Particle acceleration in GRBs

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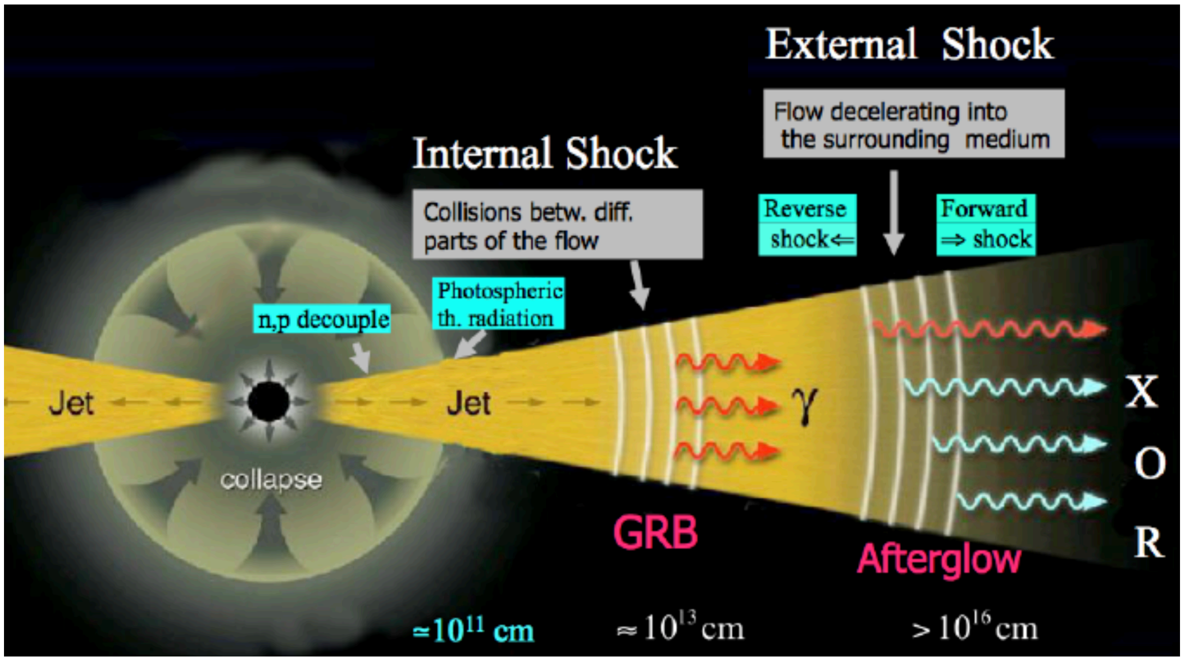
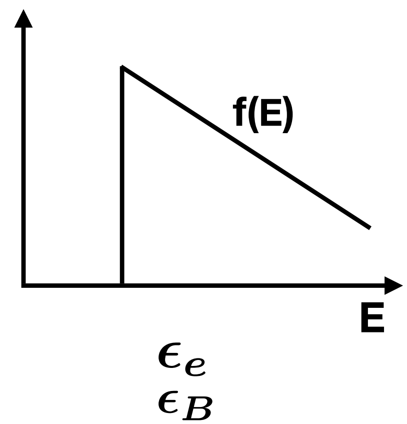
Topics:

- Collisionless shocks
- Radiation-mediated shocks
- Magnetically dominated jets
- Pair creation
- Free neutrons
- High-energy gamma-ray emission
- Neutrino emission
- UHECRs

1990s: cooking phenomenological models



Meszaros 2001



GENERATION OF MAGNETIC FIELDS IN THE RELATIVISTIC SHOCK OF GAMMA-RAY BURST SOURCES

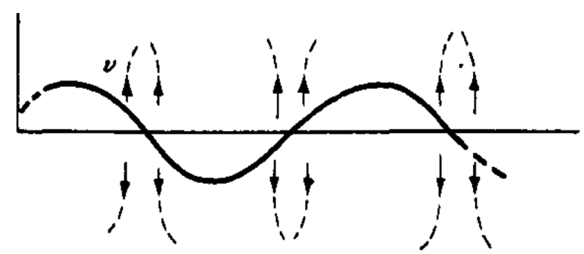
Mikhail V. Medvedev[1] and Abraham Loeb[2]
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
Received 1999 April 26; accepted 1999 July 14

ABSTRACT

We show that the relativistic two-stream instability can naturally generate strong magnetic fields with 10^{-5}–10^{-1} of the equipartition energy density, in the collisionless shocks of gamma-ray burst (GRB) sources. The generated fields are parallel to the shock front and fluctuate on the very short scale of the

Kahn 1958; Parker 1958; Weibel 1959

Moiseev, Sagdeev 1963:

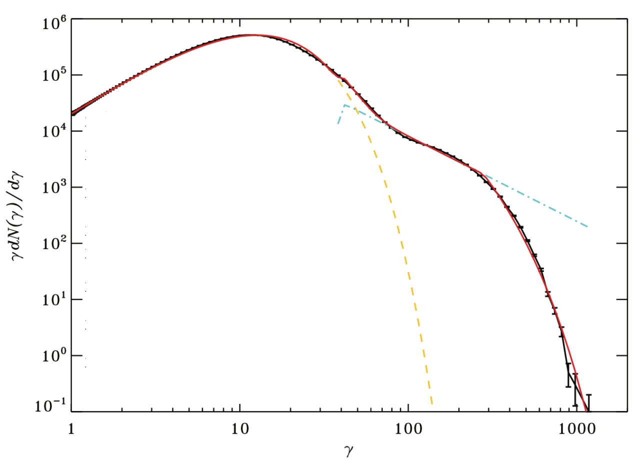


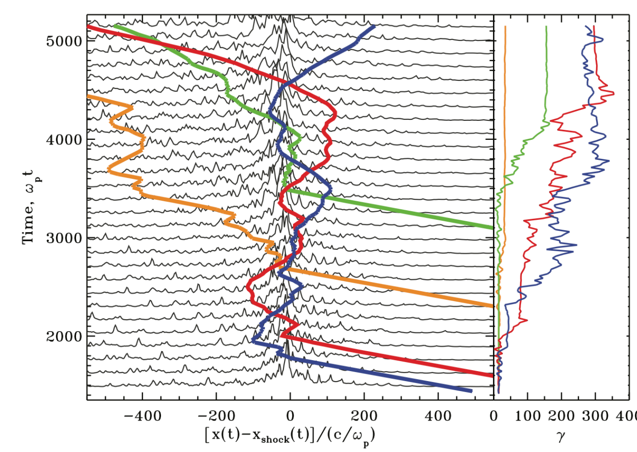
Are particles accelerated in shocks?

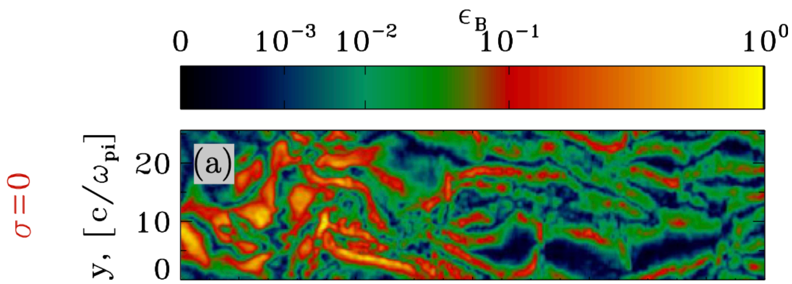
PARTICLE ACCELERATION IN RELATIVISTIC COLLISIONLESS SHOCKS: FERMI PROCESS AT LAST?

Anatoly Spitkovsky[1]

Received 2008 February 28; accepted 2008 May 21; published 2008 July 8







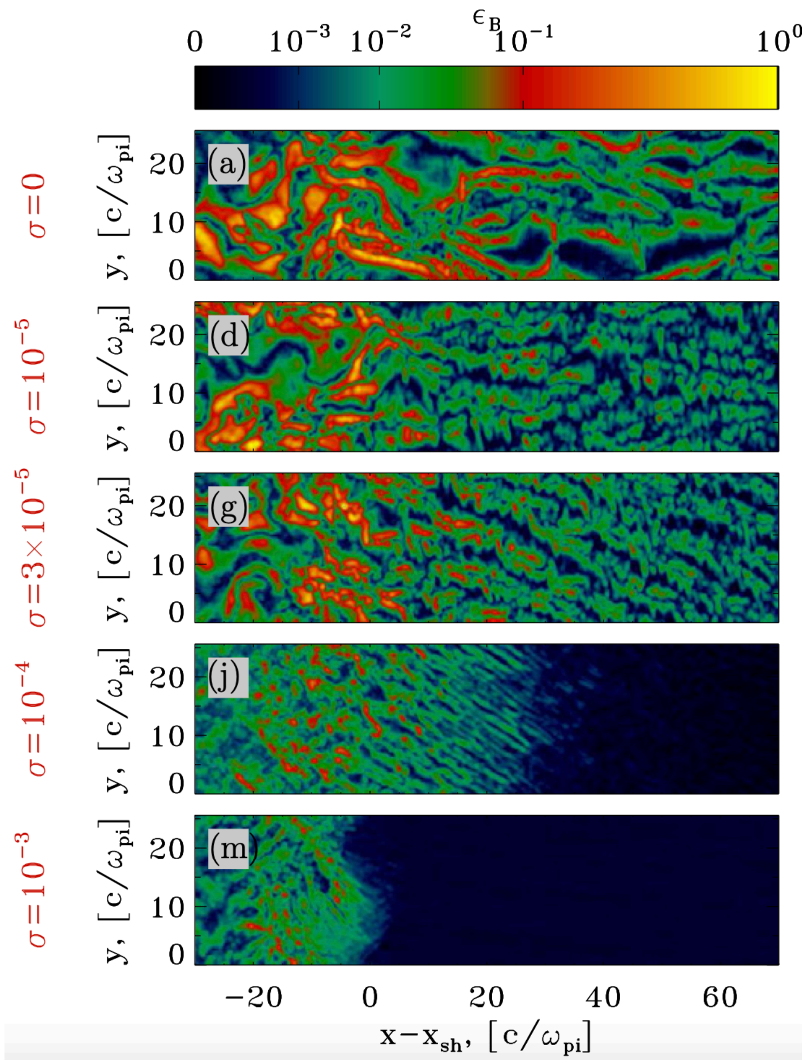
$$t_{acc} = \eta \frac{r_L}{c} \longrightarrow t_{scat} \sim \frac{r_L^2}{\lambda c}$$

particle scattering by magnetic filaments:

$$\gamma_{max,i} \approx 0.25\, \gamma_0 (\omega_{pi} t)^{1/2}$$

In GRB blast waves, particles reach PeV energies

Sironi et a. 2013

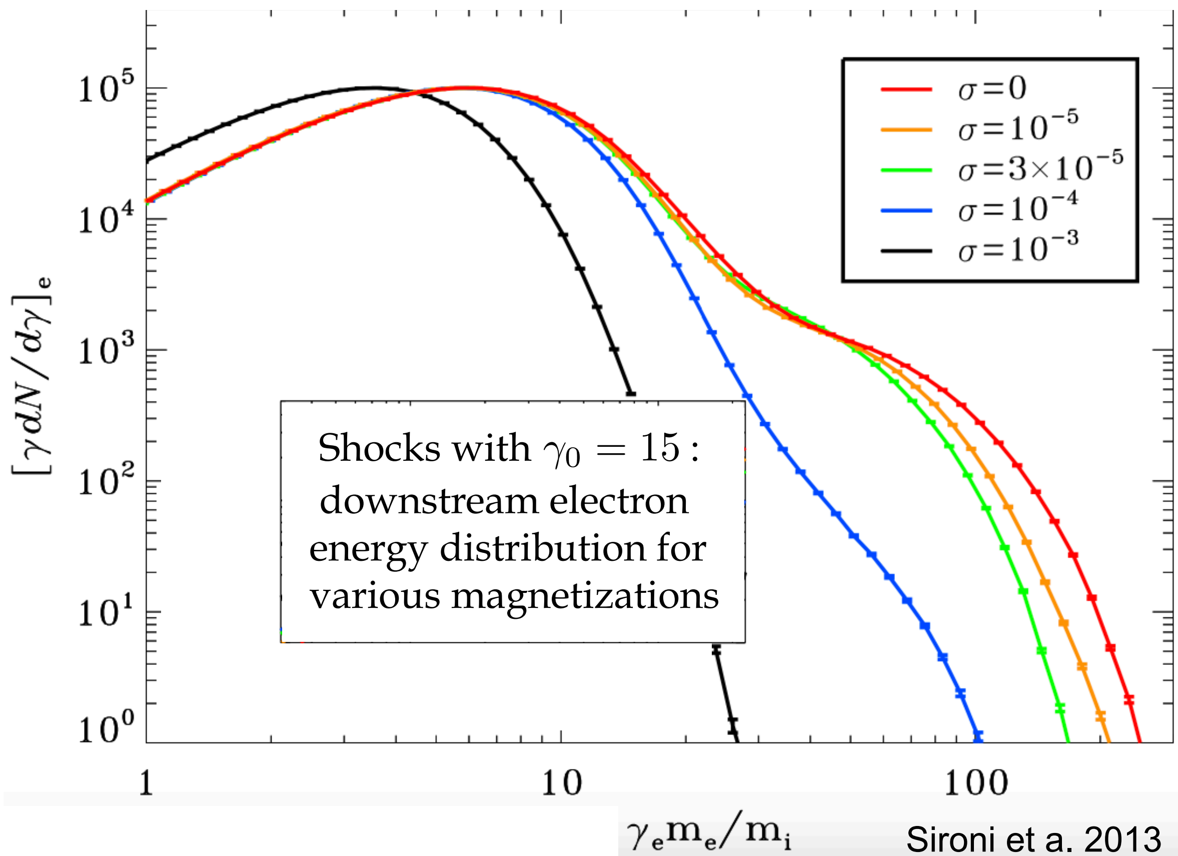


role of
initial (upstream)
magnetization:

$$\sigma \equiv \frac{B_0^2}{4\pi n_0 m c^2}$$

$\sigma > 10^{-4}$ suppresses
turbulence and
particle acceleration

Lemoine, Pelletier 2010
Sironi et a. 2013



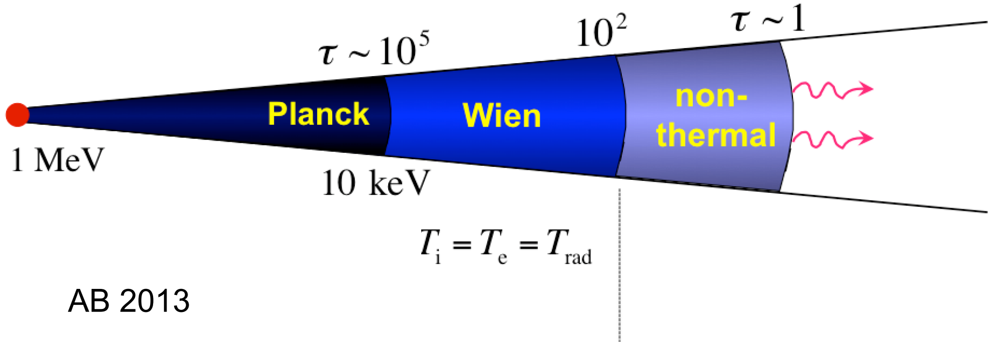
Nonthermal component is ~10% at low sigma and suppressed at modest sigma

Internal shocks in GRB jets carry transverse magnetic field
=> Fermi acceleration does not operate
=> scenario of shock synchrotron does not work

The synchrotron shock scenario was not really required or preferred by data.

GRB spectra are better explained as dissipative photosphere emission.

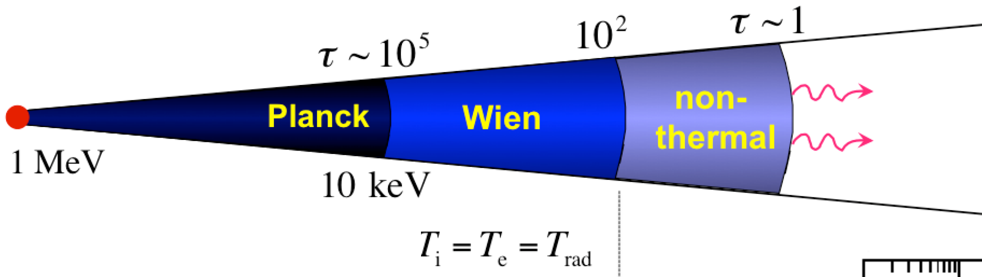
Nonthermal photospheric emission



AB 2013

Thompson 1994
Eichler and Levinson 2000
Rees Meszaros 2005
Pe'er et al. 2006
Giannios 2008
AB 2010
Levinson 2012
Thompson, Gill 2014

Nonthermal photospheric emission



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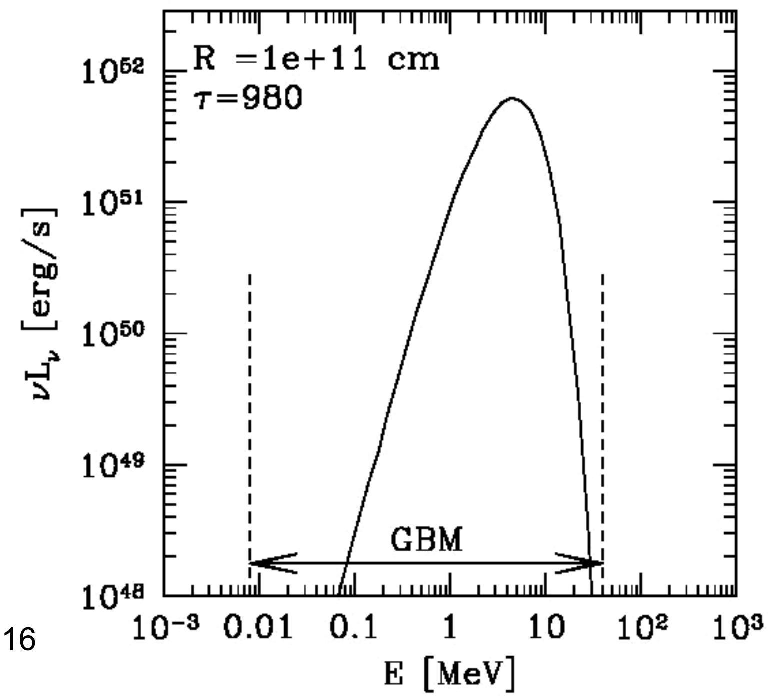
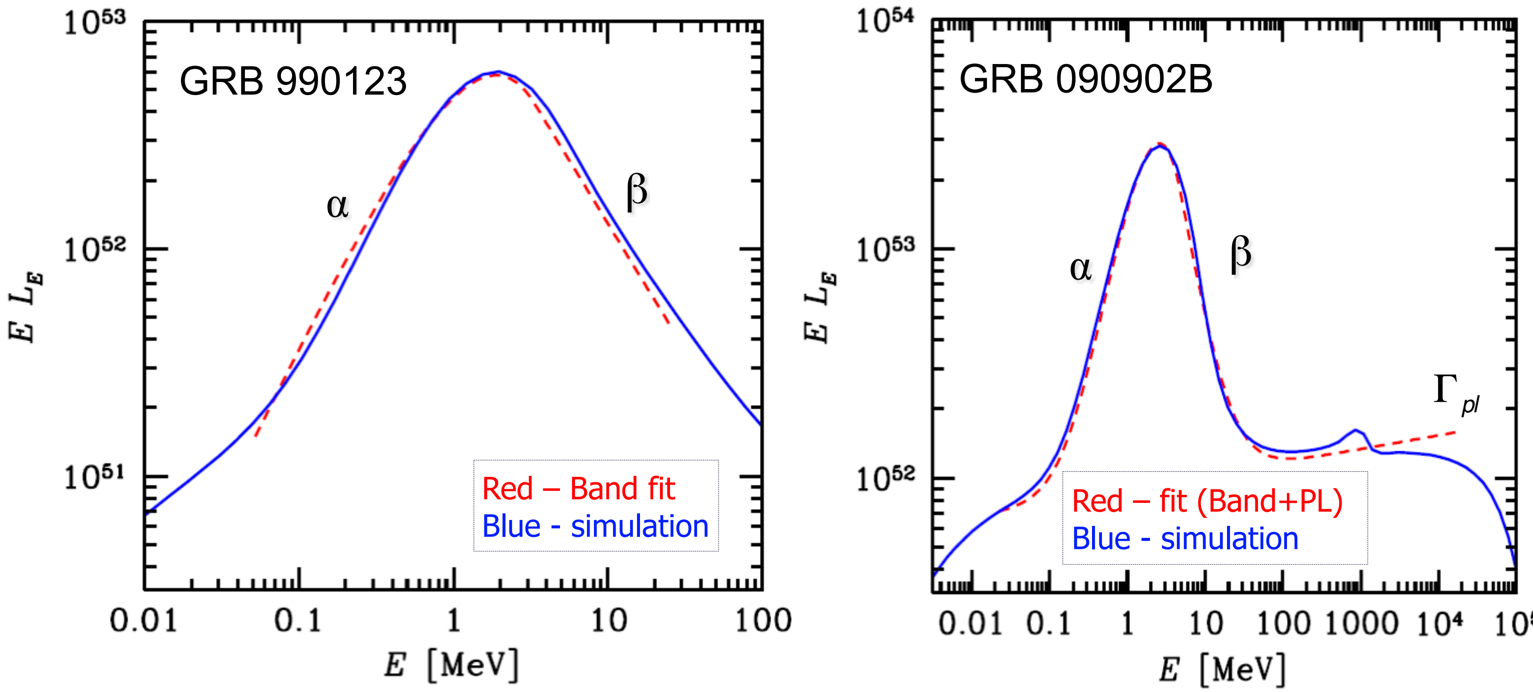


Vurm & AB 2016



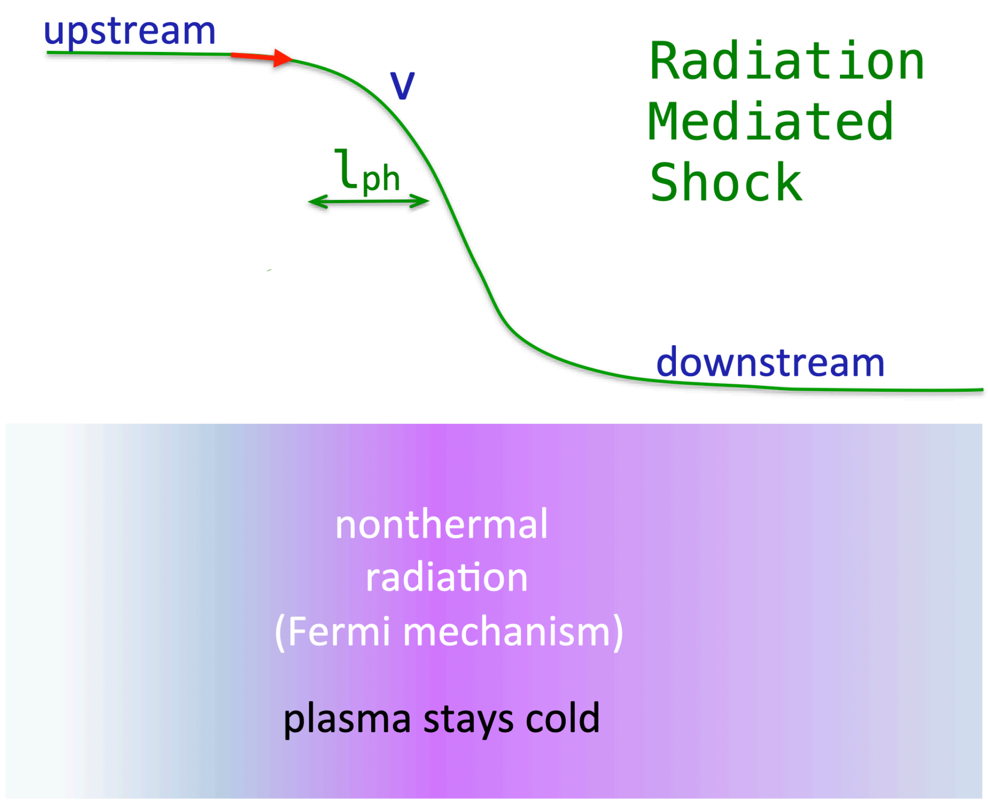
=> 1. $\sigma = 0.01 - 0.1$

2. Nonthermal heating (energetic particle injection) comparable to thermal

Are particles accelerated in subphotospheric shocks?

