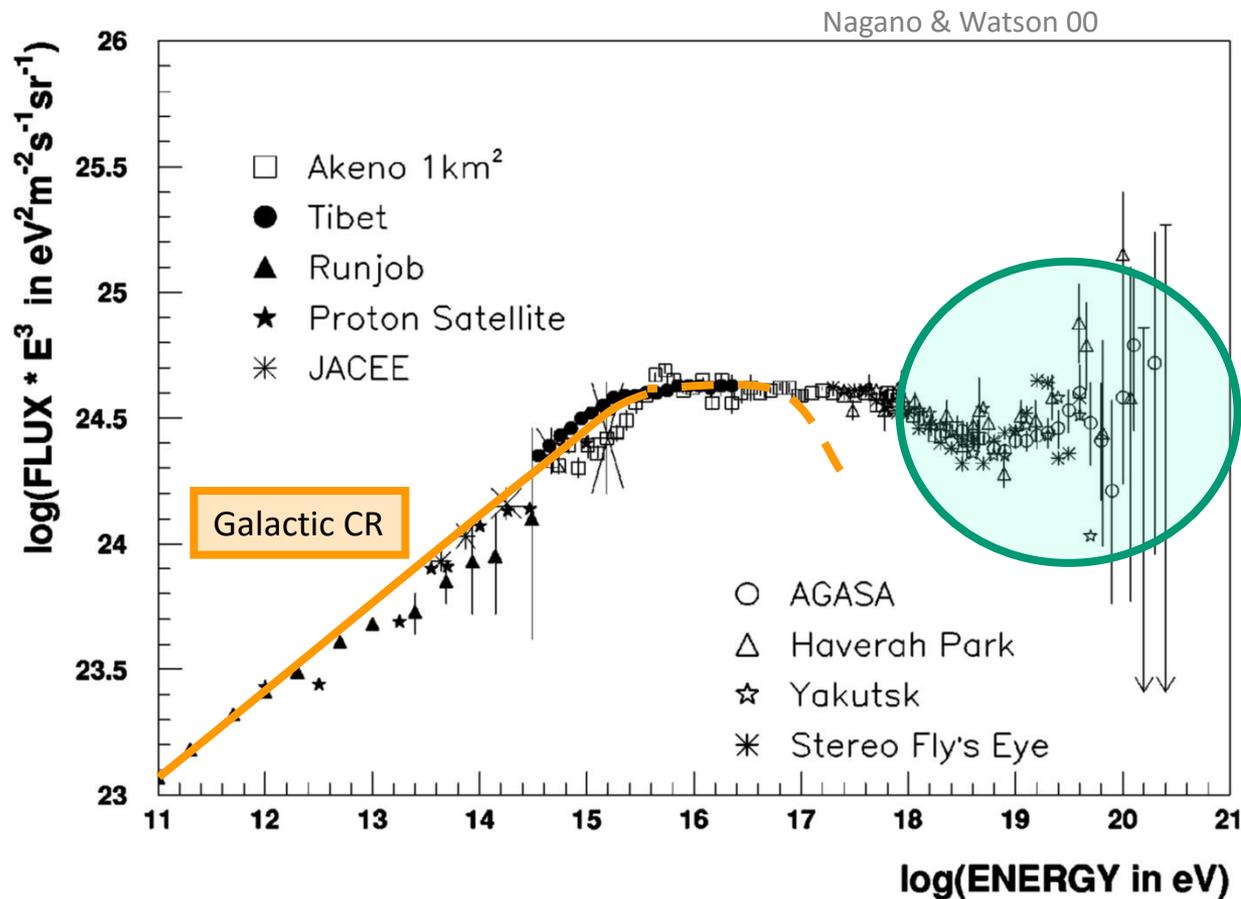


Particle acceleration to extreme rigidities

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→ *chemical composition, or rigidity $E/(eZ)$ at a given energy, controls the phenomenology at ultra-high energies:*

(1) sources of 10^{20} V are much more extreme than sources of 10^{18} V particles:

... e.g., a few candidate sources for 10^{20} eV protons vs *dozens* of candidate sources of 10^{20} eV iron...

