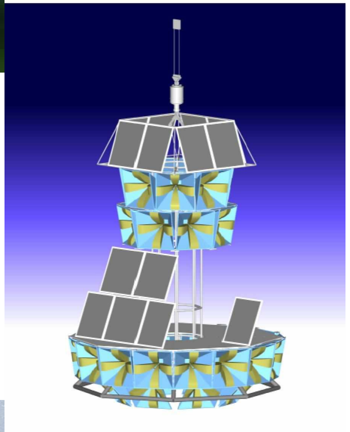
Probing the high energy universe with cosmic rays and neutrinos



Subir Sarkar
University of Oxford



European Astroparticle Physics Town Meeting, Munich, 23-25 November 2005

We are now witnessing a renaissance in γ-ray astronomy

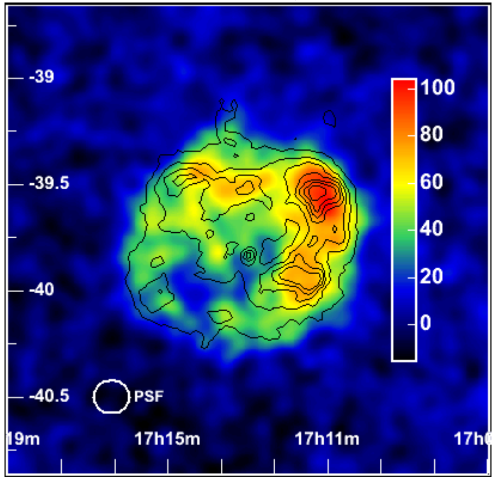
→ the sources of (low energy) cosmic rays may soon be identified – **SNRs**?

➢ Do the observed γ-rays arise from hadronic interactions (π^0 decays) , or from inverse-Compton scattering by (radio synchrotron emitting) electrons ?

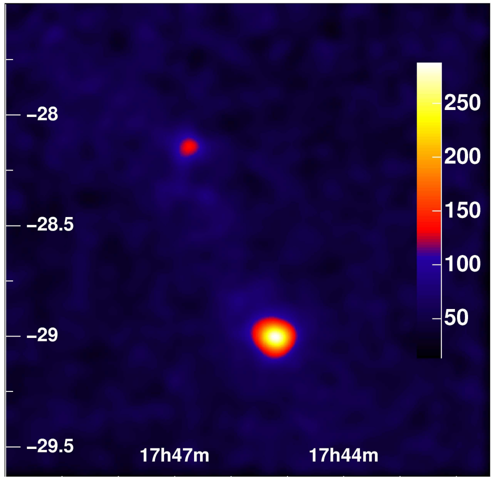
➢ Can 1st-order Fermi acceleration at SNR shocks explain the spectrum (injection, magnetic field amplification, diffusion losses vs anisotropy) ?

➢ What are the ‘unidentified’ γ-ray sources in the Galactic plane – are there other source classes (micro-quasars, pulsars, …), acceleration mechanisms ?

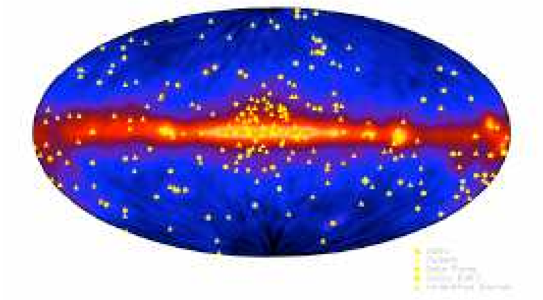
RXJ1713.7-3946 (HESS 2004)



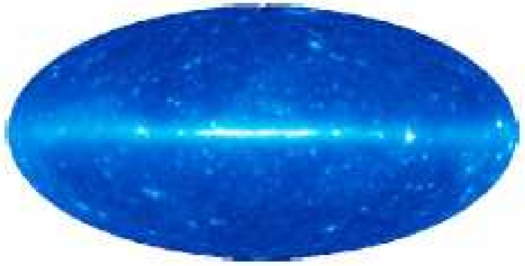
Galactic Centre (HESS 2004)



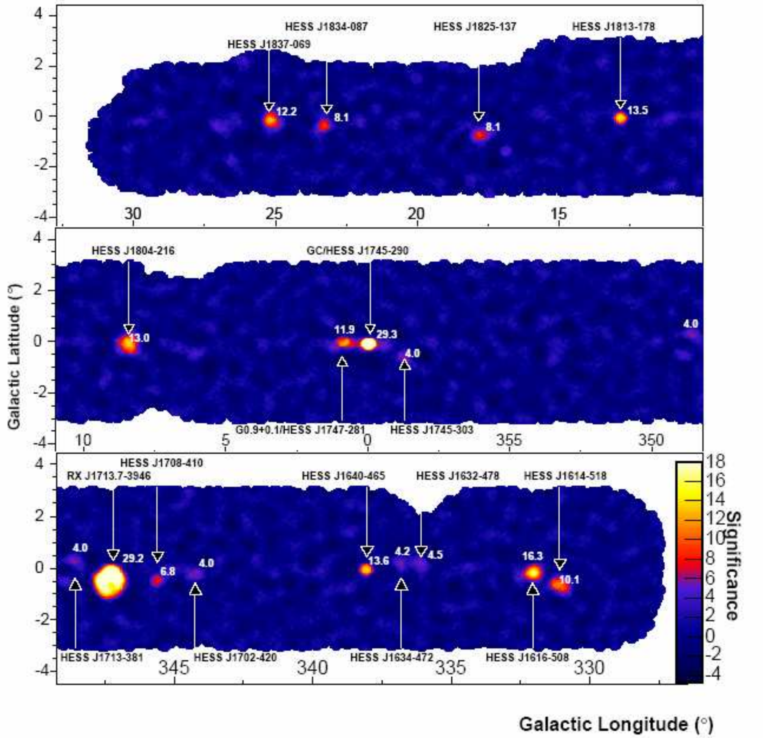
EGRET 1991 - 2000



GLAST 2007 - ?

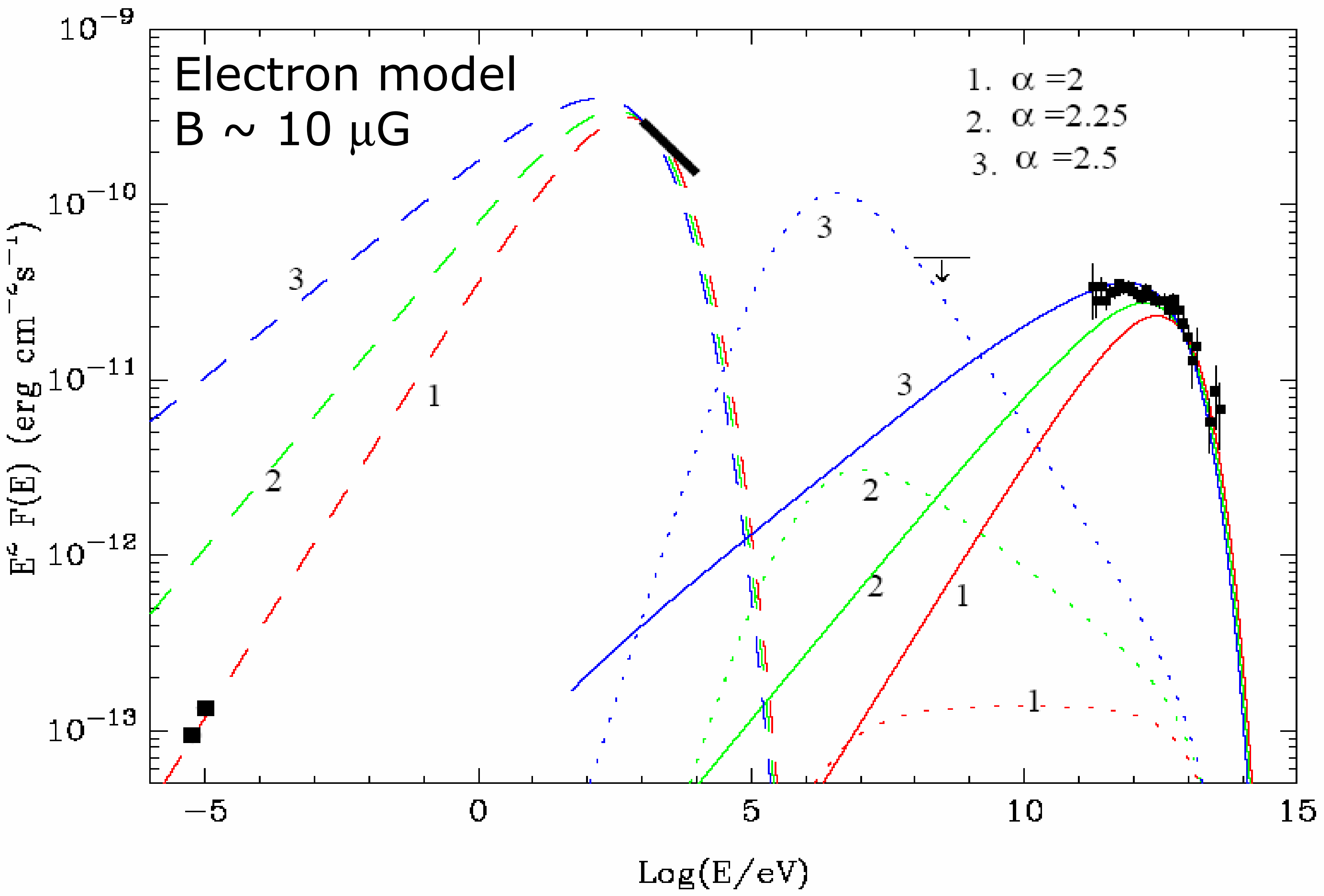


HESS Southern Plane Survey 2005



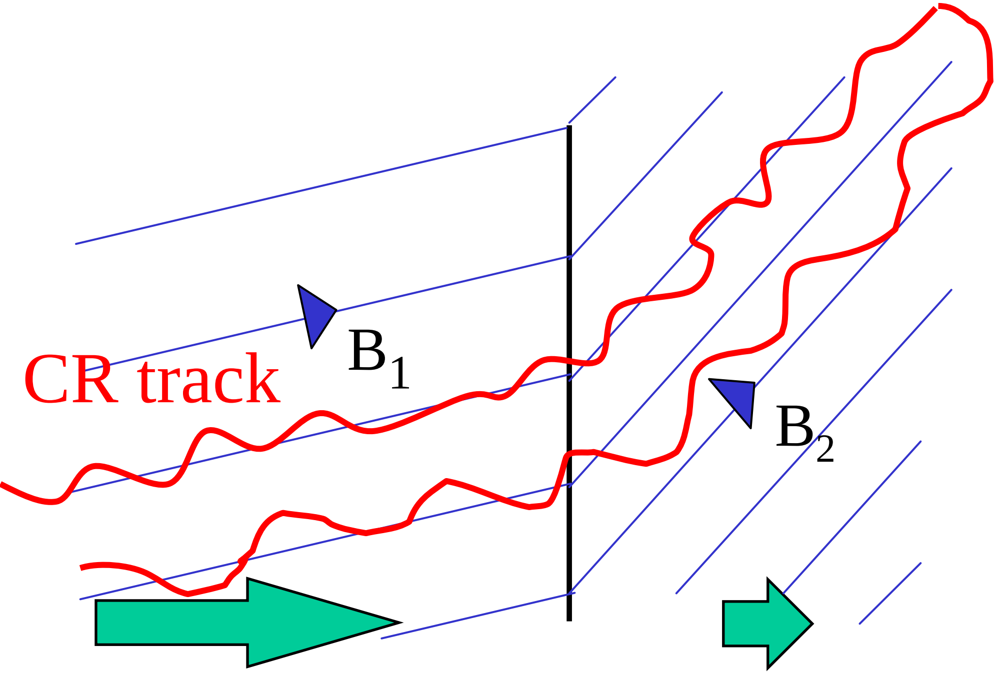
To *unambiguously* identify the sources of cosmic rays we need to observe **high energy cosmic rays** (undeflected by B fields) *and* **neutrinos** (from π^0 decays)

Primary population: e or p ?



(Werner Hoffmann, ICRC2005)

1st-order Fermi acceleration



High velocity plasma

Low velocity plasma

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

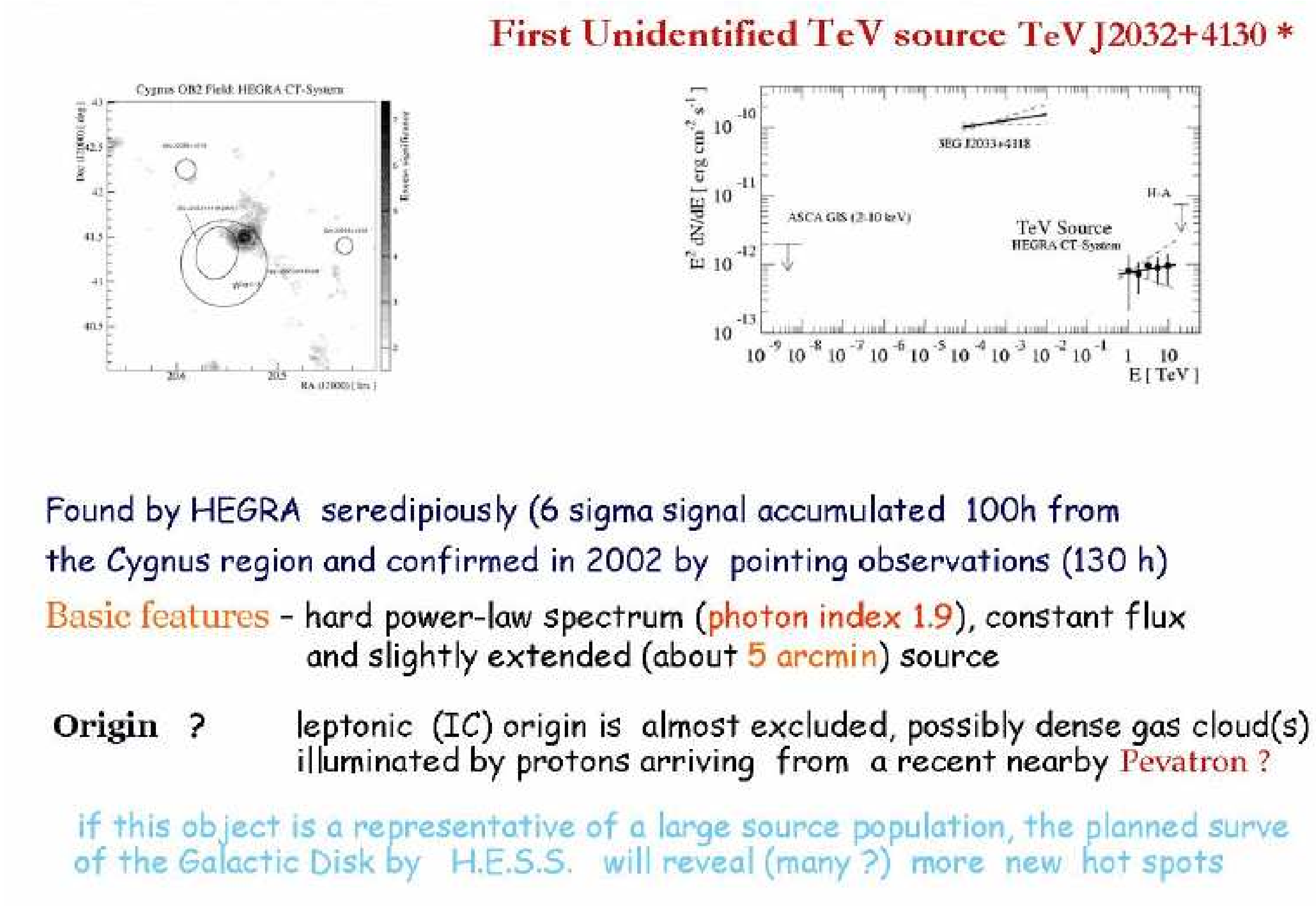
Allowing for propagation effects can match observed spectrum $\propto \varepsilon^{-2.7}$

… due to scattering on magnetic field irregularities, cosmic ray recrosses shock many times, gaining energy each time

(Courtesey: Tony Bell)

But this model cannot easily account for:

- ►why cosmic ray anisotropy does not increase as $\varepsilon^{0.7}$
- ►smooth continuation of the spectrum beyond ‘knee’
- ►absence of π^0 γ-rays from young SNRs (e.g. Cas A)
- ► high efficiency required for conversion of shock KE ~15%



First Unidentified TeV source TeV J2032+4130 *

Found by HEGRA seredipiously (6 sigma signal accumulated 100h from the Cygnus region and confirmed in 2002 by pointing observations (130 h)

