Particle Acceleration at Ultra-Relativistic Shocks

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The Variable Multi-Messenger Sky
Polish-German WE-Heraeus-Seminar
07-10 November 2022

Further details in:
Kirk & Reville, ApJL (2010)
Reville & Bell, MNRAS (2014)
Huang, Kirk, Giacinti, Reville (2022)
Kirk, Reville, Huang (submitted)
Huang, Reville, Kirk, Giacinti (in prep.)

Why would we want to study particle acceleration at ultra-relativistic shocks?

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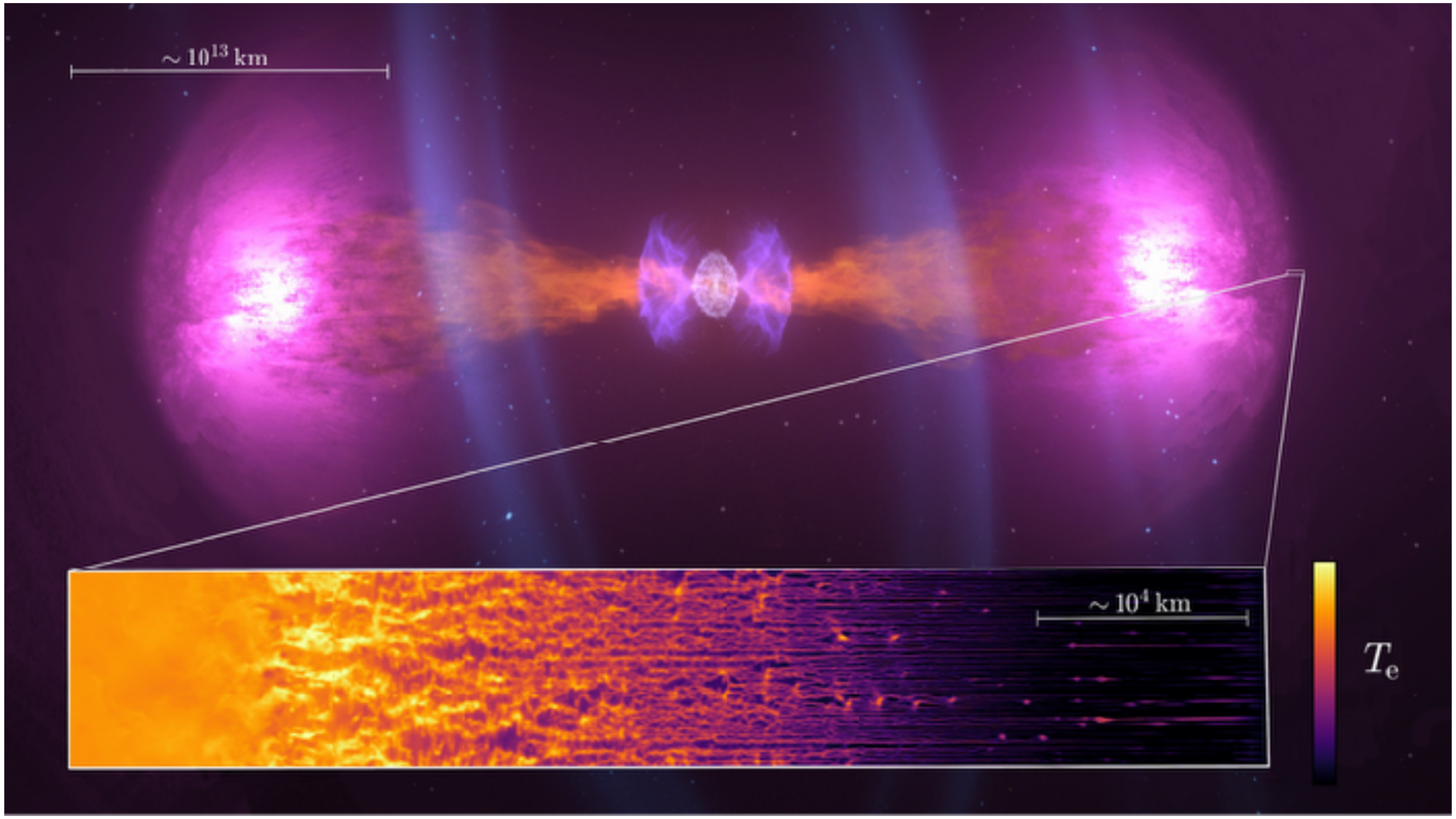
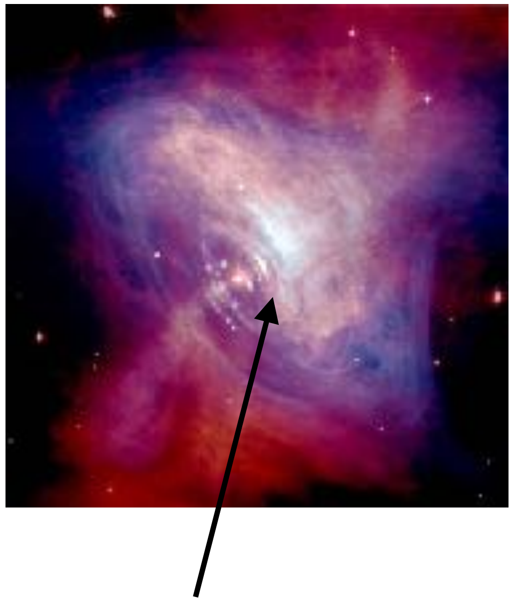
Lessons from kinetic simulations



Credit: Arno Vanthieghem

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

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

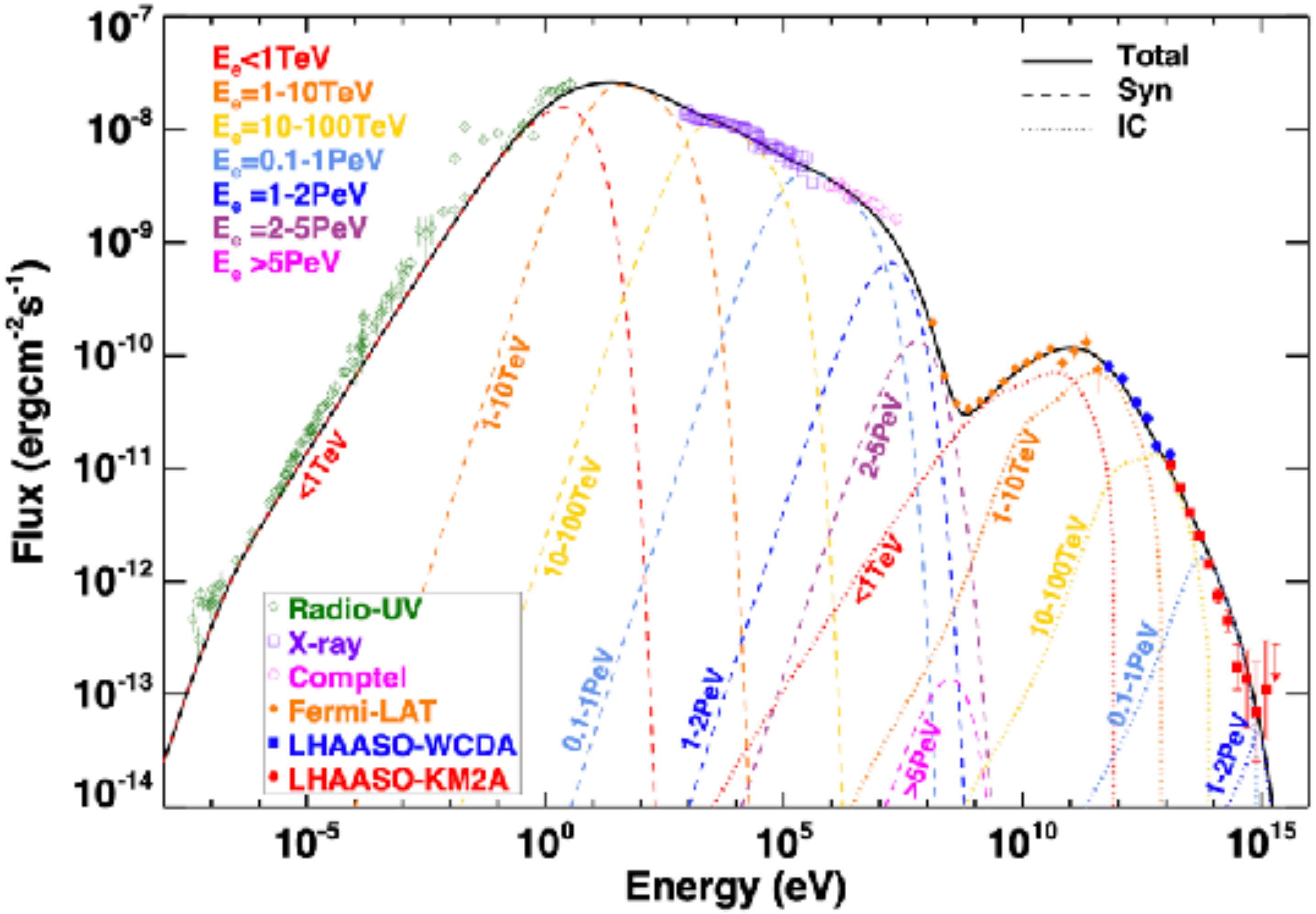
$$\Gamma_{\rm sh} \sim 10^3 - 10^6$$

Magnetisation

$$\left(\sigma = \frac{\text{Poynting Flux}}{\text{Enthalpy Flux}}\right)$$

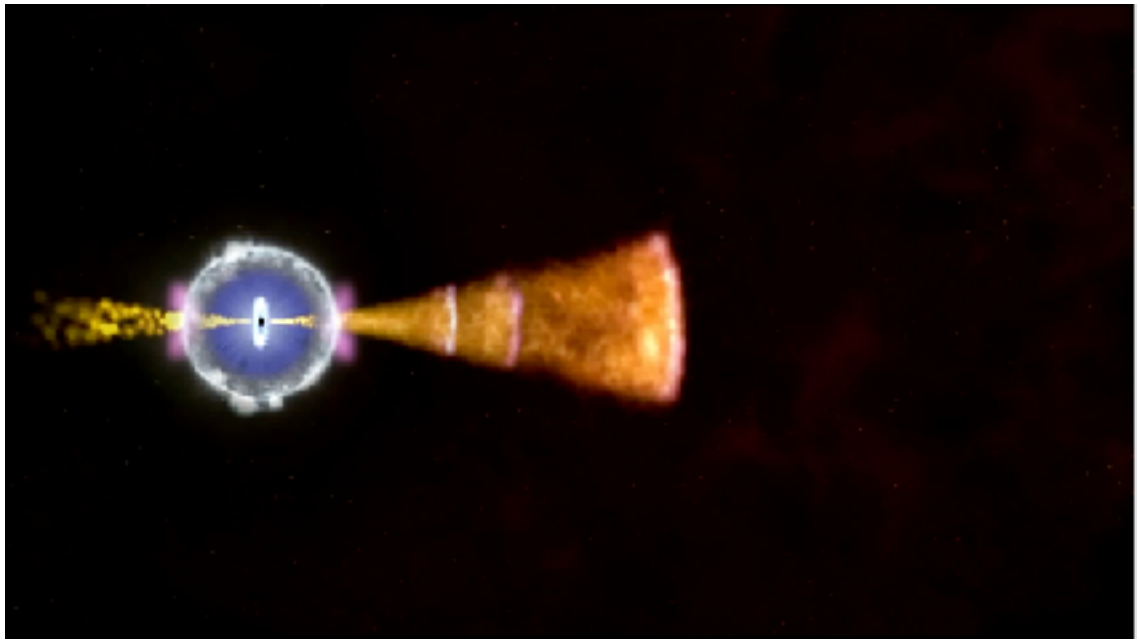
unknown but probably large

LHAASO collaboration 21



PeV photons = electrons > PeV
An almost perfect accelerator!!

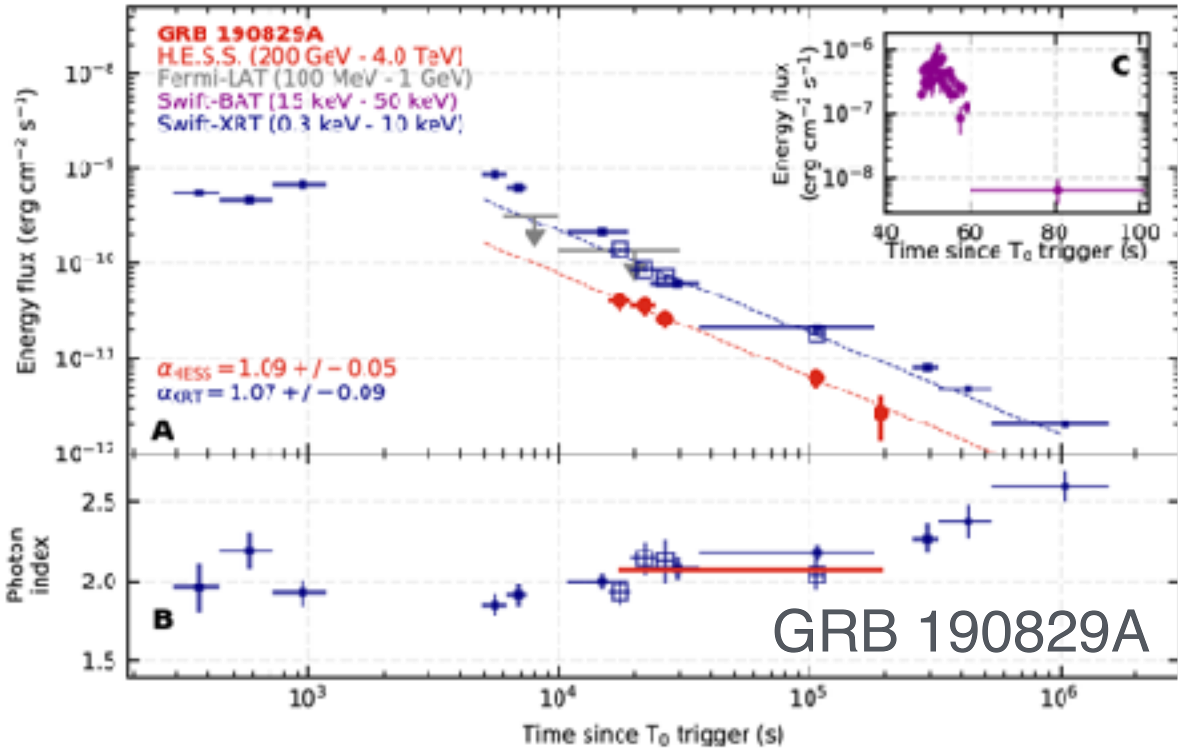
Observational Constraints - GRBs

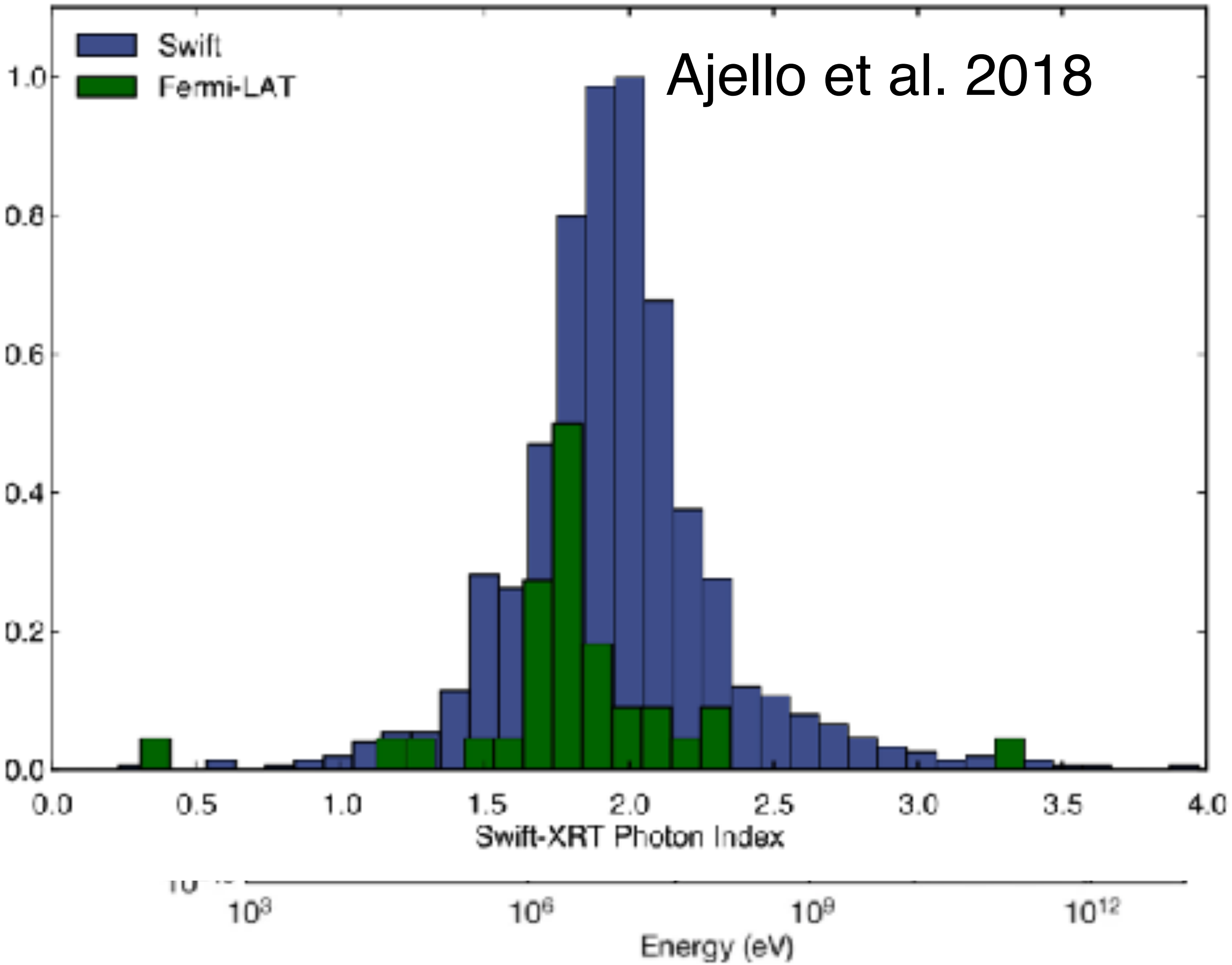


5 GRB afterglows detected to date in VHE domain
(possibly 1 prompt by LHAASO)

Afterglow shock "well defined"

