The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2246-11

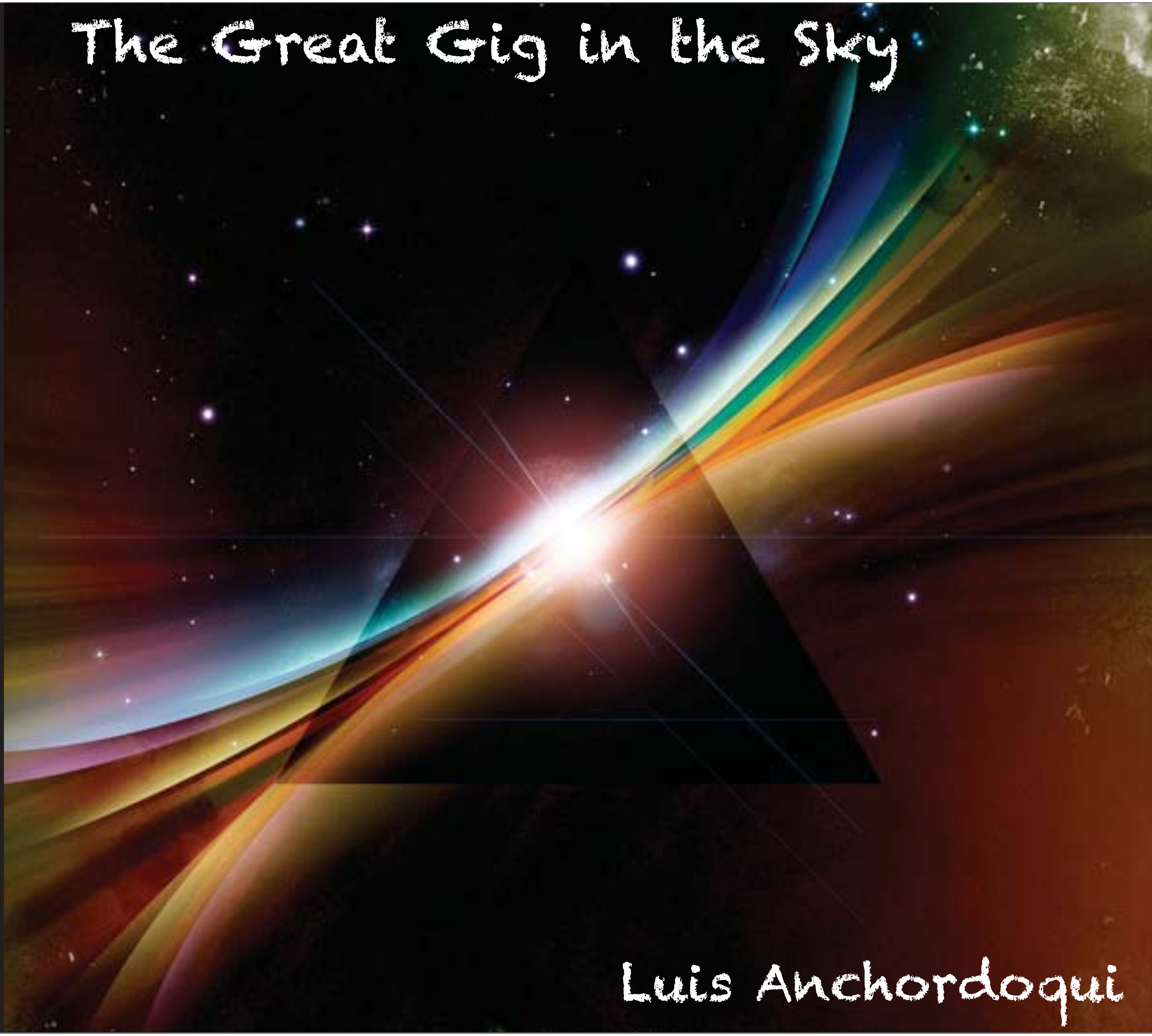
Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

The great gig in the sky

Luis ANCHORDOQUI
Univ. of Wisconsin at Milwaukee
USA

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it


The Great Gig in the Sky
Luis Anchordoqui

General Idea

UHE emission from Cen A dominates high-end of CR spectrum

[Farrar & Piran, arXiv:0010370]

☛ directional neutrons and neutrinos become markers in sky

Outline

- Overview of recent UHECR observations
- Bounds on extragalactic $\vec{B}$-fields
- Dissecting Cen A with gamma ray observations
- UHECR emission from Cen A
- UHECν emission from Cen A
- Conclusions

Based on LAA, Goldberg, Weiler, Phys. Rev. Lett. 87 (2001) 081101; astro-ph/0103043
updated in arXiv:1103.0536

1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum further, into the energy range 10^{21}-10^{22} eV.

This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

the catastrophic

intense isotropic radiation first detected by Penzias and Wilson[3] at 4080 Mc/sec (7.35 cm) and now confirmed as thermal in character by measurements of Roll and Wilkinson[4] at 3.2 cm wavelength. It is not essential to the present argument that the origin of this radiation conform exactly to the primeval-fireball model outlined by Dicke, Peebles, Roll, and Wilkinson[5]; what matters is only that the radiation exists and pervades the observable universe. The transparency of space at the pertinent wavelengths, and the consistency of intensity observations in numerous directions,

$$E^{\rm th}_{p\gamma_{\rm CMB}} = \frac{m_\pi\,(m_p + m_\pi/2)}{\omega_{\rm CMB}} \approx 6.8\times 10^{10}\left(\frac{\omega_{\rm CMB}}{10^{-3}\ {\rm eV}}\right)^{-1}\ {\rm GeV}$$

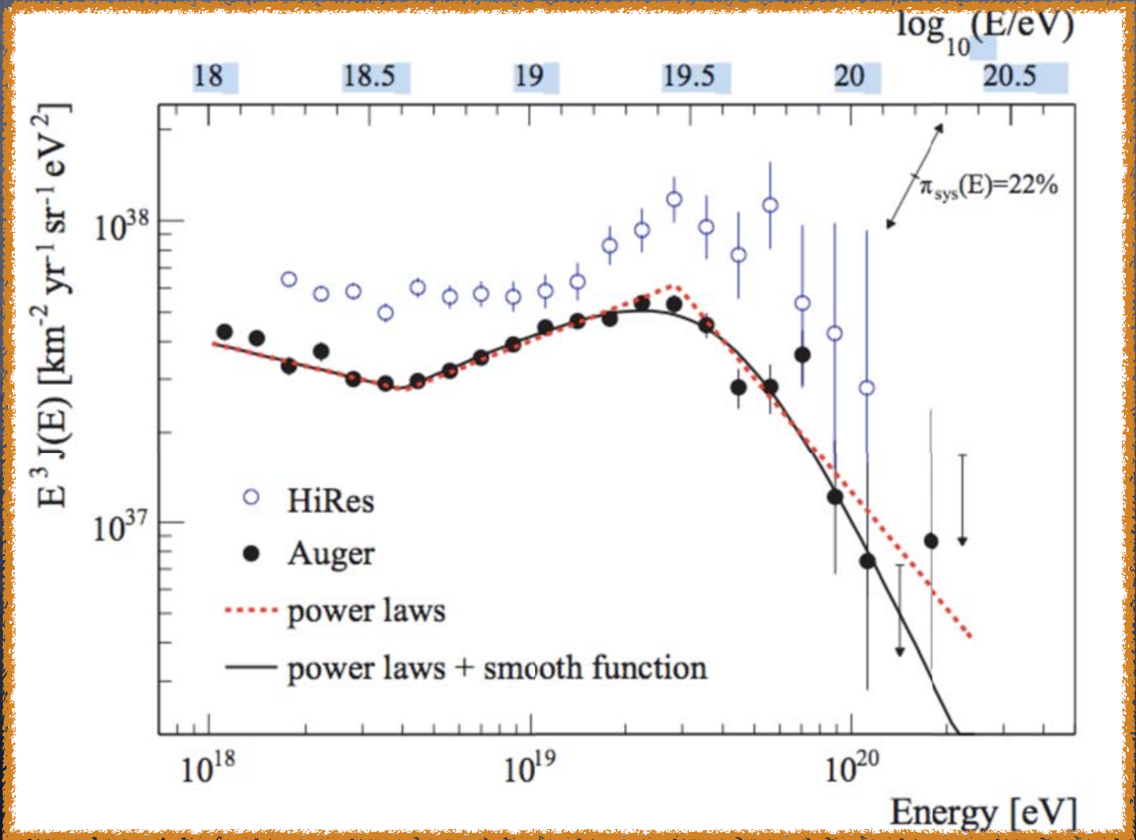
GZK suppression ☛ interaction with CMB degrades CR energies

☛ predicted within a year of discovery of CMB

↓ Zatsepin & Kuzmin, JETP Lett.4 (1966) 78

Suppression of energy spectrum

- First hint of suppression $3.5\sigma - 8\sigma$ ☛ reported 9 years ago (depending on experiment normalization)
  [Bachall & Waxman, Phys. Lett B556 (2003) 1]
- HiRes Collaboration ☛ 5.3σ [Phys. Rev. Lett. 100 (2008) 101101]
- Pierre Auger Collaboration ☛ 20σ [Phys. Lett. B 685 (2010) 239]



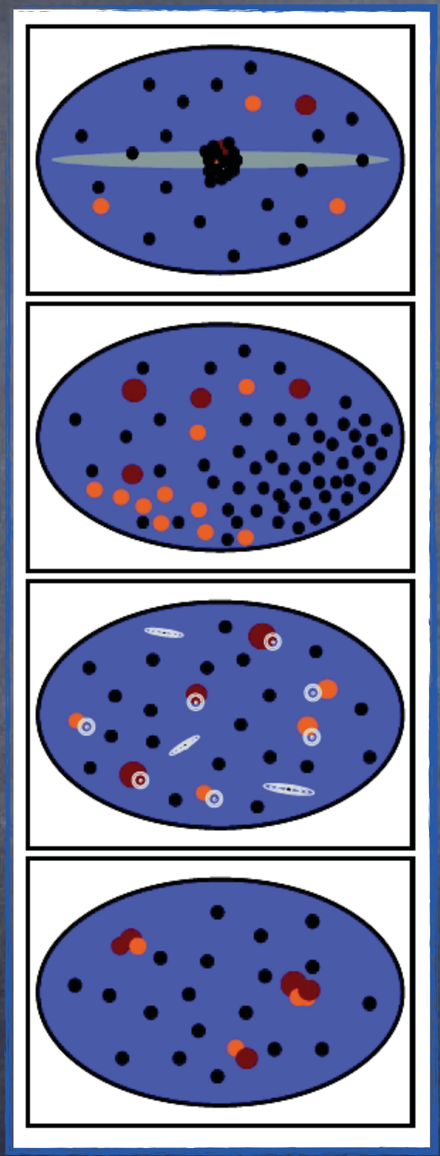
History of anisotropy searches

Galactic center

Multipole searches

Point sources (correlation with AGN, GRB, etc.)

Clusters (autocorrelation)



