ΛCDM Cosmology

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Outline

- What is ΛCDM?
- Evidence for ΛCDM
  - Baryon Acoustic Oscillations (BAO)
  - Cosmic Microwave Background (CMB)
- Some tension in cosmology
  - The Hubble constant - neutrino connection

ΛCDM: A good fit to the data:

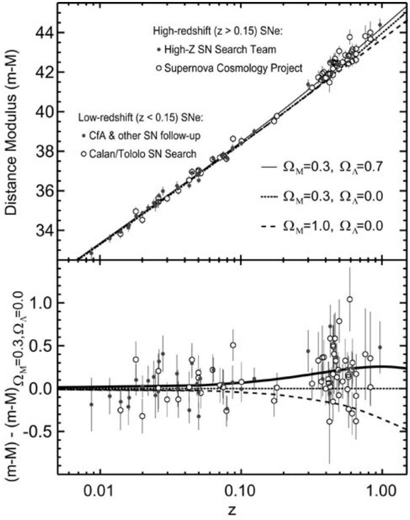
A mixture of

- baryons, and Cold-Dark-Matter (CDM)
- vacuum energy (Λ)
- photons and 3 light neutrinos
- $\sim$scale-invariant initial fluctuations

describes well our observations:

- Distances to objects *vs.* redshift (first evidence of Λ)

Supernovae are faint $\Rightarrow$ far $\Rightarrow$ acceleration $\Rightarrow$ Λ

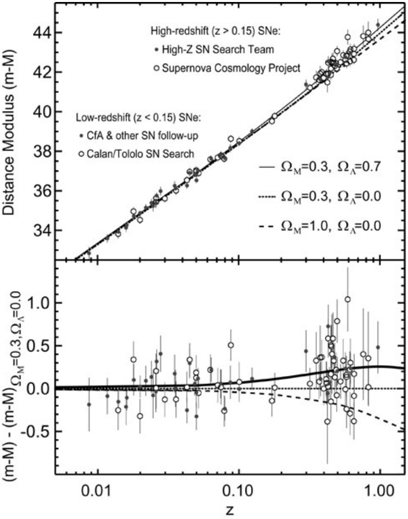


$\log 1/\mathit{Flux} \propto \log \mathit{distance}^2$

vs. redshift z

(SCP and HighZ: 1998)

Supernovae are faint ⇒ far ⇒ acceleration ⇒ Λ



$\log 1/Flux \propto \log distance^2$
vs. redshift z
(SCP and HighZ: 1998)

Distance-density connection:

- Hubble law: Distance
  = redshift / expansion rate
- Large distances
  ⇒Small expansion rate
  (in past)
  ⇒ acceleration
- acceleration ⇒ Λ (GR)

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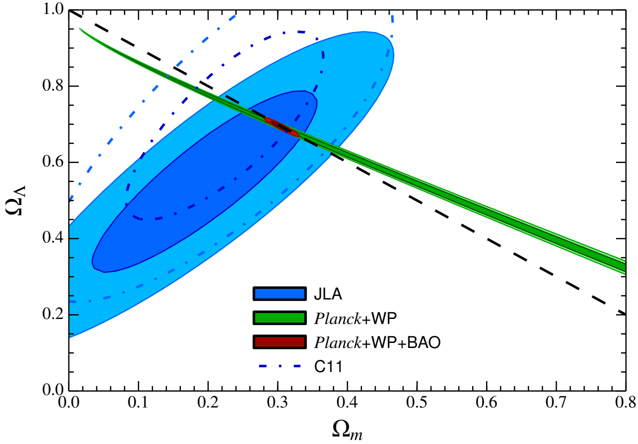
describes well our observations:

- Distances to objects *vs.* redshift
- Expansion rate *vs.* redshift (deceleration→acceleration)
- Statistics of Cosmic-Microwave Background (CMB) fluctuations
- Statistics of density fluctuations (galaxy counts) on large scales
- Gravitational lensing of backgrounds on foreground structure
- Gravitational formation of large objects (clusters of galaxies and maybe galaxies)

