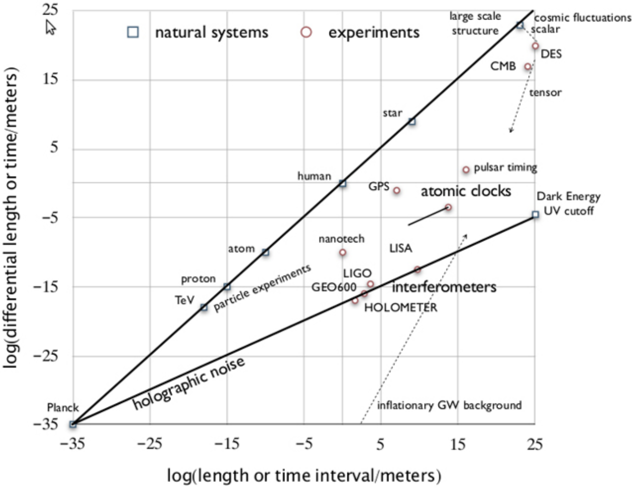
Background

Length Scales



Wonder

For it is through wondering that human-beings both now and at first began to philosophize, wondering first about the strange things close at hand, and then little by little in this way devotedly exerting themselves and coming to impasses about greater things, such as about the attributes of the moon and things pertaining to the sun and the stars and the coming-into-being of the whole. (Aristotle, Metaphysics, I.2, 982b11-17)

We "know" that the Earth is Round

THEORY

- **Aristotle** Every portion of the Earth tends toward the center until by compression and convergence they form a sphere. (De caelo, 297a9-21)

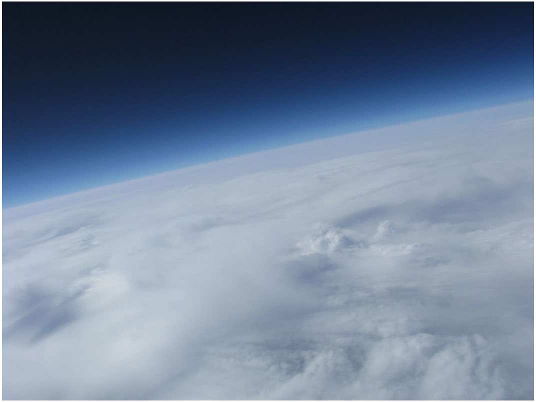
CIRCUMSTANTIAL EVIDENCE

- **Sailors** see tops of mountains; mast disappears last
- **Travelers** see Sun and stars at different elevations
- **Shadow** of earth on moon during eclipse is round
- **Eratosthenes** measured circumference at Summer Solstice in 340 B.C. to $\sim$ 10%
- **Magellan et al.** circumnavigation 1519-1522

DIRECT OBSERVATION

- **NNHS** you could repeat this
- **NASA** you'll need more funding for this.

Naperville North High School



Weather Balloon Launched to 100,000 ft

Apollo 17

December 7, 1972

Limits

Physical Cosmology Is matter all that matters?

Observation $\leftrightsquigarrow$ Model What if 2 models explain all observations?

Model $\leftrightsquigarrow$ Interpretation How to pick the “best” interpretation?

Not Fair Questions (but great questions for other discussions!)

- Why is there something rather than nothing?
- What is before the beginning?
- What is man and why is he here?

Godel’s Incompleteness a theory cannot be both consistent and complete

- Wolpert applies this in “Physical limits of inference” (arXiv.0708.1362v2)

Are you sure about that?

- **Perception** your own observation
- **Introspection** perception with a special object
- **Memory** iirc
- **Reason** mathematics, geometry, logic
- **Testimony** because I said so!

Different criteria for justifying knowledge.
Which ones are used in scientific methods?

Scientific Methods

(note the s)

Observation $\leftrightsquigarrow$ Model $\leftrightsquigarrow$ Interpretation

- A good mathematical model uses a "few" parameters to describe "many" observations.
- We "know" this model is true.
- Gives us powers of prediction
- Allows us to manipulate matter to do wonderful things. (aka Technology or Engineering.)

- grow more and better food cheaper
- walk on the moon
- see inside your body without cutting you open
- ...
- make us more wealthy

The story of $F_G = Gm_1 m_2 / r^2$

- allows stable orbits
- always attracts
- explains the motion of apples, moons, and planets

BUT

- does not explain details of orbits (precession)
- mass bends light
- gravitational redshift

Olber's Paradox

Model Infinite Static Universe, with uniform distribution of stars

Predict What would the sky look like?

Observe What does the sky look like?

