Einstein's Universe and Beyond

Professor Lynn Cominsky
Sonoma State University

Outline

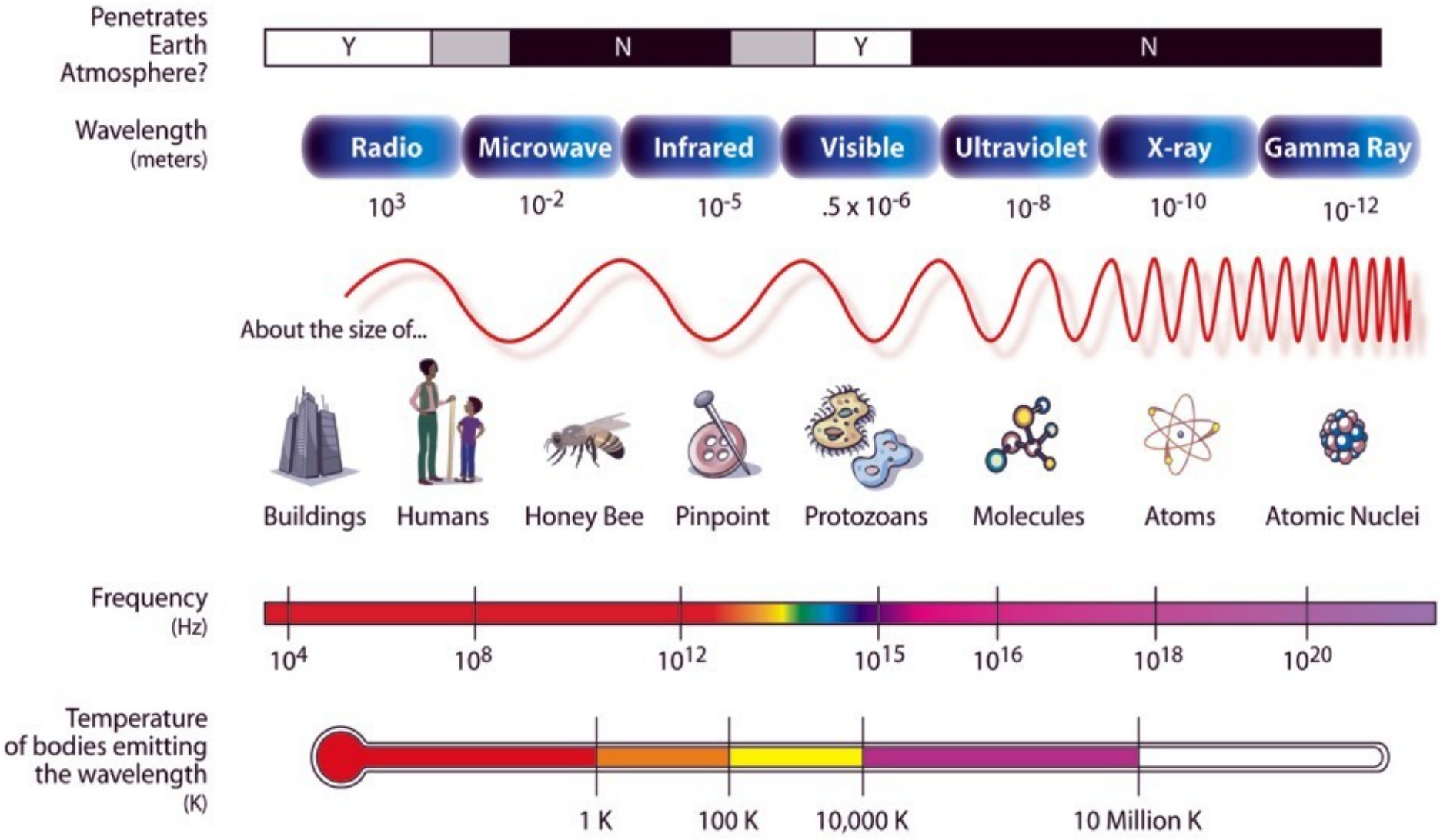
- A little background
- Einstein, Mass and Energy
- What's the Matter?
- Matter and Energy in the Universe
- Going Beyond Einstein
- Some Last Words

How do we see the Universe?

- We see light across the entire energy spectrum:
  - Radio waves (cold gas)
  - Infrared (warm dust)
  - Visible and ultraviolet (hot stars and galaxies)
  - X-rays and gamma-rays (stellar explosions, BHs)

HST/Eskimo nebula

THE ELECTROMAGNETIC SPECTRUM

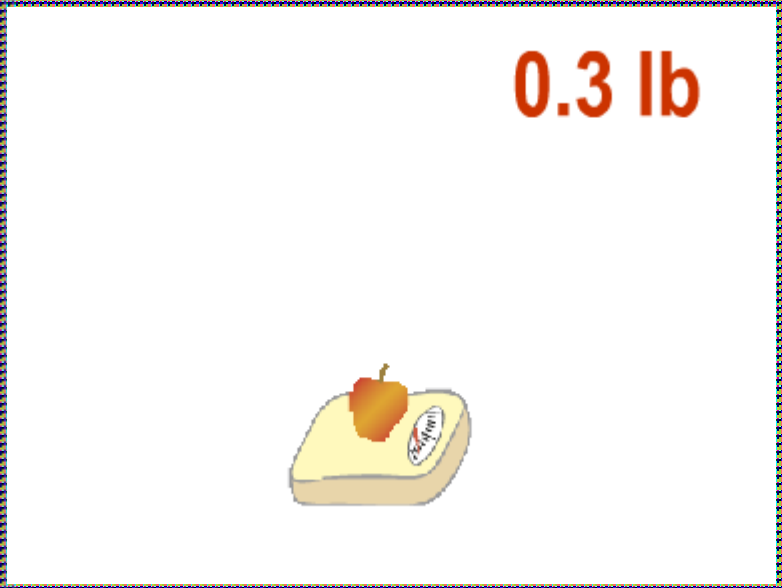


What do we see in the Universe?

- Most of our everyday experiences are with normal matter and visible light
- But, just as visible light is only one small part of the entire electromagnetic spectrum....
- Normal matter is only a small part of the total matter-energy content of the Universe

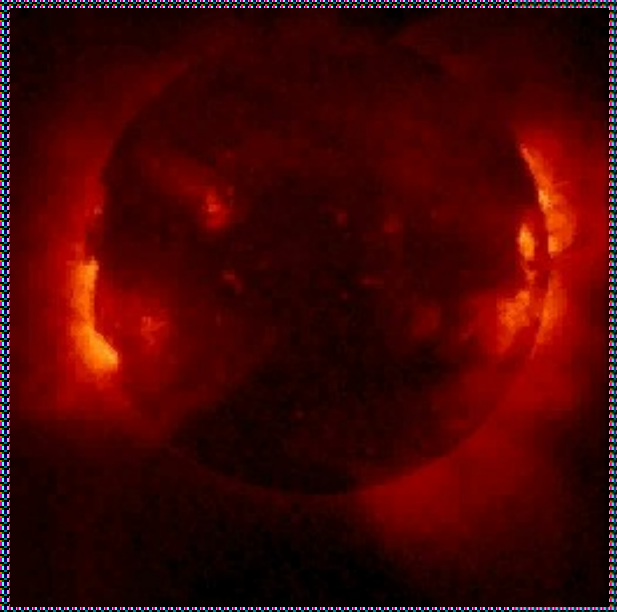
Mass conservation

- In most everyday situations, mass is *conserved*.
- $M_1 + M_2 = M_{1+2}$
- *Conservation* means that the masses add up → the equation is *balanced*



Mass conservation

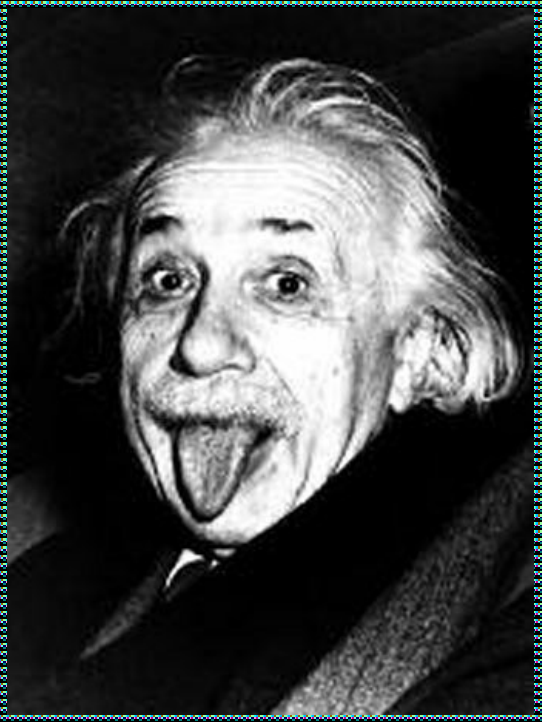
- **BUT:** Mass is not conserved in extreme environments, such as inside the Sun or at particle accelerators



Sun's image in X-rays from Yohkoh

SLAC

Mass and energy



- Einstein's most famous equation:

$$E = mc^2$$

- Einstein realized that mass and energy were equivalent and interchangeable
- SO: It is the total of mass & energy that really counts when we try to add up what is in the Universe.

