High energy cosmic rays and the potential for new physics discovery

Haim Goldberg
Northeastern University, Boston

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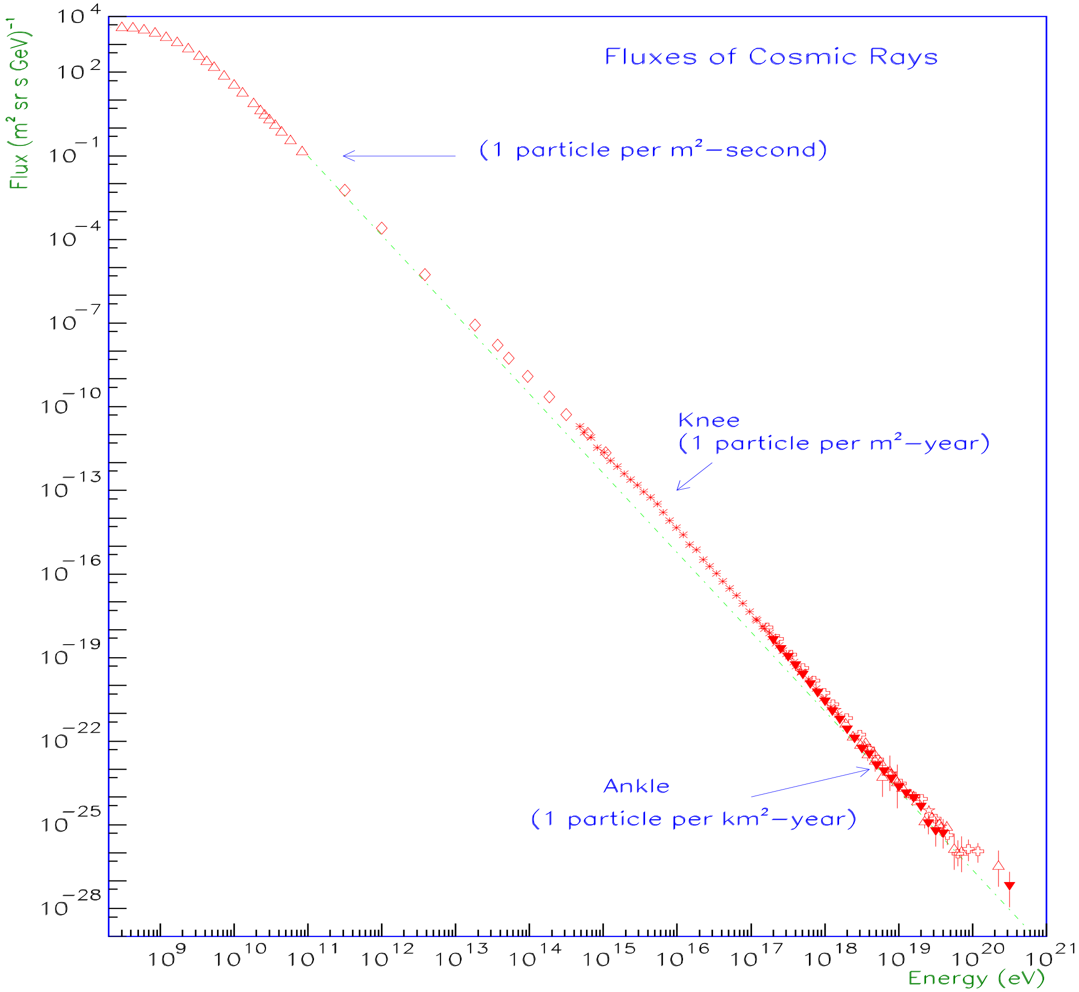
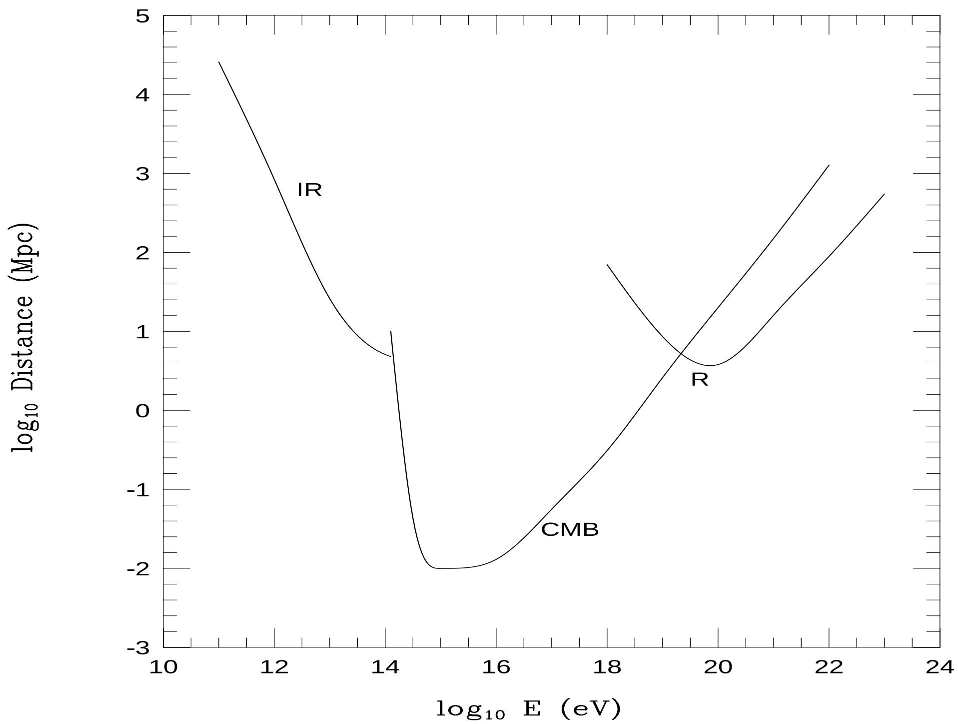
- **Lightening review of cosmic rays: spectrum, sources, losses**
- **Examples of New Physics discovery:**
  - **Split supersymmetry**
  - **High energy neutralinos in cosmic rays (decay of relics)**
  - **Anomalous neutrino interactions at high energies (general treatment, TeV black holes, sphalerons)**
  - **Quantum decoherence**

The cosmic ray spectrum



Cosmic ray horizons

- **protons** – pion photoproduction on CMB; GZK horizon at 50–100 Mpc
- **nuclei** – photodisintegration on CMB; $\sim$ same horizon
- **photons** – pair production off CMB, IR, radio and B; window for distant UHE photons only if $B < 10^{-12}$ G.



