# Astrophysics of ultra-high energy cosmic rays

Martin Lemoine

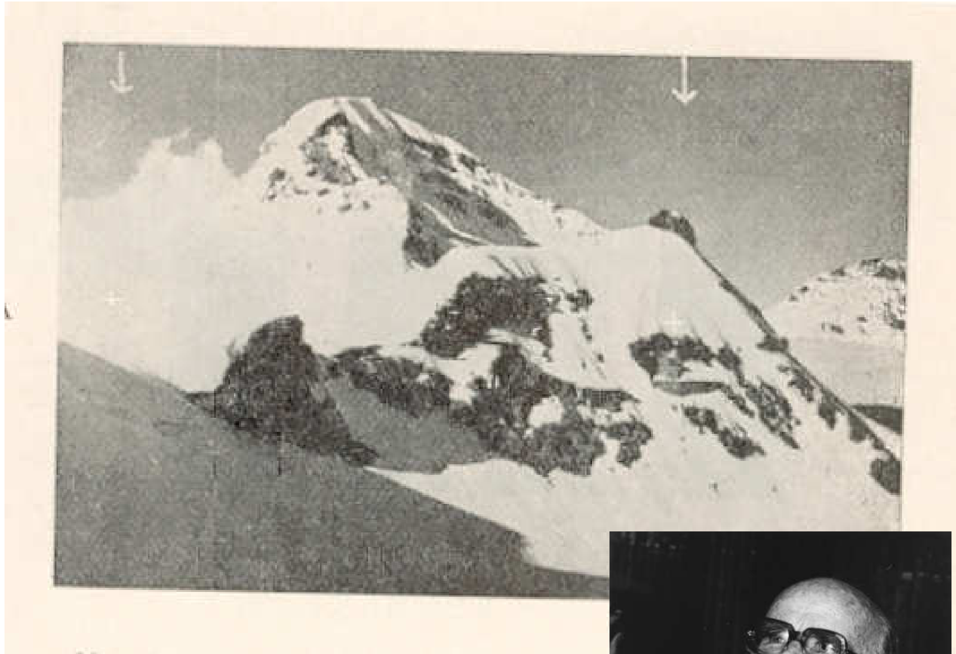
Institut d'Astrophysique de Paris

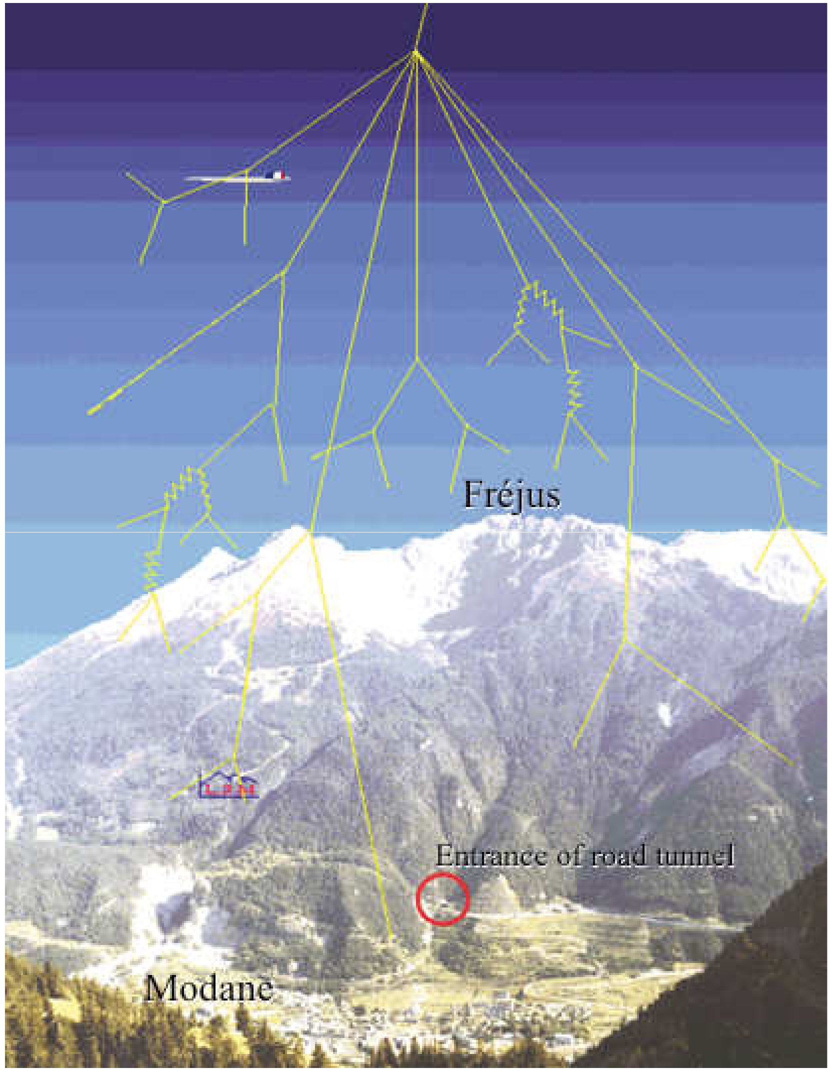
CNRS, Université Pierre & Marie Curie

# Introduction - giant air showers

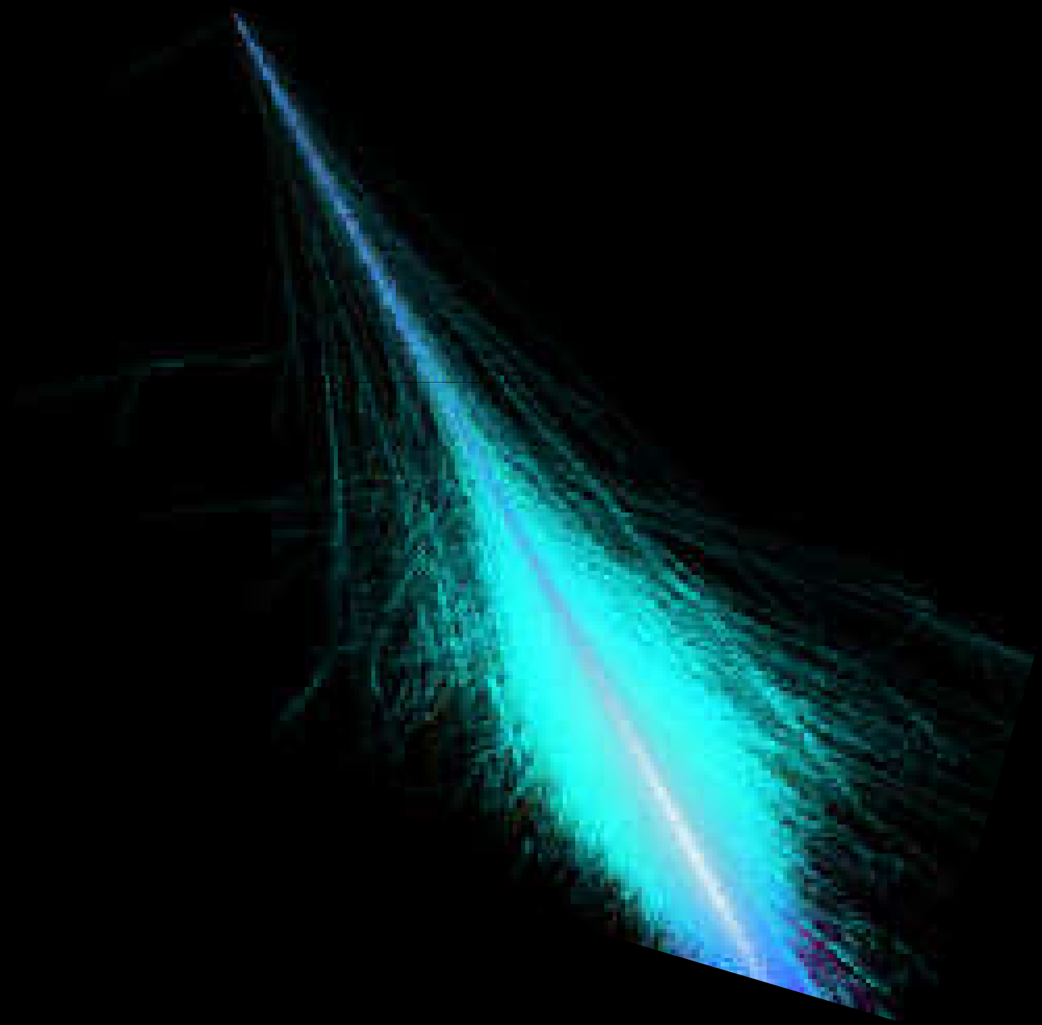
- (P. Auger 1938) :

  timing coincidence experiments lead to the detection of giant air showers with energy $\gtrsim 10^{15}$ eV…

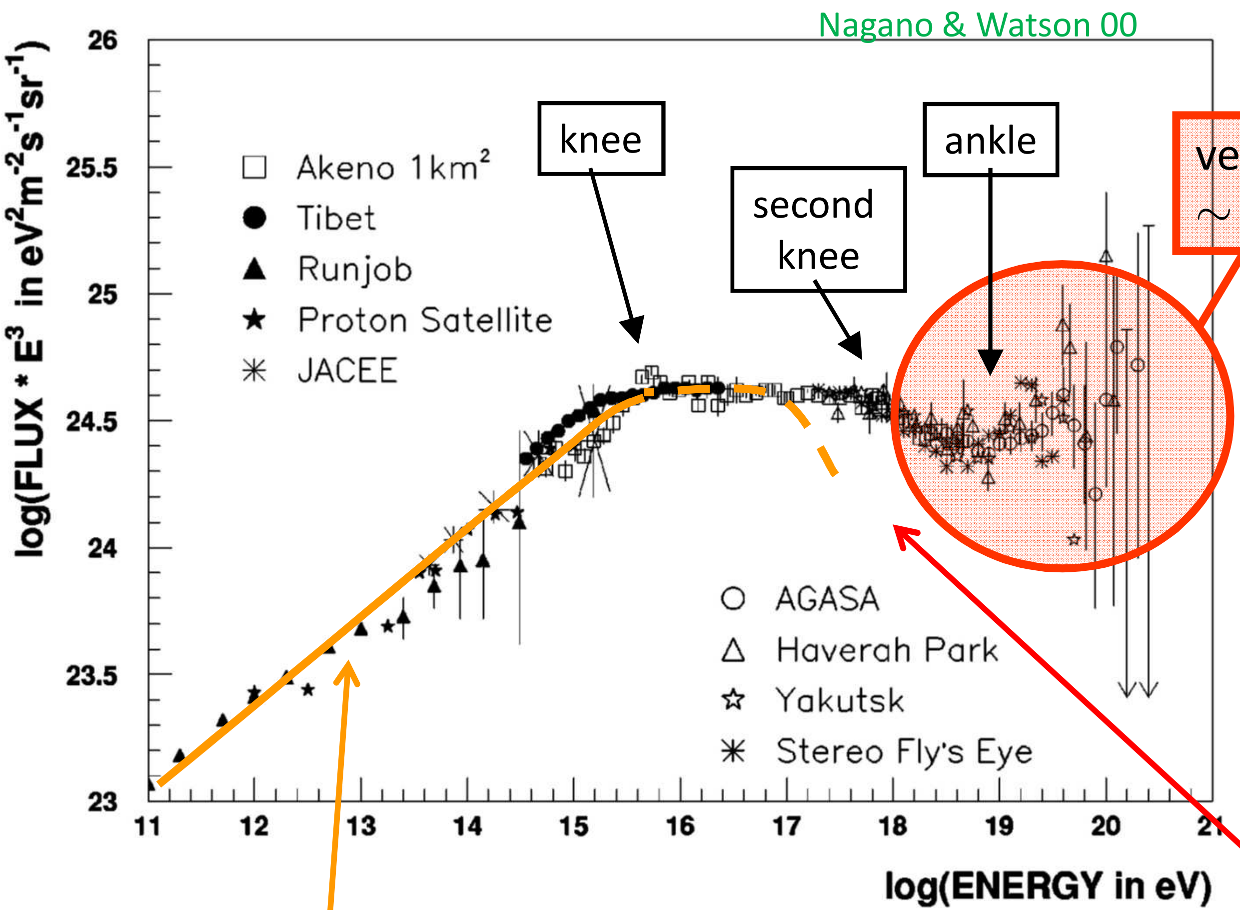




# Introduction - giant air showers



# Introduction - all particle CR spectrum

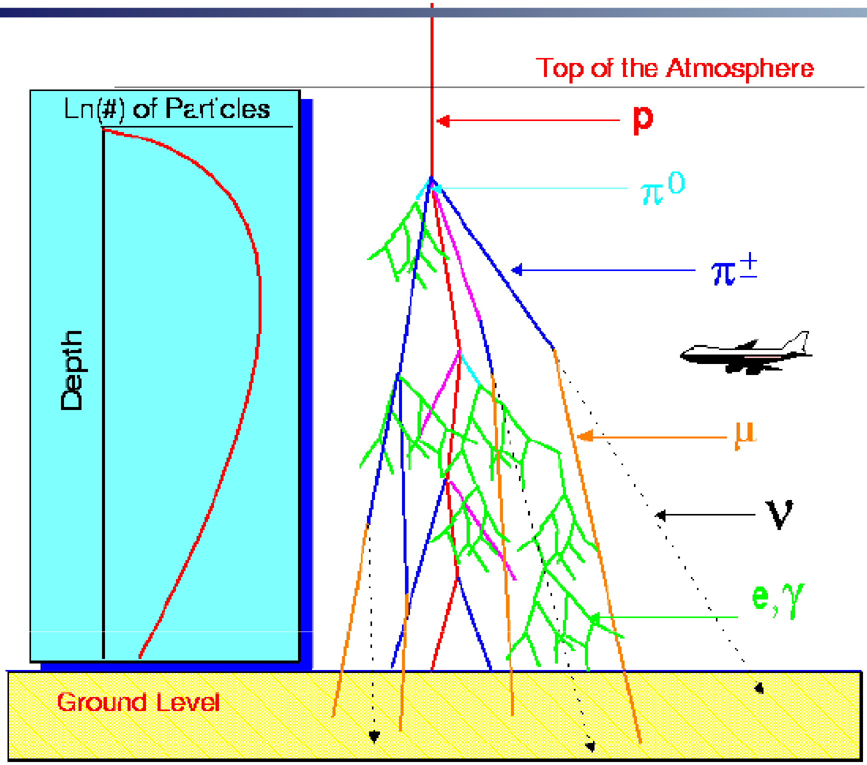


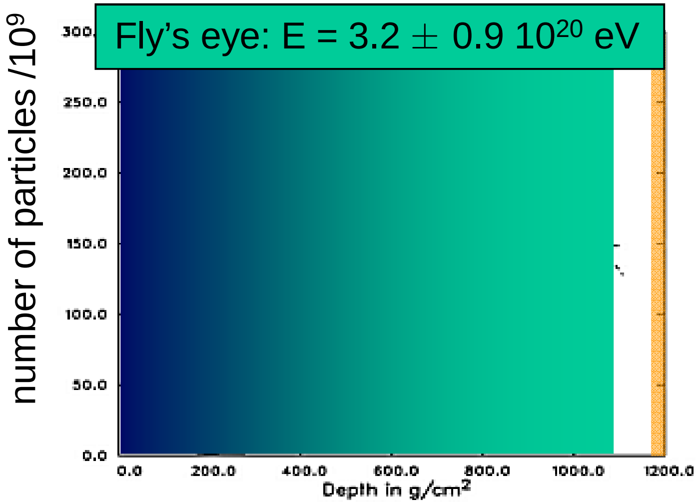

very small flux at UHE: $\sim$ 1/km$^2$/century at $10^{20}$eV

‘low’ energy cosmic rays likely originate in Galactic supernovae remnants …

**at ‘high’ energy... ???**
**where does 'high' energy starts?**
**where do the cosmic rays come from?**
**how many different components ?**

