Dark Energy Missions +

Some Remaining Puzzles in Observational Cosmology

Review for Final Exam

Layout of the Course

Feb 3: Introduction / Overview / General Concepts
Feb 5: Age of Universe / Distance Ladder / Hubble Constant
Feb 10: Distance Ladder / Hubble Constant Distant Measures
Feb 12: SNe science / Baryonic Content / Dark Matter Content of Universe
Feb 17: Dark Matter + Cosmic Microwave Background
Feb 19: Cosmic Microwave Background + Large Scale Structure
Feb 26: Large Scale Structure / Baryon Acoustic Oscillations + Dark Energy
Mar 5: Dark Energy / Clusters / Cosmic Shear
Mar 12: Cosmic Shear / Dark Energy Missions
Mar 19: No Class
Mar 26: Other Unresolved Questions / Review for Final Exam

Apr 11: Final Exam

Today

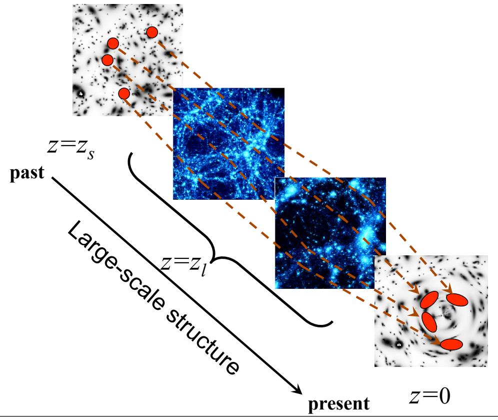
Final Exam

April 11, 2025
13:15-16:15

Review Material from Last Week

Probing the Nature of Dark Energy: Using Cosmic Shear

Gravitational lensing from collapsed masses has a systematic imprint on the shapes of galaxies, seen over large areas of sky, i.e., cosmic shear...



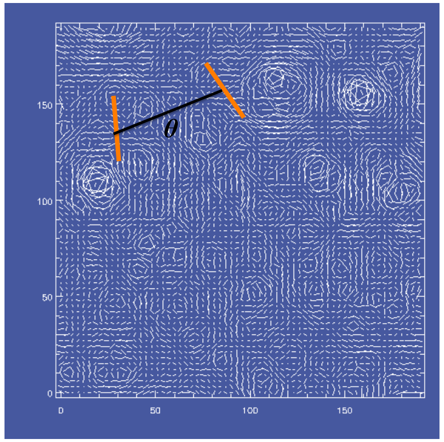
observables

$$\gamma = \frac{a-b}{a+b}$$

$$\gamma_1 = \gamma \cos 2\varphi$$

$$\gamma_2 = \gamma \sin 2\varphi$$

Determine correlation of shear measurement on different angular scales θ



- Correlated images of distant galaxies over all angular scales
- Use images of all distant galaxies
- Correlation function method to measure the cosmic shear signals
- The lowest one is 2pt function

Credit: Takada

Convert from to angular power spectrum using Fourier transform again:

Correlation Function Type Parameters

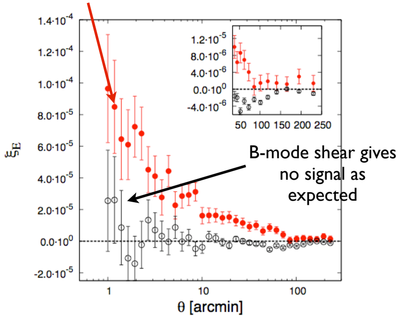
$\xi_{++}(\phi)$ $\langle\gamma_+\rangle(\theta)$

Power Spectrum Type Parameters

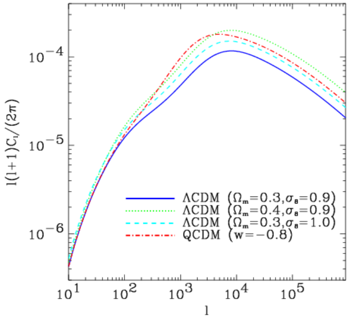
$P_\gamma(l)$ $P_\kappa(l)$ $C_{\gamma_i\gamma_j}(\ell)$

Fourier Transform

E-mode shear gives a signal



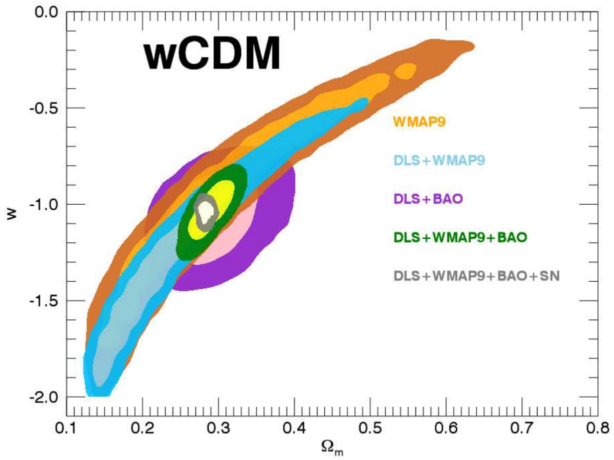
B-mode shear gives no signal as expected



Refregier et al.

What constraints can we set on w with weak lensing experiments?

DEEP LENS SURVEY



Jee+2015

So the game is to determine the w parameter and how it depends on redshift

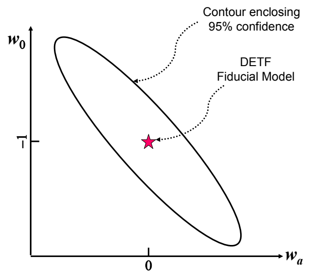
There are four standard methods:

1. Supernovae Ia
   - -- use of standard candles to establish distance-redshift relation
   - -- first established existence of dark energy 10 years ago
2. Baryonic Acoustic Oscillations
   - -- gives us a standard rod to establish distance-redshift relation and Hubble parameter-redshift relation with low systematics
3. Galaxy Clusters
   - -- provide us with sensitive probe of growth of structure
   - -- early evidence for low Ω_m
4. Weak Gravitational Lensing
   - -- provide us with sensitive probe of growth of structure
   - -- powerful technique still in process of realizing full potential

---

Power of the techniques in constraining dark energy are quantified in terms of the "Figure of Merit"

The <u>DETF figure of merit</u> is the reciprocal of the area of the error ellipse enclosing the 95% confidence limit in the w_0–w_a plane. Larger figure of merit indicates greater accuracy.



The DETF figure of merit is defined as the reciprocal of the area of the error ellipse in the w_0–w_a plane that encloses the 95% C.L. contour. (We show in the Technical Appendix that the area enclosed in the w_0–w_a plane is the same as the area enclosed in the w_p–w_a plane.)

By combining multiple techniques, one can make huge gains in terms of the "Figure of Merit," i.e., constraining both w and w_a.

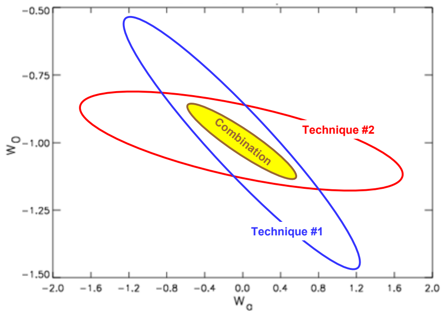
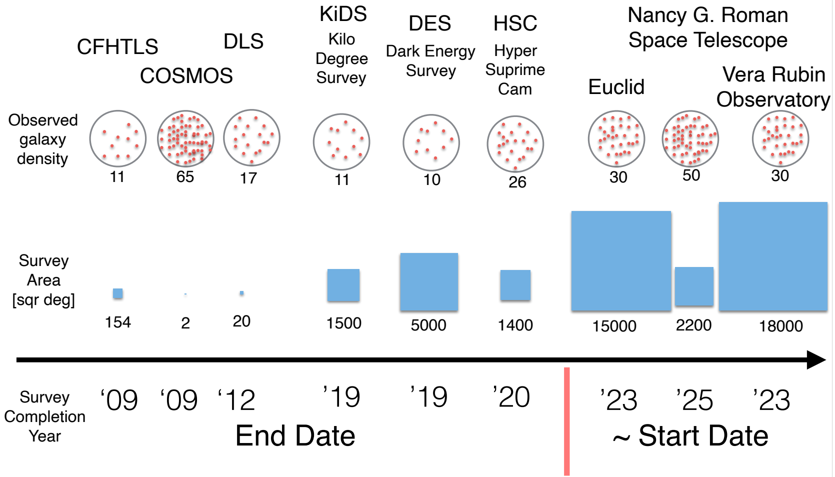


Illustration of the power of combining techniques. Technique #1 and Technique #2 have roughly equal DETF figure of merit. When results are combined, the DETF figure of merit is substantially improved.

