

# Ultra-High Energy Cosmic Radiation

and what it teaches us about  
astro- and fundamental physics

- General facts and the experimental situation
- Acceleration (“bottom-up” scenario)
- Cosmic magnetic fields and their role in cosmic ray physics
- Neutrinos: Connection to cosmic rays and detection
- New physics (“top-down” scenario)
- New interactions and new particles

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<http://www.iap.fr/users/sigl/homepage.html>

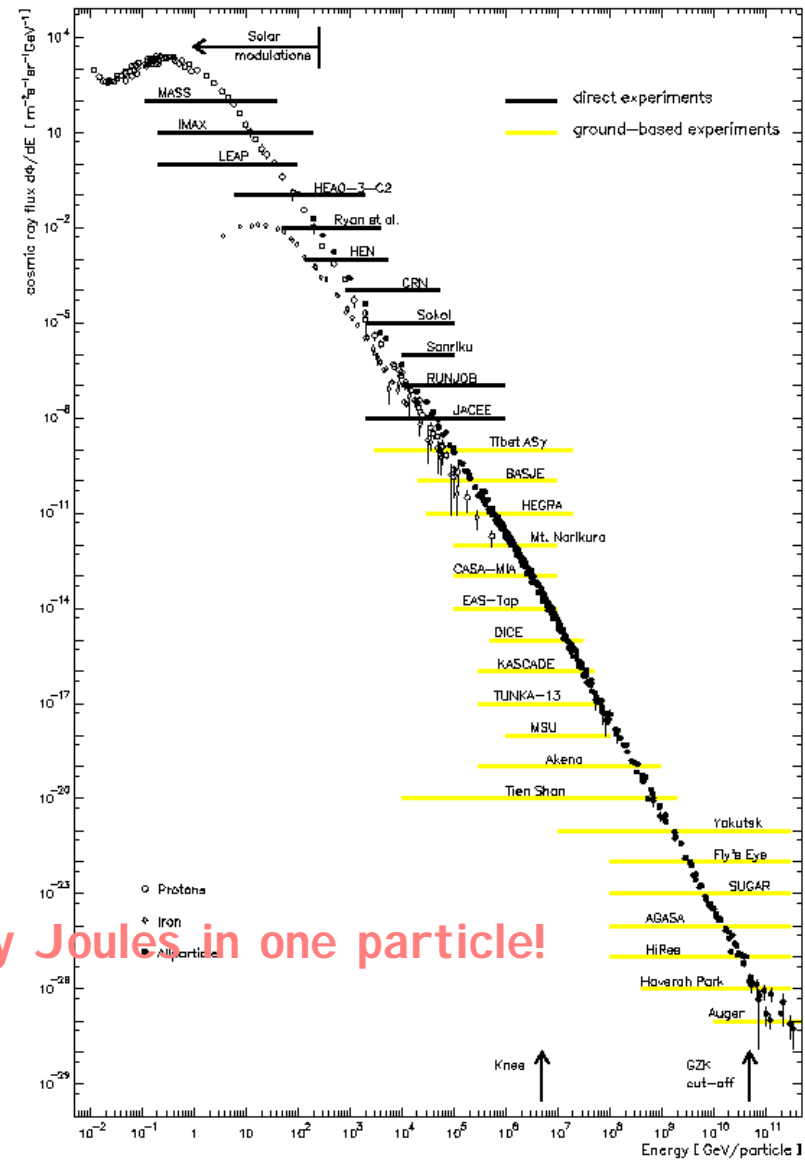
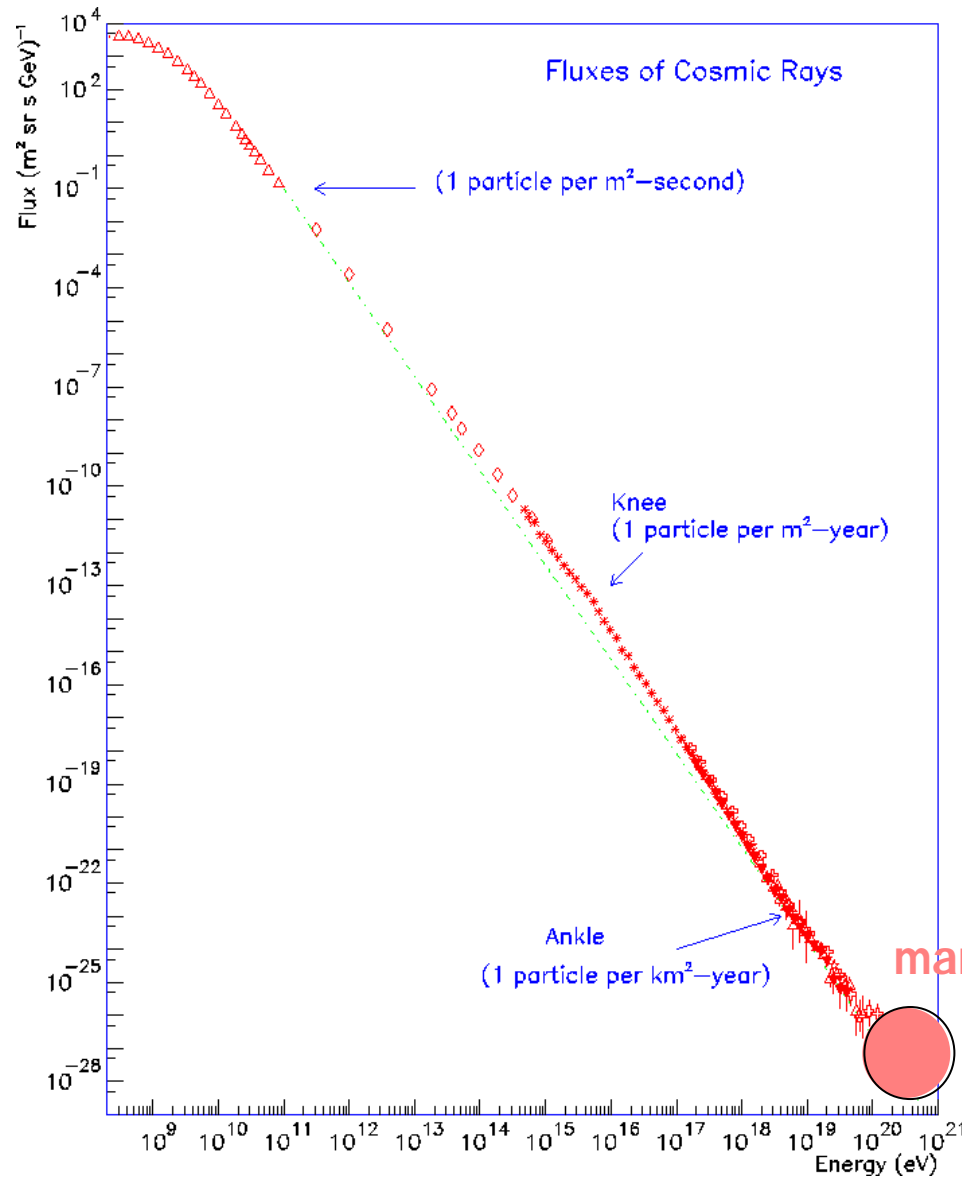
Further reading:

short review: Science **291** (2001) 73

long review: Physics Reports **327** (2000) 109

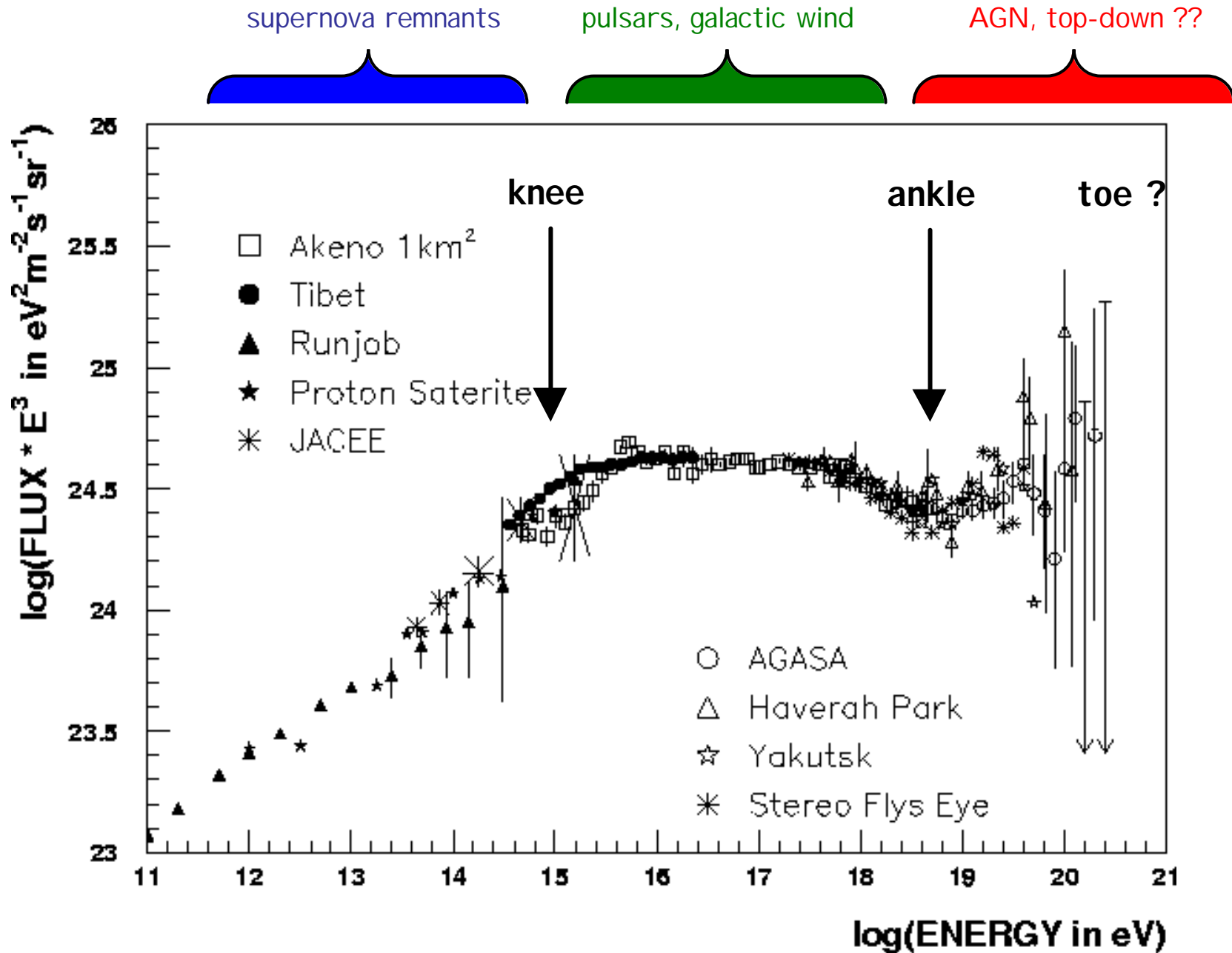
review collection: Lecture Notes in Physics **576** (2001) (eds.: M.Lemoine, G.Sigl)

The cosmic ray spectrum stretches over some 12 orders of magnitude in energy and some 30 orders of magnitude in differential flux:

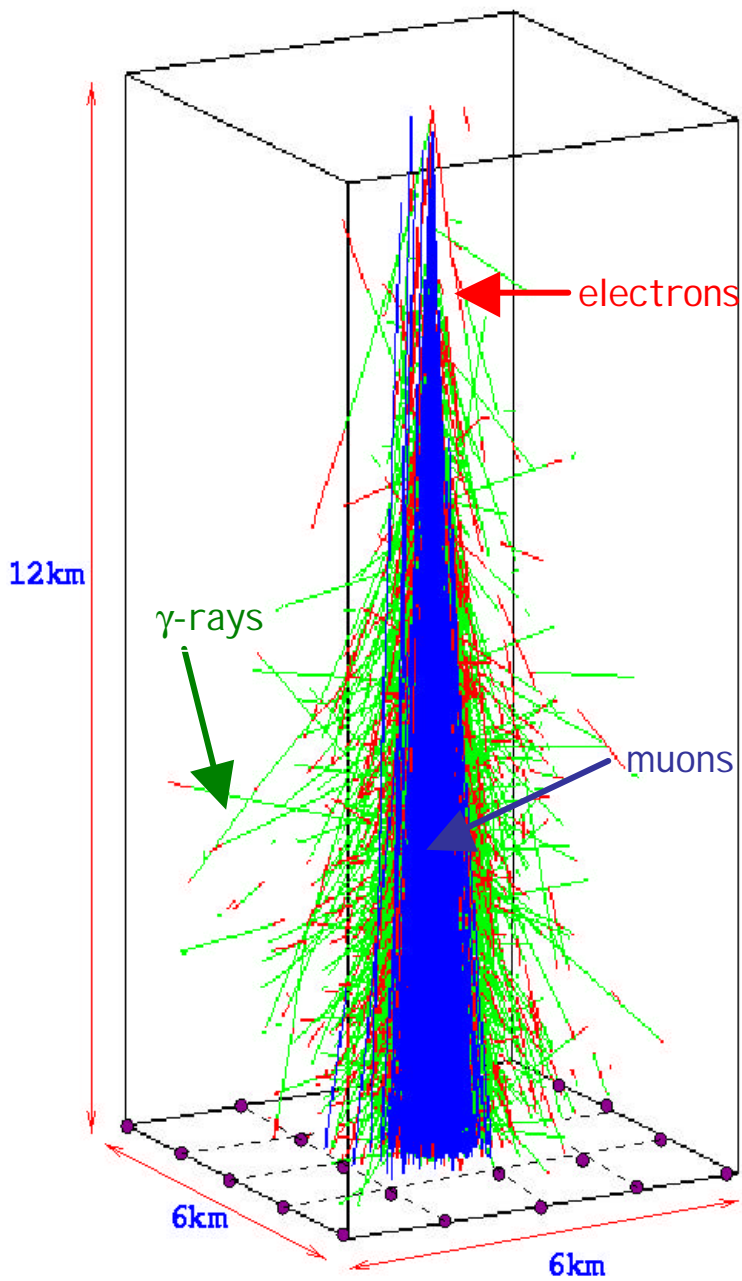


many Joules in one particle!

# The structure of the spectrum and scenarios of its origin



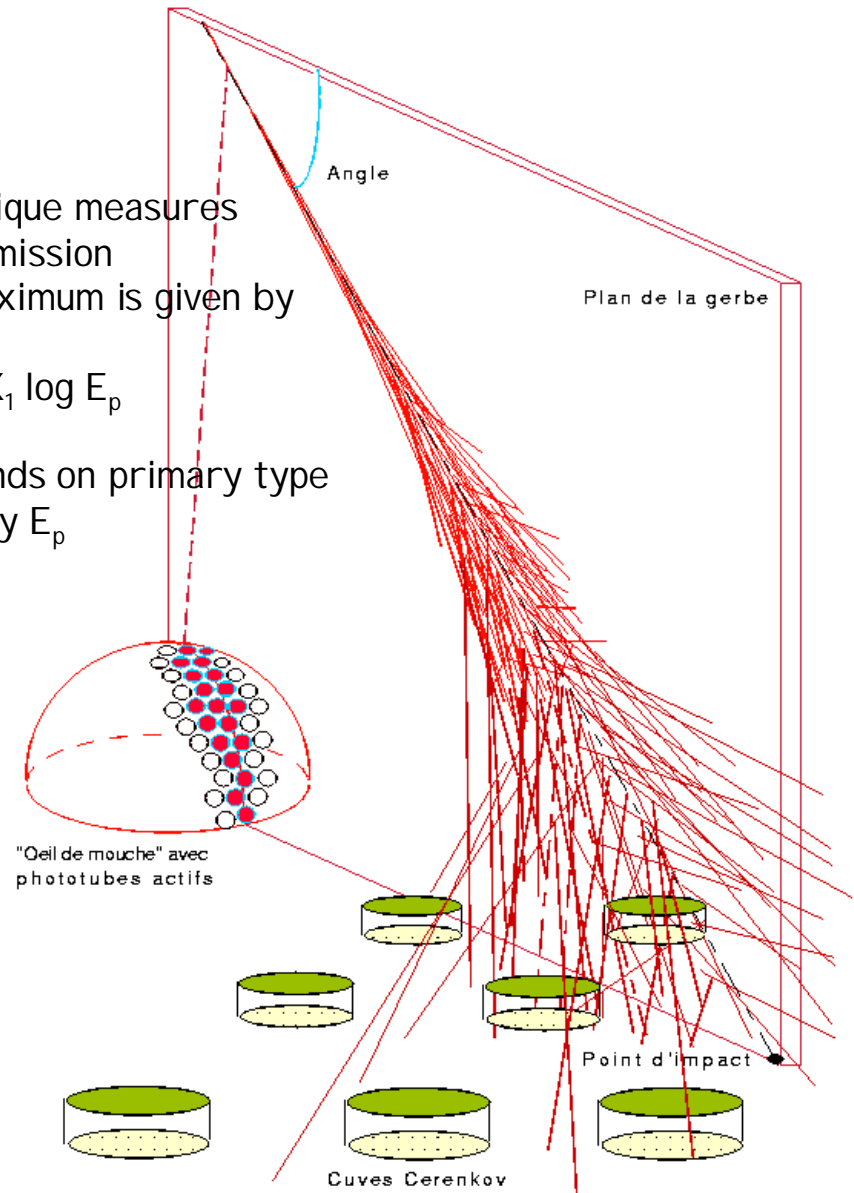
# Atmospheric Showers and their Detection



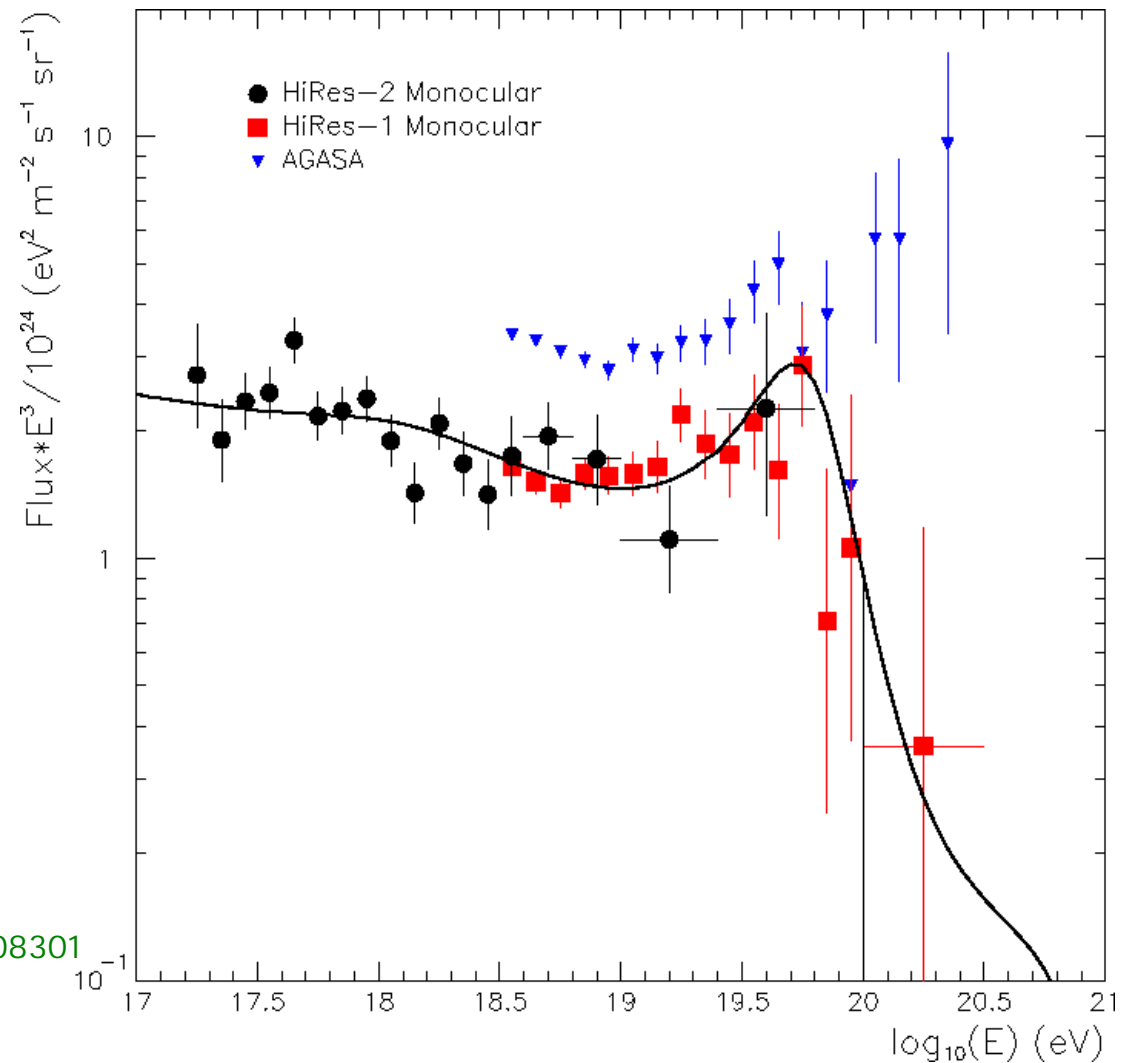
Fly's Eye technique measures fluorescence emission  
 The shower maximum is given by

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

where  $X_0$  depends on primary type  
 for given energy  $E_p$



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

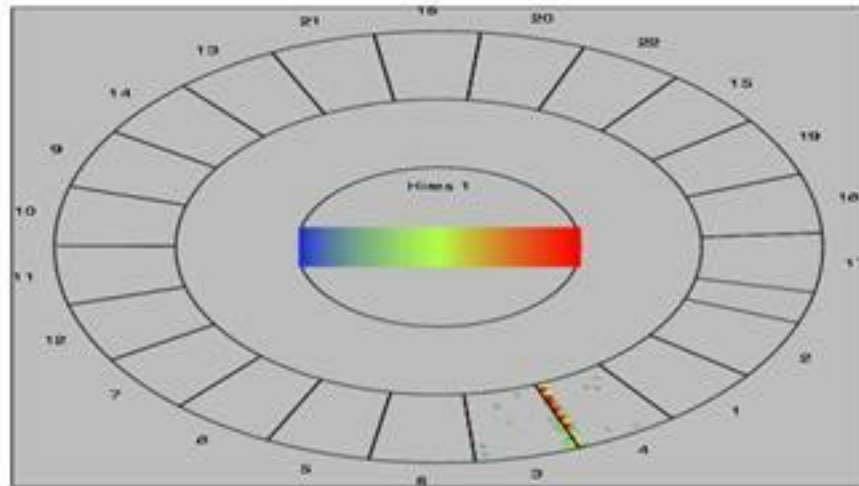
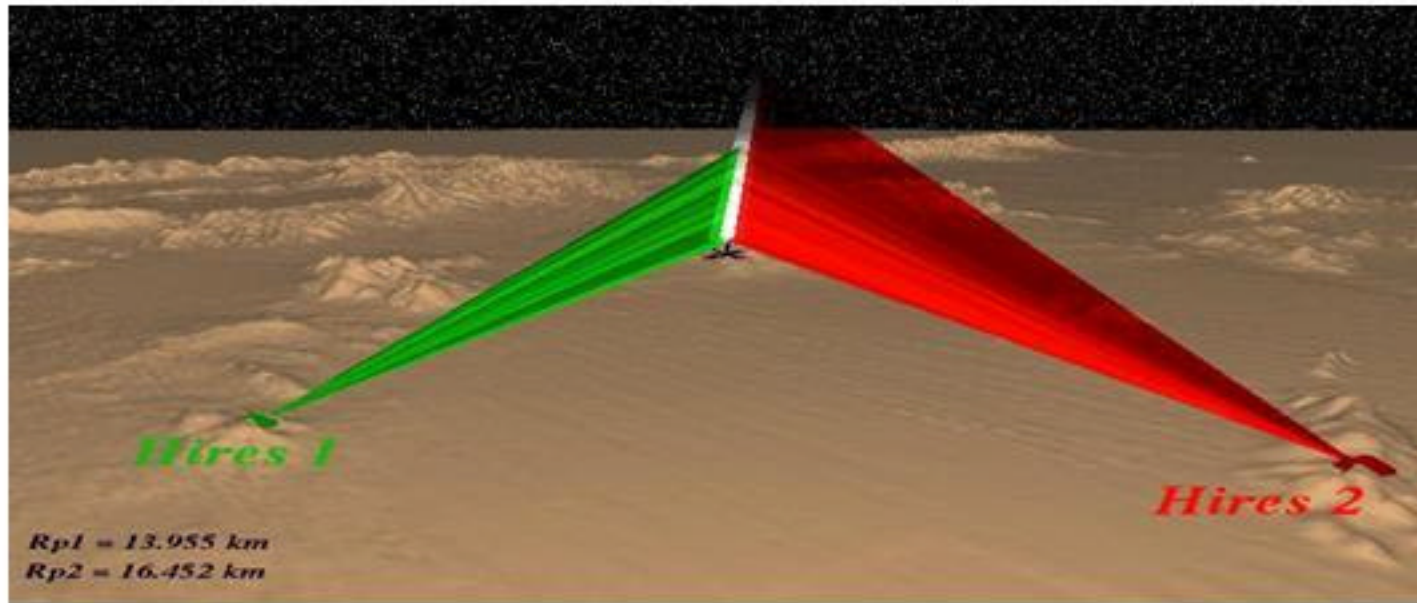


HiRes collaboration, astro-ph/0208301

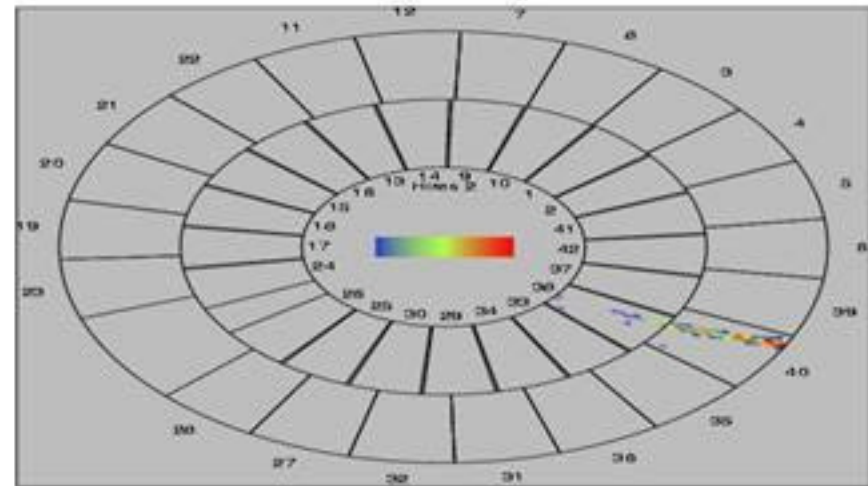
Lowering the AGASA energy scale by about 20% brings it in accordance with HiRes up to the GZK cut-off, but not beyond.

May need an experiment combining ground array with fluorescence such as the Auger project to resolve this issue.

# Stereo Event E ~50 EeV



HiRes1



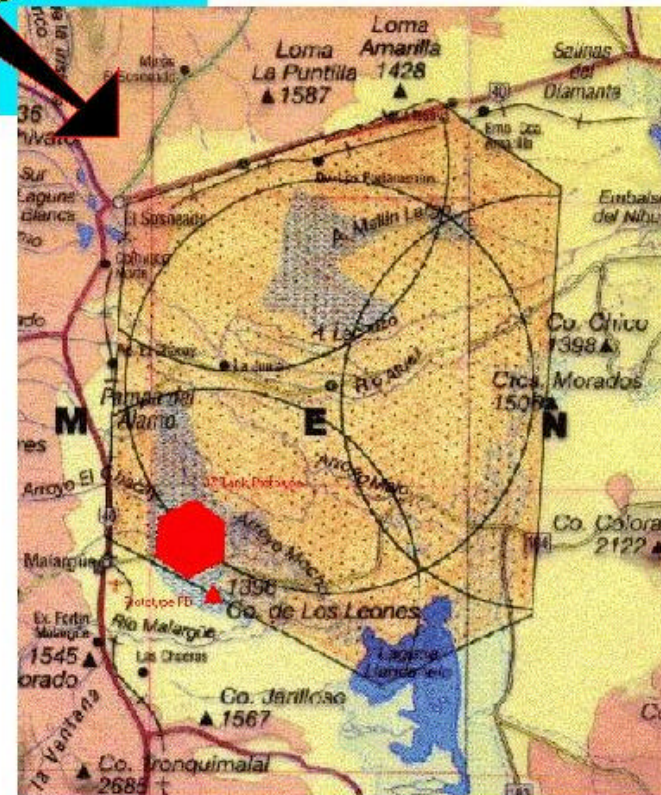
HiRes2

## Next-Generation Ultra-High Energy Cosmic Ray Experiments

compare to AGASA acceptance  $\sim 230 \text{ km}^2\text{sr}$

Experiments	starting date	acceptance in $\text{km}^2\text{sr}$	angular resolution	energy resolution
High - Res Fly's Eye	since 1999	350-1000	few degrees in stereo mode	$\sim 40\%$ mono $\sim 10\%$ stereo
Telescope Array	maybe with Auger North	1700-5000	$\sim 1^\circ ?$	$\sim 20\% ?$
Auger ground	full size in about 2004	$>7000$	$< 2^\circ$	$\sim 15\%$
Auger hybrid	$\sim 2004$	$>700$	$\sim 0.25^\circ$	$\sim 8\%$
EUSO/OWL space-based	$>2010$	$\sim 10^5 ?$	$\sim 1^\circ ?$	$<30\% ?$
radio detection	???	$>1000 ?$	few degrees ?	???

The southern Auger site is under construction.



Contour of site (3000 km-sq)

In red: engineering array

Circles: average range of the fluorescence det.

