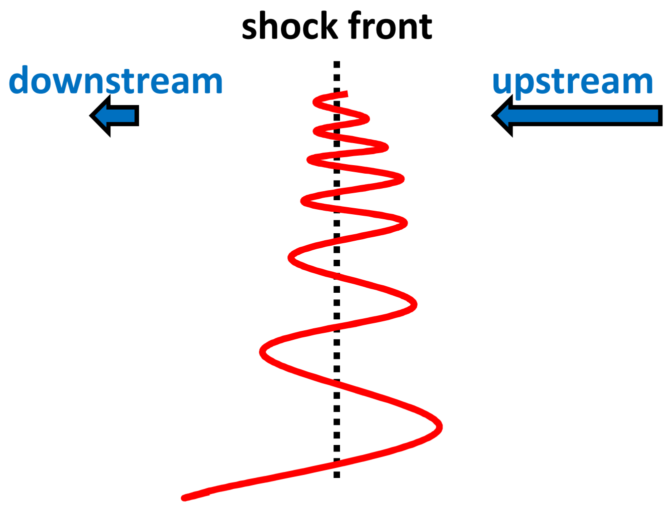
Acceleration to ultra-high energies...
... on the origin of ultra-high energy cosmic rays

Martin Lemoine

Institut d'Astrophysique de Paris

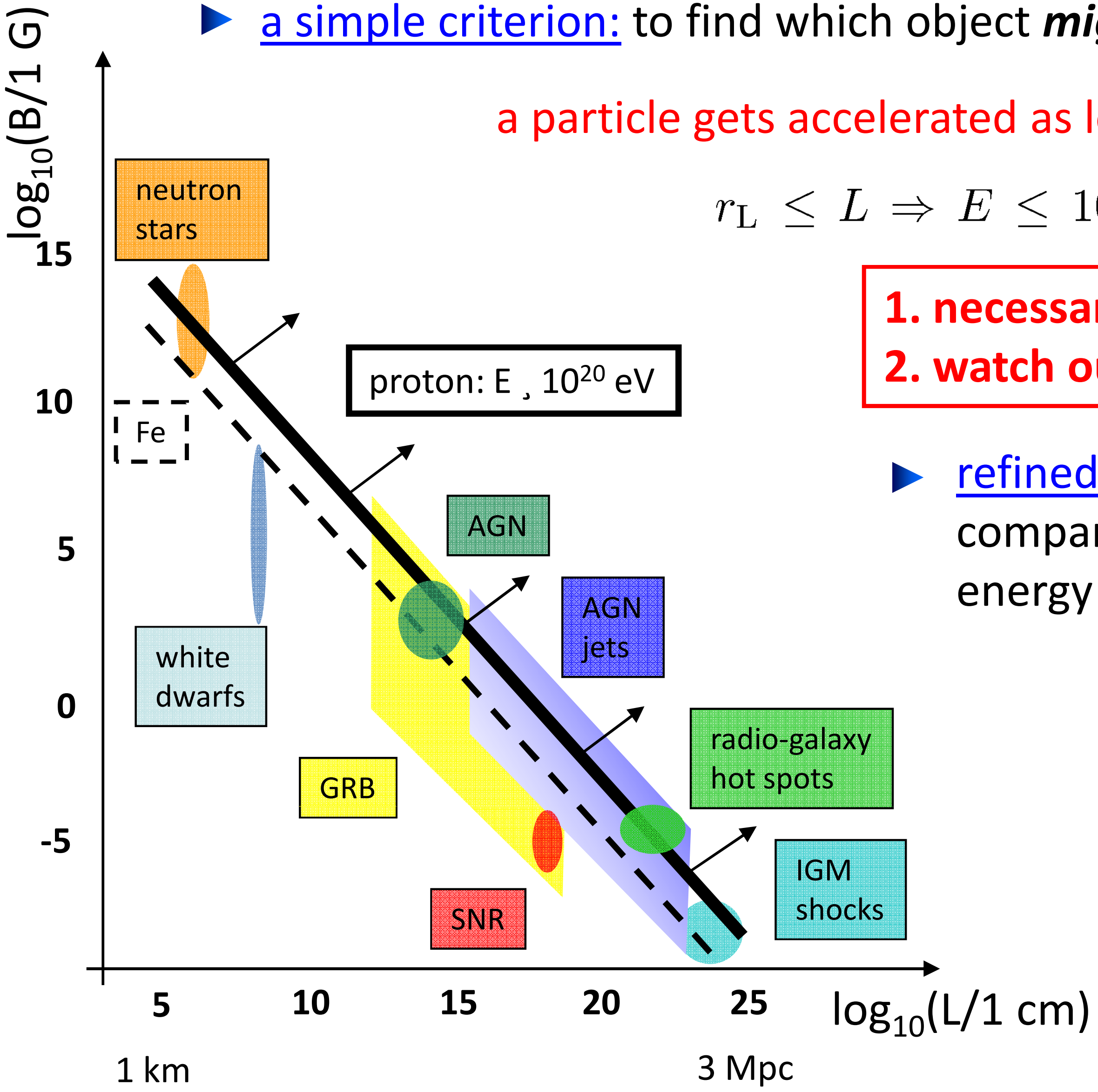
CNRS, Université Pierre & Marie Curie



Acceleration – Hillas criterion

Hillas 84

- a simple criterion: to find which object *might* be a source of UHE cosmic rays:



a particle gets accelerated as long as it is confined in the source:

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

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

- refined criterion:
  compare acceleration timescale with energy loss timescale and escape timescale

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

t_{acc} depends on acceleration mechanism

t_{esc} depends on magnetic field

t_{loss} depends on environment

⇒ requires an object by object study…

Norman et al. 95

… magnetars, gamma-ray bursts and radiogalaxies are promising candidates…

General principles of particle acceleration

► Standard mechanism:

1. Lorentz force: $\mathbf{F} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right)$

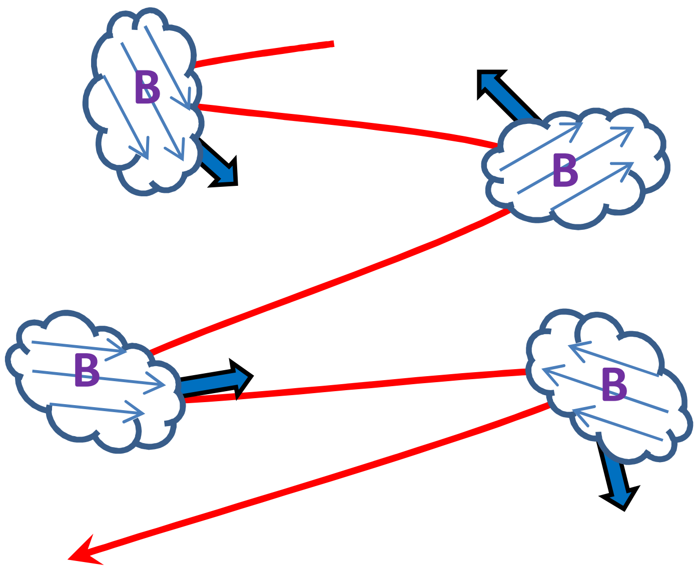
$\rightarrow$ particle is accelerated through **E** field

2. near infinite conductivity: $\mathbf{E}_{|\mathrm{p}} \simeq 0$ in plasma rest frame

$\rightarrow$ **E** field is in general 'motional', i.e. if plasma moves at velocity v_p

$\mathbf{E} \simeq -\frac{\mathbf{v}_p}{c} \times \mathbf{B}$ in laboratory frame

► Applications: **stochastic Fermi acceleration** e.g. Fermi (49)



... particle gains energy through its scatterings with magnetized moving disturbances, e.g. turbulence...

... powerlaw $dN/dE \propto E^{-s}$, with $s \sim 1$?...

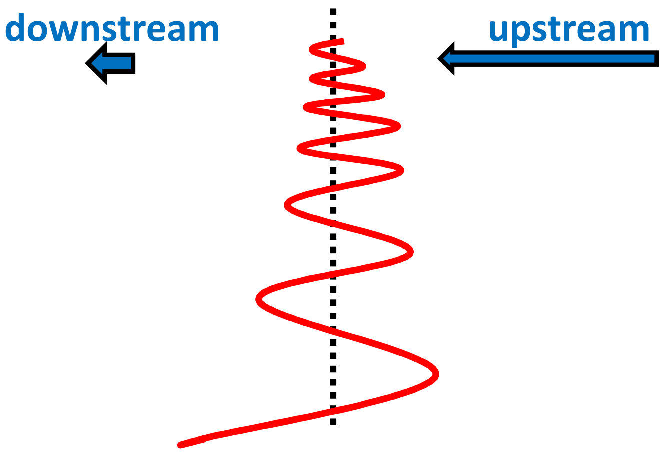
... non-relativistic regime **very slow** as

$t_{acc}/t_L \sim g/\beta_A^2$, $g \sim t_{scatt}/t_L \gtrsim 1$ and $\beta_A \sim 10^{-5}\, B_{\mu G}\, n_0^{-1/2}$

... relativistic regime:. **not well known**... (Pelletier 99)

Fermi shock acceleration

Fermi shock acceleration e.g. Bell (78), Blandford & Eichler (87)



... particle gains energy through its repeated interactions with both sides of the shock wave...

