Particle acceleration at relativistic shock waves

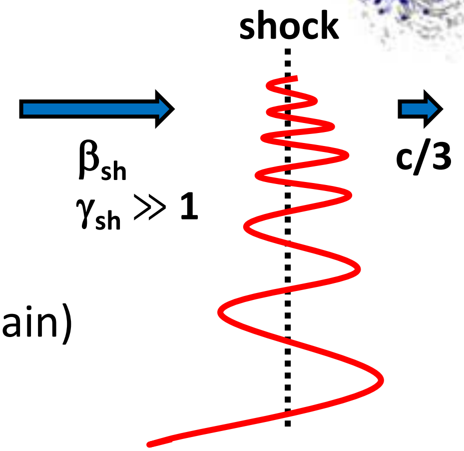
Martin Lemoine
Institut d'Astrophysique de Paris
CNRS, Université Pierre & Marie Curie

Outline:

1. **Test particle picture and microphysics**
2. **Consequences for acceleration … and some open questions**

Work in collaboration with Guy Pelletier (IPAG)

Particle acceleration at relativistic shock waves



Test particle picture:

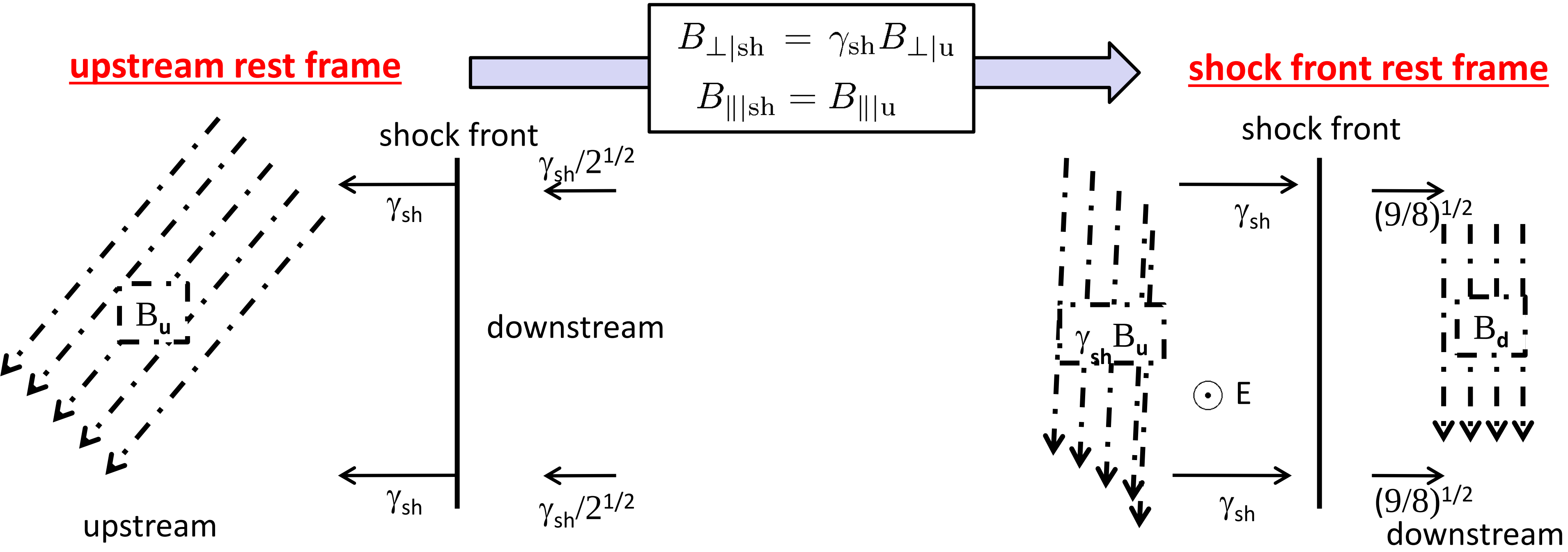
→ particles gain energy by bouncing across the shock front,

exploiting the convective electric fields : $\delta E = -\frac{v}{c} \times \delta B$

→ if scattering is effective, competition between scattering (energy gain)

and advection (escape) leads to a power-law $dN/dp \propto p^{-s}$, $s \sim 2.3$

(Bednarz & Ostrowski 98, Kirk et al. 00, Achterberg et al. 01, ML & Pelletier 03, Keshet & Waxman 05)



upstream rest frame

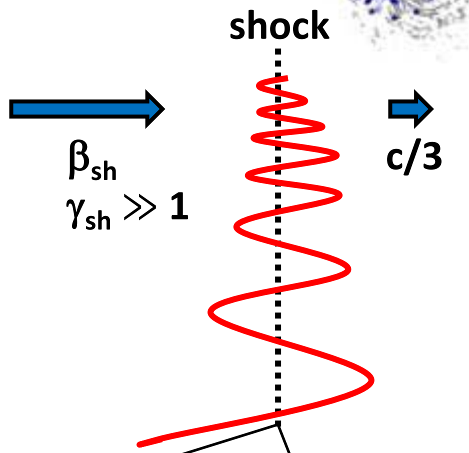
$$B_{\perp|\mathrm{sh}} = \gamma_{\mathrm{sh}} B_{\perp|\mathrm{u}}$$
$$B_{\||\mathrm{sh}} = B_{\||\mathrm{u}}$$

shock front rest frame

⇒ ultra-relativistic shock waves are mostly perpendicular (superluminal) (Begelman & Kirk 90)