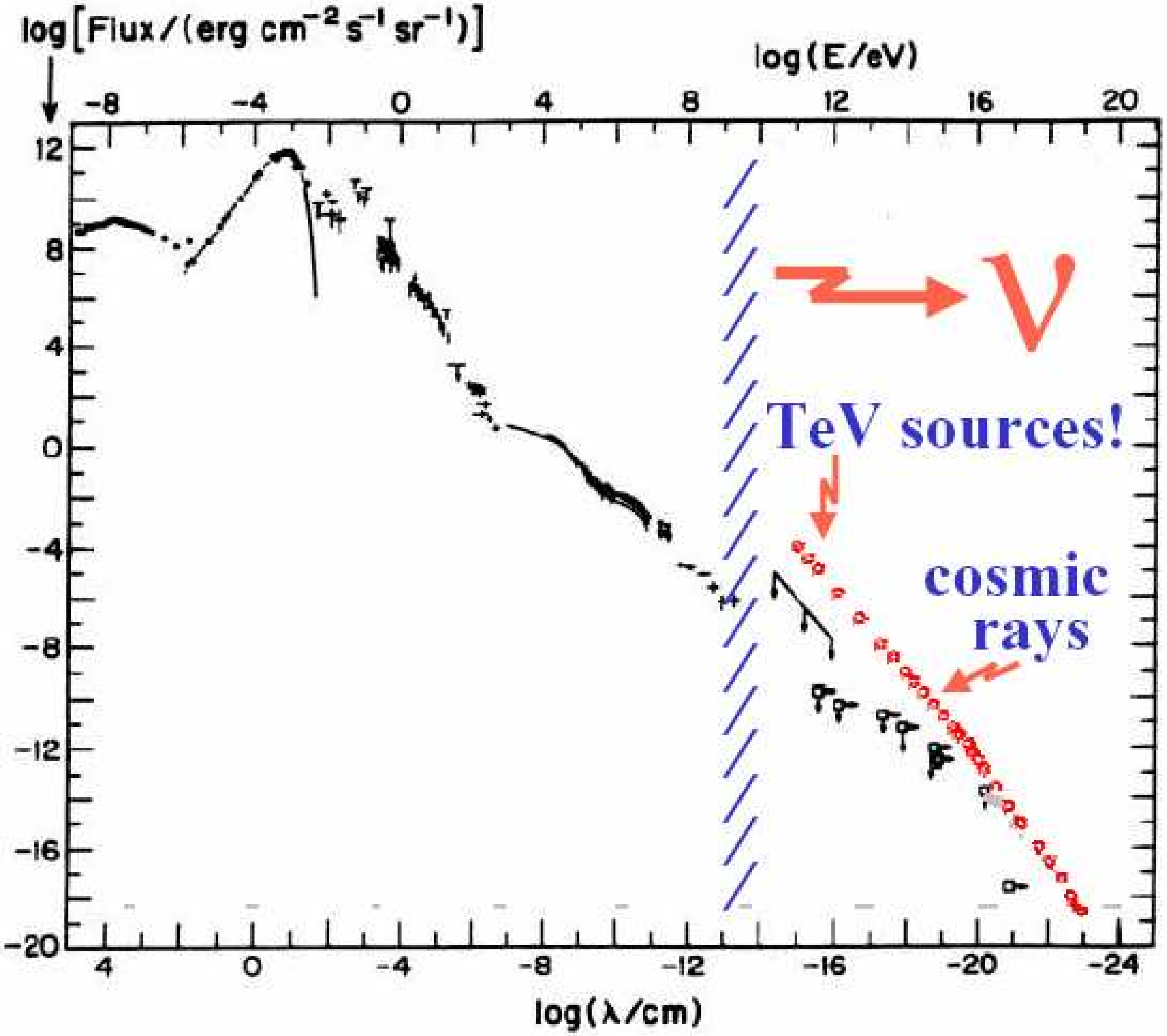
Basic features - hard power-law spectrum (photon index 1.9), constant flux and slightly extended (about 5 arcmin) source

Origin ? leptonic (IC) origin is almost excluded, possibly dense gas cloud(s) illuminated by protons arriving from a recent nearby Pevatron ?

if this object is a representative of a large source population, the planned surve of the Galactic Disk by H.E.S.S. will reveal (many ?) more new hot spots

(Felix Aharonian, KITP 2005)

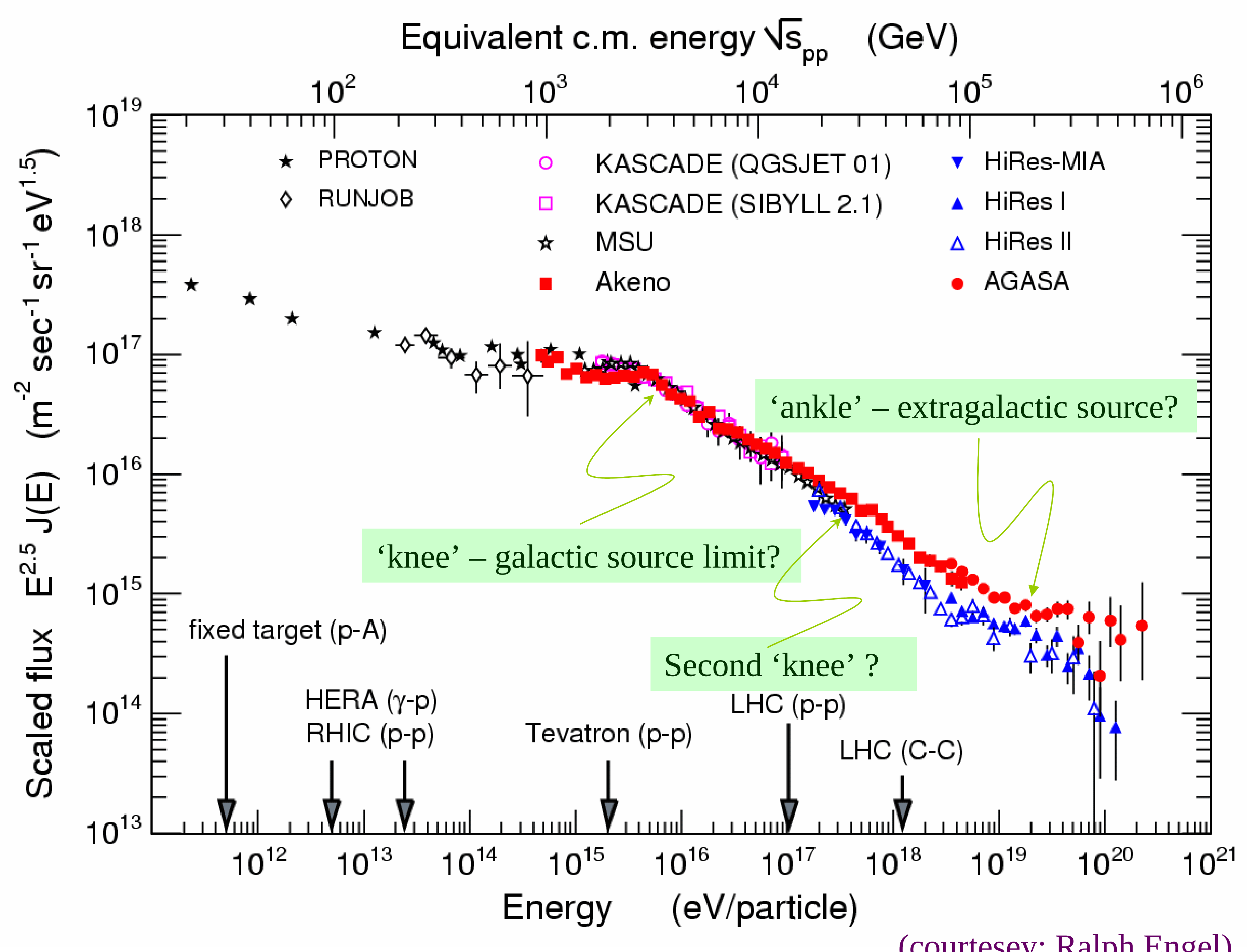
Also we cannot see the universe at energies > few TeV, since photons are attenuated through $\gamma\gamma \rightarrow e^+e^-$ on the cosmic infrared & microwave backgrounds



(courtesey: Francis Halzen)

But using cosmic rays we should be able to 'see' up to ~ 6 x 10^{10} GeV before they get attenuated through photopion interactions on the CMB … while the universe is effectively transparent to neutrinos at *all* energies

Moreover by studying cosmic ray interactions we can probe *new physics* beyond the reach of terrestrial accelerators …



‘ankle’ – extragalactic source?

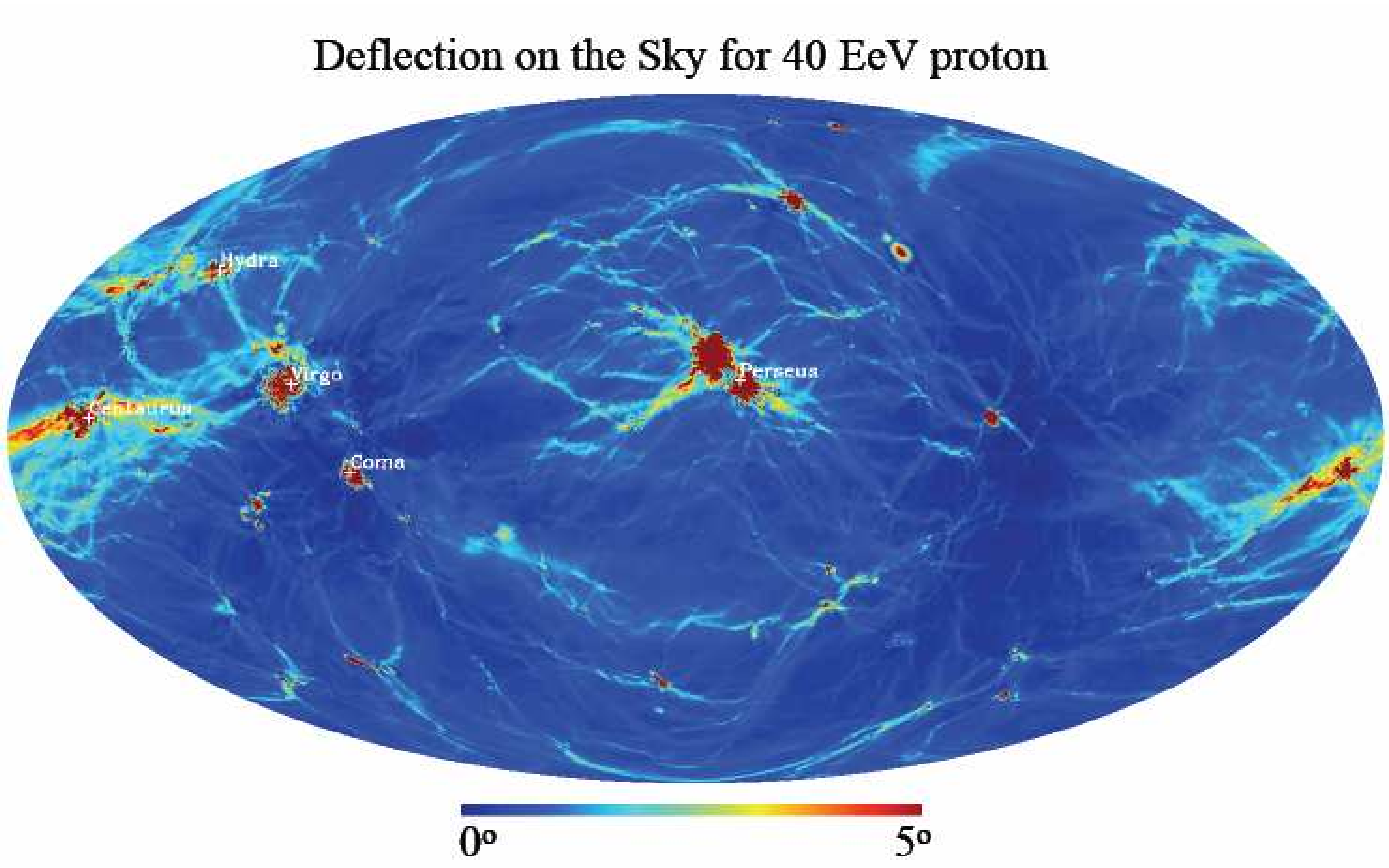
‘knee’ – galactic source limit?

Second ‘knee’ ?

(courtesey: Ralph Engel)

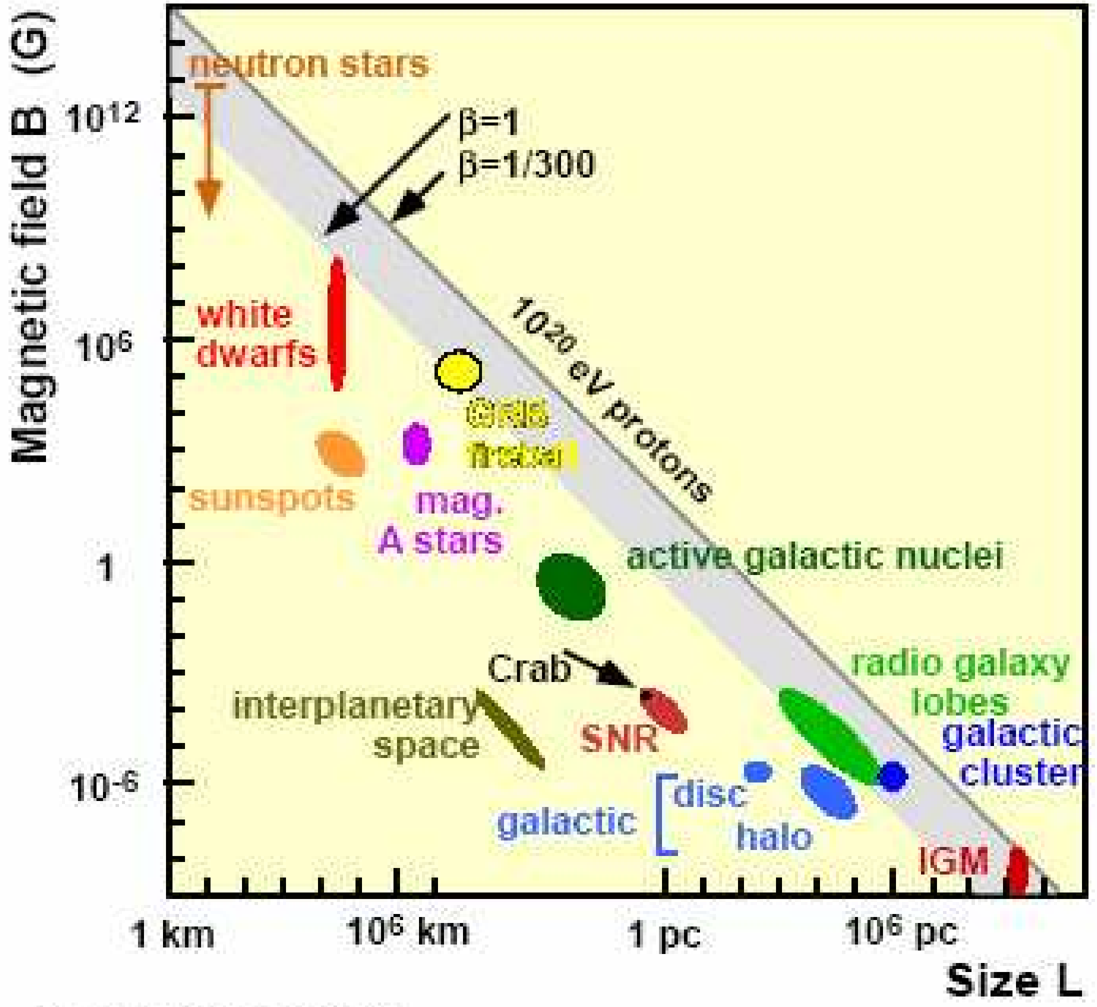
‘Constrained’ simulation of local large-scale structure including magnetic fields shows that deflections are small, except in the cores of rich galaxy clusters

Dolag, Grasso, Springel & Tkachev (2003) … but see Armengaud, Sigl & Miniati (2004)



So charged particle *astronomy* should be possible at energies above ~4x10^{19} eV

Are there any plausible cosmic accelerators for such enormous energies?



A.M. Hillas 1984

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

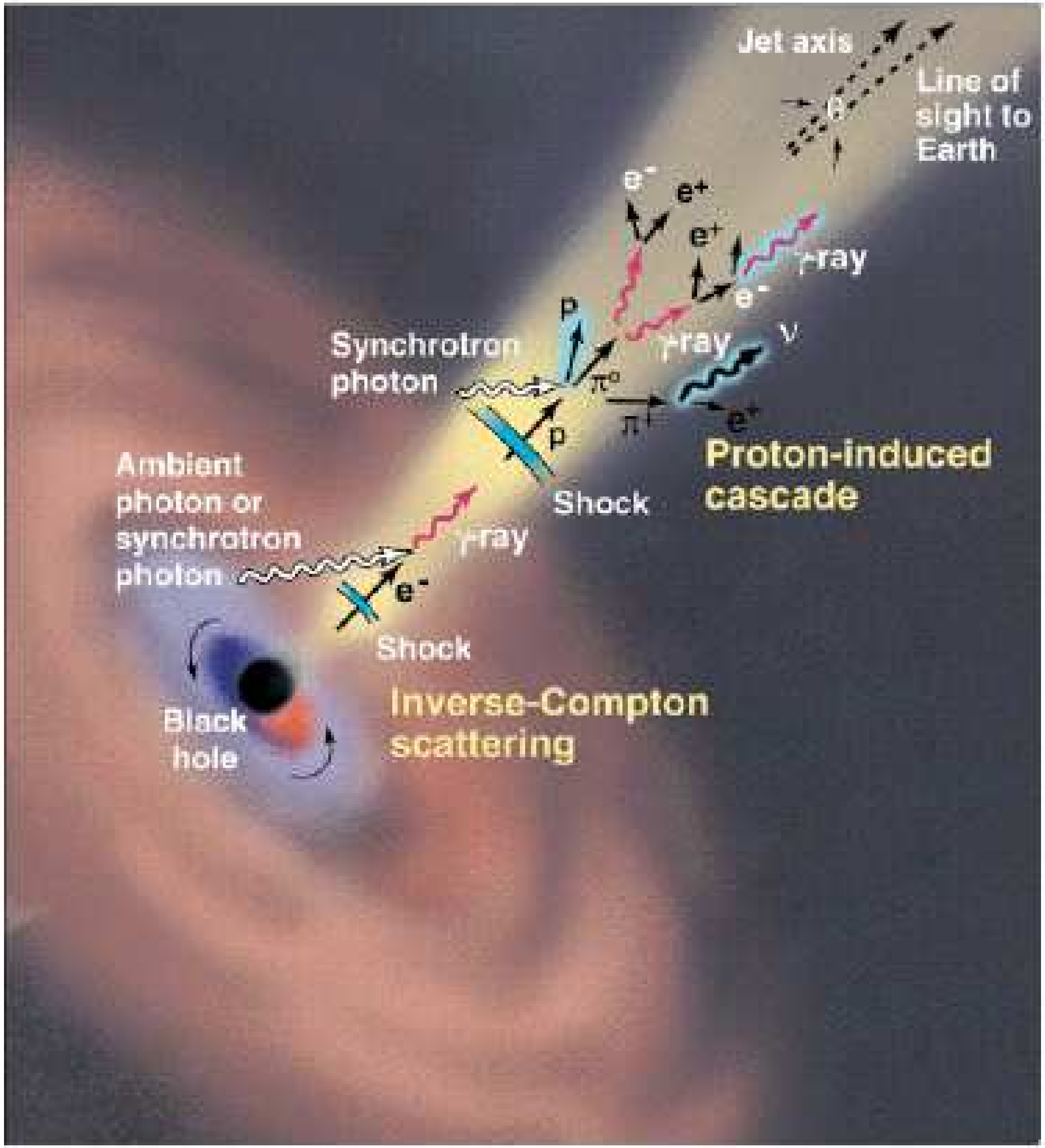
$B_{\mu G} \times L_{kpc} > 2\, (c/v)\, E_{EeV} / Z$

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.

