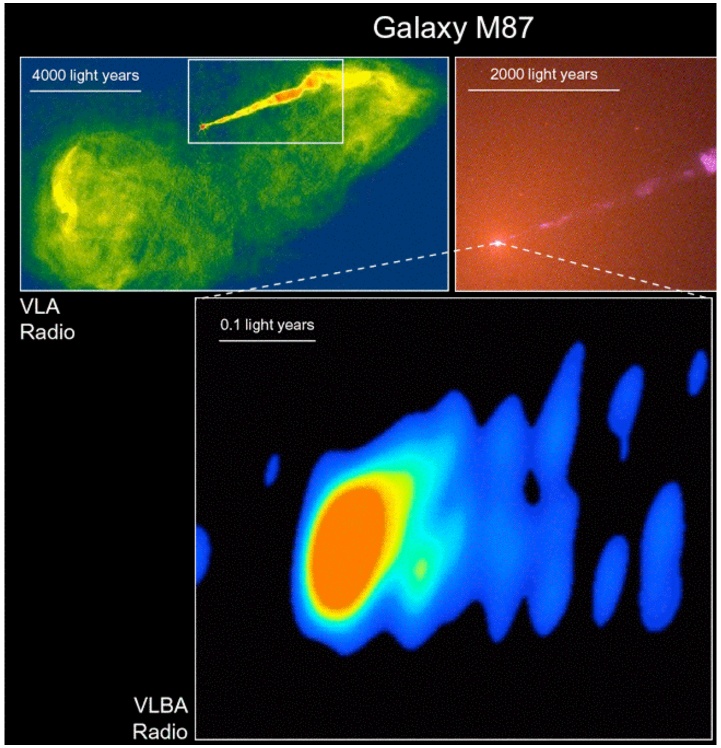
High Energy Astroparticle Physics
The theoretical viewpoint



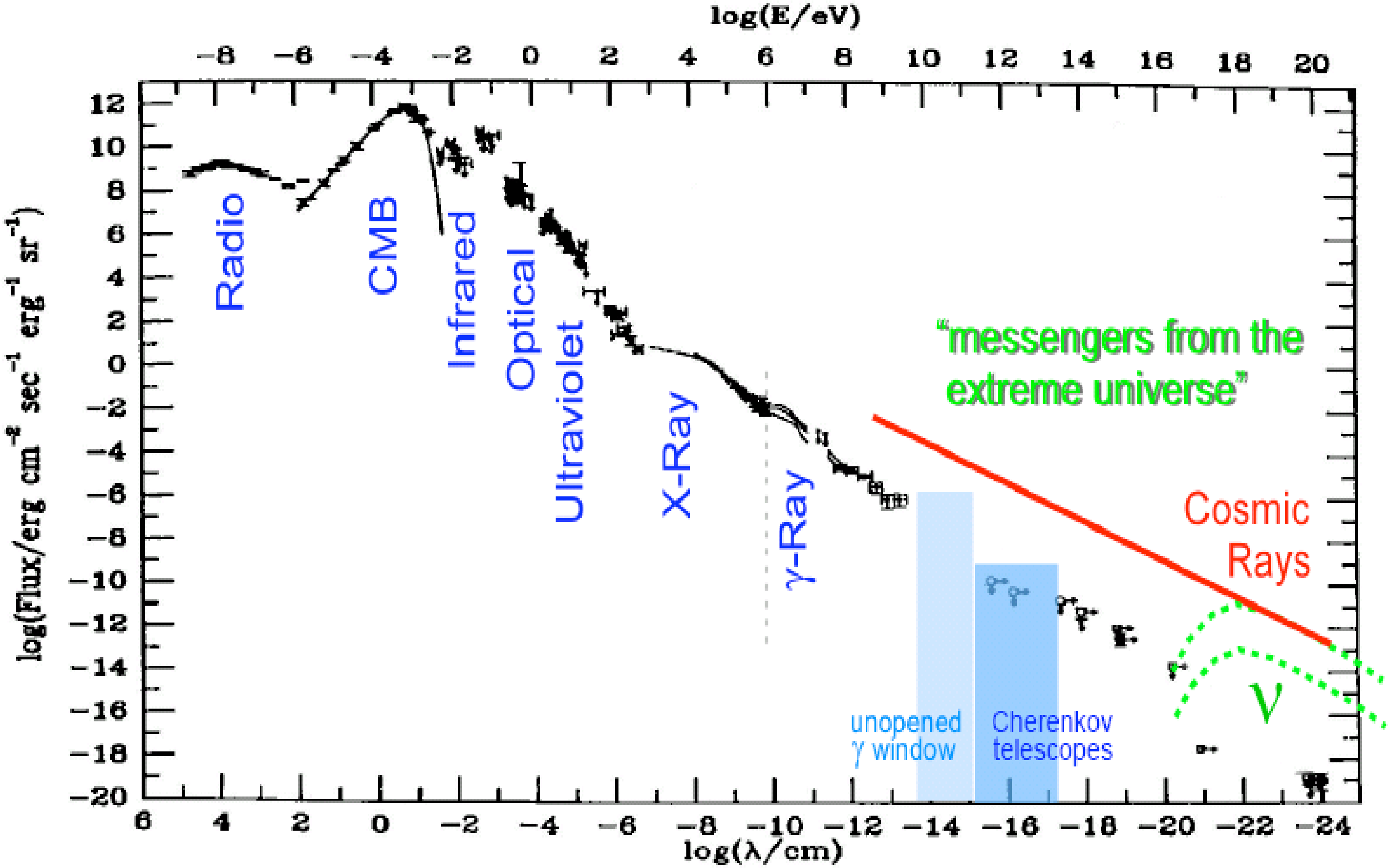
Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics, Oxford

ASPERA *Preparatory Workshop for the Astroparticle Roadmap Phase II*, Paris, 19-20 July 2007

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

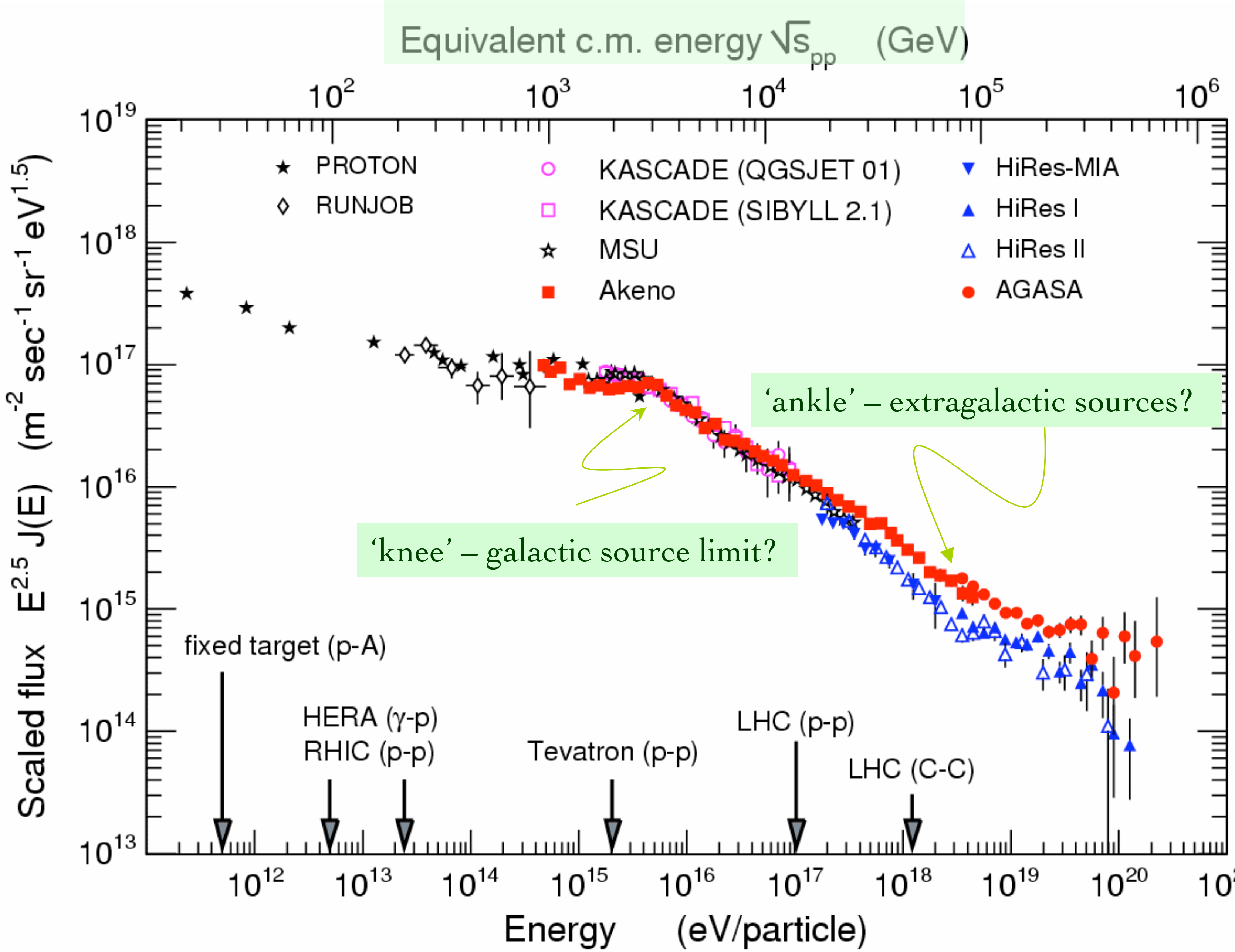
… beyond this energy they are attenuated through $\gamma\gamma \rightarrow e^+e^-$ on the CIB/CMB



But using **cosmic rays** we should be able to 'see' up to ~6 x 10^{10} GeV (before they get attenuated through $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$ … on the CMB)

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

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



(courtesey: Ralph Engel)

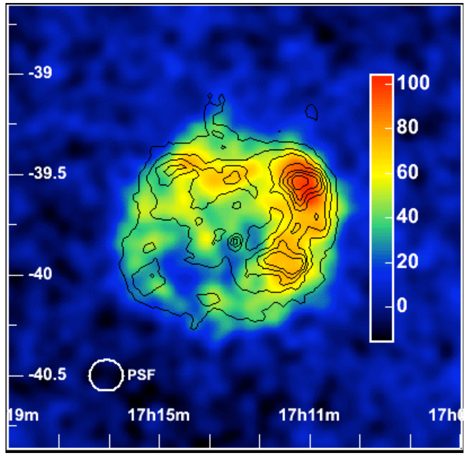
We are witnessing a renaissance in γ-ray astronomy

→ the sources of low energy cosmic rays may soon be known – **SNRs**?

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

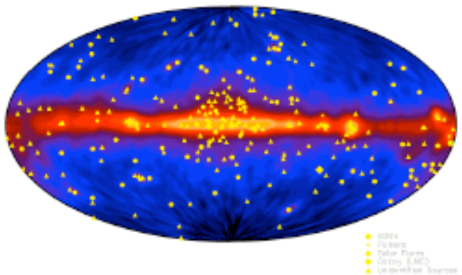
➢ Can 1st-order Fermi acceleration at SNR shocks explain the spectrum (injection, magnetic field amplification, diffusion losses vs anisotropy) ?

➢ What are the 'unidentified' γ-ray sources in the Milky Way – are there new source classes (micro-quasars, PWNs, binaries …), acceleration mechanisms ?

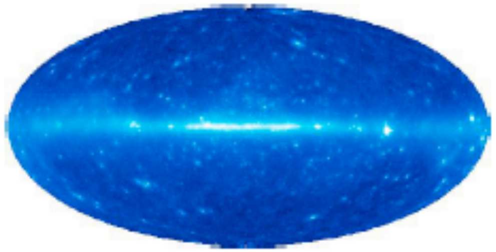


RXJ1713.7-3946 (HESS 2004)

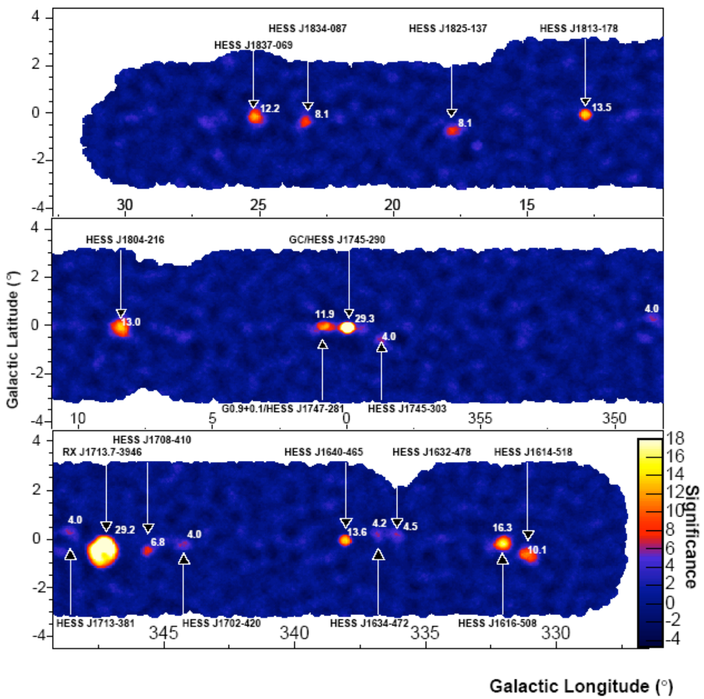
EGRET 1991 - 2000



GLAST 2007 - ?

