Einstein, String Theory, and the Future

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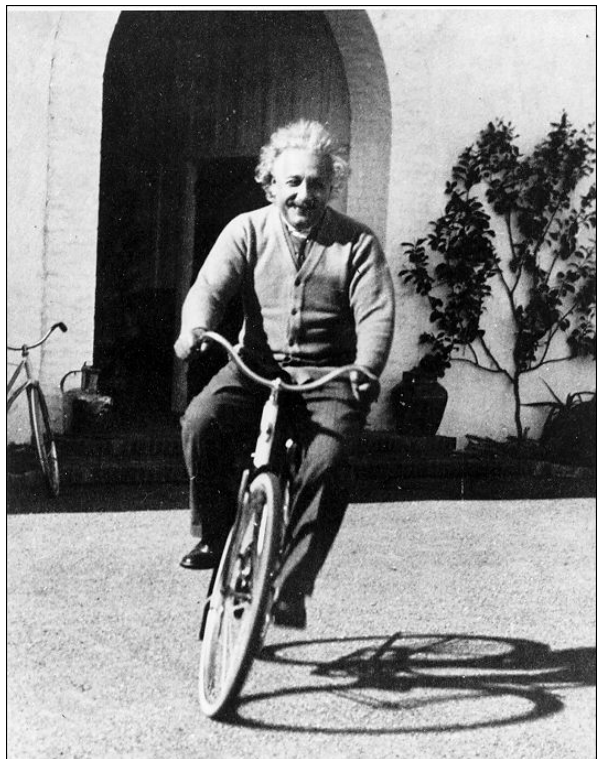
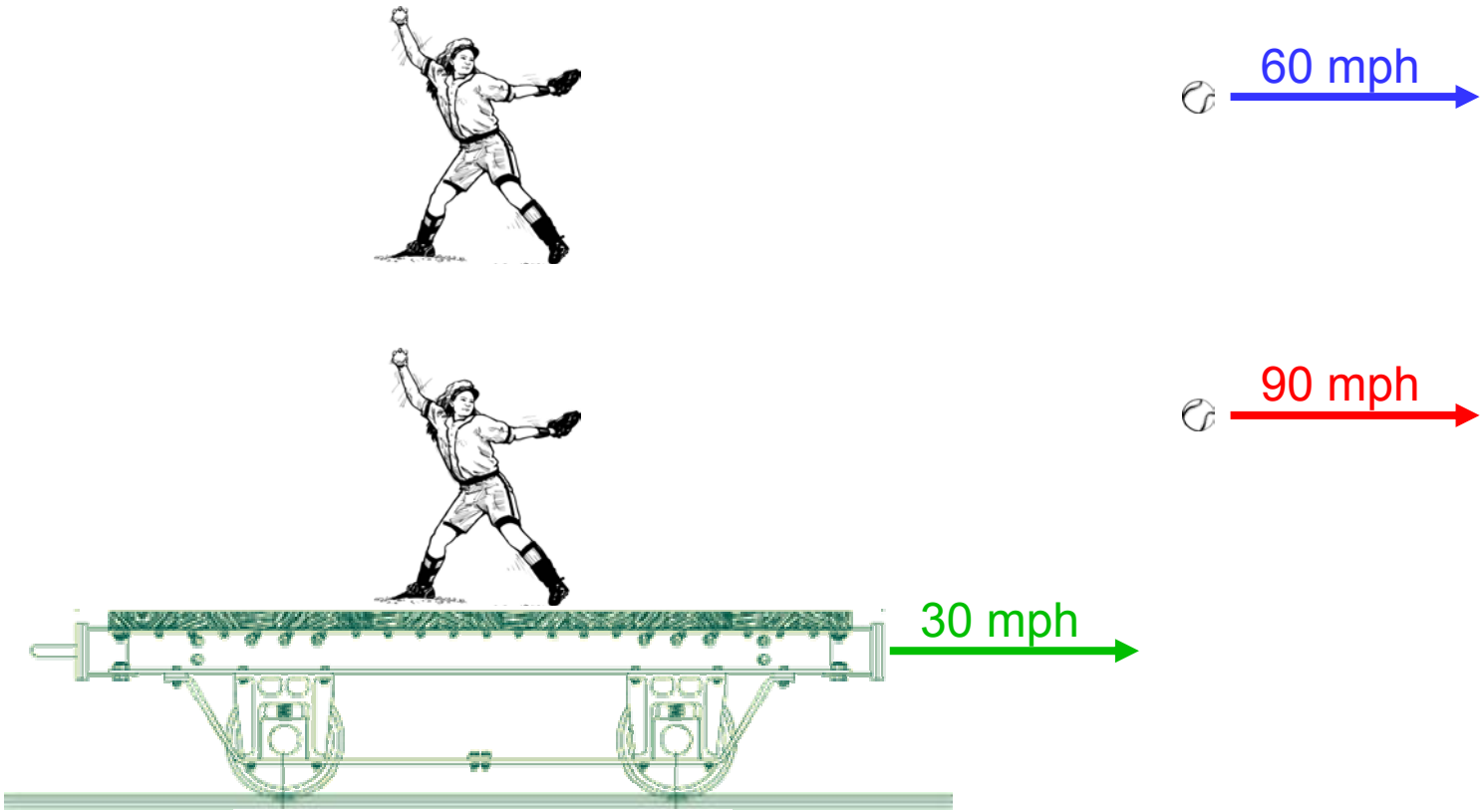
Einstein: A Century of Relativity
Skirball Cultural Center, Los Angeles
29 January 2005

Relativity in a Nutshell

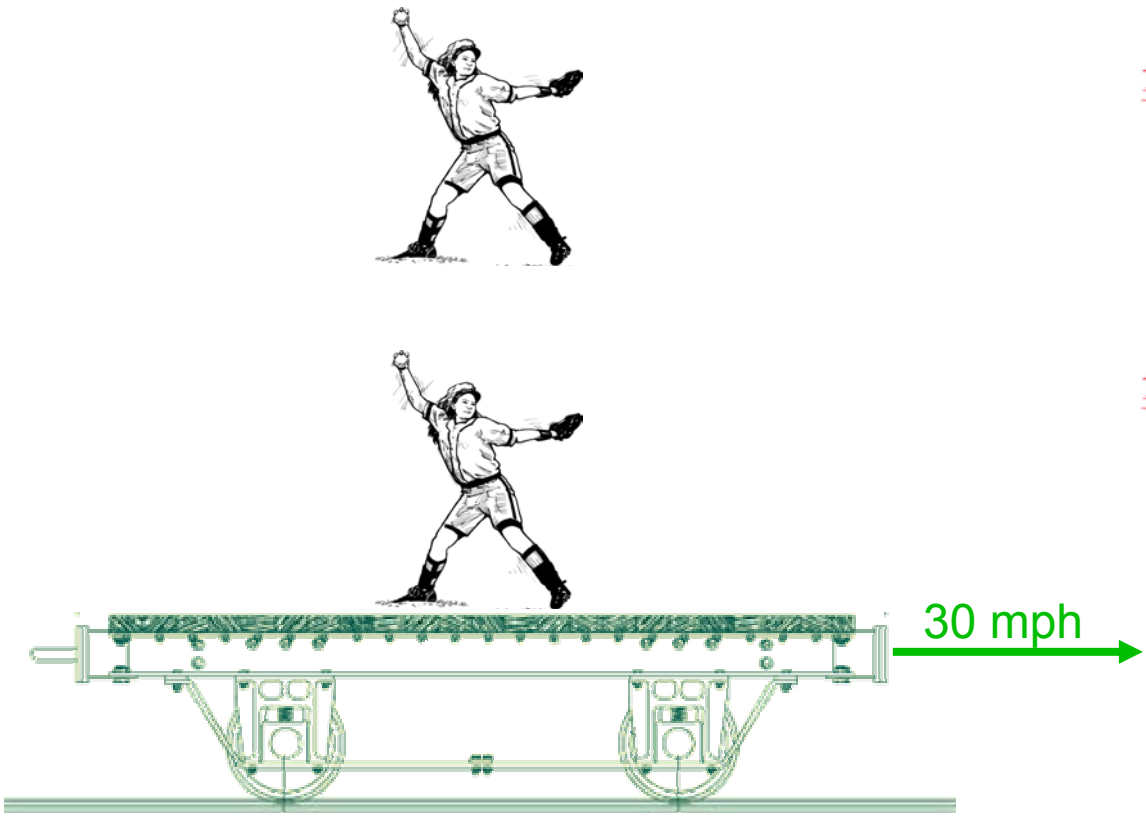


Common Sense Physics



$$V_{new} = V_{old} + V_{train}$$

Weird Physics



$$v_{new} = v_{old}$$

$$v_{new} = \frac{v_{old} + v_{train}}{1 + v_{old} v_{train} / v_{light}^2}$$

small

Classical Physics (1687)

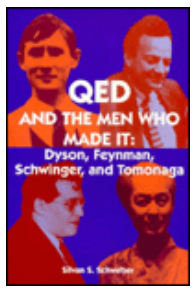
heavy

fast

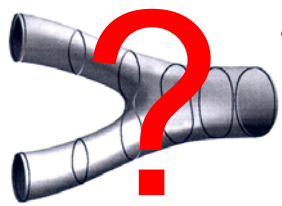
Quantum Mechanics (1905)

