(Relativistic) collisionless shock waves in the very high energy Universe…

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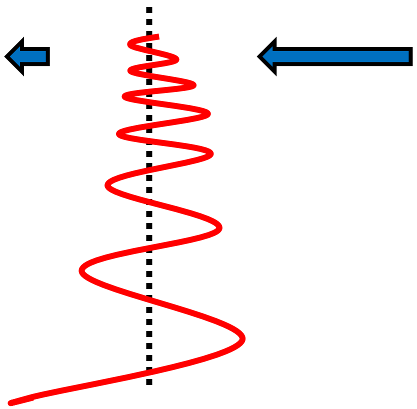
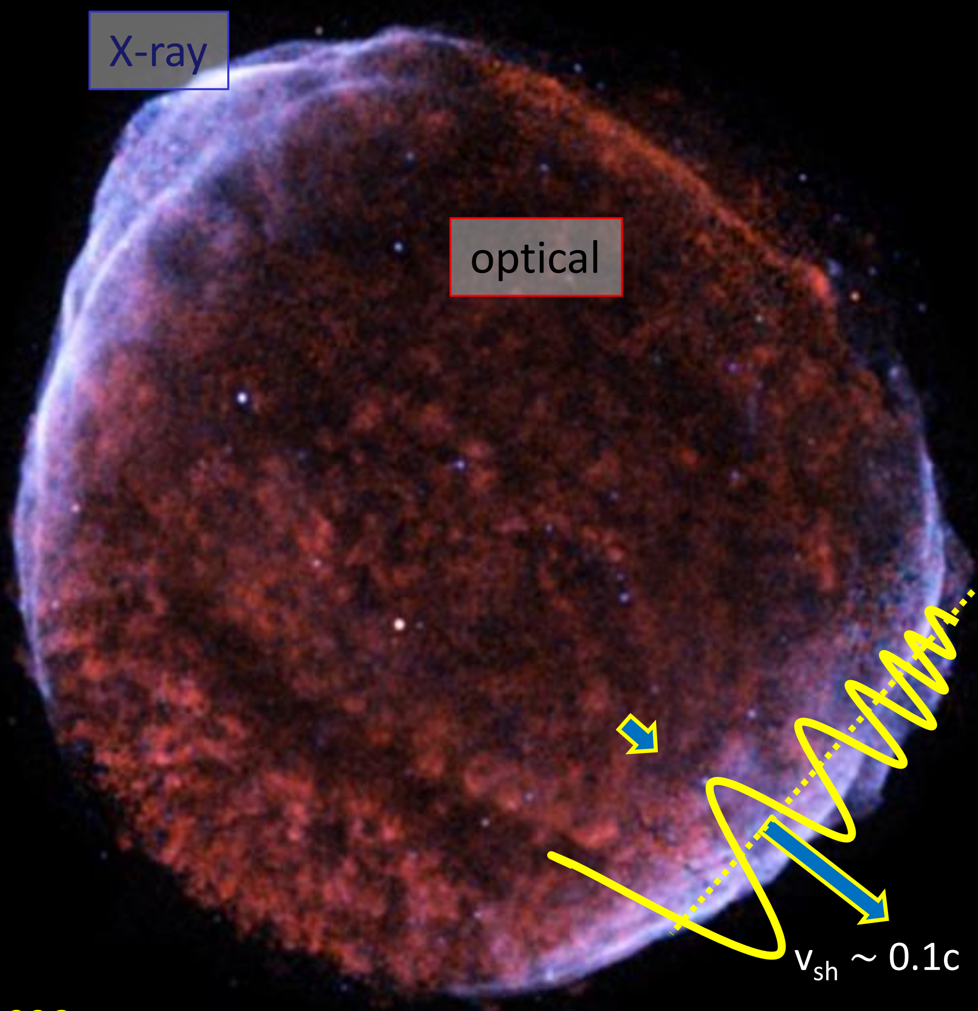


… in collaboration with:

Guy Pelletier (IPAG), Laurent Gremillet (CEA), Arno Vanthieghem (IAP)

Supernova remnant forward shock waves



SN1006

Fermi mechanism at shock waves:

→ a (test-)particle gains energy by bouncing back and forth on magnetic inhomogeneities on both sides of the shock…

(or by drifting along motional E fields in quasi-perpendicular shocks)…

→ competition between energy gain and escape (downstream) leads to a power-law…

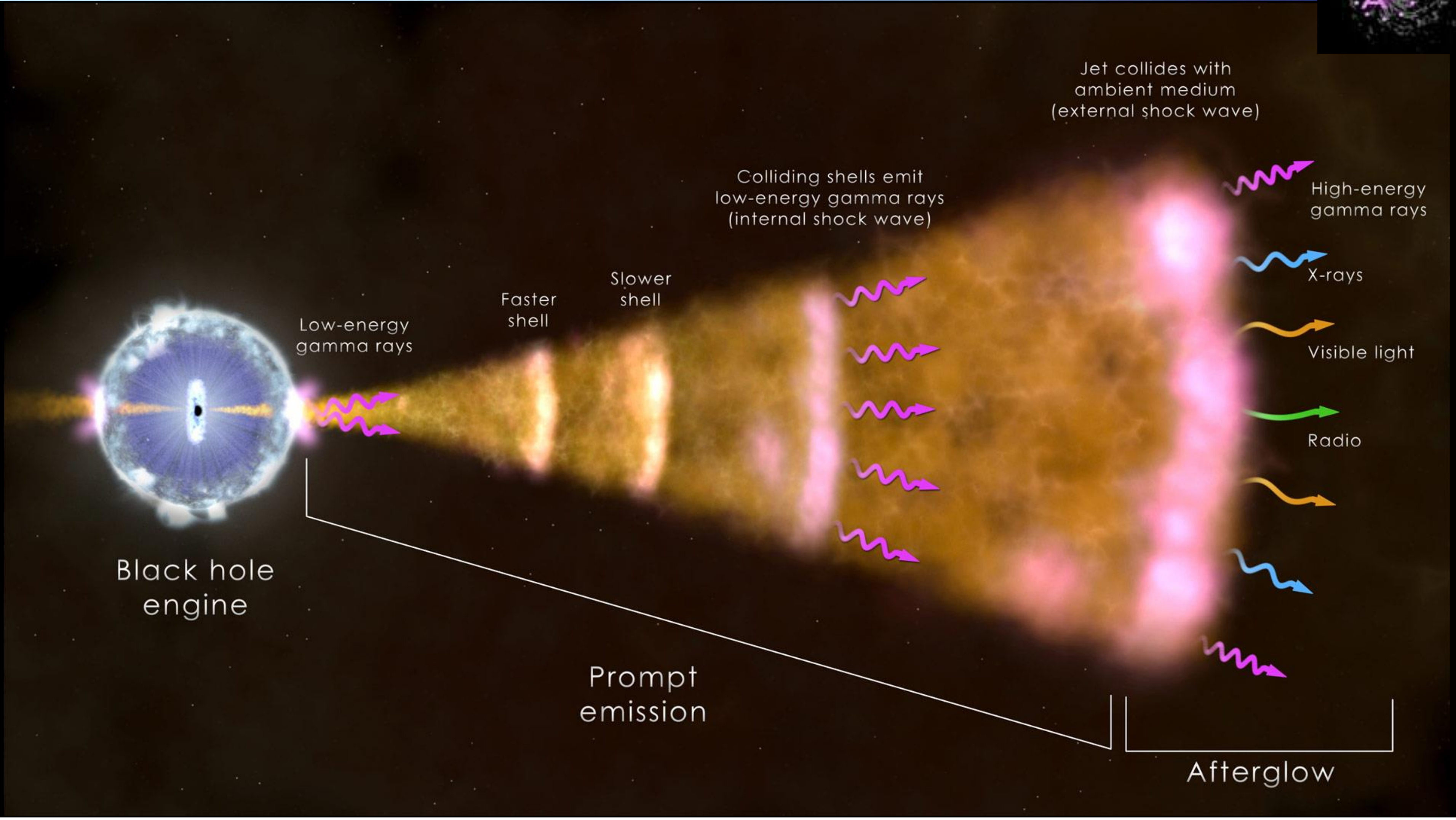
$$\frac{\mathrm{d}N}{\mathrm{d}p} \propto p^{-s}$$

with index:

$$s = 1 + \frac{t_{\rm acc}}{t_{\rm esc}} \simeq 2.0 + \mathcal{O}\left[\left(\frac{v_{\rm sh}}{c}\right)^2\right]$$

