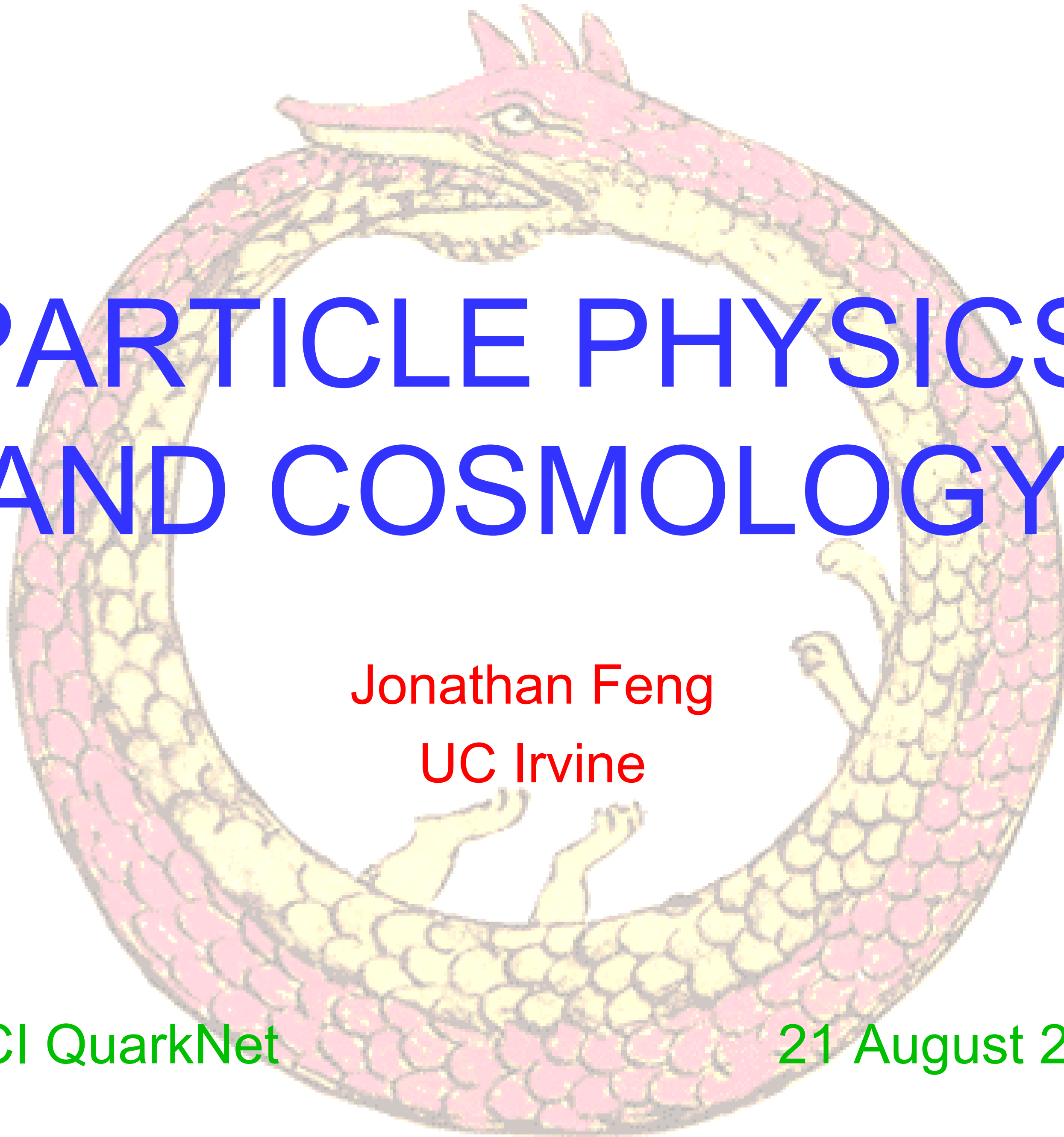


PARTICLE PHYSICS AND COSMOLOGY

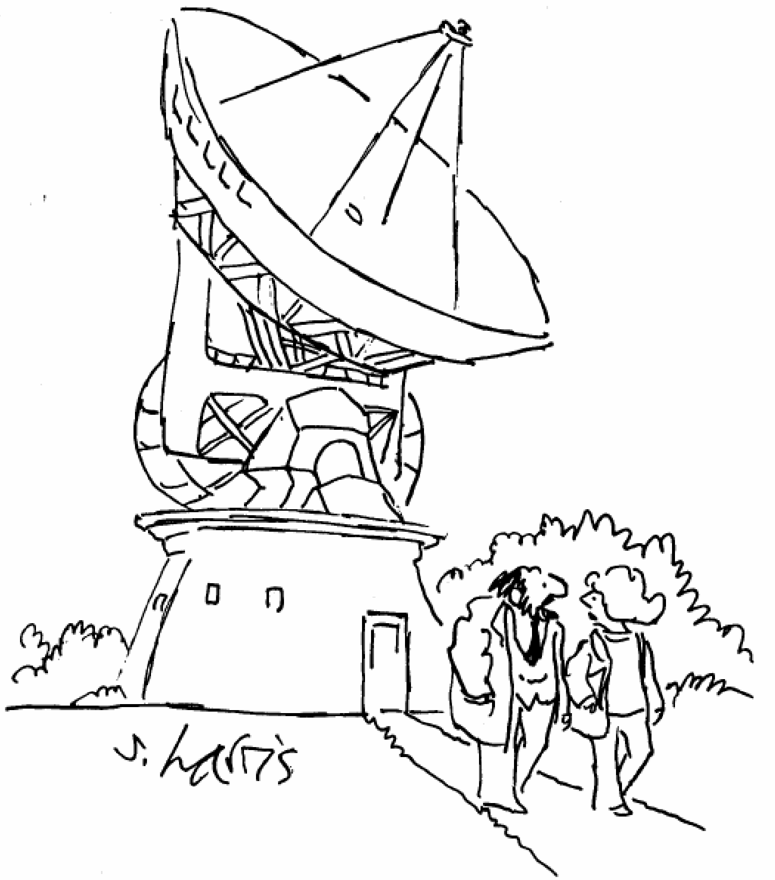
Jonathan Feng

UC Irvine

UCI QuarkNet

21 August 2003

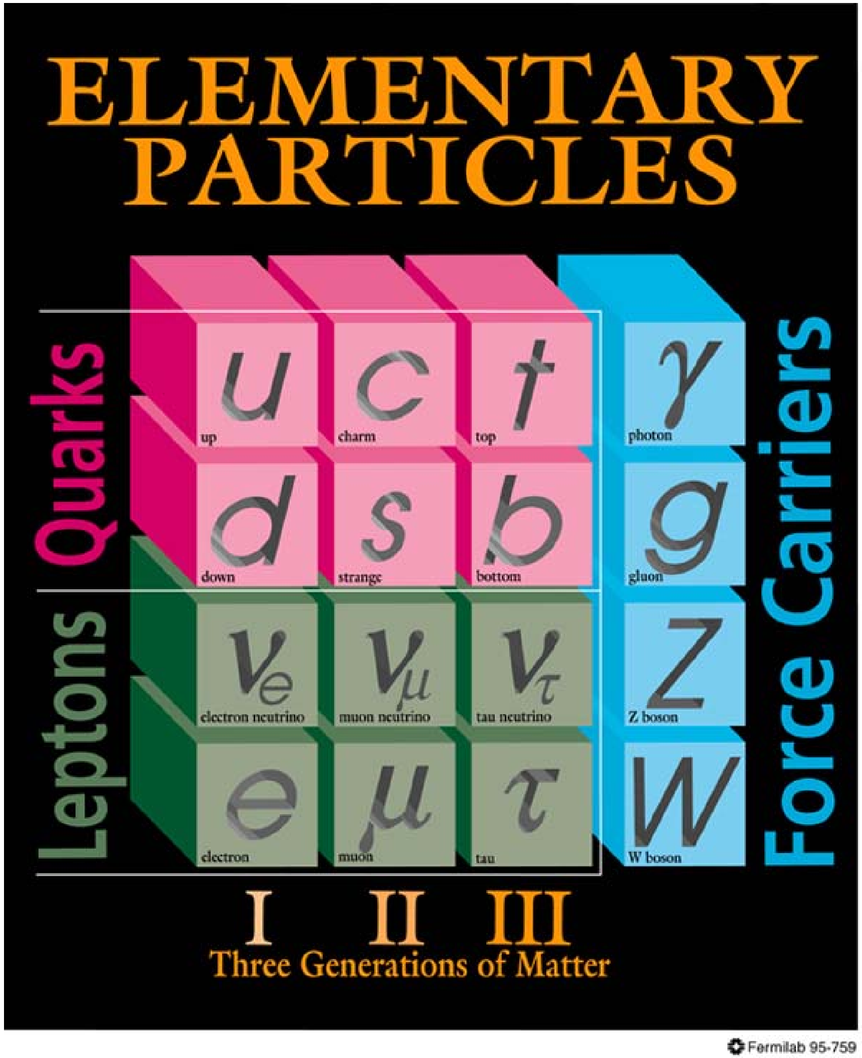
CONNECTING THE VERY, VERY SMALL WITH THE REALLY, REALLY BIG



"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."

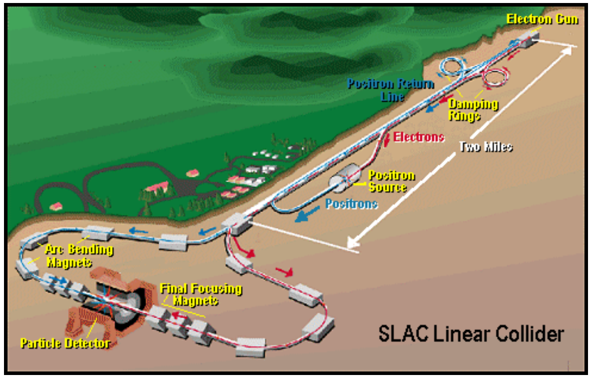
Standard Model of Particle Physics