Special Relativity (1905)

General Relativity (1915)

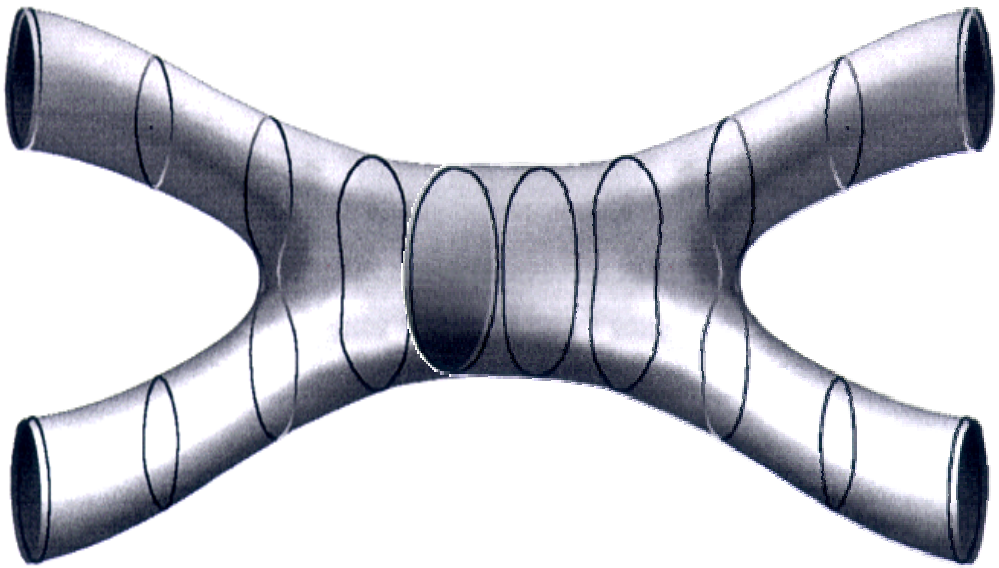


Quantum Field Theory (1940's)

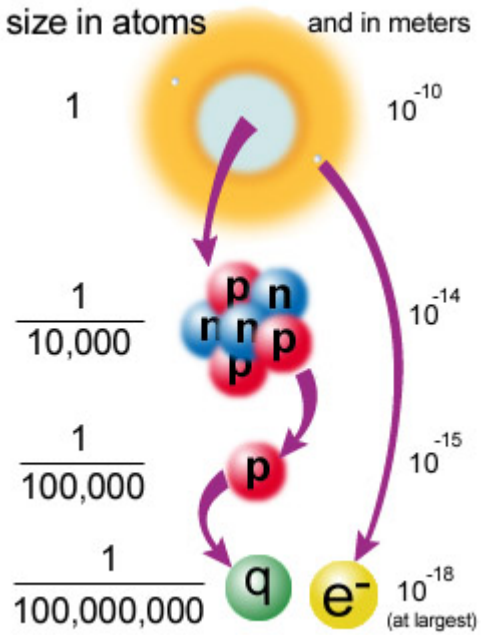


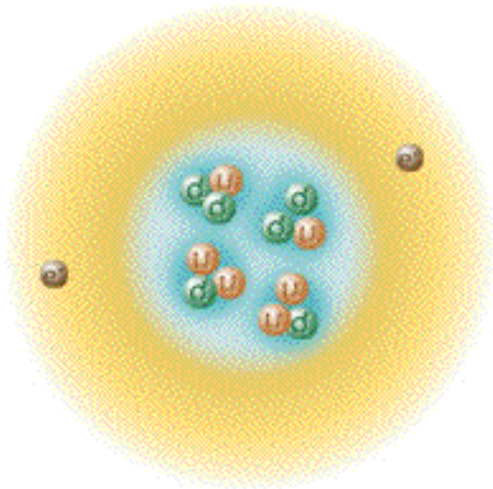
String Theory ?

What is String Theory?

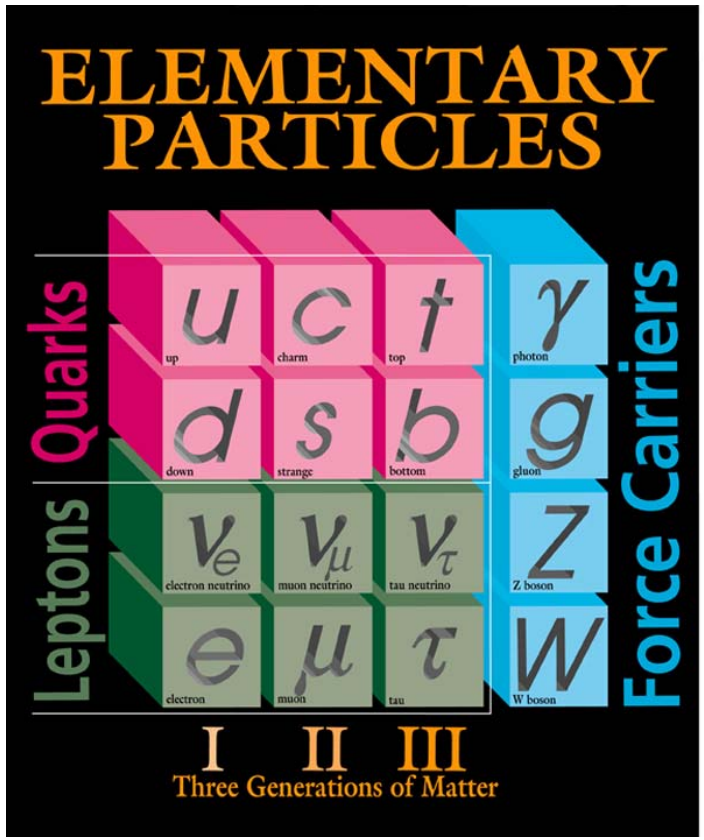


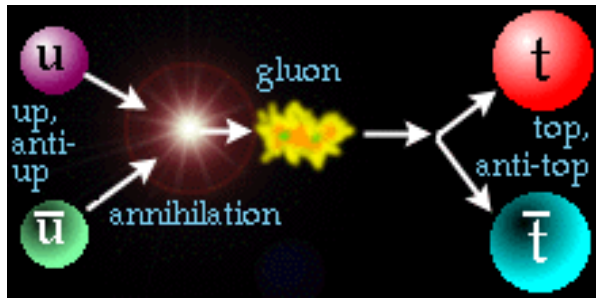
Standard Model of Particle Physics: The Modern Theory of Matter

