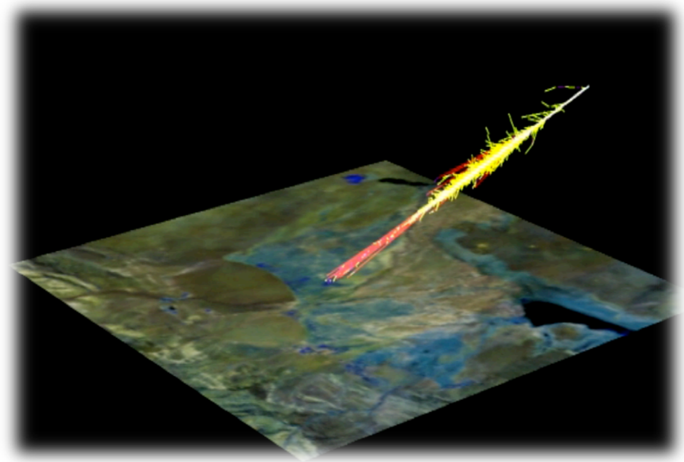
Searching for Quantum Gravity with High-energy Cosmic Rays and Neutrinos

John Kelley
Radboud University Nijmegen

Seminar, Utrecht University
May 3, 2010

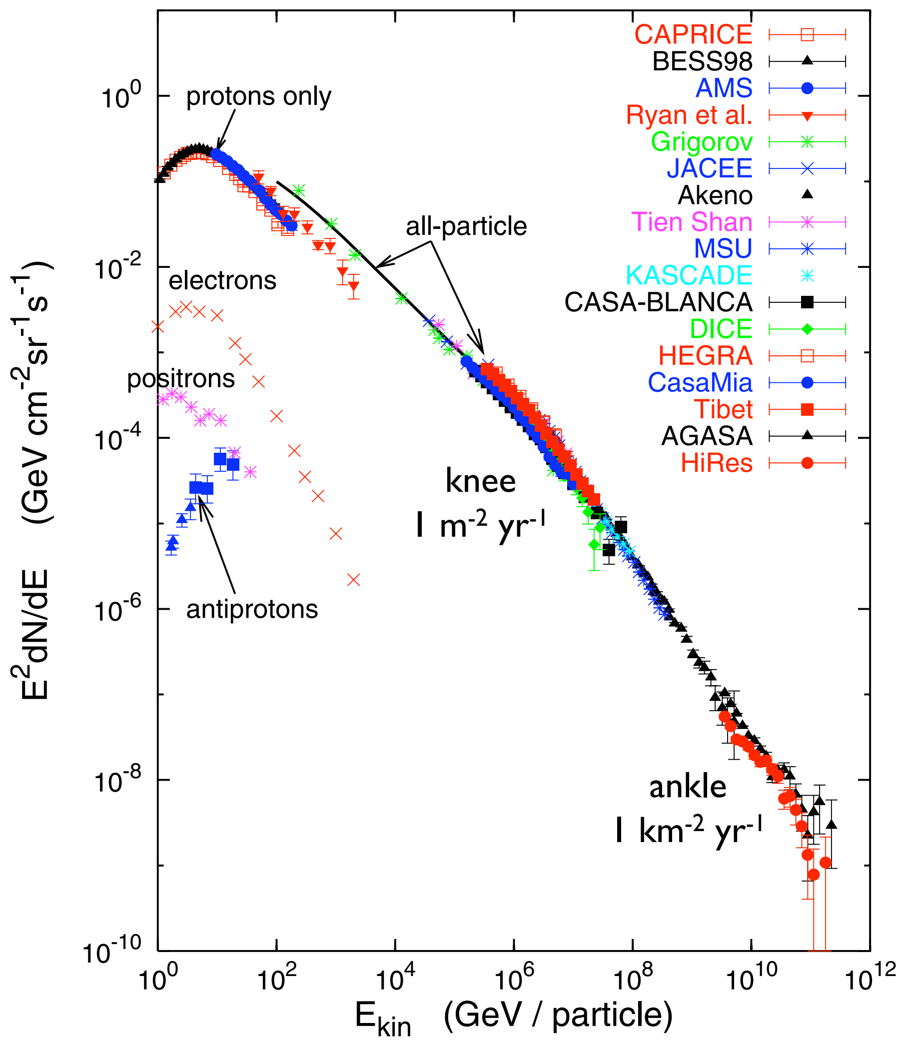
Outline

1. Ultra-high energy cosmic rays
2. Spectral cutoff and Lorentz violation
3. Current experimental status
4. The neutrino connection
5. Future plans



Cosmic Ray Spectrum

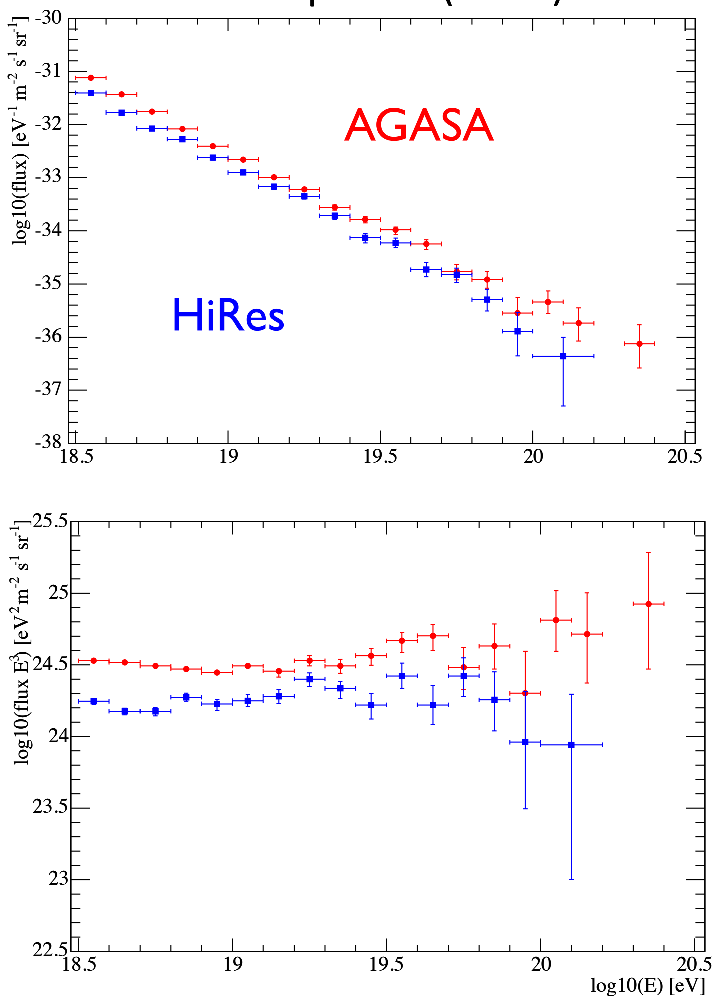
- Charged particles with steep power law spectrum
- Low flux at high energy: detect via extensive air showers
- “Knee” and “ankle”: transition in source population, composition
- Composition: protons vs. heavy nuclei?



Gaisser 2004

Ultra-High Energy Cosmic Rays (UHECR)

UHECR spectra (2004)



× E^3

- Highest energy particles known in the Universe
- Composition unknown
- Sources + acceleration mechanism unknown
  - extragalactic
  - AGN? GRBs?
  - top-down models now disfavored
- Cutoff in spectrum or not?

GZK Effect

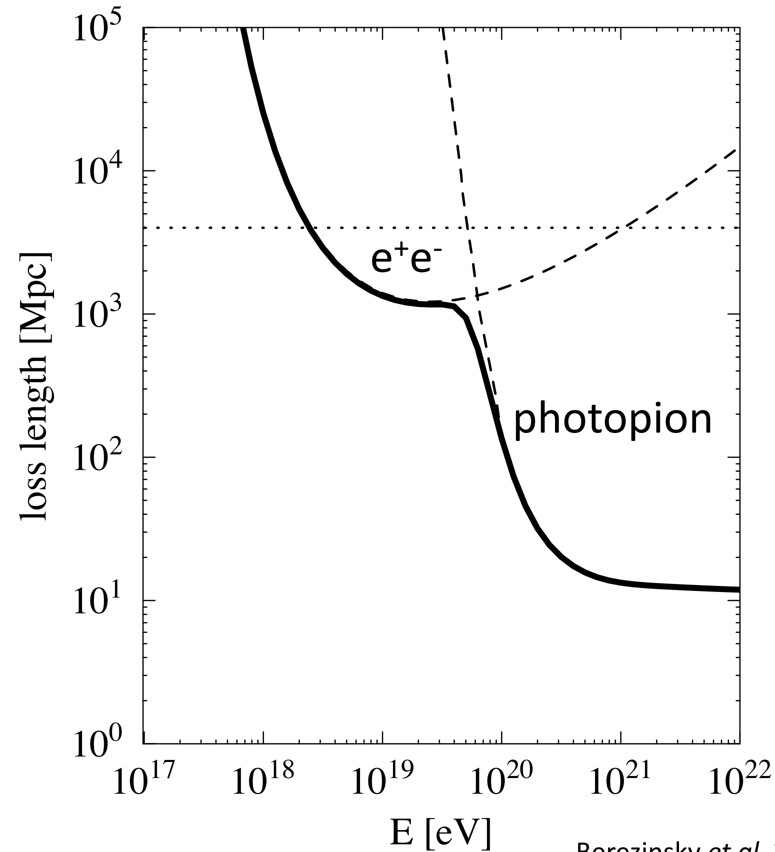
- Suppression ("cutoff") due to interaction with CMB photons (Greisen-Zatsepin-Kuzmin)

$$p + \gamma \rightarrow \Delta(1232\ \mathrm{MeV}) \begin{array}{l} \rightarrow \quad p + \pi^0 \\ \rightarrow \quad n + \pi^+ \end{array}$$

- Threshold ~ 6×10^{19} eV

- If spectrum keeps going…
  - Sources unexpectedly close?
  - New physics (e.g. violation of Lorentz invariance)?
  - Situation 4-5 years ago totally unclear

proton loss length



Berezinsky *et al.* 2007

Violation of Lorentz Invariance (VLI)

- Lorentz symmetry violation possible in various QG formulations

- Appealing as a (relatively) low-energy probe of quantum gravity
  - UHECR: boost factors of 10^{11}!

- Effective field-theoretic approach by Glashow & Coleman, Colladay & Kostelecký*, *et al.*

  - Standard Model Extension (SME): all renormalizable VLI terms to SM

example: $\mathcal{L} \longrightarrow \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi$

  - Recently: higher dimension non-renormalizable terms (permitted in SUSY)
  - Large parameter space and rich phenomenology

*see e.g. hep-ph/9809521

VLI and the GZK Effect

$$E^2 = p^2 + m^2 + \epsilon p^2 + \eta \frac{p^4}{M_{\rm Pl}^2}$$

Equivalent to:

$$E^2 = \vec{p}^{\,2} c_{MAV}^2 + m^2 c_{MAV}^4$$

$$m \rightarrow m/(1+\epsilon) \qquad c_{MAV} = \sqrt{(1+\epsilon)}$$

c_{MAV}: maximal attainable velocity

Can be distinct for each particle type!

$c_\pi > c_p$: GZK threshold altered

see e.g. Scully & Stecker, 0811.2230

η_π η_p also alter or suppress GZK interaction

Depending on sign, can also allow:

$$p \rightarrow p + \gamma$$

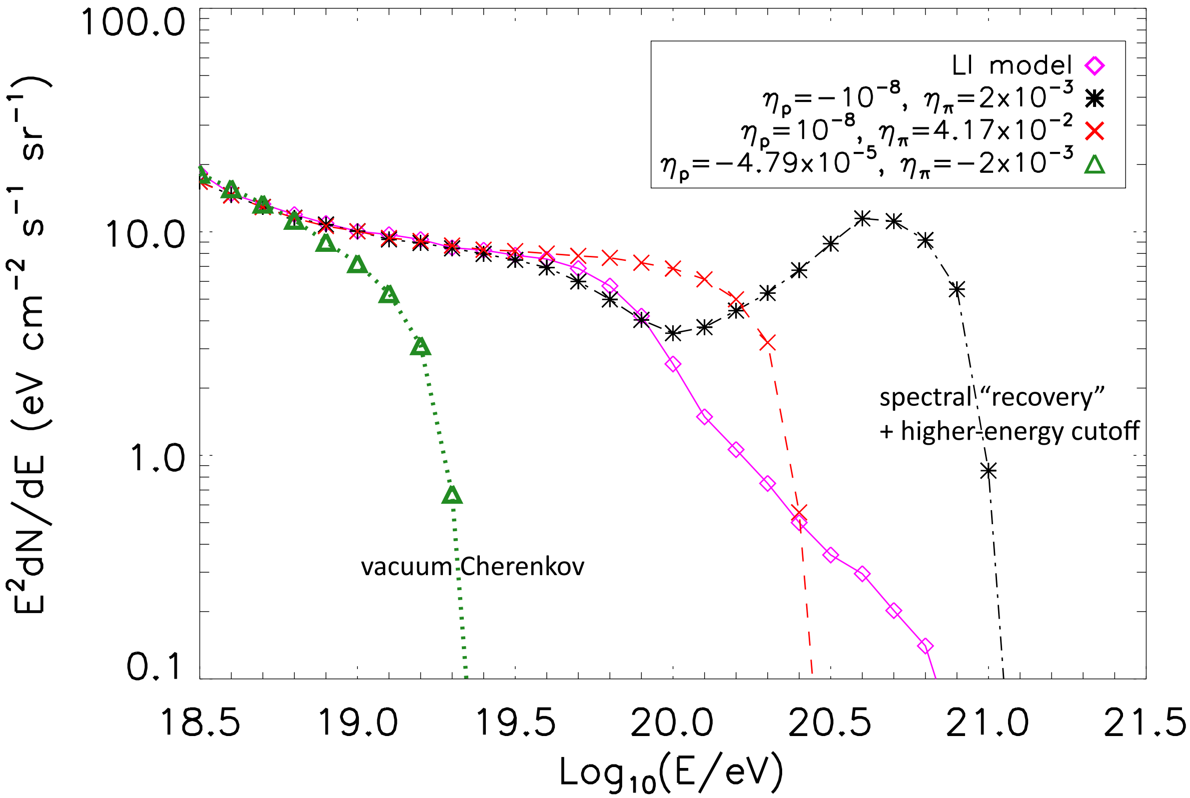
$$p \rightarrow p + \pi$$

"Vacuum Cherenkov" radiation

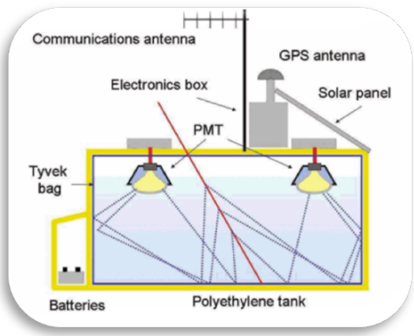
see e.g. Maccione *et al.*, 0902.1756

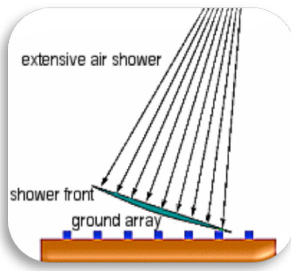
Predicted Spectra

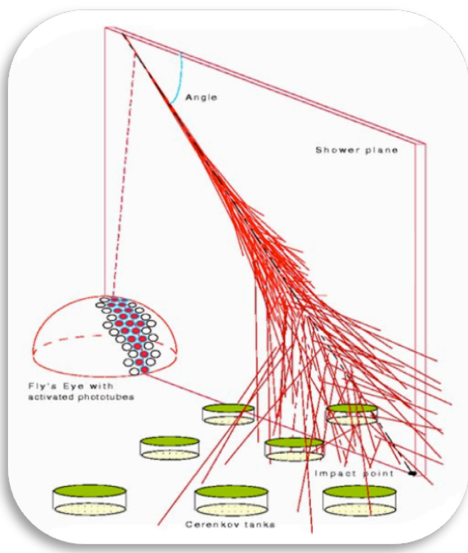
Maccione *et al.* 2009



Cosmic Ray Air Shower Detection





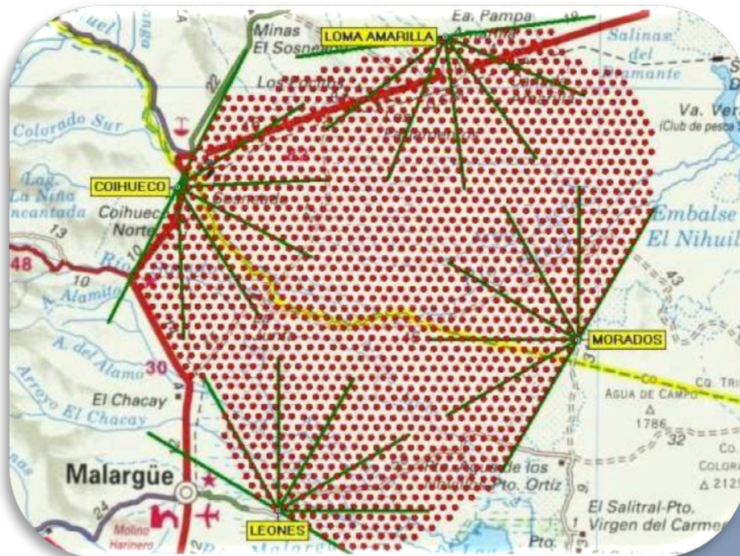


- Water (or ice) Cherenkov tanks
  - detect EM shower front on ground
  - near-100% duty cycle

- Fluorescence telescopes
  - follow Nitrogen fluorescence as shower develops
  - good for calorimetry, measurement of shower maximum (particle ID)
  - duty cycle is ~10%

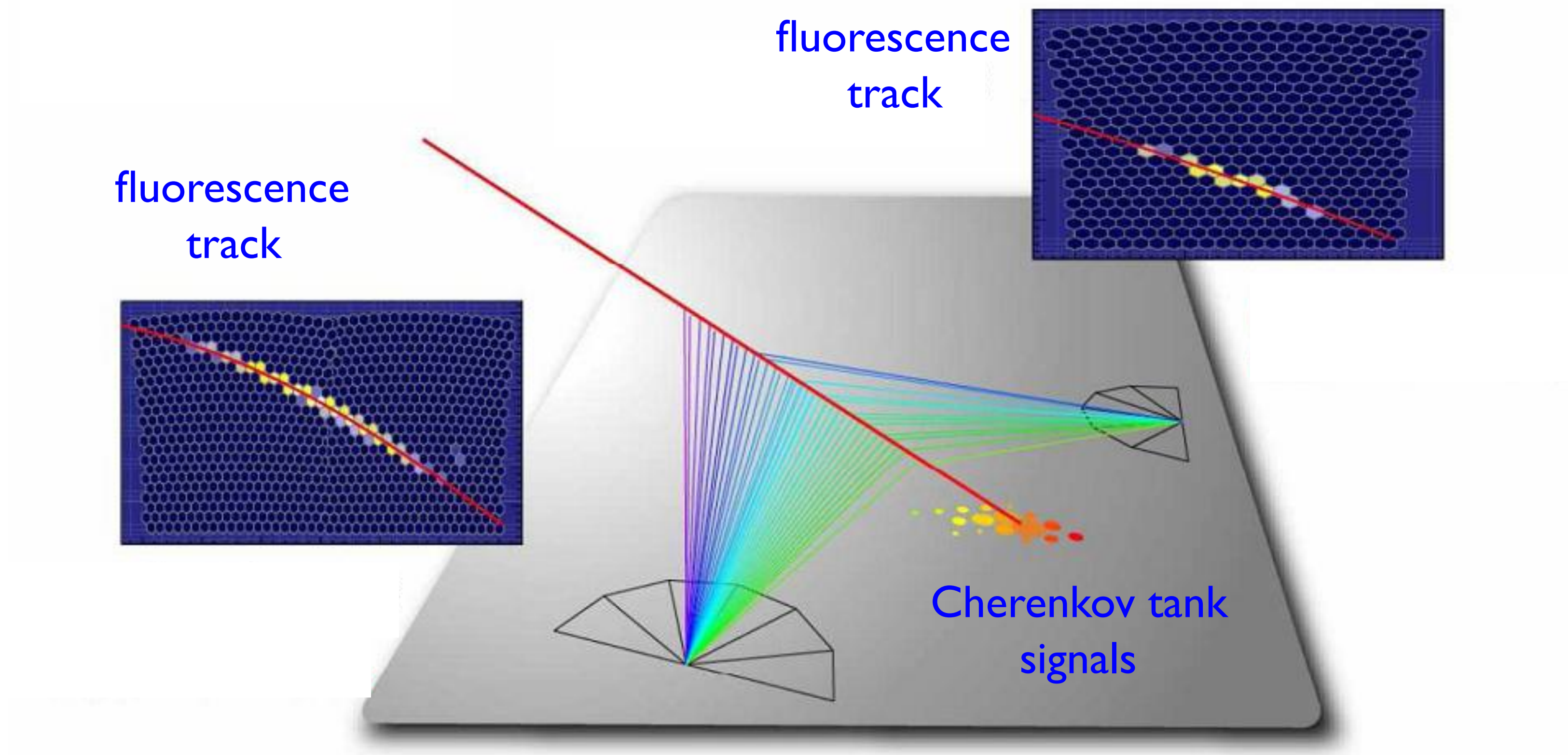
Pierre Auger Observatory

- Hybrid air shower detector
- Southern site (3000 km^2) in Argentina completed 2008
- Northern site (21000 km^2) planned for Colorado, U.S.A.



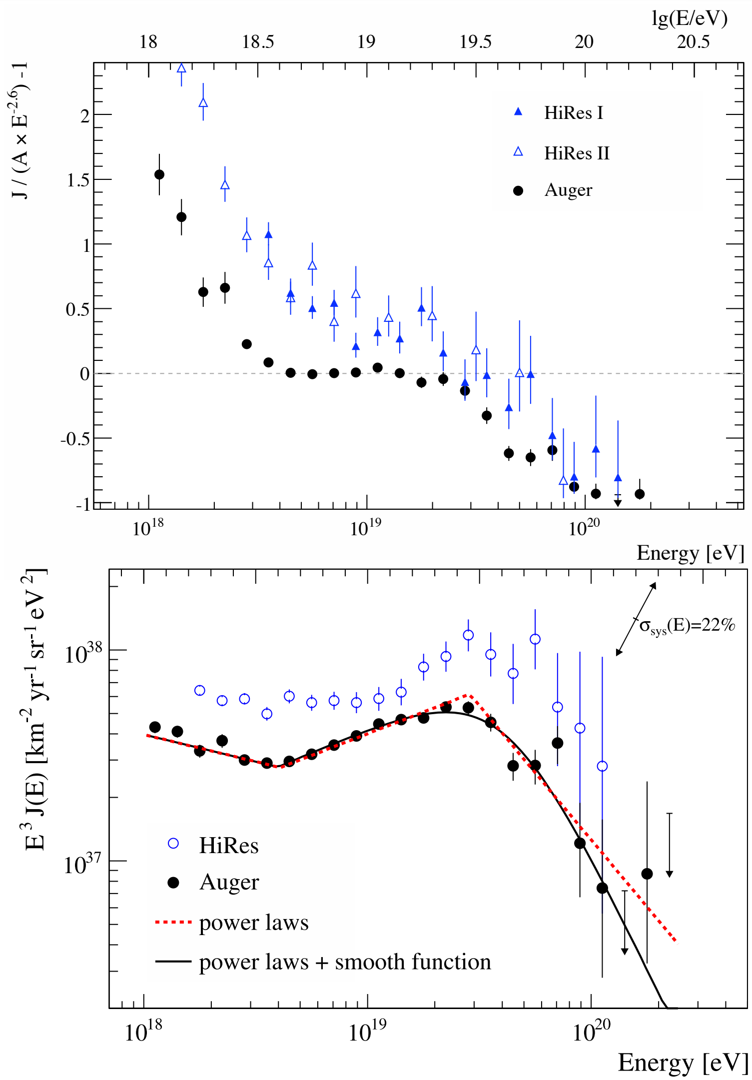
Auger South

Hybrid Detection



Hybrid observation: energy cross-calibration, better angular resolution

Latest Results: UHECR Energy Spectrum



Abraham *et al.* Phys. Lett. B **685** (2010)

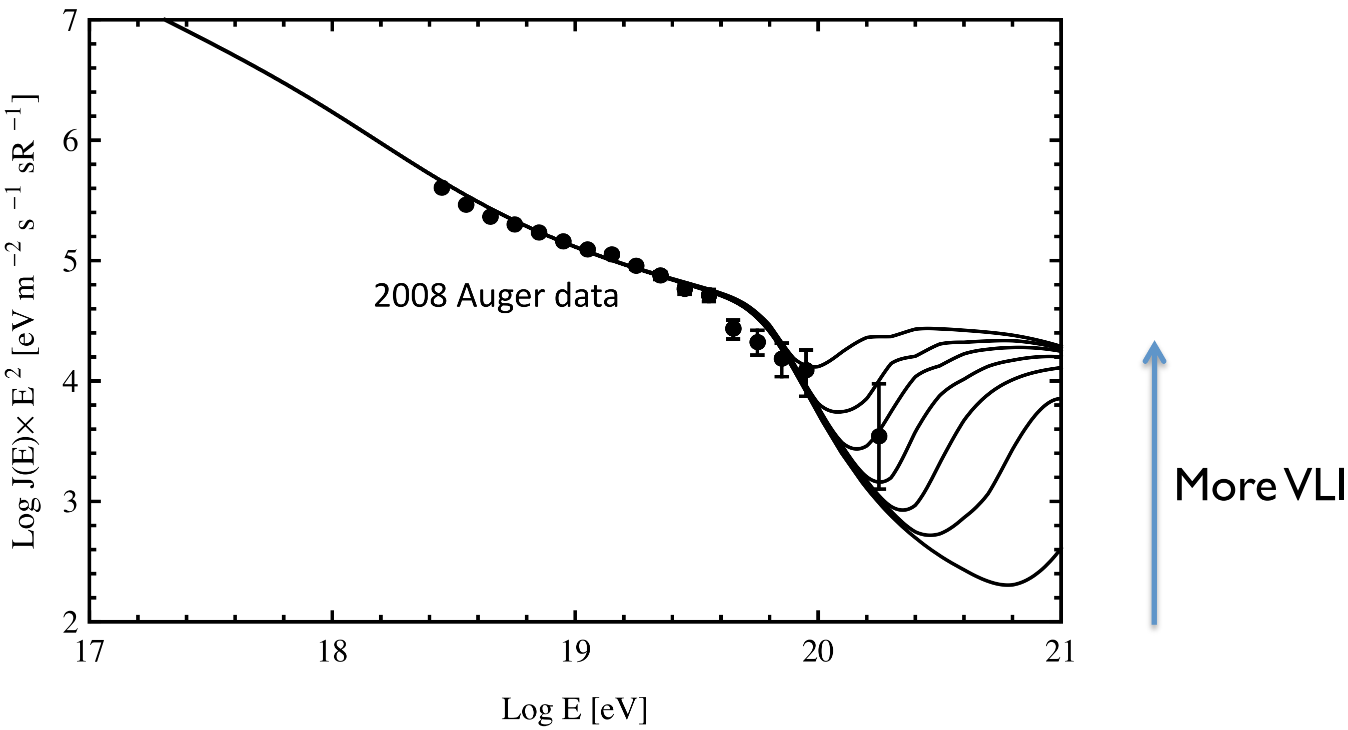
- 2008: Continuation of spectrum rejected at 6σ
- 2009: combined FD + SD spectrum
- Suppression energy consistent with GZK onset

