ULTRAHIGH-ENERGY COSMIC RAYS

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PHENO SYMPOSIUM
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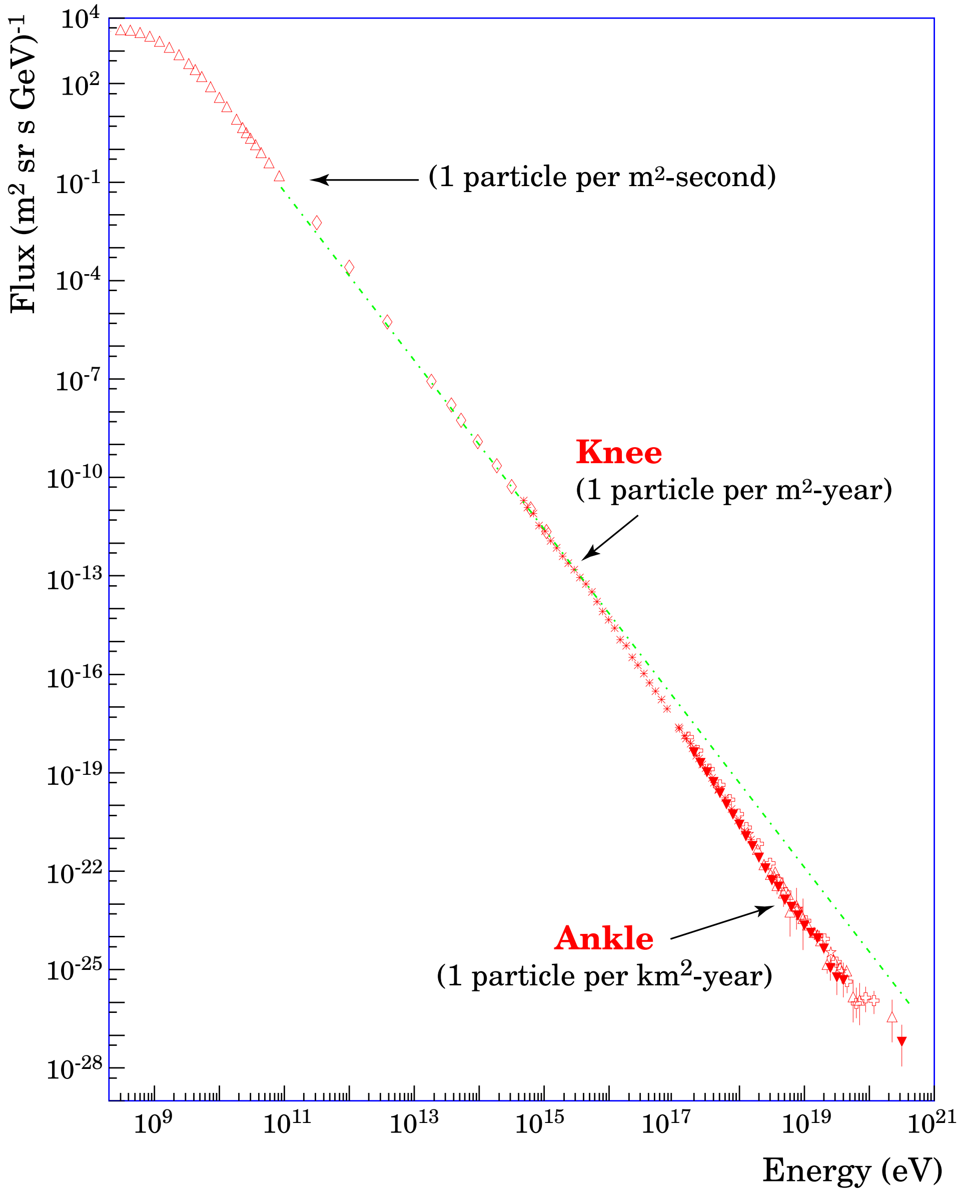
The Cosmic Ray Spectrum



Kampert, Swordy (2001)

THE UHE END

Selected Topics:

I. The GZK Paradox

II. The Dawn of UHE ν Astrophysics

III. The Potential for Fundamental Breakthroughs at the Energy Frontier

Experiments

Ground arrays
AGASA, Auger

Fluorescence Detectors (Ground-based)
HiRes, Auger, Telescope Array

Fluorescence Detectors (Space-based)
EUSO, OWL

Neutrino Telescopes (Under-ice)
AMANDA, IceCube

Neutrino Telescopes (Underwater)
ANTARES, NESTOR, NEMO

Radio/Cherenkov
GLUE, RICE, ANITA, SALSA, nuTel

Acoustic
SADCO

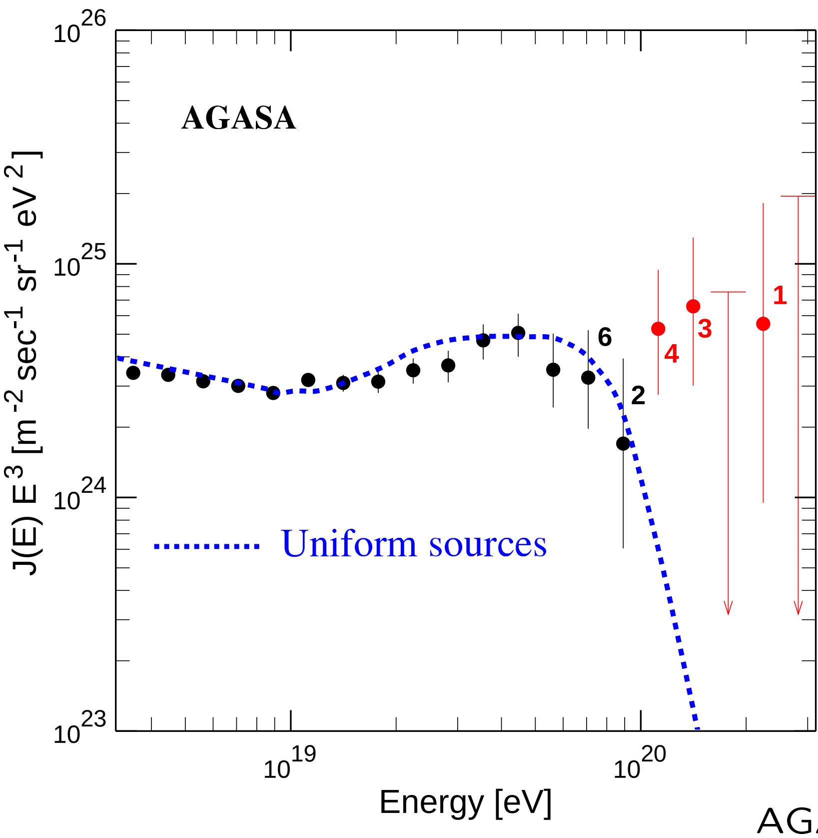
GZK PARADOX

Greisen (1966)
Zatsepin-Kuz'min (1966)

Extreme energy protons lose energy through

$$p\gamma_{\text{CMB}} \rightarrow \Delta^{+} \rightarrow N\pi$$

No local sources $\Rightarrow E_{\text{cutoff}} \sim 10^{20}$ eV



AGASA (1998)

(Similar cutoffs for other known stable particles.)

