Particle acceleration at relativistic shock waves … and gamma-ray bursts

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Outline:

1. **Particle acceleration and relativistic collisionless shocks**

2. **Microphysics of gamma-ray burst afterglows**

Relativistic Fermi acceleration - small scale turbulence

Test particle picture:

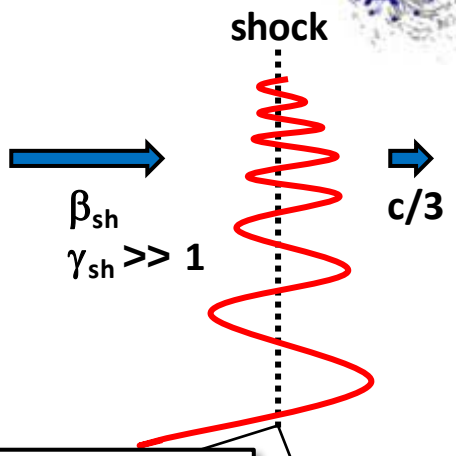
→ particles gain energy by bouncing across the shock front,

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

→ if $\gamma_{sh} \gg 1$, advection beats acceleration unless particles

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

(r_g gyroradius of accelerated particles, λ_B length scale of δB)
(ML et al. 06, Niemiec et al. 06, Pelletier et al. 09)

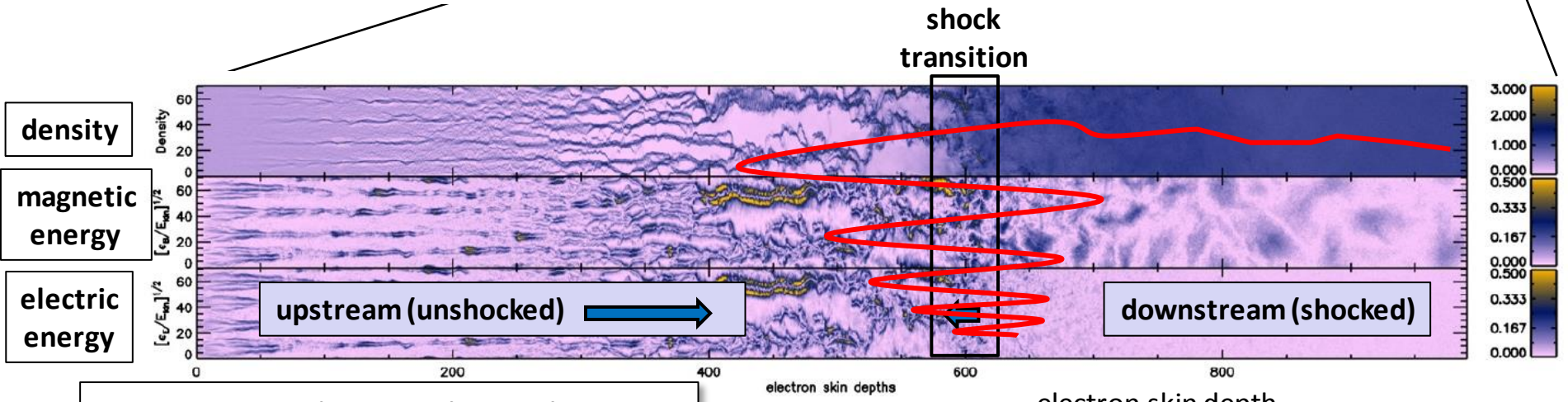


$\Leftarrow \quad \sigma < \epsilon_B^2 \left(\lambda \omega_p / c\right)^2$

weak magnetization!

PIC simulations:

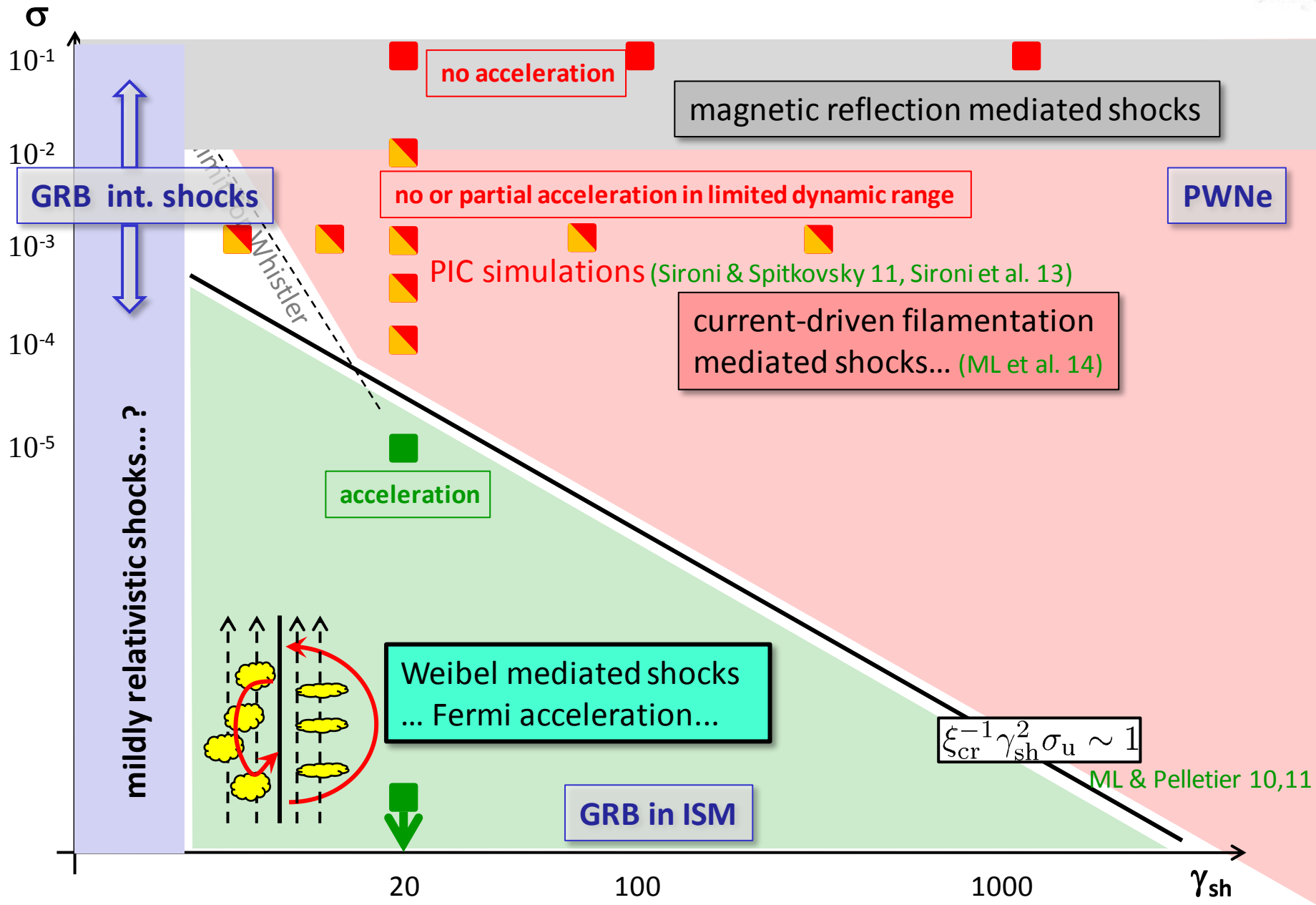
(e.g. Spitkovsky 08, Nishikawa et al. 09, Martins et al. 09, Sironi & Spitkovsky 09, 11, 13, Haugbolle 11)



unmagnetized: B=0, ultra-relativistic

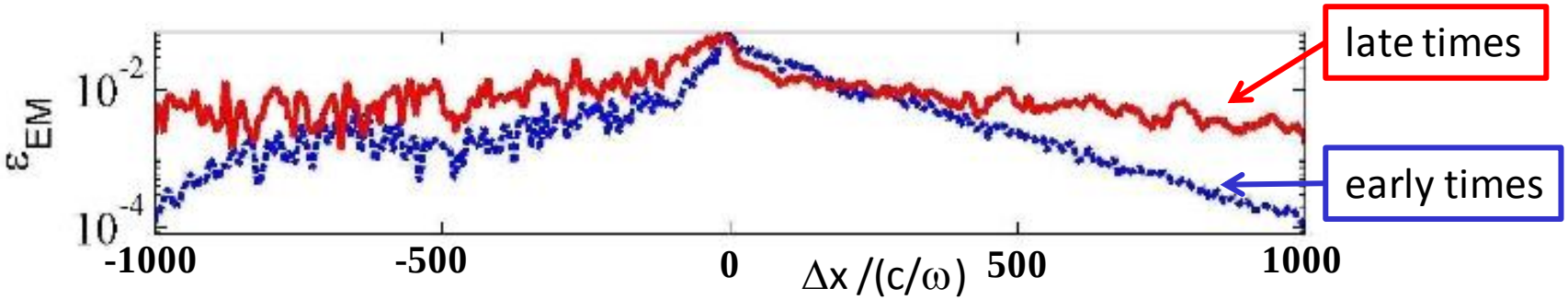
electron skin depth

Phase diagram for relativistic shock acceleration



Caveats and open questions

Most PIC simulations have not converged to a stationary state! (Keshet et al. 09)



$\varepsilon_B = \delta B^2 / (16\pi\, \gamma_{sh}^2\, n_u\, m\, c^2)$

→ Keshet et al. 09: **time = $10^4\ \omega_p^{-1}$ ⇔ ~ 0.1% of a dynamical timescale for a GRB!**

→ theoretical extrapolation is needed!

Main open questions:

→ phase space still largely unexplored… **mildly relativistic shocks = terra incognita**

→ high energy particles stream further away and modify the precursor: how?