► If they are nearby, then observed UHECRs should point back to them

► If they are far away then the spectrum should exhibit the ‘GZK cutoff’



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.

However no evidence yet that *protons* are actually accelerated in such objects

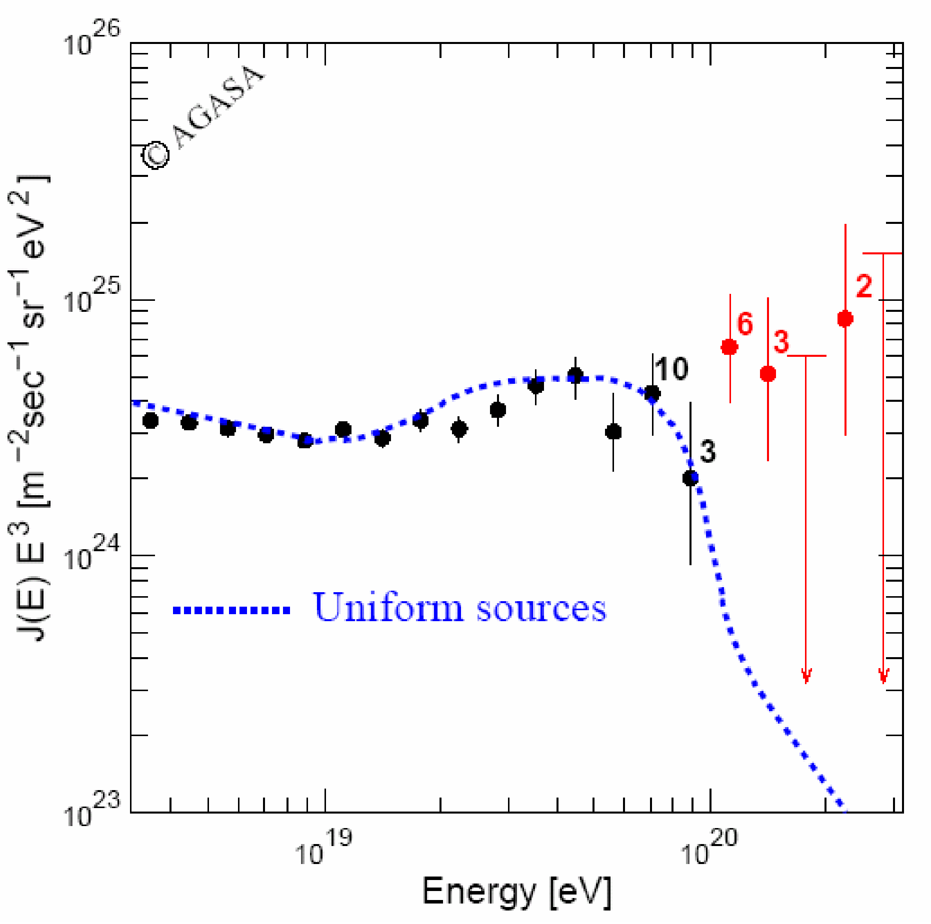
► No UHECRs point back to nearby active galaxies like M87 or Cen A

► Neutrinos not detected from AGN (during ‘orphan flare’ in 1ES1959+650?)

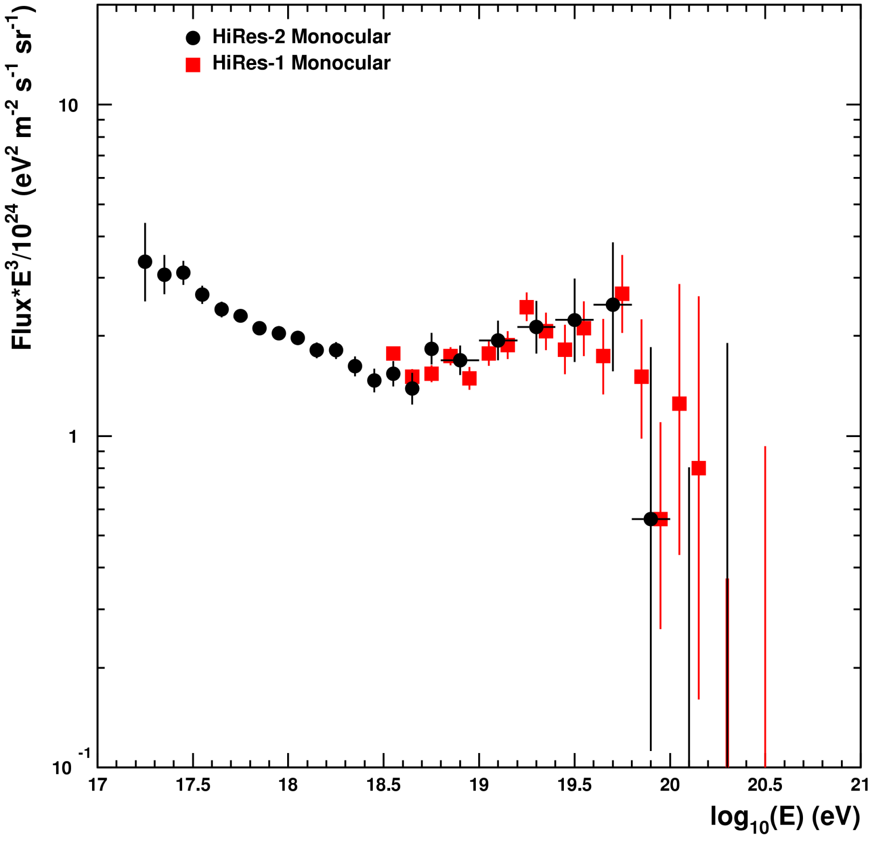
Where is the GZK cutoff?

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

AGASA spectrum continues smoothly!

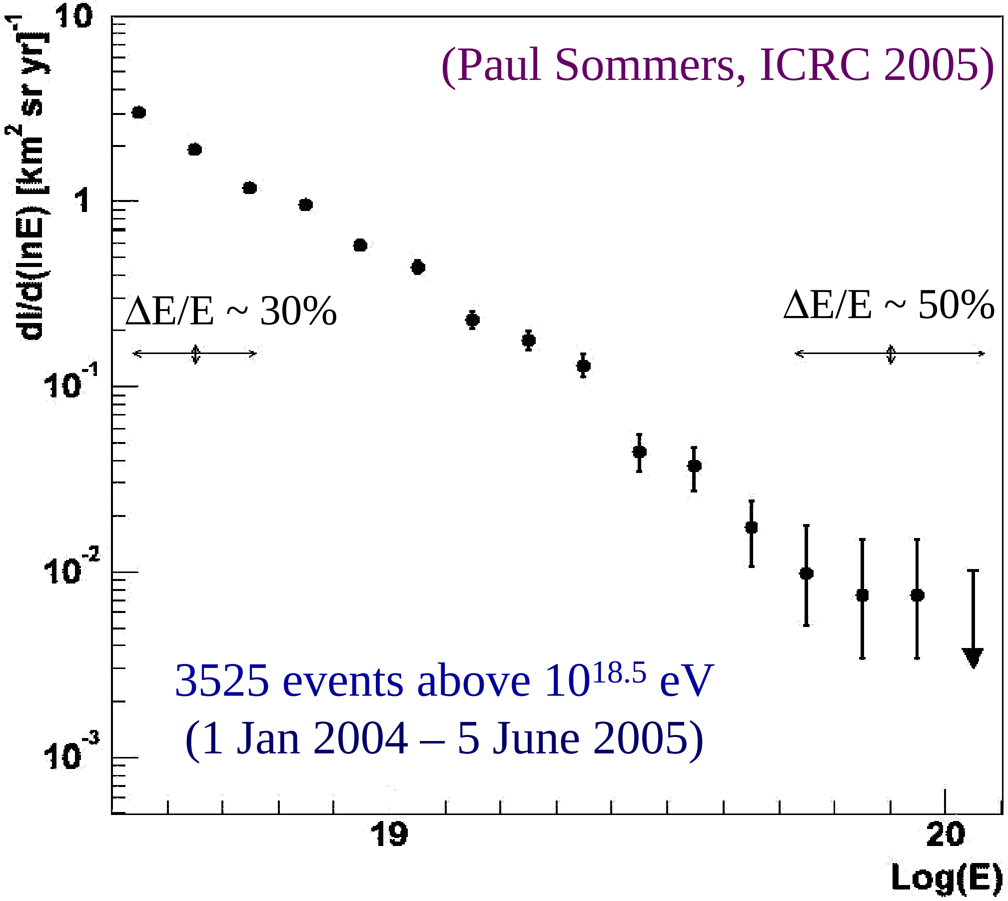


… but HiRes sees expected suppression



Is there a ~25% energy calibration mismatch between analyses of air shower and air fluorescence data?

Auger has now an exposure comparable to AGASA and HiRes … presented first spectrum based on air shower data *calibrated* by air fluorescence detector data



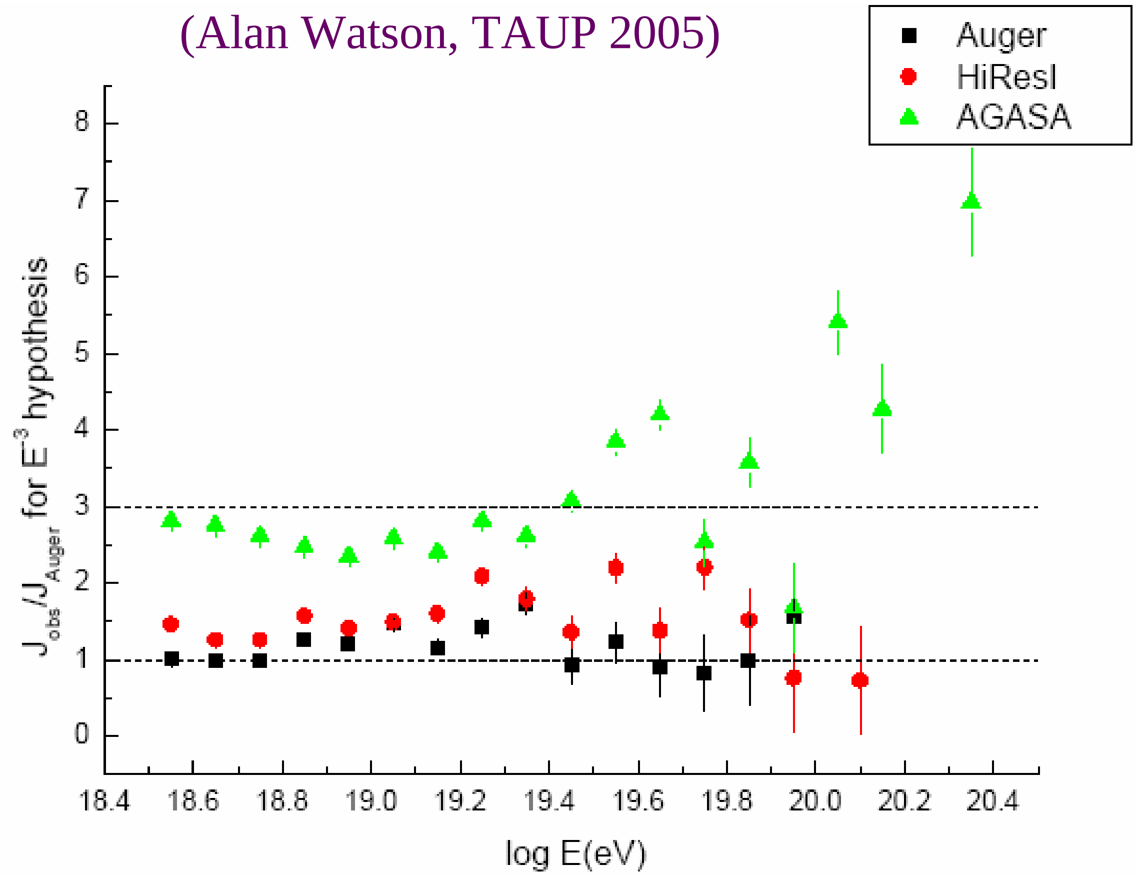
(Paul Sommers, ICRC 2005)

ΔE/E ~ 30%

ΔE/E ~ 50%

3525 events above $10^{18.5}$ eV
(1 Jan 2004 – 5 June 2005)

(Alan Watson, TAUP 2005)

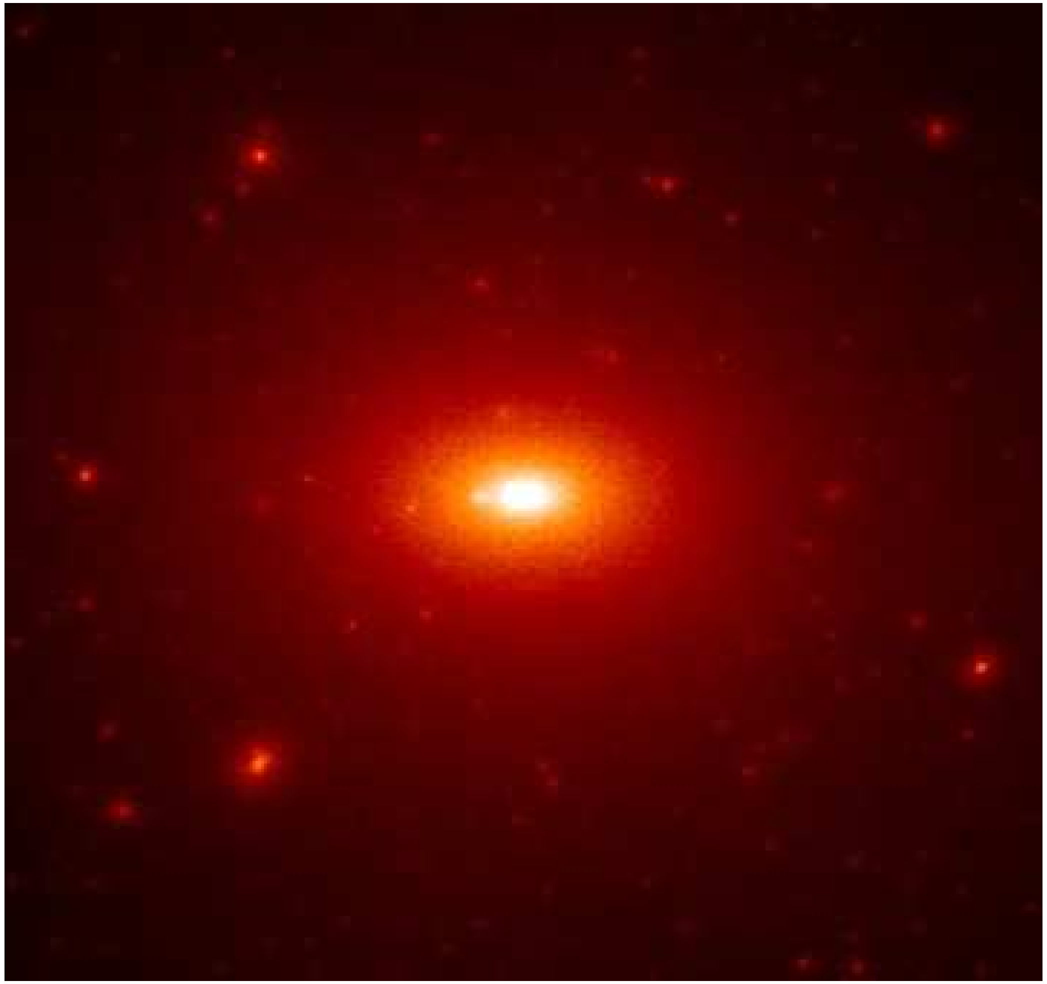


Need to be cautious … require better understanding of systematic errors and more statistics before a definite conclusion can be drawn!

Perhaps the trans-GZK cosmic rays are produced *locally* in the Galactic halo

… from the slow decays of metastable **supermassive dark matter** particles
(created at the end of inflation through gravitational field fluctuations)

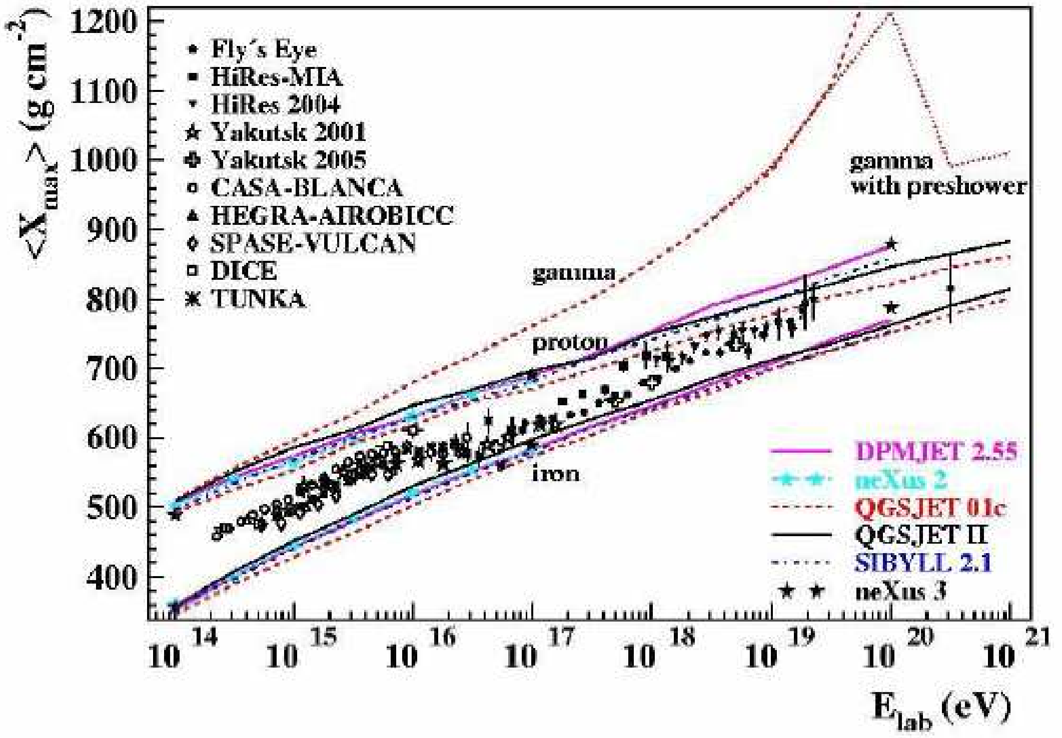
→ **energy spectrum** determined by QCD fragmentation (matches AGASA data)
→ **composition** dominated by photons rather than nucleons (disfavoured by Auger)
→ **anisotropy** due to our off-centre position **(**~5% dipole towards Galactic Centre – crucial test!)



