Insights on Particle Acceleration at Relativistic Shocks from GRB afterglows

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Further details in:
Kirk & Reville, ApJL (2010)
Reville & Bell, MNRAS (2014)
Zhiqiu Huang, Kirk, Giacinti, Reville, to appear in ApJ (arXiv: 2112.00111)

Role of Ultra-relativistic shocks

Pulsars, winds and nebulae

Unique plasma laboratories

$e^{\pm}$ pair winds

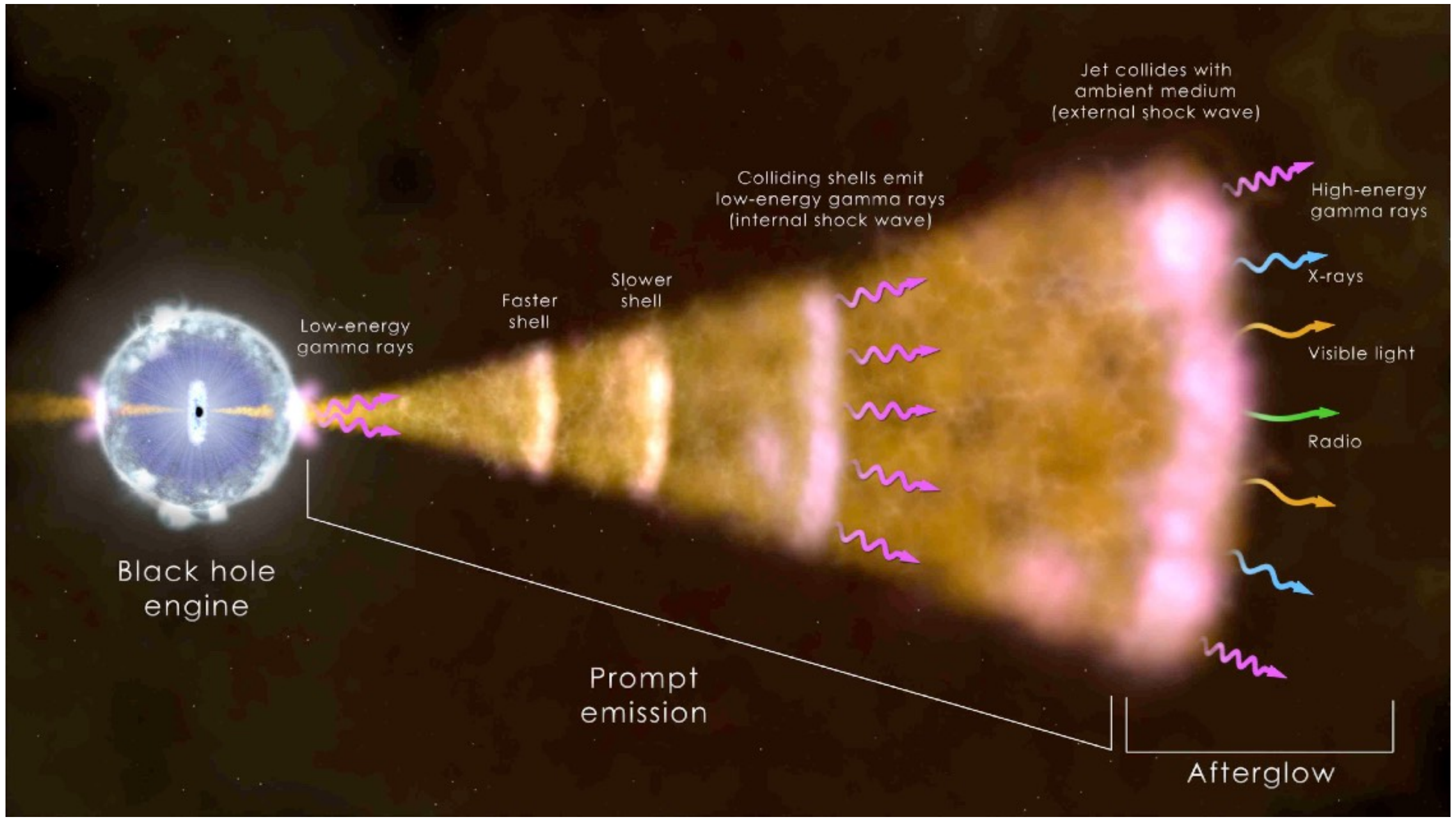
Local CR $e^{\pm}$ sources

Astrophysical background in DM searches

GRBs & their afterglows

GW / MMs

Sources of UHECRs?



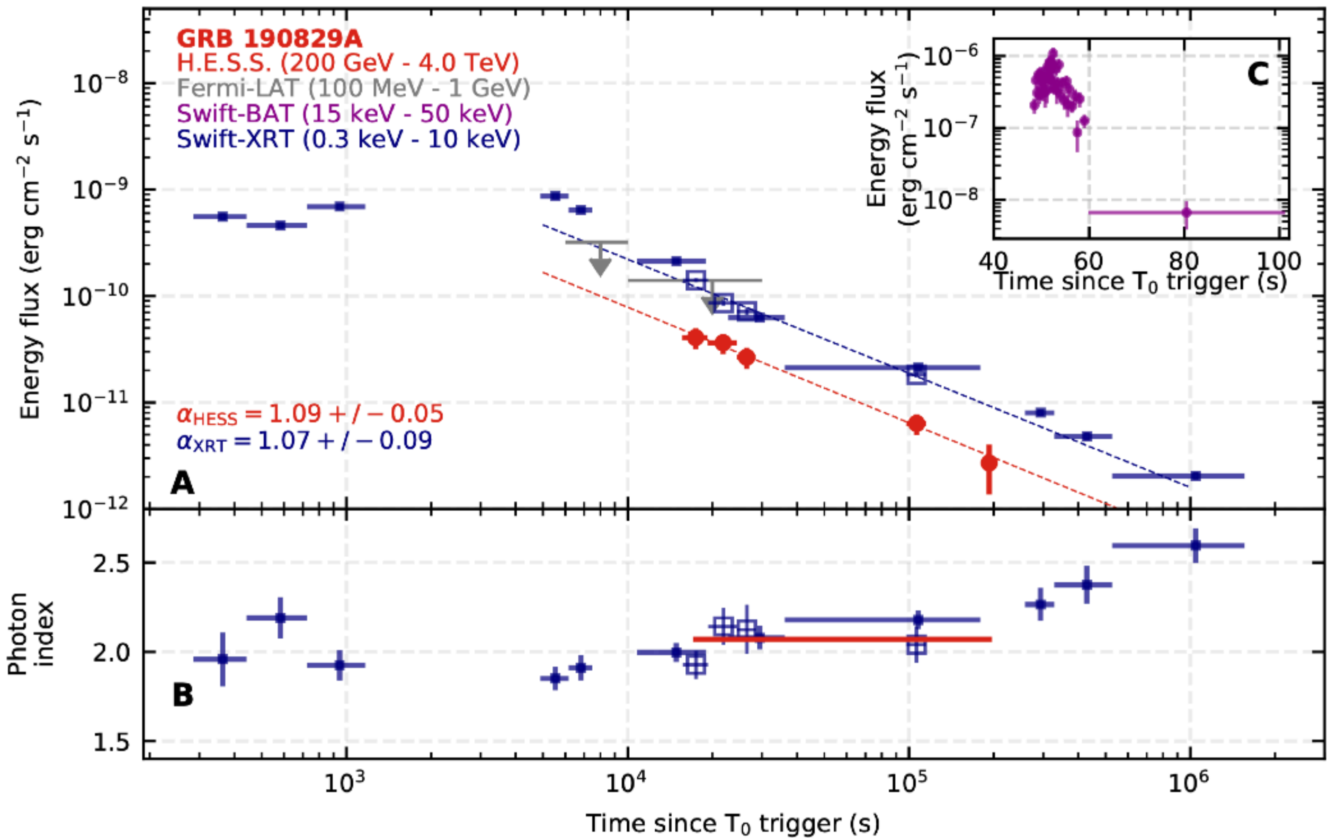
Images credit: NASA

GRB afterglows in the TeV domain

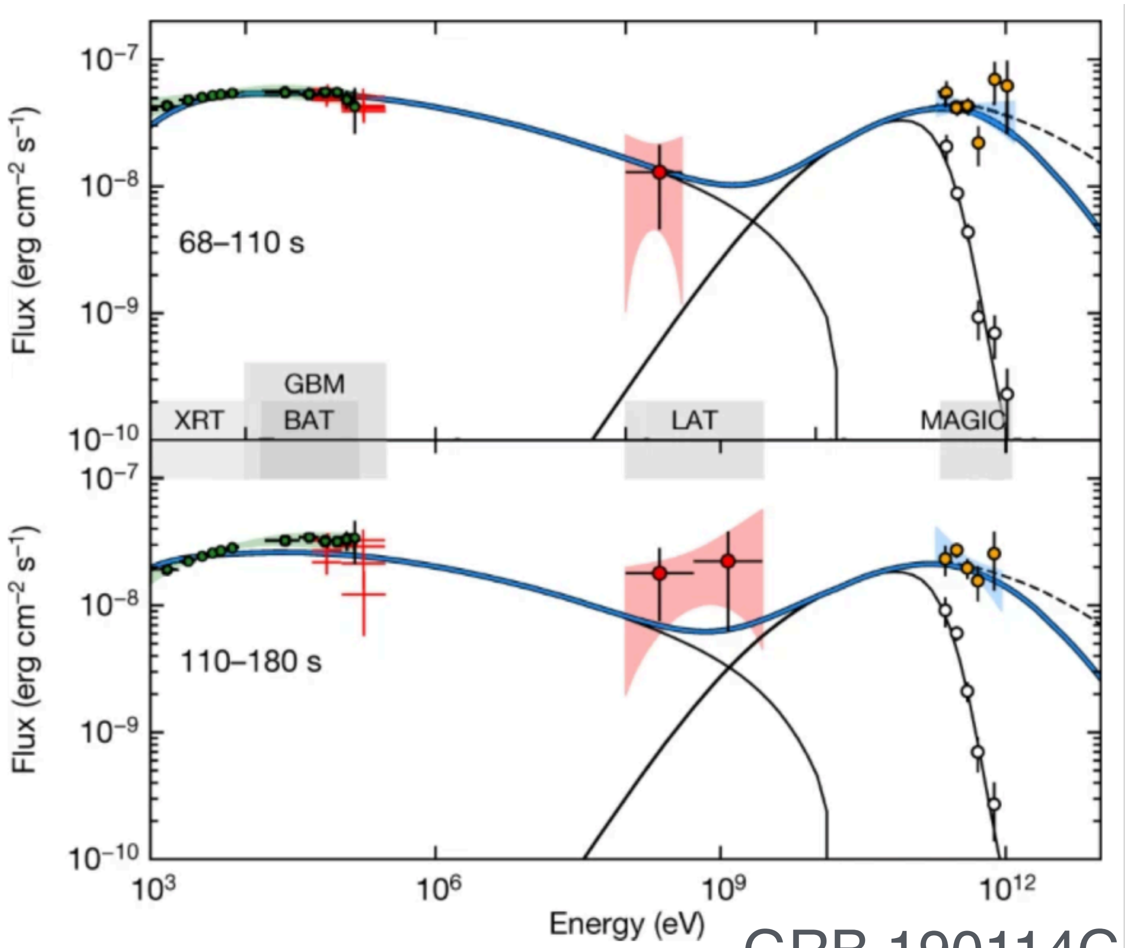
4 GRB afterglows detected to date in TeV domain
(See Moderski's & Sitarek's talks yesterday)

MAGIC collab. (2019)

HESS collab. (2020)



