Relativistic shocks:
uniting particle acceleration with radiation

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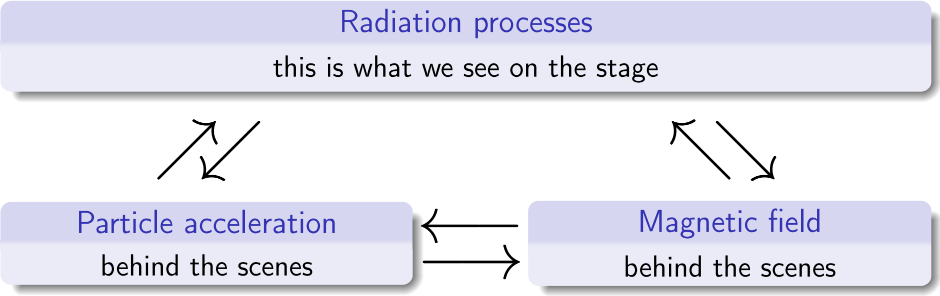
Outline

1. Building blocks of relativistic shocks physics
2. Common scenario (with questions)
3. Alternative scenario (with answers)

Main building blocks



Radiation processes

this is what we see on the stage

Particle acceleration

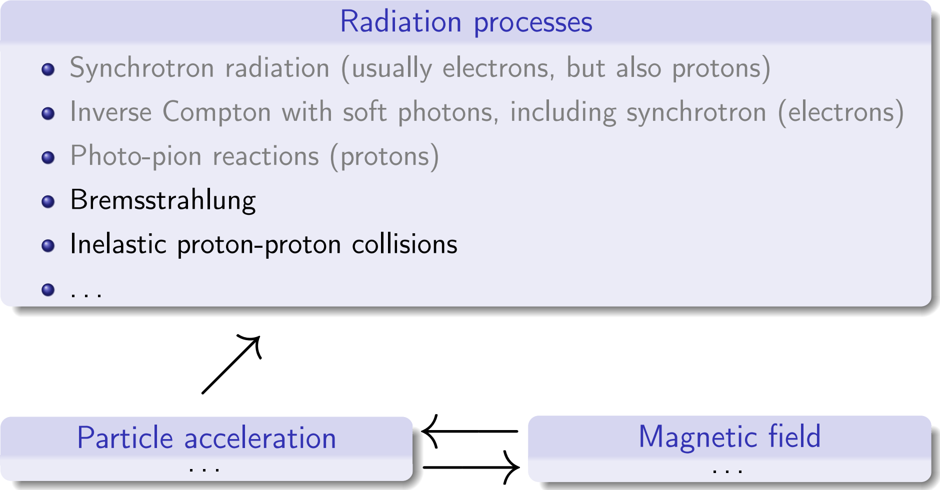
behind the scenes

Magnetic field

behind the scenes

Shocks in dense (collisional) environment

internal shocks in jets from GRB's central engine,
hypernovae shock breakout



Radiation processes

- Synchrotron radiation (usually electrons, but also protons)
- Inverse Compton with soft photons, including synchrotron (electrons)
- Photo-pion reactions (protons)
- Bremsstrahlung
- Inelastic proton-proton collisions
- . . .

Particle acceleration

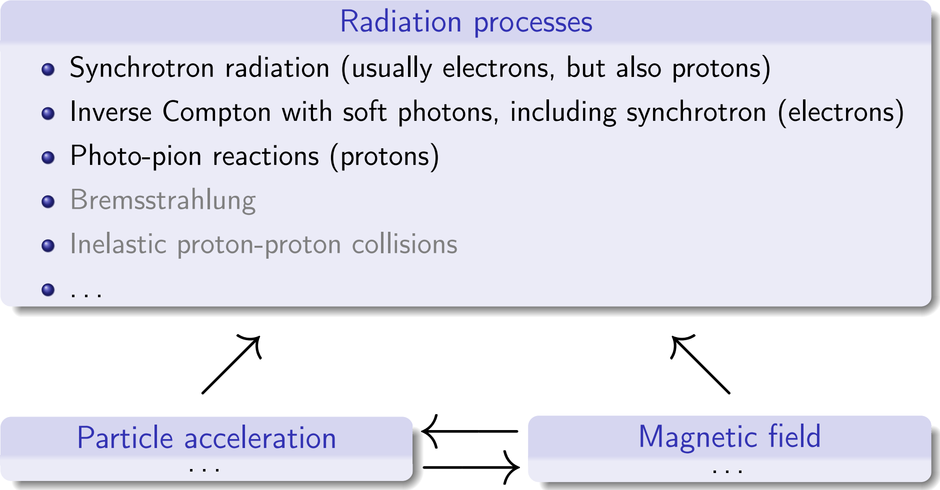
. . .