The relativistic Fermi process and micro-turbulence

Test particle picture:



→ if scattering is effective, competition between scattering and advection (escape) leads to a power-law $dN/dp \propto p^{-s}$, $s \sim 2.3$

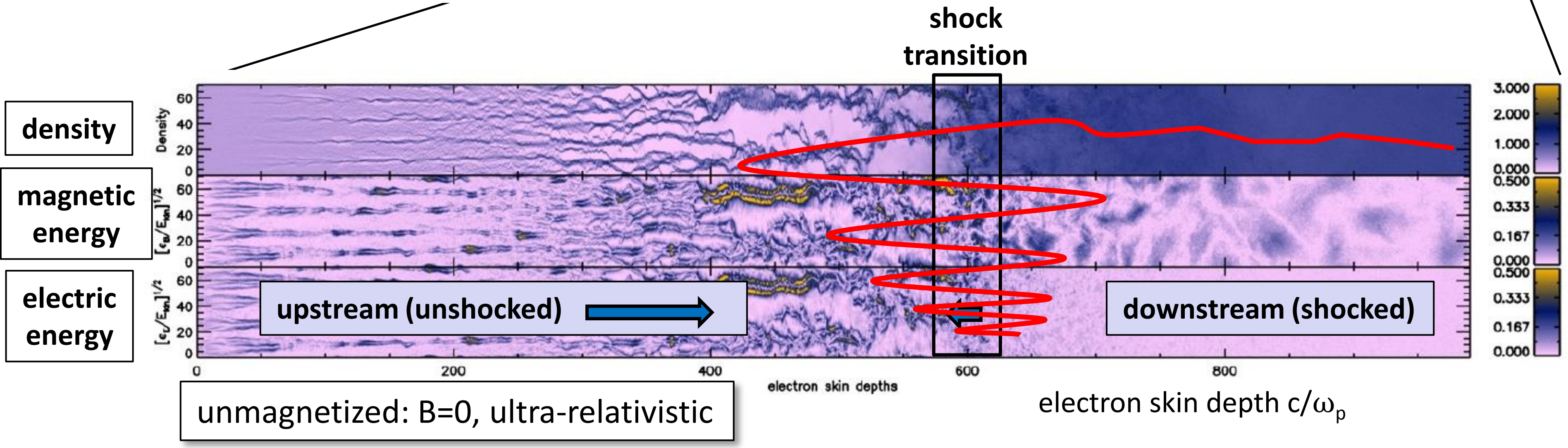
→ **if $\gamma_{sh} \gg 1$**, advection beats acceleration unless particles scatter in small-scale turbulence $\lambda_{\delta B} < r_g$, $\delta B > B$ and $r_g < \lambda_{\delta B}\, \delta B/B$

(r_g gyroradius of accelerated particles, $\lambda_{\delta B}$ length scale of δB)

(ML et al. 06, Niemiec et al. 06, Pelletier et al. 09, ML & Pelletier 10, 11, Plotnikov et al. 13)

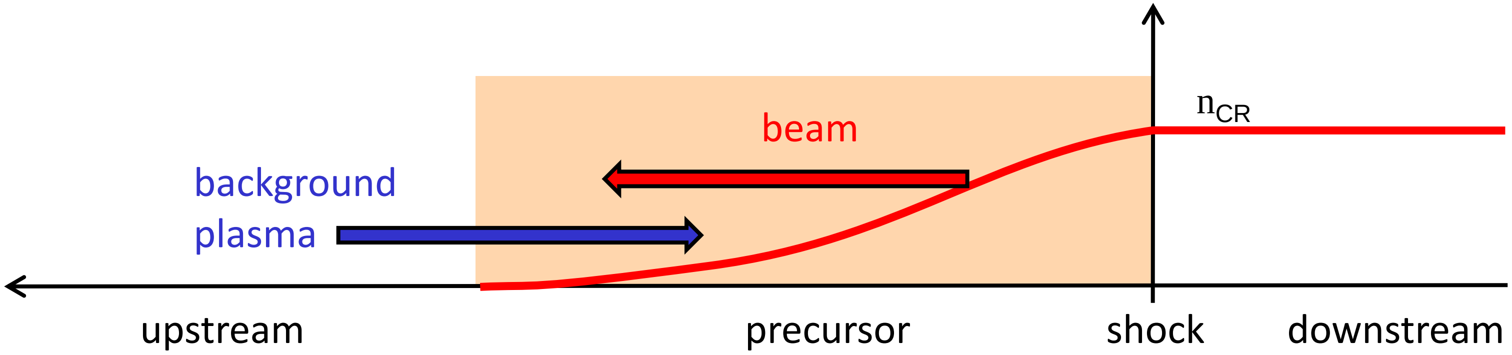
PIC simulations:

(e.g. Spitkovsky 08, Nishikawa et al. 09, Martins et al. 09, Sironi & Spitkovsky 09, 11, 13, Haugbolle 11)



unmagnetized: B=0, ultra-relativistic

Micro-instabilities at a relativistic shock front



→ fast instabilities at ultra-relativistic shocks:

Weibel/filamentation (e.g. Medvedev & Loeb 99): anisotropic instability at low magnetization, builds up δB starting from zero B

current-driven (ML et al. 14a, 14b): driven by the gyration current around B, works at moderate magnetization

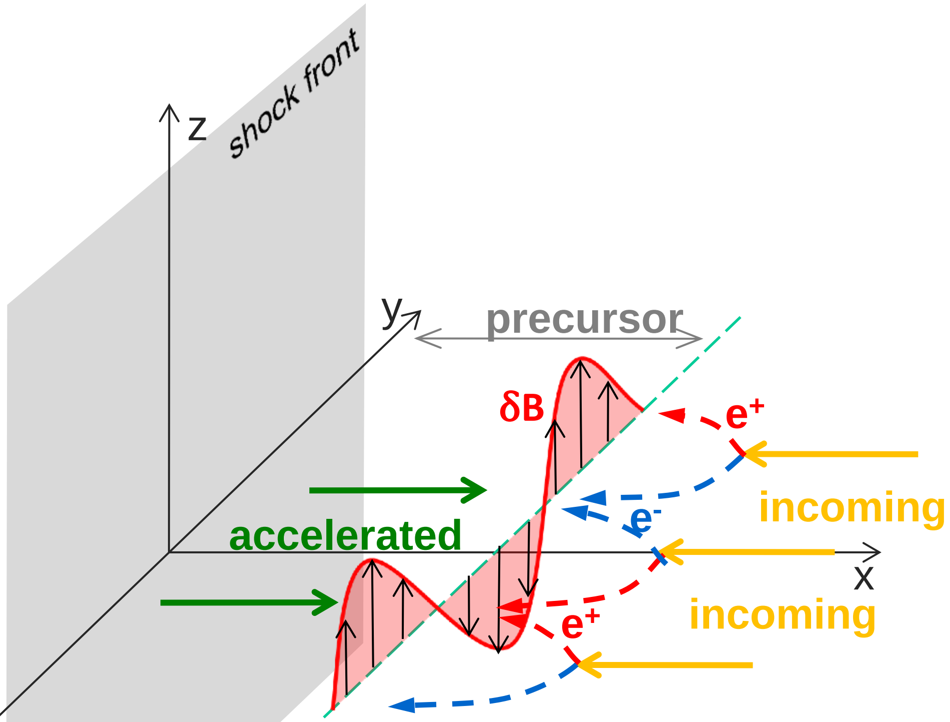
→ **main limitation: very short precursor, (upstream frame) length ~ $r_{L,0}/\gamma_{sh}^{3}$ ~ γ_{sh}^{-1} c/ω_c**

(no gyroresonant interaction at $\gamma_{sh} \gg 1$!)

→ many other potential instabilities at mildly relativistic shock waves (MHD regime)

Instabilities at ultra-relativistic collisionless shocks

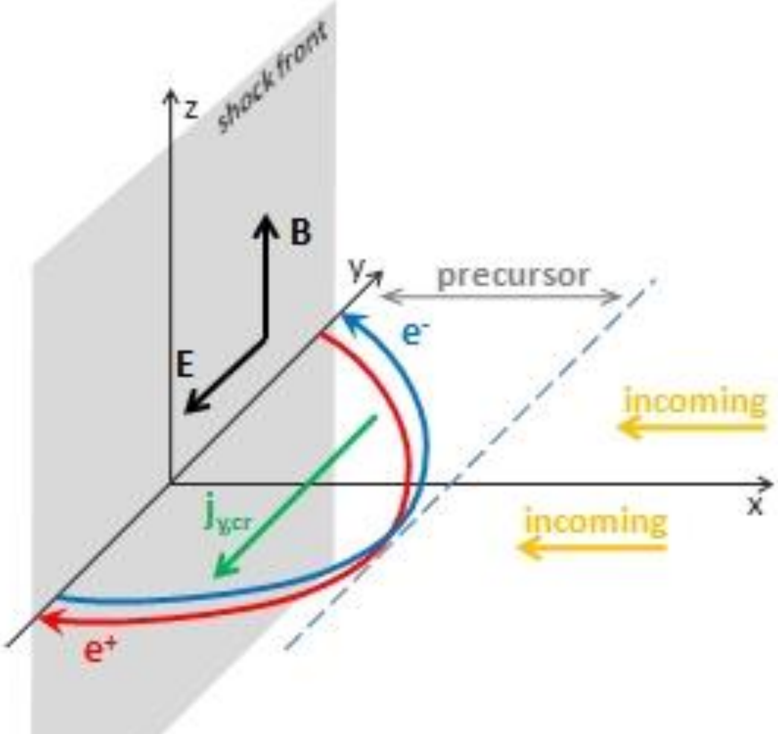
Filamentation (Weibel) instability



→ a perpendicular mode pinches the plasmas in current filaments by charge separation; the current feeds the fluctuation.