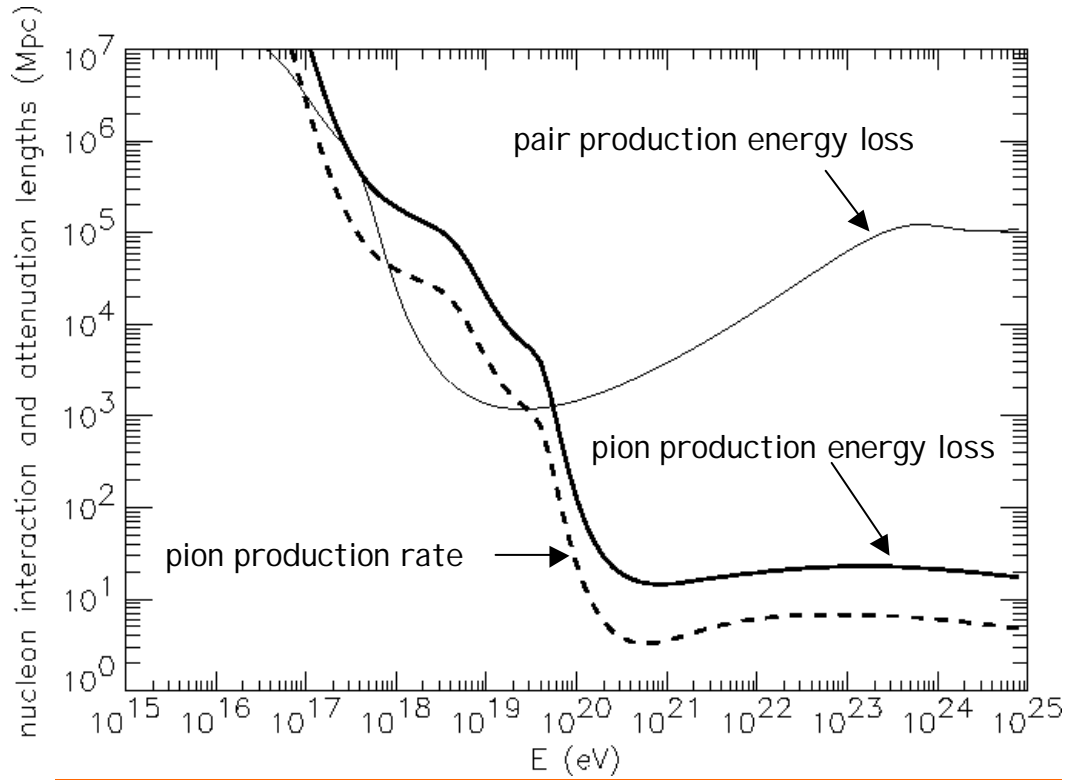
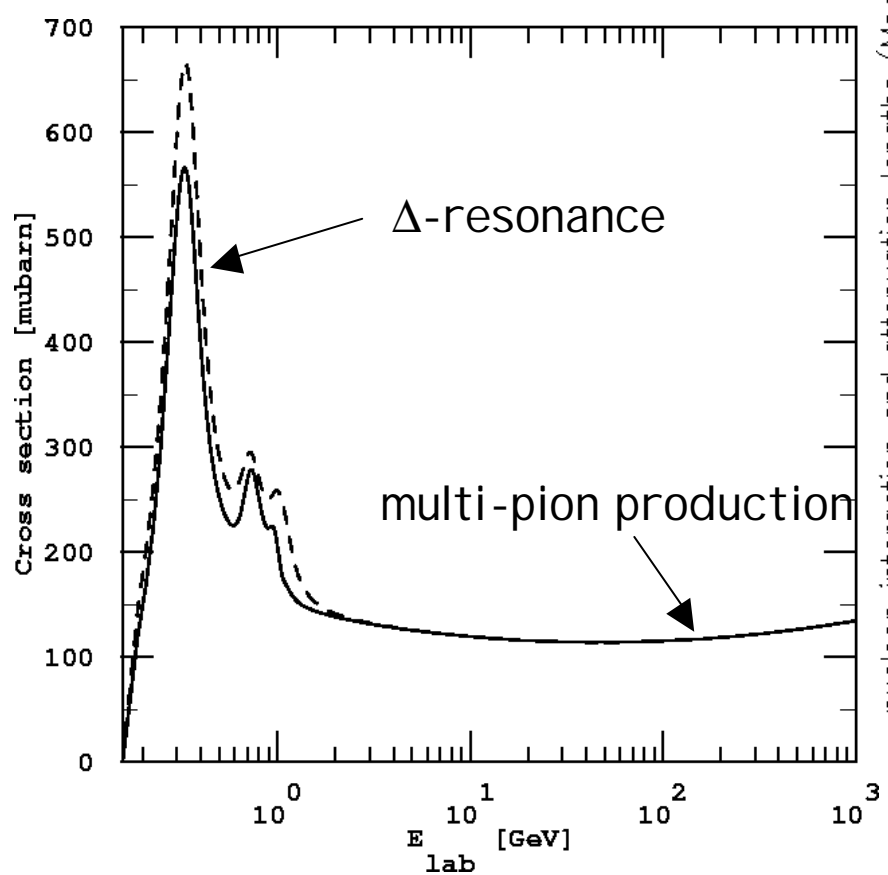
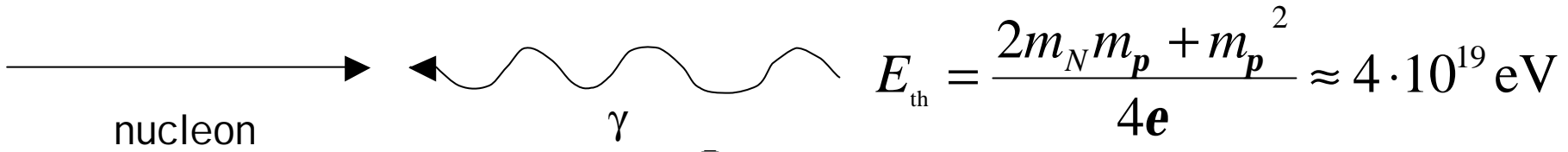
Dots: the 1600 detector stations (tanks)

## **The Ultra-High Energy Cosmic Ray Mystery consists of (at least) Three Interrelated Challenges**

- 1.) electromagnetically or strongly interacting particles above  $10^{20}$  eV lose energy within less than about 50 Mpc.**
- 2.) in most conventional scenarios exceptionally powerful acceleration sources within that distance are needed.**
- 3.) The observed distribution seems to be very isotropic (except for a possible interesting small scale clustering)**

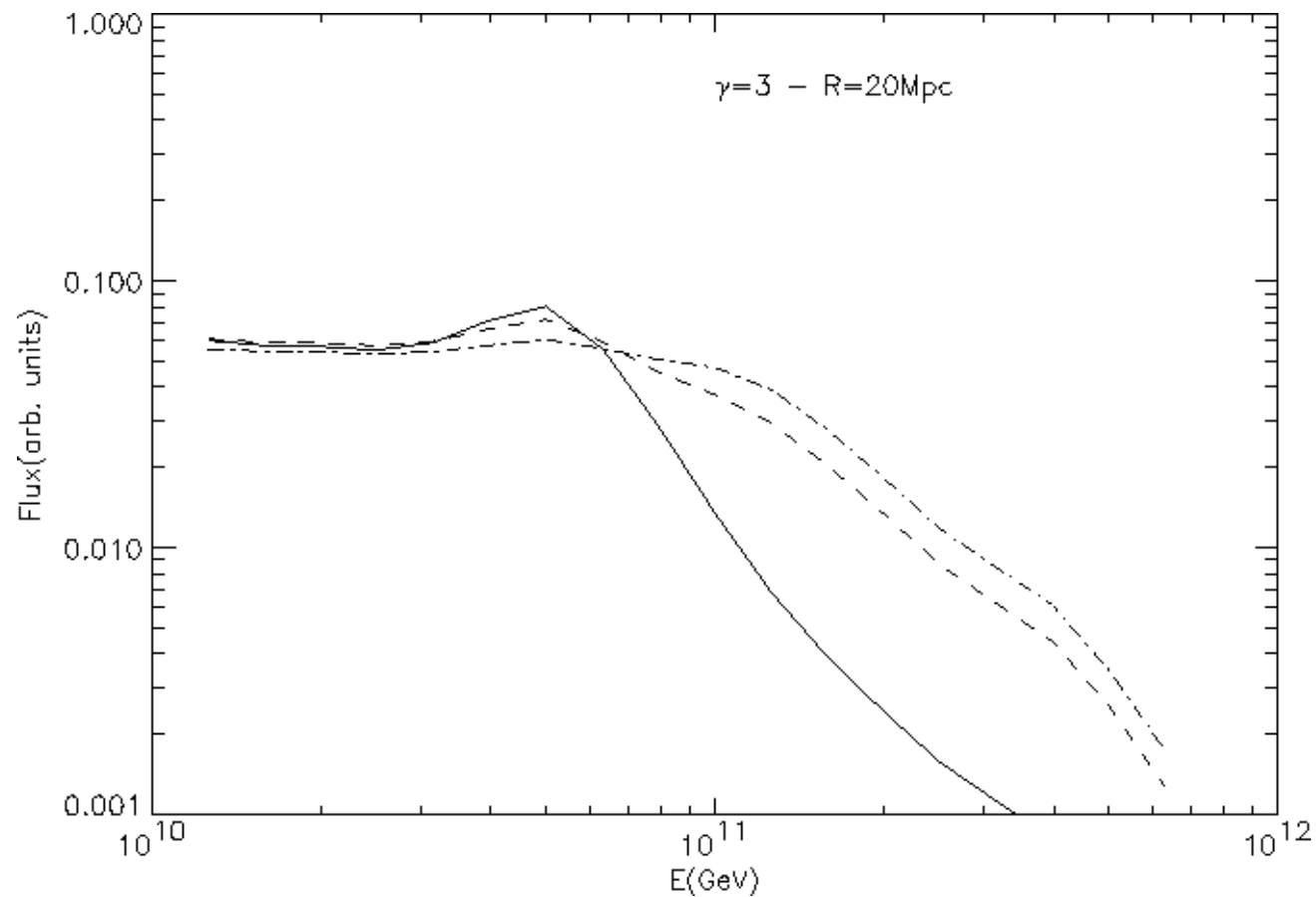
# The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



⇒ sources must be in cosmological backyard  
 Only Lorentz symmetry breaking at  $>10^{11}$   
 could avoid this conclusion.

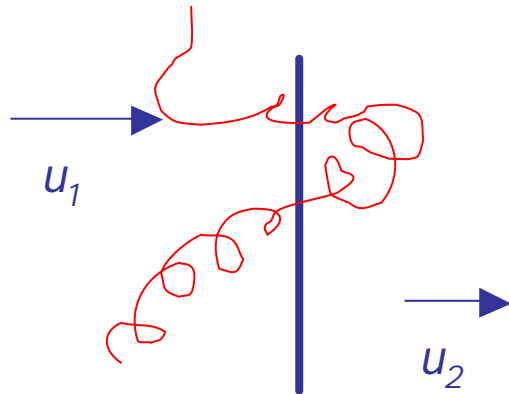
What the GZK effect tells us about the source distribution (in the absence of strong magnetic deflection)



Observable spectrum for an  $E^{-3}$  injection spectrum for a distribution of sources with overdensities of 1, 10, 30 (bottom to top) within 20 Mpc, and otherwise homogeneous.

# 1<sup>st</sup> Order Fermi Shock Acceleration

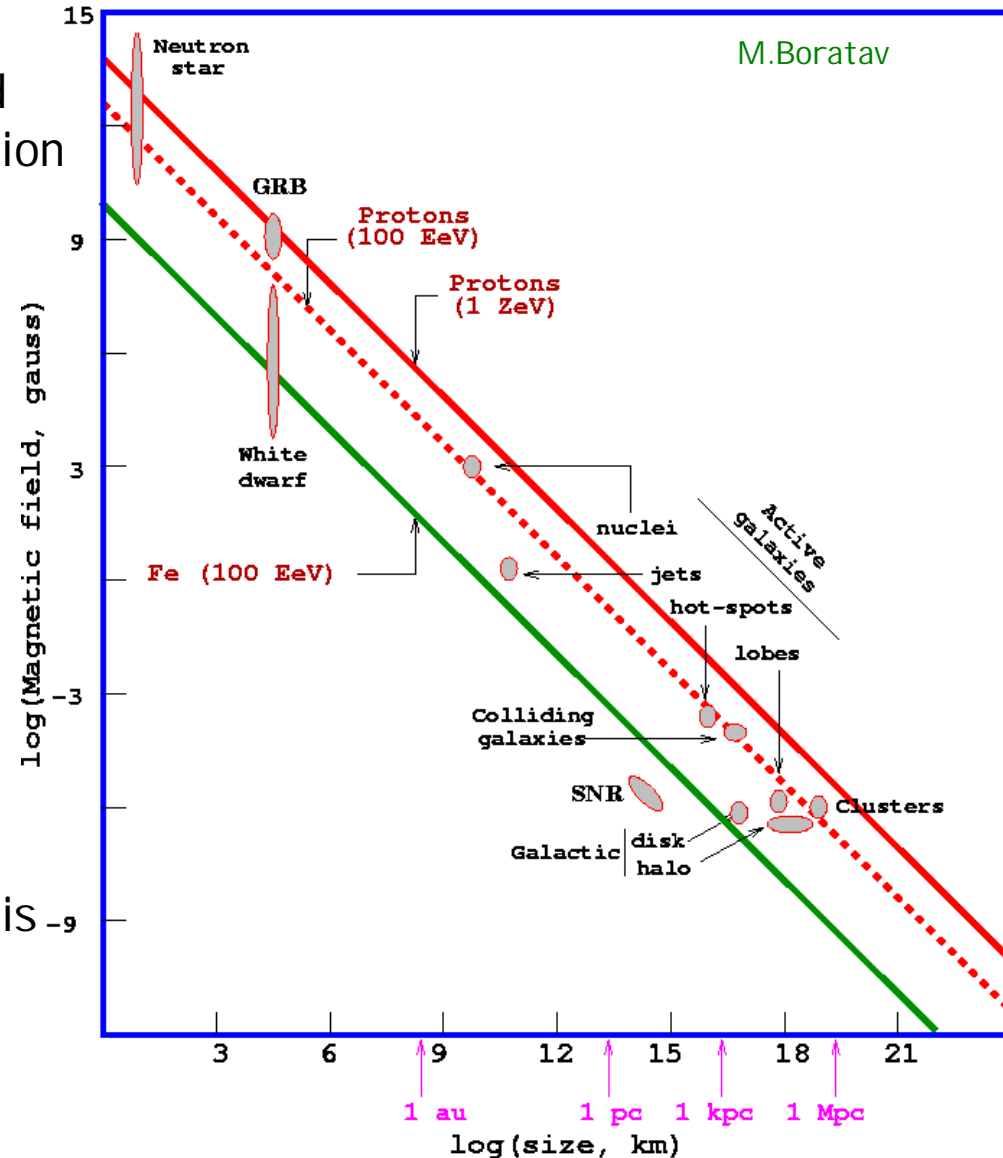
This is the most widely accepted scenario of cosmic ray acceleration



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

## Hillas-plot

(candidate sites for  $E=100$  EeV and  $E=1$  ZeV)



$E_{max} \propto ZBL$  (Fermi)

$E_{max} \propto ZBL\Gamma$  (Ultra-relativistic shocks-GRB)

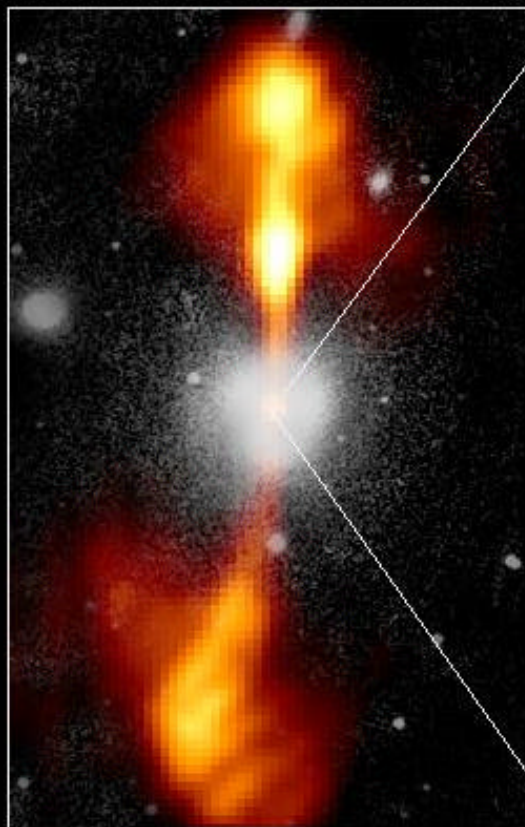
A possible acceleration site associated with shocks in hot spots of active galaxies

# Core of Galaxy NGC 4261

Hubble Space Telescope

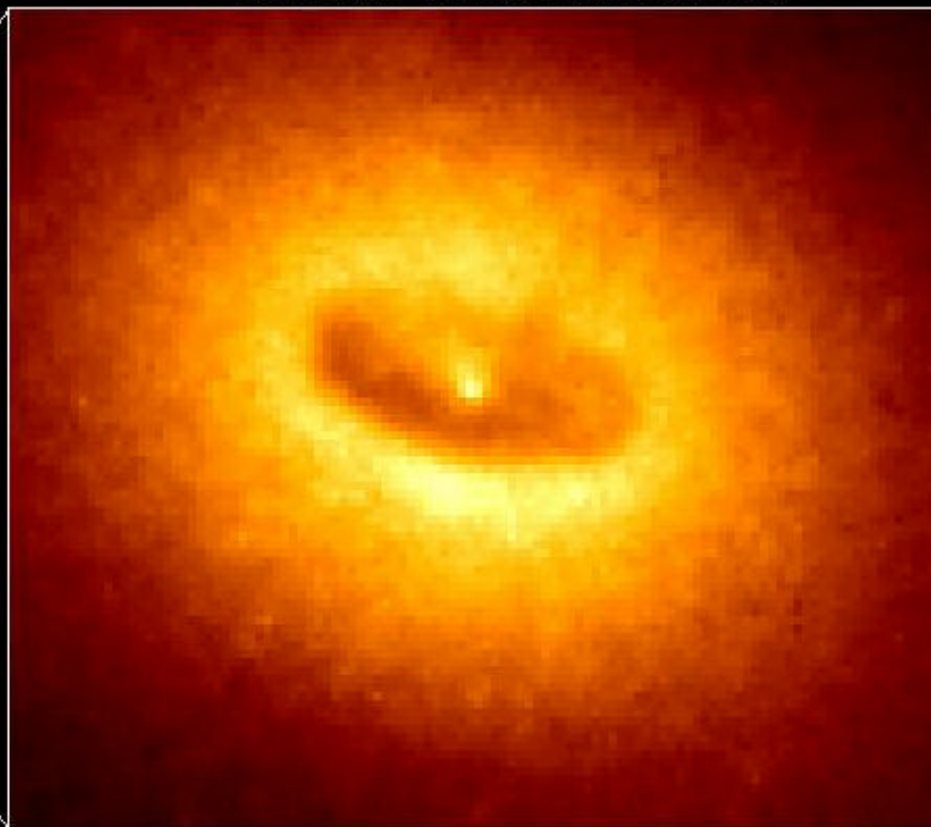
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image



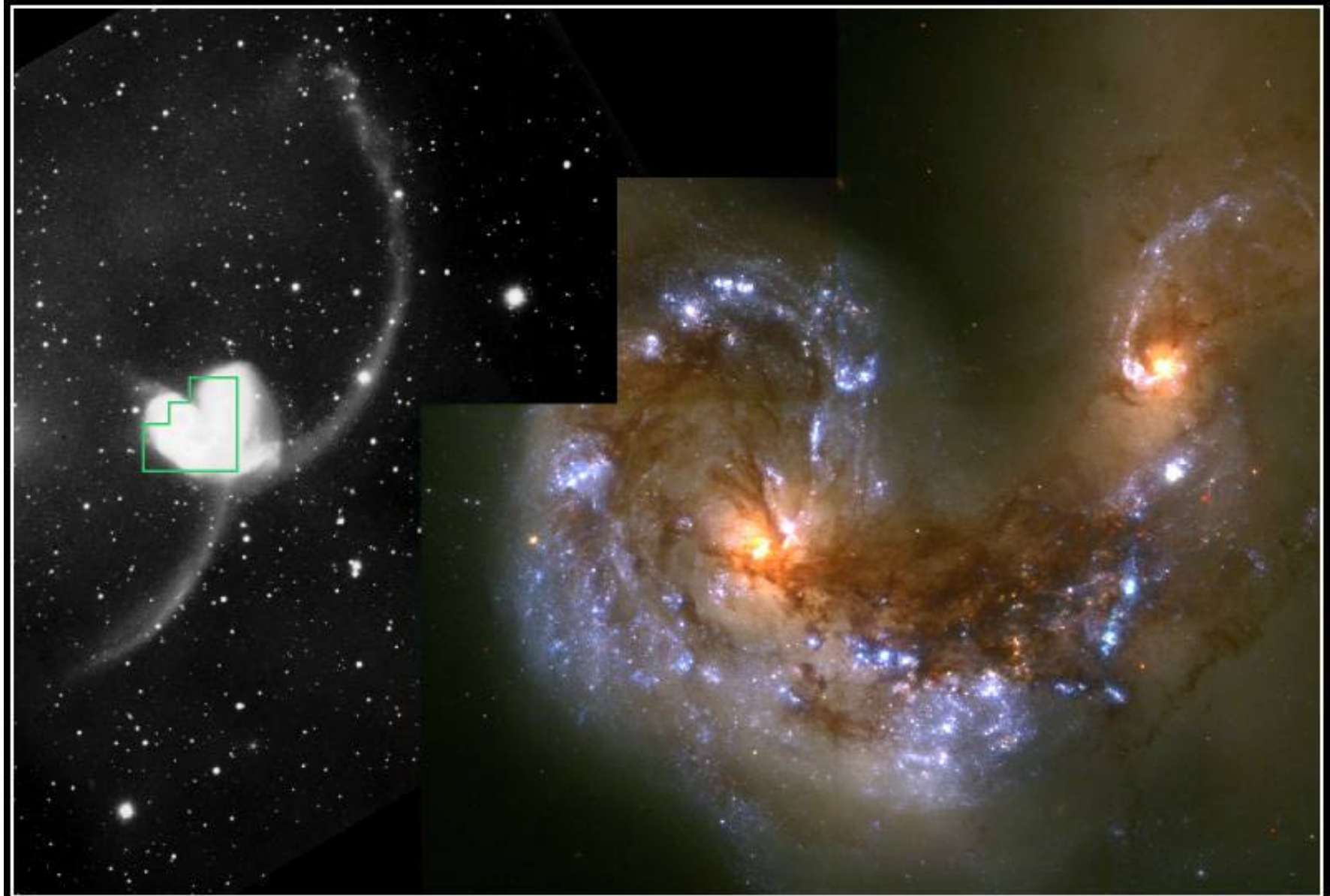
380 Arc Seconds  
88,000 LIGHTYEARS

HST Image of a Gas and Dust Disk



17 Arc Seconds  
400 LIGHTYEARS

A possible acceleration site associated with shocks formed by colliding galaxies



**Colliding Galaxies NGC 4038 and NGC 4039**

HST • WFPC2

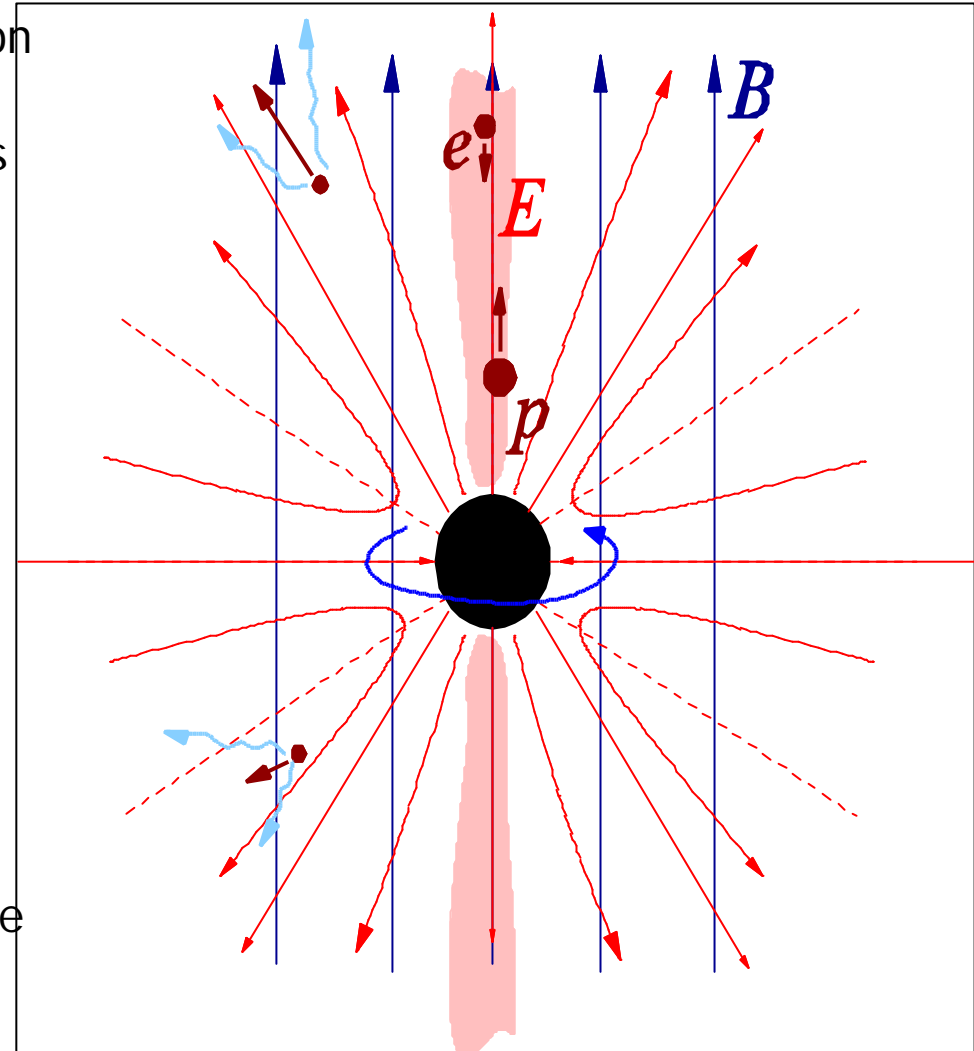
PRC97-34a • ST Sci OPO • October 21, 1997 • B, Whitmore (ST Sci) and NASA

## Supermassive black holes as linear accelerators

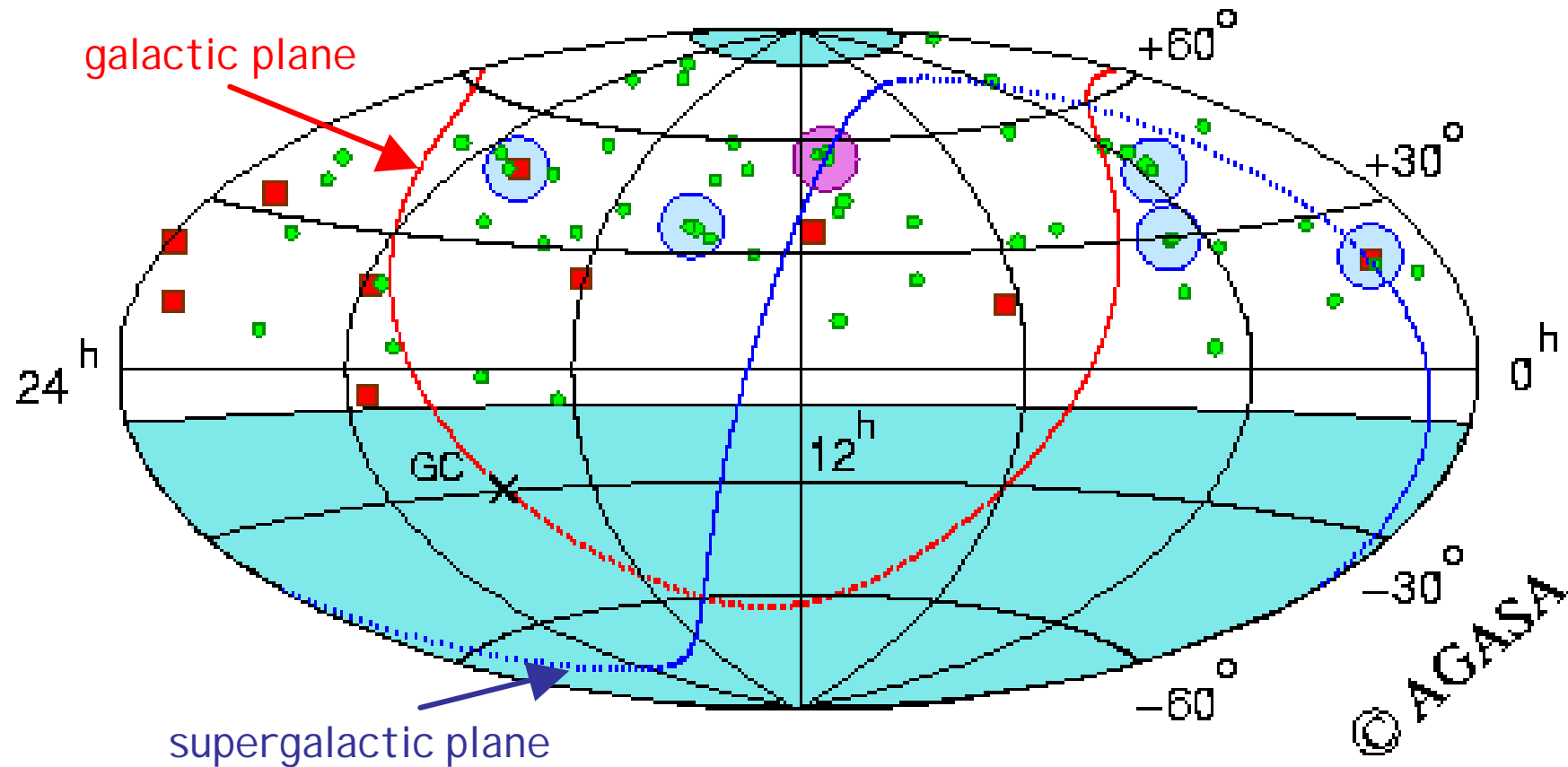
Particles accelerated along the rotation axis do not suffer from significant energy losses and can achieve energies up to

$$E_{\max} = 10^{20} \left( \frac{M_{\text{bh}}}{10^8 M_{\text{sun}}} \right) \left( \frac{B}{10^4 \text{ G}} \right) \text{eV}$$

**S.Colgate** suggested that helical magnetic fields produced during formation of galaxies around central black holes occasionally reconnect. Resulting electric fields can accelerate cosmic rays up to  $\sim 10^{23}$  eV.



## Arrival Directions of Cosmic Rays above $4 \times 10^{19}$ eV



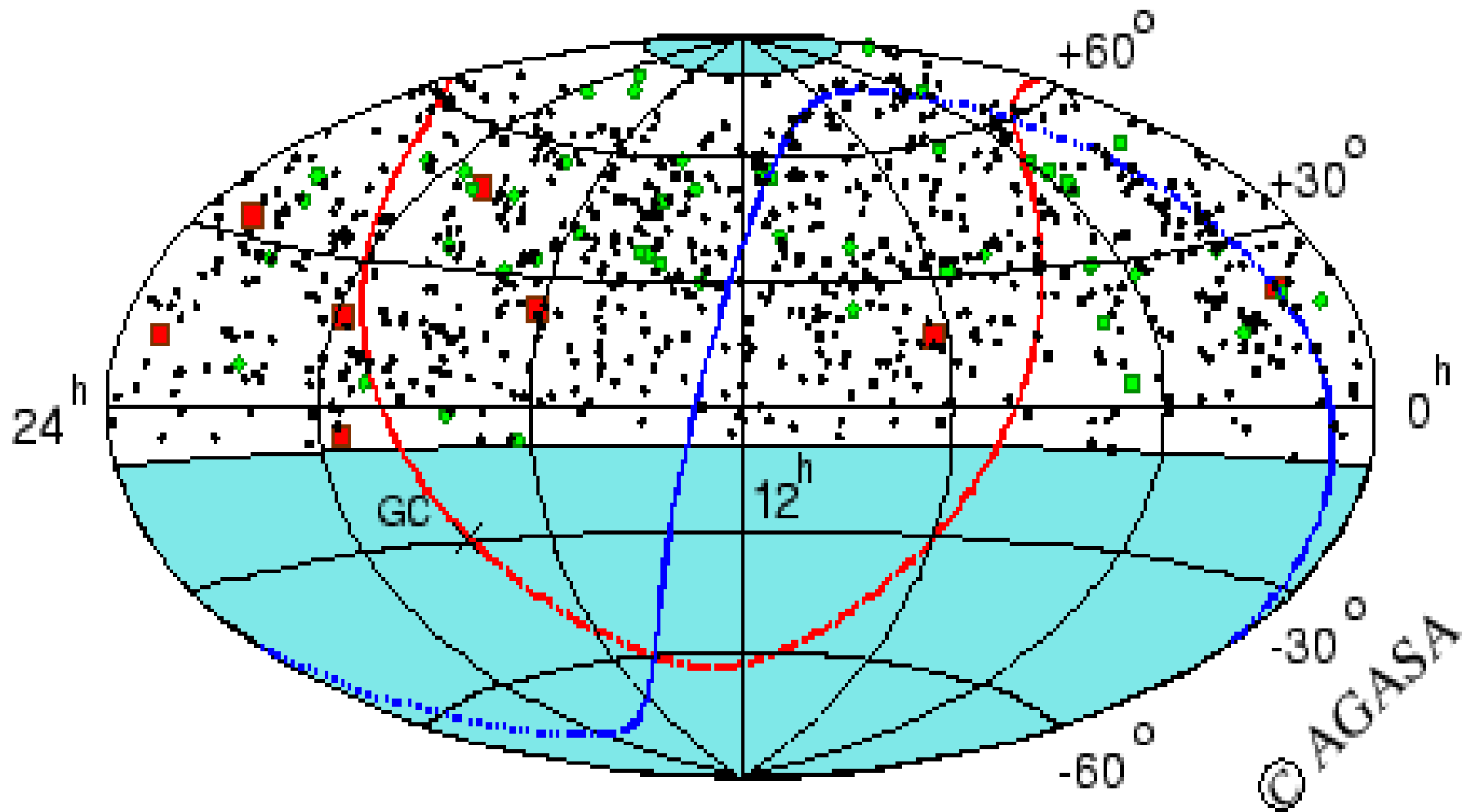
Akeno  $20 \text{ km}^2$ , 17/02/1990 – 31/07/2001, zenith angle  $< 45^\circ$

**Red squares** : events above  $10^{20}$  eV, **green circles** : events of  $(4 - 10) \times 10^{19}$  eV

Shaded circles = clustering within  $2.5^\circ$ .

Chance probability of clustering from isotropic distribution is  $< 1\%$ .

