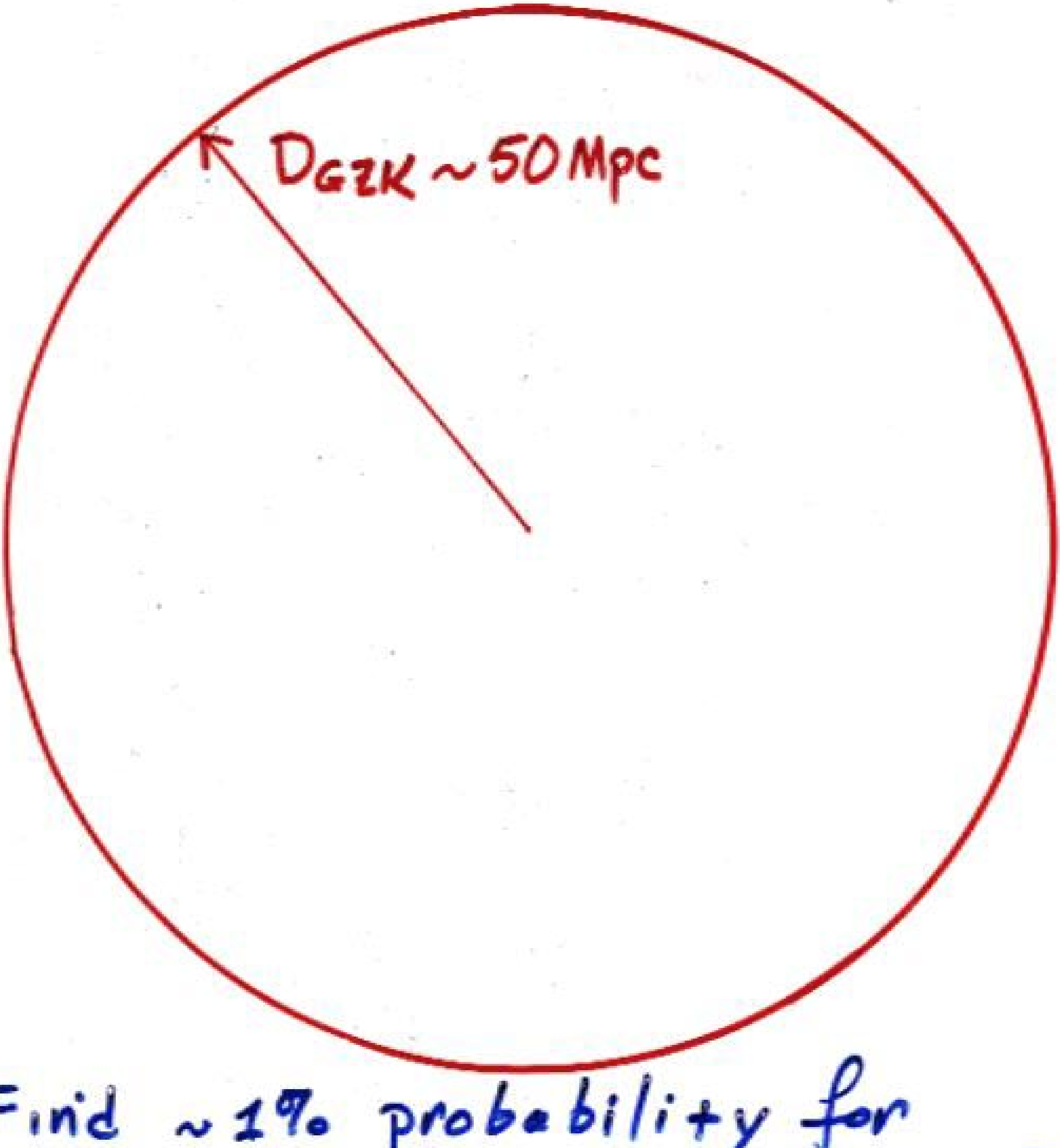
Cosmic Ray

NEUTRINOS

above 10^{20} eV

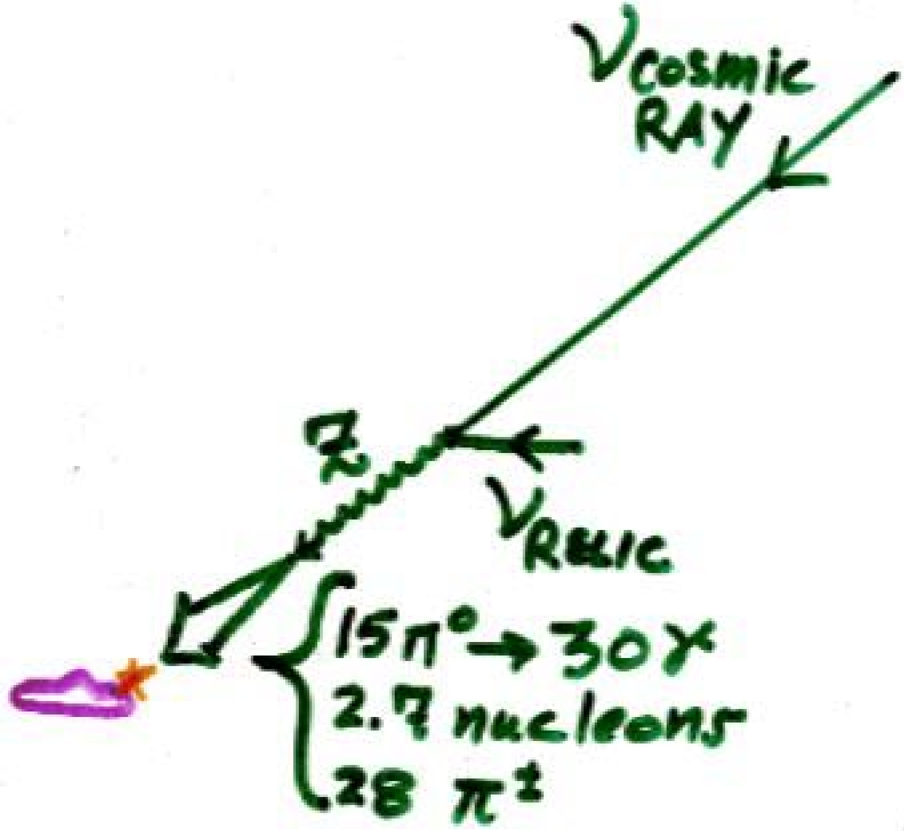
[and below 10^{-3} eV]

Tom Weiler



Find ~1% probability for resonant $\nu \rightarrow$ z-burst within D_{GZK}

TW, hep-ph/9710431
Astropart. Phys.
Also, Fargion, Mele, Salis
astro-ph/9710029



OUTLINE

THE CνB

- WHAT IS IT? (overview)
- ATTEMPTS at DETECTION
- THE $\nu_{CR} + \nu_{relic}$ annihilation hypothesis, for
  - Neutrino Spectroscopy
  - Super-GZK Cosmic Rays DATA
- More on the CνB (details)
- The future - Cosmic Ray viewpoint

COSMIC ν BKGD

*where particle physics/cosmology merge

Analogous to 2.73K CMB,

liberated at $t \sim 500{,}000$ yrs

$T \sim$ eV

[Planck]

$z \sim 1100$

when $e^- + p \xrightarrow{\text{"recombined"}}$ hydrogen

(plasma) (transparent)

$\exists$ (Xpt'l challenge) CνB

liberated at $t \sim 1$ sec

$T \sim$ MeV

when $\Gamma_{weak} = \sigma_{weak}\, n$

fell below $\Gamma_{expansion} = H$.

Normalizing to CMB, $T_\nu \sim 1.95$K

$z_D \sim 10^{10}$

with $T_\nu \sim 2K$,

$\langle p_\nu \rangle \sim 3T \sim 6 \cdot 10^{-4}\,eV$

$\Rightarrow$ Non Relativistic if $m_\nu \gtrsim 6 \cdot 10^{-4}\,eV$

Since $\langle E_\nu \rangle \sim \frac{p^2}{2m} \sim \frac{10^{-7}\,eV}{(m_\nu/eV)}$,

way subthreshold for CC,

& NC provides no particle tag,

Searches are necessarily*

INDIRECT !

