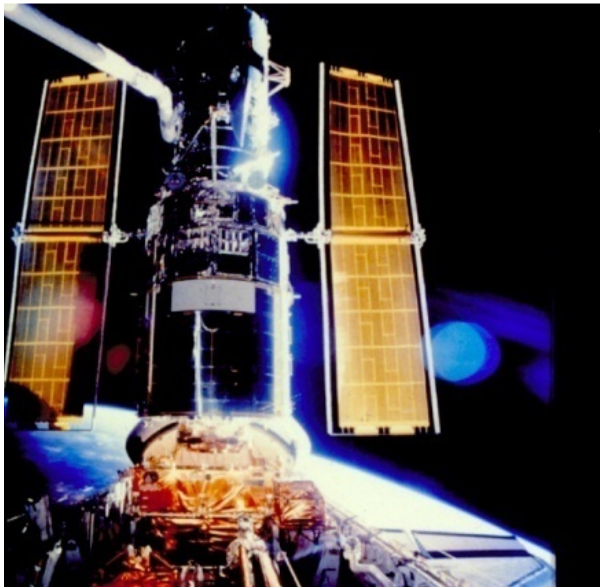
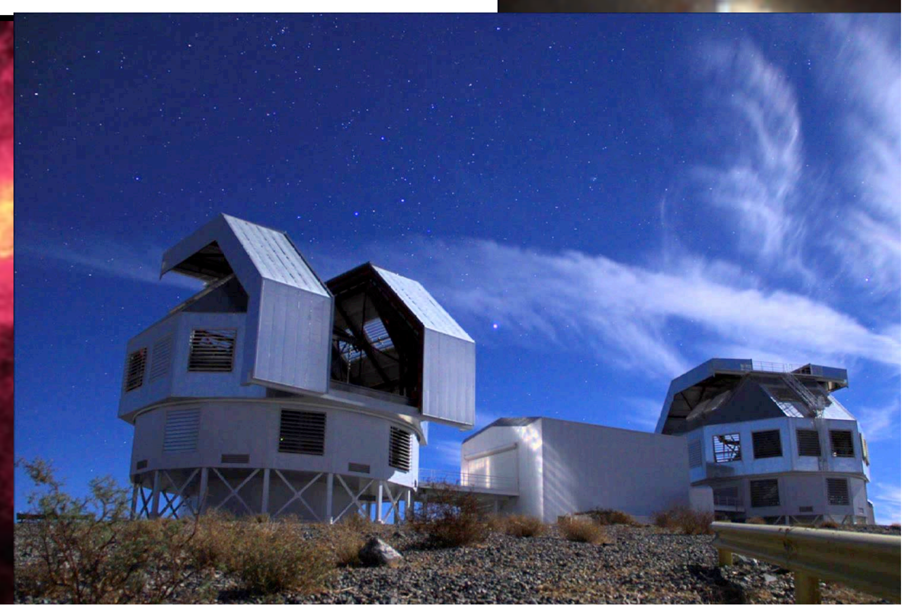
Measuring Cosmological Parameters



Wendy Freedman
University of Chicago

November 4, 2015
Fermilab



Measuring Cosmological Parameters

1) The Current Cosmological Model
   - Motivation for higher accuracy
2) Dark Energy
   - History / Status
   - The Carnegie Supernova Project
3) The Hubble Constant
   - History / Status
   - The Carnegie/Chicago Hubble Project
4) The Future

1)
Current State of Cosmology

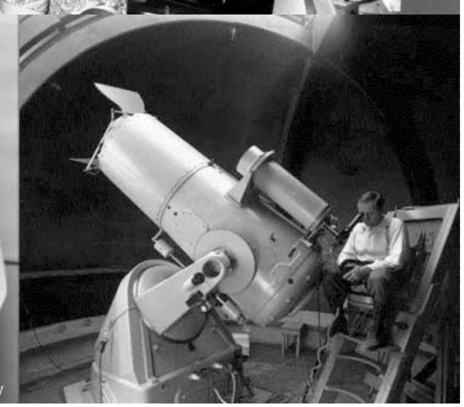
Observational Cosmology

3 Major Discoveries of 20th Century (Optical Astronomy):

1. Expansion of the Universe
2. Distribution of Dark Matter
3. Acceleration of the Universe







Dynamics of the Universe

Dynamics of the Universe

1

$$\mathbf{H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} \pm \frac{k}{a^2} + \frac{\Lambda}{3}}$$

2

$$\mathbf{\left(\frac{\ddot{a}}{a}\right)^2 = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}}$$

$+$ve acceleration if $\frac{P}{\rho} < -\frac{1}{3}$

Some Nomenclature: Cosmological parameters

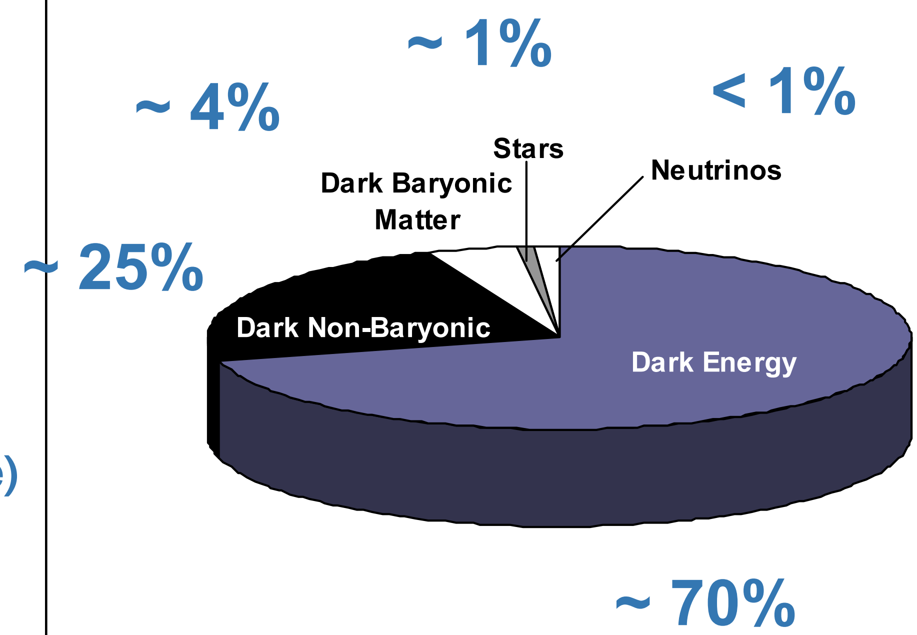
- H_o is the Hubble expansion parameter today
- $\Omega_M \equiv \rho_M / \rho_c$ is the fraction of the matter energy density in the critical density(G=c=1 units)
- $\Omega_\Lambda \equiv \rho_\Lambda / \rho_c$ is the fraction of the dark energy density (in this case a cosmological constant) in the critical density $\rho_c \equiv \frac{3H^2}{8\pi}$
- $\mathbf{w} \equiv \frac{\mathbf{P}}{\boldsymbol{\rho}}$ is the equation of state for dark energy
- $\mathbf{w(a) = w_0 + (1 - a)w_a}$ describes the evolution of w

The Standard Cosmological Model: Lambda Cold Dark Matter (ΛCDM)

Inflation predictions:

- spatially flat universe
- perturbations
  - ✓ power-law
  - ✓ nearly scale-invariant
  - ✓ gaussian
  - ✓ adiabatic
  - ✓ growing mode
  - ✓ scalar (density)
  - and tensor (gravitational wave)

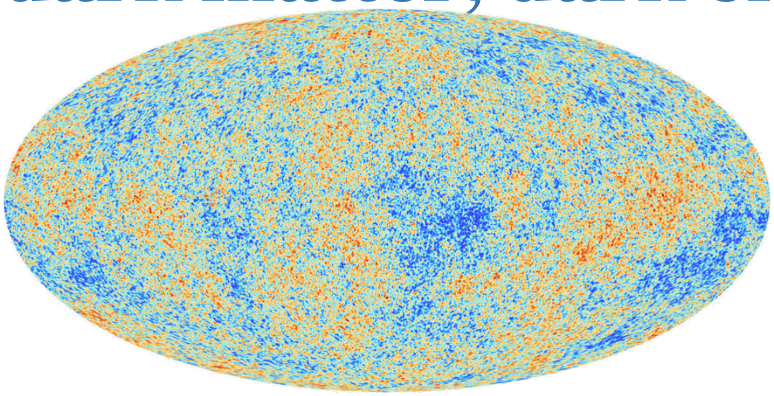
- 30% matter
- 70% dark energy

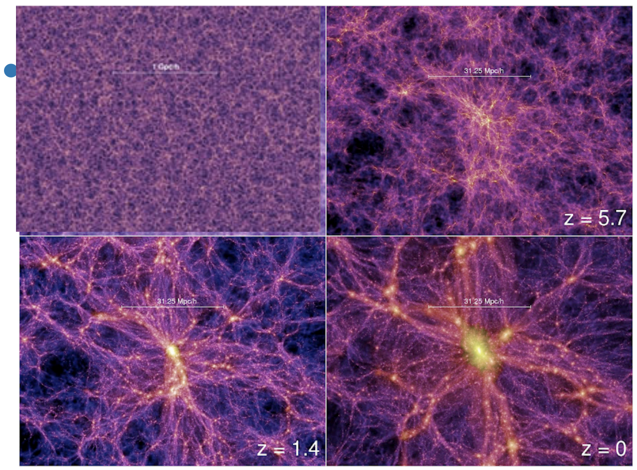


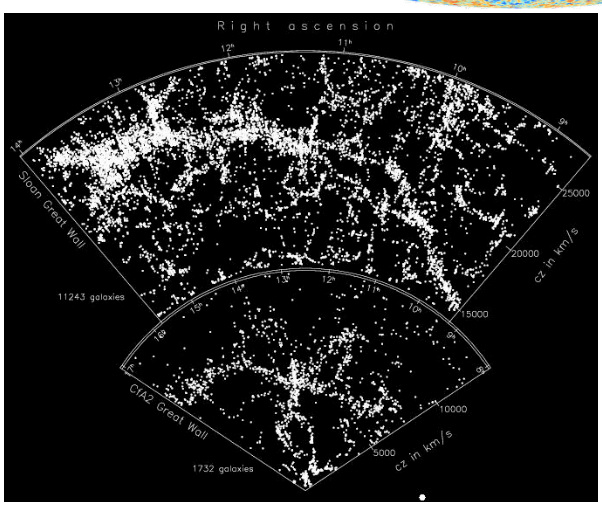
Cosmological Parameters

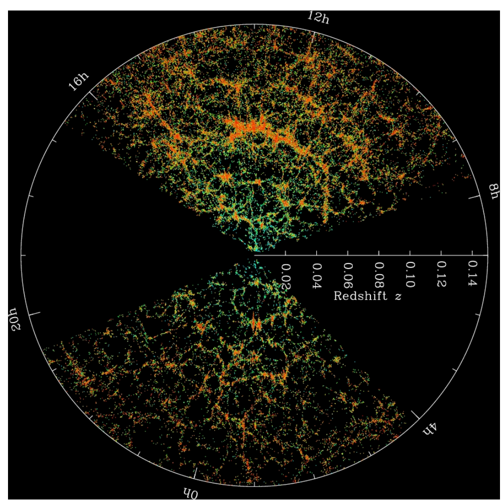
Standard Model of Cosmology: Successes

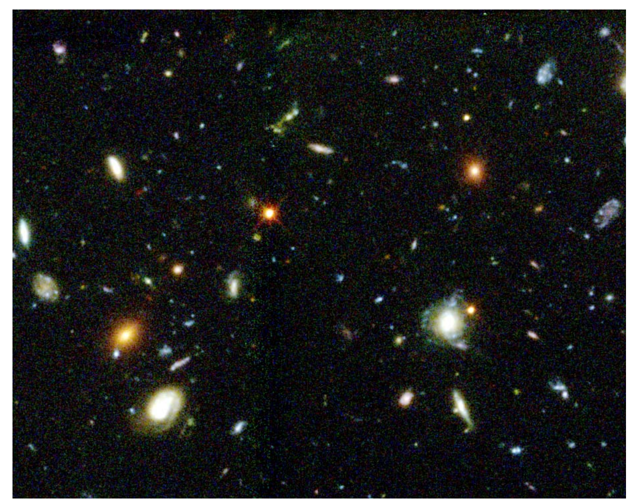
Inflation, gravitational instability plus cold dark matter, dark energy…







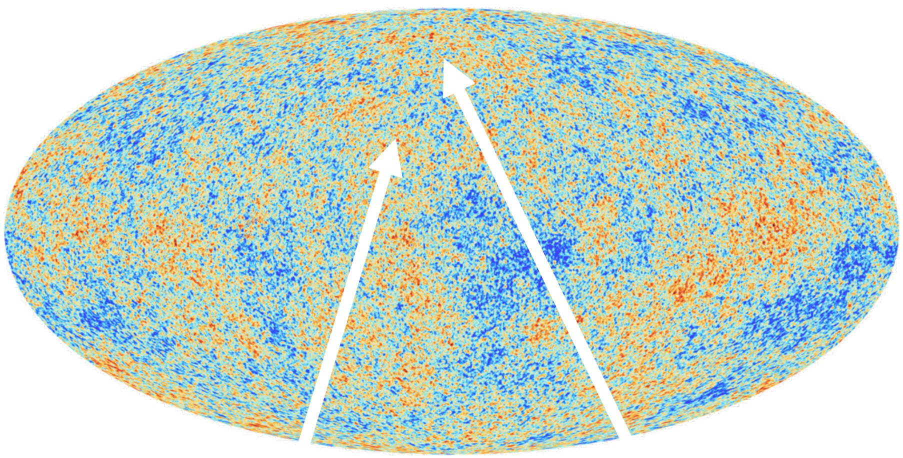




Critical Missing Pieces to the Current Standard Model

- Cold dark matter dominates the matter density and is in an unknown form
- The overall mass-energy density is dominated by dark energy, for which there is currently no theory
- The dynamics of inflation depends on particle physics at high energy, and nothing is known of the hypothetical scalar field that drives inflation

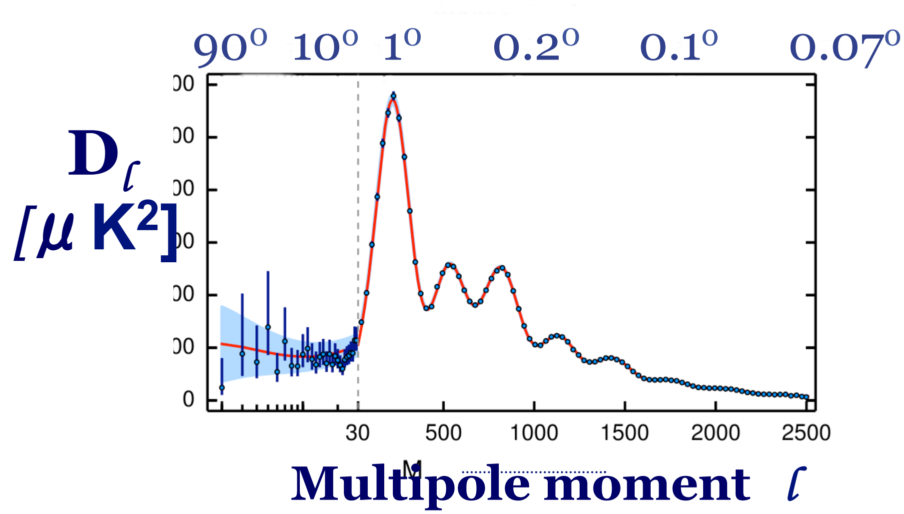
CMB Anisotropies



$$T_1(\theta_1,\phi_1) \quad T_2(\theta_2,\phi_2)$$

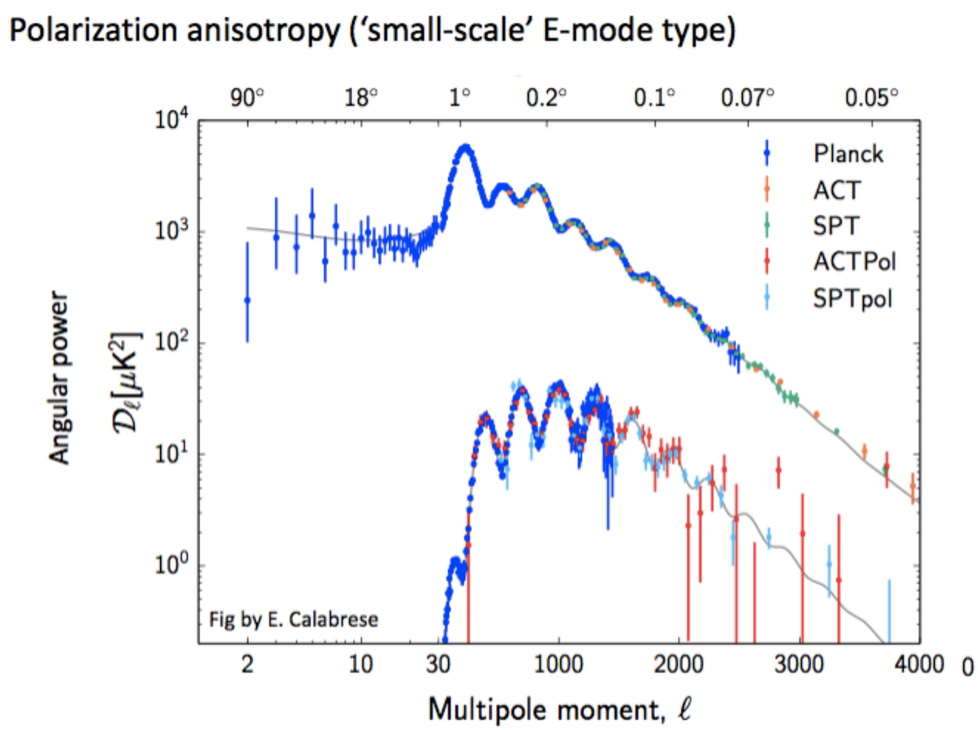
$$\langle T_1 T_2 \rangle = \sum a_{lm} Y_{lm}(\theta,\phi)$$

$$\langle |a_{lm}|^2 \rangle^{1/2} \equiv C_l$$



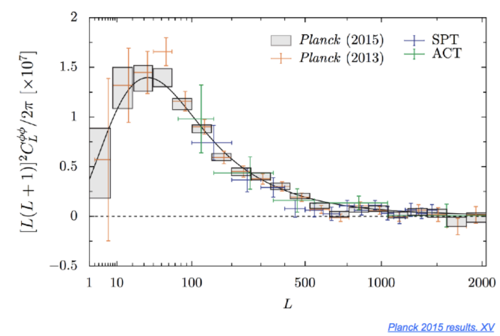
$\ell = 200$, $\theta = 1^o$

Planck 2015 + ACT + SPT Angular Power Spectrum



A 6-parameter ΛCDM model provides an excellent fit to the Planck 2015, ACT and SPT data

Planck lensing – 40σ!



E. Calabrese

Cosmic Microwave Background Anisotropies

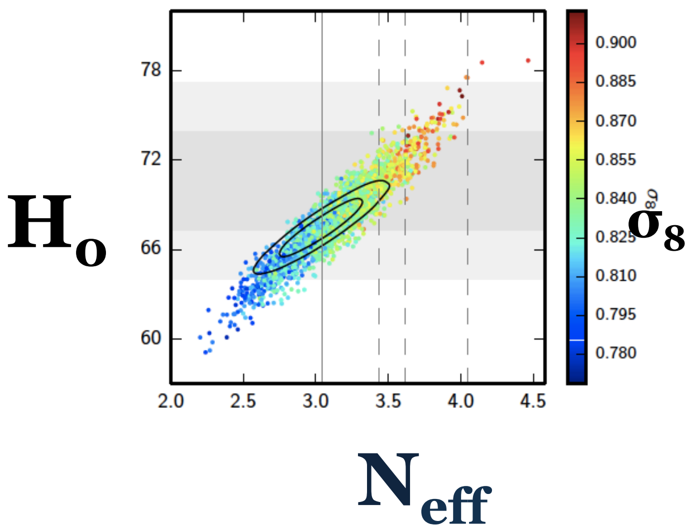
Planck Cosmological Parameters (2015)

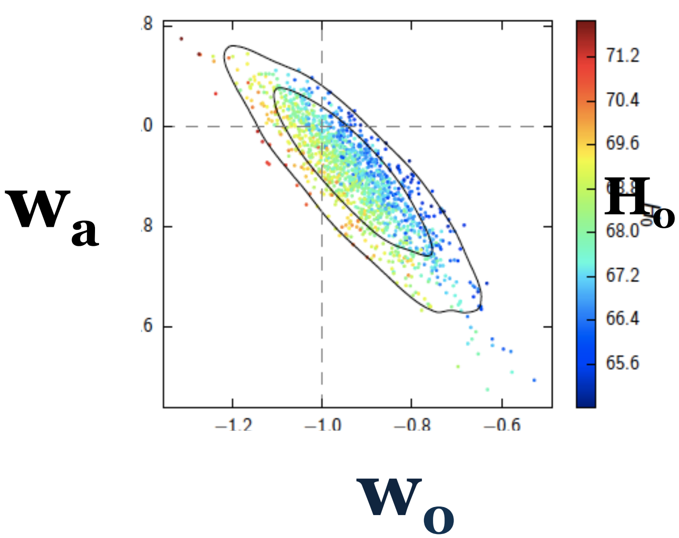
H_0	67.8 ± 0.9 km/s/Mpc
Ω_M	0.308 ± 0.012
Ω_Λ	0.692 ± 0.012
n_s	0.9677 ± 0.0060
w	$-1.54^{**}\,{}_{-0.50}^{+0.62}$ (** -1.02 Add BAO+SNIa+H_o)

Based on temp + lensing data
** For w also BAO+SNIa+H0

Planck 2015 Cosmology Paper XIII

Planck Cosmology 2015





The nearly exact degeneracy -- i.e., nearly the same CMB anisotropies in models with different geometries but the same matter content –

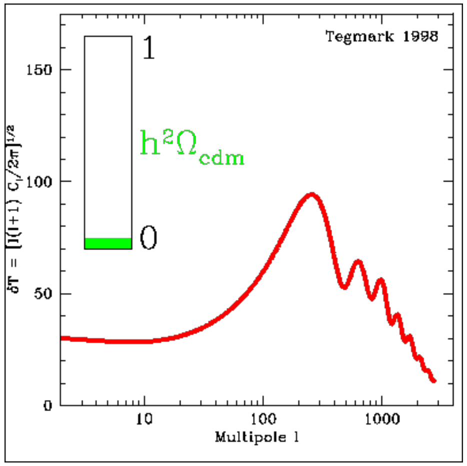
Is a limit to deriving parameters such as the Hubble constant from CMB data alone

It also means that an accurate independent measure of H_o provides a key means of constraining other cosmological parameters in combination with CMB anisotropies.