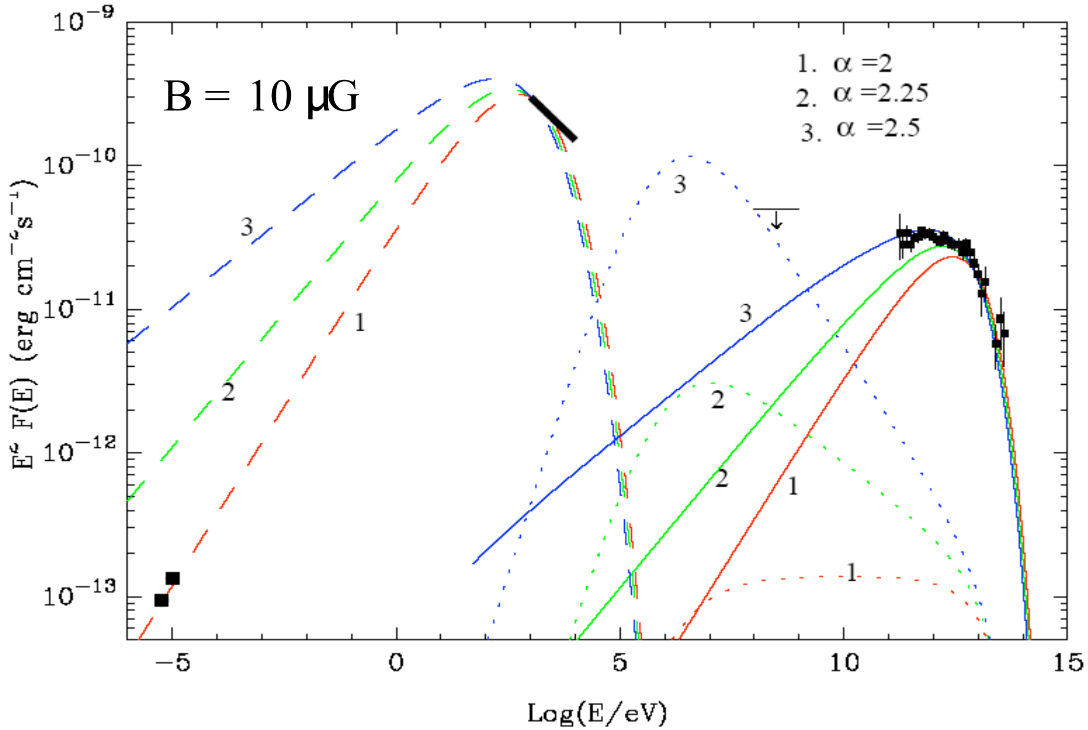


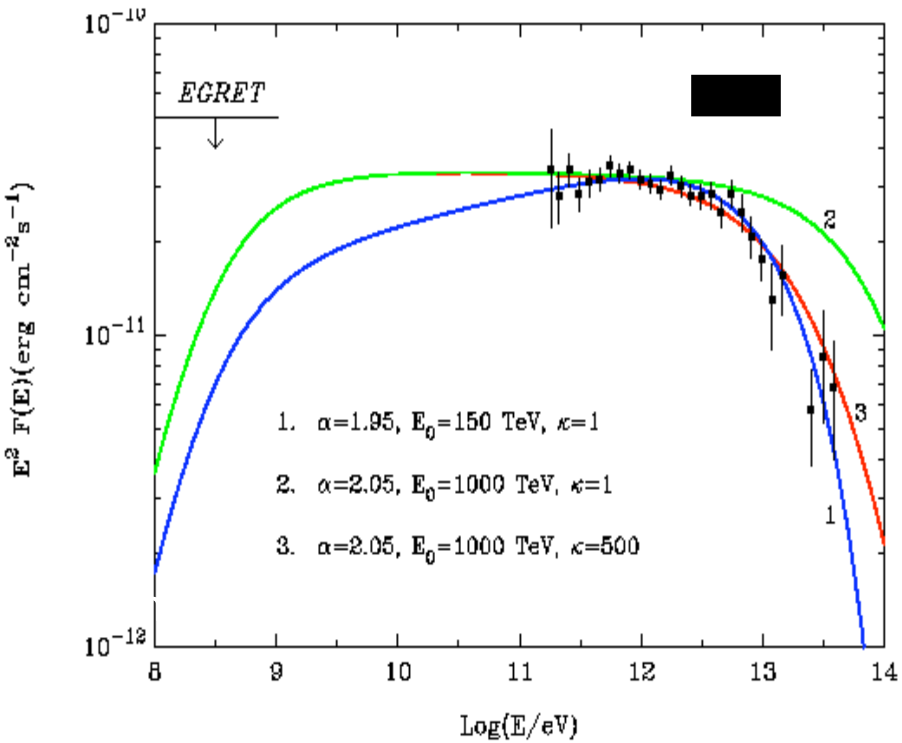
HESS Southern Plane Survey 2005



Much progress has been made but these questions are *not* yet fully answered … to *unambiguously* identify the cosmic ray sources, we need observations of **TeV neutrinos** and also **better theory**!

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

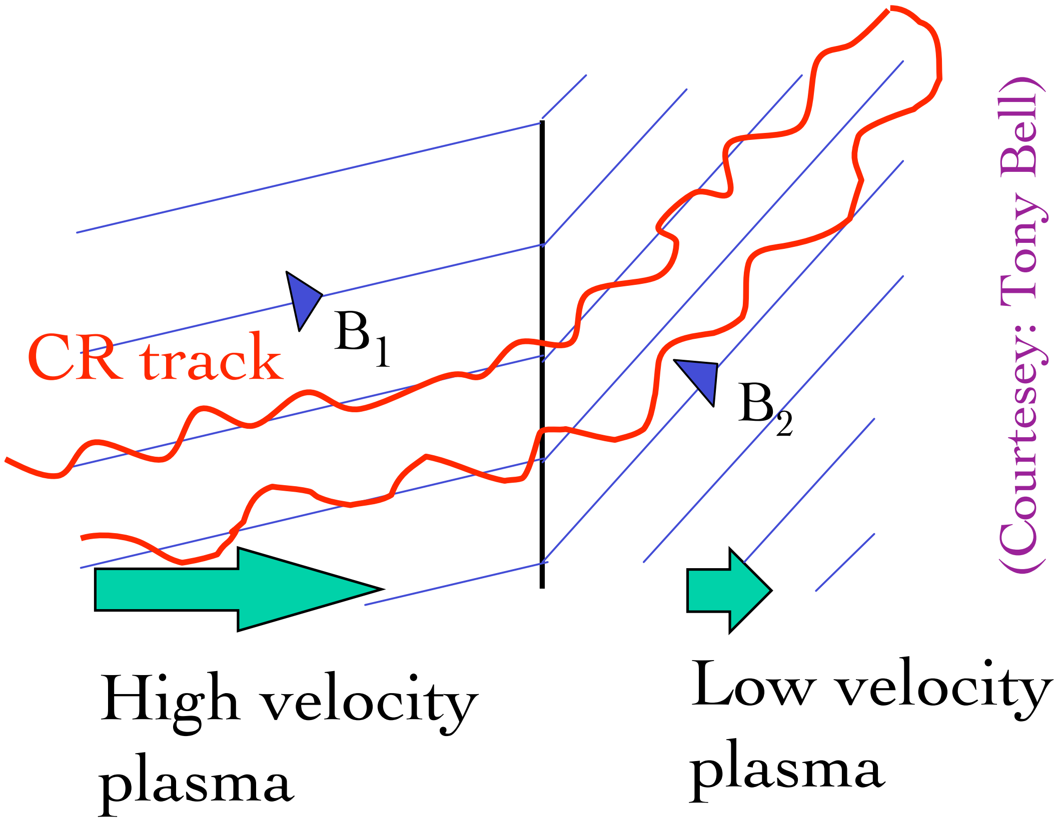




γ-ray emission well fitted by IC scattering of ~10^2 TeV electrons on CMB/starlight … alternatively γ-rays may be from decays of π^0s produced by ~10^3 TeV protons

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

1^{st}-order Fermi acceleration



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

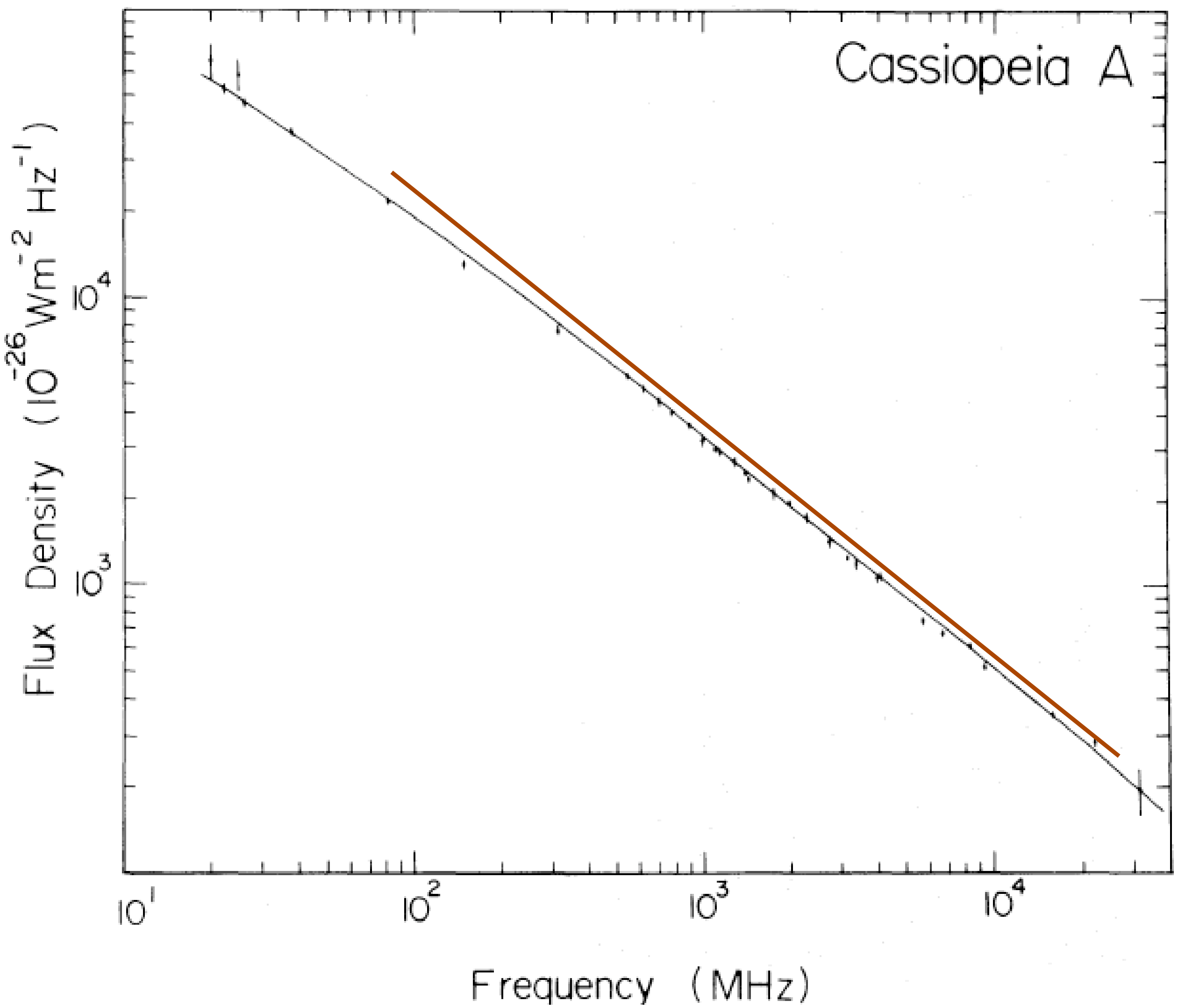
Invoking diffusion loss time-scale $\propto \varepsilon^{-0.7}$ can *match* the observed spectrum $\propto \varepsilon^{-2.7}$

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⇒*concave* spectra cf. observed *convexity*..