→ leads to a filamentation of the precursor in longitudinal currents of alternate polarity with toroidal in plane magnetic fields

Perpendicular current driven

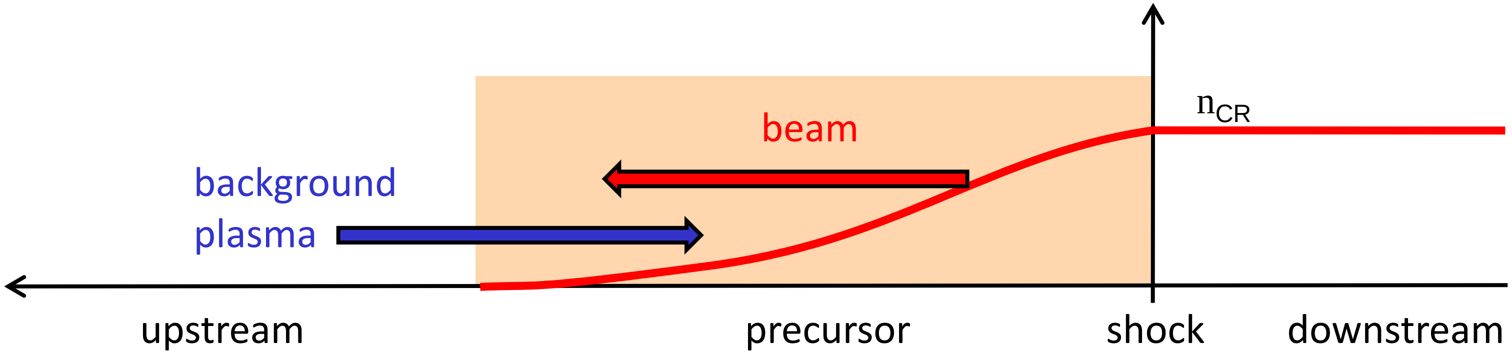


→ reflected/accelerated particles gyrate in background B field and induce a perpendicular current in the shock precursor

incoming

→ background plasma compensates current: slow-down along shock normal and instability

Micro-instabilities at a relativistic shock front



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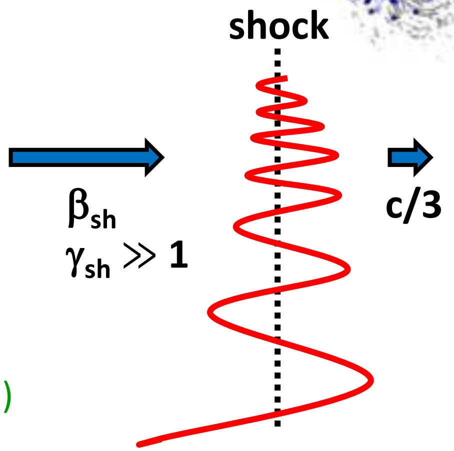
The relativistic Fermi process and micro-turbulence



Test particle picture:

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scatter in small-scale turbulence $\lambda_{\delta B} < r_g$, $\delta B > B$ and $r_g < \lambda_{\delta B}\, \delta B/B$

(r_g gyroradius of accelerated particles, $\lambda_{\delta B}$ length scale of δB)
(ML et al. 06, Niemiec et al. 06, Pelletier et al. 09, ML & Pelletier 10, 11, Plotnikov et al. 13)

Some consequences:

→ to trigger acceleration: $\sigma \;<\; \epsilon_B^2 \left(\lambda_{\delta B}\omega_{\rm p}/c\right)^2$

i.e. a weakly magnetized environment

→ acceleration to γ_{max} is limited (at least) by: $\dfrac{E_{\rm max}}{E_{\rm min}} \;<\; \left(\dfrac{\epsilon_B^2}{\sigma}\right)^{1/2} \left(\lambda_{\delta B}\omega_{\rm p}/c\right)$

i.e, the larger $\varepsilon_B{}^2/\sigma$, the larger $\gamma_{max}/\ \gamma_{min}$