Axford+ 77, Krimsky 77, Bell 78, Blandford & Ostriker 78

Motivations: gamma-ray bursts

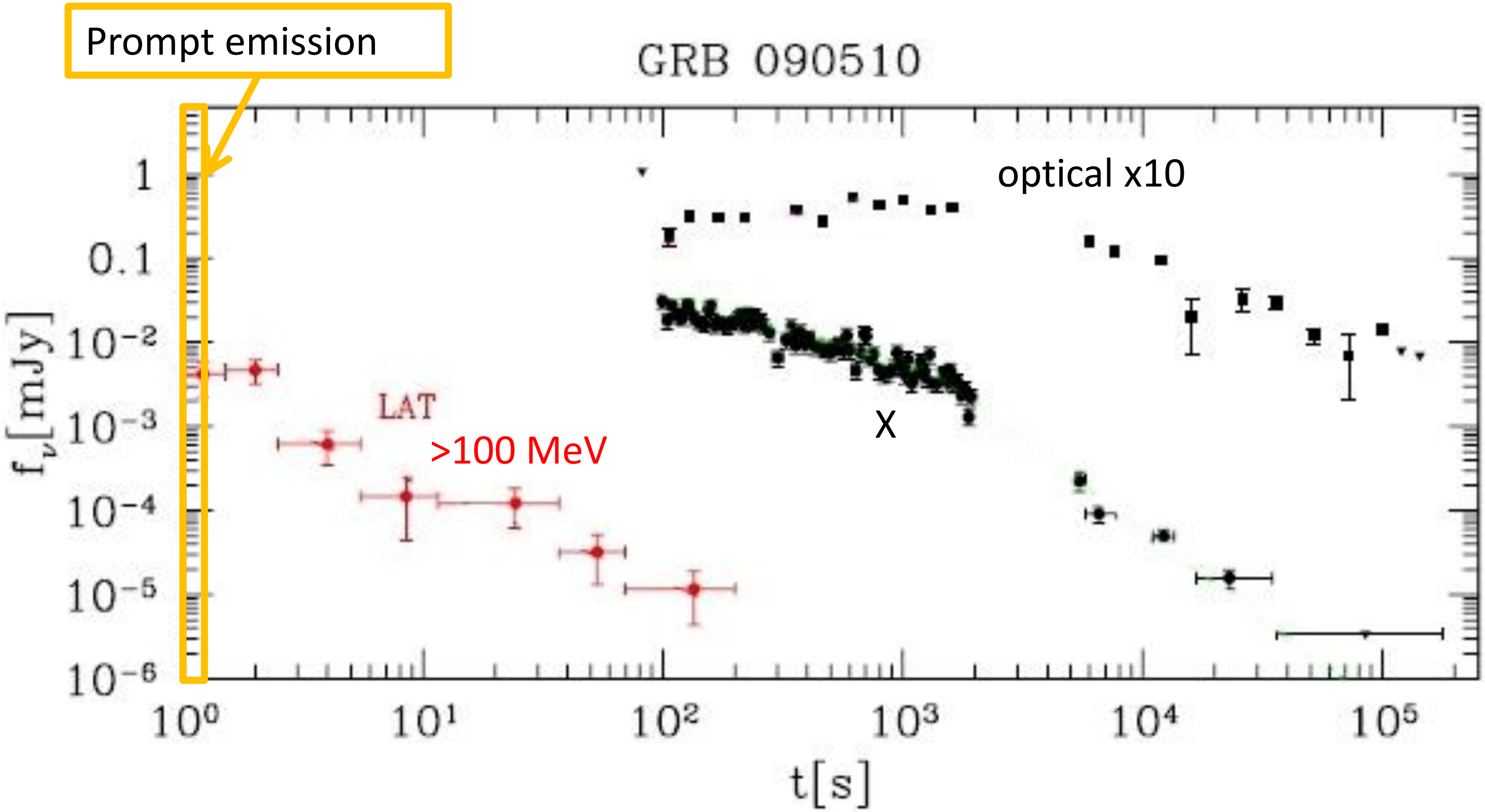


Gamma-ray burst:

- output energy: $E \sim 10^{46}\,\mathrm{J}\,\frac{\Delta\Omega}{4\pi} \sim 0.1 M_\odot c^2 \frac{\Delta\Omega}{4\pi}$
- typical bulk Lorentz factor: $\Gamma_{\mathrm{jet}} \equiv \left[1 - (v_{\mathrm{jet}}/c)^2\right]^{-1/2} \sim 100 - 1000$

Motivations : gamma-ray bursts

Multiwavelength data for GRB 090510 (prompt duration 0.9sec!)

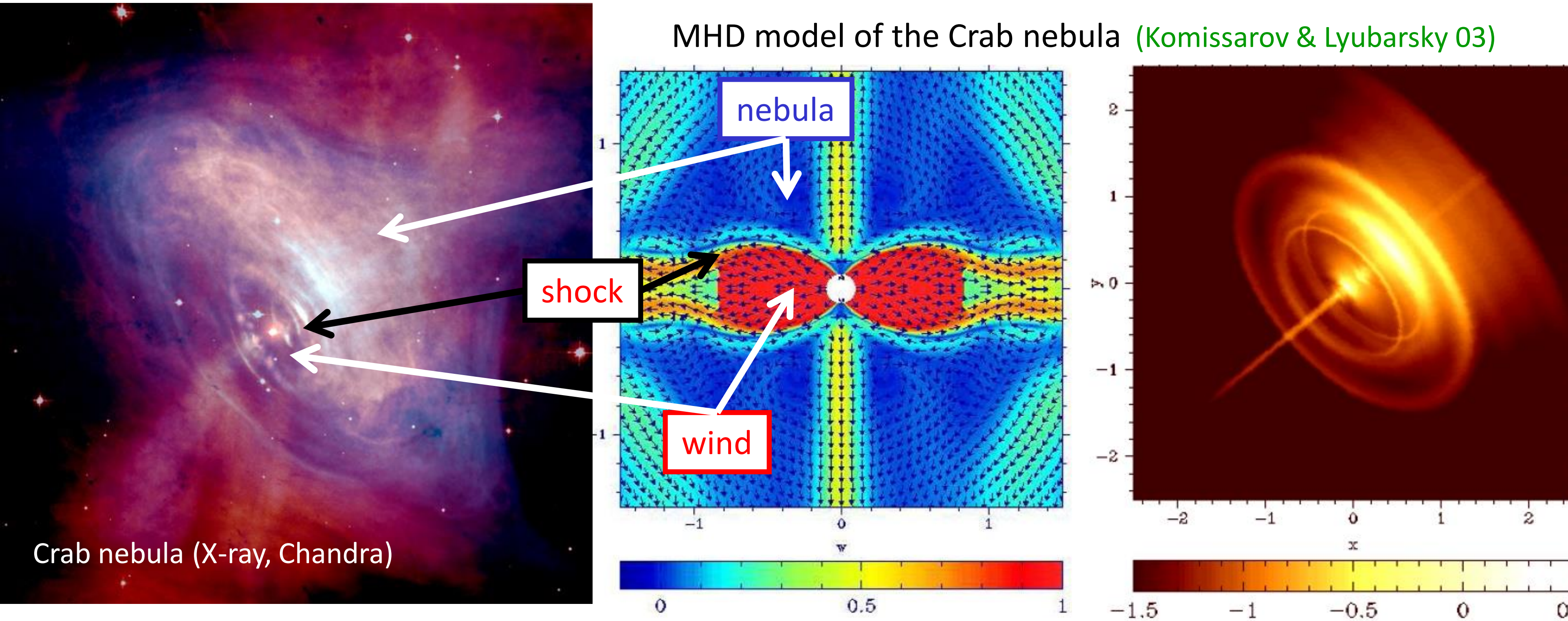


Afterglow emission: interpreted as synchrotron (+inverse Compton?) radiation from electrons accelerated at the external shock wave (interaction of the wind with the ISM)…

Kumar & Barniol-Duran 09, 10

Motivations: pulsar wind nebulae

MHD model of the Crab nebula (Komissarov & Lyubarsky 03)



<u>Modelling of the nebular emission:</u> (e.g. Aharonian & Atoyan 96)

- synchrotron emission seen up to 100MeV, inverse Compton emission beyond…

- electrons are heated up to a Lorentz factor $\sim 10^6$ …
- acceleration proceeds up to maximal Lorentz factor $\sim 10^9$!

- physics of the termination shock? Moderate magnetization, Lorentz factor $\sim 10^4$ - 10^6 ?!

Motivations: origins of (UHE) cosmic rays

Connection to VHE cosmic ray physics:

→ fast acceleration rate is crucial to reach UHE

e.g. to produce $10^{20}E_{20}$ eV particles, source must output luminosity:

$$L_B \gtrsim 10^{45}\, E_{20}^2\, Z^{-2}\, \left(t_{\rm acc}/t_{\rm g}\right)^2\ {\rm erg/s}$$

… and for sub-relativistic shocks, $t_{acc} \gg t_g$

→ relativistic shocks are outstanding dissipation agents:

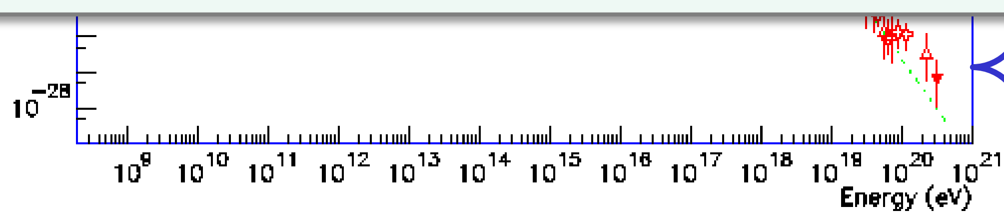
e.g. 10% of incoming $\gamma^2\, nmc^2$ available for dissipation into non-thermal powerlaw
… if acceleration takes place…

… vs: to match the UHECR flux above 10^{19}eV, a transient source needs to output

$$E_{\rm UHECR} \approx 10^{53}\,{\rm erg}\,\dot n_{-9}^{-1} \qquad (\dot n\ {\rm in\ Mpc^{-3}yr^{-1}})$$

c flux of relativistic particles

on non-thermal processes in
e…



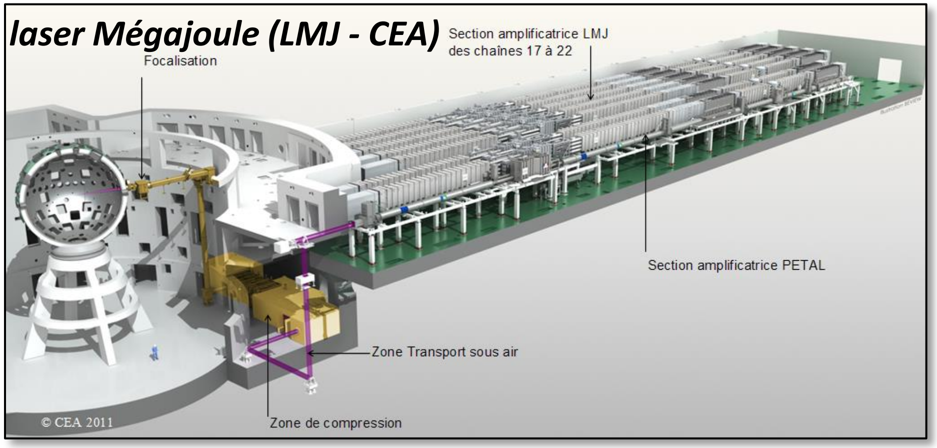
-high energy cosmic rays (UHECR)

