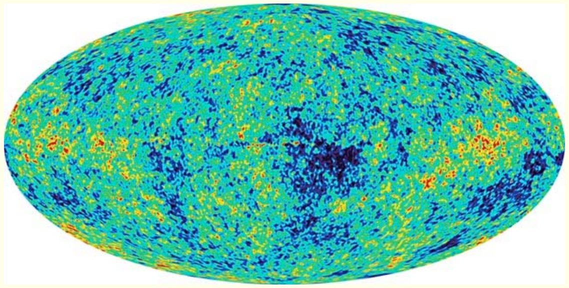


The Age of Precision Cosmology

Can we see the Big Bang?

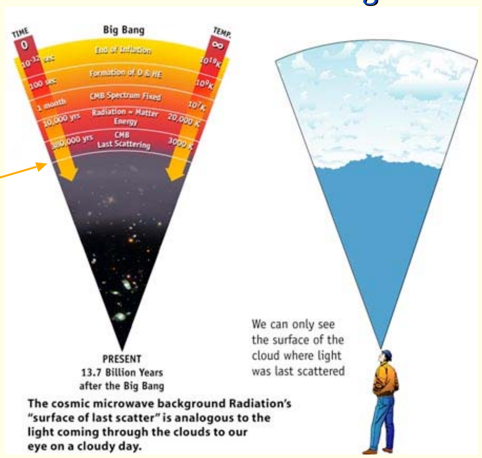
What's our Universe made of?

The Cooling Universe

- Expanding → cooling (diluting energy content): must've been really hot early on
  - You can't *begin* to imagine: many quadrillions of degrees (*cf.* center of sun is *only* 15 million degrees K)
- As the Universe cools…
  - Quarks condense out
  - Protons & neutrons condense
  - Atomic nuclei form: one minute elapsed so far
  - Electrons condense onto nuclei to make neutral atoms
    - 380,000 years old, Universe 1000 times smaller than today
    - A cozy 3,000 degrees Kelvin now (cooler than sun's surface)
    - Only now can light travel unimpeded by free electrons
    - It's this "recombination" that forms the "wall" to our vision
- If looking far away is looking back in time, can we *see* the Big Bang, then?
  - YES…Well, sort-of

Surface of Last Scattering

Universe becomes transparent

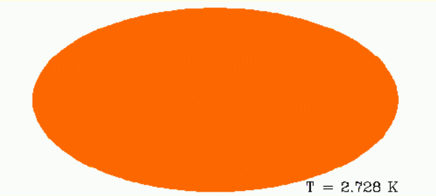


The COsmic microwave Background Explorer

similar projection of earth

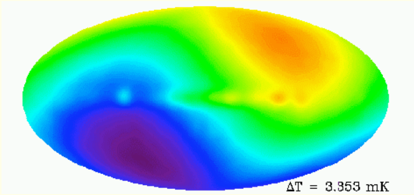
COBE satellite, launched 1991

All-sky elliptical projection



COBE All-sky image looks *completely* uniform; 2.7 degrees above absolute zero.
The Universe has expanded 1000 times since this light began its journey in the 3000°K plasma.
This is us looking at the Big Bang!

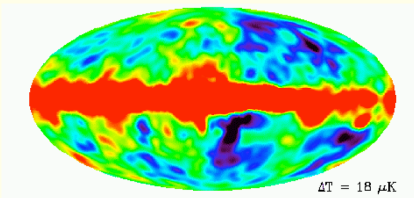
Processed COBE Data reveals structure in CMB



Subtracting off 2.728°K shows *dipole*, indicating motion

Moving towards→blue, away from→red (Doppler shift) at a speed of 368 km/s

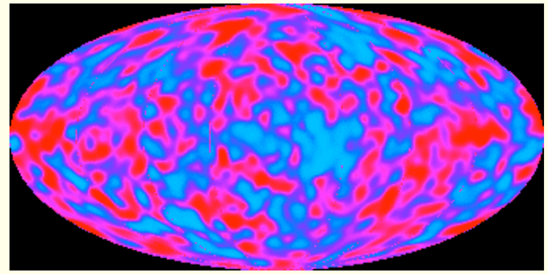
Dipole amplitude is one part per thousand of 2.7°K.