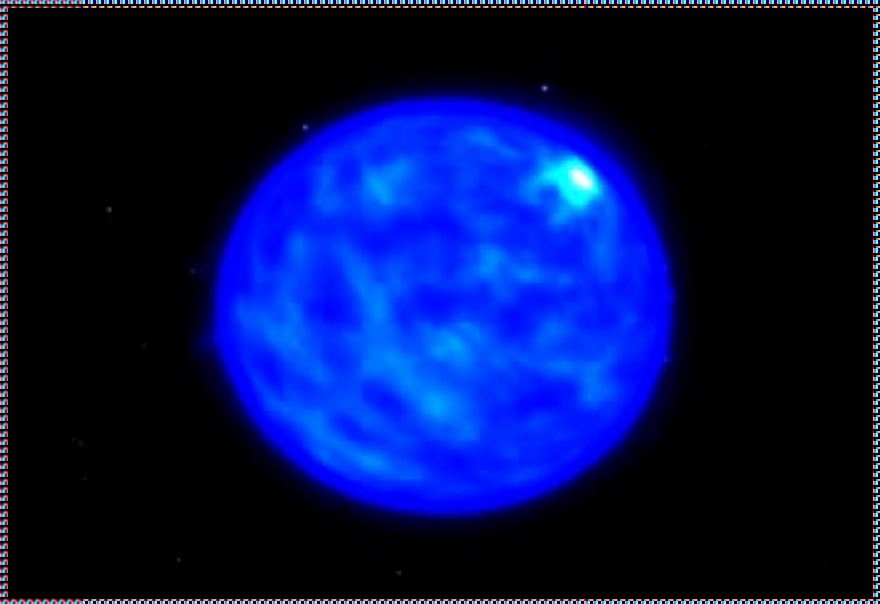
Creating Energy from Mass

- When two oppositely charged particles meet in flight, they can **annihilate** to create two gamma-ray photons traveling in opposite directions

- The rest mass of an electron or its anti-particle, the positron, is 511 keV/c^2
- **So**: Annihilation creates 2 gamma-rays with E= 511 keV

Explosions in Space

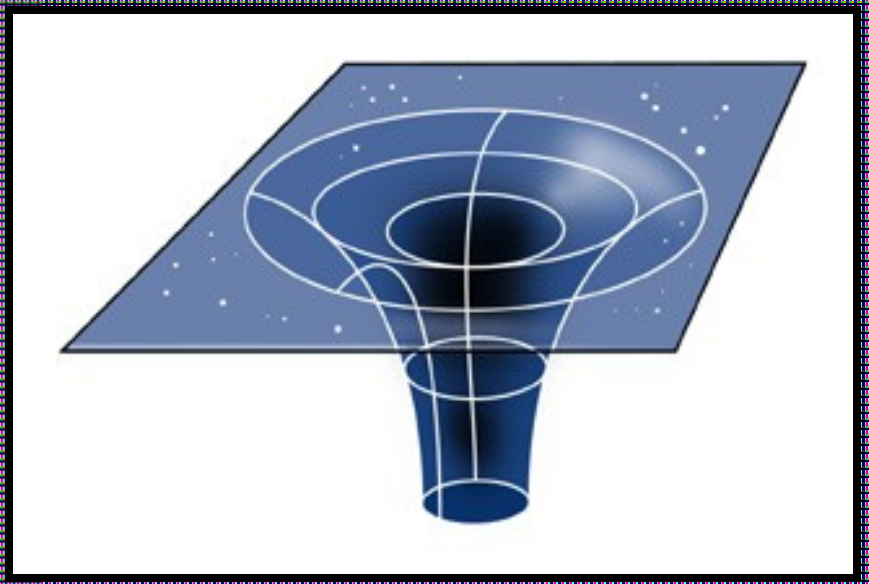
- Energy is also created from mass when stars explode
- Supernovae herald the deaths of stars
- Gamma-ray Bursts signal the deaths of even more massive stars
- They are the birth cries of black holes



Every time we see a GRB, a black hole is being born!

Einstein and black holes

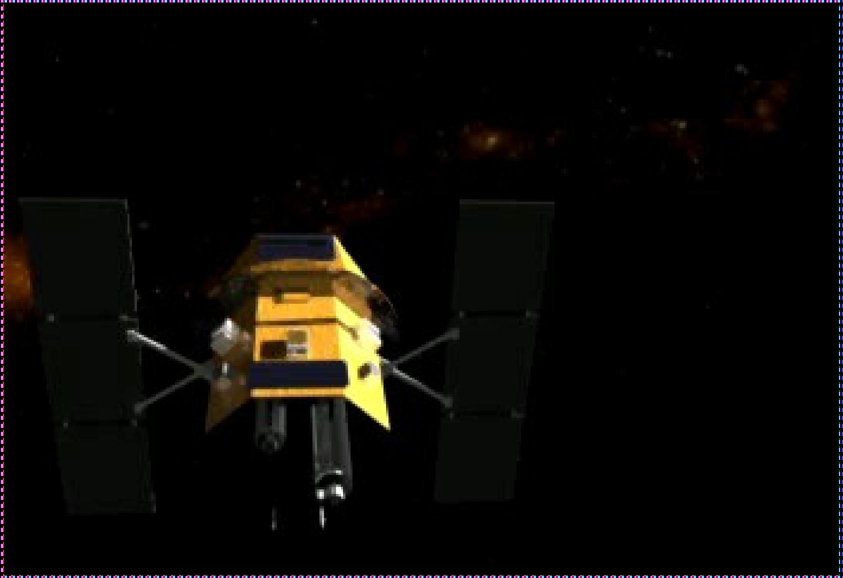
- Theory of General Relativity predicted the existence of black holes
- Singularities in spacetime where not even light can escape, once it has crossed the event horizon



$R = 2GM/c^2$

Swift Gamma-ray Burst Mission

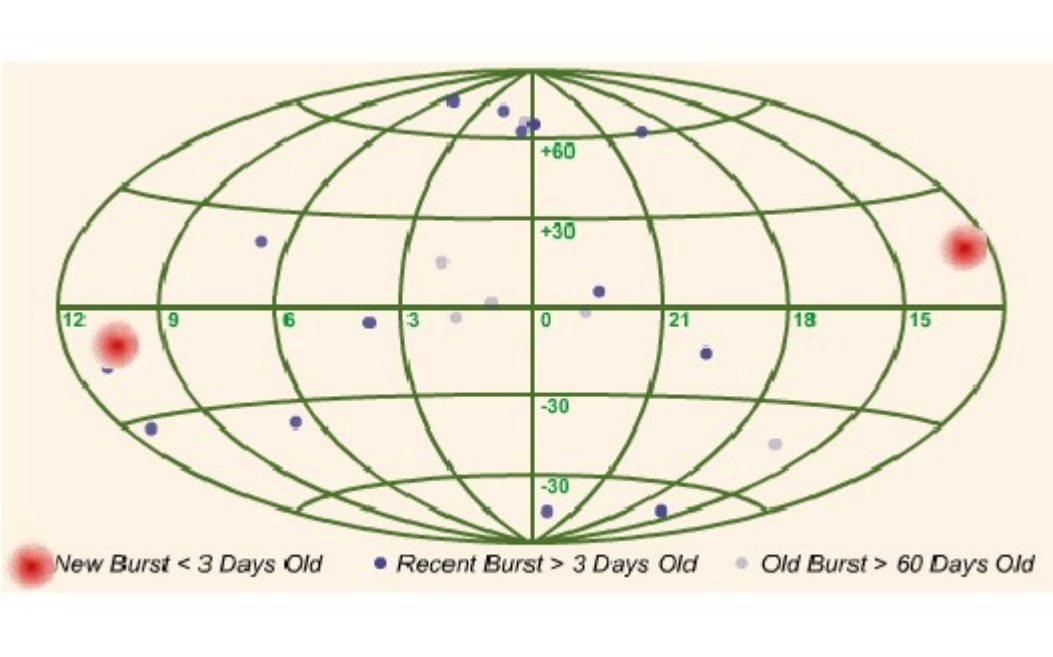
- Studies Gamma-Ray Bursts with a “swift” response
- Launched 11/20/04
- Is seeing 2 GRBs per week
- http://swift.sonoma.edu

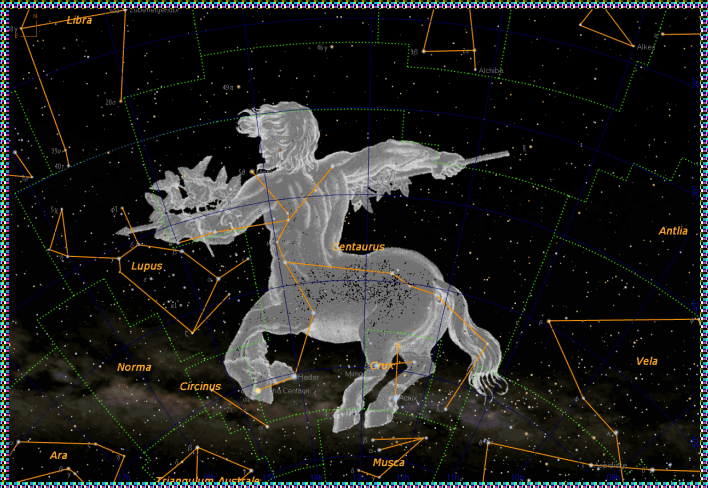


Each GRB has the energy of a billion billion Suns!

