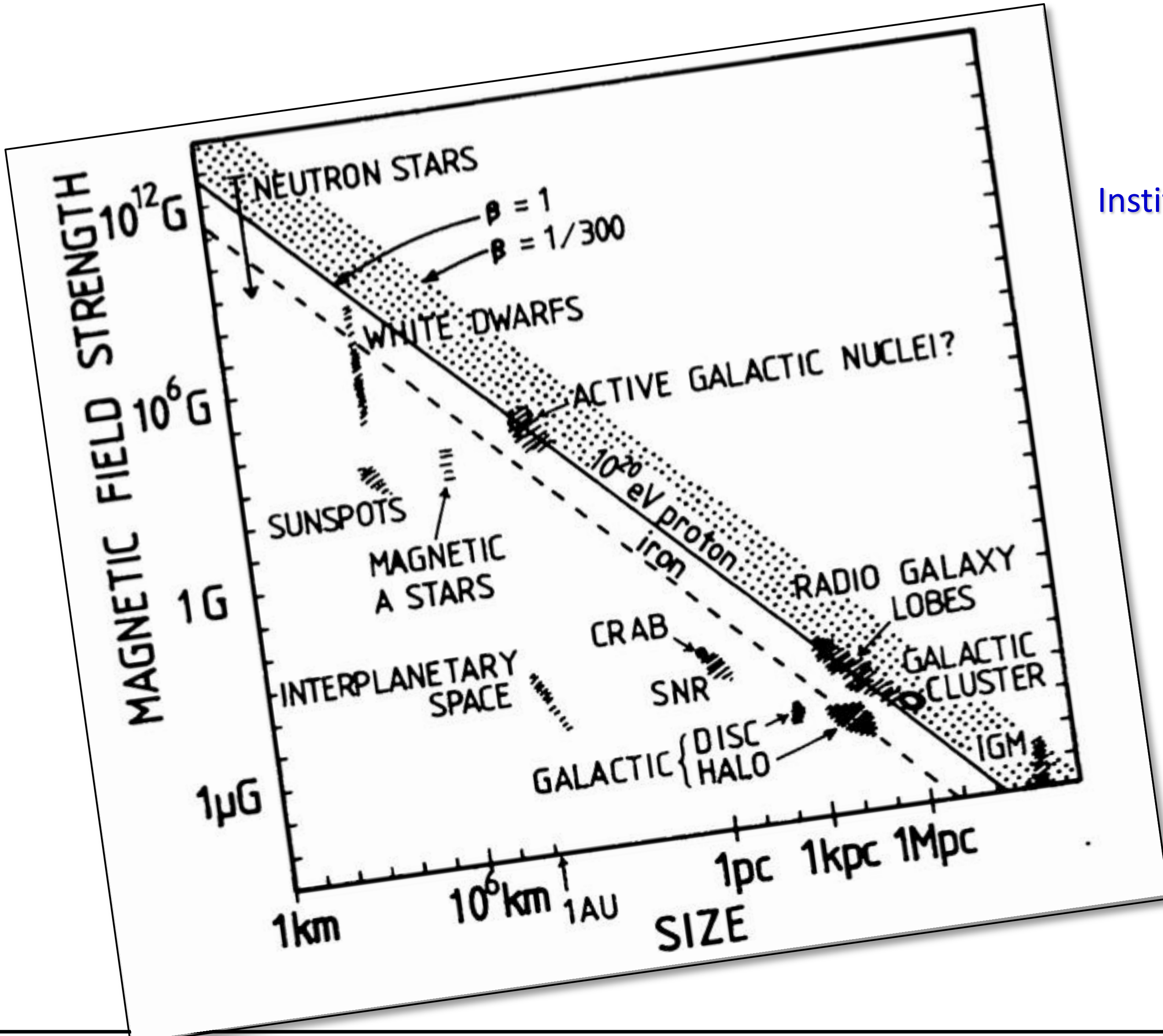
The challenge of accelerating particles to 10^{20} eV



