Particle acceleration in relativistic outflows

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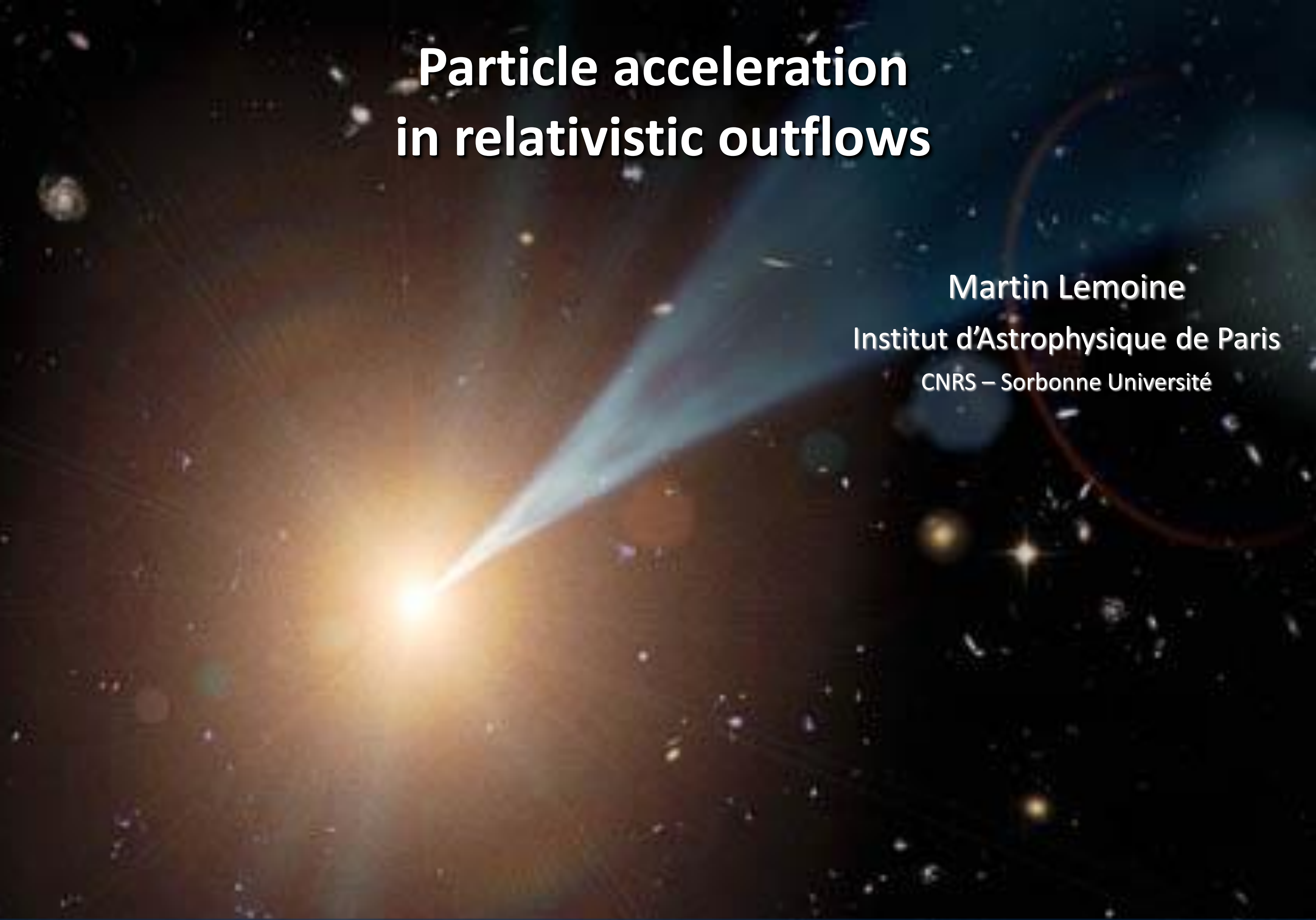


Acceleration in radio-galaxies, blazars...

HST-1	EC starlight photons (e.g. Stawarz+2006)	
Inner Jet (sub-parsec)	leptonic (IC)	decelerating flow (upstream IC) (e.g. Georganopoulos+2005)
		spine-shear (IC interplay) (e.g. Tavecchio+2008)
		multiple SSC components/differential beaming (e.g. Lenain+ 2008)
		reconnection & IC (e.g. Giannios+ 2010)
	hadronic	proton synchrotron & p-γ (e.g. Reimer+ 2004)
		jet-star interactions / pp (e.g. Barkov+ 2012)
		combined lepto-hadronic (e.g. Reynoso+ 2011)
BH vicinity	rotational acceleration & IC (e.g. Rieger & Aharonian 2008)	
	gap-type particle acceleration & IC (e.g. Levinson & Rieger 2011)	

Rieger+Levinson 18

+ acceleration in the large-scale jet (shock, turbulence, shear...)

The relativistic Hillas bound

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

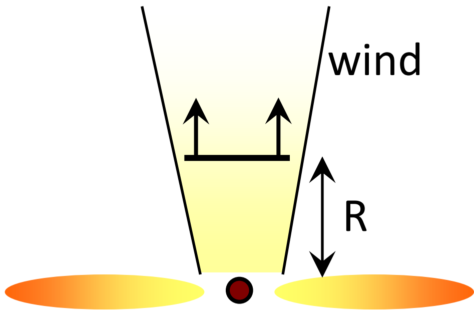
(e.g. Lovelace 76, Norman+ 95, Blandford 00, Waxman 05, Aharonian+ 02, Lyutikov & Ouyed 05, Farrar & Gruzinov 09, M.L. & Waxman 09)

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

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

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

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



→ **maximal energy:** $$\boxed{E \lesssim 10^{20}\,{\rm eV}\ Z\ \mathcal{A}^{-1}\ \left(\frac{L}{10^{45}\,{\rm erg/s}}\right)^{1/2}}$$

the bound 10^{45} ergs/s is robust: holds in the sub-relativistic limit, or as $\boldsymbol{\theta} \to 0$....
... however, the bound applies to stationary flows only...

