Dark Matter, Black Holes, and the Search for Extra Dimensions

Jonathan Feng

Department of Physics and Astronomy

Physical Sciences Breakfast Lecture Series

27 January 2004

Physical Sciences

Mathematics | Physics and Astronomy | Chemistry | Earth System Science

Particle Physics

Nuclear Physics

Atomic Physics

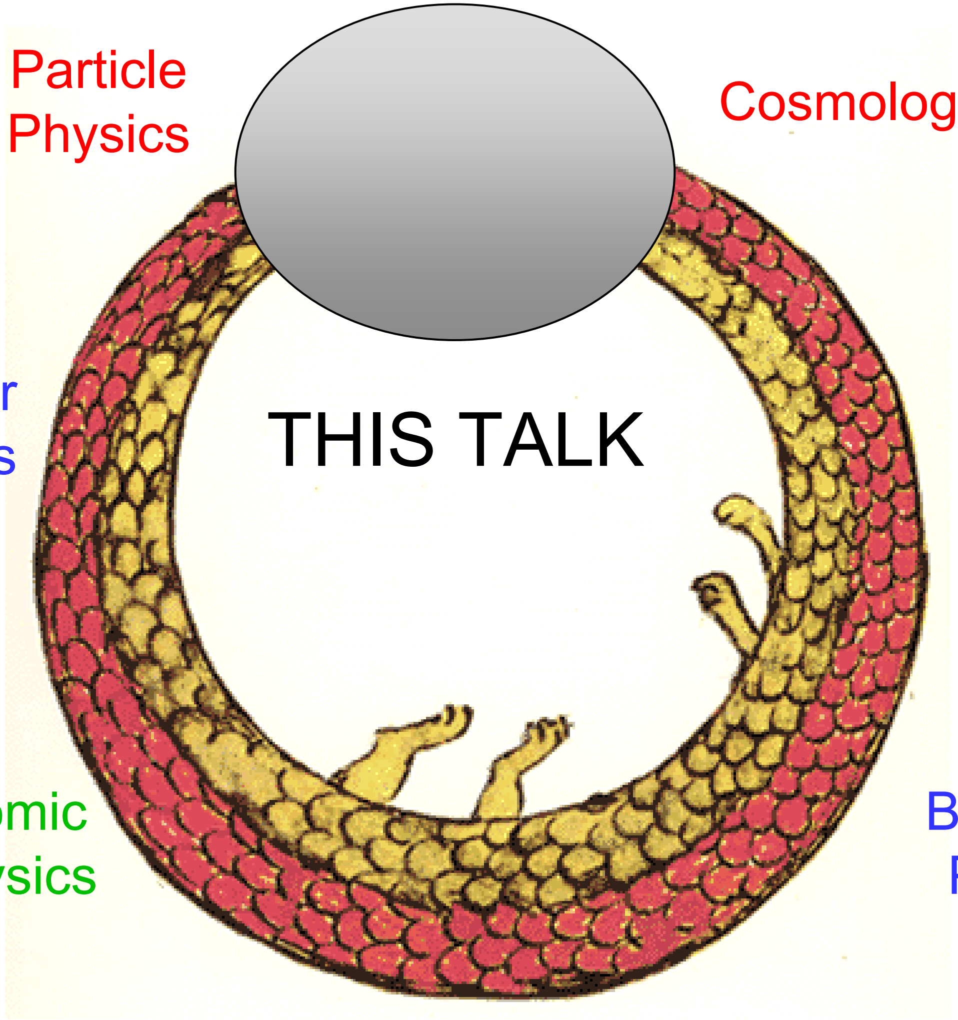
Condensed Matter Physics

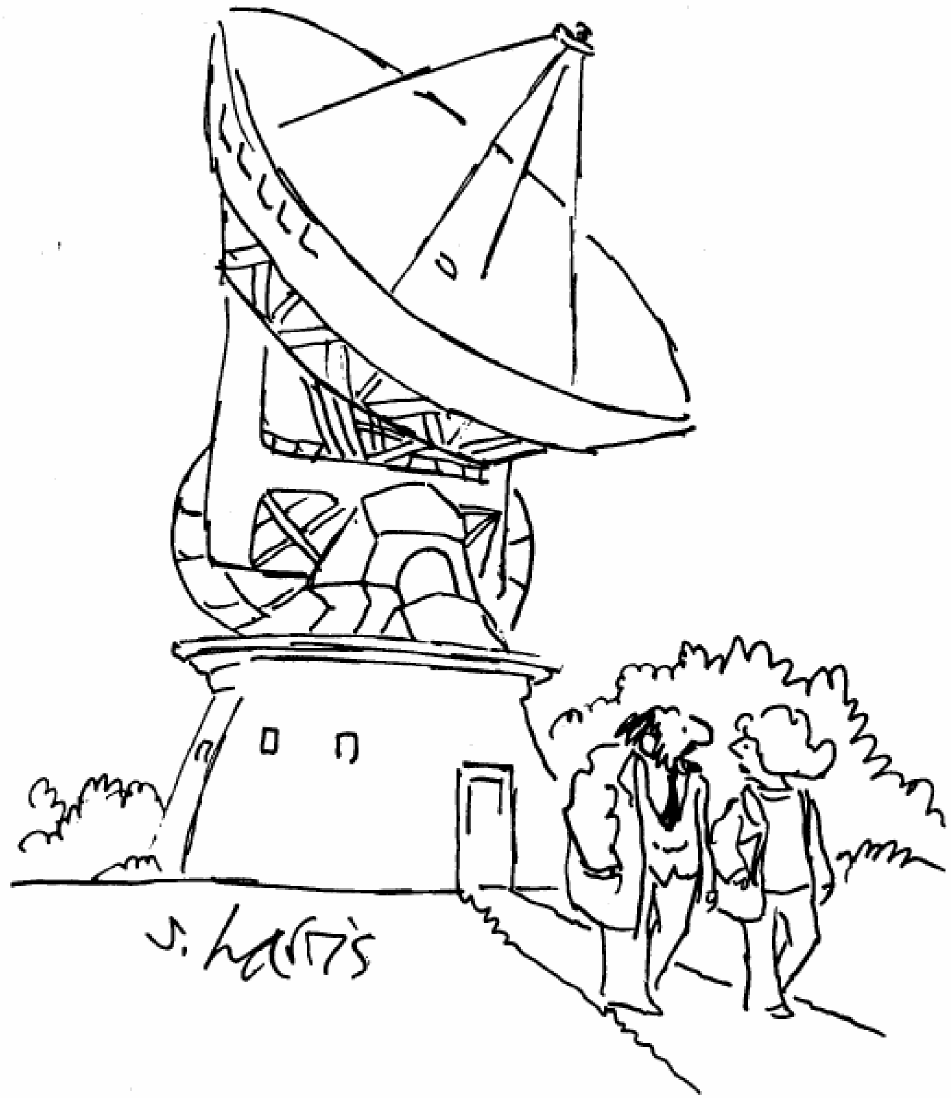
Biological Physics

Astrophysics

Cosmology

small ⟷ big


Particle Physics
Cosmology
THIS TALK
Nuclear Physics
Astrophysics
Atomic Physics
Biological Physics
Condensed Matter Physics