AGASA & SUGAR: yes

Auger: not at this level

No evidence yet

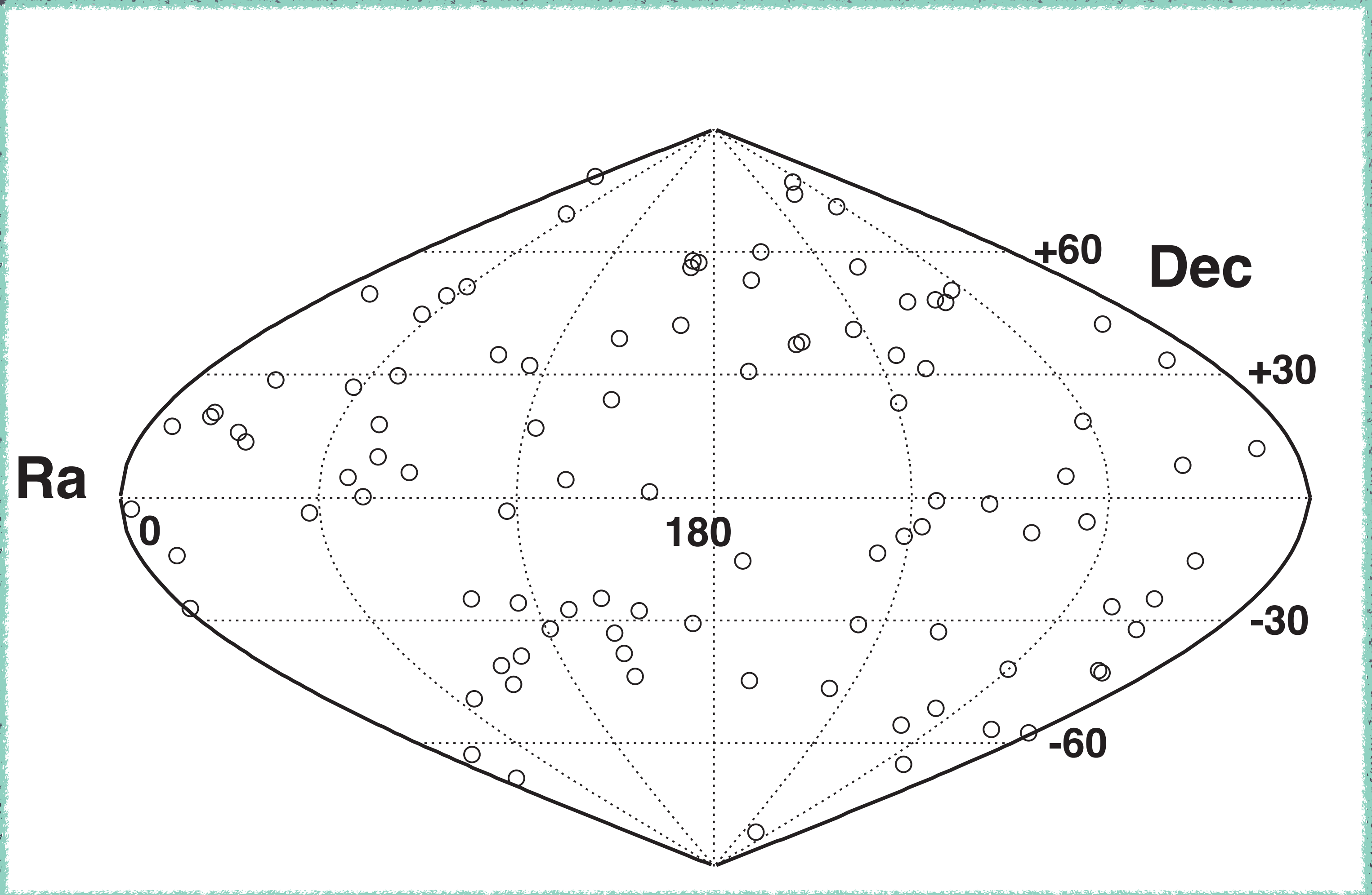
No evidence yet

AGASA: yes

HIRES: no

Auger: not at this level

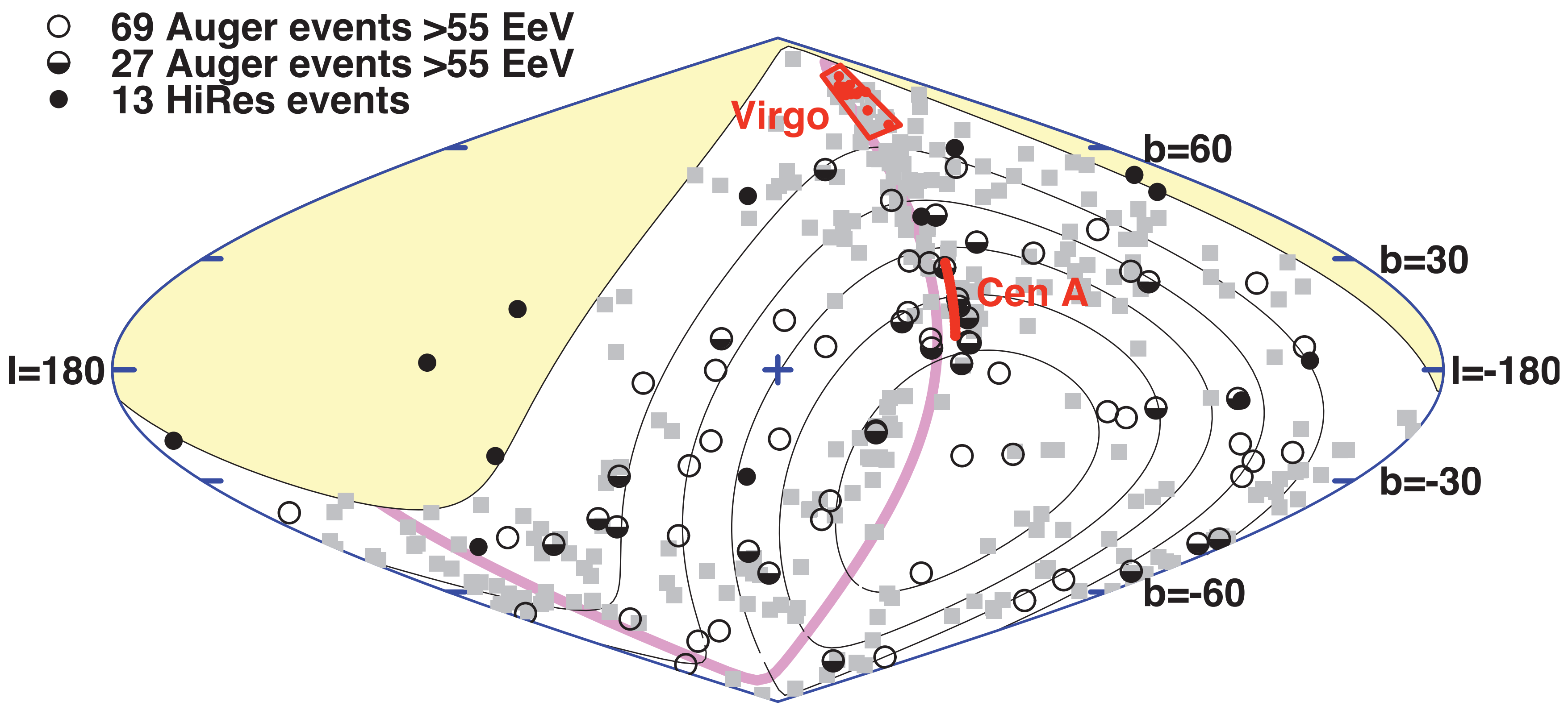
AGASA - SUGAR arrival directions



99 events observed above 40 EeV by SUGAR and AGASA
$(\theta < 55^\circ)$ $(\theta < 45^\circ)$

[LAA et al., Phys. Rev. D 68 (2003) 083004]

HiRes - Auger arrival directions



[Letessier-Selvon & Stanev, arXiv:1103.0031]

A posteriori analysis on Cen A region

- Maximum departure from isotropy ☛ for ring of 18°

  13 events observed ☛ expectation of 3.2 from isotropy

- There are no events coming from less than 18° around M87

- Centaurus cluster lies 45 Mpc behind Cen A

- Could some of the events come from Centaurus cluster rather than Cen A?

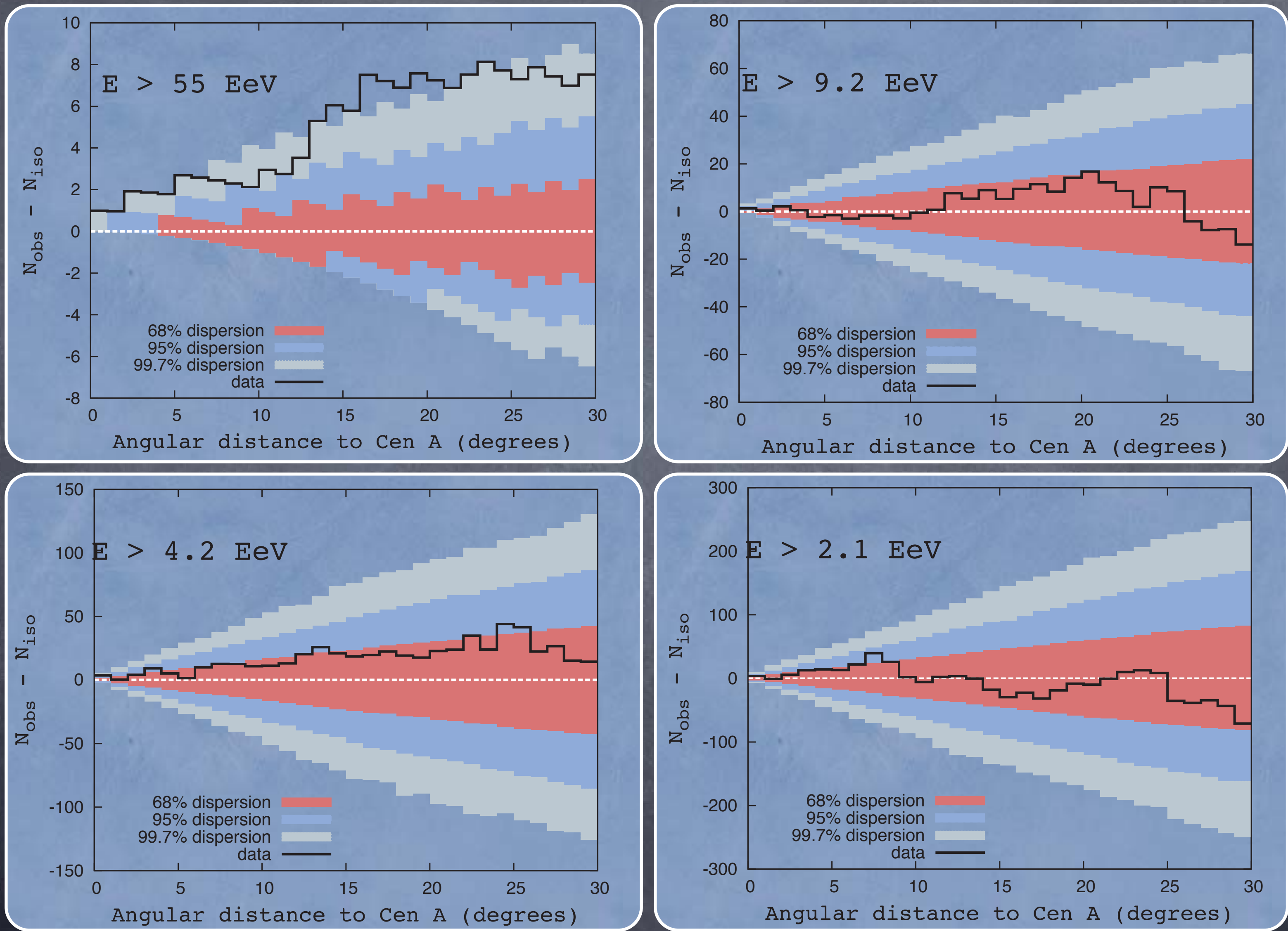
- This does not appear likely
  because Centaurus cluster is farther away than Virgo cluster
  for comparable CR luminosities one would expect
  small fraction of events coming from Virgo

- Events emitted by Cen A and deflected by magnetic fields could still register as correlation due to overdense AGN population lying behind Cen A ☛ resulting in spurious signal

[Gorbunov, Tinyakov, Tkachev, Troitsky, arXiv:0804.1088]

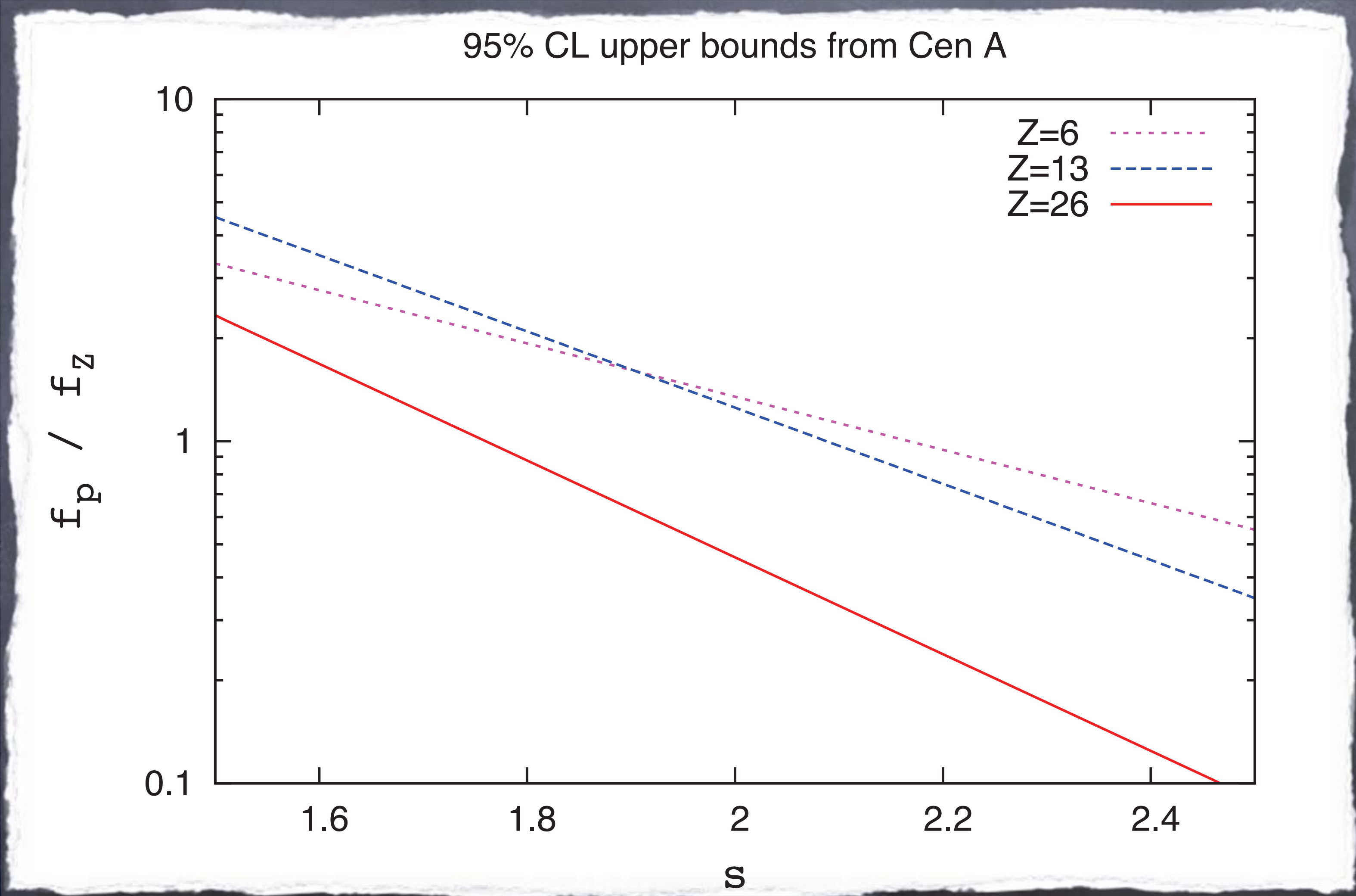
If particles responsible for Cen A excess are heavy nuclei proton component should lead to excess at EeV energies

[Lemoine & Waxman, JCAP 11 (2009) 9]



[Pierre Auger Collaboration, arXiv:1106.3048]

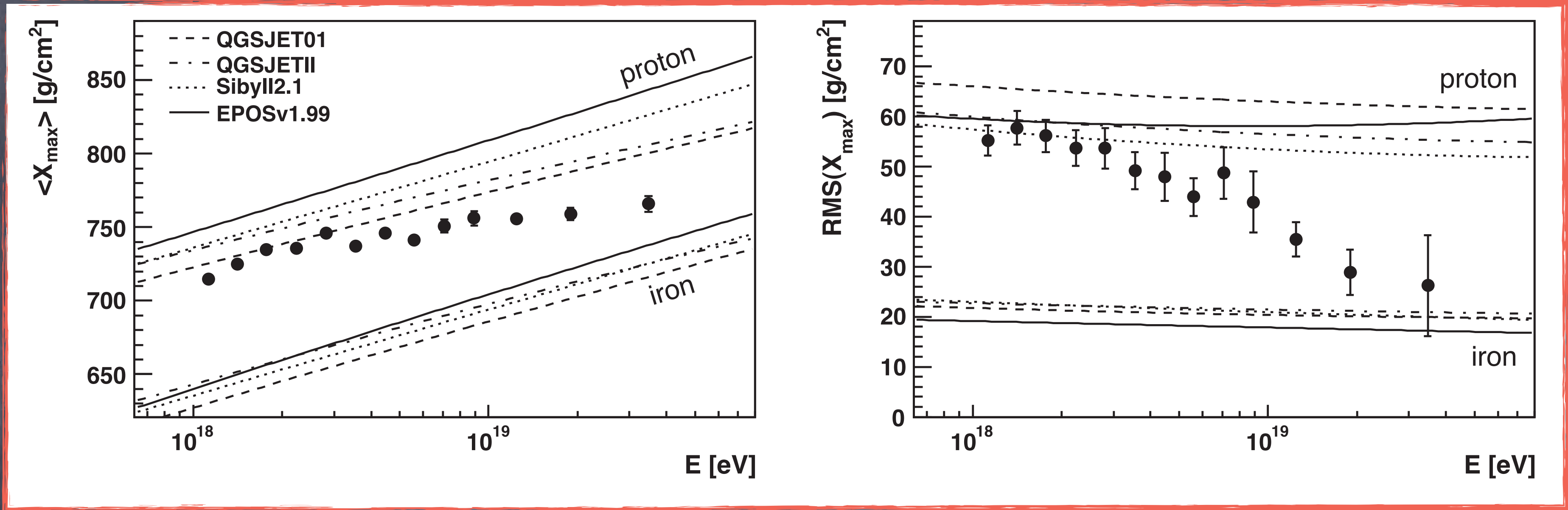
Required proton-to-nucleus ratio for heavy nuclei excess