But also compare with fluorescence results:

AGASA and HiRes:

- Disagree on flux
- Agree that there is no clear GZK cutoff

Prospects for Resolution

Pierre Auger Observatory (2004)

Hybrid detector:

- 3000 km^2 ground array
- 4 fluorescence detectors

should see ~ 1000 events with $E \gtrsim 10^{19.5}$ eV

Energy resolution: $\sim 10\%$

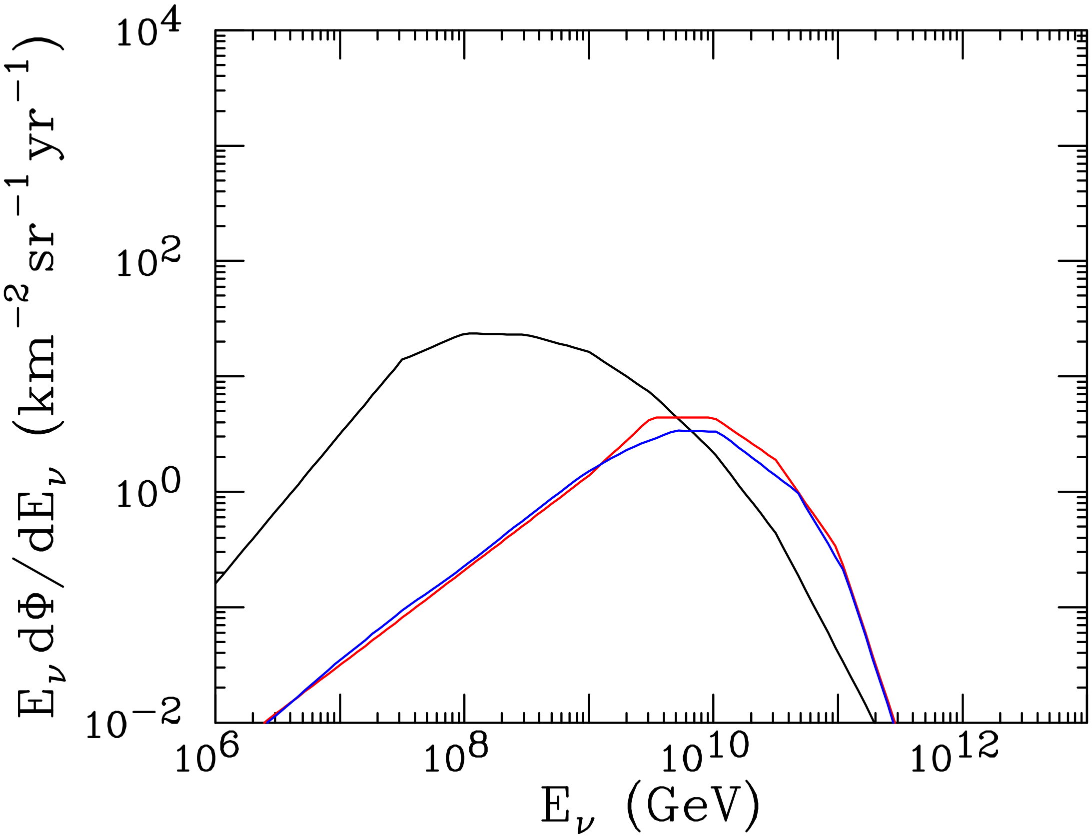
Angular resolution: $\sim 1^\circ$

Will probe GZK feature, clustering, chemical composition, . . .

UHE NEUTRINOS

So far, no evidence for UHE neutrinos. However, GZK is a 'guaranteed' source:

$$p\gamma_{\mathrm{CMB}} \to n\pi^+ \to pe^-\bar{\nu}_e + e^+\nu_e\bar{\nu}_\mu + \nu_\mu$$



Stecker (1979)
Hill, Schramm (1985)
Protheroe, Johnson (1996)
Engel, Seckel, Stanev (2001)