SNIa, CMB, BAO constraints on $(\Omega_M, \Omega_\Lambda)$

$(\Omega_M, \Omega_\Lambda) =$ (matter,vacuum) densities relative to critical density
$3H_0^2/8\pi G \sim 10^{-26}\mathrm{kg\ m}^{-3}$



Universe is spatially flat:
$\Omega_\Lambda + \Omega_M \sim 1 \pm 0.01$

Flat-ΛCDM parameters from CMB fluctuations

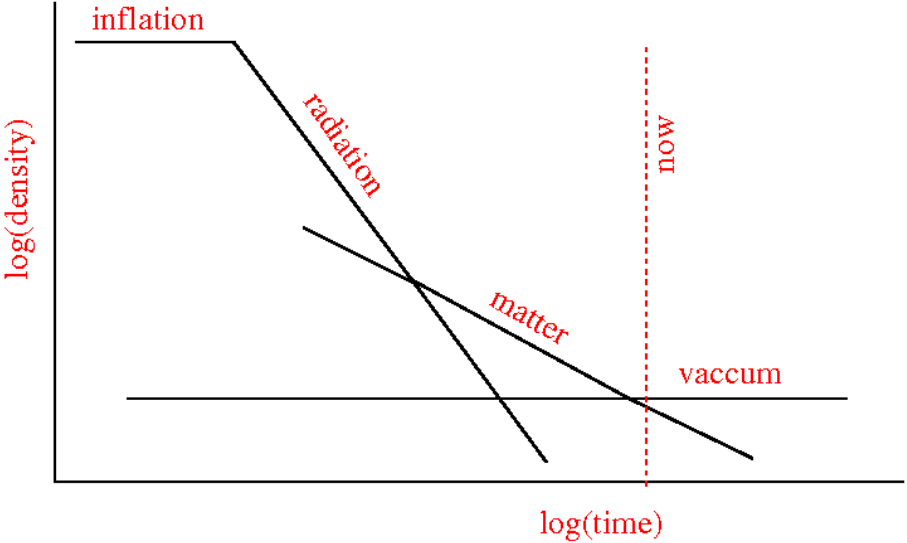
Planck 2015 (arXiv:1502.01589) (TT + LowP)
Densities relative to critical density

- $\Omega_c = 0.315 \pm 0.013$
- $\Omega_\Lambda = 1 - \Omega_M = 0.685 \pm 0.013$
- $\Omega_b = 0.04904 \pm 0.0005$

plus

- $H_0 = 67.31 \pm 0.96$
- $A_s = (21.95 \pm 0.79) \times 10^{-10}$
  Amplitude of primordial scalar perturbations
- $n_s = 0.9655 \pm 0.0062$
  spectral index for scalar perturbations
- $\tau = 0.078 \pm 0.019$
  optical depth to last-scattering surface (reionization)

The density of the universe *vs.* time in ΛCDM



A good fit, but many unanswered questions

- Does the value of the vacuum energy density have an explanation? ($\rho_\Lambda \sim 0.7 \times 10^{-26}\ \mathrm{kg\,m^{-3}}$)
- What is the CDM? (Wimps, axions, sterile neutrinos. primordial black holes)
- Why are there baryons but no anti-baryons? (CP violation)
- What generated inflation and scale-invariant fluctuations?
- What came before inflation?
- Is General Relativity the correct way to gravitate on large scales?

The relics of an earlier time (standard story)

Particle and nuclear physics generated the species

- CDM (freeze-out of some new stable species)
- Baryon-anti-baryon asymmetry (CP violation)
- Nuclei: ${}^1H$, ${}^2H$, ${}^3He$, ${}^4He$.......