GRB 190829A



GRB 190114C

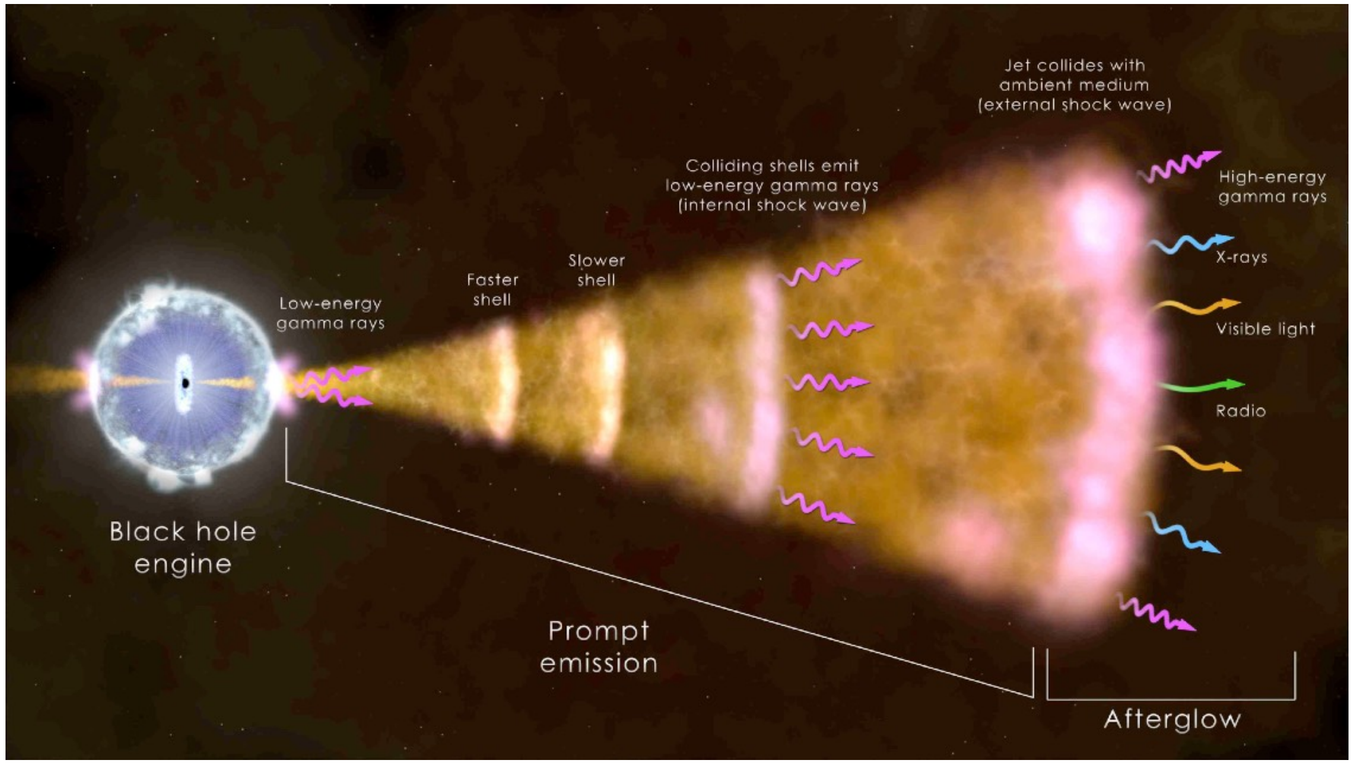
The presence of TeV electrons highlights key question of maximum energy

GRB afterglow - shock physics

External shock is a “relatively” clean environment.

- Electron-ion plasma
- Low magnetisation ($B^2/4\pi \ll w \approx \rho c^2$)
- Self-similar hydro-dynamic evolution

$$\sigma = B^2/4\pi w$$



Particles are accelerated at the external shock via shock acceleration

- $$\frac{dN_{\text{inj}}}{dAdtdE} \propto E^{-p}$$
- Magnetic field and electrons take ϵ_e and ϵ_B of the internal energy resp.

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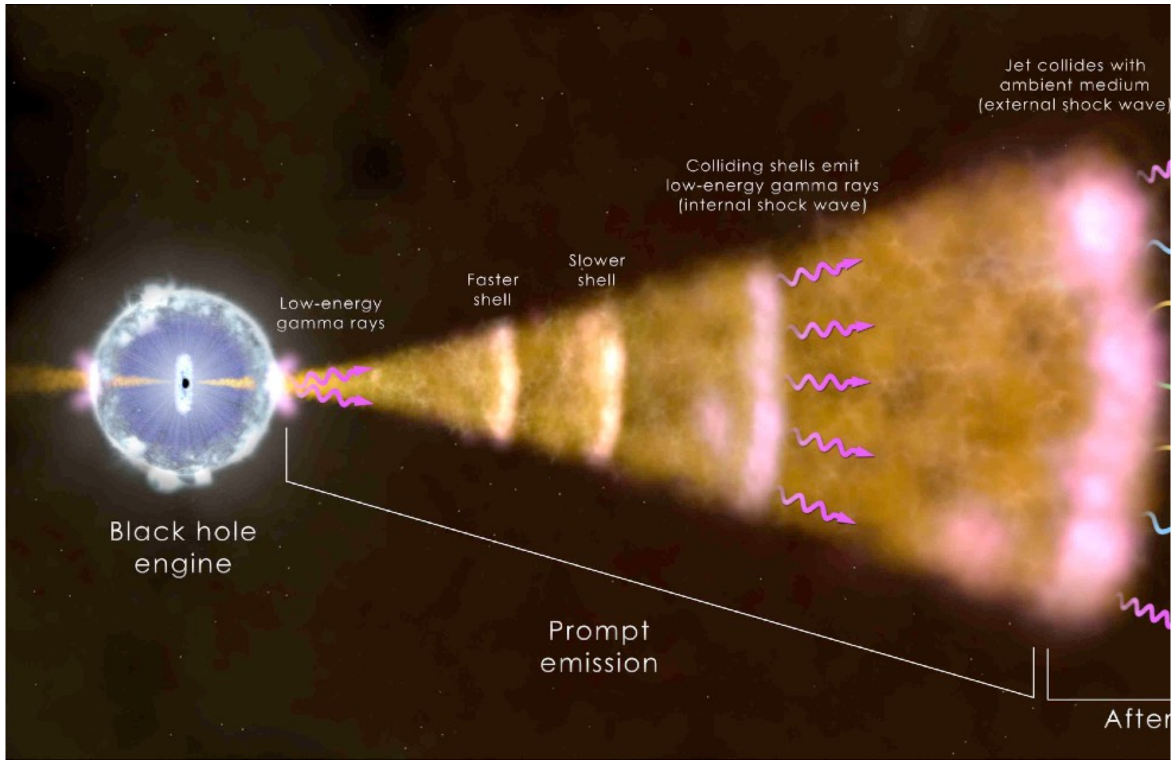
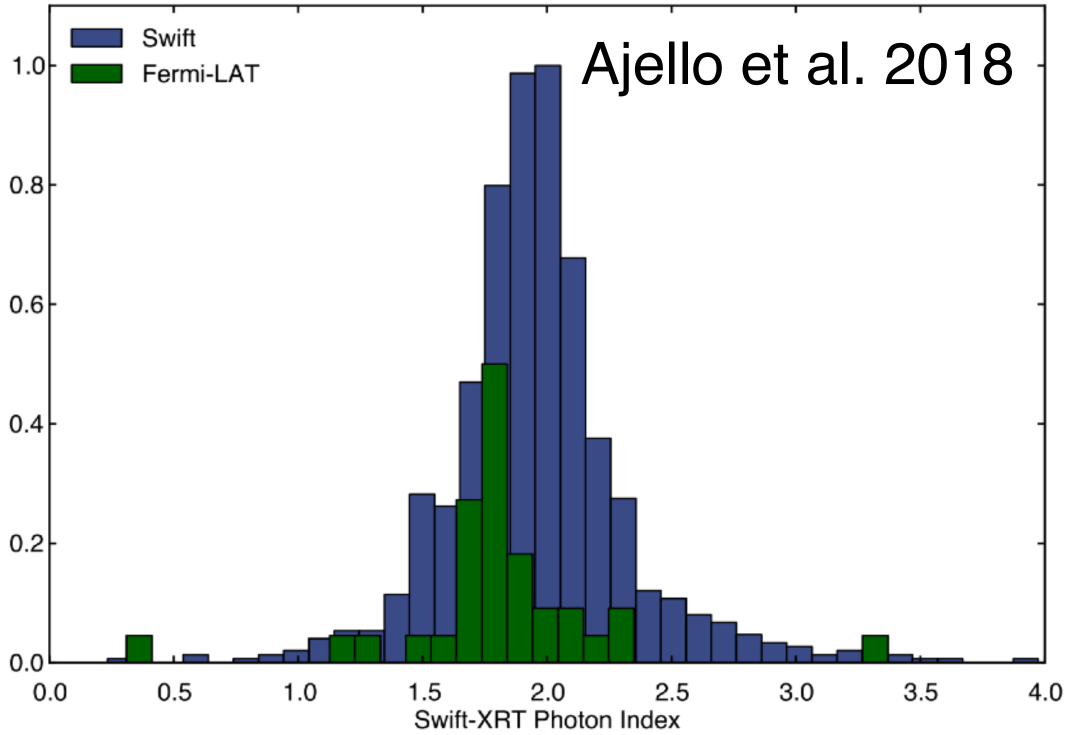




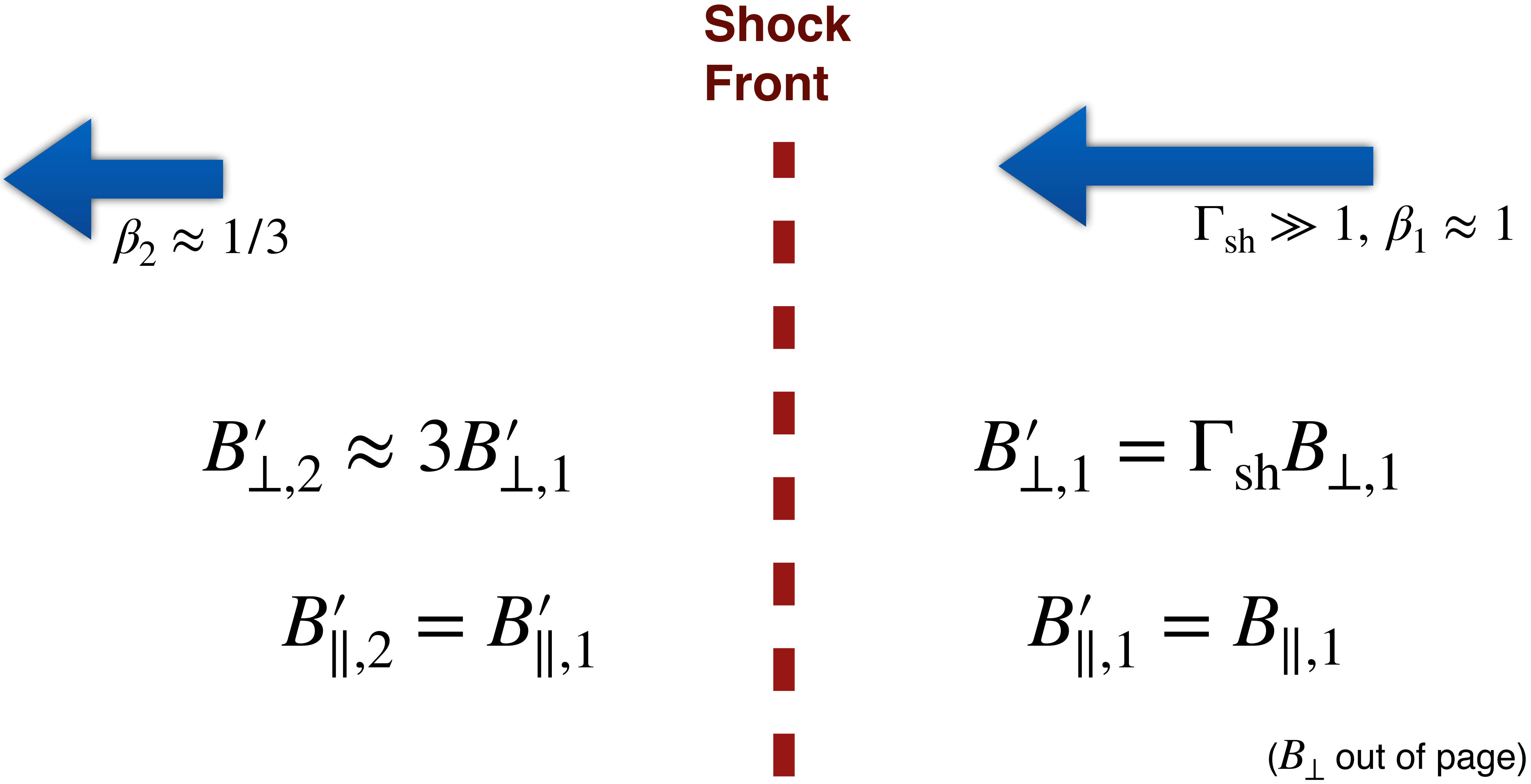
Ajello et al. 2018

Are the observations consistent with shock acceleration theory?

