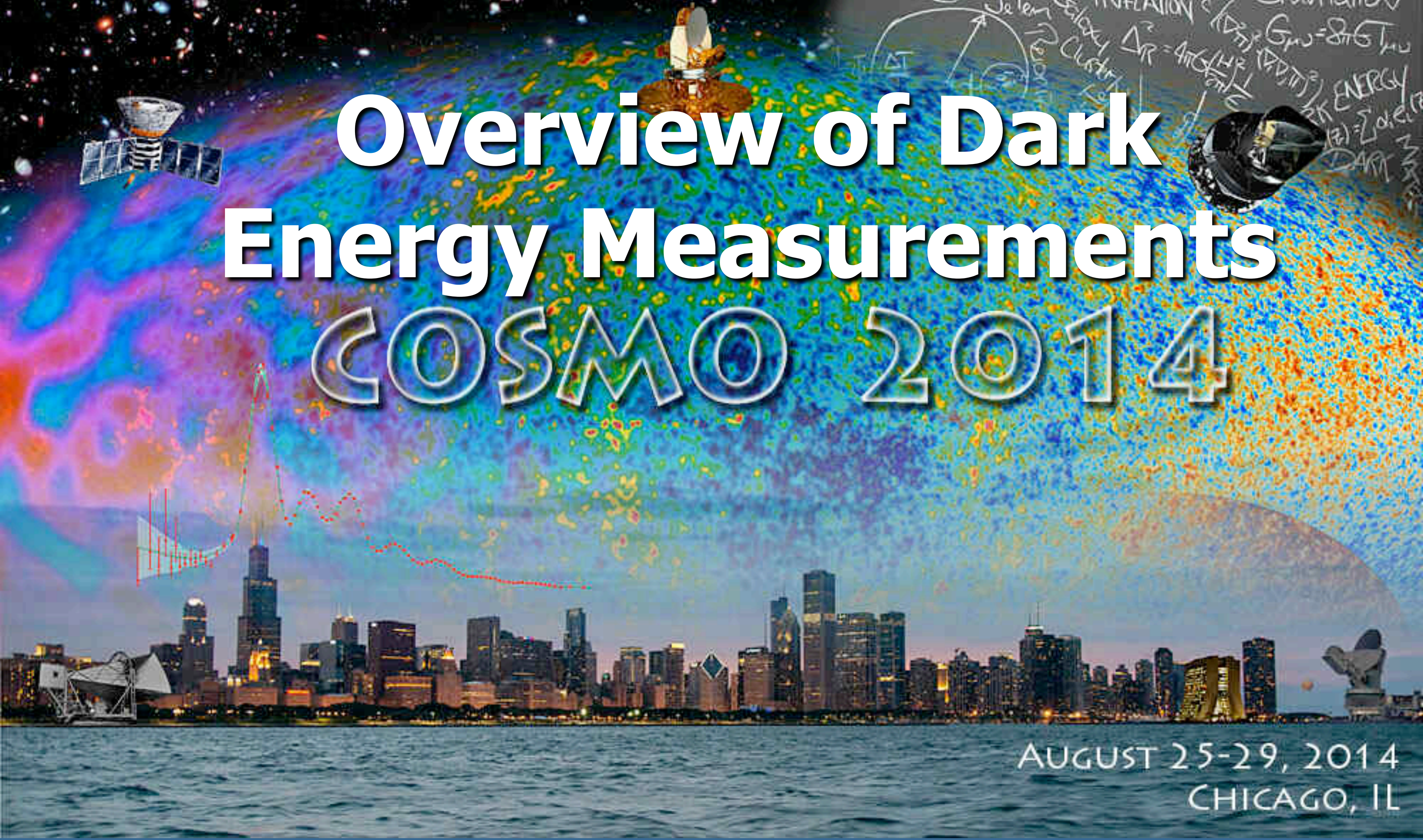
Overview of Dark Energy Measurements



Wendy L. Freedman

Historical Summary

- **1980:**
  - **Visible universe Ω_b ~0.005**
  - **Observers: Ω_M= 0.2**
  - **Inflation, flat universe: Ω=1**
  - **Dark Matter: Ω=0.995 (surmised)**
  - **$50 < H_0 < 100$ km s^{-1} Mpc^{-1}**

- **2014:**
  - **Visible universe Ω_b= 0.04**
  - **Inflation, flat universe: Ω=1**
  - **Matter: Ω_M =0.3**
  - **Dark Energy: Ω_{DE} =0.7**
  - **$67 < H_0 < 73$ km s^{-1} Mpc^{-1}**

Dark Energy

- **Challenges**
  - **Why is the energy of the vacuum so small?**
    - **Why is $\rho_{vac} \approx 10^{-120} M^4_{Planck}$?**
  - **Coincidence problem:**
    - **Why is $\rho_{vac} \approx \rho_{matter}$?**
- **Characterize by equation of state**
  - **$p = w\,\rho$**
  - **For vacuum energy, w = -1 (for all time)**

$$\boxed{H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right]}$$

- **Is the dark energy dynamical?**
  - **$w \neq -1$ or $w' \neq 0$**
  - **$w(a) = w_0 + (1-a)w_a$**

- **Radiation dominates early in the Universe**
- **Dark energy dominates now**

Interpretation of Observed Acceleration

- Repulsive gravity? Fluid with negative pressure?
  - Vacuum energy constant in time (Einstein's cosmological constant)?
  - Field with energy density varying with time? Quintessence?
- Large-scale inhomogeneities?
- Does GR break down on cosmological scales?
- Are we asking the right question(s)?