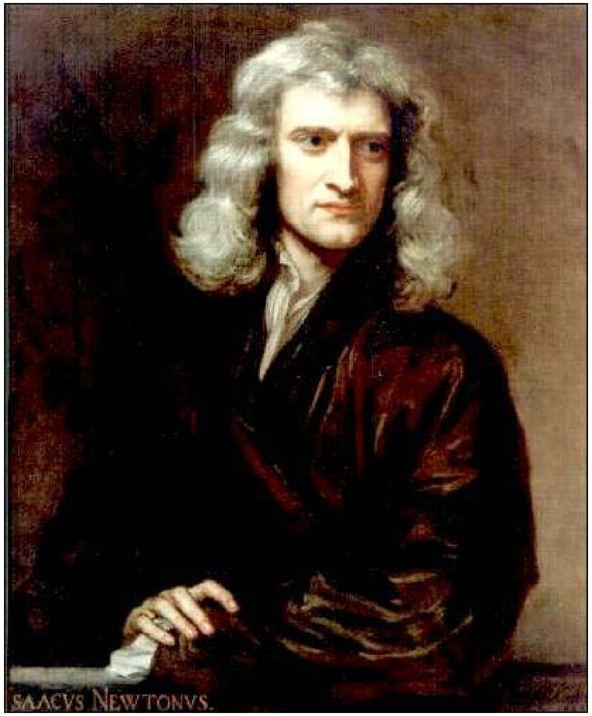


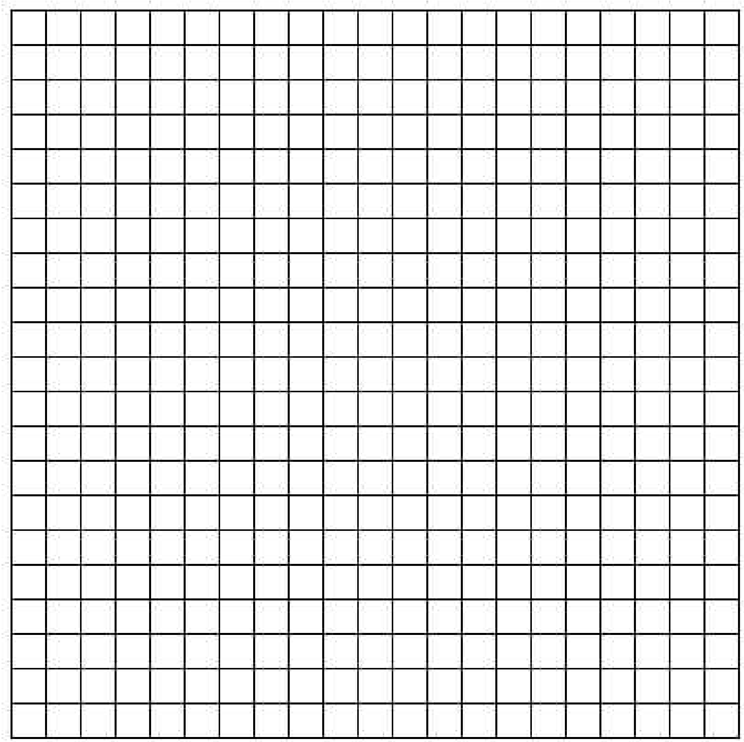
"I'LL BE WORKING ON THE LARGEST AND SMALLEST OBJECTS IN THE UNIVERSE — SUPERCLUSTERS AND NEUTRINOS. I'D LIKE YOU TO HANDLE EVERYTHING IN BETWEEN."

Extra Dimensions

- (x, y, z, t) + w, v,…? Science fiction?
- No – a hot topic at the interface of particle physics and cosmology:
  - How does gravity work?
  - What is our world made of?
  - What is the history (and future) of the universe?
- How did this happen?

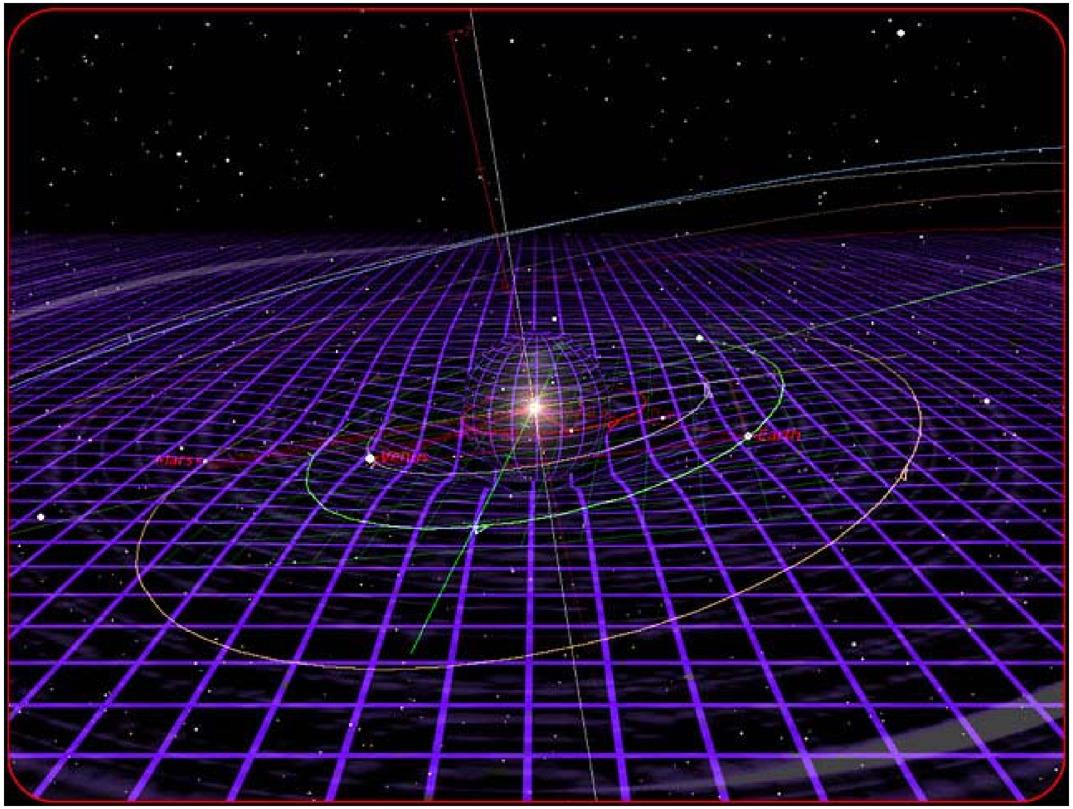
Isaac Newton





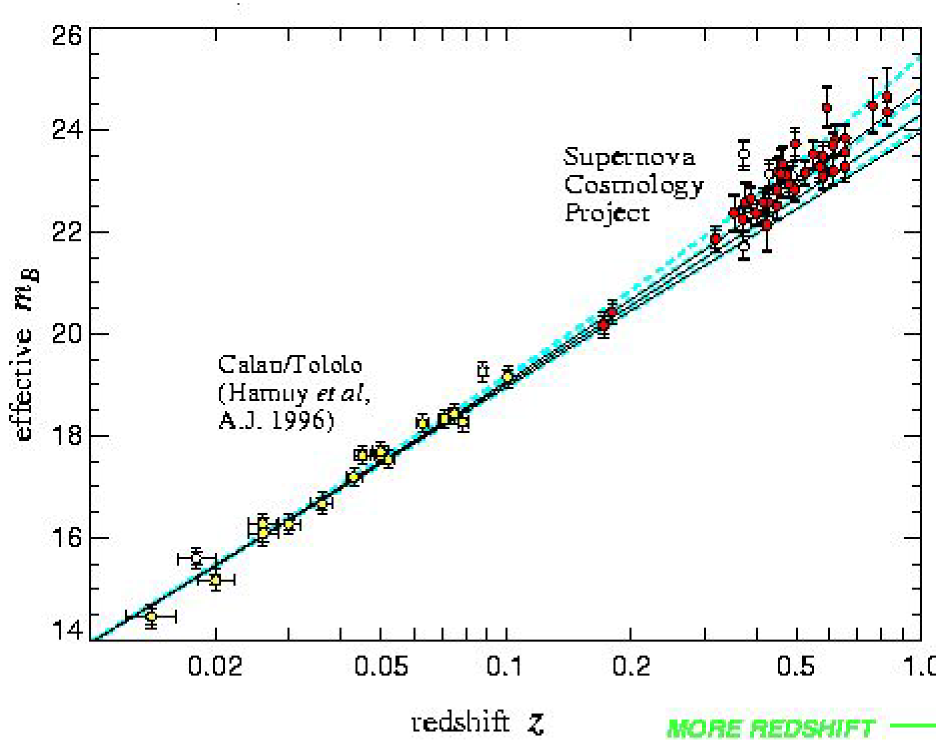
1687: Space and time are the static stage on which physical processes act

