Quest for Black Holes and Superstring Excitations in Cosmic Ray Data

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COSMO – 03

- Thorne Hoop Conjecture
- Spacetime's Unseen Dimensions
- Globe Conjecture
- Hawking Evaporation
- Black Holes from Cosmic Rays
- Cross Section
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- Limits on TeV-Scale Gravity
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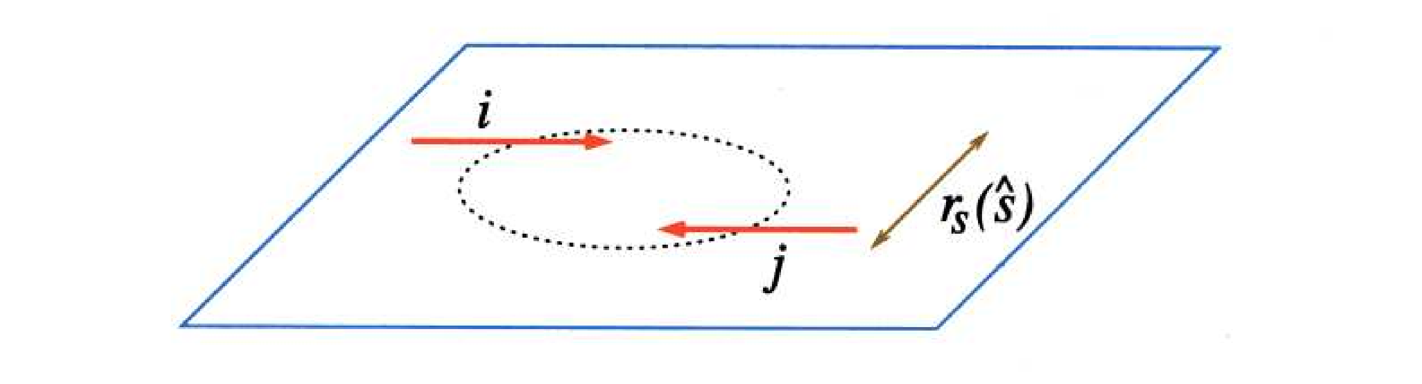
hep-ph/0309082

Thorne Hoop Conjecture

Horizons forms $\Leftrightarrow$ $M_{\rm BH}$ compacted into a region whose circumference in every direction $< 2\pi r_s$



BH production in particle collisions

Amati-Ciafaloni-Veneziano- 't Hooft (1987)

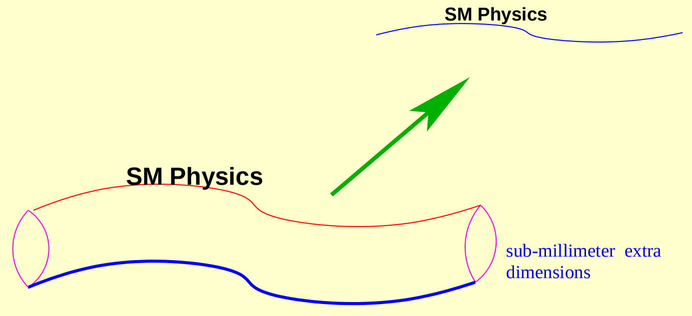
$D = 4$ dimensions $\Leftrightarrow$ $M_D \approx 10^{19}$ GeV

