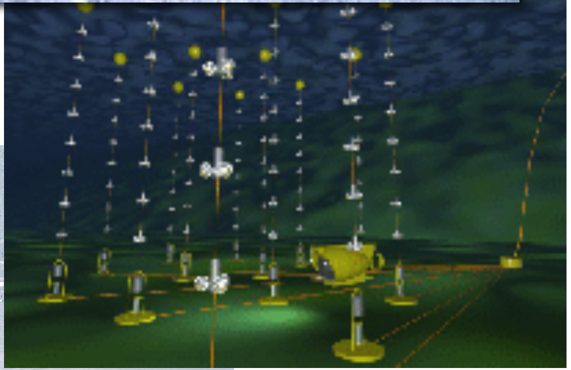
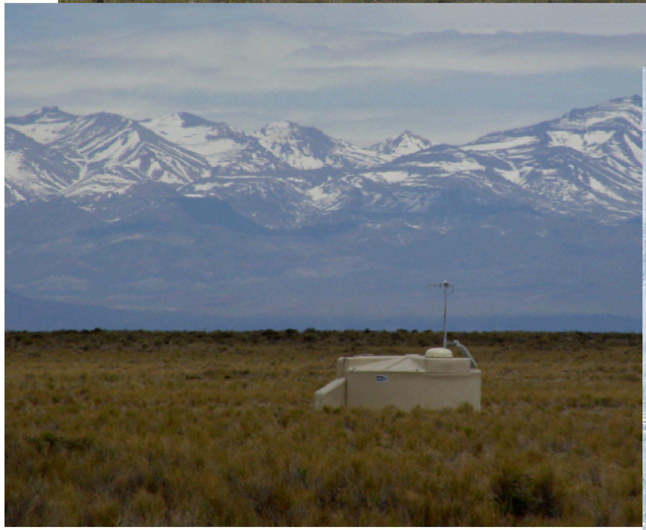
Seeing the high energy universe

Subir Sarkar

Lecture 1

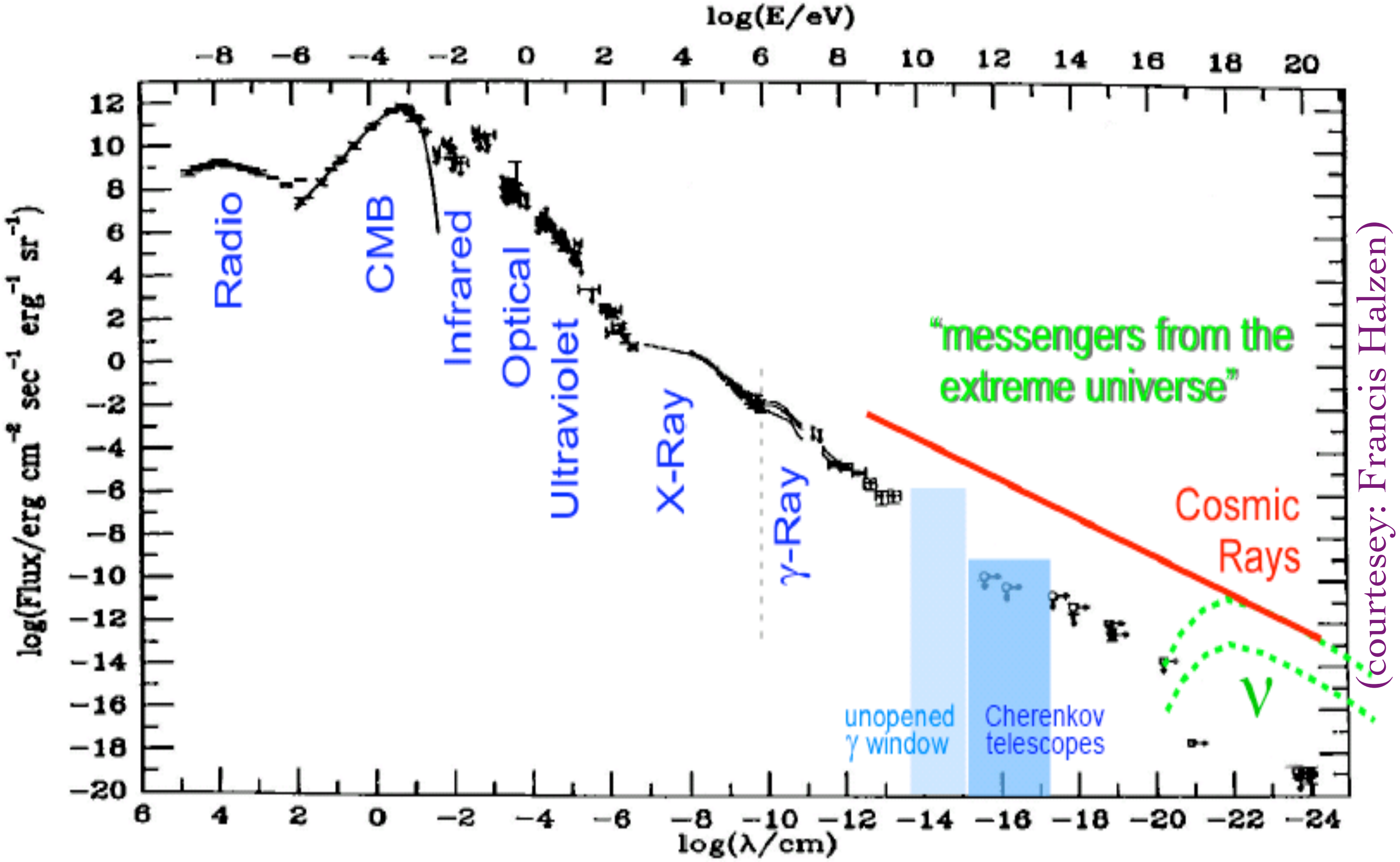




UK HEP Young Experimentalists and Theorists Institute, IPPP Durham, 10-12 Jan 2010

We can *see* the universe directly with **photons** up to a few TeV

… beyond this energy they are attenuated through $\gamma\gamma \rightarrow e^+e^-$ on the CIB/CMB

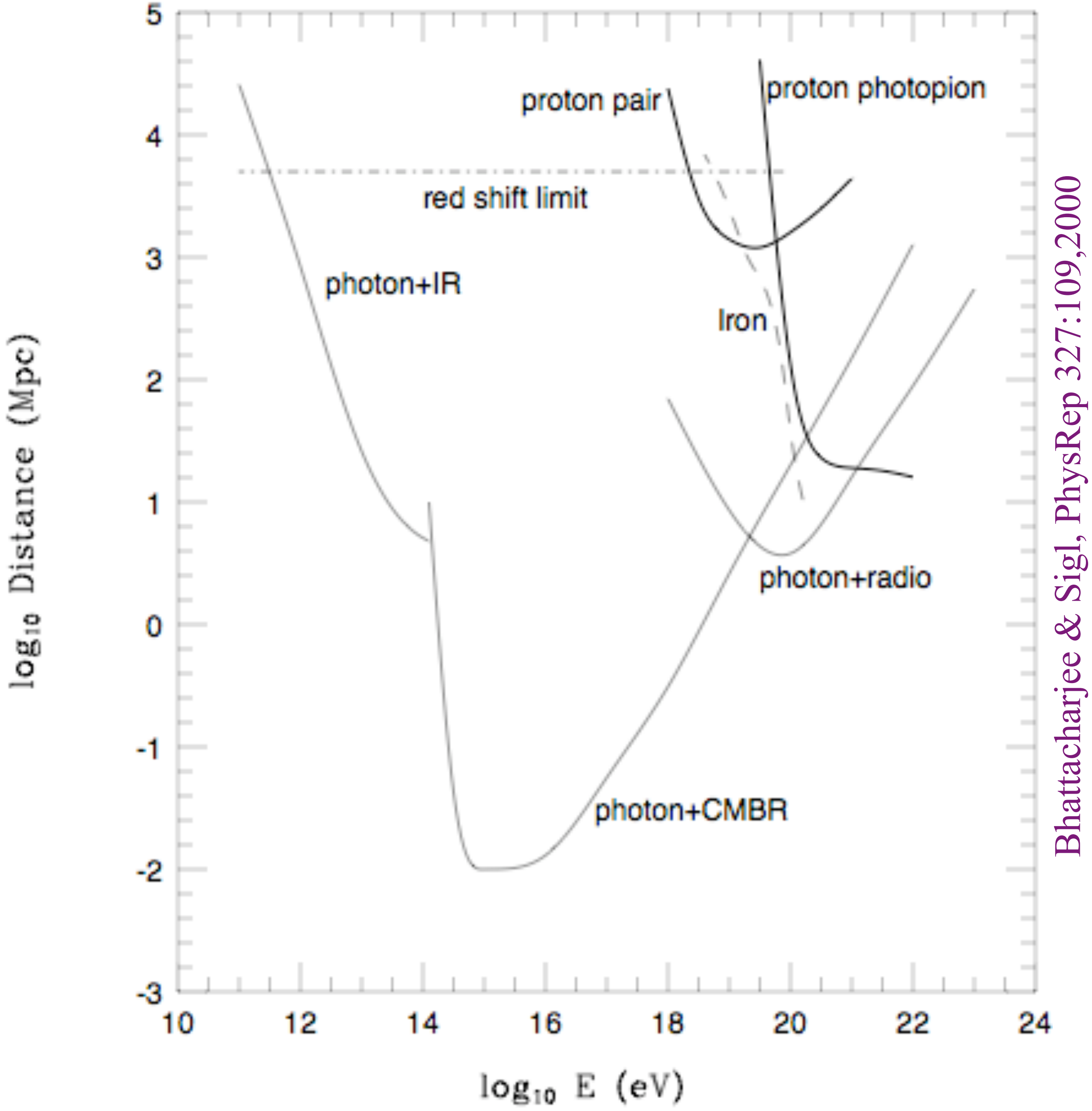


(courtesey: Francis Halzen)

Using **cosmic rays** we should be able to ‘see’ up to ~ 6 x10^{10} GeV
(before they get attenuated by $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+, p\pi^0$, on the CMB)

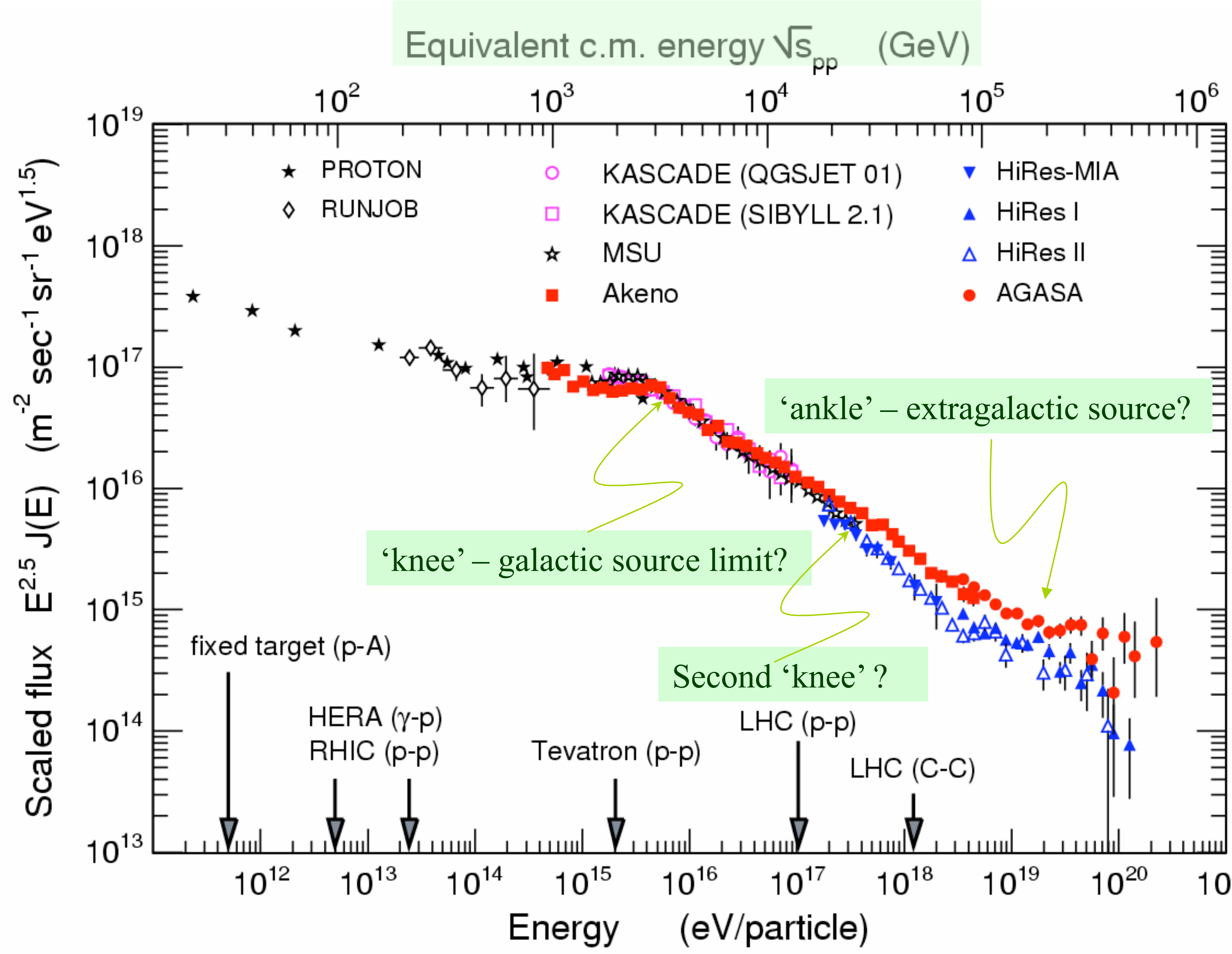
… and the universe is transparent to **neutrinos** at nearly *all* energies

Attenuation of cosmic messengers



Bhattacharjee & Sigl, PhysRep 327:109,2000

By studying cosmic ray (p, γ, ν) interactions we can also 'see' into the *microscopic universe,* well beyond the reach of terrestrial accelerators



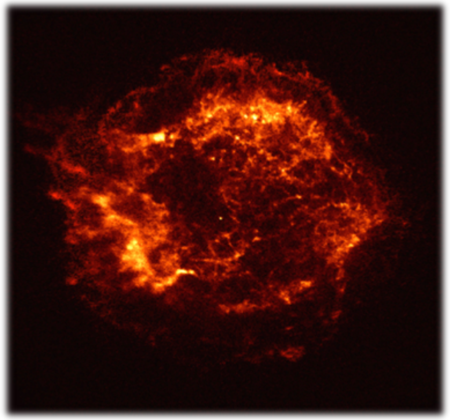
'ankle' – extragalactic source?

'knee' – galactic source limit?

Second 'knee' ?

(courtesey: Ralph Engel)

The sources of galactic cosmic rays have long been presumed to be supernova remnants



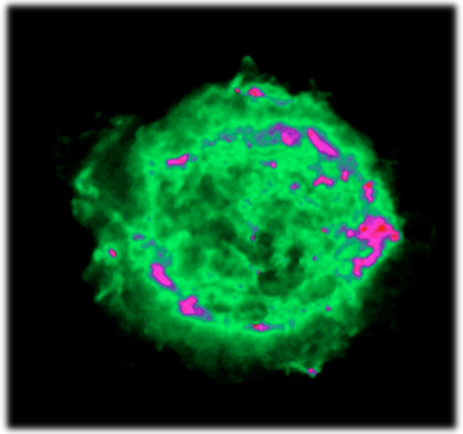
Cassiopeia A: Chandra

Direct evidence for acceleration of electrons (to > 40 TeV) from observation of synchrotron emission: radio ➔ X-rays

Energetics:

• GCR energy density	$0.3\,\mathrm{eV\,cm^{-3}}$
• Volume of extended halo	$\pi(15\,\mathrm{kpc})^2\,3\,\mathrm{kpc} \simeq 5.7\times10^{67}\,\mathrm{cm}^3$
⇒ Total GCR energy	$1.7\times10^{58}\,\mathrm{GeV} \simeq 2.8\times10^{55}\,\mathrm{erg}$
• Residence time of CRs in Galaxy	$20\,\mathrm{Myr}$
⇒ Power needed	$1.4\times10^{48}\,\mathrm{erg\,yr^{-1}}$
• Galactic SN rate	$0.03\,\mathrm{yr^{-1}}$
⇒ Required output/SN (remnant)	$4.6\times10^{49}\,\mathrm{erg}$

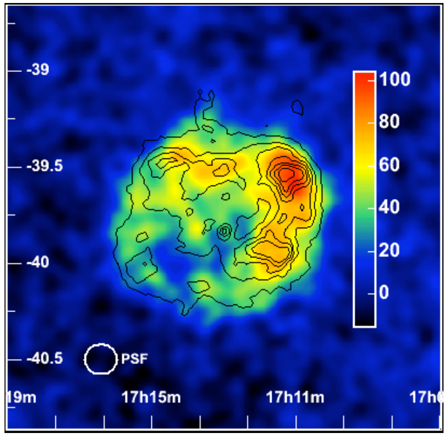
This is only a few % of the benchmark kinetic energy of 10^{51} erg produced in a SN explosion



Cassiopeia A: VLA

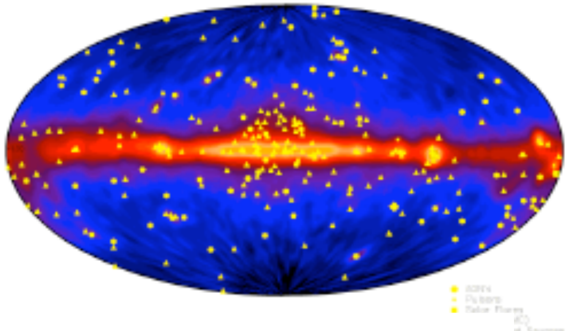
It had been hoped that advances in γ-ray astronomy would test the hypothesis … however although some SNRs *have* been detected new questions are raised:

- ➢ Do the observed γ-rays arise from hadronic interactions (π^0 decays) , or from inverse-Compton scattering by (the radio synchrotron emitting) electrons ?
- ➢ Can 1st-order Fermi acceleration at SNR shocks explain the spectrum (injection, magnetic field amplification, diffusion losses versus anisotropy) ?
- ➢What are the 'unidentified' γ-ray sources in the Milky Way – are there new source classes (micro-quasars, PWNs, binaries …), acceleration mechanisms ?

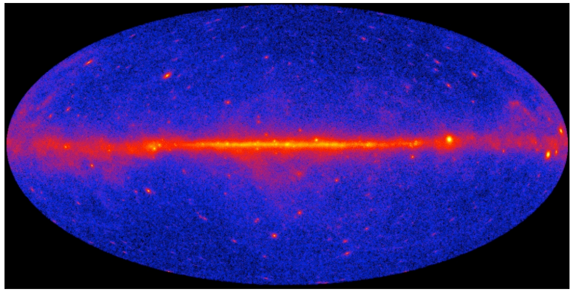


RXJ1713.7-3946 (HESS, 2004)

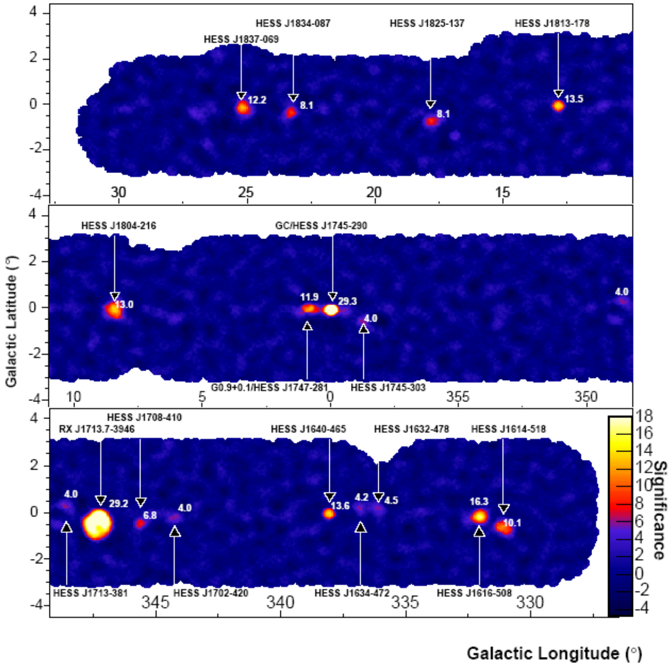
EGRET 1991 - 2000



Fermi (GLAST) 2009 -



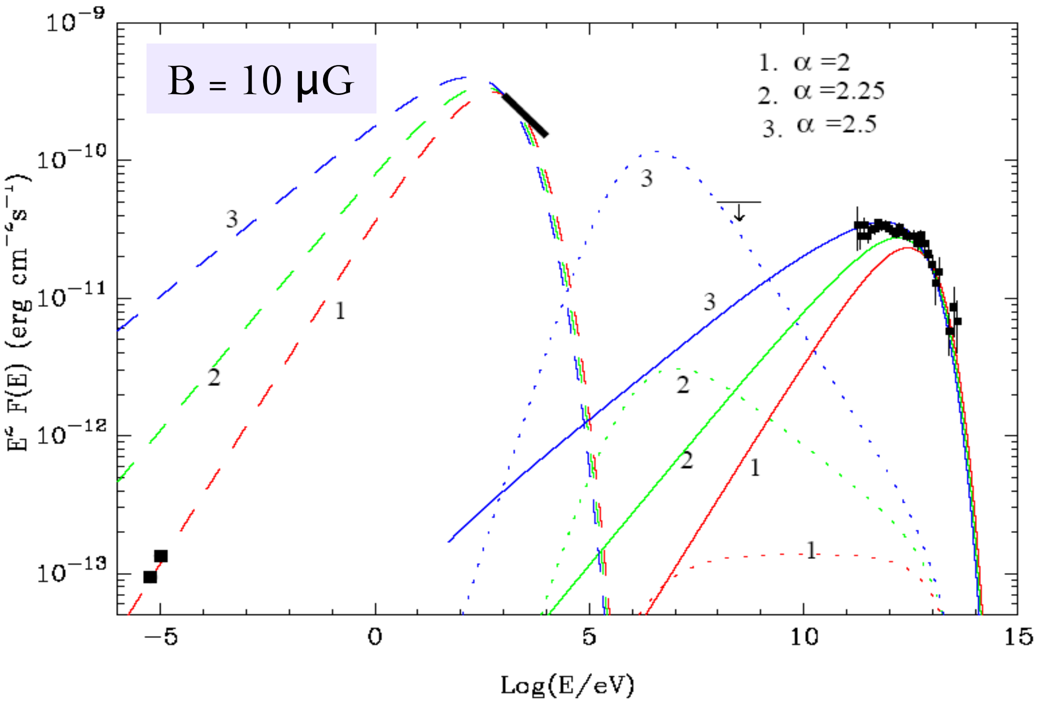
HESS Southern Plane Survey 2005

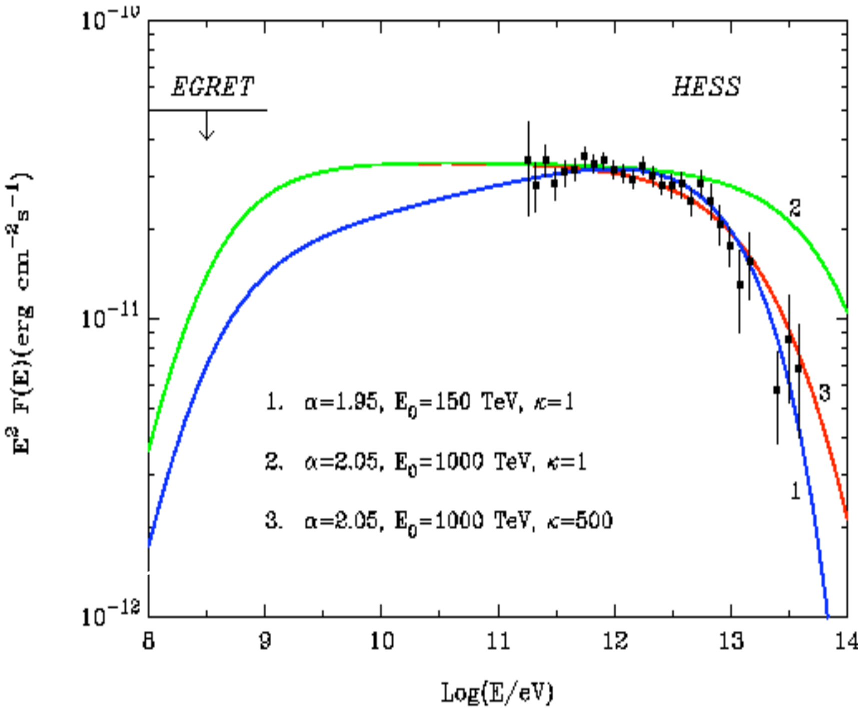


Much progress has been made but these questions are not fully answered …

To *unambiguously* identify the cosmic ray sources, we need to see **TeV neutrinos** … also **ultra high energy cosmic rays** may point to the sources .

