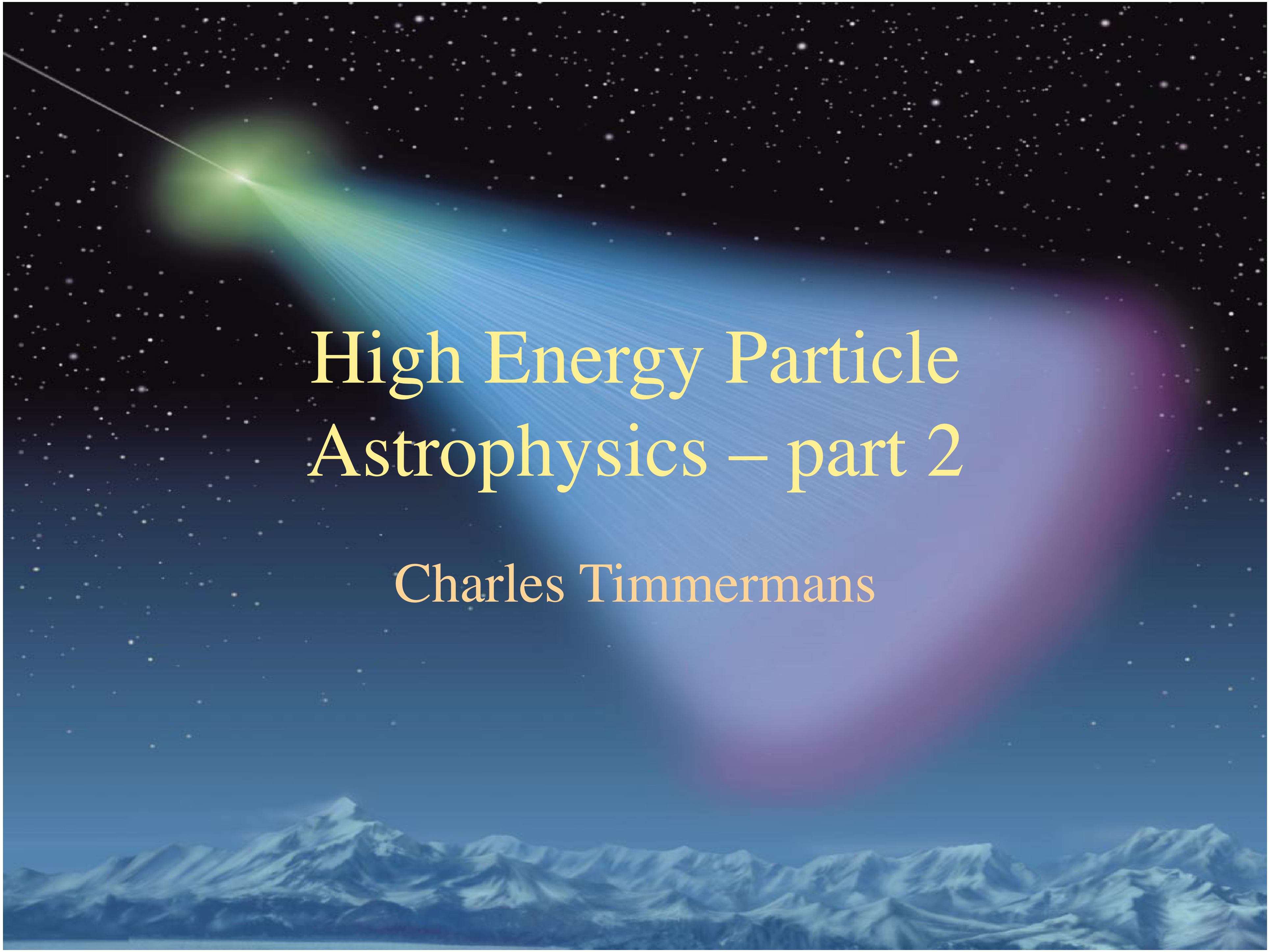


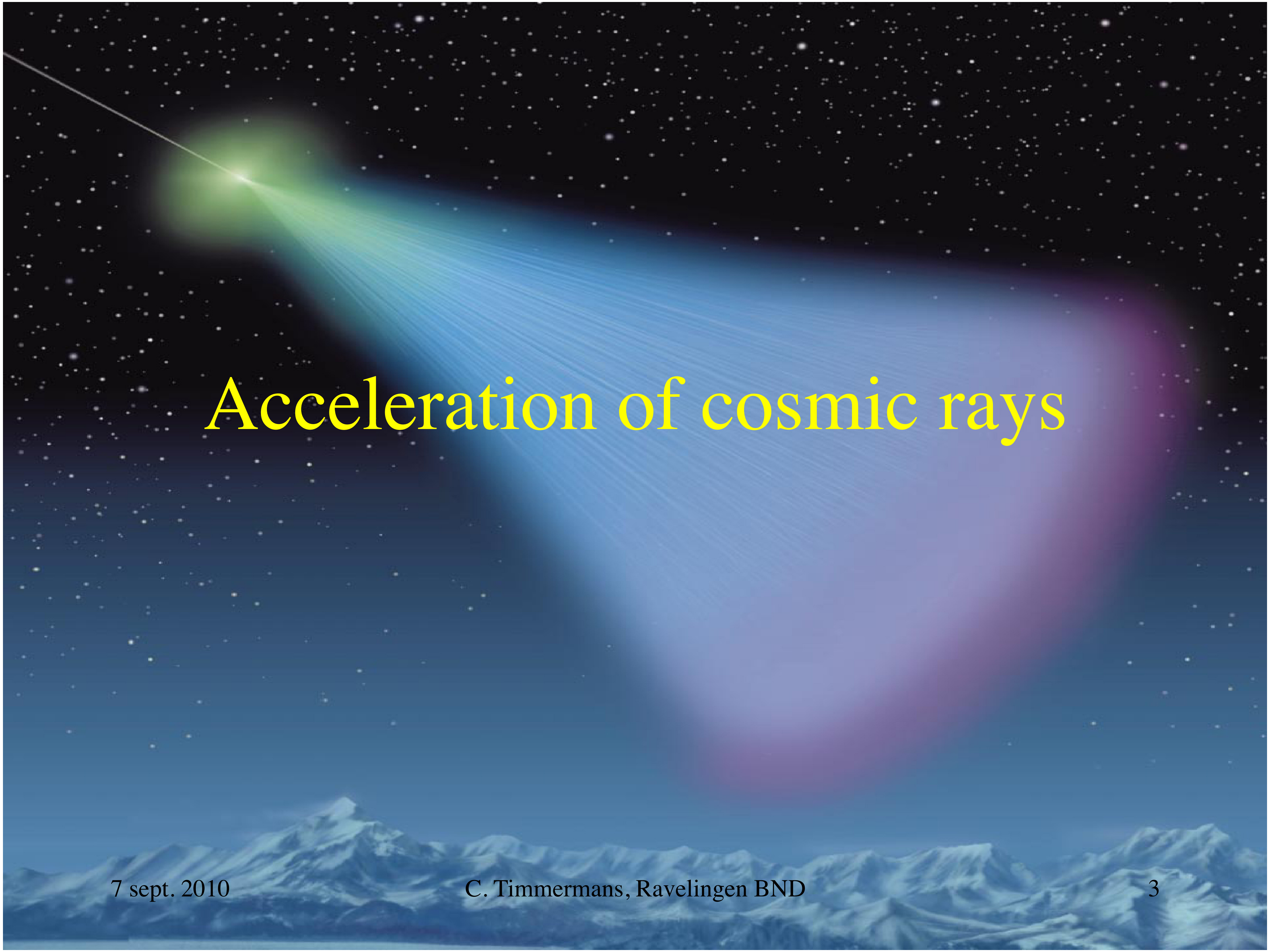
High Energy Particle Astrophysics – part 2

Charles Timmermans

Contents of the Lectures

- Lecture 1+2: Air Showers and Detectors
  - Thomas K. Gaisser, Cosmic Rays and Particle Physics, Cambridge University Press, 1990
  - Detection and interaction of particles
- Lectures 3+4: Results in High Energy Astroparticle physics
  - Cosmic Ray air shower detectors, neutrino telescopes and TeV gamma detectors

Acceleration of cosmic rays



General comments

- Assume interactions with energy gain per interaction:

$$\Delta E = \zeta E_0$$

  - After n encounters:

$$E = (1+\zeta)^n E_0$$

- Probability to escape P_{esc}. Thus probability to stay in acc. region for *n* cycles $(1\text{-}P_{esc})^n$

- Number of particles above certain energy:

$$N(E>E_n) \propto \sum_{i=n}^{\infty} (1\text{-}P_{esc})^i = 1\text{-}\sum_{i=1}^{n\text{-}1} (1\text{-}P_{esc})^i = \frac{(1\text{-}P_{esc})^n}{P_{esc}}$$

- Number of encounters to reach energy E_n
  - $n = \ln(E_n/E_0)/\ln(1+\xi)$

General comments

- Thus

$$N(\mathrm{E}>\mathrm{E}_n) \propto \frac{(1\text{-}P_{esc})^{\frac{(\ln(\mathrm{E}_n)-\ln(\mathrm{E}_o))}{\ln(1+\zeta)}}}{P_{esc}}$$

$$\ln N(\mathrm{E}>\mathrm{E}_n) \propto \ln(1\text{-}P_{esc})\frac{\ln\left(\frac{\mathrm{E}_n}{\mathrm{E}_0}\right)}{\ln(1+\zeta)}-\ln(P_{esc})$$

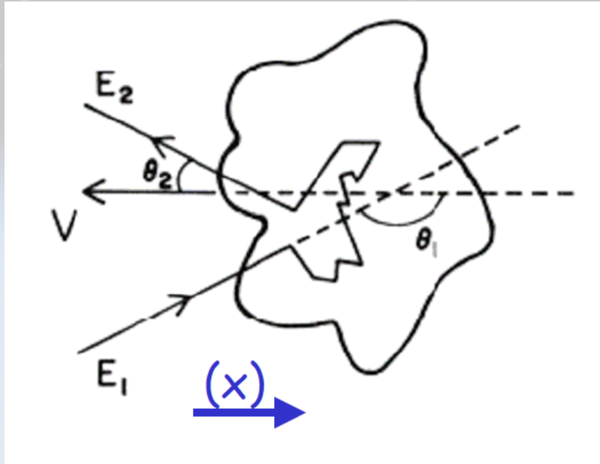
$$N(\mathrm{E}>\mathrm{E}_n) \propto \frac{\left(\frac{\mathrm{E}_n}{\mathrm{E}_0}\right)^{\frac{\ln(1-P_{esc})}{\ln(1+\zeta)}}}{P_{esc}}$$

- If ξ and P_{esc} are small $N(\mathrm{E}>\mathrm{E}_n) \propto \frac{\left(\frac{\mathrm{E}_n}{\mathrm{E}_0}\right)^{-\frac{P_{esc}}{\zeta}}}{P_{esc}}$
- A power spectrum with $\alpha = \frac{P_{esc}}{\zeta} = \frac{1}{\zeta}\cdot\frac{T_{cycle}}{T_{esc}}$
- The spectral index is: $\alpha\text{-}1$ (differential)

- You just need to know:
  - The energy gain per encounter
  - The frequency of encounters
  - The escape time
- This will then provide the source spectrum of cosmic rays

Fermi Acceleration

- Particle hits magnetic mirror
- In rest-frame mirror: incoming and outgoing energies are the same
- Mirror moves, so energy is lost (mirror moves in same direction as particle) or gained:



$$\xi = \frac{\Delta E}{E_1} = \frac{1-\beta_{cloud}\cos(\theta_1)+\beta_{cloud}\cos(\theta_2)-\beta_{cloud}^2\cos(\theta_1)\cos(\theta_2)}{1-\beta_{cloud}^2} - 1$$

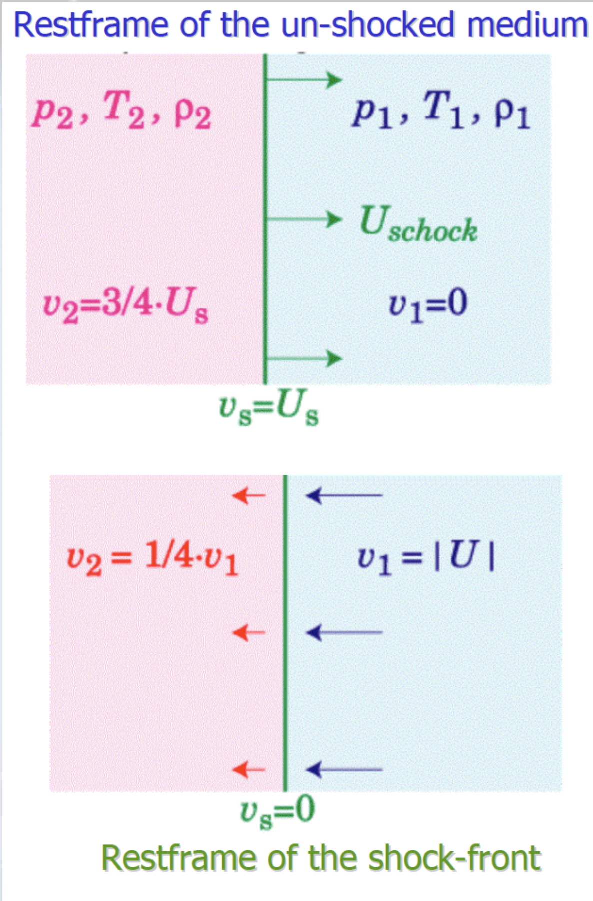
- 2 effects:
  - Net energy gain head-on slightly larger than tail-collision losses
  - More head on collisions
- Net gain!

$$\zeta = \frac{4}{3}\beta_{cloud}^2$$

Very Inefficient!

Collision on shocks

- The gain on head-on collisions is $2\beta/(1-\beta^2)$
- A shock originates if plasma moves faster than speed of sound
- From hydrodynamics: Plasma velocity after shock is about ¾ of shock front velocity
- In all frames: velocity difference is ¾ of shock front velocity

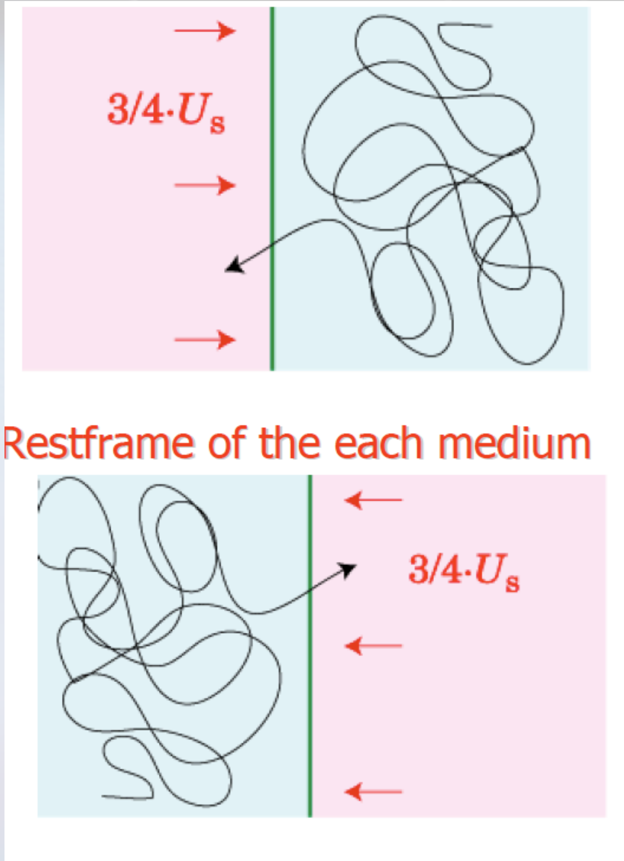


Collision on shocks

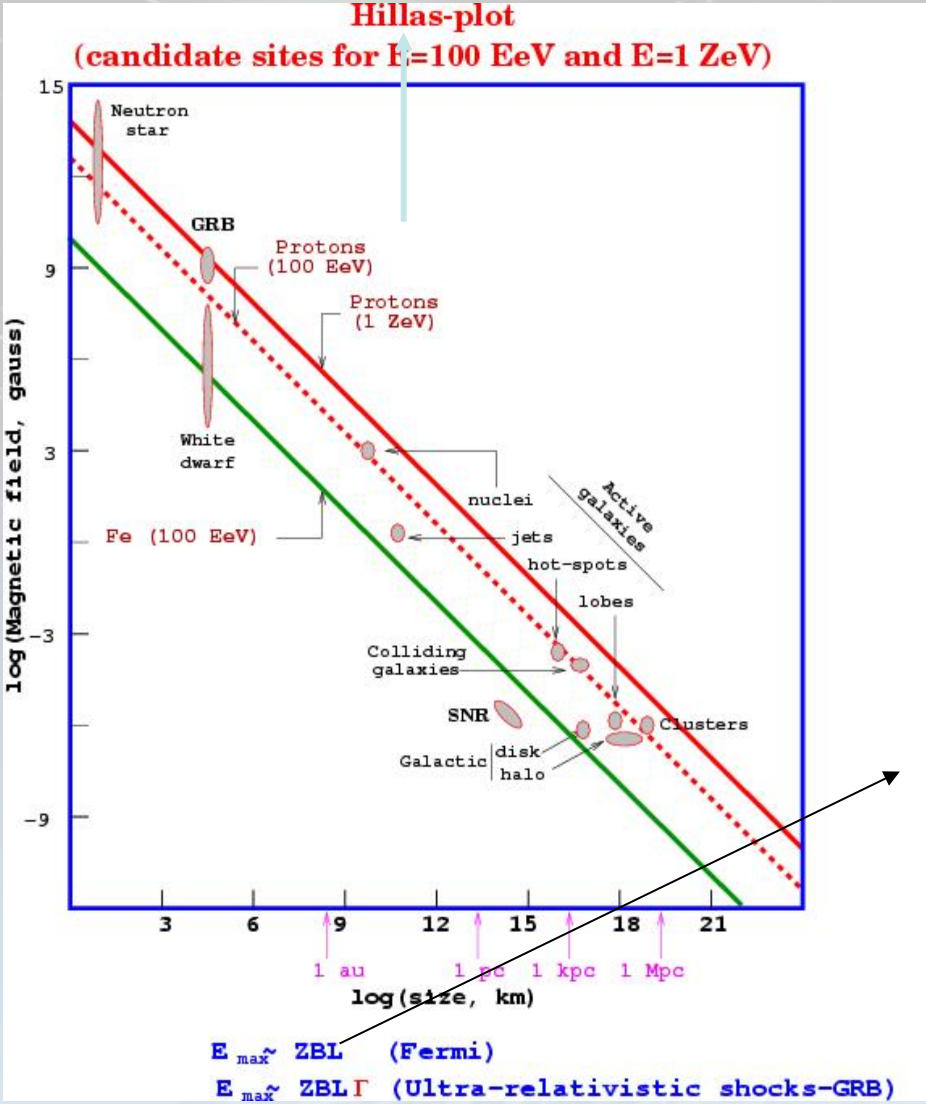
- Particles cross shock front, undergo electric scattering. This creates a random walk
- In rest frame of the medium diffusion takes place
- In each medium, the other arrives with a speed of ¾ V_{shock}
- Now all collisions are almost head-on. Averaging over all angles:

$$\zeta = \frac{4}{3}\beta = 4\frac{|V_2 - V_1|}{3c}$$

- This is a lot faster!



Maximal Energy



Source magnetic field keeps test particles confined to the shock region.

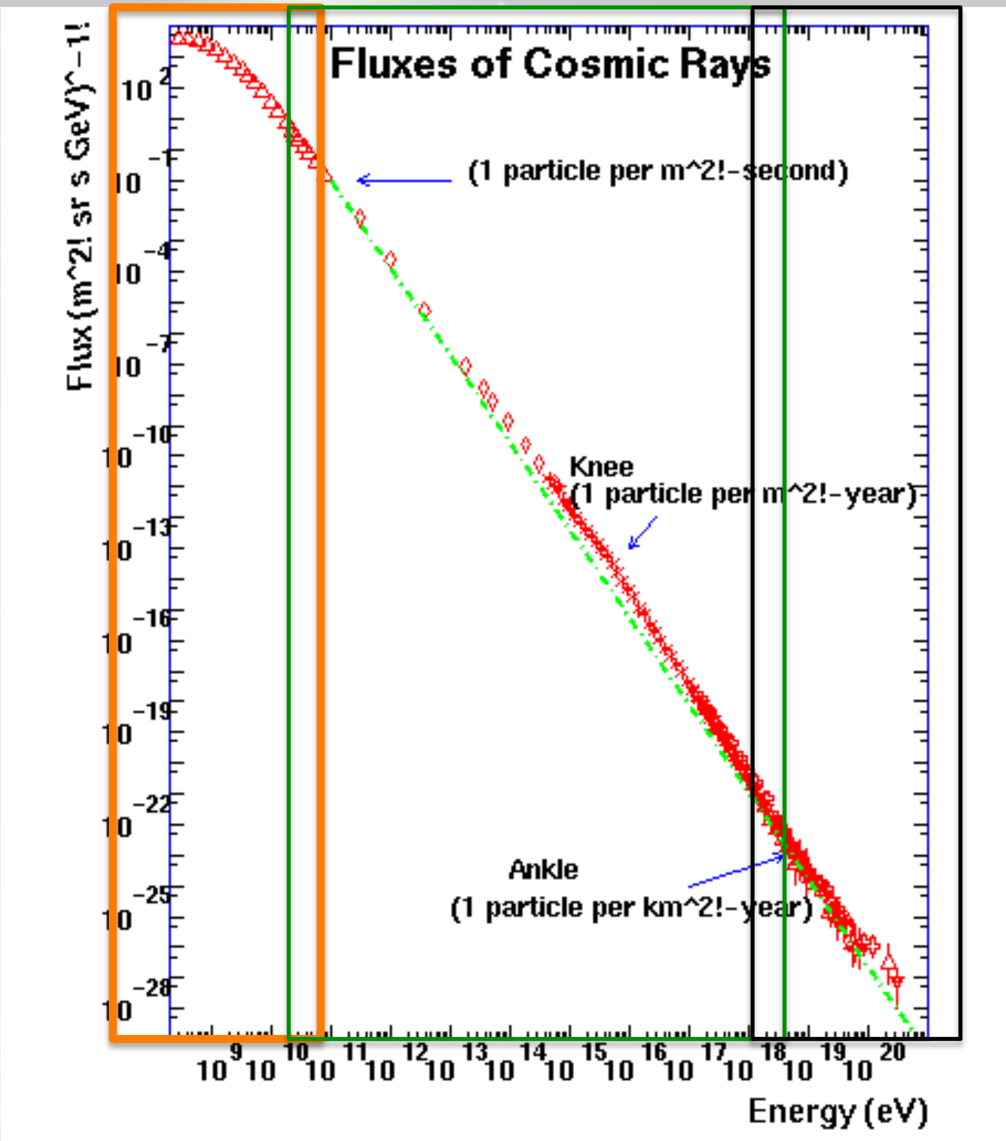
Larmor Radius needs to be small compared to the size of the shock region.

$R_L = p/qB$

$P_{max} = qRB$

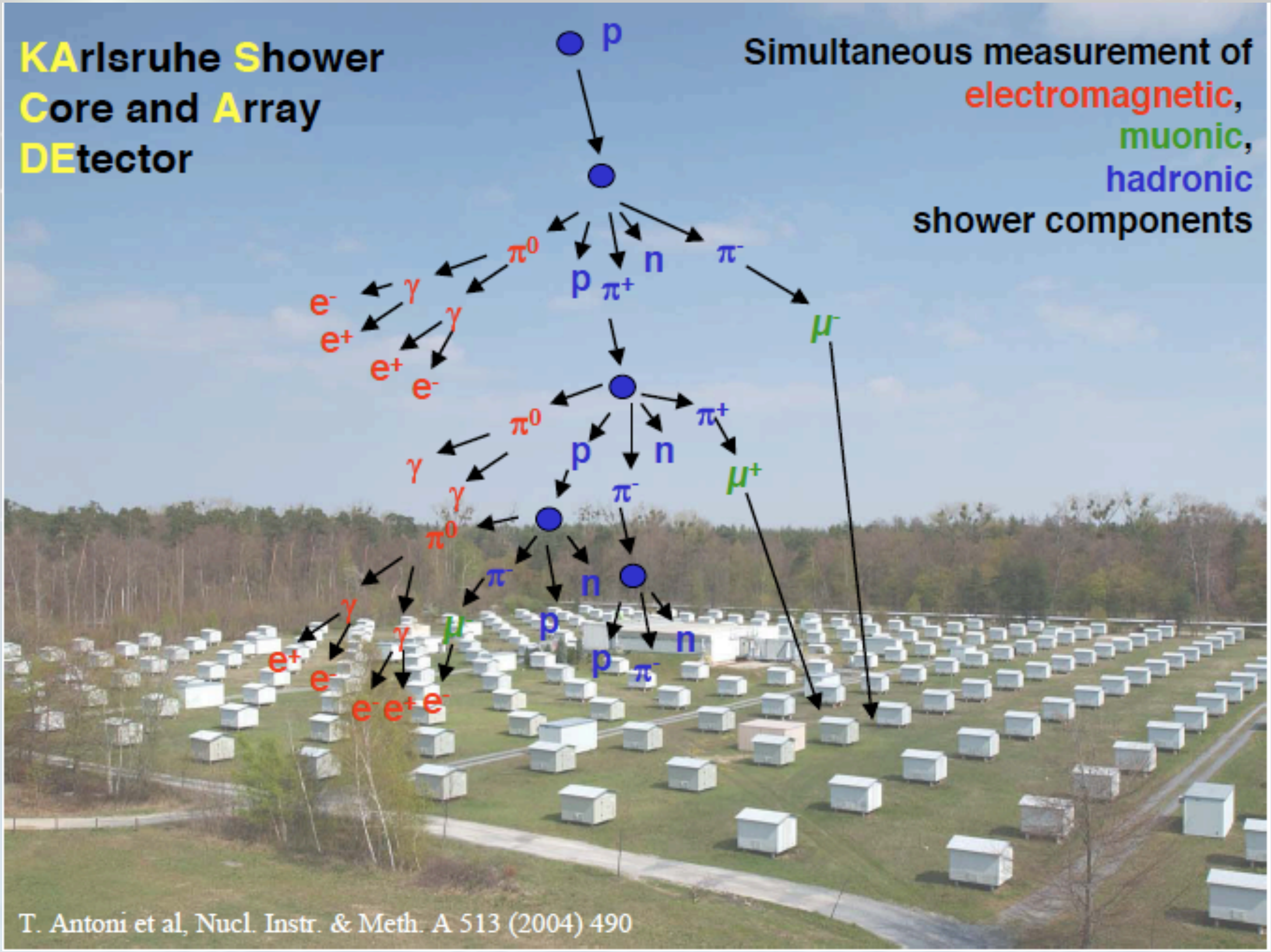
Large magnetic fields or large objects provide high energies

