Neutrino Clustering In CDM Halos: Implications For Ultra High Energy Cosmic Rays

(Singh & Ma; astro-ph/0208419)

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Introduction and Motivation

- Interaction of Protons & Photons with the CMB Predicts a Cutoff in the Cosmic Ray Flux (GZK) at $\sim 4 \times 10^{19}$ eV
  (Greisen 1966; Zatsepin & Kuzmin 1966)
  ⇒ GZK Zone ~ 50–100 Mpc
- Atleast 30 Events Above the Predicted GZK Cutoff Have Been Observed
  (Yoshida et al. 1995; Bird et al. 1994; Efimov et al. 1991 etc.)
- Possible Solutions (Some)
  - AGNs Dont Work Because They Are $\gtrsim 100$ Mpc Away and Would Require Unrealistic Energies (eg. Sigl, Schramm & Bhattacharjee 1994)
  - γ-Rays Have Both Observational and Theoritical Constraints
  - Exotic Particles & Dynamics Come With Their Own Problems (eg. Weiler & Kephart 1996)
  - Z-Burst Model

nature of the EECRs.

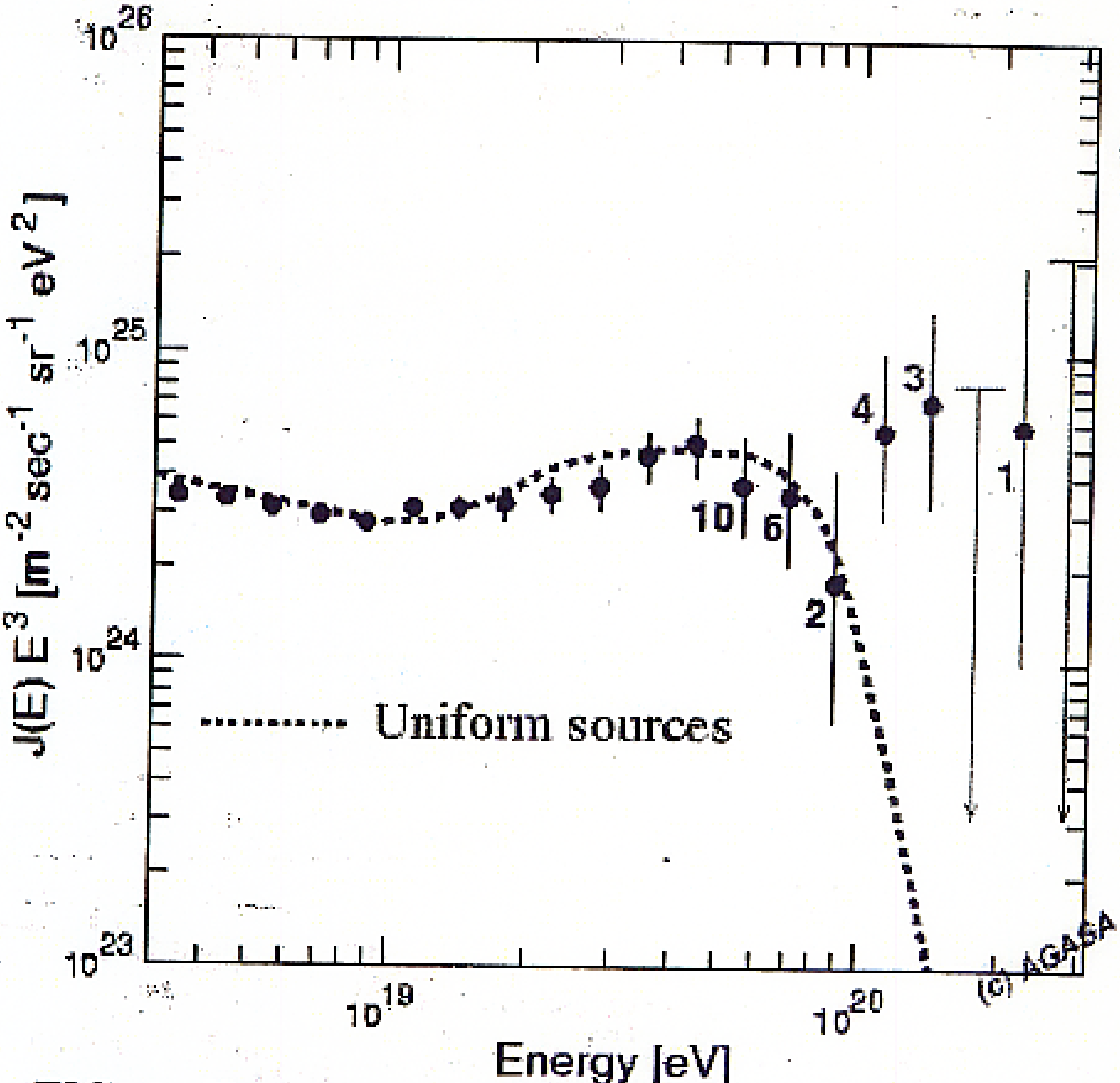

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FIG. 1. Extreme-energy cosmic ray spectrum as observed by AGASA. Error bars correspond to 68 % C.L. and the numbers count the events per energy bin. The dashed line revealing the GZK cutoff is the spectrum expected from uniformly distributed astrophysical sources (from the AKENO website [12]).

THE Z-BURST MODEL

- IMPORTANT $\nu\bar{\nu}$ INTERACTION FOR THE PROBLEM IS,

$$\nu\bar{\nu} \longrightarrow Z^0 \longrightarrow \text{HADRONS}$$

- THE INTERACTION IS RESONANT WITH

$$E_\nu^{RES} = 4.2 \times 10^{21}\,eV \left(\frac{1\,eV}{m_\nu}\right)$$

  - CROSS-SECTION GOES UP BY ~5 ORDERS OF MAGNITUDE

- Z-BURST CONTRIBUTION TO THE UHECR FLUX IS PROPORTIONAL TO THE INCOMING FLUX OF HIGH ENERGY NEUTRINOS AND NUMBER DENSITY OF RELIC NEUTRINOS, n_ν

- CONSTRAINTS ON ν MASS

$$1.8\,eV > m_\nu > 0.07\,eV$$

(ELGAROY ET AL. 2001, FUKUDA ET AL. 2000)

