Super-GZK UHECR

and particle physics

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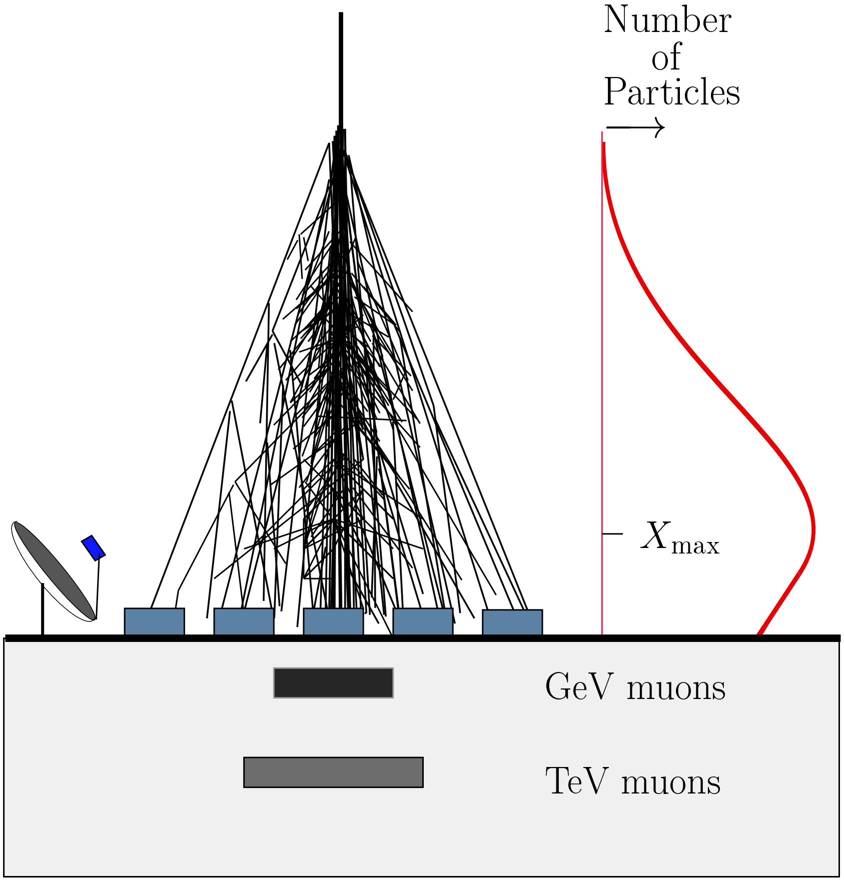
- Cosmic rays of different energy reach Earth. Low fluxes at high energies, uncertainties due to low statistics and hadronic interactions. Great experimental improvement is currently taking place.

- "Controversial" evidence of a flux at high energy, above what is expected within the Standard Model. Many theoretical explanations suggested.

- Axions mix with photons in external $\vec{B}$. Potentially good messengers, due to negligible interaction with the background. Specific predictions, testable at the forthcoming Auger experiment. Work with Csaba Csáki, Nemanja Kaloper, and John Terning '03

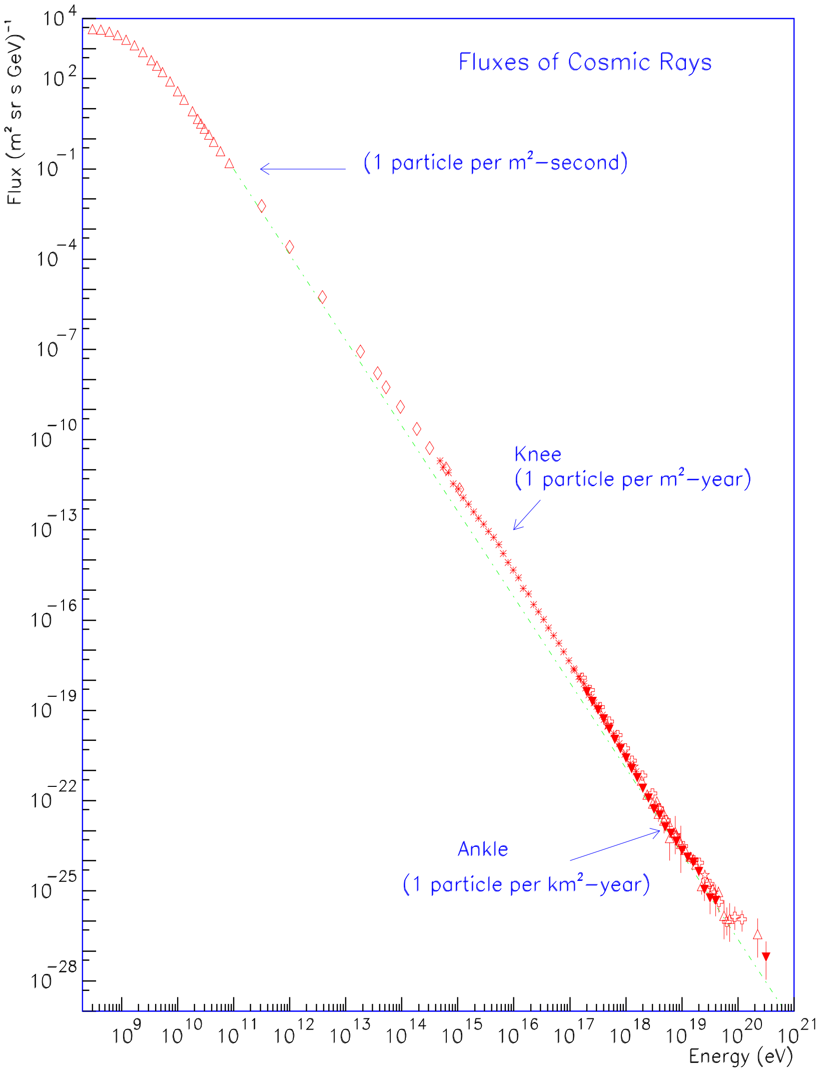
Various reviews, e.g. Nagano, Watson '00; Anchordoqui, Paul, Reucroft, Swain, '02



Scintillators or Čerenkov detectors: Volcano Ranch, 884m^2; Haverah Park, 12Km^2; Yakutsk, 18Km^2; SUGAR, 70Km^2; AGASA, 100Km^2

Fluorescence: Fly's Eye 3.3Km; HiRes 12.6Km

AUGER: 1600 Čerenkov detectors on 3000Km^2.
4 fluorescence detectors



Anchordoqui et al. '02

- Correlation with galaxy below the ankle. Iron $\to$ proton (Bird *et al.*, '93, HiRes).