Fluxes of Cosmic Rays

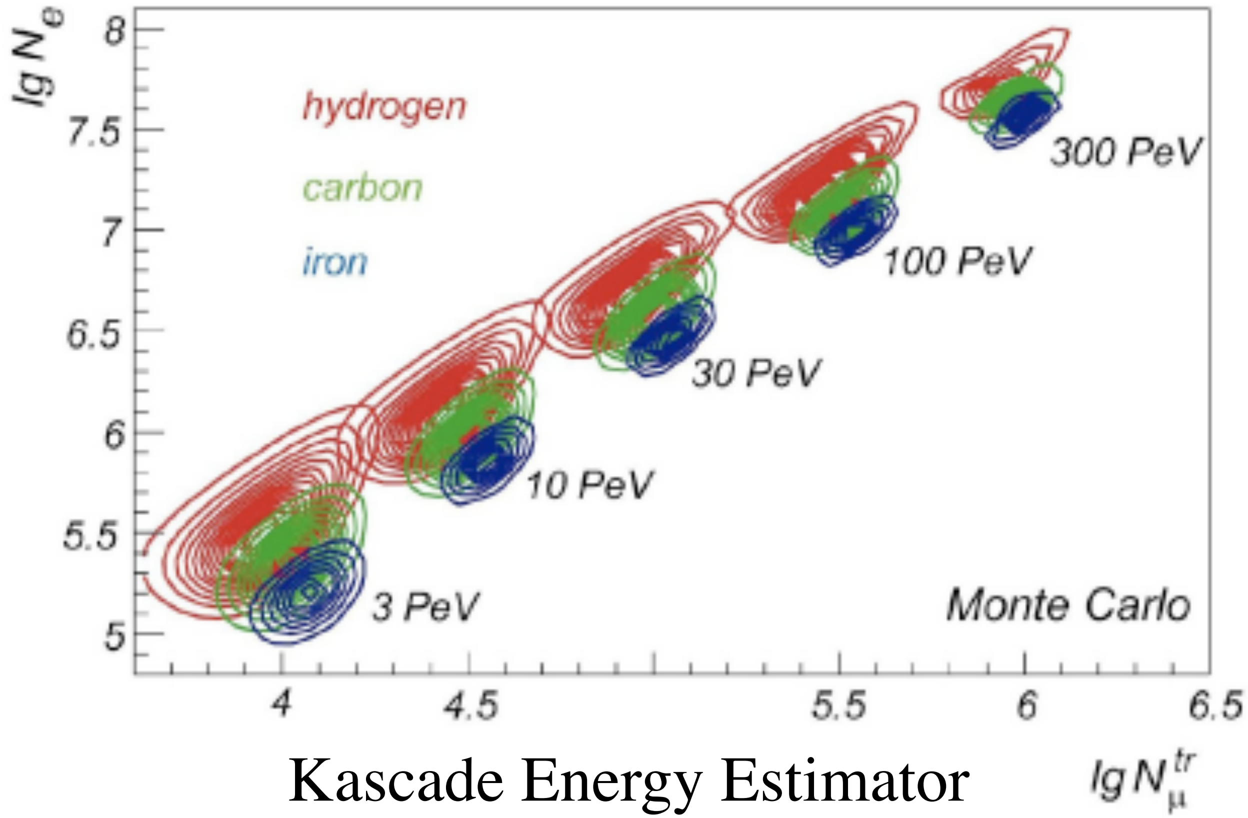


- Below ~10^{11} eV: Solar Modulation
- Below ~ 10^{18} eV Galactic origin
- Highest energies: Extra galactic

Next: Focus at the knee



Kascade Composition



Kascade Energy Estimator

Heavier particles:

Shower Maximum goes up: Less electrons reach Earth

Muon Number goes up a little bit (see yesterday)

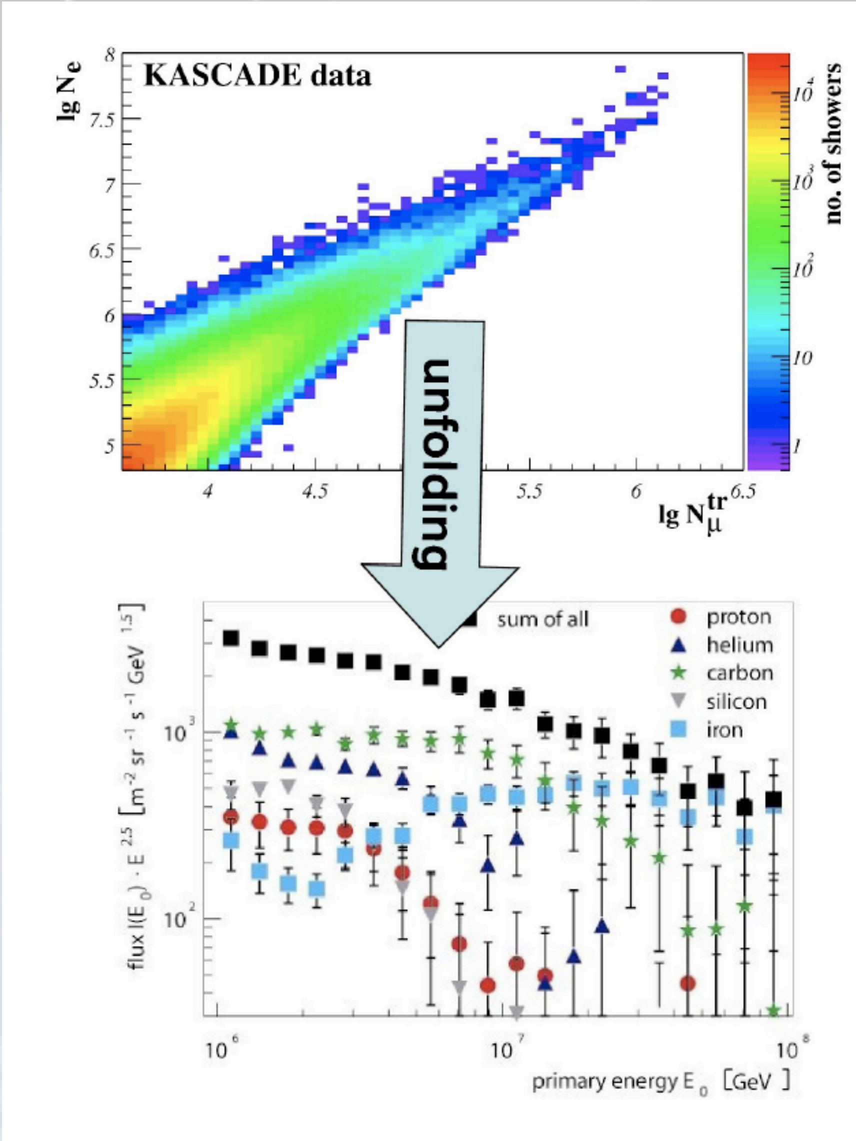
Kascade Composition Result

From electron and muon component:

Composition becomes heavier above the knee

Explanation: Accelerators (SNR) run out of steam

Can we get more evidence for this explanation?



HESS

Four telescopes,
107 m^2 mirror area each

960 PMT cameras, field of view 5^o

Observation in moonless nights, ~1000 h / year

Each night several objects are tracked and ~300 images recorded per second

First analysis (almost) online in the same night on PC cluster in Namibia

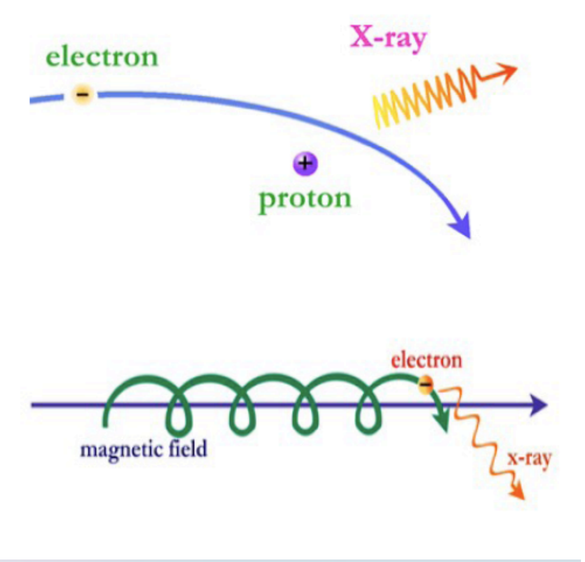
Final analysis and calibration in Europe

Energy threshold:
~ 100 GeV

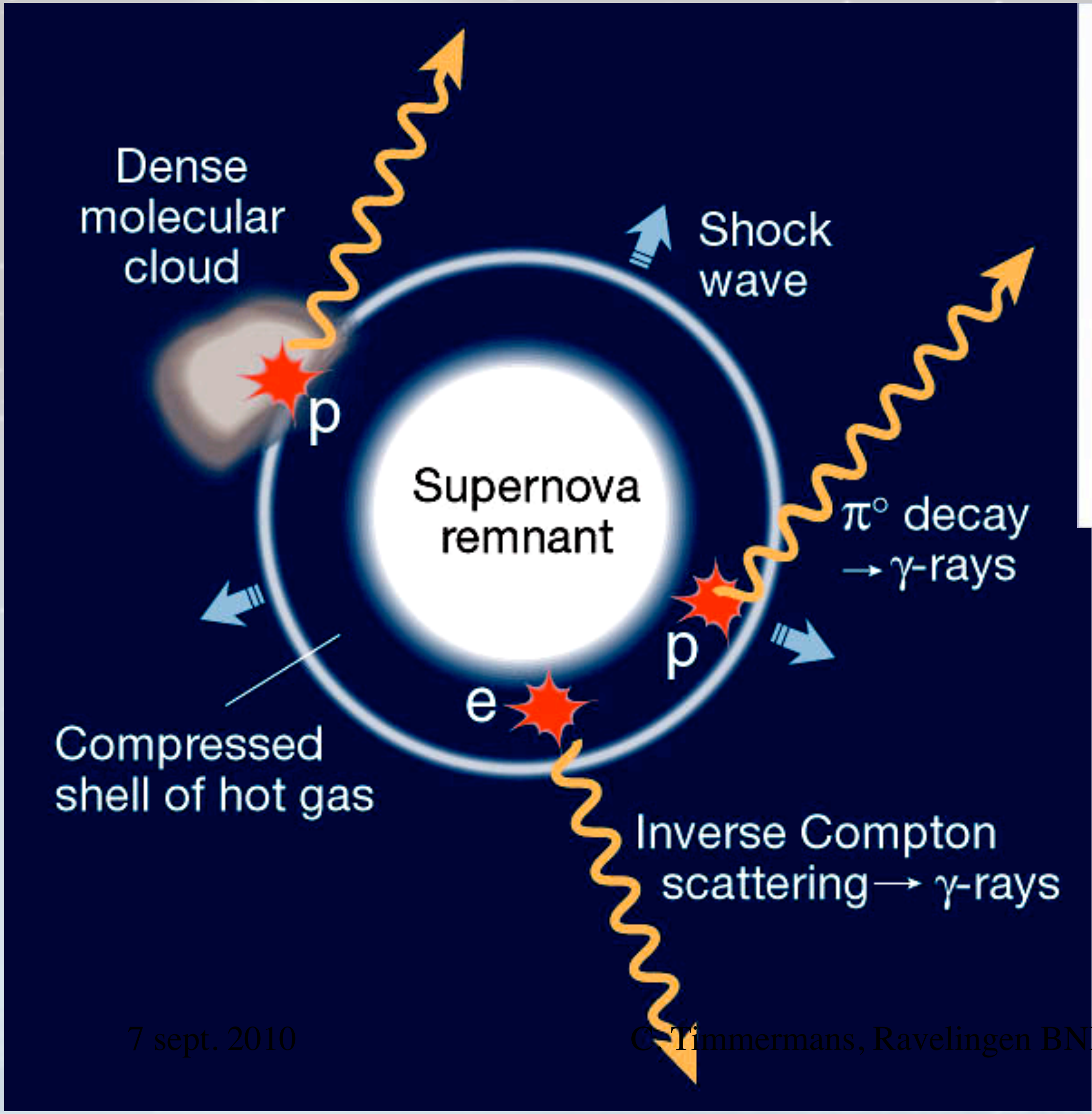
Sensitivity:
1% Crab in 25 h

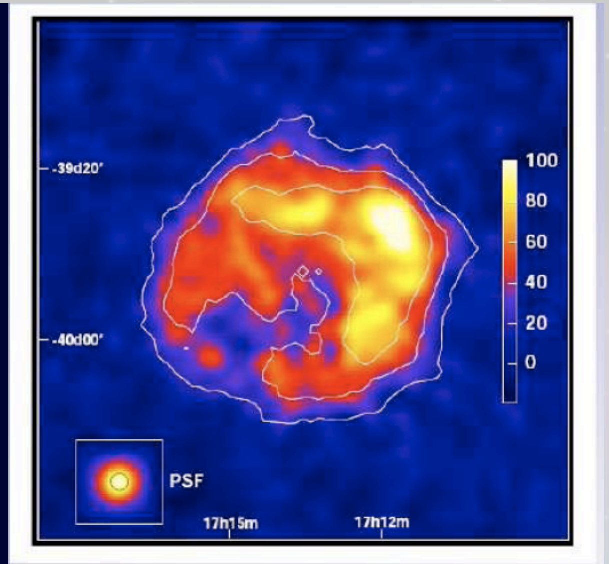
Production of high energy gamma rays

- Same standard processes as described in air shower physics:
  - Bremsstrahlung (electrons in matter)
  - Synchrotron radiation
  - Inverse Compton (low energy photons scattered by high energy electrons to high energies
  - Synchrotron-Self-Compton (TeV electrons create a dense photon field, scattered to high energy by IC)
  - π^0 decay into 2 photons (Hadronic!)



SNR shell

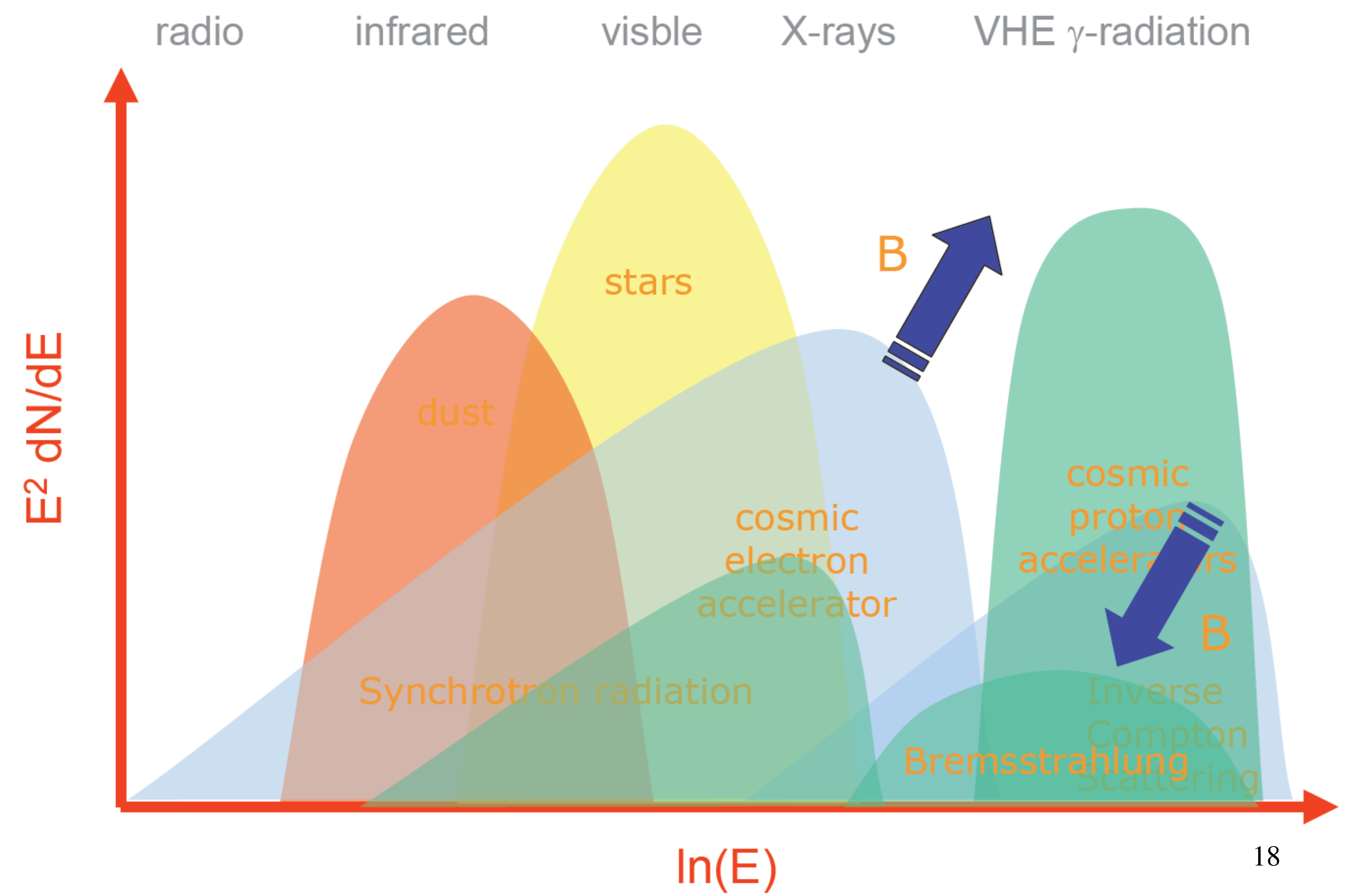




RX J1713.7-3946

Very strong gamma emission in the shell region

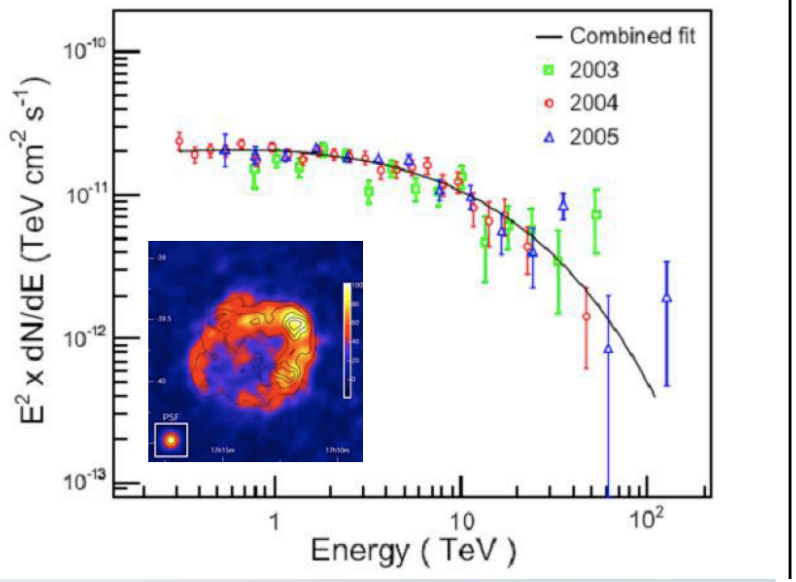
Cosmic ray acceleration in the shell of a SNR


radio
infrared
visble
X-rays
VHE γ-radiation
E² dN/dE
stars
dust
B
cosmic
electron
accelerator
cosmic
proton
accelerators
B
Synchrotron radiation
Inverse
Compton
Scattering
Bremsstrahlung
ln(E)

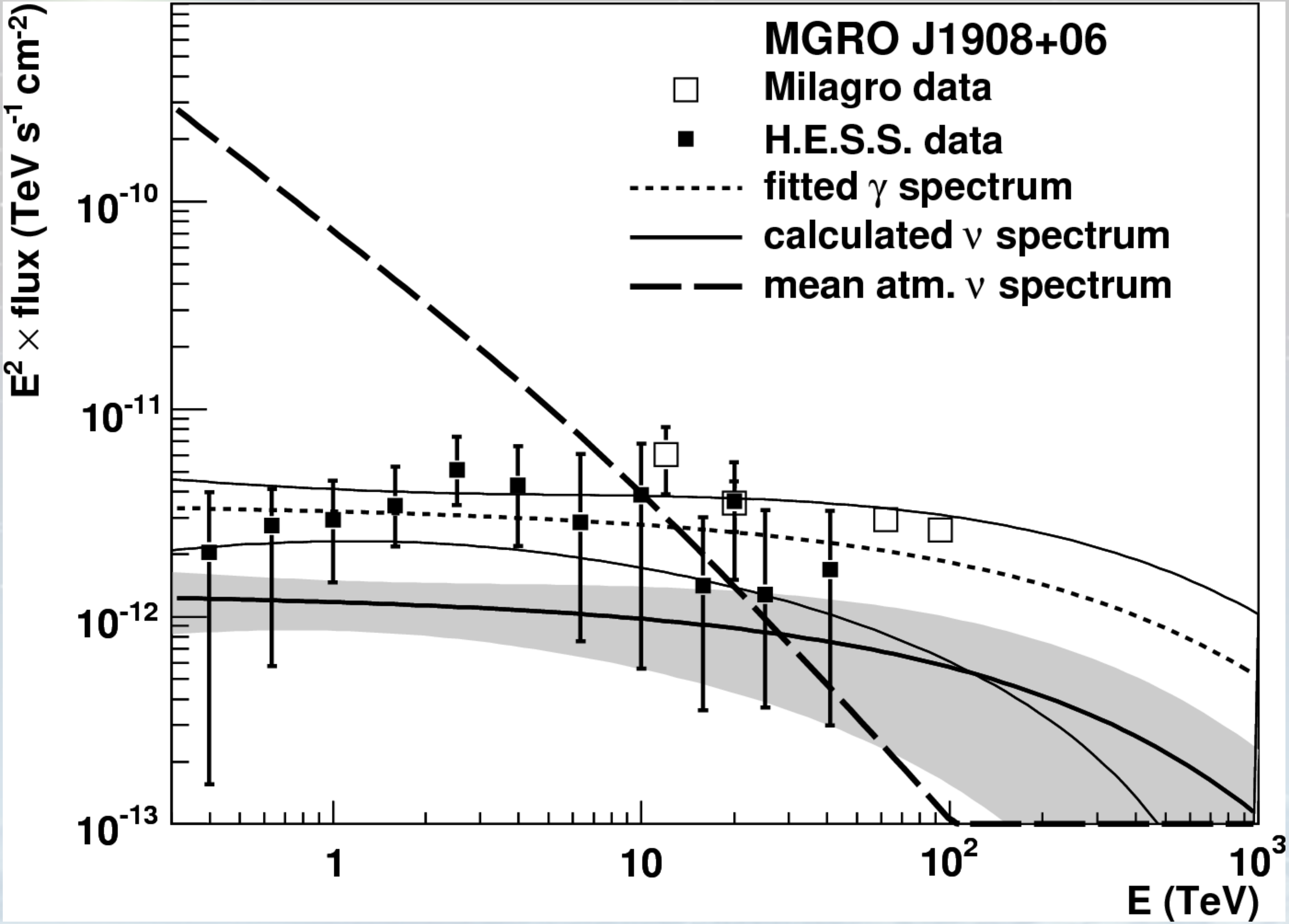
What are the sources at the knee?

- TeV photons may help out:
  - HESS sources seem to run out at ~30 TeV
  - π^0 carries about 15% of proton energy (same boost)
  - Proton cut-off ~200 TeV
- One needs 150 TeV photons to move protons to 1 PeV!

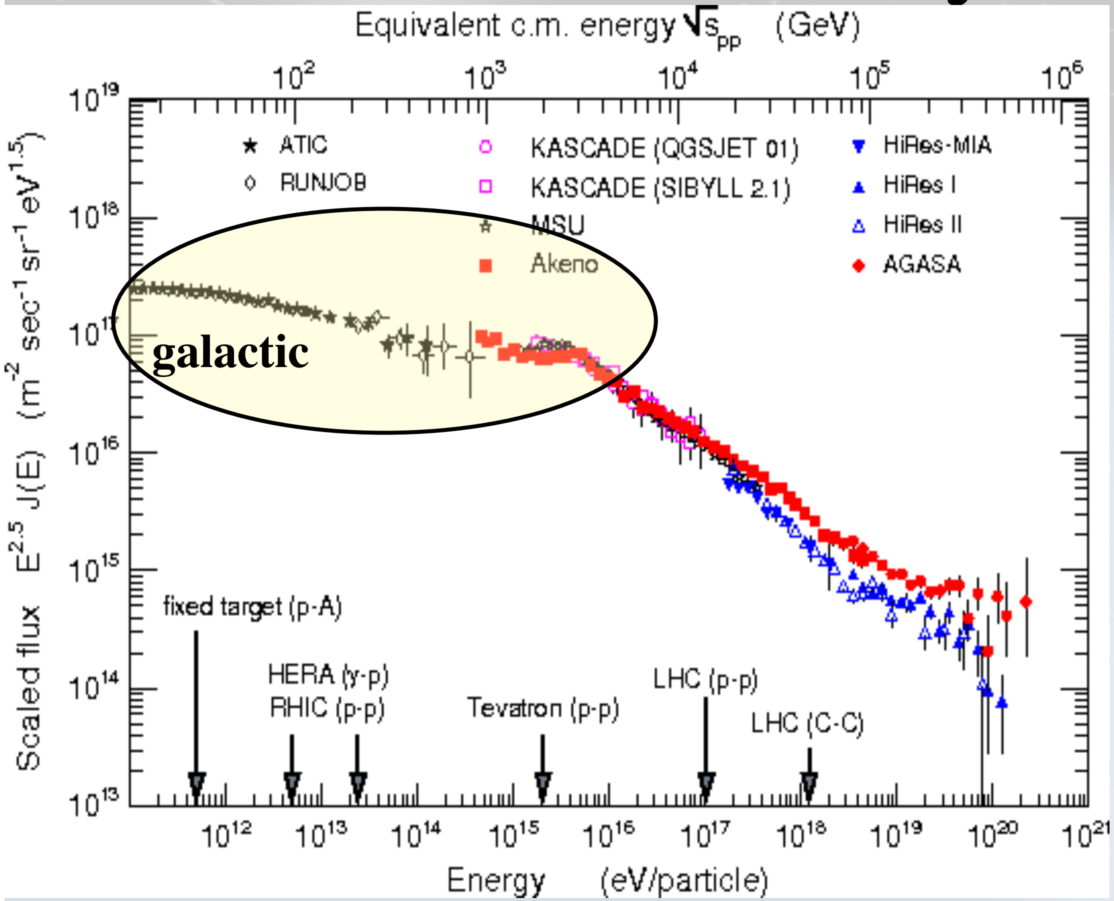
arXiv:0710.1767v1



MGRO J1908+06: A Pevatron??



Cosmic Rays and SNR



observed energy density of galactic CR:

~ 10^{-12} TeV/cm^3

supernova remnants:

10^{50} TeV every 30 years

use steady state of CR

with lifetime ~10^6 years

Size Milky Way ~ 10^{67} cm^3

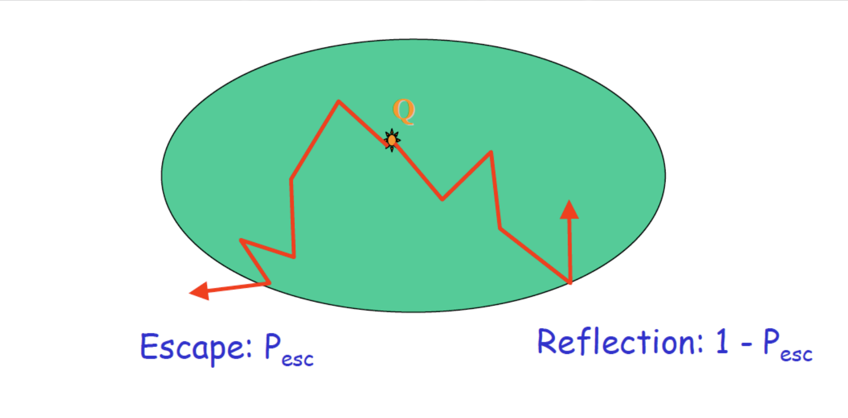
~ $(10^{50}\ 10^6)/(30\ 10^{67})$

= 10^{-12} TeV/cm^3

SNRs provide the environment and energy to explain the galactic cosmic rays!