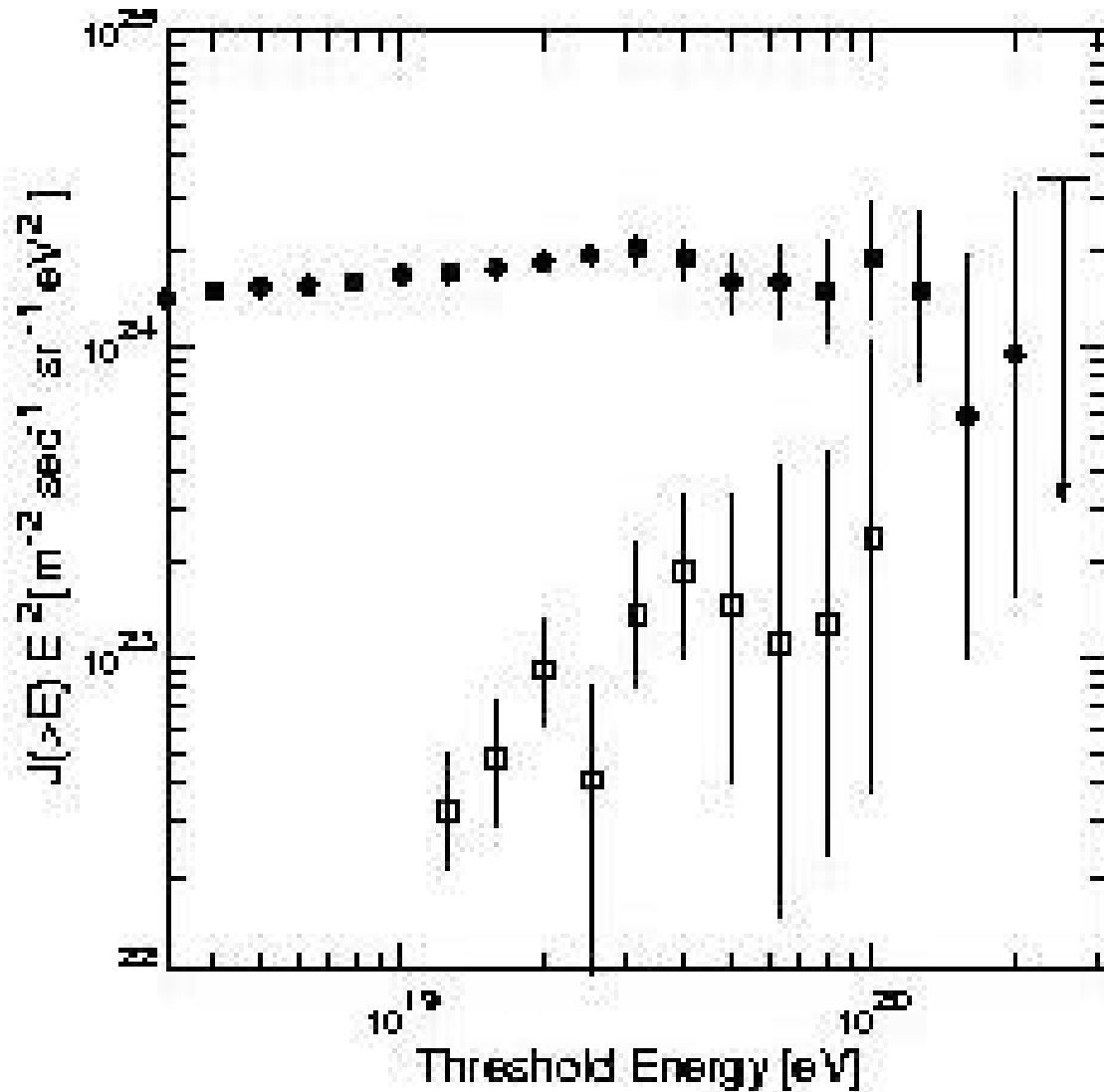
Arrival Directions of Cosmic Rays above  $10^{19}$  eV



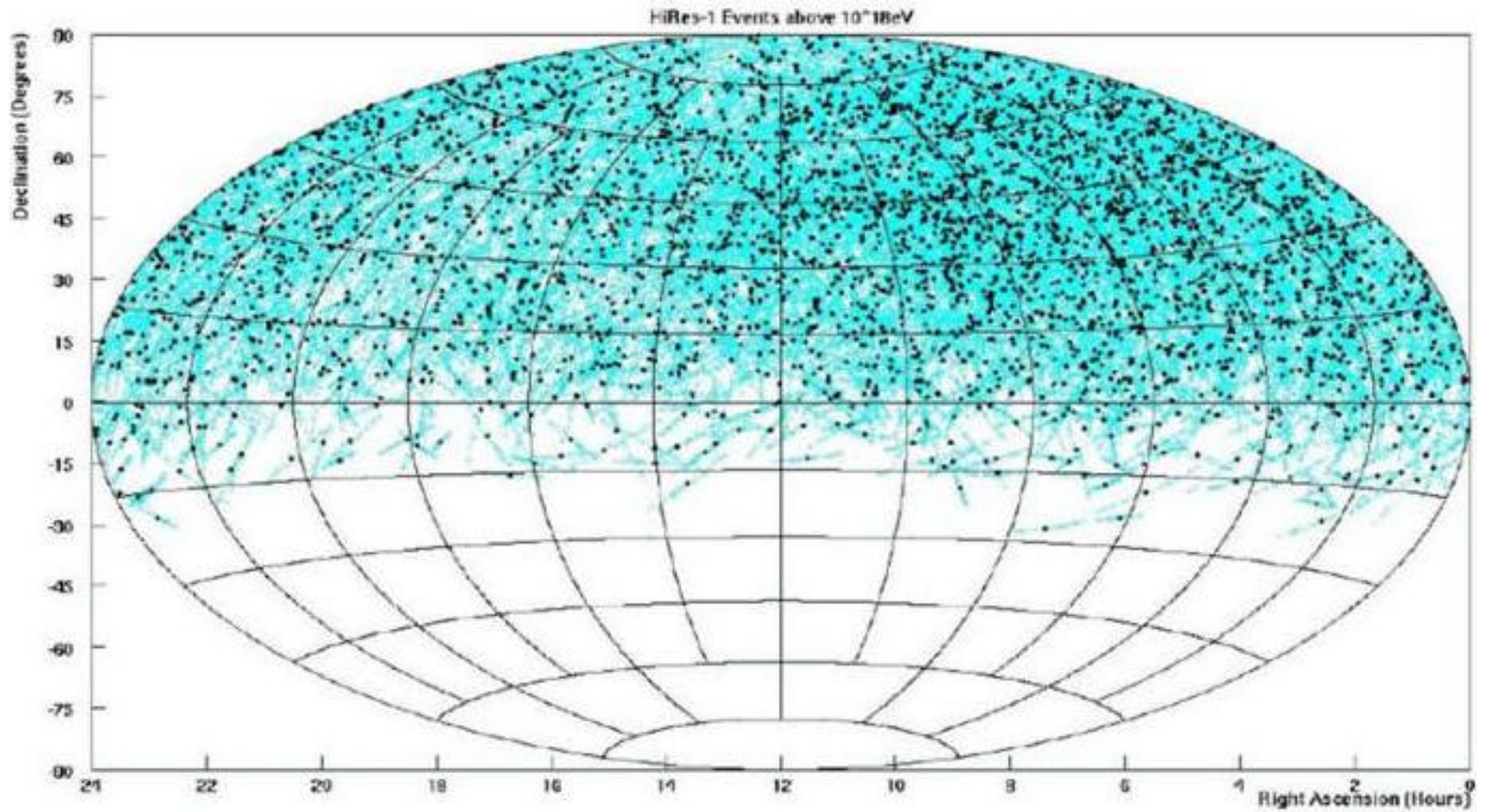
## Spectrum of the clustered component in the AGASA data

Possible explanations of clustering:

- \* point-like sources of charged particles in case of insignificant magnetic deflection
- \* point-like sources of neutral primaries
- \* magnetic lensing of charged primaries



HiRes sees no significant anisotropy above  $10^{18}$  eV



# Cosmic Magnetic Fields and their Role in Cosmic Ray Physics

1.) Magnetic fields are main players in cosmic ray acceleration.

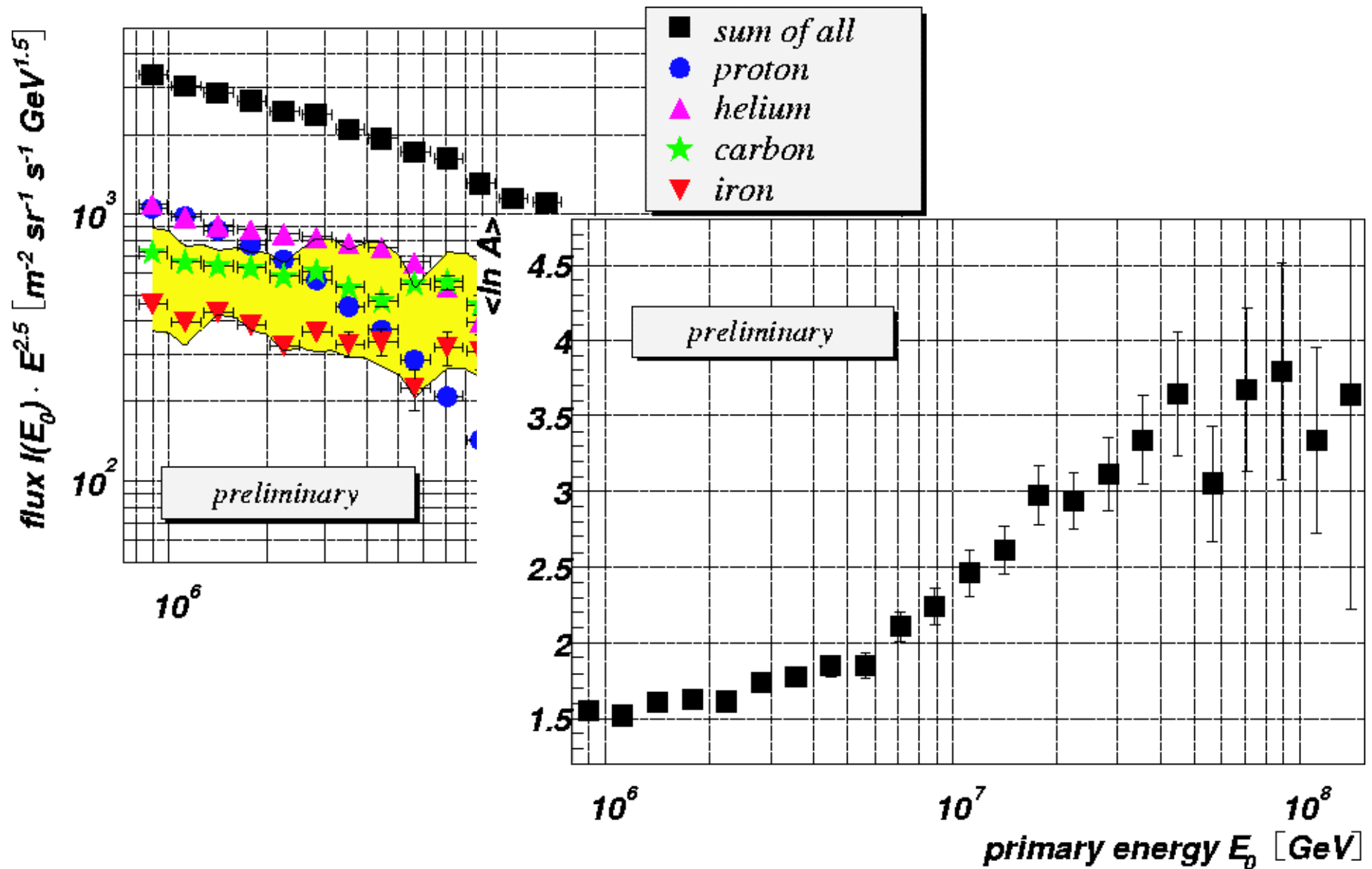
2.) Cosmic rays up to  $\sim 10^{18}$  eV are partially confined in the Galaxy.

Energy densities in cosmic rays, in the galactic magnetic field, in the turbulent flow, and gravitational energy are of comparable magnitude.

The galactic cosmic ray luminosity  $L_{\text{CR}}$  required to maintain its observed density  $u_{\text{CR}} \sim 1 \text{ eV cm}^{-3}$  in the galactic volume  $V_{\text{gal}}$  for a confinement time  $t_{\text{CR}} \sim 10^7$  yr,  $L_{\text{CR}} \sim u_{\text{CR}} V_{\text{gal}} / t_{\text{CR}} \sim 10^{41}$  erg/sec, is  $\sim 10\%$  of the kinetic energy rate of galactic supernovae.

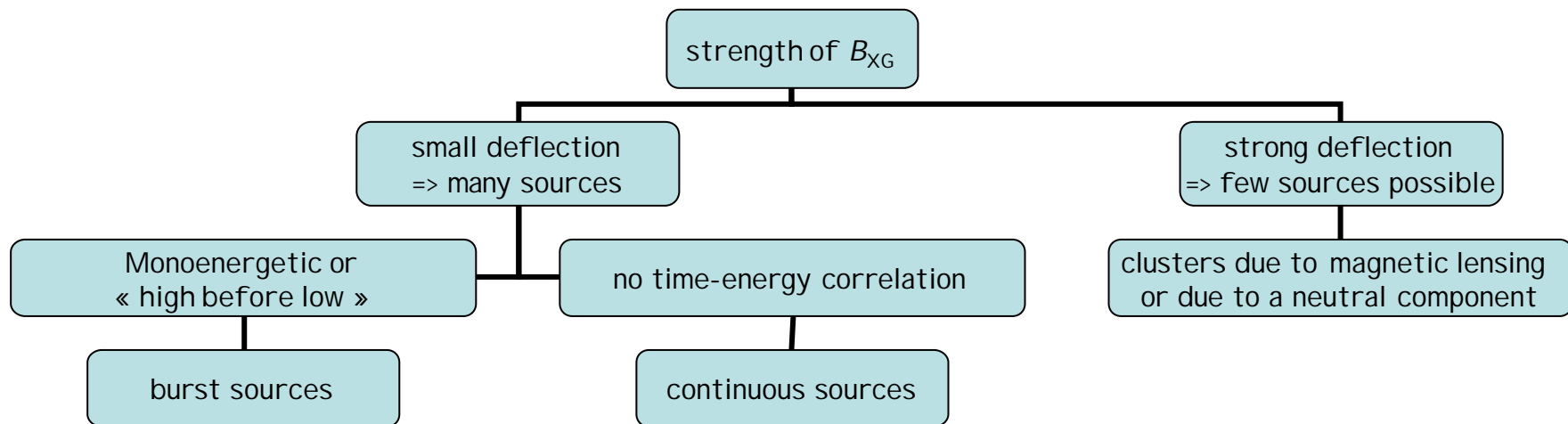
However, there are still **problems with this standard interpretation**:  
Upper limits on  $\gamma$ -ray fluxes from supernova remnants are below predictions from interactions of accelerated cosmic rays with ambient medium!

3.) The knee is probably a deconfinement effect as suggested by rigidity dependence measured by KASCADE:

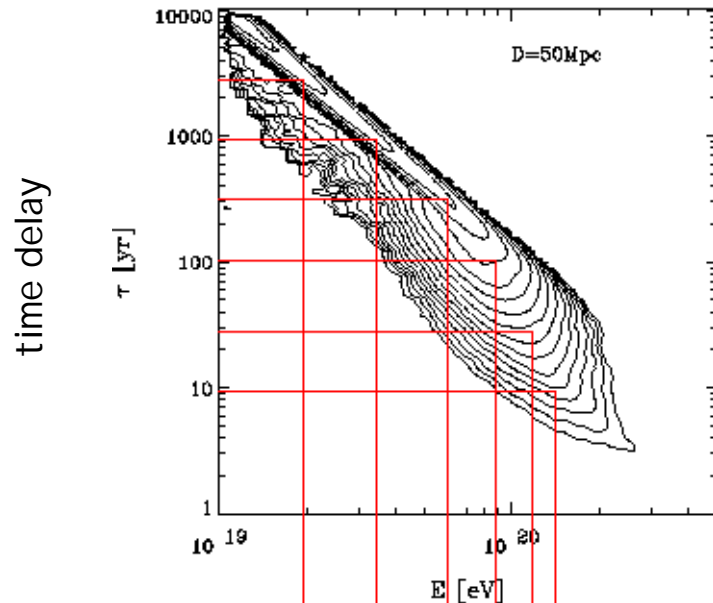


4.) Cosmic rays above  $\sim 10^{19}$  eV are probably extragalactic and may be deflected mostly by extragalactic fields  $B_{\text{XG}}$  rather than by galactic fields.

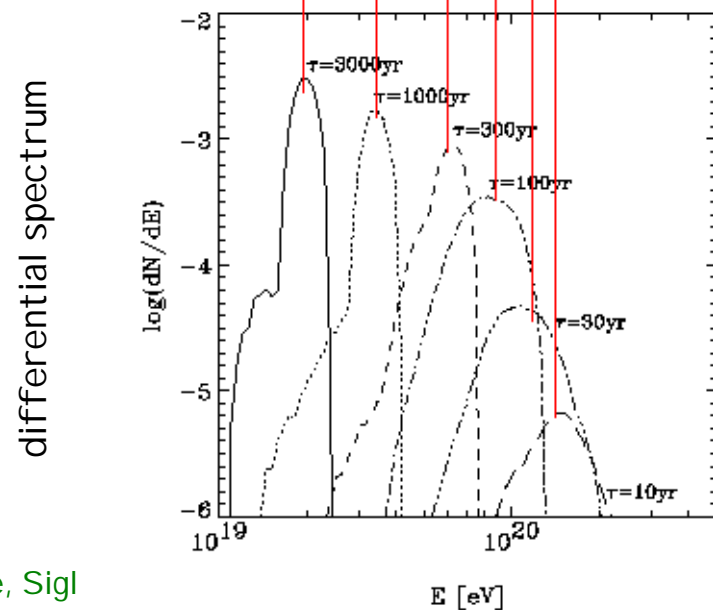
However, very little is known about about  $B_{\text{XG}}$ : It could be as small as  $10^{-20}$  G (primordial seeds, Biermann battery) or up to fractions of micro Gauss if concentrated in the local Supercluster (equipartition with plasma).



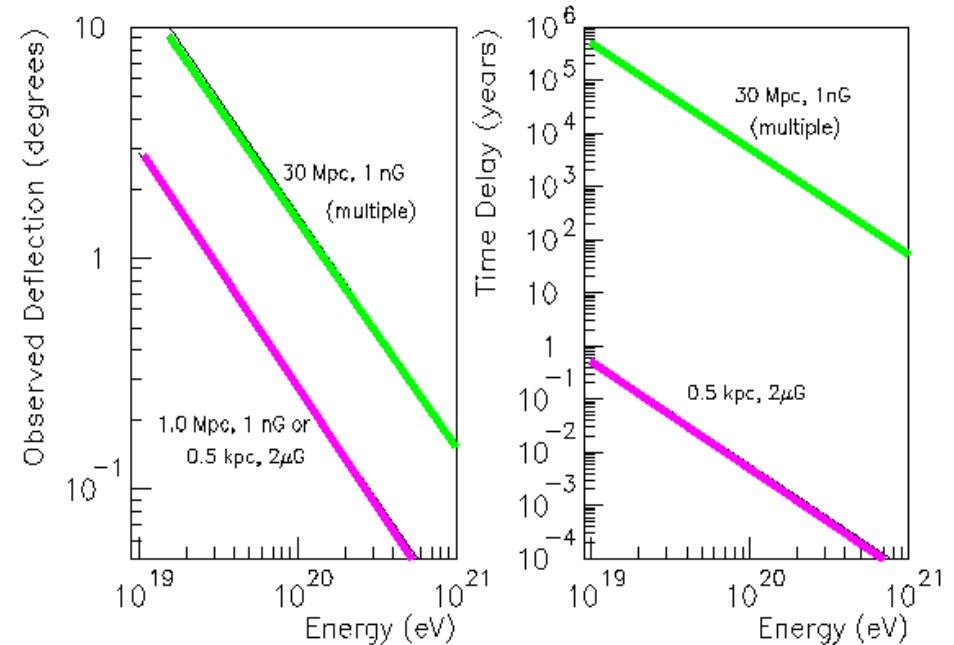
Example:  
 Magnetic field of  $10^{-10}$  Gauss, coherence scale 1 Mpc  
 burst source at 50 Mpc distance



cuts through the energy-time distribution:



To get an impression on the numbers involved:



$\Delta\theta$  for a vertical shower:

	10 EeV	100 EeV
Array alone	$2^\circ$	$<1^\circ$
Hybrid	$0.25^\circ$	$0.20^\circ$

## Transition rectilinear-diffusive regime

Neglect energy losses for simplicity.

Time delay over distance  $d$  in a field  $B_{\text{rms}}$  of coherence length  $l_c$  for small deflection:

$$t(E, d) \cong \frac{d\mathbf{q}(E, d)^2}{4} \cong 1.5 \times 10^3 Z^2 \left( \frac{E}{10^{20} \text{ eV}} \right)^{-2} \left( \frac{d}{10 \text{ Mpc}} \right)^2 \left( \frac{B_{\text{rms}}}{10^{-9} \text{ G}} \right)^2 \left( \frac{l_c}{1 \text{ Mpc}} \right) \text{ yr}$$

This becomes comparable to distance  $d$  at energy  $E_c$ :

$$E_c \cong 4.7 \times 10^{19} \left( \frac{d}{10 \text{ Mpc}} \right)^{1/2} \left( \frac{B_{\text{rms}}}{10^{-7} \text{ G}} \right) \left( \frac{l_c}{1 \text{ Mpc}} \right)^{1/2} \text{ eV}$$

In the rectilinear regime for total differential power  $Q(E)$  injected inside  $d$ , the differential flux reads

$$j(E) = \frac{Q(E)}{(4pd)^2}$$

In the **diffusive regime** characterized by a diffusion constant  $D(E)$ , particles are confined during a time scale

$$t(E, d) \cong \frac{d^2}{D(E)}$$

which leads to the flux

$$j(E) \cong \frac{Q(E)t(E)}{(4\mathbf{p})^2 d^3} = \frac{Q(E)}{(4\mathbf{p})^2 dD(E)}$$

For a given power spectrum  $B(k)$  of the magnetic field an often used (very approximate) estimate of the diffusion coefficient is

$$D(E) \cong \frac{r_g(E)}{3} \frac{B_{\text{rms}}}{\int_{1/r_g(E)}^{\infty} dk k^2 \langle B^2(k) \rangle},$$

where  $B_{\text{rms}}^2 = \int_0^{\infty} dk k^2 \langle B^2(k) \rangle$ , and the gyroradius is

$$r_g(E) \cong \frac{E}{ZeB_{\text{rms}}} \cong 110 Z^{-1} \left( \frac{E}{10^{20} \text{ eV}} \right) \left( \frac{B_{\text{rms}}}{10^{-6} \text{ G}} \right)^{-1} \text{ kpc}$$

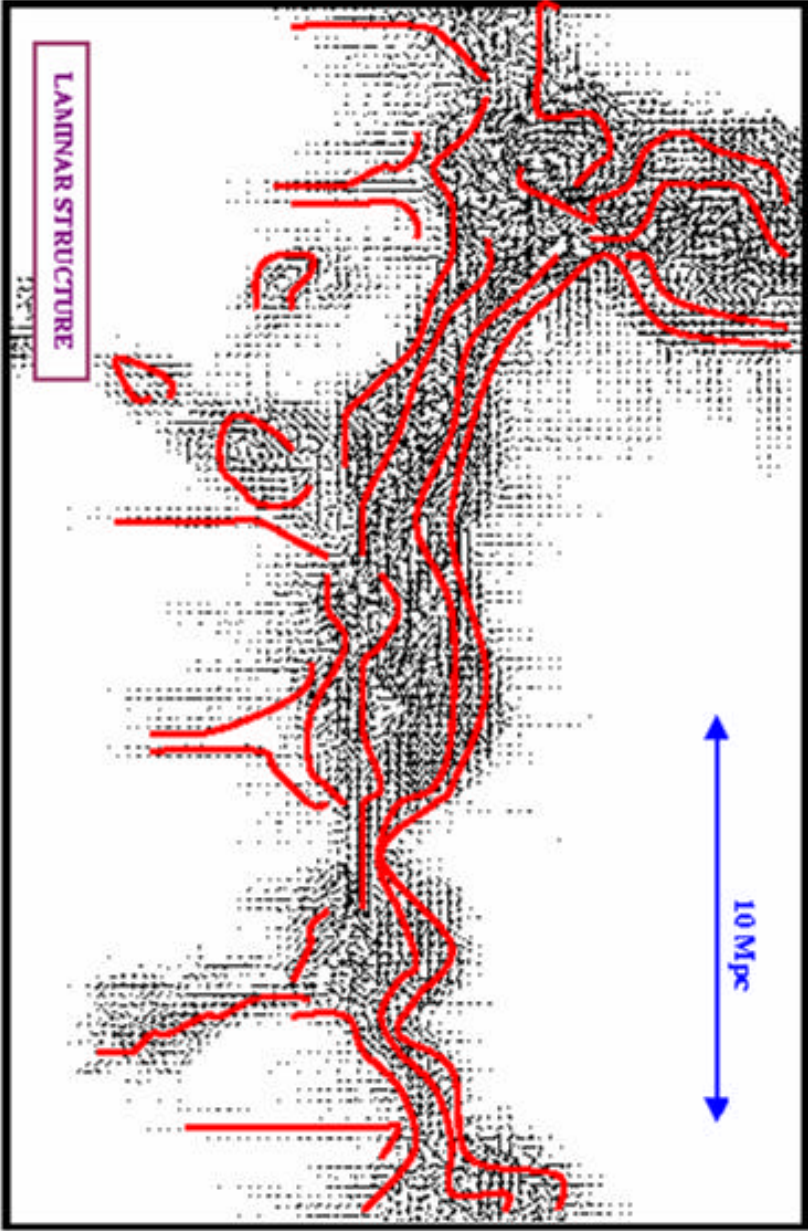
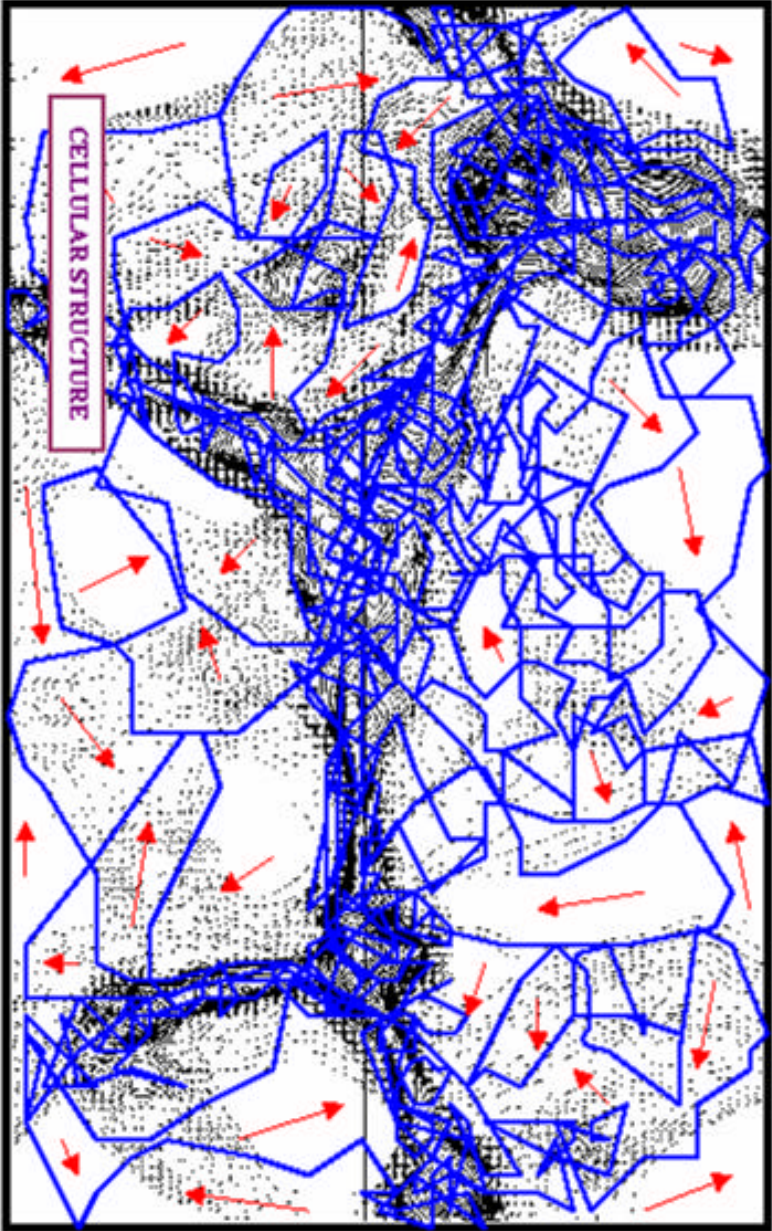
If  $E \ll E_c$  and IF energy losses can be approximated as continuous,  $dE/dt = -b(E)$  (this is not the case for pion production), the local cosmic ray density  $n(E, \vec{r})$  obeys the diffusion equation

$$\partial_t n(E, \vec{r}) + \partial_E [b(E)n(E, \vec{r})] - \vec{\nabla} \cdot [D(E, \vec{r}) \vec{\nabla} n(E, \vec{r})] = q(E, \vec{r})$$

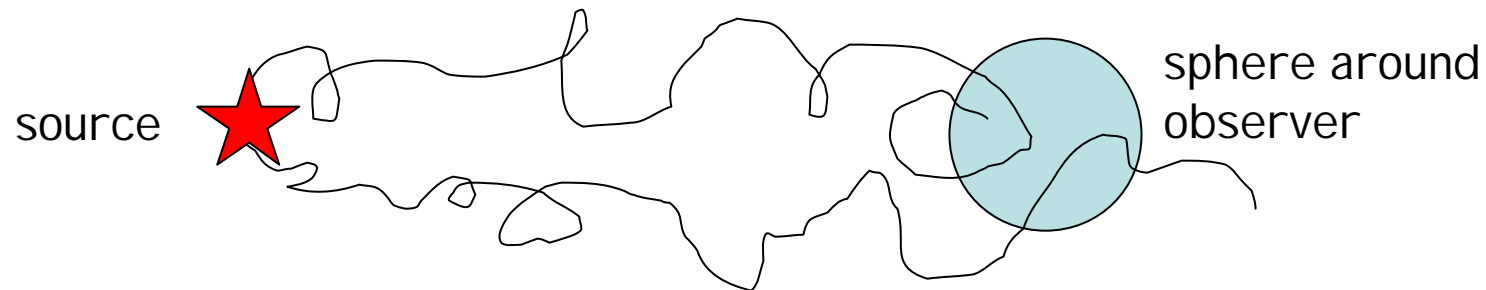
Where now  $q(E, \vec{r})$  is the differential injection rate per volume,  $Q(E) = \int d^3 \vec{r} q(E, \vec{r})$ . Analytical solutions exist (Syrovatskii), but the necessary assumptions are in general too restrictive for ultra-high energy cosmic rays.

**Monte Carlo codes are therefore in general indispensable.**

# Strong, highly structured fields in our Supergalactic Neighbourhood ?

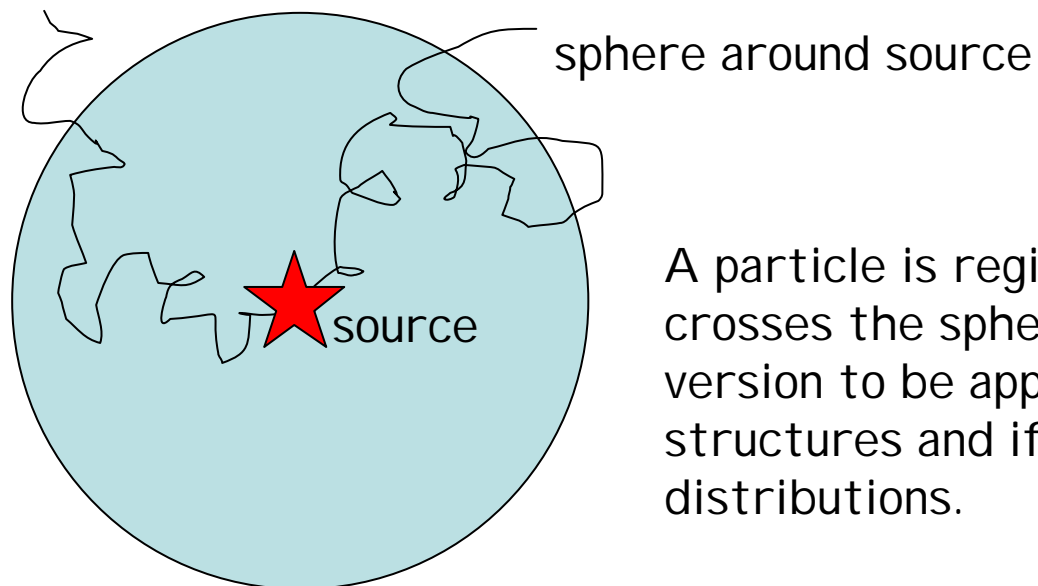


## Principle of deflection code



A particle is registered every time a trajectory crosses the sphere around the observer. This version to be applied for individual source/magnetic field realizations and inhomogeneous structures.

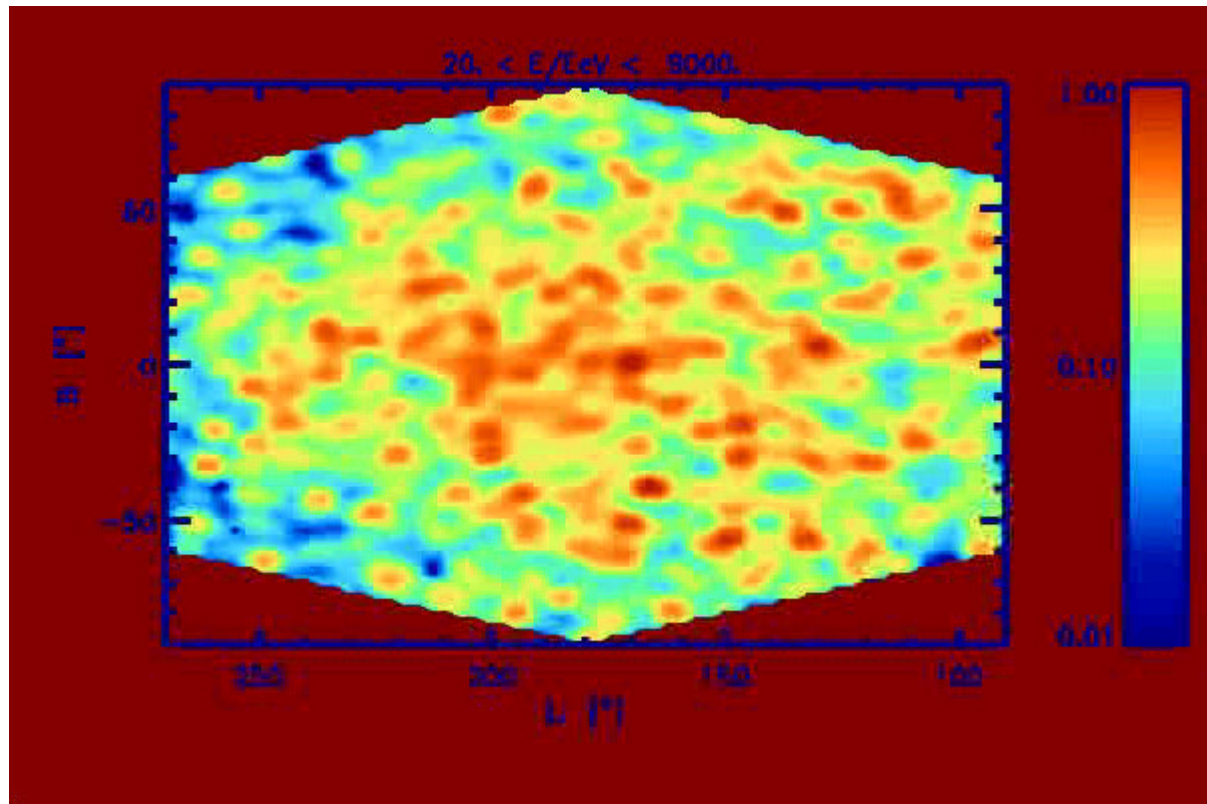
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A particle is registered every time a trajectory crosses the sphere around the source. This version to be applied for homogeneous structures and if only interested in average distributions.

## Effects of a single source: Numerical simulations

A source at 3.4 Mpc distance injecting protons with spectrum  $E^{-2.4}$  up to  $10^{22}$  eV  
A uniform Kolmogorov magnetic field,  $\langle B^2(k) \rangle \sim k^{-11/3}$ , of rms strength  $0.3 \mu\text{G}$ ,  
and largest turbulent eddy size of 1 Mpc.