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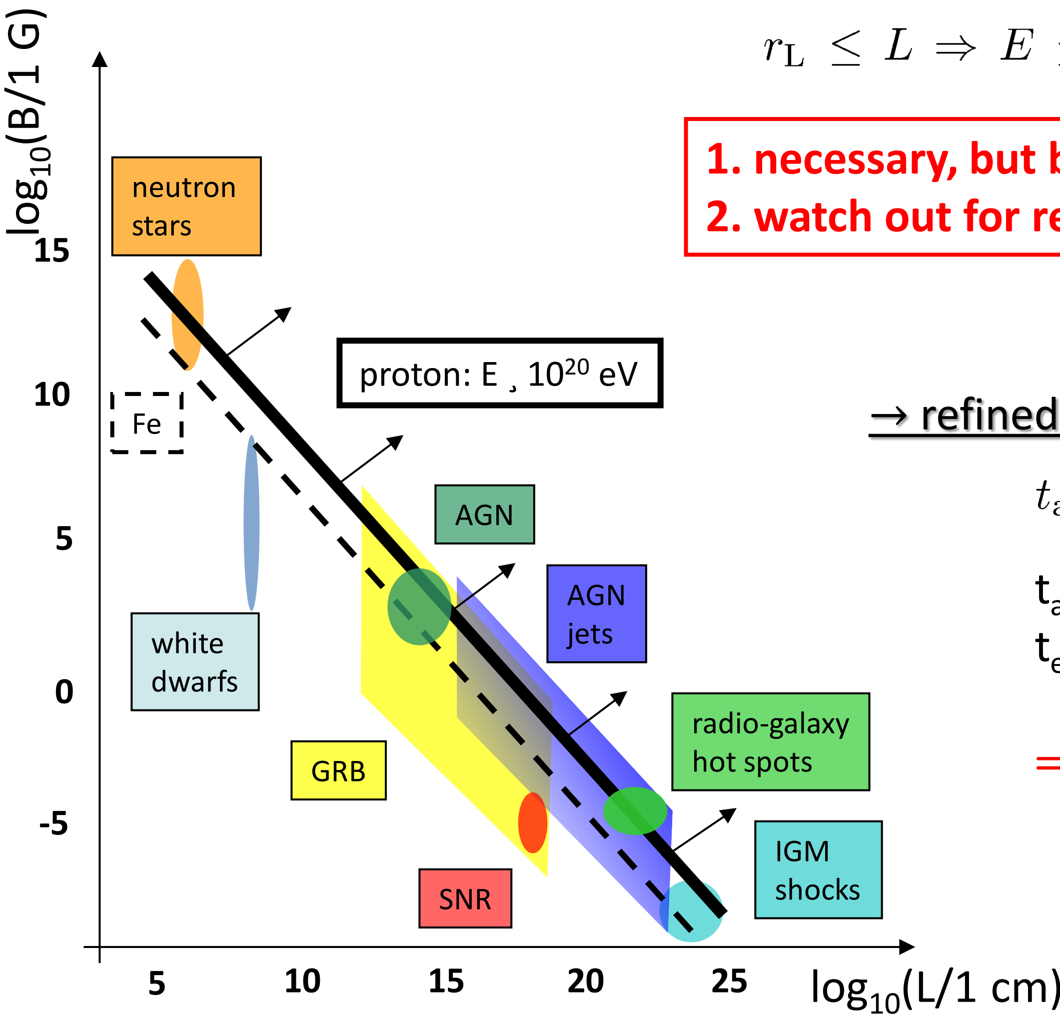
Acceleration – Hillas criterion

Hillas 84

<u>Hillas:</u> to find which object ***might*** be a source of UHE cosmic rays:

$$r_{\rm L} \leq L \Rightarrow E \leq 10^{20}\,{\rm eV}\, Z B_{\mu{\rm G}} L_{100\,{\rm kpc}}$$



1. necessary, but by no means sufficient!
2. watch out for relativistic effects!

<u>→ refined criterion:</u>

$$t_{\rm acc} \leq t_{\rm loss}, \quad t_{\rm esc}$$

t_{acc} depends on acceleration physics
t_{esc} , t_{loss} depends on source physics

⇒ requires an object by object study…

Norman et al. 95

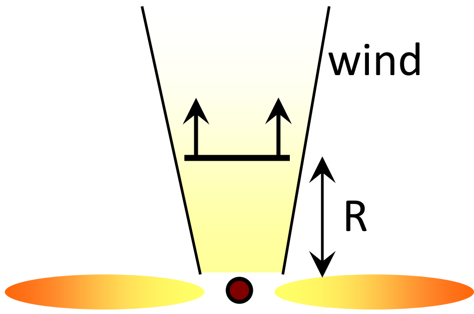
The relativistic Hillas bound

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

→ 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 magnetic luminosity: $L_B \gtrsim 0.7\times 10^{45}\,{\rm erg/s}\ \Theta^2\Gamma^2\beta^3\,\mathcal{A}^2\,Z^{-2}\,E_{20}^2$

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...