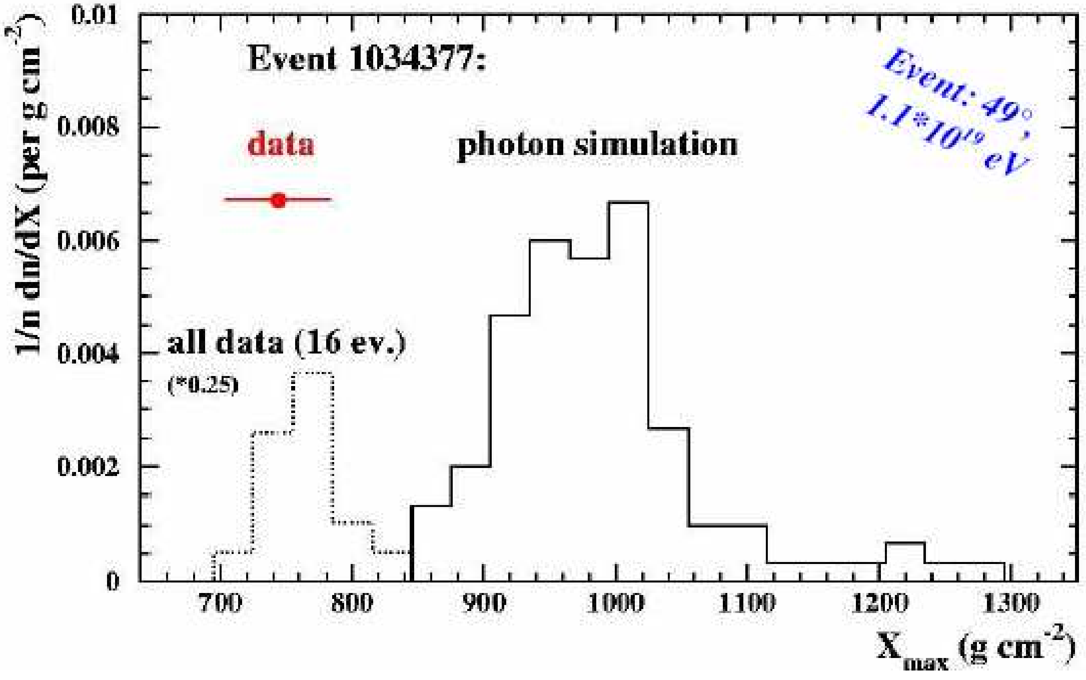
Simulation of Milky Way halo (Stoehr *et al* 2003)

(Berezinsky, Kachelreiss & Vilenkin 1997; Birkel & Sarkar 1998)

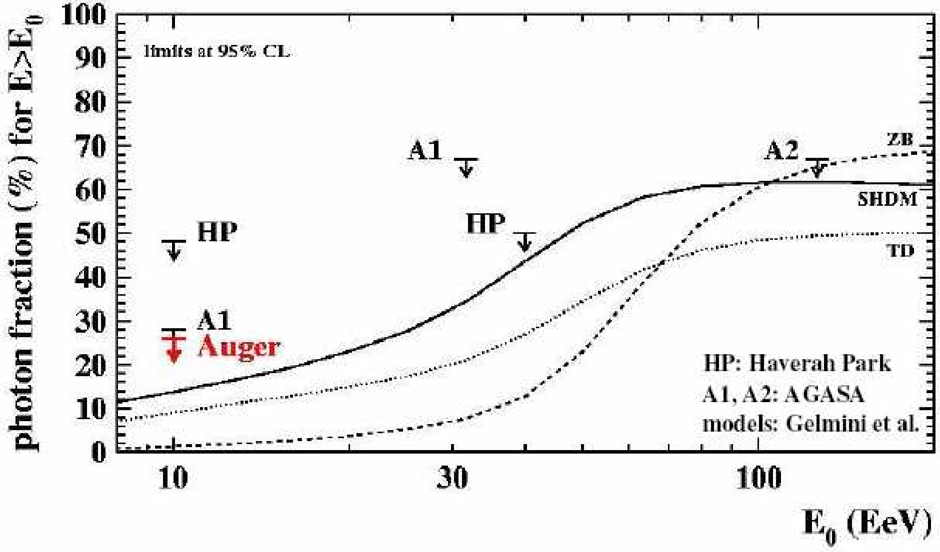
Photon discrimination with X_{max}



Example



New upper limit



Auger has confirmed that the highest energy particles interact like nucleons, *not* photons

Disfavours (alhough does not yet rule out) top-down models of UHECR origin (modulo uncertainties in UHE γ propagation through the low frequency cosmic radio background)

(Markus Risse, ICRC2005)

But are the UHECR primaries protons?

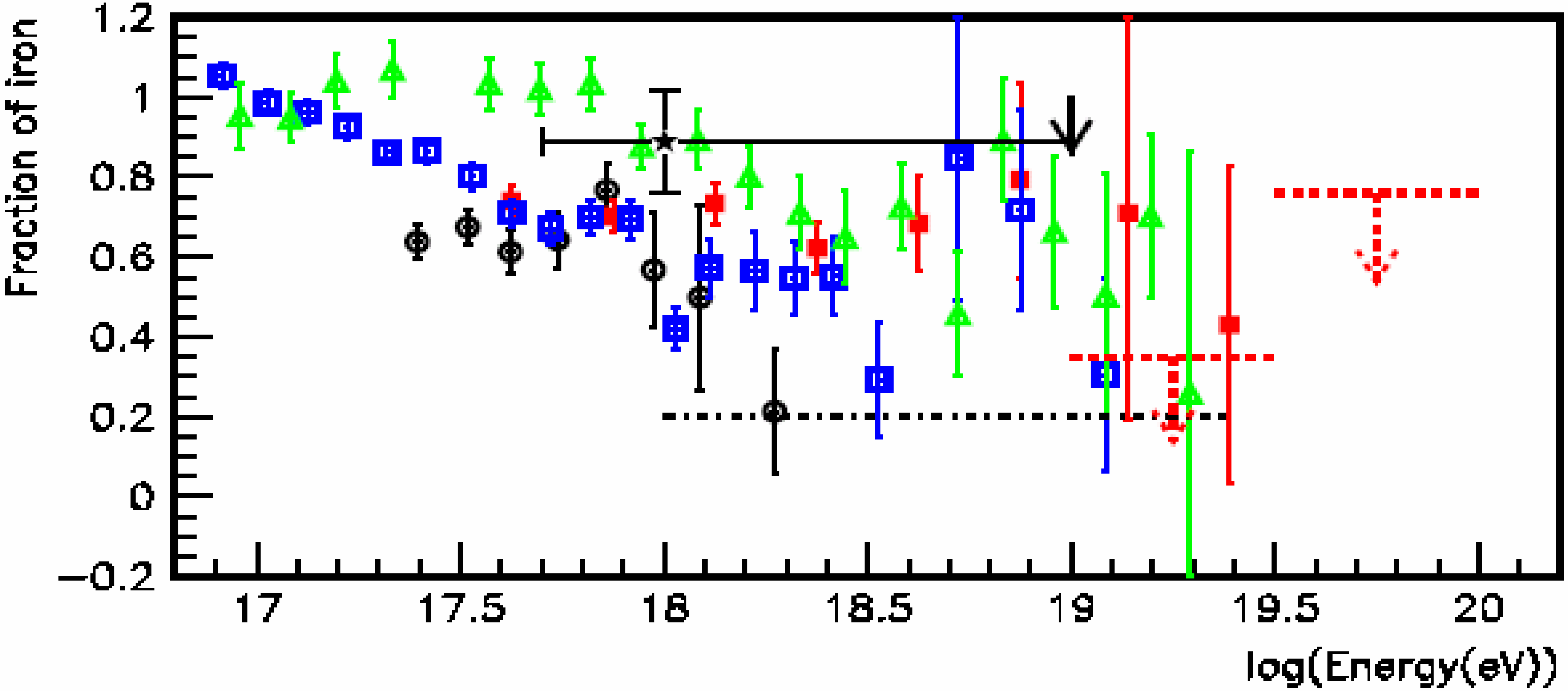
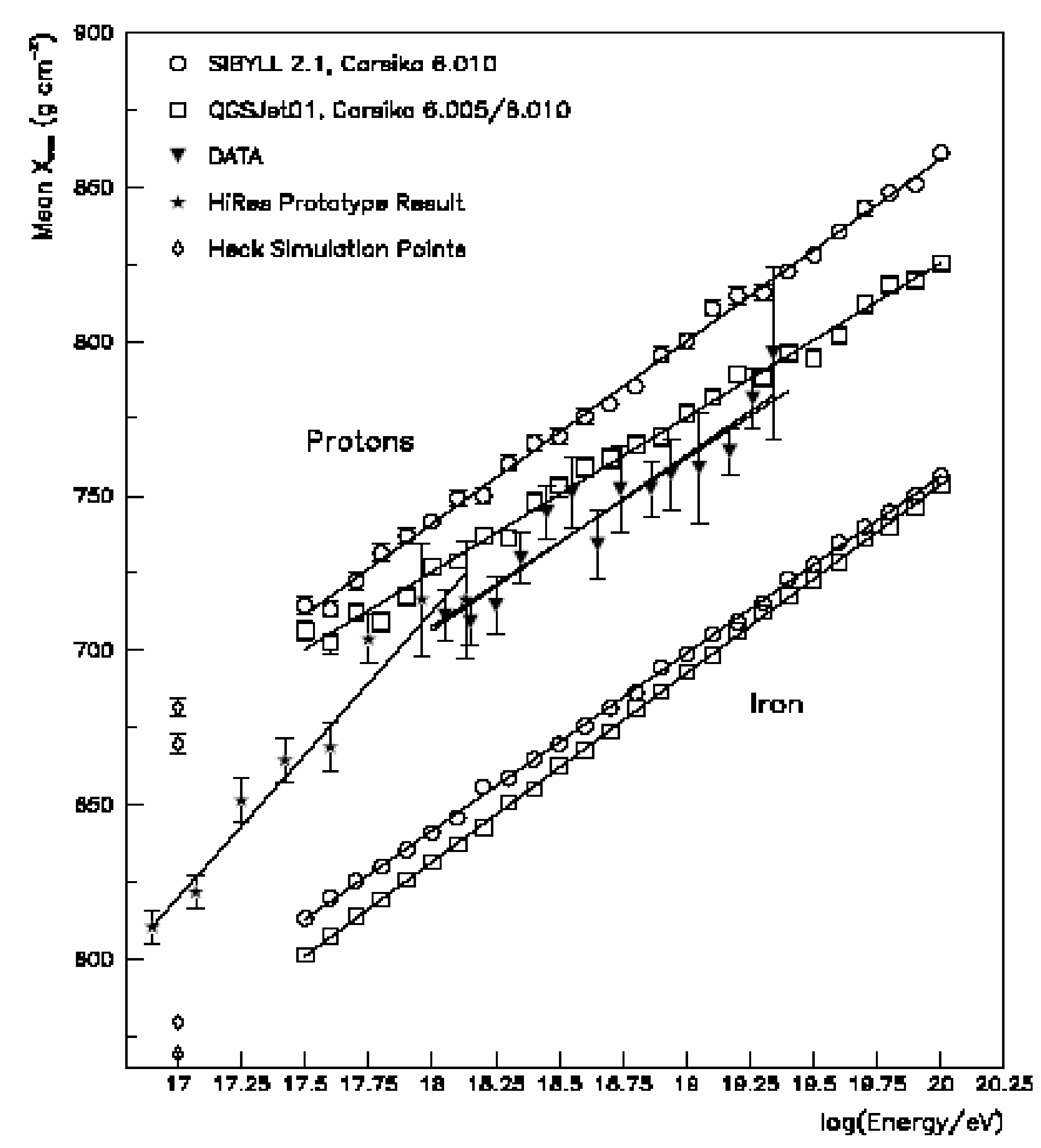


FIG. 21: Iron fraction from various experiments: Fly's Eye (△), AGASA A100 (■), AGASA A1 (□) using SIBYLL 1.6 ([228] and references therein) and Haverah Park [216], using QGSJET98 (○)). The mean composition determined in [217] with the corresponding error for the Volcano Ranch energy range using QGSJET98 (⋆) is shown. The solid line arrow indicates the recent result using rise time measurements from Haverah Park [224]. The dashed arrow lines represents upper limits obtained by the AGASA Collaboration with QGSJET98 [199]. The dot dashed horizontal line corresponds to results reported by the HiRes Collaboration [205]

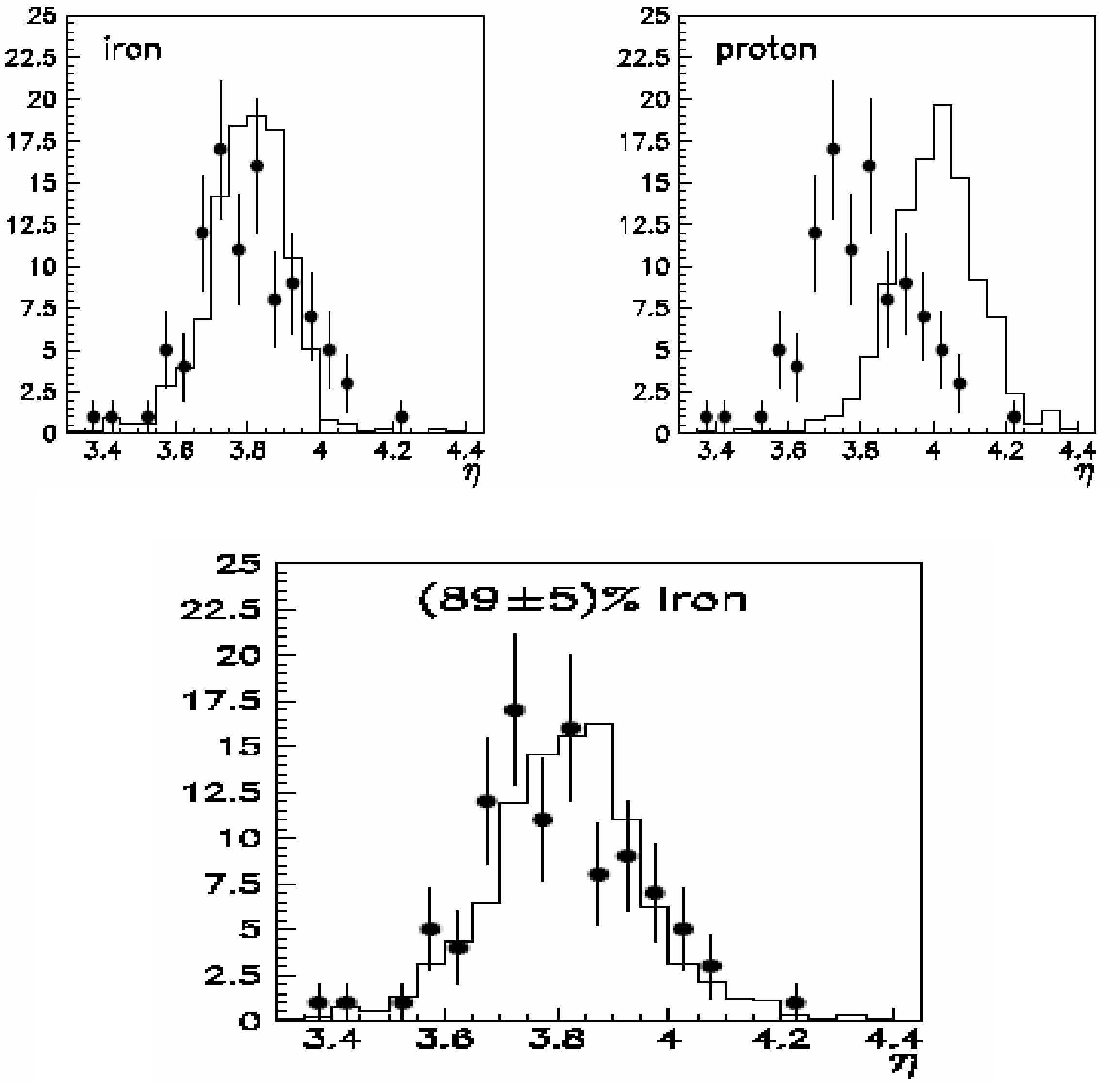
Dova, Mancenido, Mariazzi McCauley & Watson (2004)

Different techniques suggest different composition at high energies … rather sensitive to modelling of air showers

