DISCOVERING A NEW UNIVERSE AT THE SMALLEST SCALES

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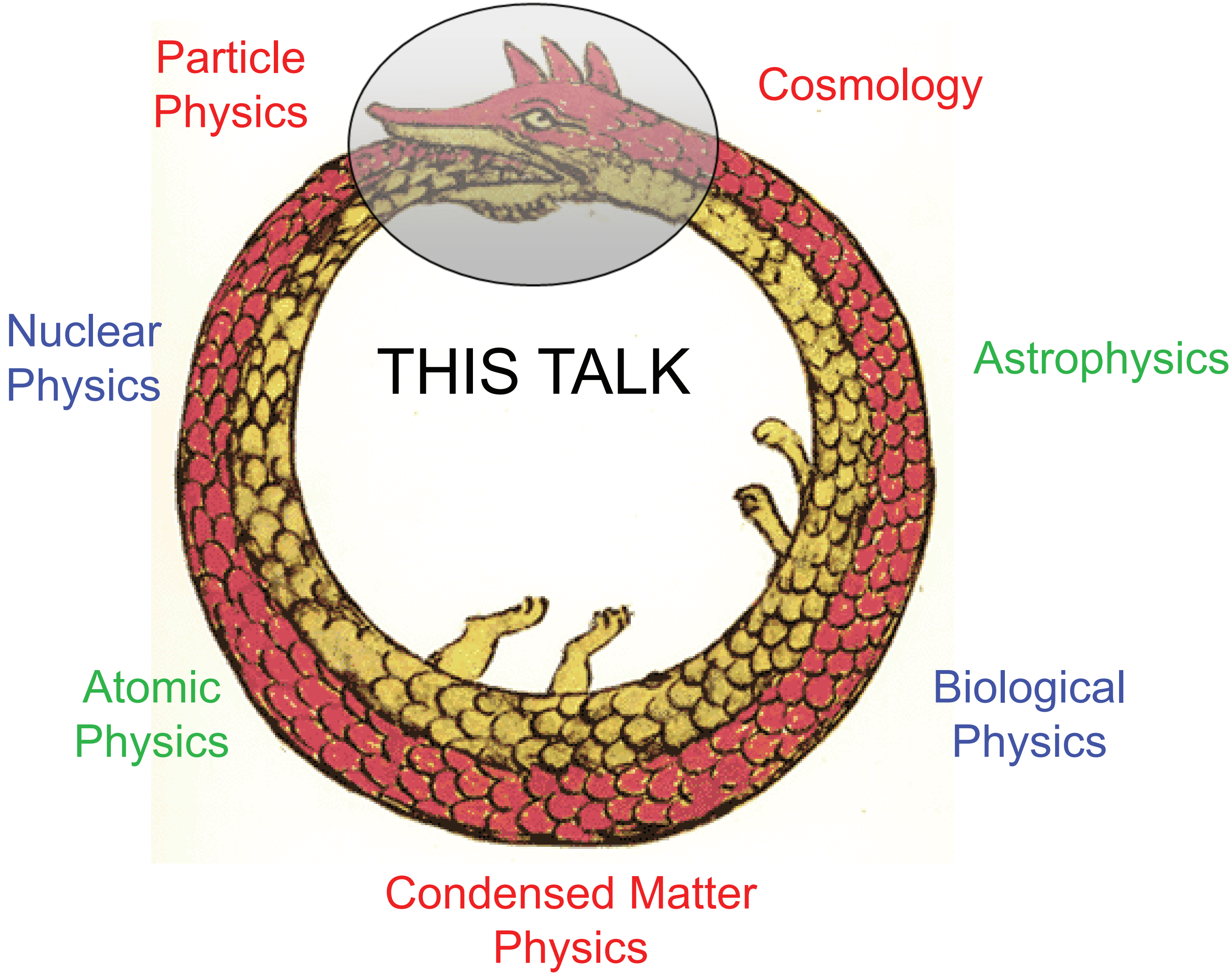
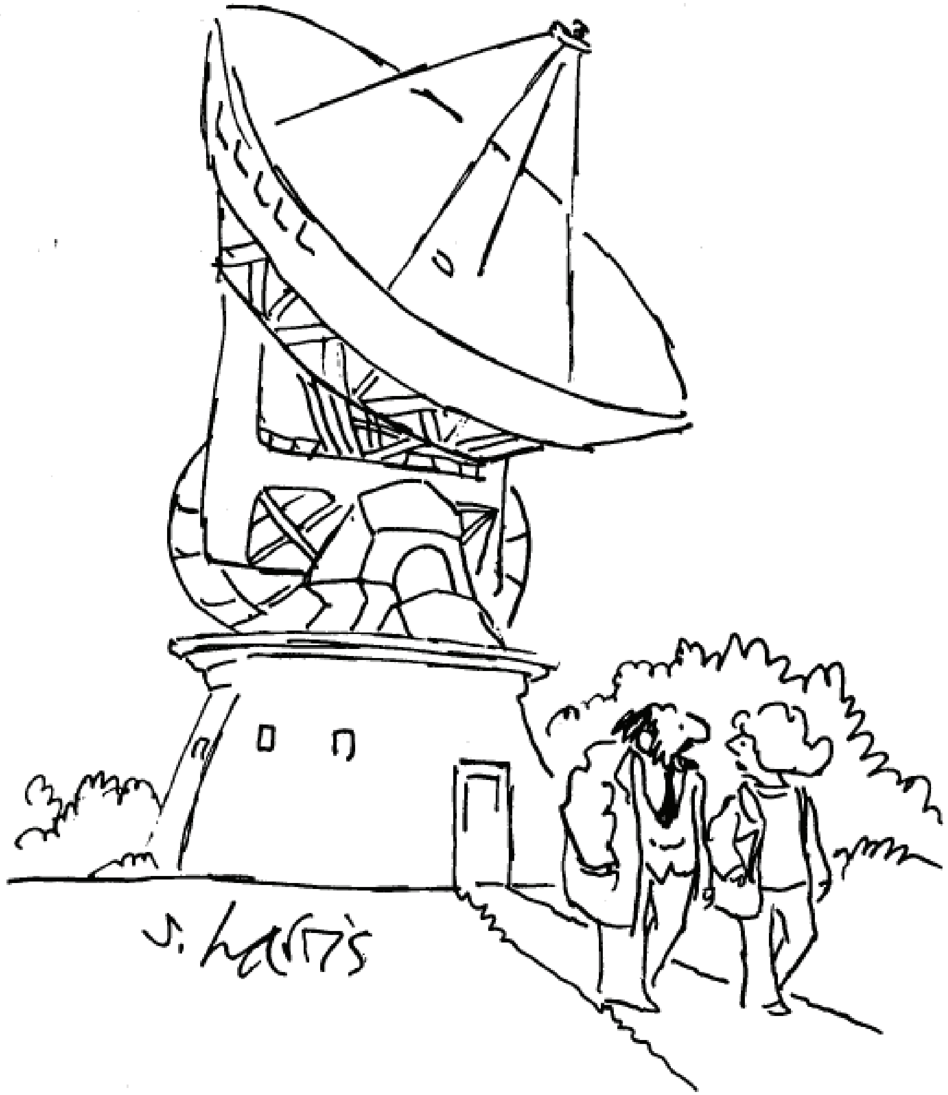
NEW UNIVERSE AT THE SMALLEST SCALES?

- The Universe is very big.
- The smallest scales – atoms, nuclei, protons – are very small.
- What do these have to do with each other?
- In fact, studies of the very big and the very small have become intimately related, and their connection is among the exciting frontiers in science.

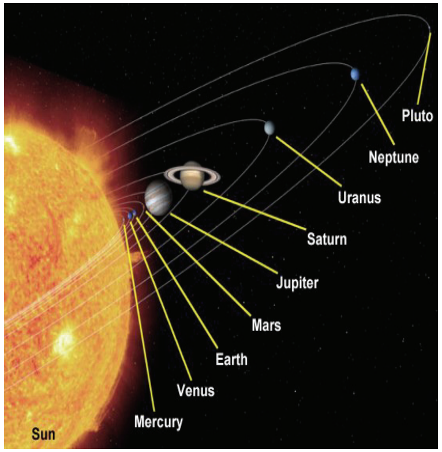
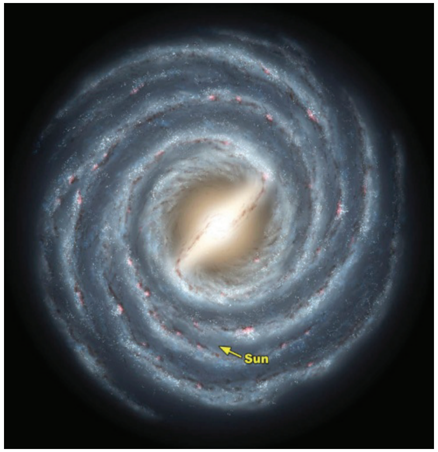
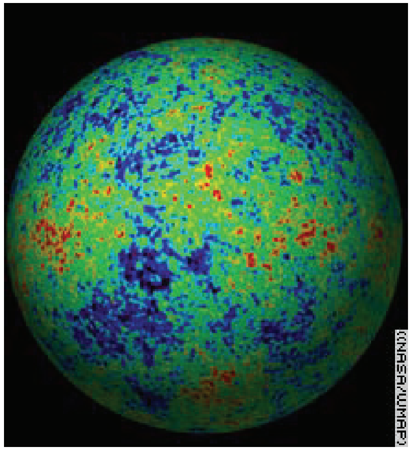


Particle Physics
Cosmology
THIS TALK
Nuclear Physics
Astrophysics
Atomic Physics
Biological Physics
Condensed Matter Physics

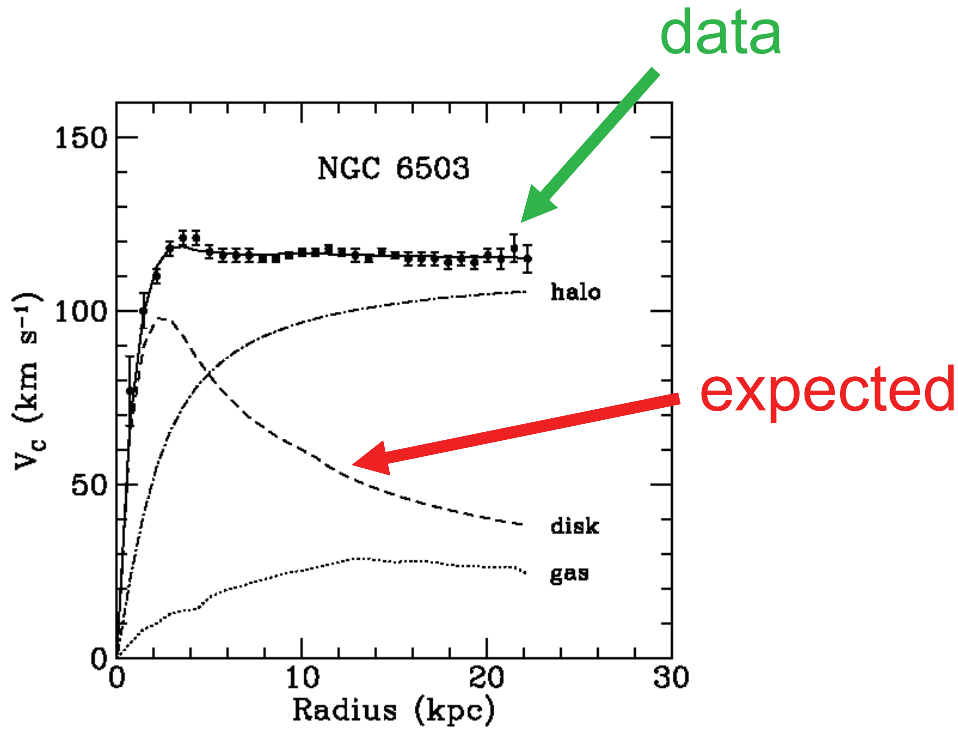


"I'LL BE WORKING ON THE LARGEST AND SMALLEST OBJECTS IN THE UNIVERSE—SUPERCLUSTERS AND NEUTRINOS. I'D LIKE YOU TO HANDLE EVERYTHING IN BETWEEN."

