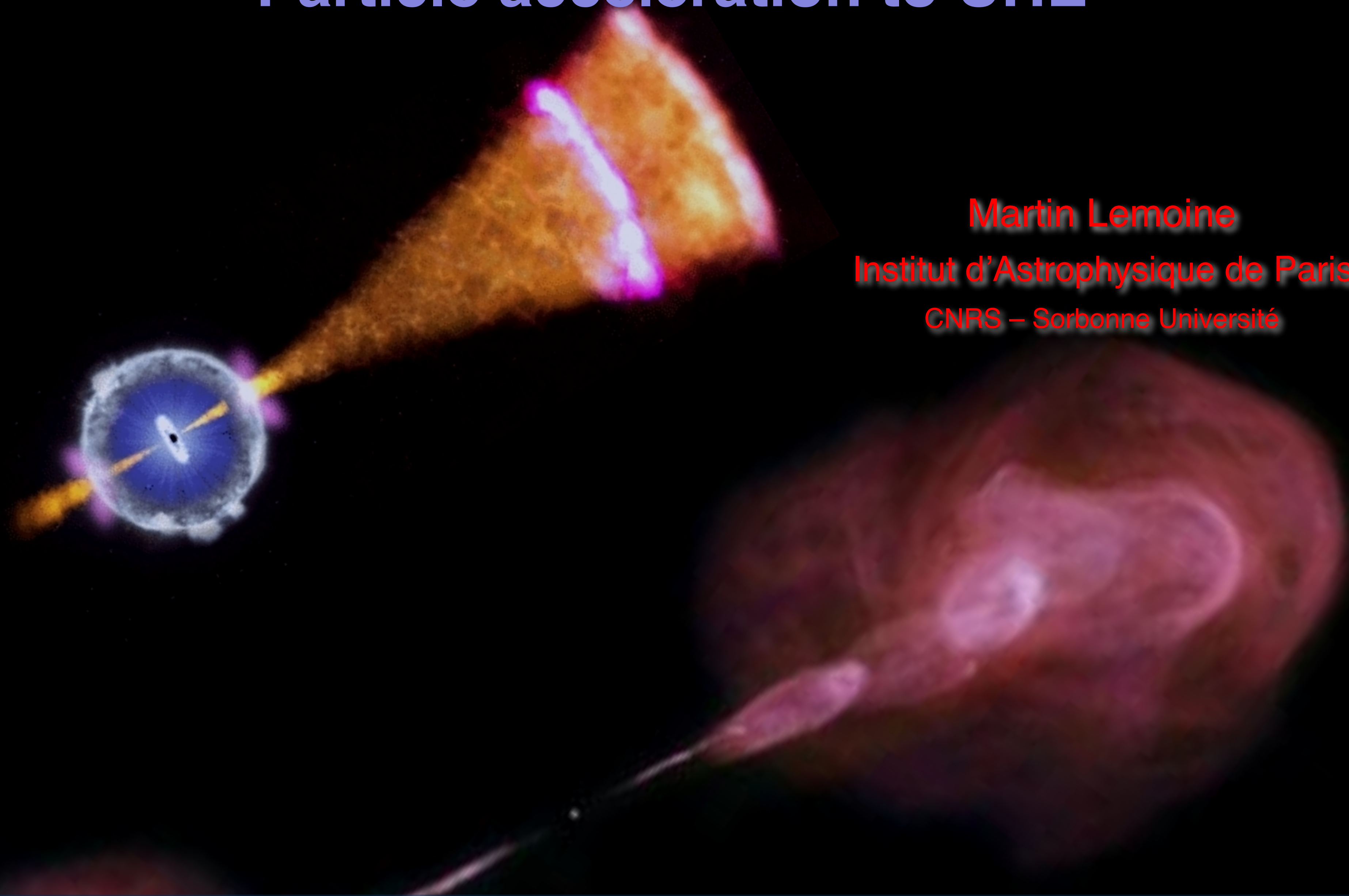
Particle acceleration to UHE



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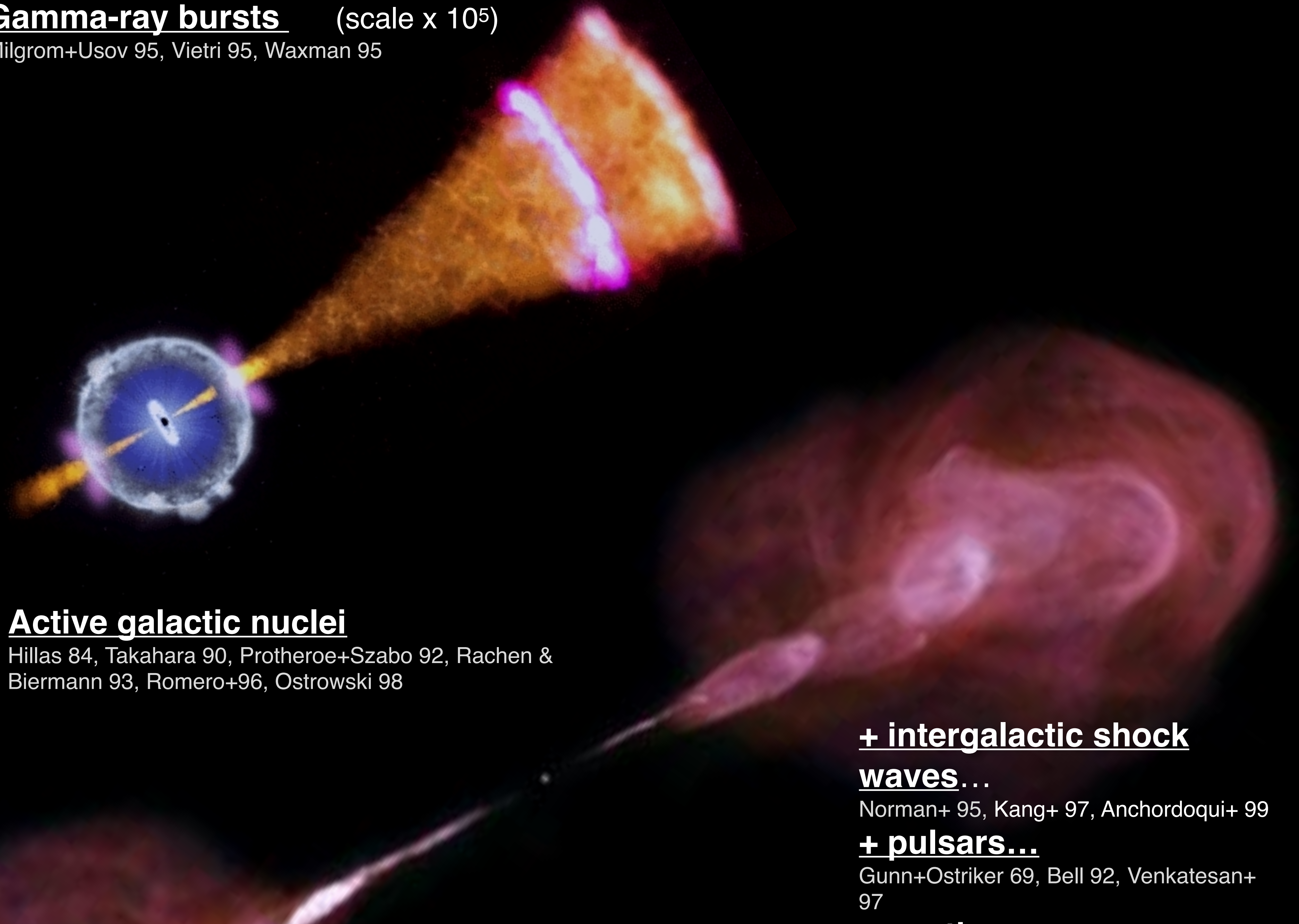
Usual suspects… twenty years ago…



