On connecting gamma-ray sources with UHECRs

(i) **"The Origin of Cosmic Rays" – skipped**, will take whole seminar to be comprehensive even for the E > $10^{-18.5}$ eVs only -> "extragalactic"

(ii) **Assumption #1 – protons only**, ignoring realistic composition -> the role of the GZK cutoff, consequences for gamma-ray astronomy

(iii) **Assumption #2 – UHRCRs are pointing towards their acceleration sites** and not caused by a diffuse acceleration process or one-source scenario

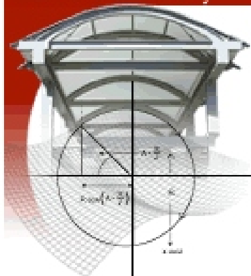
brief: deflections due to intergalactic magnetic fields

(iv) **Assumption #3 – UHECR data indeed show clustering** of UHECR events

SUGAR, Haverah Park, Yakutsk, the AGASA claim, the HIRES result, anticipation of AUGER,

(v) **Assumption #4** – the ways of handling the statistical challenge is always correct in the publications [apparently, it's not!]

Instead of an introduction -> "The Origin of Cosmic Rays"



School of Humanities and Sciences

Department of **Physics**

Events

The Hofstadter Memorial Lectures

Monday-Tuesday, April 3 and 4, 2006

Professor James Cronin
2006 Robert Hofstadter Memorial Lecturer

William R. Hewlett Teaching Center at the Science and Engineering Quad (TCSEQ)
Room 201
370 Serra Mall, Stanford University

We are pleased to announce that the annual Robert Hofstadter Memorial Lectures will be given this year by James W. Cronin, Professor Emeritus of Physics and Astronomy, Enrico Fermi Institute at the University of Chicago. Professor Cronin is the recipient of numerous awards, including the 1980 Nobel Prize for Physics and the National Medal of Science in 1999. He is a member of the National Academy of Sciences, the American Physical Society, and a Fellow of the American Academy of Arts and Sciences. Prof. Cronin is also the spokesperson emeritus and U.S. Principal Investigator for the Pierre Auger Project.

The Hofstadter lectures are scheduled for Monday, April 3, 2006 (an evening public lecture at 8:00 PM) and Tuesday, April 4 (an afternoon colloquium at 4:15 PM). Both lectures will be held at Stanford University, and we hope that you will plan to attend.

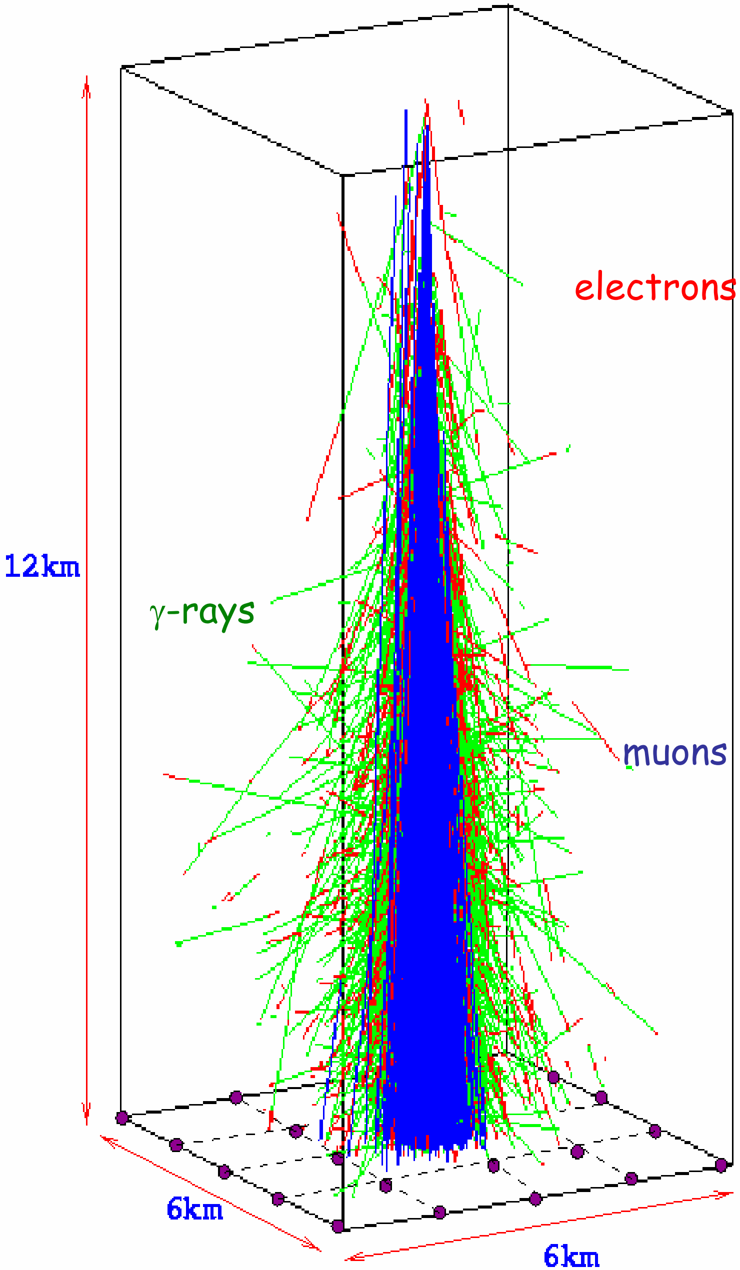
Evening Public Lecture (8:00 PM on Monday, April 3, 2006)
"COSMIC RAYS: A FASCINATING SCIENTIFIC HISTORY"

In 1912 it was discovered that radiation arrived on earth from outer space. The story of this discovery is linked with adventure, false starts and scientific rivalry. We will present some vignettes

Colloquium: Tuesday, April 4, 2006:

James W. Cronin, The University of Chicago
"The Pierre Auger Observatory for Highest Energy Cosmic Rays"

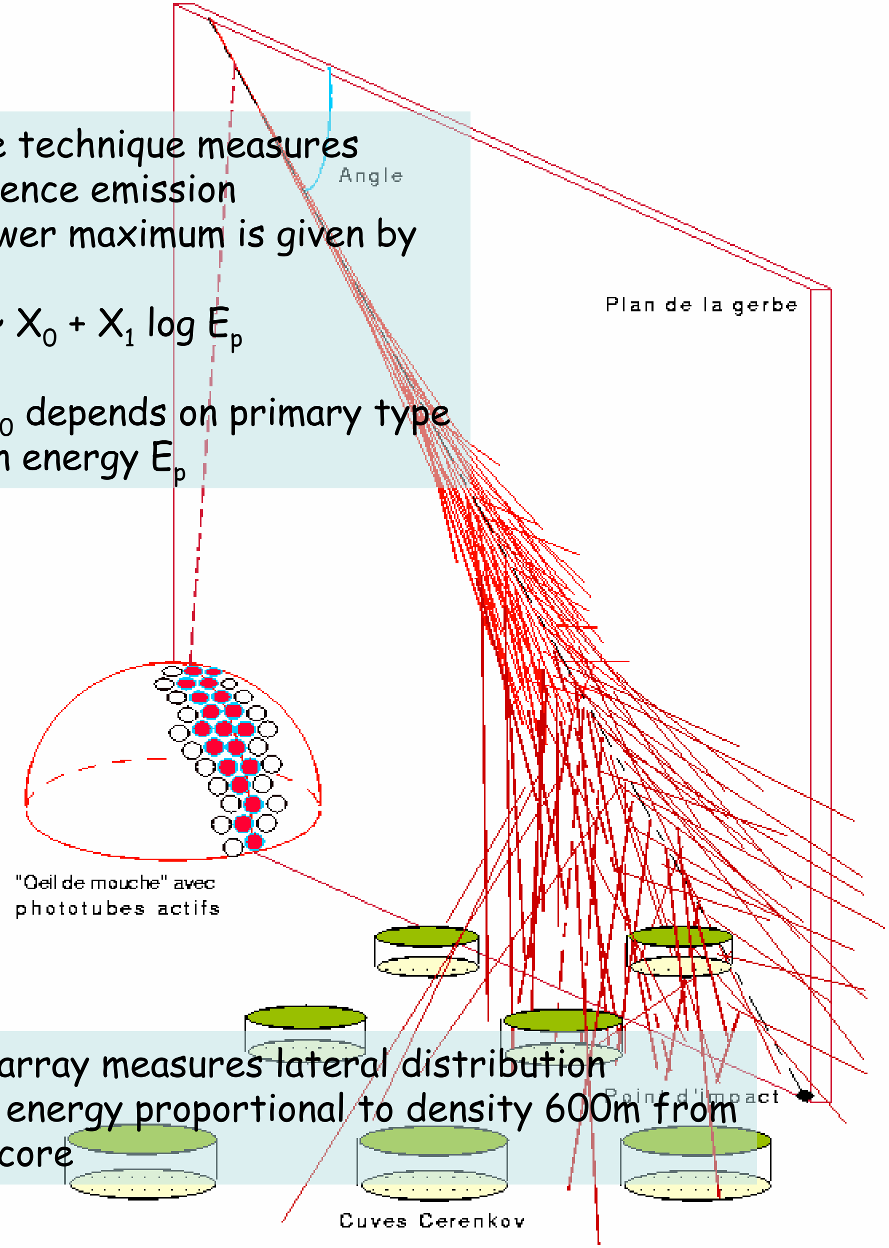
Atmospheric Showers and their Detection



Fly's Eye technique measures fluorescence emission
The shower maximum is given by

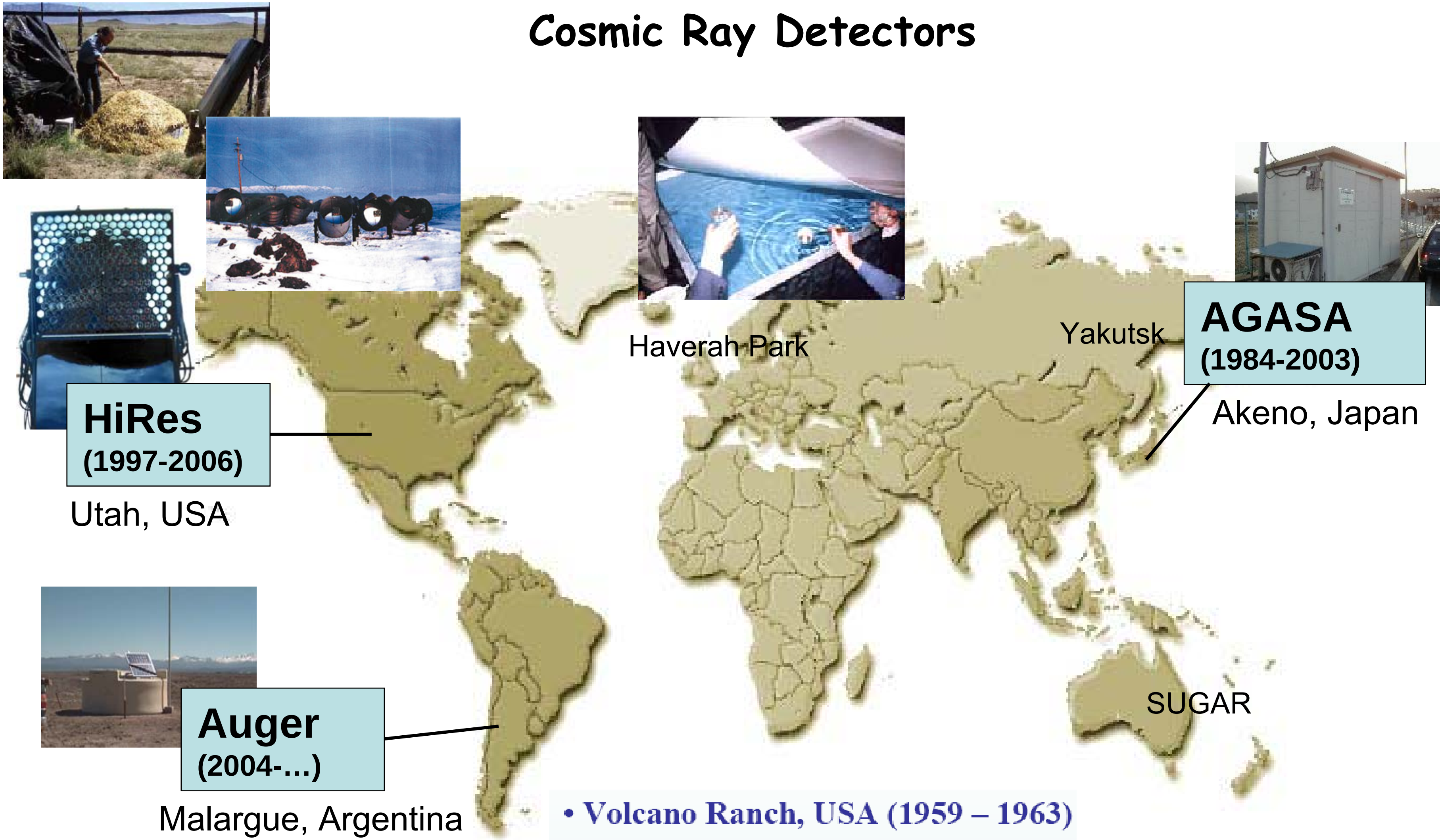
$$X_{max} \sim X_0 + X_1 \log E_p$$

where X_0 depends on primary type for given energy E_p



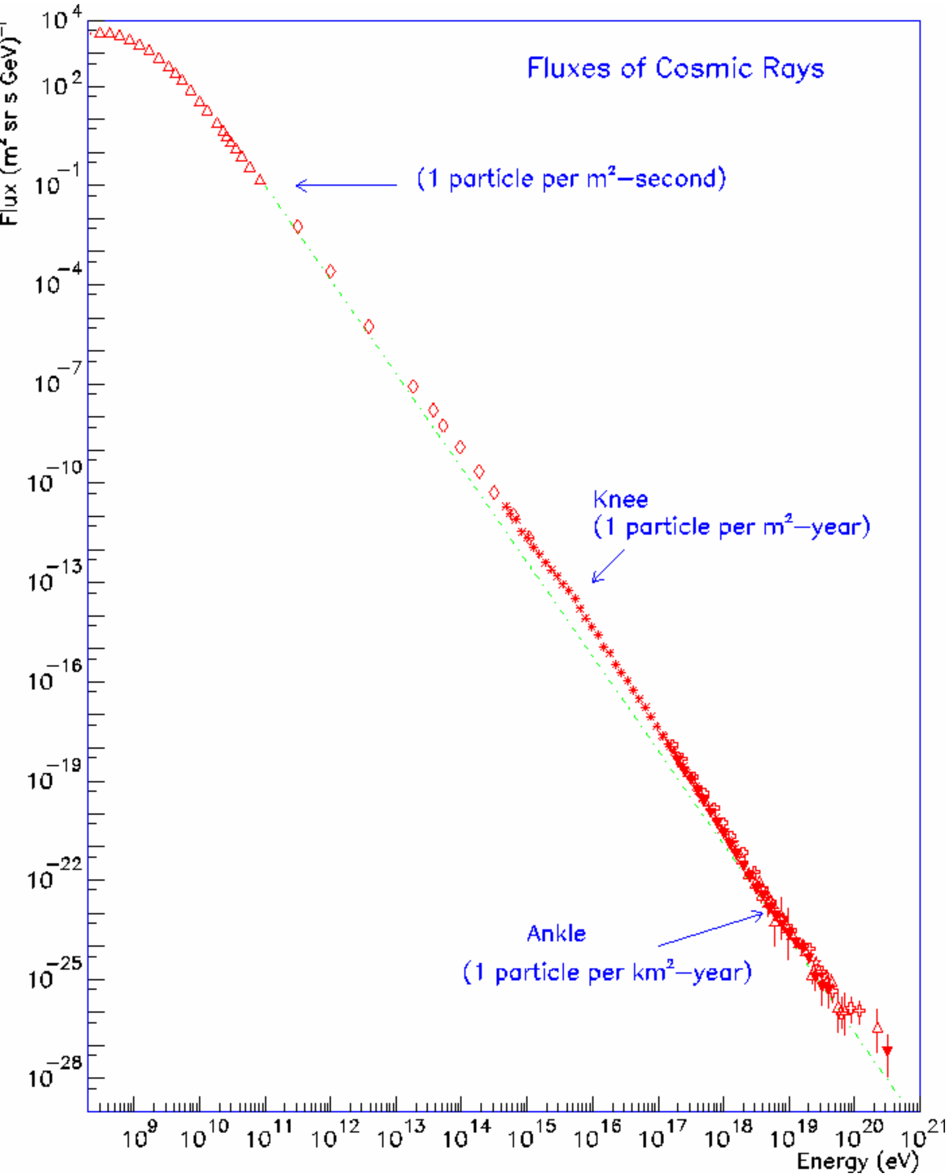
Ground array measures lateral distribution
Primary energy proportional to density 600m from shower core