Magnetic field

. . .

Shocks in rarefied (collisionless) environment

blazars, GRB afterglows, pulsar termination shocks,
microquasars, gamma-ray binaries



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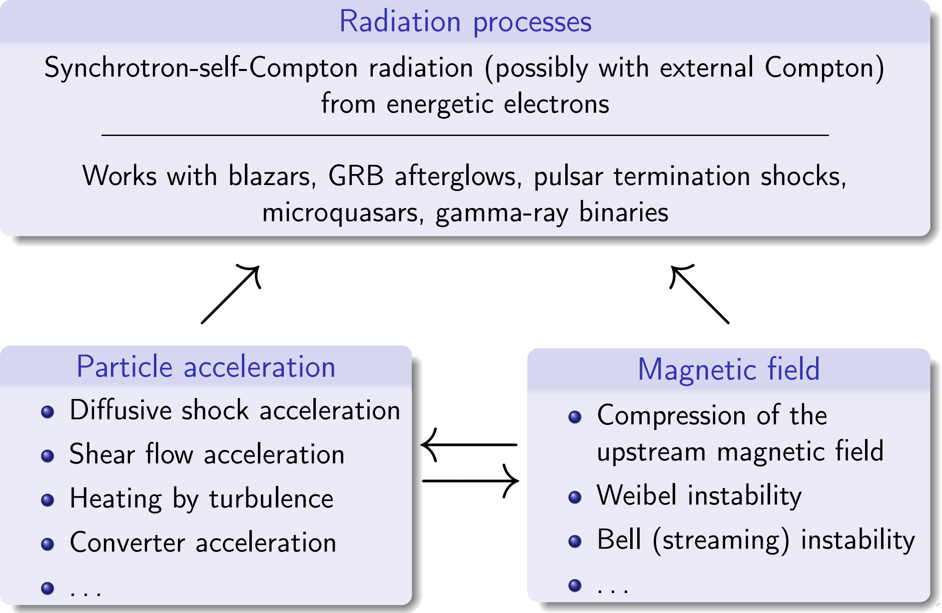
Particle acceleration

. . .

Magnetic field

. . .

Into the first principles



Radiation processes

Synchrotron-self-Compton radiation (possibly with external Compton) from energetic electrons

Works with blazars, GRB afterglows, pulsar termination shocks, microquasars, gamma-ray binaries

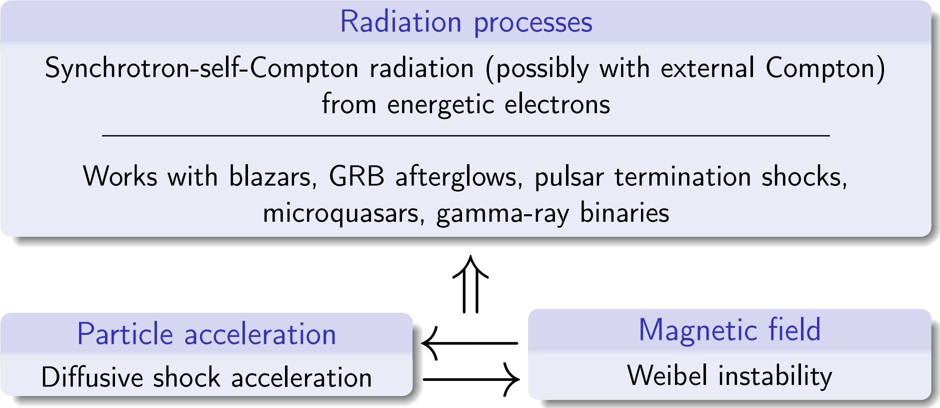
Particle acceleration

- Diffusive shock acceleration
- Shear flow acceleration
- Heating by turbulence
- Converter acceleration
- . . .

Magnetic field

- Compression of the upstream magnetic field
- Weibel instability
- Bell (streaming) instability
- . . .

Common approach



Radiation processes

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Particle acceleration

Diffusive shock acceleration

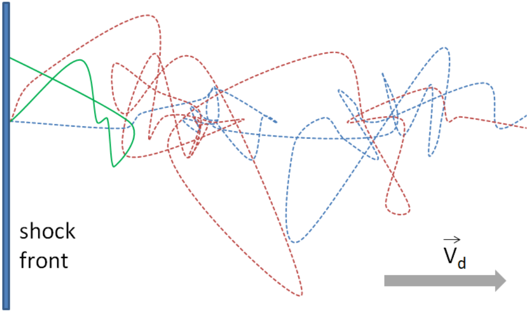
Magnetic field

Weibel instability

Analytically, even the reduced problem is too complicated.