VLI Limits from UHECR Data

Scully & Stecker, Astropart. Phys. **31** (2009) 220

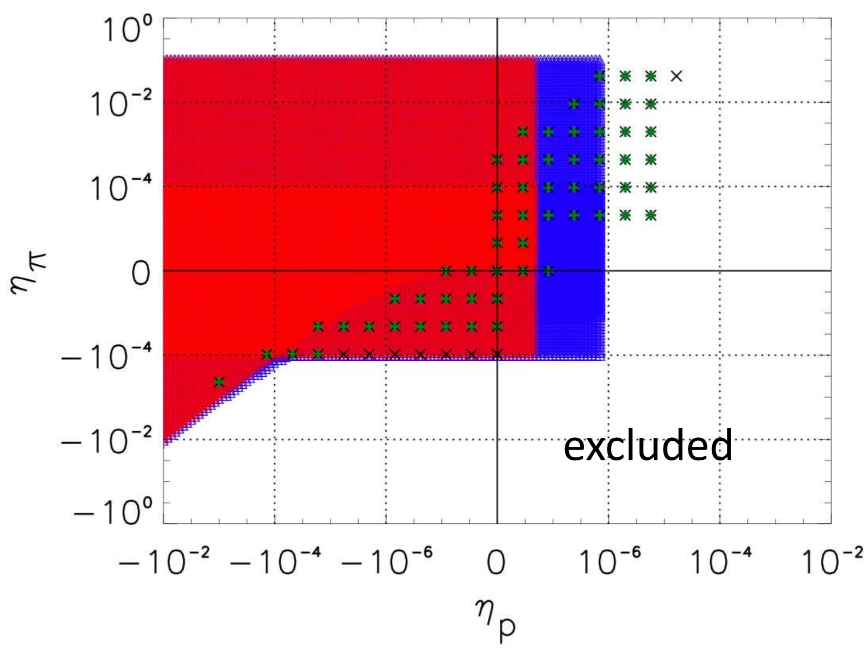
MAV case (1 σ CL):

$c_\pi - c_p < 6 \times 10^{-23}$



VLI Limits, Cont.

Maccione *et al.*, JCAP 0904 022 (2009)



Higher-dimension (p^4) VLI (99% CL):

$$-10^{-3} \lesssim \eta_p \lesssim 10^{-6}$$

$$-10^{-3} \lesssim \eta_\pi \lesssim 10^{-1} \qquad (\eta_p > 0)$$
$$\lesssim 10^{-6} \qquad (\eta_p < 0)$$

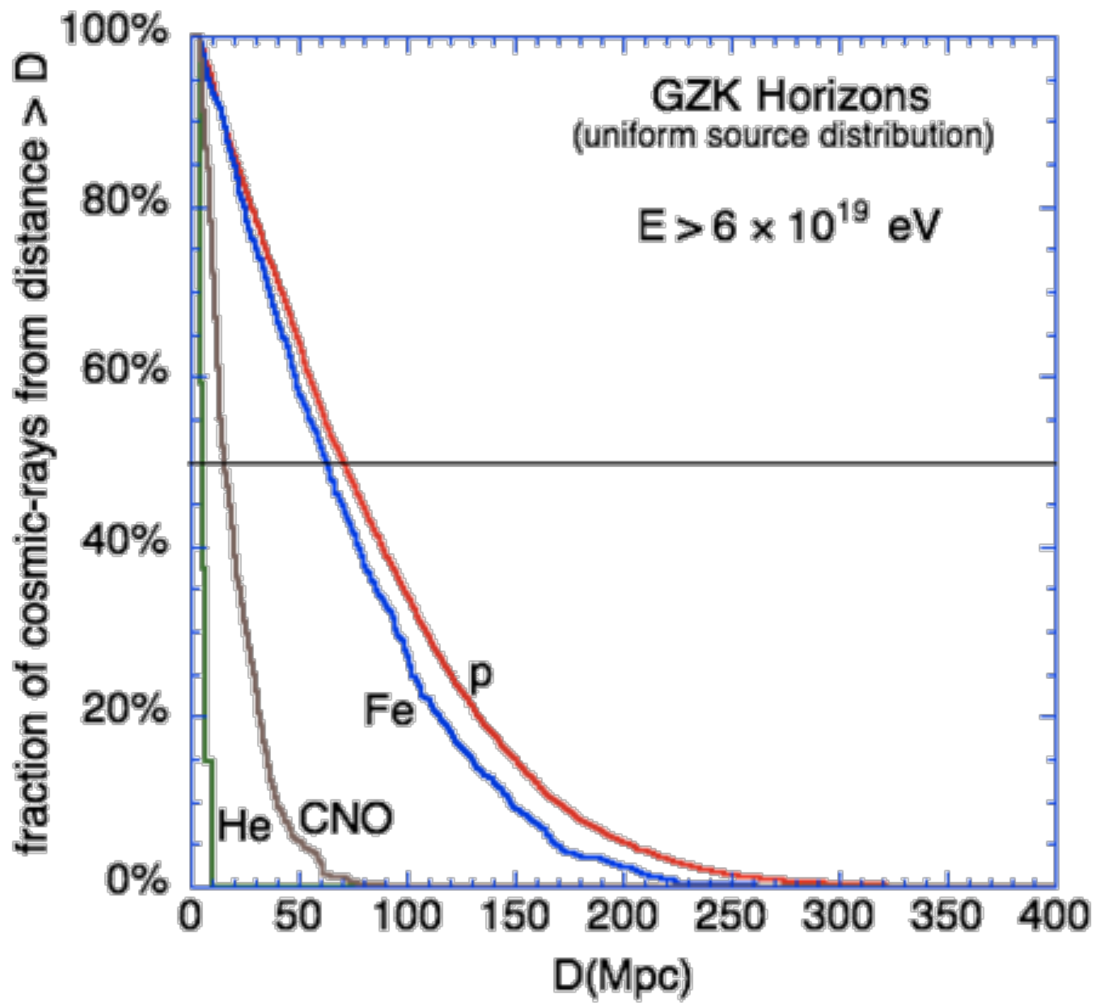
Upper limits below natural expectation (M_p already factored out!)

Caveats

- VLI analyses assume UHECRs are protons
- Cutoff at source could mimic GZK feature
  – see e.g. the "disappointing model" by Aloisio *et al.*
- There are other ways one can break LI
  – e.g. rotational asymmetry

Trans-GZK Composition

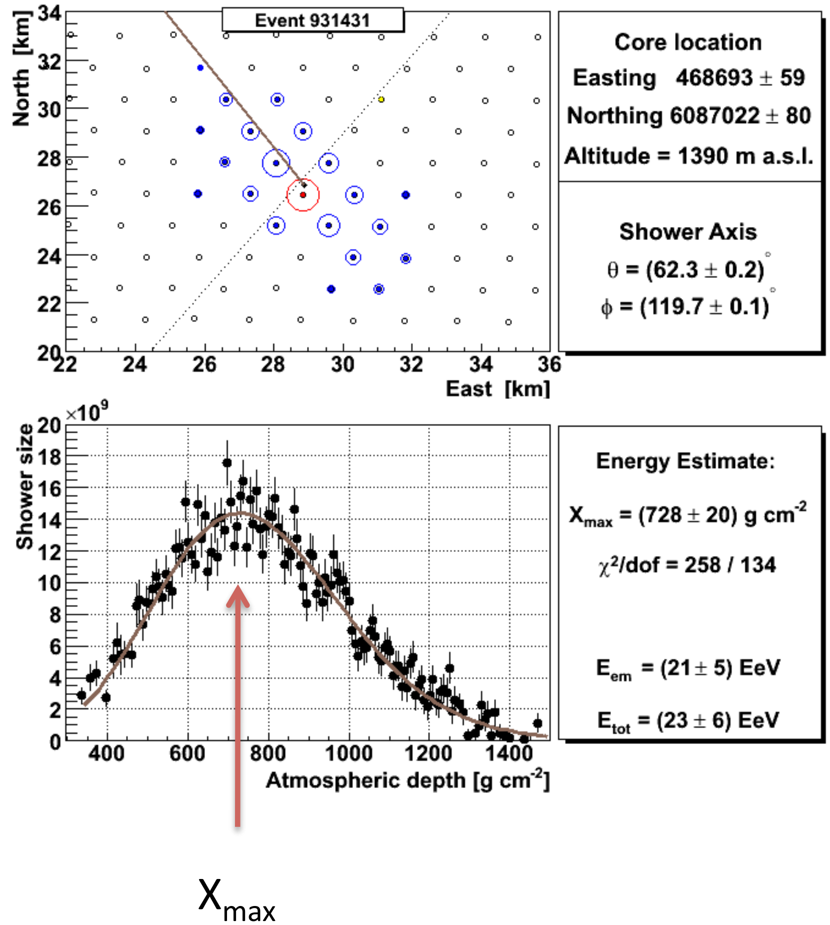
- Lighter nuclei photodisintegrate quickly
- Mostly protons and/or iron nuclei expected at the highest energies



Composition

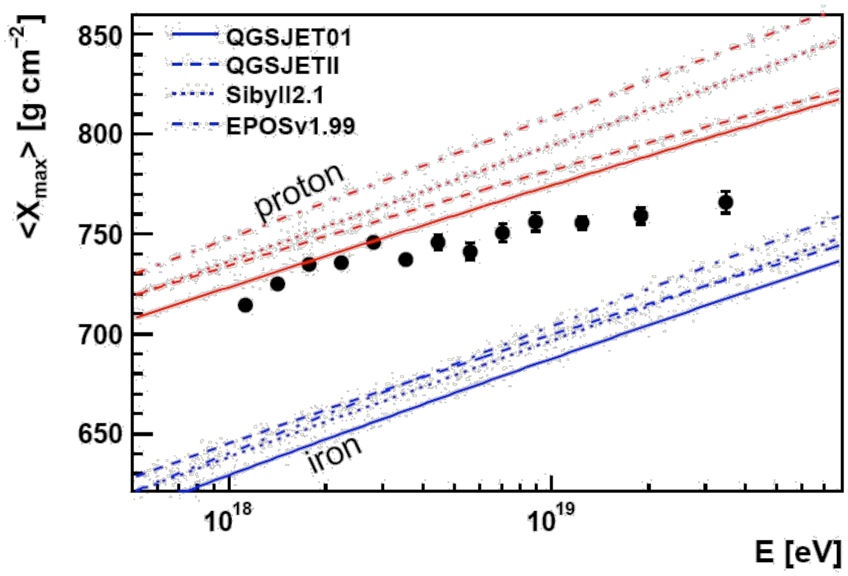
- Slant depth X_{max} (integrated density) of shower maximum in atmosphere
  - energy and composition-dependent
  - higher in atmosphere for heavier nuclei (interact, lose energy sooner)

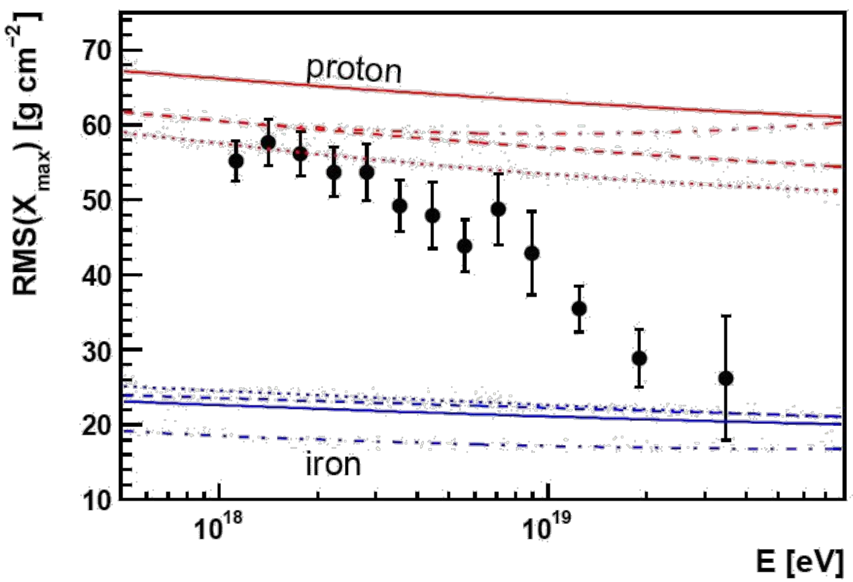
- Shower-to-shower fluctuations of X_{max}
  - iron showers (~superposition of 56 single-nucleon showers of 1/56 energy) have fewer fluctuations

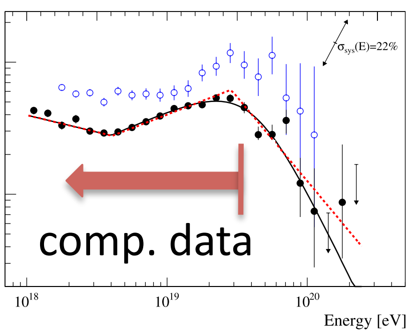


Latest Auger Results: Composition

Abraham *et al.*, PRL **104** (2010) 091101







Both indicate composition getting heavier…
or protons behaving very differently than expected?