- Isotropy at highest energies. Proton dominance Ave et al., although a significant photon component cannot be excluded

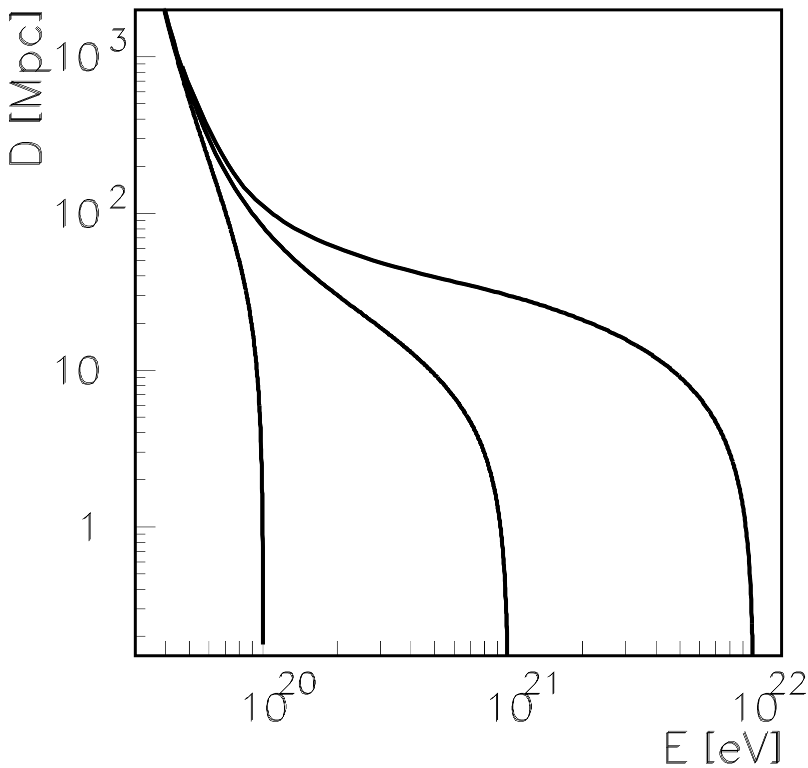
- Possible correlation with (specific) AGN. Some clustering in the data

The Greisen-Zatsepin-Kuzmin cutoff

The intergalactic medium is not transparent to nucleons of high energy (G; Z,K; '66)

Anchordoqui *et al.*,'97

$$p\,\gamma_{\text{CMB}} \to \Delta \to \begin{array}{c}\pi^+ n \\ \pi^0 p\end{array}$$



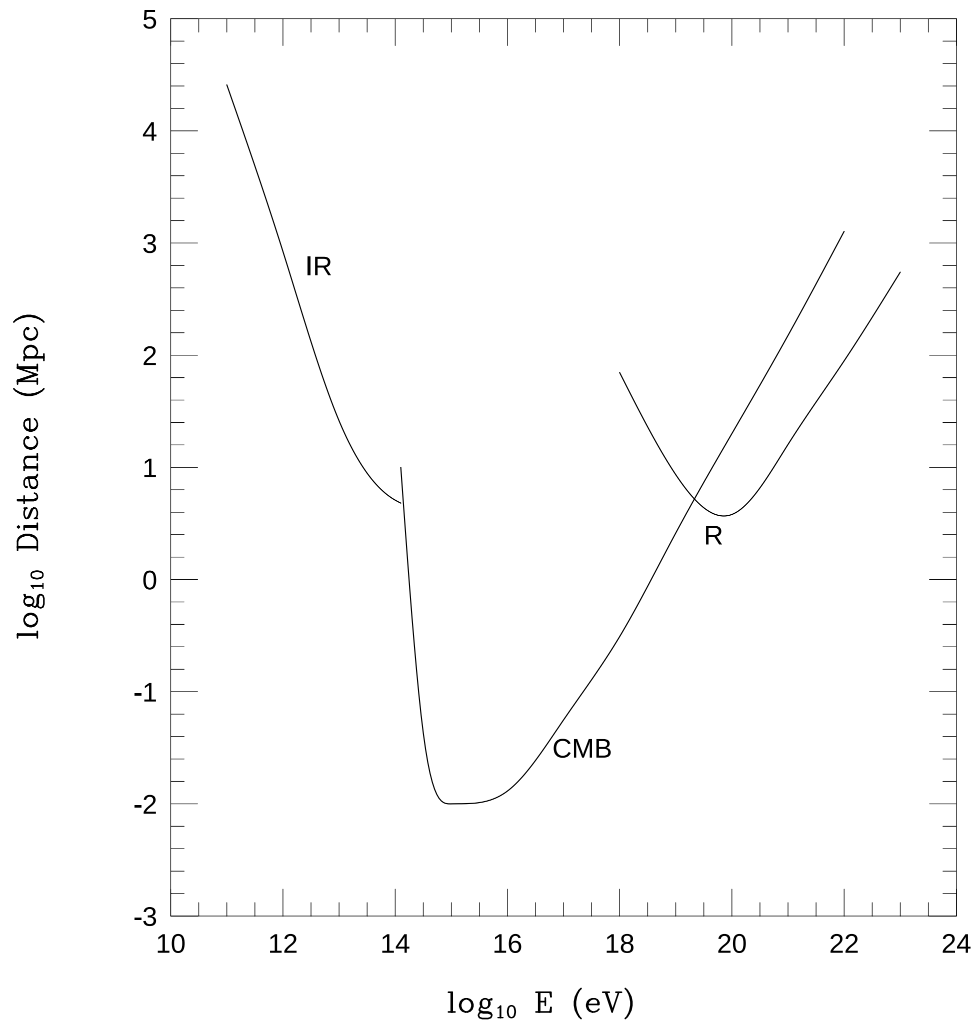
E_0 [eV]	R_{GZK} [Mpc]
10^{20}	100
$2 \cdot 10^{20}$	20
$3 \cdot 10^{20}$	10

$1/e$ of the protons have

still $E > E_0/2$

- Photons are absorbed via pair production due to scattering against CMB and radio photons (perturbative QED), resonant at

$$E_{\mathsf{CM}} = m_e \;\Rightarrow\; w \sim 2.5 \cdot 10^{-9}\,\mathrm{eV}\,\left(10^{20}\,\mathrm{eV}/E\right)$$



Protheroe and Johnson, '96

(Turtle *et al.* '62; Clark, Brown, Alexander '70)

GZK cutoff ?

