Black Holes and Extra Dimensions

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Harvey Mudd Colloquium
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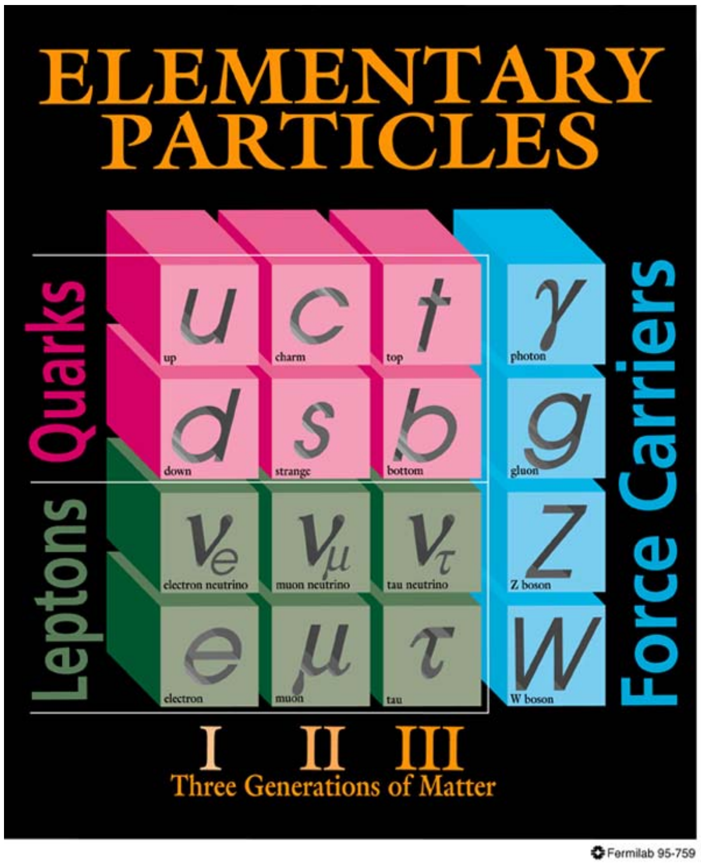
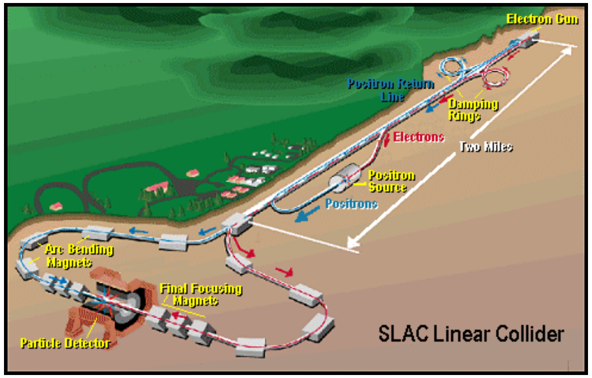
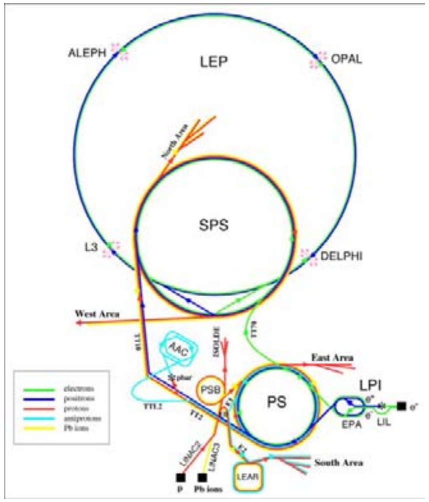
The Standard Model

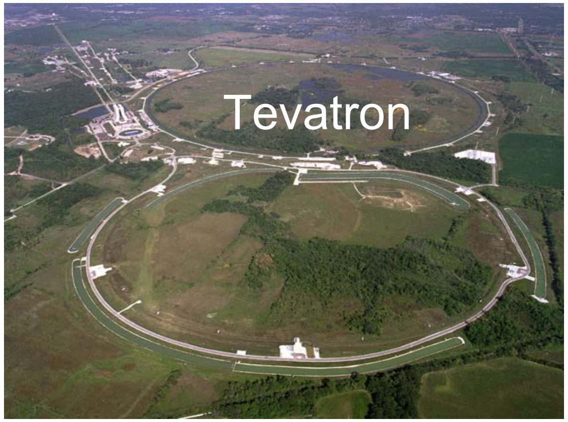


Carrier	Force	Group
γ photon	E&M	U(1)
g gluon	Strong	SU(3)
Z *W*	Weak	SU(2)

Precise Confirmation





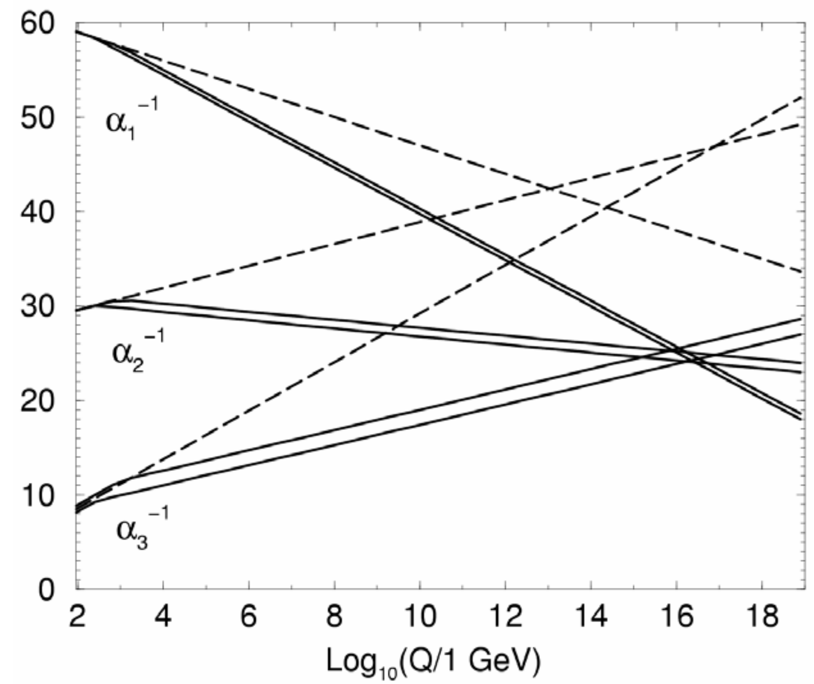


In terms of coupling strengths:

$$\frac{\Delta\alpha_1}{\alpha_1} \sim 10^{-8} \qquad \frac{\Delta\alpha_2}{\alpha_2} \sim 10^{-3} \qquad \frac{\Delta\alpha_3}{\alpha_3} \sim 10^{-2}$$

Force Unification

- Forces are similar in strength
- There is even a beautiful explanation of why the coupling constants have the values they do
- Unification at high energies and short distances (with supersymmetry)



Martin (1997)

Dashed – Standard Model
Solid – Supersymmetry

What's Wrong with this Picture?