Stars

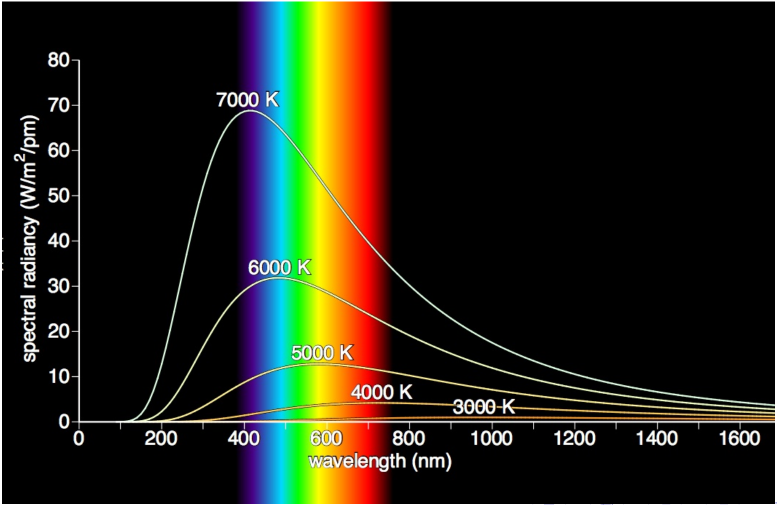
Solar Power

What is the source of the Sun's energy?
We need a "model" consistent with what we know about the Sun

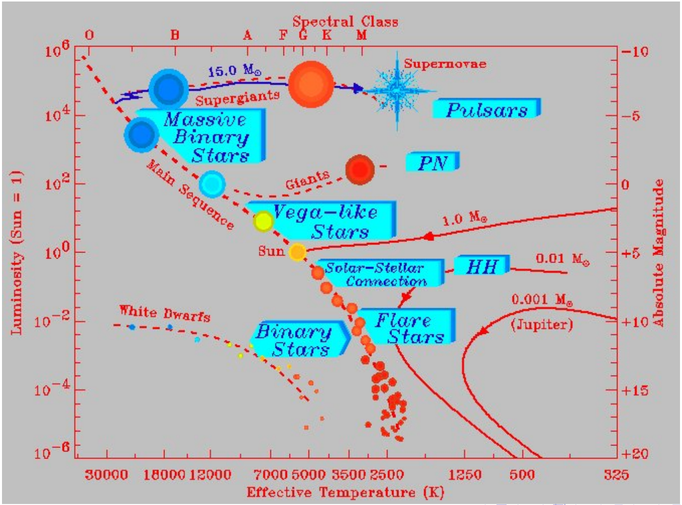
- $M_{Sun} = 2 \times 10^{33} grams$
- $T_{Sun} > T_{Earth} > T_{Rocks} \sim 4 \times 10^9$ years

Model	Duration (years)
Chemical Burning	6.3×10^3
Gravitational Potential Energy	16×10^6
Fusion	100×10^9 (simple estimate)

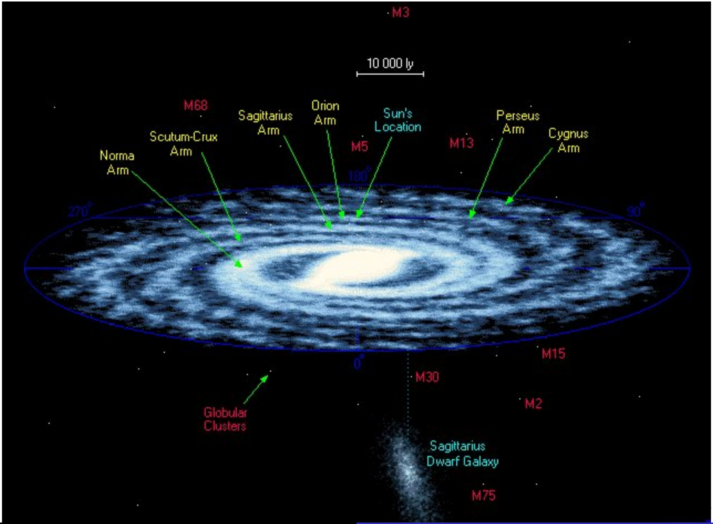
Stars and Black Body Radiation



The Lives of Stars



A Map of the Milky Way



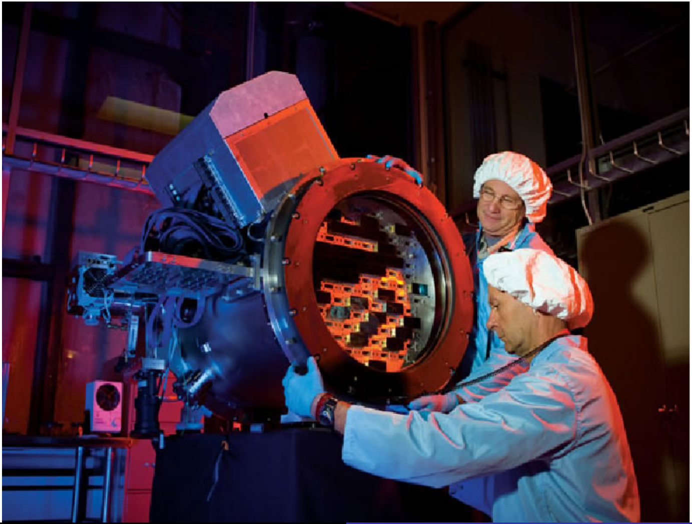
Looking Out from the Milky Way

Stars Essentials for Cosmologists

- one number (T) describes overall color and lifetime
- heavy stars are hot and bright and burn out fast
- turn that around: given how bright a star is, we know the mass
- various things can make a star get brighter all of a sudden (nova); if a star is heavy enough, it ends with a bang (Super Nova); a star that is just under this mass can slowly siphon stuff from a neighbor. When it gets to the limit it is SNIa – all blow up with the same mass
- metals from previous generations "contaminate" the astmosphere giving absorption lines

From Stars to the Big Bang

The Business End of Modern Cosmology Telescope



What else is out there?