But data run out just at GZK-like feature…

The Neutrino Connection

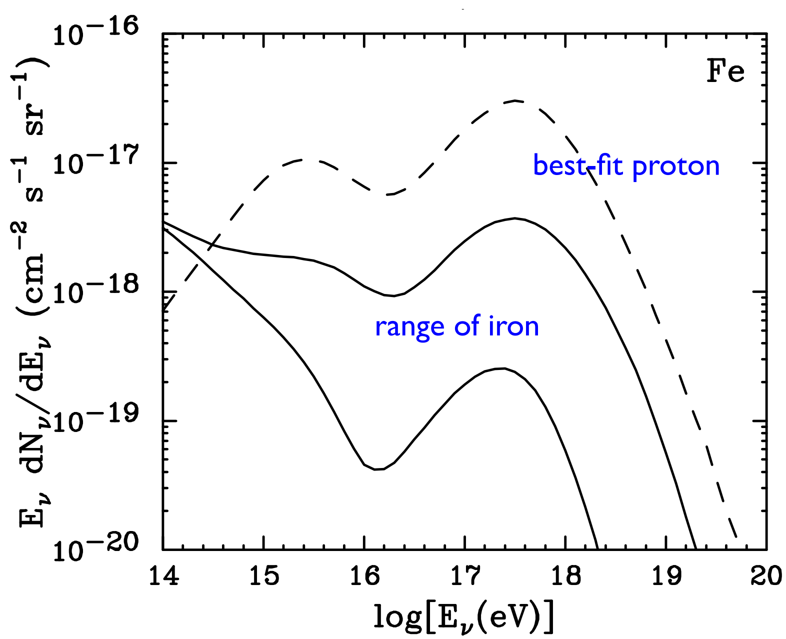
- GZK process also produces UHE neutrinos!

$$p\gamma \rightarrow n\pi^+ \rightarrow n\mu + \nu_\mu.$$

- Nuclei will tend to photodisintegrate first (reduced flux)

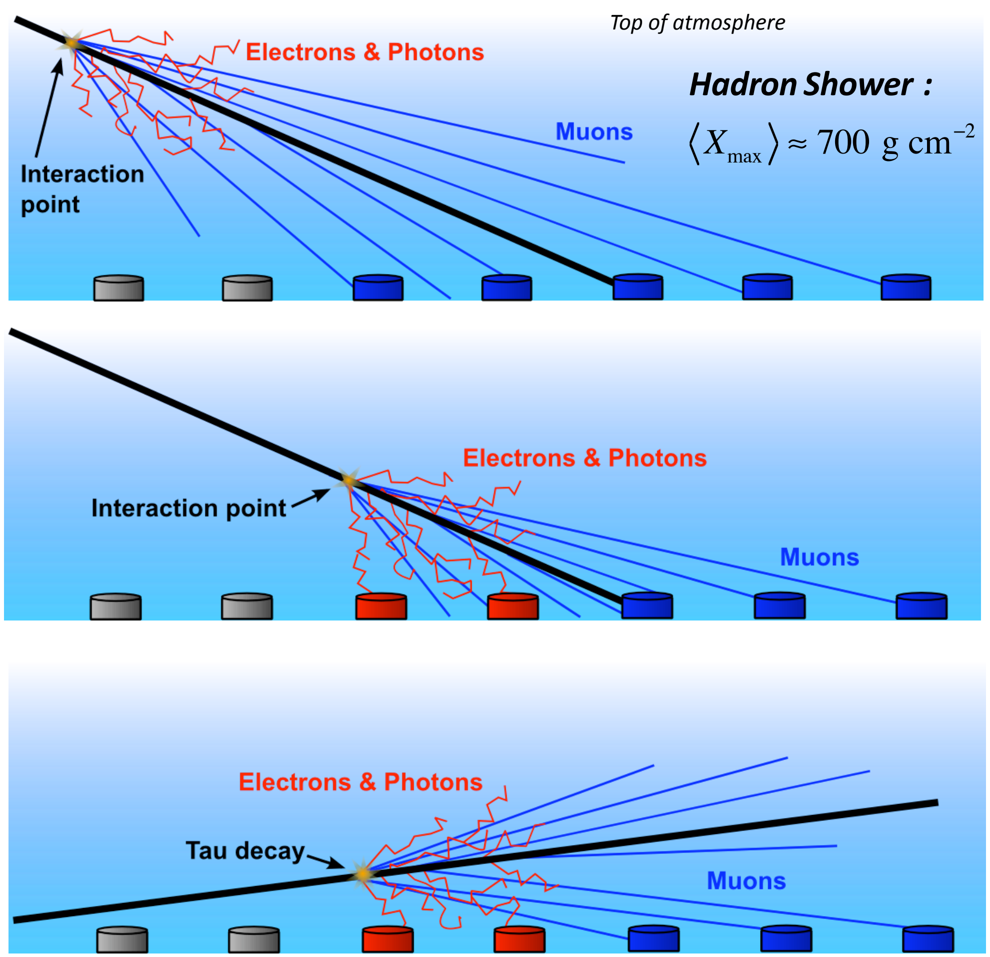
- Measurement of GZK neutrino flux:
  - source spectrum
  - source evolution with redshift
  - composition

GZK neutrino flux



Anchordoqui *et al.* 2007

Neutrino Detection via Air Showers

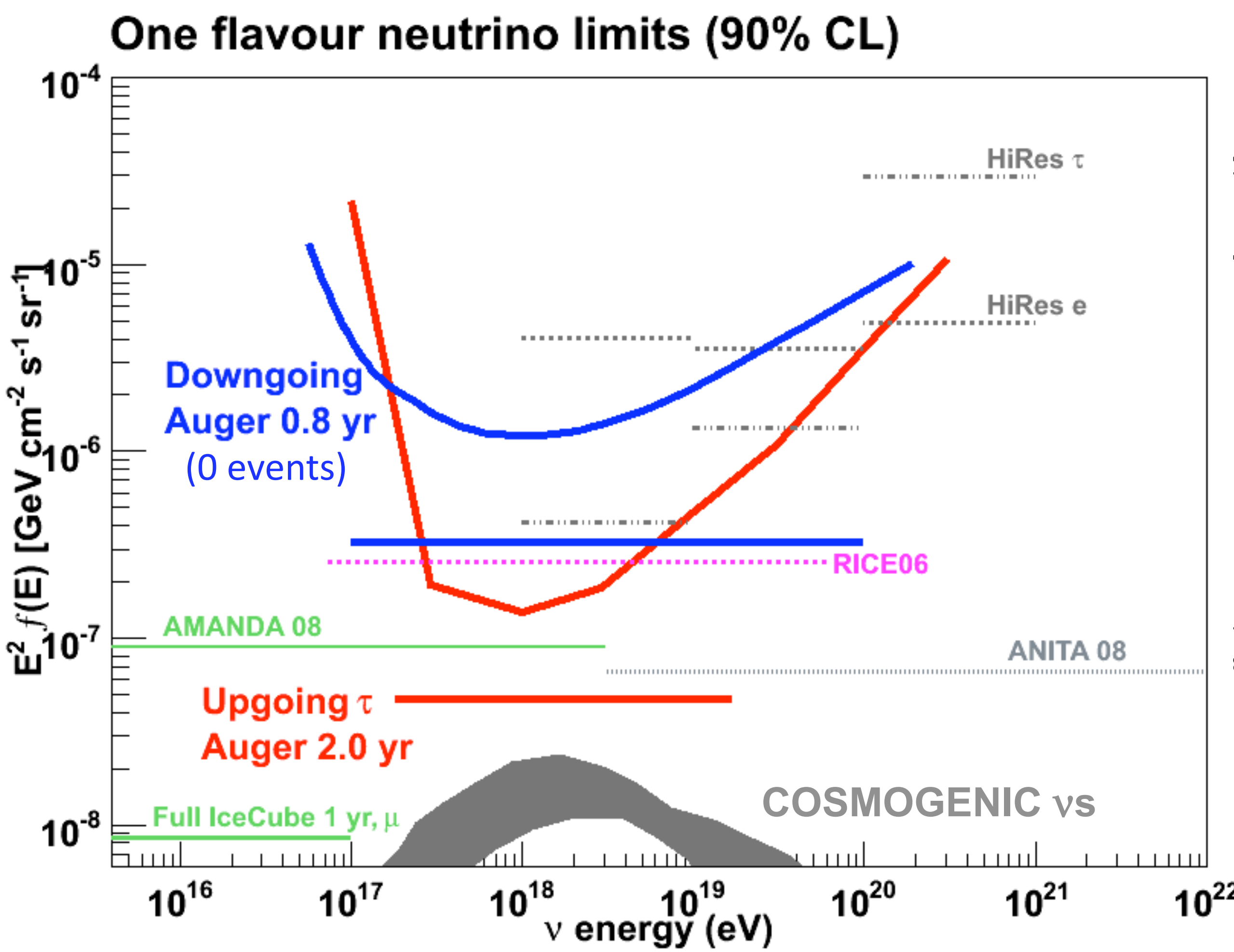


"normal" inclined shower:
only muons left

neutrino-induced shower:
young EM component
(broad signals in tanks)

tau decay from Earth-skimming ν_τ:
dense target, but only one flavor

Limits on Diffuse Neutrino Flux



J. Tiffenberg, ICRC 2009, arXiv:0906.2347 [astro-ph]

The Neutrino Connection (II)

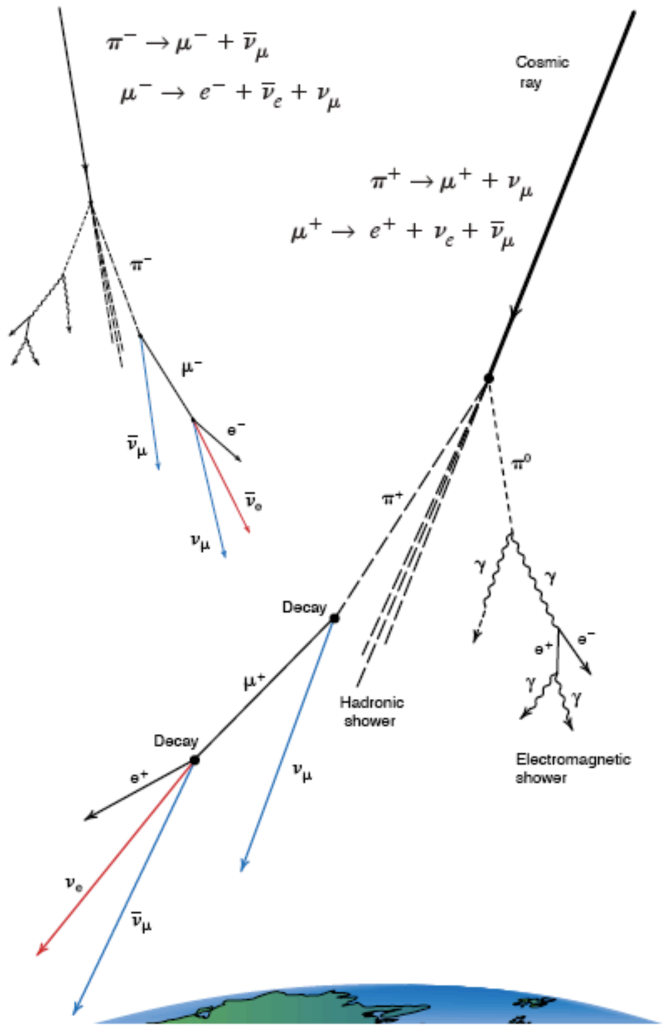


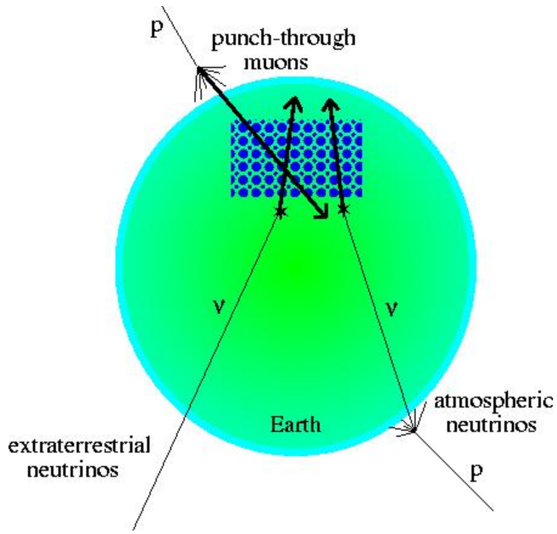
Figure from Los Alamos Science **25** (1997)