Elongation rate: HiRes

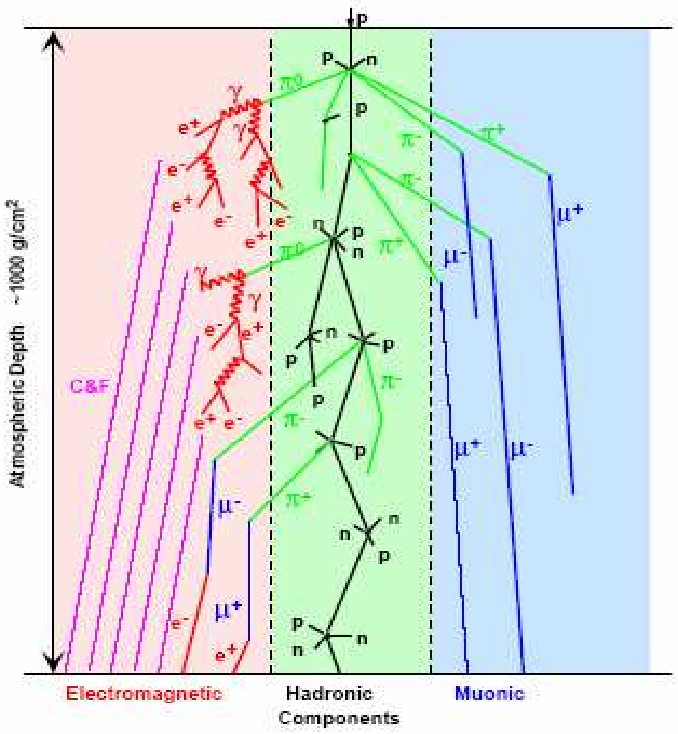


Lateral distribution function: Volcano Ranch



Shower Development

(courtesey: Johannes Knapp)



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

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

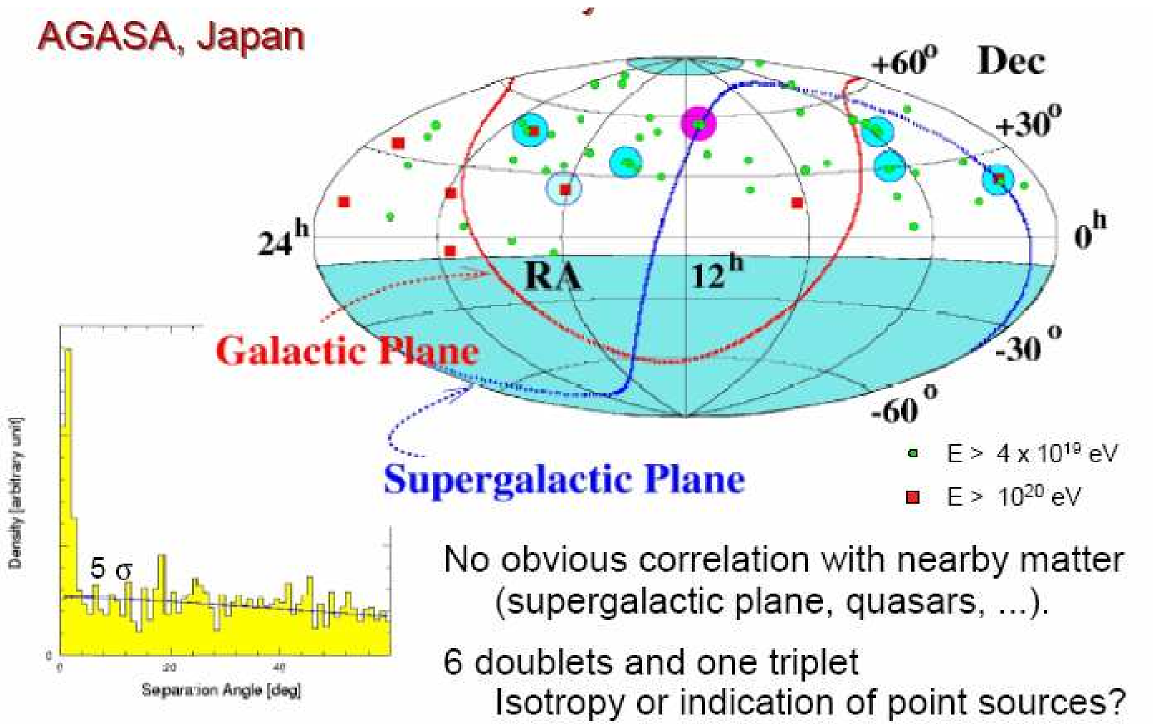
Complex interplay with many correlations
requires MC simulations

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)**

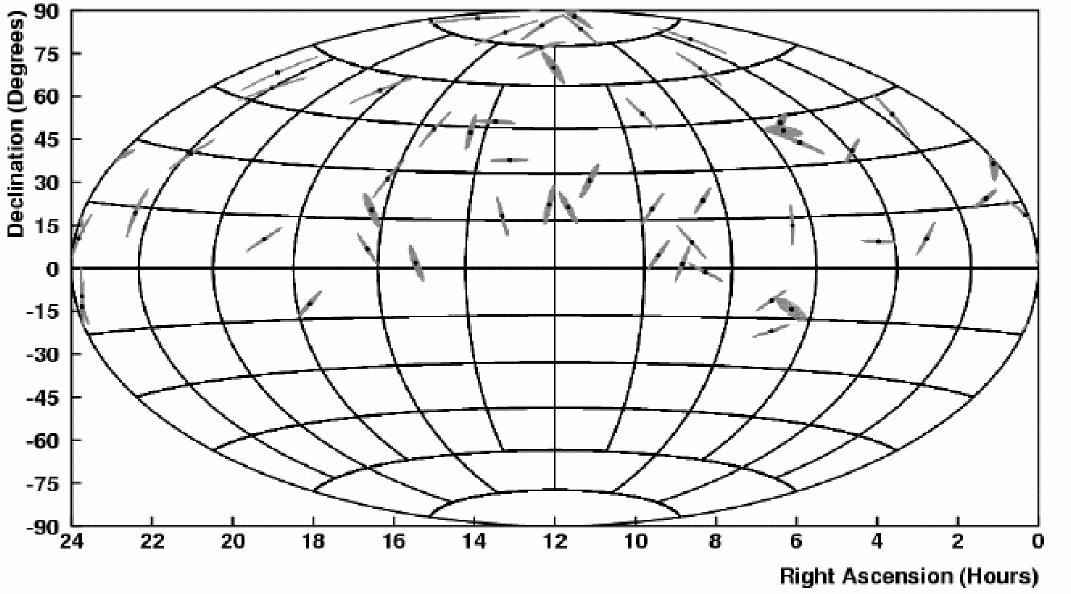
Expect significant input from forthcoming LHC experiments (CASTOR, TOTEM …)

Small-angle clustering of UHECRs?



No obvious correlation with nearby matter
(supergalactic plane, quasars, ...).

6 doublets and one triplet
Isotropy or indication of point sources?



By contrast, HiRes (with superior angular resolution) has seen *no* evidence for small-angle clustering

But HiRes *does* see correlations with BL Lacs

(active galaxies - 'blazars'- in which the jet from the BH points directly towards us)

Veron 11th Catalogue:

178 objects with magnitude < 18

Excess number of BL Lacs seen along arrival directions of events > 10^{19} eV, with separation angles consistent with the HiRes angular resolution of ~0.6°

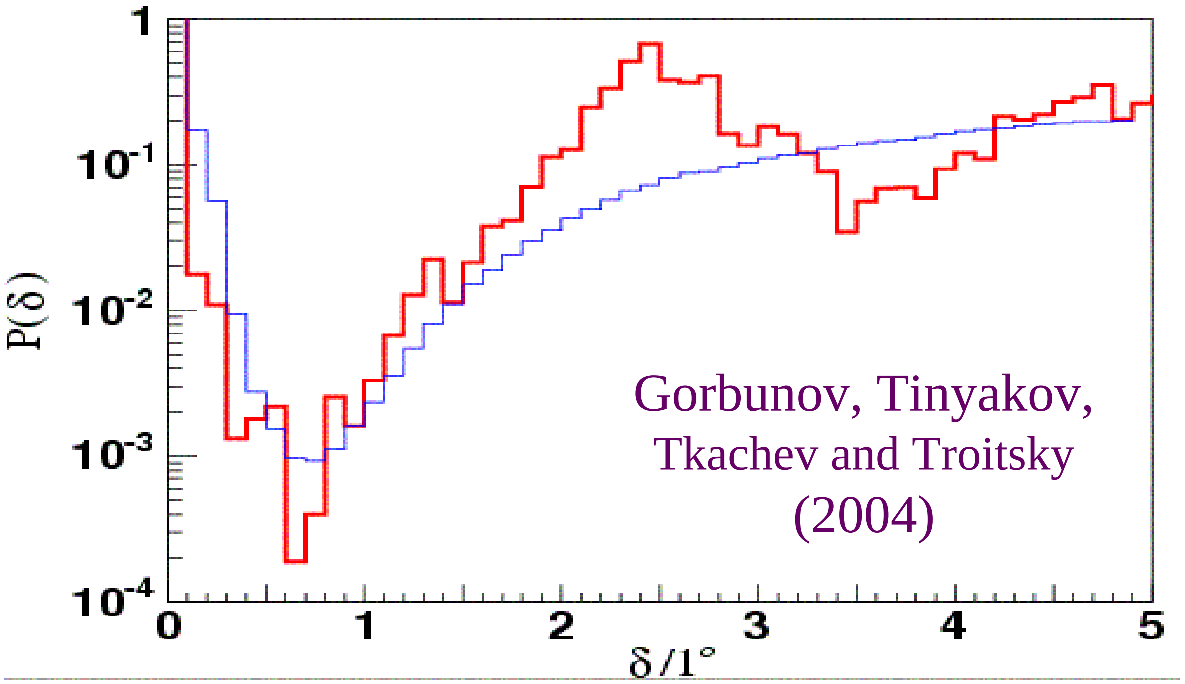
See 11 pairs within 0.8°, but expect ~3

⇒ probability ~ 5×10^{-4}

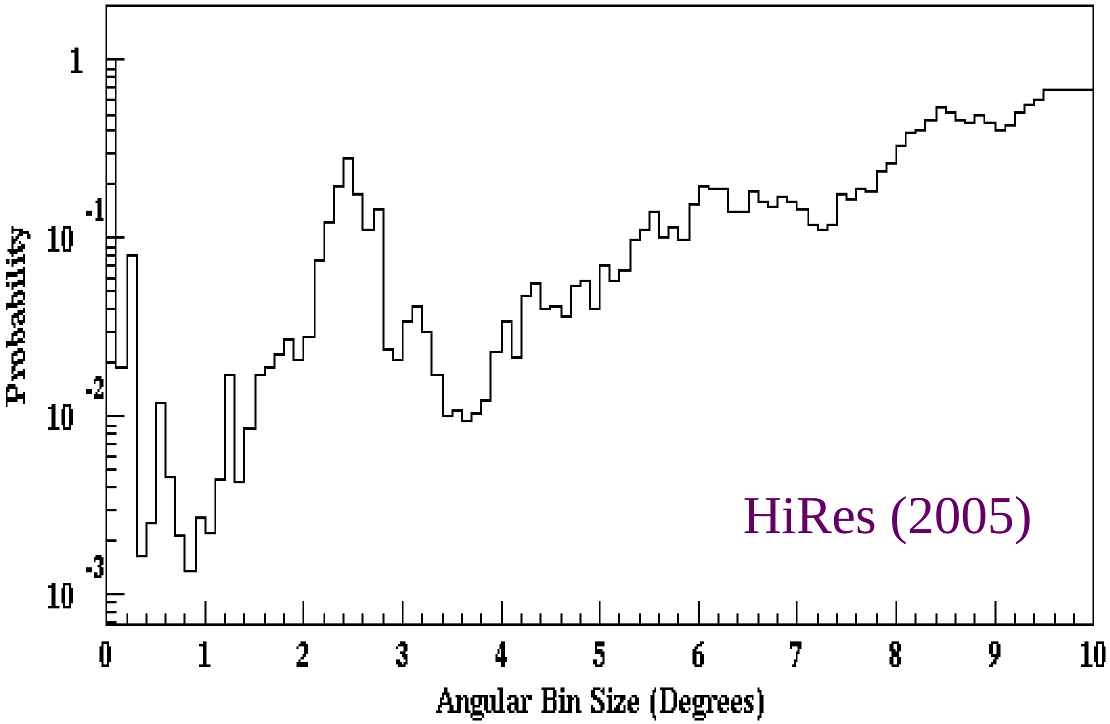
But these BL Lacs are hundreds of Mpc distant!

Few % of primaries must be *neutral* @ 10^{10} GeV

(charged particles would have been deflected by galactic and extragalactic magnetic fields)



Gorbunov, Tinyakov, Tkachev and Troitsky (2004)



HiRes (2005)

Colliders and Cosmic Rays

The Tevatron reaches energies of ~2 TeV

… and the LHC will achieve ~14 TeV

But EeV cosmic ray hitting O or N nucleus in atmosphere

$\Rightarrow$ ~40 TeV centre-of-mass!

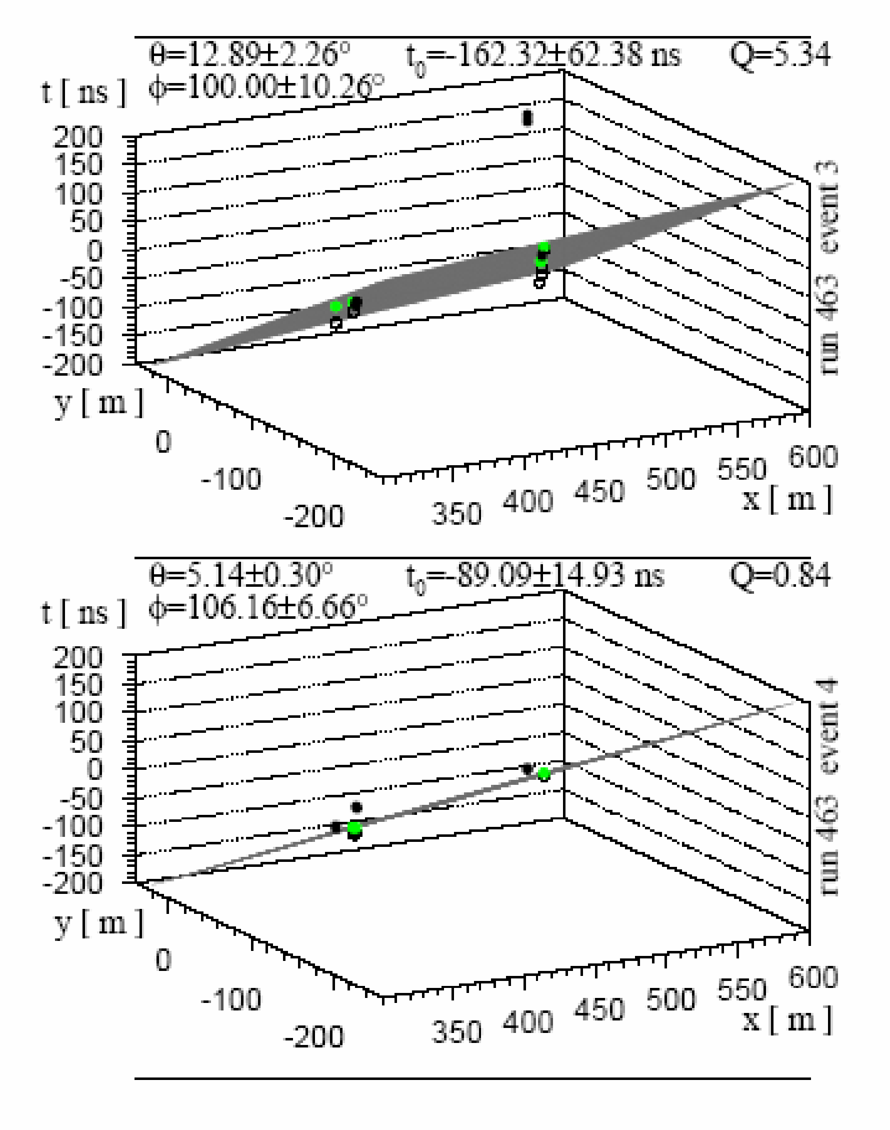
Admittedly the effect of new physics will be rather hard to see in hadron-initiated air showers (#-secn TeV^{-2} vs GeV^{-2})

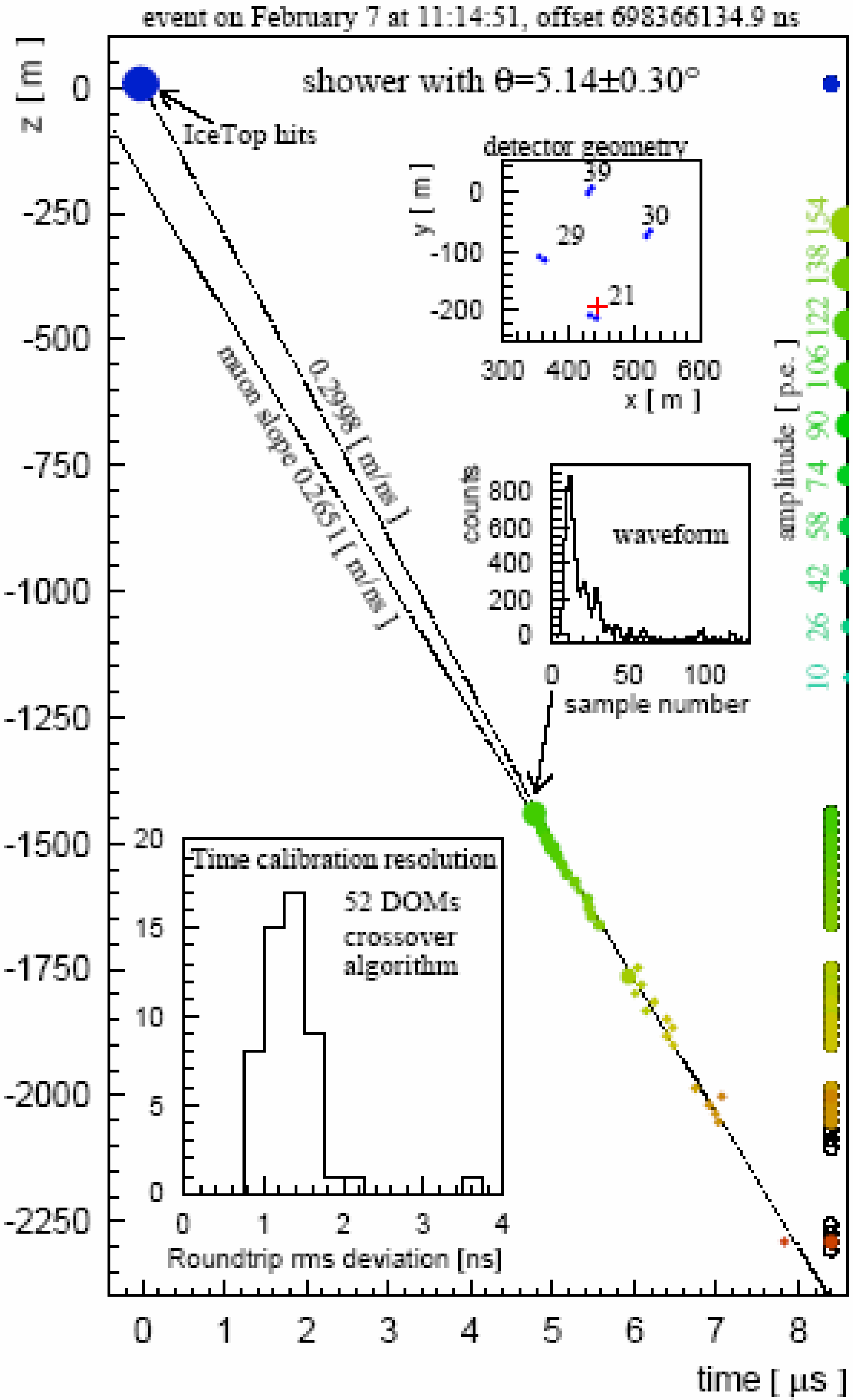
... but may have a dramatic impact on neutrino interactions!