GZK Resolutions

Bottom-up

E.g., Z bursts

$$\nu + \nu_{\text{CNB}} \to Z \to \text{ hadrons}$$

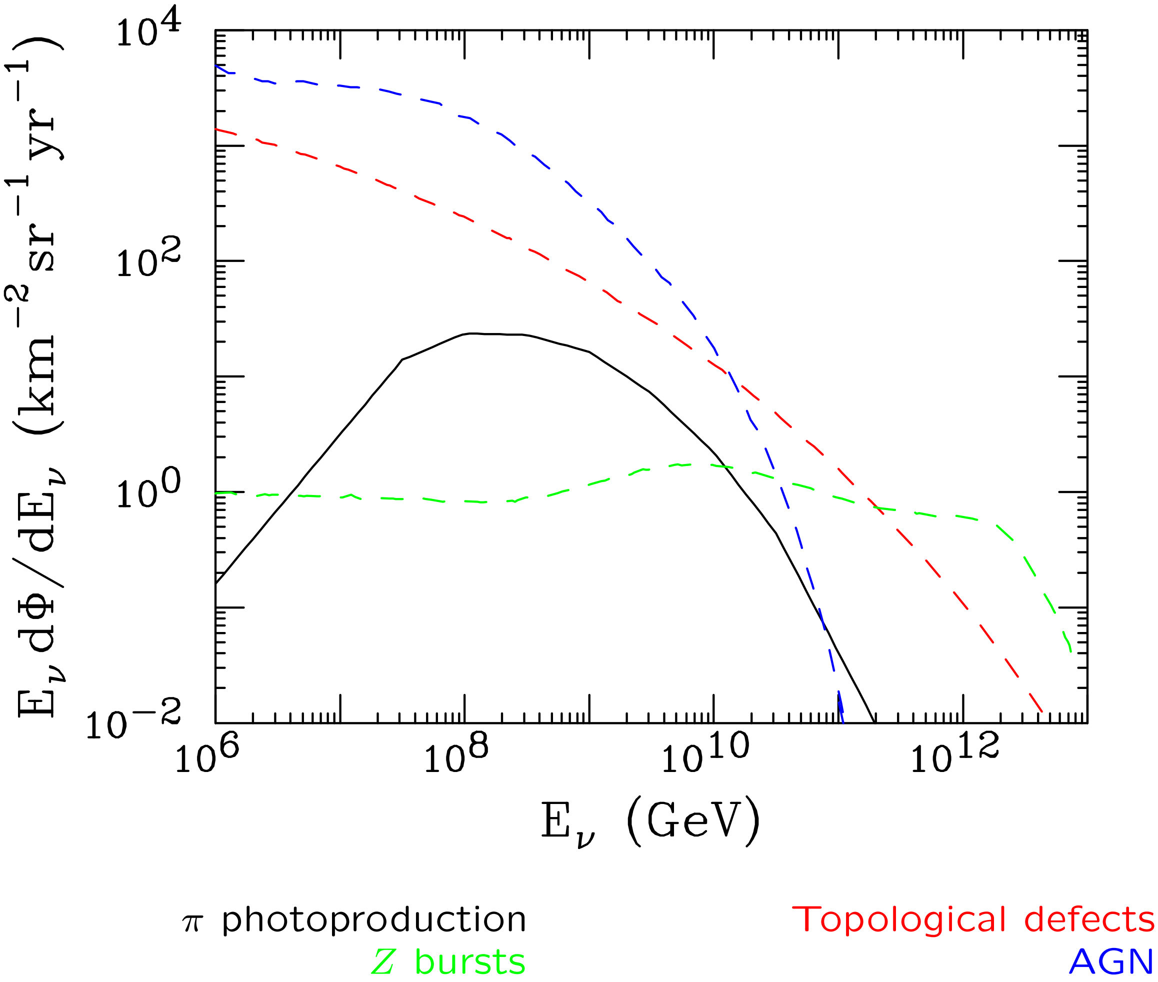
Weiler
Fargion

Top-down

E.g., topological defect decay

$$\text{TD} \to \text{ hadrons (+ neutrinos, typically)}$$

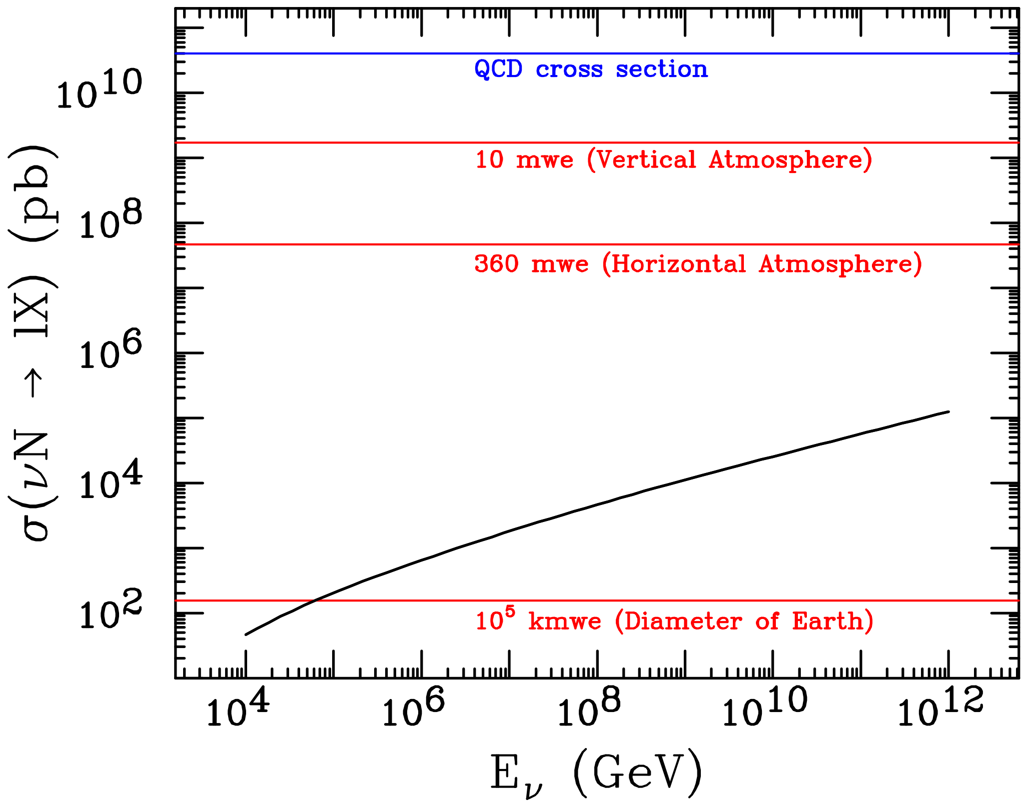
The GZK paradox motivates many new ν possibilities.



$E_\nu d\Phi/dE_\nu$ (km^{-2}sr^{-1}yr^{-1})
10^4
10^2
10^0
10^{-2}
10^6
10^8
10^{10}
10^{12}
E_ν (GeV)
π photoproduction
Z bursts
Topological defects
AGN

Detection

SM charged-current cross section:



For $E_\nu \gtrsim 10^8$ GeV:

- No upgoing νs
- Quasi-horizontal atmospheric showers
  $\sim 0.1 - 1$ event/year at Auger

Capelle, Cronin, Parente, Zas (1998)
Diaz, Shellard, Amaral (2001)

Another possibility

Exploit Earth as large volume converter:

$\nu \to \ell$ in the Earth, ℓ detected in the Earth.

$\pi \to \nu_\ell \Rightarrow$ two possibilities:

$\ell = \mu$: standard "up-going" ν signal. Detection in neutrino telescopes (AMANDA, IceCube, ANTARES, etc.)

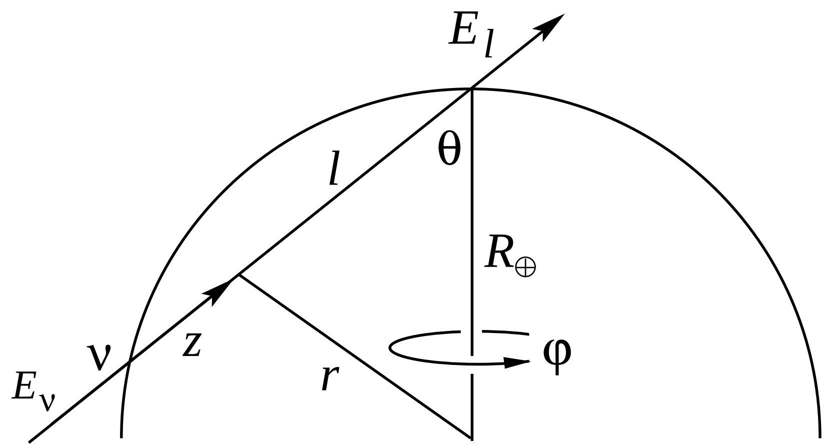
$\ell = e$: Cascades generate radio waves through the Askaryan effect. Detection for νs passing through Earth and moon.

Zas, Halzen, Stanev (1991)
Gorham, Saltzberg *et al.* (2001)

Earth-skimming neutrinos

After 1998: $\ell = \tau$ is equally likely.

Athar (2000)



$\nu \to \ell$ in the Earth, ℓ escapes, is detected in Earth's atmosphere.