Numerically (PIC simulations) we do not intentionally limit modelling to the processes specified above.

Particle acceleration: analytics



Effective width of downstream "reflection layer" is $\simeq \dfrac{1-\beta_d}{\beta_d}$ mean free paths

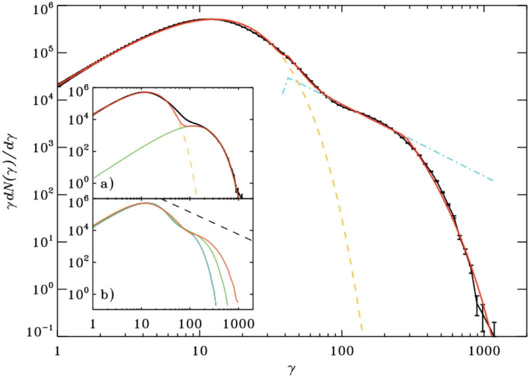
This is only $\simeq$ 2 m.f.p. in relativistic shocks ($\beta_d = 1/3$) — diffusion approximation is questionable

Expectations

- No Fermi acceleration with regular magnetic field
- Within diffusion approximation accelerated particles form a power-law distribution with $p = \dfrac{\beta_d^3 - 2\beta_d^2 + 2\beta_d + 1}{1-\beta_d}$, that is $p = \dfrac{20}{9} \simeq 2.22$

Keshet & Waxman 2005

Particle acceleration: numerical results



High-energy tail has cut-off which moves towards higher energies as simulations runs longer

The tail approaches a power-law with $p = 2.4 \pm 0.1$

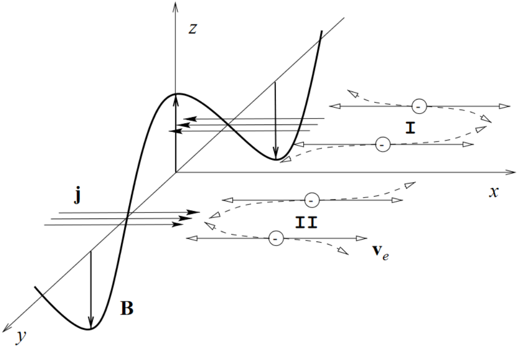
From Spitkovsky ApJ 682 (2008)

Note the subtlety

Unlike real shocks, in 2D simulations $\beta_d = \dfrac{1}{2}$.

In this case, the diffusion-approximation theory predicts $p = 13/4 = 3.25$

Magnetic field: Weibel (filamentation) instability



From Medvedev & Loeb ApJ 526 (1999)

Fastest-growing mode:

$$k_m = f(A)\frac{\omega_p}{\gamma^{1/2}c},\ f(A) \lesssim 1$$

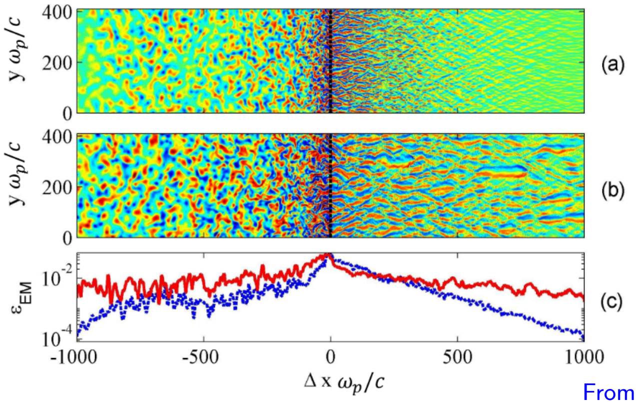
Decay time $\left(\sim \frac{\omega_p^2}{\gamma\,(ck_m)^3}\right)$

is of the order of growth time

and 5-7 orders of magnitude smaller than the synchrotron cooling time

- works in unmagnetized shocks
- generates strong enough turbulent magnetic field
- this magnetic field is presumably short-lived

Magnetic field: numerical results



One of the longest simulations still does not converge to a steady state

(a) $t = 2250\ \omega_p^{-1}$

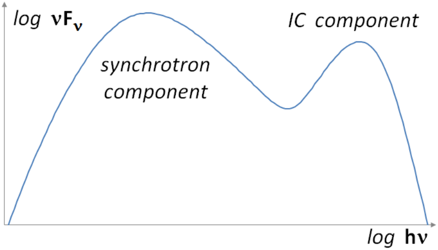
(b) $t = 11925\ \omega_p^{-1}$

From Sironi, Keshet & Lemoine Space Sci. Rev. 191 (2015)