GRB Skymap – http://grb.sonoma.edu

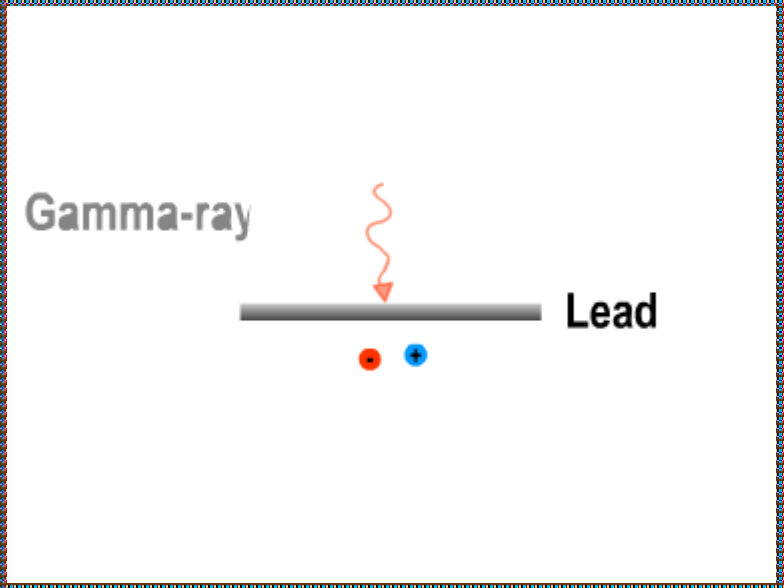
- Shows GRBs as they occur in realtime
- Also constellations, skymaps, other info



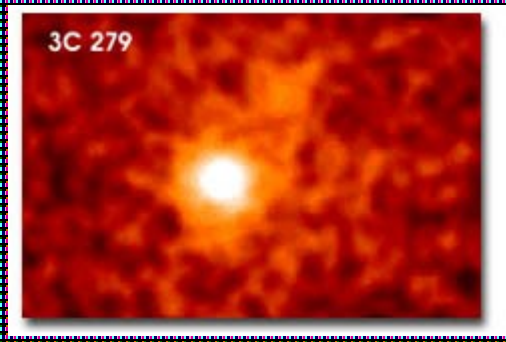


Creating Mass from Energy

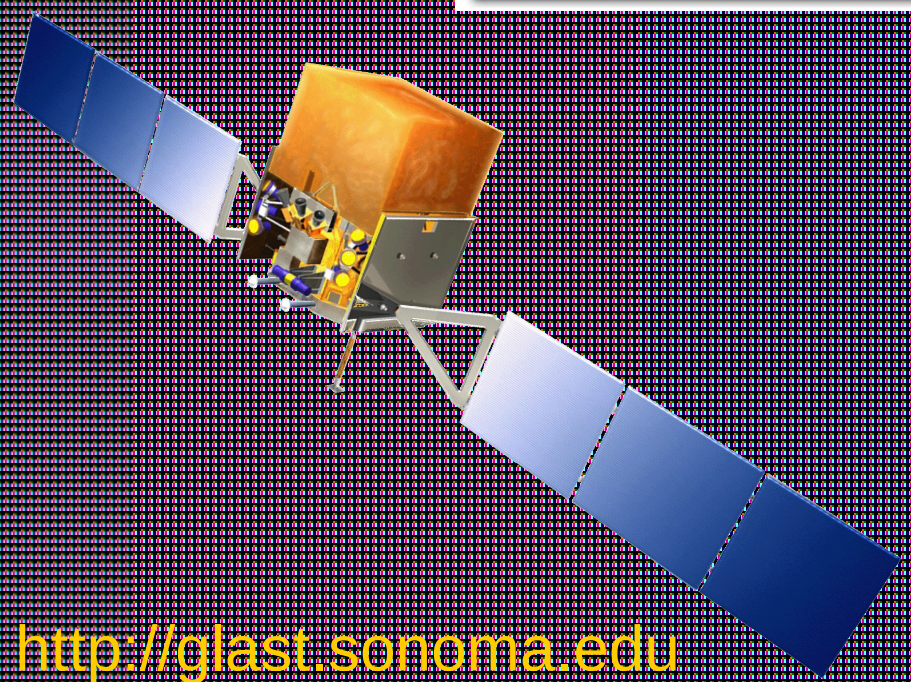
- Pairs of oppositely charged particles can be produced from a single energetic gamma-ray photon, interacting with converter material



Pair production in space



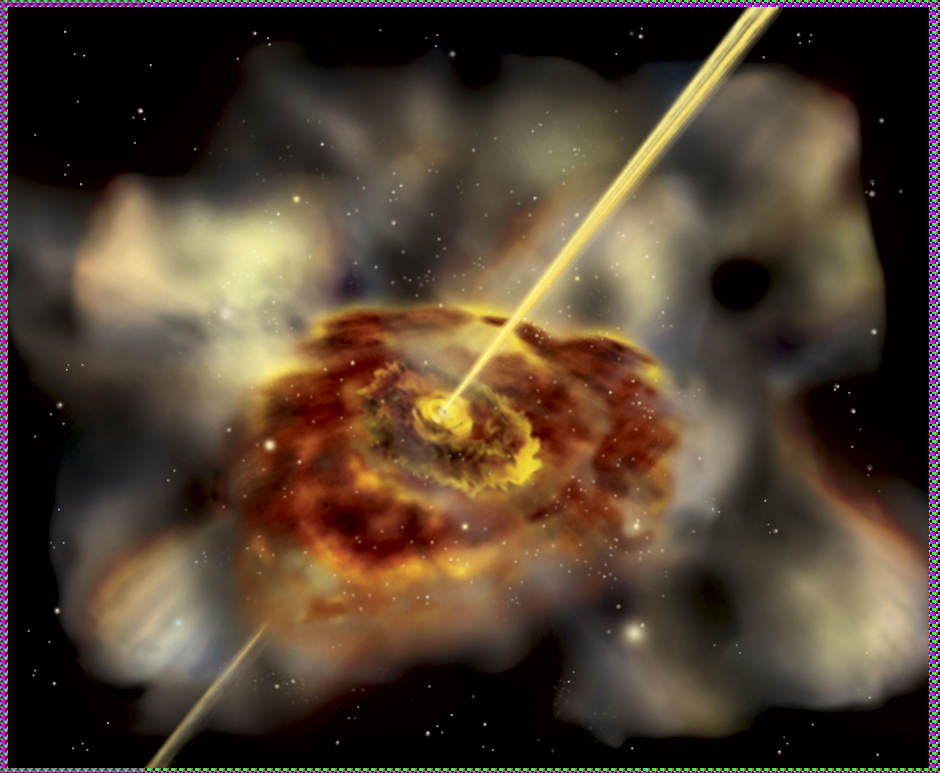
- NASA is launching a telescope in 2007 that uses pair production to track gamma-rays from space to their sources – often huge black holes!



http://glast.sonoma.edu

GLAST sees the Universe

- The Gamma-ray Large Area Space Telescope will locate thousands of super-massive black holes that are beaming jets of gamma-rays towards the Earth
- We want to figure out what types of matter are in the jets and how they are made



Three states of matter?