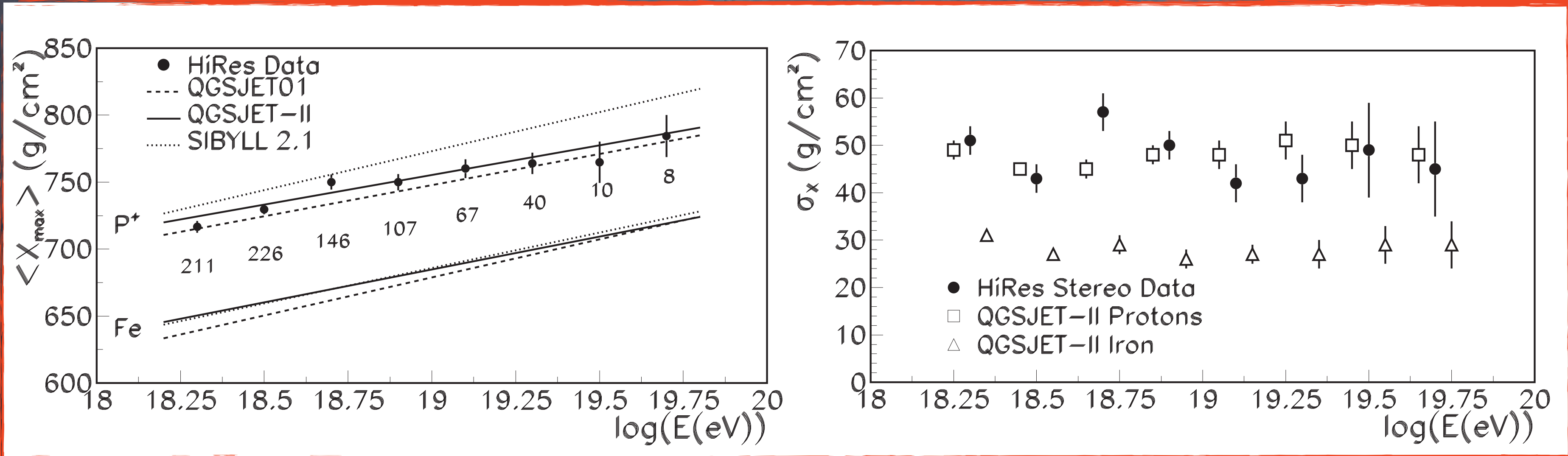
[Pierre Auger Collaboration, arXiv:1106.3048]

Hereafter consider proton primaries beyond GZK suppression

$\langle X_{\max} \rangle$ and $\mathrm{RMS}(\langle X_{\max} \rangle)$



[Pierre Auger Collaboration, Phys. Rev. Lett. 104 (2010) 091101]



[HiRes Collaboration, Phys. Rev. Lett. 104 (2010) 161101]

Two component admixture

For $\langle X_{\max} \rangle$

$$\langle X_{\max} \rangle = (1-\alpha)\langle X_{\max} \rangle_p + \alpha \, \langle X_{\max} \rangle_{\mathrm{Fe}}$$

For $\sigma(\langle X_{\max} \rangle)$

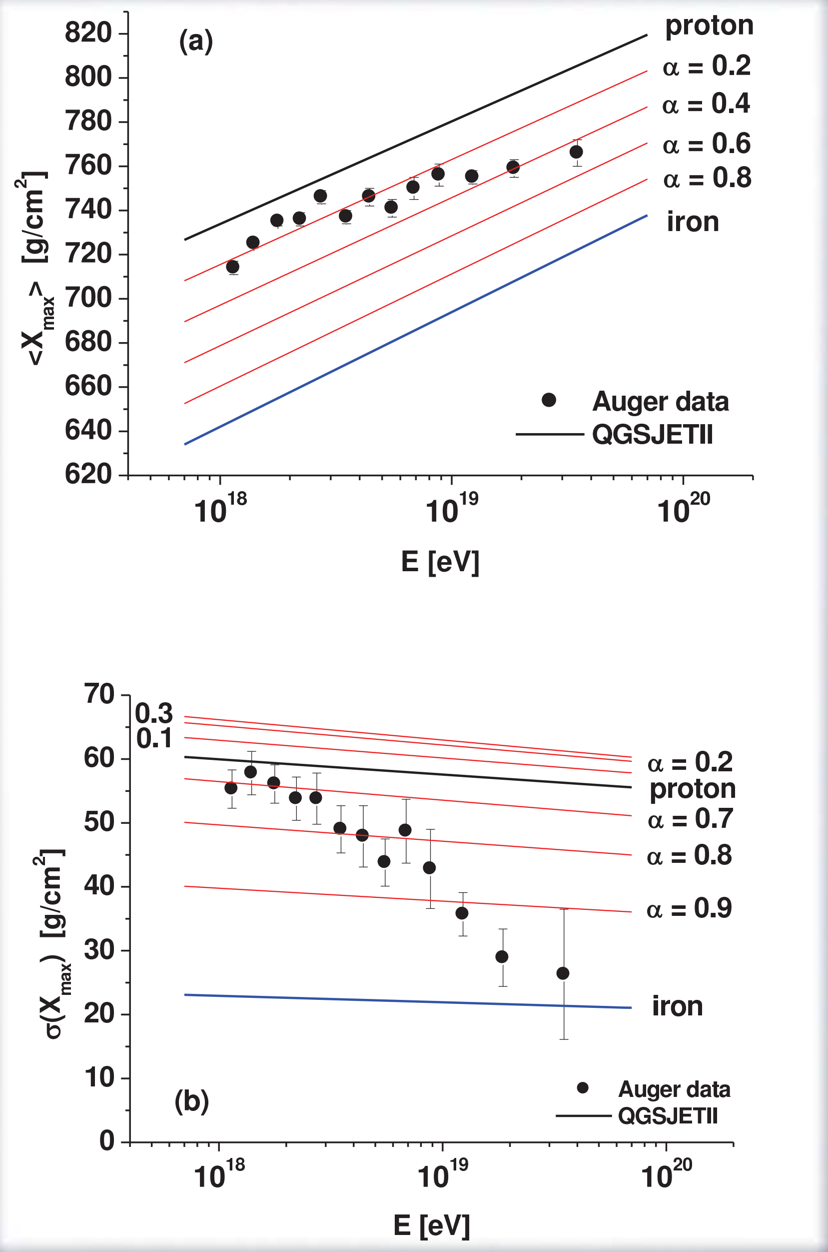
non monotonic dependence on α

$$\begin{aligned} \sigma^2 &= (1-\alpha)\,\sigma_p^2 + \alpha\,\sigma_{\mathrm{Fe}}^2 \\ &+ \alpha\,(1-\alpha)\,(\langle X_{\max}\rangle_p - \langle X_{\max}\rangle_{\mathrm{Fe}})^2 \end{aligned}$$

has maximum at

$$\alpha = \frac{1}{2}\left[1 - \frac{\sigma_p^2 - \sigma_{\mathrm{Fe}}^2}{(\langle X_{\max}\rangle_p - \langle X_{\max}\rangle_{\mathrm{Fe}})^2}\right]$$

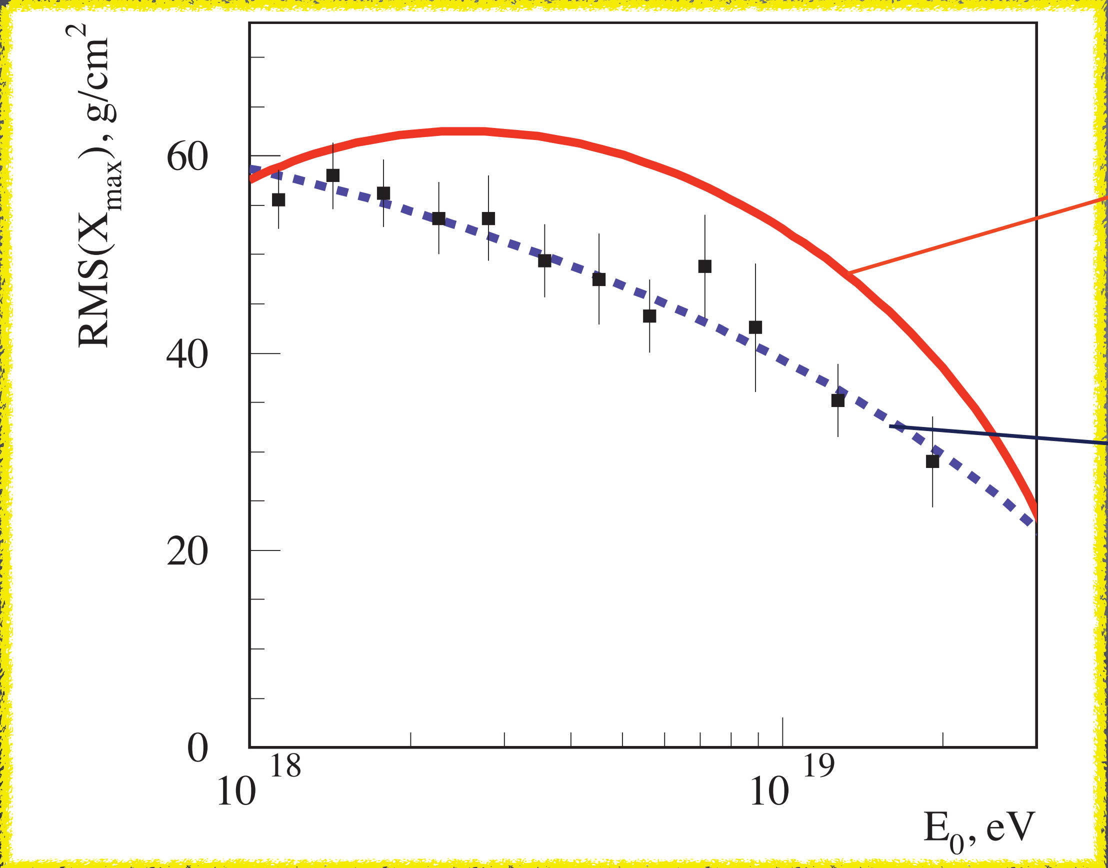
[Wilk & Wlodarczyk, arXiv:1006.1781]



Two component admixture (cont'd)

Partial abundance f_p changing smoothly between 1 and 30 EeV

$$f_p(E) = f_p(1\ \text{EeV})\ [1 - \log(E/\text{EeV})/1.5]$$



$f_p(1\ \text{EeV}) = 1$

$f_p(1\ \text{EeV}) = 0.4$

[Ostapchenko, arXiv:1006.1781]

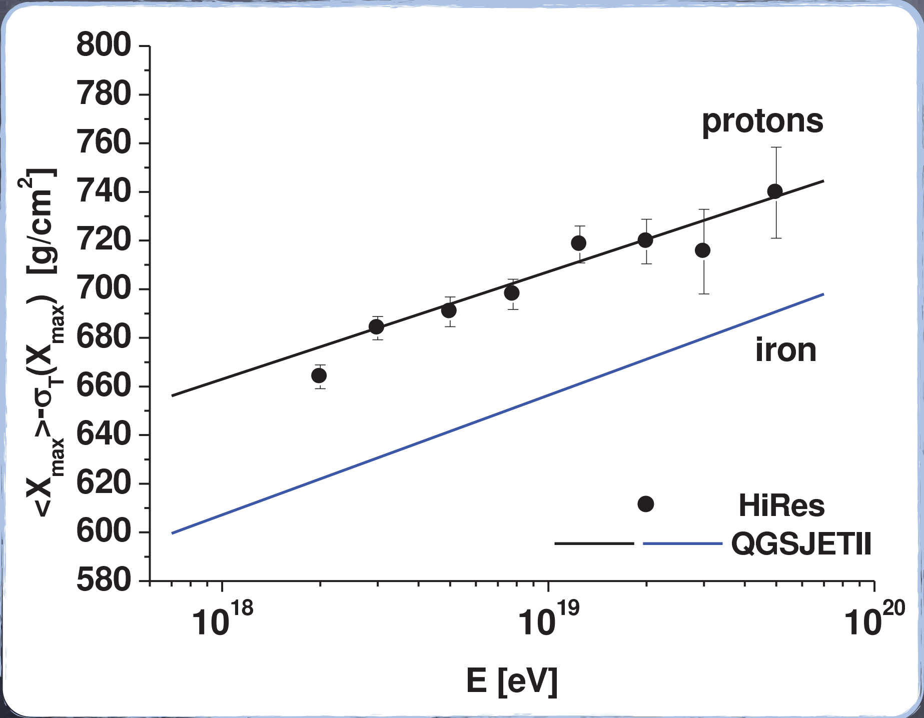
BUT RECALL in Auger data ☛ $\frac{dX_{\max}}{d\log E} > 0 \qquad 1\ \text{EeV} < E < 3\ \text{EeV}$

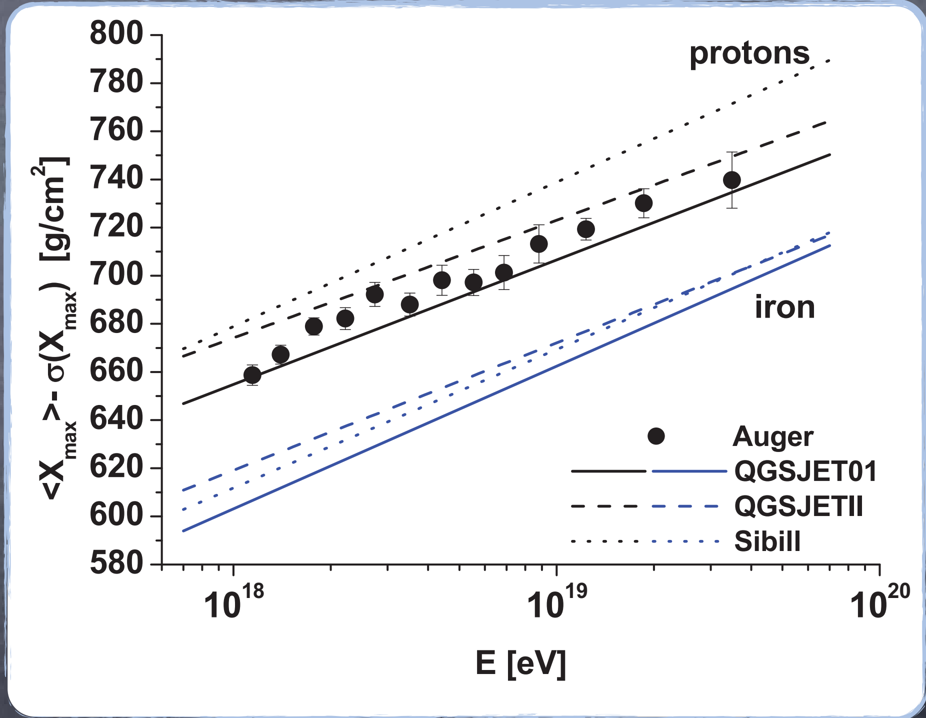
Reconciling HiRes & Auger measurements

Ratio of shower attenuation length to proton interaction length particularly sensitive to mean inelasticity and its fluctuations

$k = \Lambda/\lambda$ [Block, Halzen, Stanev, Phys. Rev. D 62 (2000) 077501]