VERY BIG: STATUS REPORT

solar system	galaxy	galactic cluster	universe
			
10^{12} meters	10^{17} meters	10^{23} meters	$> 10^{26}$ meters

EVIDENCE FOR DARK MATTER

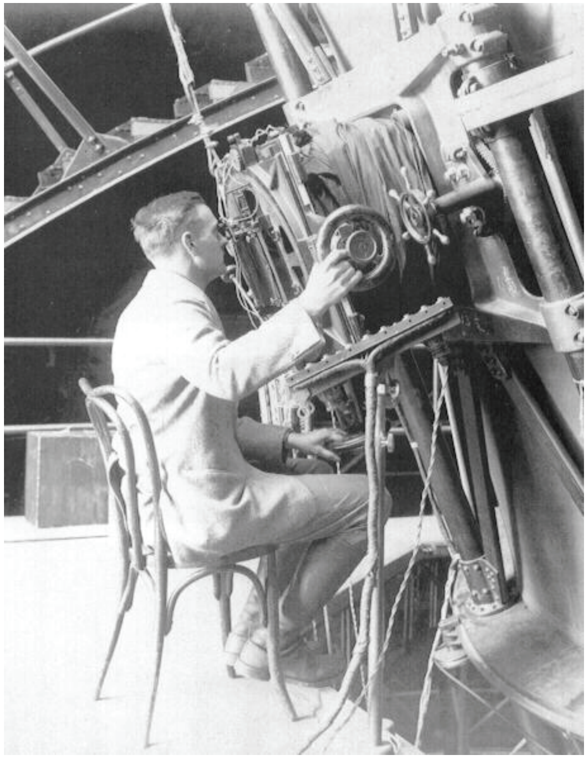


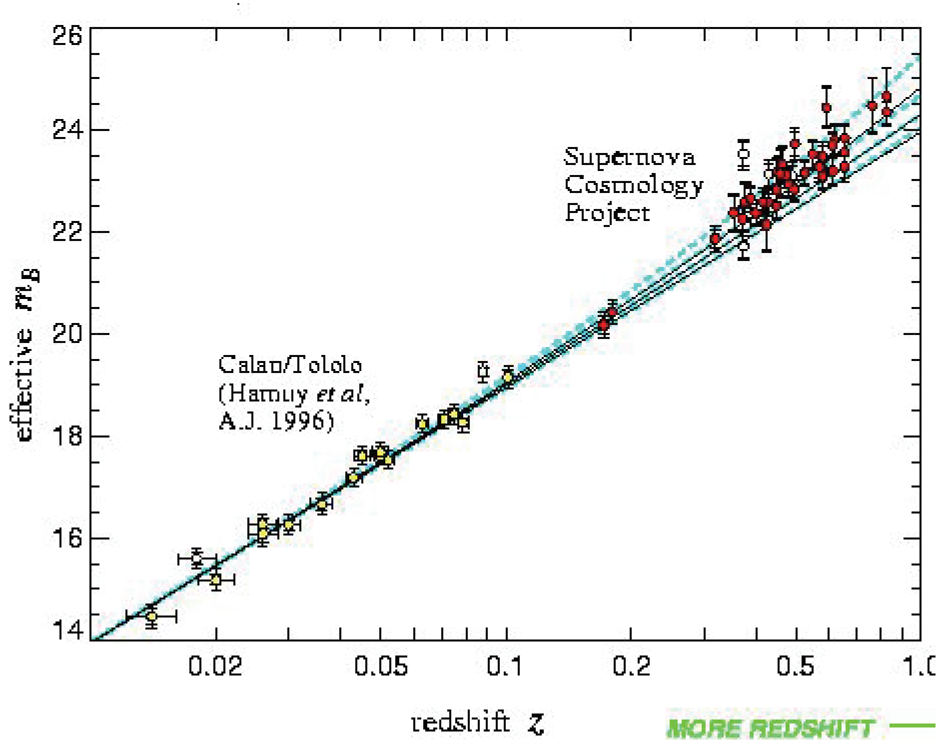
Begeman, Broeils, Sanders (1991)

Galaxies and clusters of galaxies rotate too fast
→ dark matter

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

EVIDENCE FOR DARK ENERGY





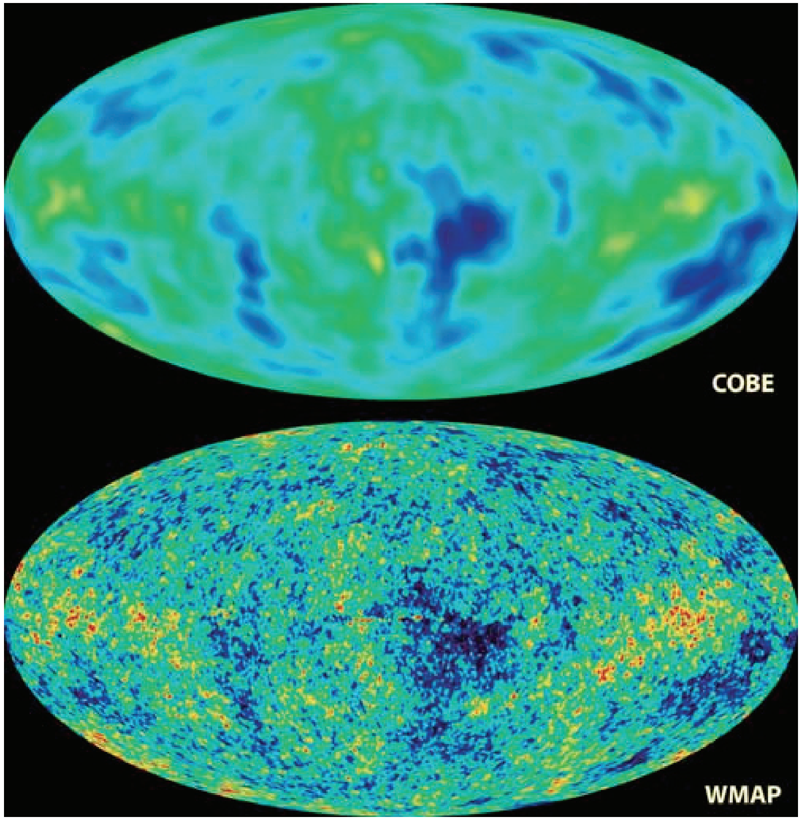
Hubble (1929): The universe is expanding

Supernovae (1998): and accelerating → dark energy

EVIDENCE FOR BOTH

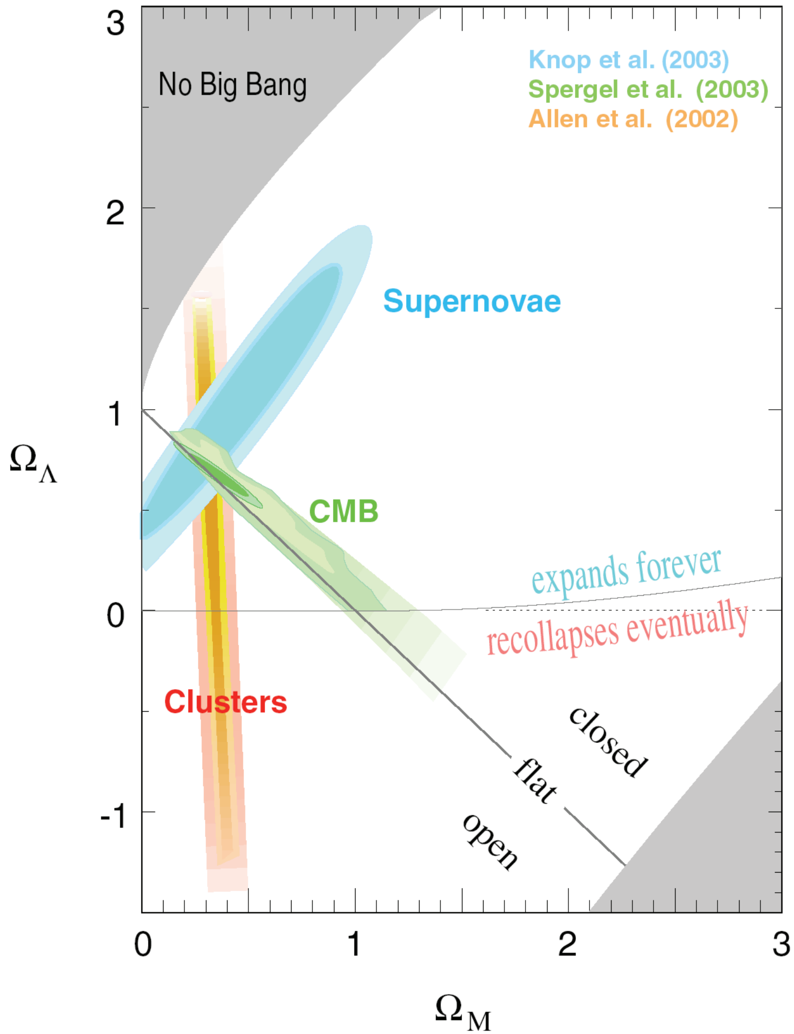
1990

2003



Cosmic Microwave Background (2003): Universe has dark matter, dark energy, or both

COMPOSITION OF THE UNIVERSE



Three measurements agree:

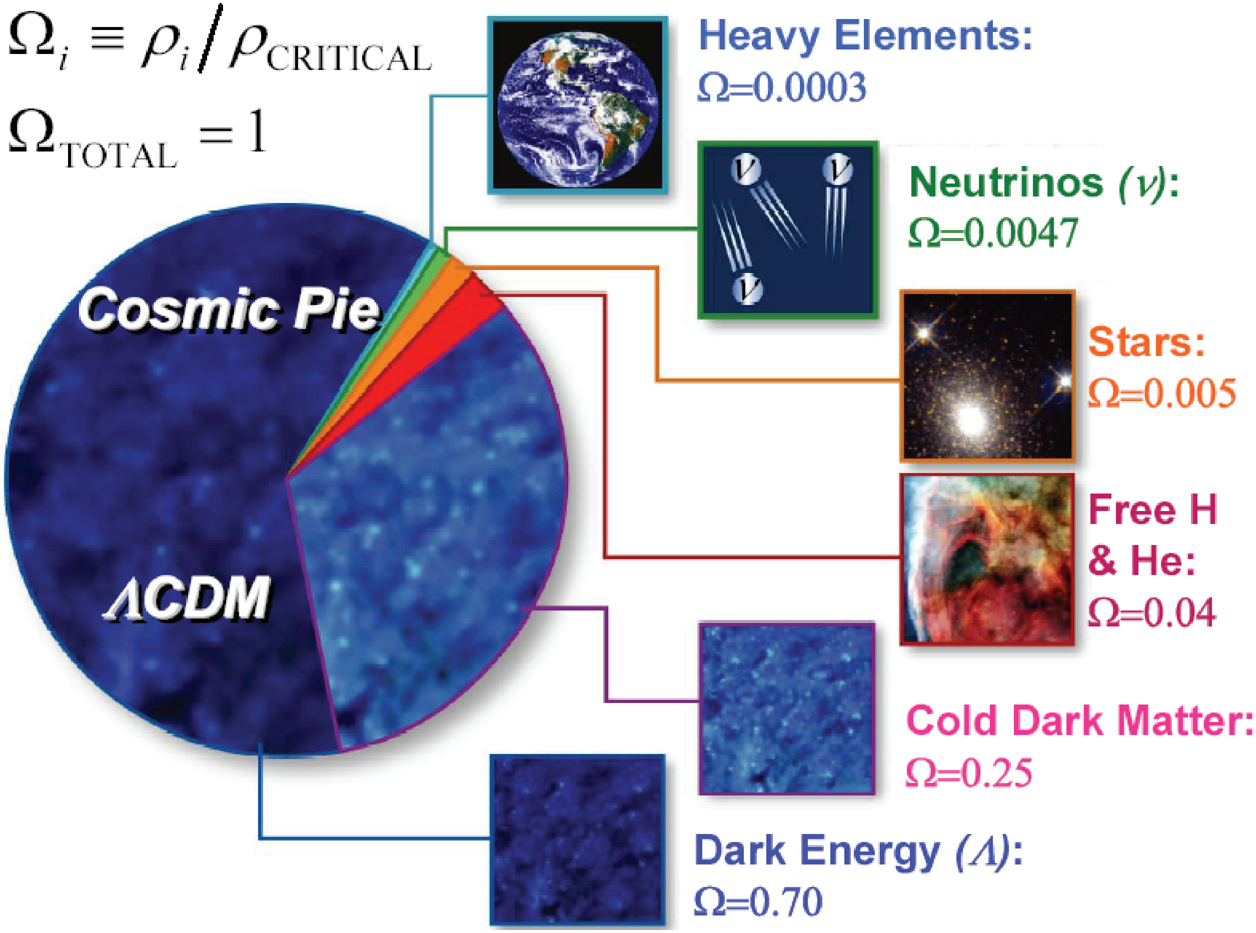
Dark Matter: 25%
Dark Energy: 70%
Normal Matter: 5%

Two must be wrong to change this conclusion

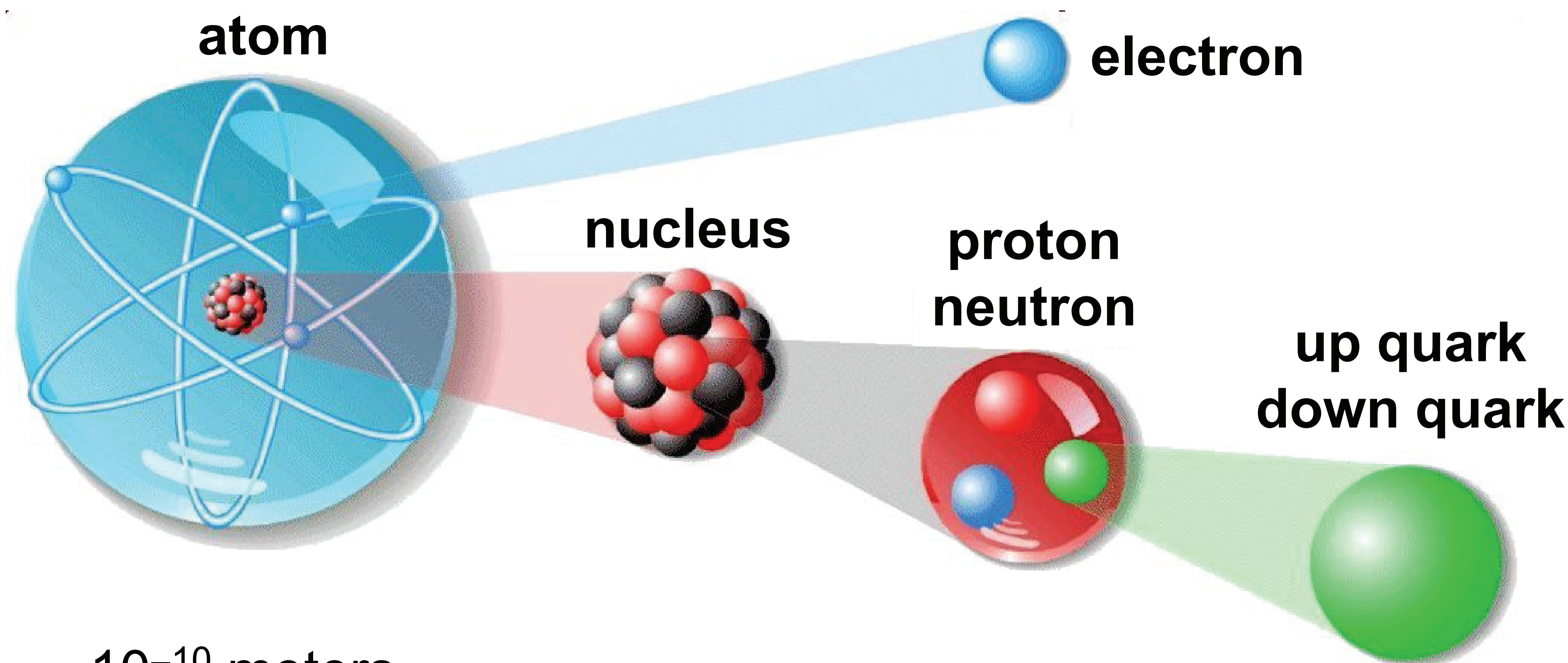
COMPOSITION OF THE UNIVERSE

$$\Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}}$$

$$\Omega_{\text{TOTAL}} = 1$$



VERY SMALL: STATUS REPORT



10^{-10} meters (thickness of human hair ~ 10^{-5} m)

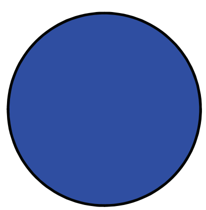
10^{-14} meters

10^{-15} meters

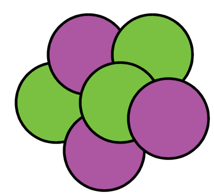
$< 10^{-18}$ meters

MICROSCOPES

Higher energies → shorter wavelengths



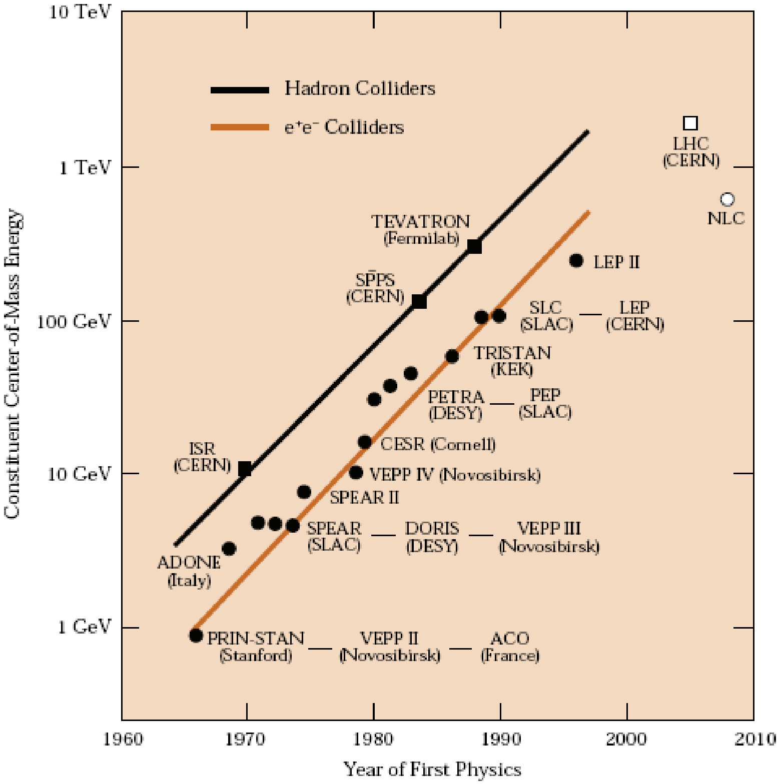
low resolution



high resolution

PARTICLE COLLIDERS

E. O. Lawrence's Cyclotron (1930s)

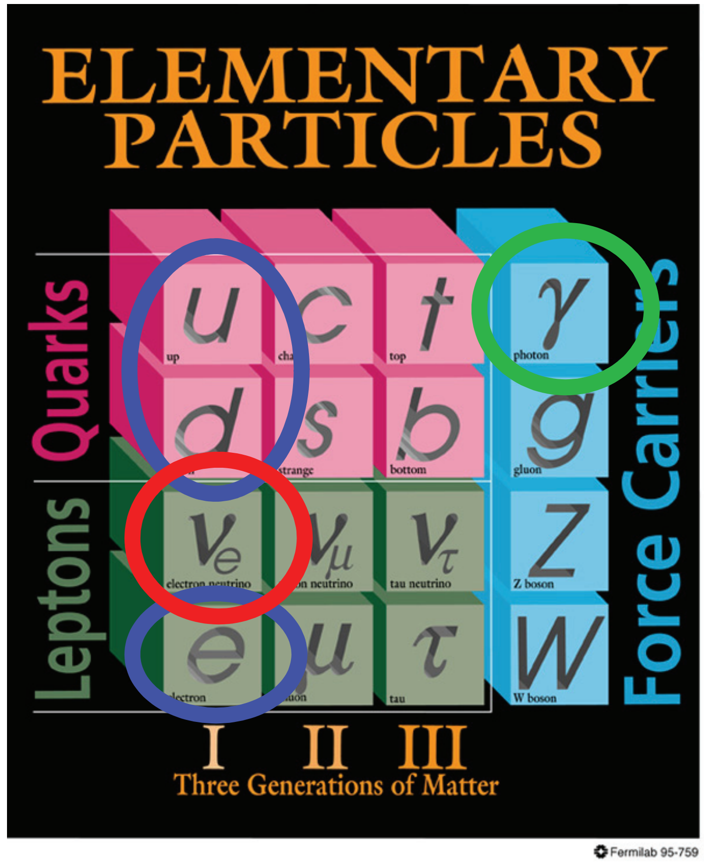


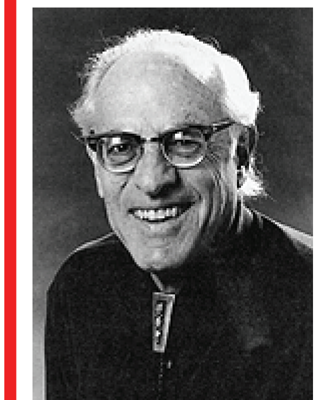
Livingston Plot: Moore's Law for Particle Colliders