- No GZK cutoff from AGASA. Hires consistent with GZK Abu-Zayyard et al.'02. However, assuming sources within 50 Mpc implies a number of sources $\gg$ the one inferred from AGASA clustering Kachelriess, Semikoz, Tortola '03

- Bahcall, Waxman '03: (i) fluxes in agreement at $E < 10^{20}$ eV if normalized to each other, (ii) only AGASA inconsistent with GZK

- Calibration of several experiments has been changed. Energy re-assessment of Haverah Park Ave et al. '03 "erased" 4 events. Idem for 7 preliminary events from HiRes Jui '00. Change in Yakutsk spectrum Ivanov, Knurenko, Sleptsov '03. If Hillas conversion factor applied to SUGAR (to agree with AGASA at $E \sim 10^{18}$ eV, Bellido et al. '03) events beyond GZK, otherwise no event at $E > 10^{20}$ eV

Top-down origin

$\boxed{\text{Topological defects}}$ Hill '83; Bhattacharjee, Sigl '00

Could form at nonthermal phase transitions. UHECR due to annihilation. Potential problems: too many γ, $d \sim H^{-1}$, Parker limit, alignment with $\vec{B}$ close to the Earth (monopoles)

$\boxed{\text{Super heavy dark matter}}$

Berezinsky, Kachelriess, Vilenkin '97; Kuzmin, Rubakov '98

$$10^{13} < \frac{m_X}{\text{GeV}} < 10^{16} \;\; ; \; \tau_X \gg t_0 \;\; ; \; \Omega_X \ll \Omega_{\text{CDM}}$$

- Gravitational production Kuzmin, Tkachev, '98; Chung, Kolb, Riotto '99. Nonthermal production Kolb, Chung, Riotto '98

- Very long life-time. Either discrete symmetries (10 or 11 dim. operators), or istanton-like suppression $\tau \sim m_X^{-1} \exp\left(4\pi/\alpha_x\right)$, $\alpha \sim 1/10$ (criptons, Ellis, Lopez, Nanopoulos '90)

- Mostly $\pi \to \gamma, \nu$. Only $\sim 3\%$ hadrons. γ constrained but not ruled out, Ave et al. 00,'01. ν may be seen at AUGER, Parente, Zas '96

- Clustering: $\sim 10\%$ of DM may be clumped (num. simul.), these may give some clustering, Blasi, Sheth '00; Evans, Ferrer, Sarkar '03. Not favoured, but not ruled out ($\Delta\theta$)

- Higer flux from galactic center, i.e. from the Southern hemisphere. Definite check at AUGER, Evans, Ferrer, Sarkar '02. Right now, no hints for anisotropy Benson et al '99; Anchordoqui et al. '03

- Although less accurate in $\Delta\theta$, strong constraints from SUGAR. Kachelriess, Semikoz '03: $E_X > 6 \cdot 10^{19}$ eV; Kim, Tinyakov '03: not more than 50% at $E > 4 \cdot 10^{19}$ eV

Lorentz violation

(Spontaneous) breaking of Lorentz symmetry may result in no GZK bound, Sato, Tati '72; Kirzhnits, Chechin '72; Gonzalez-Mestres '97,'98; Coleman, Glashow, '98,'99

Specific example, different maximal velocities for different particles, Coleman, Glashow, '98,'99

$$\delta_{\Delta p} \equiv c_\Delta - c_p \gtrsim 3.5 \times 10^{-25}$$

avoids π production by kinematics. No direct bound on $\delta_{\Delta p}$. Bound from energy loss (Čerenkov radiation) of UHE protons, $\delta_{p\gamma} \lesssim 3 \times 10^{-23}$, Coleman, Glashow, '99

UHECRON

- $\tilde{g}$ (LSP) containing hadrons, Farrar '96; Berezinsky, Kachelriess '97; Chung, Farrar, Kolb '98

Produced in $p\bar{p}$ scatterings; $m > 1.5$ GeV avoids π production; showers similar to protons for $m \lesssim 3$ GeV, Albuquerque, Farrar, Kolb '99; Berezinsky, Kachelriess, Oatapchenko '02

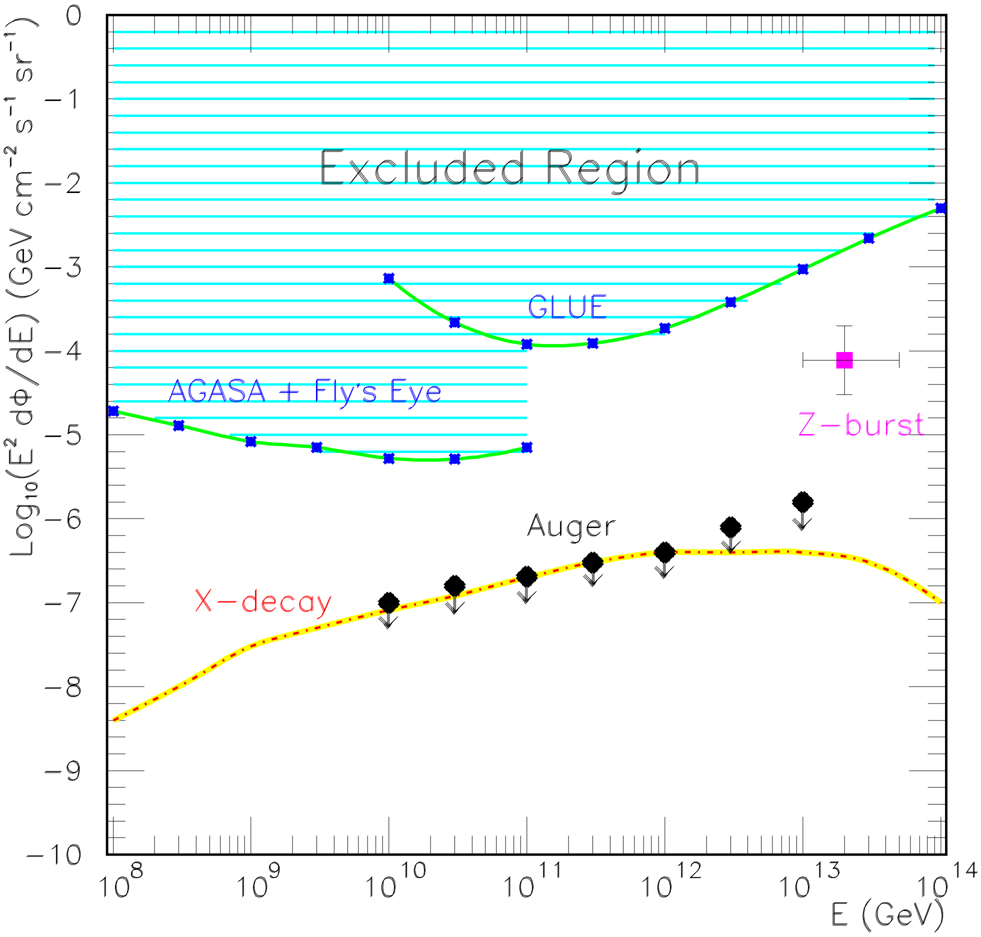
Now light gluino window closed, Janot '03. Moreover limits on "wild hydrogen", Voloshin, Okun '86, or "anomalous deuterium"