New observable with fluctuations in k strongly suppressed

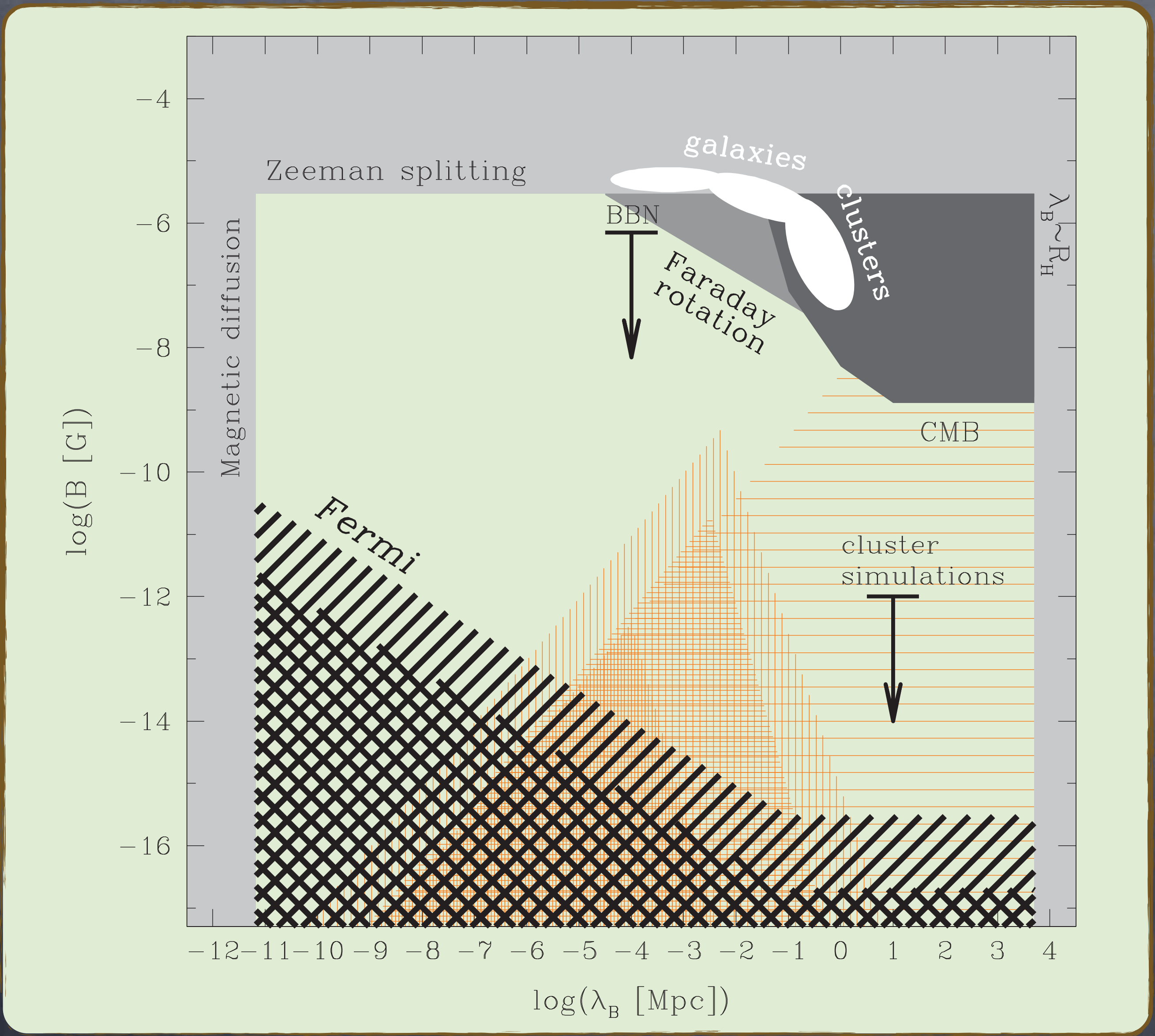




[Wilk & Wlodarczyk, arXiv:1006.1781]

Hereafter consider proton primaries beyond 1 EeV

Bounds on extragalactic magnetic field



[Neronov & Vovk, Science 328 (2010) 73]

RMS constrain B-fields of any origin but CMB distortions only primordial Bs

Extragalactic magnetic field

- Bounds on line of sight component of Xtragalactic B-field from Faraday RM of linearly polarized emission of radio sources

$$\mathrm{RM}_{\mathrm{rad/m^2}} \propto \int_0^d n_e \, B \, dl$$

- Original analysis considered $\Lambda = 0$ and $\Omega = 1$ yielding

$$B(\lambda_B/\mathrm{Mpc})^{1/2} \lesssim 10^{-9}\ \mathrm{G}$$

[Kronberg, Rep. Prog. Phys. (1994) 325]

- Care must be taken: cosmological effects must be included!

$$B \lesssim 3 \times 10^{-7}\ (\Omega_b h^2/0.02)^{-1}\ (h/0.72)\ (\lambda_B/\mathrm{Mpc})^{-1/2}\ \mathrm{G}$$

[Blasi, Burles, Olinto, Astrophys. J. 514 (1999) L79]
[Farrar & Piran, Phys. Rev. Lett 84 (2000) 3527]

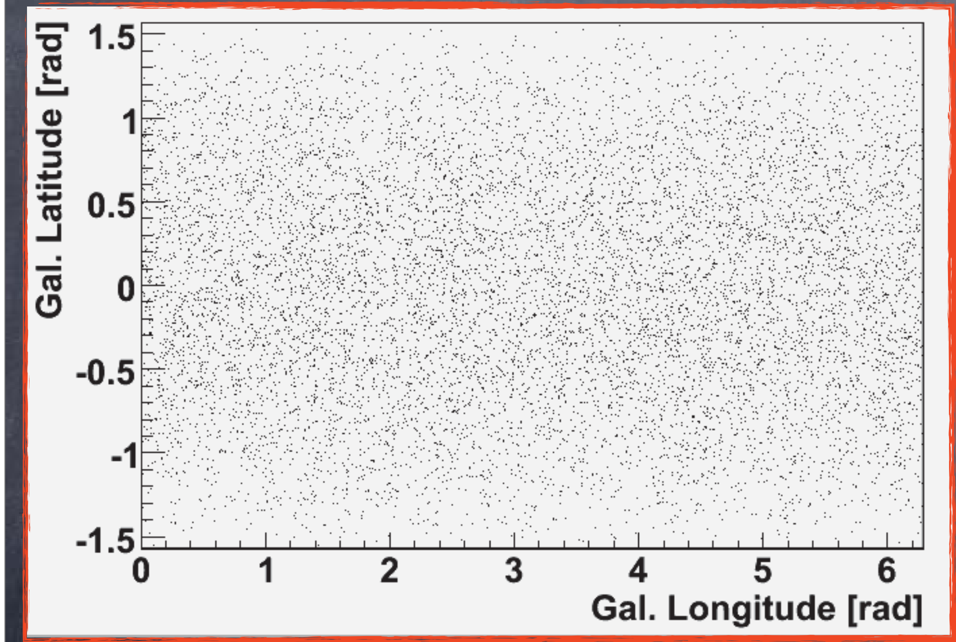
Measurement of Xtragalactic $\vec{B}$-field

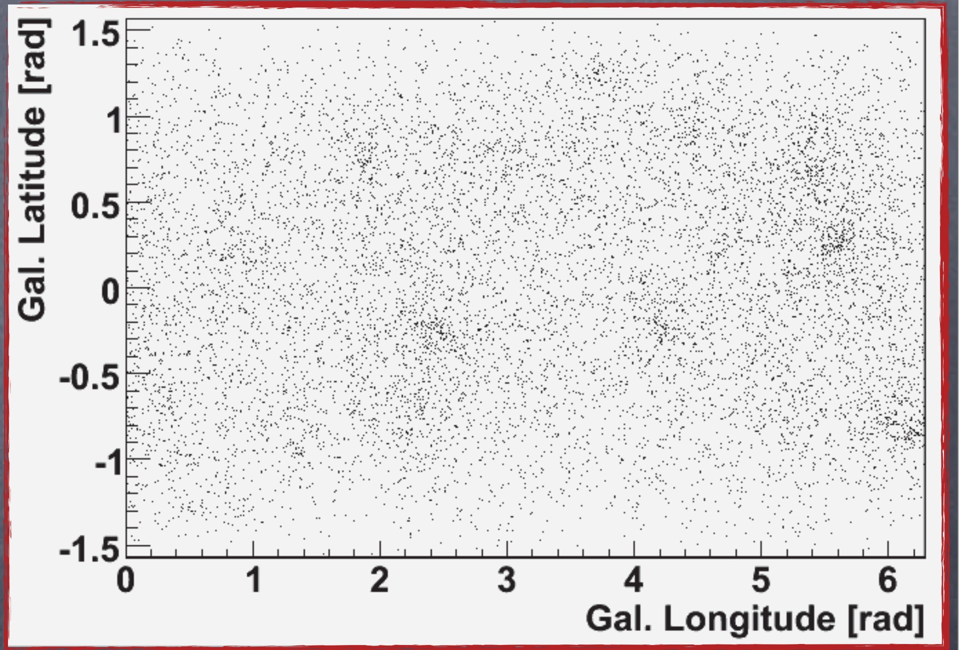
Can we distinguish these two scenarios?

Isotropy

"toy data"

10 sources with magnetic fields

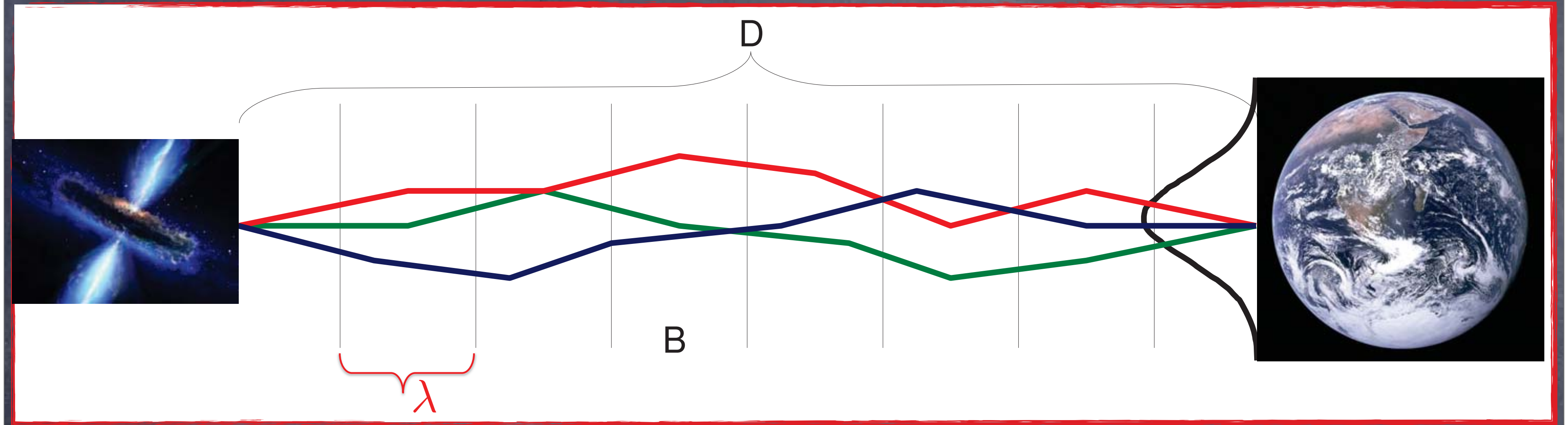




10,000 simulated UHECRs with Energy above 5 EeV

Erdmann & Schiffer Astropart. Phys. 33 (2010) 201

Generalities of simulated data set



- Assume circles of radius λ with constant magnetic field B
- Random field direction in each area (random walk)

$$\sigma_\theta(E) \propto \frac{(D\,\lambda)^{1/2}\,B}{E} = \frac{C_{\mathrm{Field}}}{E/\mathrm{EeV}}$$

Parameters used

$$D = 50\ \mathrm{Mpc}$$

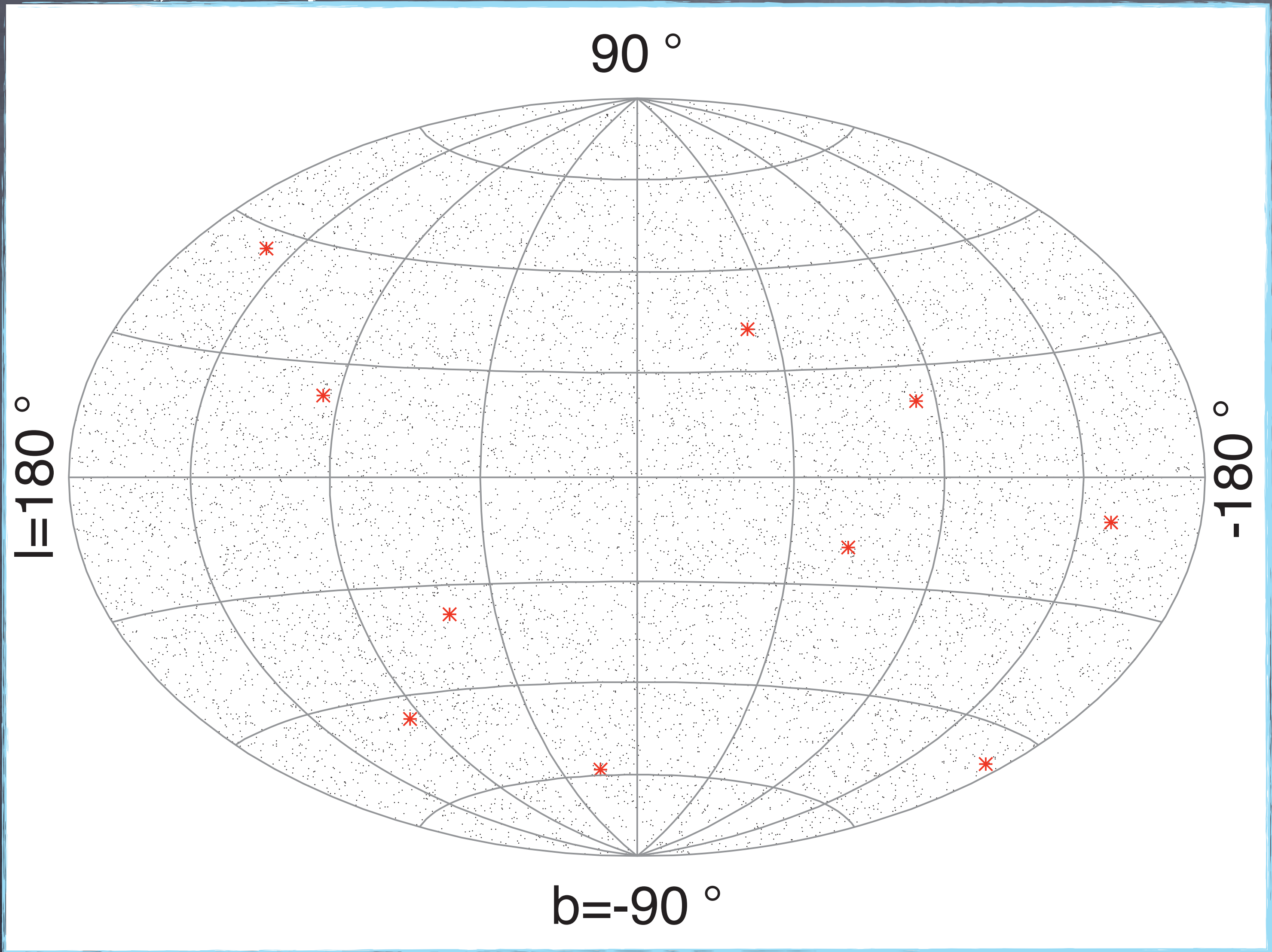
$$\lambda = 1\ \mathrm{Mpc}$$

$$B = 3\ \mathrm{nG}$$

Gives ☛ $C_{\mathrm{field}} = 10$

- Coherent deflection on Galactic $\vec{B}$-field
  Stanev Astrophys. J. 479 (1997) 290