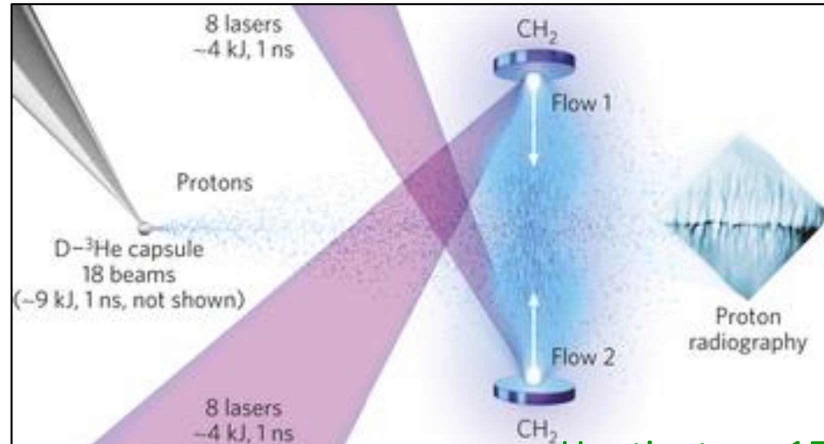
…the most energetic particles in the observable Universe …

~ 1 /km²/century above 10^{20} eV

Motivations: fundamental & laboratory astrophysics

Generation of a (sub-relativistic) collisionless shock in giant laser facilities:



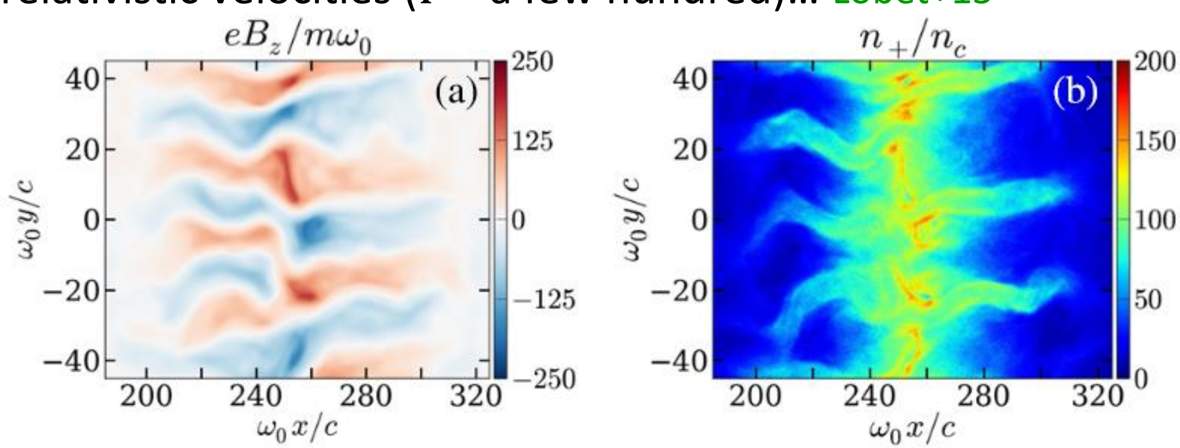


Huntington+ 15

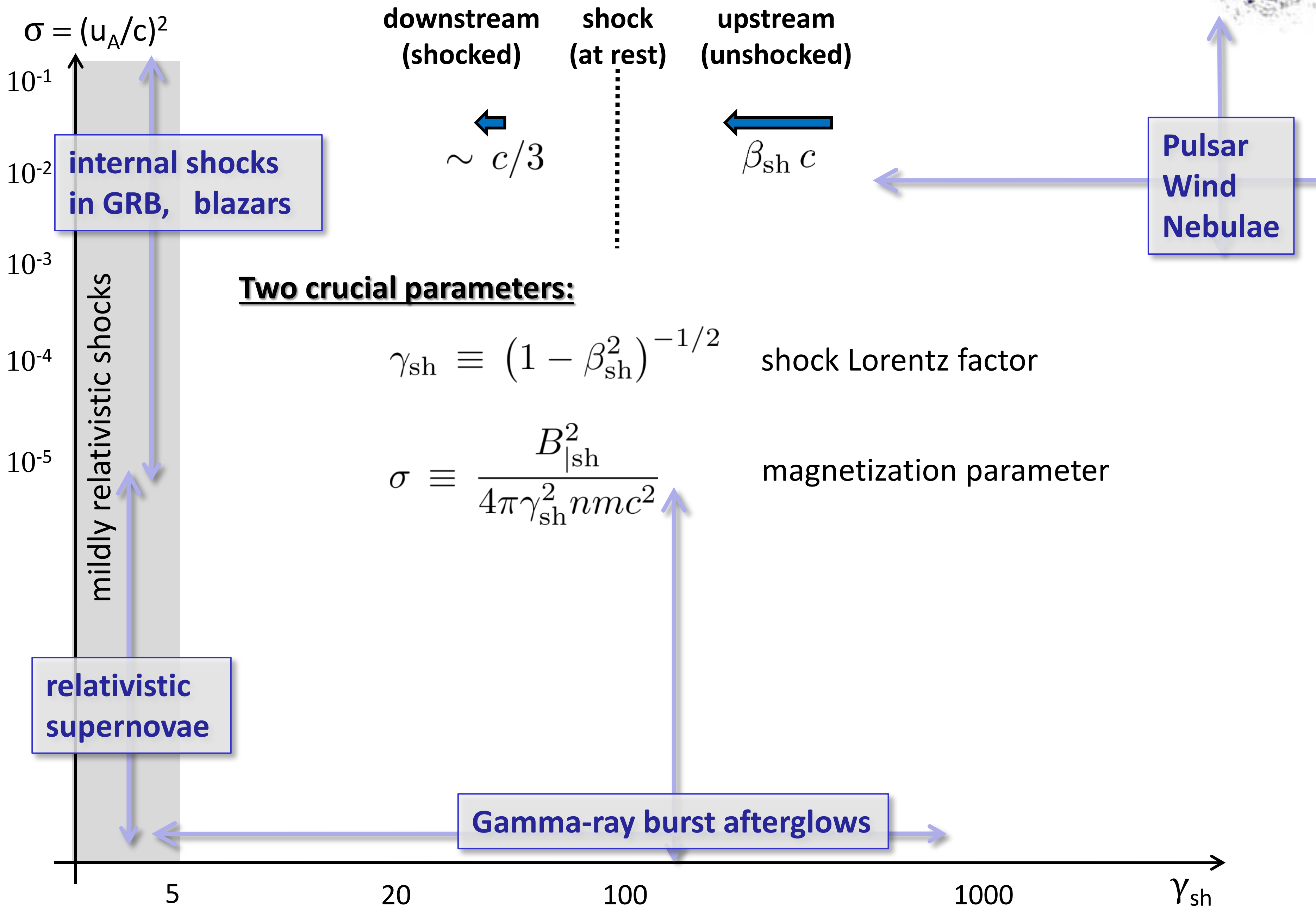
Generation of a relativistic pair collisionless shock in future laser facilities:

→ irradiation of solid foils by short pulse (~60 fs), high energy (~100 kJ) lasers at peak intensity ~ 10^{23} - 10^{24} W/cm^2 generates plasmas of electrons and positrons outflowing at relativistic velocities (Γ~ a few hundred)… Lobet+15

B $\gtrsim 10^6$ T



Notations



Two crucial parameters:

$$\gamma_{\rm sh} \equiv \left(1-\beta_{\rm sh}^2\right)^{-1/2}$$ shock Lorentz factor

$$\sigma \equiv \frac{B_{|\rm sh}^2}{4\pi\gamma_{\rm sh}^2 nmc^2}$$ magnetization parameter

Notes of caution

Microphysics is essential to phenomenology:

e.g. post-shock temperature sets typical/peak energy of radiating electrons…

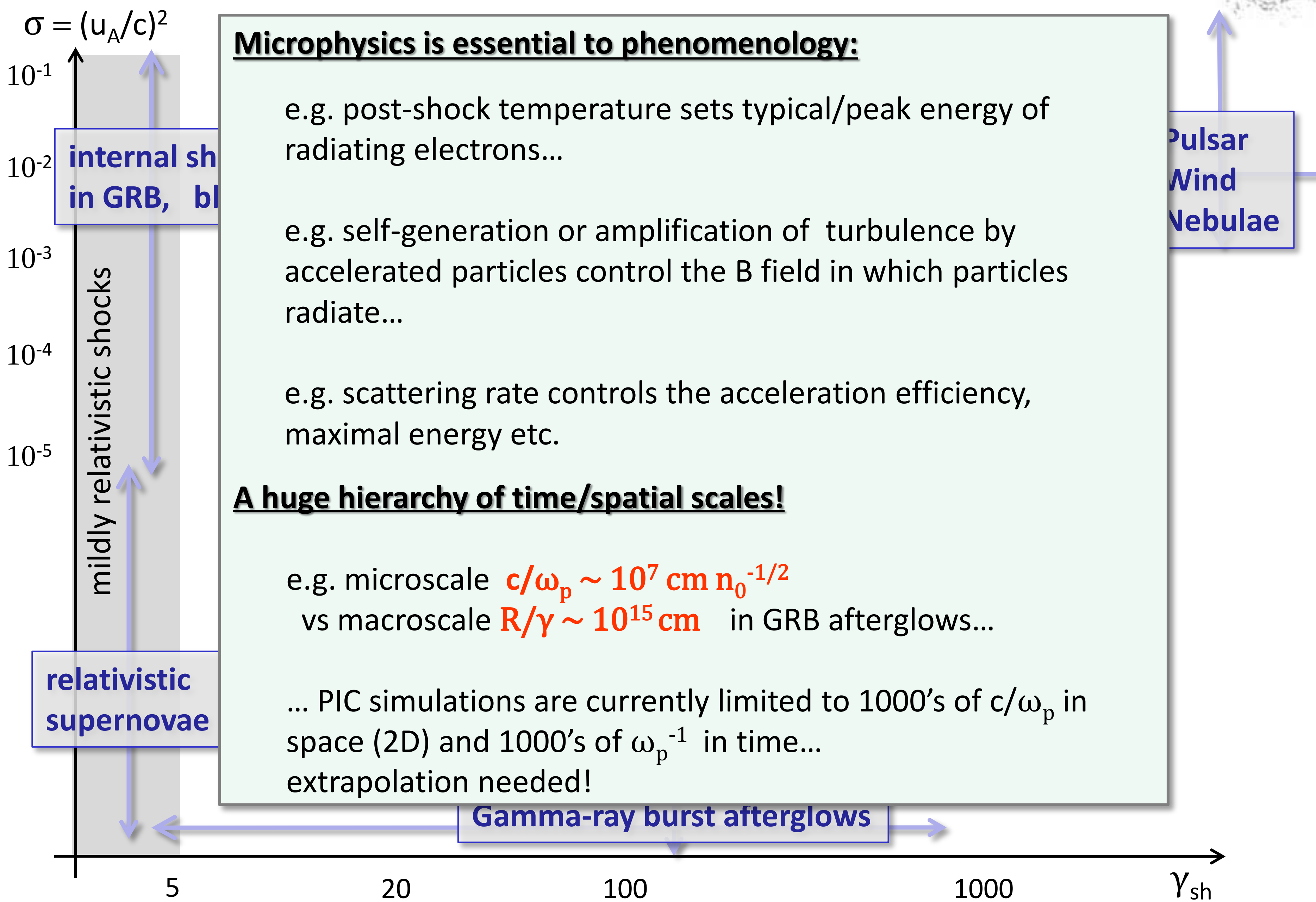
e.g. self-generation or amplification of turbulence by accelerated particles control the B field in which particles radiate…

e.g. scattering rate controls the acceleration efficiency, maximal energy etc.