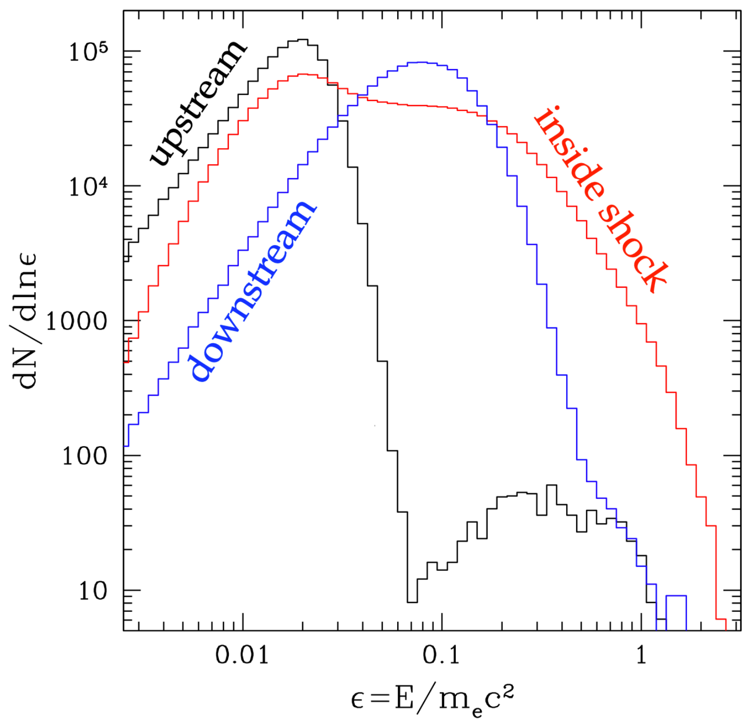
(+ sources of TeV-PeV neutrinos?)

Radiation Mediated Shock



Levinson 2012
AB 2017
Lundman, AB, Vurm 2018
Ito et al. 2018

Full simulation (radiative hydrodynamics)



AB 2017

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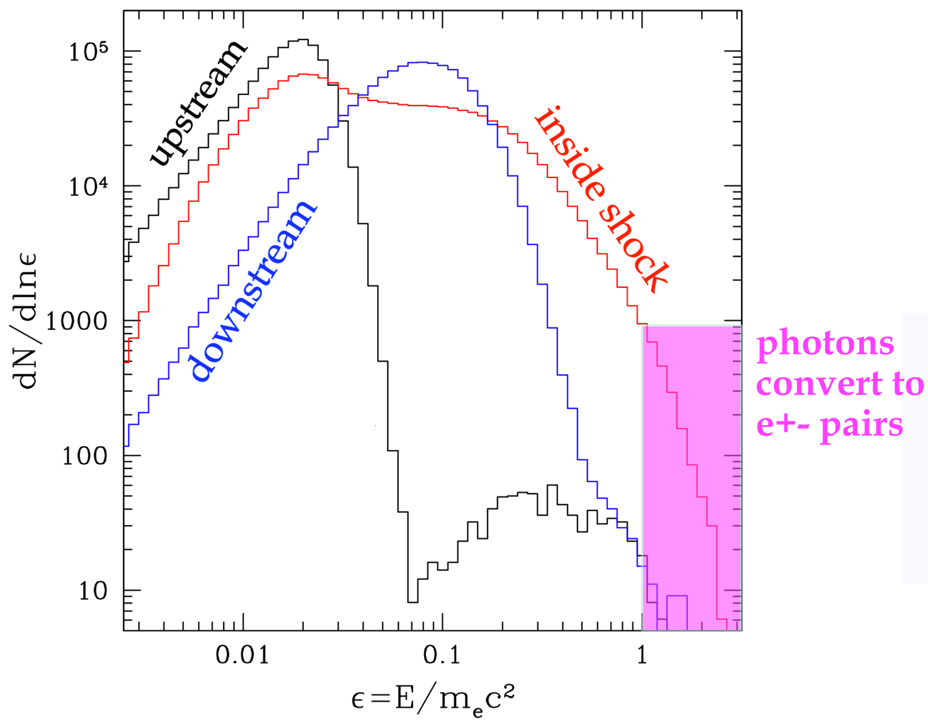
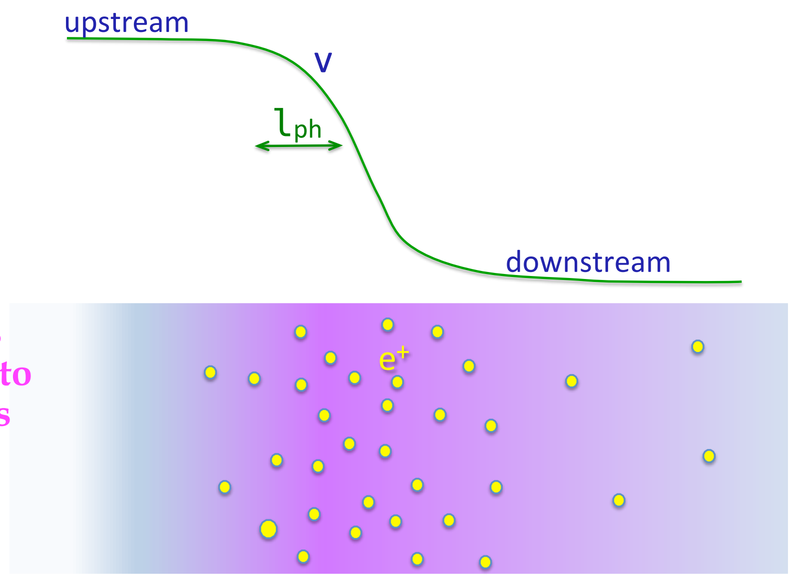
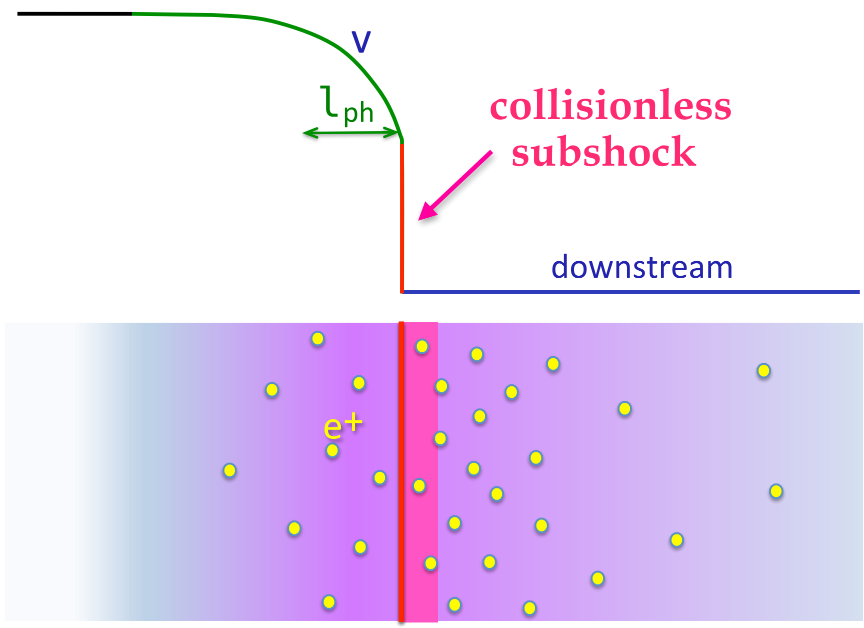




AB 2017

Magnetized plasma: $\sigma \sim 0.01 - 0.1$

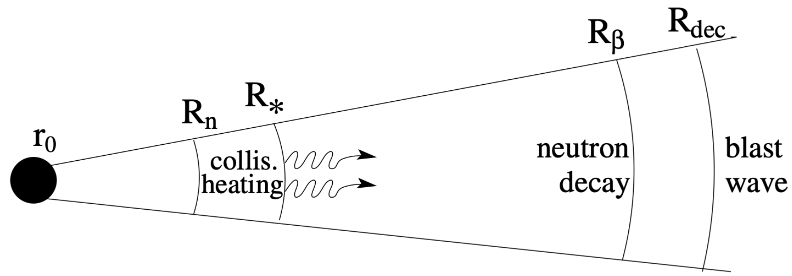


— still no Fermi acceleration

AB 2017

Neutron component in GRB jets

Derishev et al. 1999, 2003
Bahcall, Meszaros 2000
AB 2003, 2010



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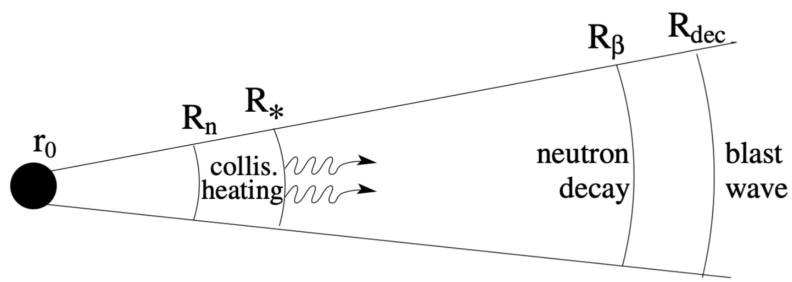
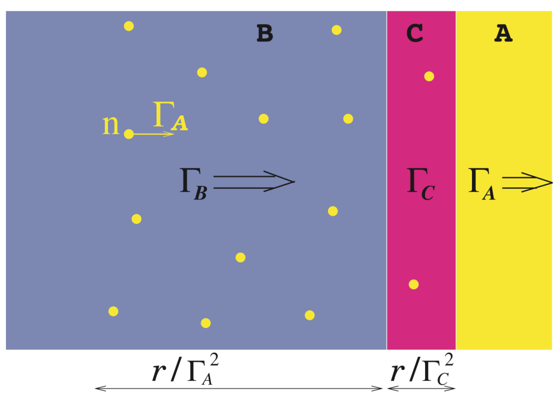


internal shocks



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Derishev et al. 1999, 2003
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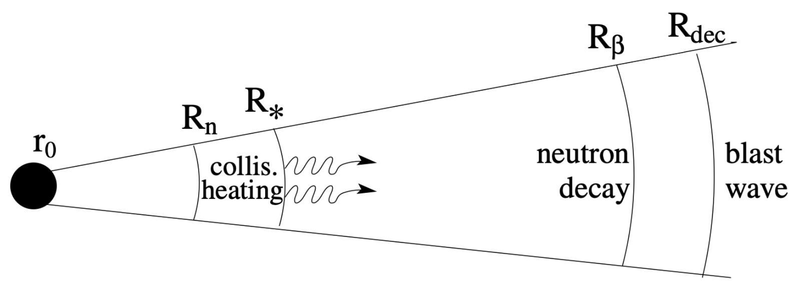
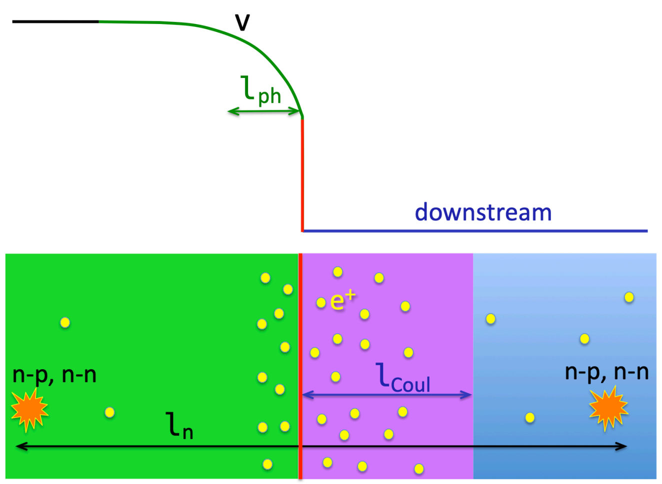
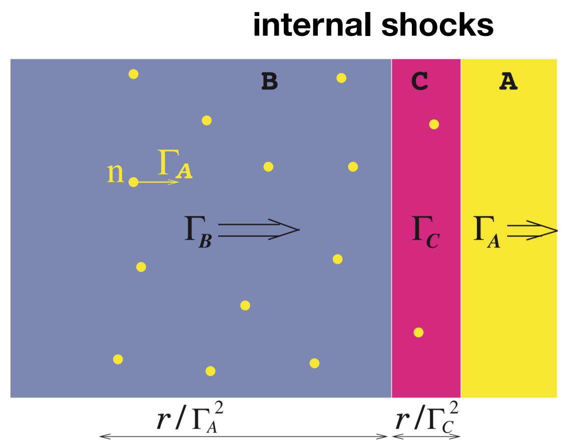
AB 2003, 2010







converter acceleration?