Skymap of simulated data set



Arrival directions of signal data set ● and sources ✶

Erdmann & Schiffer Astropart. Phys. 33 (2010) 201

Region of Interest

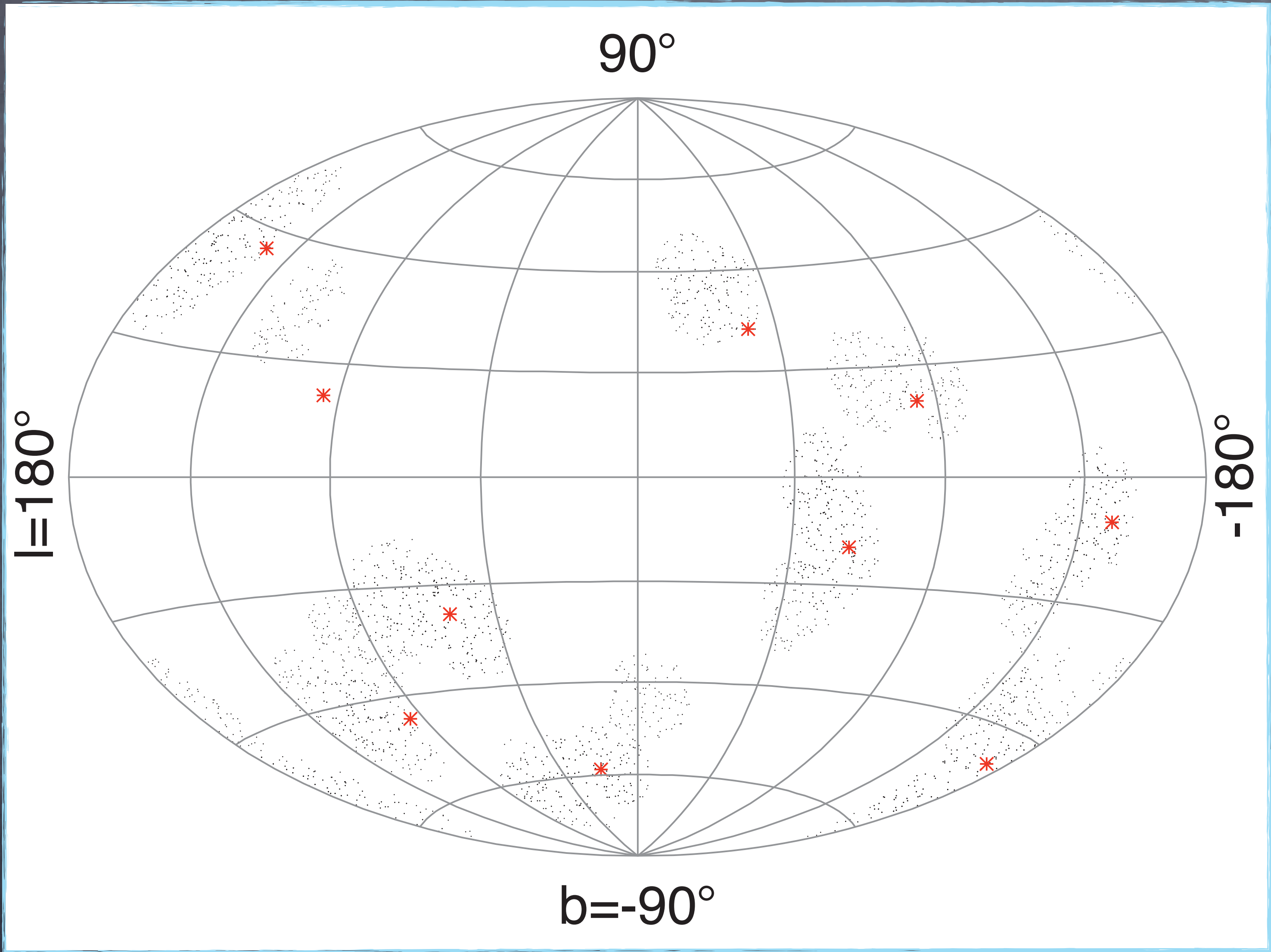
- ROI ☛ region close to UHECR source candidate
- No CR source has been identified so far ☛ apply iterative cone algorithm to find ROI with increased probability of containing source

1. Select all UHECRs with energies above $E_{min} = 60 EeV$ as initial seeds
2. For all seeds define corresponding ROI by assigning all UHECRs with $\alpha < \alpha_{max} = 0.2$
3. Calculate center-of-mass for each ROI using energies of UHECRs as weights
4. Use ROI center-of-mass as new seed and iterate starting from item 2

(Note that every UHECR can be part of several ROIs)

- Algorithm is processed in total three times
- Last resulting ROIs are taken for further analysis

Reconstructed ROIs



UHECR belonging to ROI ● and sources ✶

Erdmann & Schiffer Astropart. Phys. 33 (2010) 201

Energy-energy Correlations

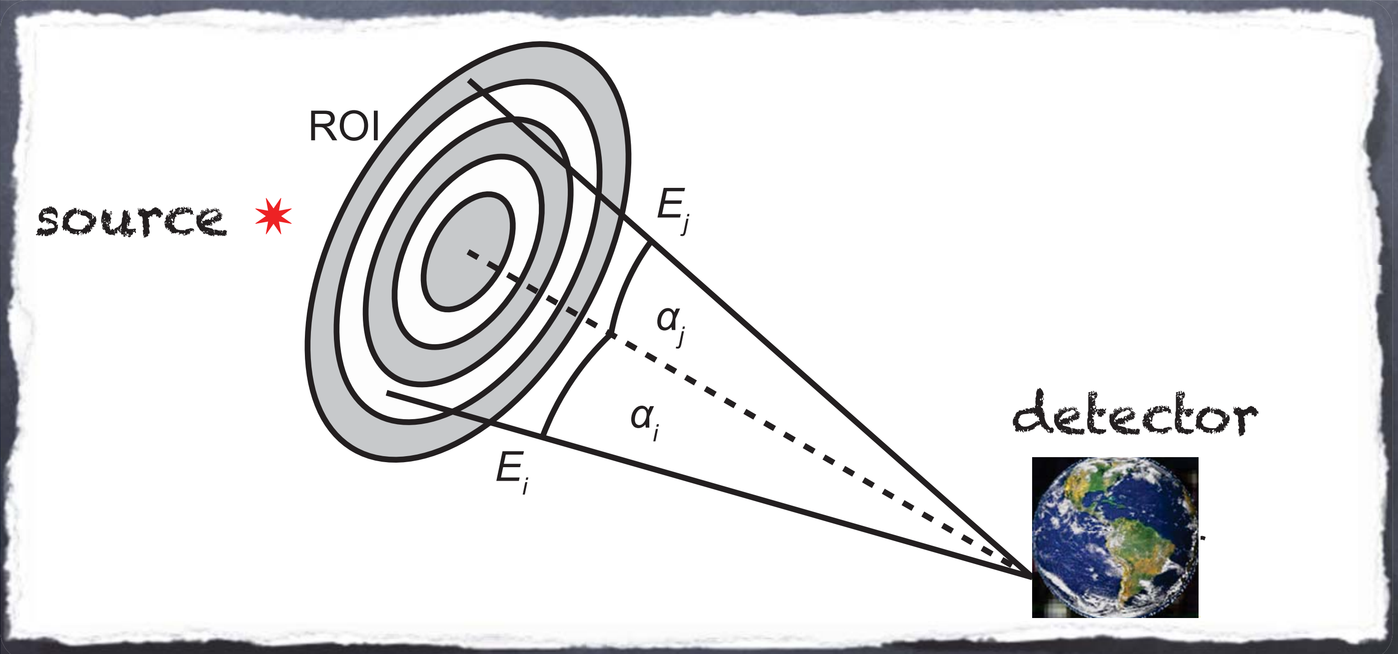
Define energy-energy correlation between UHECRs i and j

$$\Omega_{ij} = \frac{\left(E_i(\alpha_i) - \langle E(\alpha_i)\rangle\right)\left(E_j(\alpha_j) - \langle E(\alpha_j)\rangle\right)}{E_i(\alpha_i)E_j(\alpha_j)}$$

E_i ☛ energy of UHECR i

α_i ☛ angular distance with respect to ROI center

$\langle E(\alpha_i)\rangle$ ☛ average energy of UHECR arriving within same ring relative to ROI center



Angular ordering of UHECRs

- Calculate Ω_{ij} of all pairs of UHECRs that belong to same ROI
- Each Ω_{ij} is filled into a histogram at both α_i and α_j
- Background contribution ☛ $\Omega_{ij} < 0$

(one being above and other below corresponding average energy values)

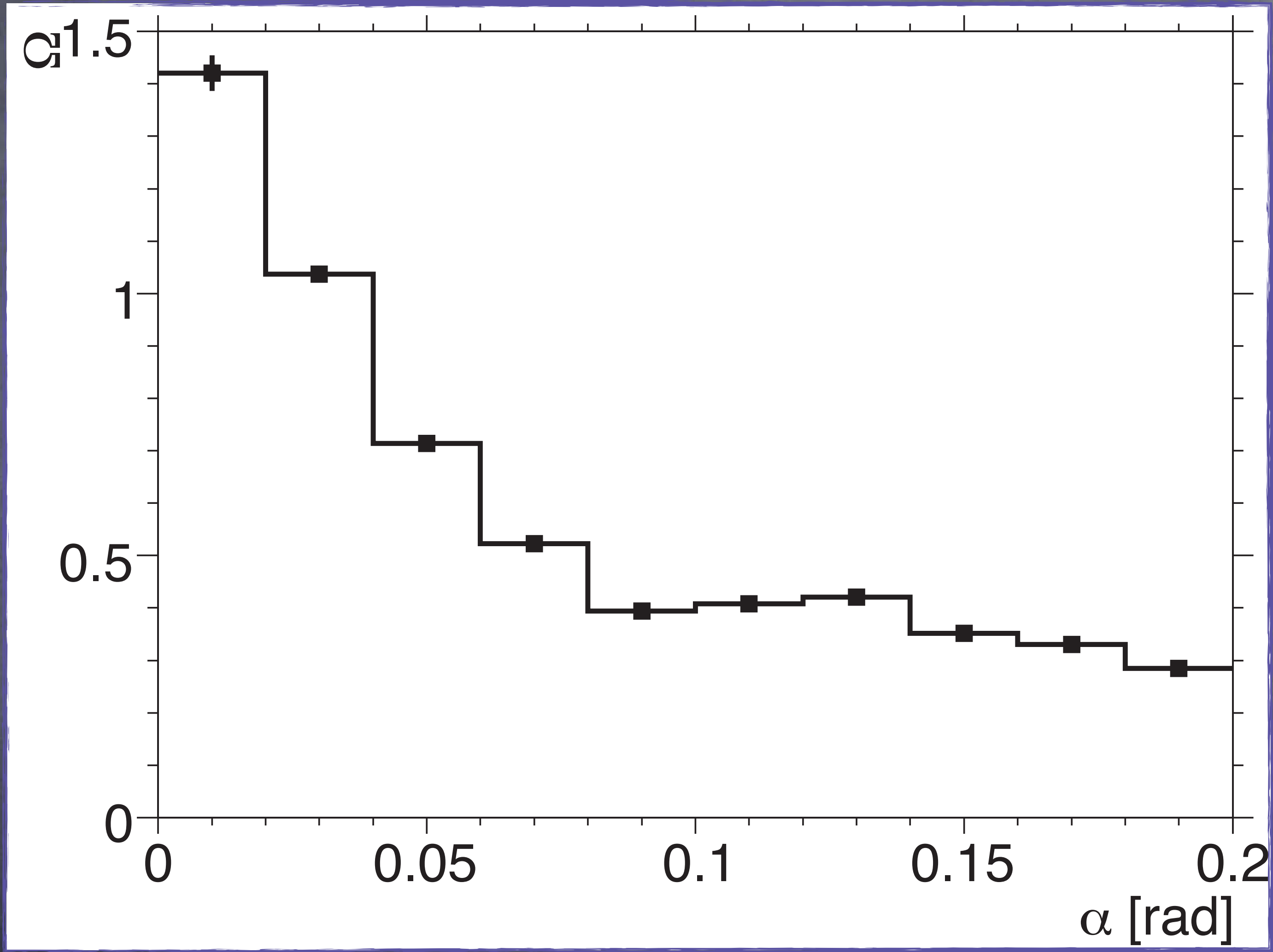
- Signal contribution ☛ $\Omega_{ij} > 0$

(both with energy above or below average energy at corresponding $\Delta\alpha$)

- For every bin $\Delta\alpha$ calculate average value Ω and uncertainty

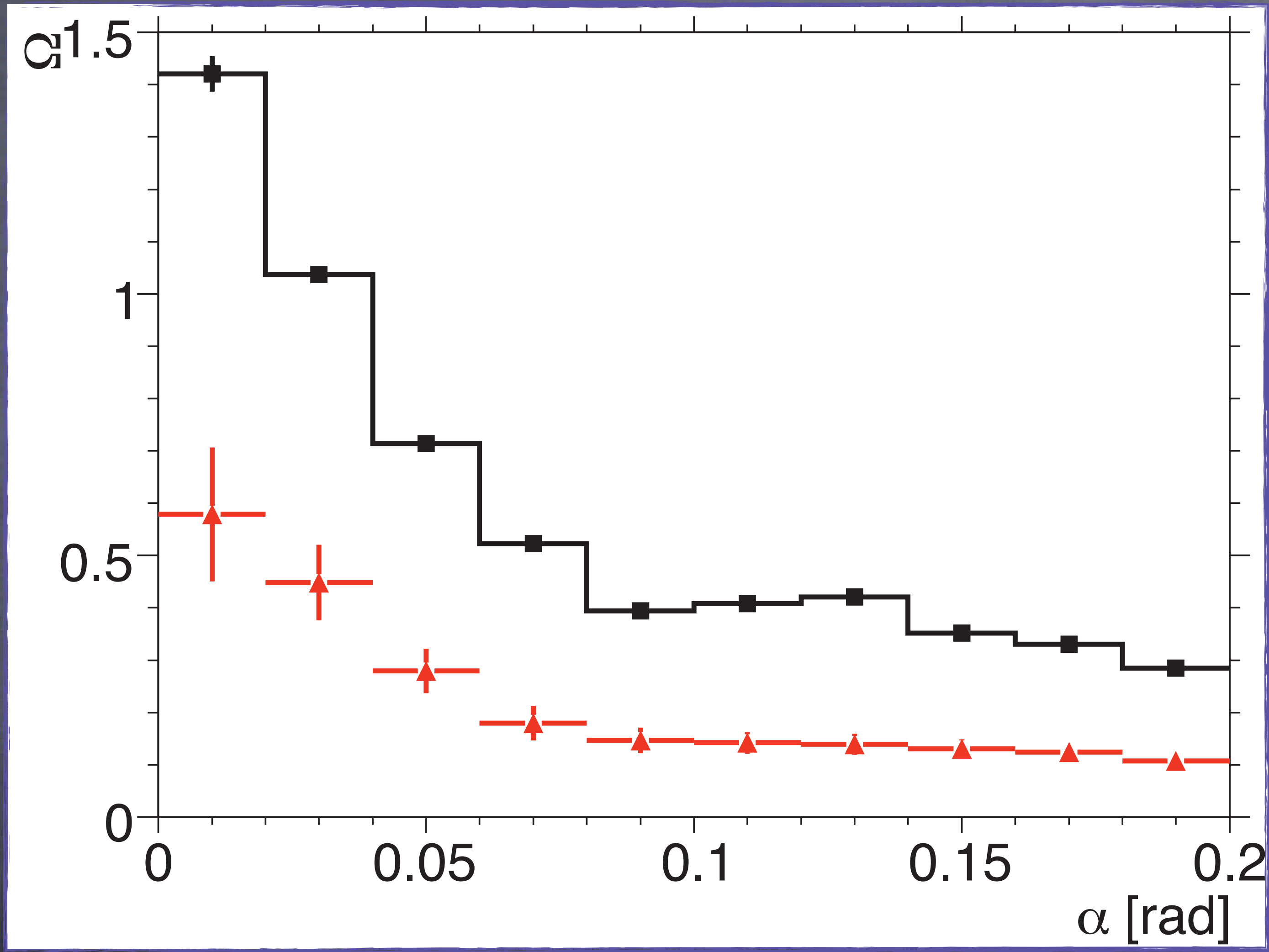
Overall ☛ larger Ω for mixing of coherently arriving UHECRs than for exclusively isotropic arrival directions