BASIC BUILDING BLOCKS

Atoms

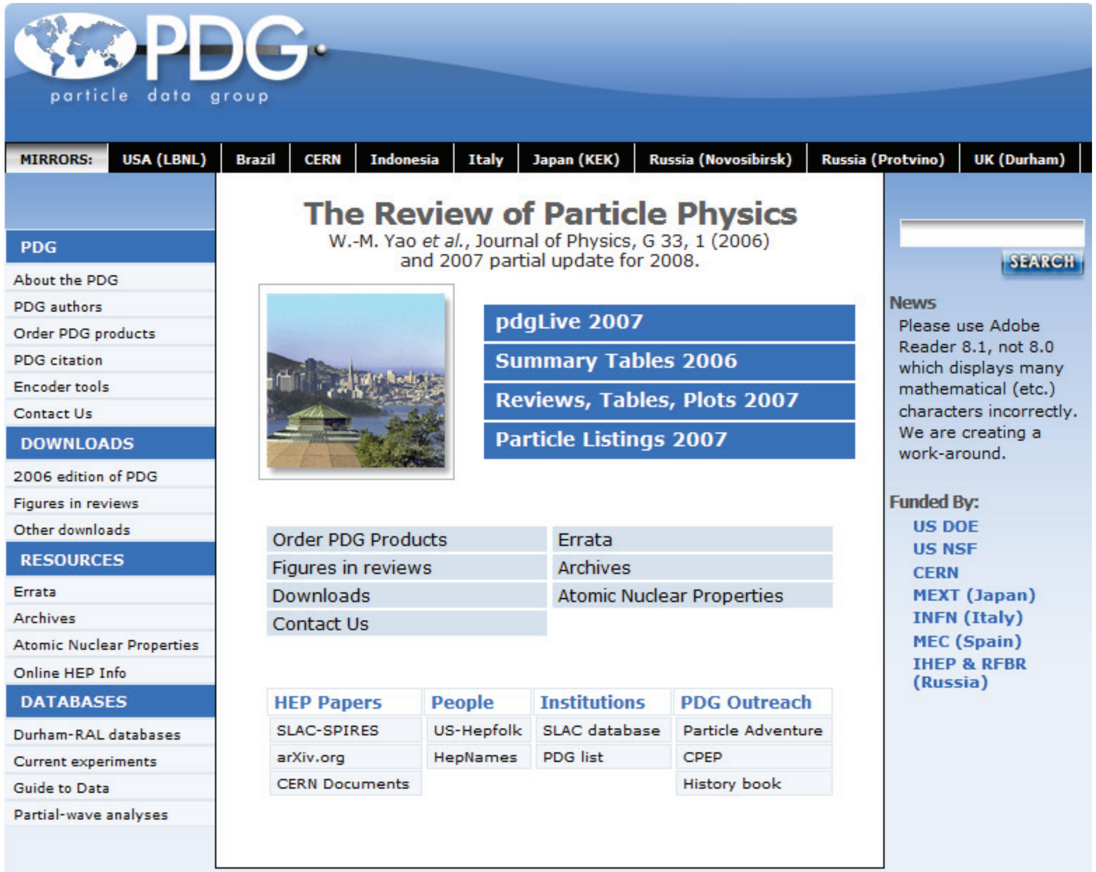
Light





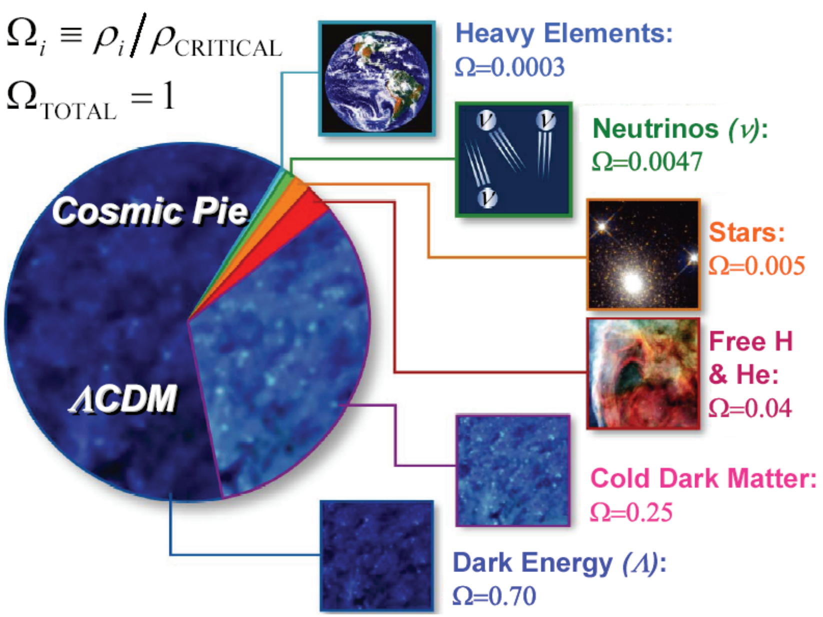
Frederick Reines
1995 Nobel Prize
for the Detection
of the Neutrino

Precise Confirmation



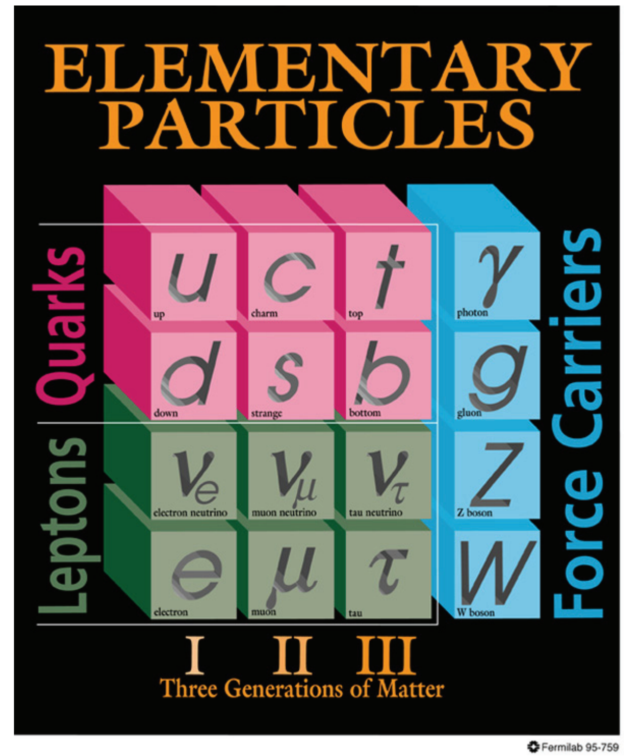
Explains all measured properties of elementary particles down to 10^{-16} m.

PROBLEM!



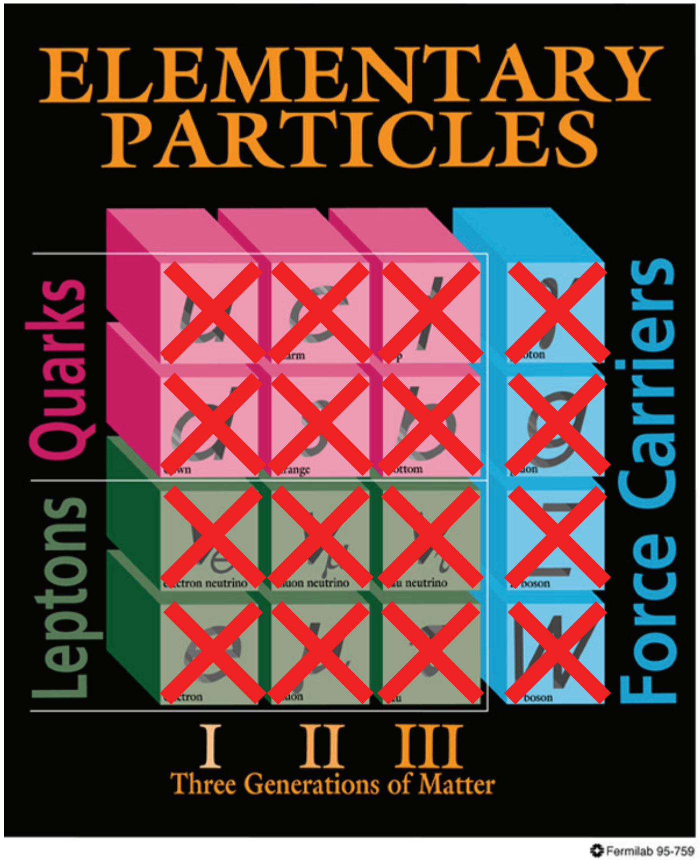
$\Omega_i \equiv \rho_i / \rho_{\rm CRITICAL}$
$\Omega_{\rm TOTAL} = 1$
Cosmic Pie
ΛCDM
Heavy Elements:
Ω=0.0003
Neutrinos (ν):
Ω=0.0047
Stars:
Ω=0.005
Free H
& He:
Ω=0.04
Cold Dark Matter:
Ω=0.25
Dark Energy (Λ):
Ω=0.70

vs.



ELEMENTARY
PARTICLES
Quarks
Leptons
Force Carriers
u up
c charm
t top
γ photon
d down
s strange
b bottom
g gluon
νe electron neutrino
νμ muon neutrino
ντ tau neutrino
Z Z boson
e electron
μ muon
τ tau
W W boson
I II III
Three Generations of Matter
Fermilab 95-759