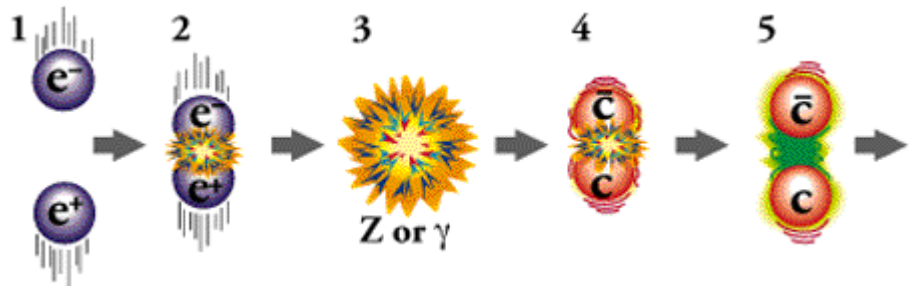




Elementary Particles and Interactions



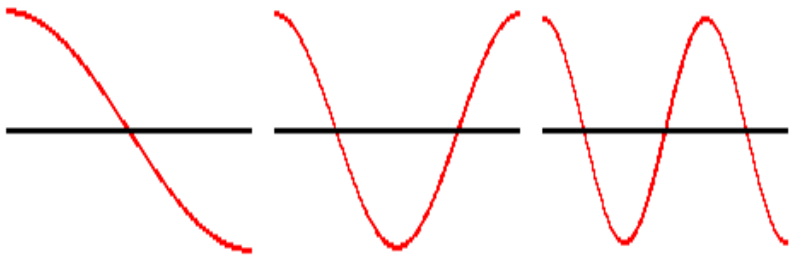


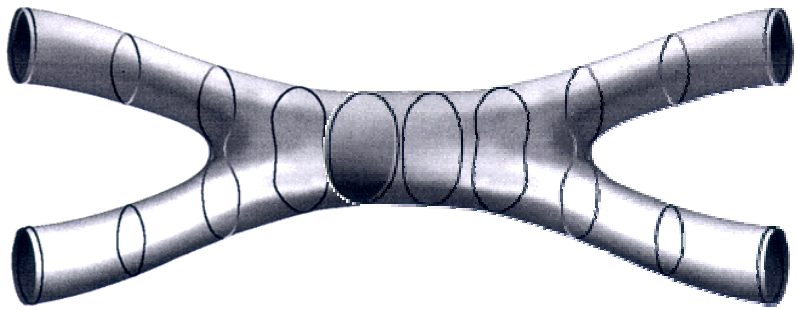


In String Theory, Particles are Strings

Different Vibrations → Different Particles

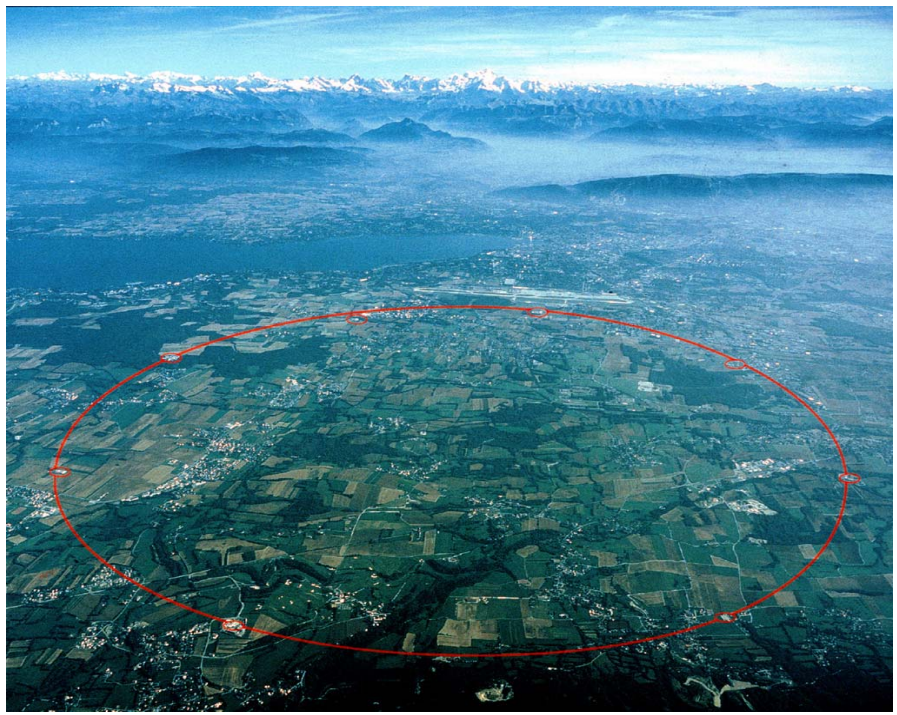
String Combinations → Particle Interactions





String theory realizes Einstein's dream of a unified theory

Is String Theory Right ?



Is String Theory Testable?

- It depends.
- Is it falsifiable?

  No – not yet, anyway.

- Does it predict anything that could have observable consequences?

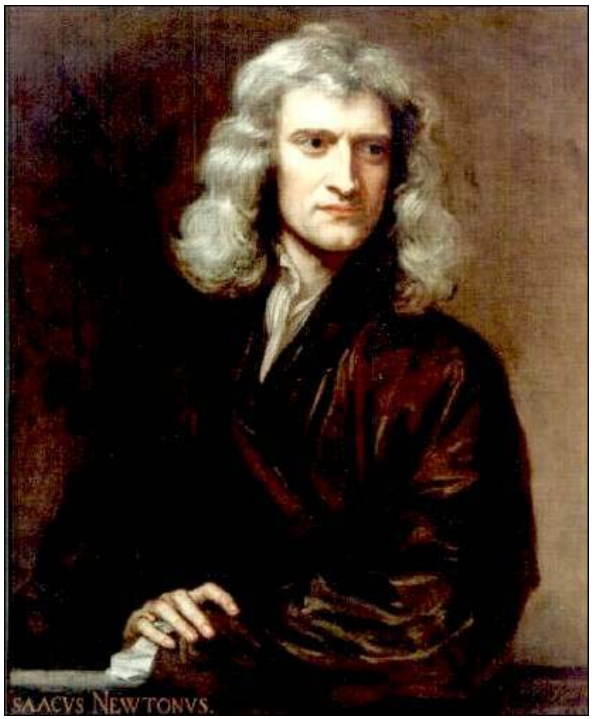
  Yes – string theory → extra dimensions!

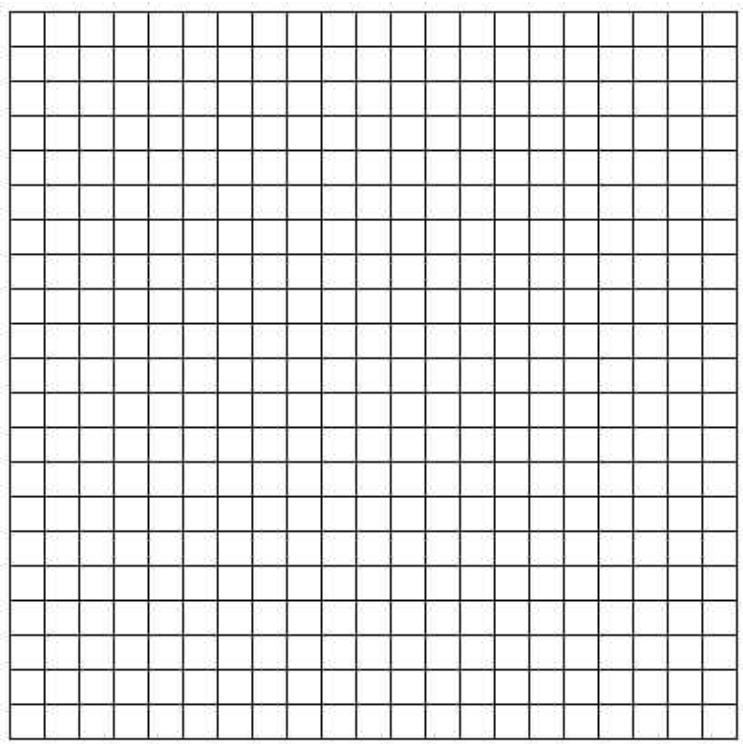
Extra Dimensions

- $(x, y, z, t) + w, v, \ldots$? Science fiction?
- No – a major topic in science today:

  What is our world made of?
  How does gravity work?
- How did this happen?

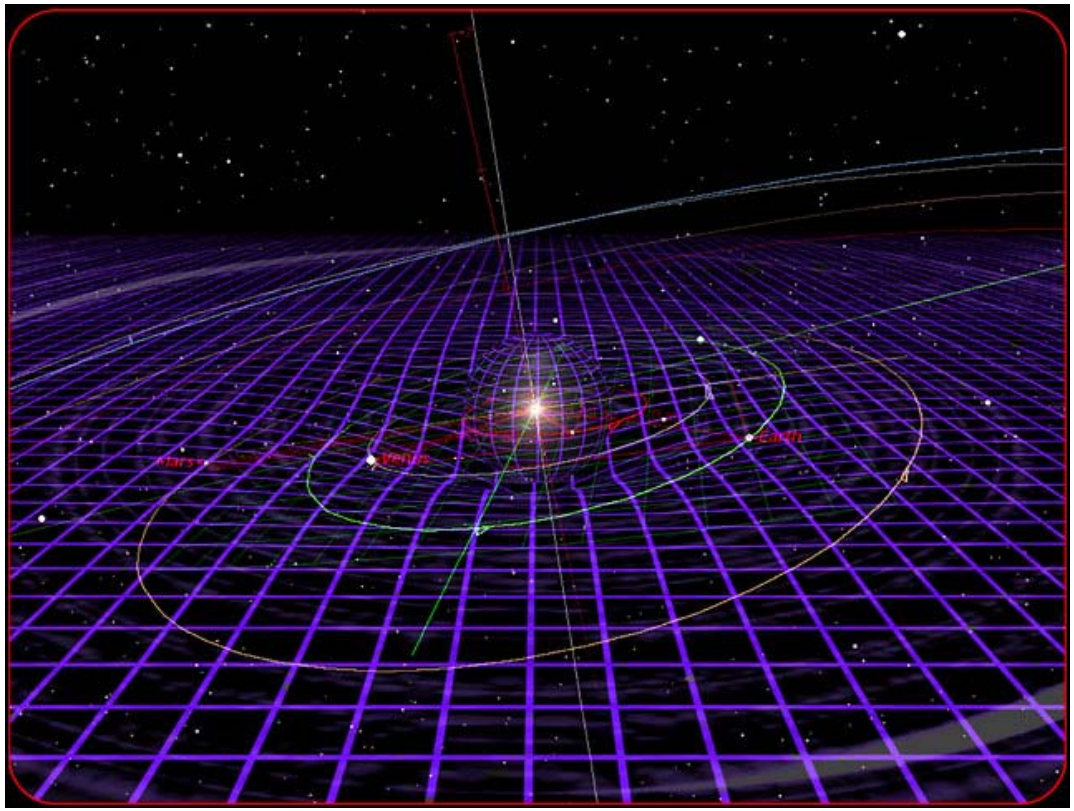
Isaac Newton





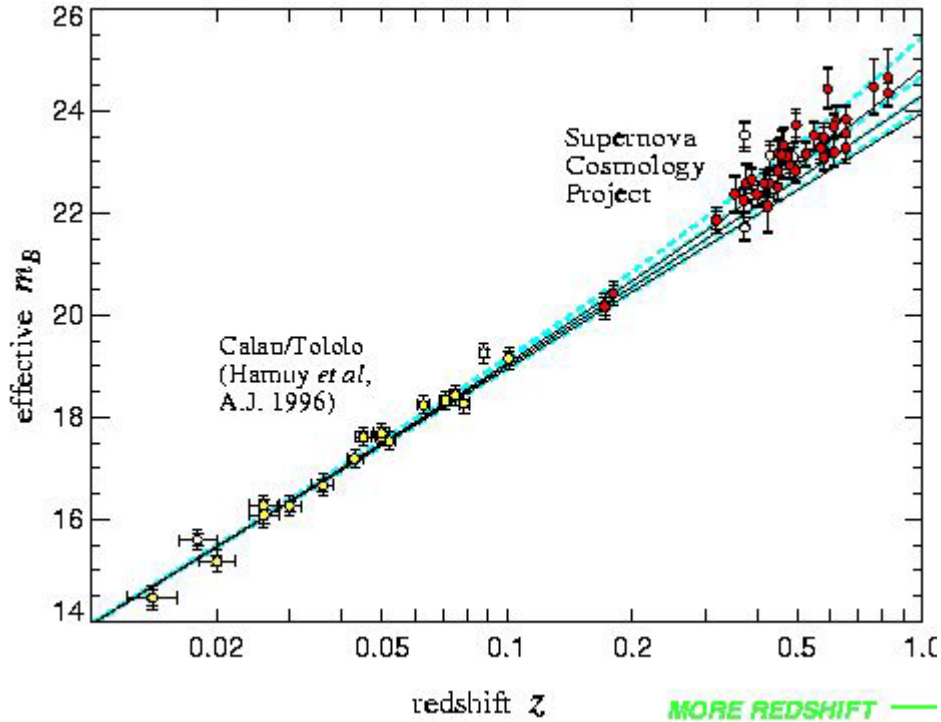
1687: Space and time are the static stage on which physical processes act