Gamma-ray bursts (scale x 10^5)

Milgrom+Usov 95, Vietri 95, Waxman 95

Active galactic nuclei

Hillas 84, Takahara 90, Protheroe+Szabo 92, Rachen & Biermann 93, Romero+96, Ostrowski 98

+ intergalactic shock waves…

Norman+ 95, Kang+ 97, Anchordoqui+ 99

+ pulsars…

Gunn+Ostriker 69, Bell 92, Venkatesan+ 97

Usual suspects… now…

<u>Powerful transients:</u> high and low luminosity GRBs, relativistic SNe, fast spinning magnetars/pulsars…

High luminosity GRB:
Milgrom + Usov 95, Vietri 95, Waxman 95, Rachen + Meszaros 96, Gallant + Achterberg 99, Pelletier + Kersale 00, Dermer + Humi 01, Waxman 01, Scully + Stecker 02, Gialis + Pelletier 03, Waxman 04, Rieger + Duffy 06, Asano+ 09, 10, Razzaque+ 10, Giannios 10, Eichler + Pohl 11, Metzger+ 11, Baerwald+ 15, Globus+ 15, Asano + Meszaros 16, Samuelsson+ 19

Low-luminosity GRBs / Relativistic SNe:
Murase+ 06, Budnik+ 08, Wang+ 08, Liu+ 11, Chakraborti+ 11 , Liu + Wang 12, Zhang + Murase 18, Zhang+ 18, Boncioli+ 19

Magnetar WNe/ Pulsar WNe :
Bell 92, Blasi+ 00, de Gouveia dal Pino + Lazarian 01, Arons 03, Vietri+ 03, Fang+ 13, Lemoine+ 15, Fang+ 18, Kirk + Giancinti 19

<u>Active galactic nuclei:</u>

Blazar/Radio-galaxy jet+lobe:
Takahara 90, Rachen + Biermann 93, Ostrowski 98, Farrar + Piran 00, Tinyakov + Tkachev 01, Gorbunov+ 02, Lyutikov + Ouyed 07, Atoyan+Dermer 08, Gorbunov + 08, Dermer+ 09, Hardcastle+ 09, O'Sullivan+ 09, Dermer + Razzaque 10, Gopal-Krishna+ 10, Biermann+ deSouza 12, Murase+ 12, Ptuskin+ 13,Caprioli 15, Wang + Loeb17, Eichmann+ 18, Liu+ 17, Resconi+ 17, Kimura+ 18, Matthews+ 18,19,Fang + Murase18,Rieger 19

AGN Core:
Protheroe + Szabo 92, Boldt + Ghosh 99, Levinson 00, Levinson + Boldt 00, Torres+ 02, Dempsey + Rieger 09, Istomin + Sol 09, Neronov + 09, Rieger + Aharonian 09, Dutan + Caramete 14, Moncada+ 17

+ intergalactic shock waves (clusters, starbursts)…
Norman+95, Kang+ 97,Anchordoqui+ 99, + 01, Murase+ 08, Kotera +09, Malkov +11, Anchordoqui 18, Romero+ 18

+ other transients: e.g. tidal disruption

Connections to many (contemporaneous) fields of physics…

Experimental astroparticle physics:

… a data-starved field of research!

e.g., chemical composition and anisotropies fundamental clues…

High-energy astrophysics:

e.g. the origin, dynamics, energy content and dissipative physics of (relativistic) jets…

e.g. environments of compact objects…

Multi-messenger astrophysics:

e.g. neutrinos unambiguous signatures of hadron acceleration…

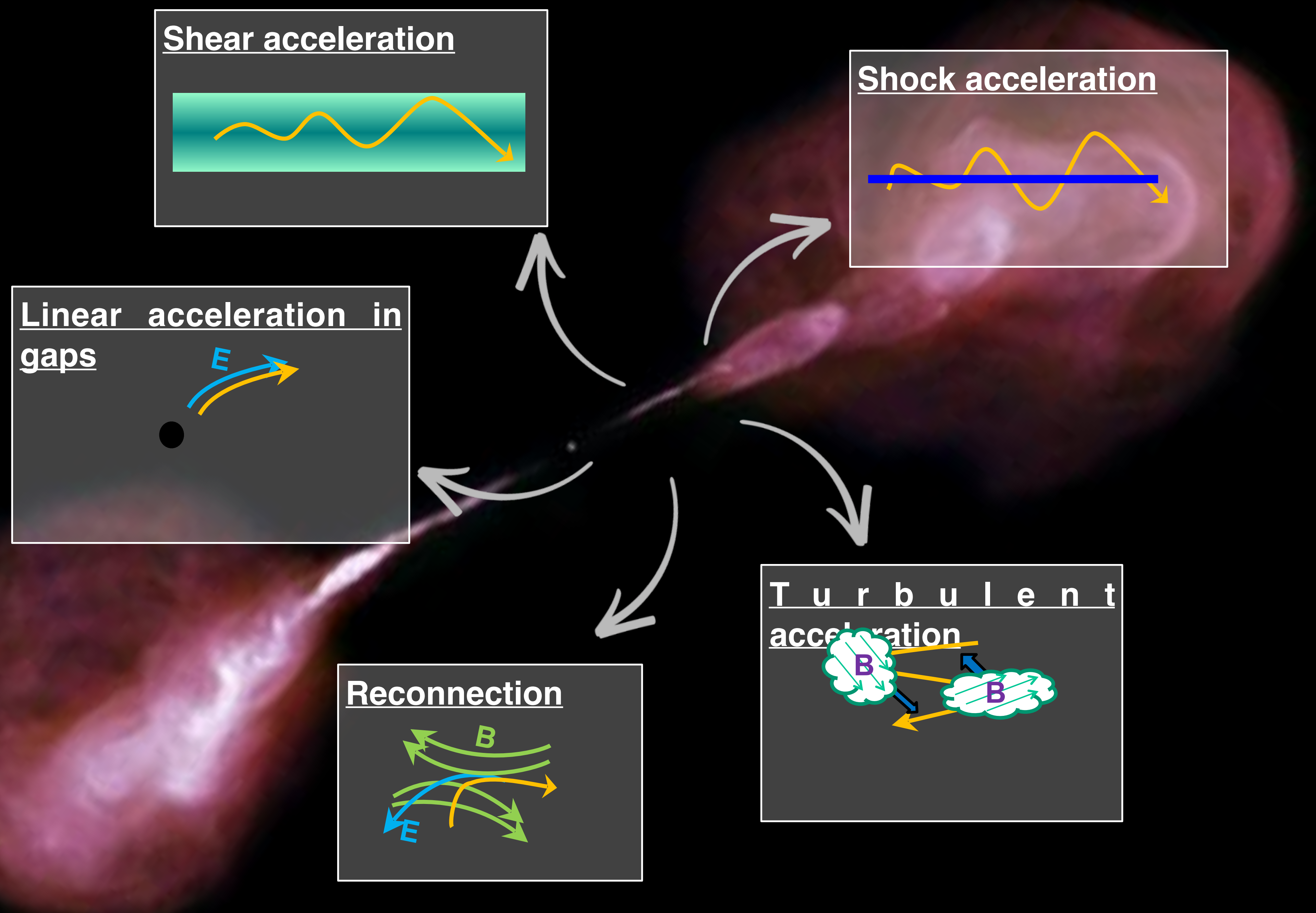
e.g. photons indirect probes of the physical conditions…

