Acceleration of cosmic rays
- general principles and extreme energies -

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Outline:

1. Some remarks on acceleration schemes
2. Acceleration to ultra-high energies
3. Ultra-relativistic shock physics

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General principles of particle acceleration

Standard lore:

→ Lorentz force: $$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right)$$

→ recall: $\boldsymbol{E} \cdot \boldsymbol{B}$ and $\boldsymbol{E}^2 - \boldsymbol{B}^2$ Lorentz scalars

Case 1: $\boldsymbol{E} \cdot \boldsymbol{B} = 0 \text{ and } \boldsymbol{E}^2 - \boldsymbol{B}^2 < 0$

→ generic because it corresponds to ideal MHD assumptions…

→ ∃ a frame in which $\mathbf{E}_{|p}$ vanishes… particle follows helical orbits around $\mathbf{B}_{|p}$, no acceleration provided…

→ acceleration occurs if some force or scattering pushes the particle across **B** along **E**…

→ examples: Fermi-type scenarios (turbulence, shear, shocks)

Case 2: $\boldsymbol{E} \cdot \boldsymbol{B} \neq 0 \text{ or } \boldsymbol{E}^2 - \boldsymbol{B}^2 > 0$

→ acceleration can proceed unbounded along **E** (or at least $\mathbf{E}_{\parallel}$)…

→ examples: reconnection, gaps

General principles of particle acceleration

Standard lore:

→ Lorentz force: $$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right)$$

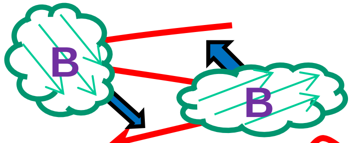
Ideal MHD: $\boldsymbol{E}_{|\mathrm{p}} \simeq 0$ in plasma rest frame

→ ***E*** field is 'motional', i.e. if plasma moves at velocity $\boldsymbol{v}_\mathrm{p}$: $\boldsymbol{E} \simeq -\frac{\boldsymbol{v}_\mathrm{p}}{c} \times \boldsymbol{B}$

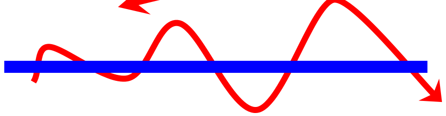
→ need some force or scattering to push particles across *B*

→ lower bound to acceleration timescale: $t_\mathrm{acc} = \frac{p}{\beta_\mathrm{p} e B} = \frac{t_\mathrm{g}}{\beta_\mathrm{p}}$

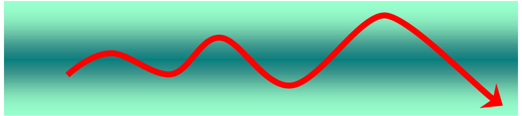
→ examples:
- turbulent Fermi acceleration



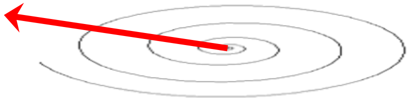
- Fermi acceleration at shock waves



- acceleration in sheared velocity fields

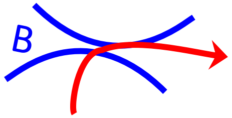


- magnetized rotators

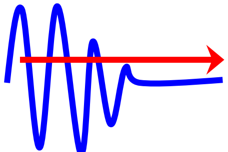


Beyond MHD:

→ examples:
- reconnection



- wakefield/ponderomotive acceleration



General principles of particle acceleration

Some caveats to bear in mind:

→ **‘test-particle picture’** ≠ **‘non-linear picture’**

acceleration in fixed e.m. structure | acceleration + backreaction on e.m. structure

… a crucial distinction in most scenarios and for most of phenomenology:

e.g., amplification of pre-existing turbulence by accelerated particles appears necessary in supernovae remnants (or to reach PeV energies)…

e.g., in relativistic shock waves, magnetized turbulence can even be self-generated from scratch by accelerated particles…

… so far, only Fermi-shock scenarios try to account for this backreaction: see A. Bykov…
… others assume a simple test-particle picture!

