Ultra High Energy Cosmic Rays
and
New Physics

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discoveries

- antimatter (e^+)
- new leptons (μ)
- new bosons (π)
- new quark flavours (s)
- ⋮

anomalies

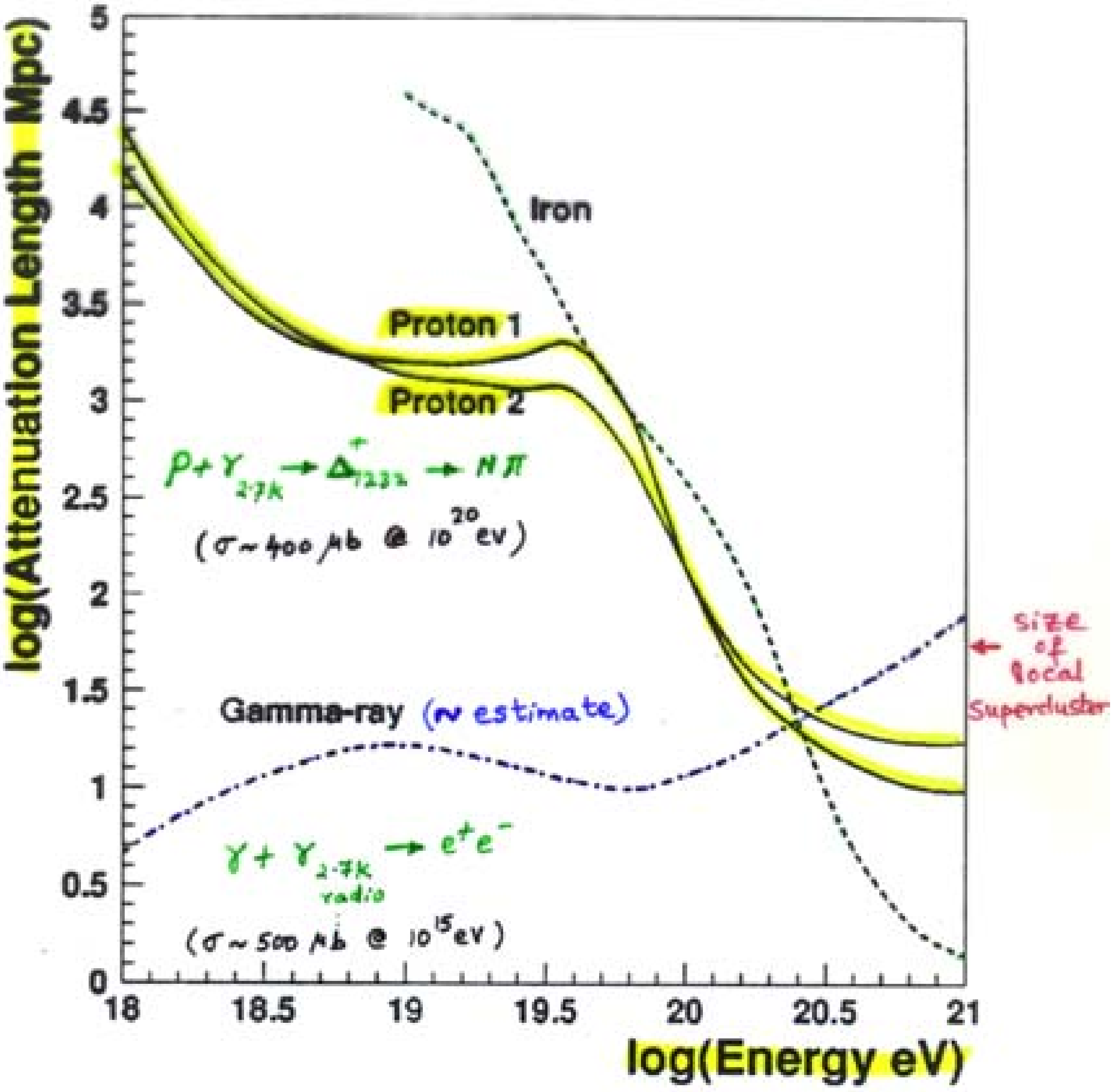
- fractional charges ×
- magnetic monopoles ×
- 'Centauro' events ×
- ⋮

Cosmic rays observed beyond the GZK cutoff

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

(hep-ph/0202013)

M. Nagano and A. A. Watson
RMP 72(2000)689



(~ estimate)

$p + \gamma_{2.7K} \rightarrow \Delta^{+}_{1232} \rightarrow N\pi$

$(\sigma \sim 400\ \mu b\ @\ 10^{20}\ eV)$

$\gamma + \gamma_{\substack{2.7K \\ radio}} \rightarrow e^{+}e^{-}$

$(\sigma \sim 500\ \mu b\ @\ 10^{15}\ eV)$

← size of local supercluster

FIG. 4. The attenuation length of proton, iron, and gamma-ray primaries in the microwave, infrared, and radio background radiations as a function of energy. Proton 1 is from Yoshida and Teshima (1993) and proton 2 from Protheroe and Johnson (1996). Results from Rachen and Biermann (1993) and Berezinsky and Grigor'eva (1988) lie between protons 1 and 2. That of iron is from Stecker and Salamon (1999). That of gamma rays in the total low-energy photon background down to kHz frequencies is shown by the dot-dashed curve from Bhattacharjee and Sigl (1998).

Volcano Ranch

New Mexico

19 plastic scintillation counters (3·3 m^2) covering 8 km^2
19 muon detectors (3·3 m^2)

10^{20} eV event detected in 1962

→ energy subsequently revised to $1{\cdot}4\times10^{20}$ eV

J. Linsley
(AIP Proc. 433, 1998)

AGASA data (2003)

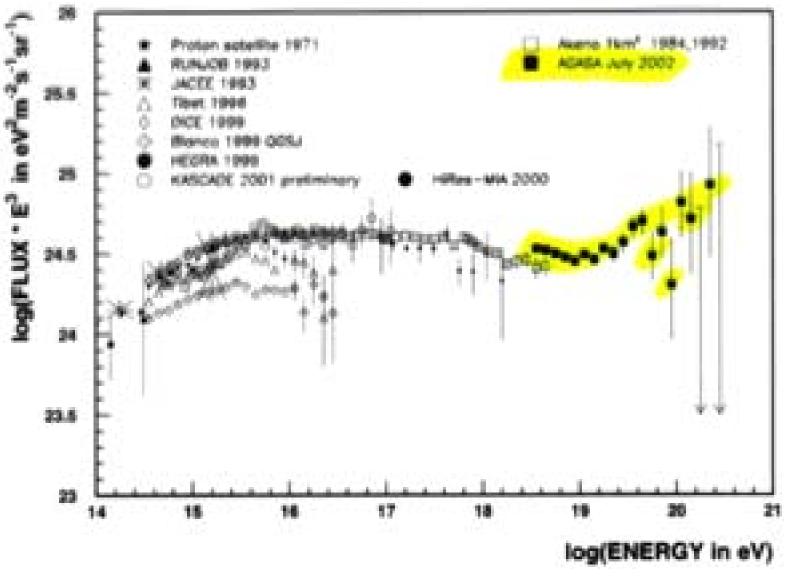


Fig. 17. Cosmic ray energy spectrum over a wide energy range. The present AGASA energy spectrum is shown by closed squares. The spectrum from the Akeno 1km^2 array is shown by open squares. The Akeno-AGASA energy spectrum covers more than 5 decades of energy and is in reasonable agreement with most energy spectra below 10^{18}eV.

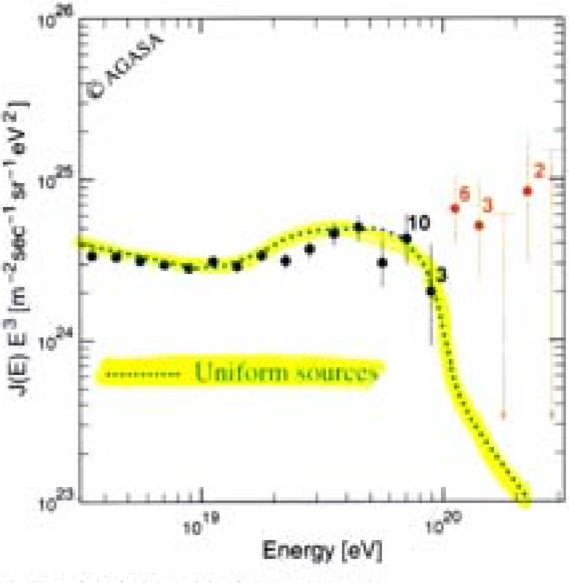


Fig. 14(b). Same plot but only the spectrum.

cosmologically
distant sources
(GZK cutoff)
ruled out
at $\gtrsim 4\sigma$

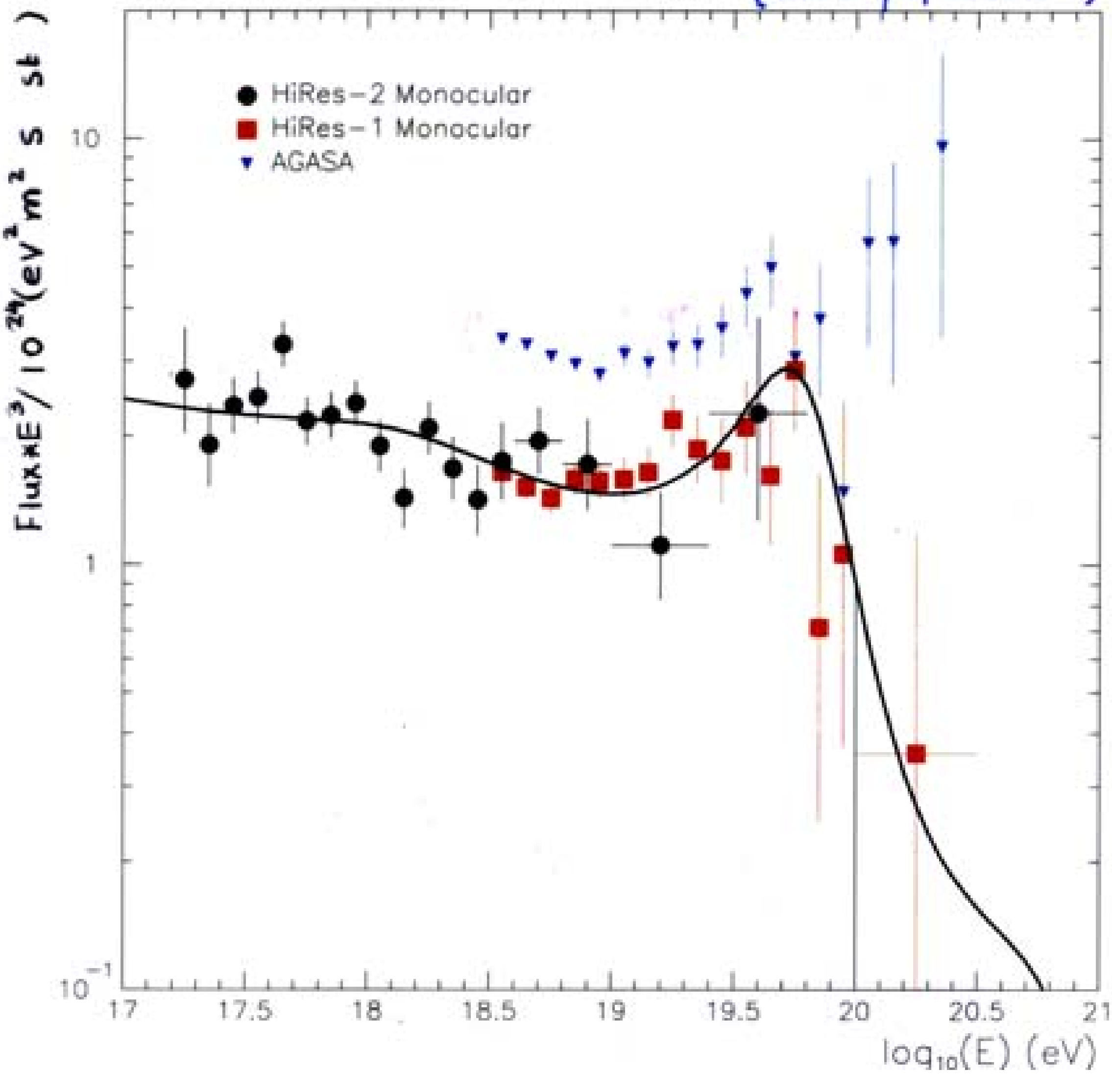
Takeda et al
(astro-ph/0209422)

HiRes data however appears to be consistent with the GZK cutoff ?!

energy calibration discrepancy ?