Photometric Dark Energy Surveys



	Observed galaxy density	Survey Area [sqr deg]	Survey Completion Year
CFHTLS	11	154	'09
COSMOS	65	2	'09
DLS	17	20	'12
KiDS Kilo Degree Survey	11	1500	'19
DES Dark Energy Survey	10	5000	'19
HSC Hyper Suprime Cam	26	1400	'20
Euclid	30	15000	'23
Nancy G. Roman Space Telescope	50	2200	'25
Vera Rubin Observatory	30	18000	'23

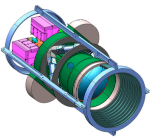
End Date

~ Start Date

Credit: Krause

KIDS / DES

- ground based imaging survey at CTIO 4m telescope of Southern region (SZE-survey overlap)
- camera: 520Mpix, 2.2deg^2 FoV
- start: next year
- 5,000deg^2 in 4bands: g r i z
- DE probes: GC, BAOs, WL, SNIa
- objects: galaxies, galaxy clusters (with photometric redshifts)
- redshift range: $0<z<1.3$
- DE constraints: σ_w~5-15%



Source: http://www.darkenergysurvey.org/

Dome and Facility Design

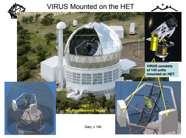
VERA C. RUBIN OBSERVATORY

Nancy Roman Telescope


Wide-Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets
WFIRST-AFTA
Final Report
by the
Science Definition Team (SDT) and WFIRST Project

The Hobby-Eberly Telescope
Dark Energy Experiment

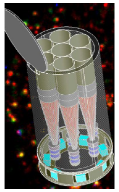
VIRUS Mounted on the HET



e-ROSITA X-ray Telescope

c)

- space-based X-ray cluster survey
- currently build at MPE in Garching
- start: 2012
- all sky coverage
- DE probes: GC, BAOs
- objects: 100,000 galaxy clusters
- redshift range: $0<z<1.5$
- DE constraints: σ_w~5%
- requires large ground-based follow-up program for identification and redshifts

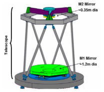


R. Fassbender: Introduction to Observational Cosmology I – WS09/10

Euclid Telescope

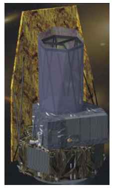
d) E on

- space-based optical/NIR imaging and spectroscopy survey
- 20,000deg^2 extragalactic survey
- start: >2016
- DE probes: WL, BAOs, GC
- σ_w~2%



similar mission plans in US for JDEM, (Joint Dark Energy Mission) likely with a stronger focus on SN Ia

Source: M. Schweitzer (MPE)

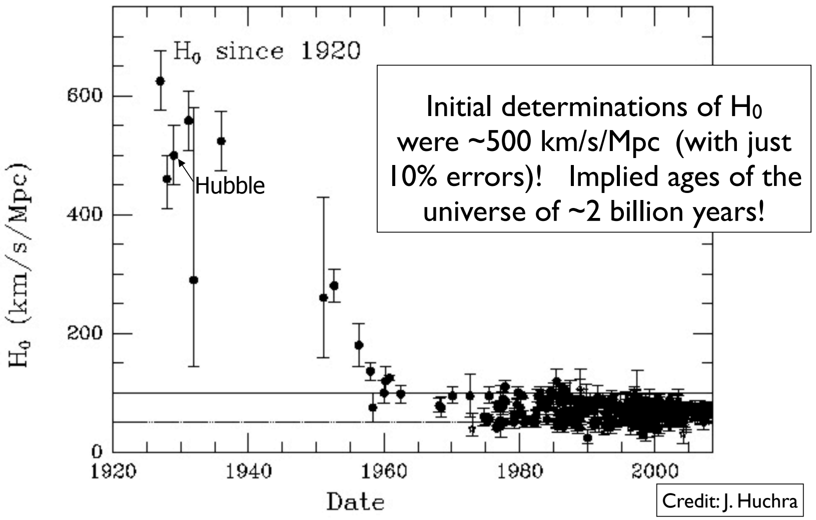


New Material for This Week

Unsolved Tensions between Different Probes Trying to Measure the Cosmological Parameters

Focus on
H_0 = Hubble Constant

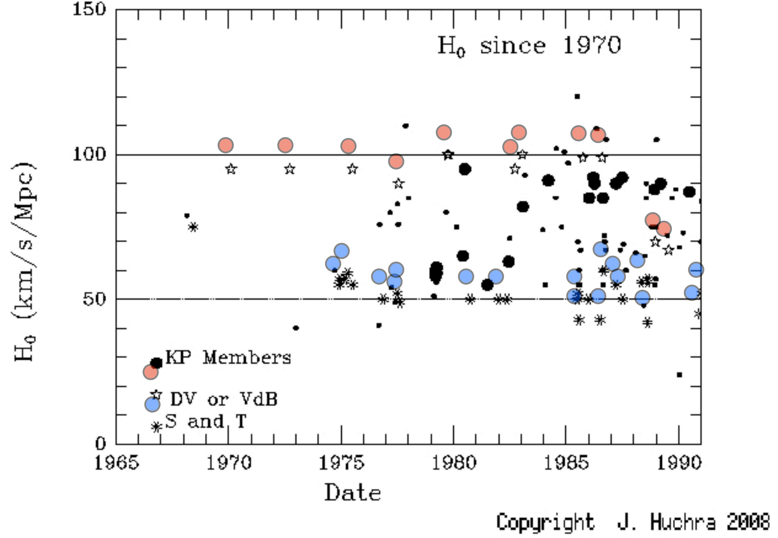
Hubble constant determinations vs. time (from Lecture 2)



Initial determinations of H_0 were ~500 km/s/Mpc (with just 10% errors)! Implied ages of the universe of ~2 billion years!

Credit: J. Huchra

Hubble constant determinations vs. time (from Lecture 2)

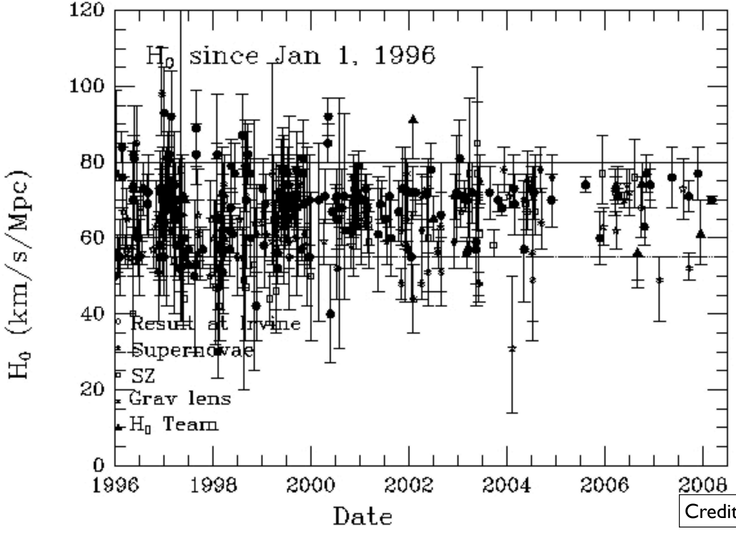


Copyright J. Huchra 2008

Hubble constant determinations vs. time

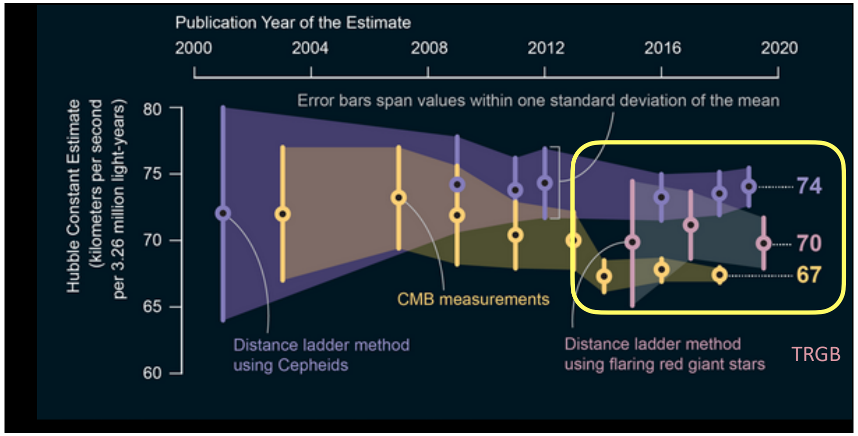
(after observations began with Hubble Space Telescope)