Albert Einsten



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

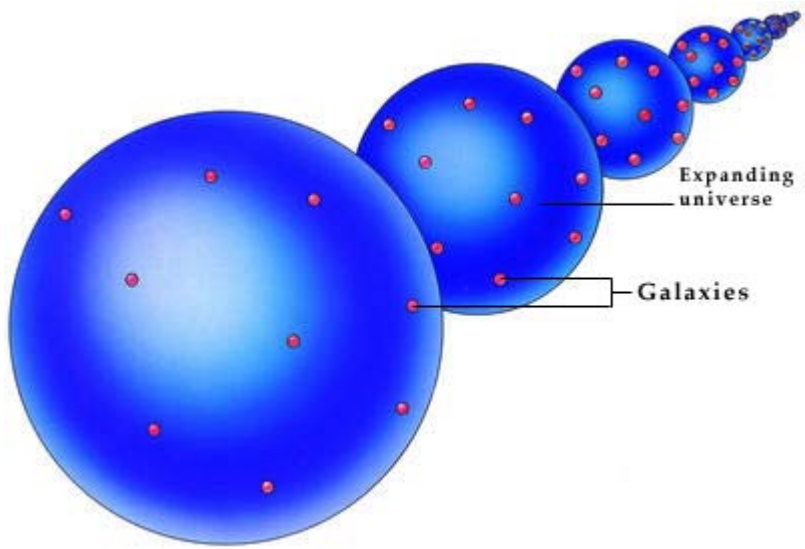
Edwin Hubble



1929: The universe is expanding

The Big Bang

- The universe does not expand into space – space itself expands
- Extrapolating back, space was small – the Big Bang

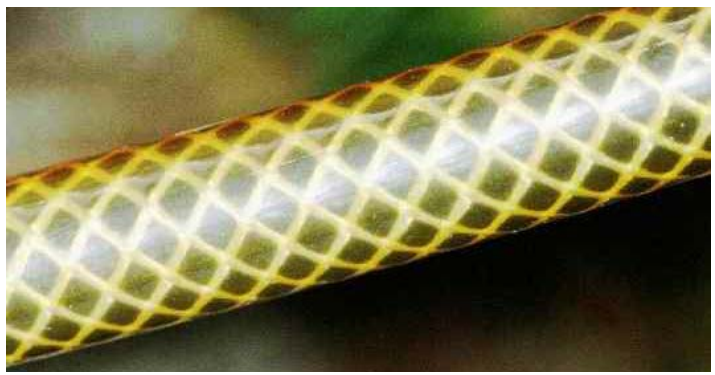


- Other dimensions could exist but still be small. String theory requires 6 extra dimensions.
- How can we test this possibility?

Dark Matter

Small 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.

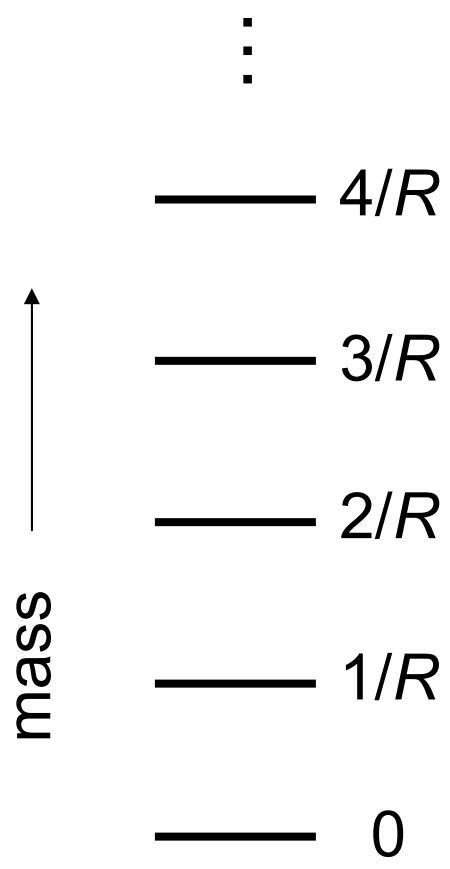


Extra Dimensional Matter

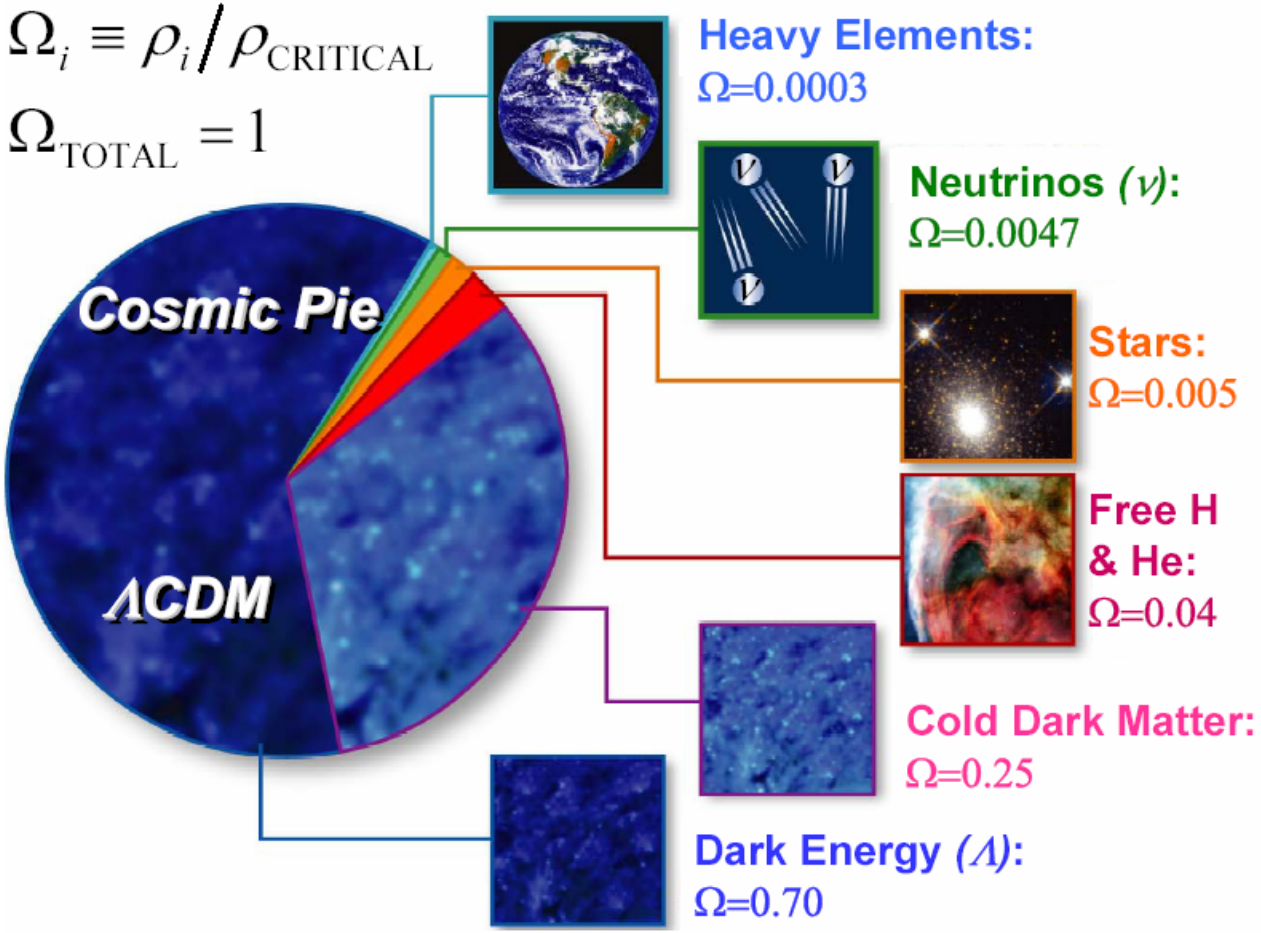
- However, particles can move in the extra directions.
- From our viewpoint, we will see this as new particles with masses

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

  Each known particle has an infinite "tower" of copies.
- Extra dimensions → many new particles – what good are these?

