PUZZLES IN THE HIGHEST ENERGY COSMIC RAYS

Tom Weiler

Weiler - 02

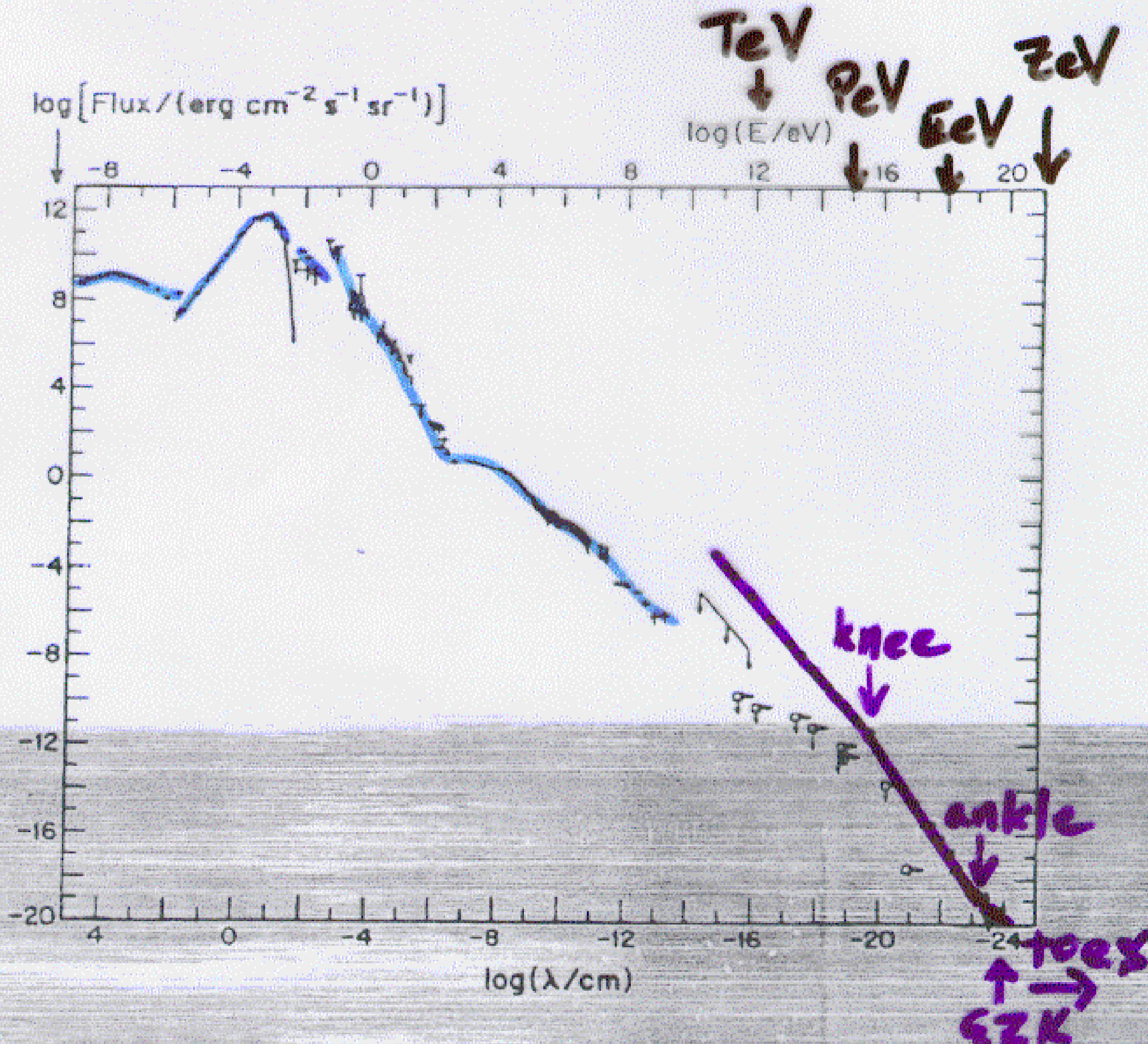
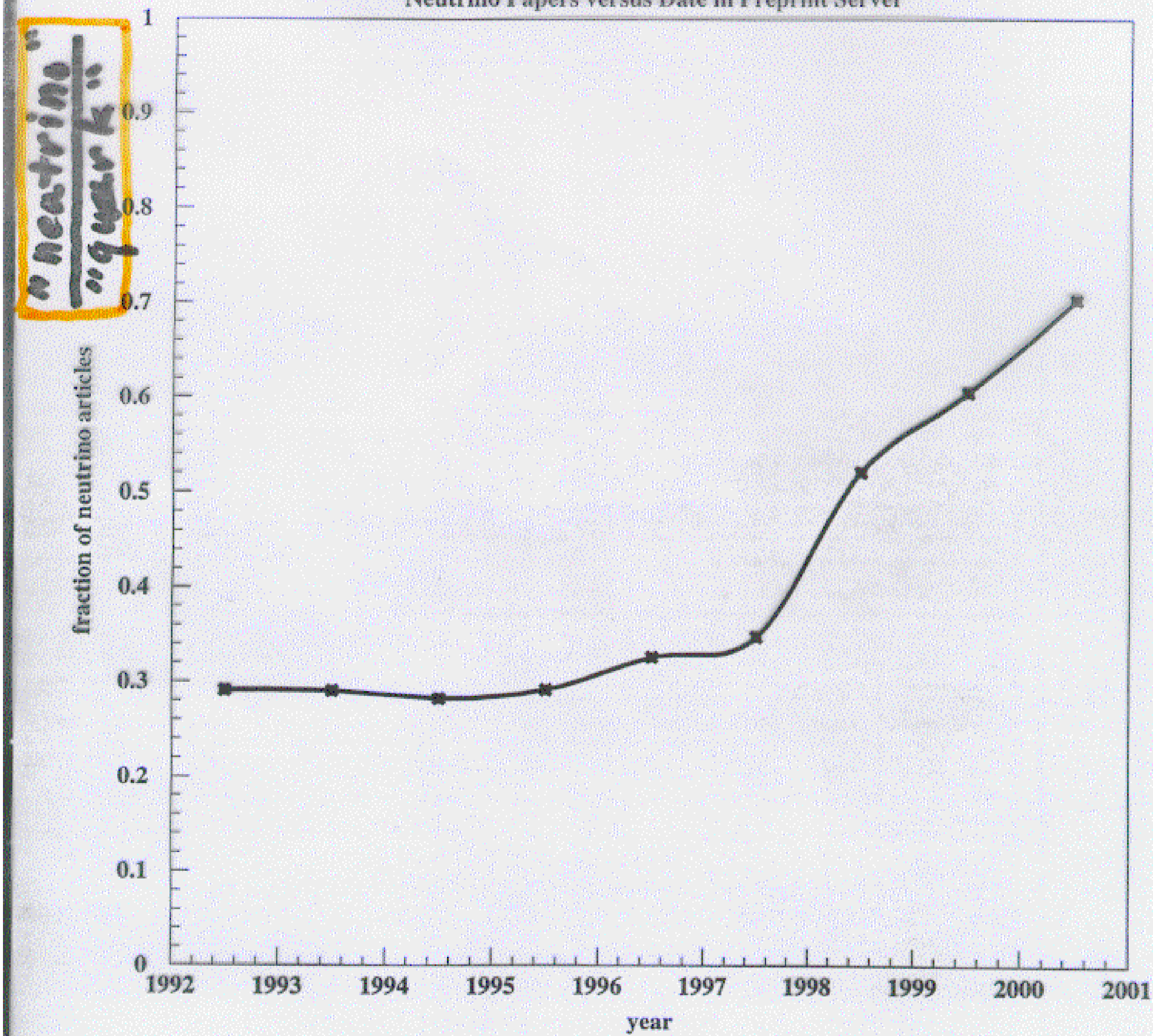


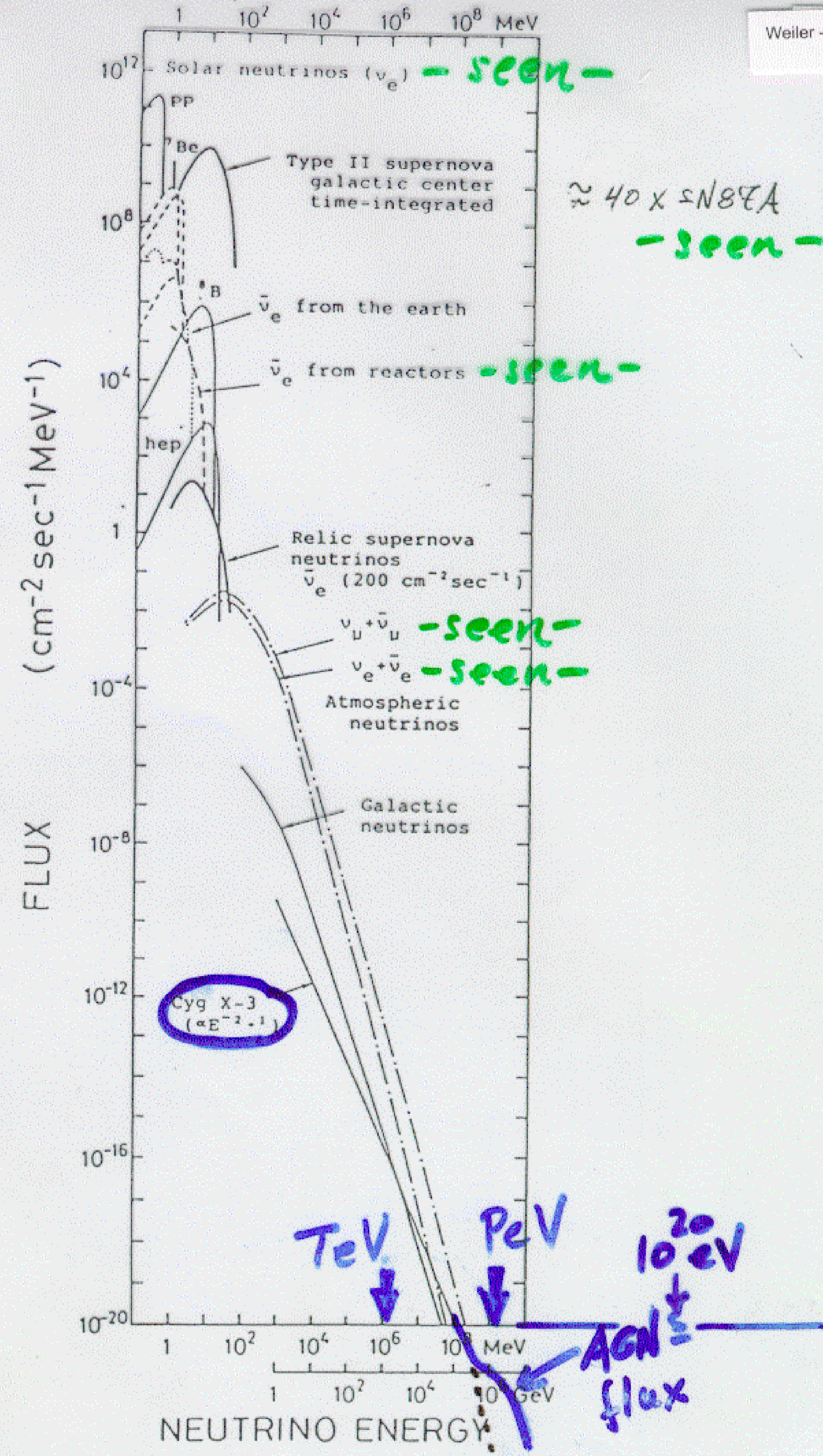
Figure 1. Flux of gamma rays as a function of wavelength and photon energy. In the TeV–EeV energy range the anticipated fluxes are dwarfed by the cosmic ray flux which is also shown in the figure.