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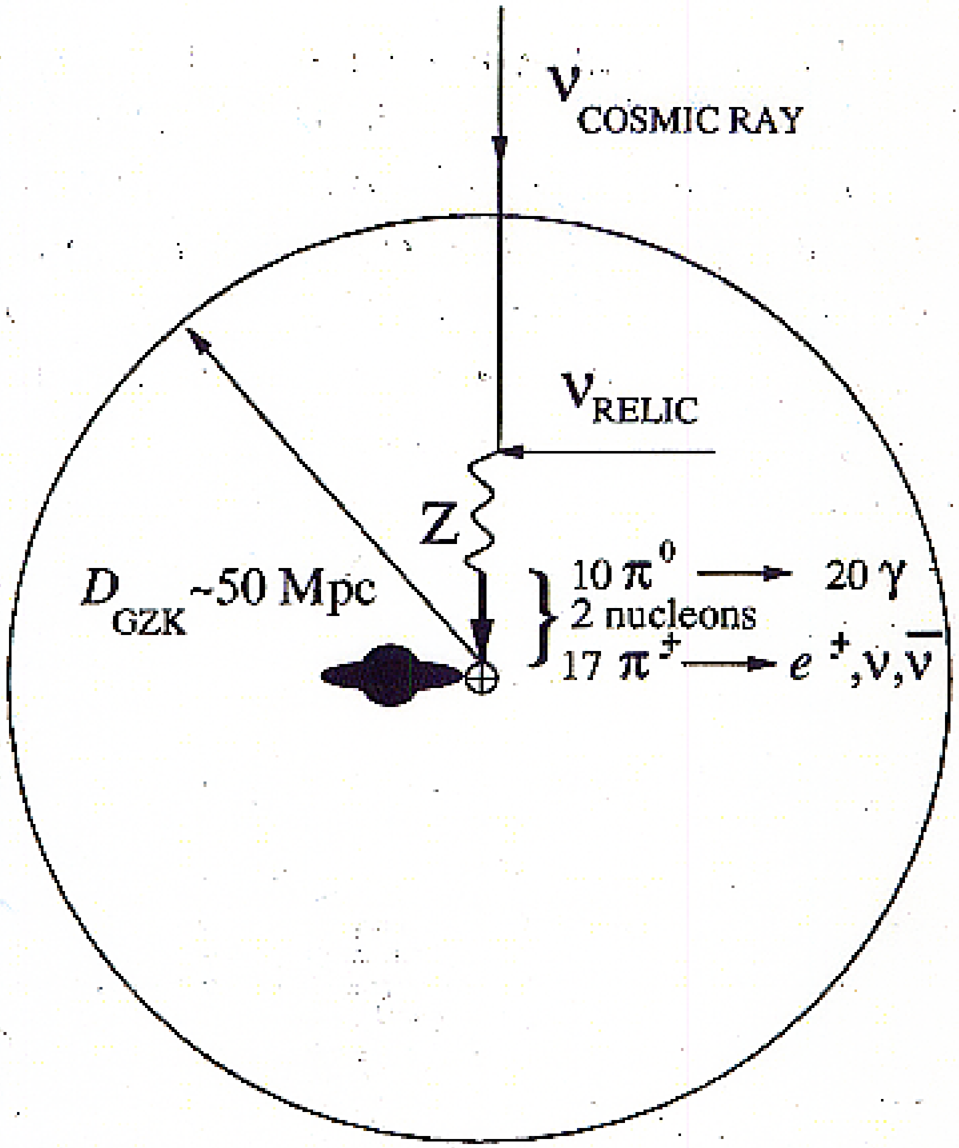

Figure 4: Schematic diagram showing the production of a Z–burst resulting from the resonant annihilation of a cosmic–ray neutrino on a relic (anti)neutrino. If the Z–burst occurs within the GZK zone ($\sim$ 50 to 100 Mpc) and is directed towards the earth, then photons and nucleons with energy above the GZK cutoff may arrive at earth and initiate super–GZK air–showers.

Calculation Of ν Clustering In CDM Halos

— The Thermal Velocity Of νs Is,

$$v_{th} \simeq 160(1+z)\left(\frac{1\,eV}{m_\nu}\right)\ kms^{-1}$$

$$(z=2\,;\ m_\nu = 1\,eV \Rightarrow v_{th} \simeq 500\ kms^{-1})$$

⇒ They Start Clustering Significantly Only After CDM Halos Have Taken Shape

— Problem Reduces To The Time Evolution Of ν Phase Space Density In Gravitational Potential Wells

— Start With The Collisionless Boltzmann Eq.

$$\frac{1}{a}\frac{\partial f}{\partial \tau} + \frac{\vec{q}}{m_\nu a^2}\cdot \nabla_x f - m_\nu \ddot{a}\, a\, \vec{x}\cdot \nabla_q f - m_\nu \nabla_x \phi \cdot \nabla_q f = 0$$

f : Phase Space Density

a : Scale Factor

$\vec{x}$: Comoving Spatial Coordinate

$\vec{q}$: Comoving Momenta

τ : Conformal Time

ϕ : Gravitational Potential

– EXPAND THE PHASE SPACE DENSITY INTO THE PRIMORDIAL + SPATIALLY DEPENDENT PART

$$f(x,q,\tau) = f_0(q) + f_1(x,q,\tau)$$

– BOLTZMANN EQ. BECOMES,

$$\frac{1}{a}\frac{\partial f_1}{\partial \tau} + \frac{\vec{q}}{m_\nu a^2}\cdot \nabla_x f_1 - m_\nu \nabla_x \phi_1 \left(\nabla_q f_0 + \nabla_q f_1 \right) = 0$$

