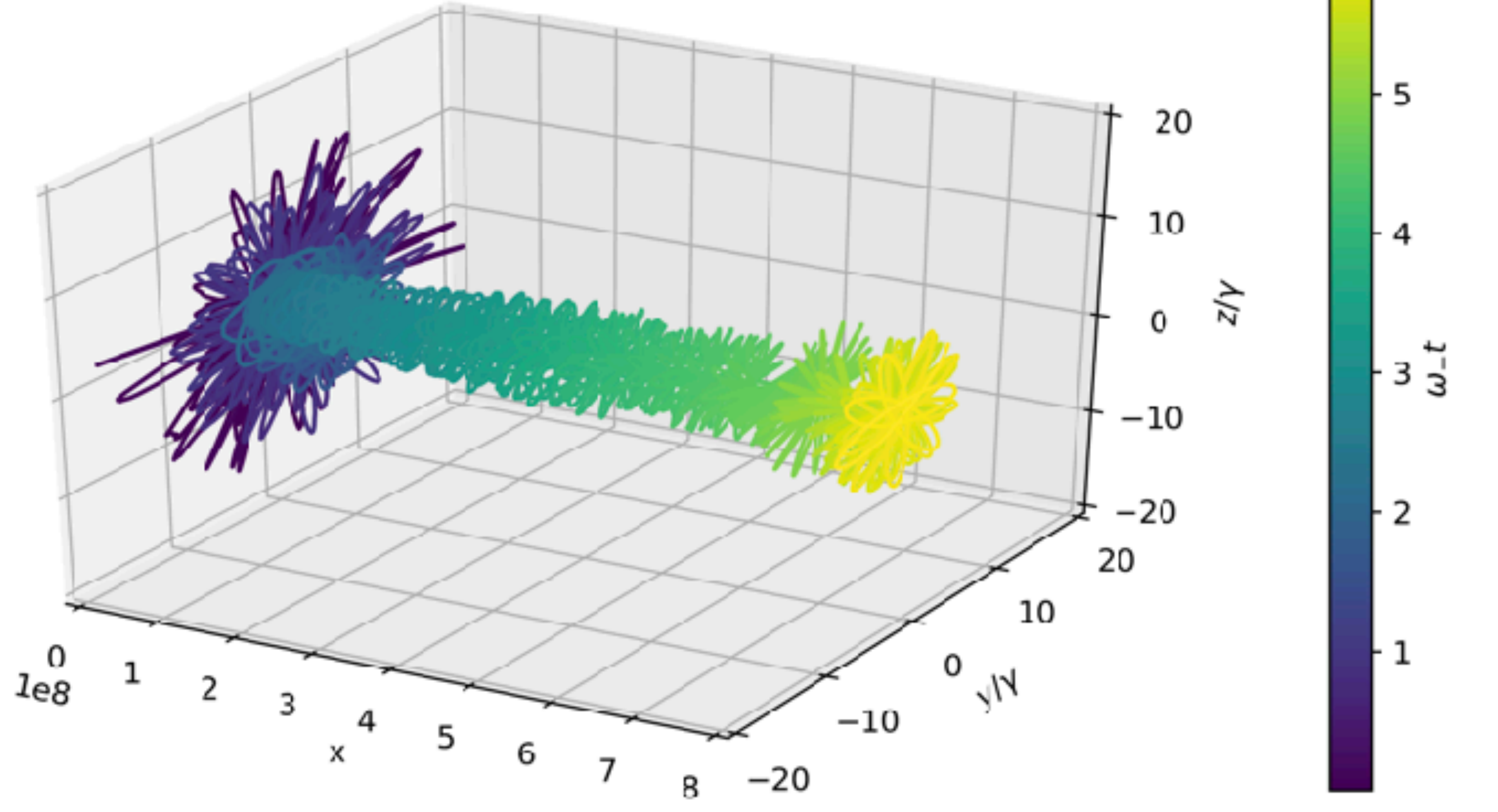
Because scattering is weak (an assumption), particles close to axis stay there.

