Summary - conclusions

Acceleration (theory):

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

→ p shock acceleration: either mildly relativistic shocks (GRB internal shocks, blazar internal shocks, trans-relativistic supernovae) or magnetized relativistic shocks with dissipation (in young msec pulsars)

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…

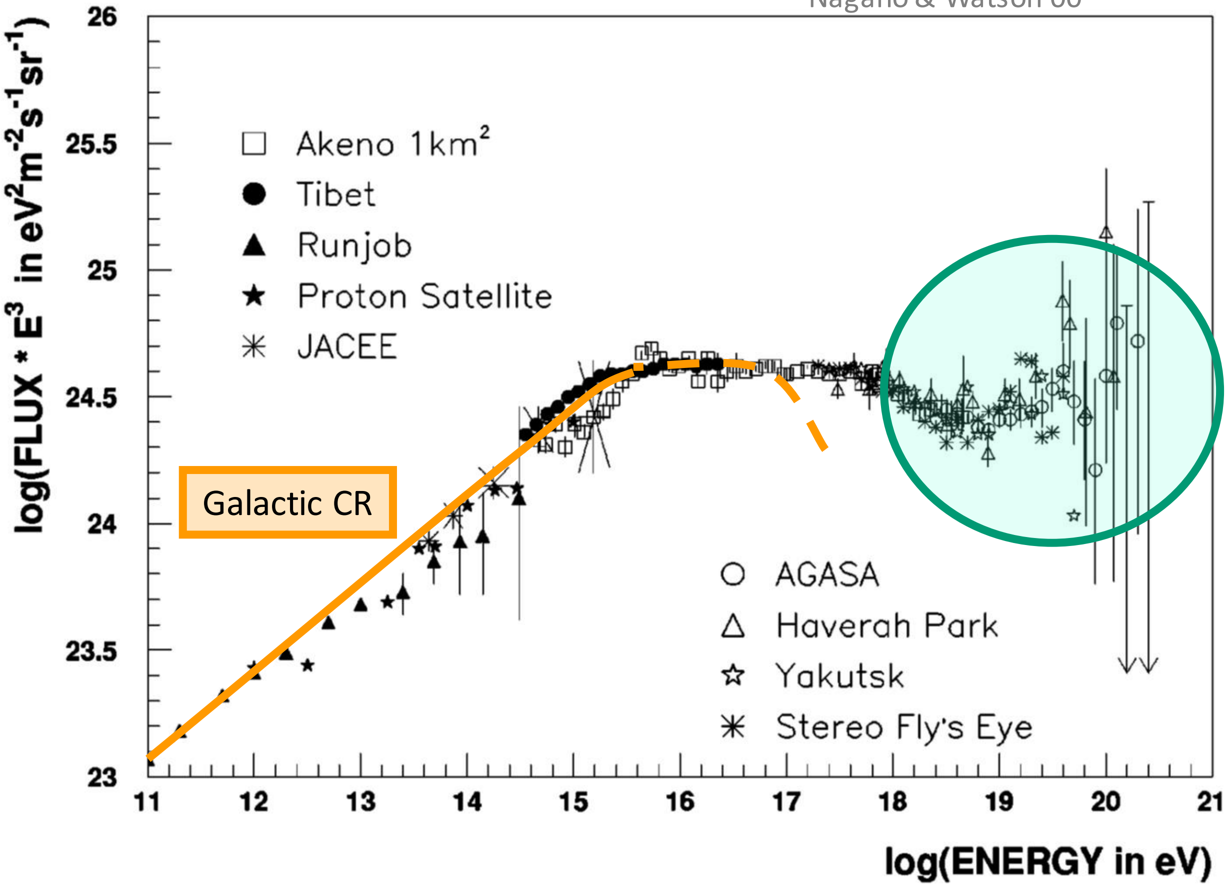
Particle acceleration to extreme rigidities

Martin Lemoine

Institut d'Astrophysique de Paris

CNRS, Université Pierre & Marie Curie

Nagano & Watson 00



Galactic CR

Motivations

→ 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

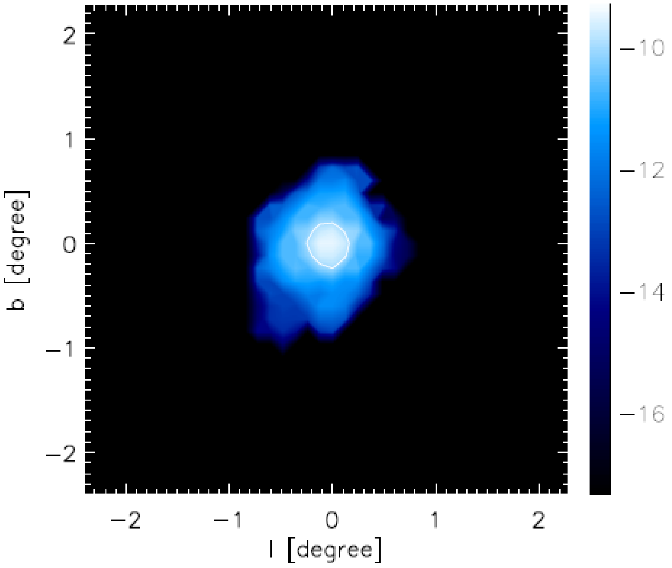
… e.g., secondary photons and neutrino signals