Albert Einsten



1915: Spacetime is an active player:
curves, expands, shrinks, …

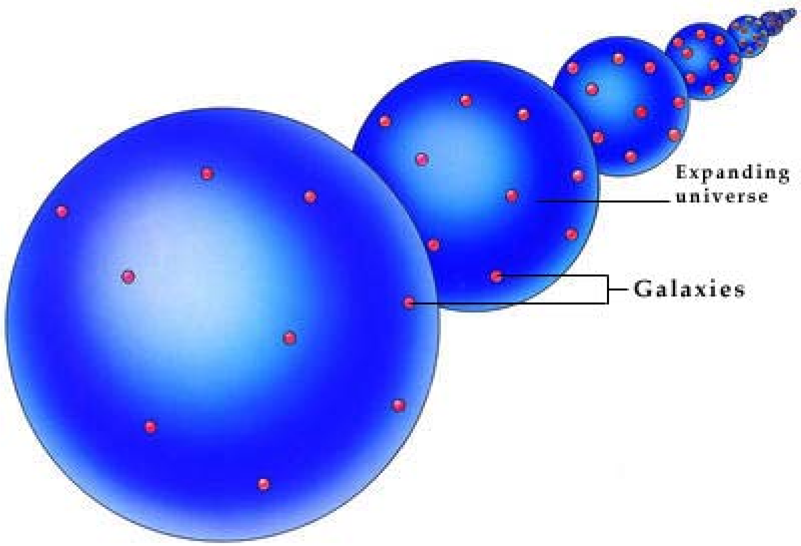
Edwin Hubble



Hubble (1929): The universe is expanding

Small Dimensions

- The universe does not expand into space – space itself expands

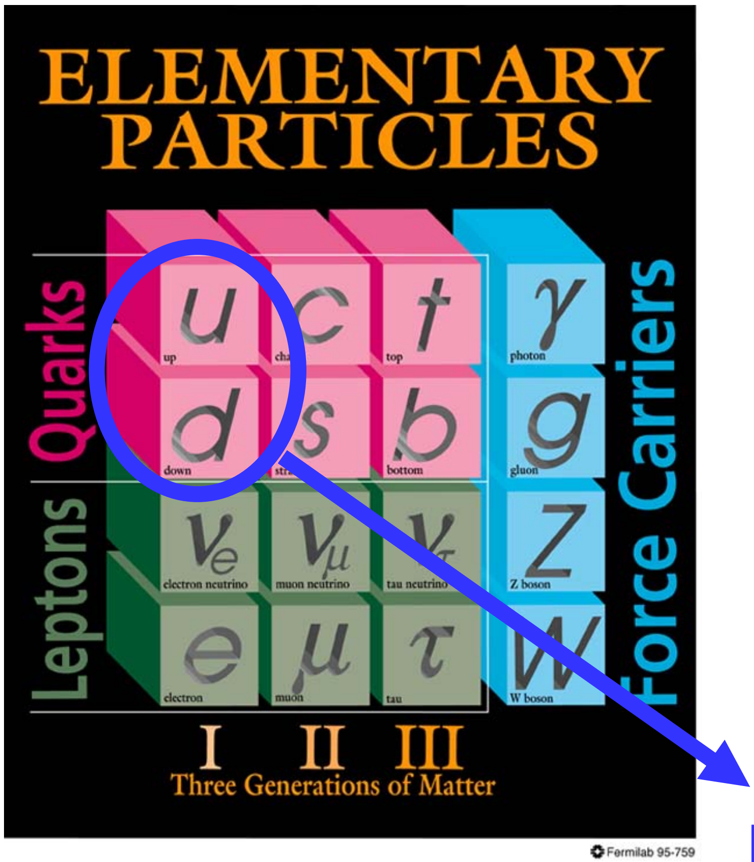


- Extrapolating back, space was small – the Big Bang

- Other dimensions could exist but still be small. In fact, string theory (quantum physics + gravity) *requires* 6 extra spatial dimensions.

- How can we test this possibility?

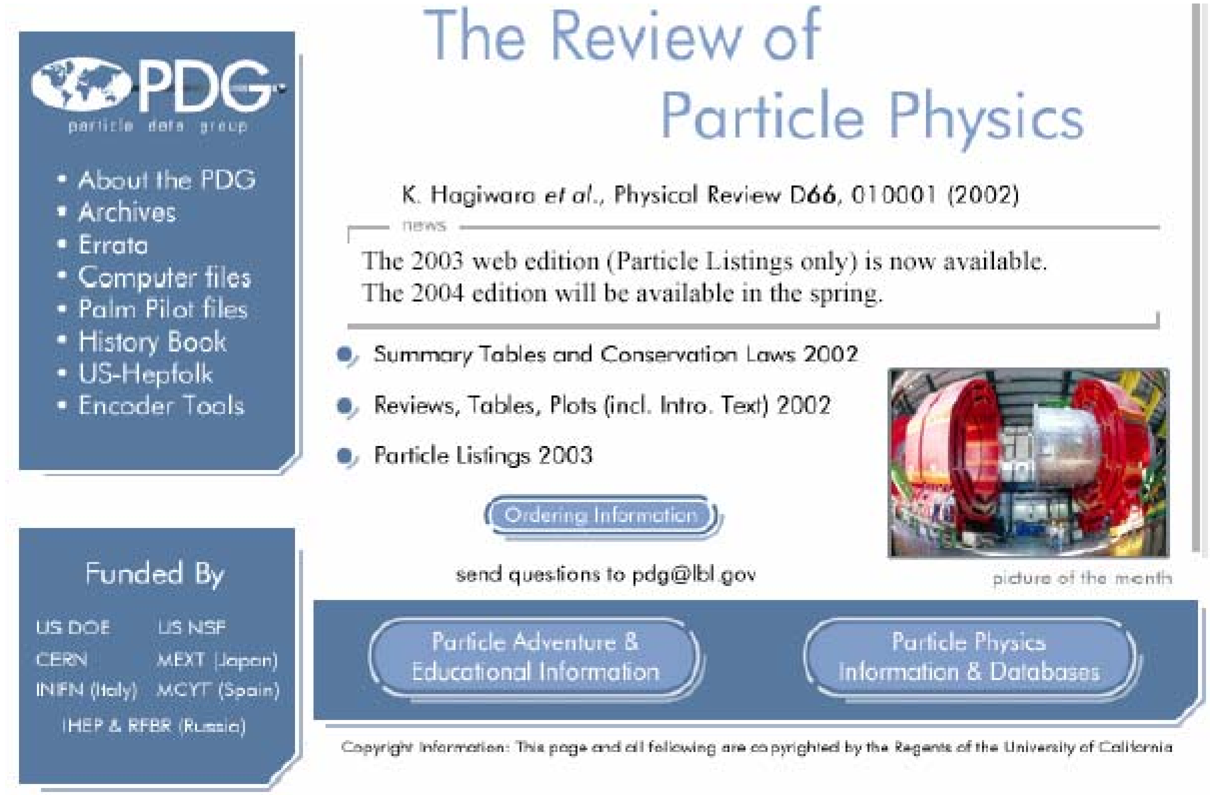
Standard Model of Particle Physics



protons, neutrons

Particle	Force
γ photon	E&M
g gluon	Strong
Z *W*	Weak

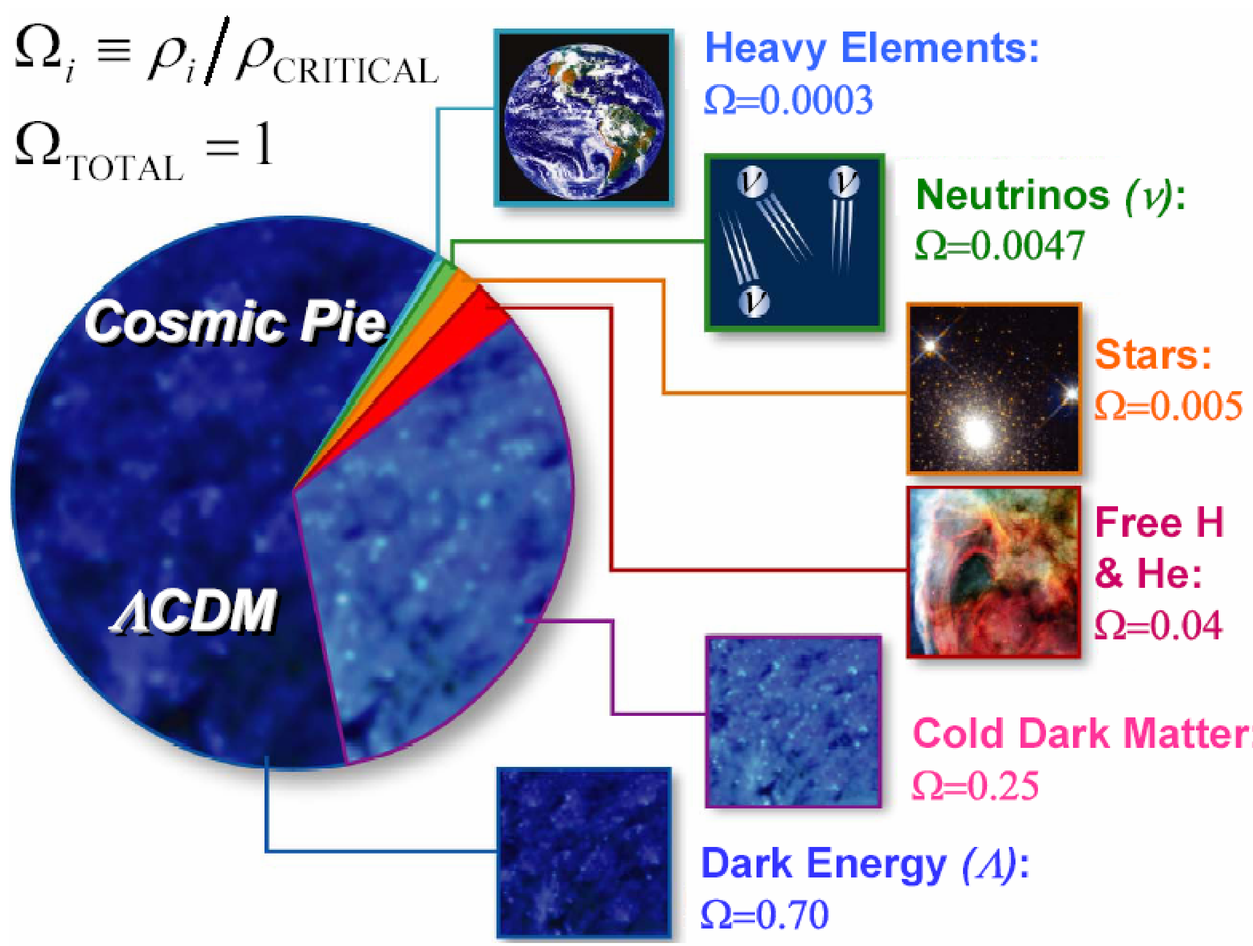
Precise Confirmation



Explains all measured properties of elementary particles down to 10^{-16} m.