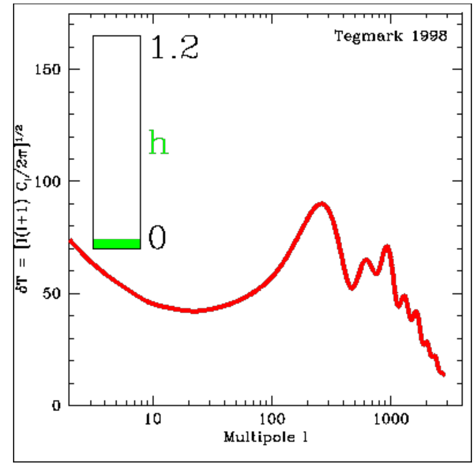
$\Omega_b h^2$, $\Omega_c h^2$ well measured

CMB Anisotropies

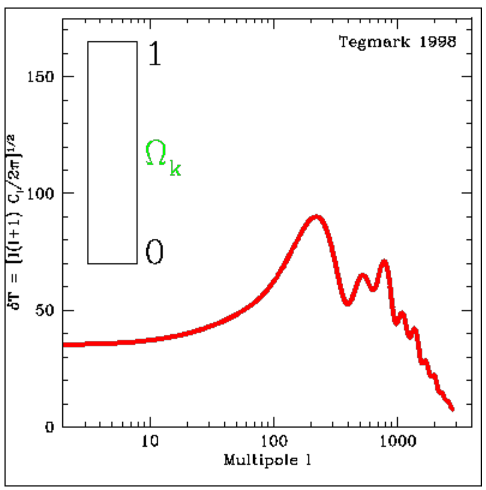
- $\Omega_{CDM}h^2$



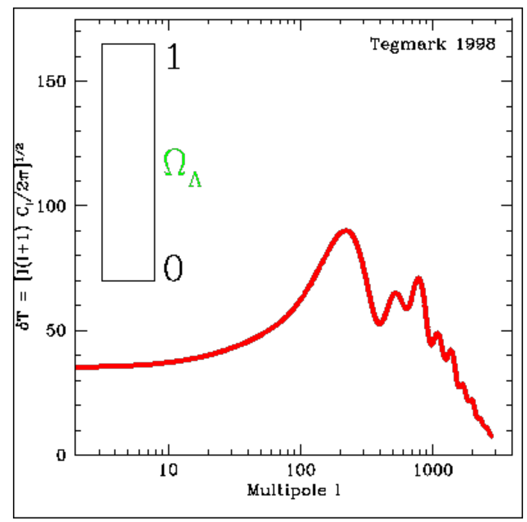
- H_0



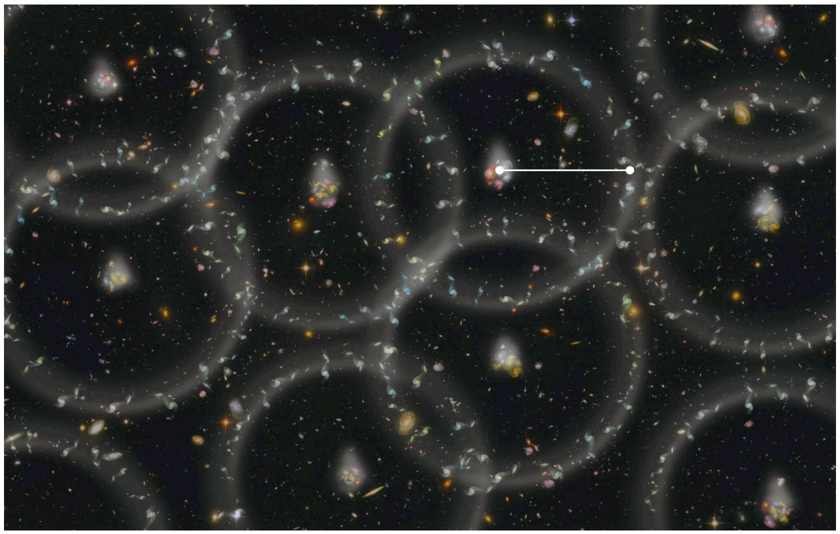
- Ω_k



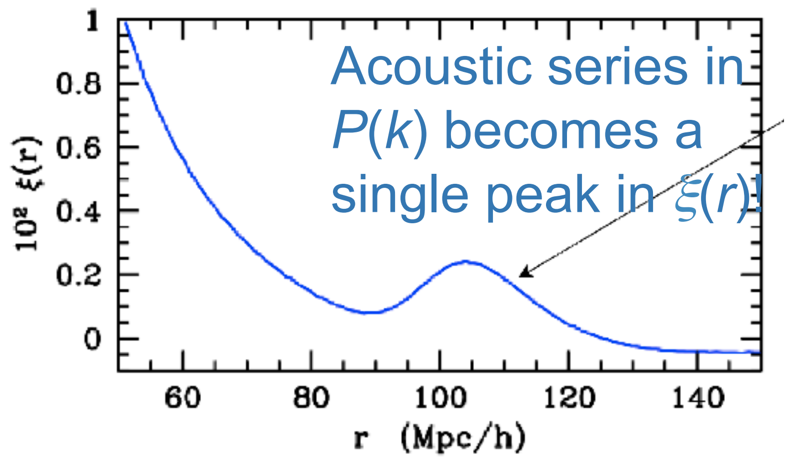
- Ω_Λ



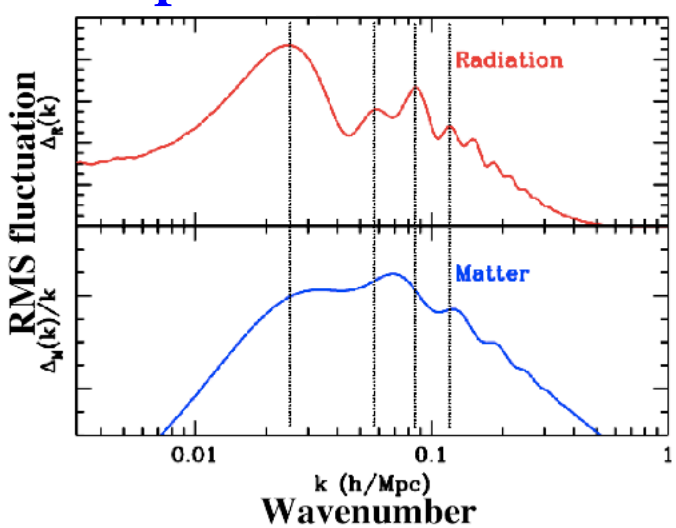
Baryon Acoustic Oscillations



Correlation function



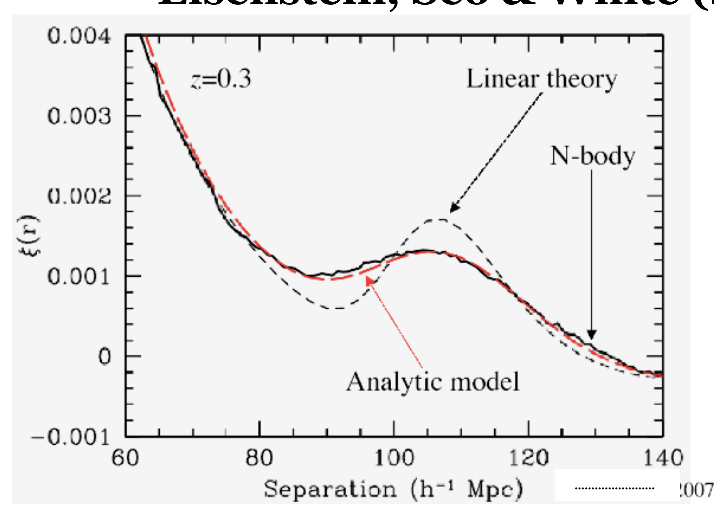
Power spectrum



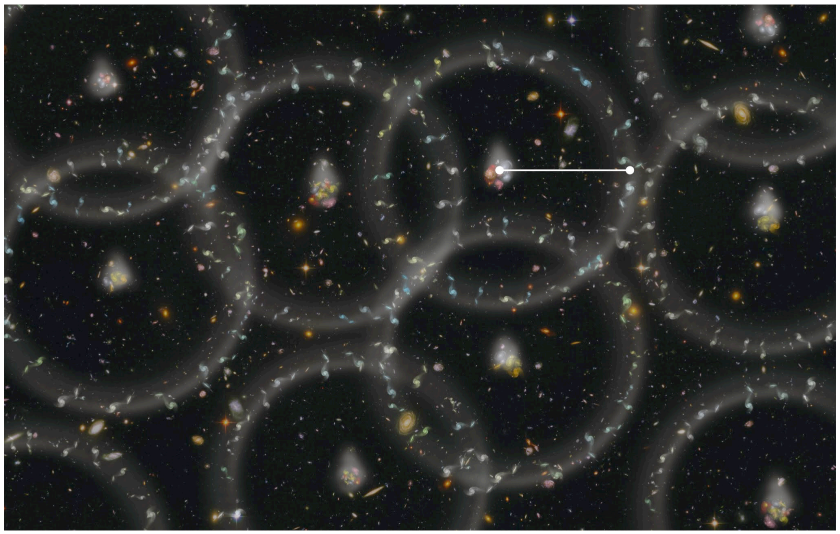
Marti

Non-linearities

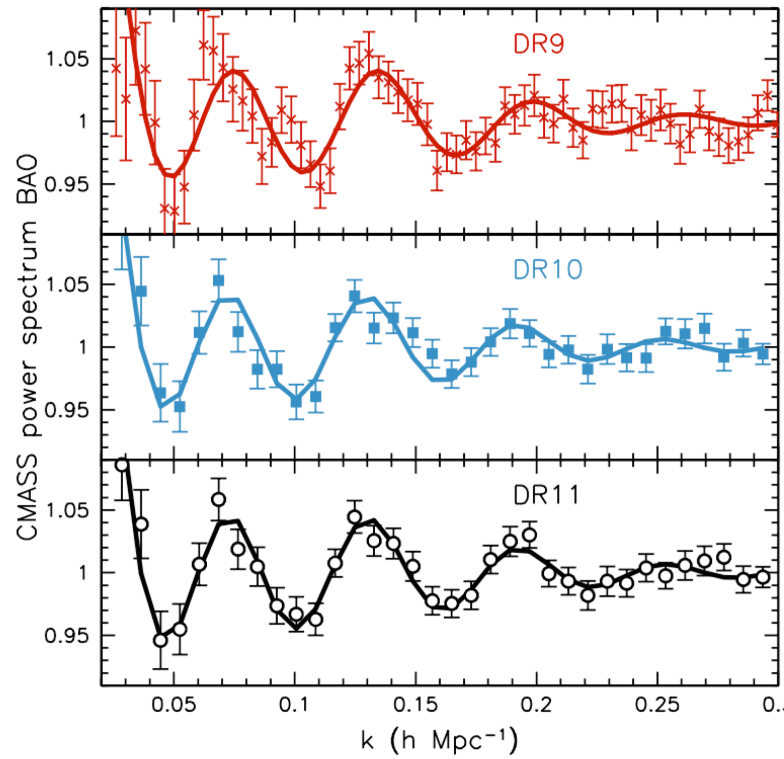
Eisenstein, Seo & White (2007)



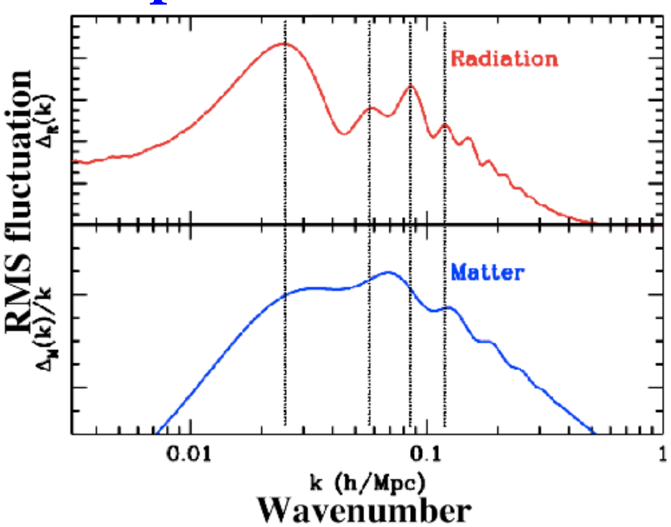
Baryon Acoustic Oscillations



Correlation function



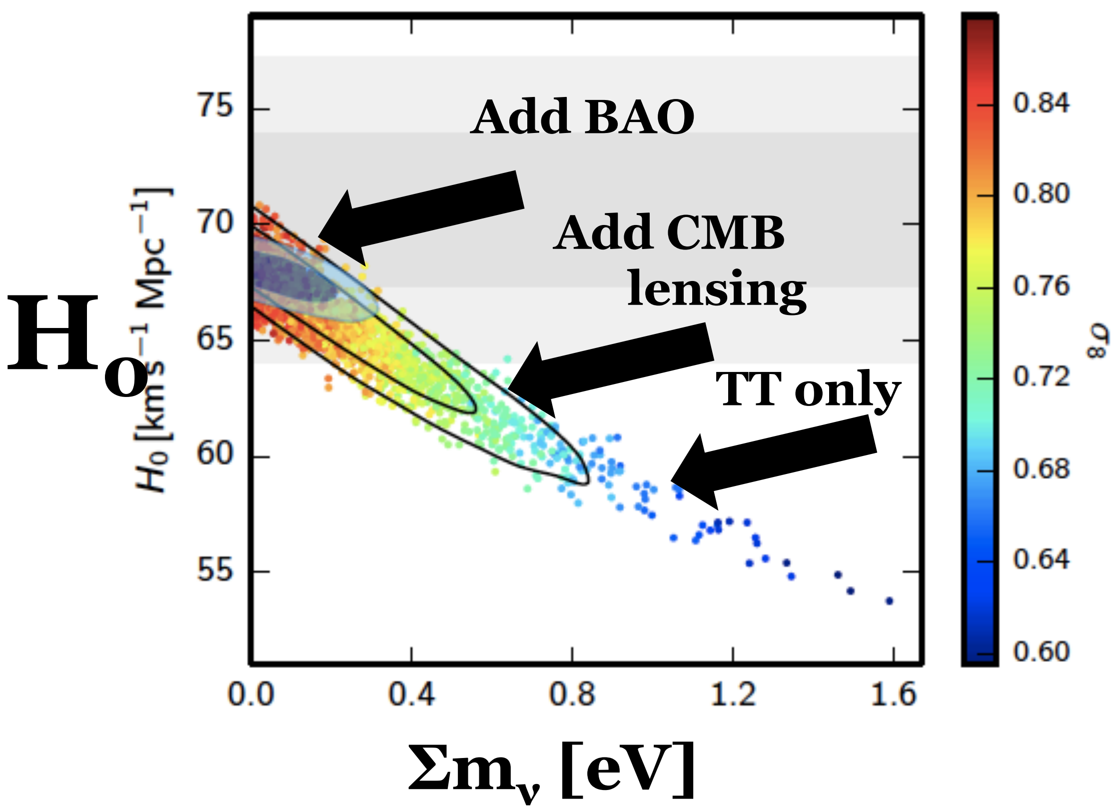
Power spectrum



Marti

Anderson et al. (2014)
BOSS survey

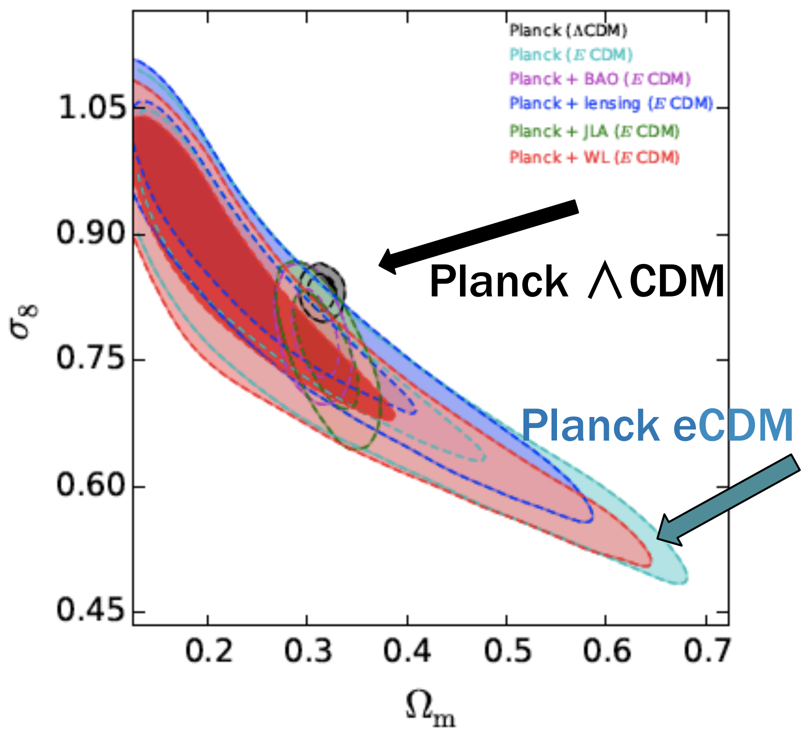
BAO + Planck 2015: Σm_ν



- TT + pol + lensing + BAO + H_o + SNIa
- Σm_ν < 0.23 eV [95% CL]
  Best estimate
- Σm_ν < 0.49 eV [95% CL]
  Planck TT; TE; EE+lowP

Planck 2015 XIII

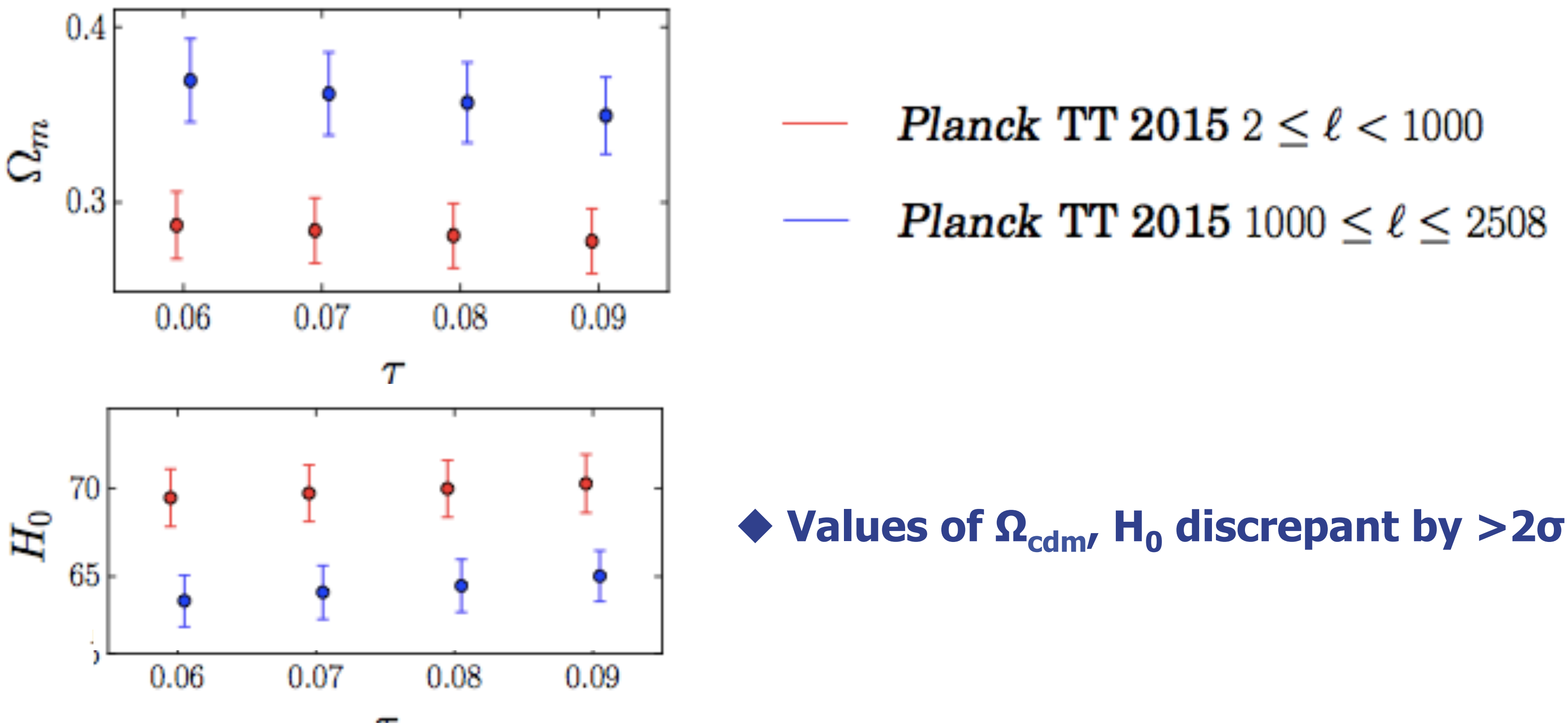
Planck: Relaxing Parameter Constraints



- **Planck 2015 data**
- **12-parameter fit (including w, N_{eff}, r)**
- **Biggest effects:**
  - Hubble constant
  - σ_8, r.m.s. amplitude of density fluctuations
- practically undetermined from Planck measurements alone even when external datasets such as BAO are included