→ lowering AGASA energies by ~20% would match HiRes below E_{GZK}, ... but 7 events would still be $> E_{GZK}$

(astro-ph/0208301)

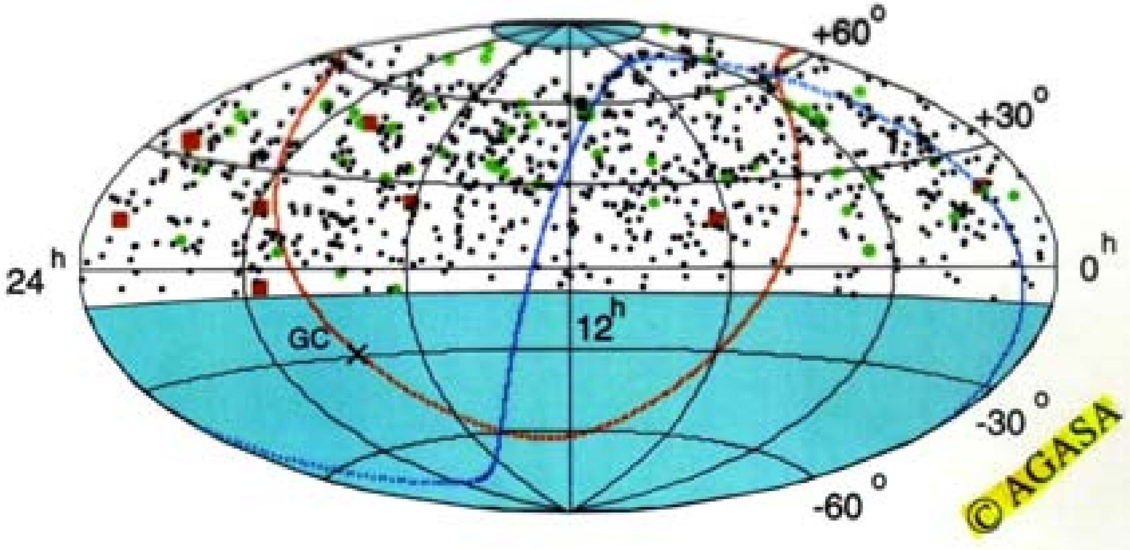


overall isotropy ... some events clustered

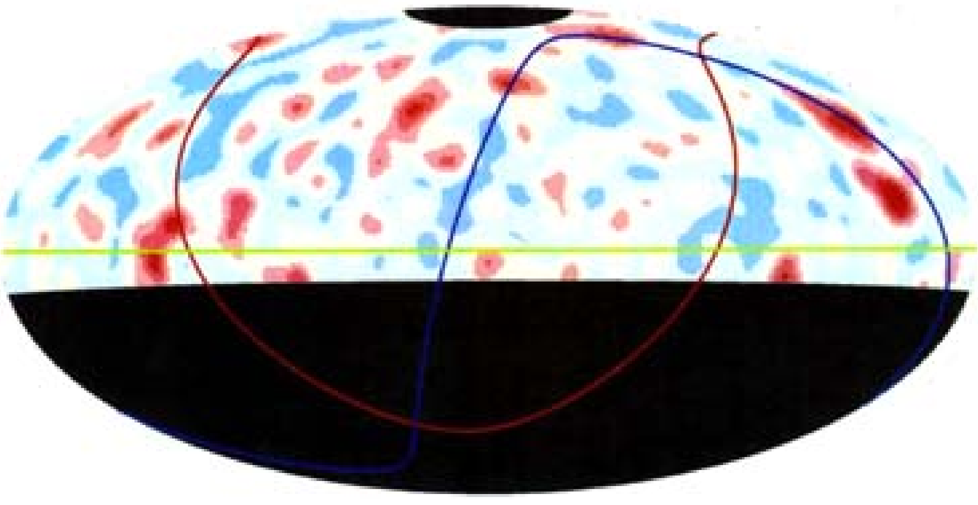
No significant correlations
with astrophysical sources (BL Lacs...)

at $(4-6)\times 10^{19}$ eV
→ chance probability ~1%

Arrival Directions ($\geq 10^{19}$eV)



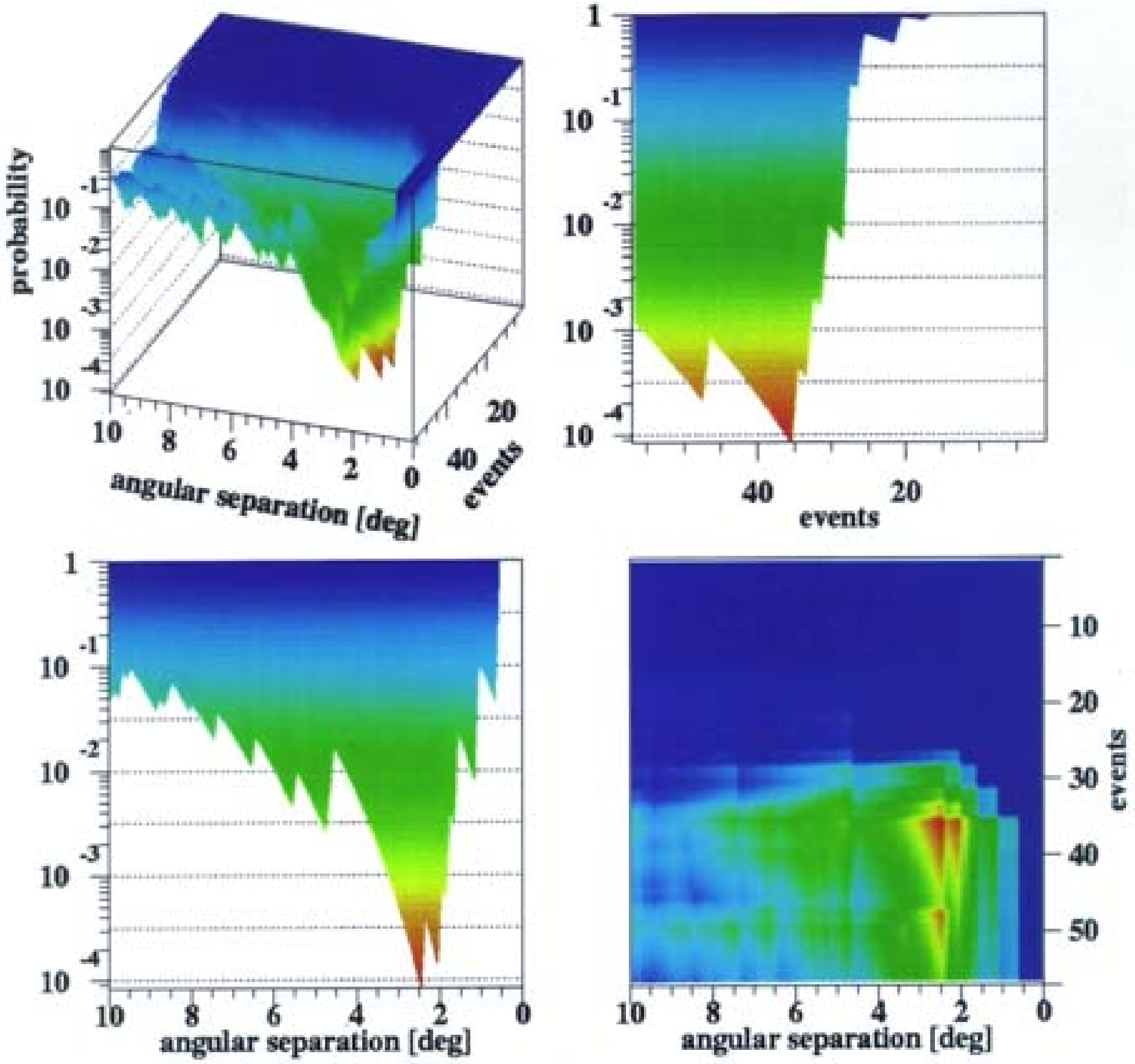
■ $\geq 10^{20}$eV
● $(4-10)\times 10^{19}$eV
• $(1-4)\times 10^{19}$eV



Scan of AGASA events with $E > 4 \times 10^{19}$ eV

$P_{min} = 8.4 \times 10^{-5}$ and $P_{chance} = 0.35\%$ for the clustering signal at $N = 36$, $\theta = 2.5^\circ$ (6 pairs)

Finley & Westerhoff
(astro-ph/0309159)



... however if the AGASA data is split into 2 sets (30 events before Oct '95, 27 events afterwards)

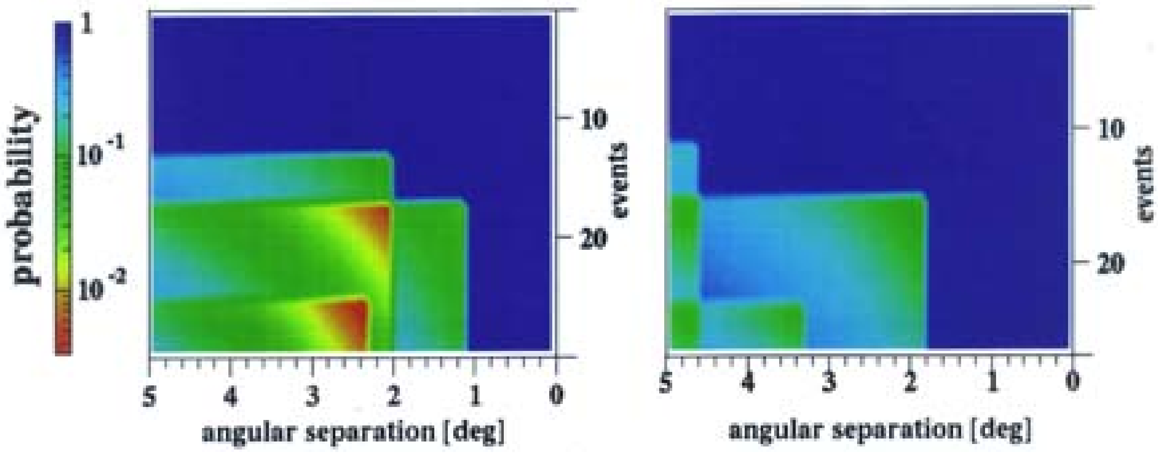
then:

$P_{chance} = 4.4\%$ (at $\theta_c = 2.4^\circ$, $N_c = 26$)
for first dataset

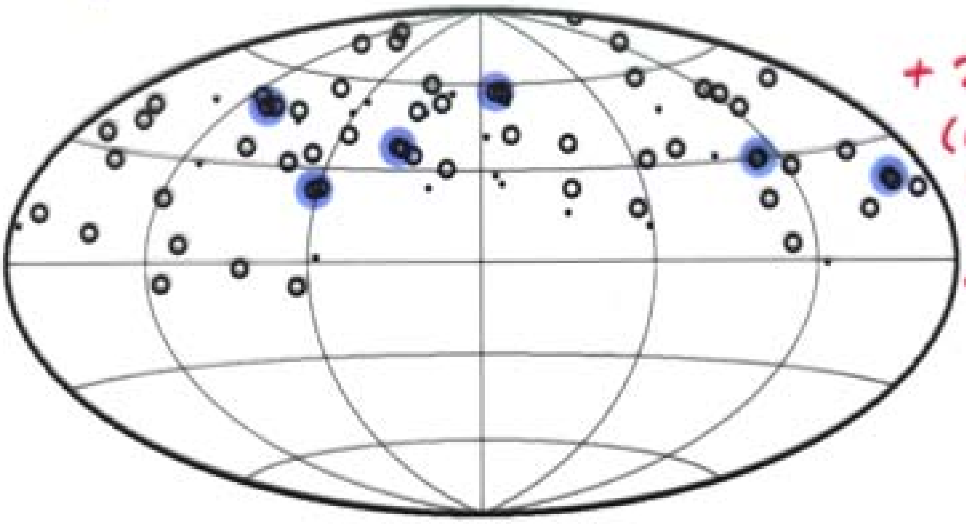
$P_{chance} = 27\%$ (at $\theta_c = 4.7^\circ$, $N_c = 16$)
for second data set

$\Rightarrow$ no significant evidence for clustering!