Nebulae

Thomas Wright in 1750 – An original theory or new hypothesis of the Universe: Milky Way is a flattened disk; nebulae are "outside".

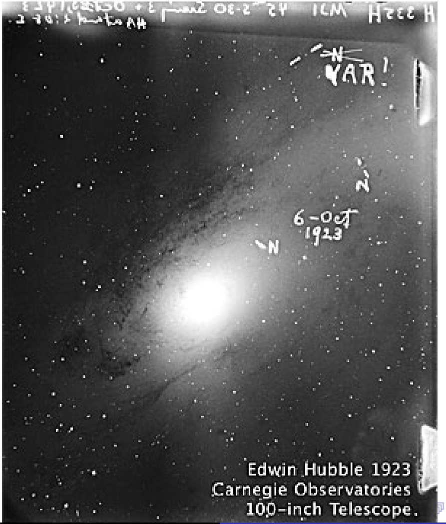
Immanuel Kant in 1755 –coined the term "Island Universes"

Vesto Slipher in 1912 – looking for signs of life in galaxy spectra, saw they were mostly receding, not gravitationaly bound to Milky Way.

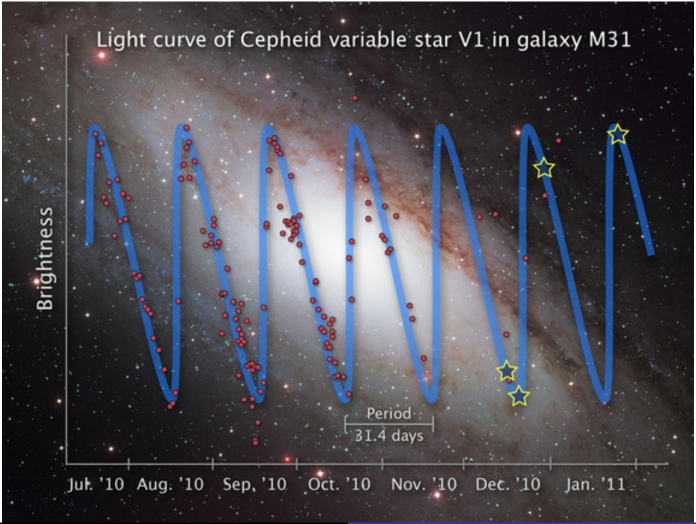
Harlow Shapley and Heber Curtis in 1920 – the "Great Debate"

Andromeda Nebula – M31

Andromeda Nebula – Hubble V1



Andromeda Nebula – Hubble V1



Henrietta Leavitt – Cepheid Period/Luminosity

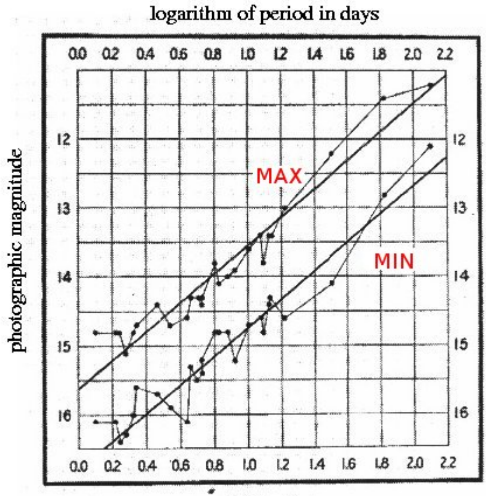


Fig. 2.

Hubble Diagram – Original

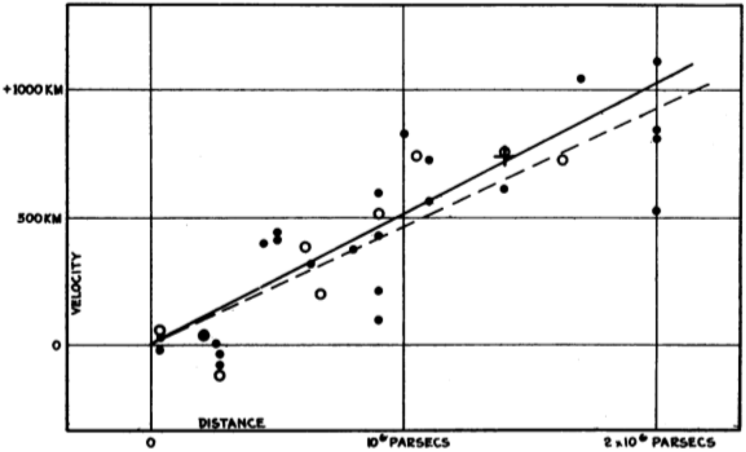
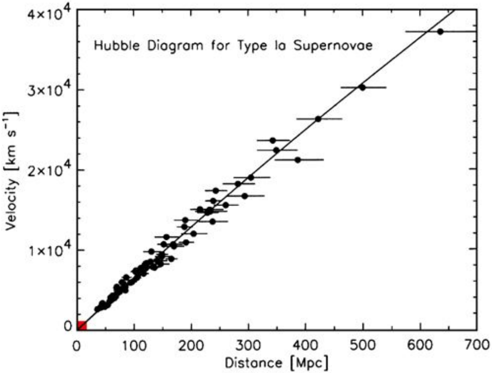