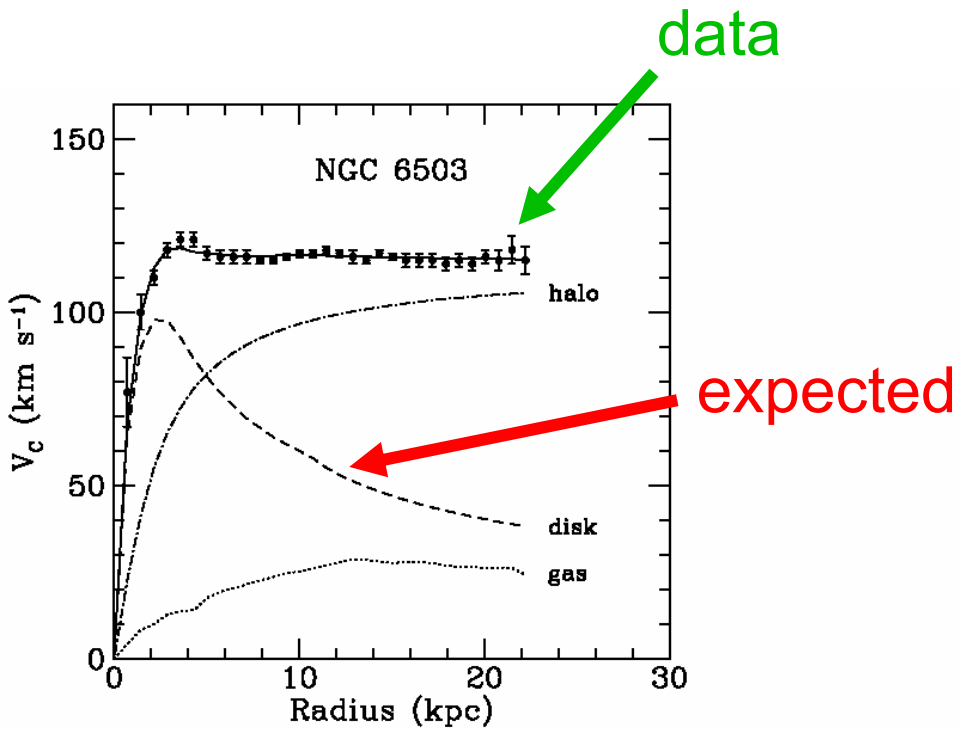


Standard Model of Cosmology



Dark Matter

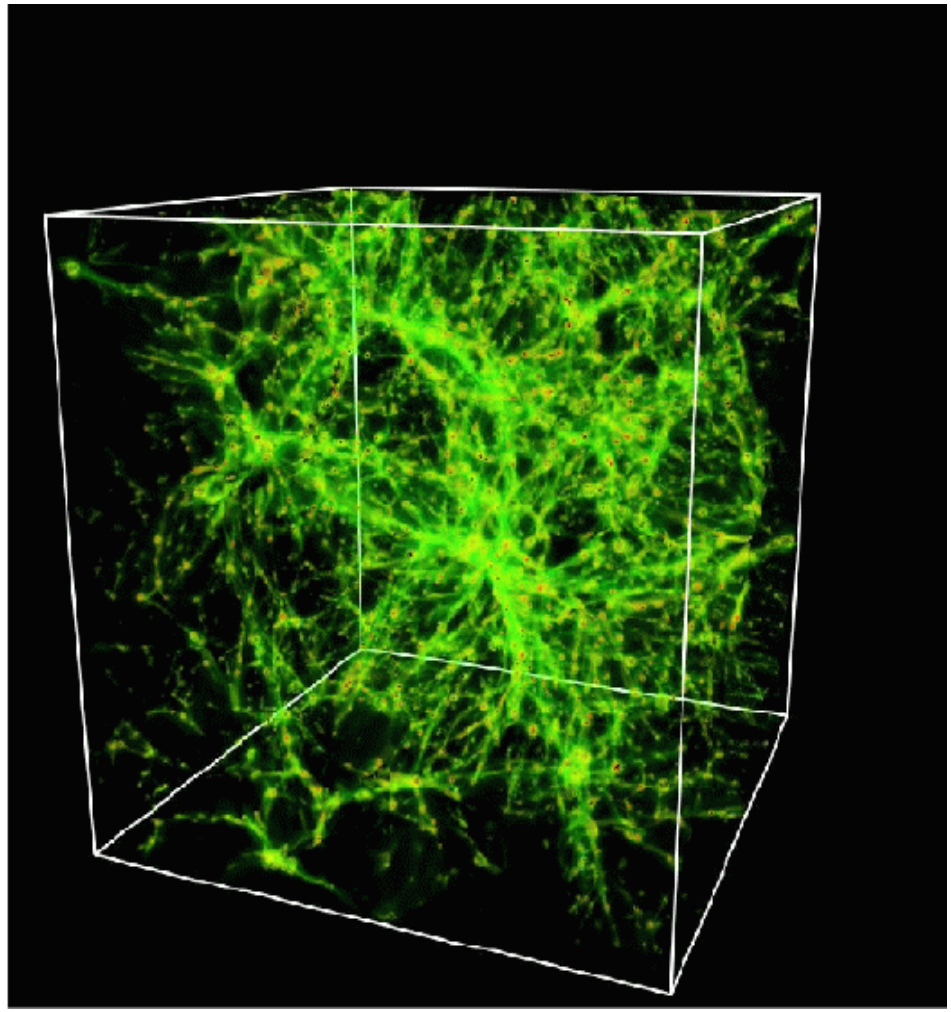
Dark matter is required to hold galaxies together



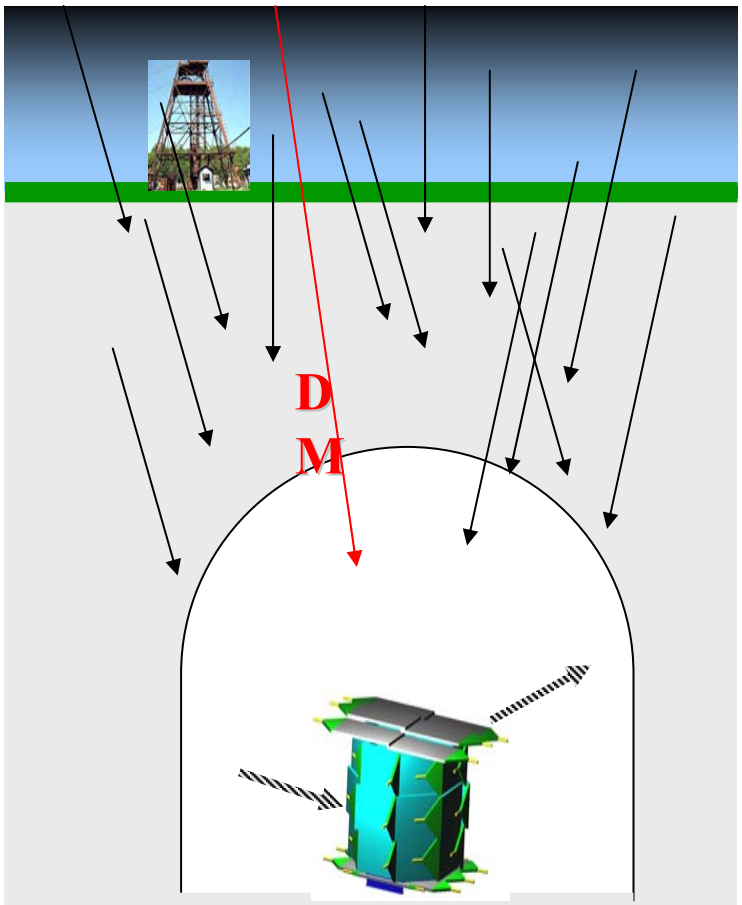
Begeman, Broeils, Sanders (1991)

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

- *A lot* of dark matter is required to hold galaxies together
- It cannot all be made of known particles
- It must be some new form of matter – maybe a sign of extra dimensions!