Bjorken
Fargion
Domokos, Kovesi-Domokos
Bertou, Billoir, Deligny, Lachaud, Letessier-Selvon (2001)
Feng, Fisher, Wilczek, Yu (2001)
Kusenko, Weiler (2001)

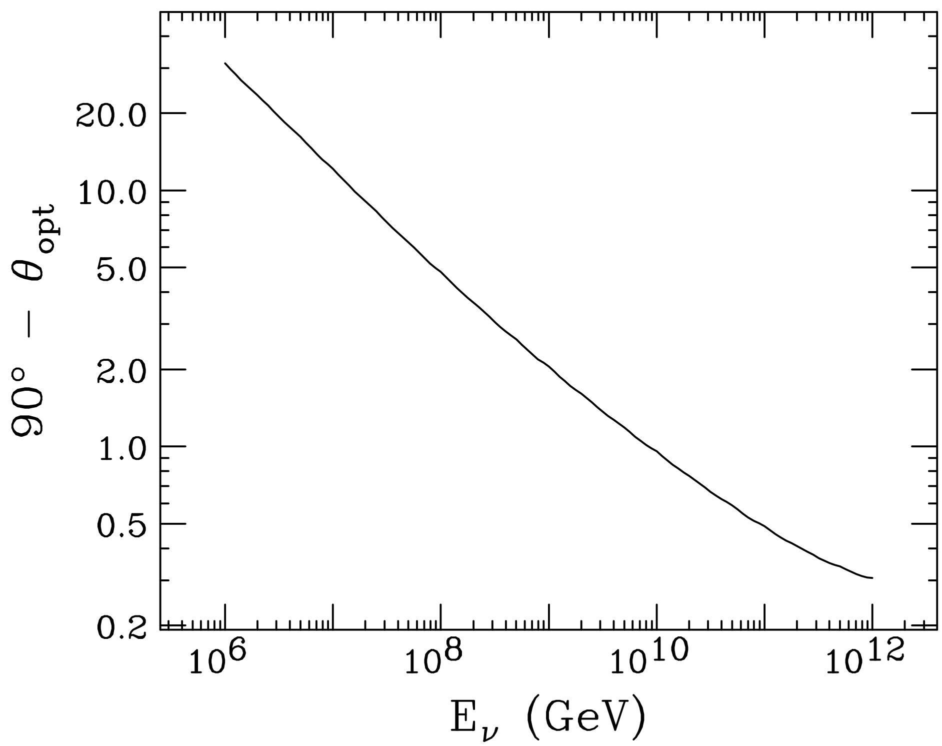
Exploits

- Earth as large volume converter
- Atmosphere as large volume detector
- τ lifetime $\Rightarrow \tau$ travels ~ 10 km, just right!

Optimal angle

$$\theta_{\text{opt}} \quad : \quad \int_0^{2R_\oplus \cos\theta_{\text{opt}}} \frac{dz'}{L^{\nu}_{CC}(E_\nu, \theta_{\text{opt}}, z')} \equiv 1$$

$\theta < \theta_{\text{opt}}$: ν shadowed
$\theta > \theta_{\text{opt}}$: ν rarely converts



Neutrinos must be within $\sim 1^\circ$ of horizontal.

Decay length is

$$\lambda_\tau = c\tau_\tau \frac{E_\tau}{m_\tau} \approx 49 \text{ km } \frac{E_\tau}{10^9 \text{ GeV}}$$

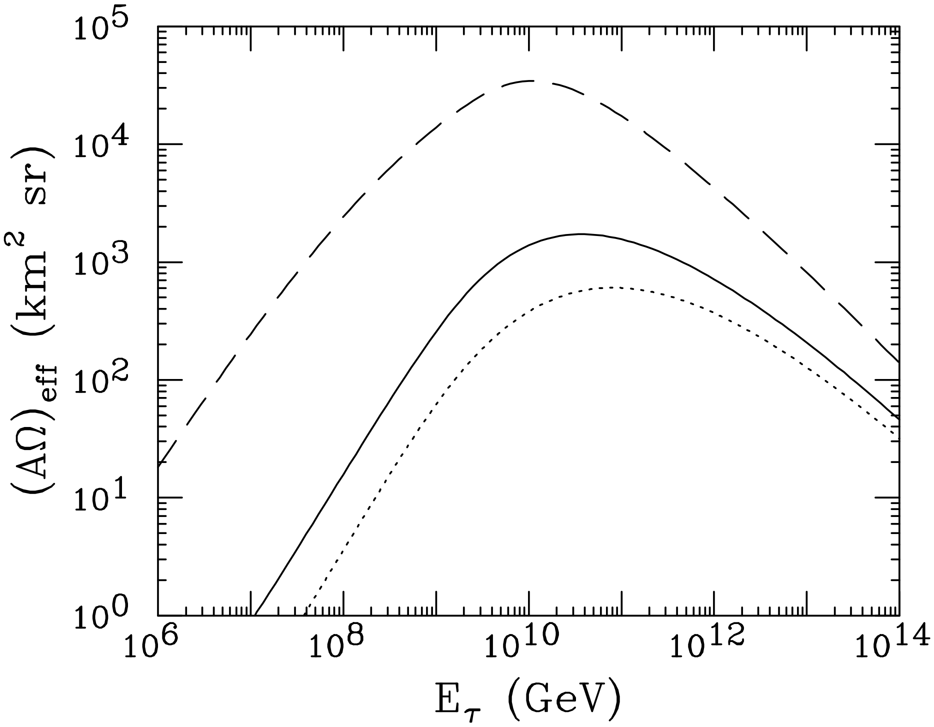
Taus lose energy through bremsstrahlung, pair production, photonuclear interactions.

$E_\tau \rightarrow 0.1 E_\tau$ in 11 km.

Dutta, Reno, Sarcevic, Seckel (2000)

So taus travel $\sim$ 10 km in Earth, but decay not far from surface.

Apertures



Effective apertures at Fly's Eye (dotted), HiRes (solid), and Telescope Array (dashed).

Apertures rise with energy until time dilation causes decay to be too high for detection (curvature of Earth).

Aperture and flux peaks coincide.

Result: $\mathcal{O}(1)$ event/year at Auger for 'guaranteed' flux.

ENERGY FRONTIER

Nature's collider:

- $\sqrt{s} = \sqrt{2m_N E} \gtrsim 100$ TeV*

- Construction cost: \$0

- Operating budget: \$0/yr

Ultrahigh-energy cosmic rays are the energy frontier.

* For luminosity, see above.

At 100 TeV, many possibilities for new physics.

E.g., extra dimensions and low-scale gravity $\Rightarrow$ cross sections modified by graviton effects.

Nussinov, Shrock (1998)
Jain, McKay, Panda, Ralston (2000)
Tyler, Olinto, Sigl (2000)
Alvarez-Muniz, Halzen, Han, Hooper (2001)
$\vdots$

Perturbative analyses are valid for energies below M_D, the fundamental Planck scale.

Black Holes

Strong gravity $\Rightarrow$ black hole formation.