Lower limit on luminosity of the source:

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

10^{20} V or 10^{20} eV …. ??

What is the rigidity of ultra-high energy cosmic rays?

1. **Z ~ 1 :**

   → **sources of E/eZ = 10^{20}V are much more extreme than sources of 10^{19}V particles…**
   e.g.: a few candidate sources for 10^{20}eV protons vs *dozens* of candidate sources of 10^{20}eV iron…

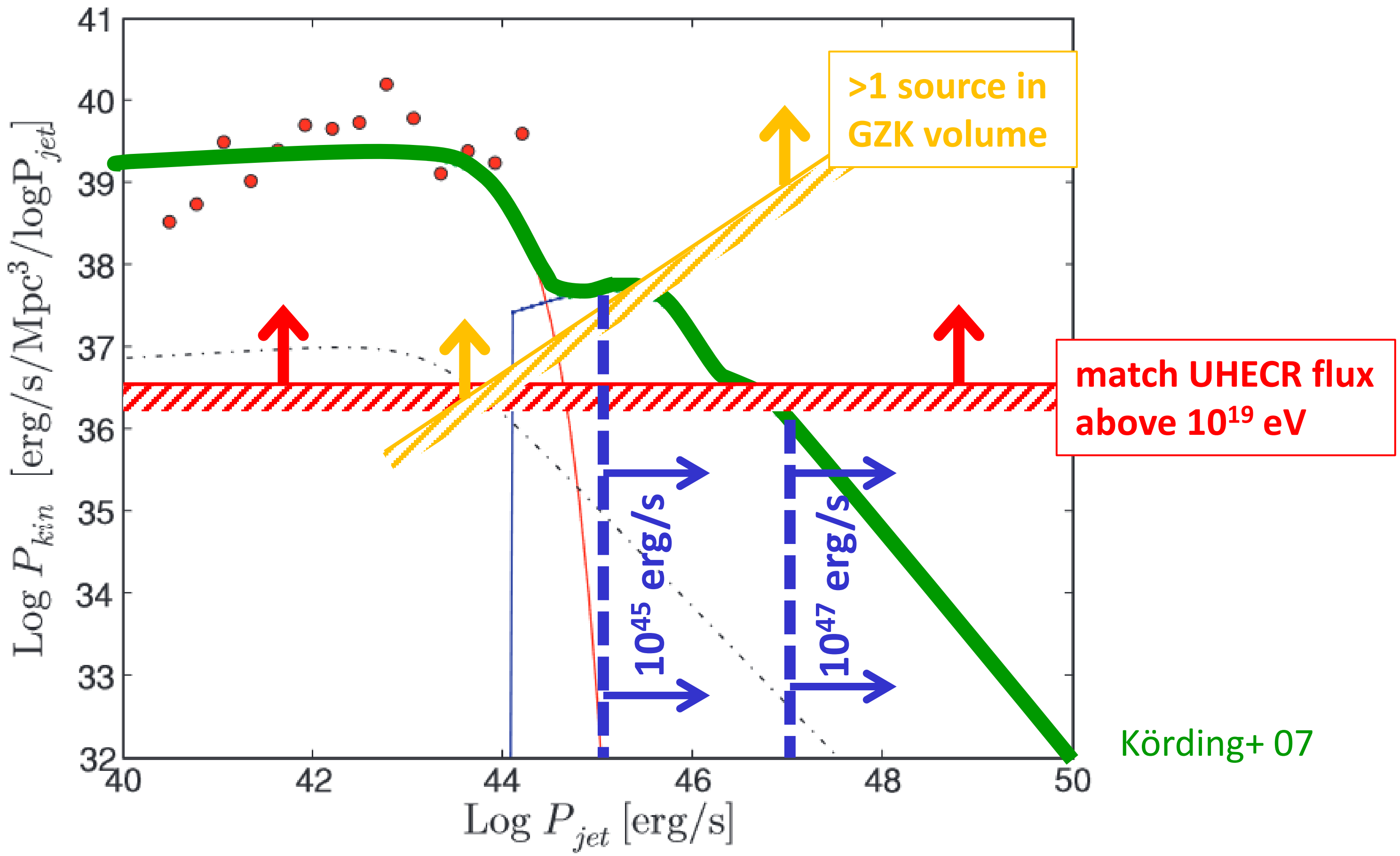
   → but, ***composition data and absence of GZK neutrinos constrain f_p***…