- magnetic field is short-lived; persists for longer distance in longer runs
- energy share in the magnetic field at shock's front $\epsilon_{\rm B} \sim 0.01$
- energy share in accelerated electrons $\epsilon_e \sim 0.1$

Synchrotron plus inverse Compton

Characteristic appearance:
spectral energy distribution (SED)
with two widely separated humps



Injection function

"core + power-law", mimics acceleration's output:

$$Q_{\mathrm{inj}}(\gamma) \propto \frac{\gamma^2 - 1}{(\gamma_{\mathrm{b}} + \gamma)^{p+2}}$$

in analytic work often replaced by

$$Q_{\mathrm{inj}}(\gamma) \propto \begin{cases} 0\,, & \gamma < \gamma_{\mathrm{m}} \\ \gamma^{-p}\,, & \gamma \geq \gamma_{\mathrm{m}} \end{cases}$$

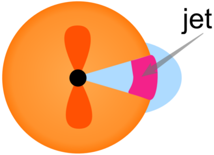
$+$

Elementary processes

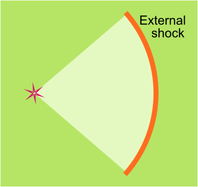
- synchrotron radiation
- electron-photon scattering (with QED cross-section)
- two-photon pair production (with QED cross-section)

Vary γ_{b}, B, ϵ_e/ϵ_B, p, and cooling time (size) to obtain an SED fit.

First GRB afterglow at TeV



prompt emission



afterglow

Afterglow emission comes from decelerating shock whose temporal evolution is well understood

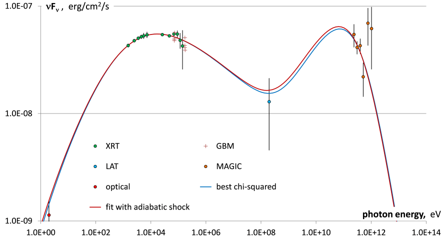
announced Jan 15, 2019

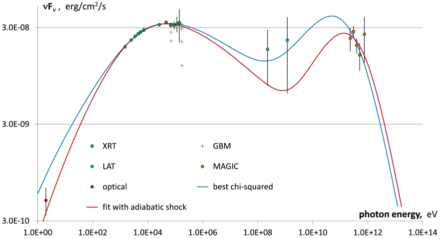
- Observation time $50 \div 1000$ s from trigger (early afterglow)
- Photons' energy ~ 300 GeV
- Luminosity $L_{TeV} \simeq 0.4 L_{keV}$

MAGIC Collaboration Nature 575 (2019)

GRB 190114C time evolution

ED & T.Piran arXiv:2106.12035





$t_{\rm obs} = 90$ s: $\gamma_{\rm b} = 6500$, $\epsilon_B = 0.0061$, $\epsilon_e = 0.12$

$(p = 2.5,\ E_{\rm kin} = 3 \times 10^{53}\ \text{erg})$

$t_{\rm obs} = 145$ s: $\gamma_{\rm b} = 16700$, $\epsilon_B = 0.0027$, $\epsilon_e = 0.096$

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A surprise? Not really — ED & T.Piran, MNRAS 460 (2016)

$\gamma_{\rm b}$ increases as shock decelerates, while ϵ_e stays approximately constant

$\Rightarrow$ fraction of upstream electrons being accelerated decreases with time

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The fraction of internally absorbed radiation remains constant at $\simeq 10\%$

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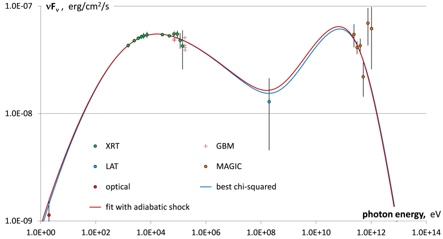

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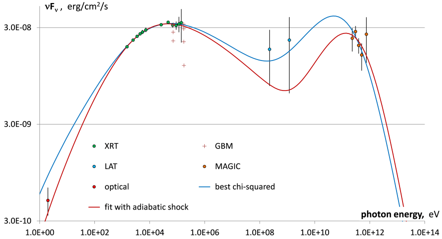