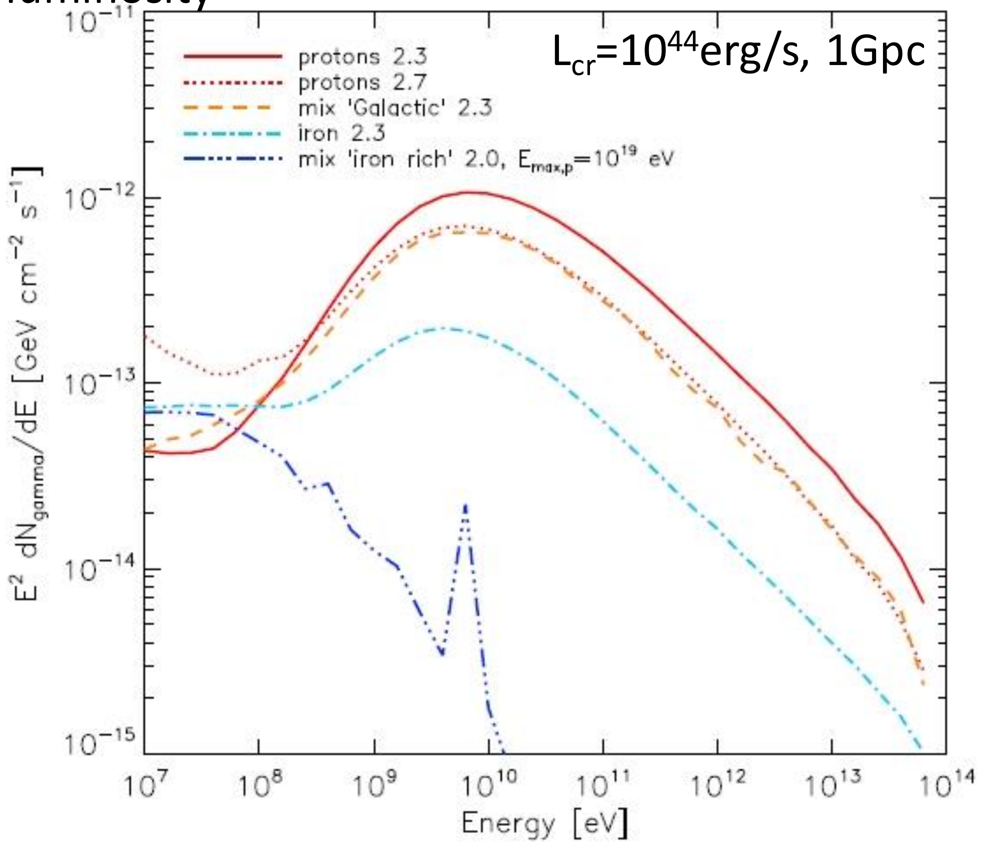
GeV photon halo from a UHECR source

→ a possible signature of UHECR acceleration: a gamma-ray halo / secondary flux from a powerful source, from synchrotron radiation of secondary electrons (Aharonian 02, Gabici & Aharonian 05, Kotera+ 11):

N + $\gamma_{CMB/IRB}$ → e.m. cascade down to GeV-TeV
electron synchrotron to GeV

→ detection with CTA requires a large CR luminosity of protons above 10^{19}eV:
$L_{cr} \sim 10^{46}$ erg/s for a distance 1Gpc...





see also Essey+ 10,11, Murase+ 12

Motivations

→ ***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:

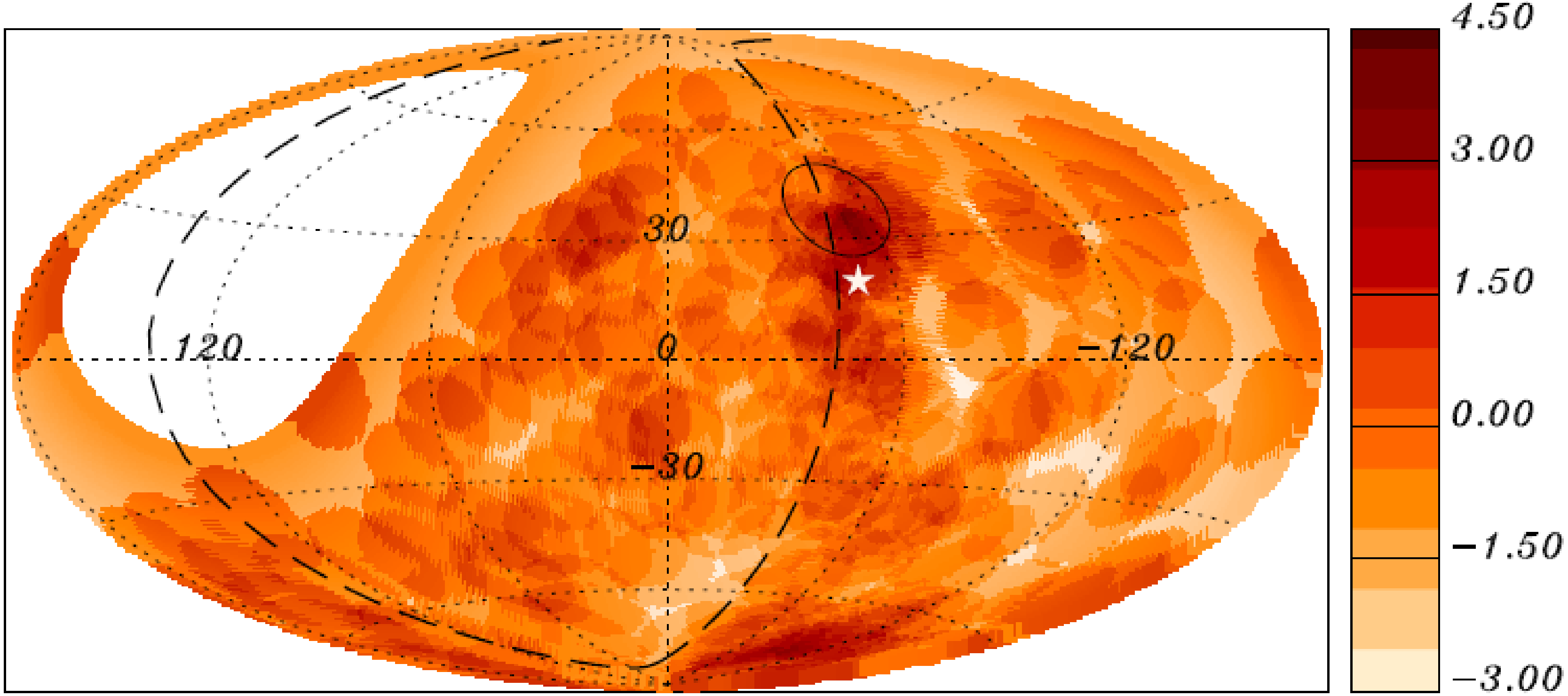
… e.g., anisotropies at ultra-high energies with deflections of a few deg, vs large deflections for iron-like primaries