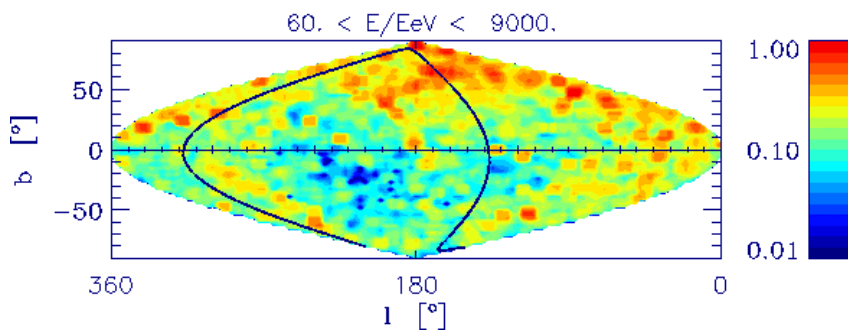
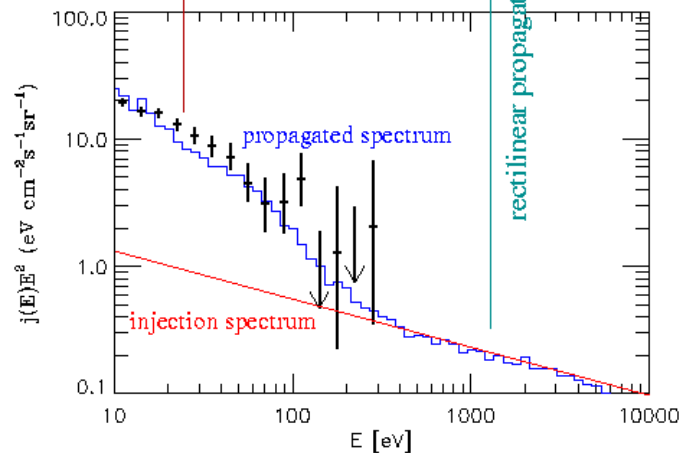
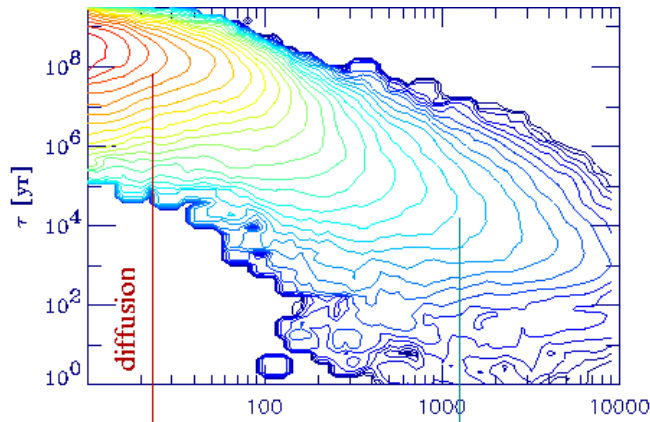
$10^5$  trajectories,  
251 images between  
20 and 300 EeV,  
 $2.5^\circ$  angular resolution

I sola, Lemoine, Sigl

### Conclusions:

- 1.) Isotropy is inconsistent with only one source.
- 2.) Strong fields produce interesting lensing (clustering) effects.

## Summary of spectral effects



$$t(E) \propto E^{-2} \quad \text{in rectilinear regime}$$

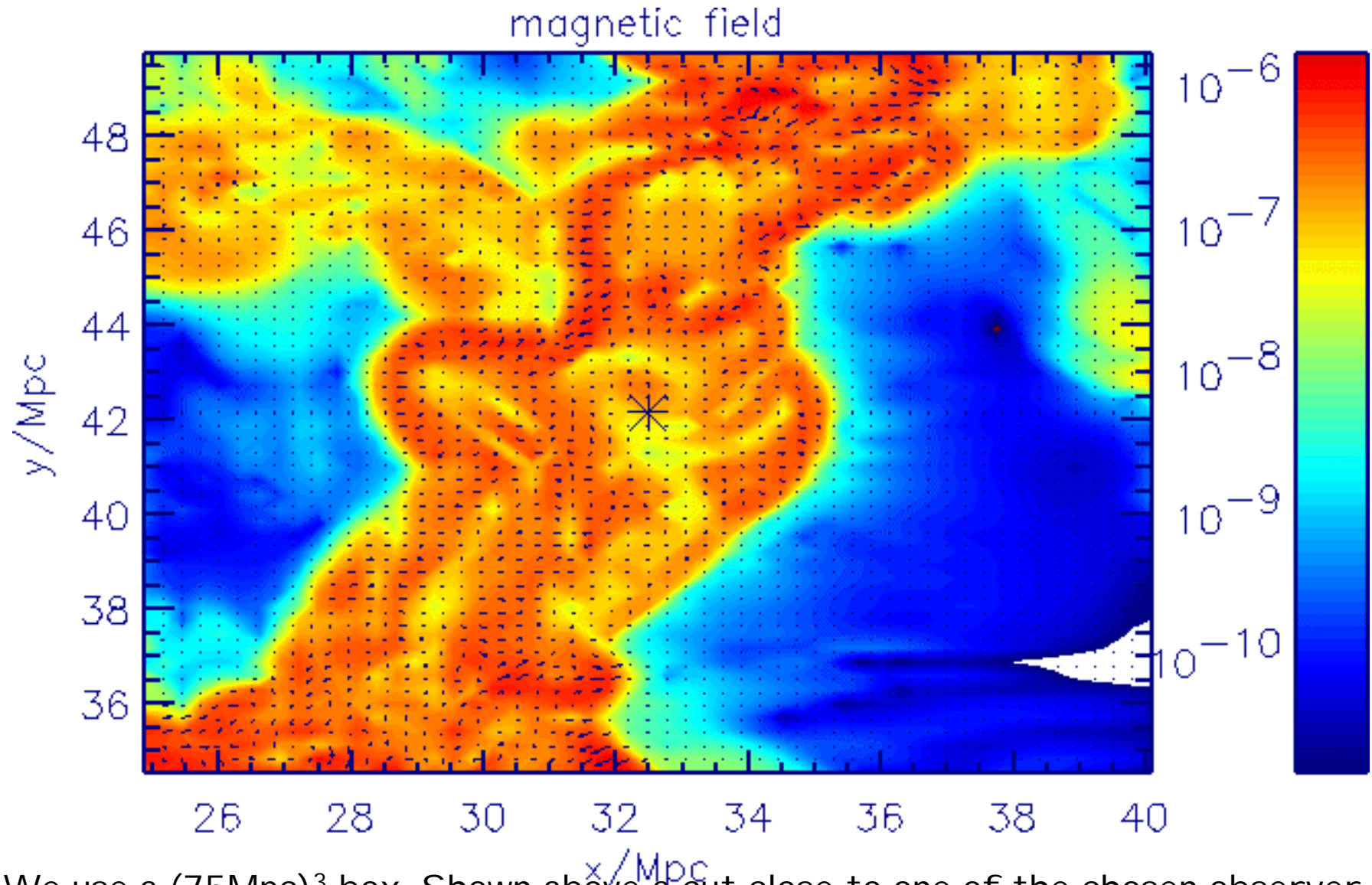
$$t(E) \cong \frac{d^2}{D(E)} \quad \text{in diffusive regime}$$

$$j(E) \propto Q(E) \quad \text{in rectilinear regime}$$

$$j(E) \propto \frac{Q(E)}{D(E)} \quad \text{in diffusive regime}$$

Continuous source distribution following the Gaussian profile.  
 $B=3 \times 10^{-7}$  G,  $d=10$  Mpc

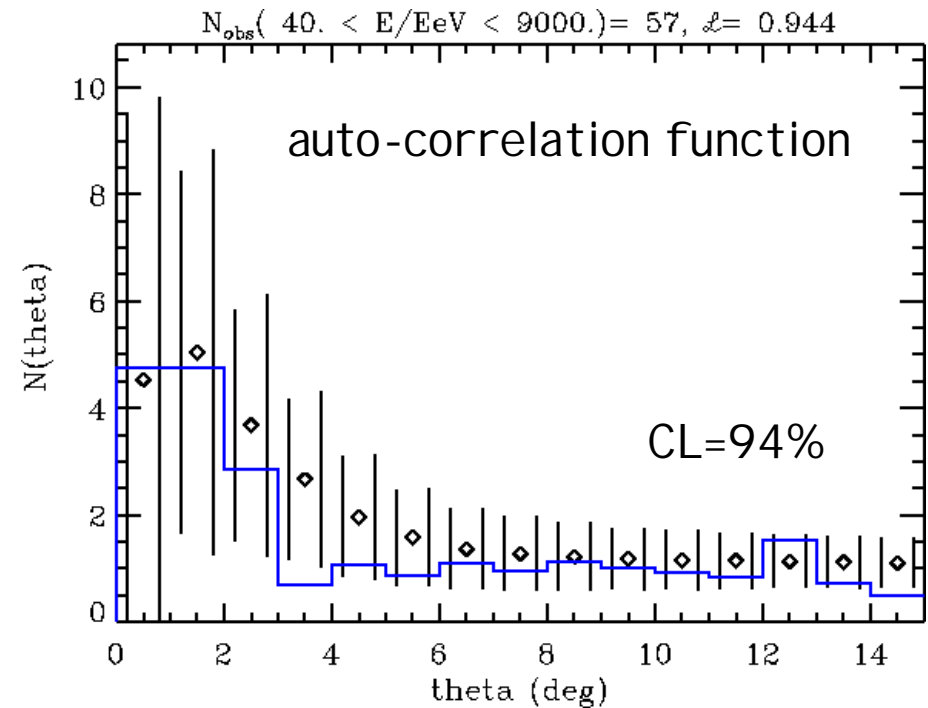
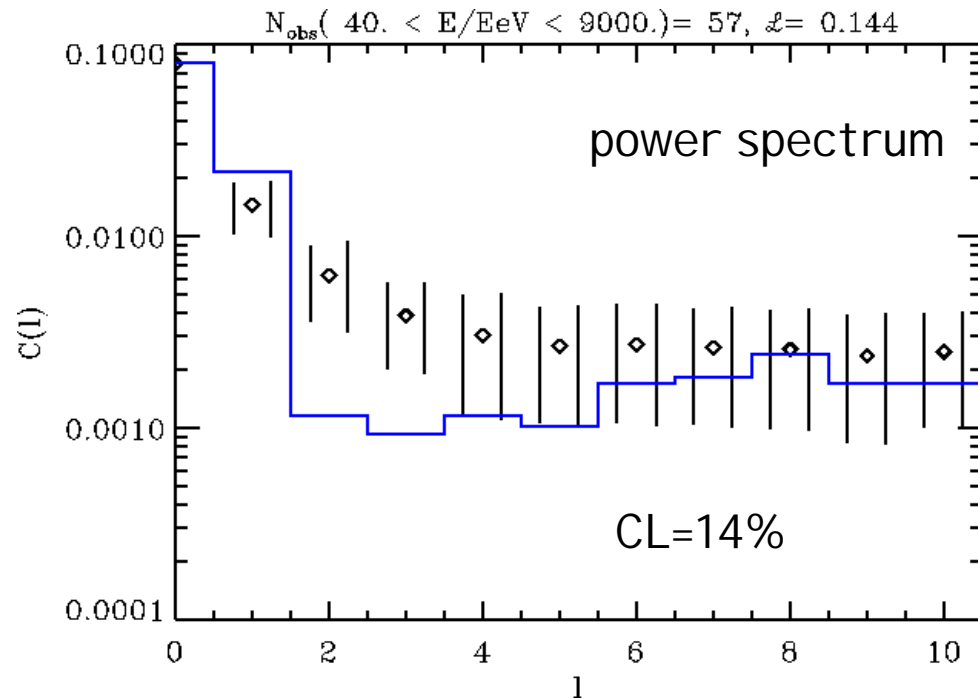
# Supergalactic Neighbourhood and Magnetic Fields from Large Scale Structure Simulations are Strongly Structured



We use a  $(75\text{Mpc})^3$  box. Shown above a cut close to one of the chosen observer positions where  $B=1.3 \times 10^{-7}$  Gauss.

## How many sources in a strongly structured and magnetized environment?

Assume source density follows baryon density; 100 identical sources.  
Normalized magnetic fields from large scale structure simulations.

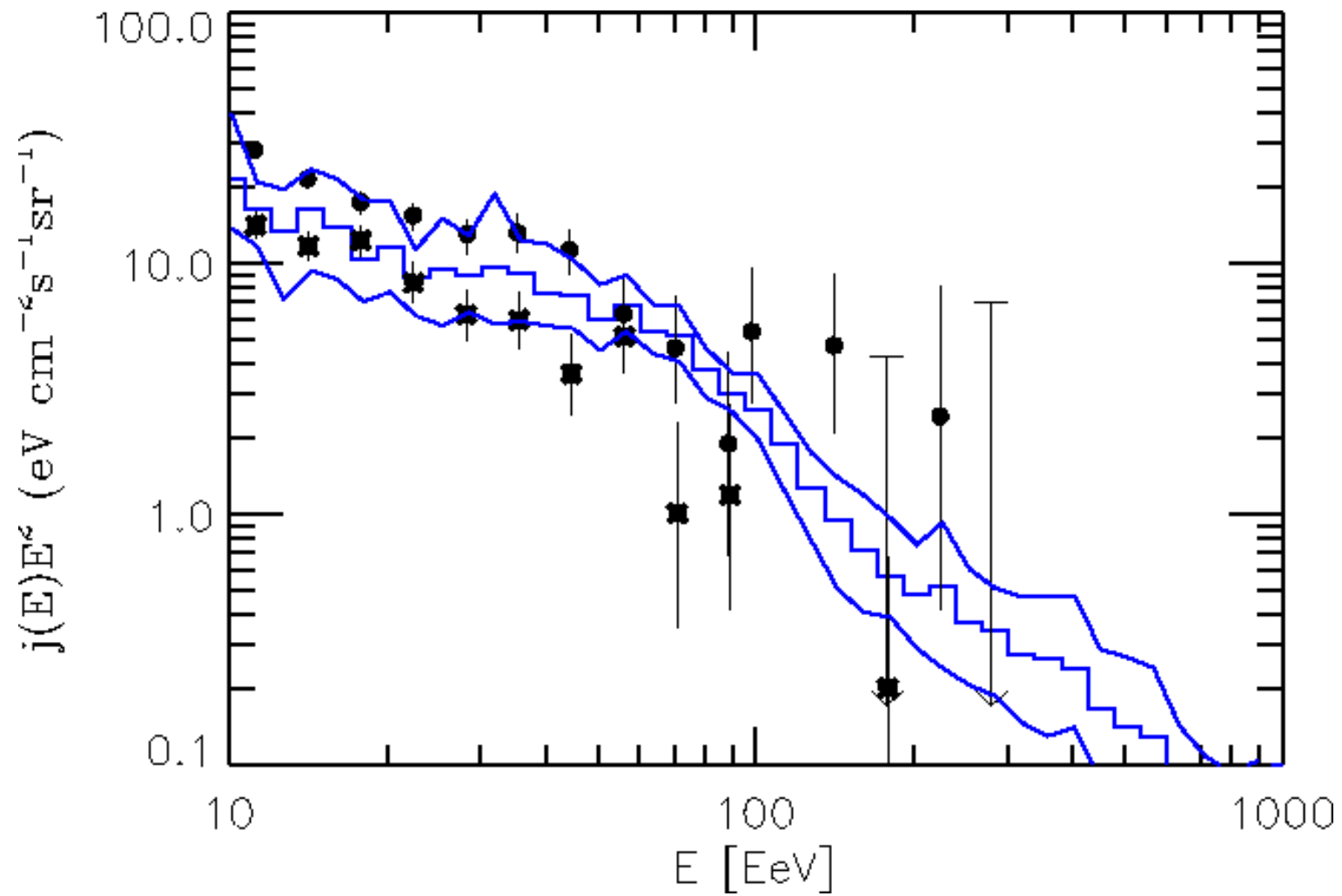


Diamonds=simulations; statistical and total (including cosmic variance) error bars  
Histogram=AGASA data.

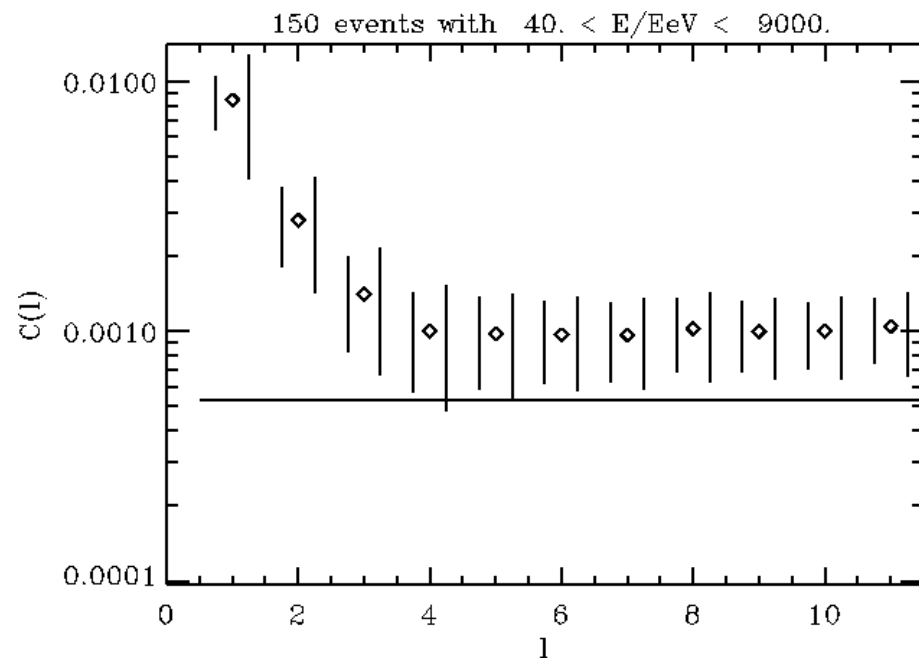
Sigl, Miniati, Ensslin, Sigl, astro-ph/0302388

Current (AGASA) data can be fit with 10-100 sources if observer is surrounded by fields  $\sim 0.1$  micro Gauss.

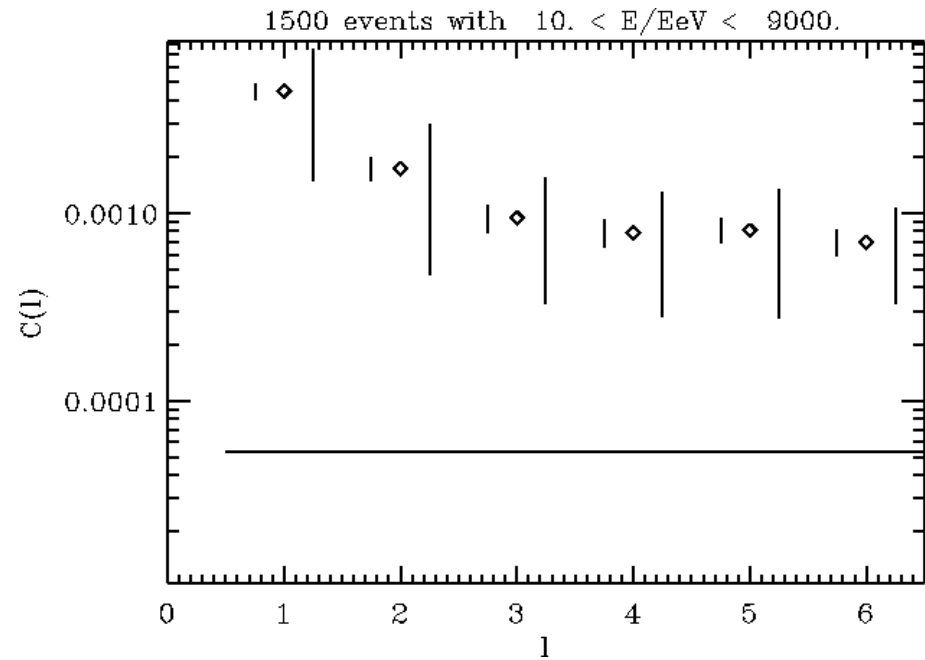
The spectrum in this scenario lies between AGASA (dots) and HiRes (stars) observations for an  $E^{-2.4}$  injection spectrum



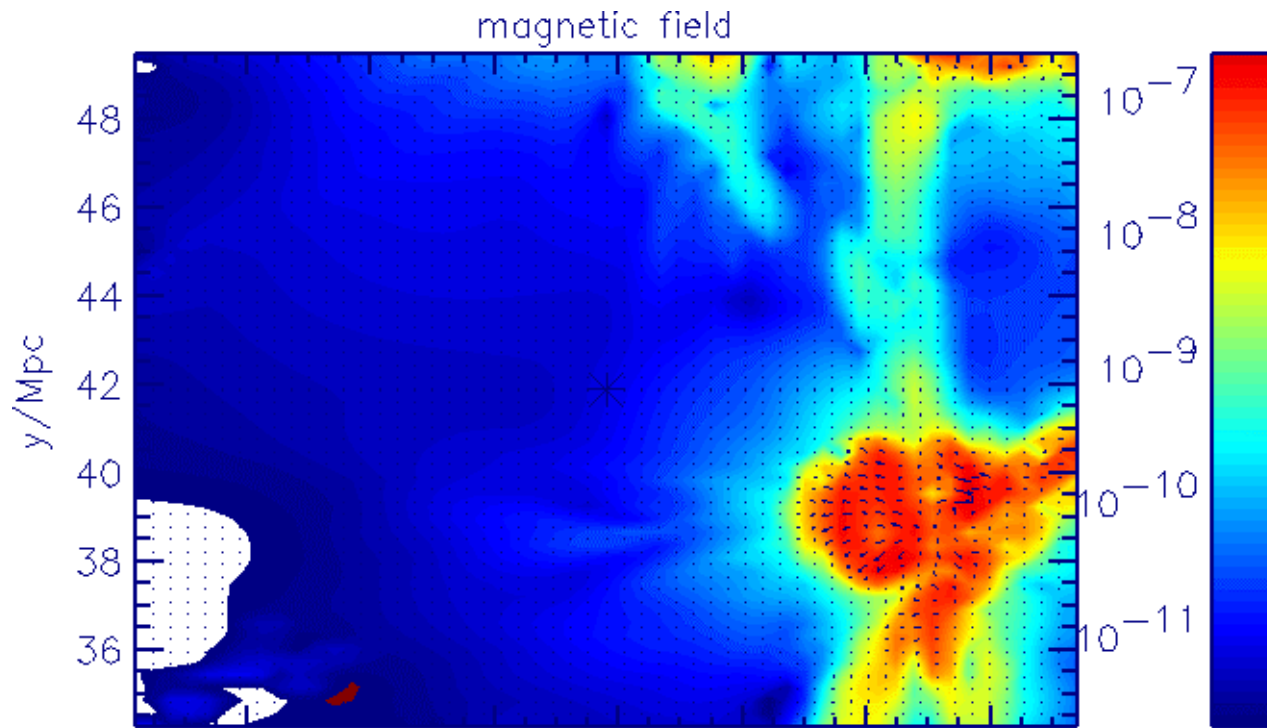
## Other consequences of simulations in strongly structured magnetic fields



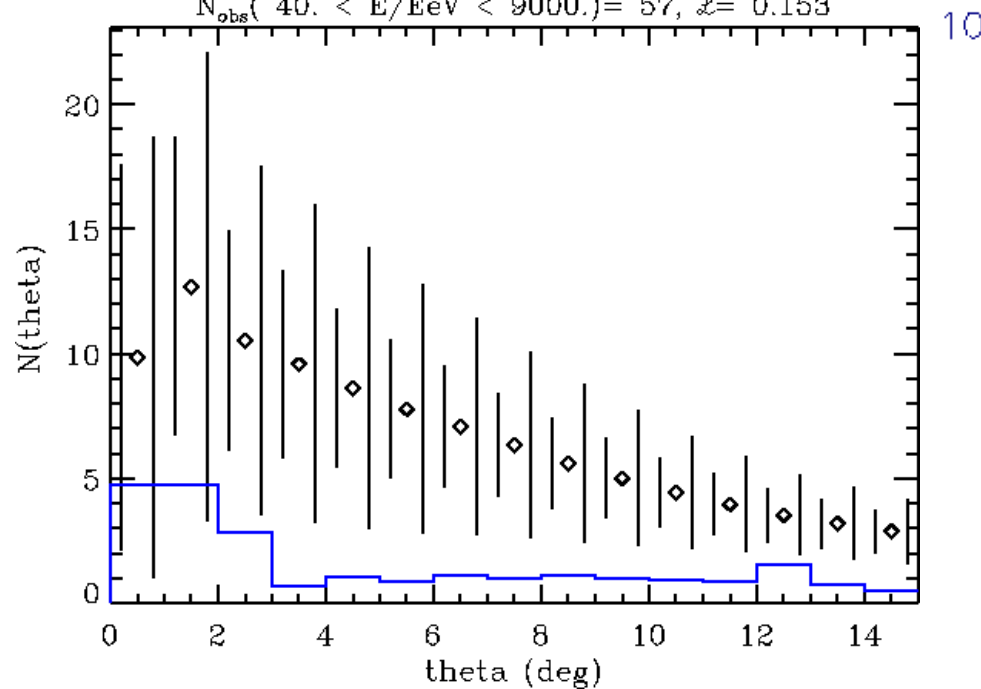
Deviations from isotropy for low multipoles should be easy to detect above  $4 \times 10^{19}$  eV with a full sky detector.



At  $10^{19}$  eV contribution from sources beyond  $\sim 50$  Mpc should dominate by factor  $\sim 3$  to be consistent with isotropy observed by AGASA.  
Numerically hard, but under study



$N_{\text{obs}}(40. < E/\text{EeV} < 9000.) = 57, \ell = 0.153$

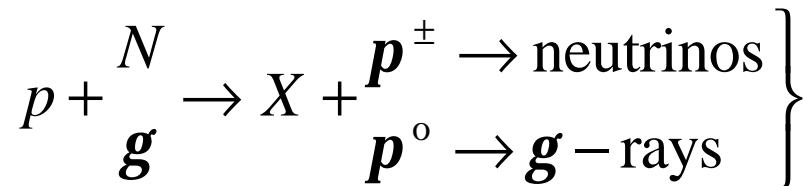


10 If, however, Earth is surrounded by fields  $\ll 10^{-7}$  Gauss, which is more likely, the autocorrelations fit much worse.

INDEPENDENTLY OF WHETHER OR NOT THERE IS A GZK-CUTOFF, THIS IS A PROBLEM FOR SOURCES FOLLOWING THE LARGE SCALE STRUCTURE.

# Ultra-High Energy Cosmic Rays and the Connection to $\gamma$ -ray and Neutrino Astrophysics

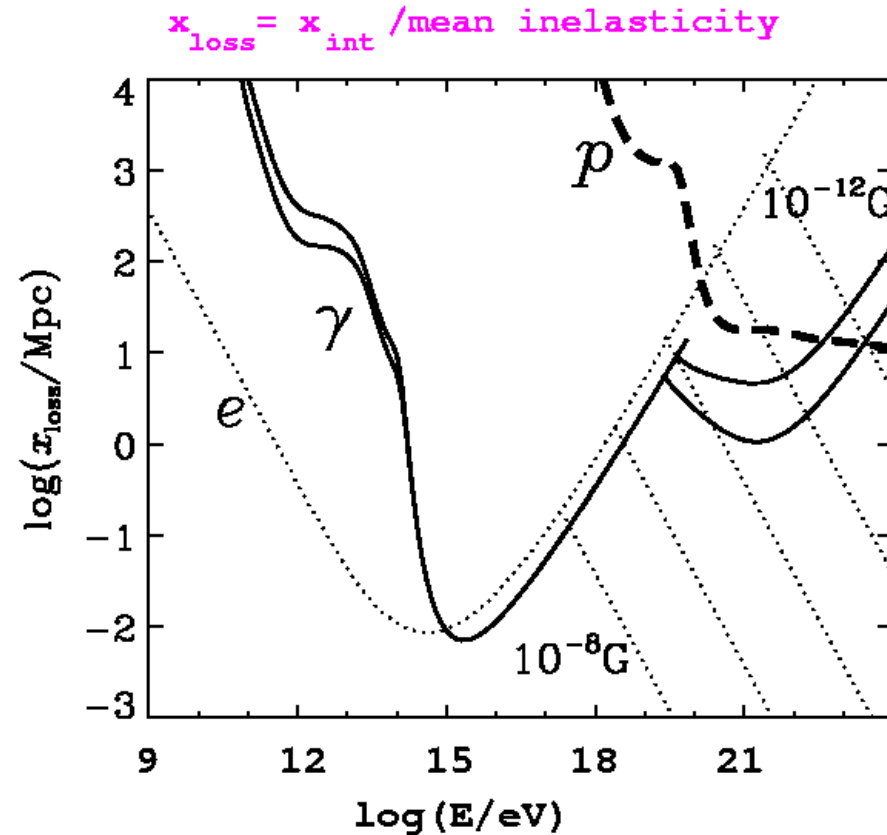
accelerated protons interact:



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

The neutrino spectrum is unmodified, whereas  $\gamma$ -rays pile up below the pair production threshold on the CMB at a few  $10^{14}$  eV.

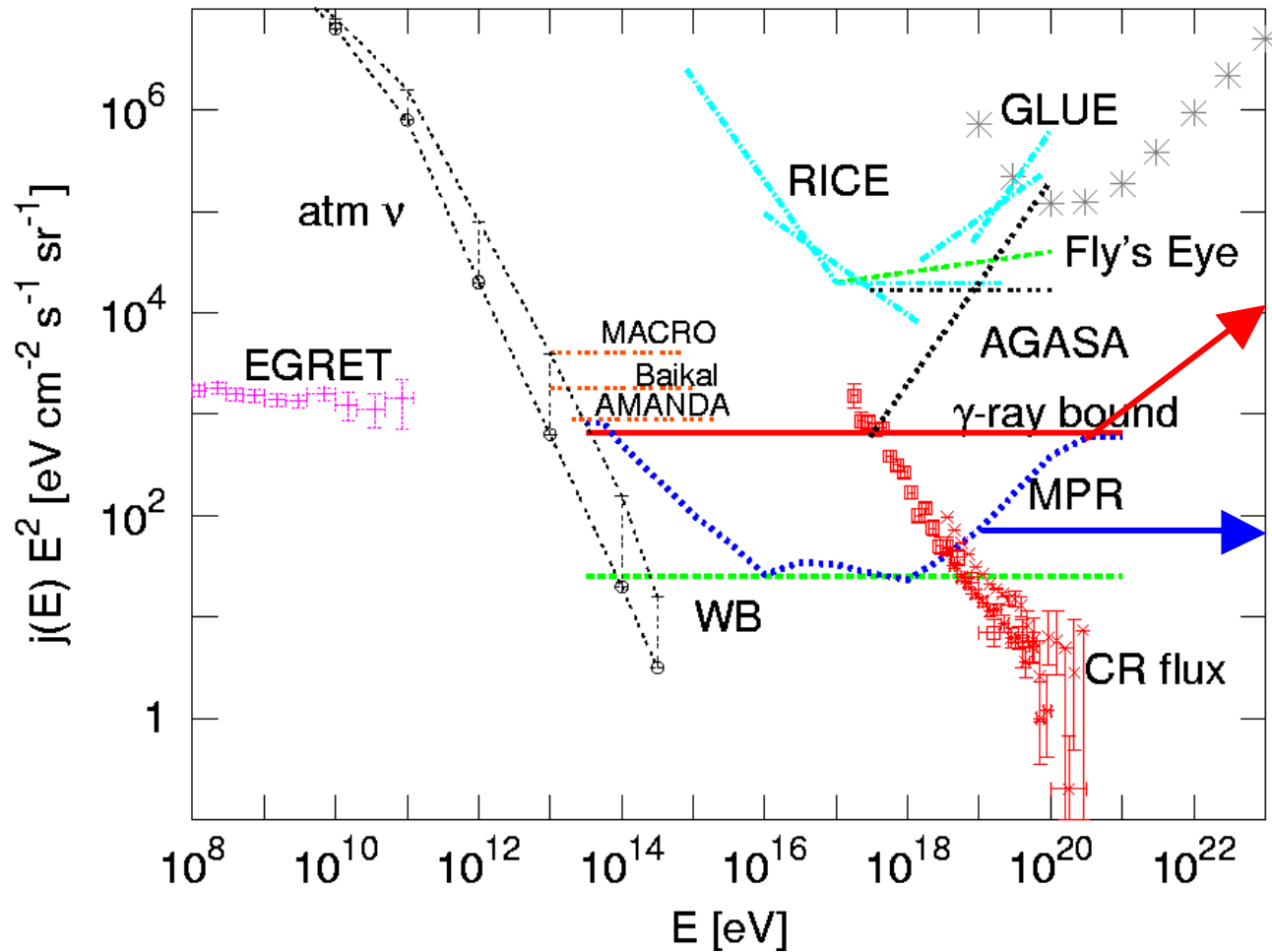
The Universe acts as a calorimeter for the total injected electromagnetic energy above the pair threshold. This constrains the neutrino fluxes.