Extreme plasma astrophysics:

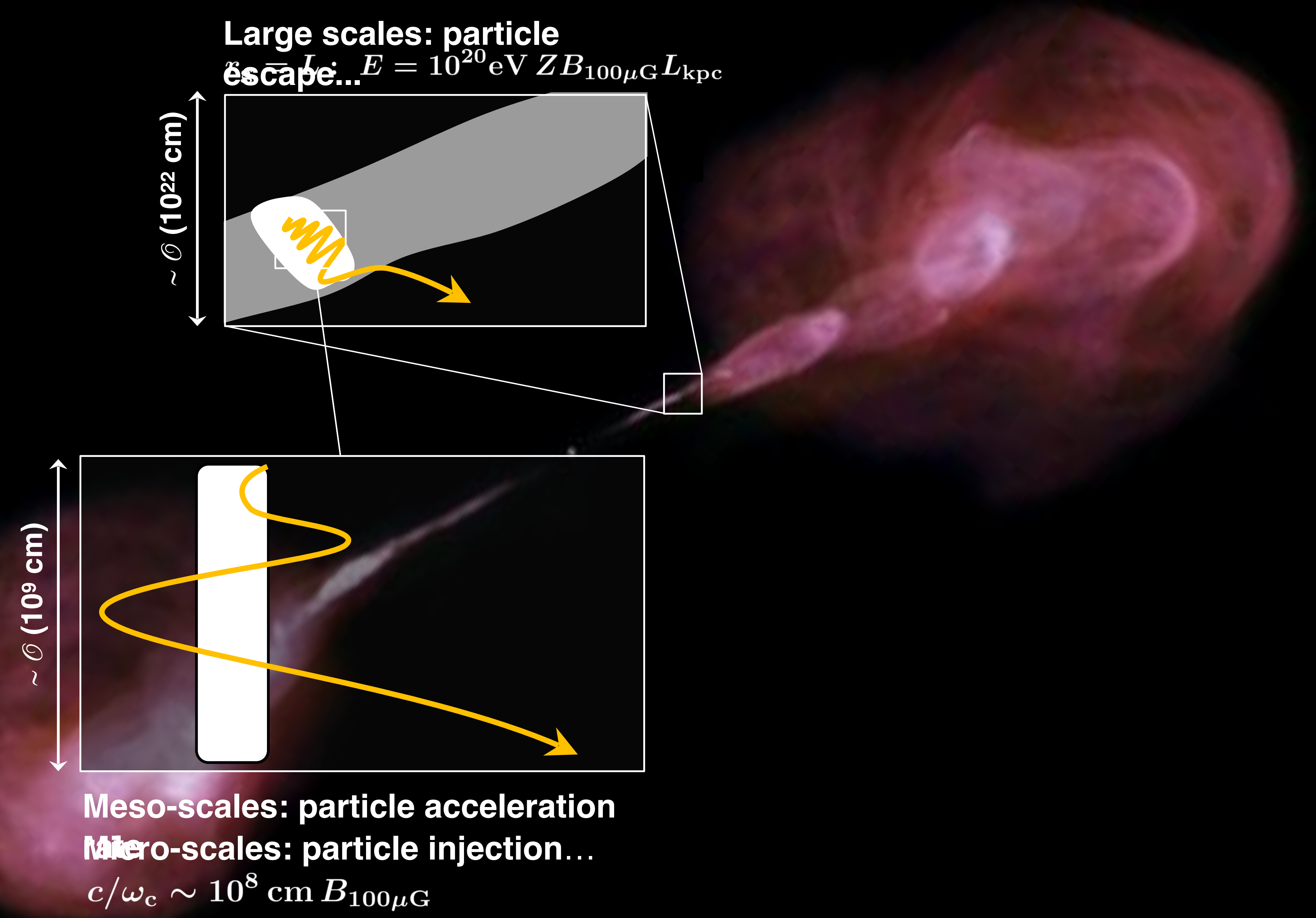
e.g. (highly?) magnetized, highly energetic collisionless plasmas with bulk (or random?) velocities $v \sim c$…

e.g. plasmas in strong gravity/radiation fields…

Various (more or less known) acceleration scenarios…



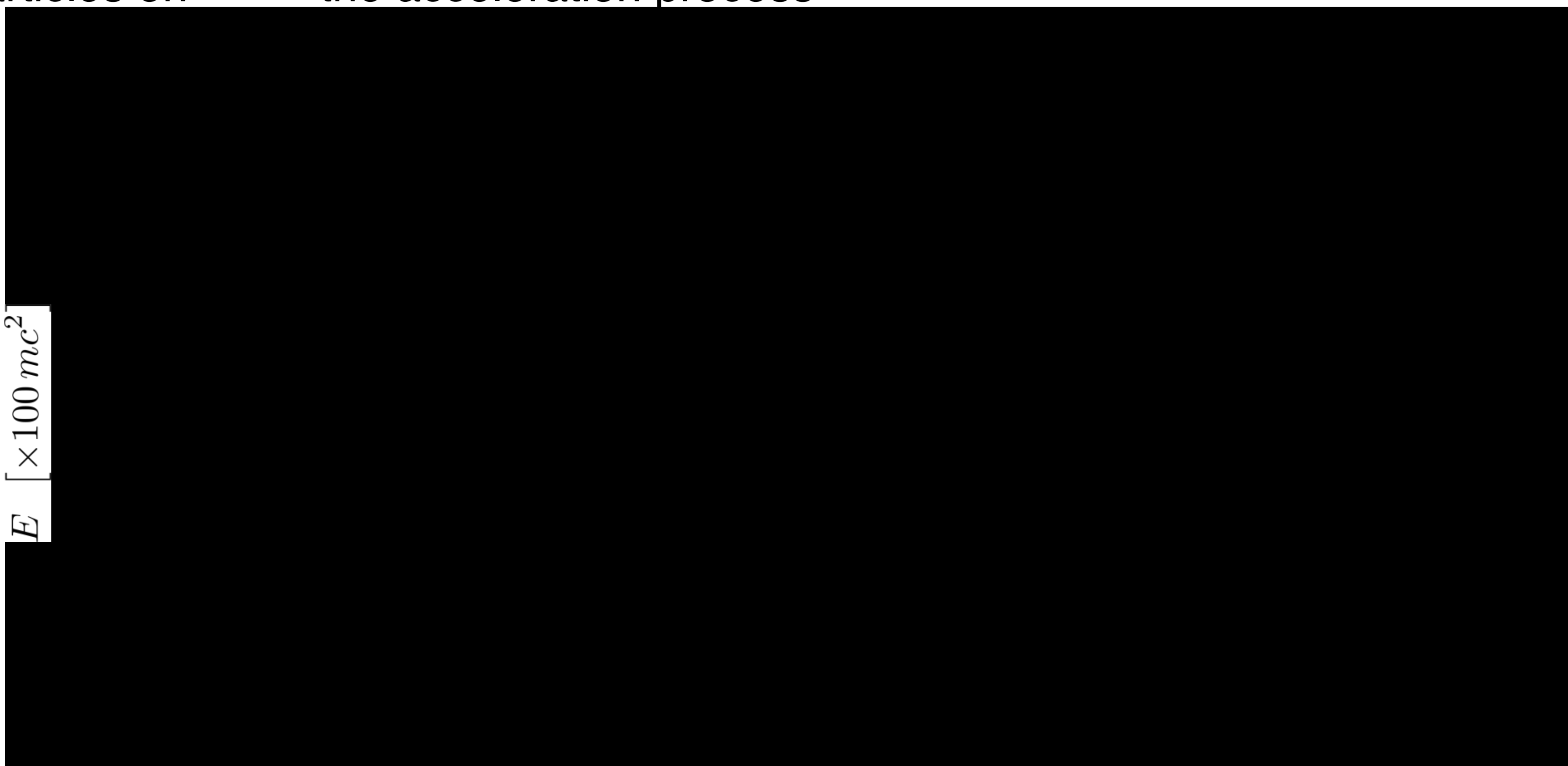
A challenge of scales…



Numerical simulations of particle acceleration…

… HPC numerical simulations (Monte Carlo, particle-in-cell, MHD+PIC, hybrid …) allow to explore the physics of acceleration to unprecedented details...