Summary of Current Results

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

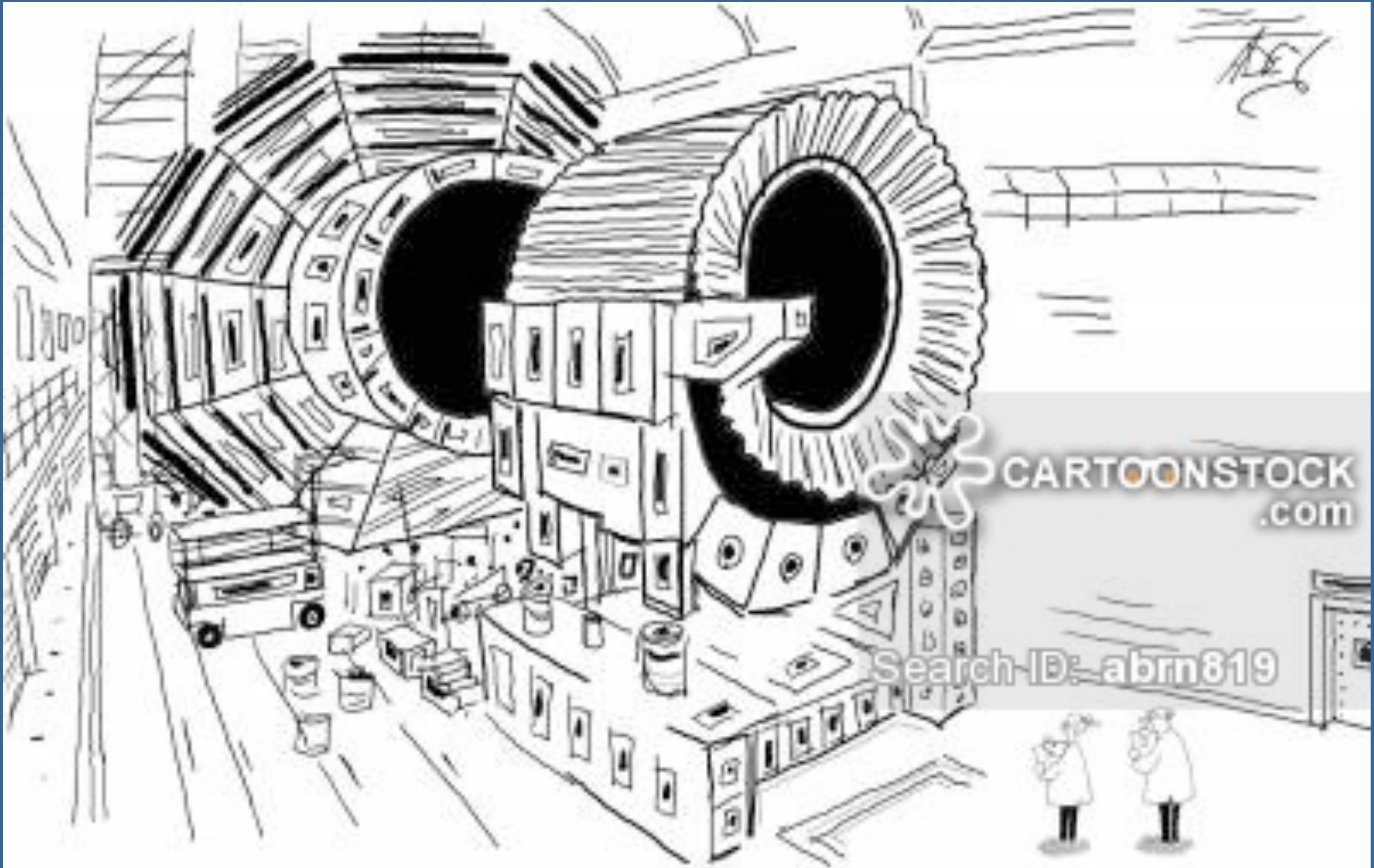
- **Knop et al (2003), Riess et al (2004), Astier et al (2006), Wood-Vasey et al (2007), Frieman et al (2009), Freedman et al (2009), Eisenstein et al (2005), Kamutsu et al (2009), Hicken et al (2009), Kessler et al (2009), Amanullah et al 2010, Conley et al 2011, Suzuki et al 2011, Riess et al 2011, 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 …**

Summary of Current Results

- Results to date consistent with
  - $w = P / \rho = -1.0 \pm 10\%$
  - i.e., All results to date consistent with a cosmological constant
  - And we are no closer to any understanding of dark energy

Caveats

- Dark Matter: no detection
- Dark Energy: no viable theory (evidence for acceleration but not that dark energy is causing it)
- Is GR complete?
- In a historical context: we still need to keep vigilant to the possibility of epicycles



"If all else fails - it makes a great frothy latte."

Cosmological Framework

Density fluctuations increase their amplitude with time.
Quantify this by the *growth factor g:*

$$\ddot{g} - 2H\dot{g} = 4\pi G\rho_m g = \frac{3\Omega_m H_0^2}{2a^3} g$$

e.g., weak lensing
clusters

If general relativity is correct there is a one-to-one mapping of D(z), the distance-redshift relation, and g(z).

$$D(z) = \int_{t(z)}^{t_0} \frac{c\,dt'}{a(t')} = \int_0^z \frac{c\,dz'}{H(z')}$$

e.g., supernovae
baryon oscillations

"Frankly, I even find it hard to believe some of the things I've been coming up with."

The Dark Energy Task Force

Observational Program (Dark Energy Task Force: Albrecht et al 2006)

- $H(z)$
  - $d_L(z)$
    - supernovae
    - clusters
  - $d_A(z)$
    - baryon oscillations
    - strong lensing
    - weak lensing
  - $V(z)$
    - clusters
    - strong lensing

- Growth of Structure, g(z)
  - clusters
  - weak lensing
  - $P(k,z)$

- Test gravity
  - solar system
  - millimeter scale
  - accelerators
  - $P(k,z)$

Dark Energy Measurement Methods

- Supernovae
- Baryon Acoustic Oscillations
- Weak Lensing
- Cluster Surveys
- CMB plus BAO, SNeIa, LSS, H_0

What is Needed?

- **Test for and minimize systematics!**
- **<u>All</u> methods**

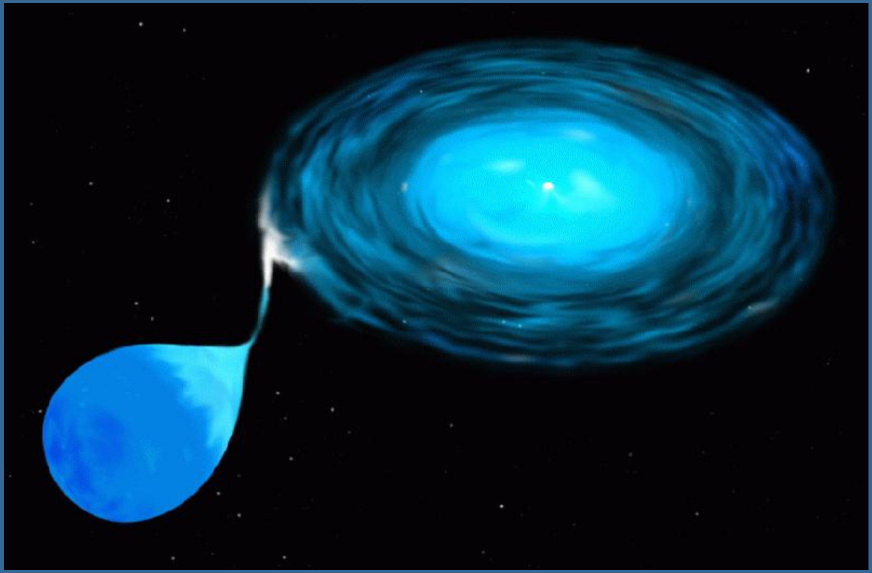
Supernovae

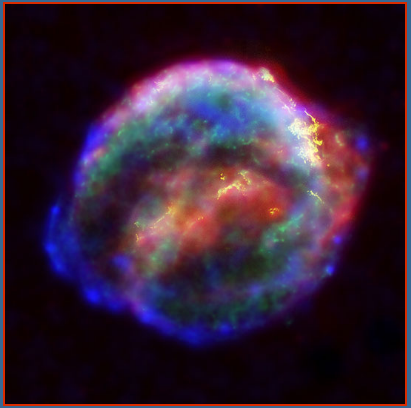
Type Ia Supernovae

- Supernovae
  - H(z) to z ~ 2
  - Ongoing and future ground-based and space projects
  - Cosmic variance not an issue
  - Small quantified dispersion
  - Key challenges: photometric calibration, evolution, metallicity, reddening, degeneracy of w with Ω_m