Included processes:

- Electrons: inverse Compton; synchrotron rad (for fields from pG to 10 nG)
- Gammas: pair-production through IR, CMB, and radio backgrounds
- Protons: Bethe-Heitler pair production, pion photoproduction

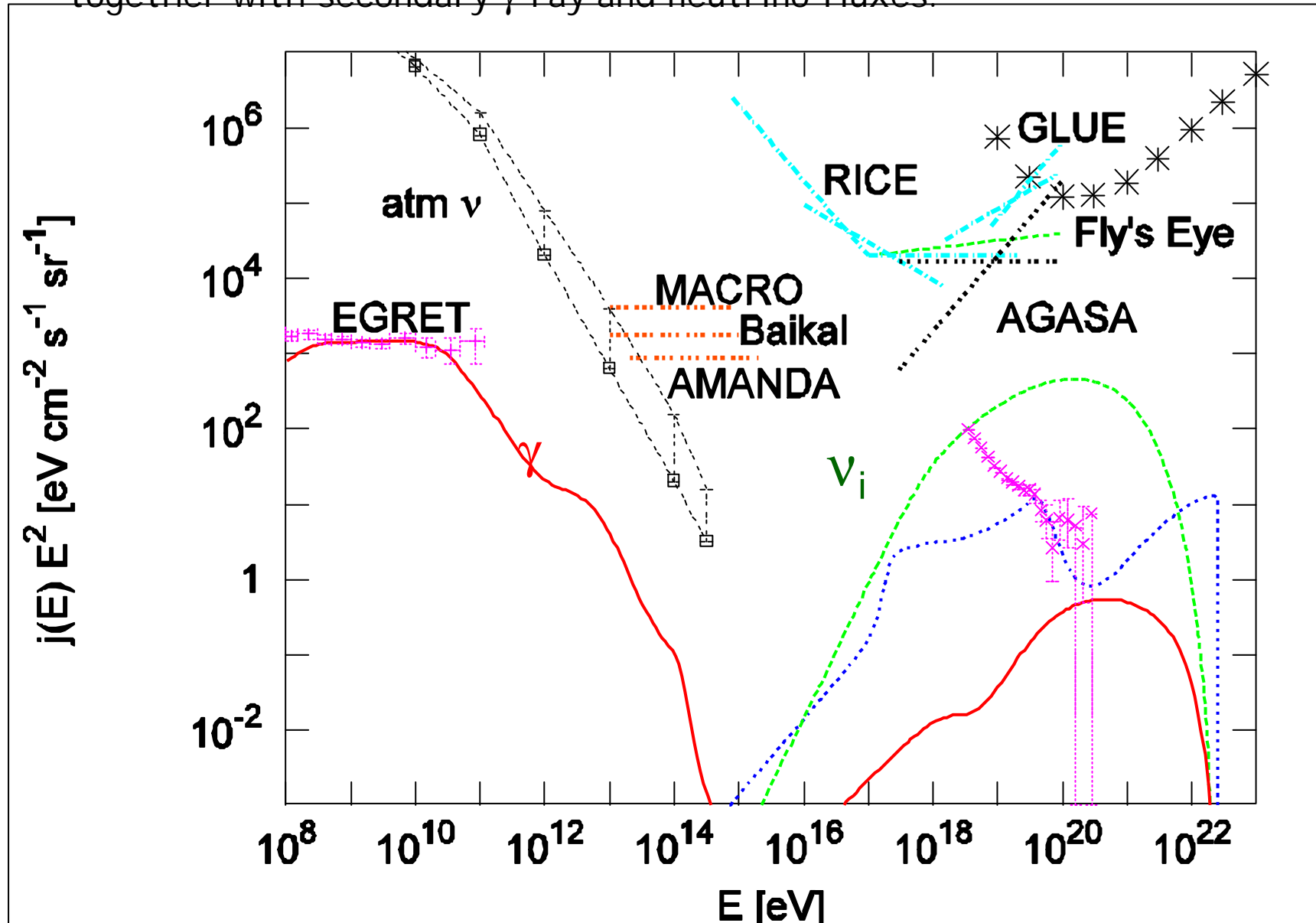
The total injected electromagnetic energy is constrained by the diffuse  $\gamma$ -ray flux measured by EGRET in the MeV - 100 GeV regime



Neutrino flux upper limit for opaque sources determined by EGRET bound

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

Example: diffuse sources injecting  $E^{-1}$  proton spectrum extending up to  $2 \times 10^{22}$  eV with  $(1+z)^3$  up to redshift  $z=2$ . Shown are primary proton flux together with secondary  $\gamma$ -ray and neutrino fluxes.



# Propagation of nucleons, photons, electrons, and neutrinos

In one dimension propagation is governed by Boltzmann equations for differential spectrum of species  $i$ ,  $n_i(E)$ :

$$\frac{\partial n_i(E)}{\partial t} = \Phi_i(E) - n_i(E) \int d\varepsilon n_b(\varepsilon) \int_{-1}^{+1} d\mu \frac{1 - \mu\beta_b\beta_i}{2} \sum_j \sigma_{i \rightarrow j} \Big|_{s=\varepsilon E(1-\mu\beta_b\beta_i)} \\ + \int dE' \int d\varepsilon n_b(\varepsilon) \int_{-1}^{+1} d\mu \sum_j \frac{1 - \mu\beta_b\beta'_j}{2} n_j(E') \frac{d\sigma_{j \rightarrow i}(s, E)}{dE} \Big|_{s=\varepsilon E'(1-\mu\beta_b\beta_j)},$$

where:

$\Phi_i(E)$  =injection spectrum,

$n_b(\varepsilon)$  =diffuse background neutrino or photon density at energy  $\varepsilon$ ,

$\mu = \cos(\text{angle between background and in-particle}),$

$\beta$  =particle velocities,

$\sigma_{i \rightarrow j}$  = cross sections for processes  $i \rightarrow j$ ,

$s$  =center of mass energy.

Background spectrum between  $\sim 10^{-8}$  eV and  $\sim 10$  eV

propagated particles between 100 MeV and  $10^{16}$  GeV (GUT scale)

transport equations (including cosmology, i.e. redshift-distance relation) solved by implicit methods.

## Processes taken into account

### Nucleons:

- (multiple) pion production:  $N\gamma_h \rightarrow N(n\pi)$  with subsequent pion decays: leads to “GZK-effect”.
- pair production by protons:  $p\gamma_h \rightarrow pe^+e^-$ : relevant below GZK threshold (similar to triplet pair production below)
- Neutron decay:  $n \rightarrow pe^-\bar{\nu}_e$

### Electromagnetic channel:

- pair production and inverse Compton scattering:  $\gamma\gamma_h \rightarrow e^+e^-$  and  $e\gamma_h \rightarrow e\gamma$ : leading order processes with

$$\sigma_{PP} \simeq 2\sigma_{ICS} \simeq \frac{3}{2}\sigma_T \frac{m_e^2}{s} \ln \frac{s}{2m_e^2} \quad (s \gg m_e^2).$$

- double pair production:  $\gamma\gamma_h \rightarrow e^+e^-e^+e^-$ : dominates at highest energies with

$$\sigma_{DPP} \simeq \frac{43\alpha^2}{24\pi^2}\sigma_T \quad (s \gg m_e^2).$$

- triplet pair production:  $e\gamma_h \rightarrow ee^+e^-$ : dominant at highest energies with

$$\sigma_{TPP} \simeq \frac{3\alpha}{8\pi}\sigma_T \left( \frac{28}{9} \ln \frac{s}{m_e^2} - \frac{218}{27} \right) \quad (s \gg m_e^2),$$

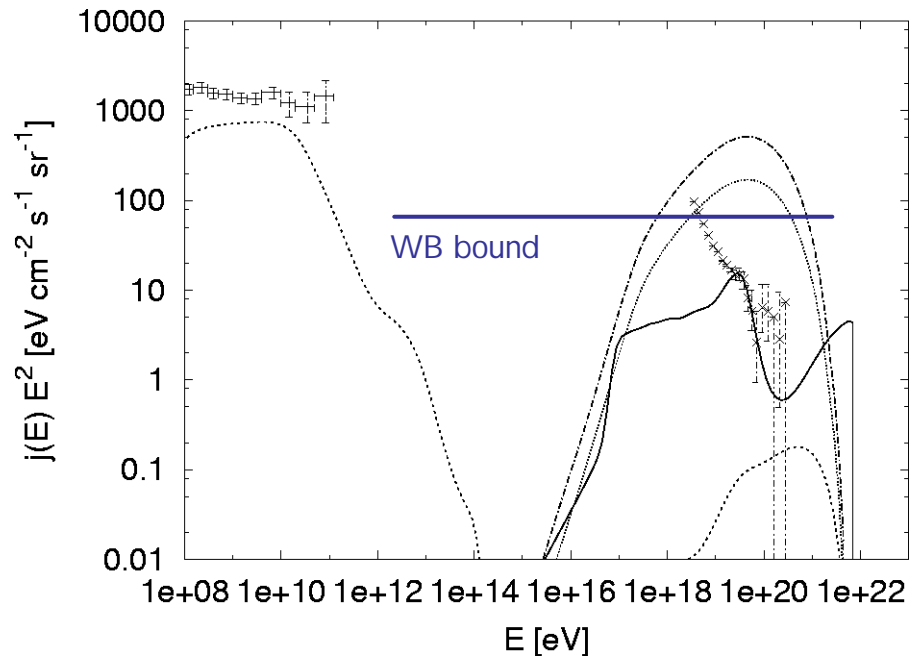
with fractional energy loss  $\eta$  of leading  $e$

$$\eta \simeq 1.768 \left( \frac{s}{m_e^2} \right)^{-3/4} \quad (s \gg m_e^2).$$

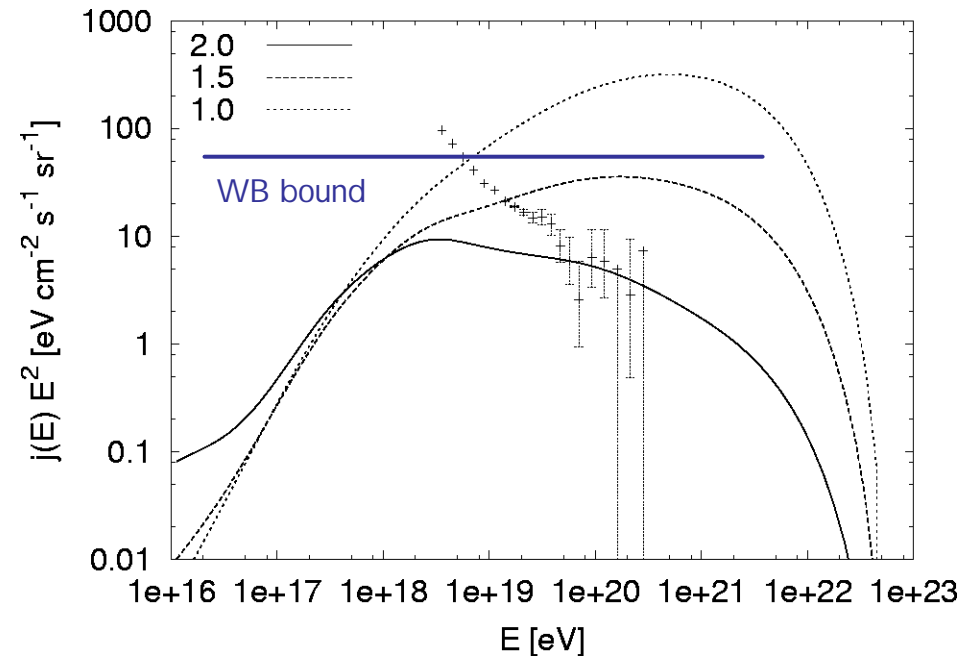
- synchrotron loss of electrons and positrons in cosmic magnetic fields:  $eB \rightarrow e\gamma$ .  
Energy loss given by

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T \frac{B^2}{8\pi} \left( \frac{Zm_e}{m} \right)^4 \left( \frac{E}{m_e} \right)^2.$$

The cosmogenic neutrino flux produced by pion production by cosmic rays during propagation can violate the Waxman-Bahcall bound for injection spectra harder than  $\sim E^{-1.5}$  and source luminosities increasing with redshift



$\gamma$ -ray and cosmic ray fluxes must be consistent with observations.



Example: dependence on injection spectral index

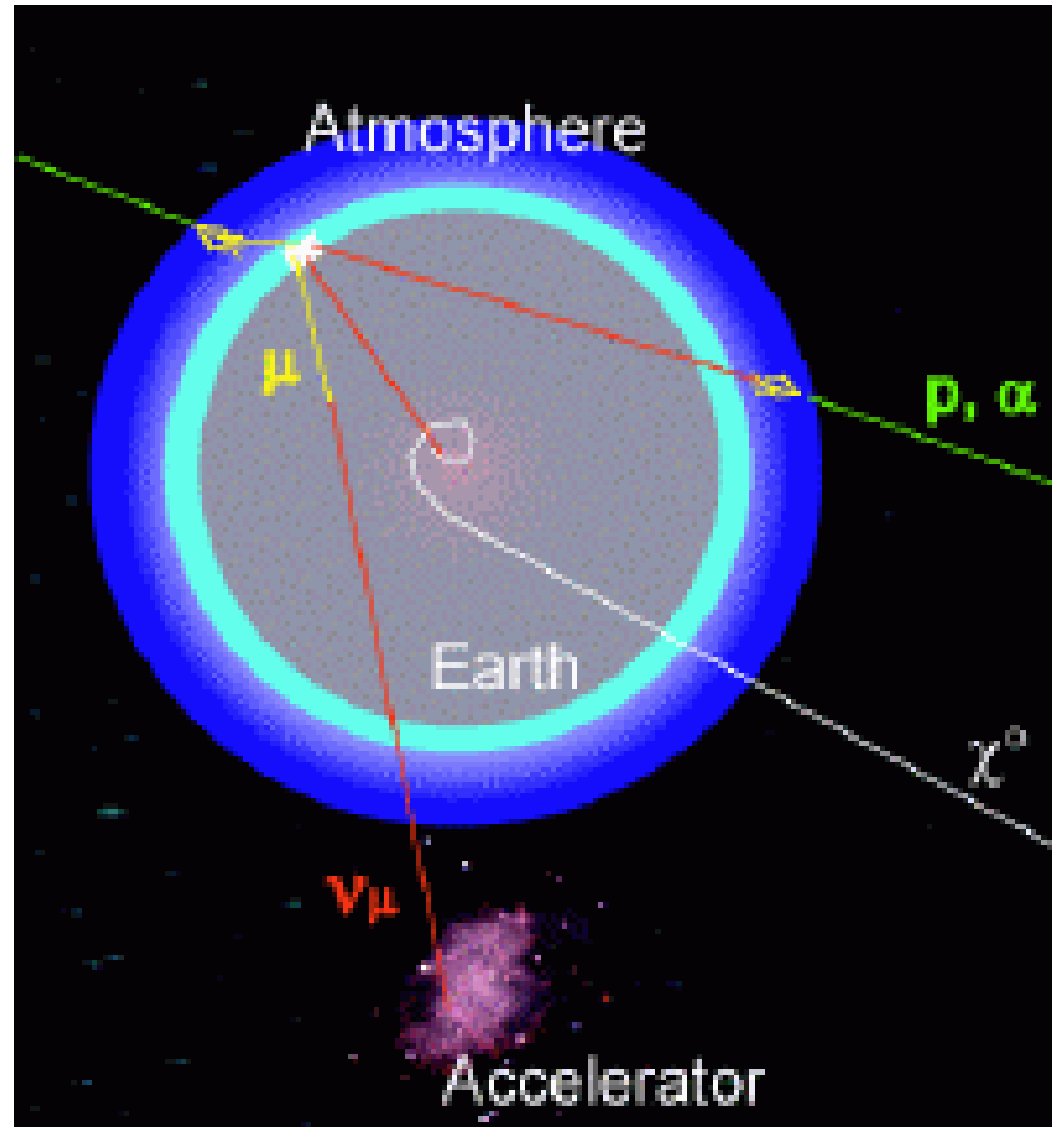
## Ultra-High Energy Neutrino Detection: Traditional and New Ideas

Mostly uses the charged-current reactions:  $\nu_i + N \rightarrow l_i + N$ ,  $i = e, \mu, \tau$

- 1.) detect Cherenkov radiation from muons in deep sea or ice  
**AMANDA, ANTARES, BAIKAL, NESTOR**  
aims at 1 km<sup>3</sup> for  $E > 100$  GeV to 1 TeV
- 2.) horizontal air showers for electron and  $\tau$ -neutrinos  
**PIERRE AUGER, MOUNT**  
for  $E > 10^{18}$  eV, increased efficiency for  $\tau$ -neutrinos if surrounded by mountains on 100 km scale which is decay length of produced taus.
- 3.) detection of inclined showers from space for  $E > 10^{20}$  eV  
**EUSO, OWL**
- 4.) detection of radio emission from negative charge excess of showers produced in air, water, ice, or in skimming rock.  
**RICE (in South-pole ice), GLUE (radio-telescope observing the moons rim), ANITA, ...**
- 5.) acoustic detection in water: hydrophonic arrays
- 6.) Earth-skimming events in ground arrays or fluorescence detectors.

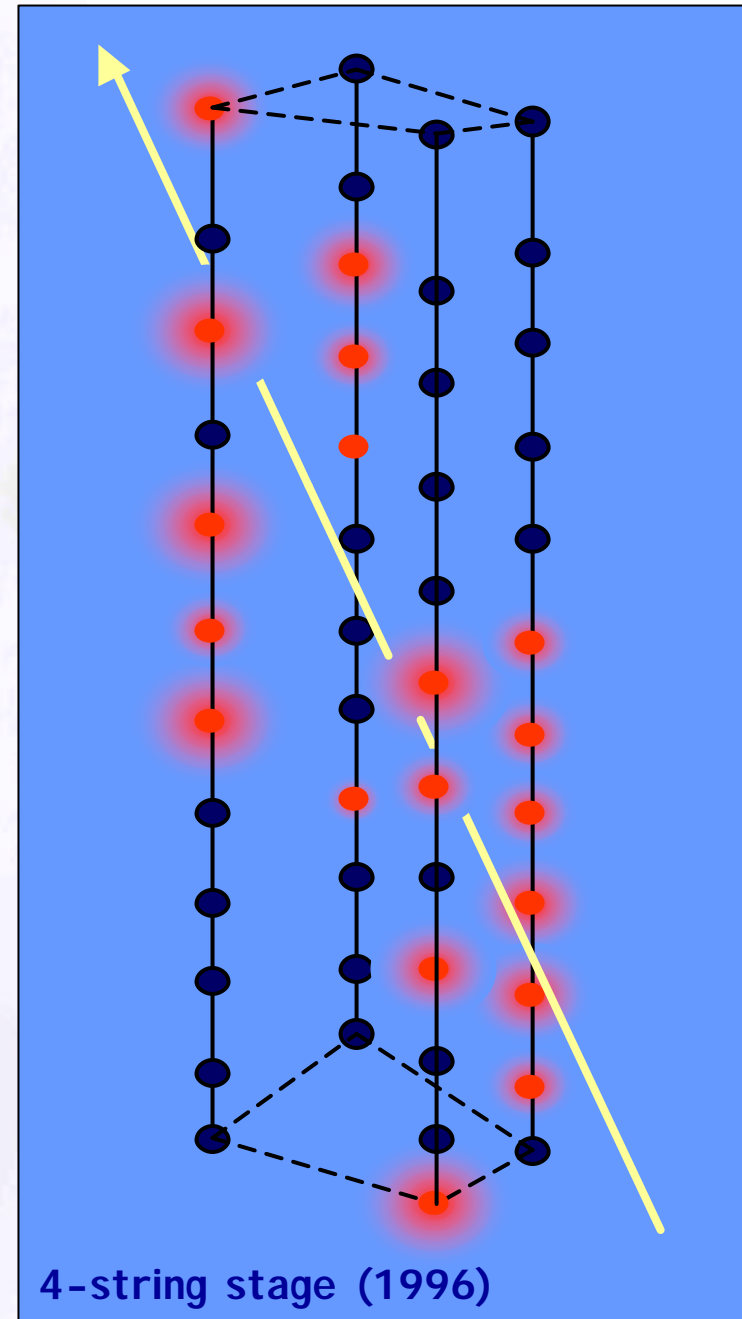
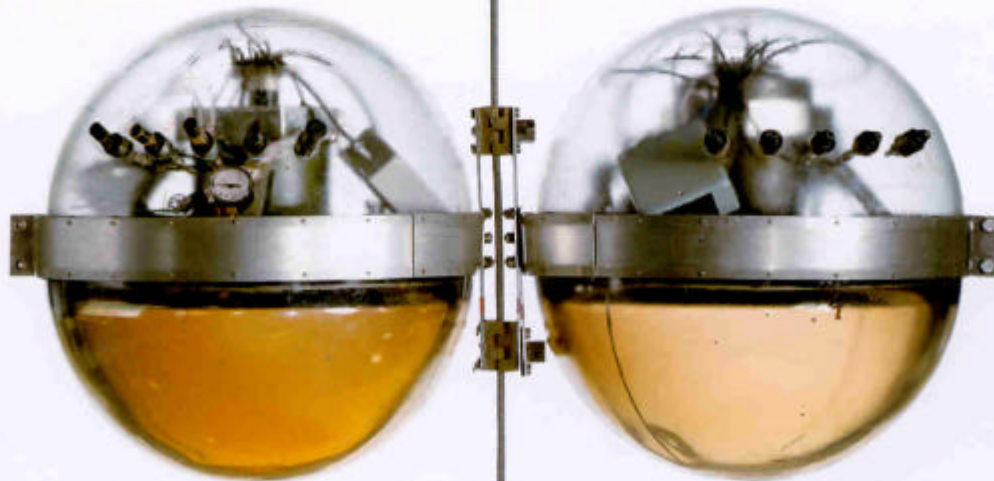
## Experimental Detection of $E < 10^{17}$ eV Neutrinos

- Neutrinos coming from above are secondary from cosmic rays
- Neutrino coming from below are mixture of atmospheric neutrinos and HE neutrinos from space
- Earth is not transparent for neutrinos  $E > 10^{15}$  eV
- Former/current experiments: **MACRO, Baikal, AMANDA**
- Future experiments: **ANTARES, ICECUBE, NEMO, NESTOR...**

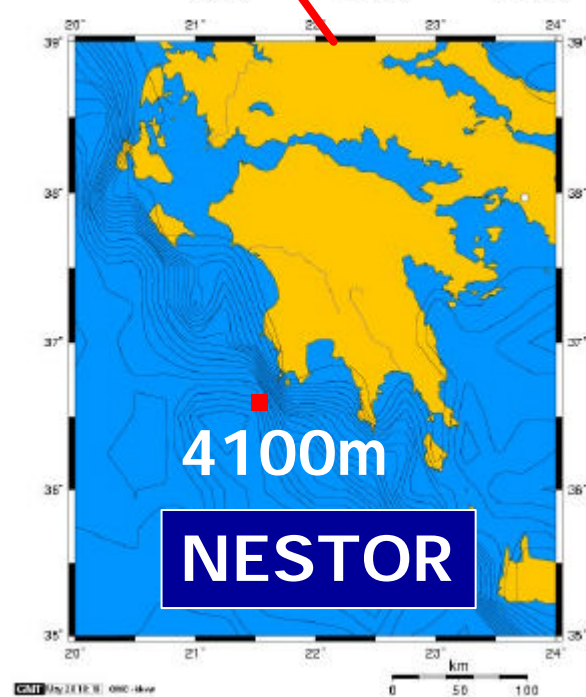
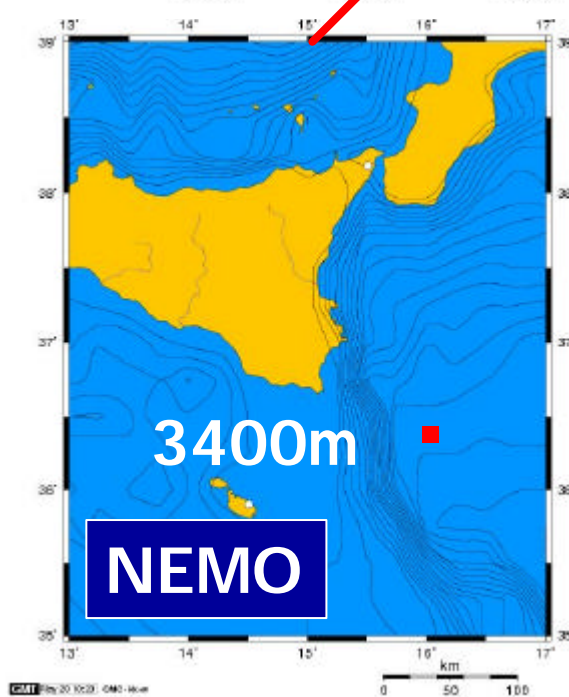
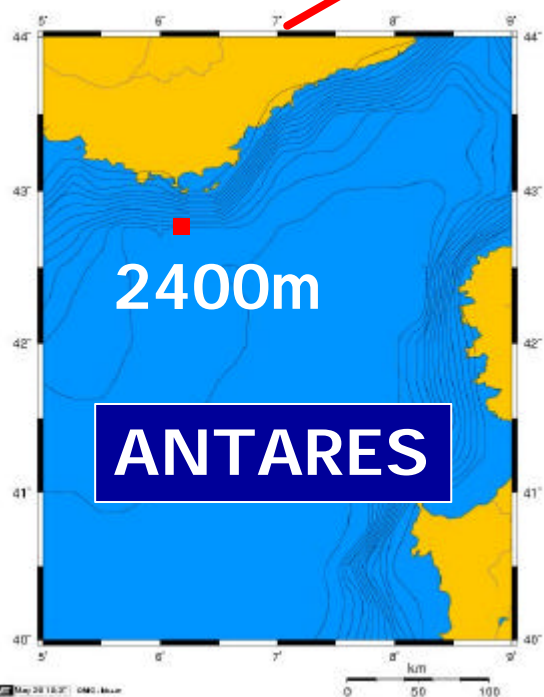
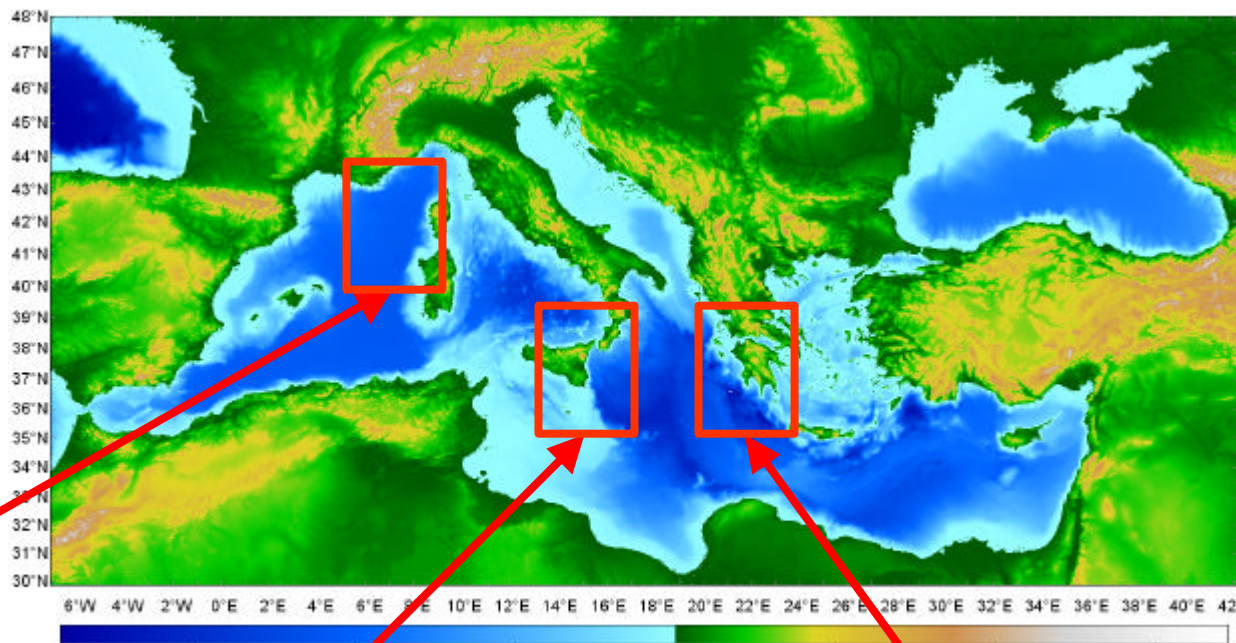


# Lake Baikal

First underwater telescope  
First neutrinos underwater



# Mediterranean Projects



## NESTOR

	<b>1991 - 2000</b>	<b>R &amp; D, Site Evaluation</b>
Summer	2002	Deployment 2 floors
Winter	2003	Recovery & re-deployment with 4 floors
<b>Autumn</b>	<b>2003</b>	<b>Full Tower deployment</b>
	2004	Add 3 DUMAND strings around tower
	2005 - ?	Deployment of 7 NESTOR towers

## ANTARES

	<b>1996 - 2000</b>	<b>R&amp;D, Site Evaluation</b>
	2000	Demonstrator line
	2001	Start Construction
September	2002	Deploy prototype line
December	2004	10 (14?) line detector complete
	2005 - ?	Construction of km <sup>3</sup> Detector

## NEMO

	<b>1999 - 2001</b>	<b>Site selection and R&amp;D</b>
	2002 - 2004	Prototyping at Catania Test Site
	2005 - ?	Construction of km <sup>3</sup> Detector

# IceCube

- 80 Strings
- 4800 PMT
- Instrumented volume:  $1 \text{ km}^3$
- Installation: 2004-2010

$\sim 80.000 \text{ atm. v per year}$

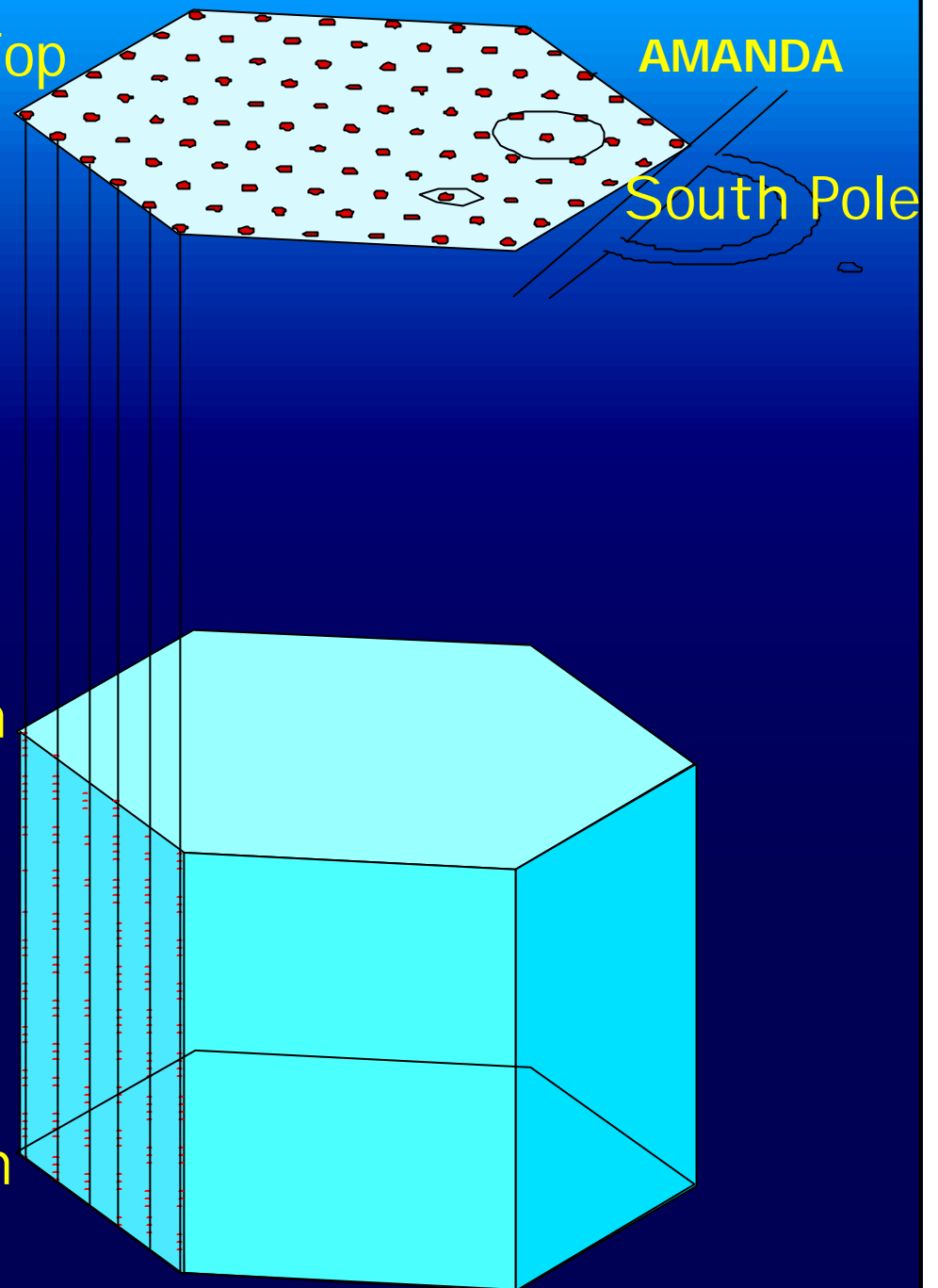
1400 m

2400 m

IceTop

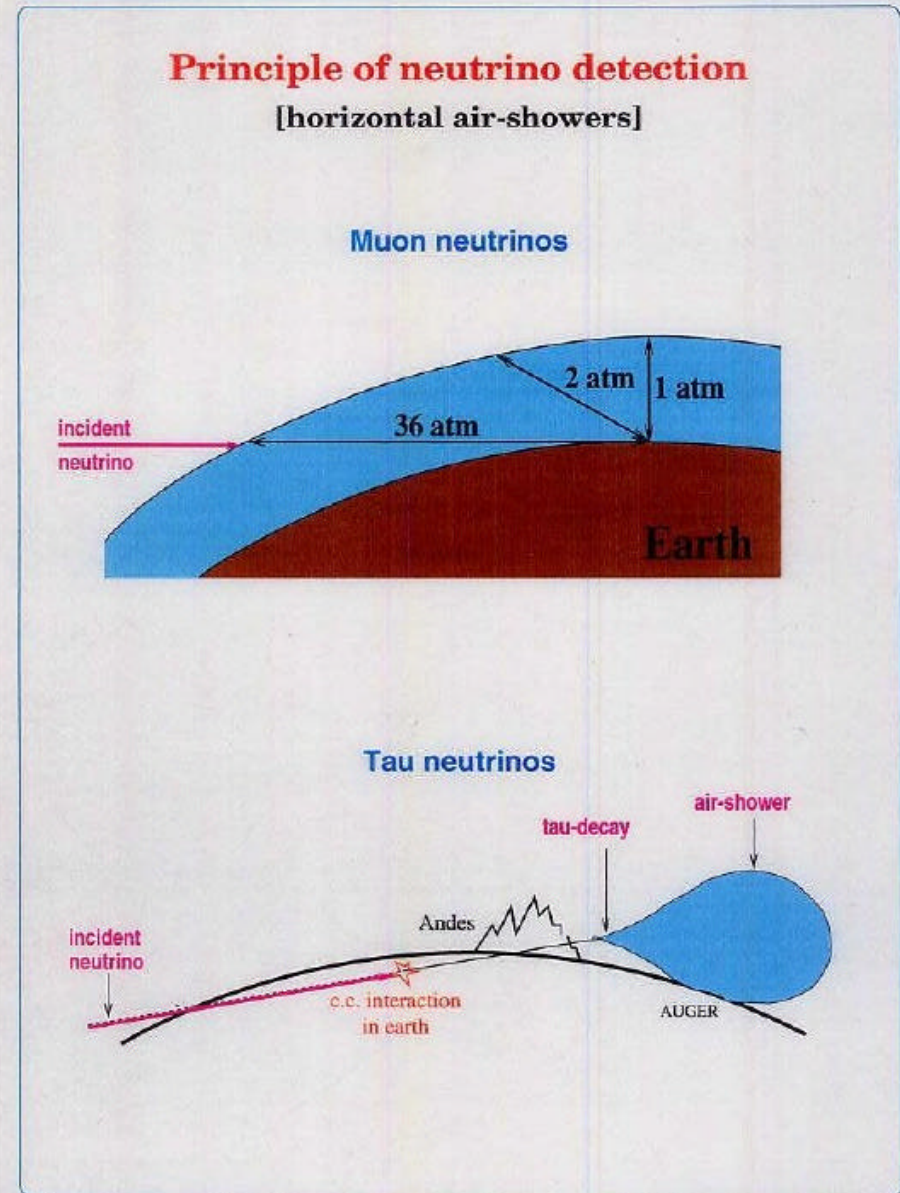
AMANDA

South Pole

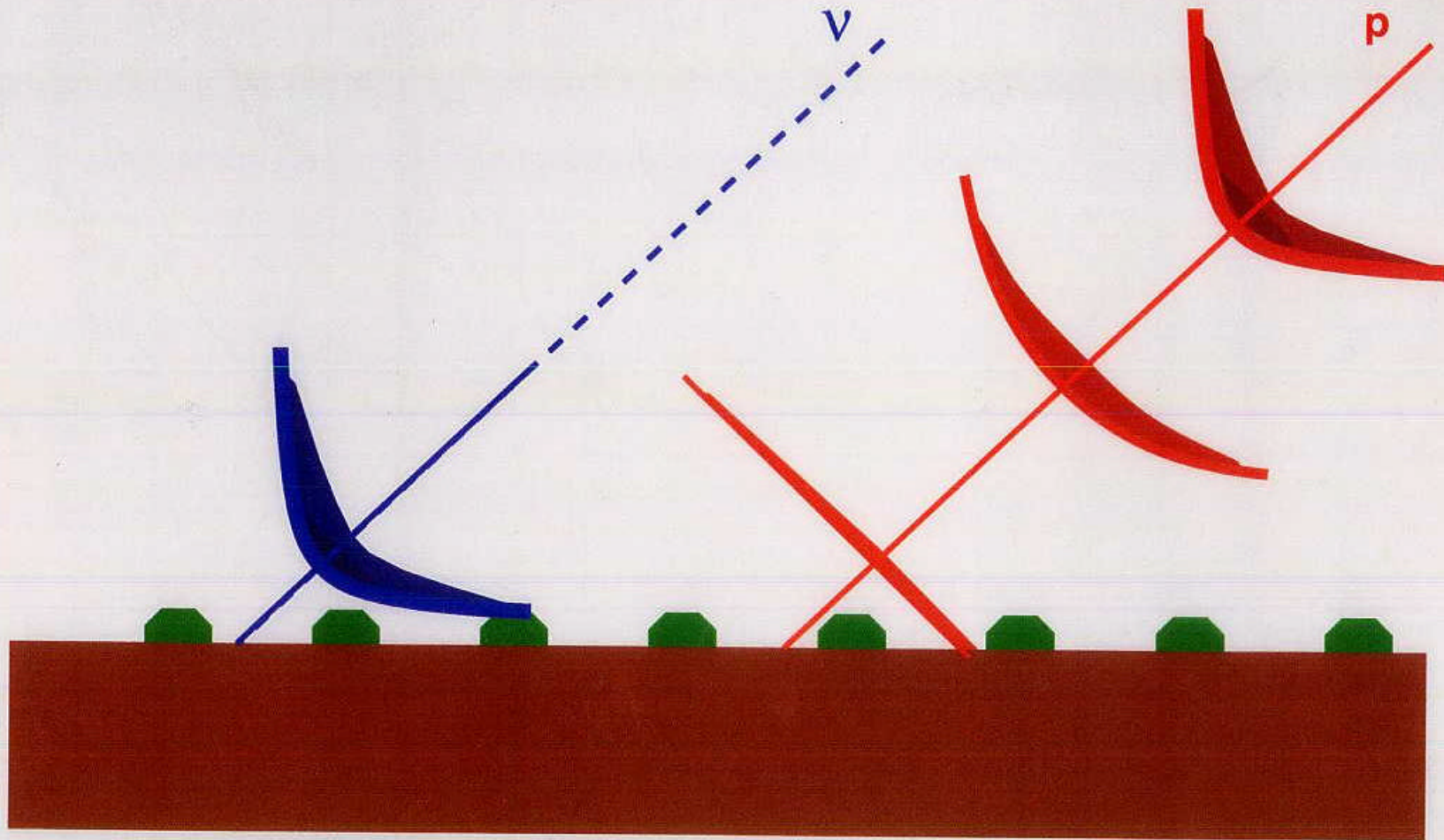


# Air Shower Detection of UHE ( $E > 10^{17}$ eV) Neutrinos

- Neutrinos are not primary UHECR
- Horizontal or Earth-skimming air showers – easy way to detect neutrinos
- Former/current experiments:  
**Fly's Eye, AGASA**
- Future experiments:  
**Pierre Auger, OWL/EUSO...**