Non-perturbative: semi-classical and thermodynamic description valid for $M_{\text{BH}} \gtrsim M_D$.

In 4 dimensions,

- $M_4 \simeq 10^{19}$ GeV
- BHs confined to astrophysics

In (4+n) dimensions,

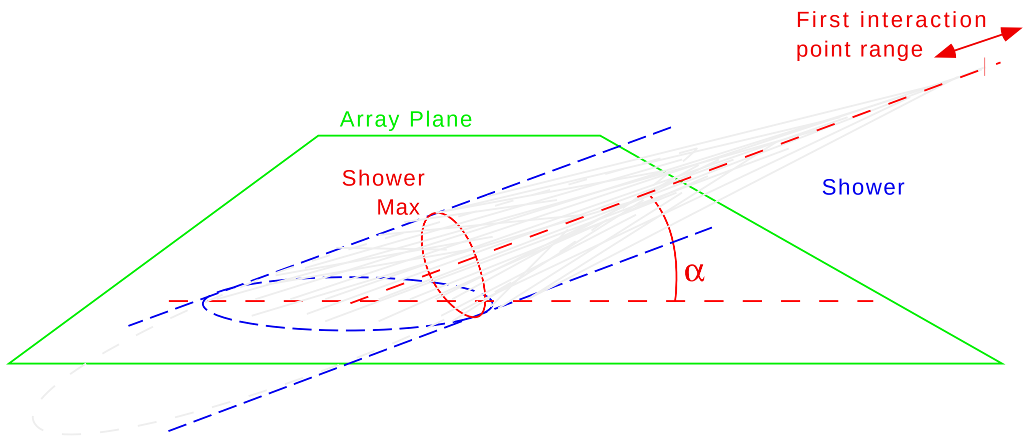
- $M_D \sim$ TeV
- BHs $\rightarrow$ experimental particle physics

(LHC: $\sqrt{s} = 14$ TeV)

Thomas, Giddings (2001)
Dimopoulos, Landsberg (2001)

Cosmic Rays: $E \gtrsim 10^{19}$ eV $\Rightarrow \sqrt{s} \gtrsim 100$ TeV

BHs $\rightarrow$ particle astrophysics



No black holes seen $\Rightarrow$ stringent bounds

$M_D \approx 1$ TeV $\Rightarrow$

- 100s of BHs before LHC turns on
- 1st evidence for extra dimensions
- exp. study of Hawking evaporation

⋮

Feng, Shapere (2001)
Anchordoqui, Goldberg (2001)
Emparan, Masip, Rattazzi (2001)

BHs in extra dimensions

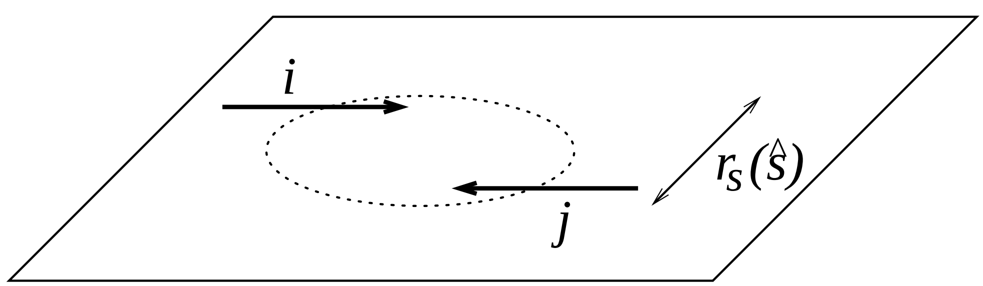
For a Schwarzschild BH ($Q = J = 0$),

$$r_s(M_{\mathrm{BH}}^2) = \frac{1}{M_D}\left[\frac{M_{\mathrm{BH}}}{M_D}\right]^{\frac{1}{1+n}}\left[\frac{2^n\pi^{\frac{n-3}{2}}\Gamma\left(\frac{3+n}{2}\right)}{2+n}\right]^{\frac{1}{1+n}}$$

Myers, Perry (1986)

In classical GR, expect a BH to form when two partons pass within $r_s(\hat{s})$ of each other:

$$\hat{\sigma}(ij \to \mathrm{BH})(\hat{s}) \approx \pi r_s^2(\hat{s})$$



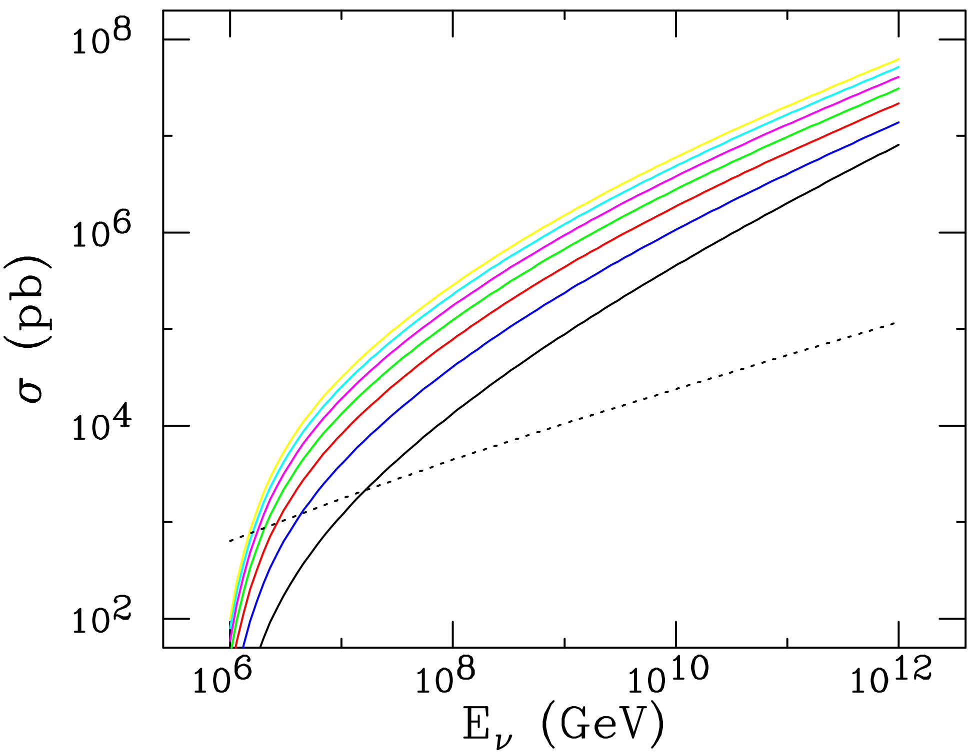
Banks, Fischler (1999)
Voloshin (2001)

Numerical evidence from 4D axisymmetric collisions: $M_{\mathrm{BH}} \approx 0.8\sqrt{\hat{s}}$.