Note also, $\langle v_\nu \rangle \equiv \frac{\langle p \rangle}{m} = \frac{6 \cdot 10^{-4}}{(m_\nu/eV)}$.

Possible Neutrino Mass Spectrum:

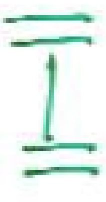
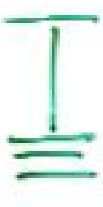
From oscillations, $\delta m^2_{jk} \equiv m_j^2 - m_k^2$

$\Rightarrow m_j \gtrsim \sqrt{\delta m^2_{jk}}$

$$\sqrt{\delta m^2_{LSND} \sim 0.3 - 2\,eV^2} \sim 0.5 \text{ to } 1.5\,eV$$

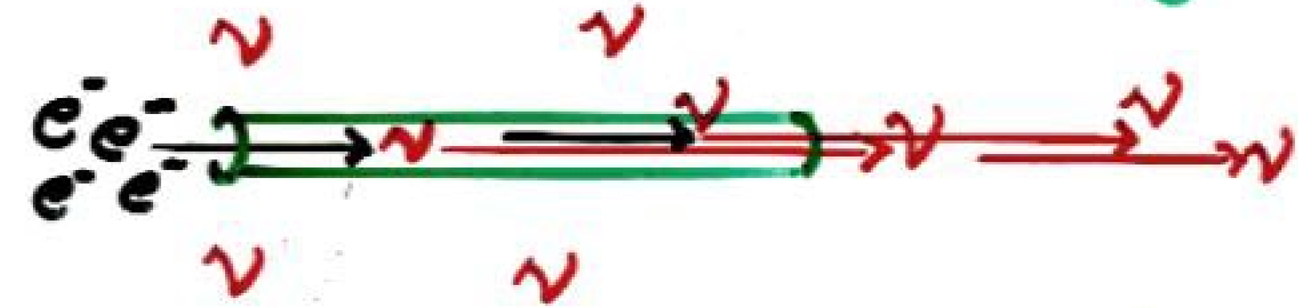
$$\sqrt{\delta m^2_{atm} \sim 10^{-3 \pm 0.5}} \sim 10^{-1} \text{ to } 10^{-2}\,eV$$

$$\sqrt{\delta m^2_{sun} \sim 10^{-5} \text{ or } 10^{-10}} \sim 3\times10^{-3} \text{ or } 10^{-5}\,eV$$

w/  preferred over (BGG) 

$\Rightarrow$ 2 ν's @ $m_\nu \gtrsim eV$.

Direct Detection via TeV Linac Scattering



Production Rate $= I_{acc} \dfrac{L_{acc}}{\lambda_{e\nu}}$

$$= \left(\frac{I}{Amp}\right)\left(\frac{L_{acc}}{km}\right)\left(\frac{n_\nu}{300\,cm^{-3}}\right)\left(\frac{\sigma_{e\nu}}{10^{-44}\,cm^2} \sim \frac{E_e}{TeV}\frac{m_\nu}{eV}\right)$$

$$* \ 10^{-10}/yR$$

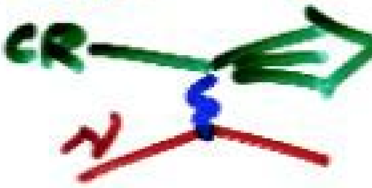
⊗ Detection Probability

$$\theta_\nu \sim \frac{1}{\gamma_\nu} \sim 10^{-12}\left(\frac{TeV}{E_\nu}\right)\left(\frac{m_\nu}{eV}\right)$$

$$= \frac{L_{Det}}{\lambda_{\nu N}} \sim \left(\frac{L_{Det}}{km}\right)\left(\frac{n_N}{10^{25}\,cm^{-3}}\right)\left(\frac{\sigma_{\nu N}}{10^{-35}\,cm^2} \sim \frac{E_\nu}{TeV}\right)\cdot 10^{-4}$$

TRANSPARENCY

of the CνB



$$\lambda_{CR} = \frac{1}{n_\nu \sigma} \quad , \quad \sigma_{weak} \sim \frac{G_F^2 s}{\pi} \sim \frac{2}{\pi} G_F^2 m_\nu E_{CR}$$

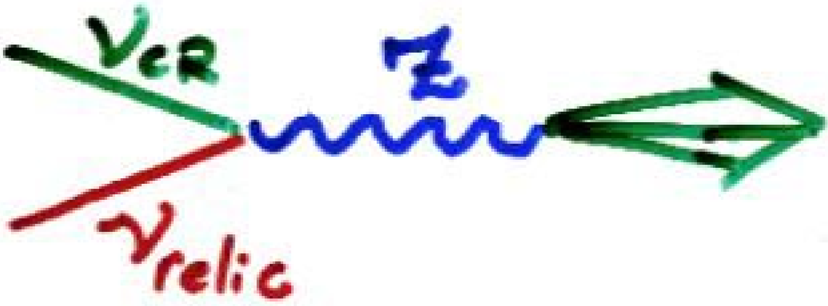
$$= \frac{1}{\Omega_\nu}\left(\frac{10^{23}\,eV}{E_{CR}}\right) D_H$$

with $D_H = H_0^{-1} = 5\, h_{65}^{-1}$ Gpc.

Also, σ_{weak} saturates at $\frac{G_F^2 M_W^2}{\pi}$,
(mod ln's)

$$\Rightarrow \quad \lambda_{CR} \gtrsim 10^4 \left(\frac{50\, cm^{-3}}{n_\nu}\right) D_H$$