→ **acceleration time scale $\sim t_g$ $\ll$ source time scale $\sim R/\beta c$**
… acceleration microphysics often distinct from source macrophysics…

e.g., current Particle-in-cell (PIC) simulations can probe $10^4\ \omega_p^{-1}$, which remains a tiny fraction (<0.001) of the dynamical timescale of a GRB

⇒ theory + simulations on microphysical scales often idealize the source…
… while phenomenology on macrophysical scales idealize the microphysics…

Acceleration – a luminosity bound

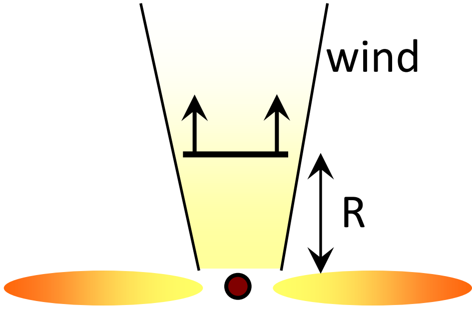
(e.g. Lovelace 76, Norman+ 95, Blandford 00, Waxman 05, Aharonian+ 02, Lyutikov & Ouyed 05, Farrar & Gruzinov 09, M.L. & Waxman 09)

<u>A generic case:</u> acceleration in an outflow

→ acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm g}$

A >> 1, A ~ 1 at most:

- for non-relativistic Fermi I, $A \sim (t_{\rm scatt}/t_{\rm g}) / \beta_{\rm sh}^2$



→ time available for acceleration (comoving frame): $t_{\rm dyn} \approx \dfrac{R}{\beta\Gamma c}$

→ maximal energy: $t_{\rm acc} \le t_{\rm dyn} \Rightarrow E_{\rm obs} \le \mathcal{A}^{-1} ZeBR/\beta$

→ 'magnetic luminosity' of the source: $L_B = 2\pi R^2\Theta^2 \dfrac{B^2}{8\pi}\Gamma^2\beta c$

→ lower bound on total luminosity: $L_{\rm tot} \ge 0.65 \times 10^{45}\, \Theta^2\Gamma^2\mathcal{A}^2\beta^3 Z^{-2} E_{20}^2\, {\rm erg/s}$

10^{45} ergs/s is robust:

for $\beta \to 0$, $\mathcal{A}^2\beta^3 \ge 1/\beta \ge 1$

for $\Theta\Gamma \to 0$, $L_{\rm tot} \ge 1.2 \times 10^{45}\, \mathcal{A}\beta \dfrac{\kappa}{r_{\rm L} c} Z^{-2} E_{20}^2\, {\rm erg/s}$

<u>Lower limit on luminosity of the source:</u> $L_{\rm tot} > 10^{45}\, Z^{-2}\, {\rm erg/s}$

low luminosity AGN: $L_{\rm bol} < 10^{45}$ ergs/s
Seyfert galaxies: $L_{\rm bol} \sim 10^{43}$-10^{45} ergs/s
high luminosity AGN: $L_{\rm bol} \sim 10^{46}$-10^{48} ergs/s
gamma-ray bursts: $L_{\rm bol} \sim 10^{52}$ ergs/s

⇒ only most powerful AGN jets, GRBs
or young magnetars for UHE protons...
... many (many) others for heavy nuclei?

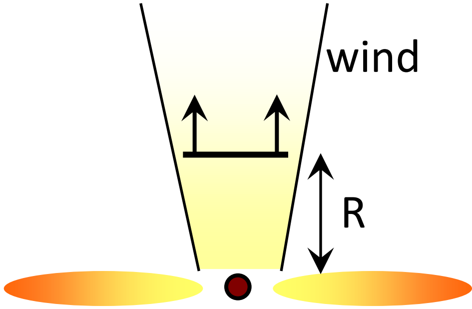
Acceleration – a luminosity bound

A generic case: acceleration in an outflow

(e.g. Lovelace 76, Norman+ 95, Blandford 00, Waxman 05, Aharonian+ 02, Lyutikov & Ouyed 05, Farrar & Gruzinov 09, M.L. & Waxman 09)

→ acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm g}$

→ **A $\gg$ 1 in most acceleration scenarios:**



e.g. in Fermi-type, **A ~ interaction time/t_g / energy gain**

sub-relativistic Fermi I: $\mathcal{A} \sim (t_{\rm scatt}/t_{\rm g})/\beta_{\rm sh}^2$
and $t_{scatt} > t_g$ (saturation: Bohm regime!)

sub-relativistic stochastic: $\mathcal{A} \sim (t_{\rm scatt}/t_{\rm g})/\beta_{\rm A}^2$

sub-relativistic reconnection flow: $\mathcal{A} \sim 10/\beta_{\rm A}$ (on reconnection scales)

relativistic Fermi I: $\mathcal{A} \sim t_{\rm scatt}/t_{\rm g}$ in shock frame, much more promising?

relativistic reconnection: $\mathcal{A} \sim 10$ (on reconnection scales)

… comparing t_{acc} and t_{dyn} bounds the luminosity of the source to reach UHE:

$$L_{\rm tot} \geq 0.65 \times 10^{45}\, \Theta^2 \Gamma^2 \mathcal{A}^2 \beta^3 Z^{-2} E_{20}^2 \,{\rm erg/s}$$

Extreme acceleration, but also high output

Energy output of a source:

→ to match the flux above 10^{19} eV, $\dot{u}_{\rm UHECR} \sim 10^{44}\,{\rm erg/Mpc^3/yr}$ (Katz+ 10)

→ per source, assuming it is steady: $L_{\rm UHECR} \sim 10^{43}\,n_{-7}^{-1}\,{\rm erg/s} \quad (n\,{\rm in\,Mpc^{-3}})$

→ per transient source: $E_{\rm UHECR} \approx 10^{50}\,{\rm erg}\ \dot{n}_{-6}^{-1} \quad (\dot{n}\,{\rm in\,Mpc^{-3}yr^{-1}})$

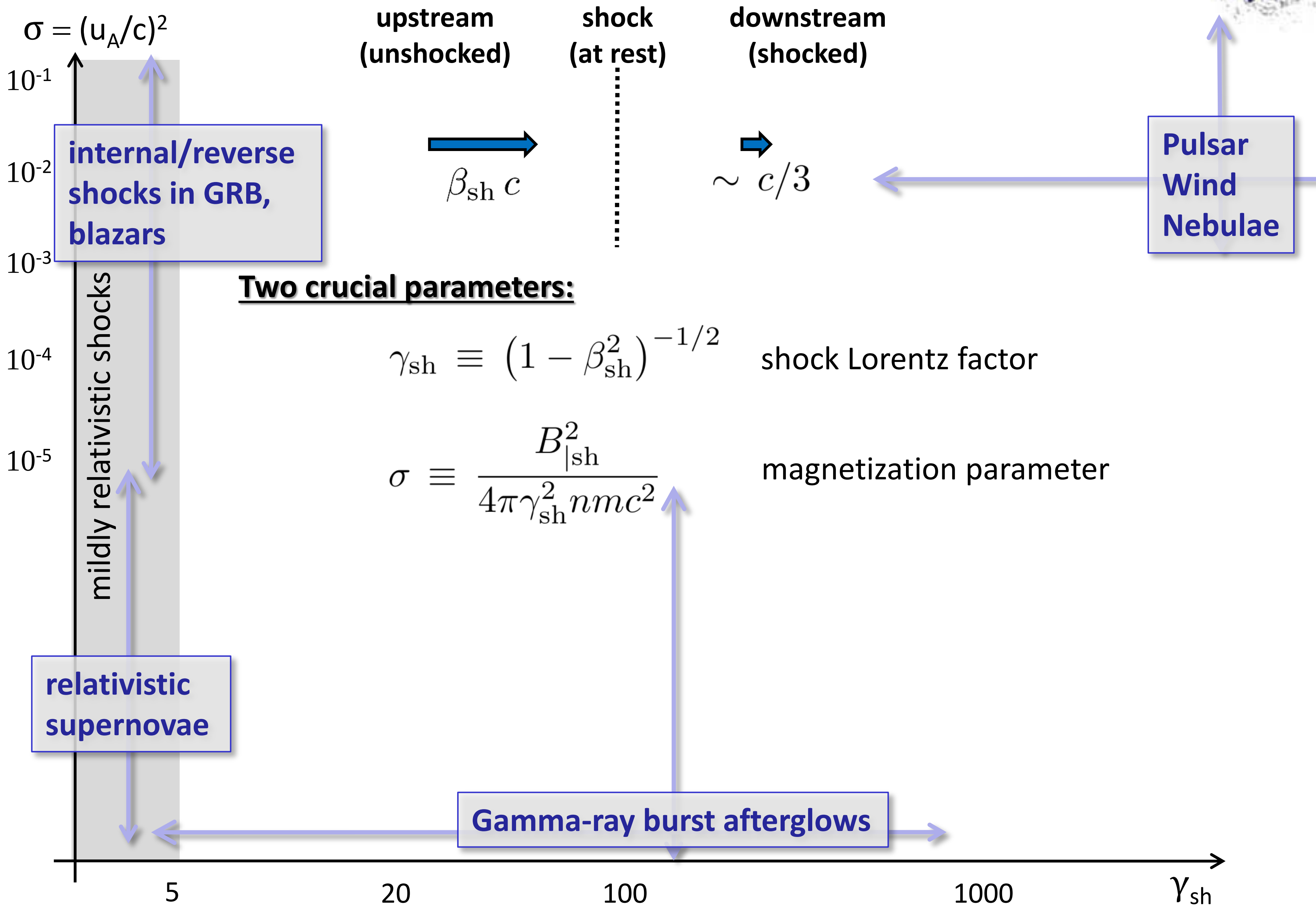
e.g.: → radio-galaxies with L > 10^{45} erg/s, about 1% efficiency