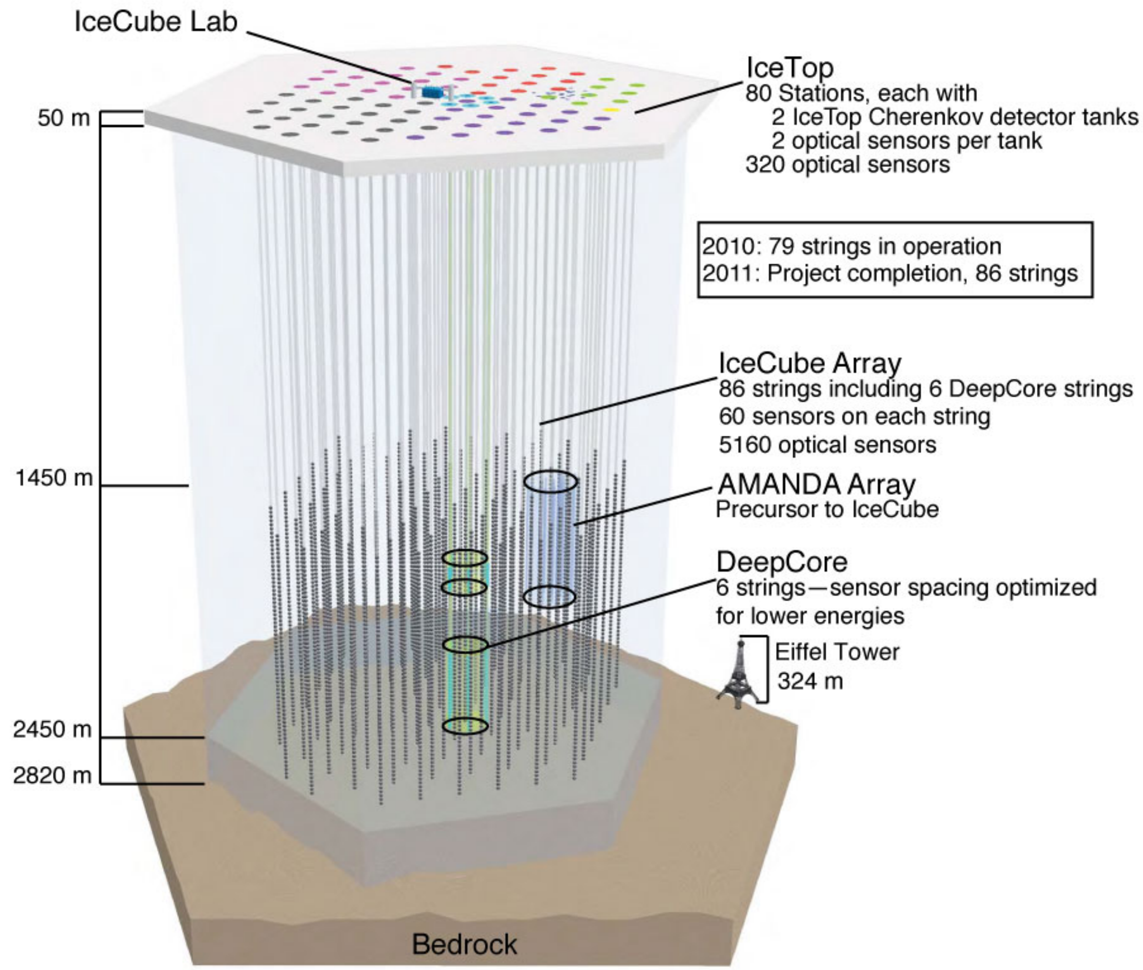
Cosmic rays air showers produce muons, neutrinos through charged pion / kaon decay

Atmospheric muon events dominate over ν by ~10^6

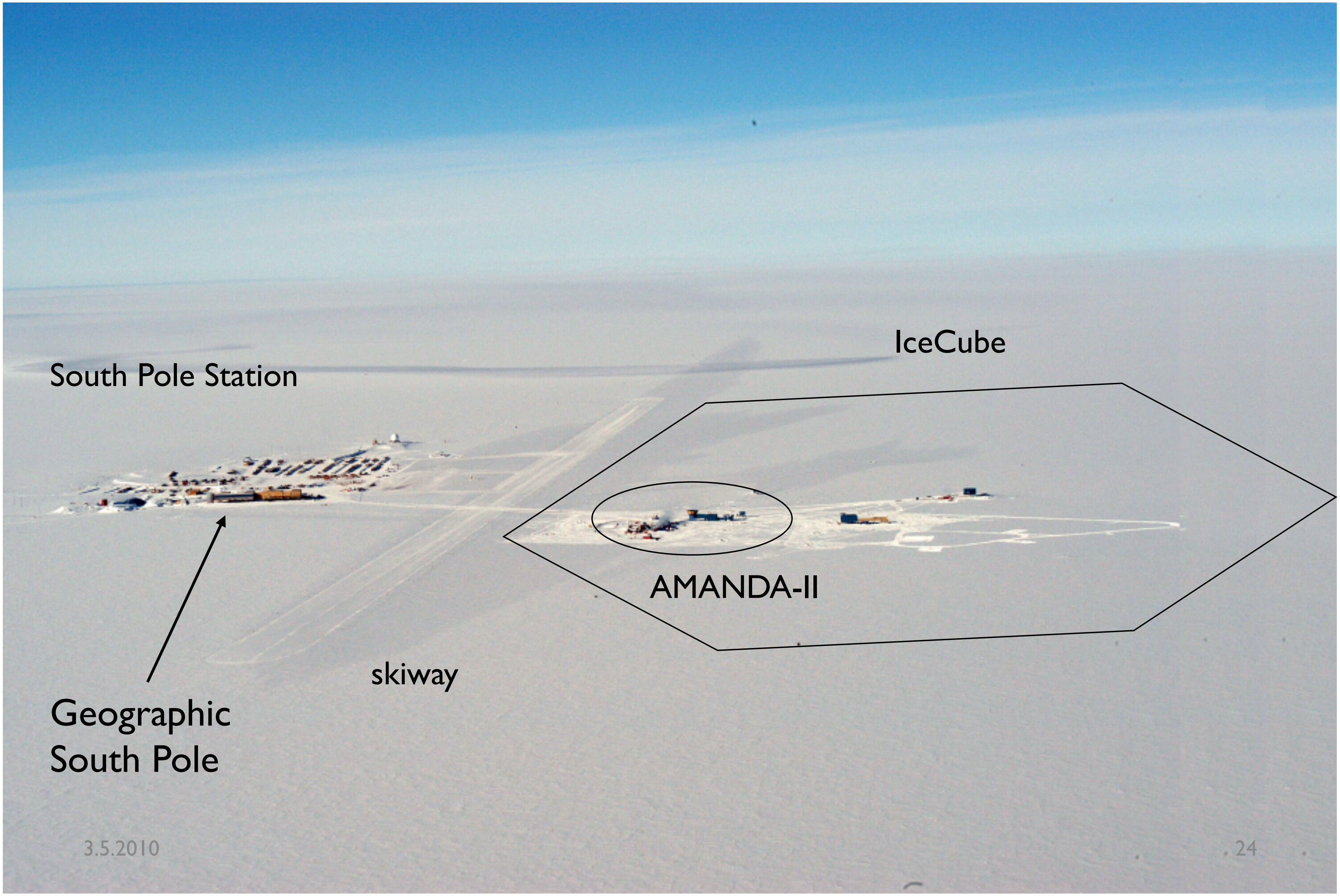
Neutrino events: reconstruct direction + use Earth as filter

IceCube

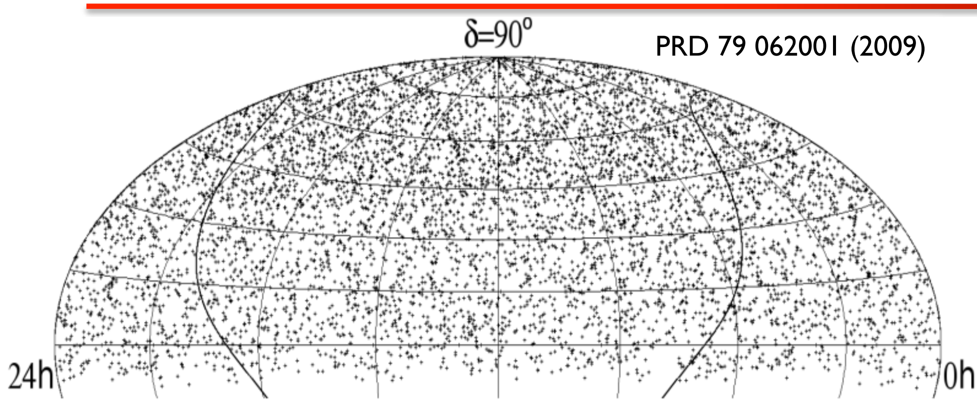

p
punch-through muons
ν
ν
Earth
atmospheric neutrinos
extraterrestrial neutrinos
p


IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
50 m
2010: 79 strings in operation
2011: Project completion, 86 strings
IceCube Array
86 strings including 6 DeepCore strings
60 sensors on each string
5160 optical sensors
1450 m
AMANDA Array
Precursor to IceCube
DeepCore
6 strings—sensor spacing optimized for lower energies
Eiffel Tower
324 m
2450 m
2820 m
Bedrock

Amundsen-Scott
South Pole Research Station

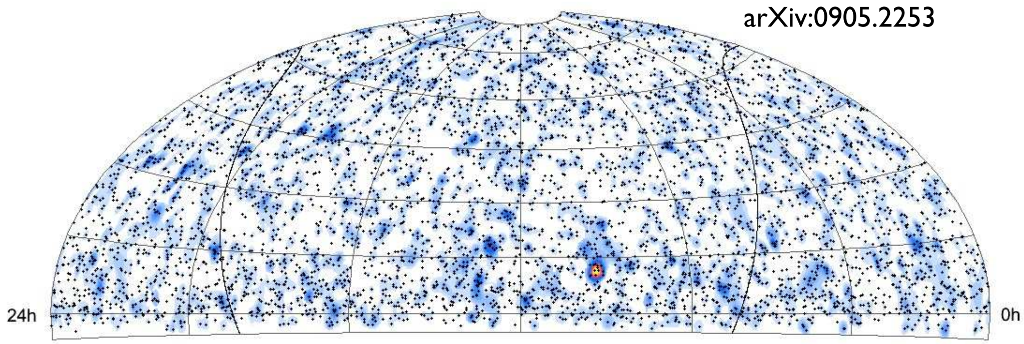


Current Experimental Status



PRD 79 062001 (2009)

2000-2006 AMANDA neutrino skymap



arXiv:0905.2253

22-string IceCube neutrino skymap (2007)

- Large sample of atmospheric neutrinos
  - AMANDA-II: 6500 events in 7 years, energy range: 0.1-10 TeV
  - One year of IceCube 22-string data: ~5700 neutrino candidates
  - One year of IceCube 40-string data: ~14000 neutrino candidates

Opportunity for particle physics with high-energy atmospheric ν…
atmospheric neutrino boost factor also > 10^{11}

Neutrino VLI

- Modified dispersion relation: $E_a^2 = \vec{p}_a^{\,2} c_a^2 + m_a^2 c_a^4.$

- Different maximum attainable velocities c_a (MAVs) for different particles: $\Delta E \sim (\delta c/c)E$

- For neutrinos: MAV eigenstates not necessarily flavor or mass eigenstates ⇒ mixing ⇒ VLI oscillations

$$\mathrm{H}_{\pm} \equiv \frac{\Delta m^2}{4E} \mathbf{U}_\theta \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{U}_\theta^\dagger + \frac{\Delta\delta_n \, E^n}{2} \mathbf{U}_{\xi_n, \pm\eta_n} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{U}_{\xi_n, \pm\eta_n}^\dagger$$

VLI + Atmospheric Oscillations

$$P_{\nu_\mu \to \nu_\mu} = 1 \; - \; \sin^2 2\Theta \; \sin^2\left(\frac{\Delta m^2 L}{4E}\,\mathcal{R}\right)$$

$$\sin^2 2\Theta = \frac{1}{\mathcal{R}^2}(\sin^2 2\theta_{23} + R^2 \sin^2 2\xi + 2R \sin 2\theta_{23} \sin 2\xi \cos\eta) \; ,$$

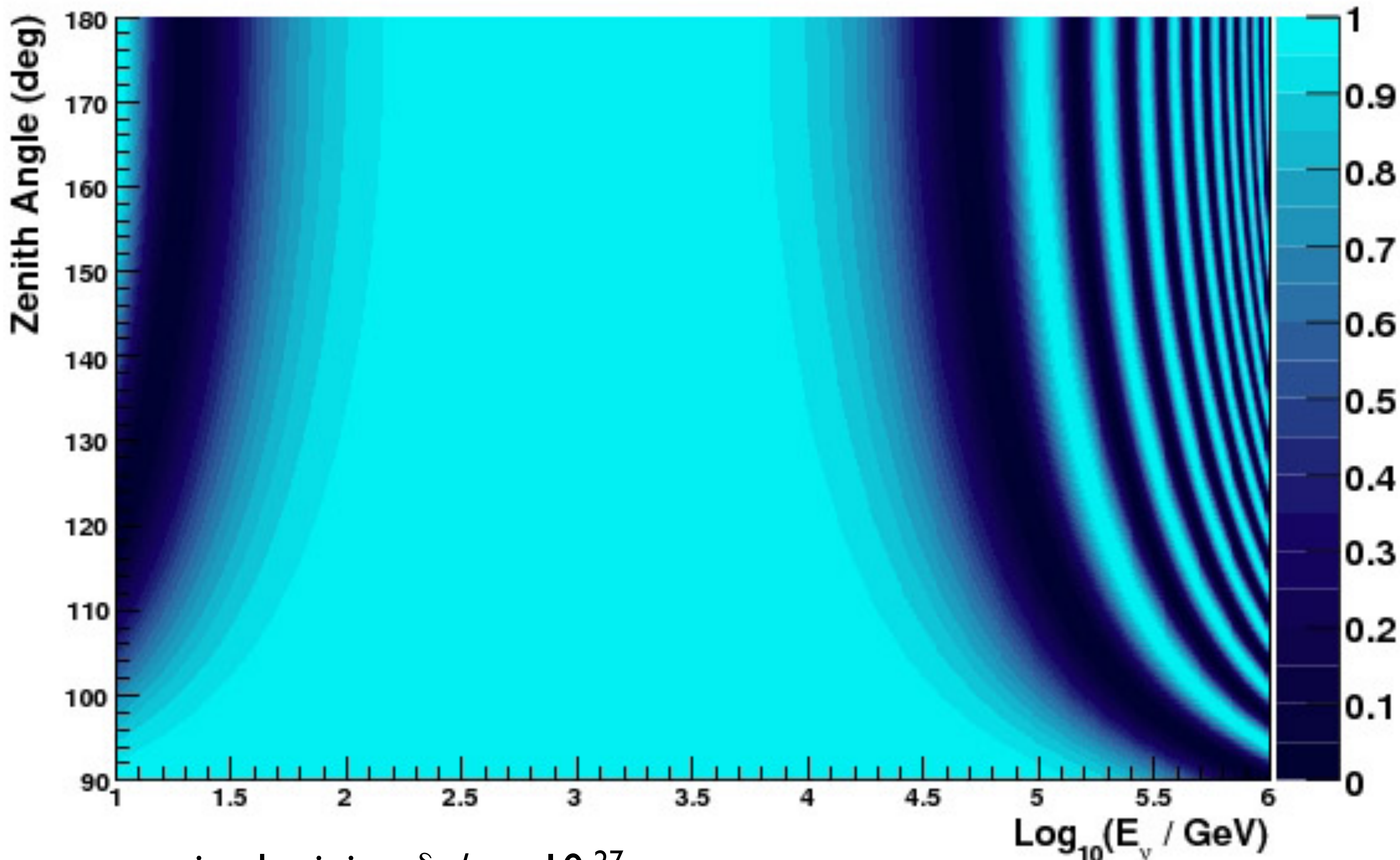
$$\mathcal{R} = \sqrt{1 + R^2 + 2R(\cos 2\theta_{23} \cos 2\xi + \sin 2\theta_{23} \sin 2\xi \cos\eta)} \; ,$$