But



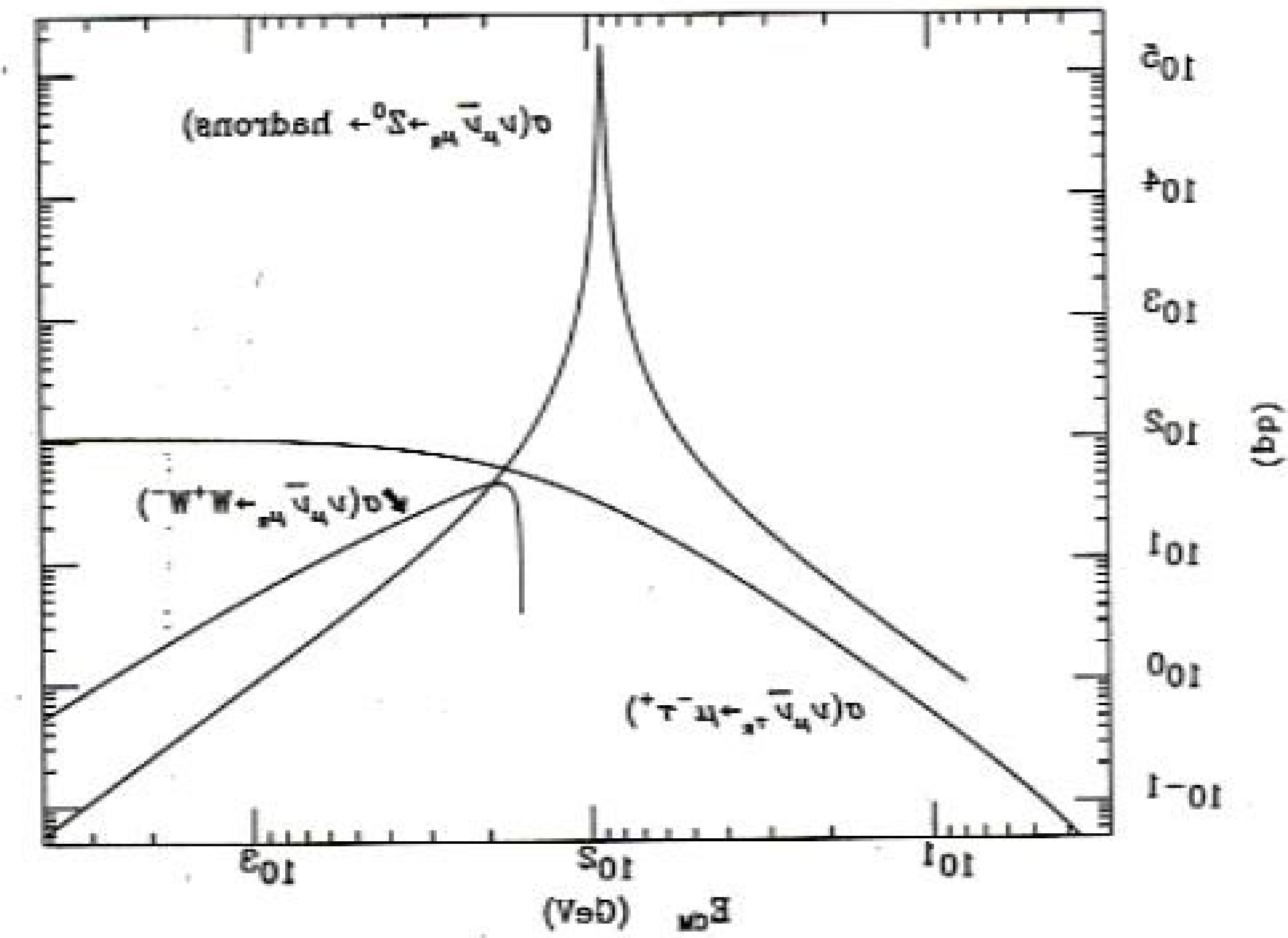
is **RESONANT**

$$\langle\sigma\rangle \equiv \int \frac{ds}{M_Z^2}\,\sigma(s) = 2\sqrt{2}\,\pi\, G_F$$

$$\lambda_{\nu\nu} = 30\left(\frac{50\,cm^{-3}}{n_\nu}\right) D_H$$

$$\therefore\ P(\nu_{CR}\nu_{relic}\text{-annihilete})\,dx$$

$$= \frac{dx}{\lambda} = 3\%\left(\frac{n_\nu}{50\,cm^{-3}}\right)\frac{dx}{D_H}$$

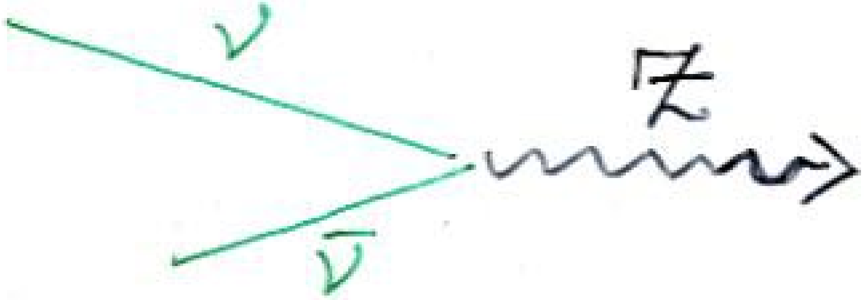


$\sigma(\nu_\mu \bar{\nu}_\mu \to Z^0 \to$ hadrons)
$\sigma(\nu_\mu \bar{\nu}_\mu \to W^+ W^-)$
$\sigma(\nu_\mu \bar{\nu}_\tau \to \mu^- \tau^+)$
(pb)
E_{cm} (GeV)

Relic Neutrino ($C\nu B$) Spectroscopy

Imagine Cosmic Ray ν annihilation on $C\nu B$:

at the Z-resonance!

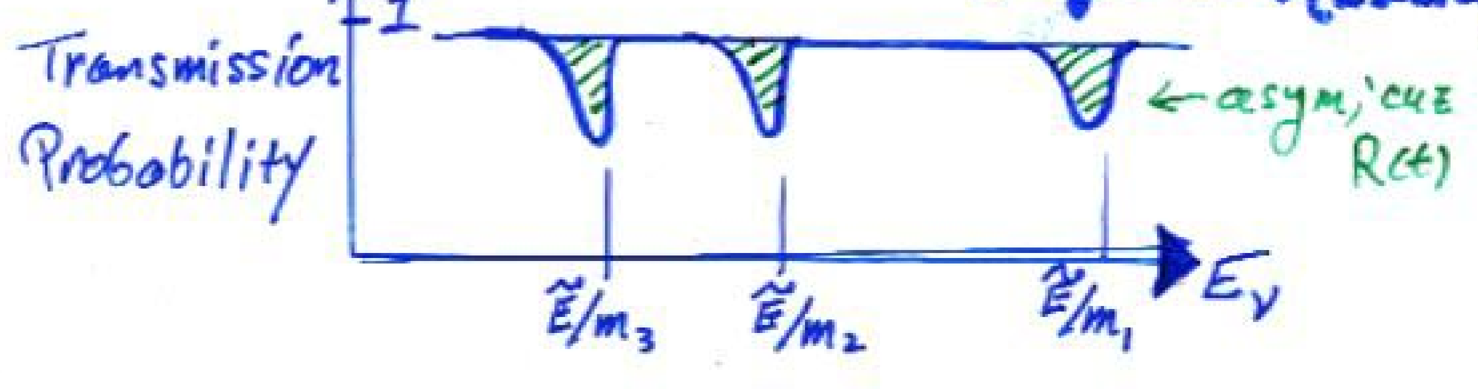


$$s = \begin{cases} M_Z^2 & \text{in CMS} \\ 2E_\nu m_\nu & \text{in LAB} \end{cases}$$

$$\Rightarrow \quad E_{Res} = \frac{M_Z^2}{2m_\nu} = \frac{4\times 10^{21}\,eV}{(m_\nu/eV)} \equiv \frac{\tilde{E}}{(m_\nu/eV)};$$

$$\Rightarrow \quad \frac{\delta E}{E_R} = \frac{2\Gamma_Z}{M_Z} \sim 6\%;$$

$\Rightarrow$ Absorption Spectrum (TW, 1982-84)
PRL (single source) Ap. J. (Σ sources);



For CR-ν's from **AGN**$\underline{s}$

GRB$\underline{s}$

$z_{source} \gtrsim 1,$

$\Rightarrow$

☆ $\frac{dx}{D_H} \sim 1$

☆ $n_\nu(z) = (1+z)^3\, n_\nu(\text{today})$

☆ Absorption Range is $\frac{E_R}{1+z} \le E_\nu \le E_R$

$\Rightarrow P_{annihilate} \sim 3\left(\frac{n_\nu}{50}\right)\% * \begin{Bmatrix}\text{Cosmological} \\ \text{Enhancement}\end{Bmatrix}$

$\longrightarrow \underbrace{10 \text{ to } 40\%}_{\text{depends on } \Omega_i\text{'s}} \underbrace{\left(\frac{n_\nu}{50}\right)}_{\text{can be } O(5)!} * |U_{\nu j}|^2$, for $z \sim 3$.