2. **Z ~ 10+ :**

   → can fit composition data, lack of GZK ν, sources less extreme….
   but ***where are the accompanying protons… ??***

   → and ***what about the anisotropies?***

Energy input of radio-galaxies



Körding+ 07

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

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

10^{20} V or 10^{20} eV …. ??

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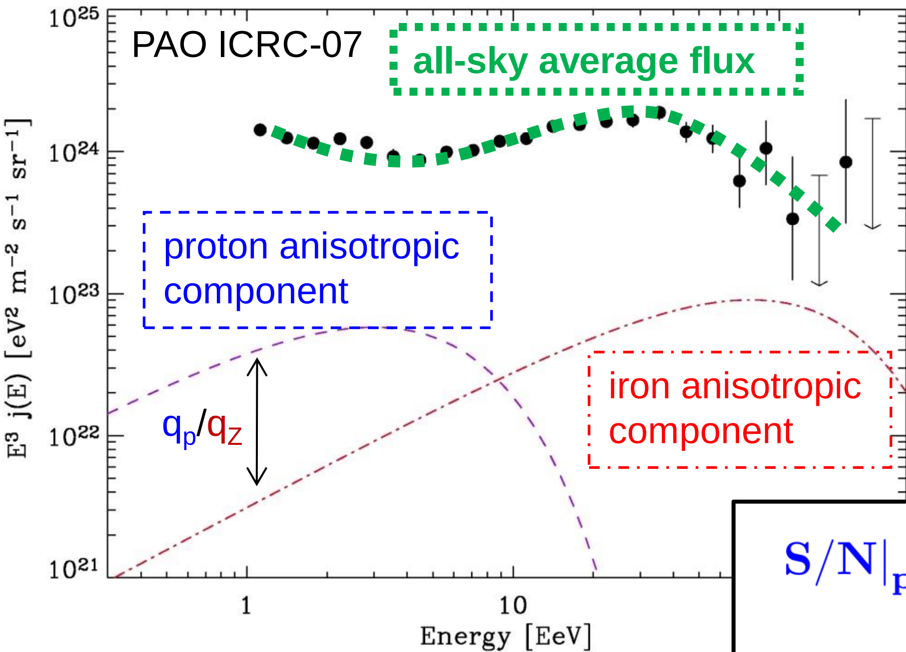
Anisotropies vs heavy composition at UHE

→ if anisotropic signal >E is due to heavy nuclei, 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, Liu+13)



Compare strength of anisotropy at E and E/Z:

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

→ if anisotropies are seen at E ~ GZK, but not at E/Z:

- **there exist protons at GZK producing the anisotropies...**
- **or, if Fe at UHE: Z $\gtrsim$ 1000 Z_o... if Si at UHE: Z $\gtrsim$ 1600 Z_o... if O at UHE: Z $\gtrsim$ 100 Z_o**

  ... sources with such high metallicities?

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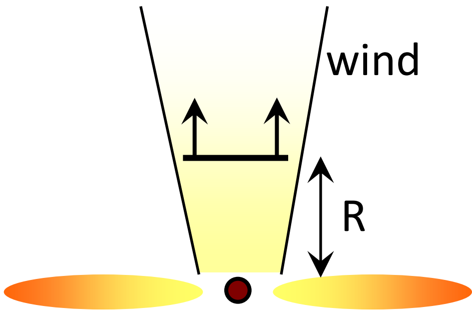

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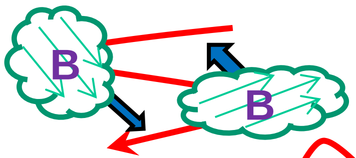
Acceleration scenarios

<u>Fermi type:</u> in highly conducting astrophysical plasmas...

