Sources of cosmic rays beyond the ankle …
… heavy composition vs anisotropies

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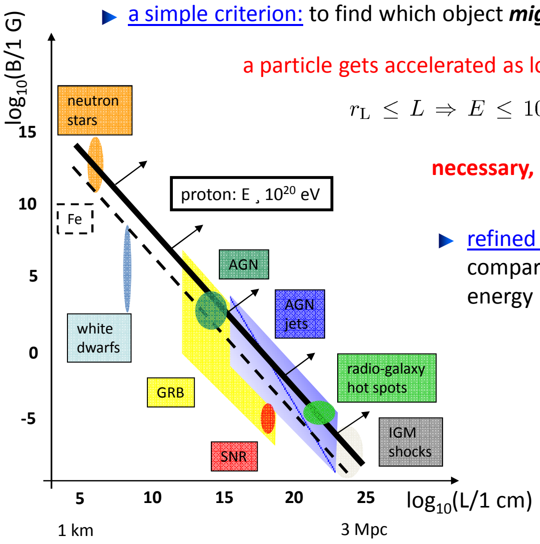
M. Lemoine & E. Waxman, arXiv:0907.1354, **JCAP 0911:009**

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:

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

necessary, but by no means sufficient!

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

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

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…

Testing the chemical composition on the sky

▶ Assume: (i) one observes an excess of events in $\Delta\Omega$ over isotropic expectations at E > E_{thr}: $\Delta N \,=\, N_{\rm obs}(>E_{\rm thr}) - N_{\rm iso}(>E_{\rm thr}) \,>\, \sqrt{N_{\rm iso}}$

(ii) at E > E_{thr}, the anisotropy signal is made of heavy nuclei, charge Z

(iii) the source(s) also produces protons, up to some energy E $\ll$ E_{thr}

▶ Then:

- there exist protons at energy E_{thr}/Z because E_{max}(p) $\gtrsim$ E_{max}(Z)/Z

  indeed: if E_{max} determined by confinement, escape, age or dynamical timescale, then E_{max} (p) = E_{max}(Z)/Z

  if E_{max} determined by energy losses then E_{max}(p) $\gtrsim$ E_{max}(Z)/Z

- at E_{thr}/Z < E < E_{max}(p), the ratio q_p(E) / q_Z(E) $\gg$ 1

  indeed: at Galactic cosmic ray source, q_p(E)/q_{iron}(E) $\sim$ 15

- the protons at E_{thr}/Z have the same rigidity than the nuclei at E_{thr}…
  they follow the same path in intervening magnetic fields…
  they thus produce a similar anisotropy pattern, up to the increased background noise (from the isotropic flux) and elemental ratio

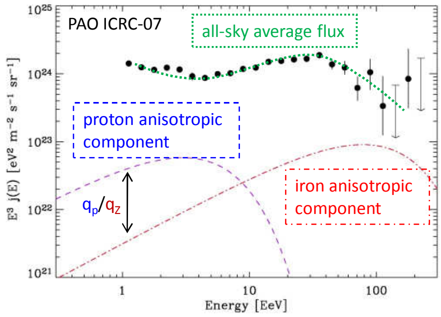
Testing the chemical composition on the sky

▶ Example:

source(s) contributing 10% of flux above 60EeV with iron nuclei,

E_{max} = 3 Z EeV, index s=2.0

composition ratio q_p : q_Z = 1: 0.06



▶ Signal to noise ratio of anisotropy pattern: $\Sigma_Z(>E_{\rm thr}) \,=\, \dfrac{\Delta N(>E_{\rm thr})}{\sqrt{N_{\rm iso}}}$

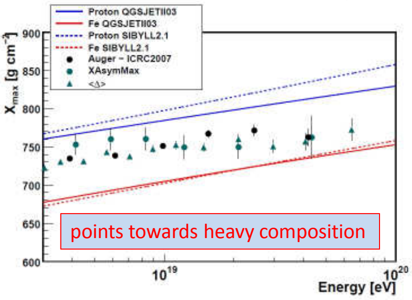
▶ Compute signal to noise ratio of anisotropy for protons at >E_{thr}/Z:

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

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

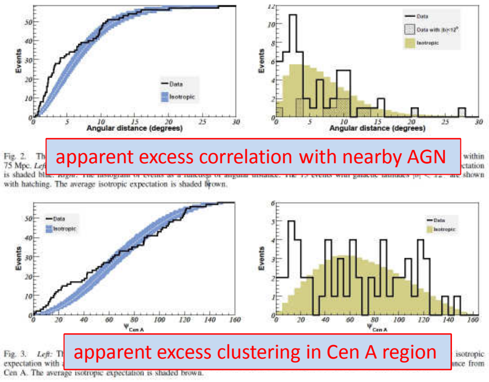
Pierre Auger data (ICRC 2009)

Wahlberg et al. 09 : chemical composition



points towards heavy composition

Hague et al. 09 : anisotropies



apparent excess correlation with nearby AGN

apparent excess clustering in Cen A region

▶ Cautionary notes:

- HiRes reports pure proton composition above 10^{19} eV (Belz et al. 09)
- $P_{coincidence} \simeq$ 1% for correlation with nearby AGN for isotropy
- clustering toward Cen A is noted a posteriori

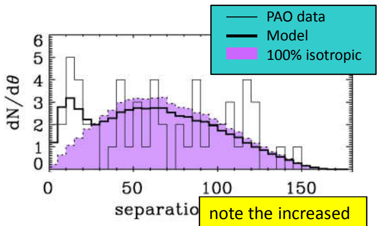
Angular clustering toward Cen A

▶ PAO results: 12 events within 18° of Cen A, but 2.7 expected if isotropic arrival directions

▶ Model: source(s) centered on Cen A, injecting iron at UHE, angular image of size $\delta\theta$ = 10° contributing 10% of flux above 60EeV

Histogram of #events
vs angular separation to CenA

E > 55 EeV



note the increased number of events

▶ Proton contribution: compute signal expected at 55/26 = 2.2 EeV from protons accelerated in source(s)….

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} / $dN_{isotropic}$

anisotropy signal
at 2 EeV at
many sigma level…

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

Discussion and implications

- Test of the chemical composition on the sky: predict a strong to very strong anisotropy around the ankle if anisotropy is detected at GZK energies *and* the composition at GZK energies is heavy...
  this argument does not depend on the modelling of intervening magnetic fields...

- Possible interpretations of the PAO data:
  - the anisotropy signals at >55EeV are not real: clustering toward Cen A is an accident, correlation with nearby AGN a coincidence... to be determined by future data!
  - the anisotropy at >55EeV is real: if anisotropies do not exist at smaller energies, the anisotropic part of the flux cannot be heavy nuclei $\Rightarrow$ light composition above 55EeV
    - the composition switches from mixed/heavy to light at 30-50 EeV? (note that the PAO sees the ankle at 4EeV...)
    - composition measurements are inaccurate, due to lack of statistics... or **systematic errors?**... to be determined by future data!
    - what about the sources of the highest energy cosmic rays?

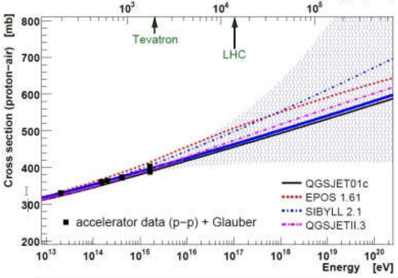
      radio quiet and radio loud AGN are disfavored by present data
      ... best model to date: bursting sources in ordinary galaxies
      (e,g, gamma-ray bursts, magnetars)

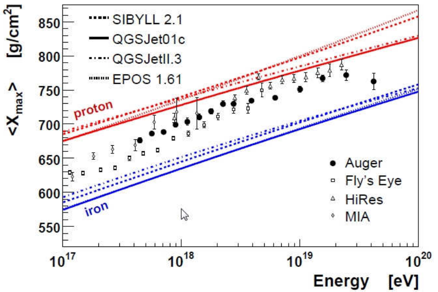
Heavy vs light composition and fundamental physics