- Theory & simulations generally find $p \gtrsim 2.2$
- Maximum energy often overlooked, despite analytic predictions.

We would like to use GRB afterglow observations to put our current understanding to the test….

Particle acceleration at Ultra-rel. shocks



Shock Front

$\beta_2 \approx 1/3$

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

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

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

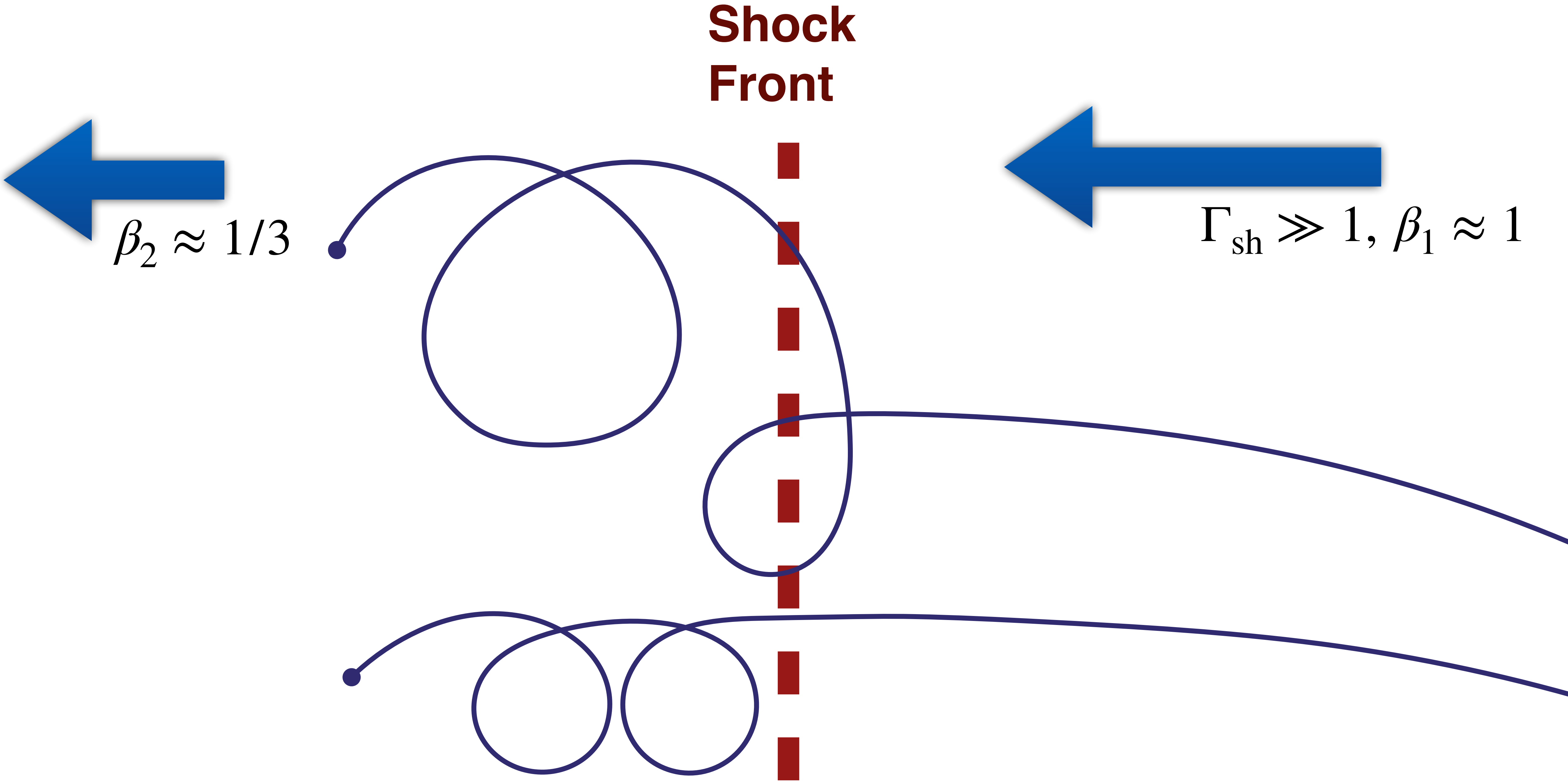
$$B'_{\parallel,2} = B'_{\parallel,1}$$

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

($B_\perp$ out of page)

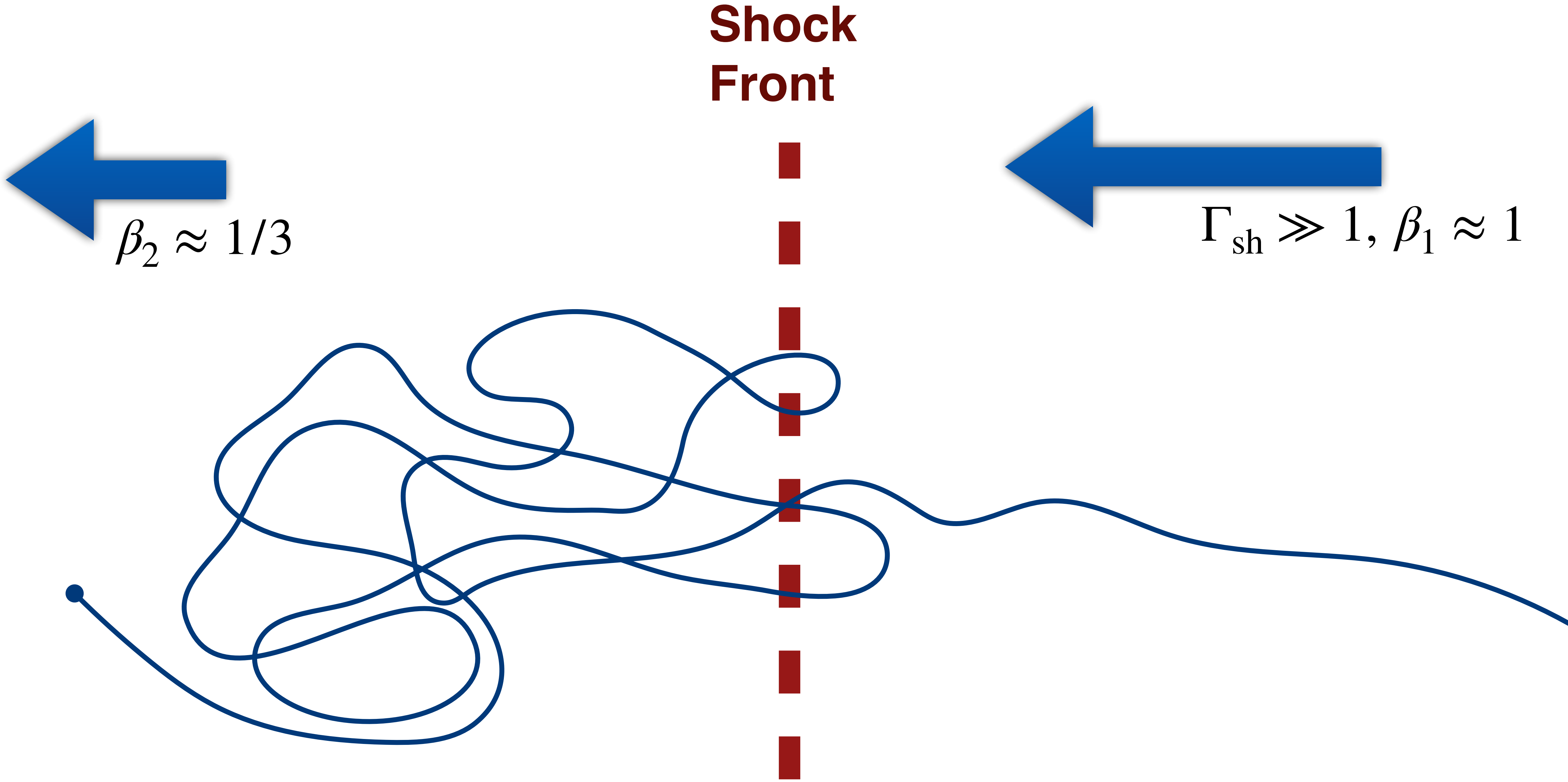
In shock frame, avg magnetic field lies in the plane of the shock

Particle acceleration at Ultra-rel. shocks



In absence of scattering, particle is limited to ≤ 3 crossings (Begelman & Kirk ’90)

Particle acceleration at Ultra-rel. shocks

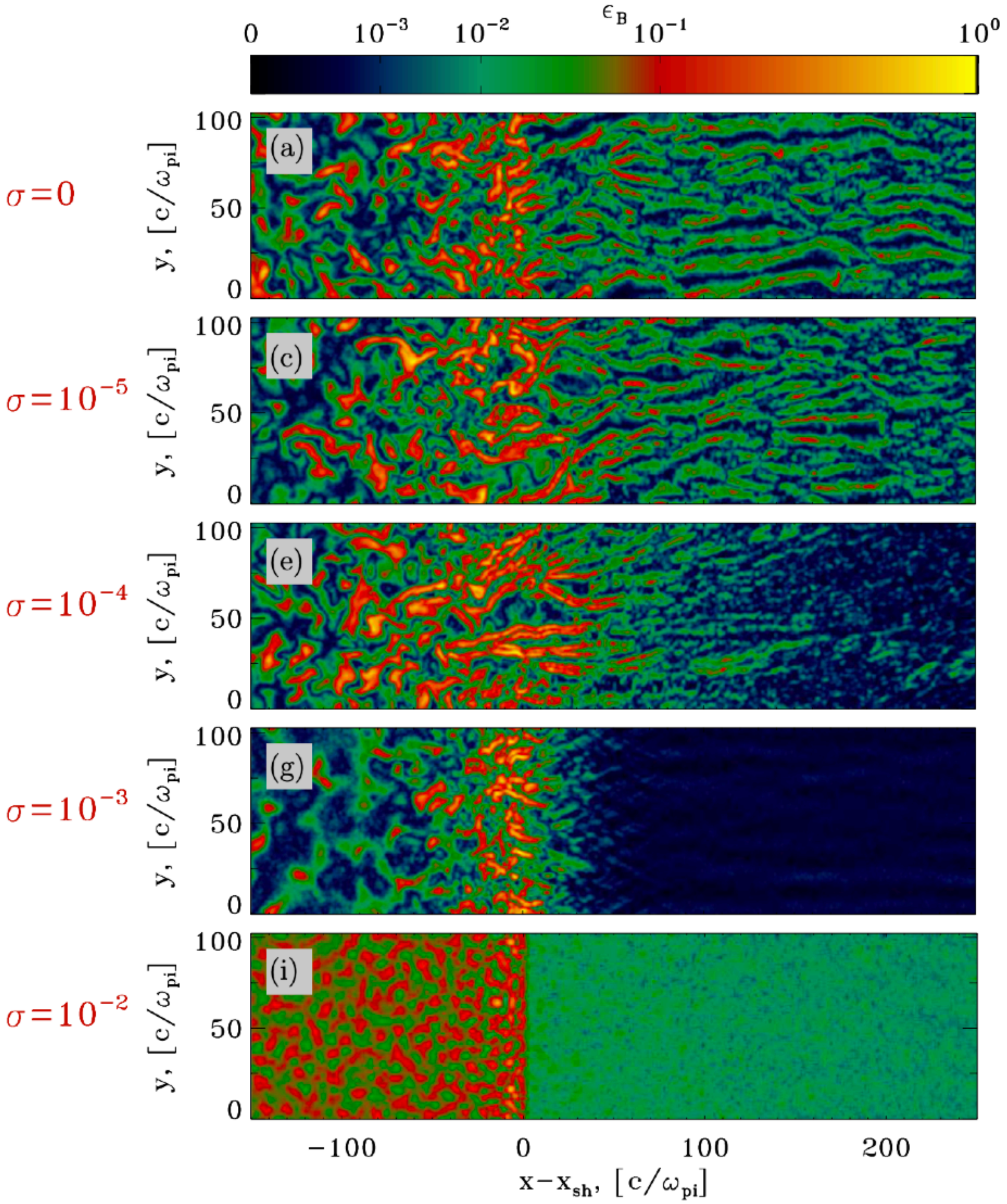


As argued by Achterberg et al ('01), to outrun the shock back into upstream, particle must scatter with $\nu_{\rm sc} \geq \omega_g$ i.e. particle ***unmagnetised***, or at the limit thereof