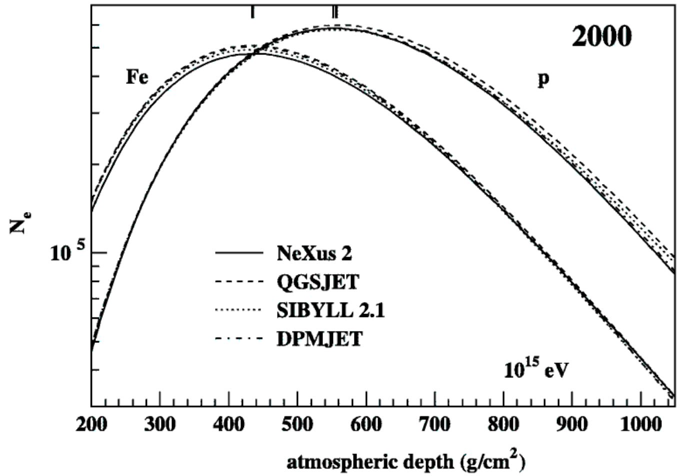
# Longitudinal shower profile

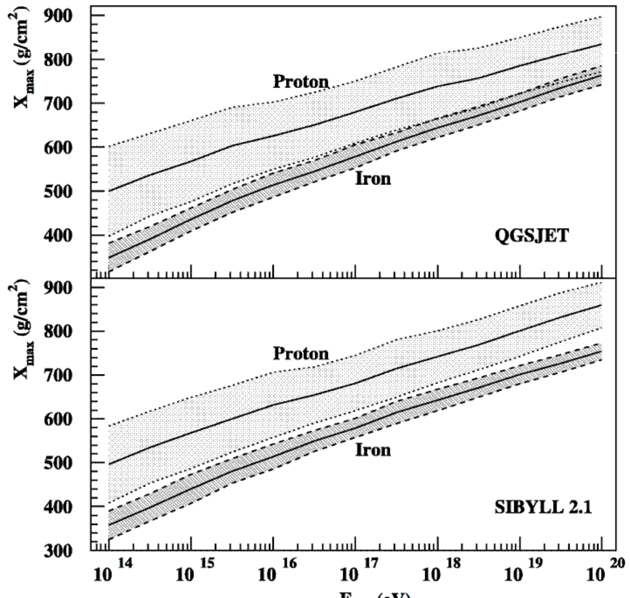



← upper atmosphere ground →

$X_{max}$

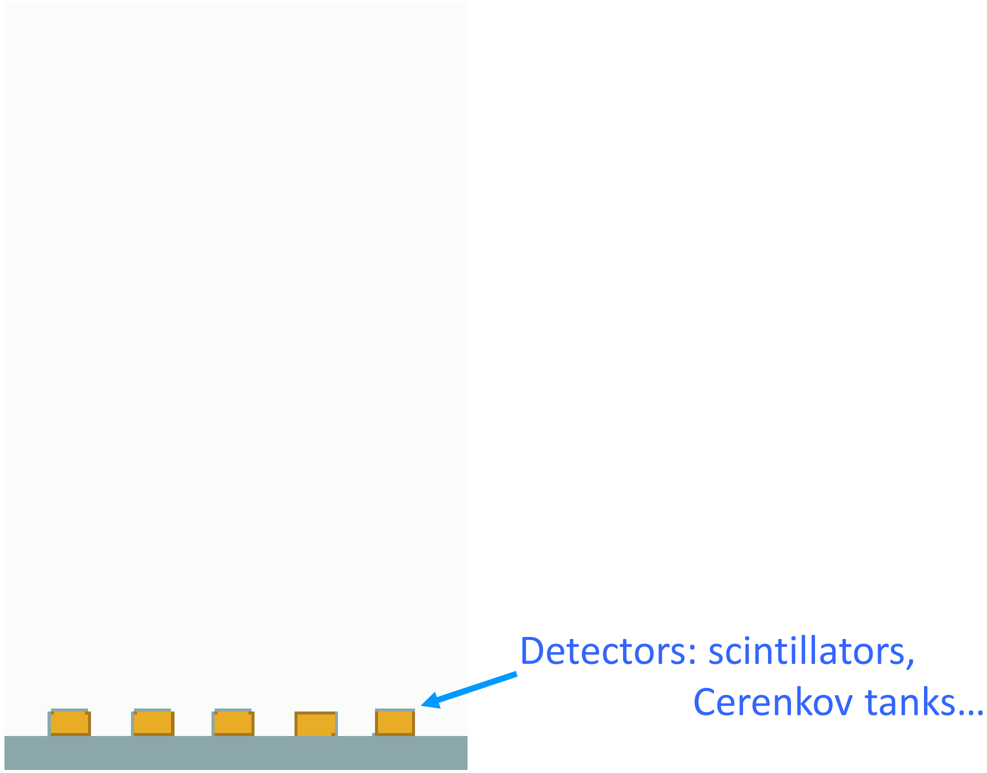


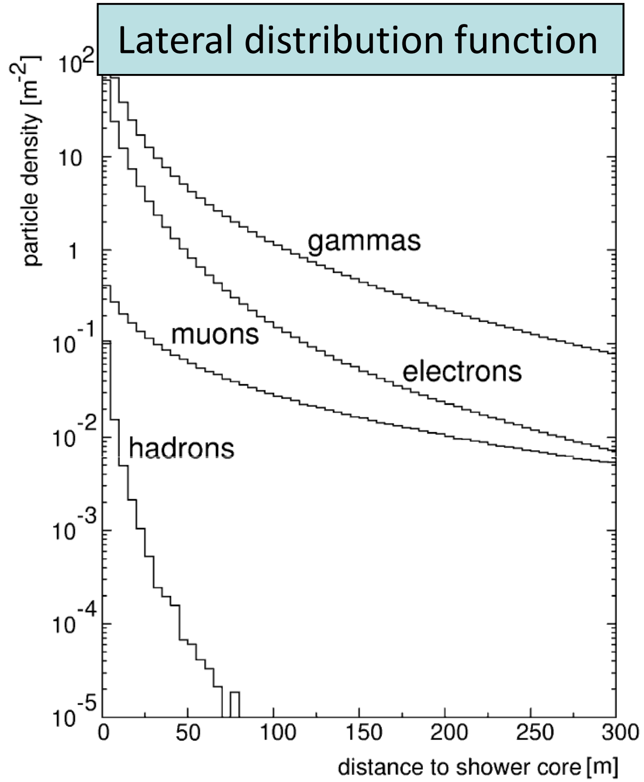




Note: strong fluctuations

... Fe-p discrimination on sample of events

# Lateral shower profile



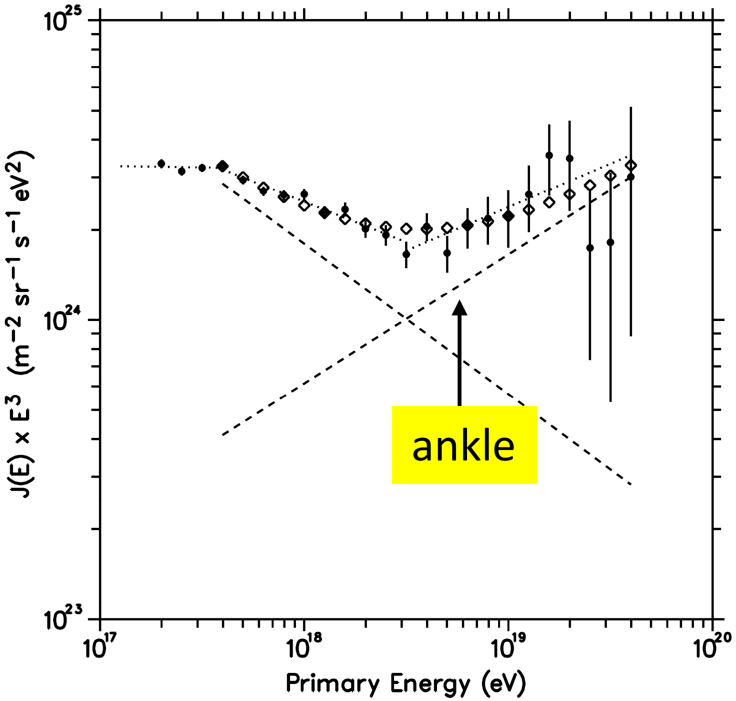

timing information on coincidence events $\rightarrow$ **geometry**

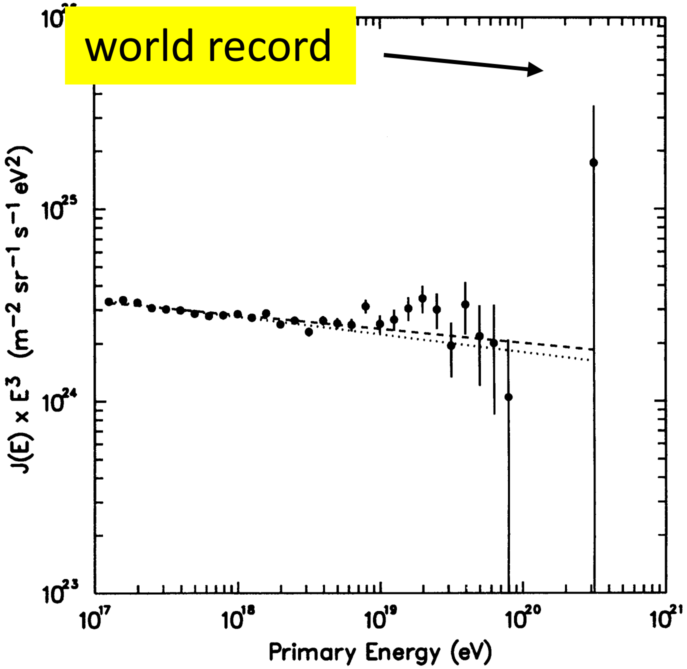
nature of secondaries $\rightarrow$ **nature of the primary**

lateral distribution function $\rightarrow$ **energy of the primary**

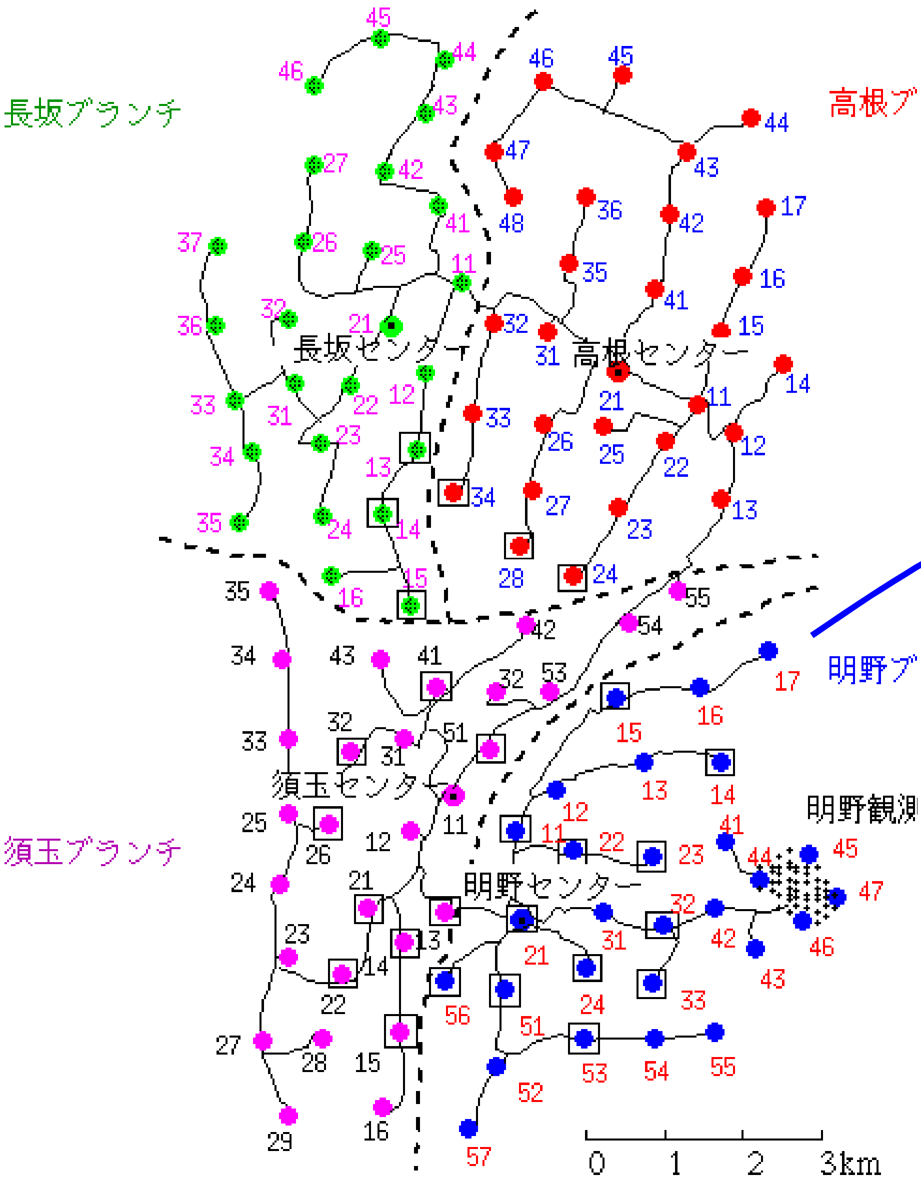
… Total energy in center of mass (for $10^{20}$ eV): $\sqrt{s} \simeq (2Em_pc^2)^{1/2} \sim 4 \times 10^{14} E_{20}\,\mathrm{eV}$

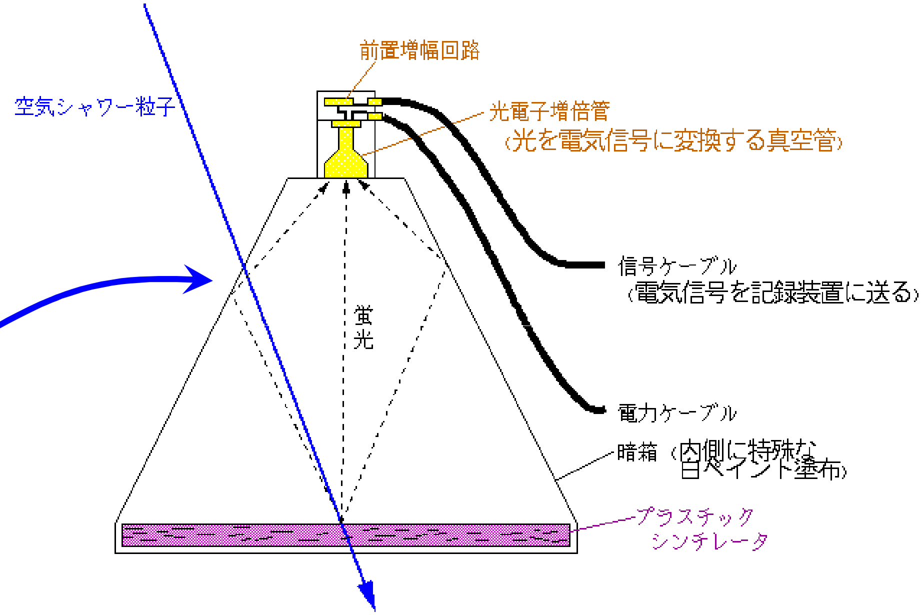
# Fly's Eye (1981 - 1993)



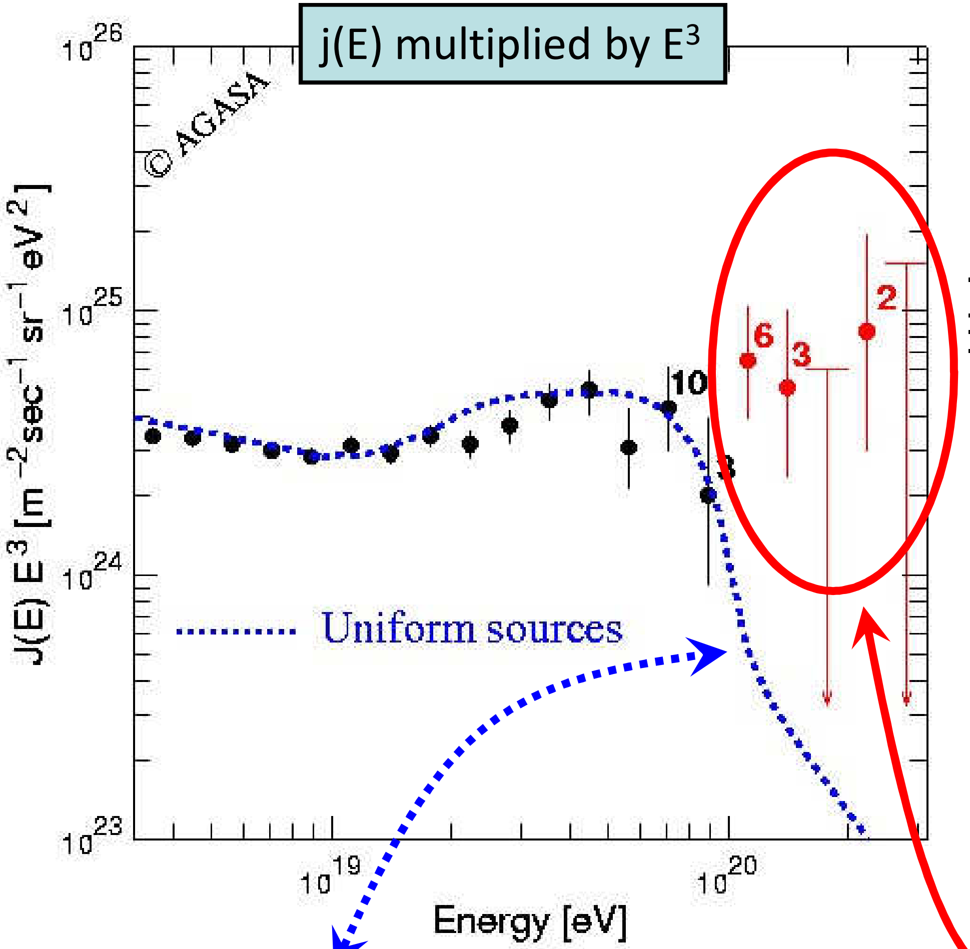



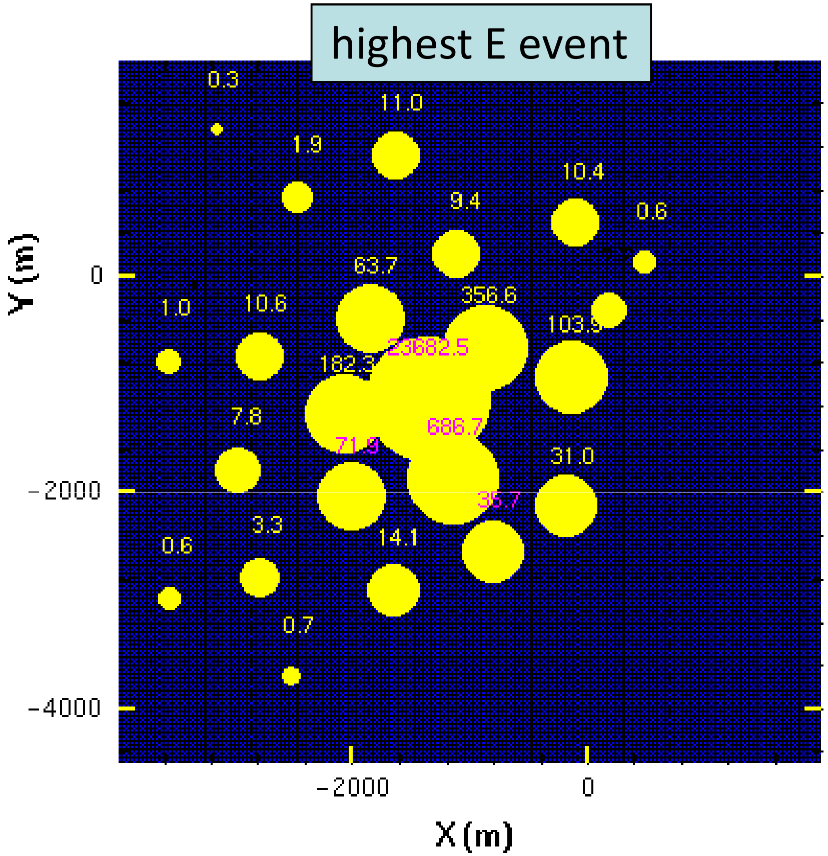
# The Akeno Giant Air Shower Array (AGASA)