$\Downarrow$

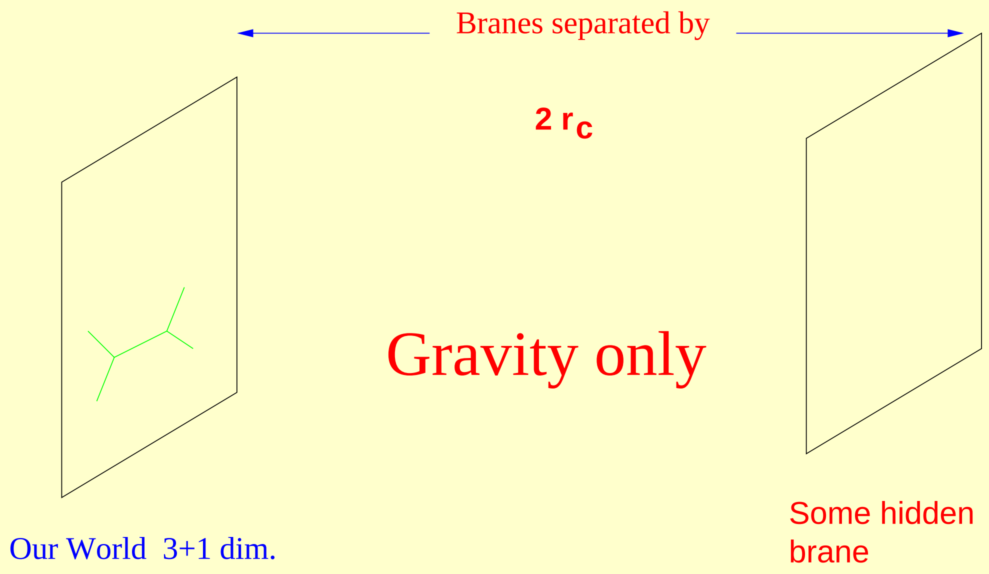
BH's Far Beyond Realm Experimental Particle Physics

Spacetime's Unseen Dimensions

Hypothesis: universe has $D = 4 + n$ dimensions



- SM lives in 4 dimensions
- Gravity spills into internal dimensions



Gravitational Strength: $8\pi\, M_D^{2+n} r_c^n \approx (10^{19}\ \mathrm{GeV})^2$

GRAVITY IS WEAK BECAUSE:

- $D = 4$ **and** $M_D \approx 10^{19}$ GeV
- $D > 4$ **and** $M_D \approx 10^3$ GeV, but r_c large in Planck units

Arkani Hamed-Dimopoulos-Dvali (1998)

Globe Conjecture

BH production in particle collisions

$D > 4 \Rightarrow$ **Horizon Formation**

$\Downarrow$

Extension of Hoop Circunference

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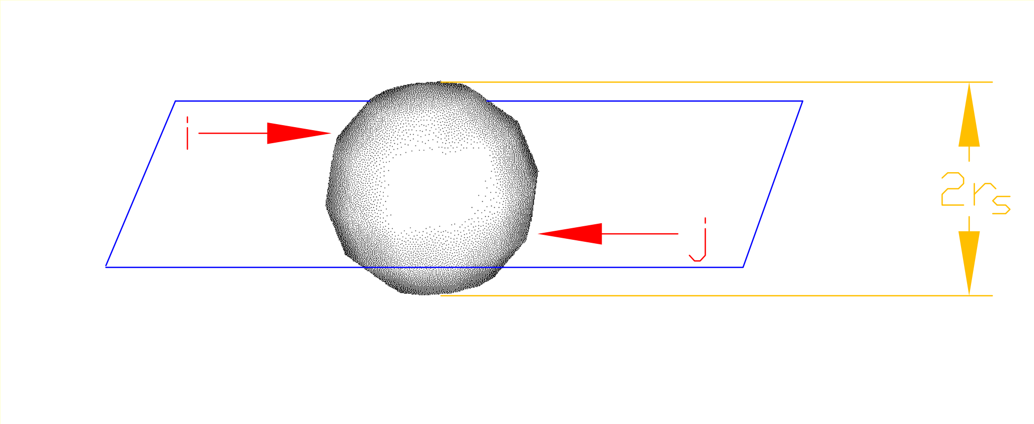
$(n+1)$ **Globe Characterizing Trapping Area**