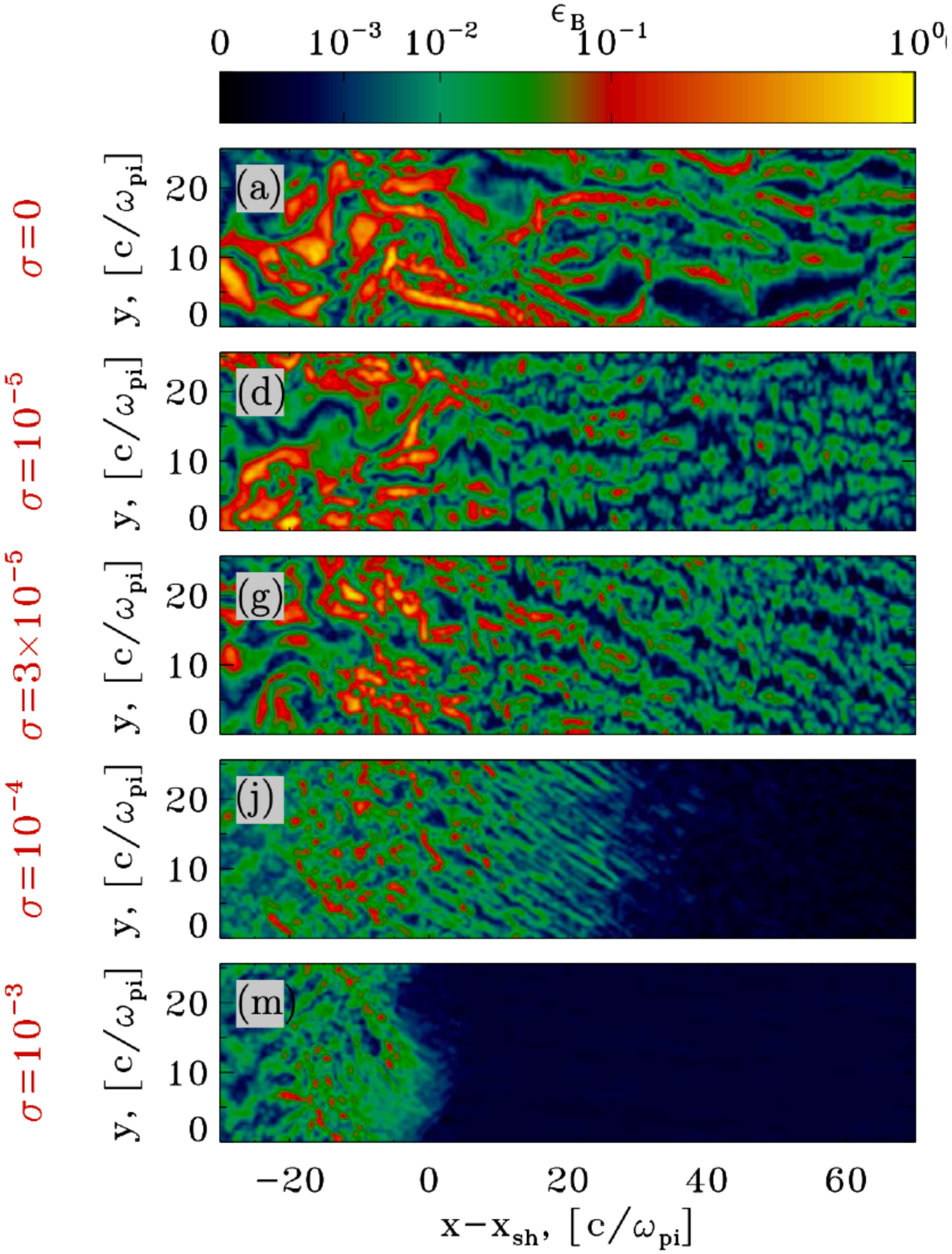
A wealth of literature using MC codes with assumed turbulence/scattering (e.g. Kirk, Schneider, Heavens, Niemiec, Ostrowski, Lemoine, Baring, etc.)

Insight from PIC simulations

2D simulations by Sironi, Spitkovsky & Arons 13,
See also talk by M. Iwamato this morning.



$m_i/m_e = 1$



$m_i/m_e = 25$

Insight from PIC simulations

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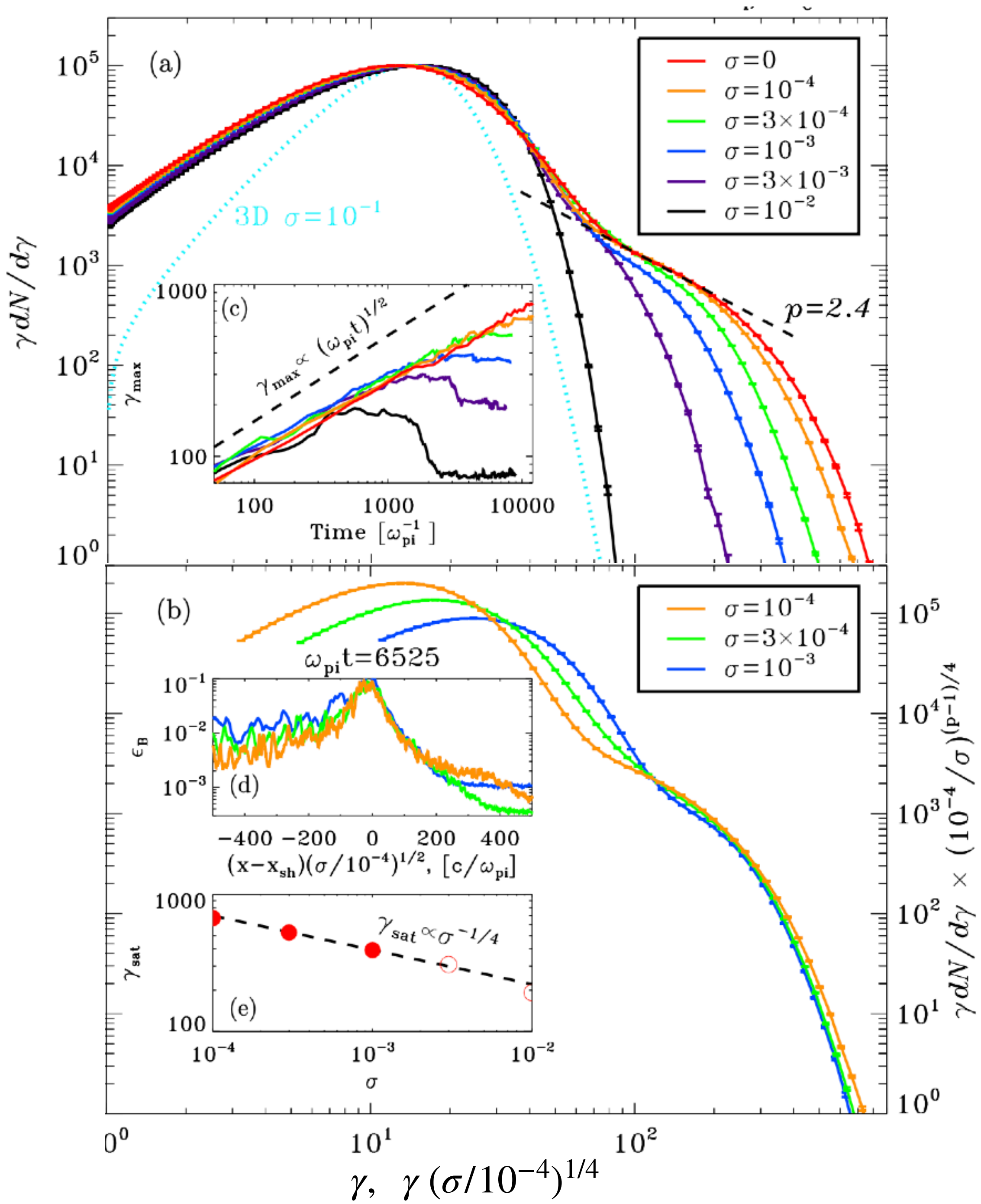
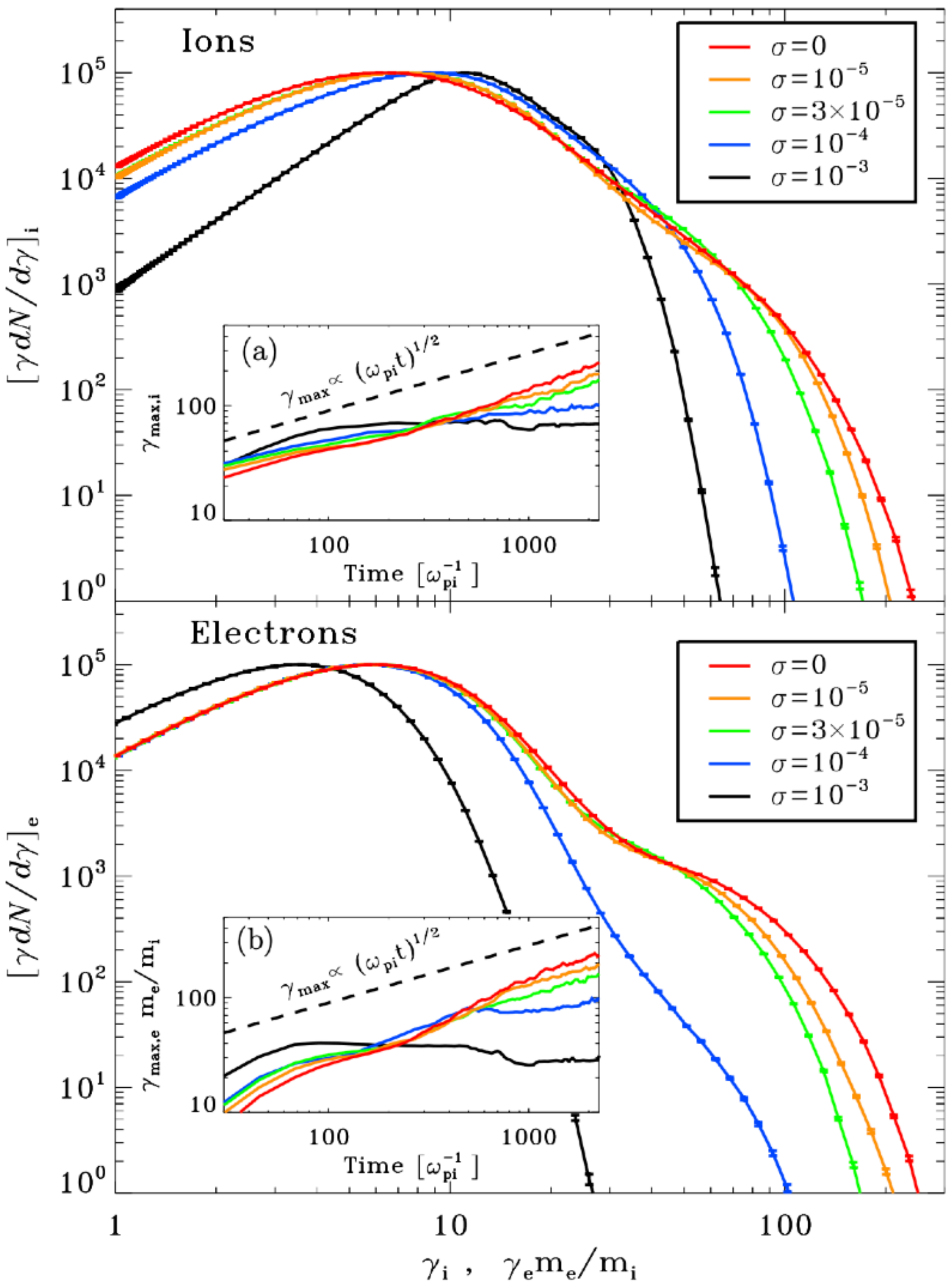
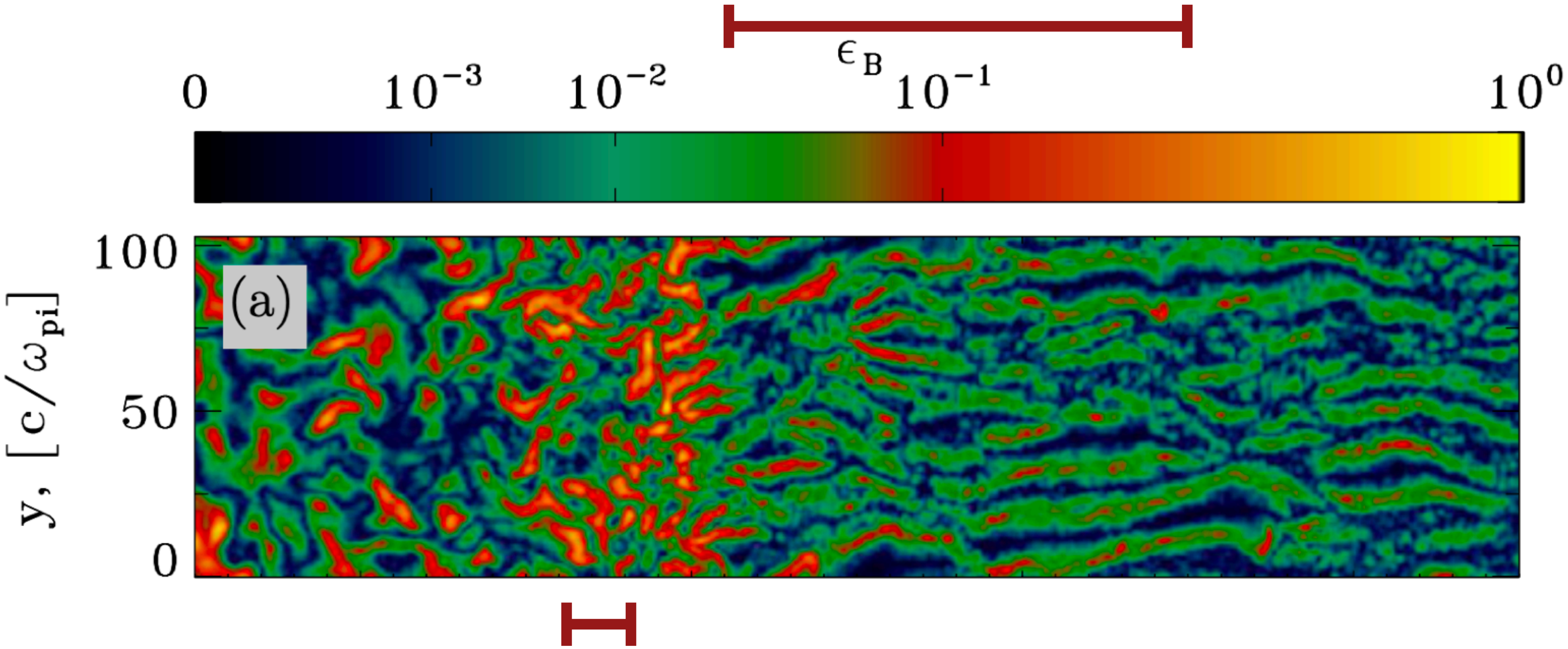