<u>For reference:</u>

low luminosity AGN: $L_{\rm bol} < 10^{45}$ erg/s

Seyfert galaxies: $L_{\rm bol} \sim 10^{43}$-10^{45} erg/s

high luminosity AGN: $L_{\rm bol} \sim 10^{46}$-10^{48} erg/s

General principles of particle acceleration

Standard lore:

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

→ 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 $\mathbf{E}_{|\mathrm{p}}$ vanishes: the plasma rest frame for ideal MHD

→ 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

Linear acceleration in magnetospheric gaps

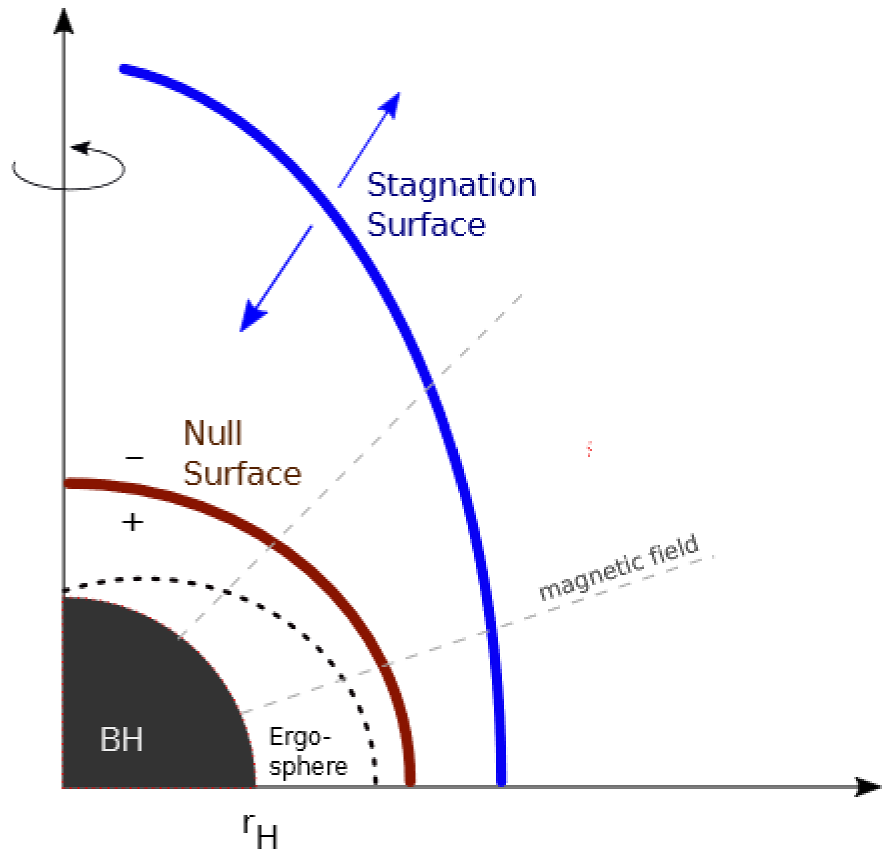
e.g. Rieger & Levinson 18 +refs

Electric gap: **E.B $\neq$ 0**

→ gap exists as long as parallel $E_{\parallel}$ is not screened by moving charges… provides voltage:

$$\Phi_E \sim -h_{\rm gap}^2\, 4\pi\, \big(\rho_e - \underbrace{\rho_{\rm G-J}}_{\boxed{\text{screening Goldreich-Julian charge density}}}\big)$$

→ fast acceleration with variability time scale $\lesssim r_{grav}/c$ …



Current questions:

→ is the gap steady or transient?

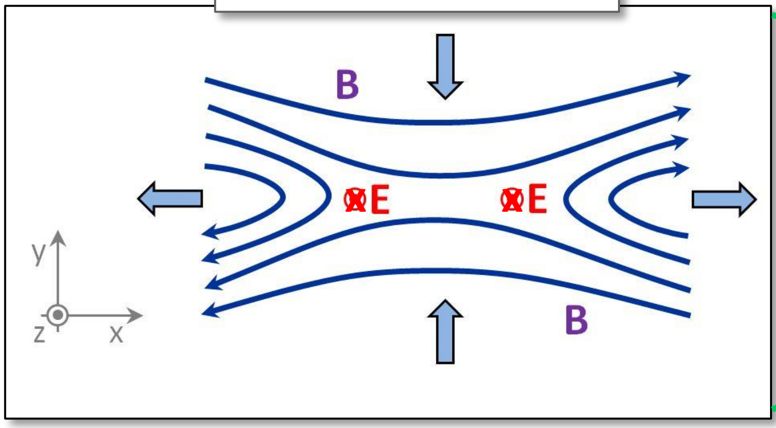
… depends notably on accretion rate, feedback of pairs etc…

→ height h_{gap}?

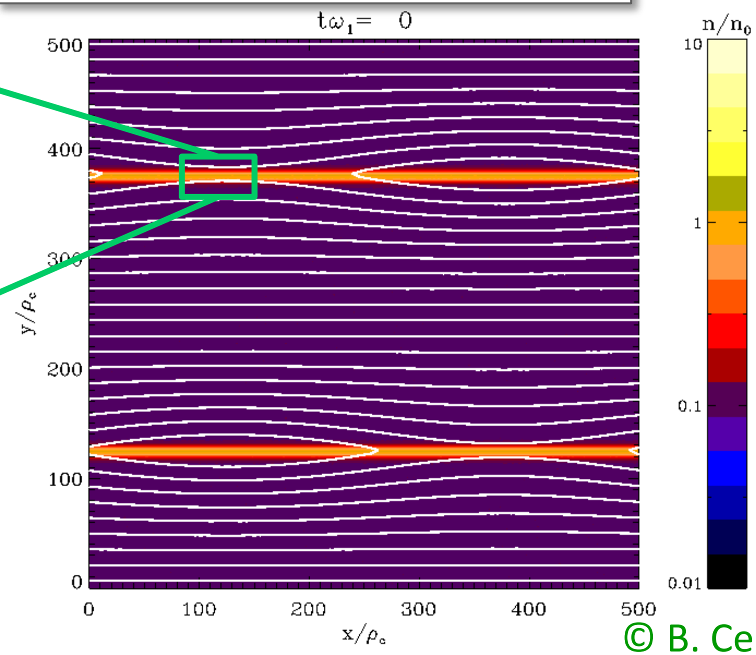
… controls luminosity and max energy…

Acceleration in reconnection flows

reconnection zone



HPC Particle-in-Cell simulation



→ in steady state model:

$$E_z = -\beta_{y,\mathrm{in}} B_x \Leftrightarrow t_{\mathrm{acc}} = \left|\frac{1}{p}\frac{\mathrm{d}p}{\mathrm{d}t}\right|^{-1} \simeq \frac{t_{\mathrm{g}}}{\beta_{\mathrm{in}}}$$

→ simulations:

(Zenitani+Hoshino 01,Uzdensky+11,Cerutti+12, Hoshino12,Melzani+13,Sironi+Spitkovsky14,Guo+14,Kagan+15…) :

… $\beta_{\mathrm{in}} \sim$ 0.1 at most in 2D reconnection

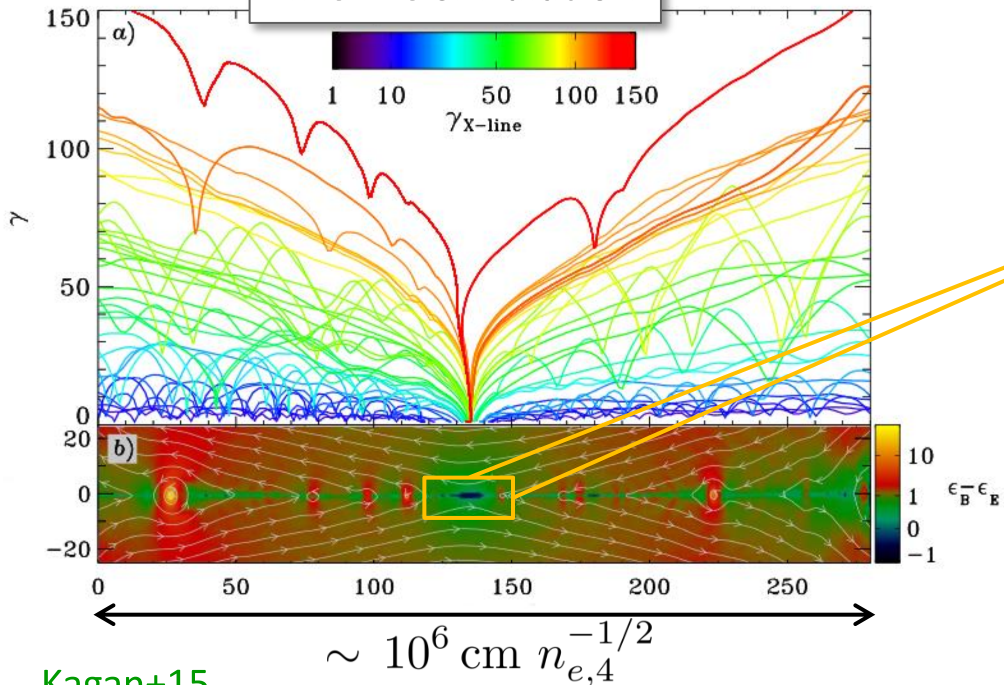
… spectral index s ~ 1 … 3+ for high…low $\sigma = B^2/(4\pi\, n\, m\, c^2)$ (magnetization)

… acceleration process: at X-point *and elsewhere in plasmoid regime*

⇒ reconnection ***appears as a fast acceleration*** process, *ideal for short-scale variable phenomena* (blazar flares, Crab flares, GRB prompt flares?)

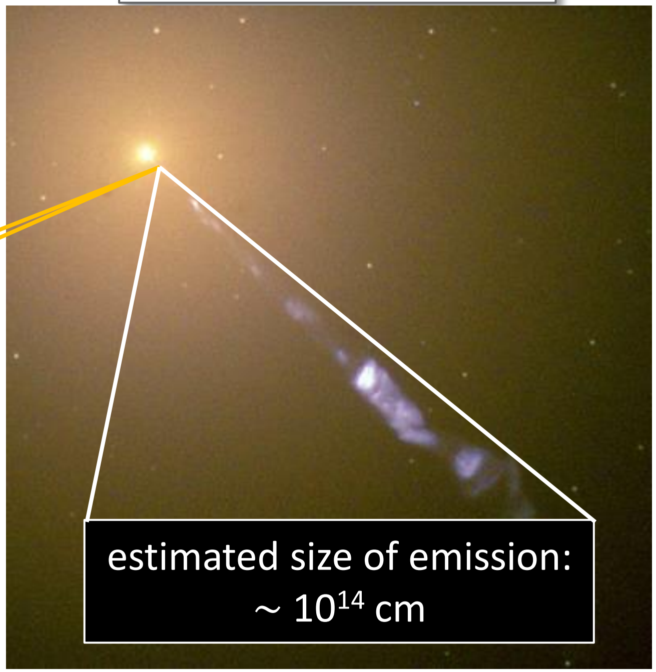
Reconnection in high-energy astrophysical sources

HPC PIC simulation



Kagan+15

astrophysical source



→ what happens at large scales, if gyroradius $r_g \gg L_{\mathrm{reconnection}}$ ...?
.... scattering in turbulence ?

... e.g. Drake+ 06, Guo+17: most of energy gained through Fermi-type processes in reconnection outflows and reconnection seeded turbulence..

Fermi scenarios

Ideal MHD: (Fermi 49)

→ Ohm's law in plasma rest frame $_{|p}$: $\mathbf{E}_{|\mathrm{p}} = \mathbf{j}/\sigma \underset{\sigma\to\infty}{\sim} 0$

… very large conductivity σ screens $E_{|p}$: no acceleration in a plasma at rest….

→ for a plasma in motion at $\boldsymbol{\beta}_{\mathbf{p}}$: $\boldsymbol{E} = -\boldsymbol{\beta}_{\mathbf{p}} \times \boldsymbol{B}$

… E is motional, acceleration related to the velocity flow ….

→ however, if **E** and **B** uniform, one can always boost to the plasma rest frame, in which acceleration does not take place: no long-term acceleration…

… acceleration requires a changing (in time or space) electromagnetic configuration… a non-uniform/non-constant stirring motion of the plasma…

→ **E.B** = 0…

… acceleration requires some transport across B-lines …

Fermi acceleration scenarios

Ideal MHD:

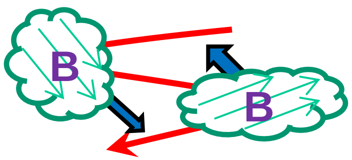
→ ***E*** field is 'motional', i.e. if plasma moves at velocity $\boldsymbol{\beta}_{\rm p}$: $\mathbf{E} = -\boldsymbol{\beta}_{\rm p} \times \mathbf{B}$

→ **need scattering to push particles across *B***

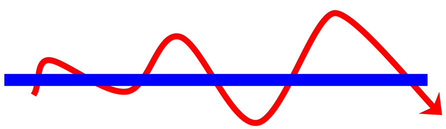
⇒ **t_{acc} scales with the scattering time (time needed to enter random walk)**

→ examples:

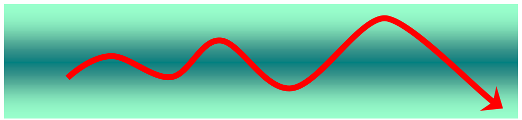
- turbulent Fermi acceleration



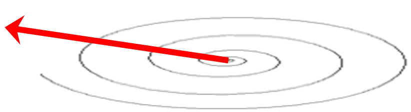
- Fermi acceleration at shock waves



- acceleration in sheared velocity fields



- magnetized rotators



Fermi scenarios: the issue of scattering

Scattering timescale vs gyrotimescale:

→ scattering timescale: time t_{scatt} it takes to deflect the particle by an angle of the order of unity,

$$t_{\rm scatt} \sim t_{\rm g}^{\alpha}\,(L/c)^{1-\alpha}$$

with L typical scale of turbulence

… in absence of specific information, assume ***(too often!):*** **$\alpha \sim 1$ Bohm regime**

… however:

→ microscopic turbulence:

$$t_{\rm scatt} \approx \frac{t_{\rm g}}{\lambda_{\rm turb.}/c}\,t_{\rm g} \propto p^2$$

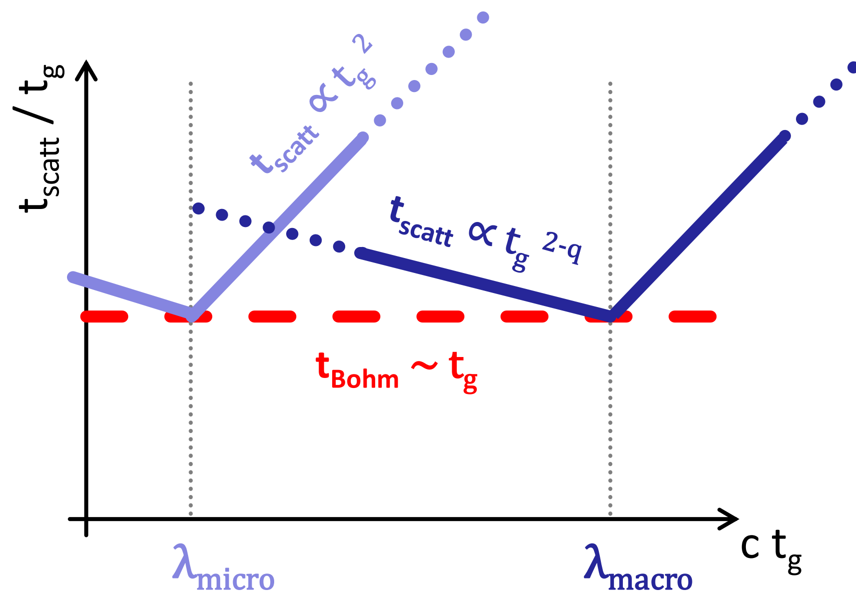
… Bohm-like at min scale $ct_L \sim \lambda_{turb}$, slow at higher energies…

→ macroscopic turbulence:

$$t_{\rm scatt} \approx t_{\rm g}^{2-q}\,(\lambda_{\rm turb.}/c)^{q-1}$$

with $|q-2| \ll 1$

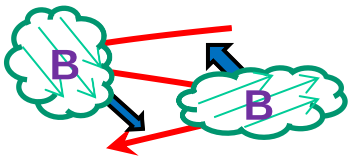
… slow at low energies, Bohm-like at max scale $ct_L \sim \lambda_{turb}$



(e.g. Casse+02)

Turbulent acceleration

Original Fermi model for acceleration:



… particle interaction with random moving scattering centers…
… acceleration becomes stochastic with diffusion coefficient:

$$\left\langle \frac{\Delta p^t \Delta p^t}{\Delta t} \right\rangle \sim \beta_u^2 \frac{p^2}{t_{\rm int}}$$

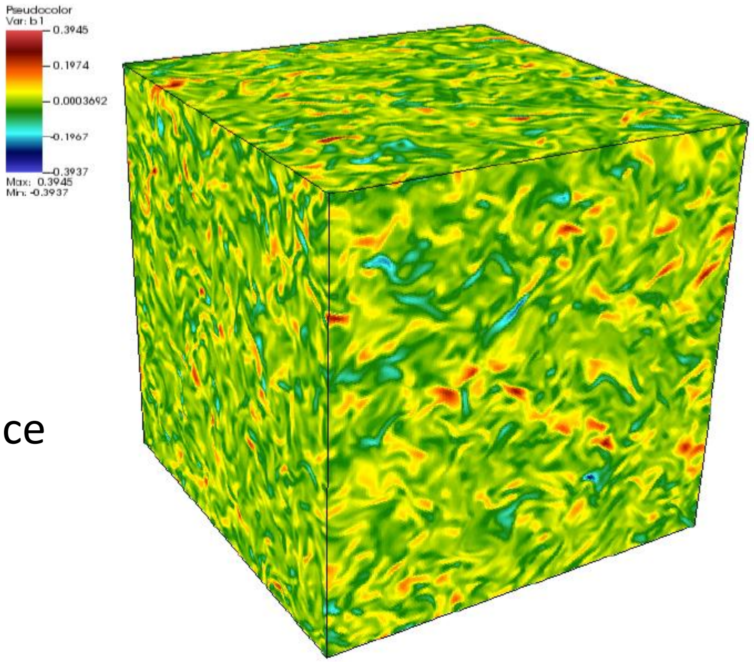
… what is t_{int} ?

Modern view, turbulent acceleration:

… particle interaction with turbulence…

… in *wave turbulence*, resonant particle-wave interactions can reduce significantly $t_{int} \approx t_{scatt}$ …
… but resonances seem absent in modern turbulence theories (Chandran 00) …

… do waves provide a faithful representation of turbulence?