- Most students are taught there are three states of matter:
  - Solids Liquids Gases

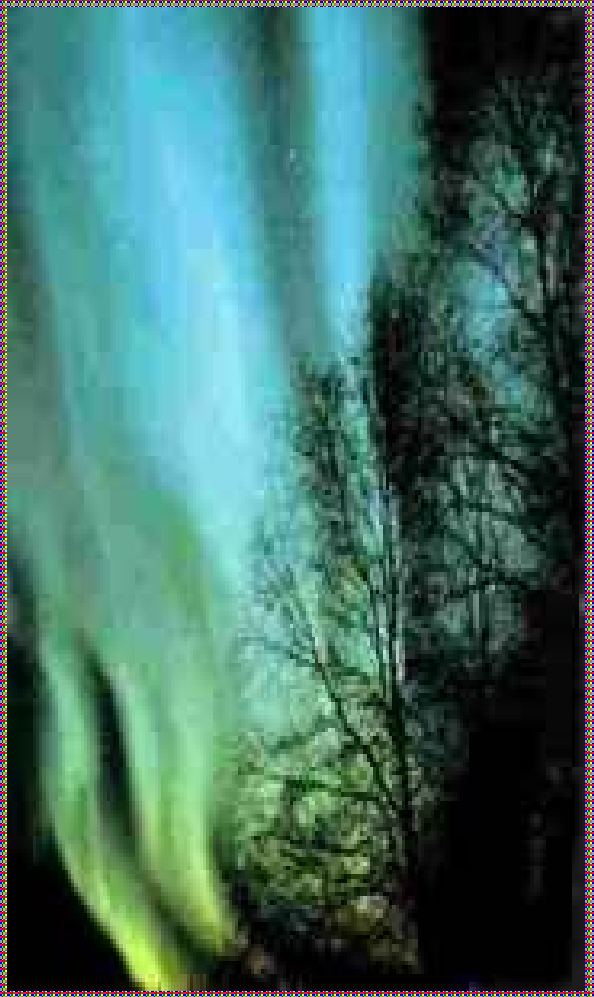
A fourth state of matter

- But even the ancients knew that there are four types of matter: Earth, Air, Water and
- FIRE

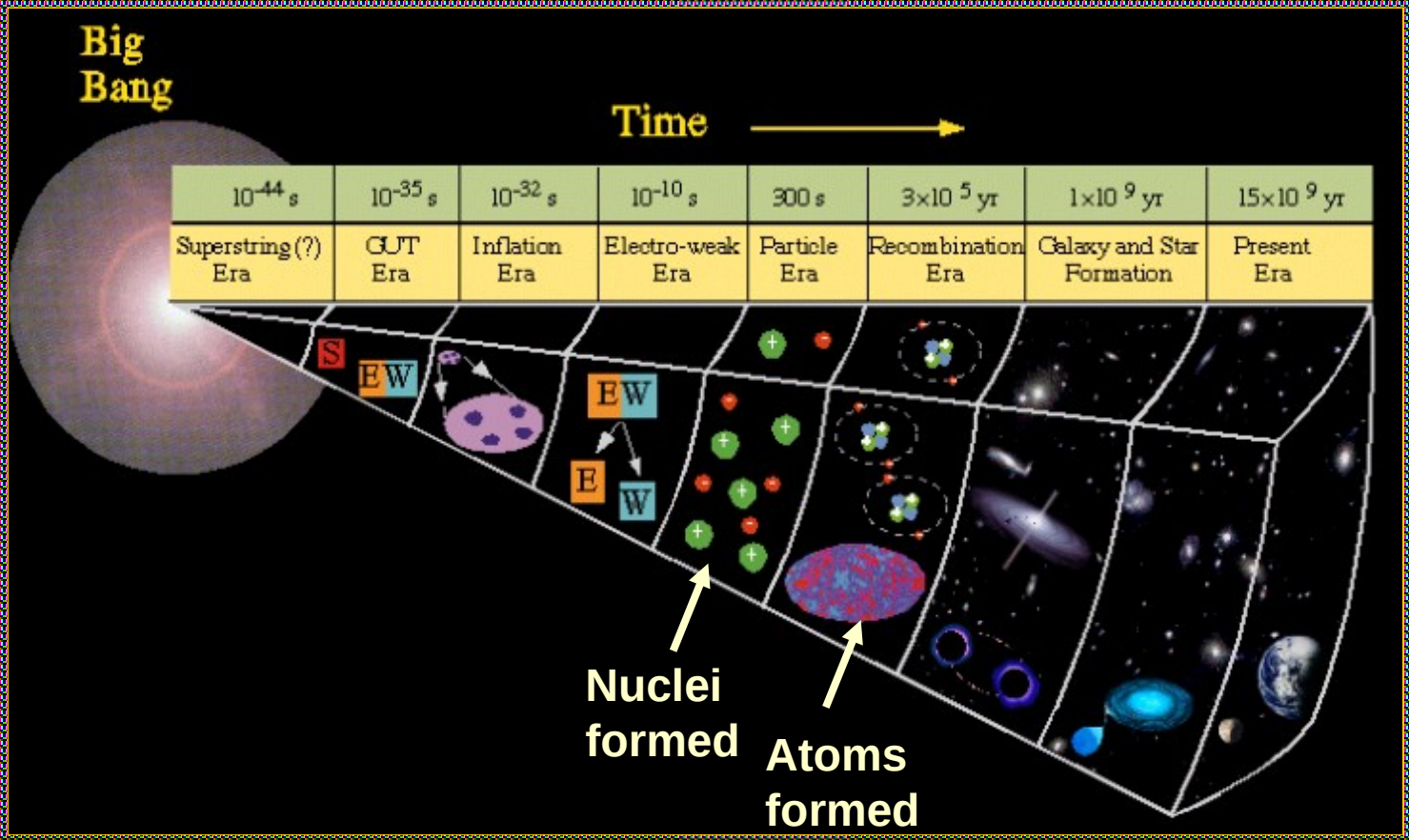
- So, what is the matter in fire?
- Or the Sun?
- Or inside fluorescent light bulbs?

Plasma – the fourth state

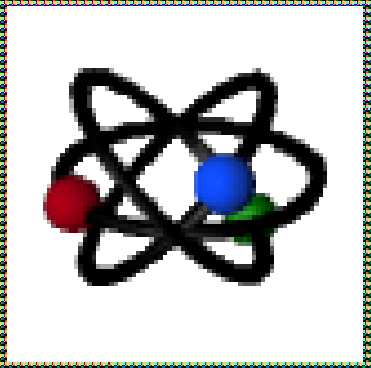
- Plasma makes up more than 99% of everything in the Universe that is luminous
- Plasma is ionized atomic matter
- Jets are made of some type of plasma - either
  - All positive particles – either protons or positrons
  - Or electrons?



Creating matter in the Universe



What's the Matter in the Universe?



- Most normal matter is in the form of atoms of hydrogen and helium
- Normal matter (even including plasma) only makes up 5% of the mass-energy budget of the Universe
- Is there matter that does not emit light?
- Can we feel it, even if we can't see it?

Dark Matter

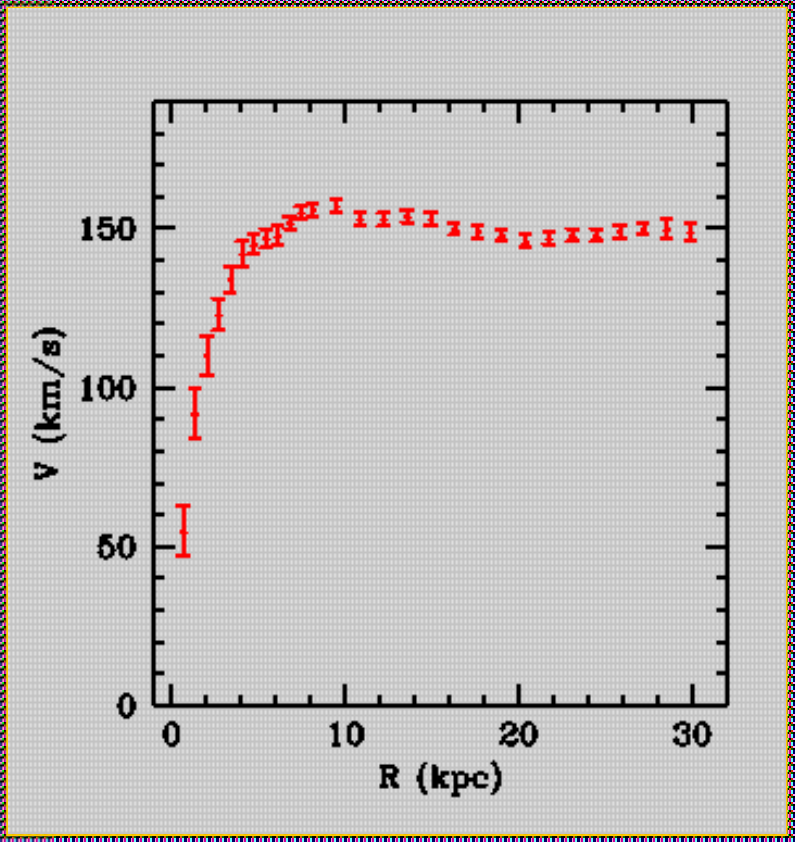
- Dark matter emits no light, but it interacts with luminous matter through gravity