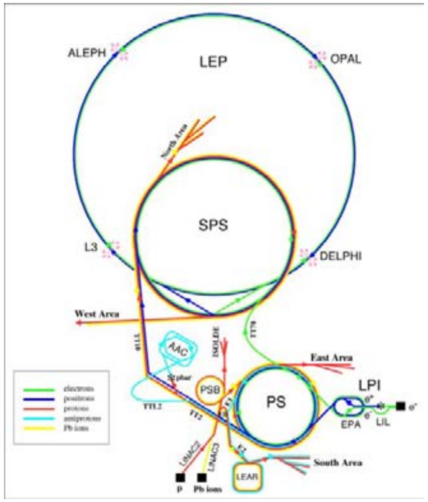
- c. 1970s
- Explains data down to length scales of 10^{-16} cm

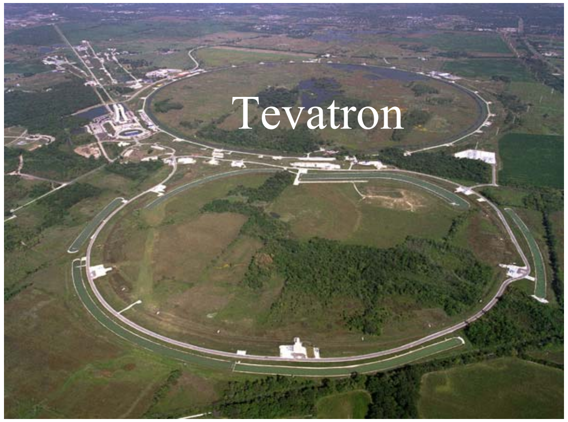


Particle Physics – Experiment

High Energy Colliders



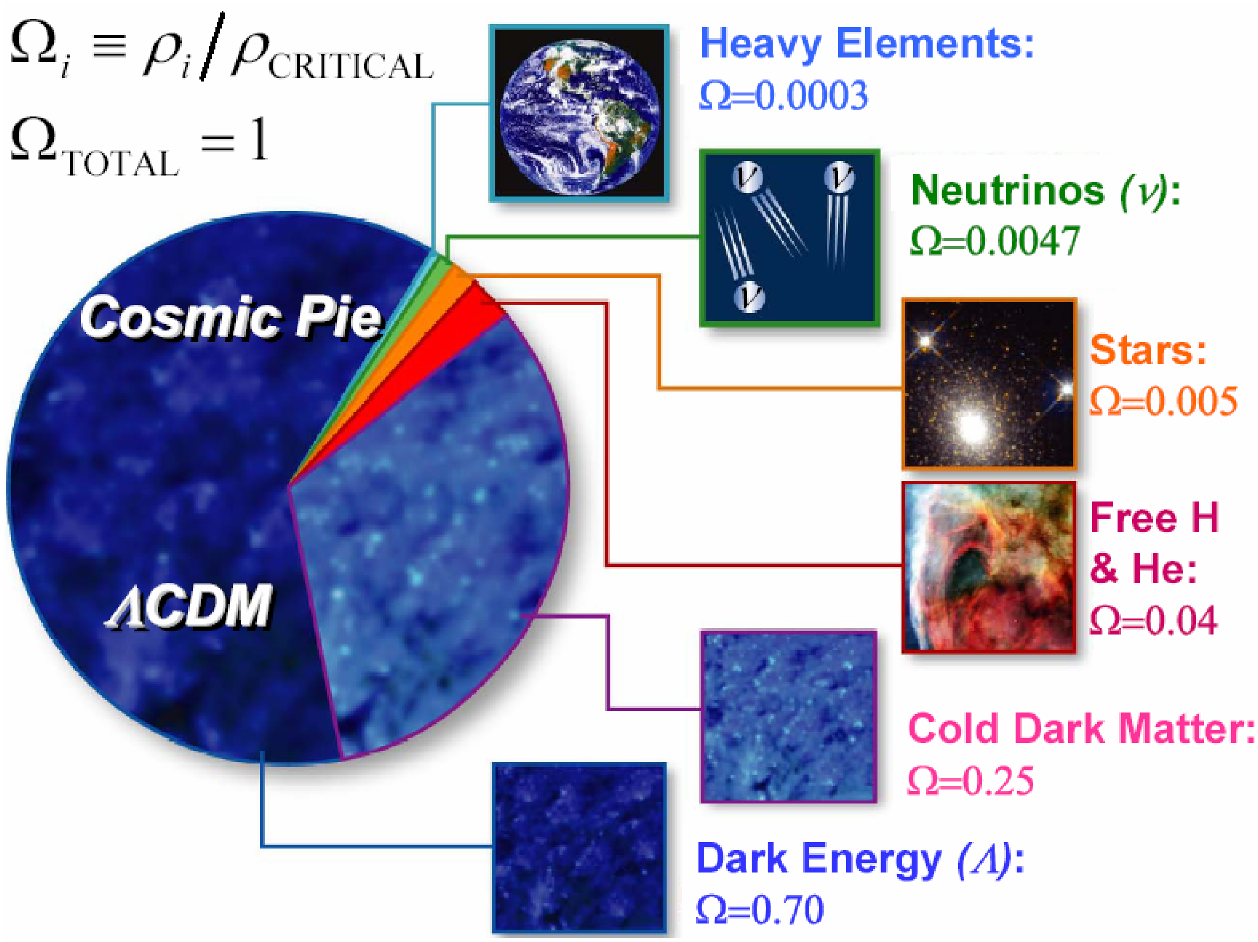




$$\frac{\Delta g_1}{g_1} \sim 10^{-8} \qquad \frac{\Delta g_2}{g_2} \sim 10^{-3} \qquad \frac{\Delta g_3}{g_3} \sim 10^{-2}$$