DARK MATTER

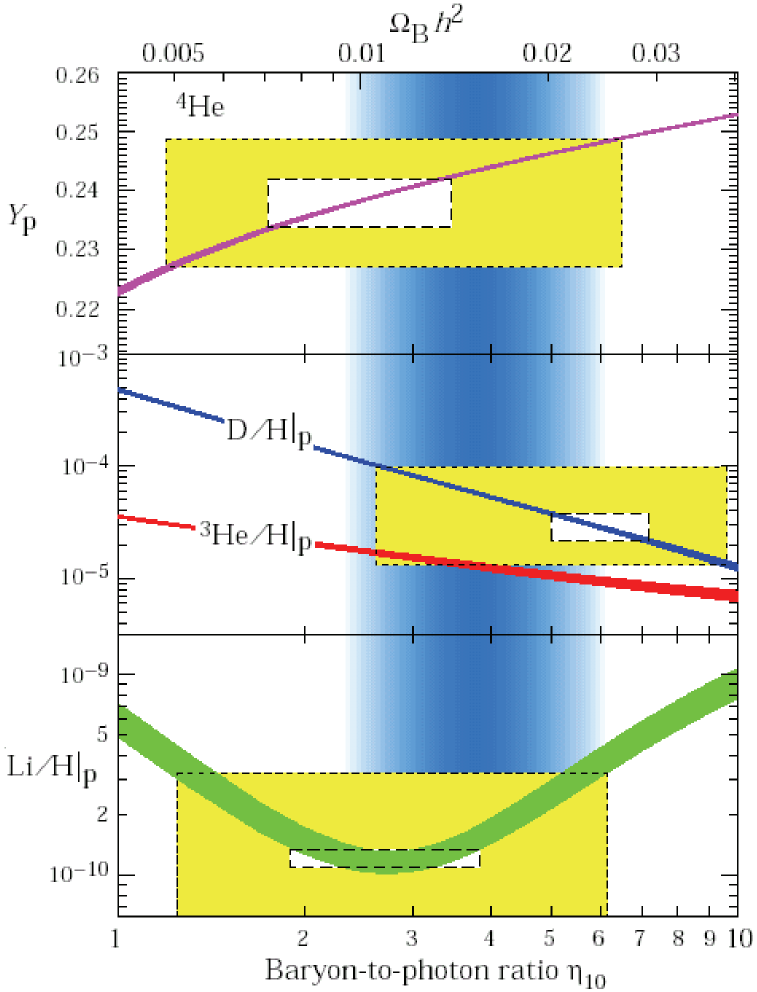


Known DM properties

- Stable
- Heavy, slow
- Not protons and neutrons

Dark matter is unambiguous evidence for new particles

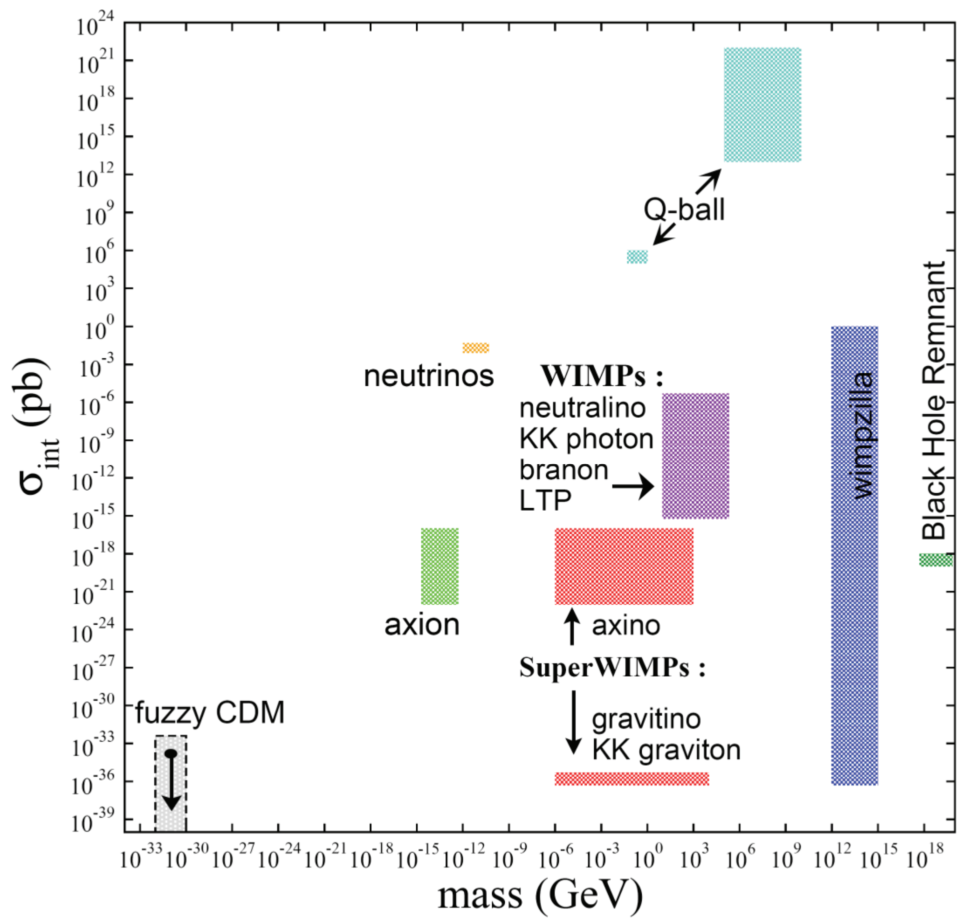
CONSTRAINING THE NUMBER OF PROTONS AND NEUTRONS



- Assume the Big Bang happened
- When the universe cooled, protons and neutrons combined to form light nuclei (He, Li)
- We can determine the number of light nuclei
- Precise agreement if protons and neutrons are 5% of the Universe
- This is Big Bang nucleosynthesis, one piece of evidence for the Big Bang

DARK MATTER CANDIDATES

- The observational constraints are no match for the creativity of theorists
- Masses and interaction strengths span many, many orders of magnitude, but many of the favored candidates may be discovered soon



HEPAP/AAAC DMSAG Subpanel (2007)

Example: DM from Extra Dimensions

- (x, y, z, t) + w, v,…? Science fiction?

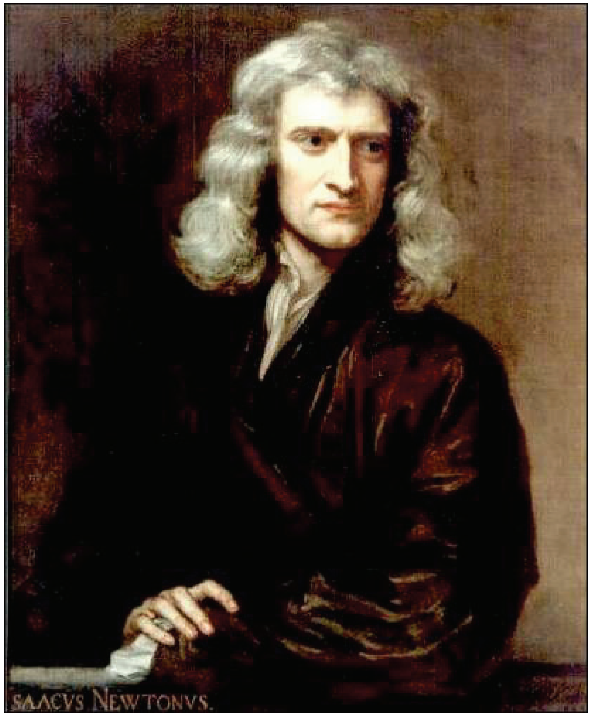
- No – a hot topic at the interface of particle physics and cosmology:

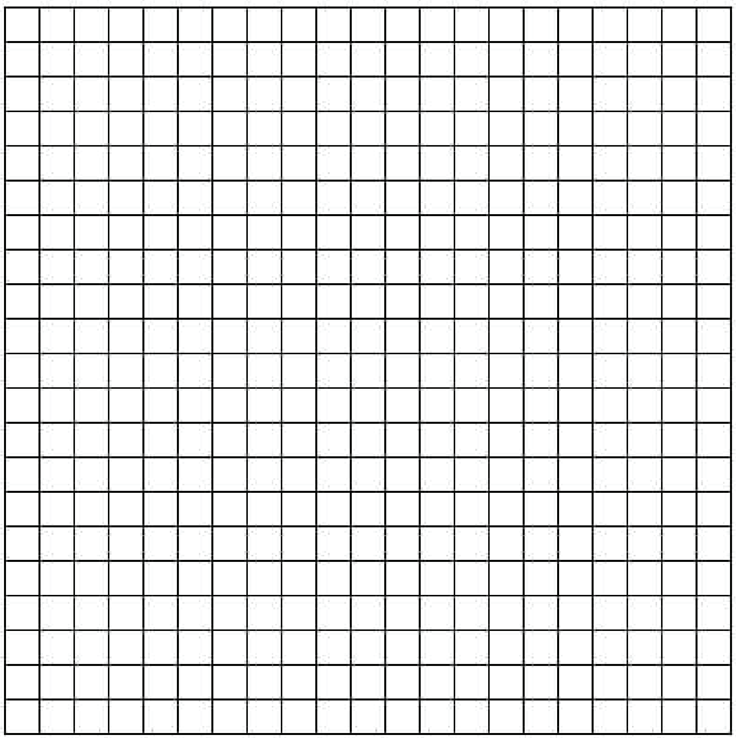
  How does gravity work?

  What is our world made of?

  What is the history (and future) of the universe?

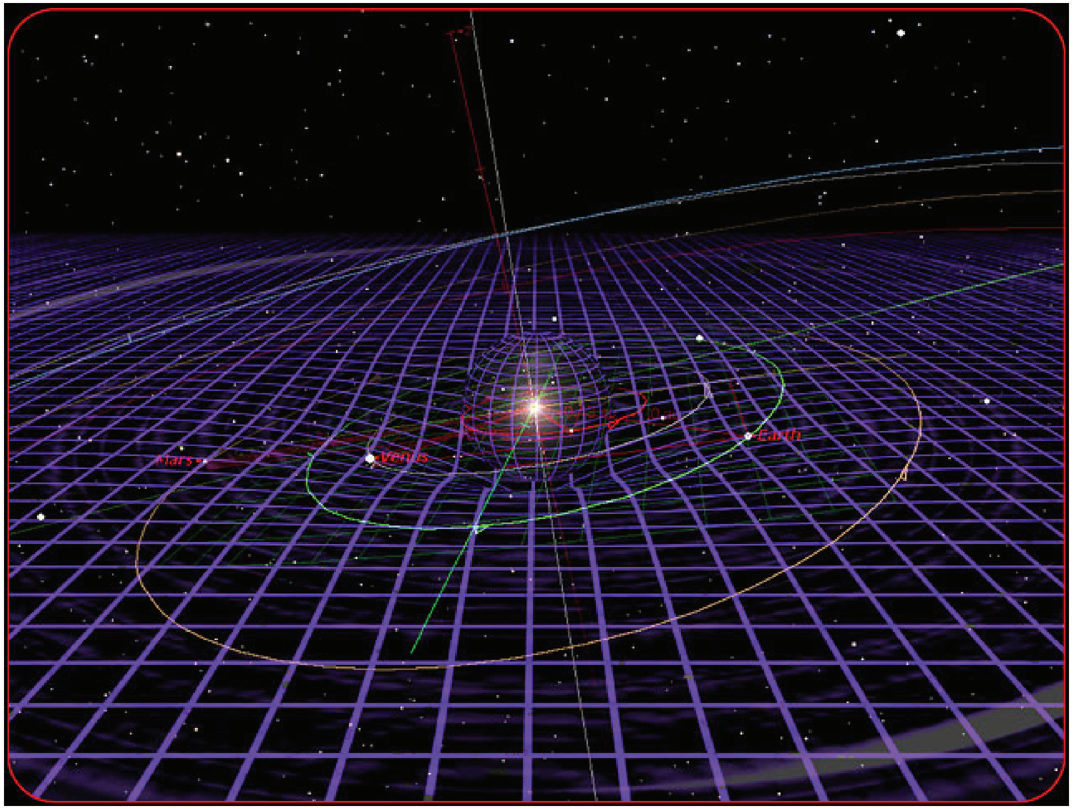
Isaac Newton





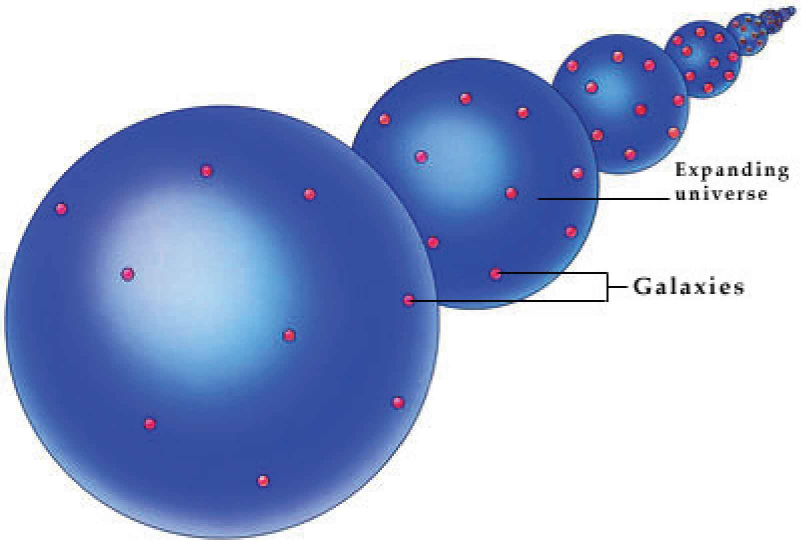
1687: Space and time are the static stage on which physical processes act

Albert Einsten



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

Small Dimensions



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

- Extrapolating back, space was small – the Big Bang

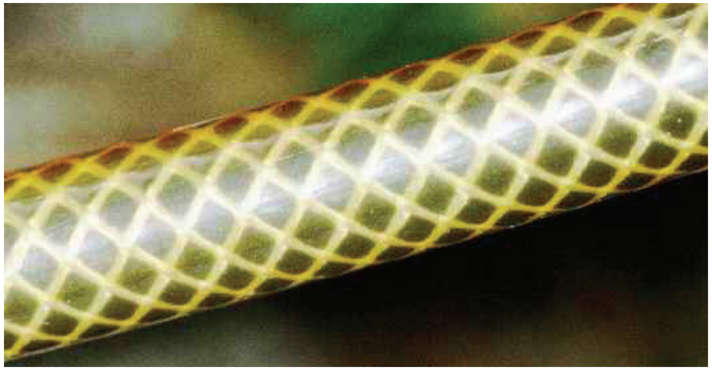
- Other dimensions could exist but still be small. In fact, string theory (quantum physics + gravity) *requires* 6 extra spatial dimensions.