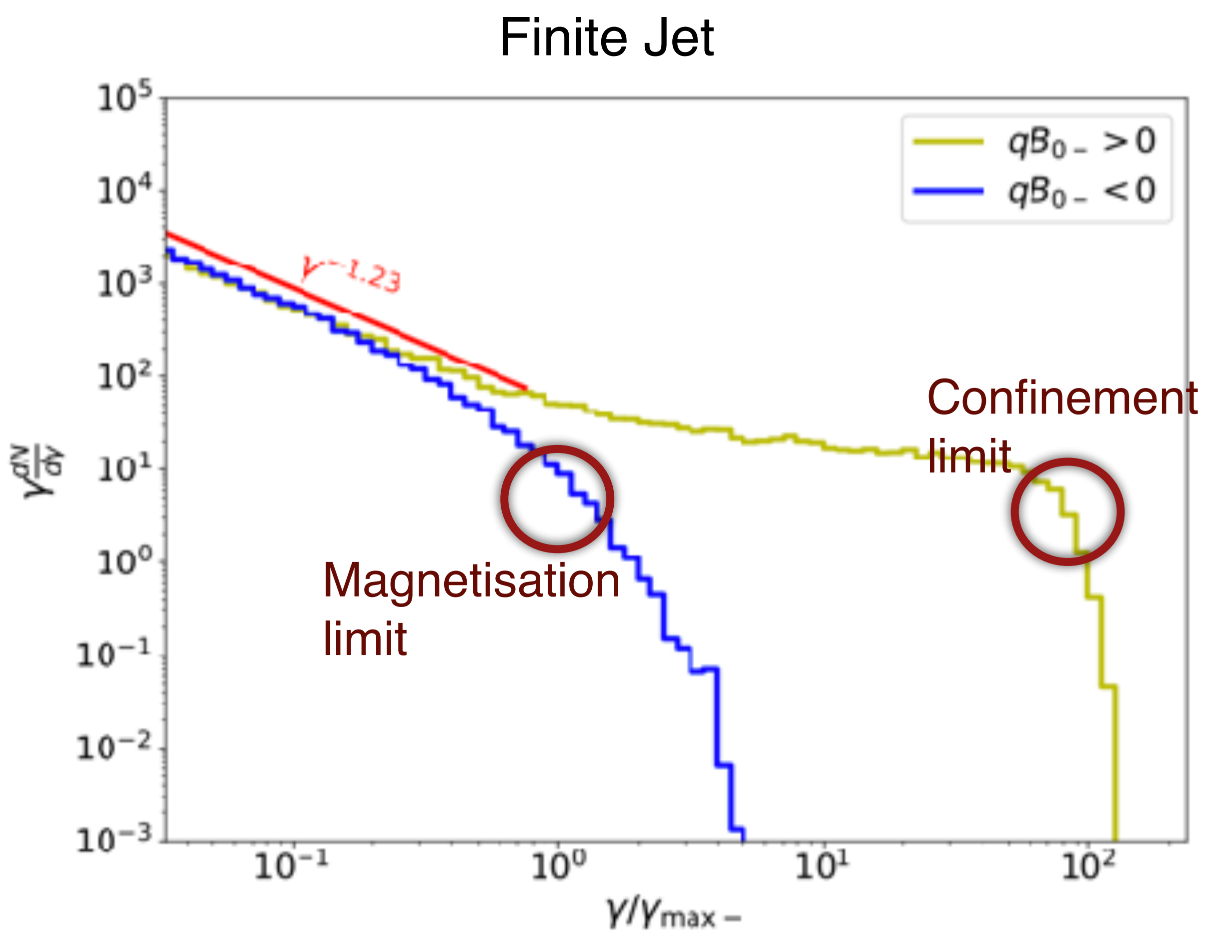
If drift →DS, particles drift downstream once magnetised ($t_{sc} > t_{gyro}$)