Primary population in ***RXJ1713.7-3946***: *e* or *p*?





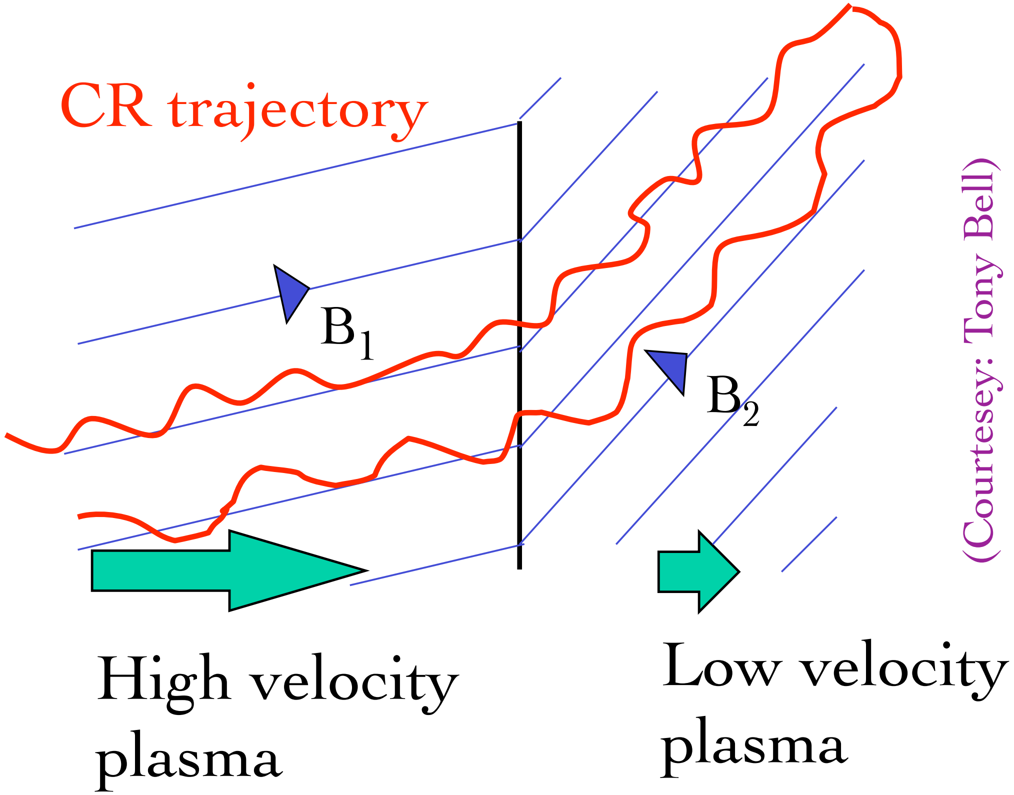
(HESS collaboration, 2006)

γ-ray emission well fitted by IC scattering of ~10^2 TeV electrons on CMB/starlight

… alternatively γ-rays may be from decays of π^0s produced by ~10^3 TeV protons

There is no *definite* evidence yet that SNRs accelerate *protons* to high energies..

First-order Fermi acceleration at SNR shocks



Shock velocity v_s: $\beta = v_s/c$

Simple diffusion theory: prob. of CR crossing shock $\geq m$ times is $(1-\beta)^m$

Average fractional energy gained at each crossing is: $\Delta\varepsilon/\varepsilon = \beta$

$\Rightarrow$ differential spectrum: $n(\varepsilon) \propto \varepsilon^{-2}$

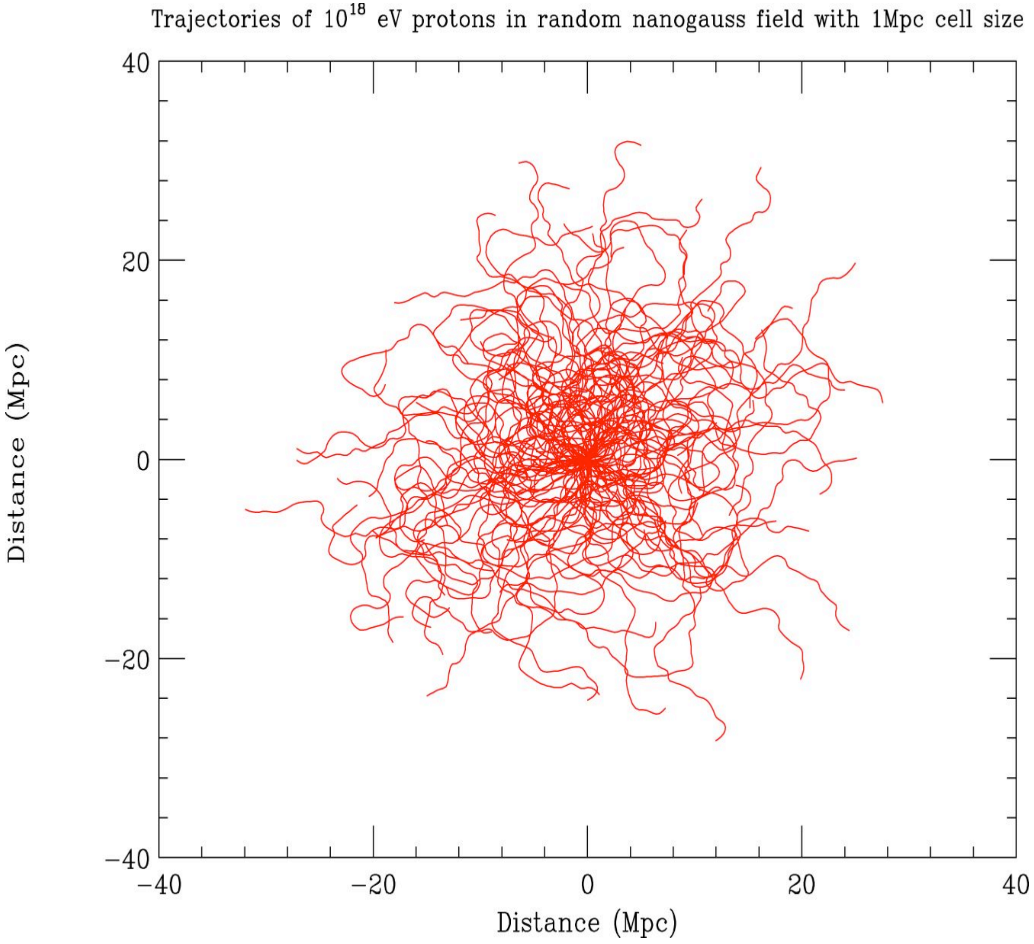
Invoking diffusion loss time-scale $\propto \varepsilon^{-0.7}$ can *match* the observed spectrum $\propto \varepsilon^{-2.7}$

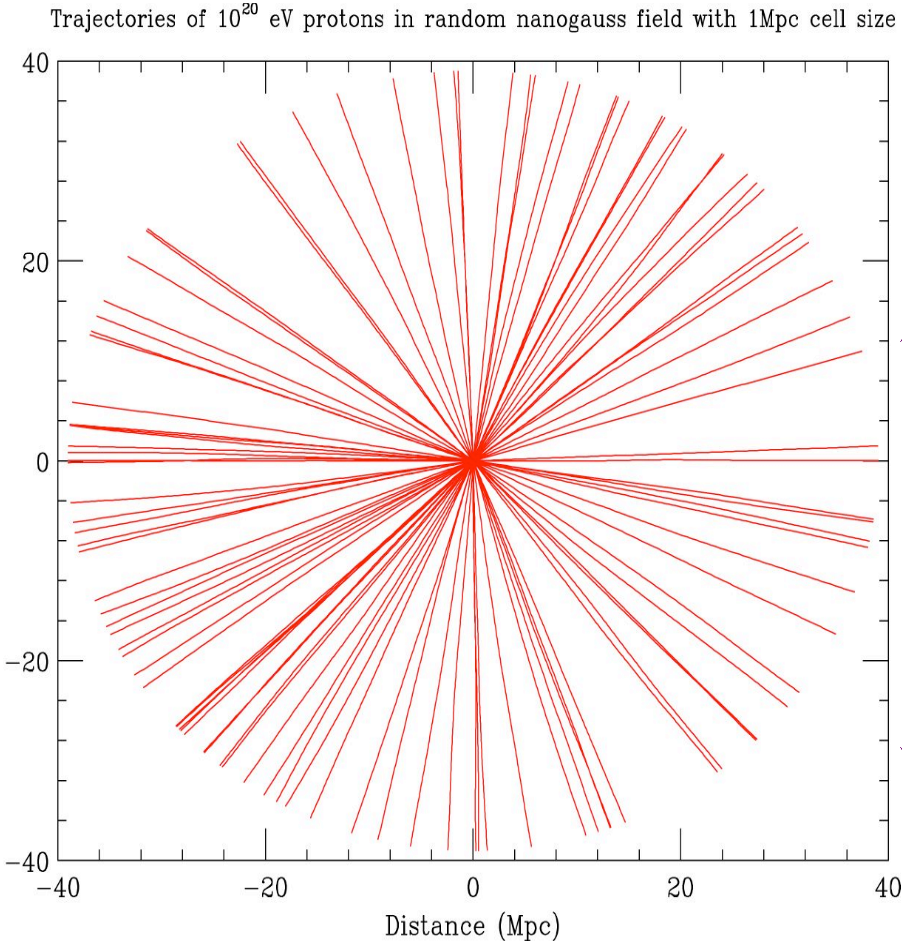
Due to scattering on magnetic field irregularities, cosmic ray crosses shock many times, gaining energy each time, so *can* yield the required ~10-15% conversion of the shock wave K.E. into particles

But this model *cannot* easily account for:

- ▶why cosmic ray anisotropy does *not* increase $\propto \varepsilon^{0.7}$
- ▶smooth continuation of the spectrum beyond the 'knee'
- ▶absence of (π^0 decay) γ-rays from *most* SNRs
- ▶ High efficiency $\Rightarrow$ *concave* spectra *cf.* observed *convexity*..

The trajectories of cosmic rays are randomised by cosmic magnetic fields … so need to go to ultrahigh energies to do cosmic ray astronomy

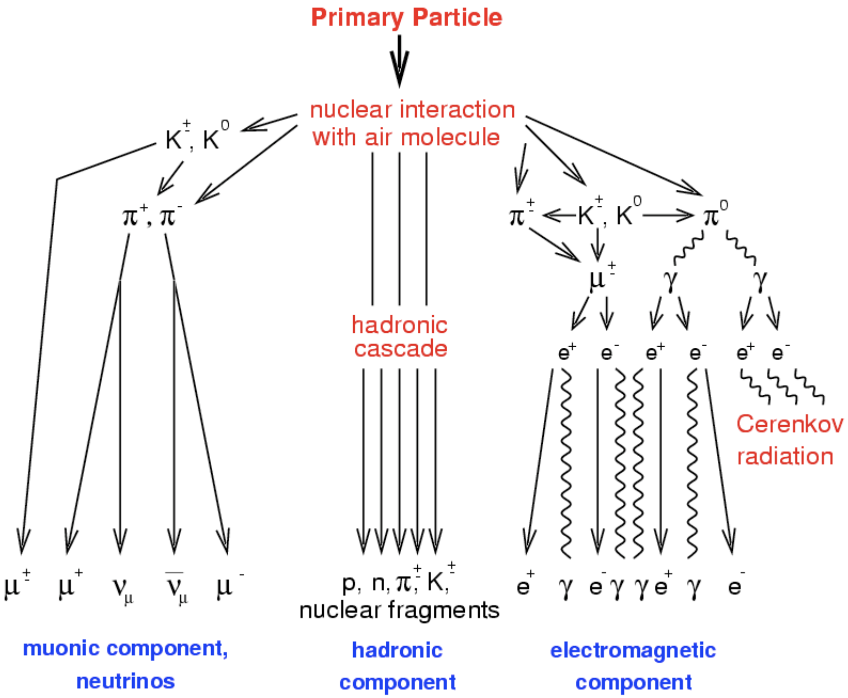

Trajectories of 10^{18} eV protons in random nanogauss field with 1Mpc cell size


Trajectories of 10^{20} eV protons in random nanogauss field with 1Mpc cell size

(courtesey: Jim Cronin)

No anisotropies have been detected for cosmic rays up to the 'knee' (~10^{18} eV) – at higher energies they can no longer be deflected by Galactic magnetic fields

To study ultrahigh energy cosmic rays must use the Earth's atmosphere as detector



Primary Particle

nuclear interaction with air molecule

$K^{\pm}, K^0$

π^+, π^-

hadronic cascade

$\pi^{\pm} \leftarrow K^{\pm}, K^0 \rightarrow \pi^0$

$\mu^{\pm}$

γ γ

e^+ e^- e^+ e^- e^+ e^-

Cerenkov radiation

μ^+ μ^+ ν_μ $\bar{\nu}_\mu$ μ^-

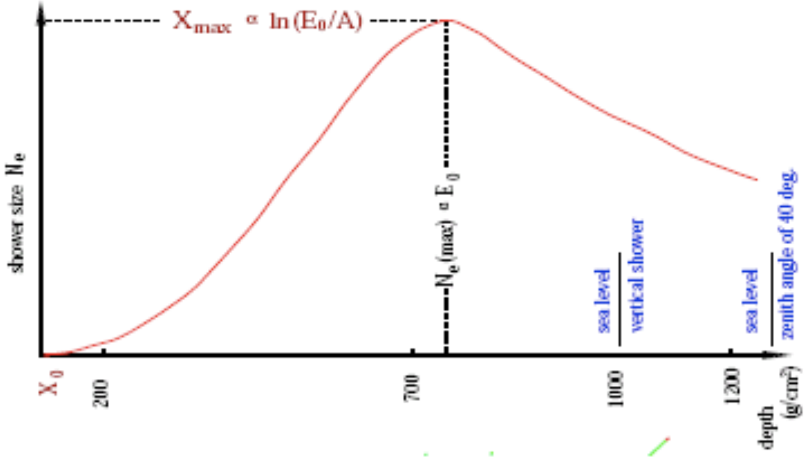
$p, n, \pi^{\pm}, K^{\pm}$, nuclear fragments

e^+ γ e^- γ γ e^+ γ e^-

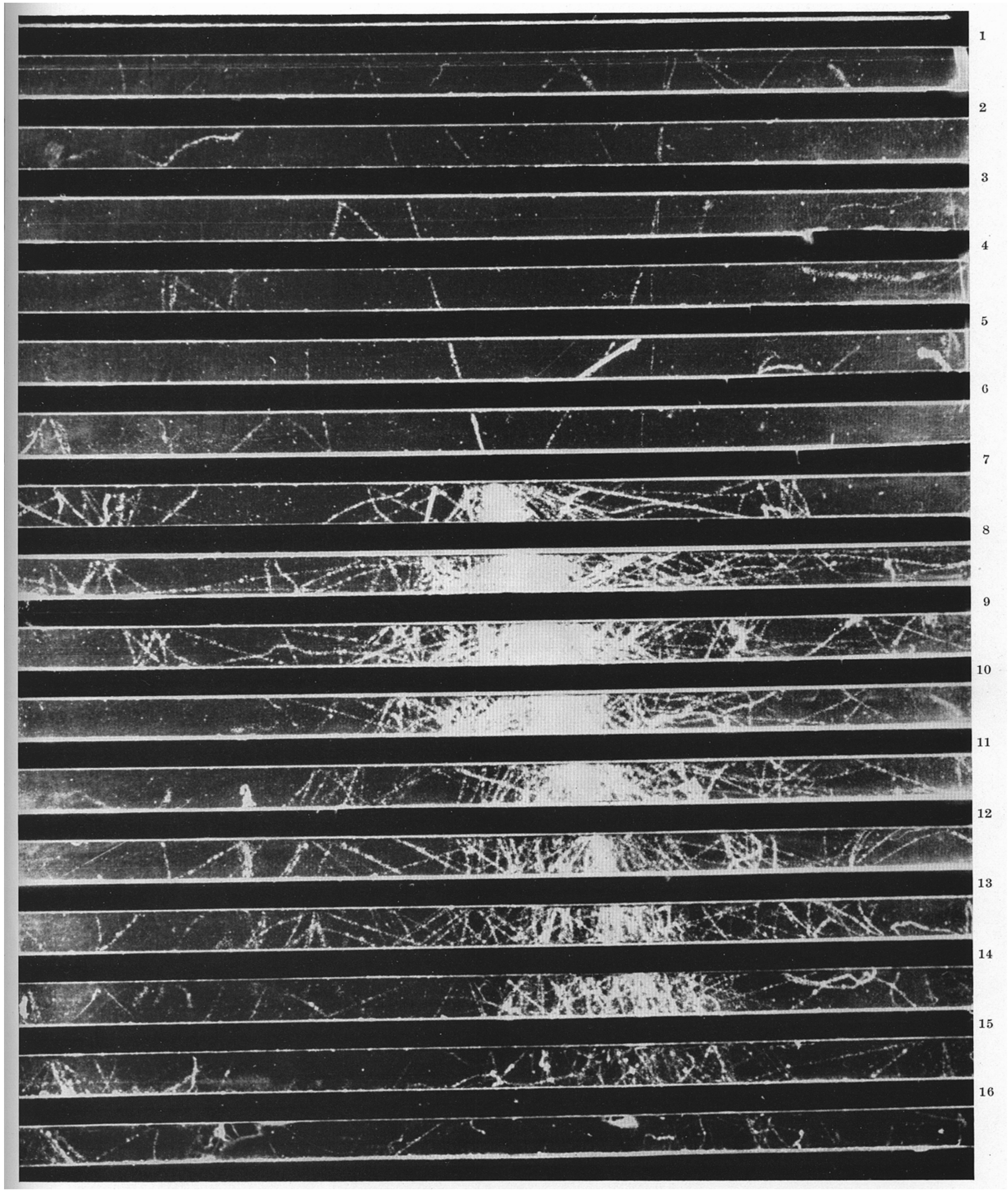
muonic component, neutrinos

hadronic component

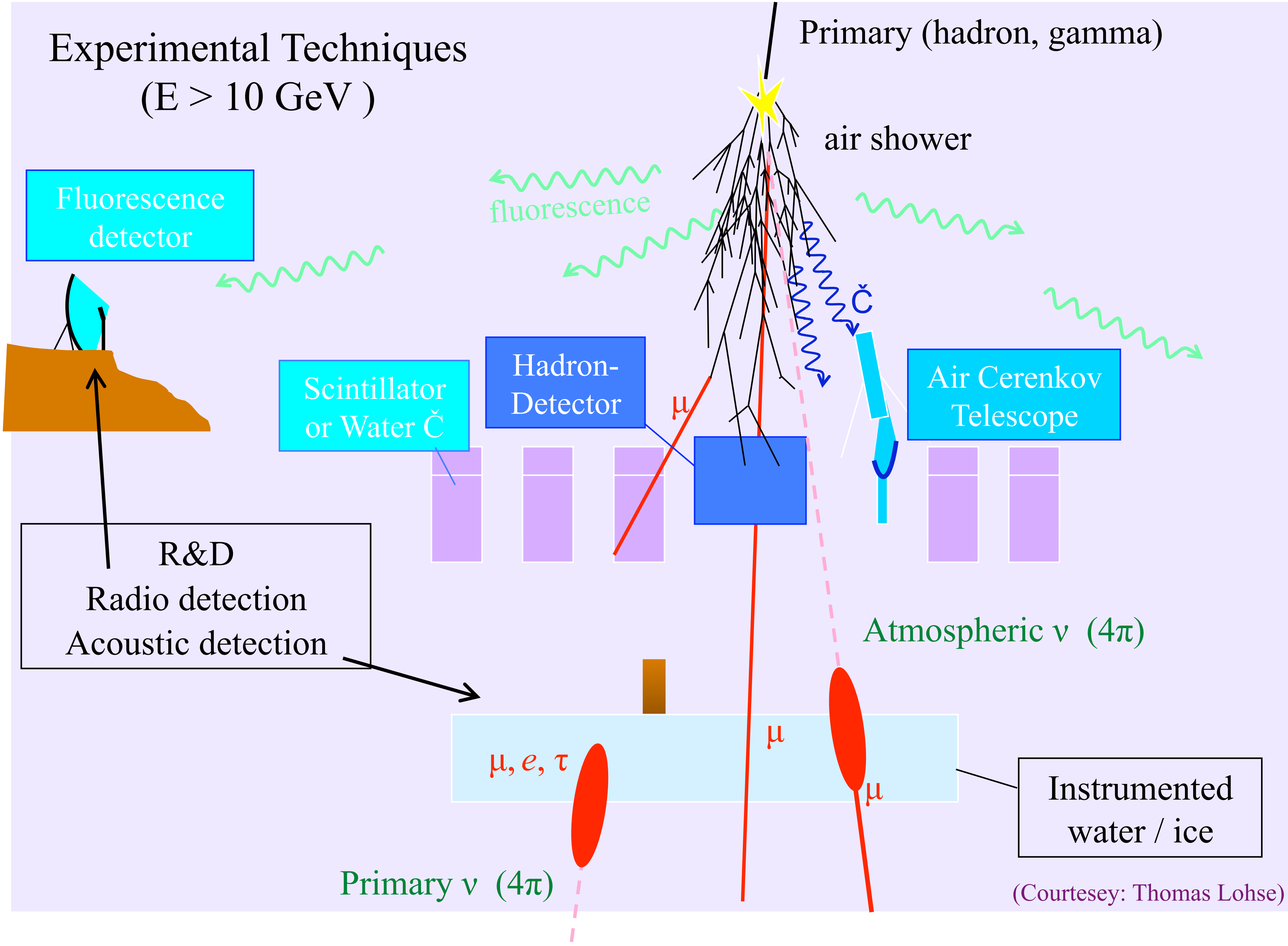
electromagnetic component



Cosmic ray shower in a cloud chamber



Experimental Techniques
(E > 10 GeV)



Primary (hadron, gamma)

Fluorescence detector

Scintillator or Water Č

Hadron-Detector

Air Cerenkov Telescope

R&D
Radio detection
Acoustic detection

Atmospheric ν (4π)