Subtracting dipole map, the Milky Way Galaxy stands out, plus variations at 18 μK.

Galaxy light can be removed because it has different spectrum than CMB (COBE had multi-color vision).

COBE's Great Finding: Anisotropy in the CMB

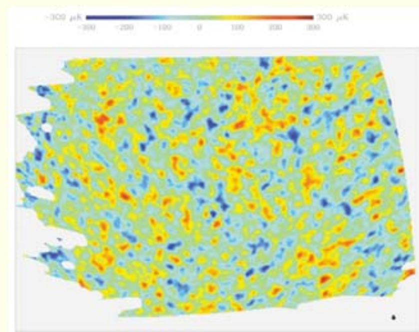


Red means cooler, blue means warmer, but only by tens of micro-Kelvins. COBE's vision was limited to 7 degree resolution, but we see structure at this scale, representing density variations in the recombining plasma when atoms first formed. These density variations reveal the seeds of galaxy formation. **This is as far back as we see—the wall to our vision.**

Next-Generation CMB Experiments

- BOOMERANG: Antarctic Balloon-born experiment.
  - Flew a 10-day circle around the pole in 1998
    - returned within 50 miles of launch point!
  - Mapped small (3%) part of sky at high resolution
  - Seeking characteristic scale of fluctuations

BOOMERANG Results: Anisotropy Bared



Patch of "blank" sky ~30° on a side: structure about 1° scale.

This structure is *real*: any expmt. to follow will find same imprint. It's our cosmic wallpaper.

These are the seeds of galaxy formation.

Fluctuations are at about one or two parts in 10,000 relative to the 2.7°K background.

Size of fluctuations tells us about the geometry of the universe.

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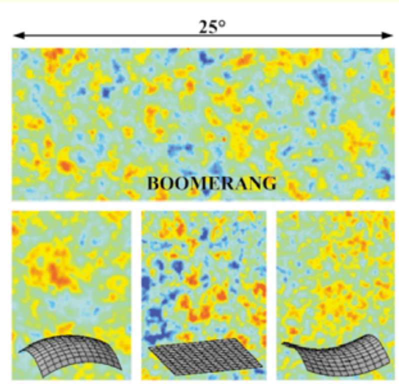
BOOMERANG: Our Universe is *Flat*



Top: BOOMERANG
Bottom: theoretical expectations

Know the *true physical size* of fluctuations from plasma physics and early cosmology (when the universe was far simpler than now).

Know how far away the structure *is*.

Apparent size of structure affected by geometry of Universe: flat→no magnification; positive curvature (closed)→looks bigger (magnified); negative curvature (open)→looks smaller (like through binoculars backwards).

Which looks right to you?

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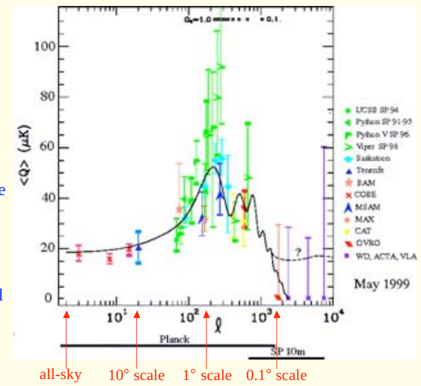
Pre-BOOMERANG State

- This complicated plot shows where measurements stood in 1999
- Theorists predicted a sort-of ringing structure (black curve) to the CMB bumps
- The data (with error bars) are all over the place!
  - note COBE only pertains to the crudest (largest) structures
- My reaction at the time:
  - the theorists are nuts—no way will we see this funky structure: the real universe will surprise us all
- Note how many independent teams are chasing after same goal



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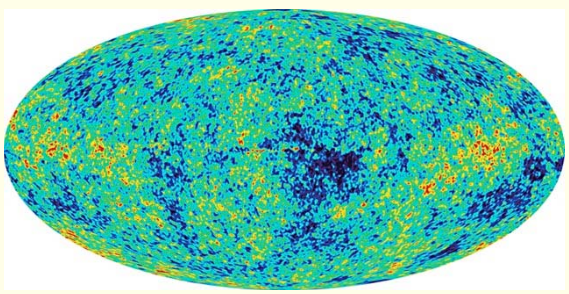
WMAP Adds new results (2003)