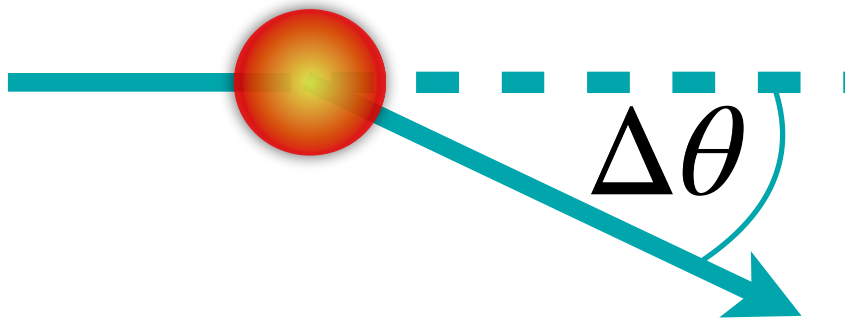
$m_i/m_e = 1$ $m_i/m_e = 25$

Taking parameters from PIC simulations

Characteristic strength $\epsilon_B \sim 0.1$



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



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

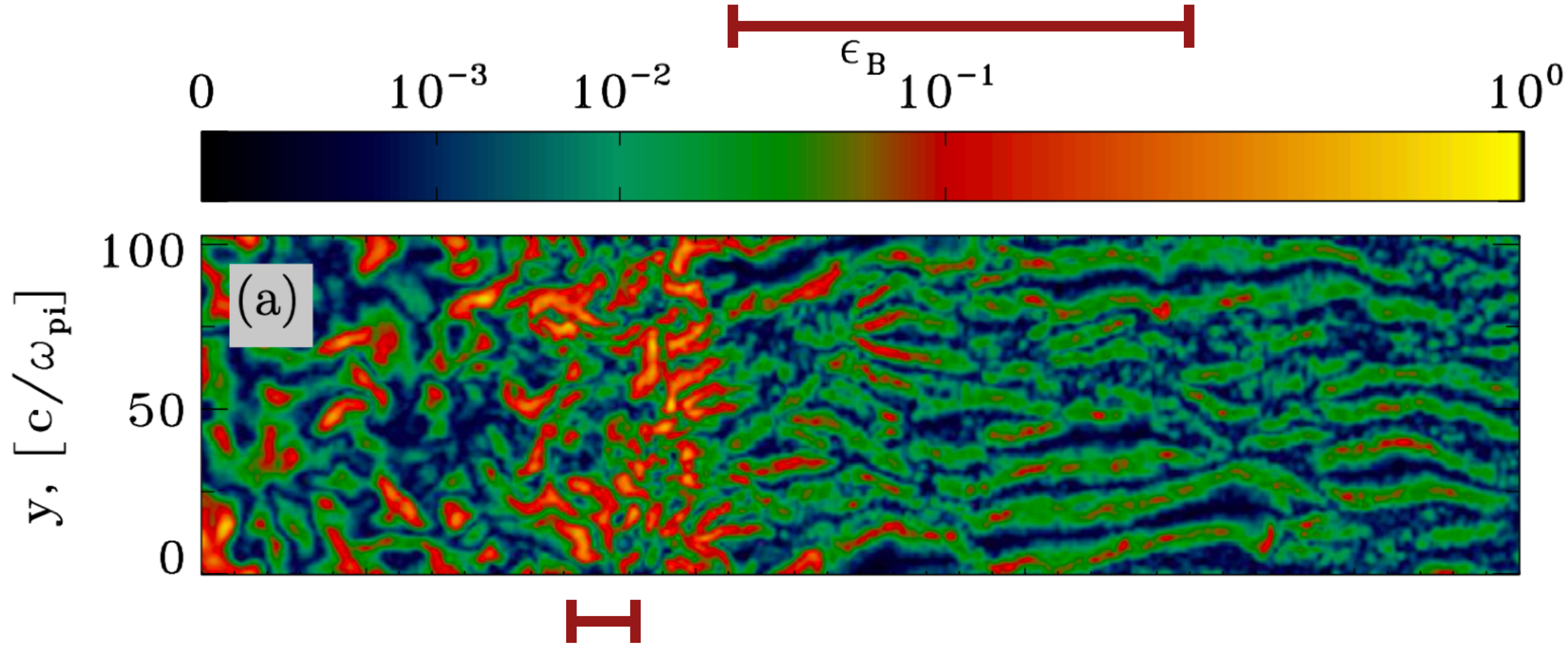
Useful quantity:
Electron strength parameter:

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

$$= \Gamma_{\rm sh}\epsilon_B^{1/2}\frac{\lambda}{c/\omega_{pp}}\frac{m_i}{m_e} \sim 10^4\frac{\Gamma_{\rm sh}}{10}$$

Taking parameters from PIC simulations

Characteristic strength $\epsilon_B \sim 0.1$



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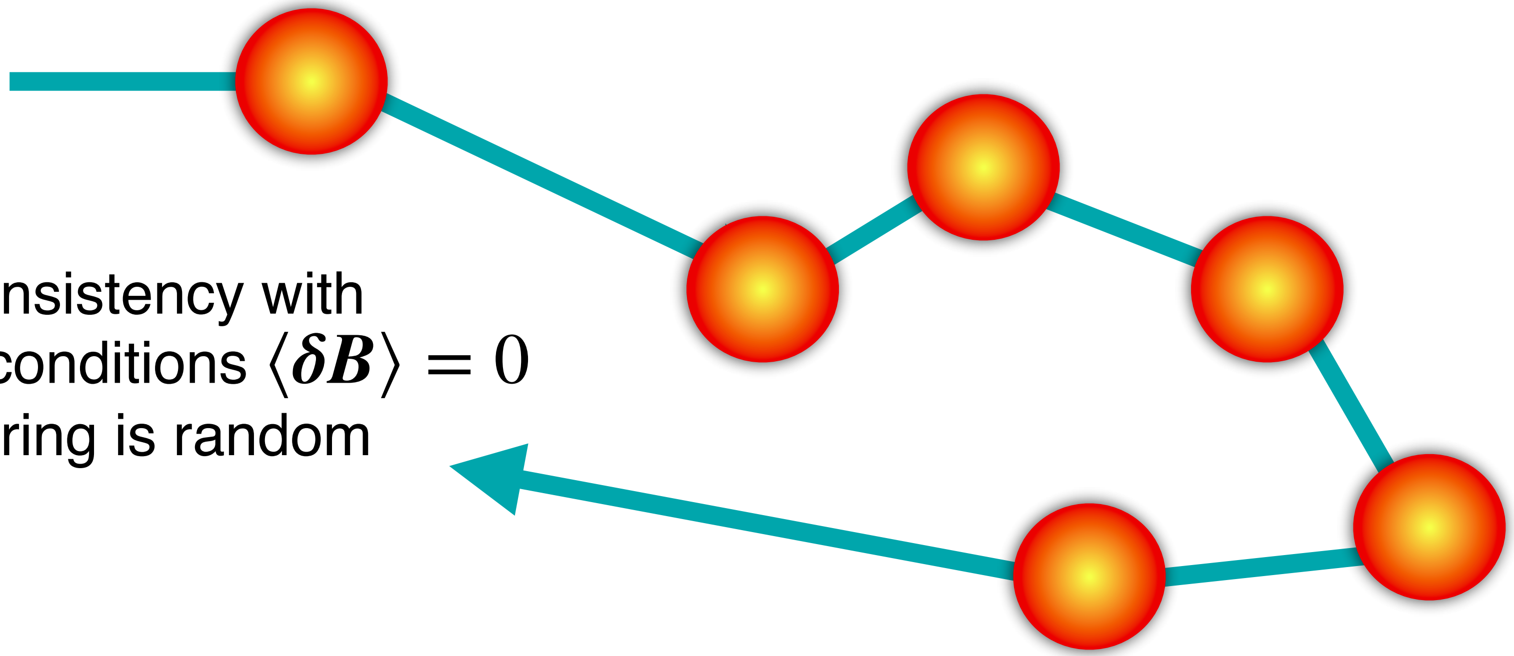