From Halzen

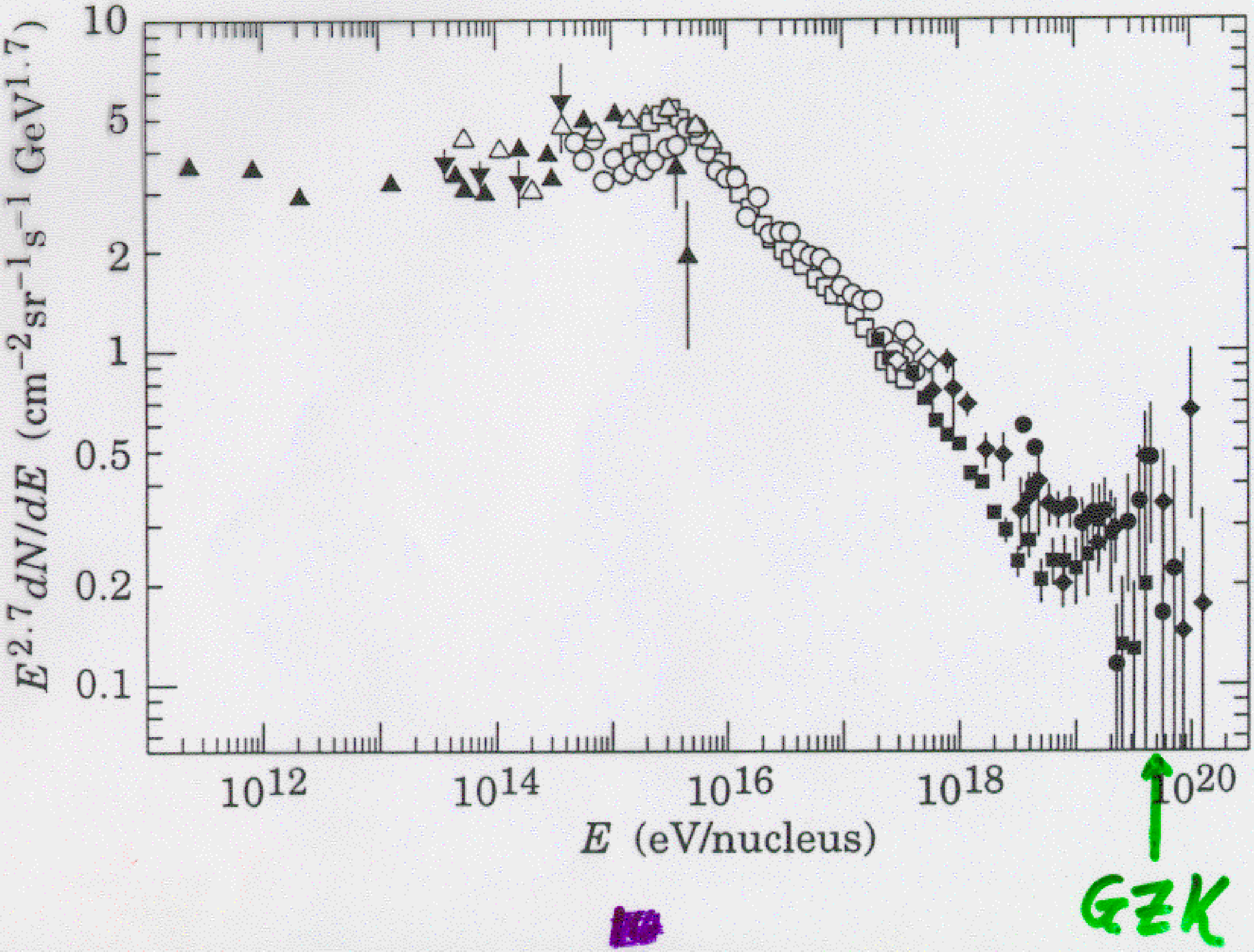
Neutrino Papers versus Date in Preprint Server



from John Learned

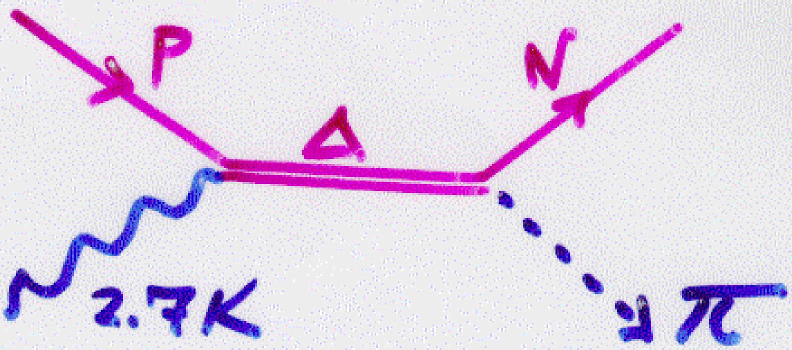

Solar neutrinos (ν_e)
-seen-
PP
^{7}Be
Type II supernova
galactic center
time-integrated
≈ 40 x SN87A
-seen-
^{8}B
$\bar{\nu}_e$ from the earth
$\bar{\nu}_e$ from reactors
-seen-
hep
Relic supernova
neutrinos
$\bar{\nu}_e$ (200 cm^{-2}sec^{-1})
$\nu_\mu + \bar{\nu}_\mu$
-seen-
$\nu_e + \bar{\nu}_e$
-seen-
Atmospheric
neutrinos
Galactic
neutrinos
Cyg X-3
($\propto E^{-2.1}$)
TeV
PeV
10^{20} eV
AGN
flux
FLUX
(cm^{-2} sec^{-1} MeV^{-1})
NEUTRINO ENERGY
MeV
GeV

Weiler - 05



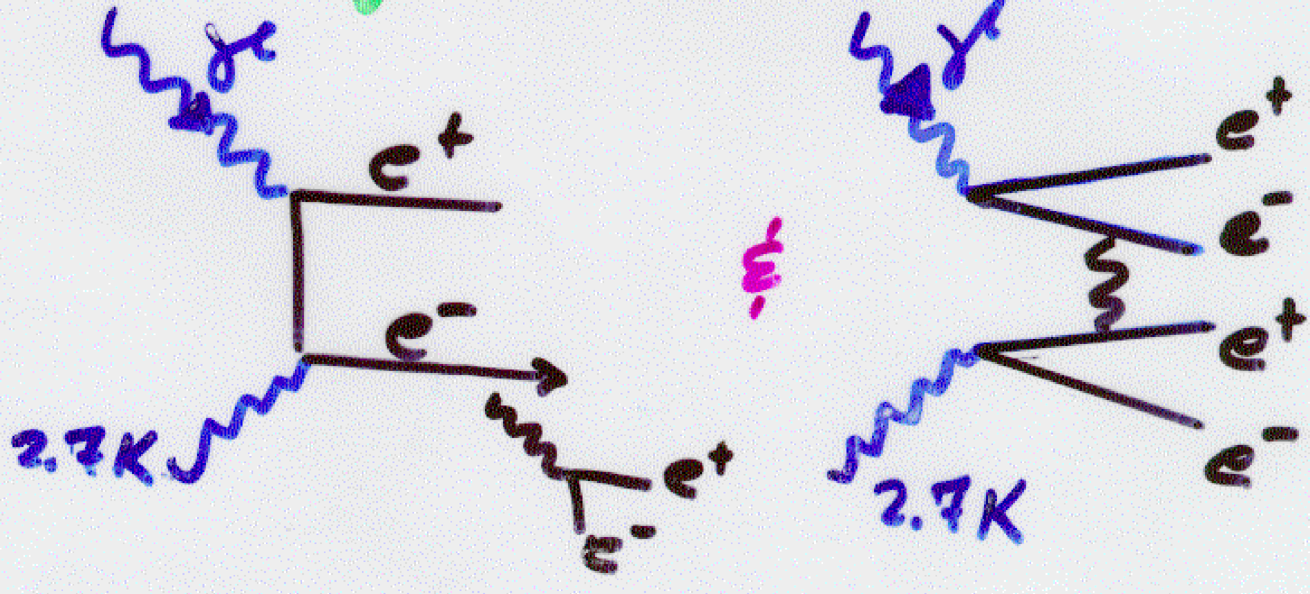
$E^{2.7}dN/dE$ (cm^{-2}sr^{-1}s^{-1} GeV$^{1.7}$)
10
5
2
1
0.5
0.2
0.1
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
E (eV/nucleus)
GZK