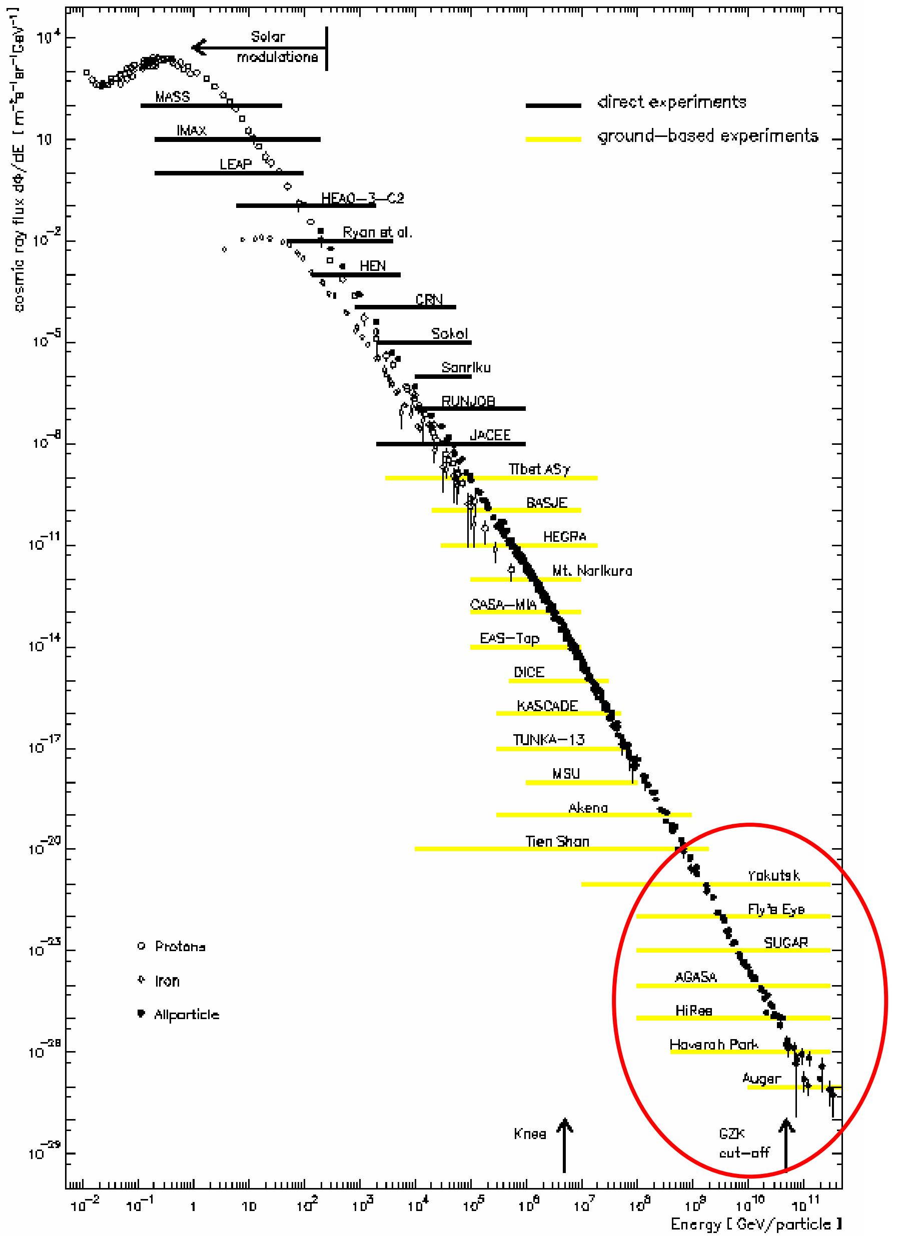
Cosmic Ray Detectors



- Volcano Ranch, USA (1959 – 1963)
- SUGAR, Australia (1968 – 1979)
- Haverah Park, UK (1968 – 1987)
- Jakutsk, Russia (1970 – today)
- Fly's Eye, USA (1981 – 1992)
- AGASA, Japan (1990 – 2004)
- HiRes, USA (1998 – today)

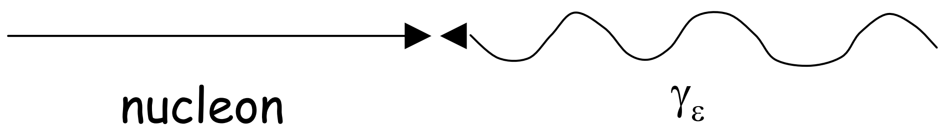
All-particle CR spectrum





Greisen-Zatsepin-Kuzmin effect – « GZK-cutoff »

Nucleons can produce pions on the cosmic microwave background



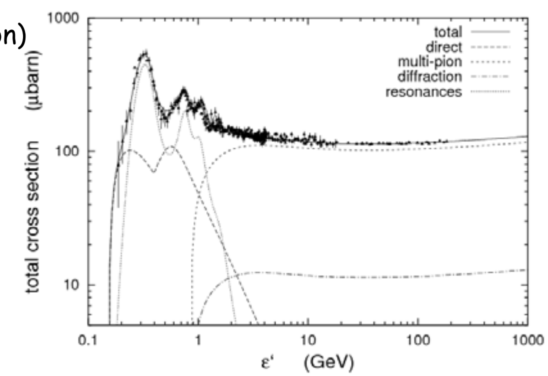
$$E_{\text{th}} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon_{CMB}} \approx 4\cdot 10^{19}\,\text{eV}$$

Assumption #1: $\boxed{\text{protons only}}$ – simplification, but utterly unrealistic

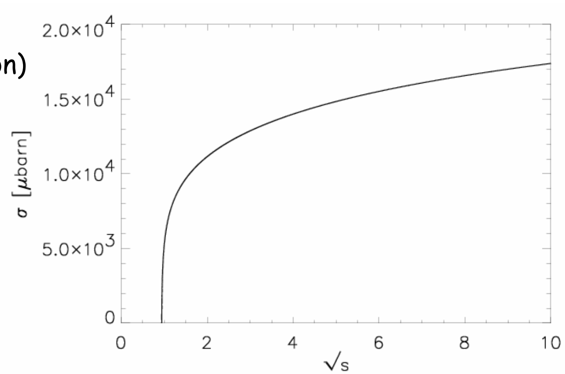
(indredients composite of heavy + p + γ)

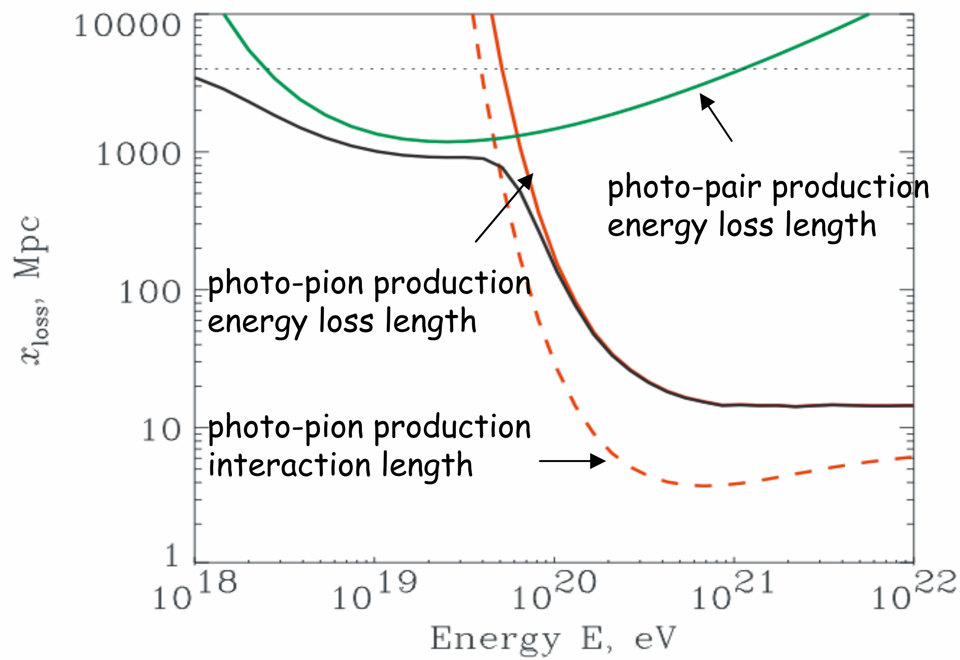
p-γ-cross sections

(photomeson production)



(photo-pair production)





-> sources must be in cosmological backyard

[Lorentz symmetry breaking at $\Gamma > 10^{11}$/exotic primaries could avoid this conclusion.]

Hillas' plot

Fermi acceleration

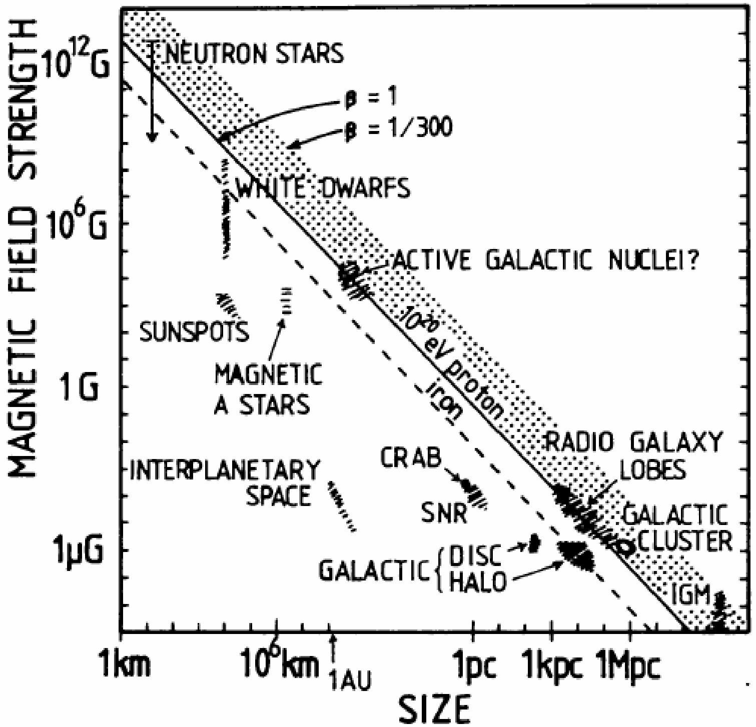


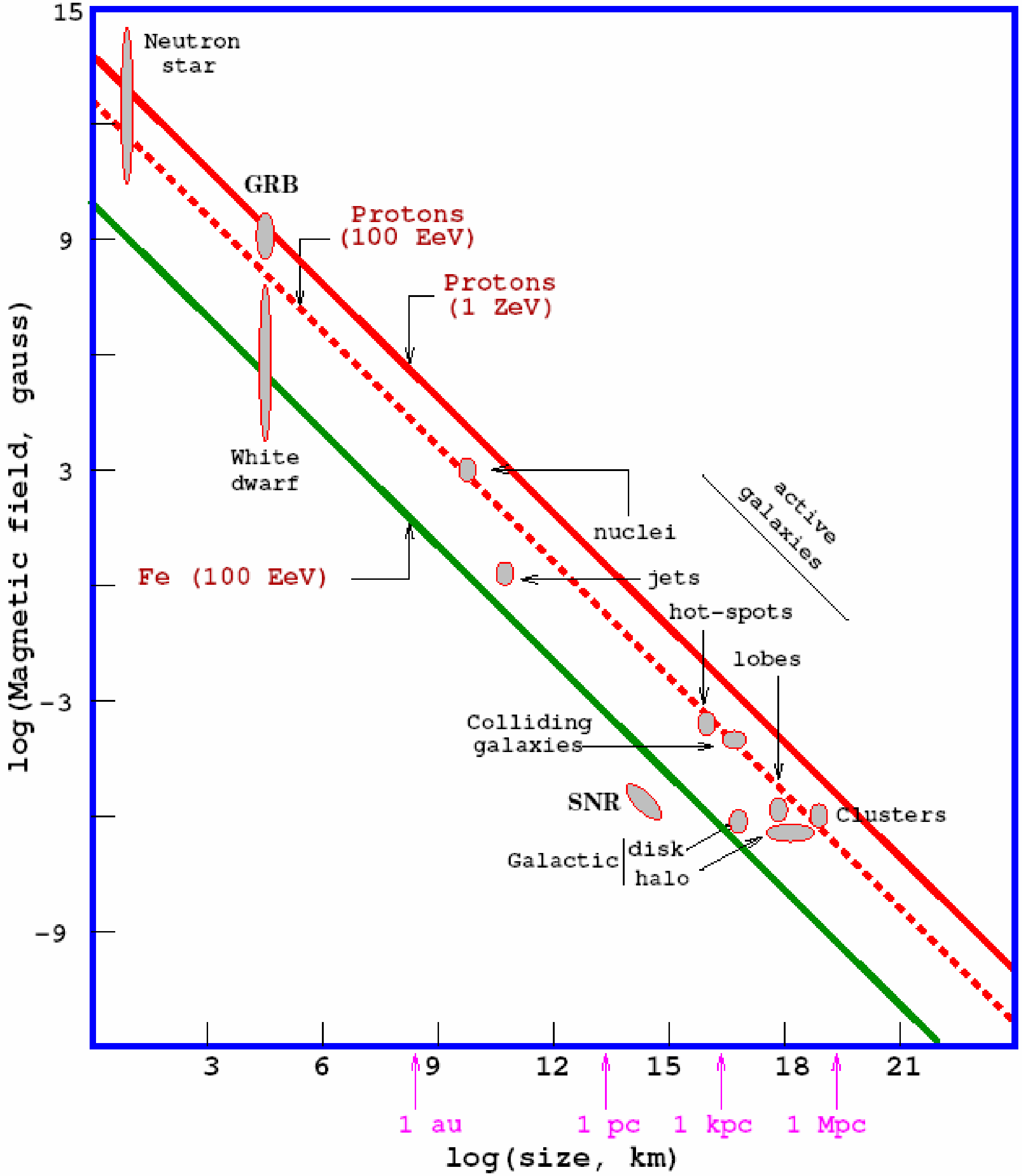
Figure 1 Size and magnetic field strength of possible sites of particle acceleration. Objects below the diagonal line cannot accelerate protons to 10^{20} eV.