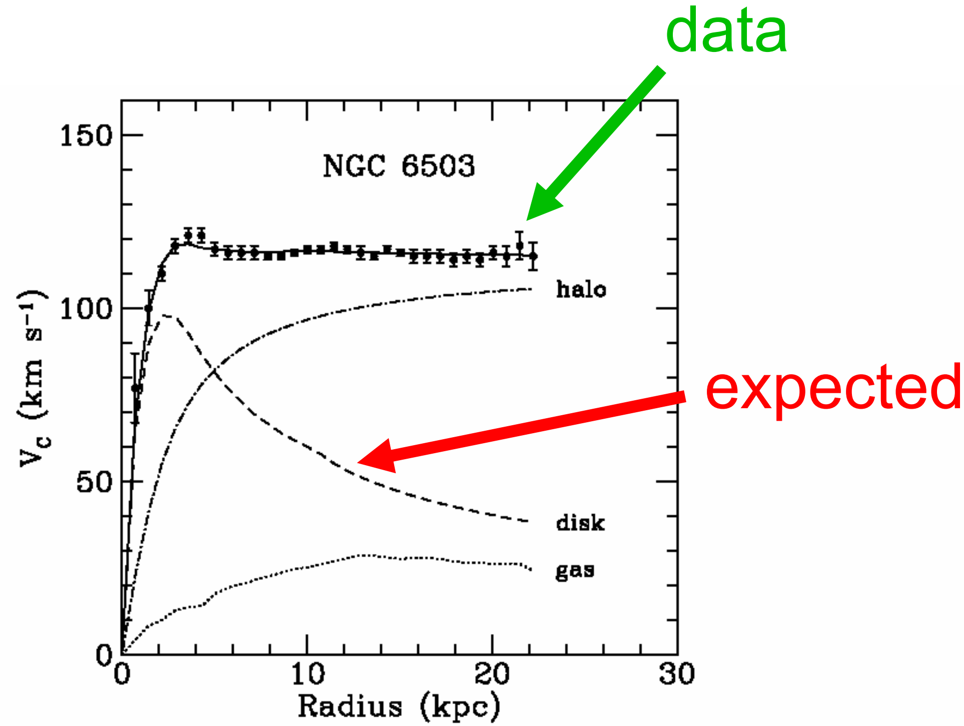
Standard Model of Cosmology

- c. 2003
- Explains data up to lengths of 10^{26} m



What’s Wrong with these Standard Models?

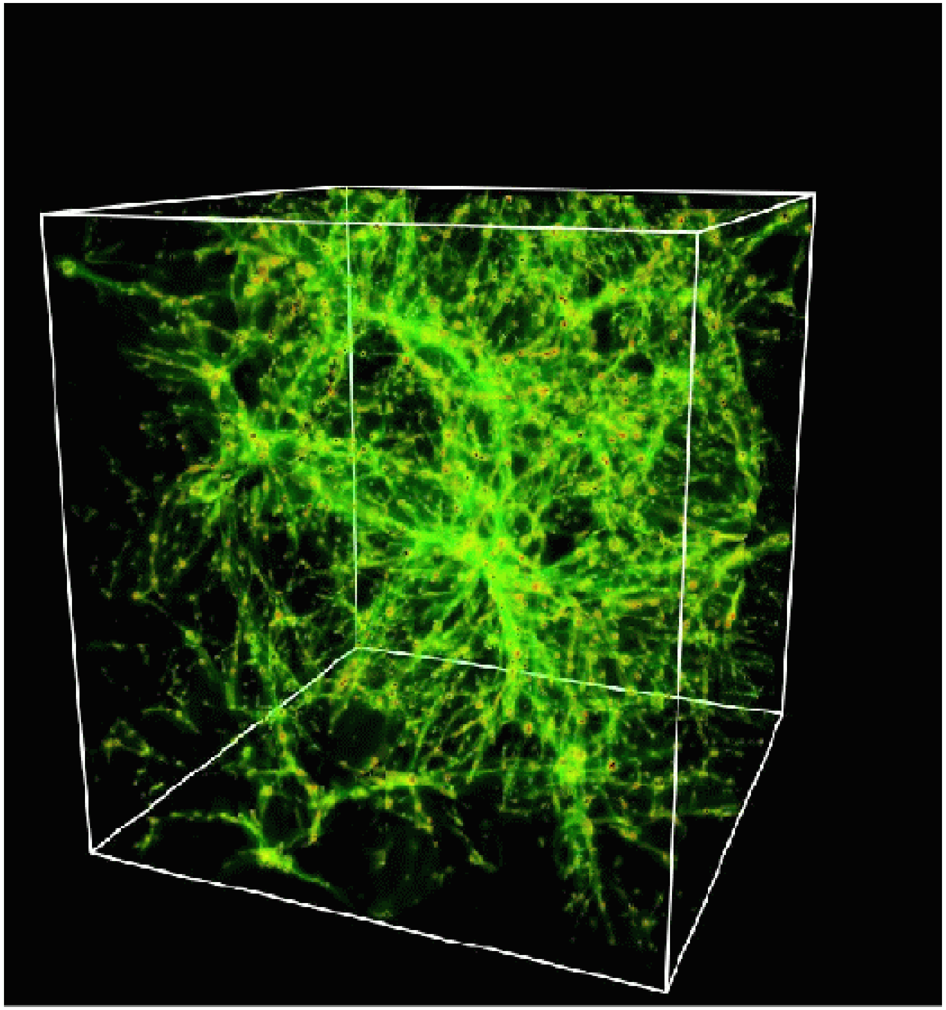
Dark matter is required to hold galaxies together



Begeman, Broeils, Sanders (1991)

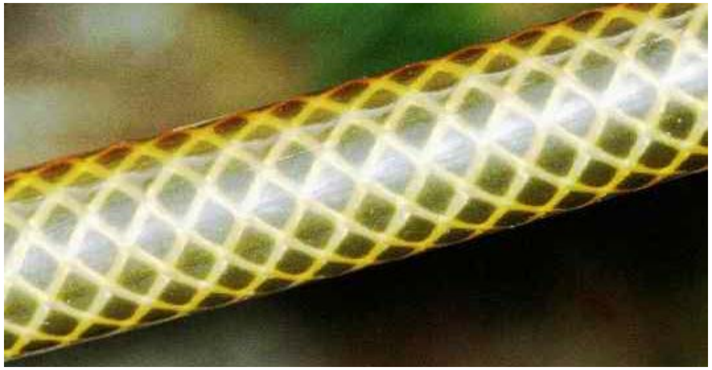
$$\frac{Mv^2}{r} = \frac{GMM_{\text{tot}}}{r^2} \Rightarrow v \sim r^{-1/2}$$

- *A lot* of dark matter is required to hold galaxies together
- It cannot all be made of protons
- It must be neutral, stable, heavy
- It must be some new form of matter



Extra Dimensions

- Suppose all particles propagate in extra dimensions, but these are curled up in circles.
- We will not notice them if the circles are very small.

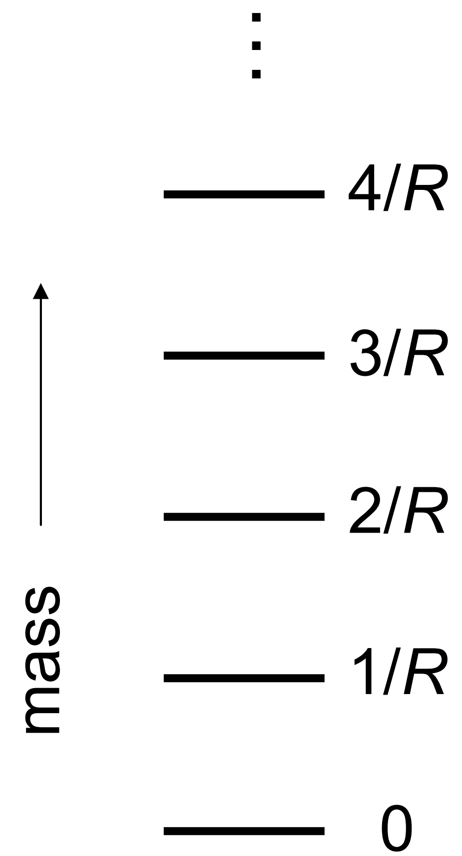


Extra Dimensional Matter

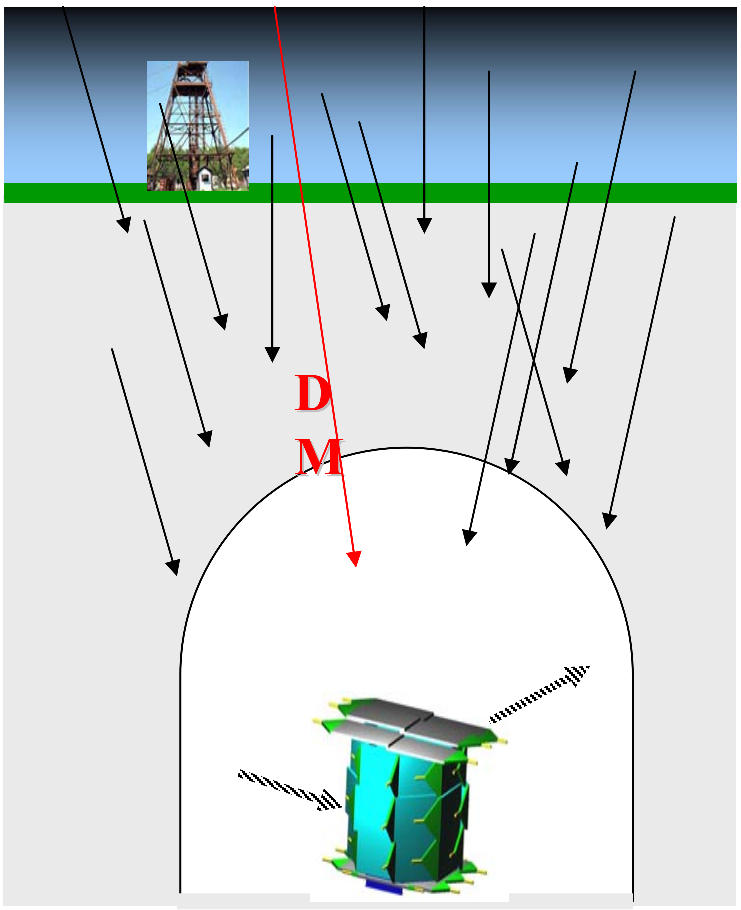
- However, the momentum in the extra directions will be quantized.
- From our viewpoint, we will see this as new particles with masses