Whole-sky map at BOOMERANG quality
Exact match to BOOMERANG map
This *is* our wallpaper—we're stuck with it

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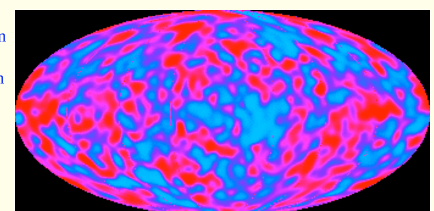
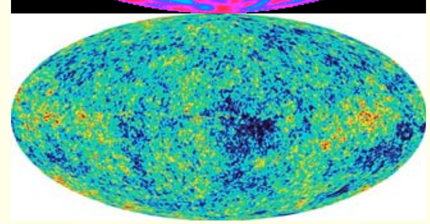
COBE vs WMAP

Limited resolution

Only hints at truth





Fully resolved

COBE structure still present

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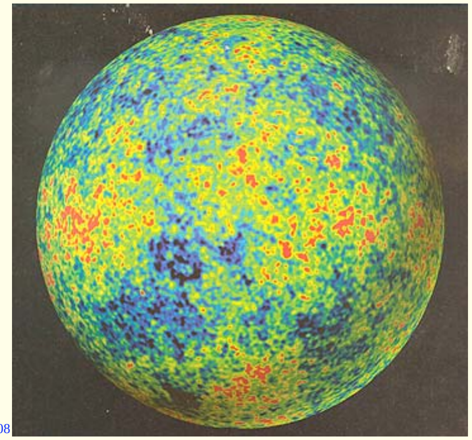
Wicked Way to View It:



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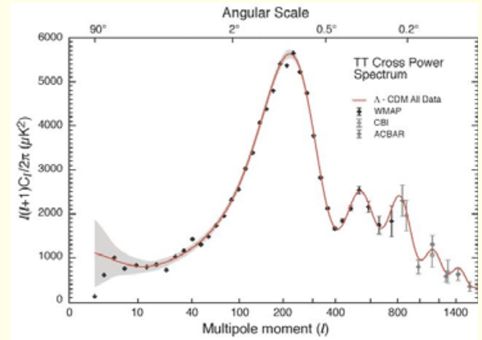
And the Result…



WOW! Whatever the theorists were smokin', it put them right on target!

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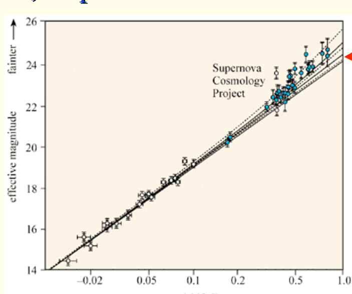
Meanwhile, Supernovae Indicate Acceleration

Farther Away

Closer



"Should" lie along this line.

But they're just a bit higher.

Farther away than expected.

Expansion is *accelerating*!

Distant supernovae ("standard candles") appear farther away than they "should."
"Should" represents the case wherein the Hubble expansion is *linear*,
or *unaccelerated*. That is, redshift is strictly proportional to distance.

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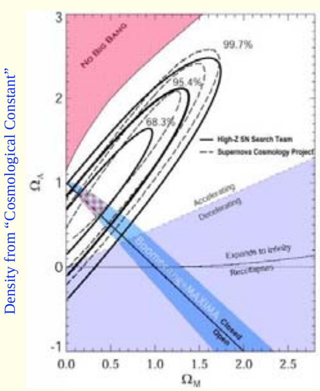
Putting It All Together

Density from "Cosmological Constant"



Matter Density

- **Based on CMB structure scale:**
  - Universe is flat
  - parallel lines remain parallel forever
- **Together with supernova studies, other CMB studies:**
  - See plaid checked region…
  - Universe is accelerating!
  - Cosmological Constant, Λ
  - Vacuum repulsive energy
- **Two independent (and competing) groups found same result**
  - dashed vs. solid ellipses
- **Clustering of galaxies separately indicates $\Omega_M \approx 0.3$**