$$R = \frac{\delta c}{c} \frac{E}{2} \frac{4E}{\Delta m^2_{23}}$$

- For atmospheric ν, conventional oscillations turn off above ~50 GeV (*L/E* dependence)
- VLI oscillations turn on at high energy (*L E* dependence), depending on size of *δc/c*, and distort the zenith angle / energy spectrum (other parameters: mixing angle ξ, phase η)

González-García, Halzen, and Maltoni, hep-ph/0502223

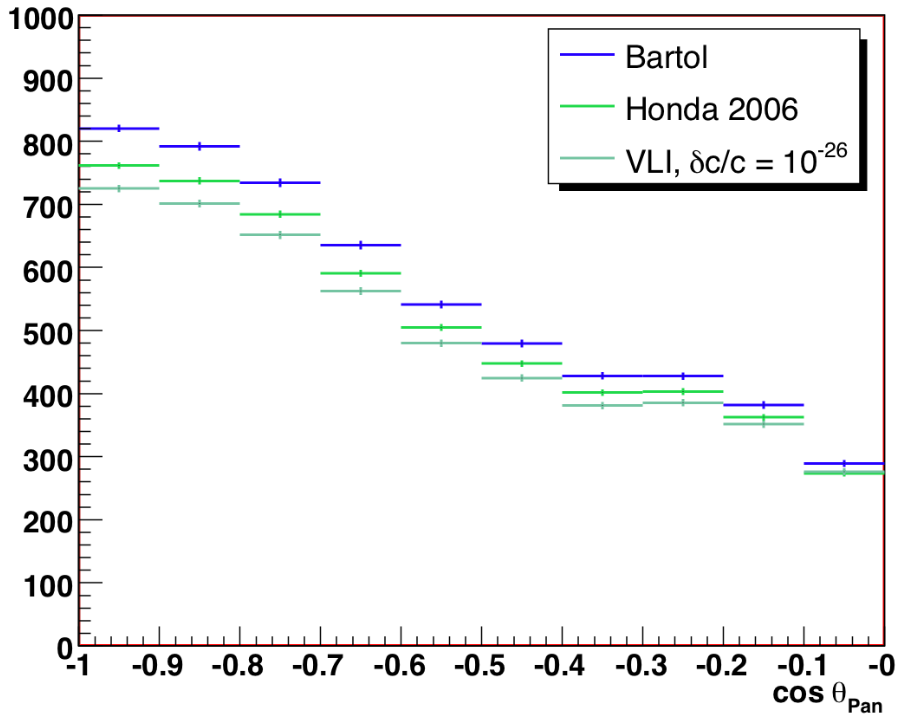
VLI Atmospheric ν_μ Survival Probability



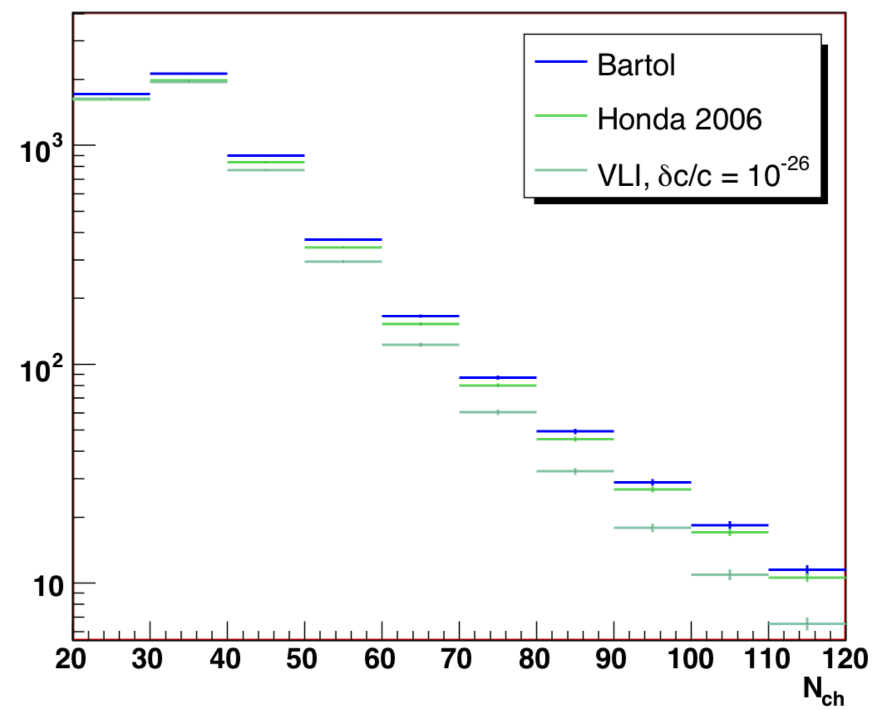
maximal mixing, $\delta c/c = 10^{-27}$

Simulated Observables (AMANDA 2000-2006)

reconstructed zenith angle

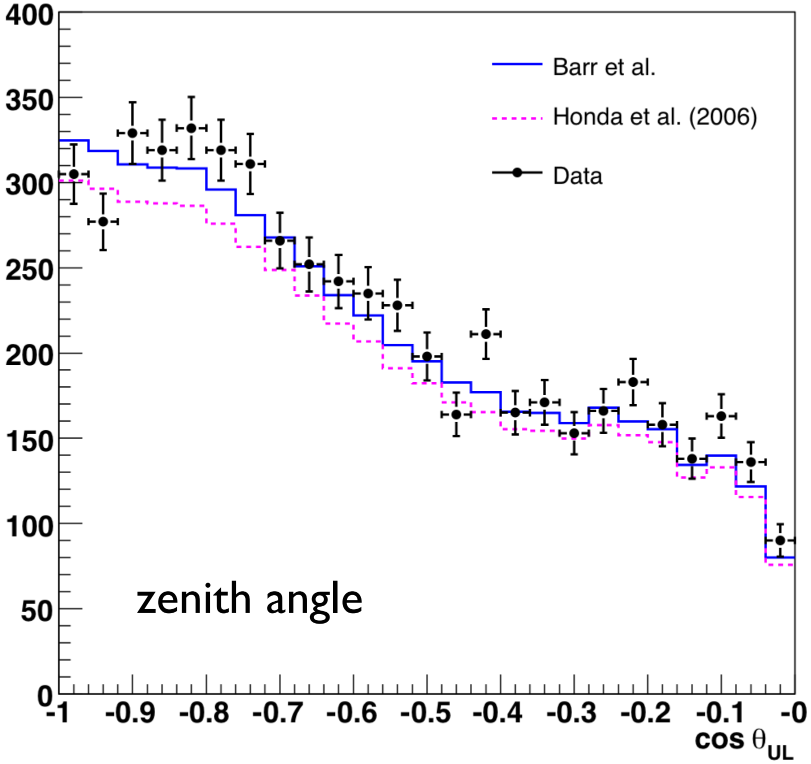


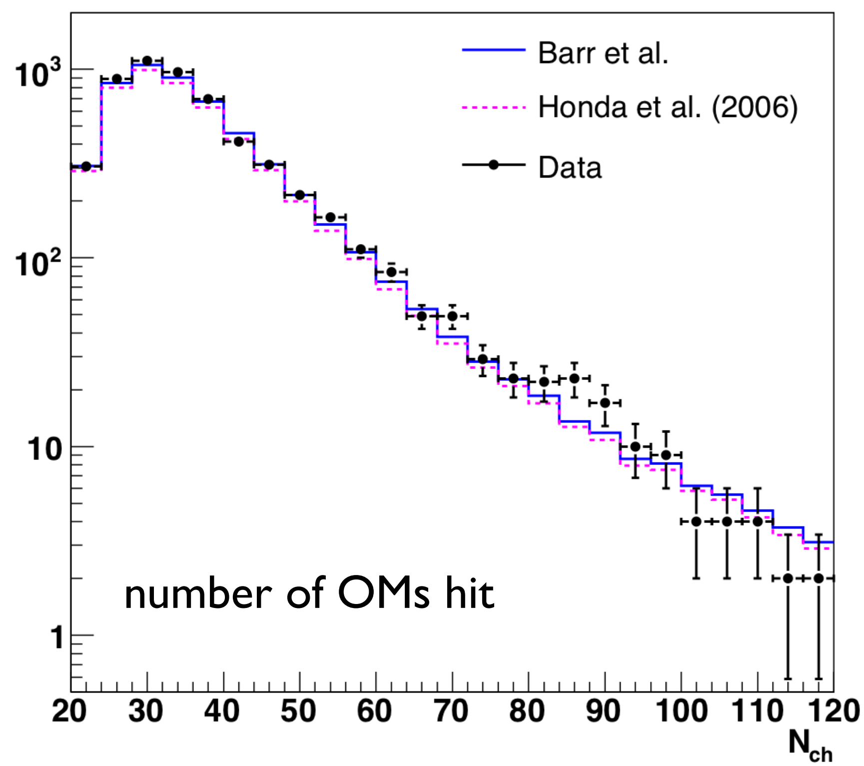
$N_{channel}$ (energy proxy)



VLI signature: deficit at high energy, near vertical

Results: Observables (AMANDA 2000-2006)

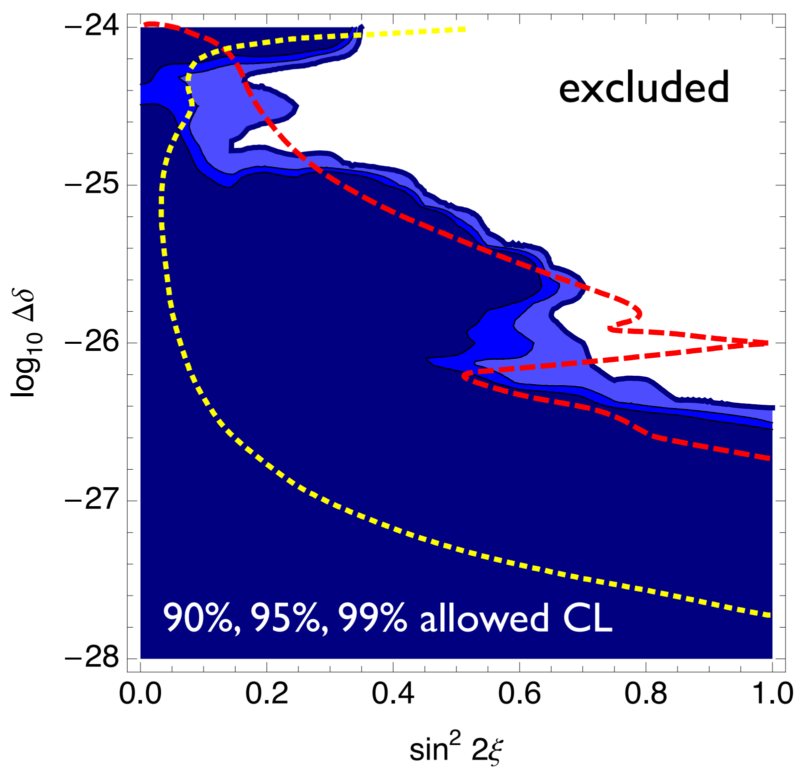




Data consistent with atmospheric neutrinos + O(1%) background

Results: VLI upper limit

Abbasi *et al.*, PRD **79**, 102005 (2009)



maximal mixing

- SuperK+K2K limit*:

  $\delta c/c < 1.9 \times 10^{-27}$ (90%CL)

- AMANDA 2000-2006 data:

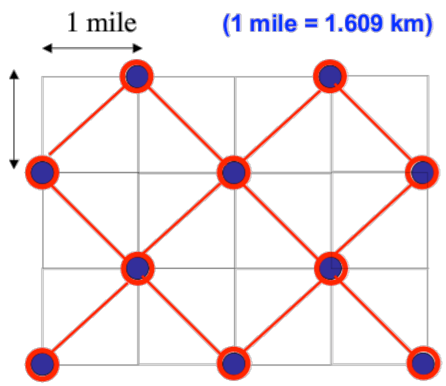
  $\delta c/c < 2.8 \times 10^{-27}$ (90%CL)