$$\left[\frac{V_{n+1}}{\Omega_{n+1}\, r_s^{n+1}}\right]^{\frac{1}{n+1}} < 1$$

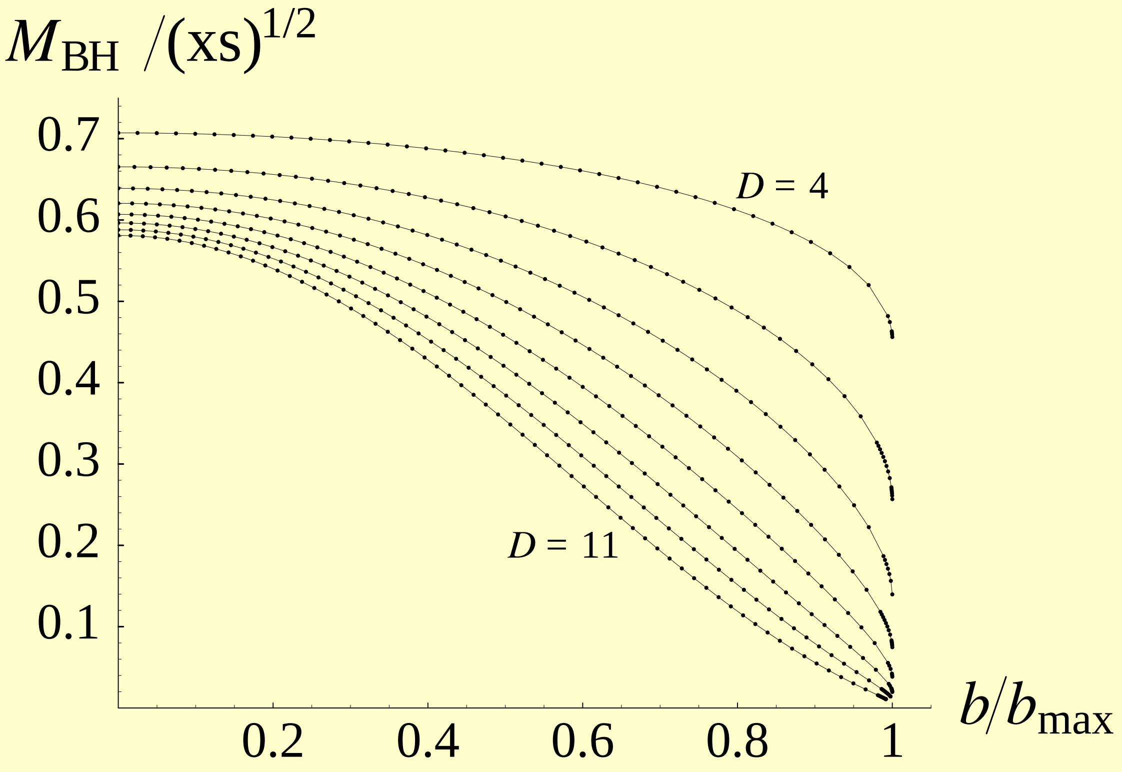
- $\Omega_{n+1} \equiv$ volume of unit $(n+1)$-sphere
- $V_{n+1} \equiv (n+1)$ submanifold of $(4+n)$ BH horizon
- $r_s = \frac{1}{M_D}\left[\frac{\sqrt{\hat{s}}}{M_D}\right]^{\frac{1}{1+n}} \left[\frac{2^n \pi^{(n-3)/2}\Gamma(\frac{n+3}{2})}{n+2}\right]^{\frac{1}{1+n}}$

Globe Conjecture (cont'd)

$D > 4 \rightsquigarrow$ Spheroid Prolate Horizons

$\Downarrow$

Classical Gravitational Radiation



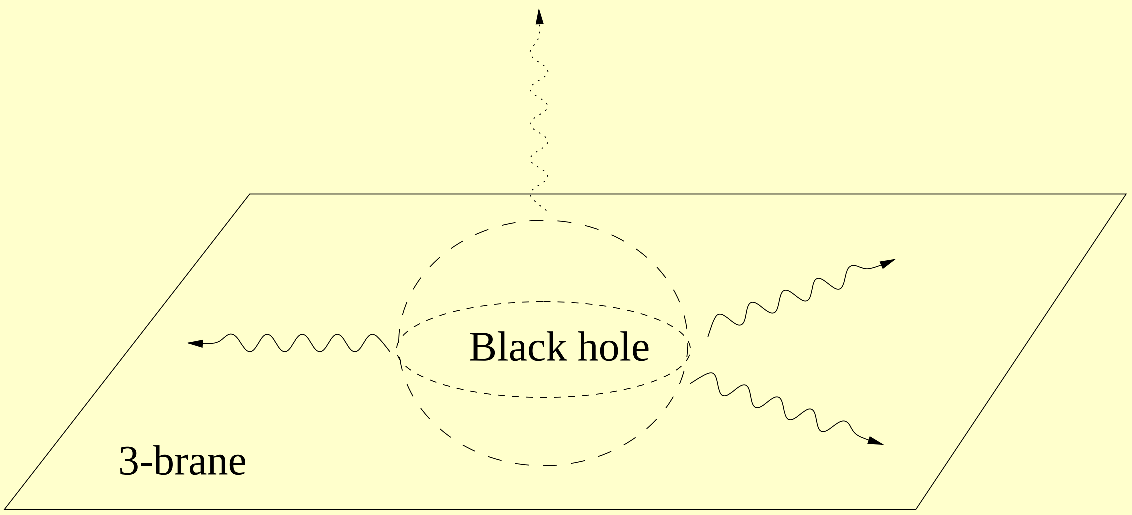
- $b \equiv$ impact parameter
- $b_{\rm max} = \sqrt{F(n)}\; r_s$
- $y \equiv M_{\rm BH}/\sqrt{\hat{s}}$