Inflation generated the fluctuations

- gravitational waves (not yet detected)
- density perturbations ⇒ sound waves

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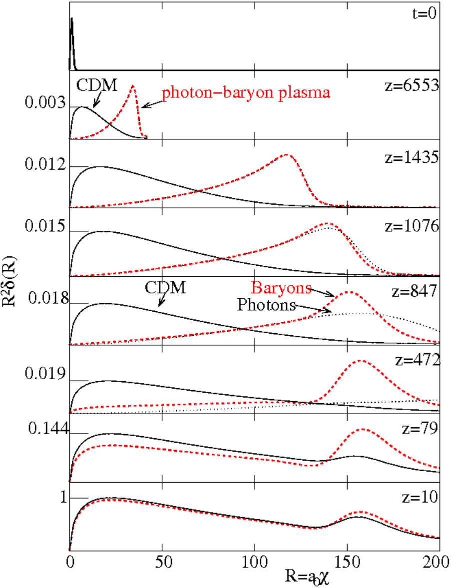
The study of the relic sound waves provides the most solid foundation of ΛCDM cosmology

- BAO: density correlations at $z < 3$.
  BAO= Baryon Acoustic Oscillations
- CMB: Anisotropy spectrum
  Frozen waves on last-scattering surface

Propagation of a baryon-photon sound wave



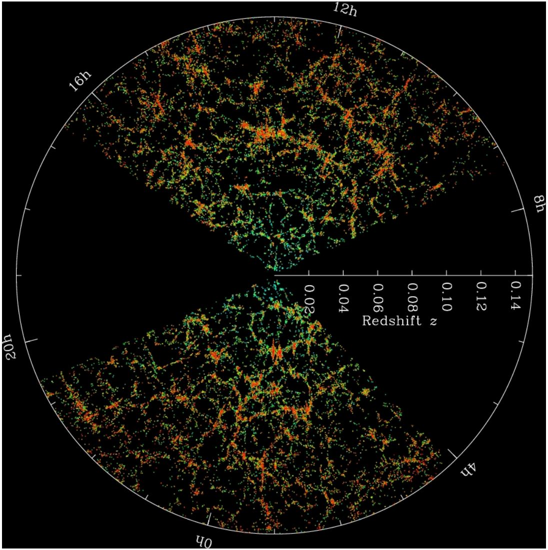
$t = 0$ (end of inflation)

$c_s \sim c/\sqrt(3)$
(γ,p,e plasma)

Wave stops at recombination
($r \sim 150\mathrm{kpc}$)

Today: Enhanced correlation at
$r_d = 147.5\mathrm{Mpc}$
"the sound horizon"

Enhanced correlation at $r_d = 147.5$ Mpc



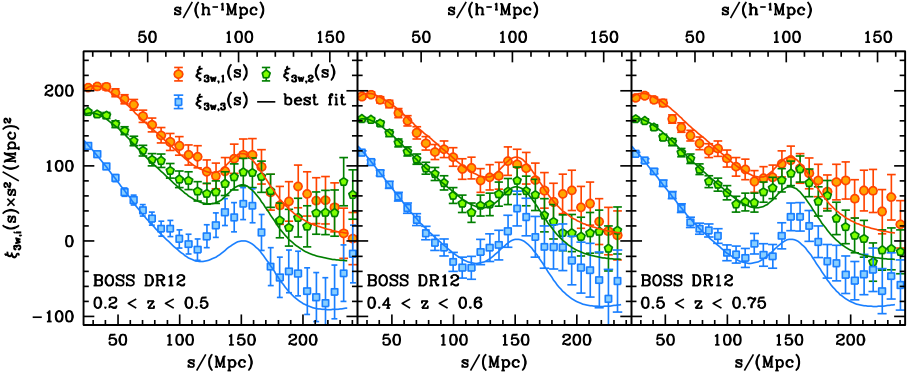
A slice of the nearby universe ($z < 0.14$) from the Sloan Digital Sky Survey (SDSS)

Much interesting structure on scales $<$ 100Mpc.
But no obvious sign of a preferred length
$\Rightarrow$ statistical analysis

Enhanced correlation at $r_d = 147.5$ Mpc

Galaxy-galaxy correlation function in three redshift ranges:

$0.2 < z < 0.5$ $0.4 < z < 0.6$ $0.5 < z < 0.75$



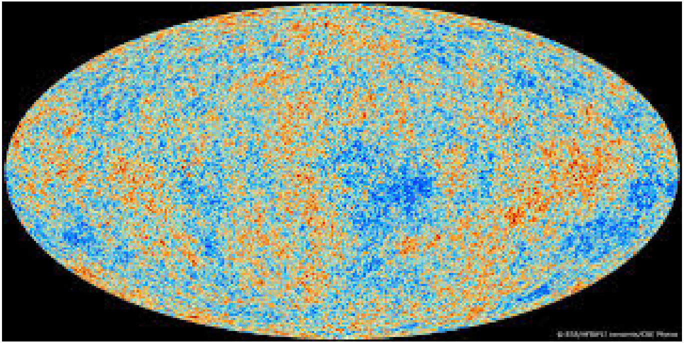
Transverse (angular) direction

Radial (redshift) direction

BAO peak=ruler written on the sky (almost too good to be true!)

Frozen waves on our redshift$= 1070$ surface

Planck all-sky temperature map:



$T_0(1 - 10^{-5})$

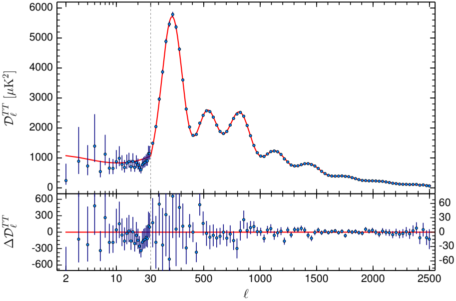
$T_0(1 + 10^{-5})$

$T_0 = 2.728\mathrm{K}$

Looks like a mess, but the wavelength spectrum is very suggestive.

$$T(\theta,\phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta,\phi) \qquad \ell \sim D(z = 1070)/\lambda$$

Harmonic spectrum of CMB, $C_\ell = \langle a_{\ell m} \rangle$



Peaks correspond to modes that were at an amplitude extrema at $z = 1070$; they have wavelengths that are harmonics of r_d.

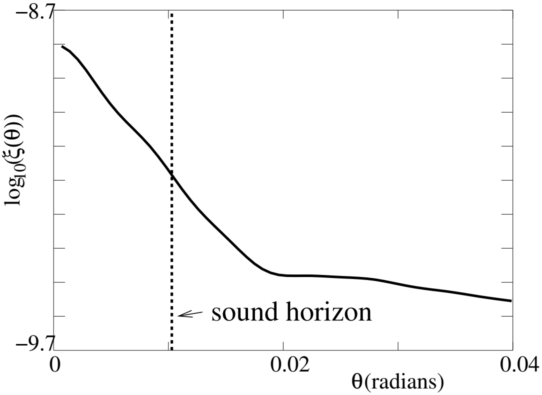
$$\lambda \sim r_d/n$$

corresponding to

$$\ell \sim D(z = 1070)/\lambda$$

- Peak heights tell us about composition of the universe at $z = 1070$.
- Angular scale tells us how far the $z = 1070$ surface is from us.

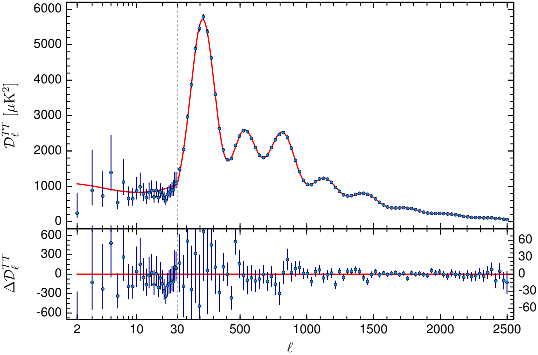
Temperature correlation function



$$\frac{\langle (T(\vec{\theta}_1) - T_0)(T(\vec{\theta}_2) - T_0)\rangle}{T_0^2}$$

Large correlations for $\theta < 2r_d/D(z_{rec})$
Small (primordial) correlations for $\theta > 2r_d/D(z_{rec})$