- The dog that didn't bark – where's gravity?
- Many deep problems, but one obvious one:

Gravity is extraordinarily weak. It is important in everyday life only because it is universally attractive.

- More quantitatively:

$$F_{\text{EM}} = \frac{q_1 q_2}{r^2} \qquad\qquad F_{\text{gravity}} = G_N \frac{m_1 m_2}{r^2}$$

Even for the heaviest elementary particles (e.g., *W* bosons, top quarks)

$$F_{\text{gravity}} \sim 10^{-32} F_{\text{EM}}$$

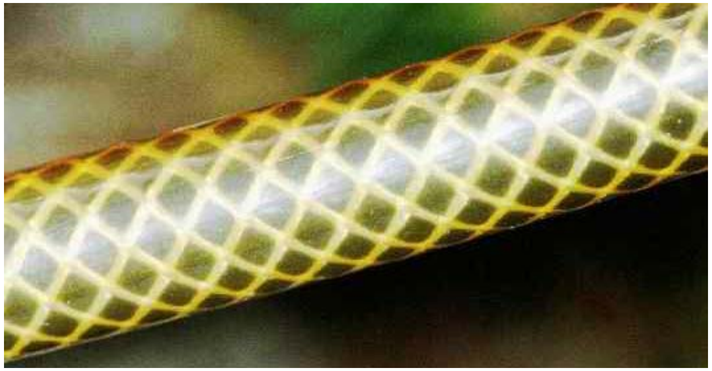
- Gravity is comparable for masses (or energies) ~ 10^{15} TeV, far beyond experiment (M_{weak} ~ 1 TeV).

- The Hierarchy Problem: Why is gravity so weak? Maybe it isn't…

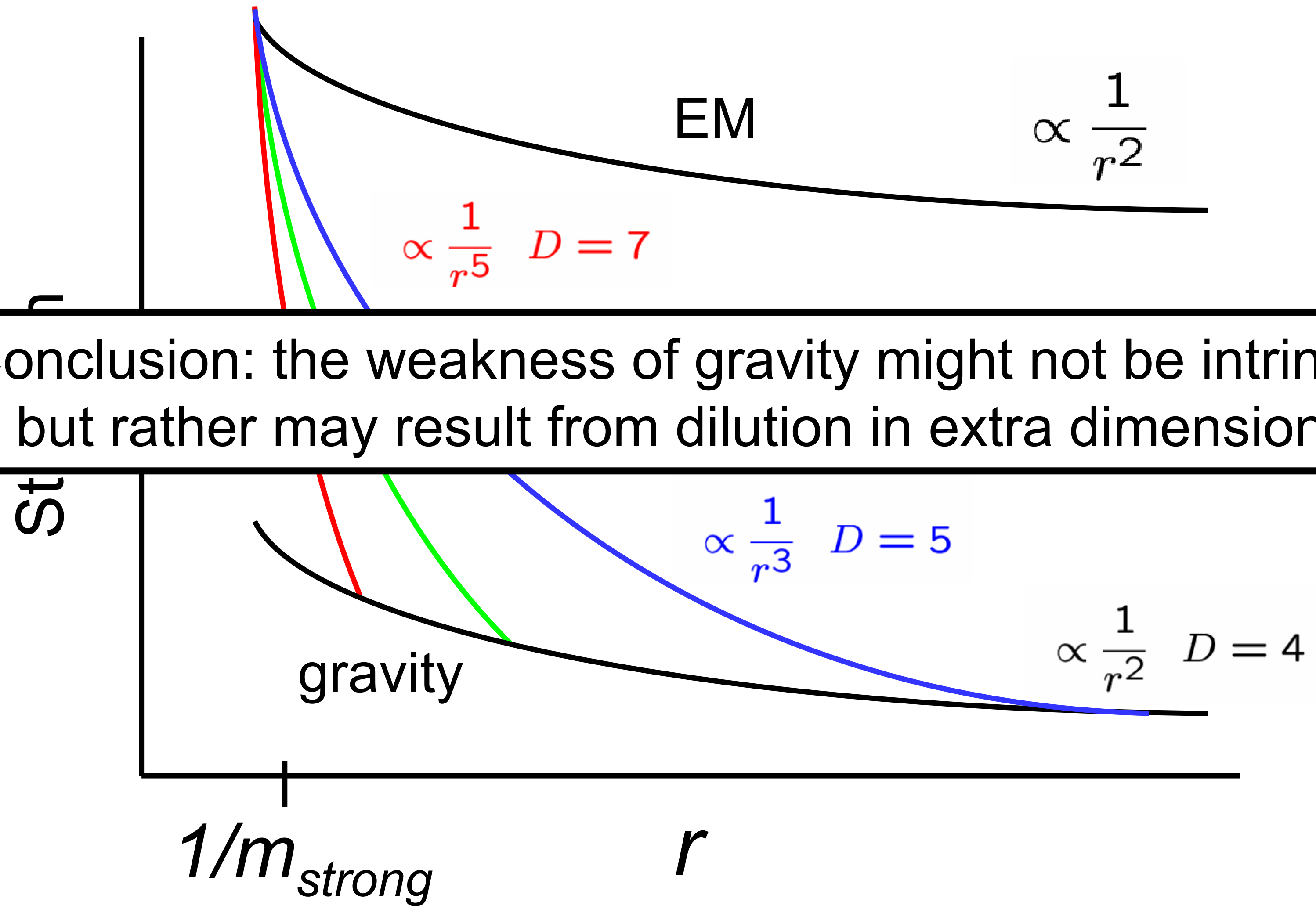
Extra Dimensions

- Suppose photons are confined to D=4, but gravity propagates in n extra dims of size L.