Di Valentino, Melchiorri & Silk 2015

Tensions with Planck 2015 High-l Data

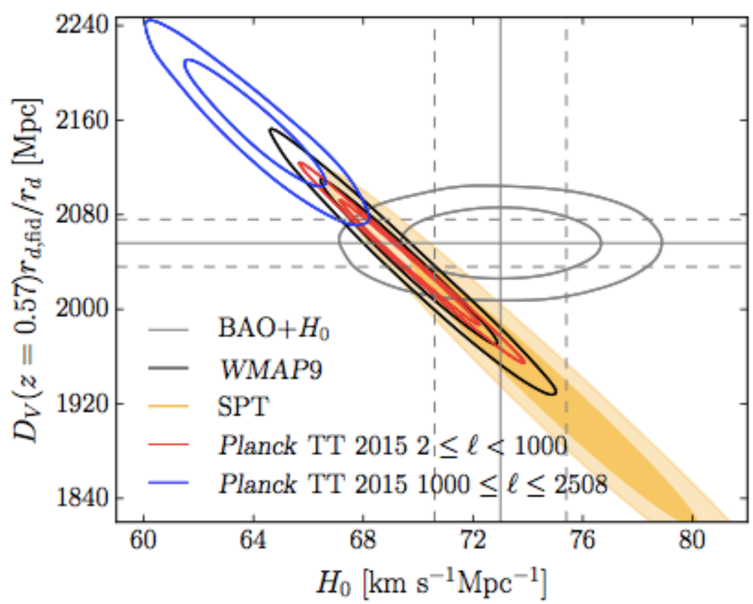


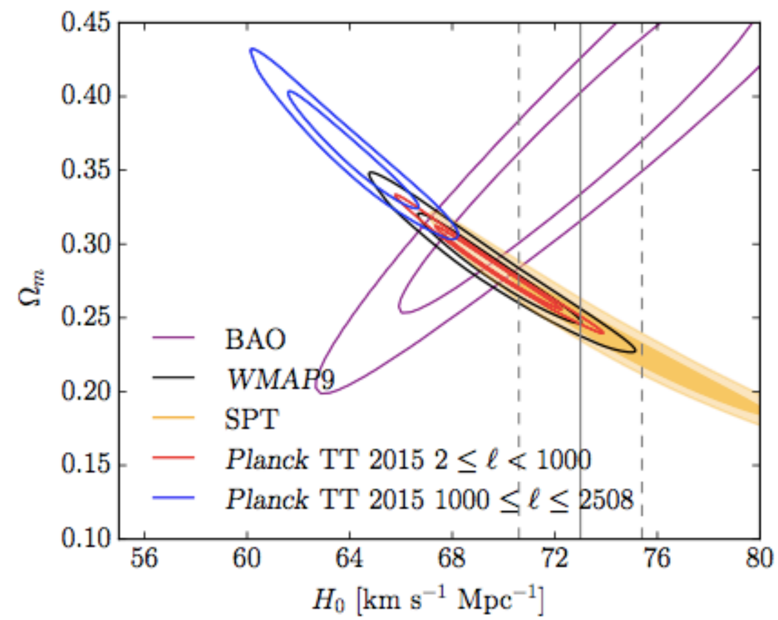
◆ **Values of Ω_{cdm}, H_0 discrepant by >2σ**

Addison et al. 2015 arXiv:1511.00055

Tensions with Planck 2015 High-ℓ Data

Addison et al. 2015





- Planck l ≥ 1000 constraints are discrepant with the BAO and distance ladder measurements at the 2.5σ and 3.0σ levels
- WMAP9 and Planck l < 1000 constraints are consistent with both within 1σ

- **Values of Ω_{cdm} discrepant by 2.5σ**
- **Again tension between Planck l>1000 and BAO.**

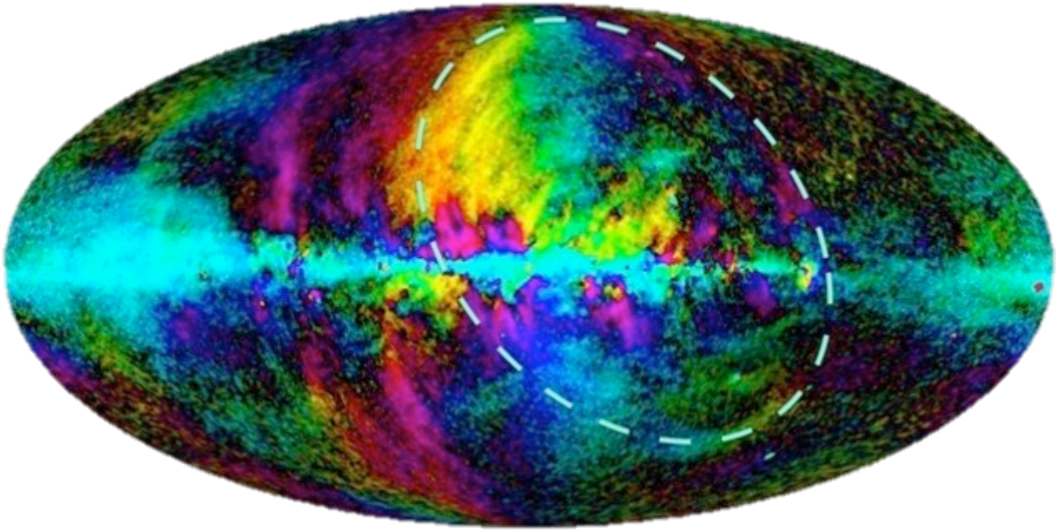
Determinations of H_o and w:

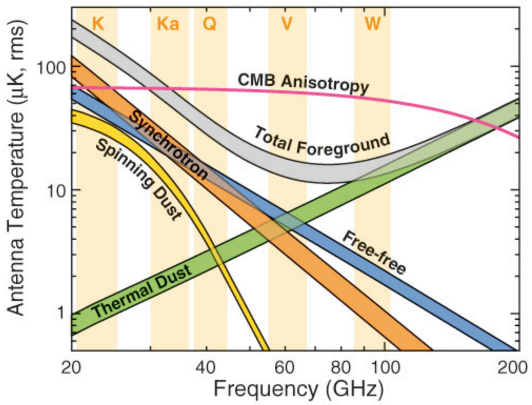
- Indirect (CMB)
- Direct (Distances)

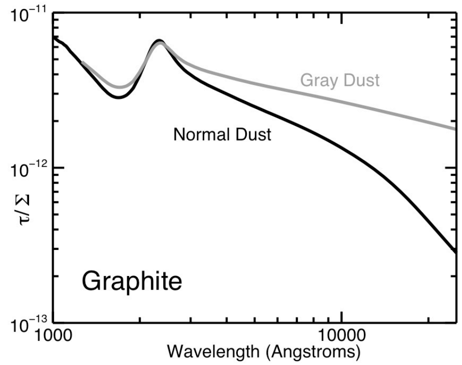
How To Achieve These Goals

- **Direct Distances**
  - Use Properties of stars as probes of distance
  - Stellar Evolution well understood theoretically
  - Measurements straightforward
  - Empirical tests
  - Many independent methods
  - Steadily improving accuracy: few percent level now achievable

Astrophysical Dust: Removing the Screen







Accuracy vs Precision

Precision

Accuracy

2)
Dark Energy

Summary of Current Results

- **Results to date consistent with**
  - $w = P / \rho = -1.0 \pm 10\%$
  - No information on evolution of w

- Knop et al (2003), Riess et al (2004), Astier et al (2006), Wood-Vasey et al (2007), Frieman et al (2009), Freedman et al (2009), Eisenstein et al (2005), Kamutsu et al (2009), Hicken et al (2009), Kessler et al (2009), Amanullah et al 2010, Conley et al 2011, Suzuki et al 2011, Riess et al 2011, Blake et al, Padmanabhan et al 2012, Ade et al 2013, Weinberg et al 2013, Rest et al 2013, Anderson et al 2014, Betoule et al 2014 …

Dark Energy Measurement Methods

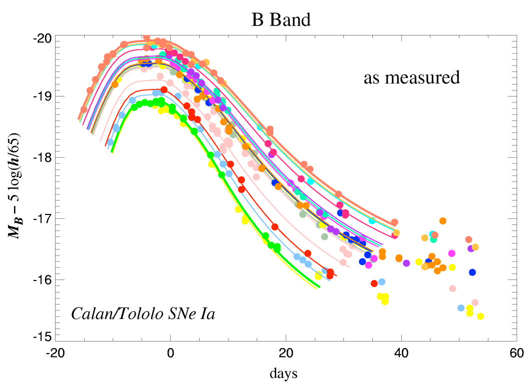
- **Supernovae**
- Baryon Acoustic Oscillations
- Weak Lensing
- Cluster Surveys
- CMB plus BAO, SNeIa, LSS, H_o

Type Ia Supernovae

- Progenitor is a CO white dwarf accreting material from a binary companion.
- As the white dwarf approaches the Chandrasekhar mass, a thermonuclear runaway is triggered.
- "Standardizable candles"

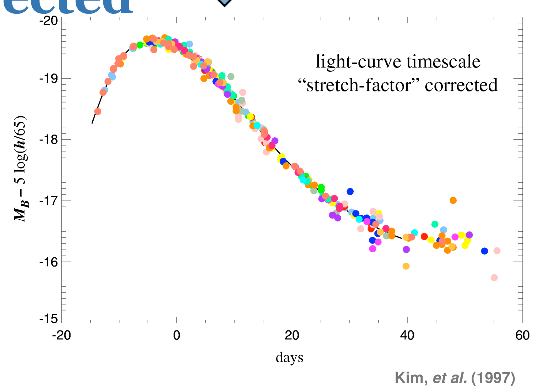
Use of SNe Ia to Measure Distances

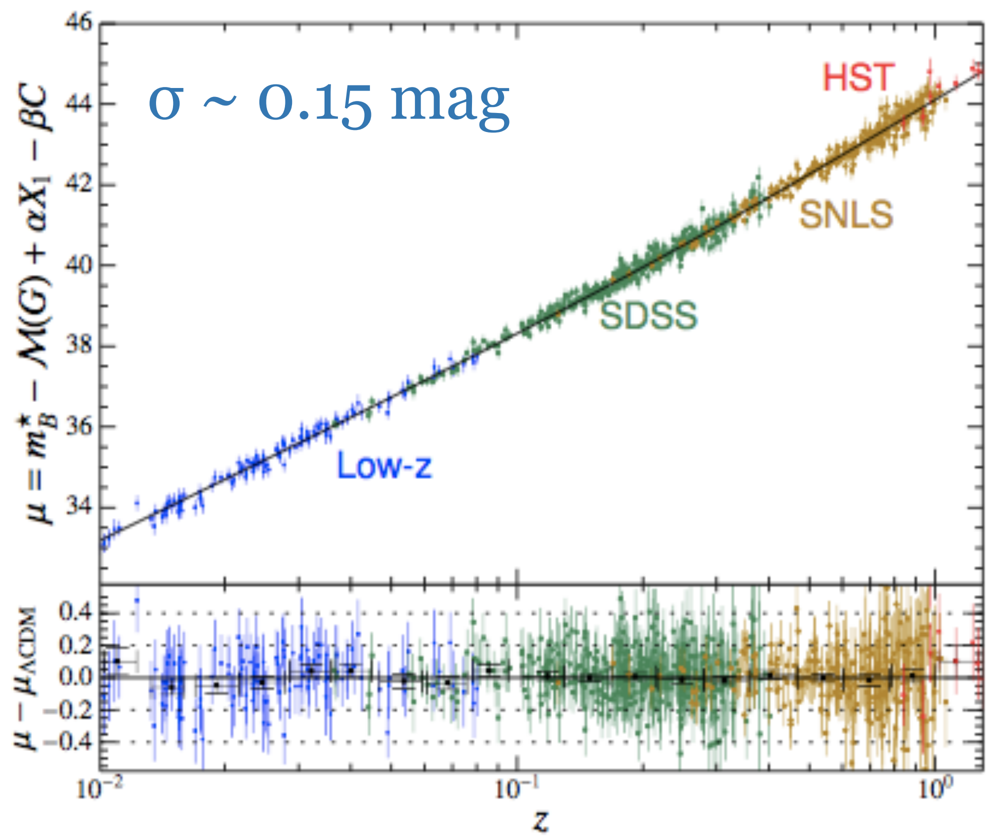
As measured



'Stretch' factor

Corrected

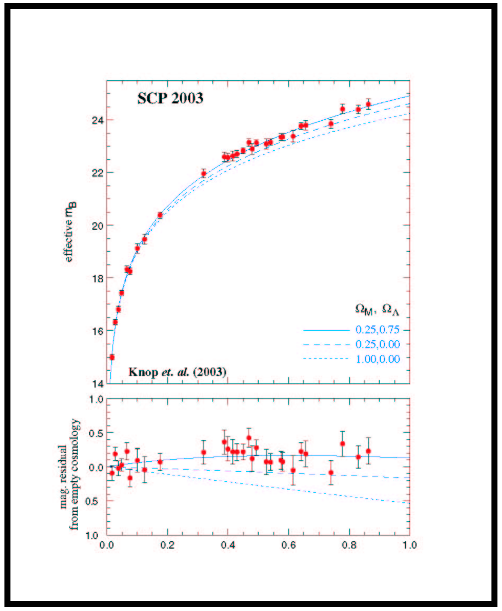




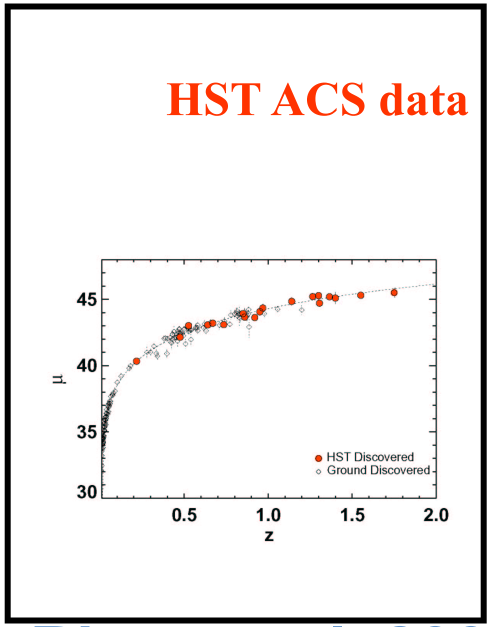
Betoule et al. 2014

$\mu_0 = m - M = 5\log d_L + 25$ where d_L is in Mpc

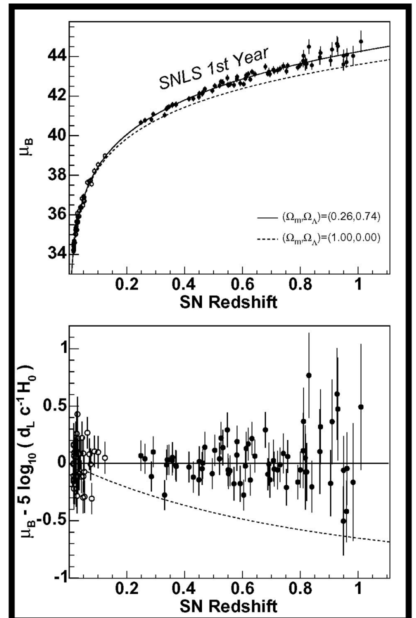
SNe Ia and Cosmology



Knop et al. 2003

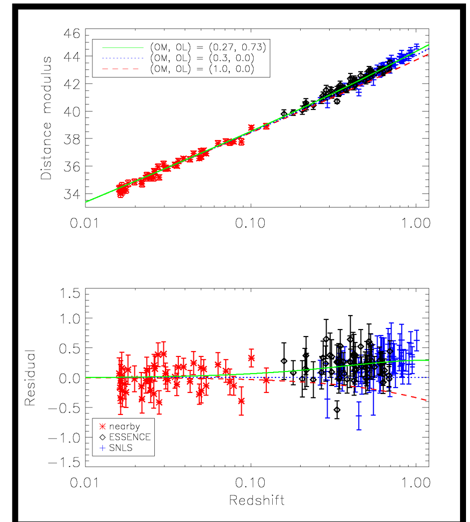


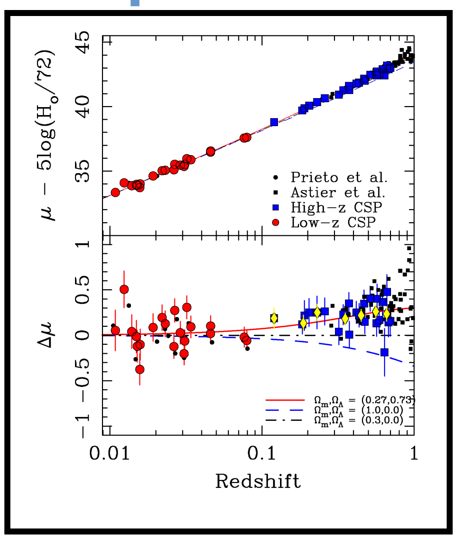
Riess et al. 2004



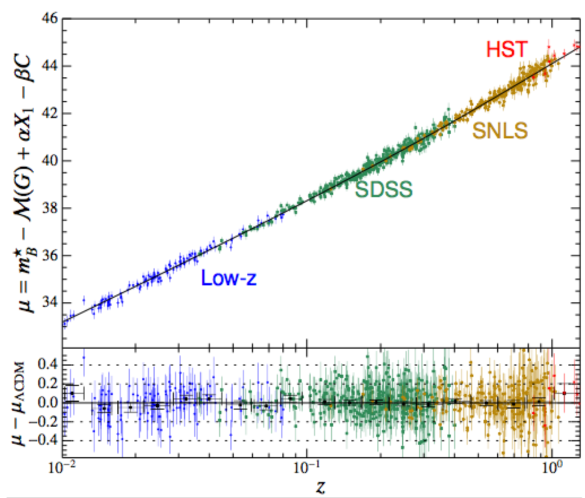
Astier et al. 2006

Wood-Vasey et al. 2007

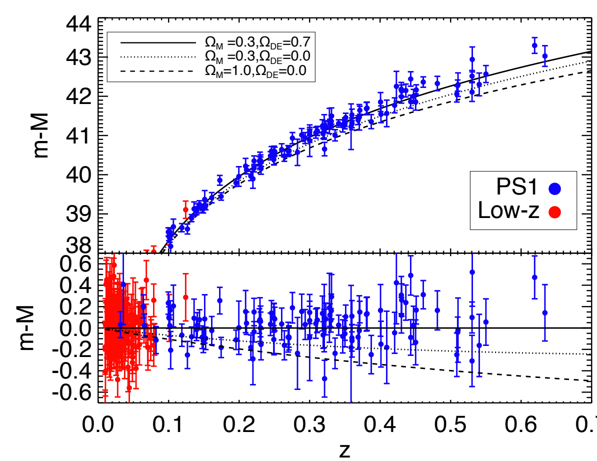




WLF et al. 2009



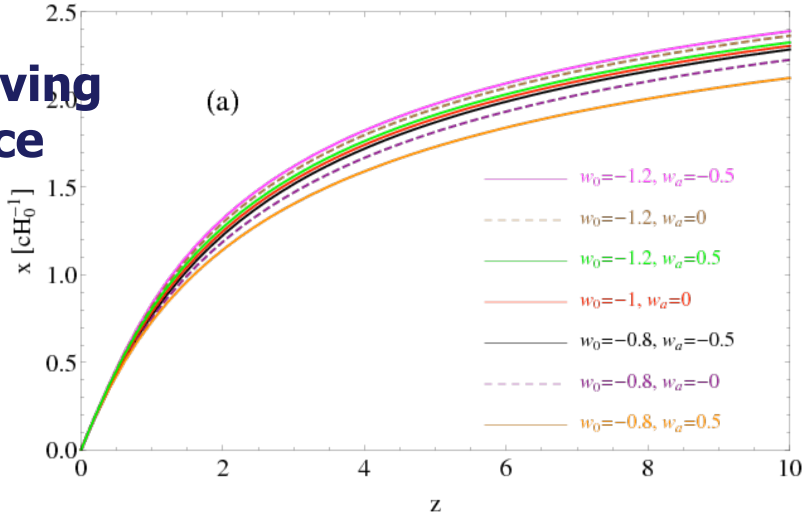
Betoule et al. 2014



Rest et al. 2014

Challenge for Measuring Time Evolution of Dark Energy

Co-moving distance



z

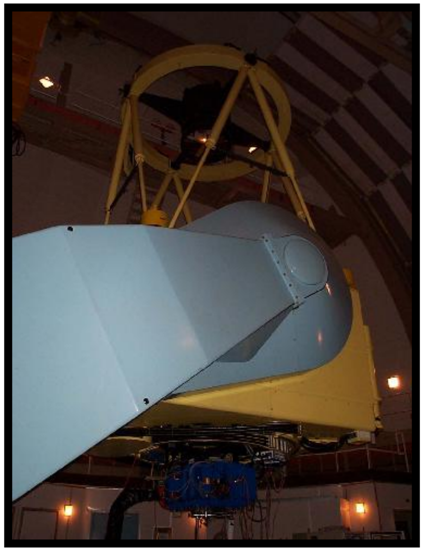
- 7 dark energy models with different equations of state

