Welcome back to 8.033!

Alan Guth
Summary of cosmology so far:

Key formula summary

- **FRW metric:**
  \[
  d\tau^2 = dt^2 - a(t)^2 \left( \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\varphi^2 \right)
  \]

- **Hubble parameter:**
  \[
  H \equiv \frac{\dot{a}}{a}
  \]

- **Dimensionless current Hubble parameter:**
  \[
  h \equiv H_0 / (100\text{ km s}^{-1}\text{ Mpc}^{-1}) \approx H_0 \times 9.7846G
  \]

- **Friedmann equation:**
  \[
  H^2 = \frac{8\pi G}{3} \rho - \frac{k c^2}{a^2} = H_0^2 [\Omega_{\gamma}(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{\Lambda}]
  \]

- **Cosmological parameter measurements (2005):**
  - \( \Omega_b \approx 0.05 \),
  - \( \Omega_{\Lambda} \approx 0.25 \),
  - \( \Omega_{\Lambda} \approx 0.7 \),
  - \( \Omega_k \approx 0 \),
  - \( h \approx 0.70 \),
  - \( \Omega_m \equiv \Omega_b + \Omega_d \approx 0.3 \),

- **Age of the Universe at redshift \( z \):**
  \[
  t(z) = \int_z^{\infty} \frac{dz'}{(1+z')H(z')}
  \]
• Friedmann equation:

\[ H^2 = \frac{8\pi G}{3} \frac{\rho}{\rho} - \frac{k c^2}{a^2} \]

\[ = H_0^2 \left[ \Omega_\gamma (1 + z)^4 + \Omega_m (1 + z)^3 + \Omega_k (1 + z)^2 + \Omega_\Lambda \right] \]

• Cosmological parameter measurements (2005):

  - \( \Omega_b \approx 0.05 \),
  - \( \Omega_d \approx 0.25 \),
  - \( \Omega_\Lambda \approx 0.7 \),
  - \( \Omega_k \approx 0 \),
  - \( h \approx 0.70 \),
  - \( \Omega_m = \Omega_b + \Omega_d \approx 0.3 \),

• Age of the Universe at redshift \( z \):

\[ t(z) = \int_z^\infty \frac{dz'}{(1 + z')H(z')} \]
Evidence 1:
The Universe is expanding!
\[ v = Hr \]
Evidence 2:
Cosmic microwave background exists
$T \approx 2.726K$
Evidence 3: 

Big Bang Nucleosynthesis happened 
(correctly predicts the abundance of light elements)
Evidence for Big Bang:

• Observed galaxy recession (Hubble’s law)
• Existence of CMB
• Correct predictions of big bang nucleosynthesis
• Darkness of night sky! (Olber)
• Distant objects look younger

Evidence for what, exactly?

Our entire observable universe was once as hot as the core of the Sun, doubling its size in under a second.

• Not evidence for a singularity
Today’s topic: Cosmology roundup

• See nyd_darkenergy.pdf (Thanks Anthony Kesich!)
• Evidence for Big Bang?
• What do we know? Common misconceptions
• What don’t we know? Hot research questions
• My “day job”
THE COSMIC SMÖRGÅSBORD

CMB

GALAXY SURVEYS

DISTANT SUPERNOVAE

GRAVITATIONAL LENSING

BIG BANG NUCLEOSYNTHESIS

GALAXY CLUSTERS

LYMAN ALPHA FOREST

All images courtesy of NASA.
Mysteries for you to solve:

• What is dark matter?
• How did it all begin?  
  (buzz word: inflation)
• How will it all end  
  (buzz word: dark energy)
Mystery 1: How will it 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.
Distant light is \{ dimmed, redshifted \}.
Distant light is \{-dimmed, -redshifted\}

Redshift

Dimming

Figure by MIT OCW.
Distant light is \{-dimmed, -redshifted\}

Standard candles, rulers or clocks

\[
\begin{array}{c|c}
\text{Distance [Mpc]} & \text{Velocity [km/sec]} \\
20000 & 10000 \\
30000 & 20000 \\
\end{array}
\]

Figure by MIT OCW.
H = d\ln a/dt, \quad H^2 \propto \rho
\[ H = \frac{d \ln a}{dt}, \quad H^2 \propto \rho \]

Figure 1 from Yun Wang & Max Tegmark, ”New Dark Energy Constraints from Supernovae, Microwave Background, and Galaxy Clustering”

Mystery 2: What is dark matter?
**Brief History of our Universe**

- **Fluctuation generator**
- **Fluctuation amplifier**

**INFLATION**

- fraction of a second
- 379,000 years
- 13.7 billion years

**CMB last scattering**

- first stars
- present day

**Hot Dense Smooth**

- Cool Rarefied Clumpy

400 million years

Image courtesy of WMAP/NASA.
What do we want to measure?
Evidence 4:
The fine details of cosmic clumpiness
\[ z = 1000 \]
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

Figure by MIT OCW.
$z = 0.8$

ΛCDM 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 survey

Figure by MIT OCW.
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001
Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)
Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

Image courtesy of Wikipedia.
Figure removed due to copyright restrictions.