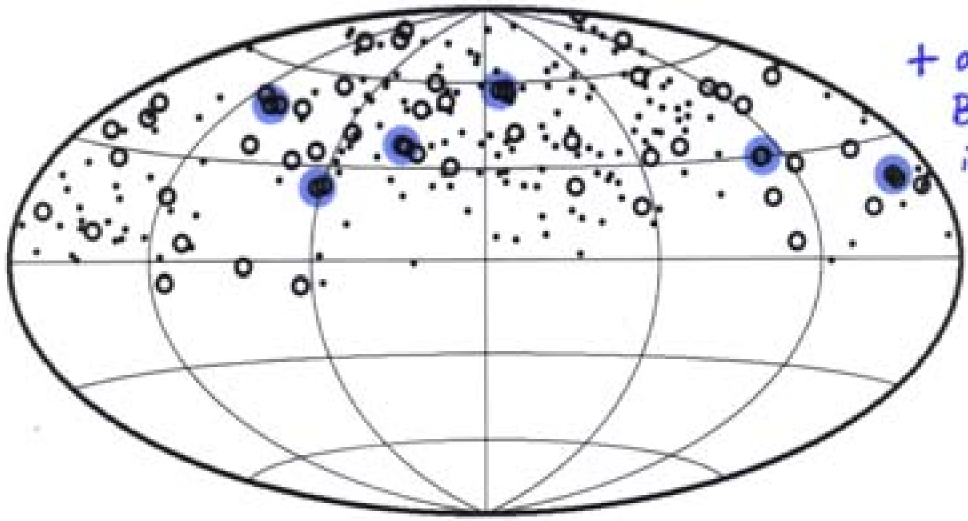
Finley & Westerhoff
(astro-ph/0309159)



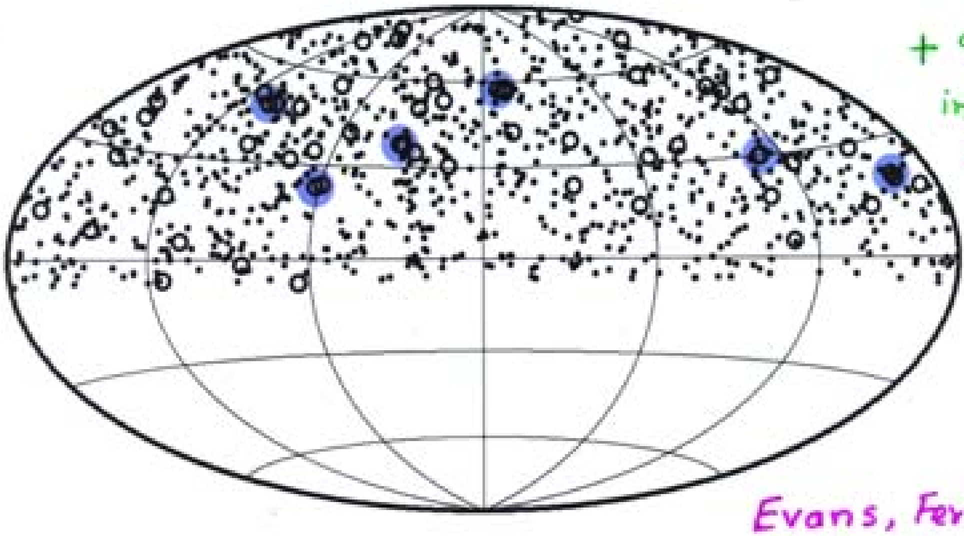
Sky distribution of 57 events with $E > 4 \times 10^{19}$ eV



+ 22 BL Lacs
(with cuts
on redshift,
magnitude
and radio flux)



+ all 306
BL Lacs
in catalogue



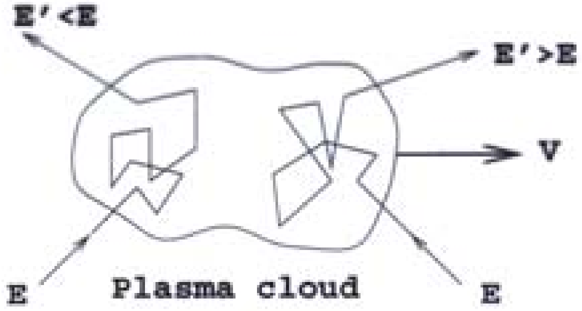
+ 915 GRBs
in BATSE
catalogue

Evans, Ferrer & Sarkar
(astro-ph/0212533)

Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

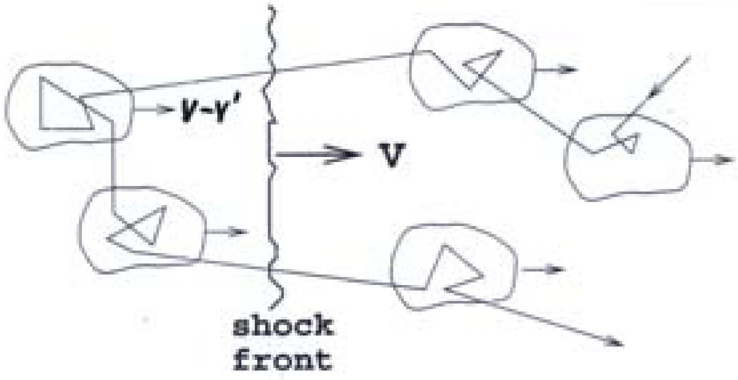
2nd order :
randomly distributed magnetic mirrors



$$\frac{\Delta E}{E} \sim \beta^2 \qquad \beta = \frac{V}{c} \lesssim 10^{-4}$$

[Slow and inefficient]

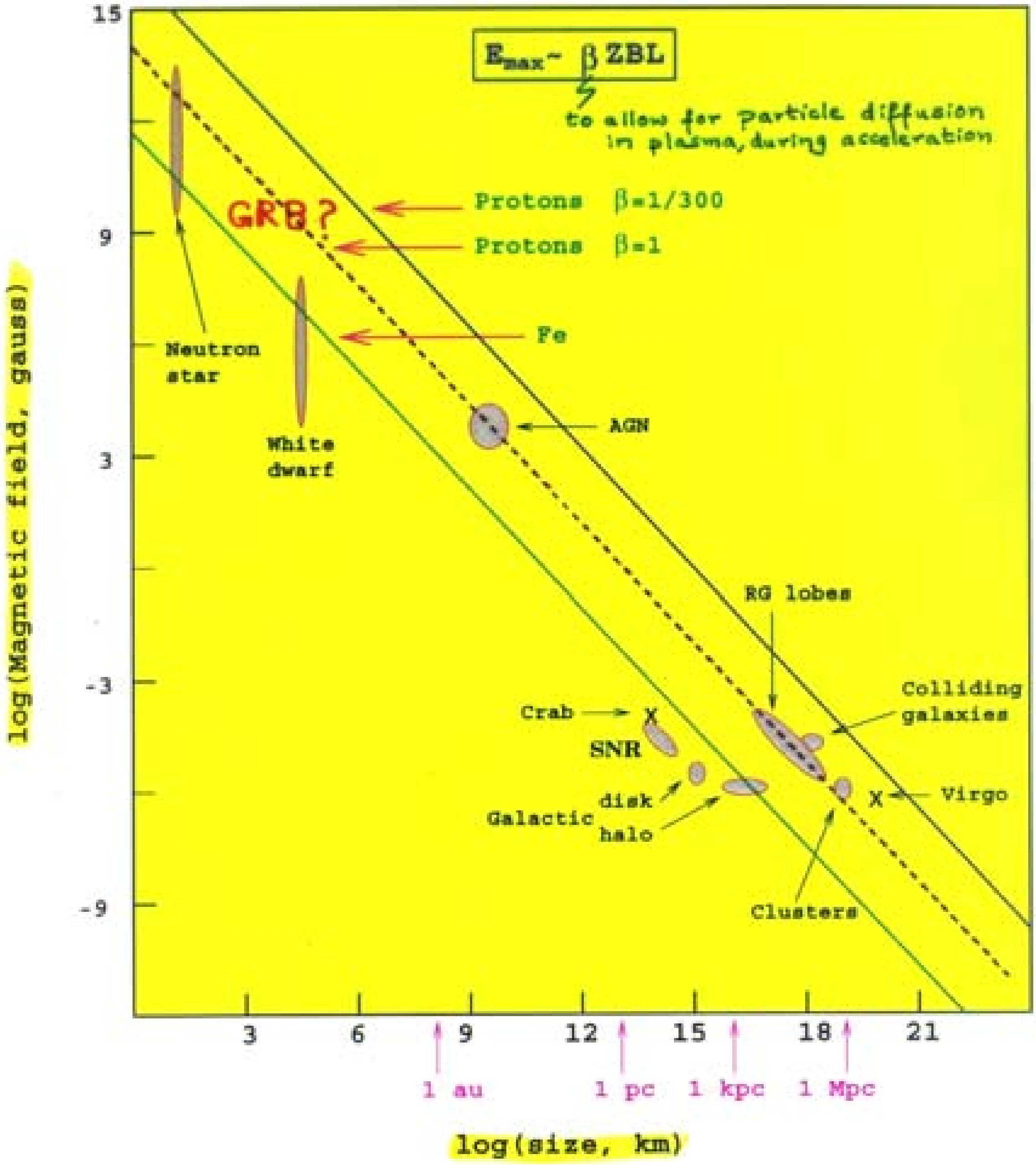
1st order :
acceleration in strong shock waves
(supernova ejecta, RG hot spots...)



$$\frac{\Delta E}{E} \sim \beta \qquad \beta = \frac{V}{c} \lesssim 10^{-1}$$

$B_{\mu G} \otimes L_{kpc} \gtrsim 2\beta^{-1} E_{GeV}/Z$ ... for confinement

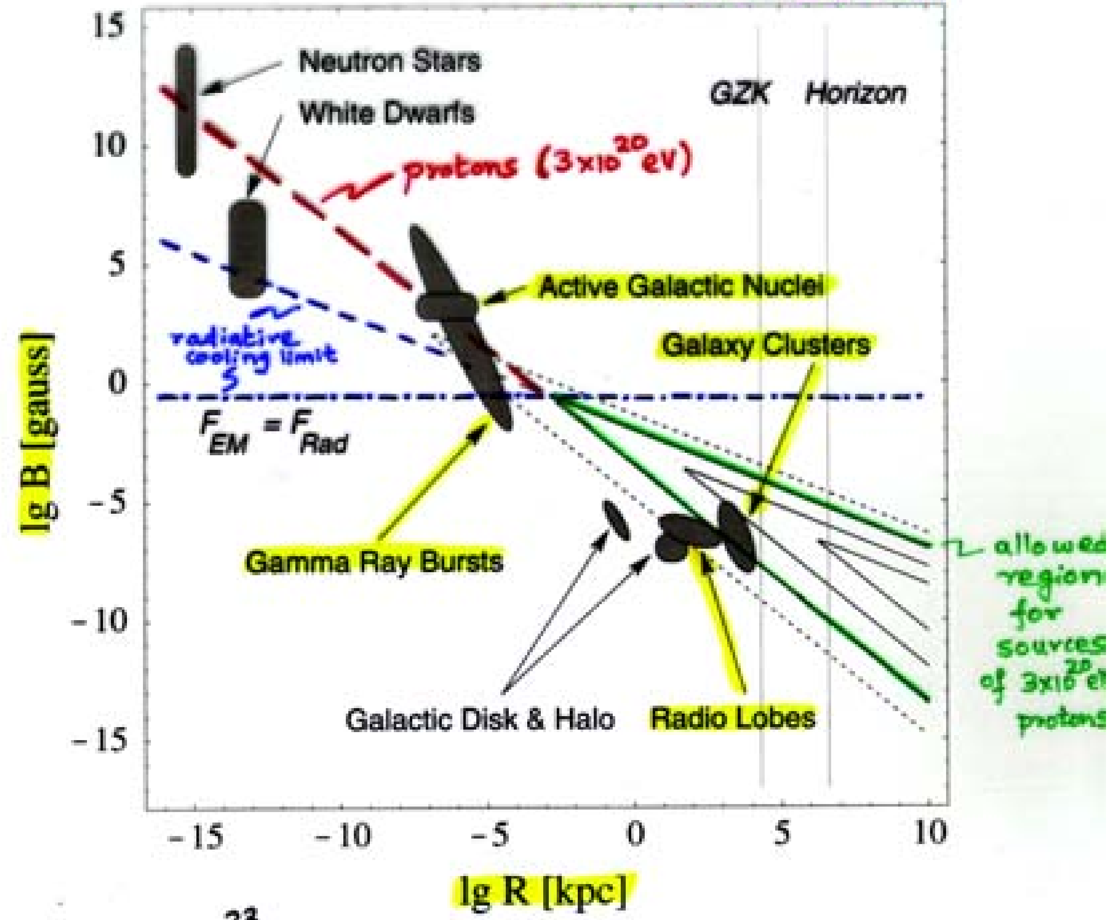
Hillas-plot (candidate sites for E=100 EeV)



Hillas, ARAA 22(1984)425

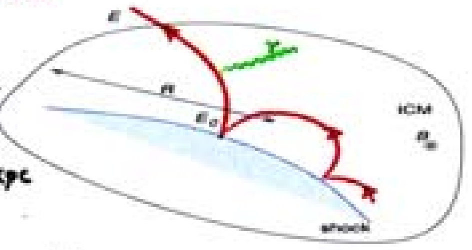
Requirements of astrophysical sources

Hillas (ARAA 22, 425, '84)



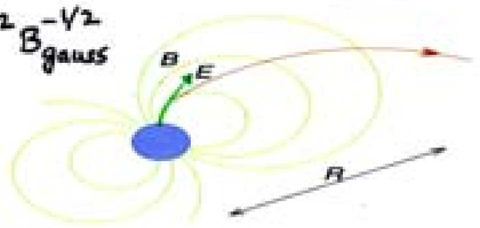
$$E_{acc} = ZeBR \simeq 9\times10^{23}\,\text{eV}\; Z\, B_{gauss} R_{kpc}$$

⇒ confinement criterion



$$E_{cr} \simeq \begin{cases} 3\times10^{16}\,\text{eV}\,\dfrac{(A/Z)^4}{B_{gauss}^2 R_{kpc}} \\ 10^{20}\,\text{eV}\,A^2 Z^{-3/2} B_{gauss}^{-1/2} \end{cases}$$

inefficient (diffusive) acceleration



efficient (inductive) acceleration

⇒ radiative cooling limit

Combining the limits:

$$R_{kpc} > 6\times10^{-5}\left(E/3\times10^{20}\,\text{eV}\right)^3 Z^2 A^{-4}$$

Medvedev (astro-ph/0303271

⇨ Is an astrophysical solution ruled out?