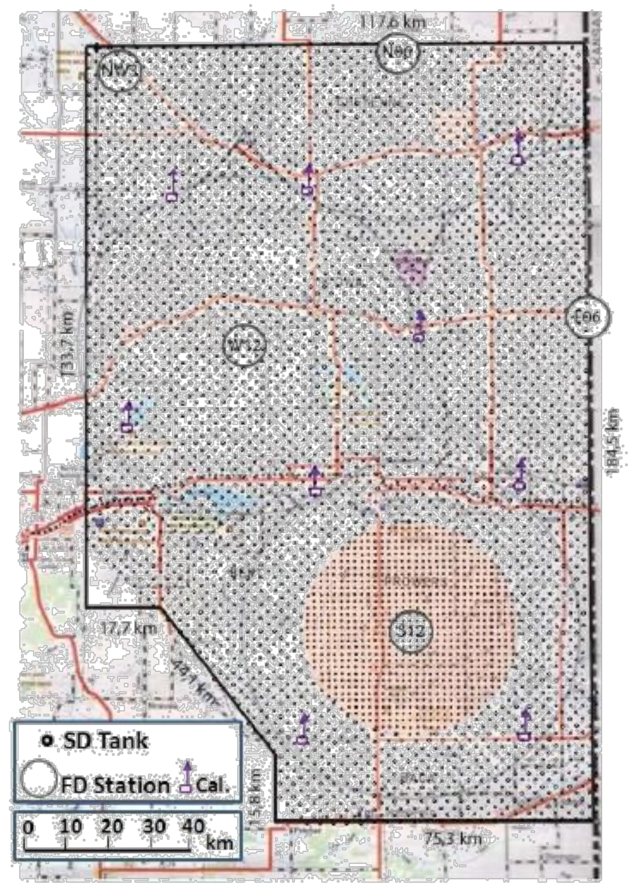
- IceCube 40-string analysis underway
  - 10-year 80-string sensitivity ~ 10^{-28}
  - also searching for sidereal variations

*González-García & Maltoni, PRD **70** 033010 (2004)

The Future: UHECRs

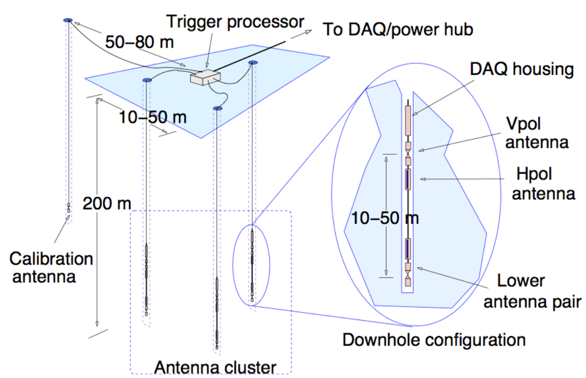
- Auger North: 21000 km^2
- Precision spectrum
  - can test VLI "recovery" scenarios
- UHE composition studies

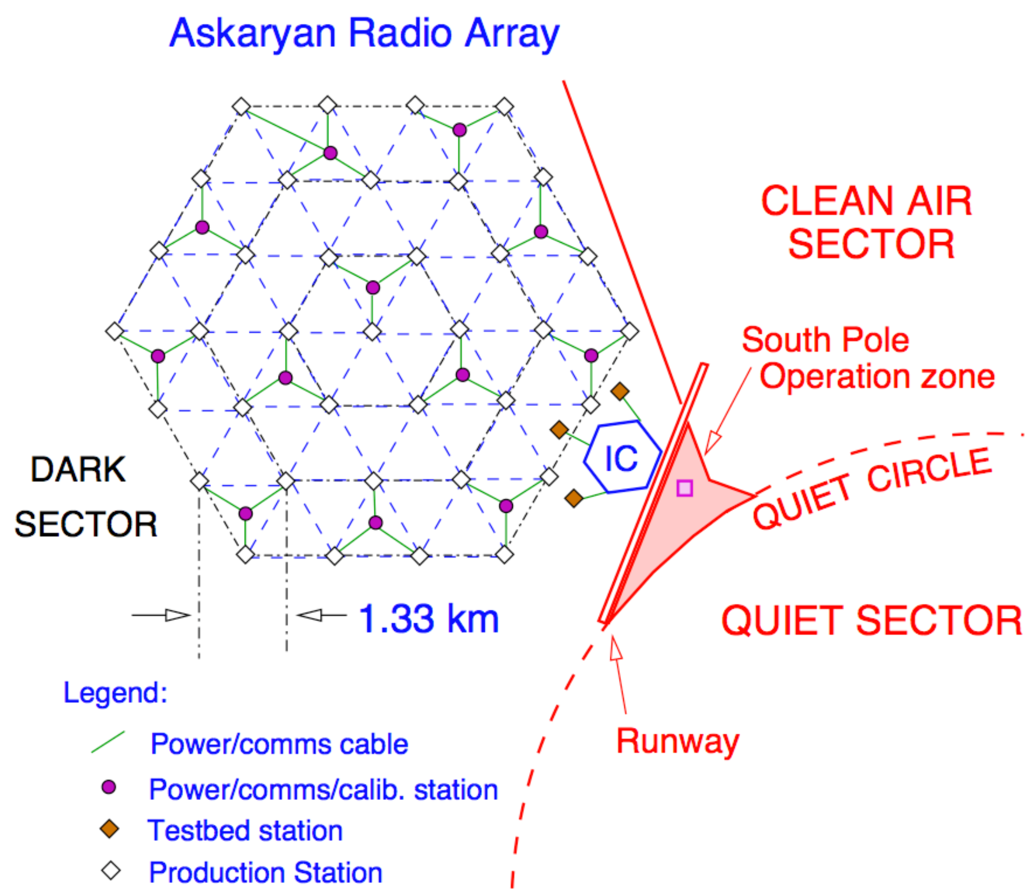




The Future: GZK Neutrinos

- Radio-frequency extension of IceCube
- GZK neutrino rates up to 25 events / year
- New "test beam" for QG effects





Summary

- High-energy cosmic rays allow very sensitive tests of Lorentz invariance
  - limit differences in MAV from 10^{-23} to 10^{-27}
  - higher dimension model limits probe Planck regime
  - tested scenarios are very specific
  - assumptions about UHECR composition, source spectra

- Next-generation experiments:
  - composition of highest-energy UHECRs
  - spectral features test various models
  - possibility of first detection of GZK neutrino flux

Thank you!

Czech Republic	Argentina
France	Australia
Germany	Brazil
Italy	Bolivia*
Netherlands	Mexico
Poland	USA
Portugal	Vietnam*
Slovenia	**Associate Countries*
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UHECR Anisotropy

- Extragalactic protons above 50 EeV or so should point back to sources (within a few degrees)

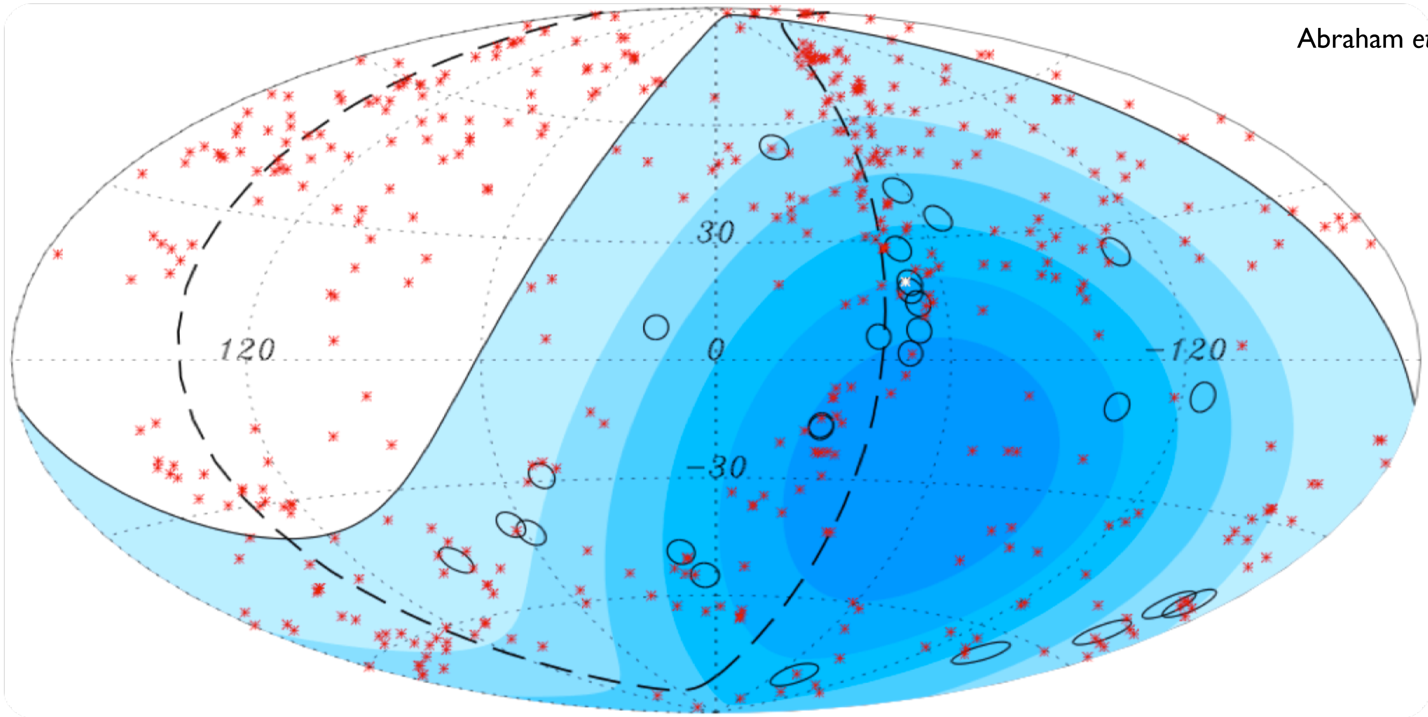
$$\theta(E,Z) \approx \left(\frac{L}{L_{\rm coh}}\right)^{0.5} \alpha \approx 0.8^\circ \left(\frac{10^{20}\,{\rm eV}}{E}\right) \left(\frac{L}{10\,{\rm Mpc}}\right)^{0.5} \left(\frac{L_{\rm coh}}{1\,{\rm Mpc}}\right)^{0.5} \left(\frac{B}{1\,{\rm nG}}\right) Z,$$

Hooper *et al.* 2008

- Pre-Auger: claims of excess from galactic center, BL-Lacs, etc.

- Anisotropy with low statistics is a tricky business

Anisotropy, cont.



2007: 27 events above 55 EeV (ovals); correlation with nearby AGN (red crosses) with chance P ~ 2 × 10^{-3}

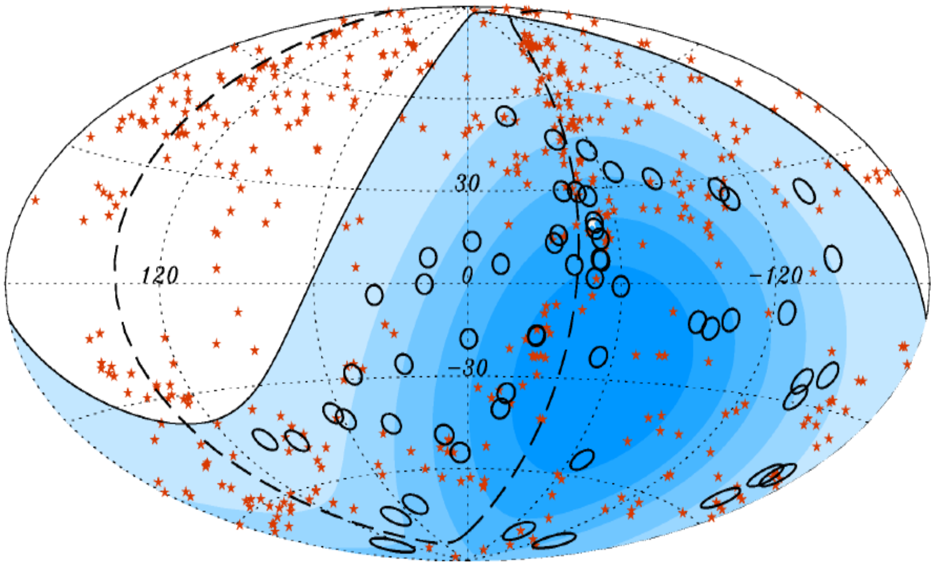
Isotropy rejected at ~99% confidence level

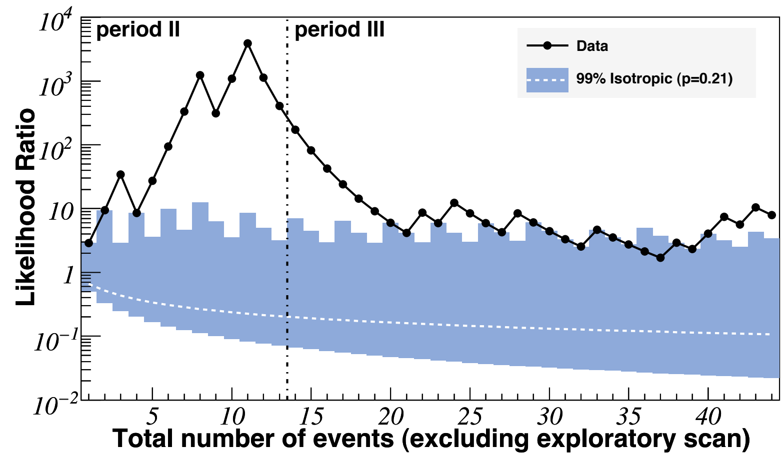
Separate analyses: No correlation found with galactic center or BL-Lacs