Sources

- AGN's (linear Fermi mechanism)
- Accretion shock waves
- Relativistic jets
- Magnetars
- Starburst galaxies (collective effects)
- GRB fireballs
- Top down mechanisms
- + many more

New physics: Split SUSY at Auger

Anchordoqui, Nunez, HG, PRD71:065014,2005

- Split Supersymmetry: fine-tune to small Higgs mass, scalar masses are large, gluino mass O(TeV), long-lived

$$\tau_0 \simeq 25 \text{ yr} \left(\frac{\text{TeV}}{M_{\tilde{g}}}\right)^5 \left(\frac{M_{\text{SUSY}}}{10^{11} \text{ GeV}}\right)^4$$

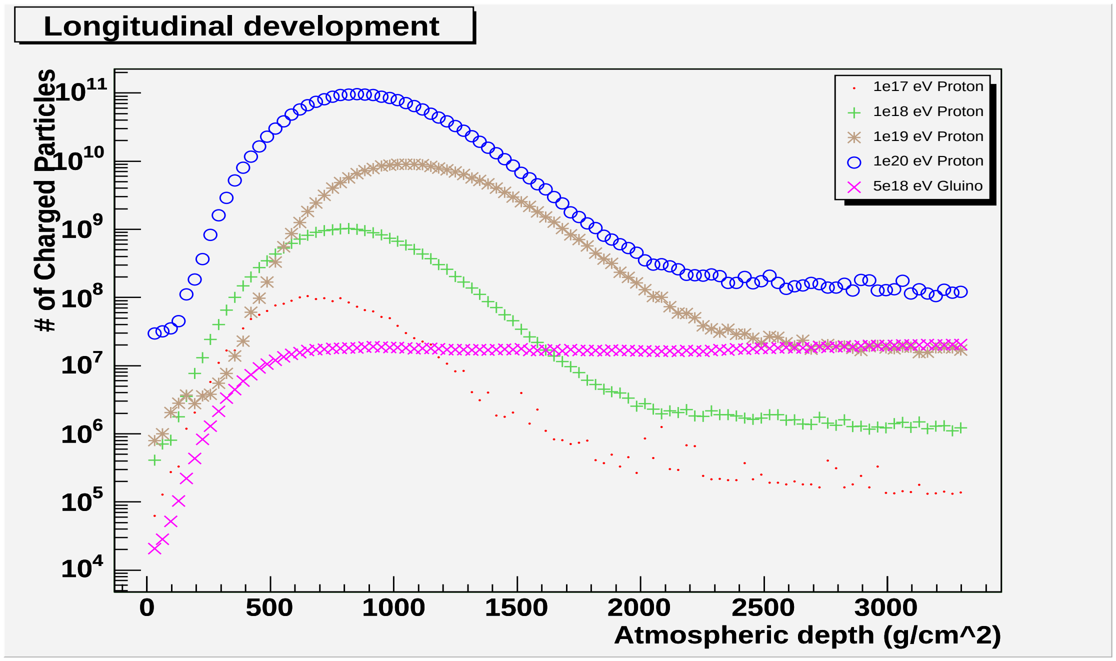
Arkani-Hamed,Dimopoulos, JHEP 0506:073,2005

- isotope relic abundance $\longrightarrow M_{\text{SUSY}} \lesssim 10^{13}$ GeV

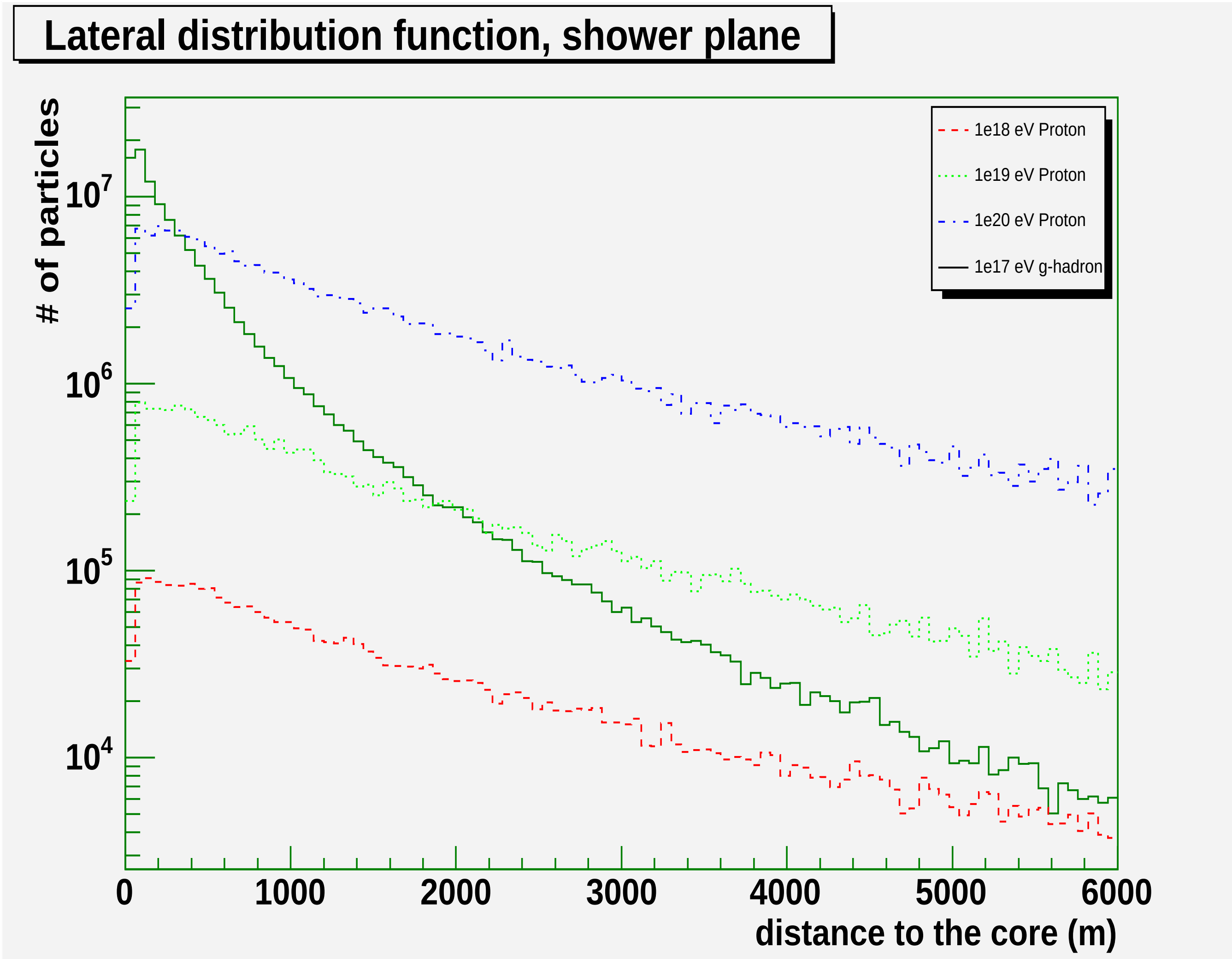
- bound from BBN: decaying $\tilde{g}$'s $\longrightarrow$ baryons which break apart ^{4}He $\longrightarrow$ excess D and Li Arvanitaki et al, hep-ph/0504210 $\longrightarrow M_{\text{SUSY}} < 10^{12}$ GeV