Yes unless intergalactic magnetic fields are strong enough (~μG) to isotropise 10^{20} eV protons <u>and</u> there are sources which can accelerate such particles within the local supercluster

(M87? Cen-A?)

<u>Possibilities for new physics</u>

⇨ exotic primary (e.g. SUSY hadron : Chung, Farrar, Kolb '97)

— ruled out experimentally ?

⇨ Strongly interacting neutrino primaries (e.g. through KK graviton exchange : Kachelriess & Plümacher 00)

— insufficient #section

⇨ 'Z-bursts' (annihilations of UHE neutrinos on relic ~0·1 eV ν bkgd) [Weiler '97, Fargion et al '99]

— rate too low

⇨ Annihilations / decays of relic topological defects (Hill '83)

— GZK processing, hence potentially excessive γ-ray bkgd

⇨ Decays of WIMPZILLAs clustered as halo DM (Berezinsky, Kachelriess, Vilenkin '97, Birkel & Sarkar '98)

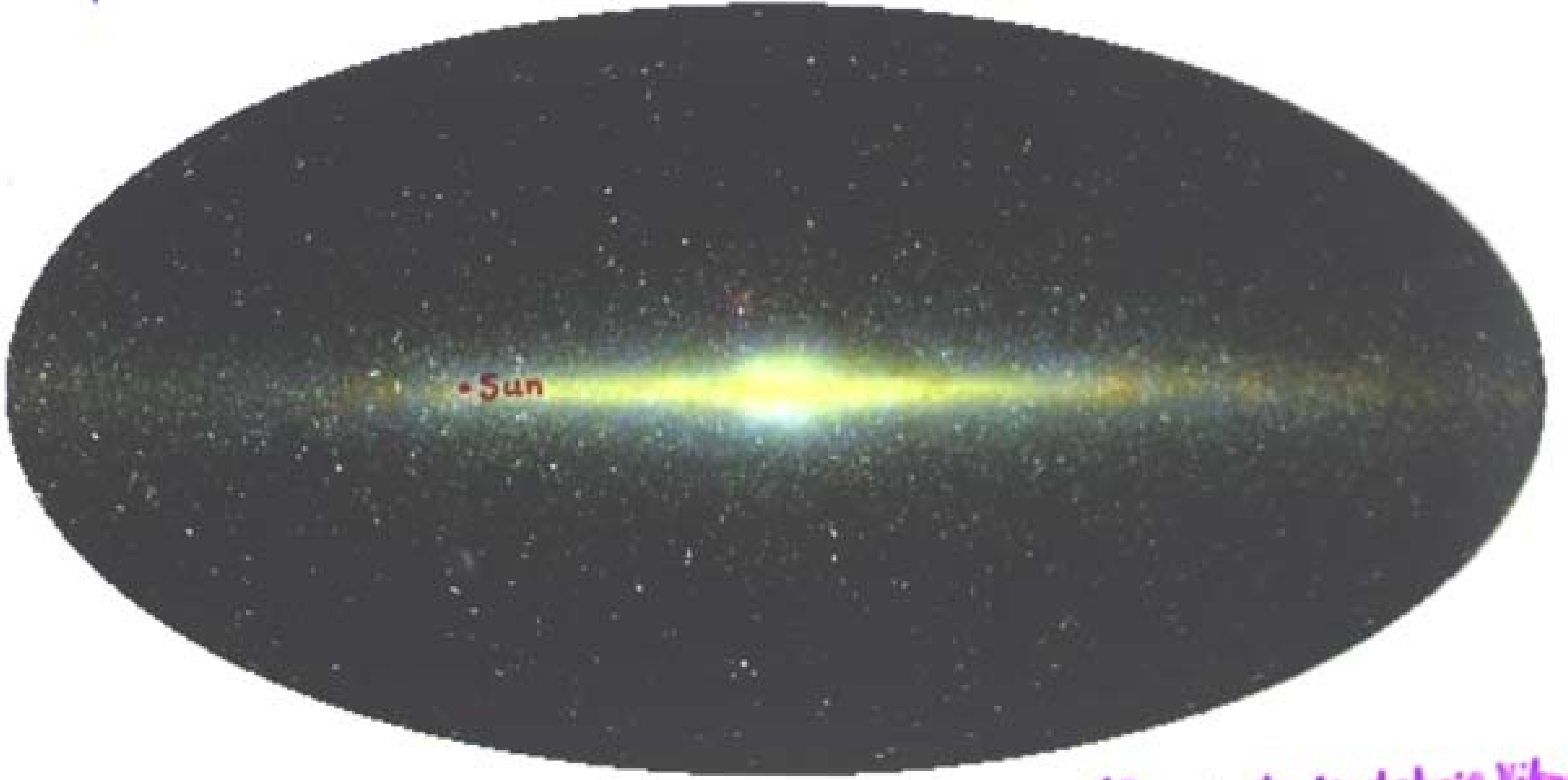
— energetics ✓

— composition ?

— anisotropy / clustering ✓

— spectrum ✓

Perhaps the post-GZK cosmic rays are produced locally in the Galactic halo through the slow decays of metastable supermassive particles clustered as cold dark matter ...



→ Spectrum determined by QCD fragmentation
... mostly γs and νs + some nucleons

→ Expect small anisotropy due to our off-centre position

(Berezinsky, Kachelrieß, Vilenkin
Birkel & Sarkar '98)

What should the universe be made of?

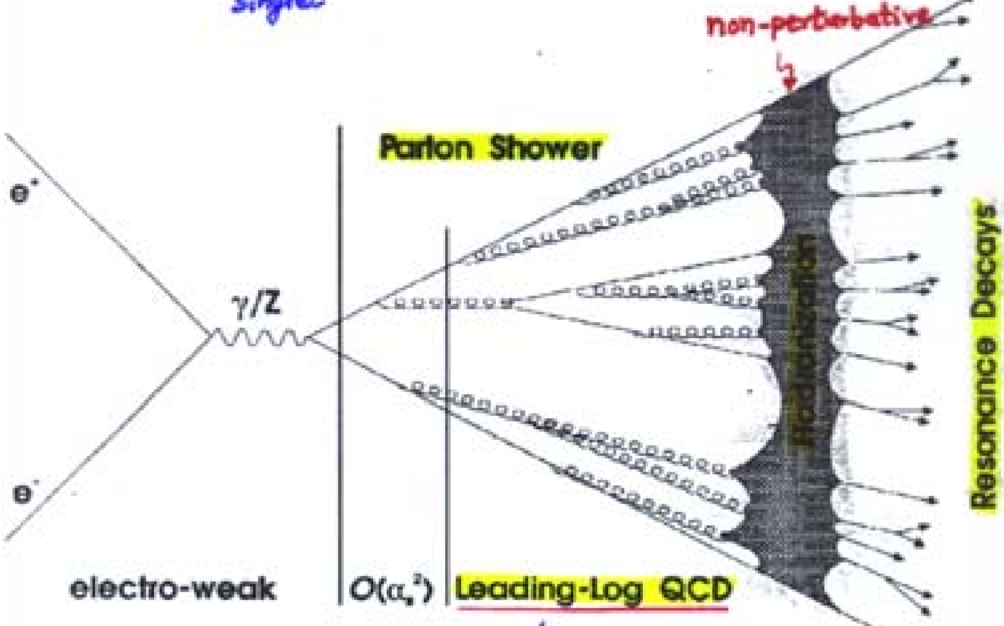
Mass scale	Particle	Symmetry	Stability	Production	Abundance
Λ_{QCD}	nucleon	B	$\tau > 10^{31}$ yr (dim-5, SUSY-GUTs)	~~thermal →~~ leptogenesis ? Affleck-Dine ?	~~$\Omega_B \sim 10^{-10}$~~ $\Omega_B \sim 0.05$
$G_F^{-1/2}$	LSP	R_P	? (could be violated)	thermal →	$\Omega_{LSP} \sim 1$
Λ_{HS} $\sim (G_F^{-1/2} M_P)^{1/2}$	'crypton'	discrete (model dependent)	$\tau \sim \frac{1}{M_X}\left(\frac{M_P}{M_X}\right)^{2(N-3)}$ $\sim 10^{10-18}$ yr $(N=8)$ for $M_X \sim \Lambda_{HS}$	gravitational field fluc. → inflaton decay ?	$\Omega_X \sim 1$
M_S	KK states	?	?	?	?

Conclusion : No definite indication from theoretical considerations
.... must decide by experiment !

Modelling the decay of a massive particle

$e^+e^- \rightarrow (X) \rightarrow q\bar{q} \rightarrow \text{jets}$: Fragmentation

colour singlet



Solution

DGLAP evolution of parton distributions – $\ln(Q^2)$ terms

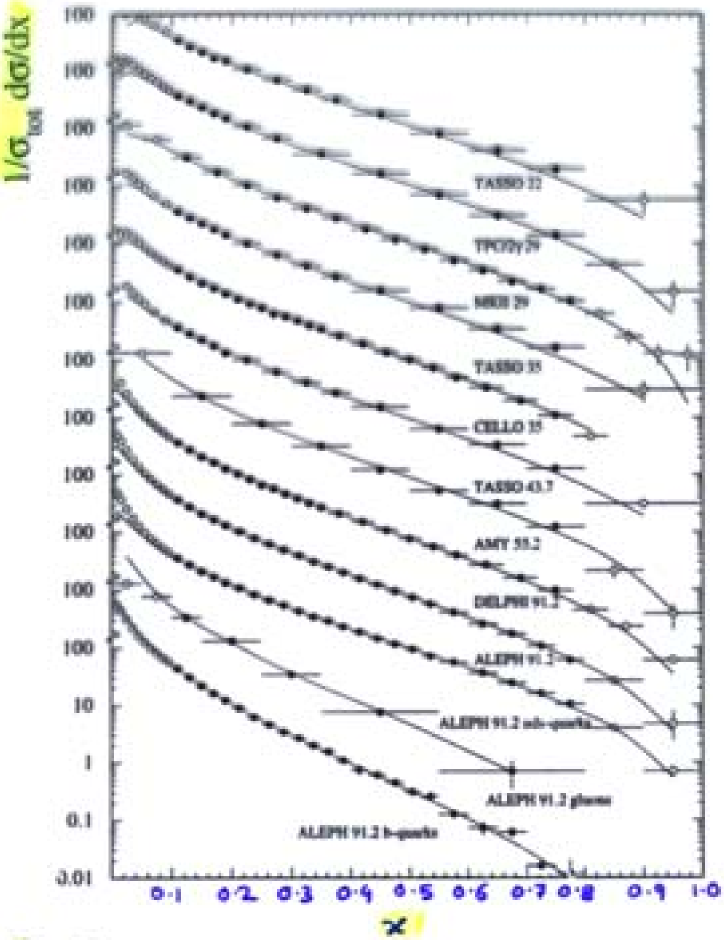
\+ next-to-leading corrections – $\ln(x)$ terms

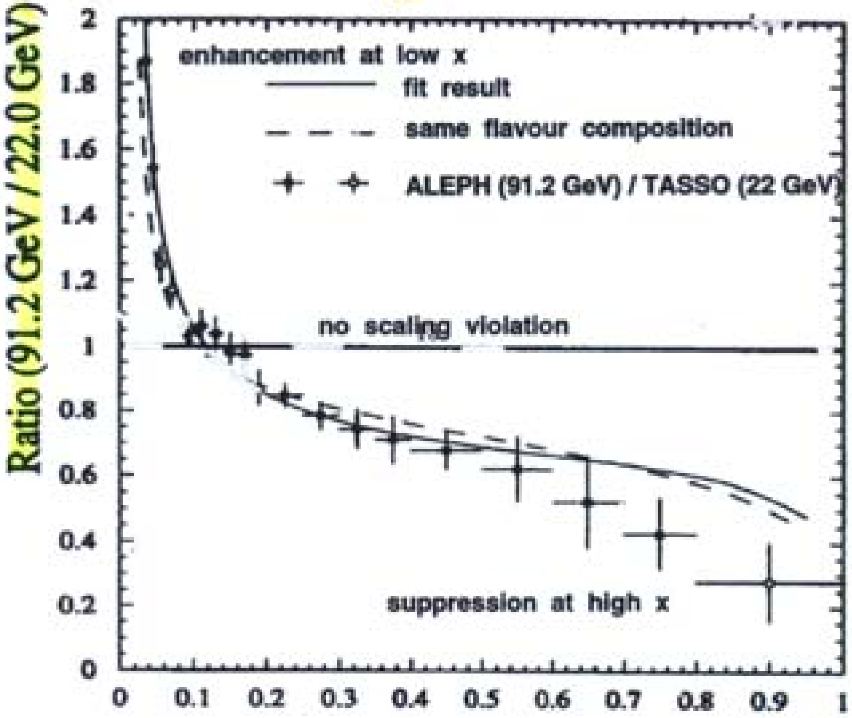
numerical → Coherent branching formalism in shower simulation code

analytic → Modified leading logarithmic approximation at $x \ll 1$

... the non-perturbative hadronization process is modelled semi-empirically, e.g. cluster model (HERWIG), string model (LUND)