Propagation of Cosmic Rays in the galaxy

The leaky box model:



Assumptions:
1) source spectrum Q(E)
2) No decay
3) No energy loss
4) Interactions with inter stellar medium
5) Diffusion out of the galaxy
6) Constant density of cosmic rays

Propagation of Cosmic Rays in the galaxy

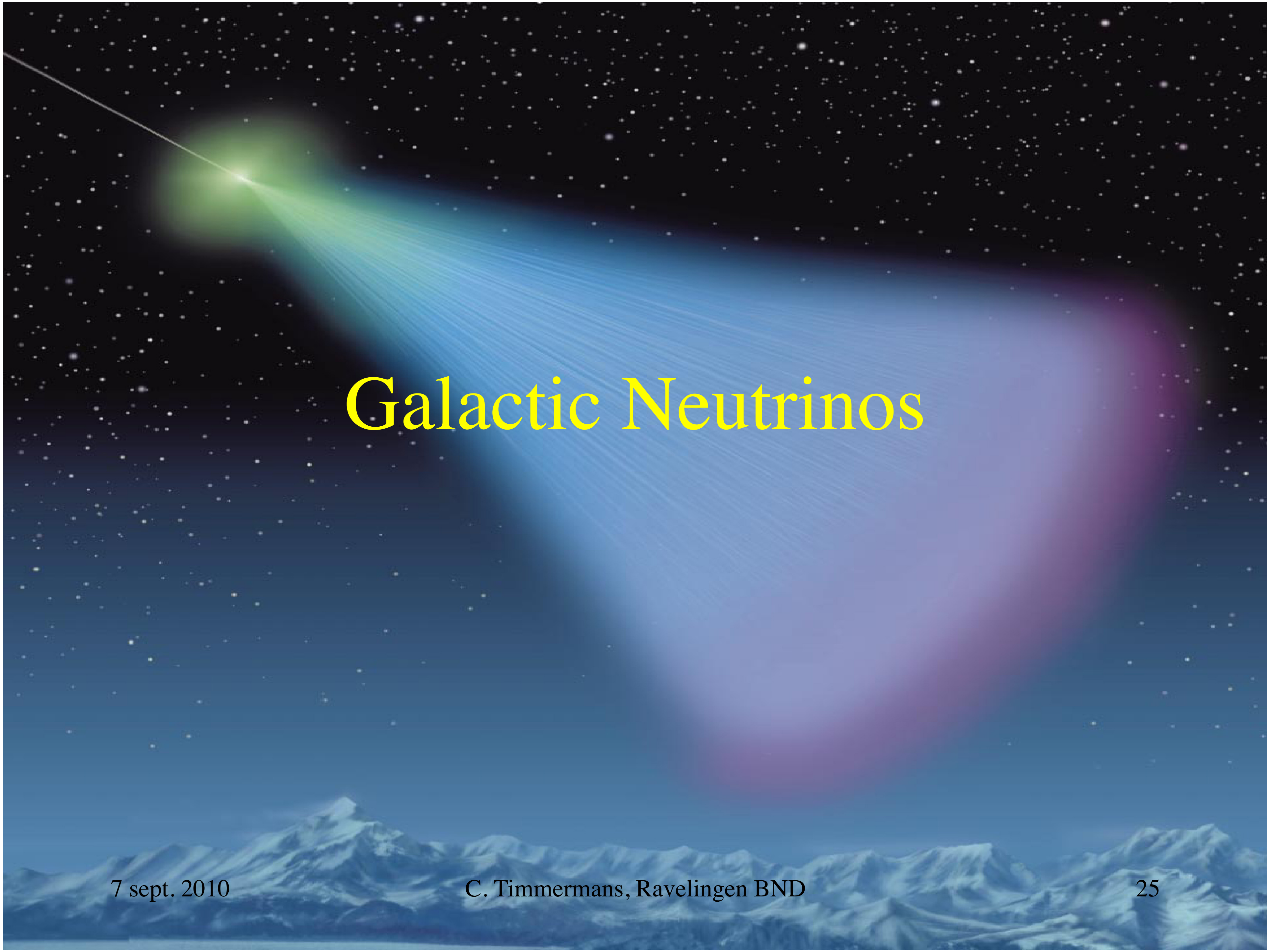
$\cancel{\dfrac{dN_i(E,\underline{\mathbf{r}},t)}{dt}} = +\; Q_i(E,\underline{\mathbf{r}},t)$	Sources, acceleration
$+\nabla(D_i \nabla N_i)$	Diffusion $-N/\tau_{esc}$
$\cancel{-\dfrac{\partial}{\partial E}(b_i N_i)}$	Energy loss
$-\bar{n}\cdot v_i \sigma_i N_i$	Loss by interaction (spallation) with the ISM (n=1/cm^3)
$\cancel{-\dfrac{N_i}{\gamma\tau_i}}$	Loss by radioactive decay
$+\sum_{j>i} \bar{n}\cdot v_i \sigma_{ij} N_j$	Production by interactions of heavier nuclei with ISM
$\cancel{+\sum_{j>i} \dfrac{N_j}{\gamma\tau_j}}$	Production by decay of heavier nuclei

Propagation of Cosmic Rays in the galaxy

- Simple Solution

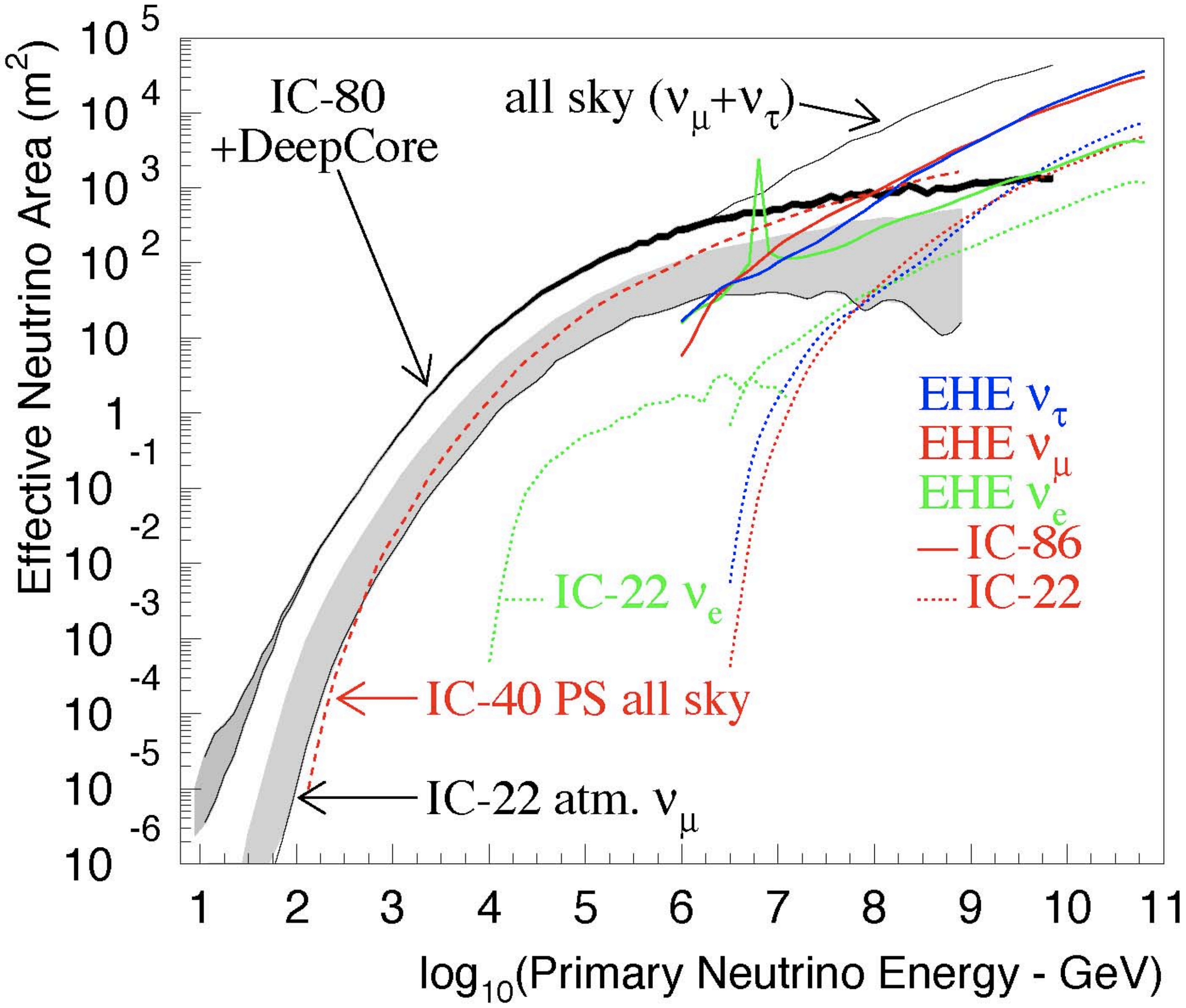
$$N_i(E) = \frac{\tau_{esc}(E) \cdot Q_i(E)}{1 + \lambda_{esc}(E) / \lambda_{int}}$$

- Interaction length easily evaluated from proton-nucleus cross section (galactic density equals 1 proton/cm^3)
- Looking at abundances, one gets λ_{esc} = 5-10 g/cm^2
- This corresponds to an escape time (= $\lambda_{esc}/\beta c \varrho_{ism}$) of 10^6 years



Galactic Neutrinos

IceCube Neutrino effective areas



Area at 100 TeV (1TeV)
AMANDA-II: 3m^2 (0.005)
IceCube 86: 100m^2 (0.3)

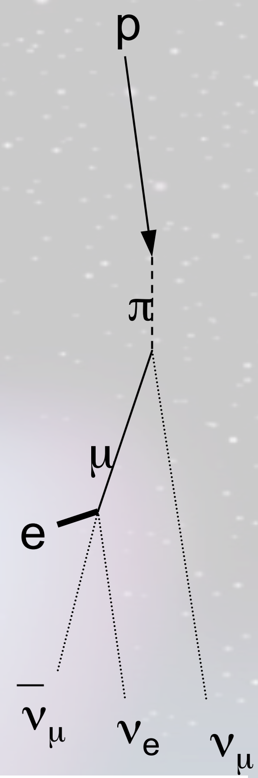
Deep Core lowers threshold from 100 GeV to 10 GeV.

Effective area for ν_μ
Strong rise with energy:
- $\sigma \propto E_\nu$
- Increase of muon range with energy up to PeV

Guaranteed neutrino sources

- The atmosphere (pion and kaon decay)
- The Galactic plane: Cosmic rays interact with interstellar matter
- Sources of cosmic rays (SNR)
- Cosmogenic neutrinos (from interaction of cosmic rays with CMB)

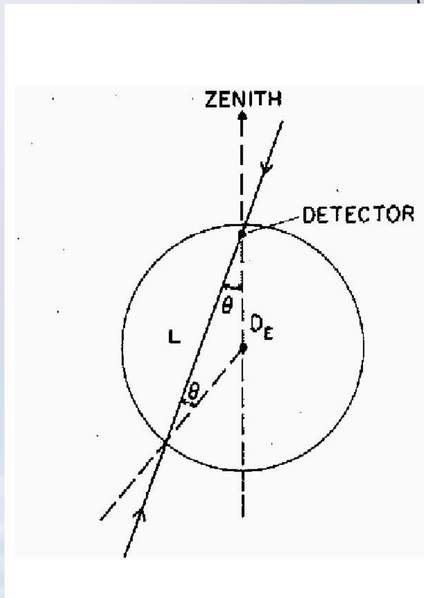
Atmospheric neutrino beam



- Cosmic-ray protons produce neutrinos in atmosphere
- For E_ν < GeV muons decay, so $\nu_\mu/\nu_e \sim 2$ expected
- **$\nu_\mu/\nu_e \sim 1$ observed!**

- Oscillation theory: Wolfenstein; Mikheyev & Smirnov

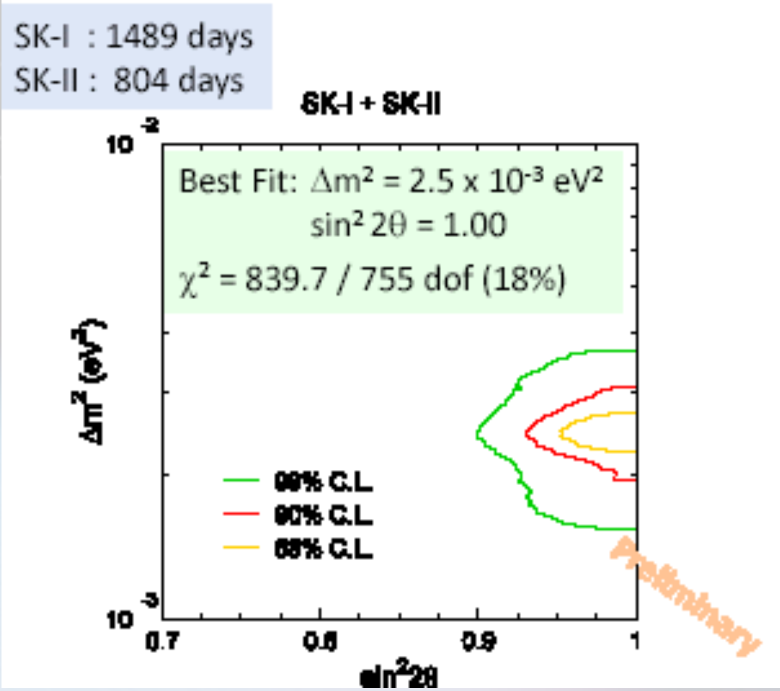
$$P(\nu_\mu \longleftrightarrow \nu_\tau) = \sin^2 2\theta \, \sin^2\left(\frac{1.27\, L(\mathrm{km})\, \delta m^2(\mathrm{eV}^2)}{E_\nu(\mathrm{GeV})}\right)$$



- Detector up-down symmetric
- Compare 2 pathlengths
  - Upward: 10,000 km
  - Downward: 10 – 20 km
  - E_ν dependence characteristic of oscillations

Atmospheric ν

$\nu_\mu \leftrightarrow \nu_\tau$, $\delta m^2 = 2.5 \times 10^{-3}\ eV^2$
maximal mixing



Yumiko Takenaga, ICRC2007

Solar neutrinos

$\nu_e \leftrightarrow \{\nu_\mu,\nu_\tau\}$, $\delta m^2 \sim 10^{-4}\ eV^2$
large mixing

3-flavor mixing

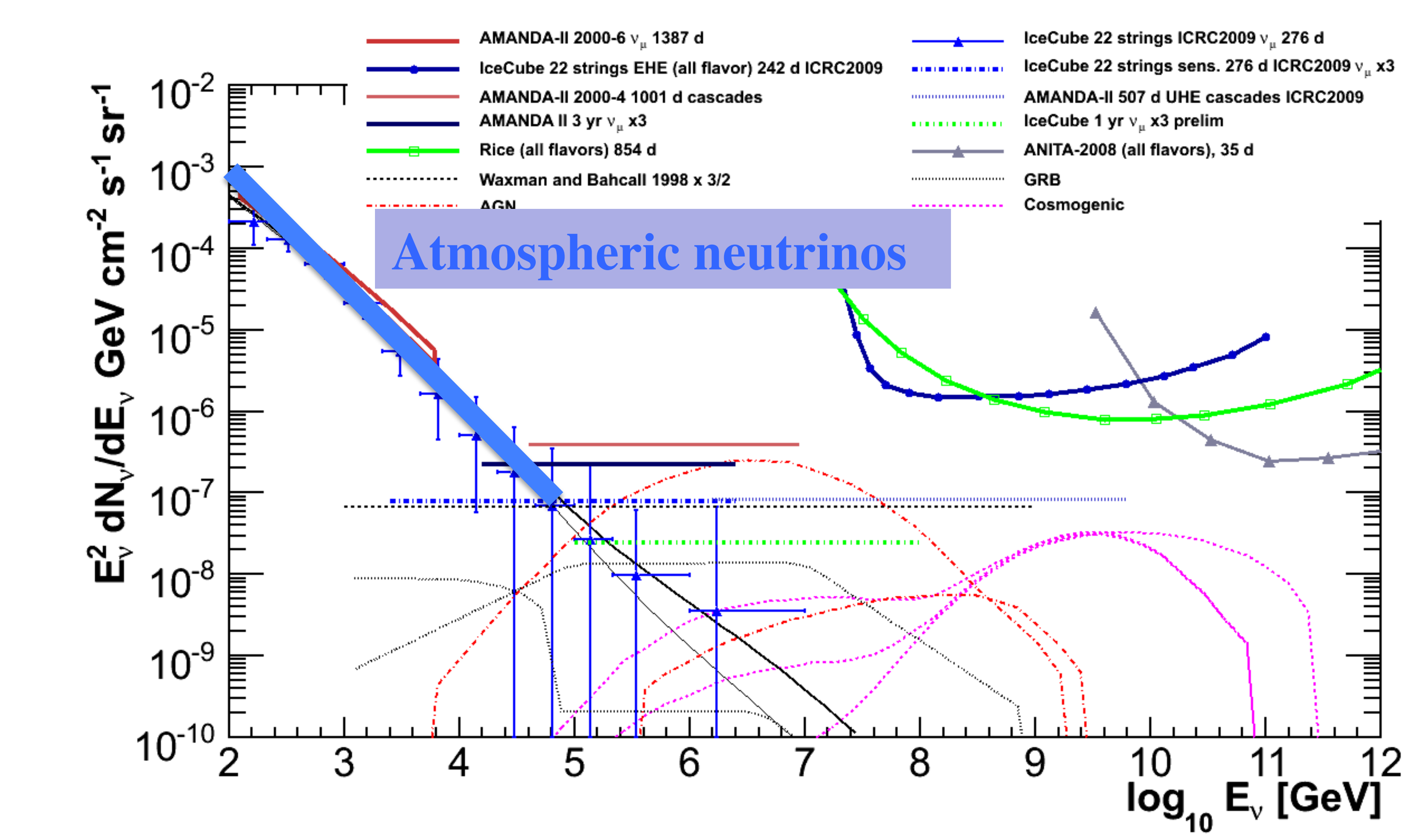
Flavor state $|\nu_\alpha) = \Sigma_i U_{\alpha i} |\nu_i)$, where $|\nu_i)$ is a mass eigenstate

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13} \\ 0 & 1 & 0 \\ -S_{13} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

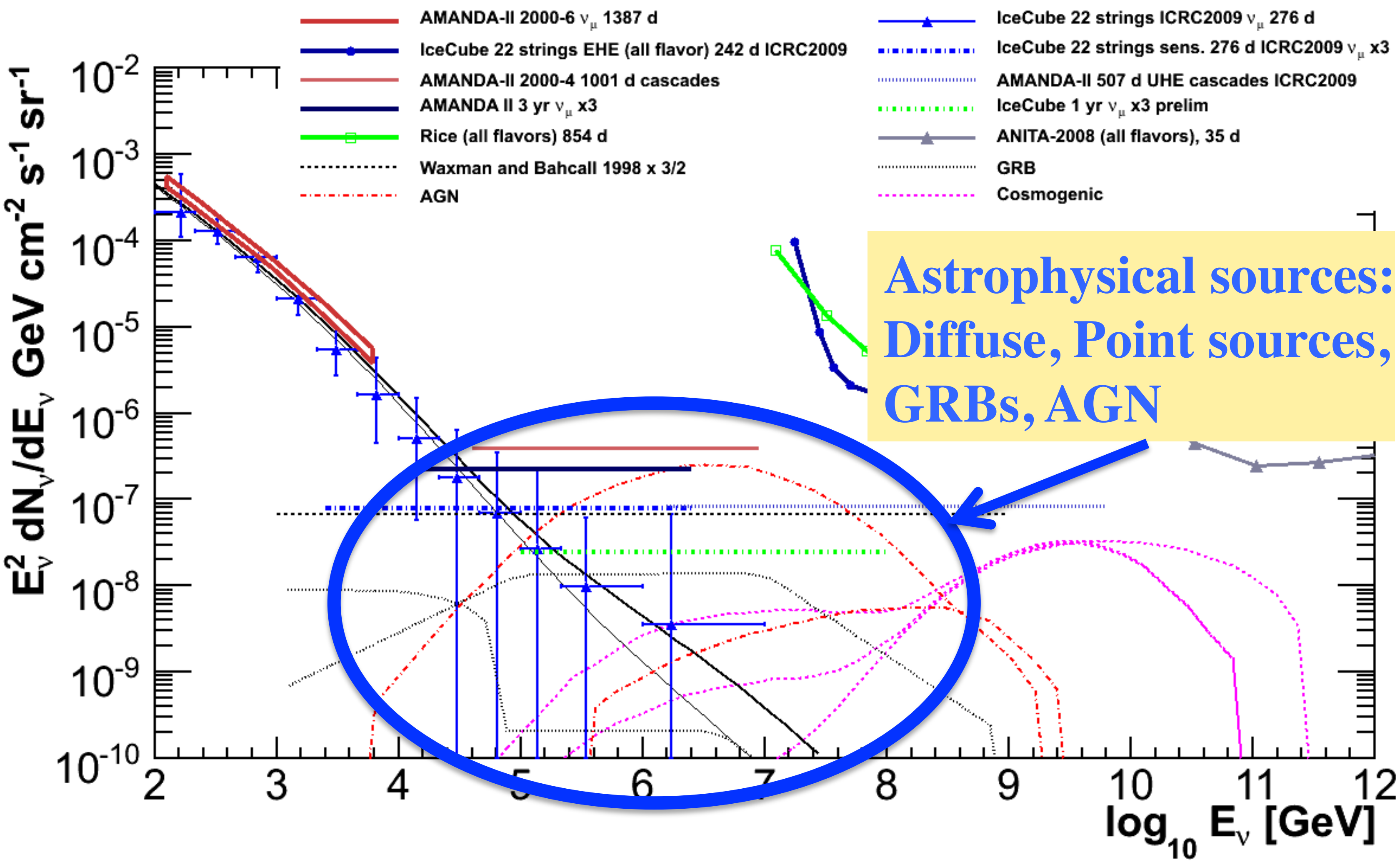
Major discovery for particle physics!

Not so good for neutrino astronomy: $\nu_\mu \rightarrow \nu_\mu/2$

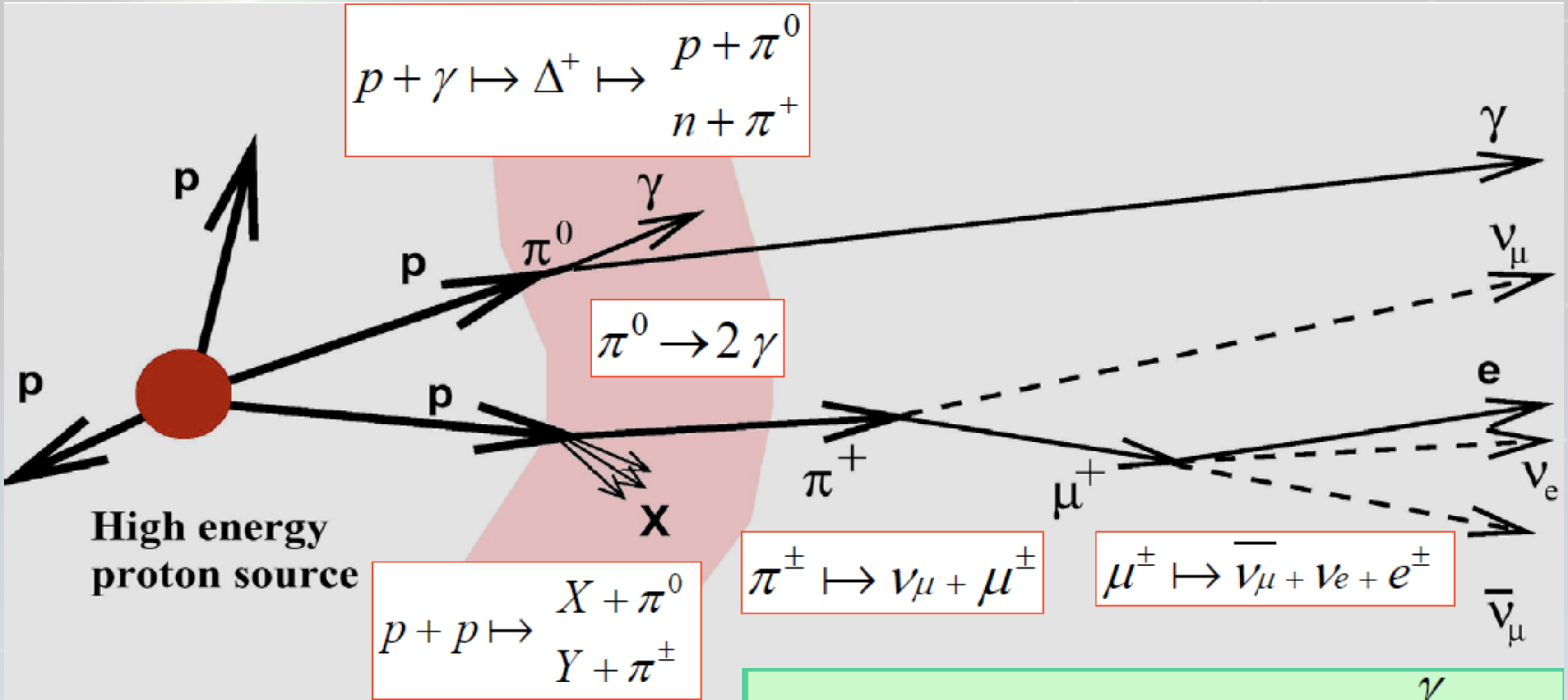
Neutrino fluxes and limits



Neutrino fluxes and limits



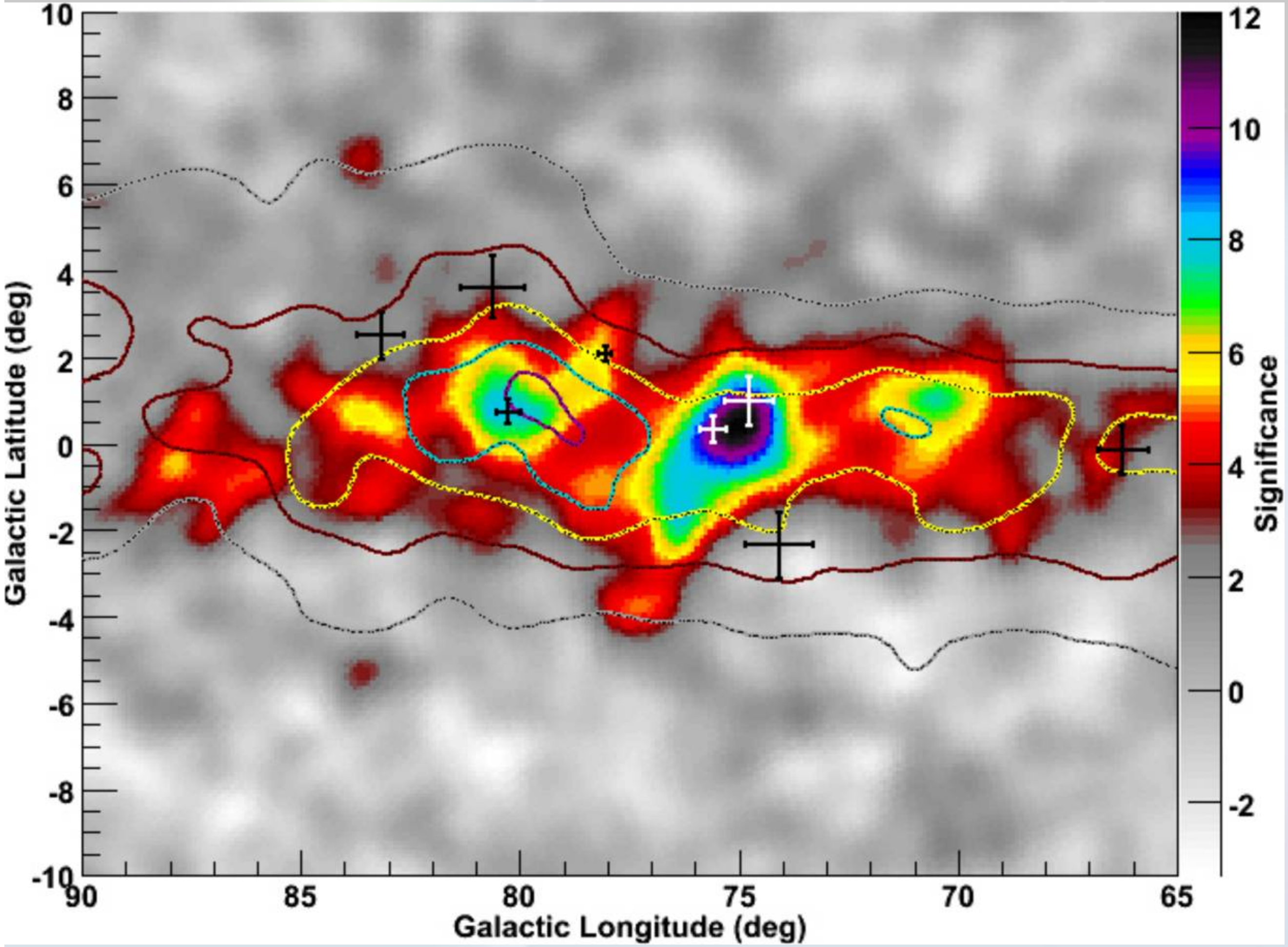
Multi-Messenger Approach



Charged Cosmic Rays, Photons and neutrinos are related.