(2) light particles leave stronger signatures of their sources:

... e.g., anisotropies at ultra-high energies with deflections of a few deg, vs large deflections for iron-like primaries

... e.g., secondary photons and neutrino signals

→ Outline:

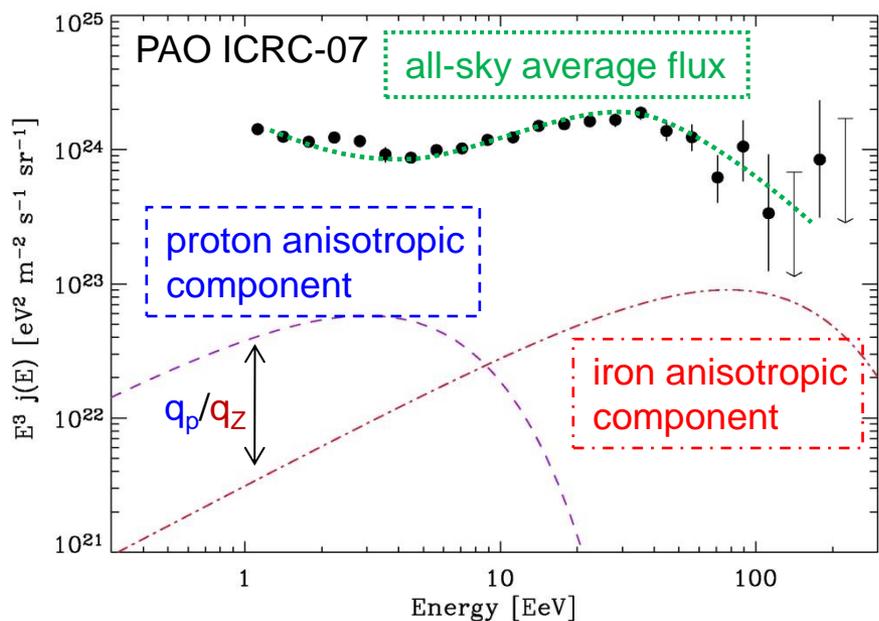
1. Phenomenology: anisotropies vs chemical composition at UHE
2. Theory: (relativistic shock) acceleration to ultra-high rigidities



Anisotropies vs heavy composition at UHE

→ if anisotropic signal $>E$ is due to heavy nuclei, then one should detect a stronger anisotropy signal associated with protons of same magnetic rigidity at $>E/Z$ eV...

argument independent of intervening magnetic fields... (M.L. & Waxman 09)



- injection shaped by rigidity, $s=2$:
 $E_{\text{max}} \propto Z$
- composition: $q_p/q_{\text{Fe}} = 1/0.06$ as in sources of GCR

→ signal-to-noise at low energy vs that at high energy:

$$S/N|_p (> E/Z) \simeq \underbrace{\alpha_{\text{loss},Z}}_{> 1} \underbrace{Z^{-0.85}}_{< 1} \underbrace{\frac{N_p}{N_Z}}_{\gg 1} S/N|_Z (> E)$$

$\gg 1$

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→ if anisotropies are seen at $>E$, say >50 EeV, but not at any E/Z , with $Z \sim 6-26$, then the following assertions cannot hold simultaneously:

- (1) the anisotropy signal at $>E$ is real (=not a statistical accident)
- (2) the composition at energies $>E$ is heavy: O, Si, Fe...
- (3) the sources have a "reasonable" metallicity $N(Z>6)/N(Z=1) \ll 1$

⇒ if anisotropies are not statistical accidents, there exist GZK protons, or the source metallicity is extraordinarily large...