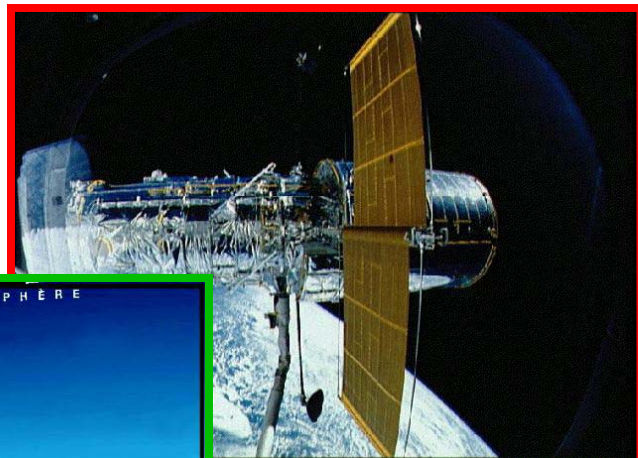
Standard Model of Cosmology

- c. 2003
- Explains data up to length scales of 10^{28} cm

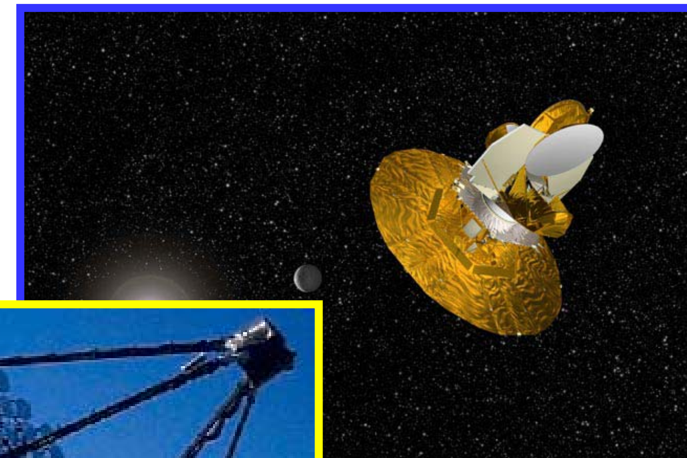


Cosmology – Experiment

Satellites, telescopes



HST



WMAP

Auger

Whipple

Connections – Theory

Why do particle physicists care about cosmology?

Cosmology poses fundamental questions:

- What is dark matter?
- What is dark energy?
- Why is there more matter than anti-matter?

The standard model of particle physics is amazingly successful, but…

It's missing 96% of the universe, and we don't understand why the remaining 4% is still here.

Connections – Experiment

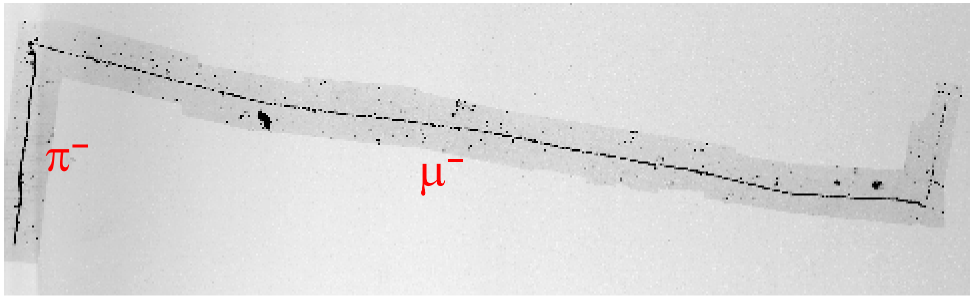
- Cosmology also provides tools to help answer these questions
  - Ultrahigh energy collisions now
  - Ultrahigh energies from the Big Bang

… for FREE !

- Drawbacks
  - “Experimental rates” are low – need BIG detectors
  - Cosmological “experiments” were done a long time ago
  - Cosmological “experiments” are irreproducible

Cosmic Rays – Past

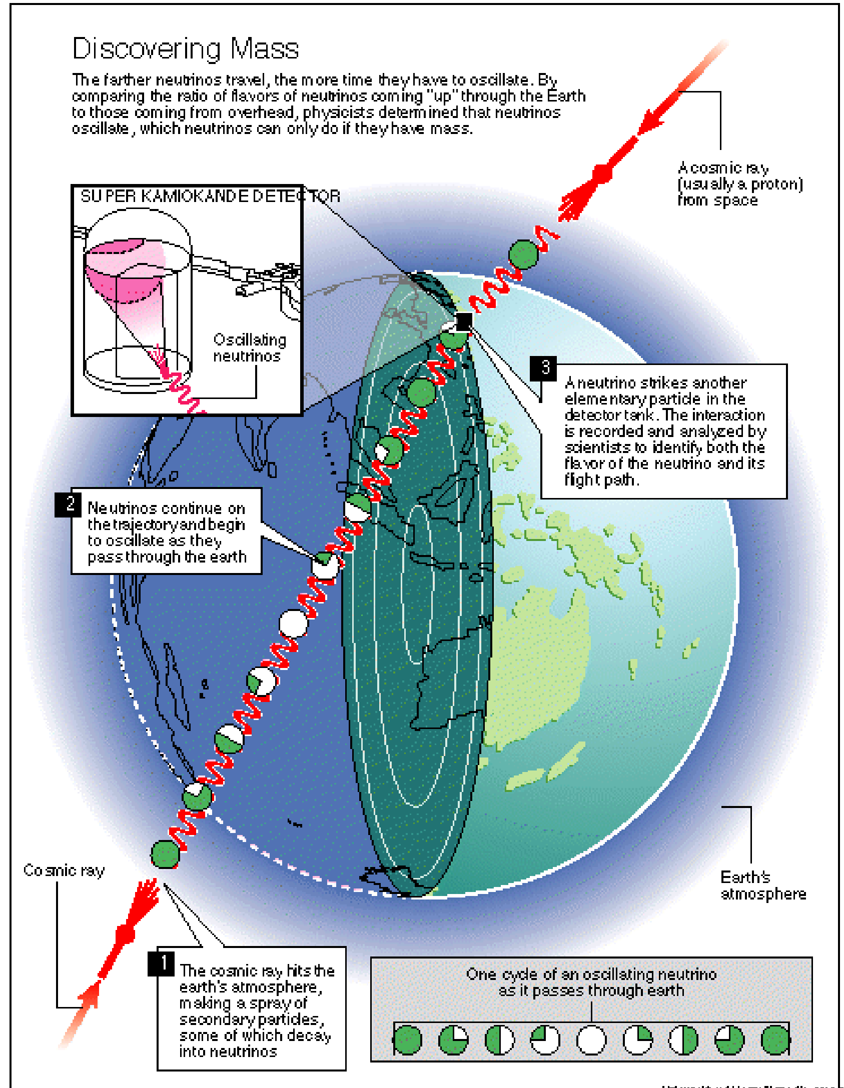
- 1935 Yukawa postulates the pion with mass ~ 100 MeV.
- 1937 Anderson discovers the "mesotron" in cosmic rays with mass ~ 100 MeV.