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae

Hubble Diagram – Modern

Fig. 3. The Hubble diagram for type Ia supernovae



Kirshner, Robert P. (2004) Proc. Natl. Acad. Sci. USA 101, 8-13

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PNAS

Do we “know” the Universe is expaning?

It did not help adherents of the Big Bang that Gamow was its most vocal supporter. Or that Einstein, now living out his remaining years in Princeton as the world’s most famous scientist, was still philosophically more comfortable with a static universe.

Or, most important, that [Ralph] Alpher and [Robert] Herman’s prediction of the cosmic background radiation, which could not plausibly be accounted for in steady-state cosmology, had been all but forgotten during the 1950s. With problems on both sides, neither was a clear winner. This was how matters stood until the early spring of 1965, cosmology stalemated.

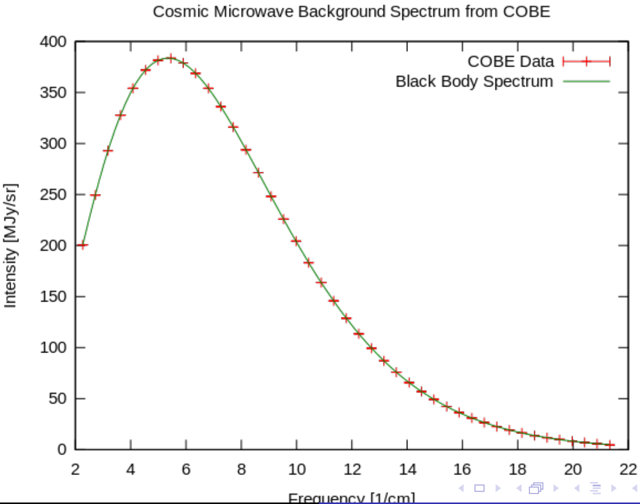
Do we “know” the Universe is expaning?

Had Arno Penzias and Robert Wilson known in 1964 of the prediction of Alpher and Herman sixteen years earlier, the two Bell scientists would have been spared a year’s work trying to uncover the source of the noise in their horn antenna. Had [Robert] Dicke been aware of the prediction, he could have begun work on his own antenna years earlier without having to wait for Jim Peebles to do the theoretical calculations from scratch.

John C. Mather, John Boslough, The Very First Light, New York: Basic Books, 1996, pp. 49-50.

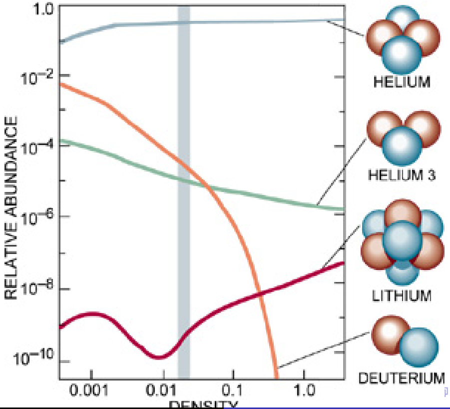
Penzias and Wilson – Cosmic Microwave Background

COBE – measures 3 degree K



BBN – Big Bang Nucleosynthesis

The fact that helium is nowhere seen to have an abundance below 23% mass is very strong evidence that the Univwerse went through an early hot phase.



HALFTIME

- We "know" that the Universe is Expanding
- We'll talk about HOW it is expanding in the second half
- And what we are doing about it.

Precision Cosmology

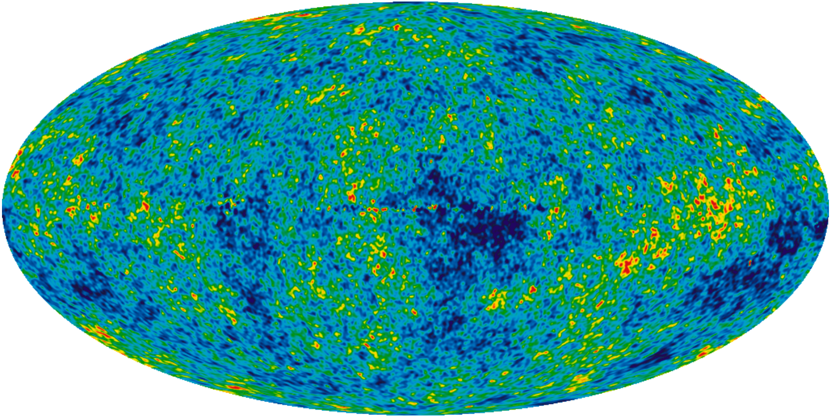
The Cosmological Principle

Homogenous the Universe is the same everywhere

Isotropic the Universe looks the same in all directions

- We assume that the Universe is “playing fair” with us
- A stronger condtion would be to make it the same at all times
- We can test how “good” these assumptions are, but not completely