Scaling violations in e^+e^- fragmentation





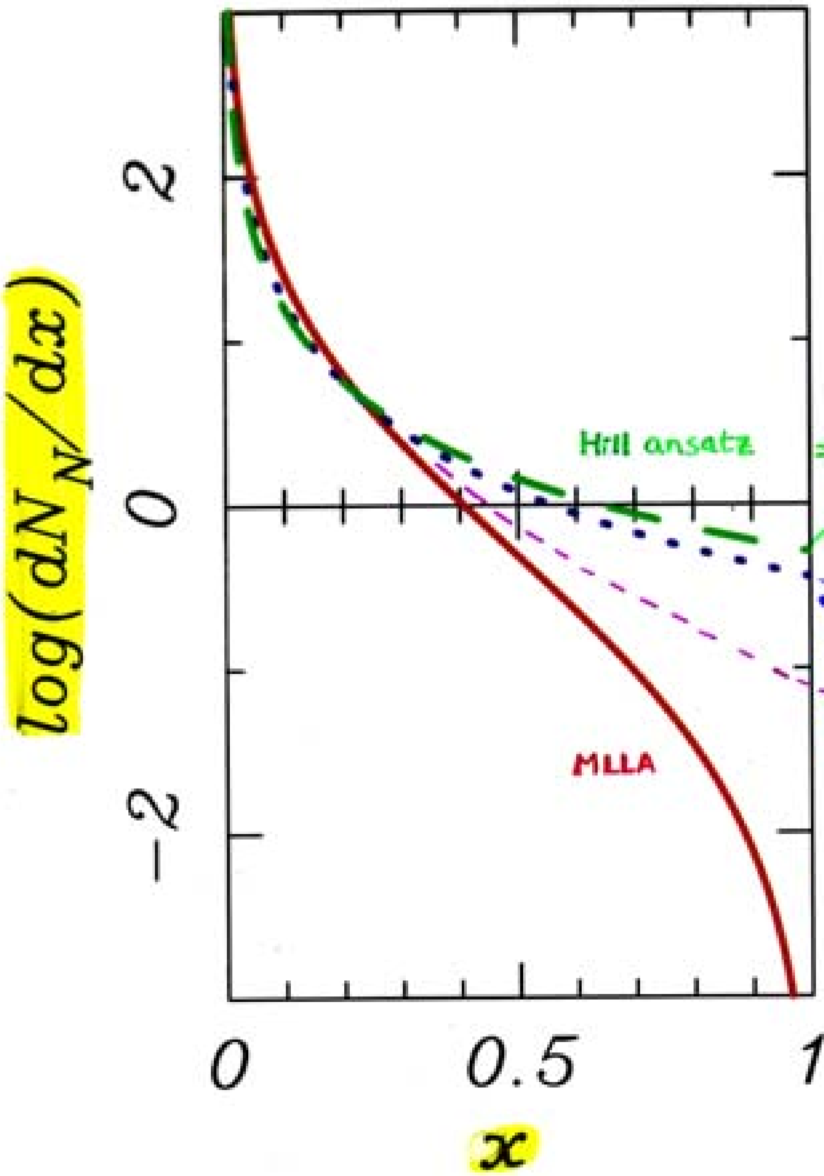
$x = 2E_h/\sqrt{s}$

Fragmentation functions used for study of 'top down' models

MLLA – valid only at $x \ll 1$, cannot be normalised

Hill ansatz – good fit at low energies (upto TeV)

... but does not account for scaling violations upto higher energies



$$= 0.08\,\frac{e^{2.6\sqrt{\ln(1/x)}}\,(1-x)^2}{x\sqrt{\ln(1/x)}}$$

$$= \frac{15}{16}\,x^{-3/2}\,(1-x)^2$$

DGLAP evolution of measured FFs (schematic)

→ correct answer lies in between these approximations

UHECR Spectrum from X Decay

Galactic halo populated with X particles, mass $M_X > 3 \times 10^{11}$ GeV, number density n_X and lifetime $\tau_X > t_0 \sim 10^{10}$ yr. Injection spectra:

$$\Phi^h(E) = \frac{n_X}{\tau_X} \frac{1}{\Gamma_X} \frac{d\Gamma(X \to h + \ldots)}{dE}. \tag{45}$$

Spherical halo radius R_{halo}. Differential flux from X decay reaching the upper layers of the Earth atmosphere

$$J^h(E) = \frac{1}{4\pi} R_{\text{halo}} \Phi^h(E). \tag{46}$$

In terms of FFs

$$E^3 J^h(E) = B x^3 D^h(x, M_X^2). \tag{47}$$

Common constant B for the Galactic flux of baryons, neutrinos and photons (excluding photon processing in the Galactic low frequency radio background)

Total flux: "low" energy component plus X contribution (assume baryons to be the observed UHECR):

$$E^3 J(E) = \frac{k}{E^m} + B x^3 D^{baryon}(x, M_X^2). \tag{48}$$

$$\begin{aligned} m &= 0.2 \pm 0.05, & (49) \\ k &= (2.31 \pm 0.16) \times 10^{24}\ \text{eV}^2\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1} \\ &\quad \times \left(6.3 \times 10^{18}\ \text{eV}\right)^{0.20 \pm 0.05} & (50) \end{aligned}$$

DGLAP Equations

Inclusive Decay Width $d\Gamma(X \to h + \ldots)$:

$$\frac{1}{\Gamma_X}\frac{d\Gamma_X}{dx} = \sum_a \int_x^1 \frac{dz}{z}\frac{1}{\Gamma_a}\frac{d\Gamma_a(y,\mu^2,M_X^2)}{dy}\bigg|_{y=x/z} D_a^h(z,\mu^2), \tag{7}$$

where $x \equiv 2E_h/M_X$ and $z \equiv E_h/E_a$.

Dokshitzer–Gribov–Lipatov–Altarelli-Parisi (DGLAP) equations:

$$\frac{\partial D_a^h(x,\mu^2)}{\partial \ln \mu^2} = \sum_b \frac{\alpha_s(\mu^2)}{2\pi} P_{ba}(x,\alpha_s(\mu^2)) \otimes D_b^h(x,\mu^2), \tag{8}$$

$$A(x) \otimes B(x) \equiv \int_x^1 \frac{dz}{z} A(z) B(\frac{x}{z}). \tag{9}$$

Splitting function branching $a \to b$:

$$P_{ba}(x,\alpha_s) = P_{ba}(x) + O(\alpha_s). \tag{10}$$

Evolution parameter:

$$\tau \equiv \frac{1}{2\pi b} \ln \frac{\alpha_s(\mu_0^2)}{\alpha_s(\mu^2)}, \tag{11}$$

with $\beta(\alpha_s) = -b\alpha_s^2$

Standard Model Equations

Two parton species: quarks q_k, $k = 1, \ldots n_F$ and gluons g, with n_F the total number of flavours.

$$\begin{aligned} D_{q_k^+} &\equiv D_{q_k} + D_{\bar{q}_k}, && (12) \\ D_q &\equiv \sum_k D_{q_k^+}, && (13) \\ D_{q_k^-} &\equiv D_{q_k} - D_{\bar{q}_k}, && (14) \\ D_{Q_k} &\equiv D_{q_k^+} - \frac{1}{n_F} D_q. && (15) \end{aligned}$$

The non-singlet functions D_{q_k} and D_{Q_k} obey the equations

$$\begin{aligned} \partial_\tau D_{q_k^-} &= P_{qq} \otimes D_{q_k^-}, && (16) \\ \partial_\tau D_{Q_k} &= P_{qq} \otimes D_{Q_k}, && (17) \end{aligned}$$

while the evolution of the singlet function D_q is coupled to the evolution of the gluon function D_g as

$$\partial_\tau \begin{pmatrix} D_q \\ D_g \end{pmatrix} = \begin{pmatrix} P_{qq} & 2n_F P_{gq} \\ P_{qg} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} D_q \\ D_g \end{pmatrix}. \qquad (18)$$

Supersymmetric Equations

Quarks q_k, squarks s_k, $k = 1, \ldots n_F$, gluons g and gluinos λ. SM linear combinations plus

$$\begin{aligned} D_{s_k^+} &\equiv D_{s_k} + D_{\bar{s}_k}, && (19) \\ D_s &\equiv \sum_k D_{s_k^+}, && (20) \\ D_{s_k^-} &\equiv D_{s_k} - D_{\bar{s}_k}, && (21) \\ D_{S_k} &\equiv D_{s_k^+} - \frac{1}{n_F} D_s. && (22) \end{aligned}$$

The non-singlet function $D_{q_k^-}$ and $D_{s_k^-}$ evolve together, as do D_{Q_k} and D_{S_k}:

$$\begin{aligned} \partial_\tau \begin{pmatrix} D_{q_k} \\ D_{s_k^-} \end{pmatrix} &= \begin{pmatrix} P_{qq} & P_{sq} \\ P_{qs} & P_{ss} \end{pmatrix} \otimes \begin{pmatrix} D_{q_k^-} \\ D_{s_k^-} \end{pmatrix}, && (23) \\ \partial_\tau \begin{pmatrix} D_{Q_k} \\ D_{S_k} \end{pmatrix} &= \begin{pmatrix} P_{qq} & P_{sq} \\ P_{qs} & P_{ss} \end{pmatrix} \otimes \begin{pmatrix} D_{Q_k} \\ D_{S_k} \end{pmatrix}. && (24) \end{aligned}$$

The singlet functions for quarks and squarks, D_q and D_s, are coupled to the gluon and gluino functions, D_g and D_λ, as

$$\partial_\tau \begin{pmatrix} D_q \\ D_g \\ D_s \\ D_\lambda \end{pmatrix} = \begin{pmatrix} P_{qq} & 2n_F P_{gq} & P_{sq} & 2n_F P_{\lambda q} \\ P_{qg} & P_{gg} & P_{sg} & P_{\lambda g} \\ P_{qs} & 2n_F P_{gs} & P_{ss} & 2n_F P_{\lambda s} \\ P_{q\lambda} & P_{g\lambda} & P_{s\lambda} & P_{\lambda\lambda} \end{pmatrix} \otimes \begin{pmatrix} D_q \\ D_g \\ D_s \\ D_\lambda \end{pmatrix}. \tag{25}$$

DGLAP: Initial Conditions and Evolution Steps

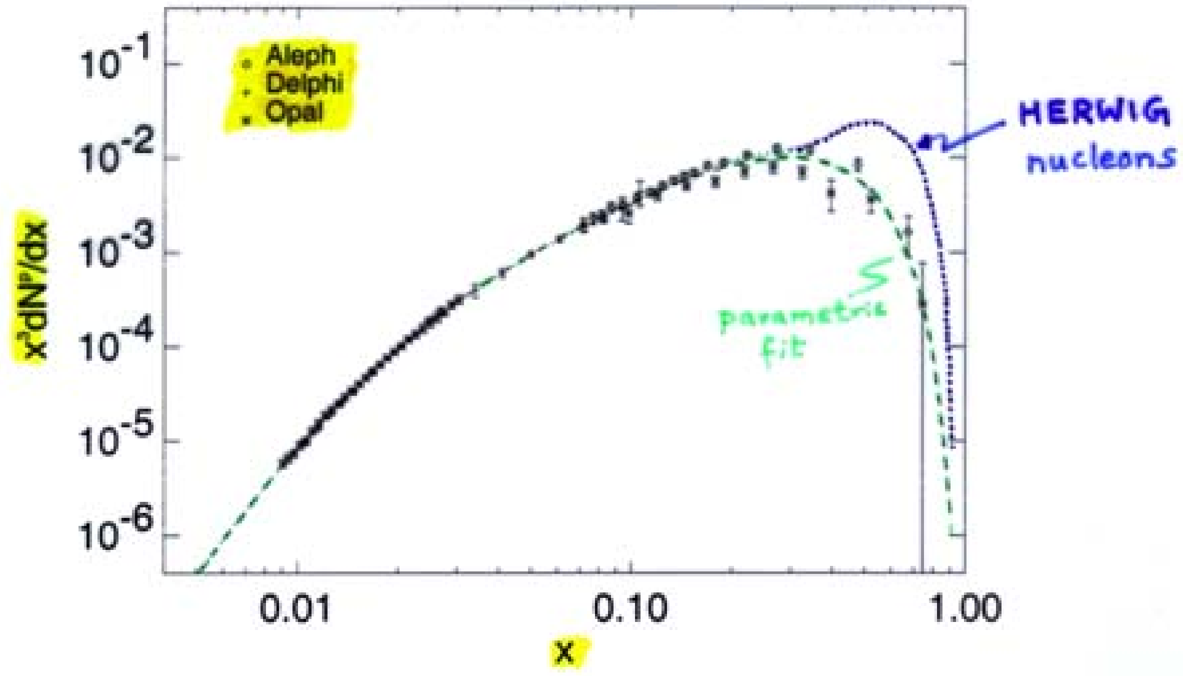
Start evolution at the energy scale M_Z. Evolve baryon $p+n$, photon γ and neutrino $\nu_e+\nu_\mu+\nu_\tau$ fragmentation functions (FF) to the superheavy mass scale M_X.