- 1941-45 WW II.
- 1946 Powell and Occhialini discover pions π^- (139 MeV) in cosmic rays. Mesotrons identified as muons μ^- (106 MeV).
- 1946 Rochester and Butler discover kaons K^0 (494 MeV) in cosmic rays.
- 1948 First man-made pions π^- and π^0 (134 MeV) produced at Berkeley 184-inch cyclotron.

Cosmic Rays – Present

- Neutrino masses and mixings discovered through cosmic rays at SuperKamiokande in 1998
- Man-made neutrino sources provide evidence for mixings at KamLAND in 2002



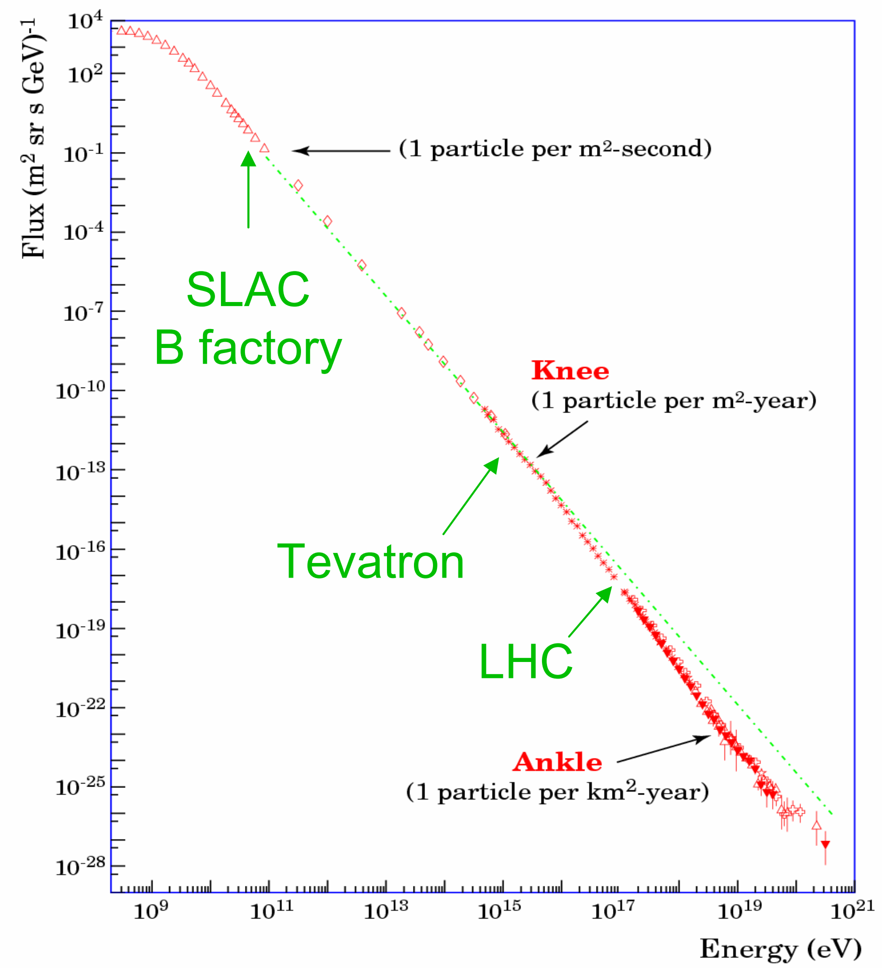
Cosmic Rays – Future

- Cosmic rays observed with energy E_{CR} ~ 10^{19} eV (~ major league fastball)

- For fixed target collisions, the center-of-mass energy is $E_{CM} = (2\ E_{CR}\ m_p)^{1/2}$, so