HESS collab. (2020)

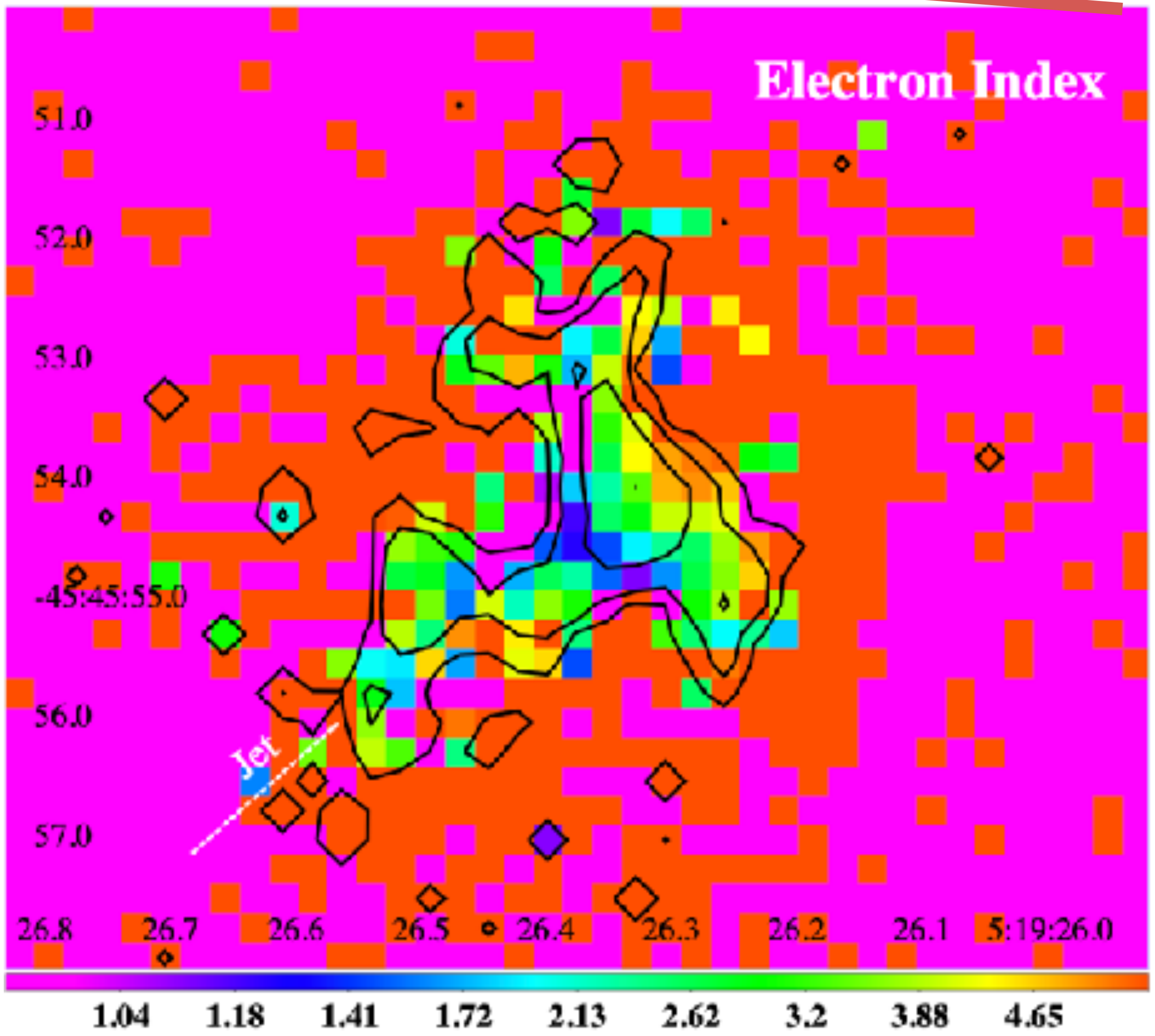




The requirement of >TeV electrons brings questions on maximum energy
For weakly magnetised shocks to focus

Observational Constraints - AGN

Pictor A
(Credit: Chandra)



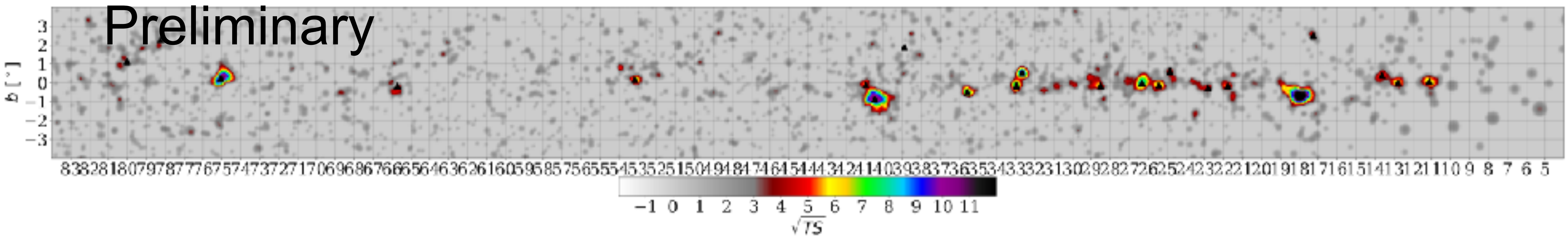
Thimmappa et al. ‘22

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

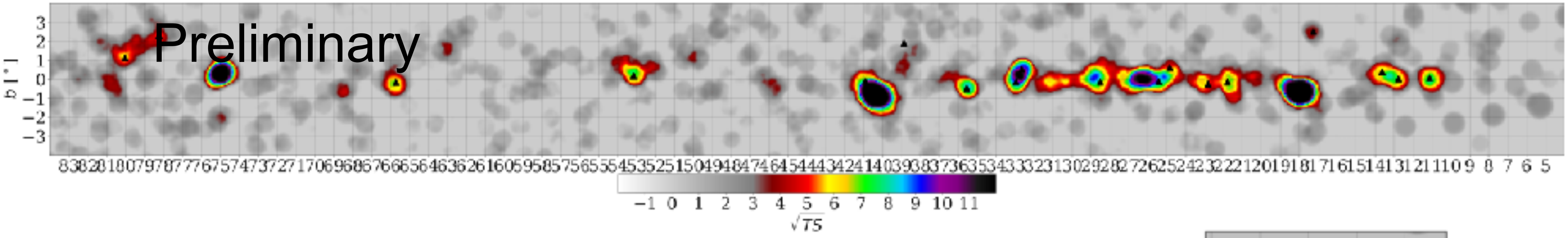
X-ray synchrotron - electron energies of 100 TeV or more.
B fields $B \sim 0.1 - 1$ **mG -> Shock magnetisation** $\sigma \sim 10^{-3} - 10^{-1}$

Pushing to the highest energies (>100 TeV)

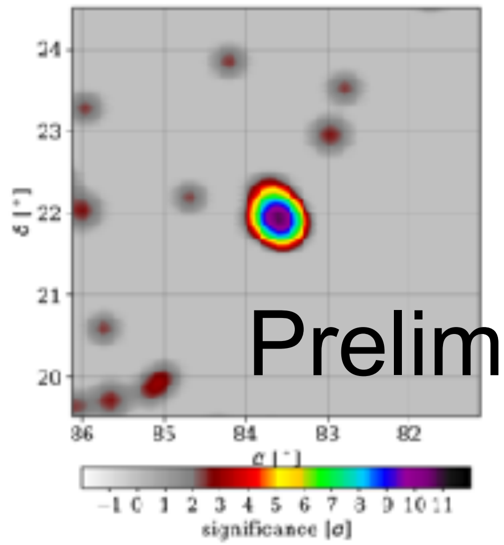
Point Source Analysis



0.5° Extended Source Analysis



- Pass 5 - 18 sources are identified above 100 TeV
  (compared to 3 in Pass 4)
- Most high energy sources appear to be extended, but Crab is point-like



Preliminary

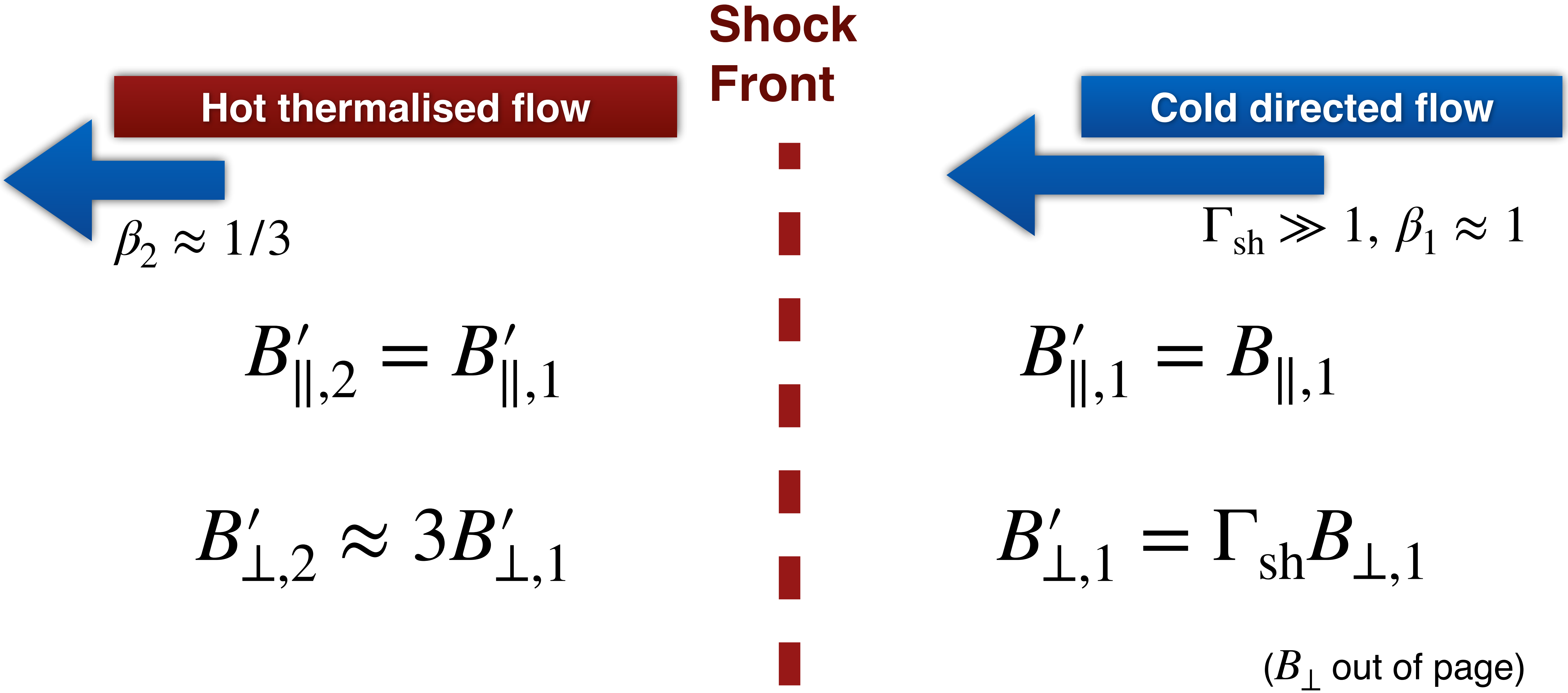
Crab
>100 TeV

Taken from Jordan Goodman’s presentation at Gamma 22

Key Questions

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

Ultra-relativistic (ideal MHD) shocks



Shock Front

Hot thermalised flow

$\beta_2 \approx 1/3$

Cold directed flow

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

$$B'_{\|,2} = B'_{\|,1}$$

$$B'_{\perp,2} \approx 3B'_{\perp,1}$$

$$B'_{\|,1} = B_{\|,1}$$

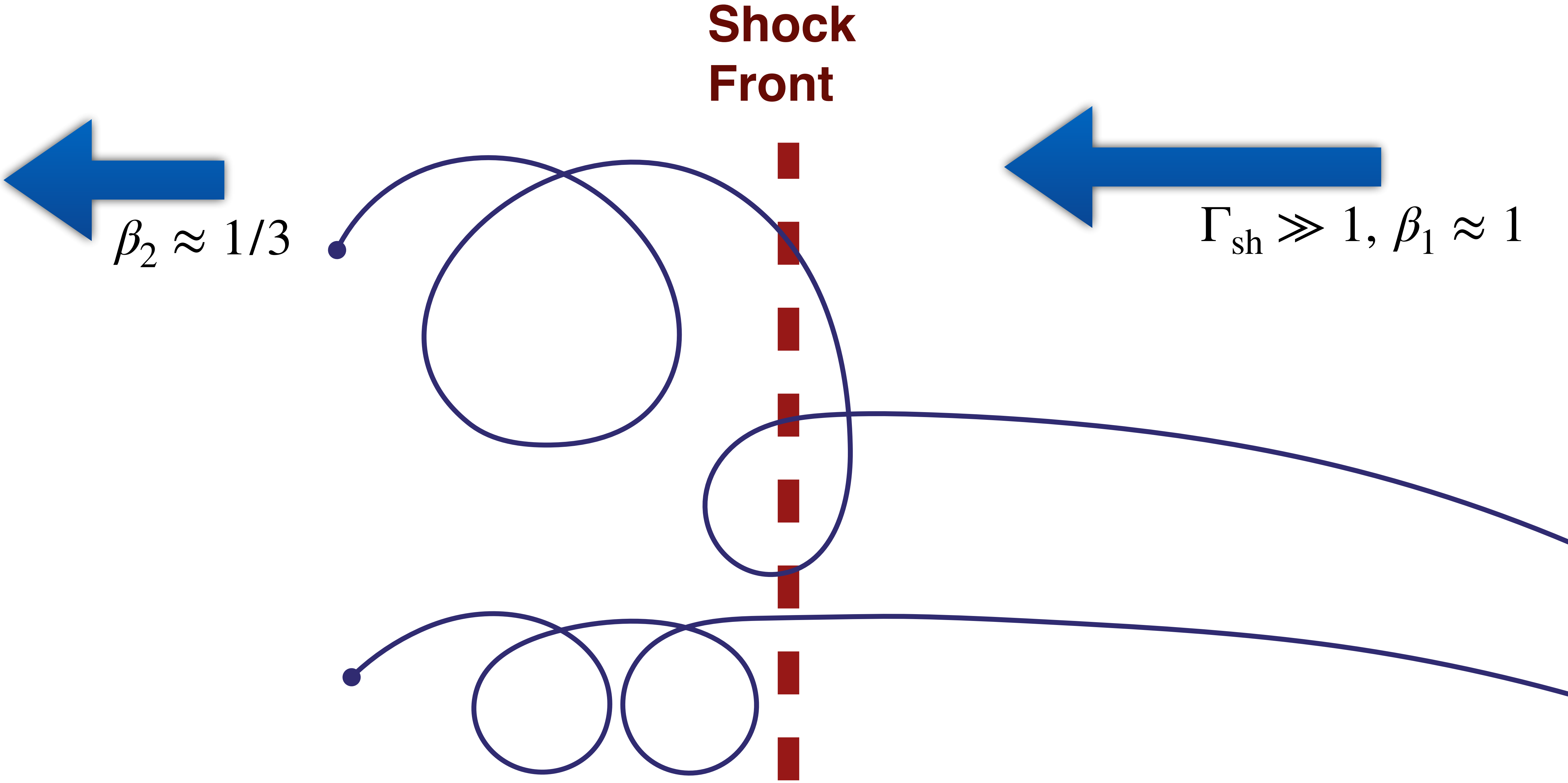
$$B'_{\perp,1} = \Gamma_{\rm sh} B_{\perp,1}$$

($B_\perp$ out of page)

Unless $B_\perp / B_\| < \Gamma_{\rm sh}^{-1}$ in far upstream,

In shock frame avg magnetic field is approx. in plane of shock

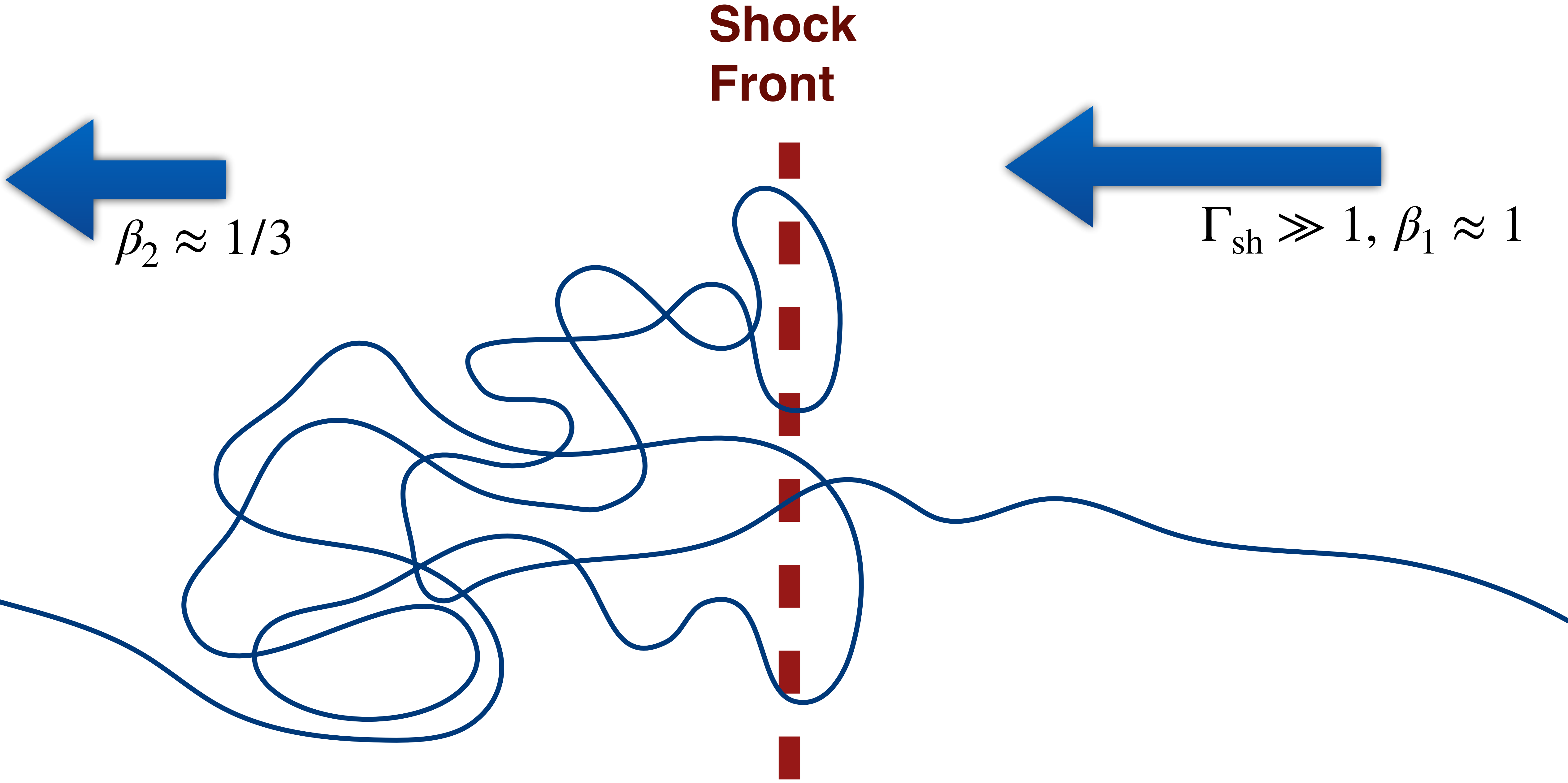
In the absence of scattering.....