Instrumented water / ice

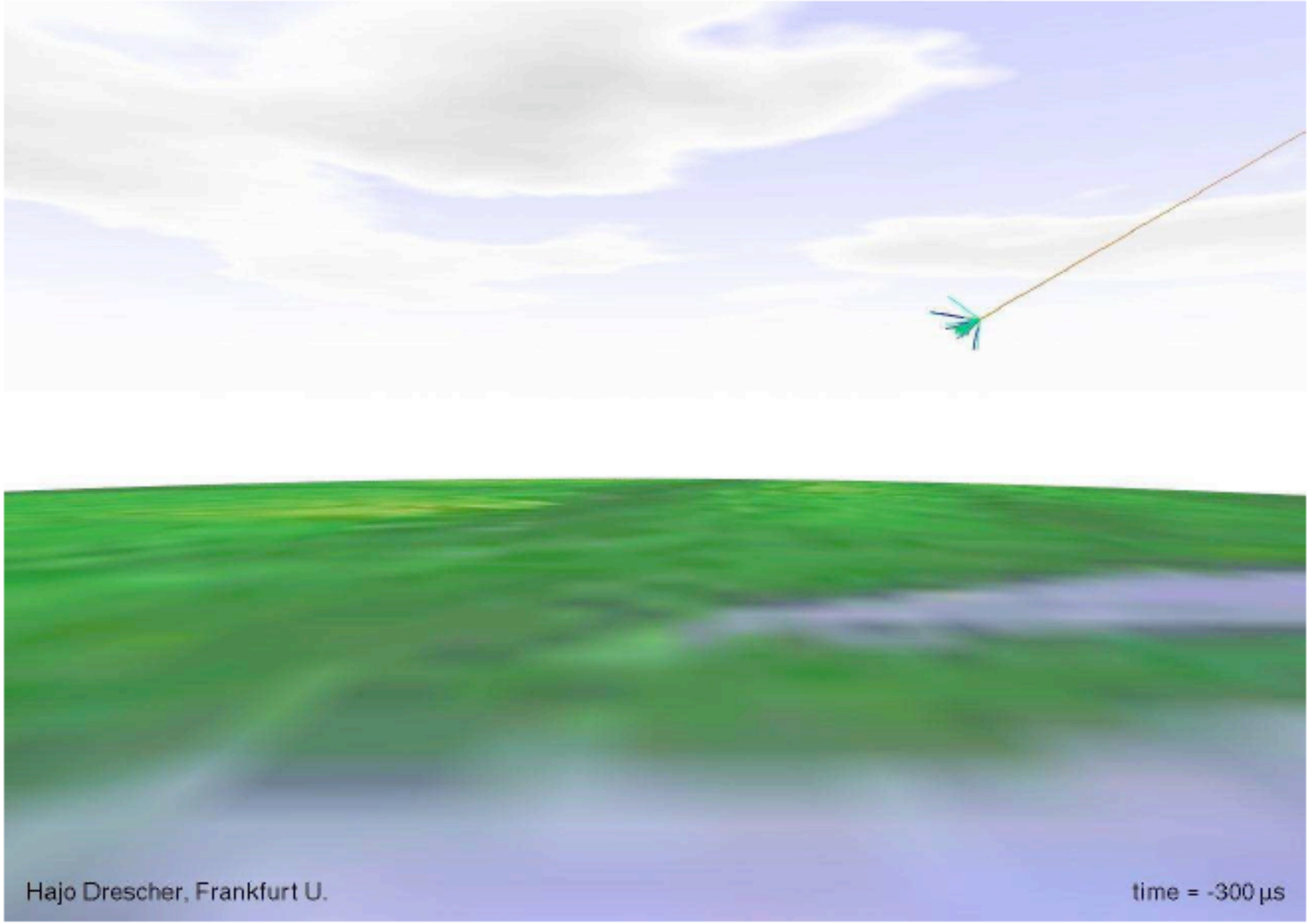
Primary ν (4π)

(Courtesey: Thomas Lohse)

Ultra High Energy Cosmic Rays

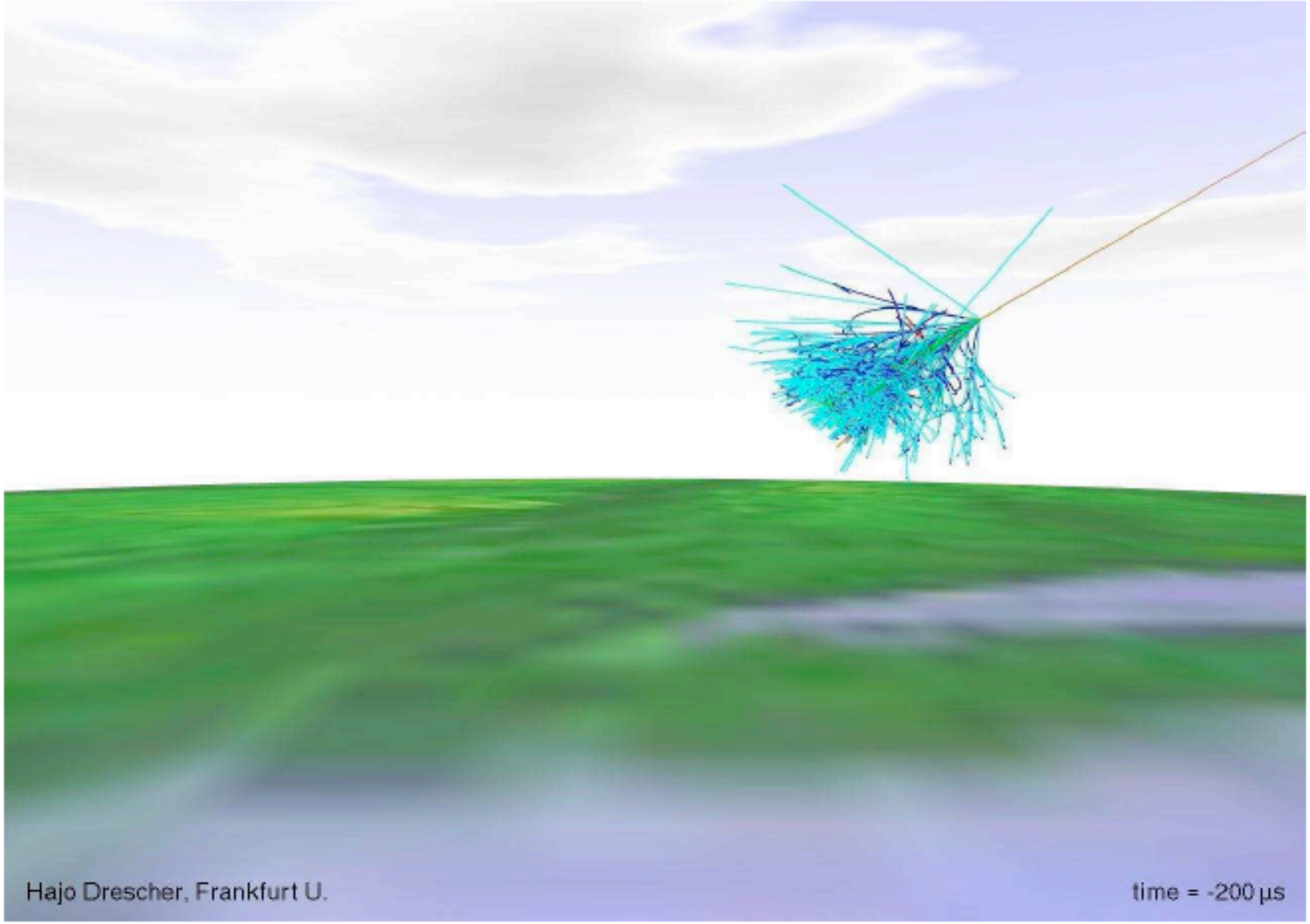
Gammas; Electrons + Positrons; Muons; Hadrons

Ultra High Energy Cosmic Rays



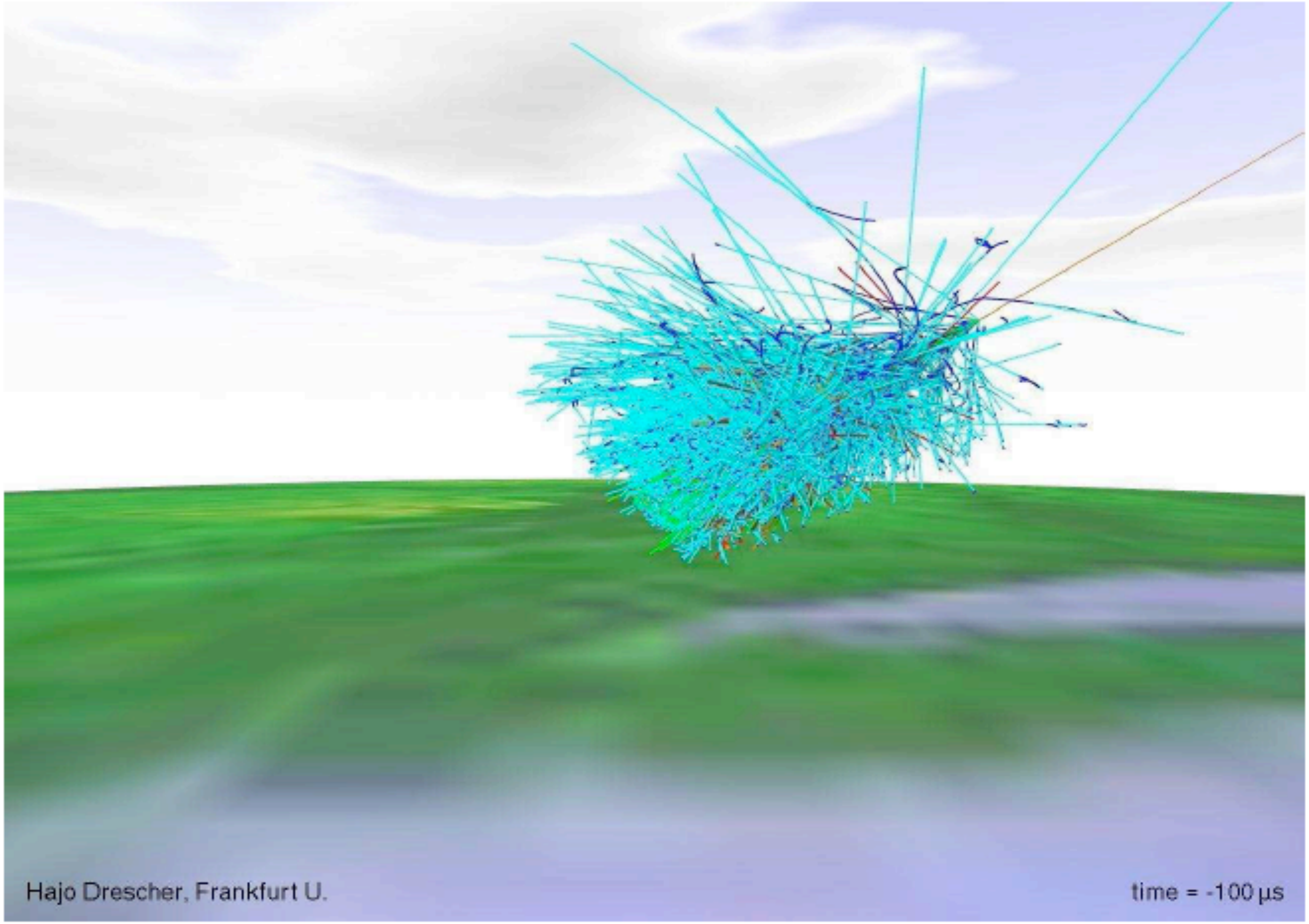
Gammas; Electrons + Positrons; Muons; Hadrons

Ultra High Energy Cosmic Rays



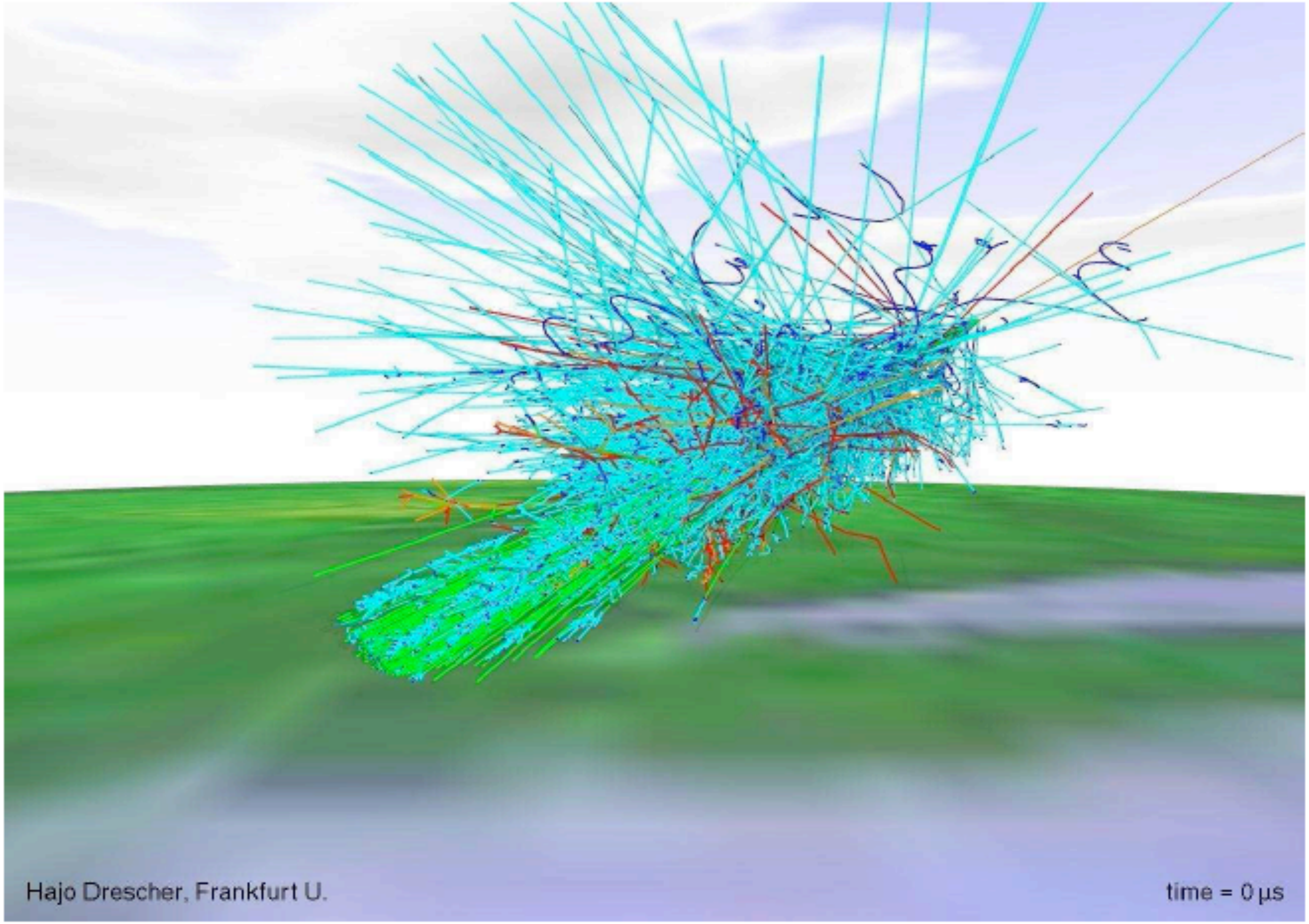
Gammas; Electrons + Positrons; Muons; Hadrons

Ultra High Energy Cosmic Rays



Gammas; Electrons + Positrons; Muons; Hadrons

Ultra High Energy Cosmic Rays



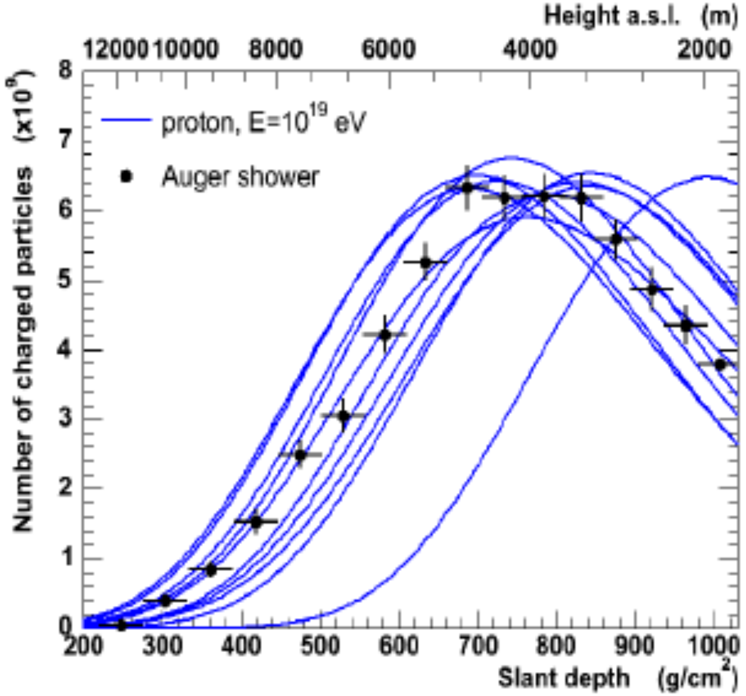
Hajo Drescher, Frankfurt U.

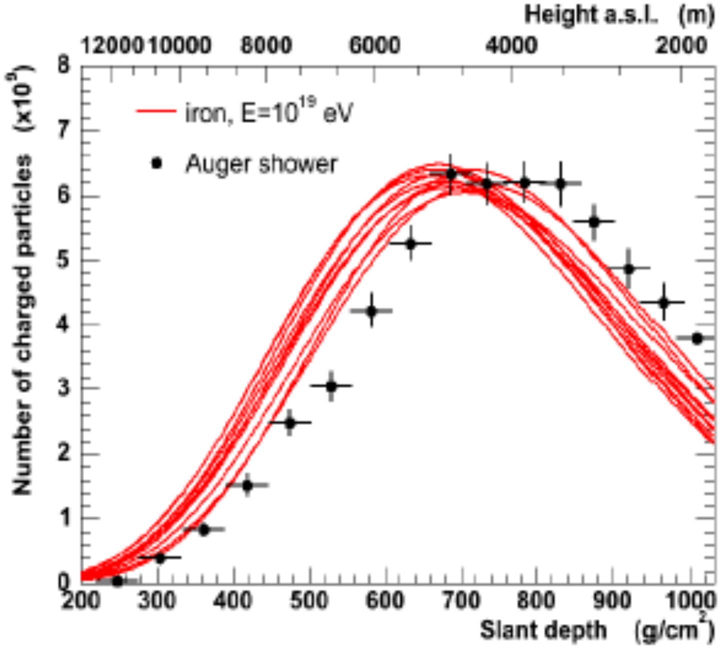
time = 0 µs

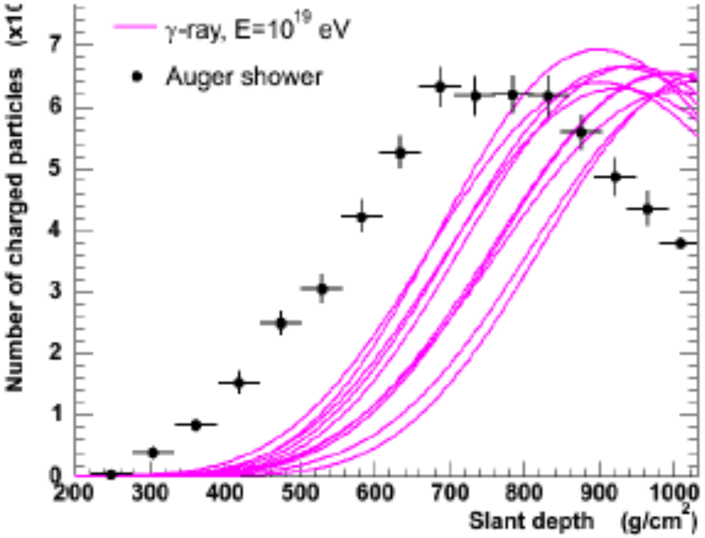
Gammas; Electrons + Positrons; Muons; Hadrons

