"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)

Dark matter and ultrahigh energy cosmic rays

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Cosener's House Workshop on Cosmic Particles, 18-20 February 2004

What should the world be made of?

Mass scale	Particle	Symmetry/ Quantum number	Stability	Production	Abundance
Λ_{QCD}	nucleon	baryon number	τ > 10^{31} yr dim-5 SUSY-GUTs	freeze-out from thermal equilibrium	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$!
$1/\sqrt{G_F}$	neutralino?	R-parity?	violated?	freeze-out from thermal equilibrium	$\Omega_{LSP} \sim 1$
$\Lambda_{\text{hidden sector}}$ $\sim(M_{Pl}/\sqrt{G_F})^{1/2}$	'crypton'?	discrete (very model-dependent)	$\tau \sim 10^{10\text{-}18}$ yr for $m_x \sim \Lambda_{hs}$	not in thermal equilibrium … Inflation →	$\Omega_X \sim 1$
M_{string} ; M_{Pl}	Kaluza-Klein states?	?	?	?	?

No definite indication from theory … must decide by experiment!

Apart from the CMB, we have no evidence for any other *thermal* relic of the Big Bang

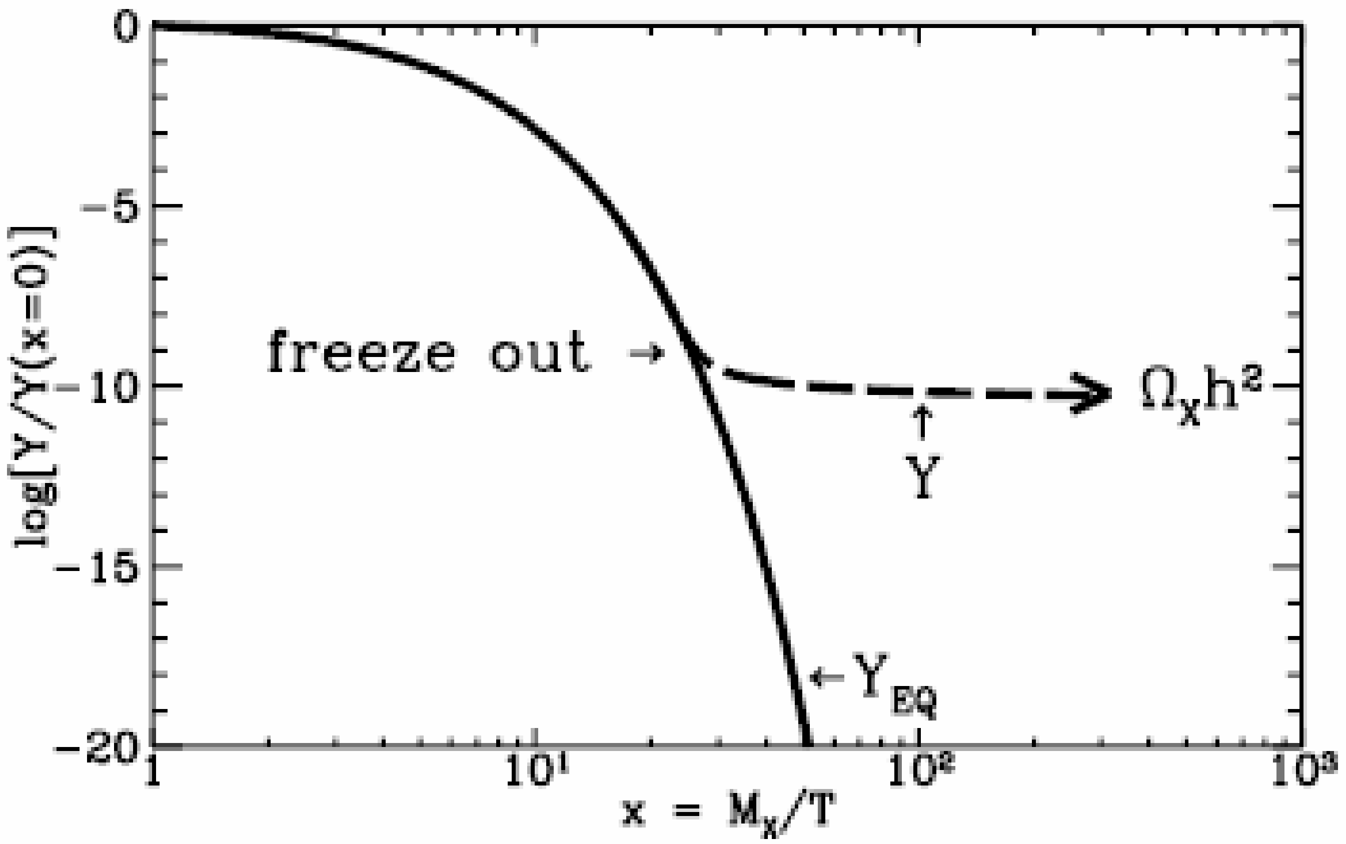


Figure 1. A thermal relic starts in LTE at $T \gg M_X$. When the rates keeping the relic in chemical equilibrium become smaller than the expansion rate, the density of the relic relative to the entropy density freezes out.

Superheavy dark matter particles (“wimpzillas”) can be produced with $\Omega_x \sim 1$ at the end of inflation → due to the *changing* gravitational field acting on vacuum quantum fluctuations of the dark matter field (Chung, Kolb, Riotto 1998)

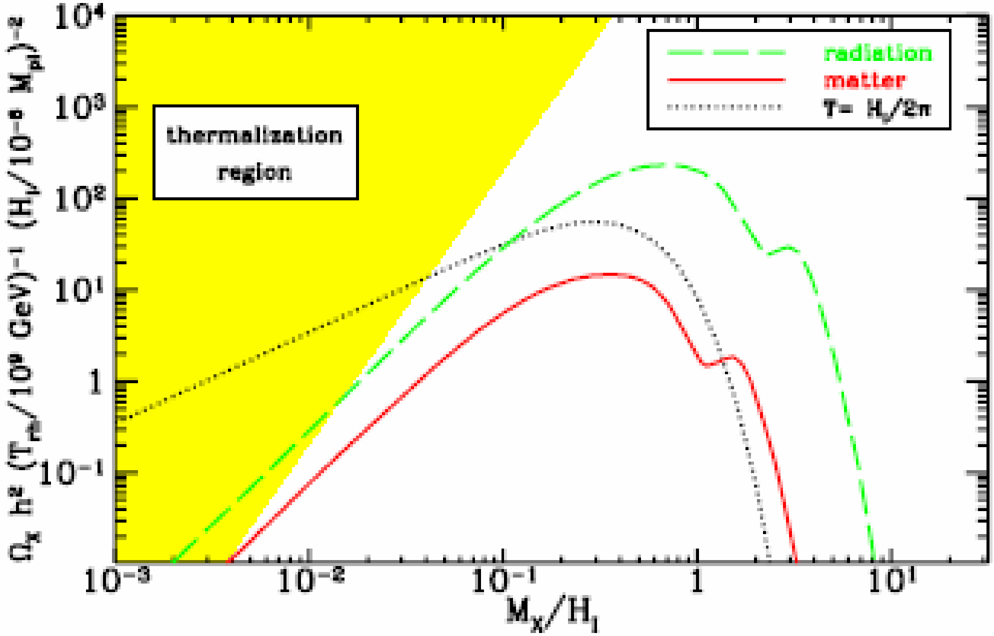
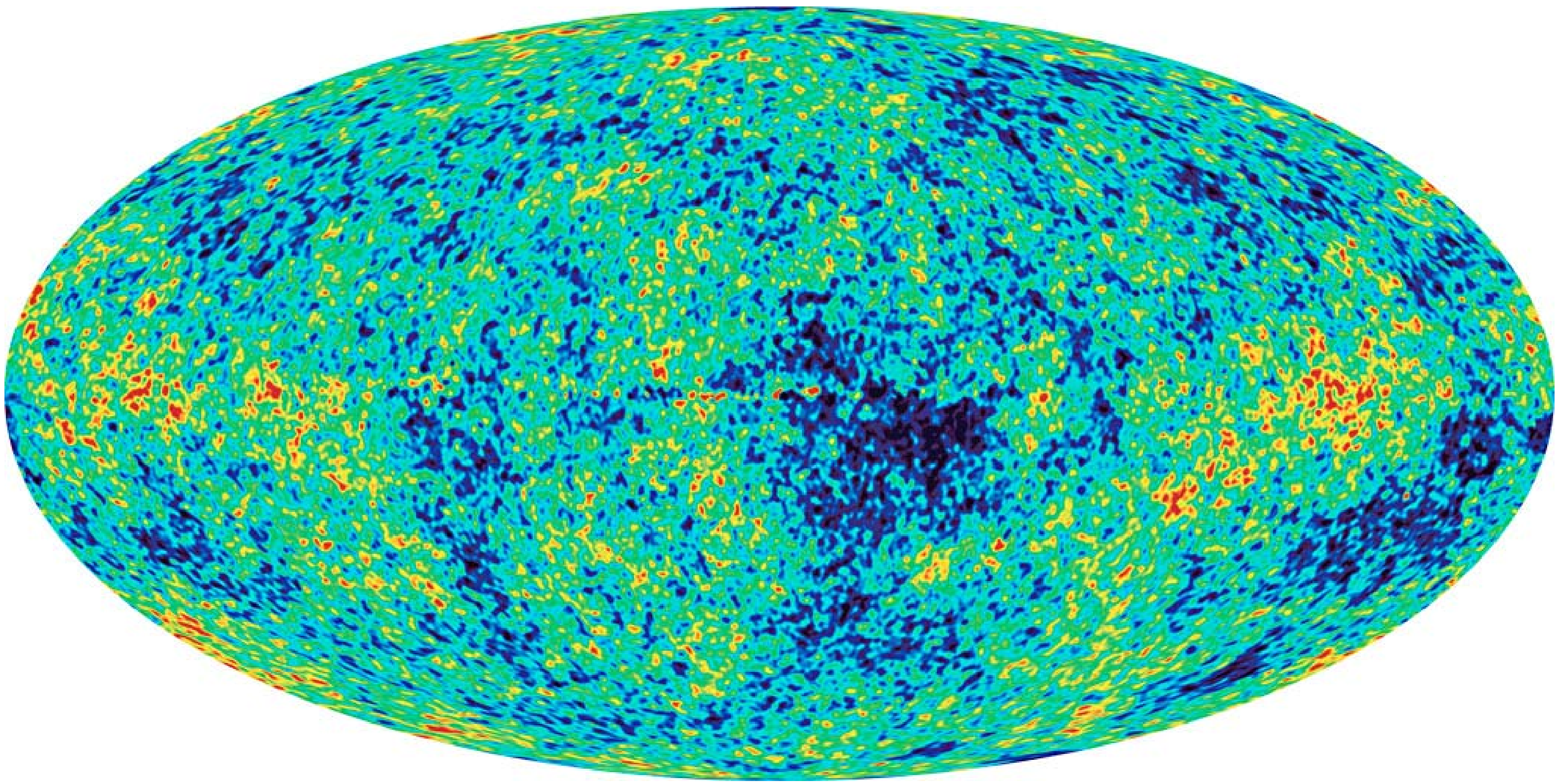