Particle is limited to ≤ 3 crossings (Begelman & Kirk ’90)

We need an effective scattering/thermalisation process.

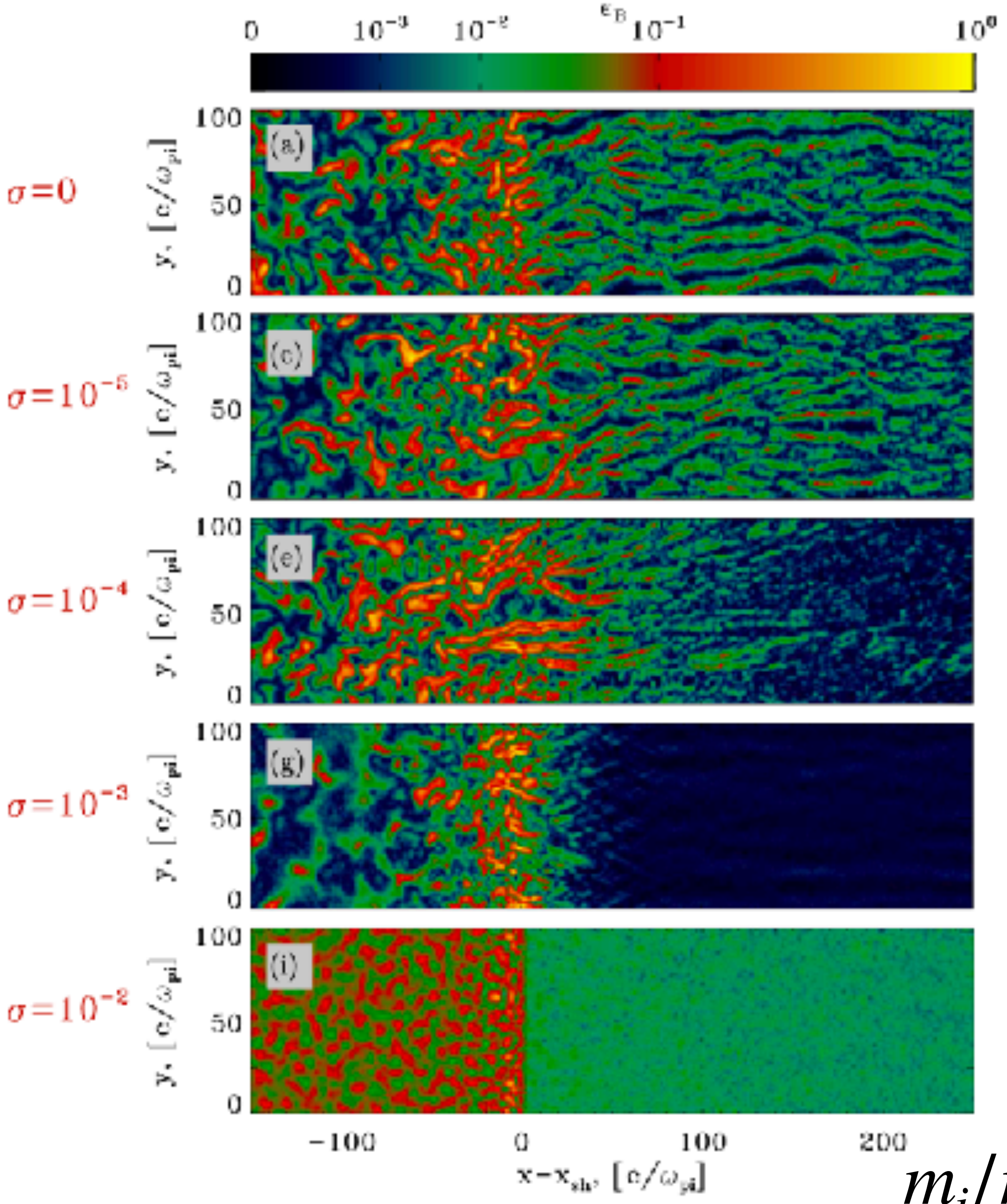
What does scattering do?



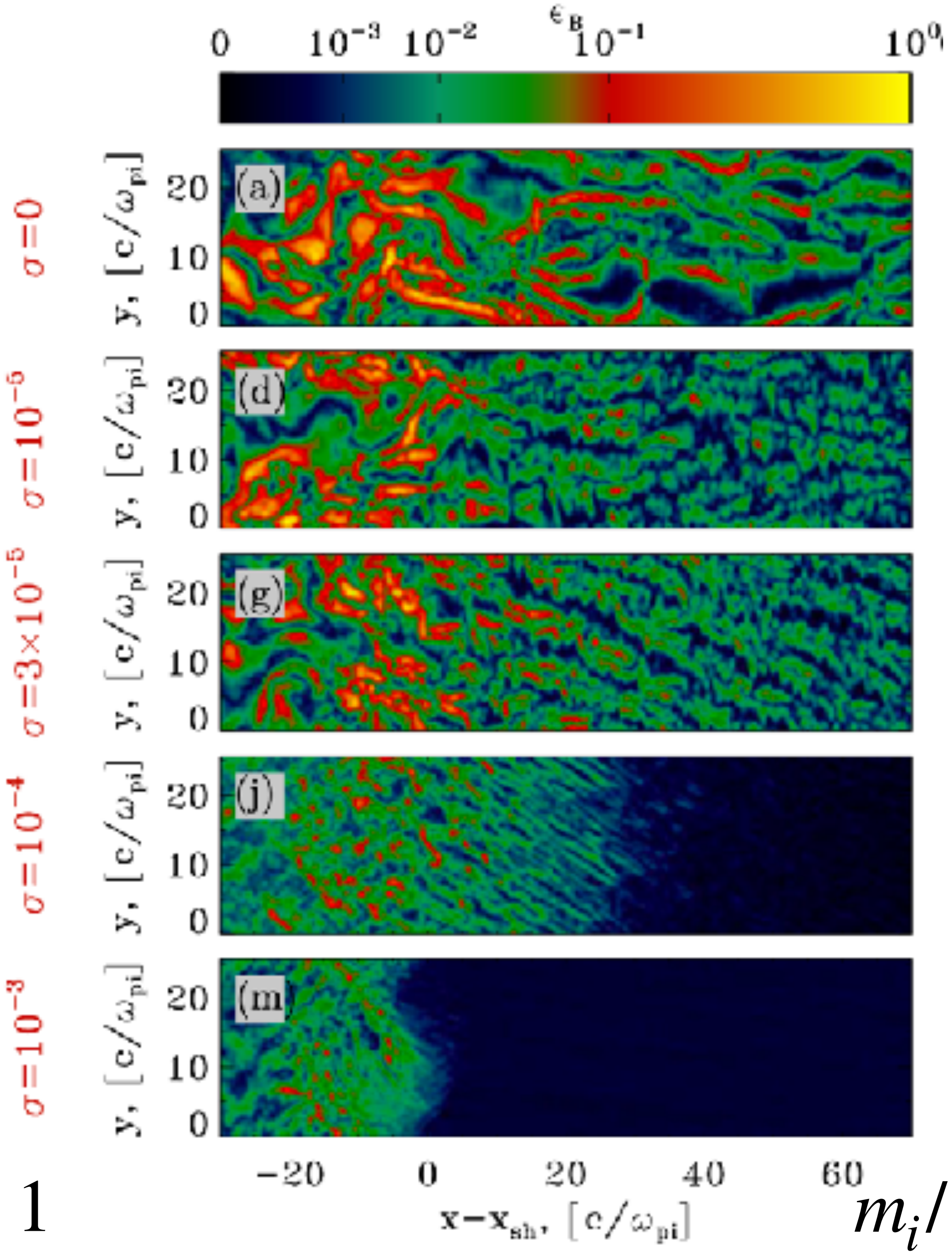
So how to scatter?

Insights from PIC simulations

2D simulations by Sironi, Spitkovsky & Arons 13



$m_i/m_e = 1$

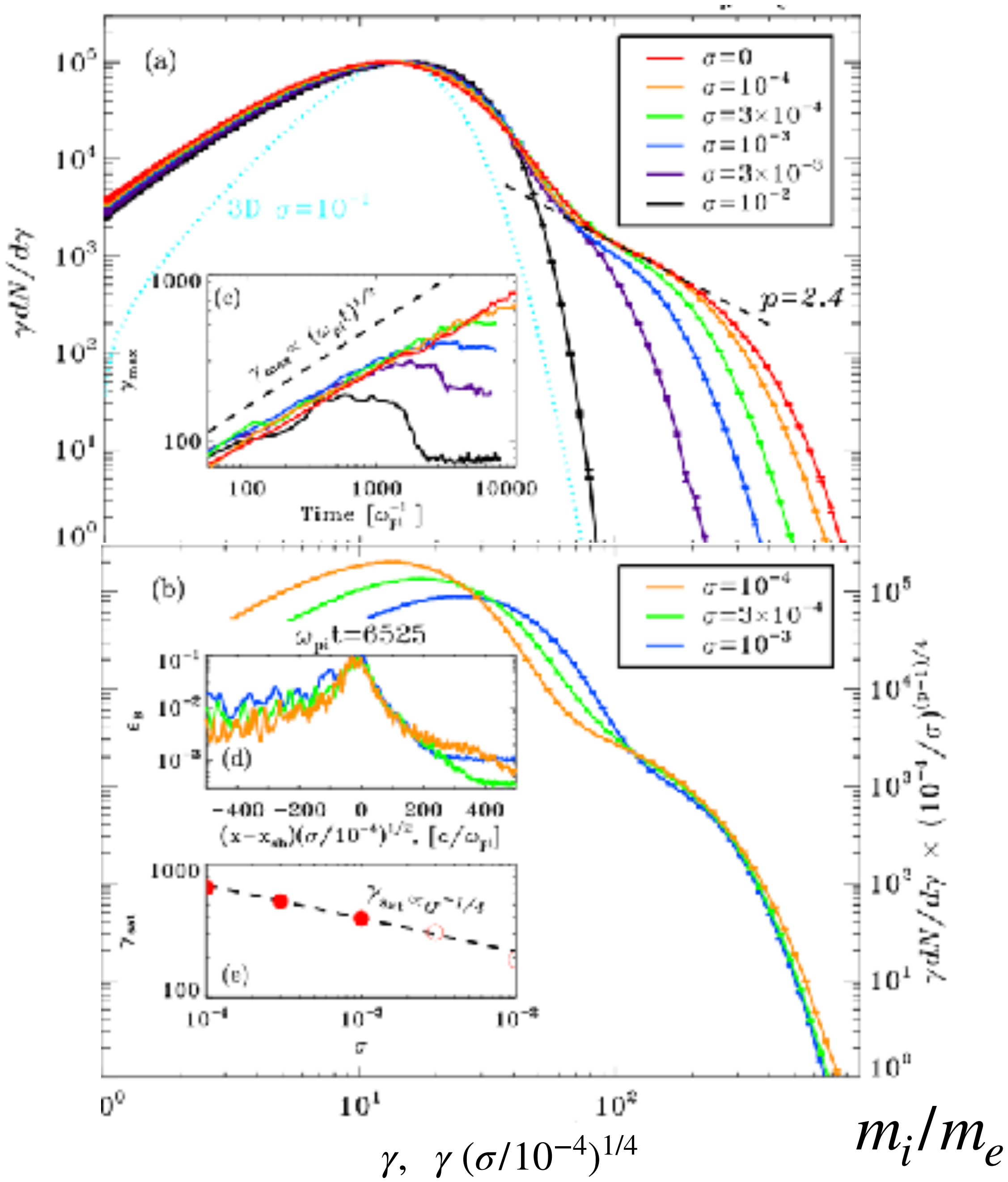


$m_i/m_e = 25$

Conclusion: only weakly magnetised shocks are “turbulent”

Insights from PIC simulations

2D simulations by Sironi, Spitkovsky & Arons 13



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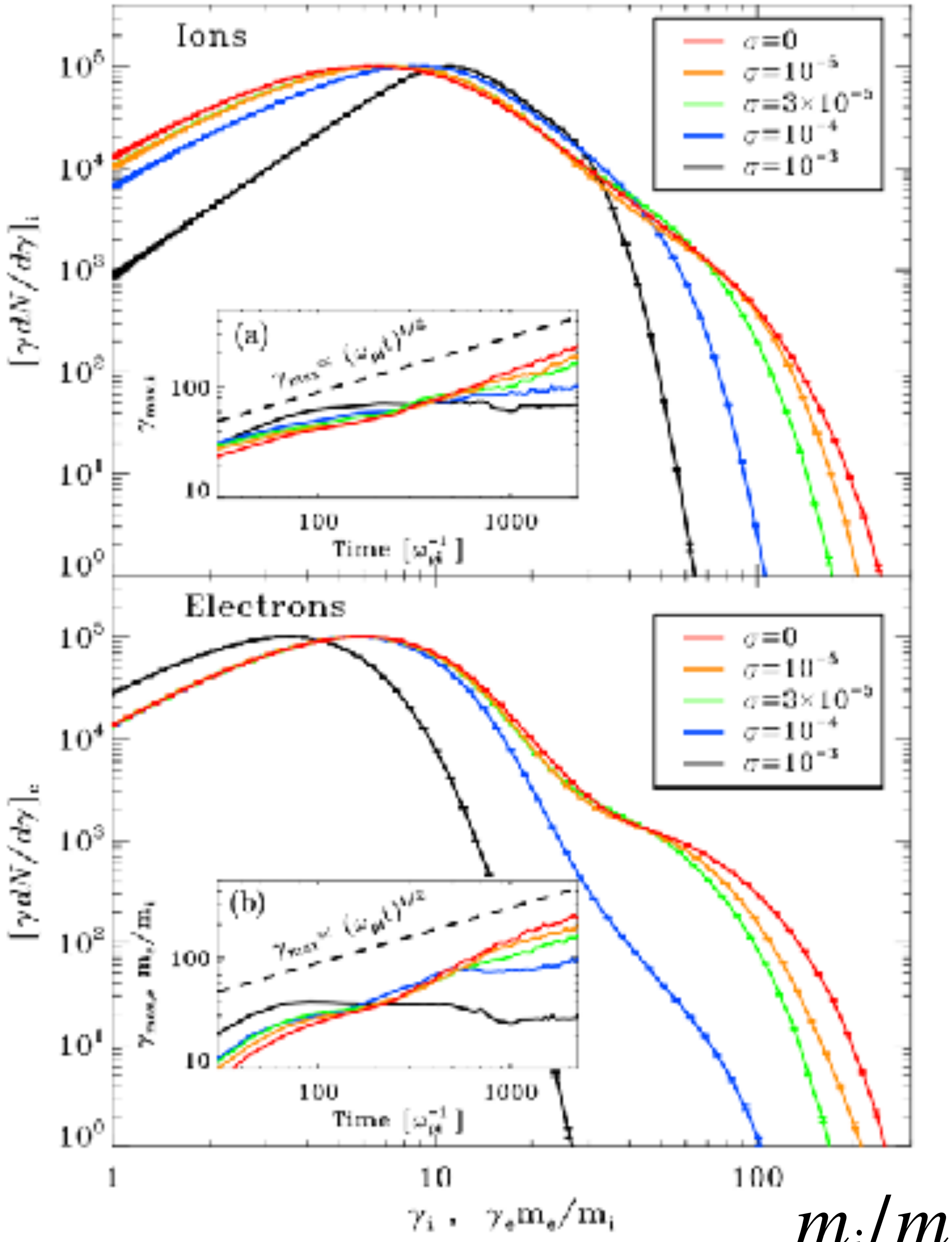
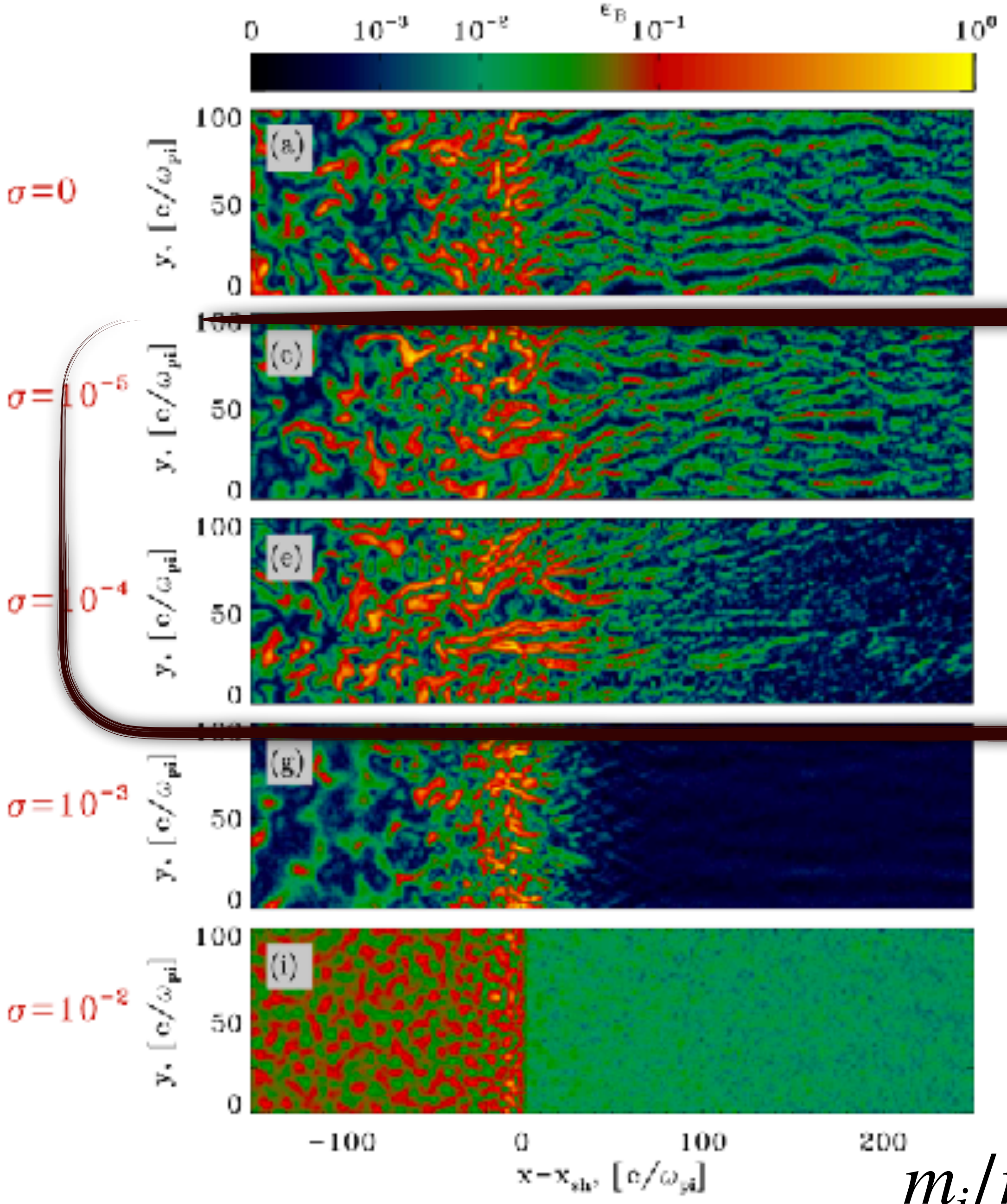


$m_i/m_e = 25$

Bulk of particles are thermalised, but for $\sigma < 10^{-3.5}$ (approx) non-thermal spectra appears to be an inevitable outcome.