Properties of G air showers

- G's from astrophysical source, air shower in atmosphere. cp Hewett et al hep-ph/0408248: G's created in atmosphere, flux limited for $M_G > 200$ GeV
- inelasticity $\sim (1\ \mathrm{GeV}/M_G)$, minishowers, no distinct $X_{\max}$ J. Gonzalez et al, hep-ph/0504210, 0504260



Lateral Shower Profile



Flux requirement, neutrino association

- For one event/yr at PAO, require

$$\int_{E_{G,\,\mathrm{min}}}^{E_{G,\,\mathrm{max}}} J_G(E_G)\, dE_G \approx 1.4\times10^{-21}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

- Production at source associated with neutrino production via pion decay

$$\int J_\nu(E_\nu)\, dE_\nu = \frac{2}{3}\,\frac{\sigma_{\mathrm{inel}}}{\sigma_{pp\to G}(\hat{s}_{\mathrm{min}})}\,\frac{\langle N_\nu\rangle}{N_G}\int J_G(E_G)\, dE_G$$

- Expected neutrino flux

$$J_\nu(1.5\times10^{12}\ \mathrm{GeV}) \approx 4.4\times10^{-30}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

Comparison with limits and a lower bound on $M_{\rm SUSY}$

- **Within a factor of 2 of limits set by RICE, and extrapolated cascade bounds (related to diffuse photon background set by EGRET**
- **If a few events observed in 10 yrs, and expect $\sim 1\ \mathrm{yr}^{-1}$ on basis of high energy neutrinos observed, can set a lower limit on the lifetime of M_G**

$$\frac{E_G}{M_G}\tau_0 > H^{-1} \;\rightarrow\; \tau_0 \gtrsim 100\mathrm{yr}$$

$$\rightarrow \boxed{M_{\rm SUSY} > 6 \times 10^{10}\ \mathrm{GeV}}$$

Detecting ultra-high energy neutralinos

Barbot, Drees, Halzen, Hooper, PLB563:132,2003; Anchordoqui, HG, Nath, PRD70:025014,2004

- Detect air showers produced by high energy neutralinos emitted in long-lived relic X particle decay
- Underlying process is $\tilde{\chi} + q(\bar{q}) \longrightarrow \tilde{q}(\bar{\tilde{q}}) \longrightarrow$ all
- Weak interaction strength $\longrightarrow$ restrict events to large zenith angle to eliminate hadronic bkgd
- Elimination of neutrino bkgd to be described
- Require large acceptance ~ 2400 km^3 we akin to EUSO space-based fluorescence detector

State of EUSO

- EUSO at present is planned to dock on JAXA platform on the ISS
- Riken laboratory has agree to pay for increasing eff of photomultipliers
- Most significantly, JAXA has proposed to use their HTV launcher in place of NASA shuttle
- Mature project with high promises

EUSO collaboration, Nucl. Phys. Proc. Suppl. 151, 401 (2006)

Constraints on neutralino flux

- **Normalization:** X particle density + homogenous population of astrophysical sources fits UHE proton flux
- **EGRET bounds:** photons resulting from X decay conform with EGRET limits on GeV gamma ray flux
- **Dark matter:** X density consistent with negligible contribution to WMAP dark matter fraction