… 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**

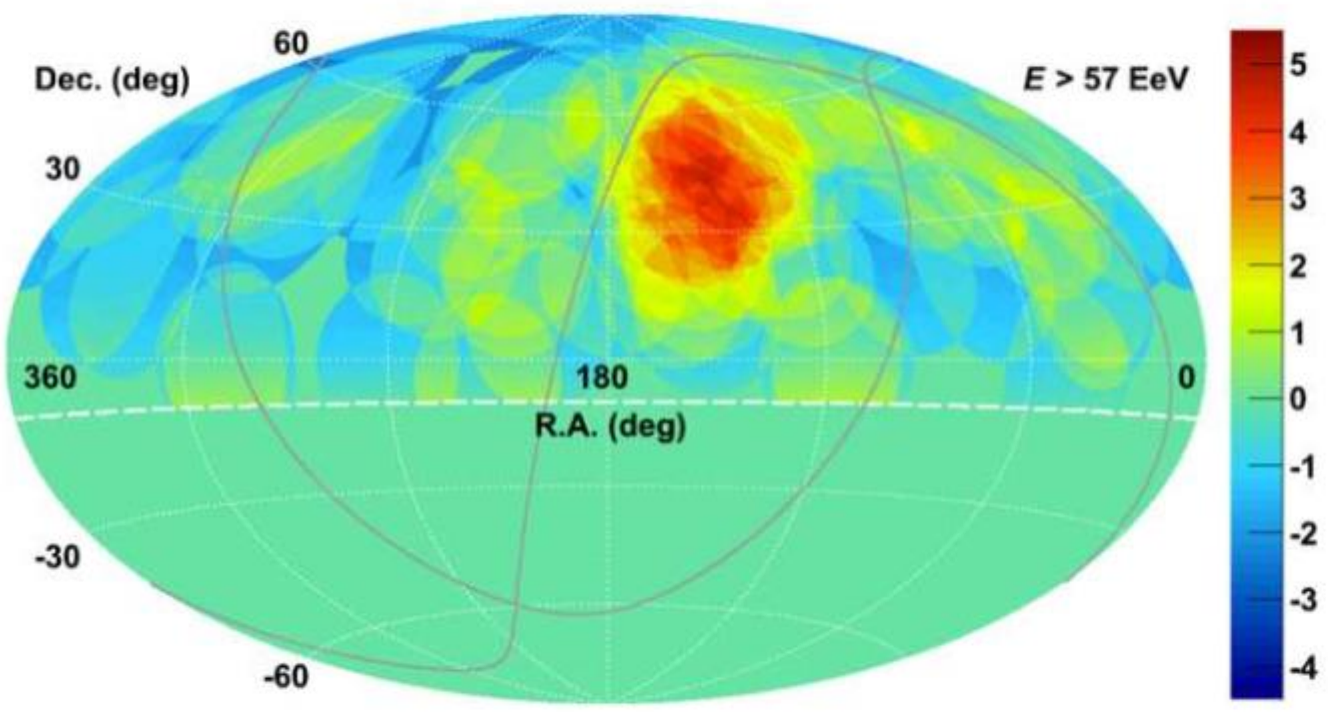
Anisotropies



Pierre Auger Observatory 2015 anisotropy map – Li-Ma excess significance:

… no significant departure from anisotropy below 1% chance probability

Anisotropies



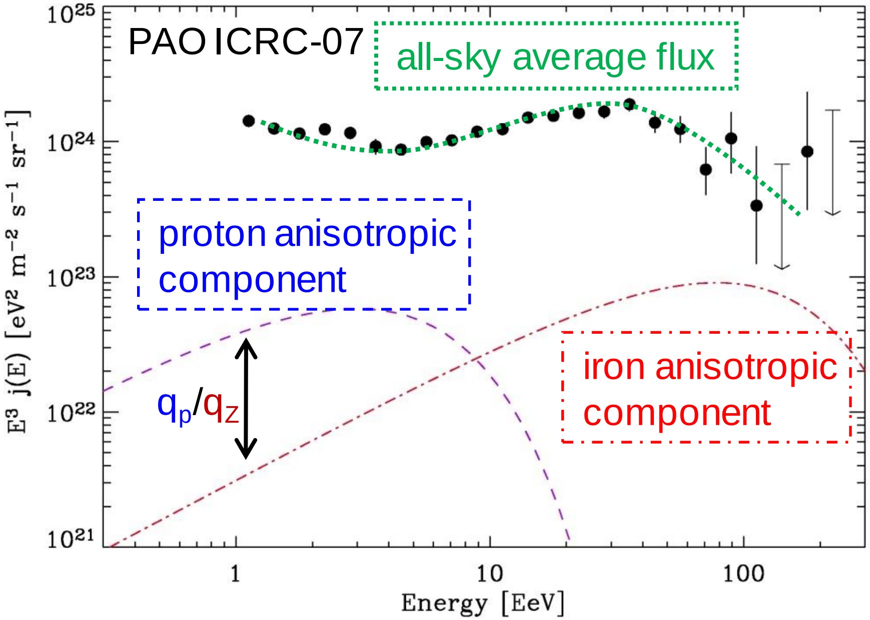
Telescope Array 2014 anisotropy map – Li-Ma excess significance:

… a hot-spot seen with a (post-trial) significance of 3.4 sigma…

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:
  $E_{max} \propto Z$
- composition: $q_p/q_{Fe} = 1/0.06$ as in sources of GCR

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

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

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)

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

→ if anisotropies are seen at >E, say >50 EeV, but not at any E/Z, with Z ~ 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...

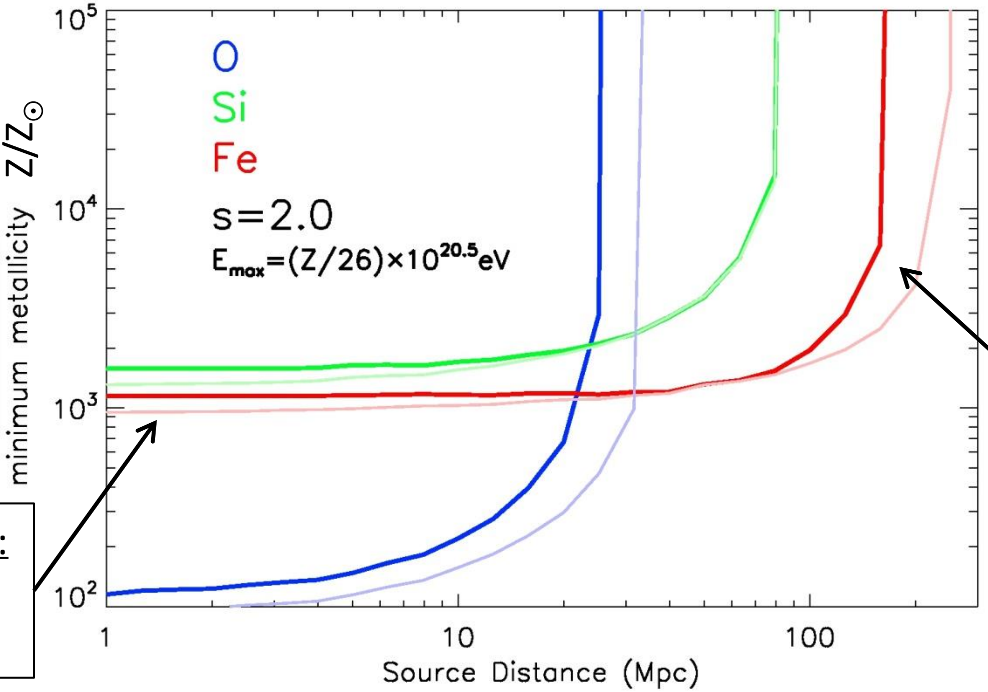
(3) the sources have a "reasonable" metallicity N(Z>6)/N(Z=1) $\ll 1$

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

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

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



Liu+ 13

minimum Z/Z$_{solar}$ to ensure: S/N$_p$ (E/Z) < S/N$_Z$(E)

close-by source:
no photo-dis.
Z → p

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

→ to assume that the anisotropies are produced by heavy nuclei thus requires a 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