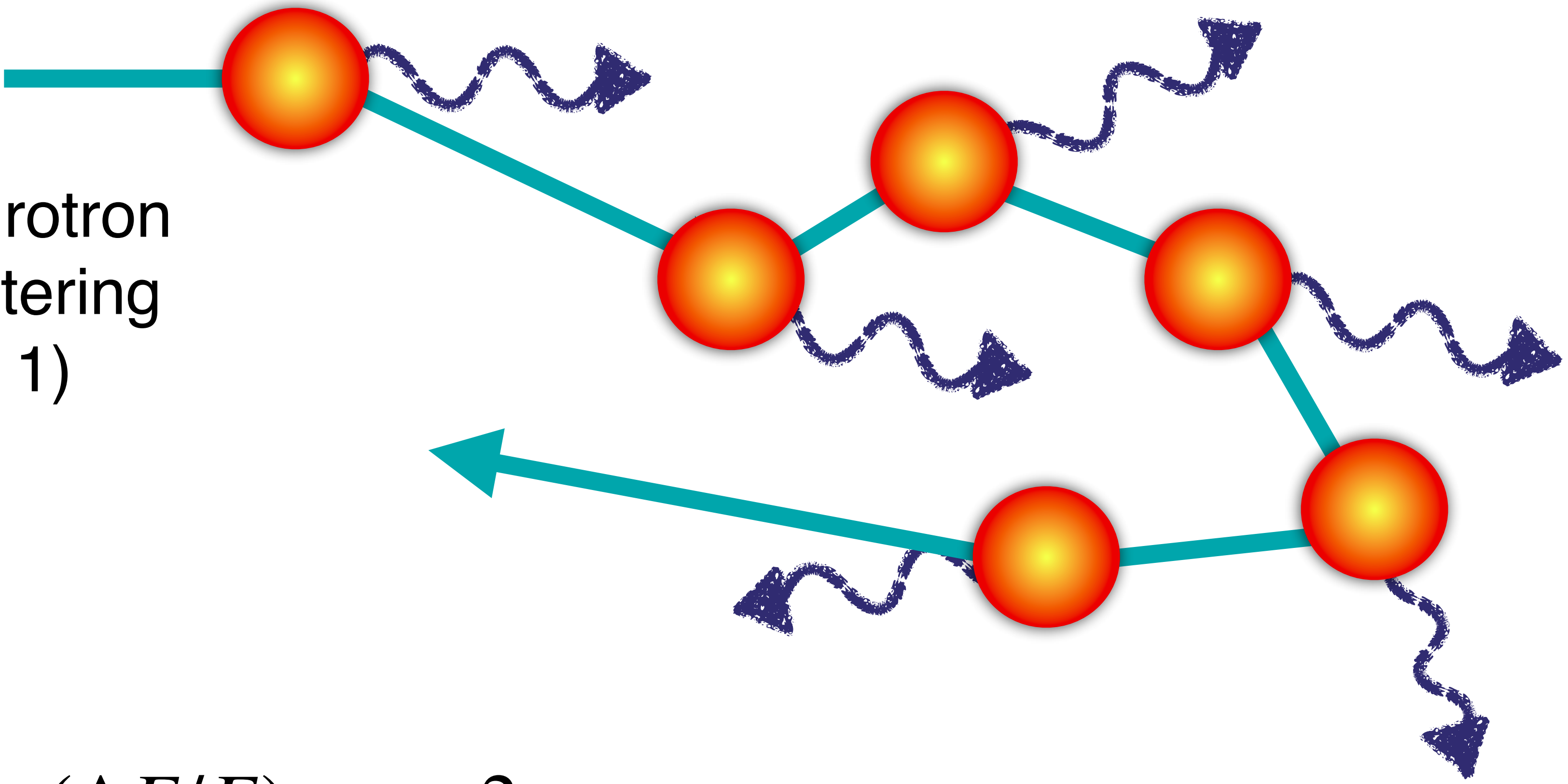
For consistency with
MHD conditions $\langle \boldsymbol{\delta B} \rangle = 0$
Scattering is random

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
$\nu_{\rm sc} = t_{\rm sc}^{-1} \approx D_\theta$

Maximum Electron Energy - I



Electron emits synchrotron photons in each scattering event (not jitter, a >> 1)

Energy gain per cycle $(\Delta E/E)_{\mathrm{gain}} \sim 2$,
electrons lose $(\Delta E/E)_{\mathrm{loss}} \sim \epsilon_B E$ per scattering, but needs $\sim \epsilon_B^{-1}$ scatterings

$$\gamma_{\mathrm{max,ds}} \approx 1.4 \times 10^6 \left[\left(\frac{\lambda}{c/\omega_{pp}} \right)^2 \frac{m_i}{m_e} n_u^{-1} \right]^{1/6}$$

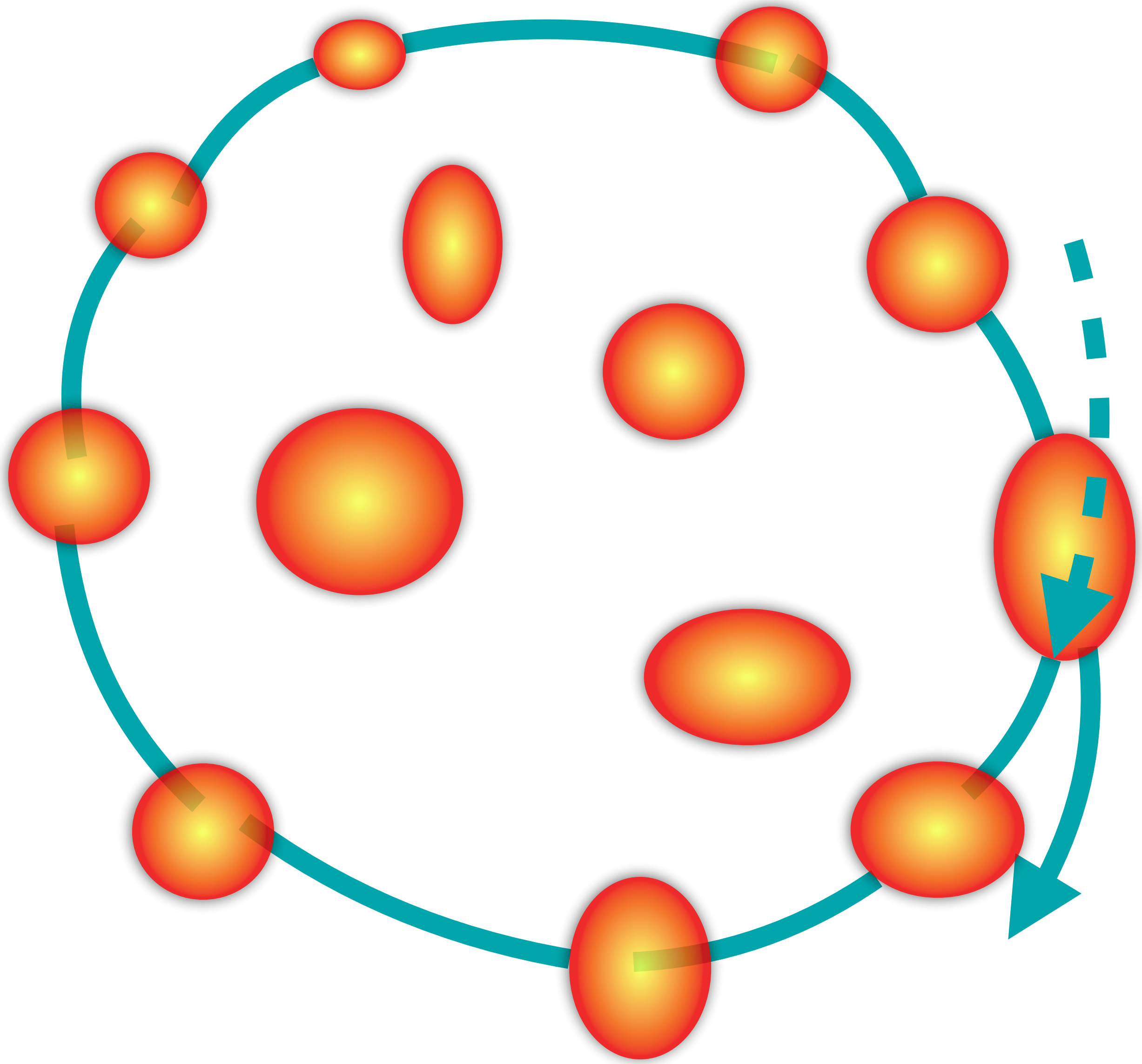
We call this the **cooling limit.**
Note it produces synchrotron photons $h\nu \ll \alpha_{\mathrm{f}}^{-1} m_e c^2$ (see Kirk & BR '10)

Maximum Electron Energy - II

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

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

(Measured in average field)

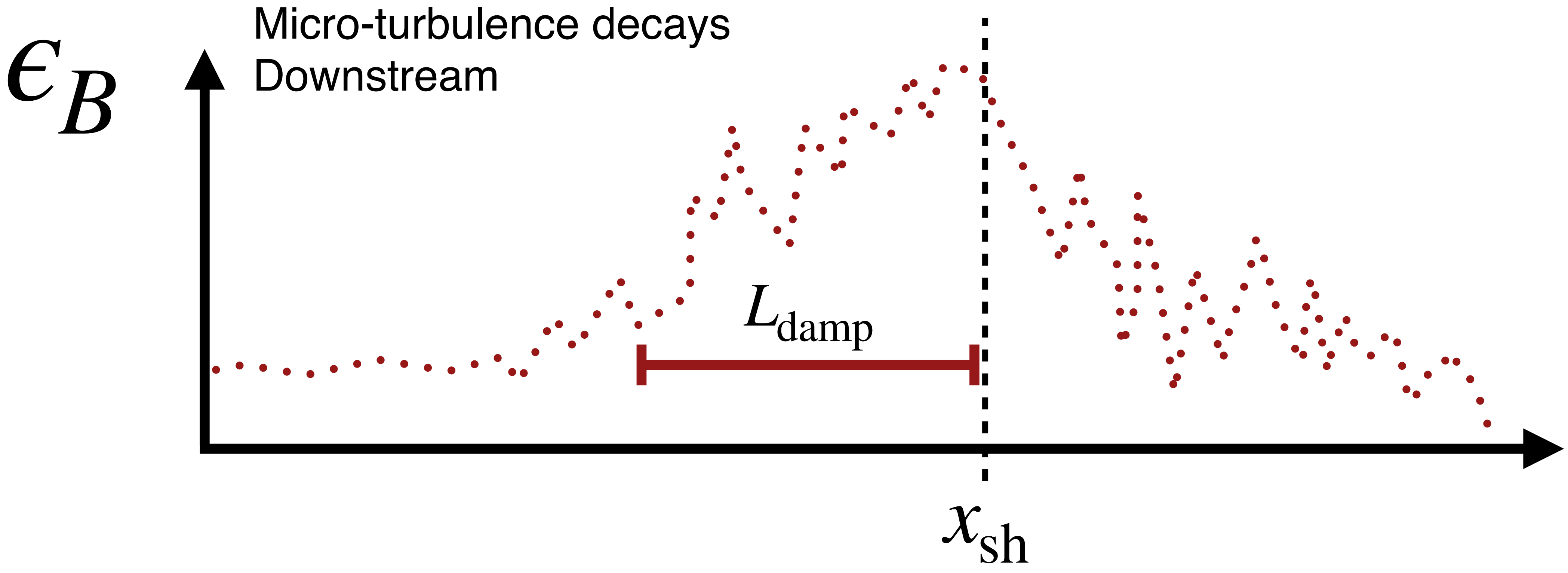


Eventually the continuous gradual deflection in large scale field dominates over the random small angle deflections

$$\gamma_{\rm max,ds} \approx \frac{\lambda}{c/\omega_{pp}} \frac{m_i}{m_e} \, \epsilon_B \, \sigma_u^{-1/2}$$