WMAP All Sky Temperature Map

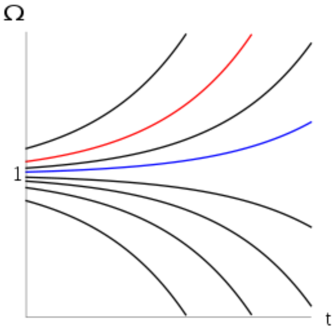


Temperature range of +/- 200 micro Kelvin

Problems with the Big Bang

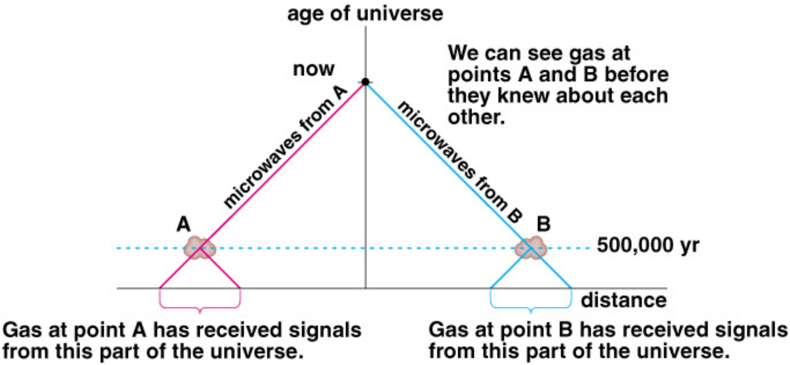
- **Flatness** if the density is ~ 1 now, it must have been really close to 1 early on
- **Horizon** why is the Cosmic Microwave Backround so uniform? How does the left side know what the right side is doing?
- **Magnetic Monopoles** where are they?

The Flatness Problem



$|\Omega - 1|$ is currently less than 0.01, and therefore must have been less than 1E-62 at the Planck era. This "fine tuning" makes cosmologists nervous.

The Horizon Problem



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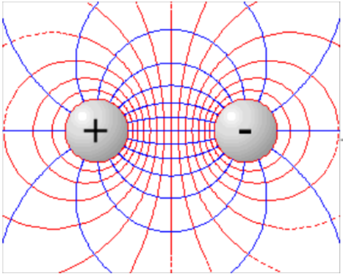
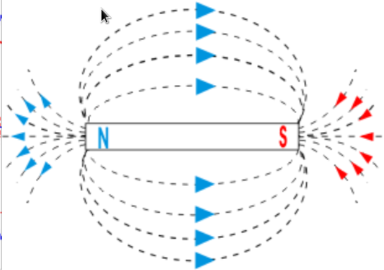
The Magnetic Monopole Problem

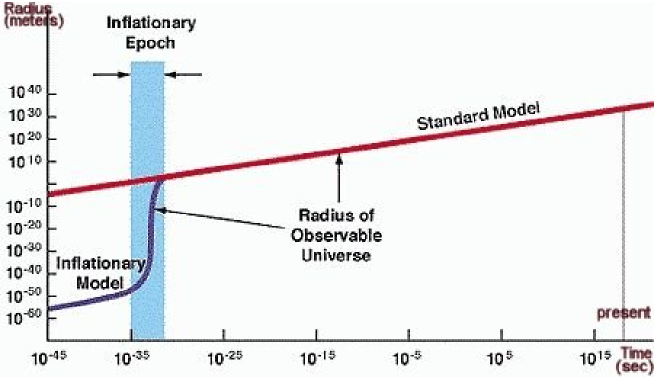




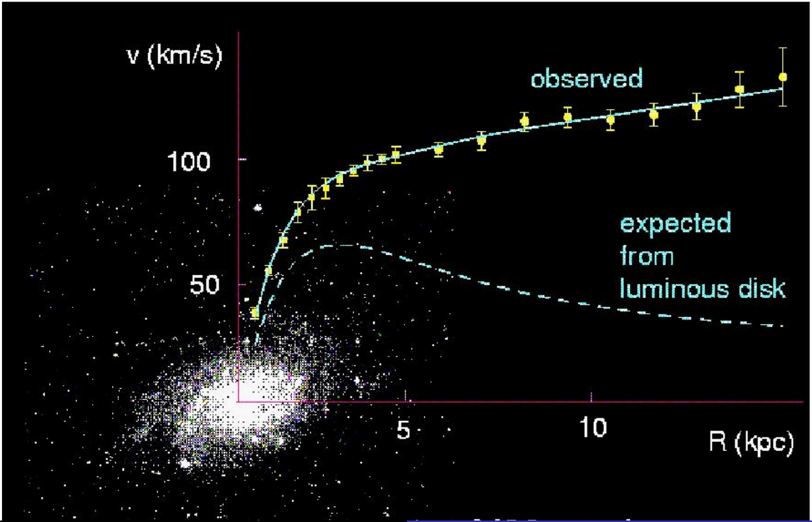
Grand Unified Theories (GUT) predict magnetic monopoles are a dominant part of the universe. BUT – we have not even seen one.