$r \ll L$, $F_{gravity} \sim 1/r^{2+n}$ $\quad$ $r \gg L$, $F_{gravity} \sim 1/r^2$



Gravity in Extra Dimensions



Conclusion: the weakness of gravity might not be intrinsic, but rather may result from dilution in extra dimensions

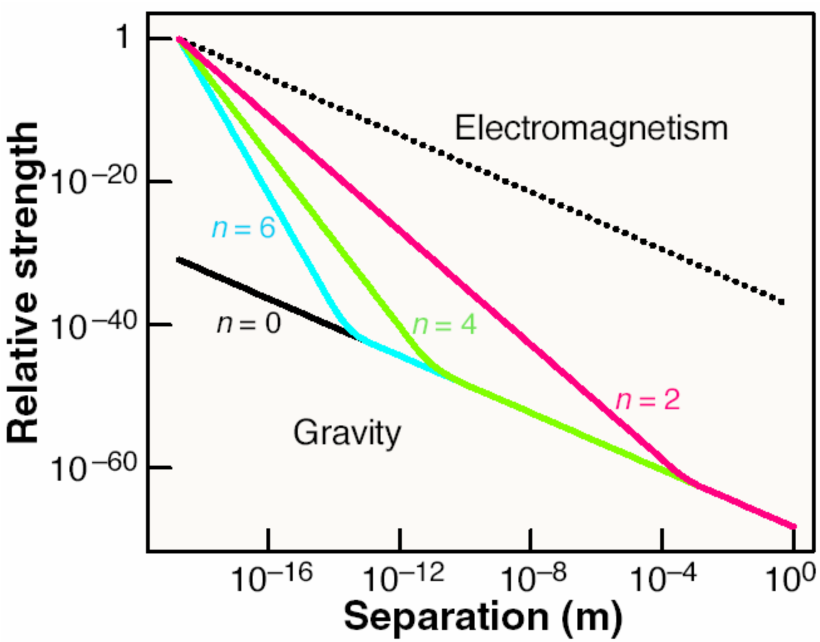
Strong Gravity at the Weak Scale

- Suppose m_{strong} is M_{weak} ~ 1 TeV

Arkani-Hamed, Dimopoulos, Dvali, PLB (1998)

$$L \sim 10^{\frac{32}{n}-19} \text{ m}$$

- The number of extra dims n then fixes L



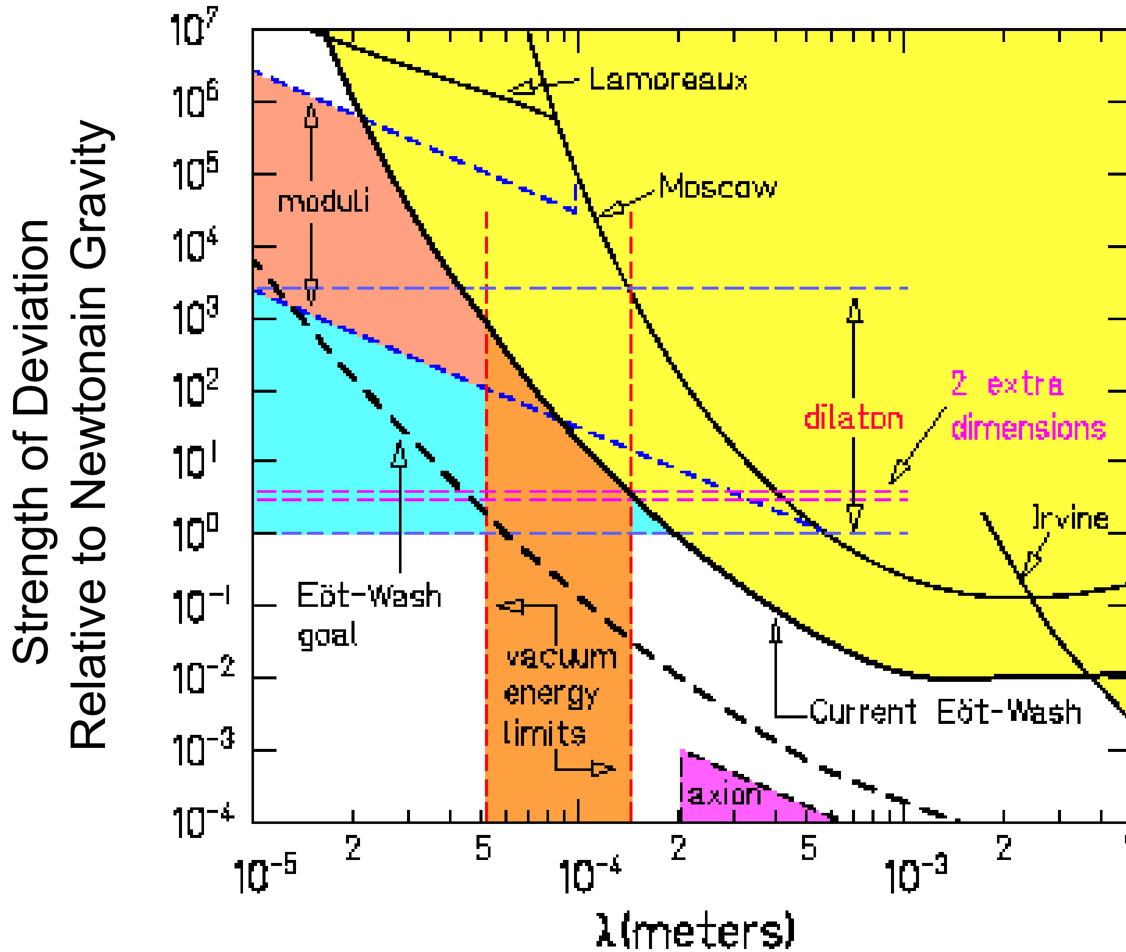
Feng, *Science* (2003)

n	L
1	10^{13} m
2	mm
3	10 nm
4	10^{-11} m
6	10 fm

Tests of Newtonian Gravity

$$L \sim 10^{\frac{32}{n}-19} \text{ m}$$

n	L
~~1~~	~~10^{13} m~~
~~2~~	~~mm~~
3	10 nm
4	10^{-11} m
6	10 fm

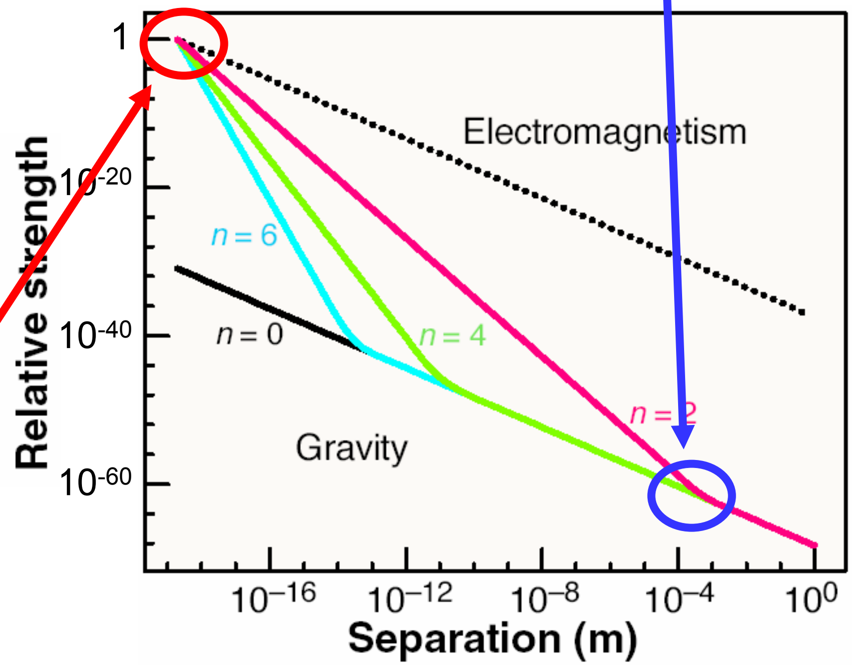


Long *et al.*, *Nature* (2003)

- Tests of Newtonian gravity eliminate n = 1,2, but are ineffective for n >2.