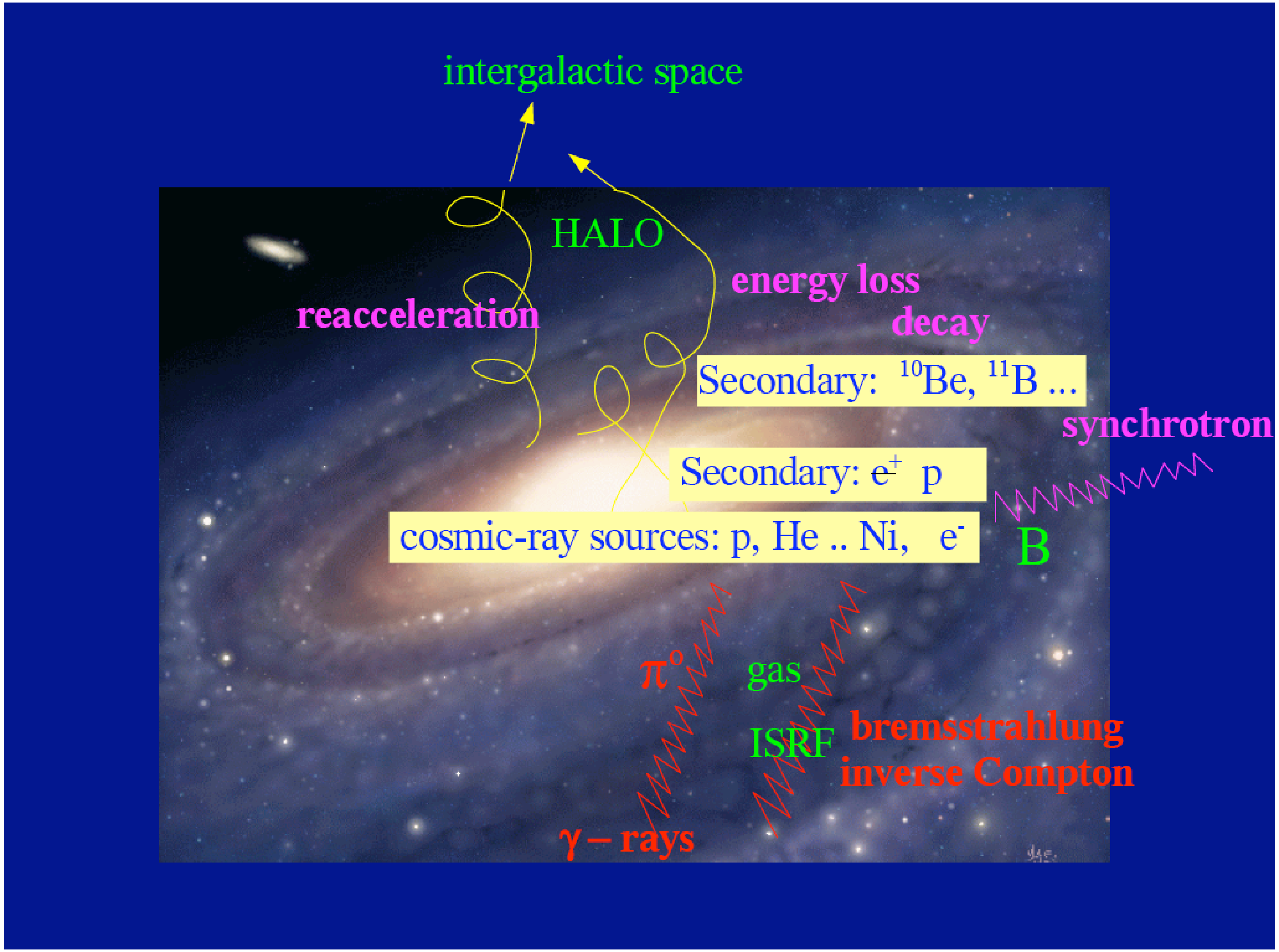
The synchrotron radio spectrum of young SNRs is a *convex* power-law



… perfectly fitted by the evolving ~**log-normal spectrum** expected from *2nd order* Fermi acceleration by MHD turbulence *behind* the shock wave (Cowsik & Sarkar 1984)

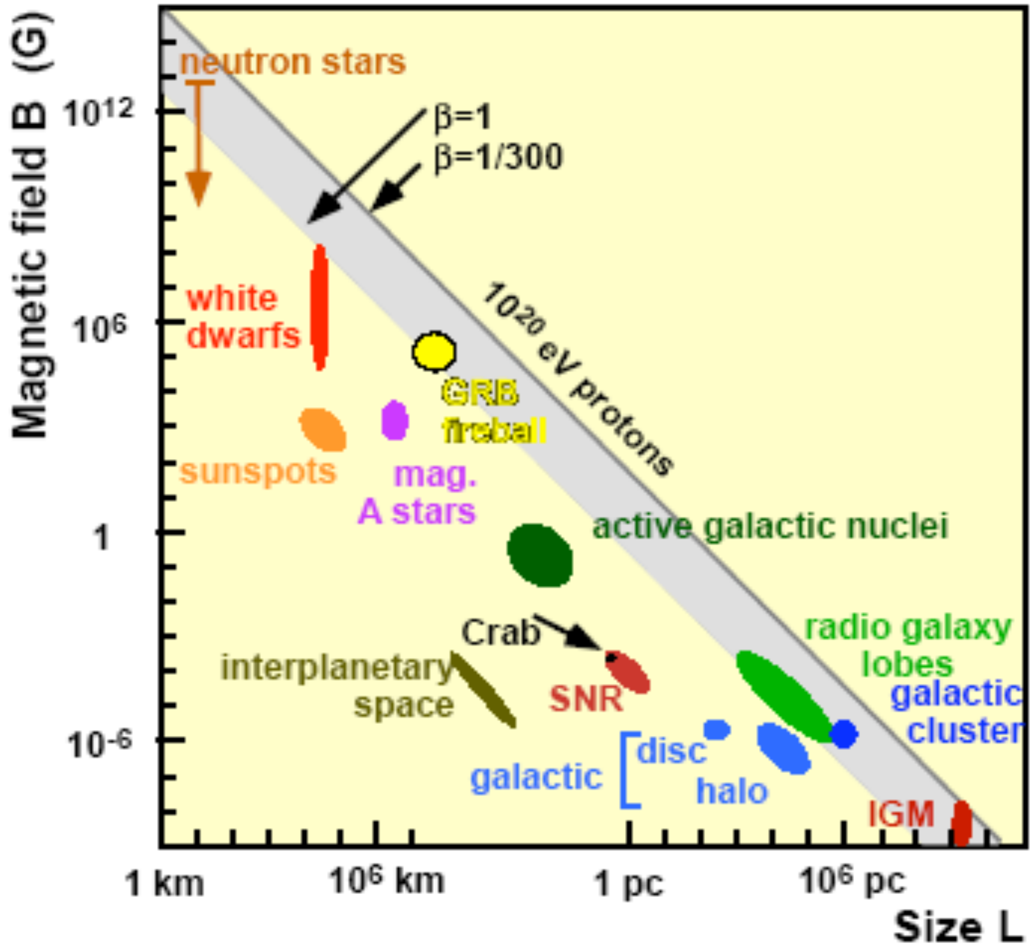
But efficient diffusive shock acceleration should give a *concave* spectrum!

GALPROP: 'Standard model' of cosmic ray propagation in the Galaxy which "fits" all the data (Strong & Mosalenko 1996 -)



New experimental data (*CREAM*, *RUNJOB*, …*IceTop*) needed to *test* the model

Are there plausible accelerators for the highest energy cosmic rays?



A.M. Hillas 1984

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

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

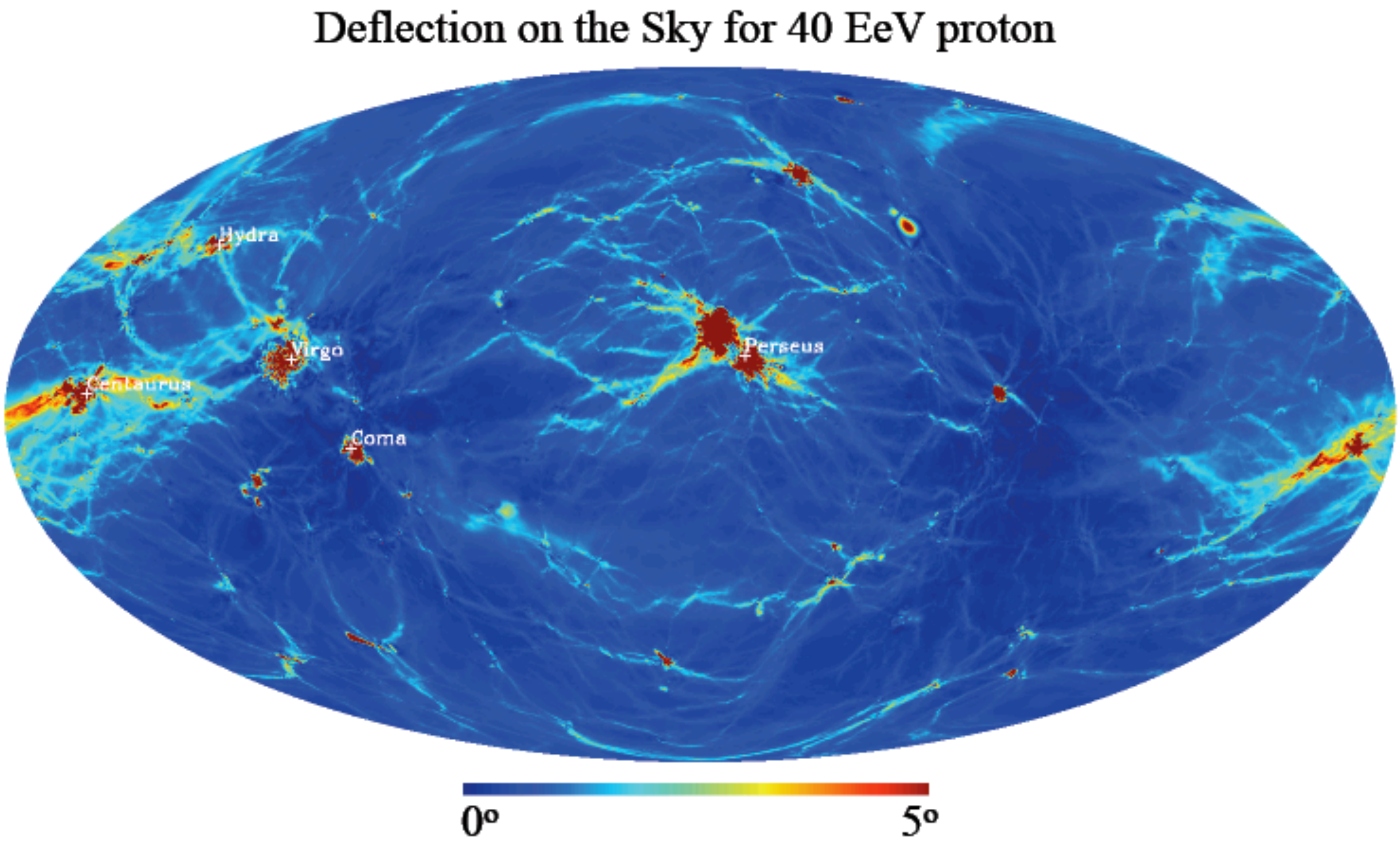
to fit gyro radius within L and to allow particle to wander during energy gain

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

▶ If their sources are nearby, why do the trajectories not point back to them?

▶ If they are far away then how do these particles get to us through the CMB?