# Energy spectrum measured by AGASA (1992 - 2003)



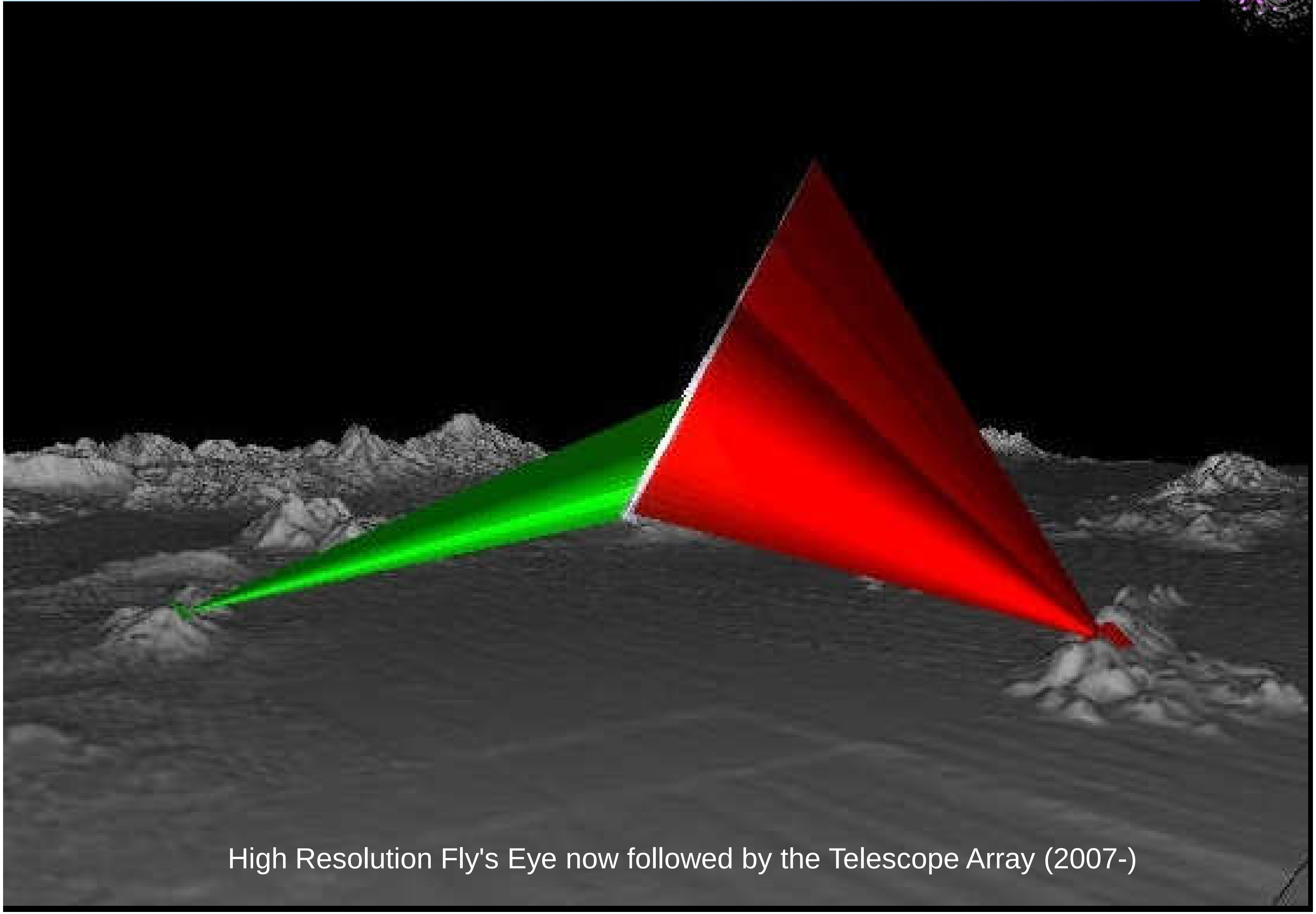




**signal expected from a population of sources located at cosmological distances**

**The mystery : trans-GZK events**

# High resolution Fly's Eye (1994-2000)

# Fluorescence telescopes

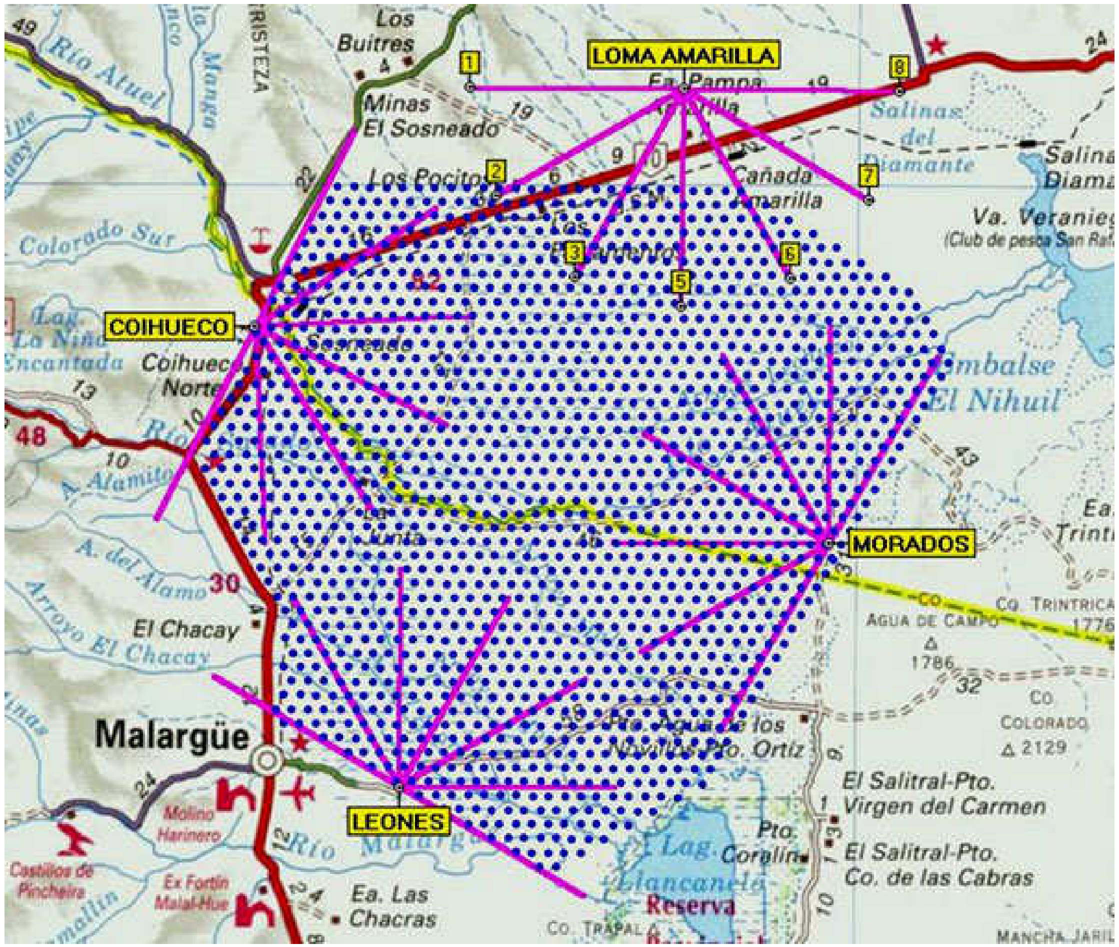


# Pierre Auger Observatory (2005-)

The Pierre Auger Observatory:

→ **the largest cosmic ray detector ever built : about 3000 km² !**

→ a combination of ground detectors and fluorescence detectors…



# Many questions ... a few hints...

- **What is the source of ultrahigh energy cosmic rays ?**

  ... what is the fundamental acceleration process to ultrahigh energies?

- **Where does the cosmic ray spectrum stop?**

  ... HiRes and Auger have detected a high energy cut-off at the expected location for the Greisen-Zatsepin-Kuzmin cut-off $\sim$ 6 $10^{19}$ eV

- **What are ultrahigh energy cosmic rays: protons, nuclei, photons, neutrinos?**

  ... the giant air showers are typical of hadronic showers

  ... HiRes sees protons at UHE, Auger sees an increasing fraction of heavies...?

- **Should we expect to see the source in the arrival directions of UHECR?**

  ... what are the effects of the Galactic and extra-galactic magnetic fields?

  ... no powerful source seen in the arrival directions of highest energy CR...?

  ... Auger has reported 99% c.l. detection of anisotropy of arrival directions!

- **Should we expect to detect photons/neutrinos/gravitational waves?**

  ... diffuse backgrounds detectable?

  ... any signal from arrival directions of UHECR ?

# Many questions ... a few hints...

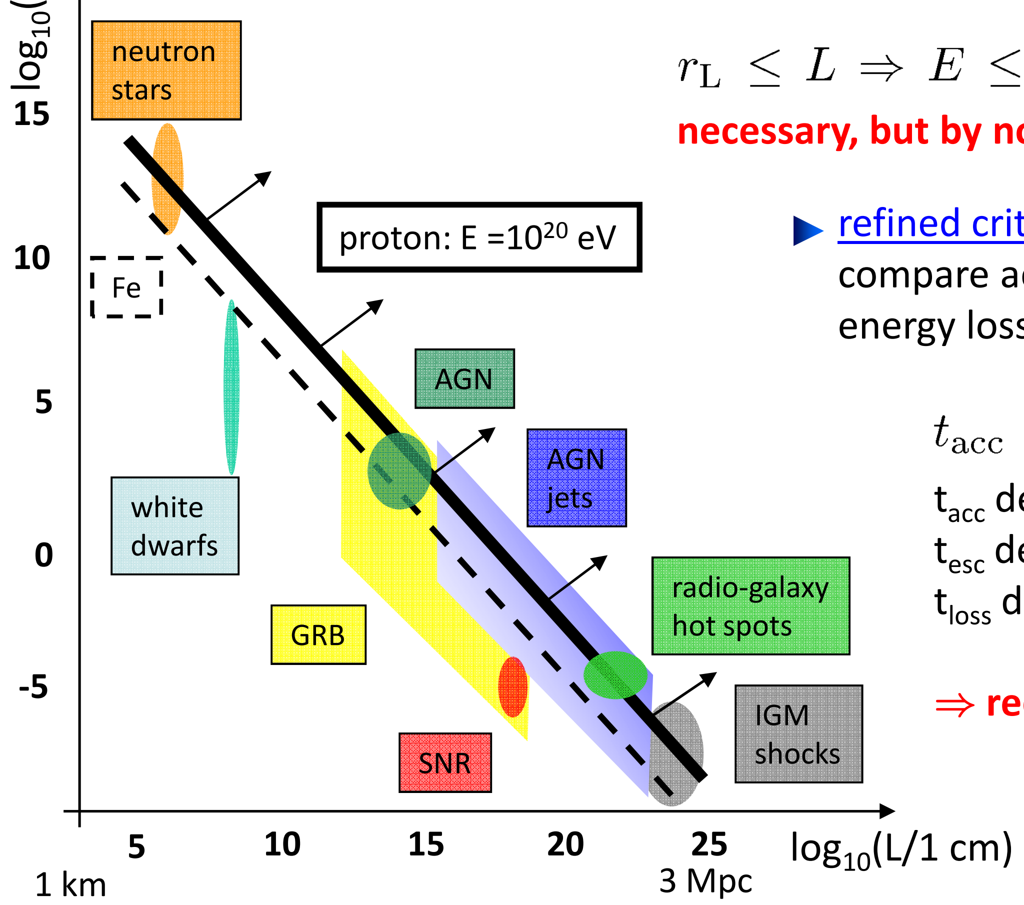
▶ **What is the source of ultrahigh energy cosmic rays ?**

▶ 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:

$$r_L \leq L \Rightarrow E \leq 10^{20}\,\mathrm{eV}\,Z B_{\mu G} L_{100\,\mathrm{kpc}}$$ Hillas 84

**necessary, but by no means sufficient!**




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

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

$t_{acc}$ depends on acceleration mechanism...
$t_{esc}$ depends on magnetic field...
$t_{loss}$ depends on environment...

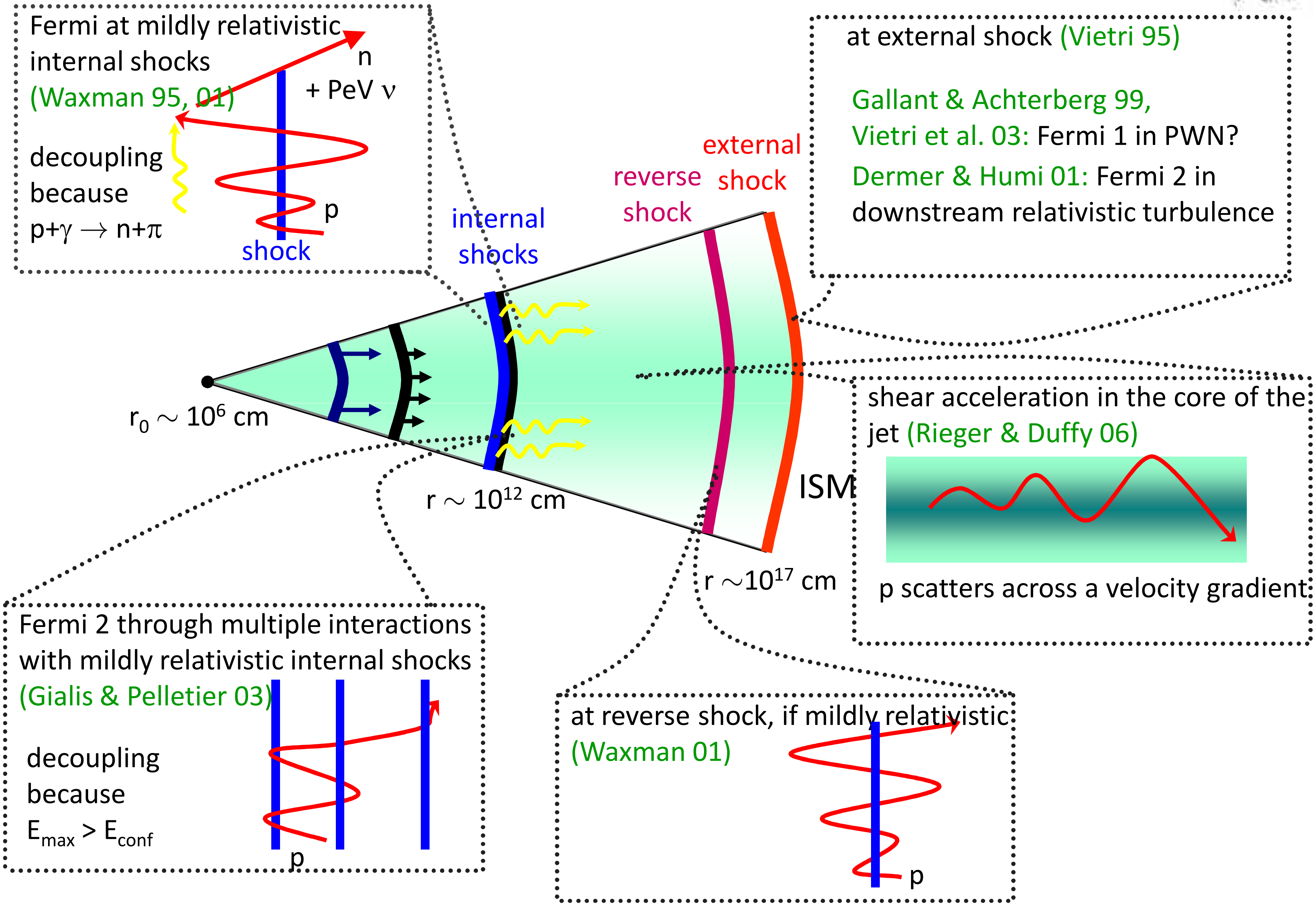
$\Rightarrow$ **requires an object by object study...**

Norman et al. 95

**... magnetars, gamma-ray bursts and giant radio-galaxies are promising candidates...**

$\rightarrow$ any signal from arrival directions of UHECR ?