  $m \sim 0, 1/R, 2/R, 3/R, 4/R, \ldots$

  Each known particle has a copy at each mass.
- One of these could be the dark matter!



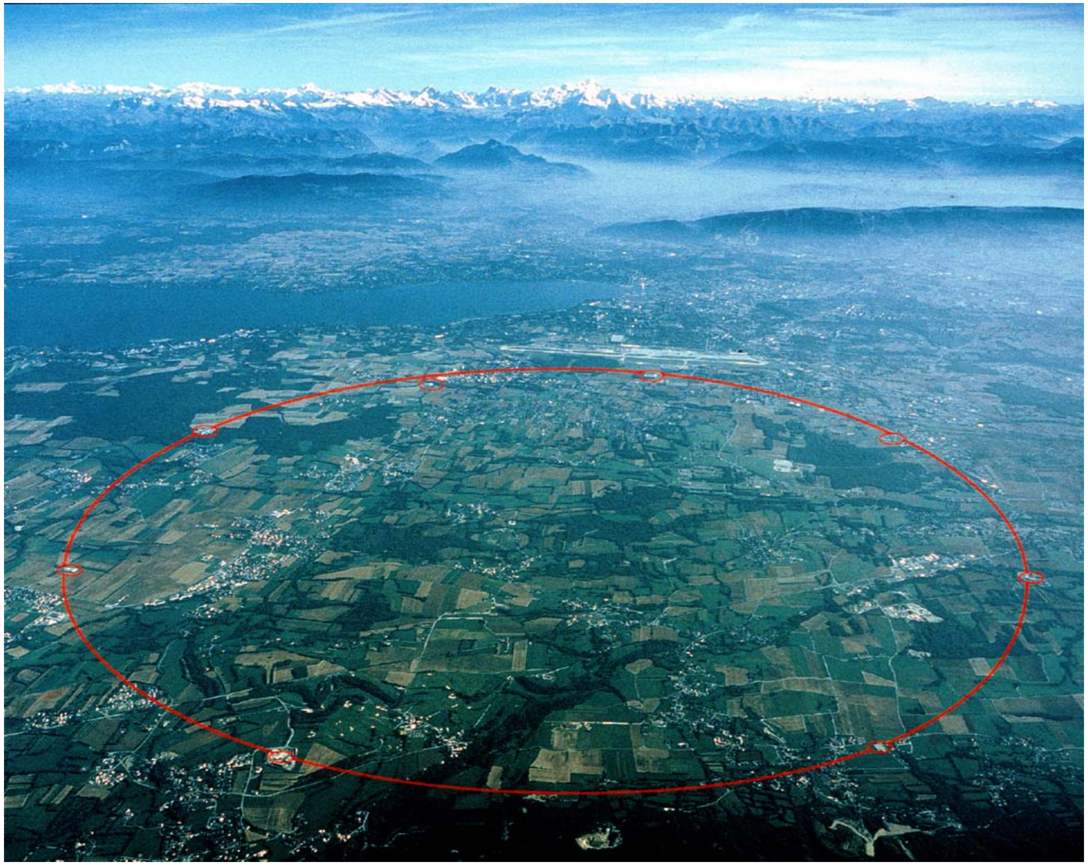
Dark Matter Detection

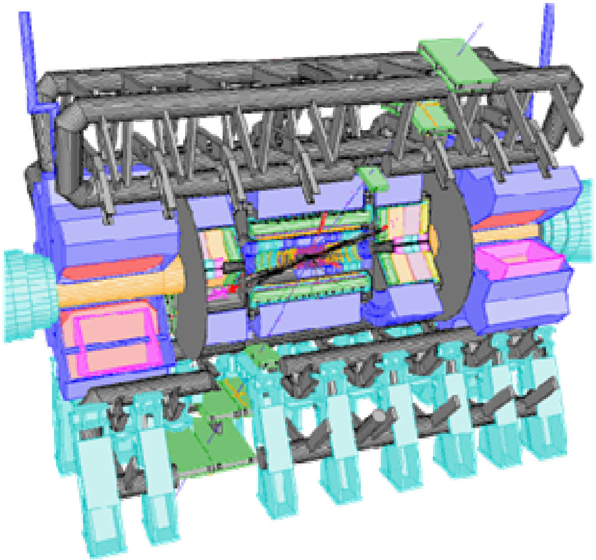


CDMS in the Soudan mine
½ mile underground in Minnesota

Dark Matter at Colliders

Large Hadron Collider at CERN, Geneva





What else is wrong with the Standard Models?

- What about gravity !?
- Many deep problems, but one obvious one:

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

- More quantitatively:

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

For two protons,

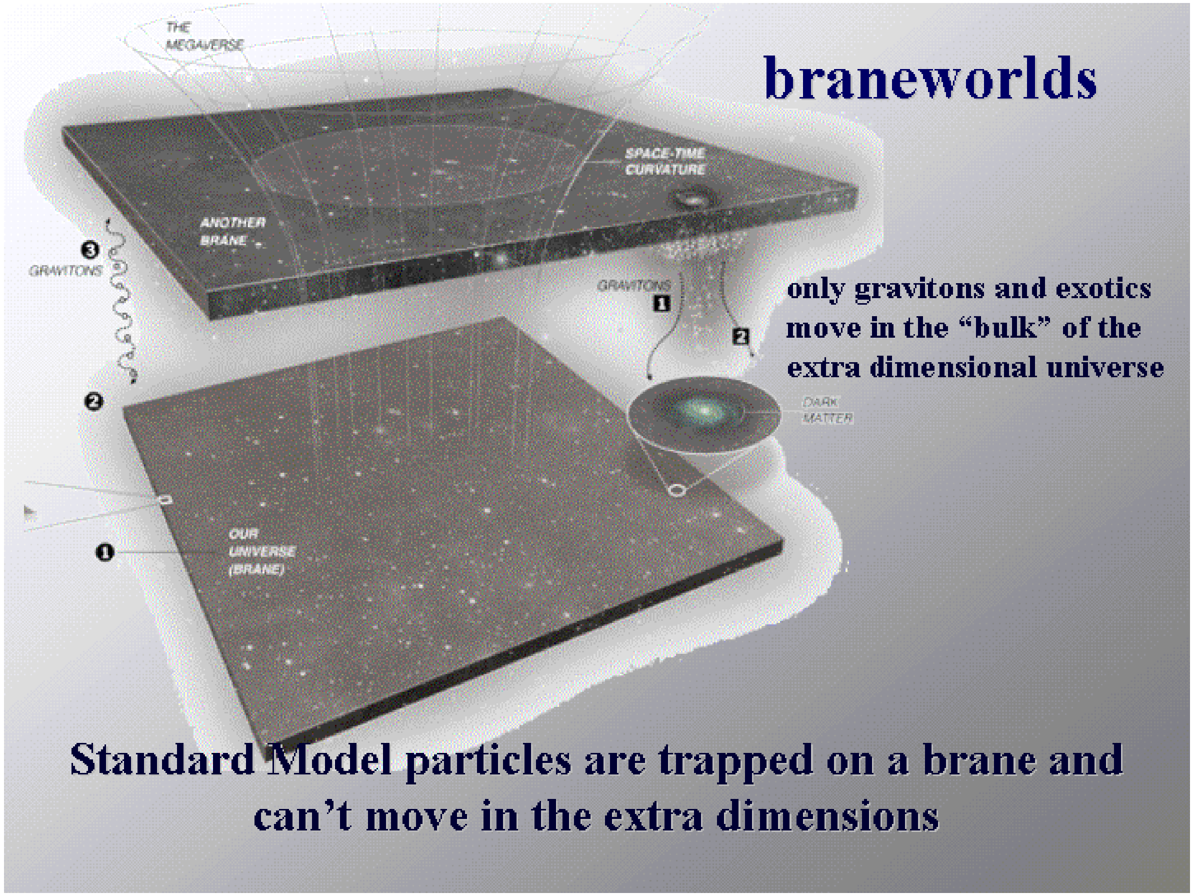
$$F_{\mathrm{gravity}} \sim 10^{-36} F_{\mathrm{EM}}$$

- Very likely, we are missing something important. Why is gravity so weak?