D'Eath, Payne (1992)

Cosmic Neutrinos

$$\sigma(\nu N \to \text{BH}) = \sum_i \int_{(M_{\text{BH}}^{\text{min}})^2/s}^{1} dx\, \hat{\sigma}_i(xs)\, f_i(x,Q)$$



For $M_D = M_{\text{BH}}^{\text{min}} = 1$ TeV and $n = 1, \ldots, 7$ from below.

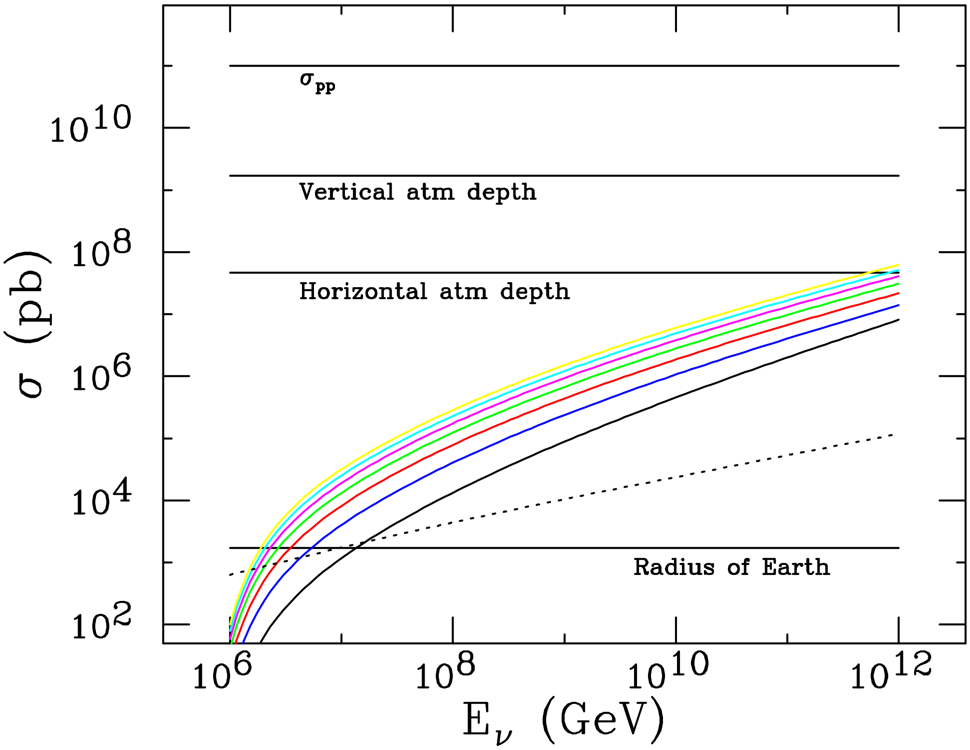
Feng, Shapere (2001)

σ large:

- Sum over partons, including gluon
- No small couplings
- $\sigma \sim E_\nu^{0.45}$ grows rapidly

Relatively insensitive to $M_{\text{BH}}^{\text{min}}$ (see below).

Length scales



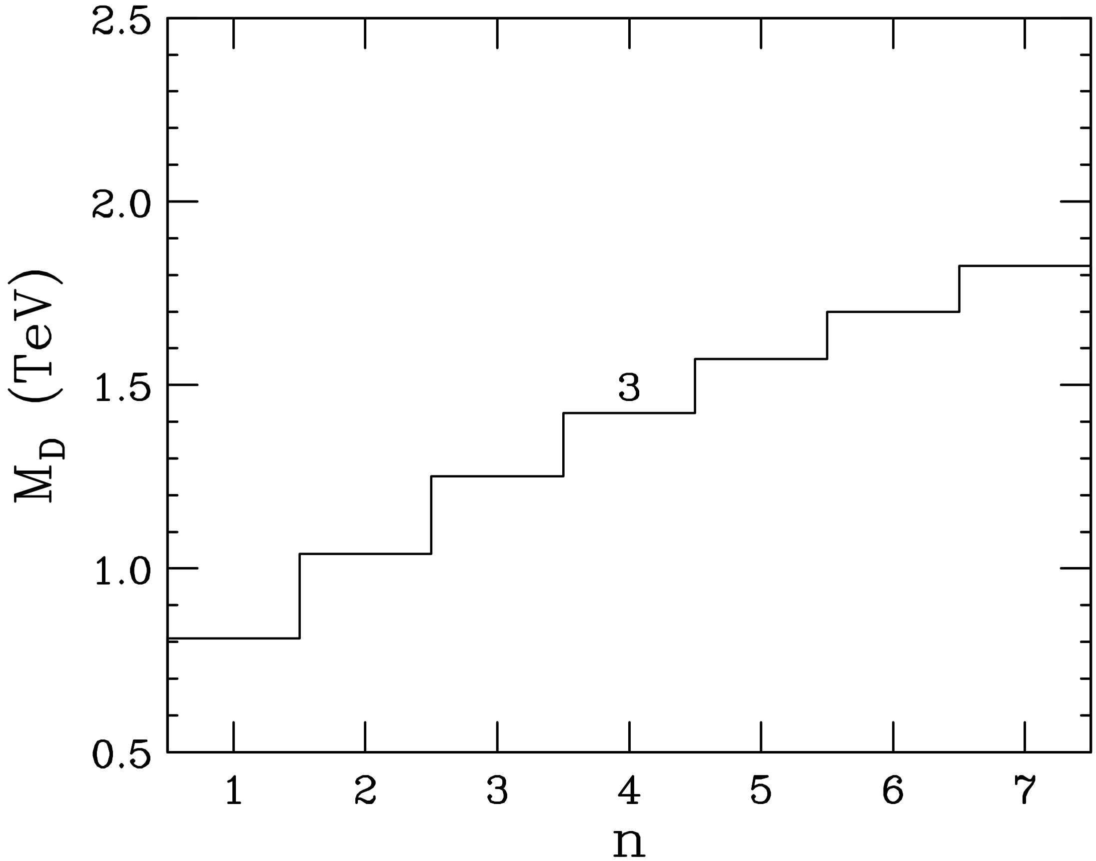
Vertical atm. depth: 10 mwe
Horizontal atm. depth: 360 mwe

- $pN \to$ BH: Hopeless

- $\nu N \to$ BH: uniform at all atm. depths

Best signal is quasi-horizontal, deep showers: maximizes signal, uses atmosphere to remove proton, nucleus background.