Recent Idea {Oct '97; T.J.W.; Fargion, Mele, Salis

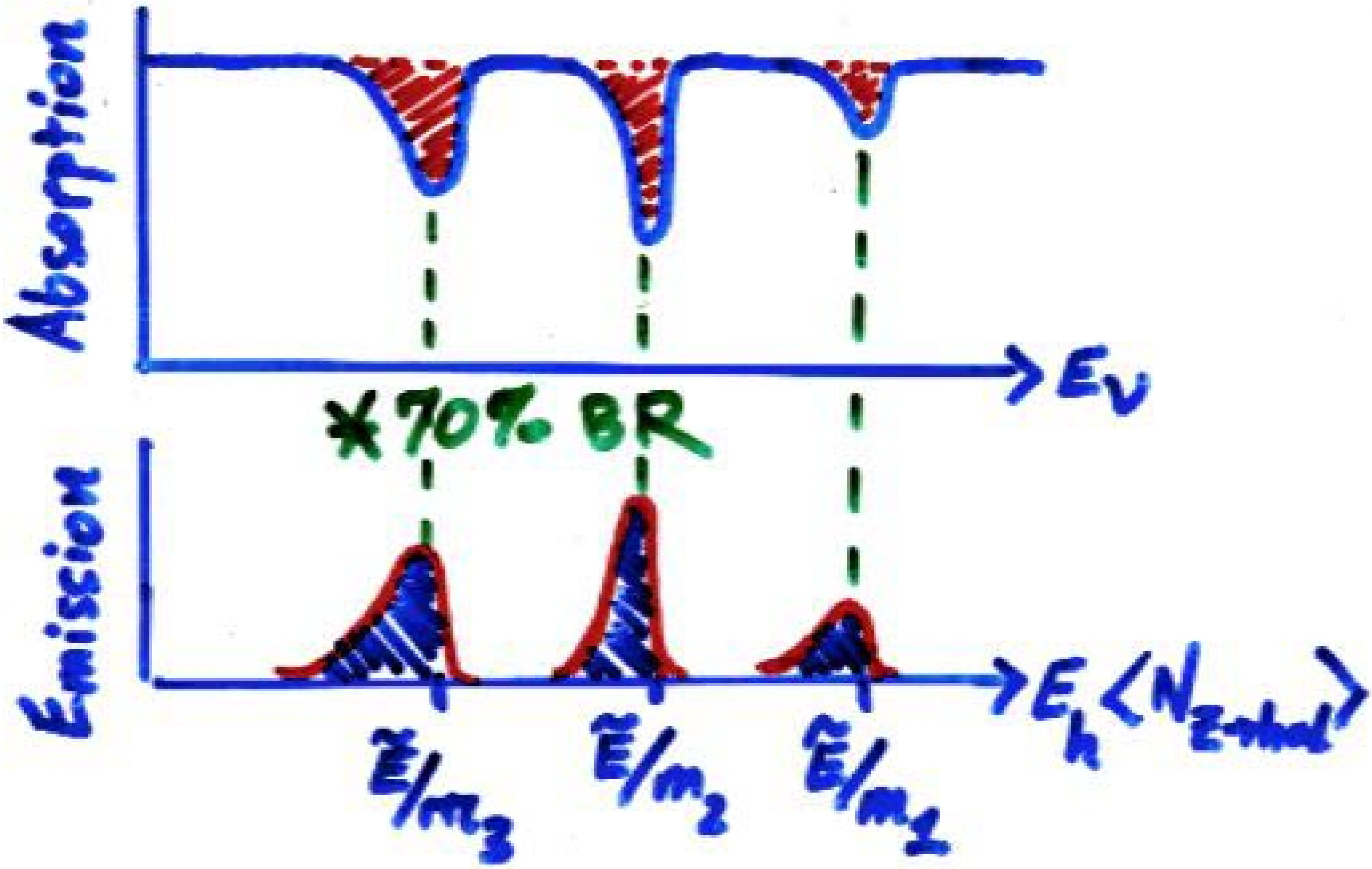
Instead of "ABSORPTION SPECTROSCOPY" [need hi stats]

Do "EMISSION SPECTROSCOPY"

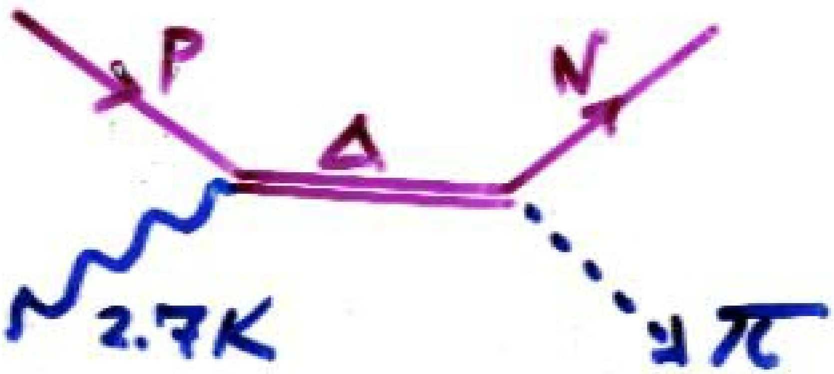
$Z \xrightarrow{70\%}$ {3 nucleons, 30 γ's

★ Low statistics fine

★ Zero Bkgd above <u>GZK</u> <u>cutoff</u>.

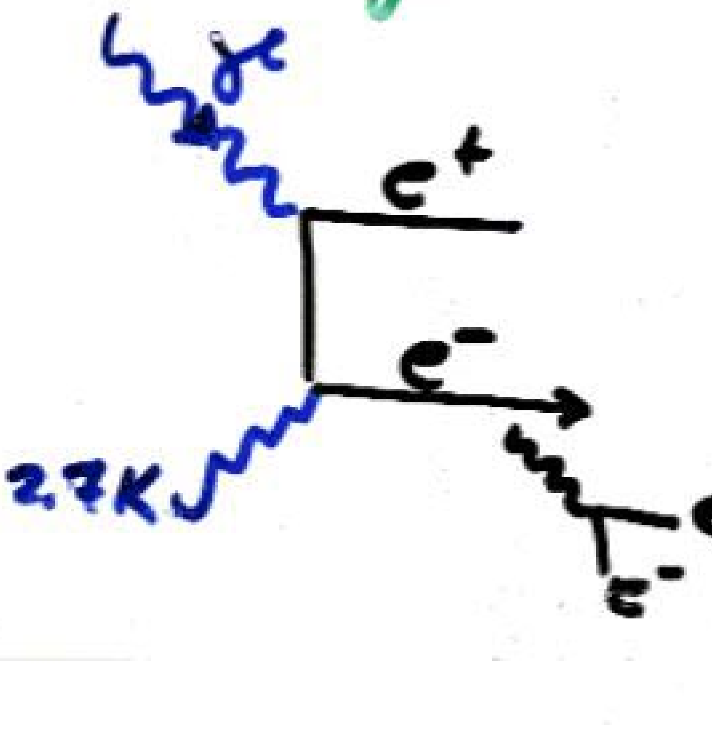


The GREISEN-ZATSEPIN-KUZMIN (GZK) CUTOFF

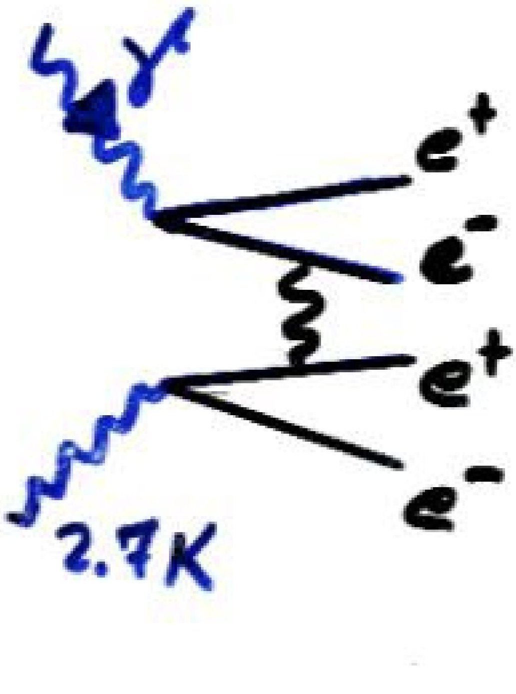


Costs $\frac{\Delta E}{E} \sim 20\%$ per 6 Mpc.