Inelastic nuclear collisions generate neutrinos and nonthermal e+-

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}, \bar{\nu}_{\mu}$$
$$\downarrow$$
$$e^{\pm} + \nu_{e}, \bar{\nu}_{\mu} + \bar{\nu}_{e}, \nu_{\mu}$$

$\Rightarrow$ Neutrino emission with energies

$$\epsilon \sim \Gamma m_{\pi} c^2 \approx 30 \left(\frac{\Gamma}{600}\right) \left(\frac{1+z}{2}\right)^{-1} \ \mathrm{GeV}$$

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$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu, \bar{\nu}_\mu$$
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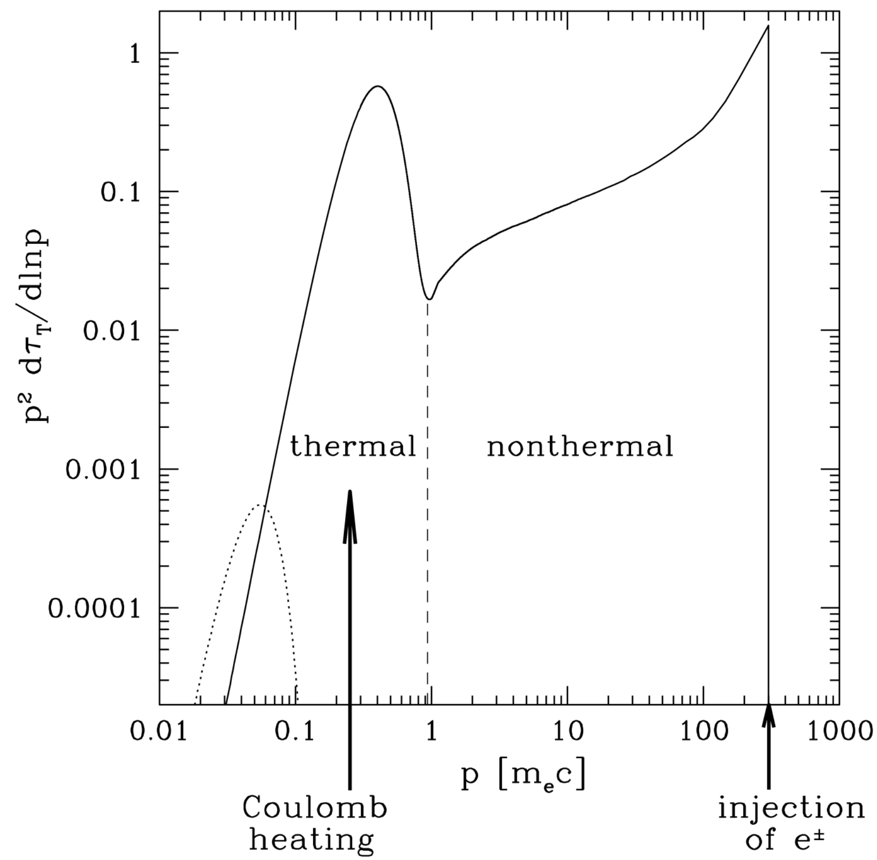
electron distribution function



Magnetically dominated jets

$$\sigma = \frac{B^2}{4\pi\rho c^2} > 1$$

Particles are energized by magnetic reconnection/turbulence

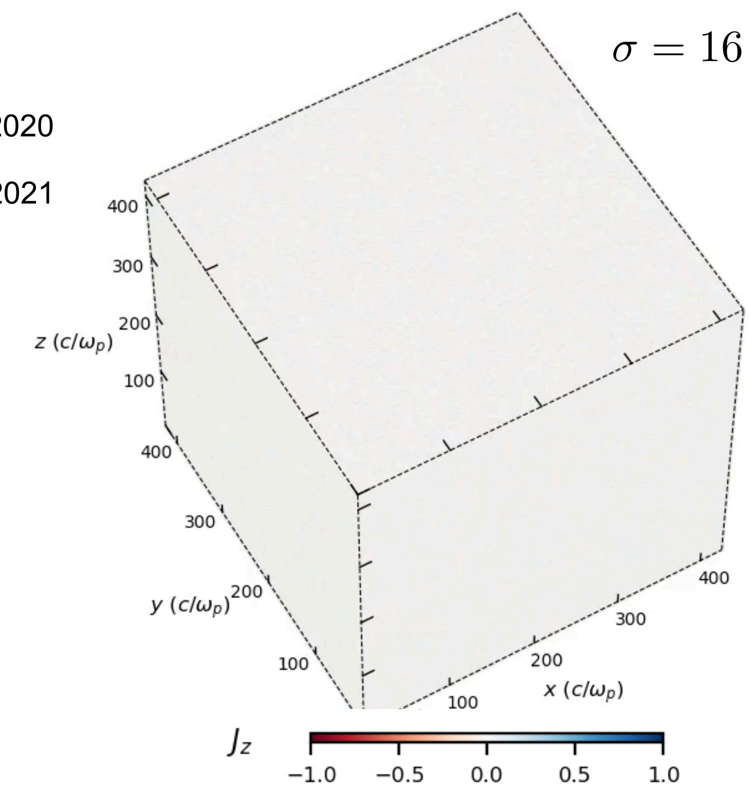
Thompson 1994, 2006
Spruit et al, 2001
Lyutikov, Blandford 2003
Zhang, Yan 2011

Turbulence (PIC simulations):

$\sigma = 16$

Zhdankin et al. 2019, 2020; Comisso, Sironi 2019, 2020

Nattila & AB 2021



Radiative turbulence:

- stochastic acceleration is suppressed by radiative losses — Nattila, AB 2021
- impulsive acceleration $\gamma_e \sim \sigma_e = \frac{B^2}{4\pi n m_e c^2}$ followed by fast cooling
- small pitch angles $\theta \sim 0.1$ affect the synchrotron spectrum — Sobacchi, Sironi, AB 2021
- synchrotron spectral peak at $E_{\rm peak} \propto B\sigma_e^2 \propto L^{1/2} R^{-1} \sigma_e^2$

Radiative reconnection:

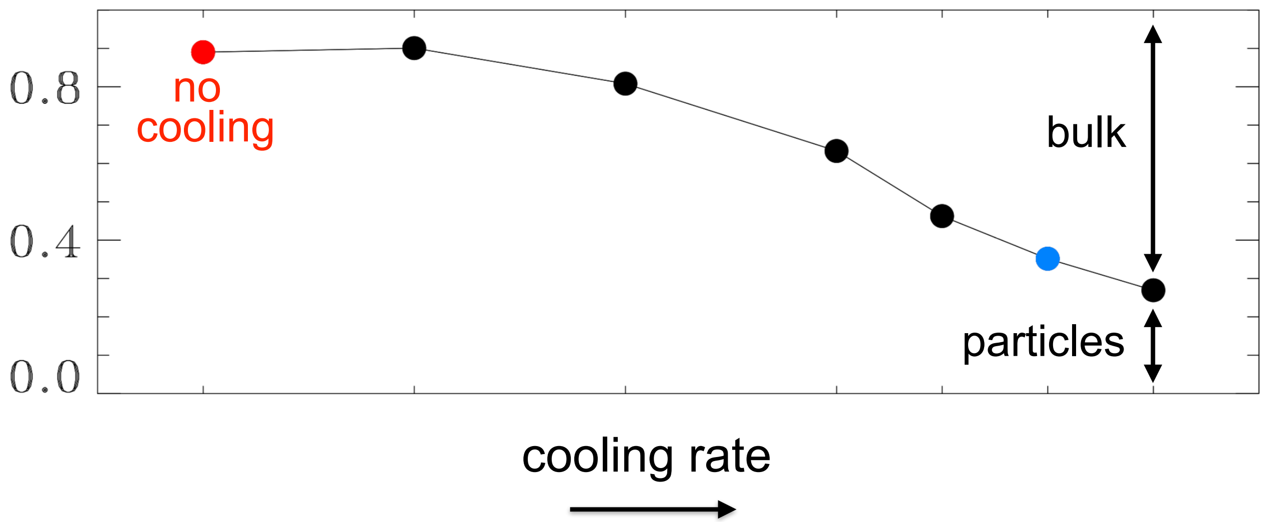
- nonthermally accelerates particles and also creates an effective temperature of ~100 keV through random bulk motions.

The resulting emission spectrum is different from observed GRBs.

AB 2017
Werner et al. 2019
Sironi & AB 2020
Mehlhaff et al. 2021
Sridhar et al. 2021

Partition of reconnection power:

individual particle heating vs. hydro (bulk) motions



~80% of energy is dissipated through drag on bulk motions

Sironi & AB 2020

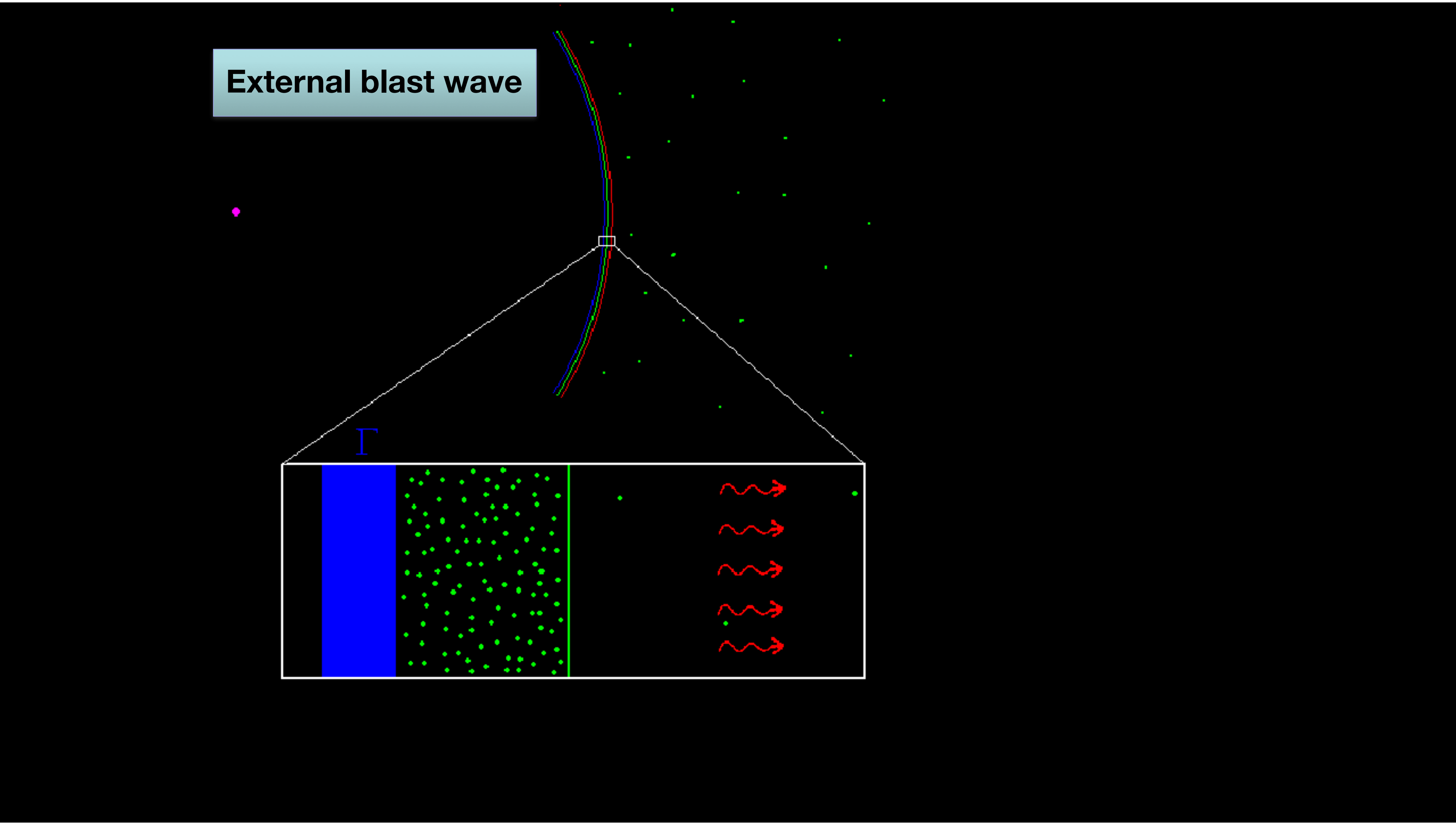
GRB jets are filled with pairs $(n_{\pm} > n_i)$