- Astrophysical probes (supernova cooling) provide even more stringent constraints, eliminate n = 2,3,4, but are ineffective for n >4.

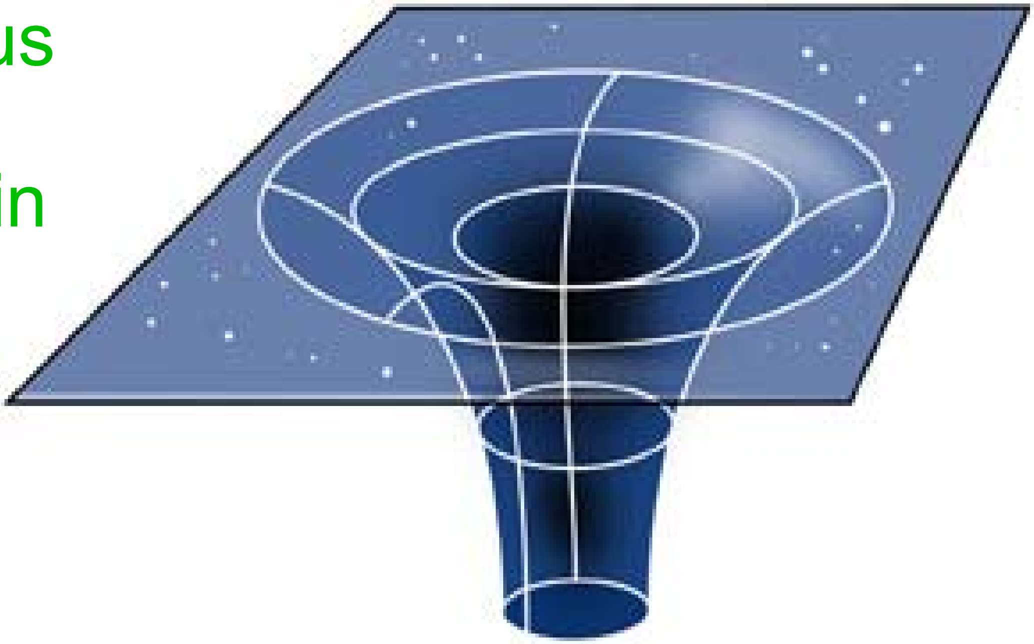
- A better strategy: probe small distances, high energies.



Feng, *Science* (2003)

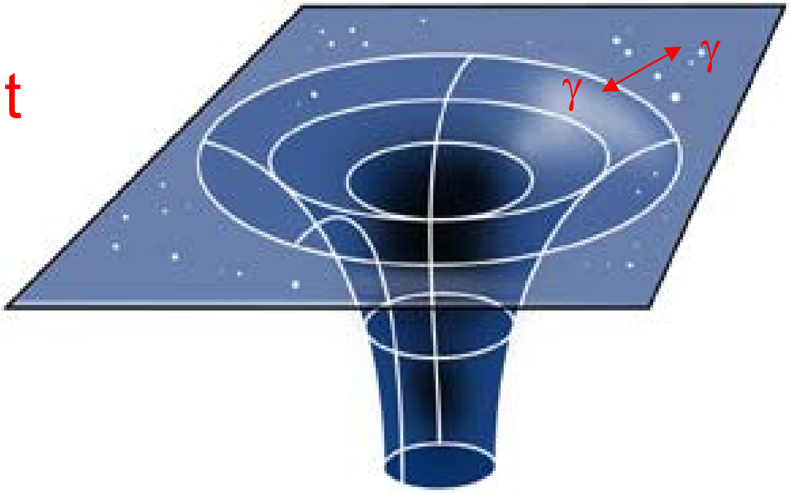
Black Holes

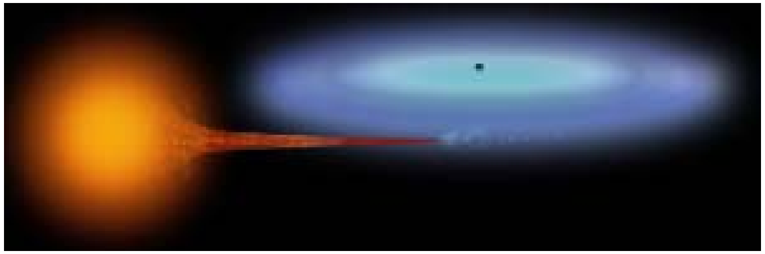
- Solutions to Einstein's equations
- Schwarzschild radius $r_s \sim M_{\mathrm{BH}}$ – requires large mass/energy in small volume
- Light and other particles do not escape; classically, BHs are stable



Black Hole Evaporation

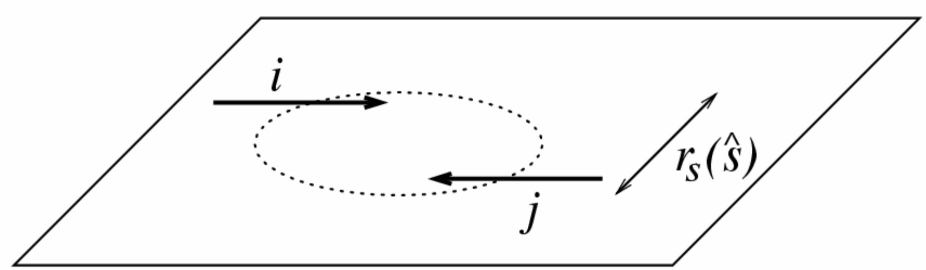
- Quantum mechanically, black holes are not stable – they emit Hawking radiation
- Temperature: $T_H \sim 1/M_{BH}$
  Lifetime: $\tau \sim (M_{BH})^3$
- For $M_{BH} \sim M_{sun}$, $T_H \sim 0.01$ K. Astrophysical BHs emit only photons, live ~ forever
- Form by accretion





BHs from Particle Collisions

- BH creation requires
  $E_{\mathrm{COM}} > m_{\mathrm{strong}}$



Penrose (1974)
D'Eath, Payne, PRD (1992)
Banks, Fischler (1999)

- In 4D, $m_{\mathrm{strong}} \sim 10^{15}$ TeV,
  far above accessible energies ~ TeV

- But with extra dimensions, $m_{\mathrm{strong}} \sim$ TeV is possible, can create micro black holes in particle collisions!