Figure 2. The contribution of gravitationally produced WIMPZILLAS to $\Omega_X h^2$ as a function of M_X/H_I. The shaded area is where thermalization *may* occur if the annihilation cross section is its maximum value. Also shown is the contribution assuming that the WIMPZILLA is present at the end of inflation with a temperature $T = H_I/2\pi$.

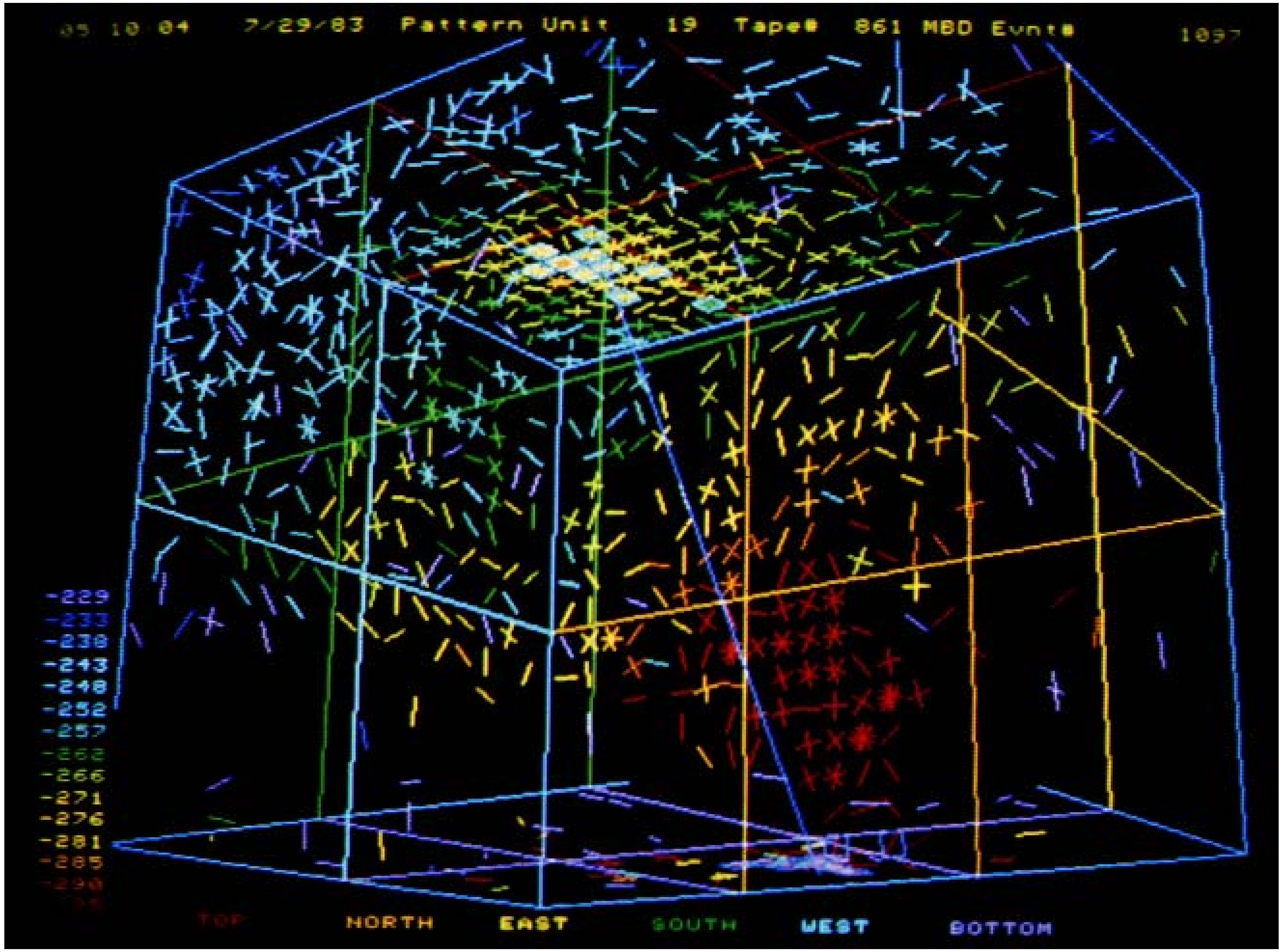
… they may constitute part (or even all) of the `cold dark matter’

The fluctuations observed in the CMB imply a period of primordial inflation, with a Hubble parameter $H \leq 1.5\text{x}10^{-5}\, M_{Pl} \approx 10^{14}$ GeV



… so it is quite possible that supermassive particles were created with a cosmologically interesting abundance

All massive particles *must* be weakly unstable due to non-renormalisable interactions
… their slow decays should eventually create high energy neutrinos



Upward going muon in IMB

Experimental upper limits on UHE cosmic neutrino fluxes set bounds on the decaying particle abundance/lifetime …