- New generic hadrons (particularly $\tilde{b}-$hadrons) studied by Kachelriess, Semikoz, Tortola '03

Light sbottom not excluded. Signatures: high ν flux (within sensitivity next experiments) and cutoff at $E \sim 10^{21}$ eV

Neutrinos escape GZK bound. Distinct signature: interact everywhere in the atmosphere. Not observed

Anchordoqui '03



$\boxed{Z\text{−burst}}$: resonant $\nu\,\nu_{\mathrm{BG}} \to Z \to \ldots$ at the peak of the Z−pole, Weiler '82

$$E_\nu \sim \frac{M_Z^2}{2\,m_\nu} \sim \frac{0.4\,\mathrm{eV}}{m_\nu}\,10^{22}\,\mathrm{eV}$$

- Interaction enhanced due to local clustering of the relic neutrinos, (Weiler '99, Fargion, Mele, Salis '99). Still, very high initial flux required. Also many γ at the source, possibly exceeding the EGRET bound, Waxman '98

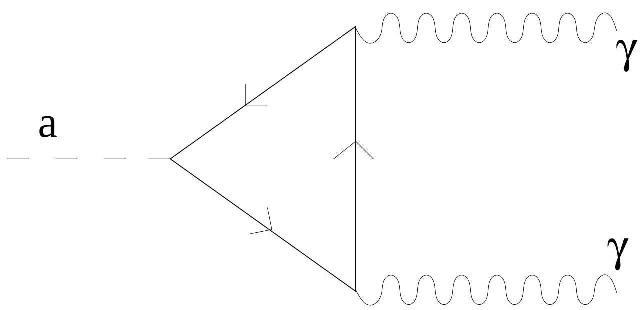
- Enhanced $\sigma_{\nu N}$ in models with large extra dimensions, due to exchange of KK modes, Nussinov, Shrock '99; Domokos, Kovesi-Domokos '99. Momentum transfer still smaller than for protons Kachelriess, Plümacher '00

- ν generated by p when they photoproduce. AUGER $\equiv$ 30 Km^3 water equivalent. ν vs. p flux important to discriminate between different UHECR mechanisms, Engel, Seckel, Stanev '01

Seek viable candidates beyond SM: axions. Possible solution to the strong CP problem (Peccei, Quinn'77; Weinberg '78; Wilczek '78).

$$\mathcal{L}_{a-\mathrm{SM}} = \frac{1}{2}\partial a\,\partial a - \frac{a}{4\,M}\,F\,\tilde{F} - \frac{a}{4\,M_s}\,G\,\tilde{G}$$

- Additional symmetry. Breaking scale sets (up to cc.) the interaction scales M, M_s. Different values considered, up to M_{GUT} or M_{string}



Axions mix with photons in an external magnetic field, Sikivie '83

$\langle\vec{B}\rangle_{\mathrm{extragalactic}} \lesssim 1\,\mathrm{nG}$ Kronberg'94

$M \gtrsim 10^{10}\,\mathrm{GeV}$ Raffelt in PDG'02

l_{GZK} mean free path γ

$L_{\mathsf{osc}} = M/B$ oscillation length

Evolution governed by the ratio

$$\delta \equiv \frac{l_{\mathsf{GZK}}}{L_{\mathsf{osc}}} \simeq 0.11 \left(\frac{B}{1\,\mathrm{nG}}\right) \left(\frac{10^{11}\,\mathrm{GeV}}{M}\right) \left(\frac{l_{\mathsf{GZK}}}{\mathrm{Mpc}}\right)$$

$$m_a < \sqrt{\mathcal{E}\,B/M} \sim 4 \cdot 10^{-6}\,\mathrm{eV}$$

Start with only photons at the source and consider first the (unrealistic) case $\vec{B} = \mathrm{const.}$

- Large mixing, $\delta \gg 1$

$$\begin{aligned} I_\gamma &\simeq \frac{1}{2}\mathrm{e}^{-\frac{y}{l_{\mathsf{GZK}}}} + \frac{1}{2}\mathrm{e}^{-\frac{y}{2l_{\mathsf{GZK}}}}\cos^2\left(\frac{\delta\,y}{2\,l_{\mathsf{GZK}}}\right) \\ I_a &\simeq \frac{1}{2}\mathrm{e}^{-\frac{y}{2l_{\mathsf{GZK}}}}\sin^2\left(\frac{\delta\,y}{2\,l_{\mathsf{GZK}}}\right) \end{aligned}$$