Micro Black Holes

- Where can we find them?
- What is the production rate?
- How will we know if we've seen one?

S. Harris

"It's black, and it looks like a hole. I'd say it's a black hole."

Black Holes at Colliders

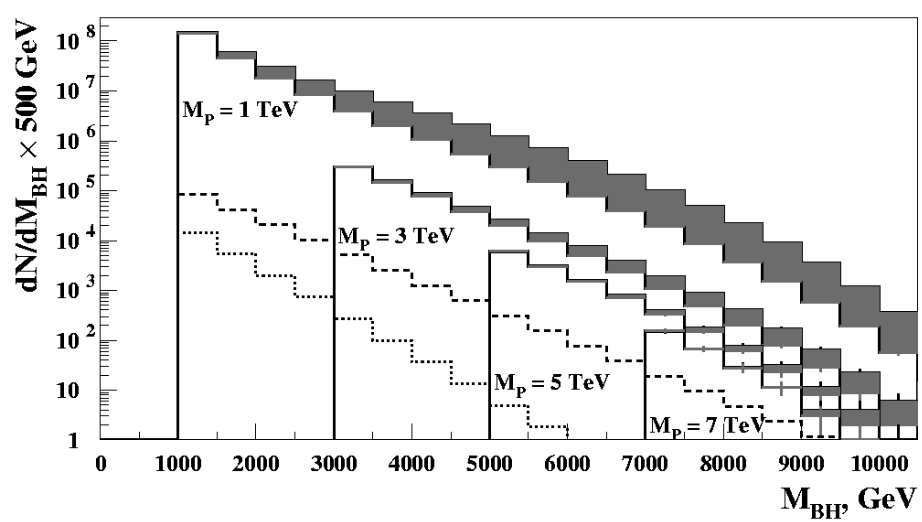
- BH created when two particles of high enough energy pass within ~ r_s .

Eardley, Giddings, PRD (2002)
Yoshino, Nambu, PRD (2003)
…

- Large Hadron Collider:
  E_{COM} = 14 TeV
  $pp \rightarrow$ BH + X

- LHC may produce 1000s of black holes, starting ~ 2008

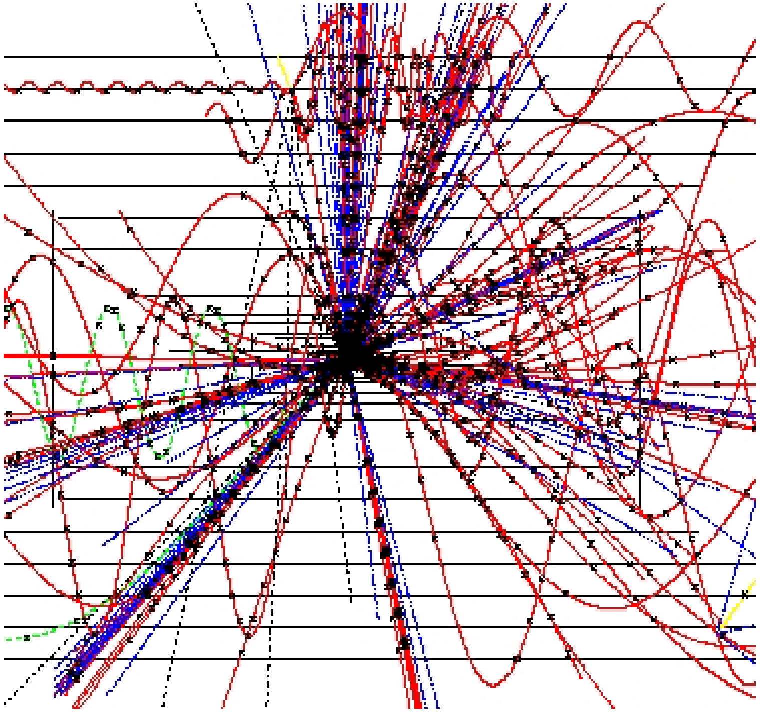
$$\sigma_{pp\to \mathrm{BH}}(\tau_{\min}, s) = \sum_{ij} \int_{\tau_{\min}}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} f_i(x) f_j(\tau/x) \hat{\sigma}_{ij}$$



Dimopoulos, Landsberg, PRL (2001)

Event Characteristics

- For microscopic BHs, $\tau \sim (M_{BH})^3 \sim 10^{-27}$ s, decays are essentially instantaneous
- $T_H \sim 1/M_{BH} \sim 100$ GeV, so not just photons: $q,g : l : \gamma : \nu,G = 75 : 15 : 2 : 8$
- Multiplicity ~ 10
- Spherical events with leptons, many quark and gluon jets

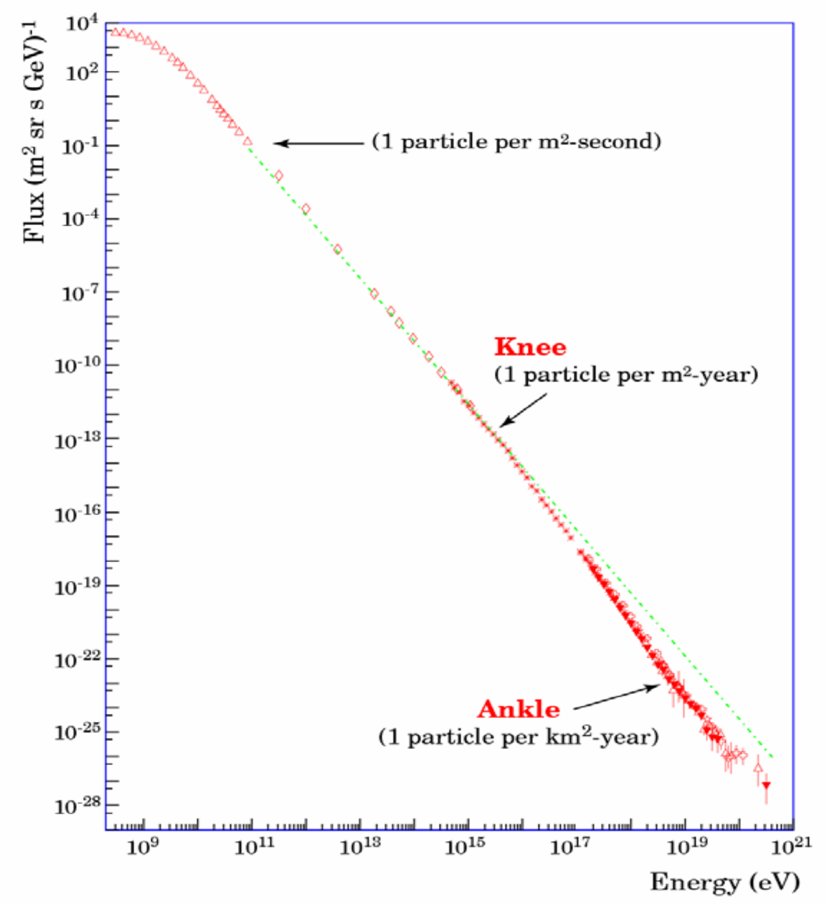


De Roeck (2002)

Black Holes from Cosmic Rays

- Cosmic rays – Nature's free collider
- Observed events with 10^{19} eV produces

  E_{COM} ~ 100 TeV
- But meager fluxes. Can we harness this energy?