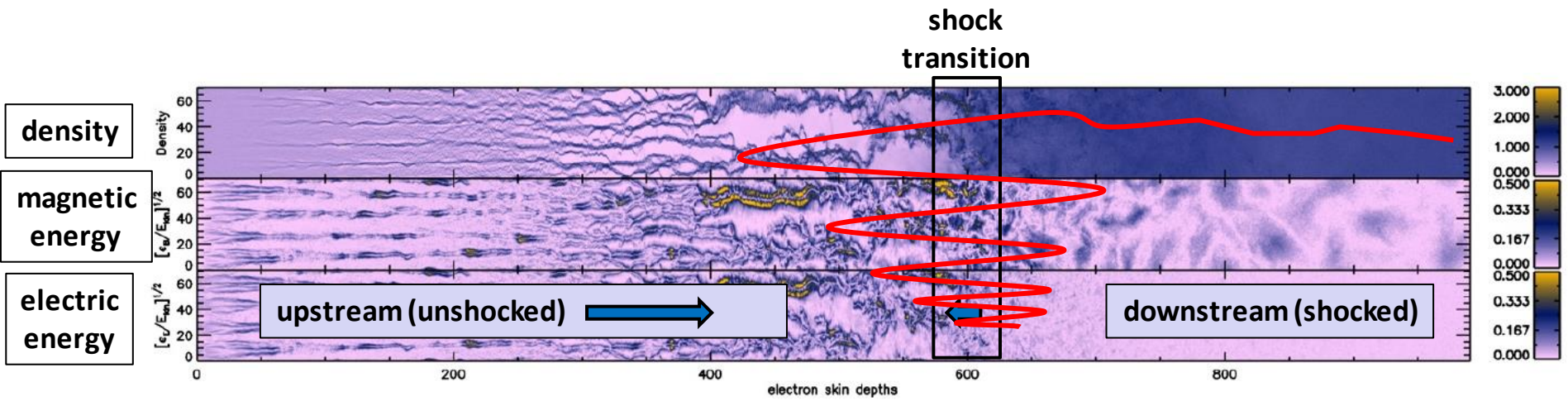
→ other instabilities on larger (MHD?) scales?

→ acceleration at magnetized shocks, e.g. PWNe up to $\gamma_e \sim 10^9$?

Relativistic Fermi acceleration - unmagnetized limit

PIC simulations:

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



→ supra-thermal particles stream ahead of the shock and excite plasma instabilities (Weibel/filamentation, two-stream, current-driven etc.), which build δB…

→ δB builds a magnetic barrier (~ 10% of equipartition) which mediates the shock transition…

→ δB on c/ω_p scales provides the scattering required for acceleration…

→ δB provides the turbulence in which particles radiate (?) (Medvedev &Loeb 99)

Maximum energy

Maximum energy:

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

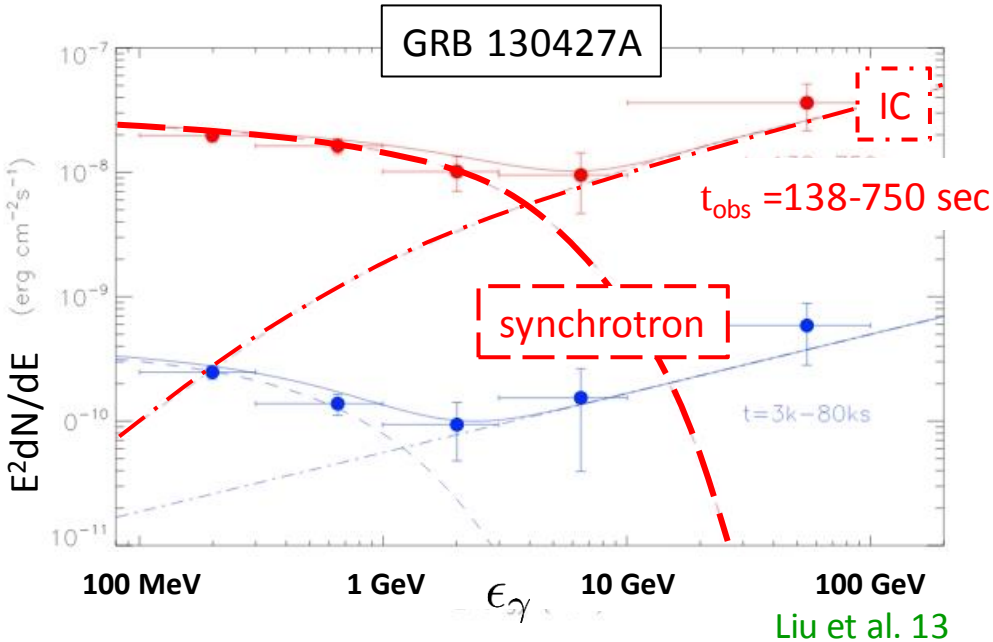
→ max energy for electrons by comparing $t_{acc} \sim t_{scatt}$ to synchrotron loss, with $t_{scatt} \sim r_g^2/(\lambda_B c)$ and $\lambda_B \sim 10\, c/\omega_p$, implies a maximum synchrotron photon energy:
(e.g. Kirk & Reville 10, Plotnikov et al. 13, Wang et al. 13, Sironi et al. 13):