Anisotropy spectrum shape ⇒ $(\Omega_M h^2, \Omega_b h^2)$



Spectrum shape (relative peak heights) gives

- matter/radiation
- baryons/matter

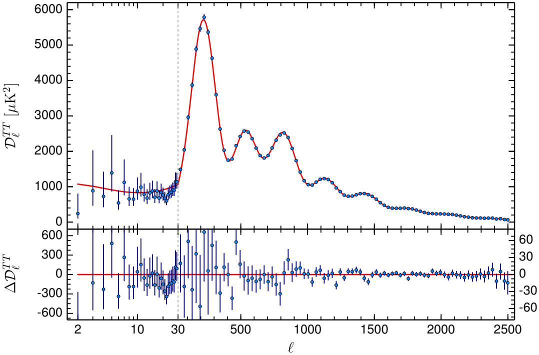
⇒ $\Omega_M H_0^2, \Omega_b H_0^2$

⇒ r_d can be calculated $= 147.33 \pm 0.49$Mpc

The (simplified) primary effects [Hu et al. 2001 ApJ 549, 669]:

- $(\ell < 30) \Rightarrow A_s$ (primordial fluctuations)
- $Peak1/(\ell < 30) \Rightarrow \Omega_M h^2/\Omega_R h^2$ (radiation driving)
- *even peaks/odd peaks* $\Rightarrow \Omega_b h^2/\Omega_M h^2$ (baryon loading)

Anisotropy spectrum ⇒flat-ΛCDM parameters



Spectrum shape (relative peak heights) gives ρ_M/ρ_γ, ρ_B/ρ_γ
$\Rightarrow \Omega_M H_0^2, \Omega_b H_0^2$

$\Rightarrow r_d$ can be calculated
$= 147.33 \pm 0.49$Mpc

Position of first peak: $\ell_1 \sim 200 \sim D(z=1060)/r_d$
Calculating r_d then determines $D(z=1070) \Rightarrow H_0$

Flat ΛCDM: CMB is enough

Planck 2015 (arXiv:1502.01589) (TT + LowP)

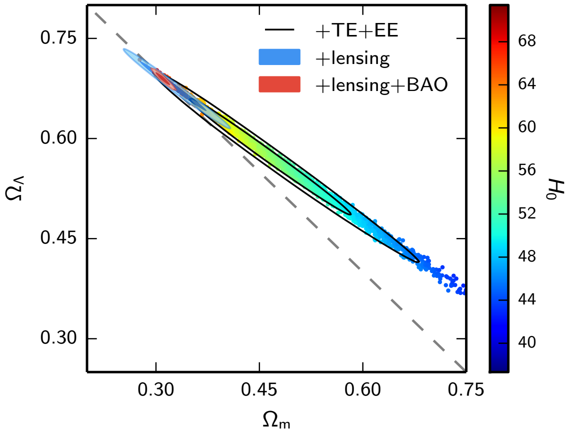
- $\Omega_M = 0.315 \pm 0.013$
- $\Omega_\Lambda = 1 - \Omega_M = 0.685 \pm 0.013$
- $\Omega_b h^2 = 0.02222 \pm 0.00023$

plus

- $H_0 = 67.31 \pm 0.96$
- $A_s = (21.95 \pm 0.79) \times 10^{-10}$
  Amplitude of primordial scalar perturbations
- $n_s = 0.9655 \pm 0.0062$
  spectral index for scalar perturbations
- $\tau = 0.078 \pm 0.019$
  optical depth to last-scattering surface (reionization)

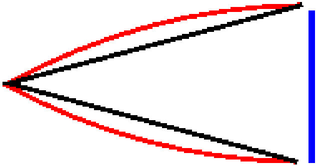
Non-flat ΛCDM: CMB not enough

Distance to $z = 1090$ now depends also on curvature:



Combinations of $(\Omega_M, \Omega_\Lambda)$ that give the same CMB spectrum

All have the same distance to $z = 1070$ but different distances at other redshifts



One BAO measurement at an intermediate redshift is sufficient to impose flatness: $\Omega_k \equiv (1 - \Omega_M - \Omega_\Lambda) = 0.0008 \pm 0.004$