# 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, 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:

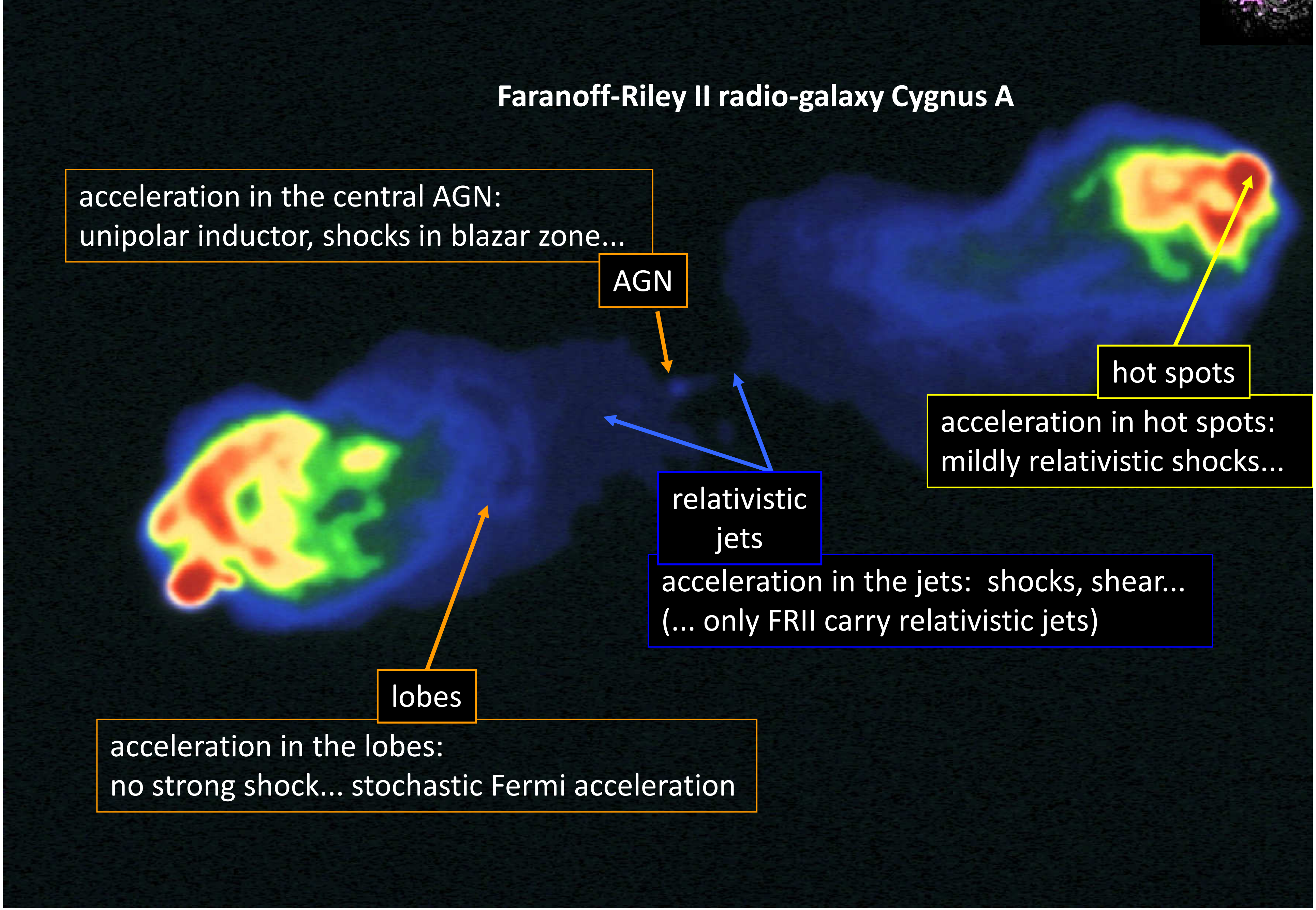
flux of UHECR above $10^{19}$ eV requires an energy input rate: $\sim$ **$10^{44}$ erg/Mpc$^3$/yr**

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

**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:**

→ 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)

→ only ~ 1% of AGN are radio-loud (jets / lobes)

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

⇒ FRII sources in steady state (e.g. Rachen & Biermann 93, ...)
or flaring FRI sources (e.g. Dermer et al. 08)

→ cumulative contribution of all radio-galaxies, e.g. Ptuskin 10

→ no apparent correlation with FRII sources

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

# Acceleration... source luminosity vs $E_{max}$

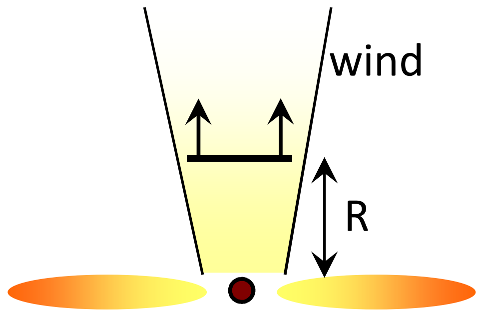
▶ A generic case: acceleration in an outflow (Lovelace 76, Norman et al. 95, Waxman 95, 05, Lyutikov & Ouyed 05, ML & Waxman 09)

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

**$\Rightarrow$ only most extreme sources for $10^{20}$eV protons...**

**...$E_{max}$ further constrained by energy losses...**

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

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

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

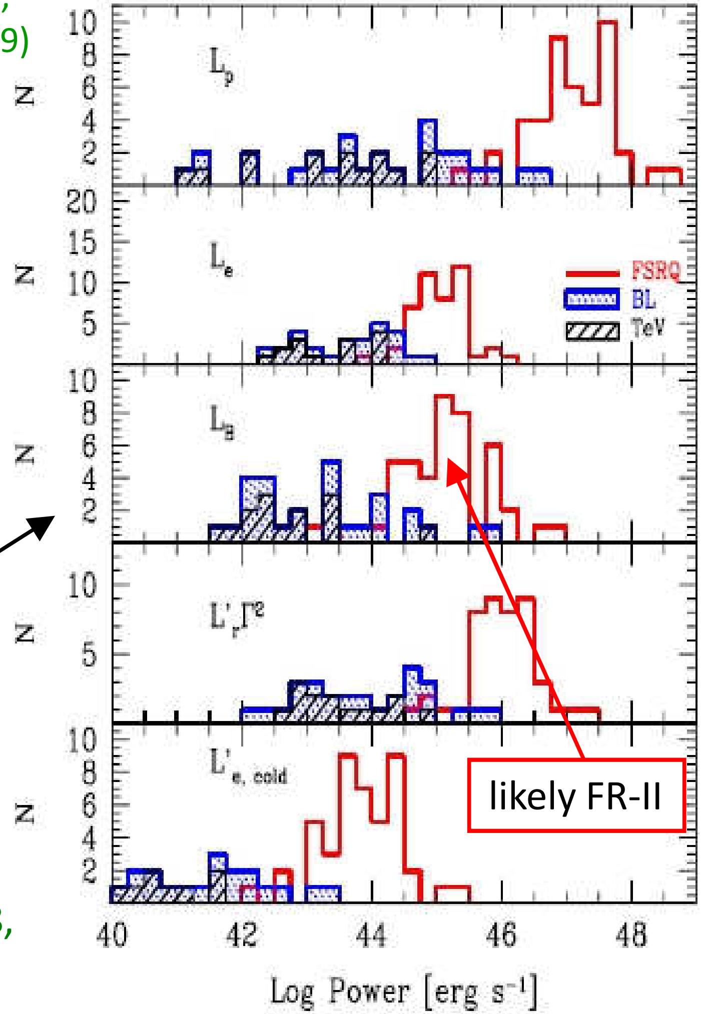
- more generally, leptonic models of the SEDs of blazars associated with FR-I radio-galaxies:

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

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

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

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




... however: PAO does not see correlation with nearby blazars (Harari 07)...
... energy losses in blazar zone? ...

**as an executive summary:**

$\rightarrow$ acceleration of protons to $10^{20}$ eV requires extraordinary conditions: magnetars, gamma-ray bursts, FRII radio-galaxies...

$\rightarrow$ magnetic luminosity: $L_B \gtrsim 10^{45} Z^{-2} E_{20}$ erg/s...

$\rightarrow$ much larger pool of candidates for acceleration of high Z nuclei...

# Many questions ... a few hints...

- **What is the source of ultrahigh energy cosmic rays ?**

  ... what is the fundamental acceleration process to ultrahigh energies?

- **Where does the cosmic ray spectrum stop?**

  ... HiRes and Auger have detected a high energy cut-off at the expected location for the Greisen-Zatsepin-Kuzmin cut-off $\sim$ 6 $10^{19}$ eV

- **What are ultrahigh energy cosmic rays: protons, nuclei, photons, neutrinos?**

  ... the giant air showers are typical of hadronic showers

  ... HiRes sees protons at UHE, Auger sees an increasing fraction of heavies...?

- **Should we expect to see the source in the arrival directions of UHECR?**

  ... what are the effects of the Galactic and extra-galactic magnetic fields?

  ... no powerful source seen in the arrival directions of highest energy CR...?

  ... Auger has reported 99% c.l. detection of anisotropy of arrival directions!

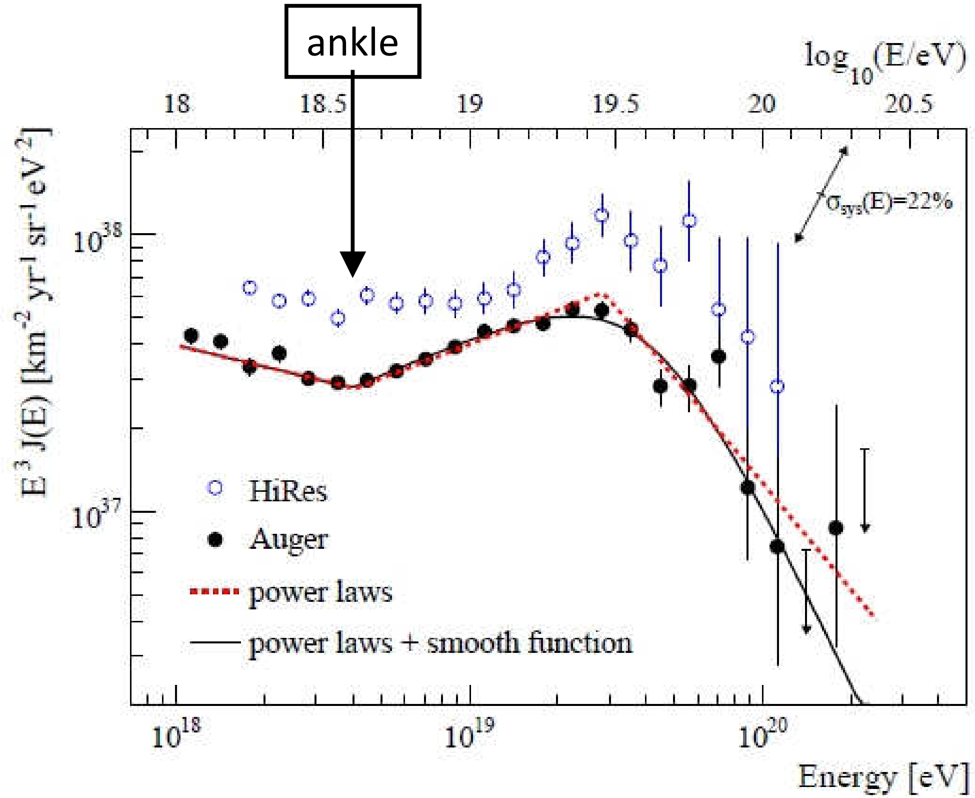
- **Should we expect to detect photons/neutrinos/gravitational waves?**

  ... diffuse backgrounds detectable?

  ... any signal from arrival directions of UHECR ?

# Many questions ... a few hints...

- What is the source of ultrahigh energy cosmic rays ?




Auger 2010
HiRes 2010

<u>Greizen-Zatsepin-Kuzmin cut-off:</u> CMB becomes opaque to pion production through $p + \gamma_{cmb} \rightarrow N + \pi$ for $E \gtrsim 6\ 10^{19}$ eV

... a similar cut-off for iron nuclei due to photodisintegration on CMB/IR, cut-offs at smaller energy for light nuclei...

$\rightarrow$ any signal from arrival directions of UHECR ?

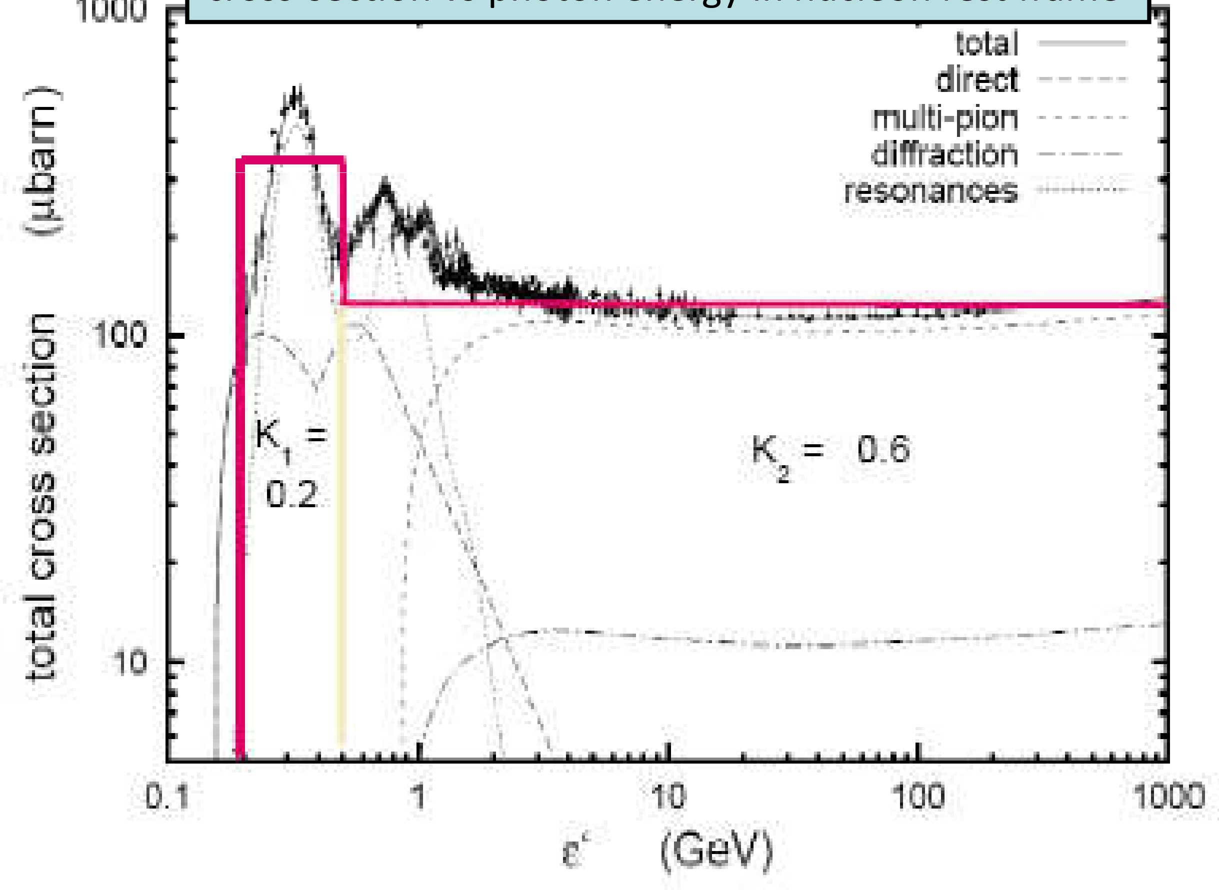
# Greisen – Zatsepin – Kuz'min cut-off

Greisen 66, Zatsepin & Kuzmin 66

UHE protons lose energy by interacting with cosmic microwave background photons to produce pions: $N + \gamma_{CMB} \rightarrow N' + \pi$

CMB photons $E_\gamma \sim 10^{-3}$ eV are seen as $\gamma$-rays in UHECR rest frame…

cross-section vs photon energy in nucleon rest frame



# Greisen – Zatsepin – Kuz'min cut-off

Threshold energy: reaction is permitted when

$$E'_\gamma \geq m_\pi c^2 \left(1 + \frac{m_\pi}{2m_p}\right)$$ nucleus rest frame

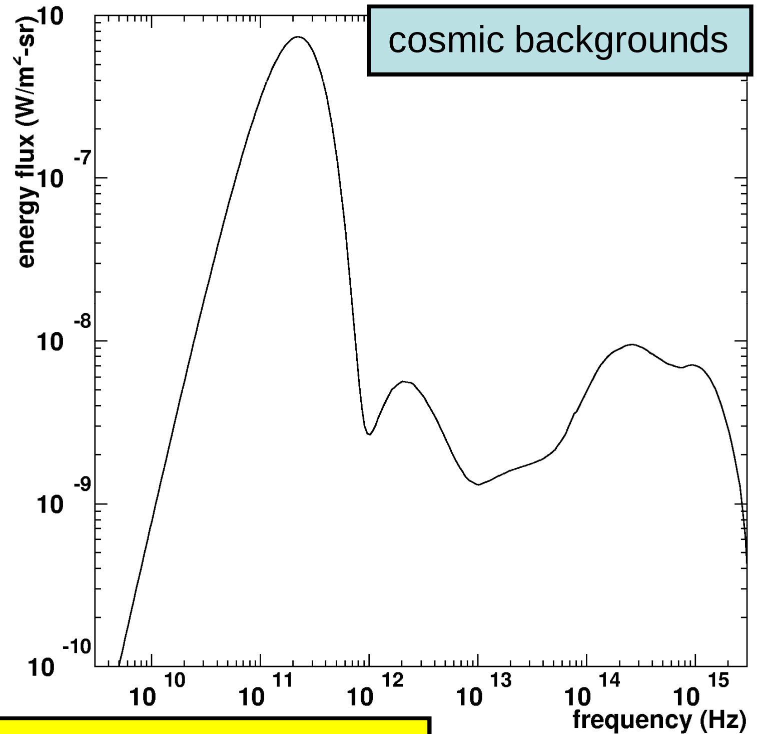
or, in the cosmic rest frame (frame where CMB is isotropic):

$$E_p \geq \frac{m_\pi (m_\pi + 2m_p) c^4}{2E_\gamma (1 - \cos\theta)} \simeq 6 \times 10^{19}\,\mathrm{eV}$$

Energy loss: $\epsilon \equiv \frac{\Delta E_p}{E_p} \sim \frac{m_\pi}{m_p} \sim 15\%$

Interaction length: $\lambda = \frac{1}{n_\gamma \sigma_{p\gamma}} \sim 8\,\mathrm{Mpc}$

Energy loss distance: $l_{loss} \sim \frac{\lambda}{\epsilon} \sim 50\,\mathrm{Mpc!}$