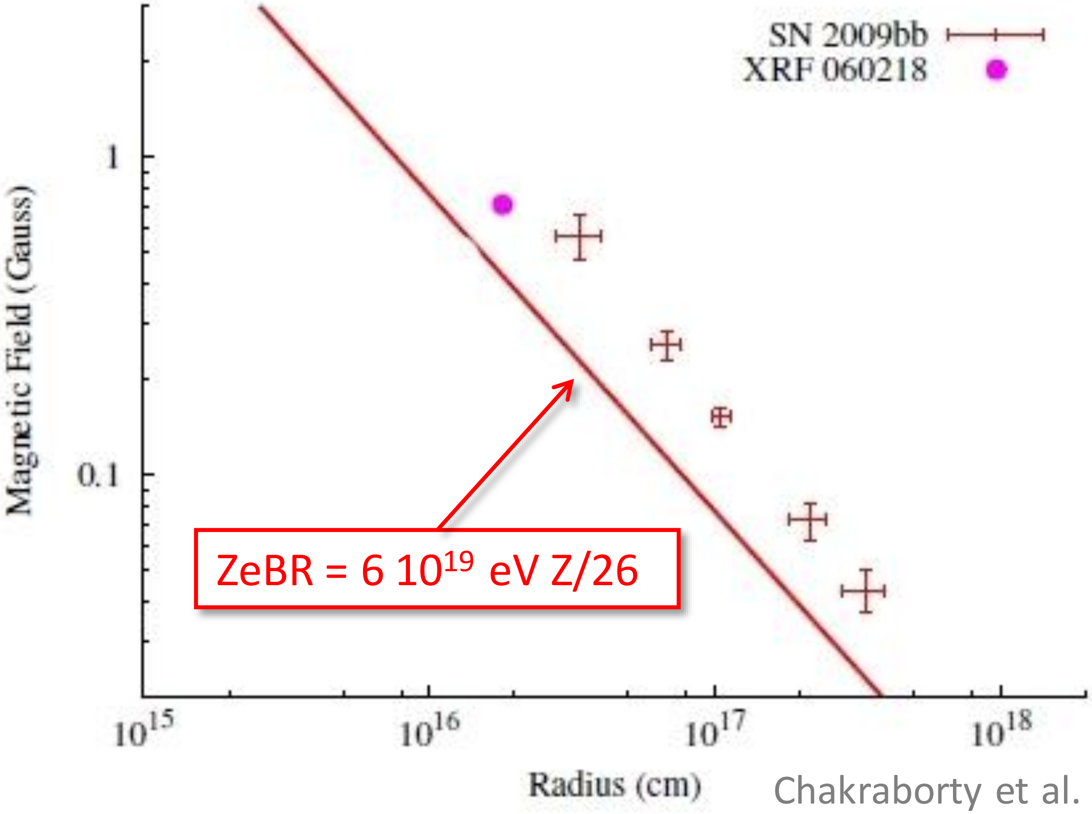
→ low luminosity GRBs, also associated to X-ray flashes, are interpreted as trans-relativistic supernovae with ejecta velocity $\gamma\beta \sim 1$ … the missing link to standard supernovae? possible sources of UHE nuclei (Wang et al. 08,Chakaborty et al. 11, Liu & Wang 12, Budnik et al. 08)

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

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

Note:

Hillas bound assumes scatering in a Bohm regime!



ZeBR = 6 10^{19} eV Z/26

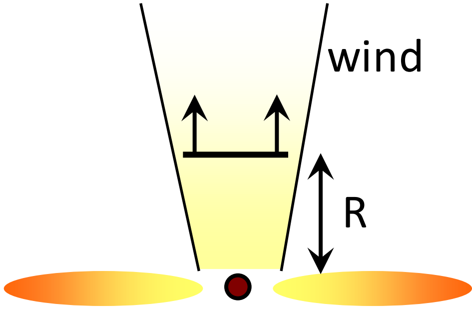
Chakraborty et al. 11

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): $t_{\rm acc} = \mathcal{A}\ t_{\rm g}$



→ **A >> 1 in most acceleration scenarios:**

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

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

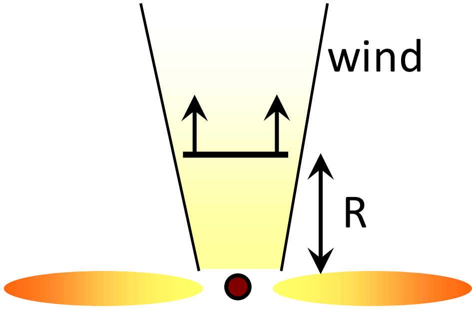
Acceleration – a luminosity bound

A generic case: 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 ~ g/$\beta_{\rm sh}^2$ with g > 1



→ 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 β → 0, $\mathcal{A}^2\beta^3 \ge 1/\beta \ge 1$

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

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

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

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

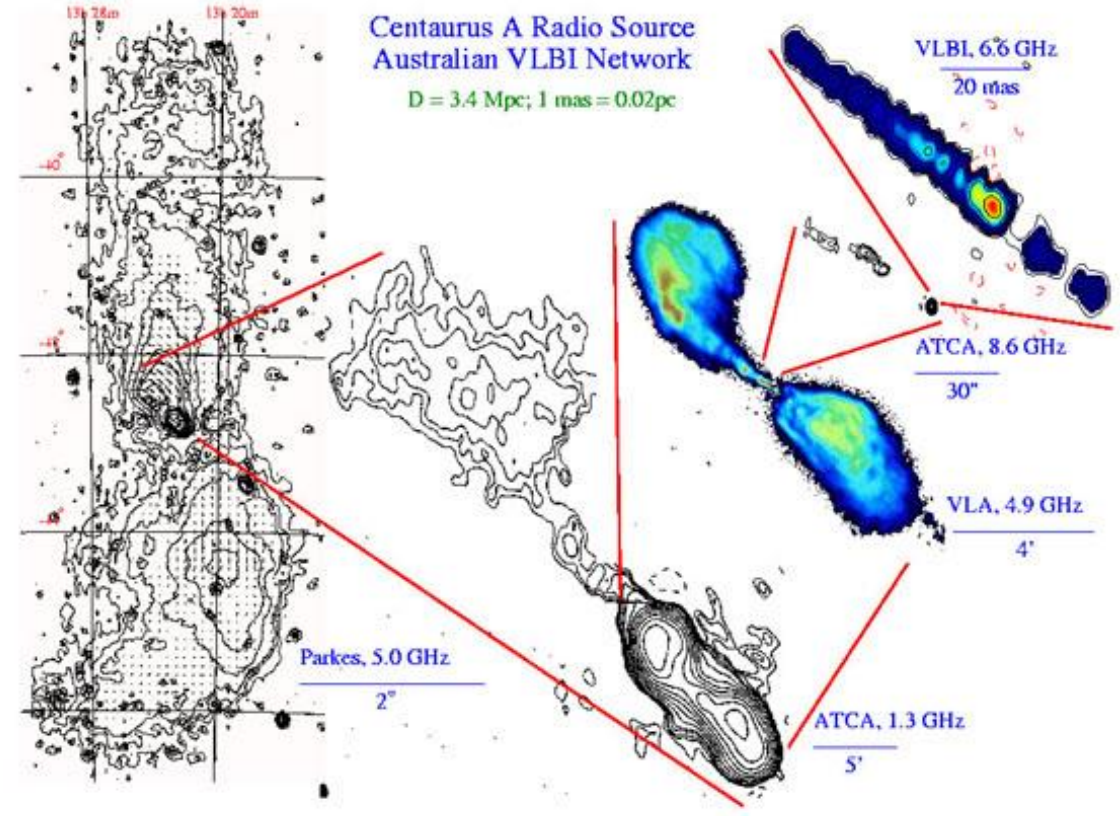
high luminosity AGN: $L_{\rm bol} \sim 10^{46}$-10^{48} ergs/s