To efficiently accelerate a particle it must cross the shock(s) several times. A general estimate of the maximal energy that can be achieved is given by the requirement:

$$R_g = E/(Z\, e\, B) \sim R$$

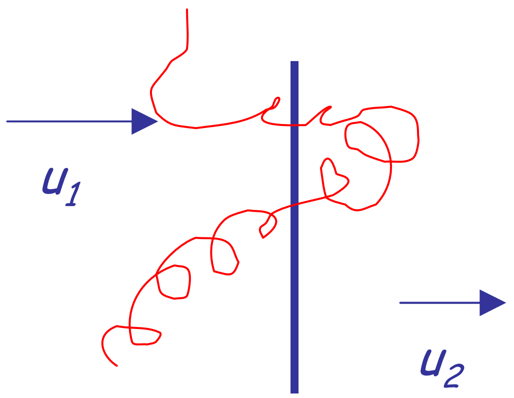
where Rg is the gyroradius and R is the size of the accelerating region. This can be written as:

$$R \sim 110\ Z^{-1} E_{20}/B_{-6}\ \text{kpc}$$



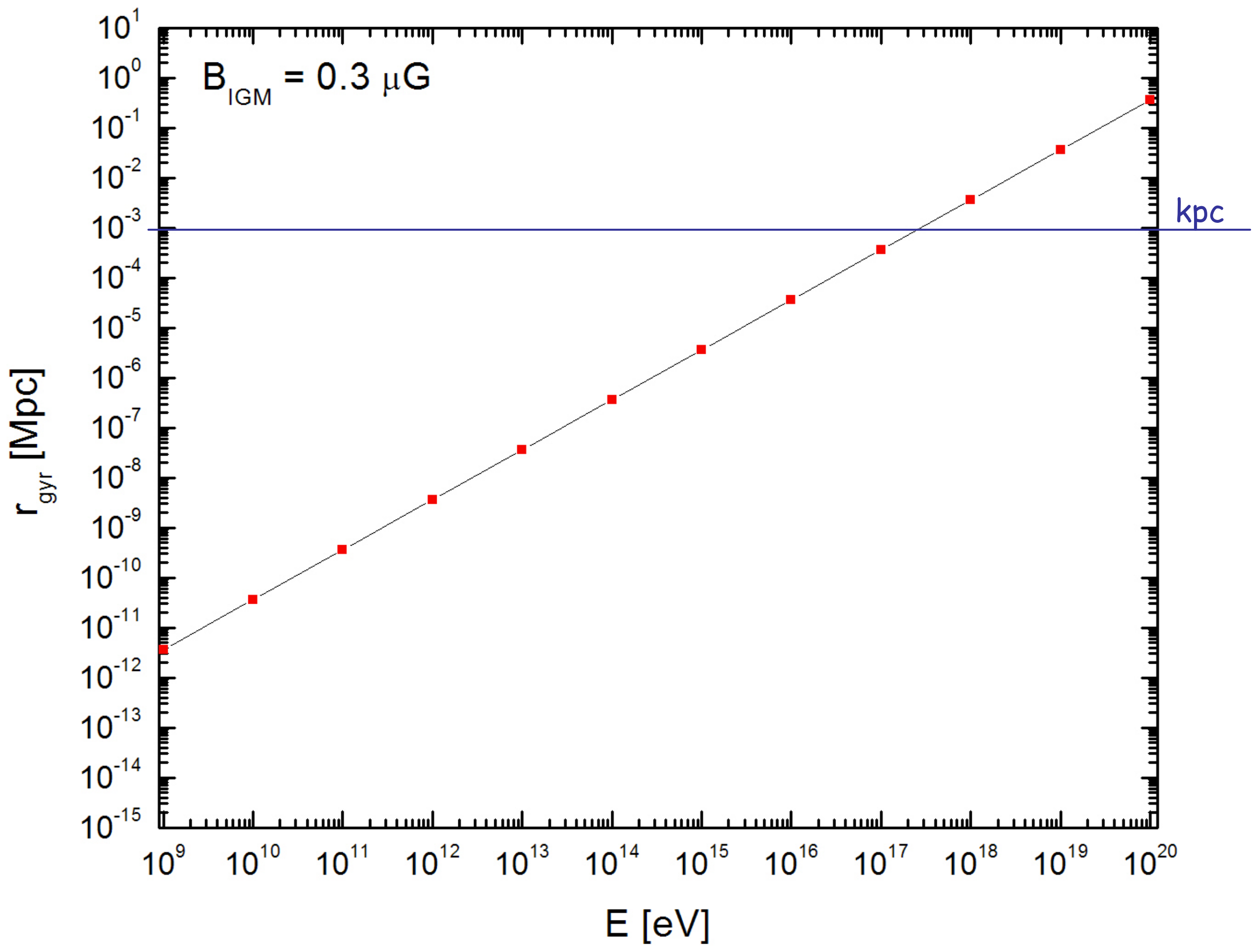
Hillas' plot

Fermi acceleration



The fractional energy gain per shock crossing depends on the velocity jump at the shock. Together with loss processes this leads to a spectrum E^{-q} with $q > 2$ typically.
When the gyroradius becomes comparable to the shock size, the spectrum cuts off.

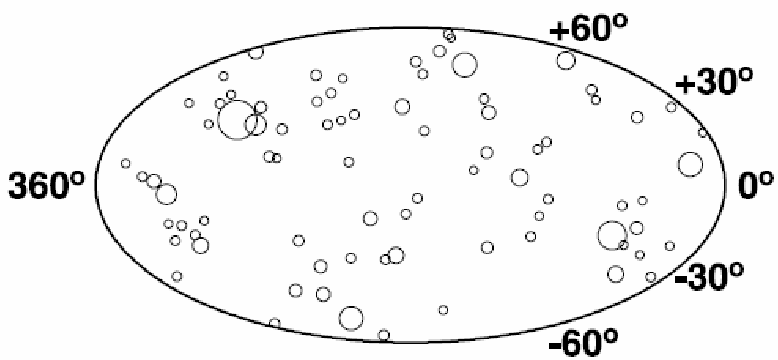
Speaking about r_{gyr} at UHE/EHEs …



If sources too far, deflections will substancially influence the propagation of UHE/EHE nuclei on their trajectory through the IGM

UHECR propagation

(a) by considering a specific source/source distribution/source density model

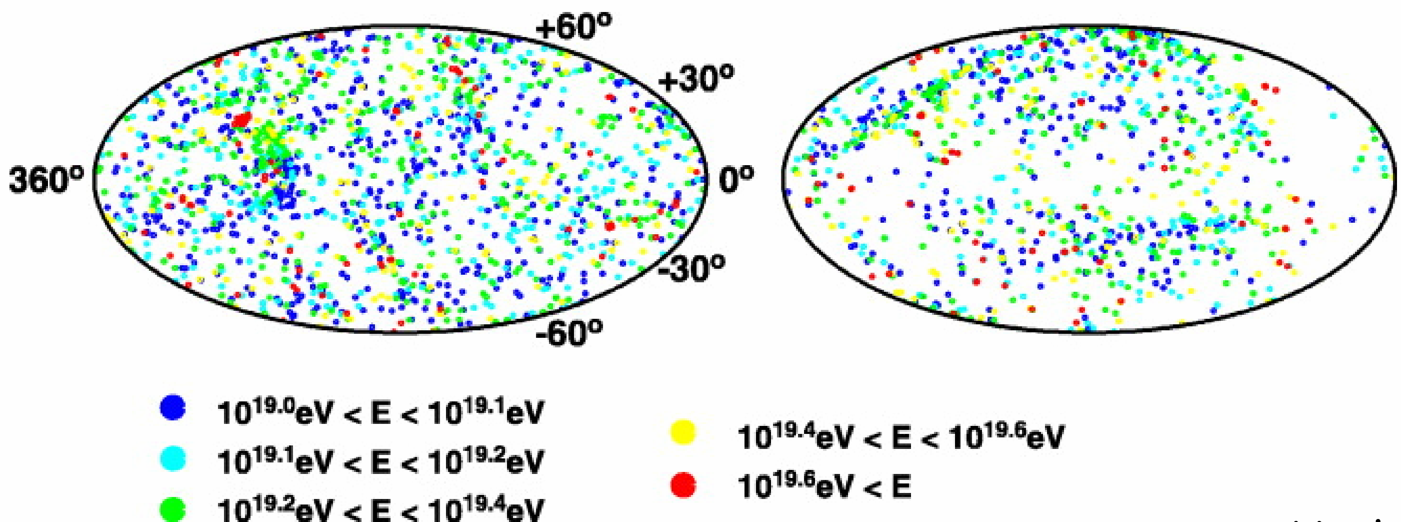


assumed sources

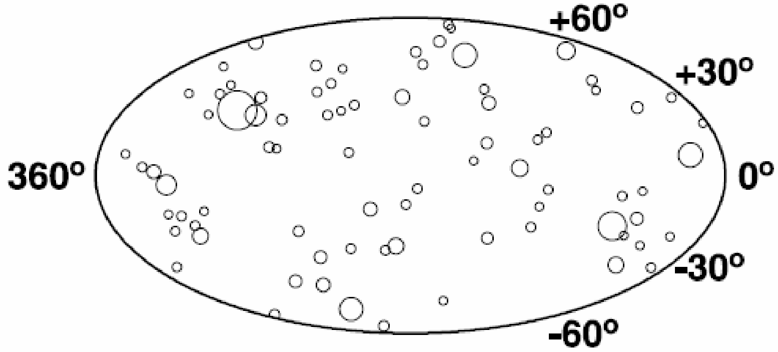
(within 300 Mpc)

Arrival directions of protons with $E > 10^{19.0}$ eV at the Earth (*left*) expected for the source model of Fig. 2 in Galactic coordinates. Events are shown by color according to their energies. The event number within $-10^{\circ} \leq \delta \leq 80^{\circ}$ is set to be equal to the one observed by the AGASA (775; Takeda et al. 2001). The total number of events is ~1500. *Right*: Mapping of the sources that actually give rise to events shown in the left panel. Note that this mapping differs from the distribution of the sources shown in Fig. 2.

normalized to AGASA statistics



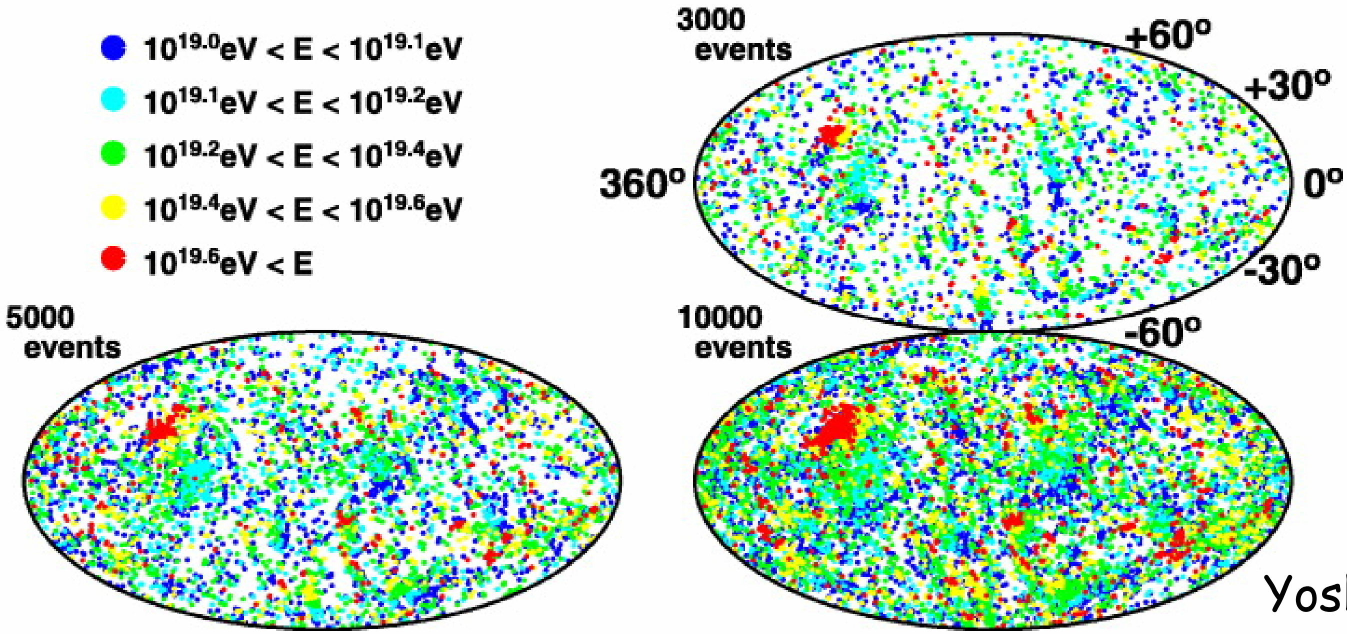
Yoshiguchi 2003,2004



assumed sources

(within 300 Mpc)

Arrival directions of protons with $E > 10^{19.0}$ eV at the Earth expected for the source model of Fig. 2 in Galactic coordinates. Events are shown by color according to their energies. It is noted that the expected event rate by the Auger experiment is ~3000 per year above 10^{19} eV.