Energy/composition: shower profile

Detailed MC simulation: 10 showers
zenith angle 35°, QGSJET



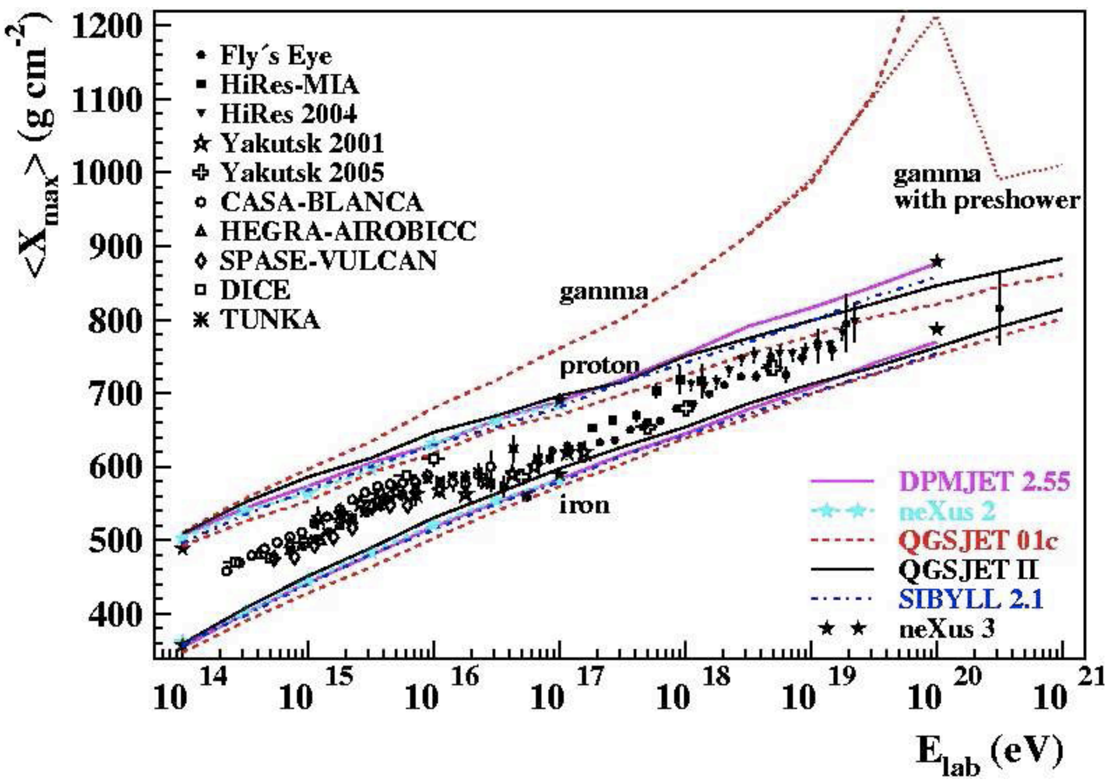




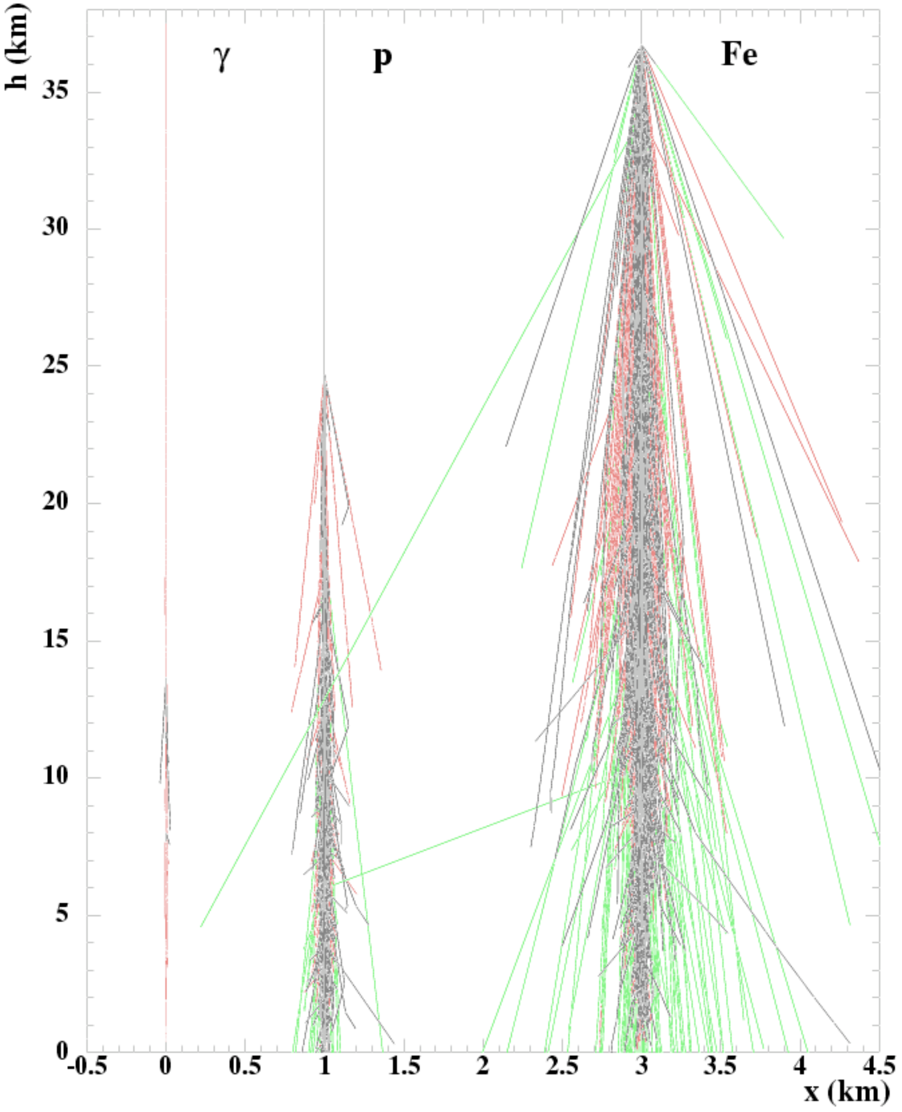
(Courtesey: Johannes Knapp)

$$N^{A}_{max} = N_{max}, \qquad X^{A}_{max} \sim \lambda_{e} \ln(E_0/A)$$

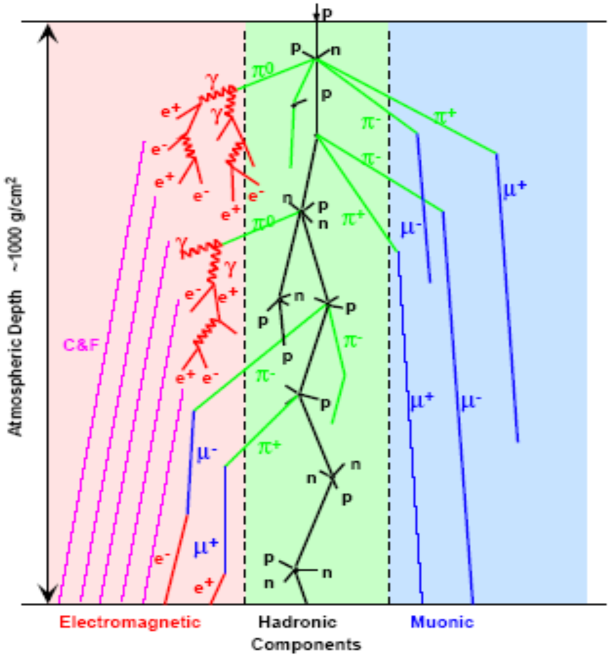
Can discriminate between hadrons and photons … harder to distinguish between p and Fe nuclei



To determine the chemical composition of UHE cosmic rays we rely presently on Monte Carlo simulations … many ongoing attempts to quantify shower variables that correlate with the identity of the primary



Shower Development



Fluorescence & (isotropic)
Cherenkov-Light (forward peaked)

p, n, π : near shower axis
μ, e, γ : widely spread

e, γ : from π^0, μ decays ~ 10 MeV
μ : from $\pi^\pm$, K, ... decays ~ 1 GeV

$N_{e,\gamma} : N_\mu$ ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

Details depend on:
interaction cross-sections,
hadronic and el.mag. particle production,
decays, transport, ...
at energies well above man-made accelerators

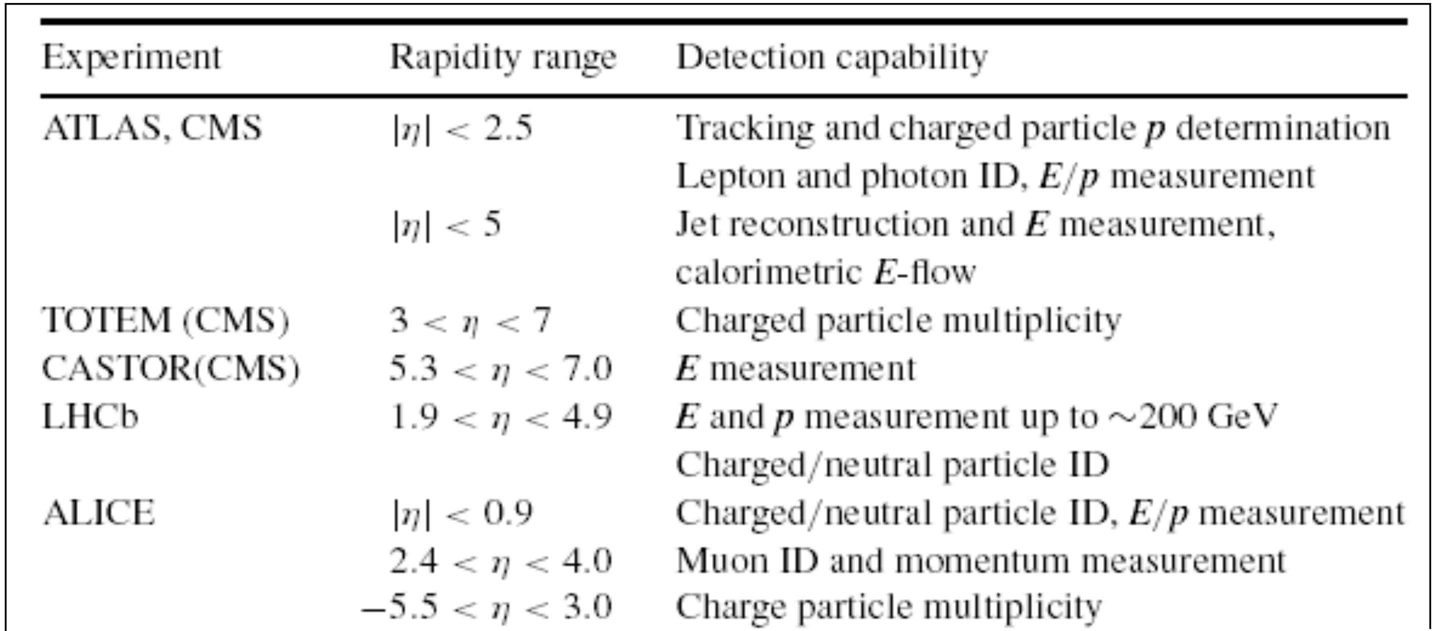
Complex interplay with many correlations
requires MC simulations

(Courtesey: Johannes Knapp)

Main sources of uncertainty

- Minijet cross-section (parton densities, range of applicability)
- Transverse profile function (total #-secn, multiplicity distribution)
- Energy dependence of leading particle production
- Role of nuclear effects (saturation, stopping power, QGP)

Expect important input from LHC experiments (CASTOR, TOTEM, LHCf …)

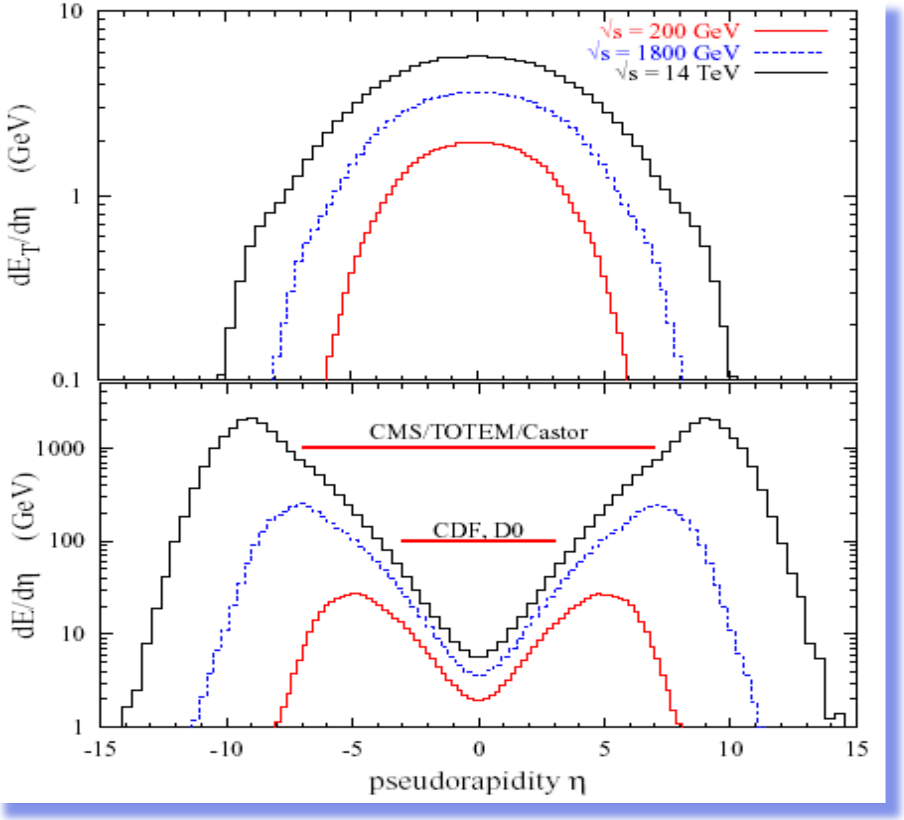


Experiment	Rapidity range	Detection capability
ATLAS, CMS	$\|\eta\| < 2.5$	Tracking and charged particle p determination Lepton and photon ID, E/p measurement
	$\|\eta\| < 5$	Jet reconstruction and E measurement, calorimetric E-flow
TOTEM (CMS)	$3 < \eta < 7$	Charged particle multiplicity
CASTOR(CMS)	$5.3 < \eta < 7.0$	E measurement
LHCb	$1.9 < \eta < 4.9$	E and p measurement up to ~200 GeV Charged/neutral particle ID
ALICE	$\|\eta\| < 0.9$	Charged/neutral particle ID, E/p measurement
	$2.4 < \eta < 4.0$	Muon ID and momentum measurement
	$-5.5 < \eta < 3.0$	Charge particle multiplicity
	$2.3 < \eta < 3.5$	Photon multiplicity

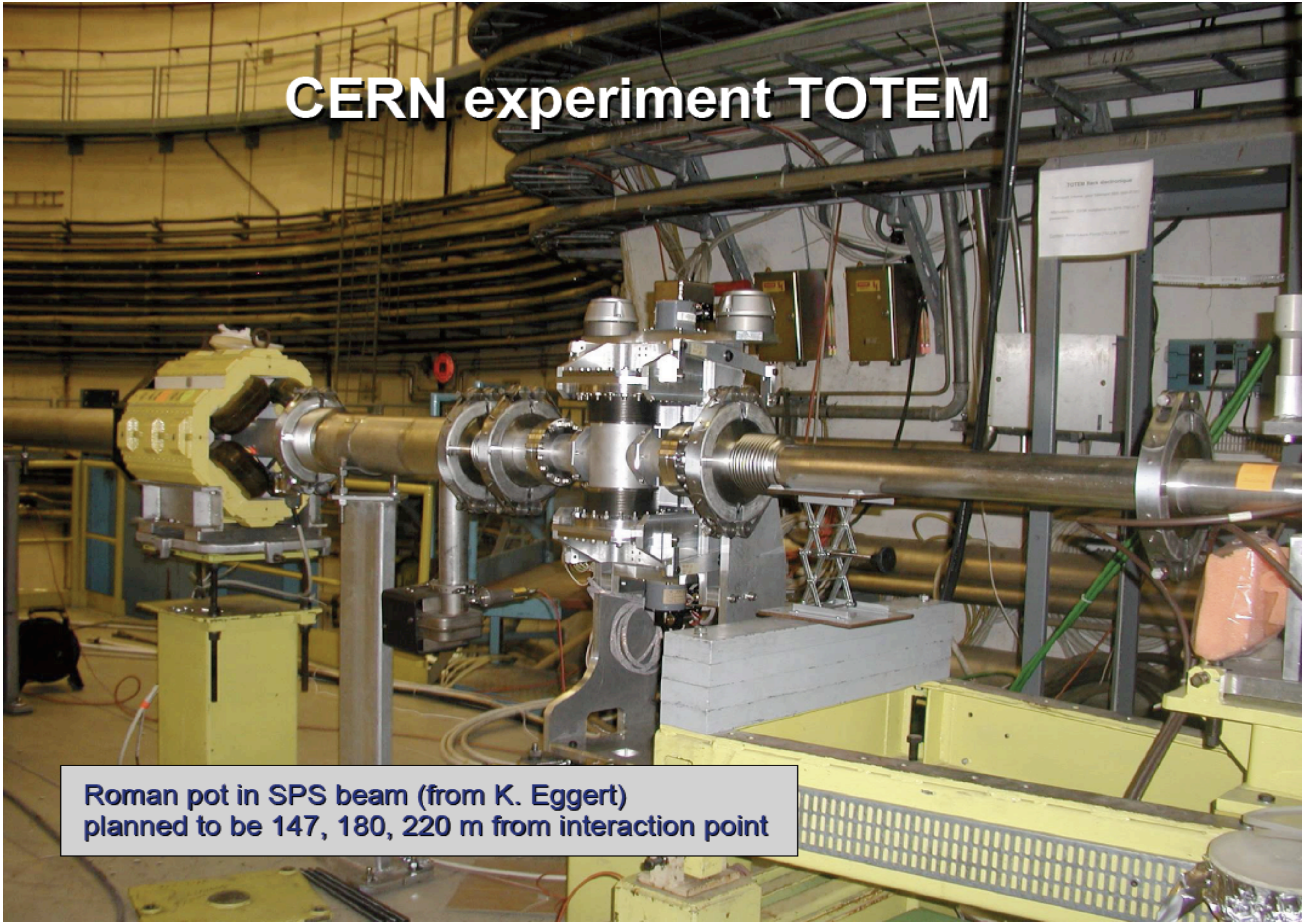
However collider experiments focus mainly on high p_T events, in contrast to the *very* forward region of interest to cosmic ray physics

The kinematic region most relevant to cosmic ray shower models is $|\eta| > 10$ … this will *not* be probed even at the LHC

However, CASTOR/CMS/TOTEM/LHCf will perform crucial tests of popular shower MCs (QGSJET, SIBYLL, DPMJET, NeXus …)

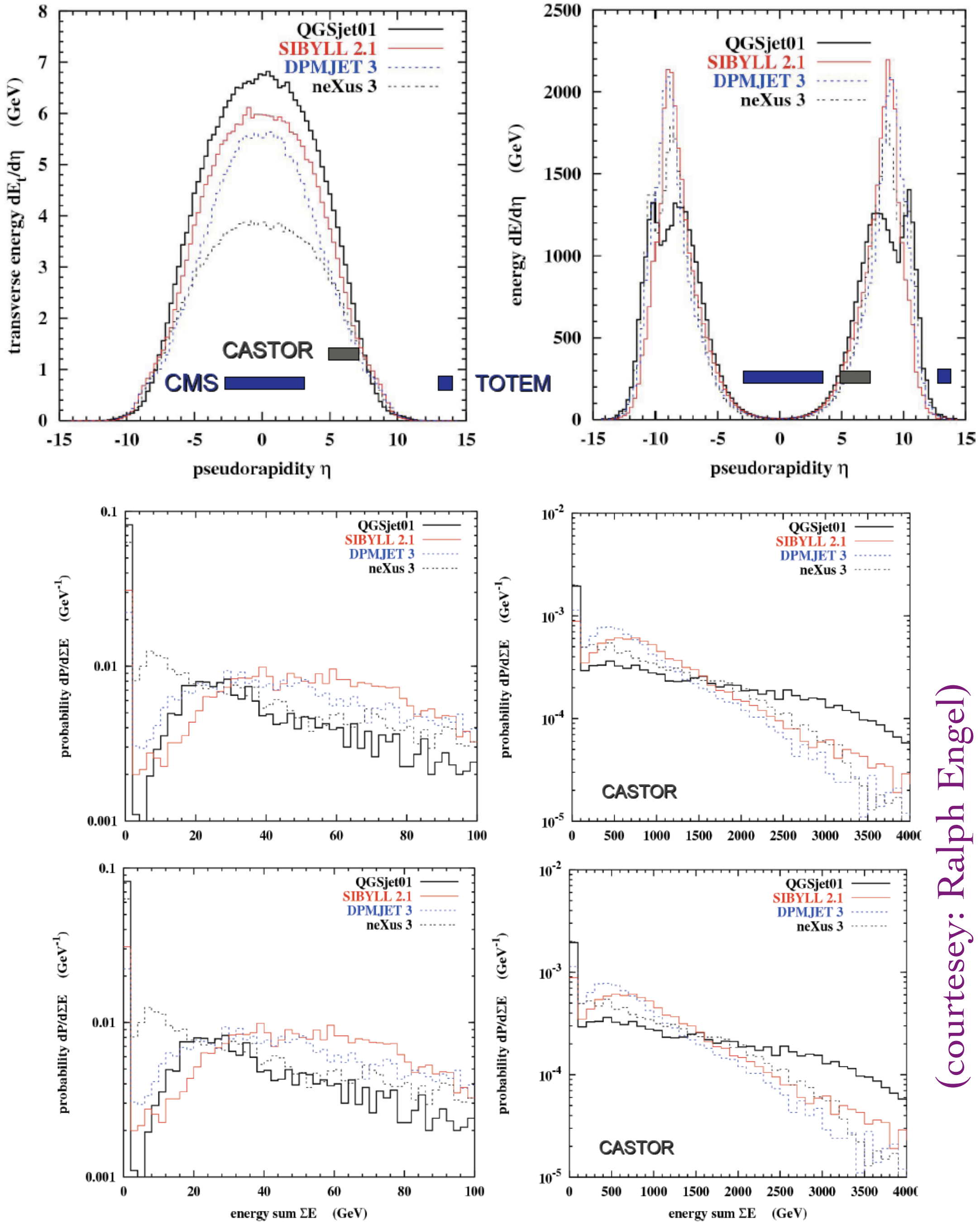


CERN experiment TOTEM



Roman pot in SPS beam (from K. Eggert)
planned to be 147, 180, 220 m from interaction point