... powerlaw is generic due to competition between energy gain and escape out of site... index $s \sim 2$

... non-relativistic regime: well-known, but **slow**

$$t_{acc}/t_L \sim g/\beta_{sh}^2, \quad g \sim t_{scatt}/t_L \gtrsim 1$$

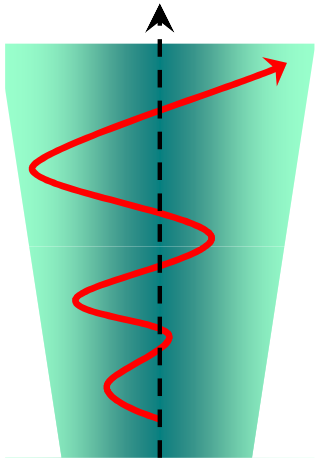
... relativistic regime: **not well known...**

$\rightarrow \gamma_{sh} \gg 1$: likely not efficient in ultra-relativistic limit (Lemoine & Pelletier 10)

$\rightarrow \beta_{sh}\,\gamma_{sh} \sim 1$: $t_{acc}/\,t_L \sim g$, likely efficient in mildly relativistic limit

Shear acceleration and others

Fermi shear acceleration e.g. Bosch-Ramon, Rieger & Duffy (07)



... particle gains energy by exploring a velocity gradient, e.g. a stratified flow perpendicular to the jet axis...

... powerlaw is generic due to competition between energy gain and escape out of site... index s $\sim$ 2

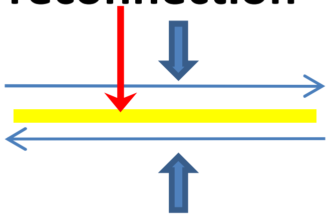
... acceleration timescale depends on the (unknown) parameters of stratification, but at confinement limit, in non to mildly relativistic regime:

$$t_{acc}/t_L \sim g/\Delta\beta^2, \quad g \sim t_{scatt}/t_L \gtrsim 1$$

... in relativistic regime: appears efficient, but scattering issue?

Other types of acceleration mechanisms:

reconnection



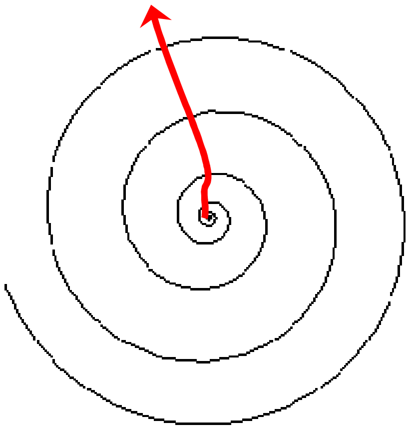
... uncertain...

... see however de Gouveia dal Pino & Lazarian (05), Giannios (10) for coupled reconnection + Fermi, $t_{acc}/t_L \sim 2\pi$

ponderomotive, wakefield ... ? e.g., Chen (02), Hoshino (08)

Magnetized rotators

magnetized rotator / unipolar inductor: rotating conductor with magnetic field, leading to a motional electric field **E** = -**v** x **B** /c, hence to potential drop between center and infinity



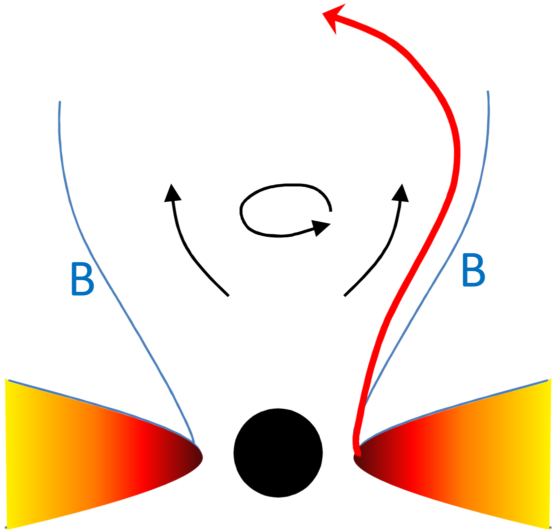
in a pulsar/magnetar wind, voltage drop in principle allows for

$$E_{\rm max} \sim 0.6 \times 10^{22}\, Z\, \left(\frac{B}{10^{15}\,{\rm G}}\right) \left(\frac{R}{10\,{\rm km}}\right)^3 \left(\frac{P}{1\,{\rm ms}}\right)^{-2}\,{\rm eV}$$

e.g. Gunn & Ostriker 69, Miller et al. 97, Blasi et al. 00, Arons 03

... how to experience voltage drop without suffering losses? (Arons 03: surf-riding on B wave)

... composition: light ions?