Current Bounds

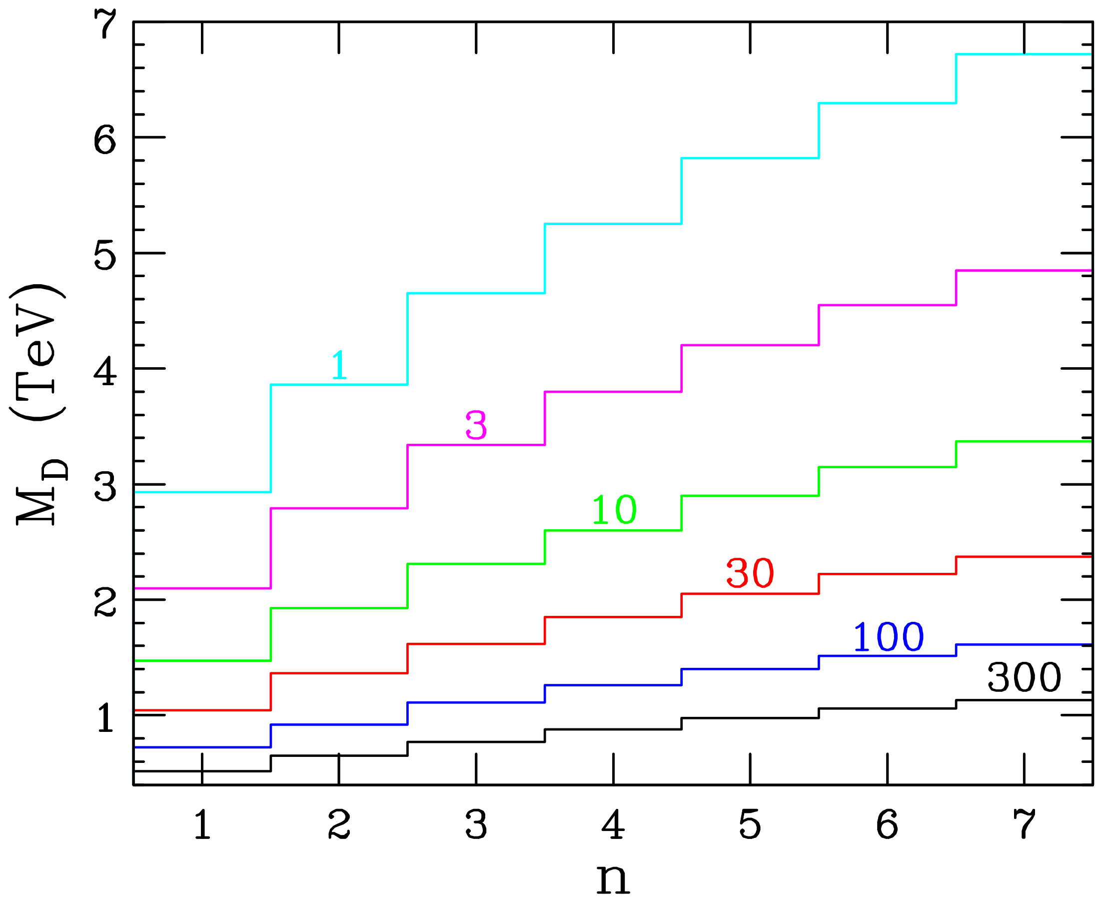


Number of black holes expected at the AGASA ground array to date. $M_{\text{BH}}^{\text{min}} = M_D$.

Anchordoqui, Feng, Goldberg, Shapere (2001)

No events seen $\Rightarrow$ for $n \geq 4$, $M_D \gtrsim$ 1.4$-$1.8 TeV, most stringent bounds to date.

Future Prospects

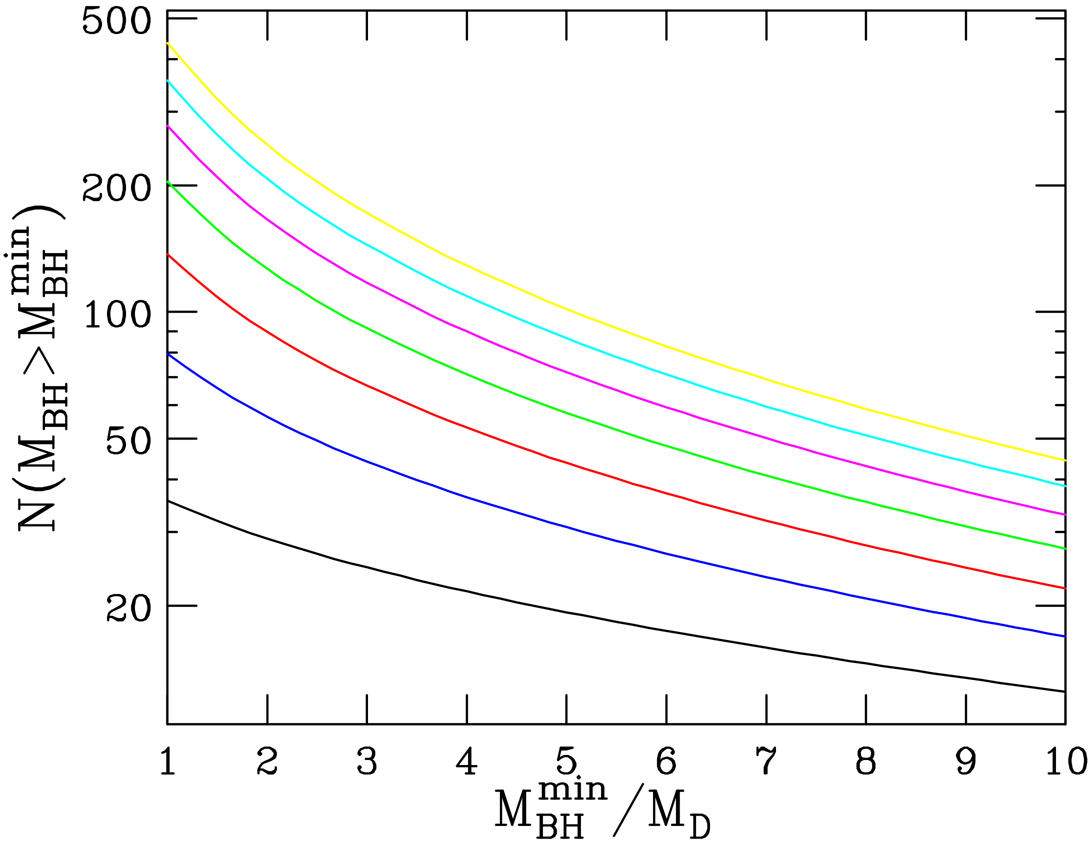


Number of black holes expected at the ground array in 5 Auger site-years. $M_{\rm BH}^{\rm min} = M_D$.

$M_D = 1$ TeV $\Rightarrow$ 30 − 300 BH events.

If no events seen, $M_D \gtrsim 5$ TeV for large n.

$M_{\rm BH}^{\rm min}$ Dependence



For $M_{\rm BH}^{\rm min} = 5M_D$, event rates are reduced by factors of 2 for $n = 1$ and 4 for large n.