(from Lecture 2)



Credit: J. Huchra

Hubble constant determinations vs. time



An apparent discrepancy has arisen between the value of the Hubble constant derived from nearby studies using a Cepheid distance ladder

and that measured from the CMB (particularly Planck)

H_0 tension

Riess etal (2019):

H_0 = 74.03 ± 1.42 km/s/Mpc

(1.9% measurement)

Planck (2019):

H_0 = 67.44 ± 0.58 km/s/Mpc

(0.9% measurement)

Discrepant by 6.59 km/s/Mpc

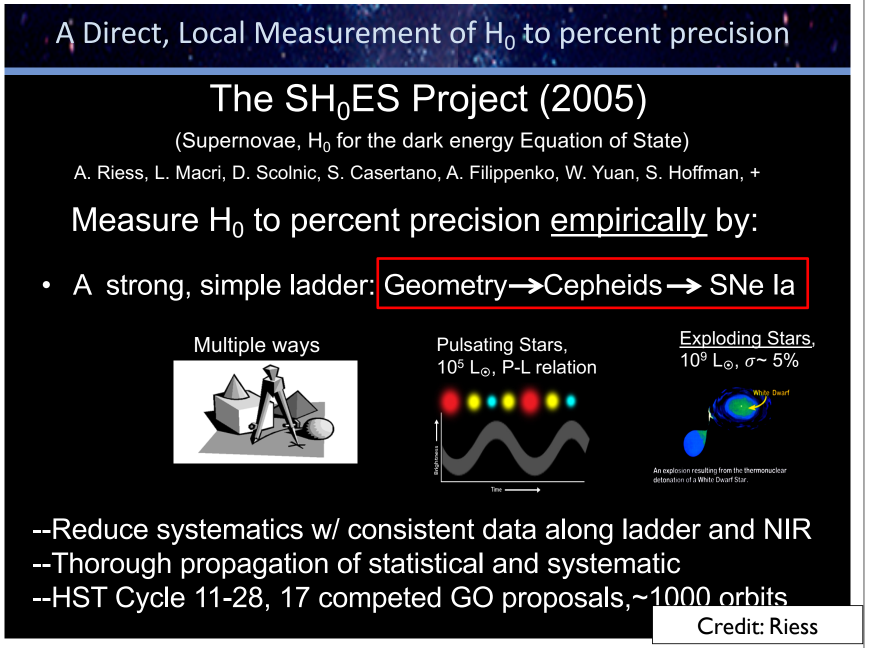
(≈ 10% discrepancy, or 4.3σ)

As Adam Riess emphasises *this is not a small discrepancy.*

Credit: Efsthathiou

Hubble Constant

from Distance Ladder made with Cepheids



A Direct, Local Measurement of H_0 to percent precision

The SH_0ES Project (2005)

(Supernovae, H_0 for the dark energy Equation of State)

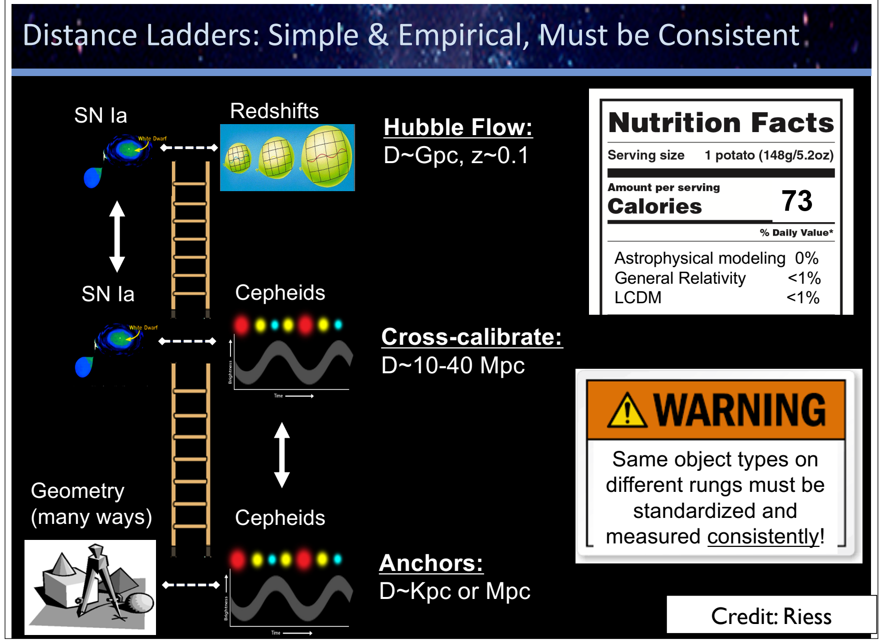
A. Riess, L. Macri, D. Scolnic, S. Casertano, A. Filippenko, W. Yuan, S. Hoffman, +

Measure H_0 to percent precision empirically by:

- A strong, simple ladder: Geometry → Cepheids → SNe Ia

--Reduce systematics w/ consistent data along ladder and NIR
--Thorough propagation of statistical and systematic
--HST Cycle 11-28, 17 competed GO proposals,~1000 orbits

Credit: Riess



Distance Ladders: Simple & Empirical, Must be Consistent

Hubble Flow:
D~Gpc, z~0.1

Cross-calibrate:
D~10-40 Mpc

Anchors:
D~Kpc or Mpc

Nutrition Facts

Serving size 1 potato (148g/5.2oz)

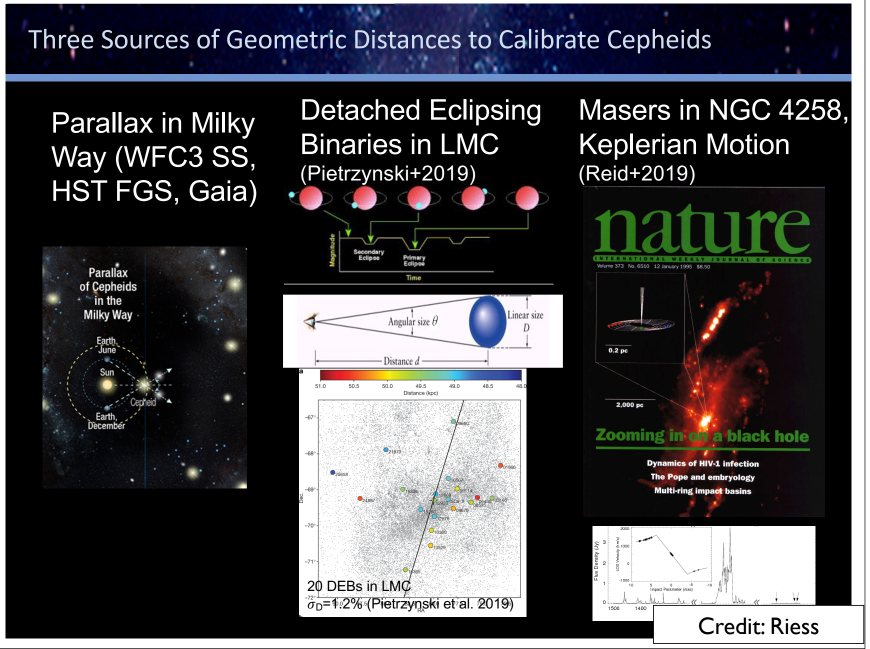
Amount per serving

Calories	73
	% Daily Value*
Astrophysical modeling	0%
General Relativity	<1%
LCDM	<1%

⚠ WARNING

Same object types on different rungs must be standardized and measured consistently!