HST/CL0024+1654

The blue arcs are images of a blue galaxy that is being lensed gravitationally by dark matter in the yellow-orange galaxy cluster

Dark Matter

- Dark matter holds in rapidly orbiting stars in the outer parts of galaxies
- The outer stars and gas would fly away if dark matter did not exist



NGC 3198

Dark Matter

- Dark matter holds x-ray heated gas inside of clusters of galaxies

Overlay of visible light image of galaxy cluster with x-ray heated gas (purple)

Dark matter vs. normal matter

- Of all the matter that we can see and feel
  - Dark Matter is 80%
  - "Normal matter" is only 20%
- Yet, the total amount of matter (including dark matter) is only 30% of what is needed to balance the mass-energy budget of the Universe

Cosmic Microwave Background

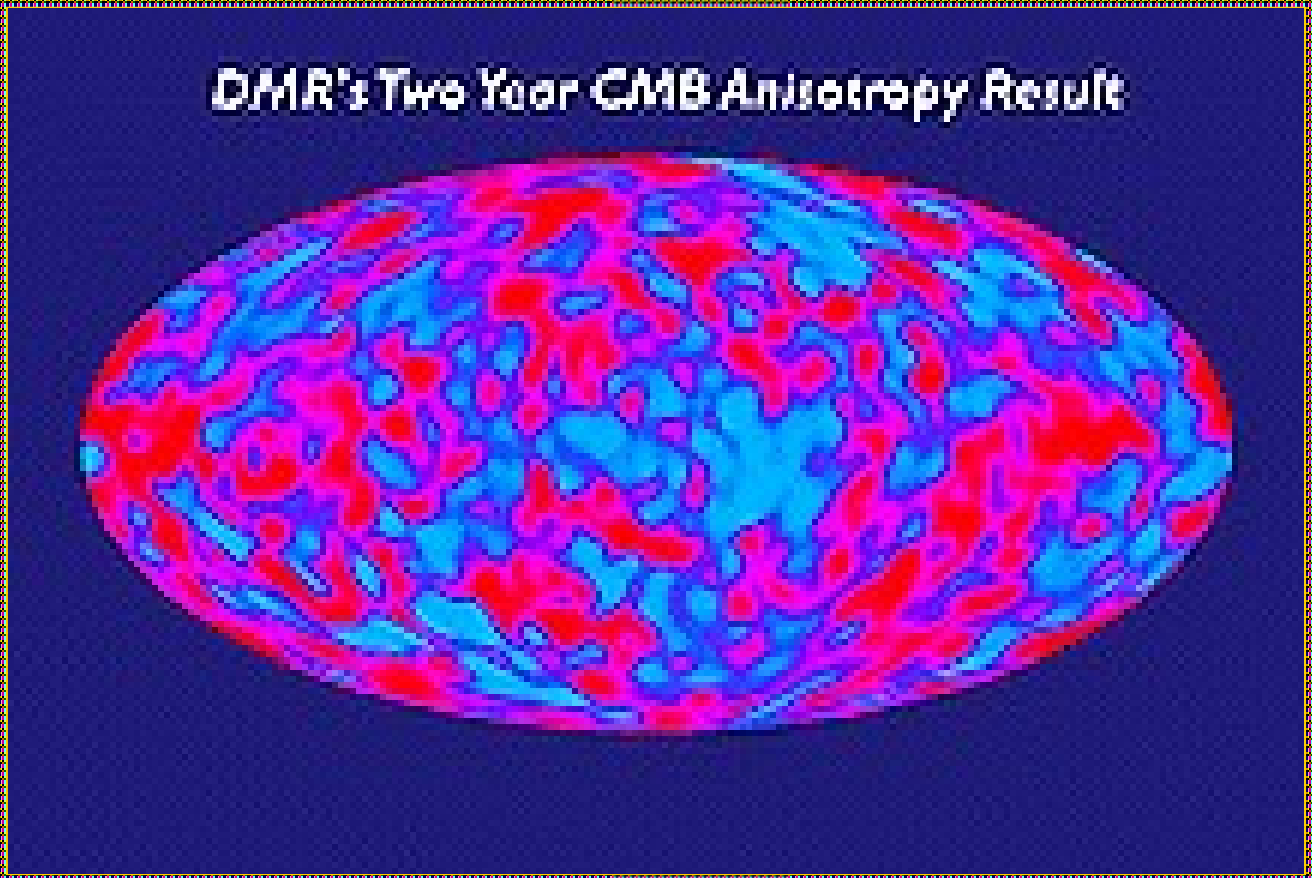
- Discovered in 1965 by Arno Penzias and Robert Wilson who were working at Bell Labs
- Clinched the hot big bang theory

We are seeing remnant heat from a time when the Universe was only a few hundred thousand years old

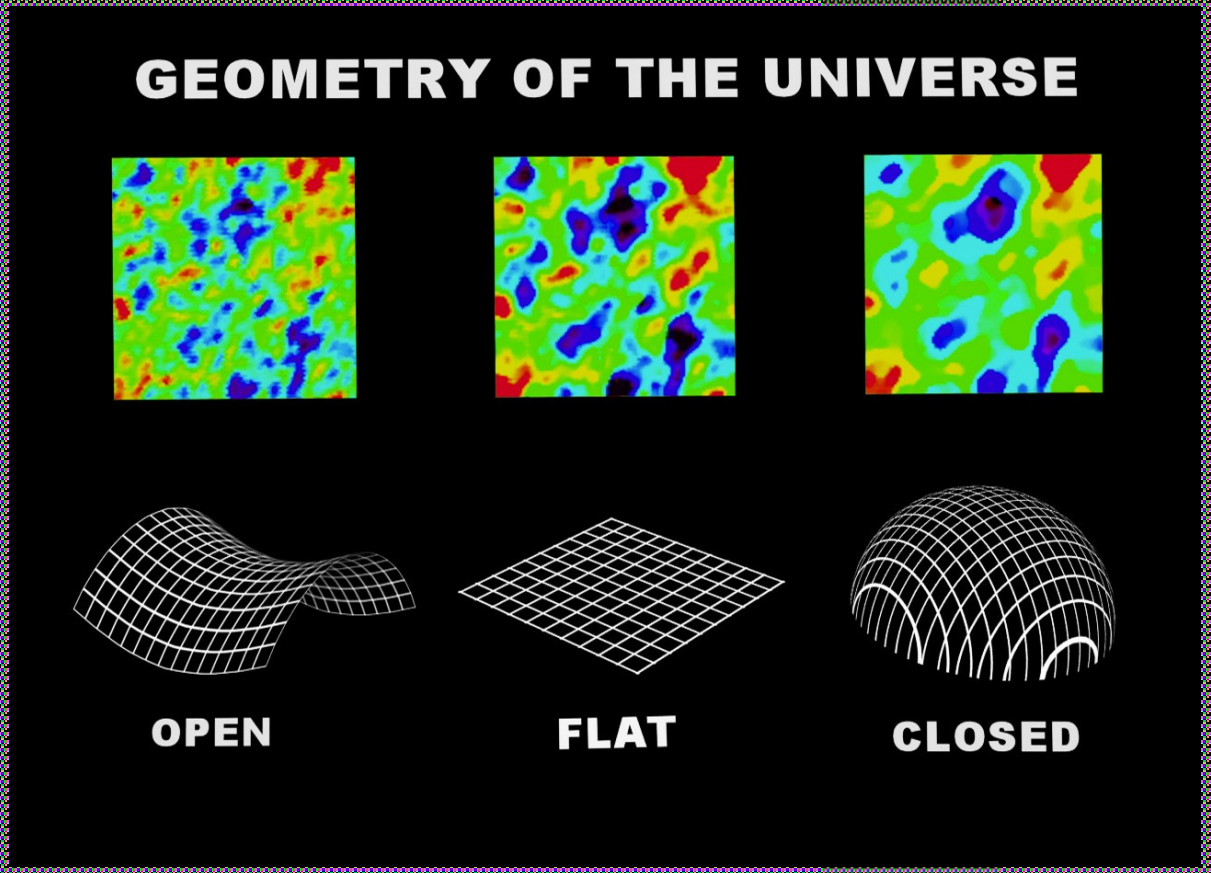
Cosmic Background Explorer (1989-1993)

- Differential Microwave Radiometer
- PI George Smoot
- Discovered fluctuations in the CMB
  - The CMB is uniform to within parts in a hundred thousand
  - These small fluctuations led to all the structure in today's Universe

"Wrinkles on the face of God"