B_x in relativistic MHD turbulence (256^3)
© C. Demidem

Stochastic acceleration in relativistic wave turbulence

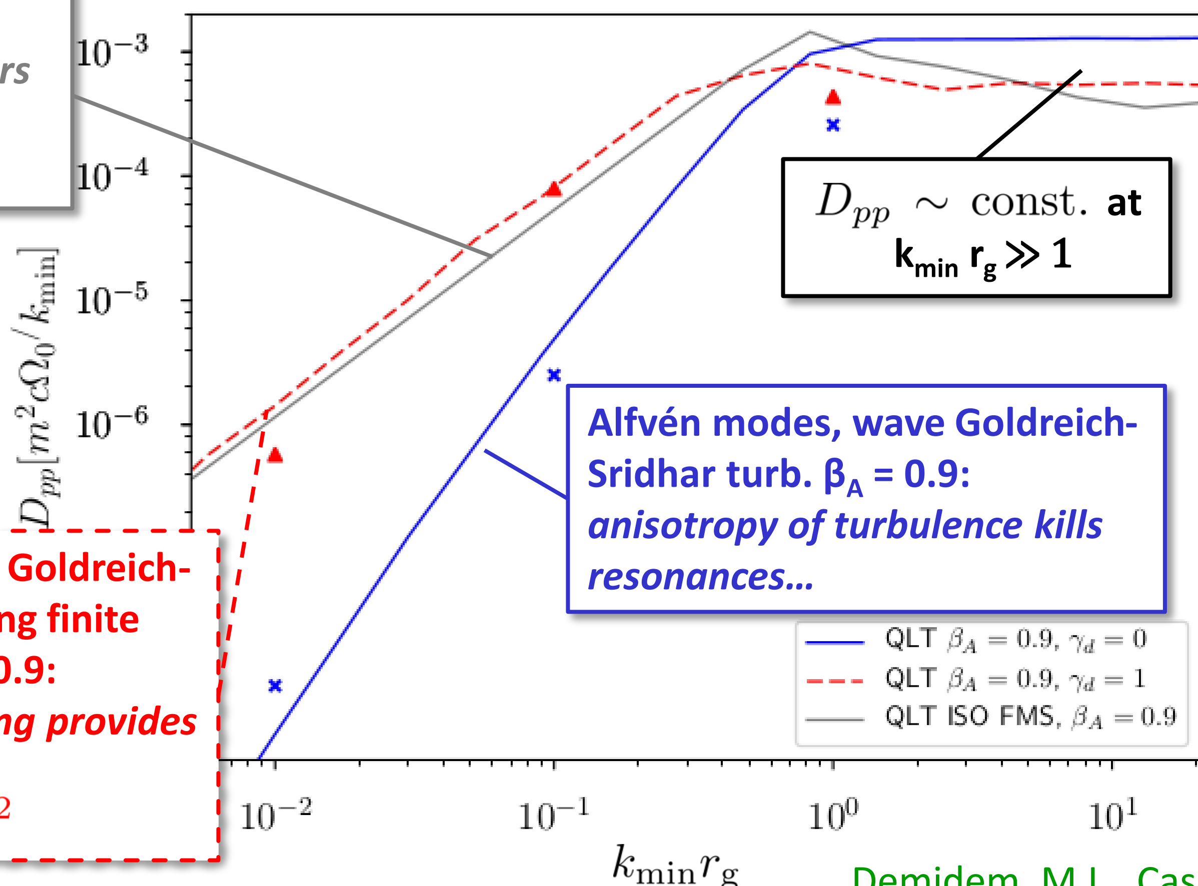
Particle-wave resonant interaction: $k_{\|} v_{\|} - \omega + nc/r_{\rm g} = 0$ (from quasi-linear theory)

...breaks into: $k \sim r_{\rm g}^{-1}$ gyroresonance, or

$v_{\|} \sim \omega / k_{\|}$ Landau = transit time damping (TTD)

[for comparison, Bohm regime: $D_{pp} \sim 0.1\, k_{\rm min} r_{\rm g}$ ...]

Fast modes, isotropic wave turb. $\beta_A = 0.9$: *TTD disappears in relativistic limit,* $D_{pp} \propto p^{5/3}$



$D_{pp} \sim$ const. **at $k_{\rm min}\, r_{\rm g} \gg 1$**

Alfvén modes, wave Goldreich-Sridhar turb. $\beta_A = 0.9$: ***anisotropy of turbulence kills resonances...***

Alfvén modes, wave Goldreich-Sridhar turb. including finite mode lifetime, $\beta_A = 0.9$: ***resonance broadening provides acceleration with*** $D_{pp} \propto p^2$

Demidem, M.L., Casse 19

Non-resonant acceleration in relativistic turbulence

<u>Beyond quasi-linear theory:</u> follow transport of particle in momentum space in a continuous sequence of (non-inertial) local plasma rest frames, where the electric field vanishes at each point… (M.L. 19)

… evolution of energy in local plasma rest frame $\frac{\mathrm{d}\hat{p}^{\hat{t}}}{\mathrm{d}\tau} = e^{\beta}{}_{\hat{b}}\, e^{\gamma}{}_{\hat{c}}\, \frac{\partial}{\partial x^{\gamma}} e^{\hat{t}}{}_{\beta}\, \frac{\hat{p}^{\hat{b}}\hat{p}^{\hat{c}}}{m}$

with $e^{\beta}{}_{\hat{b}}$ vierbein [~ local Lorentz transform] to comoving plasma frame

… then, to lowest order in $\mathbf{u}^2$ (sub-relativistic flow):

$$\begin{cases} \left\langle \frac{\Delta p^t \Delta p^t}{\Delta t} \right\rangle = \frac{\sqrt{2}}{3} p^2 t_{\rm scatt} \left[\langle \theta^2 \rangle + \frac{3}{5} \langle \sigma^2 \rangle + \frac{3}{\sqrt{2}} \langle a^2 \rangle \right] & \left(t_{\rm scatt} \lesssim k_{\rm min}^{-1} c^{-1} \right) \\ \left\langle \frac{\Delta p^t \Delta p^t}{\Delta t} \right\rangle = \frac{4}{\pi} \frac{p^2}{k_{\rm min}^2 t_{\rm scatt}} \left[\langle \theta^2 \rangle + \frac{3}{5} \langle \sigma^2 \rangle + \frac{3}{2} \langle a^2 \rangle \right] & \left(t_{\rm scatt} \gtrsim k_{\rm min}^{-1} c^{-1} \right) \end{cases}$$

with: $\langle \theta^2 \rangle \equiv \langle \boldsymbol{\nabla} \cdot \mathbf{u}^{\ 2} \rangle$ stochastic compression/dilatation

$\langle \sigma^2 \rangle \equiv \left\langle u_{(i,j)}\, u^{(i,j)} \right\rangle - \frac{1}{3} \langle \theta^2 \rangle$ turbulent shear acceleration

$\langle a^2 \rangle \equiv \langle u_{i,0}\, u^{i}{}_{,0} \rangle$ stochastic time shear/acceleration

A modern view on turbulent acceleration

Diffusion coefficient:

... define: $\eta = \dfrac{\langle \delta B^2 \rangle}{B^2 + \langle \delta B^2 \rangle}$ fraction of turbulent energy density

... define: q index of turbulent power spectrum between k_{min} and k_{max}

wave turbulence:

... for fast magnetosonic modes: $D_{pp} \sim \kappa_{\rm F}\, \eta_{\rm F}\, \beta_{\rm F}^2 \dfrac{p^2}{k_{\rm min} c} (r_{\rm g} k_{\rm min})^{q_{\rm F}-2}, \quad \kappa_{\rm F} \sim 0.1$

... for Alfvén modes: $D_{pp} \sim \kappa_{\rm A}\, \eta_{\rm A}\, \beta_{\rm A}^2 \left| \dfrac{\Im \omega}{\Re \omega} \right| \dfrac{p^2}{k_{\rm min} c}, \quad \kappa_{\rm A} \sim 0.1$

$\left[t_{\rm scatt} \lesssim (k_{\rm min} c)^{-1}\right]$

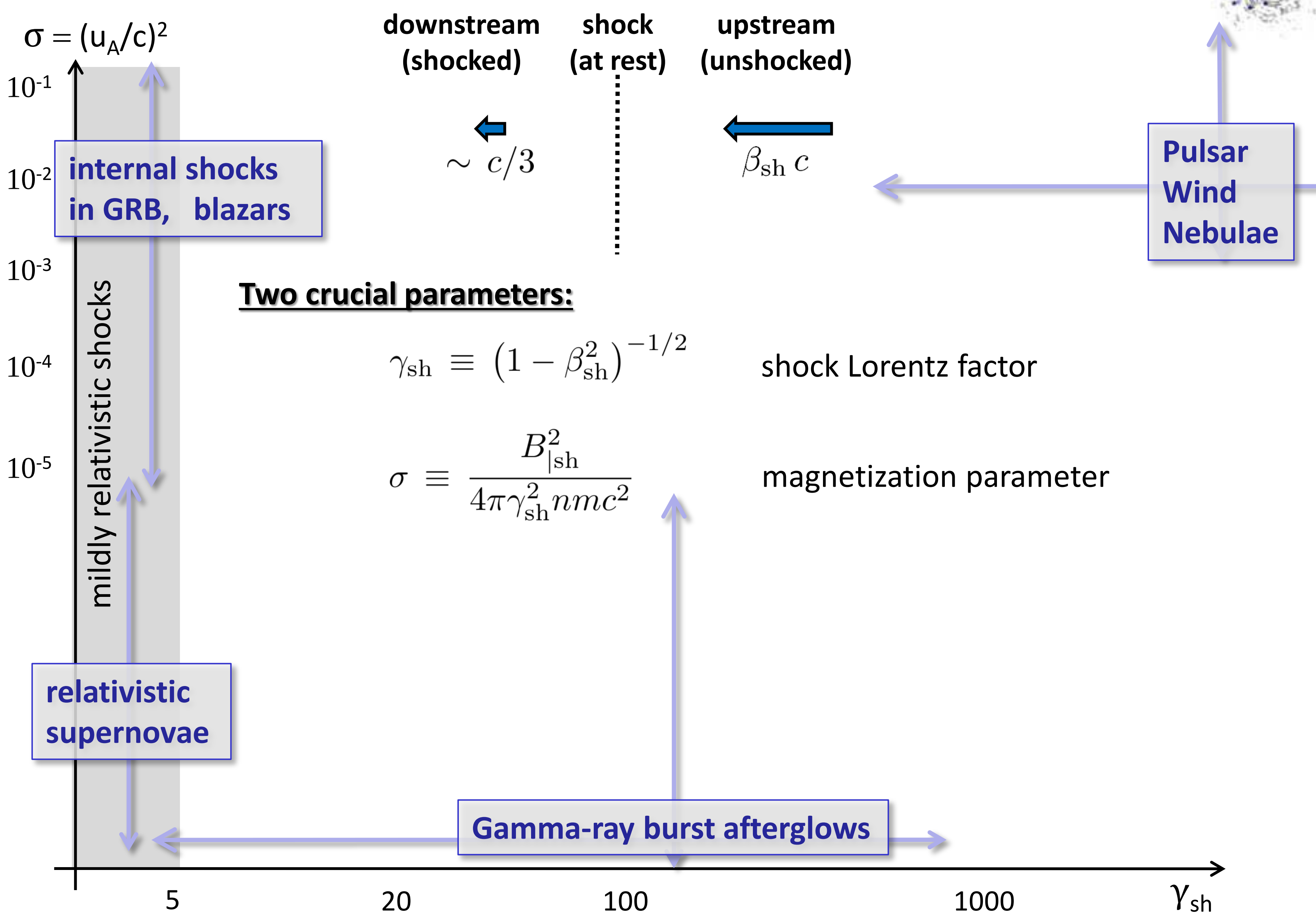
generic turbulence, non-resonant acceleration:

... assuming $t_{\rm s} \sim (k_{\rm min} c)^{-1}$: $D_{pp} \sim \kappa_{\rm NR} \langle \beta^2 \rangle \dfrac{p^2}{k_{\rm min} c}, \quad \kappa_{\rm NR} \sim 0.1$

Acceleration timescale: $t_{\rm acc} \equiv \dfrac{p^2}{D_{pp}} \sim p^{\epsilon} \langle \beta^2 \rangle^{-1} \eta^{-1} \, (k_{\rm min} c)^{-1}$

with ε ≪ 1, 'hard sphere' model...