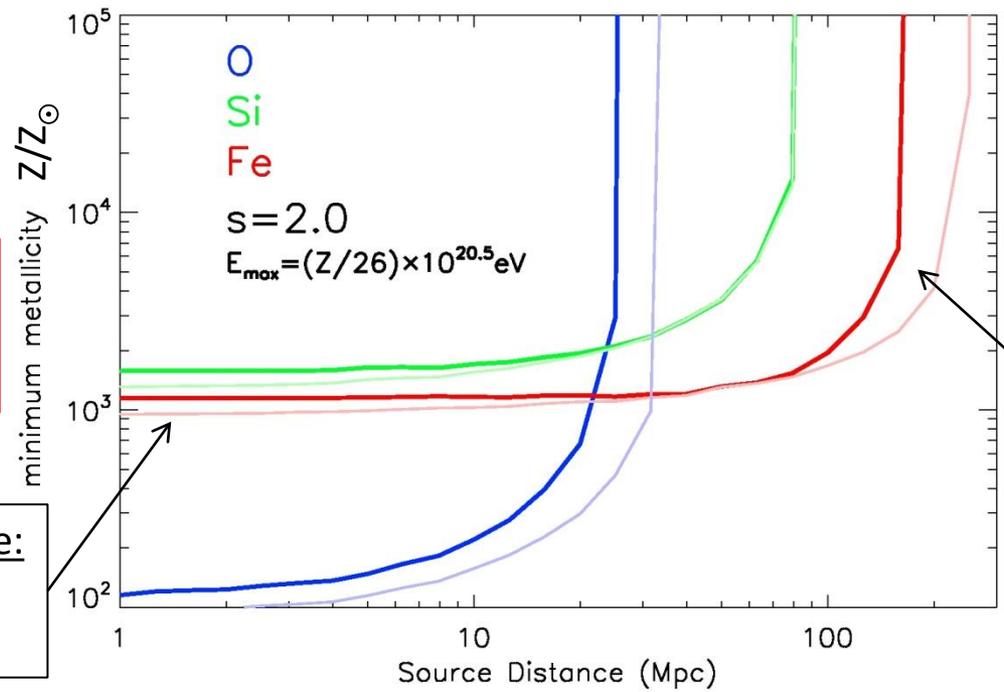
*NB: does not depend on spectral index of injection spectrum...
only assumption: particle spectra are shaped by rigidity...*



Anisotropies vs heavy composition at UHE

→ taking into account photodisintegration, nuclei with energy $>2E$ produce protons with energy $>E/Z$, which add up to the anisotropy signal... Liu+ 13

$$S/N|_p (> E/Z) \simeq Z^{-0.85} A \left[\frac{M_p}{M_Z} + 2^{1-s} f_{\text{photodis.}} (> 2E) \right] S/N|_Z (> E)$$



Liu+ 13

minimum Z/Z_{solar} to ensure: $S/N_p (E/Z) < S/N_Z (E)$

close-by source: no photo-dis. $Z \rightarrow p$

remote source: secondary p's from photo-dis. of $>2E$ nuclei produce anisotropies at E/Z

→ anisotropies at E could thus be produced by heavy nuclei **only** if the source metallicity:
 if Fe at UHE: $Z \gtrsim 1000 Z_{\odot}$; if Si at UHE: $Z \gtrsim 1600 Z_{\odot}$; if O at UHE: $Z \gtrsim 100 Z_{\odot}$
 ... sources with such high metallicities?

Acceleration to UHE in low luminosity GRBs



→ low luminosity GRBs, also associated to X-ray flashes, are interpreted as trans-relativistic supernovae with ejecta velocity $\gamma\beta \sim 1$... the missing link to standard supernovae?
possible sources of UHE nuclei (Wang et al. 08, Chakaborty et al. 11, Liu & Wang 12, Budnik et al. 08)