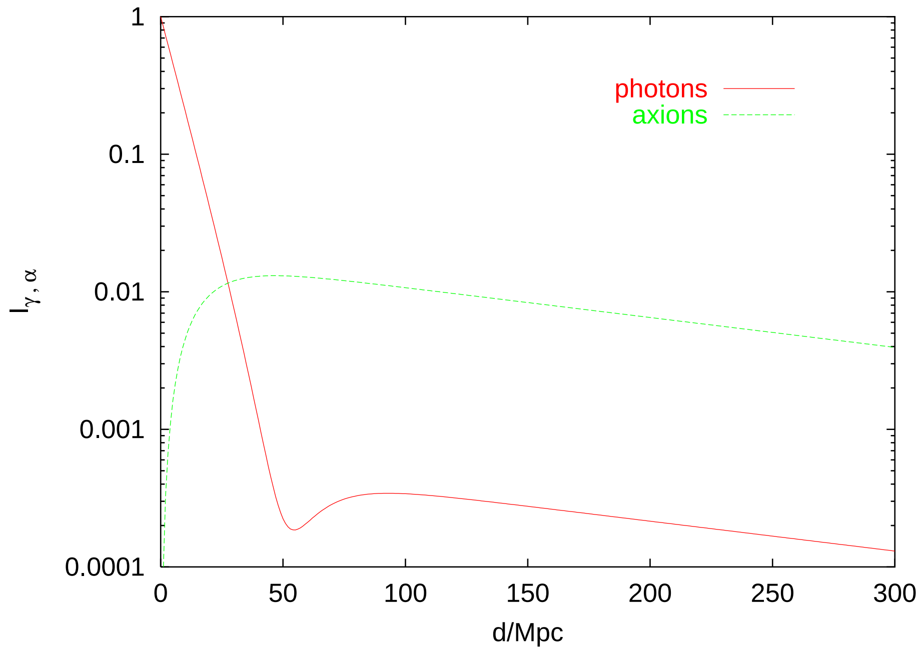
One decoupled photon polarization, plus quanta which are “half photons” and “half axions”

- Small mixing, $\delta \ll 1$

$$I_\gamma \simeq \frac{1}{2} e^{-\frac{y}{l_{\mathrm{GZK}}}} + \frac{\left[\left(1-\delta^2\right) e^{-\frac{1-\delta^2}{2 l_{\mathrm{GZK}}} y} - \delta^2 e^{-\frac{\delta^2 y}{2 l_{\mathrm{GZK}}}}\right]^2}{2\left(1-4\delta^2\right)}$$

$$I_a \simeq \frac{\delta^2}{2} \left[e^{-\frac{y}{2 l_{\mathrm{GZK}}}} - e^{-\frac{\delta^2 y}{2 l_{\mathrm{GZK}}}} \right]^2$$

Mode with mean free path $l_{\mathrm{GZK}}/\delta^2 \gg l_{\mathrm{GZK}}$

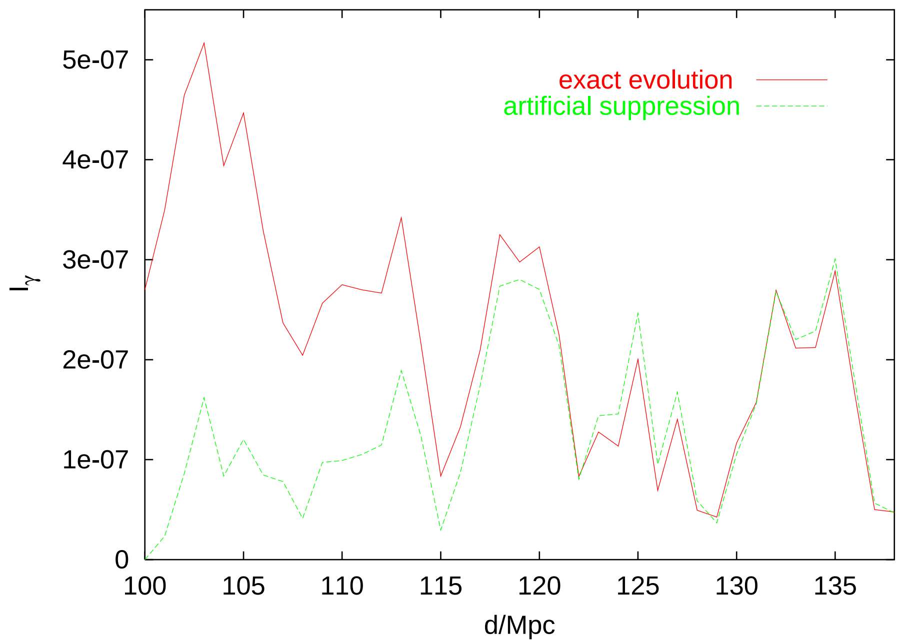


$\delta \simeq 0.1$

$\delta = L_{\mathrm{osc}}/l_{\mathrm{GZK}}$ amplitude for $|\gamma\rangle \to |a\rangle$ within each l_{GZK}

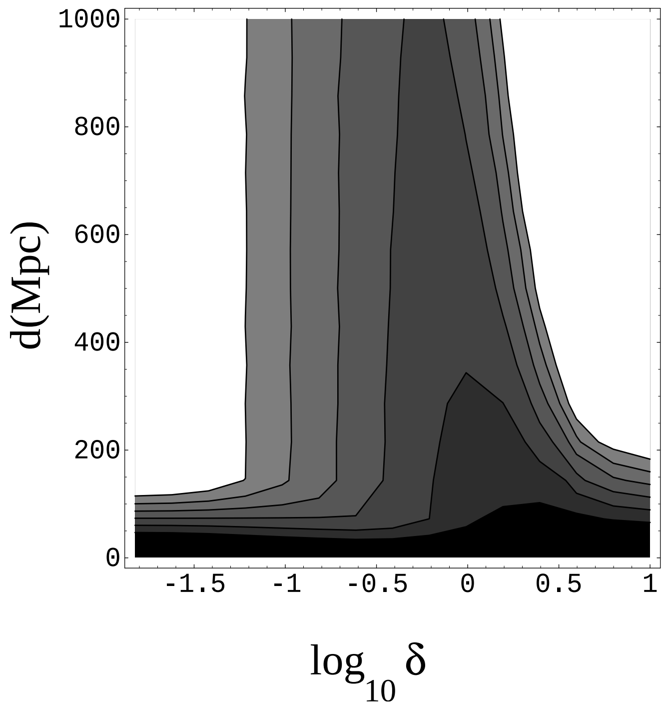
Domains of constant magnetic field, of length ~ 1 Mpc. We assume $|\vec{B}| = n\,G$ everywhere, but random orientation