Courtesy of Nature. Used with permission.
Figure 4 from Tegmark et al, “Cosmological Constraints from the SDSS Luminous Red Galaxies”,
Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

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Temperature fluctuation $\delta T$ (µK)

- Inflation with $\Lambda$
- Open Universe
- Inflation w/o $\Lambda$
- Cosmic Strings

Multipole $l$

Figure by MIT OCW.

Guth & Kaiser 2005, Science
Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

Lyman Alpha Forest Simulation: Cen et al 2001
astro-ph/0407378

Image courtesy of NASA.
Figure 1 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

Gravitational lensing

Galaxy Cluster Abell 2218
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

Image courtesy of NASA.
Lensing

What you HAVE:

What you SEE:

Figure by MIT OCW.
Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)
Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

But the best is yet to come...
Open Universe

Temperature fluctuation $\delta T$ (µK)

Multipole $l$

Inflation with $\Lambda$

Inflation w/o $\Lambda$

Cosmic Strings

Figure by MIT OCW.

Tegmark & Zaldarriaga, astro-ph/0207047 + updates
Figure 4 from Guth and Kaiser,
Dark matter par movie
Using WMAP3 + SDSS LRGs:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matter budget parameters:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Omega_{\text{tot}}$</td>
<td>$1.003^{+0.010}_{-0.009}$</td>
<td>Total density/critical density</td>
</tr>
<tr>
<td>$\Omega_{\Lambda}$</td>
<td>$0.761^{+0.017}_{-0.018}$</td>
<td>Dark energy density parameter</td>
</tr>
<tr>
<td>$\omega_b$</td>
<td>$0.0222^{+0.0007}_{-0.0007}$</td>
<td>Baryon density</td>
</tr>
<tr>
<td>$\omega_c$</td>
<td>$0.1050^{+0.0041}_{-0.0040}$</td>
<td>Cold dark matter density</td>
</tr>
<tr>
<td>$\omega_\nu$</td>
<td>$&lt; 0.010$ (95%)</td>
<td>Massive neutrino density</td>
</tr>
<tr>
<td>$w$</td>
<td>$-0.941^{+0.087}_{-0.101}$</td>
<td>Dark energy equation of state</td>
</tr>
<tr>
<td><strong>Seed fluctuation parameters:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_s$</td>
<td>$0.690^{+0.045}_{-0.044}$</td>
<td>Scalar fluctuation amplitude</td>
</tr>
<tr>
<td>$r$</td>
<td>$&lt; 0.30$ (95%)</td>
<td>Tensor-to-scalar ratio</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.953^{+0.016}_{-0.016}$</td>
<td>Scalar spectral index</td>
</tr>
<tr>
<td>$n_t + 1$</td>
<td>$0.9861^{+0.0096}_{-0.0142}$</td>
<td>Tensor spectral index</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$-0.040^{+0.027}_{-0.027}$</td>
<td>Running of spectral index</td>
</tr>
</tbody>
</table>

Image courtesy of NASA.
Mystery 3: How did it begin?
DAWN OF TIME

tiny fraction of a second

inflation

380,000 years

13.7 billion years

Image courtesy of WMAP/NASA.
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.
\[ H = \frac{d \ln a}{d t}, \quad H^2 \propto \rho \]
Evidence #1 for inflation:

Space is very flat

$$\Omega_{\text{tot}} = 1.003 \pm 0.010$$

MT et al 2006, astro-ph/0608632

Figure by MIT OCW.
How flat is space? $\Omega_{\text{tot}} = 1.003 \pm 0.010$

Figure 15 from Tegmark et al, “Cosmological Constraints from the SDSS Luminous Red Galaxies”

Figure 1 from Yun Wang & Max Tegmark, ”New Dark Energy Constraints from Supernovae, Microwave Background, and Galaxy Clustering” Phys Rev Lett 92, 241302 (2004).

Figure removed due to copyright restrictions.
What we’ve called “the Big Bang” wasn’t the beginning, but the end…

…of inflation!

Mysteries for you to solve:

• What is dark matter?
• How did it all begin?  
  (buzz word: inflation)
• How will it all end  
  (buzz word: dark energy)
Summary of what we know about our metric.
Coming next…

BLACK HOLES