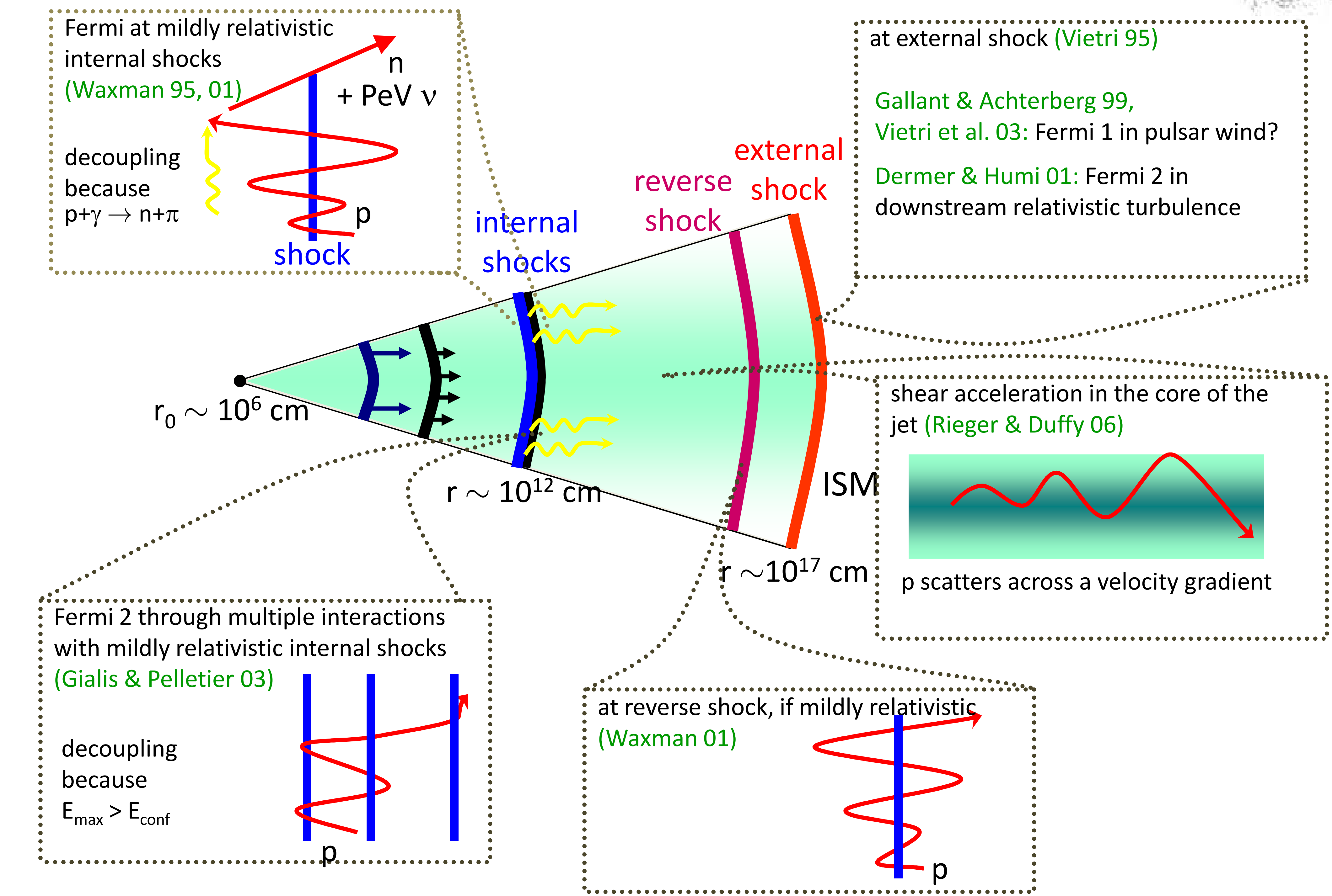
in a spinning black hole magnetosphere, voltage drop in principle allows for (e.g. Berezinsky et al. 90)

$$E_{\rm max} \sim 10^{19}\, Z\, \left(\frac{M}{10^8\,M_\odot}\right) \left(\frac{B_{\rm h}}{10^2\,{\rm G}}\right)\,{\rm eV}$$

... same question: how to experience voltage without suffering losses...

... composition: mostly protons?

Acceleration to UHE in gamma-ray bursts fireballs



Acceleration to UHE in gamma-ray bursts fireballs

▶ **Notes:**

→ acceleration in internal shocks may lead to a neutrino signal at the Waxman-Bahcall limit, which is now probed by Ice Cube... detection of PeV neutrinos would imply acceleration of p to >10^{17} eV... absence of detection would not rule out acceleration to UHE...

→ radiative signatures of proton acceleration to ultra-high energies? (Asano et al. 09, 10, Razzaque et al. 10)

→ acceleration at the external shock appears difficult... in the reverse shock?