Type Ia Supernovae

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





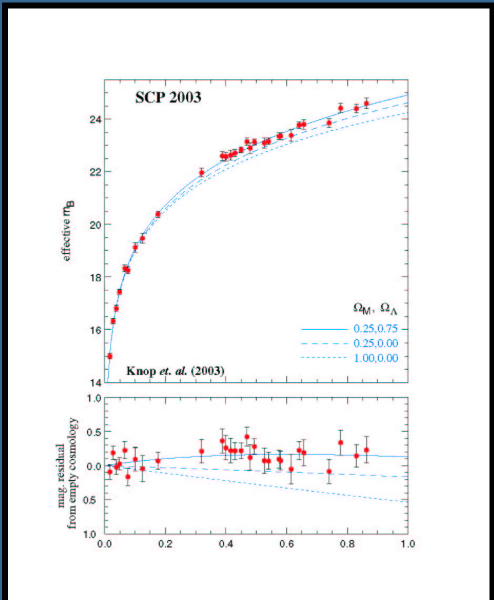
Inverse-square law: Flux = Luminosity / $4\pi\, d_L^{\,2}$

$$d_L(z) \propto r(z)(1+z)$$

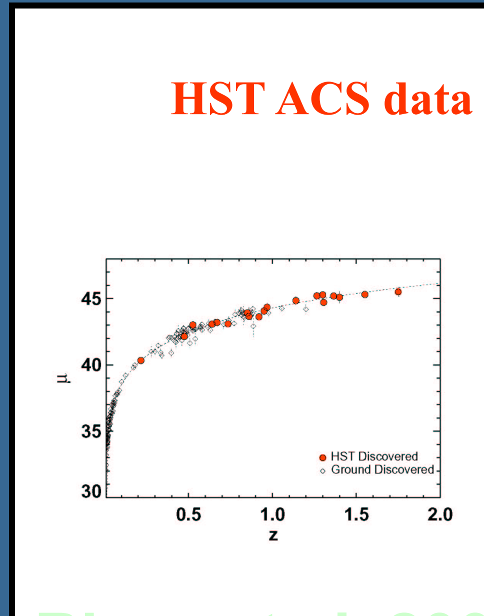
$r\,(z)$ determined from

$$\int_0^{r(z)} \frac{dr'}{\sqrt{1-kr'^2}} = \int_0^{z} \frac{dz'}{H(z')}$$

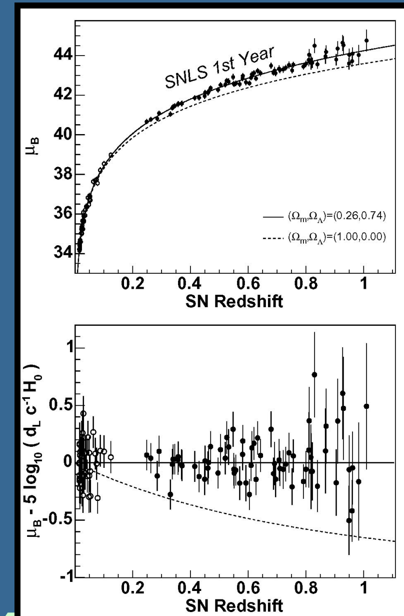
SNe Ia and Cosmology



Knop et al. 2003

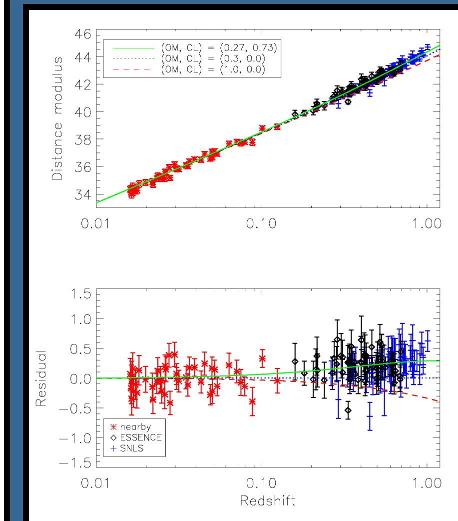


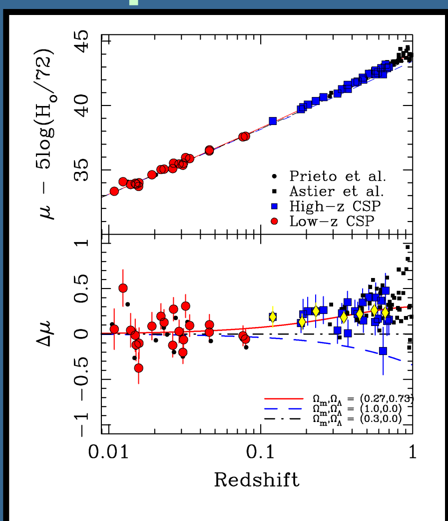
Riess et al. 2004



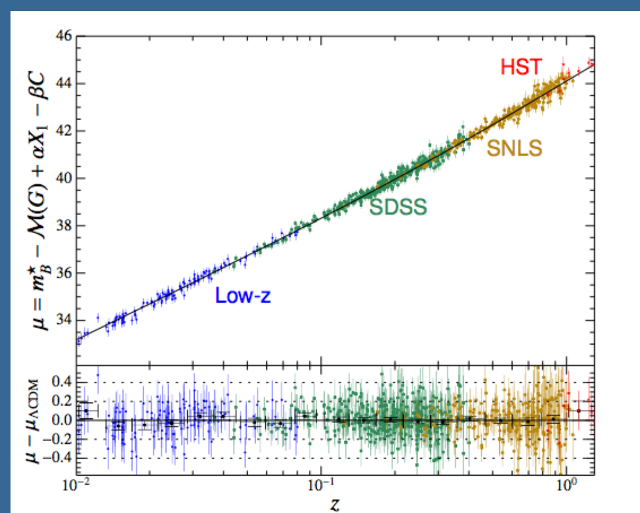
Astier et al. 2006

Wood-Vasey et al. 2007

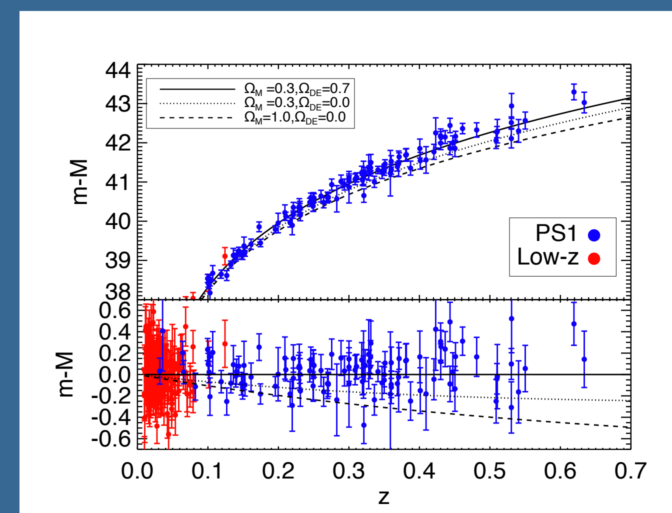




WLF et al. 2009

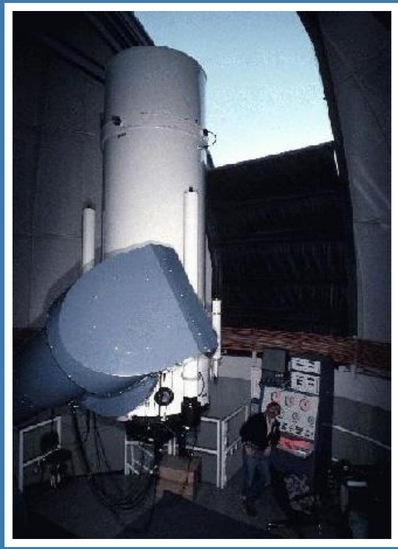


Betoule et al. 2014



Rest et al. 2014

Carnegie Supernova Project (CSP)



Swope 1-meter

Dupont 2.5-meter

Magellan 6.5-meter

Low z:

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

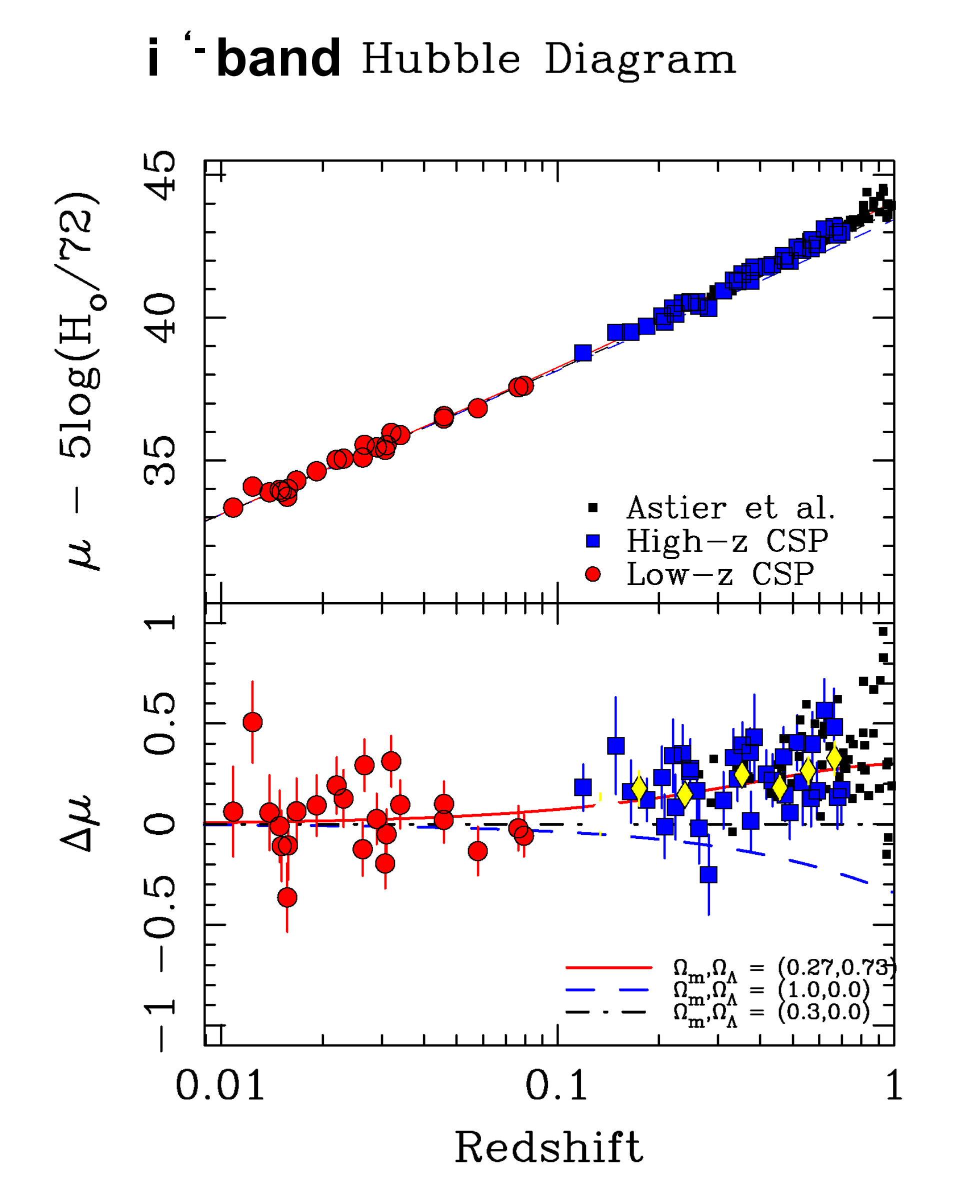
0 < z < 0.1

High z:

- YJ photometry
- Magellan 6.5-meter

0.1 < z < 0.7

Carnegie Supernova Project (CSP)



CSP data:

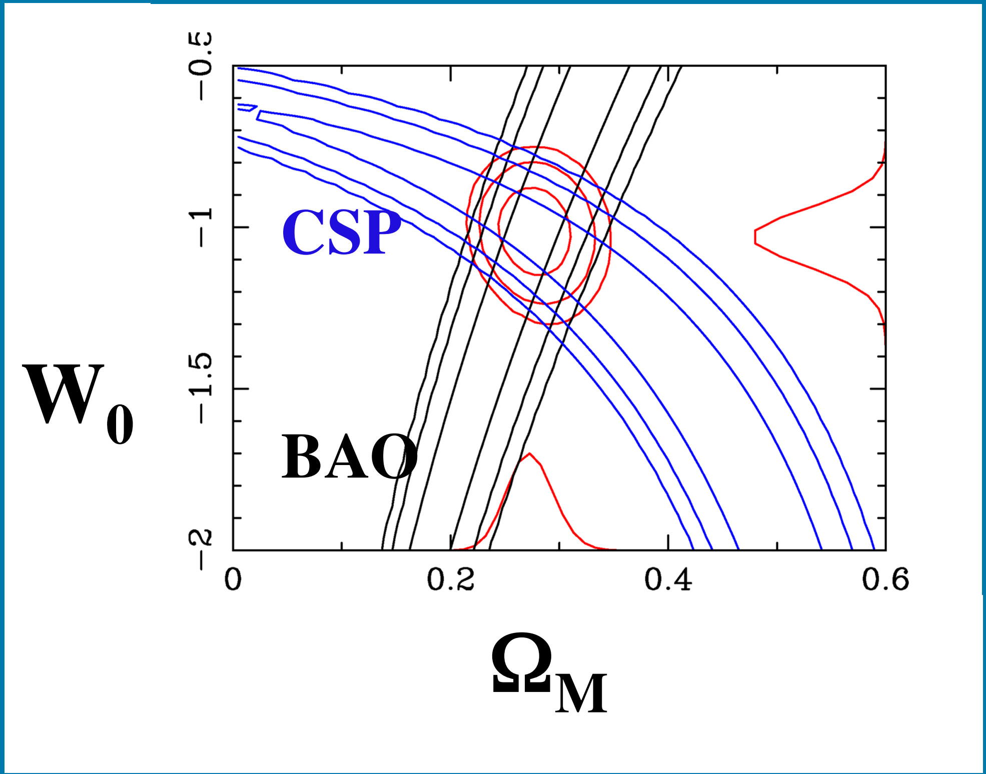
35 Type Ia supernovae
0.18 < z < 0.68

21 Type Ia supernovae
0.01 < z < 0.07

First I-band Hubble diagram at z > 0.07

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

Carnegie Supernova Project



Joint constraints: CSP+BAO
(BAO: Eisenstein 2005):