Insights from PIC simulations

2D simulations by Sironi, Spitkovsky & Arons 13



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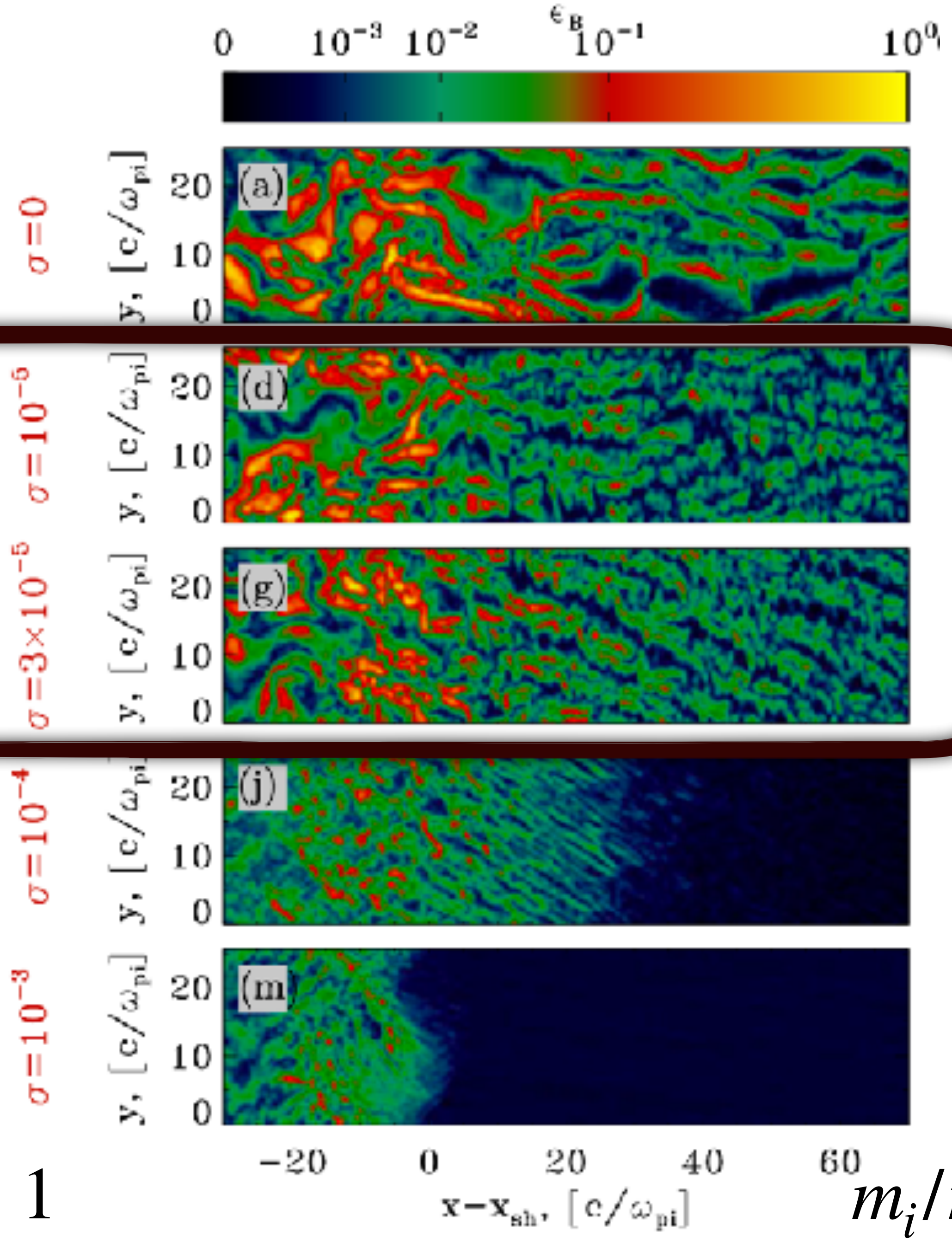
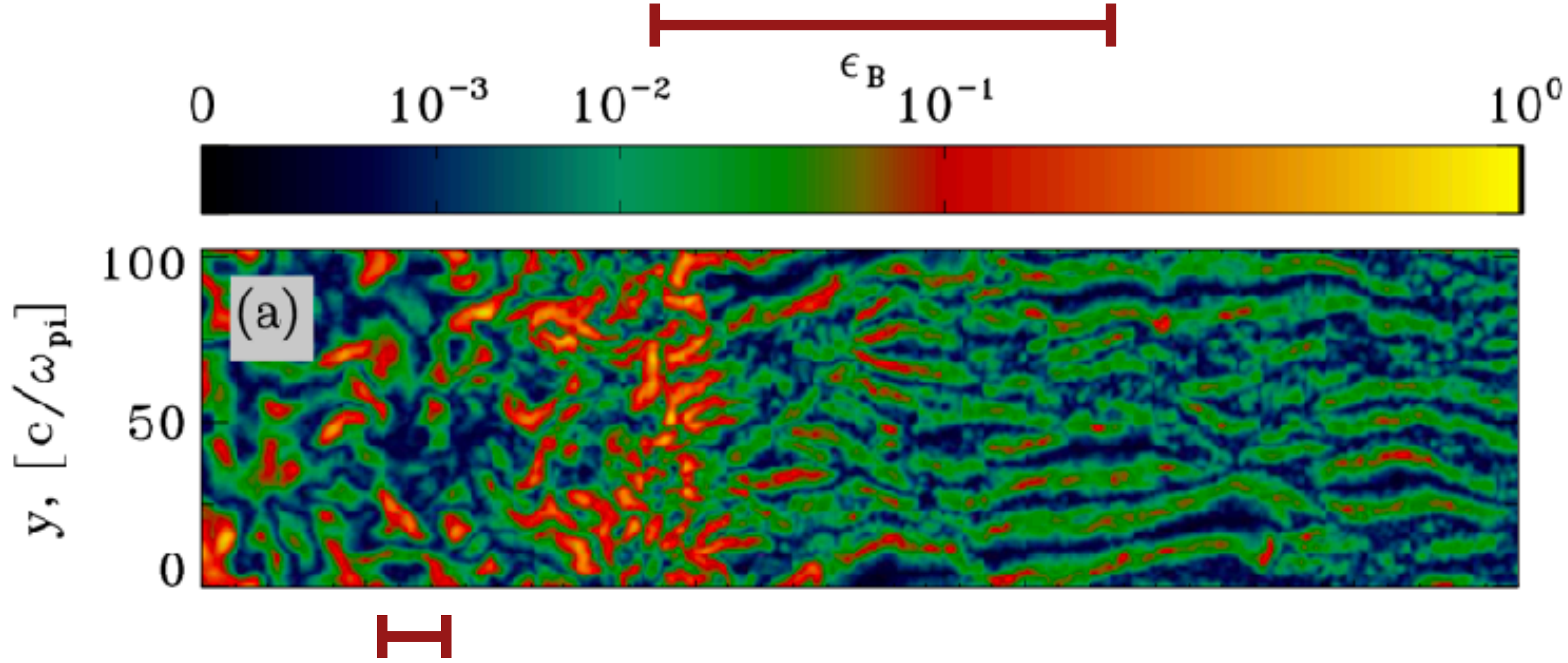


$m_i/m_e = 25$

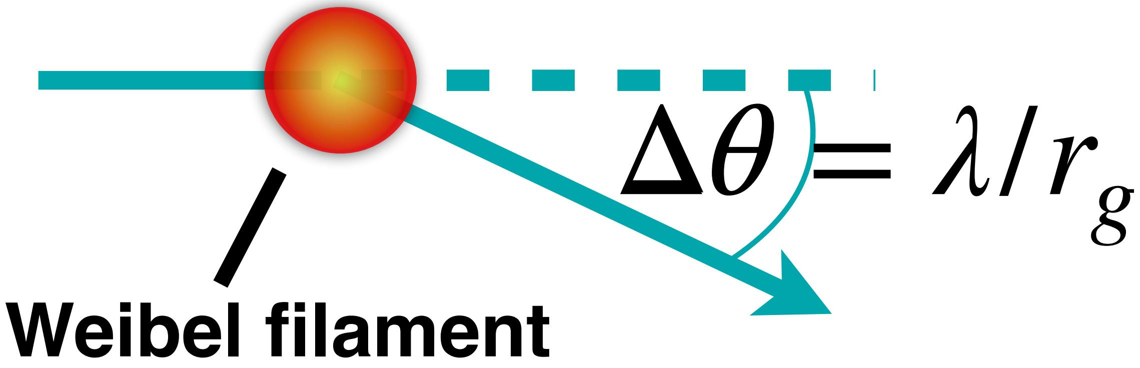
Focus for now on “weakly magnetised” shocks $0 < \sigma \ll 10^{-3}$

Scattering on Weibel filaments

Characteristic strength $\epsilon_B \sim 0.01 - 0.1$



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



$$\Delta\theta = \lambda / r_g$$

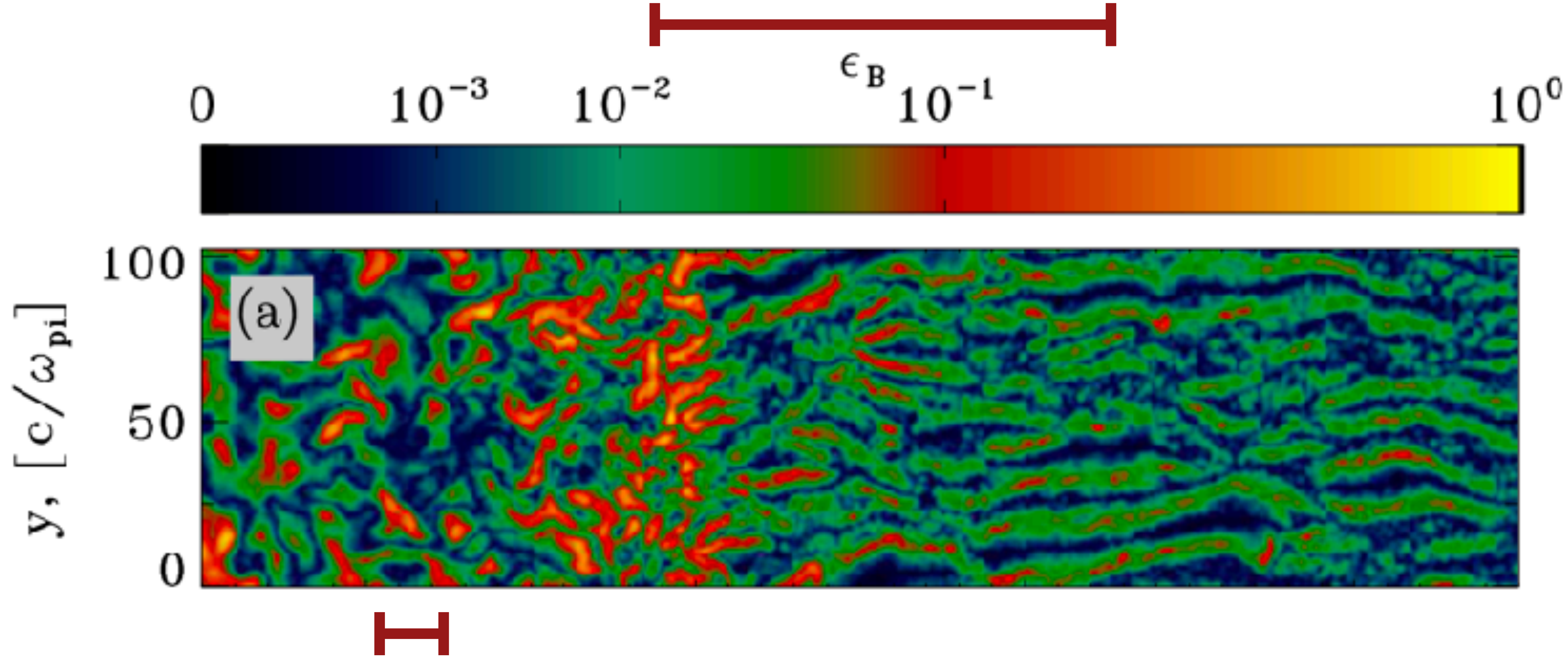
Weibel filament

Electron strength parameter:

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

Scattering on Weibel filaments

Characteristic strength $\epsilon_B \sim 0.01 - 0.1$



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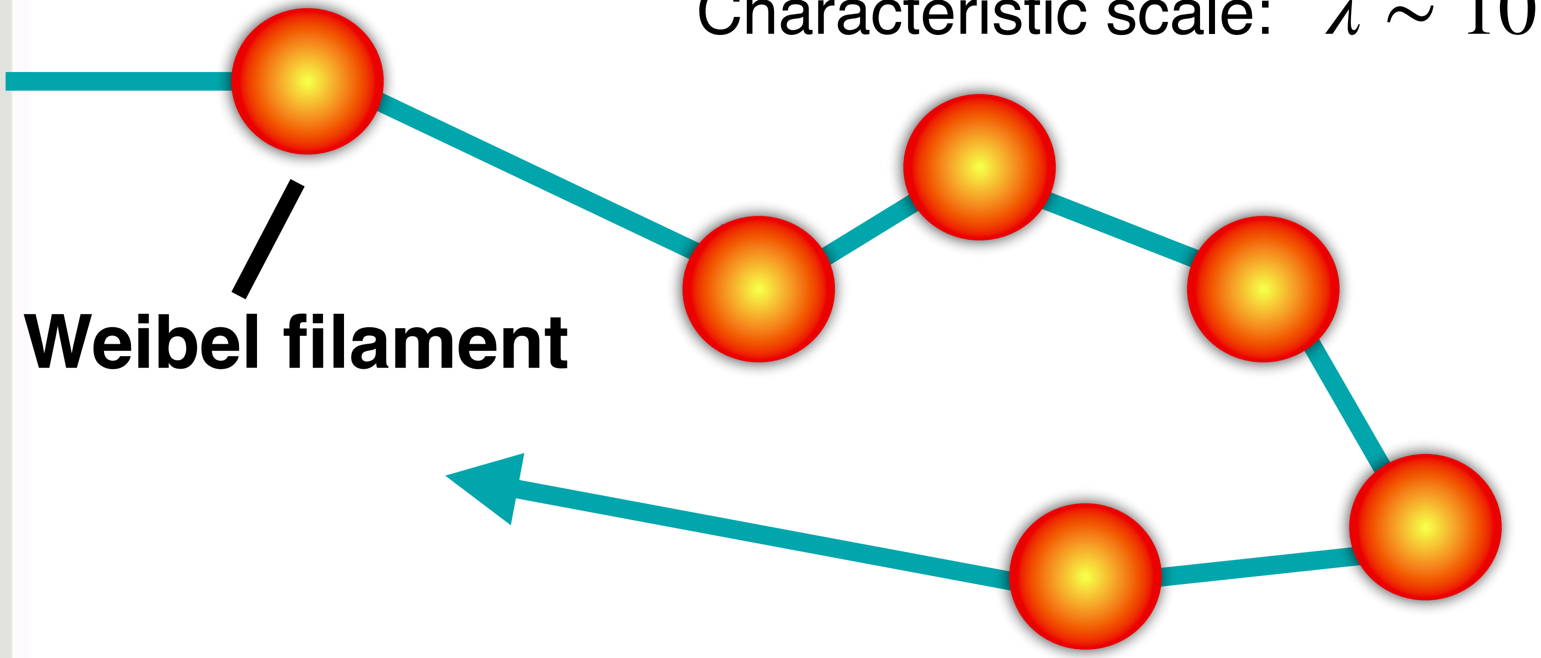


Particle diffuses in angle

$$D_\theta = \left\langle \frac{\Delta\theta^2}{2\Delta t} \right\rangle \approx \frac{a^2}{\bar{\gamma}^2}\frac{c}{\langle\lambda\rangle}$$