→ strongest 'difficulty' for GRB model is production rate:

flux of UHECR above 10^{19} eV requires an energy input rate: $\sim$ **10^{44} erg/Mpc^3/yr**

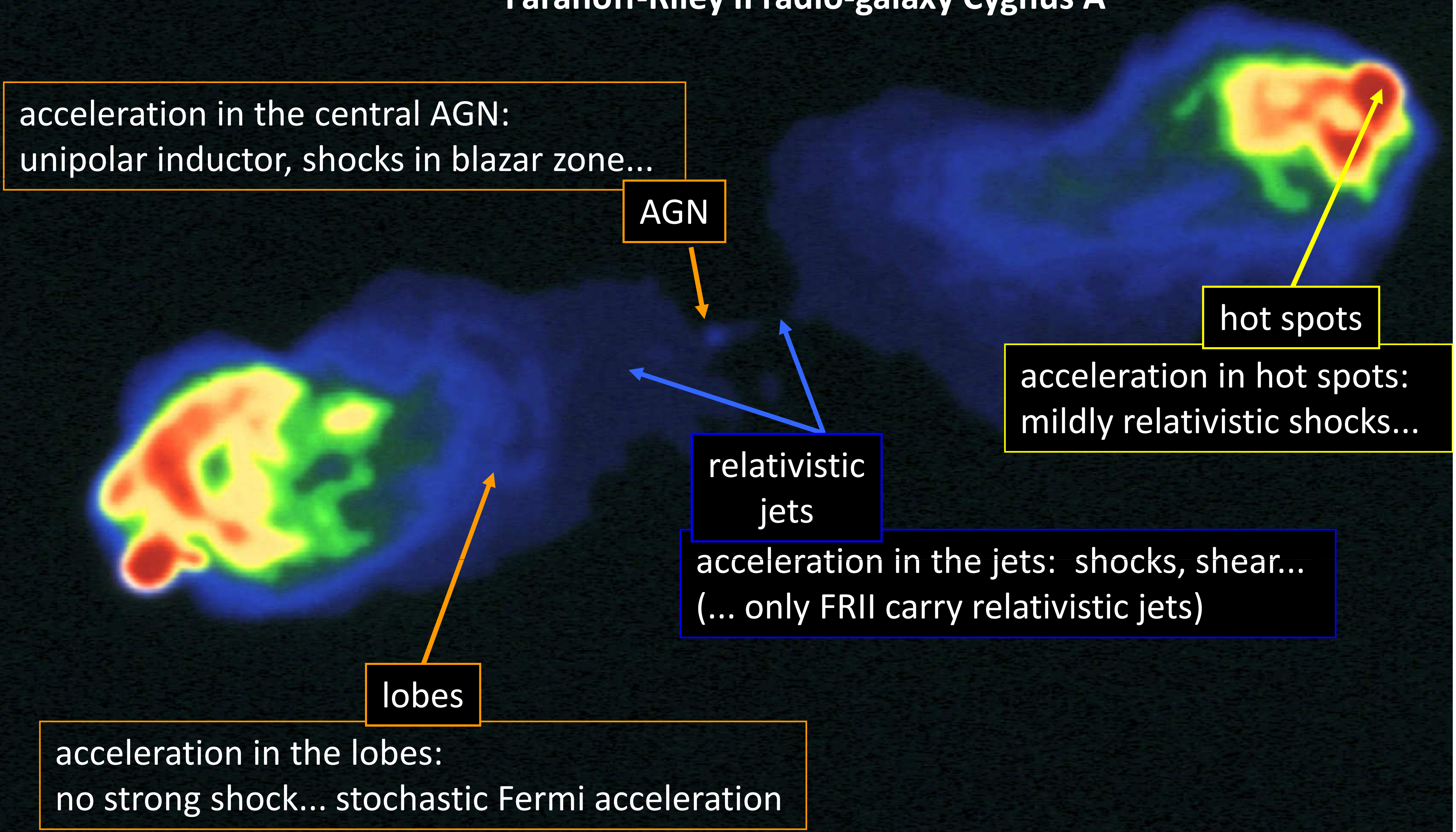
with a GRB rate $\dot{n}_{\rm GRB}$ this requires: $E_{\rm UHECR/GRB} \approx 10^{53}\,{\rm erg}\left(\frac{\dot{n}_{\rm GRB}}{1\,{\rm Gpc}^{-3}{\rm yr}^{-1}}\right)^{-1}$

i.e., $E_{\rm UHECR/GRB} / E_{\gamma/\rm GRB} \sim 10$ - ...?

→ chemical composition of UHECR: expected to be light, but heavy enrichment is also possible, if nuclei survive spallation and photodisintegration in the flow (Murase et al. 08, Wang et al. 08)

Acceleration – powerful radio-galaxies

Faranoff-Riley II radio-galaxy Cygnus A



Acceleration – powerful radio-galaxies

Notes:

$\rightarrow$ acceleration in the central zone is strongly inhibited by radiative losses...