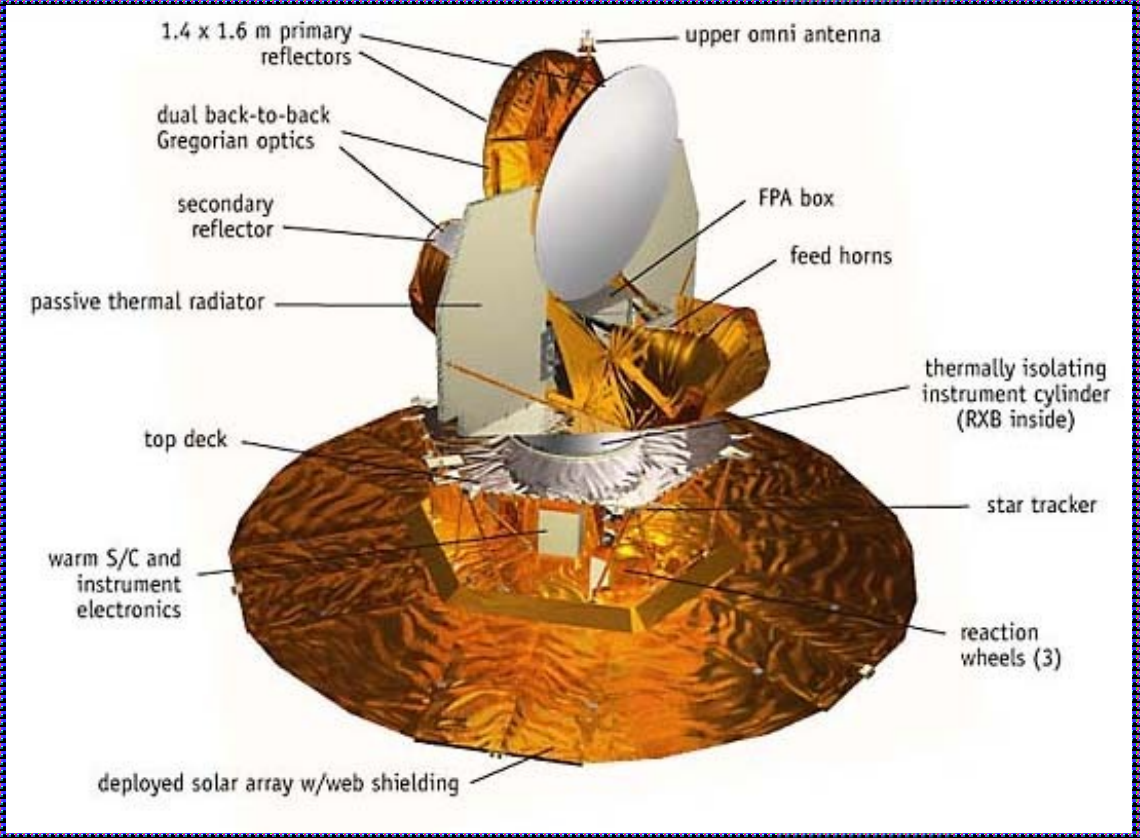


Fluctuations and geometry



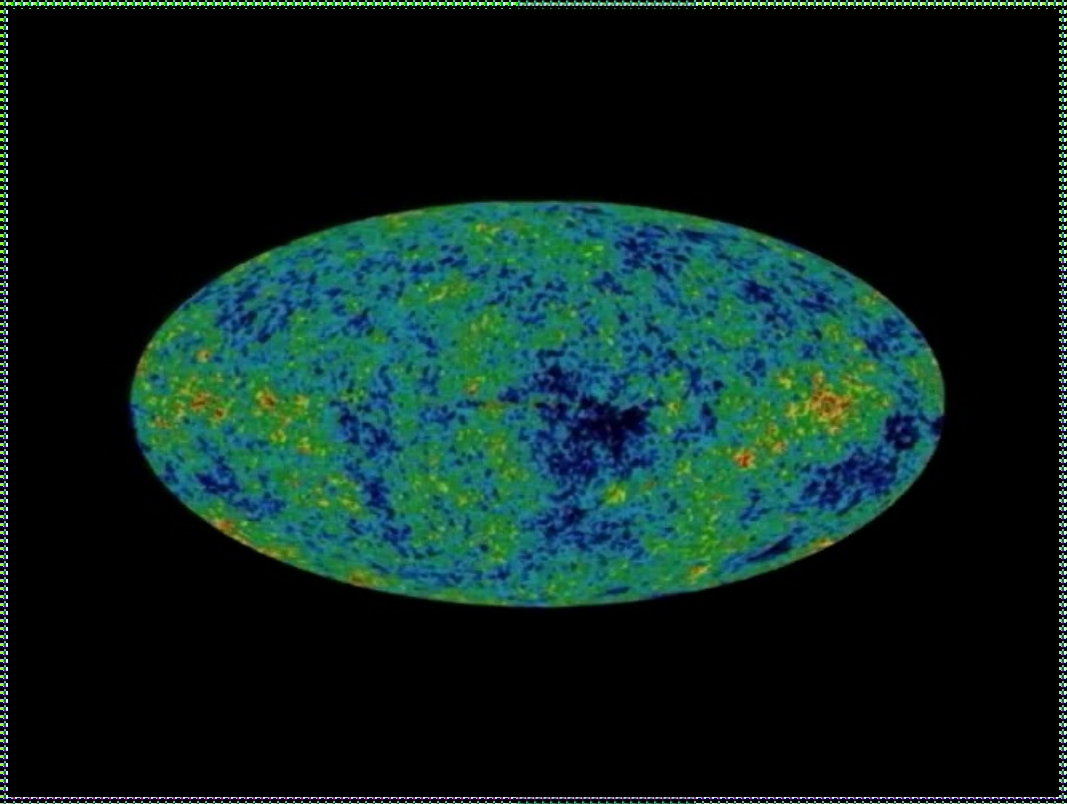
- The size of the fluctuations gives us direct information about the geometry of the Universe
- A flat Universe has typical fluctuations about 1 degree in size

Wilkinson Microwave Anisotropy Probe (2001-present)



- PI Charles Bennett
- WMAP surveys the CMB with much higher angular resolution than did COBE
- Fluctuation sizes indicate the Universe is FLAT

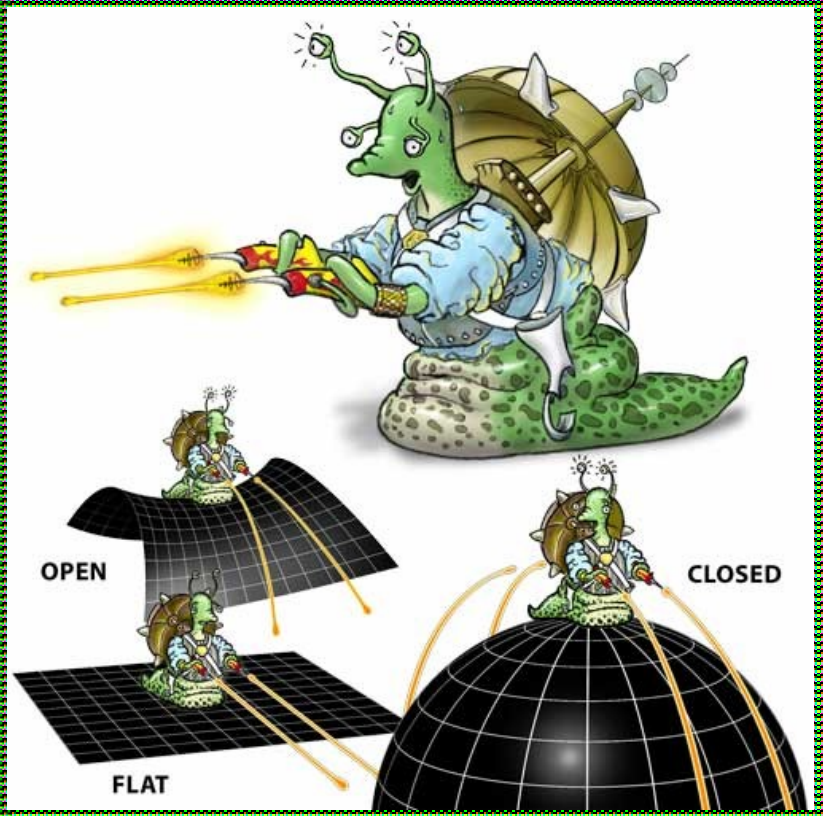
Formation of Structure



Credit: NASA/WMAP

What is a flat Universe?