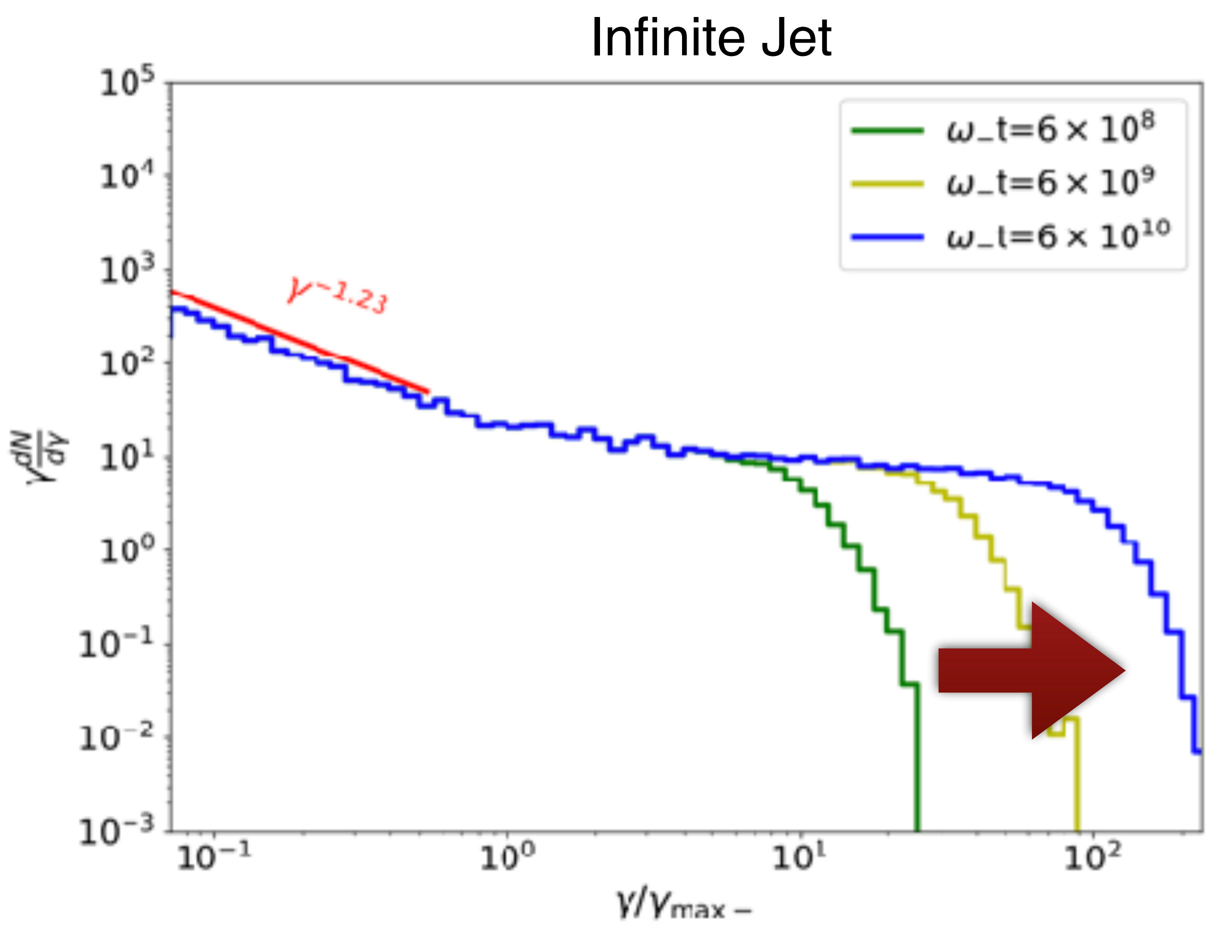
If drift → US, **particles accelerated to radiation reaction / confinement (i.e. Hillas) limit**