Similarly,



&



AGASA (Japan)

$E > 10^{19}$ eV	581	
$> 4 \cdot 10^{19}$	47	$D_{50\%} = 130$ Mpc
$> 10^{20}$	6	19 Mpc

World Sample:

$> 10^{20}$	13*	19 Mpc

* including John Linsley/Volcano Ranch 1963

AGASA, PRL 81, 1163 (98)

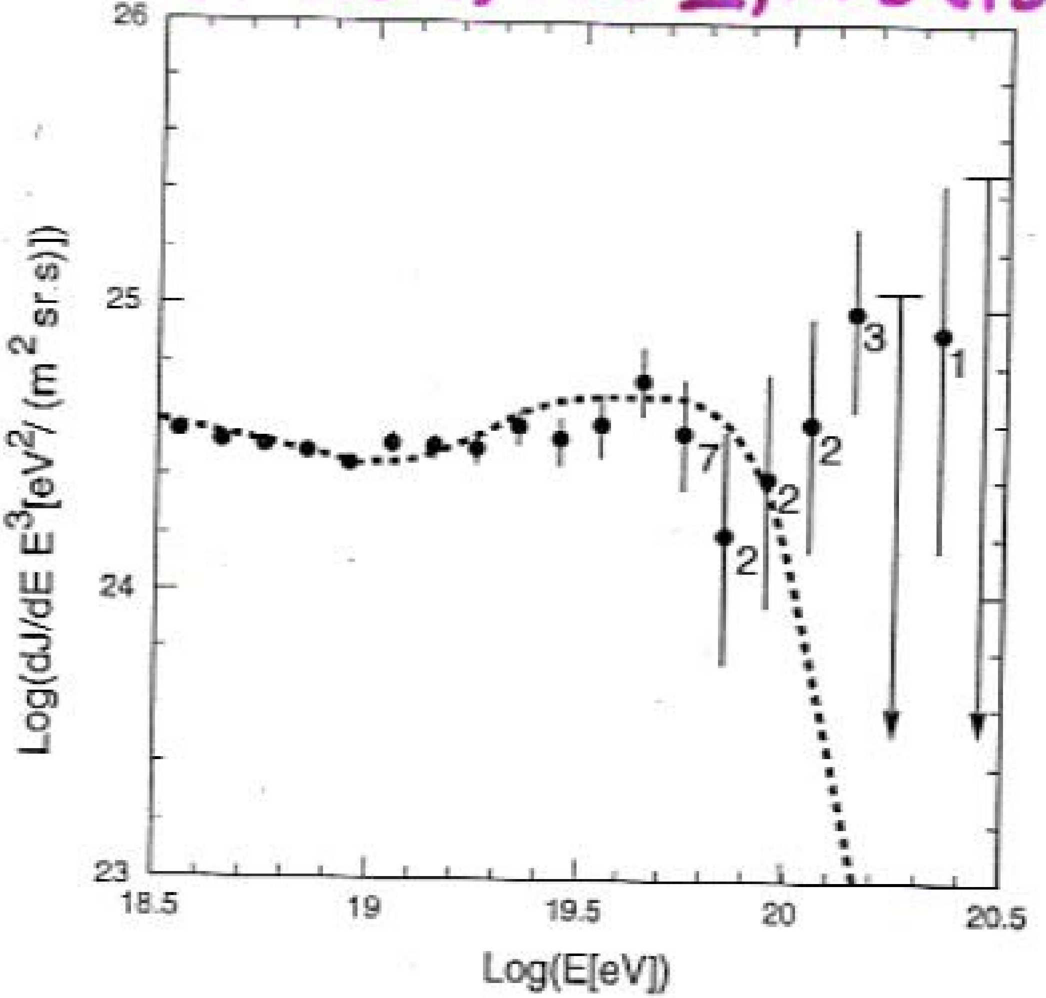


FIG. 2. Energy spectrum observed with AGASA. The vertical axis is multiplied by E^3. Error bars represent the Poisson upper and lower limits at 68% and arrows are 90% C.L. upper limits. Numbers attached to points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe, taking account of the energy determination error [11].

Birkel & Sarkar

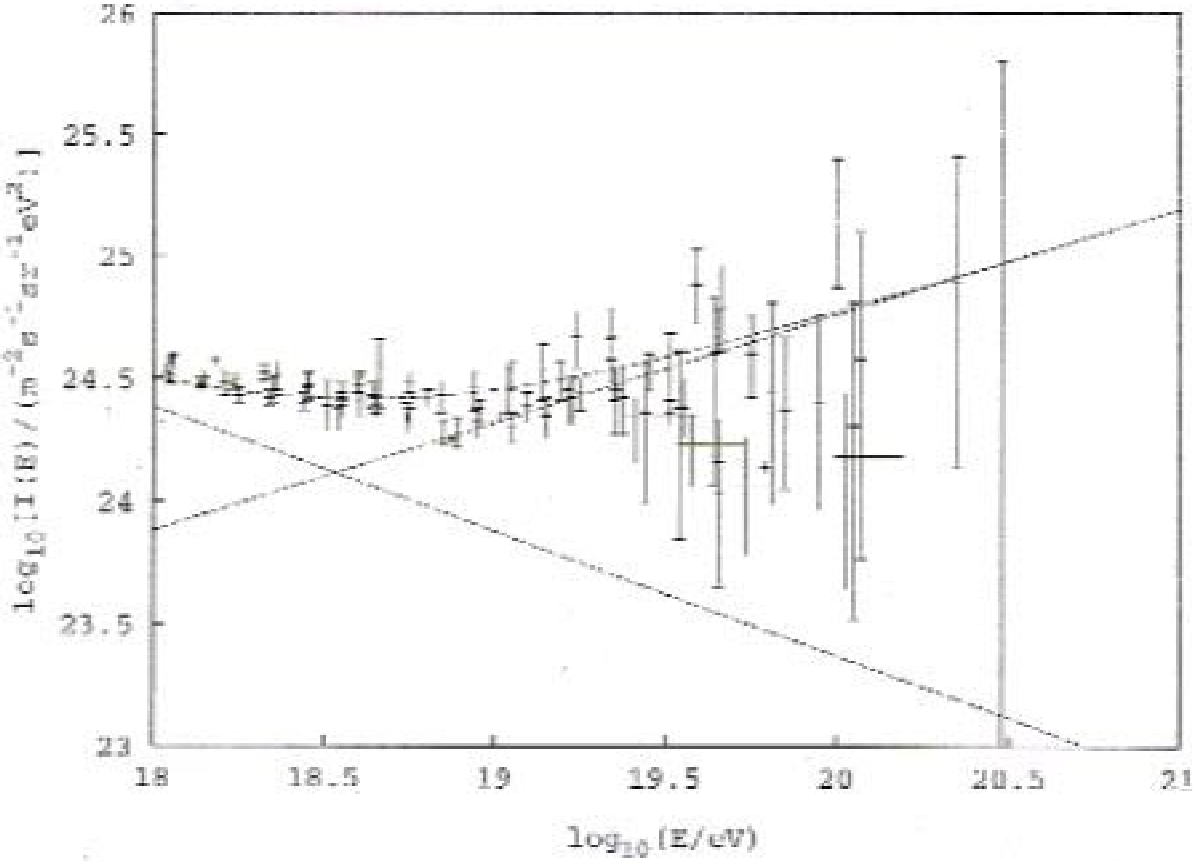


FIG. 1. The high energy cosmic ray spectrum beyond the 'ankle'. (Note that the differential flux has been multiplied by E^3.) The data shown are from AGASA, stereo Fly's Eye, Haverah Park and Yakutsk and are AGASA-normalized [8]. The highest energy monocular Fly's Eye event at 3×10^{20} eV is also shown. A fit to the spectrum from the superposition of a steeply falling and a flatter power law (dashed lines) is indicated [2].

↳ Fly's Eye PRL

AGASA sees

3 pairs and 1 triplet

within $\theta_{resolution} \sim 2.5^\circ$

P(chance) < 1°

Highly Significant:

- Cosmic $\vec{B}$ bends charged-particles
- Bend is E-dependent

No Bending ⇒
- close source [unlikely]
- no $\vec{B}$ [untenable]
- $Q = 0$

No GZK Cutoff ⇒
- close source
- $Q = 0$, mag. moment ~ 0

$\boxed{\nu\text{'s ARE PROPAGATING PARTICLE ?!}}$

RU-98-21

astro-ph/9806242 17 Jun 1998

PRL

Correlation between Compact Radio Quasars and Ultra-High Energy Cosmic Rays

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(June 17, 1998)

Abstract

Some proposals to account for the highest energy cosmic rays predict that they should point to their sources. [We study the five highest energy events ($E > 10^{20}$ eV) and find they are all aligned with compact, radio-loud quasars. The probability that these alignments are coincidental is 0.005, given the accuracy of the position measurements and the rarity of such sources. The source quasars have redshifts between 0.3 and 2.2.] If the correlation pointed out here is confirmed by further data, the primary must be a new hadron or one produced by a novel mechanism. (large F_ν).