Tests of air shower simulation models to be performed by LHC experiments

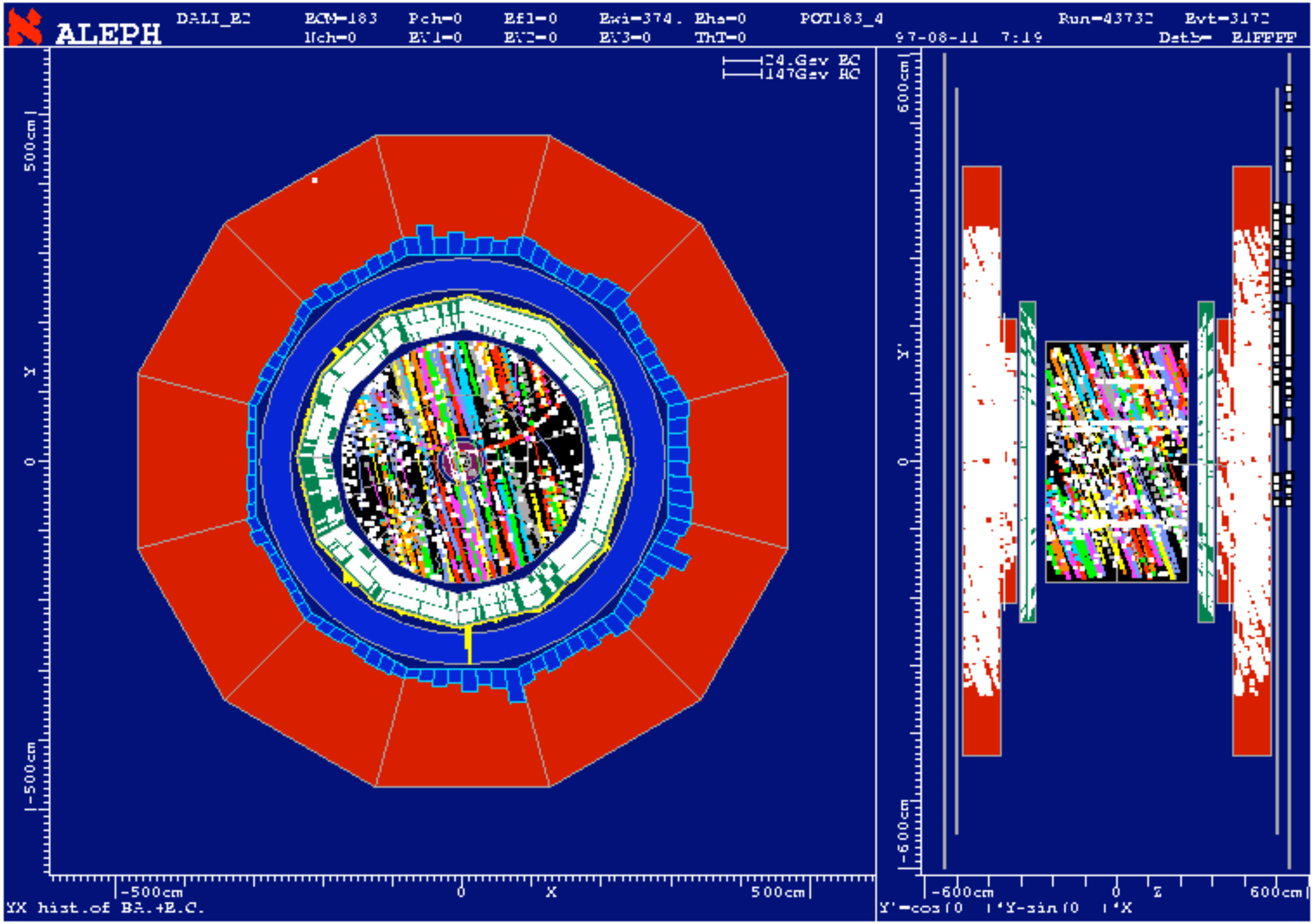


Central detector: -3 < η < 3

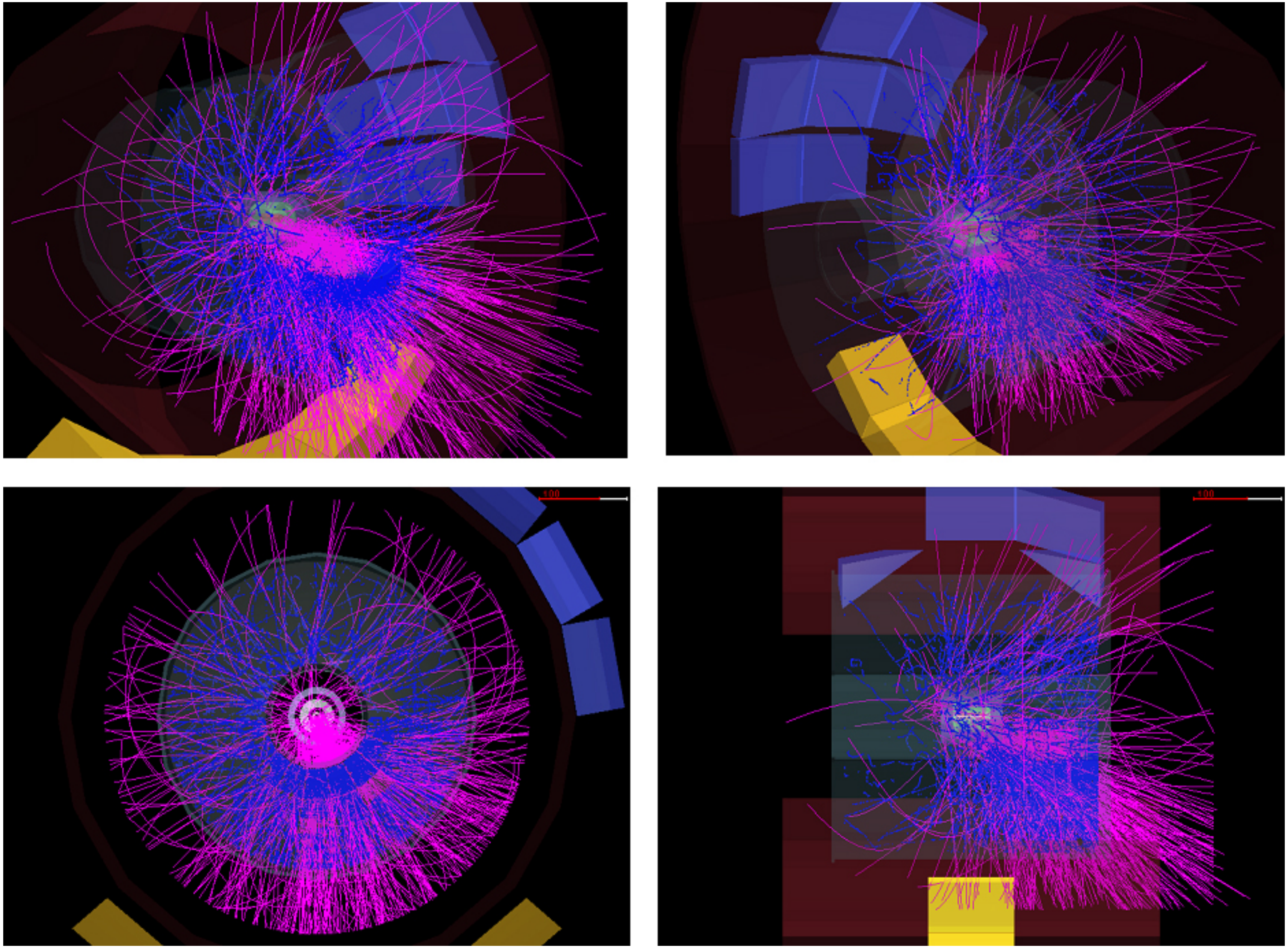
Forward detector: 5 < η < 7

(courtesey: Ralph Engel)

This is what a PeV event (⇒TeV cms) looks like in a LEP detector …

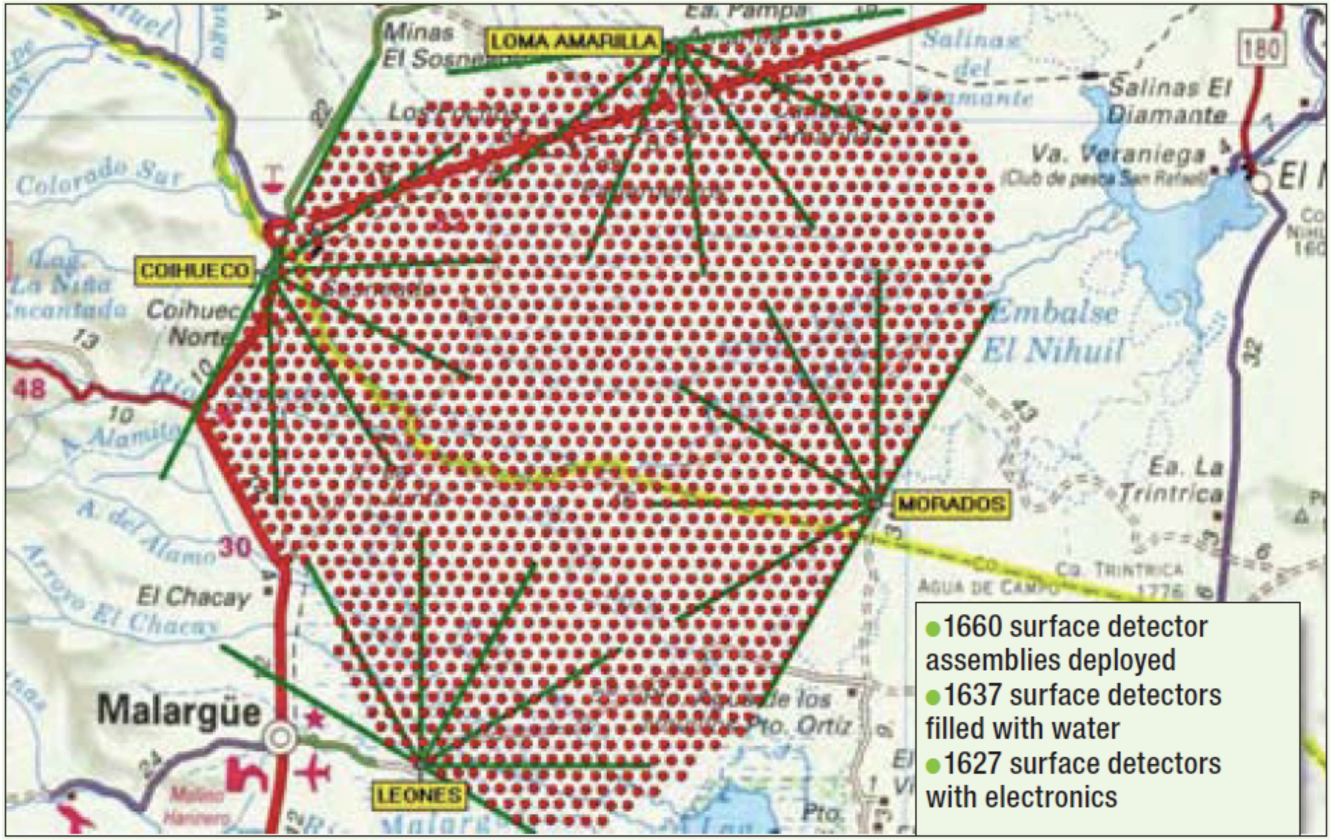


This is what a PeV cosmic ray event (⇒ TeV cms) looks like in a LHC detector

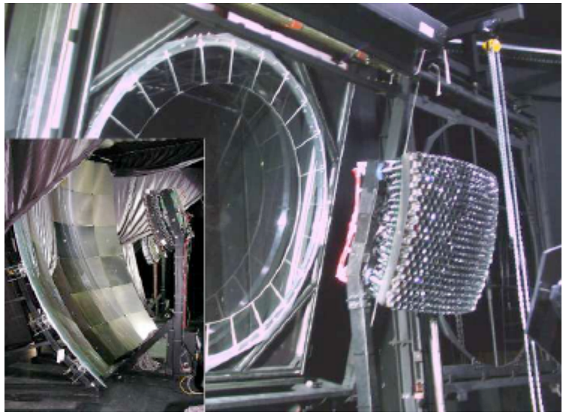


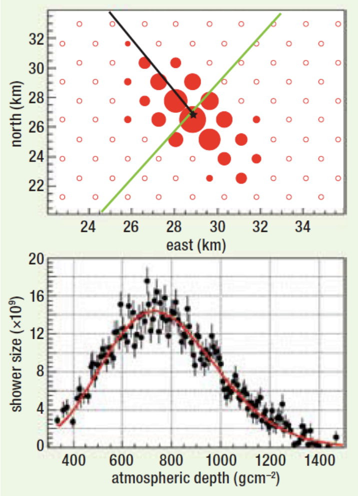
Courtesey: ALICE collaboration, CERN

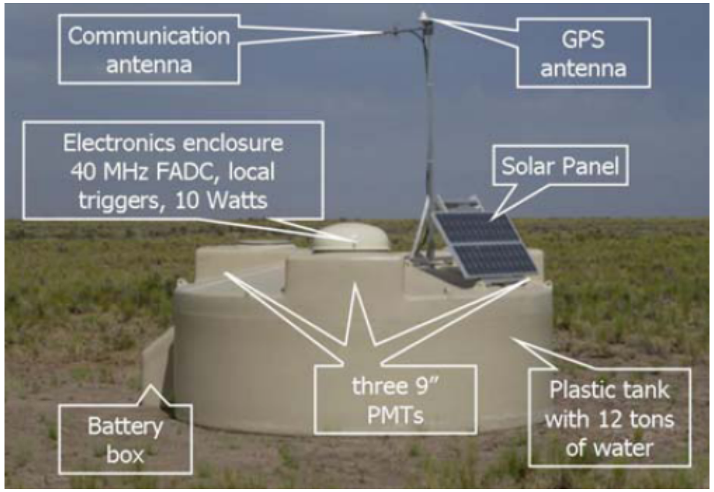
The Pierre Auger Observatory (Malargue, Argentina)



- 1660 surface detector assemblies deployed
- 1637 surface detectors filled with water
- 1627 surface detectors with electronics








75¢
10^{20} eV
OBSERVATORIO PIERRE AUGER MALARGÜE MENDOZA ARGENTINA
REPÚBLICA ARGENTINA
CORREO OFICIAL
2007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DE RAYOS COSMICOS
MENDOZA, 17 DE MARZO DE 1999


RUSSIA
CANADA
UNITED STATES
MEXICO
CHINA
INDIA
BRAZIL
AUSTRALIA
INDONESIA
Antarctica
January 2002

Surface detector array: installation of electronics - Mar 2006

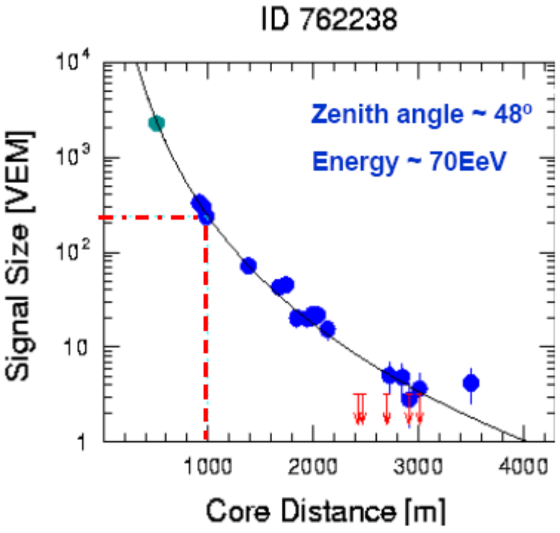
Auger Energy Determination: Step 1

The energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.

The detector signal at 1000 m from the shower core

- called the ground parameter or S(1000)
- is determined for each surface detector event using the lateral density function.

S(1000) is proportional to the primary energy.



For the surface array, the acceptance is simple to calculate and there are lots of events but the energy calibration depends on semi-empirical simulations

For the fluorescence detectors, the acceptance is harder to estimate and the event statistics are low but the energy determination is essentially calorimetric …

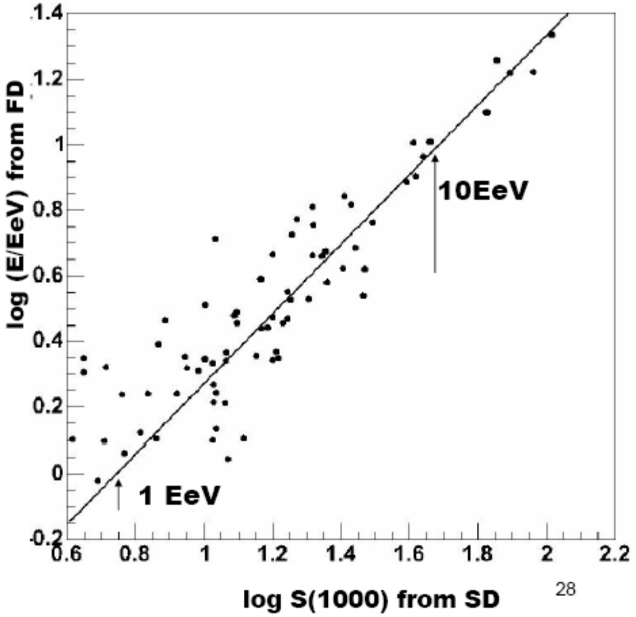
Auger Energy Determination: step 2

Hybrid Events with STRICT event selection:

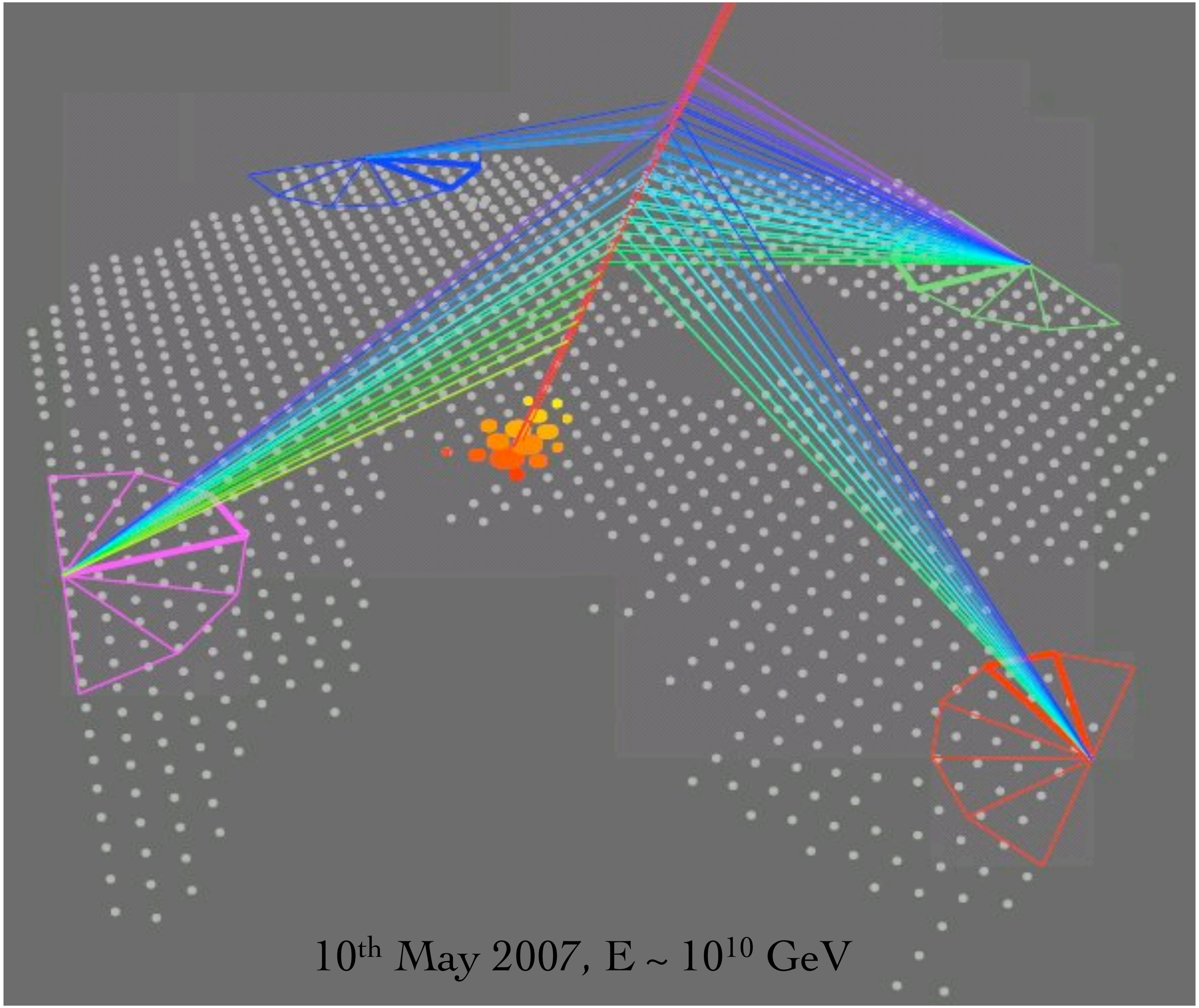
aerosol content measured

track length > 350 g cm^{-2}

Cherenkov contamination $<10\%$

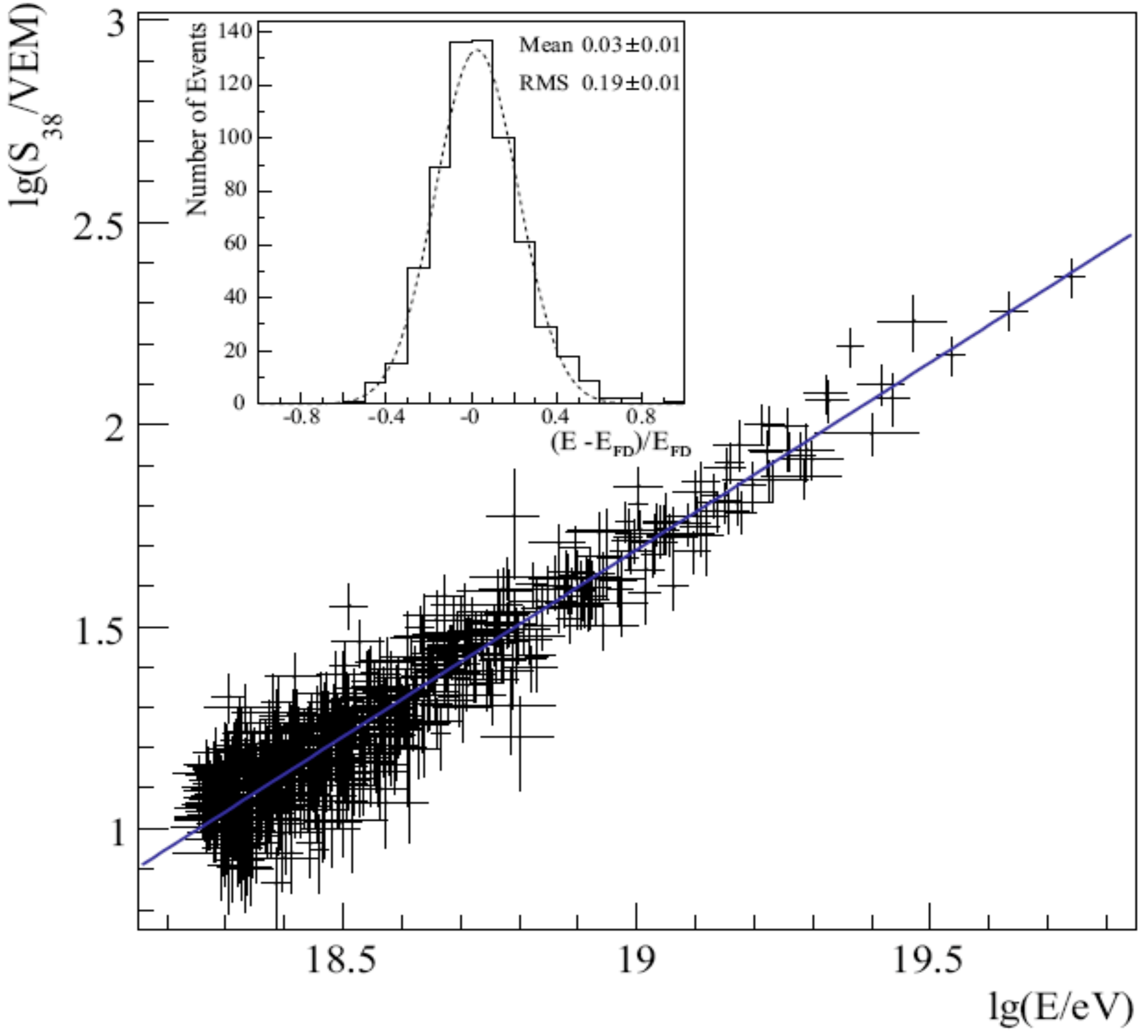


Auger is a *hybrid* detector, combining the advantages of both techniques



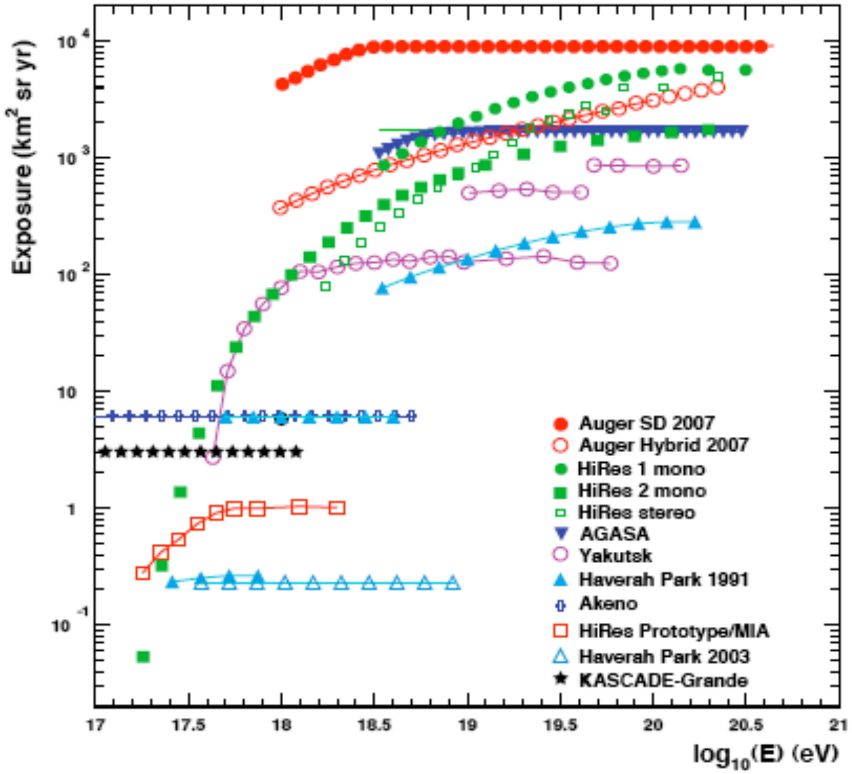
10th May 2007, E ~ 10^{10} GeV

Energy Scale from FD



(Auger collaboration, PRL 101:061101,2008)

Major remaining uncertainty ➔ efficiency of fluorescence light emission
… being re-measured at Argonne (also depends on atmospheric conditions)



Auger has overtaken the cumulative exposure of *all* previous experiments
- it will remain the major facility for UHECR studies into the next decade ...