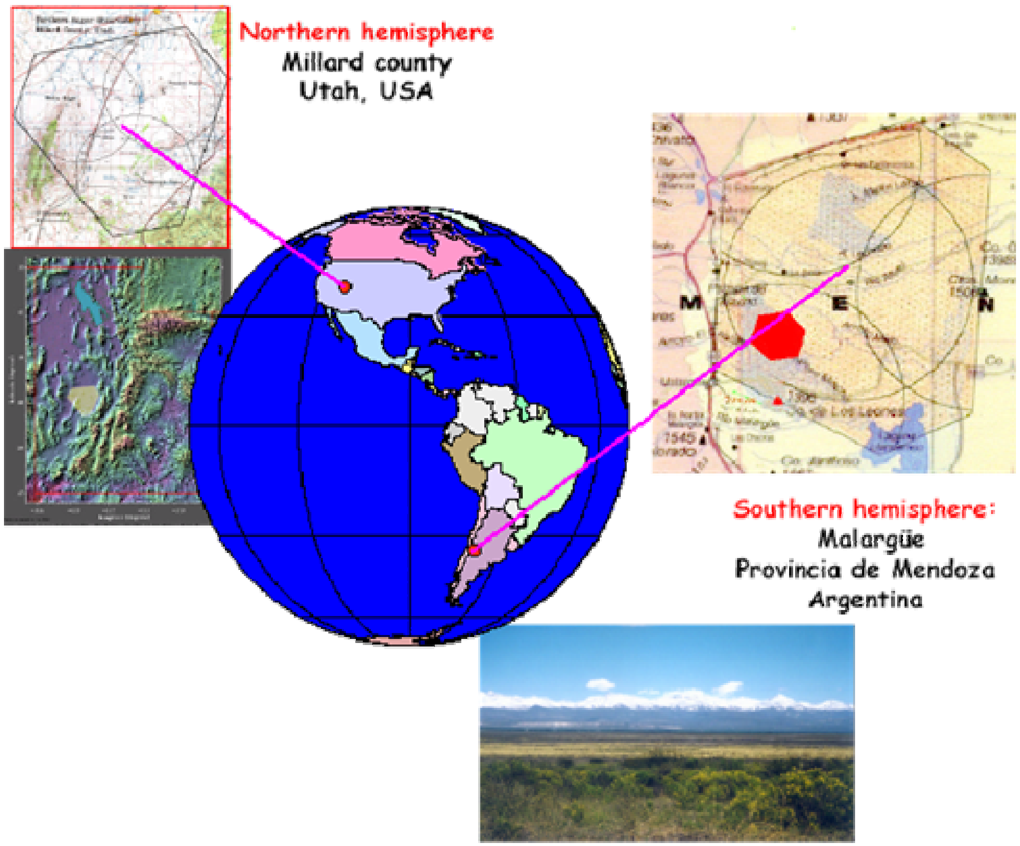
E_{CR}~10^{19} eV → E_{CM}~100 TeV

- Higher energies than any man-made collider

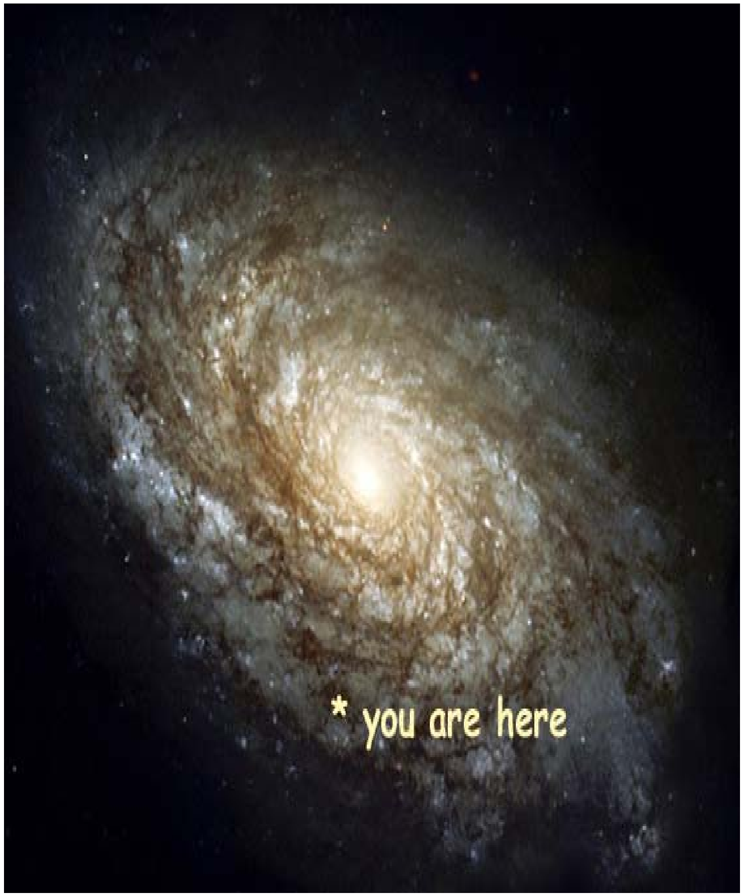


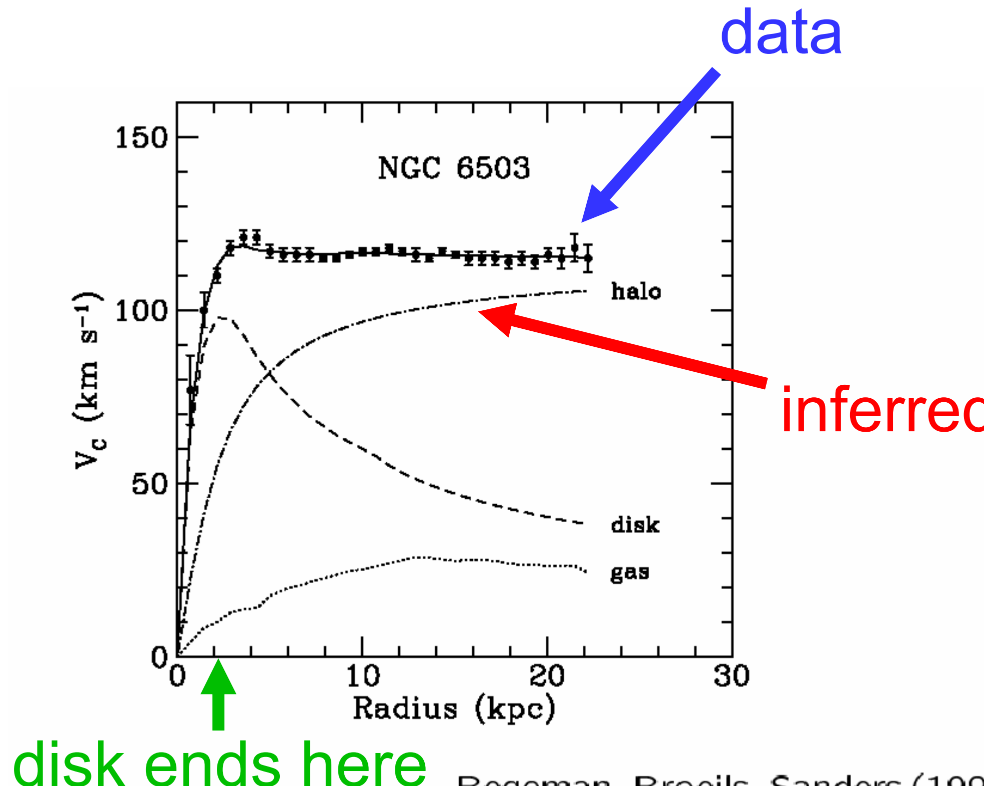
Cosmic Rays – Future

Black Hole produced here



Dark Matter



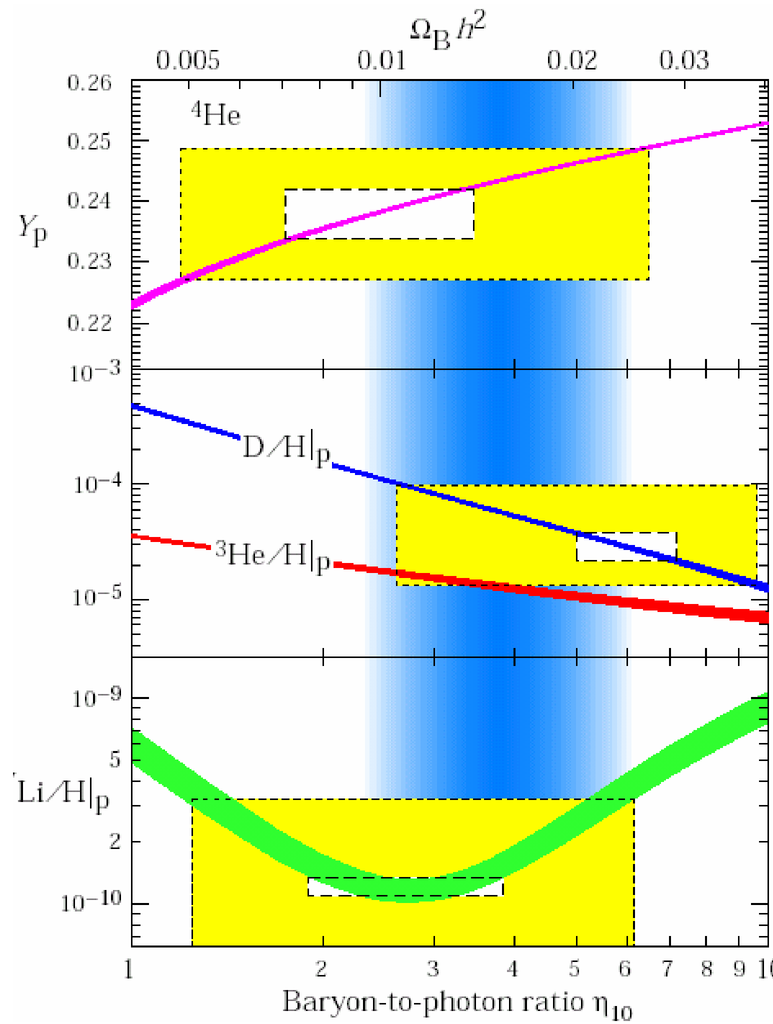


Begeman, Broeils, Sanders (1991)

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

Big Bang Nucleosynthesis

- What is the halo made of? Not atoms!
- As the universe cools, protons form nuclei. The number of protons determines the amount of light elements in the universe.
- All light elements agree: protons make up 4% of the universe's mass, whereas the required amount of halo matter is 29%. The remaining 25% is *dark matter*.



What is Dark Matter?