The GREISEN-ZATSEPIN-KUZMIN (GZK) CUTOFF



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

Similarly,



Attenuation of cosmic rays

– sigl

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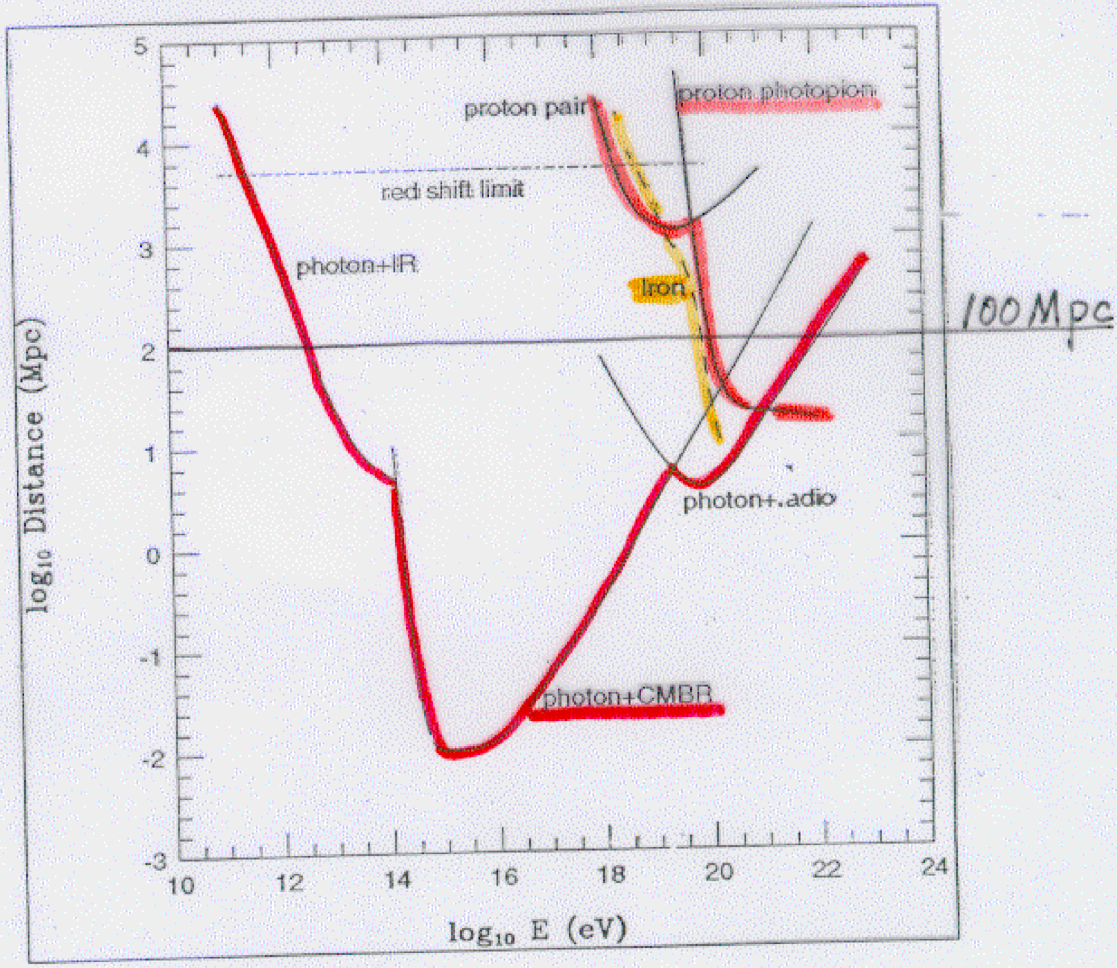
Attenuation length vs energy



All particles except neutrinos
undergo interactions with the CMBR :

This is the GZK cutoff

AGASA (Japan)

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

World Sample:

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

* including John Linsley/Volcano Ranch 1963

+ 7 more, reported by HiRes at ICRC 7/99.

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AGASA, PRL 81, 1163 (98)

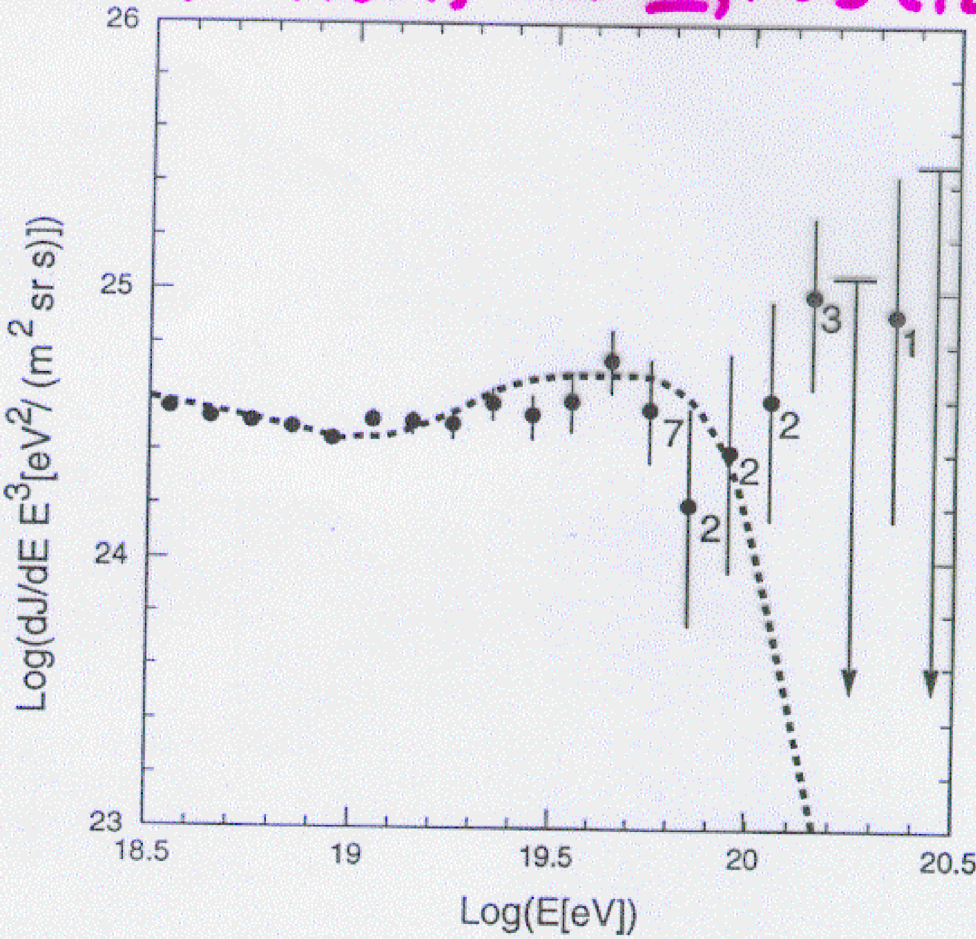

FIG. 2. Energy spectrum observed with AGASA. The vertical axis is multiplied by E^3. Error bars represent the Poisson upper and lower limits at 68% and arrows are 90% C.L. upper limits. Numbers attached to points show the number of events in each energy bin. The dashed curve represents the spectrum expected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

AGASA sees

3 pairs and 1 triplet

within $\theta_{resolution} \sim 2.5°$

P(chance) < 1°

Highly Significant:

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

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

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

ν's ARE PROPAGATING PARTICLE ?!

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RU-98-21

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

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(June 17, 1998)

PRL

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

THEORY CHALLENGES

- Energetics

  $3 \cdot 10^{20}$ eV ~ 50 Joules ~$10^{-8} M_P$

  Shock jocks: $E \sim ZeB\xi$

  [note: $E_{monopole} \sim g_D B\xi$.
  makes $M < 10^{15}$ GeV monos relat'tic]

  [Kephart, Weiler, Wick, Bierman '99]

- Propagation

  D_{GZK} ~ 50 Mpc for 10^{20} eV nucleon
  ~ 10 Mpc for photon

  ⟺ new physics above GZK cutoff?

- Large Scale Isotropy,
  Small Scale Anisotropies

Conjectured Origins

- Nearby "Accelerators"
  - Galactic Supershocks
  - Magnetars (Fe isotropized by big B)
  - M87 or (now quiescent) AGNs w/ " "
  - Nearby GRBs
  - Late DKing SuperMassive Particles
    - GUT masses
    - 10^{13-14} GeV "Wimpzillas"
    - Q-balls
    - Topological Defects (e.g. Vortons)
    - Monopolonium

- Relativistic Dust

Origins (continued)

Exotic Primaries

- Glueballino ($\tilde{g}g$), S^0 baryon ($\tilde{g}uds$) } light gluino
- Monopoles w/ $M \lesssim 10^{20}$ eV

$[E_K \sim g_0 B \xi \sqrt{n} \sim 10^{22\pm2}$ eV$]$

Exotic Physics

- Broken Lorentz Invariance
- $\frac{1}{M_P}$ operators $\left[\frac{E_{CR}}{M_P} \sim 10^{-8} (E/10^{20}\text{eV}) \right]$
- Metric foam/Q. Gravity

Origins (continued)

⊙ Neutrino Primaries

- $\nu_{CR} + \nu_{C\nu B} \rightarrow Z$ burst $\left(\gamma_Z = 10^{10}\, E_\nu / 10^{21}\mathrm{eV}\right)$
- Strong $\sigma_{\nu N}$ ($E \gtrsim 10^{20}$ eV)

Discriminators

- **Anisotropies**
  - large scales: SGC
    - Local Group
    - Gal. Cluster
    - Halo
    - Galaxy
  - small scales: pairing, tripping, ...