Strong dependence with b

Yoshino-Nambu (2002)

Hawking Evaporation

BH decays visibly to SM fields



- Hawking Temperature: $T = \frac{n+1}{4\pi\, r_s}$

  $\Downarrow$
- Hawking wavelength $\lambda \sim \frac{2\pi}{T} >$ BH size

  $\Downarrow$
- BH $\approx$ point radiator $\Rightarrow$ emits mostly s-waves

  $\Downarrow$
- Decays with equal probability on 3-brane/bulk

  $\Downarrow$
- Many more particles on 3-brane

Emparan-Horowitz-Myers (2000)
Dimopoulos-Landsberg (2001)

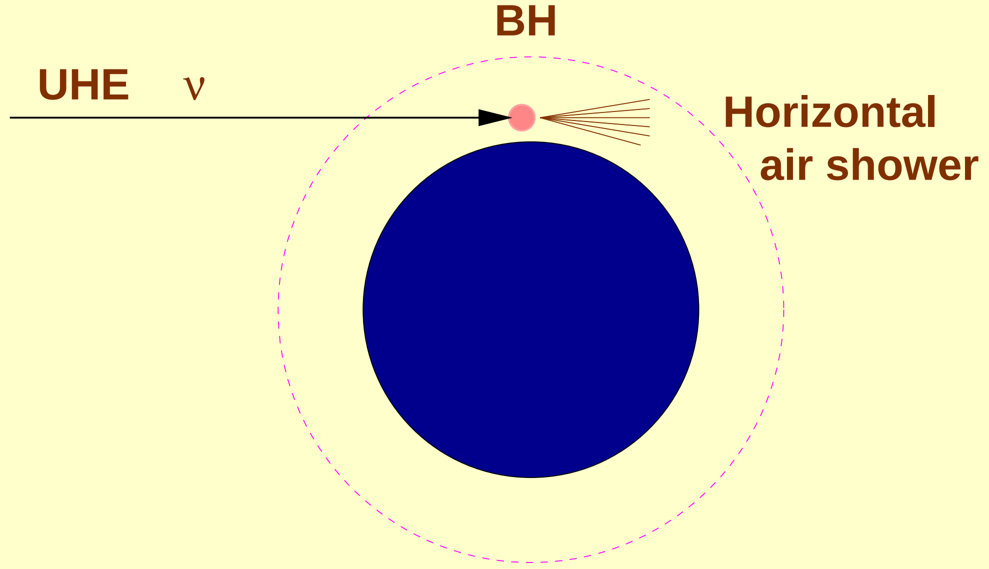
BH's from Cosmic Rays

- **cosmic ray collisions in upper atmosphere**

$$\Downarrow$$

$$\sqrt{s} \text{ up to } 10^5 \text{ GeV}$$

- $\sigma_{\rm QCD}$ dominates $\sigma_{\rm BH}$ by 5 orders of magnitude
- **BH production by hadronic cosmic rays unobservable**
- $\sigma_{\nu N \to {\rm BH}}$ orders of magnitude larger than SM but much less than hadronic



- **Nearly Horizontal Showers Are Especially Interesting**
- **Hadronic Background Largely Filtered by Atmosphere**

Feng-Shapere (2001)