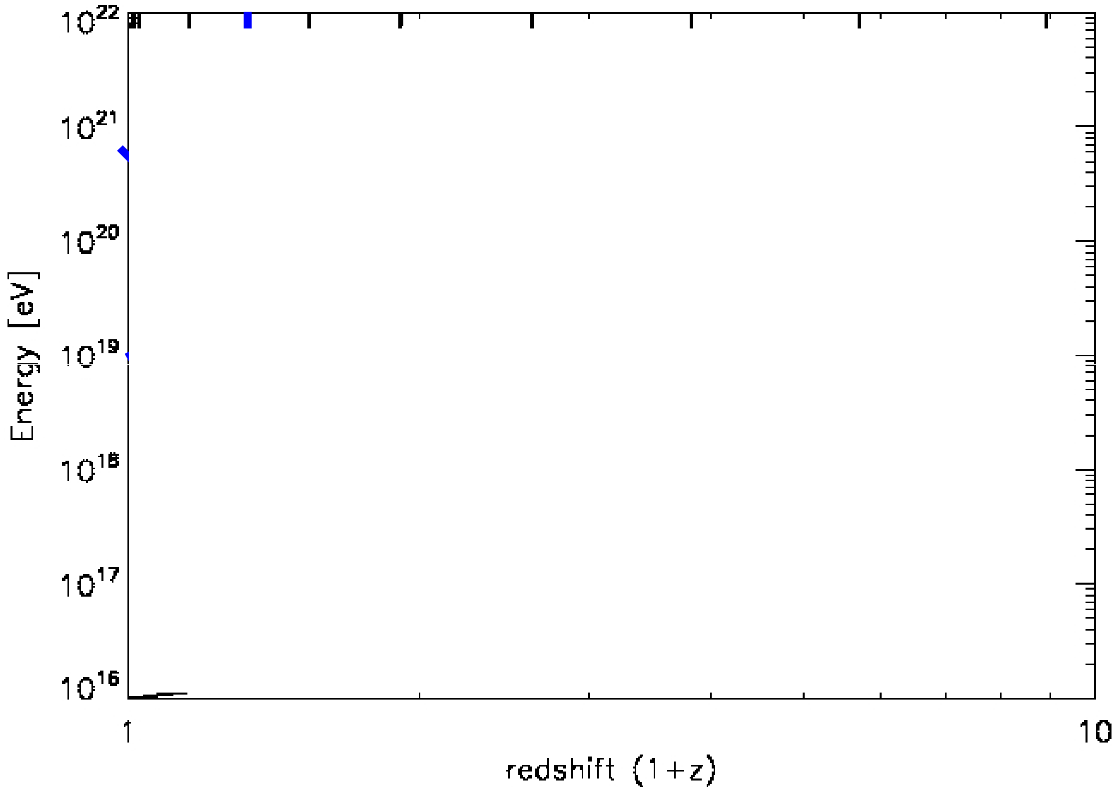



**⇒ The Universe is opaque to protons with energy ≥ $6 \times 10^{19}$ eV !**

# Greisen-Zatsepin-Kuzmin cut-off

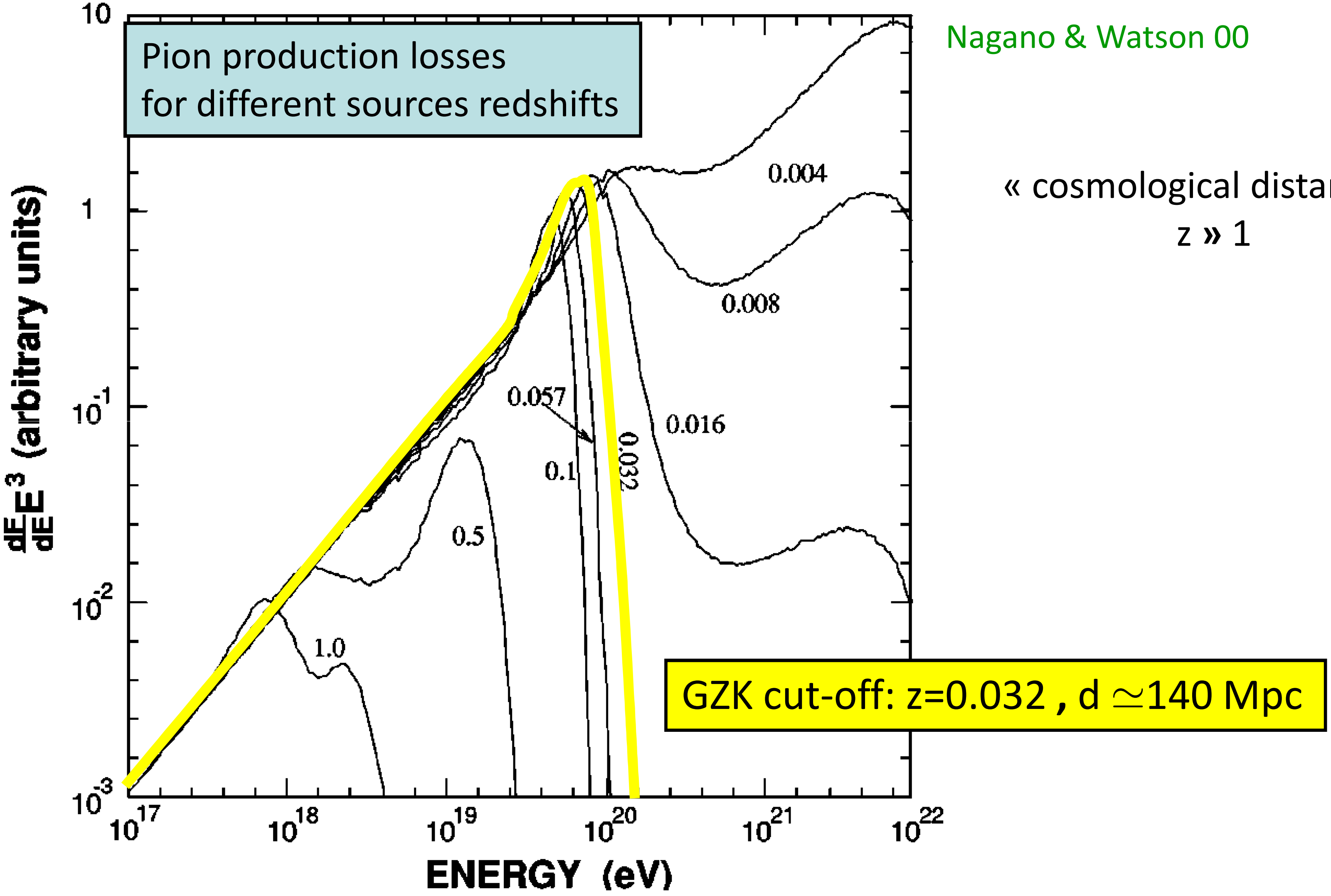
Greisen 66, Zatsepin & Kuzmin 66

- GZK cut-off: the Universe becomes opaque to protons of energy ¸ 6 $10^{19}$ eV (in the cosmic rest frame) as a result of pion production on the CMB, with characteristic energy loss length 100 Mpc




- Consequence: **the source of: >$10^{20}$ eV particles must lie within ∼100 Mpc**
  **>4 $10^{19}$ eV particles must lie within ∼1000 Mpc**

# Greisen – Zatsepin – Kuz'min cut-off

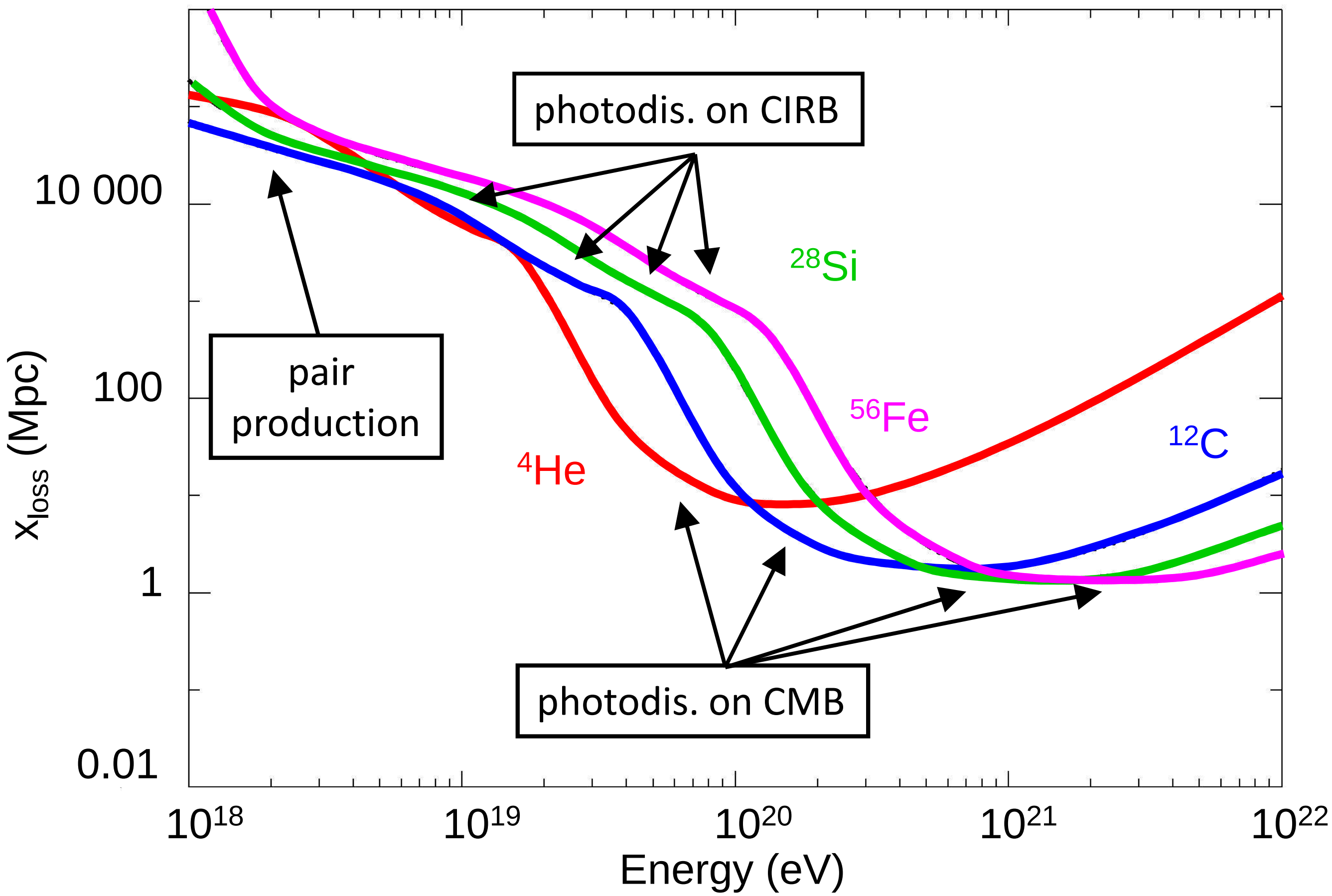



Nagano & Watson 00

« cosmological distance »:
z » 1

# Nuclei : photodisintegration losses

Bertone et al. 02




intermediate mass nuclei are very fragile at high energies...

in practice, at the detector:

**either protons or heavy (Si-Fe-?) nuclei at GZK (6 $10^{19}$ eV) energies**

**as an executive summary:**

$\longrightarrow$ detected cut-off at GZK energies may point to...

... pion production of UHE protons...
... photodisintegration of Si-Fe nuclei...
... or even, to the maximal energy at the source...

# Many questions ... a few hints...

- **What is the source of ultrahigh energy cosmic rays ?**

  ... what is the fundamental acceleration process to ultrahigh energies?

- **Where does the cosmic ray spectrum stop?**

  ... HiRes and Auger have detected a high energy cut-off at the expected location for the Greisen-Zatsepin-Kuzmin cut-off $\sim$ 6 $10^{19}$ eV

- **What are ultrahigh energy cosmic rays: protons, nuclei, photons, neutrinos?**

  ... the giant air showers are typical of hadronic showers

  ... HiRes sees protons at UHE, Auger sees an increasing fraction of heavies...?

- **Should we expect to see the source in the arrival directions of UHECR?**

  ... what are the effects of the Galactic and extra-galactic magnetic fields?

  ... no powerful source seen in the arrival directions of highest energy CR...?

  ... Auger has reported 99% c.l. detection of anisotropy of arrival directions!

- **Should we expect to detect photons/neutrinos/gravitational waves?**

  ... diffuse backgrounds detectable?

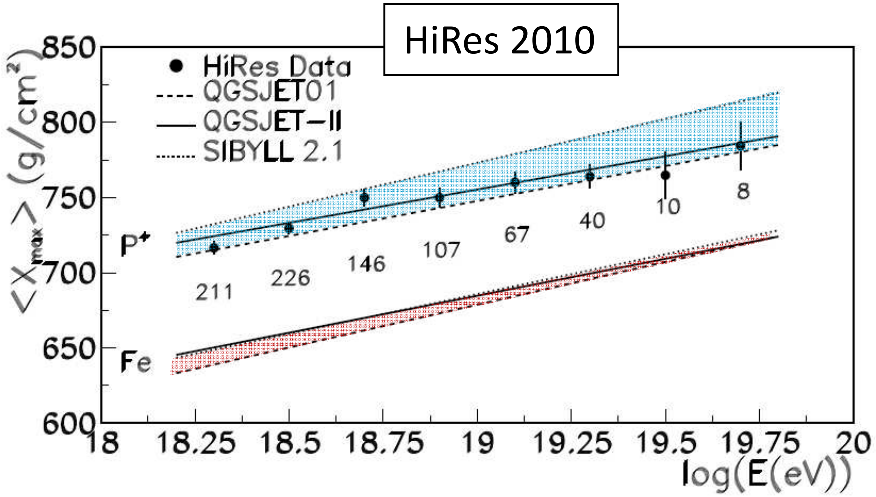
  ... any signal from arrival directions of UHECR ?

# Many questions ... a few hints...

► What is the source of ultrahigh energy cosmic rays ?

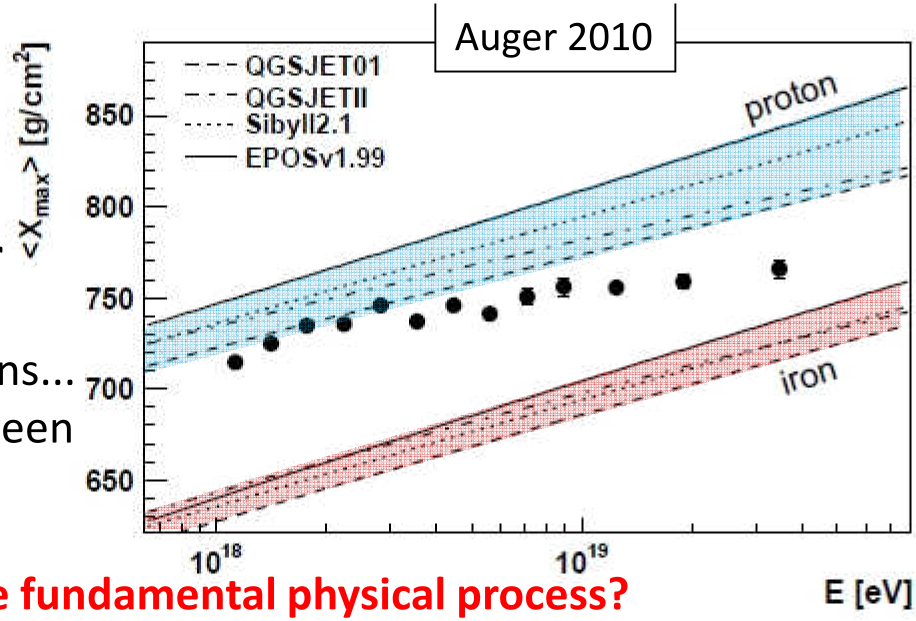
**HiRes:**

**light** composition above ankle




**Auger:**

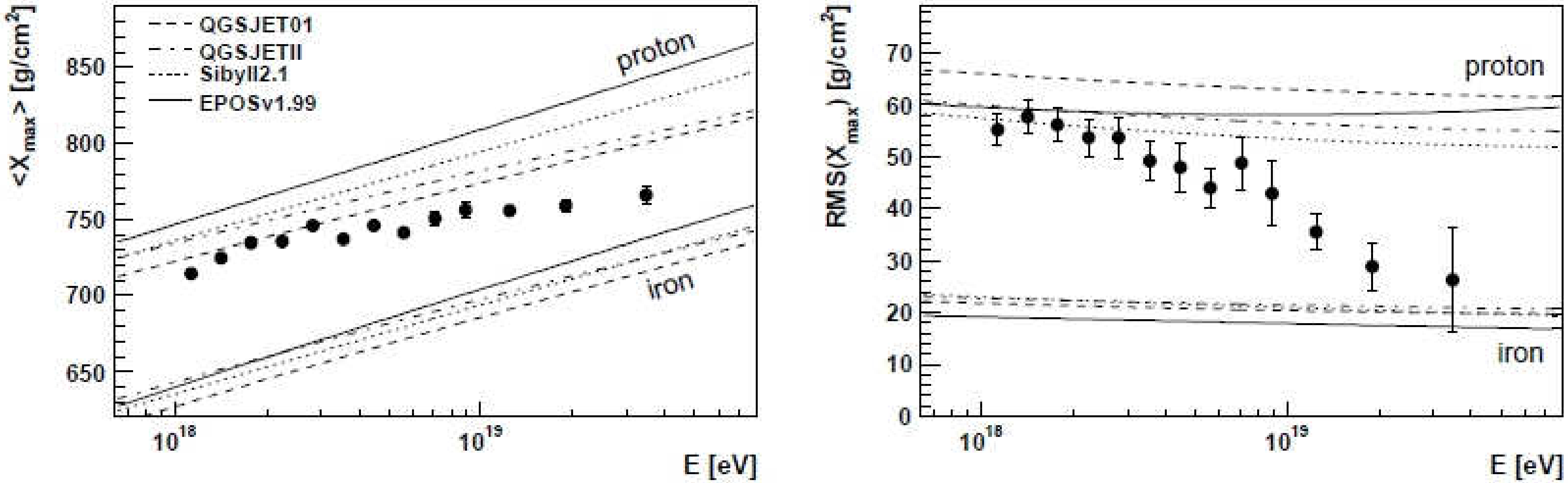
composition becomes **heavier** above ankle...
also seen in shower fluctuations...
with some inconsistency between various observables...