→ can *in principle* probe **beyond the Standard Model** physics by observing **ultra-high energy neutrinos**

This can be done with both km^3 size neutrino detectors (e.g. IceCube) as well as with air shower arrays (e.g. Auger)

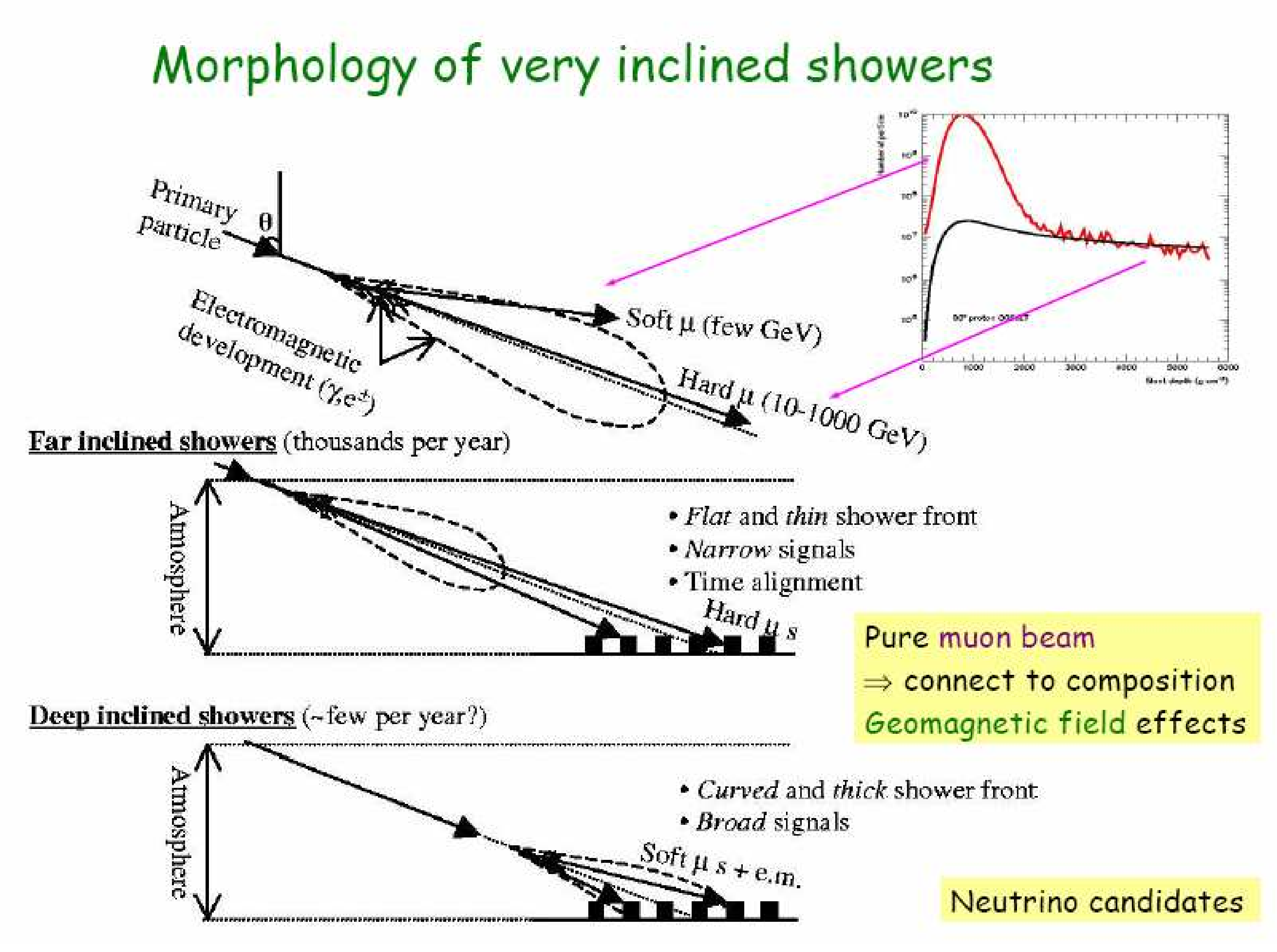
First event (downgoing μ) in IceCube





Auger can see ultra-high energy neutrinos as inclined deeply penetrating showers

Capelle, Cronin, Parente & Zas (1998); Coutu, Bertou & Billoir (1999)



Morphology of very inclined showers

Far inclined showers (thousands per year)

- *Flat* and *thin* shower front
- *Narrow* signals
- Time alignment

Pure muon beam

⇒ connect to composition

Geomagnetic field effects

Deep inclined showers (~few per year?)

- *Curved* and *thick* shower front
- *Broad* signals

Neutrino candidates

… no confirmed neutrino events yet

(Lukas Nellen, ICRC 2005)

Likely sources of UHE cosmic neutrinos

GZK interactions of extragalactic UHECRs on the CMB

(supposedly "guaranteed" cosmogenic neutrino flux … in fact *reduced* if the primaries are heavy nuclei rather than protons)

UHECR candidate accelerators (γ–ray bursts, active galactic nuclei, micro-quasars, …)

("Waxman-Bahcall flux" … note this depends on energy at which extragalactic UHECRs begin to dominate over the galactic flux)

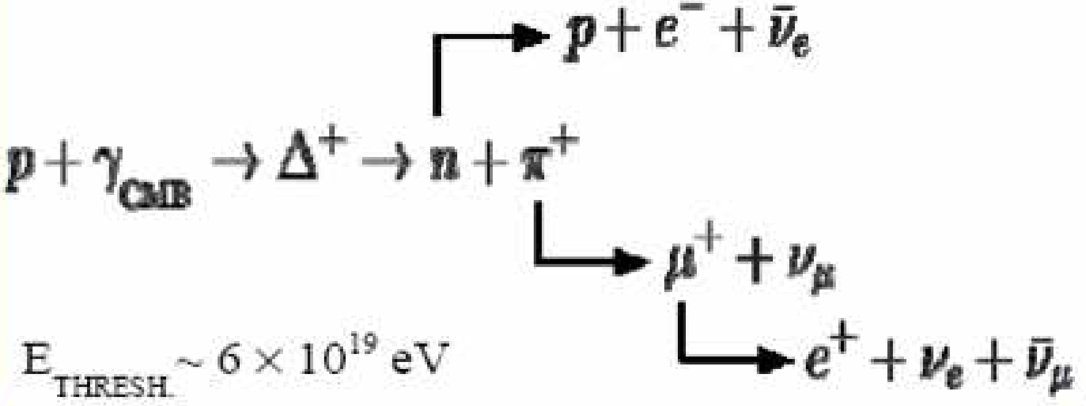
Decays of superheavy dark matter particles

(subject to bound on associated UHE photon flux)

Cosmogenic neutrinos

(courtesey: Dave Waters)

GZK mechanism :



$\rightarrow p + e^- + \bar{\nu}_e$

$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$

$\rightarrow \mu^+ + \nu_\mu$

$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

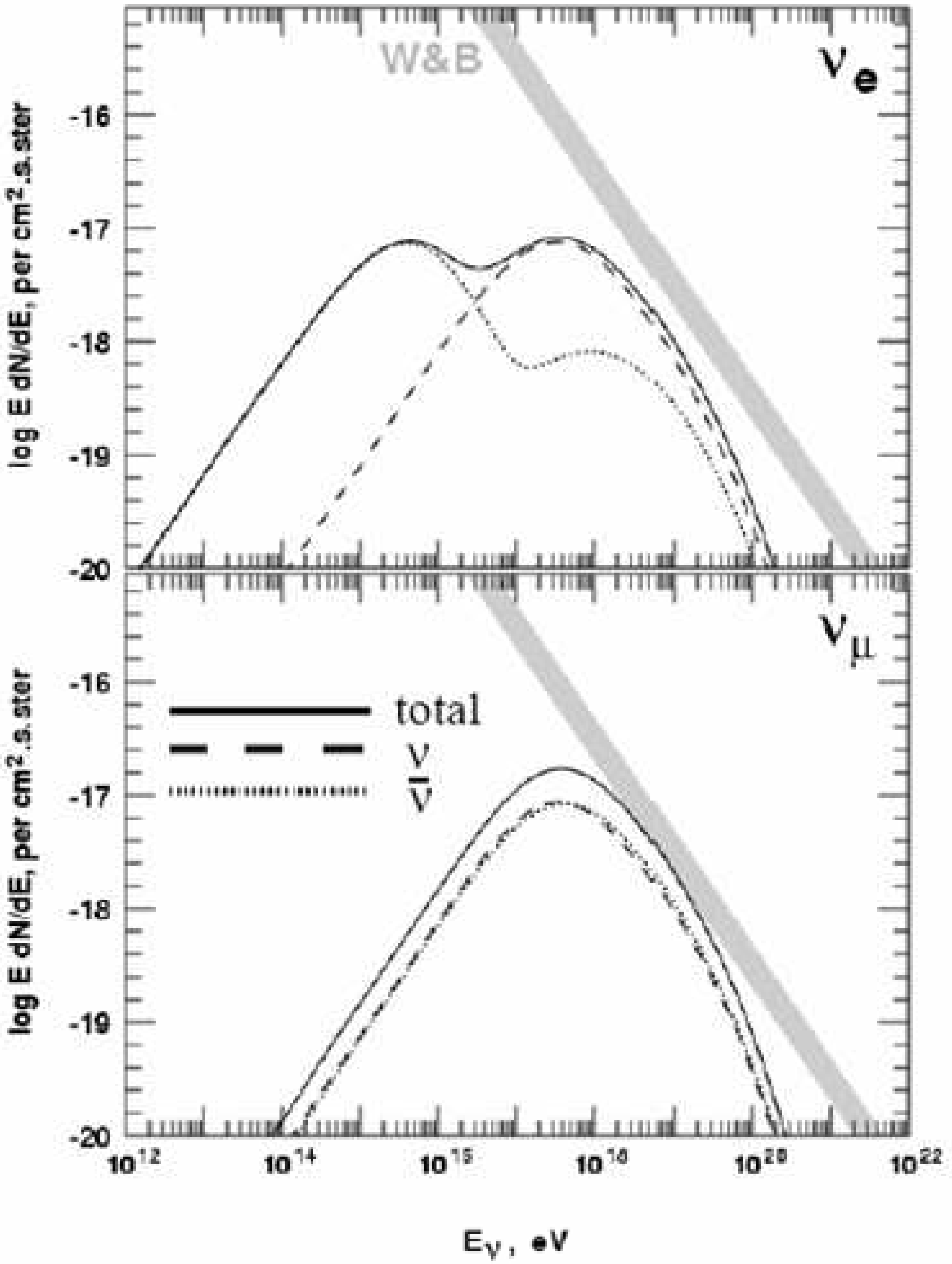
$E_{THRESH} \sim 6 \times 10^{19}$ eV

- Uncertainties in flux calculations :
  - UHECR luminosity; $\rho_{CR}(\text{local}) \neq \langle\rho_{CR}\rangle$
  - injection spectrum
  - cosmological evolution of sources
  - IRB & optical density of sources

↓

factors of ~2 uncertainty each;
factor of ~4 overall (?)

Engel, Seckel, Stanev (2001)



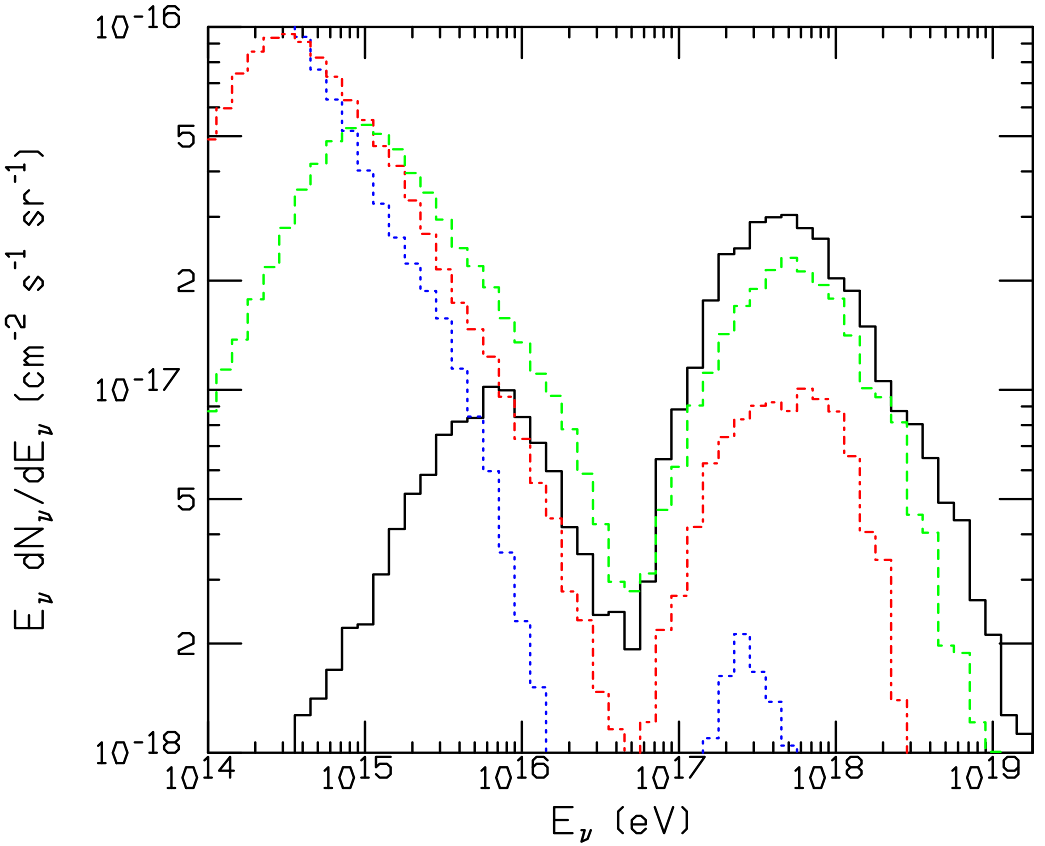
But the nature of the primaries is crucial – if Fe instead of p, then would rather photodissociate rather than produce π's so 'guaranteed' ν flux will be *reduced*

The nucleons from their break up can create π's only if above the GZK threshold so the EeV neutrino peak from pion decays is depressed but the additional neutrons from photodisintegrations β-decay to boost the PeV neutrino peak

(Hooper, Sarkar & Taylor 2004; Ave, Busca, Olinto & Watson 2004)

Event rates/yr in km^3 detector

Primaries	Showers	Muons (>PeV)	Muons (>10 TeV)
p	0.57	0.72	1.16
^{4}He	0.42	0.50	0.80
^{16}O	0.19	0.23	0.73
^{56}Fe	0.036	0.042	0.17



The sources of cosmic rays must also be sources of neutrinos

Waxman-Bahcall Bound :

- $1/E^2$ injection spectrum (Fermi shock).
- Neutrinos from photo-meson interactions in the source.
- Energy in ν's related to energy in CR's :

$$E_\nu^2\,\mathrm{d}N_\nu/\mathrm{d}E_\nu \sim 0.25 \times \epsilon \times t_H \times E_{CR}^2\,\mathrm{d}\dot{N}_{CR}/\mathrm{d}E_{CR}$$

Fraction of CR primary energy converted to neutrinos

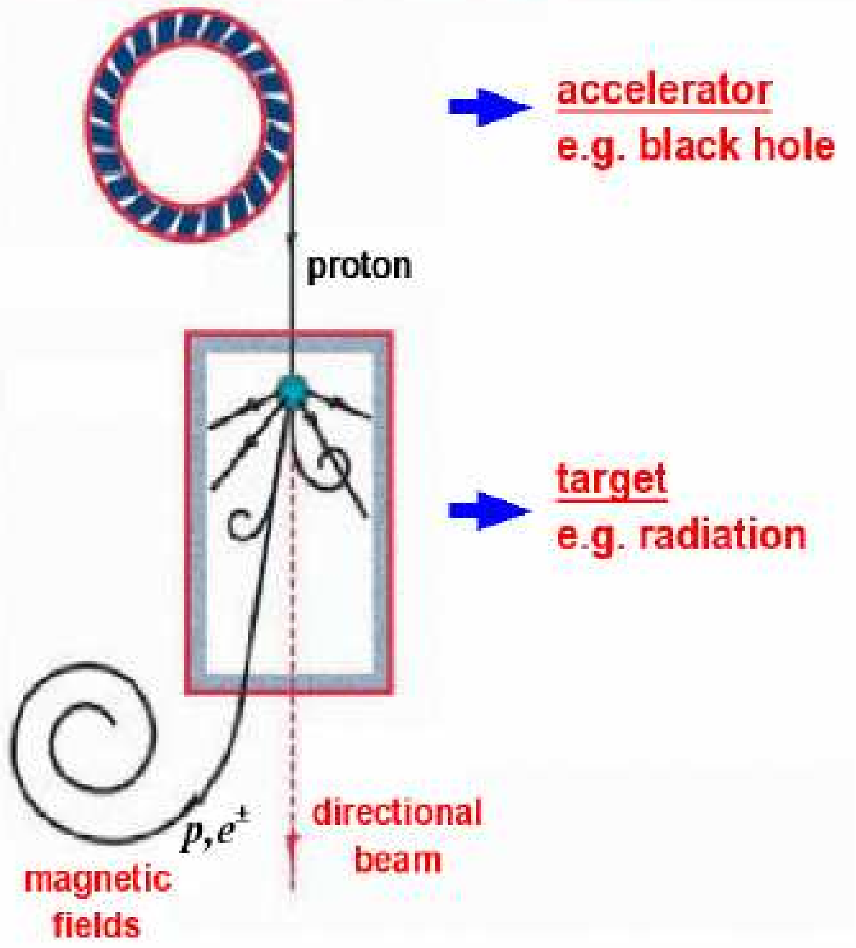
Hubble time

From rate of UHE CR's (10^{19}-10^{21} eV)

$$\Rightarrow \quad E_\nu^2\Phi_\nu \lesssim 5\times10^{-8}\ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