Cross Section

❋ Inclusive production of BHs proceeds through different final states for different classical impact parameters

$\Downarrow$

Lower cutoff on the parton momentum fraction is a function of b

❋ For $M_{\rm BH} \geq M_D$, $J_{\rm max} = b_{\rm max}\,\sqrt{\hat{s}}/2 \geq 7 \gg 1$

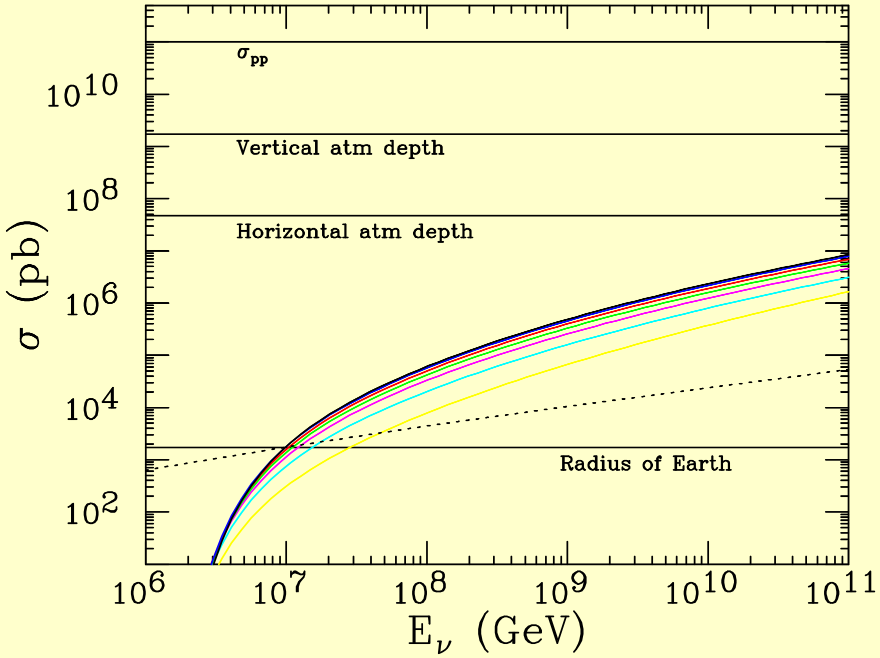
Sums on J can be replaced by sums over b

❋ νN cross section $\rightsquigarrow$ b-weighted average over parton cross sections

❋ $d\hat{\sigma} = 2\pi F(n)\, b\, db$

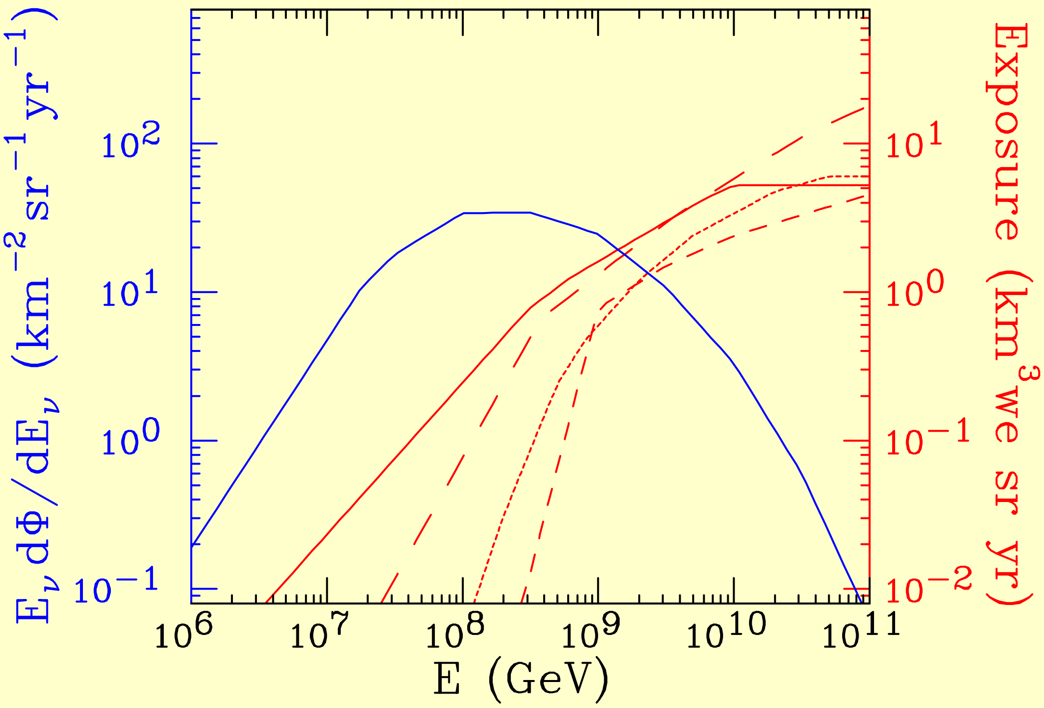
Cross Section (cont'd)