A huge hierarchy of time/spatial scales!

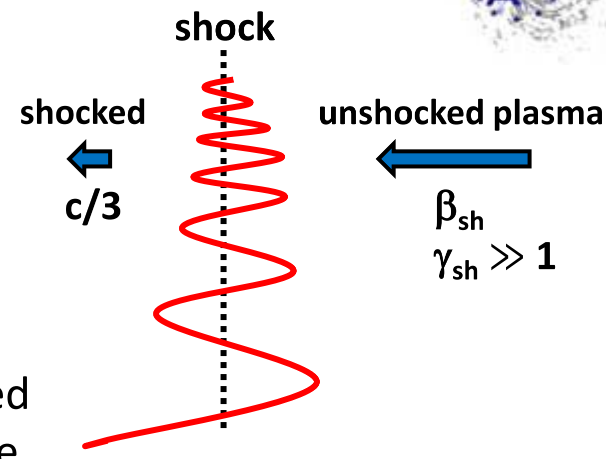
e.g. microscale $c/\omega_p \sim 10^7\,\mathrm{cm}\; n_0^{-1/2}$
vs macroscale $R/\gamma \sim 10^{15}\,\mathrm{cm}$ in GRB afterglows…

… PIC simulations are currently limited to 1000's of c/ω_p in space (2D) and 1000's of ω_p^{-1} in time…
extrapolation needed!



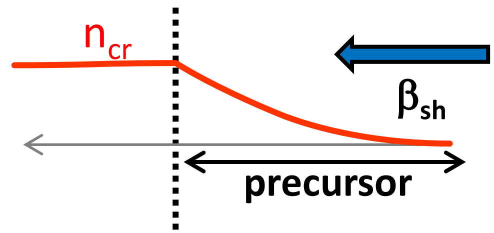
The relativistic Fermi process and micro-turbulence

A modern view of the Fermi process:



→ Fermi acceleration takes place through repeated scatterings of a particle in a turbulence around a shock front

→ in relativistic shocks, electromagnetic instabilities triggered by the interpenetration of the background plasma and the accelerated particles generate the turbulence which mediates the collisionless shock and which accelerates particles ! (ML+ 06, Spitkovsky 08, Pelletier+09)



Zooming-in with Particle-In-Cell simulations:

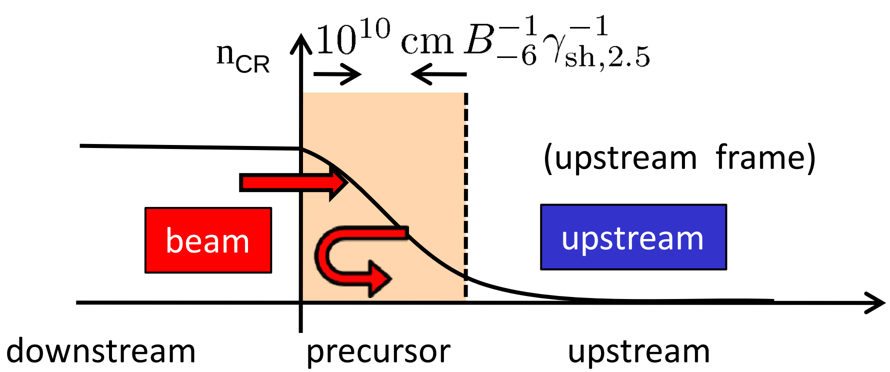
(Spitkovsky 08, Sironi+09,11, 13, Nishikawa+09, Martins+09, Haugbolle11 ….)

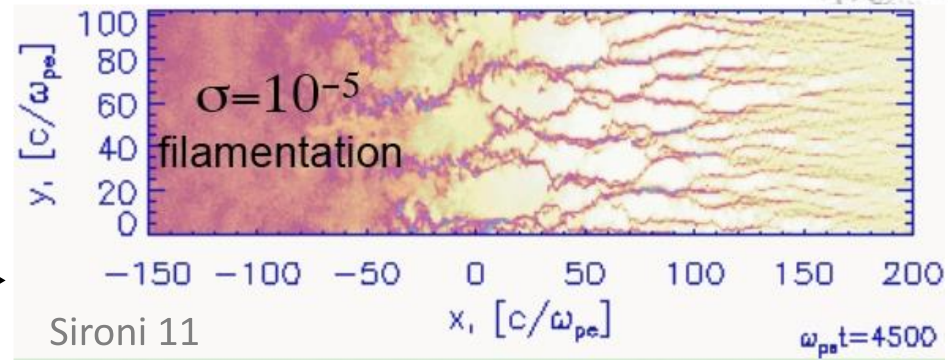
→ PIC code: electromagnetic N-body code solving Maxwell + dynamical equations with particle distribution modelled by particles on a (spatial) grid…

→ allows to solve for kinetic physics and to probe non-linear relationship between particles and (collective) fields…

→ however: time-consuming, longest PIC so far: $\sim 10^4\ \Omega_p^{-1}$ or 0.1% of a dynamical timescale of a gamma-ray burst afterglow…

Micro-instabilities at a relativistic shock front





→ shock reflected and shock accelerated particles move in upstream background field with Lorentz factor γ_{sh}^2, along shock normal:

an unmagnetized beam of Lorentz factor γ_{sh}^2 and opening angle $1/\gamma_{sh}$

→ neutral beam instabilities: (e.g. Bret 09)

Weibel/filamentation (Gruzinov & Waxman 99, Medvedev & Loeb 99, Lyubarsky & Eichler 06, Wiersma & Achterberg 04, 07, Bret et al. 08, ML & Pelletier 10, 11; Rabinak et al. 10, Shaitsultanov et al. 11)

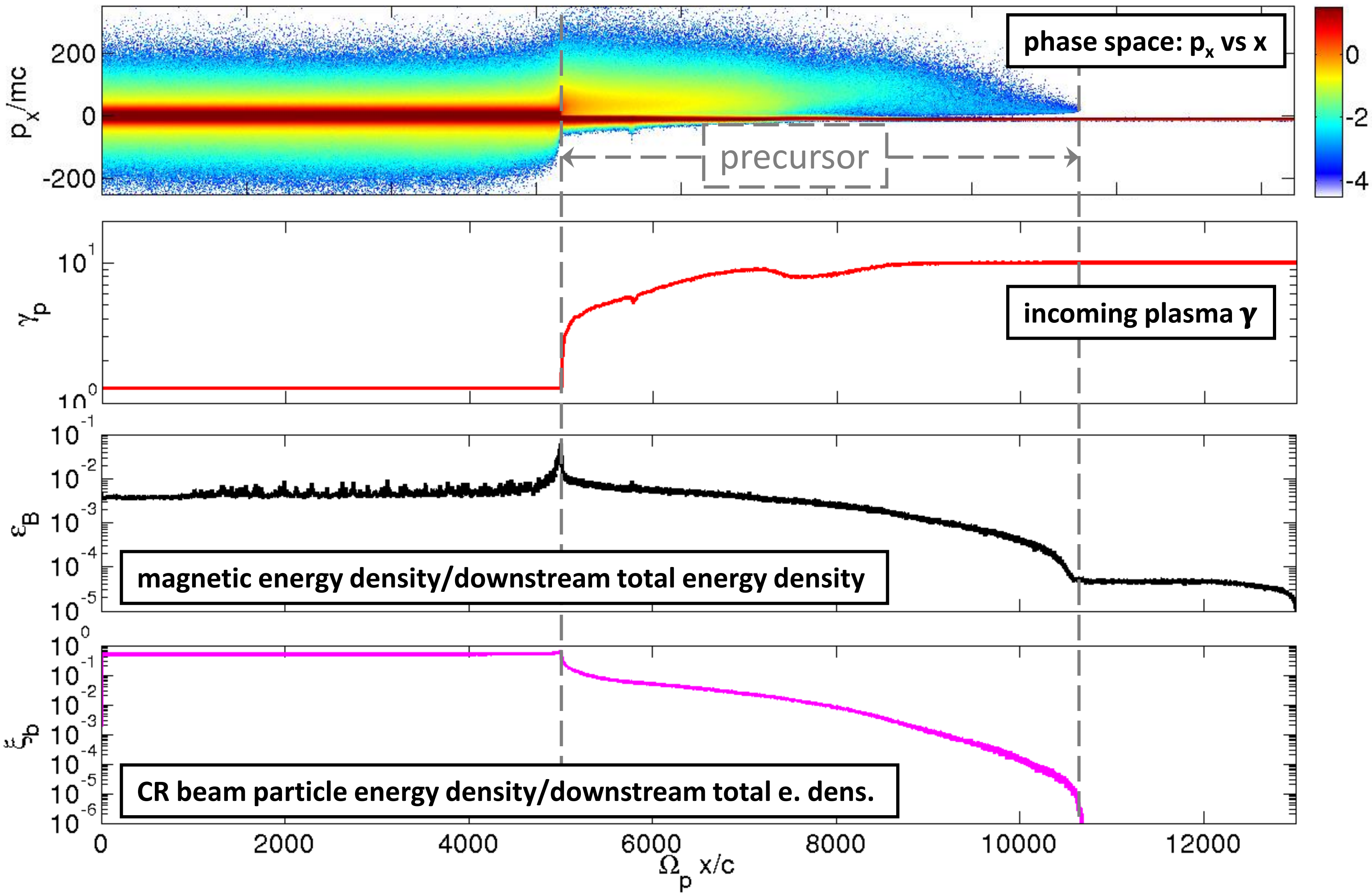
oblique two stream: Bret et al. 05, 08, ML & Pelletier 10,11

