Summary of Observational Cosmology

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The Four Pillars of Big Bang Cosmology

Expansion
Cosmic Microwave Background (CMB)
Nucleosynthesis (BBN)
Structure Formation

Questions
Dark Matter
Dark Energy
Baryogenisis
Olber’s paradox

If the universe is static, infinitely large and with an infinite number of stars distributed uniformly, then the night sky should be bright.
Expansion rate given by Hubble constant $v = H_0 r$, with value $H_0 \approx 70 \text{km/s/Mpc}$

1 parsec (pc) = 3.3 light-years. The milky way is 16 Kpc in diameter.
1) Expansion

Top shows that for small $Z \ll 1$, expansion is linear.
Bottom: Linear expansion divided out, showing that the Hubble law becomes non-linear for large $Z$.
Results strongly favor flat ($k=0$) universe with $\Omega_{Vac} \approx 0.7$. 
Type 1A Supernovae

Supernovae examples from Hubble.

Type 1A identified by light “curve” (intensity vs time) and used as standard candles.
2) Cosmic Microwave Background (CMB)

photon decoupling: Universe becomes transparent to CMB photons at $T=10^4\text{K (1eV)}$ at time 380,000 y. Red shift $Z \approx 1000$ where

$$Z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} - 1, \quad \Omega_\gamma \approx 10^{-5}$$
Temperature fluctuations in the CMB after removing Doppler shift and background from the galactic plane.

\[ \delta T_0 \approx 60 \mu K \]

\[ \frac{\delta T_0}{T_0} = 2 \times 10^{-5} \]
Temperature fluctuations result from density fluctuations whose size can be calculated (acoustic waves in plasma), and therefore act as “standard rulers” on the surface of last scattering.

Correlation function,

$$C(\theta) = \left< \frac{\delta T(\hat{n})}{T} \frac{\delta T(\hat{n}')}{T} \right>,\,$$

averaged over $\hat{n} \cdot \hat{n}' = \cos(\theta)$

$$\Omega_{\text{vac}} \approx 0.7$$
3) Nucleosynthesis (BBN)

The primordial abundances of $^4$He, D, $^3$He, and $^7$Li as predicted by Big-Bang nucleosynthesis as a function of the baryon-to-photon ratio $\eta$. The bands show the 95% CL range. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of $\eta$. 

![Graph showing primordial abundances of light elements](image)
4) Structure Formation

\[ \Omega_{\text{matter}} = 0.168 \text{ with } \Omega_{\text{baryonic}} / \Omega_{\text{matter}} = 0.17 \]
\[ \Omega_{\text{tot}} = 1.02 \pm 0.02, \]
consistent with \( \Omega = 1 \) (flat) universe
\[ \Omega_{\text{vac}} = 0.73 \pm 0.04 \]
\[ \Omega_b = 0.044 \pm 0.004 \]
\[ \Omega_{\text{matter}} = \Omega_{\text{dark}} + \Omega_b = 0.27 \pm 0.04 \]
\[ t_{\text{big bang}} = 13.7 \pm 0.2 \text{ Gyr} \]
What the Universe is made of?

70% Dark Energy—what is it?
25% Dark Matter—what is it?
Dark Matter and Structure problem

Typical galactic rotation curve.

\[ \rho_{Dark} \approx 0.3 \text{GeV/cm}^3 \]

interaction rate of \(< 1 \text{ event/kg/day} \)
Strong Lensing
Einstein Ring
Large Scale Structure

Need dark matter to form large filamentary structure, galaxy clusters and galaxies. This is a computation of the large scale structure based on GR with only dark matter.
Weakly Interacting Dark Matter: There is no known particle ("Standard Model") with the necessary properties: stable, heavy $M > 10\,\text{GeV}$, weakly interacting. A new particle like the supersymmetric photon, the "photino"?
Figure: How dark matter would make S1 and S2 signals in the XENON1T detector.
Figure 26.1: Upper limits on the SI DM-nucleon cross section as a function of DM mass.

XENON 1T 3.3 T LUX 370 kg
next generation: LZ 10 Ton, XENONnT 8.3 Ton shown is LZ TPC in SURF, South Dakota
Neutron Electric Dipole Moment (EDM)

Why is the neutron electric dipole moment so small?