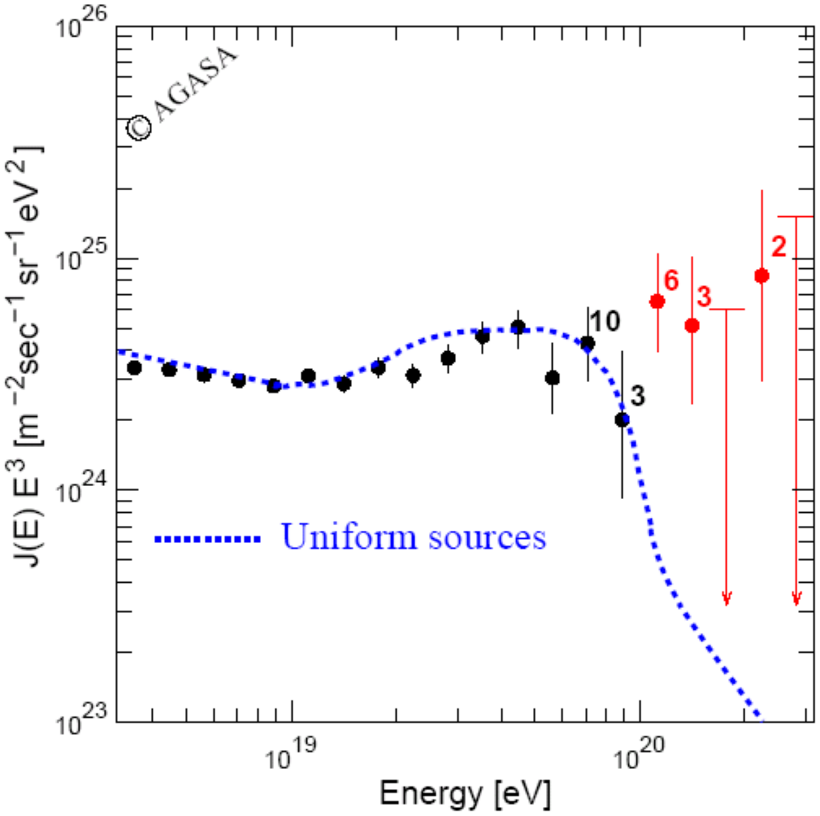
(until the launch of satellite-borne air fluorescence detectors e.g. Super-EUSO)

Experiment	status	km^2 sr yr	# events	
		@ 50 EeV	> 10 EeV	> 50 EeV
Haverah Park	1962-1987	~ 245	106	10
Yakutsk	1974-present	~ 900	171	6
AGASA	1993-2005	1620	886	46
HiRes-I mono	1997-2006	~ 4500	561	31
HiRes-II mono	1999-2006	~ 1500	179	12
HiRes stereo	1999-2006	~ 2400	270	11
Auger	2004- (Feb'09)	~ 13500	1644	38
TA	2007-present	860×yrs		

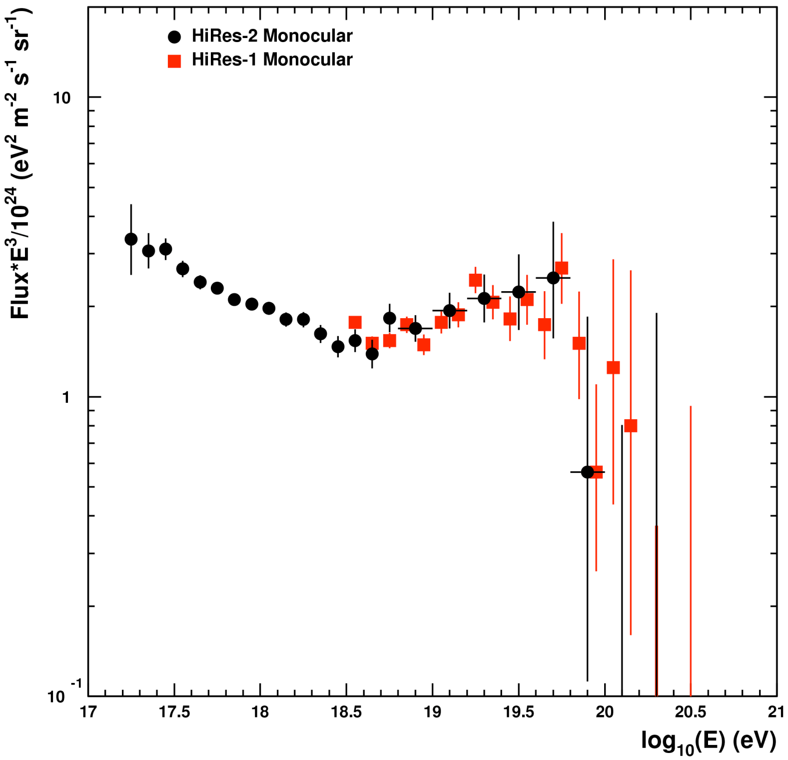
Where is the GZK cutoff?

$$
\begin{array}{l}
\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow\; p + e^{-} + \bar{\nu}_e \\
p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+} \\
\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow \mu^{+} + \nu_{\mu} \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow\; e^{+} + \nu_e + \bar{\nu}_{\mu}
\end{array}
$$

AGASA spectrum continues smoothly!



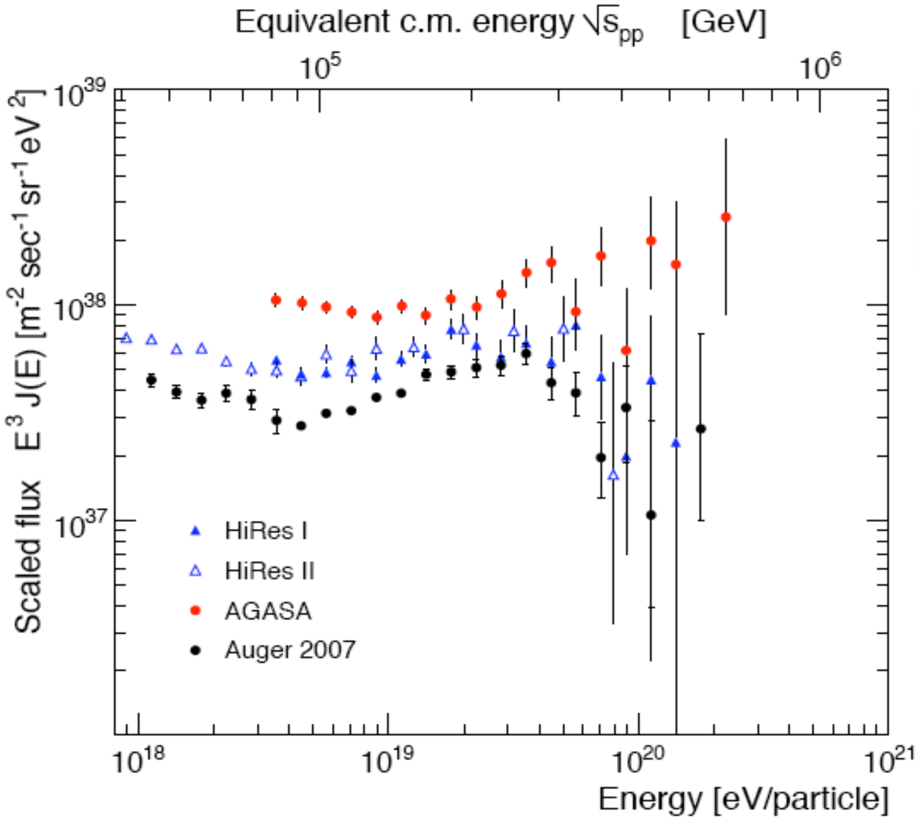
… but HiRes sees expected suppression

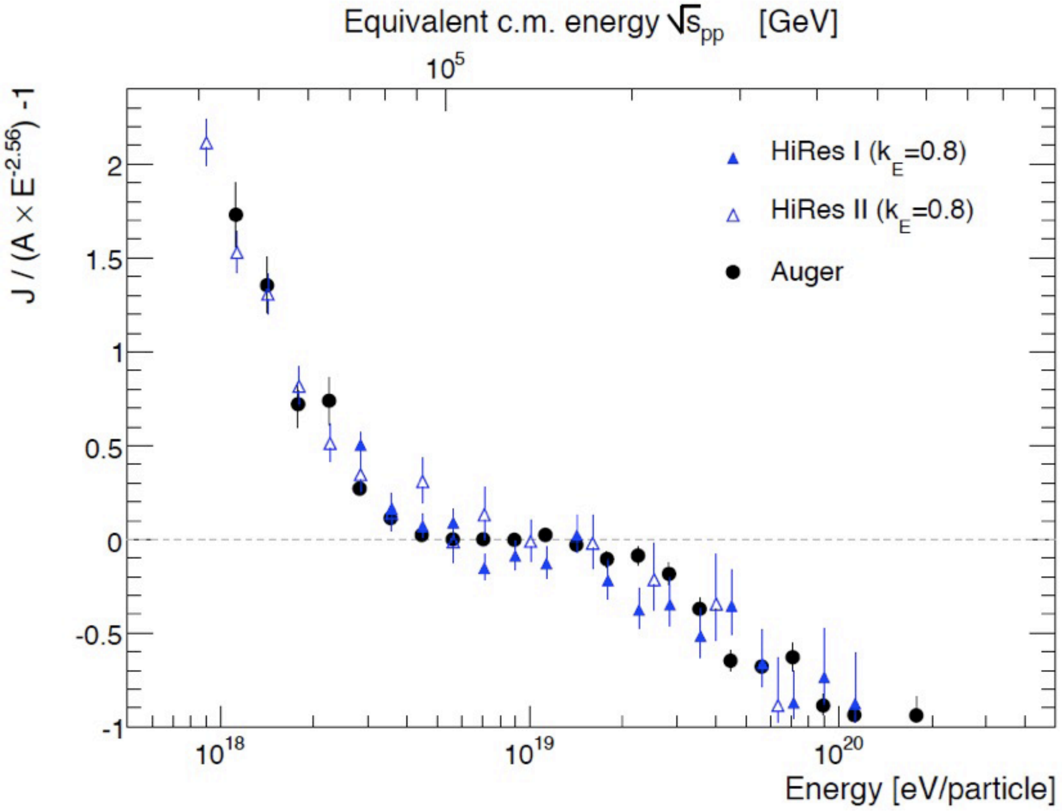


Is there a ~25% energy calibration mismatch between surface arrays and air fluorescence detectors?

Auger has now resolved the puzzle … the flux *is* suppressed beyond E_{GZK}

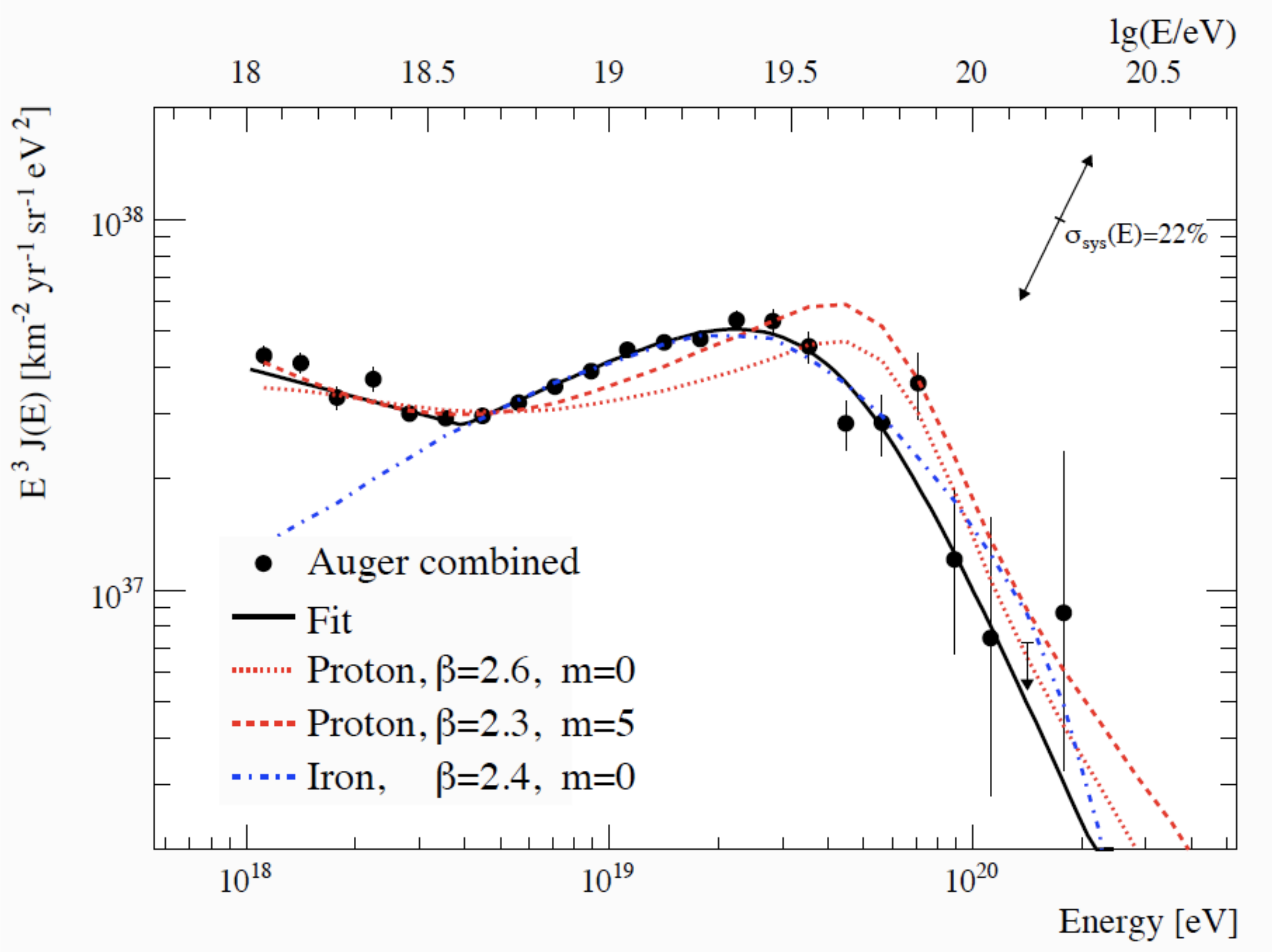
Hence the sources of ultra high energy cosmic rays must be extragalactic





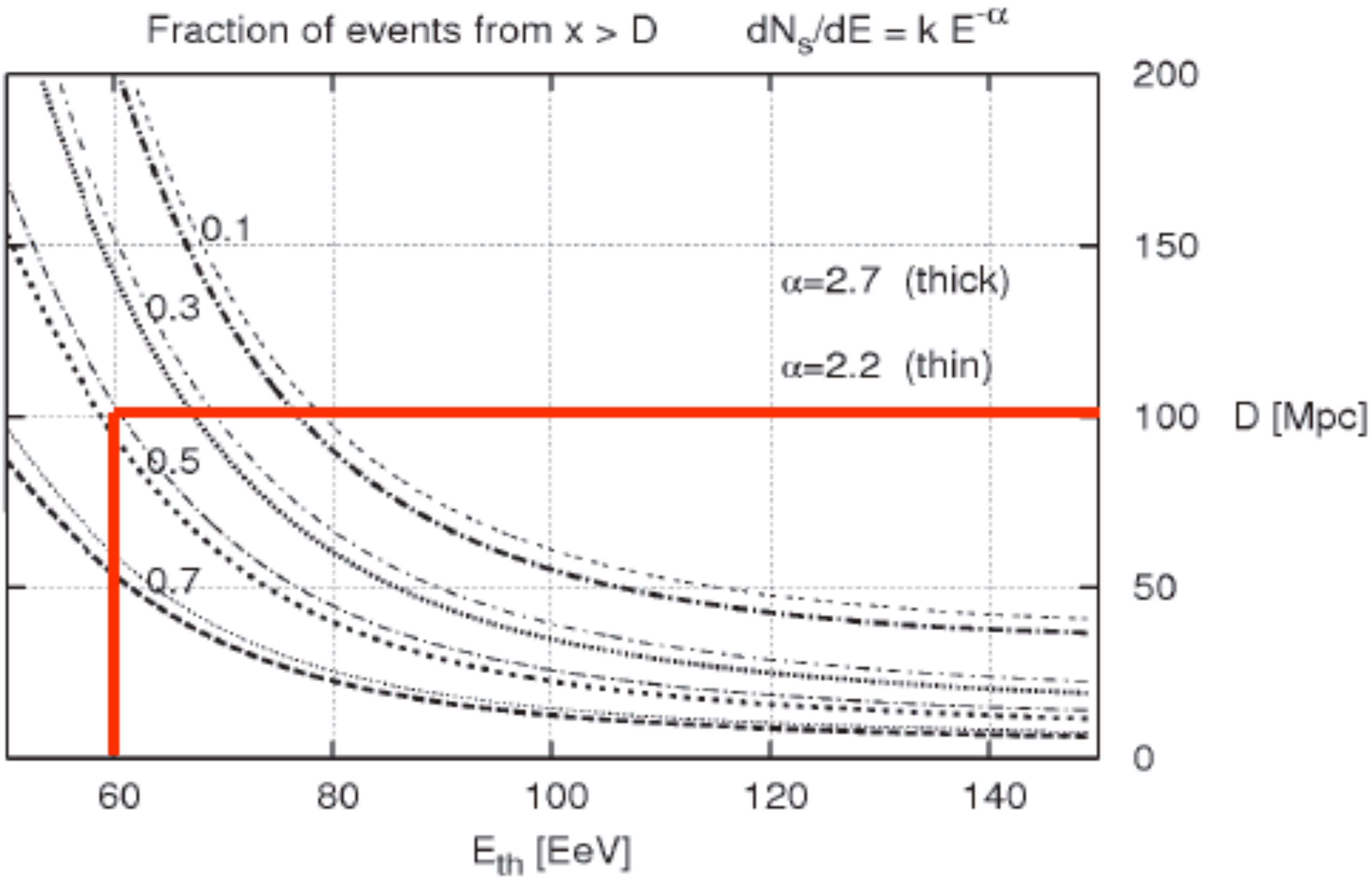
Measurement of the spectral shape near the cut-off will, with sufficient statistics, establish whether this is indeed the 'GZK suppression' (presently the spectrum is also consistent with heavy primary nuclei undergoing photodissociation on the CIB)

Present data on the energy spectrum *cannot* distinguish between primary protons (with source density evolving with redshift as $(1+z)^5$) and nuclei (no evolution)



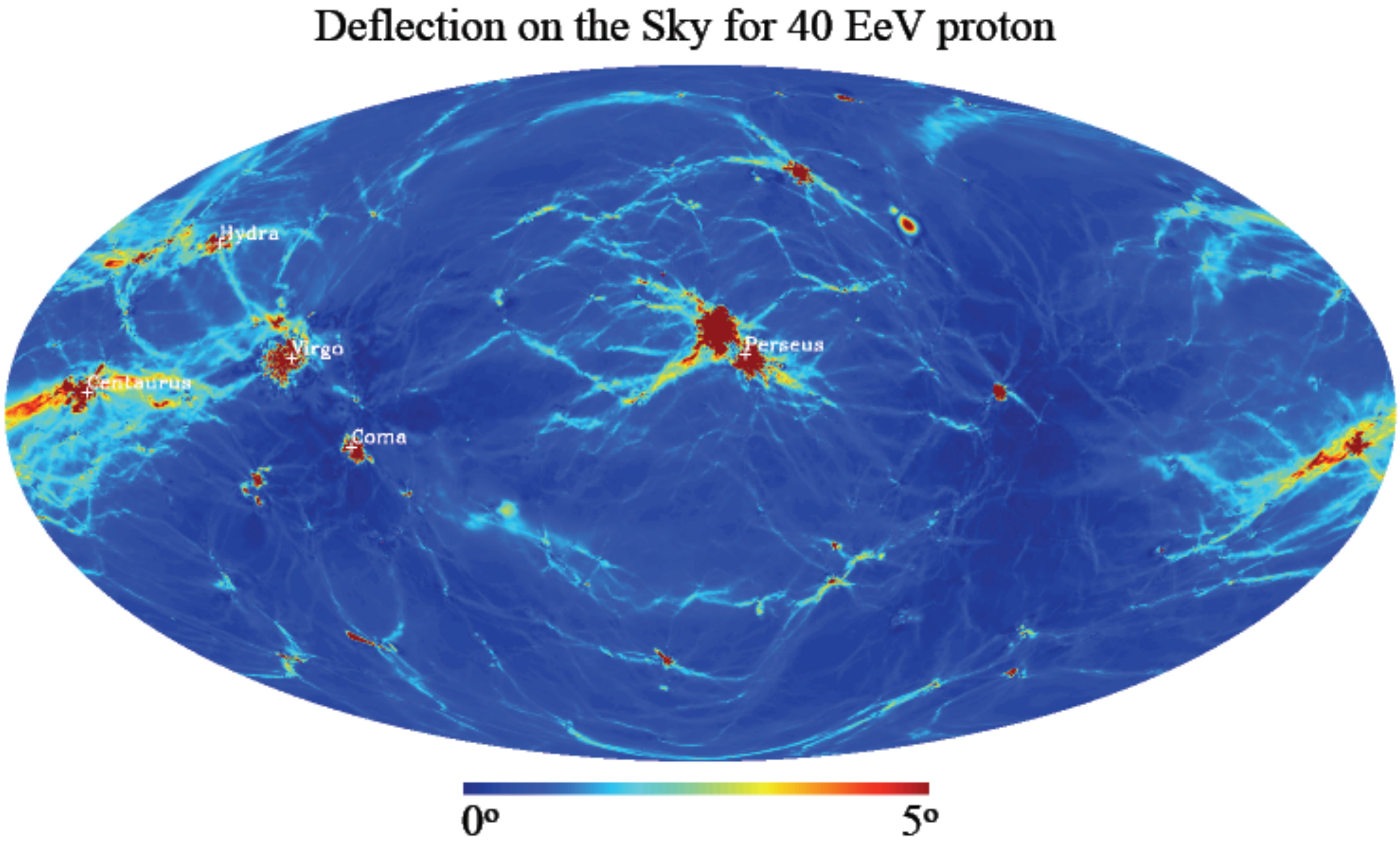
… the 'cosmogenic' neutrino flux is however quite different in the two cases

At these high energies the sources must be *nearby* … within the ‘GZK horizon’



This is true whether the primaries are protons or heavy nuclei …

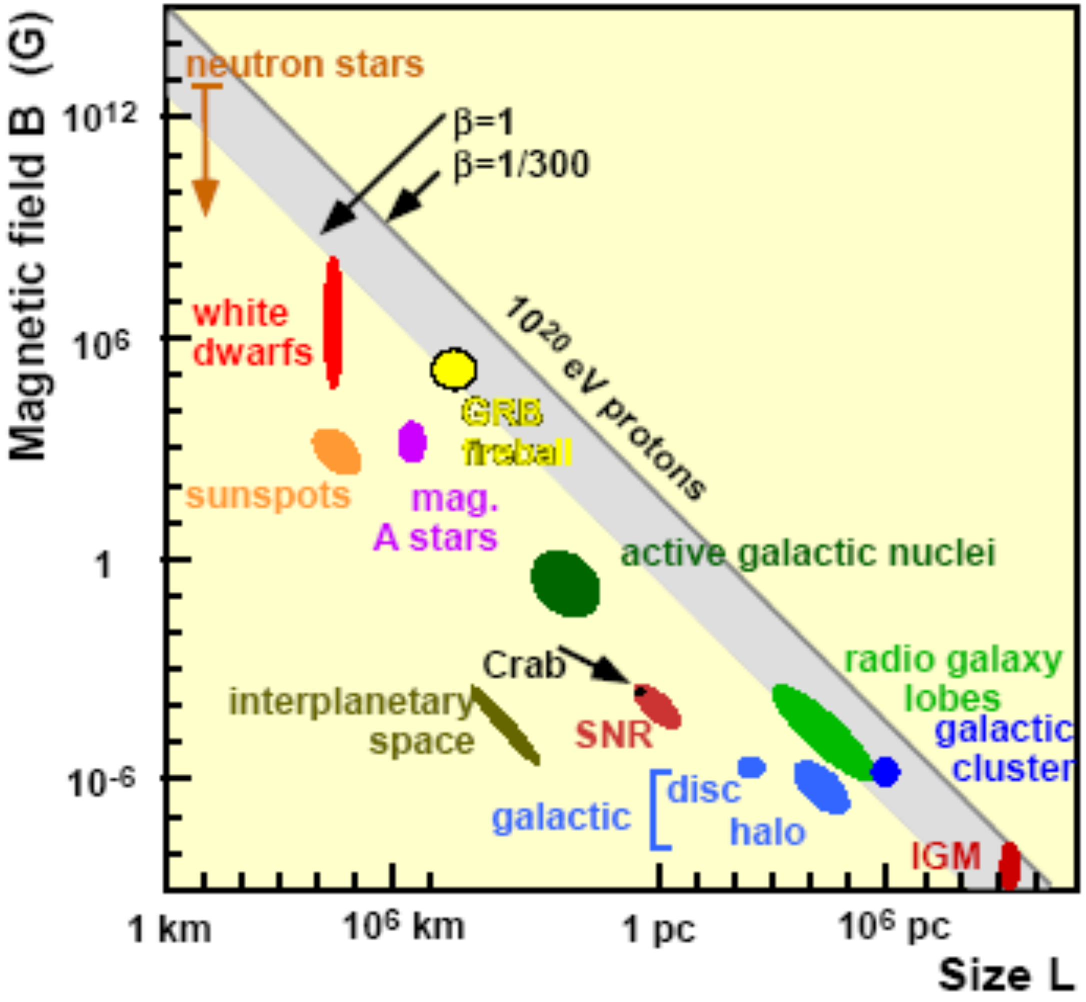
So we should be able to see which objects the UHECRs *point back* to …



‘Constrained’ simulation of local large-scale structure including magnetic fields suggests that deflections are small, except in the cores of rich galaxy clusters

Dolag, Grasso, Springel & Tkachev, JCAP 0501:009,2005

Are there any plausible cosmic accelerators for such enormous energies?