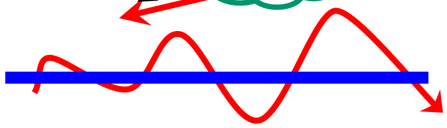
→ ***E*** field is 'motional', i.e. if plasma moves at velocity $\boldsymbol{\beta}_{\rm p}$: $\mathbf{E} = -\boldsymbol{\beta}_{\rm p} \times \mathbf{B}$

→ need some agent -- e.g. scattering -- to push particles across B, to explore the non-uniform E, B configuration!

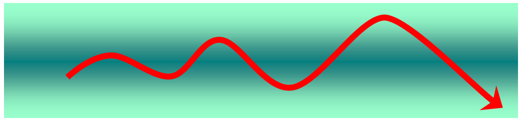
→ examples: - turbulent Fermi acceleration



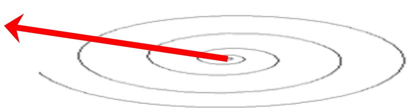
- Fermi acceleration at shock waves



- acceleration in sheared velocity fields

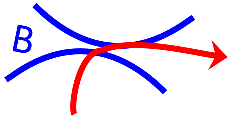


- magnetized rotators

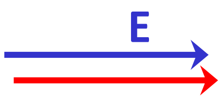


<u>Beyond MHD:</u>

→ examples: - reconnection



- gaps



A ratio $t_{acc} / t_g \sim 1$?

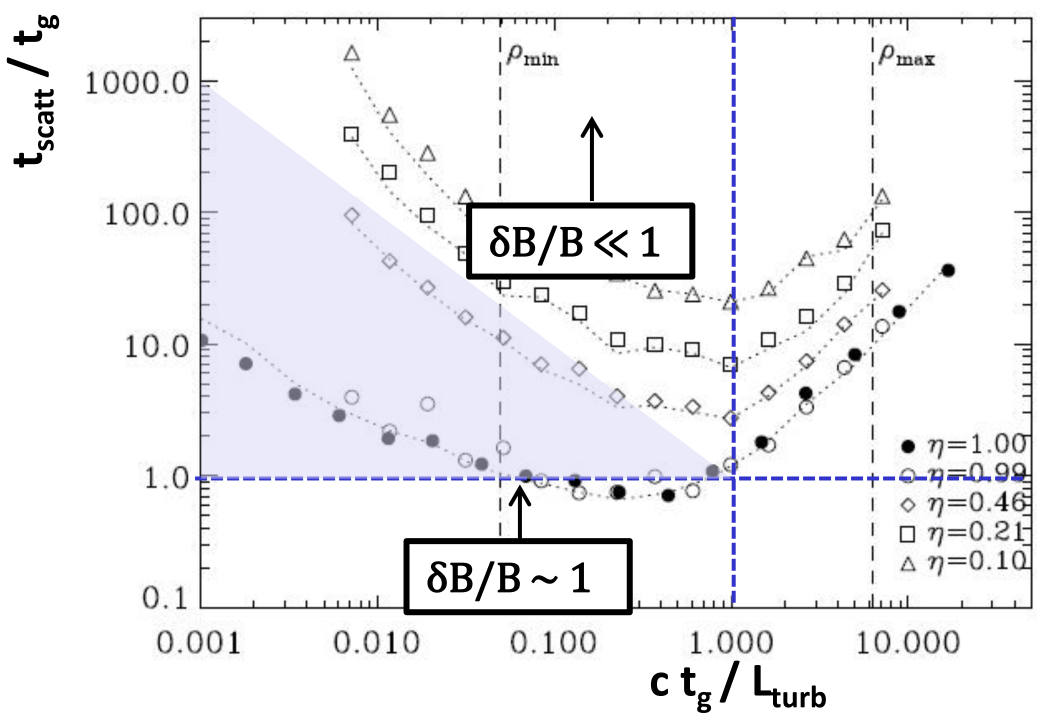
t_{acc} vs t_{scatt}: Fermi acceleration ~ explore a non-uniform/non-constant **E**, **B** configuration…
… define scale length L_Δ scale of variation:

$$\frac{t_{\rm acc}}{t_{\rm scatt}} \sim \beta_u^{-2} \begin{cases} \left(\dfrac{L_\Delta}{t_{\rm scatt}}\right)^2 & (t_{\rm scatt} \ll L_\Delta) \\ \mathcal{O}(1) & (t_{\rm scatt} \gg L_\Delta) \end{cases}$$

e.g. shear, non-res. turbulence

e.g. shock, resonant turbulence

t_{scatt} vs t_g: a problem of particle transport in turbulence…



Casse, ML, Pelletier 02

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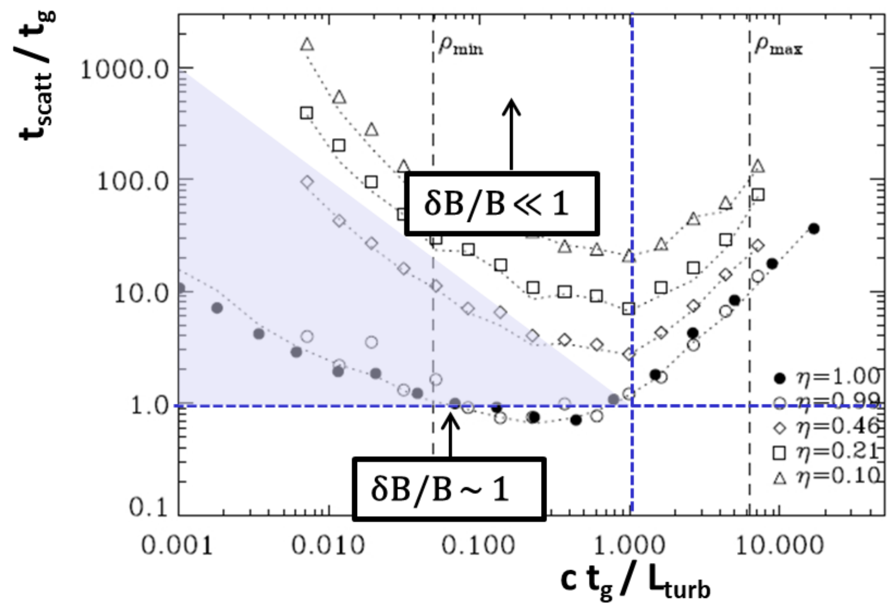

$$\frac{t_{acc}}{t_g} = \mathcal{A} \sim 1$$ requires:

… a relativistic flow $\beta_u \sim 1$… i.e. $E \sim B_{tot}$

… full turbulence on large scales: $\delta B \gtrsim B$

… Bohm at the confinement energy: $L_{turb} \sim R_{source}$

Note: … e.m. counterpart from electrons depends on t_{acc}/t_g well below $E_{conf} \sim e\,B\,R$

Particle acceleration in 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…*** scattering timescale $\propto E^2$…
i.e., $\mathcal{A} \gg 1$