- Uncertainties in the extrapolation of the pp cross-section to high energies:

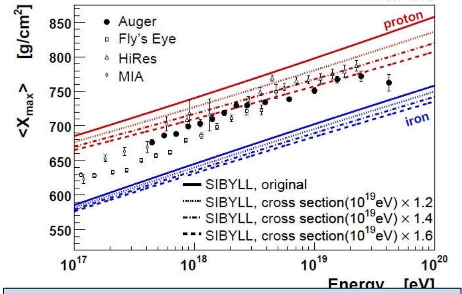
... existing X_{max} results could be reconciled with a pure proton composition if the p-p cross-section at energies $s^{1/2} \gtrsim$ 100 TeV is underestimated by $\sim$ 40-60%

(Wibig 08, Ulrich et al. 09, but see Wibig 09)





current estimates for σ_{pp}



$\sigma_{pp} \times [1 + a \log(E/E_0)]$ with a $\simeq$ 0.5, E_0=10EeV

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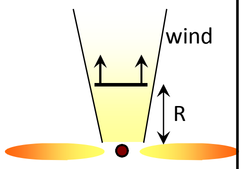
Acceleration – a luminosity bound

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

$\mathcal{A}$ > 1 is expected:



- non-relativistic Fermi I: $\mathcal{A} \sim \frac{g}{\beta_{\rm sh}^2}$
  with $\mathcal{A}$ > 1, g $\gtrsim$ 1 at most (Bohm diffusion): $g = \frac{D}{r_{\rm L} c}$
- non-relativistic Fermi II: $\mathcal{A} \sim \frac{g}{\beta_{\rm A}^2}$
- mildly relativistic Fermi I ($\Gamma_{\rm sh}\beta_{\rm sh} \sim$ 1): $\mathcal{A} \sim g$
- ultra-relativistic Fermi I:
  expect $\mathcal{A} \sim \frac{1}{\Gamma_{\rm sh}} \frac{r_{\rm L}}{\Gamma_{\rm sh}\lambda_B} \gg \frac{1}{\Gamma_{\rm sh}}$
  ($\mathcal{A} \propto r_{\rm L}$: inefficient acceleration at high energies)
- shear acceleration: $\mathcal{A} \sim \frac{\Delta r^2}{\Delta\beta^2 r_{\rm L}^2 g}$
  (if Δr $\sim$ r, $\mathcal{A}$ > 1 and $\mathcal{A}$ becomes g/$\Delta\beta^2$ at the deconfinement limit)

Acceleration – a luminosity bound

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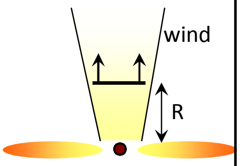
  - acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm L}$

    $\mathcal{A} \gtrsim 1$, $\mathcal{A} \sim 1$ 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: $t_{\rm acc} \leq t_{\rm dyn} \Rightarrow E_{\rm obs} \leq \mathcal{A}^{-1} ZeBR/\beta$
  - '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: $L_{\rm tot} \geq 0.65 \times 10^{45}\, \Theta^2\Gamma^2\mathcal{A}^2\beta^3 Z^{-2} E_{20}^2\, {\rm erg/s}$

    10^{45} ergs/s is robust: for $\beta \to 0$, $\mathcal{A}^2\beta^3 \geq 1/\beta \geq 1$