$E_{max} \lesssim 10^{19}$ eV (e.g. Protheroe & Szabo 92, Norman et al. 95)

$\rightarrow$ only $\sim$ 1% of AGN are radio-loud (jets / lobes)

$\rightarrow$ enormous luminosities are required to provide proper conditions for acceleration of protons to $\sim 10^{20}$ eV in jets, hot spots

$\Rightarrow$ FRII sources in steady state (e.g. Rachen & Biermann 93, ...)

or flaring FRI sources (e.g. Dermer et al. 08)

$\rightarrow$ cumulative contribution of all radio-galaxies, e.g. Ptuskin 10

$\rightarrow$ no apparent correlation wtih FRII sources

$\rightarrow$ chemical composition: mostly protons (at least up to $E_{max,p}$, heavier nuclei beyond? e.g. Aloisio et al. 09, Allard et al. 08)

Acceleration – a luminosity bound

(Lovelace 76, Norman et al. 95, Waxman 95, 05, Lyutikov & Ouyed 05, Lemoine & Waxman 09)

- A generic case: acceleration in an outflow
  - acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm L}$

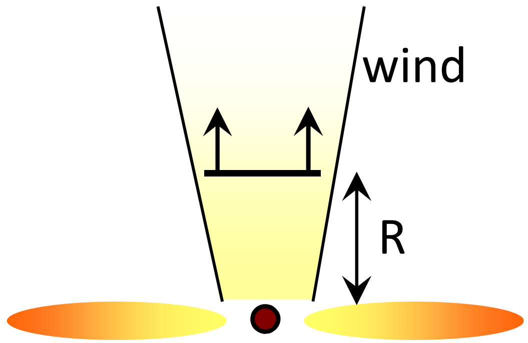
    $\mathcal{A} \gtrsim 1$, $\mathcal{A} \sim 1$ at most:

    - for non-relativistic Fermi I, $\mathcal{A} \sim g/\beta_{sh}^2$ with $g \gtrsim 1$

  - 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 $\beta \to 0$, $\mathcal{A}^2\beta^3 \ge 1/\beta \ge 1$

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



- 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
  high luminosity AGN: $L_{\rm bol} \sim 10^{46}$-10^{48} ergs/s
  gamma-ray bursts: $L_{\rm bol} \sim 10^{52}$ ergs/s

  $\Rightarrow$only most powerful AGN jets, GRBs or magnetars for protons

Acceleration – in FR-I radio-galaxies?

- **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)
  - in steady state:

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

    $\Rightarrow$**too small to account for 10^{20} eV protons ...**

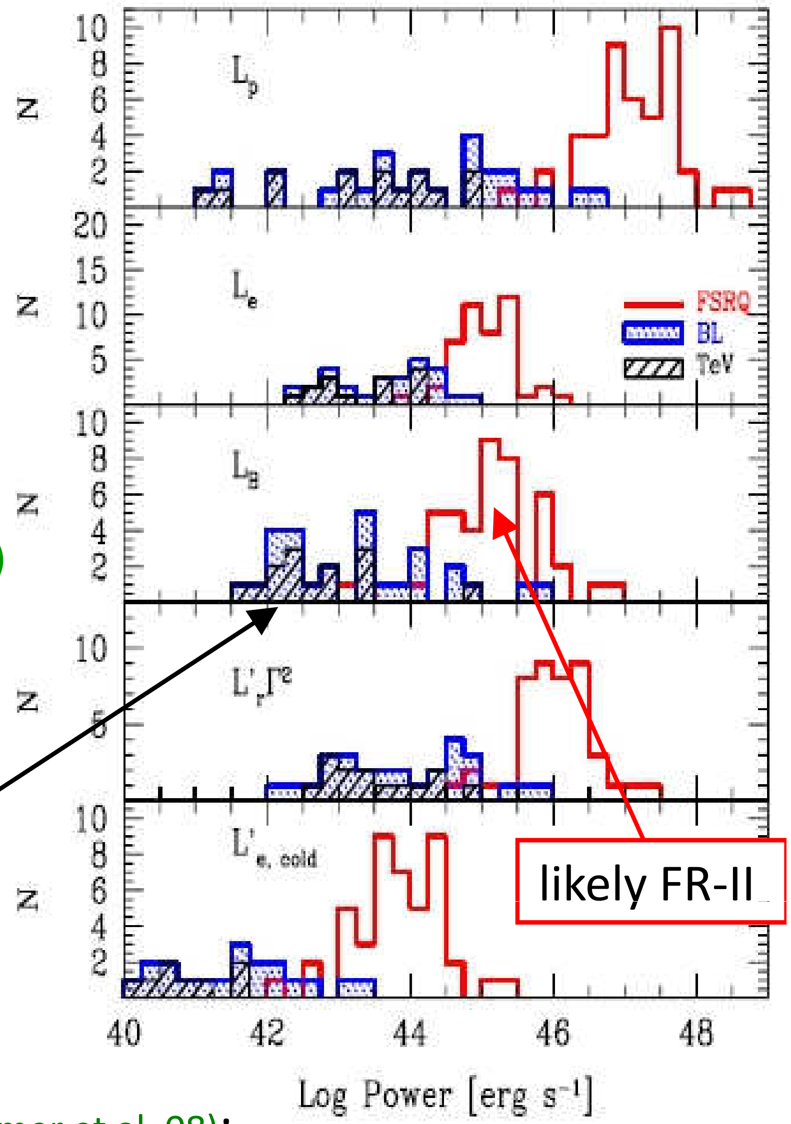
    $E_{\rm max} \sim Z \times 10^{18}\,{\rm eV}$ in jet/lobe (Lemoine & Waxman 09)