Cosmic Inflation

The "scalar field" of GUT (invented for particle physics) drives an exponential expansion.

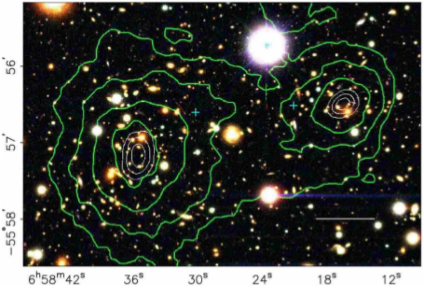


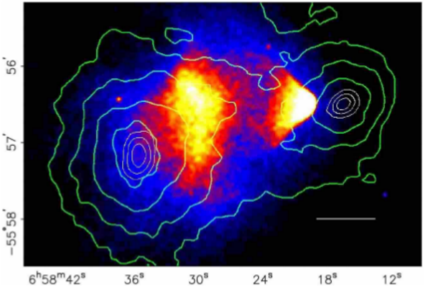
Dark Matter – galaxy rotation curve



Dark Matter – strong gravitational lensing

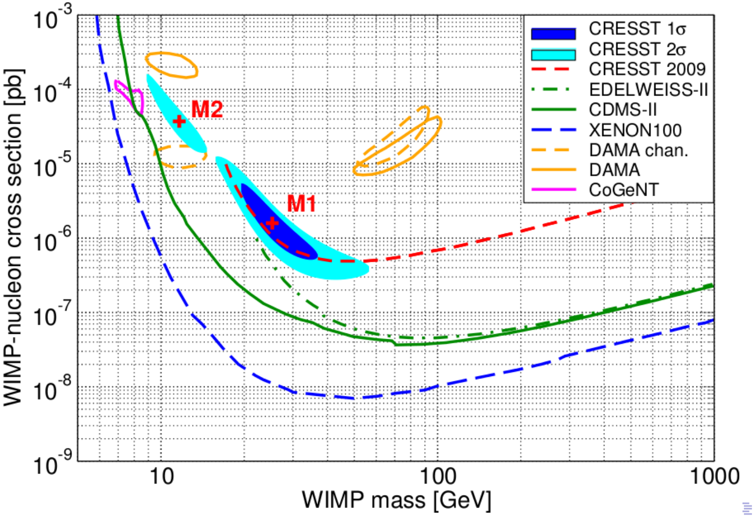
Dark Matter – weak gravitational lensing





Dark Matter – direct detection of Particles

Dark Matter – direct detection



Dark Matter – indirect detection

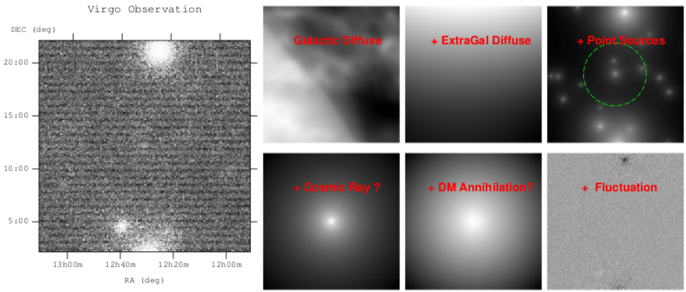
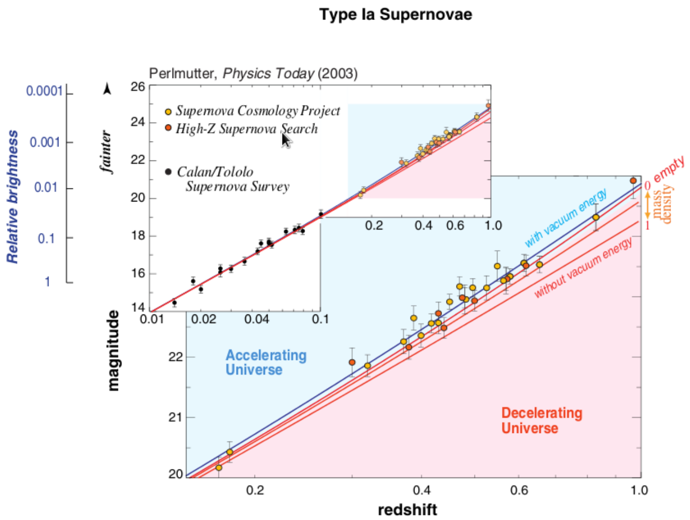