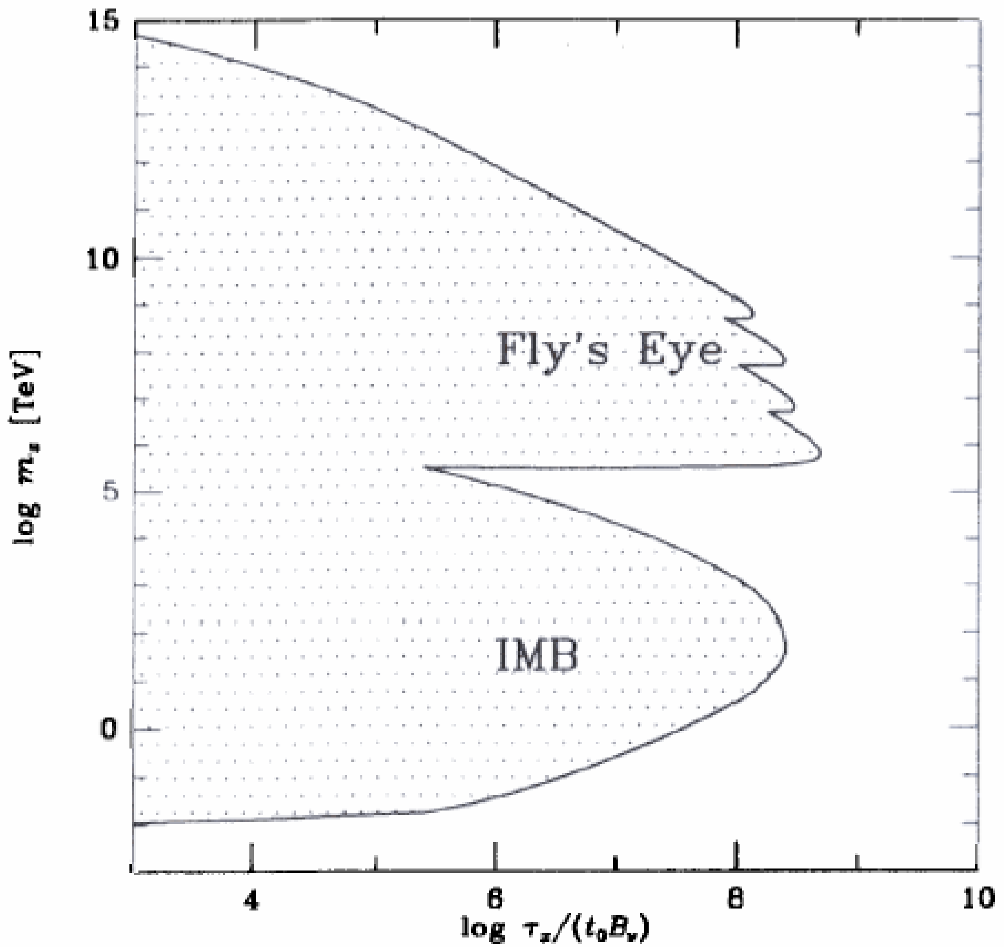
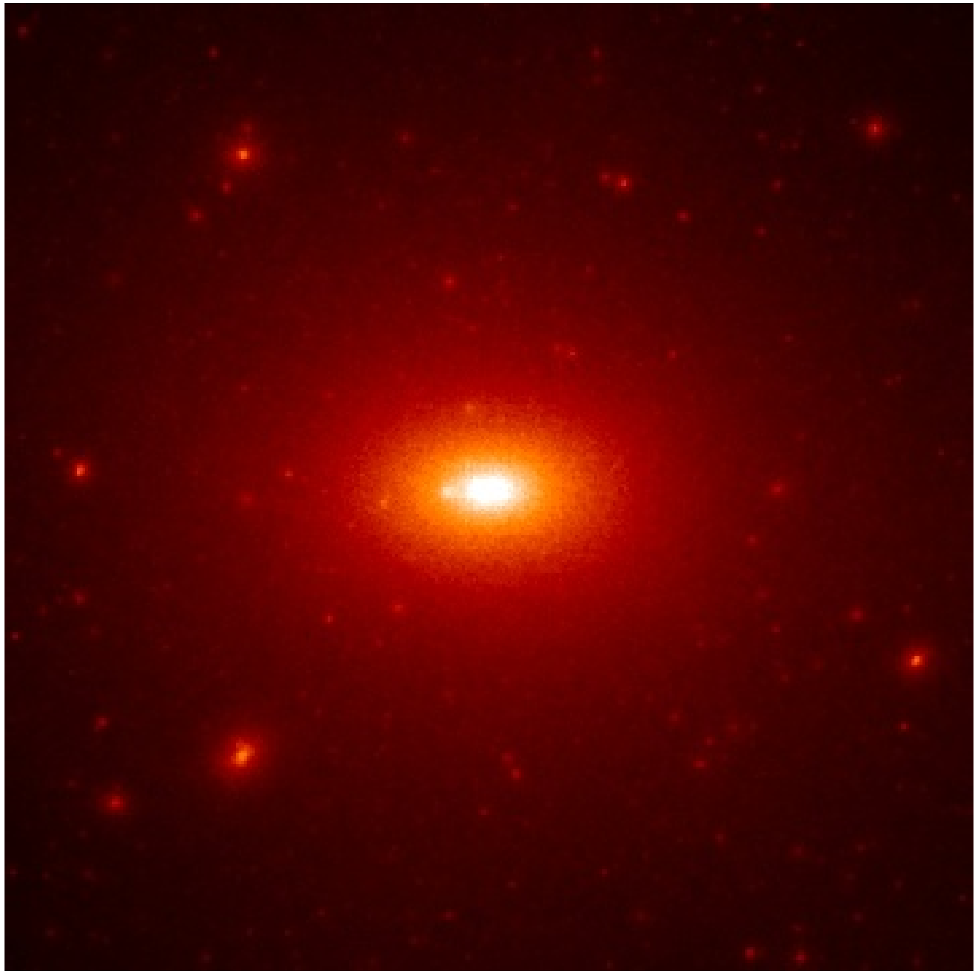


Fig. 6. The lower bound on the x-particle lifetime versus its mass for a present density $\Omega_{x0} h^2 = 1$ in the relic particles.

(Gondolo, Gelmini & Sarkar 1993)

Perhaps the trans-GZK cosmic rays are produced *locally in the Galactic halo* from the slow decays of metastable supermassive dark mater particles

→ energy spectrum determined by QCD fragmentation
→ expect dipole anisotropy due our off-centre position

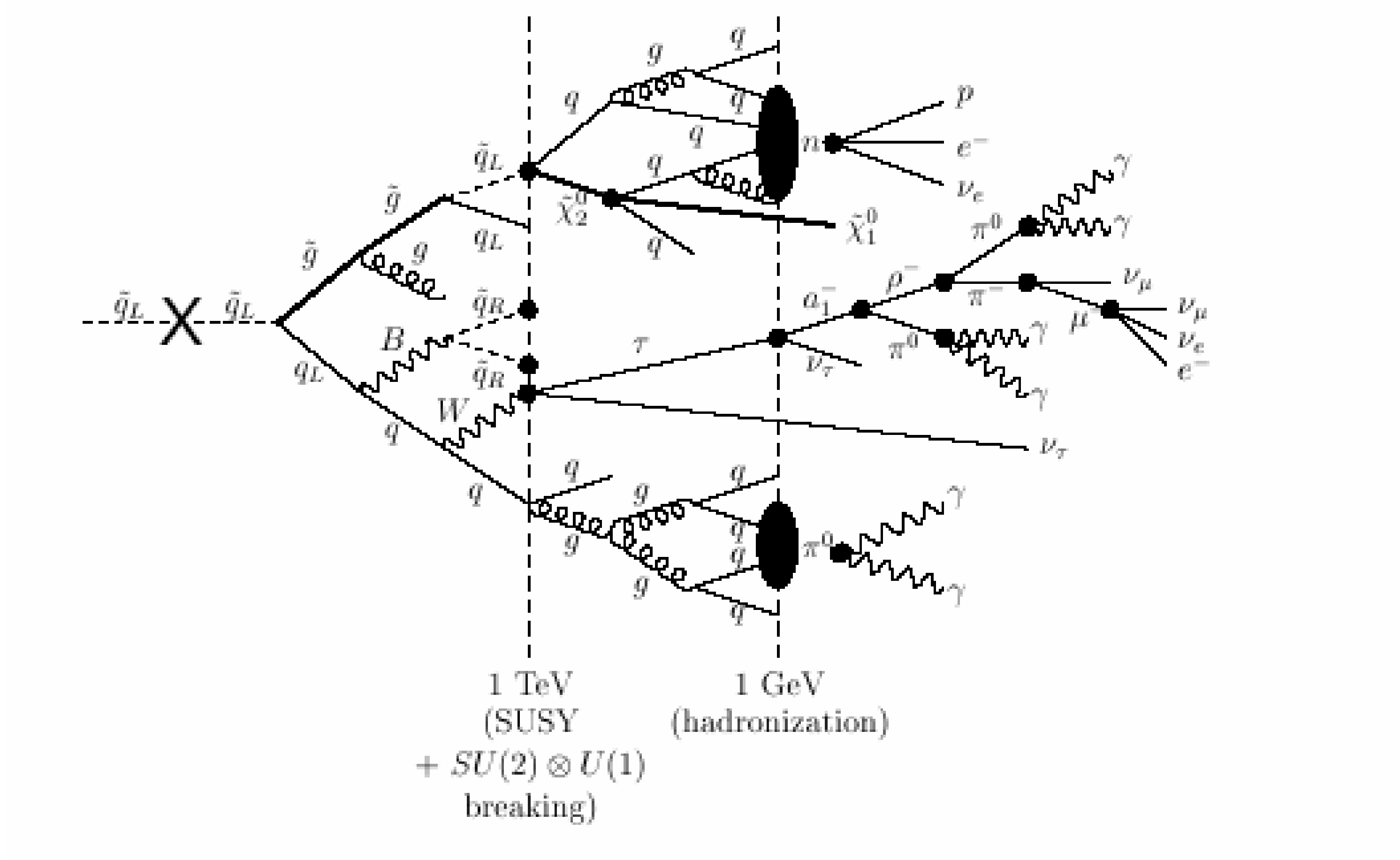


Simulation of Milky Way halo (Stoehr *et al* 2003)