Credit: Riess



Three Sources of Geometric Distances to Calibrate Cepheids

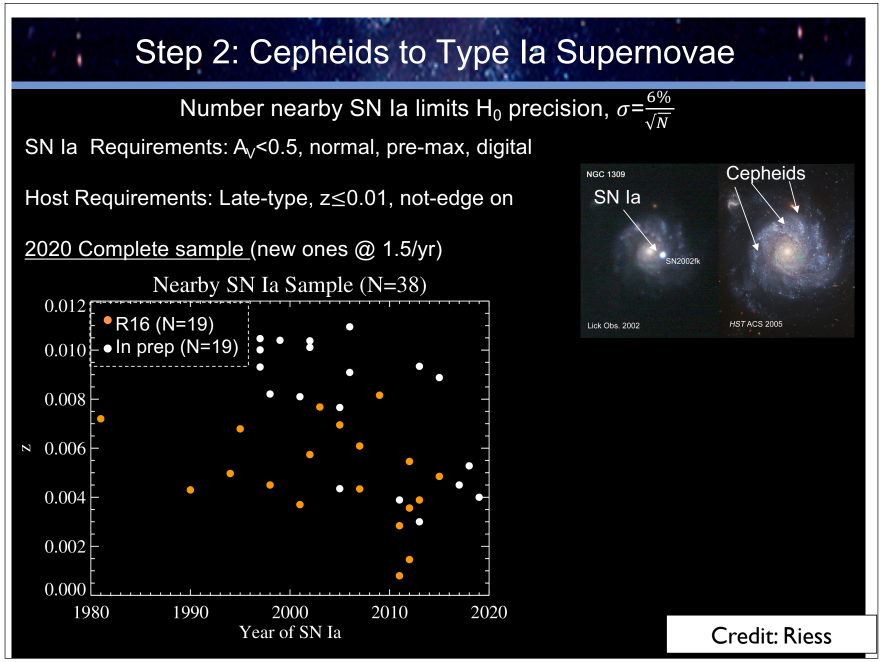
Parallax in Milky Way (WFC3 SS, HST FGS, Gaia)

Detached Eclipsing Binaries in LMC
(Pietrzynski+2019)

Masers in NGC 4258, Kepleriam Motion
(Reid+2019)

20 DEBs in LMC
σ_D=1.2% (Pietrzynski et al. 2019)

Credit: Riess



Step 2: Cepheids to Type Ia Supernovae

Number nearby SN Ia limits H_0 precision, $\sigma = \frac{6\%}{\sqrt{N}}$

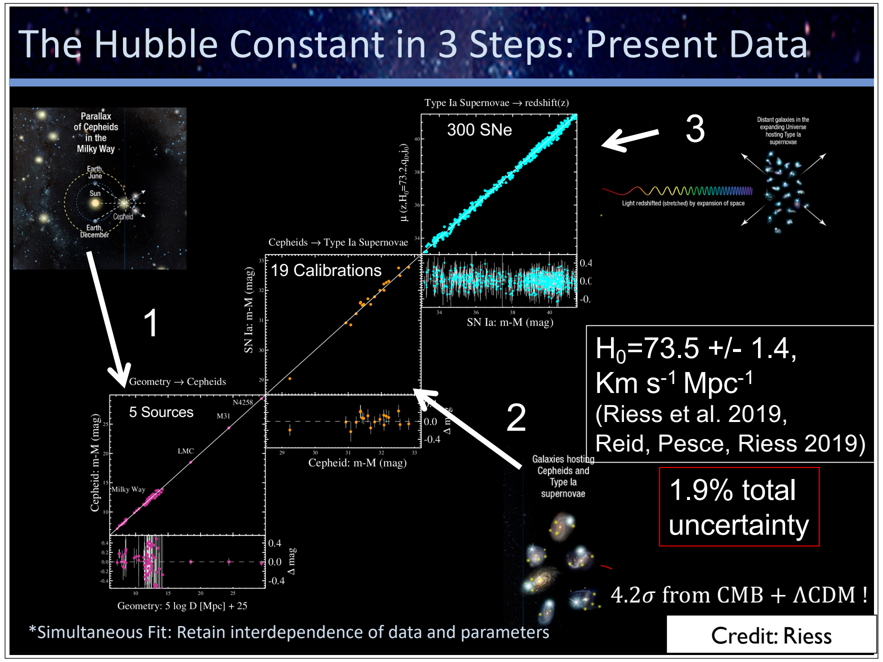
SN Ia Requirements: A_V<0.5, normal, pre-max, digital

Host Requirements: Late-type, z≤0.01, not-edge on

2020 Complete sample (new ones @ 1.5/yr)

Nearby SN Ia Sample (N=38)

Credit: Riess



The Hubble Constant in 3 Steps: Present Data

H_0=73.5 +/- 1.4, Km s^{-1} Mpc^{-1} (Riess et al. 2019, Reid, Pesce, Riess 2019)

1.9% total uncertainty

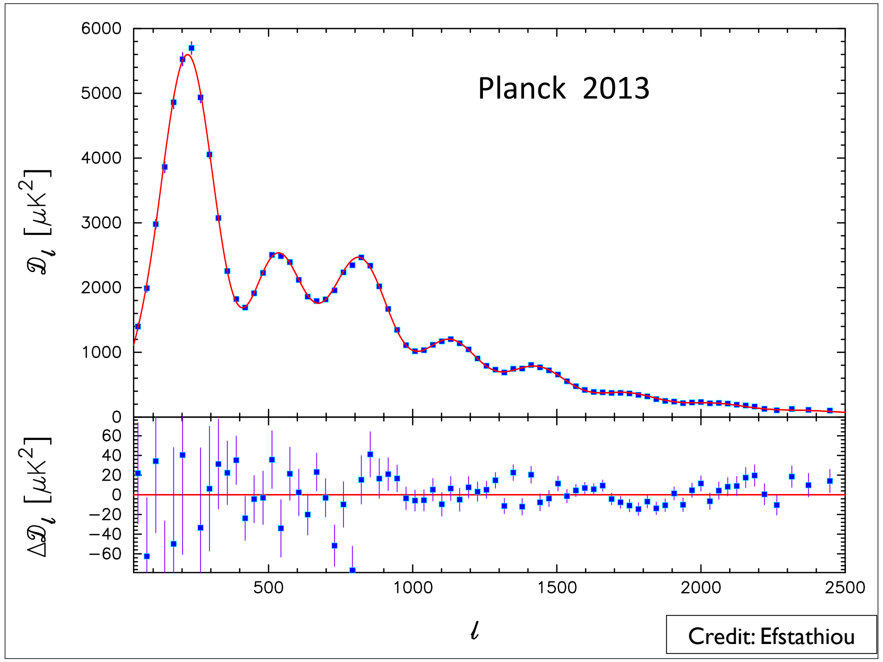
4.2σ from CMB + ΛCDM !

*Simultaneous Fit: Retain interdependence of data and parameters

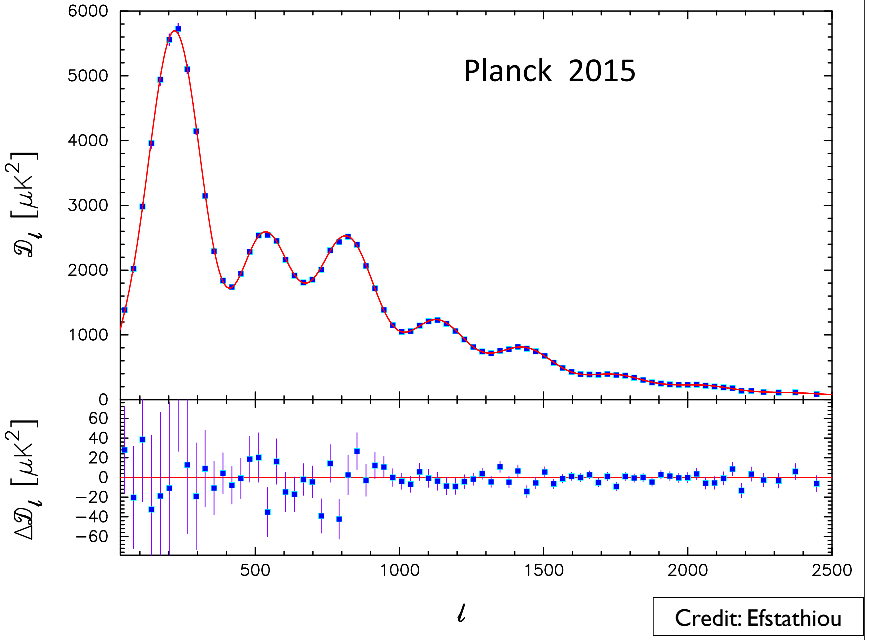
Credit: Riess

Hubble Constant

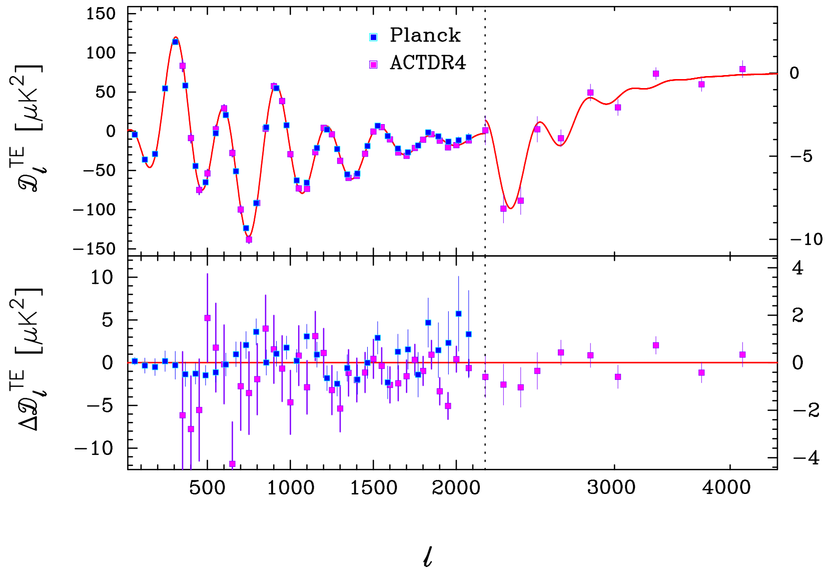
from CMB experiments (most recently Planck)