- How can we test this possibility?

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

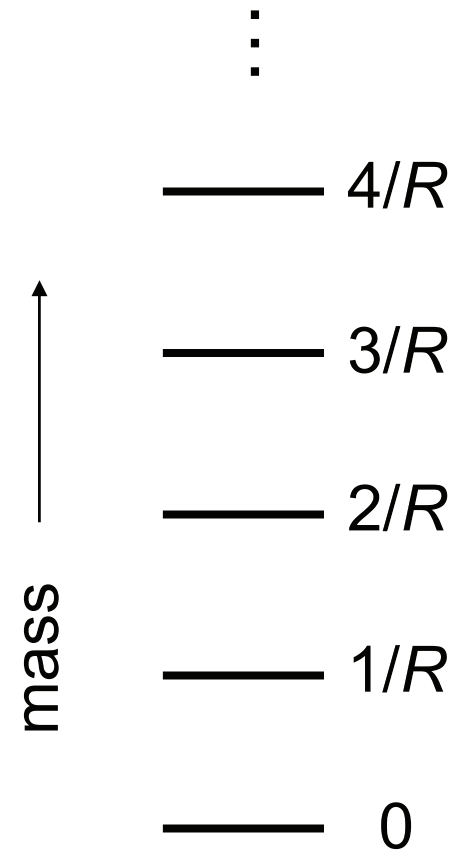
- However, the momentum in the extra directions will be quantized.

- From our viewpoint, we will see this as new particles with masses

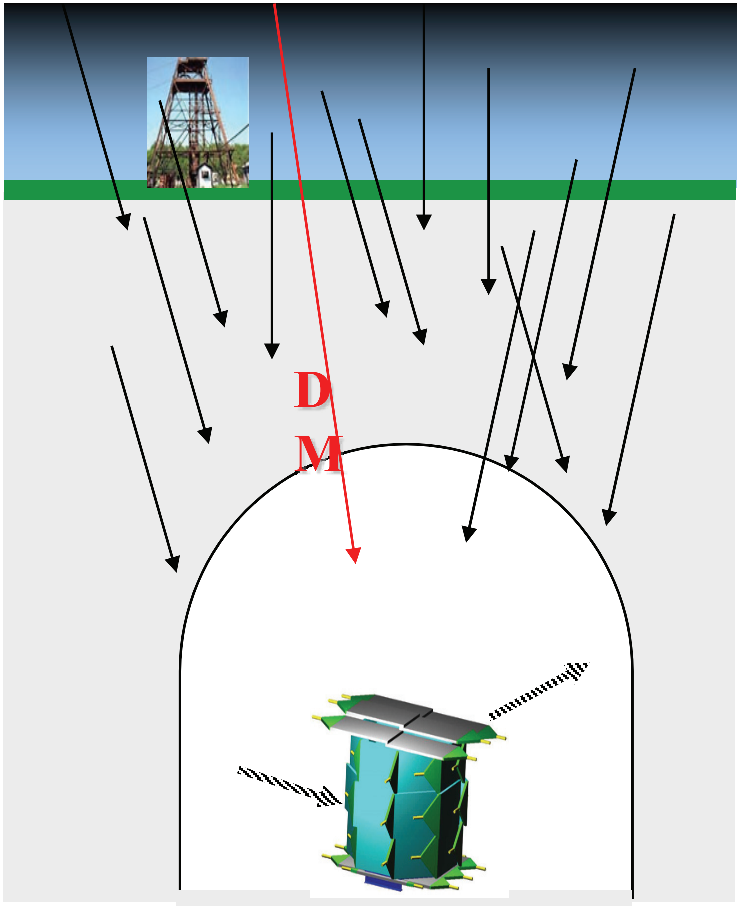
  $m \sim 0, 1/R, 2/R, 3/R, 4/R, \ldots$

  Each known particle has a copy at each mass.

- One of these could be the dark matter!



Dark Matter Direct Detection



CDMS in the Soudan mine
½ mile underground in Minnesota

Indirect Detection

Dark Matter Madlibs!

Dark matter annihilates in ____________________ to
a place

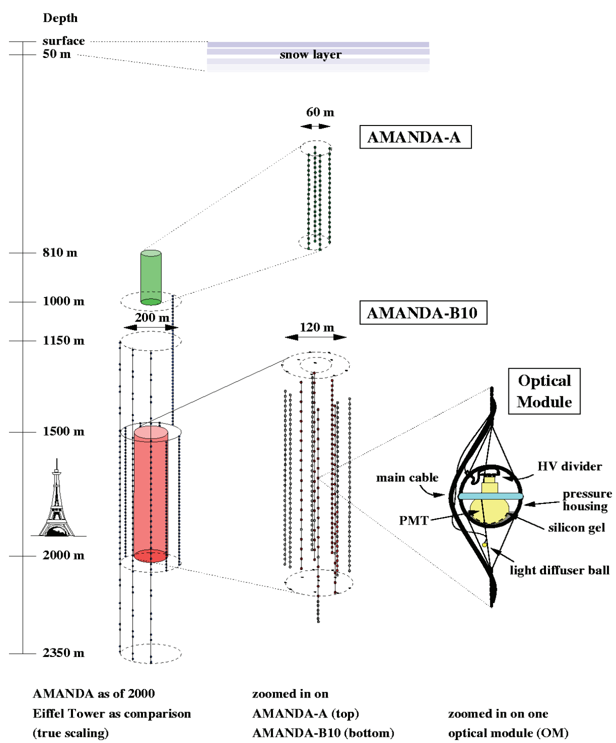
____________ , which are detected by ________________ .
particles an experiment

Dark Matter annihilates in __the galactic center__ to
a place

__photons__ , which are detected by _Cerenkov telescopes_ .
some particles an experiment

Dark Matter annihilates in __the center of the Sun__ to
a place

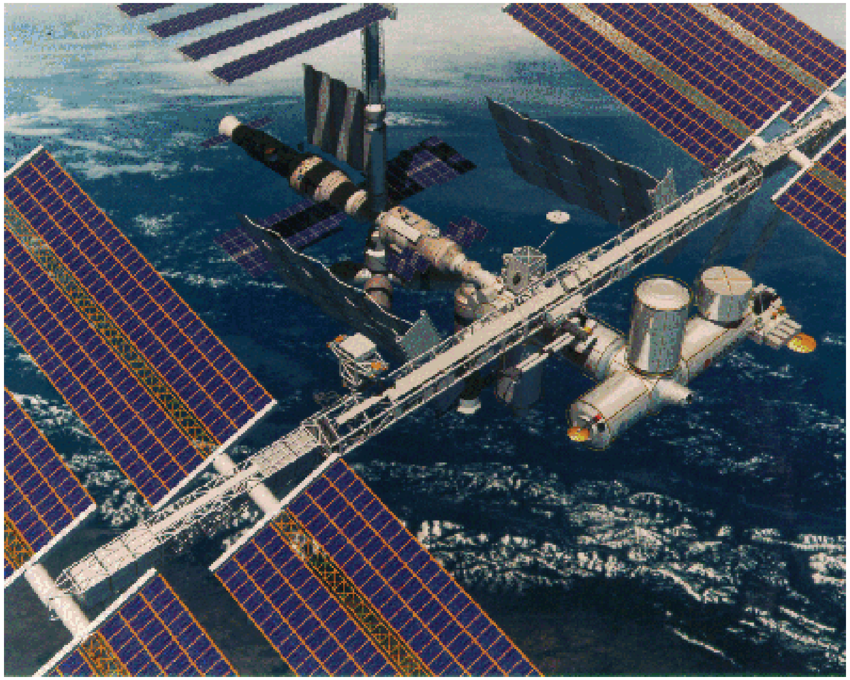
__neutrinos__ , which are detected by __AMANDA, IceCube__ .
some particles an experiment



AMANDA in the Antarctic Ice

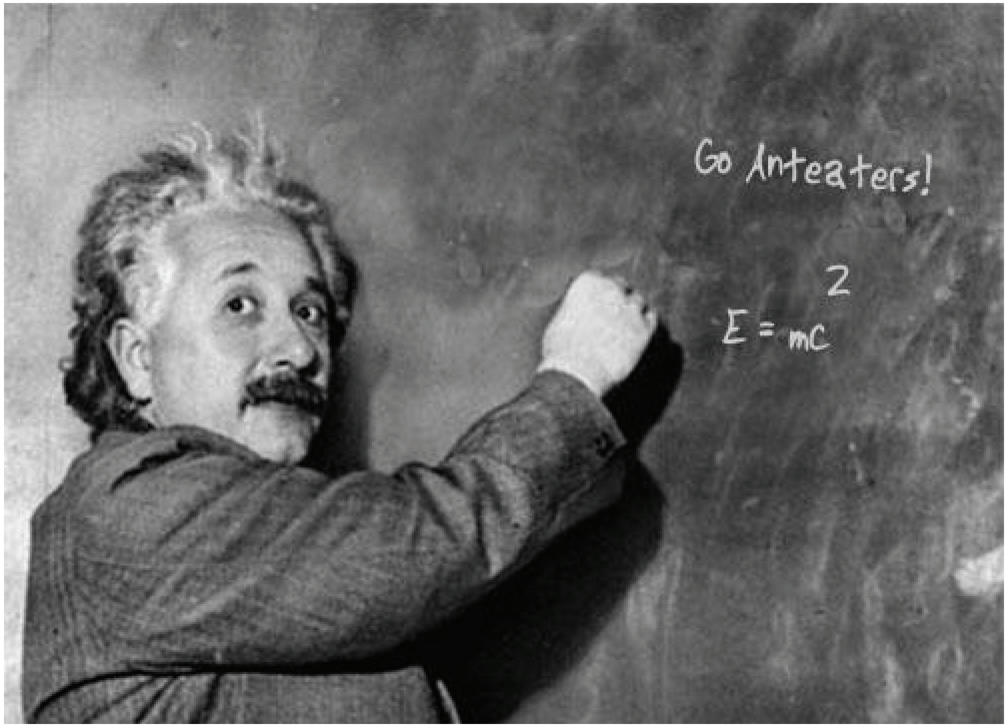
Dark Matter annihilates in ______the halo______ to
a place