\pacs{}

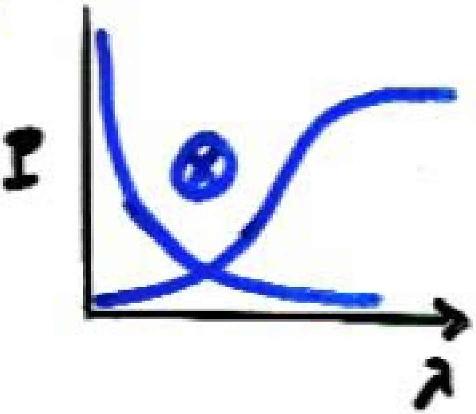
Typeset using REVTEX

With Absorption Spectroscopy, high opacity is desirable.

Not so with "local" Emission Spectroscopy.

$$P = P(\text{annihilate at} < D_{GZK}) * P(\text{survive at } D_H)$$

$$\simeq \frac{D_{GZK}}{\lambda}\, e^{-D_H/\lambda}$$



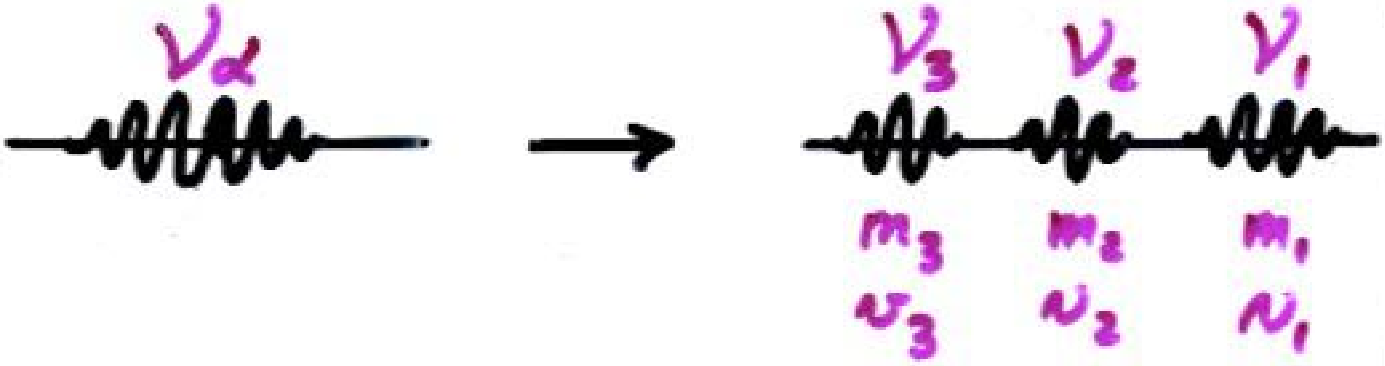
Exponential suppresses $\lambda < D_H$, so find

$$P_{max} = P(\lambda = D_H) = \frac{D_{GZK}}{e\, D_H}$$

$$\sim \frac{1}{e}\,\frac{50\text{ Mpc}}{5\text{ Gpc}} \sim 0.3\%$$

CνB = flavor

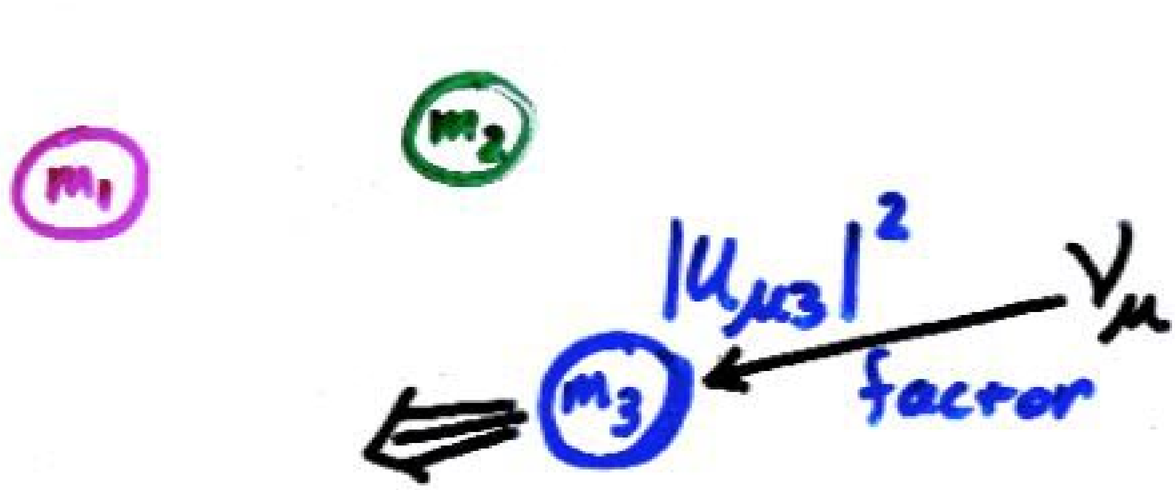
Decoherence after 12-15 Gyr



with $v_j \sim \frac{3T}{m_j}$

$$P(\nu_j) = \sum_\alpha |U_{\alpha j}|^2 P(\nu_\alpha)$$

$$\overset{\text{T-eq}^{\text{m}}}{=} \frac{1}{N} \sum_\alpha |U_{\alpha j}|^2 = \frac{1}{N} \qquad \forall j.$$

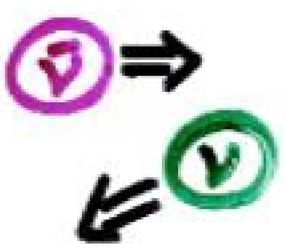


Dirac vs. Majorana

When relativistic,
100% polarized:

$\Downarrow$ red-shift by $z_0 \sim 10^{10}$

Nonrelativistic today,
Unpolarized:

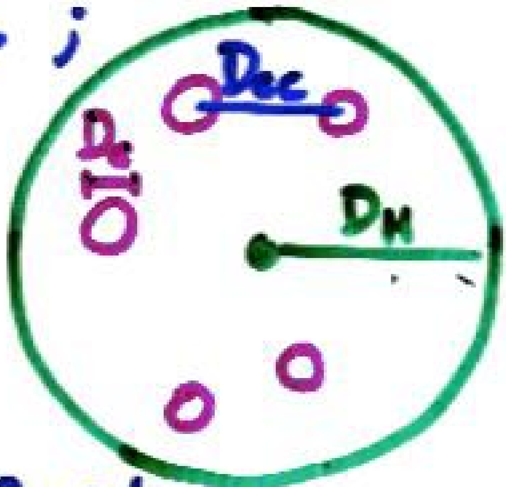


ie $\begin{pmatrix} \nu_L \\ \bar{\nu}_R \end{pmatrix} \xrightarrow{\text{red-shift}} \begin{pmatrix} \underbrace{\boxed{\begin{matrix} 50\%\ \nu_L \\ 50\%\ \bar{\nu}_R \end{matrix}}}_{\text{active}} + \underbrace{\boxed{\begin{matrix} 50\%\ \nu_R \\ 50\%\ \bar{\nu}_L \end{matrix}}}_{\substack{\text{sterile if } \nu_D \\ \text{active if } \nu_M}} \end{pmatrix}$

$\therefore$ Dirac CVB half as active as Majorana CVB.