Dissipation creates pairs

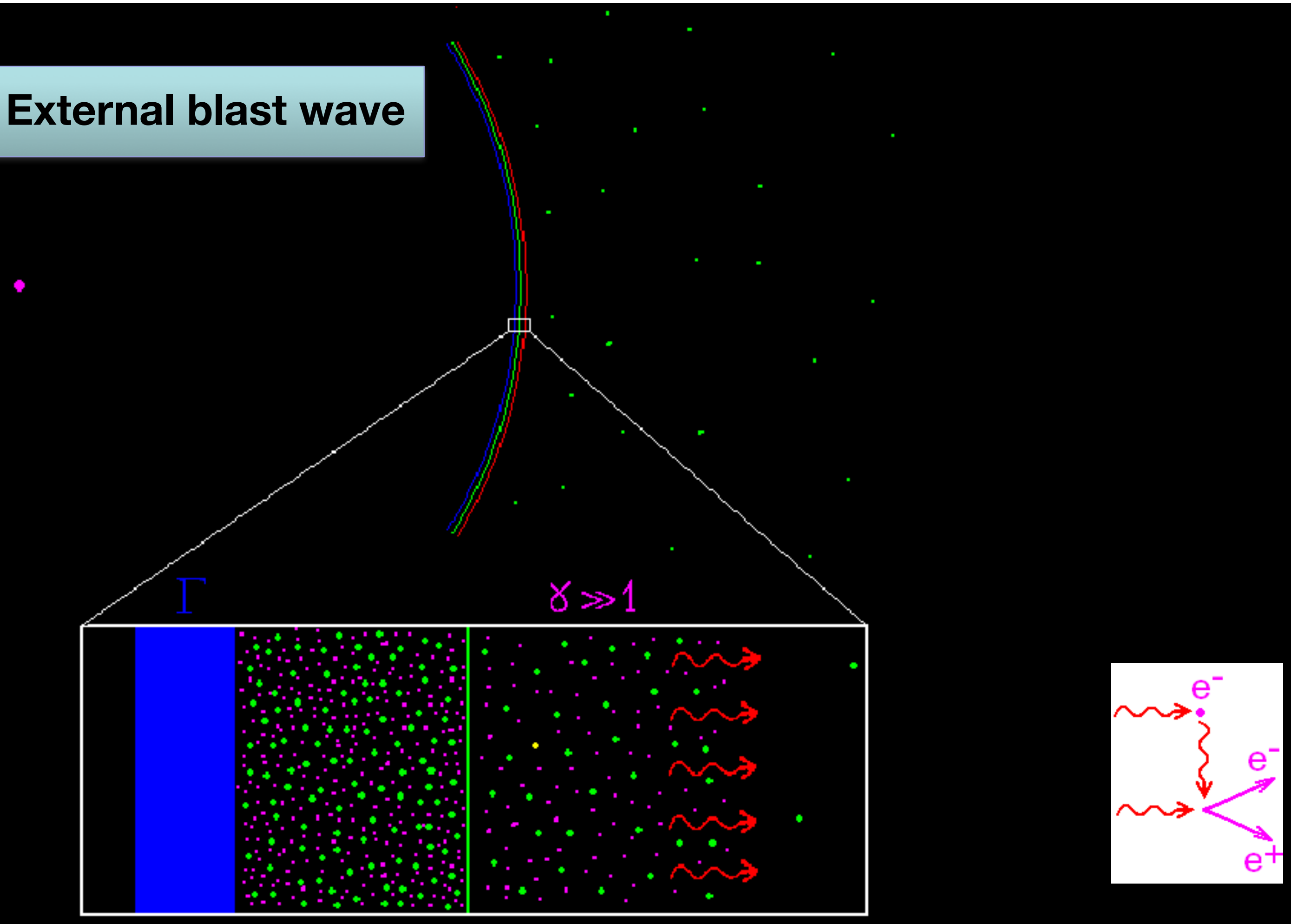
(internal shocks, nuclear collisional heating, reconnection, turbulence)

Pair freeze out: $Z_{\pm} = \dfrac{n_{\pm}}{n_i} \gtrsim 10$

External blast wave

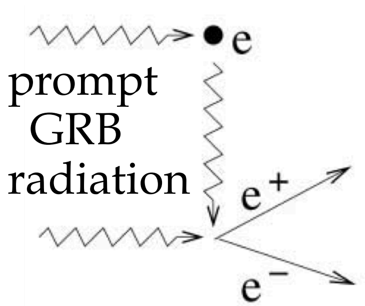


External blast wave

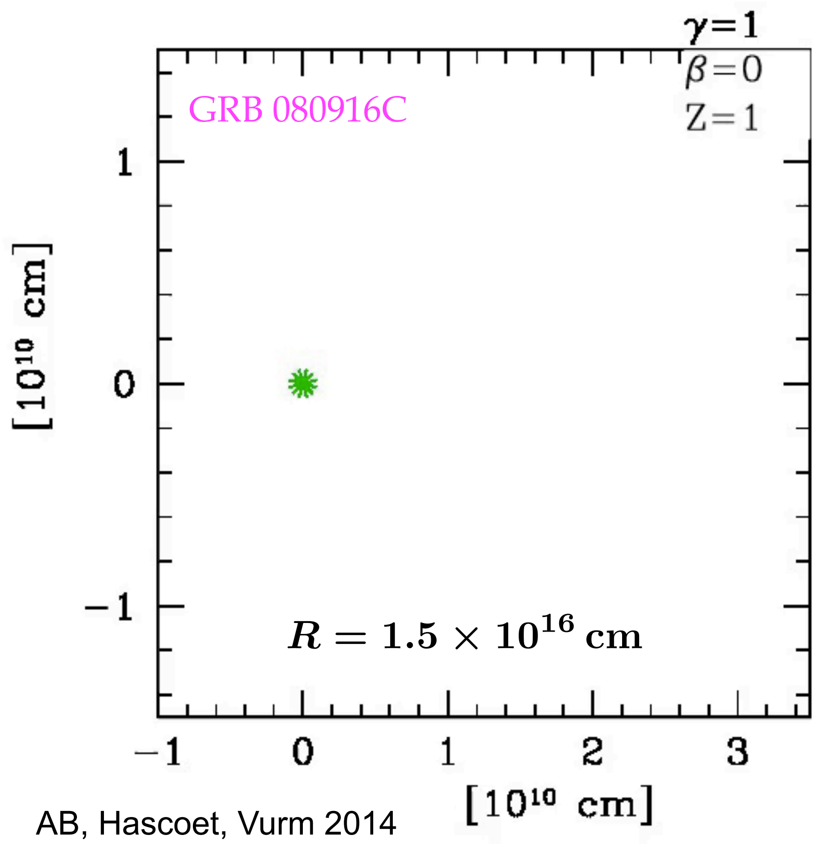


Thompson, Madau 2000; AB 2002

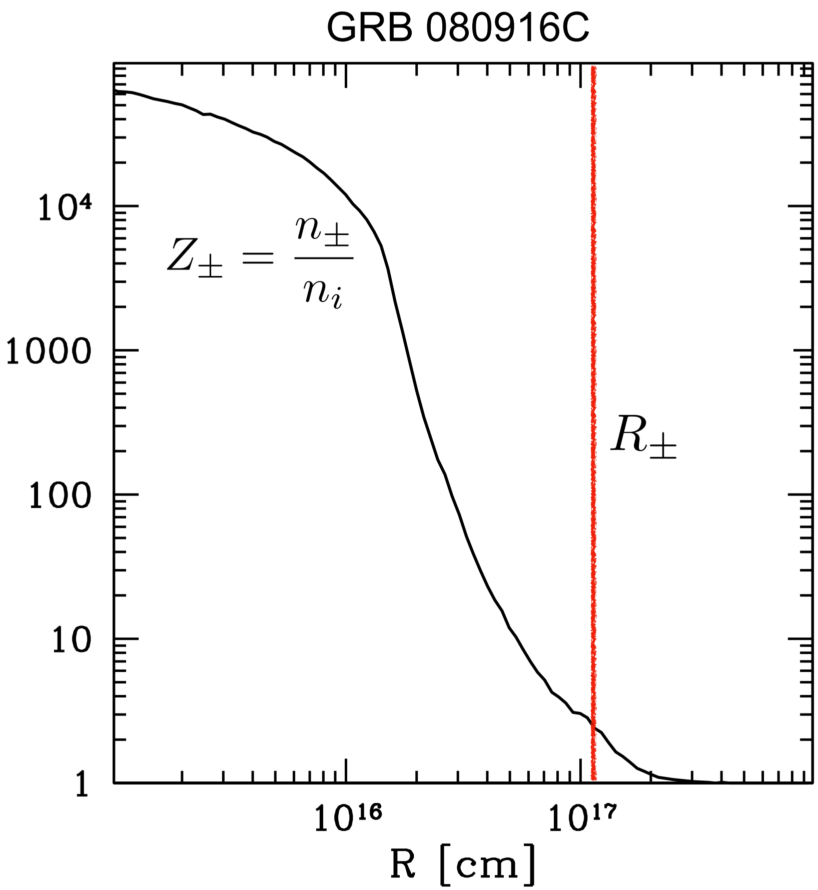
External medium gets filled with e+- pairs



each ambient particle gets "dressed" in $Z_{\pm}$ pairs

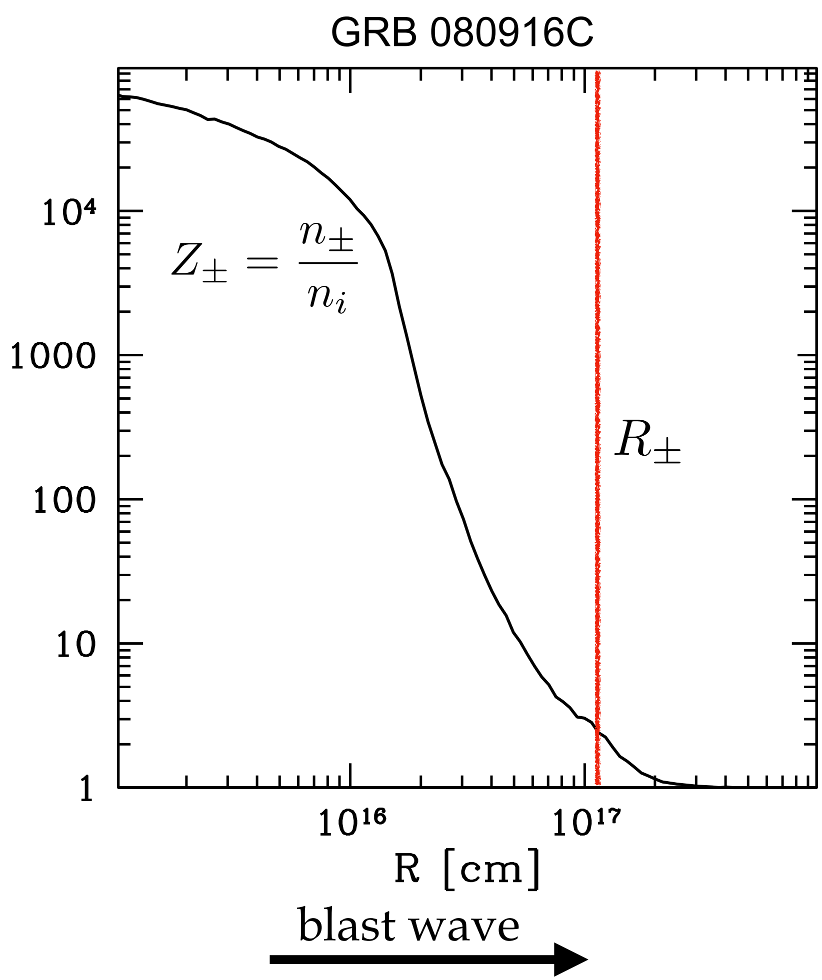


AB, Hascoet, Vurm 2014



$$R_{\pm} \approx 10^{17} \left(\frac{E_{\rm iso}}{10^{54} {\rm erg}} \right)^{1/2} \ {\rm cm}$$