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

Modelling the decay of a supermassive particle

$e^+e^- \rightarrow X \rightarrow$ partons $\rightarrow$ jets



Perturbative evolution of parton cascade
… tracked by DGLAP equation

Non-perturbative fragmentation
… modelled semi-empirically

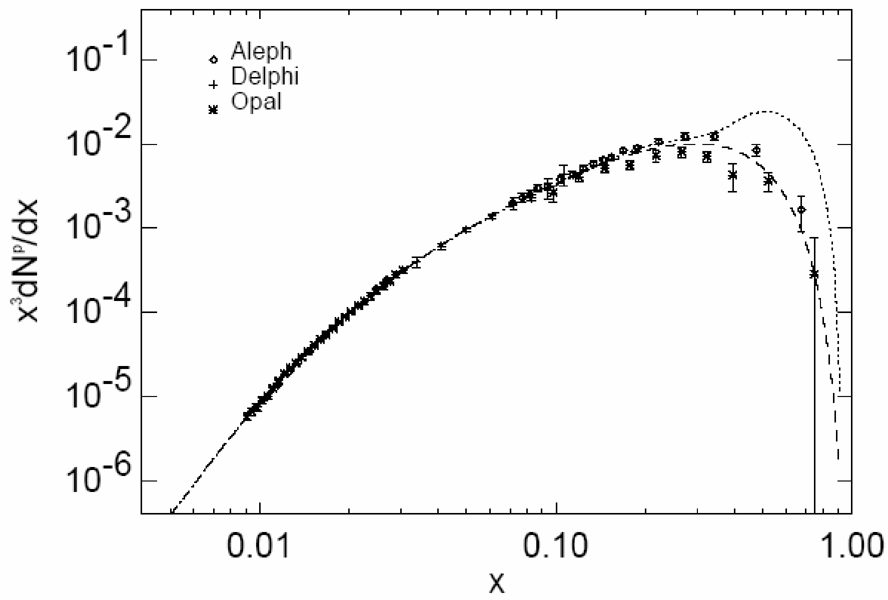


FIG. 1. The fragmentation spectrum of protons at the Z^0 mass peak, as measured by ALEPH, DELPHI and OPAL at LEP; the dashed line is a parametric fit [86]. The dotted line is the spectrum simulated with HERWIG, illustrating its tendency to overproduce baryons at high x.

Take measured fragmentation functions at the Z^0 peak …

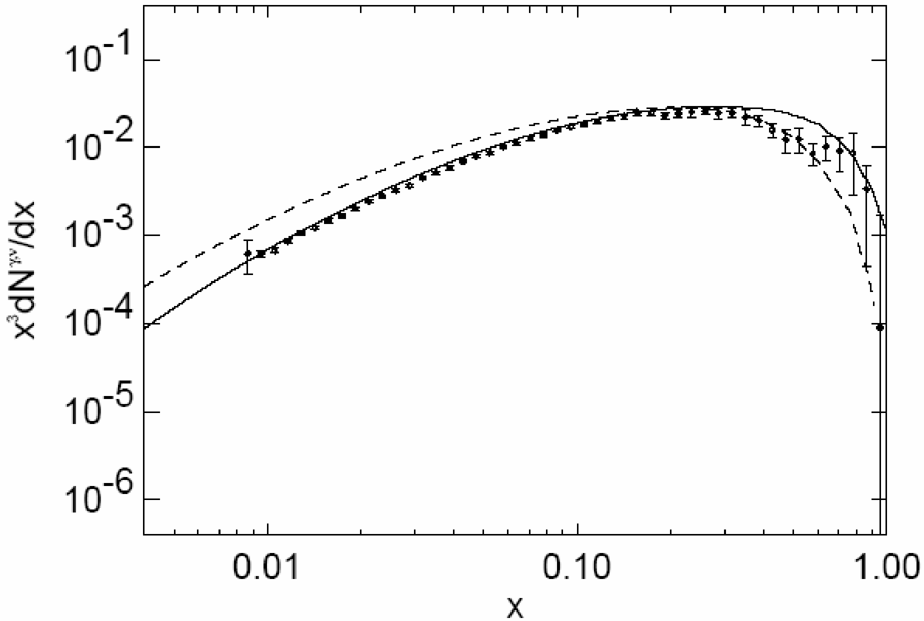


FIG. 2. The fragmentation spectrum of photons at the Z^0 mass peak, as measured by ALEPH at LEP; the solid line is the spectrum simulated with HERWIG. The fragmentation spectrum of neutrinos from HERWIG is also shown as the dashed line.

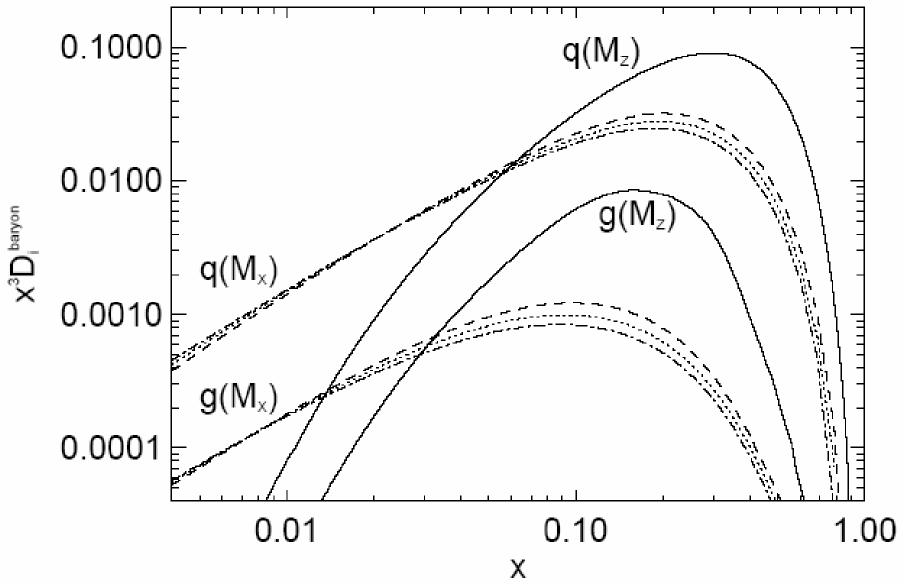


FIG. 3. Standard Model fragmentation functions for baryons from quarks and gluons, at the initial scale M_Z (solid lines) and evolved to a decaying particle mass scale of 10^{10} GeV (dashed line), 10^{12} GeV (dotted line) and 10^{14} GeV (dot-dashed line), illustrating scaling violations

… and evolve them using DGLAP eqns to mass scale m_x

(Sarkar & Toldra 2001)

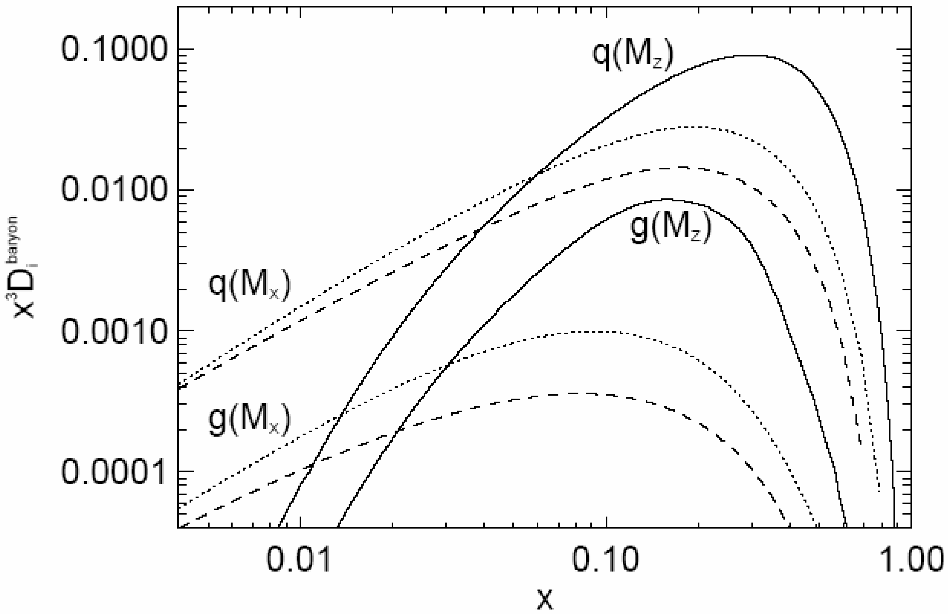


FIG. 4. Fragmentation functions for baryons from quarks and gluons, at the initial scale M_Z (solid lines) and evolved to a decaying particle mass scale of 10^{12} GeV, for SM evolution (dotted lines), and, the more pronounced, SUSY evolution (dashed lines) taking $M_{\rm SUSY} = 400$ GeV.