– EQUATION HAS AN INTEGRAL SOLUTION IF $\nabla_q f_1$ IS DROPPED

– SINCE f_1 IS DETERMINED BY THE CLUSTER PROPERTIES AND THAT SIGNIFICANT CLUSTERING HAPPENS ONLY IF $v_{th} \ll \sigma_v$

$$\Rightarrow \frac{\nabla_q f_1}{\nabla_q f_0} \sim \frac{f_1/\sigma_v}{f_0/v_{th}} \sim \frac{\delta\rho_v/\sigma_v^4}{\bar{\rho}_v/v_{th}^4} \sim \delta_v \left(\frac{v_{th}}{\sigma_v}\right)^4$$

$$\Rightarrow \quad \nabla_q f_1 \lesssim \nabla_q f_0$$

– SIMILAR APPROACH USED TO CALCULATE ν CLUSTERING AROUND COSMIC STRING SEEDS. (BRANDENBERGER, KAISER & TUROK 1987)

- TAKE FOURIER TRANSFORM (NO CONVOLUTION NOW!!), INTEGRATE OVER 'q', AND TAKE THE INVERSE FOURIER TRANSFORM TO OBTAIN THE DENSITY PROFILES OF ν's IN CDM HALOS.

WHY CHOOSE THE BOLTZMANN EQ. APPROACH?

- CALCULATIONS TAKE NEGLIGIBLE TIME
- CAN OBTAIN DENSITY PROFILES BELOW THE SCALE OF RESOLUTION OF N-BODY SIMULATIONS.

$M_{HALO} = 1.35 \times 10^{15} M_\odot$ (KOFMAN ET AL. 1996)