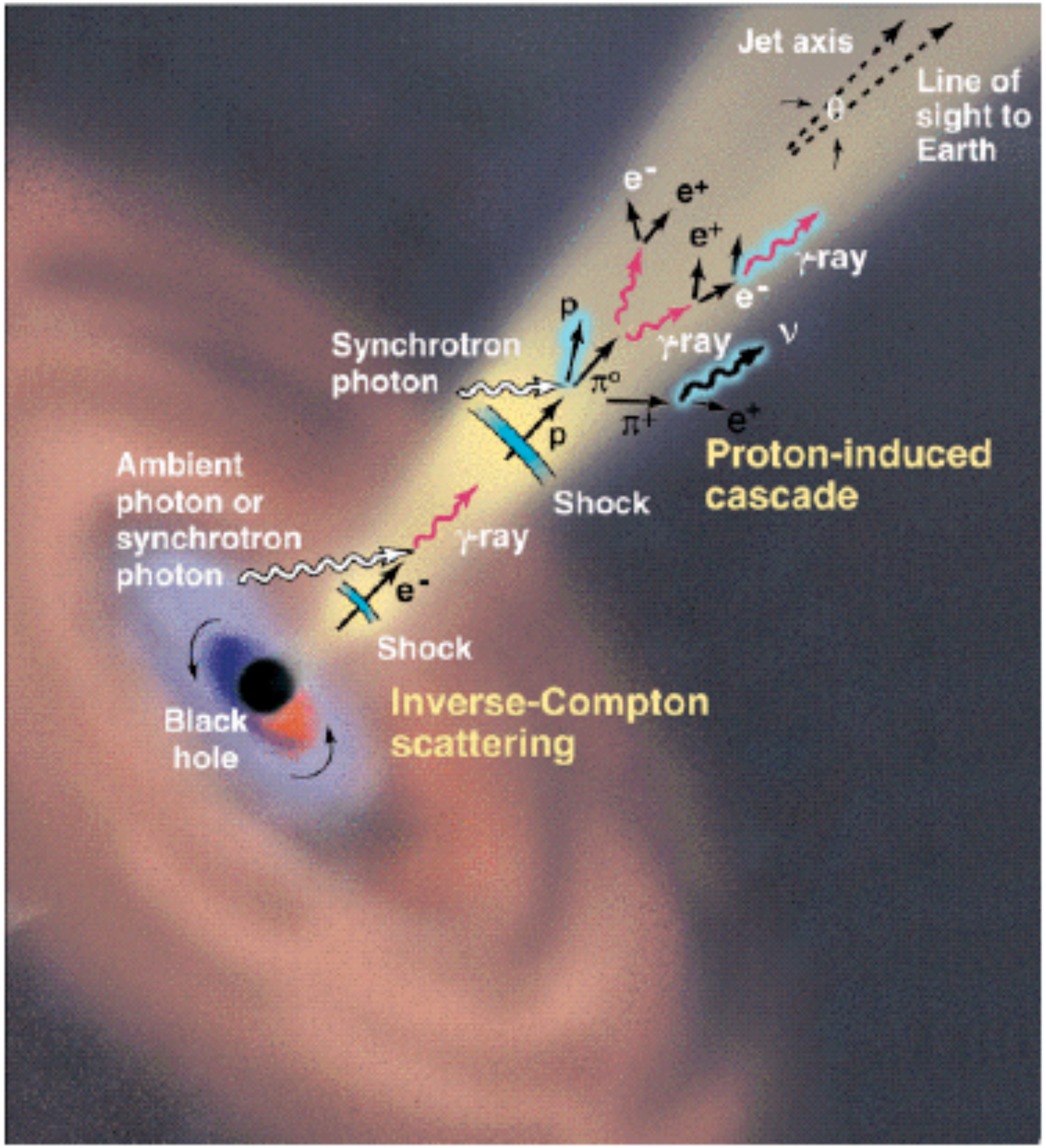
‘Constrained’ simulation of local large-scale structure including magnetic fields suggests that **charged particle astronomy** should be possible out to redshift z ~ 0.1



Dolag *et al* (2003)

So if the sources are astrophysical and not too far away then we should be seeing **autocorrelations** in the sky maps and **cross-correlations** with e.g. AGNs

But what if the fields are *stronger* (Sigl *et al* 2004) or if the primaries are *nuclei*, …?



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.

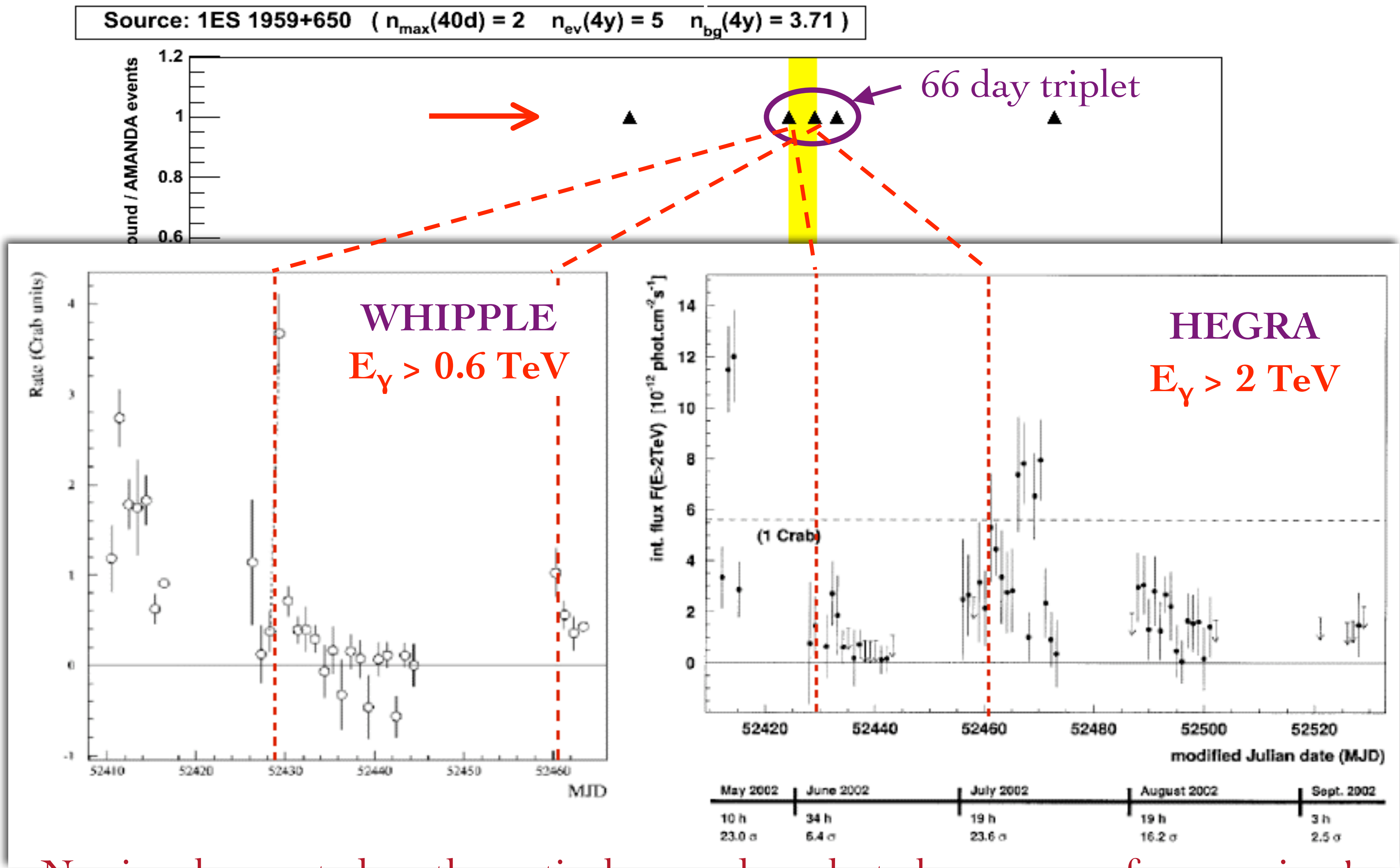
But *no* UHE cosmic rays point back to nearby objects like M87 or Cen A

Previous claims of correlations with BL Lacs not significant due to *a posteriori* cuts on data

Essential to perform ***blind tests*** or ***specify prescription*** beforehand

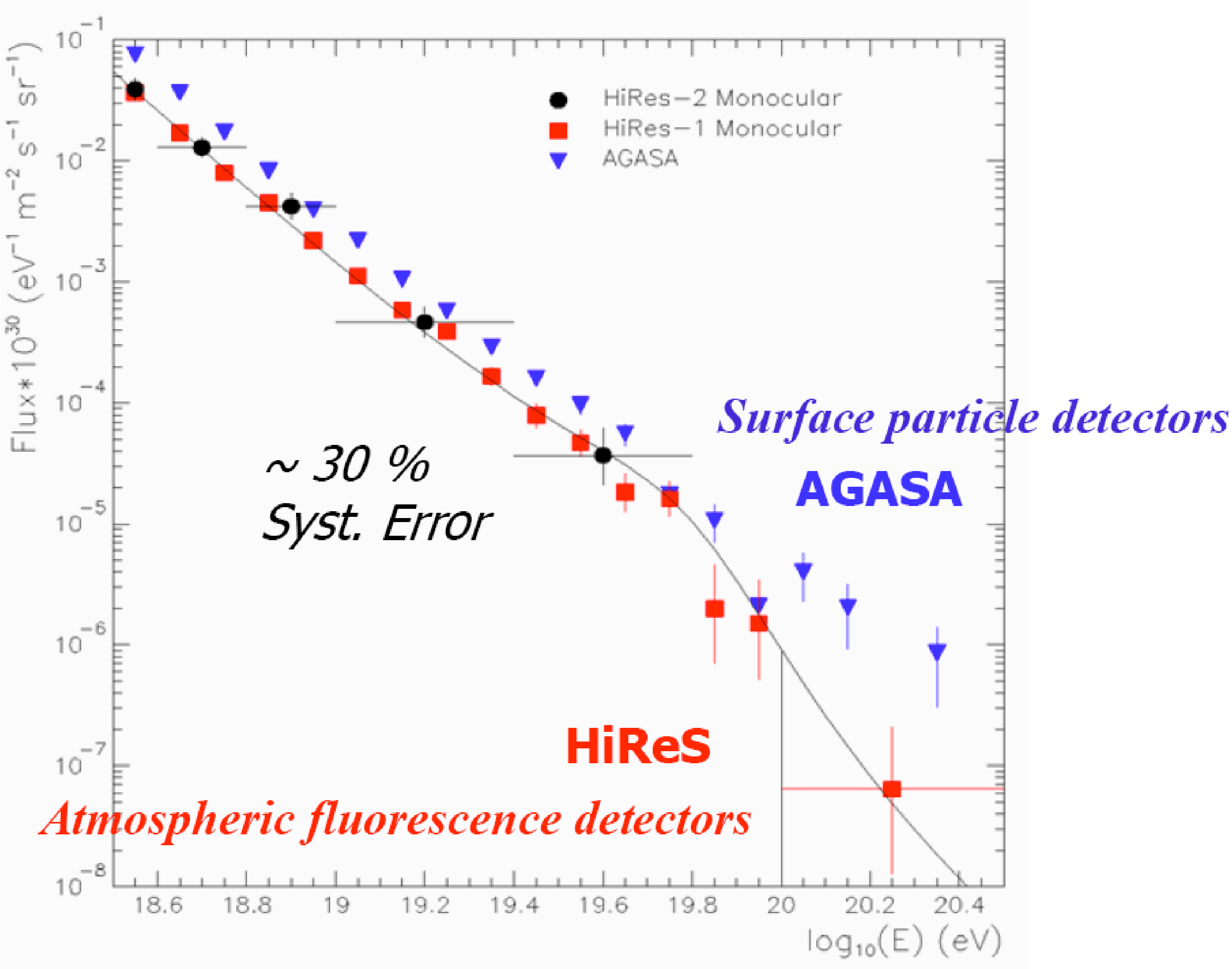
… moreover must account for *bias* in source catalogue, magnetic *deflections* etc

AMANDA events coincident with 'orphan flare' in *1ES1959+650*



No signal expected on theoretical grounds … but always room for surprises!