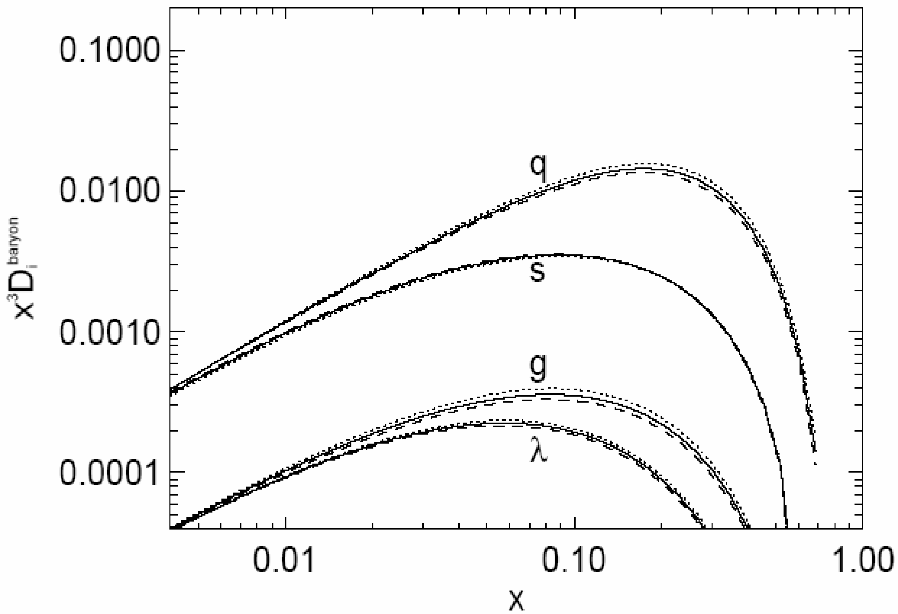


FIG. 5. Dependence of (s)parton fragmentation functions evolved from M_Z up to $M_X = 10^{12}$ GeV on $M_{\rm SUSY} = 200$ GeV (dashed lines), 400 GeV (solid lines), 1 TeV (dotted lines).

Most of the energy is released as neutrinos, with some photons and a few nucleons …

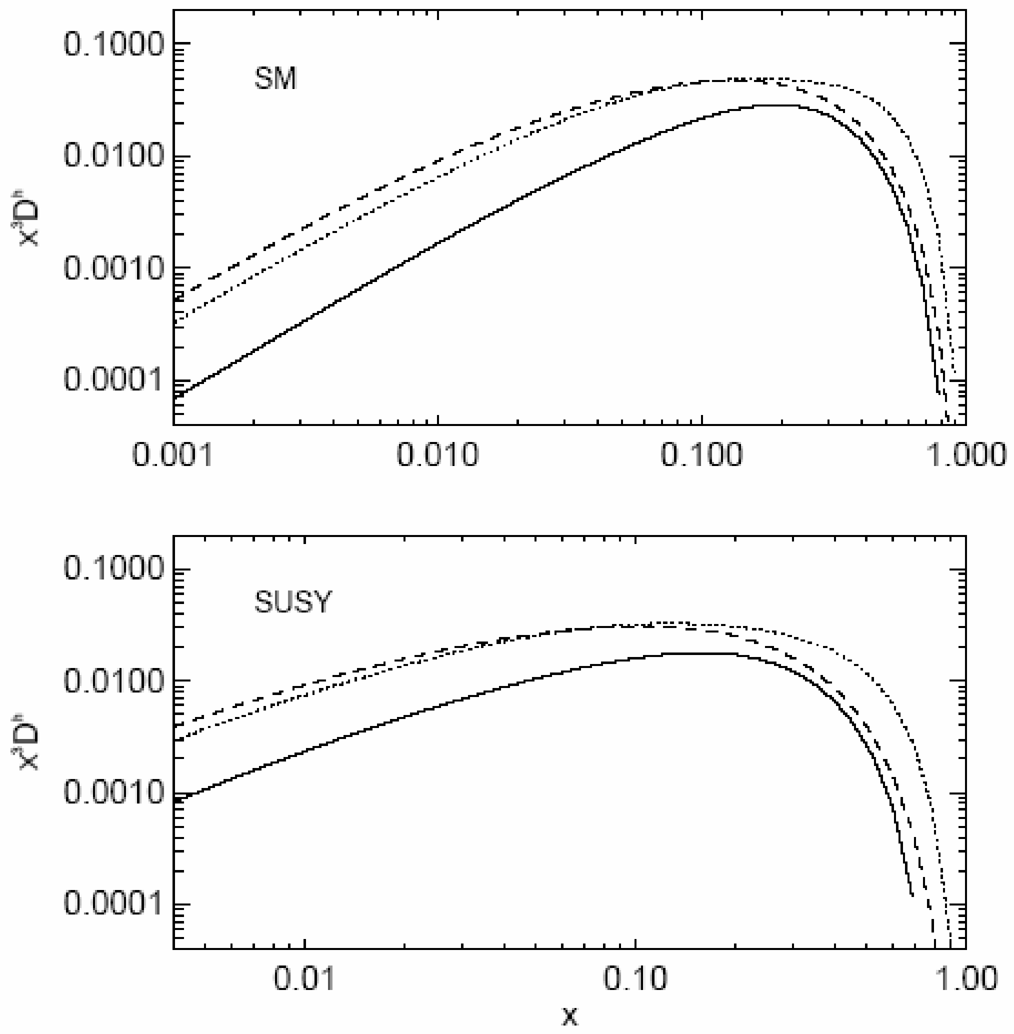


FIG. 6. Fragmentation functions for baryons (solid lines), photons (dotted lines) and neutrinos (dashed lines) evolved from M_Z up to $M_X = 10^{12}$ GeV for the SM (top panel) and for SUSY with $M_{SUSY} = 400$ GeV (bottom panel).

Similar results obtained by others (Barbot & Drees 2003, Aloisio, Berezinsky & Kachelreiss 2004)

The fragmentation spectrum matches the 'flat component' of cosmic rays at trans-GZK energies

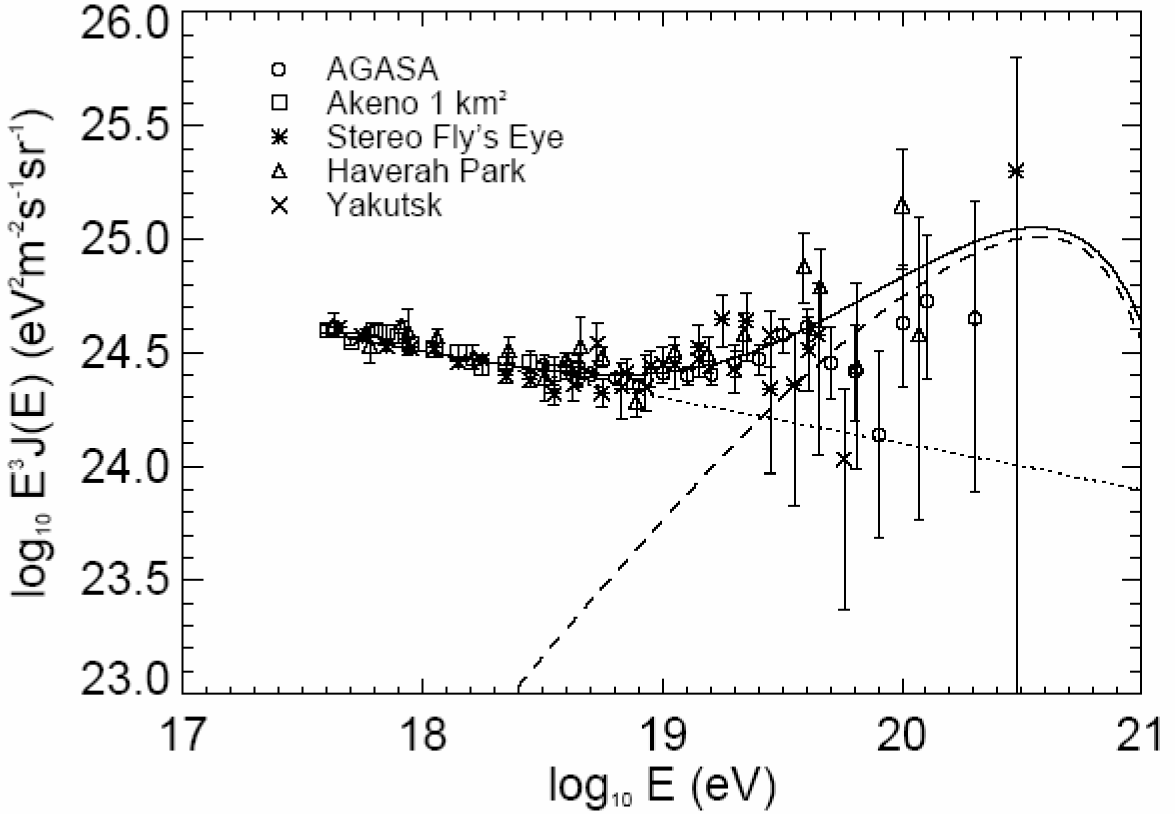


FIG. 8. The best SUSY evolution fit to the cosmic ray data with a decaying particle mass of 5×10^{12} GeV. The dotted line indicates the extrapolation of the power-law component from lower energies, while the dashed line shows the decay spectrum; the solid line is their sum.