Relativistic shock physics

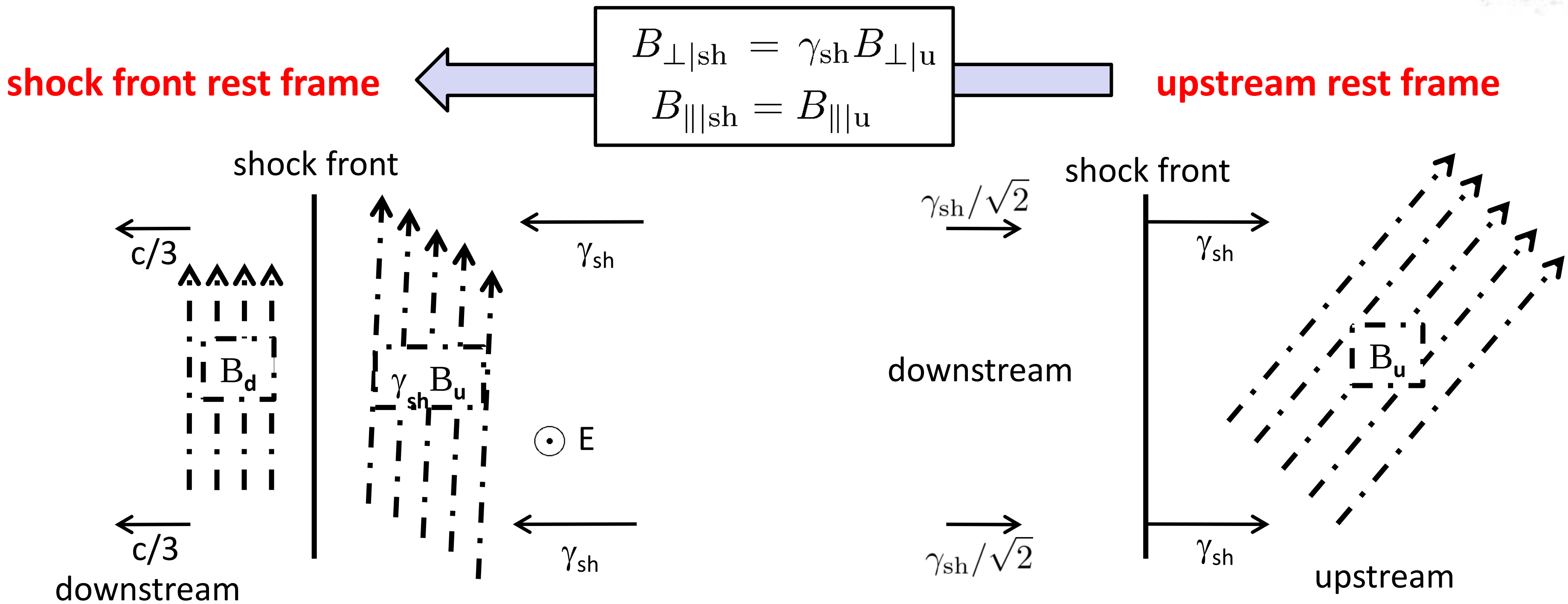


Two crucial parameters:

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

$$\sigma \equiv \frac{B_{|\rm sh}^2}{4\pi\gamma_{\rm sh}^2 nmc^2}$$ magnetization parameter

Relativistic shocks: superluminality is generic



⇒ ultra-relativistic shock waves are mostly perpendicular (superluminal)

superluminal shock: point of contact between magnetic field line and shock surface moves along shock surface at velocity > c…

… meaning that **if particles are tied to field lines, they cannot undergo Fermi cycles**!

… hence no acceleration at relativistic shocks, unless particles are unlocked off field lines through **scattering in small scale turbulence…** (ML, Pelletier, Revenu 06)

Particle acceleration at relativistic shocks

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

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

mildly relativistic shocks

relativistic supernovae , shocks in rel. jets (GRB, AGN…)

→ ***magnetization hampers acceleration* at** $u_{sh} = \beta_{sh}\gamma_{sh} \gg 1$, …
… the shock is superluminal: particles are advected on faster than they can scatter …

Pulsar Wind Nebulae

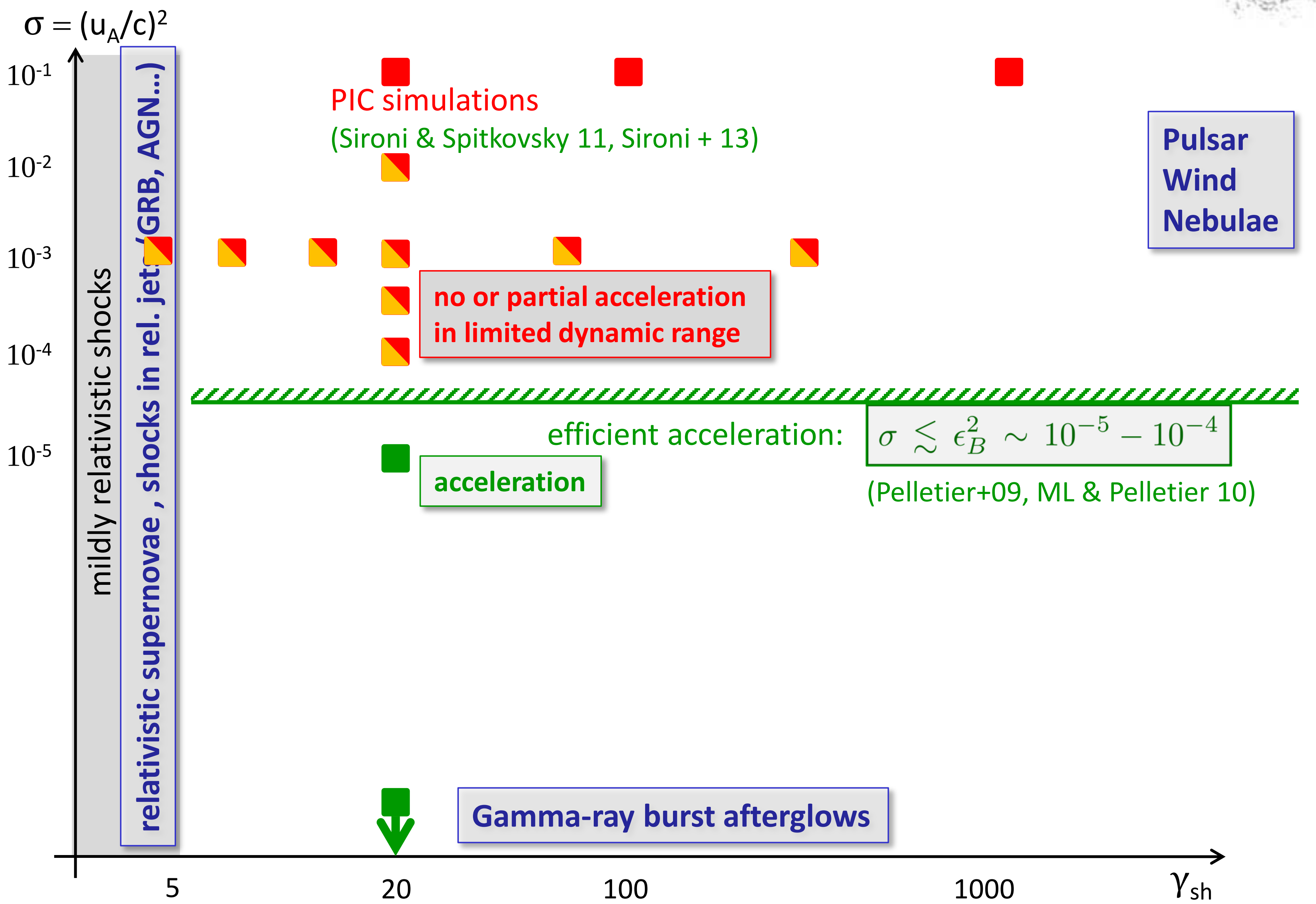
→ ***if scattering is effective*, relativistic shocks provide very fast acceleration with $t_{acc} \sim t_{scatt}$ in shock rest frame, spectral index ~2.2**