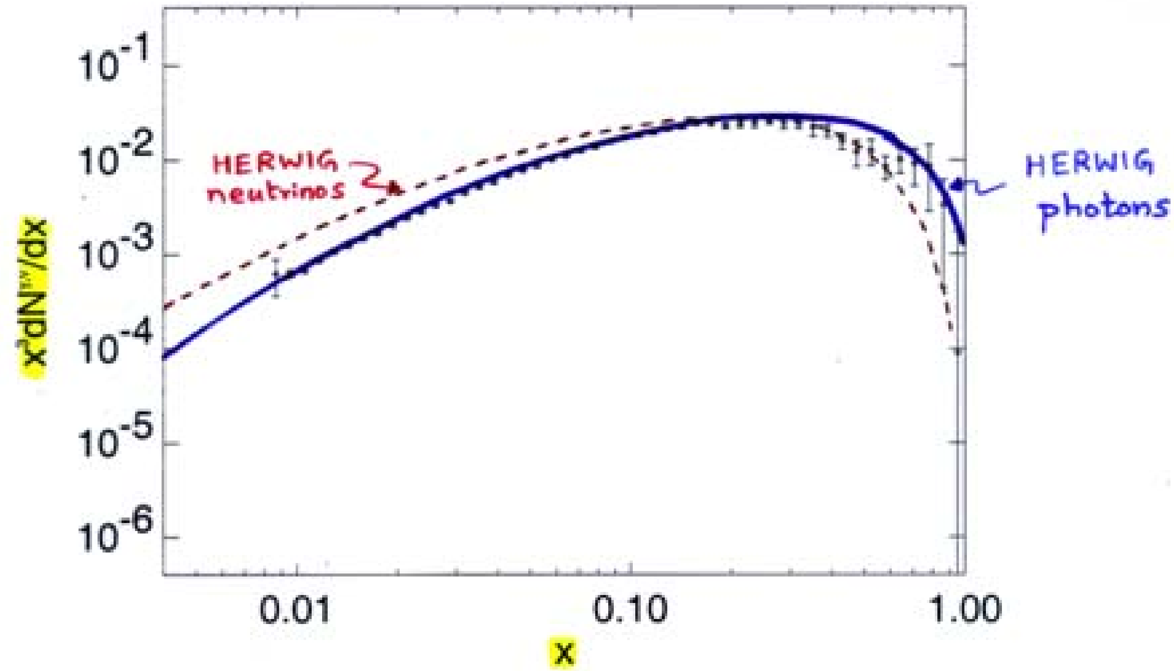
- Baryons. Use LEP data. HERWIG overproduces baryons at high x.
- Photons. Use LEP data. HERWIG fits well the data.
- Neutrinos. No data available. HERWIG fits well meson data. Neutrinos mainly stem from $\pi^\pm$ and K decay ⇒ use HERWIG output.

Assume flavour universality in the decay of X ⇒ evolve only quark and squark singlets, gluon and gluino.

- In the SM evolve FFs from M_Z to M_X using the q, g coupled equations in the whole energy range.
- In a SUSY model evolve FFs from M_Z to M_{SUSY} using the SM equations. M_{SUSY} is the SUSY breaking scale. All spartons taken to be degenerate with a common mass M_{SUSY}. Then take $D_q(x, M^2_{SUSY})$ and $D_g(x, M^2_{SUSY})$ obtained with SM evolution, set $D_s(x, M^2_{SUSY}) = 0$ and $D_\lambda(x, M^2_{SUSY}) = 0$ and evolve them to the final scale M_X using the SUSY equations, coupled q, g, s, λ equations.

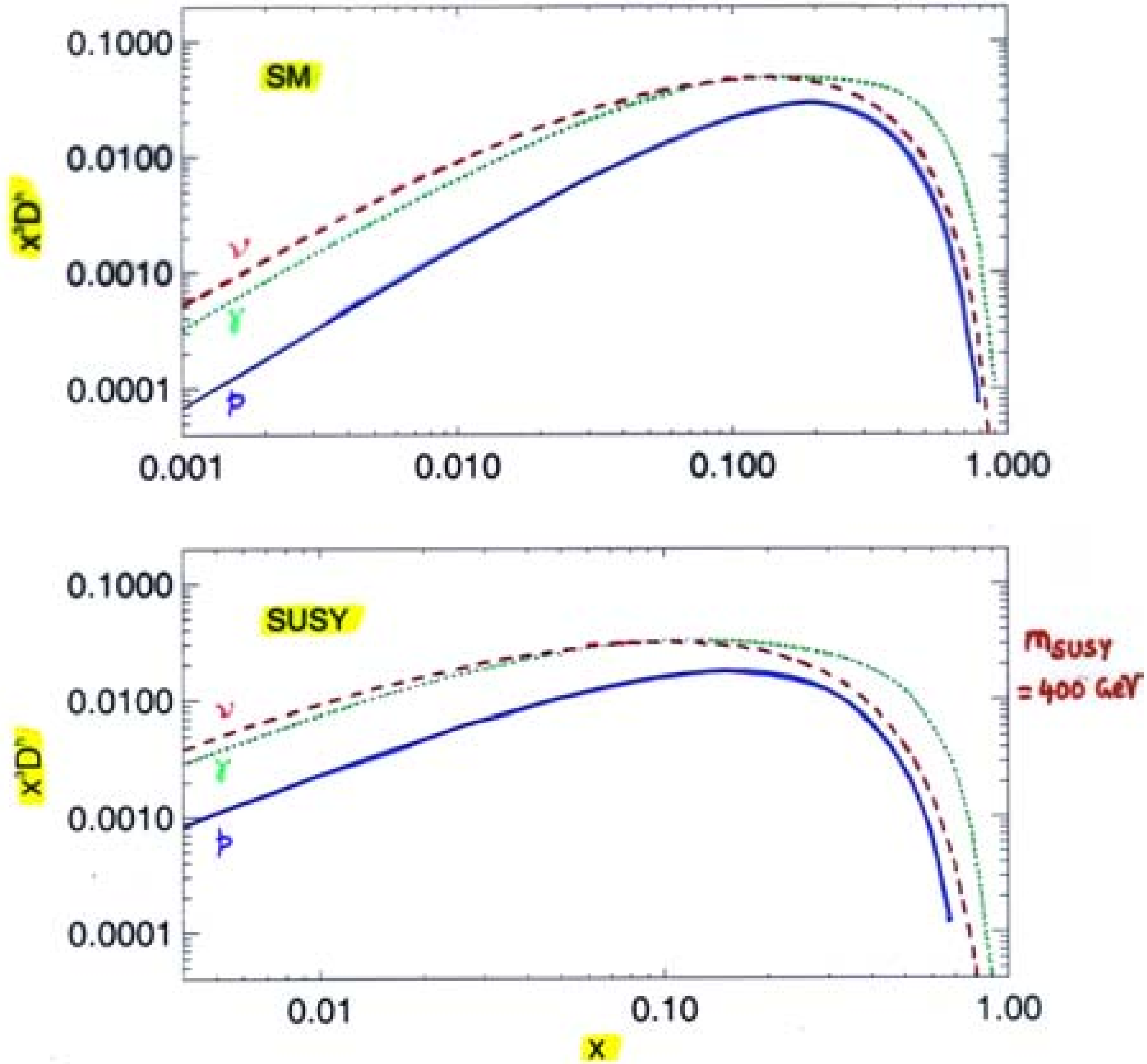
Fragmentation functions at m_{Z^0}





Sarkar & Toldra
(hep-ph/0108018)

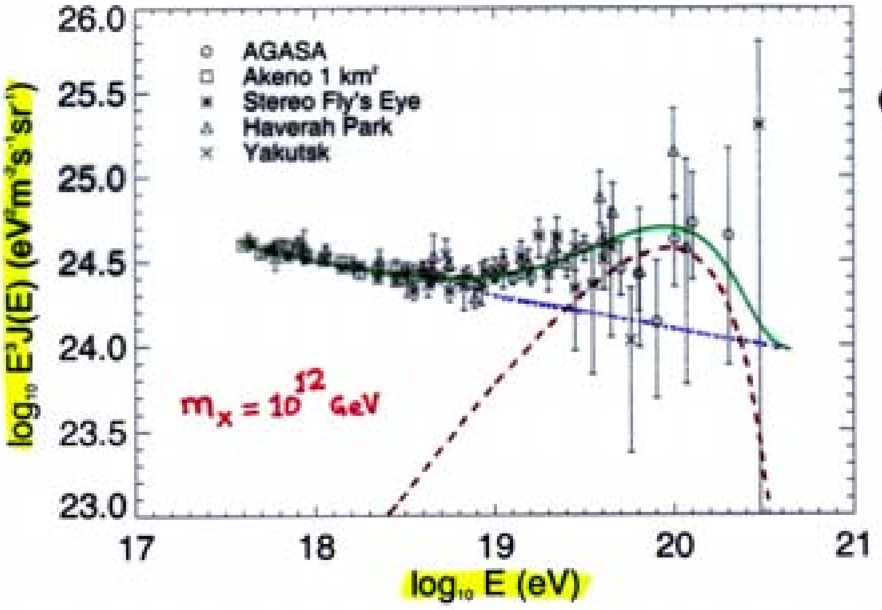
Fragmentation functions at 10^{12} GeV



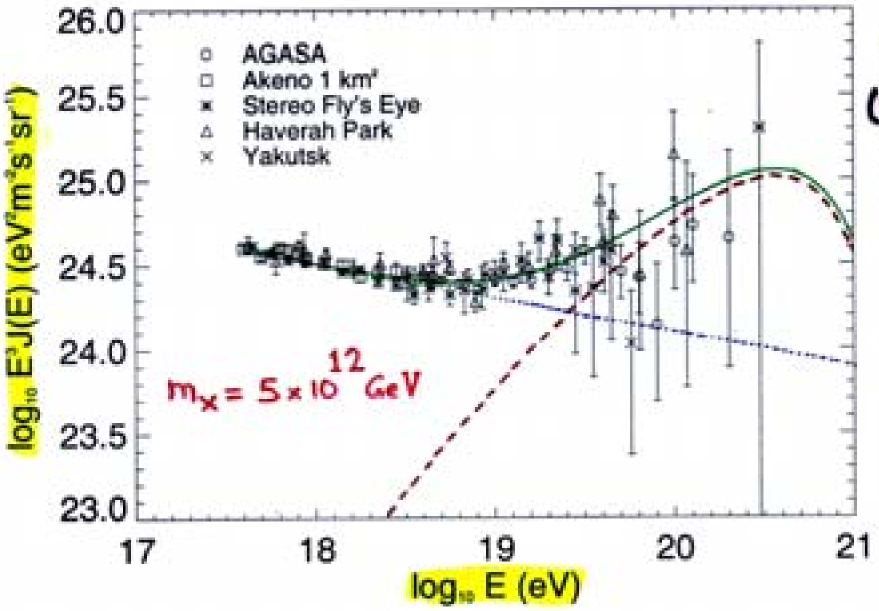
... evolved from m_{Z^0} using DGLAP eqns.