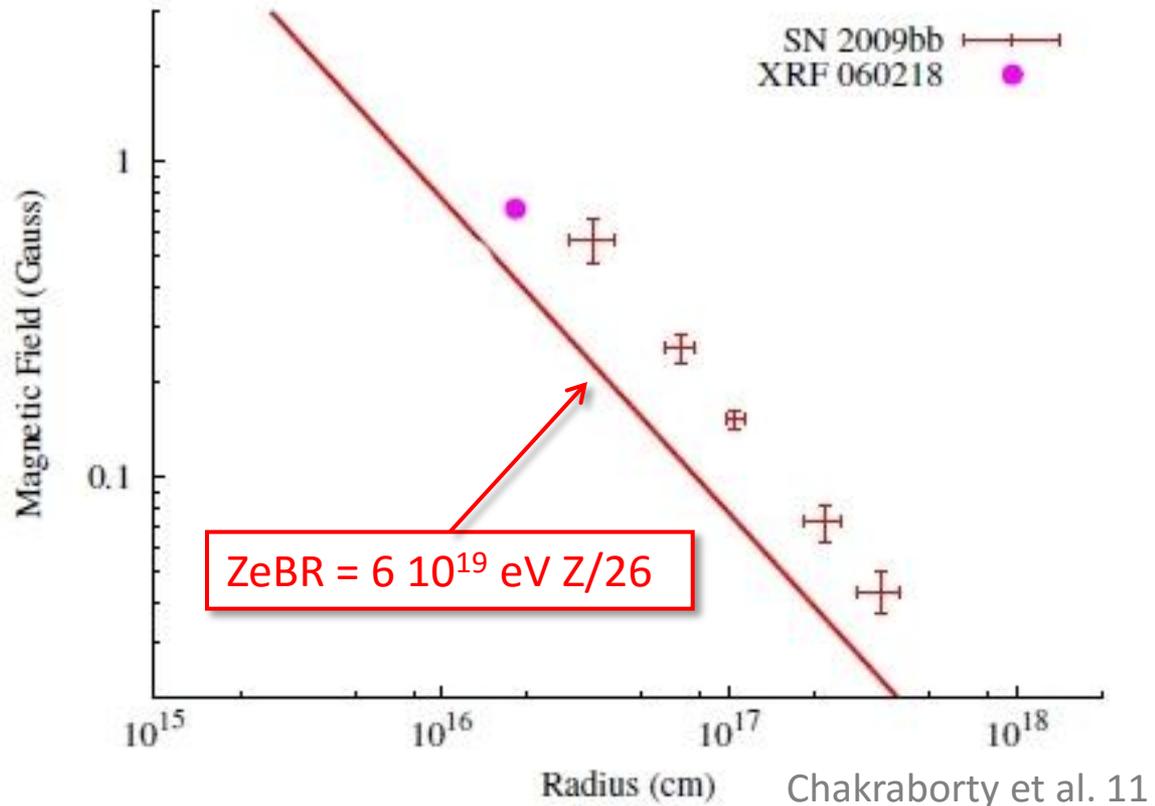
energy budget OK: $\dot{n}_{\text{LLGRB}} \sim 10^{-7} - 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1}$, $E \sim 10^{50} \text{ erg}$

maximal energy: $E_{\text{max}} \sim Z \times 10^{18} - 10^{19} \text{ eV}$ ⇒ heavy nuclei at UHE

Note:

Hillas bound assumes scattering in a Bohm regime!

... Bohm regime: $t_{\text{scatt}} \simeq t_g$



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)

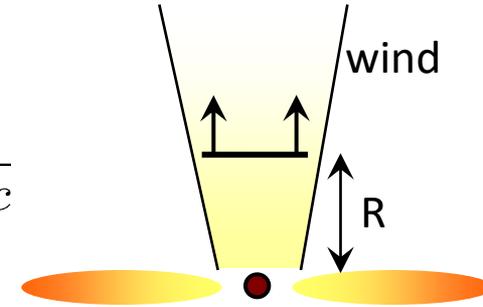
A generic case: acceleration in an outflow

→ acceleration timescale (comoving frame): $t_{\text{acc}} = \mathcal{A} t_g$

$\mathcal{A} \gg 1$, $\mathcal{A} \sim 1$ at most:

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

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



→ maximal energy: $t_{\text{acc}} \leq t_{\text{dyn}} \Rightarrow E_{\text{obs}} \leq \mathcal{A}^{-1} Z e B R / \beta$

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

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

10^{45} ergs/s is robust:

for $\beta \rightarrow 0$, $\mathcal{A}^2 \beta^3 \geq 1/\beta \geq 1$

for $\Theta \Gamma \rightarrow 0$, $L_{\text{tot}} \geq 1.2 \times 10^{45} \mathcal{A} \beta \frac{\kappa}{r_{\text{LC}}} Z^{-2} E_{20}^2 \text{ erg/s}$

Lower limit on luminosity of the source:

$$L_{\text{tot}} > 10^{45} Z^{-2} \text{ erg/s}$$

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

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

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

gamma-ray bursts: $L_{\text{bol}} \sim 10^{52}$ ergs/s

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

Extreme acceleration, but also high output



Energy output of a source:

→ to match the flux above 10^{19} eV, $\dot{u}_{\text{UHECR}} \sim 10^{44}$ erg/Mpc³/yr (Katz+ 10)

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

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

e.g.:

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

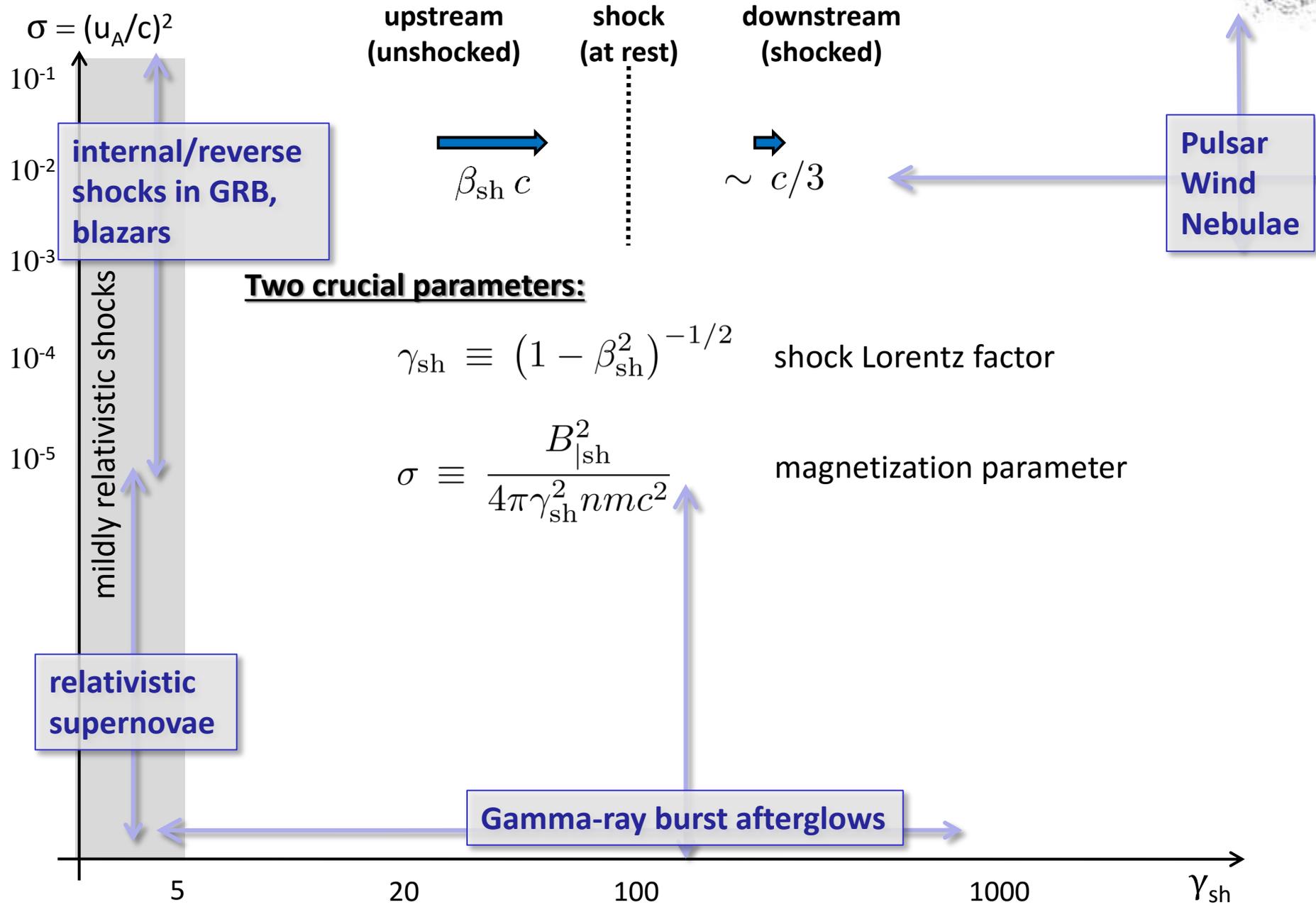
→ for the whole radio-galaxy population, $nL \sim 3 \cdot 10^{47}$ erg/Mpc³/yr, typically from sources with $L \sim 10^{43}$ erg/s...

... if injecting CNO to match flux at 10^{19} eV and if metallicity is \sim solar, requires an overall efficiency in high energy CR of a few percent!