- Must be neutral, very long-lived, heavy.
- All known particles are easily eliminated.
- Dark matter is the best evidence that the standard model of particle physics is incomplete, and motivates many extensions.
- Some candidates:
  - WIMPs (e.g., neutralinos)
  - Axions

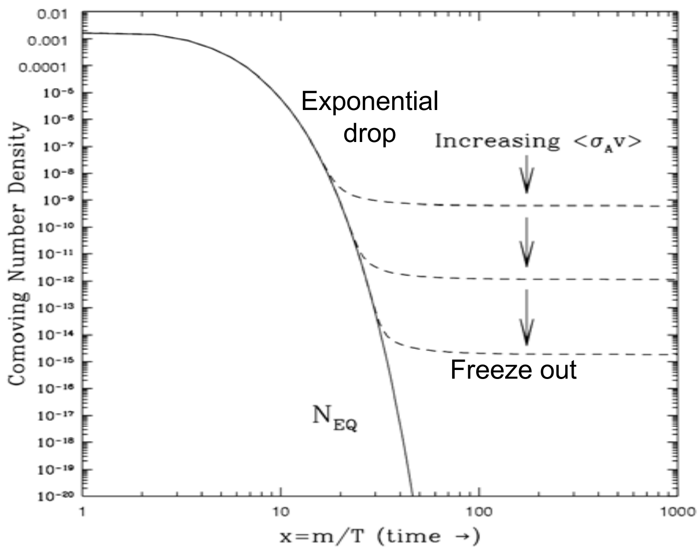
WIMPs

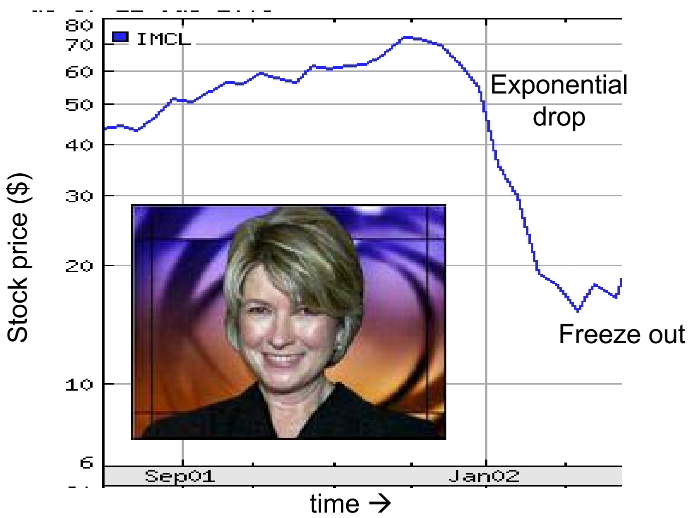
- Among the best candidates so far: weakly-interacting massive particles. These particles have weak interactions only.

- They are produced in the Big Bang, and interact via
  SM + SM ↔ WIMP + WIMP. As the universe expands, they become diluted, and eventually can't find each other – they "freeze-out." Their relic density is determined by their interaction strength.

- WIMPs are automatically left with the right amount to be dark matter.

WIMPs





- Universe cools, leaves a residue of dark matter with $\Omega_{DM} \sim 0.1\ (\sigma_{Weak}/\sigma)$
- 13 Gyr later, Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidences? Maybe, but worth investigation!

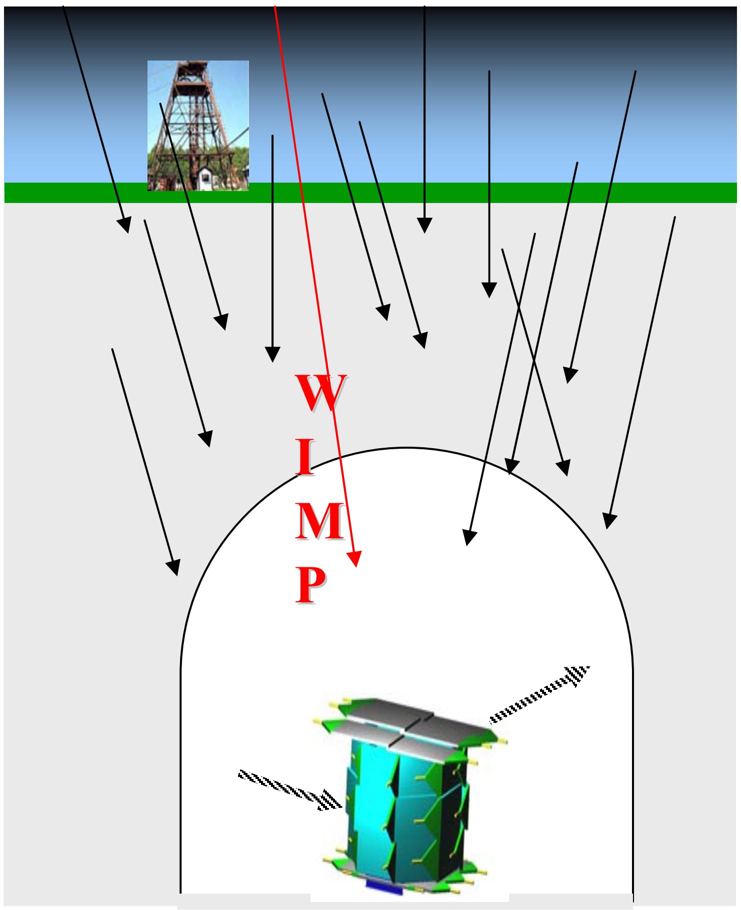
Supersymmetric WIMPs

Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2						$\tilde{G}$ gravitino
1	γ	Z^0				
1/2	$\tilde{\gamma}$ Photino	$\tilde{Z}^0$ Zino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$