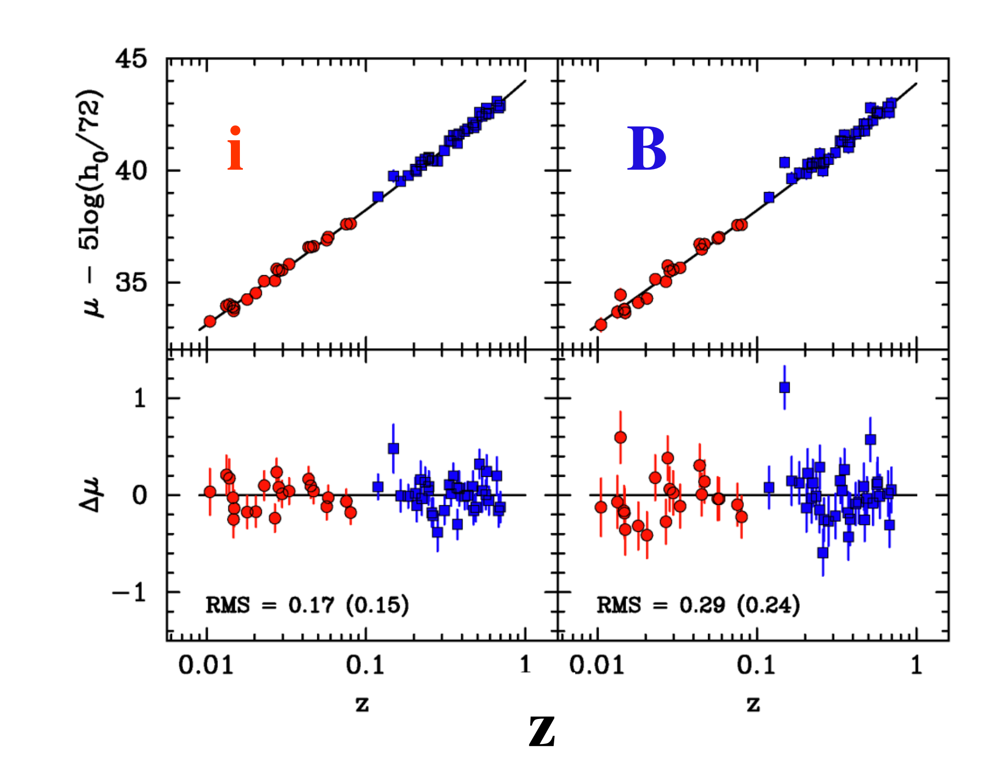
$\Omega_M = 0.27 \pm 0.02$ (stat)
$w_0 = -1.05 \pm 0.13$ (stat)
± 0.09 (sys)

Systematic errors included

Assume flatness

WLF et al. 2009

Uncorrected Hubble Diagrams



rms i-band: ±0.17 mag

rms B-band ±0.29 mag

What if ignore reddening?

i-band:

Ω_m = 0.29 ±0.03 (stat)

w_0 = -0.90 ±0.14 (stat)

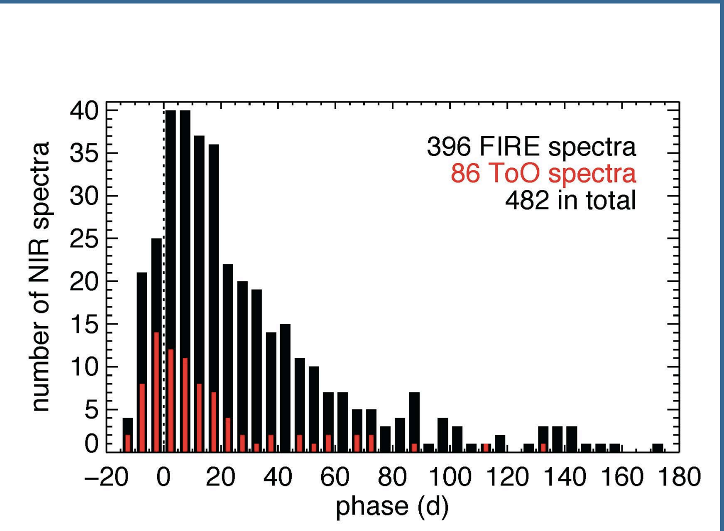
B-band:

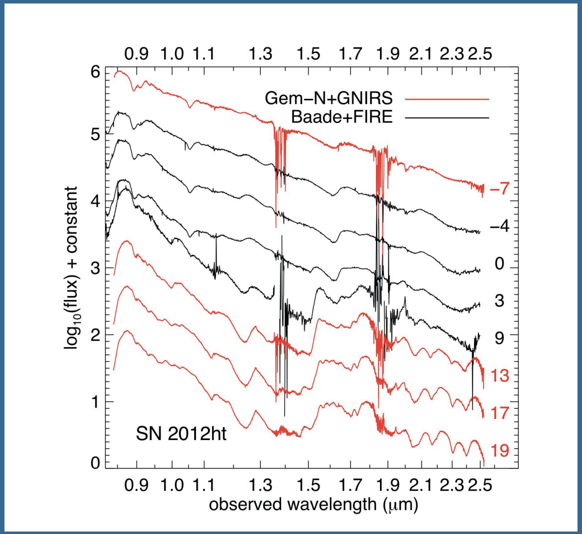
Ω_m = 0.31 ±0.03 (stat)

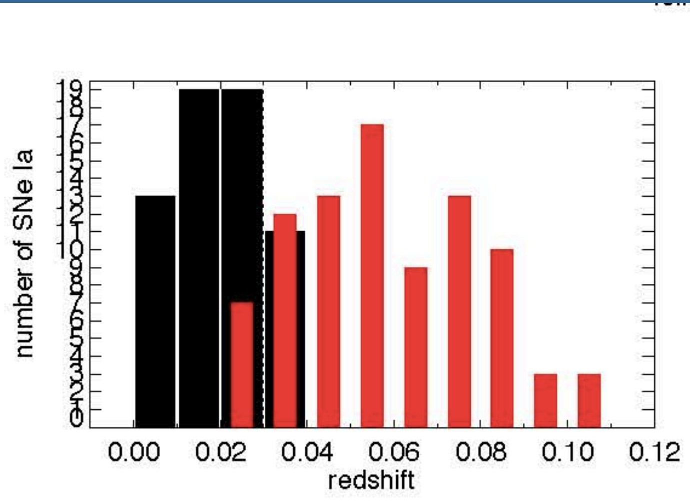
w_0 = -0.70 ±0.21 (stat)