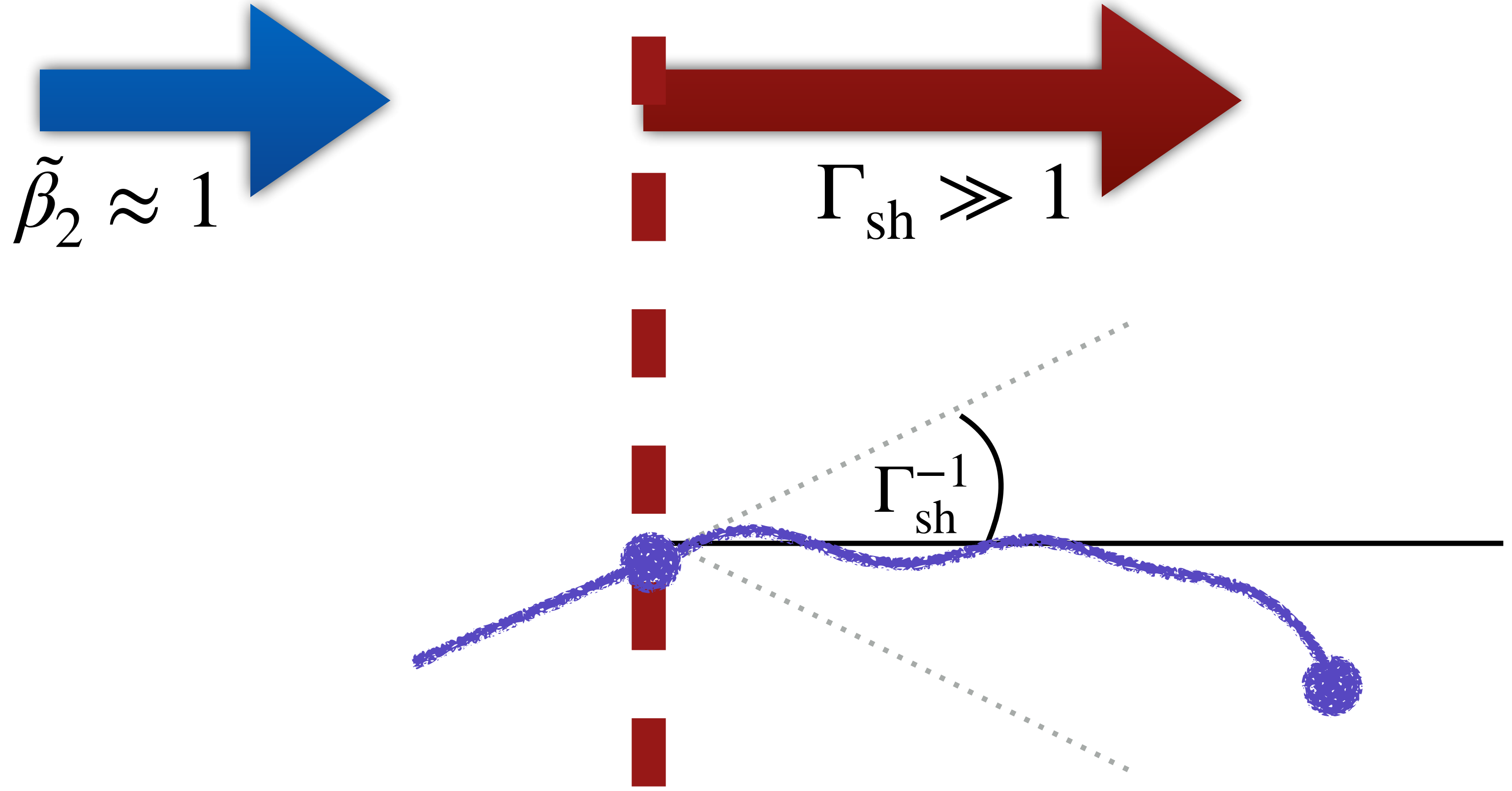
Note isotropisation time

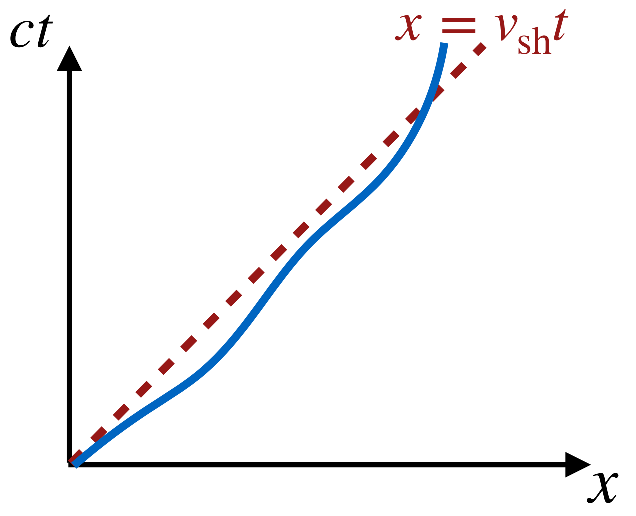
$$t_{\rm sc} = \nu_{\rm sc}^{-1} \approx D_\theta^{-1} \propto \bar{\gamma}^2$$

Particle acceleration at Ultra-rel. shocks

UPSTREAM
REST FRAME

**Shock
Front**





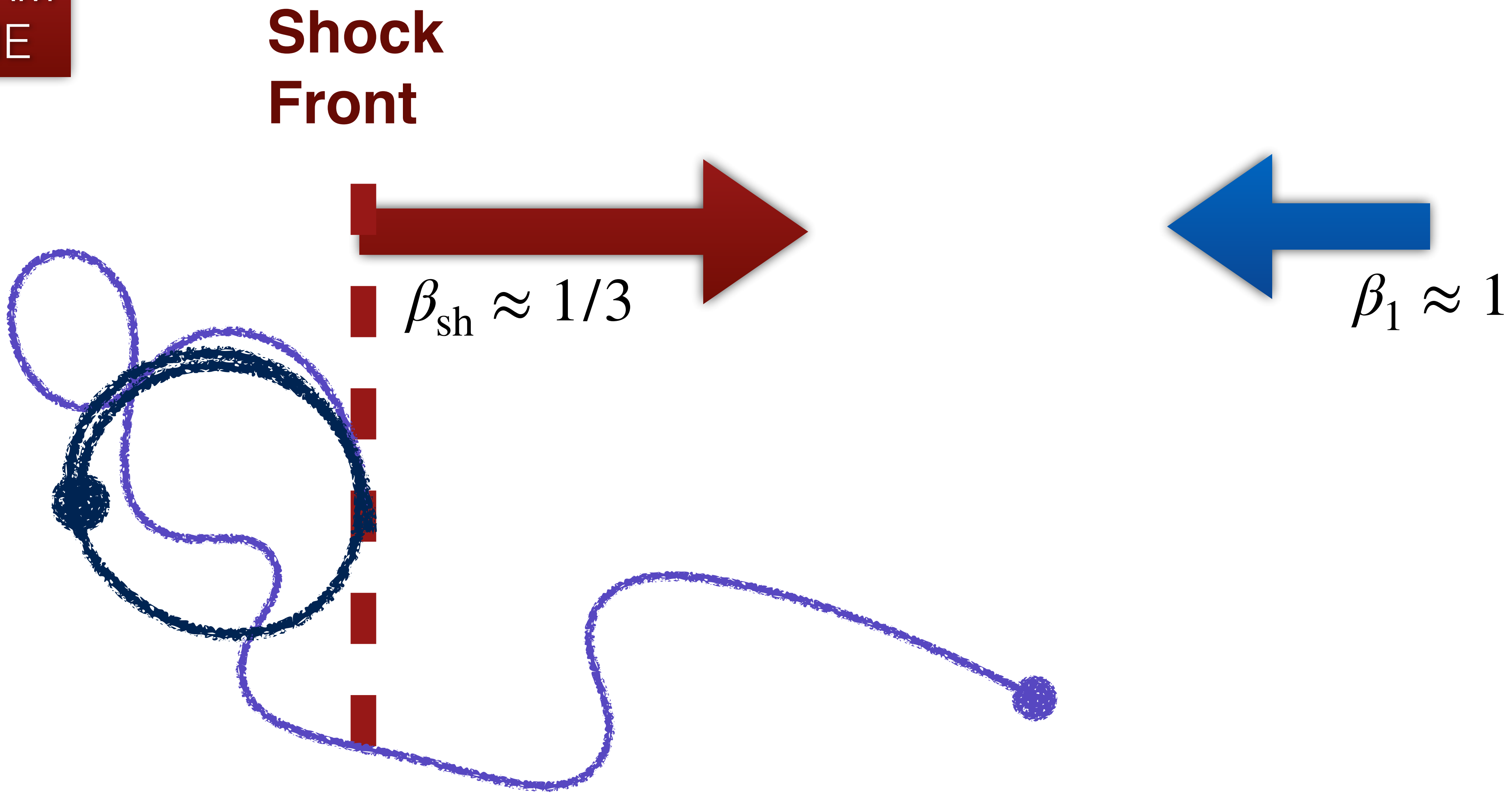
Any particle overtaking shock has $\mu > \beta_{\rm sh}\ (\theta < \Gamma_{\rm sh}^{-1})$

Seen from upstream frame, particle doesn't get far

The larger $\Gamma_{\rm sh}$, the easier to scatter out of loss cone

Particle acceleration at Ultra-rel. shocks

DOWNSTREAM
REST FRAME



**Shock
Front**

$\beta_{\rm sh} \approx 1/3$

$\beta_1 \approx 1$

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

If $\nu_{\rm sc} < \Omega_g$ -> Game Over??

If $\nu_{\rm sc} > \Omega_g$ -> Particle can diffuse back to shock

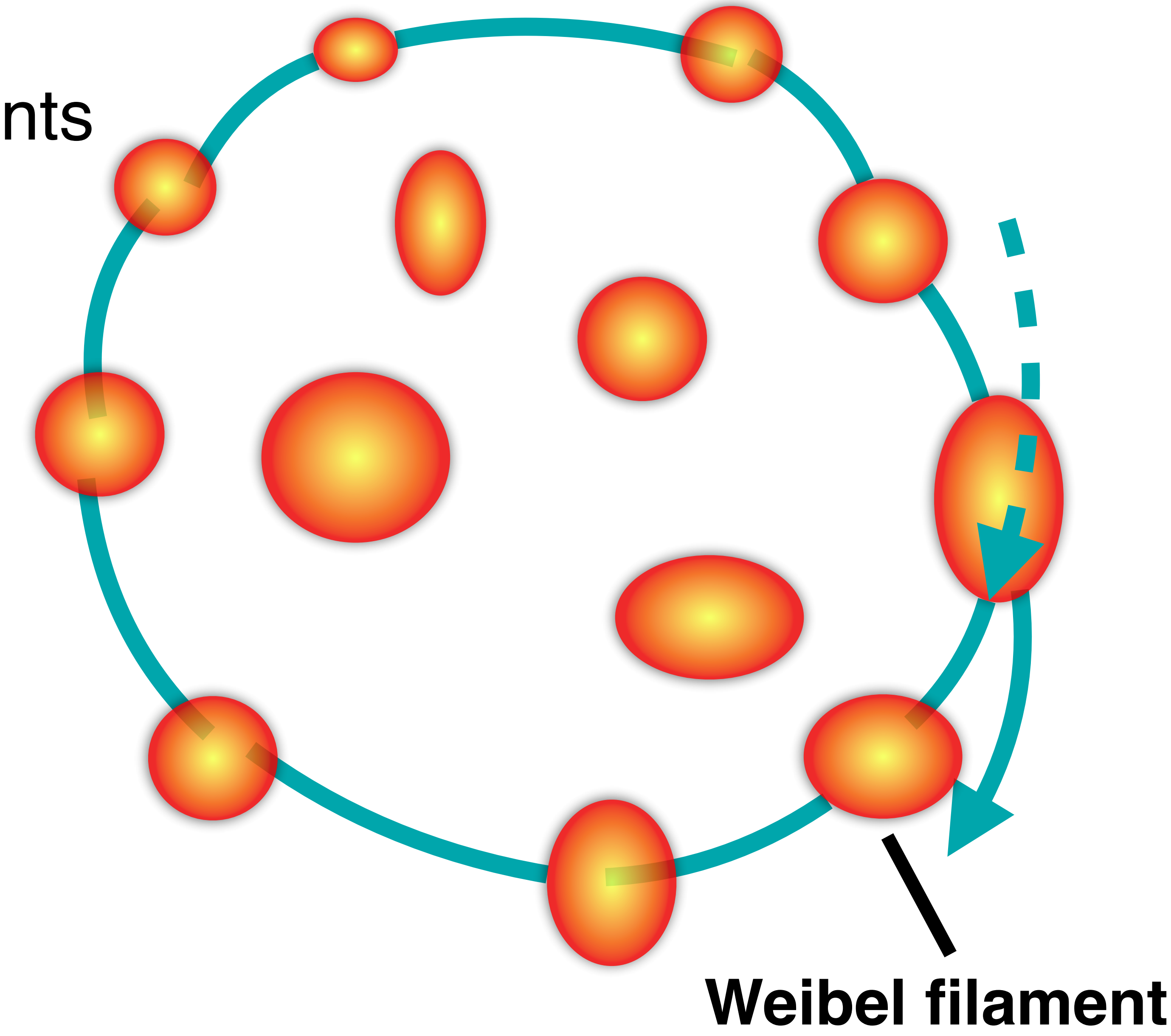
Maximum Electron Energy

But scattering on Weibel filaments

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

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

(Measured in average field)

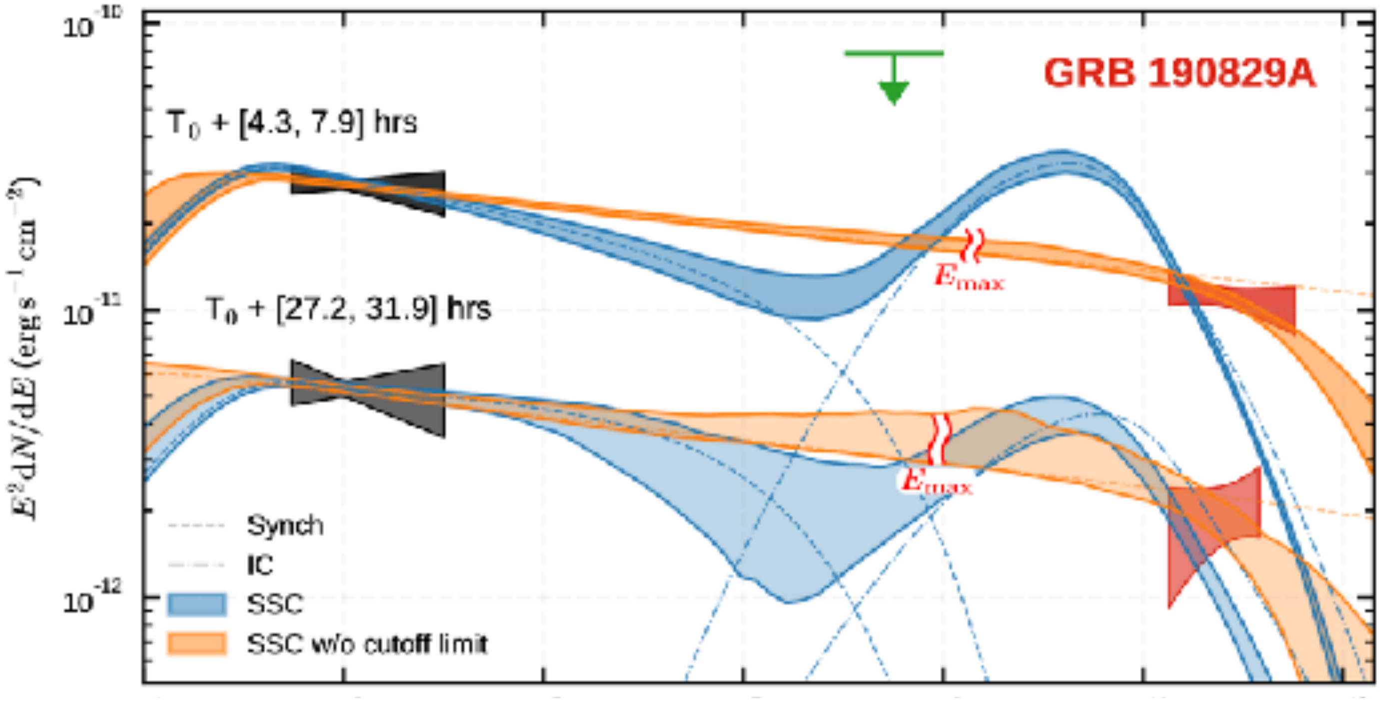


Suggests a critical energy, from $t_{\rm sc} = t_{\rm gyro}$

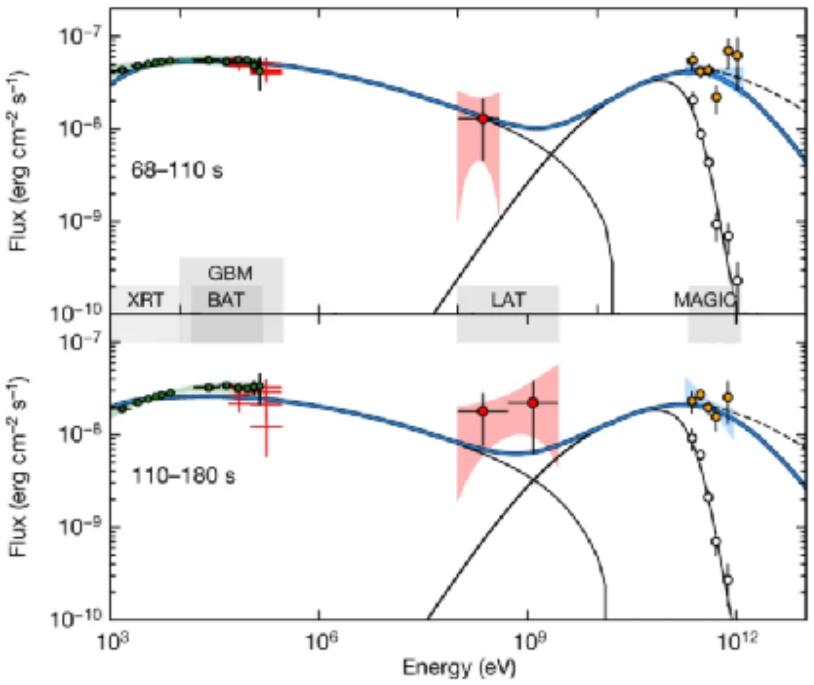
This energy is low, and possibly in tension with observations (BR & Bell ’14, Huang et al. ’22)