This is the **magnetised limit,** has important implication for **UHECR** acceleration (Achterberg et al. 01, Lemoine & Pelletier 10, BR & Bell 14)

Maximum Electron Energy - III



If particle penetrates far downstream: $ct_{\mathrm{sc}} > L_{\mathrm{damp}}$, it can not return to shock

setting $L_{\mathrm{damp}} = L_0 \sigma_{\mathrm{us}}^{-1/2} c/\omega_{\mathrm{pp}}$

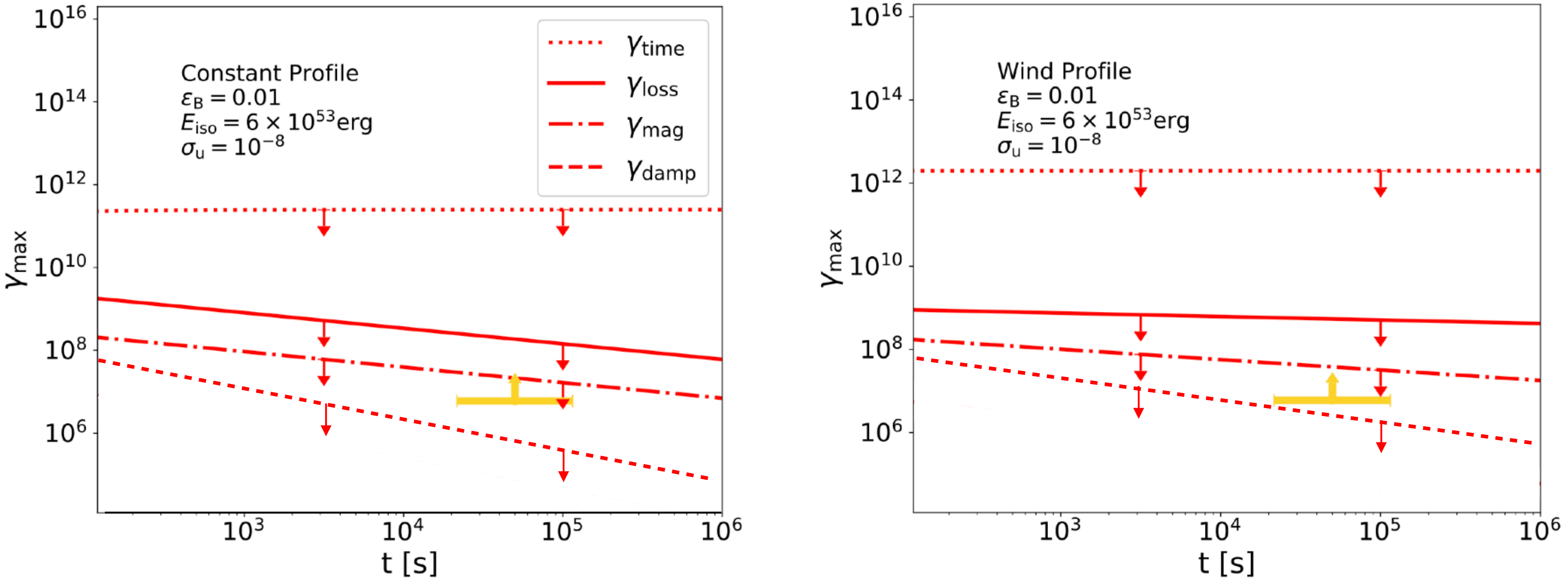
$$\gamma_{\mathrm{max,ds}} \approx \left(L_0 \frac{\lambda}{c/\omega_{pp}} \epsilon_B \right)^{1/2} \frac{m_i}{m_e} \bar{\gamma}\, \sigma_u^{-1/4}$$

We call this the **damping limit.**

For most circumstances it is the most restrictive (unless $L_0 \gg 1$)

Max. energy in self-similar blast wave

Doppler boosted $\gamma_{\max}$, using Blandford & McKee solution



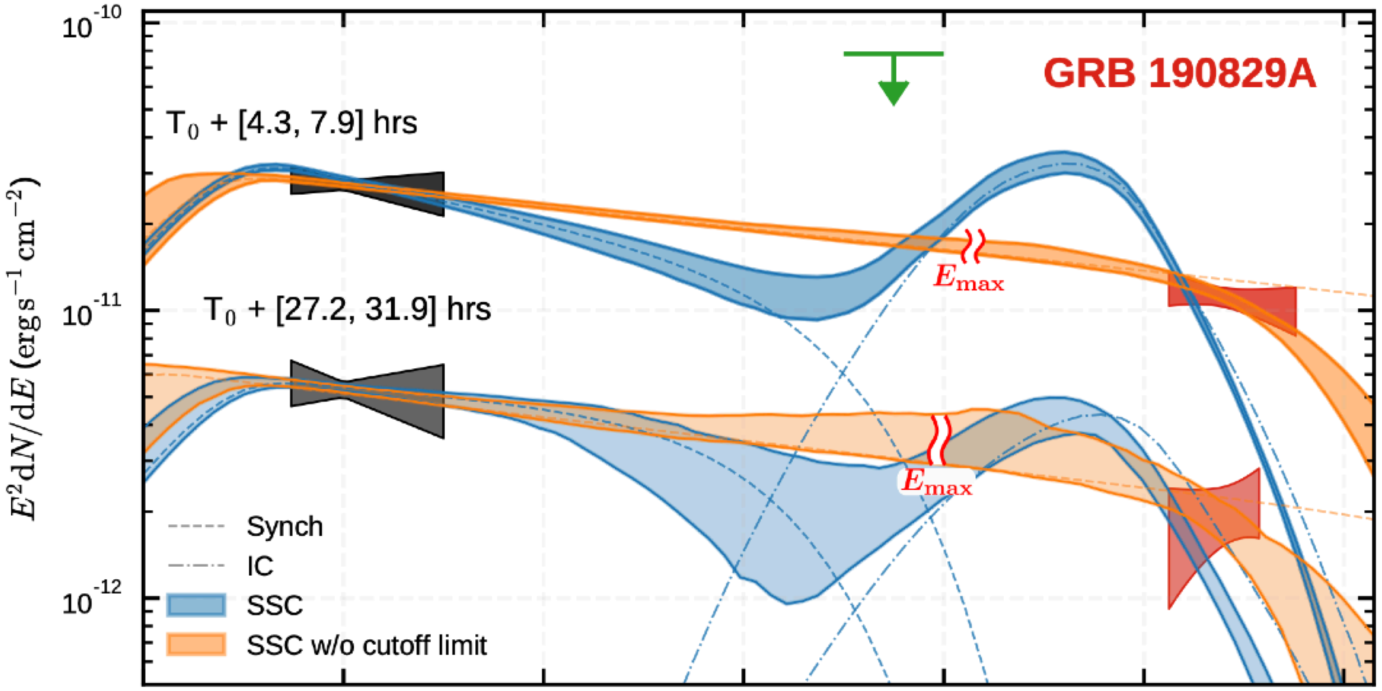
Both cases fixed to ambient Alfvén velocity $\mathrm{v}_A \approx 50\ \mathrm{km\ s}^{-1}$, $\epsilon_B = 0.01$

Many Single zone models of GRB afterglows assume $\epsilon_B \ll 0.01$.
A potential challenge for the single zone shock models of GRBs?

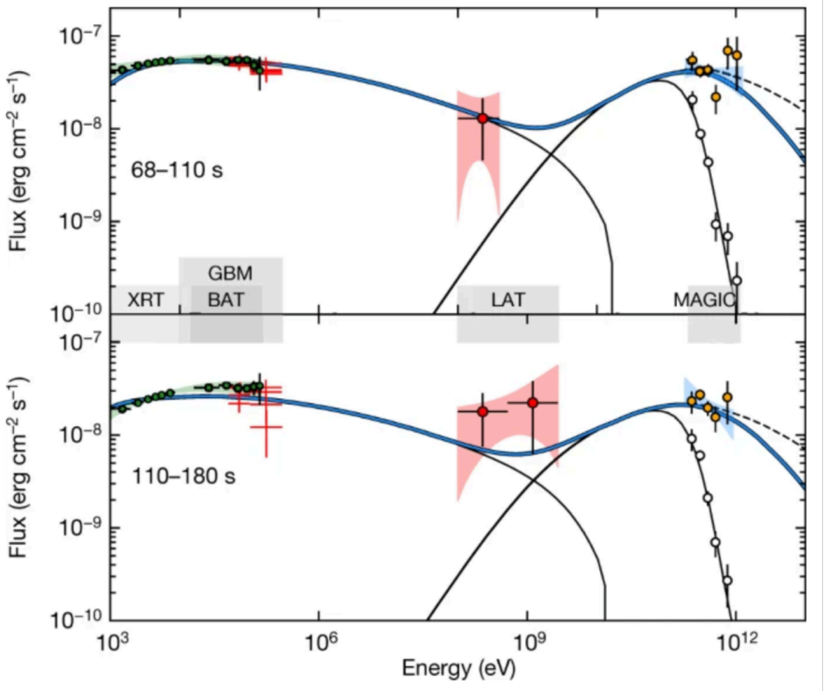
Z. Huang et al. ApJ in press

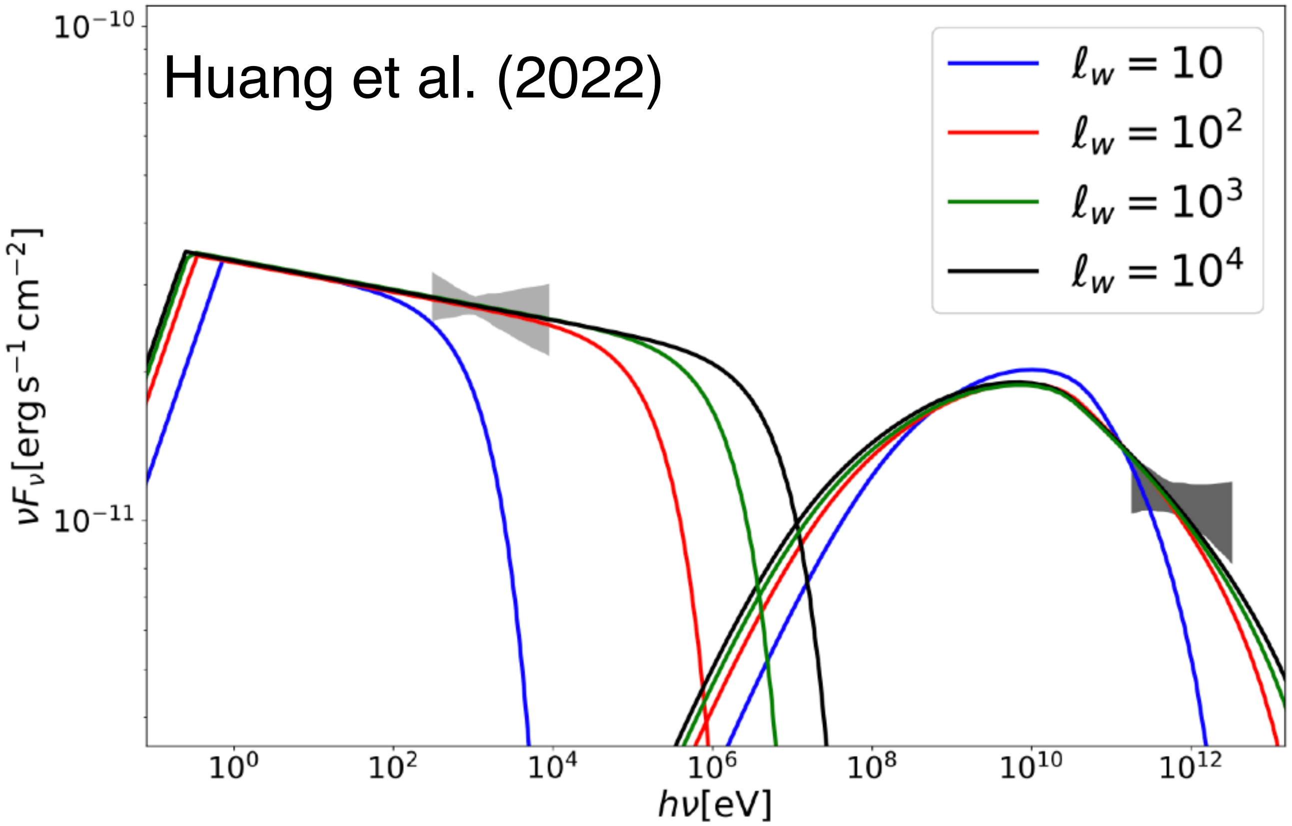
Application to TeV detected Afterglows

HESS Collaboration 2020



MAGIC collab. (2019)