A.M. Hillas 1984

(Courtesey: Johannes Knapp)

$B_{\mu G} \times L_{kpc} > 2\, E_{EeV} / Z$

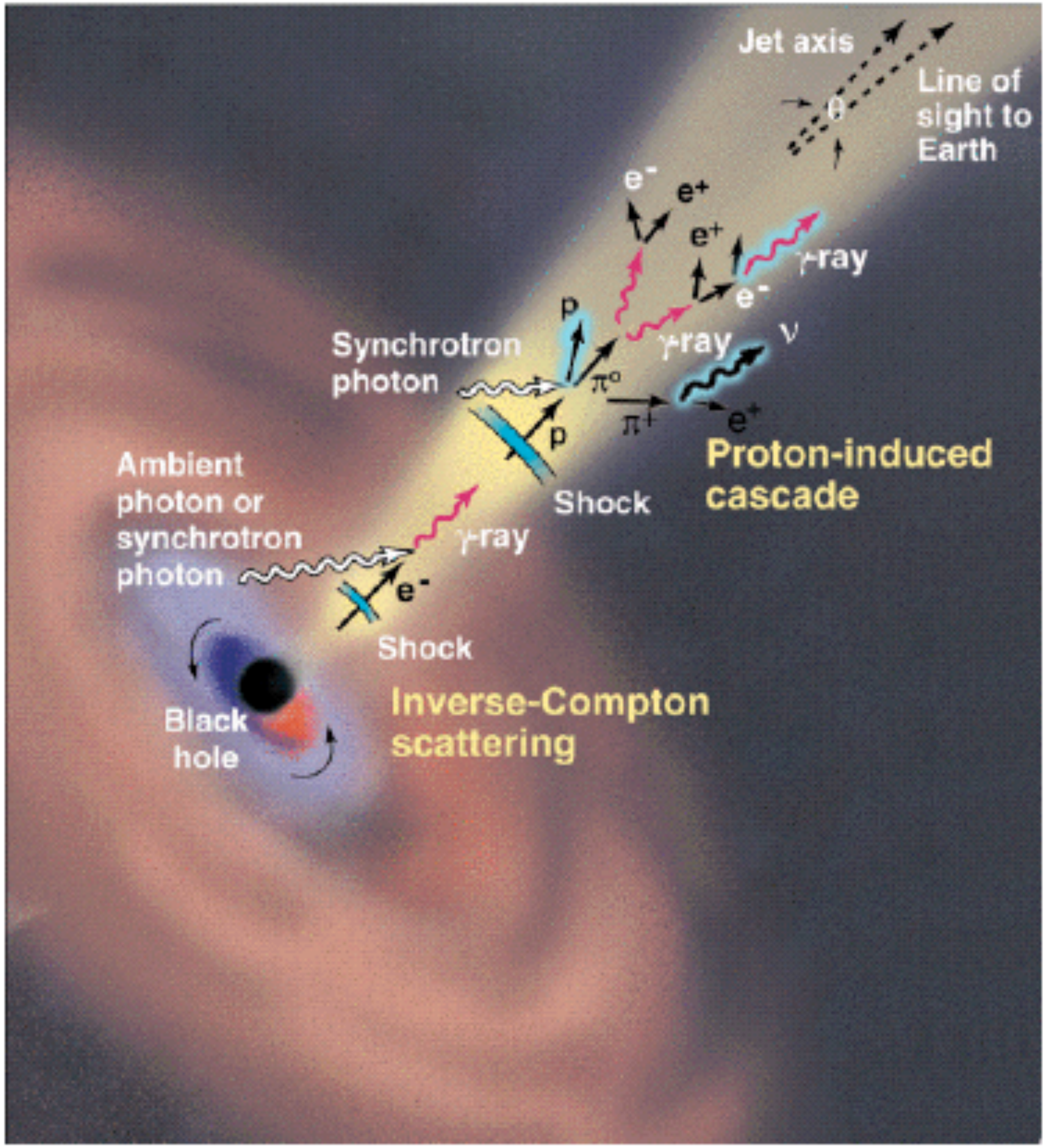
$B_{\mu G} \times L_{kpc} > 2\, (c/v)\, E_{EeV} / Z$

to fit gyro radius within L and to allow particle to wander during energy gain

But also:
gain should be more rapid than losses due to magnetic field (synchrotron radiation) and photo-reactions.

NB: It is much easier to accelerate heavy nuclei, rather than protons

Whatever their sources (within the GZK 'horizon' of ~100 Mpc), the observed UHECRs should point back to them, *if* magnetic deflections are not too large



Active galactic nuclei

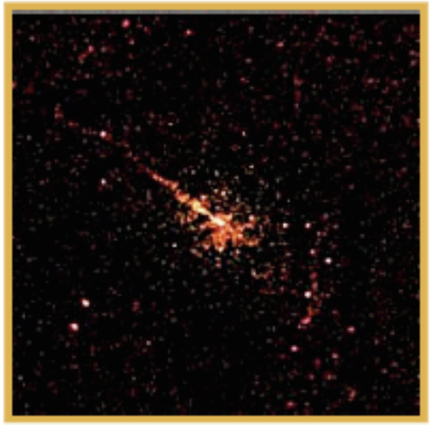
- Current paradigm:
  - **Synchrotron Self Compton**
  - External Compton
  - Proton Induced Cascades
  - Proton Synchrotron
- Energetics, mechanism for jet formation and collimation, nature of the plasma, and particle acceleration mechanisms are still poorly understood.

TeV γ-rays have been seen from AGN, however no *direct* evidence so far that protons are accelerated in such objects

… renewed interest triggered by possible correlations with UHECRs - e.g. 2 Auger events within 3^0 of Cen A

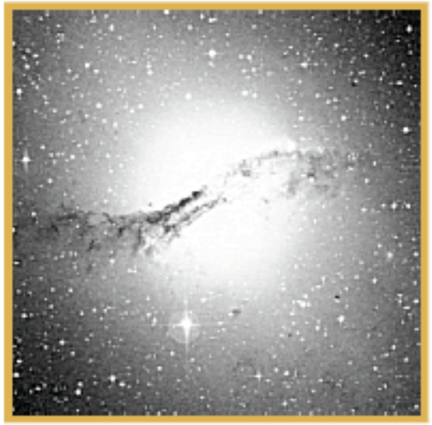
Centaurus A – Peculiar Galaxy

Distance: 11,000,000 ly light-years (3.4 Mpc) Image Size = 15 x 14 arcmin Visual Magnitude = 7.0



X-Ray: Chandra

Ultraviolet: GALEX

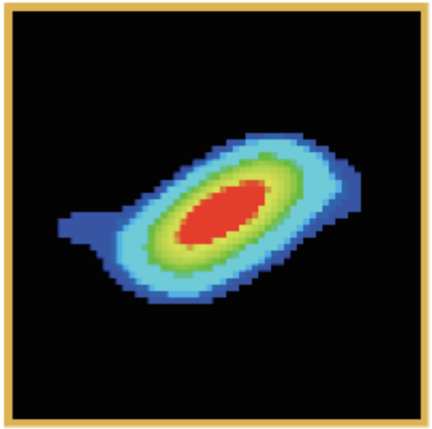


Visible: DSS

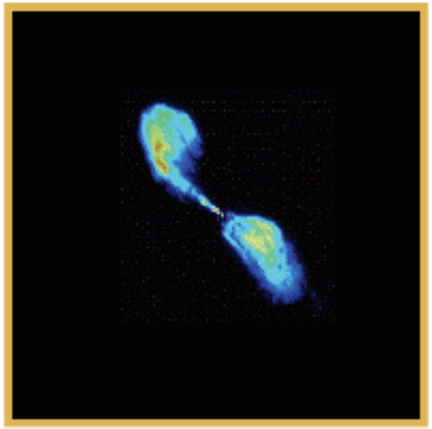
Visible: Color ©AAO

Near-Infrared: 2MASS

Mid-Infrared: Spitzer



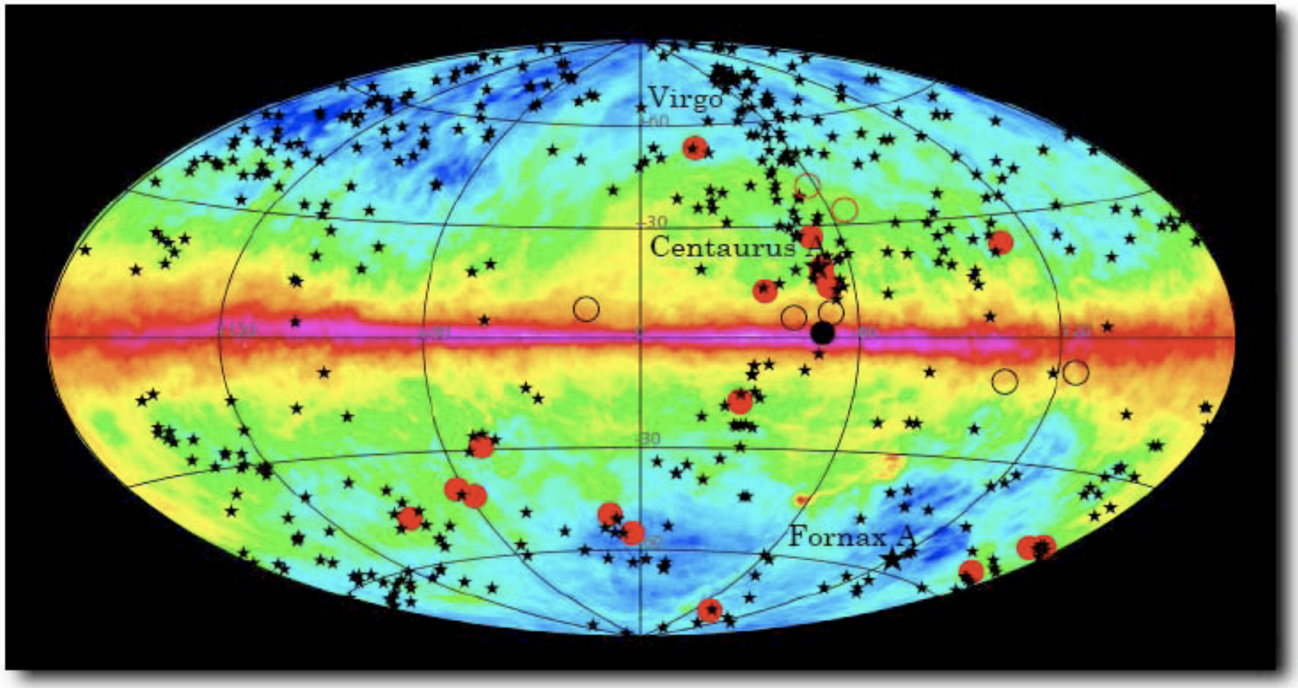
Far-Infrared: IRAS

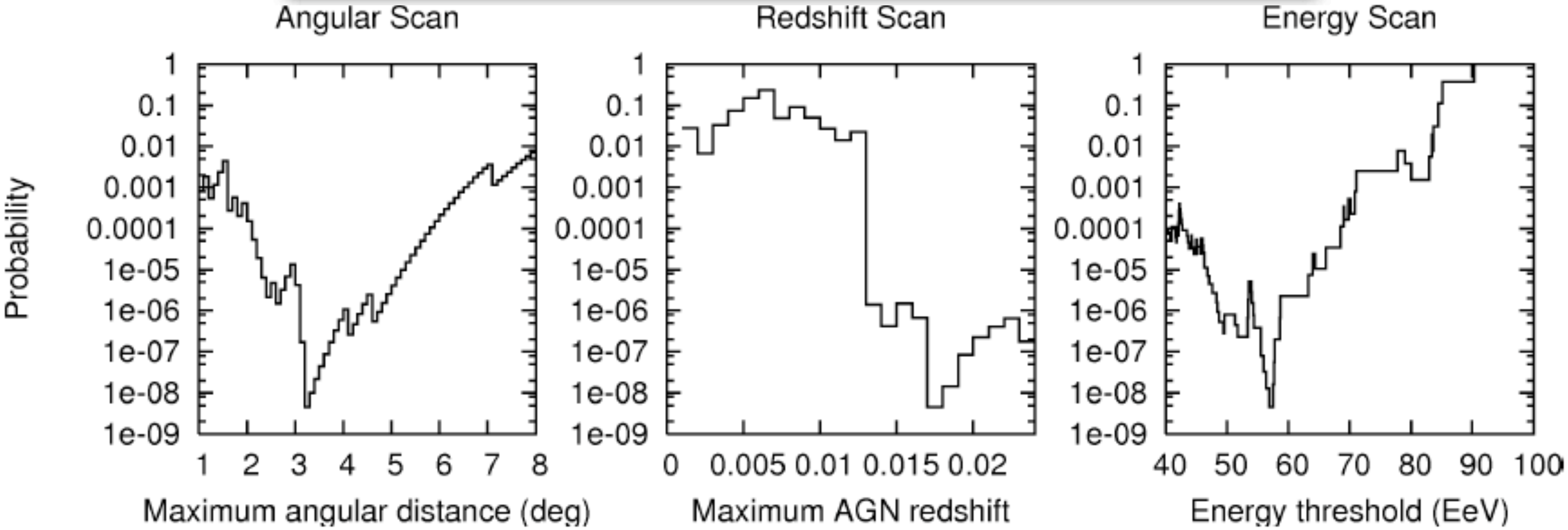


Radio: VLA

What would it look like when ‘seen’ in ultrahigh energy cosmic rays or neutrinos?

The UHECR arrival directions do correlate with nearby AGN!

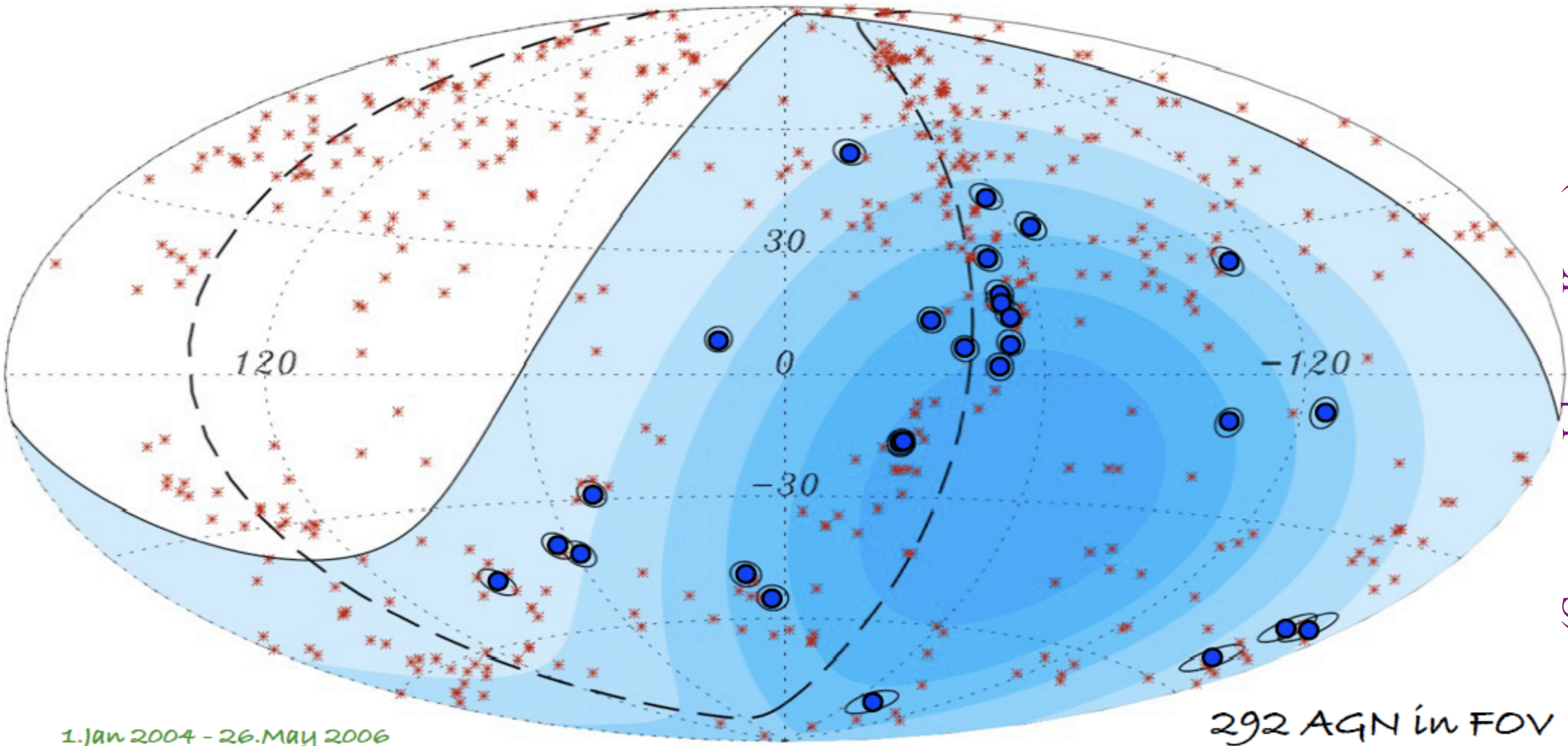



Angular Scan

Redshift Scan

Energy Scan

The observed correlations imply that the deflections are small i.e. that the primaries are protons …



(Courtesey: Johannes Knapp)

1.Jan 2004 - 26.May 2006

scan: 15 evts, 12 correlate with AGN (3.2 exp.) for $R<3.1°$, $z < 0.018$, $E > 56$ EeV

no scan: 13 evts, 8 correlate with AGN (2.7 exp.) independent sample

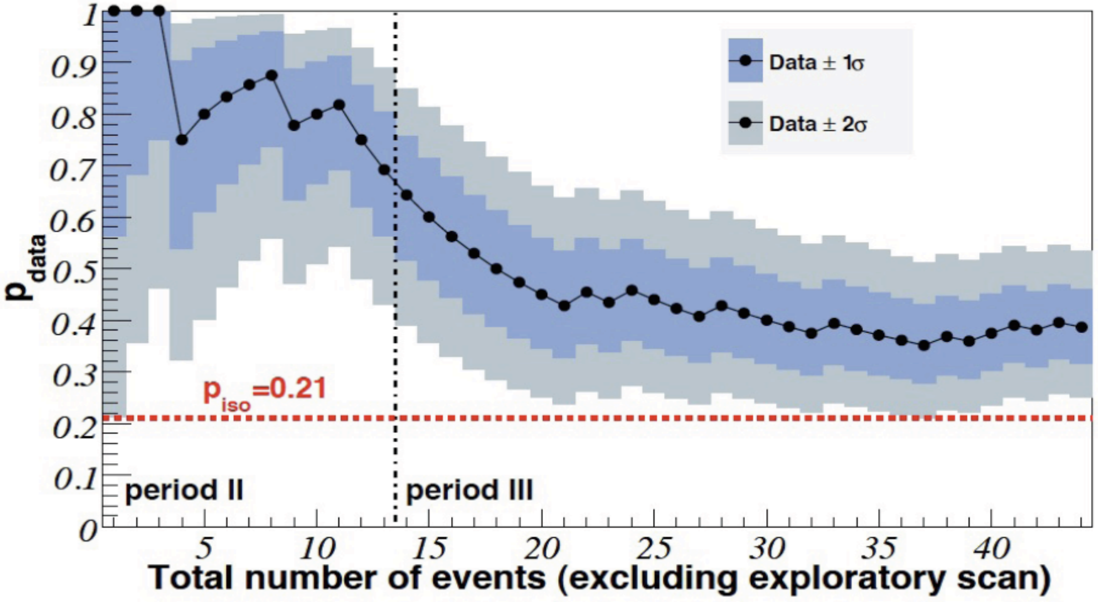
27.May 2006 - 31.Aug 2007

$p \approx 0.21$ $P < 1.7 \times 10^{-3}$

total data: 1.2 Auger-years

UHECR isotropy is rejected with > 99% confidence level, are of extragalactic origin.