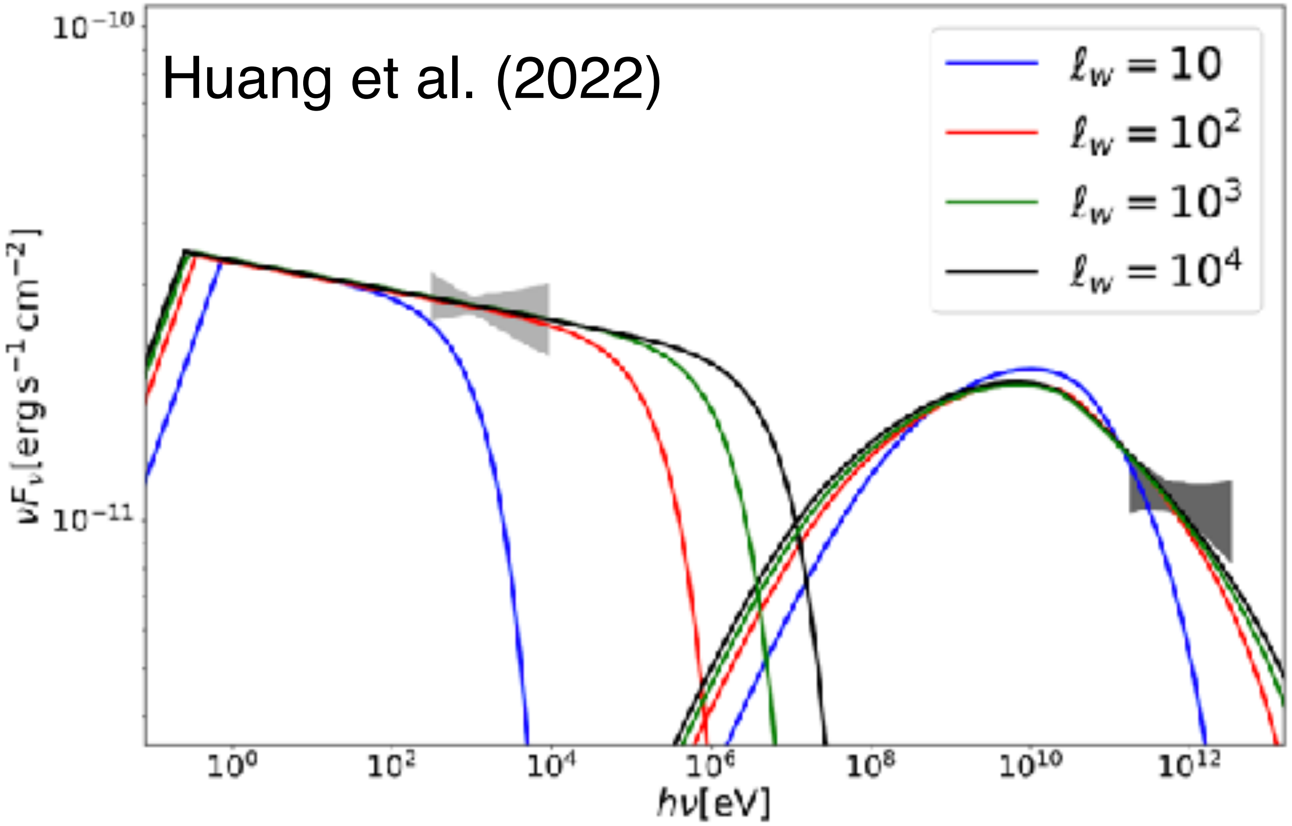
Application to TeV detected Afterglows

HESS Collaboration 2020



MAGIC collab. (2019)




Huang et al. (2022)

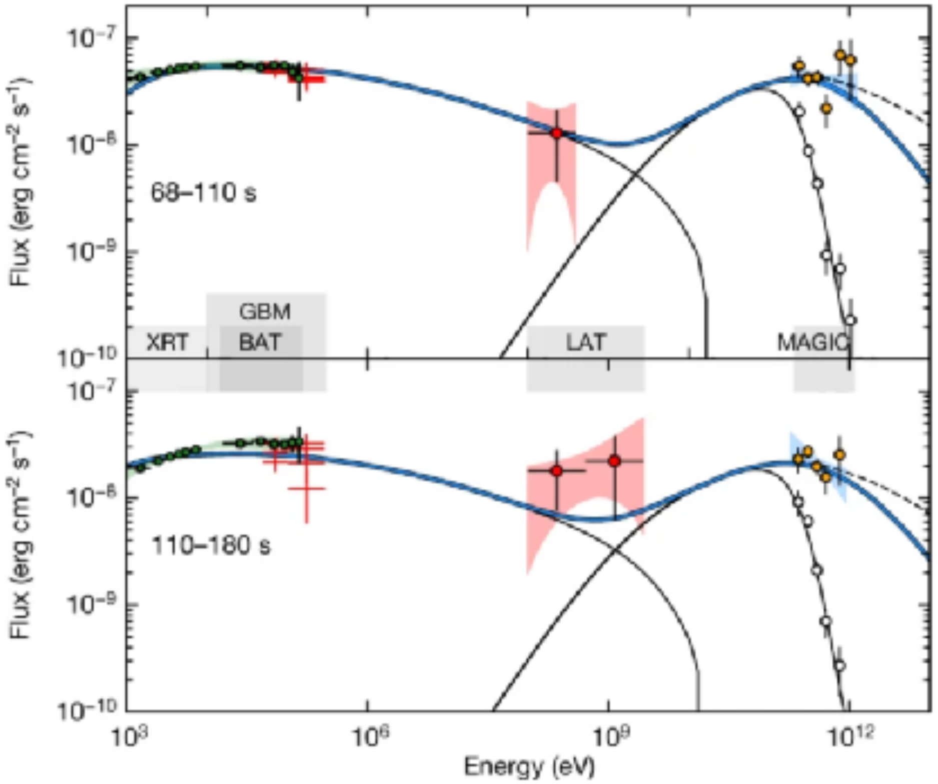
$$\lambda = \ell_{\rm w} \frac{c}{\omega_{\rm p}}$$

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

Is that it?

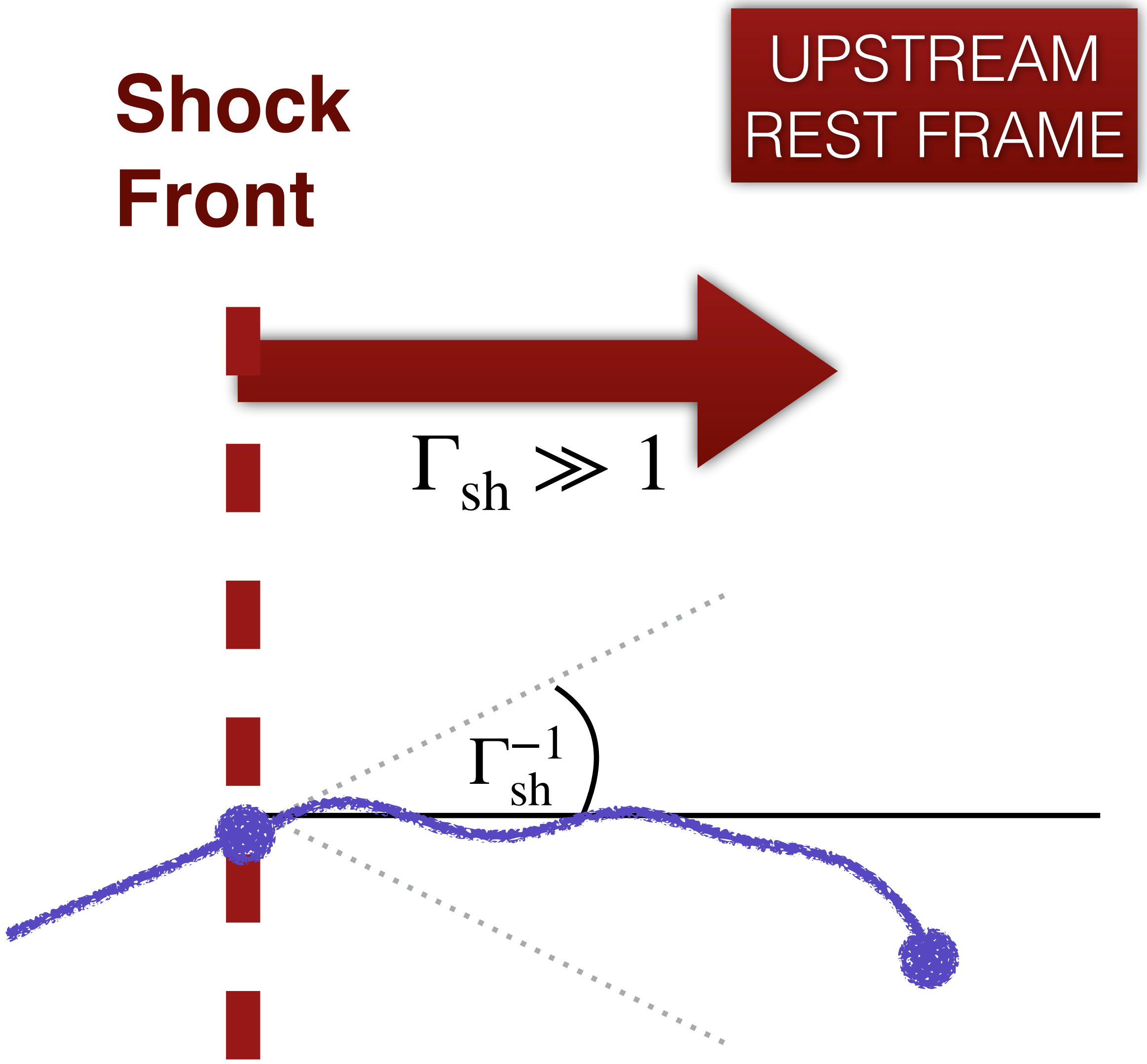
- Are particles only accelerated at weakly magnetised shocks?
- Is the maximum synchrotron energy always << burn-off limit (cooling time= gyro time : $h\nu/m_e c^2 \approx \alpha_f^{-1}$)
- This appears to be contradicted by observations
  e.g. acceleration is slow,
  small ϵ_B inferred in many GRBs,

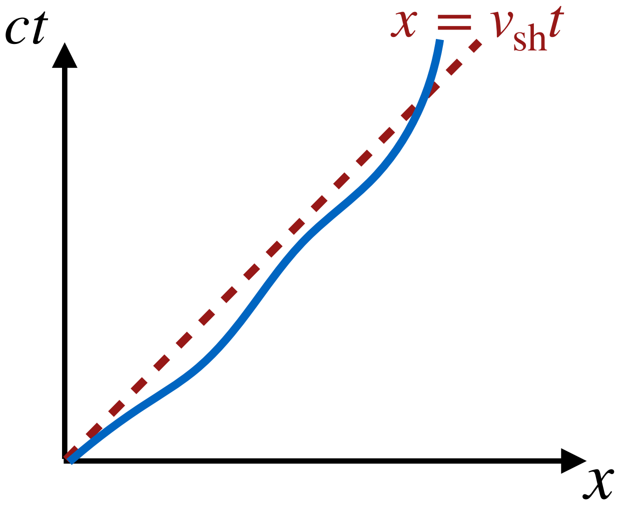
MAGIC collab. (2019)



So what else is there?

Particle acceleration at Ultra-rel. shocks





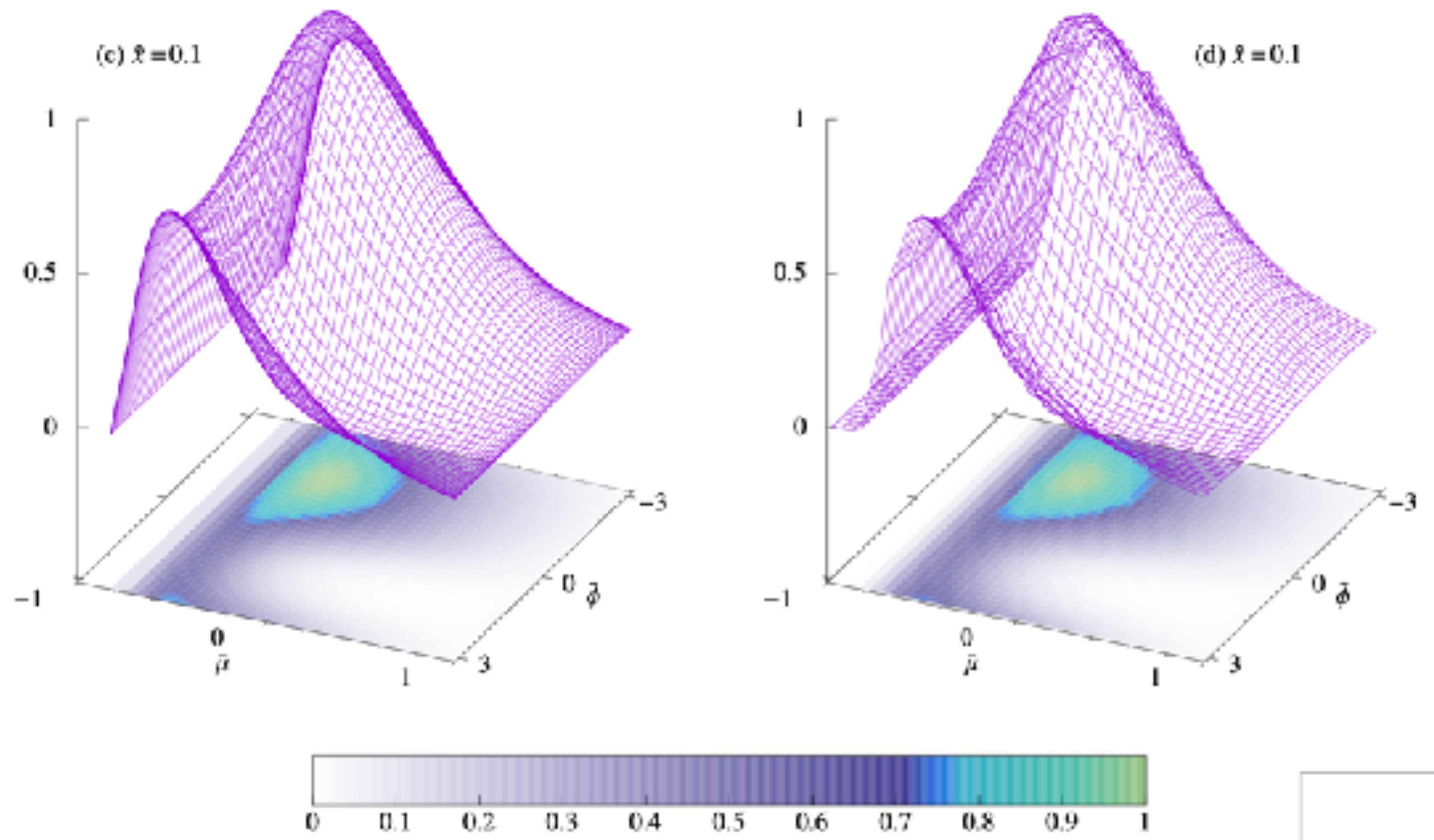
Returning particles carry a sizeable energy flux

$$T^{01} = \eta_{ref}\Gamma_{\rm sh}^{4} n_0 m_p c^2$$

Drives large scale instabilities in upstream (BR & Bell 14)

Fluid like instabilities are inherently 3D, difficult to probe with PIC simulations
Upstream and downstream trajectories are uncorrelated

Return to Bohm



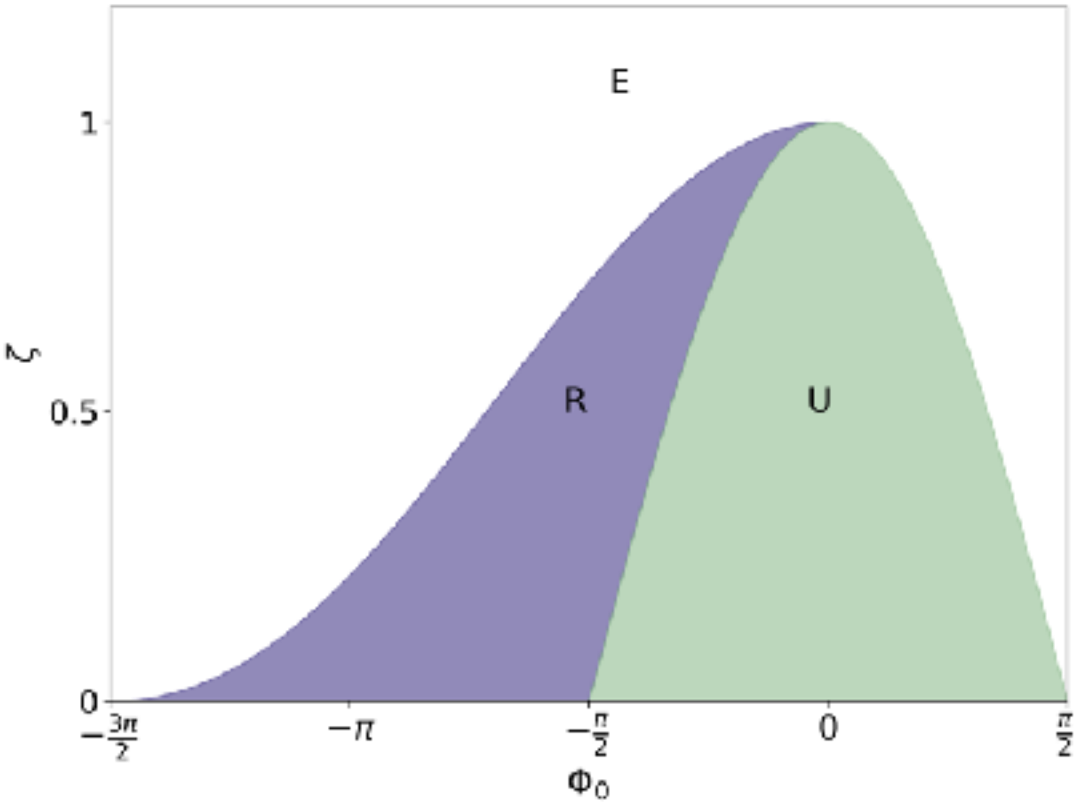
nsider the extreme case of pure
ing us, no scattering ds