Enhancement from ν Clustering:

$$\xi \equiv \frac{n_\nu}{\langle n_\nu \rangle} = \frac{V_{uni}}{N_c V_c} ;$$



$$N_c = \frac{V_{uni}}{L_{cc}^3} ;$$

$$\Rightarrow \xi \sim \left(\frac{L_{cc}}{L_c}\right)^3 \xrightarrow[\substack{L_c \sim 20\,\mathrm{Mpc} \\ L_{cc} \sim 100\,\mathrm{Mpc}}]{\text{S-Cluster}} \sim 100$$

$*$ Path Length $\sim \frac{L_c}{D_H}$, $\xrightarrow[\substack{5000\,\mathrm{Mpc} \\ \text{for } h=.6}]{20\,\mathrm{Mpc}} 4 \cdot 10^{-3}$;

$\Rightarrow$ "Local" Rate $\sim L_{cc}^3 / L_c^2 D_H \sim 0.4$

$\Rightarrow P$(z-burst within SCluster) $\sim 1\%$

LEPTON ASYMMETRY increases ν-DENSITY

$$|n_\nu - n_{\bar\nu}| = 0.025\,[\pi^2\xi + \xi^3]$$

$$\xi \gtrsim 1 \quad \approx \quad n_\nu + n_{\bar\nu}$$

From BBN & from Structure Formation,

$$-0.06 \lesssim \xi_{\nu_e} \lesssim 1.1$$

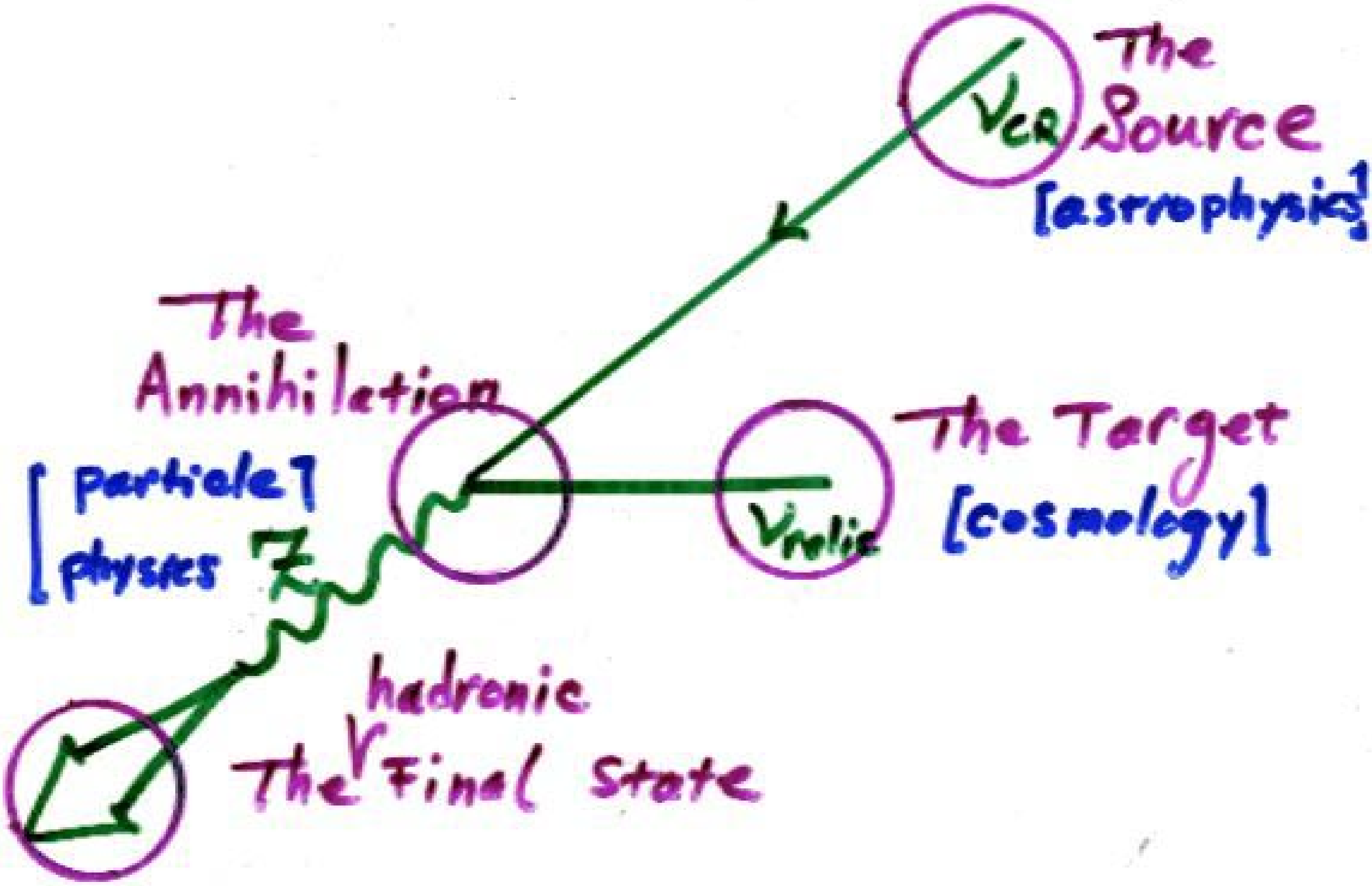
$$|\xi_{\nu_{\mu,\tau}}| \lesssim 6.9$$

Gelmini, Kusenko (99):

$P\left(\begin{smallmatrix}\text{Local}\\ \text{annihilation}\end{smallmatrix}\right)$ optimized (ie $\lambda \sim D_H$)

with $\xi = 5$

$\leftrightarrow \quad n_\nu = 30 \times n_\nu(\xi = 0)$.



Flux of "Z-bursts" produced in distance D is

$$F_Z(D) = \int dE\, F_\nu(E,0)\left[1 - e^{-\sigma_{ann}(E)\,\Sigma(D)}\right]$$

where relic column density is

$$\Sigma(D) = \int_0^D n_{\nu_{relic}}(x)\,dx\ ;$$

$$\simeq \underbrace{E_R\, F_\nu(E_R, 0)}_{\text{source}} \underbrace{\left[\int \frac{dE}{E_R}\,\sigma_{ann}(E)\right]}_{\text{annihilation}} \underbrace{\Sigma(D)}_{\text{target}}$$