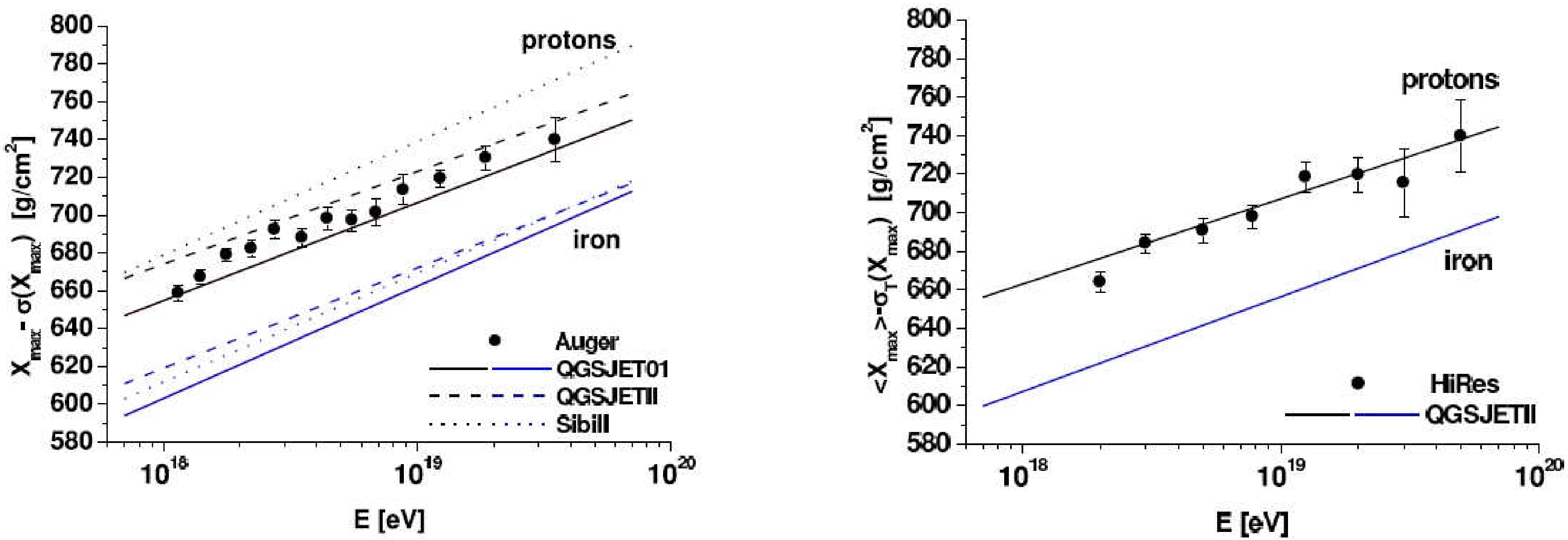

**... discrepancy related to some fundamental physical process?**
**... a proton or iron composition bears a crucial impact on phenomenology...**

! any signal from arrival directions of UHECR ?

# Composition measurement by PAO




... however, debate is not closed, e.g. analysis of Wilk & Wlowdarczyk 10:



**as an executive summary:**

$\longrightarrow$ discrepant measurements of composition...

$\longrightarrow$ HiRes, PAO and TA have similar values of $X_{max}$ within error bars...

$\longrightarrow$ whether one is dealing with protons or iron at UHE has drastic consequences for phenomenology...

p: few candidate sources, small angular deflection

Fe: more candidate sources, large angular deflection...

# Many questions ... a few hints...

- **What is the source of ultrahigh energy cosmic rays ?**

  ... what is the fundamental acceleration process to ultrahigh energies?

- **Where does the cosmic ray spectrum stop?**

  ... HiRes and Auger have detected a high energy cut-off at the expected location for the Greisen-Zatsepin-Kuzmin cut-off $\sim$ 6 $10^{19}$ eV

- **What are ultrahigh energy cosmic rays: protons, nuclei, photons, neutrinos?**

  ... the giant air showers are typical of hadronic showers

  ... HiRes sees protons at UHE, Auger sees an increasing fraction of heavies...?

- **Should we expect to see the source in the arrival directions of UHECR?**

  ... what are the effects of the Galactic and extra-galactic magnetic fields?

  ... no powerful source seen in the arrival directions of highest energy CR...?

  ... Auger has reported 99% c.l. detection of anisotropy of arrival directions!

- **Should we expect to detect photons/neutrinos/gravitational waves?**

  ... diffuse backgrounds detectable?

  ... any signal from arrival directions of UHECR ?

# Propagation – transport in extra-galactic magnetic fields

Homogeneous turbulence: $\delta\theta_i^2 \simeq 2^\circ E_{20}^{-2} B_{-9}^2 \lambda_{0.1\mathrm{Mpc}} R_{100\mathrm{Mpc}}$

if B follows large scale structure:

$\rightarrow$ particles of different energies experience different Universes:

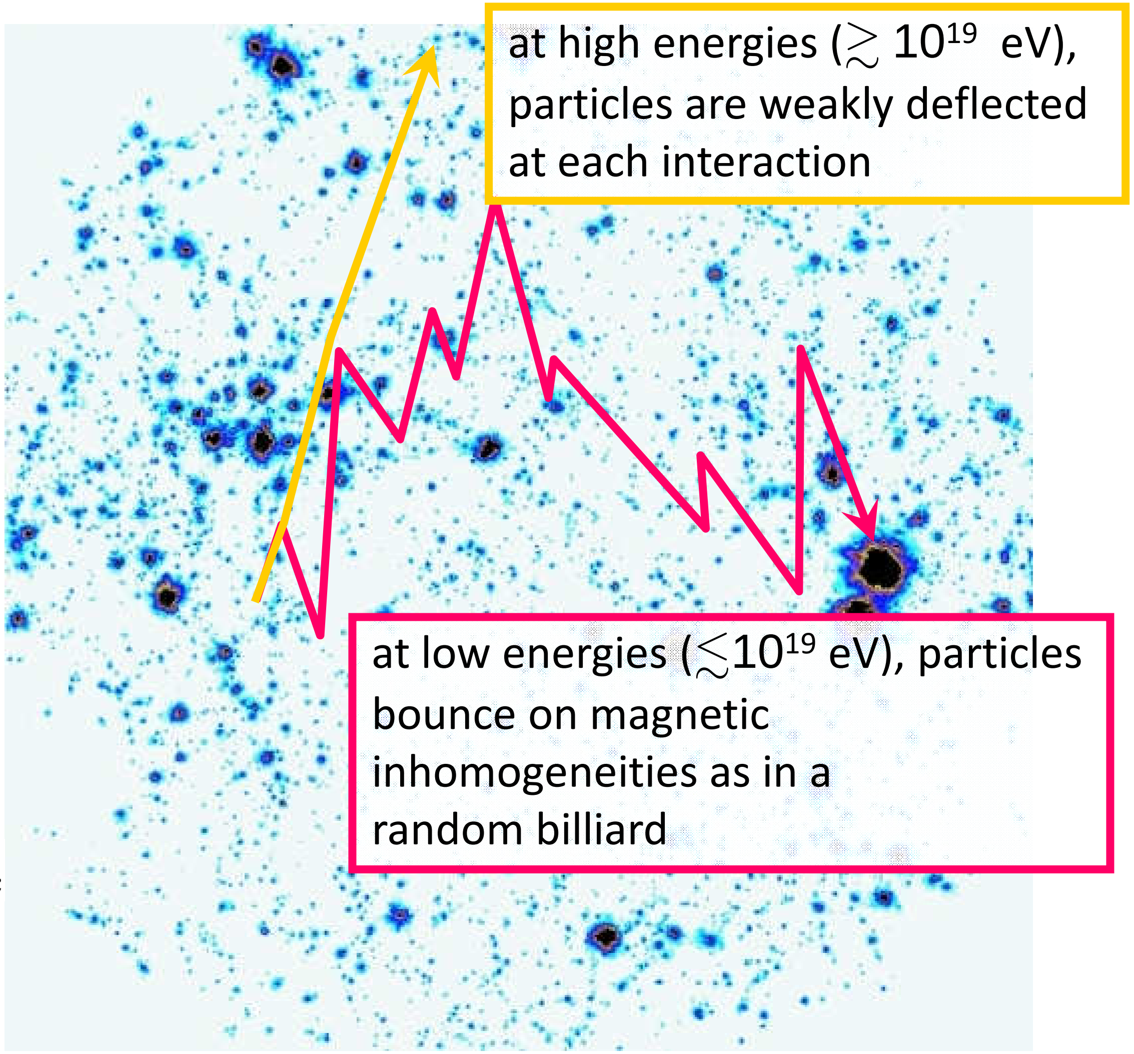
at low energies, opaque to scattering....

at high energies, few interactions with little deflection:

$$\delta\theta_i^2 \simeq 1.7^\circ E_{20}^{-2} B_{-8}^2 \lambda_{0.1\mathrm{Mpc}} R_{1\mathrm{Mpc}}$$

per interaction

(Kotera & ML 08)



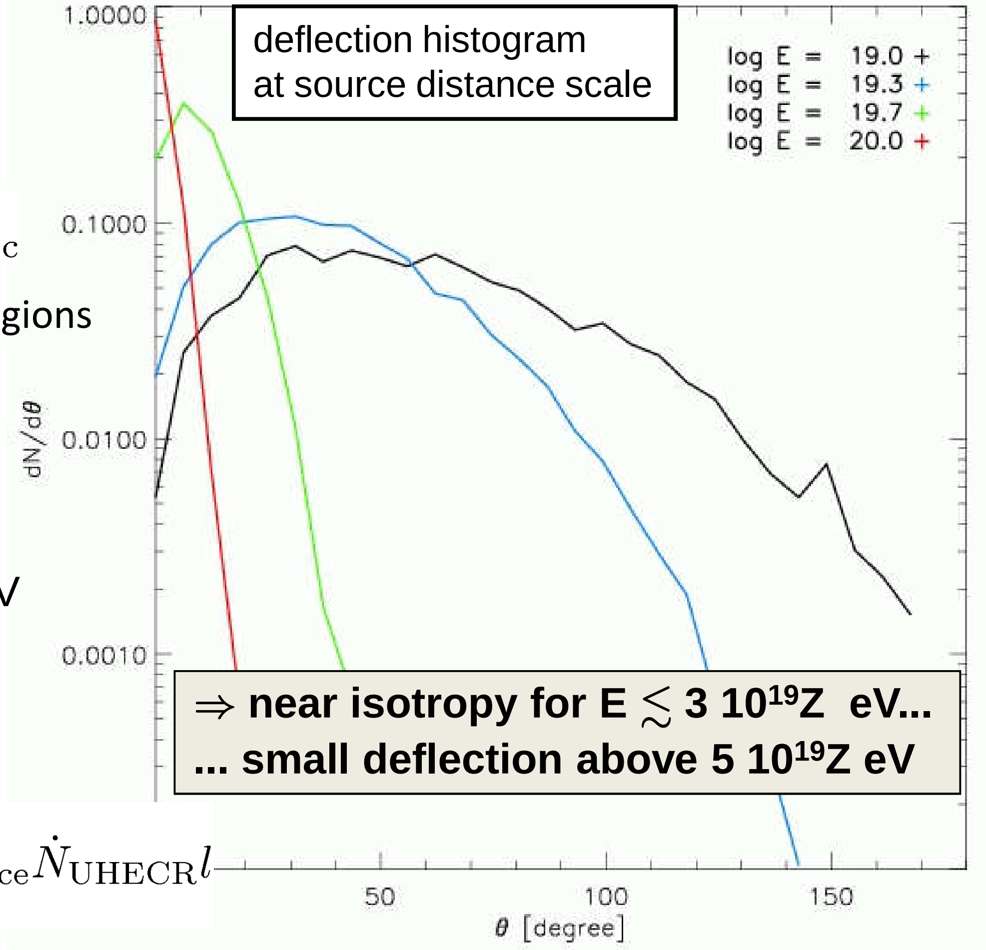

Donnert et al. 06

# Expected angular deflection

- localized regions of enhanced magnetic fields:
  - typical values R $\sim$ 1 Mpc, n $\sim$ $10^{-2}$ Mpc$^{-3}$, B $\sim$ $10^{-8}$ G for polluted regions
    $\Rightarrow$ mean free path to interaction $\sim$ 30 Mpc

    or interactions with magnetized filaments surrounded by magnetized accretion shocks, with r $\sim$ 1Mpc, B $\sim$ $10^{-8}$ G, inter-distance ~ 30-40 Mpc

Kotera & ML 08




  - then, per interaction:

$$\delta\theta_i \simeq 1.7^\circ E_{20}^{-1} B_{-8} \lambda_{0.1\mathrm{Mpc}}^{1/2} R_{1\mathrm{Mpc}}^{1/2}$$

(+multiple interactions with polluted regions in filaments)

  - total deflection angle: $\delta\alpha^2 = \frac{\tau}{3}\delta\theta_i^2$

    and $\tau = \frac{\mathrm{distance}}{\mathrm{mfp}} \sim 3$ at $10^{20}$ eV

  - note: source distance scale $\simeq$ $l_{max}(E)$

$$F(<l) = \int_{r\le l} \mathrm{d}^3r\, n_{\mathrm{source}} \frac{\dot N_{\mathrm{UHECR}}}{4\pi r^2} = n_{\mathrm{source}} \dot N_{\mathrm{UHECR}} l$$

**$\Rightarrow$ near isotropy for E $\lesssim$ 3 $10^{19}$Z eV...**
**... small deflection above 5 $10^{19}$Z eV**

# Propagation – small angular deflection

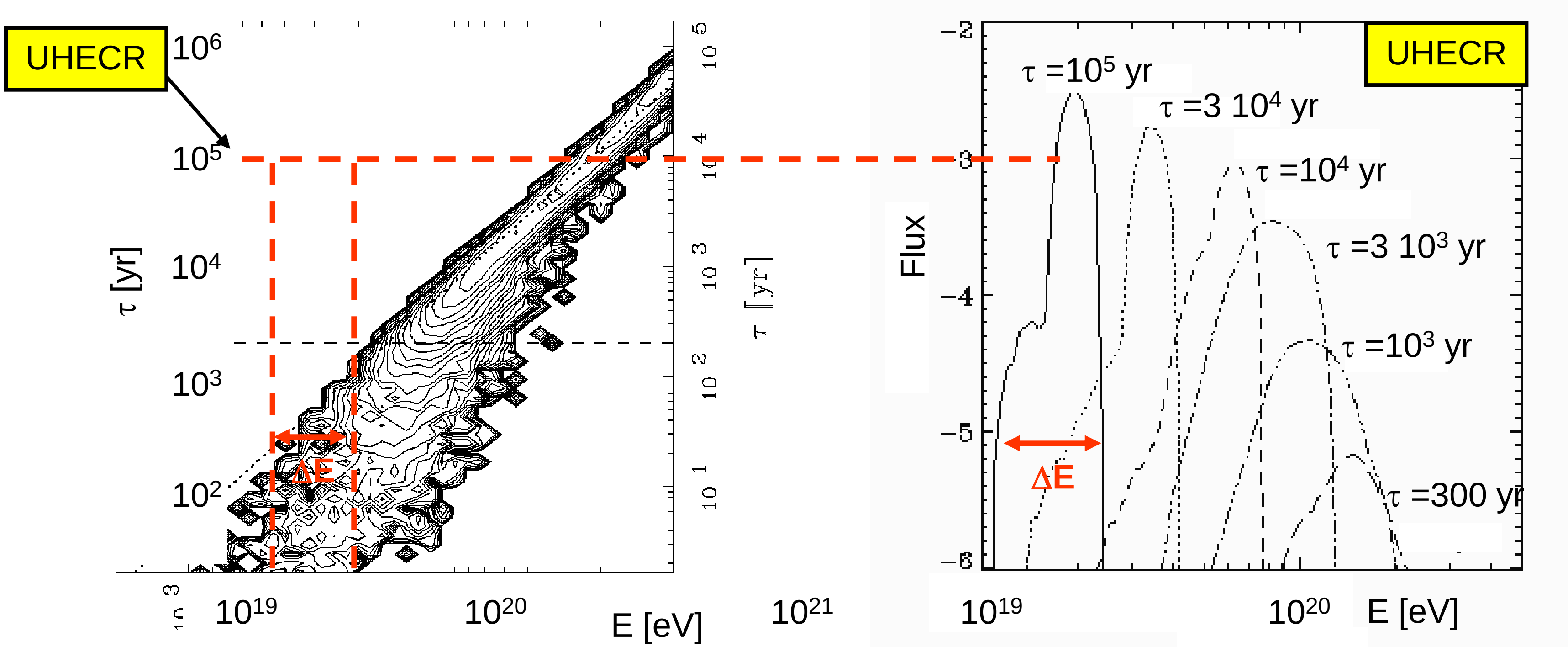
- <u>High energy or weak magnetic fields:</u> particle executes a random walk on magnetic inhomogeneities and suffers a time delay and angular deflection:

$$\theta_B \simeq 2.5^o \ d_{100\,\mathrm{Mpc}}^{1/2} E_{20}^{-1} B_{-9} l_{\mathrm{coh,Mpc}}^{1/2}$$

$$\tau_B \simeq 1.5 \cdot 10^5 \,\mathrm{yrs} \ d_{100\,\mathrm{Mpc}}^2 E_{20}^{-2} B_{-9}^2 l_{\mathrm{coh,Mpc}}$$

Miralda-Escudé & Waxman 96

- <u>Application:</u> for a bursting source (e.g. gamma-ray burst),
  → **the lack of temporal coincidence could explain the lack of observed counterpart…**
  → **gamma-ray burst are seen only in a limited bandwidth**