Latest Results: Anisotropy

2009: 58 events above 55 EeV

Hague *et al.* 2009 (ICRC)



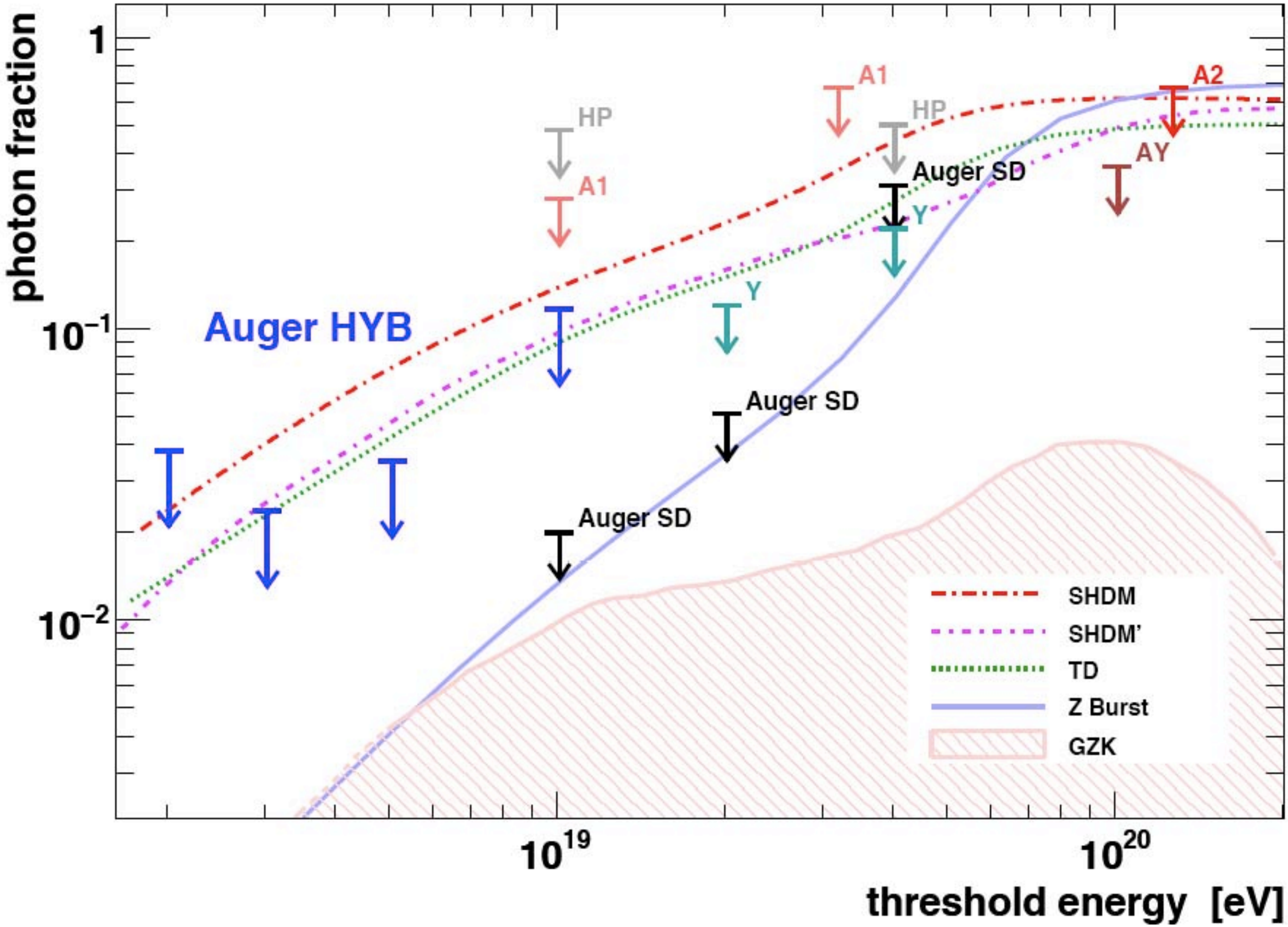


Correlation with original AGN catalog weakens

A posteriori investigations of:

- Centaurus A region
- correlations with other catalog(s) e.g. SWIFT-BAT

New prescriptions will allow tests of significance


photon fraction
1
10^{-1}
10^{-2}
10^{19}
10^{20}
threshold energy [eV]
Auger HYB
Auger SD
Auger SD
Auger SD
HP
HP
A1
A1
A2
AY
Y
Y
SHDM
SHDM'
TD
Z Burst
GZK

Decoherence + Atmospheric Oscillations

characteristic exponential behavior

1:1:1 ratio after decoherence

$$P[\nu_\mu \to \nu_\mu] = \frac{1}{3} + \frac{1}{2}\Bigg(e^{-\gamma_3 L}\cos^4\theta_{23} + \frac{1}{12}e^{-\gamma_8 L}(1-3\cos 2\theta_{23})^2 + 4e^{-\frac{\gamma_6+\gamma_7}{2}L}\cos^2\theta_{23}\sin^2\theta_{23}\Bigg(\cos\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2-\left(\frac{\Delta m_{23}^2}{E}\right)^2\right|}\right] + \sin\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2-\left(\frac{\Delta m_{23}^2}{E}\right)^2\right|}\right]\frac{(\gamma_6-\gamma_7)}{\sqrt{\left|(\gamma_6-\gamma_7)^2-\left(\frac{\Delta m_{23}^2}{E}\right)^2\right|}}\Bigg)\Bigg)$$

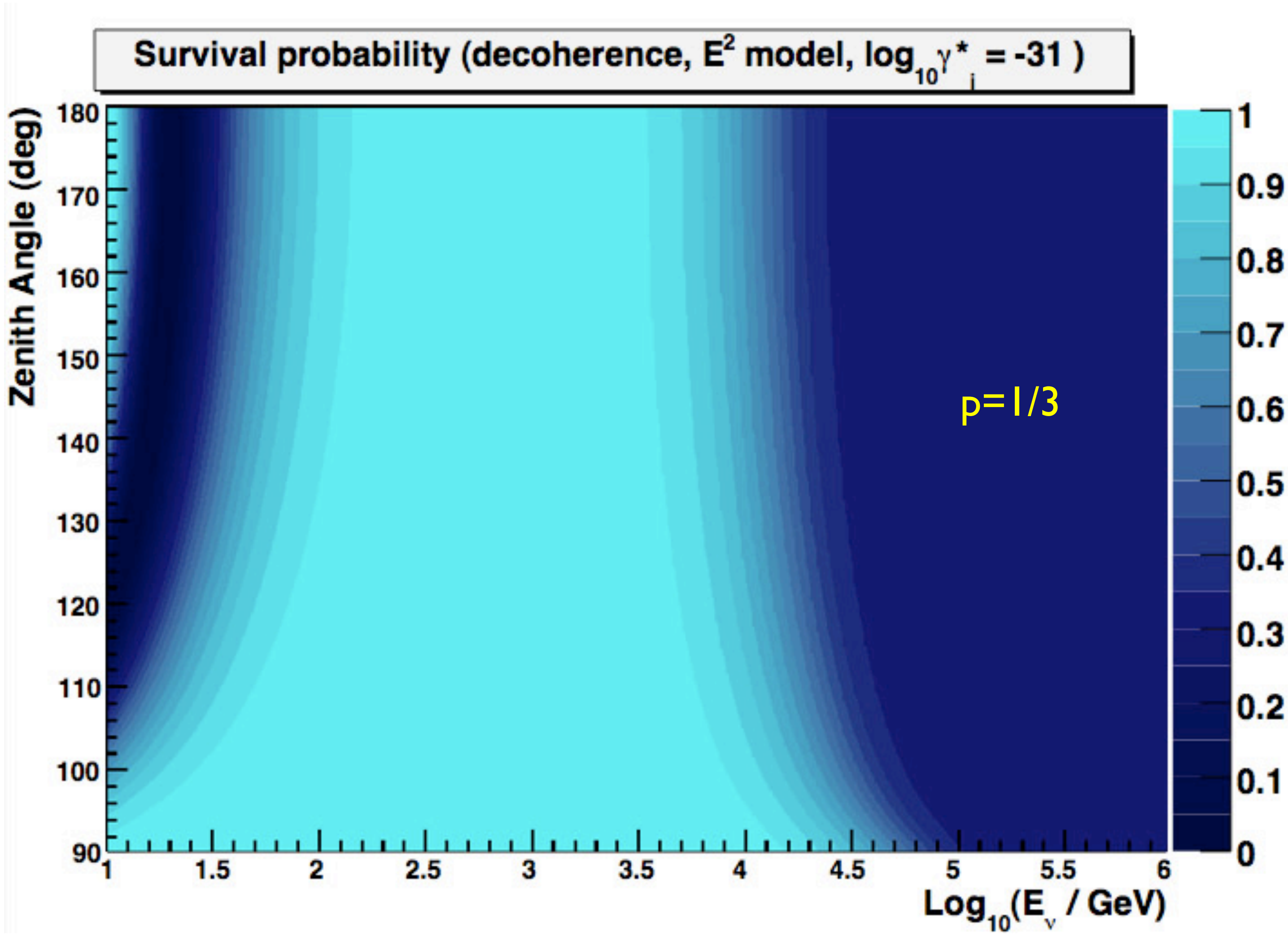
derived from Barenboim, Mavromatos *et al.* (hep-ph/0603028)

Energy dependence depends on phenomenology: $\gamma_i = \gamma_i^* \; E^n, \quad n \in \{-1, 0, 2, 3\}$

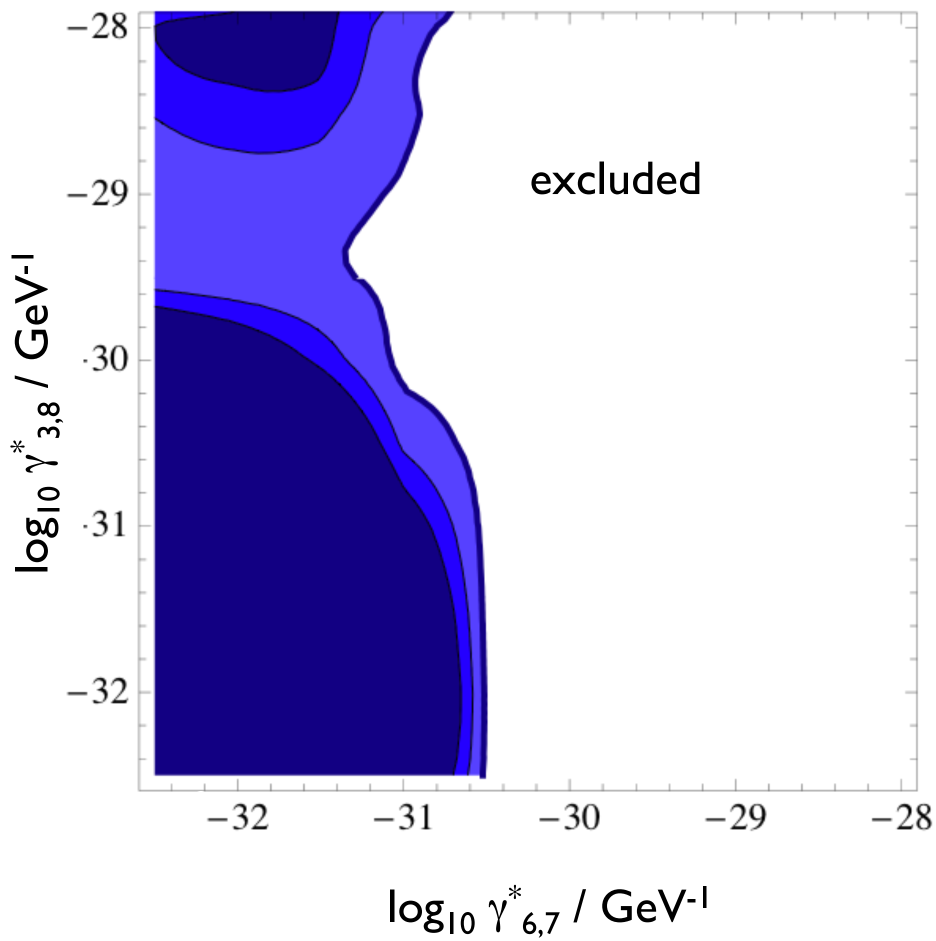
$n = -1$	$n = 0$	$n = 2$	$n = 3$
preserves Lorentz invariance	simplest	recoiling D-branes*	Planck-suppressed operators‡

*Ellis *et al.*, hep-th/9704169 ‡ Anchordoqui *et al.*, hep-ph/0506168

QD Atmospheric ν_μ Survival Probability



Results: QD upper limit



E^2 model (E, E^3 limits also set)

- SuperK limit‡ (2-flavor):

  $\gamma_i < 0.9 \times 10^{-27}$ GeV^{-1} (90% CL)

- ANTARES sensitivity* (2-flavor):

  $\gamma_i \sim 10^{-30}$ GeV^{-1} (3 years, 90% CL)

- This analysis:

  $\gamma_i < 1.3 \times 10^{-31}$ GeV^{-1} (90% CL)

* Morgan *et al.*, astro-ph/0412618

‡ Lisi, Marrone, and Montanino, PRL **85** 6 (2000)