    ... note: proton acceleration in the last GRBs of Cen A could account for part of the anisotropy (Lemoine & Waxman 09)
    ... and that Cen A lies in the direction of strongest matter concentration for Auger (Ghisellini et al. 08 , Kashti & Waxman 08, Kotera & Lemoine 08)

  - more generally, leptonic models of the SEDs of blazars associated with FR-I radio-galaxies:

    $L_B \sim 10^{42} - 10^{44}\,{\rm erg/s}$ (Celotti & Ghisellini 08)

    in Cen A: $L_B \sim 2 \times 10^{42}$ erg/s (Lenain et al. 08)



  - flares / proton blazars (e.g. Farrar & Gruzinov 08, Rachen 08, Dermer et al. 08):

    higher luminosity $\Rightarrow$ acceleration of p to 10^{20} eV?

    ... however: PAO does not see correlation with nearby blazars (Harari 07)...
    ... energy losses in blazar zone? ... highest energy Auger event lies 30° away from the nearest blazar or FRII ...

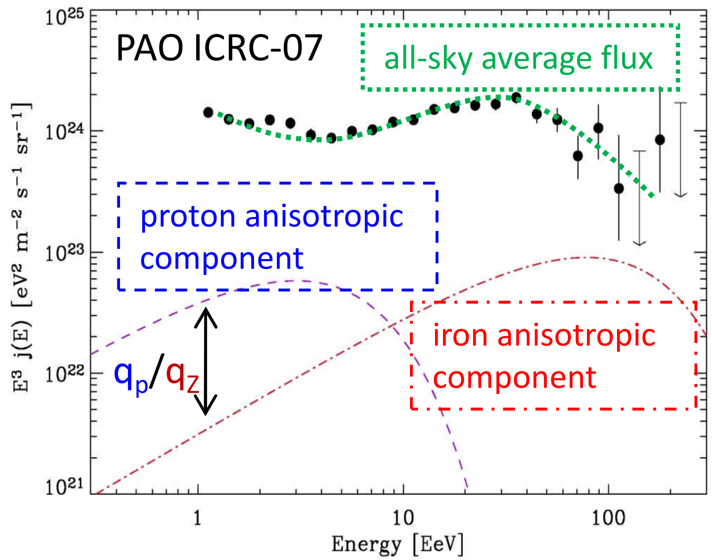
Testing the chemical composition on the sky

▶ Test: 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... (Lemoine & Waxman 09)

▶ Example:

source(s) contributing 10% of all-sky flux above 60EeV with iron nuclei, in some direction of the sky

E_{max} = 3 Z EeV, index s=2.0
GCR composition ratio $q_p : q_Z$ = 1: 0.06



▶ Signal to noise ratio of anisotropy pattern:

$$\Sigma_Z(>E_{\rm thr}) = \frac{\Delta N(>E_{\rm thr})}{\sqrt{N_{\rm iso}}}$$

▶ Compute signal to noise ratio of anisotropy for protons at >E_{thr}/Z:

$$\Sigma_p(>E_{\rm thr}/Z) = \Sigma_Z(>E_{\rm thr})\ \underbrace{\frac{q_p(E_{\rm thr}/Z)}{q_Z(E_{\rm thr}/Z)}}_{\gg 1}\ \underbrace{Z^{s-(s_{\rm obs}+1)/2}}_{\simeq Z^{0.2}>1}\ \underbrace{\alpha_{\rm loss}}_{}$$

$$\alpha_{\rm loss} = \frac{q_{{\rm prop.},p}(E_{\rm thr}/Z)}{q_p(E_{\rm thr}/Z)}\ \frac{q_Z(E_{\rm thr})}{q_{{\rm prop.},Z}(E_{\rm thr})} \geq 1$$

... anisotropy expected to be (much) stronger at E_{thr} / Z ...