Gamma-ray burst afterglows

5 20 100 1000 γ_{sh}

Particle acceleration in relativistic shocks

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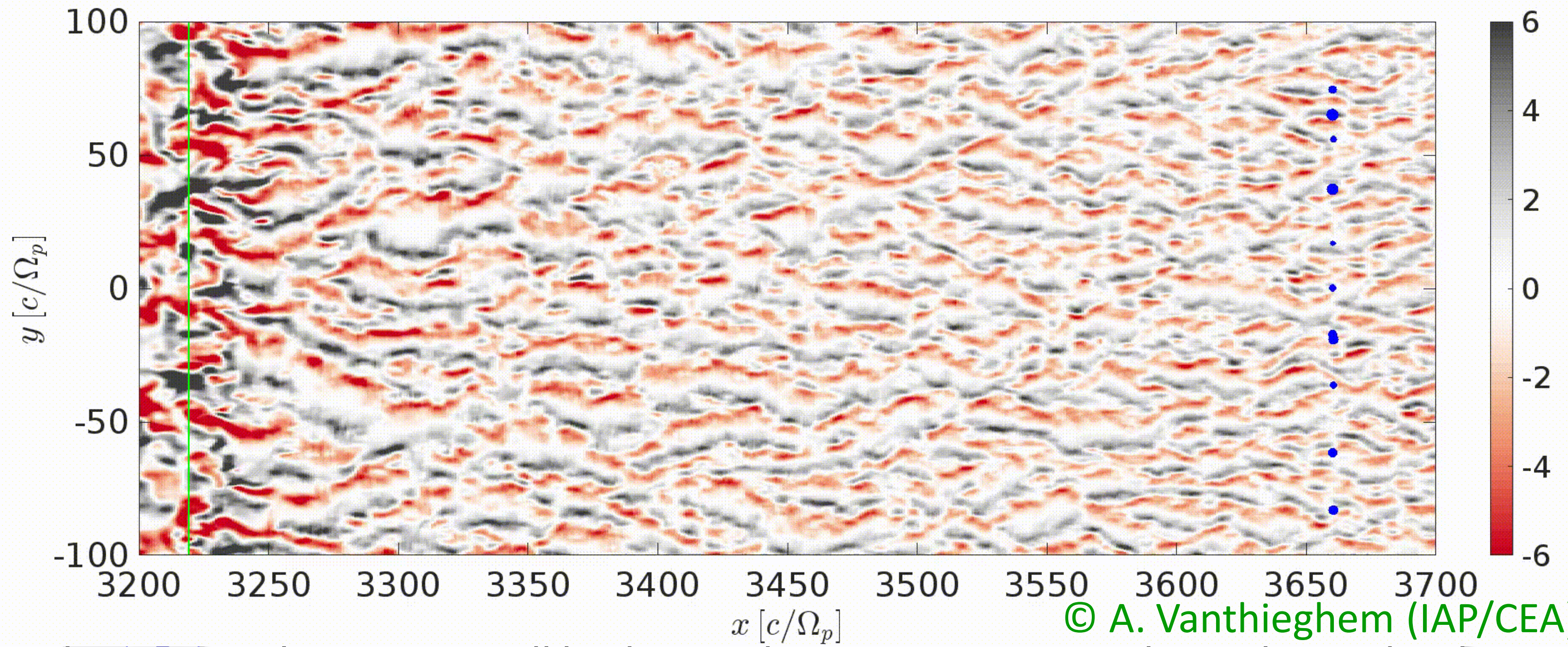

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mi

relativistic superno

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10^{-2}

10^{-3}

10^{-4}

10^{-5}

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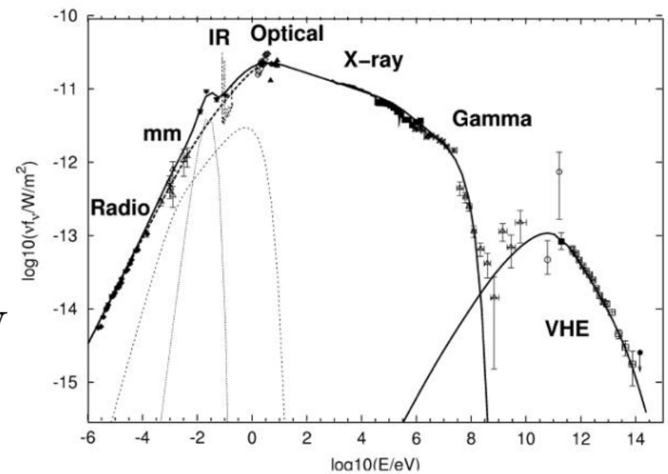
→ **theory may not be complete:** predicts no acceleration at pulsar wind termination shock, while SED suggests Fermi-type acceleration at Bohm regime:

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), possible acceleration at termination shock + confinement up to 10^{20}eV for protons … (ML+15)