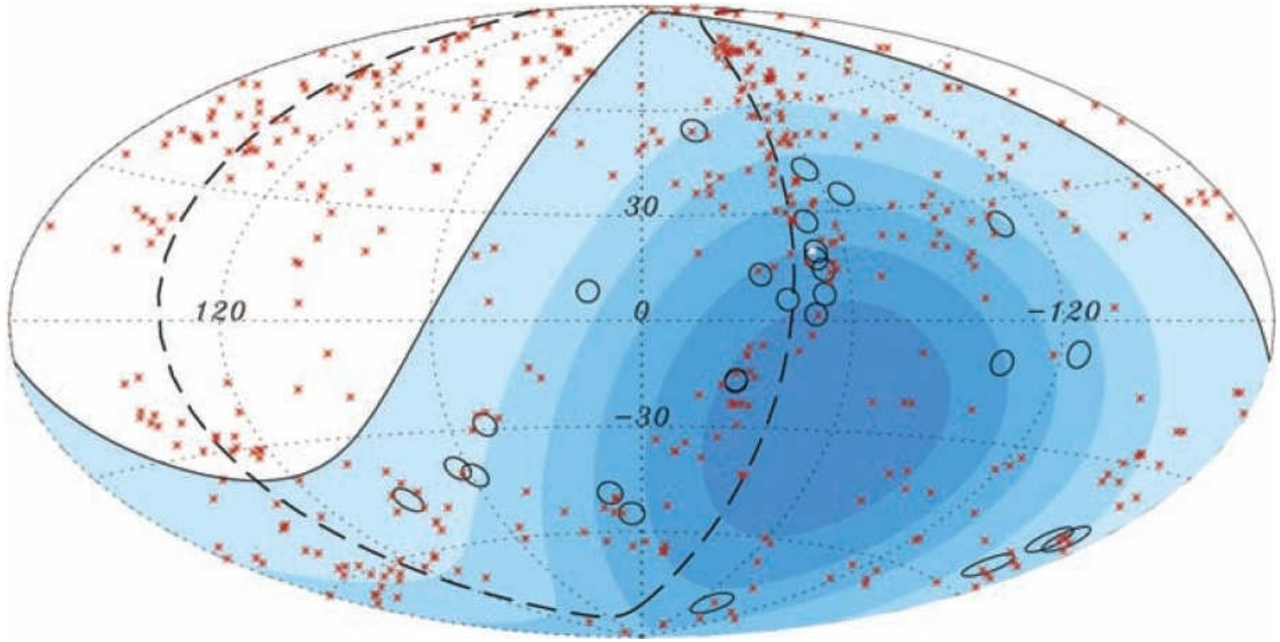



(photons arrival time: τ = 0)

M.L., Sigl, Olinto, Schramm 97

# Many questions ... a few hints...

- **What is the source of ultrahigh energy cosmic rays ?**

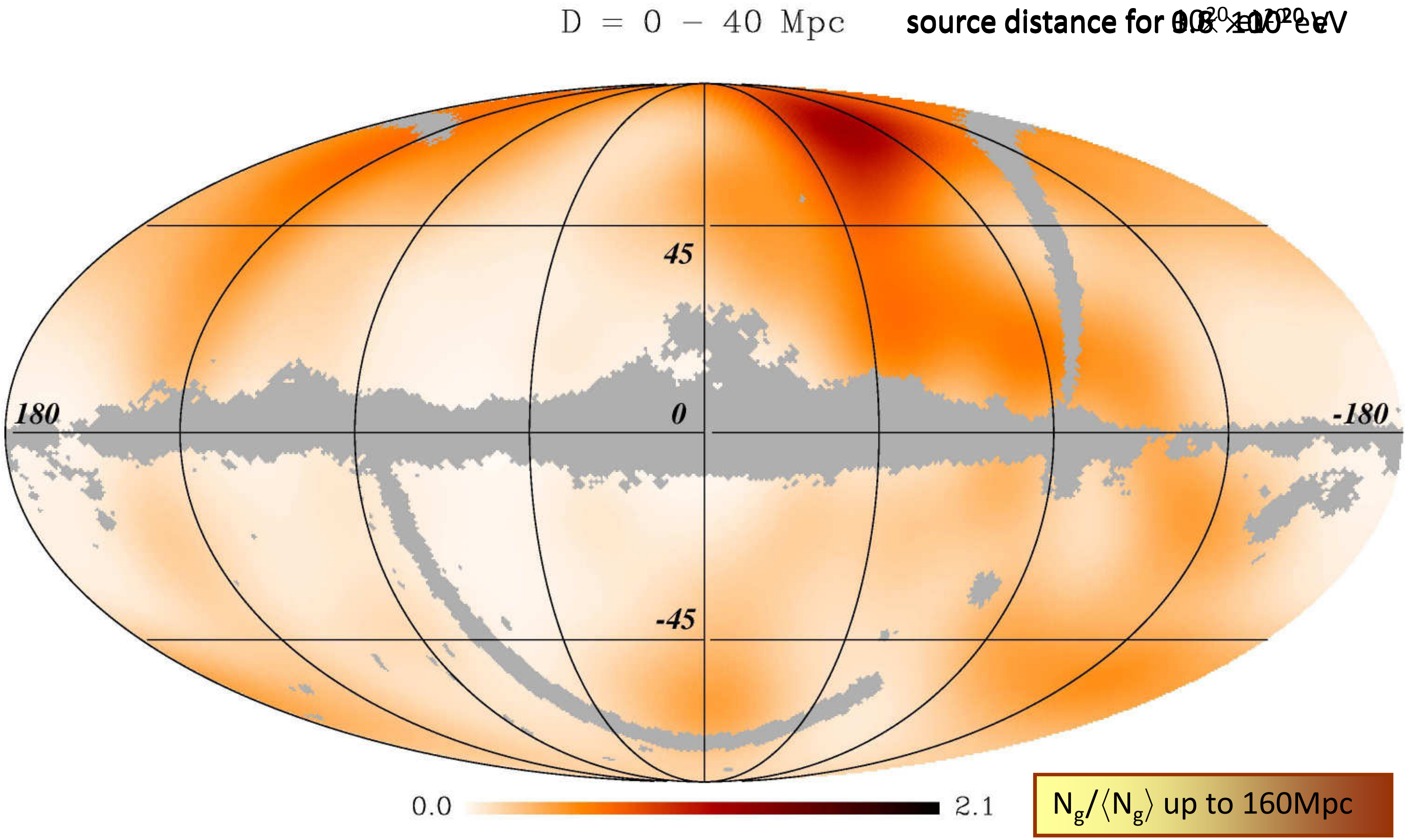



Auger (07,08) has reported excess correlation of UHECR arrival directions with nearby (weak) AGN -- **as of 2009, 99% c.l. rejection of isotropy of arrival directions ...**
... but HiRes rejects correlation with galaxy and AGN catalogs at 95% cl...

excess of events in the region of Centaurus A... but note that direction of Cen A coincides with direction of largest amount of extra-galactic matter within 200Mpc!

arrival directions (as of 2008) agree with a distribution according to large scale structure
(Kashti & Waxman 08)

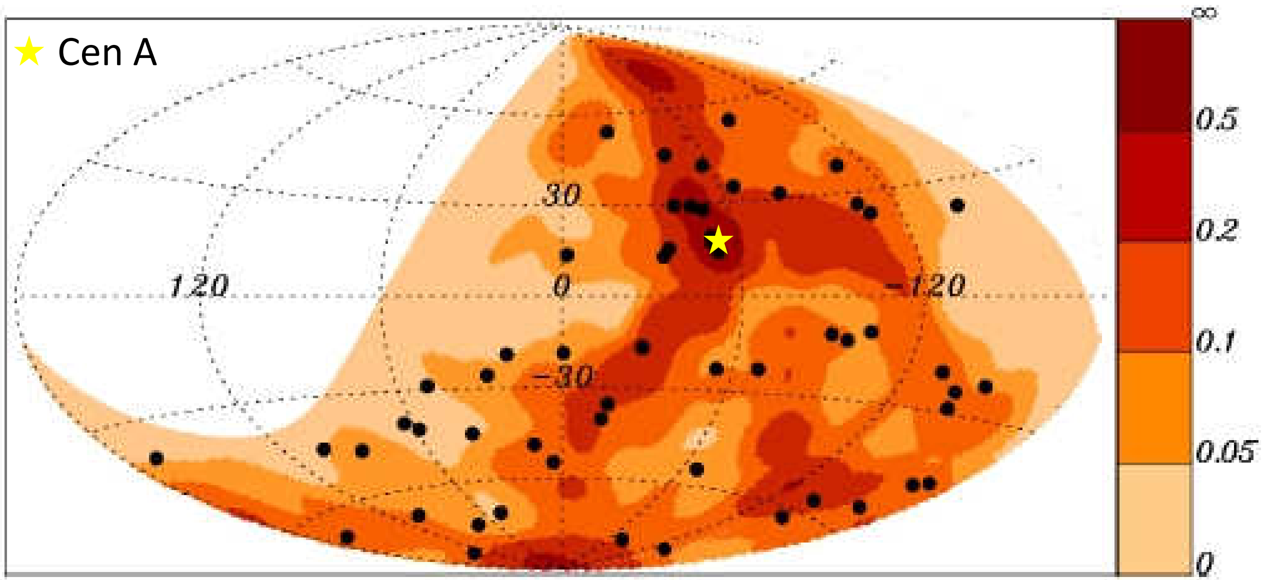
# Propagation – flux vs distance



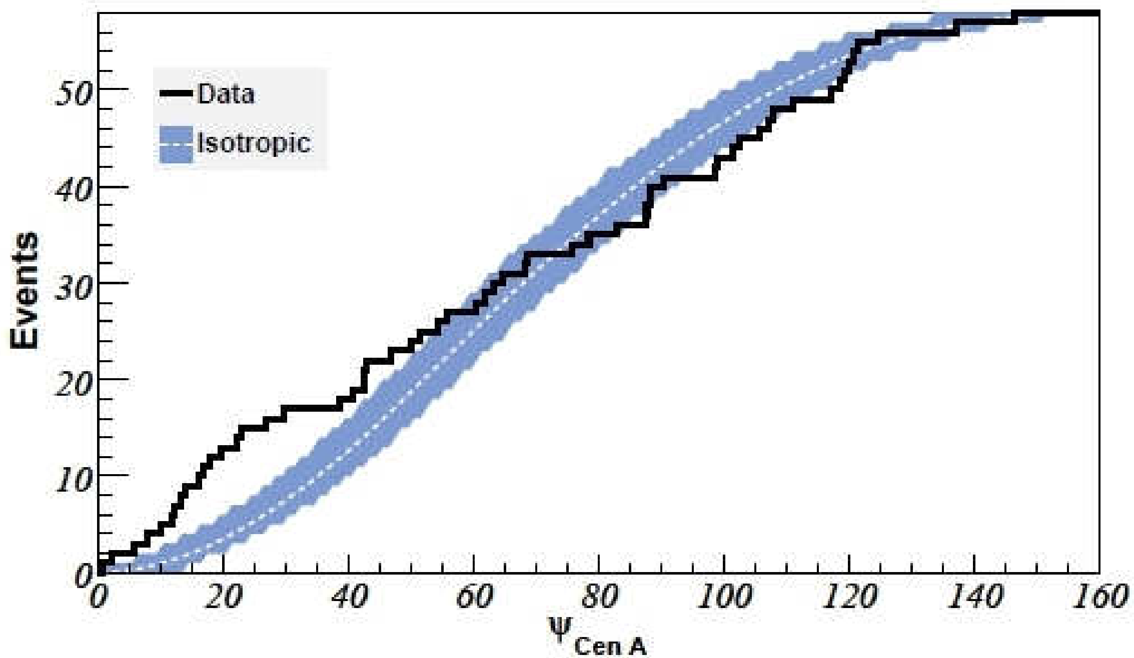

Kotera & ML 08: same map can be used to calculate angular deflection as a function of direction in the sky

# Anisotropies seen by PAO

PAO 09




number of events as a function of angular distance to CenA...



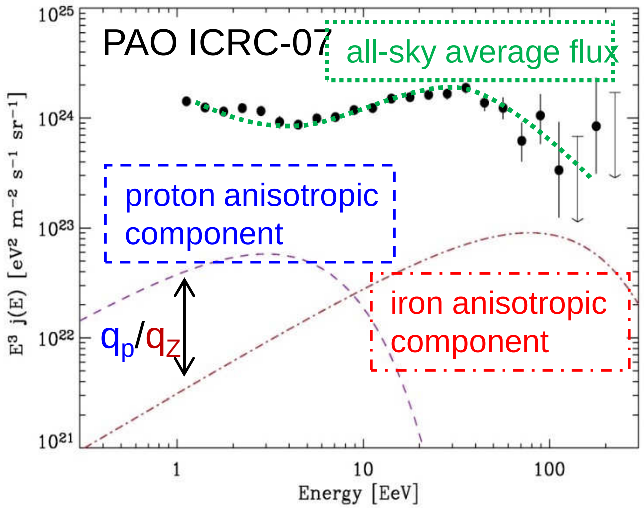
# Testing the chemical composition on the sky

- 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...** (ML & 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 $>E_{thr}/Z$:

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

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

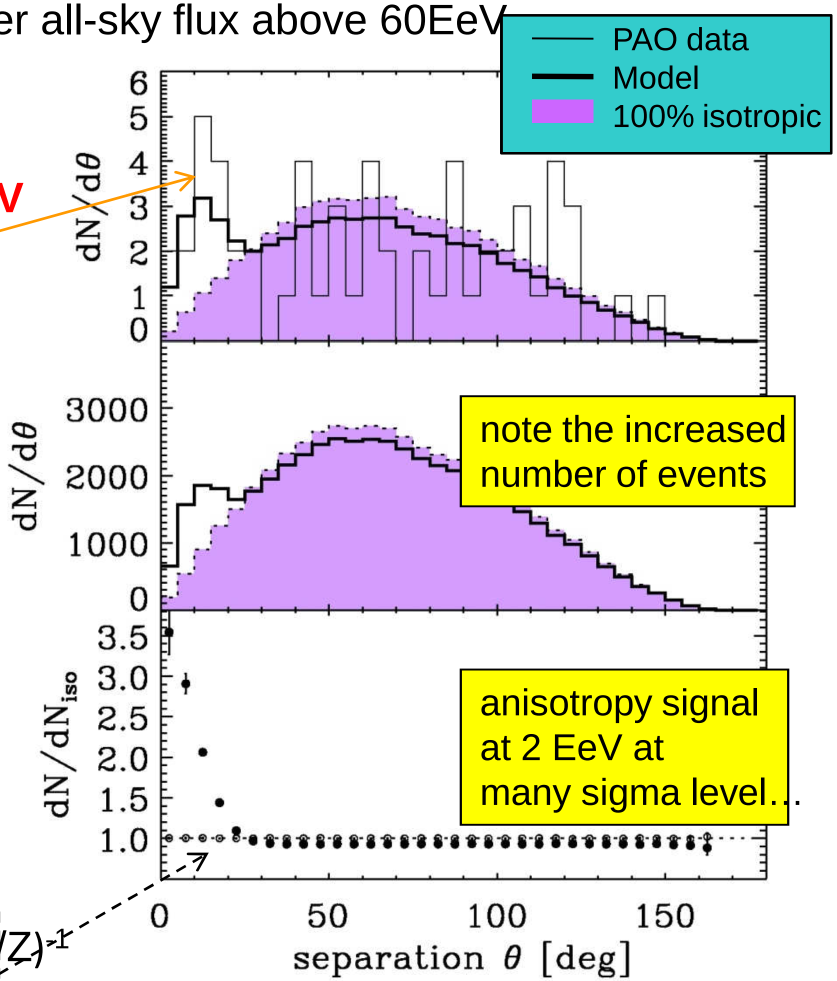
# Testing the chemical composition on the sky

- 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 $\delta\theta = 10^{\circ}$, 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$^{\circ}$ 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

**as an executive summary:**

$\rightarrow$ the source is not seen in the arrival directions because...

... angular deflection is large for high Z nuclei...

... or, temporal coincidence is lost between photons and UHECR..

$\rightarrow$ anisotropies, if any, strongly favor proton composition
if no similar anisotropy is seen at $E/Z \sim$ EeV...
(assuming a single type of source model!)

# Many questions ... a few hints...

- **What is the source of ultrahigh energy cosmic rays ?**

  ... what is the fundamental acceleration process to ultrahigh energies?

- **Where does the cosmic ray spectrum stop?**

  ... HiRes and Auger have detected a high energy cut-off at the expected location for the Greisen-Zatsepin-Kuzmin cut-off $\sim$ 6 $10^{19}$ eV

- **What are ultrahigh energy cosmic rays: protons, nuclei, photons, neutrinos?**

  ... the giant air showers are typical of hadronic showers

  ... HiRes sees protons at UHE, Auger sees an increasing fraction of heavies...?

- **Should we expect to see the source in the arrival directions of UHECR?**

  ... what are the effects of the Galactic and extra-galactic magnetic fields?

  ... no powerful source seen in the arrival directions of highest energy CR...?

  ... Auger has reported 99% c.l. detection of anisotropy of arrival directions!