Eliminating the neutrino background

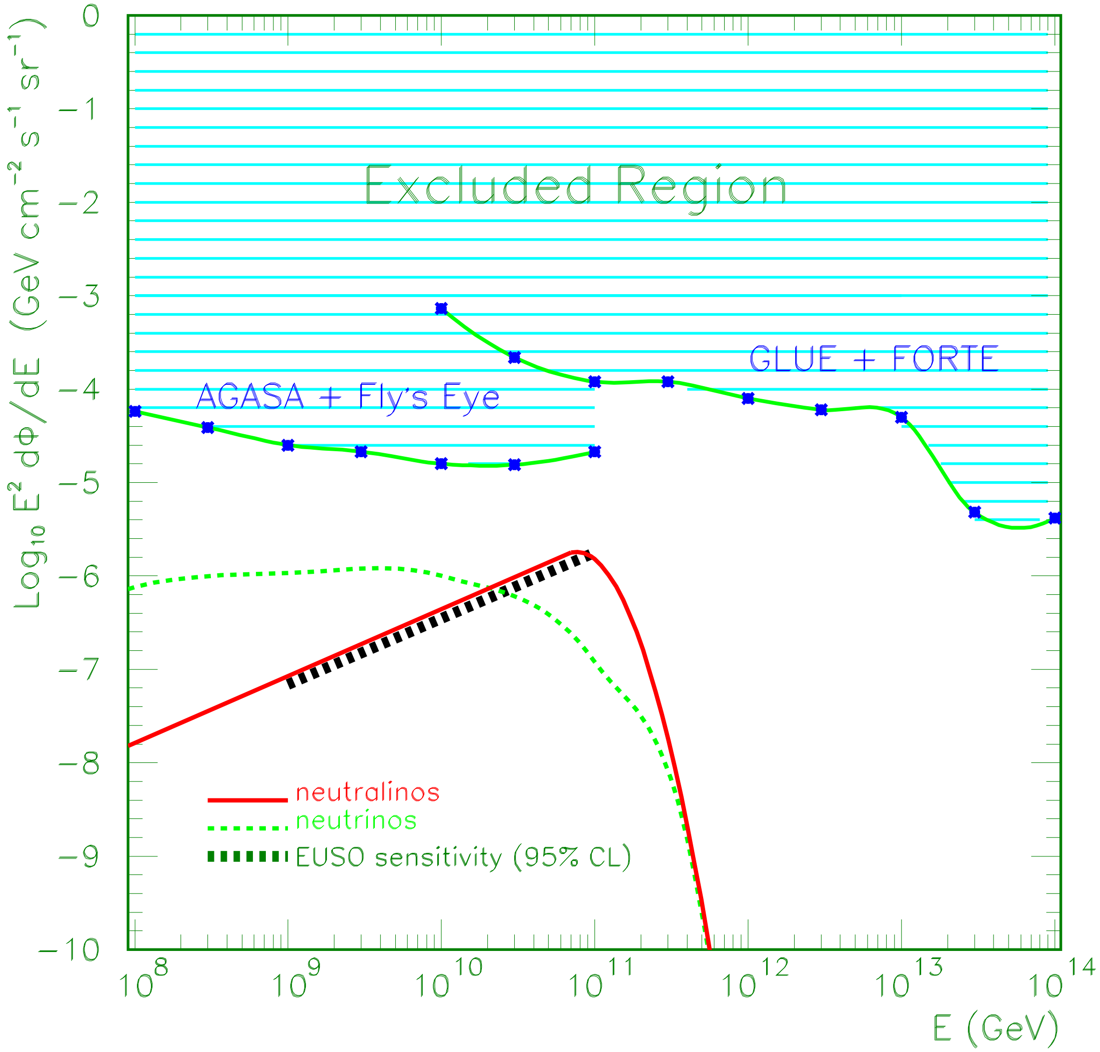
- **For a small range of squark masses, neutralino cross sections are**
  - **sufficiently smaller than neutrino cross sections so that restricting upcoming showers to pass through enough earth would screen out neutrinos**
  - **sufficiently large to give enough events in the atmosphere**
- **For bino-type neutralinos, $m_{\tilde{q}} \simeq 1$ TeV does the job**

Event rate at EUSO

$$\mathcal{N} = \int_{E_{\tilde{\chi}}^{\min}}^{E_{\tilde{\chi}}^{\max}} dE_{\tilde{\chi}} \; N_A \; P \; \frac{d\Phi}{dE_{\tilde{\chi}}} \sigma_{\tilde{\chi}N} \; A \; \epsilon_{\rm DC} \; t,$$

- Estimate neutrino bkgd is about 0.3 events in 3 years
- Require 3.09 neutralino events for significance at 95% CL
- For parameters given, find $\sim$ 4 or 5 events
- Results in figure to follow

EUSO sensitivity to neutralino flux



IceCube and anomalous neutrino interactions

Anchordoqui, Feng, HG, PRL 96:021101,2006

UHE hadronic cosmic rays $(E > 10^{10}\ \mathrm{GeV})$ expected to be accompanied by UHE neutrinos:

$$p + \gamma \rightarrow n + \pi^+, \quad \pi^+ \rightarrow e^+ \nu_e\, \nu_\mu\, \bar{\nu}_\mu$$

or

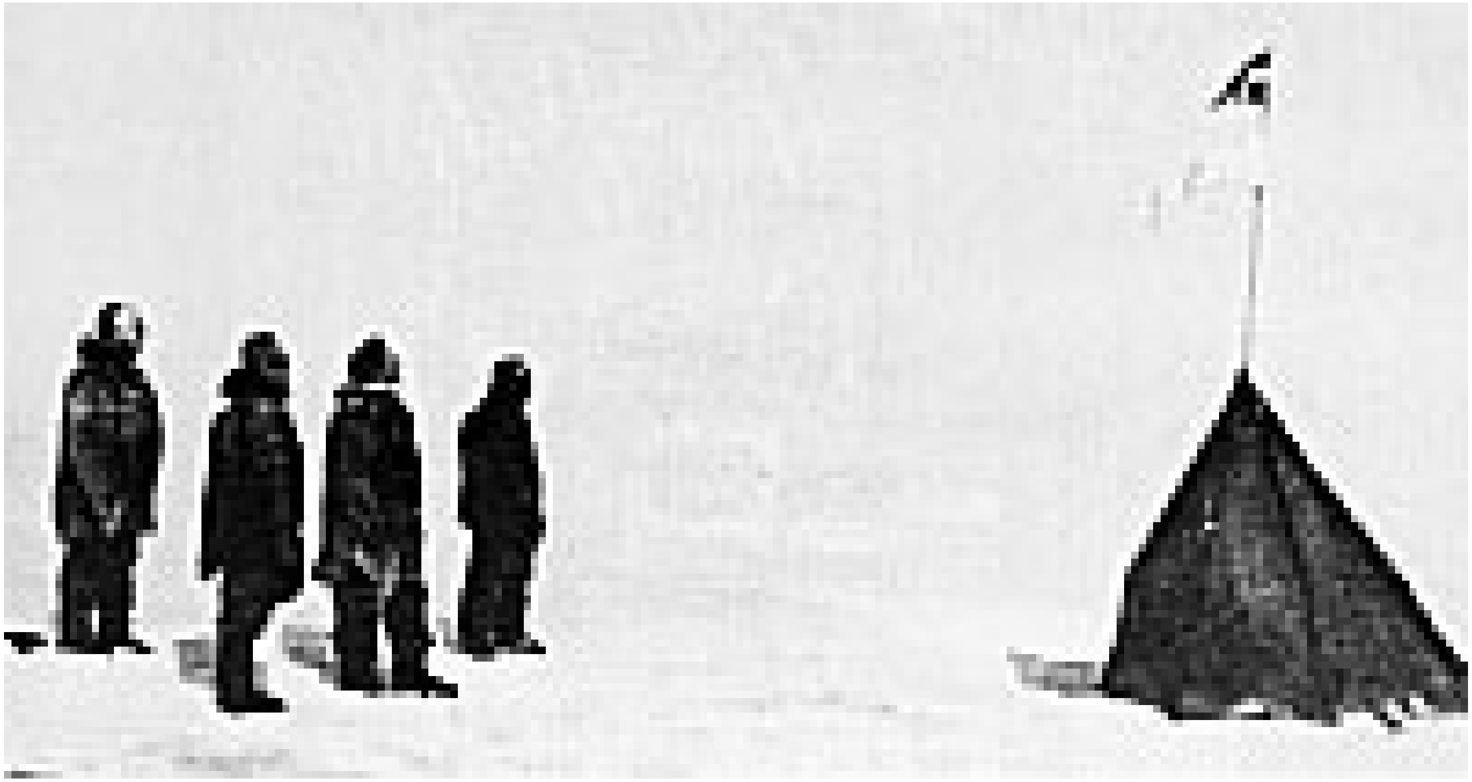
$$p + p \rightarrow \mathrm{nucleons} + \pi\text{'s}, \quad \pi^\pm \rightarrow e^\pm + \nu\ \text{'s}$$