Sarkar & Toldra
(hep-ph/0108098)

Fit to UHECR data with halo DM decay spectrum



SM
evolution



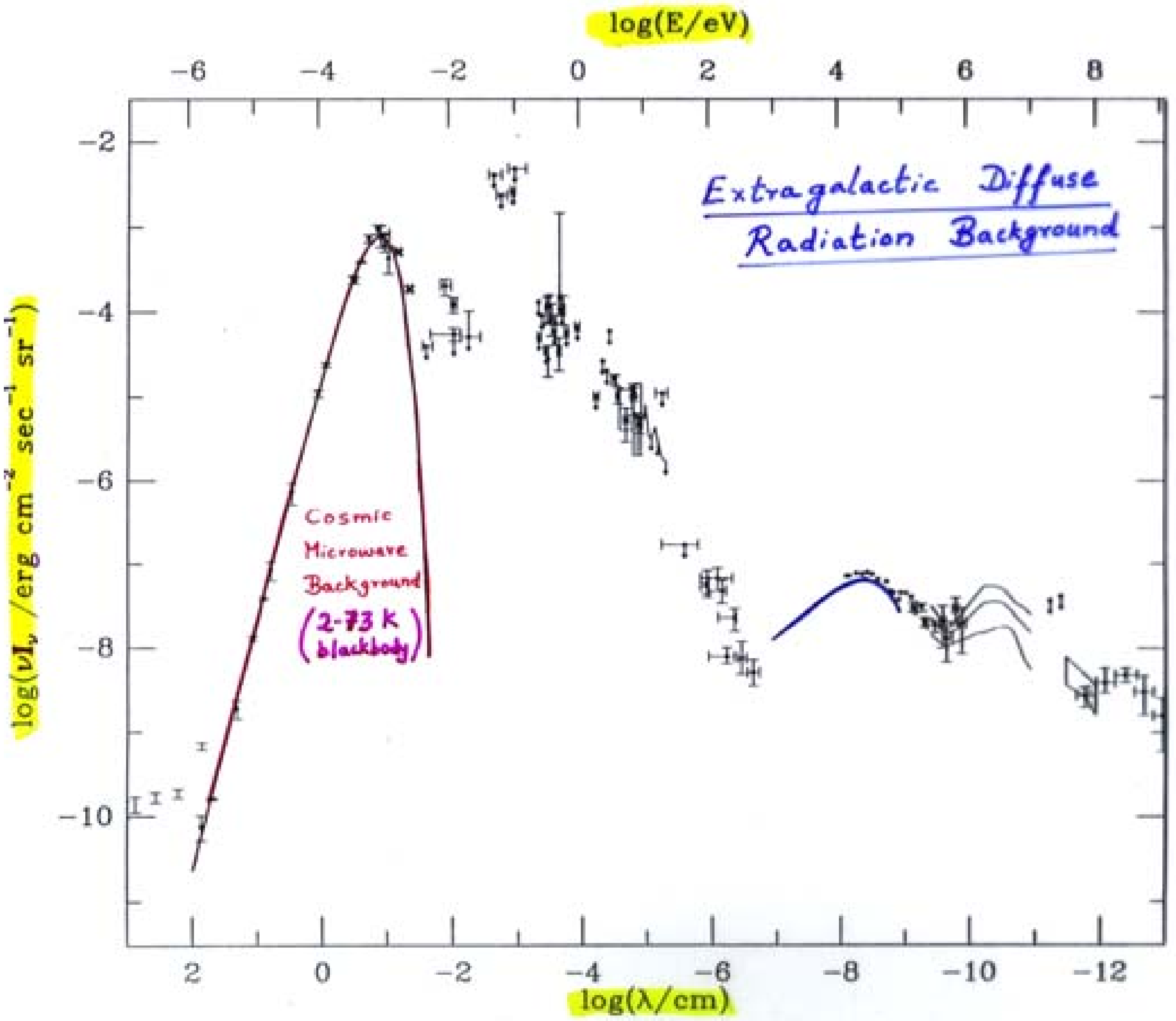
SUSY
(m_{SUSY}=400GeV)
evolution

normalisation ⇒ $\frac{\tau_x}{t_0} \sim 2 \times 10^9 \xi_x$

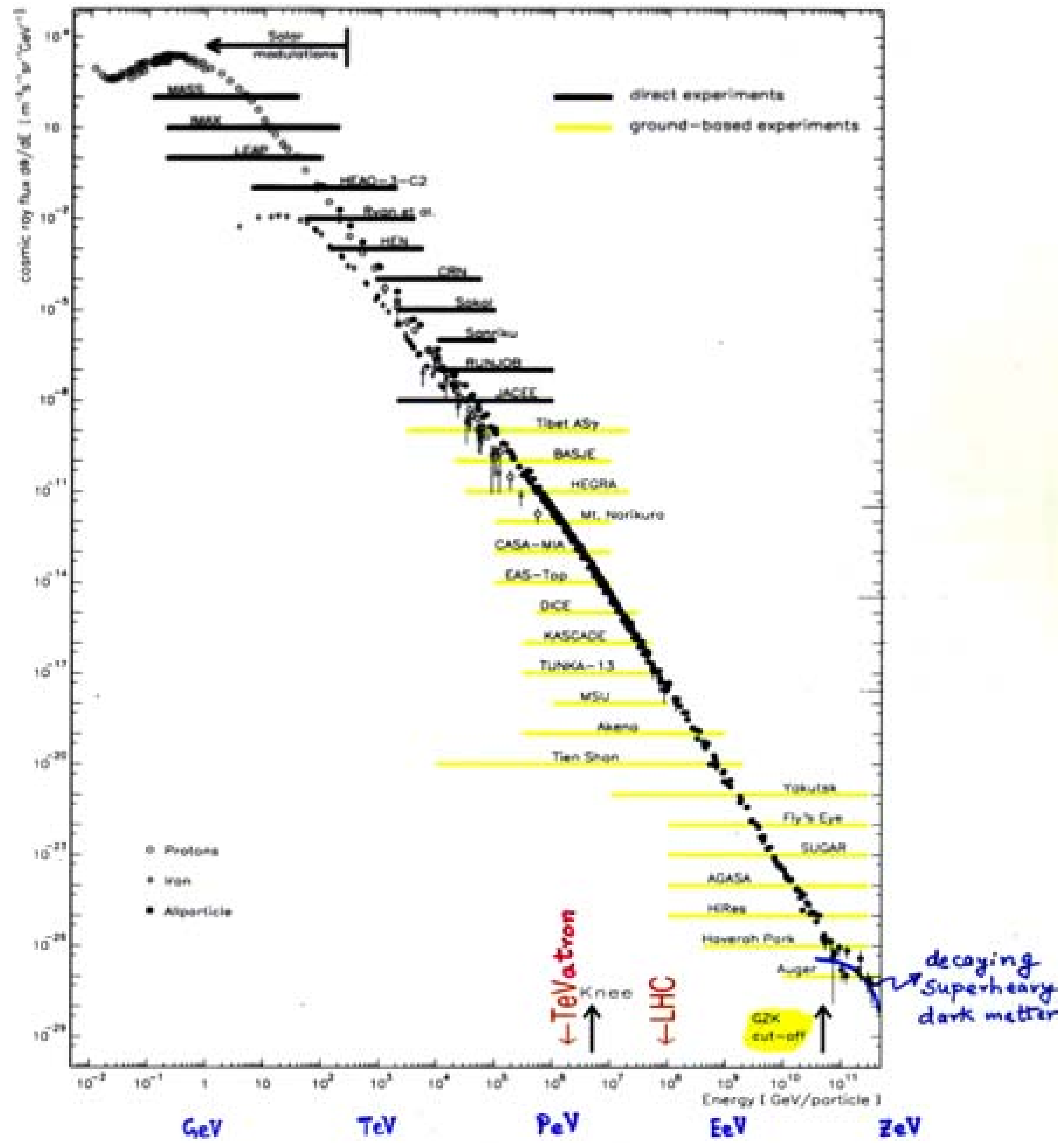
τ_x/t_0: $\sim 10^{10}$ yr

ξ_x: fraction of halo DM in x particles

Sarkar & Toldra
(hep-ph/0108098)

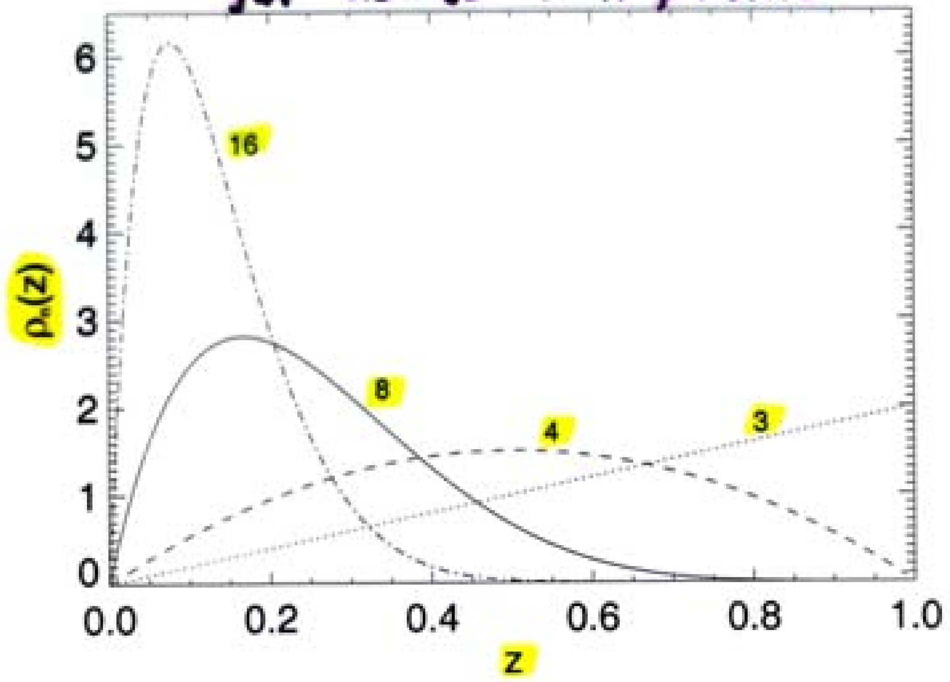

Extragalactic Diffuse Radiation Background
Cosmic Microwave Background
(2·73 K blackbody)
log(E/eV)
−6
−4
−2
0
2
4
6
8
$\log(\nu I_\nu\ /\mathrm{erg\ cm^{-2}\ sec^{-1}\ sr^{-1}})$
−2
−4
−6
−8
−10
log(λ/cm)
2
0
−2
−4
−6
−8
−10
−12

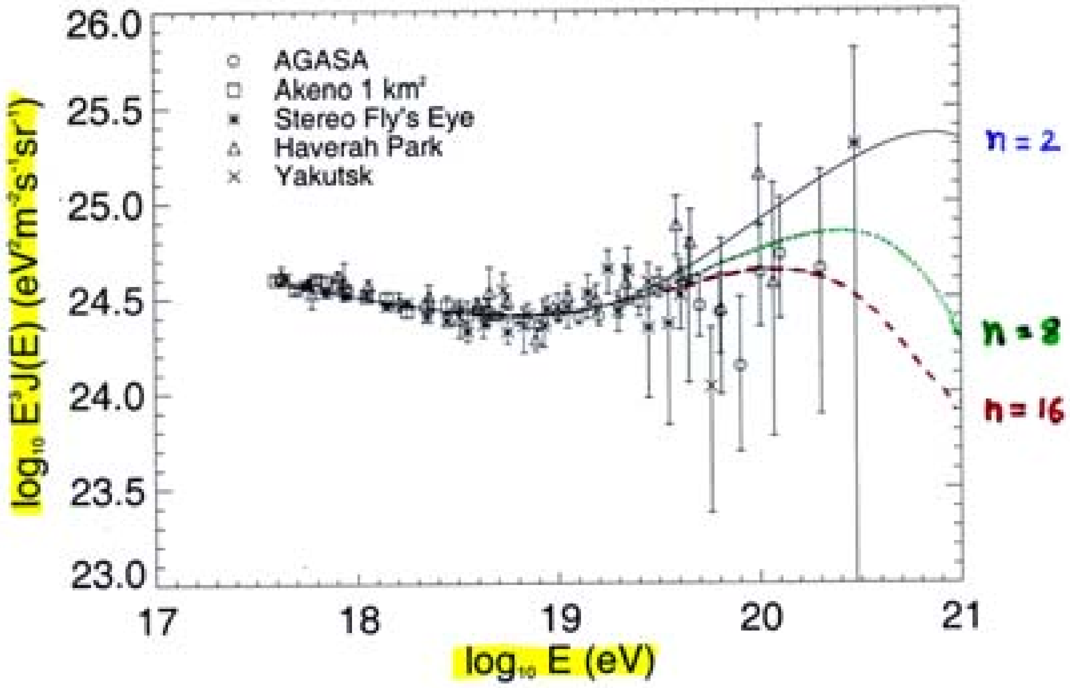
Energy spectrum of primary cosmic rays



(from B. Wiebel-Sooth, Dissertation, University. of Wuppertal, WUB-DIS-98-9, Sept. 1998)

Prob. density of final state phase-space for decays → n partons





... better fit to data for multi-body decays

Sarkar & Toldra
(hep-ph/0108098)

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The asymmetric position of the Sun in the Galaxy → small anisotropy of UHECRs from halo DM

(Dubovsky & Tinyakov '98, Berezinsky & Mikhailov '99, Medina-Tanco & Watson '99)