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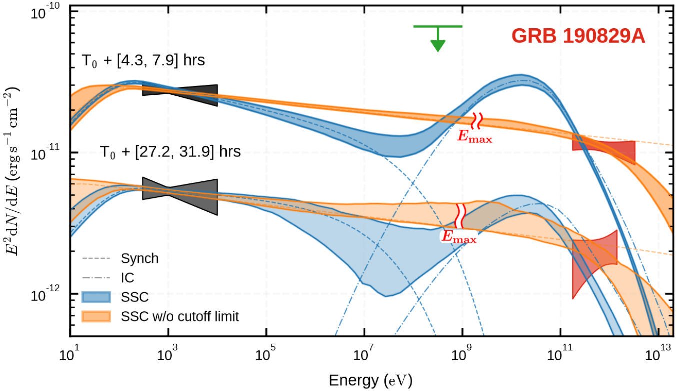
GRB 190829A — common scenario fails again



From H.E.S.S. Collaboration Science 372 (2021)

Common scenario (blue lines) is not consistent with observations.
Radiating electrons must be much more energetic.

Critical view on common scenario in context of relativistic shocks

Problems with magnetic field

- magnetized upstream prohibits particle acceleration
- turbulent magnetic field generated with unmagnetized upstream is hopelessly short-lived

Confusing distribution of accelerated particles

- particle distribution in PIC simulations is much harder than (optimistic) theoretic predictions — is it really Fermi acceleration?
- typical energy of emitting electrons does not follow shock's Lorentz factor

Internal absorption of high-energy radiation

- high-energy inverse Compton photons annihilate with low-energy synchrotron photons producing electron-positron pairs
- this happens both downstream and *upstream* of the shock
- absorbed fraction $\ll 1$ can be large by relativistic-shock standards!

Various conversion cycles

Leptonic conversion cycle

① $e^- + \gamma_{soft} \rightarrow e^- + \gamma_{hard}$ ② $\gamma_{hard} + \gamma_{soft} \rightarrow e^- + e^+$

Hadronic conversion cycles

Electromagnetic channel (low density environment)

① $p + \gamma_{soft} \rightarrow n + \pi^+$ ② $n + \gamma_{soft} \rightarrow p + \pi^-$ (or $n \rightarrow p + e^-$)

Collisional channel (high density environment)

① $p + p \rightarrow n + p + \pi^+$ ② $n + p \rightarrow p + p + \pi^-$ (or $n \rightarrow p + e^-$)

In a uniform emitting zone all these are merely dissipation (cascade):
energy of individual particles decreases at each conversion
while the number of particles goes up

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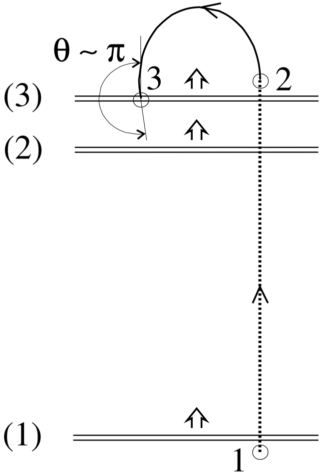
Converter acceleration mechanism



1. Electron produces high-energy IC photon
2. The photon overtakes the shock and produces e^-e^+ pair in the upstream
3. Shock catches up with isotropized particles and boosts them

Energy gain factor $\sim \Gamma^2$ in each cycle

Derishev, Aharonian, Kocharovsky & Kocharovsky, PRD 2003

Converter acceleration mechanism

Efficiency of converter acceleration = $p_c\Gamma^2$

acceleration cycle probability p_c =

probability of photon escape from downstream ($\simeq 1/3$) ×

× relative efficiency of IC radiation ($= y/(1+y)$) ×

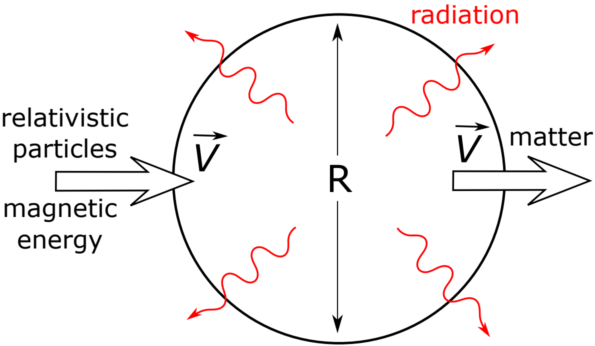
× radiative cooling efficiency

Depending on efficiency of converter acceleration:

- $p_c\Gamma^2 \ll 1$ — forget about it
  (non-relativistic shocks or extremely inefficient shocks)
- $p_c\Gamma^2 \sim 1$ — can be put to good use
- $p_c\Gamma^2 \gg 1$ — goes wild and tears apart our carefully built models

- Is inequality $p_c \lesssim 1/\Gamma_{sh}^2$ realistic? (GRBs have $\Gamma_{sh} \sim$ hundreds)
- How does the shock know about its "allowed" value of p_c?