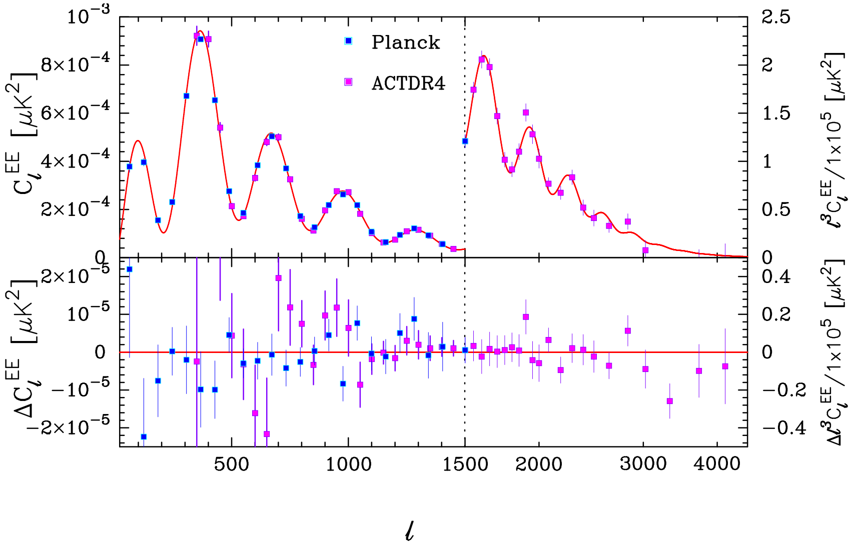
Credit: Efstathiou



Credit: Efstathiou

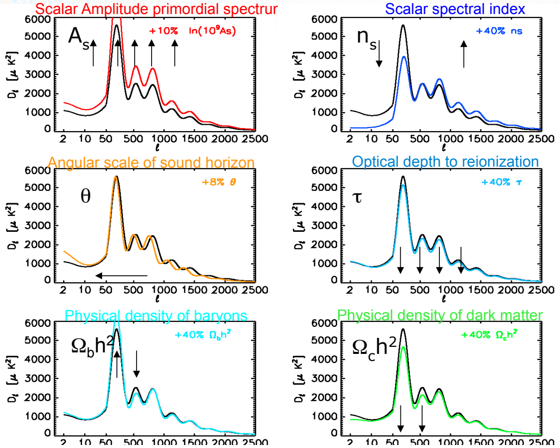


Credit: Efstathiou



Credit: Efstathiou

6 ΛCDM parameters



- Initial conditions A_s, n_s:

$$\mathcal{P}_\mathcal{R}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$$

- Acoustic scale of sound horizon θ
- Reionization τ

- Dark Matter density $\Omega_c h^2$
- Baryon density $\Omega_b h^2$

Assumptions:
- Adiabatic initial conditions
- Neff=3.046

- 1 massive neutrino 0.06eV.
- Tanh reionization (Δz=0.5)

Credit: Galli

Baseline ΛCDM results 2018

(Temperature+polarization+CMB lensing)

	Mean	σ	[%]
$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.7
$\Omega_c h^2$ DM density	0.1200	0.0012	1
100θ Acoustic scale	1.04092	0.00031	0.03
τ Reion. Optical depth	0.0544	0.0073	13
$\ln(A_s 10^{10})$ Power Spectrum amplitude	3.044	0.014	0.7
n_s Scalar spectral index	0.9649	0.0042	0.4
H_0 Hubble	67.36	0.54	0.8
Ω_m Matter density	0.3153	0.0073	2.3
σ_8 Matter perturbation amplitude	0.8111	0.0060	0.7

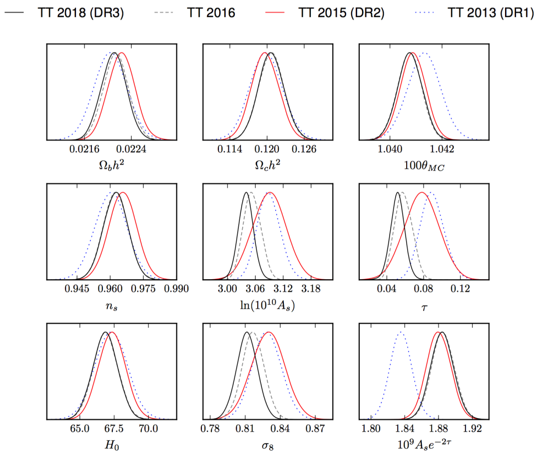
Robust against changes of likelihood, <0.5σ.

- Most of parameters determined at (sub-) percent level!
- Best determined parameter is the angular scale of sound horizon θ to 0.03%.
- τ lower and tighter due to HFI data at large scales.
- n_s is 8σ away from scale invariance (even in extended models, always >3σ)
- Best (indirect) **0.8%** determination of the Hubble constant to date.

Credit: Galli

Take away message stable across releases

Changes across releases compatible with statistical fluctuations and systematics corrections.



ΛCDM is a good fit to the data
No evidence of preference for classical extensions of ΛCDM

Just a few (2-3σ) outliers.

Credit: Galli

No "classical" extension of ΛCDM where H_0 is high from Planck data alone

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10}A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
$N_{\rm eff}$	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{\rm eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_\nu, N_{\rm eff}$	0.02221 ± 0.00022	$0.1179^{+0.0027}_{-0.0030}$	1.04116 ± 0.00044	$65.9^{+1.8}_{-1.6}$	0.9582 ± 0.0086	3.037 ± 0.017
$m^{\rm eff}_{\nu,\,\rm sterile}, N_{\rm eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	. . .	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_P	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
$Y_P, N_{\rm eff}$	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

More "sophisticated" extensions needed…

Planck collaboration 2018, 1807.06209

Credit: Galli

CMB measurements

Planck 2018	H_0=67.4±0.5
Reid+ 2019	H_0=73.5±1.4

- WMAP and SPT give somewhat larger but still consistent with Planck values of H_0
  - WMAP9* H_0=70 ± 2.2 [Km/s/Mpc] (Hinshaw et al. 2013)
  - SPT-SZ H_0=73.3 ± 3.5 (Aylor et al. 2017)
  - SPTPol (TE,EE) H_0 =71.2 ± 2.12 (Henning+17)
  - ACTPol (TT,TE,EE) H_0 =67.3 ± 3.6 (Louis+17)
- Are these consistent with the low H_0 Planck measurement? When adding BAO, yes!
  - Combining WMAP ACT and SPT with BAO to decrease errors low H_0
    - WMAP9+BAO (BOSSDR11+6dFGS+Lyman α)+high-z Sne
      H_0= 68.1 ± 0.7 (Aubourg+ 2015)
    - WMAP9+ACT+SPT + BAO (BOSS DR11+6dFGS)
      H_0 = 69.3 ± 0.7 (Bennet+ 2014)
  - Planck, WMAP and SPT are consistent with each other.

*NB: these were obtained using slightly different assumptions for

Credit: Galli

Indirect measurement of the Hubble constant from the CMB

Calculate the **physical dimension of sound horizon** assumes model for sound speed and expansion of the universe before recombination (after measuring ω_m and ω_b)

$$r_s = \int_{z_s}^{\infty} \frac{c_s(z)}{H(z)} dz$$

H(z) here is the expansion rate of the universe at **early** times

Measure the **angular scale of sound horizon** from the position of the peaks

$$D_A(z = 1100) = \int_0^z dz'/H(z')$$

Infer the distance to the last scattering surface, which depends on H_0 Friedmann equation, infer H_0.

