Cosmology:
$(13.73 \pm 0.15) \times 10^9$ years* in $(60 \pm 5)$ minutes

*Lorenzo Sorbo

UMass Amherst

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*with priors
Things people have *always* wanted to know about the Universe
- and questions cosmologists claim to address -

- Did it exist forever or it had a beginning?
- Is it finite or infinite?
- **What is it made of?**
- How is it going to end?
Birth of modern ("scientific") cosmology

-1905–’16: Einsteinformulates his theory of General Relativity

-1922–’35: Friedmann, Lemaitre, Robertson, Walker apply General Relativity to the whole Universe: [Hypothesis: homogeneity and isotropy]

\[
\frac{d_{\text{physical}}(t)}{d_{\text{comoving}}} = a(t)
\]

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

Spatial curvature of the Universe

Hubble parameter

Energy density of cosmological matter
Observational support in 1929: Edwin Hubble discovers that galaxies are receding from us with a velocity proportional to their distance!

$H \neq 0 \Rightarrow$ The Universe is expanding!
Expansion of the Universe $\Rightarrow$ Evolution of the Universe

Clock = redshift factor $z \quad a = a_0/(z+1)$

Today: $z=0$
Before: $z>0$
How do we characterize matter?

Fluids characterized by energy density $\rho$ and pressure $p$

$$dU = T \, dS - p \, dV$$

Equation of state parameter $w \equiv p/\rho$

$w = 0$ nonrelativistic stuff

$w = 1/3$ ultrarelativistic stuff

$$\dot{\rho} + 3 \, H (\rho + p) = 0$$

$$\rho \propto 1/a^{3(1+w)}$$
Matter domination vs Radiation Domination

\[ \rho_{\text{matter}} \propto a^{-3} \]
Matter domination vs Radiation Domination

\[ \rho_{\text{matter}} \propto a^{-3} \]

\[ \rho_{\text{radiation}} \propto a^{-4} \]

Today
Matter domination vs Radiation Domination

\[ \rho_{\text{matter}} \propto a^{-3} \]

\[ \rho_{\text{radiation}} \propto a^{-4} \]

Matter-radiation equality \( z \approx 3100 \)

\[ \log(\rho) \]

\[ \log(a) \]

Today
Matter domination vs Radiation Domination vs Cosmological Constant (?) Domination \([w=-1]\)

\[
\rho_{\text{matter}} \propto a^{-3}
\]

\[
\rho_{\text{radiation}} \propto a^{-4}
\]

Matter-radiation equality \(z \approx 3100\)

Today

\[
\rho_{\text{CC}} \propto a^0
\]
How to measure the amount of energy density in a fluid?

Define critical density:

$$\rho_c \equiv \frac{3H^2}{8\pi G}$$

For a fluid $\psi$ with energy density $\rho_\psi$, define

$$\Omega_\psi = \frac{\rho_\psi}{\rho_c}$$

(Def such that $\Omega_{\text{tot}} = 1$ in a Universe with no curvature)
The matter budget

- Photons
- Baryons
- Neutrinos
- Dark Matter
- Dark Energy

Known knowns

Known unknown

Unknown unknown
Photons

Cosmological photons (homogeneous and isotropic) first detected by Penzias and Wilson 1965
Cosmic Microwave Background Radiation (CMB)

Subsequent measurements ⇒ CMB spectrum almost perfectly thermal

The Early Universe was (almost) perfectly thermalized!
Photons

\[ Q_\gamma \propto T^4 \quad \text{and} \quad Q_\gamma \propto a^{-4} \]

\[ T = T_0 \frac{a_0}{a} \]

Temperature of photons can be used as a clock.
Interaction of different species in the thermal soup described by the **Boltzmann Equation**

\[
E \frac{\partial f_\psi}{\partial t} - H \vec{p}^2 \frac{\partial f_\psi}{\partial E} = \mathcal{C}[f_\psi]
\]

\( f_\psi (E, t) \) = distribution function of species \( \psi \)

Collisional Integral (interactions with other species)

Integral form: \( (n_\psi = \# \text{ density of } \psi \text{s}) \)

\[
\frac{dn_\psi (t)}{dt} + 3Hn_\psi (t) = \frac{g}{(2\pi)^3} \int \mathcal{C}[f_\psi (E, t)] \frac{d^3 p}{E}
\]
If this term is negligible:

Species in thermal equilibrium

$$f_\psi \propto e^{-E/kT}$$

# density of particles with mass $\gg$ temperature exponentially suppressed

(unless symmetries imply # conservation)
If this term is negligible:

**Species out of equilibrium**

\[ n_\psi \propto a^{-3} \]

**even nonrelativistic particles**

**can have significant abundance**
Baryons

Protons and neutrons kept in equilibrium by EW interactions

They get out of equilibrium at $T \approx 1 \text{ MeV}$:

**Big Bang Nucleosynthesis**

Solution of Boltzmann equations

Calculation of primordial abundances of $\text{H, D, T, } ^3\text{He, } ^4\text{He, } ^7\text{Li...}$
Baryons

Abundance of primordial elements depends only on one phenomenological parameter

$$\eta_B = n_{\text{Baryons}}/n_\gamma$$

Observations of abundance of elements agree with each other (!) and give

$$\eta_B \approx 6 \times 10^{-10}$$

(From PDG 2006)
Where does $\eta_B$ come from?

**Baryogenesis**

Three ingredients needed:

- B violation
- C and CP violation
- Departure from thermal equilibrium

...and plenty of models...
Electrons

Number density determined by $\eta_B$ (electric neutrality)

More interesting: $e^-p\leftrightarrow H\gamma$ reaction falls out of equilibrium at $T\approx 0.3\text{ eV}$

Recombination

(at $z=1088$, $t=370,000\text{ yers}$)

After recombination no free ions:
Universe is transparent to radiation (CMB)
Log($\rho$)

Matter-radiation equality (~1 eV)

Today

Nucleosynthesis (1 MeV)

Recombination (~0.3 eV)
Neutrinos

Cosmological neutrinos not observed
Their abundance inferred indirectly from BBN $(1.4 < N_\nu < 4.9)$

$e^+e^-$ annihilation occurs after $\nu$ decoupling

# density of a $\nu$ family < # density of photons
Summary of known knowns

- Photons \( \Omega_\gamma \approx 5 \times 10^{-5} \)
- Atoms \( \Omega_B \approx 0.04 \)
- Neutrinos \( \Omega_\nu \approx 5 \times 10^{-4} - 0.01 \)
Dark Matter

First suggested by Zwicky (1933) to explain motion of galaxies in clusters

Strong observational support from study of galaxy rotation curves
Dark Matter

Results of measurements:

$v(r)$ if there was only luminous matter in the galaxy

Measured $v(r)$
Dark Matter

More evidence: gravitational lensing (see Dell’Antonio tomorrow!)
Dark Matter

More evidence: X rays

visible

mass distribution from lensing

X rays

“bullet cluster”

FIG. 1.— Shown above in the top panel is a color image from the Magellan images of the merging cluster 1E0657−558, with the white bar indicating 200 kpc at the distance of the cluster. In the bottom panel is a 500 ks Chandra image of the cluster. Shown in green contours in both panels are the weak lensing $\kappa$ reconstruction with the outer contour level at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the $\kappa$ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue +s show the location of the centers used to measure the masses of the plasma clouds in Table 2.

How much dark matter?

Different measurements in clusters give

$$\rho_{\text{DM}} \approx 5 \times \rho_{\text{Baryon}}$$

Ordinary matter + Dark matter \Rightarrow \Omega \approx 0.3
What are the properties of DARK MATTER?

- It clumps, like dust
- It interacts very weakly with ordinary matter (weak scale interactions favored)
- It represents ~ the 80% of the matter content in structures
- Susy neutralino an excellent candidate - see Mc Kinsey on Friday (but also axions, gravitinos, primordial black holes...)
Why do we care about $\Omega$?

$\Omega = 1$ is an *unstable* equilibrium point:

- evolution of the Universe brings $\Omega$ away from 1

If $\Omega$ is close to 1 today, it should have been **VERY** close to 1 in the past!
If $\Omega = 0.3$ today, then $\Omega$ should have been equal to $0.99999999999999999993$ at the time of nucleosynthesis.

Much more elegant to assume $\Omega = 1$, always.

moreover, we have a mechanism to generate $\Omega = 1$: Inflation

...but where is the remaining matter that allows us to go from $\Omega = 0.3$ to $\Omega = 1$?
Using Friedmann’s law to determine the content of the Universe

Derive $\rho(t)$, $p(t)$ from

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

and measures of $H(t)$

$$\dot{\rho} + 3H(\rho + p) = 0$$

$\dot{a}(t)$

$\dot{d}_{\text{physical}}(t) = a(t) \dot{d}_{\text{comoving}}$

$\dot{d}_{\text{physical}}(t) = a(t) \dot{d}_{\text{comoving}}$

Easy to measure (redshift)

Difficult to measure

UNKNOWN!
Measuring distances from us...