EDM would violate CP. Why violation is so small is called the “strong CP” problem. New $U(1)$ symmetry, new extremely light ($\sim 10\mu eV$) boson, the axion Dark Matter axions can convert to two photons (resonant microwave cavity) in magnetic field.
Axion Dark Matter

The ADMX G2 Experiment

ADMX is an axion haloscope, which uses a strong magnetic field to convert dark matter axions to detectable to microwave photons. The ADMX G2 experiment is one of the US Department of Energy’s flagship dark matter searches, and the only one looking for axions. The experiment consists of a large magnet, a microwave cavity, and ultra-sensitive low-noise quantum electronics.
Axion parameter space

CAST sensitive to high mass axions

ADMX results up to 2010
Achieved KSVZ sensitivity

Graham, et.al (2016)
Basic Michelson interferometer with Fabry Perot Cavities
Gravitational Waves

FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors’ most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. Top row, left: H1 strain. Top row, right: L1 strain. GW150914 arrived first at L1 and 6.9353 ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors’ relative orientations). Second row: Gravitational-wave strain projected onto each detector in the 35–350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 [37,38] confirmed to 99.9% by an independent calculation based on [15]. Shaded areas show 90% credible regions for two independent waveform reconstructions. One (dark gray) models the signal using binary black hole template waveforms [39]. The other (light gray) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of two known waveforms [40].
Gravitational Waves

![Graph showing gravitational waves](image-url)
$w = 1$ means a Cosmological constant; “quitessence”, a time varying vacuum energy? Or does General Relativity need to be modified at large distances? Various Dark Energy measurements planned.
Horizon Problem: patches of sky separated by $> 2^\circ$ were causally disconnected at time of (CMB) decoupling, yet spectrum is perfect black body implying equilibrium.

Homogeniety and Isotropy problem: Expect quantum fluctuations in early universe to create inhomogeneities.

Flatness problem: Why an almost perfectly flat geometry.

Proposed solution: Inflation (Guth)—An exponential expansion of the universe at times $10^{-34}$s due to a vacuum phase transition, releasing enormous vacuum energy, due to some (unknown) “inflaton” field. This theory predicted flat ($\Omega = 1$) universe!
CMB polarization

**Figure:** located in northern Chile @17,100 ft. Other experiments at the south pole.

Inflationary theories predict that the early Universe underwent a phase of exponential expansion during which a background of gravitational waves was produced. Those gravitational waves will then produce a primordial B-mode signal at the time of recombination.
Particle physics has an almost perfect matter-antimatter symmetry. Most of the matter-antimatter in the early universe annihilated to radiation leaving $N_p/N_\gamma \approx 6 \times 10^{-9}$ Yet there are almost no antiprotons in the universe! Particle physics has all the ingredients to produce the matter-antimatter asymmetry, but not enough. There must be new particle physics to explain this!
Majorana Neutrino

lepto-genesis – theories that explain matter-antimatter asymmetry of barons as resulting from lepton number violation from Majorana neutrino

The electron is really four separate fields. The neutrino might be only two. It might be its own anti-particle.
Neutrino-less Double Beta

A hypothetical nuclear decay that can only happen if the neutrino is its own anti-particle. Measured $^{76}$Ge $\beta\beta$ with $2\nu$ is $T(1/2) = (1.84 + 0.14 - 0.10) \times 10^{21}$ yr.

Figure: Tiny red blip at endpoint greatly exaggerated. Looking for $\tau \sim 10^{28}$ yr
Ge detectors emersed in liquid argon veto. Because we have only measured neutrino squared-mass differences, we don’t know the mass ordering. “Normal” has state which is mostly electron-neutrino as the lightest.
FIG. 8. Background energy spectra of BEGe detectors obtained during GERDA Phase II data taking. The spectra for events after LAr veto rejection and events with scintillation light coincidence are displayed separately. The overlay of the $2\nu\beta\beta$ contribution from Monte Carlo simulations in the spectrum after LAr veto highlights the suppression of the background dominated by Compton scattered $\gamma$'s at these energies.
Cosmology and Particle Physics

- **Galaxy formation**
  - Epoch of gravitational collapse

- **Recombination**
  - Relic radiation decouples (CBI)
  - $t = 400,000$ years
  - $T = 3000 \text{ K} \ (1 \text{ eV})$

- **Matter domination**
  - Onset of gravitational instability
  - $t = 3 \text{ minutes}$

- **Nucleosynthesis**
  - Light elements created - $\text{He, Li}$
  - $t = 1 \text{ second}$
  - $T = 1 \text{ MeV}$

- **Quark-hadron transition**
  - Hadrons form - protons & neutrons
  - $t = 10^{-6} \text{ s}$
  - $T = 1 \text{ GeV}$

- **Electroweak phase transition**
  - Electromagnetic & weak nuclear forces become differentiated: $\text{SU}(3)\times\text{SU}(2)\times\text{U}(1) \rightarrow \text{SU}(3)\times\text{U}(1)$
  - $t = 10^{-11} \text{ s}$
  - $T = 10^{2} \text{ GeV}$

- **Grand unification transition**
  - $\text{SU}(5) \rightarrow \text{SU}(3)\times\text{SU}(2)\times\text{U}(1)$
  - Inflation, baryogenesis, monopoles, cosmic strings, etc?
  - $t = 10^{-25} \text{ s}$
  - $T = 10^{6} \text{ GeV}$

- **The Planck epoch**
  - The quantum gravity barrier
  - $t = 10^{-35} \text{ s}$
  - $T = 10^{19} \text{ GeV}$