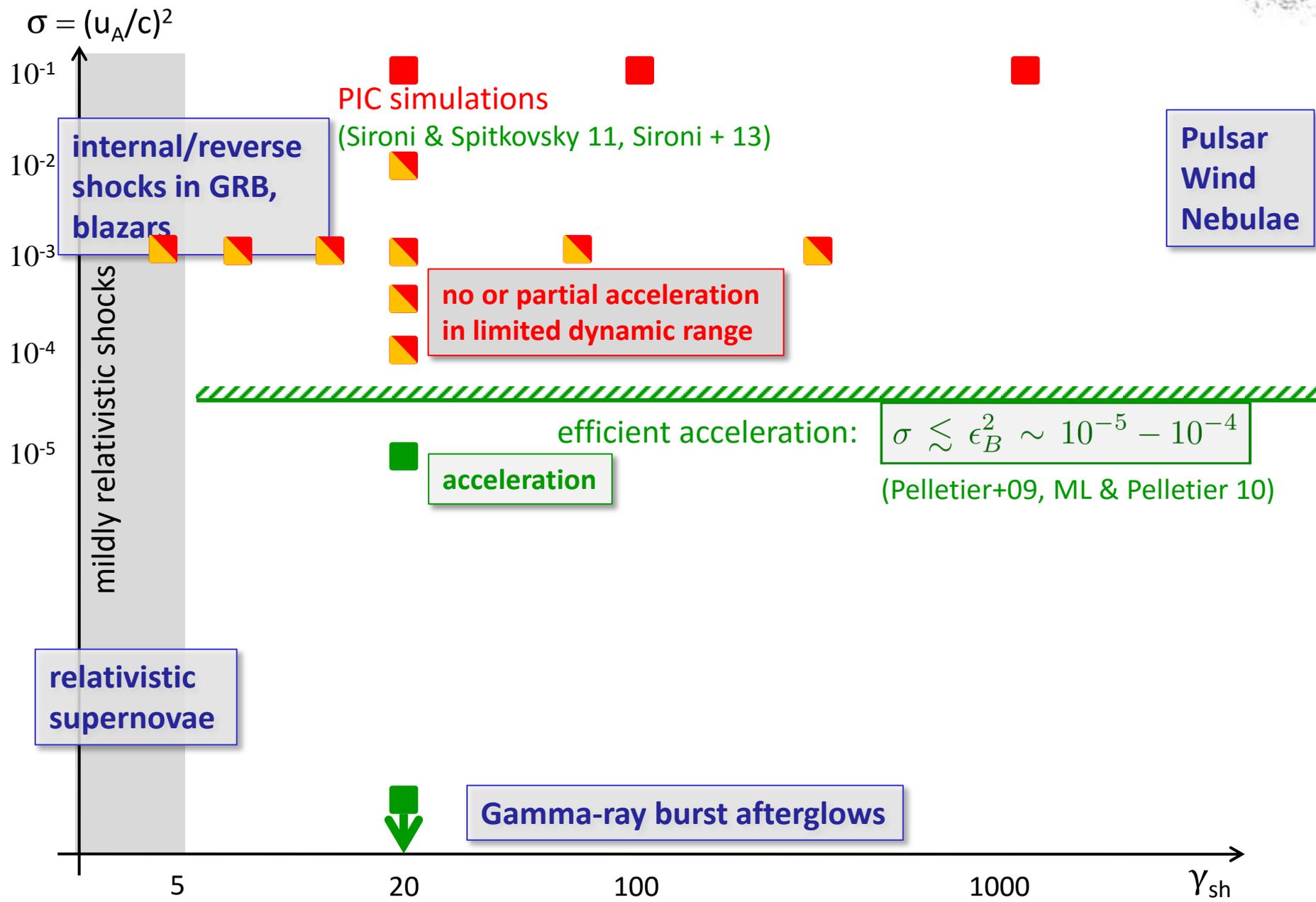
if one wants nuclei at $>E$ to circumvent luminosity bound, accounting for the protons accelerated to $>E/Z$ requires an energy input higher by M_p/M_Z ...

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

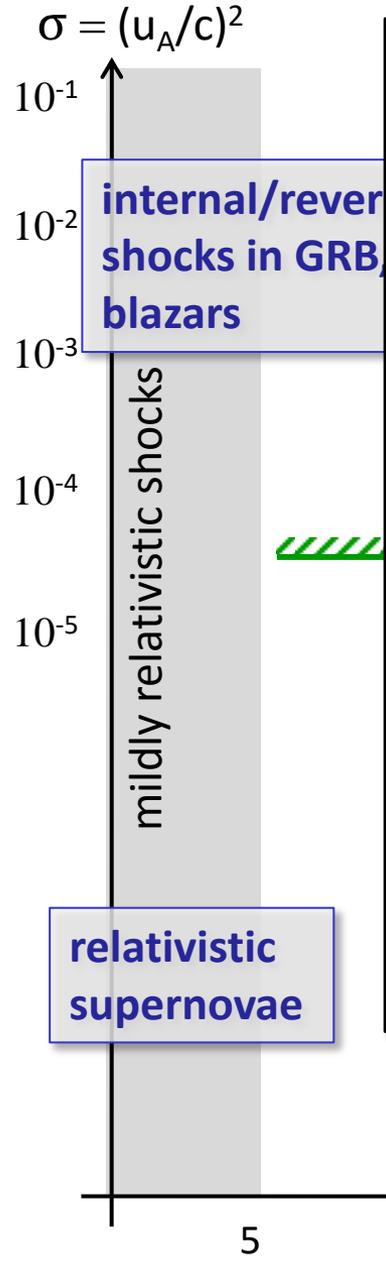
Particle acceleration in relativistic shocks