- For optically thin source (neutrons escape), can relate Φ^ν to cosmic ray flux Waxman, Bahcall PRD 59 023002 (1999)
- Find (for pp)

$$E^2\ \Phi^\nu_{\mathrm{WB}} \simeq 2 \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

  for each flavor.
- Specialize to $10^7\ \mathrm{GeV} < E_\nu < 10^{7.5}\ \mathrm{GeV}$ – minimize atmospheric background, have sufficient flux

Neutrino astronomy 1911: early assessment of South Pole site



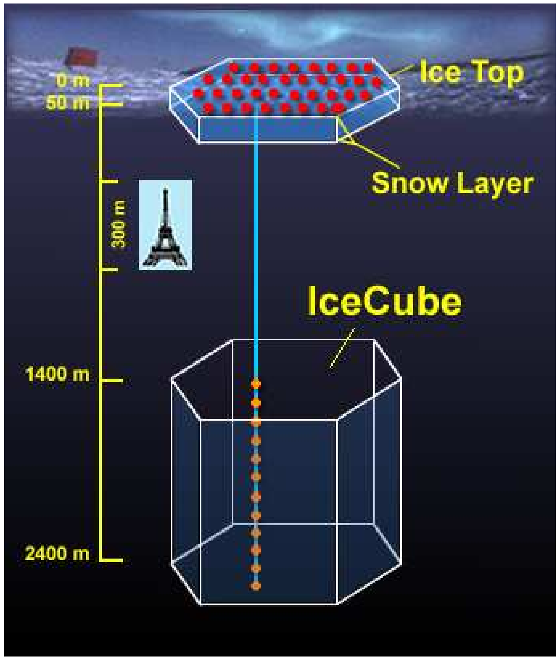
December 14th

$\Downarrow$

Expedition led by Roald Amundsen stood at the South Pole

☞ a month before Robert Scott

IceCube



Halzen, astro-ph/0311004

- **Effective Area ≈ 1 km^2**
- $E_{\rm th} \approx 100$ **GeV**
- **4800 PMT's on 80 strings**
- μ**–track angular resolution** $\Rightarrow 1^\circ \times 1^\circ$ **bin**
- **Calibration** $\Leftrightarrow$ **IceTop**
  ☞ **1 km^2 air-shower detector with 160 stations**

Tracks and Showers at AMANDA and IceCube

Tracks: Cosmic muons and CC interactions of ν_μ's

Angular resolution $1^\circ \times 1^\circ$

Showers: ν_e or ν_τ CC interactions

All NC interactions

Muon bremsstrahlung near detector

Angular resolution $10^\circ \times 10^\circ$

Up- and down-going events

Salient observation: event rates for these have different dependence on cross section

A. Kusenko, T. Weiler, PRL 88,161101 (2002)

- Down-going shower event rate can be enhanced because of a large flux or anomalously large $\sigma_{\nu N}$ or some combination of both
- Up-going rate also increases with increasing ϕ^{ν}; however, because of absorption on passage through earth, event rate decreases with increasing $\sigma_{\nu N}$
- Absorption effects will limit up-going events to those coming at just below the horizon – Earth-skimming events J. L.Feng et al, PRL 88,161102(2002)

Working equations: downgoing

$$\mathcal{N}_{\rm down} = C_{\rm down}\ \frac{\phi^\nu}{\phi^\nu_{\rm WB}}\ \frac{\sigma_{\nu N}}{\sigma_{\rm SM}}$$

- **Constant $C_{\rm down}$ depends on exposure, acceptance, and varies according to neutrino flavor from experiment to experiment**
- **$\phi^\nu_{\rm WB}$ and $\sigma_{\rm SM}$ serve only as normalization factors**
- **Specialize to electron showers, find**

$$\boxed{C_{\rm down} = 4 \text{ events}}$$

in 15 yrs

Working equations: up-going

In this case

$$\mathcal{N}_{\rm up} = C_{\rm up}\ \frac{\phi^\nu}{\phi^\nu_{\rm WB}}\ \frac{\sigma^2_{\rm SM}}{\sigma^2_{\nu N}} \qquad \left(\frac{\sigma_{\nu N}}{\sigma_{\rm SM}} > 1\right)$$

- This holds for $L^\ell \ll L^\nu < R_\oplus$, corresponding to $E > 10^7$ GeV
- $\sigma_{\nu N}$ is defined with cuts so that shower energy fraction of same order as that of the CC SM process.
- Specialize to tau showers (distinctive topologies), find for 15 yr

$$\boxed{C_{\rm up} = 20 \text{ events}}$$

J.J Tseng et al ; J.Jones et al; S.I.Dutta et al

IceCube sensitivity

With estimates of $C_{\rm down}$ and $C_{\rm up}$, can determine sensitivities of IceCube to ϕ^{ν} and $\sigma_{\nu N}$

- For a given set of observed rates $\mathcal{N}_{\rm up}^{\rm obs}$ and $\mathcal{N}_{\rm down}^{\rm obs}$, two curves obtained in 2-D parameter space by setting $\mathcal{N}_{\rm up}^{\rm obs} = \mathcal{N}_{\rm up}$ and $\mathcal{N}_{\rm down}^{\rm obs} = \mathcal{N}_{\rm down}$
- Curves intersect at a point, yielding the most probable values of ϕ^{ν} and $\sigma_{\nu N}$for the given observations

Approximate likelihood analysis

- Fluctuations about this point define contours of constant χ^2 in an approximation to a multi-Poisson likelihood analysis

$$\chi^2 = \sum_i^{\text{down, up}} 2\left[\mathcal{N}^i - \mathcal{N}^i_{\text{obs}} + \mathcal{N}^i_{\text{obs}} \ln\left(\frac{\mathcal{N}^i_{\text{obs}}}{\mathcal{N}^i}\right)\right]$$