Cold Dark Matter WIMP candidates: neutralino, sneutrino

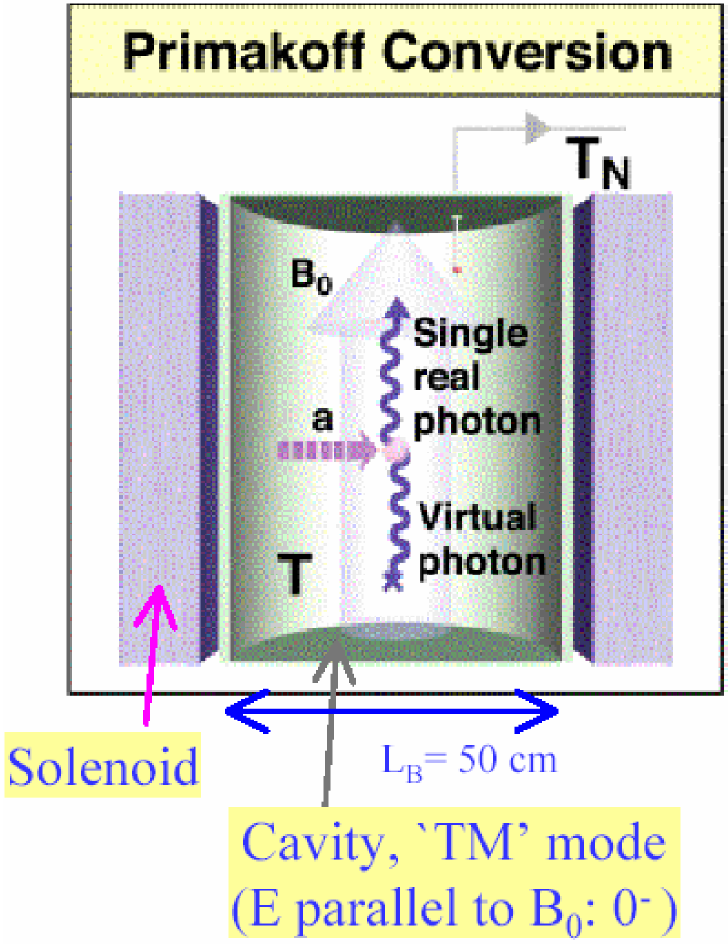
WIMP Detection



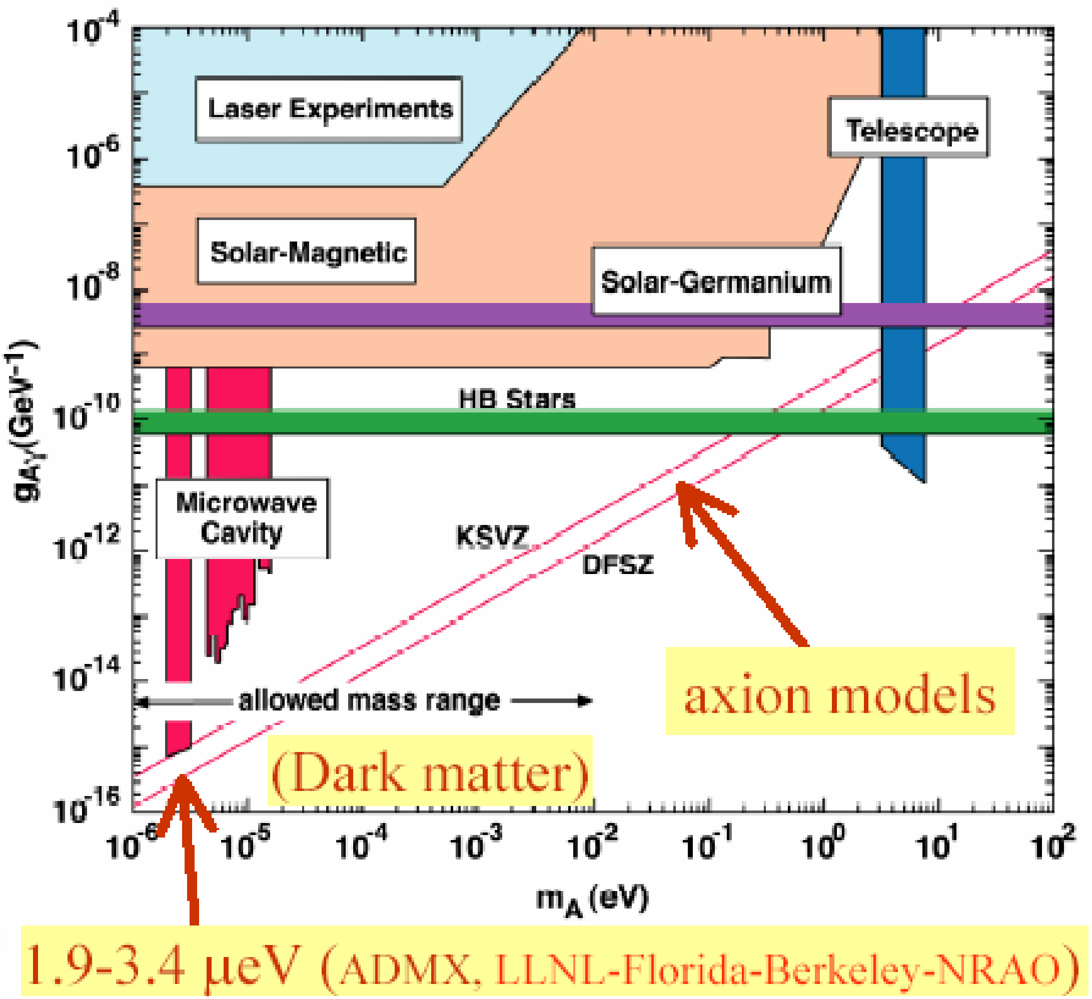
CDMS in the Soudan mine
½ mile underground in Minnesota

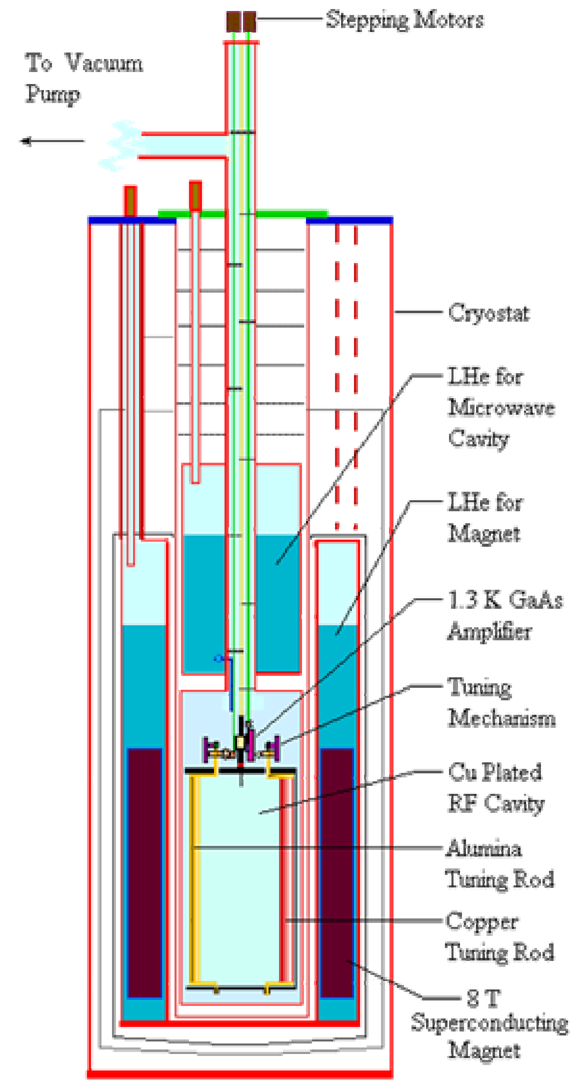
Axions

- Axions are particles predicted in theories designed to explain why CP violation is so small.
- Axions interact with photons and are very light with masses of μeV to meV.
- However, they interact *extremely* weakly.