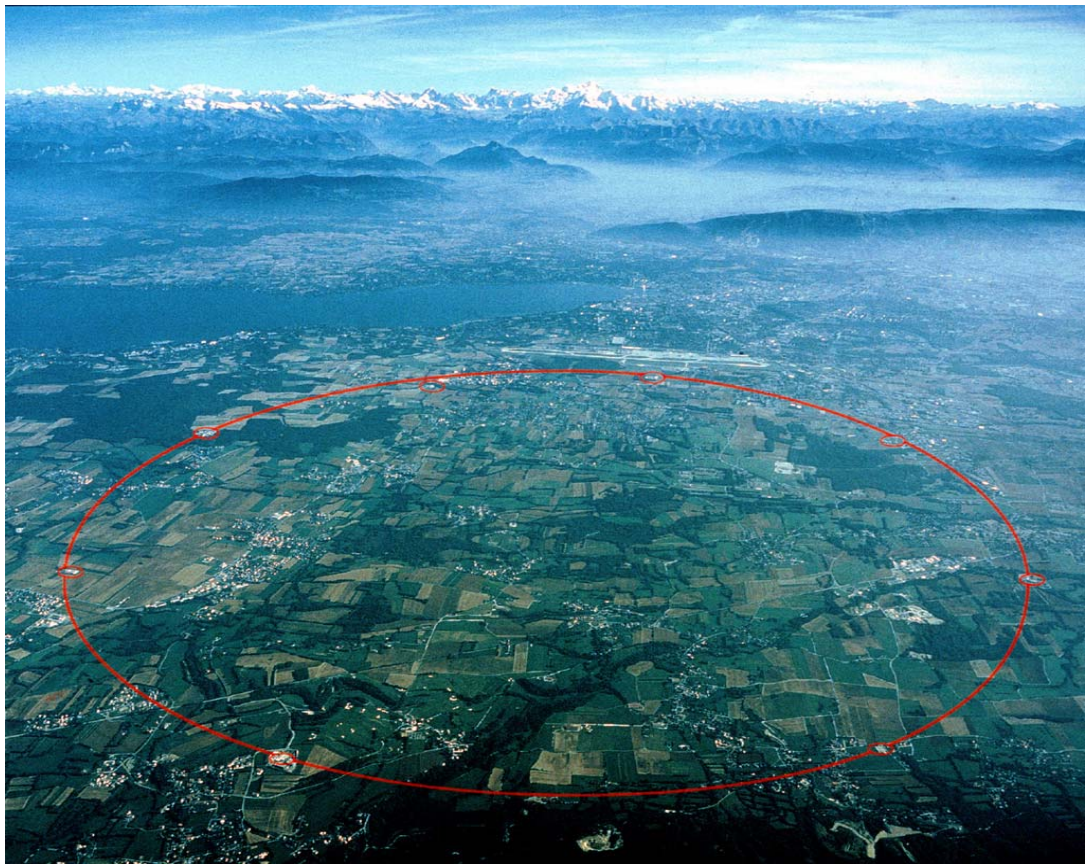
Dark Matter Detection

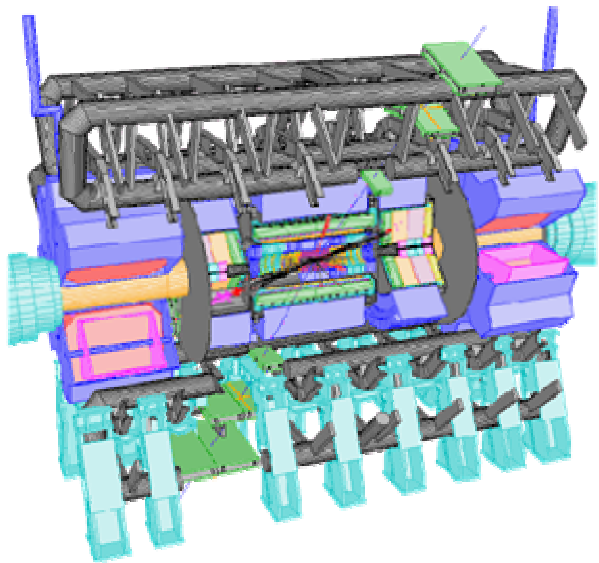


CDMS in the Soudan mine
½ mile underground in Minnesota

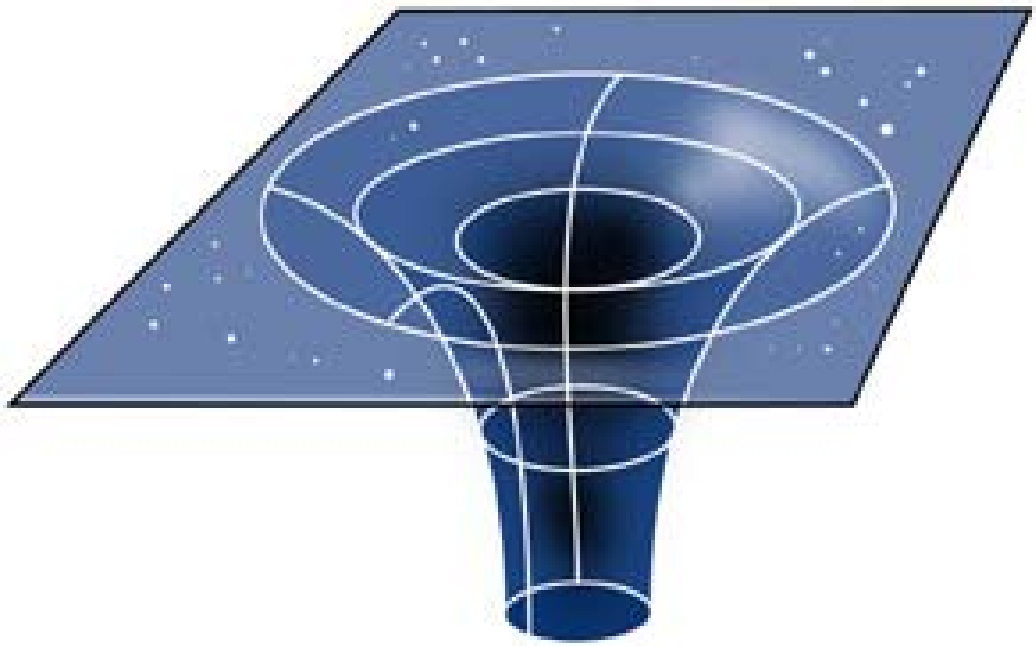
Dark Matter at Colliders

Large Hadron Collider at CERN, Geneva





Strong Gravity and Black Holes



Gravity

- Gravity is the least understood force.
- 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, for separation distance *r* ,

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

For two protons,

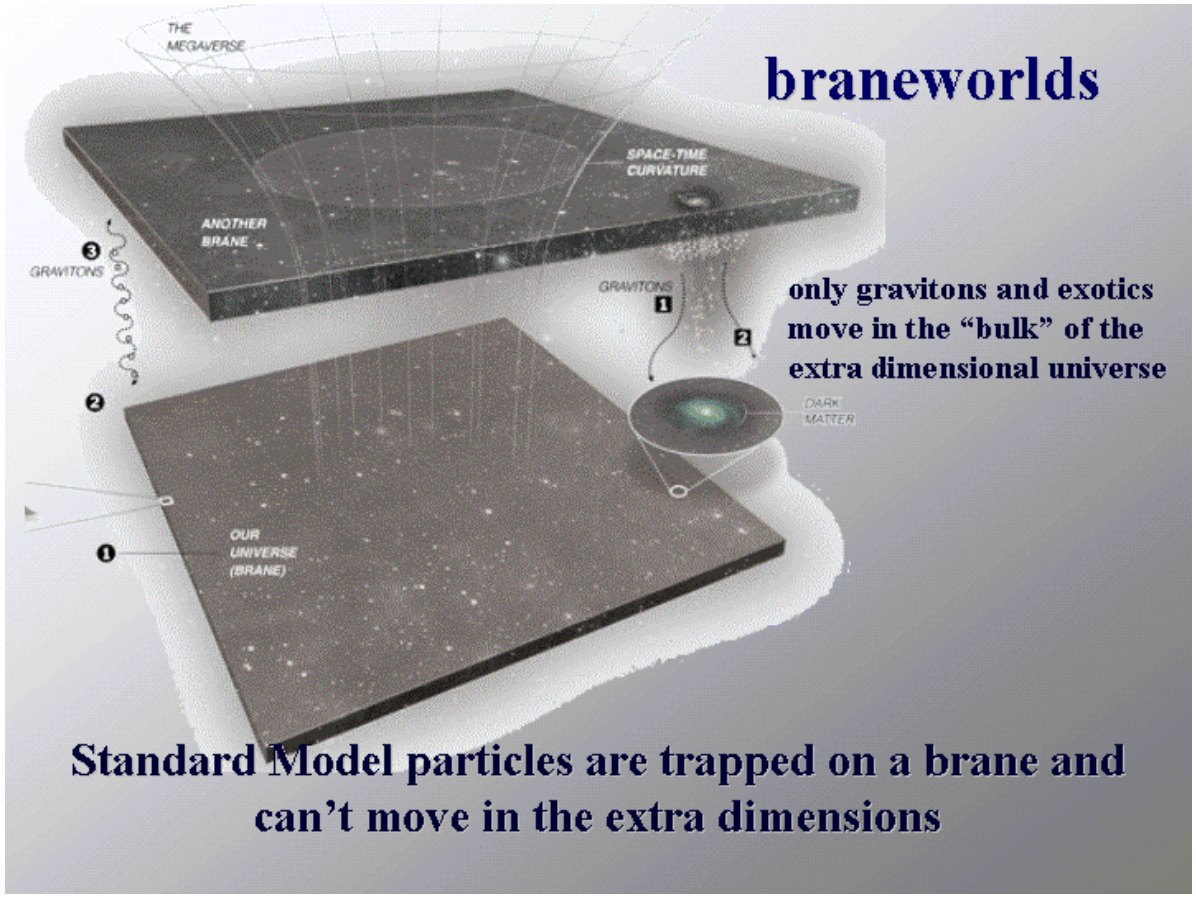
$$F_{\text{gravity}} \sim 10^{-36} F_{\text{EM}}$$