H(z) here is the expansion rate of the universe at **late** times

Expansion rate after recombination

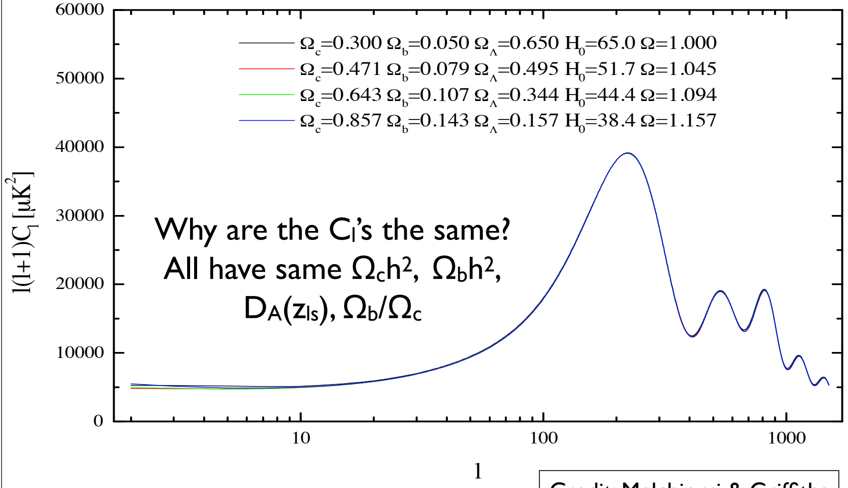
$$H^2(z)=\mathbf{H_0}^{\mathbf{2}}(\Omega_m (z+1)^3..)$$

Model dependent!

Credit: Galli

Degeneracies:

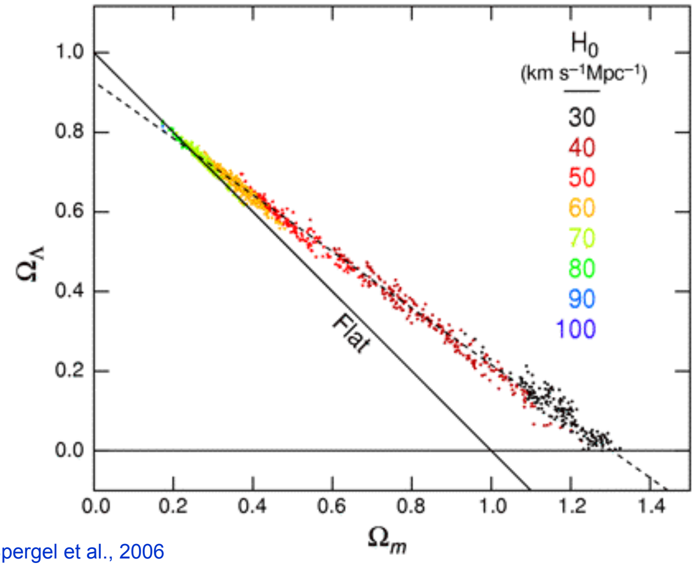
Multiple Sets of Cosmological Parameters give Same CMB Power Spectrum



Why are the C_l's the same?
All have same $\Omega_c h^2$, $\Omega_b h^2$, $D_A(z_{ls})$, Ω_b/Ω_c

Credit: Melchiorri & Griffiths

Degeneracies in Deriving H_0 from CMB

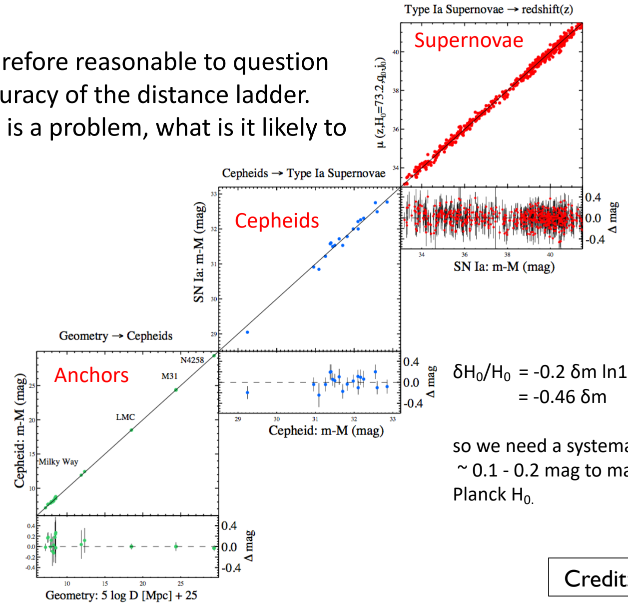


Spergel et al., 2006

Are there problems with H_0 from Cepheids + Distance Ladder?

Perhaps — see next slide

It is therefore reasonable to question the accuracy of the distance ladder.
If there is a problem, what is it likely to be?



$$\delta H_0/H_0 = -0.2\ \delta m \ln 10$$
$$= -0.46\ \delta m$$

so we need a systematic of ~ 0.1 - 0.2 mag to match the Planck H_0.

Credit: Efsthathiou

Does the SH$_0$ES team (who uses Cepheid) agree?

Not so much…

Robust? Seven Sources of Cepheid Geometric Calibration

Independent Geometric Source	**σ_D**	**H_0**
NGC 4258 $H_2$0 Masers: Reid, Pesce, Riess 2019	1.5%	72.0
LMC 20 Detached Eclipsing Binaries: Pietzrynski+ 2019 + 70 HST LMC Cepheids: Riess+(2019) AGREES WITH GAIA EDR3	1.3%	74.2
Milky Way 10 HST FGS Short P Parallaxes: Benedict+2007 --also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2
Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess+ 2018	3.3%	75.7
Milky Way 50 Gaia+HST, Long P Parallaxes: Riess+ 2018	3.3%	73.7
Milky Way Short P Cepheid Binary Gaia Companion Parallax: Breuval+20	3.8%	72.7
Milky Way Short P Cepheid Cluster Gaia Parallax: Breuval+20	3.2%	73.6

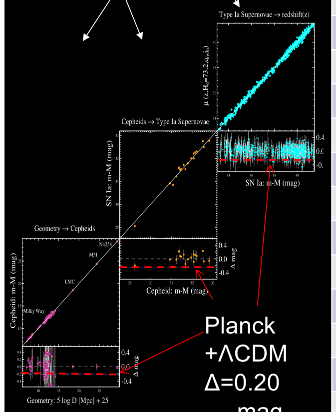
Consistent Results ($\leq 2\sigma$), *Independent Systematics*

Credit: Riess

Systematics? 23 Analysis Variants—we propagate variation to error

Best Fit:

$$5\log H_0 = M_B^0 + 5a_B + 25$$



Planck +ΛCDM Δ=0.20 mag

Analysis Variants	**H_0**
Best Fit (2019)	73.5
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.4
Reddening Law: Bulge-like (N15)	73.9
No Cepheid Outlier Rejection (normally 2%)	73.8
No Correction for Cepheid Extinction	75.2
No Truncation for Incomplete Period Range	74.6
Metallicity Gradient: None (normally fit)	74.0
Period-Luminosity: Single Slope	73.8
Period-Luminosity: Restrict to P>10 days	73.7
Period-Luminosity: Restrict to P<60 days	74.1
Supernovae z>0.01 (normally z>0.023)	73.7
Supernova Fitter: MLCS (normally SALT)	75.4
Supernova Hosts: Spiral (usually all types)	73.6
Supernova Hosts: Locally Star Forming	73.8
Optical Cepheid Data only (no NI	[illegible]

Credit: Riess

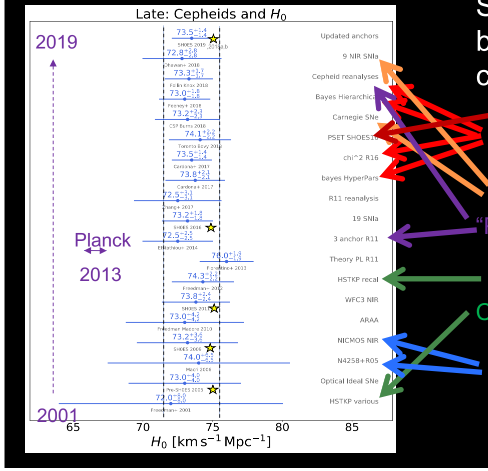
FAQ Frequently Asked Questions: technical, see backup slide

- Could we live in a giant void (9% in H_0)?
  No, LSS Theory and SN Ia mag-z limit $\sigma\sim0.6\%$ in H_0
  Odderskov et al. (2016) , Wu & Huterer (2017), Kenworthy, Scolnic, Riess 2019
- Is HST WFC3-IR flux scale linear to 1%?
  Yes, calibrated to $\sigma=0.3\%$ in H_0 across 15 mag
  Riess, Narayan, Calamida 2019
- Does Cepheid crowding compromise accuracy?
  No, amplitude data confirms locality of crowding
  Riess, Yuan, Casertano, Macri, Scolnic 2020
- Is there a difference in SN Ia at ends of distance ladder?
  No, correlations of Hubble residuals < $\sigma=0.3\%$ in H_0
  Jones et al 2018