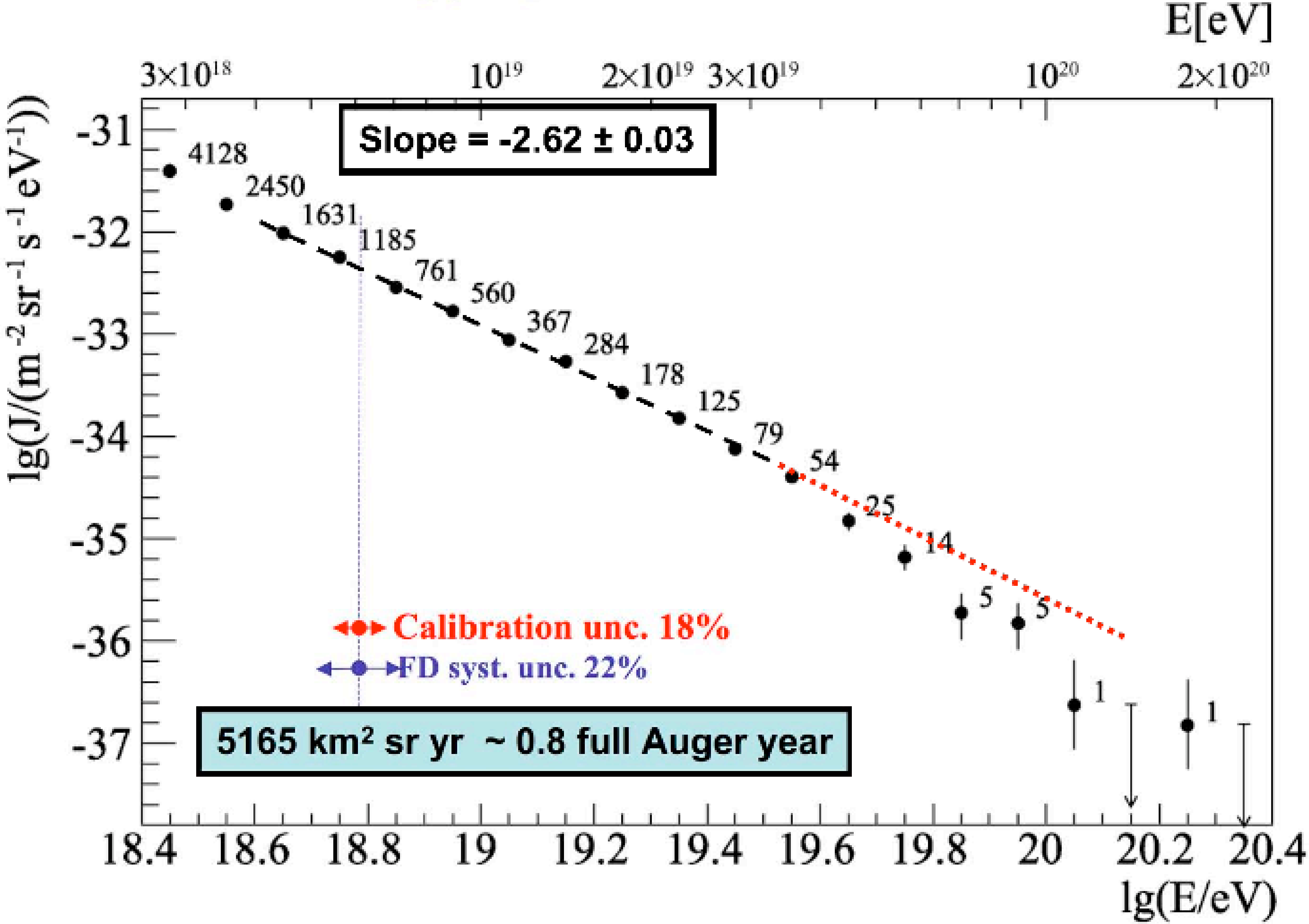
Where is the GZK cutoff?



AGASA found spectrum continues smoothly but HiRes saw expected suppression

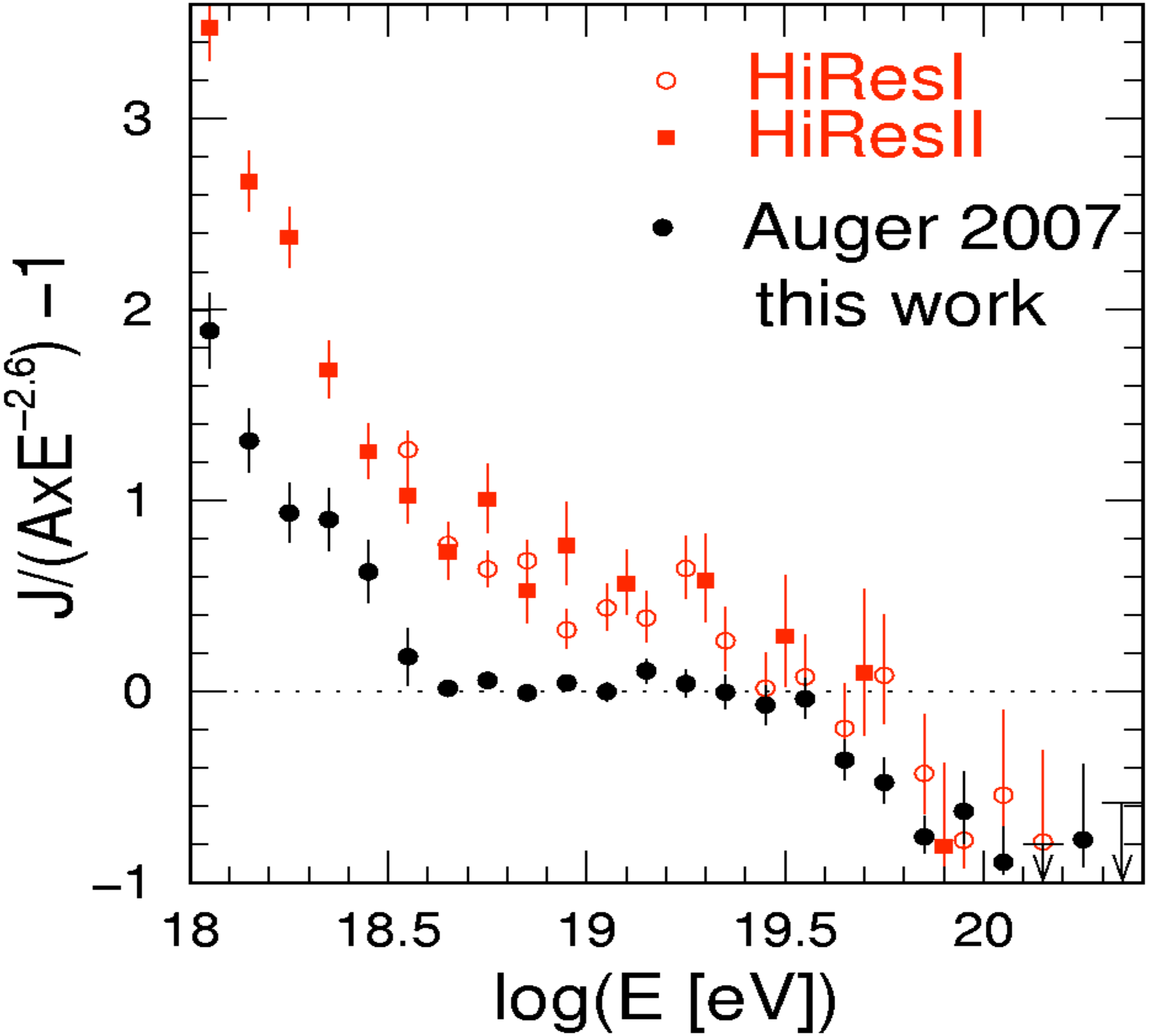
… speculation about possible mismatch in energy scales between the 2 techniques

Auger has now an exposure exceeding *all* previous experiments …
with the surface detector data calibrated by air fluorescence detectors



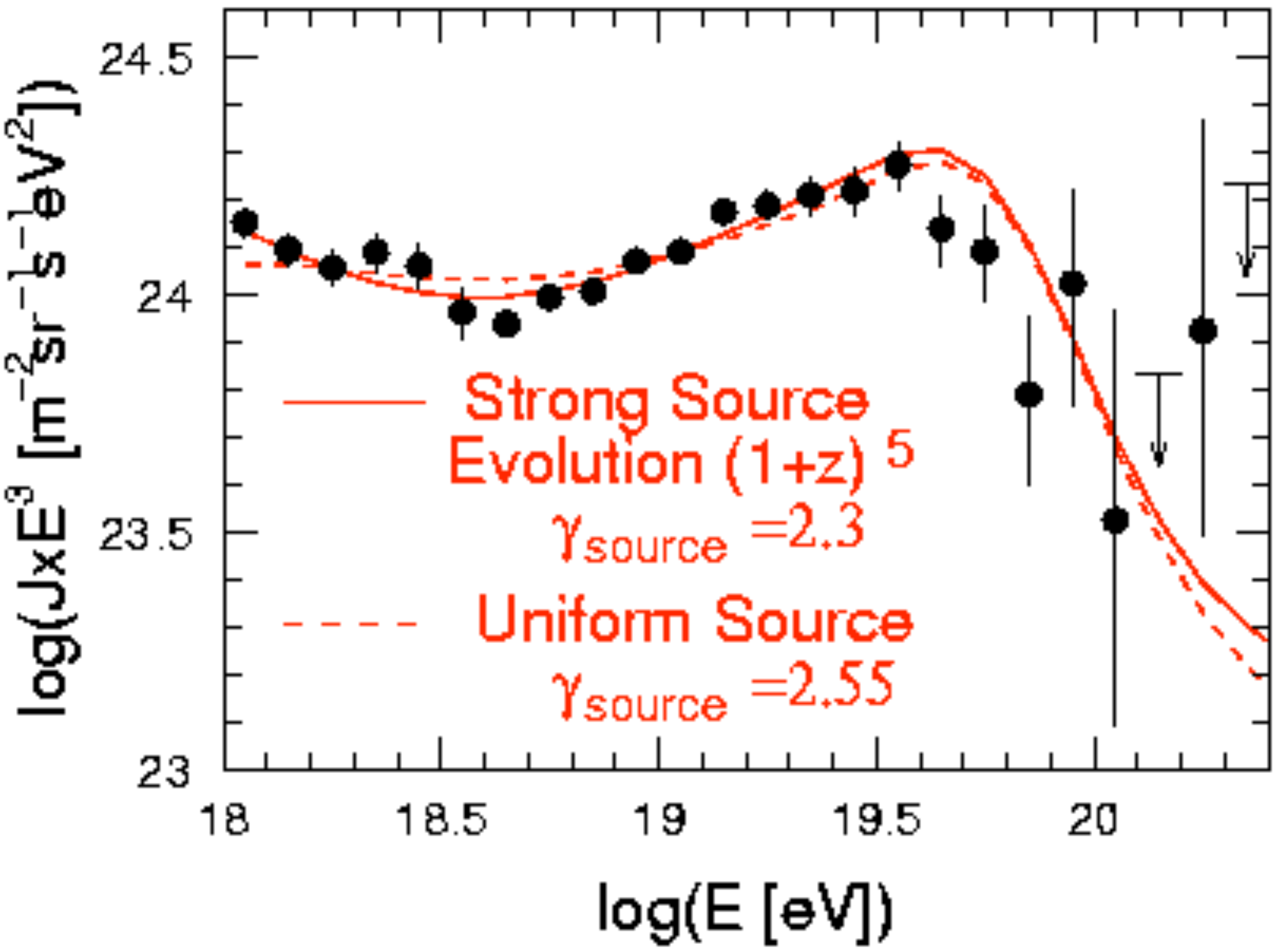
(Alan Watson, ICRC 2007)

There are disagreements with previous air fluorescence experiments …



(Alan Watson, ICRC 2007)