A “spherical cow” emitting zone



Energy inflow rate:

$$\dot{E}_{el} = E_{el} \times V/R$$

Energy outflow rate:

$$\dot{E}_{rad} = E_{rad} \times c/R$$

Synchrotron cooling balance: $L_{sy} = \kappa_{sy}\dot{E}_{el} \quad \Rightarrow \quad e_{sy} = (V/c)\,\kappa_{sy}e_{el}$

Synchrotron power: $P_{sy} = \frac{4}{3}(\gamma^2 - 1)\sigma_{\mathrm{T}}\,e_{\mathrm{B}}\,c$

Inverse Compton power: $P_{IC} = \frac{4}{3}(\gamma^2 - 1)\kappa_{\mathrm{KN}}\sigma_{\mathrm{T}}\,e_{sy}\,c$

Compton dominance

Introduce Compton potential, ϵ_{sy}/ϵ_B

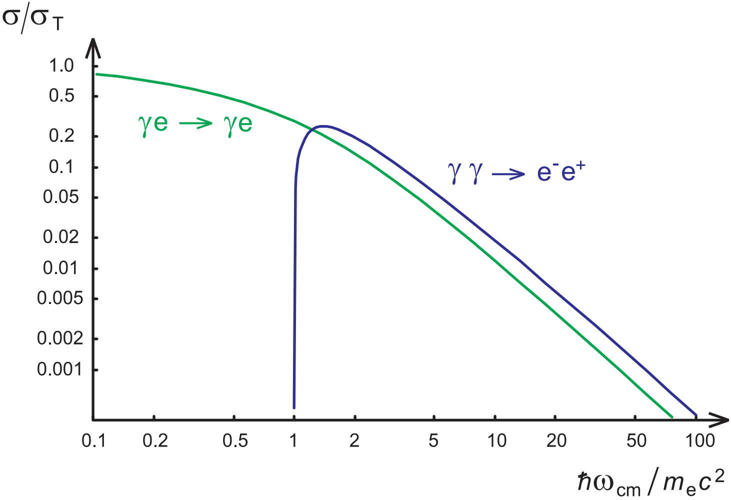
For a relativistic shock it equals $\kappa_{sy}\,(\epsilon_e/\epsilon_B)$

Ratio of inverse Compton to synchrotron power

$$\eta_{IC} \equiv \frac{L_{IC}}{L_{sy}} \simeq \begin{cases} \kappa_{KN}\,\kappa_{sy}\,(\epsilon_e/\epsilon_B)\,, & \eta_{IC} \ll 1 \\ \left[\kappa_{KN}\,\kappa_{sy}\,(\epsilon_e/\epsilon_B)\right]^{1/2}\,, & \eta_{IC} \gg 1 \end{cases}$$

$\kappa_{KN} \leq 1$ takes into account Klein-Nishina effect

IC cooling and absorption



In the Klein-Nishina regime, the timescales for inverse Compton cooling and for absorption of IC photons are the same

Two ways to tame converter acceleration

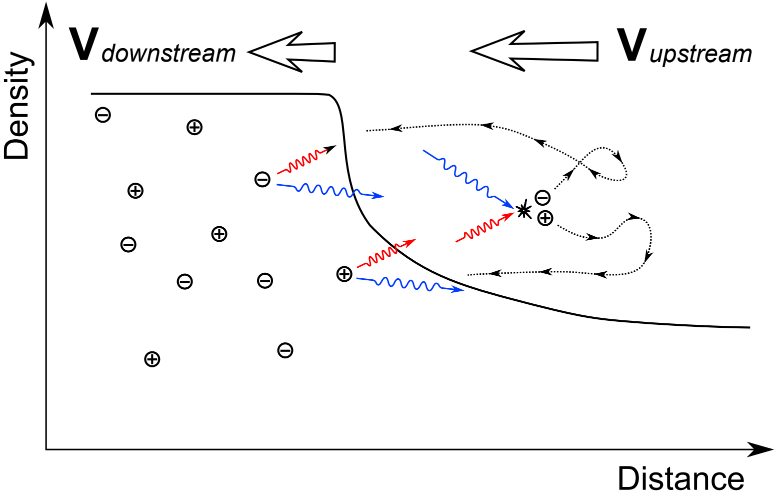
Reduce radiation efficiency below $\sim 1/\Gamma$