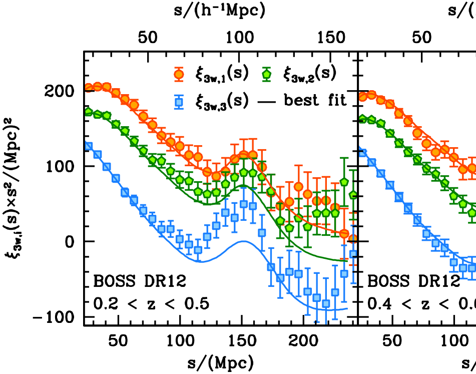
BAO Peak $\Rightarrow D_M(z)$ and $c/H(z)$

Galaxy positions are found in (z, θ, ϕ) space, For an ensemble of galaxies near redshift z, the BAO peak in the correlation function in the radial direction is at

$$\Delta z_{BAO} = \frac{r_d}{c/H(z)}$$

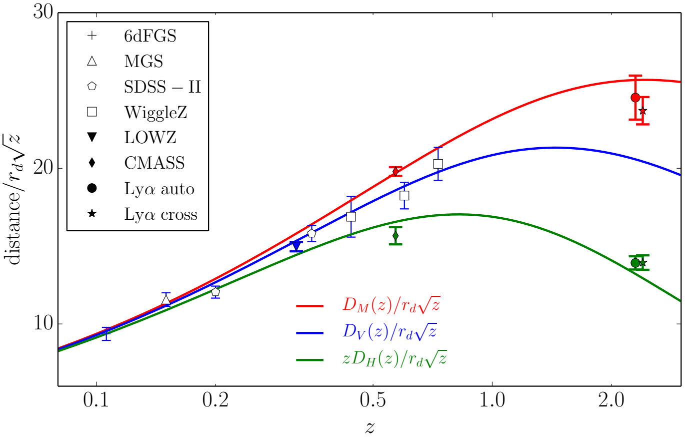
and in the transverse direction at

$$|\Delta\vec{\theta}_{BAO}| = \frac{r_d}{D_M(z)}$$



Using CMB-calibrated value of r_d and the measured values of Δz_{BAO} and $|\Delta\vec{\theta}_{BAO}|$ determines $D_M(z)$ and $c/H(z)$.

Two BAO Hubble diagrams $D_M(z)/r_d$ vs. z

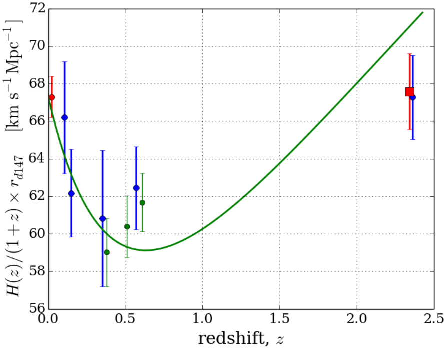


$D_M(z)$

$D_H(z) = c/H(z)$

The (only) problem with BAO: not enough nearby galaxies to measure the correlation function at $z < 0.1$

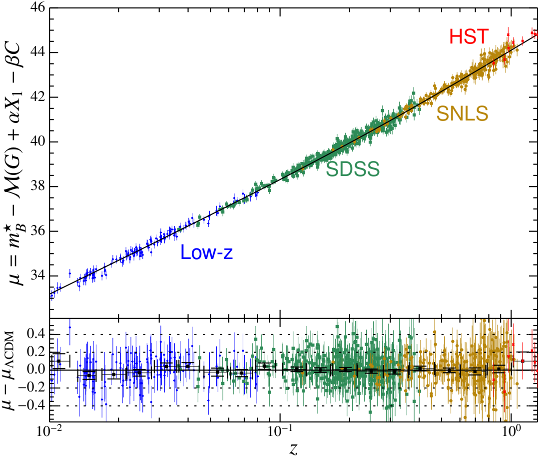
BAO $H(z) \Rightarrow$ deceleration→acceleration



ΛCDM prediction

Data not precise enough (yet)