Science 318 (2007) 938

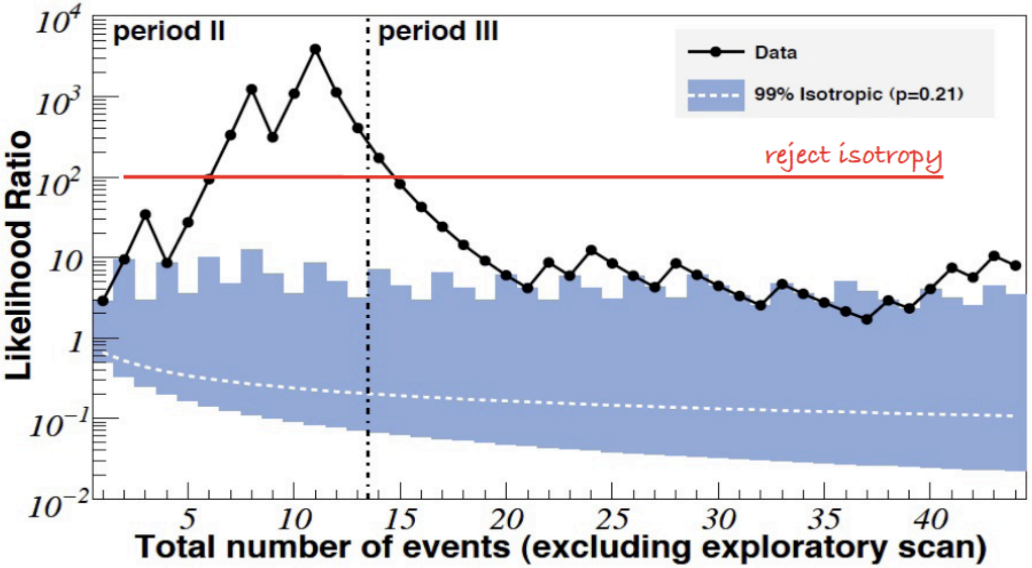


But subsequently the strength of the correlations has diminished

… although 17 out of 44 post-scan events still correlate – so the sky distribution is still *anisotropic*

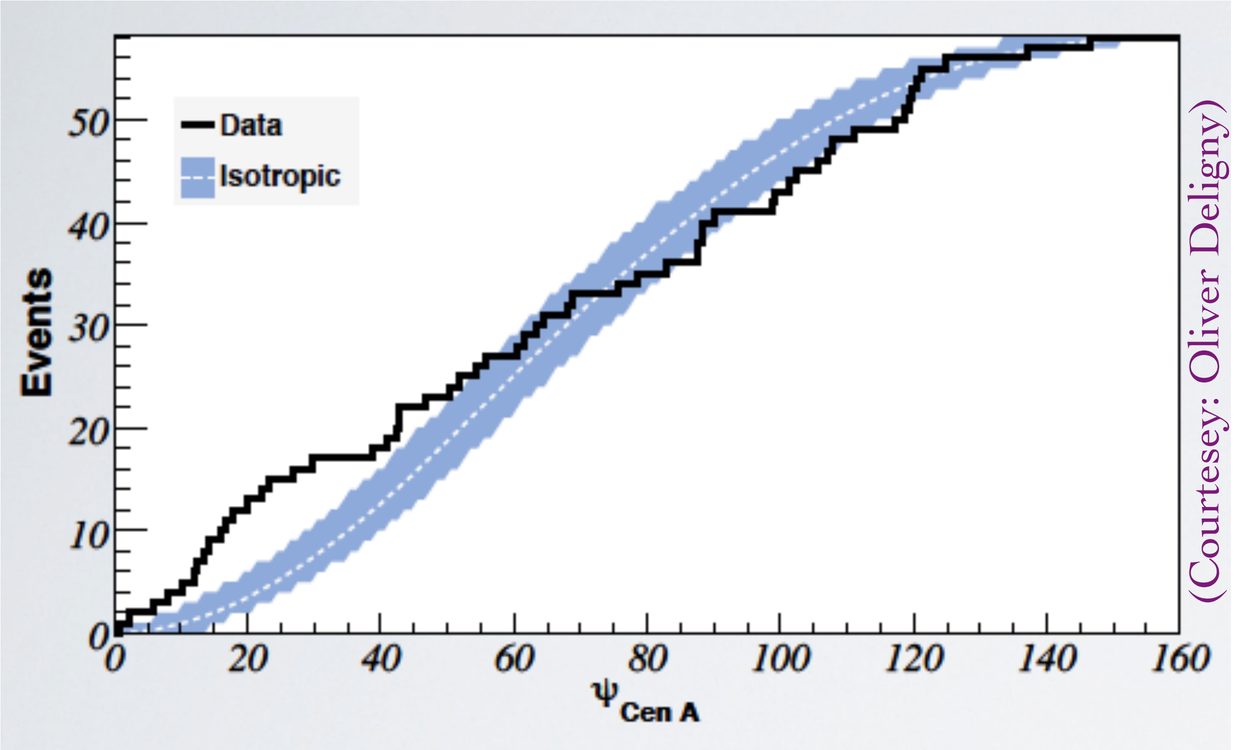
$$R = \frac{\int_{p_{\mathrm{iso}}}^{1} p^k (1-p)^{N-k} \, dp}{{p_{\mathrm{iso}}}^k (1-p_{\mathrm{iso}})^{N-k+1}}$$

The argument for proton primaries, based on the observed correlations (within 3 degrees), is thus not so strong any longer …



Maximum excess in a circular window of 18^0 around Centaurus A
(12 events observed versus 2.7 expected)

KS test: 2% of isotropic realisations have a maximum departure from isotropy greater than or equal to the maximum departure observed



(Courtesey: Oliver Deligny)

By contrast, *no* events (>55 EeV) observed in a 20^0 circular window around Virgo
… however the exposure was low (only 1.2 events expected from isotropy)

Many studies continue to be performed of correlations with various catalogues of likely sources …

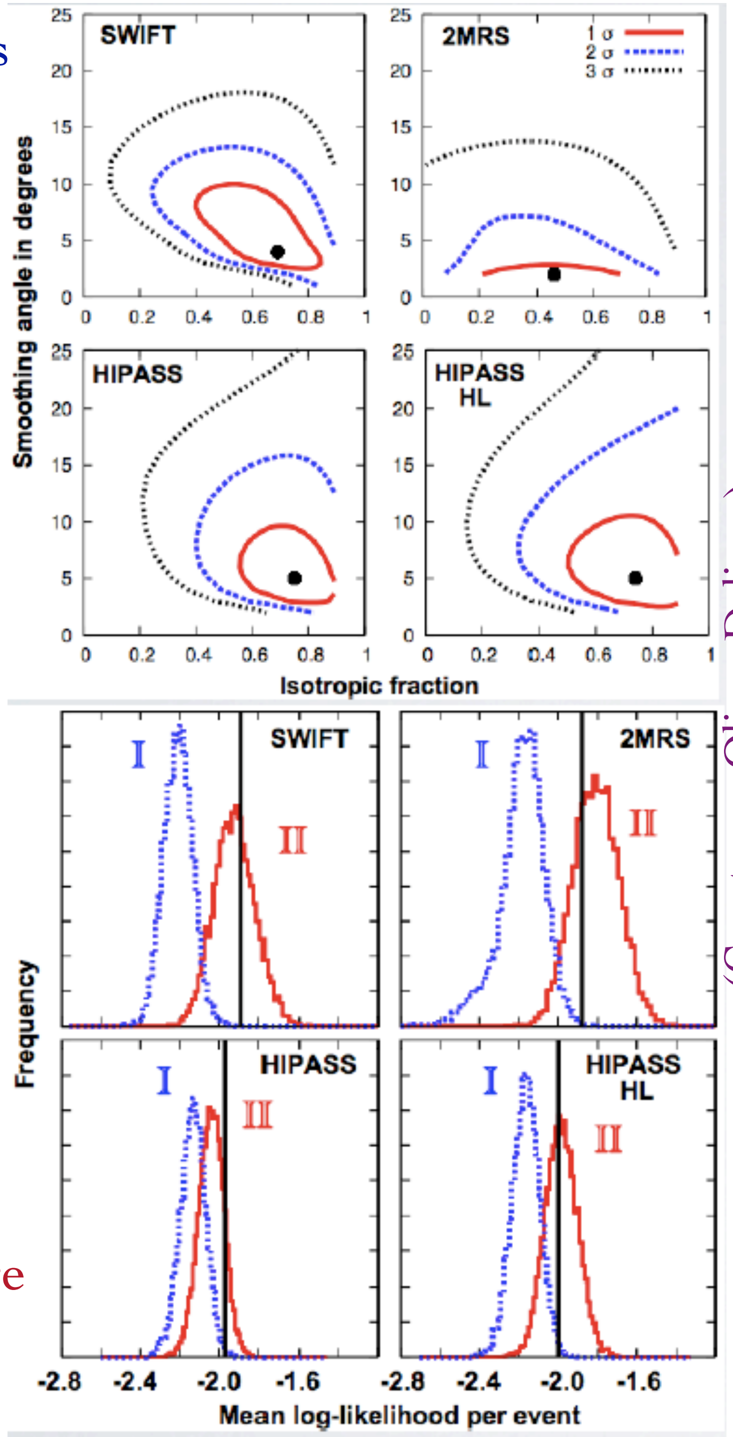
SWIFT-BAT (uniform all-sky hard X-ray survey - 261 Seyfert galaxies and AGN)

2MRS (~15,000 galaxies tracing the distribution of local matter)

HIPASS (3000 galaxies detected in radio, favoring gas-rich galaxies which host GRBs and magnestars)

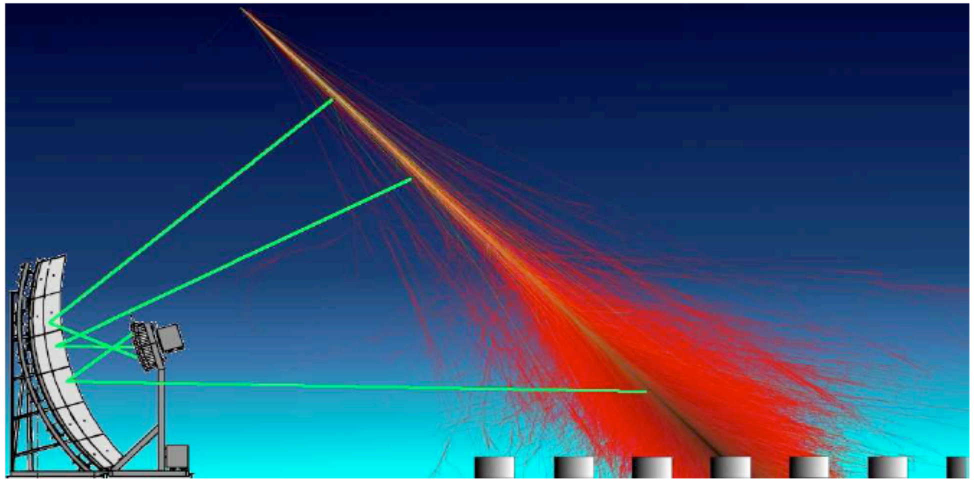
Build smooth density maps from catalogue and compare to data through log-likelihood maximisation … generate distributions by MC and obtain fraction of isotropic data sets giving higher value than data

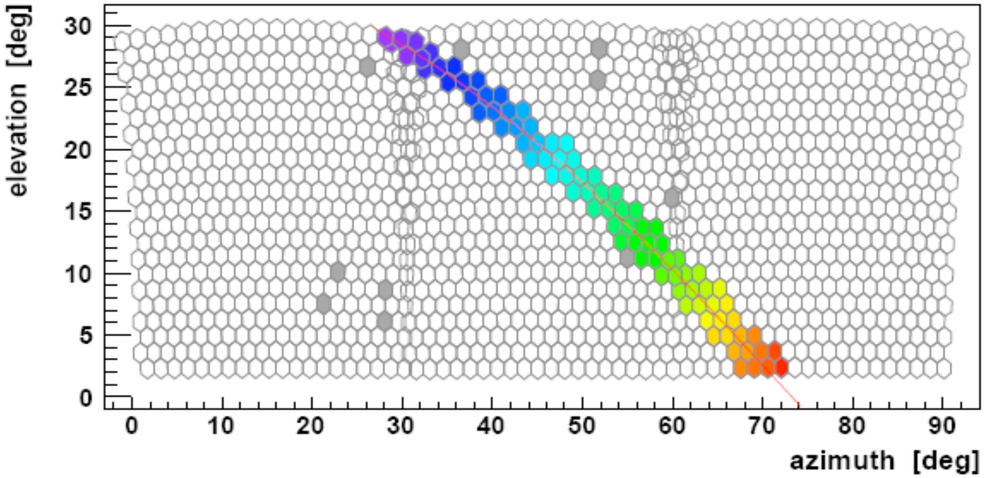
Typically find values of $O(10^{-4})$ … however unless the selection criteria are fixed *beforehand*, it is hard to gauge their significance (e.g. what is the 'penalty' for having chosen a specific catalogue/cuts on parameters?)

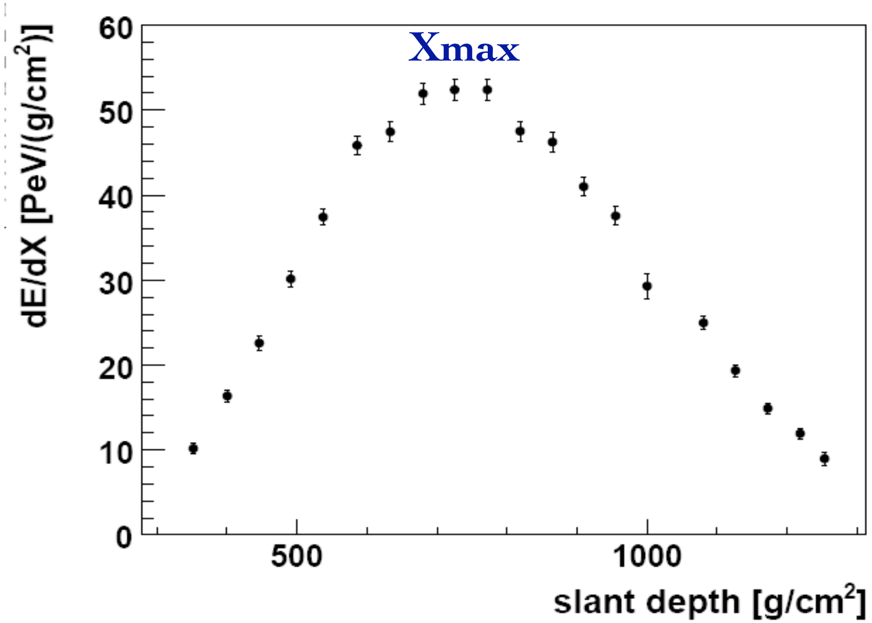


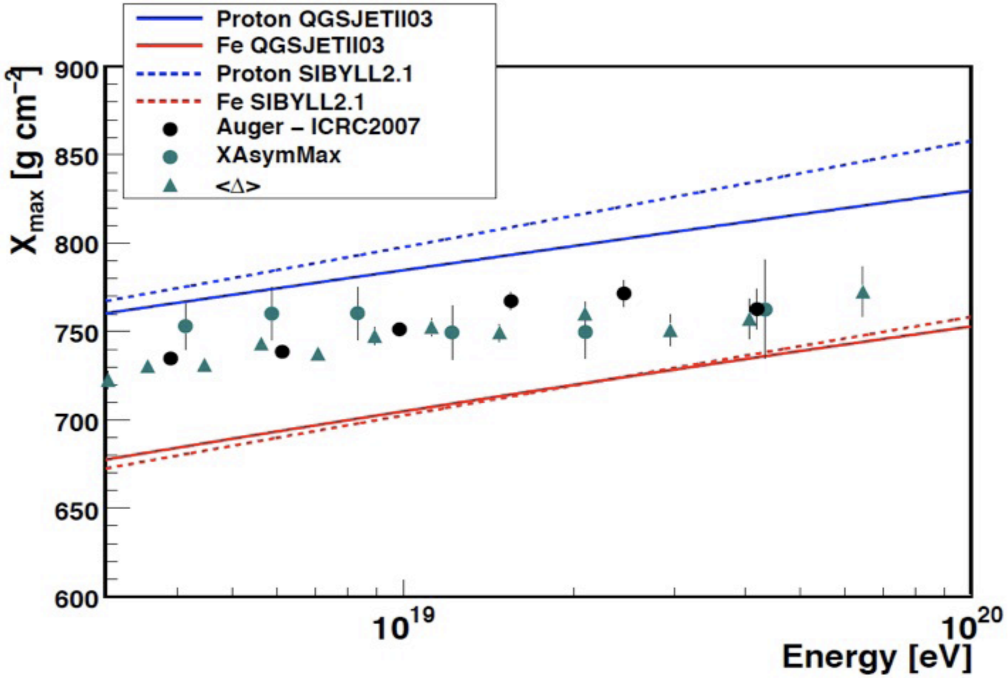
(Courtesey: Oliver Deligny)

Moreover observations at Auger of the elongation rate, risetime asymmetry, *etc* indicate an increasingly *heavier* composition at E > 10 EeV





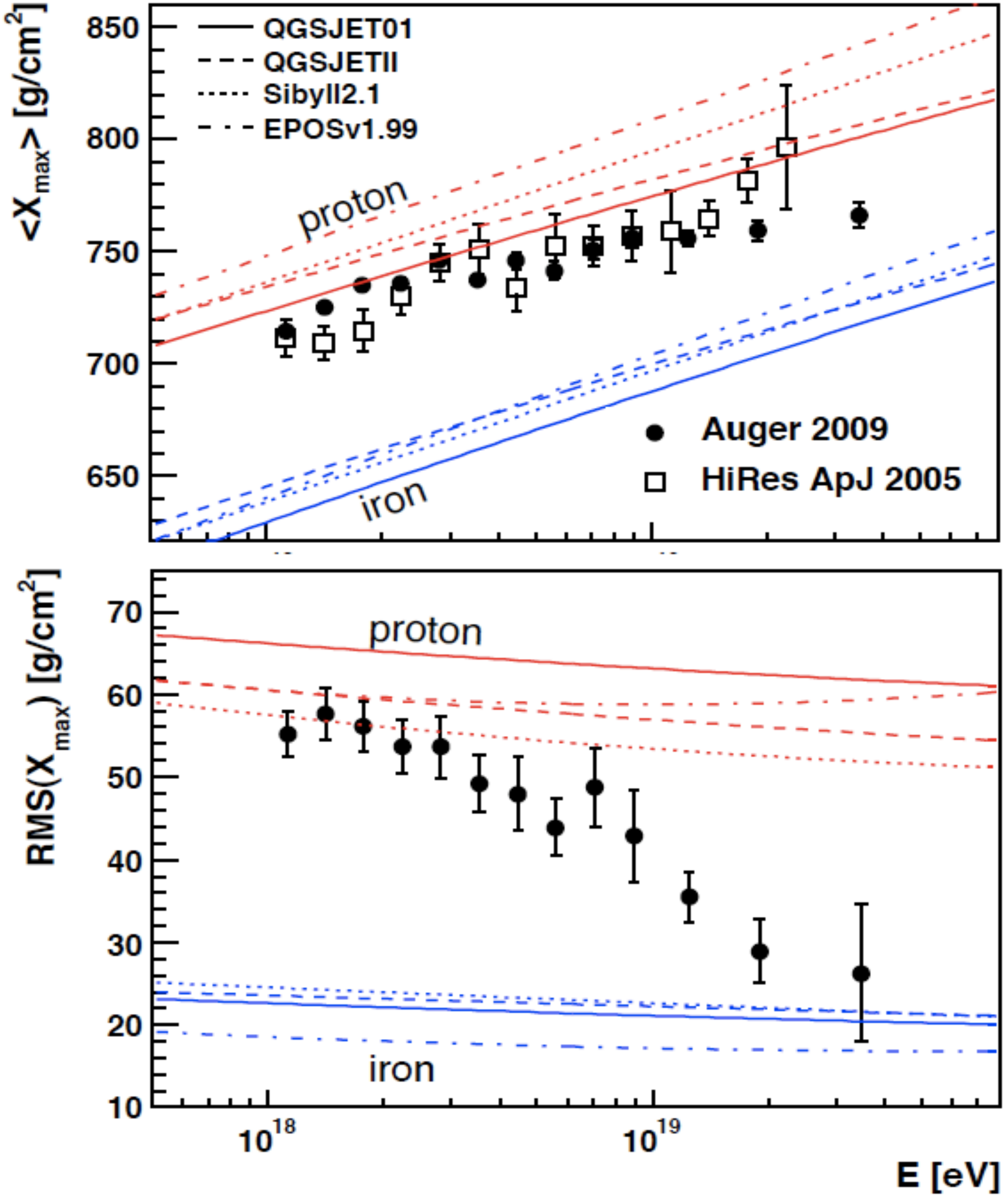




New data on the *fluctuations* of X_{max} shows this to be decreasing with energy, strengthening the evidence for a transition to a heavy composition above 10 EeV

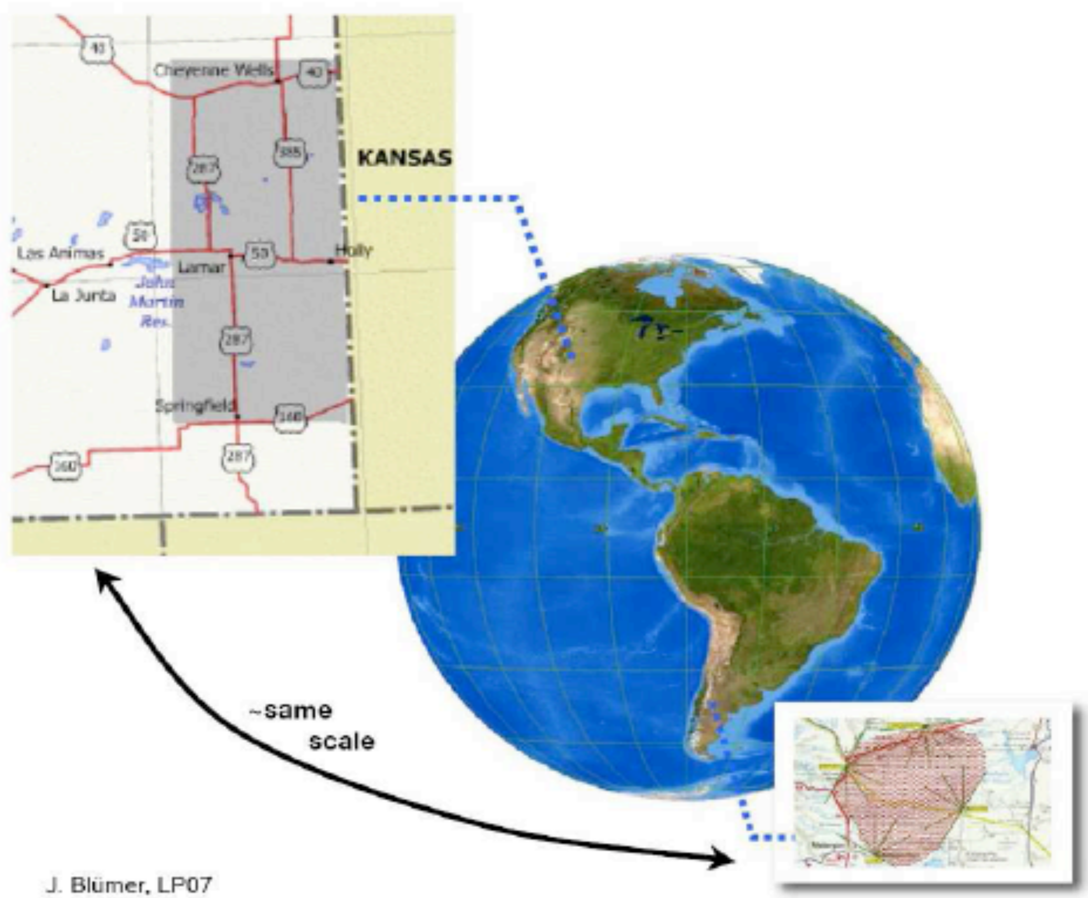
… however an *increase* of the *p*-air #-secn over the usual extrapolation can fake this apparent change

Interesting astrophysics and new particle physics are closely coupled … distinguishing between these possibilities requires more data



Outlook: Auger North

- full sky coverage $\longrightarrow$ northern hemisphere
- highest energies $\longrightarrow$ huge detector ($3 - 8 \times \mathrm{AS}$)



J. Blümer, LP07