The beginning and end of our universe

Max Tegmark, MIT
THE COSMIC SMÖRGÅSBORD

- Microwave background
- Galaxy surveys
- Supernovae Ia
- Gravitational lensing
- Big Bang nucleosynthesis
- Galaxy clusters
- Neutral hydrogen tomography
- Lyman $\alpha$ forest
What have we learned?
Summary of Lecture 1

- Afterglow Light Pattern
  - 400,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy
  - Accelerated Expansion
- Inflation
- Quantum Fluctuations?
- 1st Stars
  - about 400 million yrs.
- WMAP
- Big Bang Expansion
  - 13.7 billion years
# Summary of Lecture 2

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
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<td>$n_t + 1$</td>
<td>$0.9861 \pm 0.0096$</td>
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<td>$\alpha$</td>
<td>$-0.040 \pm 0.027$</td>
<td>Running of spectral index</td>
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MORE EVIDENCE:
The fine details of cosmic clumpiness
Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496
\( z = 1000 \)
$\Lambda$CDM local universe at $z=2.4$ ($\Lambda=0.7$, $\Omega=0.3$, $h=0.7$)
Constrained within 8000 km/s by the IRAS 1.2 Jy survey
LCDM local universe at $z=0.8$ ($\Lambda=0.7$, $\Omega=0.3$, $h=0.7$)
Constrained within 8000 km/s by the IRAS 1.2 Jy survey
Tegmark & Zaldarriaga, astro-ph/0207047 + updates

- Cosmic Microwave Background
- SDSS galaxies
- Cluster abundance
- Weak lensing
- Lyman Alpha Forest

Current power spectrum $P(k) [(h^{-1} \text{Mpc})^3]$ vs. Wavenumber $k [h/\text{Mpc}]$ vs. Wavelength $\lambda [h^{-1} \text{Mpc}]$
Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)
Current power spectrum $P(k) \left[ (\text{Mpc}^3)^2 \right]$ vs. Wavenumber $k \left[ \text{Mpc}^{-1} \right]$.

- SDSS galaxies
- Cluster abundance

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LSS

Clusters
Current power spectrum $P(k) [\text{[(h^{-1} Mpc)^3]}$

- Cosmic Microwave Background
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Wavelength $\lambda [\text{h^{-1} Mpc}]$

Wavenumber $k [\text{h/Mpc}]$

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2008:

CMB

LSS

Clusters

Lyα

Current power spectrum $P(k) [(h^{-1} \text{ Mpc})^3]$

Wavelength $\lambda$ [h$^{-1}$ Mpc]

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Lyman Alpha Forest Simulation: Cen et al 2001

You

Quasar

QSO 1422+2301

simulation

\[ \text{flux} \]

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Bright Horizons Cruise
June 1, 2010
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LSS

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Cosmic Microwave Background

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Tegmark & Zaldarriaga, astro-ph/0207047 + updates
Chema movie
GRAVITATIONAL LENSING: A1689 imaged by Hubble ACS, Broadhurst et al 2004
WHAT YOU HAVE:

WHAT YOU SEE:
CMB

LSS

Clusters

Lensing

Lyα

Current power spectrum $P(k) \, [\, (h^{-1} \text{ Mpc})^3]$ vs. Wavenumber $k \, [h/\text{Mpc}]$ vs. Wavelength $\lambda \, [h^{-1} \text{ Mpc}]$.

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Measuring cosmological parameters
par movies
### Cosmic history parameters:

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<td>$3057^{+105}_{-102}$</td>
<td>Matter-radiation Equality redshift</td>
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<td>$z_{rec}$</td>
<td>$1090.25^{+0.93}_{-0.91}$</td>
<td>Recombination redshift</td>
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<tr>
<td>$z_{ion}$</td>
<td>$11.1^{+2.2}_{-2.7}$</td>
<td>Reionization redshift (abrupt)</td>
</tr>
<tr>
<td>$z_{acc}$</td>
<td>$0.855^{+0.059}_{-0.059}$</td>
<td>Acceleration redshift</td>
</tr>
<tr>
<td>$t_{eq}$</td>
<td>$0.0634^{+0.0045}_{-0.0041}$ yr</td>
<td>Matter-radiation Equality time</td>
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<tr>
<td>$t_{rec}$</td>
<td>$0.3856^{+0.0040}_{-0.0040}$ yr</td>
<td>Recombination time</td>
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<td>$0.43^{+0.20}_{-0.10}$ yr</td>
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<td>$t_{acc}$</td>
<td>$6.74^{+0.25}_{-0.24}$ yr</td>
<td>Acceleration time</td>
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<tr>
<td>$t_{now}$</td>
<td>$13.76^{+0.15}_{-0.15}$ yr</td>
<td>Age of Universe now</td>
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Using WMAP3 + SDSS LRGs:

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How will it all end?
A decelerating universe reaches its current size in the least amount of time. The universe could eventually contract and collapse into a "big crunch" or expand indefinitely. A coasting universe (center) is older than a decelerating universe because it takes more time to reach its present size, and expands forever. An accelerating universe (right) is older still. The rate of expansion actually increases because of a repulsive force that pushes galaxies apart.
What we’ve learned about $H(z)$ from SN Ia, CMB, BAO, BBN, etc:

Assumes $k=0$

Vanilla rules OK!
How did it all begin?
Some things to ponder…
Ned Wright
How flat is space?

![Graph showing the relationship between dark energy density and matter density. The graph illustrates the allowed region for the flatness of space.]
How flat is space?

Ruled out by WMAP1

Dark energy density $\Omega_\Lambda$

Matter density $\Omega_m$

Allowed
How flat is space? Somewhat.
How flat is space? \( \Omega_{\text{tot}} = 1.003 \pm 0.010 \)