- Measuring $w(z)$ requires exquisite precision
- Need 1% distance measurements
- A measurement for the future

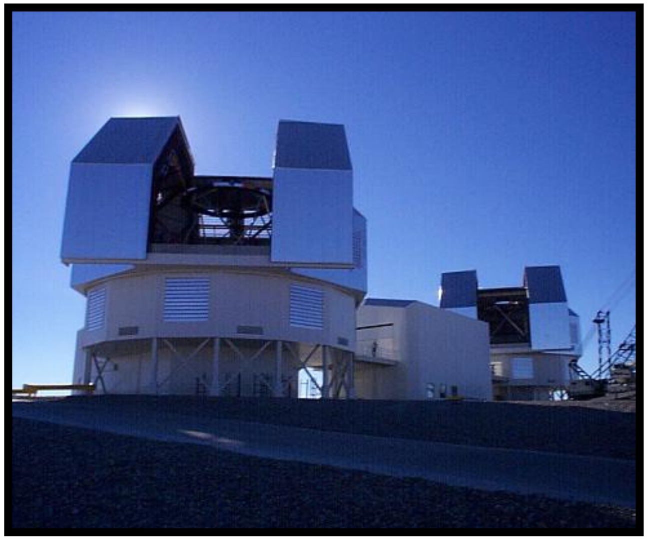
Ma (2014), Phys. Lett. B

Carnegie Supernova Project (CSP)

Swope 1-meter



Dupont 2.5-meter



Magellan 6.5-meter

CSPI: Low z: 0 < z < 0.1

- u'BVg'r'i'YJHK photometry
- 2.5-meter spectroscopy

CSPII: Low z: 0.03 < z < 0.1

- BVg'r'i'YJHK photometry

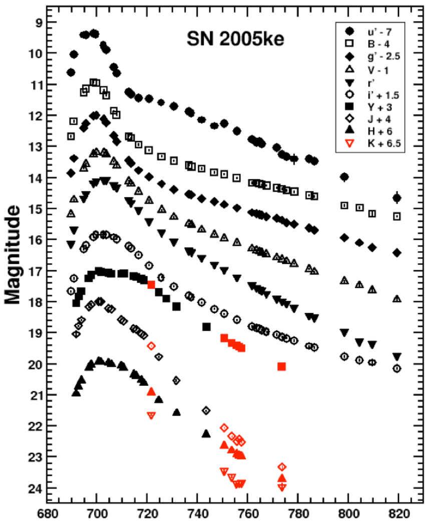
CSPI: High z: 0.1 < z < 0.7

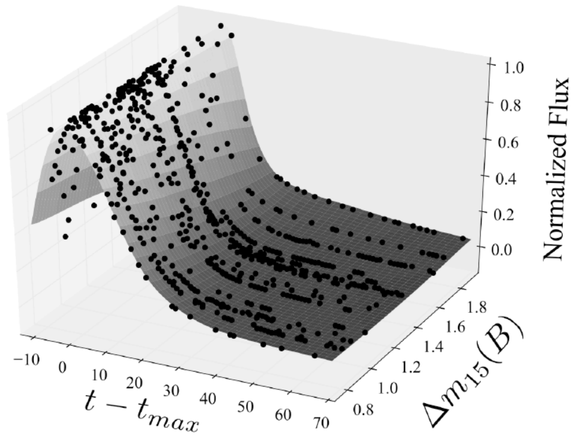
- YJ photometry
- Magellan 6.5-meter

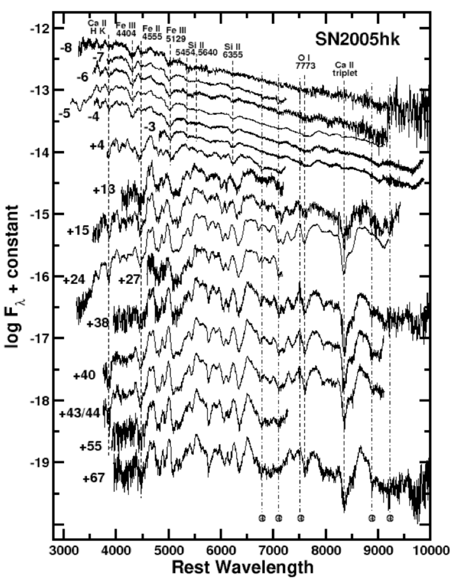
CSPII: Low z:

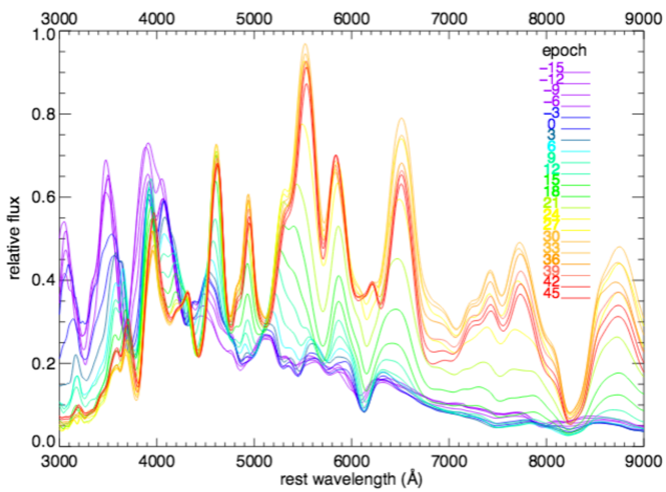
- Magellan FIRE spectroscopy

CSP: Dealing With Systematics





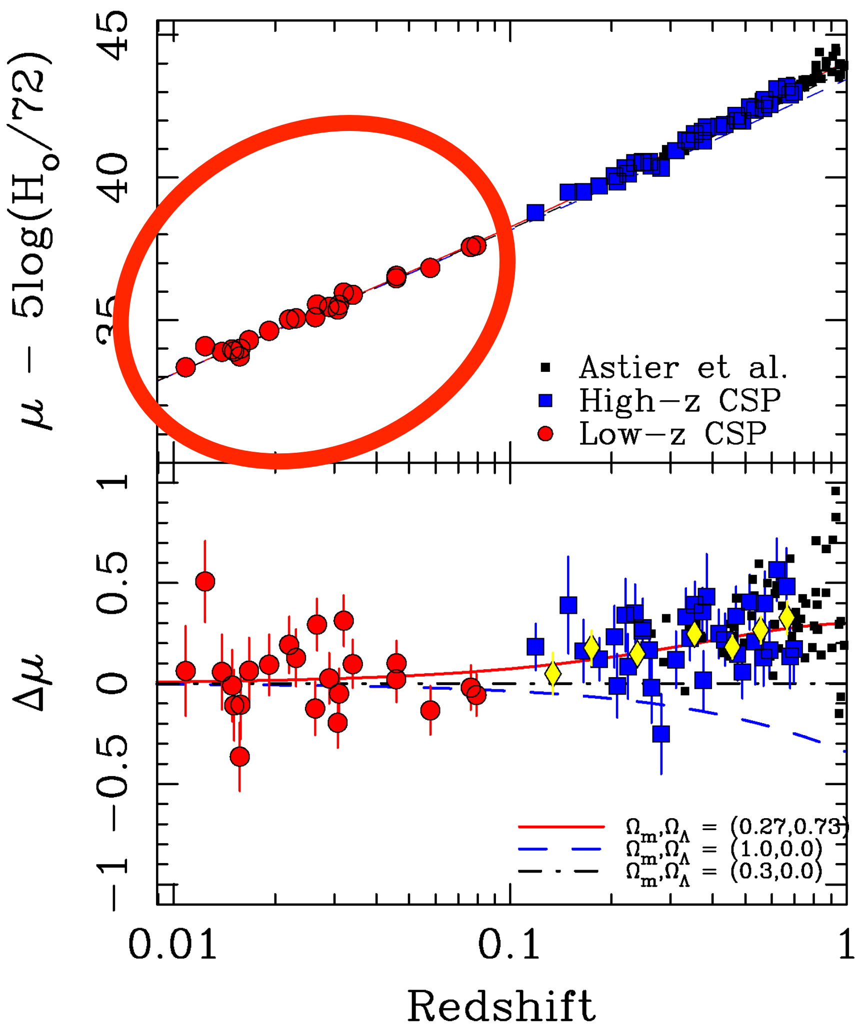




- Well-sampled:
  - Photometry
  - Spectra
- Reddening
- K-corrections
- Evolution
- Most extensive data set for dealing with systematics
- Comparison sample for future space missions (e.g., WFIRST)

Carnegie Supernova Project (CSP)

i ʻ-band Hubble Diagram



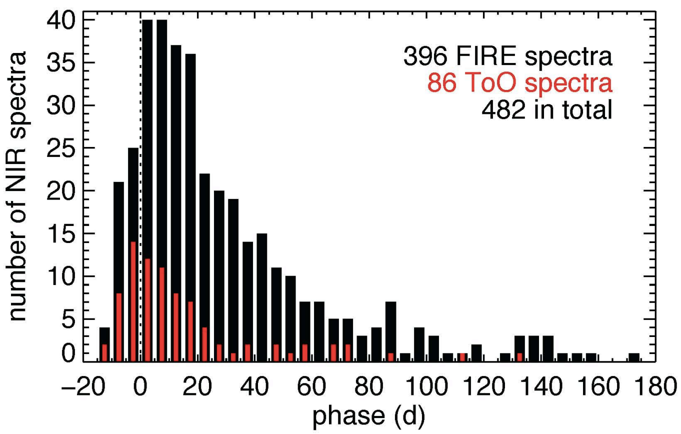
CSP data:

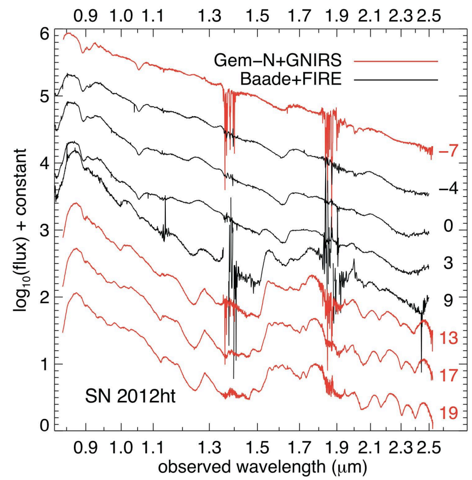
First I-band Hubble diagram at z > 0.07

$w_0 = -1.05 \pm 0.13$ (stat) ± 0.09 (sys)

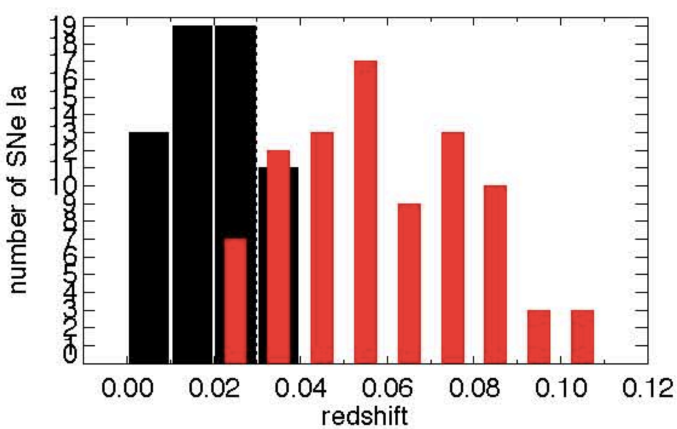
WLF et al. (2009)
Folatelli et al. (2009)

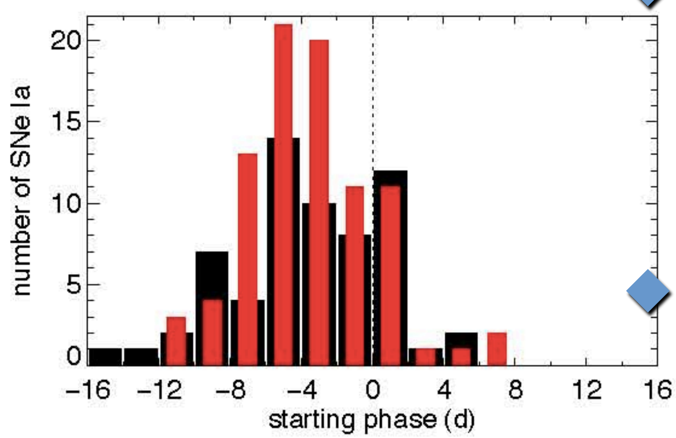
Carnegie Supernova Project (CSP) II (low z)