$$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 2 : 0 \quad \text{and} \quad \frac{\gamma}{\nu_\mu} \approx 1$$

Cygnus- Region

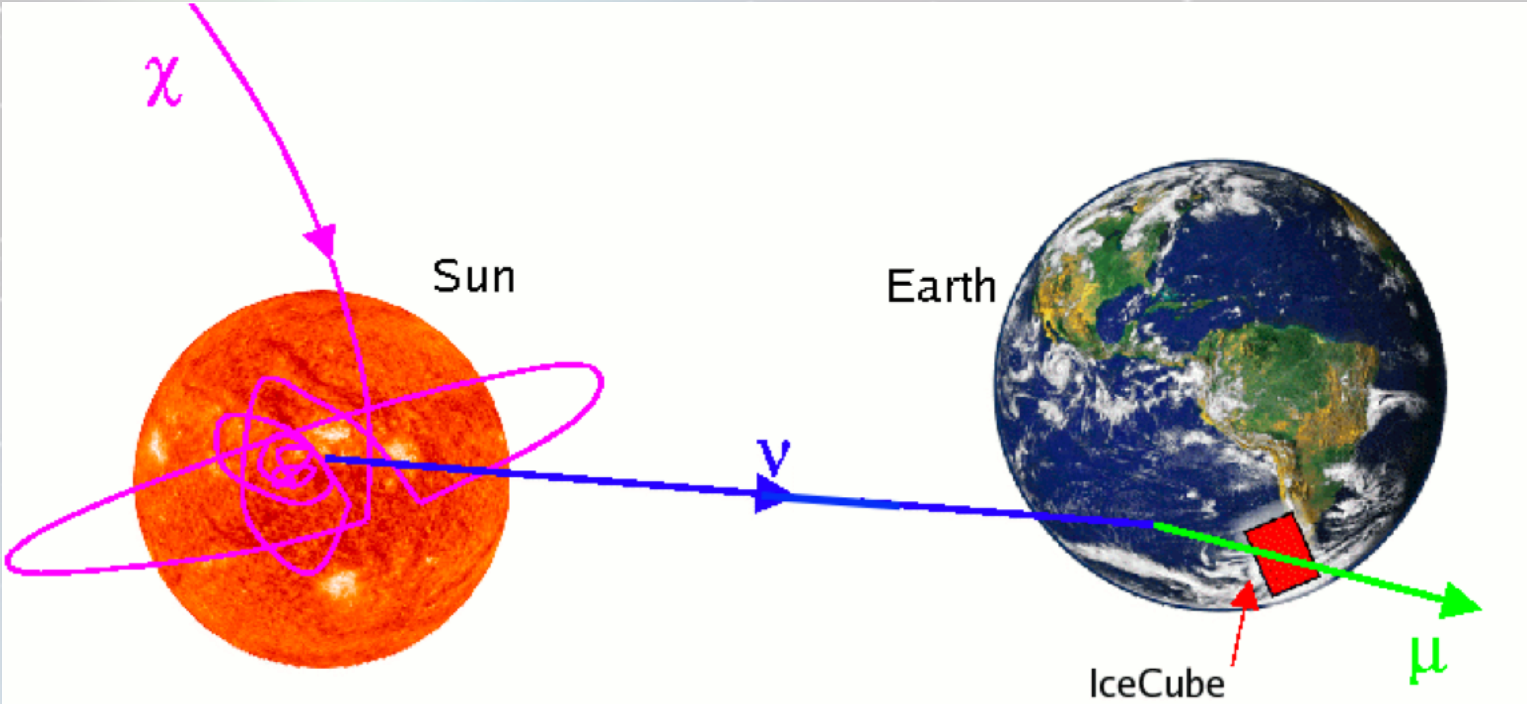


Milagro

translation of
TeV gamma rays
into
TeV neutrinos

3 ± 1 ν per year in IceCube per source

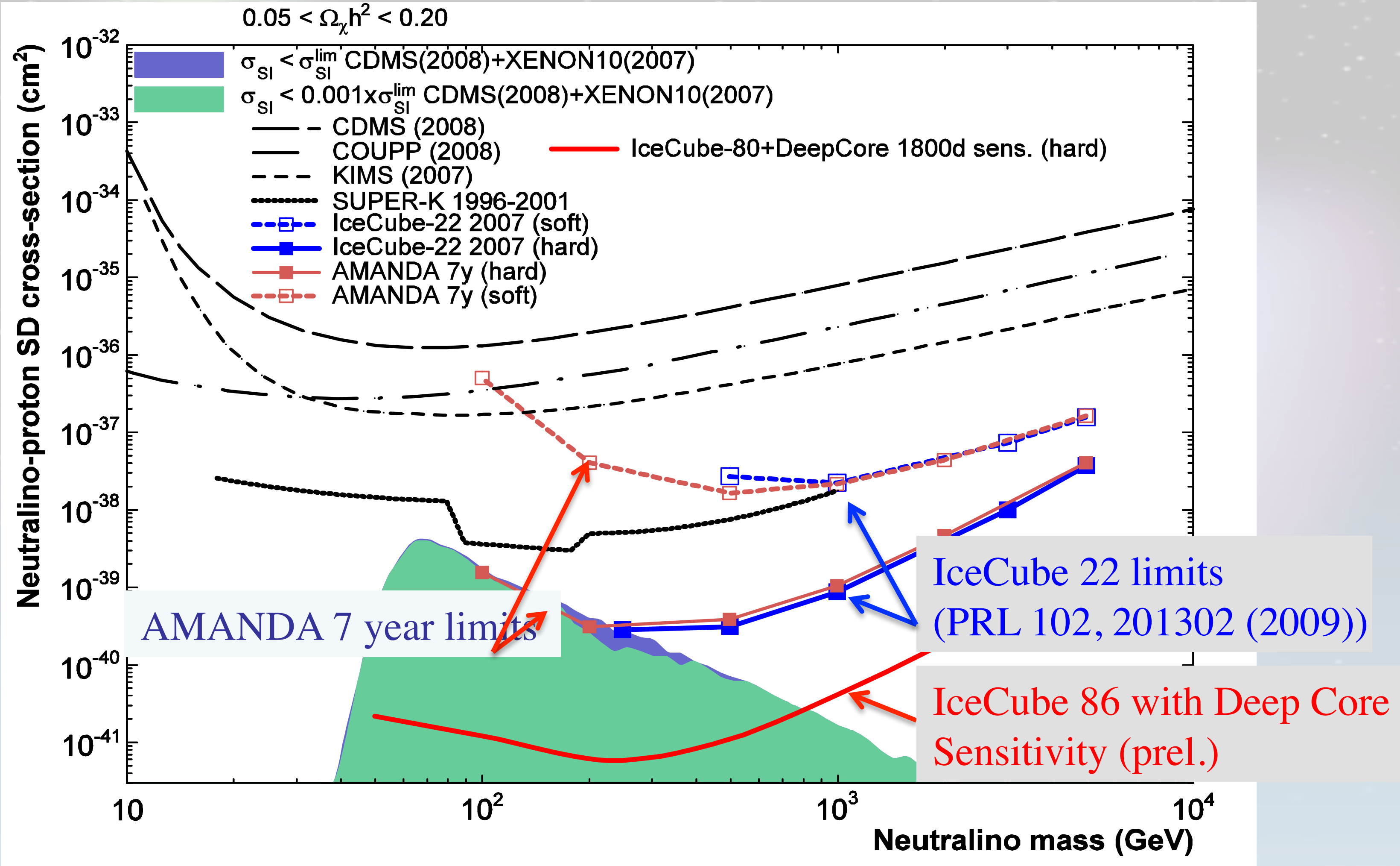
Example dark matter search: Wimps in the sun



Neutralinos annihilate in the gravity well of the sun. The resulting neutrinos are detected at Earth

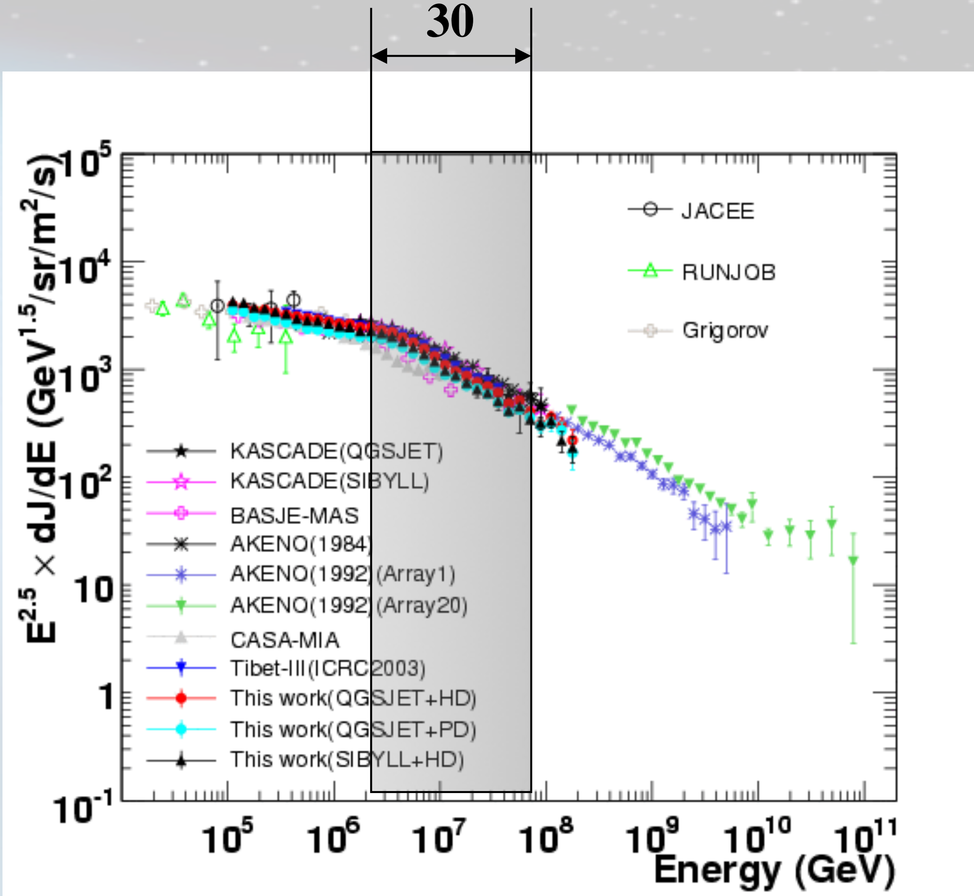
Dark Matter search:
Search for neutrinos from WIMP annihilation in the sun

$\tilde{\chi}\tilde{\chi}$

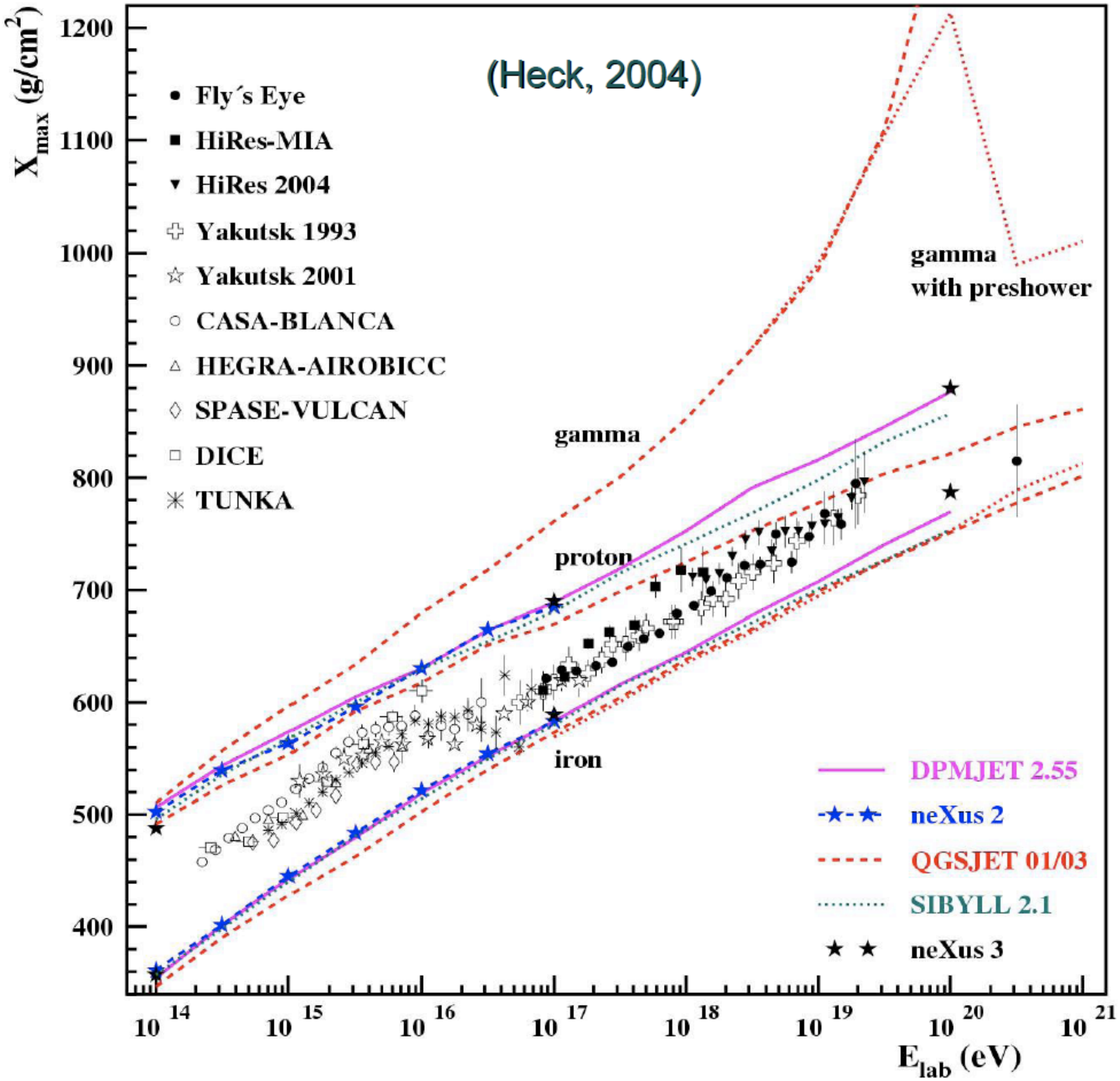


Knee as end of Galactic population?

- Acceleration, propagation
  - depend on B: $r_{gyro} = R/B$
  - Rigidity, $R = E/Ze$
  - $E_c(Z) \sim Z R_c$
- Slope change should occur within factor of 30 in energy
- With characteristic pattern of increasing A
- Problem 1: E_{knee} is higher than expected
- Problem 2: continuation of smooth spectrum to EeV



Mean depth of shower maximum



Superposition model:

$$X_{max}^{A} \sim \lambda_e \ln(E_0/A)$$

MC simulation (CORSIKA):

predictions depend on had. interaction model used for simulation

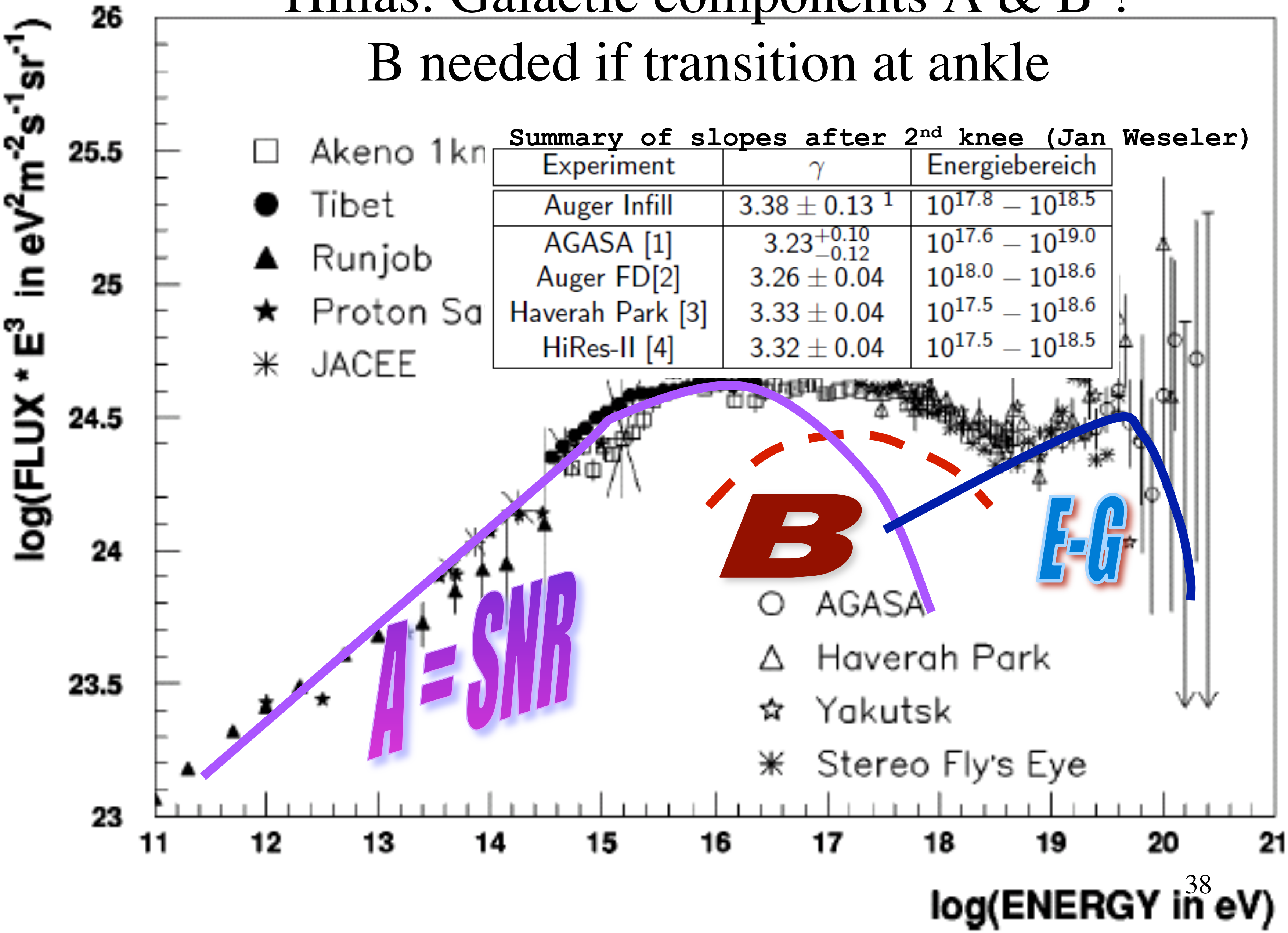
M. Nagano and A. A. Watson: Ultrahigh-energy cosmic rays

Hillas: Galactic components A & B ?

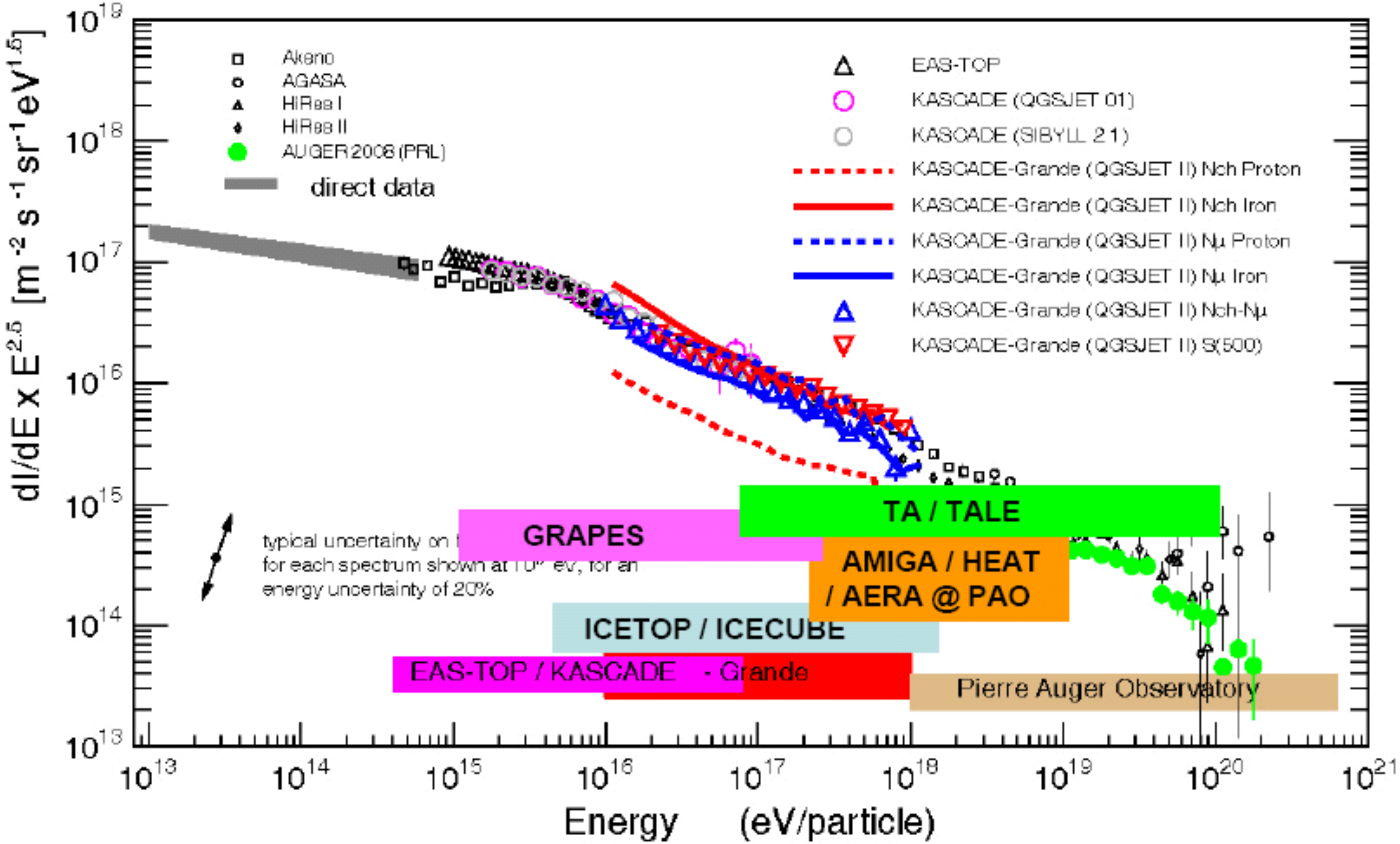
B needed if transition at ankle

Summary of slopes after 2nd knee (Jan Weseler)

Experiment	γ	Energiebereich
Auger Infill	3.38 ± 0.13 [1]	$10^{17.8} - 10^{18.5}$
AGASA [1]	$3.23^{+0.10}_{-0.12}$	$10^{17.6} - 10^{19.0}$
Auger FD[2]	3.26 ± 0.04	$10^{18.0} - 10^{18.6}$
Haverah Park [3]	3.33 ± 0.04	$10^{17.5} - 10^{18.6}$
HiRes-II [4]	3.32 ± 0.04	$10^{17.5} - 10^{18.5}$



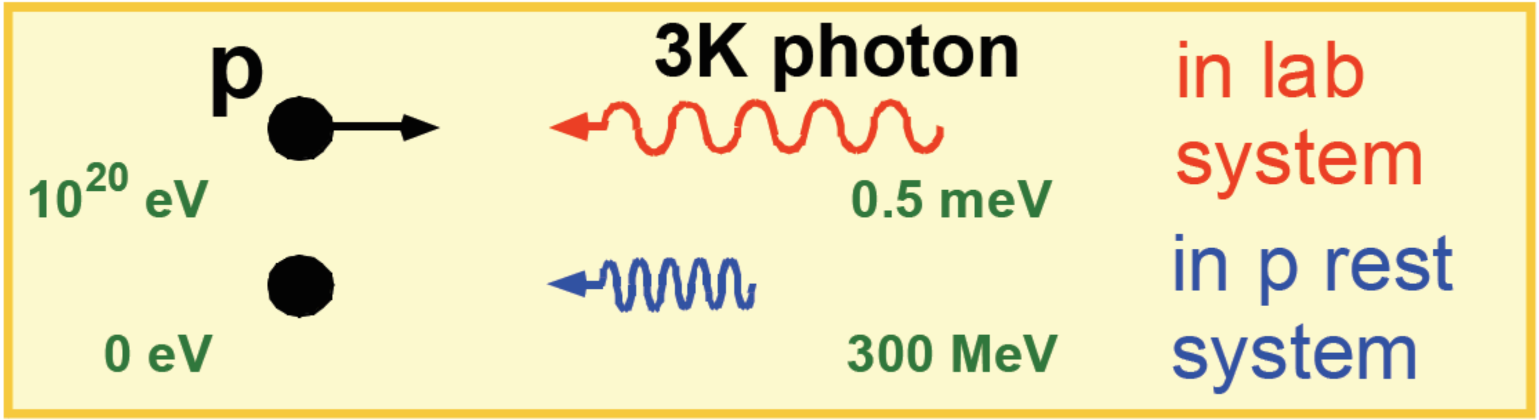
Galactic-extra galactic region: More data is needed



Extra-Galactic particles

GZK Cut-Off

Greisen Zatsepin Kuzmin



$$p + \gamma_{3K} \longrightarrow \Delta^{+} \longrightarrow p + \pi^{0} \nearrow \gamma$$

$$\longrightarrow n + \pi^{+} \searrow \nu$$

Photo-pion production

$$^{56}Fe + \gamma \longrightarrow {}^{55}Fe + n$$

Photo dissociation

Universe becomes opaque for $E > 5 \times 10^{19}$ eV.