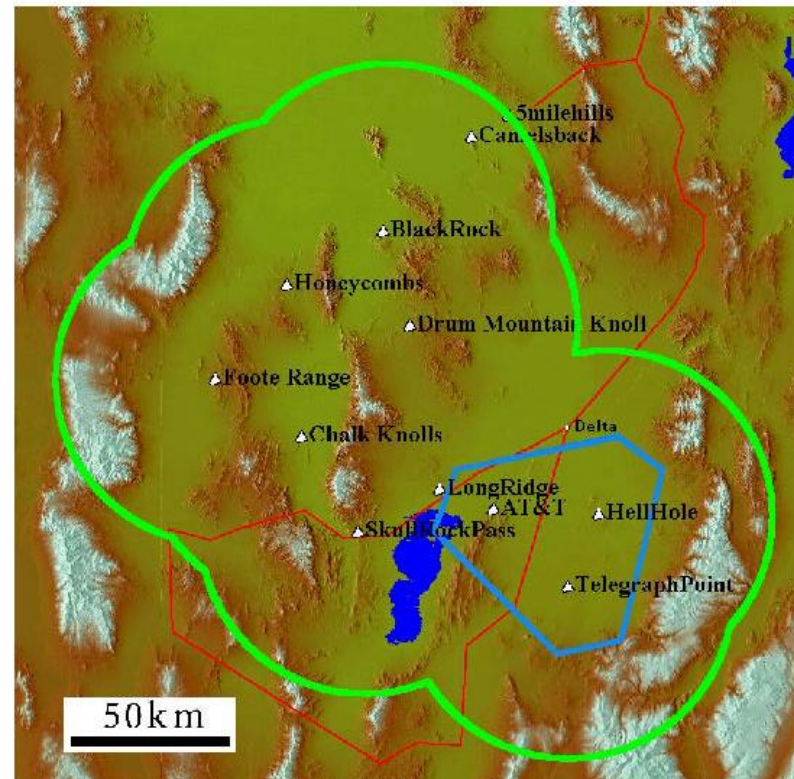
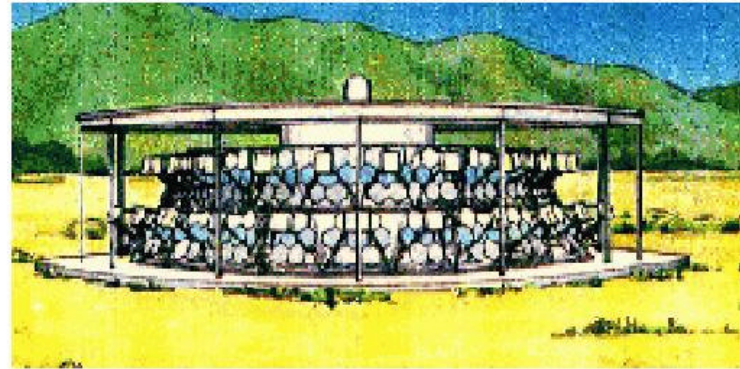
# Neutrino penetration depth



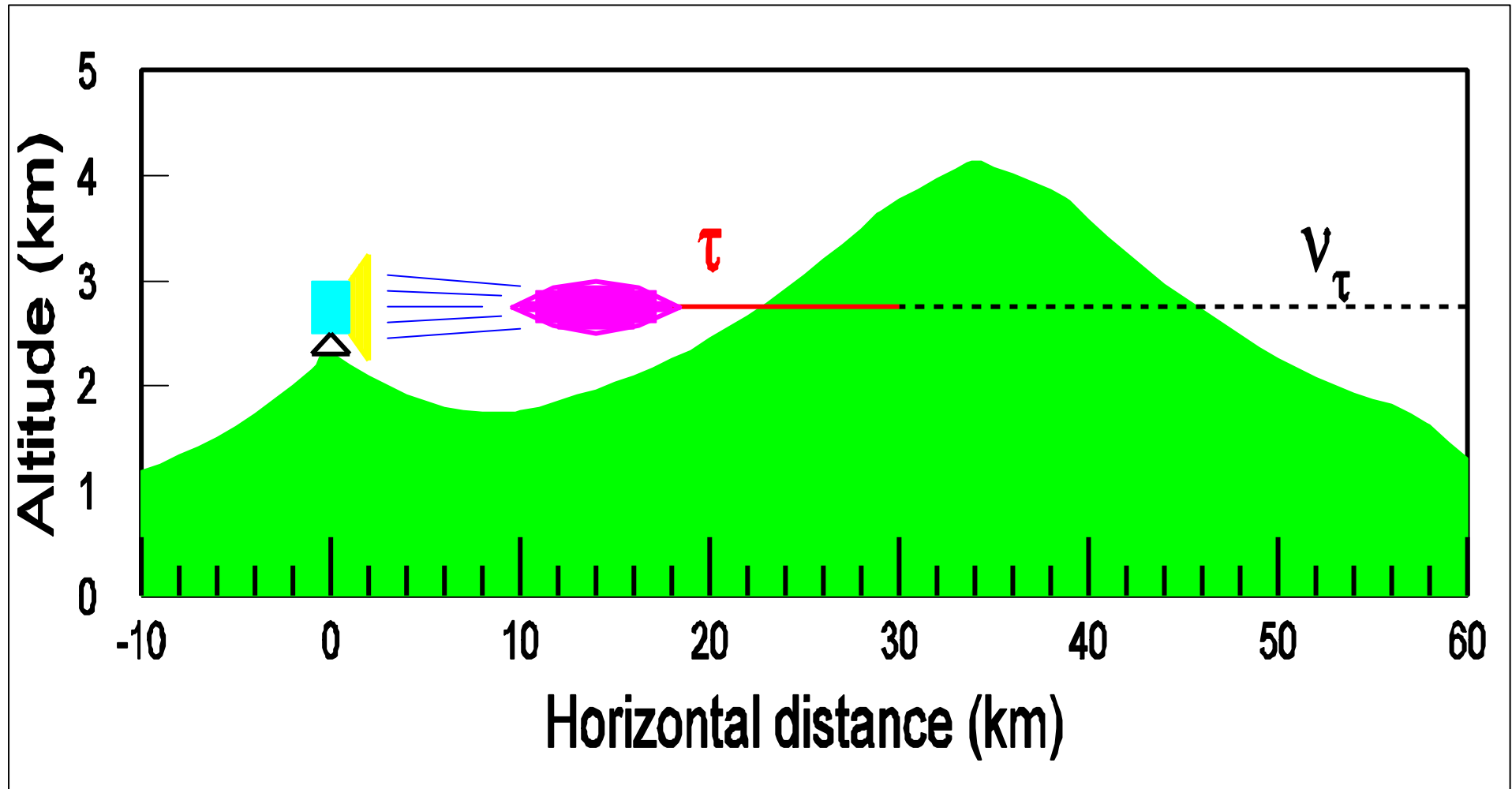
Curved shower => neutrino  
Flat shower => hadron

# Telescope Array

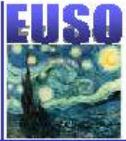
## Telescope Array Project



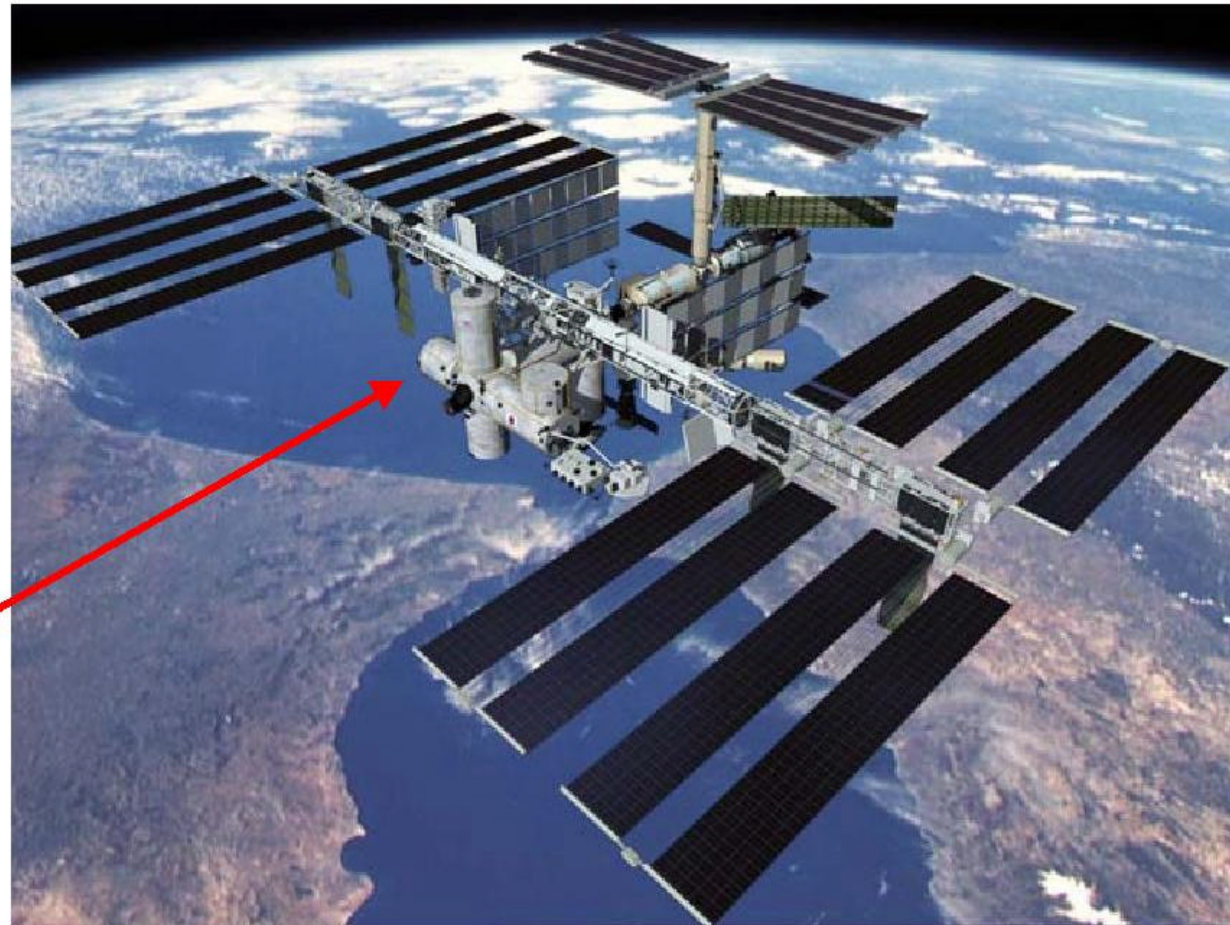
# MOUNT



# OWL/EUSO

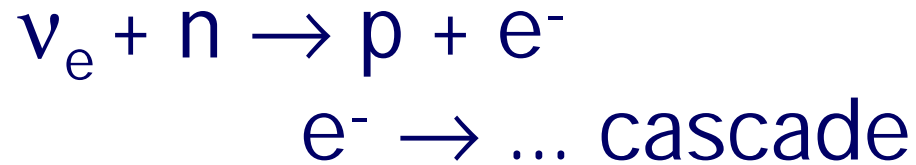


## ISS - The International Space Station



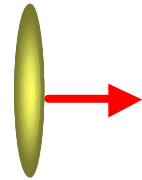
ESA  
Columbus  
Module

# Radio Detection of Neutrinos



negative charge is swept into developing shower, which acquires a negative net charge  $Q_{\text{net}} \sim 0.25 E_{\text{cascade}} \text{ (GeV)}$ .

⇒ relativist. pancake  
~ 1cm thick,  $\varnothing \sim 10\text{cm}$

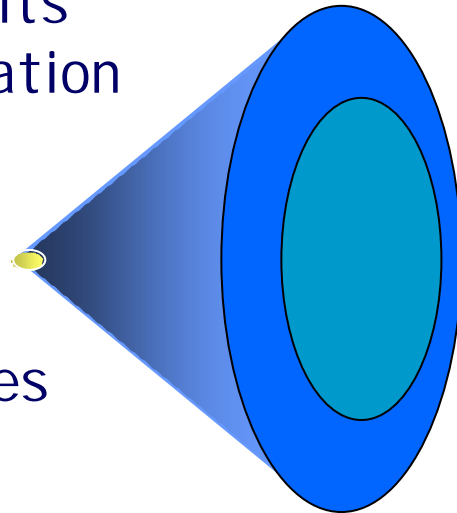


⇒ for  $\lambda \gg 10 \text{ cm}$  (radio)

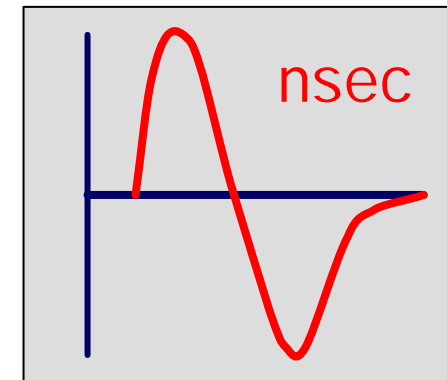
coherence

⇒ each particle emits Cherenkov radiation

⇒ C signal is resultant of overlapping Cherenkov cones



⇒ C-signal  $\sim E^2$



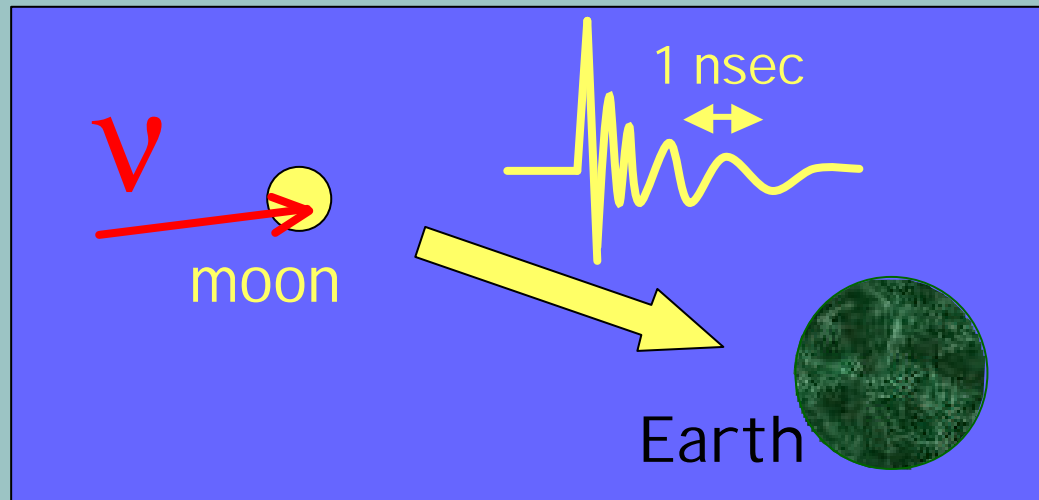
**Threshold  $> 10^{16} \text{ eV}$**



# GLUE Goldstone Lunar Ultra-high Energy Neutrino Experiment

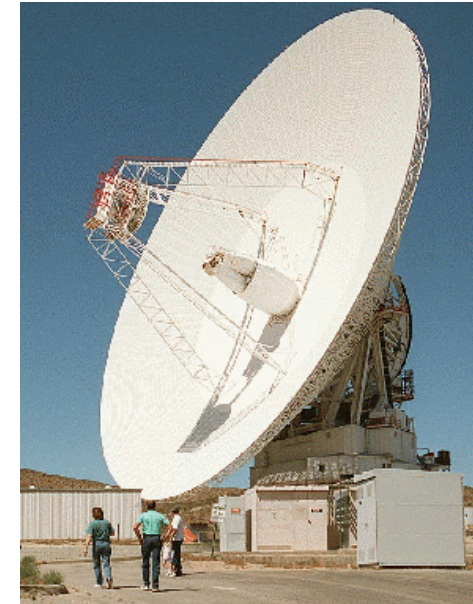
## Lunar Radio Emissions from Interactions of $n$ and CR with $> 10^{19}$ eV

Gorham et al. (1999), 30 hr NASA Goldstone 70 m antenna + DSS 34 m antenna



$$\rightarrow E^2 \cdot dN/dE < 10^5 \text{ eV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$$

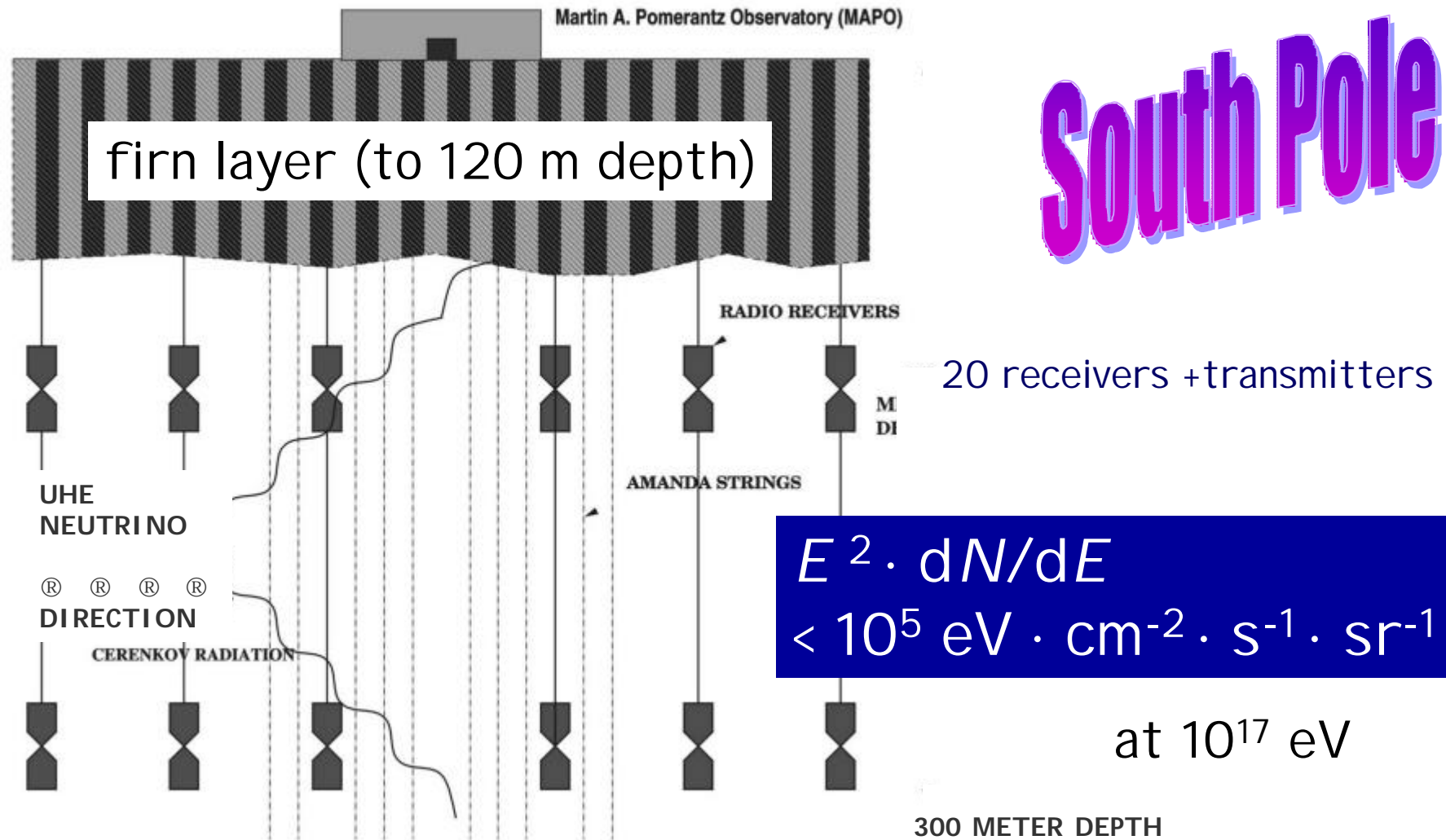
at  $10^{20}$  eV



*Effective target volume*  
~ antenna beam ( $0.3^\circ$ )  
 $\times 10$  m layer

$$\rightarrow 10^5 \text{ km}^3$$

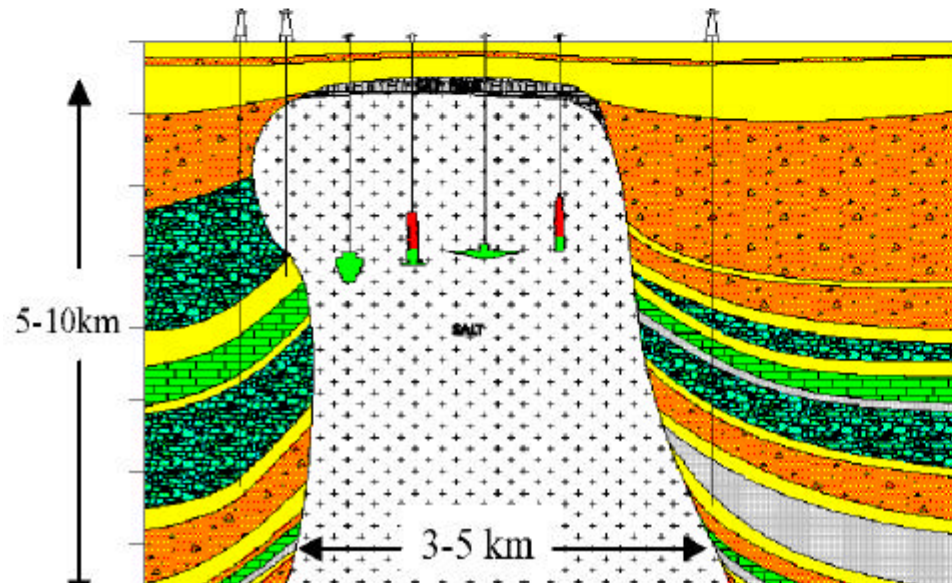
# RICE Radio Ice Cherenkov Experiment





# Natural Salt Domes: Potential PeV-EeV Neutrino Detectors

- Natural salt can be extremely low RF loss:  
~ as clear as very cold ice, 2.4 times as dense
- Typical salt dome halite is comparable to ice at -40C for RF clarity



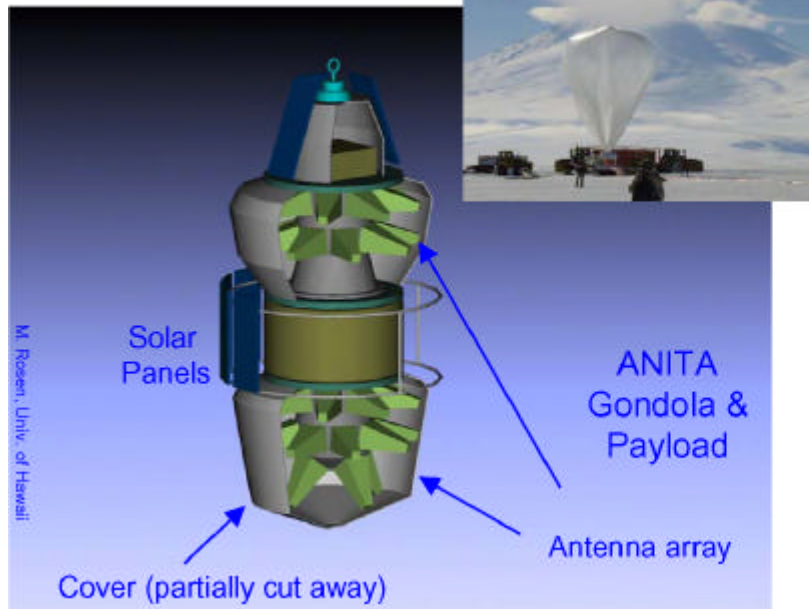
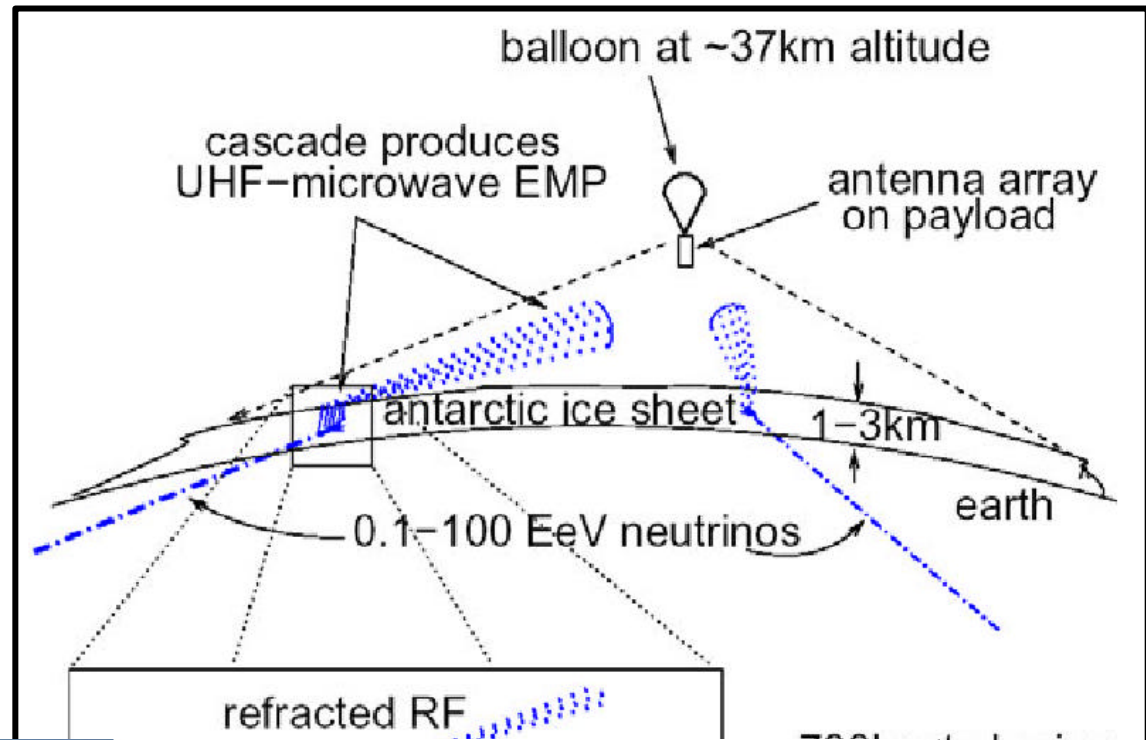
# SaISA

## Salt Dome

## Shower

## Array

# ANITA Antarctic Impulsive Transient Array

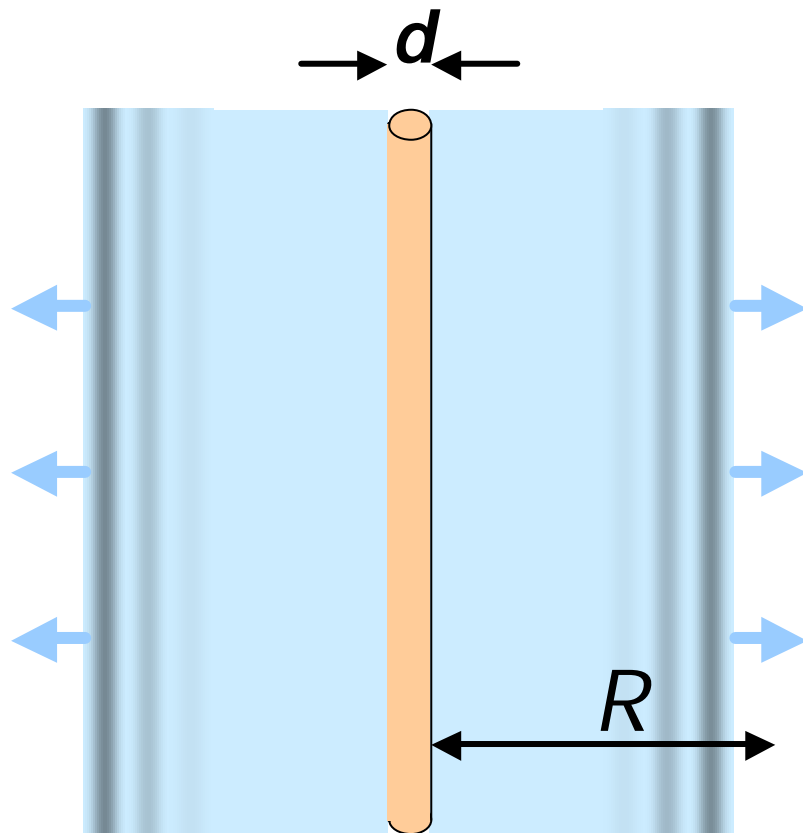
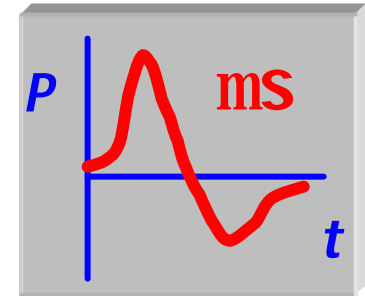


## Acoustic detection of Neutrinos

Particle cascade  $\rightarrow$  ionization

$\rightarrow$  heat

$\rightarrow$  pressure wave



Maximum of emission at  $\sim 20$  kHz

Attenuation length of sea water at 15-30 kHz: **a few km**  
(light: a few tens of meters)

? given a large initial signal,  
huge detection volumes  
can be achieved.