- Photometry now complete
- Obtaining follow up spectra

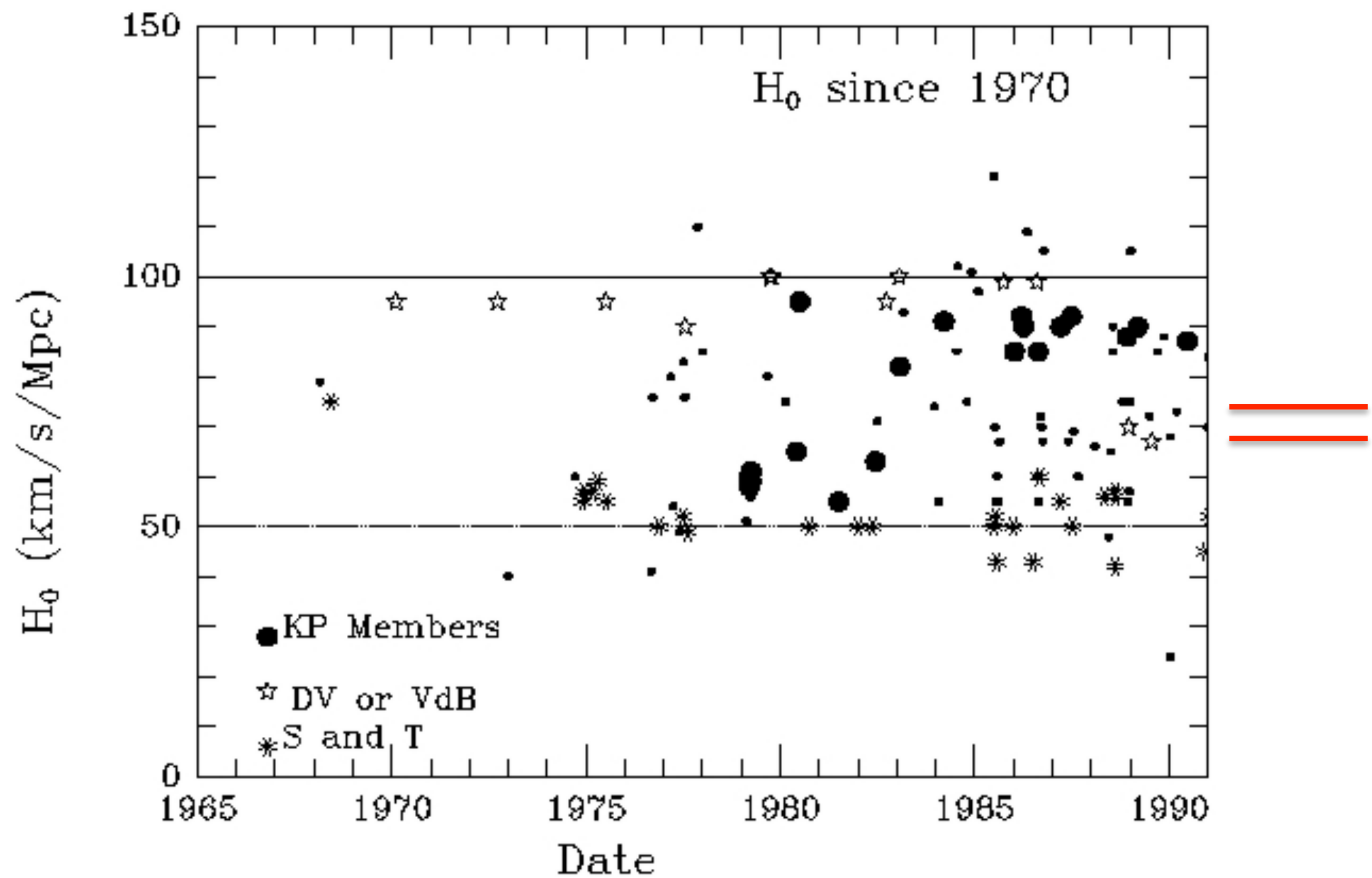




- WFIRST proposal for high-z observations
- S. Perlmutter, PI

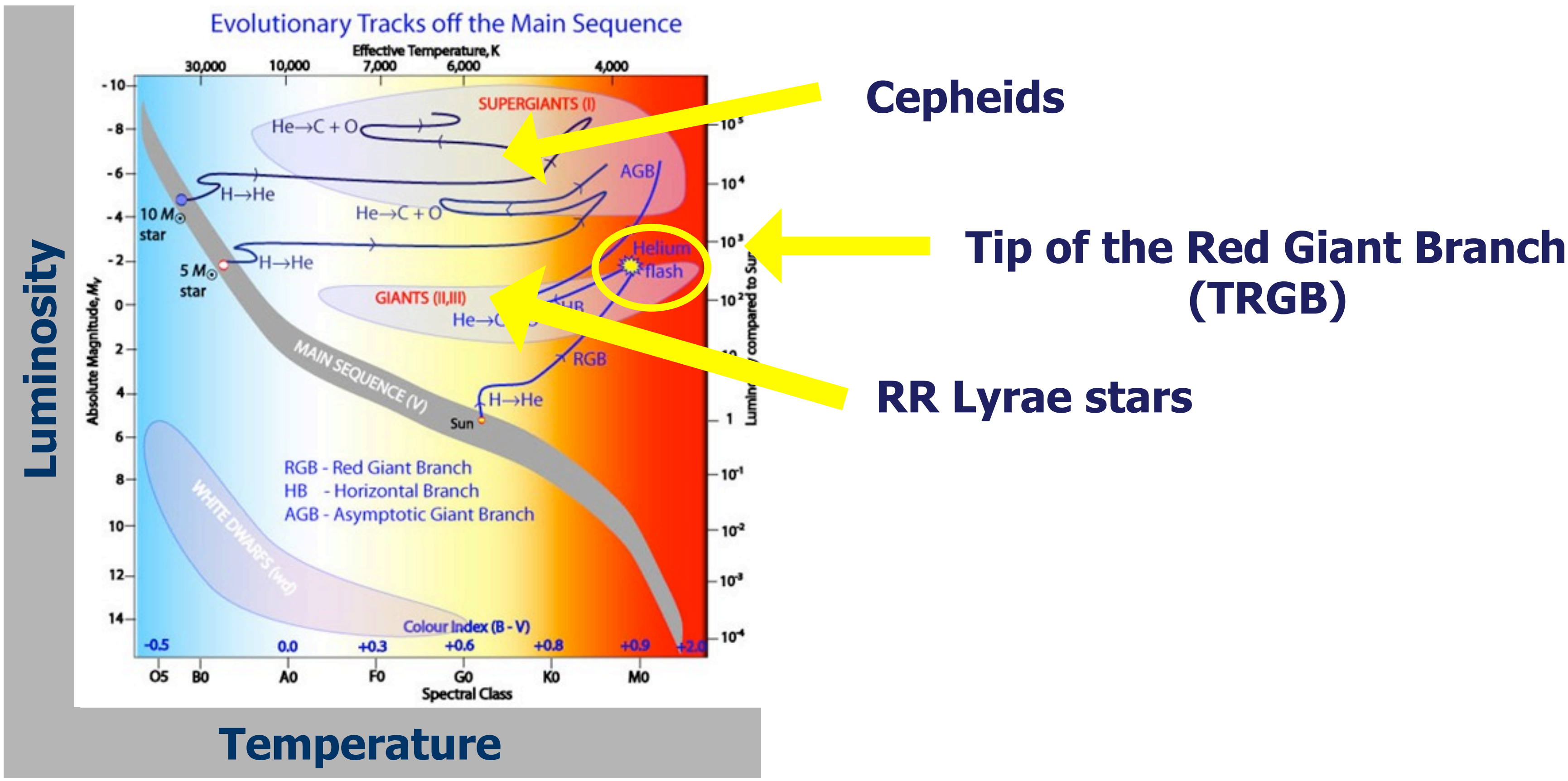
3)
The Hubble Constant

History of the Hubble Constant

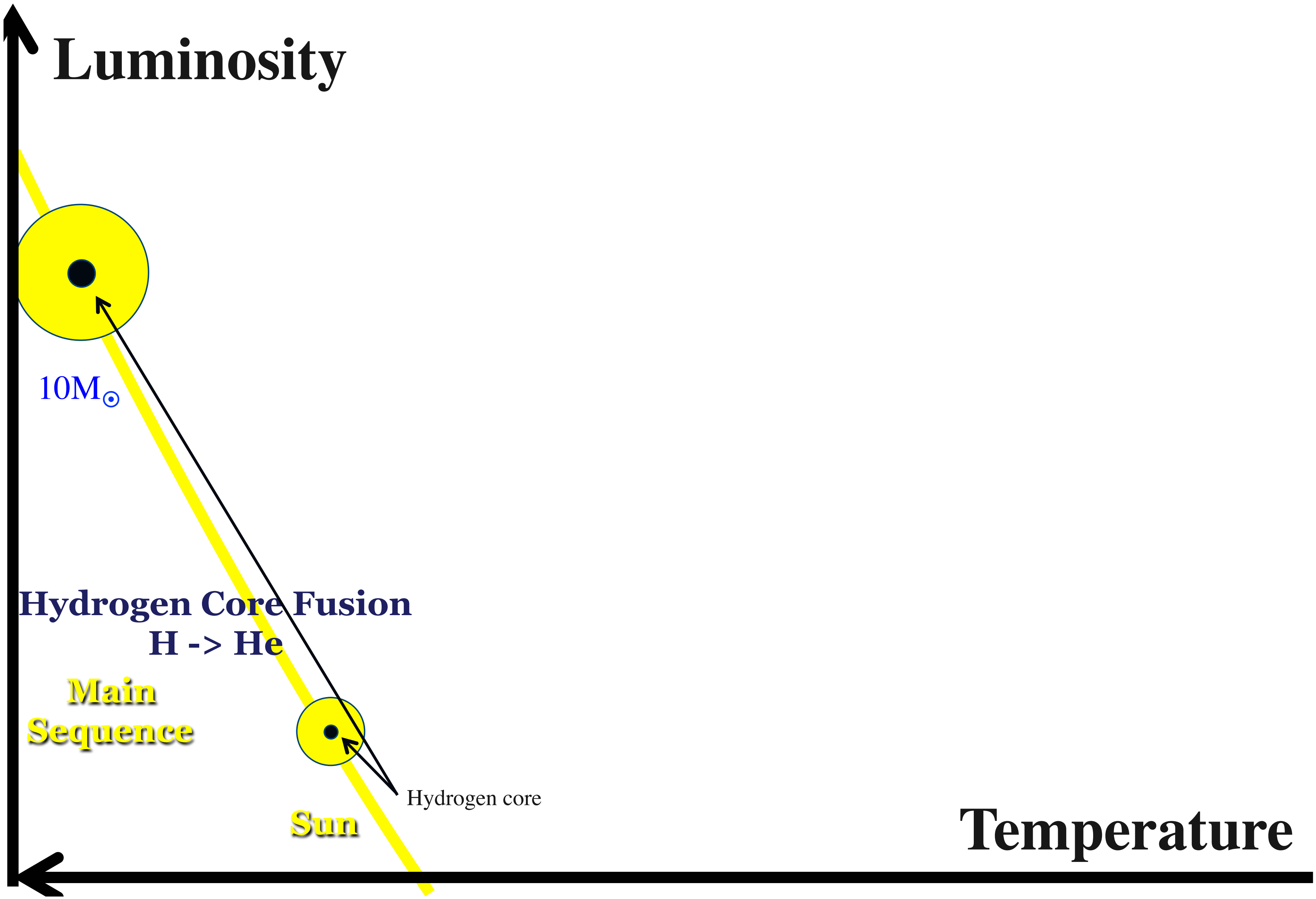


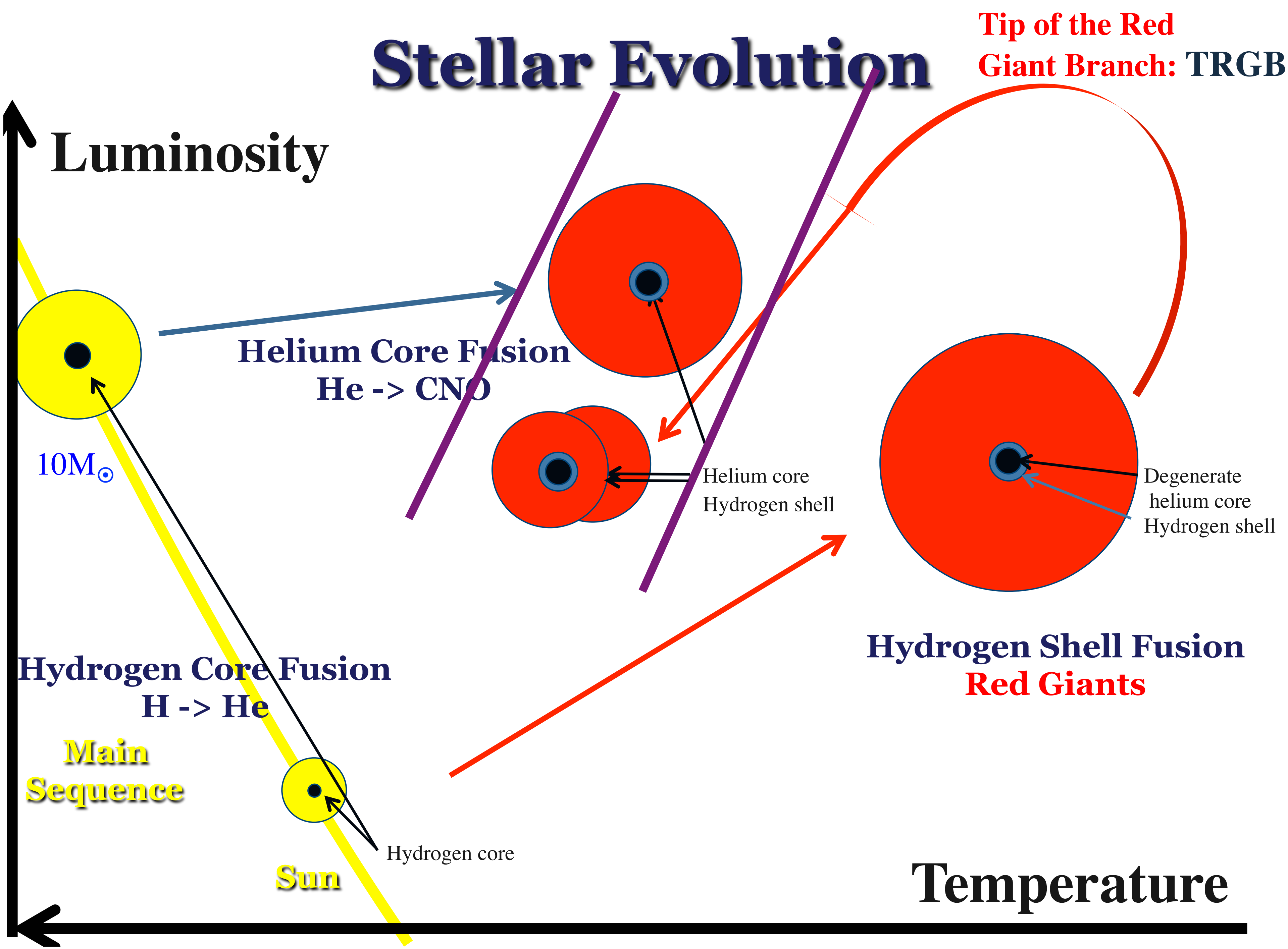
Stellar Astrophysics: Using Stars as Probes of Distance

Hertsprung – Russell Diagram



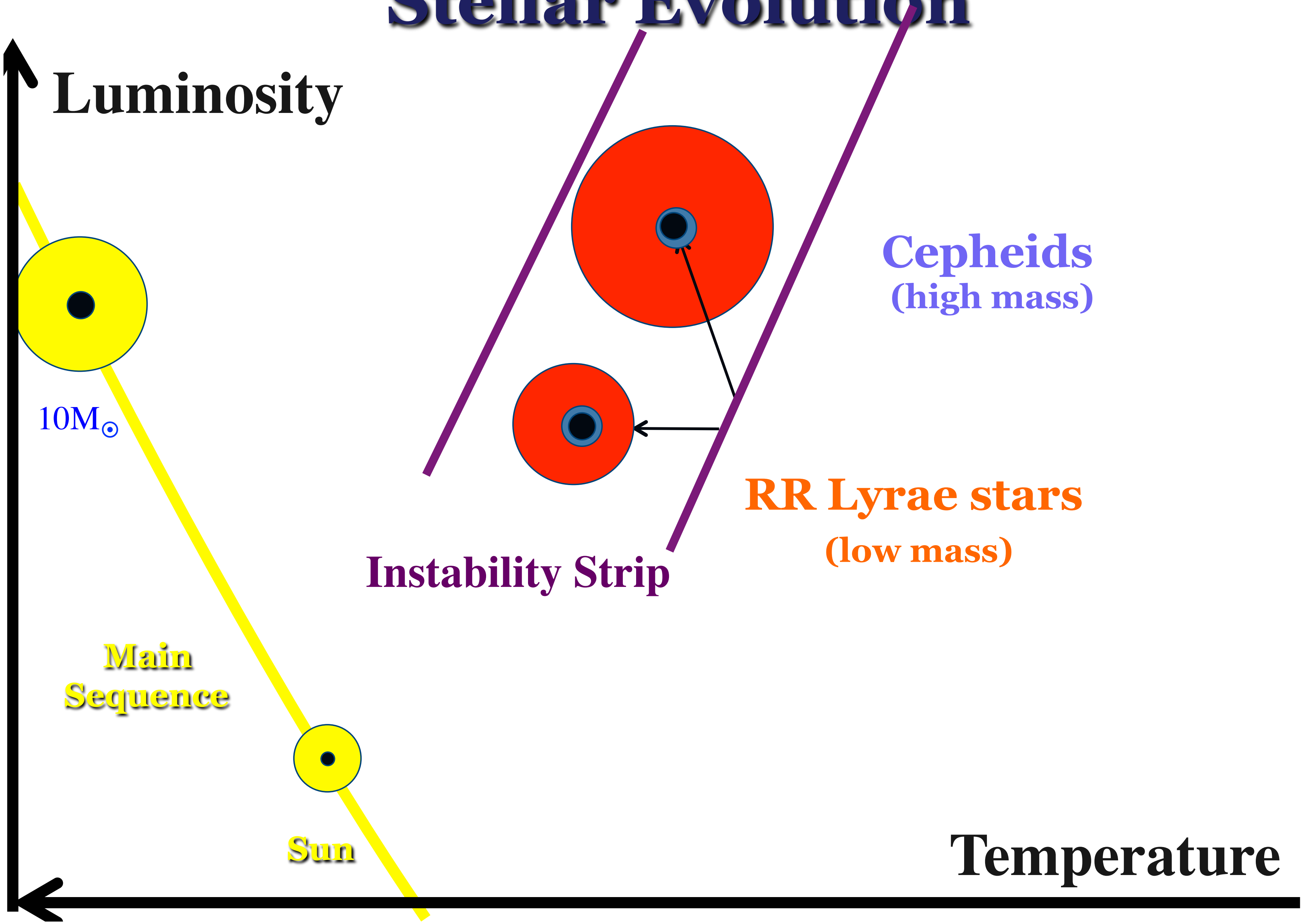
Stellar Evolution





Stellar Evolution
Tip of the Red
Giant Branch: TRGB
Luminosity
Helium Core Fusion
He -> CNO
10M$_\odot$
Helium core
Hydrogen shell
Degenerate
helium core
Hydrogen shell
Hydrogen Shell Fusion
Red Giants
Hydrogen Core Fusion
H -> He
Main
Sequence
Hydrogen core
Sun
Temperature

Stellar Evolution

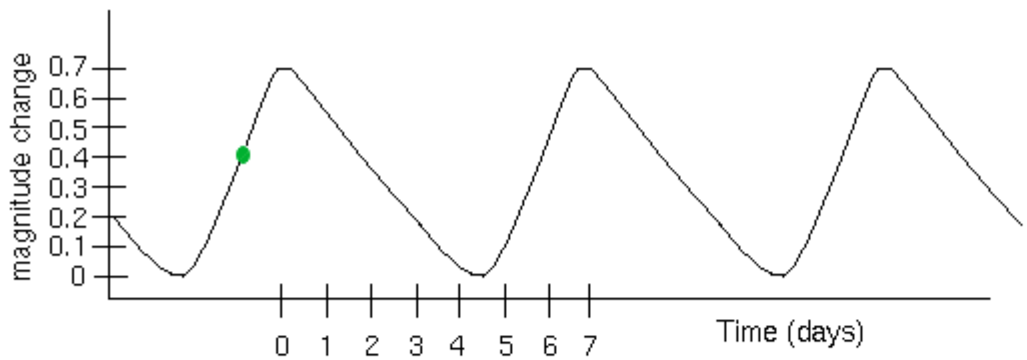


Cepheids

Physics of Cepheid Variables

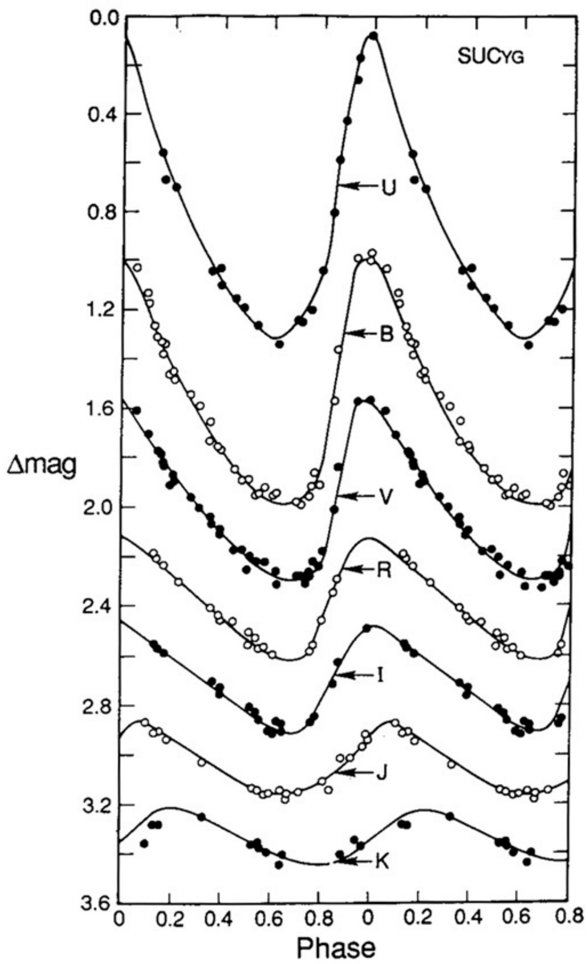
At T~4 x 10^4 K
Helium partial ionization zone

$$He^{+} \leftrightarrow He^{2+} + e^{-}.$$



$$L = 4\pi R^2 \sigma T_e^4$$

Cepheid Parameters: Optimizing Searches



Madore & Freedman (1991)

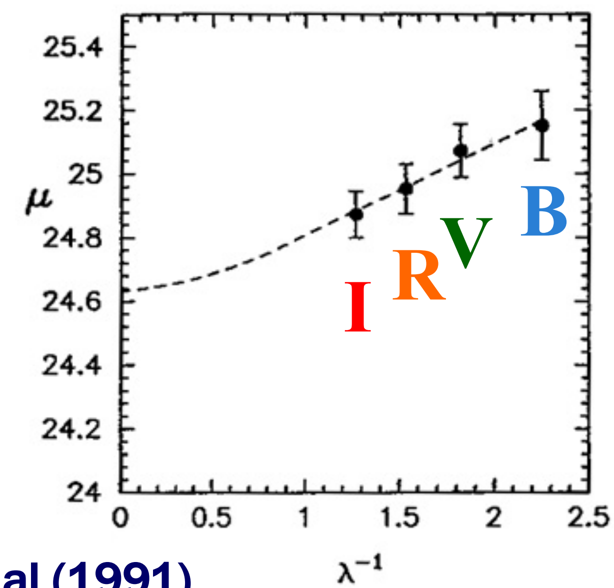
- Cepheid amplitudes **decrease** with increasing λ
- Interstellar reddening decreases as λ^{-1}

- **For detection: Cepheid searches best undertaken in the blue**
- **To minimize the effects of dust: observations best in the RED**

Multi-wavelength Distances Using Cepheids

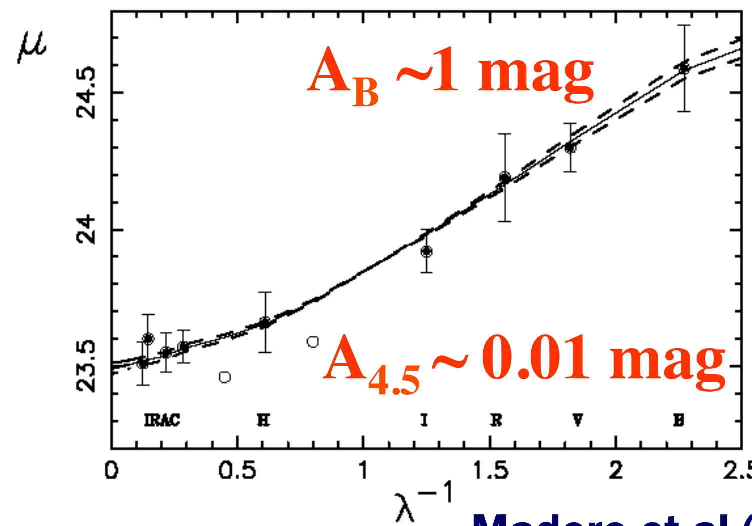
1. linear detectors: CCD's and IR arrays, <u>**HST**</u>
2. corrections for dust obscuration
3. tests for chemical composition differences

M33



WLF et al (1991)

NGC 6822



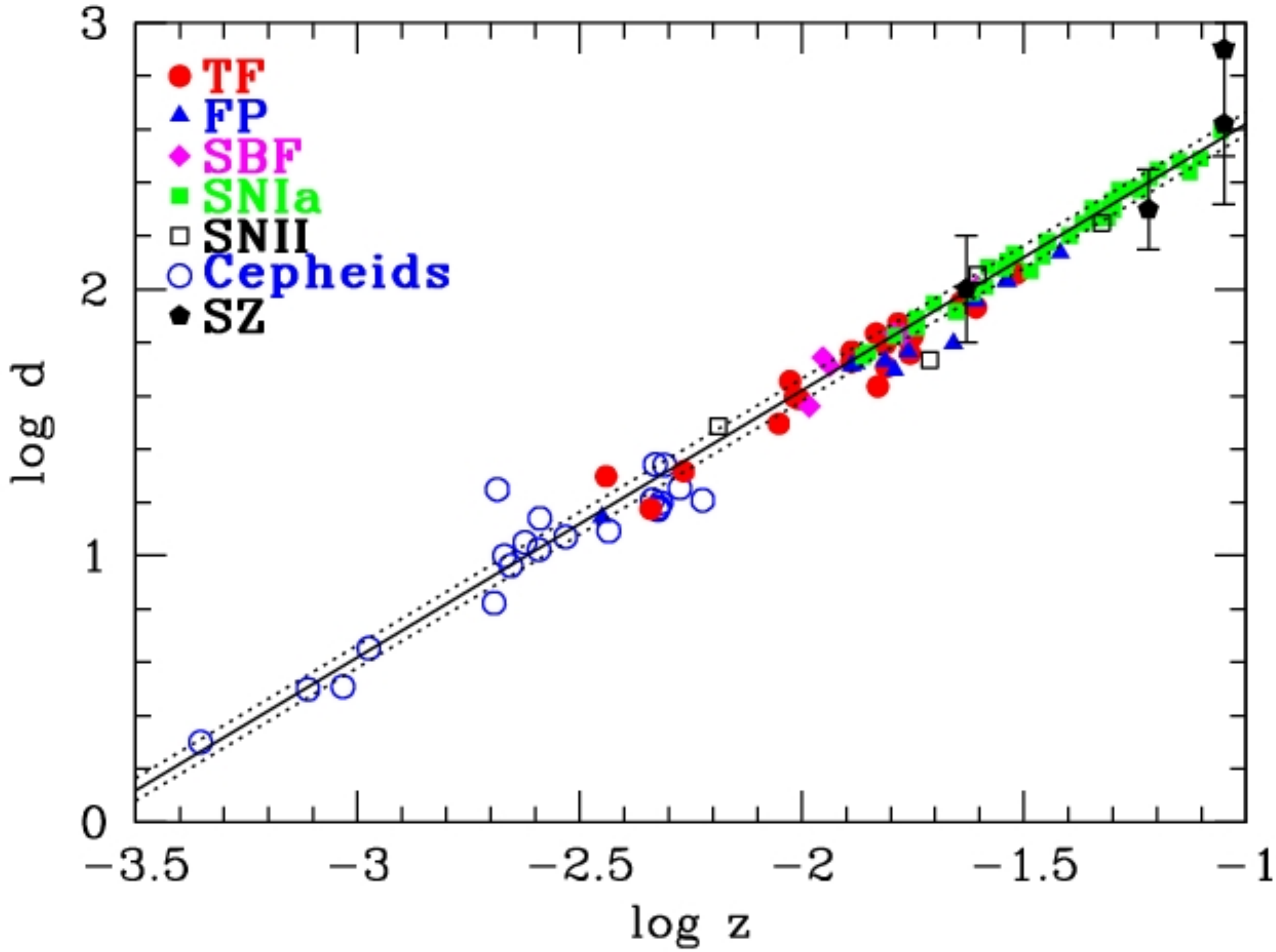
Madore et al (2009)

Distance modulus:

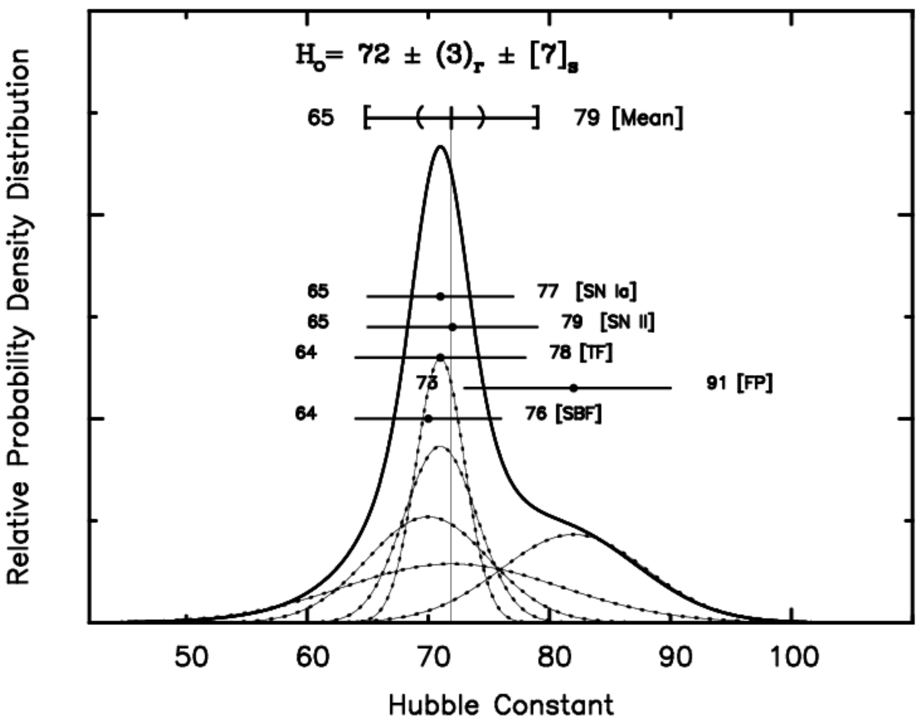
$\mu_0 = m - M = 5\log d_L + 25$ where d_L is in Mpc