Axions mix with different photon helicities in different domains. I_γ is stochastic



As before, only photons recreated in the last few l_{GZK} distances are present. Thus, results probe $\vec{B}$ relatively close to Earth

Averaging over different realizations of $\vec{B}$ (i.e., over uncorrelated line of sight), gives qualitative agreement with the case of const. $\vec{B}$

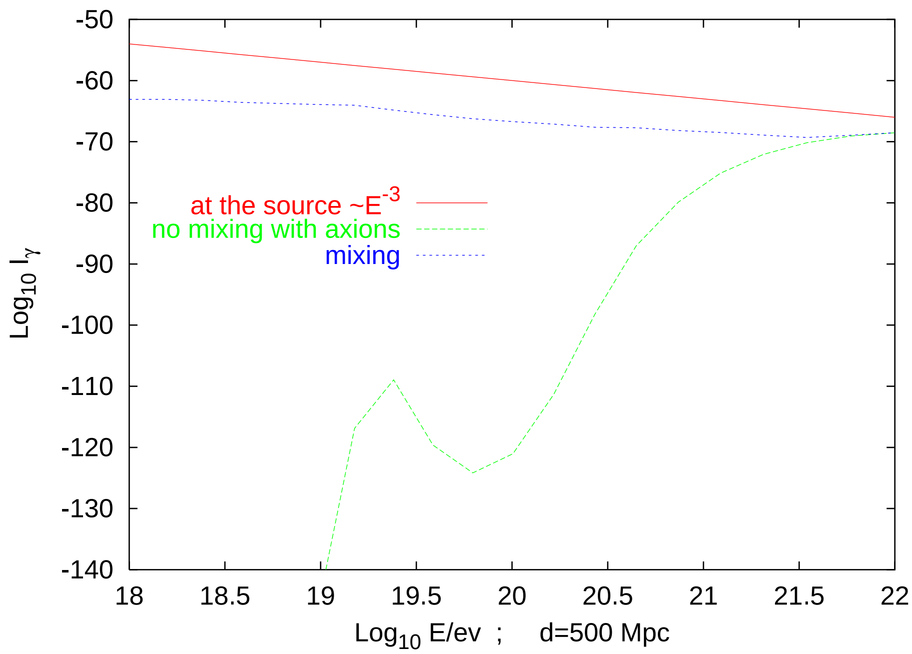


Contour lines at $I_\gamma(d)/I_\gamma(0) = 10^{-3}, 10^{-4}, \ldots, 10^{-8}$

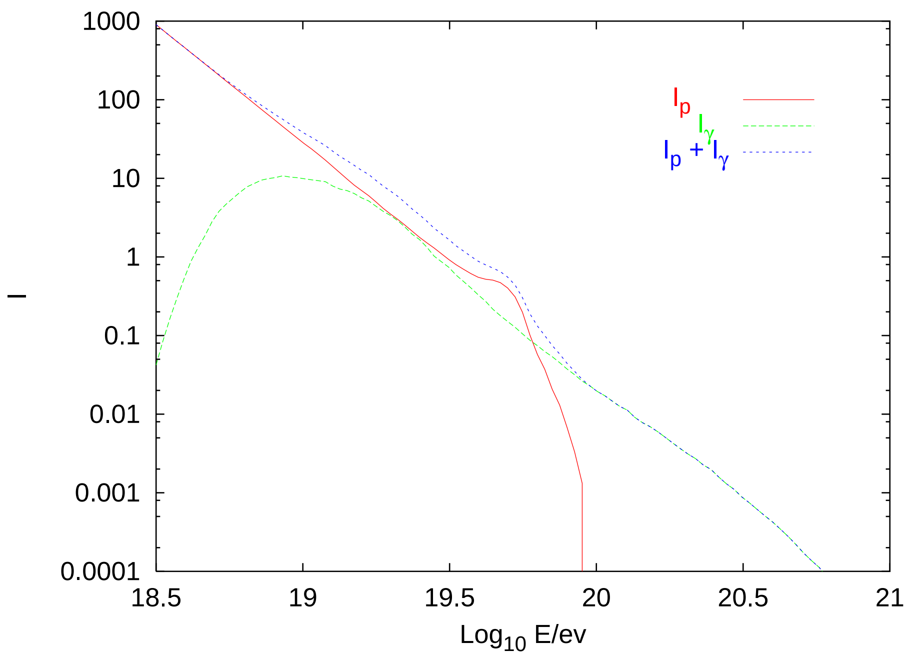
GZK suppression both at small and large δ

For B = nG, maximal effect for M in the $10^{10} - 10^{11}$ GeV range

Close to "optimal case" for $\delta \simeq 0.2$
$(B = n\,G\ ,\ M = 4 \cdot 10^{11}\ \mathrm{GeV})$



Combined $p+\gamma$ initial spectra. $I_\gamma / I_p = O\left(10^4\right)$



Dimming of SNe through $a-\gamma$ oscillations,
Csáki, Kaloper, Terning, '02

Best fit for $B = \mathrm{n\,G}\,,\quad M = 4\cdot 10^{11}\,\mathrm{GeV}$
Olive : CDM; Green : $\Omega_{\mathrm{string}} = 0.7$; Blue : $\Omega_{\Lambda} = 0.7$;

Pink : $a-\gamma$ oscillations

- For SNe, the preferred value of M comes from fitting the luminosity-distance data

- For super-GZK photons, it comes from "balancing" the oscillation and the GZK lengths

Conclusions

- If confirmed, super-GZK events call for nontrivial modification of standard physics

- Significant improvement of statistics & systematics to be expected at the forthcoming Auger experiment. Mechanism based on $a-\gamma$ mixing leads to specific predictions

  * Primary particles are photons (current statistics too poor for conclusive claim at high energies)

  * Correlation between intensity and line of sight

  * Correlation between polarization and line of sight

- Nice agreement with CKT explanation of SNe dimming; interesting coincidence with EGRET bound

Primaries discriminated from longitudinal profile and μ content of the showers. Pbms: (i) fluctuations, (ii) QCD

Nucleons $\to \Pi^{\pm} \to \mu^{\pm}$ $\qquad N_\mu \propto E^{0.85}$

$\gamma \to$ less hadronic interaction, and less muons present. The effect is however masked by the interaction with geomagnetic field. Compare N_μ in vertical and inclined ($\theta > 60^0$) events