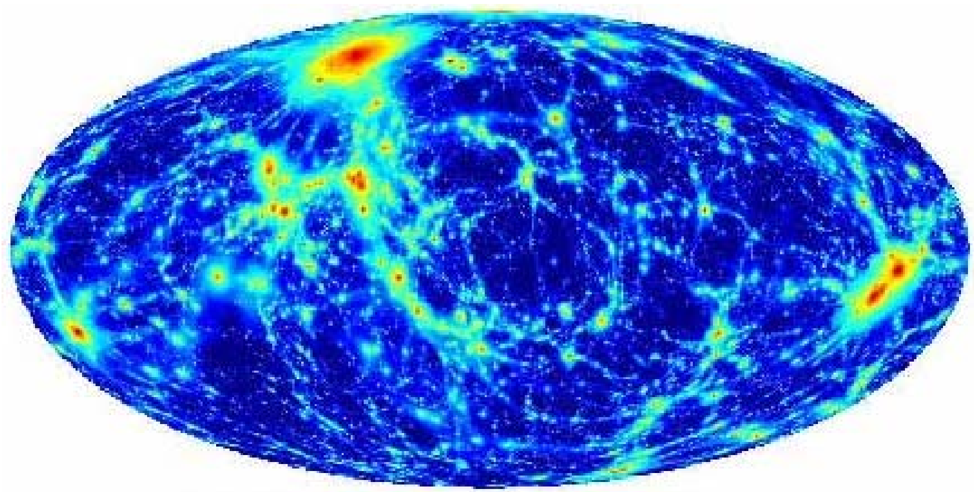


for AUGER event rates

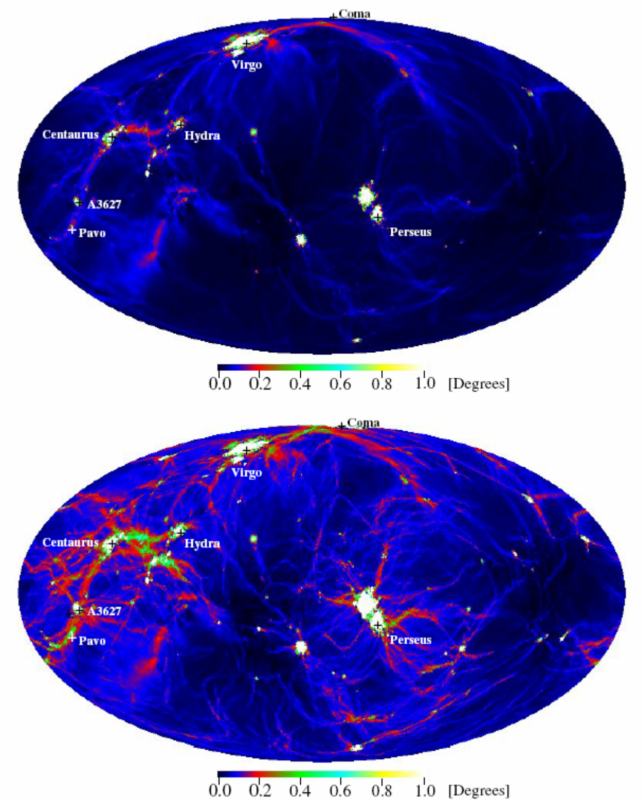
Yoshiguchi 2003,2004

(b) Sky deflection maps as result of large scale structure formation simulations

-> propagation of UHE protons in the web of extra-galactic magnetic fields



deflection maps



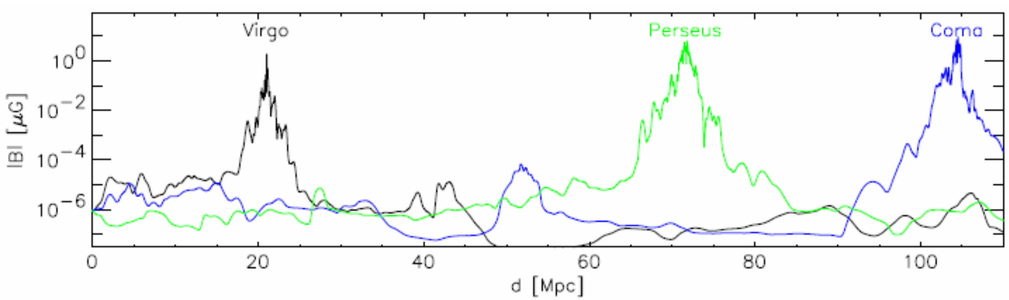


Figure 12. The magnetic field strength along three fiducial lines through the simulated volume. They are chosen to pass through the clusters Coma, Virgo

Dolag et al. 2005

Also disputed, qualitatively as well as quantitatively in terms of UHECR source distributions, values of EGMF

Not appreciably deflected -> pointing back to their accelerators

seen from Table I, may have to do with significant evolution of the characteristics of sources at large distances whose contribution increases with decreasing UHECR energy. The best fit scenario also predicts a pronounced GZK cutoff as well as considerable deflection of order 20° up to $\simeq 10^{20}$ eV. *Thus, if this scenario is further confirmed by future experiments, charged particle astronomy may not be possible.*

Sigl, Miniati & Ensslin 2004

Assumption #2 – UHRCRs pointing towards their (nearby?) acceleration sites

The UHECR data

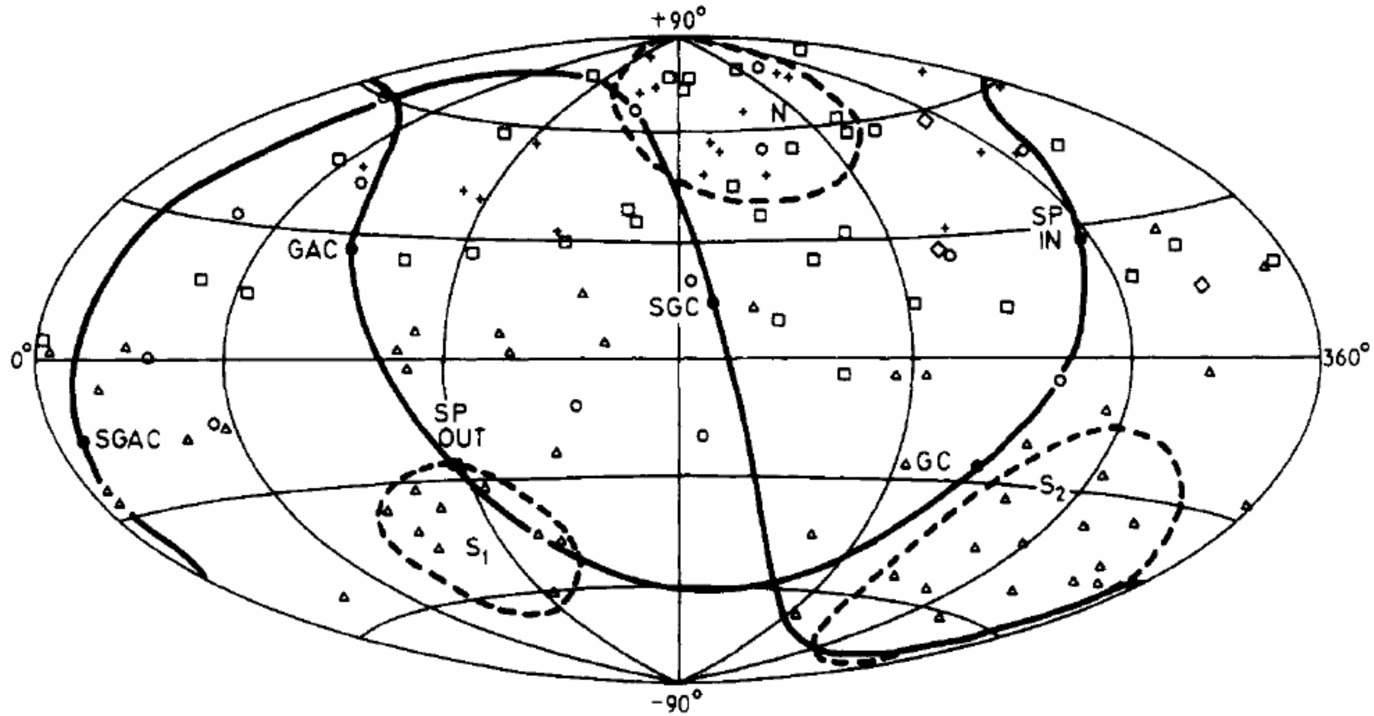


Figure 1. Aitoff equal area projection of the arrival directions of 119 showers with primary energies above 10^{19} eV (celestial coordinates). The regions of high apparent intensity are tentatively given as circles on the celestial sphere (N, S_1 and S_2). The Galactic and super-galactic equators are represented by full curves. Abbreviations: GC and GAC Galactic centre and anticentre, SP IN and SP OUT inward and outward spiral directions, SGC and SGAC super-galactic centre and anticentre. Symbols for the detecting stations: ◇ Cornell, □ Haverah Park, △ Sydney, ○ Volcano Ranch and + Yakutsk.

Kiraly & White 1975

Statistics by 1975:

Denoting by n_{ijk} the number of showers in the ith δ, kth RA interval for size i (1 for basic, 2 for double, 3 for treble cells), χ_i^2 was calculated as

$$\chi_i^2 = \sum_{j,k} \frac{(n_{ijk} - \langle n_{ijk} \rangle)^2}{\langle n_{ijk} \rangle}.$$

An analytical calculation of the random distribution of χ_i^2 is somewhat complicated because of the overlaps, but it is fairly easy by MC simulation. The chance probabilities for the observed showers are given in table 2.

Table 2. Significance levels obtained for χ^2, maxima, minima and ranges.

Cell type	χ^2	$p(\geqslant\chi^2)$%	max	$p(\geqslant \max)$%	min	$p(\leqslant \min)$%	R	$p(\geqslant R)$%
Basic	103	68·7	3	100	0	100	3	100
Double	93	41·0	8	95·8	0	71·9	8	85·5
Treble	79	32·4	16	40·6	2	18·9	14	21·2

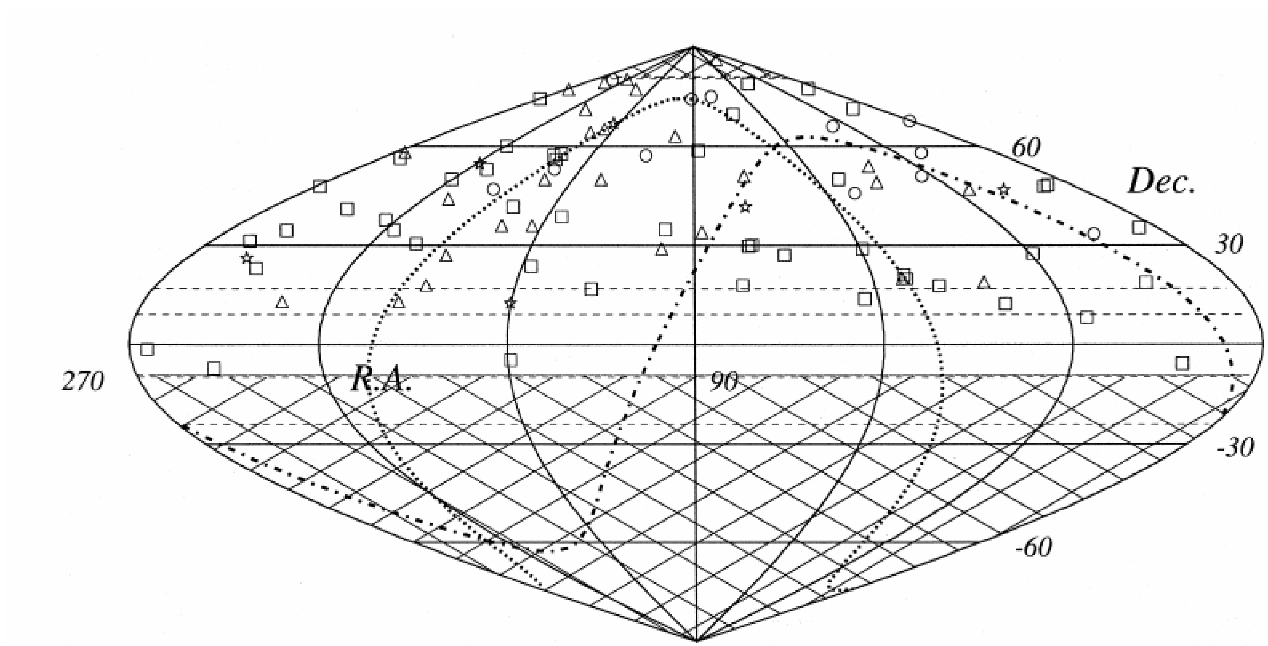
...but implications were not too spectacular in the early days

Table 1. Observed and expected numbers of showers coinciding with the selected source candidates.

The source candidates		5° circles			10° circles		
Type	Number	Observed	Expected	(Obs-Exp)/σ	Observed	Expected	(Obs-Exp)/σ
Galactic pulsars	118	13	16·3	−0·9	34	42·9	−1·7
Galactic supernova remnants	27	10	6·5	+1·4	18	17·1	+0·3
Extragalactic supernovae	92	11	9·6	+0·5	30	28·4	+0·4
Extragalactic radio sources	13	2	2·5	−0·3	4	9·6	−2·0
Extragalactic x-ray sources	39	8	10·3	−0·8	33	33·0	0·0
Seyfert galaxies	32	11	9·4	+0·7	19	23·5	−1·1
Quasars	110	19	17·5	+0·4	55	45·1	+2·1