__positrons__ , which are detected by _AMS on the ISS__ .
some particles   an experiment



Dark Matter at Colliders

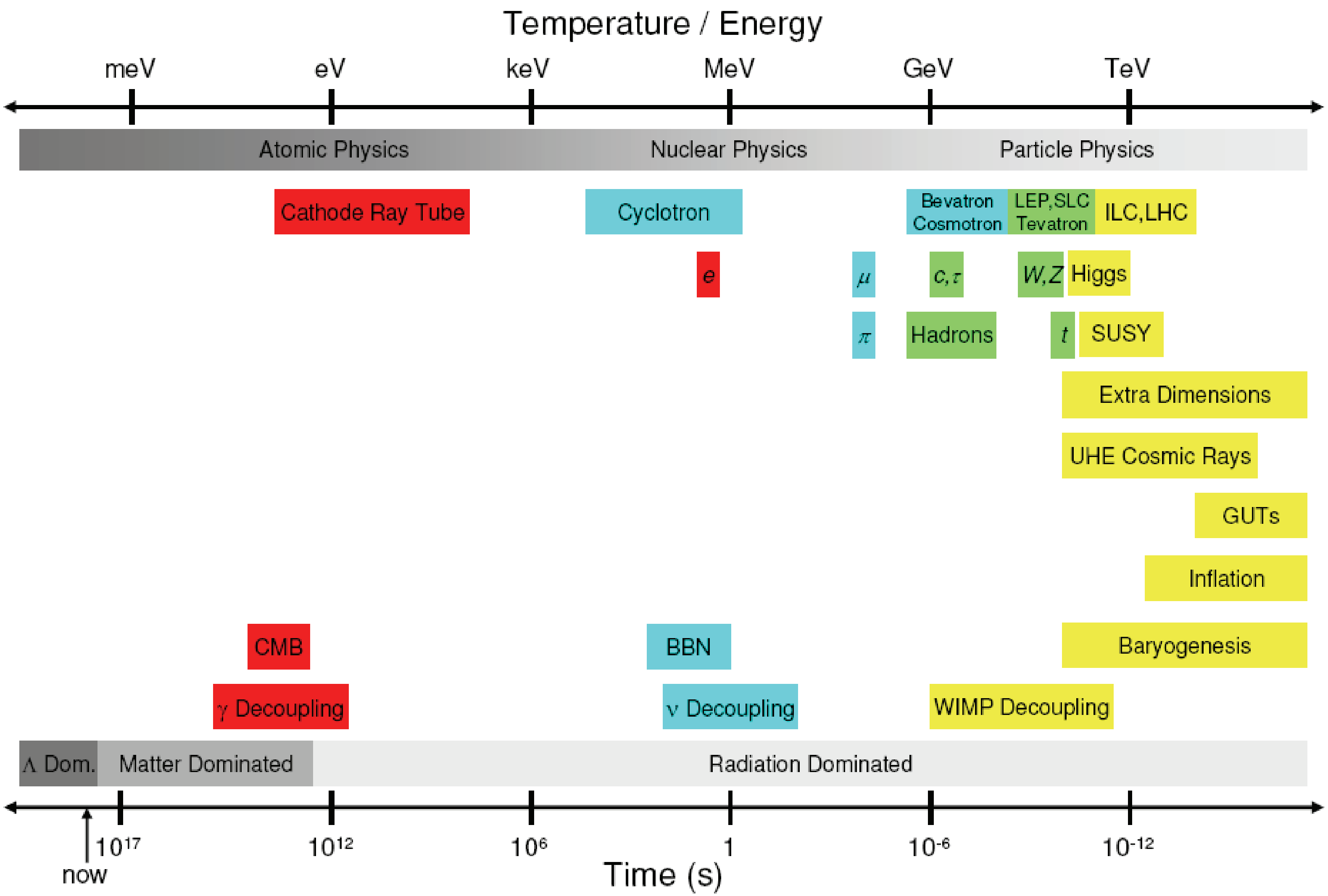
- Many dark matter candidates are heavy particles. Can we make them in the lab?



- Einstein: $E = mc^2$. Energy can be transformed into mass.

- To make new, heavy particles, simply smash together known particles at high energy.

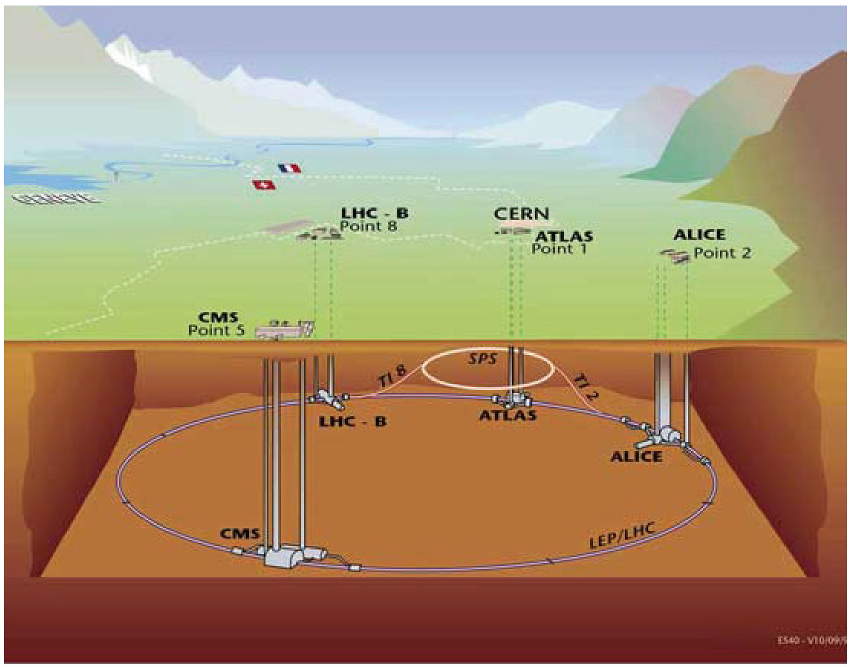
SYNERGY



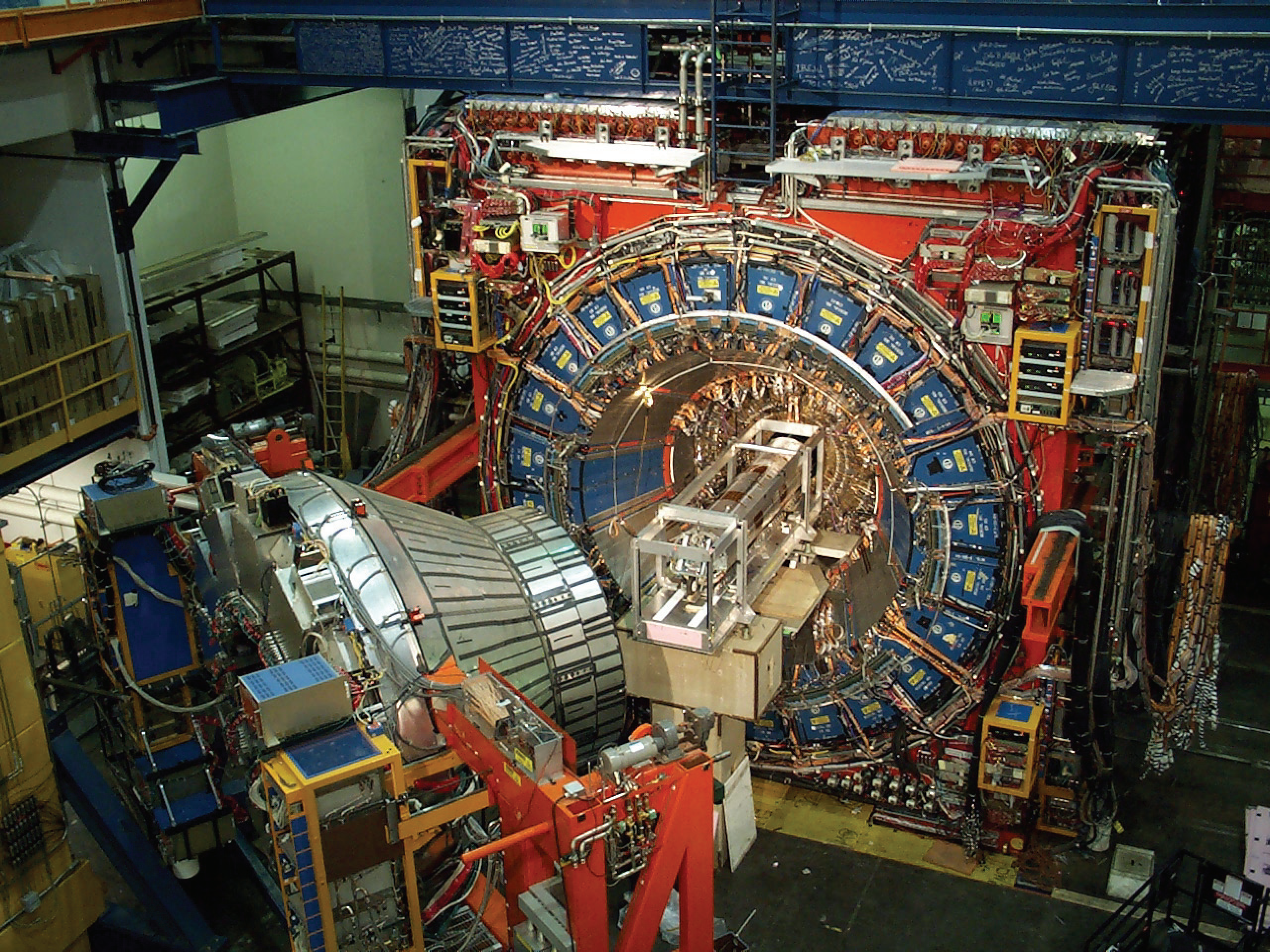
Temperature / Energy
meV
eV
keV
MeV
GeV
TeV
Atomic Physics
Nuclear Physics
Particle Physics
Cathode Ray Tube
Cyclotron
Bevatron Cosmotron
LEP,SLC Tevatron
ILC,LHC
e
μ
c, τ
W,Z
Higgs
π
Hadrons
t
SUSY
Extra Dimensions
UHE Cosmic Rays
GUTs
Inflation
CMB
BBN
Baryogenesis
γ Decoupling
ν Decoupling
WIMP Decoupling
Λ Dom.
Matter Dominated
Radiation Dominated
10^17
10^12
10^6
1
10^-6
10^-12
now
Time (s)