S. Baker and R. D. Cousins, Nucl. Instrum. Meth. A221,437(1984)

- Two illustrative cases:

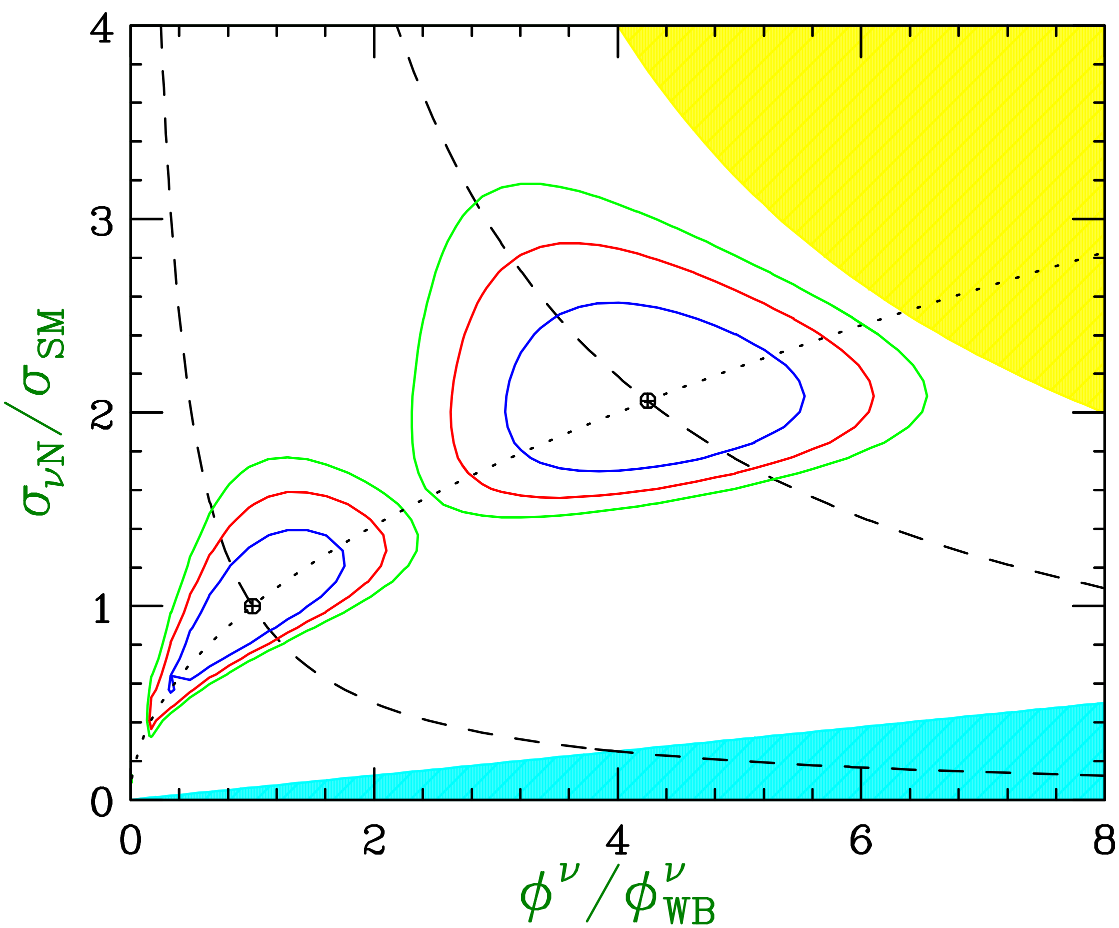
$$(\mathcal{N}^{\text{obs}}_{\text{down}},\ \mathcal{N}^{\text{obs}}_{\text{up}}) = (4, 20),$$

conforming to SM/WB expectations

$$(\mathcal{N}^{\text{obs}}_{\text{down}},\ \mathcal{N}^{\text{obs}}_{\text{up}}) = (35, 20),$$

indicating deviation from σ_{SM} and/or ϕ^{ν}_{WB}

Results



90%, 99% and 99.9% CL contours for two cases in previous slide. Lower are deviation bounds, upper signal 5σ new physics discovery (for any flux).