$$\sigma \equiv \int_0^1 2z\,dz \int_{\frac{(x_{\min} M_D)^2}{y^2(z)\,s}}^1 dx\, F(n)\, \pi r_s^2(\sqrt{\hat{s}}, n, M_D) \sum_i f_i(x, Q)$$



- $x_{\min} \equiv M_{\rm BH}/M_D$
- $z = b/b_{\max}$
- $f(x,Q) \equiv$ CTEQ6M pdf's
- $Q \approx r_s^{-1}$

Exposure and Neutrino Flux



- **Guaranteed:** $p\gamma_{\rm CMB} \to n\pi^+ \to n\mu^+\nu$

  Protheroe-Johnson (1996)

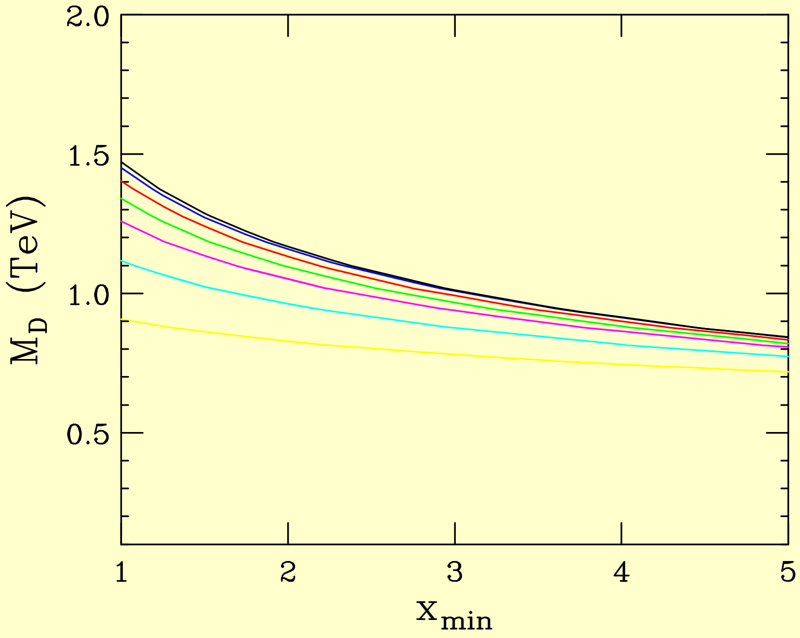
- **AGASA (solid) – Fly's Eye (dotted)**
  HiRes (short dash) – RICE (long dash)
- events observed $= 1$
- expected hadronic background $= 1.72$

$\Downarrow$

95% CL limit of 3.5 BH events

Limits on TeV-Scale Gravity

$$\mathcal{N}(x_{\min}, n, M_D) = N_A T \int dE_\nu \int_0^1 2z\, dz \int_{\frac{(x_{\min} M_D)^2}{y^2(z)\, s}}^1 dx\, \frac{d\Phi}{dE_\nu} A(yE_\nu)$$
$$\times \quad F(n)\, \pi r_s^2(\sqrt{\hat{s}}, n, M_D) \sum_i f_i(x, Q) < 3.5$$



- $A \equiv$ **Aperture**
- $N_A \equiv$ **Avogadro's Number**
- $T \equiv$ **Running Time**