Normalisation to the observed flux requires: $\tau_x \sim 2 \times 10^9\ t_0$

The observed trans-GZK UHECRs are however believed to be nucleons – not photons!

Are the photons are attenuated by pair annihilation on the (poorly known) MHz radio background?
… the lower energy photons created in the cascades would *not* conflict with the EGRET bound

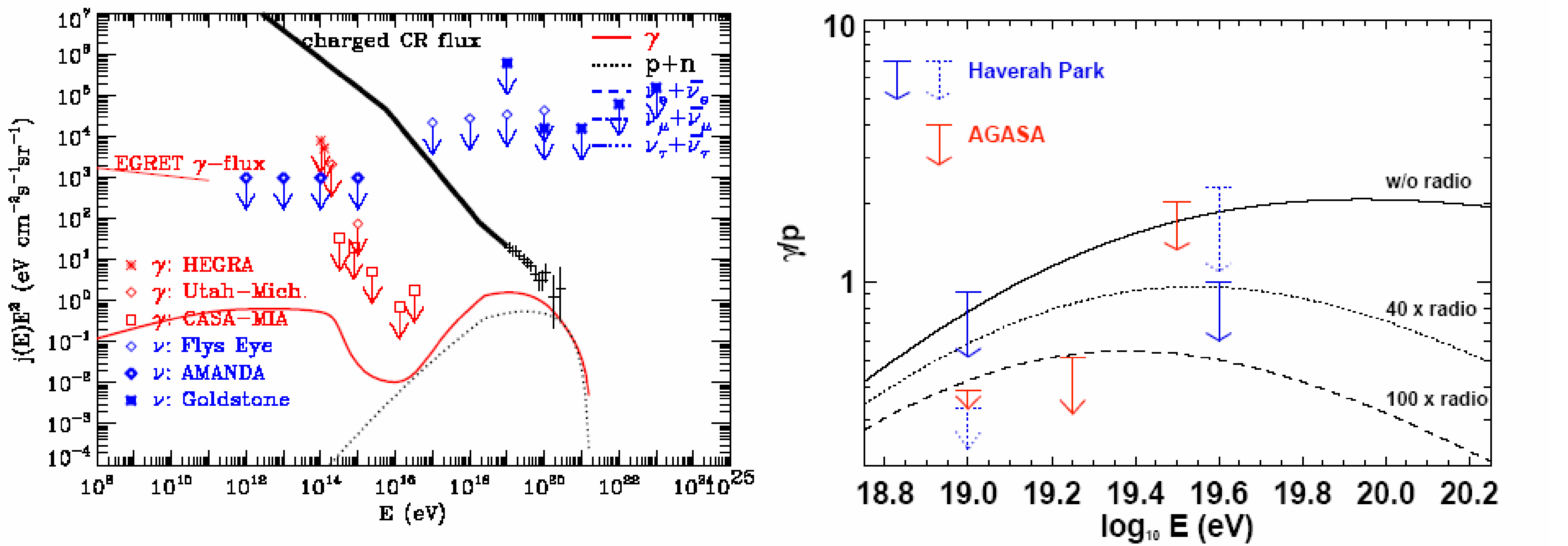
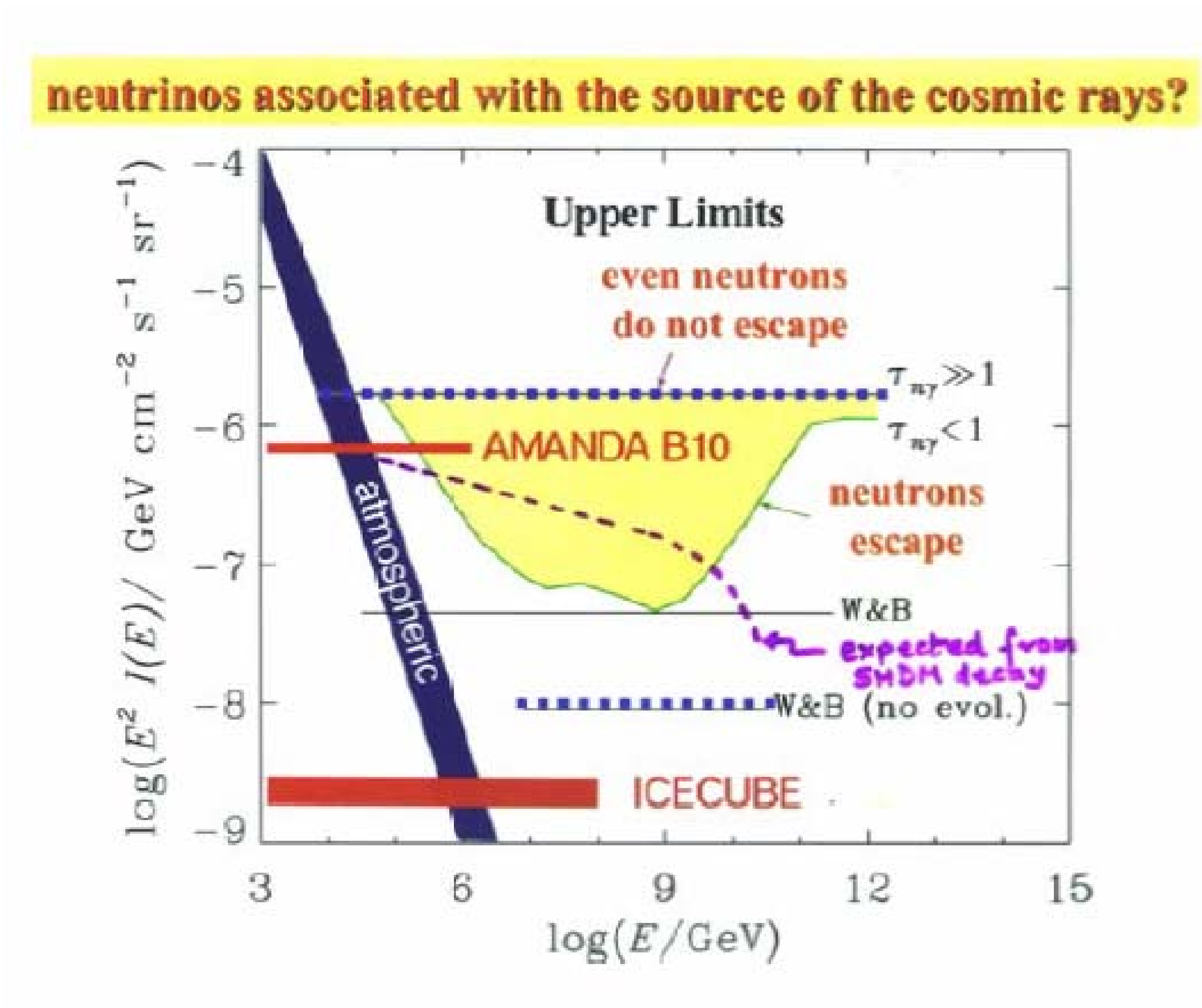


Fig. 6. The expected processing of the UHE photon spectrum from decaying dark matter in the Galactic halo is shown (left panel) for a radio background 10 times higher than is usually assumed and the γ/p ratio for various assumed values of the radio background is compared with experimental limits (right panel) [43].