→ for the whole radio-galaxy population, nL ~ 3 x 10^{47} erg/Mpc^3/yr, typically from sources with L ~ 10^{43} erg/s…
… if injecting CNO to match flux at 10^{19}eV and if metallicity is ~solar, requires an overall efficiency in high energy CR of a few percent!

if one wants nuclei at >E to circumvent luminosity bound, accounting for the protons accelerated to >E/Z requires an energy input higher by M_p/M_Z …

⇒ shock dissipation as an ideal mechanism to channel a sizable fraction of the source luminosity at UHE…

Particle acceleration in relativistic shocks



upstream (unshocked)

shock (at rest)

downstream (shocked)

$\beta_{\rm sh}\, c$

$\sim\; c/3$

internal/reverse shocks in GRB, blazars

Pulsar Wind Nebulae

relativistic supernovae

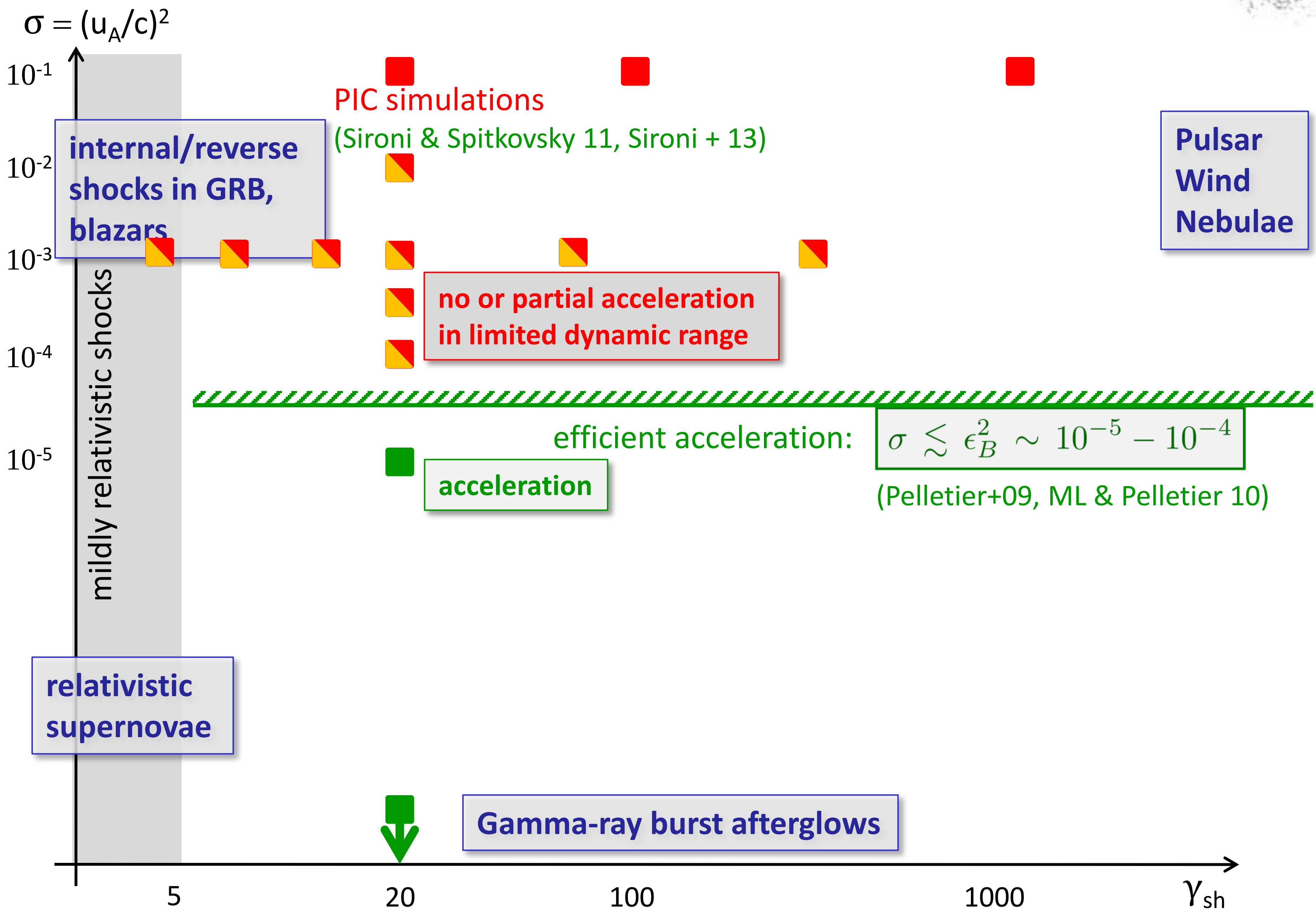
Gamma-ray burst afterglows

Two crucial parameters:

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