Credit: Riess

Cepheids+SN Ia Ladder, Most Widely Replicated: 2001-2019

Why Cepheids? Advantages: 1) longest-range 2) most calibrations 3) consistent photometry along ladder 4) most tested…



SH$_0$ES results (★) *cumulative* but compared to present… consistent

grad student problem set! (Toronto)

Different analyses

Different SNe, wavelength

“Planck People”

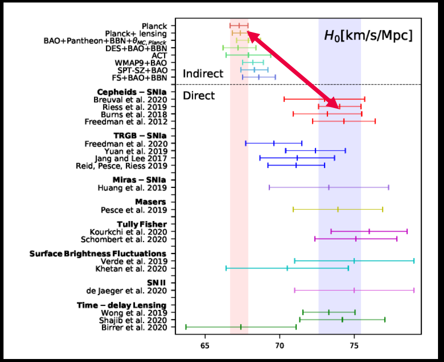
Different Team (KP), photometry, Cepheids, wavelengths

Different HST Instruments

Credit: Riess

The Hubble Constant ~~Tension~~, ~~Discrepancy~~, Problem, ~~Crisis~~

Status late 2020



Compilation from Di Valentino(2020)

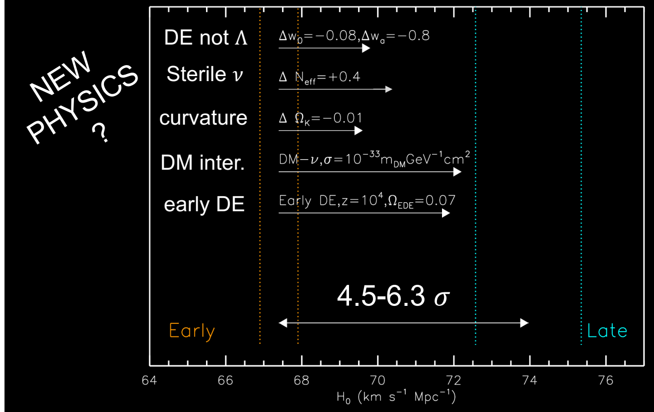
KITP 2019 (Verde, Treu, Riess 2019)

“does not appear to depend on the use of any one method, team or source”

No Cepheids: 4.5-5.3σ
No TRGB: 5.7-6.3σ
No lens: 5.0σ
No SN Ia: 4.9σ
No Cepheids or TRGB: 5.3σ
No Planck: 4.4-4.9σ
No CMB: 4.0-4.5σ
(Riess 2019, Nature Reviews)

Credit: Riess

Cause Early vs Late Difference? Newton: “Feign No Hypothesis”



“The Hubble Hunter’s Guide”, Knox and Millea, 2019: “Most Likely”: Increase Expansion Rate Pre-recombination->reduce sound horizon by 5-8%
Mechanisms: Early DE or sterile (self-interacting) neutrinos
Claims: better fit to CMB, new CMB features, cosmic birefringence as evidence of CMB coupling to EDE/ALPs or pNG Boson (Capp

Credit: Riess

The CMB people agree their method is indirect

Indirect measurement of the Hubble constant from the CMB

Calculate the **physical dimension of sound horizon** assumes model for sound speed and expansion of the universe before recombination (after measuring ω_m and ω_b)

$$r_s = \int_{z_s}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Measure the **angular scale of sound horizon** from the position of the peaks

H(z) here is the expansion rate of the universe at **early** times

$$D_A(z = 1100) = \int_0^z dz'/H(z')$$

H(z) here is the expansion rate of the universe at **late** times

Infer the distance to the last scattering surface, which depends on H_0 Friedmann equation, infer H_0.

Expansion rate after recombination

$$H^2(z)=\mathbf{H_0}^2(\Omega_m (z+1)^3..)$$

Model dependent!

Credit: Galli

Is this the only hotly debated disagreement in observational cosmology?

No!

Also a matter of σ_8

SLIDE FROM PREVIOUS LECTURE on σ_8

While deriving correlation function and Power spectrum from galaxy survey, one thing we are particularly interested in is the normalization of the power spectrum

$$P_0(k) = A\, k^{n_s}$$

(related to the A parameter here)

(n_s = 1)

This is defined using this parameter σ_8 (intended to represent the root-mean-squared fluctuations in a 8 h^{-1}Mpc volume):

$$\sigma_{8,g}^2 := \left\langle \left(\frac{\Delta n}{\bar{n}} \right)^2 \right\rangle_8 \approx 1$$

(8 h^{-1} Mpc was chosen because appeared close to 1)

Size of density fluctuations in a volume really defines the amplitude of power spectrum

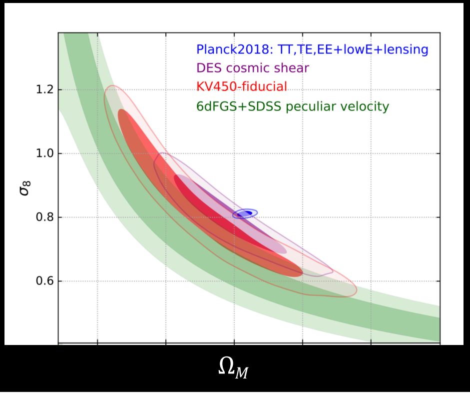
---

Tension in σ_8

Another Early vs Late Tension? Matter clumpiness, σ_8

RMS matter fluctuation, σ_8 , (r=8 h^{-1} Mpc), 0.8 Early vs late divide

~3 σ from lensing and peculiar velocities, independently



6dFGS+SDSS

Said, K et al 2020, MNRAS,497, 1275

"…deviates by more than 3σ from the latest Planck CMB measurement. Our results favour … a Hubble constant H_0 > 70 km s^{-1} Mpc^{-1} or a fluctuation amplitude σ_8 < 0.8 or some combination of these. "

Can We Believe Measurements without Explanation?

Don't sweep "problems" under the rug

"Problems" are often clues!

- ~~Precession of Mercury~~ Solved!
- ~~Solar Neutrino Problem~~ Solved!
- ~~Missing Baryon Problem~~ Solved!
- Lithium Problem
- CMB Cold Spot
- Flat rotation curves/ what/where is dark matter?
- Accelerating Universe/ why Λ so small?

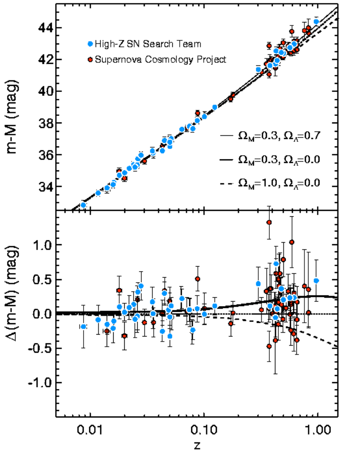
Credit: Riess

Beyond significant tensions between different cosmological probes

This is a very active field of scientific inquiry, with progress being made every year!

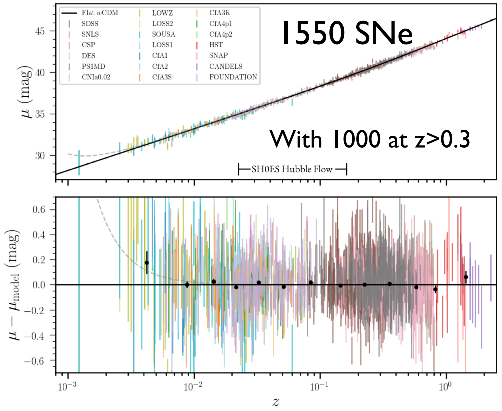
Progress in SNe surveys

Riess+1998



~50 SNe

Pantheon+ Brout+2022

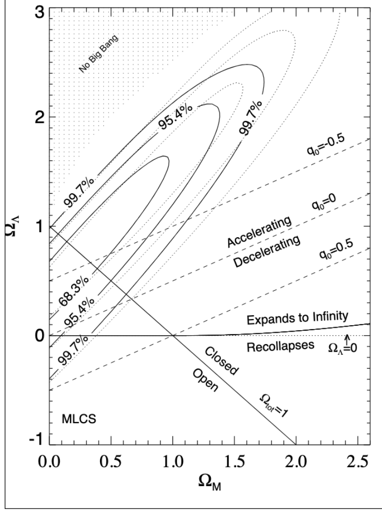


1550 SNe

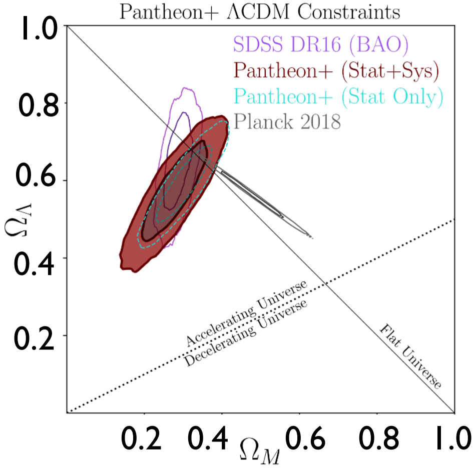
With 1000 at z>0.3

Progress in SNe surveys

Riess+1998



Pantheon+ Brout+2022



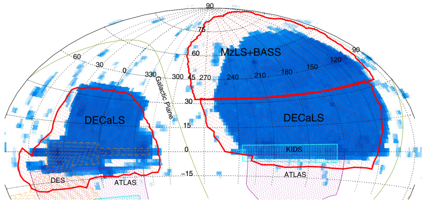
From 2 weeks ago:

DESI Survey

Dark Energy Spectroscopic Instrument (DESI) situated at
NSF Mayall 4-m telescope at Kitt Peak National Observatory

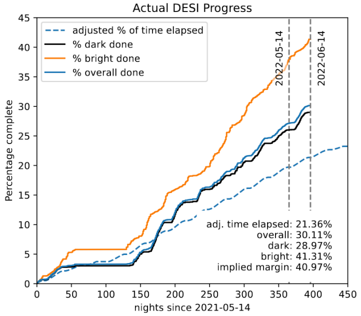
5000 redshifts per mask

Map galaxies and QSO redshifts and positions over 16000 deg^2 area



Dey+2018

Redshifts acquired slowly



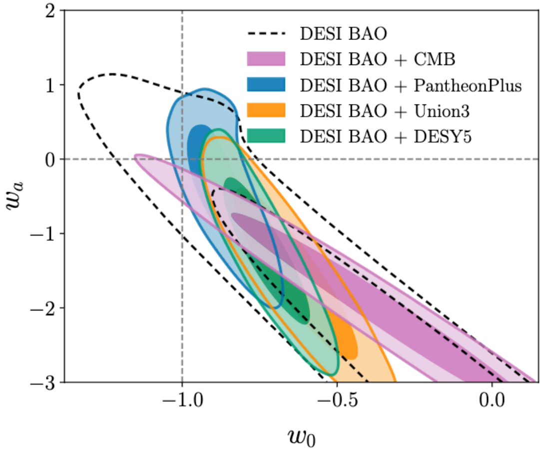
Schafsky + 2022

From 2 weeks ago:

DESI Survey

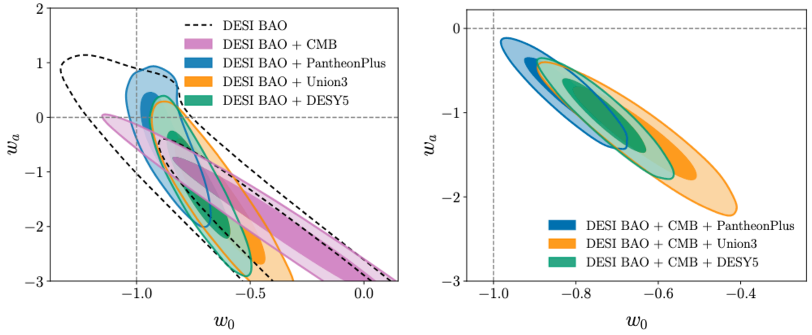
First Year Results

~2-3 sigma tension with cosmological constant model ($w_0 = -1$, $w_a = 0$)



New Paper in Last 2 Weeks

2 year results from DESI



~2.5-4 sigma tension with cosmological constant model ($w_0 = -1$, $w_a = 0$)

Final Exam

April 11, 2025
13:15-16:15

Study Guide for Exam

1. In general, please have a basic understanding of everything discussed in lecture. If you do not understand it, please read the supplementary readings, the textbook, or ask Thomas, your classmates, or me. [Questions are helpful for improving the course – since I can use your feedback to improve the clarity of the lectures.]

2. Familiarize yourself with all the homework problems and solutions to these problems given on the course web site; expect to find 1-2 problems on the exam that are very similar to homework problems.

3. Please be familiar with the three different methods of estimating the age of the universe observationally and how this compares with estimates based on the Hubble constant. Be capable of explaining the basic idea behind each.

4. Have a basic idea of how the extragalactic distance ladder is set up and the basic challenges in measuring the Hubble constant. Be able to provide a brief explanation for the techniques used to set up the distance ladder. You should also have a basic understanding of the two methods to determine H_0 which are entirely independent of the distance ladder.

Study Guide for Exam

5. Be capable of discussing in detail how we can determine the baryon and dark matter density of the universe. Have a basic understanding of the many different approaches we have to determine these quantities. You will be tested on your understanding of the basic concepts and your ability to clearly explain them.

6. Be familiar with what we can learn about the cosmological parameters from the cosmic microwave background TT, TE, EE, and BB power spectra and how these power spectra are measured. Be capable of explaining why the cosmic microwave background radiation shows a coherent polarization and what additional information the polarization signal gives us about the universe.

7. While you are not expected to precisely remember all the equations seen in class, you should be aware of the approximate scaling of important quantities against other important variables.

8. Have a solid understanding of what the matter power spectrum is and why it has the basic shape that it does and how we can constrain it on various scales. Understand how astronomers measure the clustering of galaxies in real observations, the challenges in doing so, the different types of clustering measures, and how astronomers can use clustering to constrain the matter power spectrum. How is the spatial scale of the peak of the matter power spectrum related to the cosmological parameters and why?

Study Guide for Exam

9. Have an understanding of the basic manner in which density perturbations grow with cosmic time, how this depends on the spatial scale, and how this depends upon whether the universe is radiation or matter-dominated. Also have an understanding of how baryon acoustic oscillations are introduced onto the matter power spectrum and what we can learn about the universe by thoroughly quantifying the properties of these oscillations.

10. How do astronomers describe the normalization of the power spectrum? What experiments did we discuss in class to constrain the normalization and how does each work?

11. Have a basic idea of the various approaches astronomers use to find galaxy clusters and how astronomers use galaxy clusters to constrain the cosmological model.

12. Be familiar with the four main techniques for constraining the dark energy properties of the universe (supernovae Ia, galaxy cluster searches, baryon acoustic oscillations, cosmic shear). Be capable of explaining how each works and know the basic steps that are essential to the use of each technique. What are the strengths and weaknesses of each technique?

Study Guide for Exam

13. Be familiar with the ways that quantities like the luminosity distance, angular size distance, the Hubble parameter depend on the cosmological parameters (in particular Ω_m and Ω_Λ).

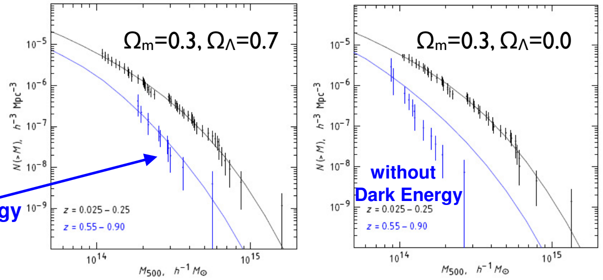
14. Have a basic understanding of which parameters the many different experiments discussed in class allow us to constrain, what (if any) degeneracies exist, and how astronomers can put together the observational constraints from many different experiments to establish the values of Ω, Ω_m, Ω_Λ, Ω_b, H_0, …

15. Be familiar with the dark energy experiments discussed in class and be able to describe each (very briefly) and answer very simple questions about each.

16. While most of the exam should be relatively easy if you have a good understanding of all the concepts and material discussed in lecture, some questions will include a few parts where I will expect a greater mastery of the course material, supplementary readings, and textbook. This material will be what I use to determine who merits very high marks in the course (>=8.5 or 9), so you should not stress if you are not able to answer all the questions on the exam perfectly.

One example exam problem:

Counting the number of galaxy clusters on the sky versus apparent mass can provide a powerful constraint on the cosmological parameters... as illustrated from the comparison below:



5 σ detection
of Dark Energy
from Clusters
alone

observed
mass function
with Dark Energy

without
Dark Energy

Vikhlinin et al. 2009 (Chandra Cluster Cosmology Project)

The angular diameter distance $D_A(z)$, comoving volume, and growth factor all depend on redshift in a characteristic way depending on the cosmology. Explain how each factor would affect the comparison shown here.