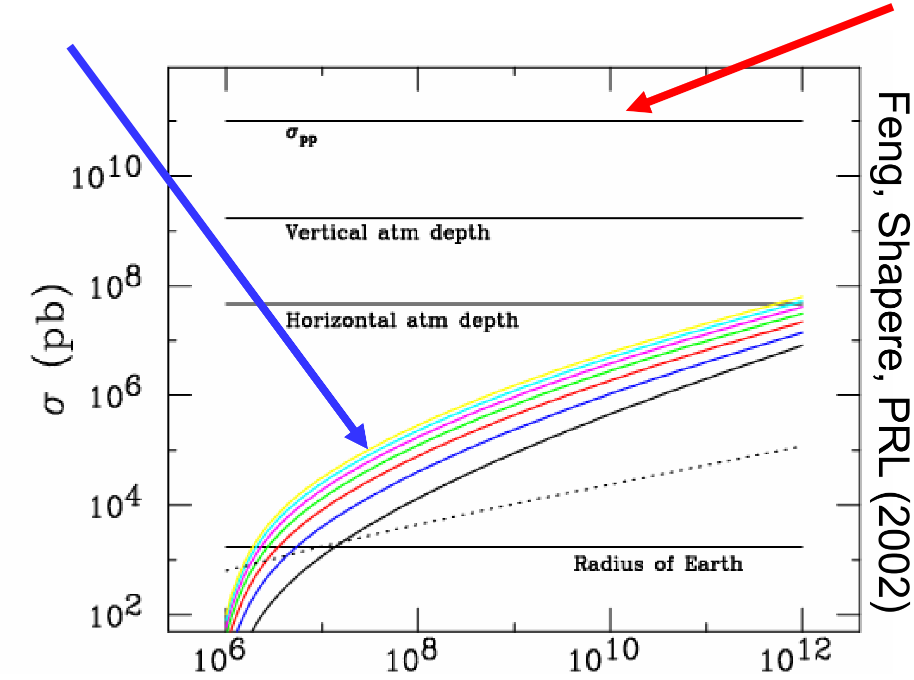
Kampert, Swordy (2001)

1^{st} Attempt

- Look for cosmic ray protons to create BHs in the atmosphere:

  $pp \rightarrow$ BH + X

- Unfortunately, protons interact through standard strong interactions long before they create a BH.



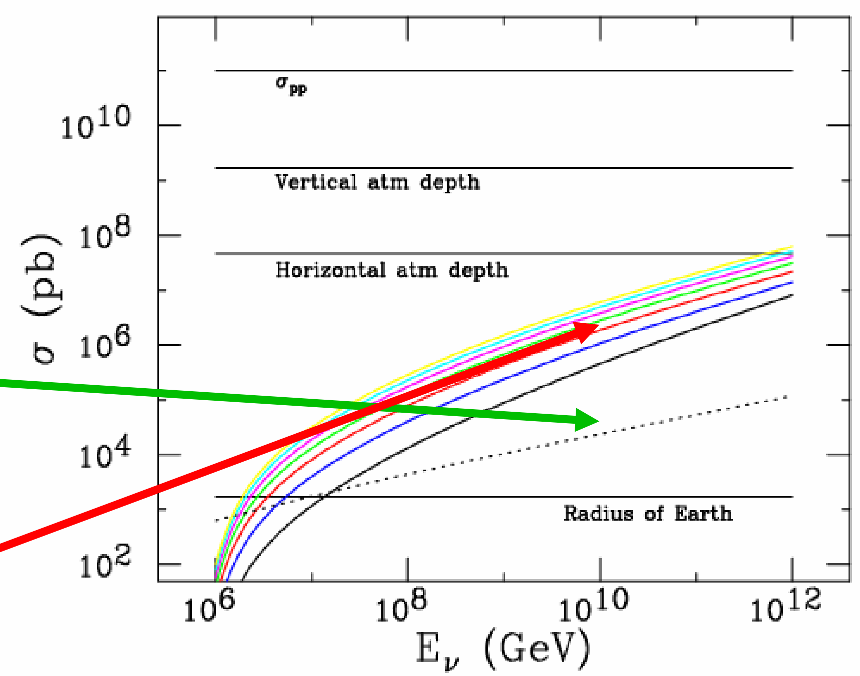
Feng, Shapere, PRL (2002)

Solution: Use Cosmic Neutrinos

- Cosmic protons scatter off the cosmic microwave background to create ultra-high energy neutrinos:

$$p + \gamma_{\text{CMB}} \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu$$

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



- These neutrinos have very weak standard interactions

- Dominant interaction:

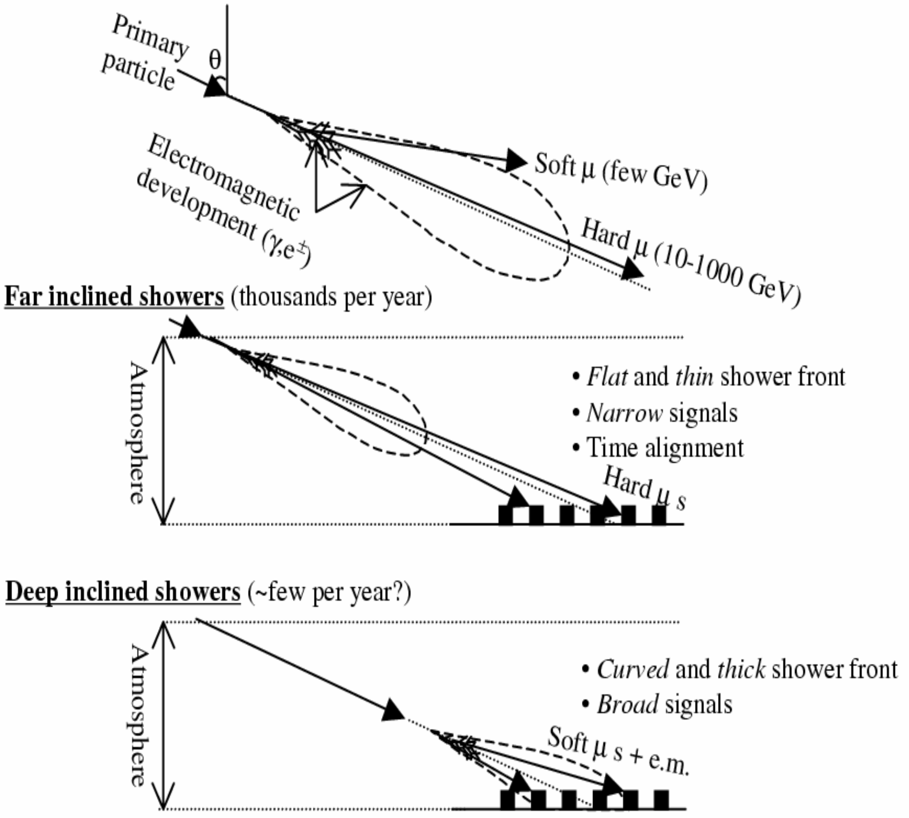
  $\nu p \rightarrow$ BH + X

Atmospheric Showers

- νp → BH gives inclined showers starting deep in the atmosphere

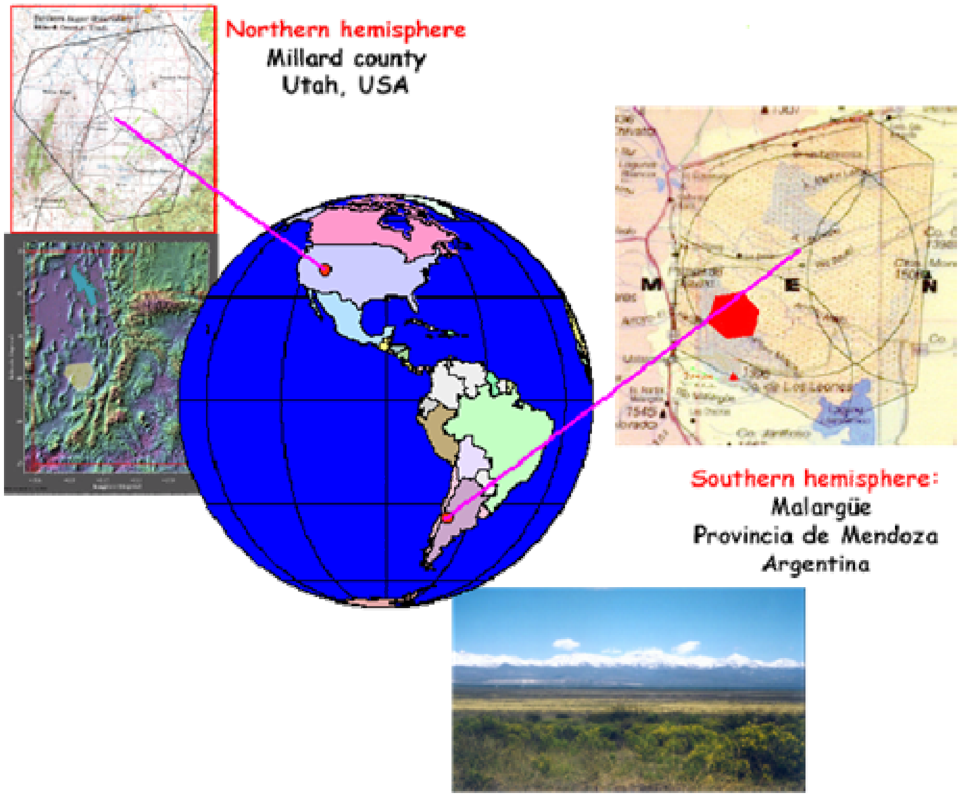
- Atmosphere filters out background from proton-initiated showers

- Rate: a few per minute somewhere on Earth



Coutu, Bertou, Billior (1999)

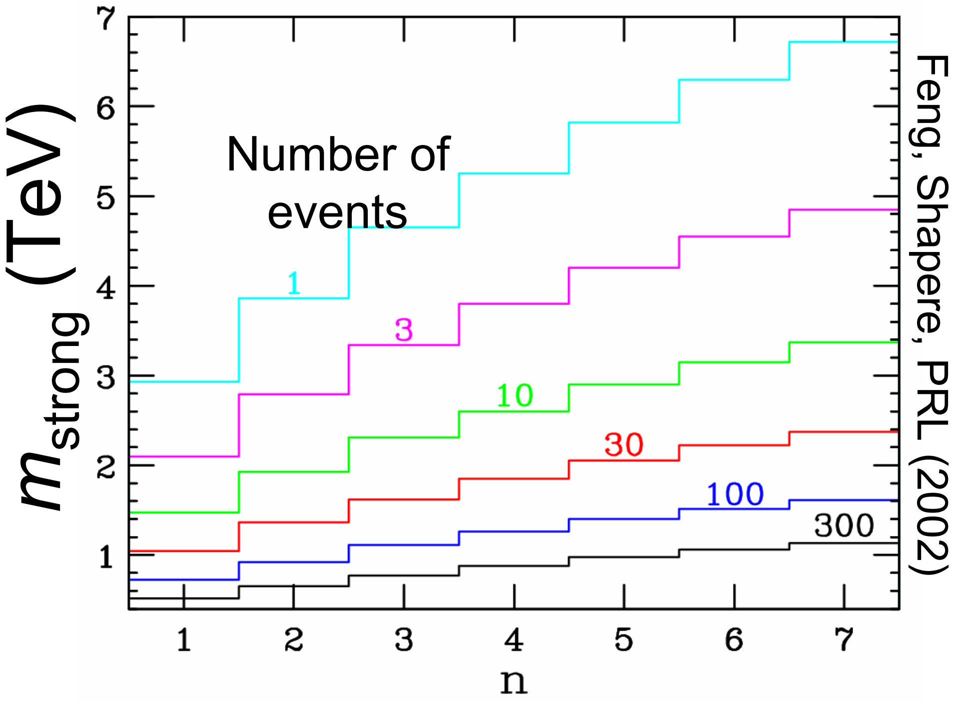
Auger Observatory



- Currently no such events seen → most stringent bound on extra dims so far.

- Auger can detect ~100 black holes in 3 years.