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Particle acceleration in relativistic shocks



→ 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)

→ slow scattering in small-scale turbulence:

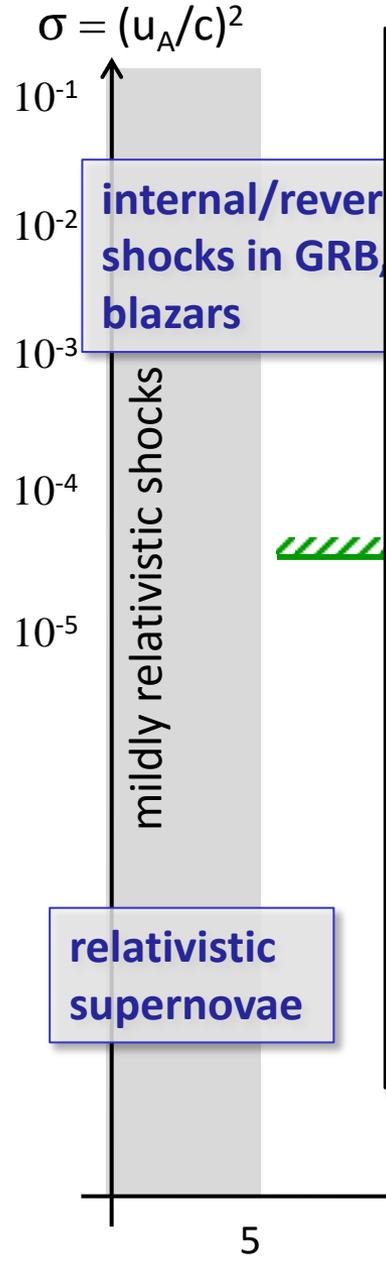
$$E_{\max} \sim 10^{16} - 10^{17} Z \text{ eV}$$

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

Pulsar Wind Nebulae

Gamma-ray burst afterglows

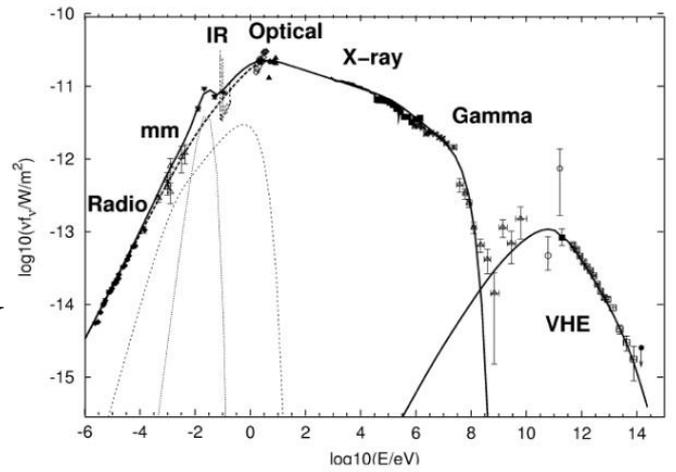
Particle acceleration in relativistic shocks



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

synchrotron limit:
 $\epsilon_{\text{syn,max}} \sim 100 \mathcal{A}^{-1} \text{ MeV}$
 $\Rightarrow \mathcal{A} \sim 1$