Signal data set



Erdmann & Schiffer Astropart. Phys. 33 (2010) 201

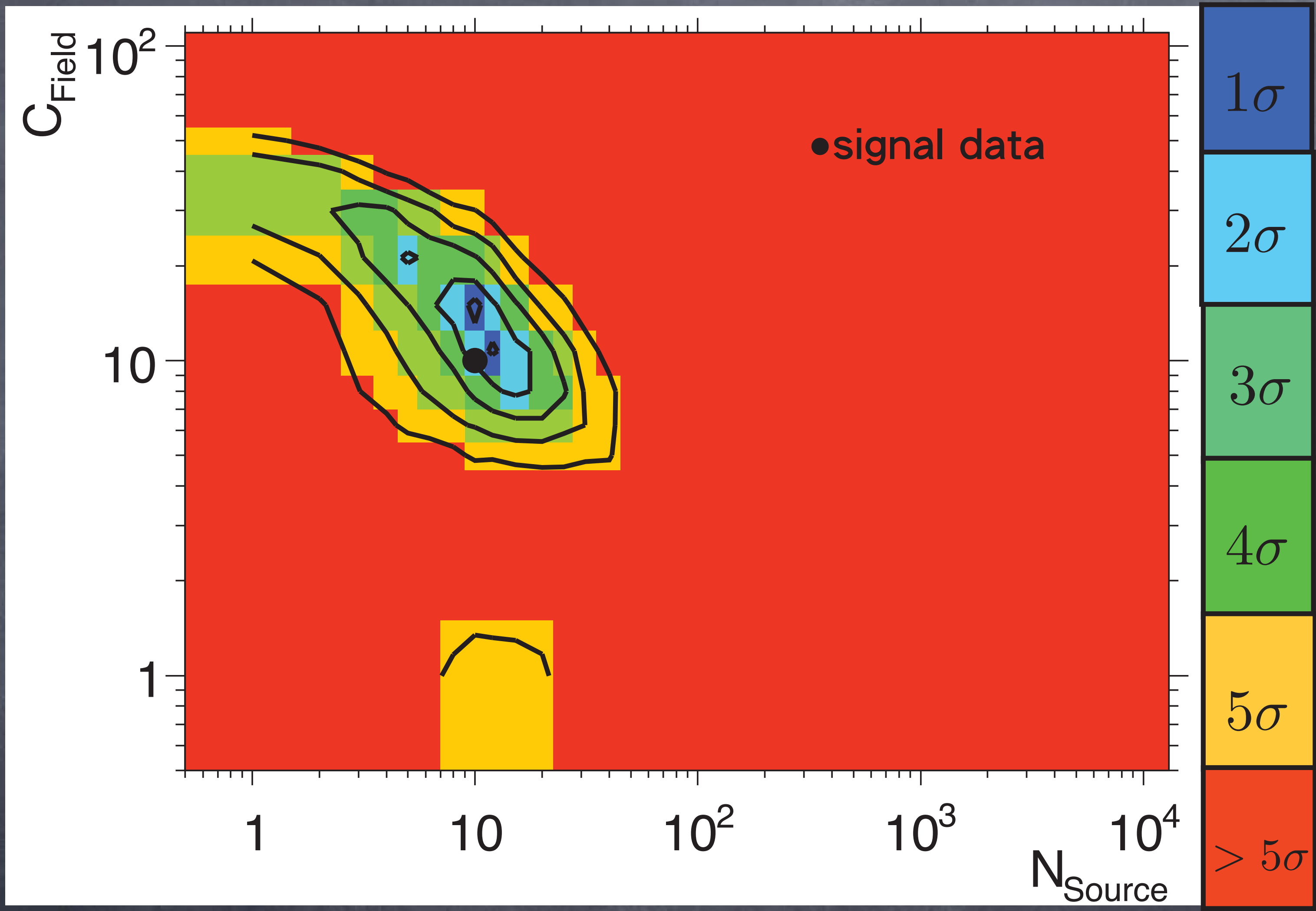
Signal data set & isotropic distribution



signal data ■ isotropic arrival directions ▲

Erdmann & Schiffer Astropart. Phys. 33 (2010) 201

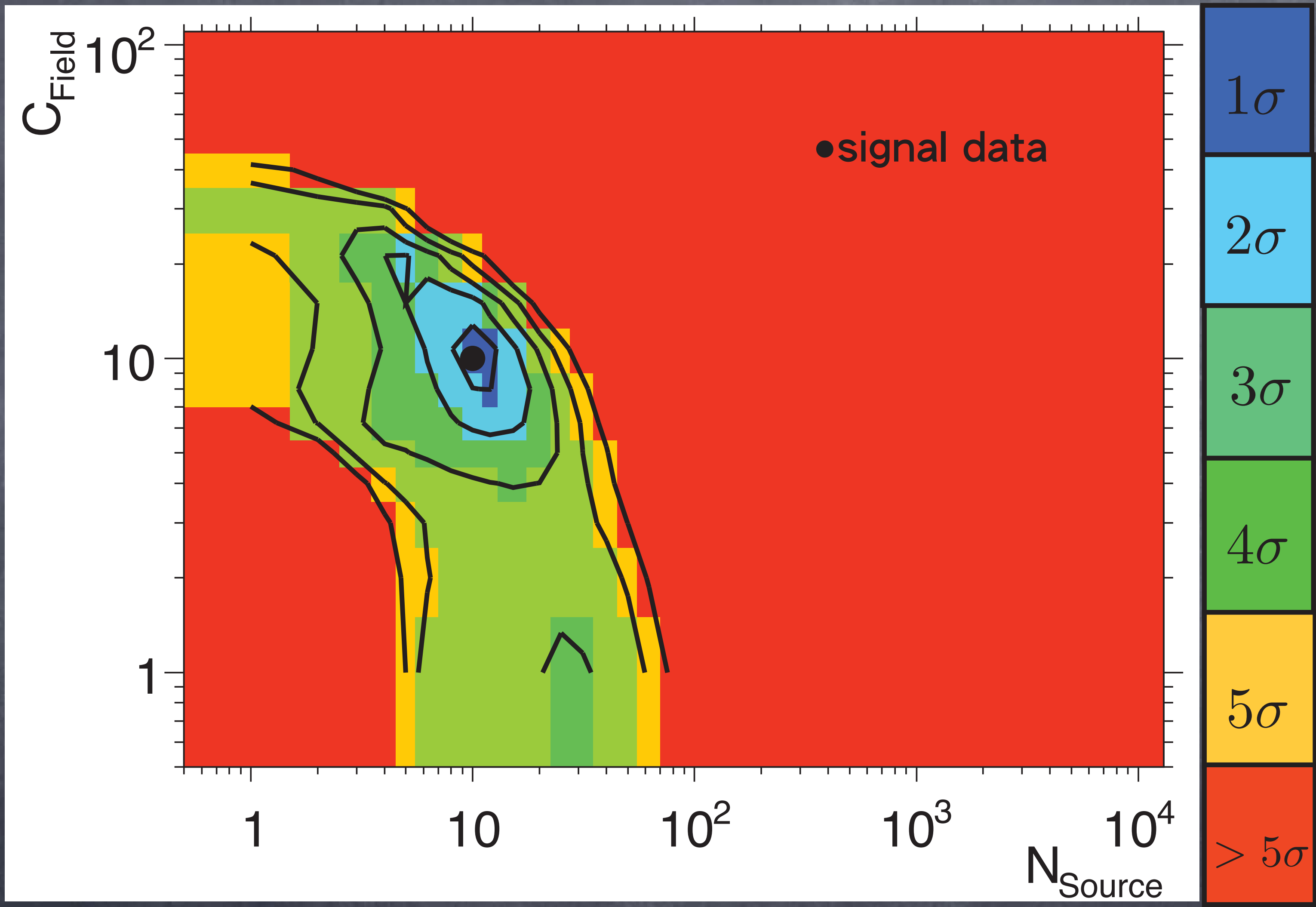
Likelihood analysis



Error contours of signal data set

Erdmann & Schiffer Astropart. Phys. 33 (2010) 201

Likelihood analysis (cont'd)



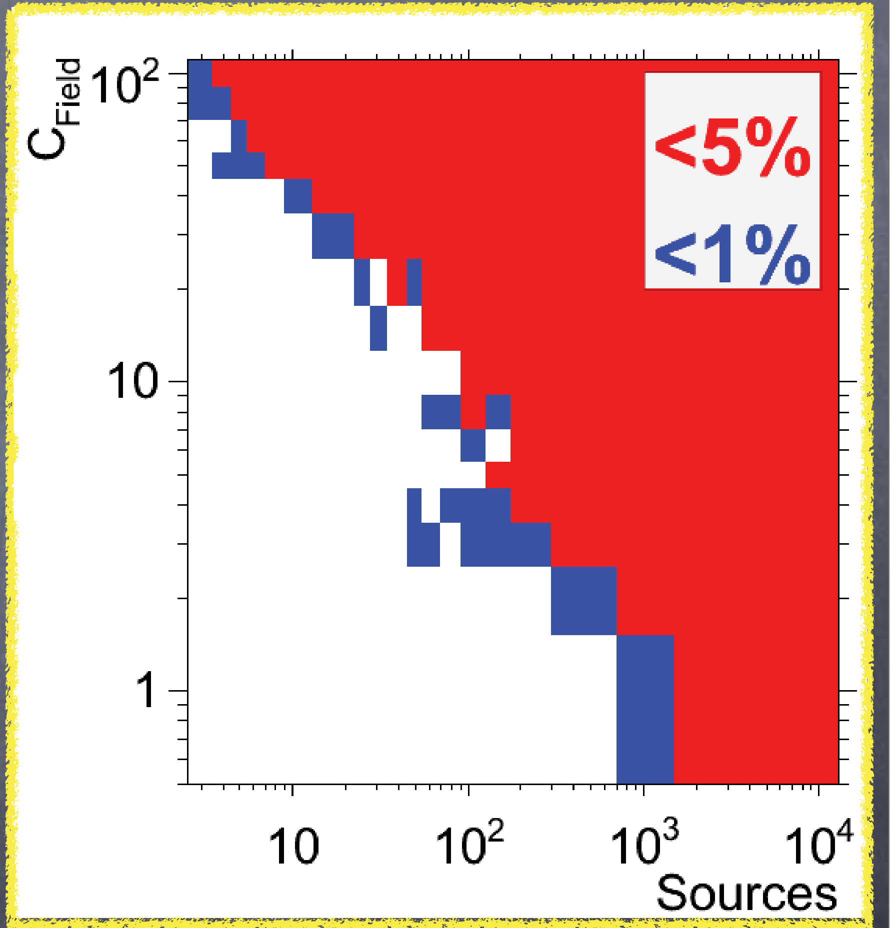
Error contours using 100 signal data sets

Erdmann & Schiffer Astropart. Phys. 33 (2010) 201

Recover isotropy

Isotropy test for 10,000 UHECR protons above 5 EeV

368 sets in $(C_{\rm Field}, N_{\rm sources})$ plane
with 100 simulated skies each



Isotropic skies require

Xtragalactic $\vec{B} \gg 1$ nG

or very large number of sources

e.g. ☛ for $C_{\rm Field} = 10$

isotropic sky $\Leftrightarrow N_{\rm sources} = 10^4$

with negligible dependence on
shape of Galactic $\vec{B}$-field

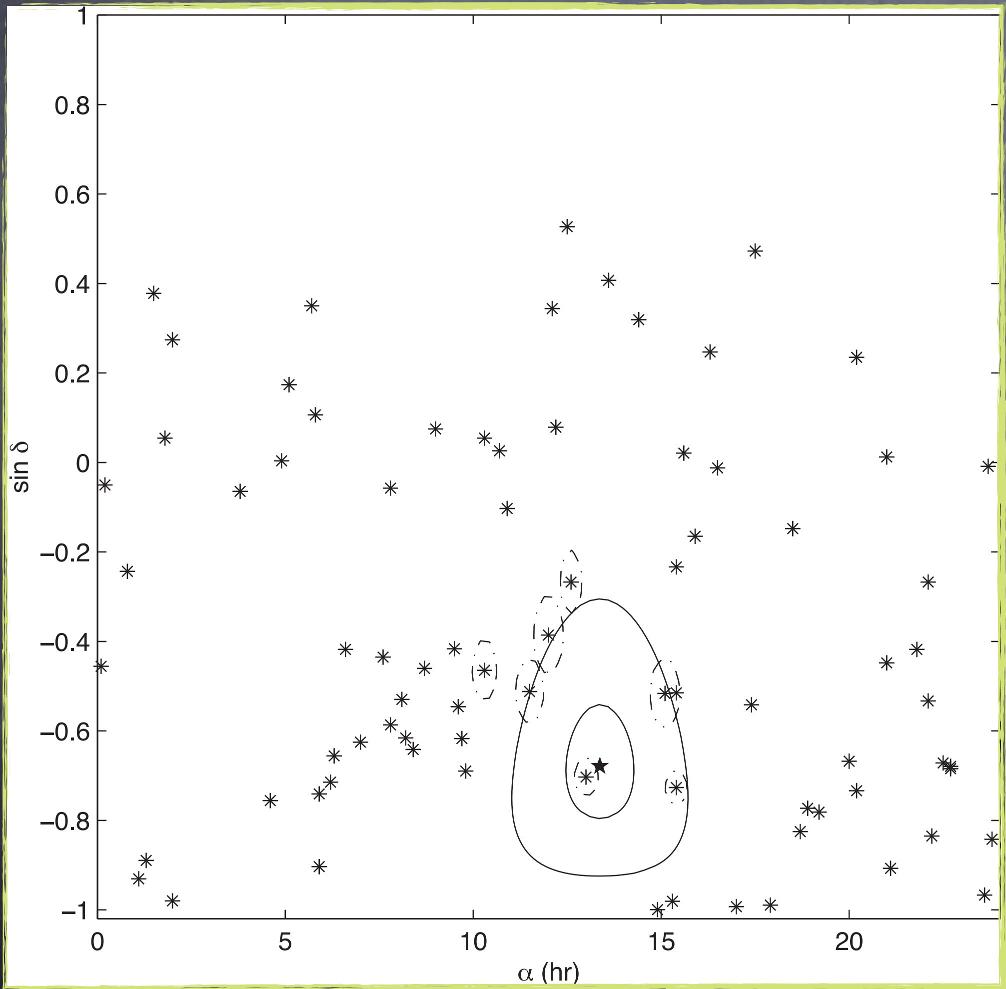
Schiffer Int. Astropart. Phys. Symposium (IAPS 2008) -- Colorado School of Mines --

Ω of Auger data sample will be released at ICRC 2011
stay tuned!!!