$$\sigma \;\equiv\; \frac{B_{|\rm sh}^2}{4\pi\gamma_{\rm sh}^2 n m c^2}$$ magnetization parameter

Particle acceleration in relativistic shocks



PIC simulations

(Sironi & Spitkovsky 11, Sironi + 13)

internal/reverse shocks in GRB, blazars

Pulsar Wind Nebulae

no or partial acceleration in limited dynamic range

efficient acceleration: $\boxed{\sigma \lesssim \epsilon_B^2 \sim 10^{-5} - 10^{-4}}$

(Pelletier+09, ML & Pelletier 10)

acceleration

relativistic supernovae

Gamma-ray burst afterglows

Particle acceleration in relativistic shocks

$\sigma = (u_A/c)^2$

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

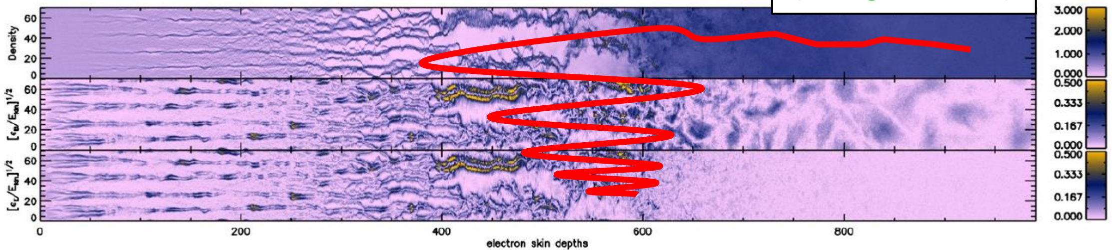
mildly relativistic shocks

internal/rever
shocks in GRB,
blazars

relativistic
supernovae

→ **very weakly magnetized ultra-relativistic external shock:** turbulence is self-generated on plasma scales through filamentation/Weibel type instabilities (Medvedev + Loeb 99, Spitkovsky 08)