→ charged current instabilities:

perpendicular current (ML, Pelletier, Gremillet, Plotnikov 14)

→ main limitation: very short precursor, length $\sim \gamma_{sh}^{-1}\, c/\omega_{ci} \sim \gamma_{sh}^{-1}\,\sigma^{-1/2}\, c/\omega_{pi}$

Zooming in on an unmagnetized collisionless shock

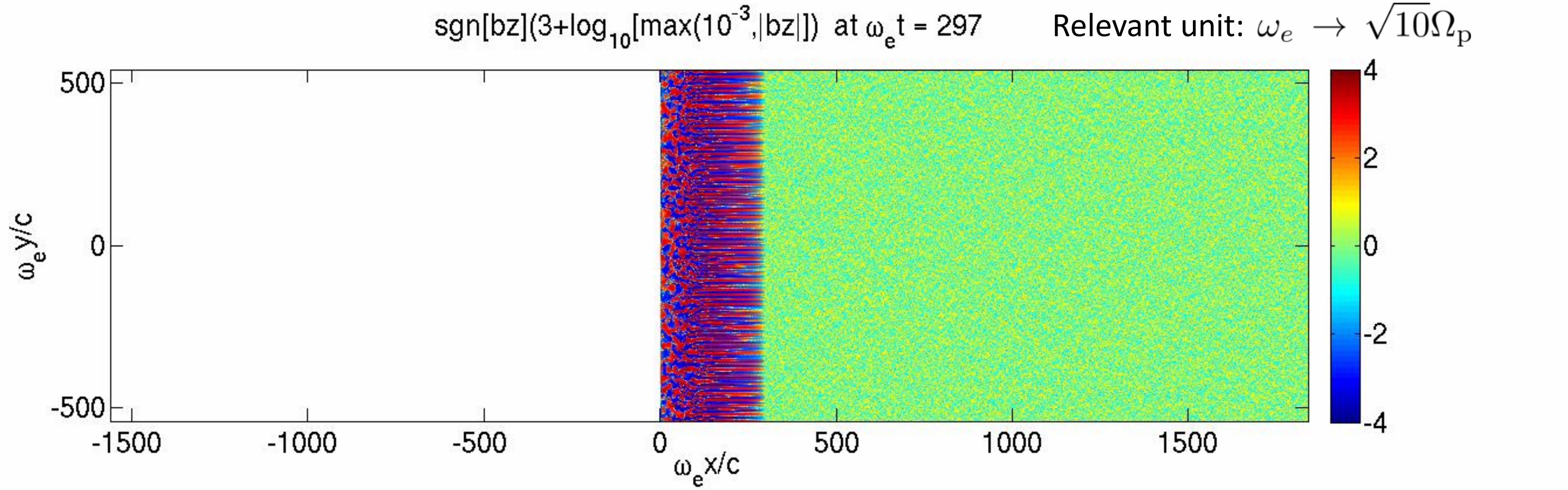


Simulations: A. Vanthieghem @ Curie-NF (CALDER: 1Mh/8000proc)

$\gamma=10$, $L_x L_y cT = 13000 \times 340 \times 10700\ (c\,\Omega_p^{-1})^3$, 2x10 part/cell, $\Delta=0.1\ c\,\Omega_p^{-1}$

Zooming in on an unmagnetized collisionless shock

Magnetic field generation in a relativistic collisionless shock (downstream rest frame):



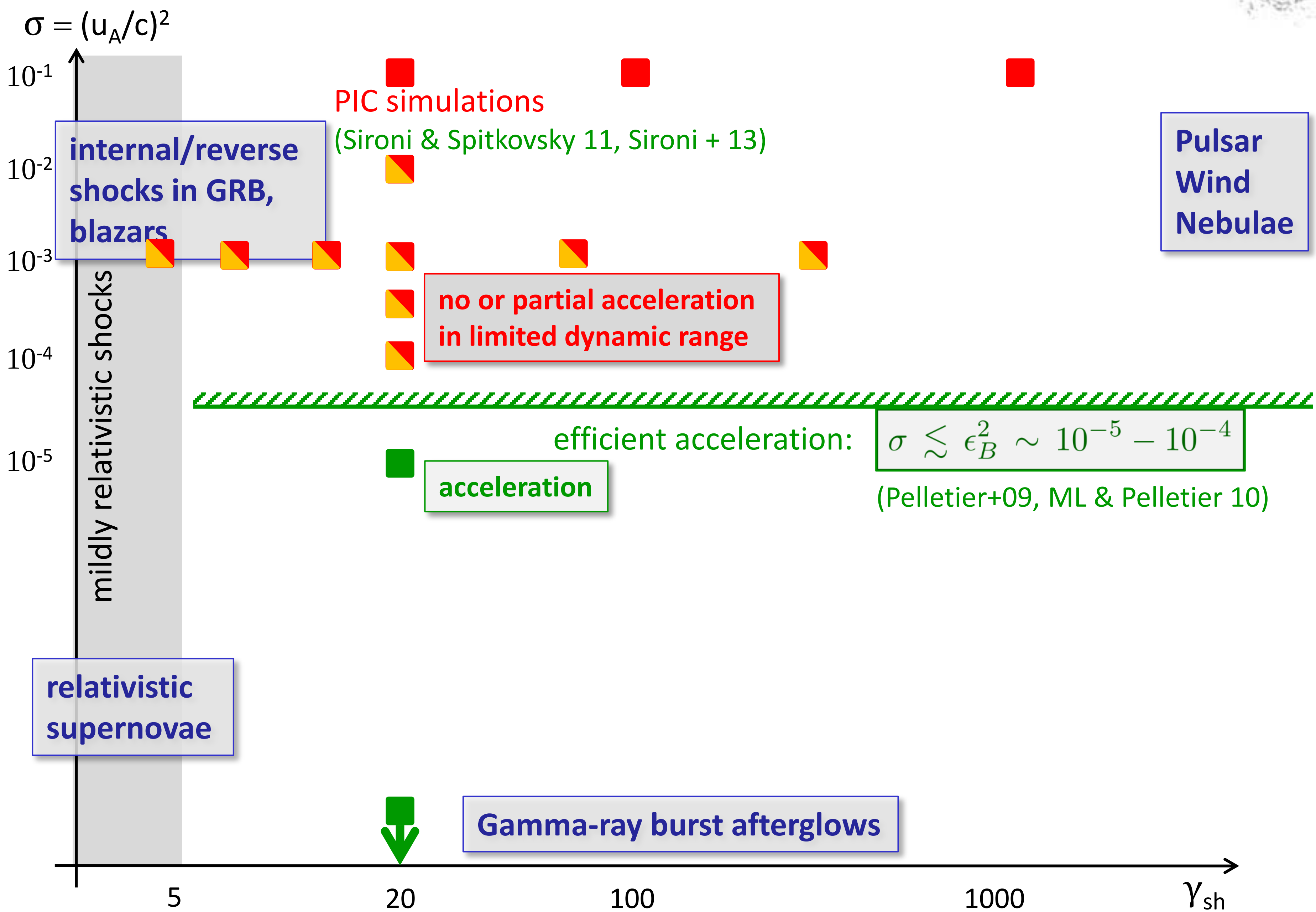
Simulations: A. Vanthieghem @ Curie-NF (CALDER: 1Mh/8000proc)

γ=10, $L_x\, L_y\, cT = 13000 \times 340 \times 10700\ (c\,\Omega_p^{-1})^3$, 2x10 part/cell, $\Delta=0.1\ c\,\Omega_p^{-1}$

… shock microphysics take place on plasma scales, orders of magnitude below the hydrodynamical scales… with important consequences for the phenomenology!

… the filamentation (Weibel) instability that develops in the precursor may: mediate the shock, sustain the acceleration process and generate the magnetized turbulence in which particles eventually radiate…

Particle acceleration in relativistic shocks



High energy synchrotron from relativistic shocks

Maximum synchrotron photon energy:

$\rightarrow$ max energy for electrons by comparing $t_{acc} \sim t_{scatt}$ to synchrotron loss, with $t_{scatt} \sim r_g^2/(\lambda_B c)$ and $\lambda_B \sim 10\, c/\omega_p$, implies a maximum synchrotron photon energy: (e.g. Kirk & Reville 10, Eichler & Pohl 11, Plotnikov+ 13, Wang+ 13, Sironi+ 13):

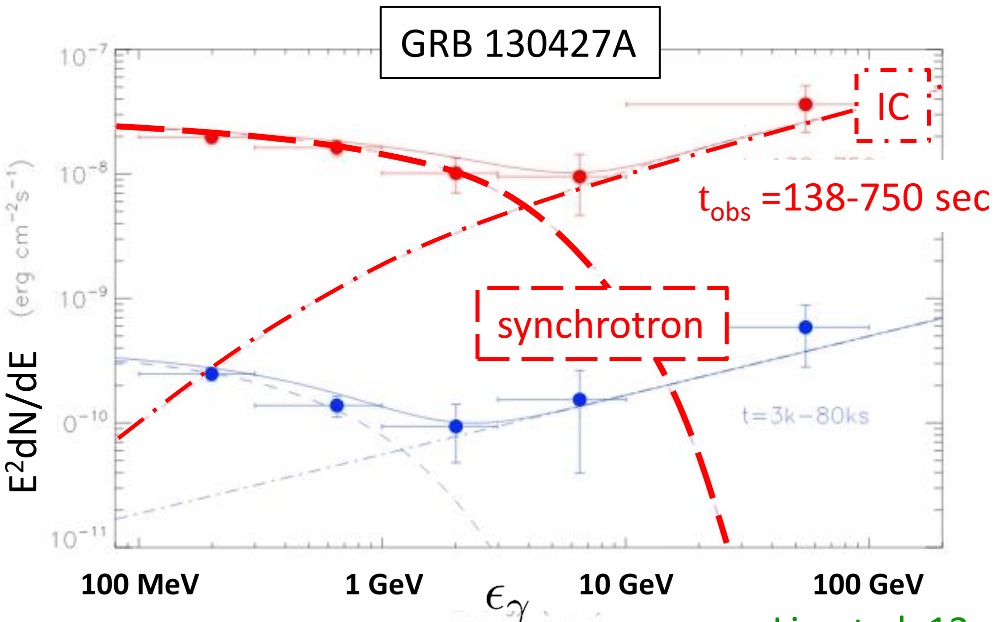
$$\epsilon_{\gamma,\max} \simeq 2\,\mathrm{GeV}\, E_{54}^{1/4} \epsilon_{B,-2}^{1/2} \lambda_1^{2/3} n_0^{-1/12}\; t_{\mathrm{obs},2}^{-3/4}$$