– not a good idea

Reduce the Lorentz factor jump at the shock front

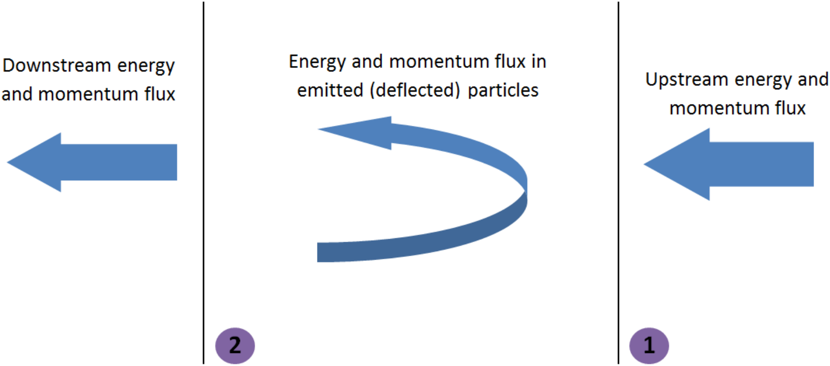
– should work, but we need a "modified shock" solution

Pair-balance shock



$$\left.\begin{array}{l}\langle\gamma\rangle > \gamma_0 \text{ — prevails absorption of IC photons} \\ \langle\gamma\rangle < \gamma_0 \text{ — prevails acceleration of electrons}\end{array}\right\} \langle\gamma\rangle \simeq \gamma_0$$

Energy-momentum transport in relativistic shocks



Downstream energy and momentum flux

Energy and momentum flux in emitted (deflected) particles

Upstream energy and momentum flux

The (flux conservation) equations

Assume that there is a steady state 1D solution

- Momentum flux conservation

$$w_1\beta_1^2\Gamma_1^2 + p_1 = w_2\beta_2^2\Gamma_2^2 + p_2 + S_{mom}$$

- Energy flux conservation

$$w_1\beta_1\Gamma_1^2 = w_2\beta_2\Gamma_2^2 - S_{en}$$

- Energy and momentum fluxes for outgoing particles

$$S_{en} = a\, w_2\beta_2\Gamma_2^2 \qquad\qquad S_{mom} = b\, S_{en}$$

w – specific enthalpy, p – pressure

Approximate solution

Assume relativistic equation of state $p = w/4$

- This is guaranteed if shock modification is strong.

Use "magic"variable $\chi = \left(3\beta + \frac{1}{\beta}\right)$

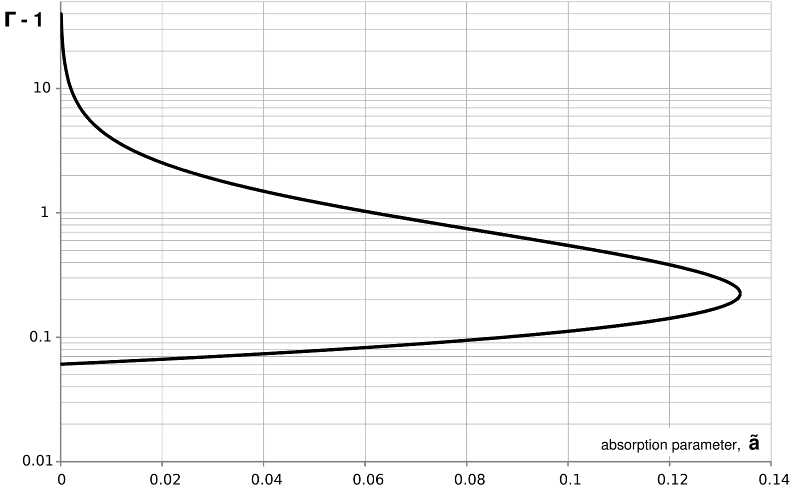
- The conservation equations become

$$\mathrm{d}\chi = -\chi\, \mathrm{d}\tilde{a}, \qquad \text{where} \qquad \tilde{a} = a(1+b)$$