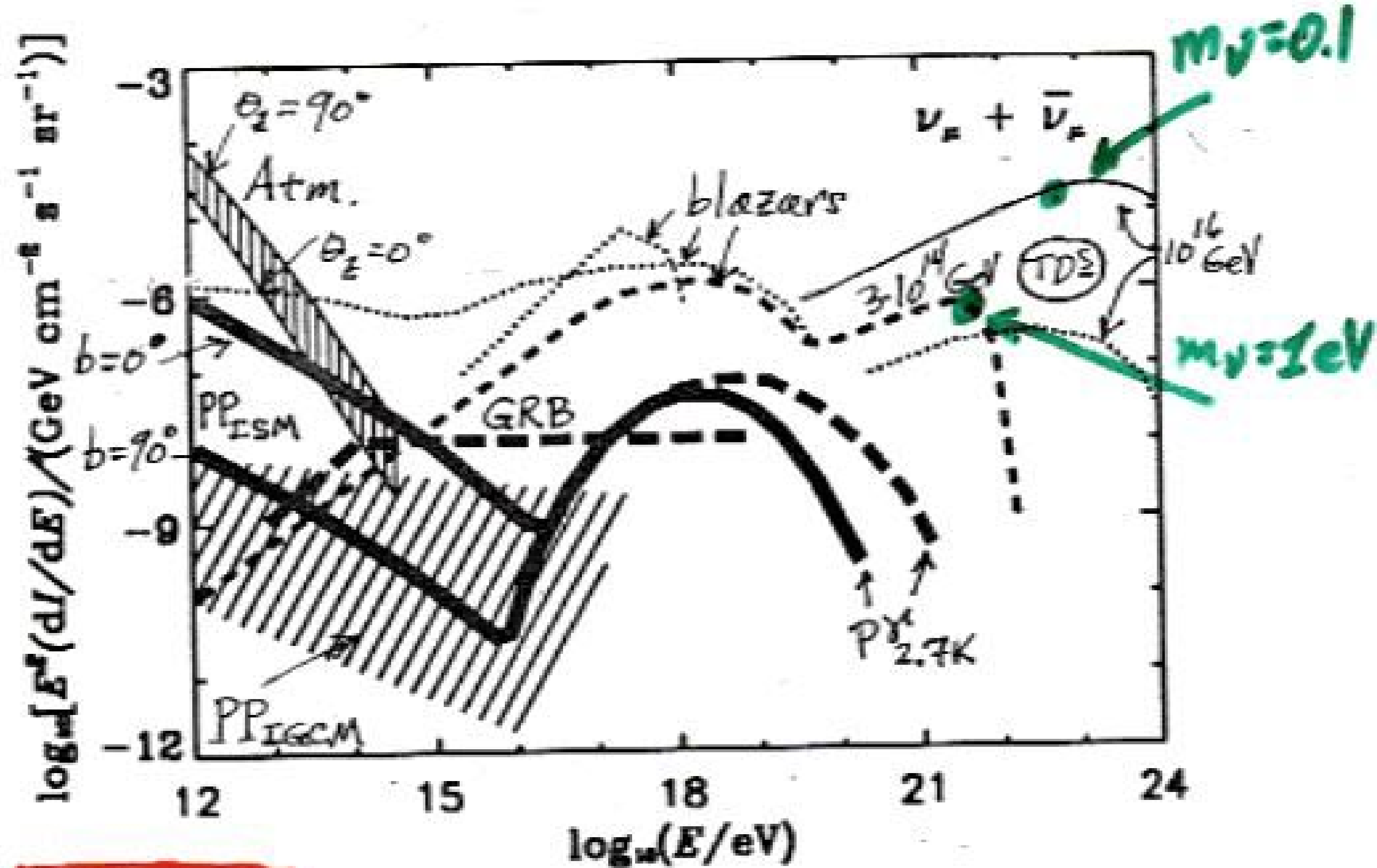
NEUTRINO FLUX ISSUE

$$F_{observed}(\geq E_{GZK})$$

$$\sim \underbrace{\mathrm{Prob}(\nu \to Z)}_{\sim 1\%} * \underset{\substack{\uparrow \\ 4\cdot 10^{21}\,\mathrm{eV}/m_{eV}}}{E_R} * F_\nu(E_R) * \underbrace{\langle N \rangle_Z}_{30}$$

$$\Rightarrow \; F_\nu(\geq E_R \sim 10^{22}) \sim 3 \cdot F_{obs}(\geq 10^{20})$$

Need $F_\nu(E_R) \sim \frac{F_{observed}(E > E_{GZK})}{E_R \, P(\nu \to Z) \langle N_{N,\gamma} \rangle}$



Protheroe: [redacted] Grand Unified Neutrino Spectrum – a personal opinion about the predicted neutrino intensities: thick solid lines – certain; long dashed lines – almost certain; short dashed lines – speculative; dotted lines – highly speculative.

Coming: ?!*?**!

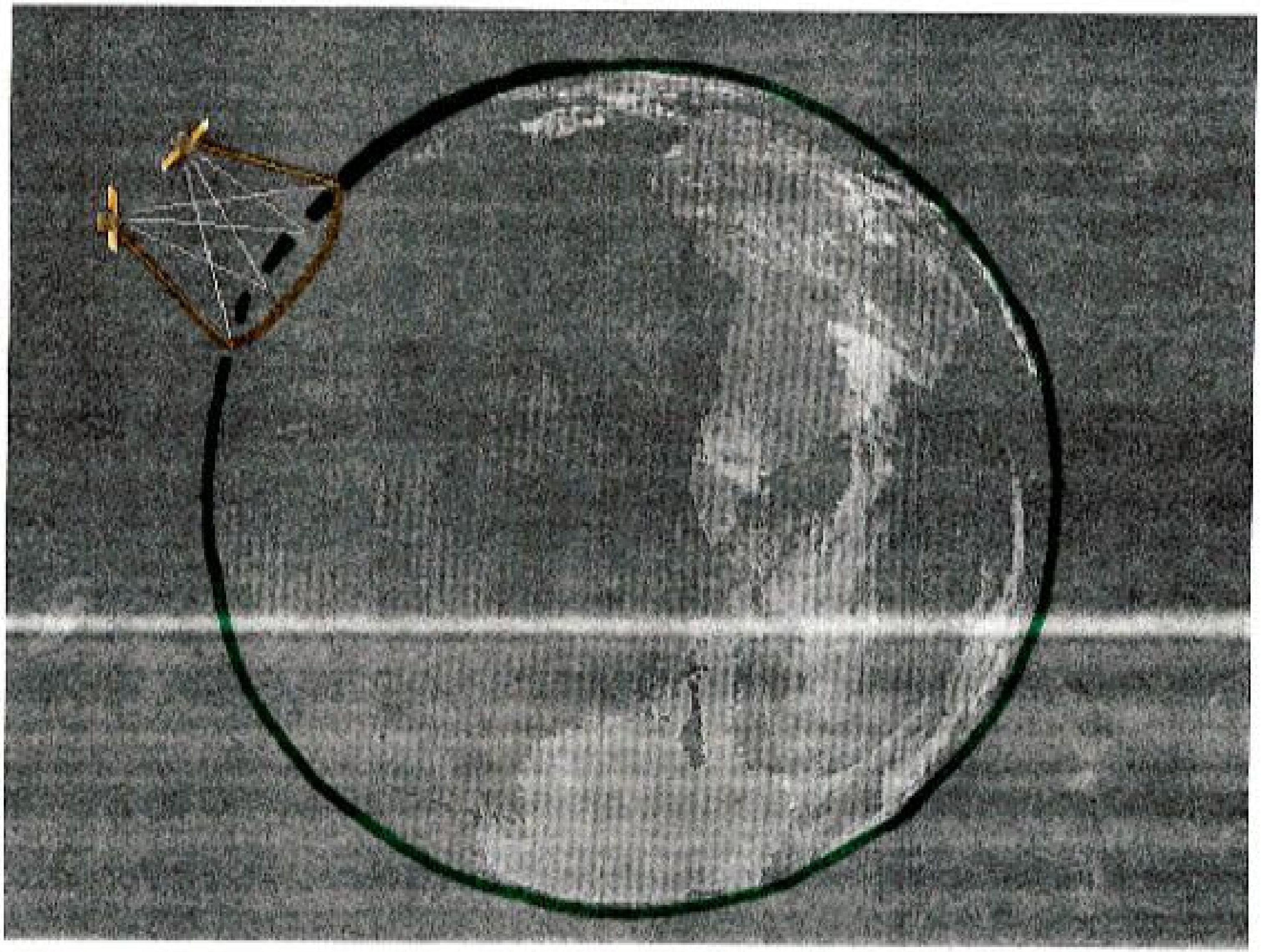
	AGASA	HiRes	Tele Array & Auger	OWL AirWatch
Area*	100	10^3	10^4	$10^5 - 10^6$
No. Evts* $> 10^{20}$ eV	1	10	100	$> 10^3$

* $km^2 \cdot$ steradian

* yR^{-1}

D. Cline: if $F_\nu(E_R)$ exists & $\theta_{\mu\tau}$ is max, then upcoming ν_τ's!

The Mission Concept for OWL Which Will Detect Cosmic Rays at the Highest Energies



Summary

[T.W. hep-ph/9710431]

If Nature provides

(i) $m_\nu \sim \text{few} \times 10^{-1 \pm 1}$ eV,

(ii) F_ν at $E = \frac{4 \times 10^{21}}{m_{eV}}$ eV,

then,

get $F_{obs}(>E_{GZK}) \sim \underbrace{P(\nu \to Z)}_{\sim 1\%} \cdot E_R F_\nu(E_R) \cdot \underbrace{\langle N \rangle_Z}_{\sim 30}$

with ν-clustering,
10^{-4} without;
up to 0.3% with Lepton Asym.

Potential payoff is HUGE—
inferring Relic ν background
(and ν-mass)
validating Big Bang back to $t = 1$ sec!