Pulsar Wind Nebulae

Gamma-ray burst afterglows

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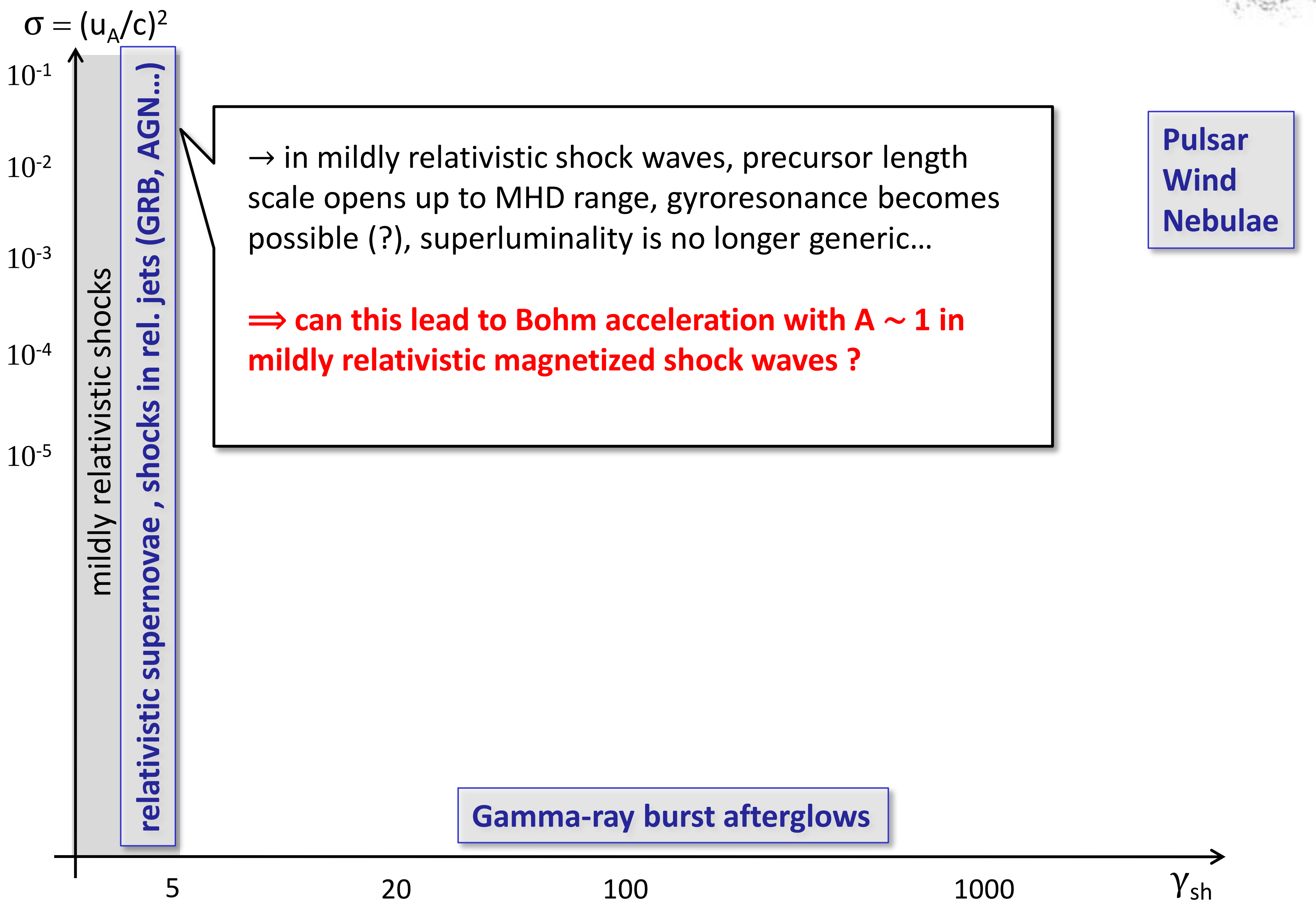
Particle acceleration in relativistic shocks



Summary

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1. WHY BOTHER WITH ULTRA-HIGH-ENERGY COSMIC RAYS?

The evidence suggests that at least some of the particles are protons (97), but their identification is not easy. Such an identification is of critical importance. If they were to turn out to be entirely highly charged nuclei, we

IS THERE REALLY A SIGNIFICANT ANISOTROPY AT HIGH ENERGIES? This question is persistently raised by critics.

Above 10^{19} eV, the pattern of arrival directions changes rapidly with energy. Haverah Park finds that above $\sim 3 \times 10^{19}$ eV there is a large excess of particles from high northern galactic latitudes, and Watson (98) considers the most likely explanation for this to be a large contribution from the Virgo supercluster.

The fast-moving "knots" in radio galaxies may be unusually effective shock waves (87) if they are large enough. But the radio galaxies in our vicinity are not so active. So, iron nuclei might possibly be accelerated to 10^{19} eV, but not protons.

From Figure 6, it appears that acceleration should be far easier if $v_S \sim c$, and although this would give a notably flatter spectrum (77), the effect has not been fully explored.