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

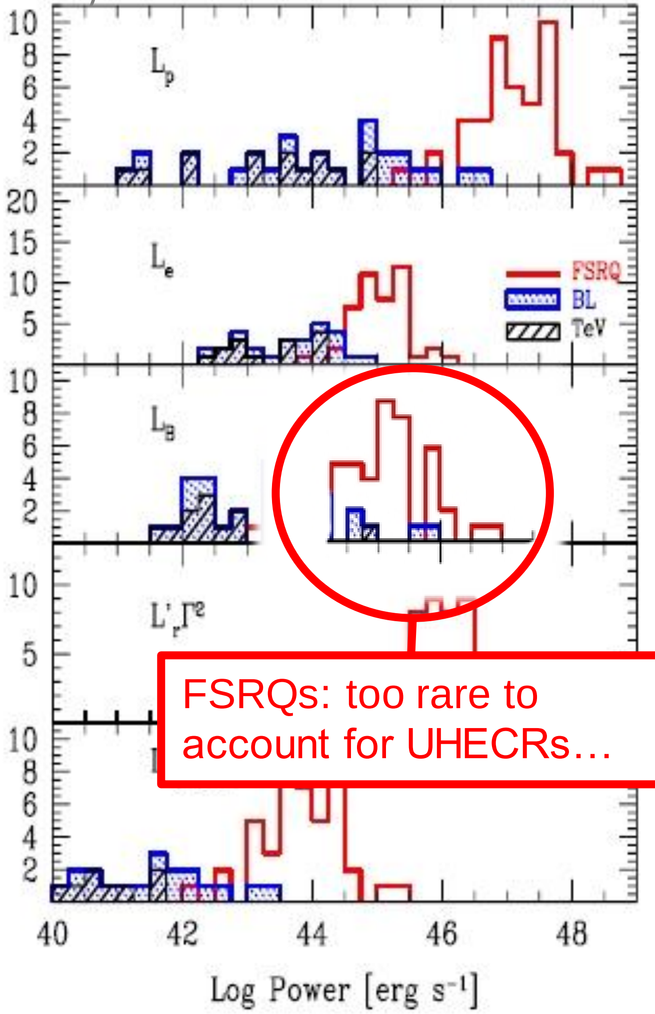
⇒ only most powerful AGN jets, GRBs or young pulsars for UHE protons…
… many (many) others for heavy nuclei?

Centaurus - a close FR I radio-galaxy

Centaurus A: (Romero et al. 96, Farrar & Piran 00, Gorbunov et al. 08, Dermer et al. 08, Hardcastle et al. 09, O'Sullivan et al. 09)



Celotti & Ghisellini 08



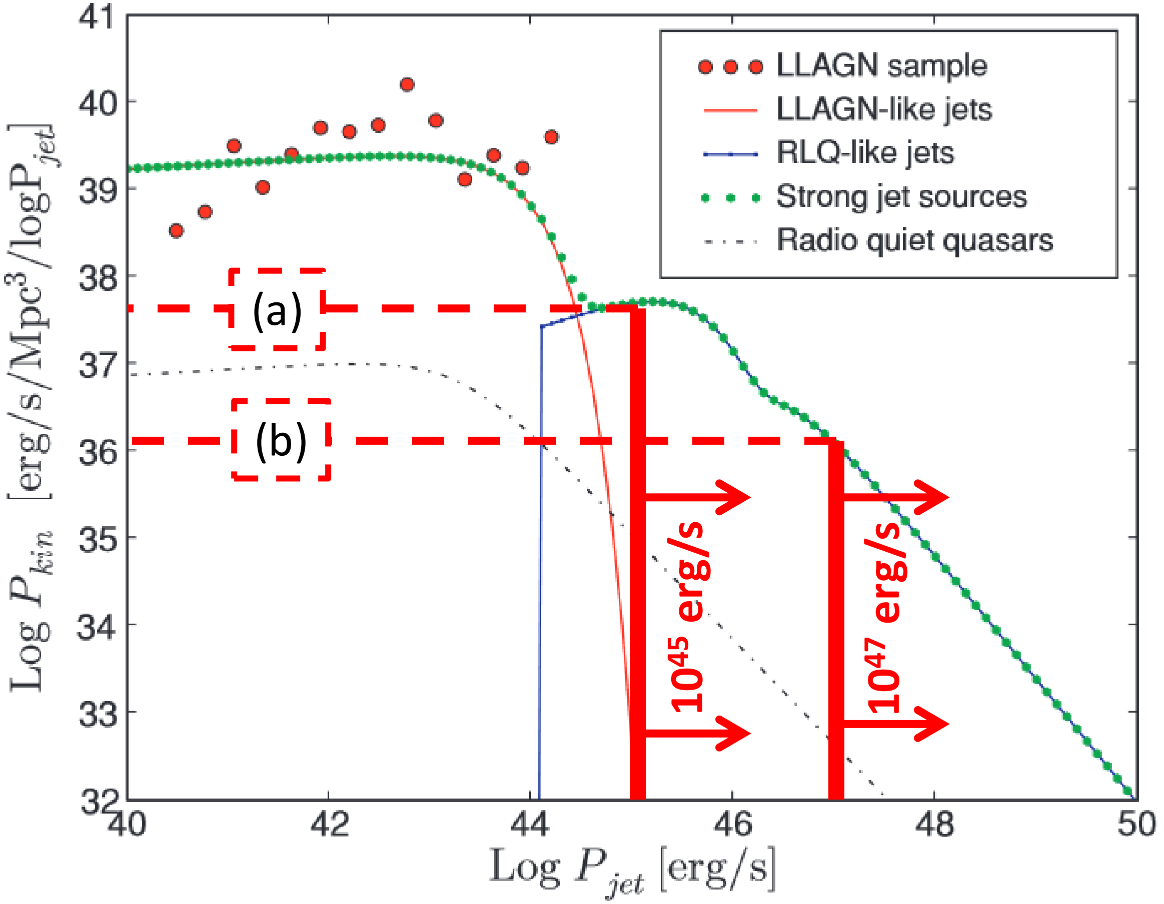
FSRQs: too rare to account for UHECRs…

jet kinetic luminosity: $L_{\rm jet} \simeq 2\times 10^{43}\,{\rm erg/s}$

⇒ **too small to account for 10^{20} eV protons …** $E_{\rm max} \sim Z\times 10^{18}\,{\rm eV}$ in jet/lobe