- *Many* qualifications and caveats.
- Can be evaded if :
  - sources are optically thick
  - neutrinos from other sources ("top-down")

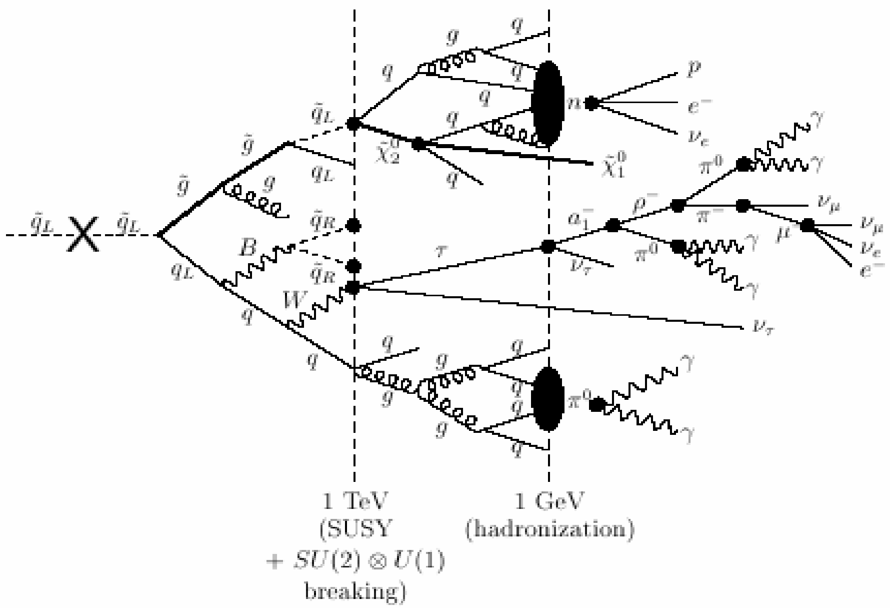
COSMIC BEAM DUMP : SCHEMATIC



(courtesey: Dave Waters)

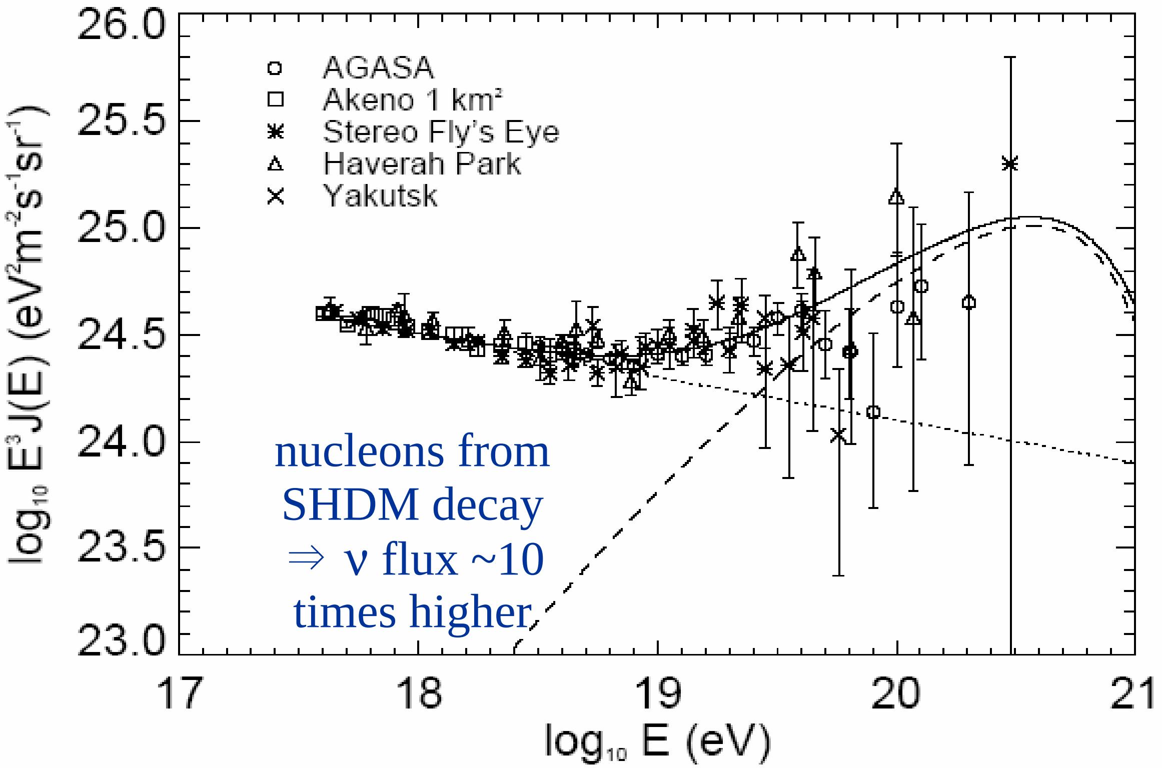
UHE neutrinos from the decay of superheavy dark matter

X → partons → jets (→ ~90% ν, ~5-9% γ, rest ~1% nucleons)



Perturbative evolution of parton cascade
… tracked by DGLAP equation

Non-perturbative fragmentation
… modelled semi-empirically



nucleons from SHDM decay ⇒ ν flux ~10 times higher

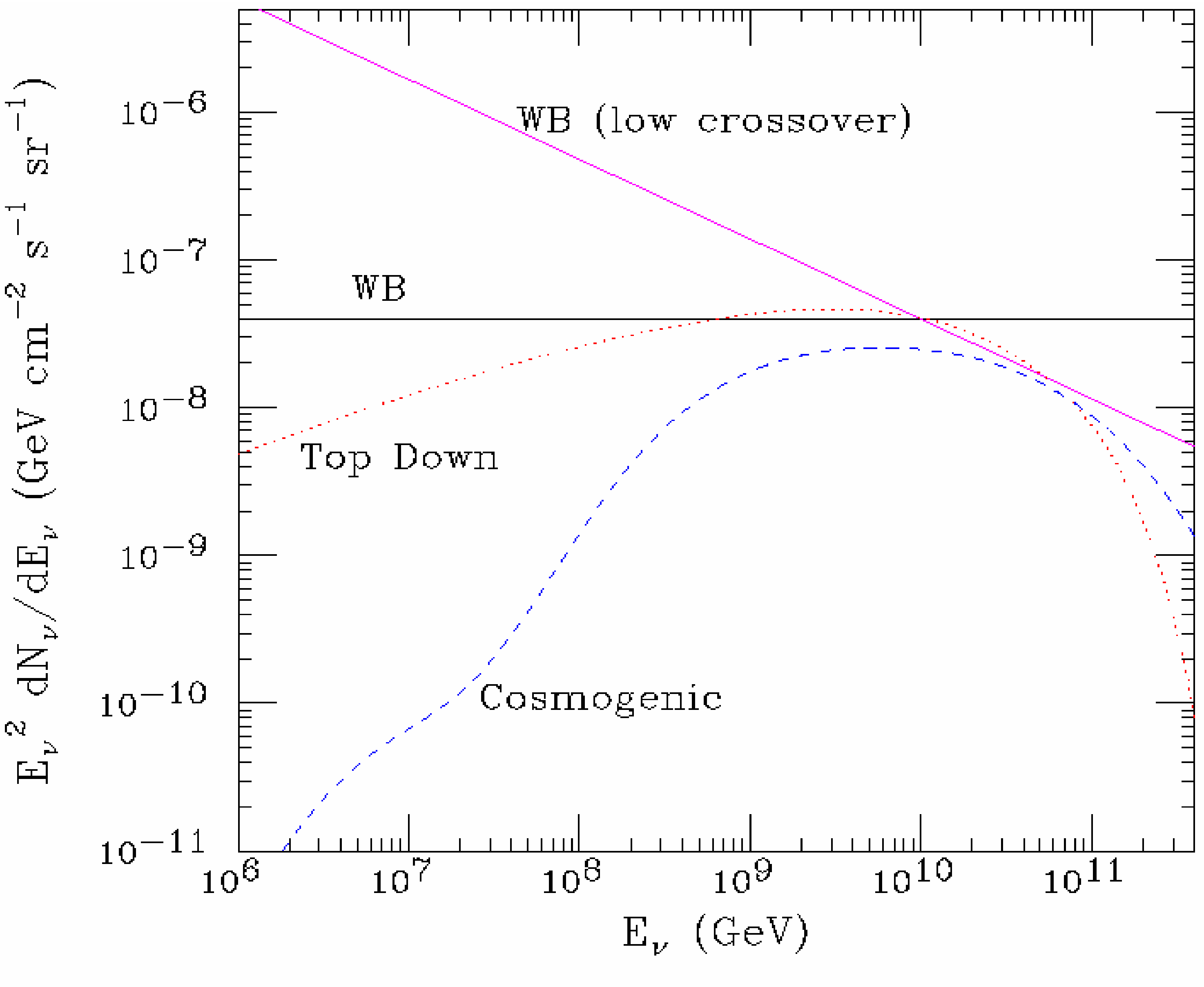
FIG. 8. The best SUSY evolution fit to the cosmic ray data with a decaying particle mass of 5×10^{12} GeV. The dotted line indicates the extrapolation of the power-law component from lower energies, while the dashed line shows the decay spectrum; the solid line is their sum.

The fragmentation spectrum matches the AGASA data at trans-GZK energies

Normalisation to the observed flux requires: $\tau_x \sim 2 \times 10^{19}$ yr

(Fodor, Katz 2001; Toldra, Sarkar 2002; Barbot, Drees 2003; Aloisio, Berezinsky, Kachelreiss 2004)

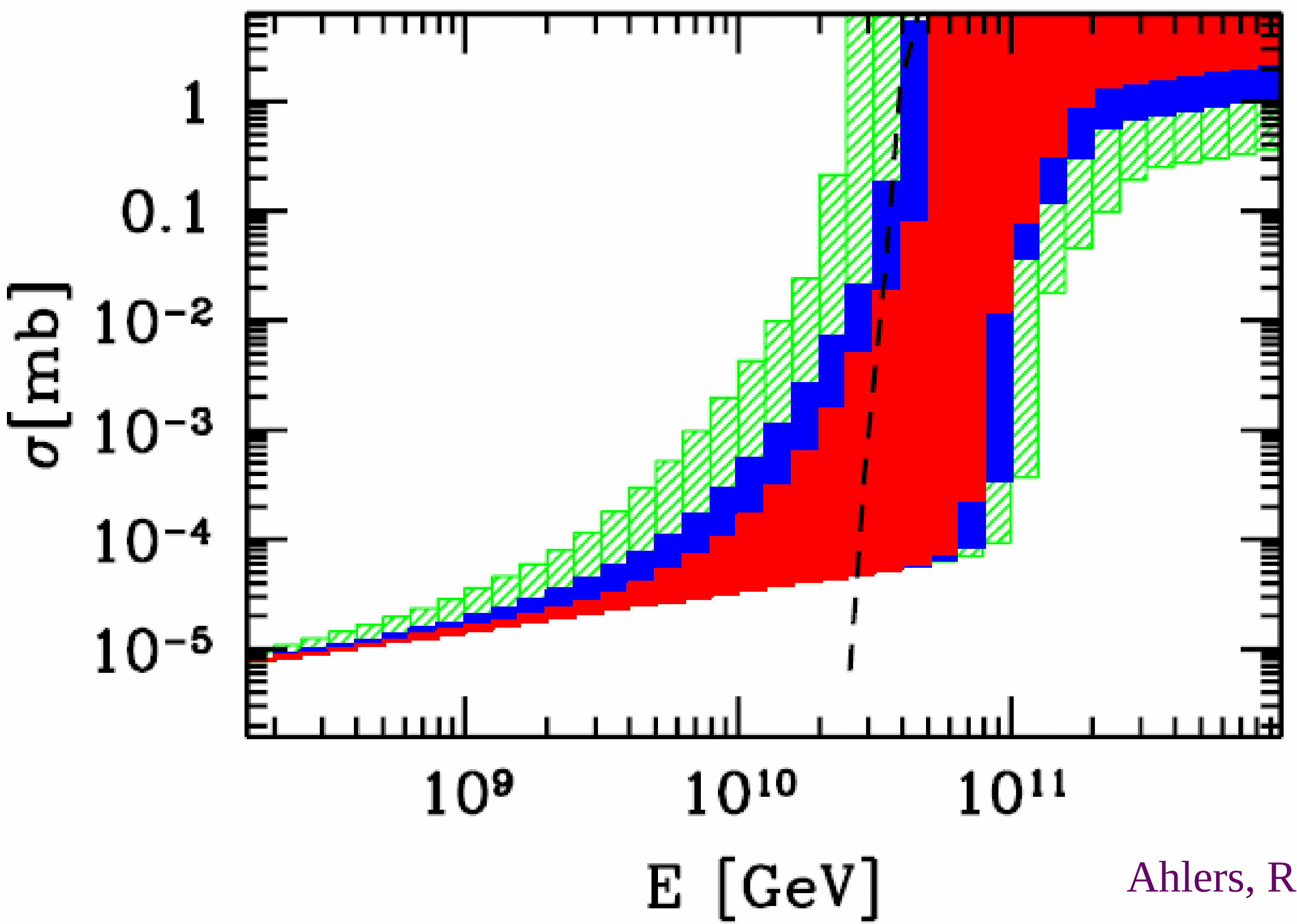
Expected UHE cosmic neutrino fluxes



Limit from AMANDA/IceCube on the diffuse ν flux can potentially constrain models in which extragalactic sources are assumed to dominate at energies as low as ~10^{18} eV (Ahlers *et al* 2005)

Electroweak instanton-induced interactions in the SM

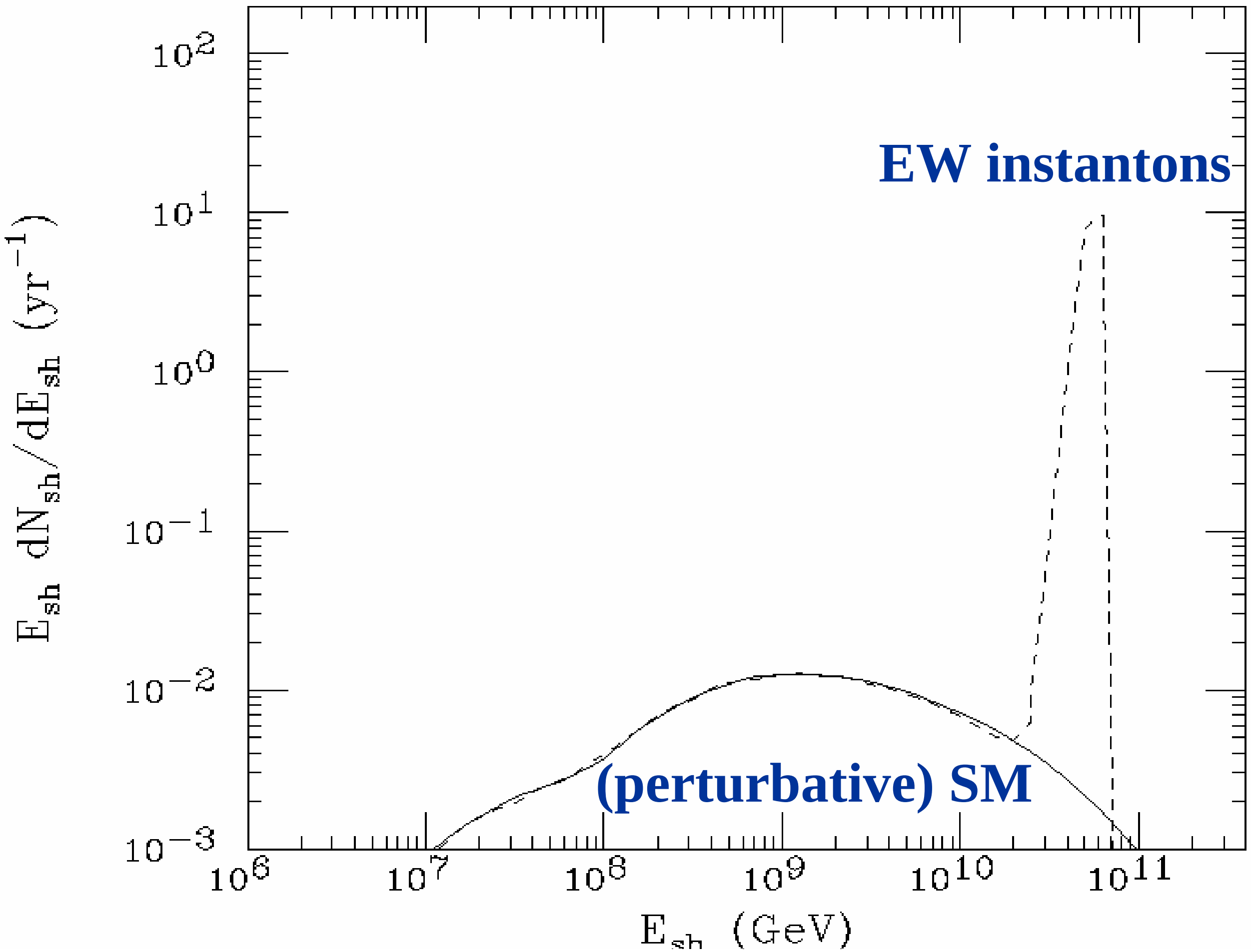
Non-perturbative transitions between degenerate SM vacuua (with different B+L #)
are exponentially suppressed below the "sphaleron" mass: $\pi M_W/\alpha_W \sim 8$ TeV
… but *huge* cross-sections are predicted for ν-N scattering at higher cms energies
(would enable neutrinos to generate apparently hadronic super-GZK air showers)