**Threshold  $> 10^{16}$  eV**

# Renewed efforts along acoustic method for GZK neutrino detection

## **Greece: SADCO**

Mediterranean, NESTOR site, 3 strings with hydrophones

## **Russia: AGAM antennas near Kamchatka:**

existing sonar array for submarine detection

## **Russia: MG-10M antennas:**

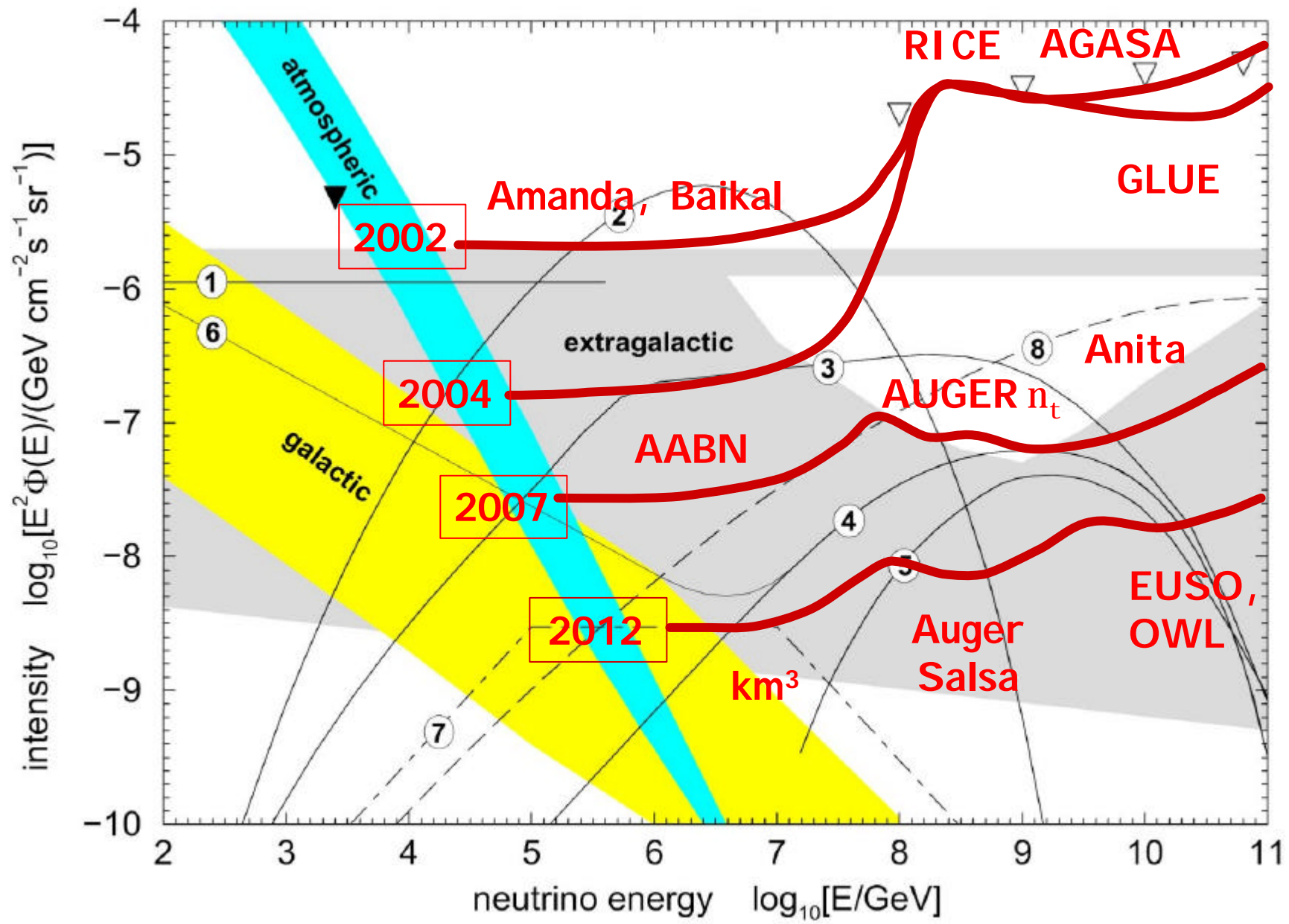
withdrawn sonar array for submarine detection

## **AUTEC: US Navy array in Atlantic:**

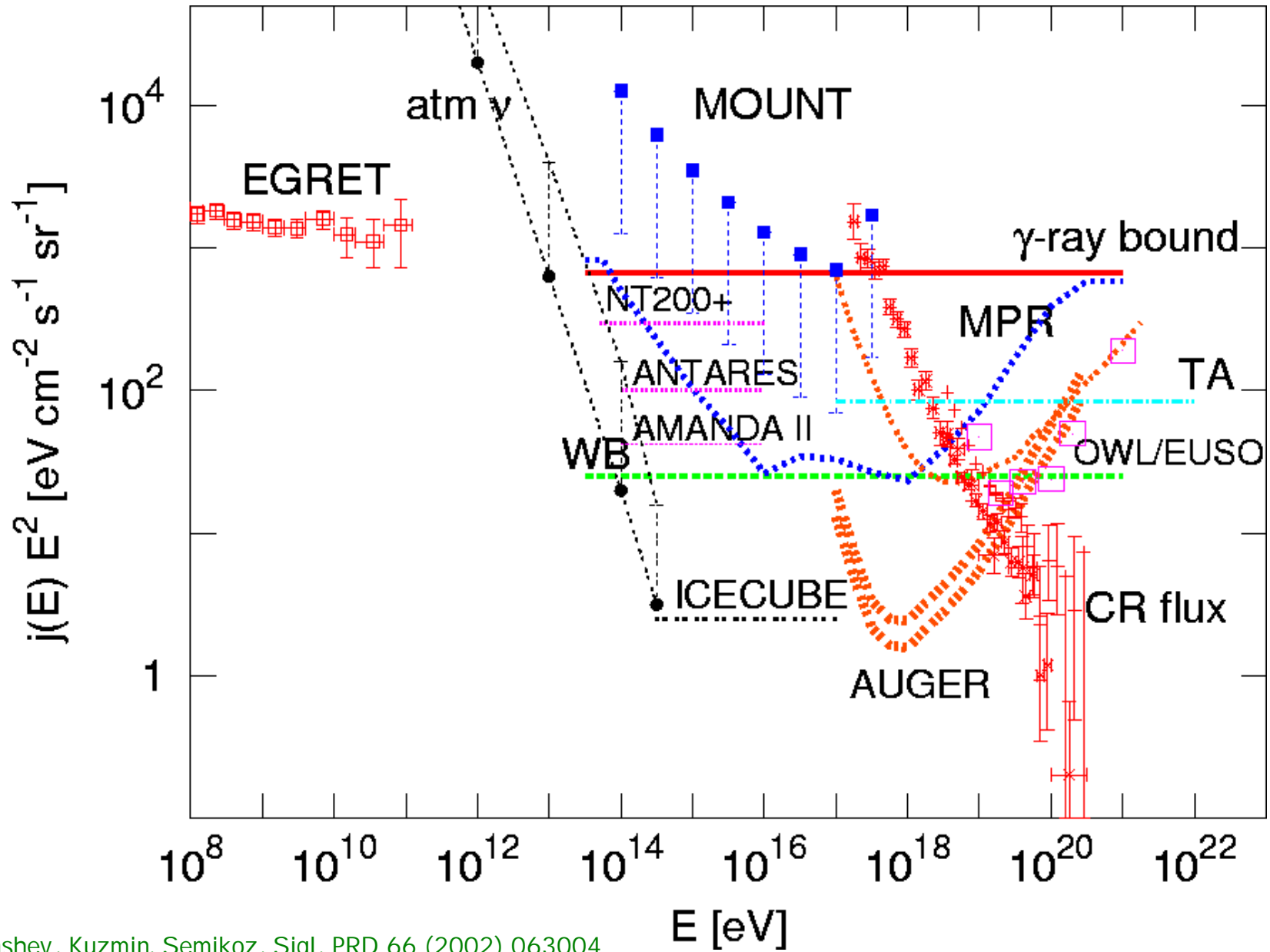
existing sonar array for submarine detection

**Antares:** R&D for acoustic detection

**IceCube:** R&D for acoustic detection



### Future neutrino flux sensitivities



## Alternative: Top-Down Scenario

Decay of early Universe relics of masses  $\approx 10^{12}$  GeV

Benchmark estimate of required decay rate:

$$\underbrace{j(E)}_{\text{measured flux}} \cong \frac{1}{4\mathbf{p}} \underbrace{l(E)}_{\text{mean free path}} \underbrace{\dot{n}_X}_{\text{decay rate}} \underbrace{\frac{dN}{dE}}_{\text{decay spectrum}} ; \text{ now assume } \frac{dN}{dE} \cong \frac{1}{m_X} \left( \frac{E}{m_X} \right)^{-a}$$

$$\Rightarrow \dot{n}_X \cong 13 \text{AU}^{-3} \text{yr}^{-1} \left( \frac{E^2 j(E)}{\text{eVcm}^{-2} \text{s}^{-1} \text{sr}^{-1}} \right) \left[ \frac{10 \text{Mpc}}{l(E)} \right] \left( \frac{E}{10^{16} \text{GeV}} \right)^{a-1.5} \left( \frac{m_X}{10^{16} \text{GeV}} \right)^{1-a}$$

with  $m_X$  the  $X$  - particle mass.

This is not a big number!

## Two types of Top-Down scenarios

1.) long-lived massive free particles (“WIMPZILLA” dark matter)

$$\Omega_X \approx 10^{-12} \left( t_X / 10^{10} \text{ yr} \right)$$

- Fine tuning problem of normalizing  $\Omega_X/t_X$  to observed flux.
- predicted  $\gamma$ -ray domination probably inconsistent with data.

2.) particles released from topological defects

$$\text{scaling} \Rightarrow \mathbf{r}_{\text{defect}} \propto \mathbf{r}_{\text{critical}} \propto t^{-2}$$

- Fine tuning problem of normalizing  $\dot{\mathbf{r}}_X \equiv f \dot{\mathbf{r}}_{\text{defect}} \propto t^{-3}$  to observed flux.

But for cosmic strings (or necklaces) the Higgs-Kibble mechanism yields

$$\mathbf{r}_{\text{string}} \approx v^2 t^{-2}, \text{ with } v = \text{symmetry breaking scale}$$

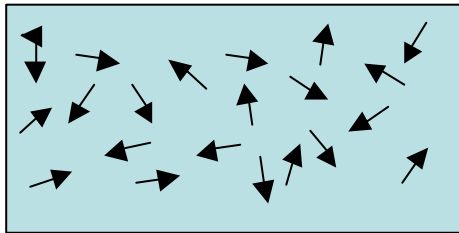
$$\text{normalization} \Rightarrow \sqrt{f} v \approx 10^{13} - 10^{14} \text{ GeV}$$

- Fine tuning problem only by few orders of magnitude if  $f \approx \mathcal{O}(1)$
- Absorption in radio background can lead to nucleon domination.

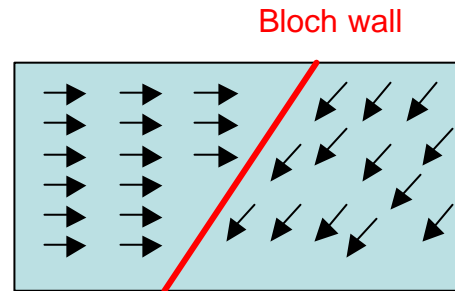
Topological defects are unavoidable products of phase transitions associated with symmetry change

Examples:

1.) Iron:



$T > T_{\text{Curie}} : G = SO(3)$



$T < T_{\text{Curie}} : H = SO(2)$

2.) breaking of gauge symmetries in the early Universe

~1 defect per causal horizon (Higgs-Kibble mechanism)

in Grand Unified Theories (GUTs) this implies magnetic monopole production which would overclose the Universe.

This was one of the motivations that INFLATION was invented.

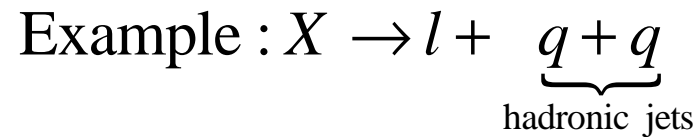
=> particle and/or defect creation must occur during reheating after inflation.

Microwave background anisotropies implies scale  $H_{\text{inflation}} \sim 10^{13}$  GeV.

=> natural scale for relics to explain ultra-high energy cosmic rays!

## Flux calculations in Top-Down scenarios

a) Assume mode of X-particle decay in GUTs

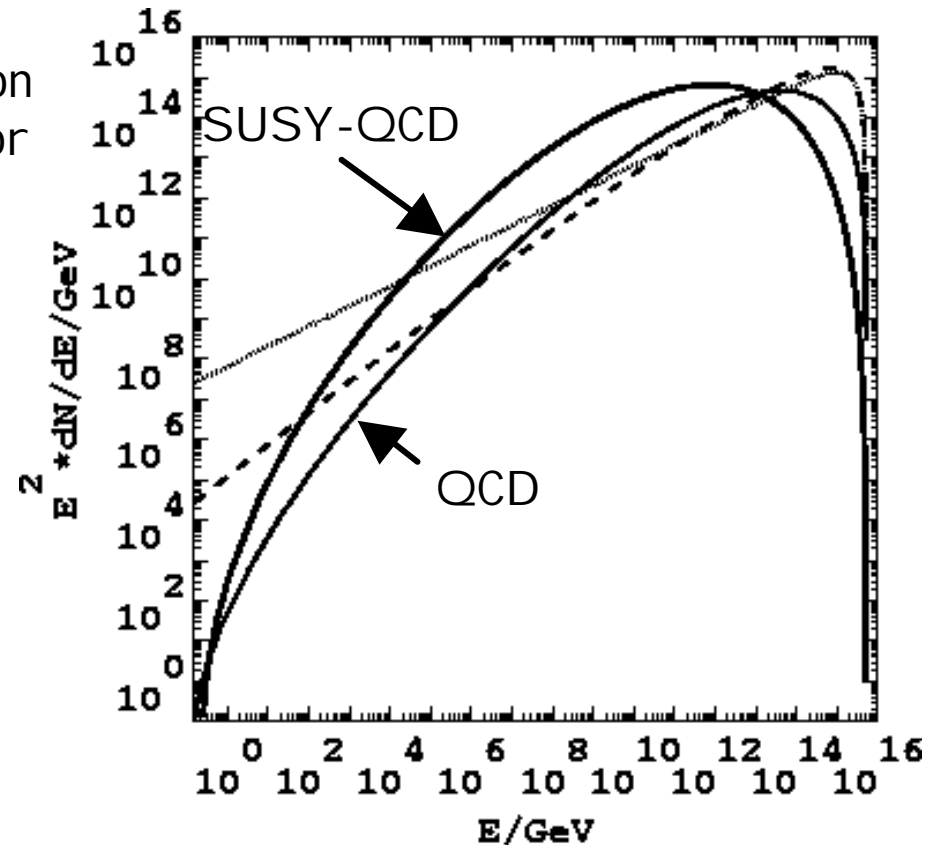


b) Determine hadronic quark fragmentation spectrum extrapolated from accelerator data within QCD:

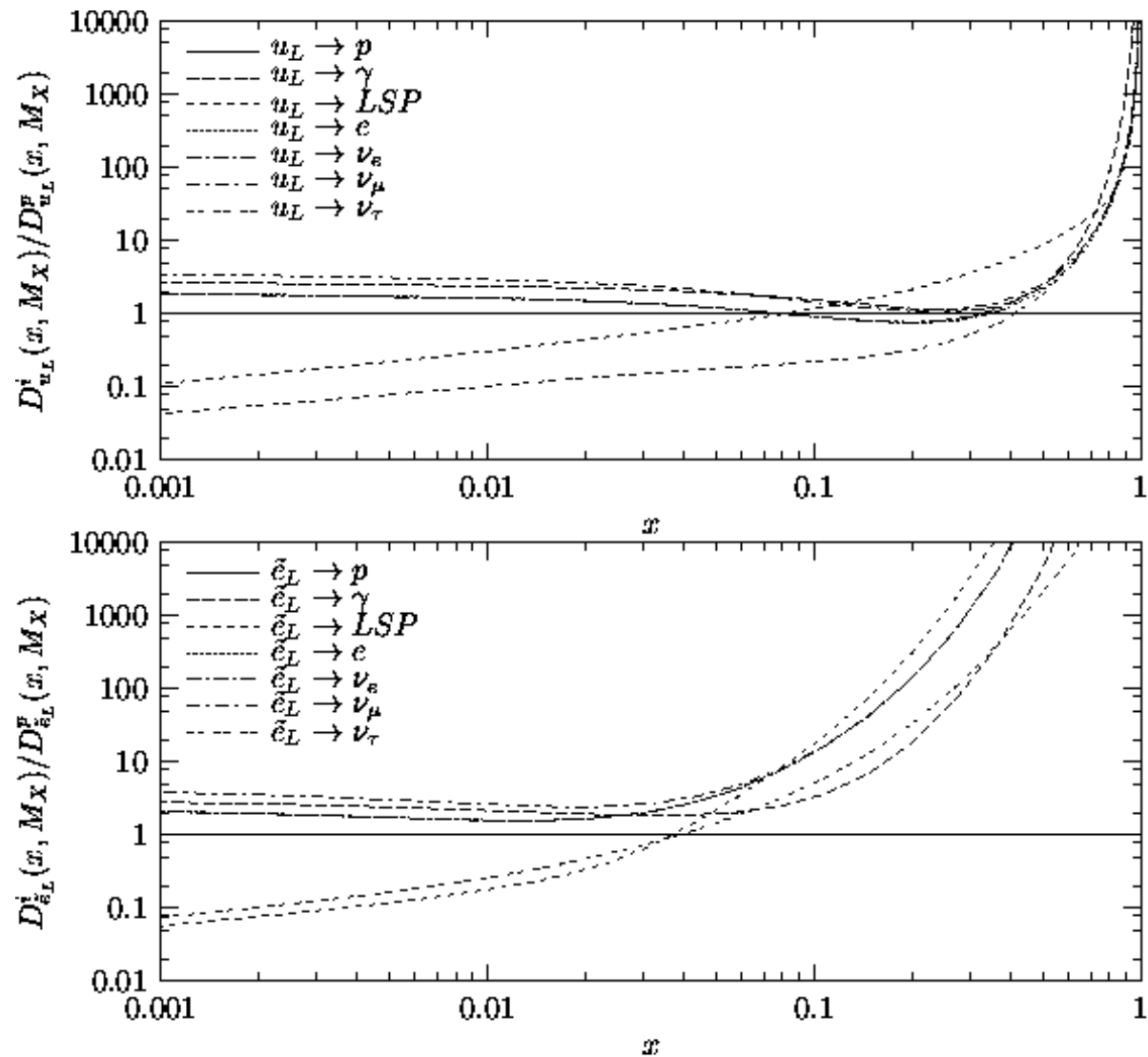
modified leading log approximation (Dokshitzer et al.) with and without supersymmetry versus older approximations (Hill). More detailed calculations by Kachelriess, Berezhinsky, Toldra, Sarkar, Barbot, Drees: results not drastically different.

Fold in meson decay spectra into neutrinos and  $\gamma$ -rays to obtain injection spectra for nucleons, neutrinos, and

c) fold in injection history and solve the transport equations for propagation



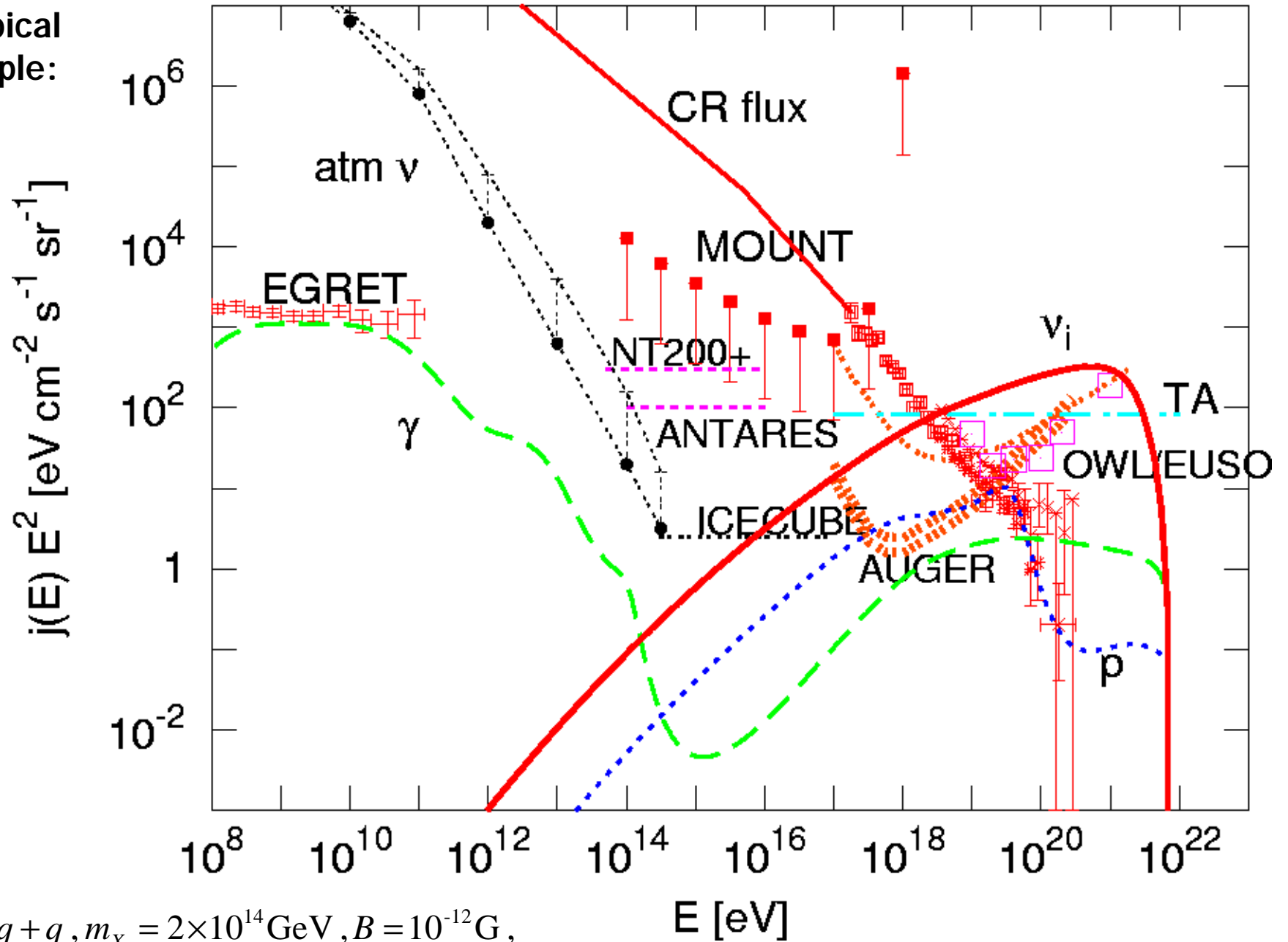




**Figure 1: Ratios of FFs  $D_I^h/D_I^p$  for different stable particles  $h$ , for an initial first or second generation  $SU(2)$  doublet quark,  $I = q_L$ , (top) or slepton,  $I = \tilde{e}_L$ , (bottom). From C. Barbot, e-print hep-ph/0210280.**

At the highest energies fluxes in increasing order are: nucleons,  $\gamma$ -rays, neutrinos, neutralinos.

A typical example:



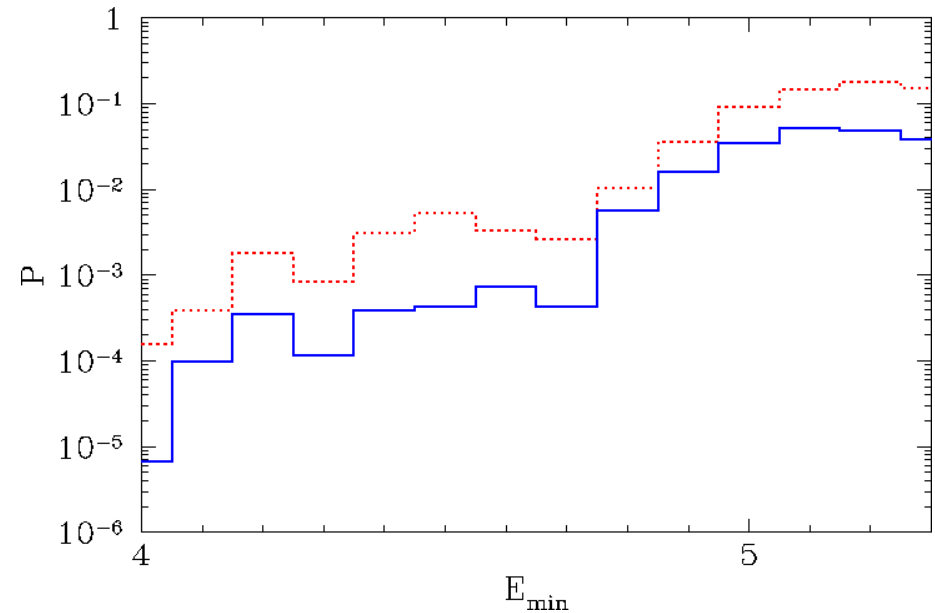
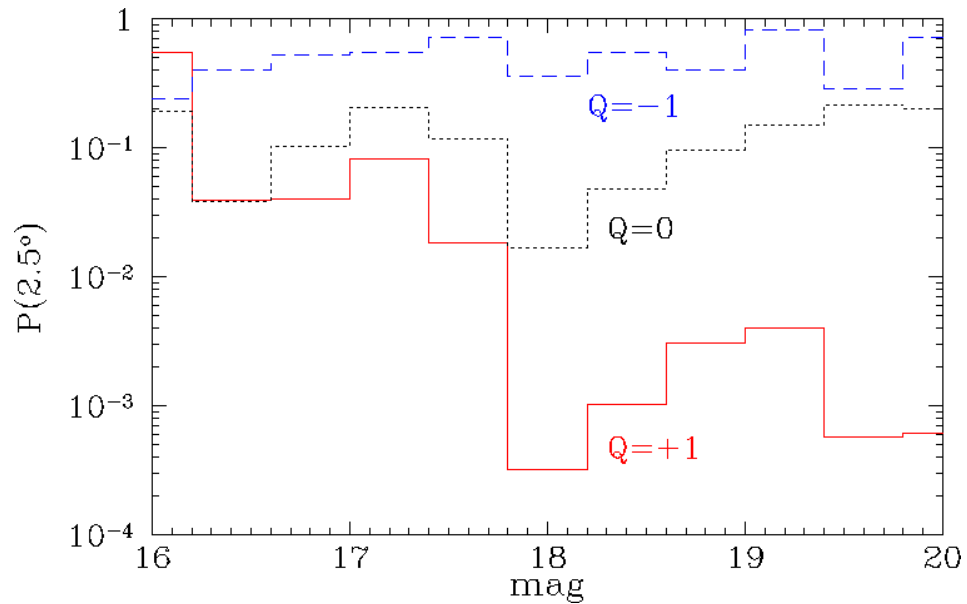
$X \rightarrow q + q, m_X = 2 \times 10^{14} \text{ GeV}, B = 10^{-12} \text{ G},$

homogeneous sources with  $\dot{r}_X \propto t^{-3}$

Kalashev, Kuzmin, Semikoz, Sigl, PRD 66 (2002) 063004

# Correlations with extragalactic Sources

Farrar, Biermann	radio-loud quasars	~1%
Virmani et al.	radio-loud quasars	~0.1%
Tinyakov, Tkachev	BL-Lac objects	~ $10^{-4}$
G.S. et al.	radio-loud quasars	~10%



Surprise: Deflection seems dominated by Our Galaxy. Sources in direction of voids?

BL-Lac distances poorly known: Are they consistent with UHECR energies ?

# Avoiding the GZK Cutoff

If correlated sources turn out to be farther away than allowed by pion production, one can only think of 4 possibilities:

## 1.) Neutrino primaries

but Standard Model interaction probability in atmosphere is  $\sim 10^{-5}$ .

→ resonant ( $Z^0$ ) secondary production on massive relic neutrinos:  
needs extreme parameters and huge neutrino fluxes.

→ strong interactions above  $\sim 1\text{TeV}$ : only moderate neutrino fluxes required.

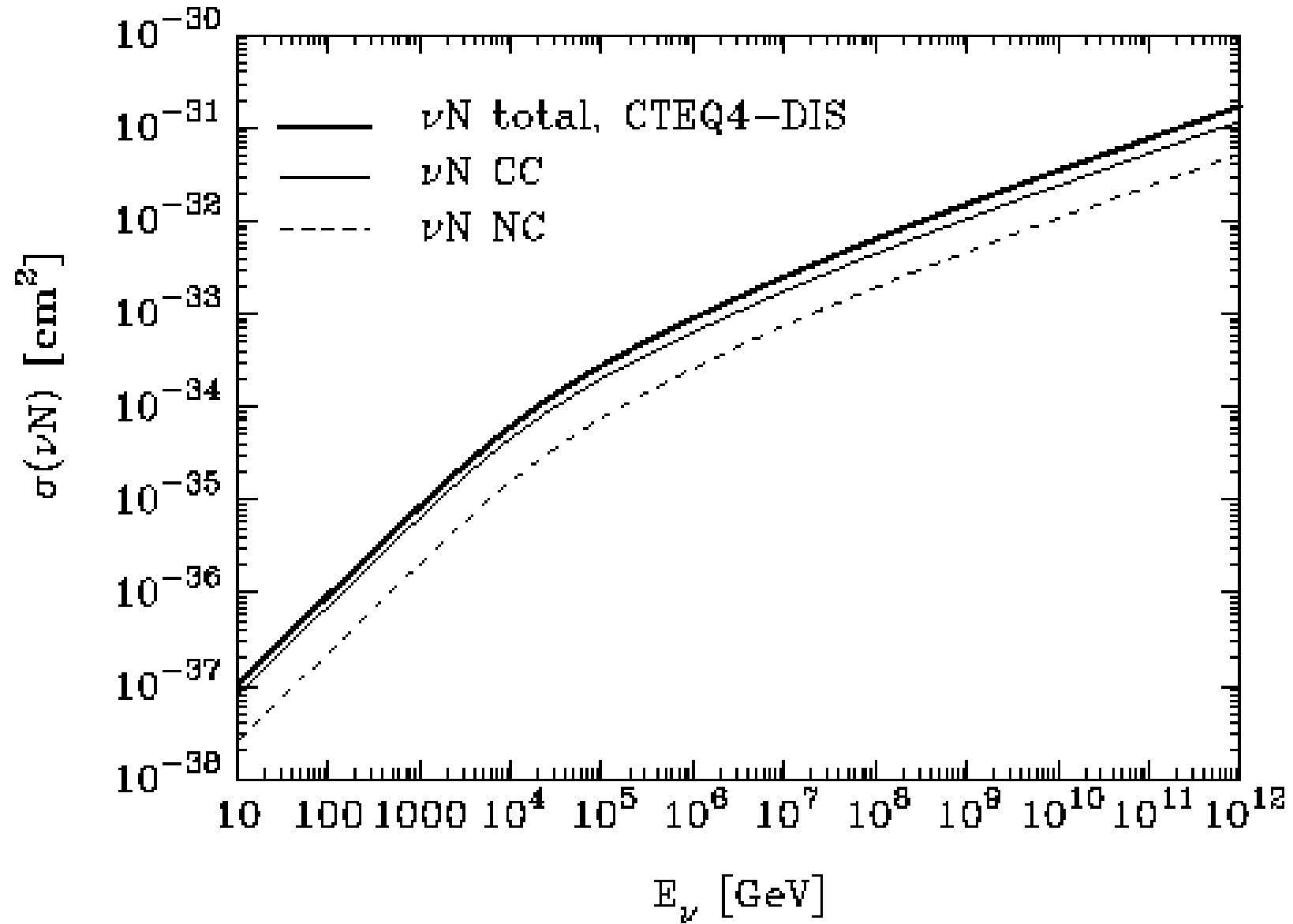
## 2.) New heavy neutral (SUSY) hadron $X_0$ : $m(X_0) > m_N$ increases GZK threshold. but basically ruled out by constraints from accelerator experiments.

## 3.) New weakly interacting light (keV-MeV) neutral particle electromagnetic coupling small enough to avoid GZK effect; hadronic coupling large enough to allow normal air showers: very tough to do.

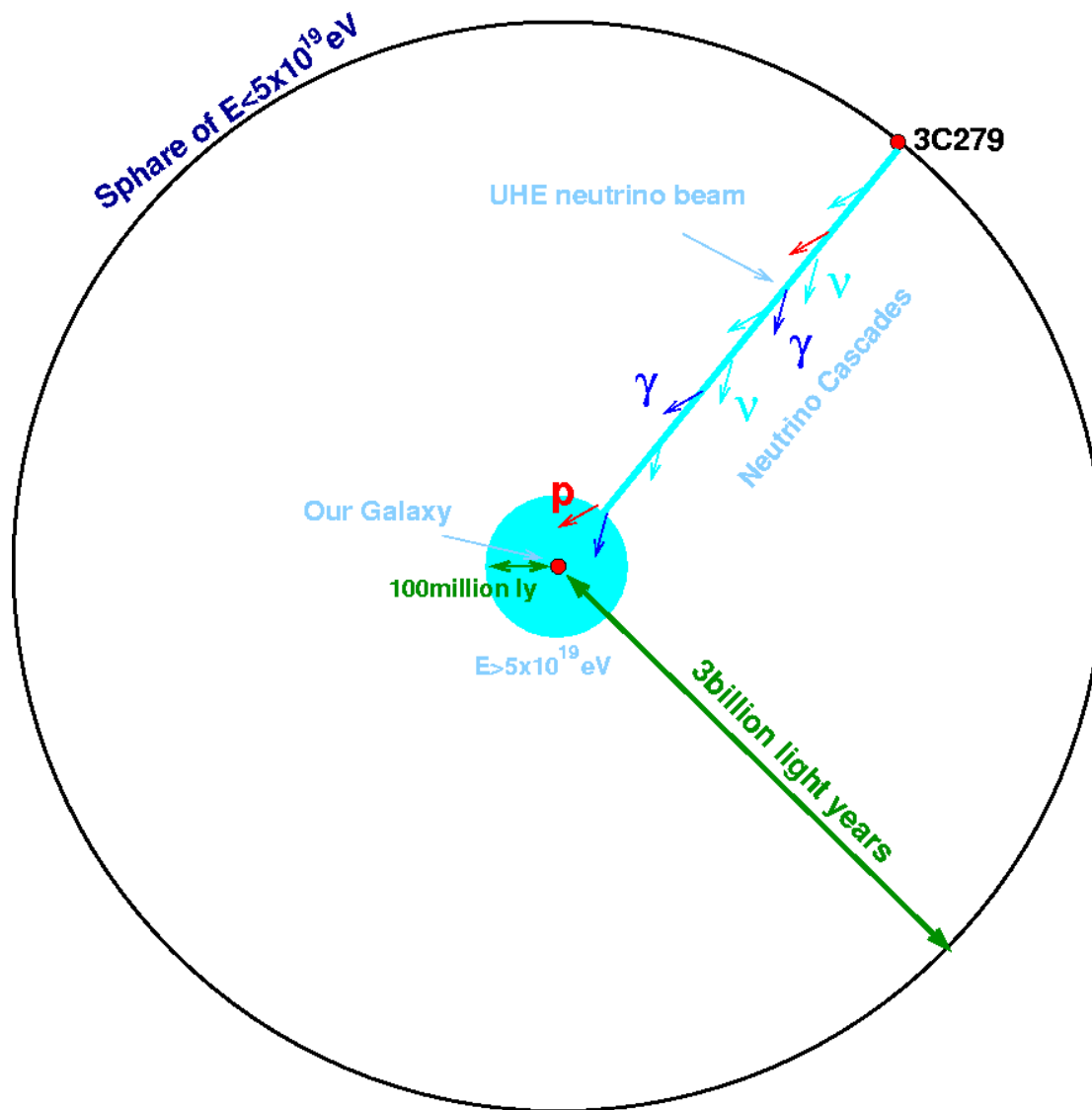
In all cases: more potential sources, BUT charged primary to be accelerated to even higher energies.