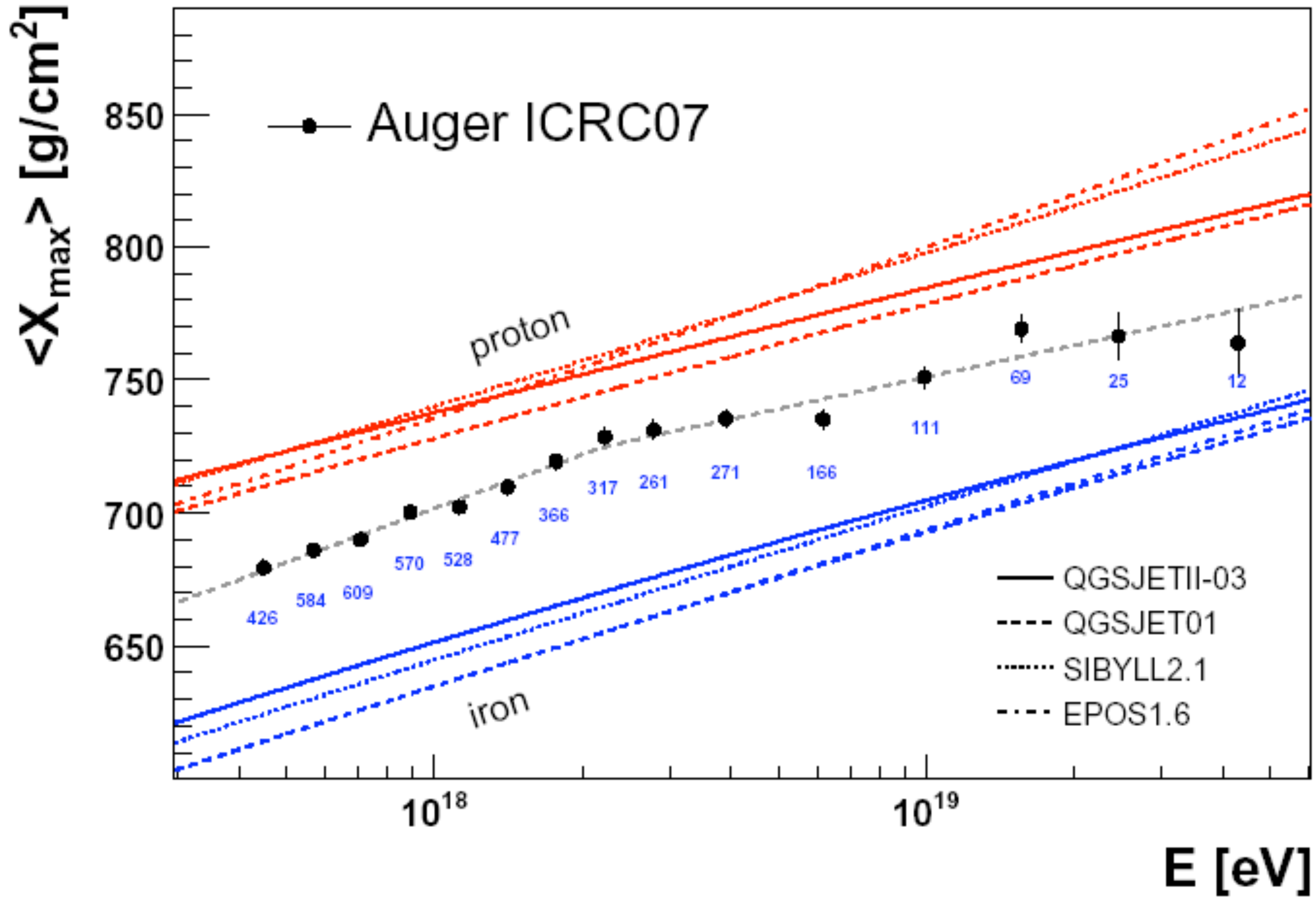
Model of 'dip' due to e^+e^- losses (Berezinsky *et al* 2005) is *not* a good fit to the data



(Alan Watson, ICRC 2007)

The 'ankle' is better explained as due to domination by a (flatter) extragalactic component with a substantial admixture of **heavy nuclei !**

… this is also indicated by the depth of shower maxima measured by the FDs

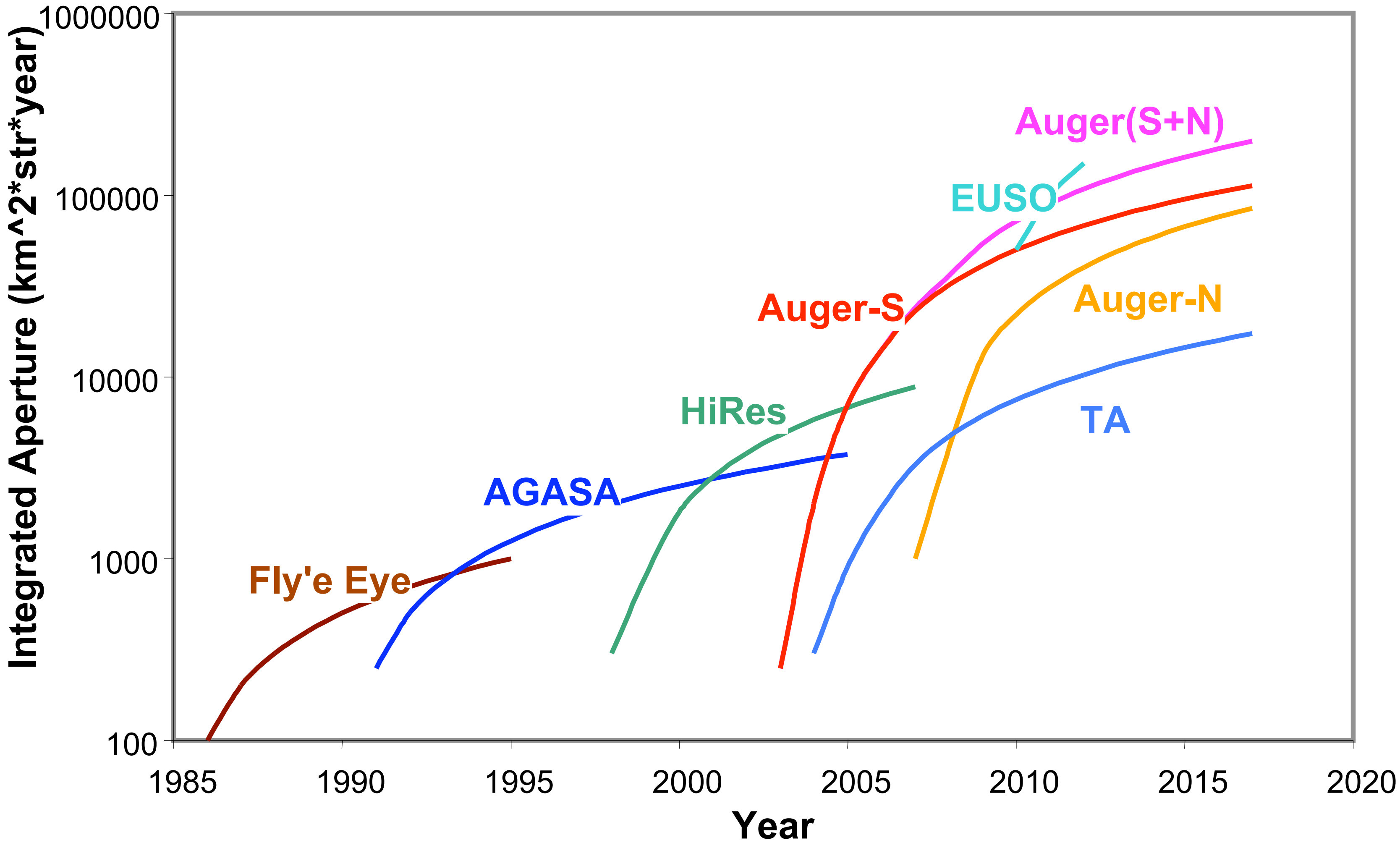


(Alan Watson, ICRC 2007)

There is evidence of increasing domination by **heavy nuclei** beyond the 'ankle'

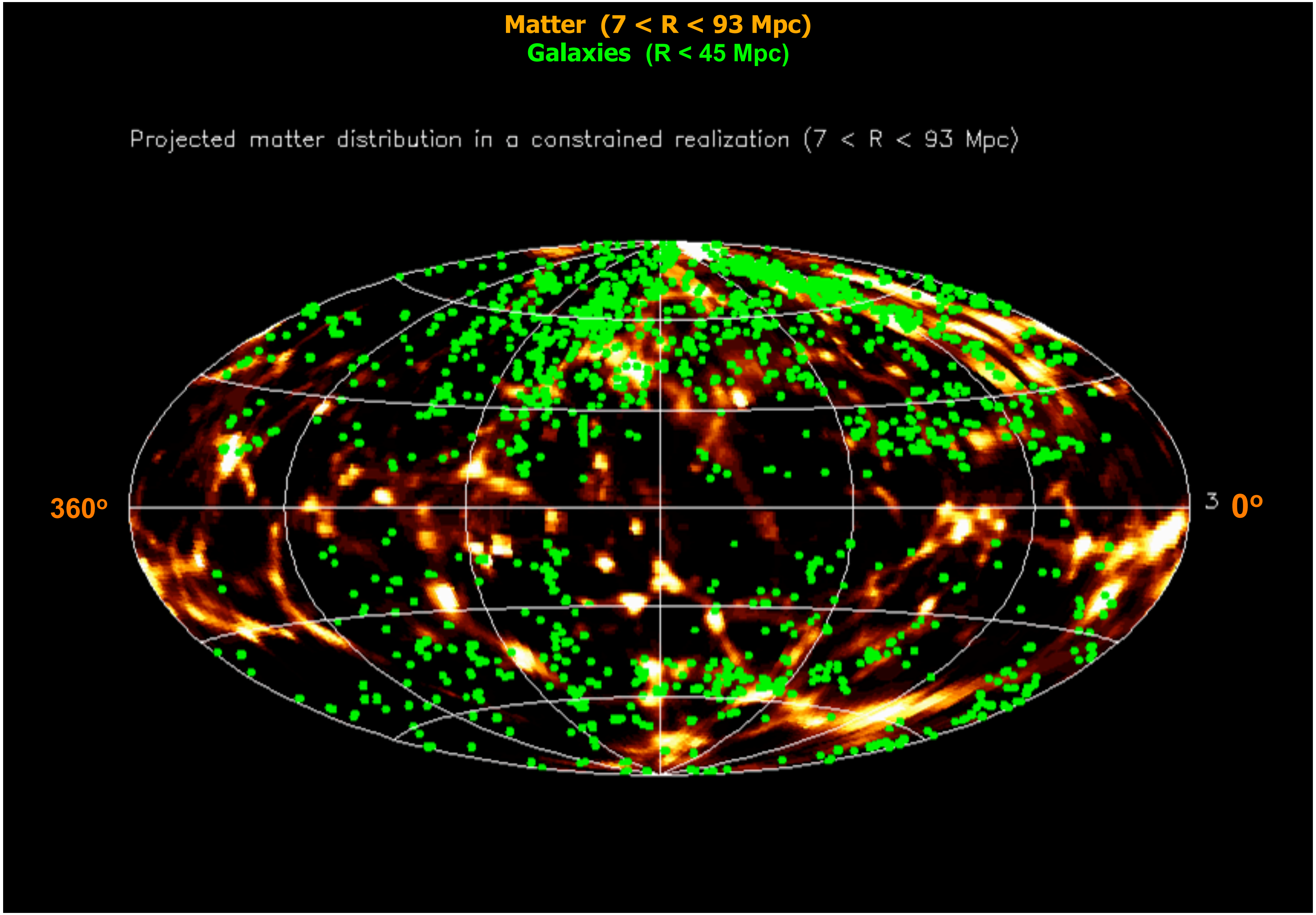
… is the steepening at higher energies really due to the GZK effect?