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

→ **long-lived GeV 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

Evolution of turbulence in GRB blast waves

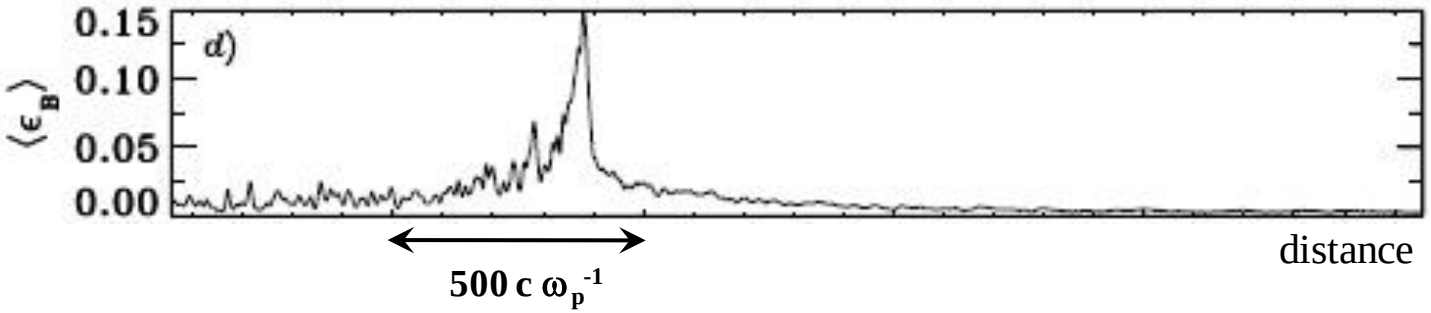
Theory vs observations/phenomenology:

→ comparison between theory, PIC sims. and GRB phenomenology overall satisfactory:
electrons are heated to $\gamma_{min} = \gamma_{sh}\, m_p/m_e \sim 10^5$,
to near equipartition $\varepsilon_e \sim 0.1\text{-}0.5$ … with a power-law tail of index $s \sim -2.2$
magnetized turbulence is excited up to $\varepsilon_B \sim 0.01$ (canonical value !?)

→ actually, a long-standing notorious problem for ε_B : turbulence lies on plasma scales c/ω_{pi}, and should decay on 100's of c/ω_{pi}, whereas observations probe the width of the blast, many orders of magnitude beyond…
⇒ origin of the magnetisation of GRB blast waves? (e.g. Gruzinov 99, Gruzinov & Waxman 99)

$$\frac{l_{\rm blast}}{c/\omega_{pi}} \approx 10^7\, t_{\rm obs,2}^{5/8}$$

$$\frac{l_{\rm cool}}{c/\omega_{\rm pi}} \approx 10^7\, t_2^{9/8} E_{53}^{-3/8} n_{-3}^{-1/8} \epsilon_{B,-2}^{-1} \epsilon_{e,-0.3}^{-1} \frac{\gamma_{\rm min}}{\gamma_e}$$

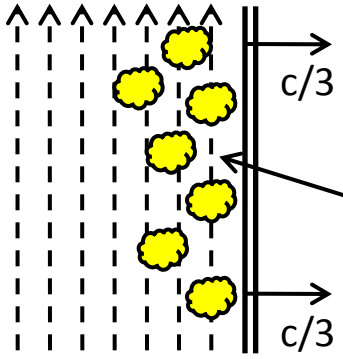


Spitkovsky 08

Evolution of turbulence in GRB blast waves

(ref. frame: shocked plasma)

how does the turbulence evolve with distance to shock?
damping or additional source of turbulence?
e.g. Gruzinov & Waxman 99, Medvedev & Loeb 99, Chang et al. 08, Keshet et al. 09, ML 13



micro-instabilities associated with the shock structure: typically on plasma scales c/ω_{pi}

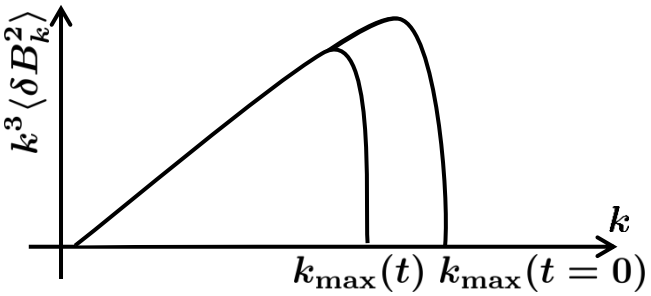
Microphysics of turbulence evolution:

→ through Landau damping, δB is expected to decay as power-law in proper time t (Chang et al. 08, ML 14):