Lower bound on Xtragalactic $\vec{B}$ -field

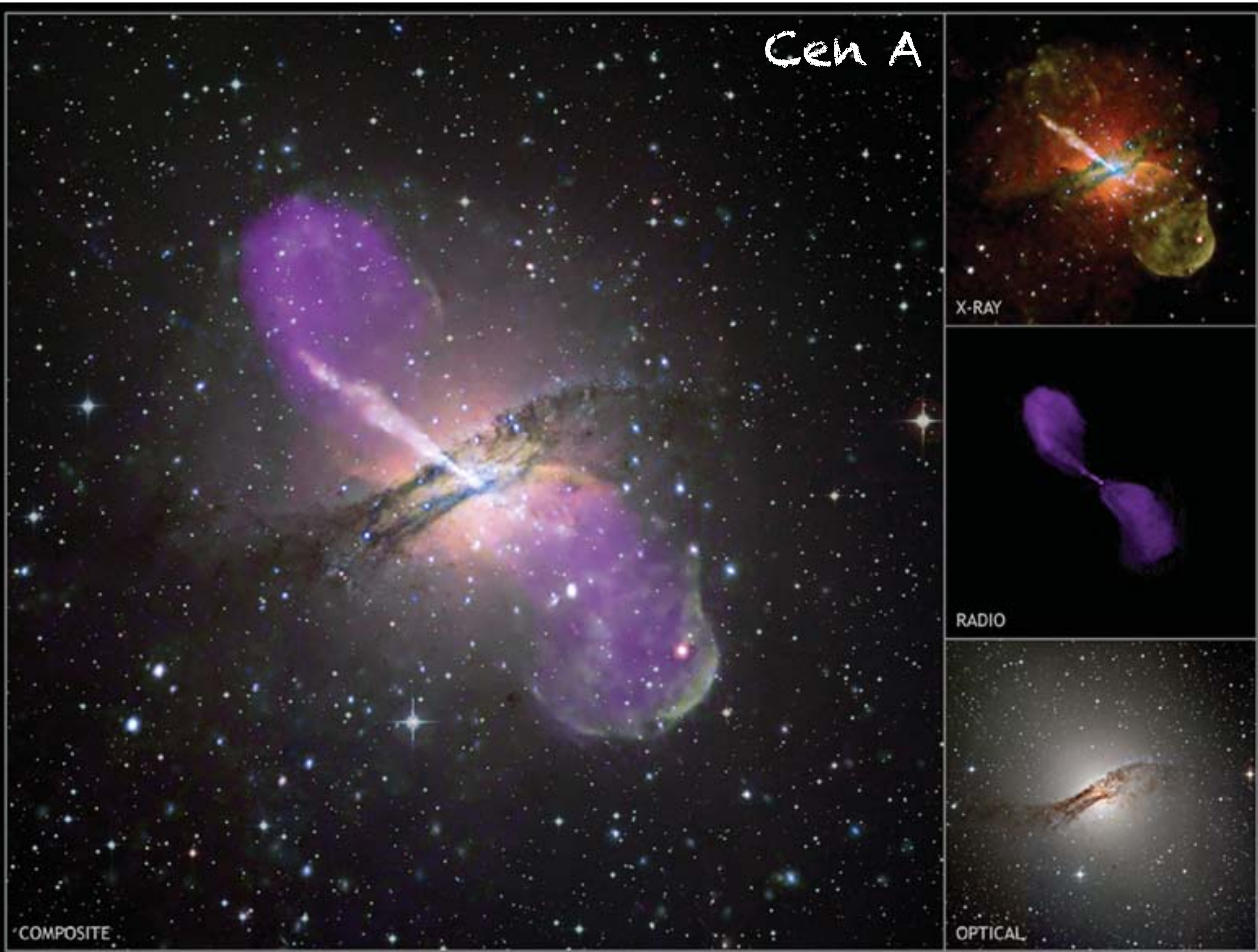
Trace backwards SUGAR data assuming Cen A UHE emission

[Winn et al., J. Phys. G 12 (1986) 675]



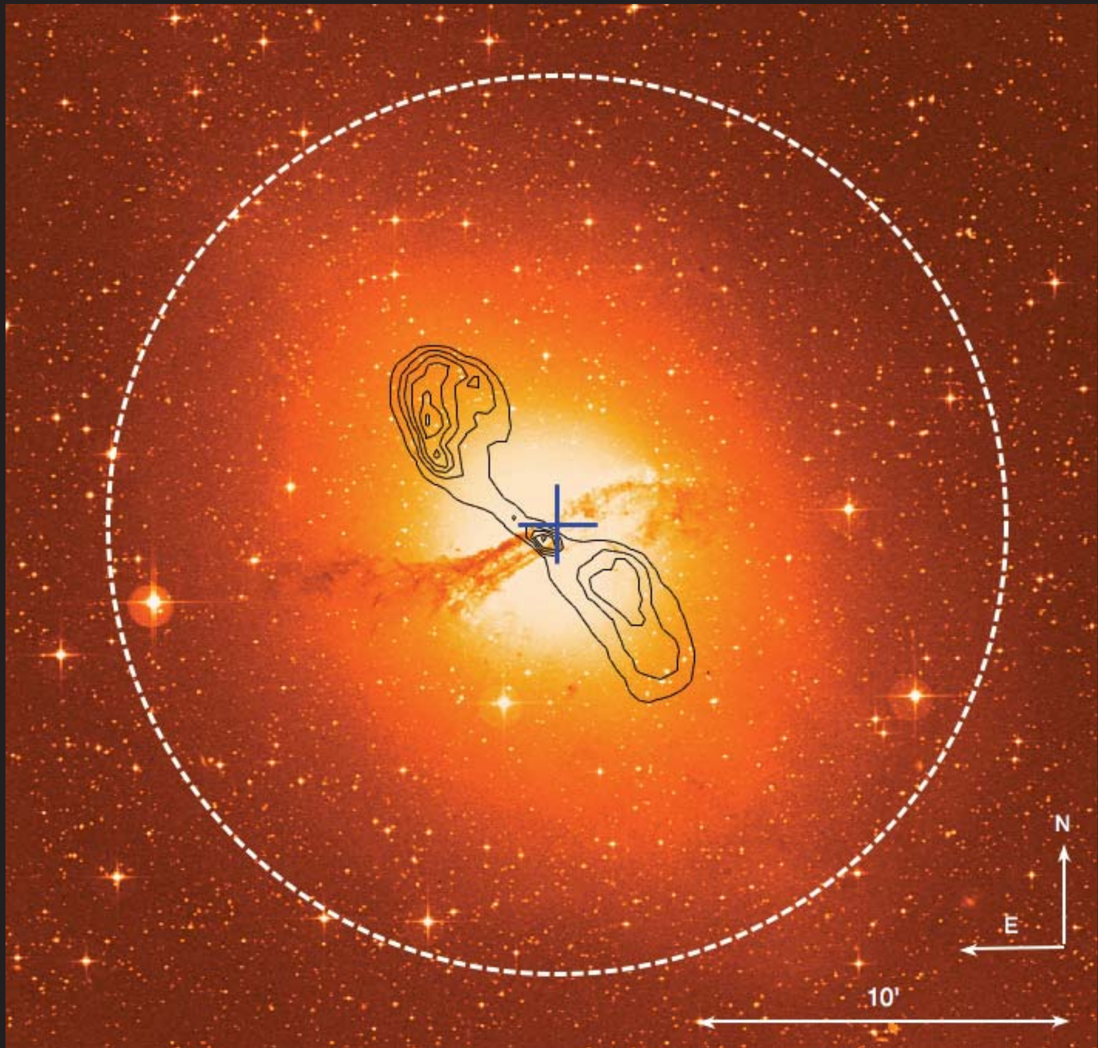
$B > 10\ \mathrm{nG}$

LAA & Goldberg, Phys. Rev. D 65 (2002) 021302



$L_{\mathrm{bol}} = 10^{43}\ \mathrm{erg/s}$ $d = 3.4\,\mathrm{Mpc}$ $L_{\mathrm{jet}} = 7.7 \times 10^{42}\ \mathrm{erg/s}$

Gamma Ray Observations



- EGRET

$$L_{\gamma>100\mathrm{MeV}} \approx 10^{41}\ \mathrm{erg/s}$$

spectral index 2.40 ± 0.28

[Astropart. Phys. 11 (1999) 221]

- H.E.S.S.

$$L_{\gamma>250\ \mathrm{GeV}} \sim 3 \times 10^{41}\ \mathrm{erg/s}$$

spectral index $2.7 \pm^{0.5\ \mathrm{stat}}_{0.2\ \mathrm{sys}}$

[Astrophys. J. 695 (2009) L40]

- Fermi-LAT

$$L_{\gamma>100\ \mathrm{MeV}} \approx 10^{41}\ \mathrm{erg/s}$$

mostly originating on radio lobes

spectral index $2.60^{+0.14}_{-0.15}\ \mathrm{stat} \pm 0.20\ \mathrm{syst}$

[Science 328 (2010) 725]

Fermi acceleration at Cen A

Acceleration time scale

$$\tau_{\rm acc} \approx \frac{40}{\pi}\,\frac{1}{c\beta_{\rm jet}^2 U}\left(\frac{E}{eB}\right)^{1/3} R^{-2/3}$$

Energy loss time scale

$$\tau_{\rm loss} \approx \frac{6\pi m_p^4 c^3}{\sigma_{\rm T} m_e^2 B^2 (1+\mathcal{Y})} E^{-1}$$

Maximum attainable energy

$$E_{20} = 1.4 \times 10^5\ B_{\mu \rm G}^{-5/4}\ \beta_{\rm jet}^{3/2}\ U^{3/4}\ R_{\rm kpc}^{-1/2}\ (1+\mathcal{Y})^{-3/4}$$

Biermann & Strittmatter, Astrophys. J. 322 (1987) 643

Containment condition

$$E_{\rm max} \simeq Z\, B_{\mu \rm G}\, R_{\rm kpc}\ {\rm EeV}$$

$\beta_{\rm jet} \sim 0.5$ ☛ Hardcastle et al. Astrophys. J. 593 (2003) 169

$B_{\mu \rm G} \sim 100$ ☛ Honda Astrophys. J. 706 (2009) 1517

$R_{\rm kpc} \sim 2$ ☛ Junkes, Haynes, Harnett, Jauncey, Astron. Astrophys. 269 (1993) 29

$U \sim 0.4$ ☛ Romero, Combi, LAA, Perez Bergliaffa, Astropart. Phys. 5 (1996) 276

Diffusion

energy loss-diffusion equation

$$\frac{\partial n(E,\mathbf{r},t)}{\partial t} = \frac{\partial [b(E) n(E,\mathbf{r},t)]}{\partial E} + \nabla [D(E,\mathbf{r},t)\, \nabla n(E,\mathbf{r},t)] + Q(E,t)\, \delta^3(x)$$

Bohm diffusion coefficient

$$D(E) = \frac{c r_L}{3} = 0.1 \left(\frac{E}{\mathrm{EeV}}\right) \left(\frac{B}{\mathrm{nG}}\right)^{-1} \mathrm{Mpc}^2\, \mathrm{Myr}^{-1}$$

idealizing emission to be uniform

$$Q(E,t) = \frac{N_{\rm tot}}{\tau} \left[\Theta(t - t_{\rm on}) - \Theta(t - t_{\rm off})\right]$$

integrated source emissivity density

$$\int Q(E,\mathbf{r}',t')\, d^3x'\, dt' = N_{\rm tot}$$

Solution for continuous emitting source
(neglecting energy losses)

$$n(E,\mathbf{r},t) = \int dt' \int d^3x'\; G(\mathbf{r}-\mathbf{r}', t-t')\; \mathcal{Q}(E,\mathbf{r}',t')$$

Green function

$$G(\mathbf{r}-\mathbf{r}', t-t') = [4\,\pi\, D\,(t-t')]^{-3/2}\;\Theta(t-t')\,\exp\{-(\mathbf{r}-\mathbf{r}')^2/4D(t-t')\}$$

$$\begin{aligned}\frac{dn(E,\mathbf{r},t)}{dE} &= \frac{dN_0}{dE\,dt}\frac{1}{[4\pi D(E)]^{3/2}}\int_{t_{\rm on}}^{t} dt'\,\frac{e^{-r^2/4D(t-t')}}{(t-t')^{3/2}} \\ &= \frac{dN_0}{dE\,dt}\frac{1}{4\pi^{3/2}D(E)r}\int_{v_1}^{v_2}\frac{dv}{v^{3/2}}\,e^{-1/v} \\ &= \frac{dN_0}{dE\,dt}\frac{1}{4\pi D(E)r}\,I(x)\end{aligned}$$

$$I(x) = \frac{1}{\sqrt{\pi}}\int_{1/x}^{\infty}\frac{du}{\sqrt{u}}\,e^{-u}$$

$$x = 4D(t-t_{\rm on})/r^2$$

Energy losses

$$-\frac{1}{E}\frac{dE}{dt} = A \exp\left[-\frac{B}{E}\right]$$

Berezinsky & Grigor'eva, Astron. Astrophys. 199 (1988) 1

$$A = (3.66 \pm 0.08) \times 10^{-8}\ \mathrm{yr}^{-1} \qquad B = (2.87 \pm 0.03) \times 10^{11}\ \mathrm{GeV}$$

For $t - t_{\mathrm{on}} = 70\ \mathrm{Myr} \Rightarrow I(x) \approx 0.4$

$$\tau_{\mathrm{delay}} \sim \left.\frac{d^2}{D(E)}\right|_{70\ \mathrm{EeV}} \sim 8 \times 10^7\ \mathrm{yr}$$

energy losses can be safely neglected

UHECR luminosity

'cause of diffusion ☛ observed $J \propto E^{-4}$ reflects $dN_0/dEdt \propto E^{-3}$

neutron rate ☛

$$\frac{dN_n}{dt} = \frac{S}{4\pi d^2} \int_{E_1}^{E_2} e^{-d/\lambda(E)} \frac{dN_0}{dEdt} dE,$$

taking

$S = 3000 \text{ km}^2$ | $\lambda(E) \simeq 9.2 \times 10^{-3}\, E_{\rm EeV}$ Mpc | $E_1 = 55$ EeV | $E_2 = 150$ EeV

$$L_{\rm CR}^{(E_1,E_2)} = 9 \times 10^{39} \text{ erg/s}$$

assume continuity of spectrum at E_1 as it flattens to E^{-2}

and taking lower bound $E_0 = 30$ EeV

$$L_{\rm CR}^{(E_0,E_1)} = 4 \times 10^{40} \text{ erg/s}$$

total ☛

$$L_{\rm CR}^{(E_0,E_2)} = 5 \times 10^{40} \text{ erg/s}$$

$L_{\rm CR}^{(E_0,E_2)} \ll L_{\rm jet}$ ☛ kinetic power of jets inflating the giant lobes

Diffuse proton background

$$\langle E^4\, J(E)\rangle = \frac{E^4 c}{(4\pi)^2\, d\, D(E)}\, \frac{dN_0}{dE\, dt}\, I(x)$$
$$\approx 1.6 \times 10^{57}\ \mathrm{eV}^3\, \mathrm{km}^{-2}\, \mathrm{yr}^{-1}\, \mathrm{sr}^{-1}$$

taking circular pixel sizes with 3° radii ☛ $\Delta\Omega \simeq 8.6 \times 10^{-3}$ sr

event rate of (diffuse) protons

$$\frac{dN_p}{dt} = S\ \Delta\Omega \int_{E_1}^{E_2} \langle E^4\, J\rangle\, \frac{dE}{E^4} = 0.08\ \mathrm{events/yr}$$

- 9 yr of operation about 6 direct neutron events against almost negligible (diffuse proton) background
- No directional signals from M87!!!