In the next decade, we expect a ~10-fold increase in the statistics of ultrahigh energy cosmic rays …



This is likely to establish correlations with extragalactic objects and challenge the present models for particle acceleration and propagation at such huge energies

Full-sky coverage is essential for this ***(Auger N+ S)***



Where there are high energy cosmic rays, there must also be neutrinos…

- **GZK interactions of extragalactic UHECRs on the CMB**

  ("guaranteed" cosmogenic neutrino flux …may be reduced if the primaries are heavy nuclei rather than protons)

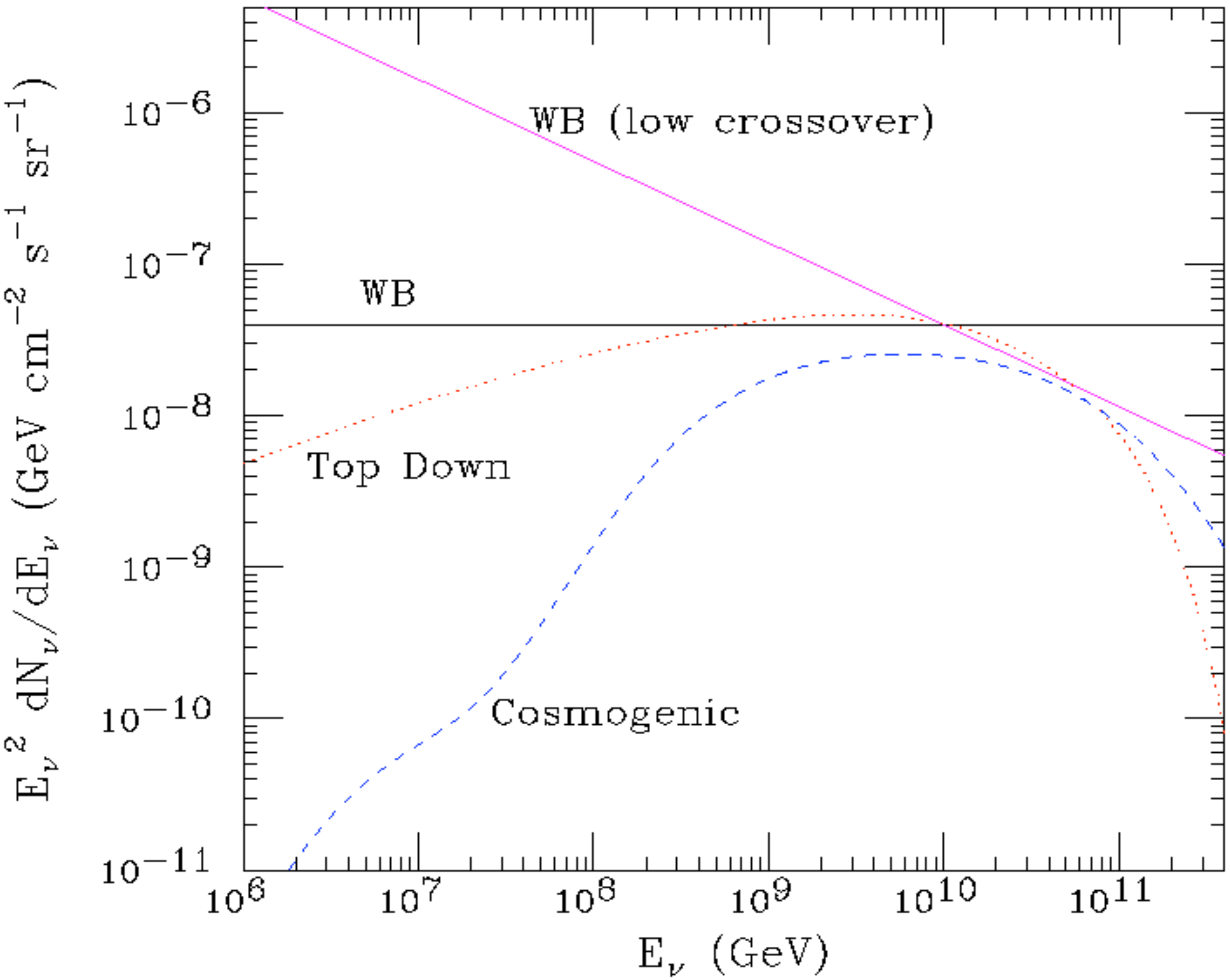
- **UHECR candidate accelerators (γ-ray bursts, active galactic nuclei, micro-quasars, …)**

  ("Waxman-Bahcall flux" - normalised to extragalactic UHECR flux hence sensitive to 'cross-over energy' above which they dominate)

- **Decays of superheavy dark matter particles?**

  (subject to bound on associated UHE photon flux … now constrained to be no higher than the Waxman-Bahcall flux)

Expected UHE cosmic neutrino fluxes

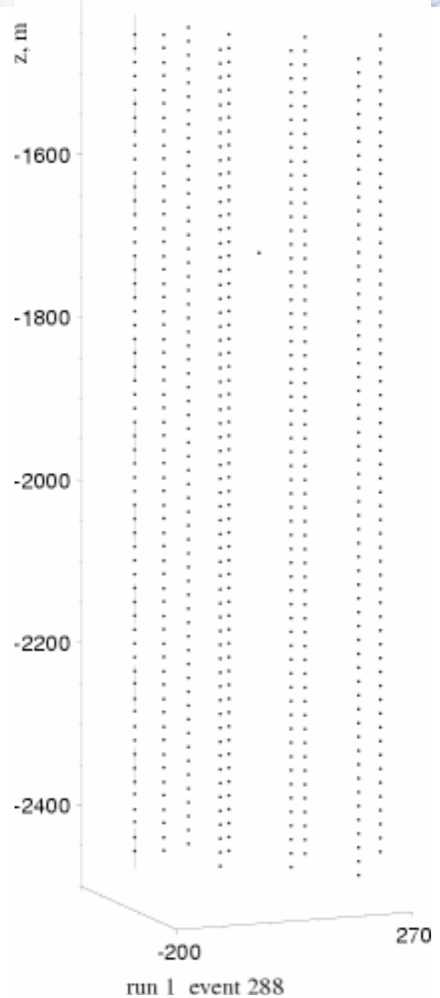


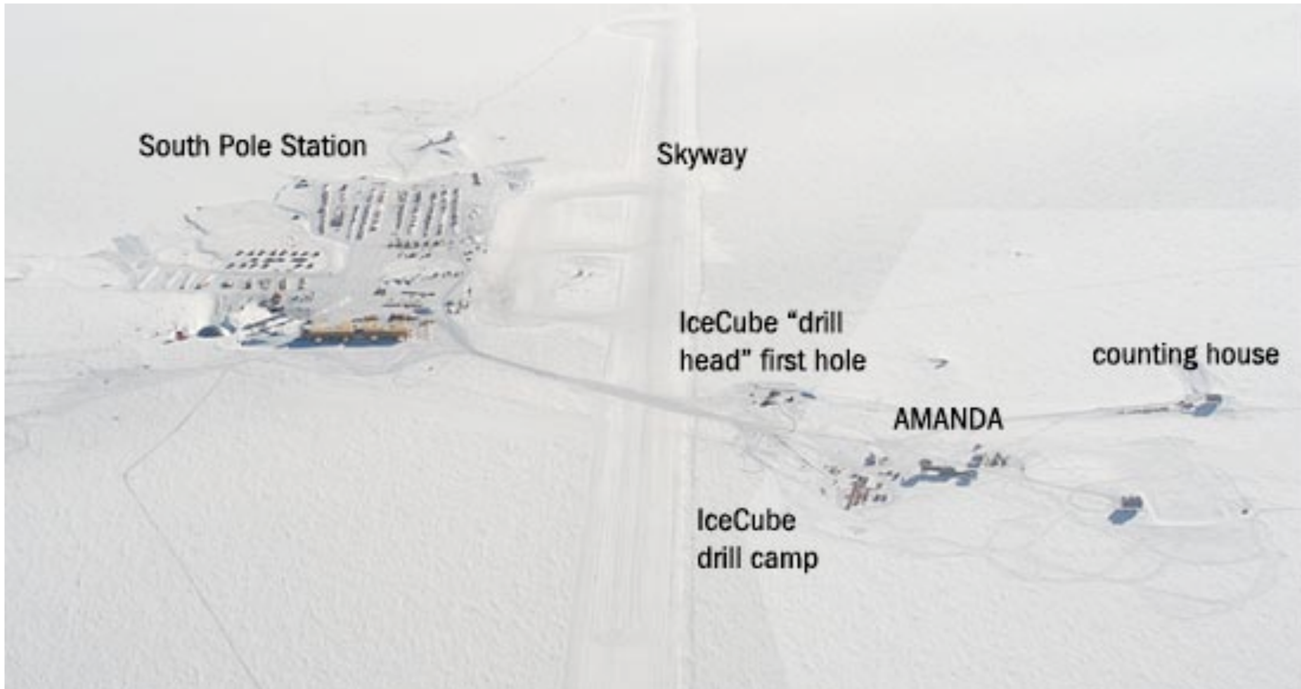
(Anchordoqui *et al* 2005)

Diffuse WB flux would be *higher* if extragalactic sources begin to dominate at ~10^{18} eV (Ahlers *et al* 2005) … close to being ruled out by ***IceCube***

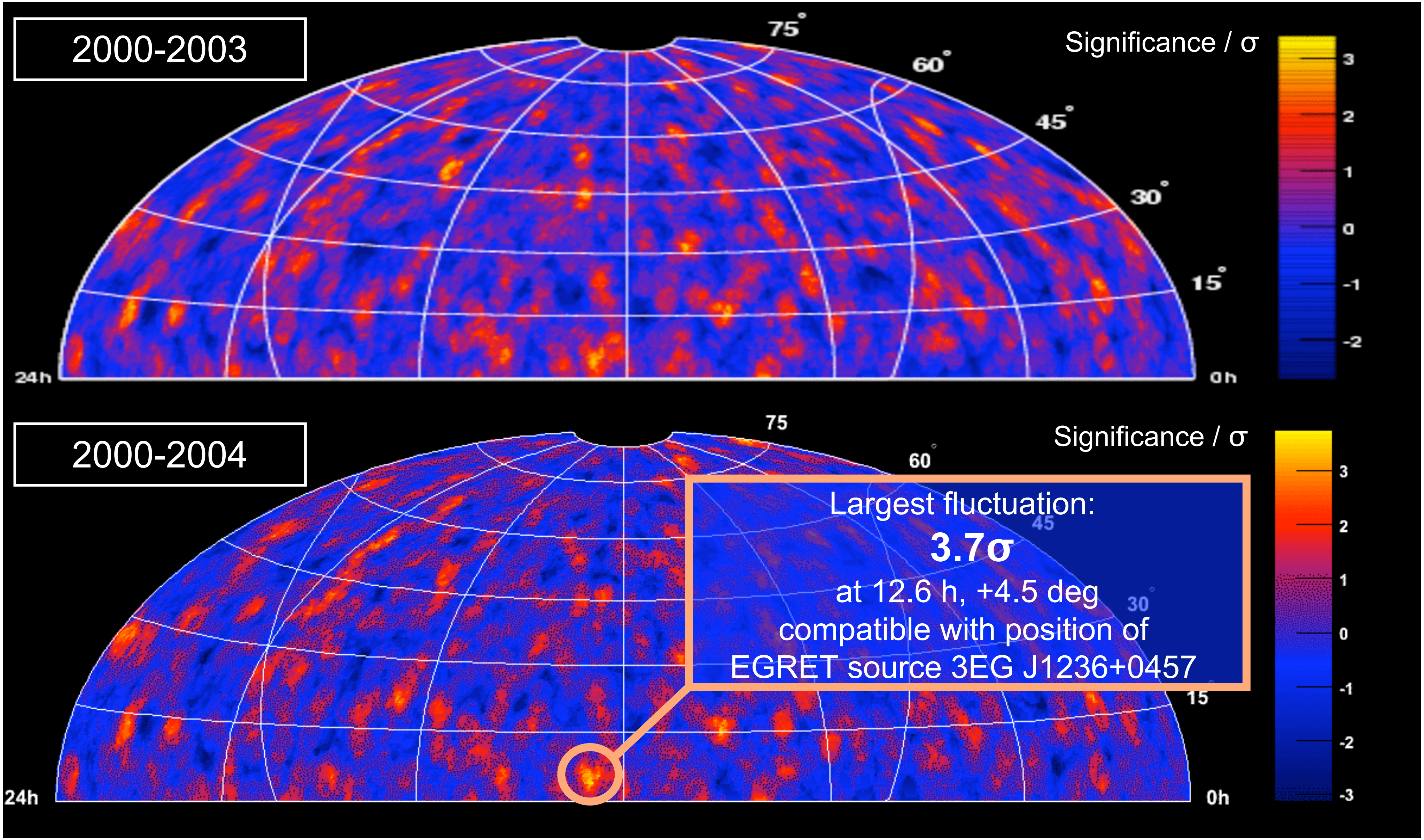
Km^3 scale ν detection is happening already at the South Pole …
optimal for extragalactic sources

KM3Net in the Mediterranean will provide *full-sky* coverage …
optimal for Galactic sources





AMANDA search for point sources of TeV-PeV neutrinos



But 69 out of 100 randomised sky maps show a higher excess!

Neutrino 2006, Santa Fe

Colliders and Cosmic Rays

The Tevatron reaches cms energies of ~2 TeV

… and the LHC will achieve ~14 TeV

But EeV energy cosmic ray hitting O or N nucleus in atmosphere

$\Rightarrow$ 40 TeV cms!