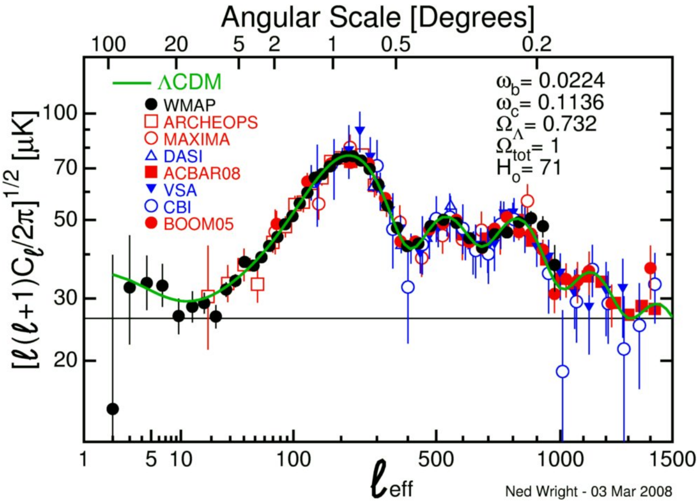
Fig. 1.— Decomposition of the Fermi-LAT image in the region of the Virgo cluster into model components. The observed photon count image from 100MeV to 100 GeV is shown on the left.

Mass of 20-60 GeV (annihilating into the b-bbar channel) consistent with Hooper et al. analysis of Galactic center.

