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

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!
COBE Data reveals structure in CMB

Subtracting off 2.728°K shows dipole, indicating motion
Moving toward 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).

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.
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?

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

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

COBE vs WMAP

Limited resolution

Limited only hints at truth

Fully resolved

COBE structure still present
Wicked Way to View It:

"Should" lie along this line.
But they're just a bit higher.
Farther away than expected.
Expansion is accelerating!

Meanwhile, Supernovae Indicate Acceleration

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.

And the Result…

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

Putting It All Together

- 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, $\Lambda$
  - Vacuum repulsive energy
- Two independent (and competing) groups found same result
  - dashed vs. solid ellipses
- Clustering of galaxies separately indicates $\Omega_m = 0.3$
More recent update (better data)

- X marks the spot
  - The only place where all three measurements agree is with $\Omega_m = 0.3$ (matter) and $\Omega_{\Lambda} = 0.7$ (dark energy)

- $\Omega$ denotes a density
- $\Omega_m = 1$ 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 $\Omega_m = 1.0$ and $\Omega_{\Lambda} = 0.0$

The Mass Budget of the Universe

- 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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| Description                      | Symbol | WMAP-only | WMAP+BAO+SN
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Age of universe</td>
<td>$t_0$</td>
<td>13.69 ± 0.15 Gyr</td>
<td>13.75 ± 0.12 Gyr</td>
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<tr>
<td>Baryon constant</td>
<td>$h_0$</td>
<td>0.71 ± 0.02</td>
<td>0.70 ± 0.015</td>
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<tr>
<td>Baryon density</td>
<td>4.6 % of stuff on periodic table</td>
<td>$\Omega_B = 0.0273 ± 0.0002$</td>
<td>0.0265 ± 0.0009</td>
</tr>
<tr>
<td>Dark matter density</td>
<td>$\Omega_m$</td>
<td>0.234 ± 0.037</td>
<td>0.233 ± 0.033</td>
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<tr>
<td>Dark matter density</td>
<td>23 % dark matter</td>
<td>$\Omega_{\Lambda}$</td>
<td>0.1058 ± 0.0062</td>
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<tr>
<td>Dark energy density</td>
<td>72 % dark matter</td>
<td>$\Omega_{\Lambda}$</td>
<td>0.742 ± 0.030</td>
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<tr>
<td>Age at decoupling</td>
<td>370,000 yrs old at CMB</td>
<td>$\Omega_m$</td>
<td>1.966 ± 0.048</td>
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<tr>
<td>Total density</td>
<td>flat within 1% error</td>
<td>$\Omega_{\Lambda}$</td>
<td>1.004 ± 0.015</td>
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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?
References and Assignment

- **WMAP, BOOMERANG and related references**
  - [http://map.gsfc.nasa.gov/](http://map.gsfc.nasa.gov/)
  - [science.nasa.gov/headlines/y2000/ast27apr_1.htm](http://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 4/11 via WebCT