(Sarkar. Sigl & Toldra 2002)



… the expected UHE neutrino flux is well above the ‘WB bound’

A high energy flux of neutralinos is also expected → may be detectable by EUSO/OWL

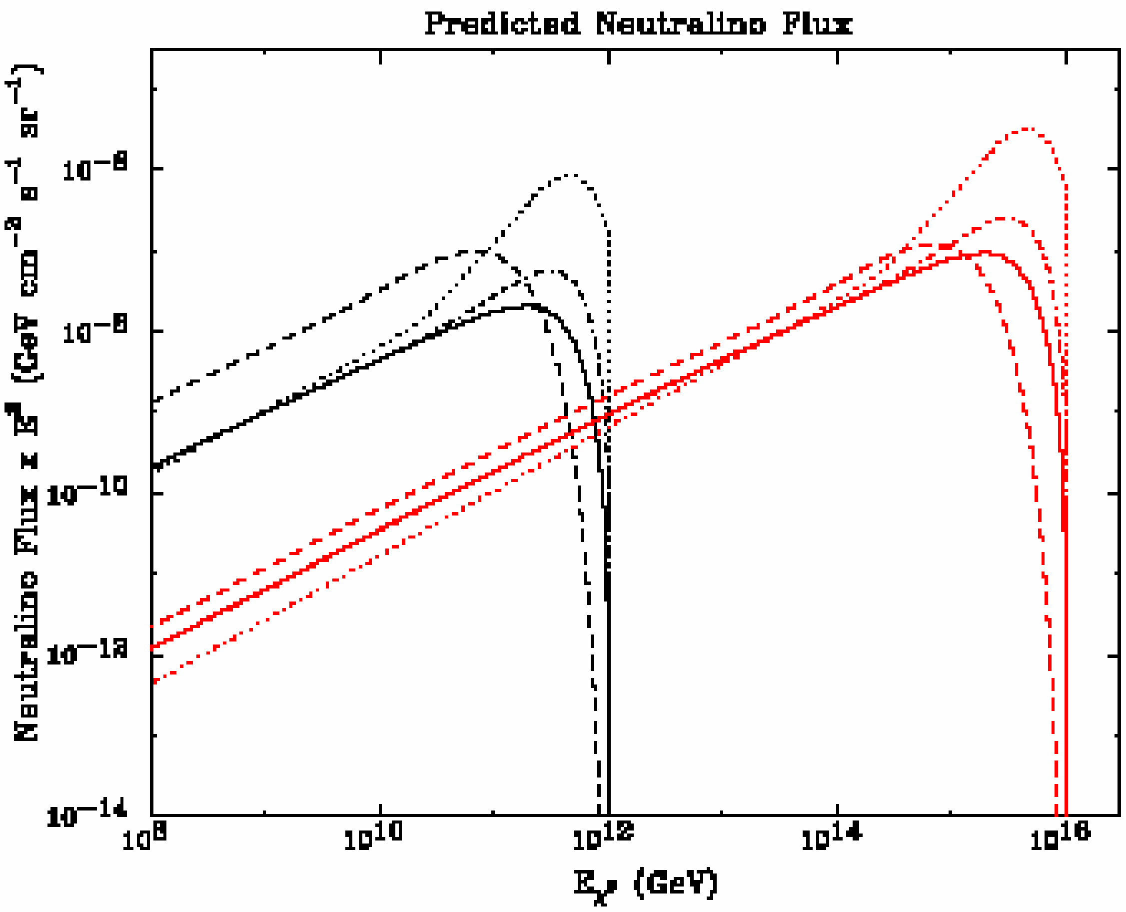


Figure 1: The spectrum of neutralino LSP's predicted for the decay of superheavy particles with mass $M_X = 2 \cdot 10^{21}$ eV (left set of curves) and $M_X = 2 \cdot 10^{25}$ eV (right) normalized [16] by the proton spectrum to the ultra-high energy cosmic ray flux, for a "galactic" distribution of sources where most UHECR events originate from X decays in the halo of our galaxy. For

(Barbot, Drees, Halzen & Hooper 2002)

Our asymmetric position in the Galaxy implies a dipole anisotropy
… magnitude dependent on assumed dark matter distribution

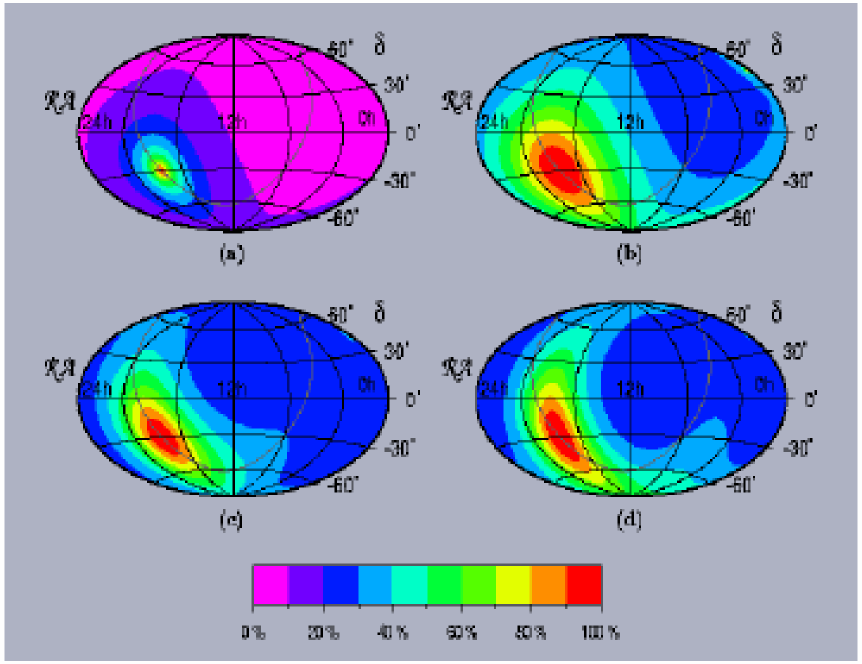


Fig. 7. Contour plots of the UHECR sky for (a) cusped, (b) isothermal, (c) triaxial and (d) tilted models of the dark matter halo of our Galaxy [44].

Auger South should be able to detect this @ 5σ with 500 events

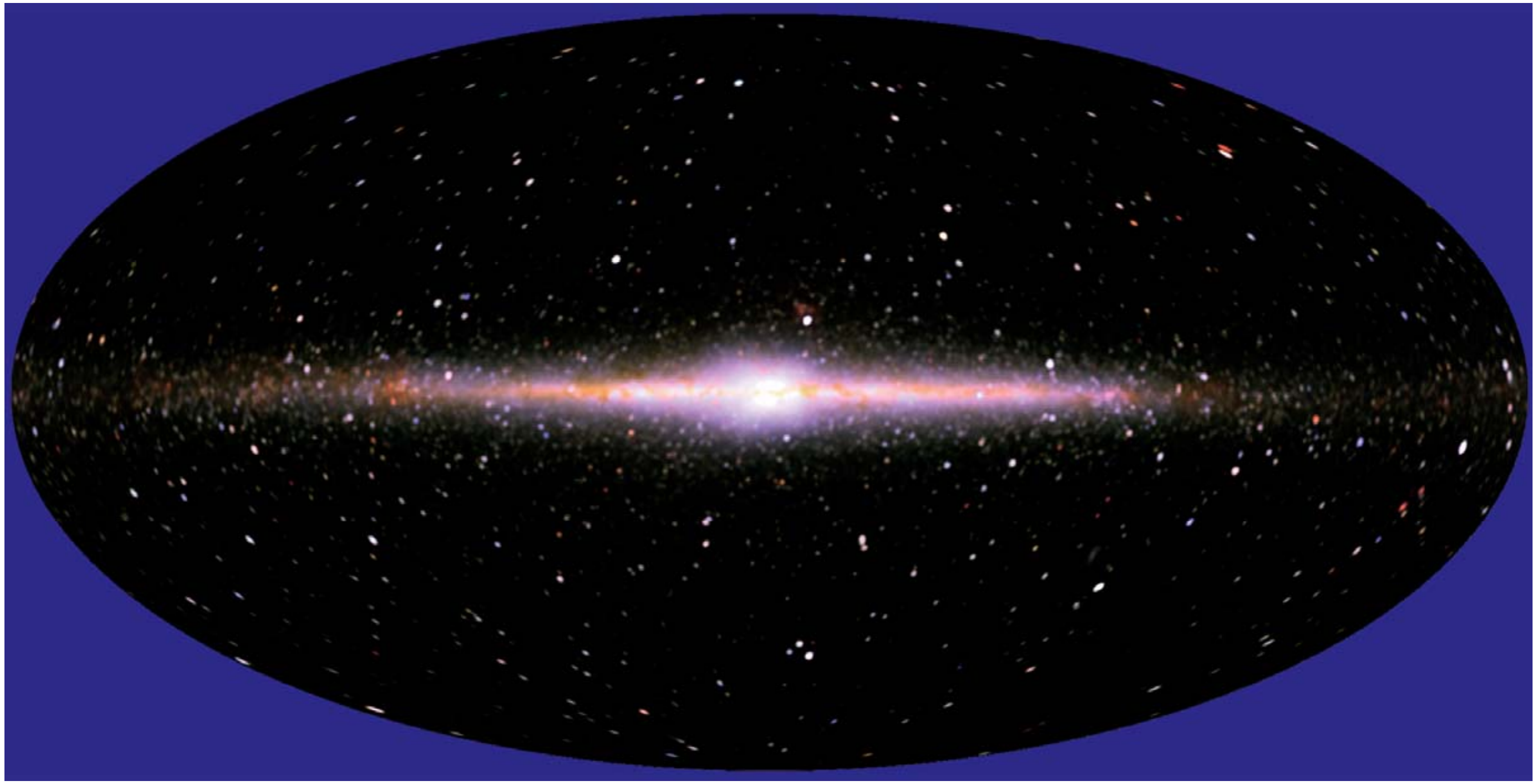
(Evans, Ferrer & Sarkar 2001)