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

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

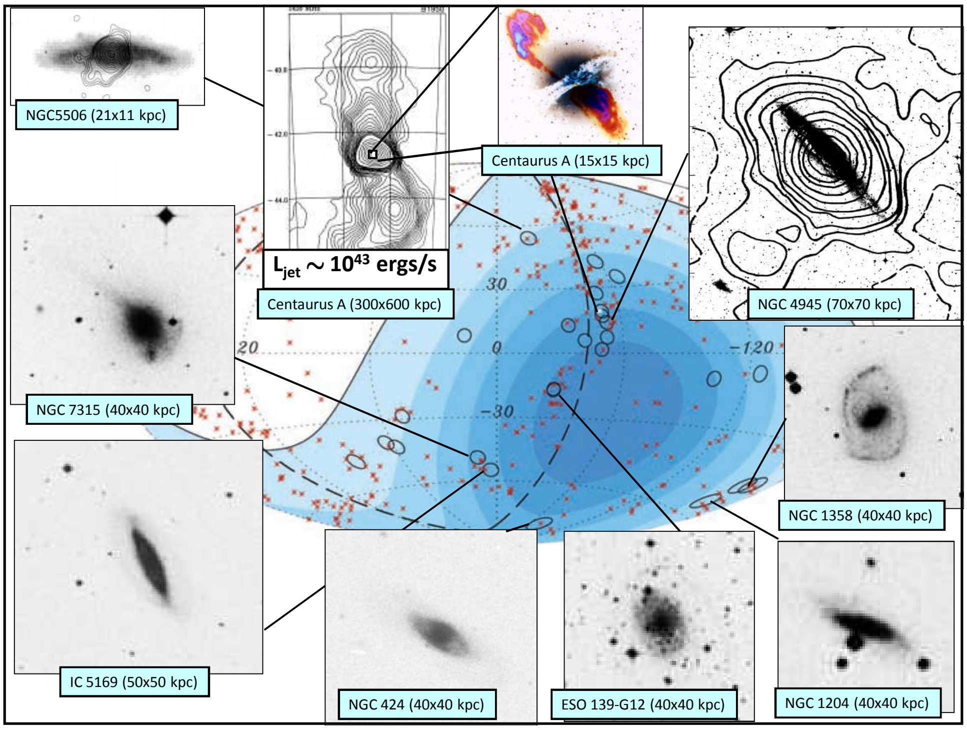
  low luminosity AGN: $L_{bol} < 10^{45}$ ergs/s

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

  high luminosity AGN: $L_{bol} \sim 10^{45}$-10^{47} ergs/s

  gamma-ray bursts: $L_{bol} \sim 10^{51}$ ergs/s

  ⇒only most powerful AGN jets, GRBs or magnetars



Acceleration – in FR-I radio-galaxies?

- search for radio-galaxy counterparts: (Fargion 08, Gorbunov et al. 08, Kachelriess et al. 08, Becker & Biermann 08, Hardcastle et al. 08)
  - 5 FR-I radio-galaxies, 2 intermediate FR-I/FR-II, 1 BL Lac/Sey1 within 3.5°, out of a PAO sample of 27 events… (Moskalenko et al. 08, Nagar & Matulich 08)
- Centaurus A:
  - angular clustering around Cen A (FR I):

    2 events within 3º

    3 events within 6º (Gorbunov et al. 08)

    9 events within 20º

    ⇒either Cen A is a source,

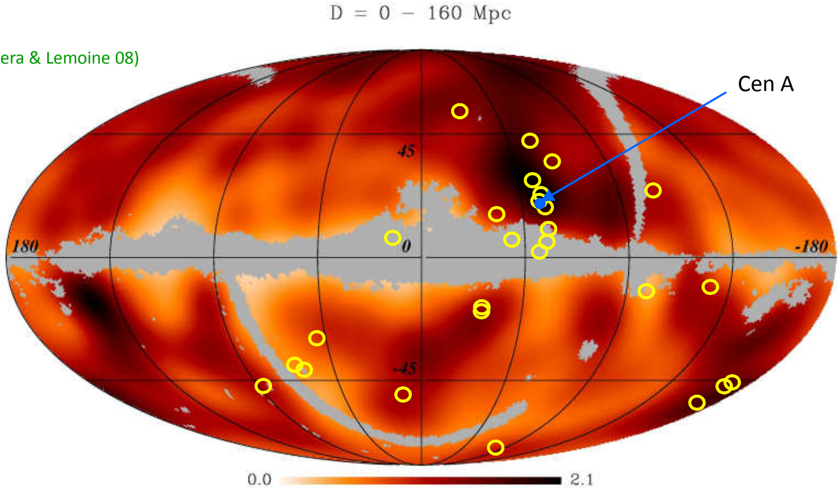
    or sources concentrate in the direction to Cen A