The SNIa Hubble diagram: $z \to 0$



log $Flux_{SNIa}$ *vs.* redshift

For $z \ll 1$

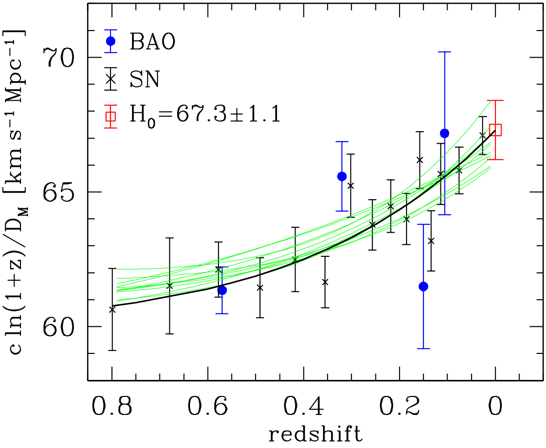
$$Flux_{Ia} = \frac{Luminosity_{Ia}}{4\pi(cz/H_0)^2}$$

Need to know $Luminosity_{Ia}$ to measure H_0

Two methods to calibrate $Luminosity_{Ia}$:

- Top-down: match SNIa distances to BAO distances.
- Bottom-up: distance ladder to nearby SNIa .

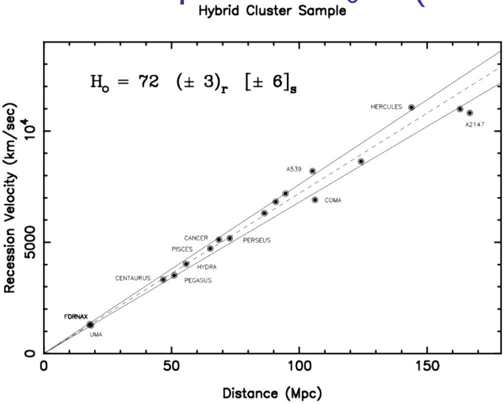
Top-down: the BAO and SNIa Hubble diagram



Calibrate SNIa luminosity by requiring $D_M(z=0.57)$ from SNIa agree with $D_M(z=0.57)$ from BAO

$\Rightarrow H_0 = 67.3 \pm 1.1$

Bottom up: $v = H_0 D$ (D from distance ladder)



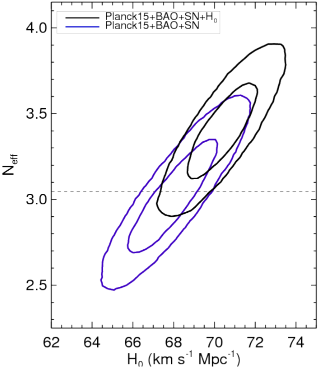
The most recent measurements with SNIa standard candles:
$H_0 = (73.0 \pm 1.8) \mathrm{km\,s^{-1} Mpc^{-1}}$
(Riess et al, arXiv:1604.01424)

- $Flux_{SNIa} = Luminosity_{SNIa}/4\pi D^2$;
- $Luminosity_{SNIa}$ calibrated in nearby galaxies with Cepheids
  Cepheids: a type of variable star:
- $Luminosity_{Cepheids}$ calibrated using nearby Cepheids of known distance in Milky Way, LMC, NGC4258 (geometric methods)

$H_0 \sim 73$ instead of ~ 68 ?

$\Rightarrow$ Sound horizon r_d shorter than we calculated.
$\Rightarrow$ Less time between inflation and Recombination
$\Rightarrow$ Faster expansion between inflation and Recombination
$\Rightarrow$ Higher energy density between inflation and Recombination

One solution: add another species of neutrinos:



Planck + H_0:
$N_\nu = 3.41 \pm 0.22$
$H_0 = 70.4 \pm 1.2$
suggesting (2σ!) a fourth neutrino species that is not completely thermalized.

ΛCDM: Conclusion

- The model fits the data with a few $\sim 2\sigma$ discrepancies.
- Its lack of a firm theoretical foundation will continue to encourage searches for alternatives:

  Modified gravity, backreaction, inhomogeneous models
- Future observations aim to see if the same ΛCDM model that explains large scales also completely explains the growth of structure.

  spectroscopic surveys: DESI, Euclid (space), SKA (21cm)
  photometric surveys: LSST