$\rightarrow$ **long-lived >100MeV emission on 1000sec can result from synchrotron afterglow** (Kumar & Barniol-Duran 09, 10, Ghisellini+ 10)

… photons above 10GeV result from IC interactions… (Wang+ 13)

in GRB130427A:

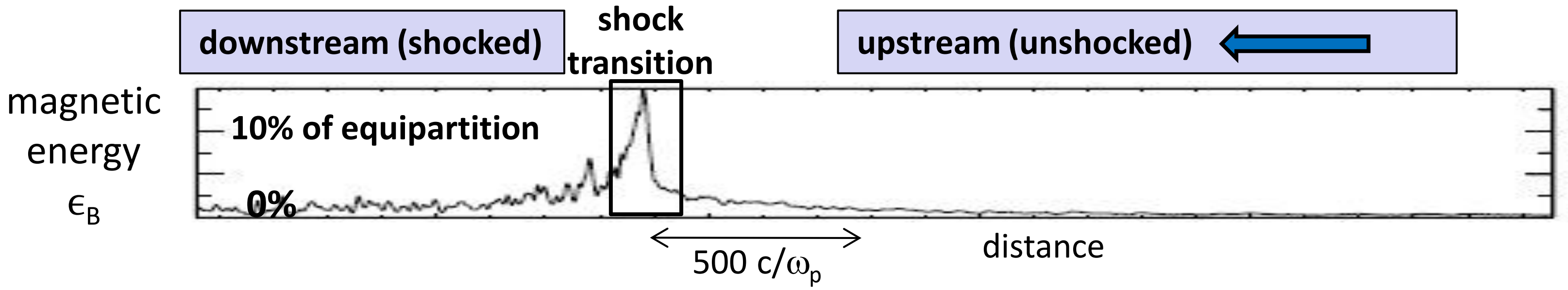
two spectral components with $\varepsilon_{\gamma,max} \sim$ GeV at 100-1000 sec for the synchrotron afterglow…



Liu et al. 13

Synchrotron spectra in relativistic blast waves

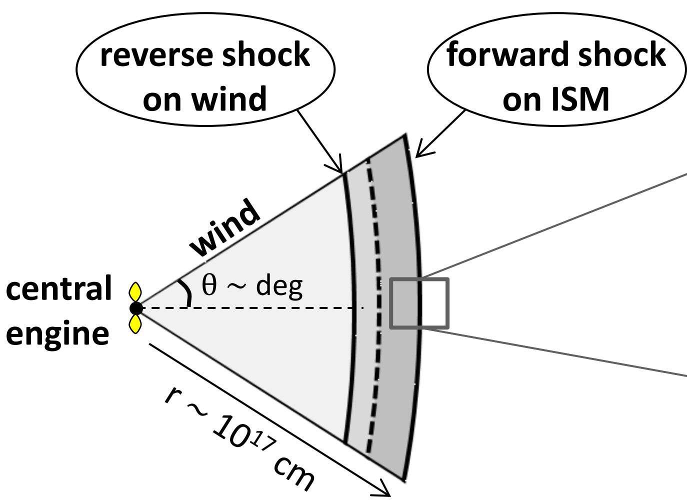
Microturbulence dissipates on short timescales:

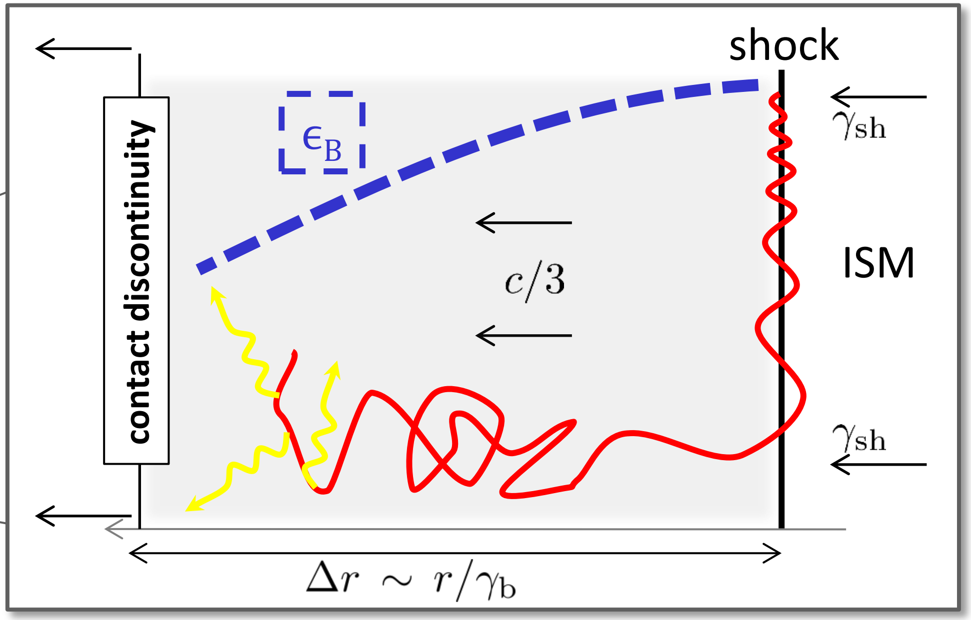


Spitkovsky 08

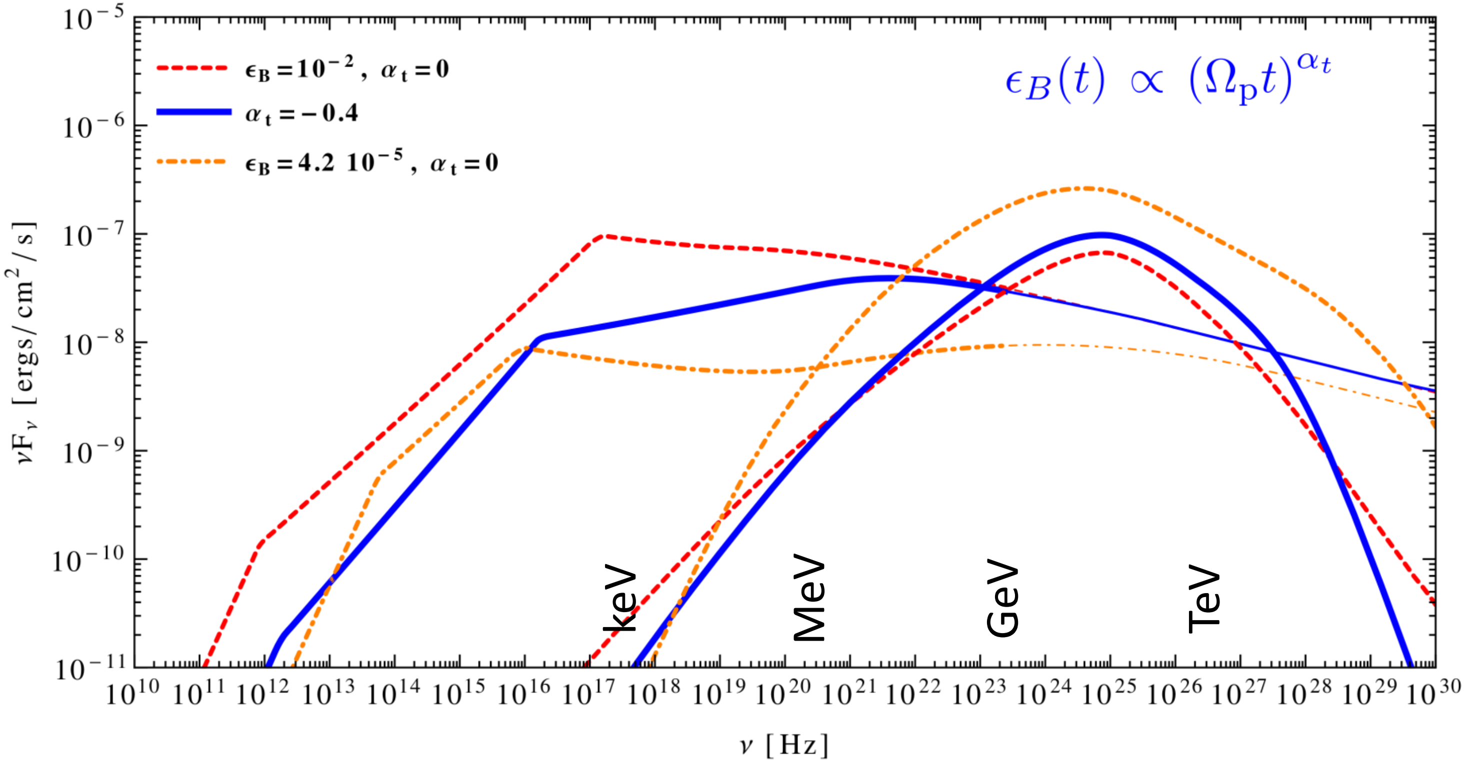
→ collisionless damping of the microturbulence leads to a position dependent ϵ_B parameter, leaving strong radiative signature in the synchrotron spectrum

(Rossi & Rees 03, Derishev 07, ML 13, 15a,b)





Synchrotron spectra in dissipative micro-turbulence



→ radiation in dissipative turbulence leaves a strong signature in the spectral flux $F_\nu(t_{obs})$: **modifies slopes and characteristic frequencies…** (Rossi, Rees 03, Derishev 07, ML 13, 15)