Stringballs

$$\mathrm{BH\,entropy} \equiv S = \frac{4\pi\, M_{\rm BH}\, r_s}{n+2}$$

$S \gg 1$ determines validity semi-calssical approximation

Giddings-Thomas (2001)

$x_{\rm min} \gtrsim 3 \qquad n \geq 5 \qquad S \gtrsim 13 \gg 1$

STRING $\rightleftharpoons$ BH
correspondence principle

r_s shrinks to ℓ_s

$\Downarrow$

adiabatic transition to massive superstring mode

Horowitz-Polchinski (1997)
Damour-Veneziano (2000)

Energy radiation continues at unchanging Hagedorn T

Amati-Russo (1999)

Stringballs (cont'd)

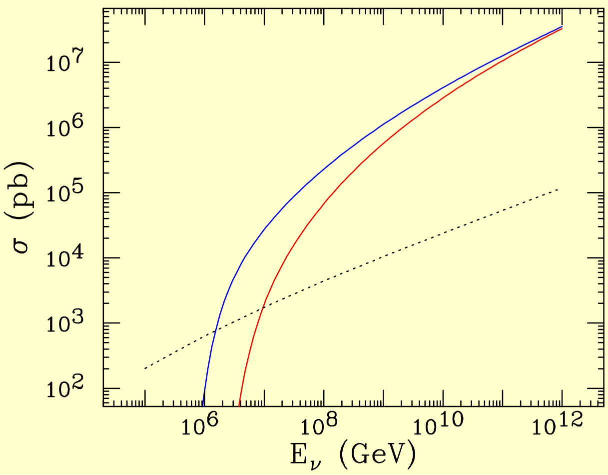
Continuity in cross section at correspondence point (at least parametrically in energy and string coupling) provides independent supportive argument

Dimopoulos-Emparan (2001)

$$\hat{\sigma}(\sqrt{\hat{s}}) \sim \begin{cases} \dfrac{g_s^2\,\hat{s}}{M_s^4} & M_s \ll \sqrt{\hat{s}} \leq M_s/g_s\,, \\ \dfrac{1}{M_s^2} & M_s/g_s < \sqrt{\hat{s}} \leq M_s/g_s^2\,, \\ \dfrac{1}{M_{10}^2}\left[\dfrac{\sqrt{\hat{s}}}{M_{10}}\right]^{2/7} & M_s/g_s^2 < \sqrt{\hat{s}}\,, \end{cases} \tag{1}$$

$M_D = (8\pi^5)^{1/8}\, M_s\, g_s^{-1/4}$ $\qquad g_s = 0.2$ $\qquad n = 6$

$$\Downarrow$$

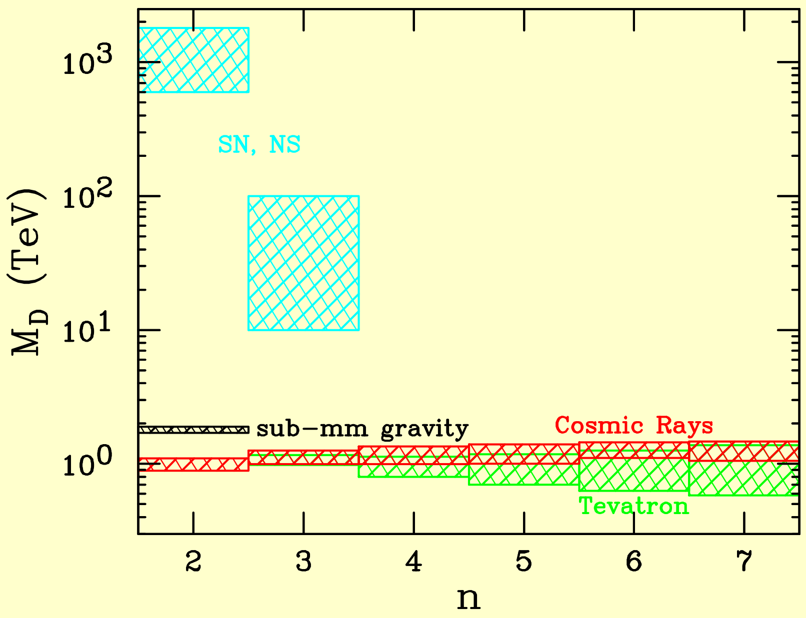


$\sigma_{\rm BH}$ **can be though off as lower limit on** σ_s **as** $M_{\rm BH} \to M_D$