The Hubble Key Project

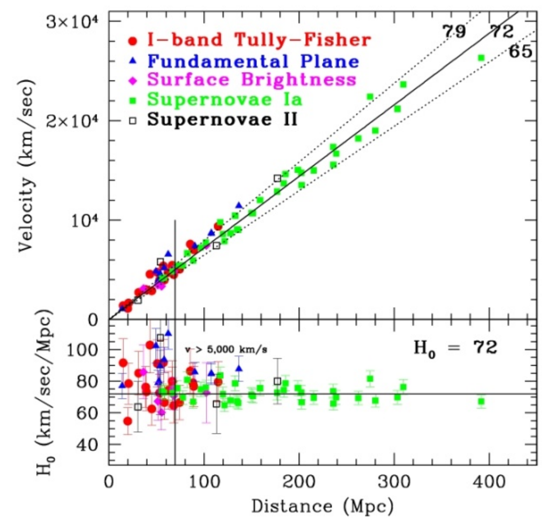
Key Project Results



Final Combined HST Key Project Results



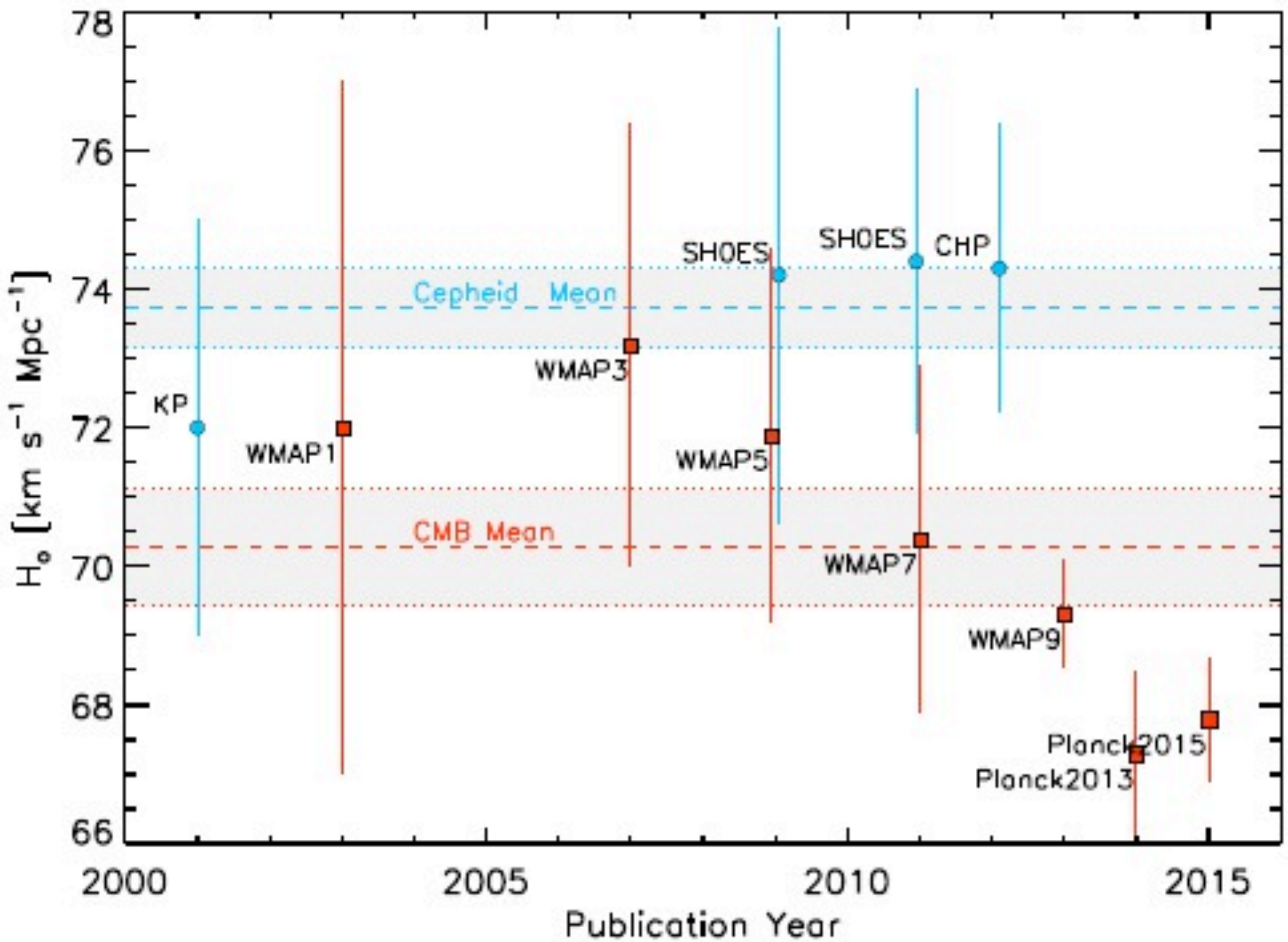
$H_0 = 72 \pm 3$ (stat.)
± 7 (sys.)
km s^{-1} Mpc^{-1}



WLF et al. (2001)

Post Hubble Key Project

H_o: Current State of the Art



"Tension" over the Expansion Rate of the Universe: Convergence or New Physics?

The Carnegie-Chicago Hubble Project

Carnegie Chicago Hubble Project (CCHP) II

Five-year program

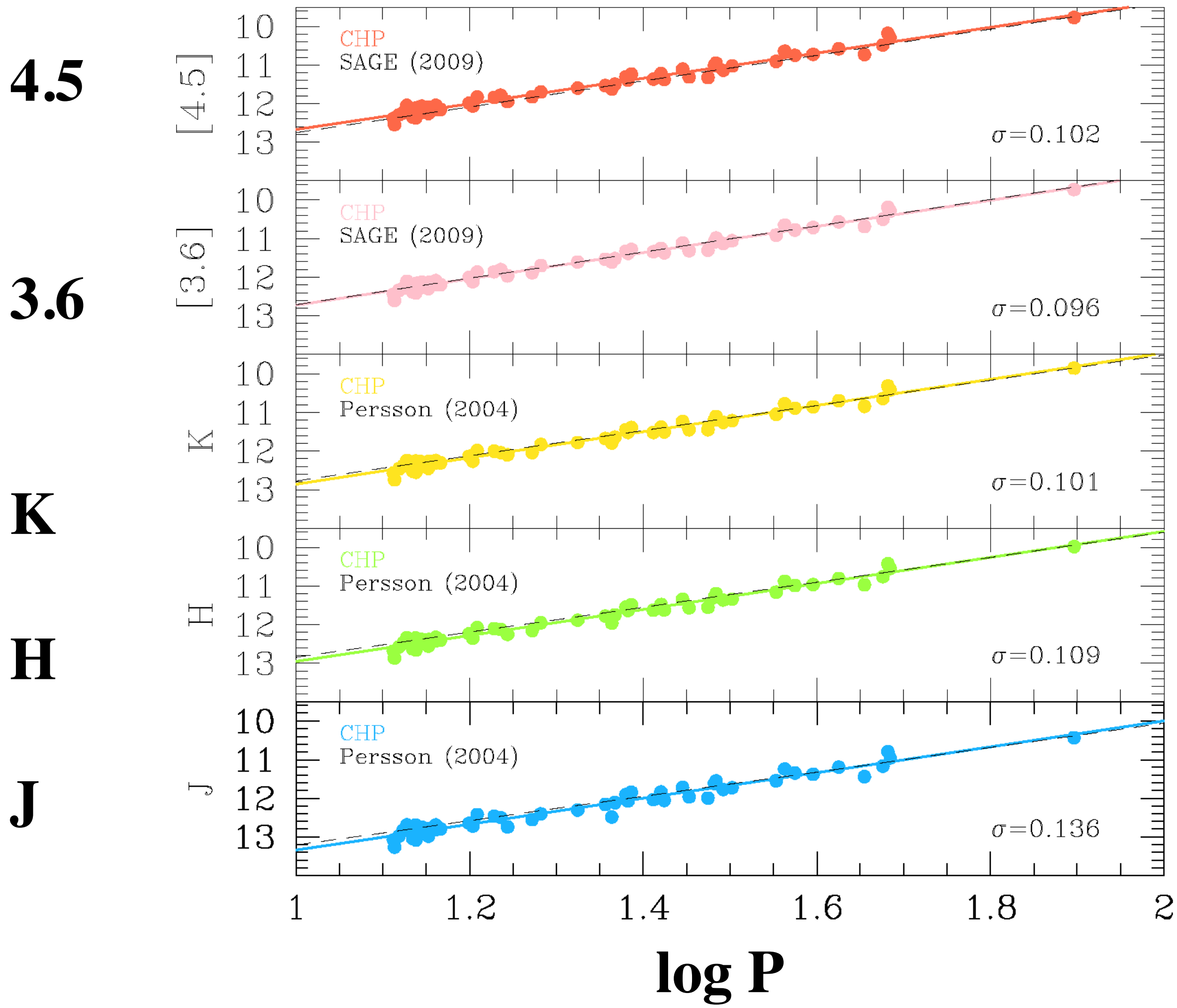
- **Science goals: To improve constraints on other cosmological parameters for which there are strong degeneracies in measurements of CMB anisotropies (Ω_Λ, w, N_{eff}, w_a , Σm_ν)**
- HST, Spitzer, Magellan, TMMT
- Recalibration of Extragalactic Distance Scale
- RR Lyrae, Cepheids, TRGB distances
- Calibrate distances for SNe Ia
- Goal: H_0 to 3%

CHP I : Spitzer as a Tool for Measuring Cepheid Distances

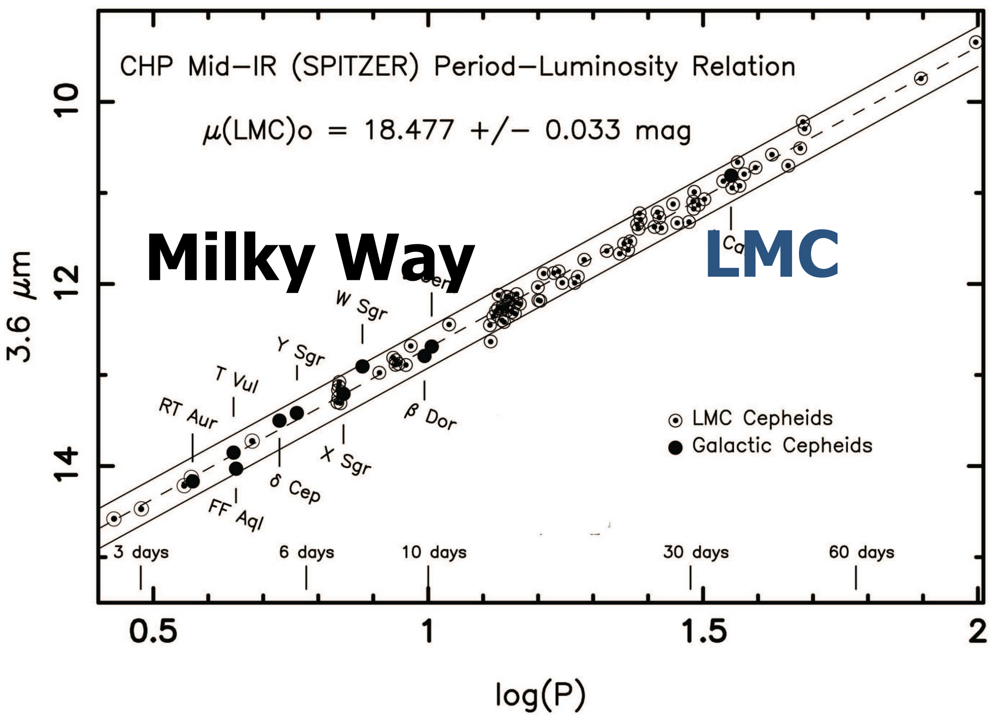
Advantage of Spitzer for the extragalactic distance scale:

- At 3.6 μm, A_λ is ~17 times smaller than at optical (V-band) wavelengths.
- Dispersion in Cepheid PL relation a factor of two to three smaller than in optical.
- Metallicity effects predicted to be negligible.

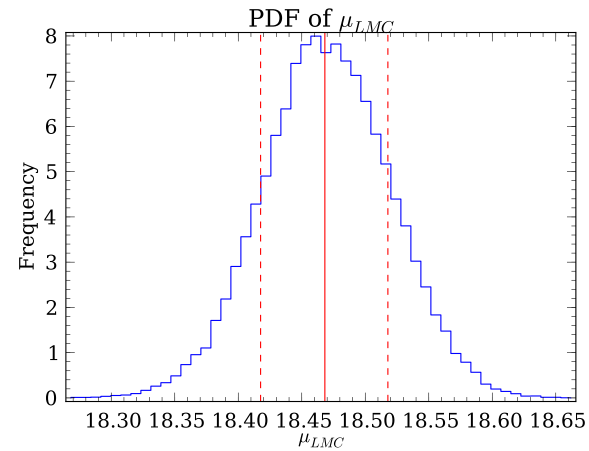
Near- and Mid-IR LMC PL (Leavitt) Relations



Comparison of Spitzer LMC and Milky Way Leavitt Laws



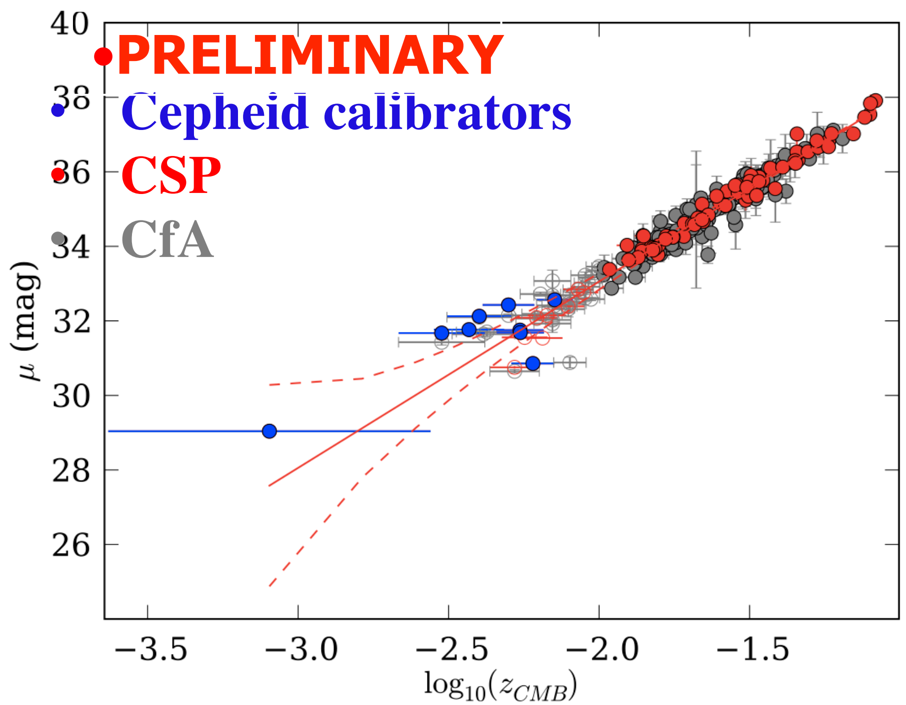
WLF *et al.* (2012)



μ_{LMC} = 18.48 ± 0.01 (stat)
± 0.03(sys)
d = 49.6 ± 0.8 kpc

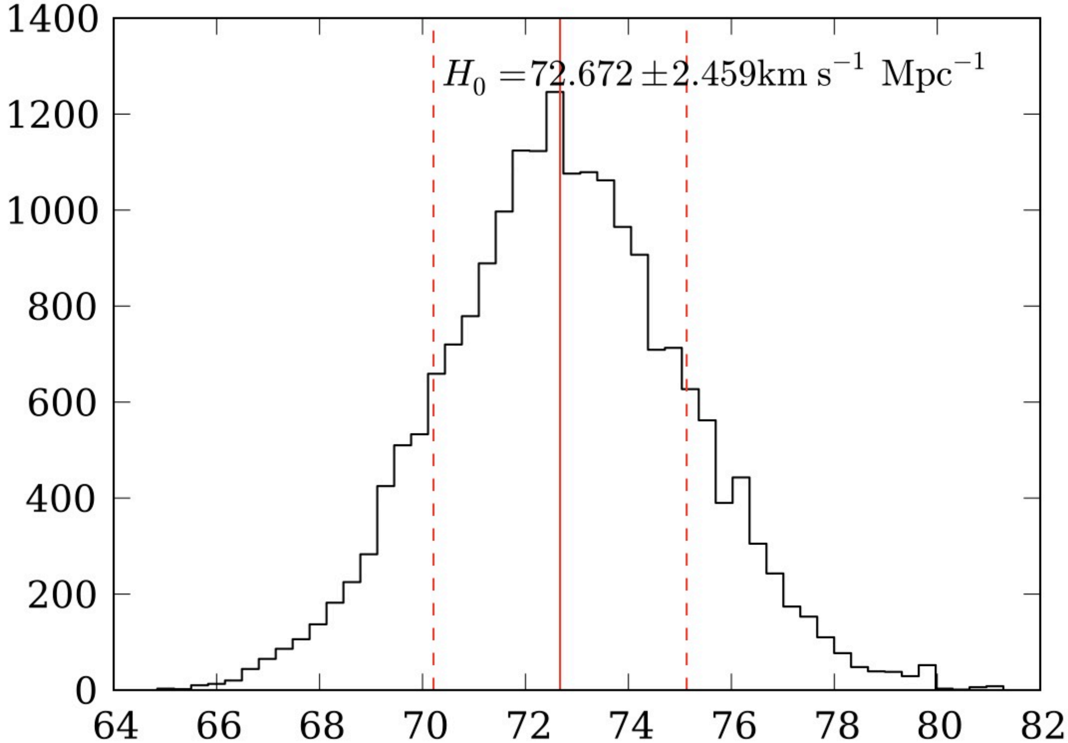
WLF *et al.* (2014)

H_o From Type Ia Supernovae



WLF et al. (2016)

MCMC histogram: Results for H_o



H_0 = 72.7 ± 2.5 km s $^{-1}$ Mpc $^{-1}$

[1 - σ standard deviation from MCMC chains]

- **LMC, N4258 + photometric zp Independent systematics; i.e., not determined from data in hand.**
- **All other parameters are nuisance parameters determined from the data**

Decreasing Systematic Errors in H_o

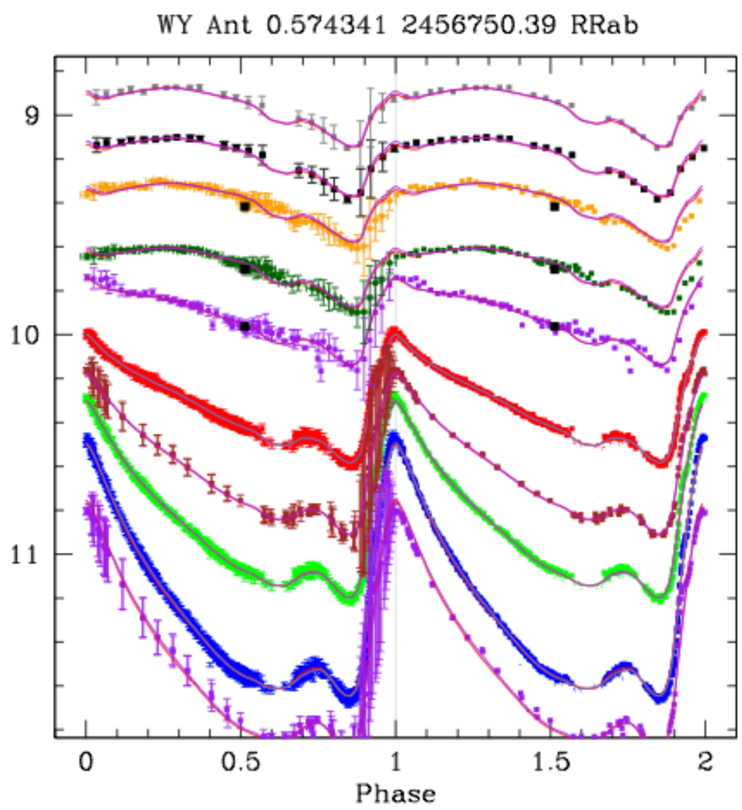
1. Develop methods independent of Cepheids and supernovae
   RR Lyrae and TRGB (σ ~2-3%)
2. Geometric Parallax calibration
   (σ ~1%)