- Composition appears to change from iron dominated at $E \sim 10^{17.5}$ eV to proton dominated at $E \sim 10^{19}$ eV (Bird *et al.*, '93, HiRes)

- At high energies, strongest limits on photon primaries given in Ave *et al.* ('00; '02) analyzing inclined Haverah Park events

Parametrization	$E > 10^{19}$ eV	$E > 4 \times 10^{19}$ eV
Nagano, Watson, '00	$< 48\%$	$< 50\%$
Szabelski *et al* '02	$< 25\%$	$< 70\%$

$\boxed{\text{BL Lac}}$

- Early data $\leftrightarrow$ compact radio-loud quasar, Farrar, Biermann '98 (also Virmani et al. '02, from SUGAR); less significance from (i) updated list (twice), Sigl. et al '02, (ii) Haverah Park energy re-assessment of Ave et al. '03

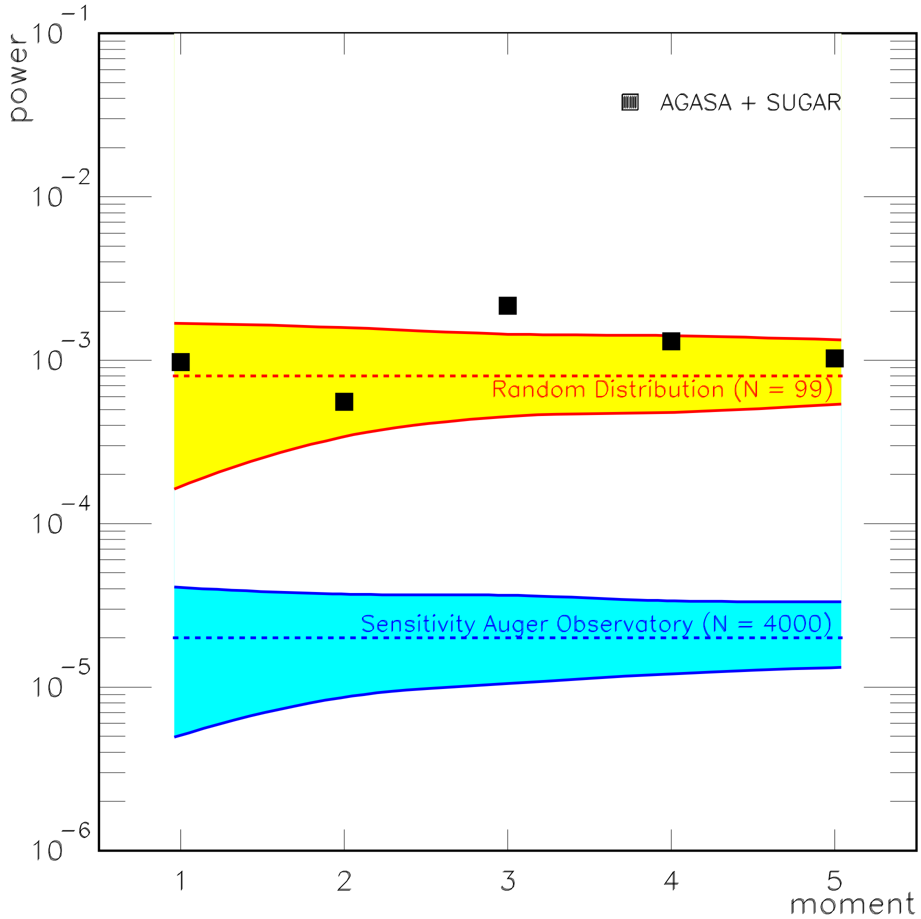
- Tinyakov, Tkachev '01,'02,'03: correlation with a suclass: BL Lacertae (AGN with jets pointing toward us). 26 Yakutsk +39 AGASA events with $E \geq 2.4 \cdot 10^{19}$ eV vs. 22 bright BL Lacs ($z > 0.1$, i.e. 10^3 sources distributed uniformly in the Universe). BL Lacs where two triplets

- EGRET $\cap$ BL Lacs $\Rightarrow$ 14 objects; 8 of them correlated with UHECR, Gorbunov et al. '02

- Significance correlation disappears if the above cuts are relaxed; question whether the high correlation is a selection effect, Evans, Ferrer, Sarkar '03

- Haverah Park + Volcano Ranch data (33 additional events) give no significant correlation Torres et al. '03

Anchordoqui, Hojvat, McCauley '03



99 events

$E > 4{\cdot}10^{19}$eV

vs. 10 yrs.

AUGER

- No apparent counterparts in the galactic or supergalactic planes. Anisotropy light within 50 Mpc. If from nearby galaxies, deflection in $\vec{B}$ may isotropy, but large $\vec{B}$ required (Ahn et al. '99, Farrar, Piran '00; Isola, Lemoine, Sigl '02)

$$\delta\theta \sim \frac{D}{\mathrm{Mpc}} \frac{B}{0.1\mu\mathrm{G}} \frac{10^{20}\mathrm{eV}}{E}$$

- Axion-photon oscillations efficient for

$$m_a < \sqrt{\frac{\mathcal{E}\,B}{M}} \simeq 4\cdot 10^{-6}\text{eV}\,\sqrt{\frac{\mathcal{E}}{10^{20}\,\text{eV}}\,\frac{B}{\text{nG}}\,\frac{4\cdot 10^{11}\,\text{GeV}}{M}}$$

- Mass from (nonperturbative) interaction with gluons

$$m_a \sim 50\,m_\pi \frac{f_\pi}{M_s} \sim 10^{-4}\,\text{eV}\,\left(\frac{4\cdot 10^{11}\,\text{GeV}}{M_s}\right)$$

For specific models, the two requirements may conflict (Gorbunov, Raffelt, Semikoz '01)