- 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

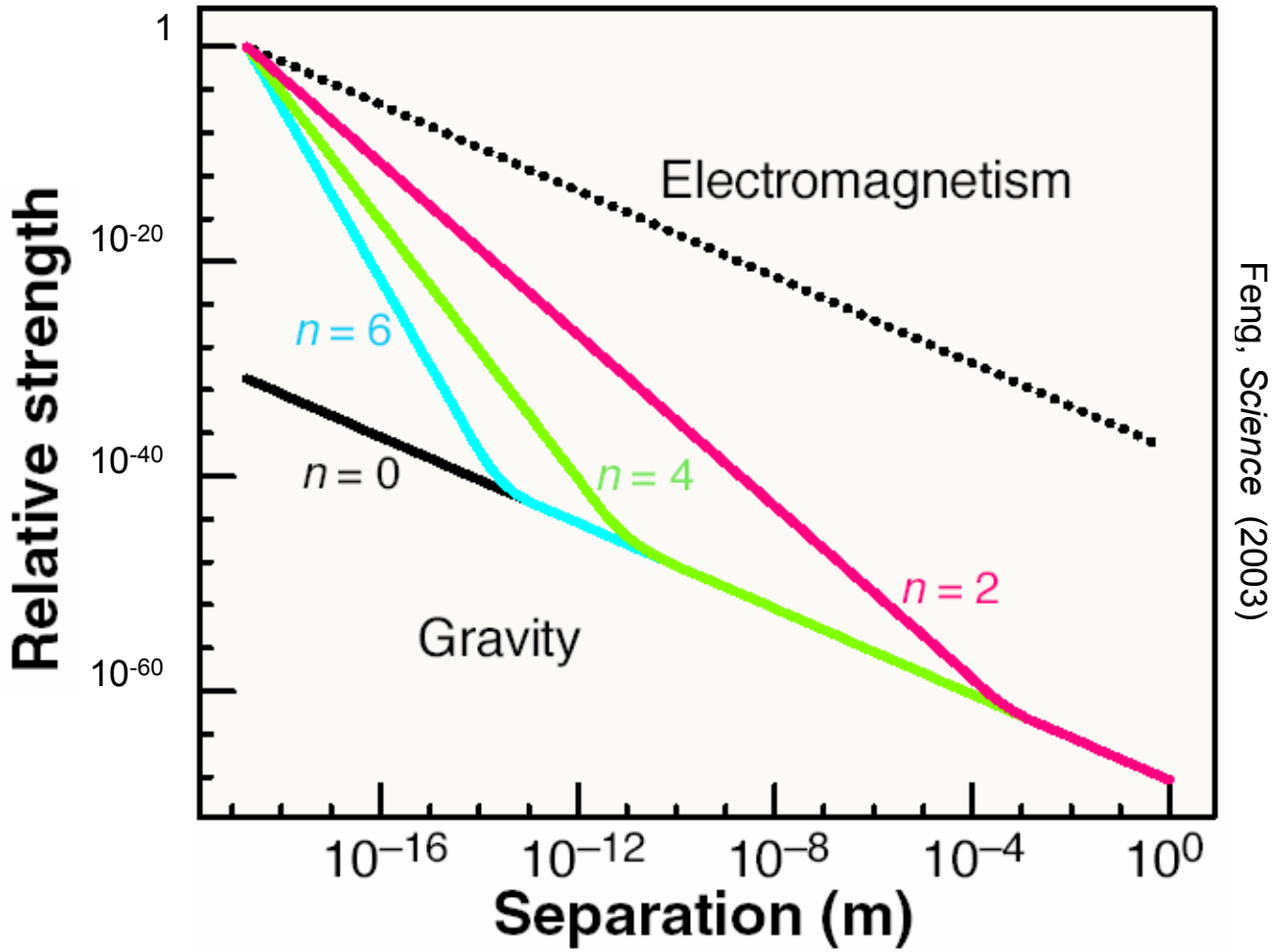


Strong Gravity

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

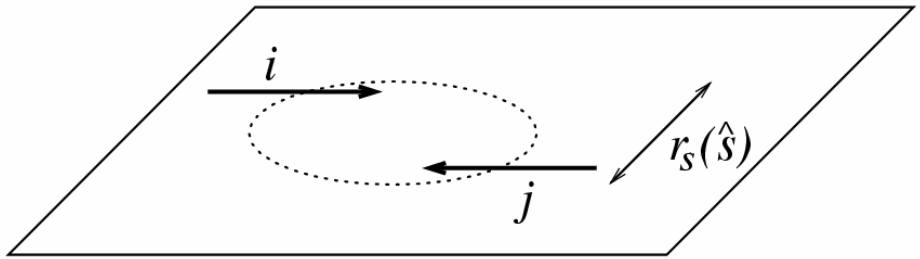
- $F_{gravity} \sim 1/r^{2+n}$ for small lengths, where n is the number of extra dimensions. Can this be true?

Yes!


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

Black Holes

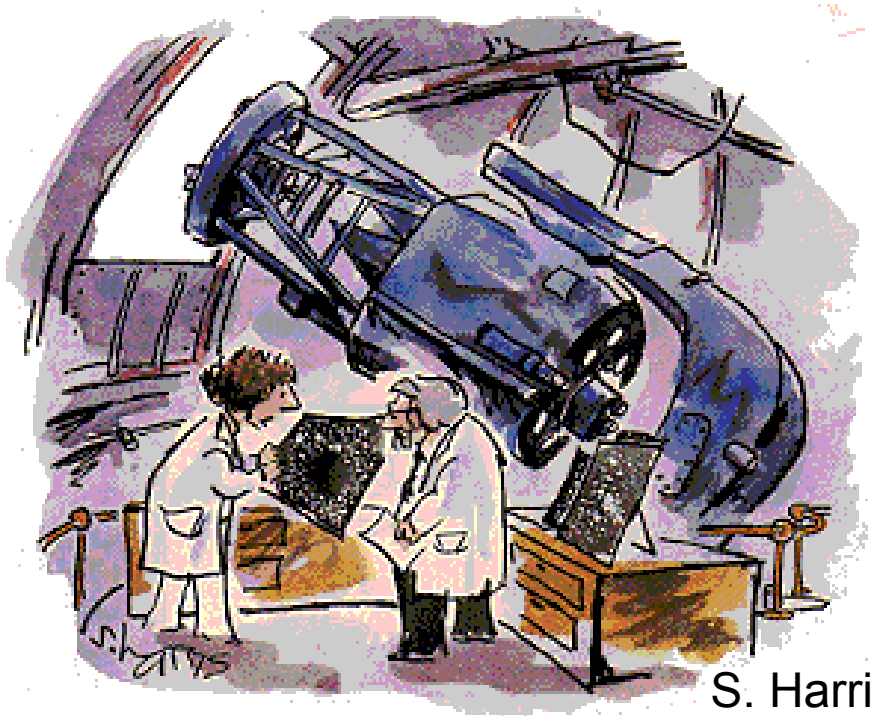
- If two particles pass close enough with enough energy, they will form a tiny black hole.



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

Micro Black Holes

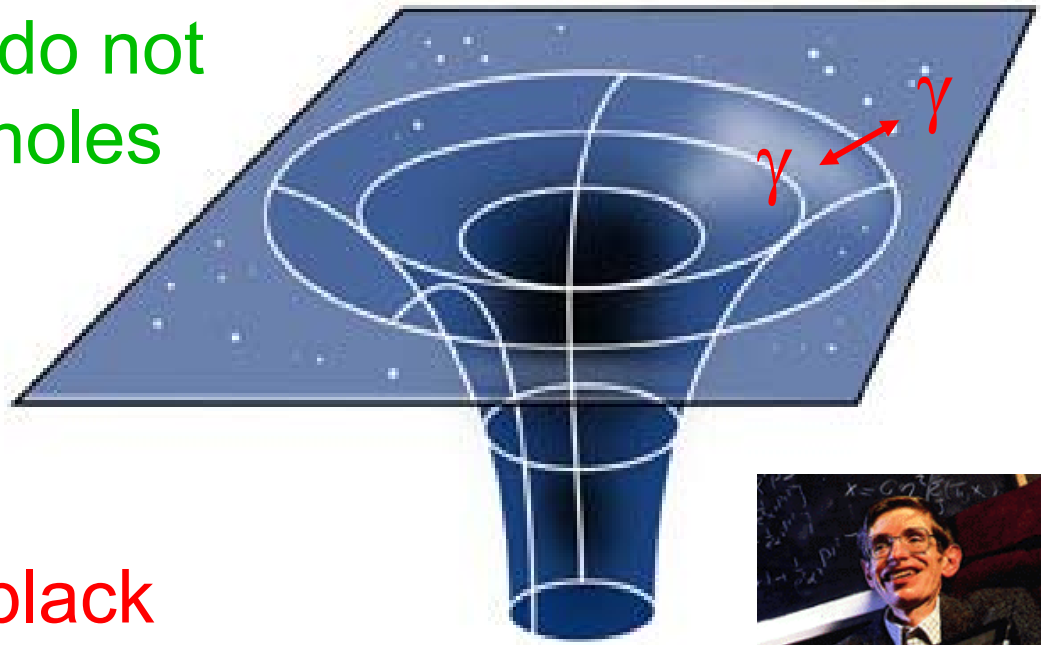
- Where can we find them?
- What will they look like?



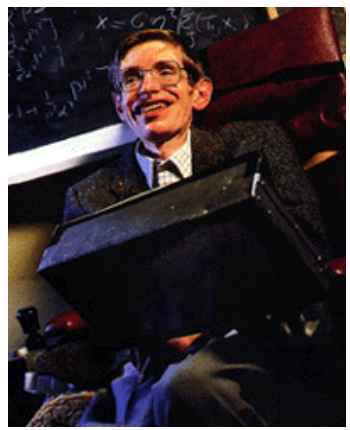
"It's black, and it looks like a hole.
I'd say it's a black hole."