$$\rho_{CDM}(r) = \frac{C}{r(r+R)^{\kappa}}$$

$h = 0.5$

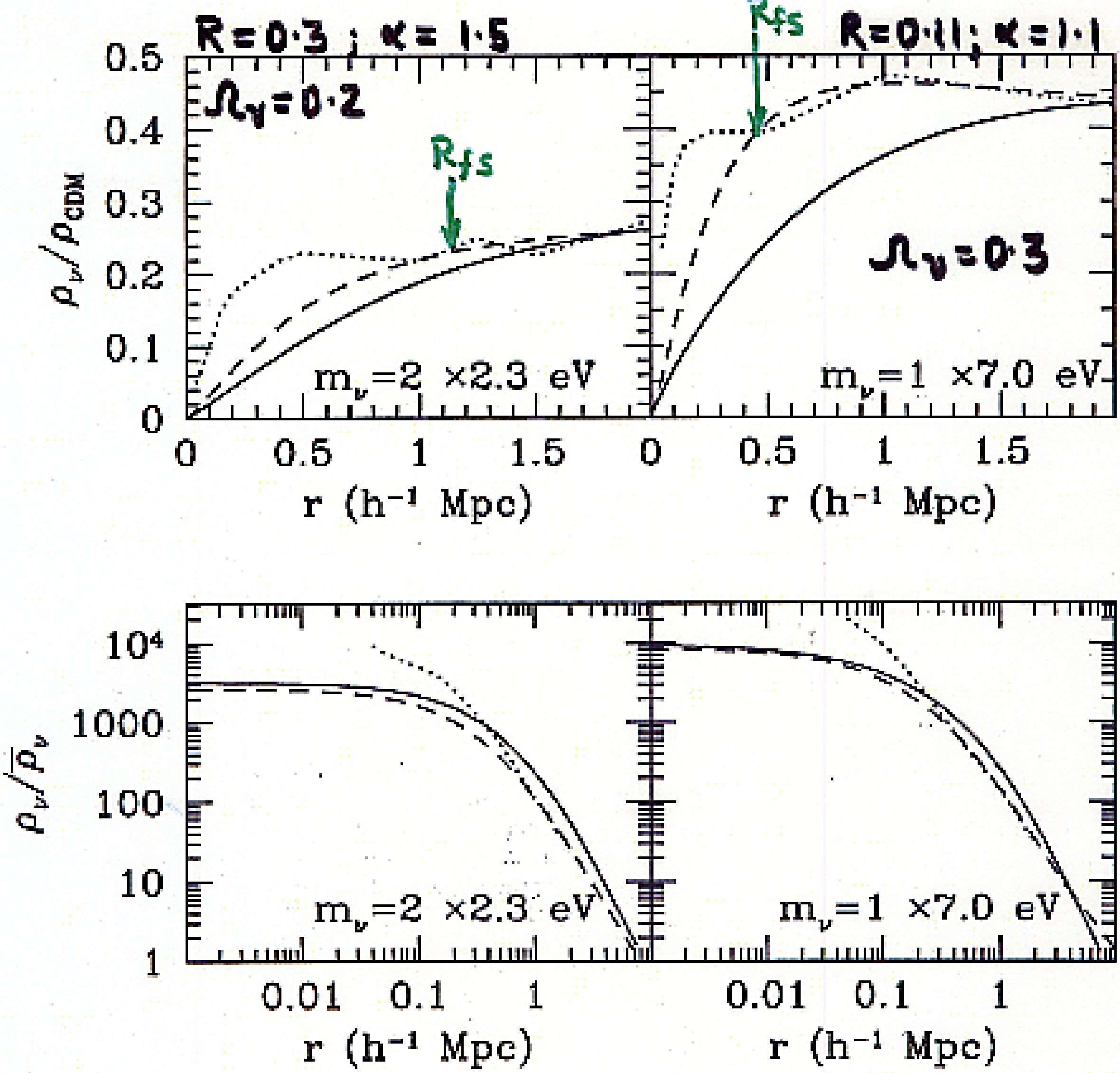

FIG. 1: Neutrino clustering calculated with our Boltzmann approach (dashed) vs. numerical simulations from [29] (dotted). The simulation resolution is 62.5 h^{-1} kpc. The upper panels show the ratio of the neutrino mass density ρ_ν to the CDM density ρ_{cdm} as a function of radius for two halos of $1.3 \times 10^{15} M_\odot$ in two cosmological models. The lower panels show $\rho_\nu/\bar{\rho}_\nu$ for the same models. The solid curves compare neutrino clustering around CDM halos with an NFW profile [27] to illustrate how neutrinos respond to different gravitational potentials.

Results For ν Clustering In CDM Halos

- Comparison With N-Body Simulations Shows Agreement Within A Factor Of 2
  - Discrepancy May Be Due To The Term We Dropped
  - Or Statistical In Nature

Physical Understanding Of The Results

- We Expect δ_ν To Be Damped With Respect To δ_{CDM} Below The Free Streaming Distance, $R_{fs} \simeq 5.82/m_\nu$ Mpc (Stebbins, Gates & Dodelson '96)
- Profile Flattens Out At $\sim 0.1\, R_{fs}$ (Bertschinger & Watts 1988)
- Weak Dependence On CDM Halo Mass
- Phase Space Constraint Is Satisfied (Tremaine & Gunn 1979, Kull, Truemann & Böhringer 1996)