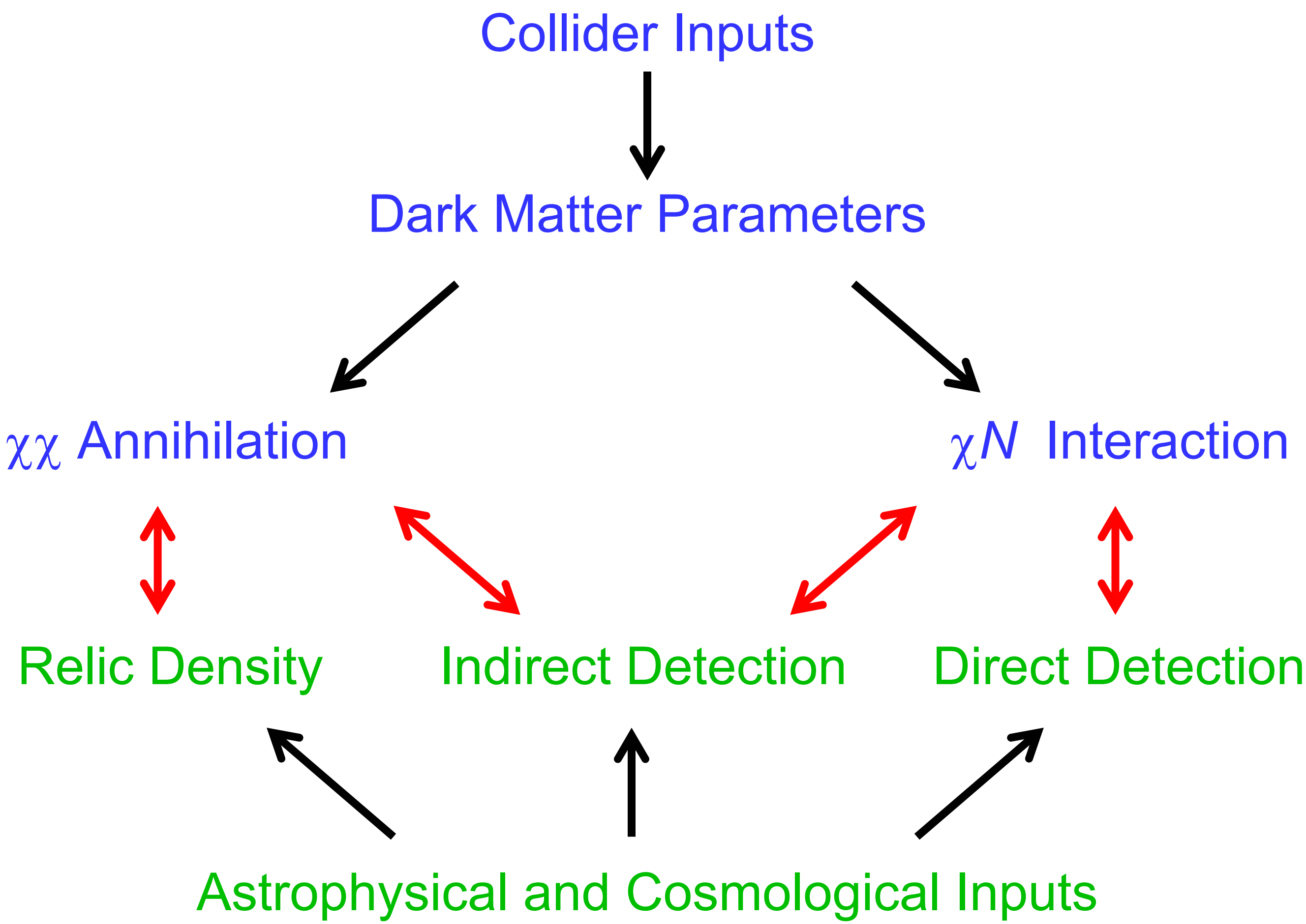


Axion Detection



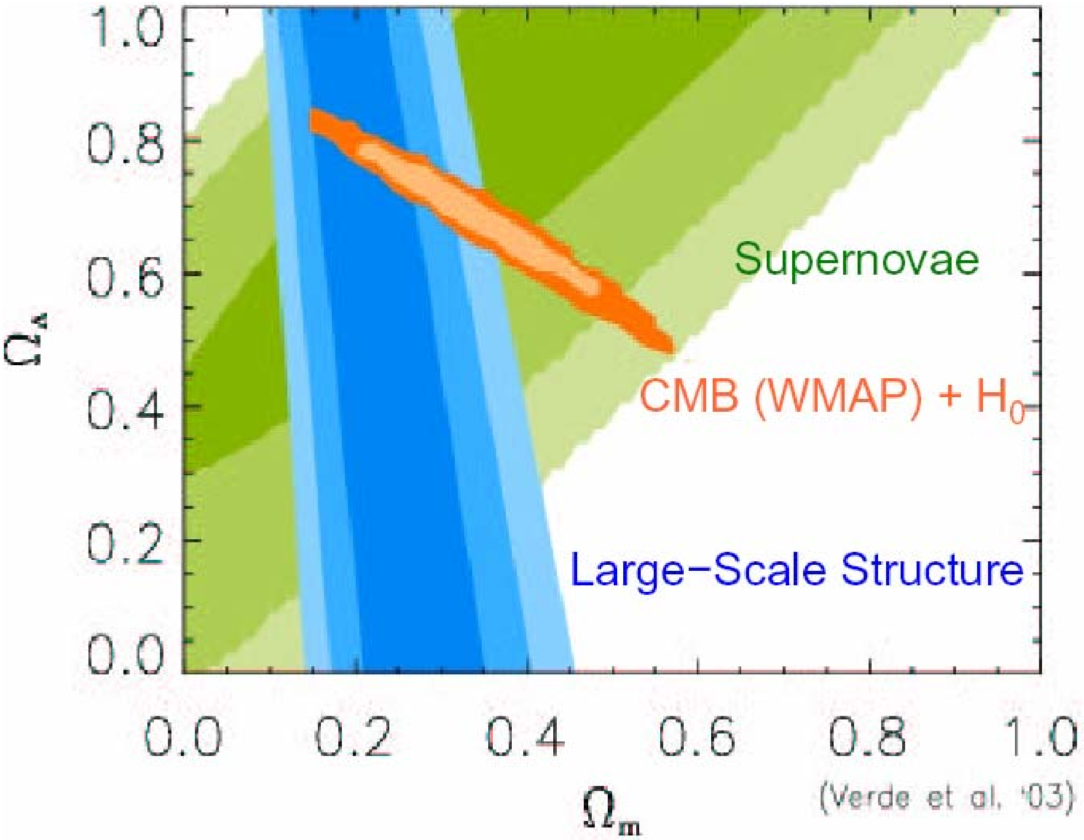


Dark Matter – Future



Dark Energy

- Cosmology → 70% of the mass of the universe is in dark energy (also known as the cosmological constant).



What is Dark Energy?

- Dark energy is the energy stored in a vacuum. From quantum mechanics, recall that an oscillator has energy $\omega\,(n \pm \frac{1}{2})$, where $\omega^2 = k^2 + m^2$; $\pm\omega/2$ is the vacuum energy. (Set $\hbar$=1.)

- In quantum field theory, we must add up vacuum energies for all wave numbers *k*. For each particle, we get

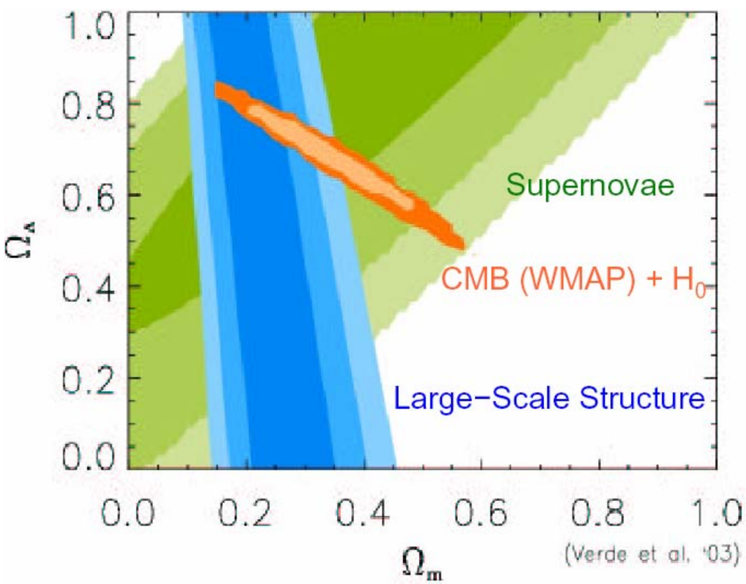
$$\pm\frac{1}{2}\int^{E} d^3k\,(k^2 + m^2)^{1/2} \sim \pm E^4,$$

where *E* is the energy scale where the theory breaks down.

Expectations for Dark Energy

- We expect $E \sim M_{Planck} \sim 10^{19}$ GeV, or at least $E \sim M_{weak} \sim$ 100 GeV. But cosmology tells us $E \sim 10^{-3}$ eV ! Independent contributions must cancel to incredible accuracy.

- Problems:
  - Why is Ω_Λ so small?
  - Why is Ω_Λ not zero?
  - Why is $\Omega_\Lambda \sim \Omega_M$?



- The cosmological constant problems are the most profound problems facing particle physics today. No reasonable solutions. (Anthropic principle?)

Summary

- Cosmology provides fundamental questions…
  - What is dark matter?
  - What is dark energy?
  - Why is there matter and not anti-matter?

- … and fundamental tools for finding the answers
  - The universe is Nature’s high energy collider

- The big and small are inextricably linked as particle physics and cosmology enter a golden era.

Ouroboros