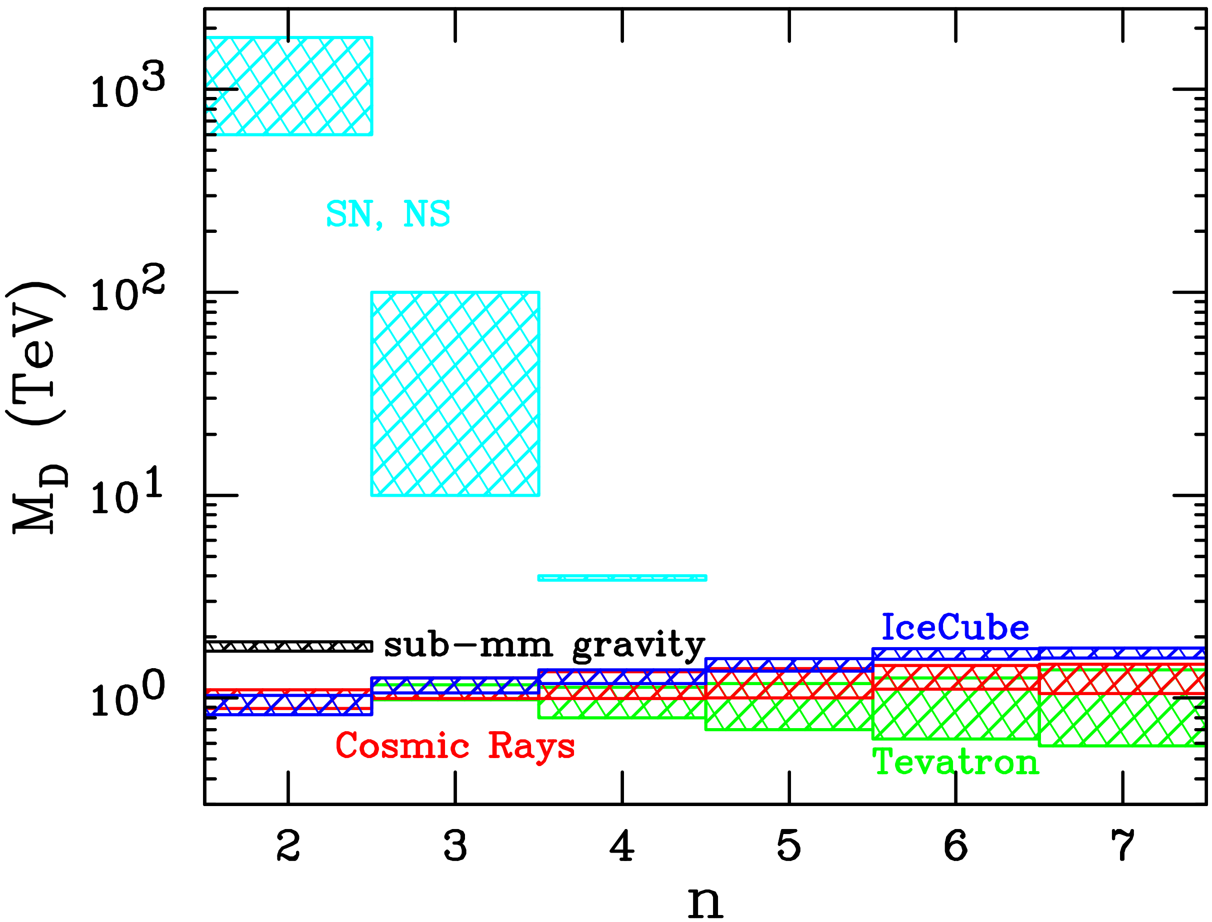
Souces of anomalies

- **multi-KK graviton exchange in non-warped TeV scale gravity models** Emparan, Masip, Rattazzi
- **BH production in these models** Feng and Shapere; Anchordoqui et al; Ahn, Cavaglia, Olinto
- **cross section enhancements due to electroweak instantons** Ahlers, Ringwald, Tu

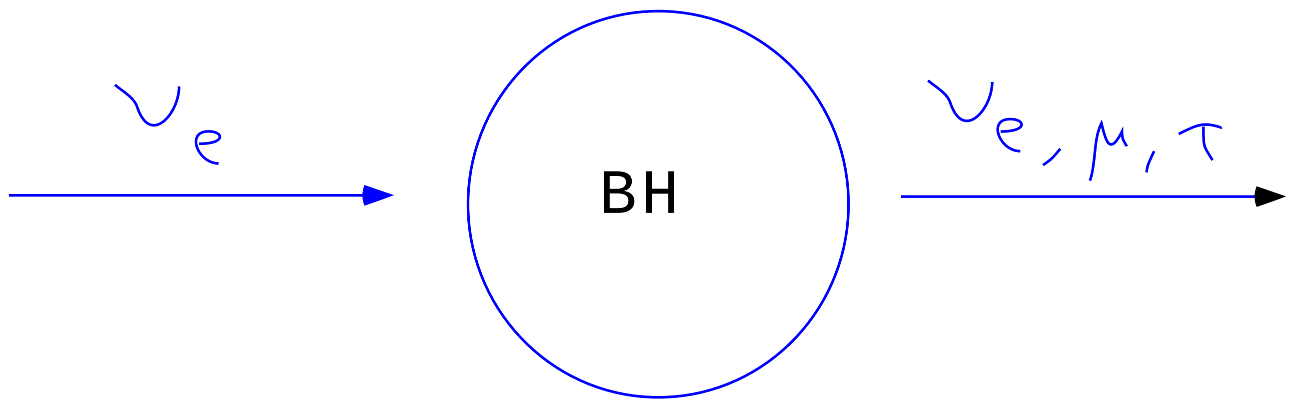
All of these are shower producing

Example of sensitivity; Large extra dimensional BH

If $\mathcal{N}_{\rm up}^{\rm obs} = C_{\rm up}$ and $\mathcal{N}_{\rm down}^{\rm obs} = C_{\rm down}$, can bound BH cross section and thus scale of TeV gravity M_D



Quantum Decoherence via neutrinos



Density matrix description

$$\rho^{\alpha}(t) \;=\; |\nu_{\alpha}(t)\rangle\langle\nu_{\alpha}(t)|$$
$$P_{\nu_{\alpha}\rightarrow\nu_{\beta}} \;=\; \mathrm{Tr}\left[\rho_{\alpha}(t)\rho_{\beta}\right]$$

Evolve $\rho^{\alpha}(t)$ using modified Liouville equation

$$\frac{\partial\rho}{\partial t} = -i[H,\,\rho] + \mathcal{D}[\rho]$$

Quantum Decoherence (cont'd)

$$\mathcal{D}[\rho] = -\frac{1}{2}\sum_j \left([b_j,\ \rho\, b_j^\dagger] + [b_j\, \rho,\ b_j^\dagger]\right)$$

- This conserves total probability Tr(ρ)
- Can be obtained as interaction with heat bath via $a^\dagger b + b^\dagger a$
- Monotonic increase of von Neumann entropy $S = -\mathrm{Tr}(\rho \ln \rho) \to b$ hermitian
- Expand in Gell-Mann matrices, $\gamma_i = \mathrm{eigenvalues\, of}\, b^\dagger b$
- Dealing with distant sources $\longrightarrow$ only γ_3, γ_8 survive oscillation, take $\gamma_3 = \gamma_8$

Working formula

$$P_{\overline{\nu}_\alpha\to\overline{\nu}_\beta} = \frac{1}{3} + \mathrm{e}^{-\overline{\gamma}\,d}\left[\frac{1}{2}\,(U_{\alpha 1}^2 - U_{\alpha 2}^2)(U_{\beta 1}^2 - U_{\beta 2}^2) + \frac{1}{6}\,(U_{\alpha 1}^2 + U_{\alpha 2}^2 - 2U_{\alpha 3}^2)(U_{\beta 1} + U_{\beta 2}^2 - 2U_{\beta 3}^2)\right]$$

Expect γ to be energy dependent

$$\overline{\gamma} = \kappa_n\ (E_\nu/\mathrm{GeV})^n, \quad n = -1, 0, 1, 2\ldots$$
$$= (E_\nu/M_{\mathrm{QG}})^{n-1}\, E_\nu$$

- $n = -1$ is analogue of oscillation,$n = 0$ like decay
- $n \geq 2$ involves large scale M_{QG}