- Two parallel light beams never cross
- Sum of all forms of Energy + Matter must add up to 100% of critical density
- So far, we have only found 30% - all the matter (including DM)



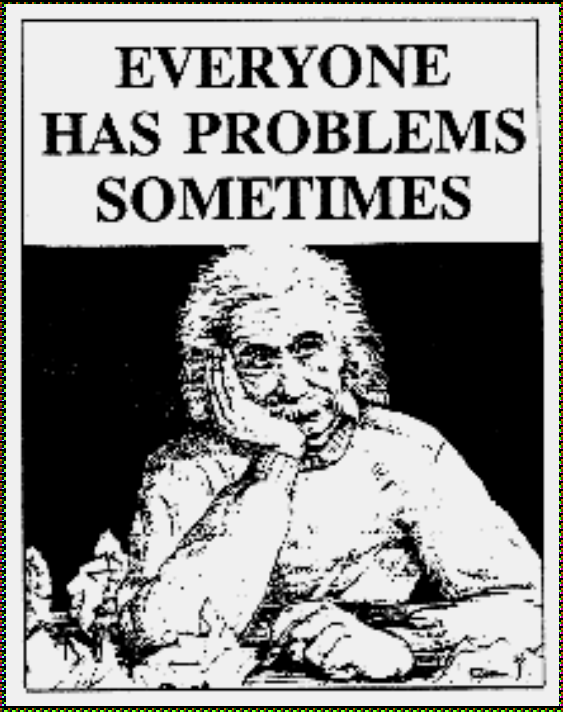
Dark Energy

- In 1998, two teams of researchers announced that they had found evidence for the acceleration of the expansion of the Universe
- Some type of new "anti-gravity" seems to be at work, driving this acceleration
- It is known as the mysterious dark energy

Einstein and the Cosmological Constant

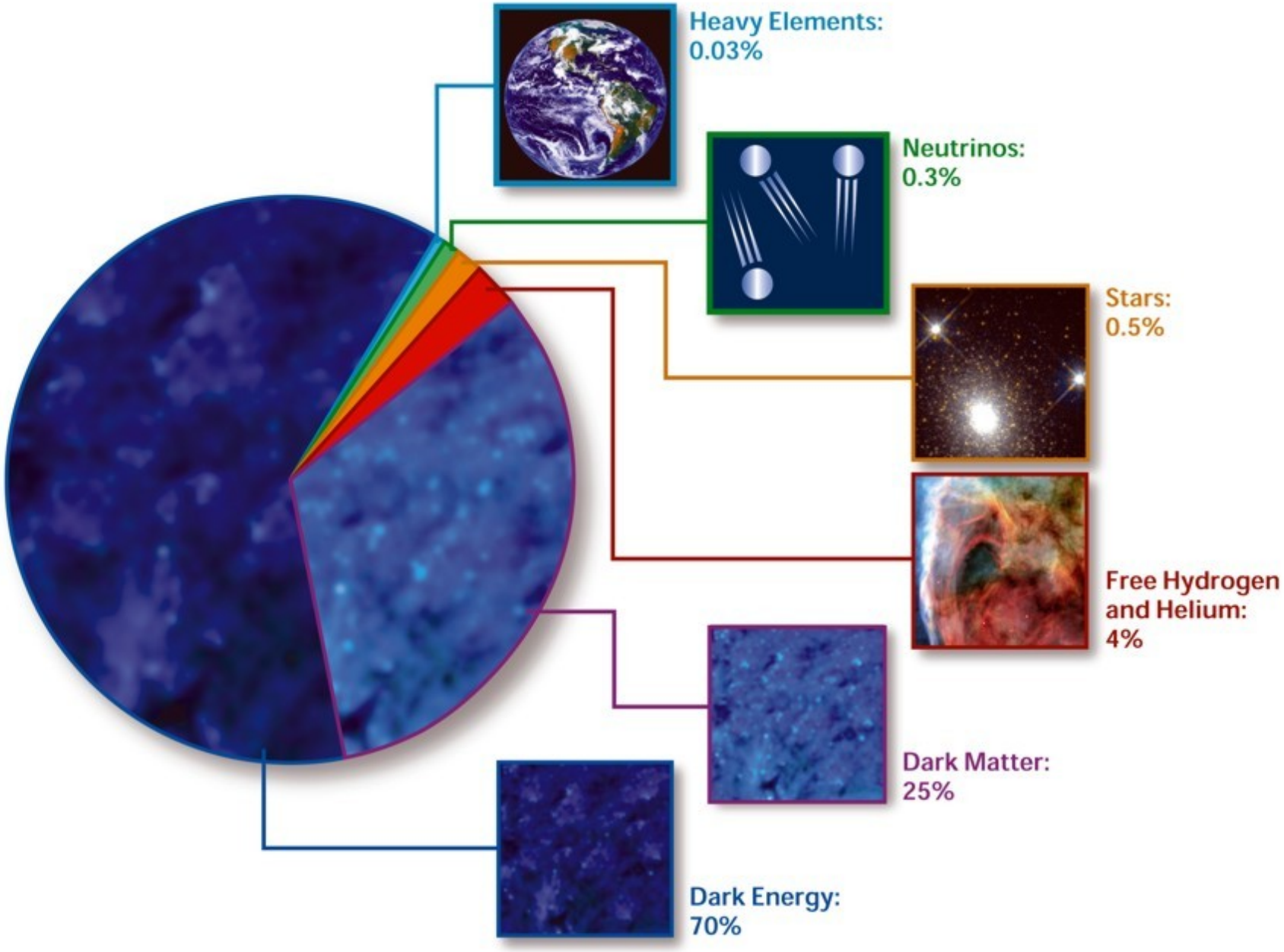
- When Einstein first formulated his equations of General Relativity, he believed in a static Universe (or steady state Universe)
- Since the equations seemed to predict an unstable universe that would either expand or contract, he "fixed" his equations by inserting a "Cosmological Constant" called Λ
- When Hubble later found that the Universe was expanding, Einstein called the creation of the Cosmological Constant his "greatest blunder"

Dark Energy

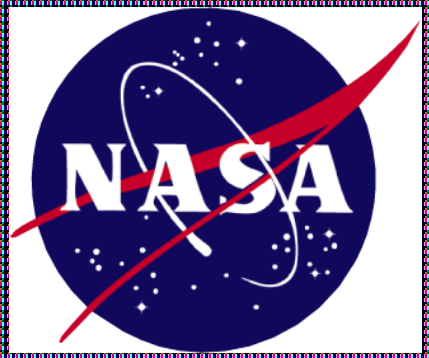


- We now see that there is indeed a "cosmological constant"
  - It acts in the opposite sense to Einstein's original idea
  - It is negative rather than positive
- As a result, Λ pushes the Universe apart even faster, rather than adding stability to an unstable Universe, as Einstein originally intended.
- It is the missing ~70% of the mass-energy!

COMPOSITION OF THE COSMOS



Going Beyond Einstein



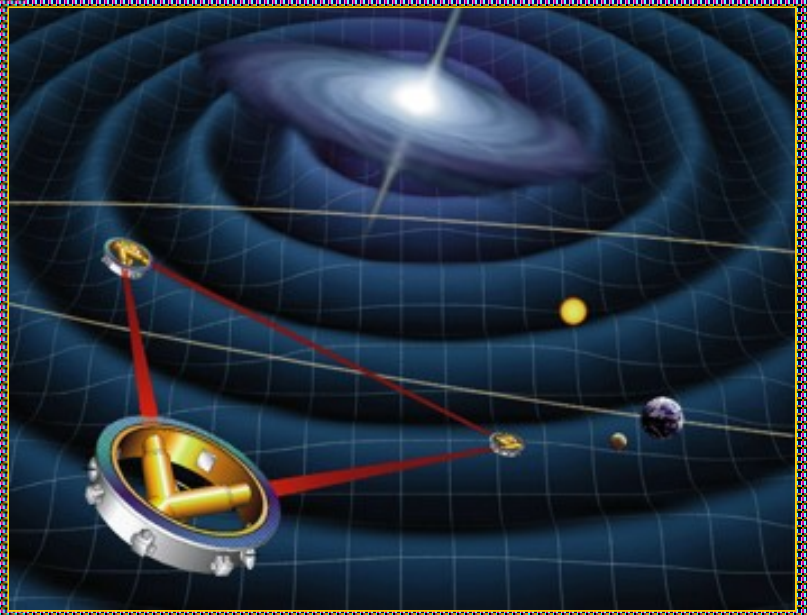
- NASA is beginning a new program to test predictions of Einstein's theories:
  - What happens at the edge of a black hole?
  - What powered the Big Bang?
  - What is the mysterious Dark Energy that is pulling the Universe apart?
- Do Einstein's theories completely describe our Universe?