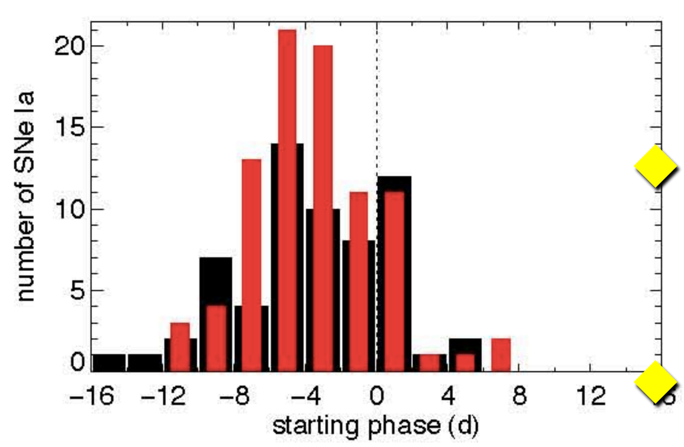
WLF et al. 2009

NEW Carnegie Supernova Project (CSP) II









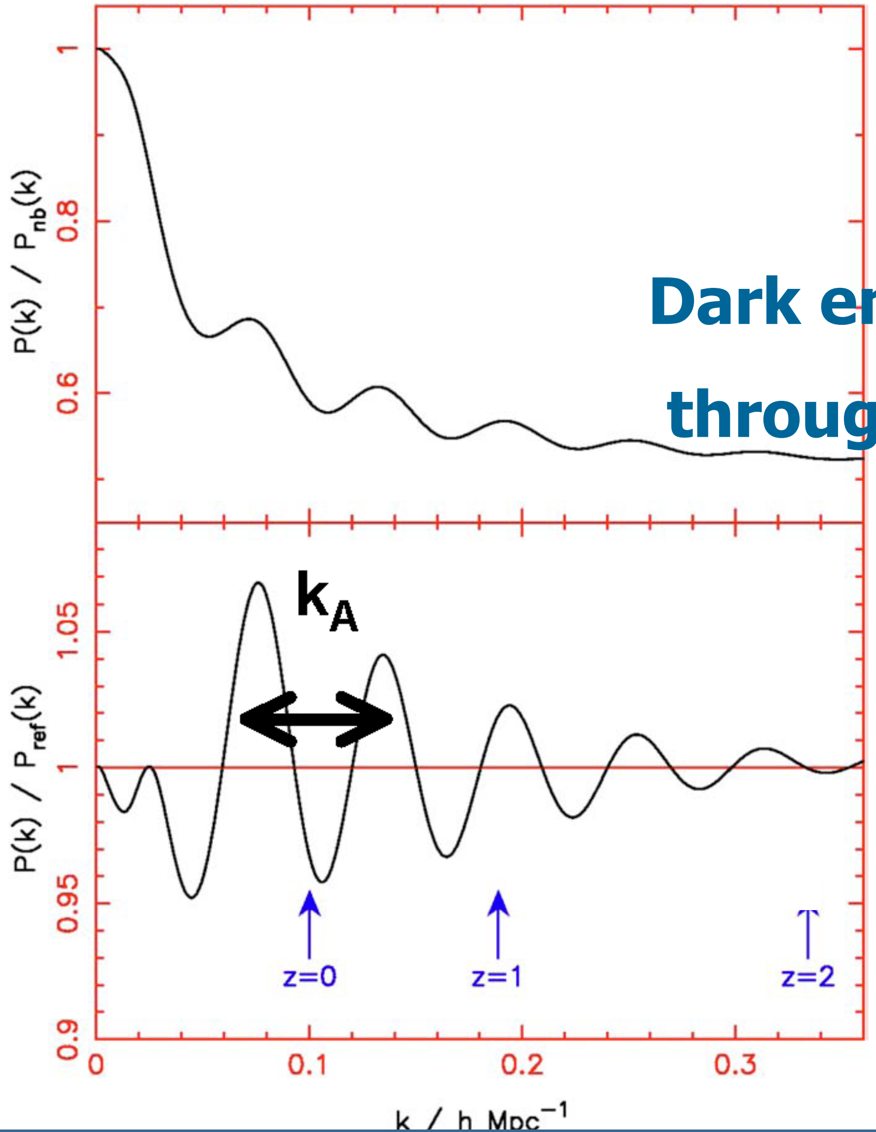
- Sample of 100 SNe Ia 0.03 < z < 0.08
- 2.5m du Pont telescope at Las Campanas
- YJH light curves + gri optical data
- Optical and NIR spectroscopy
- M. Phillips

Baryon Acoustic Oscillations

Baryon Acoustic Oscillations

$P(k)/P_{nb}(k)$

Divided by smooth fit



Dark energy enters through d_A and H

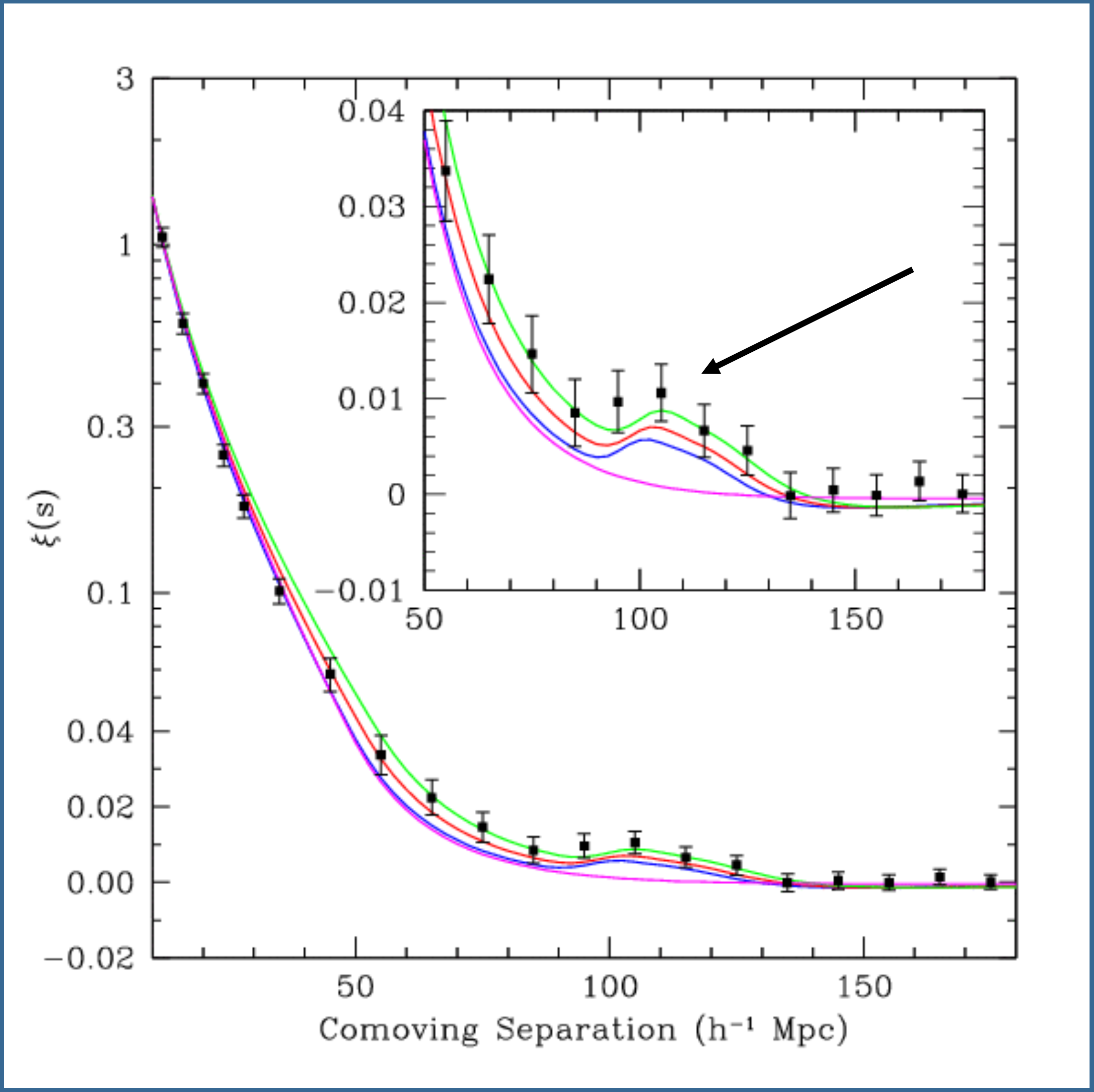
k_A is the "standard rod"

Ellis, Eisenstein

Baryon Acoustic Oscillations (BAO)

- **Baryon Acoustic Oscillations**
  - D_A to z~ 3
  - Ongoing ground and space projects
  - Key challenges: Very large surveys required, non-linearities, scale-dependent bias; what is the effect of galaxy bias on the galaxy power spectrum?