Possible Sources of UHECR's: New Challenge for TeV Astronomy

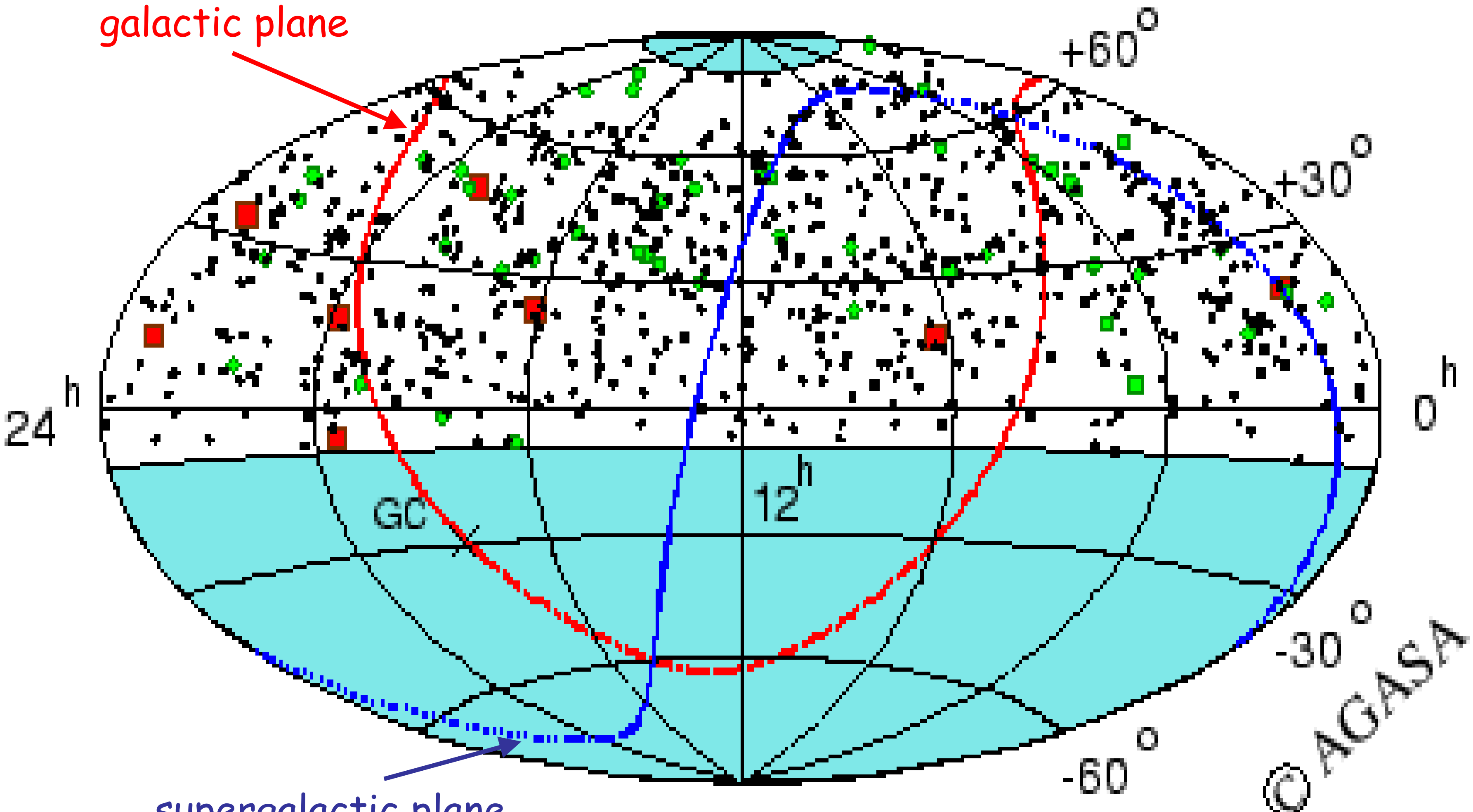
Possible Clustering into discrete sources of 92 cosmic rays with E > 4 x 10^19 eV
(results from AGASA, Havarah Park, Yakutsk, Volcano Ranch)



Marginally statistically significant correlation of Doublets and Triplets with Supergalactic Plane

Uchihori et al. 2000

Arrival Directions of Cosmic Rays above 10^{19} eV

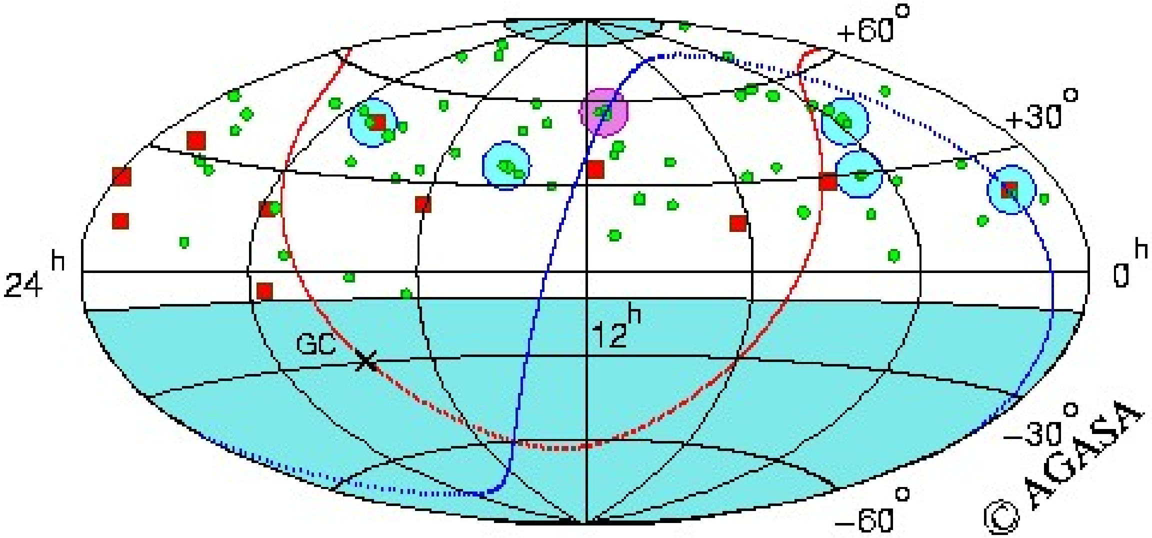


Akeno 20 km², 17/02/1990 – 31/07/2001, zenith angle < 45°

"Clusters" of Cosmic Rays ?

- AGASA claims significant small-scale clustering above 4.0×10^{19} eV
  (Chance probability of clustering from isotropic distribution is < 1%.)
- 5 doublets +1 triplet in 57 events
- Analysis criticized on statistical grounds Finley & Westerhoff APh 21(2004)359
- Lack of a well-defined a priori hypothesis (angular scale, energy cut), chance probability > 8%

Shaded circles = clustering within 2.5°.

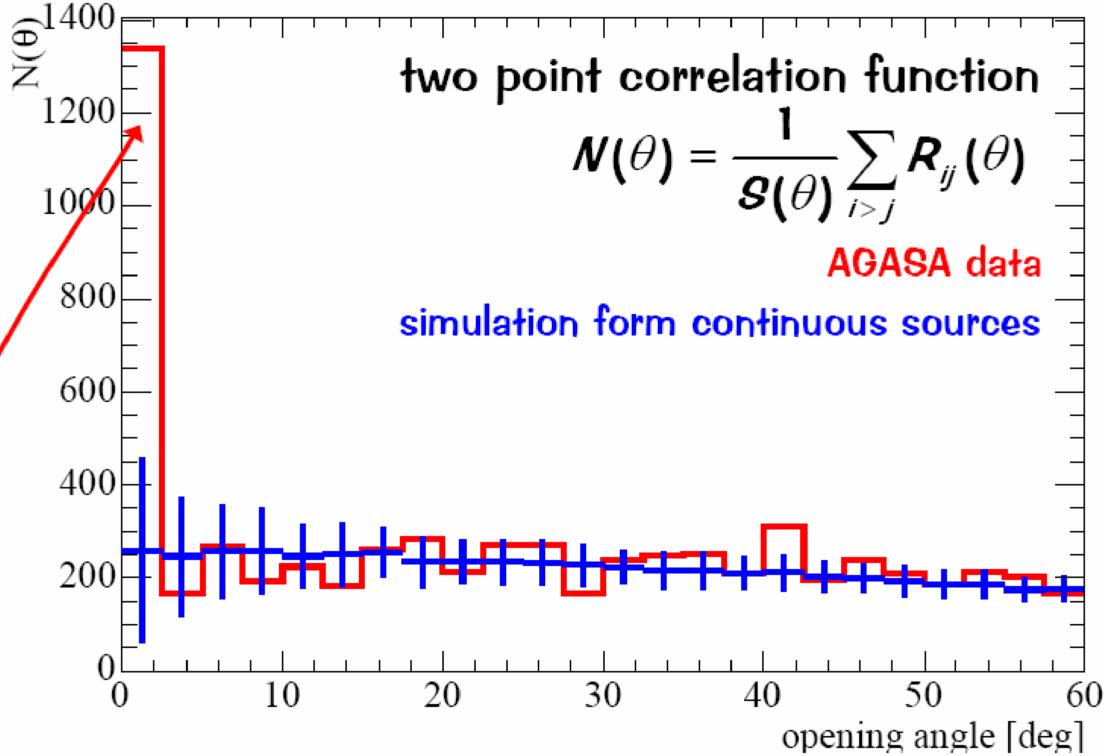


$E = 4..10\times10^{19}$ eV

$E > 10^{20}$ eV

M. Takeda at al., Astrophys. J. 522 (1999) 225

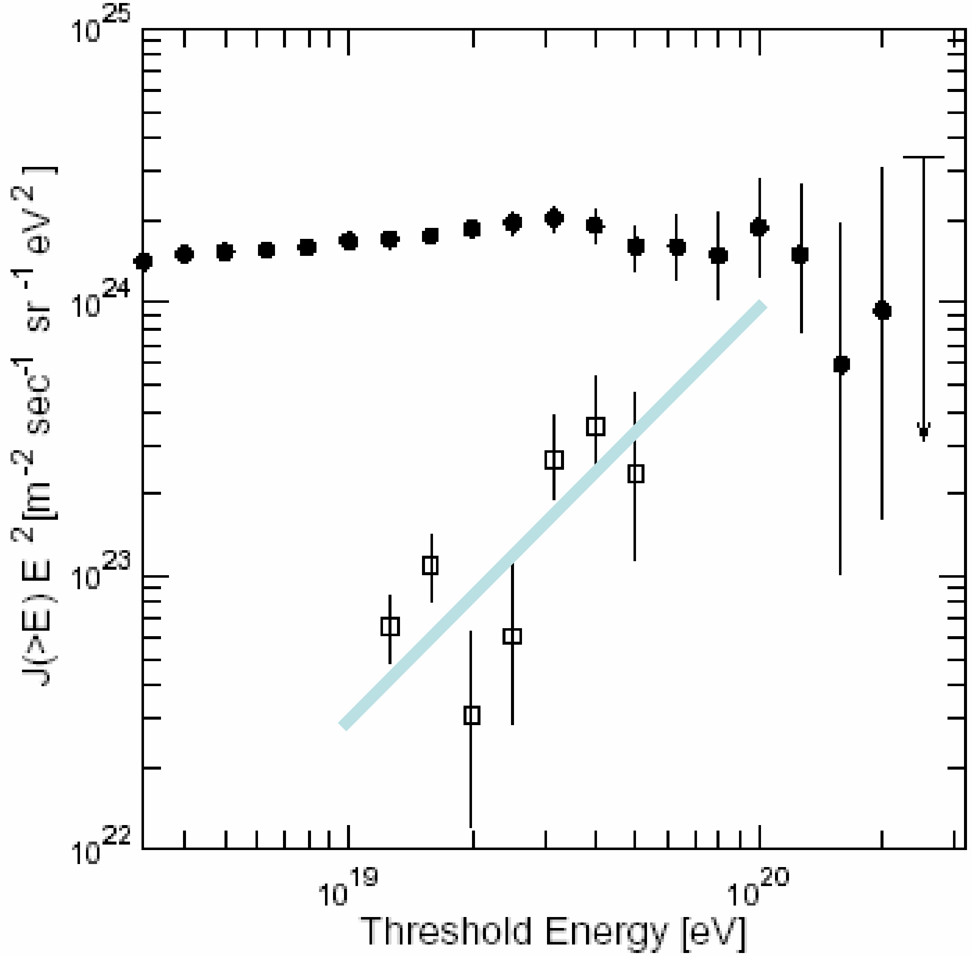
The two-point correlation function as the appropriate statistical measure (histogram of cos(θ) between all possible pairs)



1 triplet & 5 doublets on scales comparable with the angular resolution of AGASA (2.5°)

Spectrum of the clustered component in the AGASA data

Possible explanations:
- point-like sources of charged particles in case of insignificant magnetic deflection
- point-like sources of neutral primaries
- magnetic lensing of charged primaries



Confrontation with large but independent data set: HiRes Anisotropy Studies

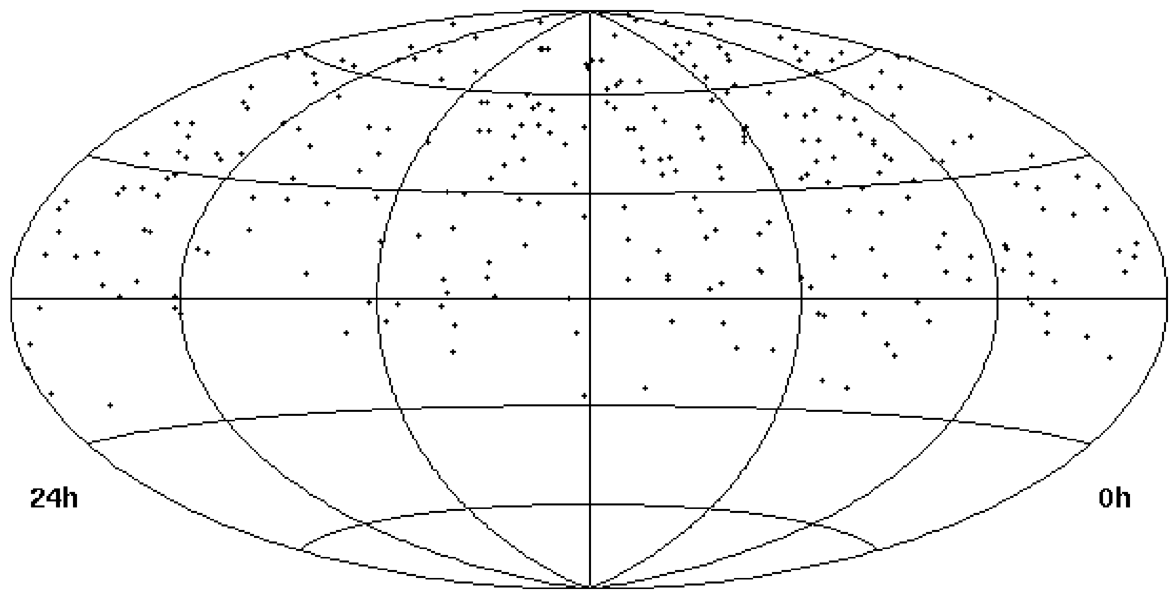
- HiRes has performed extensive searches for deviations from isotropy
  - Astrophys. J. 623 (2005) 164: Search for pointlike sources of UHECRs above 4.0×10^{19} eV Using a Maximum Likelihood Ratio Test (AGASA+HiRes Data)
  - Astrophys. J. 610 (2004) L73: Search for small-scale anisotropy (clustering)
  - Astrophys. J. 636 (2006) 680: Search for correlations of cosmic ray arrival directions with BL Lac objects

- No point sources and no deviation from anisotropy found
- No confirmation of any prior claims of anisotropy with statistically independent HiRes stereo data set

HiRes Stereo Data Set

- HiRes stereo events currently provide the sharpest image of the northern sky, with 0.6° angular resolution and a systematic error not larger than 0.2° (from star surveys and lasers)