Sources must be close !

If sources are universal: **cut-off in CR spectrum.**

Test of Lorentz Invariance for $\gamma \approx 10^{11}$!

Nuclei and the CMB

- Binding energy:

$$E_b = \Delta M_A = Zm_p + Nm_n - M_A$$

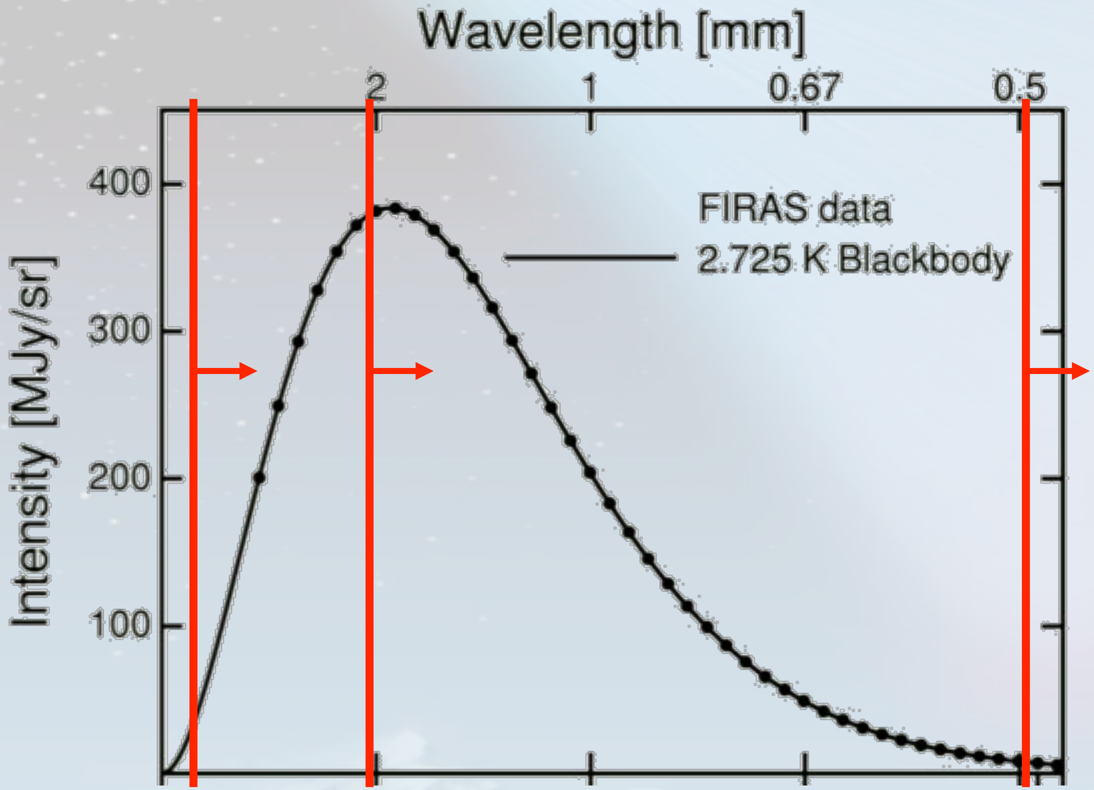
- Using semi-emperical mass formula (Weizsäcker)

$$E_b(A) = A\cdot\left[15.8 - 18.3A^{-\frac{1}{3}} - 0.18A^{\frac{2}{3}} + 1.3\cdot 10^{-3}A^{\frac{4}{3}} - 6.4\cdot 10^{-6}A^{2}\right]$$

- This is about 20 MeV/nucleon
- The 20 MeV could be obtained from the photon in the frame in which the nucleus is at rest
  - photon energy is boosted by a factor of $(1+\beta\cos(\phi))\gamma$

Nuclei and the CMB

At 55 EeV, iron travels approximately as far as protons, but lighter nuclei lose energy rapidly by photodisintegration.



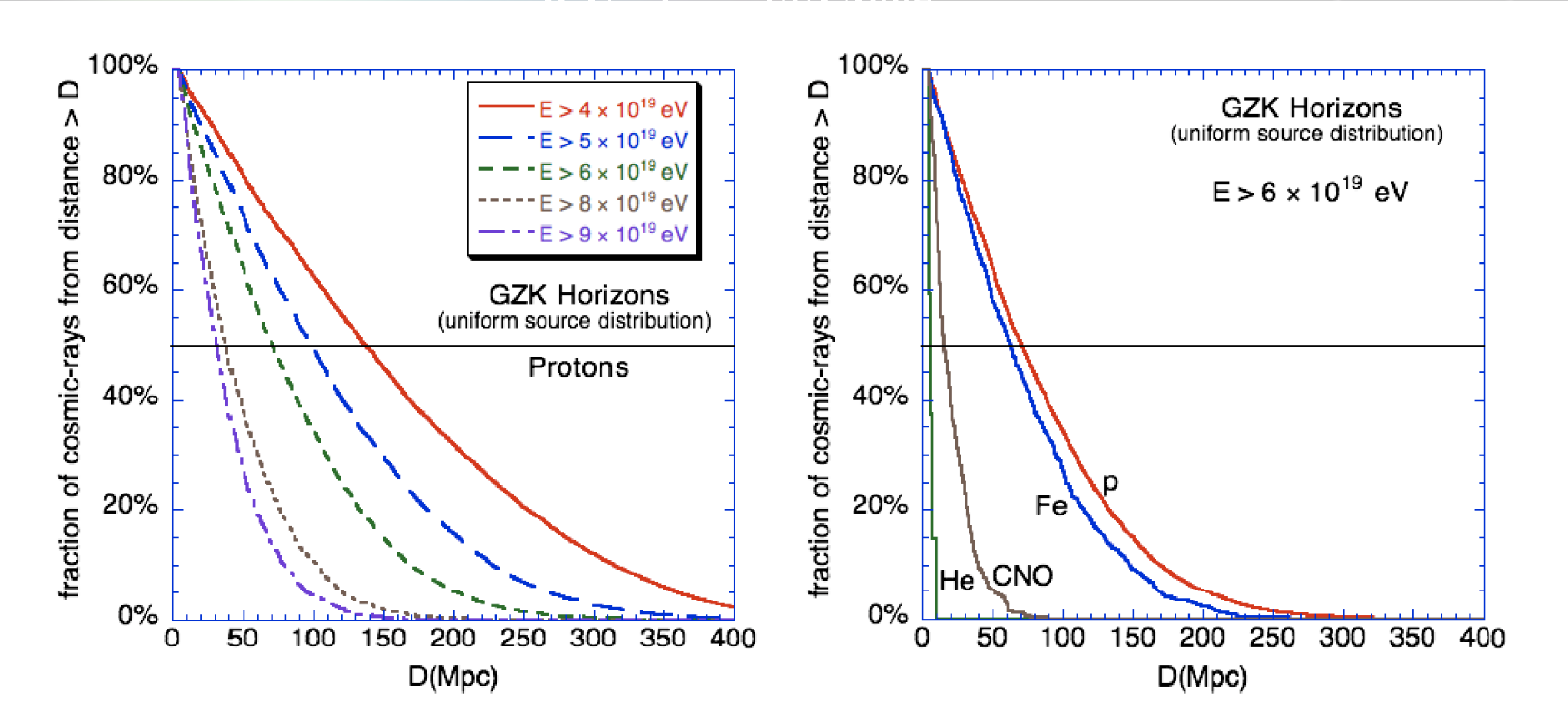
frequency (1/cm) 5 10 15 20

He CNO Fe

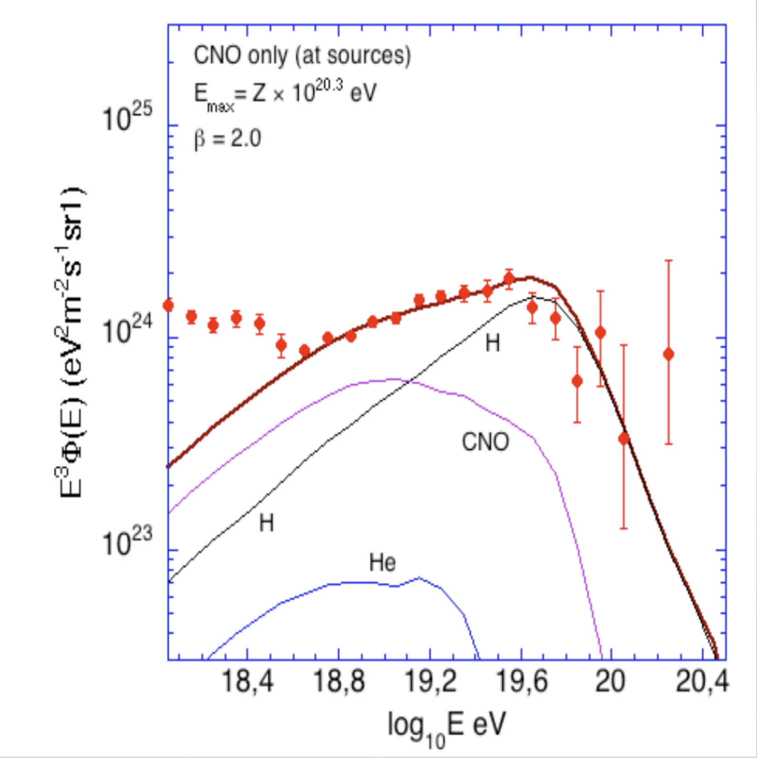
At 55 EeV, the CMB photon energy needed for photodisintegrating a nucleus depends on the Lorentz gamma factor, hence on the nuclear mass.

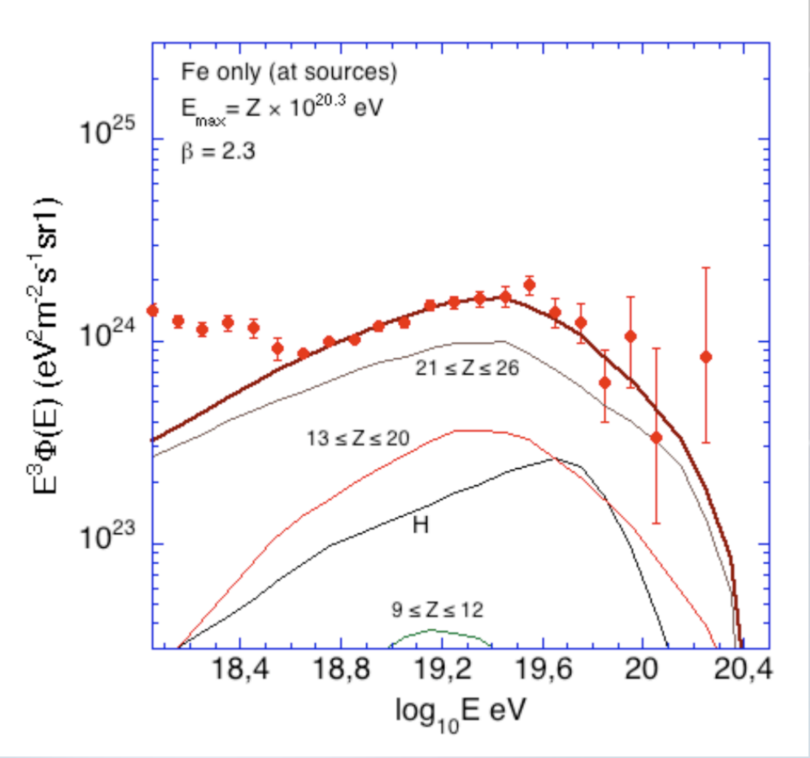
The minimum CMB photon energies are shown for He, CNO, and Fe

The GZK-distances



Composition changes in space





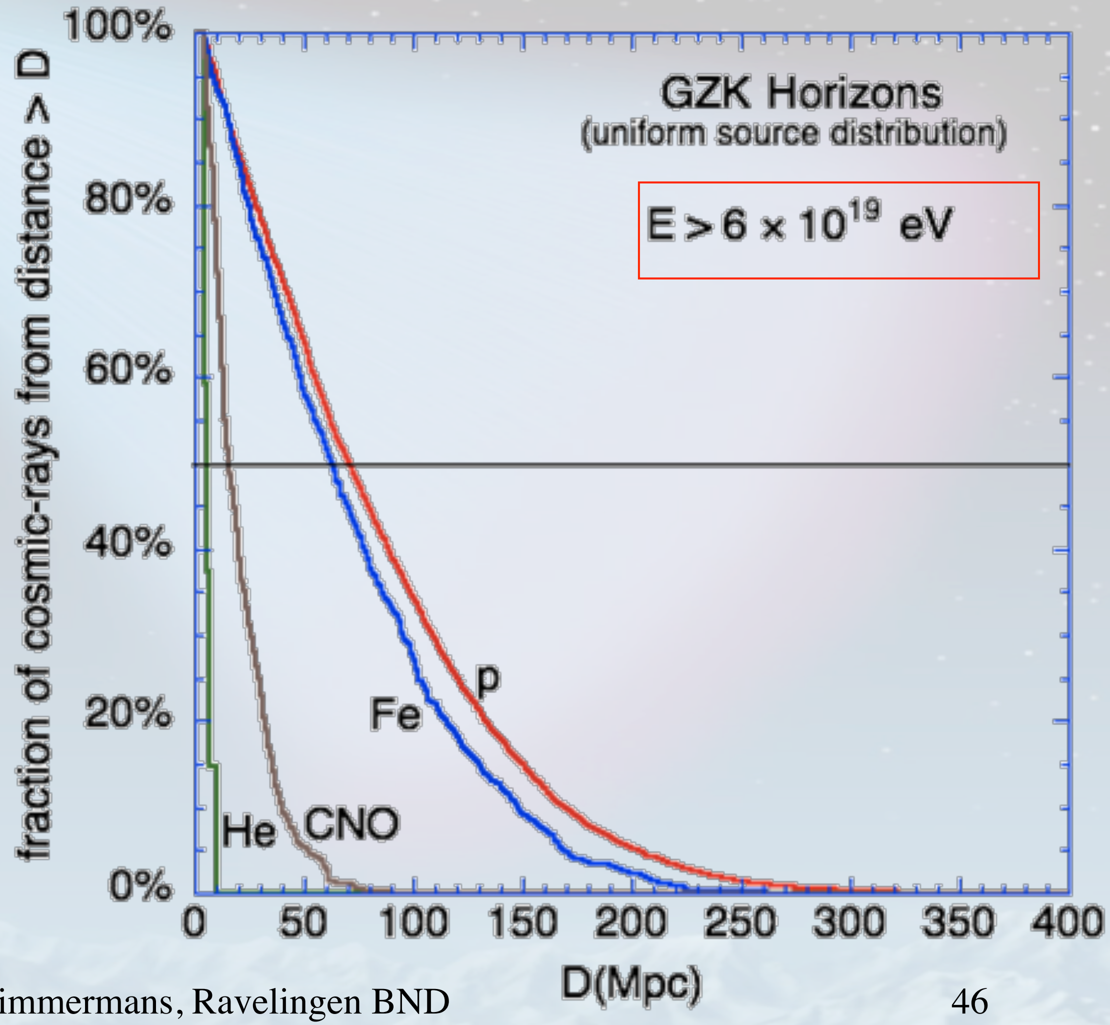
Light source composition becomes proton dominated after interactions with interstellar fields. This is not true for iron dominated sources. ***D. Allard et al., JCAP 0810 (2008)***

Trans-GZK composition is simpler

Light and intermediate nuclei photodisintegrate rapidly.

Only protons and/or heavy nuclei survive more than 20 Mpc distances.

Cosmic magnetic fields should mask anisotropy of sources if CRs are heavy nuclei.



Sommers ISVHECRi 10

Bending of charged particles in B-fields

- Extra Galactic Fields (assuming that distance to source >> coherence of B-fields in space)

$$\alpha_{\rm rms} \simeq \frac{2}{\pi}\frac{ZeB}{E}(rl_c)^{1/2}$$

Lee, Olinto, Sigl: Astrophysical Journal 455 1995

$$= 1^\circ\!.1 Z\left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1}\left(\frac{r}{10\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{l_c}{1\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{B}{10^{-9}\ \mathrm{G}}\right)$$

- Galactic Fields:

$$\delta \simeq 0.53^\circ \frac{Z}{E_{20}}\frac{B}{\mu\mathrm{G}}\frac{L}{\mathrm{kpc}}$$

Kachelriess et al 2006

  – Nb: this depends on the galactic magnetic field model

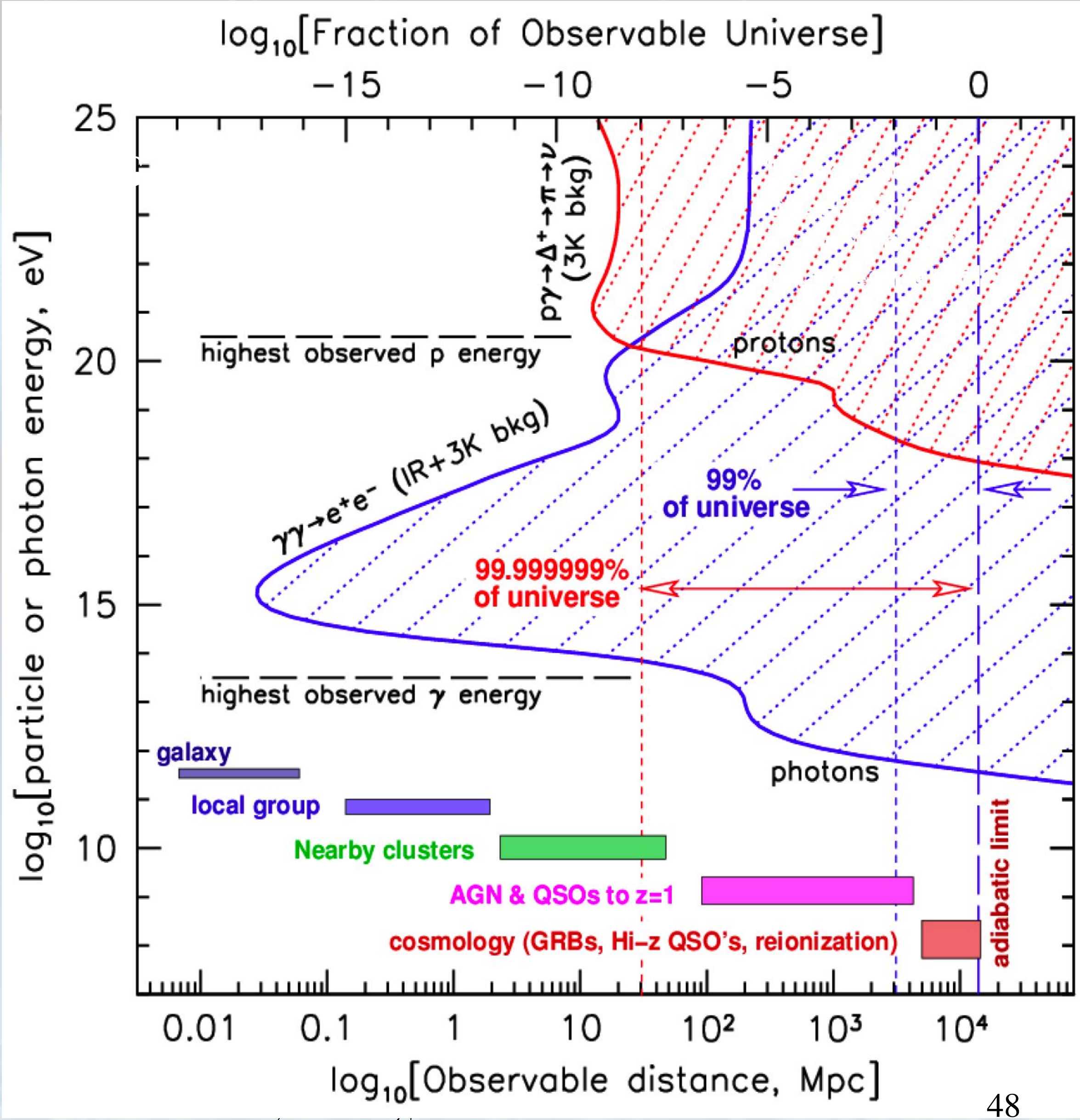
The GZK-horizon

Disadvantage:

Limited number of sources

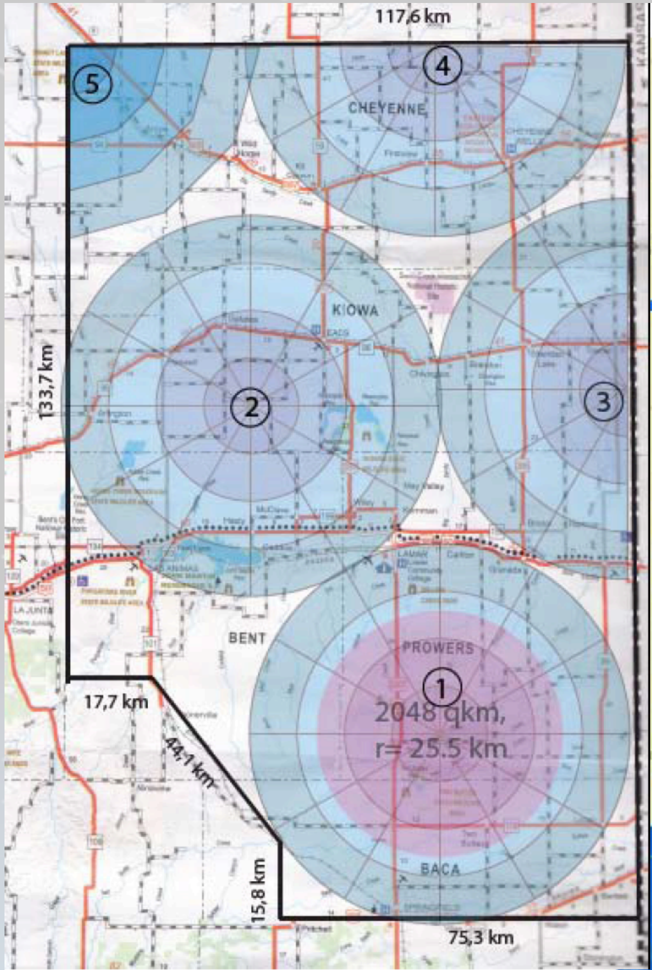
Advantages:

Limited bending
Limited number of sources



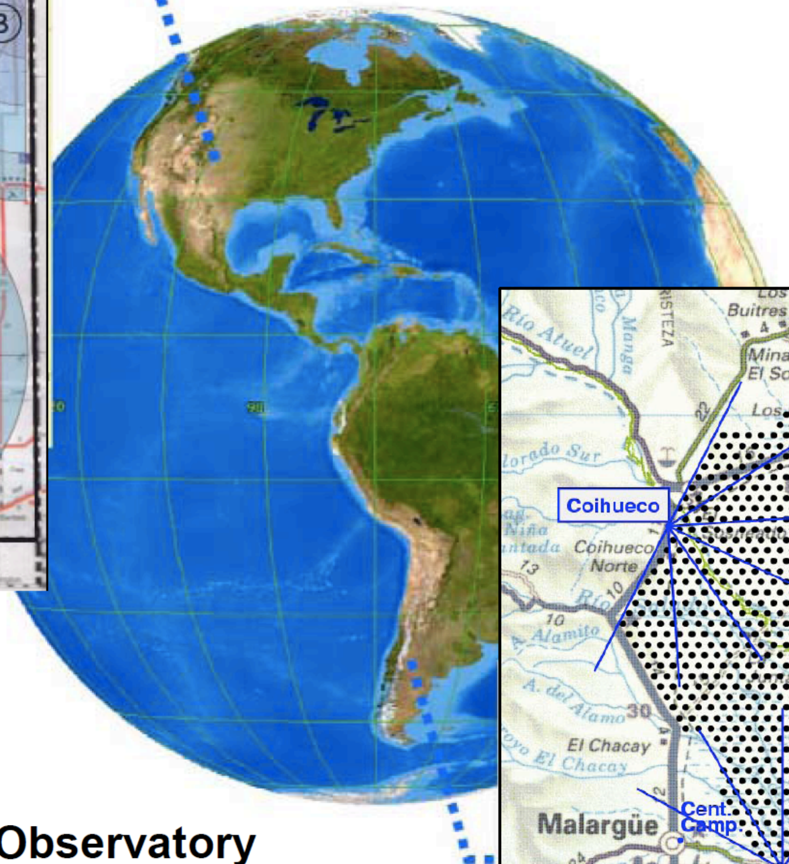
Measuring UHE Cosmic Rays

- Large detector needed
  - Characteristic flux is only 1 event/km^2/year
  - Large uptime: Surface detectors
  - Good precision: Fluorescence detectors
- Cross Calibration of surface with fluorescence limits model dependencies

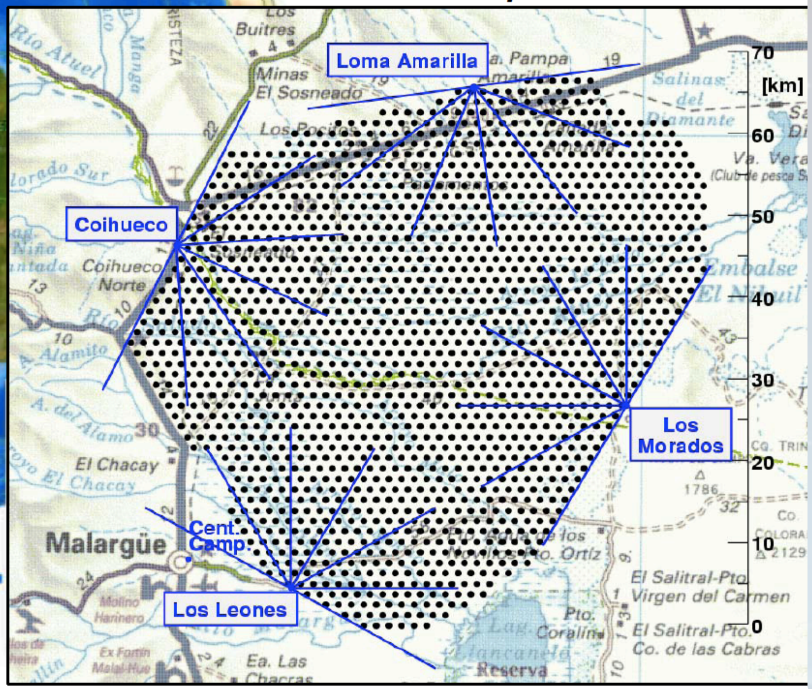


The Pierre Auger Project

High statistics
Hybrid detection
Full sky coverage



1992 Paris workshop
1996 Design report
1999 Ground breaking
2001 Engineering array
2003 Construction phase
2008 Completion