- Approximate solution in the case where $\Gamma \gg \Gamma_u \gg 1$:

$$\Gamma_u = \frac{1}{2\tilde{a}^{1/2}}$$

Precursor structure



Bulk Lorentz factors in shock-front comoving frame

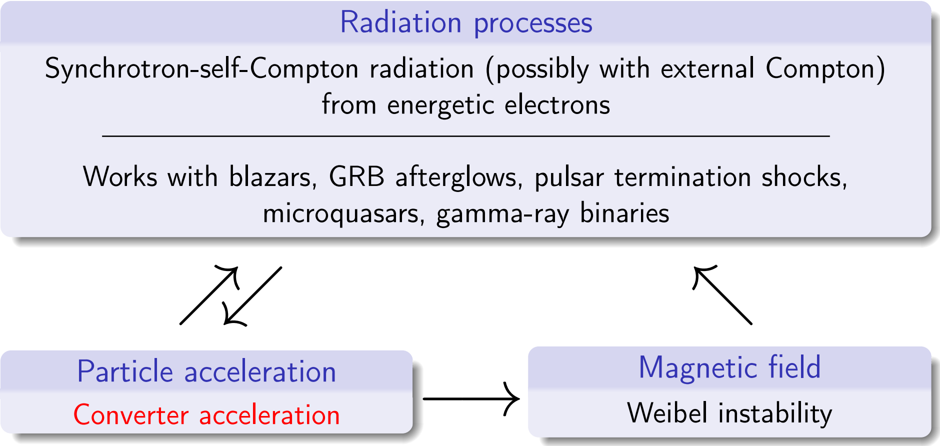
upper branch – the upstream

lower branch – the downstream.

Distribution of energetic particles

- Injected particles have approximately the same energies in the shock-front frame $\tilde{a} \propto N$
- Comoving-frame energy at injection $\gamma_i \propto \Gamma_u \propto \tilde{a}^{-1/2}$
  $$\Rightarrow \qquad N(\gamma_i) \propto \gamma_i^{-2}$$
- When a particle reaches the shock front, its Lorentz factor becomes (due to adiabatic compression) $\gamma_f \sim \Gamma_u^{1/3} \gamma_i \propto \gamma_i^{4/3}$
- The particles at the shock front have power-law distribution
  $$N(\gamma_f) \propto \gamma_f^{-3/2} \qquad \Rightarrow \qquad f(p) \propto p^{-5/2}$$

Converter-acceleration approach



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Particle acceleration

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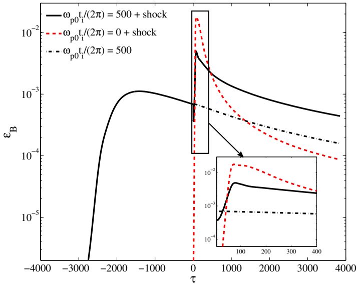
Weibel instability

This is *terra incognita* for PIC simulations —
need to learn how to distinguish and suppress unphysical instabilities

Long injection causes long decay



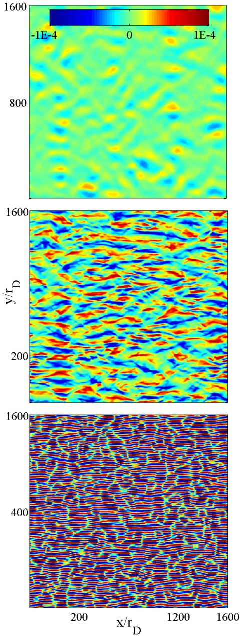
No pre-injection

Magnetization evolution shown by red line.
Magnetic field distribution shortly after shock shown in bottom panel on the right.

With pre-injection

Magnetization evolution shown by solid black line.
Magnetic field distribution:
top panel on the right — just before shock
middle panel on the right — shortly after shock

From Garasev & ED, MNRAS 461 (2016)



Pair-balance shock model

Solved problems

- undemanding to magnetic field geometry and works well with magnetized upstream
- explains persistence of downstream turbulent magnetic field in case of unmagnetized upstream
- predicts typical energy of accelerated particles (hence positions of synchrotron and inverse Compton peaks in spectra) in consistence with observations
- ensures power-law distribution of accelerated particle with comfortable index $p = 2.5$

Limitations

- applies only to relativistic shocks with Lorentz factor $\gtrsim$ several
- does not work with radiatively inefficient shocks (progressively less important with increasing shock's Lorentz factor)

Summary

- In relativistic shocks energy and momentum transport by the shock's radiation is critically important
- Results of PIC relativistic-shock simulations likely give a correct idea of particle – magnetic field coupling, but their applicability is limited by incompleteness of underlying model
- Pair-balance shock with converter acceleration is *minimal possible* modification of common collisionless shock scenario
- The pair-balance shock model answers uncomfortable questions, but poses a challenge to both theory (formulation in terms of differential equations is not possible) and numerical simulations (need consistent treatment of radiation and explore accompanying non-physical instabilities)
- Converter acceleration competes with diffusive shock acceleration and switches it off