Limits on γ

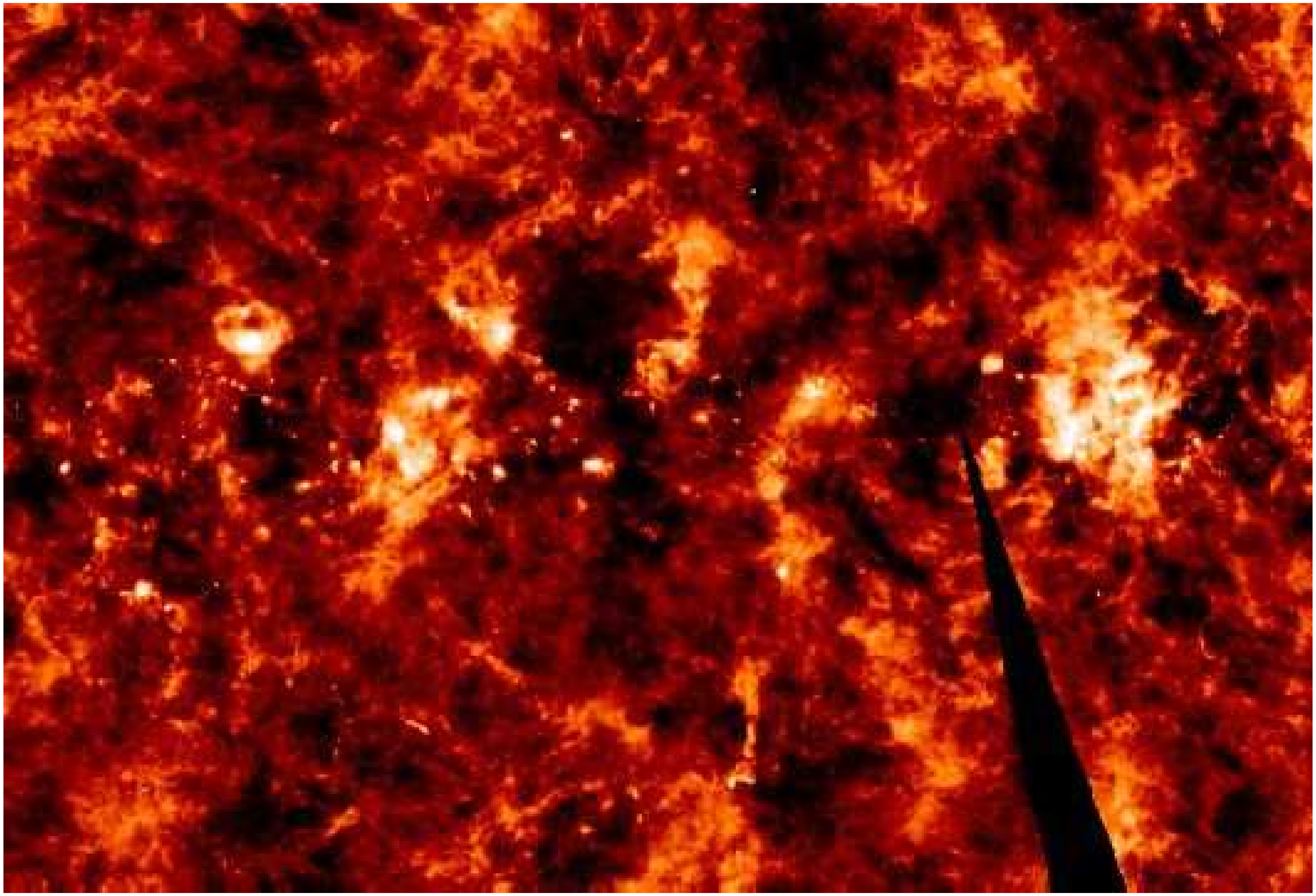
E. Lisi, A. Marrone, D. Montanino, hep-ph/0002053

- use atmospheric neutrinos ν_μ at SK and K2K
- can probe decoherence length γ^{-1} of order the oscillation length $\sim 10^3$ km to obtain limits see later
- can obtain much stronger limits if there is source of neutrinos at large distance ($\gtrsim \mathrm{kpc}$) with observed flavor mix $\neq 1:1:1$
- In what follows, IceCube is used as neutrino detection facility

Example: Neutrinos from Neutrons from Cygnus OB2

- In PRD72:065019,2005 Anchordoqui, Gonzalez-Garcia, HG, Halzen, Hooper, Sarkar, Weiler use reported (at the time) anisotropy from direction of Cygnus OB2 region ($d \approx 1.7$ kpc)
- Anisotropy identified as neutrons from photodisintegration of Fe
- $\overline{\nu}_e$'s from neutron decay evolve to $\overline{\nu}_e : \overline{\nu}_\mu : \overline{\nu}_\tau = 2.5 : 1 : 1$ after large distance – definitely not 1:1:1
- $\overline{\nu}$ fluxes fixed by n flux fixed by anisotropy

Cygnus OB2



Limits on γ

- Obtain number of tracks and showers expected from atmospheric background
- Introduce an additional background of tracks and showers due to possible 1:1:1 source of neutrinos from nearby HEGRA γ ray source
- Calculate theoretically expected number of tracks and showers as a function of the decoherence parameter $\overline{\kappa}_n$ and the HEGRA background
- Marginalize on HEGRA background to obtain bounds on $\overline{\kappa}_n$ for a given observed number of tracks and showers

Results for $\mathcal{N}_{\rm obs} = \mathcal{N}_{\rm ATM}$

Table 1: 90% CL limits on decoherence

	Cygnus OB2		SK & K2K	
n	$\kappa_{\rm max}$ (GeV)	$M_{\rm QG}^{\rm min}$ (GeV)	$\kappa_{\rm max}$ (GeV)	$M_{\rm QG}^{\rm min}$ (GeV)
-1	1.0×10^{-34}	–	2.0×10^{-21}	–
0	3.2×10^{-36}	–	3.5×10^{-23}	–
2	2.0×10^{-44}	5.0×10^{43}	9.0×10^{-28}	1.1×10^{27}
3	3.0×10^{-47}	1.8×10^{23}	–	3.3×10^{13} *

* **Obtained from limit on γ, with $\langle E_\nu \rangle \approx 100$ GeV**

Conclusion

For a wide variety of fundamental questions in particle physics

- Split Supersymmetry
- long-lived superheavy relics
- anomalous neutrino interactions at very high energies
- quantum decoherence

the new generation of detectors (Auger, IceCube, EUSO) can provide important constraints on the new physics, if not discovery.