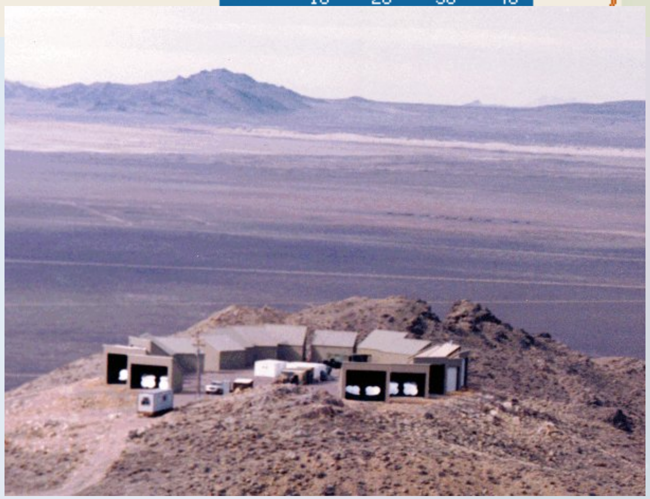


Northern Observatory
4000 detectors 20,000 km^2
39 fluorescence eyes

Southern Observatory
1600 detectors 3,000 km^2
24 fluorescence eyes

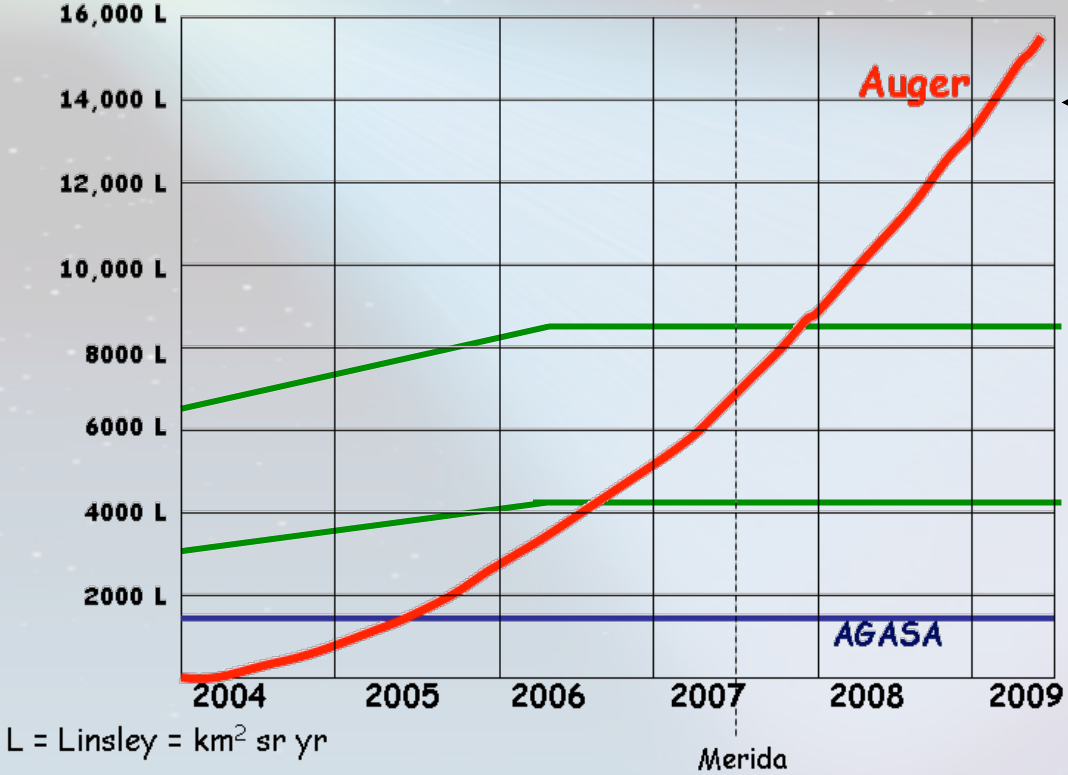
Until recently, HiRes was located on the U.S. Army's Dugway Proving Ground, ~100 miles south-west of the University of Utah

- HiRes1: @ Five Mile Hill (aka Little Granite Mountain)
- 21 mirrors, 1 ring (3^o<altitude<17^o)
- Sample-and-hold electronics (pulse height and trigger time)



- HiRes2: @ Camel's Back Ridge 12.6 km south-west of HiRes1.
- 42 mirrors, 2 rings (3^o<altitude<31^o)
- FADC electronics (100 ns period)

Exposures compared



2 years of full aperture

HiRes @ 100 EeV

HiRes @ 10 EeV

FD energy estimate

Amount of fluorescence light is proportional to energy deposited in atmosphere.

Efficiency of production depends on pressure, temperature and humidity

Attenuation of light due to Raleigh scattering off air molecules and scattering due to aerosols

Raleigh scattering: monthly averages of molecular atmosphere

Aerosols: hourly measurements of characteristics and distribution

Uncertainties on the energy estimate

Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

Energy Determination SD

1. Assign an energy related variable $S_{38}(1000)$ to an event

$S_{38}(1000)$: surface density at 1 km from the shower core for showers coming in at 38 degrees.

2. Convert this variable to an energy using hybrid events

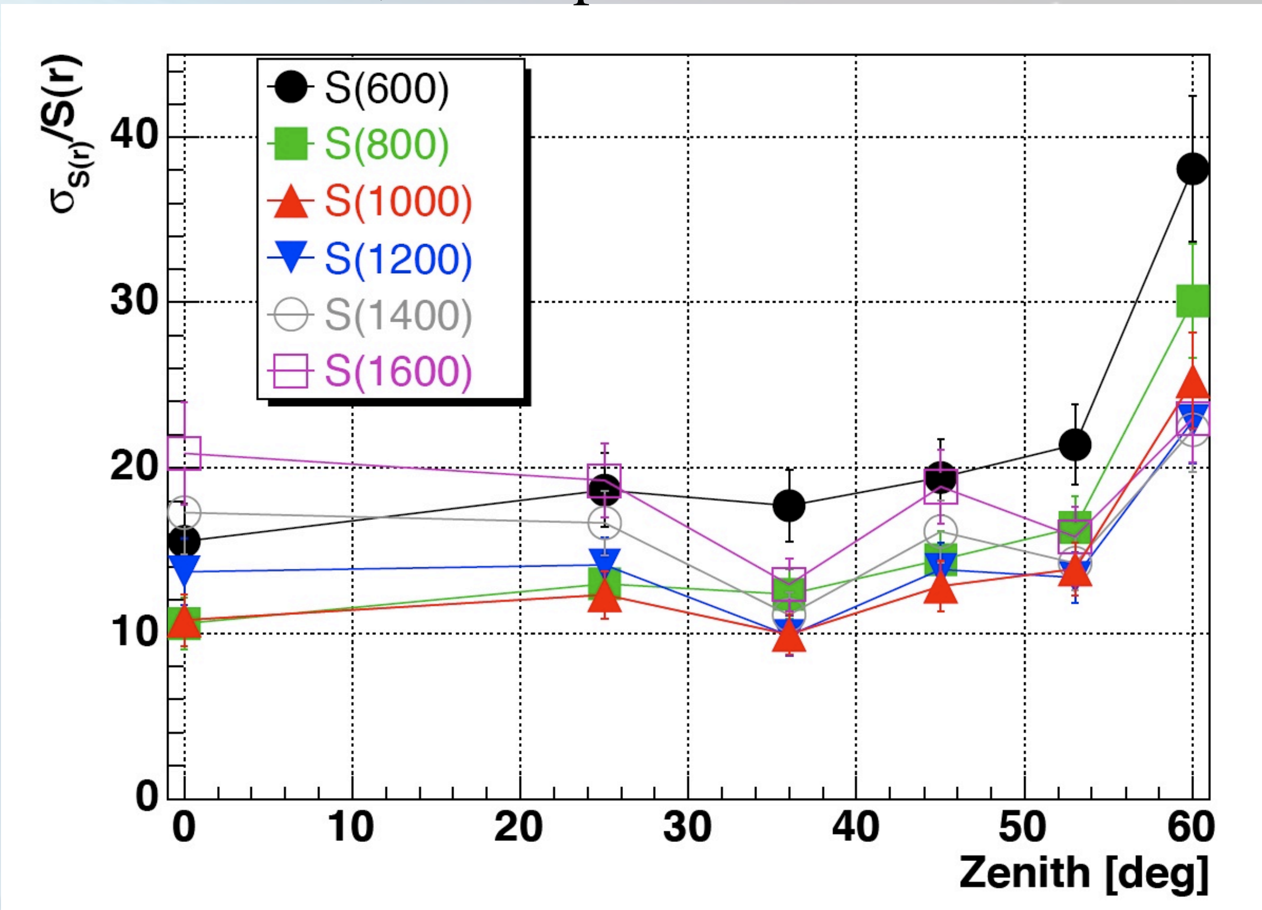
Why S(1000)?

Optimal distance from shower core which is used as energy estimator is obtained from simulation, and depends on:

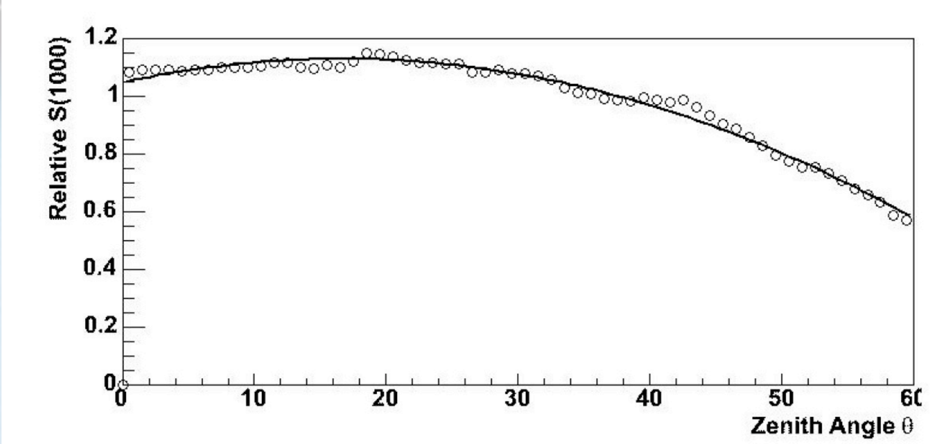
-Sampling fluctuations

-Detector resolution

-Shower fluctuations



$S_{38}(1000)$



The amount of atmosphere depends on the zenith angle

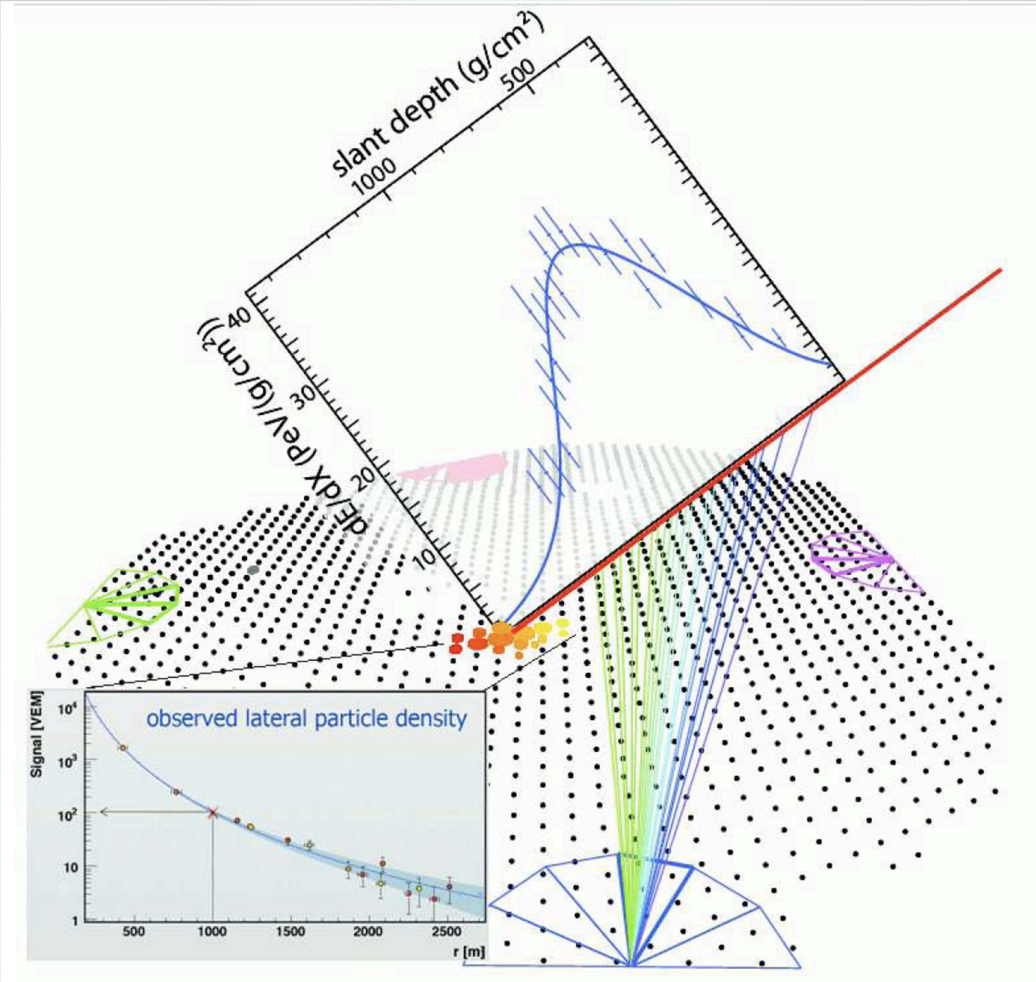
870 g cm^{-2} vertical

1740 g cm^{-2} at 60^{o}

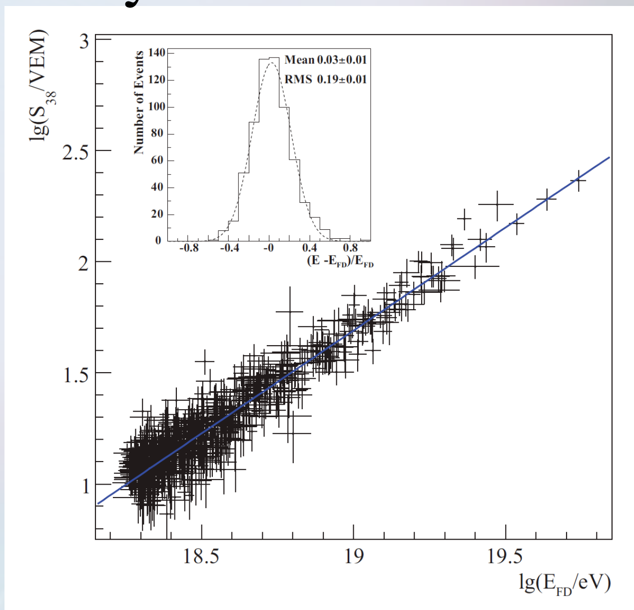
The number of particles at ground level depends on the zenith angle.

At each zenith angle S(1000) has been found for which $I(>S(1000)) = I_0$. This is the constant intensity cut (CIC) and assumes uniformity of incoming particles.

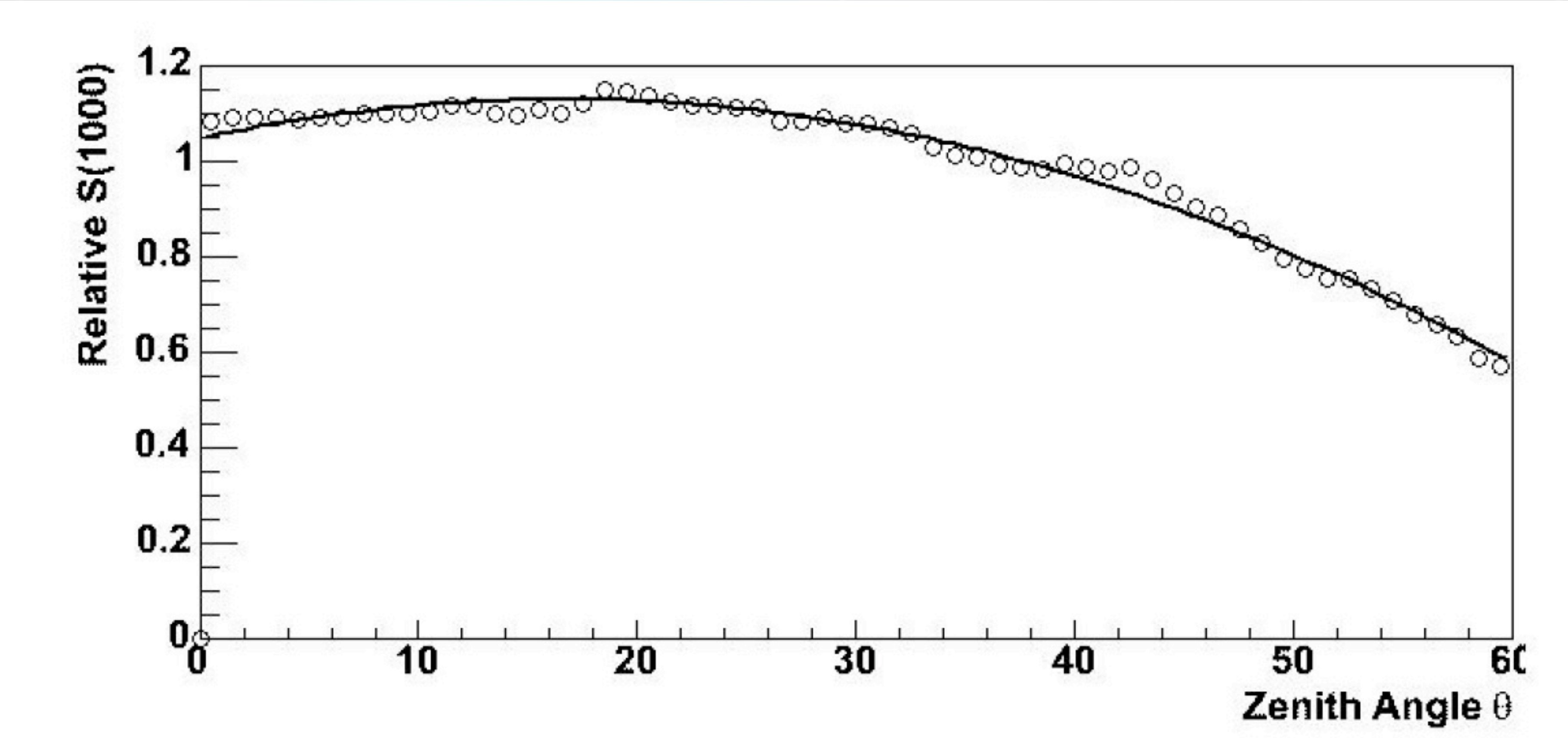
Auger Energy Measurement



Hybrid events are used to obtain a relation between the calorimetric FD measurement and particle density from SD



$S_{38}(1000)$

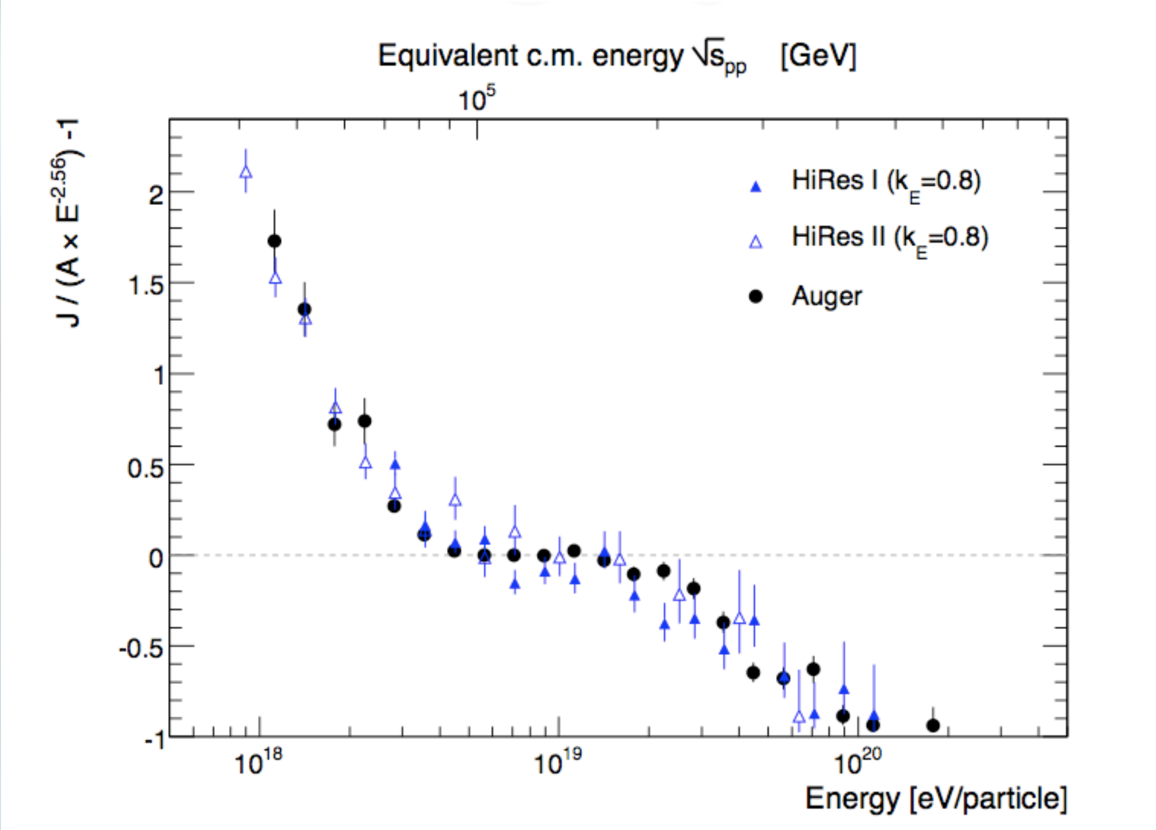


Relative S(1000)
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
Zenith Angle θ

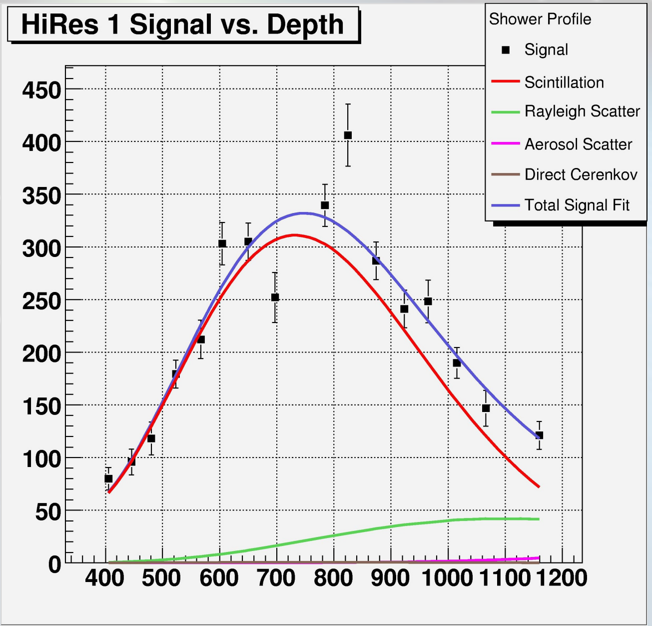
The Energy Spectrum

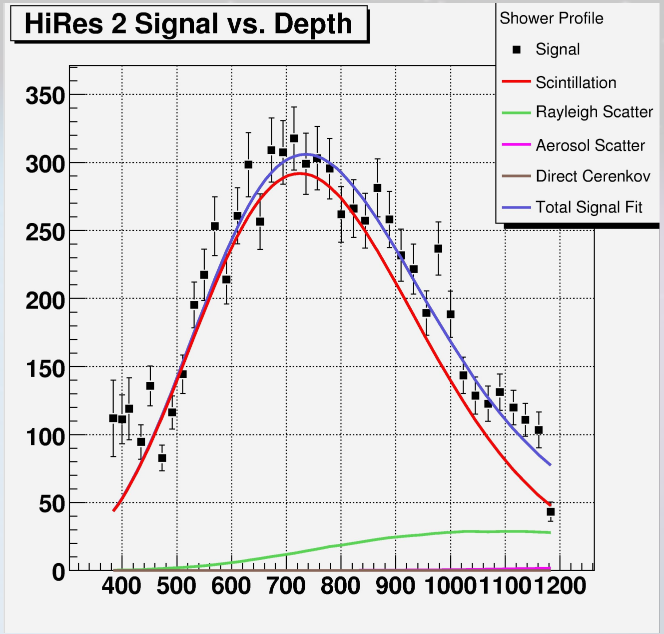
Here agreement between HiRES and Auger

Only slight disagreement in the energy scale



Measured Shower Profile





Measured shower parameters.