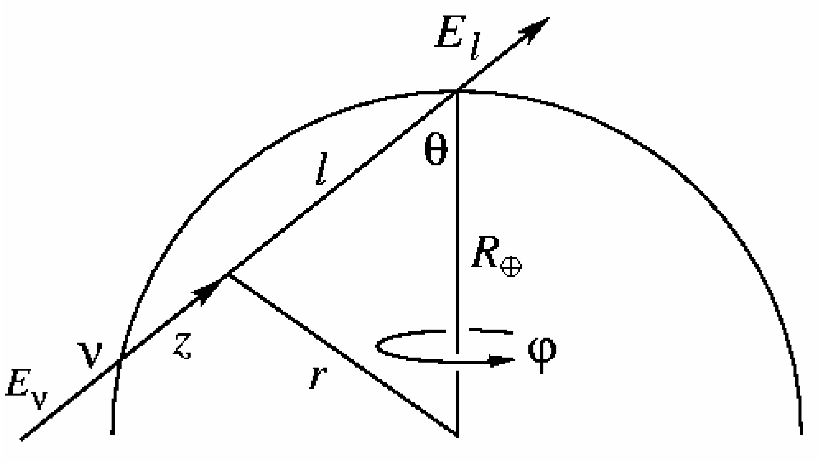
- Insensitive to number of extra dimensions *n*.



USA Today version: "Dozens of tiny 'black holes' may be forming right over our heads… A new observatory might start spotting signs of the tiny terrors, say physicists Feng and Shapere… They're harmless and pose no threat to humans."

BHs vs. SM

- BH rates may be 100 times SM rate. But
  – large BH σ ➔ large rate
  – large flux ➔ large rate



- However, consider Earth-skimming neutrinos:
  – large flux ➔ large rate
  – large BH σ ➔ small rate

Bertou et al., Astropart. Phys. (2002)
Feng, Fisher, Wilczek, Yu, PRL (2002)

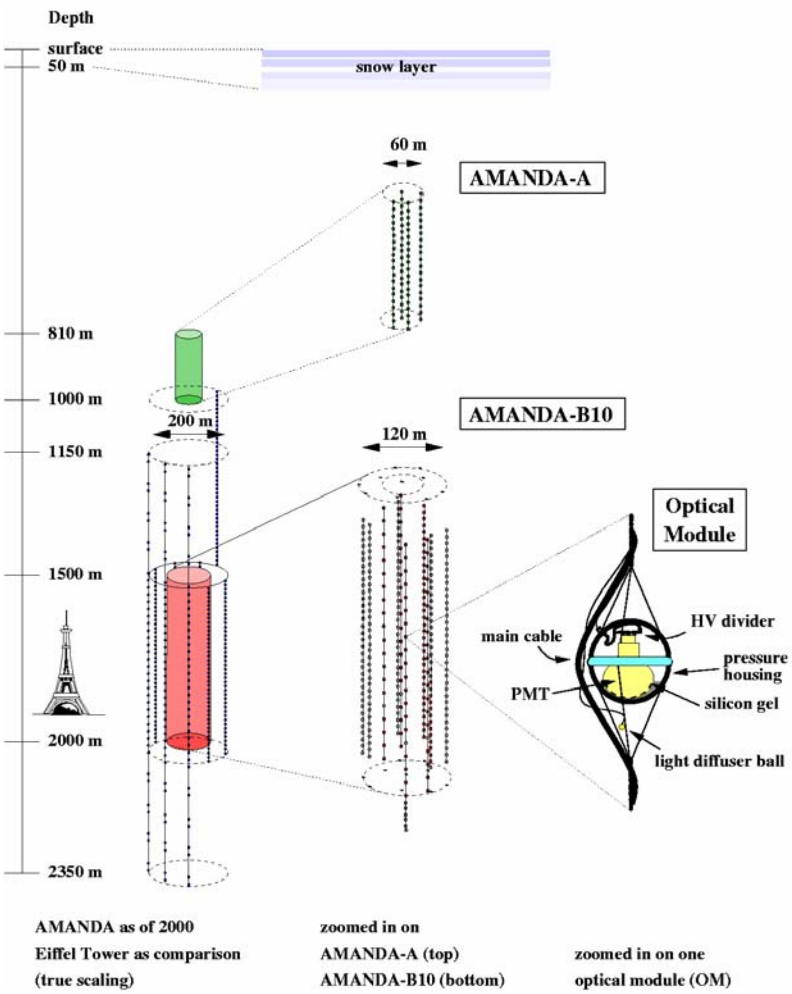
- Degeneracy is resolved by ratio of rates alone.

AMANDA/IceCube

- Neutrino telescopes: promising BH detectors

- Similar rate: ~10 BH/year

- Complementary information
  - BH branching ratios (jets vs. muons)
  - Angular distributions



Kowalski, Ringwald, Tu, PLB (2002)
Alvarez-Muniz, Feng, Han, Hooper, Halzen, PRD (2002)

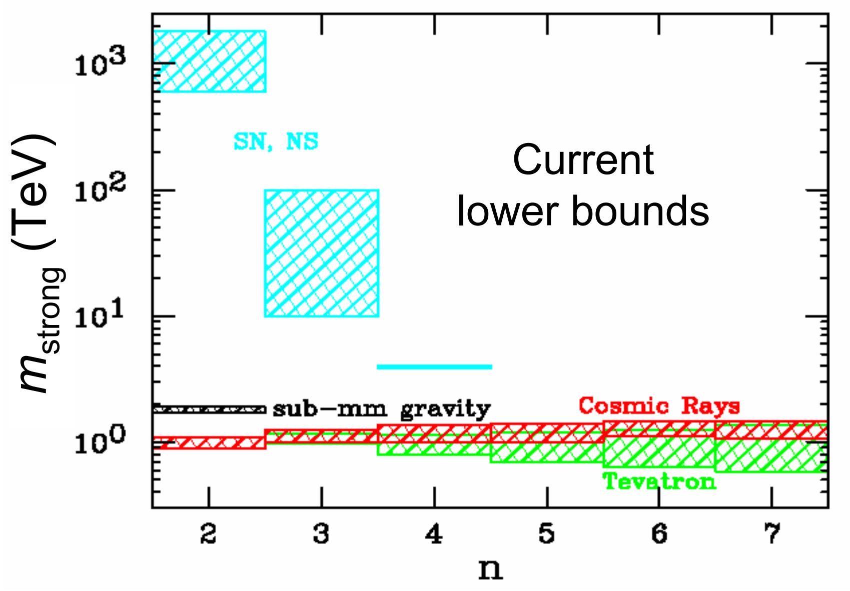
What You Could Do With A Black Hole If You Found One

- Discover extra dimensions
- Test Hawking evaporation, BH properties
- Explore last stages of BH evaporation, quantum gravity, information loss problem
- …

Conclusions

- Gravity is either intrinsically weak or is strong but diluted by extra dimensions

- Black hole production is a leading test



- If gravity is strong at the TeV scale, we will find microscopic black holes and extra dimensions in cosmic rays and colliders