→ explore the issue of injection and backreaction of accelerated particles on the acceleration process



… **an important caveat:** ab initio simulations remain limited to small scales…

Top (of the energy/length/time scales) - down…

Two critical properties of a source of UHECRs:

→ **a high output of cosmic rays:** $\dot{e}_{\rm UHECR}\,\sim\,10^{44}\,{\rm erg/Mpc^3/yr}$

Katz+10,…

… a non-trivial constraint: e.g. $L_{UHE}/L_\gamma \sim 10$ for HL GRBs…

e.g. $L_{UHE}/L \sim \mathcal{O}(1\text{-}10\%)$ for radio-galaxies…

→ **a high magnetic luminosity:**

$$L_{\rm tot}\,\gtrsim\,10^{45}\,{\rm erg/s}\,\ldots\,\left(\frac{t_{\rm acc}}{t_{\rm g}}\right)^2\left(\frac{E/Z}{10^{20}\,{\rm eV}}\right)^2$$

Hillas 84, Blandford 00, Aharonian 02, Waxman 04, Lyutikov+Ouyed 07, Lemoine+Waxman 09,…

… a non-trivial constraint… Chemical composition (Z) controls the phenomen

… to go further:

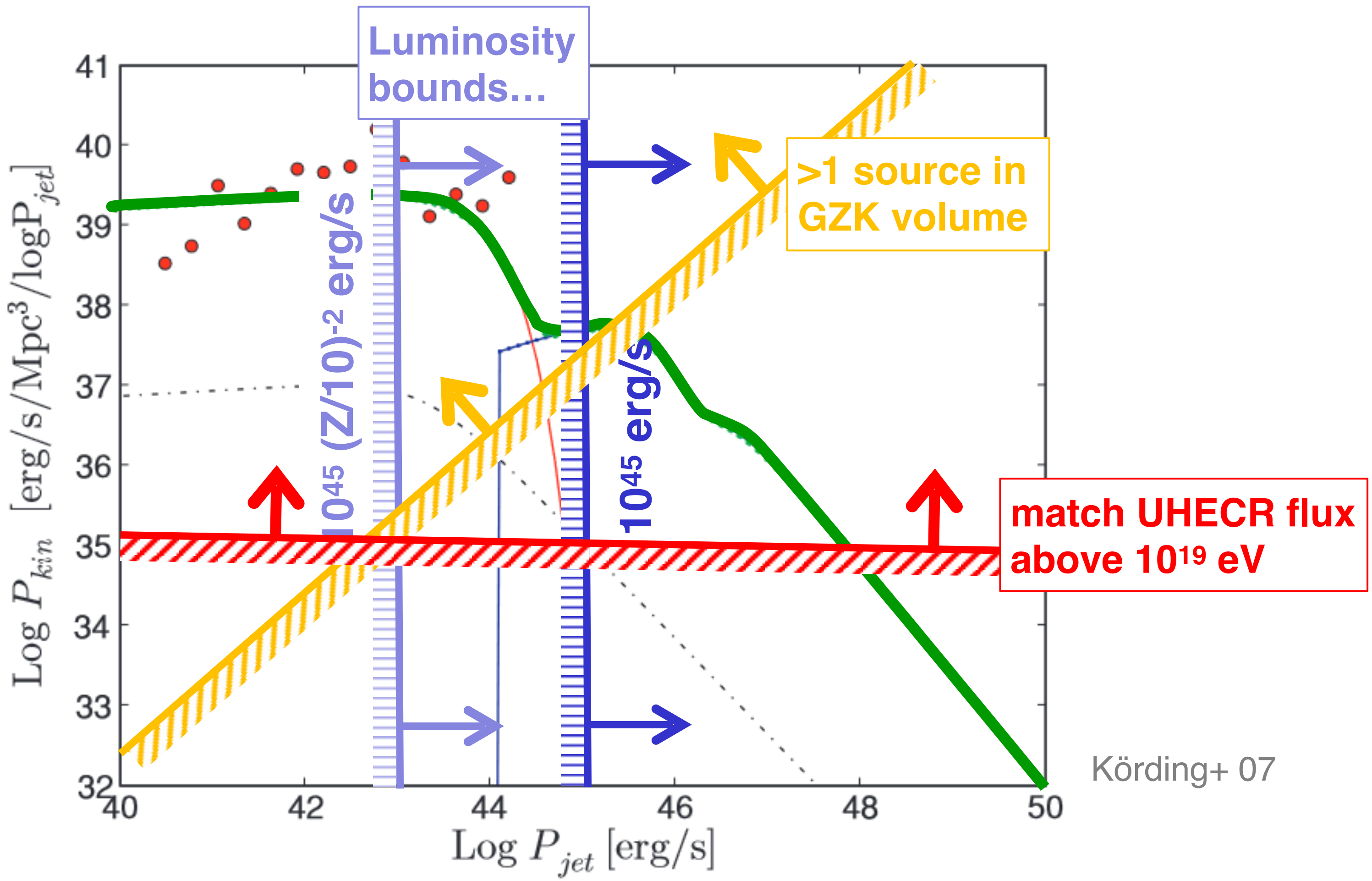
$$\ldots\left(\frac{t_{\rm acc}}{t_{\rm g}}\right)^2\,\propto\,\frac{t_{\rm scatt}}{t_{\rm g}}\begin{cases}u^2 & (u\gg1)\\ 1/u & (u\ll1)\end{cases}$$

(u 4-velocity)

$\Longrightarrow$ favors relativistic (mildly?) sources…

… to reach the confinement energy: $t_{acc} \sim t_g$!

Top - down… zooming in on the radio-galaxy population…



local radio-galaxies barely satisfy the luminosity bound: accelerate Z ~ 10+ nuclei?