271 events E > 10^{19} eV



Equatorial Coordinates

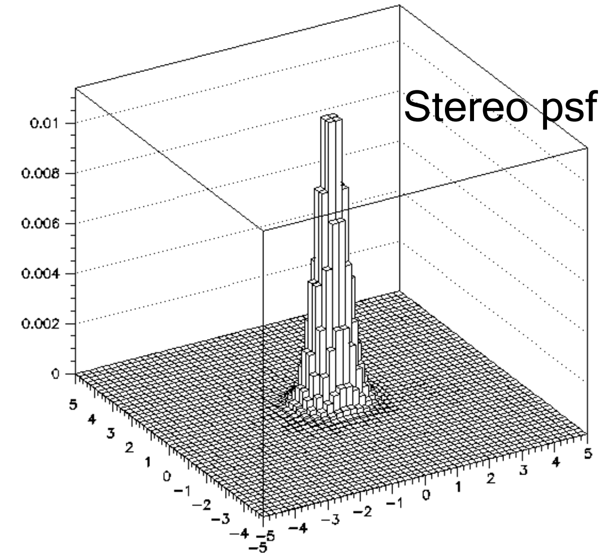
HiRes stereo data 1999 December to 2004 January

HiRes Anistropy Results

Monocular Anisotropy Results

- **Autocorrelation functions** (histogram of $\cos\theta$ between all possible pairs) for HiRes-1 monocular and AGASA events above $\sim 4\times 10^{19}$ eV
  Astropart. Phys. 22, 139 (2004)
- Search for dipole enhancement in the direction of nearby a-priori sources: **null results** for the ***Galactic Center, Cen A, M87***
  Astropart. Phys. 21, 111 (2004)
- Point source search: null result

- Search for cross-correlation with AGASA doublets and triplet:
  - Observed overlap no greater than that expected by chance from isotropic



Stereo Anisotropy Results

- Stereo angular resolution ***~0.6°***
- HiRes stereo data ($E > 10^{19}$ eV) is consistent with isotropy at all small angular scales
  Astrophys. J. Lett. 610 (2004) L73
- Search for Point Sources of Ultra-High Energy Cosmic Rays above 4.0 10^{19} eV Using a Maximum Likelihood Ratio Test
  Astrophys. Journal 623 (2005) 164

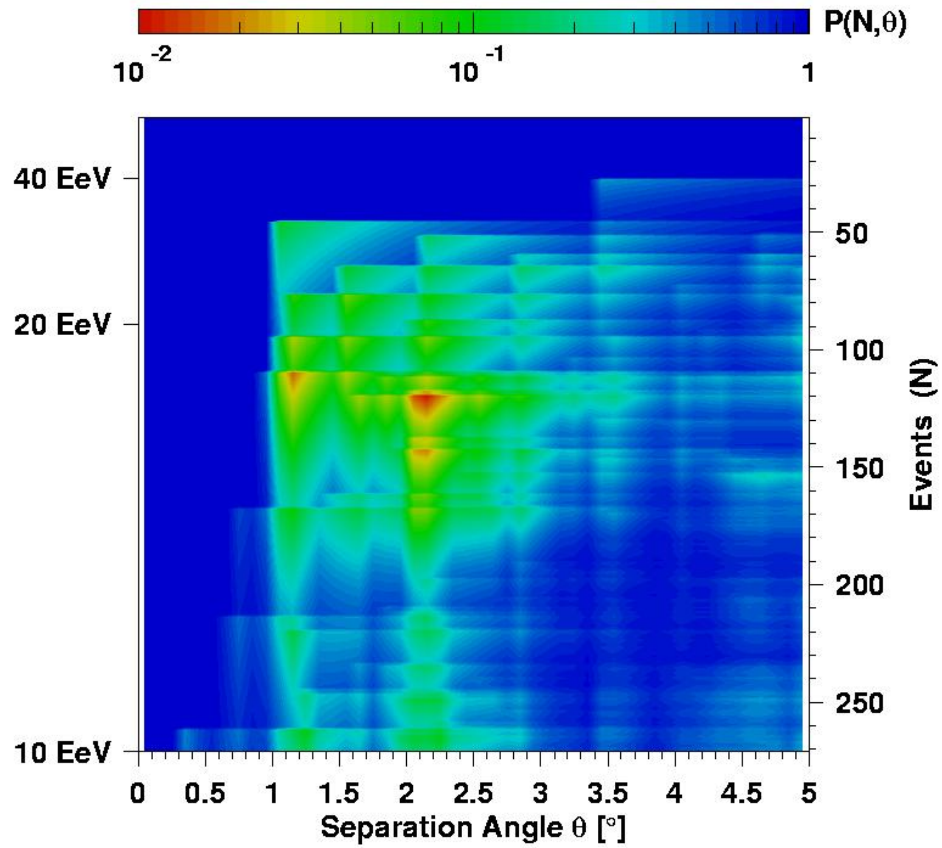
Correlations with BL Lacs ?

- Modest correlation between most luminous BL Lacertae objects and HiRes stereo events above 10^{19} eV
- $n = 11.0$ events out of 271 correlate with BL Lac objects
- Chance probability 10^{-5}
- Not a confirmation of an *a priori* claim, so needs to be confirmed with independent data
- Correlations are at $\sim 10^{19}$ eV, indicating neutral primaries ?

slides from Stefan Westerhoff

Significant Clustering ?

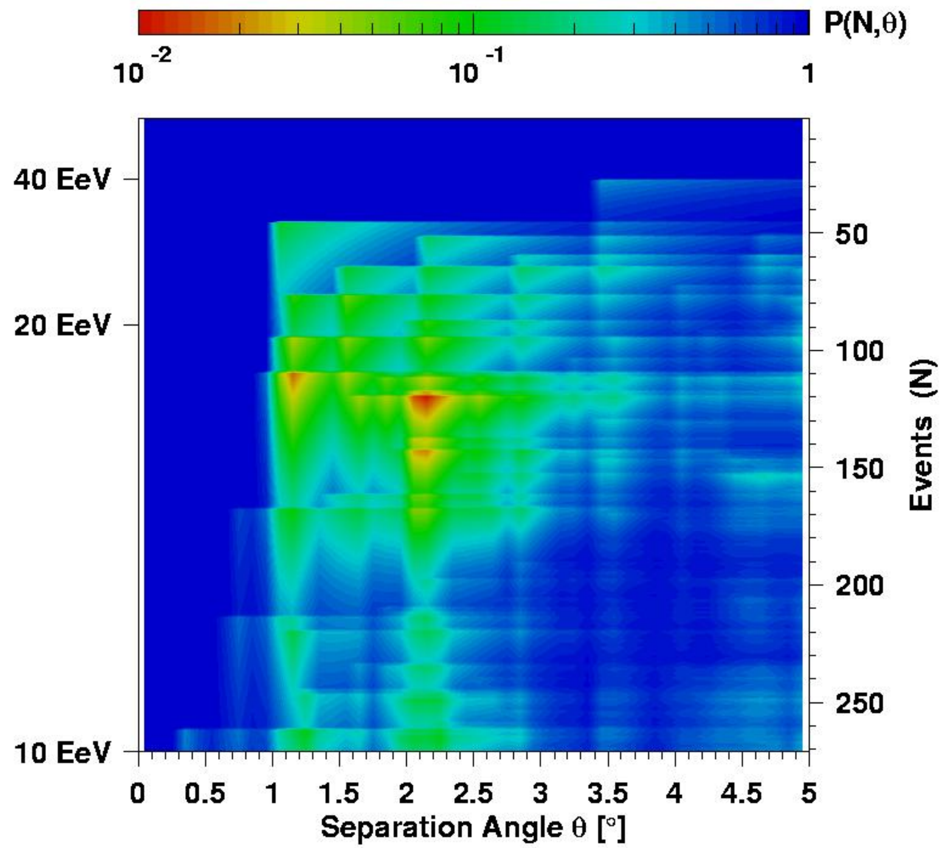
- **Lack of a priori energy threshold and angular scale for cluster search**
- **Strategy:**
  - **Scan over angular separations and energy thresholds**
  - **Identify the angular separation and energy threshold which maximize the clustering signal**
  - **Evaluate the significance by performing identical scans over Monte Carlo data sets**



slides from Stefan Westerhoff

Significant Clustering ?

- Strongest clustering signal appears at angular scale of 2.2° and an energy threshold of 1.7×10^{19} eV
- Chance probability to find equally strong signal in a scan over simulated random data sets with identical exposure is 52%
- No significant clustering found at any angular scale and any energy above 10^{19} eV



Assumption #3 – UHECR data indeed show clustering (?) -> AUGER

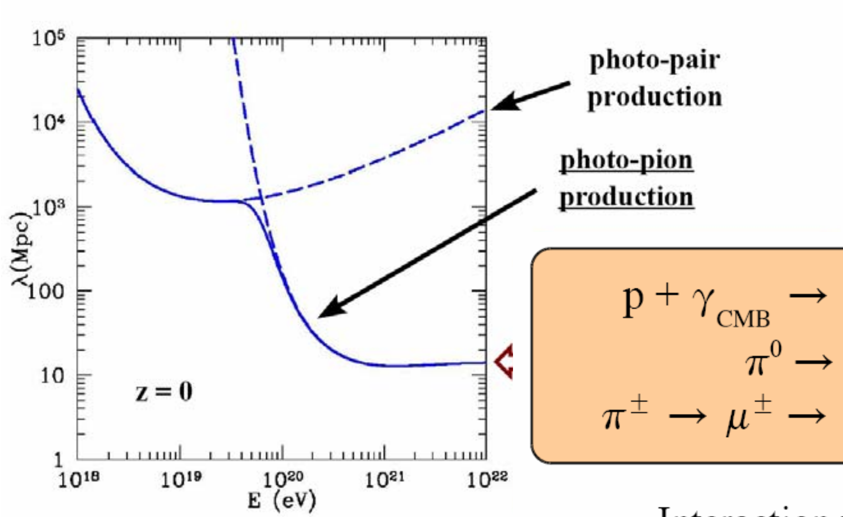
slides from Stefan Westerhoff

Study of Arrival Directions of Ultra High Energy Cosmic Rays – key for the connection to gamma-ray sources

- UHECRs may be diffuse or may come from discrete sources
- It is hard to accelerate and propagate cosmic rays without producing γ-rays: Interactions of cosmic rays with nucleons, radiation fields and magnetic fields all lead to γ-ray production
- UHECR accelerators within the GZK volume could well be detectable gamma-ray detectors!
- If not, and if the production of UHECRs is their unique property, they should still be source of TeV gamma rays
- Detection of coincident γ–ray source would confirm existence of UHECR source and provide better location

…now into the gamma-rays, finally

(a) Emission physics at UHE/EHE – the electromagnetic cascade



$$p + \gamma_{CMB} \rightarrow p\,(n) + \text{pions} \qquad E_\gamma = 10^{19}\, E_{p,20}\ \text{eV}$$
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm + \text{neutrinos} \qquad E_e = 5\cdot 10^{18}\, E_{p,20}\ \text{eV}$$

Interaction with the CMB and radio background photons:
Inverse Compton + Pair Production

$\epsilon_b E_{e/\gamma} \gg m^2 c^4$: $e \rightarrow \gamma \rightarrow e \ldots$ $\qquad$ $\epsilon_b E_{e/\gamma} \ll m^2 c^4$: EM cascade

One leading particle!!! $\qquad$ **Lots of particles**

slides by Stefano Gabici

TeV Counterpart to UHECR Source: Extragalactic Cascade

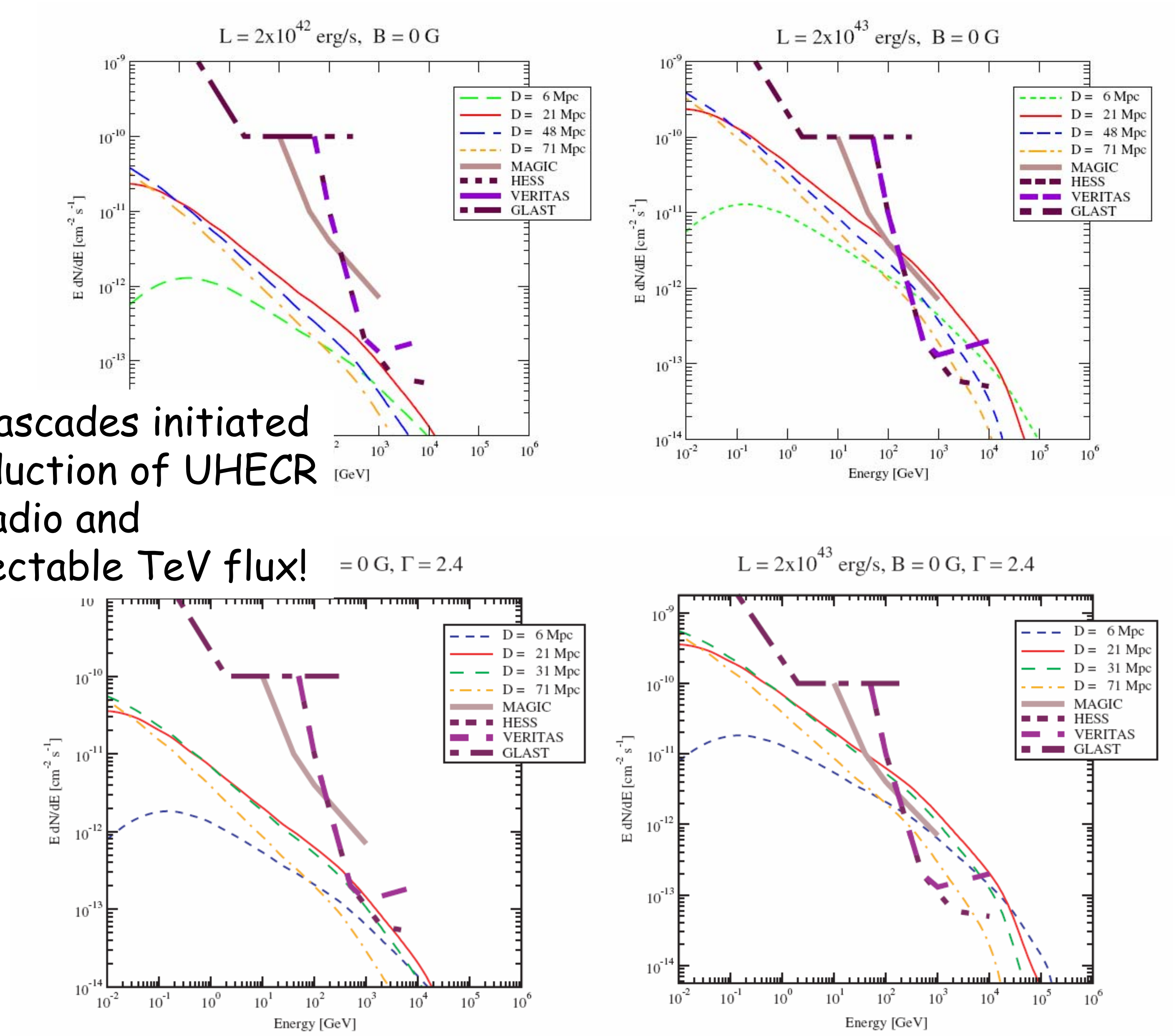
- Interactions of UHECR with the CMBR lead to the expected GZK cut-off but also produce secondary particles:

  $$p + \gamma \rightarrow p + \pi^0,\ p + \gamma \rightarrow p + e^{+} + e^{-}$$

  and hence to γ-rays via

  $\pi^0 \rightarrow \gamma\gamma$ and Inverse Compton Scattering
- These $\tilde{\gamma}$rays in turn interact with the universal radiation fields (CMBR, IR and Optical) and an electromagnetic cascade begins
- At energies << 10 TeV the universe becomes transparent to γ-rays (out to z ~0.1) and the cascade ends
- For reasonable assumptions on source strength and on extragalactic magnetic fields, such cascades should be detectable by IACTs (Ferrigno, Blasi, De Marco 2004)
- One complication is that emission may not be point-like
  - in the cascade, and from diffusion of UHECR out of acceleration region $\rightarrow$ halos (~ 1 degree)

Electromagnetic Cascades initiated
by photo-pion production of UHECR
on extragalactic radio and
CMB may give detectable TeV flux!