**Standard candle:** object whose absolute luminosity is known

![Diagram](image)

Absolute luminosity $\mathcal{L}$  
Incoming flux on Earth $\mathcal{I}$  
Distance $d = \sqrt{\frac{\mathcal{L}}{4\pi \mathcal{I}}}$

Of course, very difficult to find standard candles! Today, the most important are

**Type Ia Supernovae**
Hubble diagram (i.e. $d(z)$)

Luminosity $\Rightarrow$ Distance

Redshift $\Rightarrow$ Velocity

$q(t), p(t)$

[from Perlmutter et al (1998)]
Besides ordinary matter and dark matter, the Universe contains extra stuff that behaves like a fluid with negative pressure.

**DARK ENERGY!**

\[ \Omega_M = 0.3, \quad \Omega_{DE} = 0.7 \]

\[ \Omega_M = 0.3, \quad \Omega_{DE} = 0 \]

[from Perlmutter et al (1998)]
Constraints on the plane \((w_{\text{DE}}, \Omega_{\text{DE}})\)

[Riess et al., 2004]
What are the properties of DARK ENERGY?

• It is smoothly distributed EVERYWHERE
• It looks a lot like a cosmological constant (the energy of vacuum)
• It does not dilute away as the Universe expands
• It represents ~ the 70% of the matter content of the Universe
• We have no idea what it might be (cosmological constant? quintessence? modified gravity?)
The inhomogeneous Universe

Gravity is different from other forces:

\[
\text{equal charges attract each other}
\]

\[
\text{Instability!}
\]

Inhomogeneities (can) GROW!
Inhomogeneities were small in the past
Last interaction with matter at recombination.

CMB anisotropies: a picture of the Universe at recombination!

Map of the anisotropies: a wealth of information about the Universe

Homogeneous component (Penzias and Wilson)

Dipole (motion of the Earth)

Genuine anisotropies $\Delta T/T \sim 10^{-6}$

$T = 2.728 \, \text{K}$

$\Delta T = 3.353 \, \text{mK}$

$\Delta T = 18 \, \mu\text{K}$
WMAP
(Wilkinson Microwave Anisotropy Probe)

Launched 2001 - still taking data
Better resolution
Polarization!
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(Wilkinson Microwave Anisotropy Probe)

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Polarization!
“Fourier transform” of data ($C_l$)

Oscillations of baryon-photon fluid

Scales that were superhorizon at recombination

Large Scales

Small Scales

Angular Scale

Anisotropy Power ($\mu K^2$)

Multipole moment ($l$)
Polarization!
CMB power spectrum depends on and gives info about

- The spectrum of superhorizon perturbations at recombination
- The evolution of perturbations that entered the horizon before recombination
- The evolution of the Universe after recombination
Effects on CMB power spectrum

A lot of information, but DEGENERACIES!
$\Omega_{\text{Baryon}}$ in fantastic agreement with BBN!

Spectral index of primordial perturbations agrees with expectation from inflation

Amount of dark matter same as estimated from clusters

Priors:
$\Omega_{\text{TOT}} = 1$
dark energy = Cosmological Constant
What we see in the sky
(with galaxy surveys)
Again, Fourier transforming...

A lot of information!
(e.g. $\nu$ mass...)
Again, Fourier transforming... A lot of information!
(e.g., $v$ mass...)

FIG. 4: Measured power spectra for $b = 1.8$ (top) and $b = 1.1$ (bottom). The solid curves are uncorrelated and full window functions are shown in Figure 5. The solid curve $b = 1.8$, with $Q_{s,0} = 30$ for $A = 1.4$, is from $b = 1.8$ (top) and $b = 1.1$ (bottom). The dashed curves include the nonlinear correction of [9] for the main galaxies; see equation (4). The onset of nonlinear corrections is clearly
Conclusions

Cosmology is a powerful instrument - but a dirty one

Very useful in conjunction with a cleaner instrument (accelerators)

By looking at the sky we KNOW that there must be some Physics beyond the Standard Model

Will we be able to uncover it?