First Detections



SDSS

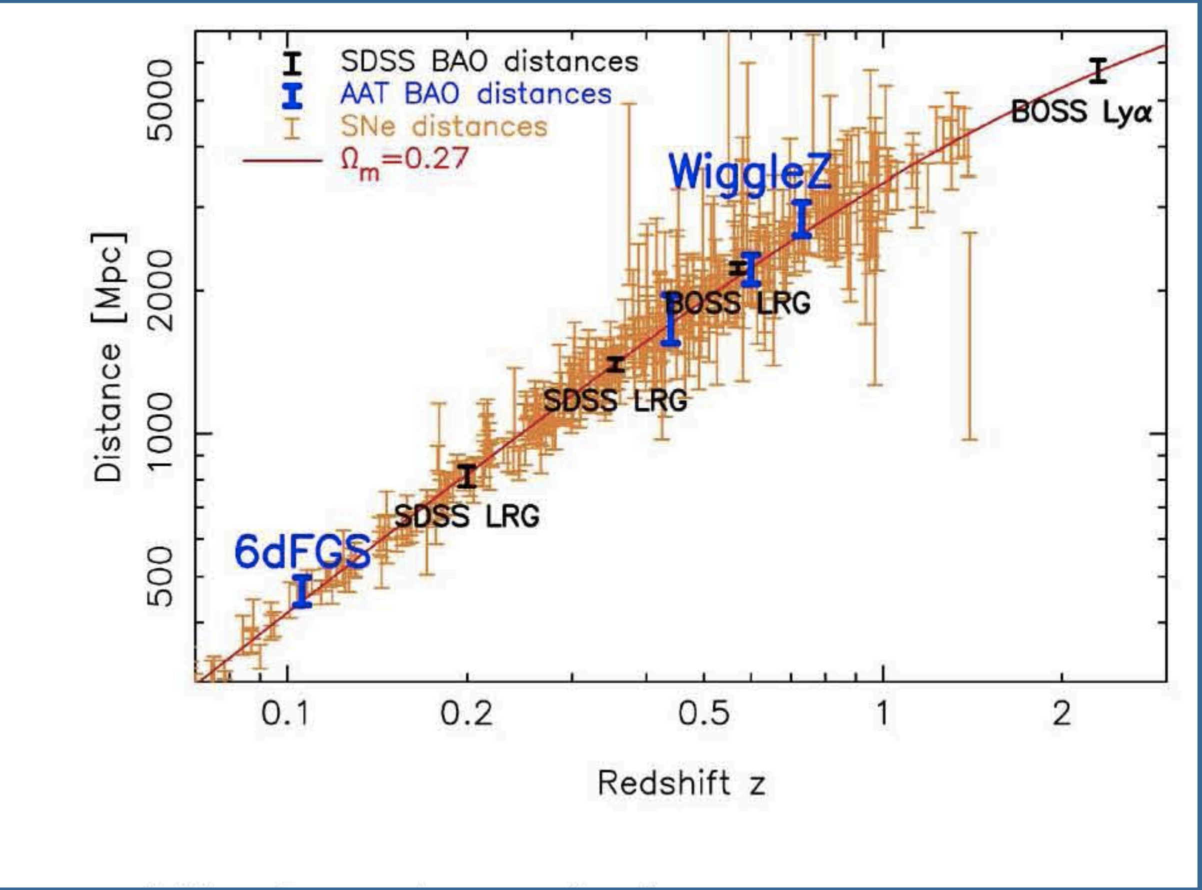
Eisenstein et al

2005

2dF

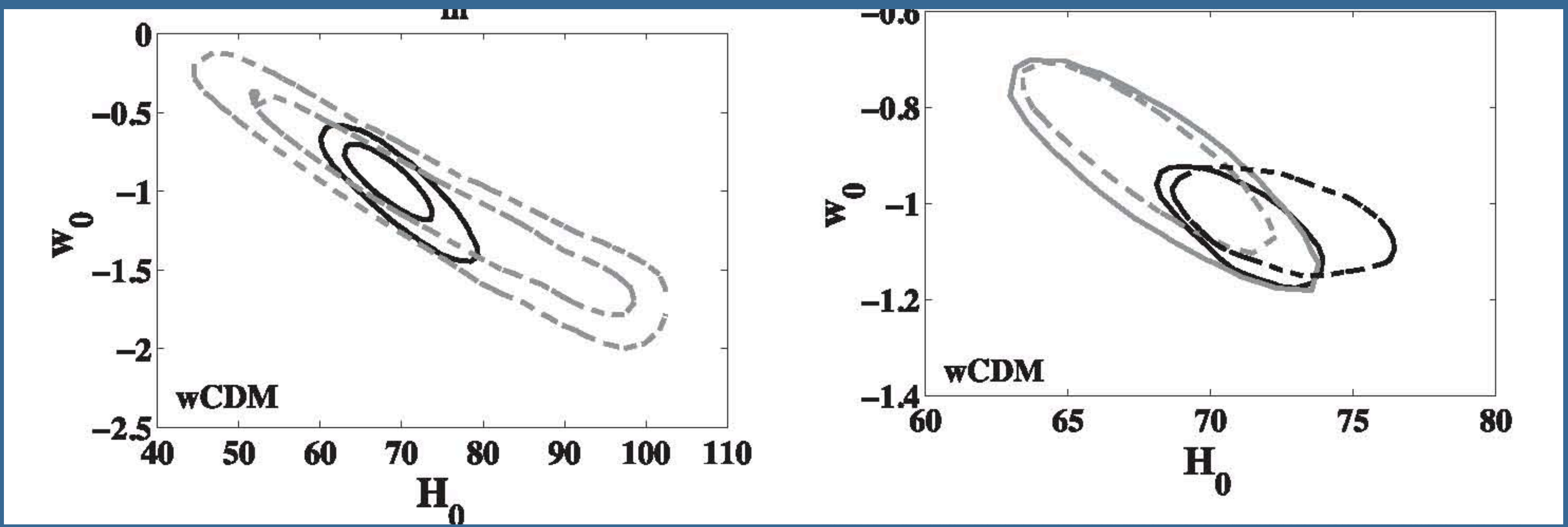
Cole et al. 2005

Comparison of SNaIe and BAO distances



Blake et al. 2011

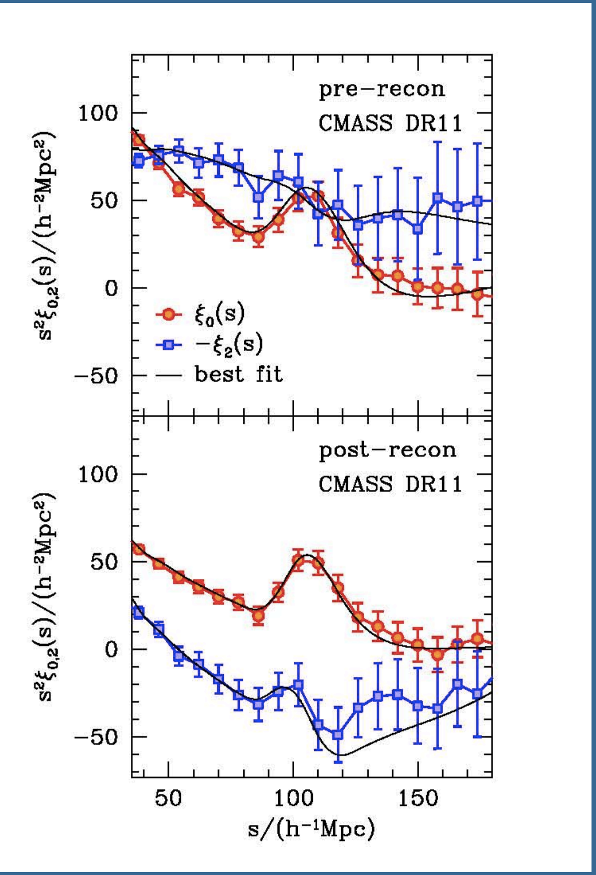
BAO Measurements of Dark Energy and H_0



BAO + CMB **BAO + CMB + SNIae**

Mehta et al. 2012

BAO with Reconstruction