(Haugbolle 11)



electron skin depth c/ω_p

→ slow scattering in small-scale turbulence: $\mathcal{A} \simeq \dfrac{r_g}{\lambda_{\delta B}} \gg 1$

$$E_{\rm max} \sim 10^{16} - 10^{17}\,Z\;\;{\rm eV}$$

(Pelletier+09, Plotnikov+11,13, Eichler+Pohl11, Sironi+13)

Pulsar
Wind
Nebulae

Gamma-ray burst afterglows

5 20 100 1000 γ_{sh}

Particle acceleration in relativistic shocks

$\sigma = (u_A/c)^2$

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

mildly relativistic shocks

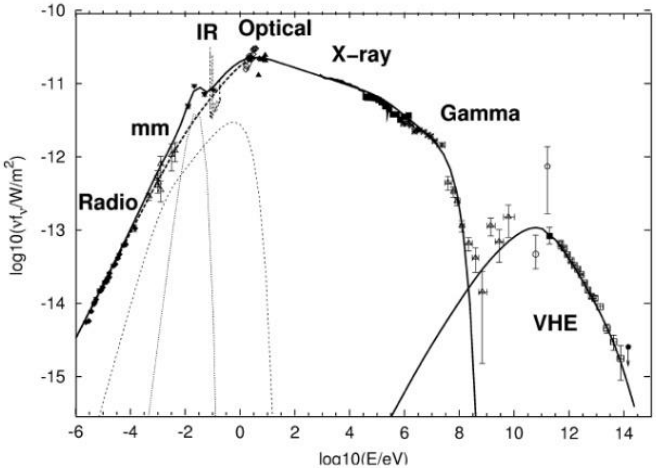
internal/rever
shocks in GRB,
blazars

→ **theory may not be complete:** predicts no acceleration at pulsar wind termination shock, while SED suggests Fermi-type acceleration at Bohm regime:
(Atoyan & Aharonian 96)

synchrotron limit:

$$\epsilon_{\rm syn,max} \sim 100\,\mathcal{A}^{-1}\,{\rm MeV}$$

$$\Rightarrow \mathcal{A} \sim 1$$



→ if extrapolated to more powerful pulsars (= few msec at birth), acceleration + confinement could proceed up to 10^{20}eV protons …
(ML+15)

Pulsar Wind Nebulae

relativistic supernovae

Gamma-ray burst afterglows

5

20

100

1000

γ_{sh}

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)