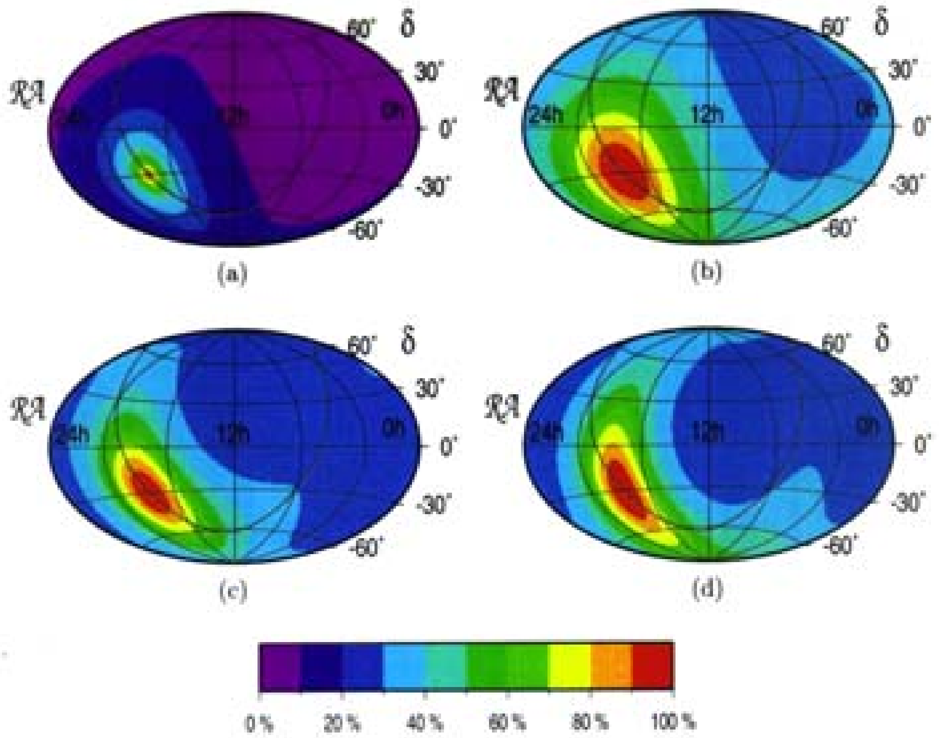
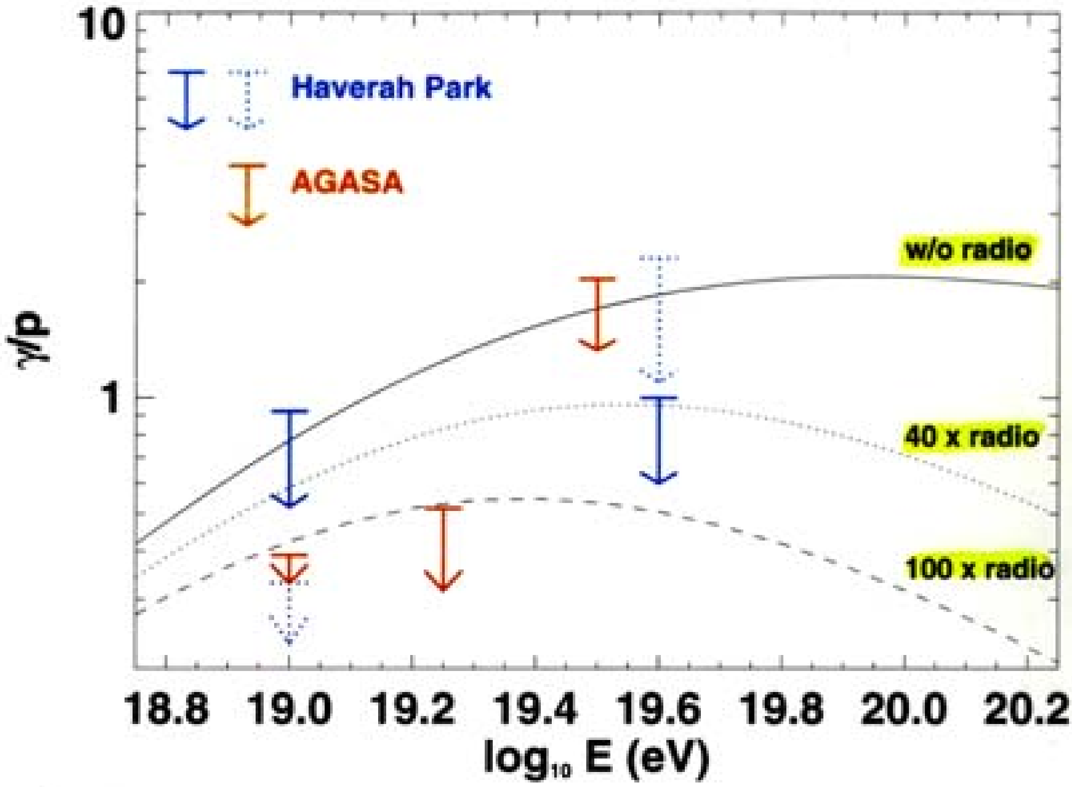

(a) (b) (c) (d)

Fig. 1.— Contour plots of the UHECR flux in equatorial coordinates for our four dark halo models, namely (a) cusped, (b) isothermal, (c) triaxial and (d) tilted. These are Hamer-Aitoff projections. The Galactic plane is marked in each figure. The effect of the halo of M31 is visible in the upper right of each plot. (Evans, Ferrer, Sarkar, astro-ph/0103085)

... present data inadequate to determine whether this anisotropy is present, but Auger South should be able to do so (~ 2005)

Experimental bounds on the γ/p ratio in UHECR do not rule out the decaying dark matter model

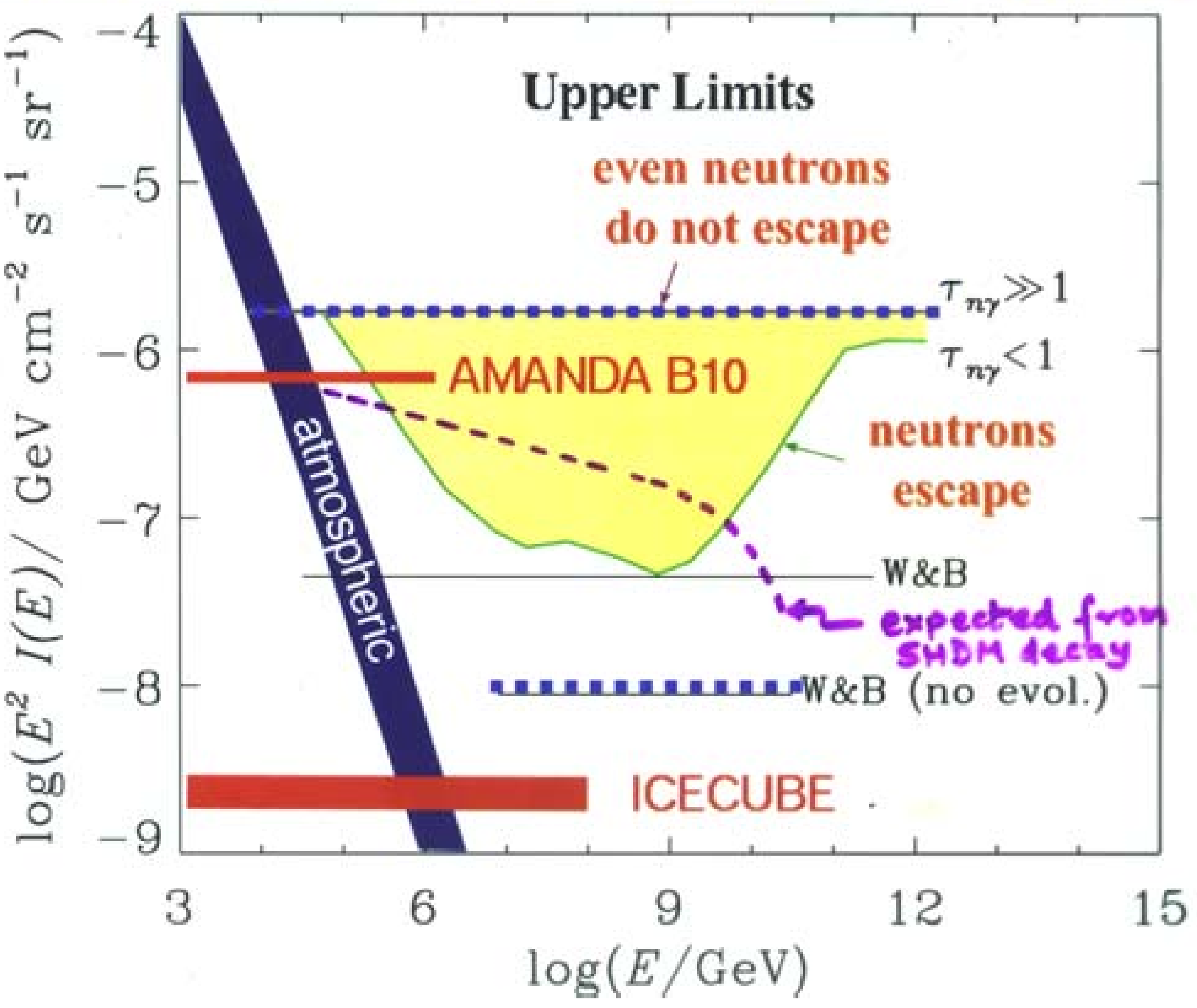


S.Sarkar, G.Sigl and R.Toldrà 2002

... the UHE γs from decaying dark matter in the Galactic halo may be significantly attenuated through $\gamma\gamma \rightarrow e^+e^-$ scattering on the (poorly known) ~1 MHz radio background

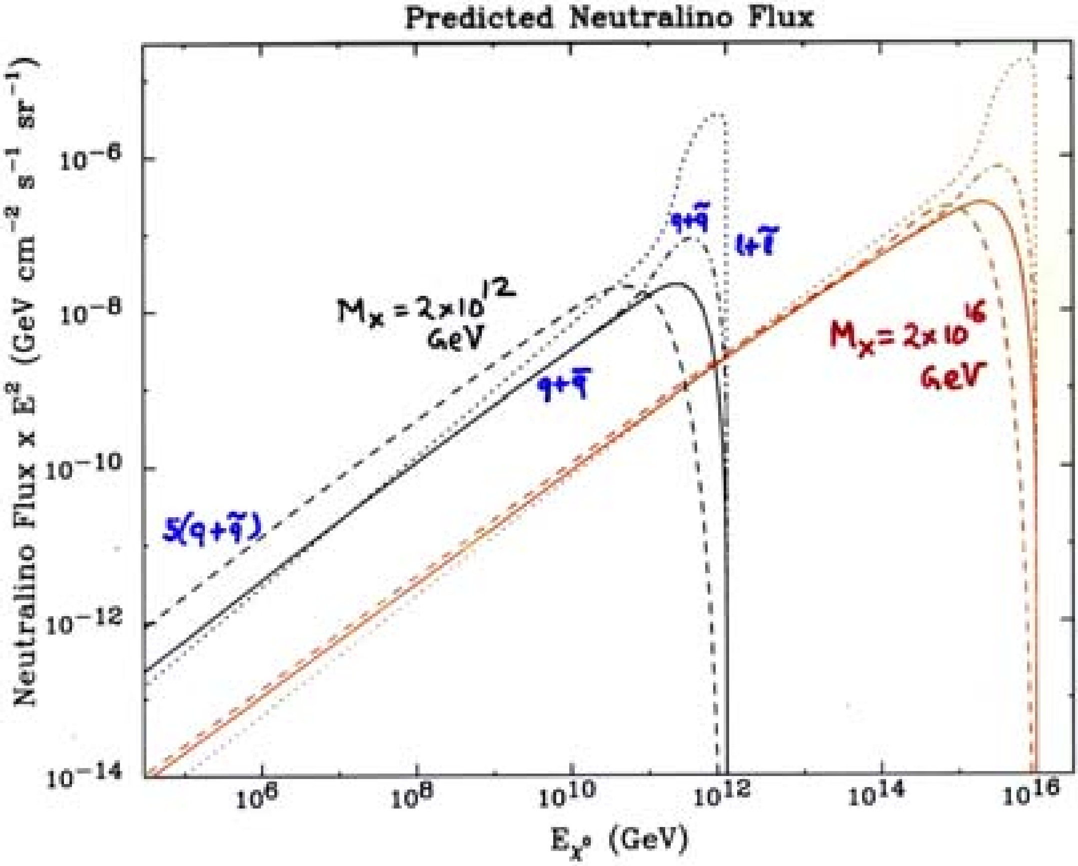
→ the processed flux at lower energies is well below the EGRET measurements at ~100 MeV

neutrinos associated with the source of the cosmic rays?



A high energy flux of neutralinos (LSP) is also predicted ...

Berezinsky & Kachelreiß '98
Barbot & Drees '02
Ibarra & Toldra '02



Barbot, Drees, Halzen, Hooper
(hep-ph/0207133)

→ can be detected by EUSO/OWL even if $\sigma_{\chi^0} = \sigma_\nu/100$

Conclusions

Ultra-high energy cosmic rays may arise from decays of $\sim 10^{12}$ GeV mass relic particles, clustered as halo dark matter

The model makes robust predictions for the energy spectrum and anisotropy so is falsifiable by ongoing/forthcoming experiments (Auger, EUSO, IceCube ...)

If true, this will be the first direct signature of physics well beyond the electroweak scale ...