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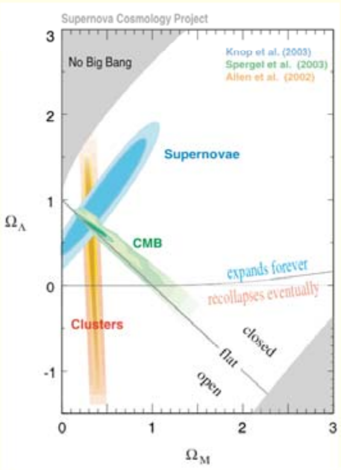
More recent update (better data)



- X marks the spot
  - The only place where all three measurements agree is with $\Omega_M \approx 0.3$ (matter) and $\Omega_\Lambda \approx 0.7$ (dark energy)
- Ω denotes a density
- Ω_M=1 means critical density: enough matter to halt expansion of universe
- There's not enough matter to stop the expansion
- Worse still, the dark energy accelerates the expansion
- Theorists wanted Ω_M=1.0 and Ω_Λ=0.0

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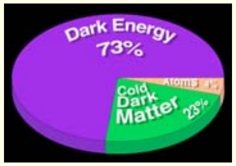
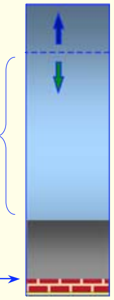


The Mass Budget of the Universe



"Critical" Density

"Dark Energy", Cosmological Constant

"Best Guess" Density of matter in the universe

Ordinary ("Baryonic") Matter, at most 5% of critical density

Stars: less than 1% of critical density

Most gravitating matter is *dark* (not in the form of shining stars).
Most of this, even, isn't in a familiar form of particle (non-baryonic).
Most of the energy density in Universe isn't mass at all!

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The Age of Precision Cosmology

Description		Symbol	*WMAP*-only	*WMAP*+BAO+SN
Parameters for Standard ΛCDM Model [a]				
Age of universe		t_0	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr
Hubble constant		H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
Baryon density	4.6 % stuff on periodic table	Ω_b	0.0441 ± 0.0030	0.0462 ± 0.0015
Physical baryon density		$\Omega_b h^2$	0.02273 ± 0.00062	0.02265 ± 0.00059
Dark matter density	23 % dark matter	Ω_c	0.214 ± 0.027	0.233 ± 0.013
Physical dark matter density		$\Omega_c h^2$	0.1099 ± 0.0062	0.1143 ± 0.0034
Dark energy density	72 % dark matter	Ω_Λ	0.742 ± 0.030	0.721 ± 0.015
Age at decoupling	376,000 yrs old at CMB	t_*	380081^{+5843}_{-5841} yr	375938^{+3148}_{-3115} yr
Total density [f]	flat within < 1% error	Ω_{tot}	$1.099^{+0.100}_{-0.085}$	1.0052 ± 0.0064

http://lambda.gsfc.nasa.gov/product/map/dr3/parameters_summary.cfm

- CMB measures ages and how much stuff
  - this is where we get 13.7 billion years
  - total = baryons + dark matter + dark energy
    - adds to critical density within 0.6% (1.0052±0.0064)

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Cosmological Conclusions

- Universe is expanding
  - We've known this since the 1920's.
- Not enough matter to gravitationally arrest expansion
  - Only about 30% of the necessary total
- Evidence that expansion is in fact accelerating
  - Other 70% of Universe's "density" may be *pushing*
- Most of the gravitating matter is in a form as yet unidentified
  - 23% out of 28% = 83% of gravitating matter mysterious
  - ordinary nuclei (called baryons) ruled out
  - probably some exotic new form of matter
- No convincing ideas for the nature of the "dark energy"
  - scalar fields, cosmological constant, GR wrong or needs modified?

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References and Assignment

- **WMAP, BOOMERANG and related references**
  - http://map.gsfc.nasa.gov/
  - http://rst.gsfc.nasa.gov/Sect20/A9.html
  - science.nasa.gov/headlines/y2000/ast27apr_1.htm
  - *How the Universe got its Spots*: Janna Levin
- **Assignments:**
  - Read supplement on Universe (access via Assignments page on course website)
  - Read Hewitt Chapter 11 through Quarks
  - Homework Exercises for *next* Friday (4/11):
    - Hewitt 1.R.15, 1.R.18, 1.E.7
    - Additional cosmology questions on course website
  - Question/Observation due 4/11via WebCT

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