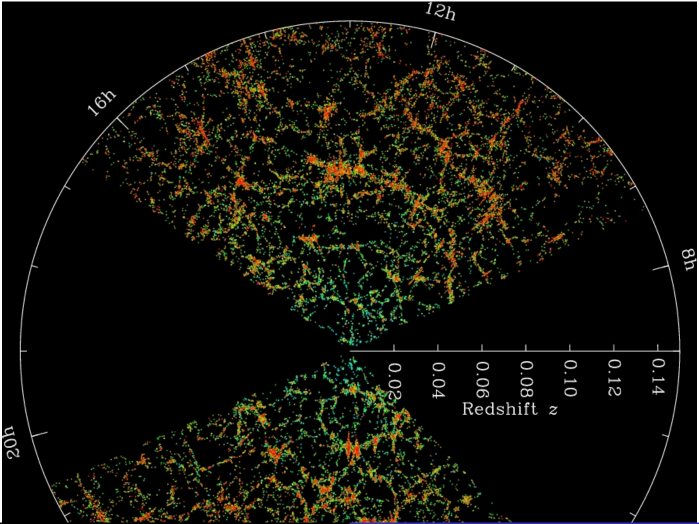
Dark Energy – first detection



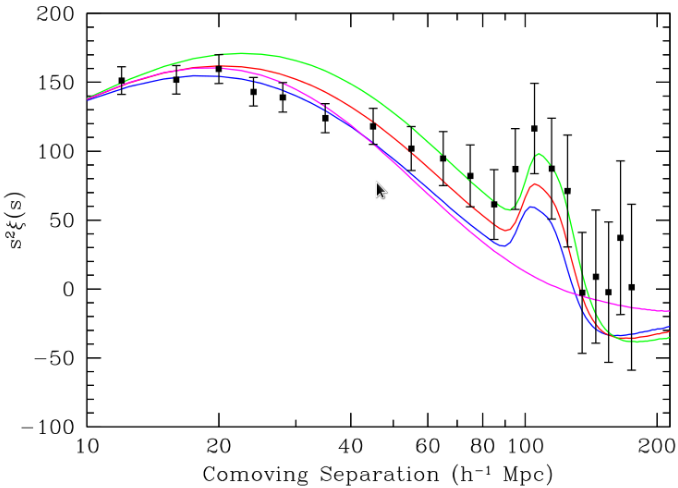
Dark Energy – CMB Anisotropies



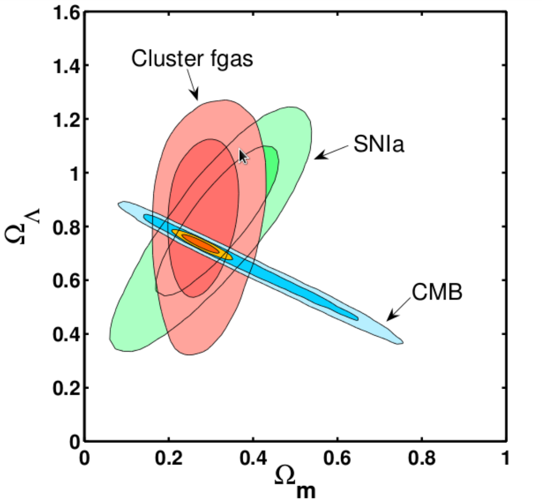
Dark Energy – Large Scale Structure



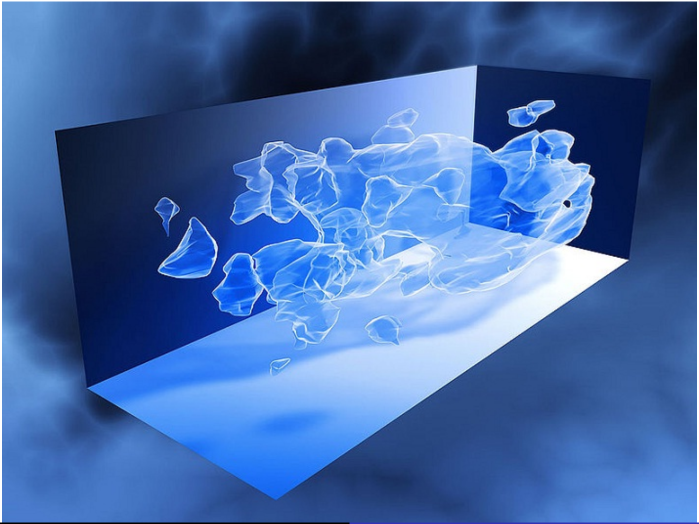
Dark Energy – Baryon Acoustic Oscillation



Dark Energy – Galaxy Clusters



Dark Energy – Weak Lensing



Lambda Cold Dark Matter Parameters

Parameter	Value	Description
t_0	$13.75 \pm 0.11 \times 10^9$ years	Age of the universe
H_0	$70.4^{+1.3}_{-1.4}$ km s^{-1} Mpc^{-1}	Hubble constant
$\Omega_b h^2$	0.0260 ± 0.00053	Physical baryon density
$\Omega_c h^2$	0.1123 ± 0.0035	Physical dark matter density
Ω_b	0.0456 ± 0.0016	Baryon density
Ω_c	0.227 ± 0.014	Dark matter density
Ω_Λ	$0.728^{+0.015}_{-0.016}$	Dark energy density
$\Delta_R{}^2$	$2.441^{+0.088}_{-0.092} \times 10^{-9}$, $k_0 = 0.002 Mpc^{-1}$	Curvature fluctuation amplitude
σ_8	0.809 ± 0.024	Fluctuation amplitude at $8h^{-1}$Mpc
n_s	0.963 ± 0.012	Scalar spectral index
z_*	$1090.89^{+0.68}_{-0.69}$	Redshift at decoupling
t_*	377730^{+3205}_{-3200} years	Age at decoupling
τ	0.087 ± 0.014	Reionization optical depth
z_{reion}	10.4 ± 1.2	Redshift of reionization

We "know" Lambda Cold Dark Matter Describes the Universe

- a few parameters describe many different observations
- there are alternate ways to account for some of the observations
- are the parameters constant in time?
- it sure would be nice to have a direct detection of dark matter
- laboratory tests of dark energy? We can't think of any.

Final Ideas

Black Holes

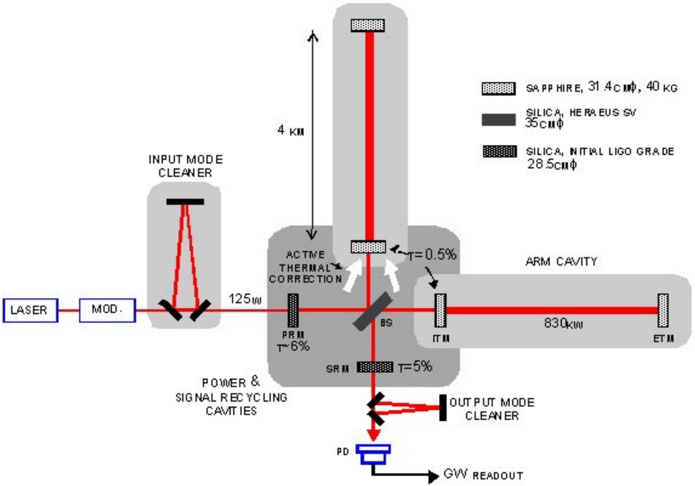
- M is contained inside $r_{sh} = \frac{2GM}{c^2}$
- light black holes evaporate
- not directly observed, but we see effects
  - rotation of stars near center of Milky Way
  - X-rays from binary systems
  - Quasars/Active Galactic Nuclei/Galaxies
- Entropy $S = \frac{\pi A k c^3}{2hG}$ where A is surface area. Normally, S is proportional to Volume $\sim$ information content.
- Leads to "holographic principle" that everything in a volume of spacetime can be written on the surface. (A hologram is a 2d "projection" of 3d space)

Gravitational Waves

Predicted by General Relativity. Sources include

- black hole/neutron star pair inspiraling
- black hole/neutron star near miss
- black hole mergers
- supernovae
- gamma ray bursts
- spinning neutron stars
- relics from inflation
- the unexpected

Advanced LIGO – gravitational wave detector



More Future Projects

The Fermilab Holometer will measure "pixel size" of spacetime

Dark Energy Survey will use the 4 methods to measure dark energy

Large Synoptic Survey Telescope will repeat the 5-year SDSS every few weeks!

CMBPOL proposed to measure CMB with higher sensitivity

Square Kilometer Array surveys the radio sky – for example Hydrogen maps using the 21cm wavelength radiation

TNGI the Next Great Idea....