Anisotropy amplitude

Downward flux at Earth per sr as function of angle θ to source

$$J(E,\theta,\mathbf{r},t) = \frac{n(E,\mathbf{r},t)\,c}{4\pi}(1+\alpha\cos\theta)$$

$$\alpha\,\cos\theta = \frac{|\mathbf{j}(E,\mathbf{r},t)|}{n(E,\mathbf{r},t)\,c}$$

incoming current flux density as viewed by observer on Earth

$$\begin{aligned} j'_i(E,x'_i,t) &= D\,\frac{\partial n(E,x'_i,t)}{\partial x'_i} \\ &= D\frac{dN_0}{dEdt}\frac{1}{(4\pi D)^{3/2}}\int_{t_{\rm on}}^{t}\frac{dt'}{(t-t')^{3/2}}e^{-(R^2+2\mathbf{R}\,.\,\mathbf{r}'+r'^2)/4D(t-t')}\,\frac{-(2R_i+2x'_i)}{4D(t-t')} \\ &= -\frac{(R_i+x'_i)}{2(4\pi D)^{3/2}}\int_{t_{\rm on}}^{t}\frac{dt'}{(t-t')^{5/2}}\,e^{-r^2/[4D(t-t')]} \end{aligned}$$

$$\mathbf{r} = \mathbf{R} + \mathbf{r}'$$

Anisotropy amplitude (cont'd)

Near $x'_i = 0$

$$j'_i(E, x'_i, t) = \frac{R_i}{2}\frac{dN_0}{dEdt}\frac{1}{(4\pi D)^{3/2}}\frac{r^2}{4D}\left(\frac{4D}{r^2}\right)^{5/2}\int_{1/x}^{\infty} du\, u^{1/2}\, e^{-u}$$

$$= \frac{R_i}{2\pi}\frac{dN_0}{dEdt}\frac{1}{r^3} I'(x)$$

$$I'(x) = \frac{1}{\sqrt{\pi}}\int_{1/x}^{\infty} du\ \sqrt{u}\ e^{-u}$$

taking ☛ $R_x = R_x = 0$ and $R_z = r\cos\theta$

$$\alpha = \frac{2D(E)}{cr}\ \frac{I'(x)}{I(x)}$$

For $E = 70$ EeV $B_{\rm nG} = 50$ $t - t_{\rm on} = 70$ Myr

$$\alpha = 0.29$$

Anisotropy amplitude (cont'd)

For a set of N arrival directions with relative exposure w_i

Rayleigh vector

$$x = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} \frac{1}{w_i} \cos \alpha_i \qquad y = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} \frac{1}{w_i} \sin \alpha_i$$

$$\mathcal{R} = \sqrt{x^2 + y^2} \qquad \mathcal{N} = \sum_{i=1}^{N} w_i^{-1}$$

$$[\cos\theta]_i = \cos(\delta_{\text{Cen A}}) \cos(\delta_i) \cos(\alpha_i - \alpha_{\text{Cen A}}) + \sin(\delta_{\text{Cen A}}) \sin(\delta_i)$$

$$\alpha = \frac{\mathcal{R}}{\langle \cos\delta \rangle \cos \delta_{\text{Cen A}}}$$

$$\Delta\alpha \approx 1.5 N^{-1/2}$$

[Sommers, Astropart.Phys. 14 (2001) 271]

[Pierre Auger Collaboration, Astropart.Phys. 34 (2011) 267]

$$\alpha = 0.25 \pm 0.18$$

Caveats

- We assumed neutrons completely dominate Cen A emission

$$\frac{dN_0}{dE\,dt} \propto (N_0^n + N_0^p)E^{-3} \qquad \frac{N_0^p}{N_0^n} \ll 1$$

this reduces number of free parameters

proton/neutron fraction depends on properties of source

e.g. photon to magnetic energy density ratio here taken as $y \sim 80$

- 3° window does not have an underlying theoretical motivation

angular range resulted from scan maximizing signal significance

Cen A covers elliptical region spanning 10° along major axis

Some care is required to select region of sky which maximizes S/N

[LAA, Denton, Goldberg, Weiler, in preparation]

Optically thin source

- It is helpful to envision CR engines as machines where protons are accelerated and (possibly) permanently confined by magnetic fields of acceleration region
- Production of neutrons and pions and subsequent decay produces neutrinos, gamma-rays, and CRs
- If the neutrino-emitting source also produces high energy CRs then pion production must be principal agent
for high energy cutoff on proton spectrum
- Conversely ☛ since protons must undergo sufficient acceleration inelastic pion production needs to be small below cutoff energy consequently ☛ plasma must be optically thin
- Since interaction time for protons is greatly increased over that of neutrons because of magnetic confinement ☛ neutrons escape before interacting and on decay give rise to observed CR flux

Optically thin source (cont'd)

- 3 conditions on:
  - characteristic nucleon interaction time scale $\tau_{\rm int}$
  - neutron decay lifetime τ_n
  - characteristic cycle time of confinement $\tau_{\rm cycle}$
  - total proton confinement time $\tau_{\rm conf}$

$$(i)\ \tau_{\rm int} \gg \tau_{\rm cycle} \qquad (ii)\ \tau_n > \tau_{\rm cycle} \qquad (iii)\ \tau_{\rm int} \ll \tau_{\rm conf}$$

- (i) ensures that protons attain sufficient energy
- (ii) and (iii) allow neutrons to escape source before decaying
- (iii) permits sufficient interaction to produce n's and nu's

Waxman-Bahcall bound

CR flux above ankle often summarized as

"one 3×10^{10} GeV particle per km square per yr per sr"

translated into energy flux

$$E\{EJ_{\rm CR}\} = \frac{3\times 10^{10}\,{\rm GeV}}{(10^{10}\,{\rm cm}^2)(3\times 10^7\,{\rm s})\,{\rm sr}} = 10^{-7}\,{\rm GeV\ cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1}$$

Derive energy density in UHECRs using flux = velocity $\times$ density

$$4\pi \int dE\,\{EJ_{\rm CR}\} = c\epsilon_{\rm CR}$$

taking $E_{\rm min} \simeq 10^{10}$ GeV and $E_{\rm max} = 10^{12}$ GeV

$$\epsilon_{\rm CR} = \frac{4\pi}{c}\int_{E_{\rm min}}^{E_{\rm max}} \frac{10^{-7}}{E}dE\,\frac{\rm GeV}{{\rm cm}^2\,{\rm s}} \simeq 10^{-19}\,{\rm TeV\,cm}^{-3}$$

Power required to generate this energy density over Hubble time

$$\mathcal{T} \approx 10^{10}\ {\rm yr}$$

Waxman-Bahcall bound (cont'd)

$$\dot{\epsilon}_{\rm CR}^{[10^{10},10^{12}]} \sim 5\times 10^{44}\ {\rm TeV\,Mpc^{-3}\,yr^{-1}} \simeq 3\times 10^{37}\ {\rm erg\,Mpc^{-3}\,s^{-1}}$$

Energy-dependent generation rate of CRs is therefore

$$E^2\frac{d\dot{n}}{dE} = \frac{\dot{\epsilon}_{\rm CR}^{[10^{10},10^{12}]}}{\ln(10^{12}/10^{10})} \approx 10^{44}\,{\rm erg\,Mpc^{-3}yr^{-1}}$$

Energy density of neutrinos ☛ $E_\nu^2\frac{dn_\nu}{dE_\nu} \approx \frac{3}{8}\epsilon_\pi\,\mathcal{T}\,E^2\frac{d\dot{n}}{dE}$

"Waxman-Bahcall bound" is defined by condition $\epsilon_\pi = 1$

$$E_\nu^2\,\Phi_{\rm WB}^{\nu_{\rm all}} \approx (3/8)\,\xi_z\,\epsilon_\pi\,\mathcal{T}\,\frac{c}{4\pi}\,E^2\frac{d\dot{n}}{dE} \approx 2.3\times 10^{-8}\,\epsilon_\pi\,\xi_z\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

$\xi_z \sim 3$ accounts for effects of source evolution with redshift

Waxman & Bahcall, Phys. Rev. D 59 (1999) 023002

Ultrahigh energy neutrinos from Cen A

Upper bound on directional flux from Cen A

$$E^2 F_{\nu_{\rm all}} = \frac{1}{4\pi d^2}\, L_{\rm CR}\, \frac{3}{8}\, \epsilon_\pi \approx 5\times 10^{-9}\ {\rm GeV\,cm^{-2}\,s^{-1}}$$

For $p\gamma \Rightarrow \epsilon_\pi \approx 1/4$ ☛ all flavor neutrino flux

$$E^2\, F_{\nu_{\rm all}} = 1.25\times 10^{-9}\ {\rm GeV\,cm^{-2}\,s^{-1}}$$

Halzen & O'Murchadha arXiv:0802.0887

within reach of Askaryan Radio Array [ARA Collaboration, arXiv:1105.2854]

Diffuse flux assuming Cen A typifies the FRI population

$\mathcal{R} \simeq 1$ horizon $\simeq 3$ Gpc $\quad n_{\rm FRI} \sim 8\times 10^4 {\rm Gpc}^{-3}$

$$E^2 J_{\nu_{\rm all}} = \frac{1}{4\pi}\, \mathcal{R}\, n_{\rm FRI}\, L_{\rm CR}\, \frac{3}{8}\, \epsilon_\pi \approx 1.5\times 10^{-8}\ {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

LAA, Goldberg, Halzen, Weiler, Phys. Lett. B 600 (2004) 202

Ultrahigh energy neutrinos (cont'd)

- Fit to CR flux + assumption of transparent sources
implies WB bound

Waxman & Bahcall Phys. Rev. D 59 (1999) 023002

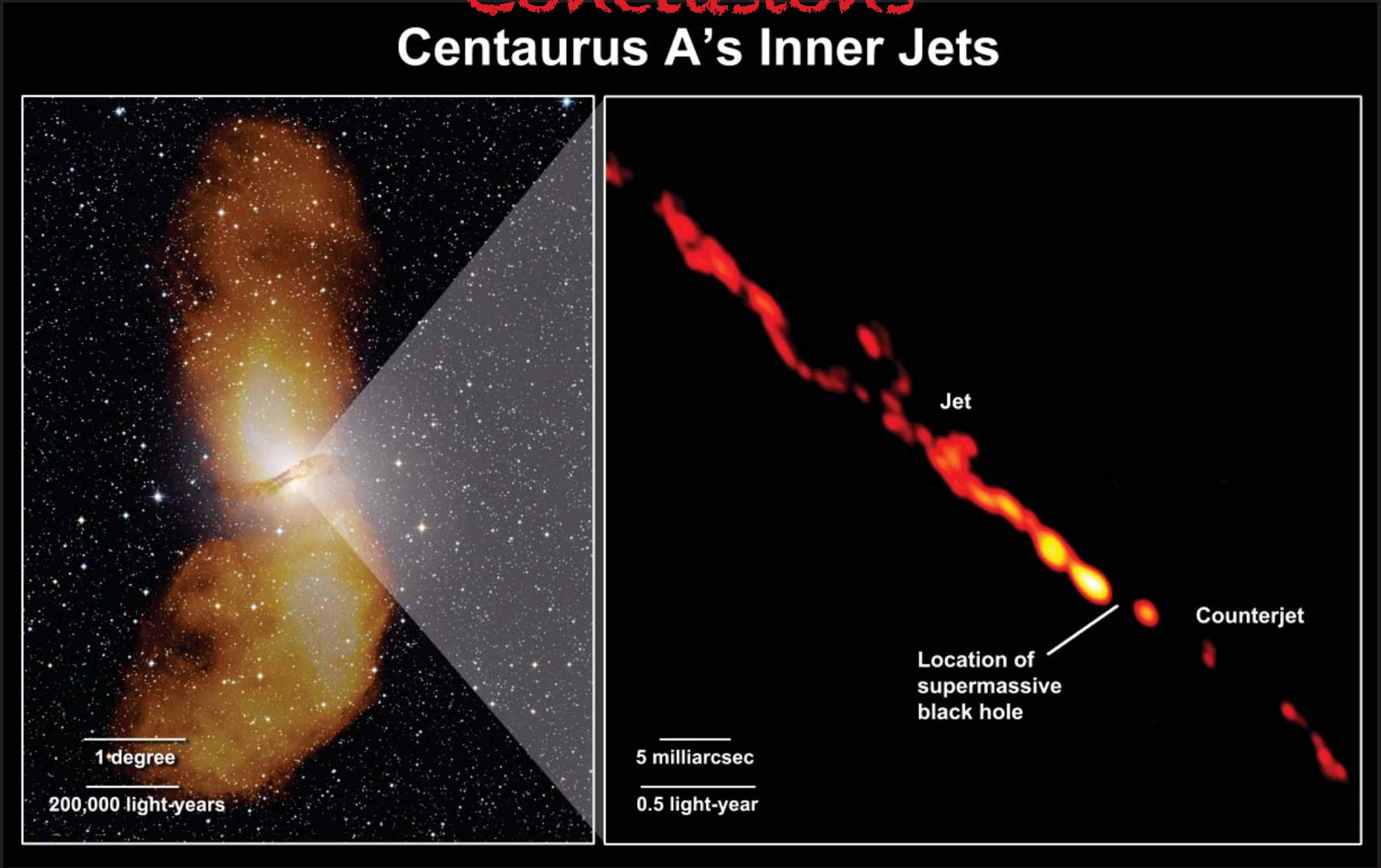
- Similar argument for Cen A
implies directional neutrino bound

- Additional transparent sources hidden by Xtragalactic B-field
should contribute to diffuse neutrino flux

- If Cen A typifies source population
maximum emission energy of CRs and neutrinos is reduced

- Reduction of maximum luminosity roughly compensates for
presence of far away neutrino sources not visible in CRs
no enhancement of WB bound due to hidden sources

Conclusions



- Existing data is consistent with hypothesis that Cen A dominates CR sky beyond GZK suppression
- Future observations from Auger, JEM-EUSO, and ARA will provide final verdict


That's all Folks!