- Maybe it isn't…

Extra Dimensions

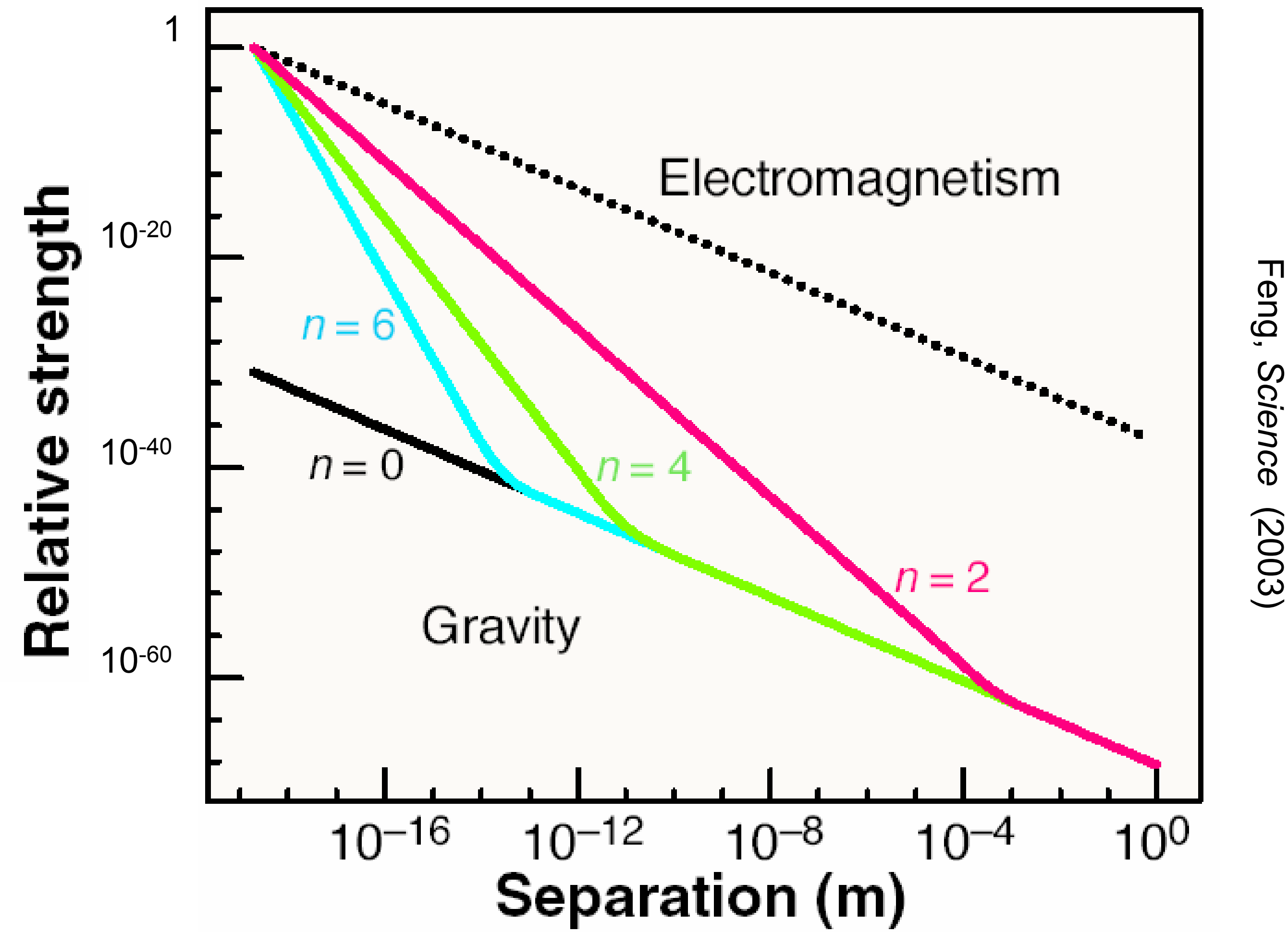
- Suppose our world is only a slice of the whole universe



Newton's Law

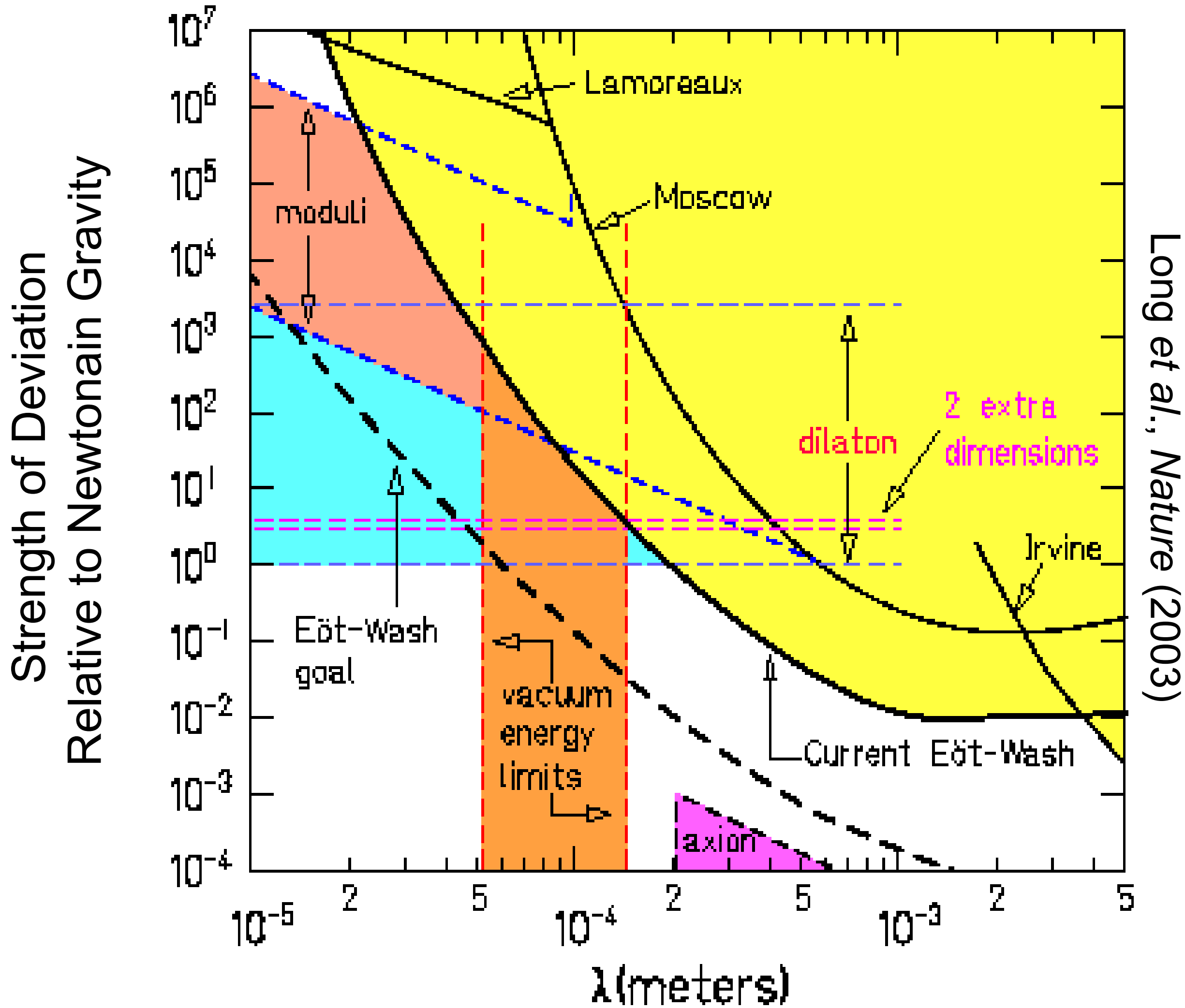
- In this case, gravity may be strong but appear weak only because its strength is diluted by extra dimensions.

- $F_{gravity} \sim 1/r^{2+n}$ for small lengths, where n is the number of extra dimensions. Can this be true?



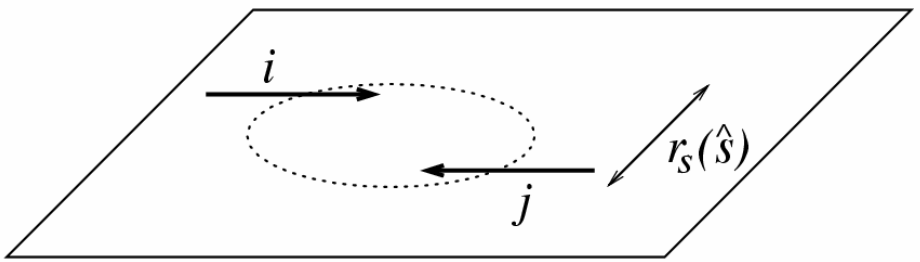
Electromagnetism
Gravity
n = 6
n = 4
n = 2
n = 0
1
10-20
10-40
10-60
Relative strength
10−16
10−12
10−8
10−4
10^0
Separation (m)
Feng, Science (2003)

Tests of Newton's Law



Black Holes

- If two particles pass close enough with enough energy, they will form a microscopic black hole



- For 3 spatial dimensions, gravity is too weak for this to happen. But with extra dimensions, gravity becomes stronger, micro black holes can be created in particle collisions!