Ferrigno, Blasi, deMarco 2005

(b) more common: plausibility arguments:

we already see energetic gamma-ray sources up to GeV/TeV

-> dominant population of persistent sources so far energetic AGN (EGRET)

(other sources also suggested, but they didn't hit the large citation mark yet
-> galaxy clusters, GRBs, colliding galaxies – *you name it*...

Somewhat controversial recent history regarding correlations of UHECR with BL Lac objects:

Farrar & Biermann, PhysRev D81 (1998) 3579
Hoffmann, PhysRev L83 (1999) 2471
Tinyakov & Tkachev, JETP 74 (2001) 445
Tinyakov & Tkachev, APh 18 (2002) 165
Gorbunov et al., ApJ 577 (2002) L93
Evans, Ferrer, and Sarkar, PhysRev D67 (2003) 103005
Torres, Reucroft, Reimer & Anchordoqui ApJ 595 (2003) L13
Finley & Westerhoff APh 21 (2004) 359
Gorbunov et al., JETP Lett. 80 (2004) 145
Stern and Poutanen, ApJ 623 (2005) L33
Gorbunov et al. MNRAS 362 (2005) L30
Gorbunov & Troitsky, APh 23 (2005) 175
ongoing...

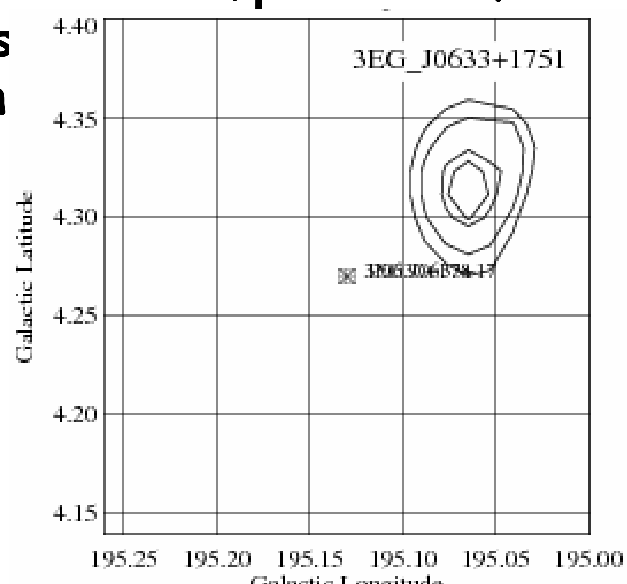
Critizism of Tinyakov & Tkachev claim due to selecting cataloged AGN for maximum S/N ratio ($z > 0.1$, < 18 mag, Veron-Cetty 9th Edition, radio flux at 6 GHz > 0.17 Jy), but compensating a posteriori the different cut adjustments by introducing a penalty factor (choice is debated, too!)

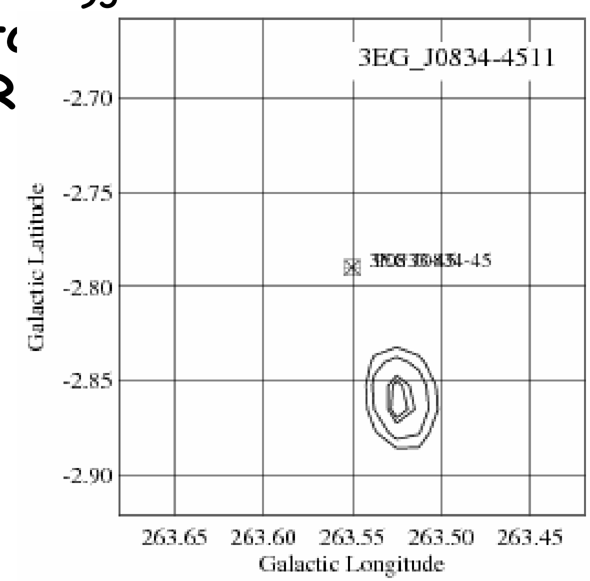
Without the arbitrary cuts, significance below 1 sigma…

Torres, Reucroft, Reimer & Anchordoqui ApJ 595 (2003) L13

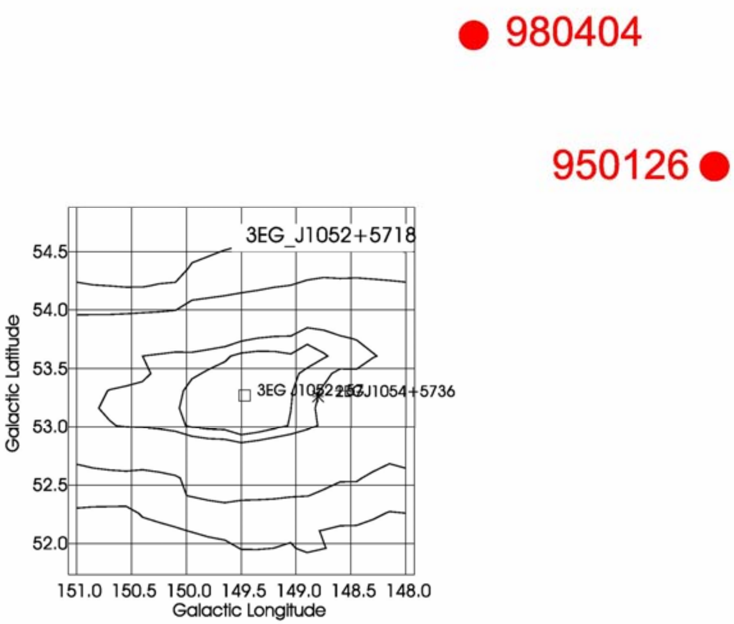
(a) The AGASA sample confronted with an independent sample
(before HiRes concluded similarly on the basis of their own data)

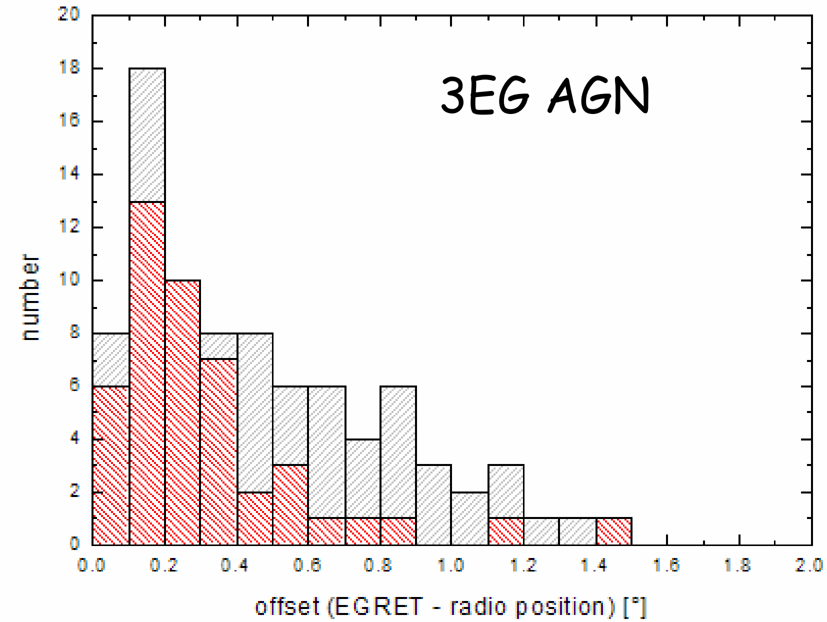
(b) Shedding light on the implication of the 2 x σ_{95} contour for correlation with the EGRET s… at… the radio position … SR

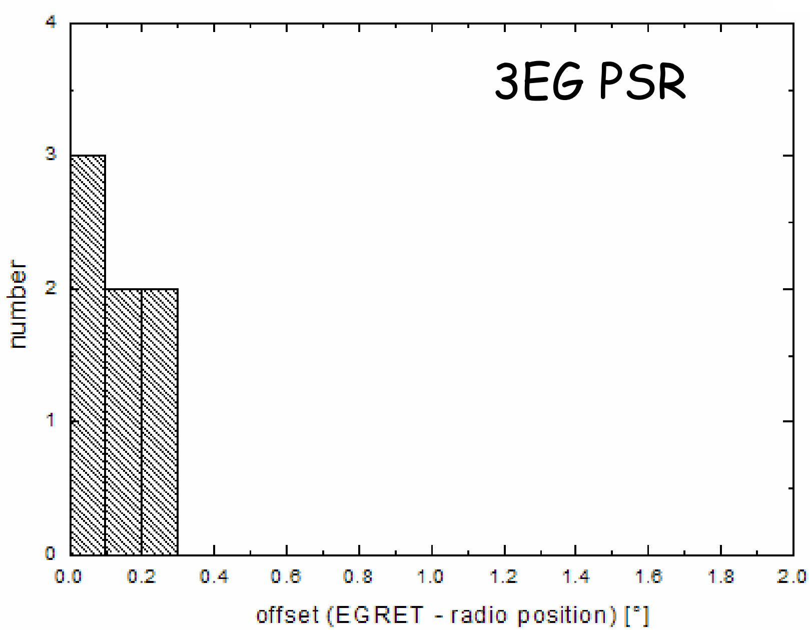


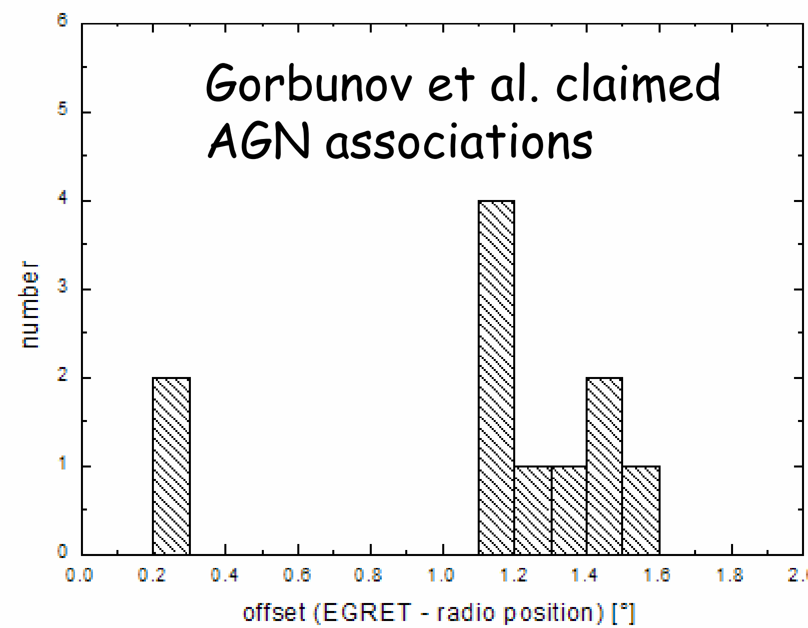


Noticed correctly, concluded wrongly…



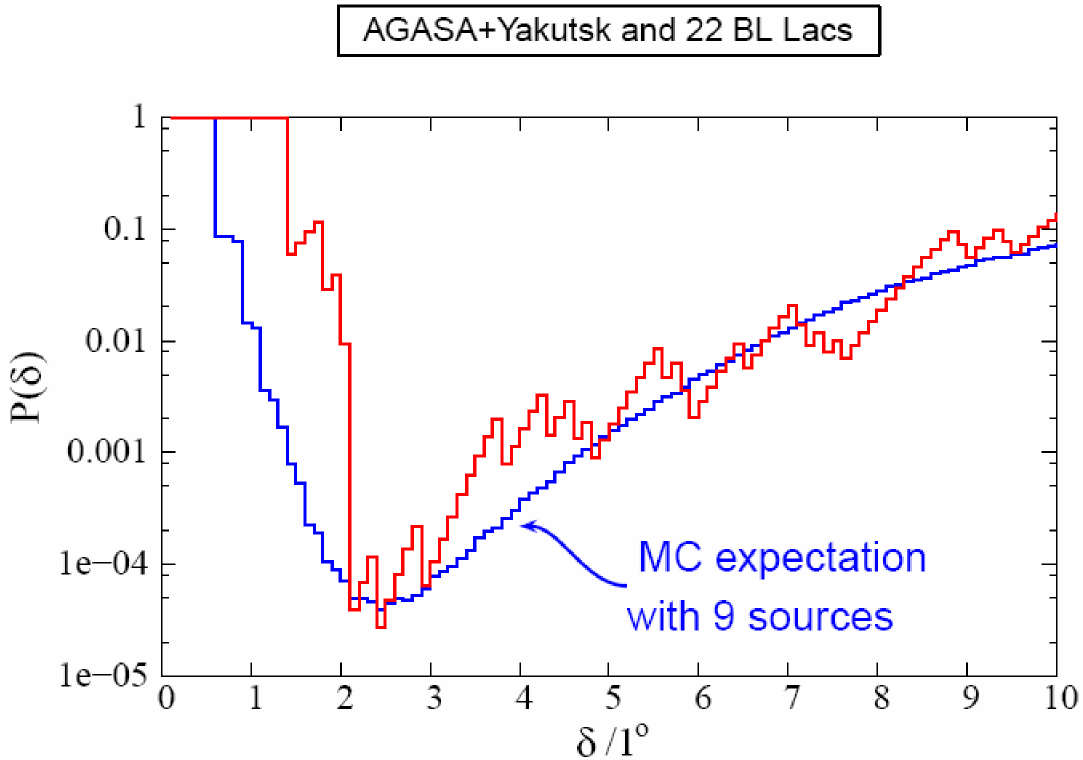






Nevertheless, the machine is under steam since 2001 …

The probability of non-association between two samples (usually UHECR & a MWL catalog) and as f(θ)



Tinyakov & I.T. (2001)

P(δ) is corrected with a panelty factor

Probability $\mathscr{P}$ calculated for the catalogs of astrophysical objects described in Section 3 and the samples of cosmic rays described in Section 4.1