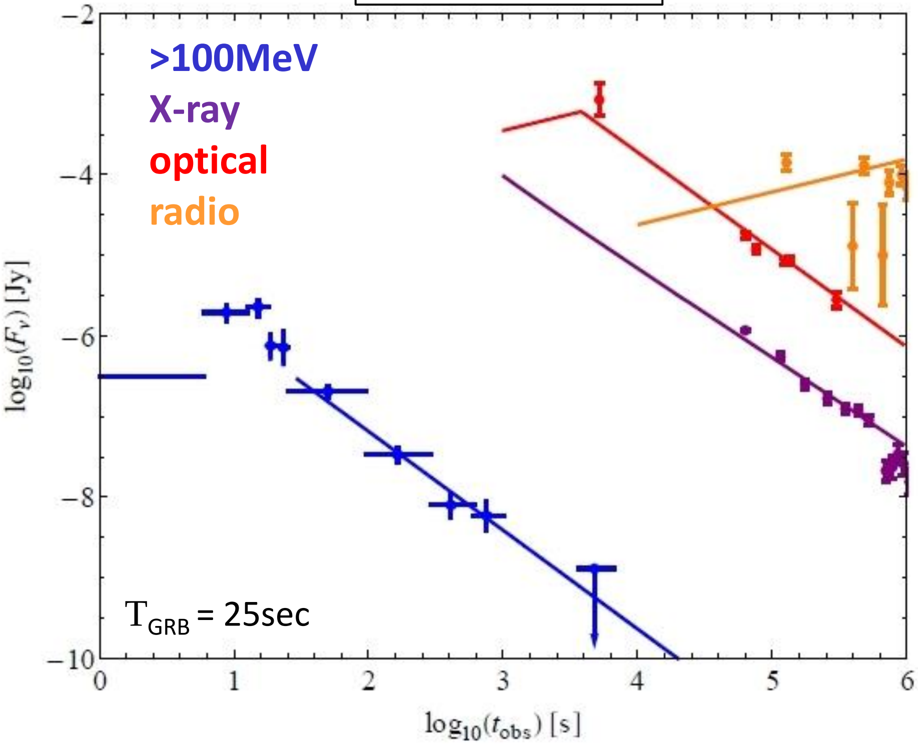
→ dissipative turbulence implies that inverse Compton cooling dominates, hence most of the flux is emitted in the >10 GeV range… a prediction for gamma-ray telescopes
(ML 13, 15)

→ multi-wavelength modelling of GRB afterglows point to net dissipation, $\alpha_t \sim -0.5$
(ML,Wang,Li 13)

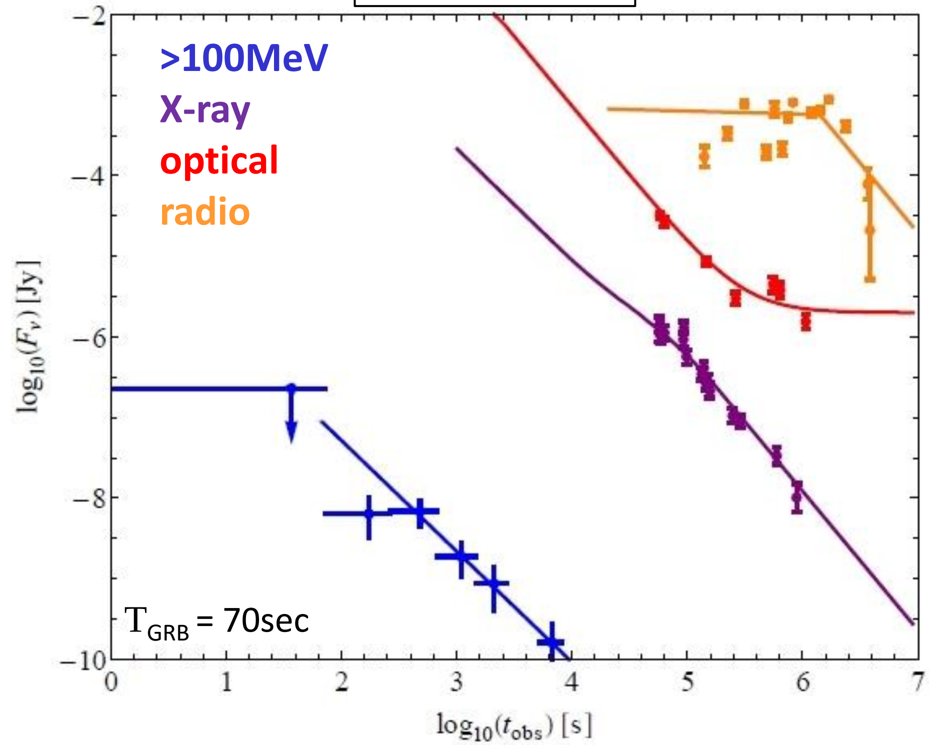
Estimate of the decay rate with multi-λ data…

… synchrotron emission of shock accelerated electrons in decaying micro-turbulence allows to reproduce the afterglows and >100MeV extended emissions of GRBs… *(ML et al. 13)*

GRB 090902B



GRB 090328



$E_{ej} \sim 1.6\ 10^{54}$ erg
$n \sim 0.012$ cm^{-3}
$\varepsilon_e \sim 0.50$, $p \sim 2.3$
$\alpha_t \sim -0.44 \pm 0.10$

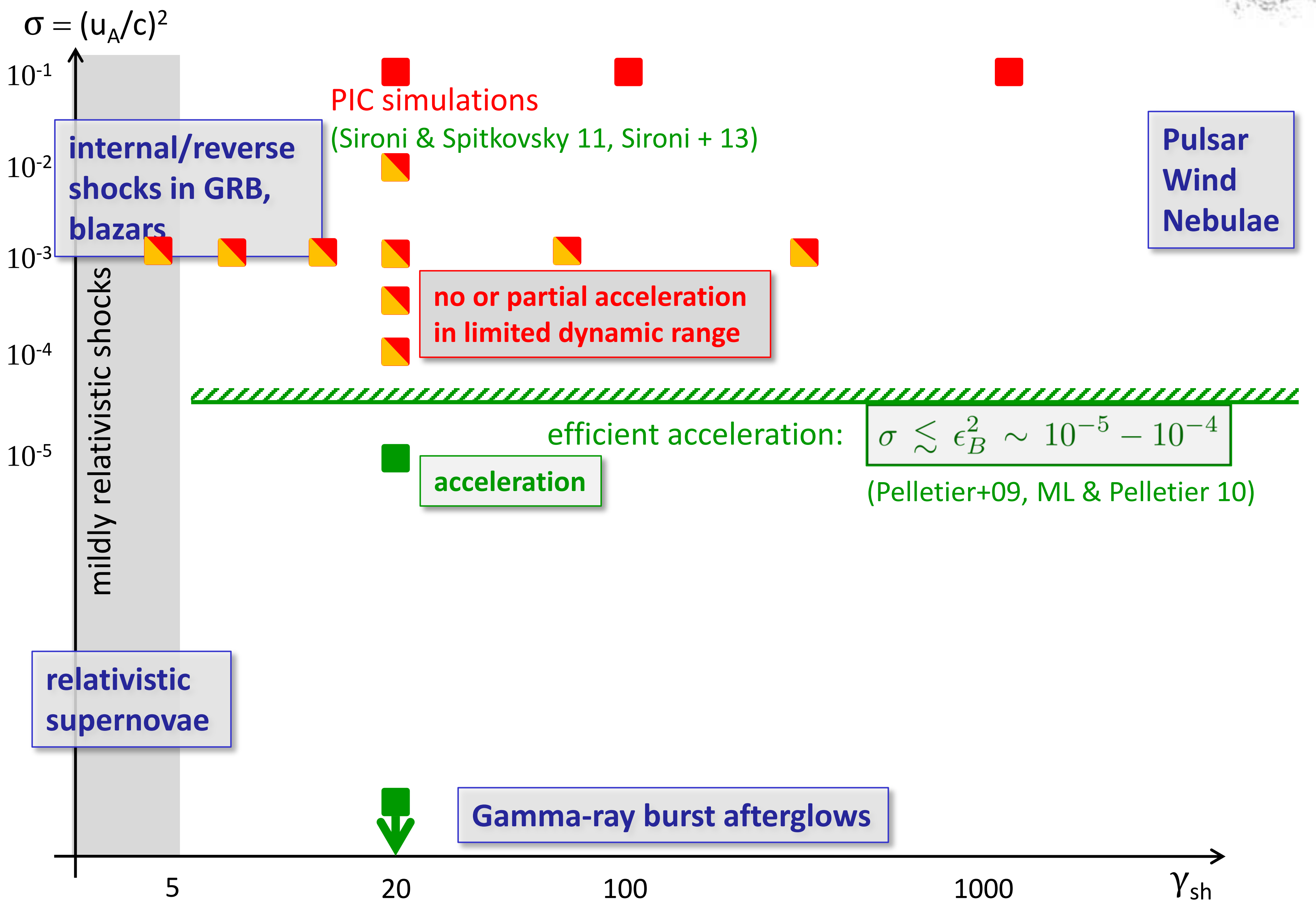
magnetic equipartition parameter:

$$\epsilon_B = 0.01 \left[t/\left(100\omega_{\rm pi}^{-1}\right)\right]^{\alpha_t}$$

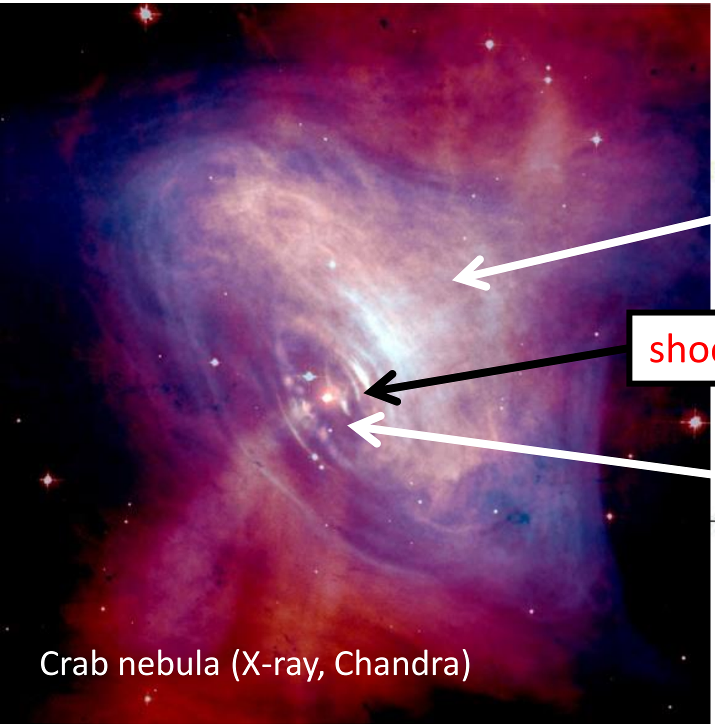
t: proper comoving time ~ distance to shock
t=0: plasma el^t crosses shock front
t>0: plama el^t suffers collisionless damping