independent of ambient density

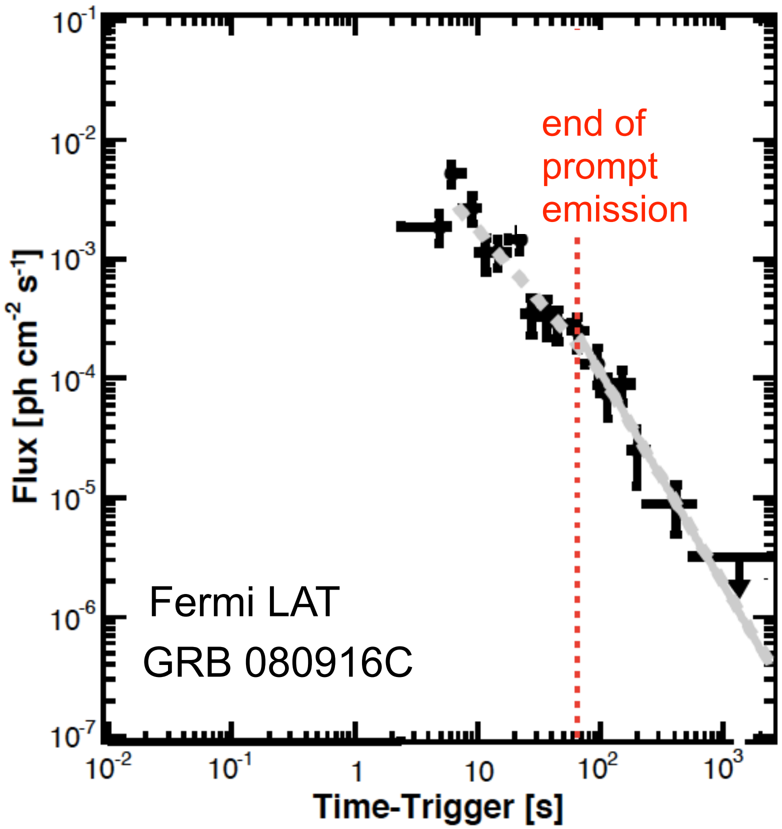


$$R_\pm \approx 10^{17} \left(\frac{E_{\rm iso}}{10^{54}{\rm erg}} \right)^{1/2} {\rm cm}$$

independent of ambient density

Early gamma-ray afterglow
= IC scattering of prompt radiation

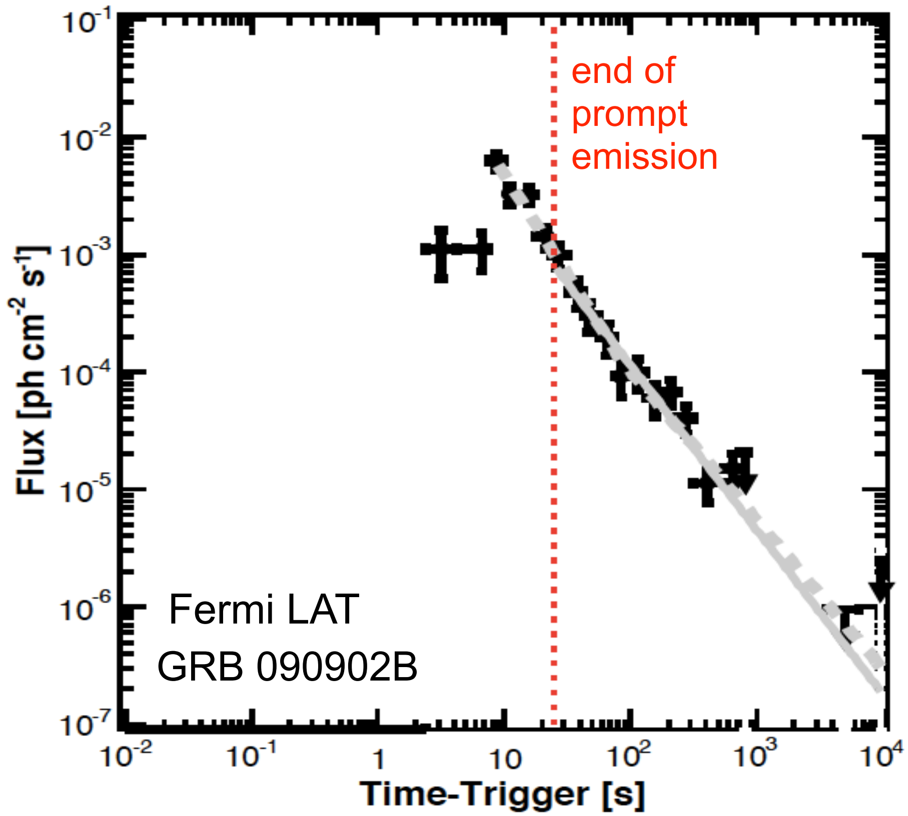
emerges when $Z_\pm < 10^4$
$(R \approx 10^{16}\ {\rm cm})$



Ackermann et al. (2013)

GeV afterglow peaks
before deceleration radius

$Z_{\pm}(R)$ (not deceleration!)
shapes the GeV afterglow peak
– its delay and sudden onset



end of
prompt
emission
Fermi LAT
GRB 090902B
Flux [ph cm^{-2} s^{-1}]
Time-Trigger [s]

Inverse Compton emission from THERMAL plasma:

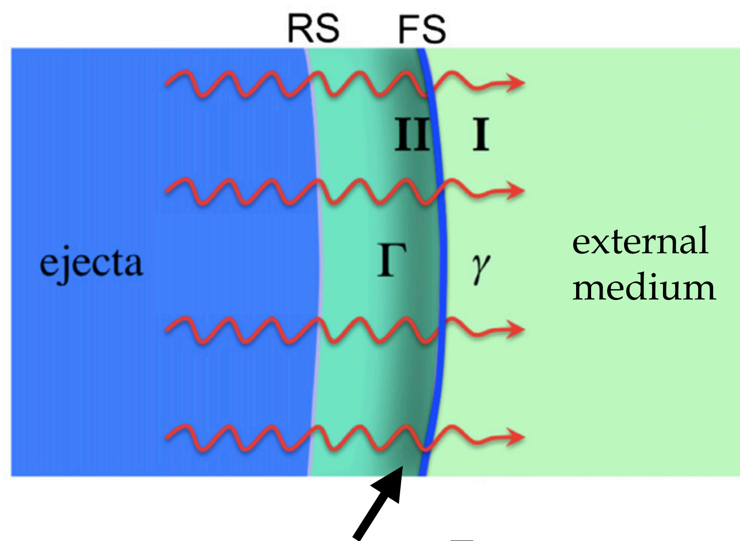
$$h\nu_{\max} \sim \Gamma \gamma_{\rm th} m_e c^2$$

remaining parameter:

external density A/R^2
(progenitor wind)

(WR wind: $A \sim 10^{11}\ \frac{\rm g}{\rm cm}$)

[explosion energy:
GRB energy / (efficiency ~0.2)]



$$\gamma_{\rm th} \sim \frac{0.3\,\Gamma m_p}{\gamma\, Z_{\pm} m_e}$$

scattering of the prompt GRB radiation in the blast wave (Monte-Carlo calculation)

AB, Hascoet, Vurm (2014)

Inverse Compton emission from THERMAL plasma:

$$h\nu_{\max} \sim \Gamma \gamma_{\mathrm{th}} m_e c^2$$

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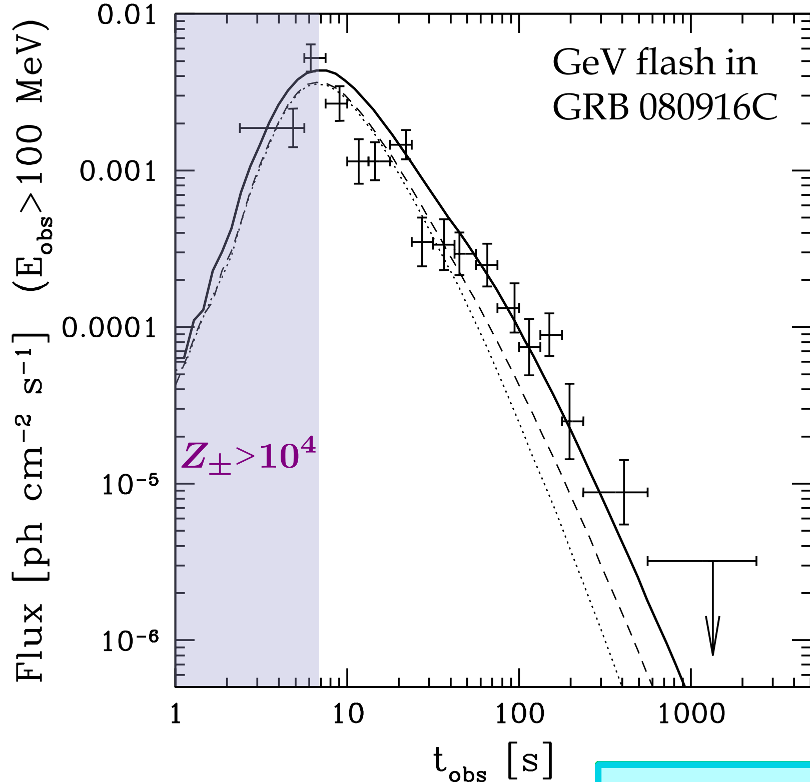
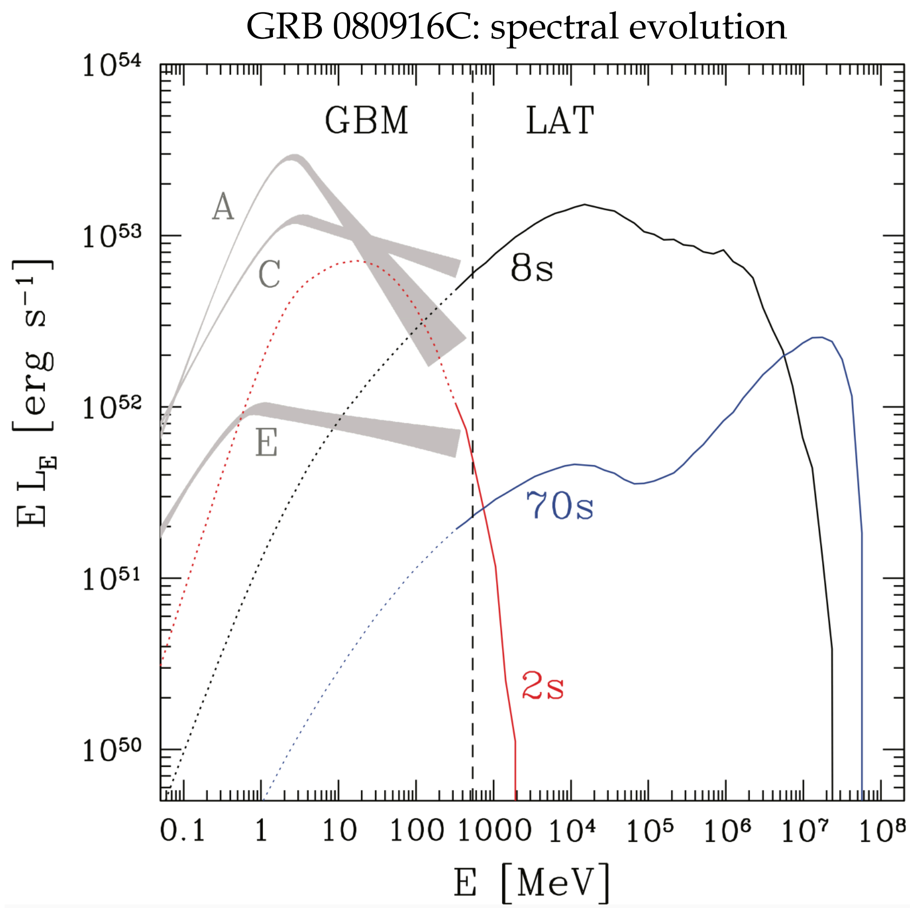


$A = 3 \times 10^{11}\ \frac{\mathrm{g}}{\mathrm{cm}}$!