$$\delta\theta \sim 0.5^\circ \sqrt{D_{Mpc}\,\lambda_{Mpc}}\; B_{nG}/E_{20}$$

- Energy - time [correlations] in θ

e.g. 1.06 ZeV event 3 yrs after 0.44 ZeV event

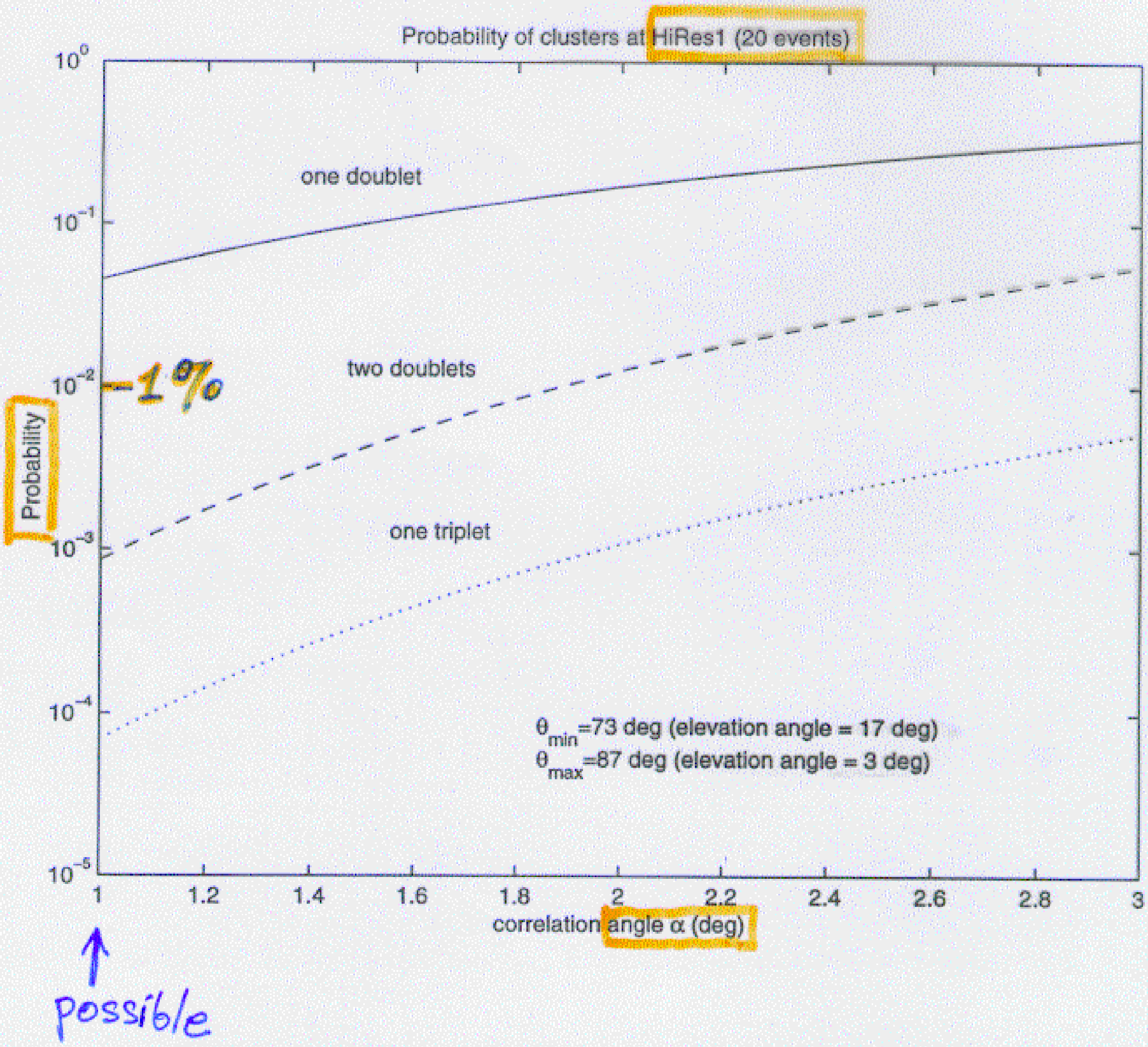
$\Rightarrow [\Delta t]_{source} \sim$ several yrs;

disfavors burst/decay models.
[GRB] [TD, SMP]

From $\Delta \equiv t(p) - t(\gamma) \sim \left(\frac{D}{Mpc}\right)\left(\frac{Z B_{nG}\,\lambda_{Mpc}}{E_{20}}\right)^2$ [300 YRS]

& $t(E_1) - t(E_2) \sim 2\,\frac{\delta E}{E}\,\Delta \sim \mathcal{O}(\Delta)$

H.Goldberg, T.W.



Discriminators cont.

- **Primary Composition**

  p vs. γ vs. Fe vs. NEW

  - Fly's Eye profile at $3 \cdot 10^{20}$ eV disfavors γ
  - e.g. particle jet models have $\frac{\gamma}{N} \sim 10$ at origin

    $$* \Longrightarrow \frac{\pi^0}{N} \sim \frac{5}{1}$$

	$\lambda(10^{20}\,eV)$
γ	10 Mpc
N	40 Mpc

- disfavors nearby particle jets
- and EGRET diffuse (Xgal) γ's at $10^{0\pm2}$ GeV in EM cascades also disfavors local jets.

- **North vs. South Hemispheres**
  - Galactic & local $\vec{B}$ different
    - eg MBZ model
  - line of sight sources different

Fly's Eye Event, $E = 3 \times 10^{20}$ eV

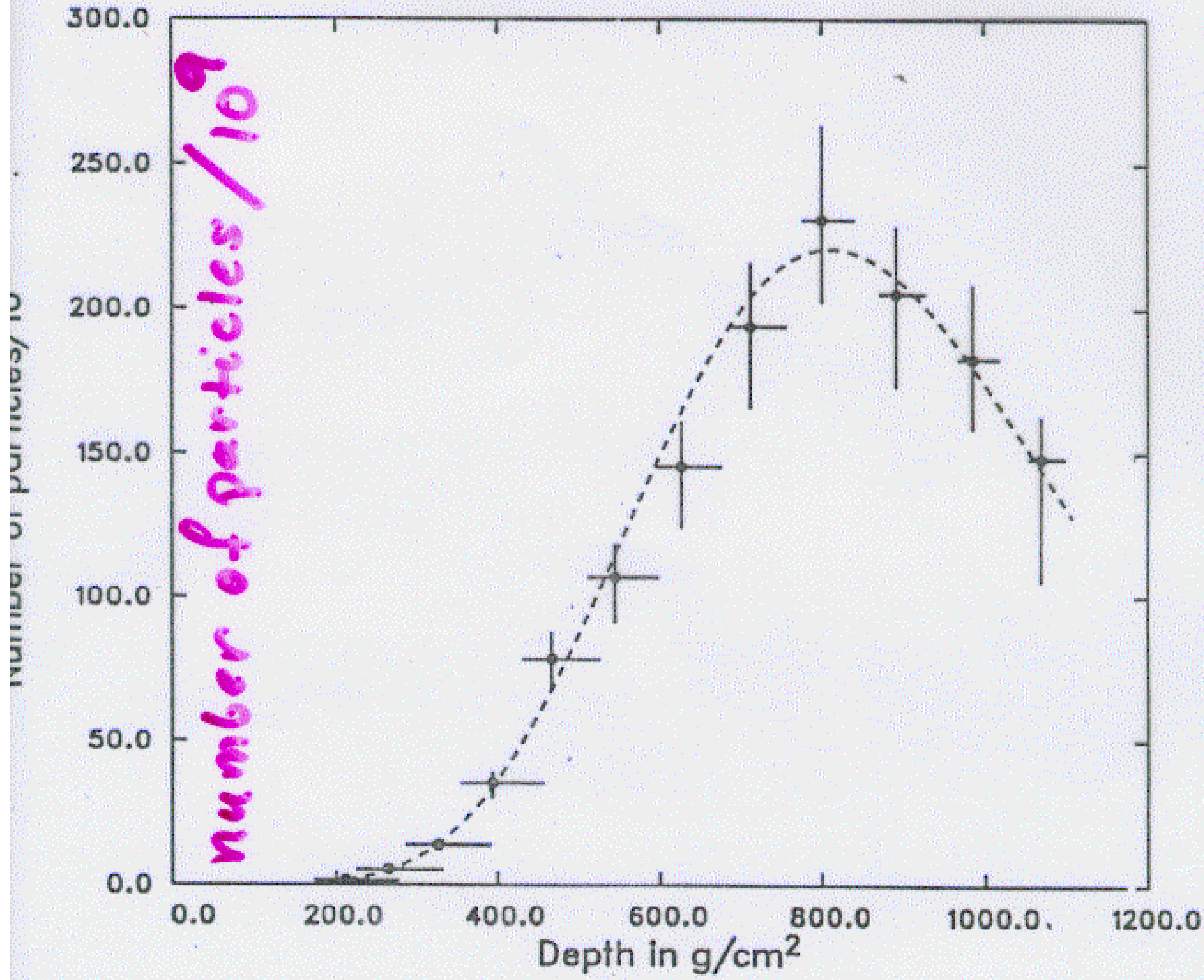


FIG. 3.—The three-parameter best-fit shower profile is shown along with points obtained from the data in 5° intervals. The size at maximum is greater than 200 billion particles.

Discriminators cont.