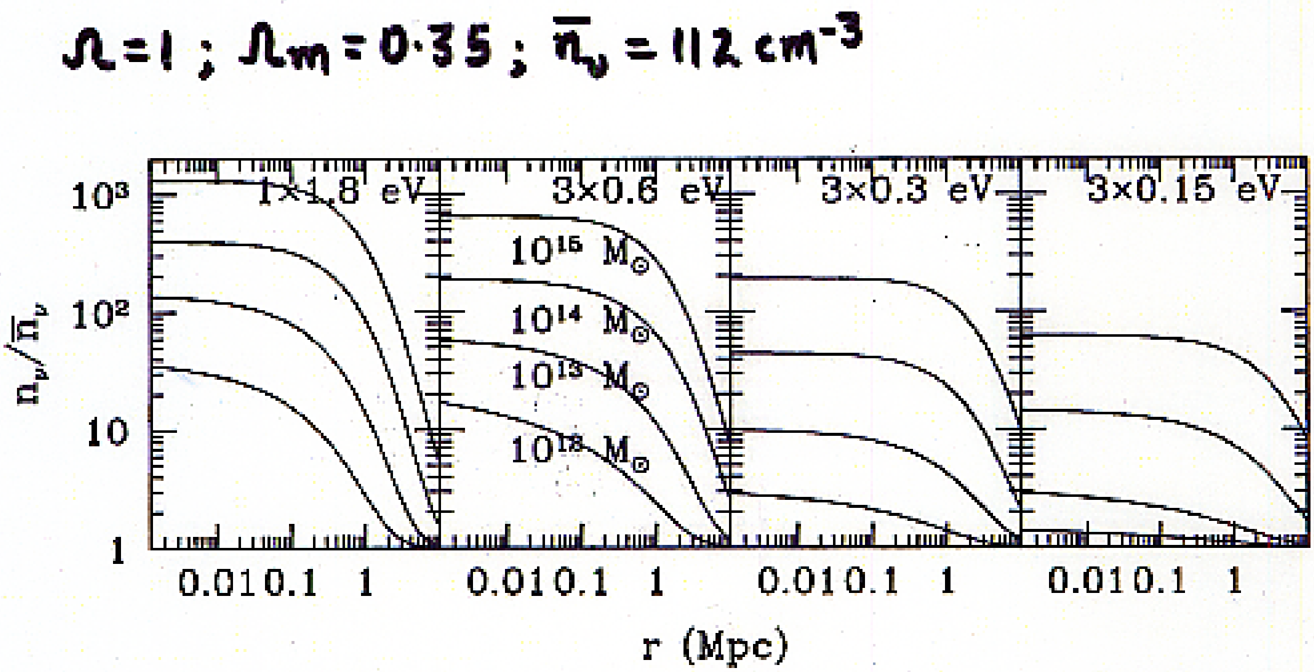

FIG. 2: Total neutrino number density $n_\nu(r)$ as a function of halo radius for different neutrino masses and halo masses at redshift 0. The curves are all normalized to $\bar{n}_\nu \approx 112\ \mathrm{cm}^{-3}$ for ease of comparison. The four panels (from left to right) show how the clustering decreases as the neutrino mass is lowered, a result of increasing neutrino thermal velocity and more effective free streaming. Within each panel, the curves show how n_ν decreases as the halo mass is lowered from 10^{15} to $10^{12} M_\odot$, a result of shallower gravitational wells and smaller halo velocity dispersions compared with the neutrino thermal velocity. This figure shows that neutrinos with $m_\nu \gtrsim 0.15$ eV cluster appreciably in $M \gtrsim 10^{12} M_\odot$ halos.

Implications For The UHECRs

- Flux Of The UHECR Spectra Due To The Z-Burst Model,

$$F(E) \propto \int_0^{\infty} dE_p \int_0^{R_{max}} dr \, (1+z(r))^3 \, n_\nu(r) \, Q_p(m_\nu) \, \frac{\partial P_p}{\partial E}(r, E_p; E)$$

E_p : Energy Of Proton Produced Via $\nu\bar{\nu}$

Q_p : Kinematical Function Of $\nu\bar{\nu} \longrightarrow Z^0$

P_p : Propogation Function Which Encodes Energy Losses As The Proton Travels Towards Us.

- Use The Anisotropy Of Mass In Our Local Universe ($r \lesssim 100$ Mpc) To Make Spectral Predictions
- Lines Of Sight Towards Virgo, Centaurus, Hydra, Perseus-Pisces And Coma Were Investigated
- A Unique Anisotropic Signature Should Be Detected By Auger (resolution $\sim 1^\circ$) If $m_\nu \gtrsim 0.2$ eV For The Z-Burst Model To Survive.....