Conclusions and Future Prospects

☞ **Limits on TeV-scale gravity:**

$n \geq 5$ $\qquad$ $M_D > 1.0 - 1.4$ TeV



- Tests of Newton's law on sub-millimeter scale
- Bounds from supernova cooling and neutron star heating
- Searches for sub-Plancking signals at the Tevatron
- Absence ν-showers mediated by BH/stringballs

☞ **Looking Forward:**

Cosmic Ray Observatories (AUGER,EUSO,OWL)
Dedicated Neutrino Telescopes (ICECUBE, RICE)
Should Probe Large Extra Dimensions up to 5 TeV

Conclusions and Future Prospects (cont'd)

Recipe for BH Discovery

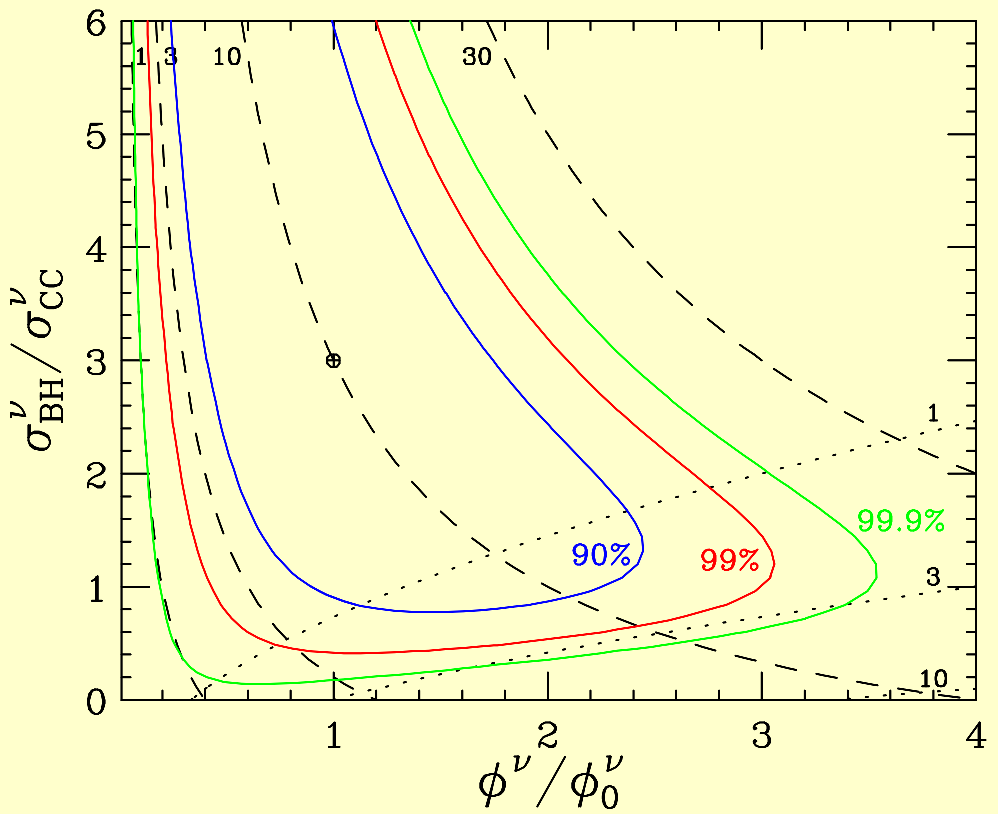
For Quasi-Horizontal neutrinos

- $\sigma_{\rm BH} \Rightarrow$ increases event rates
- $\Phi > \Phi_{\rm cosmogenic} \Rightarrow$ increases event rates

For Earth-skimmers

- $\Phi > \Phi_{\rm cosmogenic} \Rightarrow$ increases event rates
- $\sigma_{\rm BH} \Rightarrow$ rate suppressed

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



QH showers (dashed) and ES (dotted) – 5 years

LAA-Feng-Goldberg-Shapere (2001)