BE Great Observatories

Constellation X

Four X-ray telescopes flying in formation

LISA



Three satellites, each with 2 lasers and 2 test masses

Beyond Einstein Probes

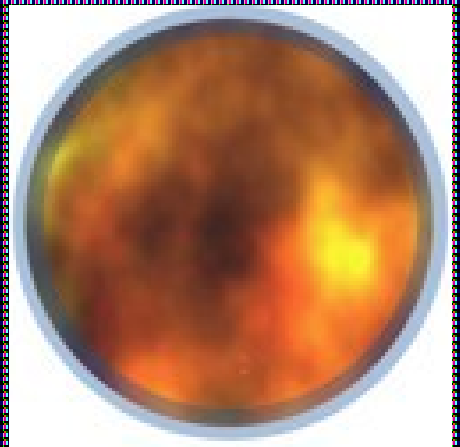
Black Hole Finder

Census of hidden Black Holes

Dark Energy

Measure expansion history

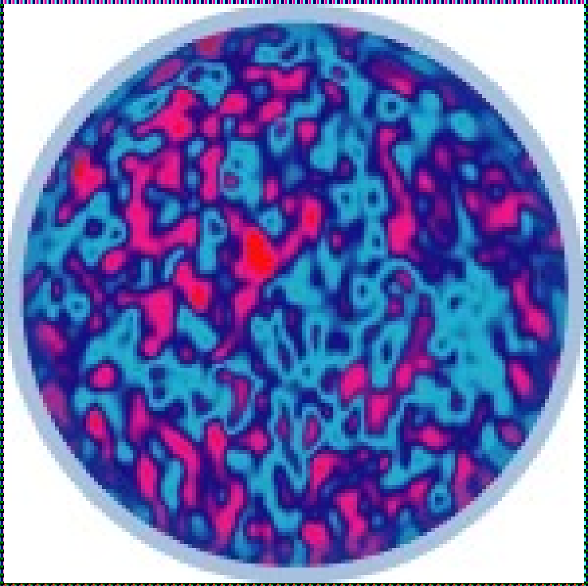
Inflation



Polarization of CMB

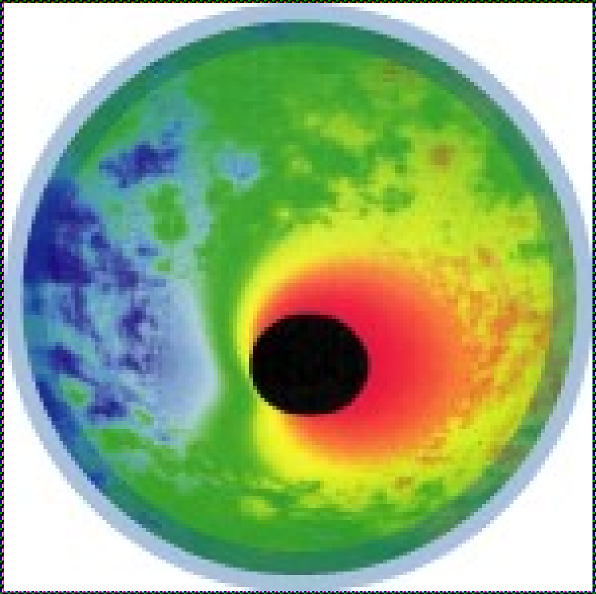
Beyond Einstein Vision Missions

Big Bang Observer



Direct detection of gravitational waves from Big Bang

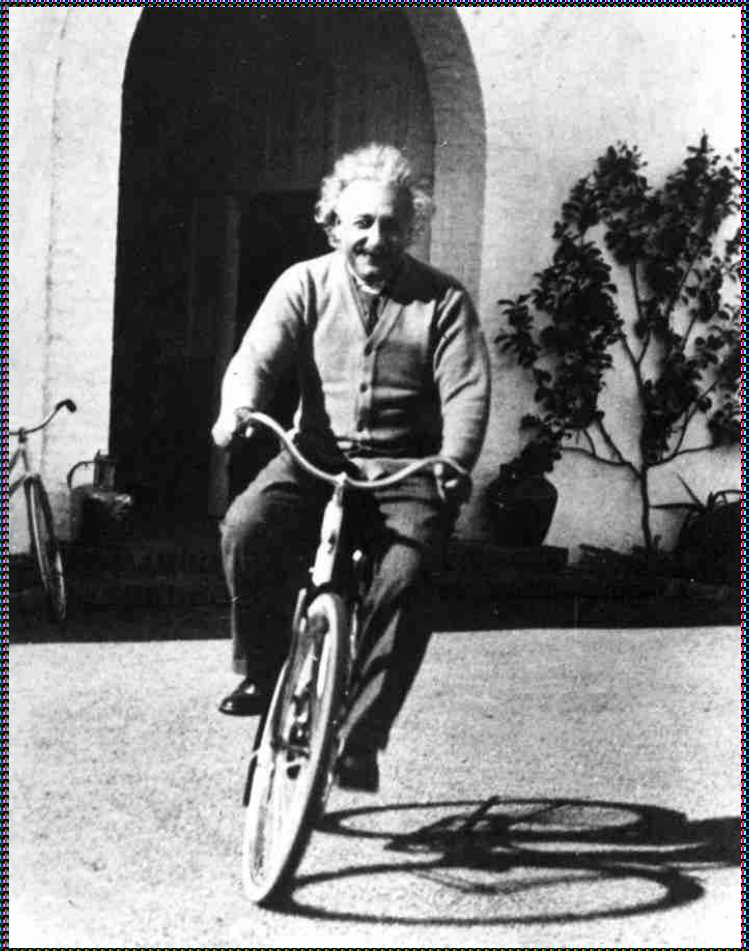
Black Hole Imager



Resolved image of the Event Horizon

Some last words from Einstein

- "The most incomprehensible thing about the Universe is that it is comprehensible"



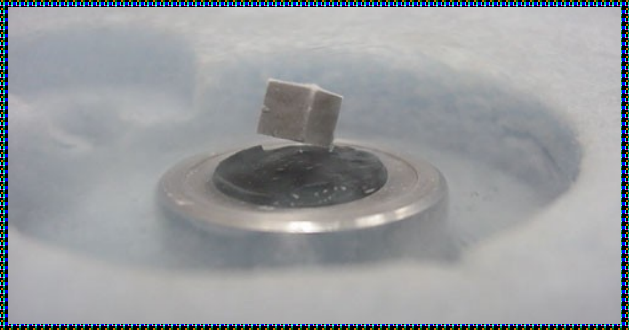
Resources

- http://glast.sonoma.edu
- http://swift.sonoma.edu
- http://grb.sonoma.edu
- http://universe.gsfc.nasa.gov
- http://wmap.gsfc.nasa.gov

Backup Slides follow

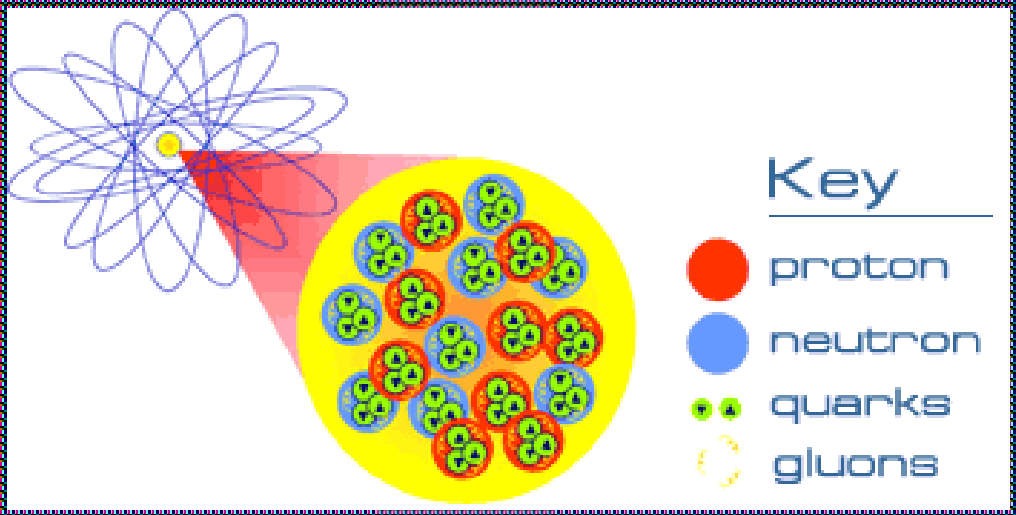
“Super” states of matter & energy

- Superfluids, superconductors, Bose-Einstein condensates and lasers
- Many Nobel prizes have been won for explaining these phenomena
- All involve unusual physical manifestations in which the particles/photons have the same properties on a quantum level



A new type of matter?

- Scientists at Brookhaven may have succeeded in breaking down nuclear matter to create a plasma from quarks and gluons



Quark-Gluon Plasma

- QGP formed:
  - after the Big Bang
  - before the formation of protons, neutrons and atoms
  - with the first light