$E_{ej} \sim 0.73 \times 10^{54}$ erg
$n \sim 1.5 \times 10^{35}\ r^{-2}$ cm^{-3}
$\varepsilon_e \sim 0.18$, $p \sim 2.5$
$\alpha_t \sim -0.48 \pm 0.11$

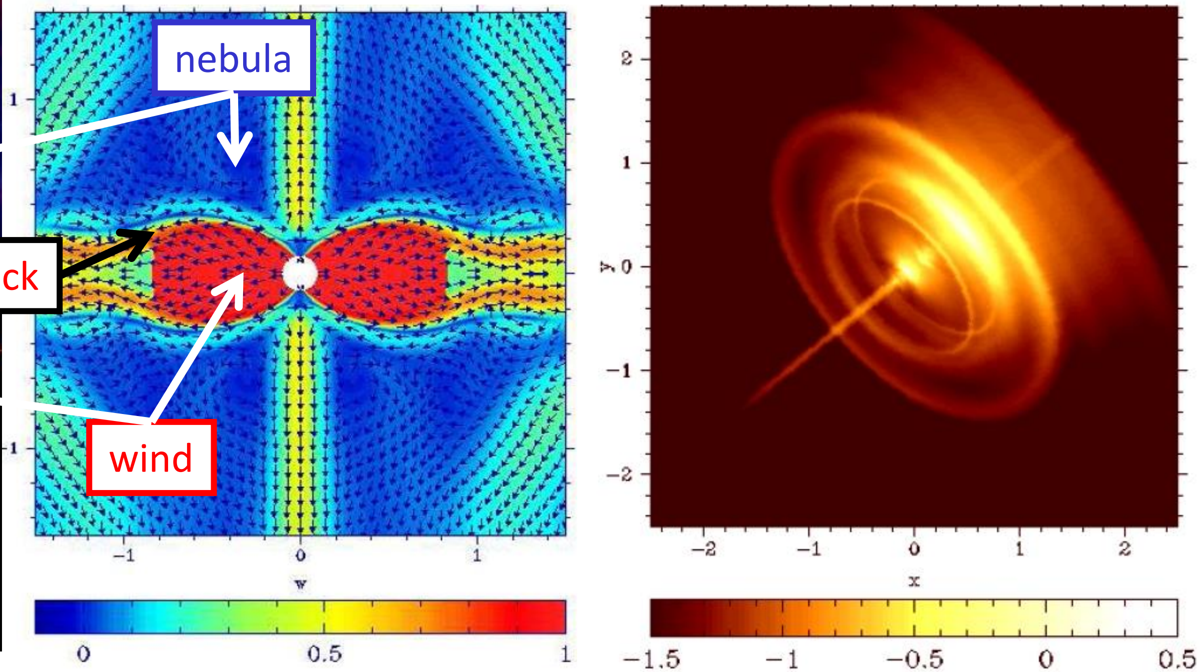
Particle acceleration in relativistic shocks



Motivations: pulsar wind nebulae



MHD model of the Crab nebula (Komissarov & Lyubarsky 03)



<u>Modelling of the nebular emission:</u> (e.g. Aharonian & Atoyan 96)

- synchrotron emission seen up to 100MeV, inverse Compton emission beyond…

… and recall: $t_{\rm acc} \simeq \mathcal{A}\frac{p}{eB} \Rightarrow \epsilon_{\rm syn,max} \simeq \mathcal{A}^{-1}\frac{m_e c^2}{\alpha_{\rm e.m.}} \sim 100\,\mathcal{A}^{-1}\,{\rm MeV}$

- electrons are heated up to a Lorentz factor ~ 10^6 …
- acceleration proceeds up to maximal Lorentz factor ~ 10^9 !

- physics of the termination shock? Moderate magnetization, Lorentz factor ~ 10^4 - 10^6 ?!

Beyond the standard simple MHD shock model?

Including radiation backgrounds:

e.g. « converter » mechanism, which sustains Fermi-type acceleration through charged – neutral conversions due to photo-interactions (Derishev+ 03)

Including magnetic annihilation:

e.g. particle acceleration at the demagnetized termination shock of PWNe through reconnection of the striped wind (Lyubarsky 03, Sironi +11)

Beyond MHD, shocks in superluminal e.m. waves:

conversion of the incoming entropy wave into a superluminal e.m. wave, destabilized in the shock precursor… (Arka, Kirk 12; Kirk+ coll.)

Corrugation of the shock front:

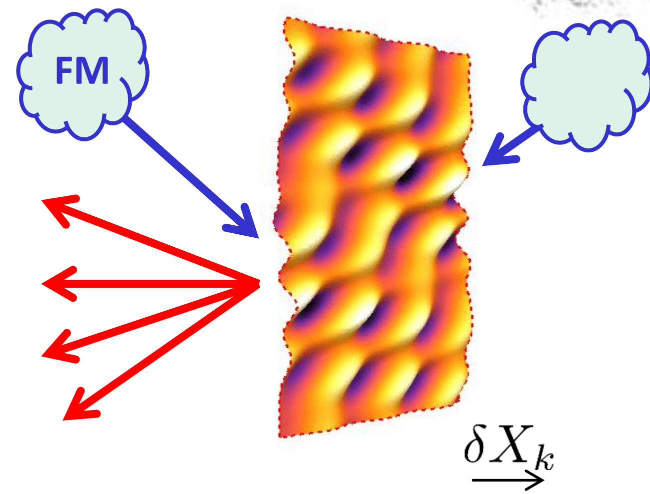
deformation of the shock front, converting incoming ordered magnetic energy into downstream turbulence… (ML+16, ML 16)

Corrugation of shock waves

Scattering on a shock front:

→ fast magnetosonic modes impinging on the shock from downstream induce corrugation, generating outgoing modes downstream …

→ modes incoming from upstream induces corrugation and outgoing modes…



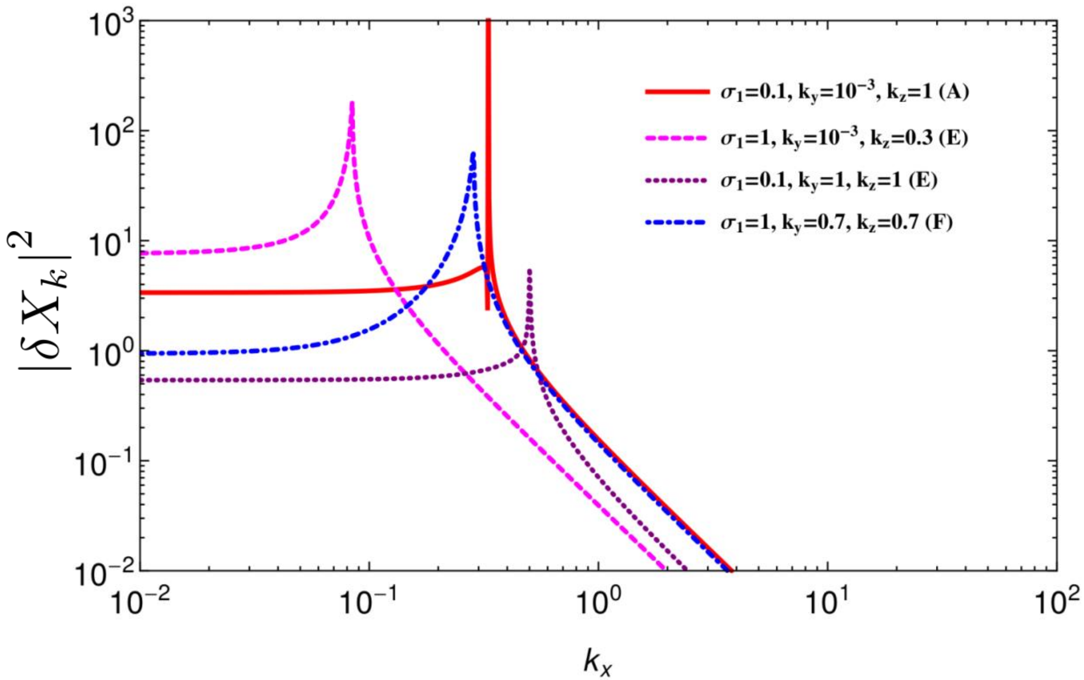
$$\boldsymbol{\mathcal{R}}_k \cdot \{\delta X_k,\, \boldsymbol{\delta\psi}_{>,\boldsymbol{k}}\} = \boldsymbol{R}_{<,\boldsymbol{k}}\delta\psi_{<,k}$$

corrugation amplitude (δX_k) — outgoing ($\delta\psi_{>,k}$) — incoming ($\delta\psi_{<,k}$)

A resonant response:

for some values of k_x, the outgoing fast magnetosonic mode surfs on the shock front, leading to a strong response of the corrugation amplitude…

(ML, Ramos, Gremillet 16, ML 16)



Summary

→ At (idealized) ultra-relativistic shocks: **particle acceleration in weakly magnetized regime only,**

$$\sigma \lesssim \epsilon_B^2 \sim 10^{-5}$$

... then, slow scattering in micro-turbulence: $t_{\rm acc} \sim r_{\rm g}^2/\lambda_{\delta B}$
hence reduced maximal energies... of order 1GeV for early afterglow synchrotron

... collisionless damping of micro-turbulence impacts synchrotron spectrum...
... expect most of GRB afterglow flux at >10GeV

→ Microphysics plays an important role in shaping the phenomenology!

→ However, **current theory is not complete:**

... extrapolation to mildly relativistic shock waves ?

... a relativistic Fermi process with Bohm scattering in PWNe ?

... other effects, such as feedback from accelerated particles, radiation, or corrugation may play an important role...