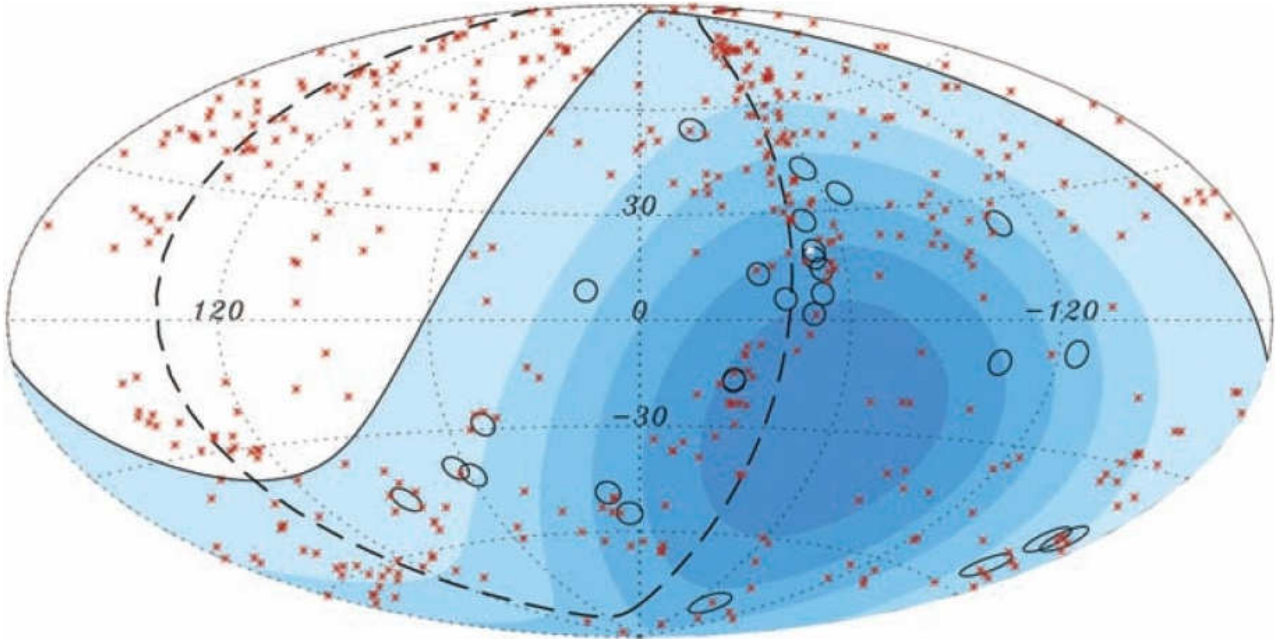
- **Should we expect to detect photons/neutrinos/gravitational waves?**

  ... diffuse backgrounds detectable?

  ... any signal from arrival directions of UHECR ?

# Many questions ... a few hints...

▶ **What is the source of ultrahigh energy cosmic rays ?**




short answer:

no counterpart in optical/IR photons $\Leftrightarrow$ no counterpart in gamma-rays, neutrinos, gravitational waves...

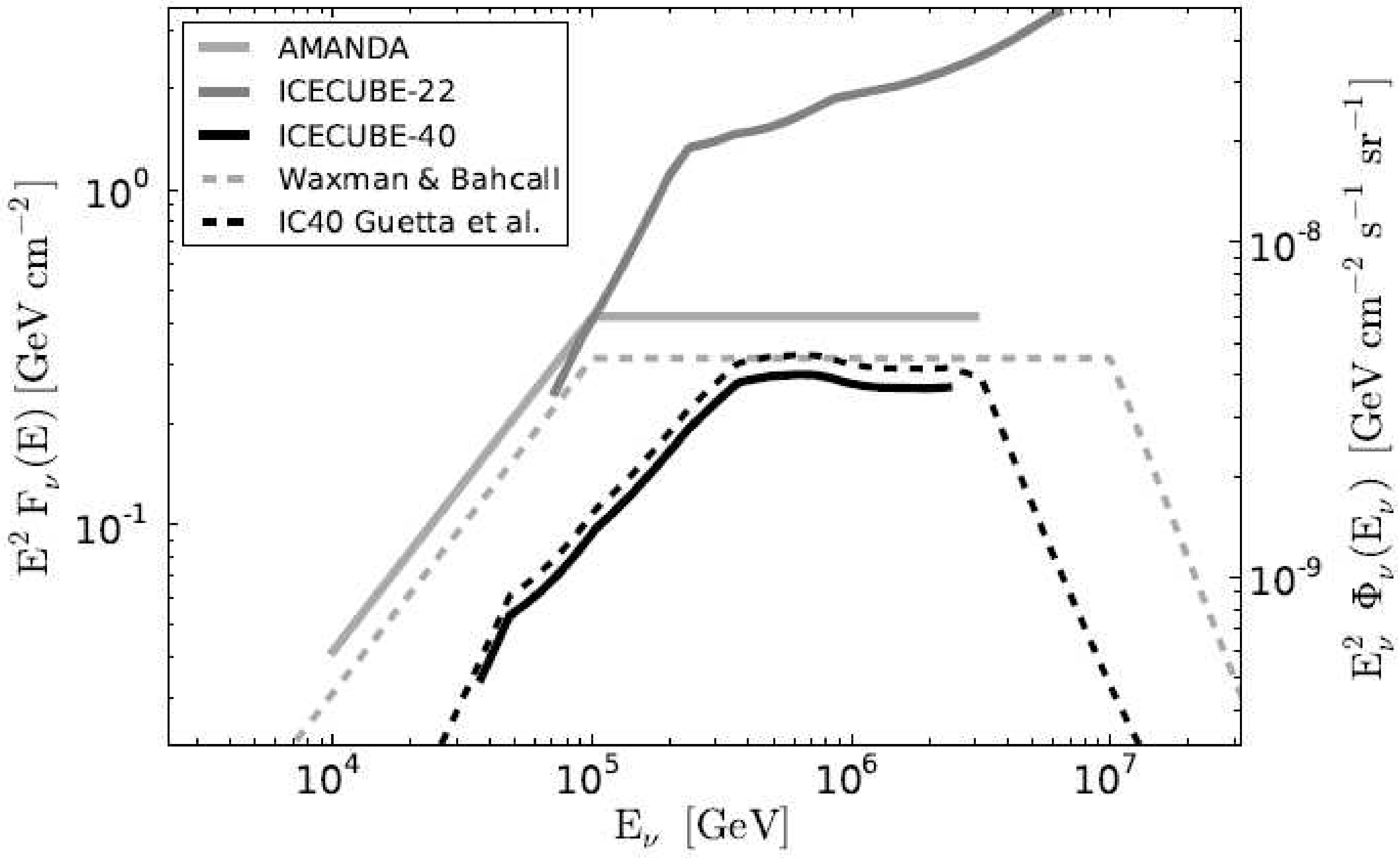
e.g.: $\rightarrow$ for gamma-ray burst sources, time delay $\sim 10^4$-$10^5$ yrs at $10^{20}$ eV

$\rightarrow$ for high Z nuclei, large angular deflection...

# Many questions ... a few hints...

▶ **What is the source of ultrahigh energy cosmic rays ?**

... but diffuse backgrounds are expected: N+$\gamma \rightarrow$ N' + $\pi$, $\pi^{\pm} \rightarrow \nu$ +... in gamma-ray burst




Ice Cube 11: no detection of PeV neutrinos from gamma-ray bursts...

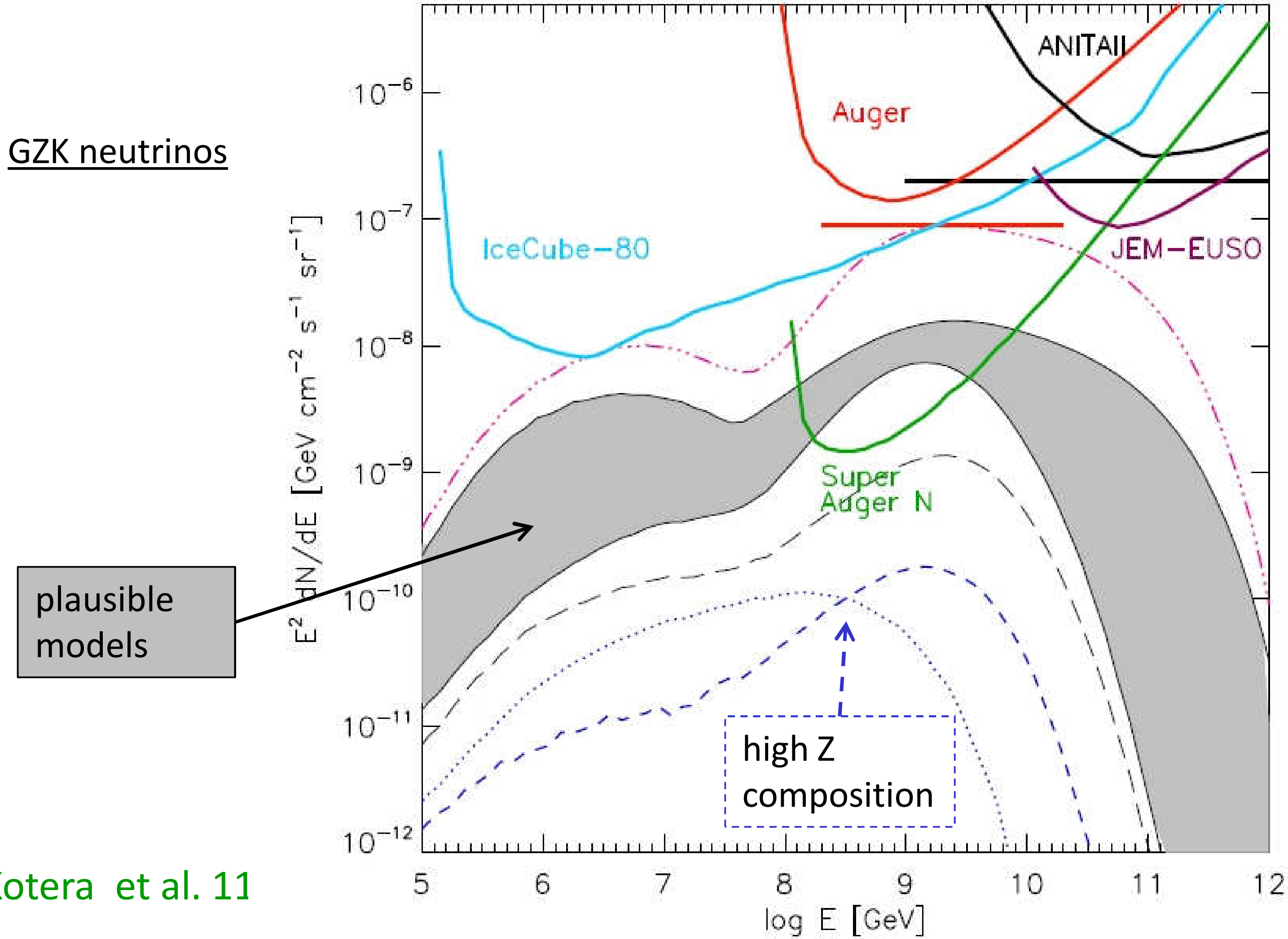
$\Rightarrow$ would exclude acceleration of p to UHE in the internal shock phase...

# Many questions ... a few hints...

▶ **What is the source of ultrahigh energy cosmic rays ?**

... but diffuse backgrounds are expected: N+$\gamma \rightarrow$ N' + $\pi$, $\pi^{\pm} \rightarrow \nu$ +... during propagation

GZK neutrinos




Kotera et al. 11

# Many questions ... a few hints...

► What is the source of ultrahigh energy cosmic rays ?

... but diffuse backgrounds are expected: N+$\gamma \rightarrow$ e.m. cascade down to GeV-TeV

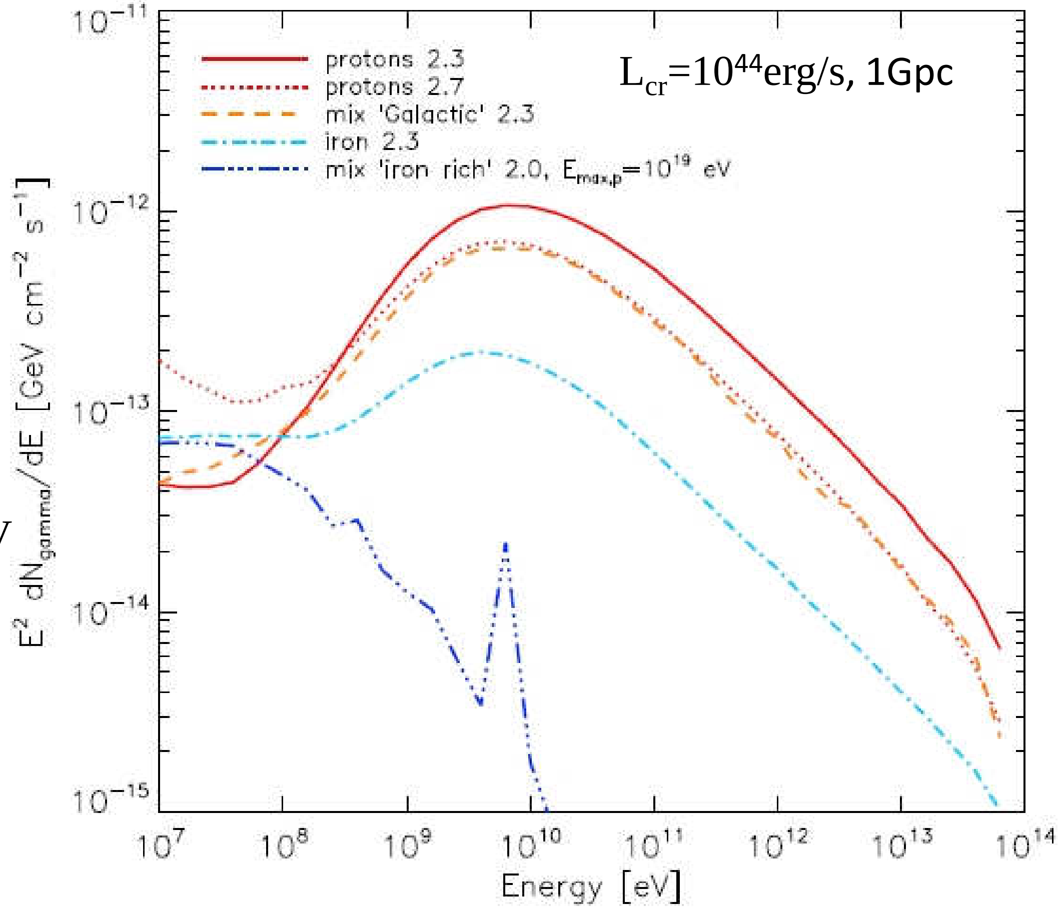
Aharonian 02, Gabici & Aharonian 05, Kotera et al. 11:

synchrotron emission from UHE electrons (p+$\gamma \rightarrow$ p + $e^+$+$e^-$)

detection with CTA requires a cosmic ray luminosity above $10^{19}$eV:

$L_{cr} \gtrsim 10^{46}$ erg/s for a distance 1Gpc...

note: halo $\rightarrow$ smoking gun signature of p acceleration to >$10^{19}$eV

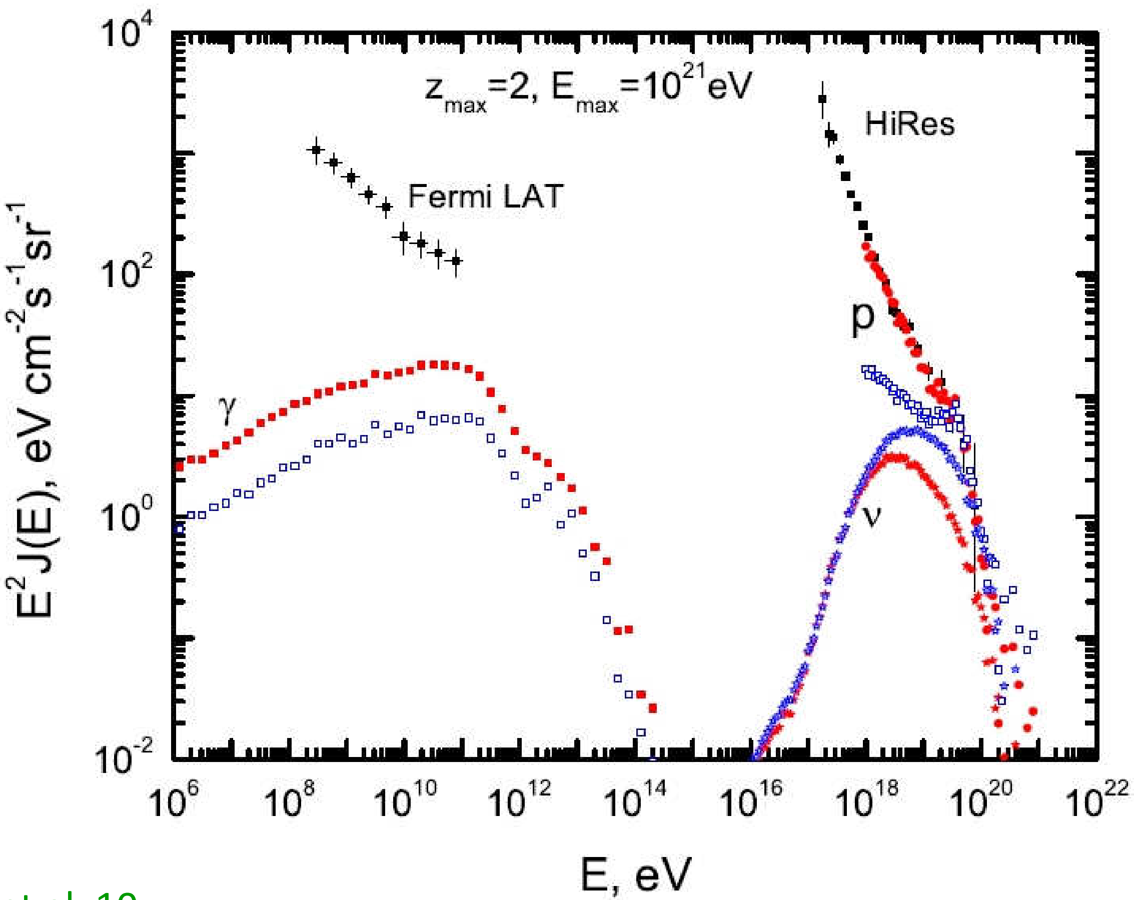



$\rightarrow$ any signal from arrival directions of UHECR ?

# Many questions ... a few hints...

▶ **What is the source of ultrahigh energy cosmic rays ?**

... but diffuse backgrounds are expected: $p+\gamma \rightarrow p + e^- + e^+$, with e.m. cascade energy transferred into GeV range as a result of the high opacity of the Universe to >TeV photons




Berezinsky et al. 10

⇒ further constrains the diffuse neutrino background...

# 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"