- **E_{max} cutoff**
  - e.g. TD/SMP $\quad E_{max} \sim \frac{M}{2}$
  - e.g. Z-bursts $\quad \mathrm{CR}\nu + \mathrm{relic}\ \nu \rightarrow Z \Rightarrow \mathrm{jet}$

    $$E_{max} \sim \frac{M_Z^2}{2m_\nu} \sim \frac{4 \cdot 10^{23}\,\mathrm{eV}}{(m_\nu/0.1\,\mathrm{eV})}$$

  - e.g. Zevatron

    $$E_{max} \sim eZB\xi \sim 10^{21}\,\mathrm{eV}$$

- $F(E<GZK)/F(E>GZK)$

  in various species, $p, \gamma, \nu, \ldots$

Cosmic Ray NEUTRINOS

above 10^{20} eV

[and below 10^{-3} eV]

Tom Weiler

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T.W. PRL '82
ApJ '84
Astropart. Phys '9
Fargion, Mele, Salis: ApJ '9

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

But 

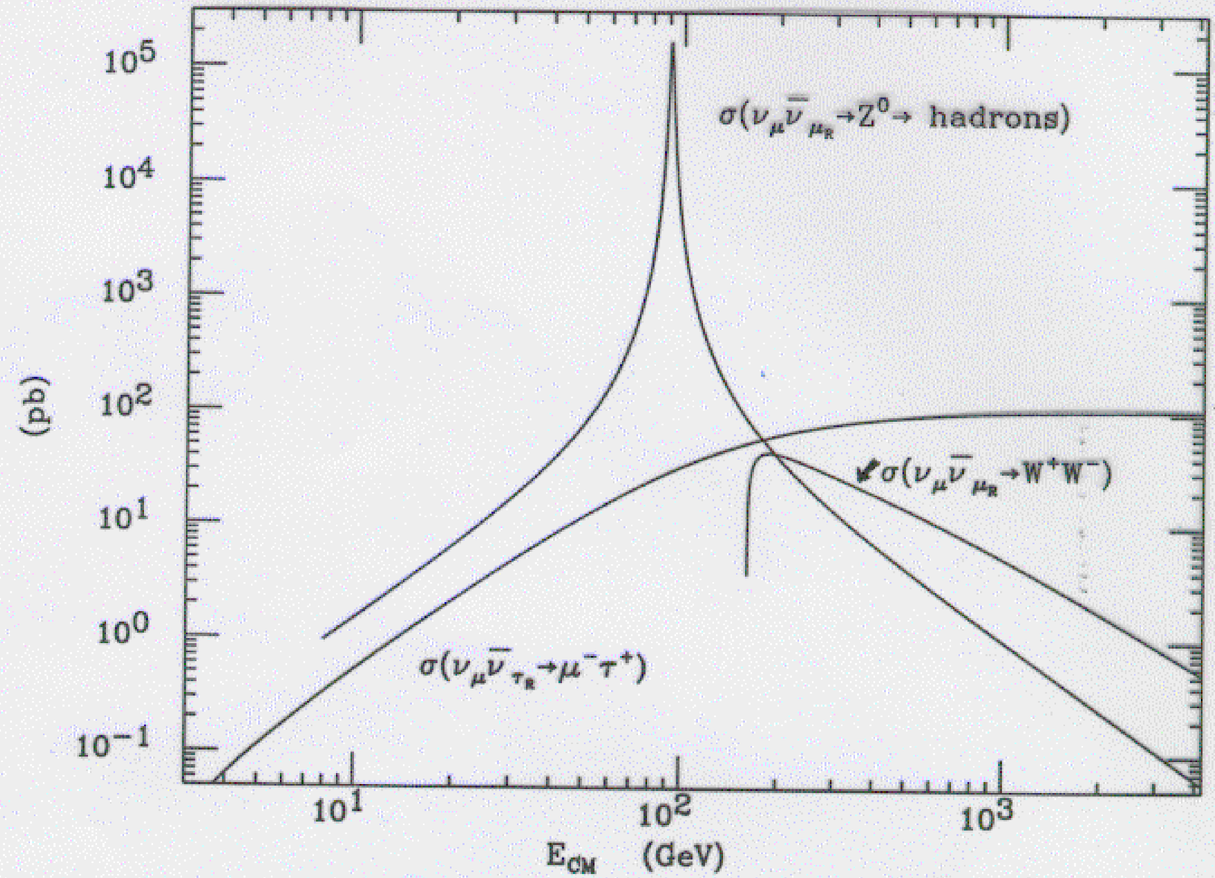
is **RESONANT**

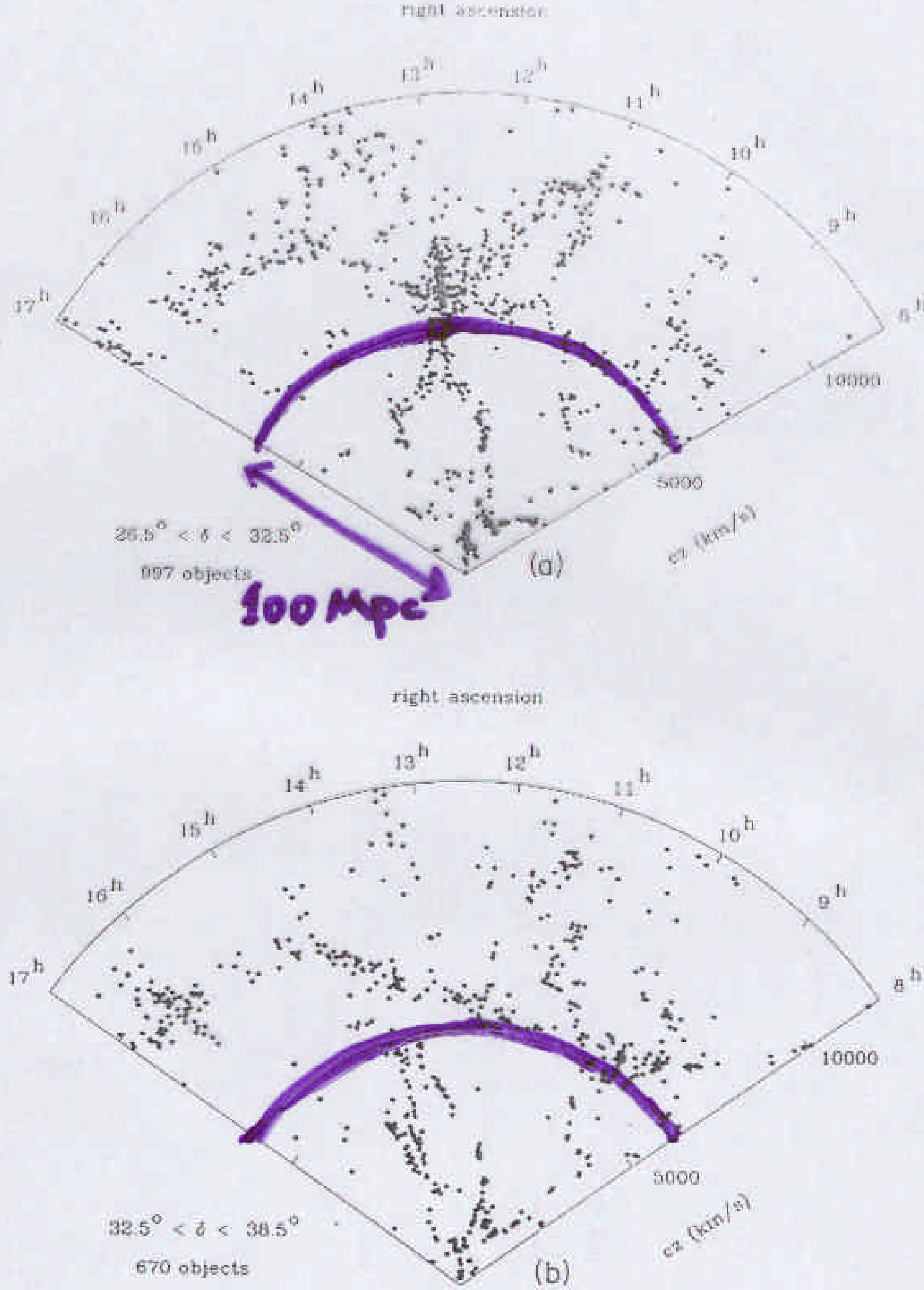
$$\langle\sigma\rangle \equiv \int \frac{ds}{M_Z^2}\,\sigma(s) = 2\sqrt{2}\,\pi\, G_F$$

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

$\therefore$ P($\nu_{CR}\,\nu_{relic}$ annihilate) dx

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


$\sigma(\nu_\mu \bar{\nu}_{\mu_R} \to Z^0 \to$ hadrons)
$\sigma(\nu_\mu \bar{\nu}_{\mu_R} \to W^+W^-)$
$\sigma(\nu_\mu \bar{\nu}_{\tau_R} \to \mu^- \tau^+)$
(pb)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^1
10^2
10^3
E_{CM} (GeV)



$$D = 17\, h_{65}^{-1} \left(\frac{v}{1000\ \mathrm{km/s}} \right) \mathrm{Mpc}$$