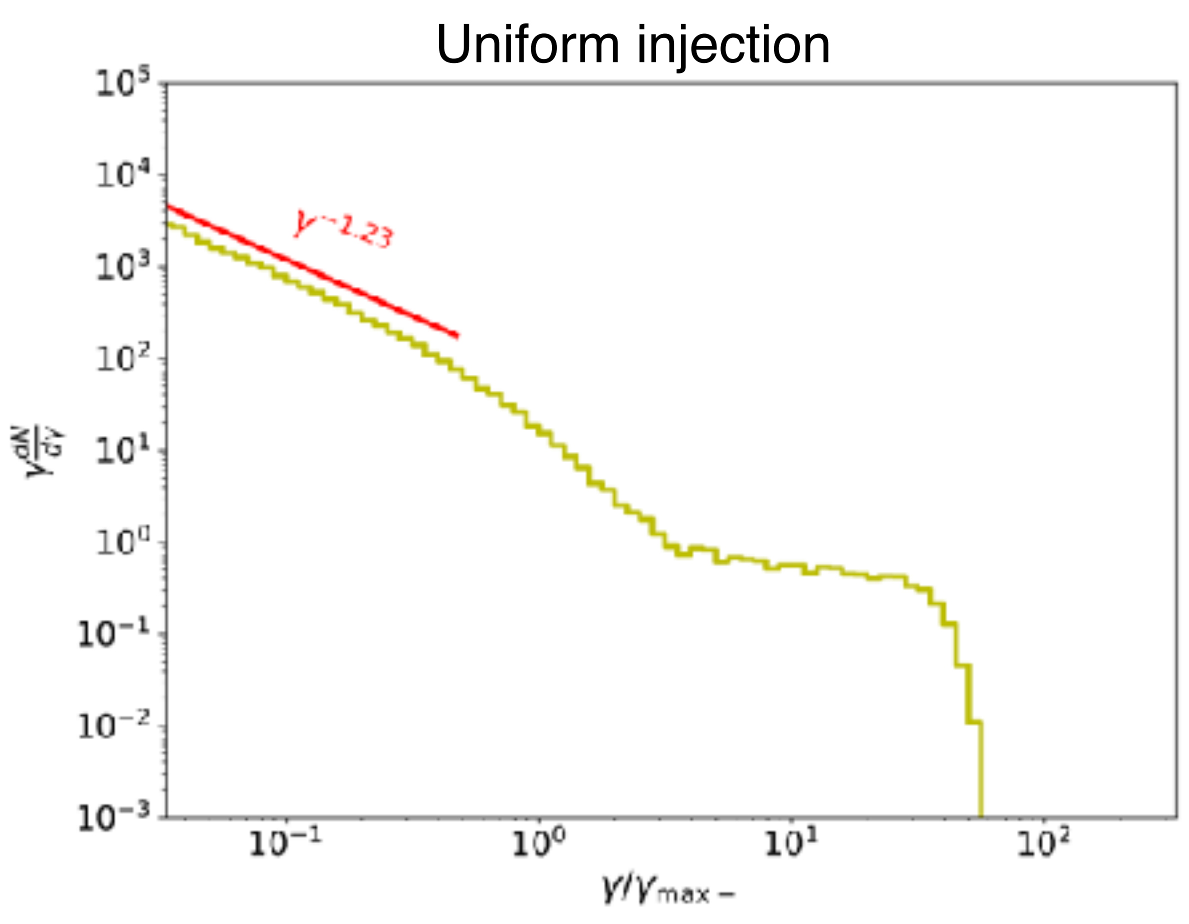
Ess. escape free (because scattering is weak), spectrum ~E^{-1}

Huang et al, 23









Conclusions

- Simulations confirm that weakly magnetised shocks admit Fermi acceleration
- Scattering on Weibel filaments is the key process, but by themselves might run into problems matching observations. Clearly environmental factors at play
- Scattering in upstream might be more important than previously thought (plasma instabilities?)
- A deeper understanding of the precursor physics/global field structure is required
- Next generation gamma-ray observatories (CTA) guarantee progress on GRB front
- Origin of UHECRs still an open question, but relativistic shocks are still a candidate
- **Nature will always find ways to tap into the acceleration potential of relativistic shocks**

THANK YOU