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

shock

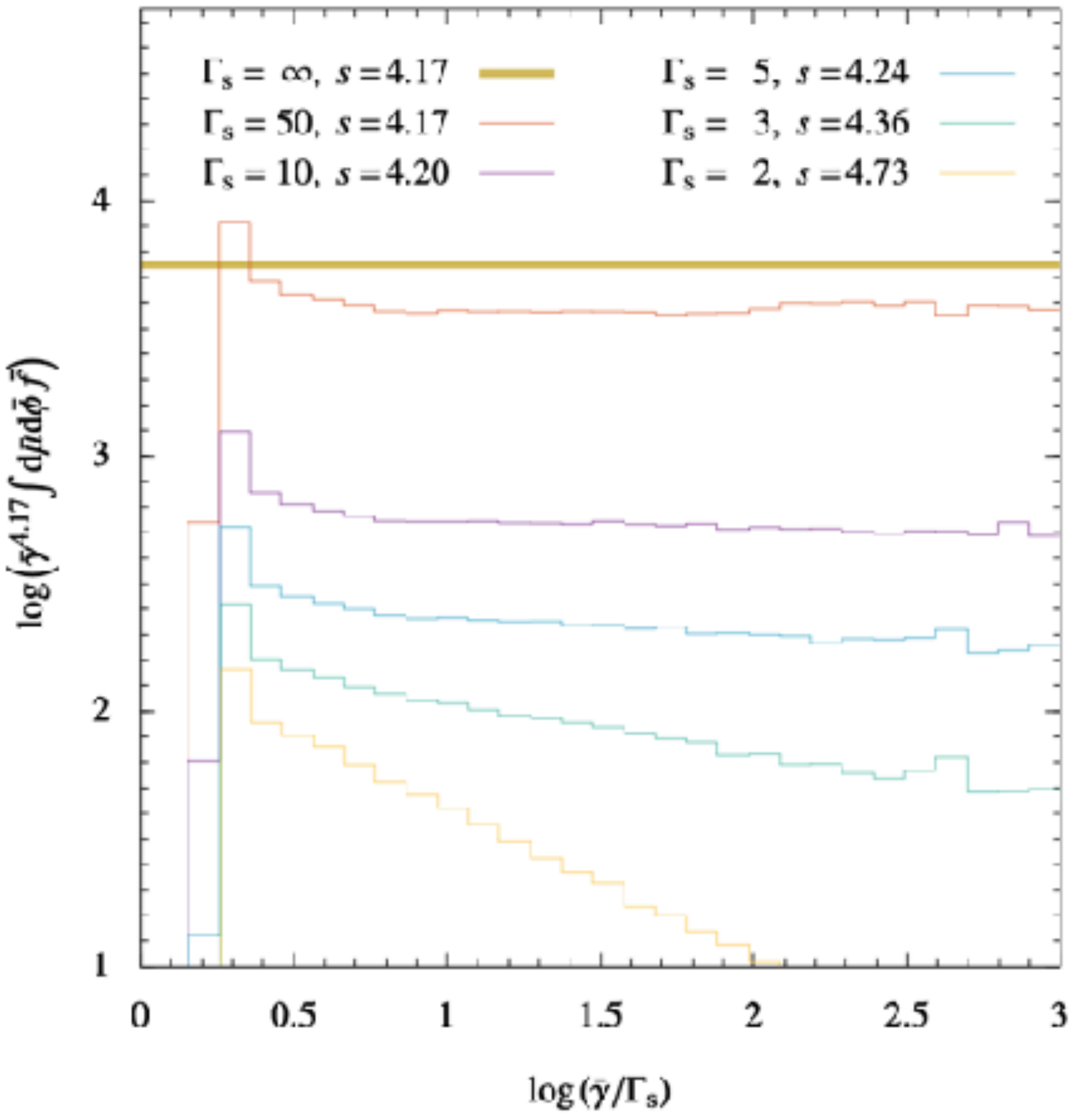
If pitch angle diffusion operates upstream (which it must in $\Gamma_{\rm sh} \to \infty$ limit) return probability is high $\sim 30 - 40\,\%$

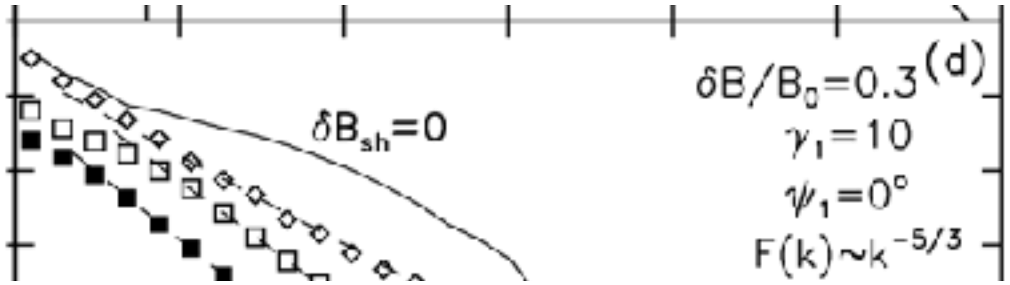
Kirk, BR & Huang, MNRAS submitted

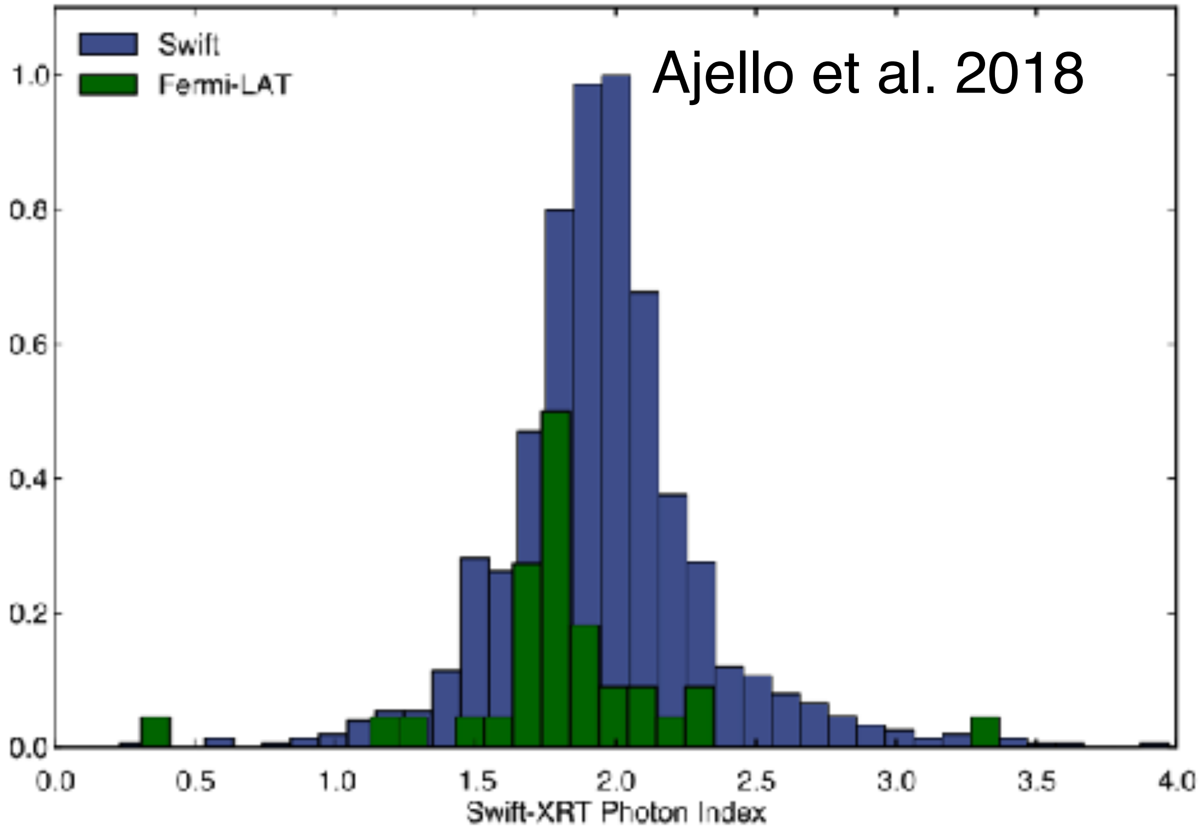


Details of plasma physics in Shock *precursor* critical

Particle spectrum





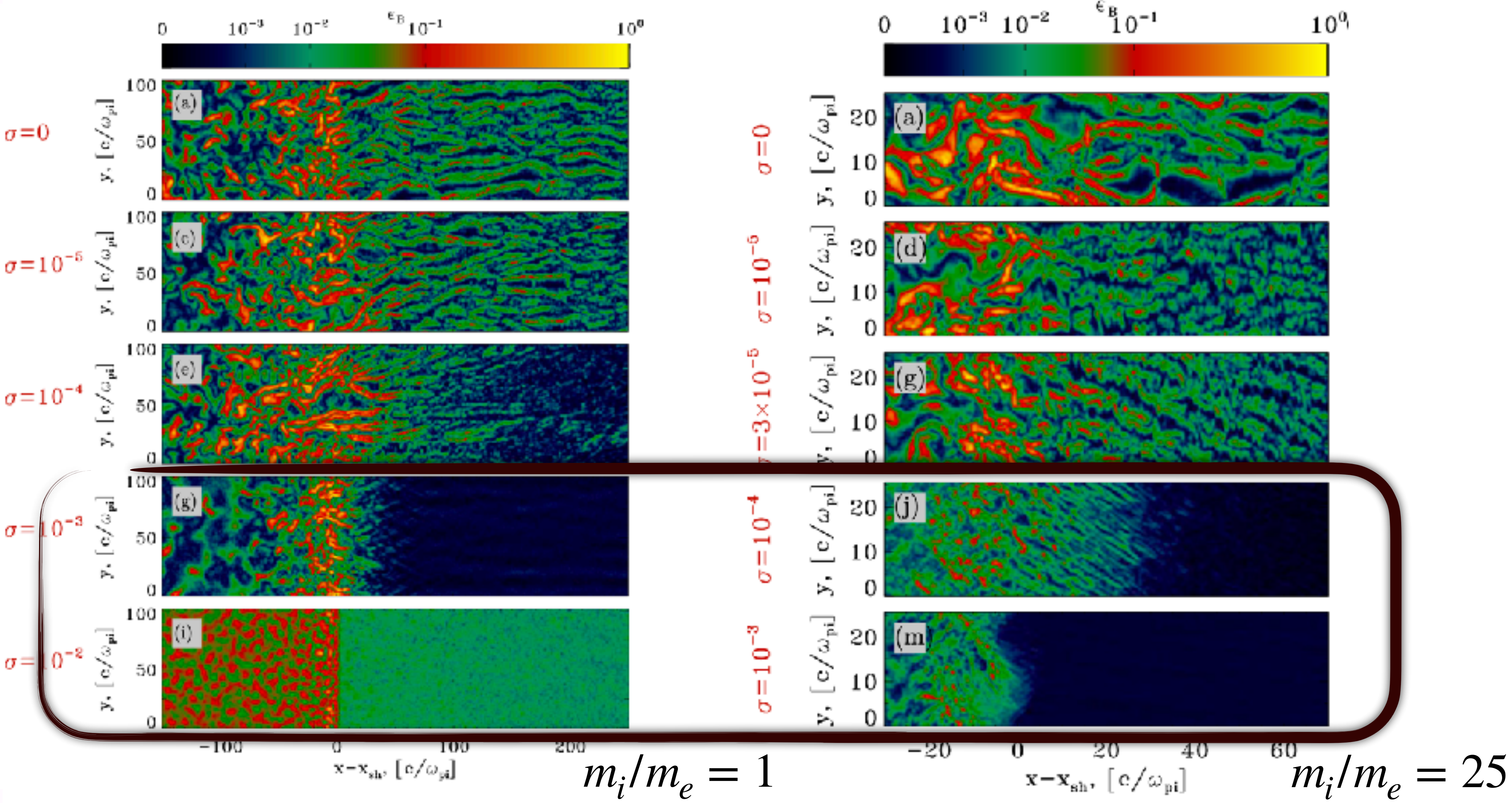


Ajello et al. 2018

Spectrum is close to (slightly harder) than the parallel shock prediction

Insights from PIC simulations

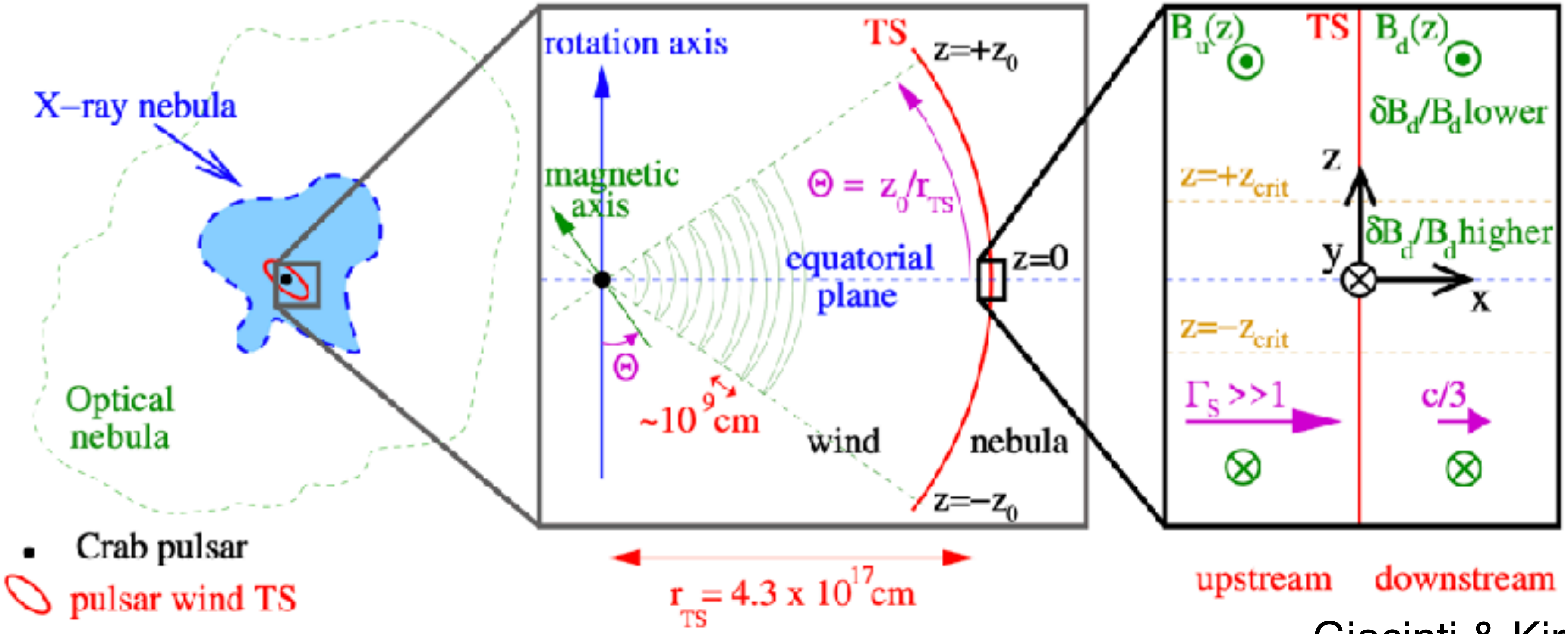
2D simulations by Sironi, Spitkovsky & Arons 13