(t: comoving time since injection through the shock ~ 3x distance to the shock)

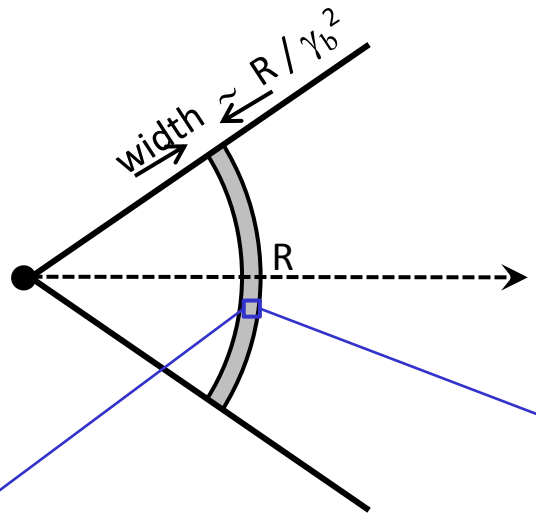
$$\frac{\mathrm{d}\left\langle \delta B^2 \right\rangle}{\mathrm{d}t} = -2\int \frac{\mathrm{d}^3k}{(2\pi)^3}\gamma_k \left|\delta B_k\right|^2 \quad \text{with (linear) damping rate} \quad \gamma_k \simeq \frac{4}{\pi}\frac{k^3c^3}{\omega_\mathrm{p}^2}$$

$$\Rightarrow \quad \epsilon_B(t) \propto k_{\max}^{n_B+3}(t) \propto t^{-(n_B+3)/3}$$



General picture

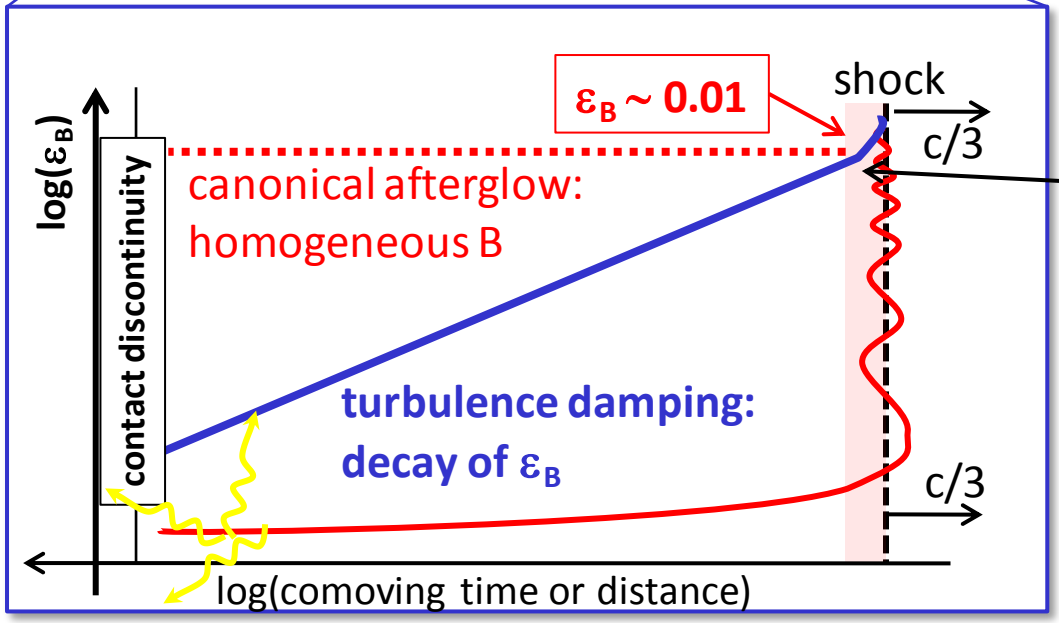
Blast wave geometry:



GRB orders of magnitude (comoving frame):

radius for afterglow: $R \sim 10^{17}$ cm
Lorentz factor: $\gamma_b \sim 100$
B field: $B_{ISM} \sim 1\ \mu G$ ($\Leftrightarrow \varepsilon_{B,ISM} \sim 10^{-9}$)

blast width: $R / (\gamma_b\, c) \sim 10^7\ \omega_{pi}^{-1}$
gyration: $t_L \sim \varepsilon_{B,-2}^{-1/2}\ (\gamma_e/\gamma_{min})\ \omega_{pi}^{-1}$
cooling: $t_{synch} \sim 10^7 \ldots (\gamma_e/\gamma_{min})^{-1}\ \omega_{pi}^{-1}$
PIC simulations: $\sim 10\,000\ \omega_{pi}^{-1}$



acceleration zone $\sim 100\ \omega_{pi}^{-1}$

$\Rightarrow$ particles get "instantaneously" accelerated to a power-law then cool in microturbulence…