Large Hadron Collider
18 miles in circumference
Operation begins in 2008-09

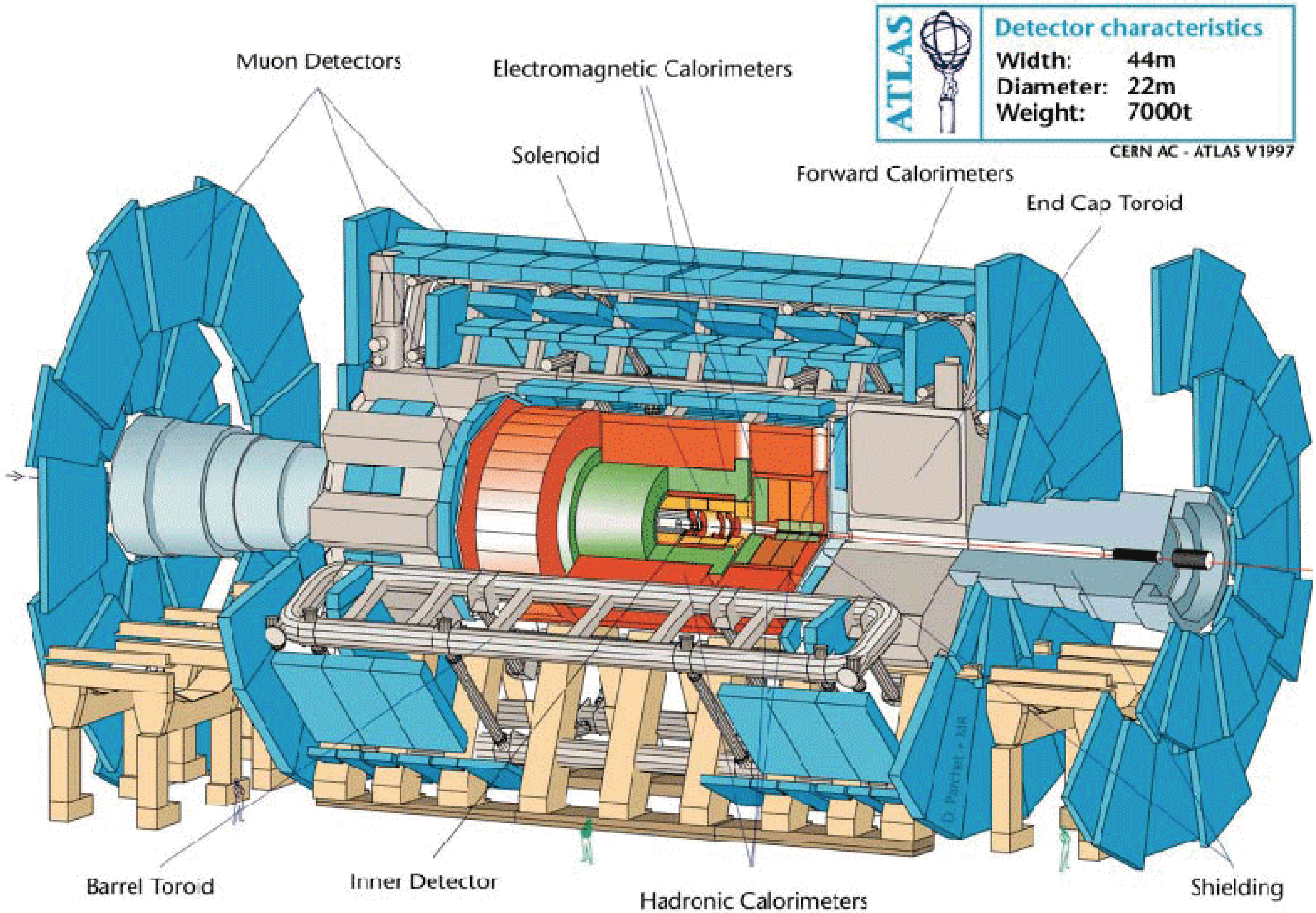
The Accelerator



Two proton beams rotate in opposite directions 100 m underground in Geneva on the French-Swiss border. The beams collide at 4 interaction points, which are surrounded by detectors.



LHC Detectors



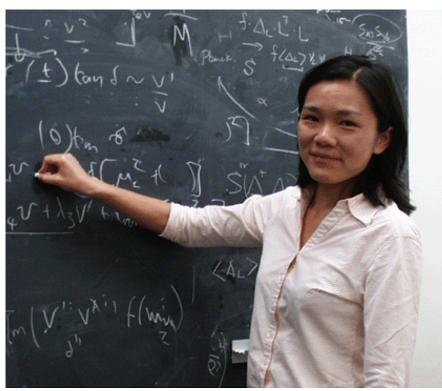
UCI Faculty Working on the LHC

Theorists

Jonathan Feng

Arvind Rajaraman

Yuri Shirman



Mu-Chun Chen

Experimentalists

Andy Lankford

Daniel Whiteson

Anyes Taffard

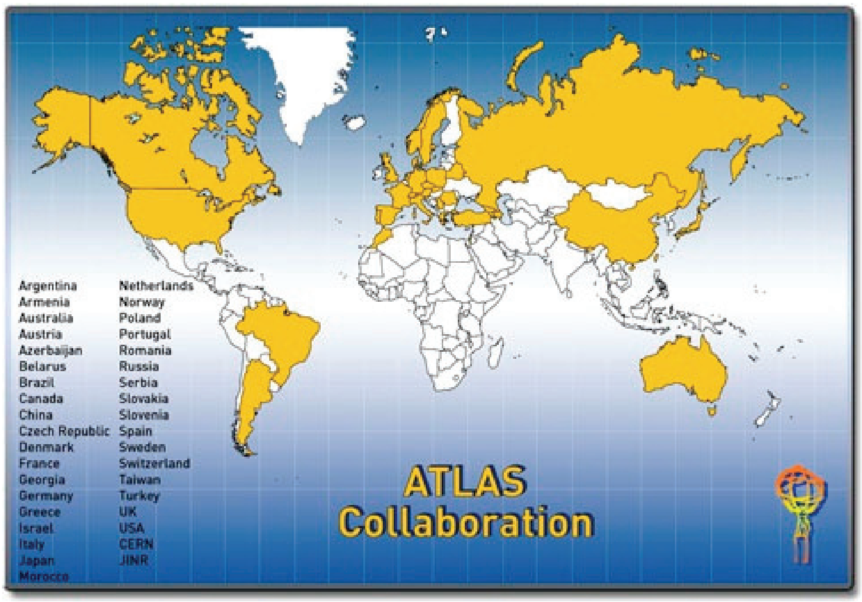
UCI @ LHC

- The main UCI experimental responsibilities are in triggering and data acquisition.
- Data acquisition: the data collected by each detector is
  - 1 Terabyte/second
  - 10,000 Encyclopedia Britannicas/second
  - 10 Libraries of Congress/minute
  - 3 300GB hard drives/second
  - 100 full length DVD movies/second
  - 10,000 times the rate your computer can store data

UCI @ LHC

Triggering: finding needles in haystacks

LHC SOCIOLOGY



In each experiment, ~2000 collaborators from ~40 countries (and growing)

The procedure for sharing data and credit is not completely clear and is a topic of heated debate

DARK ENERGY

- Heisenberg's uncertainty principle: it is impossible to simultaneously measure a particle's position and velocity precisely.
- Immediate corollary: all particle's have some energy.
- This "zero point energy" is dark energy – the fact that dark energy exists is not at all mysterious.
- The problem is that the natural value for the amount of dark energy is 10^{120} times the observed value!

Approach #1: Symmetry

- Consider a bubble, length L, height H
- L-H is a small number
- Explained by symmetry – the most symmetric shapes, spheres, minimize surface area
- Actually, gravity makes bubbles slightly lopsided, L-H ≠ 0

Approach #1

- Small numbers ↔ broken symmetry

$\Omega_\Lambda \sim 10^{120}$

??

$\Omega_\Lambda \sim 1$

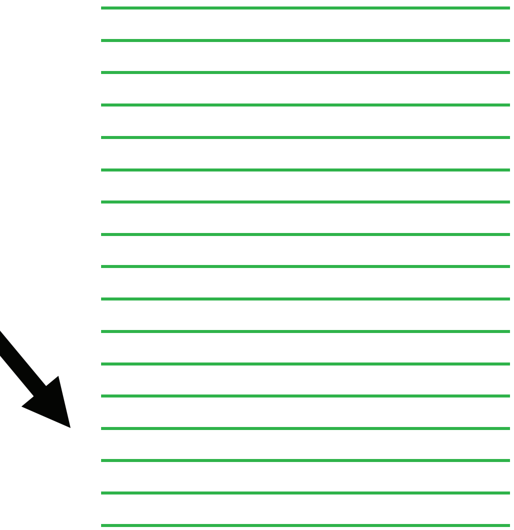
$\Omega_\Lambda = 0$

Approach #2

$\Omega_\Lambda \sim 10^{120}$

Many universes with different values of Ω_Λ

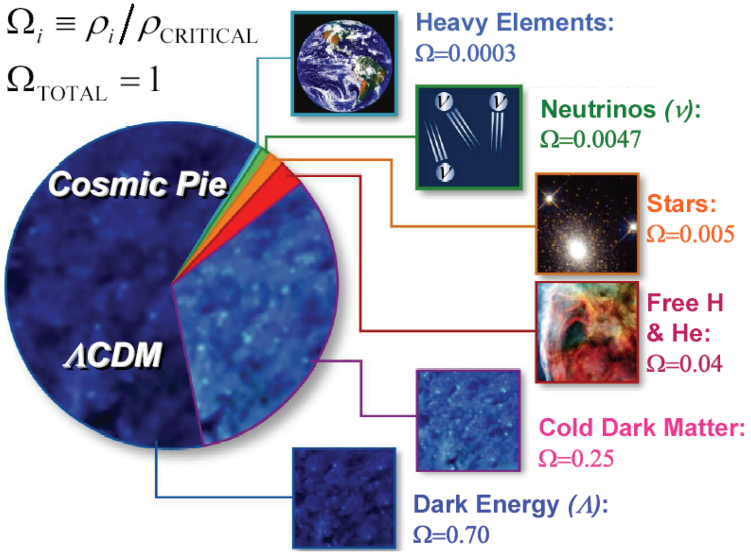
Anthropic principle:
$\Omega_\Lambda \sim 1$



- Two very different approaches
- There are others, but none is especially compelling
- Dark energy is a very difficult problem

SUMMARY

- For the first time in history, we have a complete picture of the Universe



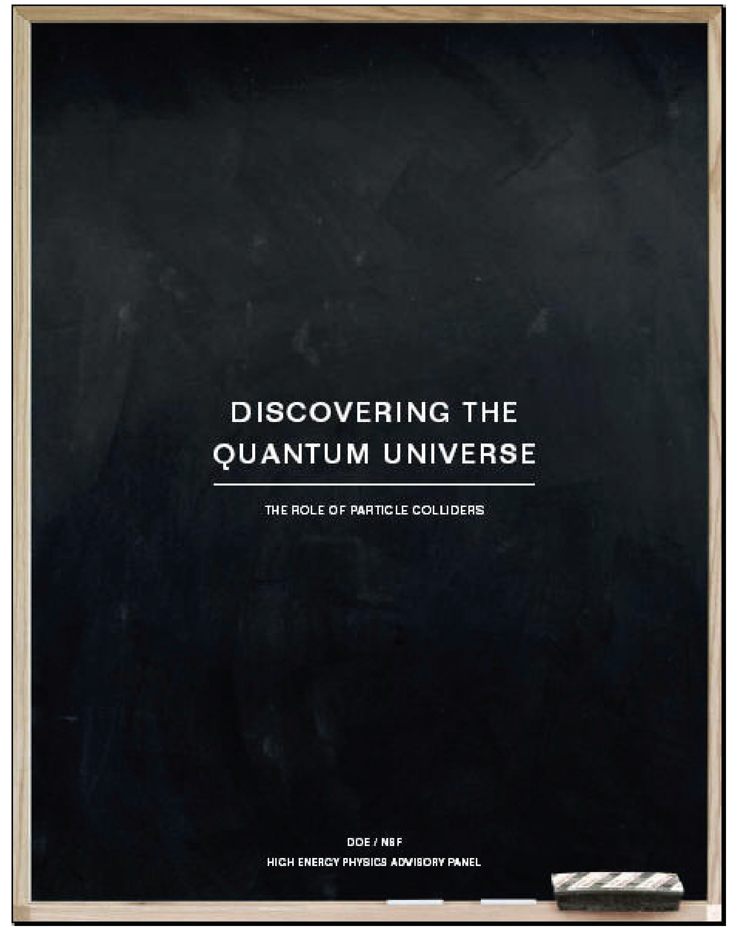
- Dark matter and dark energy require new discoveries at the smallest length scales

Historical Precedent

Eratosthenes measured the size of the Earth in 200 B.C.

- Remarkable precision (~10%)
- Remarkable result
- But just the first step in centuries of exploration

ACKNOWLEDGMENTS



Available at
http://interactions.org/quantumuniverse/qu2006/