Ahlers, Ringwald & Tu (2005)

EW instantons at Auger

Quasi-horizontal ν showers (assuming cosmogenic flux)

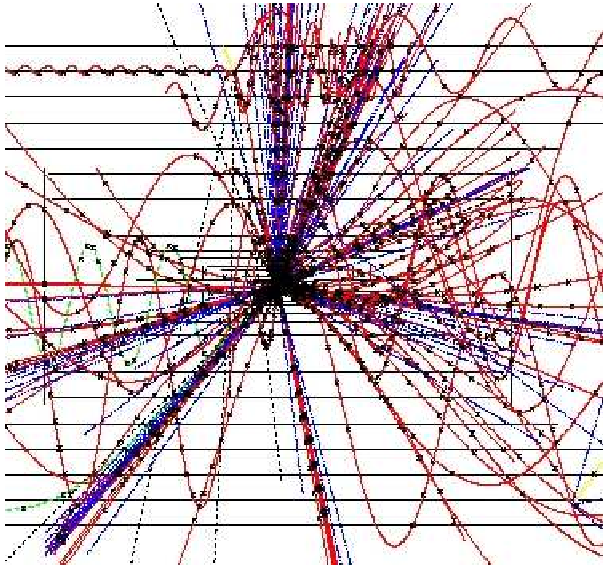


Large deviations from perturbative SM expected above 10^{10} GeV …
predict 4.3 QH showers/yr ⇒ 60 times more than for CC/NC alone

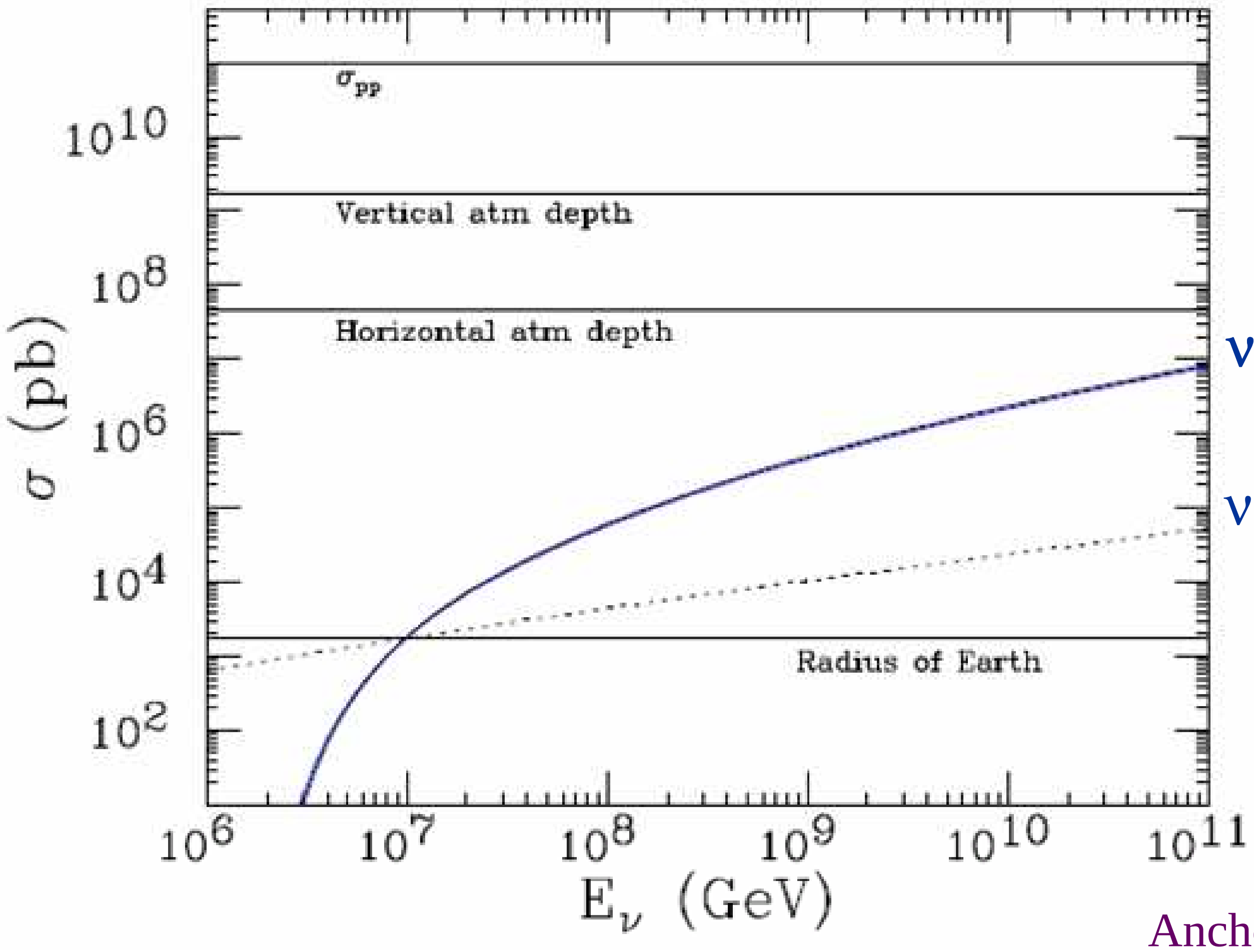
… Auger will soon give the answer

Anchordoqui, Han, Hooper & Sarkar (2005)

If gravity becomes strong at the TeV scale (as in some braneworld models) then at cms energies well *above* this scale, **black holes** will be formed with $M \sim \sqrt{\hat{s}}$ and $\sigma \sim \pi R^2_{\text{Schwarzschild}}$



De Rocek (2002)



νN: TeV QG

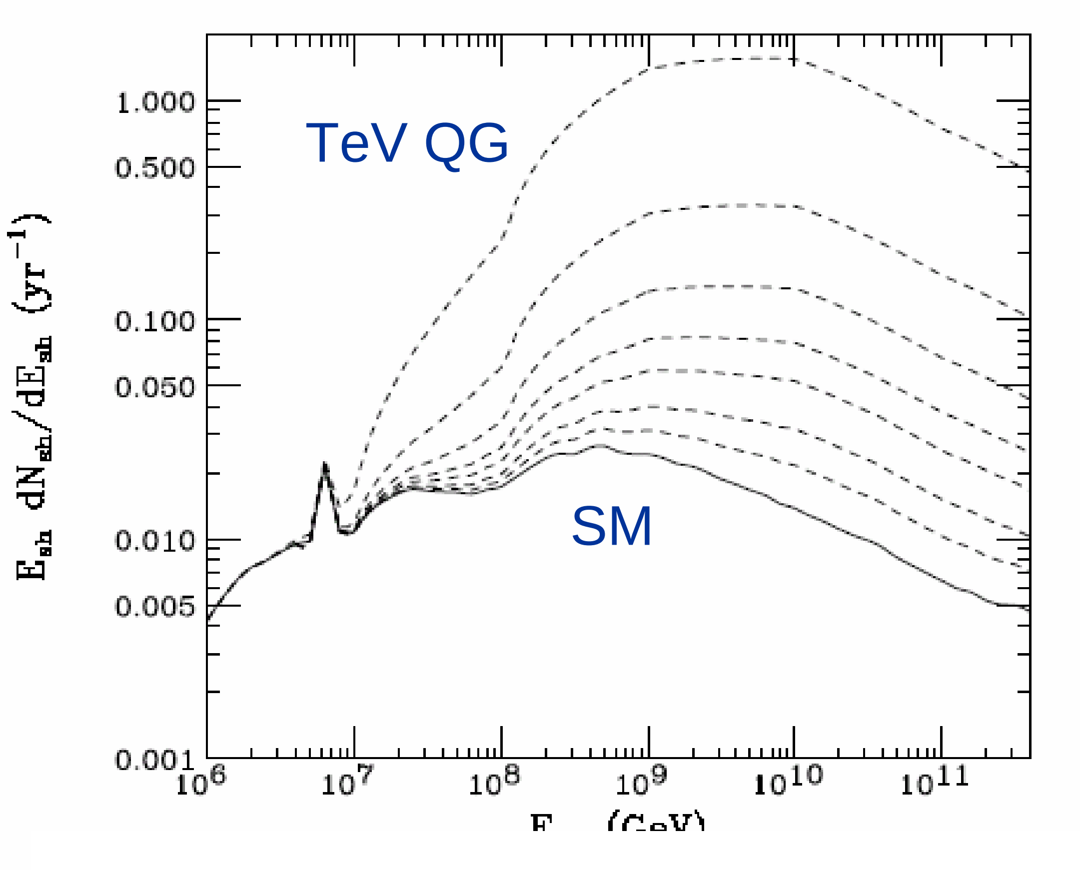
νN: SM

will rapidly evaporate by Hawking radiation (+ gravitational waves?)

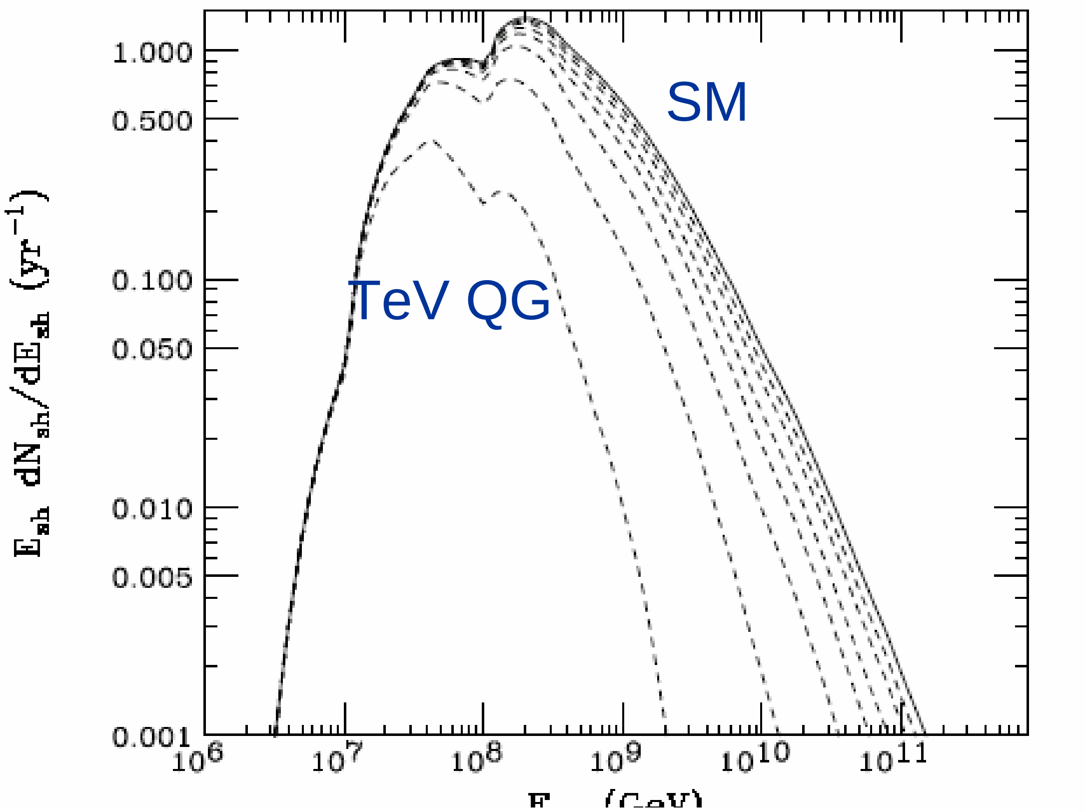
Anchordoqui, Feng, Goldberg & Shapere (2002)

Testing TeV scale quantum gravity (assuming WB flux)

Quasi-horizontal ν showers



Earth-skimming ν_τ showers



Auger is well suited for probing microscopic black hole production

QH/# ES= 0.04 for SM, but 10 for 1 TeV Planck scale!

Anchordoqui, Han, Hooper & Sarkar (2005)

Very Long Baseline Measurements

Low energy neutrino experiments have a sensitivity of at most:

$\Gamma/m \sim 10^{-4}$ sec/eV … for Solar neutrinos

High energy cosmic neutrinos can improve on this by a factor of:

$\sim 10^6$ (L/100 Mpc) (100 TeV/E)

$\Rightarrow$ powerful probe of neutrino decay, possible low energy effects of quantum gravity (decoherence, violation of Lorentz invariance)

Astrophysical accelerators generate neutrinos through charged pion decay:

$\pi^{+/-} \Rightarrow \mu\, \nu_\mu \Rightarrow e\, \nu_e\, \nu_\mu\, \nu_\mu$ so neutrinos produced in the ratio: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

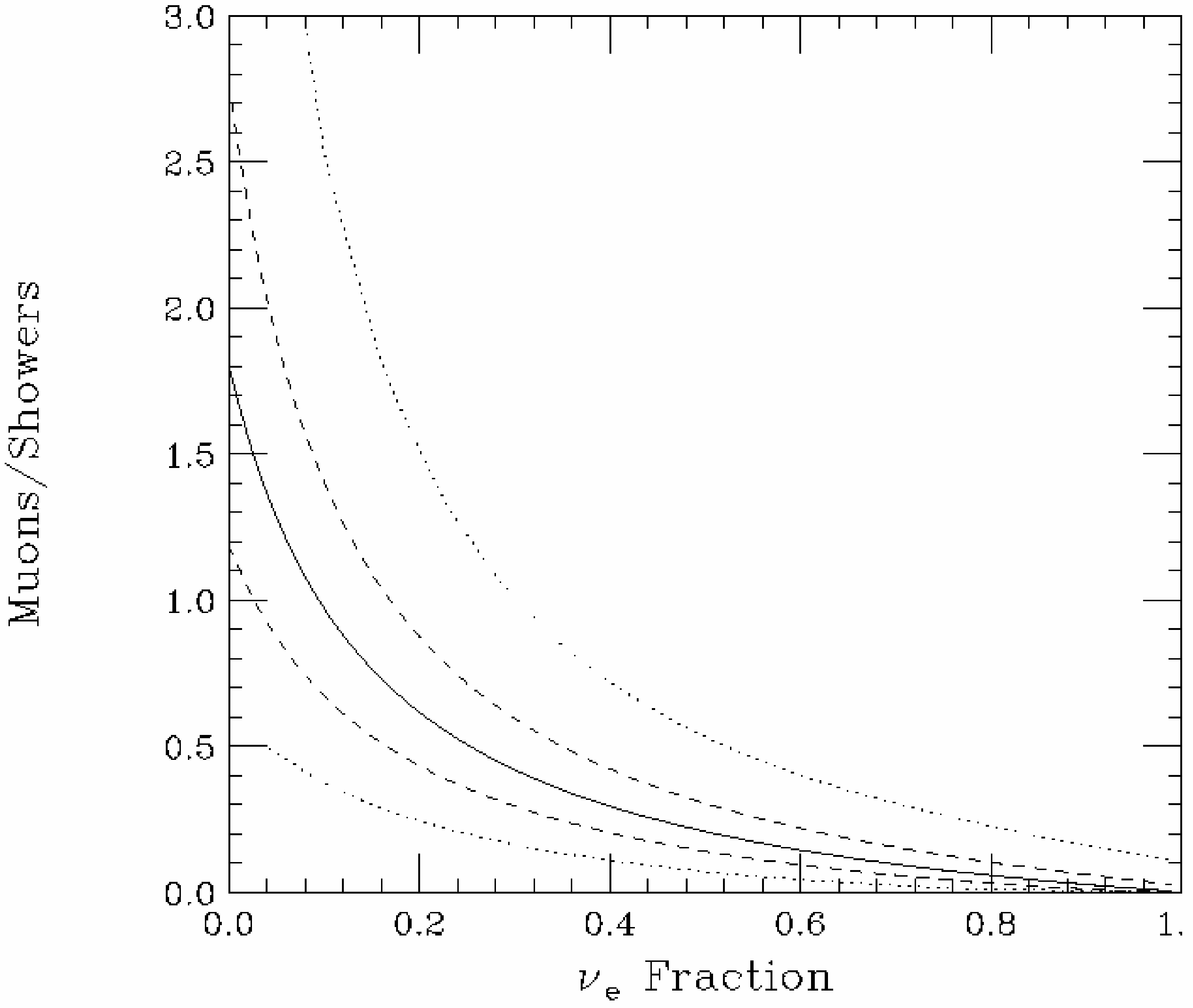
After flavour equilibration through oscillations, this becomes: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

caveat: possibly → 1:1.8:1.8 at energies >100 TeV (Kashti & Waxman 2005)

Flavour ratios at IceCube

Ratio of muons to showers translates into flavor ratio

Example: TeV threshold, $E^2\, dN/dE = 10^{-7}$, 2×10^{-8} GeV cm^{-2} s^{-1}



Beacom, Bell, Pakvasa, Hooper and Weiler (2004)

Summary

Prospects are good for the identification of the sources of medium energy cosmic rays by γ–ray astronomy ... but more work is needed on theory

Auger will soon answer crucial questions about the energy spectrum, composition and anisotropies of ultra-high energy cosmic rays

… the theoretical situation is even more challenging

The detection of ultra-high energy cosmic neutrinos is eagerly anticipated – will provide complementary information and identify the sources

Cosmic ray and neutrino observatories also provide an unique laboratory for tests of new physics beyond the Standard Model

> *“The existence of these high energy rays is a puzzle, the solution of which will be the discovery of new fundamental physics or astrophysics”*
>
> Jim Cronin (1998)