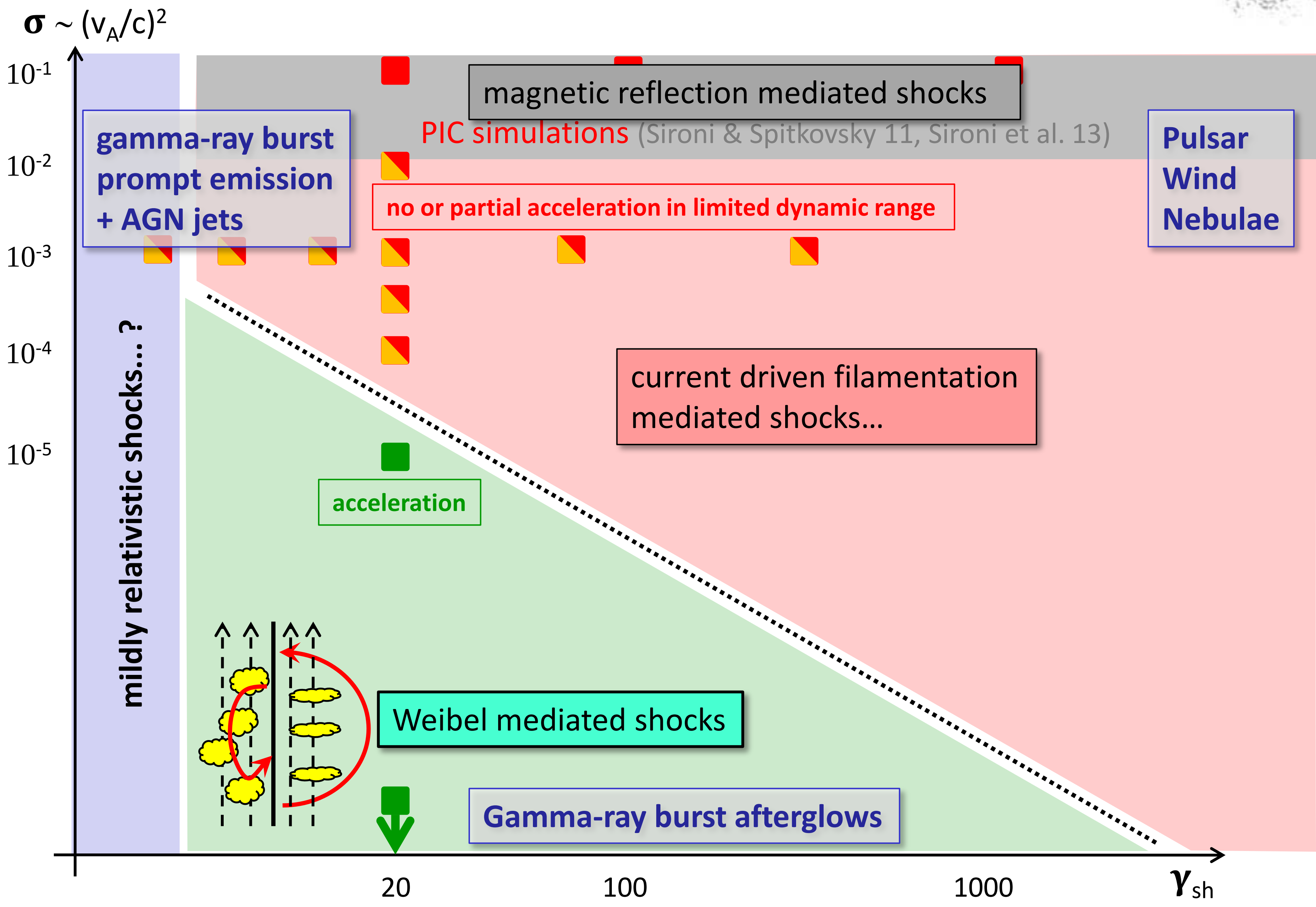
definitions:

$$\left\{\begin{array}{lll} \sigma & \equiv & \dfrac{B^2}{4\pi\gamma_{\rm sh}\left(\gamma_{\rm sh}-1\right)nmc^2} \\ \epsilon_B & \equiv & \dfrac{\delta B^2}{8\pi 4\gamma_{\rm sh}\left(\gamma_{\rm sh}-1\right)nmc^2} \\ E_{\rm min} & \sim & \gamma_{\rm sh}\, mc^2 \end{array}\right.$$

background magnetization

micro-turbulence magnetization

Phase diagram for relativistic shocks



gamma-ray burst prompt emission + AGN jets

magnetic reflection mediated shocks

PIC simulations (Sironi & Spitkovsky 11, Sironi et al. 13)

Pulsar Wind Nebulae

no or partial acceleration in limited dynamic range

current driven filamentation mediated shocks…

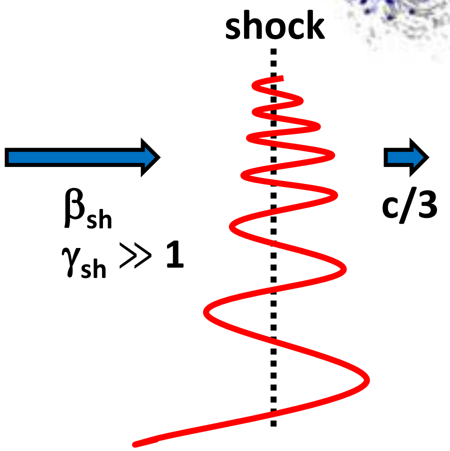
mildly relativistic shocks… ?

acceleration

Weibel mediated shocks

Gamma-ray burst afterglows

The relativistic Fermi process and micro-turbulence



Test particle picture:

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Some consequences:

→ acceleration timescale: $$t_{\rm acc} \approx t_{\rm scatt} \simeq \frac{r_{\rm g}^2}{\lambda_{\delta B} c} \propto p^2$$

i.e. acceleration to very high energies becomes difficult

explicitly, in the comoving frame (Kirk & Reville 10, Plotnikov et al. 13):

$$\gamma_{e,\rm max} \sim (n r_e^3)^{-1/6} \sim 1.5 \times 10^6\, n_0^{-1/6}$$

for e, comparing t_{acc} and t_{syn}

$$h\nu_{e,\rm max} \sim 100\,{\rm keV}\ n_0^{-1/3} B_{\rm G}$$

max synchrotron photon energy
(without Doppler boost)

$$\gamma_{p,\rm max} \sim \sqrt{t_{\rm dyn}\lambda_{\delta B}\frac{\omega_{\rm c}}{c}}$$

for p, comparing t_{acc} and
$t_{dyn} \sim r/(\gamma_{sh}\, c)$

Max synchrotron energy and GRB afterglows

Maximum energy:

→ scattering in small scale turbulence $\lambda_B < r_g$ is not as efficient as Bohm…

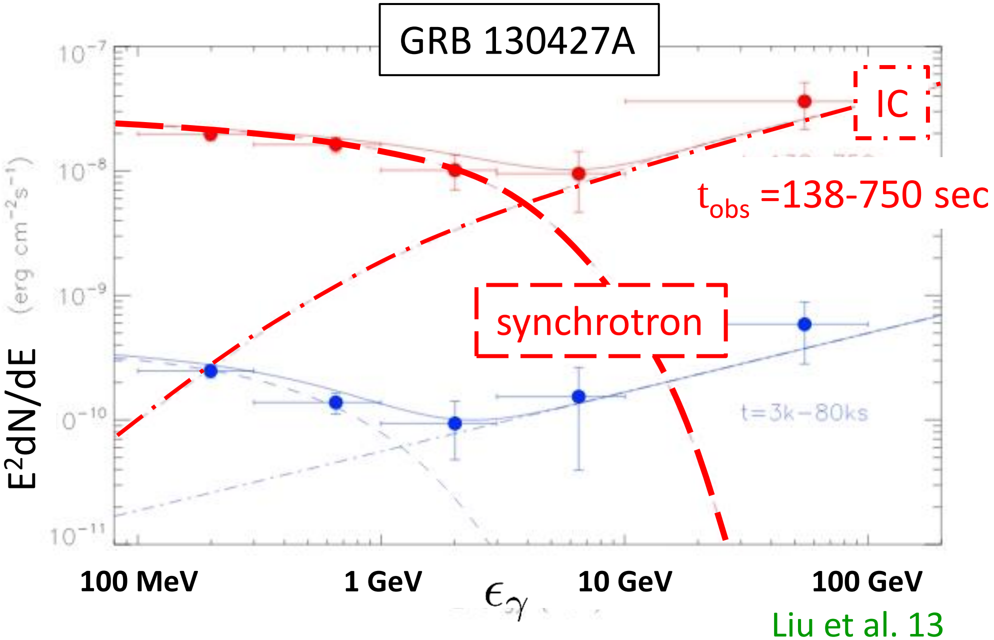
→ max energy for electrons by comparing $t_{acc} \sim t_{scatt}$ to synchrotron loss, with $t_{scatt} \sim r_g^2/(\lambda_B c)$ and $\lambda_B \sim 10\, c/\omega_p$, implies a maximum synchrotron photon energy:
(e.g. Kirk & Reville 10, Eichler & Pohl 11, Plotnikov et al. 13, Wang et al. 13, Sironi et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

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

→ long-lived >100MeV emission on 1000sec can result from synchrotron afterglow
(Kumar & Barniol-Duran 09, 10, Ghisellini et al. 10)
… photons above 10GeV result from IC interactions… (Wang et al. 13)

in GRB130427A:

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



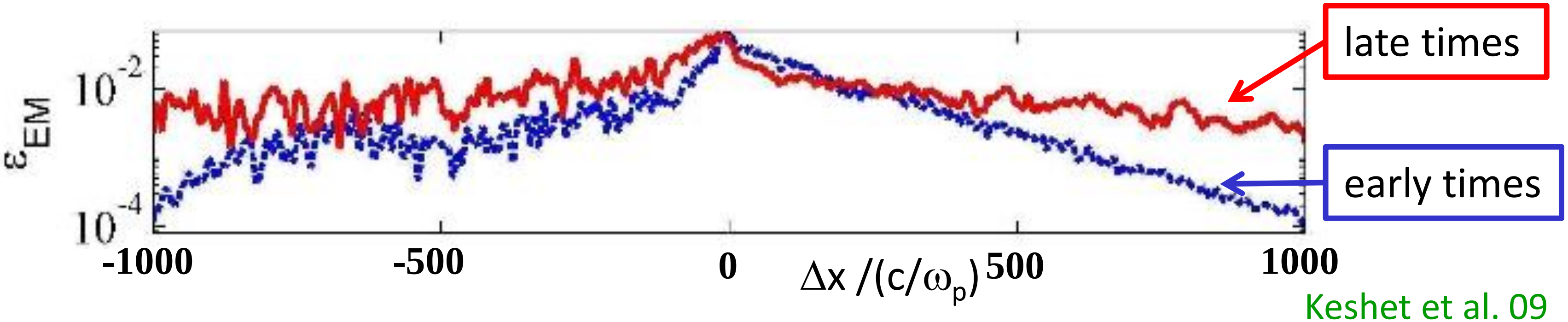
Liu et al. 13

Caveats and open questions at $\gamma_{sh} \gg 1$

→ **huge hierarchy in timescales** : for typical blazar parameters, $t_{\rm dyn} \sim 10^{11}\omega_{\rm p}^{-1}$

ω_p^{-1} sets the timescale of microphysics, PIC simulations, first Fermi cycles

t_{dyn} sets the timescale of hydrodynamic evolution, max energy Fermi cycles



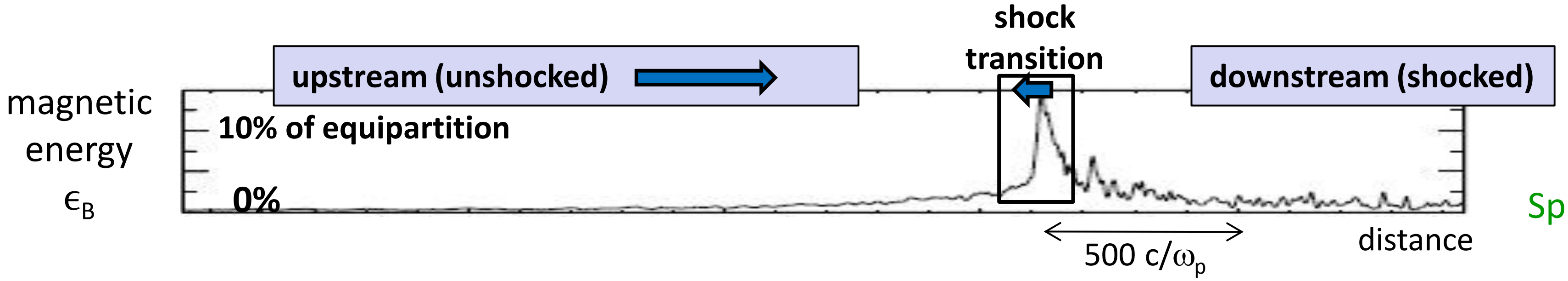
Keshet et al. 09

how do accelerated particles back-react on the shock, microturbulence ?

→ **additional sources of turbulence**?
e.g. Rayleigh-Taylor instability of the contact discontinuity (Gruzinov 01, Levinson 10), Richtmyer Meshkov instability of the shock front (e.g. Sironi & Goodman 07), unsteady shock surface ?

can it sustain the acceleration process at moderate magnetization?

Long-term evolution of the turbulence

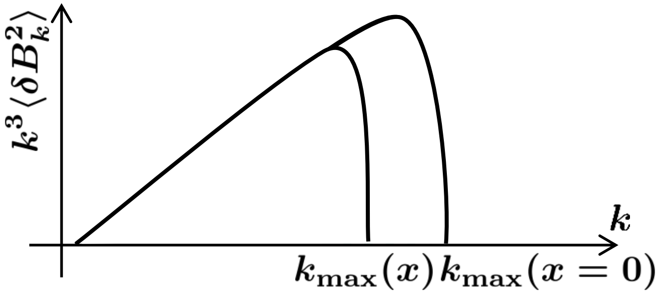


Spitkovsky 08

→ **micro-turbulence on c/ω_p scales decays fast**, on multiples of c/ω_p, through phase mixing

damping rate: $\gamma_k \simeq (kc)^3/\omega_{\rm p}^2$

$$\Rightarrow \epsilon_B(x) \propto x^{-\alpha}$$



(Chang et al. 08)

dissipation of turbulence modifies the synchrotron spectral shape of cooling electrons, because electrons of different Lorentz factors cool in different δB… (Derishev 07, ML 13,15)

… α ~ -0.5 may explain the magnetization of GRB afterglows (ML et al. 13)

Open questions in the mildly relativistic regime

→ **Microphysics of mildly relativistic shock waves $\gamma_{sh}\beta_{sh} \sim 1$: still terra incognita**…

→ **Hopes:**

- obliquity effects are less prominent than in ultra-relativistic regime…

… subluminal regime becomes relevant in larger part of phase space

- precursor length scales becomes $\geq r_g$ …

… opens up a new pool of instabilities in MHD range

(e.g. Milosavljevic & Nakar 06, Reville et al. 06, Pelletier et al. 09,
Casse & Marcowith 13, Reville & Bell 14)

… does this allow Bohm, or near-Bohm regime of acceleration?

→ **Key question:**

how high in sigma can acceleration proceed?