Synchrotron spectra in decaying microturbulence

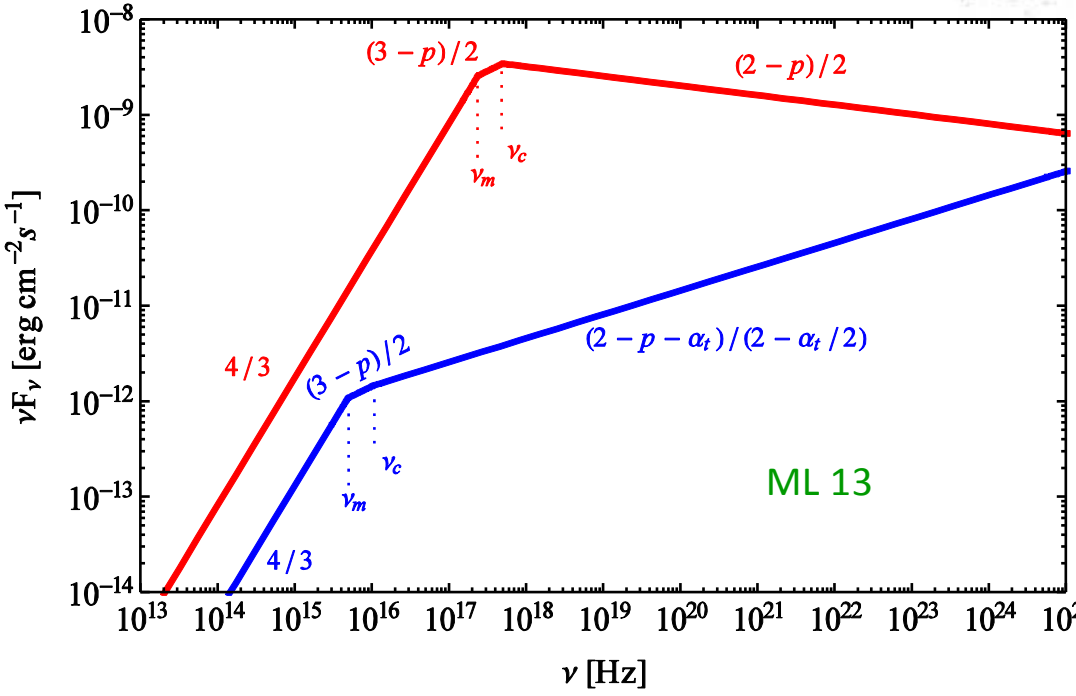
Example:

slowly decaying turbulence, α_t = -0.8,
t_{obs} = 100 sec, n = 10^{-3}cm^{-3},
E = 10^{53}ergs, with inverse Compton losses, Y=3

$$\delta B^2(t) \sim \delta B^2(t=0)\ [t/(100c/\omega_{\rm pi})]^{\alpha_t}$$

vs

homogeneous turbulence, $\varepsilon_B = 10^{-2}$



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

General trend: (for -1 < α_t < 0)

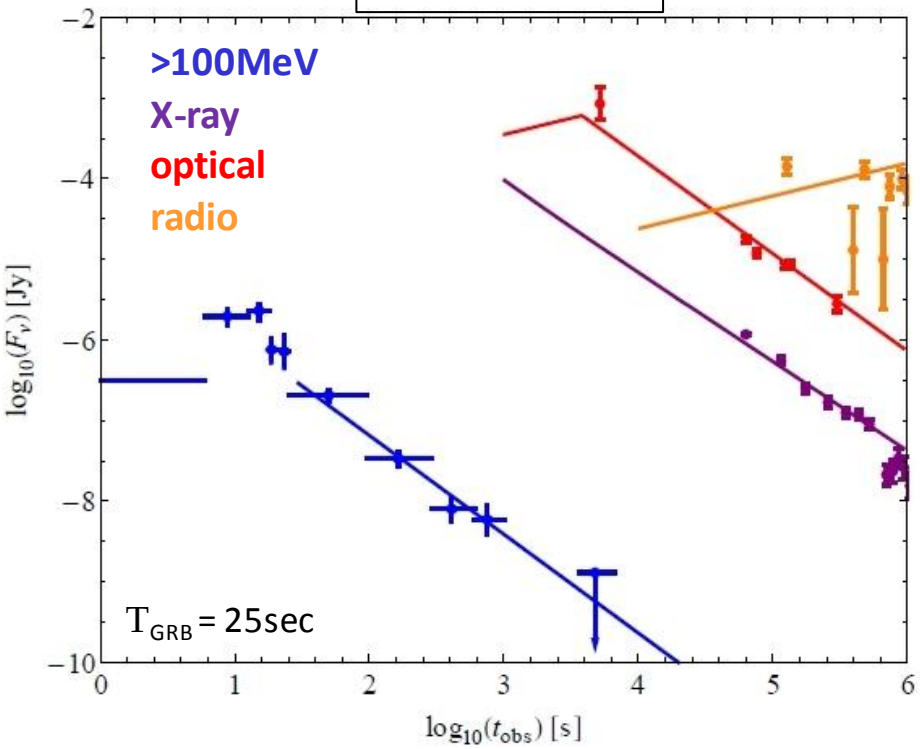
→ flux F_ν at ν comes from electrons with γ_e: $\nu_p(\gamma_e) = \nu$…