Top - down… some lessons learned…

Two critical properties of a source of UHECRs:

→ **a high output of cosmic rays:** $\dot{e}_{\mathrm{UHECR}} \sim 10^{44}\,\mathrm{erg/Mpc^3/yr}$

→ **a high magnetic luminosity:** $L_{\mathrm{tot}} \gtrsim 10^{45}\,\mathrm{erg/s}\ \ldots \left(\frac{t_{\mathrm{acc}}}{t_{\mathrm{g}}}\right)^2 \left(\frac{E/Z}{10^{20}\,\mathrm{eV}}\right)^2$

… leading contenders, for accelerating intermediate nuclei (Z ~ 10):

→ powerful radio-galaxies, L ~ 10^{44} erg/s, u ~ 1 …
→ relativistic supernovae (LLGRB), L ~ 10^{44} erg/s, u ~ 1 …

… need extreme sources for accelerating light nuclei (Z ~ 1):

→ gamma-ray bursts, fast-spinning magnetar/pulsar wind nebulae…
→ most powerful FRII like radio-galaxies

Bottom – up : the microphysics of acceleration

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

… recall however that ***E*** and ***B*** transform into each in a change of frame…
… rely on Lorentz scalars ***E.B*** and ***E² - B²*** …

Case 1: **highly conducting plasma (ideal MHD)…** $\boldsymbol{E}\cdot\boldsymbol{B} = 0 \text{ and } \boldsymbol{E}^2 - \boldsymbol{B}^2 < 0$

→ **generic for UHECR**: corresponds to ideal Ohm's law ***E = - v_p x B /c…***

(on timescales >> micro, comoving electric field is screened out)

→ **Fermi-type scenarios: magnetized turbulence, shear flows, shock waves**

Case 2: **non-MHD behavior…** $\boldsymbol{E}\cdot\boldsymbol{B} \neq 0 \text{ or } \boldsymbol{E}^2 - \boldsymbol{B}^2 > 0$

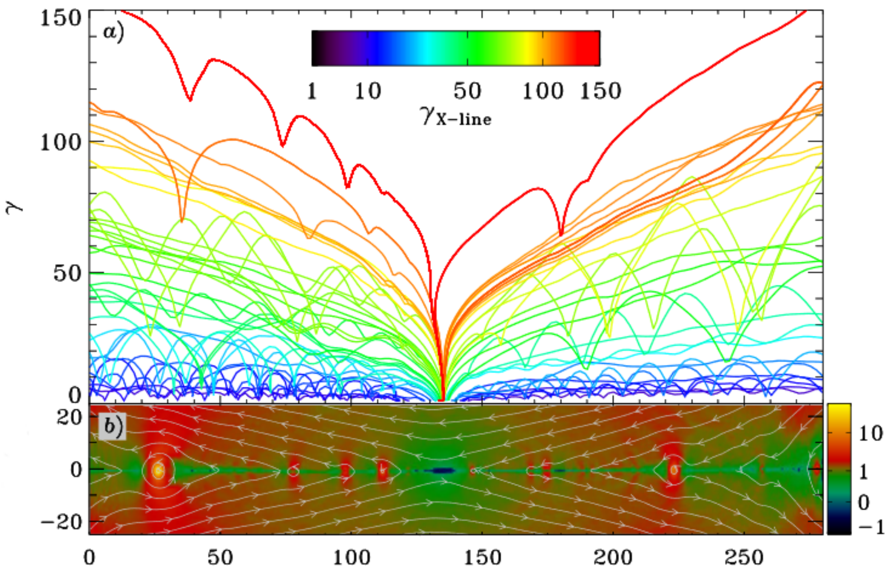
→ acceleration can proceed unbounded along **E** (or at least $\mathbf{E}_{\parallel}$)…

→ **gaps in BH magnetospheres:** possible, but many open issues, e.g. Levinson 00, Rieger 19

→ **reconnection:** unlikely, max energy in (relativistic) reconnection $\propto \sigma = u_B/u_p$

Reconnection vs acceleration to VHE

→ **acceleration proceeds in two stages**



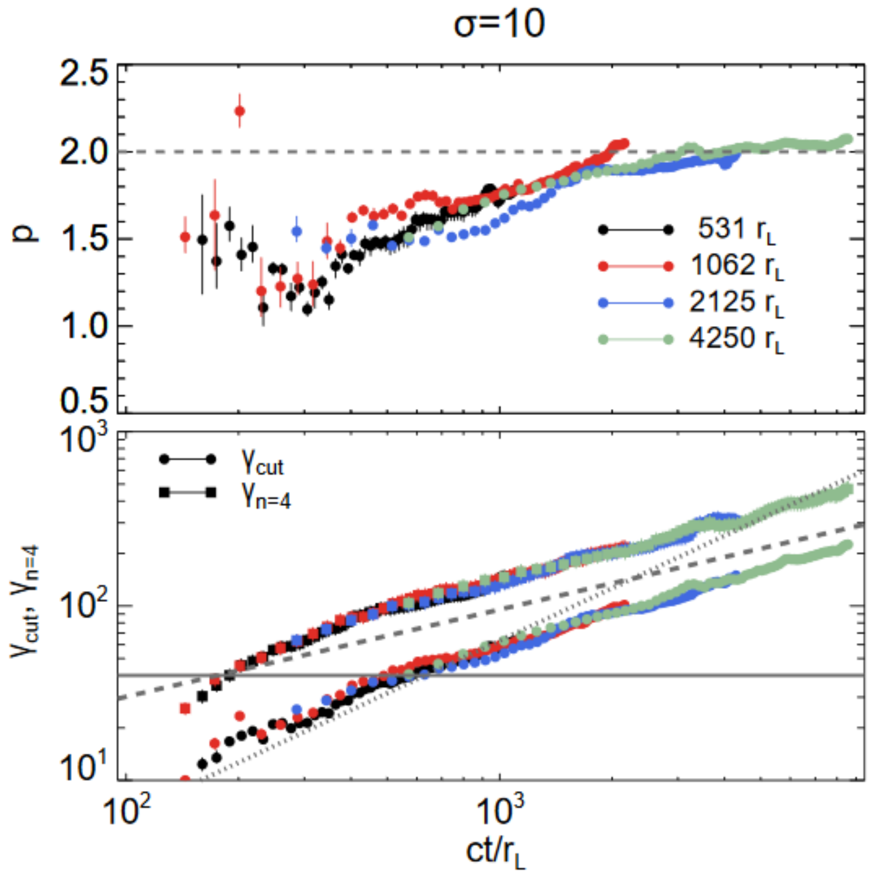
(1) acceleration at and around the annihilation regions…

a fast rate: $t_{acc} \sim 0.1\ t_g$

… leading to hard powerlaws with $p<2$ if $\sigma \gtrsim 1$…

but a cut-off at Lorentz factor $\sim 4\sigma$

(Kagan+15, Werner+16)