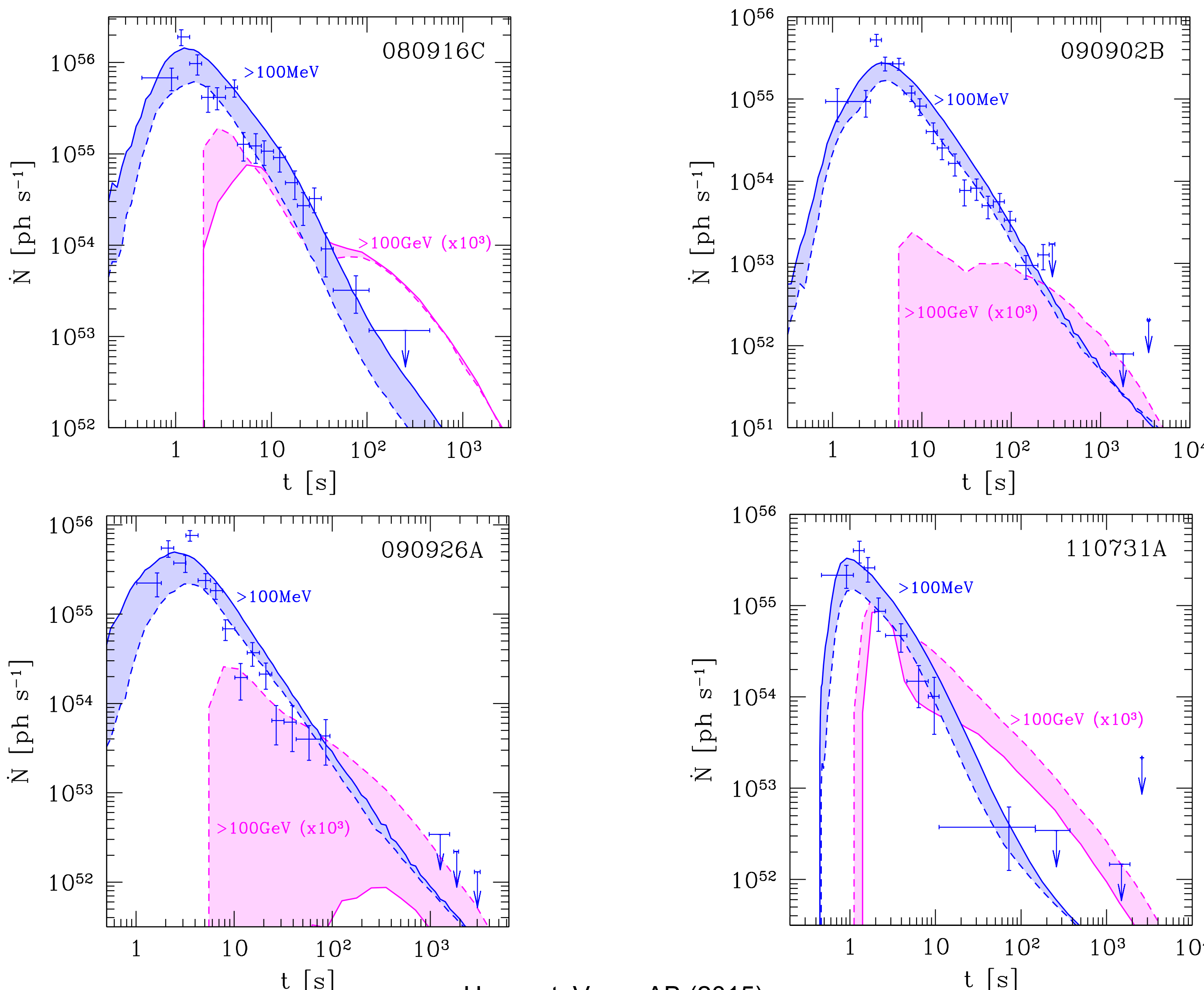
$R_{\mathrm{GeV}} \approx 10^{16}$ cm

$R_{\mathrm{dec}} \approx 8 \times 10^{16}$ cm

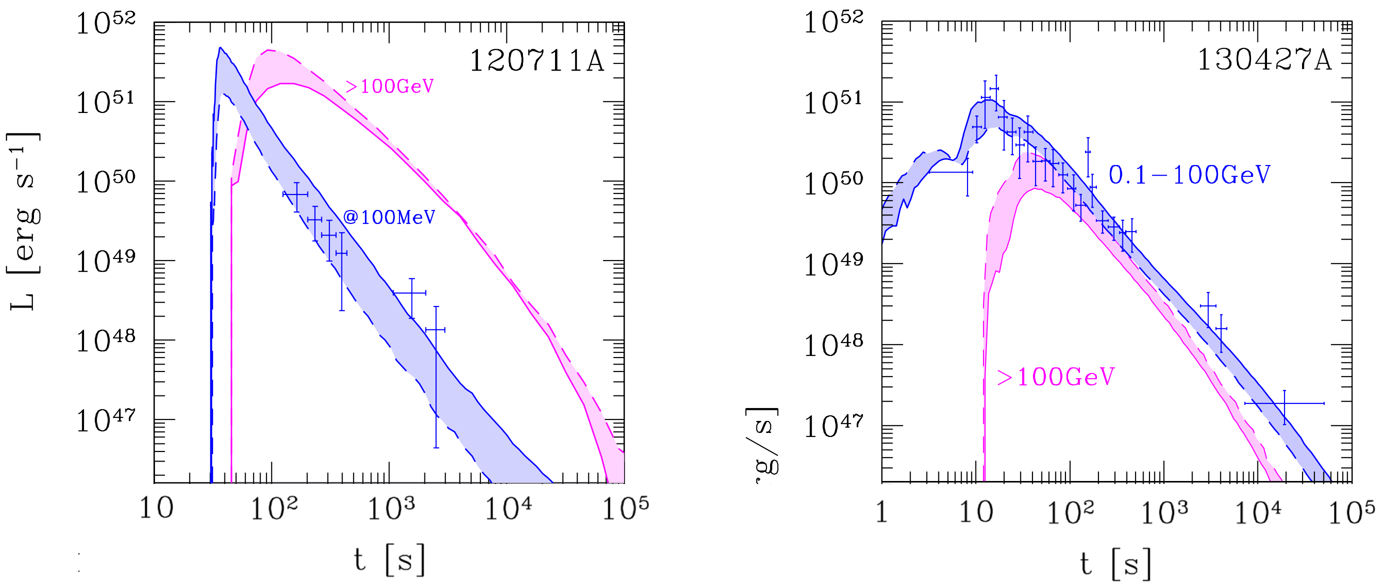
AB, Hascoet, Vurm (2014)

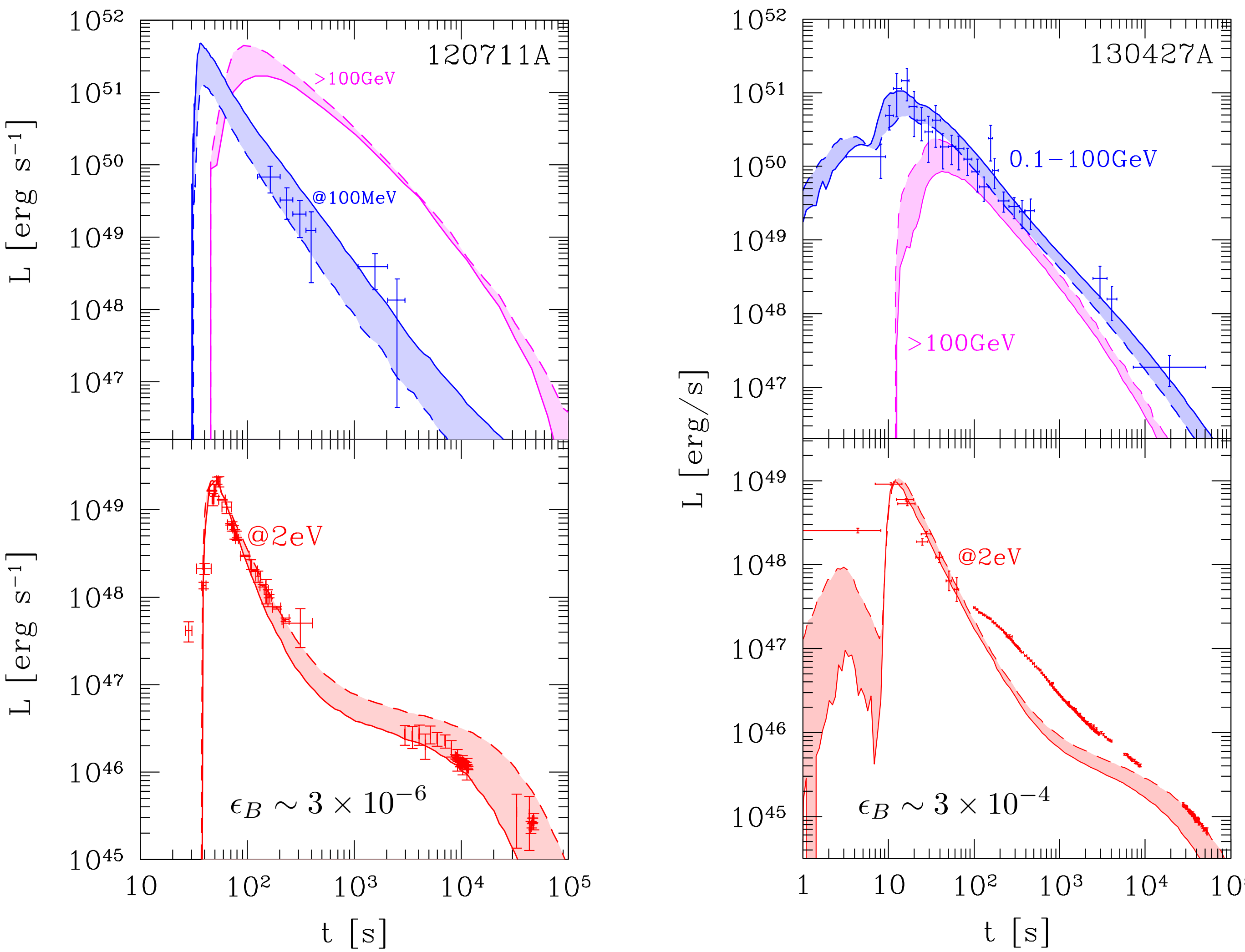


GRB 080916C: spectral evolution
GBM
LAT
A
C
E
8s
70s
2s
E L_E [erg s^-1]
E [MeV]
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^54
10^53
10^52
10^51
10^50



Hascoet, Vurm, AB (2015)


120711A
>100GeV
@100MeV
L [erg s^-1]
t [s]
130427A
0.1−100GeV
>100GeV
t [s]



120711A
>100GeV
@100MeV
@2eV
$\epsilon_B \sim 3\times10^{-6}$
L [erg s^{-1}]
t [s]
130427A
0.1−100GeV
>100GeV
@2eV
$\epsilon_B \sim 3\times10^{-4}$
L [erg/s]

WR progenitor wind parameter A:

$$\rho_{\rm w} = \frac{\dot{M}_{\rm w}}{4\pi R^2 v_{\rm w}} = \frac{A}{R^2}$$

expected $A \sim 10^{11}\,\frac{\rm g}{\rm cm}$

Fits of GeV flash in 7 GRBs:

A_{11} :

2.5	0.6
1.6	2
1.5	0.35
1.5	

Hascoet, Vurm, AB (2015)