## 4.) Lorentz symmetry violations.

# Standard Model neutrino-nucleon cross section



## The Z-burst effect



A Z-boson is produced at the neutrino resonance energy

$$E_n^{\text{res}} = 4 \cdot 10^{21} \text{ eV} \left( \frac{\text{eV}}{m_n} \right)$$

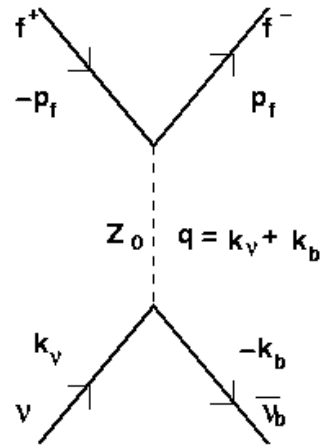
“Visible” decay products have energies 10-40 times smaller.

Main problems of this scenario:

- \* sources have to accelerate up to  $\sim 10^{23}$  eV.
- \*  $\gamma$ -rays emitted from the sources and produced by neutrinos during propagation tend to over-produce diffuse background in GeV regime.

### Neutrinos:

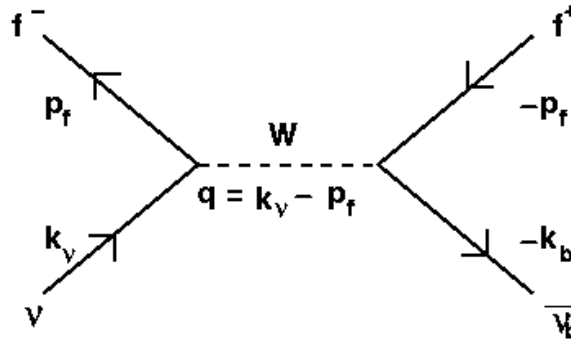
- $s$ -channel  $Z^0$ -production:  $\nu_i \bar{\nu}_i \rightarrow Z^0 \rightarrow f \bar{f}$  where  $f$  is any fermion (including hadronic fragmentation in case of quarks)



$$\frac{d\sigma_s}{d\mu^*} = \frac{G_F^2 s}{16\pi} \frac{M_Z^4}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} [g_L^2 (1 + \mu^*)^2 + g_R^2 (1 - \mu^*)^2],$$

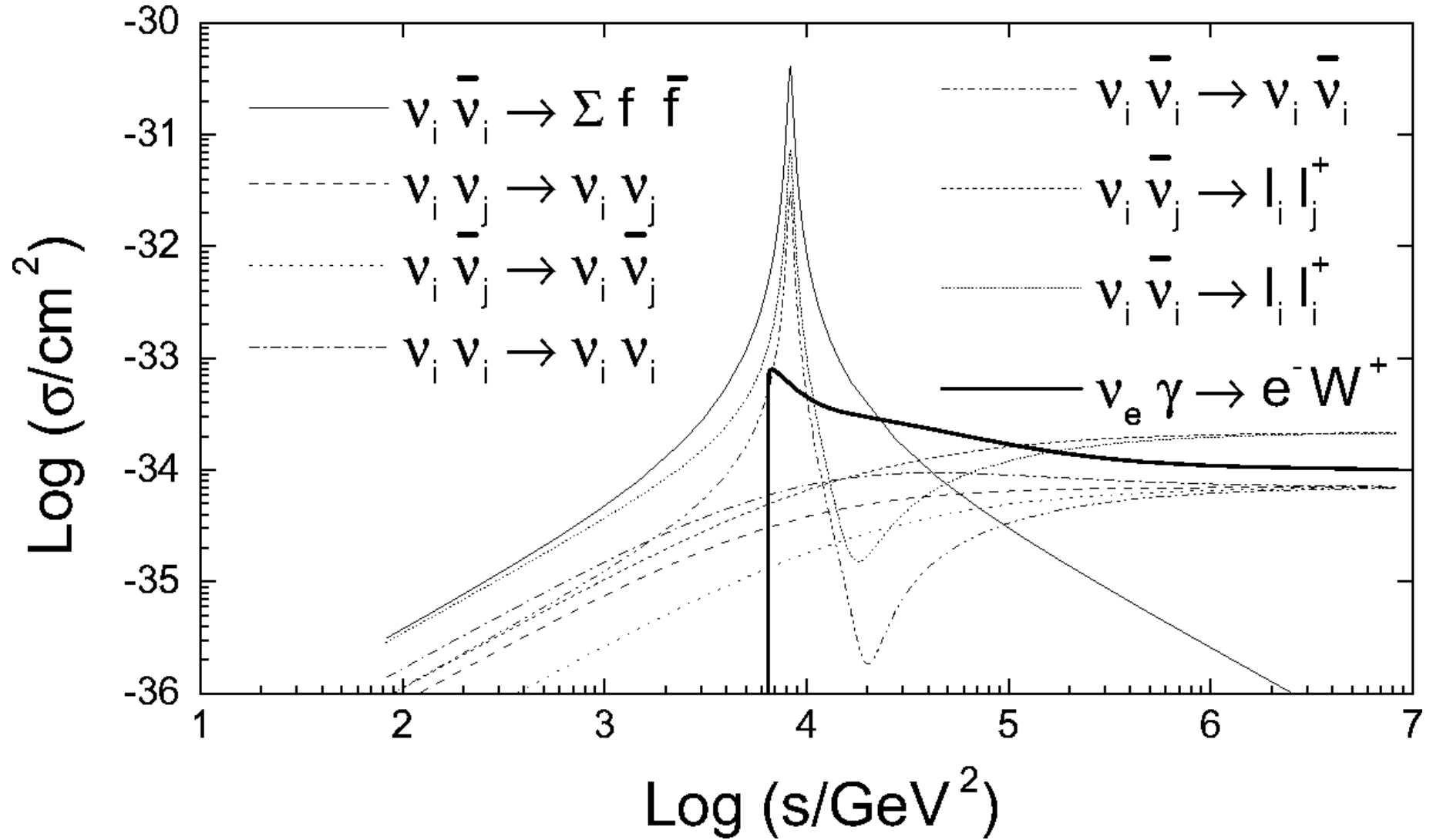
where  $\mu^* = \cos(\text{scattering angle in center of mass})$ ,  $\Gamma_Z = \text{width of } Z^0$ ,  $g_V = t_3 - q \sin^2 \theta_W$  and  $g_A = -q \sin \theta_W^2$  with  $t_3 = \text{weak isospin}$  and  $q = \text{charge}$ .

- $t$ -channel  $W^\pm$ -exchange, e.g.  $\nu_i \bar{\nu}_j \rightarrow l_i \bar{l}_j$ , where  $l_i$  is leptonic partner of  $\nu_i$ :

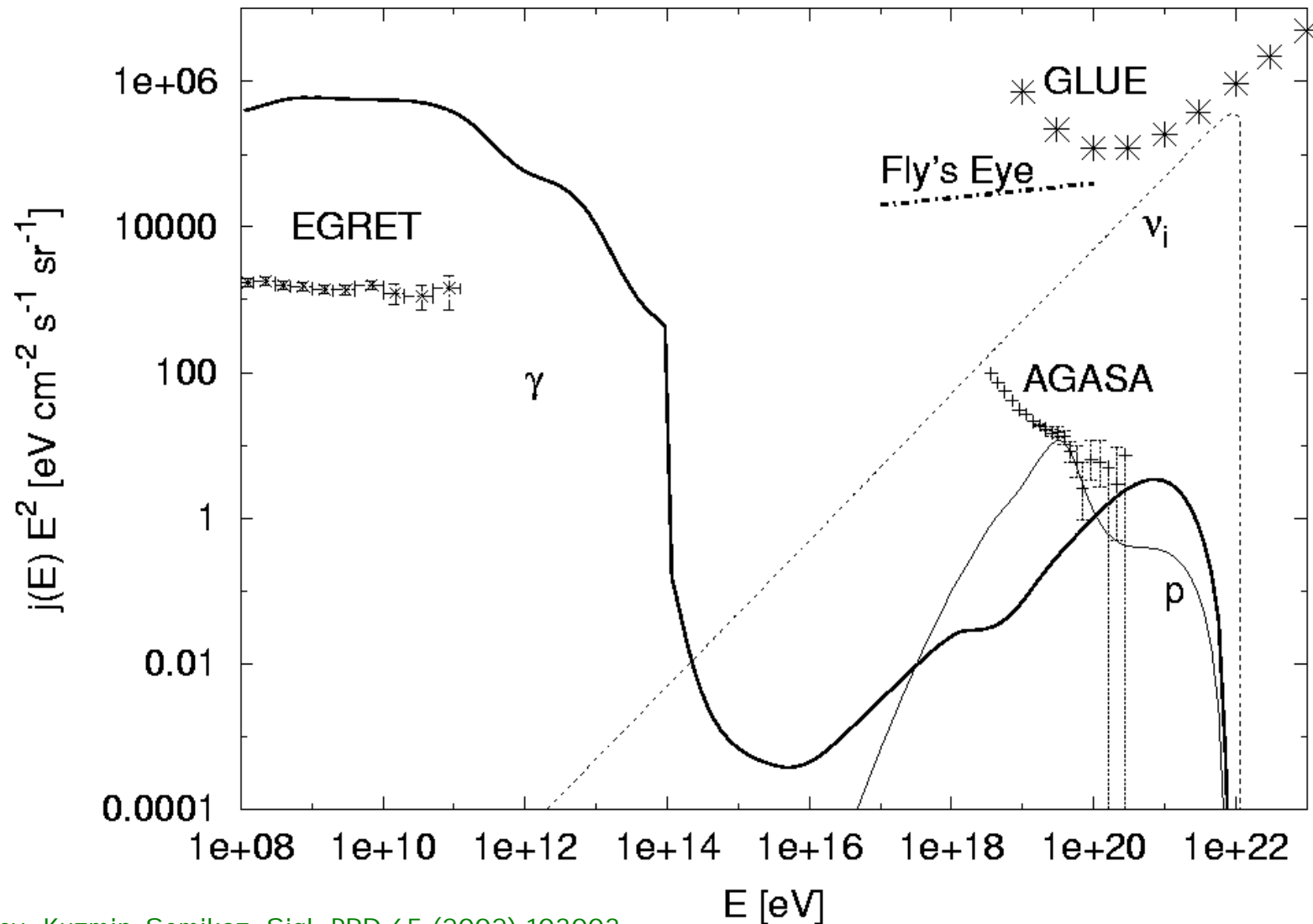


$$\frac{d\sigma_t}{d\mu^*} = \frac{G_F^2 s}{4\pi} \frac{M_W^2 (1 + \mu^*)^2}{(s(1 - \mu^*)/2 + M_W^2)}$$

# The Z-burst mechanism: Relevant neutrino interactions



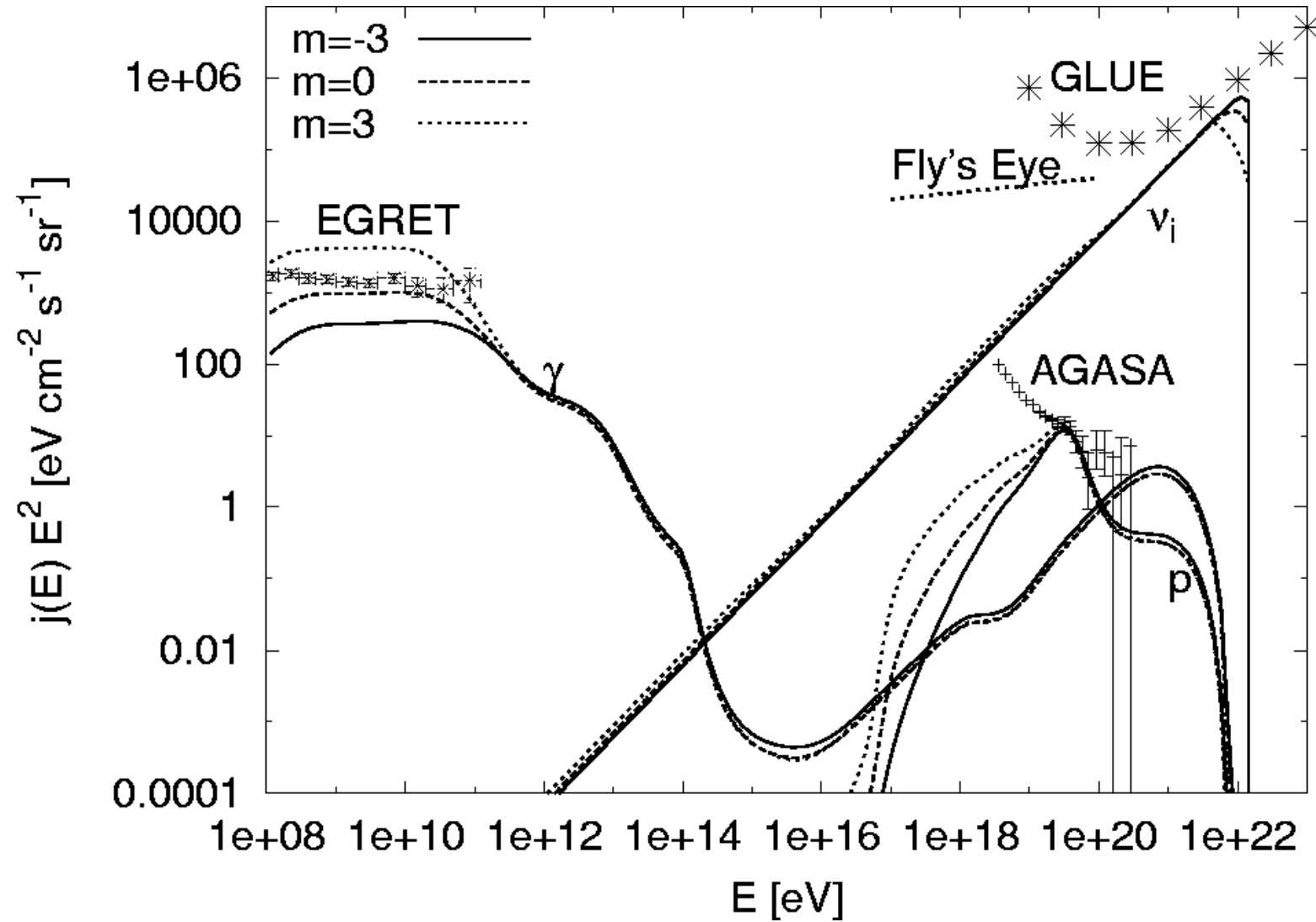
## The Z-burst mechanism: Sources emitting neutrinos and g-rays



Kalashev, Kuzmin, Semikoz, Sigl, PRD 65 (2002) 103003

Sources with constant comoving luminosity density up to  $z=3$ , with  $E^{-2}$   $\gamma$ -ray injection up to 100 TeV of energy fluence equal to neutrinos,  $m_\nu=0.5\text{eV}$ ,  $B=10^{-9}$  G.

## The Z-burst mechanism: Exclusive neutrino emitters



Kalashev, Kuzmin, Semikoz, Sigl, PRD 65 (2002) 103003

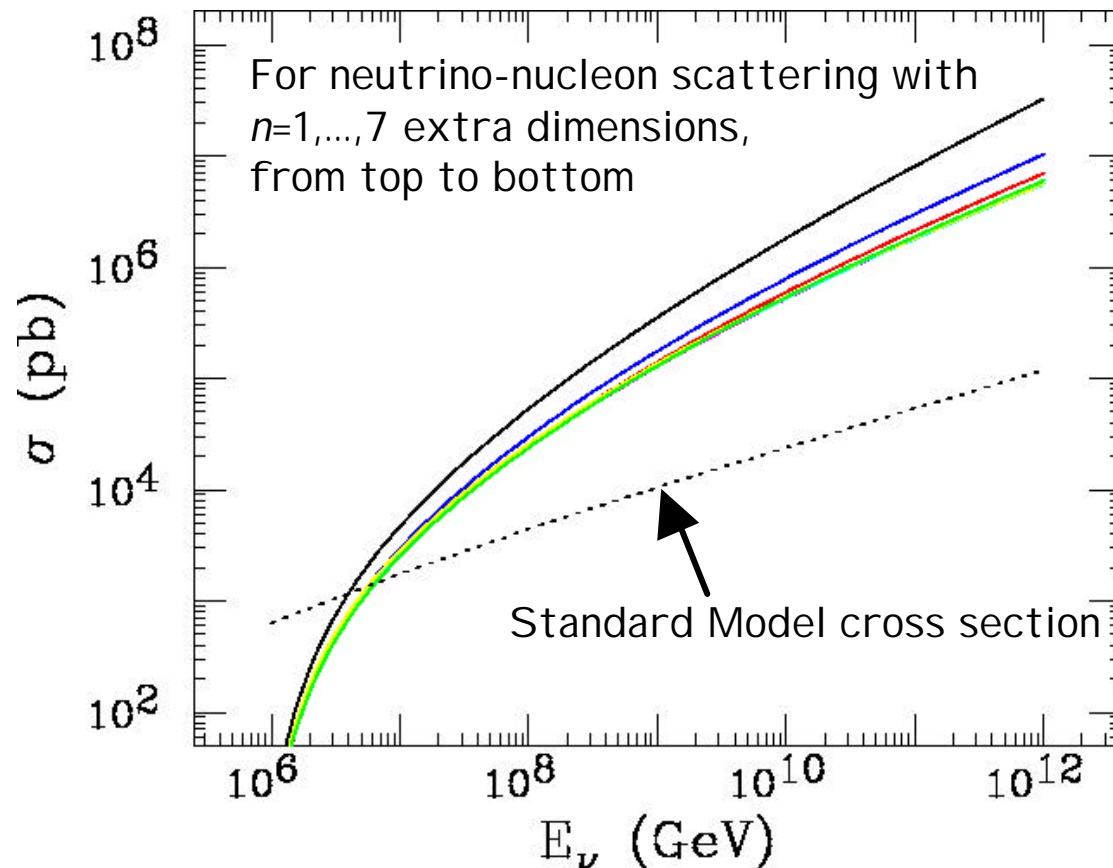
Sources with comoving luminosity proportional to  $(1+z)^m$  up to  $z=3$ ,  $m_\gamma=0.5\text{eV}$ ,  $B=10^{-9}$  G.

## Probes of Neutrino Interactions beyond the Standard Model

Note: For primary energies around  $10^{20}$  eV:

- Center of mass energies for collisions with relic backgrounds  
~100 MeV – 100 GeV ? > physics well understood
- Center of mass energies for collisions with nucleons in the atmosphere  
~100 TeV – 1 PeV ? > probes physics beyond reach of accelerators

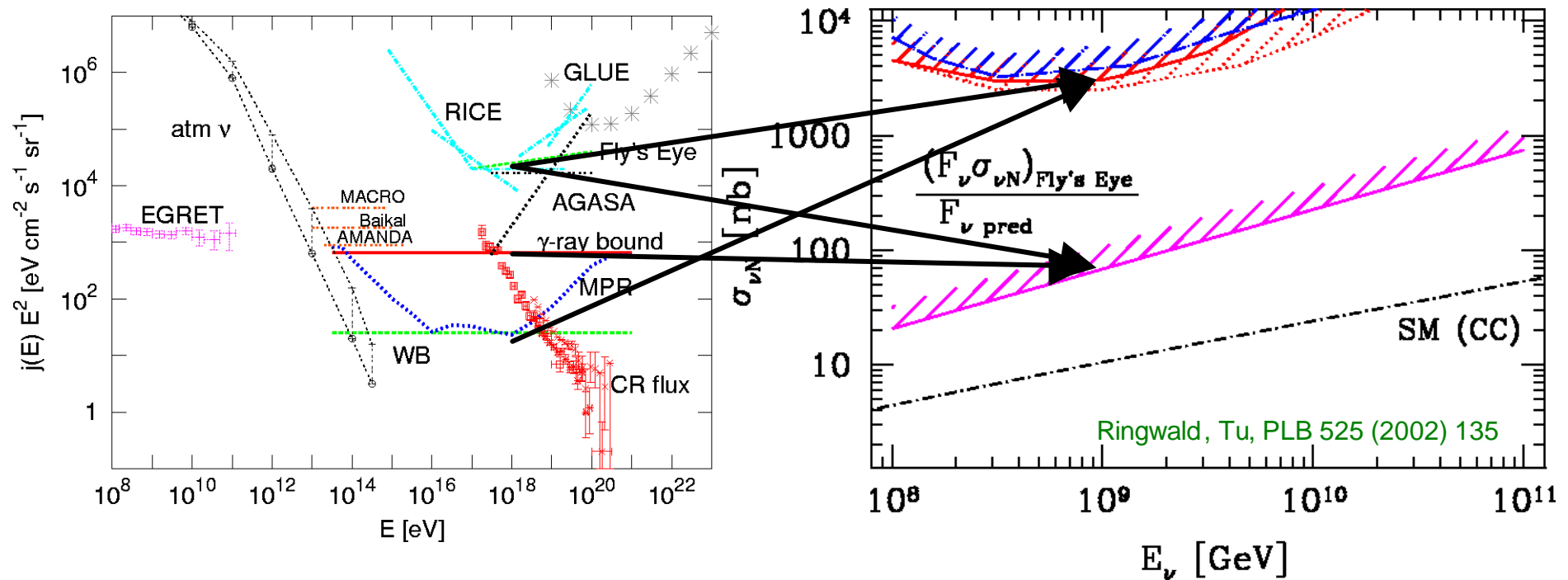
Example: microscopic black hole production in scenarios with a TeV string scale:



Feng, Shapere, PRL 88 (2002) 021303

This increase is not sufficient to explain the highest energy cosmic rays, but can be probed with deeply penetrating showers.

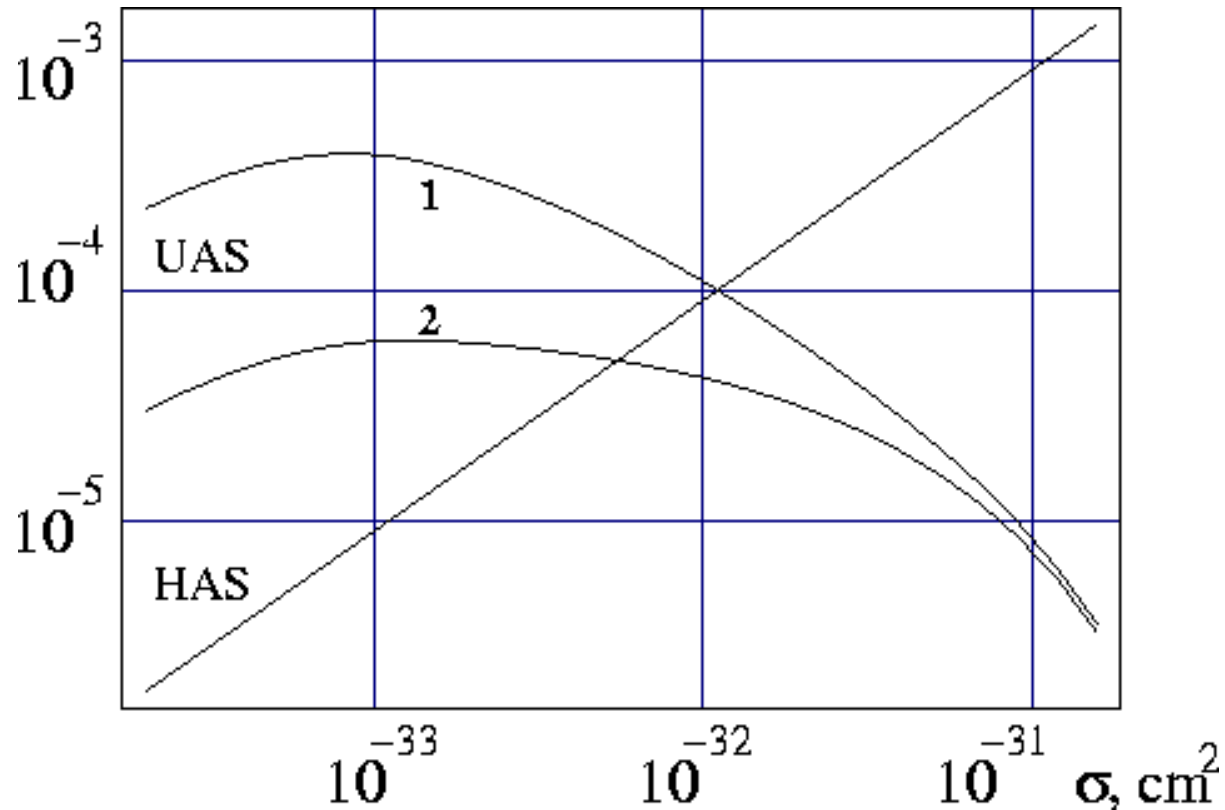
However, the neutrino flux from pion-production of extra-galactic trans-GZK cosmic rays allows to put limits on the neutrino-nucleon cross section:



Comparison of this  $N_\gamma$ - ("cosmogenic") flux with the non-observation of horizontal air showers results in the present upper limit about  $10^3$  above the Standard Model cross section.

Future experiments will either close the window down to the Standard Model cross section, discover higher cross sections, or find sources beyond the cosmogenic flux. How to disentangle new sources and new cross sections?

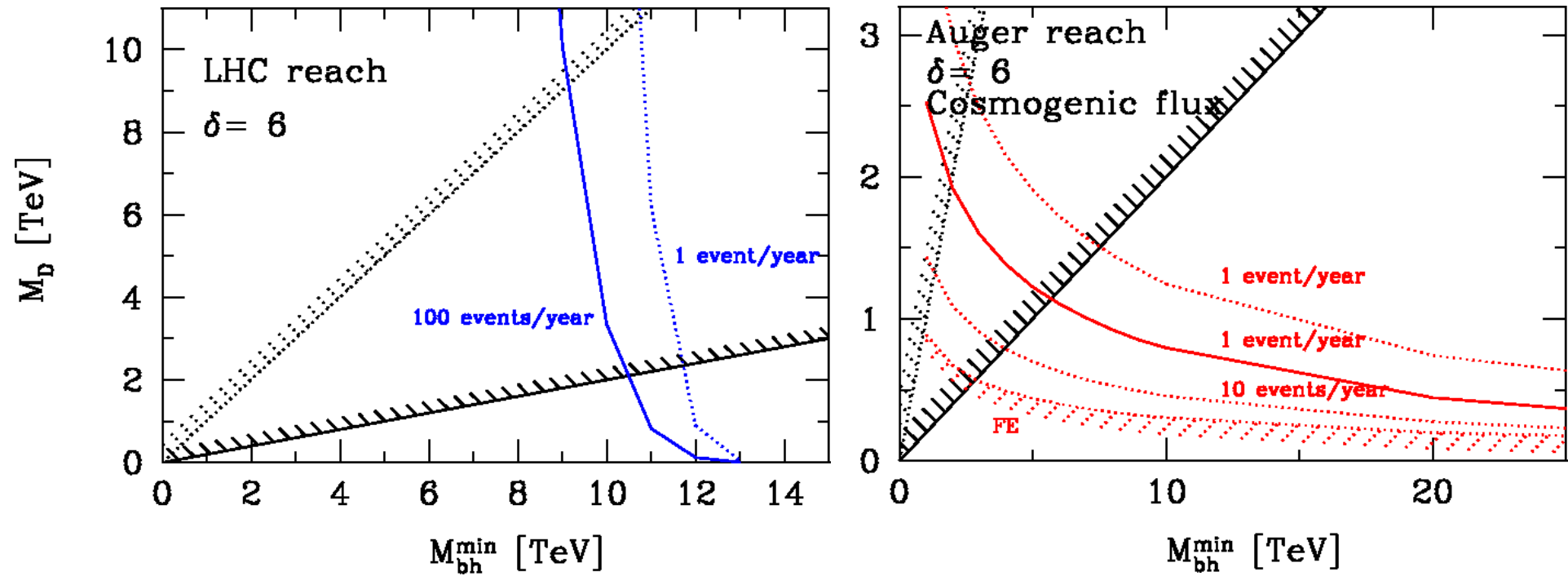
## Earth-skimming t-neutrinos



Air-shower probability per t-neutrino at  $10^{20}$  eV for  $10^{18}$  eV (1) and  $10^{19}$  eV (2) threshold energy for space-based detection.

Comparison of earth-skimming and horizontal shower rates allows to measure the neutrino-nucleon cross section in the 100 TeV range.

## Sensitivities of LHC and the Pierre Auger project to microscopic black hole production in neutrino-nucleon scattering



$M_D$  = fundamental gravity scale;  $M_{bh}^{min}$  = minimal black hole mass

LHC much more sensitive than Auger, but Auger could "scoop" LHC

# Probes of Lorentz symmetry violations

Dispersion relation between energy  $E$ , momentum  $p$ , and mass  $m$  may be modified by non-renormalizable effects at the Planck scale  $M_{\text{Pl}}$ ,

$$E^2 - p^2 \approx m^2 - \mathbf{x} \frac{p^3}{M_{\text{Pl}}} - \mathbf{z} \frac{p^4}{M_{\text{Pl}}^2} + \dots,$$

where most models, e.g. critical string theory, predict  $\mathbf{z}=0$  for lowest order.

Introducing the standard threshold momentum for pion production,  $N+\gamma \rightarrow Np$ ,

$$p_0 = \frac{2m_N m_p + m_p^2}{4e},$$

the threshold momentum  $p_{\text{th}}$  in the modified theory is given by

$$-\frac{p_0^3}{(m_p^2 + 2m_p m_N) M_{\text{Pl}}} \frac{m_p m_N}{(m_p + m_N)^2} \left[ 2\mathbf{x} \left( \frac{p_{\text{th}}}{p_0} \right)^3 + 3\mathbf{z} \frac{p_0}{M_{\text{Pl}}} \left( \frac{p_{\text{th}}}{p_0} \right)^4 + \dots \right] + \frac{p_{\text{th}}}{p_0} = 1$$

Attention: this assumes standard energy-momentum conservation which is not necessarily the case.

For  $\alpha \sim \beta \sim 1$  this equation has no solution  $\Rightarrow$  No GZK threshold!

For  $\alpha \sim 0, \beta \sim -1$  the threshold is at  $\sim 1$  PeV!

For  $\alpha \sim 0, \beta \sim -1$  the threshold is at  $\sim 1$  EeV!

Confirmation of a normal GZK threshold would imply the following limits:

$|\alpha| < 10^{-13}$  for the first-order effects.

$|\beta| < 10^{-6}$  for the second-order effects.

Energy-independent (renormalizable) corrections to the maximal speed

$V_{\max} = \lim_{E \gg 8} \alpha E / \beta p = 1 - d$  can be constrained by substituting  
 $d \approx \alpha (\beta/2)(E/M_{\text{pl}}) + (\beta/2)(E/M_{\text{pl}})^2$ .

The modified dispersion relation also leads to energy dependent group velocity  $V = \alpha E / \beta p$  and thus to an energy-dependent time delay over a distance  $d$ :

$$\Delta t = -\alpha D \frac{E}{M} \approx -\alpha \left( \frac{D}{100 \text{ Mpc}} \right) \left( \frac{E}{\text{TeV}} \right) \text{sec}$$

for  $\alpha = 0$ . GRB observations in TeV  $\gamma$ -rays can therefore probe quantum gravity.

The current limit is  $M/\alpha > 8 \times 10^{15}$  GeV (Ellis et al.).

## Conclusions

- 1.) The origin of very high energy cosmic rays is one of the fundamental unsolved questions of astroparticle physics. This is especially true at the highest energies, but even the origin of Galactic cosmic rays is not resolved beyond doubt.
- 2.) Acceleration and sky distribution of cosmic rays are strongly linked to the in part poorly known strength and distribution of cosmic magnetic fields.
- 3.) Pion-production establishes a very important link between the physics of high energy cosmic rays on the one hand, and  $\gamma$ -ray and neutrino astrophysics on the other hand. All three of these fields should be considered together.
- 4.) Within the Standard Model of particle physics, the only scenario for highest energy cosmic rays involving (massive) neutrinos uses them as messenger. This "Z burst" mechanism is probably ruled out due to excessive  $\gamma$ -ray production.
- 5.) At energies above  $\sim 10^{18}$  eV, the center-of mass energies are above a TeV and thus beyond the reach of accelerator experiments. Especially in the neutrino sector, where Standard Model cross sections are small, this probes potentially new physics beyond the electroweak scale.

## Conclusions

- 6.) In top-down models highest energy cosmic rays are not accelerated but are decay products of some relics from the early Universe. In general these models suffer from a certain amount of fine tuning (why do they kick in at energies where acceleration ceases ? They are also strongly constrained by the EGRET bound.
- 7.) The coming 3-5 years promise an about 100-fold increase of ultra-high energy cosmic ray data due to experiments that are under either construction or in the proposal stage.
- 8.) Many new ideas on a modest cost scale, especially for ultra-high energy neutrino detection, are currently under discussion.