Event by event:

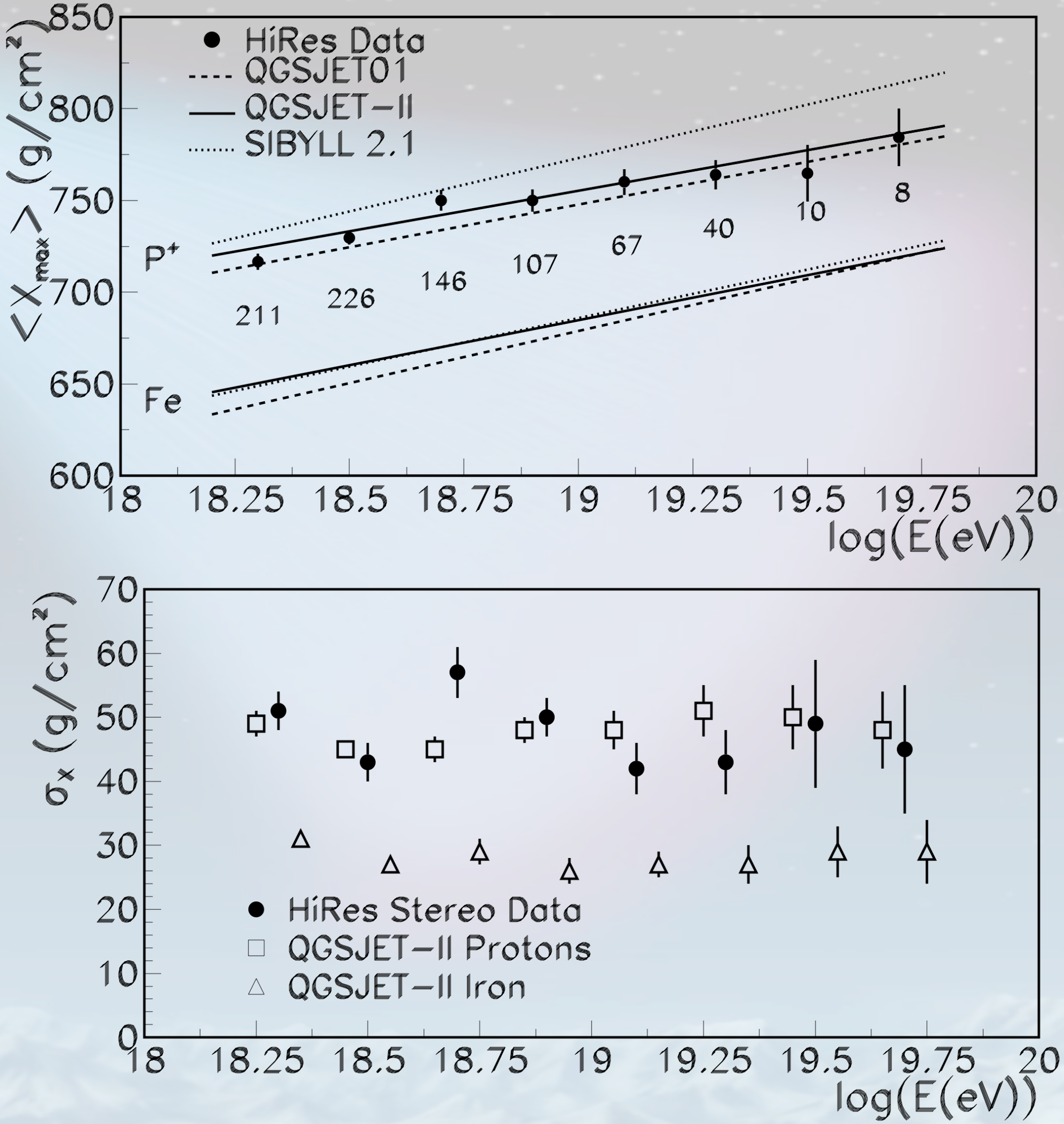
- X_{max} in g/cm^2;
- Total energy of the primary particle:
- Arrival direction

Statistically:

- Mass composition
- *p*-air inelastic cross-section

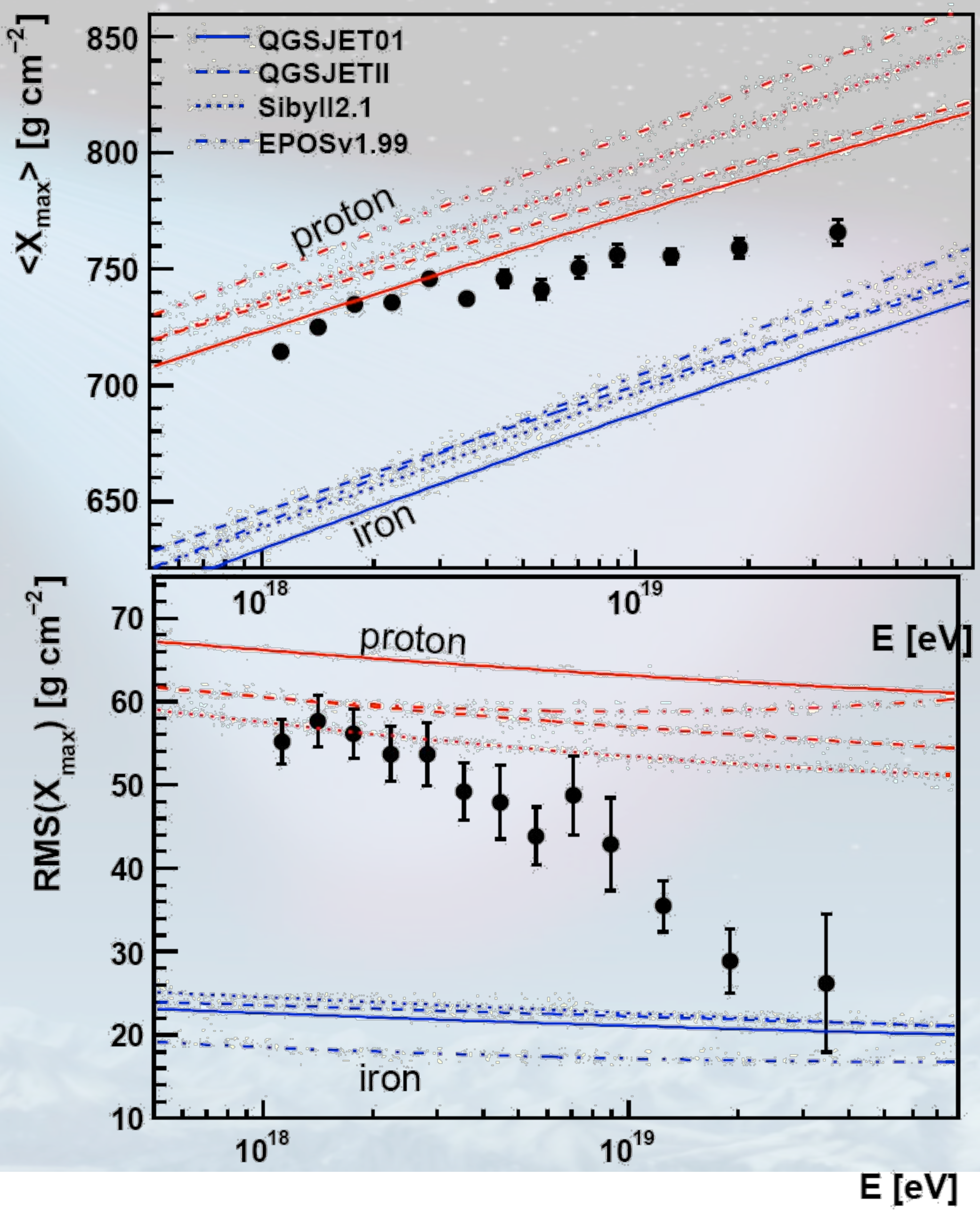
Composition Measurements

- The HiRES experiment:
  - Consistent with protons



Composition Measurements

- The Auger experiment:
  - Composition becomes heavier
  - Or protons behave differently



Cosmogenic Neutrinos

- In either case (protons or nuclei UHECRs) UHE neutrinos are produced as a biproduct of cosmic ray propagation
- For example:

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

$$\quad n \rightarrow p\, e\, \nu_e$$

$$\quad \pi^{+} \rightarrow e^{+}\, \nu_e\, \nu_\mu\, \nu_\mu$$

$$Fe^{56} + \gamma_{CMB/CIRB} \rightarrow Mn^{55} + p$$

$$Mn^{55} + \gamma_{CMB/CIRB} \rightarrow Mn^{54} + n$$

$$\quad n \rightarrow p\, e\, \nu_e$$

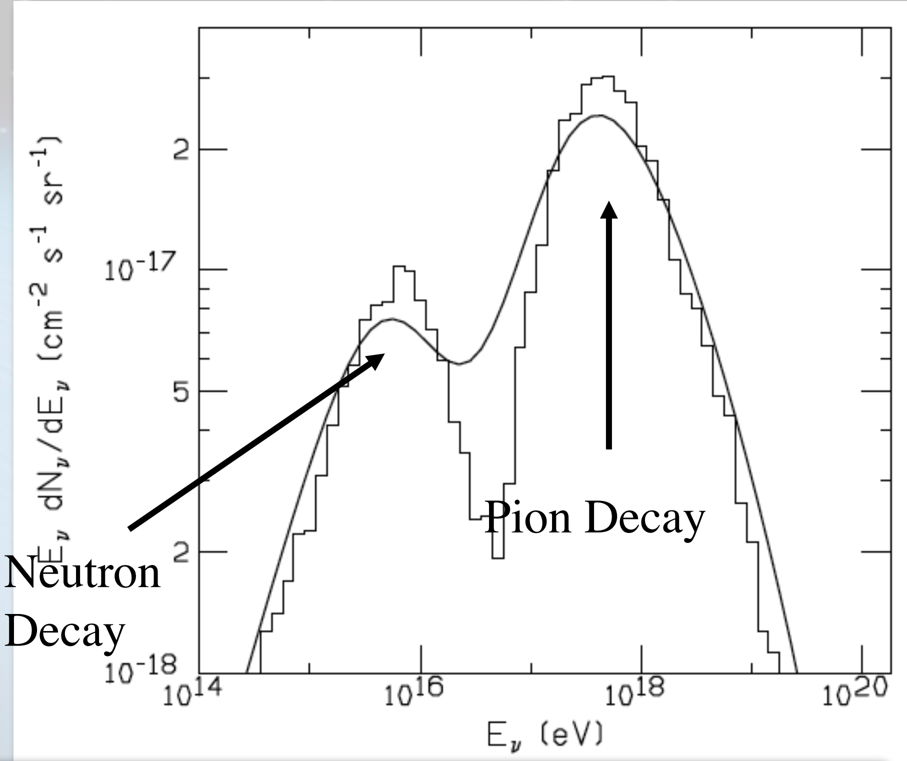
… etc.

Neutrinos!

Cosmogenic Neutrinos

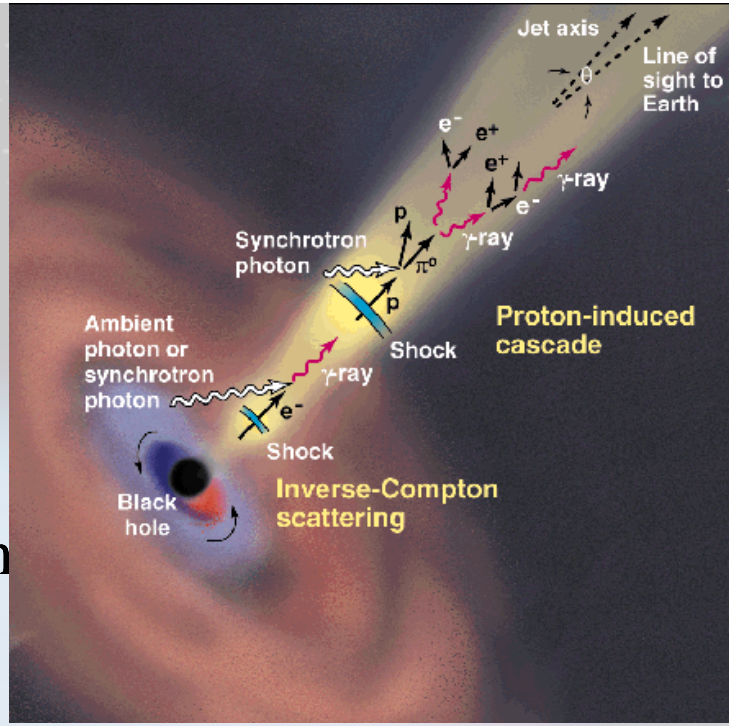
- Proton cosmic rays generate a two-component cosmogenic neutrino spectrum

- Often thought of as a guaranteed flux of UHE neutrinos



	Event Rate	Current Exposure	2008 Exposure	2011 Exposure
AMANDA (300 hits)	0.044 yr^{-1}	3.3 yrs, 0.17 events	NA	NA
IceCube, 2007 (300 hits equiv.)	0.16 yr^{-1}	NA	0.4 events	NA
IceCube, 2011 (300 hits equiv.)	0.49 yr^{-1}	NA	NA	1.2 events
RICE	$\sim$ 0.07 yr^{-1}	2.3 yrs, 0.1-0.2 events	0.2-0.3 events	0.3-0.4 events
ANITA-lite	0.009 per flight [15]	1 flight, 0.009 events	NA	NA
ANITA	$\sim$ 1 per flight	NA	1 flight, $\sim$ 1 event	3 flights, $\sim$ 3 events
Pierre Auger Observatory	1.3 yr^{-1} [19]	NA	$\sim$ 2 events	$\sim$ 5 events

Neutrinos from CR source



- CR acceleration occurs in jets
  - AGN or GRB
- Abundant target material
  - Most models assume photo-production
    - $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma\,\gamma$
    - $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$
- Ideal case (~ "Waxman-Bahcall limit")
  - Strong magnetic fields retain protons in jets
  - Neutrons escape, decay to protons & become UHECR
  - Extra-galactic cosmic rays observed as protons
  - Approximate equality of energy content:

    Energy content in neutrinos ≈ energy in UHECR

Waxman, Bahcall, PRD 59, 023002 (1998). Also TKG astro-ph/9707283v1

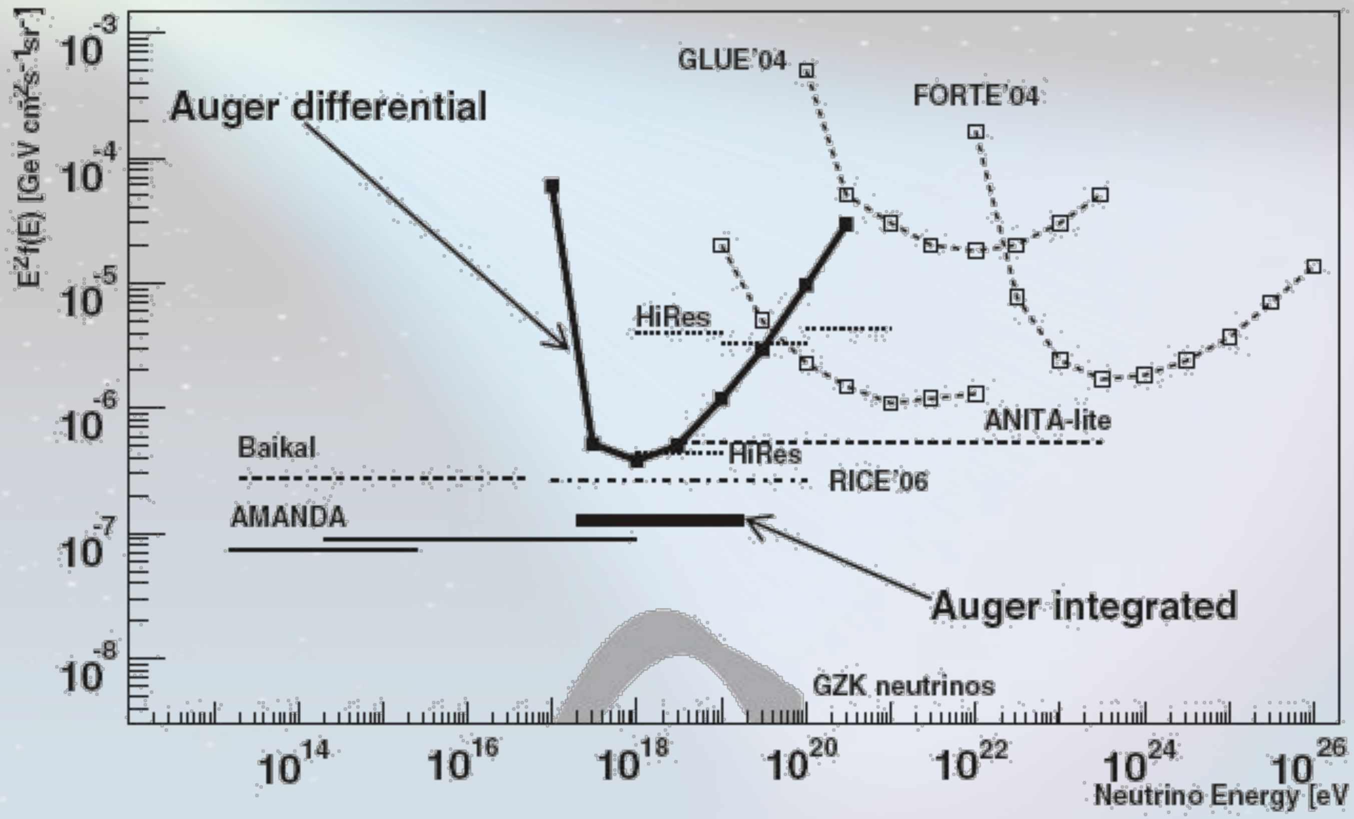
The Auger UHE Neutrino Observatory

Neutrinos can be identified as “young” showers at very great atmospheric slant depth (either upward or downward).

Auger exposure to tau Neutrinos

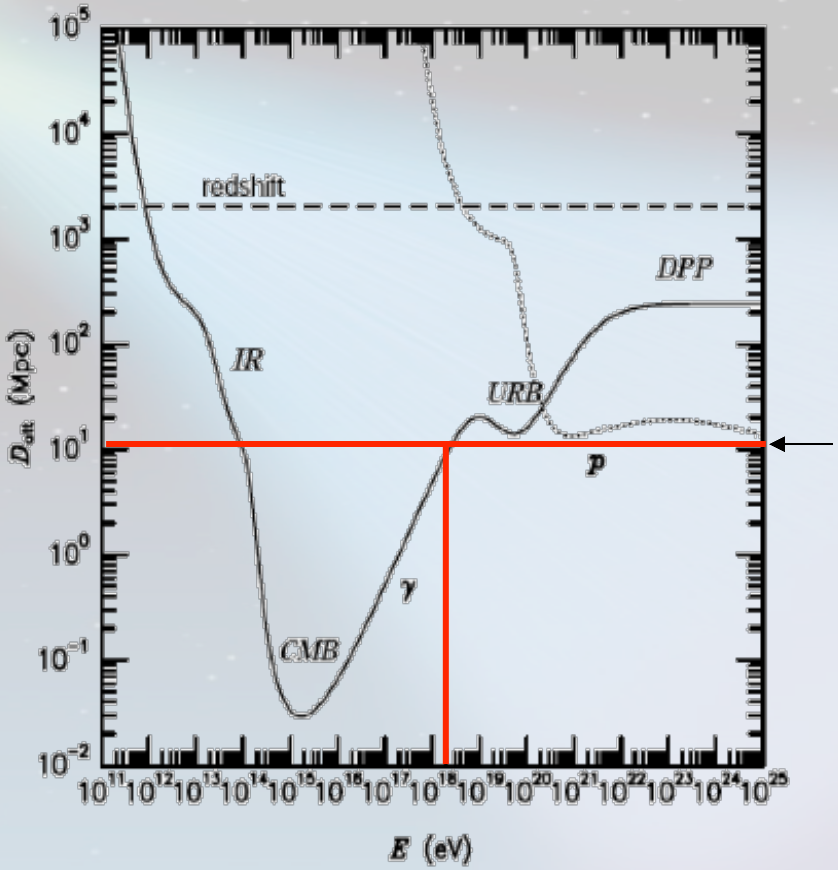
67

Limit on Tau Neutrinos



[Physical Review Letters 100 (2008), 211101]

The UHE Gamma Ray Astronomical Window



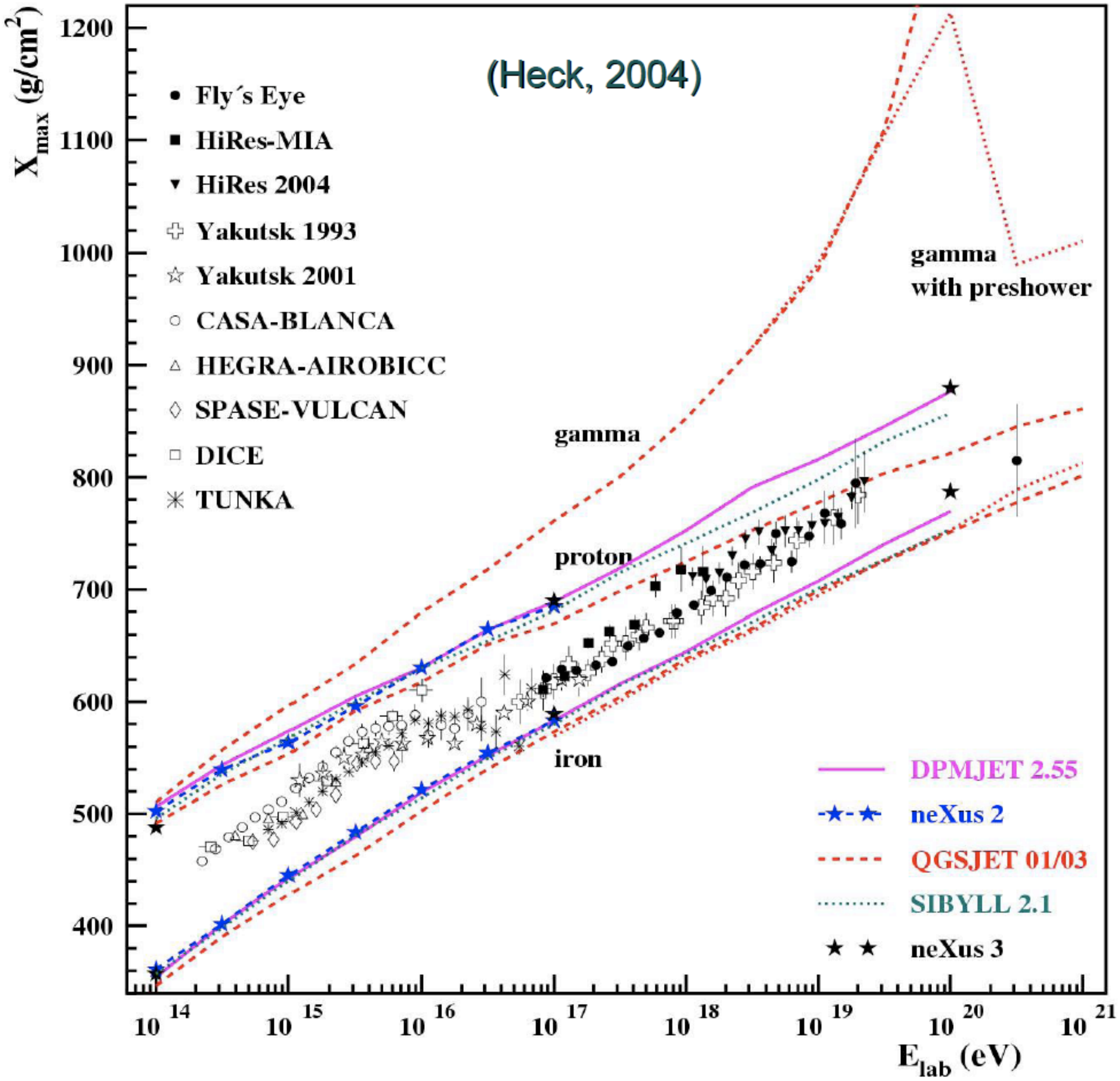
Photon attenuation length exceeds 10 Mpc for E > 2 EeV

Photon showers penetrate deeper than hadronic showers.

They can be recognized individually with hybrid measurements.

A photon component can be measured statistically by the surface array.

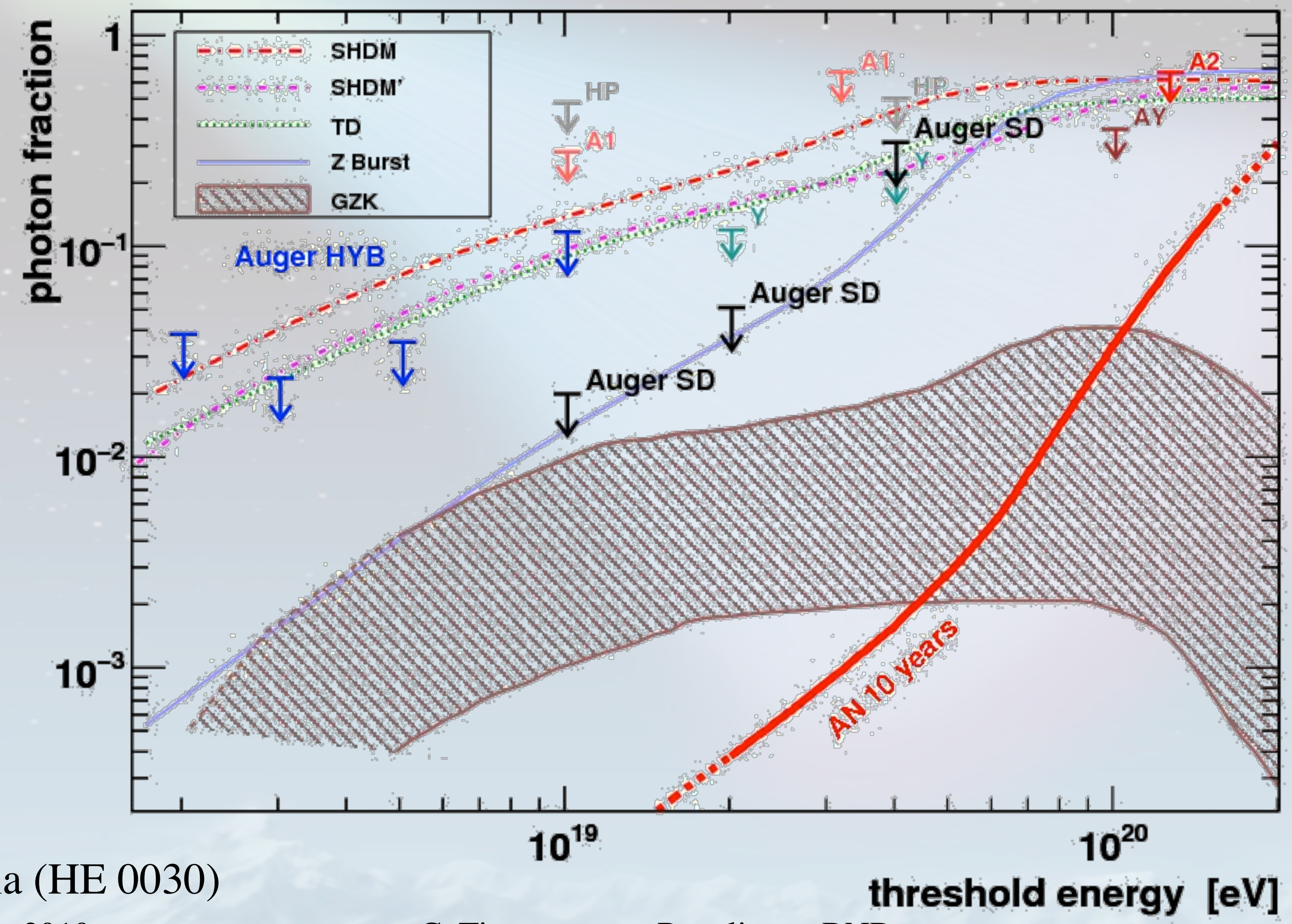
Mean depth of shower maximum



Photon shower develops deeper in the atmosphere.

UHE Photon Limits

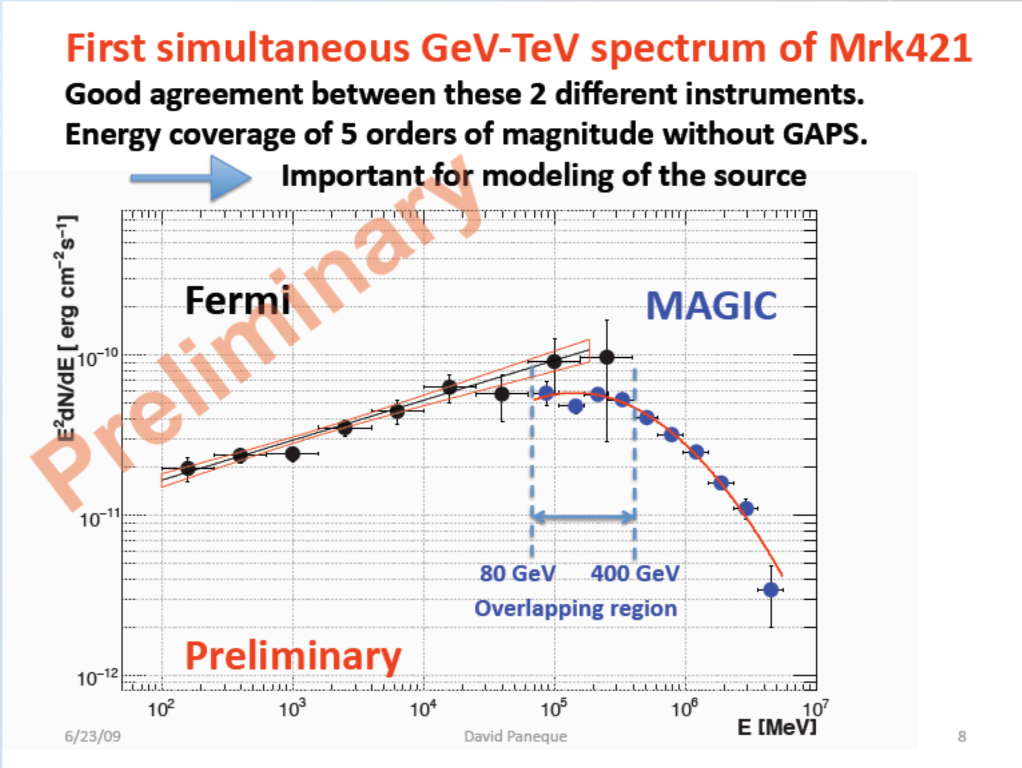
(strongly constrain top-down scenarios)



Homola (HE 0030)

Extra-galactic photons

- Ground based gamma telescopes team up with satellite expt. provides measurements on a single source. Important for electron vs hadron acceleration



Original Search for sources (2007)

null hypothesis: UHECR are uniformly distributed

Probability *P* that *k* or more out of *N* events are correlated by chance to selected objects:

$$P = \sum_{j=k}^{N} \binom{N}{j} p^j (1-p)^{N-j}$$

p: probability that an individual event has by chance an arrival direction closer than some angular distance from any member of a collection of candidate sources

Candidate Sources

12th edition of the Véron-Cetty and Véron

85221 quasars

1122 BL-lac objects

21737 active galaxies

694 are at a distance smaller than 100 Mpc

Catalog incomplete near galactic plane

incomplete at larger distances

Scanning Variables

Maximum redshift (distance = $42*z/0.01$ Mpc) of sources

Maximum angular separation ψ

- Minimum: SD angular resolution (~ 1 degree)

- Maximum: large ψ pushes p to 1 (p =0.6 for $\psi = 6^{o}$)

Energy: highest energy events are least deflected and have high probability to originate from nearby sources.