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

Confrontation to observations

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

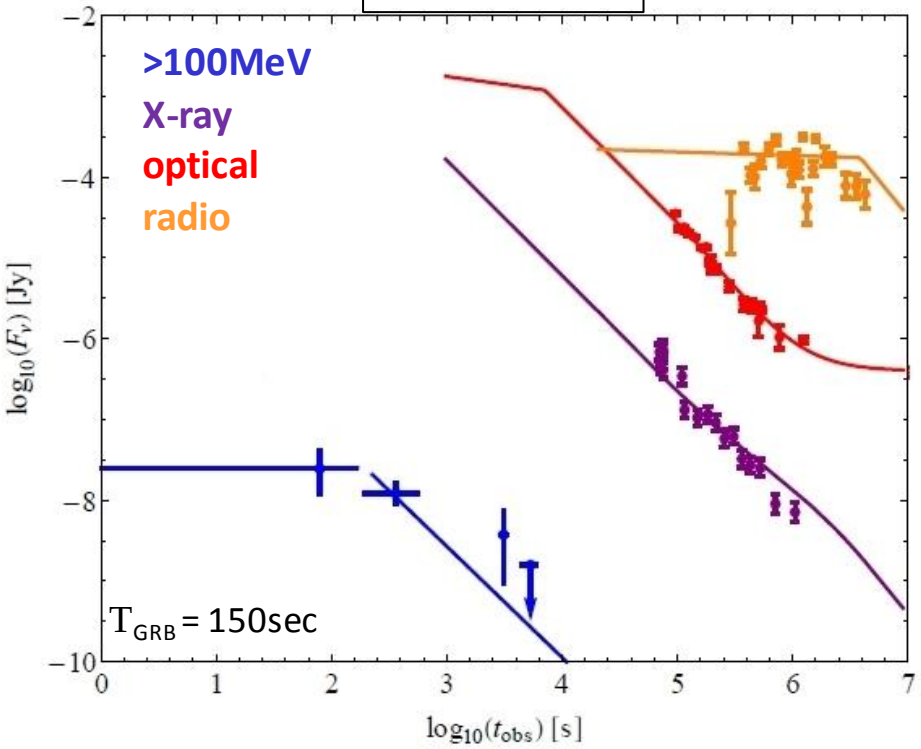
GRB 090902B



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

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

GRB 090323

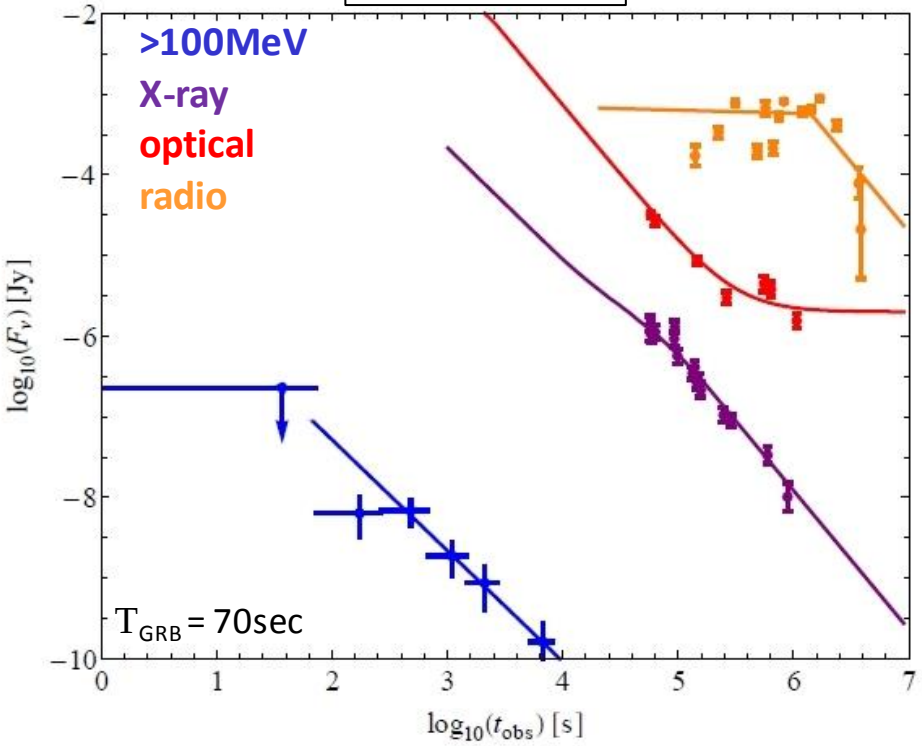


$E_{ej} \sim 5.4\ 10^{54}$ erg
$n \sim 8.4 \times 10^{35}\ r^{-2}$ cm^{-3}
$\varepsilon_e \sim 0.29$, $p \sim 2.5$
$\alpha_t \sim -0.54 \pm 0.09$