However, recall

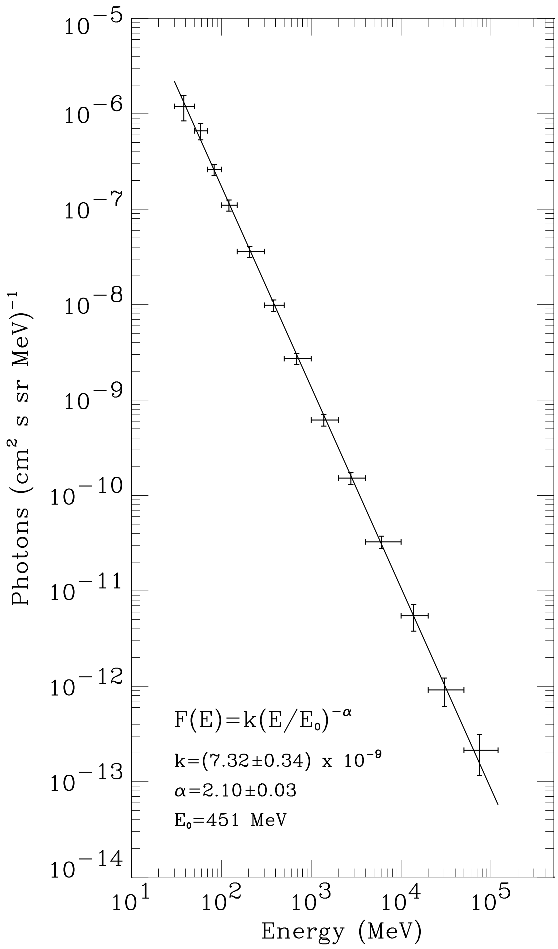
$$\mathcal{L}_{a-\text{SM}} = \frac{1}{2}\partial a\,\partial a - \frac{a}{4\,M}\,F\,\tilde{F} - \frac{a}{4\,M_s}\,G\,\tilde{G}$$

If axion is coupled to fermions with electric charge but not color, a $M_s/M \lesssim 10^{-2}$ hierarchy does not seem hard to achieve

Efficiency of the mechanism and EGRET bound

After interacting with background, γ cascade down to GeV energy, potentially exceeding EGRET bound

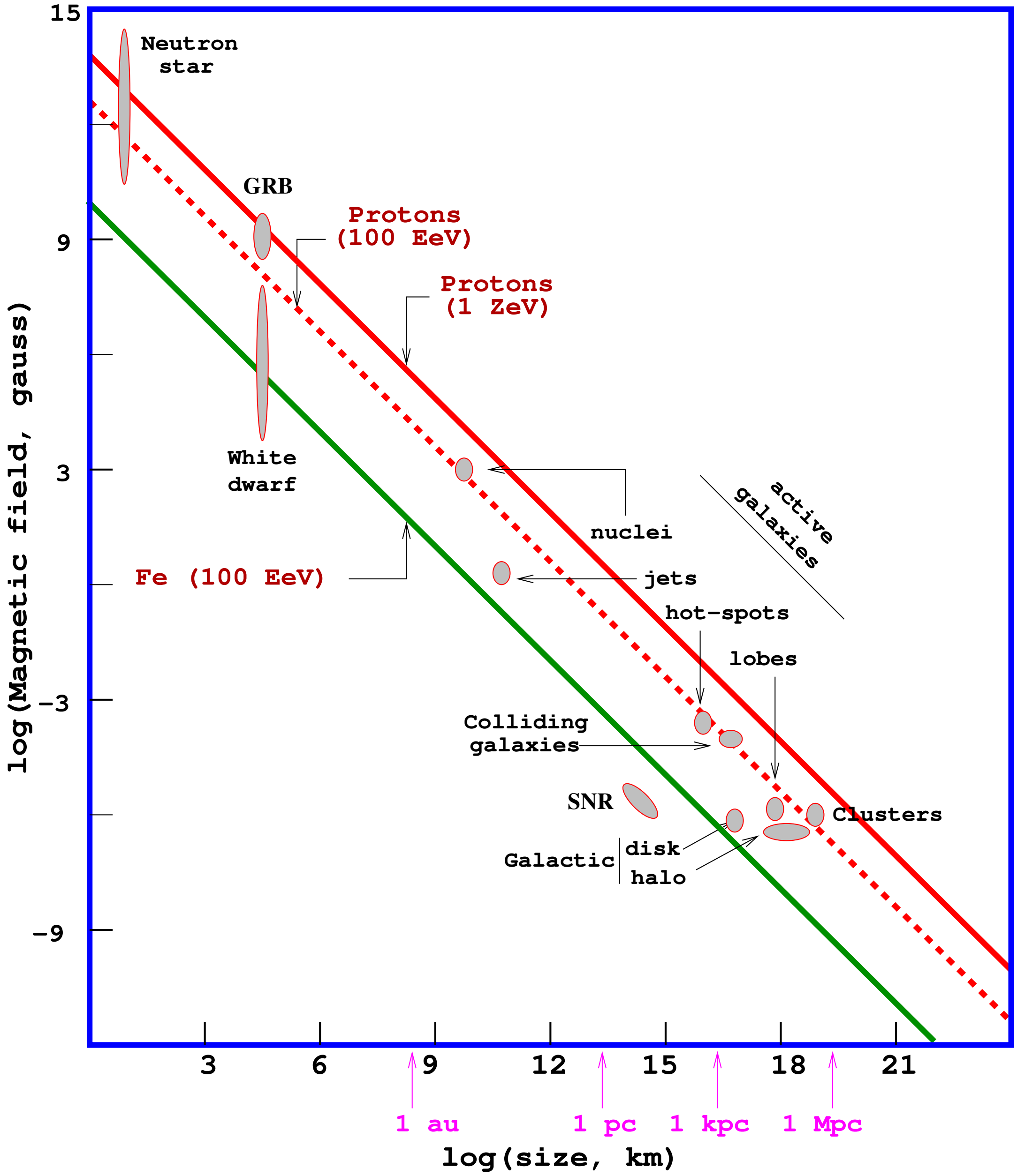
$$\frac{\mathrm{Flux}^{\mathrm{GZK}}}{\mathrm{Flux}^{\mathrm{EGRET}}} \sim 10^{-4} - 10^{-3}$$



P. Sreekumar *et al.* '98

- Axion in the initial beam
- Conversion in the galactic magnetic field
- Mixture of γ and p in high energy events

Hillas diagram, from Anchordoqui et al. '02



Larmor radius $\Rightarrow E \lesssim 10^{18}\text{eV}\, Z\, (B/\mu\text{G})\, (R/\text{Kpc})$

Fermi mechanism: scattering against magnetic cloud $\langle \Delta E \rangle / E \sim \beta^2$