Micro Black Holes

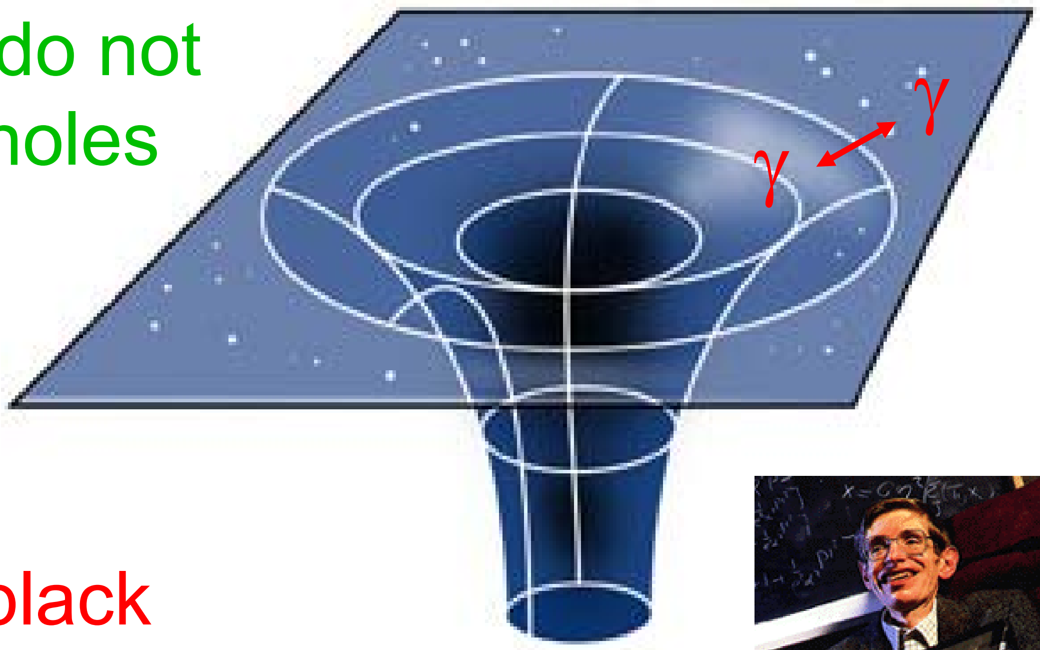
- Where can we find them?
- What is the production rate?
- How will we know if we’ve seen one?

S. Harris

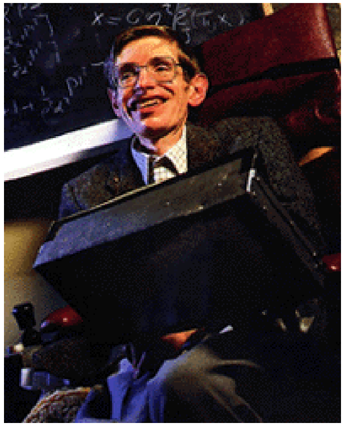
"It's black, and it looks like a hole. I'd say it's a black hole."

Black Holes

- Classically, light and other particles do not escape; black holes are black.

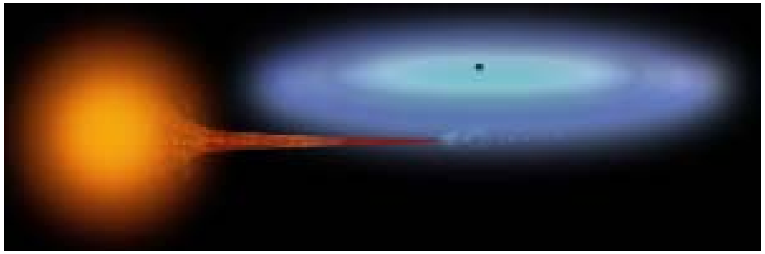


- But quantum mechanically, black holes Hawking radiate; black holes emit light!

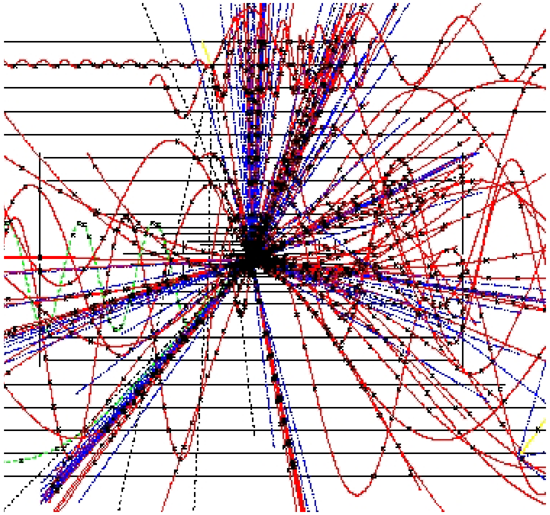


Black Hole Evaporation

- "Normal" black holes:
  - Mass: $M_{BH} \sim M_{sun}$
  - Size: kilometer
  - Temperature: 0.01 K
  - Lifetime: ~ forever



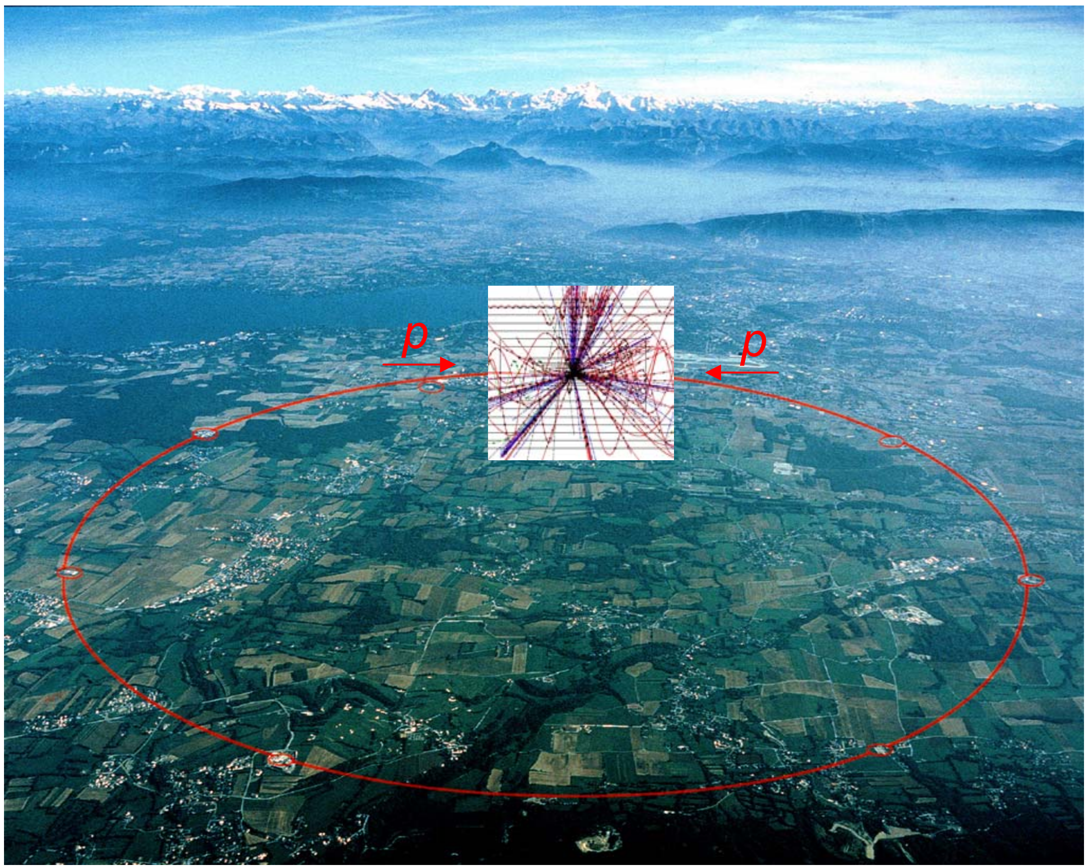
- Micro black holes:
  - Mass: $M_{BH} \sim 1000\ M_{proton}$
  - Size: 10^{-18} m
  - Temperature: 10^{16} K
  - Lifetime: 10^{-27} s

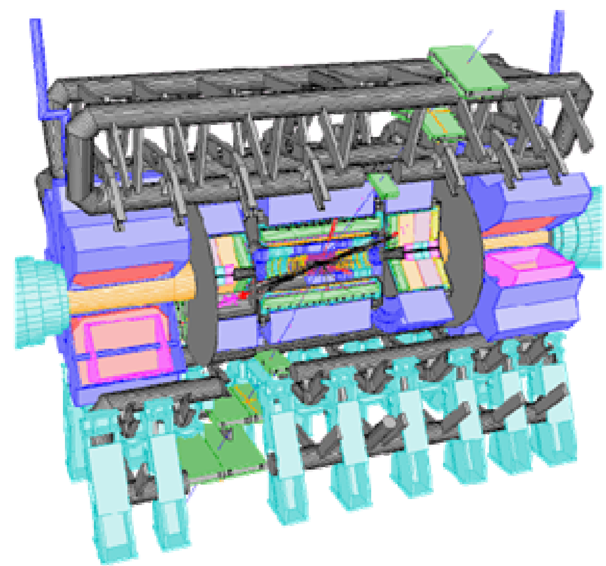


They explode!