- start at highest energy event and add one-by-one lower energy events

Anisotropy Search

Scan data such that *P* is minimal. This is NO LONGER a probability. Probability determined from MC samples that are uniformly generated.

Test sample of data: 1/2004 up to 27/5/2006.

Minimal *P* for 75 Mpc, 56 EeV, 3.1^{o}

correlate: 12/15 (3.2/15 for isotropic)

Use cuts obtained as *a priori* cuts for new data!

Running Prescription

Use the cuts on incoming data.

We reject hypothesis of isotropy if its probability is below 0.01

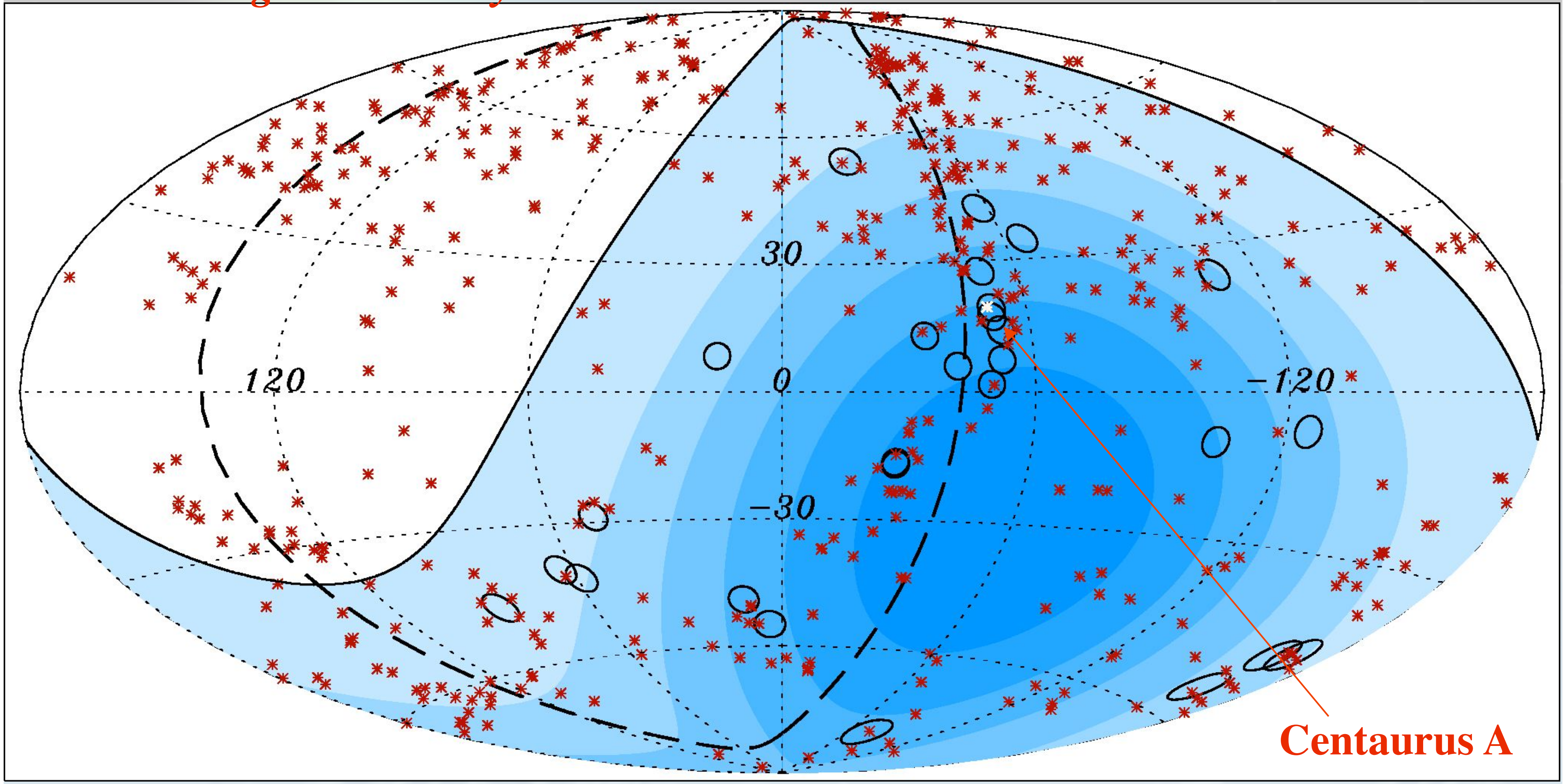
N	4	6	**8**	10	12	...	30	31	33	34
k_{min}	4	5	**6**	7	8	...	14	14	15	15

Satisfied on may 27 2007! More events are taken afterwards

The minimal correlation power should be 60%, which limits the number of events to 34 (estimated from test sample)

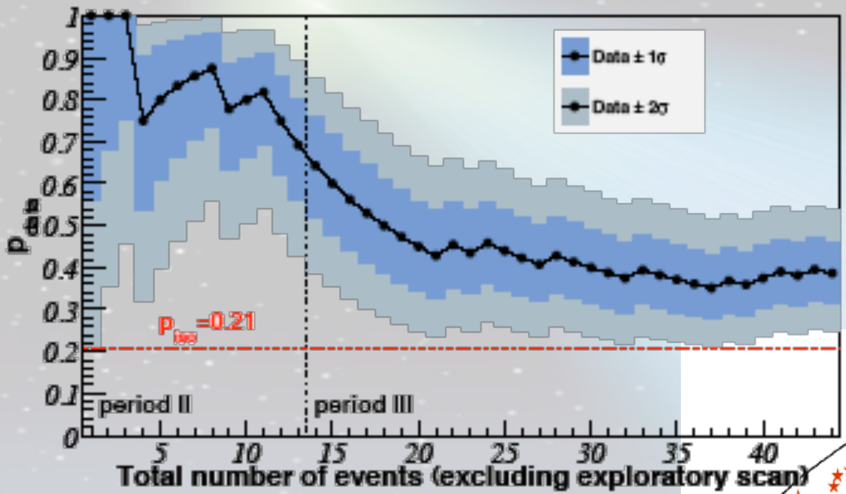
Highest Energy Events (2007)

AGN Catalog: Veron-Cetty Veron



318 AGNs in field of view observatory

Latest Results: UHE Correlations



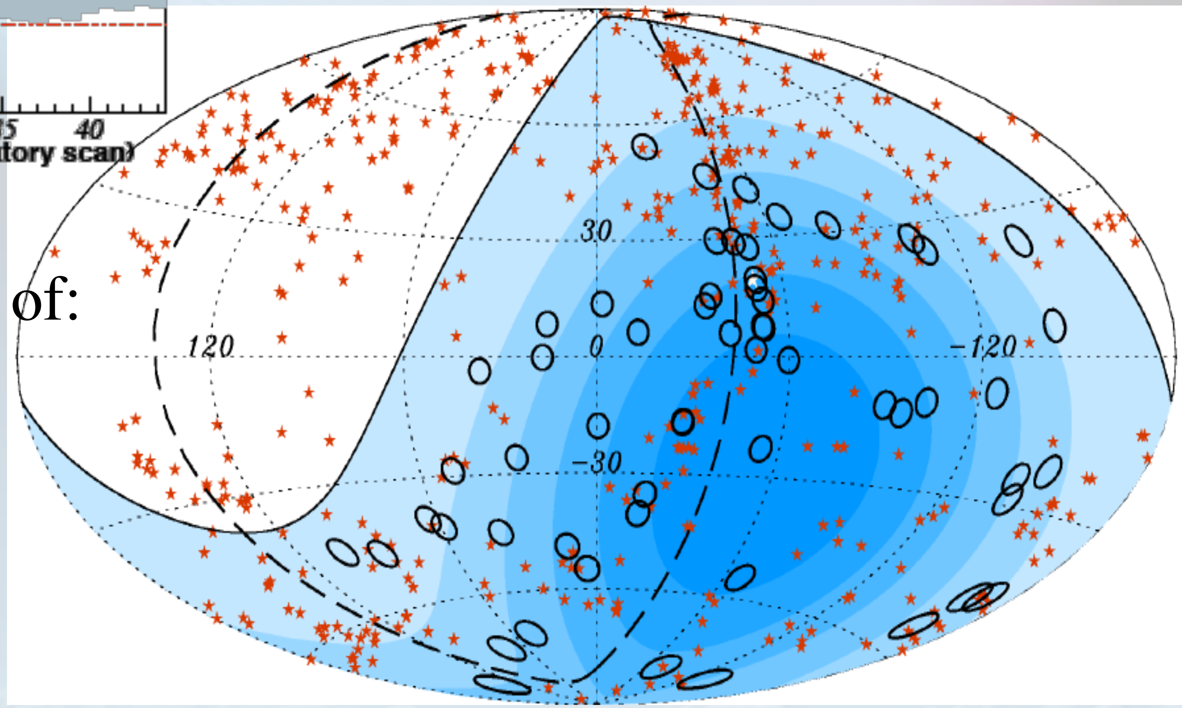
39% correlate (post exploration)

(21% expected for isotropy)

Isotropy rejected at 99.4 %

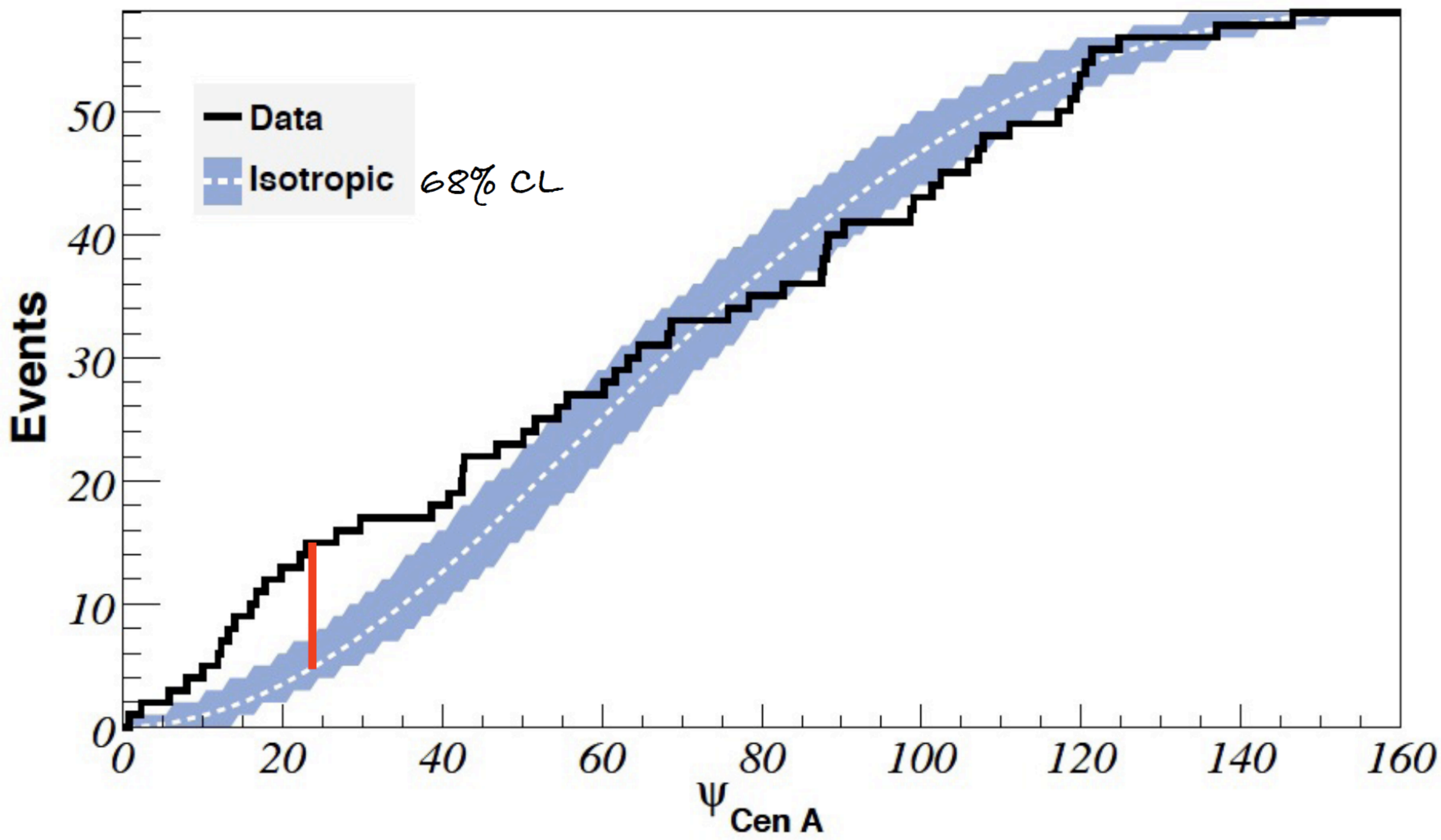
A posteriori investigations of:

- Centaurus A region
- correlations with improved catalog(s) *e.g.* SWIFT-BAT



58 events for which E> 55 EeV

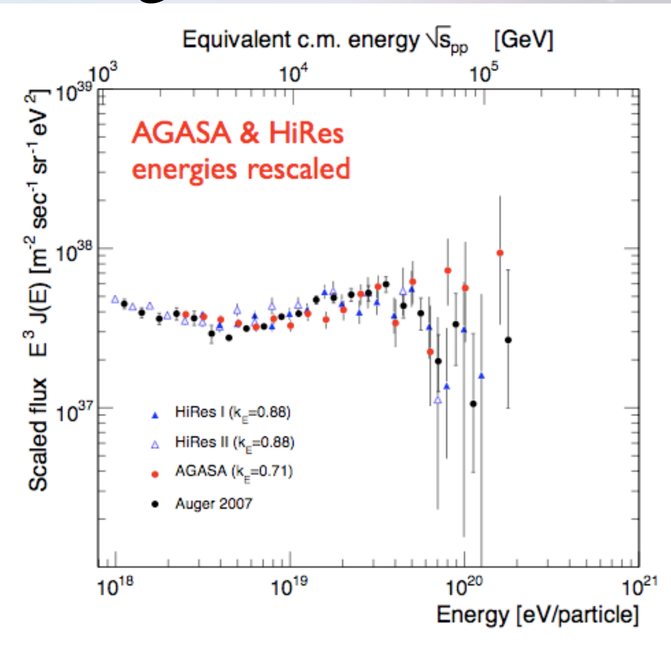
Distance: CR - Cen A



2% chance prob. for isotropic distribution

HiRes with PAO cuts

- PAO has maximum significance for < 3.1 deg., Emin=.56 EeV, Zmax=.018
- 8 pairings from 13 events in confirming set.
- Expect 2.7 chance pairings
- PAO chance prob. = 0.0017
- HiRes with PAO cuts (10% shift)
- 2 pairings from 13 events
- Expect 3.2 chance pairings
- HiRes chace prob. = .82



Pao spectrum, 10% energy shift

Extra Galactic Cosmic Ray Flux

ankle → one 10^{19} eV particle per km squared per year per sr

$$E^2 \frac{dN}{dE} = \frac{10^{19}\, eV}{(10^{10}\, cm^2)(3\times 10^7 \sec)\; sr}$$

$$= 3\times 10^{-11}\; TeV\; cm^{-2} \sec^{-1} sr^{-1}$$

total flux = velocity x density : $4\pi \int dE\,(E\,\frac{dN}{dE}) = c\,\rho_E$

$$\rho_E = \frac{4\pi}{c}\int \frac{3\times 10^{-11}}{E}\, dE\, \frac{TeV}{cm^3}$$

$$= \cdots \log \frac{E_{\max}}{E_{\min}} \cong 10^{-19}\, \frac{TeV}{cm^3}$$

Gamma Ray Bursts

300 GRB per Gigaparsec^3 per year
for 10^{10} years (Hubble time)

$$2\times10^{51}\,erg\times\frac{300}{Gpc^3\ yr}\times10^{10}\,yr=3\times10^{-19}\ \frac{erg}{cm^3}$$

$$1\,Gpc^3=2.9\times10^{82}\,cm^3\qquad Hubble\,time=10^{10}\ years$$

- correct cosmology: same answer
- Fermi: photon (electron) energy less than this ?

GRBs provide environment and energy

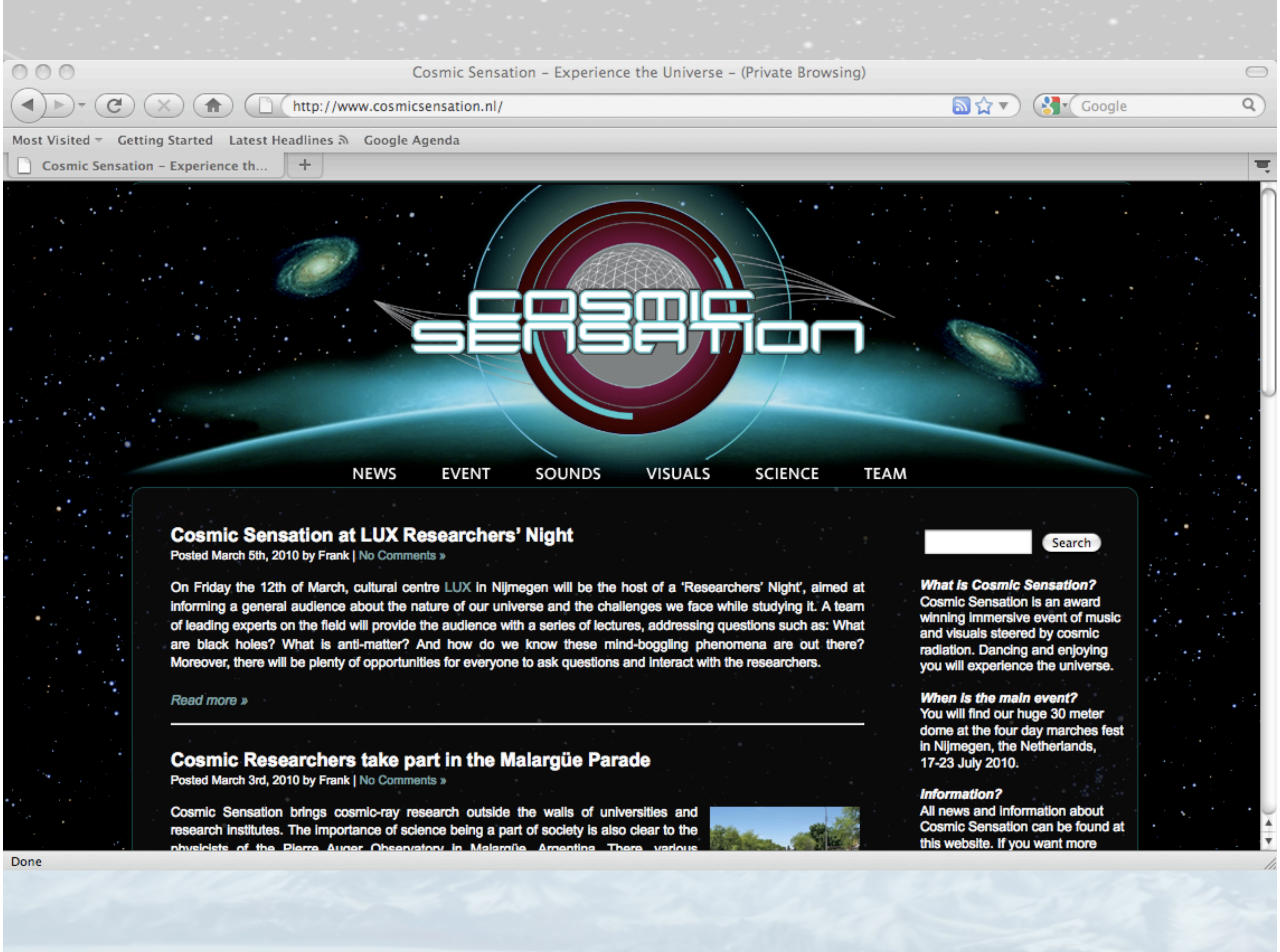
to explain the extragalactic cosmic rays!

Conclusion on UHECR

- HiRES and Auger disagree on:
  - Composition
  - Anisotropy
- Both agree on energy spectrum
- The energy content in GRB could explain the UHECR flux

Final Remarks

- The energy in cosmic rays can be understood from astrophysical sources
- The highest measured energy is hard to reach
- Anisotropy at low energies hard to explain
- The photon-cosmic ray connection is being made
- The neutrino connection should be *just around the corner*
- The transition galactic – extra galactic is not clear
- Hires and Auger disagree on almost everything
-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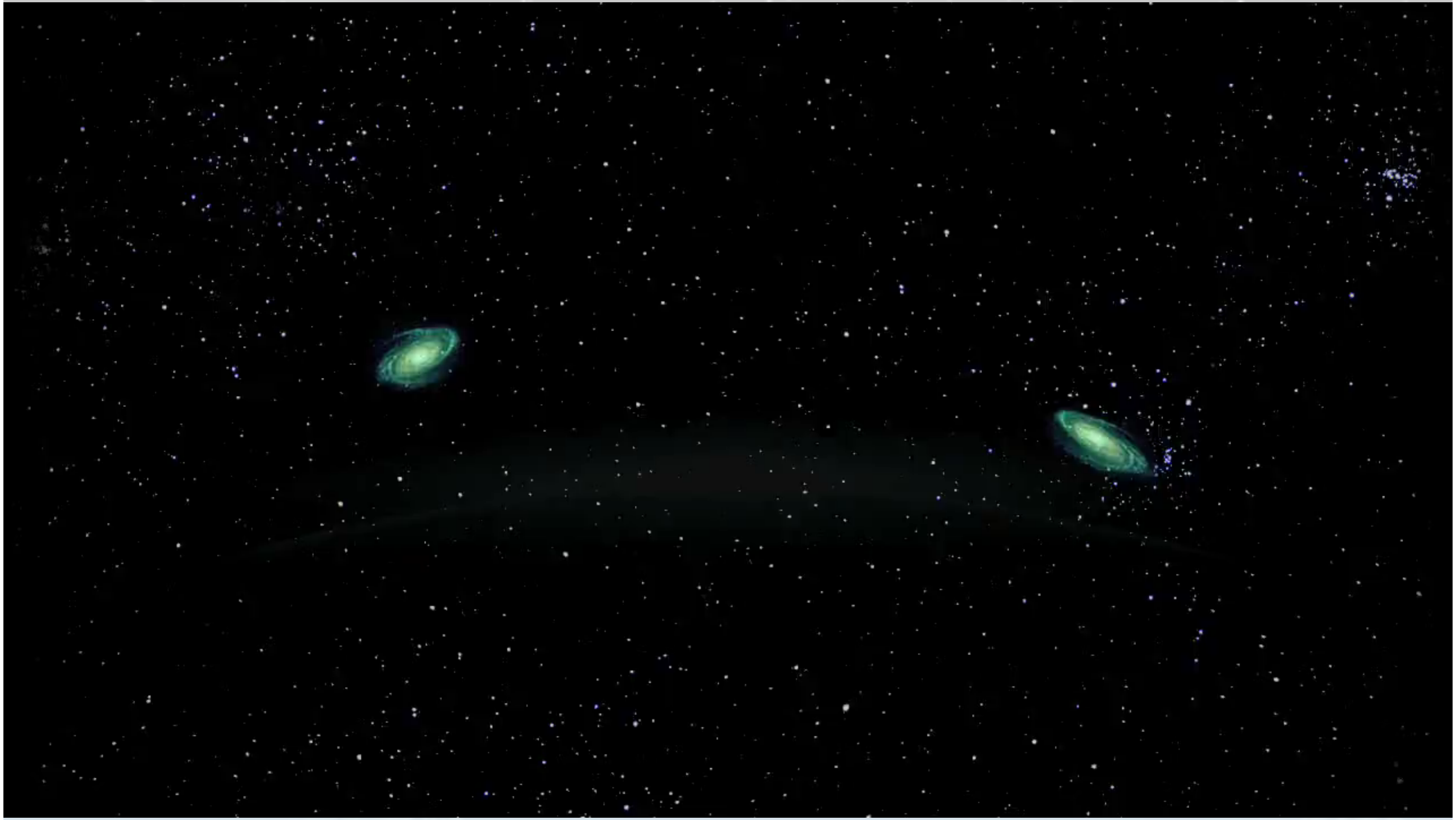
TEAM
Cosmic Sensation at LUX Researchers' Night
Posted March 5th, 2010 by Frank | No Comments »
On Friday the 12th of March, cultural centre LUX in Nijmegen will be the host of a 'Researchers' Night', aimed at informing a general audience about the nature of our universe and the challenges we face while studying it. A team of leading experts on the field will provide the audience with a series of lectures, addressing questions such as: What are black holes? What is anti-matter? And how do we know these mind-boggling phenomena are out there? Moreover, there will be plenty of opportunities for everyone to ask questions and interact with the researchers.
Read more »
Cosmic Researchers take part in the Malargüe Parade
Posted March 3rd, 2010 by Frank | No Comments »
Cosmic Sensation brings cosmic-ray research outside the walls of universities and research institutes. The importance of science being a part of society is also clear to the
Search
What is Cosmic Sensation?
Cosmic Sensation is an award winning immersive event of music and visuals steered by cosmic radiation. Dancing and enjoying you will experience the universe.
When is the main event?
You will find our huge 30 meter dome at the four day marches fest in Nijmegen, the Netherlands, 17-23 July 2010.
Information?
All news and information about Cosmic Sensation can be found at this website. If you want more
Done




COSMIC SENSATION
DANCE EVENT
2010
SEPTEMBER 30TH - OCTOBER 2ND
PARK BRAKKENSTEIN
NIJMEGEN
INFO:WWW.COSMICSENSATION.NL