(2) acceleration in the resulting large-scale turbulence…

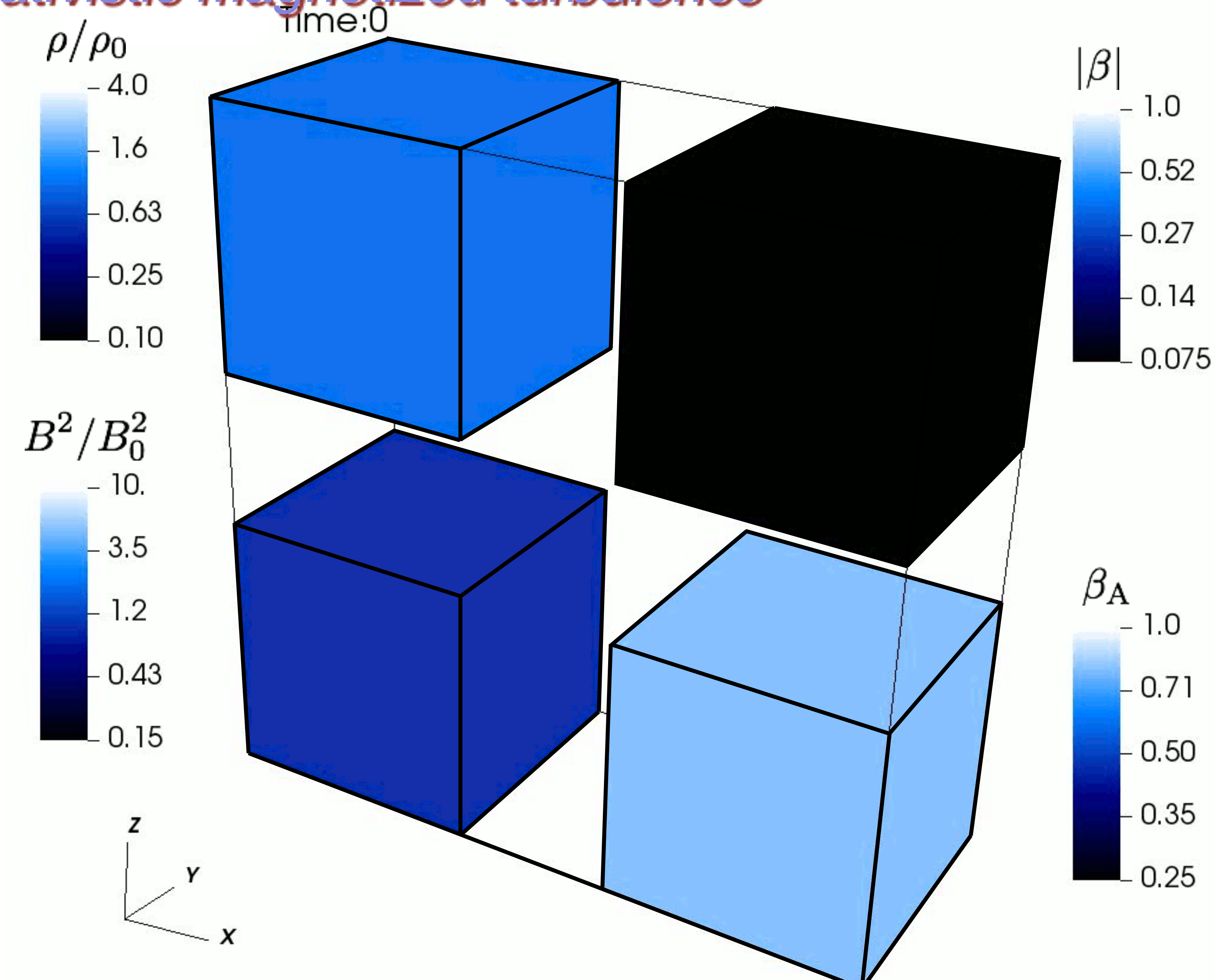
through Fermi processes!

leading to softer powerlaws…

and slow acceleration: $t_{acc} \propto t_g^{\ 2}$

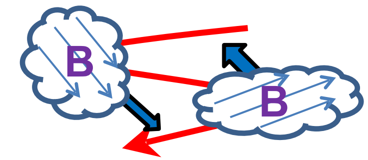
…

Relativistic magnetized turbulence



Relativistic MHD simulation (256^3, σ_0=30, u_A~5) by Camilia Demidem (Demidem+ 19, in

Relativistic magnetized turbulence



Fermi model for acceleration:

… particle interaction with random moving scattering centers…

… acceleration becomes s[illegible] coefficient: $t_{\rm acc} \sim \frac{t_{\rm int}}{\beta_u^2}$ **… what are $t_{\rm int}$? β_u ?**

… (quasilinear theory of) resonant wave-particle interactions in wave turbulence:

$t_{\rm int} \sim t_{\rm scatt}$, $\beta_u \sim \beta_A$… (Kennel + Engelmann 66… e.g. Schlickeiser 89)

… however, in (modern) anisotropic turbulence, resonances disappear…
(Chandran 00, Yan+Lazarian 02, Lynn+ 14, Demidem+ 19)

$$t_{\rm acc} \sim \frac{L_{\rm max}}{\beta_{\rm A}^2}$$

… for particle interacting with structures (~eddies) rather than waves:
(Lemoine 19, Demidem+ 19)

$$t_{\rm acc} \sim \frac{L_{\rm max}}{\langle \delta u^2 \rangle}$$

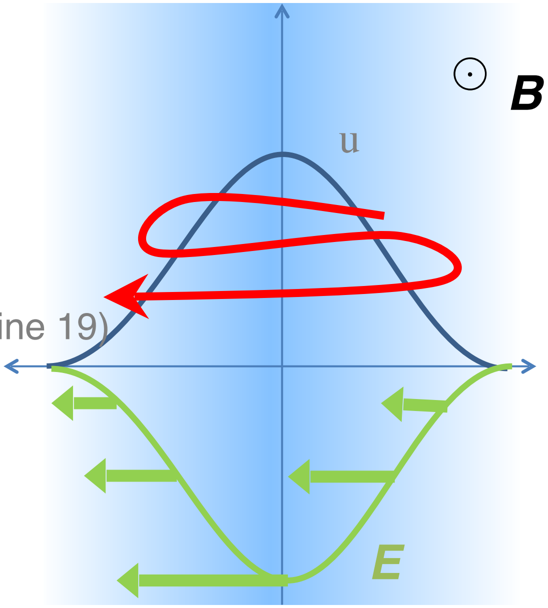
⇒ slow at (low) energies $r_g \ll L_{\rm max}$, fast at high energy…

… in recent PIC simulations:
(Zhdankin+17, Comisso+ Sironi 18,19, Wong+ 19

$$t_{\rm acc} \sim \frac{L_{\rm max}}{\langle \delta u^2 \rangle}$$

⇒ not efficient for leptons, but acceleration to close to confinement possible

Shear acceleration



particles with larger mean free paths explore larger gradient of ***E*** ⇒ faster acceleration…

Fermi shear acceleration:

… the electric field in a sheared velocity flow cannot be boosted away globally: particles gain energy by exploring the shear gradient…
(e.g. Rieger+Duffy 04, 06, 08, Liu+ 17, Rieger 19, Webb+ 18,19, Lemoine 19)

… acceleration timescale:

$$t_{\rm acc} \sim \frac{\Delta r^2}{t_{\rm scatt}} \frac{1}{\Delta u^2/\gamma_u^2}$$