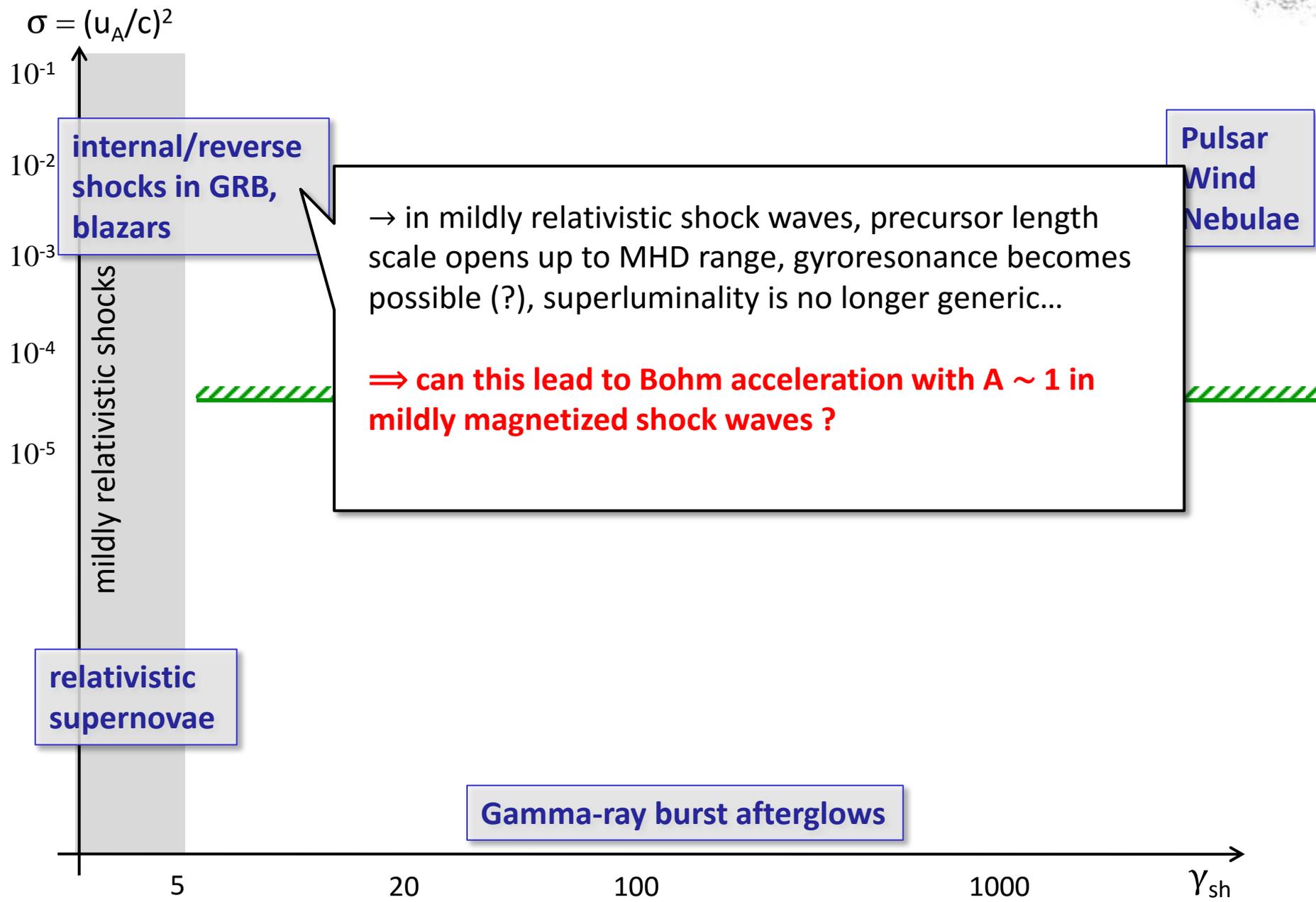
→ if extrapolated to more powerful pulsars (= few msec at birth), acceleration + confinement could proceed up to 10^{20} eV protons ...
 (ML+15)



Pulsar Wind Nebulae

Gamma-ray burst afterglows

Particle acceleration in relativistic shocks





Acceleration (theory):

→ $L_B \gtrsim 10^{45} Z^{-2} A^2 \dots \text{erg/s}$ to accelerate up to 10^{20}eV ($A = t_{\text{acc}}/t_L$)

→ p shock acceleration: either mildly relativistic shocks (GRB internal shocks, blazar internal shocks, trans-relativistic supernovae) or magnetized relativistic shocks with extra dissipation?

Phenomenology depends on the composition... a crucial issue to be solved.

→ if anisotropies exist at GZK energies but not at GZK/Z energies:
⇒ strongly suggests that anisotropies are produced by protons

Search for the origin of ultra-high rigidity cosmic rays...