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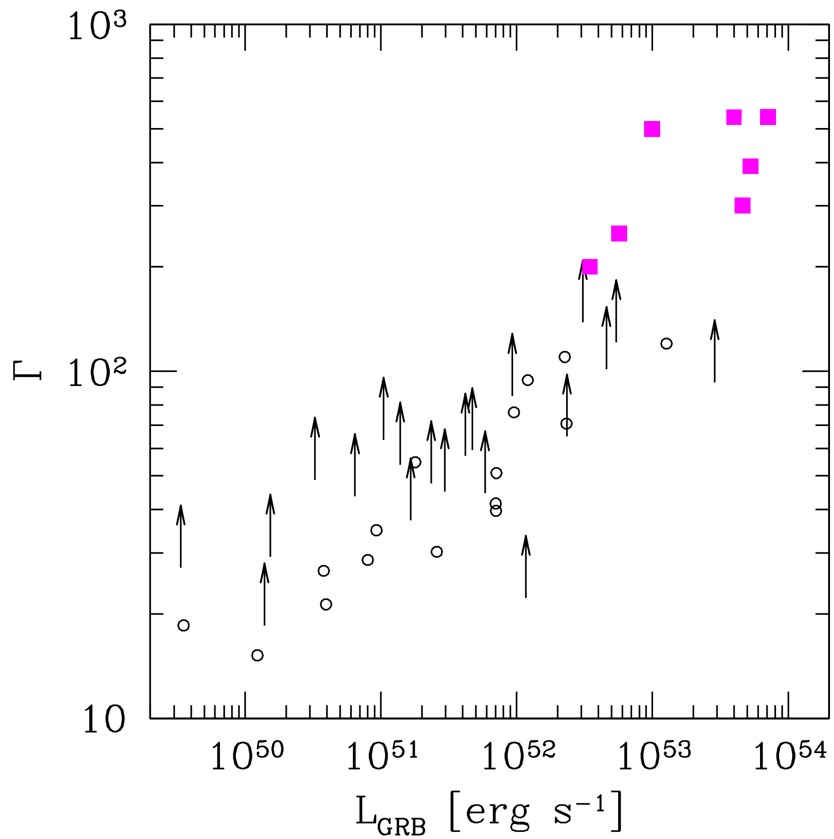

Are particles accelerated in pair-loaded shocks?

Groselj, Sironi, AB, in preparation

pair loading factor $Z_{\pm} = \{\, 0,\ 2,\ 4,\ 6,\ 12 \,\}$

upstream magnetization $\sigma = \{\, 0,\ 5 \times 10^{-6},\ 10^{-5},\ 3 \times 10^{-5},\ 10^{-4} \,\}$

$\gamma_0 = 50$

(particle-in-cell simulations; grid size up to $5,400 \times 295,000$)

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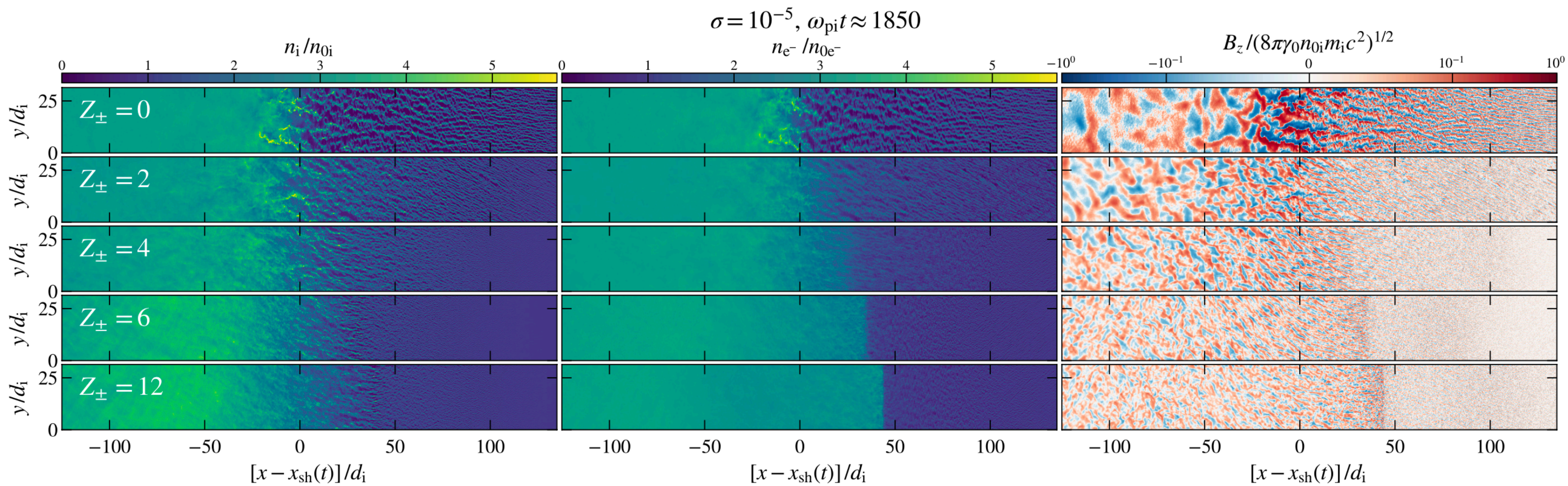


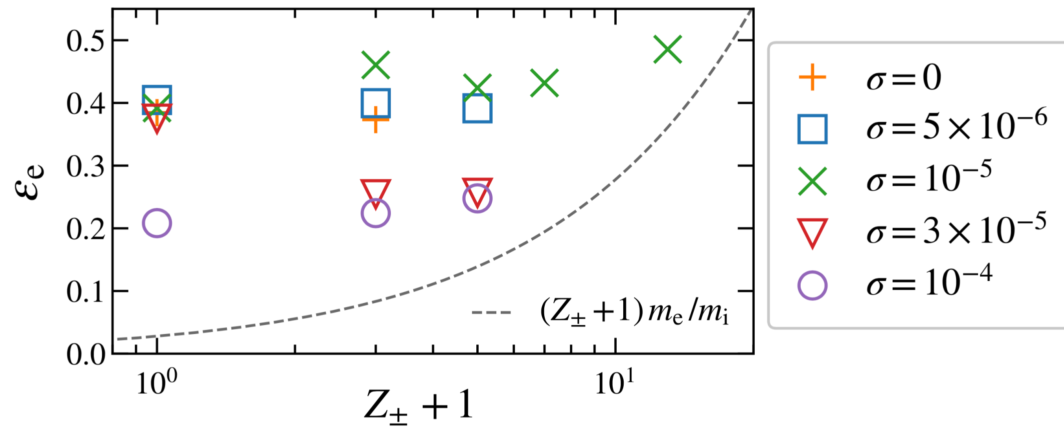
(particle-in-cell simulations; grid size up to $5,400 \times 295,000$)

- Shock heating:

$$\bar{E}_i \sim \gamma_0 m_i c^2$$

$$\bar{E}_e = \frac{\epsilon_e \gamma_0 m_i c^2}{Z_\pm + 1} \ll \bar{E}_i$$

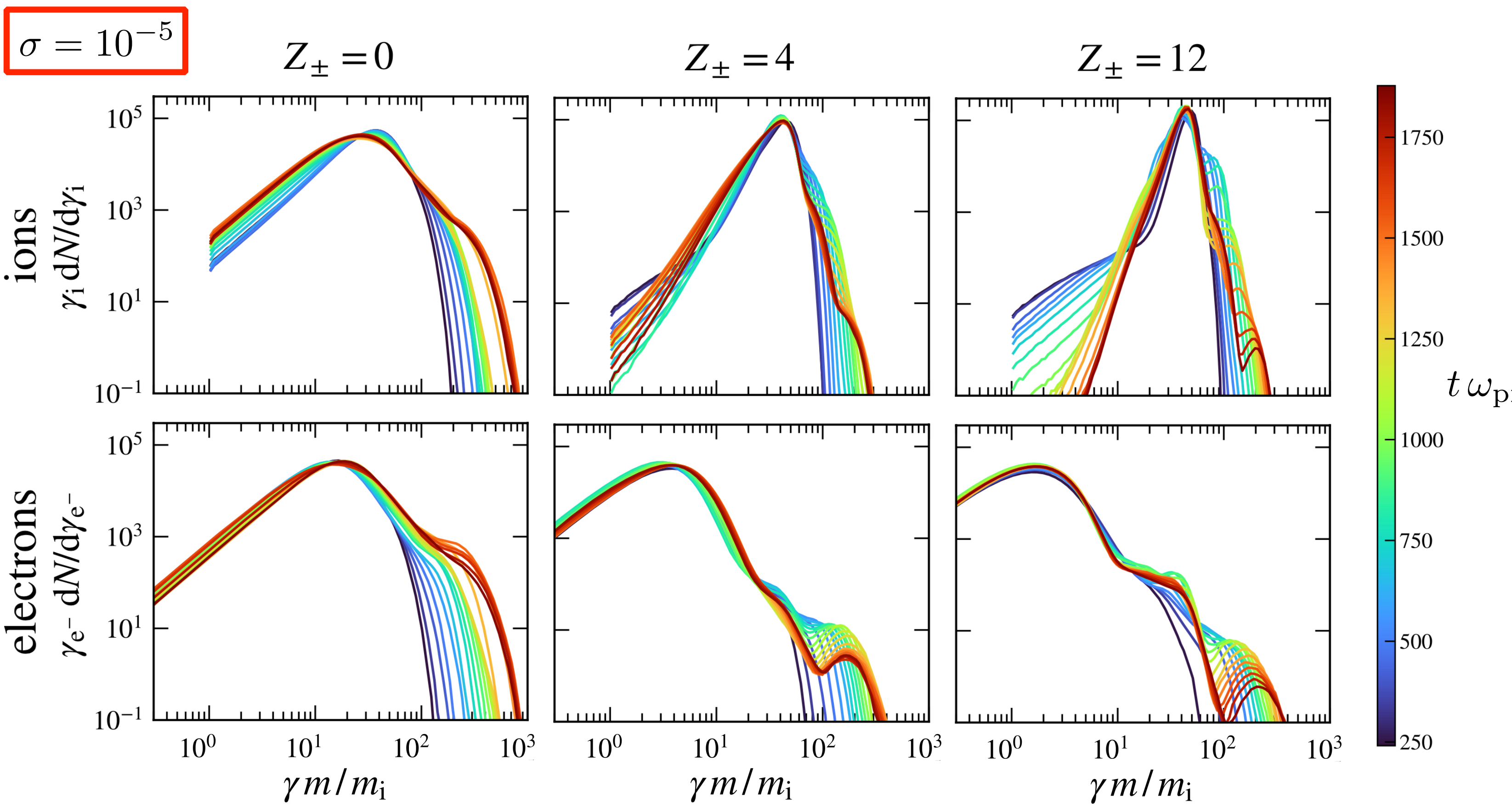
$$\epsilon_e \sim 0.3$$



- Fermi acceleration if $\sigma < \sigma_F \sim \frac{10^{-4}}{(Z_\pm + 1)^4} \left(\frac{E}{\gamma_0 m_i c^2} \right)^{-2} \quad (t_{scat} < t_{Larmor})$

no ion acceleration; limited energy range for electron acceleration

Groselj, Sironi, AB, in preparation



Groselj, Sironi, AB, in preparation

Ultra-high-energy cosmic rays?

– not through Fermi acceleration in internal shocks

– not through Fermi acceleration in external shocks

Converter? (photomeson: $n \leftrightarrow p$)

Derishev et al. 2003

threshold (fluid frame):

$$\gamma_p E_{\rm ph} > 100\,{\rm MeV}$$

$$\sigma_\nu \sim 10^{-28} - 5\times 10^{-28}\ {\rm cm}^2$$

small radii: injection problem

At large radii: $R > R_\pm \approx \left(\frac{E_{\rm iso}}{10^{54}\,{\rm erg}}\right)^{1/2}$ cm

low photomeson optical depth τ_ν

runaway acceleration if

$$\tau_\nu \Gamma_{\rm sh} \gtrsim 10$$

Summary

GRB delusions:

- internal shocks accelerate particles — suppression by B
- prompt GRBs = nonthermal synchrotron → photospheric emission
- subphotospheric shocks: PeV neutrinos → radiation-mediated shocks
- afterglow shocks propagate in a low-density ISM → WR wind
- optical flash comes from reverse shock → e+-loaded forward shock
- particle acceleration is required for GeV/TeV — mainly thermal e+-