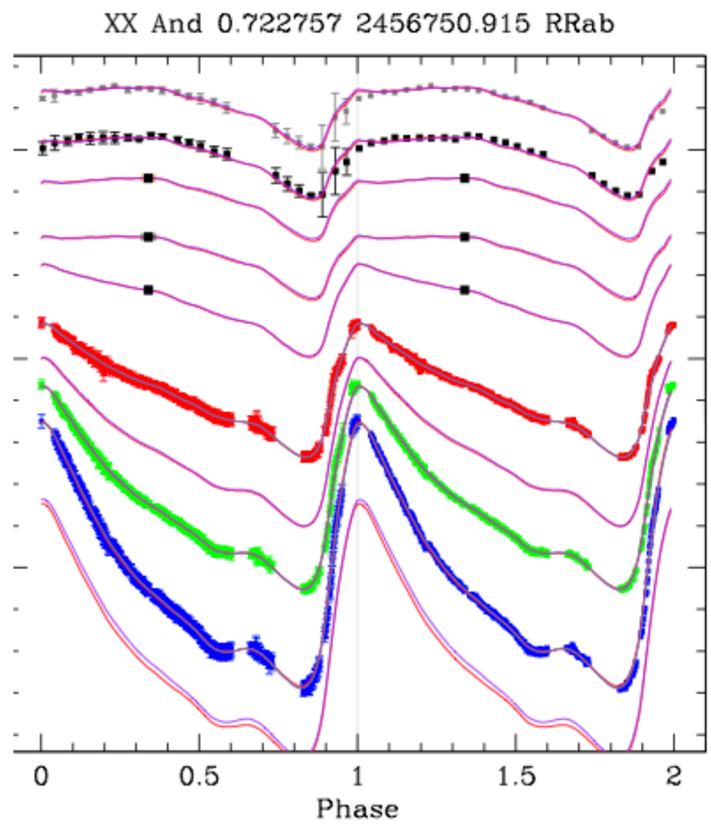
RR Lyrae Stars:
A Calibration Independent of Cepheids

TMMT***

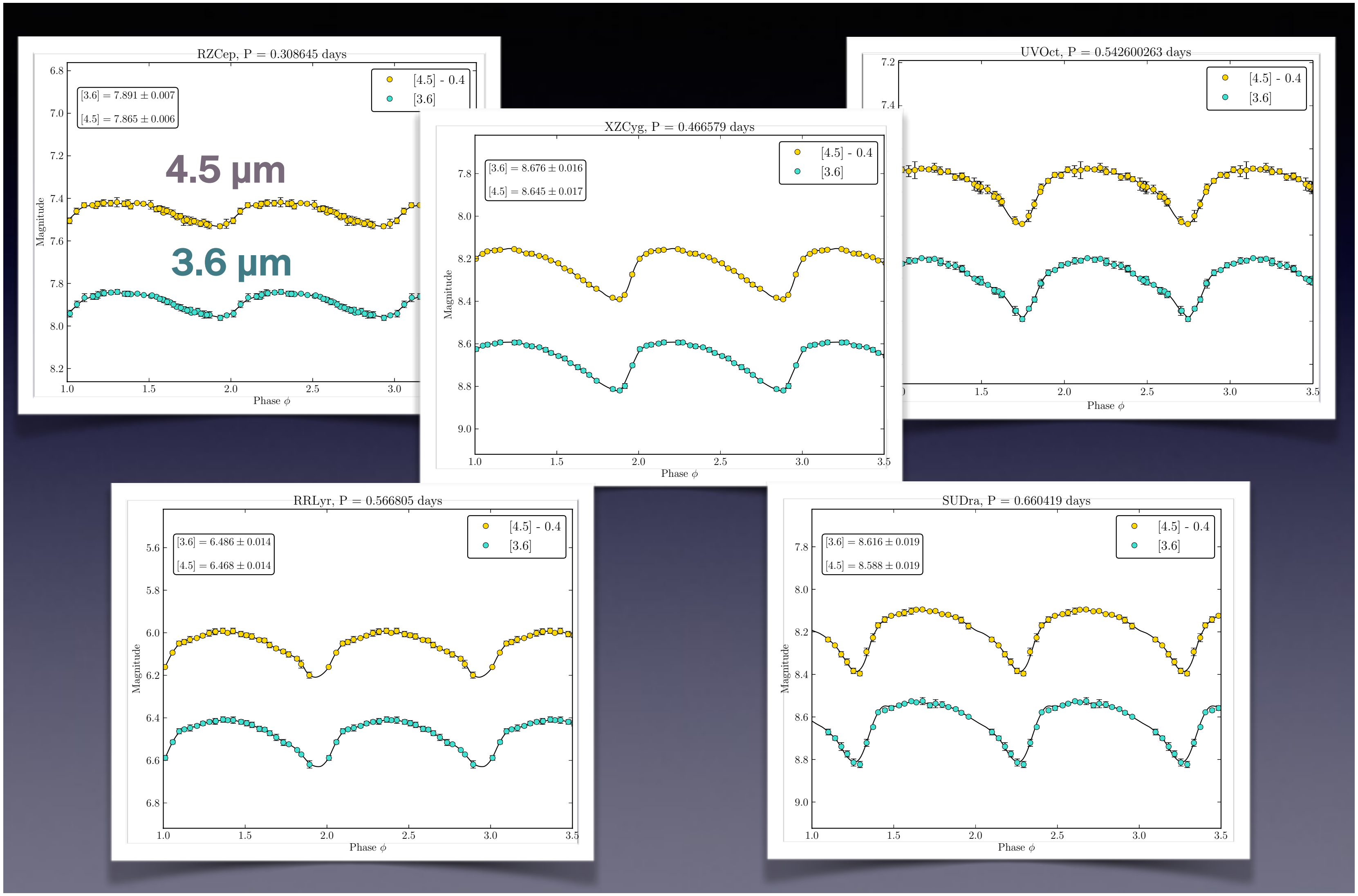
*** Three hundred Millimeter Telescope at Las Campanas looking at its dome flat screen.
Monitoring 1250 TRGB stars, 55 RR Lyrae ~20 B, V, I frames / star.

Galactic RR Lyrae Calibrators

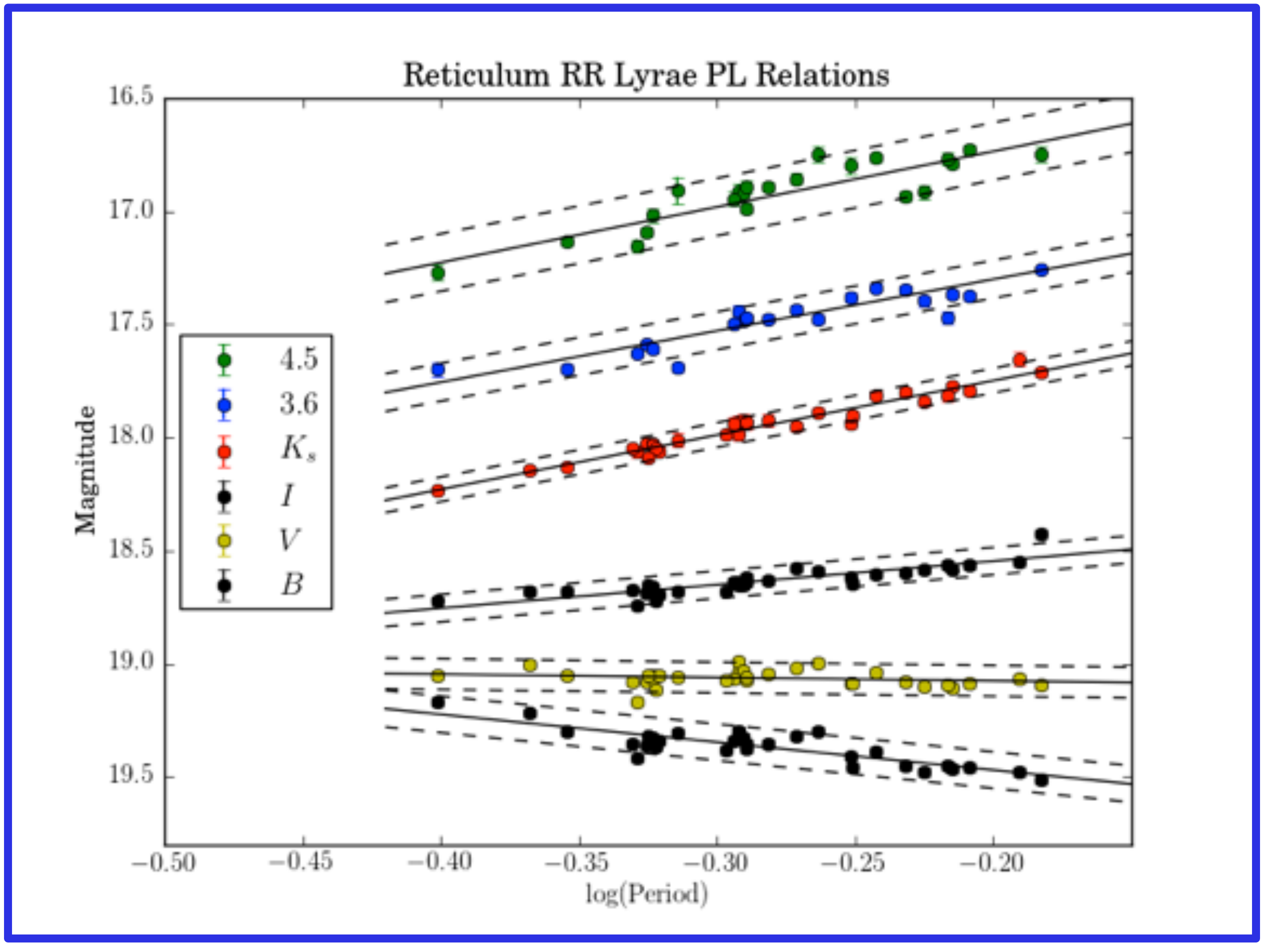




RR Lyrae Parallax Calibrator Sample



New Multi-Color RR Lyrae PL Relations



Near-IR wavelengths

σ ~ 0.05 mag

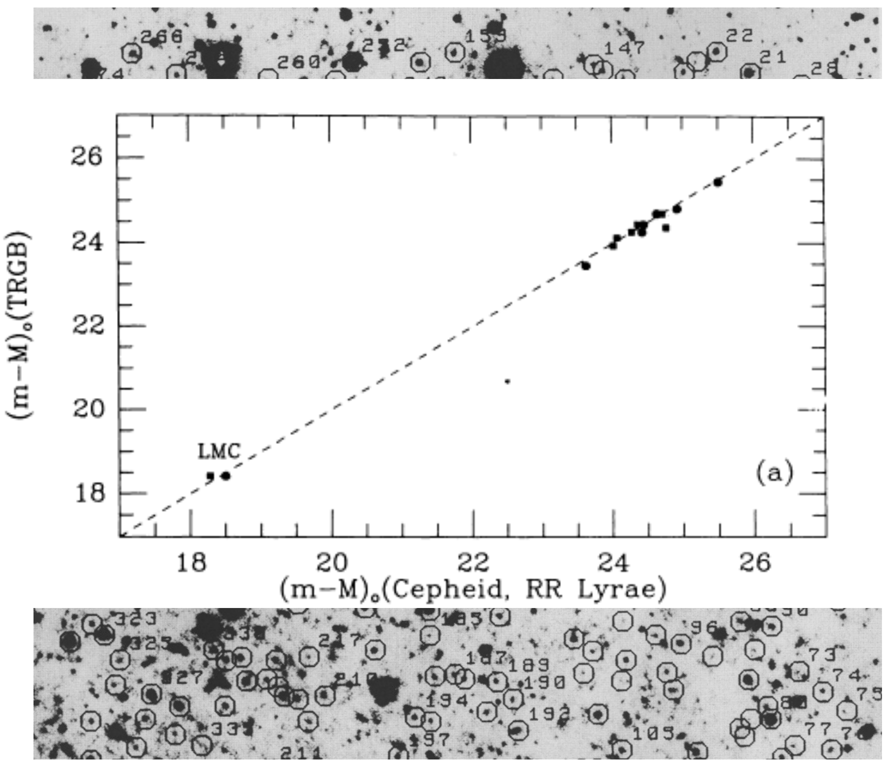
Cepheids ~ 0.1 mag

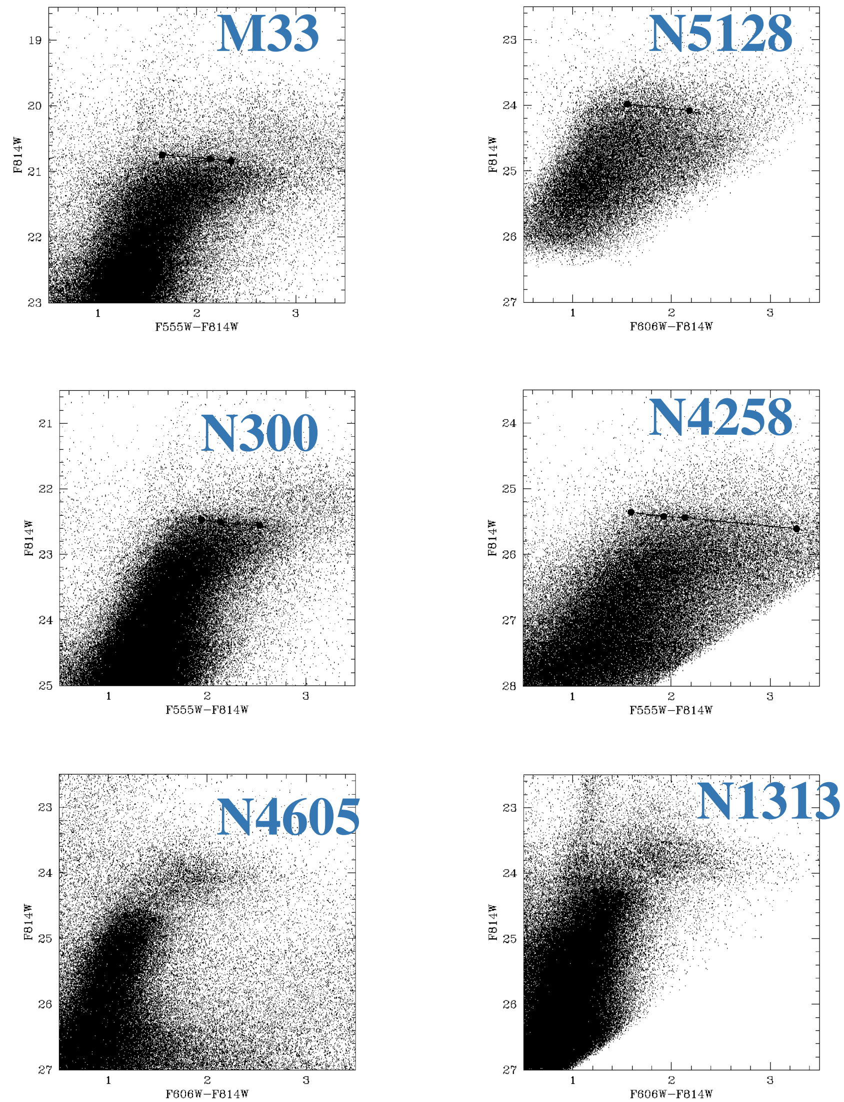
A. Monson et al.

Tip of the Red Giant Branch (TRGB) as a Distance Indicator

Lee, Freedman & Madore (1993)
Application of Sobel edge detector
Madore & Freedman (1997)

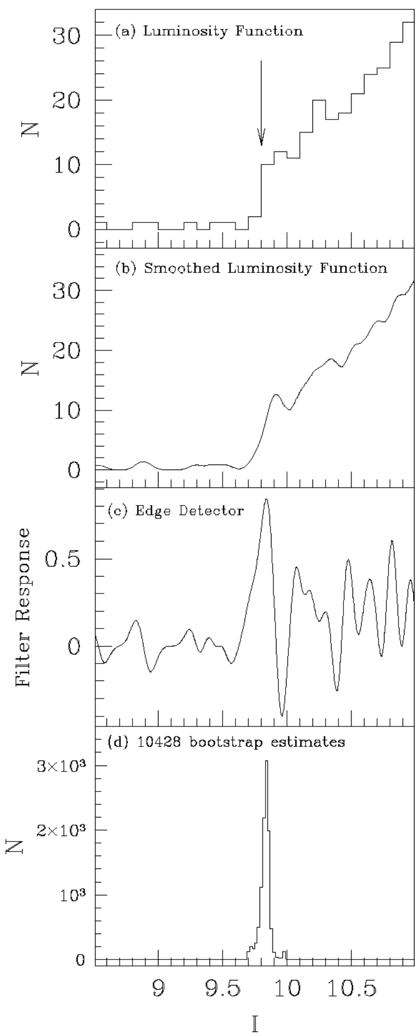
Arguably the best distance indicator for galaxies < 10 Mpc





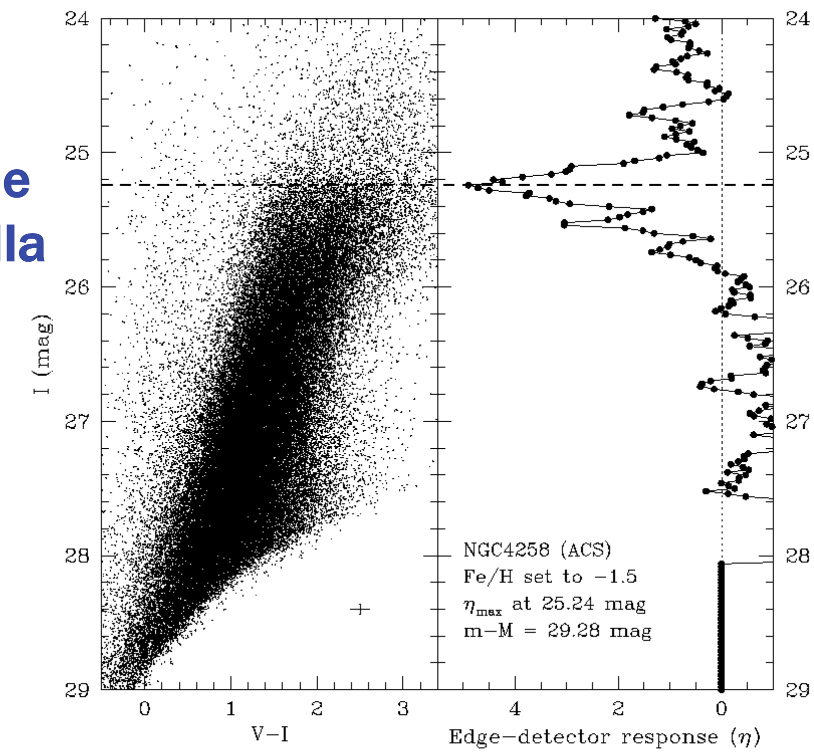
Rizzi et al. 2007

Tip of the Red Giant Branch as a Distance Indicator



CCHP II
Will double the number of SNIa calibrators

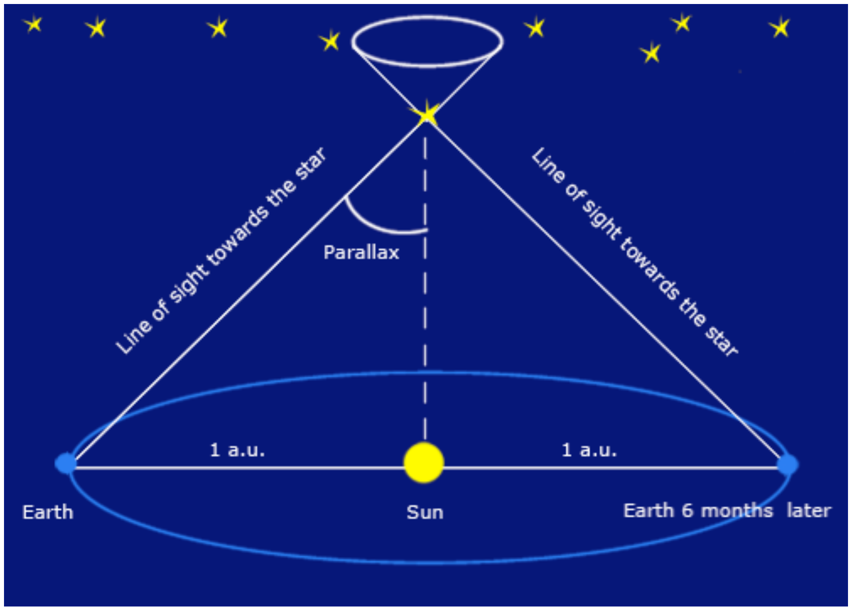
NGC 4258

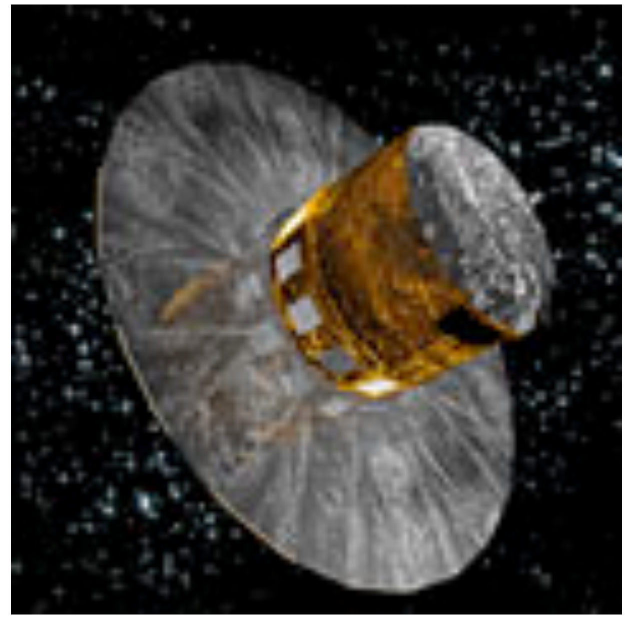


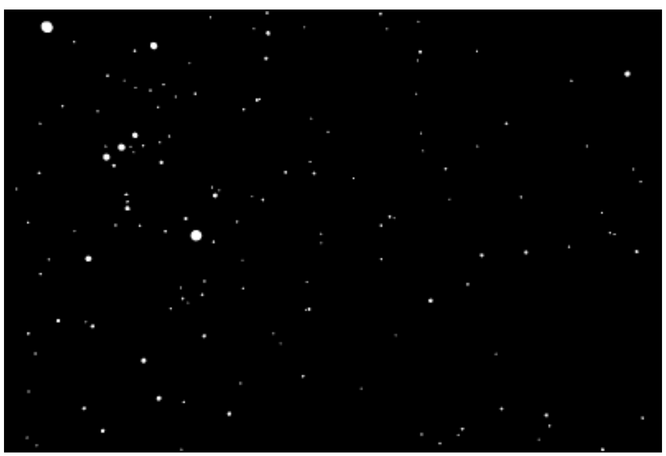
Mager, Madore, WLF (2008)