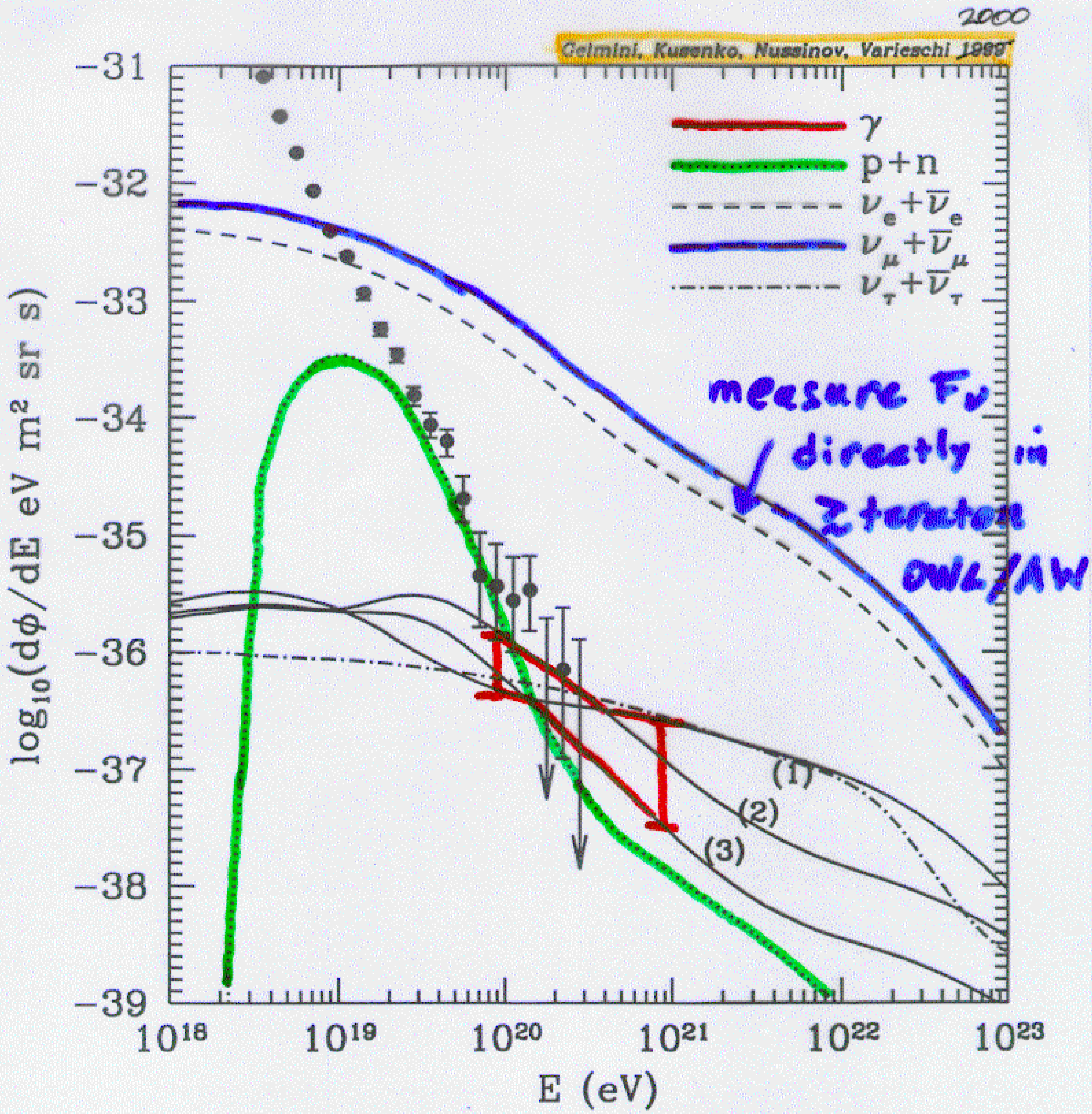
$$E_{Z\text{-burst}} = \frac{M_Z^2}{2m_\nu} = \frac{4 \cdot 10^{21}}{m_{eV}} \, eV$$

With $m_\nu > \sqrt{\delta m^2} = \begin{cases} 0.5 \text{ to } 1.5 & \text{LSND} \\ 0.1 \text{ to } 0.03 & \text{Atm} \\ 3 \cdot 10^{-3} \text{ to } 10^{-5} & \text{Sun} \end{cases}$

get $E_{Z\text{-burst}} \lesssim \begin{cases} 10^{22}\, eV & \text{LSND} \\ 10^{23}\, eV & \text{Atm} \end{cases}$

and $E_{\gamma/p/n} \lesssim \begin{cases} 3 \cdot 10^{20}\, eV & \text{LSND} \\ 3 \cdot 10^{21}\, eV & \text{Atm} \end{cases}$


MATTER
ANTI-MATTER
Relic $\bar{\nu}$'s
$\bar{\nu}_\mu$
$\bar{\nu}_\tau$
$\bar{\nu}_e$
s.harris

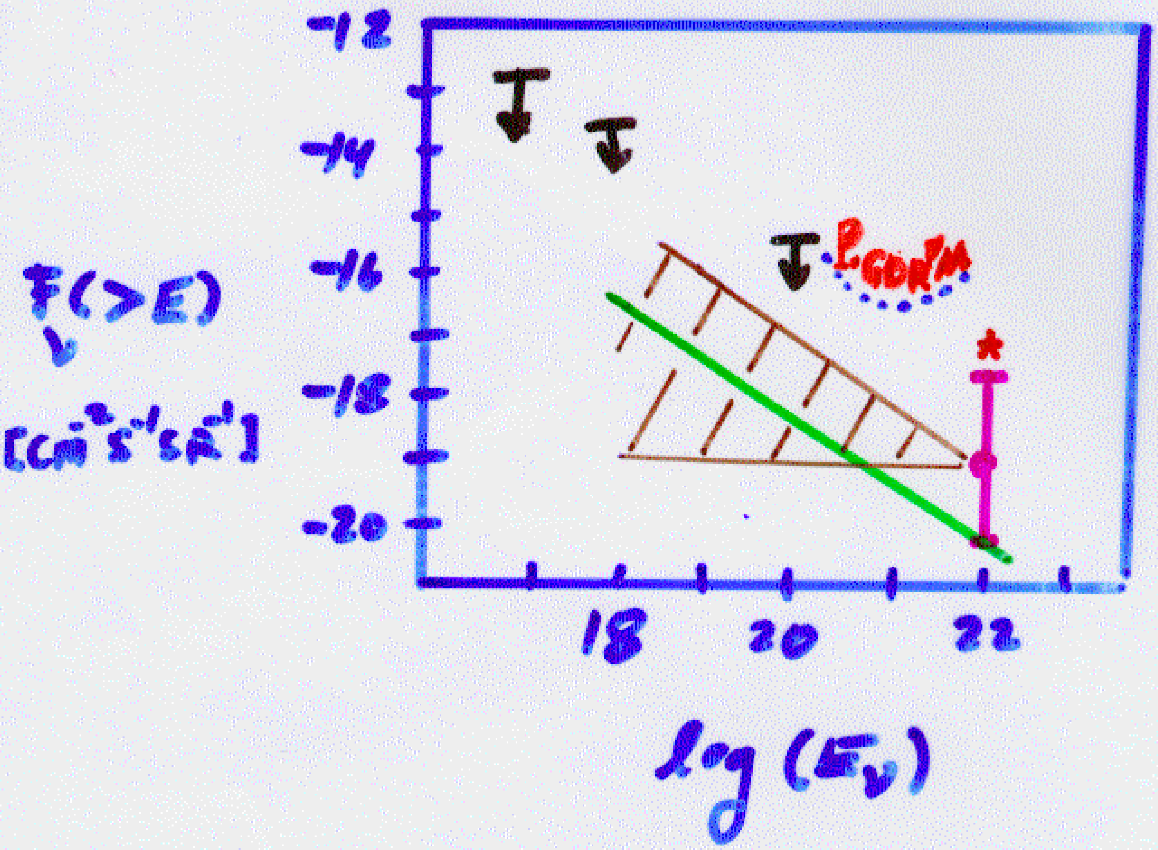

2000
Gelmini, Kusenko, Nussinov, Varieschi 1999
γ
$p+n$
$\nu_e+\bar{\nu}_e$
$\nu_\mu+\bar{\nu}_\mu$
$\nu_\tau+\bar{\nu}_\tau$
measure F_ν
directly in
OWL/AW
(1)
(2)
(3)
$\log_{10}(d\phi/dE$ eV m^2 sr s)
−31
−32
−33
−34
−35
−36
−37
−38
−39
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
E (eV)

NEUTRINO FLUX ISSUE

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

$$\sim \underbrace{Prob(\nu \to Z)}_{\sim 1\%} * \underset{\uparrow\, 4\cdot 10^{21}\,eV/m_{eV}}{E_R} * F_\nu(E_R) * \underbrace{\langle N \rangle_Z}_{20}$$

$$\Rightarrow F_\nu(\geq E_R \sim 10^{22}) \sim 5 \cdot F_{obs}(\geq 10^{20})$$



Z-burst model

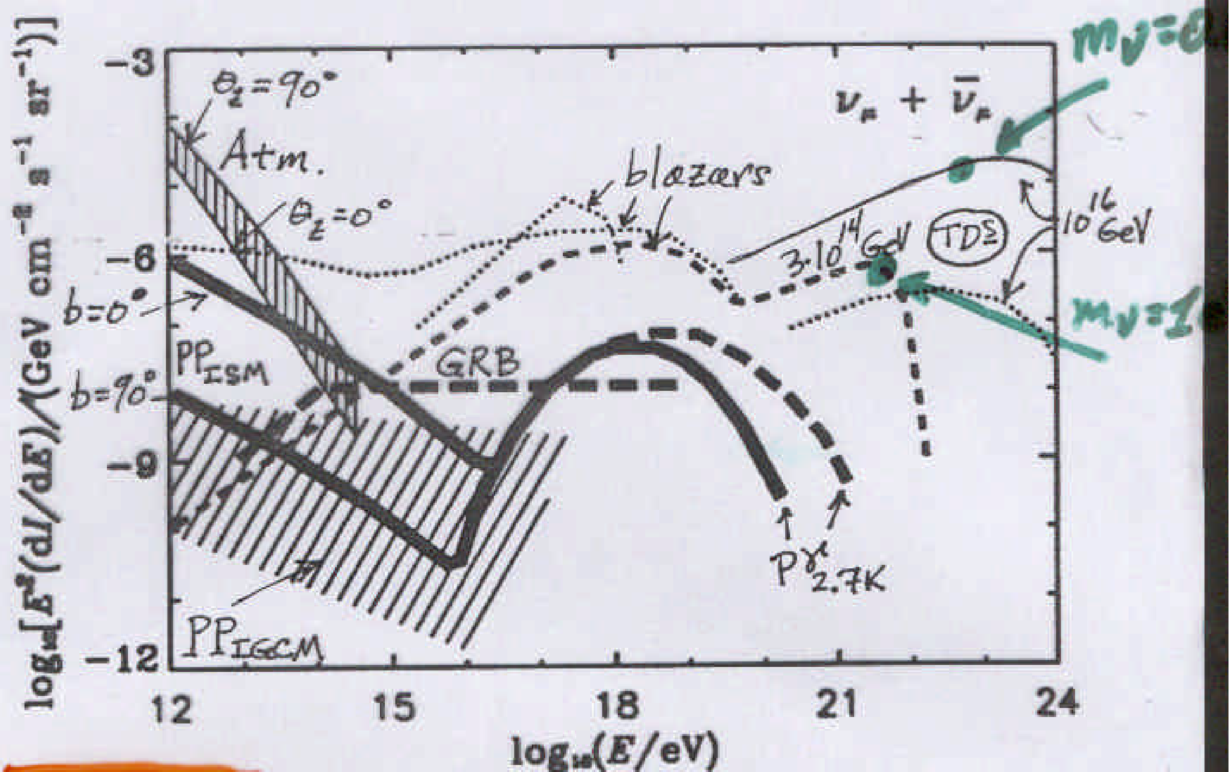
* sans ν clustering/asymm.