Acceleration – a luminosity bound

Körding+ 07: energy input of radio-galaxies



(a): energy input of 10^{45} erg/Mpc^3/yr… density 0.5 10^{-7} Mpc^{-3}

(b): energy input of 3 10^{43} erg/Mpc^3/yr… density 10^{-11} Mpc^{-3}

… to match the flux above 10^{19} eV: input rate needed 10^{44} erg/Mpc^3/yr (Katz+ 09)

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: $L_{\rm UHECR} \sim 10^{43}\, n_{-7}^{-1}\,{\rm erg/s}$ $(n\,{\rm in\,Mpc^{-3}})$

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

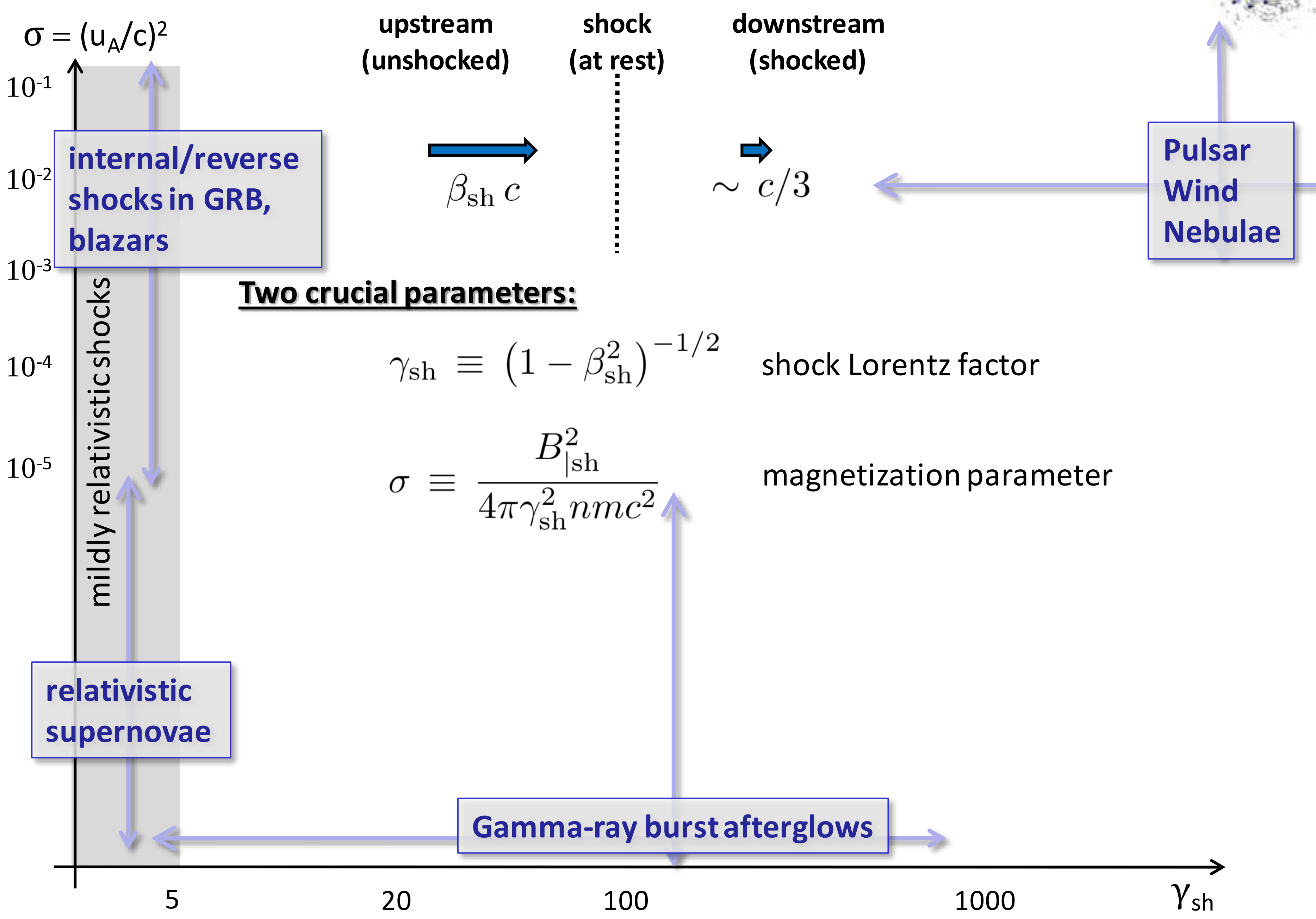
note: if one wants nuclei at >E to circumvent luminosity bound, accounting for the protons accelerated to >E/Z requires an energy input higher by M_p/M_Z …
for reference, solar composition means:

$$\left.\frac{M_{\rm H}}{M_{\rm CNO}}\right|_\odot \sim 70,\qquad \left.\frac{M_{\rm H}}{M_{\rm Si-group}}\right|_\odot \sim 1000,\qquad \left.\frac{M_{\rm H}}{M_{\rm Fe-group}}\right|_\odot \sim 500$$

e.g., for the whole population, $nL \sim 3\ 10^{47}$ erg/Mpc^3/yr, from sources with $L \sim 10^{43}$ 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!