    (Kotera & Lemoine 08, Ghisellini et al. 08)

PAO results – correlation with large scale structure

- Expected flux map (per solid angle) if sources distribute as the PSCz galaxies:

(Kotera & Lemoine 08)



PAO arrival directions exclude isotropy (99% cl) but are consistent with a distribution of sources that follows LSS (preferentially with bias) (Kashti & Waxman 08)

Largest concentration … toward Cen A

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    ⇒**either Cen A is a source,**

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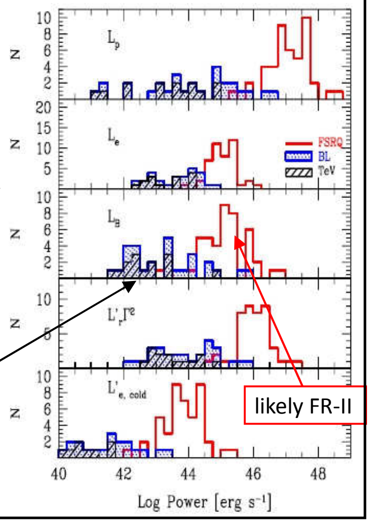
    (Kotera & Lemoine 08, Ghisellini et al. 08)
  - acceleration in Cen A?

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

    ⇒**too small to account for 10^{20} eV ...**
  - 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: $L_B \sim 2\times10^{42}$ erg/s (Lenain et al. 08)



likely FR-II

Acceleration – in proton blazars?

- Hadronic emission models for blazars:
  - a detailed modeling of VHE emission from Cen A in the framework of hadronic models is still lacking... but B is generally 1-2 orders of magnitude larger than in leptonic models

    ⇒hadronic BL Lac objects may satisfy the lower bound on L_B (Rachen 08)
  - flares up to 10^{46} erg/s in Cen A might also lead to production of UHECR... (Dermer et al. 09)
  - if acceleration of UHECR occurs in the blazar zone, the particle loses its energy through expansion losses unless excape occurs through p+$\gamma\rightarrow$ n+π conversion, with the neutrons decaying back to protons at λ_n = 0.9Mpc E/100EeV...
    (or protons decouple because B falls dramatically beyond blazar zone)

    but PAO reports no significant correlation with blazars (Harari et al. 07)...
  - blazars are too rare to account for the events of PAO: number of observed events and lack of multiplets implies lower limit on source density

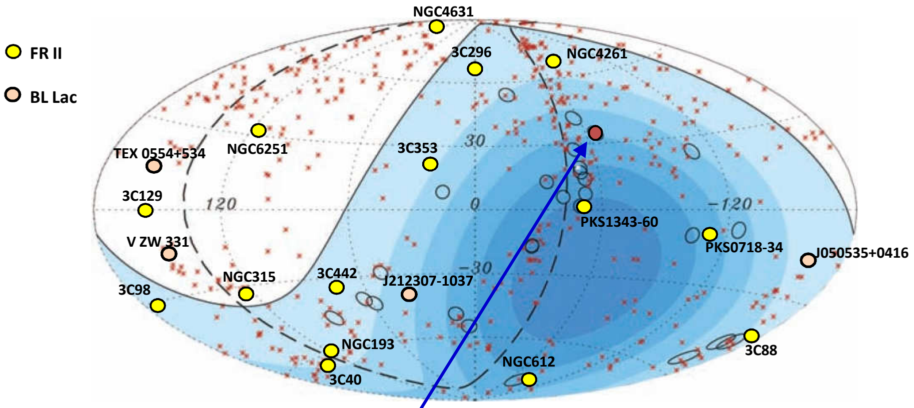
    $n_s \geq 2\ 10^{-6}$ Mpc^{-3}

Acceleration - in remote FR-II?

(e.g. Rachen & Biermann 93)

▶ Distribution on the sky of FR-II galaxies located within 130Mpc:

(Massaglia 07)



highest energy PAO event : E = 1.48 ± 0.27 × 10^{20} eV

(not counting the systematic uncertainty on energy calibration: 22%)

closest FRII: NGC4261, PKS1343-60, separation: 30°

closest blazar (with identified z): TEX0554+534, separation: 115°

Acceleration in Cen A jets and lobes?