Conclusions

►Ultrahigh energy cosmic rays and neutrinos may arise from the slow decays of ~10^{12} GeV mass relic particles, clustered as dark matter in the Galactic halo

► This makes robust predictions for the energy spectrum and anisotropy ... so is falsifiable by ongoing/forthcoming experiments (Auger, IceCube etc)

If confirmed, this will be the first *direct* signature of physics well beyond the Standard Model



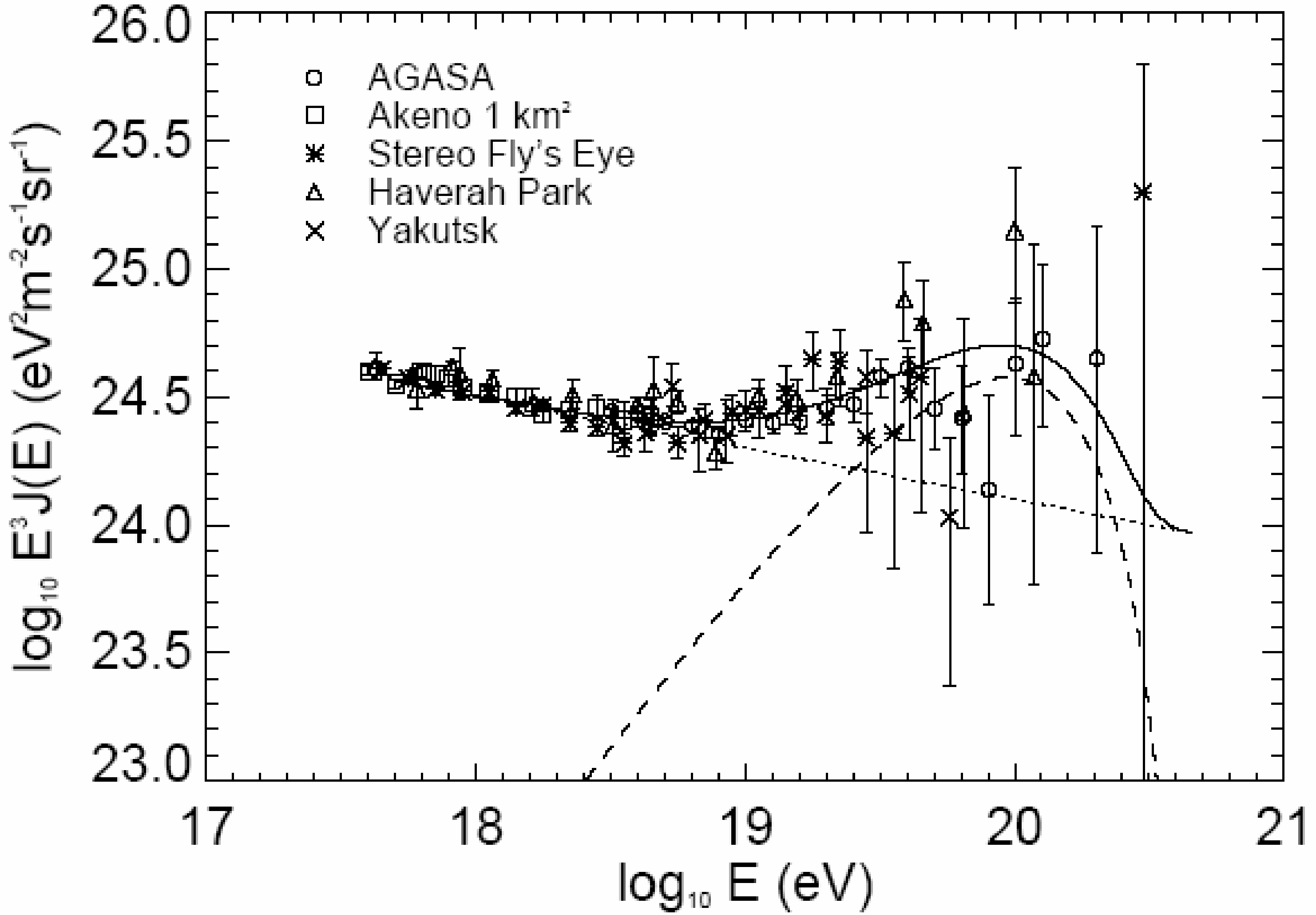
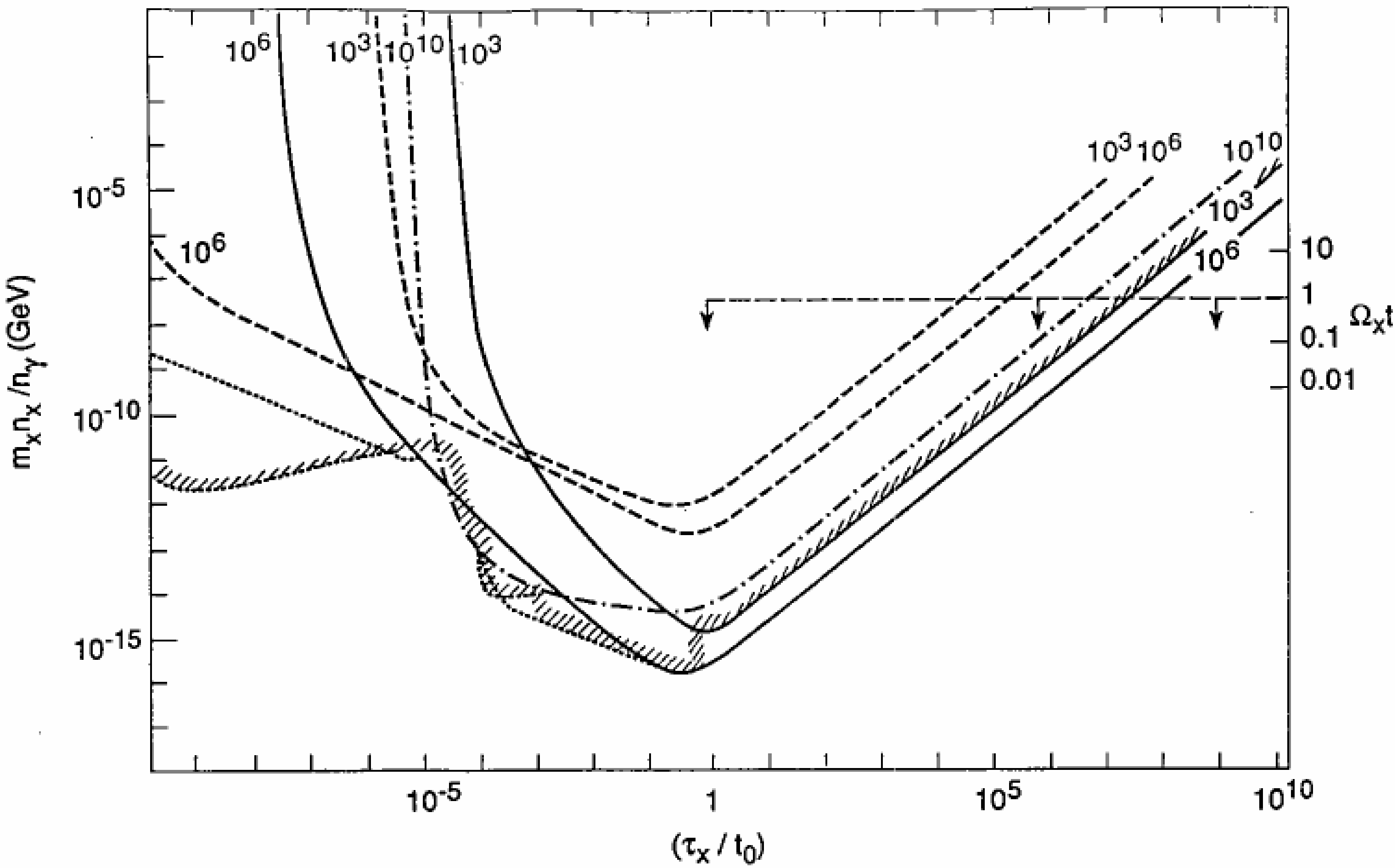


FIG. 7. The best SM evolution fit to the cosmic ray data with a decaying particle mass of 10^{12} GeV. The dotted line indicates the extrapolation of the power-law component from lower energies, while the dashed line shows the decay spectrum; the solid line is their sum.

Correlated bounds on the abundance/lifetime of massive relic particles



Ellis *et al* (1992)