⇒ 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

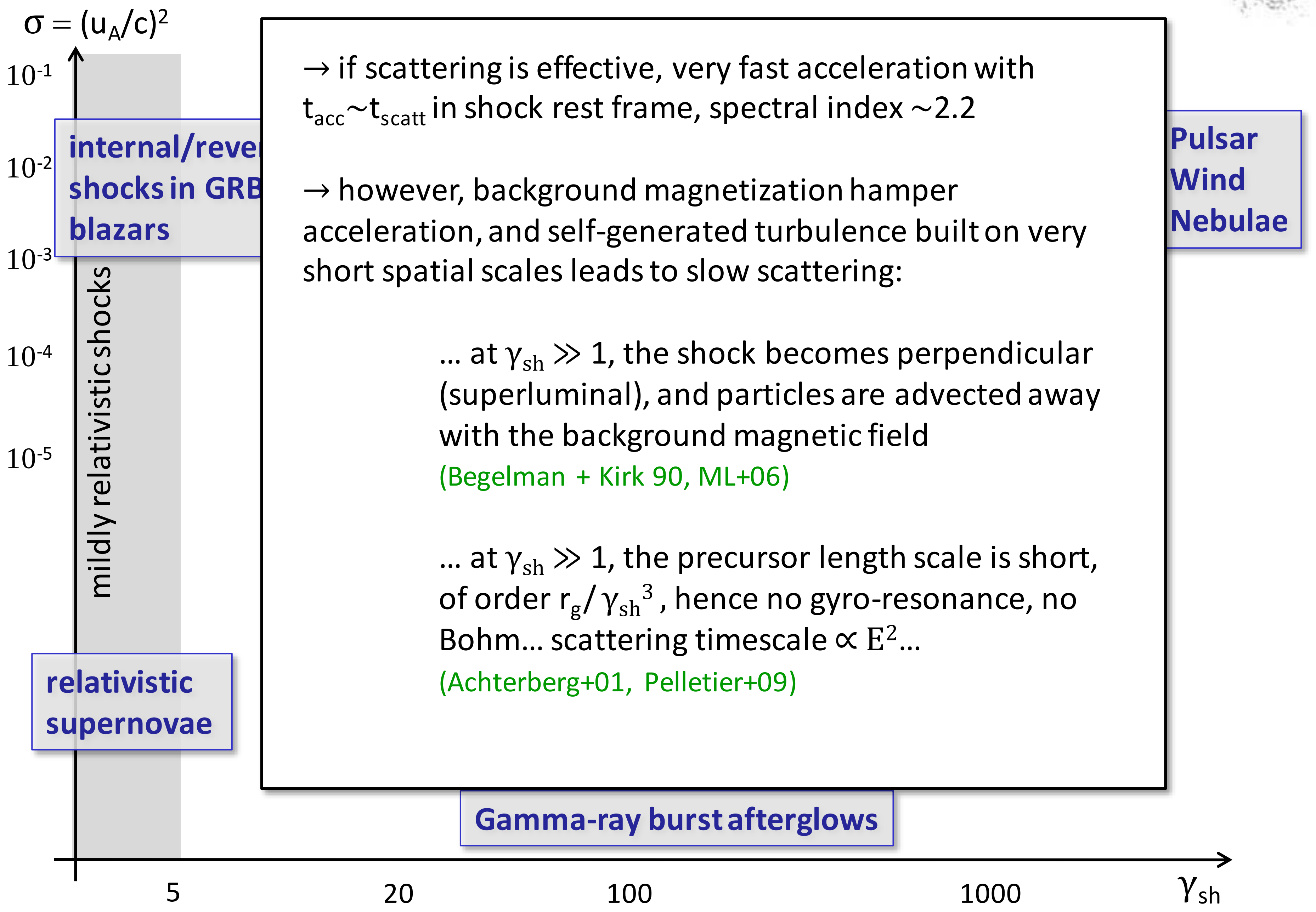
Gamma-ray burst afterglows

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



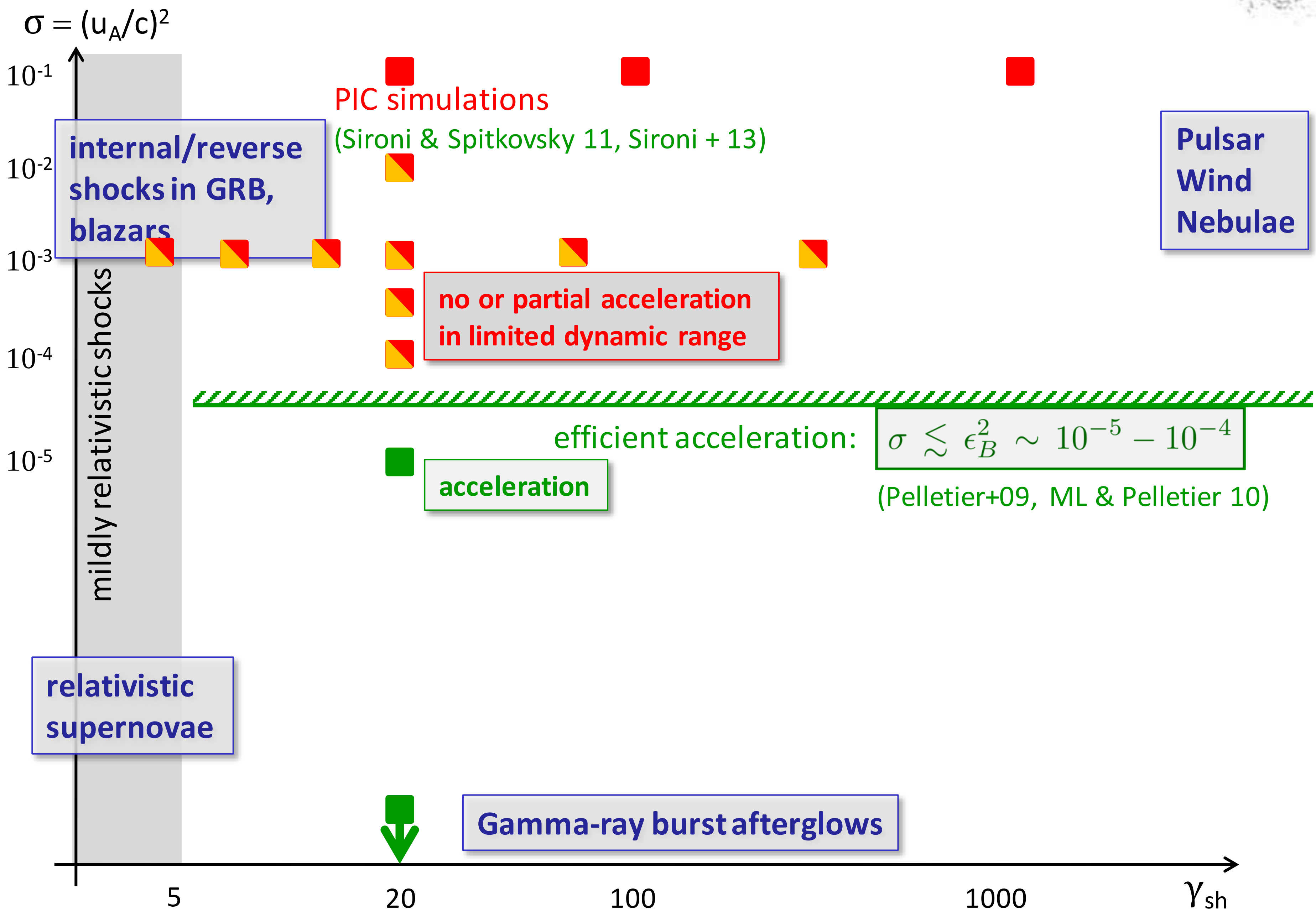
→ if scattering is effective, very fast acceleration with $t_{acc} \sim t_{scatt}$ in shock rest frame, spectral index ~2.2

→ however, background magnetization hamper acceleration, and self-generated turbulence built on very short spatial scales leads to slow scattering:

… at $\gamma_{sh} \gg 1$, the shock becomes perpendicular (superluminal), and particles are advected away with the background magnetic field
(Begelman + Kirk 90, ML+06)