Testing the chemical composition on the sky

- Test: 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... (Lemoine & Waxman 09)

- Example: source distribution around Cen A, injecting iron at UHE, making an angular image of size $\delta\theta$ = 10°, contributing 10% of Auger all-sky flux above 60EeV

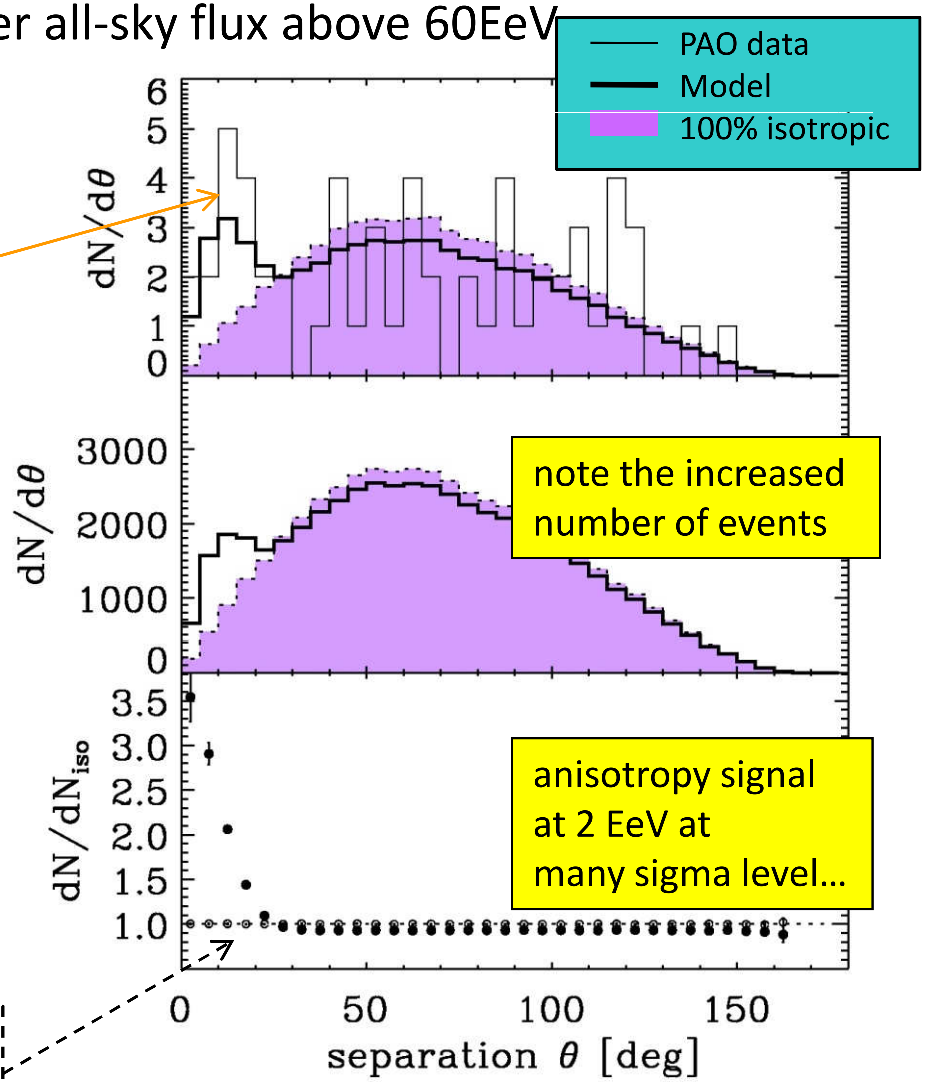
Histogram of #events
vs angular separation to CenA
E > 55 EeV

Auger (09): 12 events within 18° of Cen A
2.7 expected if isotropic arrival directions

- Proton contribution: compute signal expected at 55/26 = 2.2 EeV from protons accelerated in sources....

neglecting energy losses, s=2.0,
p : Fe = 1 : 0.06
E > 2.2 EeV

anisotropy signal at > 2.2 EeV
in terms of dN_{model} / $dN_{isotropic}$



if p instead of Fe at E > 55 EeV and $\delta\theta \propto (E/Z)^{-1}$
compatible with isotropy at > 2.2 EeV

Summary + conclusions ...

- **Acceleration to ultra-high energies:**

  $\rightarrow$ $L_B \gtrsim 10^{45}\, Z^{-2}$ ... erg/s to accelerate up to 10^{20}eV
  $\rightarrow$ leading contenders for 10^{20}eV protons :

  magnetars, gamma-ray bursts and most powerful AGN

- **Issue of chemical composition:**

  $\rightarrow$ most pressing issue: pinning down the chemical composition at GZK energies
  $\rightarrow$ search for anisotropies as a function of energy

"best case"

IF light composition at UHE + distribution of arrival directions according to LSS:

$\rightarrow$ most likely sources are bursting objects camouflaged in ordinary galaxies: gamma-ray bursts, magnetars...

$\rightarrow$ do not expect counterparts from these directions due to time delay $\gtrsim 10^4$ yrs between arrival of cosmic rays and photons/neutrinos/...

$\rightarrow$ but diffuse backgrounds ?

IF heavy composition at UHE: pessimistic scenario...

$\rightarrow$ expect substantial to large angular deflection: no source identification...?
$\rightarrow$ larger pool of source candidates... not much help from theory...
$\rightarrow$ production of secondary neutrinos/photons suppressed down to below detection?

"worst case"