Fly's Eye upper limits (80's)

— $WB = \frac{5 \cdot 10^{-14}}{E_{20}}$

TT wedge (norm'd to F_Z requirement)

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



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.

For "tuned" $M \to \nu\bar{\nu}$, see

- Gelmini, Kusenko, PRL '99
- Crooks, Dunn, Frampton, 2000

PRIMARY

✓'s ?

Cosmogenic Neutrinos

$$p + \gamma_{2.7K} \rightarrow N \, \pi$$
$$\hookrightarrow e \, \nu_e \, \nu_\mu \, \bar{\nu}_\mu$$

$F_\nu(E) \sim E_p^{-3.0}$ fits superGZK!

$\therefore$ Can explain data with

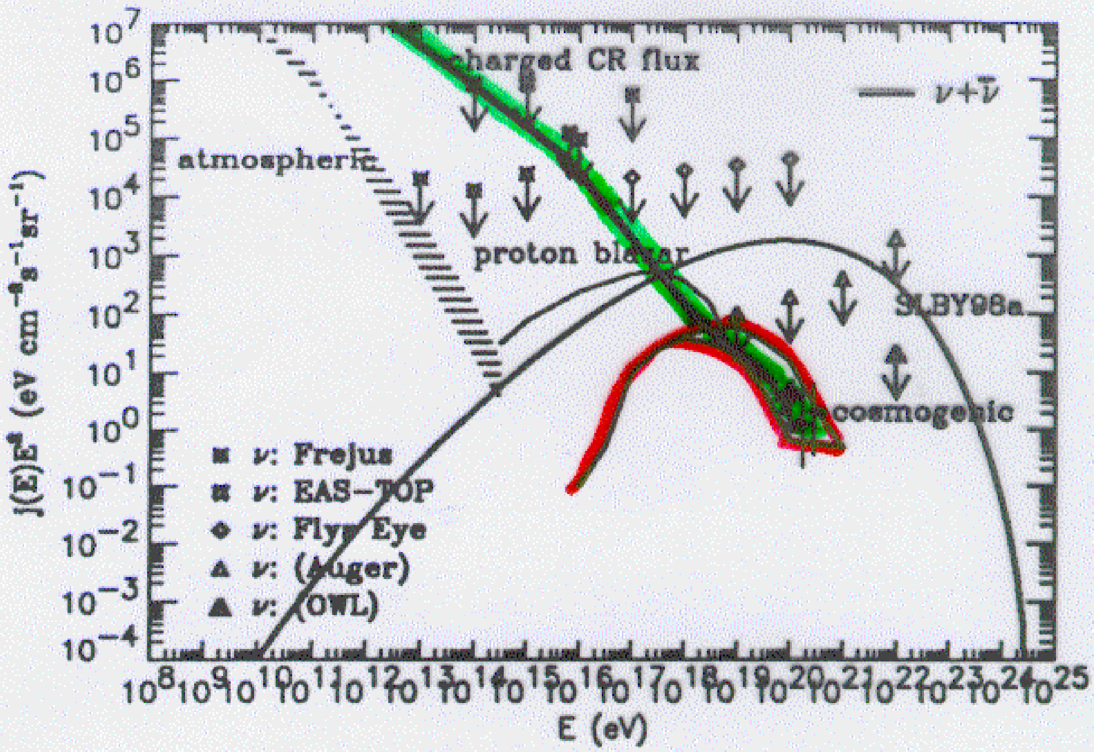
$$\sigma_{\nu N}(10^{20}\,\mathrm{eV}) \gtrsim 100\ \mathrm{mb}\,;\ \frac{\Delta E}{E} \sim 1$$

Tests:

- No penetrating ν-showers at 10^{20} eV
- Dispersion Relation [Goldberg, TW '9…

$$\Rightarrow \quad \underline{\sigma_{\nu N \to \nu N}} = \left(\frac{E}{100\,\mathrm{GeV}}\right)^2 \sigma^{el}_{\mathrm{Std.\,Model}}$$

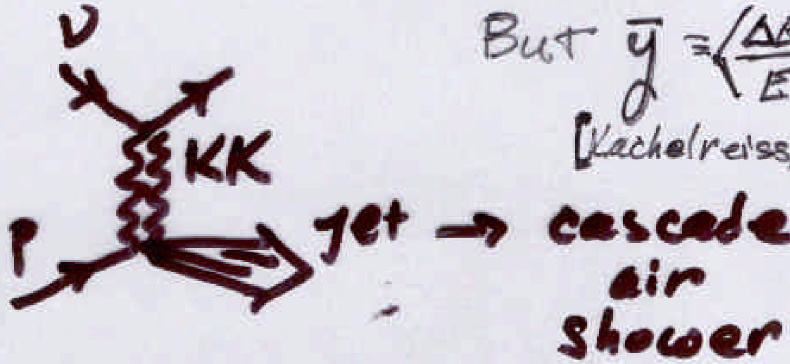
Sigl



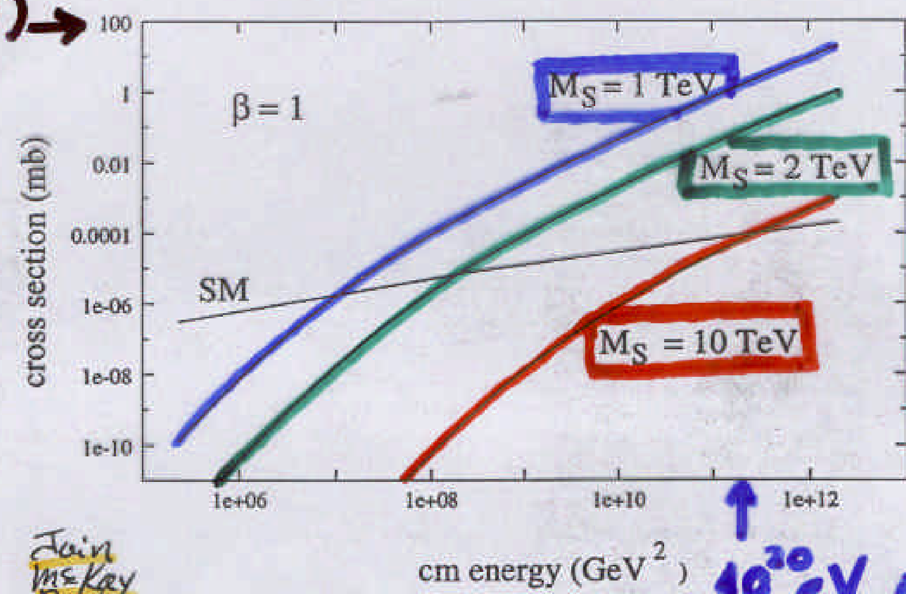
— Data

— Cosmogenic ν Flux

But $\bar{y} = \left\langle \frac{\Delta E}{E} \right\rangle \sim 10\%$
[Kachelreiss, Plumacher]



$\sigma_{p\text{-}air}(E_p \sim 10^{20}) \rightarrow$

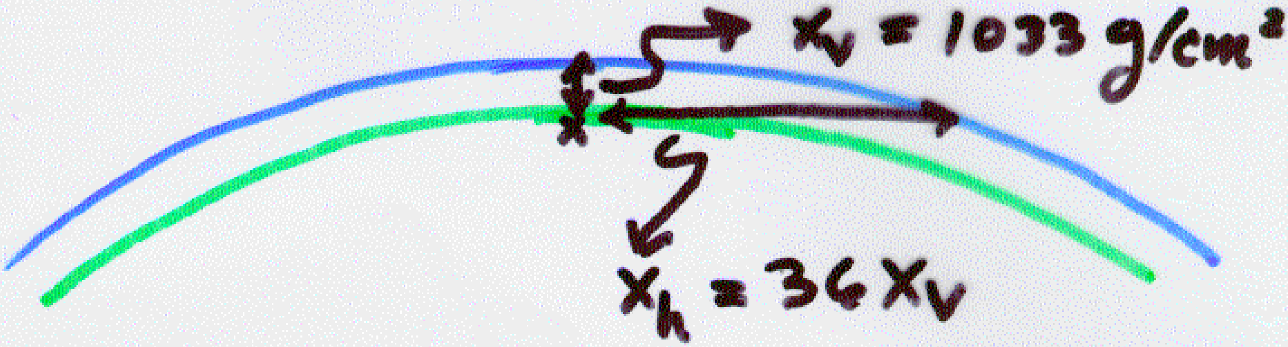


10^{20} eV E_ν

Jain McKay Panda Ralston. The νN cross section calculated by including [redacted] the graviton exchange as a function of the effective scale parameter M_S for three different values of the center of mass energy squared s.

strong $\sigma_{\nu N}(E \gtrsim 10^{20})$: Domokos, Nussinov
H. Mo, ...
Domokos², Mikulski
Jain et al.
Nussinov, Schroek

Present Limits on $\sigma_{\nu N}$:



$$\frac{X_v}{\lambda} = \frac{\sigma}{1.6\,\text{mb}}$$ [mod nuclear screening]

$$\frac{X_h}{\lambda} = \frac{\sigma}{44\,\mu\text{b}}$$

So, no penetrating horizontals [Fly's Eye]