$m_i/m_e = 1$

$m_i/m_e = 25$

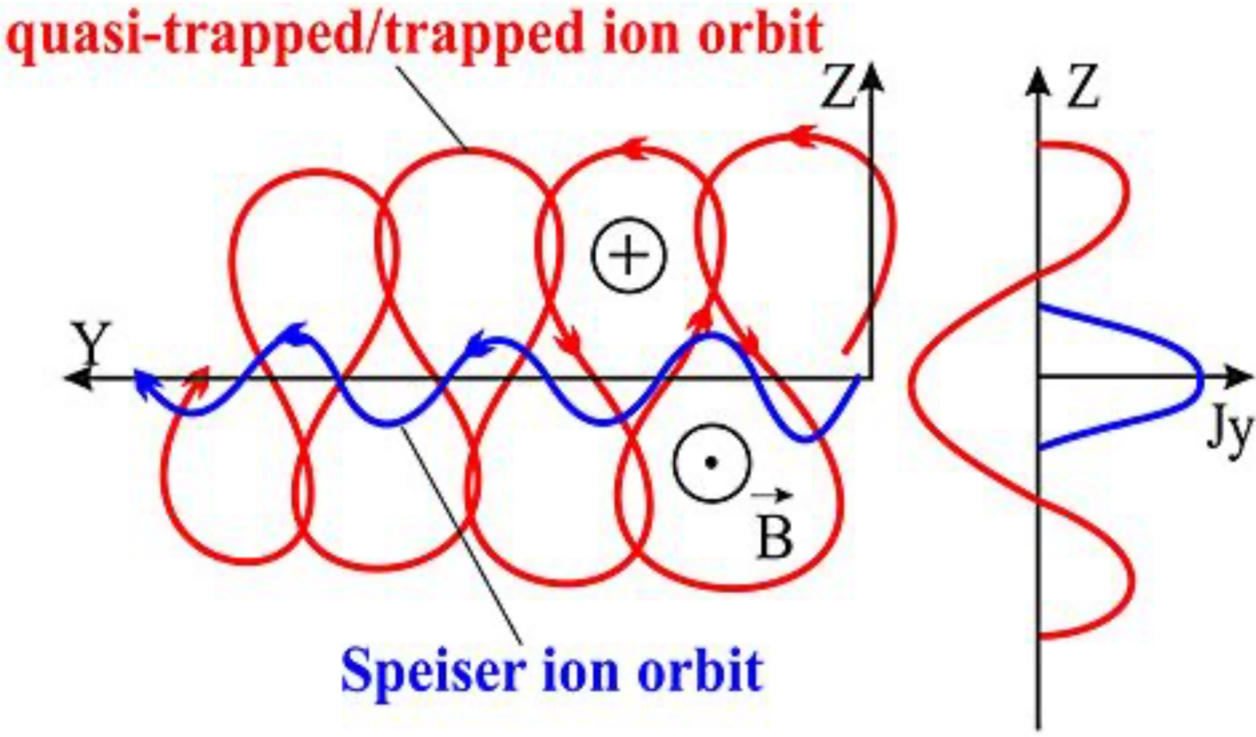
The impact of structured fields



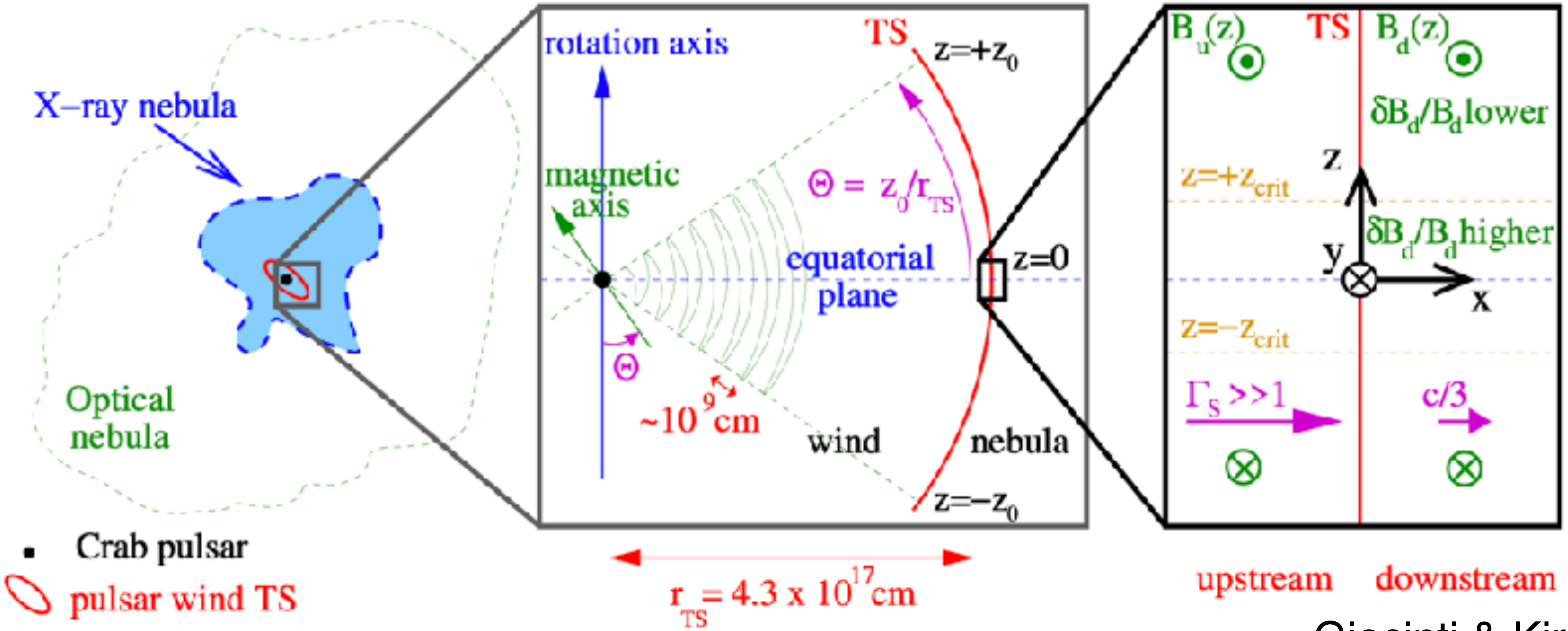
Giacinti & Kirk (2018)

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

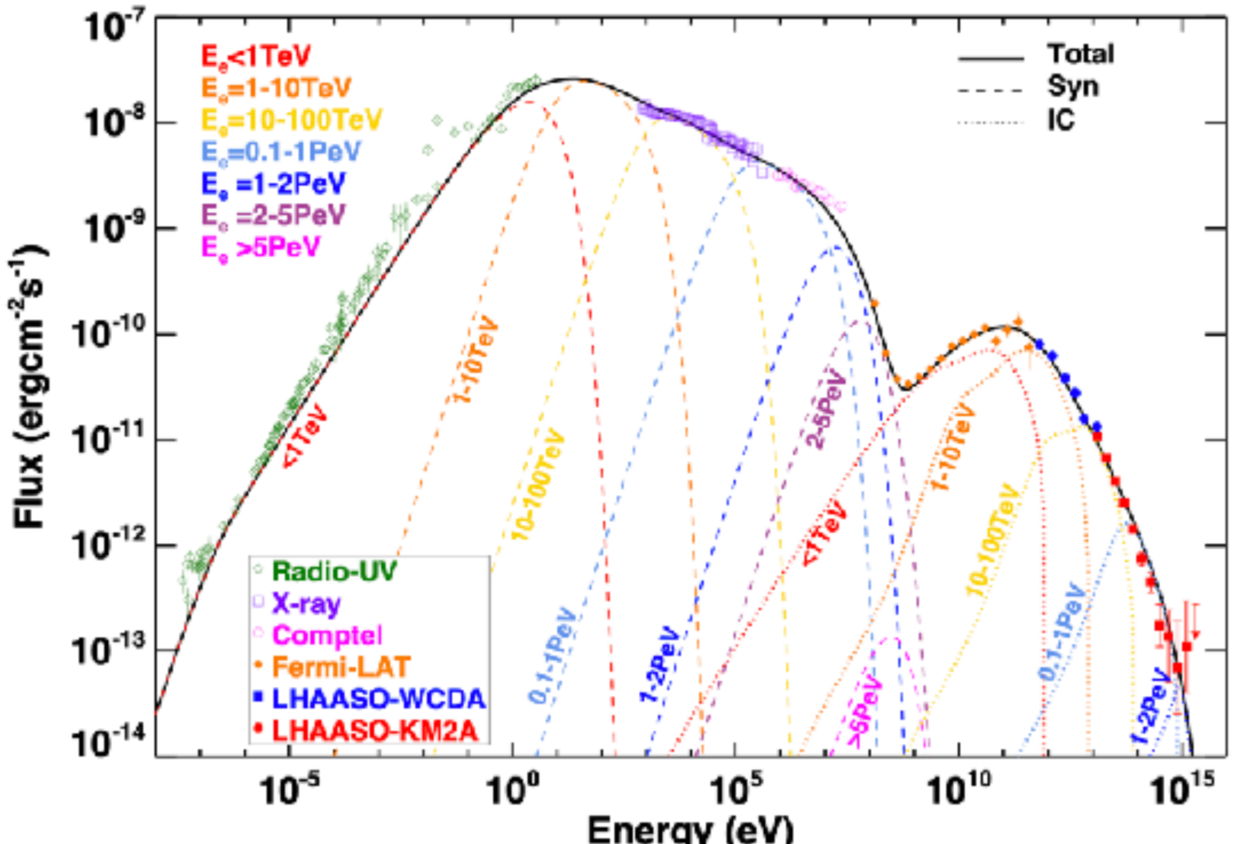
Can account for PeV γ-ray production seen ion Crab system by LHAASO (Giacinti, BR. & Kirk, in prep)

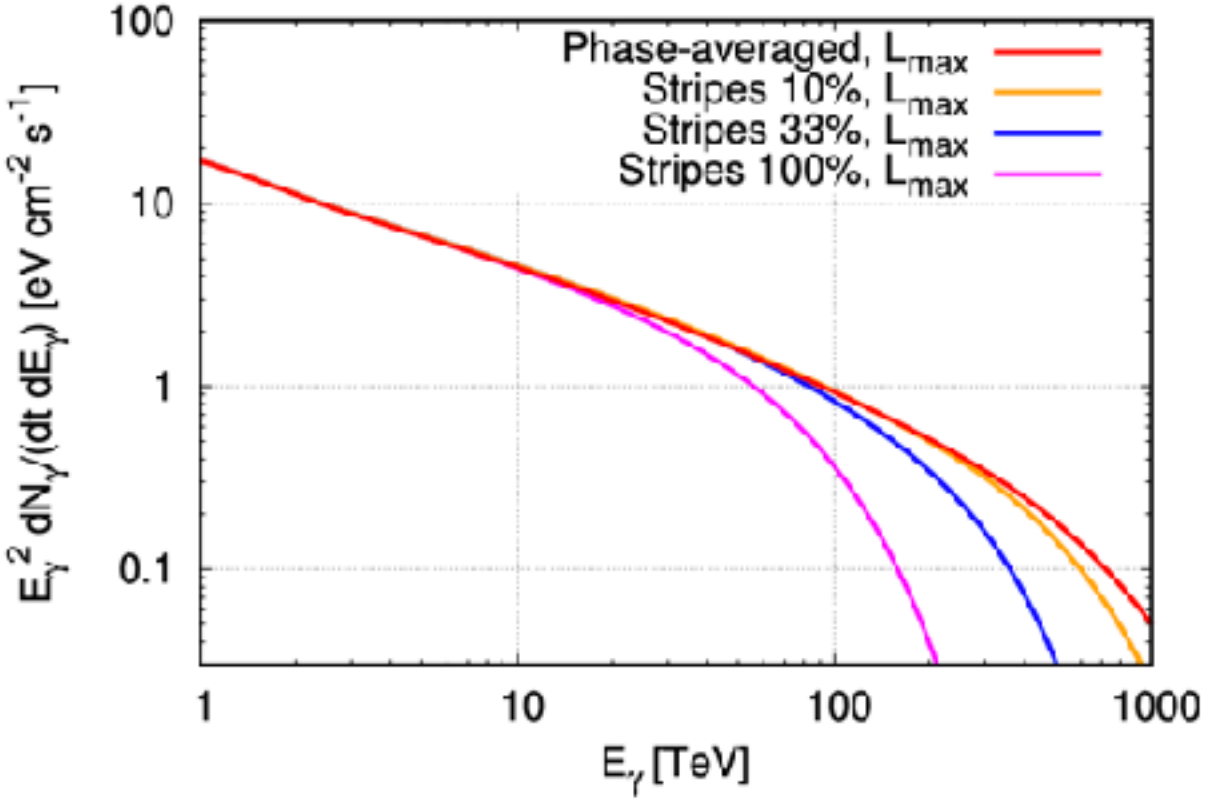


The impact of structured fields

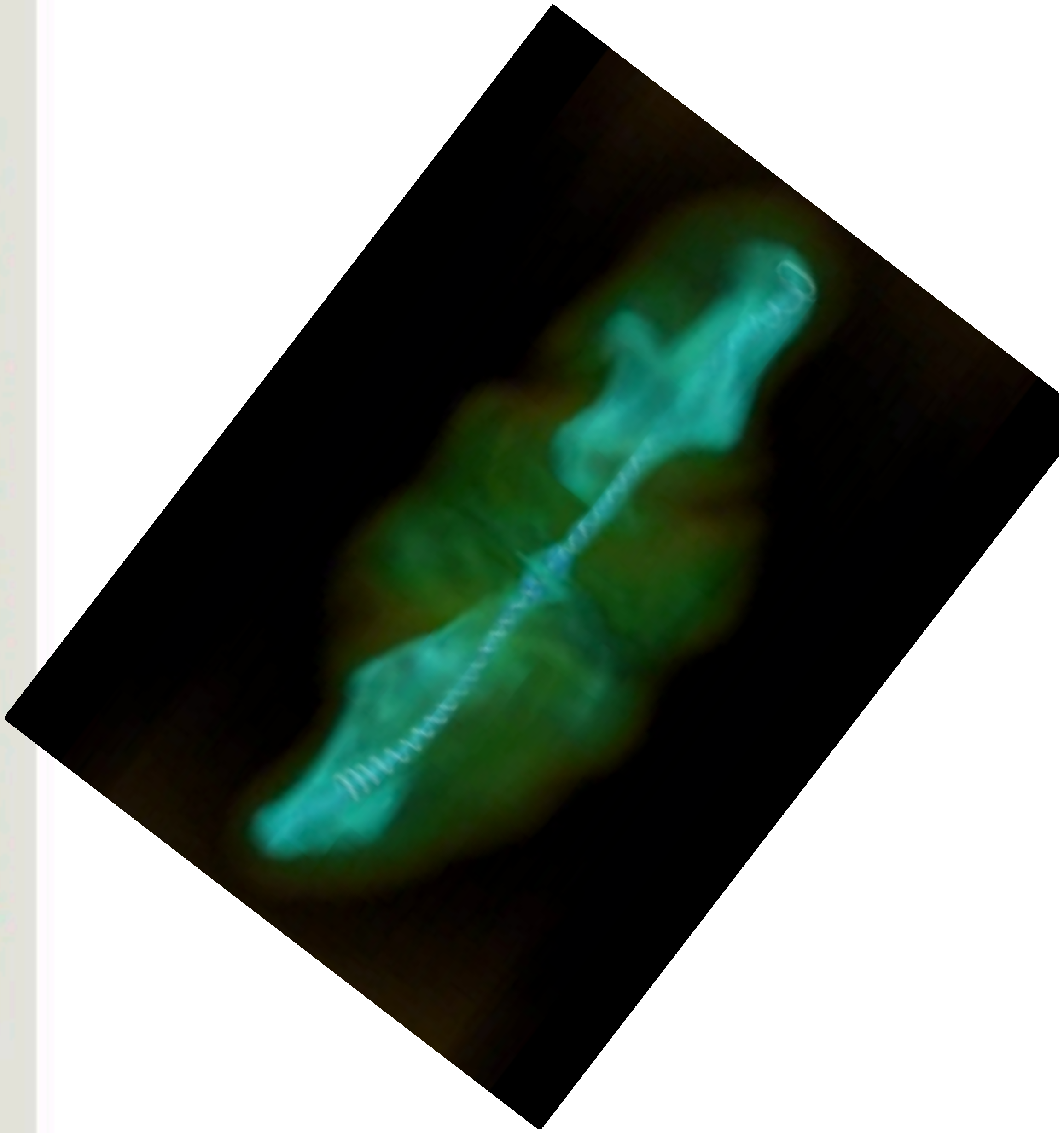


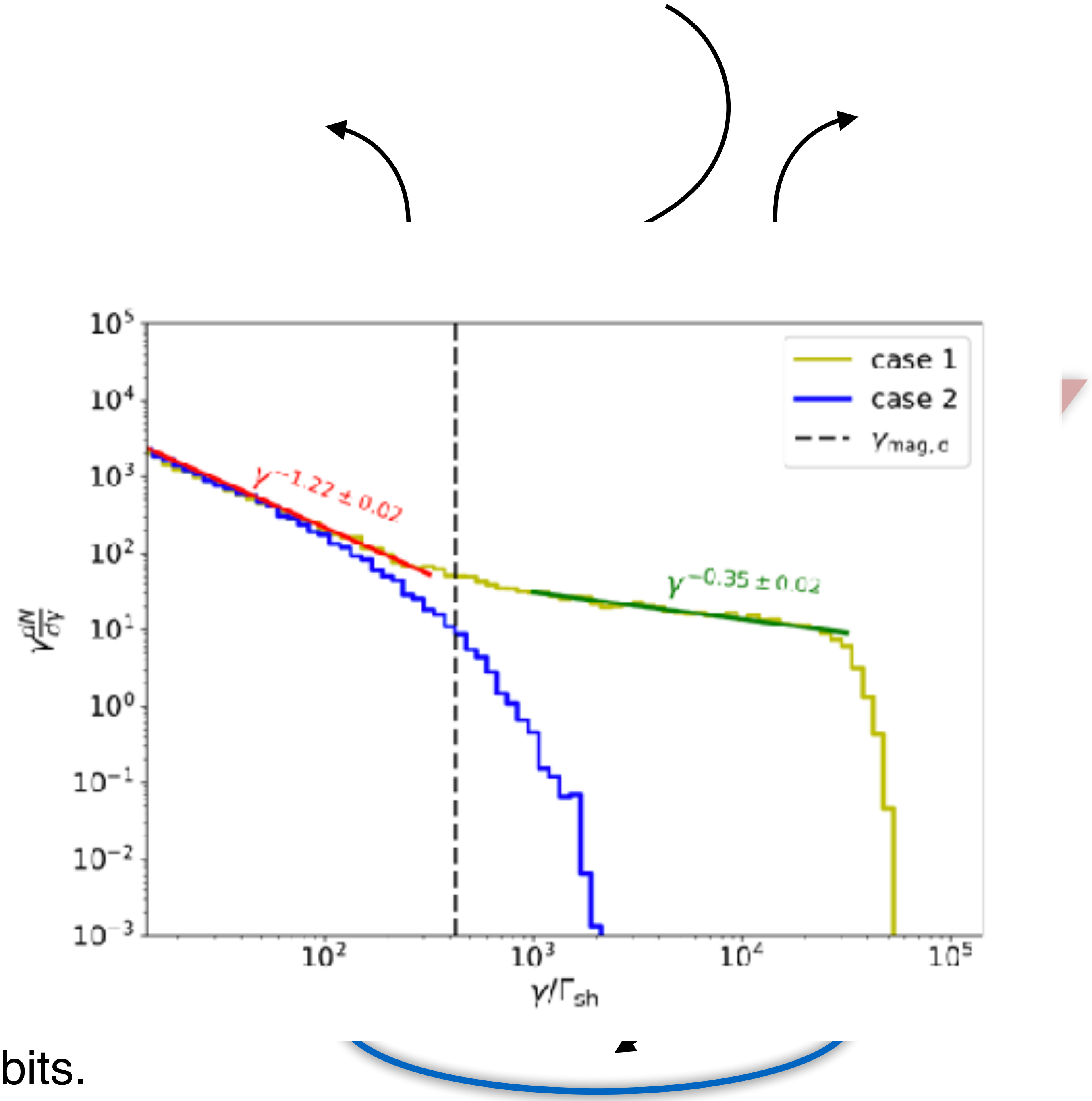
Giacinti & Kirk (2018)





Speiser orbits in jets?





Particles close to axis undergo “singular” orbits.
Charge dependent drift that returns particles to shocks

Huang et al. (in prep)

Conclusions

- Simulations confirm that weakly magnetised shocks admit Fermi acceleration
- Scattering on Weibel filaments alone is in some tension with observations (e.g. no cut-off in GRB afterglow X-ray emission)
- Contrary to common conception, scattering in upstream might be more important
- A deeper understanding of the precursor physics/global field structure is required
- Acceleration close to Bohm rate necessary to account for UHECRs and many observations (clearly we have a gap in understanding)

THANK YOU