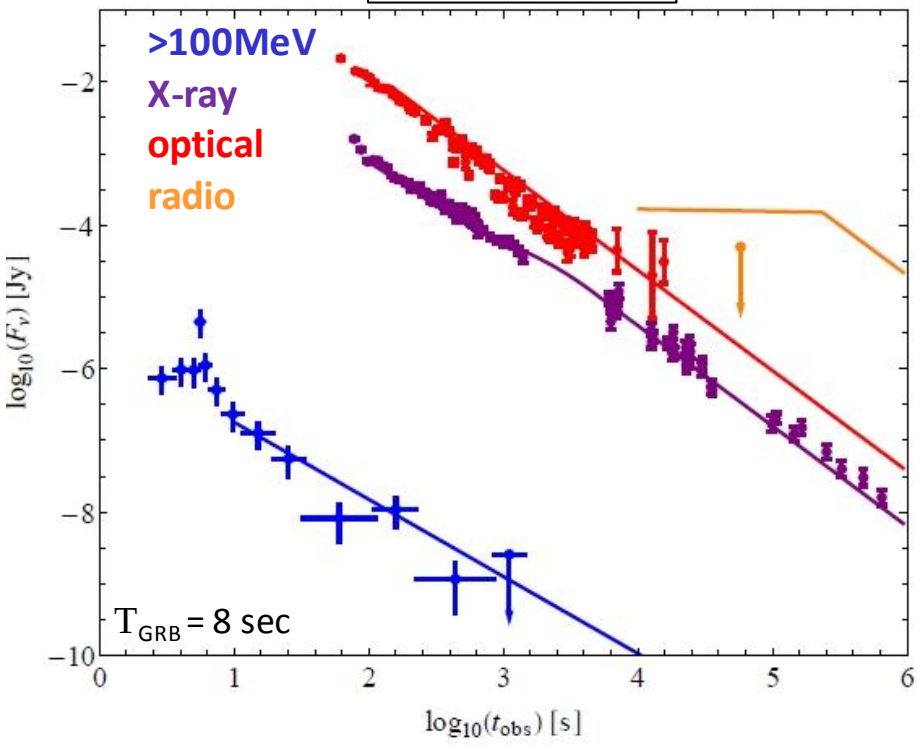
Confrontation to observations

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

GRB 090328



GRB 110731A



E_{ej} ~ 0.73 x 10^{54} erg
n ~ 1.5 x 10^{35} r^{-2} cm^{-3}
ε_e ~ 0.18, p ~ 2.5
α_t ~ -0.48 ± 0.11

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

E_{ej} >~ 6 x 10^{54} erg
n <~ 0.1 x 10^{35} r^{-2} cm^{-3}
ε_e <~ 0.04, p ~ 2.1
α_t <~ -0.35 ± 0.20

Discussion

→ a simple solution, which reconciles data and theory, for the problem of the origin of magnetization in GRB blast waves:

→ synchrotron radiation takes place in the partially decayed Weibel turbulence, which is self-generated at the (ultra-relativistic, unmagnetized) collisionless shock

→ 4 GRBs seen in radio, optical, X-ray through >100MeV point to a consistent net decay power law of the magnetic field downstream of the shock:

$\epsilon_B \propto t^{\alpha_t}$ **with: -0.5 < α_t < -0.4** (t indicates 3x distance/c to shock)

→ values for ε_B **do not agree** with other estimates by Cenko et al. for 090902B, 090323, 090328, or with Ackermann et al. (Fermi Coll.) for 110731A:

difference: these works do not account for >100MeV emission…

… so 3 constraints for 4 parameters…

degeneracy implies that $\varepsilon_B \sim 0.01$ in these works is a choice rather than a result!

→ is this even more general? What about earlier determinations of ε_B?

Does the canonical value $\varepsilon_B \sim 0.01$ hold at all?

Summary - conclusions

Particle acceleration at relativistic shock waves is intimately connected to the self-generation of turbulence…

→ shock physics in mildly relativistic regime, high or low magnetization, less ideal conditions remain to be worked out…

→ a clearer view in the past decade thanks to PIC simulations (+theory!), especially at low magnetization

A microphysical solution for the origin of magnetization in GRB blast waves:

→ **synchrotron radiation takes place in the partially decayed Weibel turbulence, which is self-generated at the (ultra-relativistic, unmagnetized) collisionless shock**

→ a broad turbulence power spectrum at the shock leads to a power-law decay:

$$\delta B^2(t) \simeq \delta B^2(t=0)\left[t/\left(100\omega_{\rm pi}^{-1}\right)\right]^{\alpha_t}$$

→ 4 GRBs seen in radio, optical, X-ray through >100MeV point to a net decay power law of the magnetic field downstream of the shock: $-0.5 < \alpha_t < -0.4$