… at small background magnetization, accelerated particles self-generate a turbulence of large amplitude…
… but ***short precursor scale*** ⇒ microinstabilities on tiny length scales… ***no Bohm…***
… hence slow acceleration: $t_{acc} \propto p^2$…

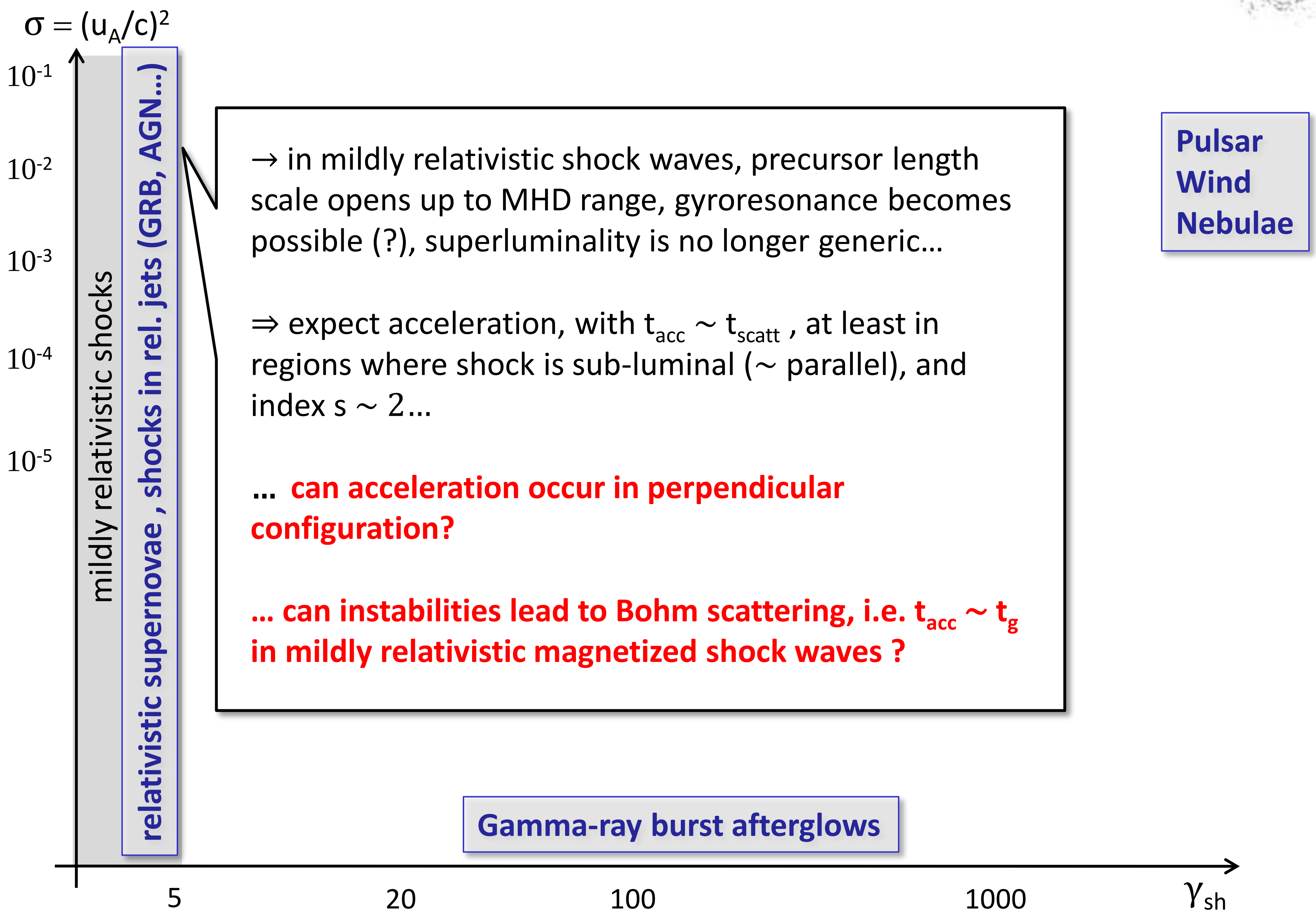
Gamma-ray burst afterglows

5 20 100 1000 γ_{sh}

Phase diagram for relativistic shock acceleration



Particle acceleration in relativistic shocks



→ in mildly relativistic shock waves, precursor length scale opens up to MHD range, gyroresonance becomes possible (?), superluminality is no longer generic...

⇒ expect acceleration, with $t_{acc} \sim t_{scatt}$, at least in regions where shock is sub-luminal (~ parallel), and index $s \sim 2$...

... **can acceleration occur in perpendicular configuration?**

... can instabilities lead to Bohm scattering, i.e. $t_{acc} \sim t_g$ in mildly relativistic magnetized shock waves ?

Summary / conclusions

Main progress in recent years/decades:

→ beyond naive test-particle acceleration in idealized flow configuration, i.e. include back reaction of acceleration / non-trivial flow configurations using high performance numerical simulation (MHD, PIC, PIC/MHD…) + theory

→ current direction: increase time and length-scale of simulations…

Some results and some questions:

→ linear acceleration:

… how do magnetospheric gaps behave: transient / steady? duty cycle, max energy?

… how does reconnection extend on large time / space / dimensionality ?

→ turbulent acceleration:

… acceleration timescale $t_{\rm acc} \sim \eta^{-1} \langle\beta^2\rangle^{-1} (k_{\rm min}c)^{-1} \ldots$

due to the combination of (broadened) resonant and non-resonant effects…?

many ongoing simulations, more to be learned…

→ shock acceleration:

… in highly relativistic regime (u≫1): acceleration limited to weakly magnetized regime, scattering in small-scale turbulence implies $t_{\rm acc} \sim (k_{\rm min}c)\, t_{\rm g}^2$

… but, in mildly relativistic regime: possibility of Bohm acceleration at magnetized shock waves ??