Bellazzini et al. (2001)

Parallax Measurements







Gaia

- A few microsecond accuracy
- Systematic survey of entire sky to 20 mag
- σ_π / π < 1% out to several kiloparsecs

Sources of Systematic Errors in H_o

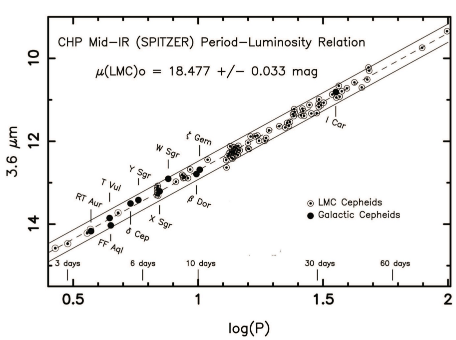
Freedman & Madore ARAA (2010) - dominant sources of error

Known	Key Project	Revisions	Anticipated	Basis
Systematics	(2001)	(2007/2009)	Spitzer/JWST	
(1) Cepheid Zero Point	±0.12 mag	±0.06 mag	±0.03 mag	Galactic Parallaxes
(2) Metallicity	± 0.10 mag	±0.05 mag	±0.02 mag	IR + Models
(3) Reddening	±0.05 mag	±0.03 mag	±0.01 mag	IR 20-30x Reduced
(4) Transformations	±0.05 mag	±0.03 mag	±0.02 mag	Flight Magnitudes
Final Uncertainty	±0.20 mag	±0.09 mag	±0.04 mag	Added in Quadrature
Percentage Error on H_0	±10%	±5%	±2%	Distances

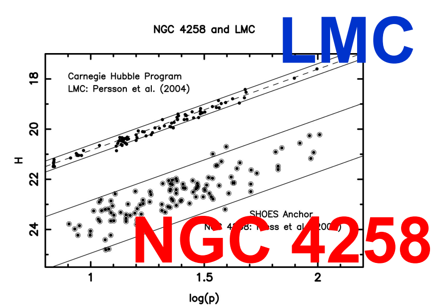
We are here

Where Improvements to Systematics Are Needed:

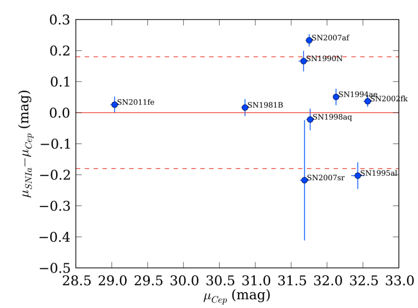
1. HST parallaxes



2. NGC 4258 scatter



3. Few SN calib.s



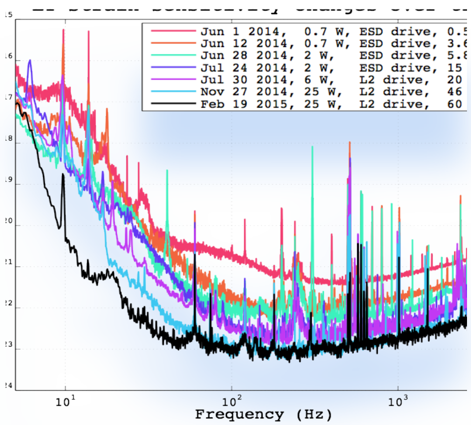
4)
Future Measurements

Other Future H_o Measurements: Target H_o to 1%: (sys + stat)

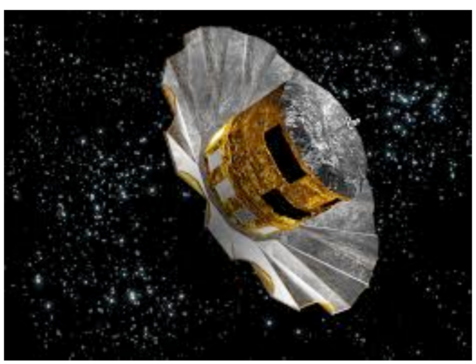
Overcoming Systematics

LIGO

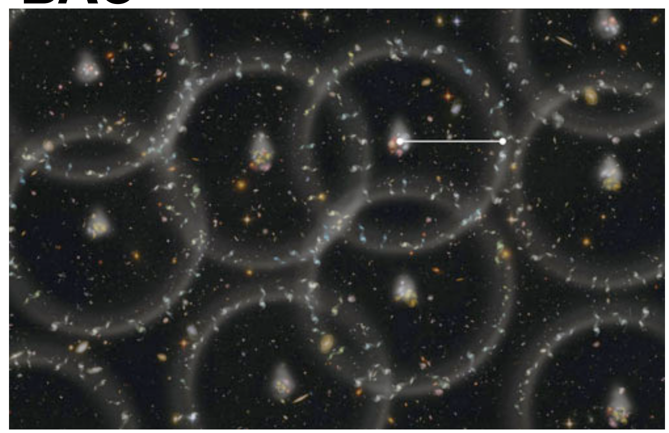
Gravitational Waves



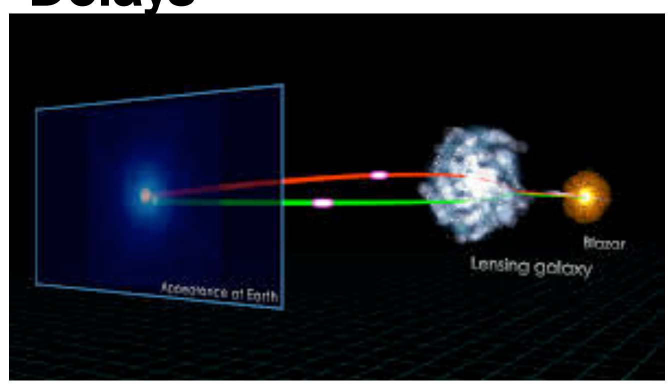
Gaia Calibration of Cepheid/RRL/SNIae



BAO



Gravitational Lens Time Delays



For robust measurement at least 3 independent methods with uncertainties at ~1% level

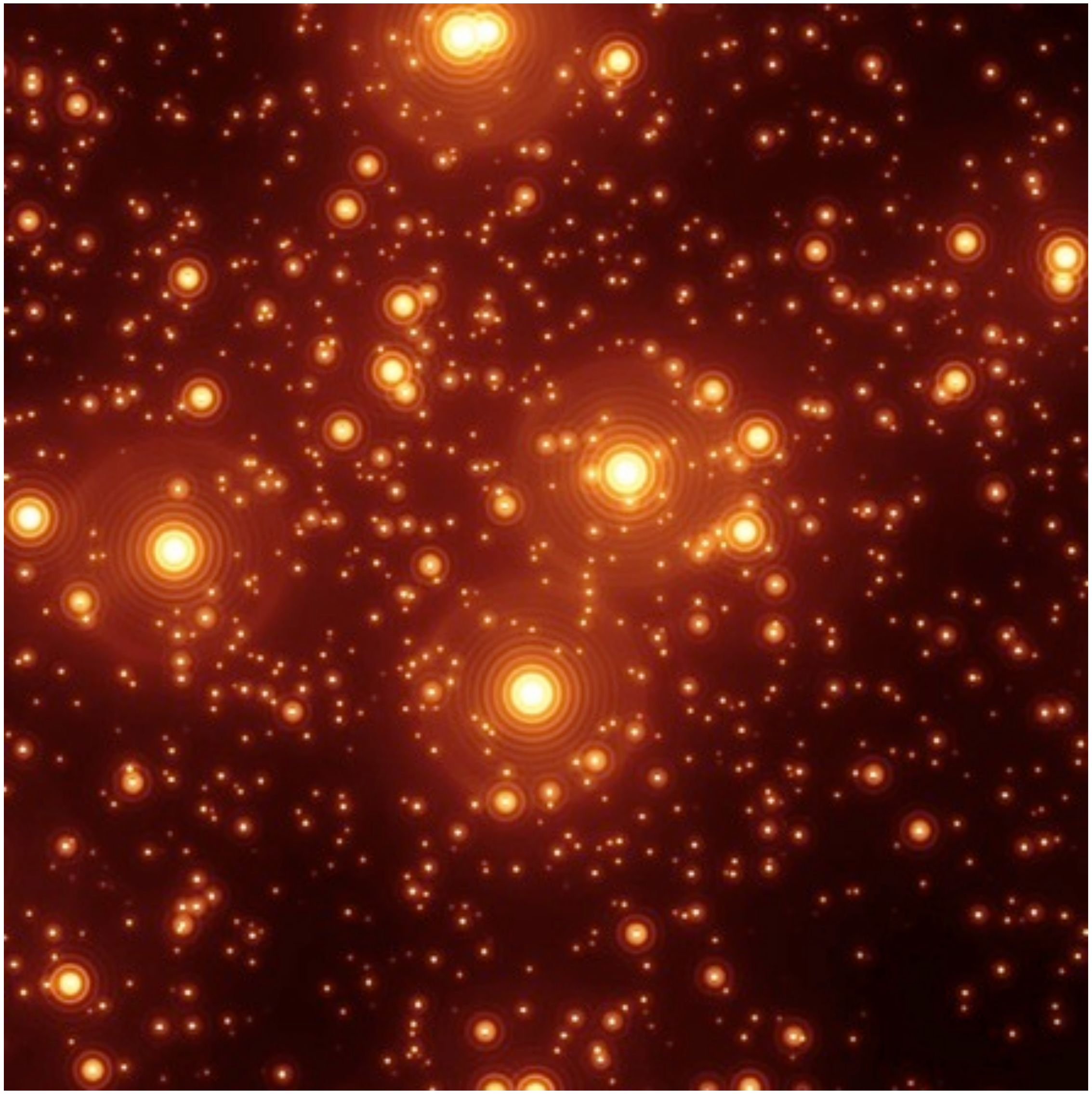
The Giant Magellan Telescope

GMT Resolution

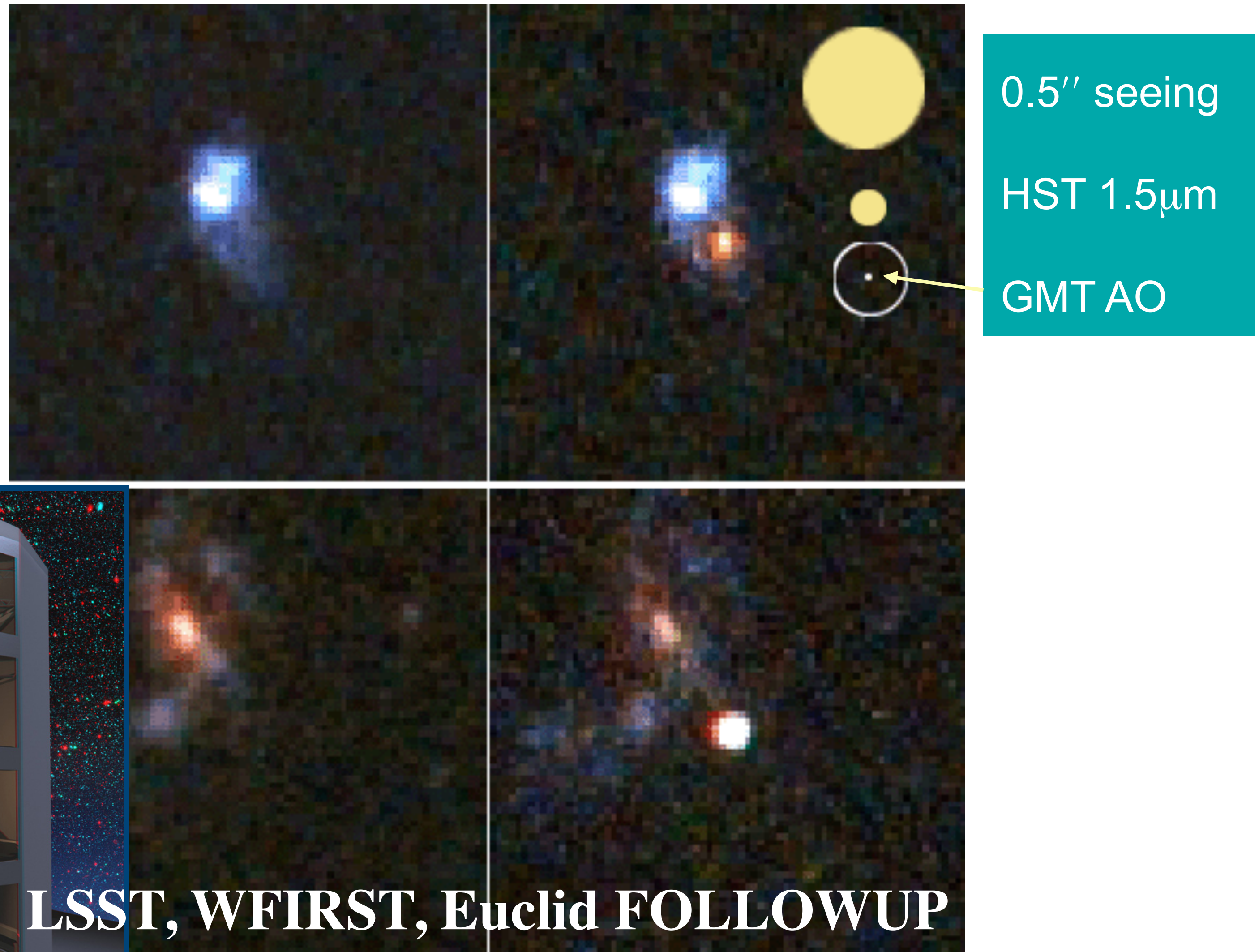
0.6” seeing

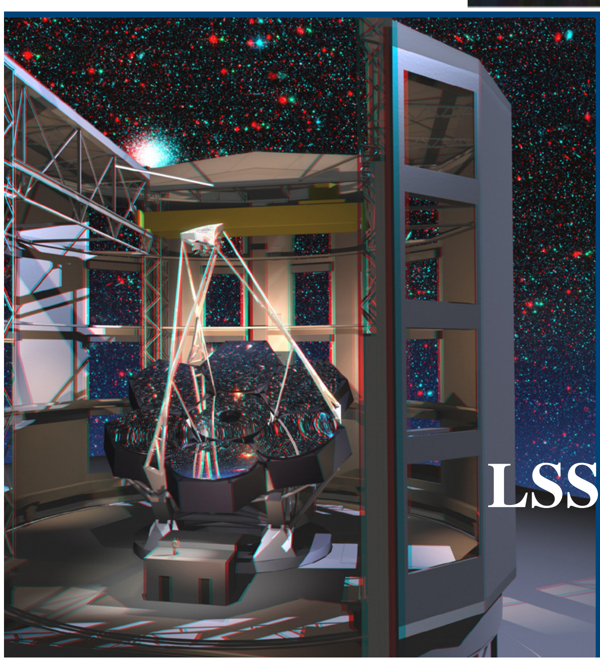
JWST + NIRCAM

GMT



The Future
SNe Ia & The GMT

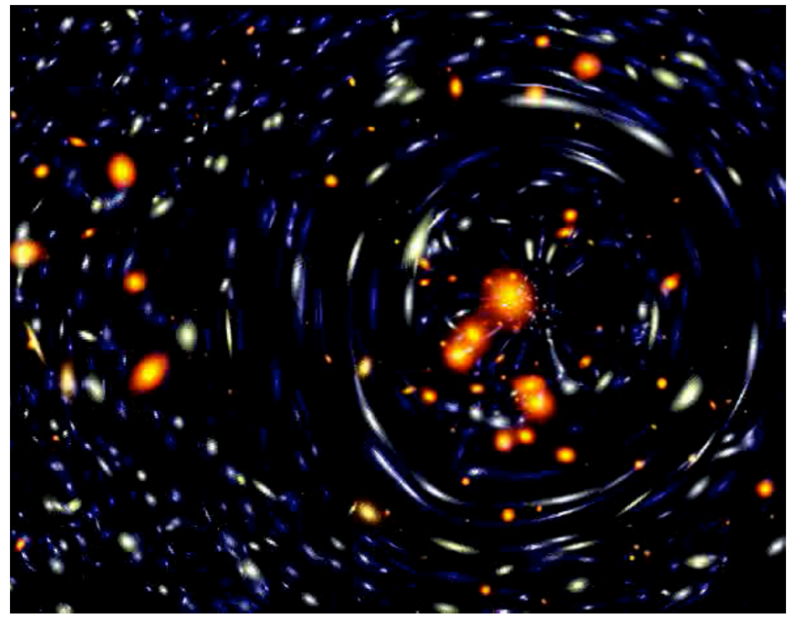




LSST, WFIRST, Euclid FOLLOWUP

LSST and Dark Energy

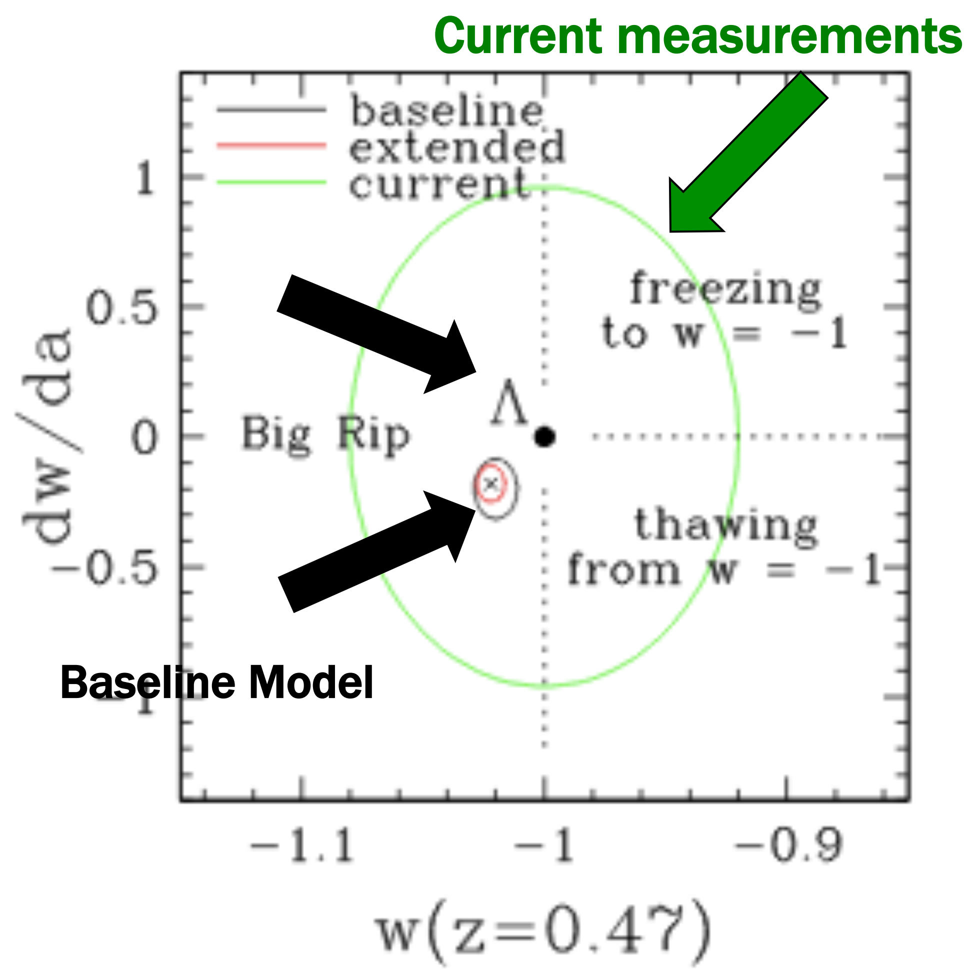
- 250,000 resolved high-redshift galaxies per square degree.
- full survey will cover 18,000 square degrees.
- Four Probes of Dark Energy:
  - Weak lensing (10^9 galaxies)
  - Clusters of galaxies
  - BAO
  - Supernovae



WFIRST
Wide-Field InfraRed Survey Telescope

mid-2020s launch

WFIRST



Current measurements
baseline
extended
current
freezing to w = −1
Λ
Big Rip
thawing from w = −1
Baseline Model
1
0.5
0
−0.5
−1.1
−1
−0.9
dw/da
w(z=0.47)

Summary of Current Results

- ΛCDM provides an excellent fit to a wide variety of observational/experimental data
- $w = P / \rho = -1.0 \pm 10\%$
- $H_0 = 70 \pm 3$ km s^{-1} Mpc^{-1} [95% CL]

Concluding Remarks

- The last couple of decades have seen a remarkable convergence on the basic properties of the cosmological model for our universe.
- The next couple of decades hold the promise of opening entirely new windows (gravitational wave detection, 21cm tomography). In the optical/IR, huge increases in resolution and/or sensitivity (the ELTs, JWST, WFIRST, DES, LSST) to open and exploit these new frontiers.
- What is the new physics beyond this current standard cosmological model?
  - A new generation of experiments and are well-poised to address this question
  - Chicagoland is well-poised to play a leading role in this effort