& $F_\nu^{\text{cosmogenic}}$ [$p\gamma_{2.7} \to \pi$'s $\to \nu$'s]

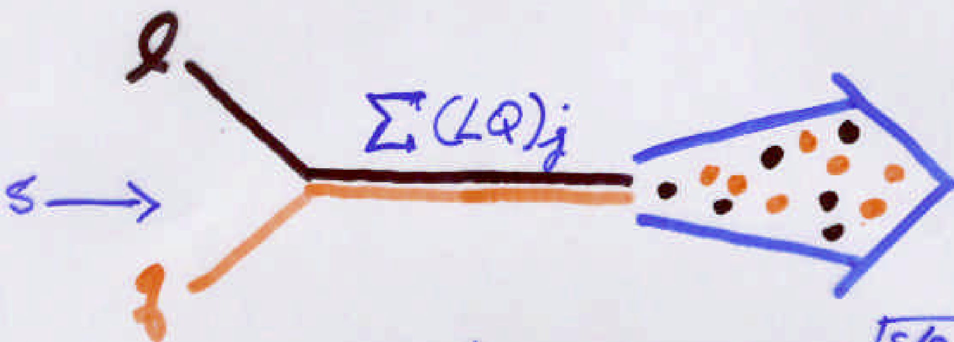
$\Rightarrow$ $\sigma_{\nu N} \notin [20\,\mu\text{b}, 1\,\text{mb}]$ [Tyler, Olinto, Sigl 2000]

Also, exclude $\sigma_{\nu N}(E) > 3 \cdot 10^{-24}\,\text{cm}^2\,(E/10^{19})$

via $\sigma_{\nu N}^{\text{elastic}}(100\,\text{GeV}) \lesssim \sigma_{SM}^{cc}$ [Goldberg, Weiler 99]

$\sigma_{\nu N}(E \gtrsim 10^{19}\,eV) \sim 1 - 10^{4}\,mb$ allowed.

Domokos², Mikulski (Nu2000 conf) propose



with $\rho_{LQ}(E) \sim e^{\sqrt{s/s_0}}$, $s_0 \sim 2M_N E_{GZK}$

Signatures:

(i) $E - \theta_Z$ correlations,

horizontals $\xrightarrow{E \to E_{GZK}} 0$

(ii) Shower profiles intermediate between γ & p.

Estimated flux for EECR with $E>10^{20}$ eV: ~ 1 event per 100 km^2 per year.

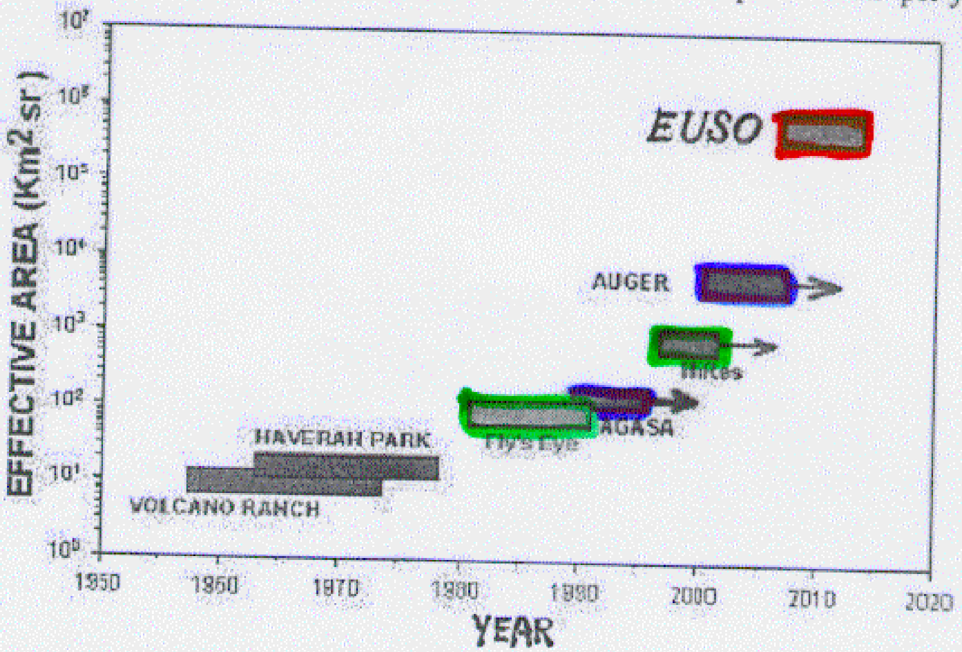


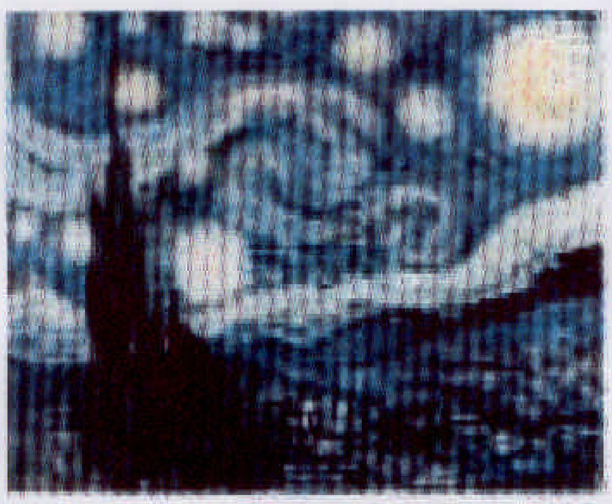
Table 1 - Effective area size of observation in unit of km^2 sr.

	AGASA	HiRes	Auger	EUSO	Super OWL
	presently in operation		*under construction*		
Effective km^2sr	150	500	~ 7 000	~10^5	~

→ *3 → *15 → *15 → *4 → 3K events/yr above 10^{20}

EUSO

Extreme Universe Space Observatory



Vincent Van Gogh, "The starry night"

An Explorative Mission Probing the Extremes of the Universe using the Highest Energy Cosmic Rays and Neutrinos

A Proposal for the ESA F2/F3 Missions

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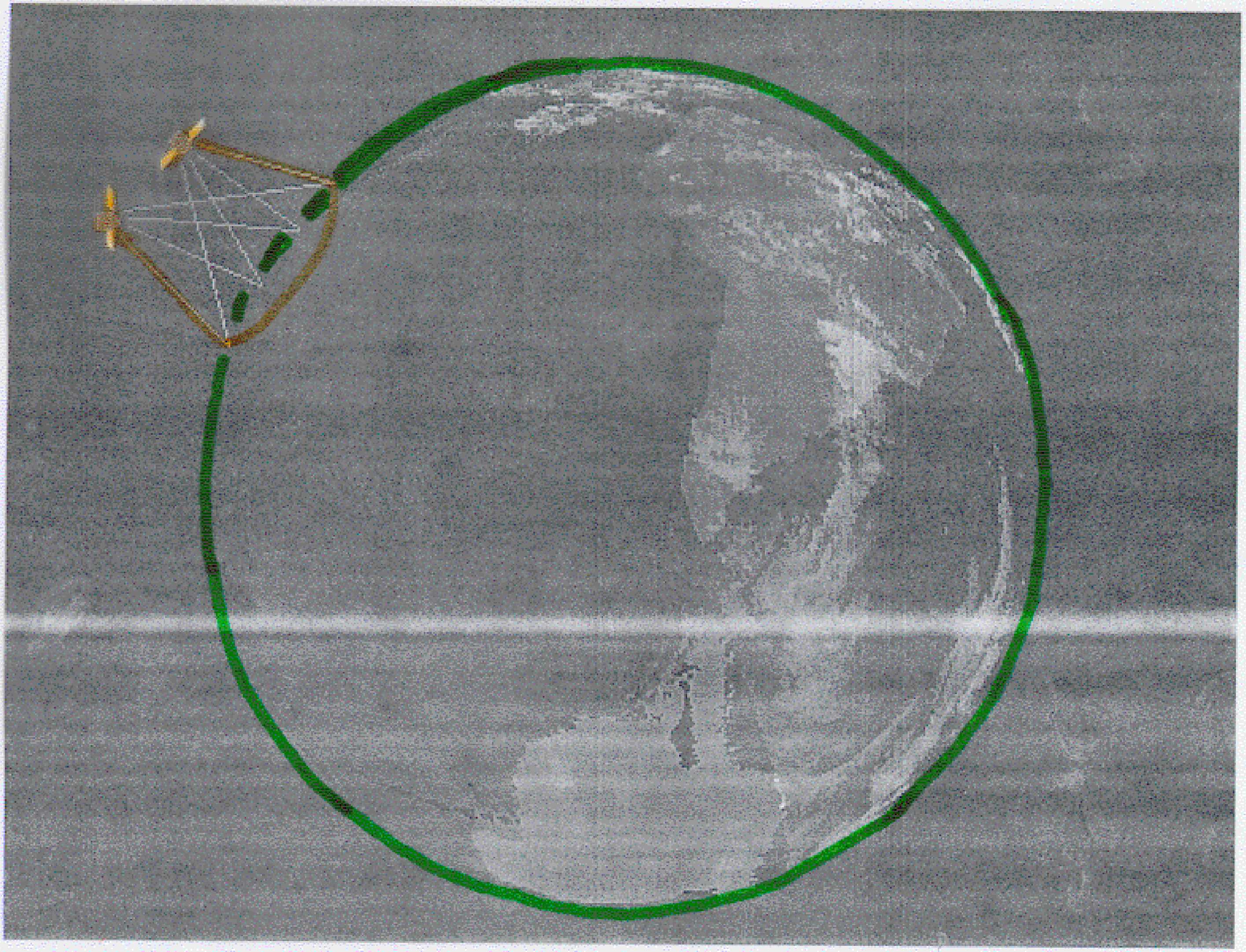
The Mission Concept for OWL/AW Which Will Detect Cosmic Rays at the Highest Energies



Or, attach to the ISS: EUSO