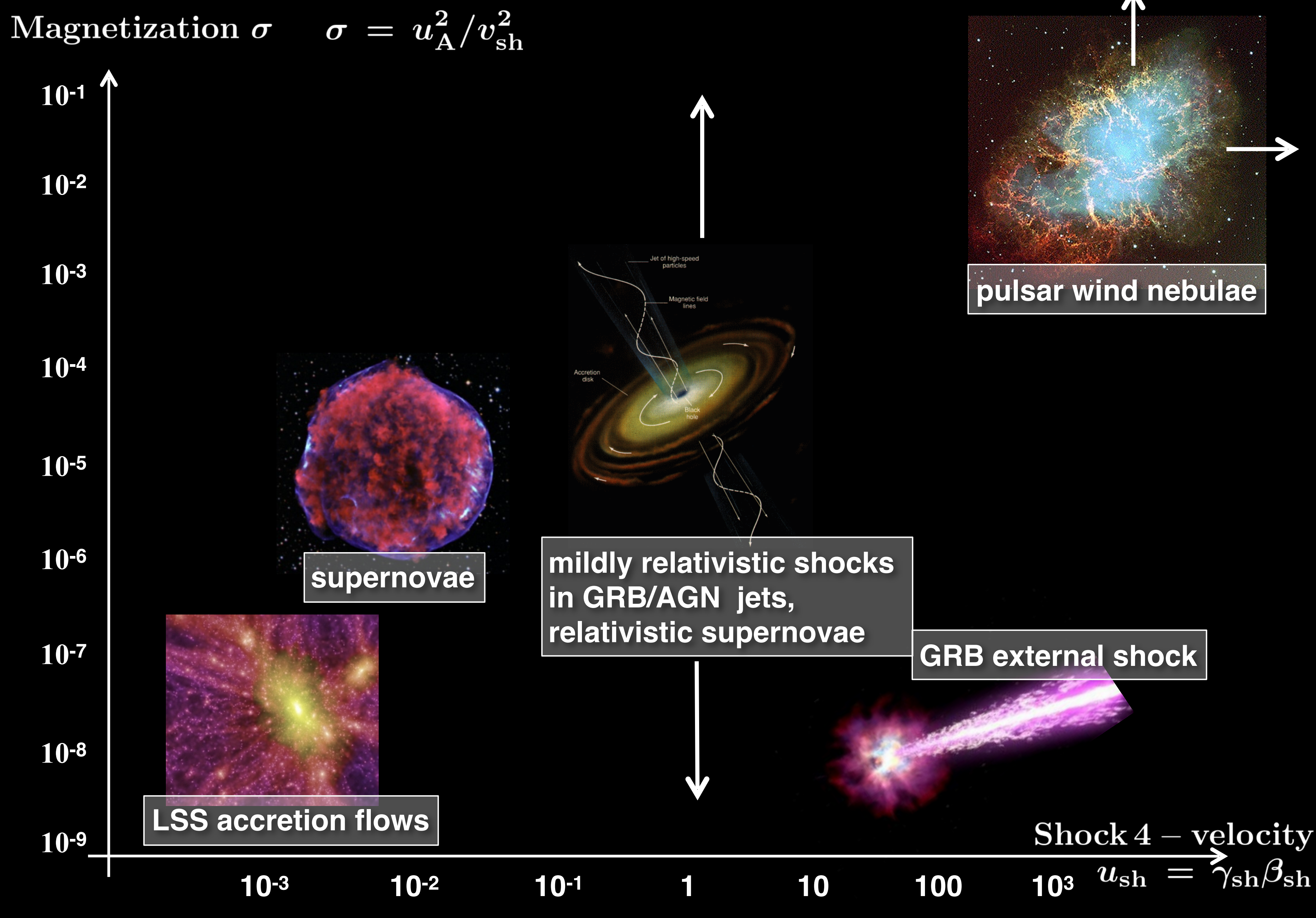
⇒ inefficient at low energies, since $t_{\rm scatt} \nearrow p$,
requires a seed population of particles

… $t_{\rm acc} \lesssim t_{\rm esc} \sim \Delta r^2 / t_{\rm scatt}$ if $\Delta u \gtrsim 1$: optimal for (mildly?) relativistic shear!

… if $L_{\rm max} \sim \Delta r$, at confinement energy $r_g \sim \Delta r$, ⇒ $t_{\rm scatt} \sim r_g \sim \Delta r$ ⇒ $t_{\rm acc} \sim r_g$
for $\Delta u \sim u \sim 1$

⇒ reacceleration of a population of energetic CRs in mildly relativistic shear may reach confinement energy… (radiative signatures? beyond test-particle?)

The (HE) astrophysical shock landscape



Particle acceleration at relativistic shock waves

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

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 $u_{sh} \gg 1$, and the shock is superluminal:** particles are advected away faster than they can scatter …
(Lemoine+ 06, Niemiec+ 06, Sironi + Spitkovsky 09, 11, Pelletier+ 09, Lemoine+Pelletier 10, Sironi+ 13)

Pulsar Wind Nebulae

… at small background magnetization, accelerated particles self-generate a microturbulence of large amplitude…

… but ***short scale ⇒ no Bohm…***
… slow acceleration: $t_{acc} \propto t_g^{\,2}$ … very slow at UHE!
Pelletier+ 09, Lemoine + Pelletier 10, Eichler + Pohl 11, Plotnikov+ 13, Sironi+ 13

Gamma-ray burst afterglows

5 20 100 1000 u_{sh}

The issue of pulsar wind nebulae…

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

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

mildly relativistic shock

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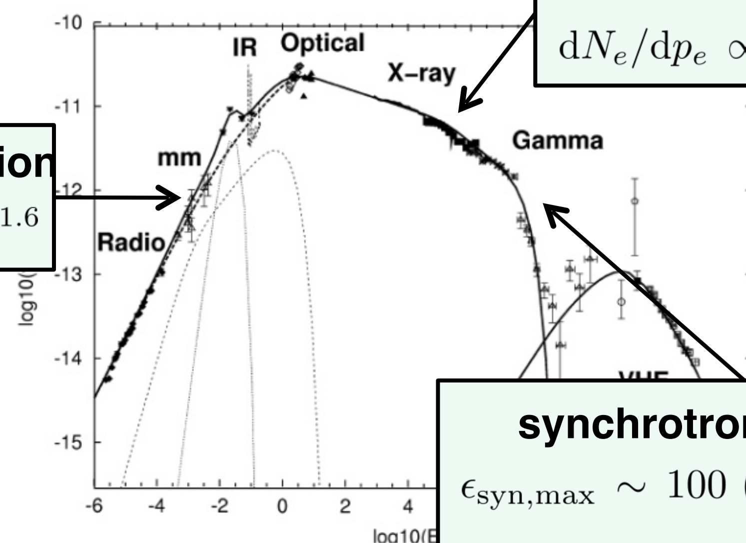
→ **theory may not be complete:** predicts no acceleration at pulsar wind termination shock, while SED suggests **Fermi-type acceleration at Bohm regime**:

(Atoyan & Aharonian 96)



pair distribution

$\mathrm{d}N_e/\mathrm{d}p_e \propto p_e^{-2.2}$

pair distribution

$\mathrm{d}N_e/\mathrm{d}p_e \propto p_e^{-1.6}$

synchrotron burn-off limit:

$$\epsilon_{\rm syn,max} \sim 100\ (t_{\rm acc}/t_{\rm g})^{-1}\ \mathrm{MeV}$$

$$\Rightarrow t_{\rm acc} \sim t_{\rm g}$$

→ **Nature realizes optimal acceleration… how?**

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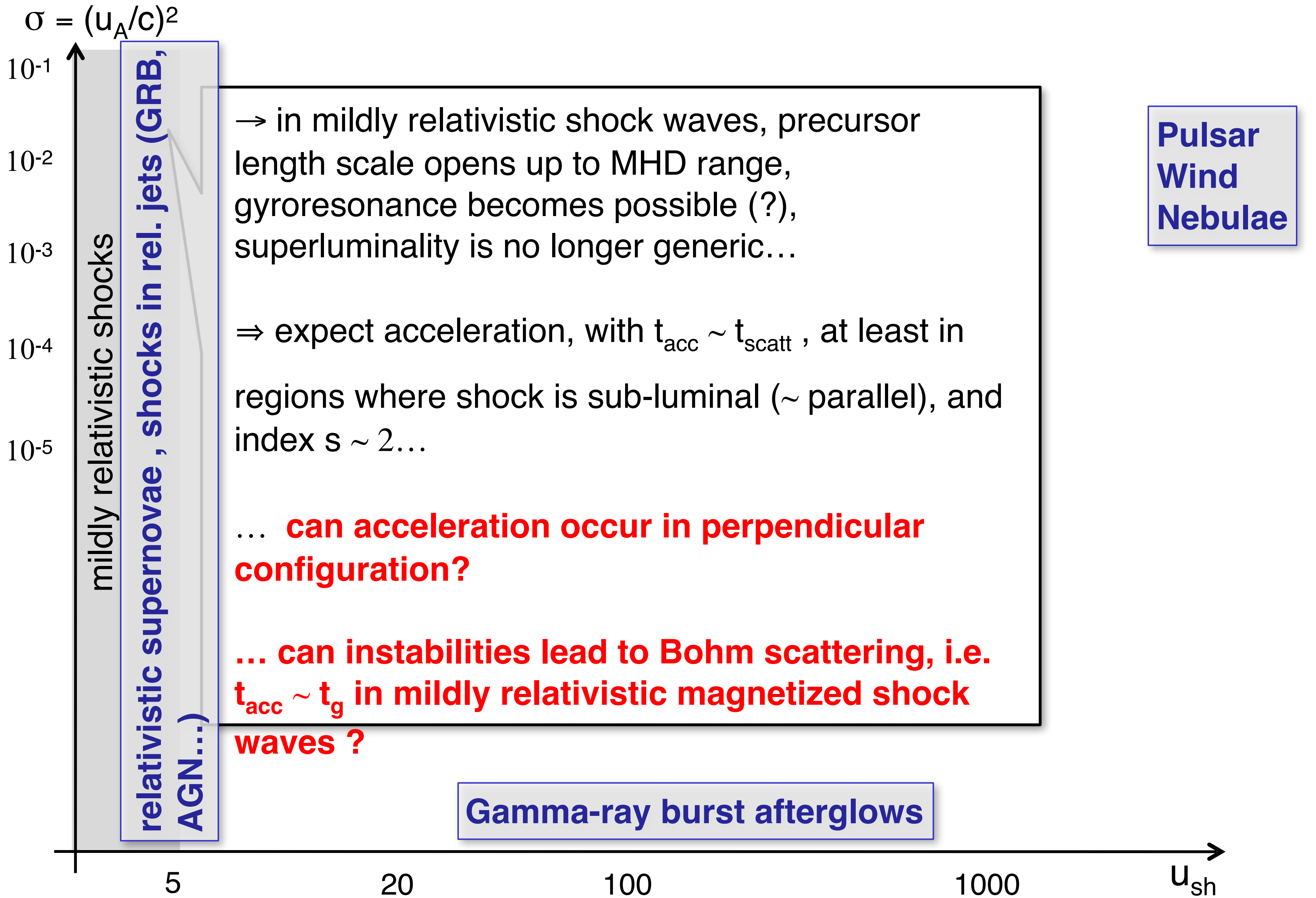
Pulsar Wind Nebulae

Gamma-ray burst afterglows

5 20 100 1000 u_{sh}

Mildly relativistic shocks… poorly explored but promising



Summary…

→ **a challenge of scales:** a complex problem on microscopic scales, needing extrapolation to macroscopic scales, in the midst of many astrophysical unknowns…

→ **Top-down, insights from phenomenology:**

$$L_{\rm tot} \gtrsim 10^{45}\,{\rm erg/s}\ \ldots \left(\frac{t_{\rm acc}}{t_{\rm g}}\right)^2 \left(\frac{E/Z}{10^{20}\,{\rm eV}}\right)^2$$

… powerful sources, likely relativistic, w/ strong dependence on Z…

→ **Bottom-up, from microphysics of acceleration upward:**

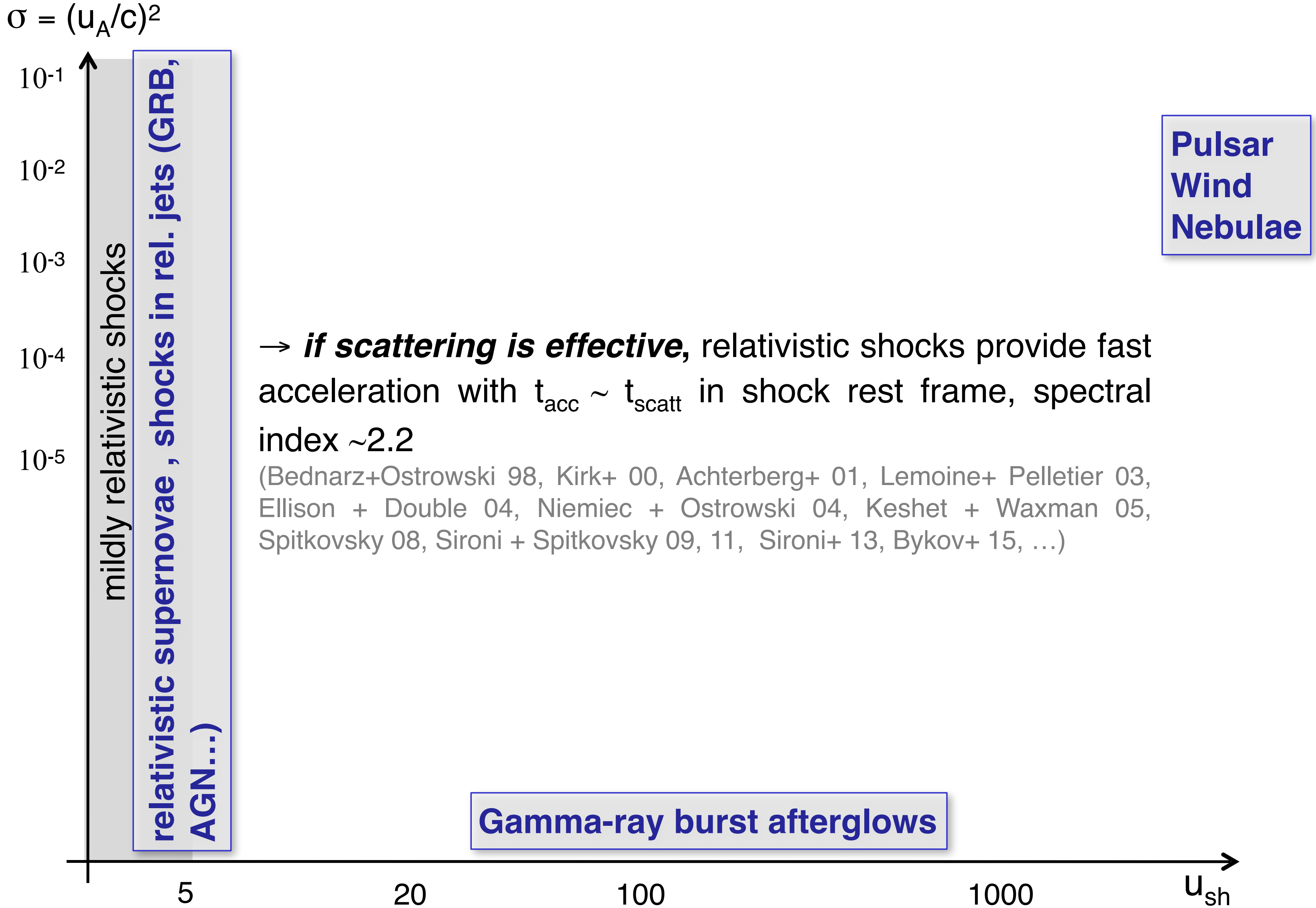
… acceleration to UHE favors Fermi-type processes in mildly relativistic flows of substantial magnetization, e.g. shocks, turbulence or shear acceleration…

→ **an interesting question:**

… are UHECRs accelerated all the way up in one source, or accelerated in one, then re-accelerated in others?

one source: the perfect accelerator / many sources: radiative

Particle acceleration at relativistic shock waves



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

(Bednarz+Ostrowski 98, Kirk+ 00, Achterberg+ 01, Lemoine+ Pelletier 03, Ellison + Double 04, Niemiec + Ostrowski 04, Keshet + Waxman 05, Spitkovsky 08, Sironi + Spitkovsky 09, 11, Sironi+ 13, Bykov+ 15, …)