Black Holes at Colliders

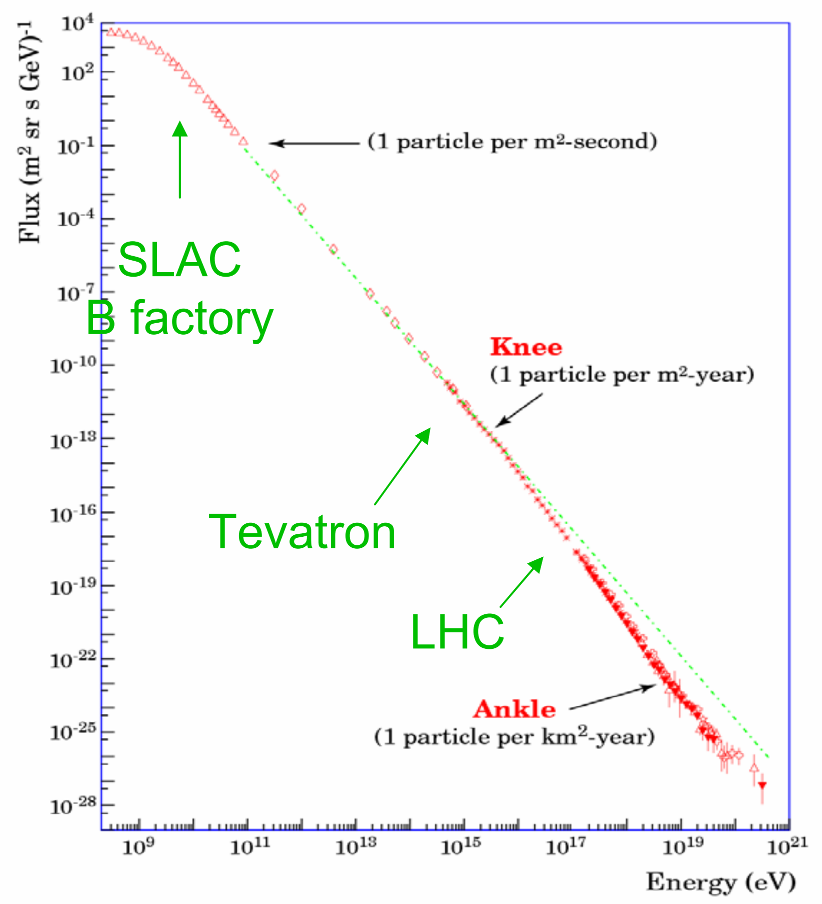
Large Hadron Collider at CERN, Geneva





Black Holes from Cosmic Rays

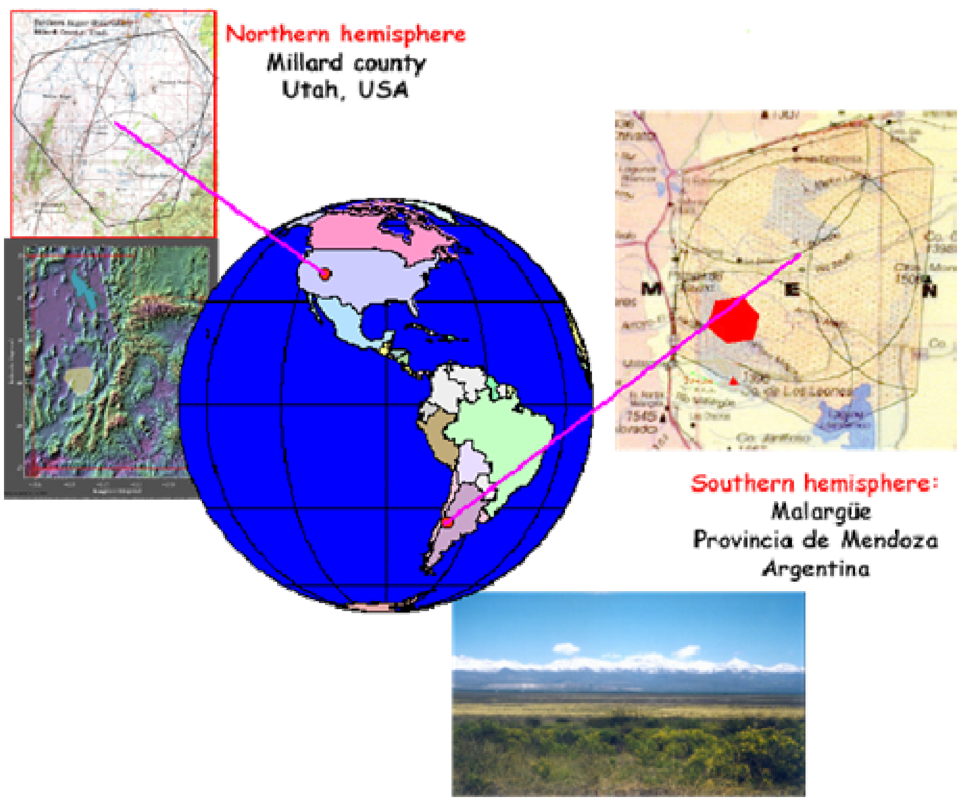
- Cosmic rays – Nature's free collider
- Observed events with higher energies than any collider
- But meager rates. Can we harness this energy?



Kampert, Swordy (2001)

Black Holes from Cosmic Rays

The Auger Observatory in Argentina

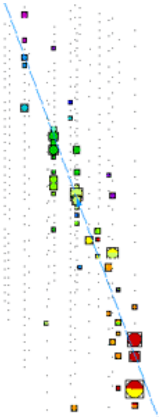


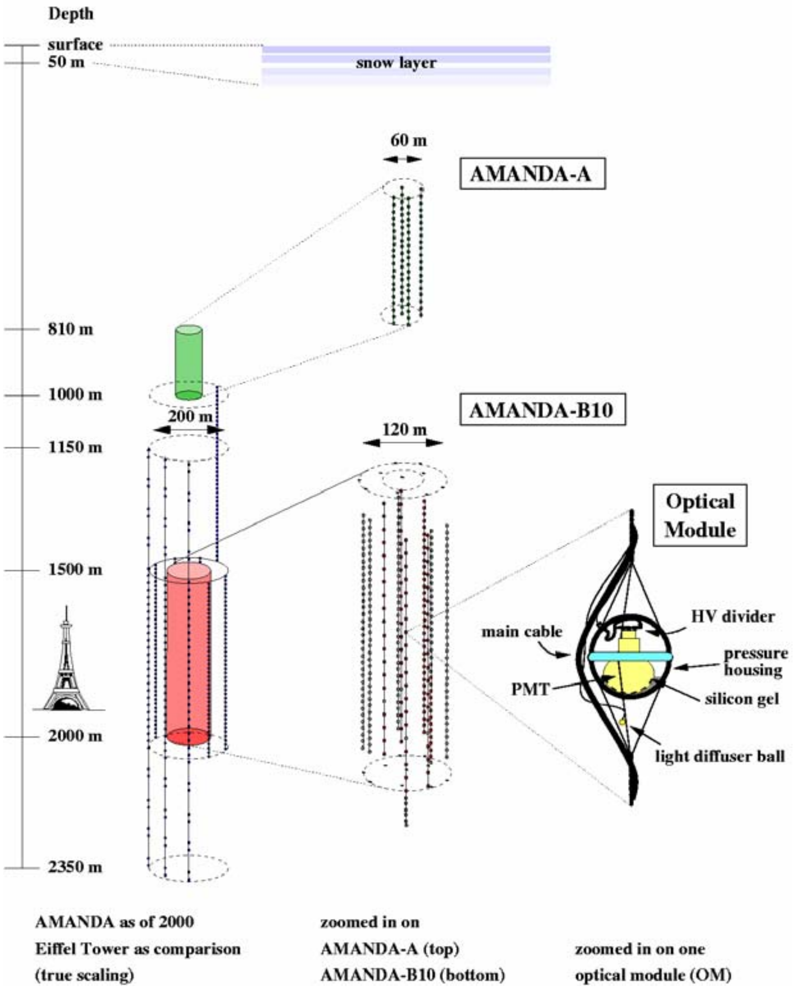
COLLISION COURSE CREATES MICROSCOPIC ‘BLACK HOLES’, 16 January 2002:

“…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.”

Black Holes from Cosmic Rays

AMANDA at the South Pole





Summary

- We are entering a golden age of synergy between studies of the very small and the very big.
- Extra dimensions may solve many known fundamental problems.
- Diverse searches are ongoing worldwide.
- Stay tuned!