▶ Acceleration in jets:

- the confinement limit $E_{max} \sim 10^{20}$ eV $Z\Gamma$ (BR/0.1 G pc) can be reached if the magnetic luminosity exceeds $L_B \simeq 0.2 \times 10^{45}\,\mathrm{erg/s}\, B_{100\,\mu\mathrm{G}}^2 R_{1\,\mathrm{kpc}}^2 \beta_{0.3}$
- accounting for self-generation of magnetic field by streaming cosmic rays, one finds that $E_{max} \sim 10^{20}$ eV can be reached if $L_{jet} \gtrsim 10^{46}$ erg/sec (Berezkho 09)

▶ Acceleration in lobes: (Hardcastle et al. 09)

- acceleration timescale: $t_{\rm acc} \simeq \dfrac{t_{\rm scatt}}{\beta_{\rm sc}^2}$

  ... for typical parameters: $n \sim 10^{-4}$ cm^{-3}, $B \sim 1\ \mu$ G, size $L \sim 100$ kpc, balancing t_{acc} at Bohm limit and t_{esc} gives:

  $$E_{\rm max} \simeq 10^{14}\,\mathrm{eV}\, B_{1\,\mu\mathrm{G}}^3\, n_{-4}^{-1}$$

  ⇒ requires $n \ll 10^{-4}$ cm^{-3} (O'Sullivan et al. 09)

- data suggests that E_{max} for electrons is $\sim 10^{11}$ - 10^{12} eV...
  But, if $t_{acc} \sim t_L$ then the maximal energy for electrons would be $\sim 10^{16}$ eV...

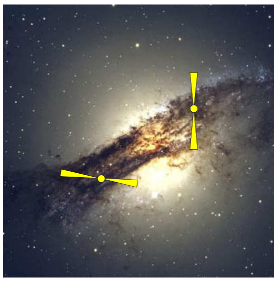
  ⇒ stochastic acceleration appears inefficient...

Bursting sources in the host galaxy of Cen A

▶ Contribution to the flux from GRBs or magnetars in Cen A?

- GRB rate in Cen A for arbitrary beam orientation: $\dot{N} \sim 10^{-5}\,\mathrm{yr}^{-1}$

  for beams pointing to Earth: $\dot{N}_{\to \mathrm{Earth}} \sim 10^{-7}\,\mathrm{yr}^{-1}$?



- expected magnetic deflection in intergalactic medium:

$$\delta\theta_{\rm IGM} \simeq 3^\circ\, B_{10\,\rm nG}\, \lambda_{100\,\rm kpc}^{1/2}\, E_{70\,\rm EeV}^{-1}$$

- time delay from Cen A to PAO:

$$\delta t_{\rm IGM} \simeq 6 \times 10^3\,\mathrm{yr}\, B_{10\,\rm nG}^2 \lambda_{100\rm kpc} E_{70\rm EeV}^{-2}$$

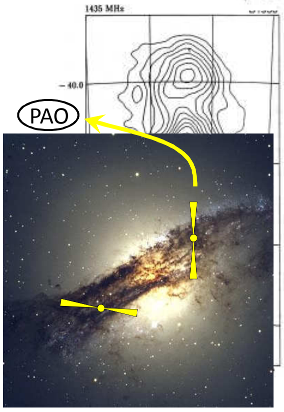
- average number of GRBs in Cen A seen directly in UHECR at any time:

$$N_{\rm GRB \to Earth} \sim 10^{-3}\, B_{10\rm nG}^2 \lambda_{100\rm kpc} E_{70\rm EeV}^{-2}$$

⇒ **highly unlikely to see direct UHECR from a GRB/magnetar in Cen A...**

Cen A GRBs with scattering on the lobes

▶ Accounting for the scattering on the lobes:



- angular deflection through crossing Cen A lobes:

$$\delta\theta_{\rm lobe} \simeq 54^\circ\, l_{100\,\rm kpc}^{1/2}\, B_{1\,\mu\rm G}\, \lambda_{100\,\rm kpc}^{1/2}\, E_{70\,\rm EeV}^{-1}$$

- time delay through interaction with lobes:

$$\delta t_{\rm lobe} \simeq 100\,\mathrm{kpc}/c \simeq 3 \times 10^5\,\mathrm{yr}$$

- number of GRBs seen through scattering on lobes:

$$\langle N_{\rm GRB|\,lobe} \rangle \simeq \dot{N}\delta t_{\rm lobes} \frac{\Delta\Omega_{\rm lobes}}{2\pi} \sim \mathcal{O}(1)$$

... through scattering on the lobes, UHECR emission from Cen A becomes continuous...

- flux from one GRB in Cen A after scattering on lobes:

$$j_{\rm CenA} \simeq 10^{-37}\, \underset{\boxed{10^{51}\ \mathrm{ergs}}}{\epsilon_{51}}\, E_{70\rm EeV}^{-2}\, \delta t_{5.5}^{-1}\, \underset{\boxed{\log(E_{\max}/E_{\min}) \sim \text{a few - 10}}}{f_\epsilon^{-1}}\, /\mathrm{eV/m^2/s}$$

∼ 2 - 25% of PAO flux within 10° of Cen A

∼ 0.25 → a few events for PAO

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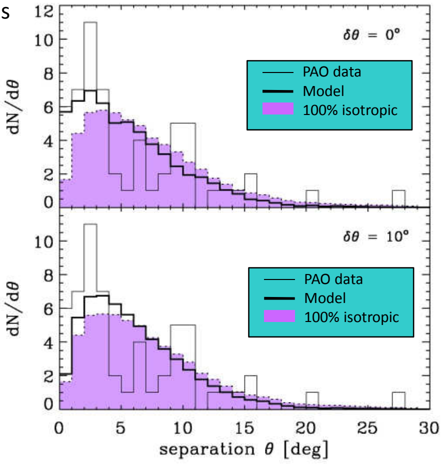
Correlation of PAO arrival directions with nearby AGN

- PAO results: 24 events out of 58 above 55EeV within 3.1° of an AGN (closer than 75Mpc)
- Model: 58 source(s) distributed as the galaxies of the PSCz survey, injecting iron at UHE, contributing 90% of the flux above 55EeV, with magnetic deflection $\delta\theta$=0° or 10°; remaining 10% flux is isotropic



Notes:

PAO: 12 events expected for isotropic arrival directions

$\delta\theta$= 0°: 19 events within 3.1°of an AGN closer than 75Mpc

$\delta\theta$= 10°: 14 events within 3.1°of an AGN closer than 75Mpc

model predict smaller # events than observed,
but discrepancy remains well within uncertainties

Expected correlation with AGN at energies >2 EeV

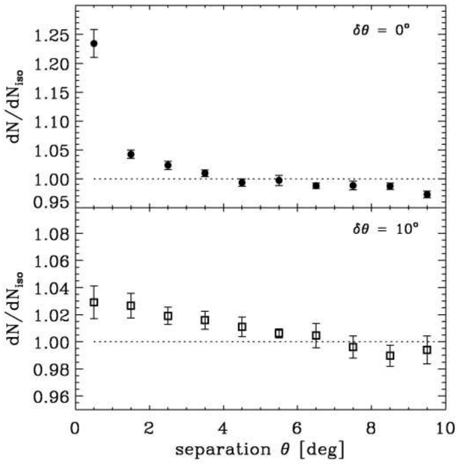
- Proton contribution at > 2.2 EeV: neglecting energy losses, spectrum s=2.0, composition ratio $q_p : q_{Fe} = 1 : 0.06$

at E > 2.2 EeV, expected # events within 3.1° of an AGN closer than 75Mpc:

10100 for 100% isotropy

10730 for model with $\delta\theta = 0°$

10340 for model with $\delta\theta = 10°$



... anisotropy is much stronger at 2EeV than at 55EeV ...