Summary and conclusions

→ **significant progress in our understanding of particle acceleration at ultra-relativistic ($\gamma_{sh}\beta_{sh} \gg 1$) collisionless shock waves:**

… good agreement between theory and PIC simulations…

… satisfactory (interesting) comparison to GRB afterglow observations…

→ **predictions:**

… acceleration successful at $\sigma \ll \epsilon_B^2 \sim 10^{-4}$

… $t_{acc} \sim r_g^2 / \lambda$

→ **some open questions:**

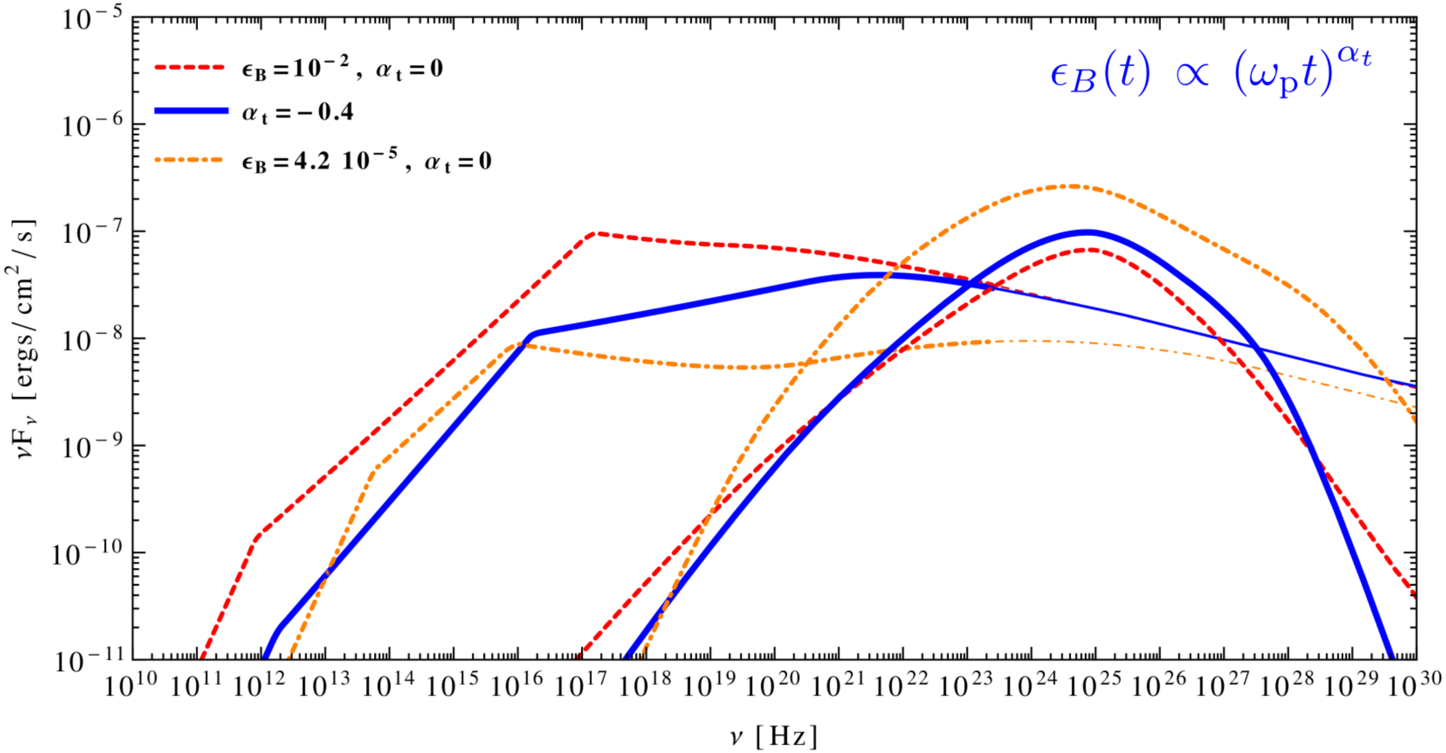
… long term evolution of the turbulence and the blast?

→ **acceleration at mildly relativistic shocks is not yet understood:**

… in particular, how high in σ can acceleration proceed?

… does acceleration proceed in a near-to Bohm regime?

Synchrotron spectra in dissipative micro-turbulence



(ML13, 15)

→ flux F_ν at ν comes from electrons with γ_e: $\nu_{syn}(\gamma_e) = \nu$…

→ $\nu_{syn} \propto \gamma_e^2$ and $t_{syn} \propto \gamma_e^{-1}$ imply that **low frequencies are produced in regions of low magnetic field, high frequencies are produced in regions of strong magnetic field…**

→ **the multi-λ spectrum provides a tomograph of the turbulence in the blast…**

→ decaying turbulence leaves a strong signature in the spectral flux $F_\nu(t_{obs})$: **modifies slopes and characteristic frequencies…**

→ **weak magnetized turbulence implies that inverse Compton cooling dominates, most of the flux is emitted in the >10 GeV range…**