BH vs. SM

BH rates may be 1000 times SM rate. But

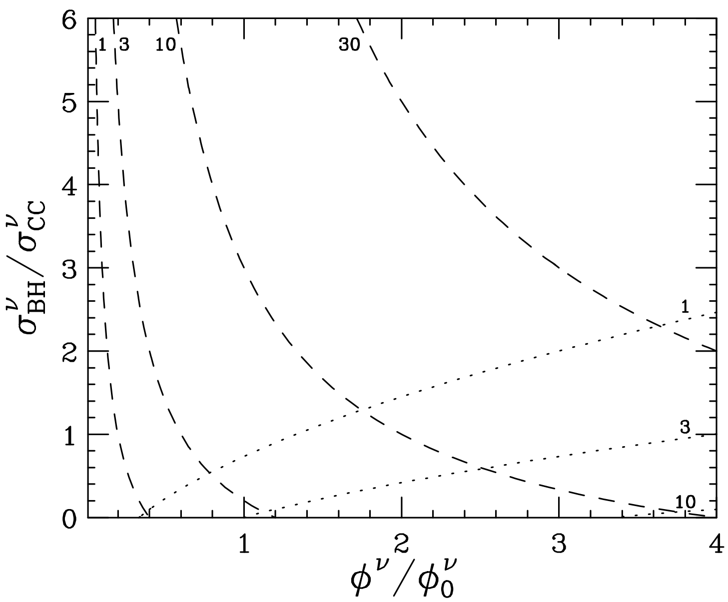
- large BH $\sigma \Rightarrow$ large rate, and
- ϕ large $\Rightarrow$ large rate.

However, consider Earth-skimming neutrinos:

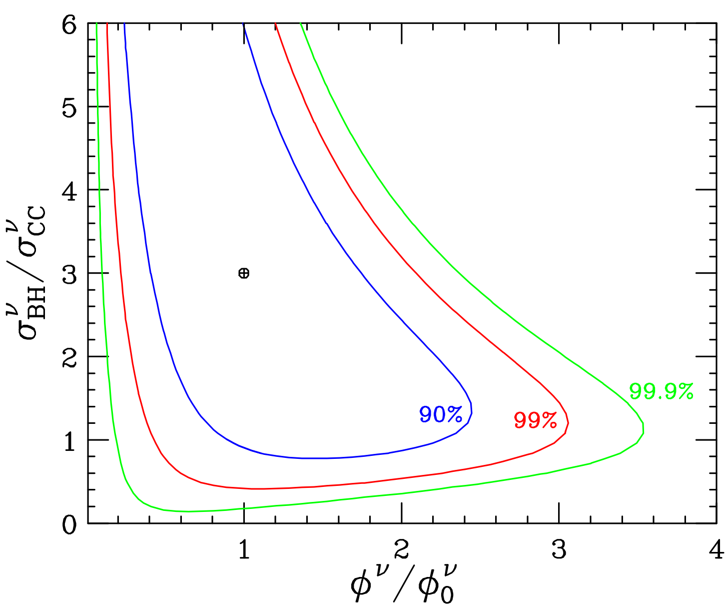
- ϕ large $\Rightarrow$ large rate, but
- large BH $\sigma \Rightarrow$ rate suppressed

BH production will be obviously non-SM-like.

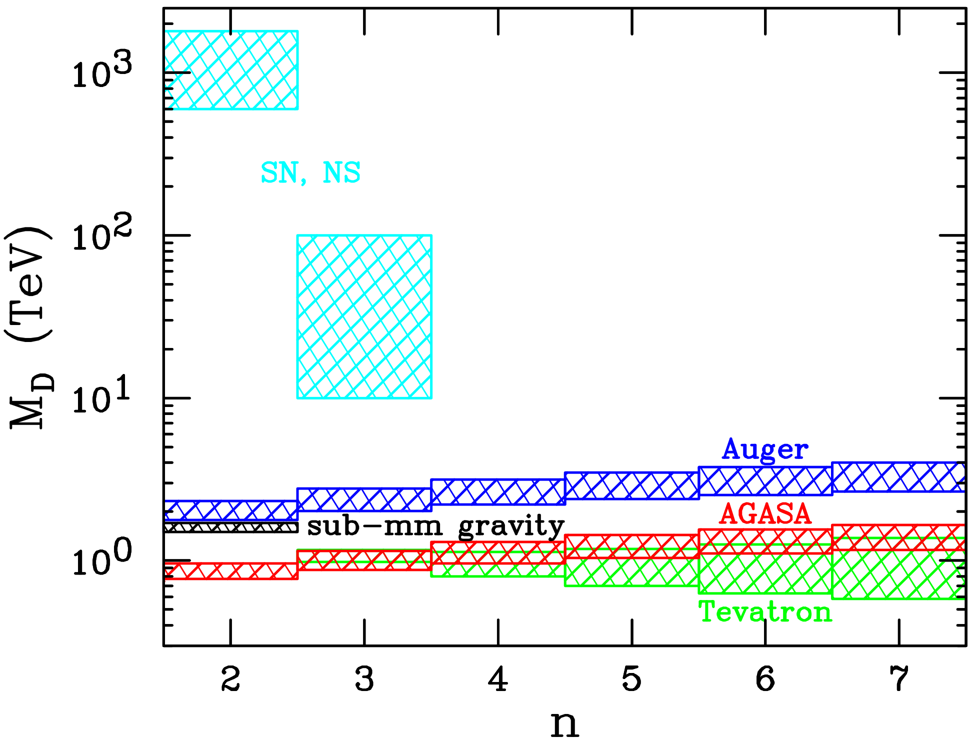
$$N_{\mathrm{QH}} \propto \phi^{\nu}(\sigma^{\nu}_{\mathrm{CC}} + \sigma^{\nu}_{\mathrm{BH}}) \quad N_{\mathrm{ES}} \propto \phi^{\nu} \frac{\sigma^{\nu\,2}_{\mathrm{CC}}}{(\sigma^{\nu}_{\mathrm{CC}} + \sigma^{\nu}_{\mathrm{BH}})^2}$$



Quasi-horizontal shower (dashed) and Earth-skimming neutrinos (dotted) in 5 years.



Black hole production by cosmic rays is a powerful window on low-scale gravity.



Fly's Eye, IceCube, EUSO/OWL, etc. . .

Uehara (2001)
Ringwald, Tu (2001)
Anchordoqui, Feng, Goldberg, Shapere (2001)
Ahn, Cavaglia, Olinto (2002)
Kowalski, Ringwald, Tu (2002)
Jain, Kar, Panda, Ralston (2002)
Alvarez-Muniz, Feng, Halzen, Han, Hooper (2002)
Anchordoqui, Feng, Goldberg (2002)
Iyer Dutta, Reno, Sarcevic (2002)
Anchordoqui, Goldberg, Shapere (2002)

Talks of McKay, Hooper this afternoon

CONCLUSIONS

Lots of interest in UHE cosmic rays:

- An outstanding problem

  GZK puzzle is still puzzling

- The continuation of a rich research program

  The dawn of UHE ν astrophysics

- Potential for fundamental breakthroughs

  BHs and new electroweak scale physics