… at $\gamma_{sh} \gg 1$, the precursor length scale is short, of order r_g/γ_{sh}^3, hence no gyro-resonance, no Bohm… scattering timescale $\propto E^2$…
(Achterberg+01, Pelletier+09)

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

(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}

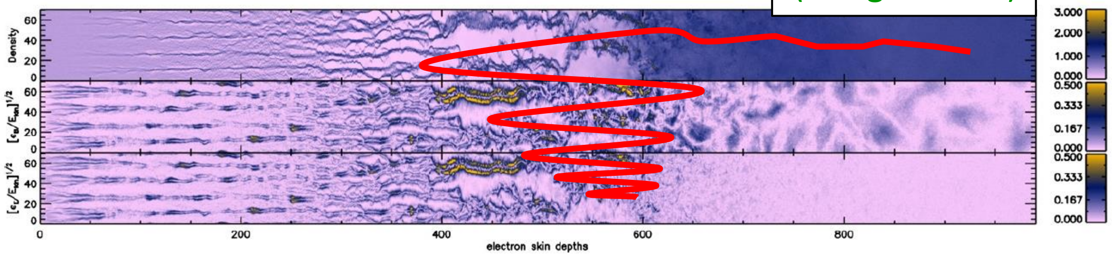
mildly relativistic shocks

internal/rever shocks in GRB, blazars

Pulsar Wind Nebulae

→ 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:

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

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

relativistic supernovae

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}

internal/rever
shocks in GRB,
blazars

mildly relativistic shocks

relativistic supernovae

Pulsar Wind Nebulae

Gamma-ray burst afterglows

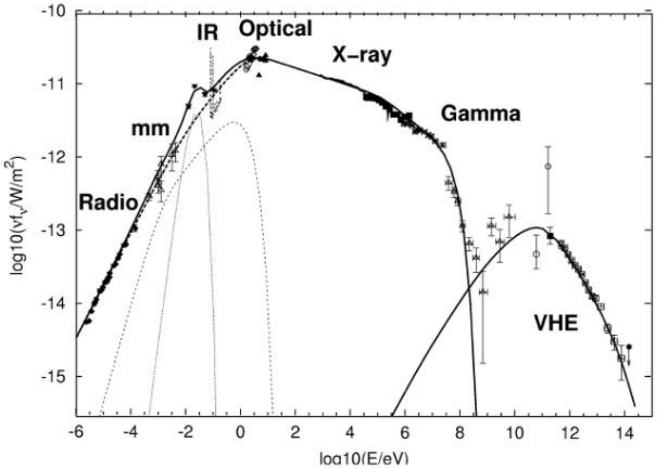
5 20 100 1000 γ_{sh}

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

synchrotron limit:

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

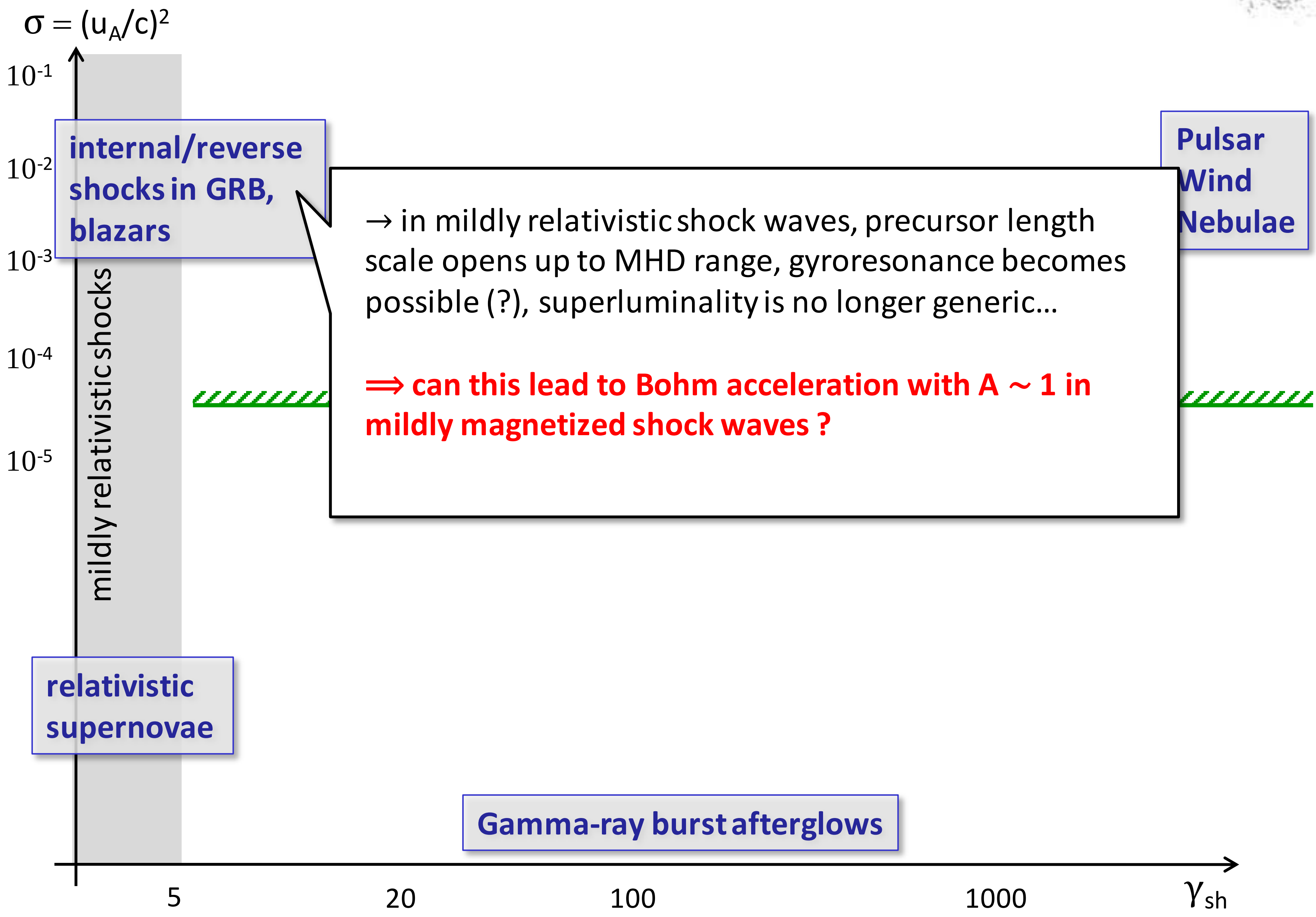
$$\Rightarrow \mathcal{A} \sim 1$$



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

(ML+15)

Particle acceleration in relativistic shocks



internal/reverse shocks in GRB, blazars

Pulsar Wind Nebulae

relativistic supernovae

Gamma-ray burst afterglows

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

⟹ can this lead to Bohm acceleration with A ∼ 1 in mildly magnetized shock waves ?