			B		B		
	Catalog	A	A*	A + Y	A + Y*	H	20+
Kuehr	1 (FSRQ)	0.23	1.00	0.20	0.88	0.69	0.73
Veron	2 (FSRQ)	0.95	0.98	0.96	0.92	0.28	1.00
Lipovetsky	3 (Sy)	0.70	**0.013**	0.45	**0.038**	0.86	1.00
Veron	4 (Sy)	0.69	0.62	0.79	0.78	0.40	0.74
Confirmed BL Lacs	5 (BL)	0.17	**0.024**	0.29	**2.9×10^{-3}**	**0.040**	0.98
HP BL Lacs	6 (BL)	0.59	0.56	0.44	0.77	0.078	0.48
Bright confirmed BL Lacs	7 (BL)	**0.027**	**$\underline{4 \times 10^{-4}}$**	0.051	**$\underline{7 \times 10^{-4}}$**	**$\underline{5 \times 10^{-4}}$**	0.87
Possible EGRET BL Lacs	8 (BL)	**7.4×10^{-3}**	0.20	**2.9×10^{-3}**	**0.027**	0.54	1.0
FRI	9 (RG)	0.56	0.56	0.58	0.46	1.00	0.49
FRII	10 (RG)	0.89	0.34	0.95	0.48	0.63	0.68
Colliding Galaxies	11 (coll.)	0.27	0.15	0.069	0.099	0.55	0.50
PDS Starburst	12 (LIG)	0.089	0.47	0.18	0.27	0.80	0.22
HCN LIGs	13 (LIG)	0.11	0.87	0.18	0.11	0.30	0.41
Selected LIGs	14 (LIG)	0.086	0.18	0.13	0.090	0.24	1.00
Dead QSO candidates	15 (dQSO)	1.00	0.17	1.00	0.22	1.00	1.00
Dead QSO cand (cuts)	16 (dQSO)	0.41	1.00	0.50	1.00	1.00	0.13
EGRET blazars	17 (γ)	0.24	0.68	0.14	0.80	0.20	0.46
UNID outside plane	18 (γ)	0.10	**5.1×10^{-3}**	0.16	**$\underline{1.2 \times 10^{-3}}$**	0.62	1.00
UNID general	18a (γ)	0.24	**0.015**	0.37	**5.8×10^{-3}**	0.82	0.61
GeV outside plane	19 (γ)	0.27	0.31	0.34	1.00	0.40	1.00
GeV general	19a (γ)	0.19	0.39	0.095	0.50	0.52	1.00
Extragalactic TeV	20 (γ)	1.00	1.00	1.00	1.00	**0.012**	1.00

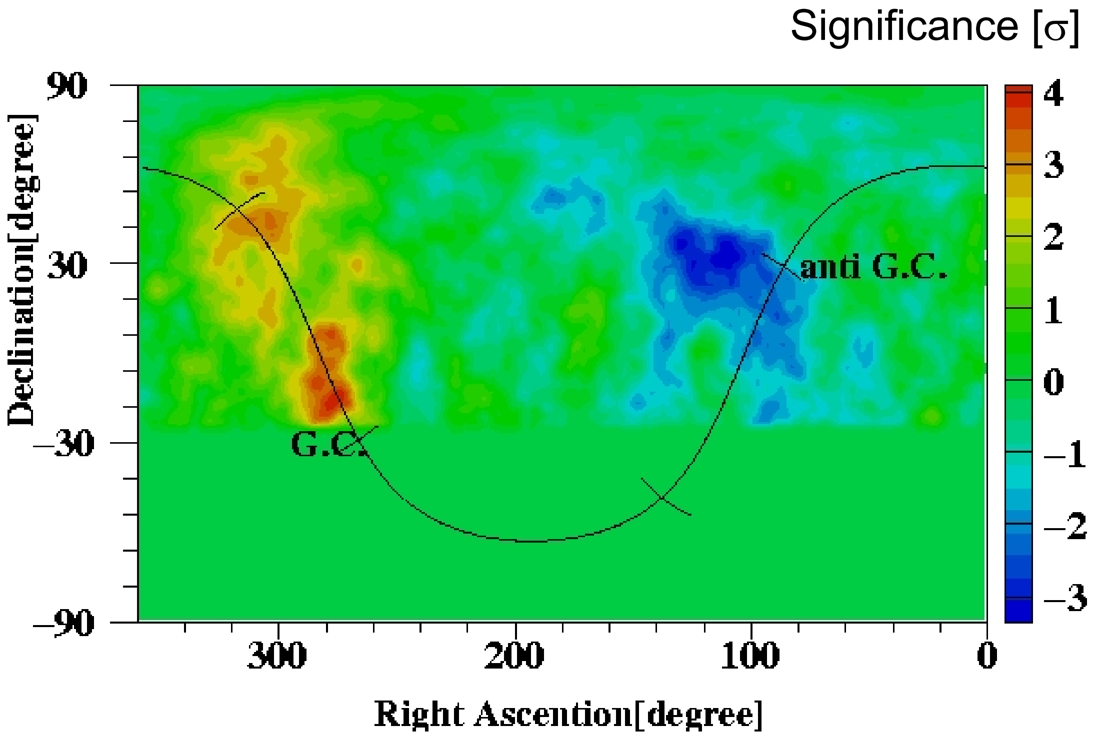
For convenience, with the number of a catalog, a reference to a section of this paper is given as follows: FSRQ—Section 3.1, Sy—Seyfert galaxies—Section 3.2, BL—BL Lac's—Section 3.3, RG—radio galaxies—Section 3.4, coll.—colliding galaxies—Section 3.5, LIG—starburst and luminous IR galaxies—Section 3.6, dQSO—dead QSO candidates—Section 3.7, γ—gamma-ray sources—Section 3.8. The columns with the results obtained with correction of the arrival directions for GMF are marked by asterisks. The values of $\mathscr{P} < 4.6 \times 10^{-2}$ (which would correspond to a 2σ effect for the Gaussian statistics) are given in bold face. The values $\mathscr{P} < 2.7 \times 10^{-3}$ (would-be 3σ) are underlined. Each value of $\mathscr{P}$ has been calculated without accounting for other tries and thus can be interpreted as a relative probability with respect to other catalogues.

Summary of BL Lac Correlation:

- "BL", m<18, all HiRes events (no E cut): $F = 2\times10^{-4}$
- "BL+HP" with m<18, HiRes E>10 EeV: $F = 10^{-5}$
- Confirmed TeV blazars, all HiRes events (no E cut): $F = 10^{-3}$
- Analysis has been a posteriori, so F values are not true chance probabilities!
- Correlations on the scale of the HiRes angular resolution (0.6°) imply that primary must be neutral (at least over most of its path). But neutrons and photons have a very short mean path (~ few Mpc) at this energy...
- The set of "correlated" events have shower profiles which are inconsistent with photons!
- Correlations must be tested with independent data before any claim can be made (done – non-confimation!, although limited statistics)
- Arrival directions of past year HiRes data have not been put forward yet. Data taking through March 2006 will yield an independent data set ~70% of the current sample size: Independent test of BL Lac correlations should be possible.
- Finally: AUGER will clarify by sheer UHECR statistics, GLAST by precision in blazar source localisation

Large-scale anisotropy studies: source at the Galactic Center ?

- **AGASA: 4 σ excess near the Galactic center**
- **Criticism: cuts are *a posteriori* and chance probability is meaningless**
  - **Integrated event density over 20º radius**
  - **Excess is observed in narrow energy band from 0.8 to 3.2 EeV**
- **However: also excess in archival SUGAR data (1968-1979)**



N. Hayashida et al., Astroparticle Phys. 10 (1999) 303
J.A. Bellido et al., Astroparticle Phys. 15 (2001) 167

Ultra-High Energy Cosmic Rays and the Connection to γ-ray and Neutrino Astrophysics

accelerated protons interact:

$$p + \begin{matrix} N \\ \gamma \end{matrix} \rightarrow X + \left. \begin{matrix} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{0} \rightarrow \gamma - \text{rays} \end{matrix} \right\}$$

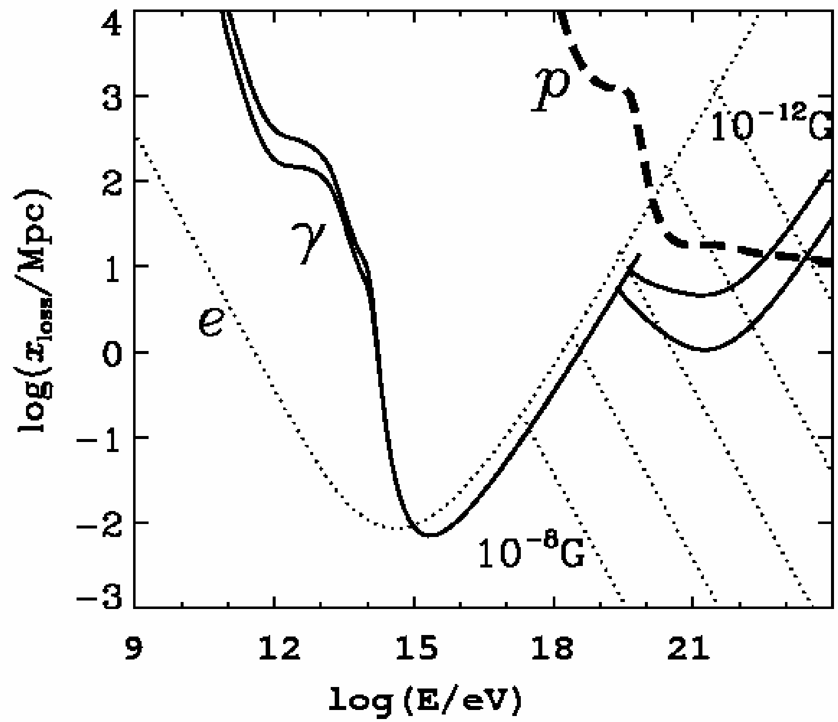
during propagation or in sources

=> energy fluences in γ-rays and neutrinos are comparable due to isospin symmetry.

Neutrino spectrum is unmodified, γ-rays pile up below pair production threshold on CMB at a few 10^{14} eV.

Universe acts as a calorimeter for total injected electromagnetic energy above the pair threshold.
=> neutrino flux constraints.

$x_{loss} = x_{int}$ /mean inelasticity



Included processes:

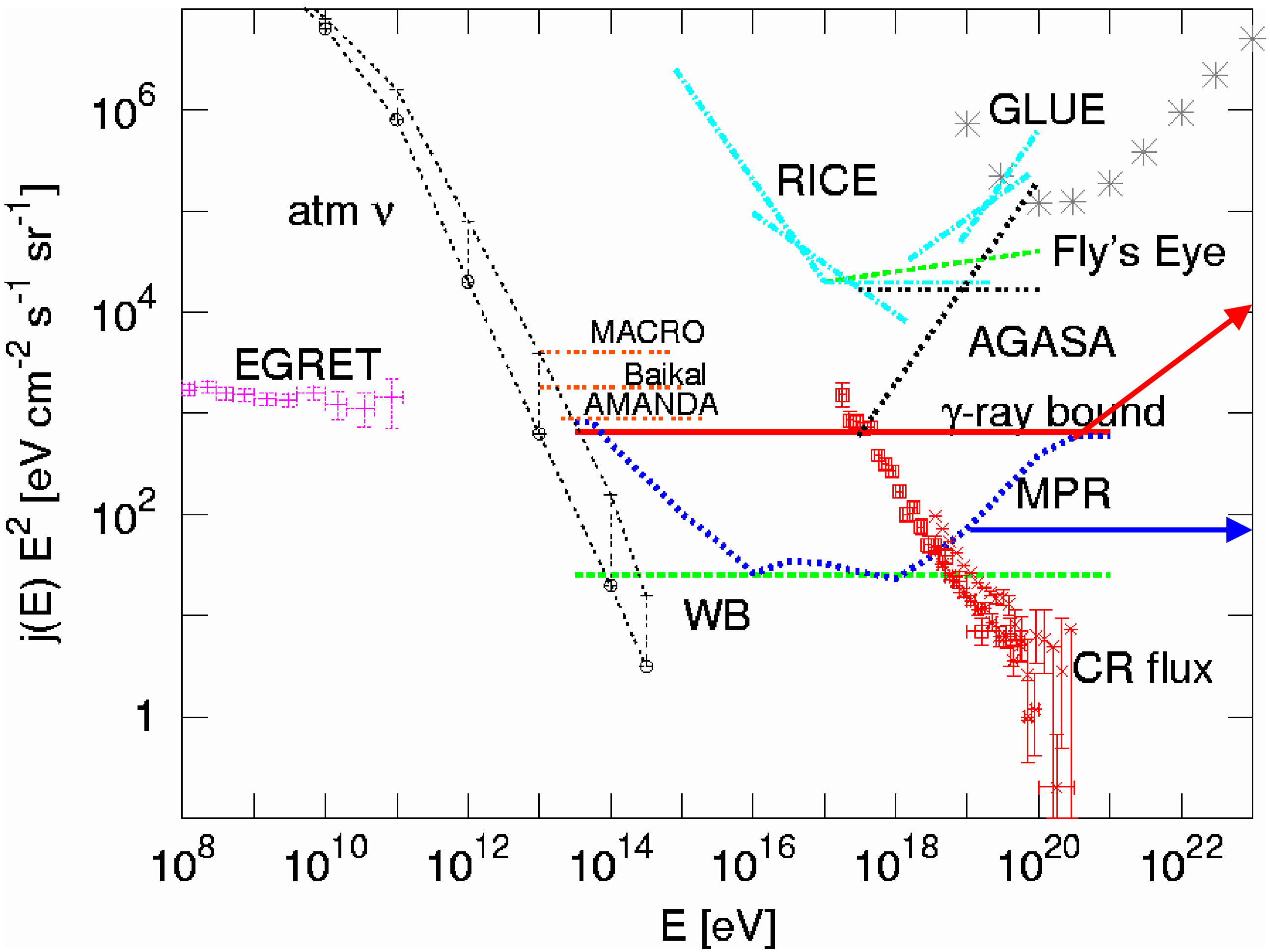
Electrons: inverse Compton; synchrotron rad (for fields from pG to 10 nG)

Gammas: pair-production through IR, CMB, and radio backgrounds

Protons: Bethe-Heitler pair production, pion photoproduction

slide by G. Sigl

Total injected electromagnetic energy is constrained by the diffuse γ-ray flux measured by EGRET in the MeV – 100 GeV regime



Neutrino flux upper limit for opaque sources determined by EGRET bound

Neutrino flux upper limit for transparent sources more strongly constrained by primary cosmic ray flux at 10^{18} – 10^{19} eV (Waxman-Bahcall; Mannheim-Protheroe-Rachen)

slide by G. Sigl

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The problem of the origin of cosmic rays will be solved by more work and less talk!

Ernest Rutherford, ca 1940