The effects of new physics is hard to see in hadron-initiated showers

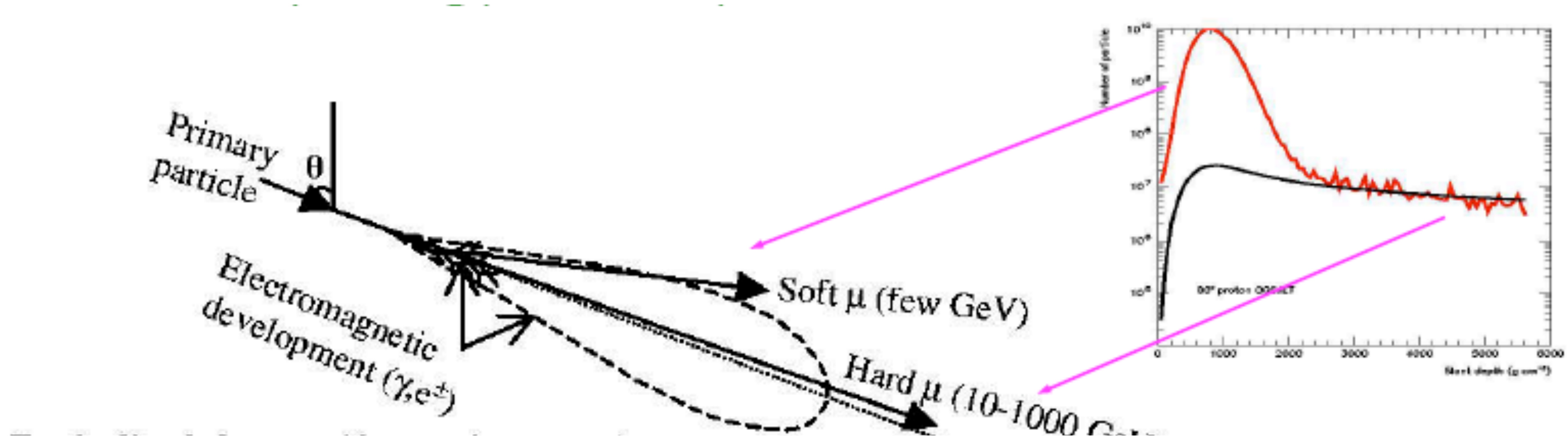
(#-secn TeV^{-2} vs GeV^{-2})

… but may have a dramatic impact on *neutrino* interactions!

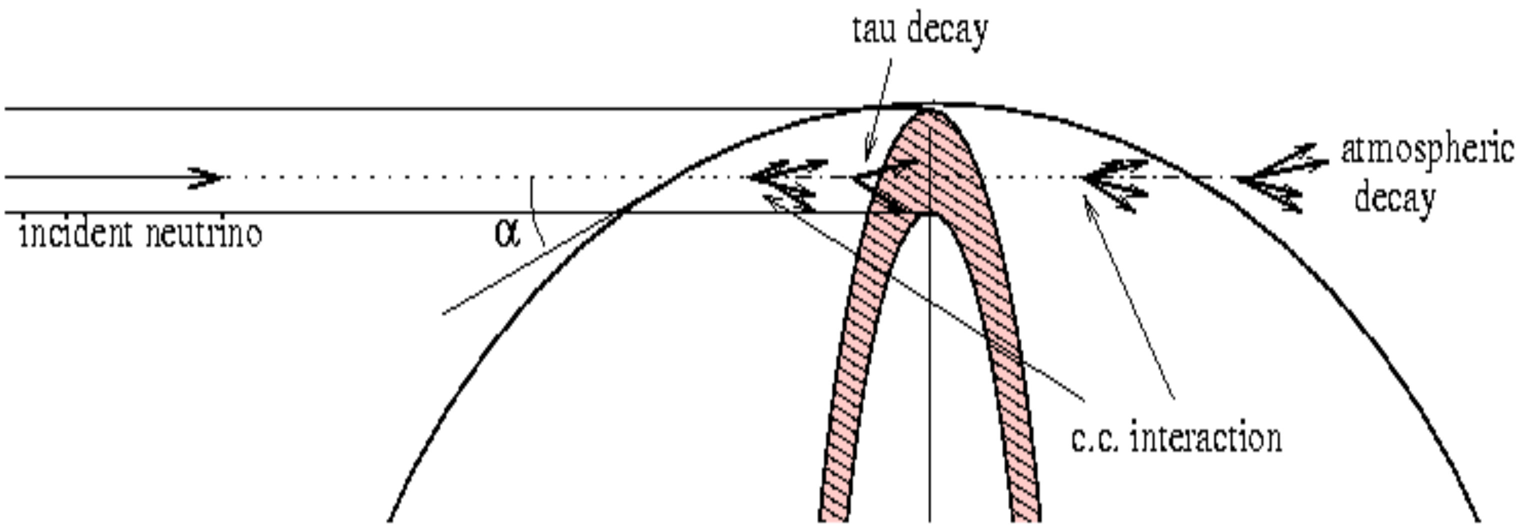
$\rightarrow$ can probe physics **beyond the Standard Model** by observing **ultra-high energy cosmic neutrinos**

An unexpected bonus – UHE neutrino detection with air shower arrays

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

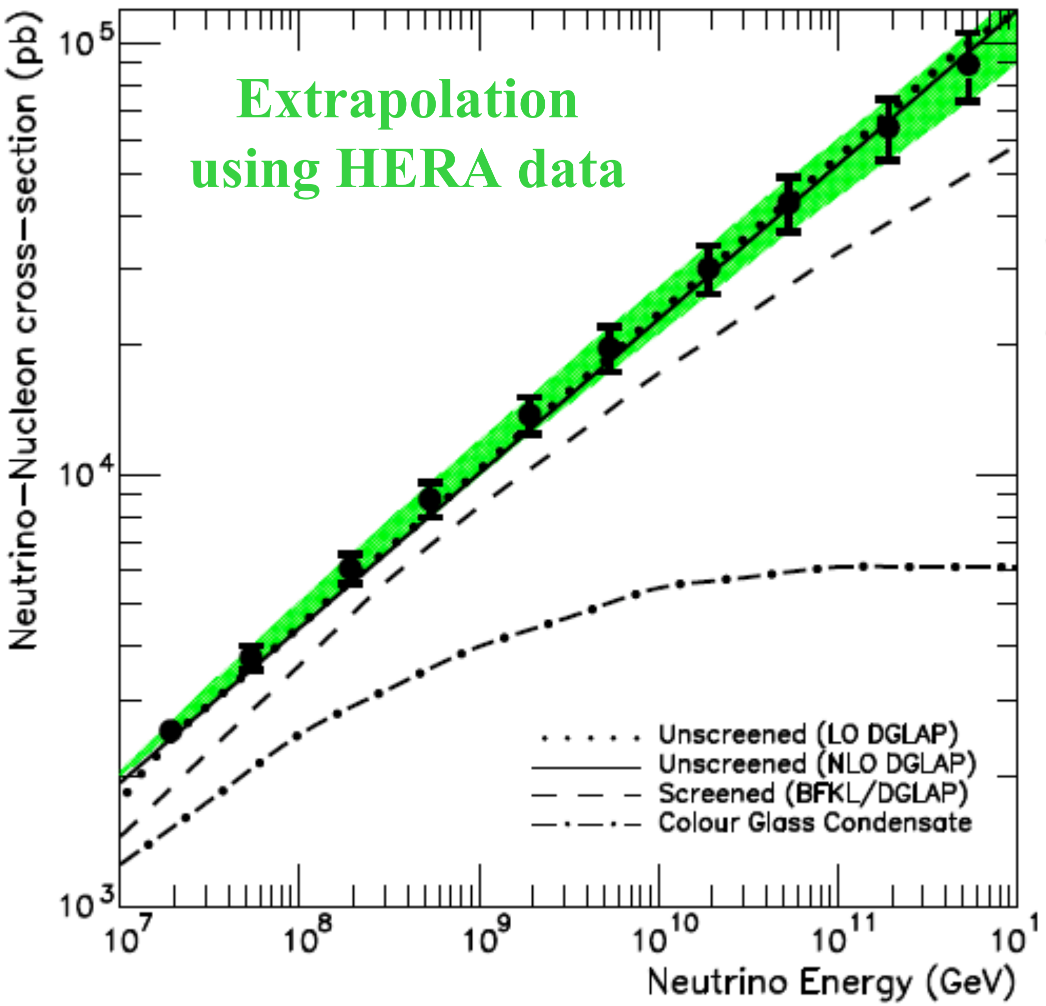


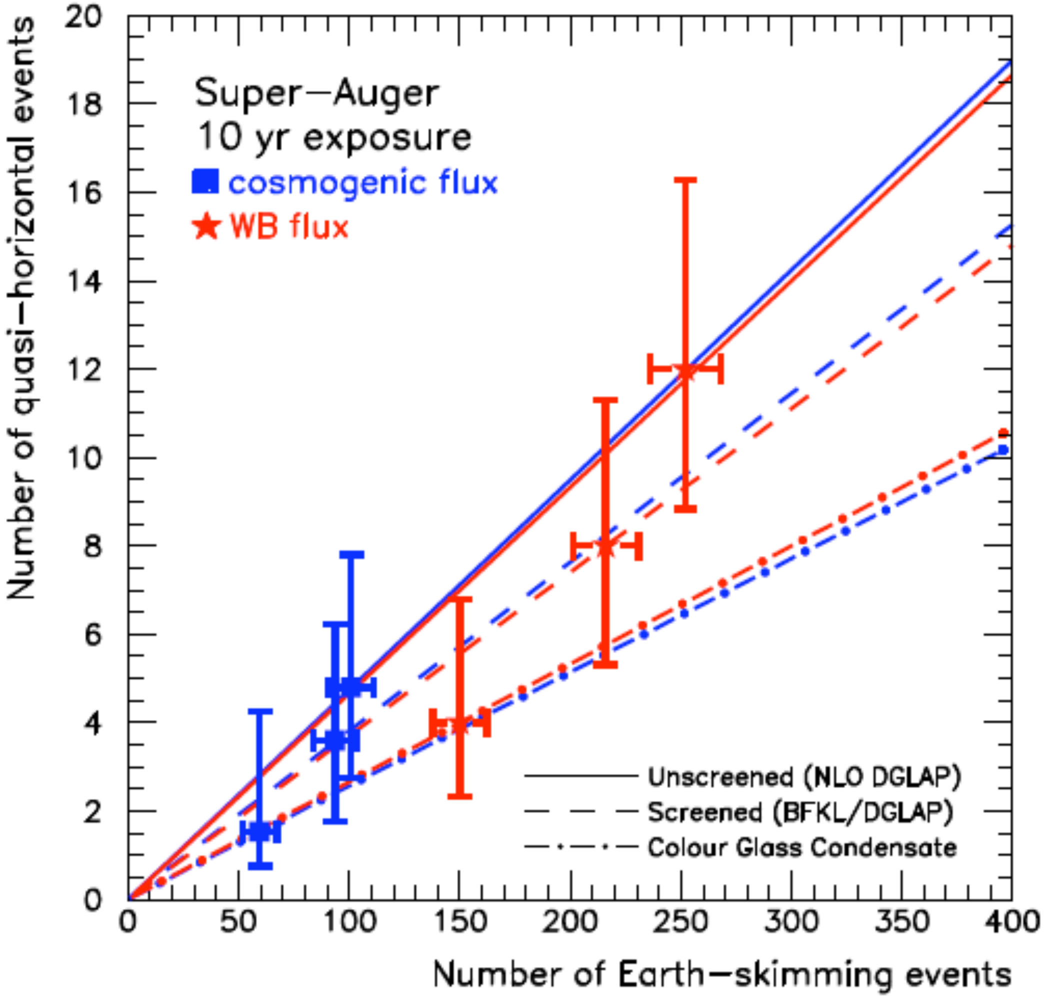
Auger can also detect Earth-skimming $\nu_\tau \rightarrow \tau$ which generates *upgoing* hadronic shower



Beyond HERA: Probing low-x QCD through deep inelastic scattering of cosmic neutrinos

Cooper-Sarkar *et al* (2006)





The steep rise of the gluon density at low-x must *saturate* (unitarity!) ⇒ suppression of the UHE ν-N #-secn

The ratio of quasi-horizontal (all flavour) and Earth-skimming (ν_τ) events *measures* the cross-section

Summary

Prospects are good for the identification of the sources of galactic cosmic rays by γ-ray astronomy - **but more work is needed on theory**

We will soon know answers to crucial questions about the energy spectrum, composition and anisotropies of extragalactic cosmic rays … **here the theoretical situation is even more challenging**

The sources of cosmic rays must also be sources of ultrahigh energy neutrinos – **their detection will provide an unique probe of both astrophysical models and new *fundamental* physics**

It is essential for the intellectual health and progress of this *interdisciplinary field* to invest in theory - not just in experiment!

… remember Paul Dirac: *"Theory names the variables"*