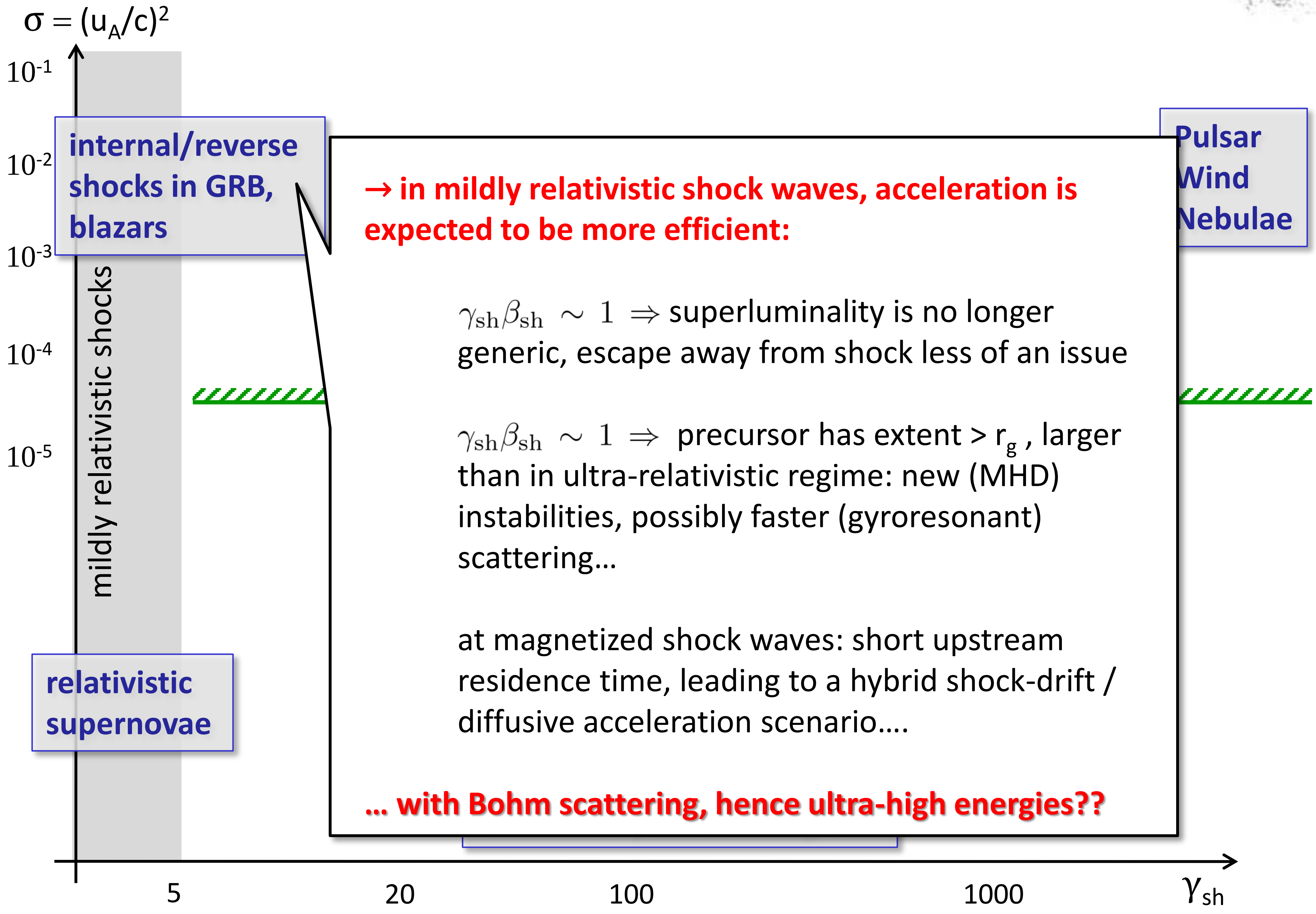
Beyond MHD, shocks in superluminal e.m. waves:

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)

Particle acceleration in relativistic shocks



→ in mildly relativistic shock waves, acceleration is expected to be more efficient:

$\gamma_{sh}\beta_{sh} \sim 1 \Rightarrow$ superluminality is no longer generic, escape away from shock less of an issue

$\gamma_{sh}\beta_{sh} \sim 1 \Rightarrow$ precursor has extent > r_g , larger than in ultra-relativistic regime: new (MHD) instabilities, possibly faster (gyroresonant) scattering…

at magnetized shock waves: short upstream residence time, leading to a hybrid shock-drift / diffusive acceleration scenario….

… with Bohm scattering, hence ultra-high energies??

Summary - conclusions

Acceleration (theory):

→ many possible acceleration scenarios to extreme energies… but:

- most rely on poorly controlled parameters or assumptions, most ignore the backreaction of accelerated particles…

- microphysical scales of acceleration << macroscopic scales of the source, so extrapolation is needed…

⇒ a modern era for acceleration scenarios, combining numerical simulations with theory and inference from experimental data…

→ relativistic shocks as sources of UHE particles are motivated by acceleration timescale and high efficiency (if/when acceleration is operative!)…

bound on magnetic luminosity: $L_B \gtrsim 10^{45}\,\mathbf{A^2}\,Z^{-2}\,E_{20}^{\;2}$ … erg/s

→ acceleration of protons to ultra-high energies in relativistic shocks:

either mildly relativistic shocks (GRB internal shocks, blazar internal shocks, trans-relativistic supernovae)

or magnetized relativistic shocks with some extra source of dissipation?