Black Holes

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

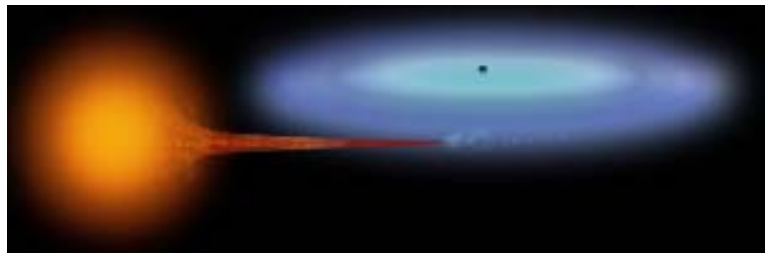


- But quantum mechanically, black holes Hawking radiate: black holes emit light!

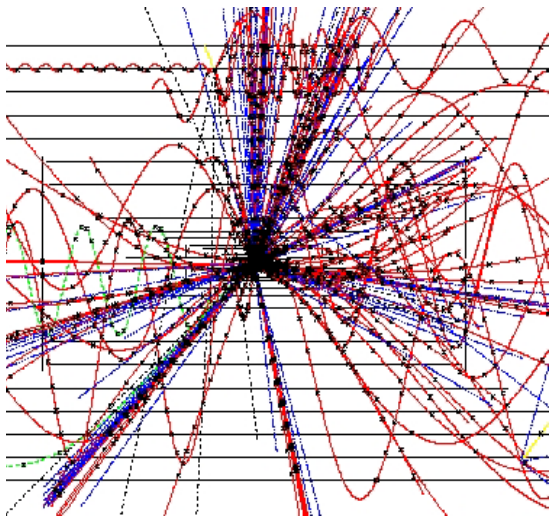


Black Hole Evaporation

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



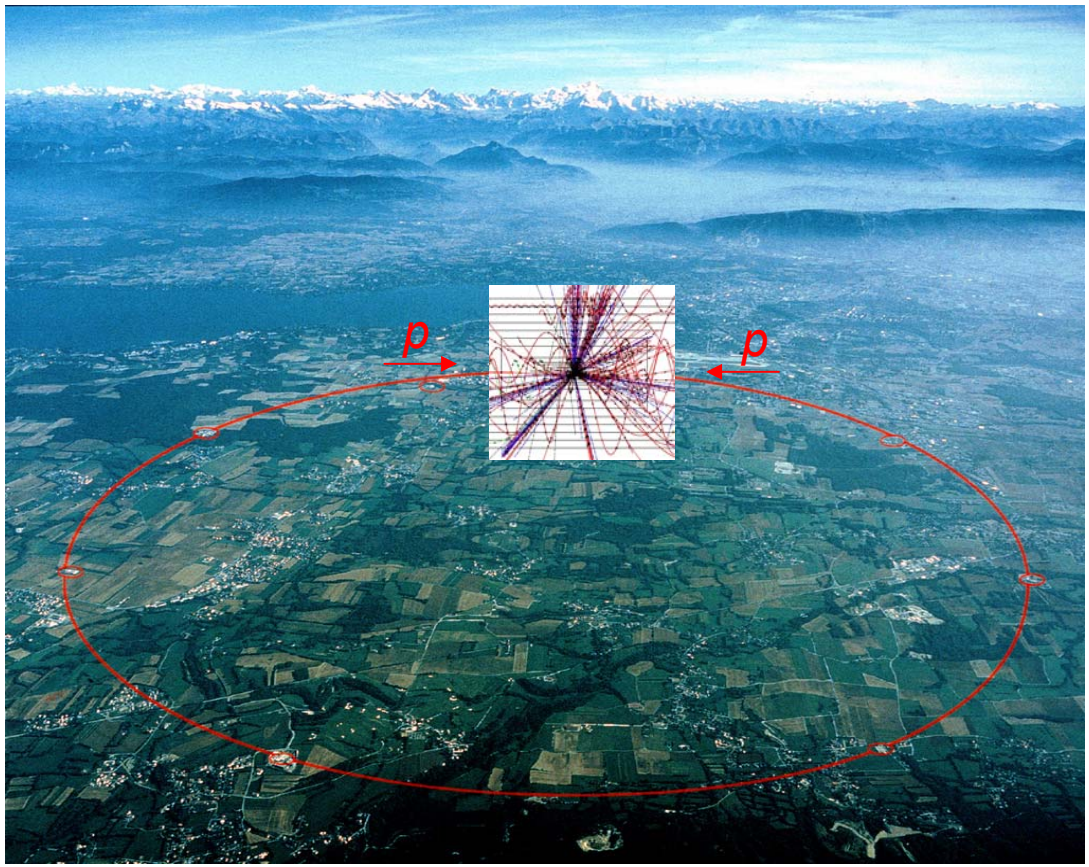
- Micro black holes:
  - Mass: $M_{BH} \sim 1000\ M_{proton}$
  - Size: 10^{-18} m
  - Temperature: 10^{16} K
  - Lifetime: 10^{-27} s

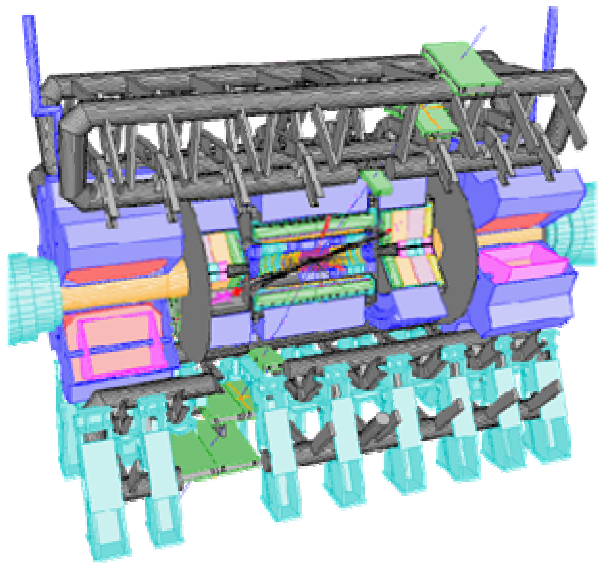


They explode!

Black Holes at Colliders

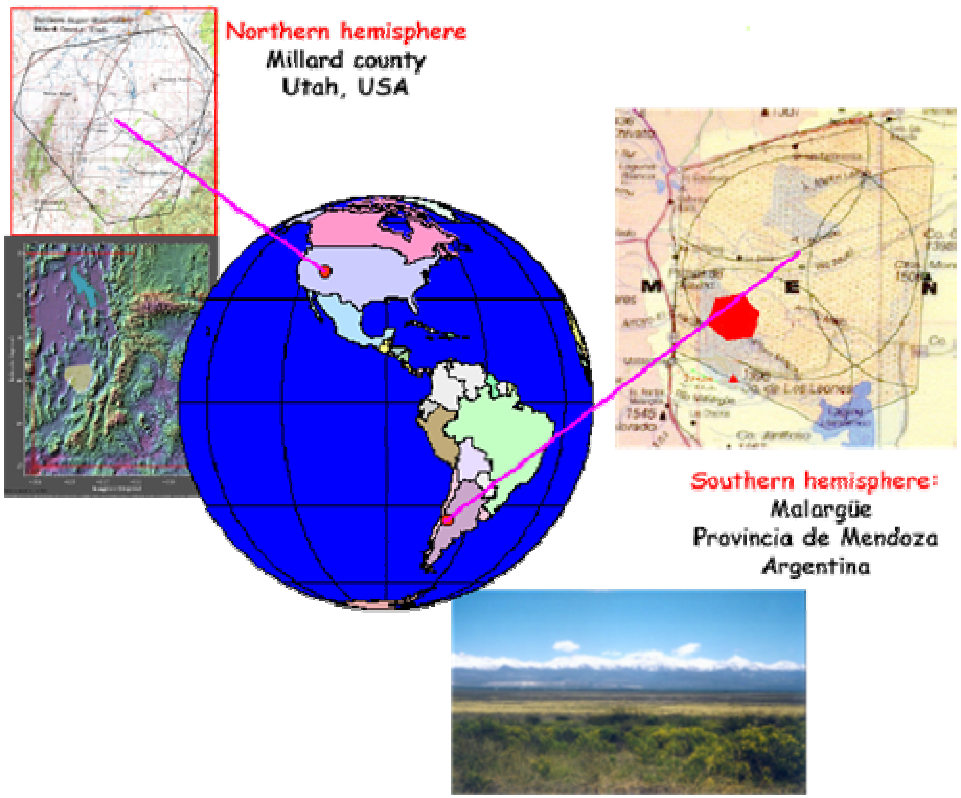
Large Hadron Collider at CERN, Geneva





Black Holes from Cosmic Rays

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.”

Summary

- A century later, Einstein's remarkable papers still are the foundation of physics, and we are still trying to realize his dream of a unified theory.
- String theory is our best attempt so far.
- Diverse experimental searches are underway. Will they be successful?

  "It's tough to make predictions, especially about the future." – Yogi Berra