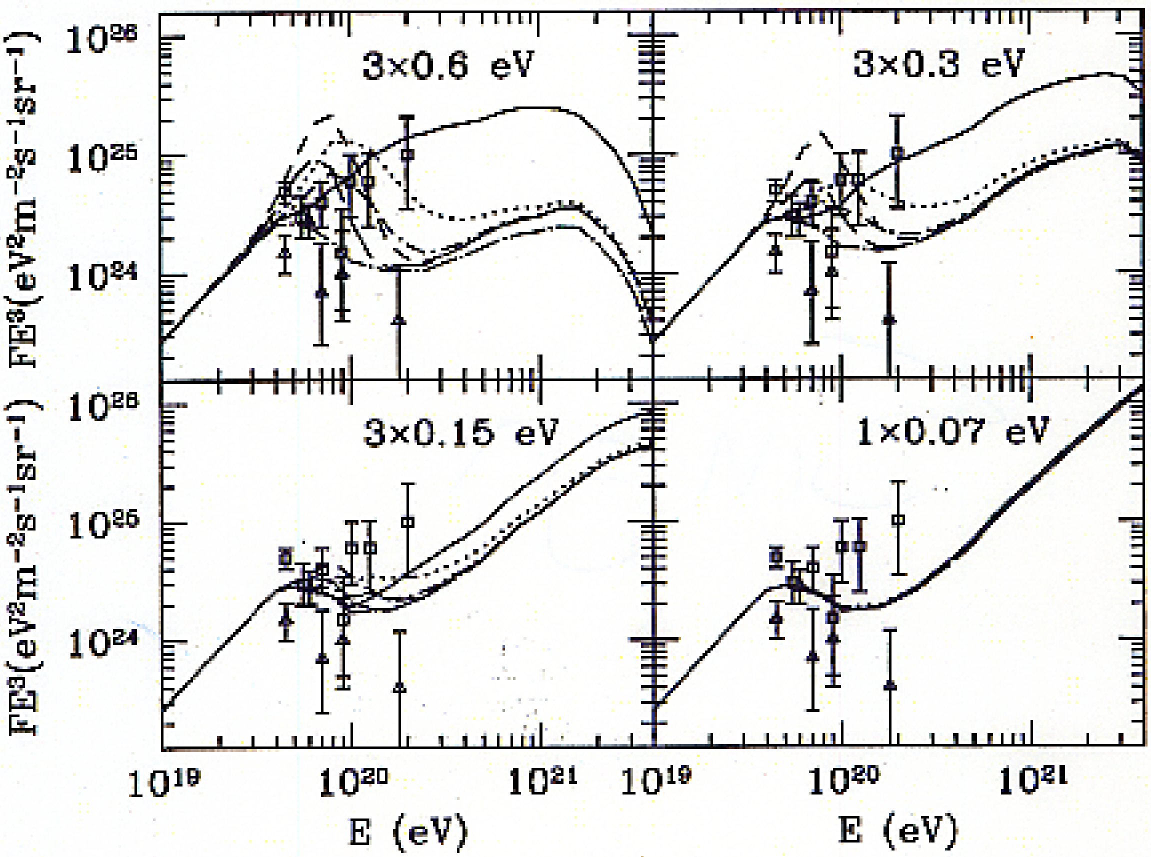

FIG. 6: Predictions for the cosmic ray flux produced in the Z-burst model using realistic neutrino overdensity computed in this paper. The four panels compare the UHECR spectrum for the same four neutrino mass models as Fig. 5. Within each panel, our predictions for the spectrum towards five of the most massive clusters in the local universe are shown: Virgo (solid), Centaurus (dotted), Hydra (dot short-dashed), Perseus-Pisces (short dashed), and Coma (long dashed). For comparison, the dot- long-dashed curve shows the spectrum when neutrino clustering is ignored (i.e. the same as in Fig. 5). For $m_\nu \gtrsim 0.3$ eV, we predict that the Z-burst model should produce distinct spectrum towards each line of sight. For $m_\nu \lesssim 0.1$ eV, neutrino clustering is insignificant and the spectrum is expected to be nearly isotropic as seen in the lower right panel. The data points are the same as in Fig. 5.