Huang et al. (2022)

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

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

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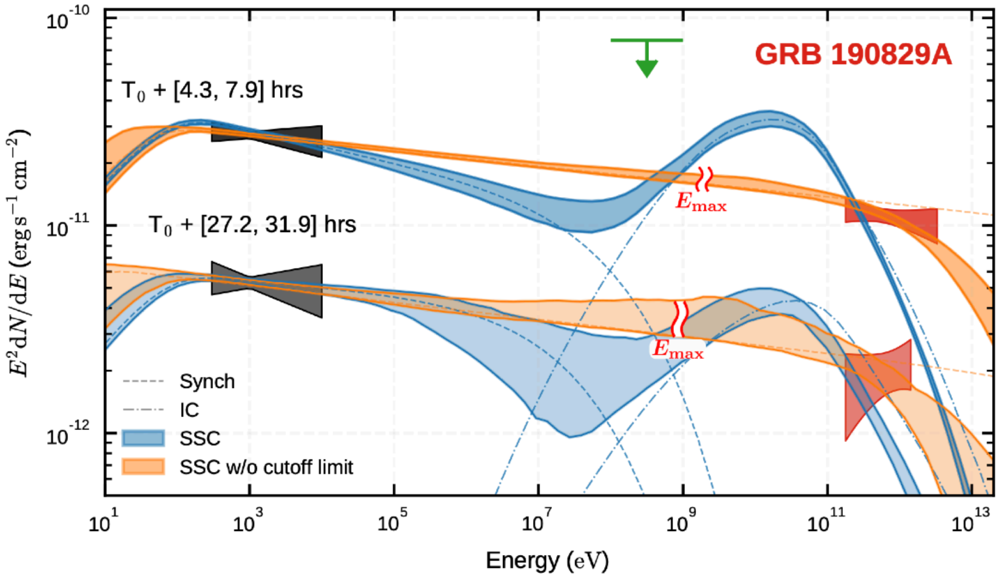

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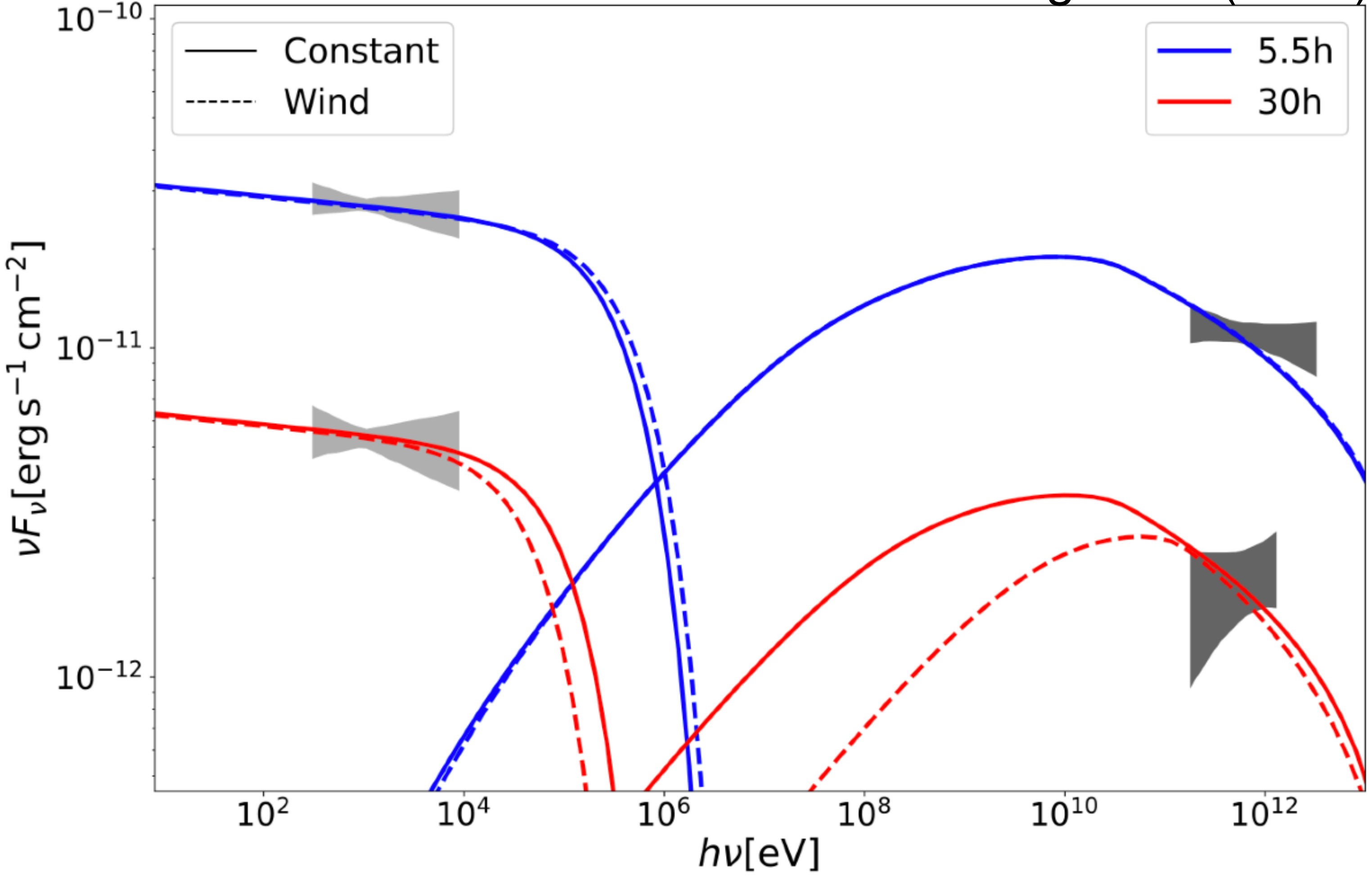
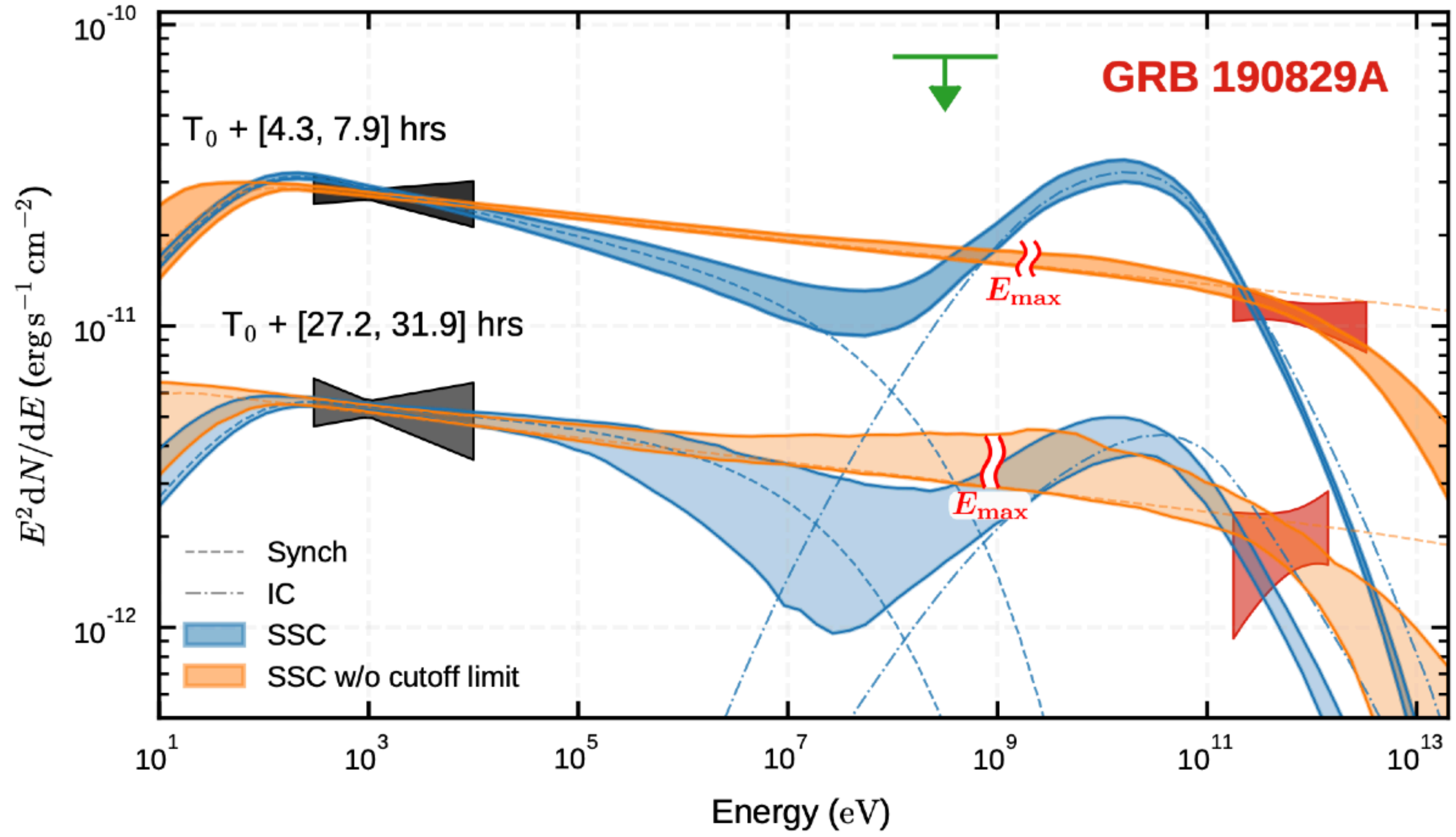


Using $\ell_{\rm w} = 100$ we attempt to fit GRB 190829A

TeV spectrum too steep to account for the HESS data in VHE gamma-rays due to Klein-Nishina suppression.

Application to TeV detected Afterglows

HESS Collaboration 2020



Should we consider serious alternatives to external shock model?

The so-called synchrotron burn-off limit at $\approx 100\Gamma_{\rm sh}$ MeV is very much a single zone concept (for example the Crab flares)

By de-coupling acceleration zone and emission zone TeV synchrotron photons are possible, but requires multi-PeV electrons (e.g. Kirk, BR & Giacinti ’21)

Conclusions

- Observations of relativistic shocks are testing our theories and providing new insight.

- TeV data provides crucial constraint on models

- Current observations reveal several gaps in our understanding
  1. To account for X-ray, we need λ much larger than PIC predictions
  2. Spectrum is generally steeper than implied by observations
  3. TeV gamma-ray spectrum is harder than theory can account for

- Larger λ, larger $E_{\max}$

$$E_{\max} \approx \left(\frac{\Gamma_{\rm sh}}{100}\right)^2 \left(\frac{\lambda_{\rm d}}{10c/\omega_{\rm pp}}\right) \left(\frac{\sigma_{\rm d}}{10^{-2}}\right) \left(\frac{\sigma_{\rm u}}{10^{-8}}\right)^{-1/2} \ {\rm PeV}$$

- Should we be considering alternatives to the external shock model?

Dziękuję bardzo