Pre and post reconstruction

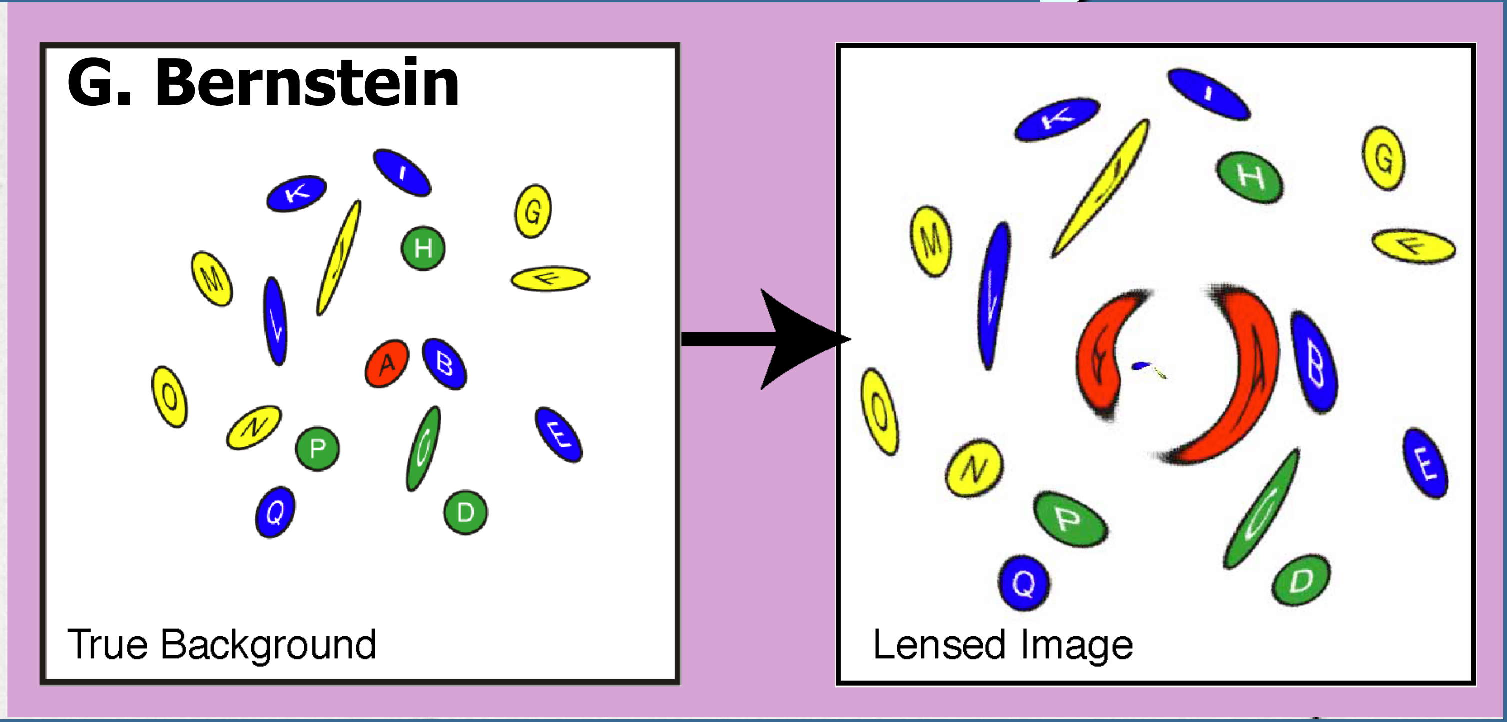
e.g., Anderson et al. (2014)

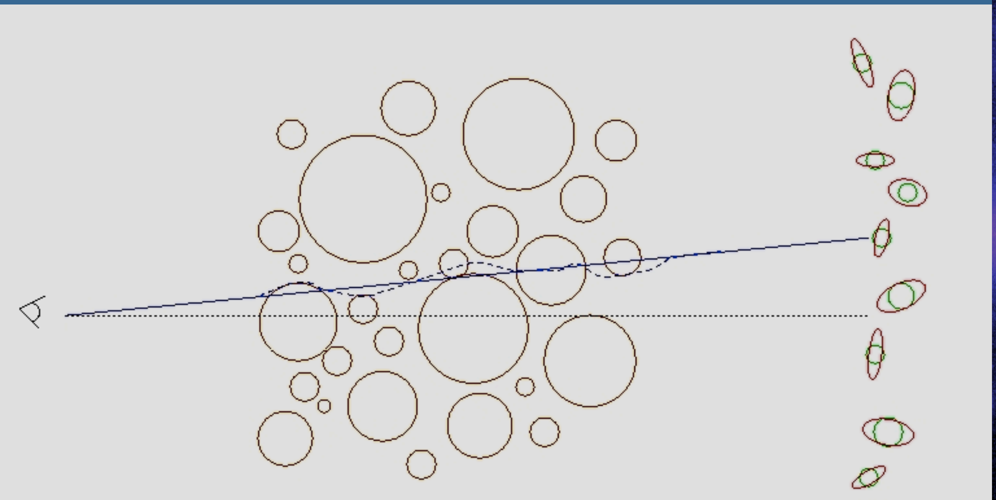
BAO in the SDSS Data Release 10 and 11 galaxy samples

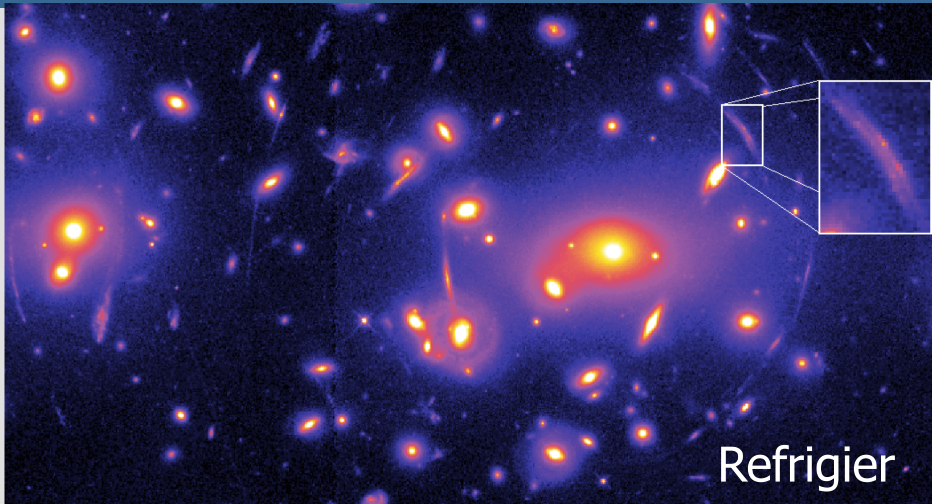
Use phase information within the density field to reconstruct linear behavior; use of mock catalogs

Weak Lensing

Weak Lensing



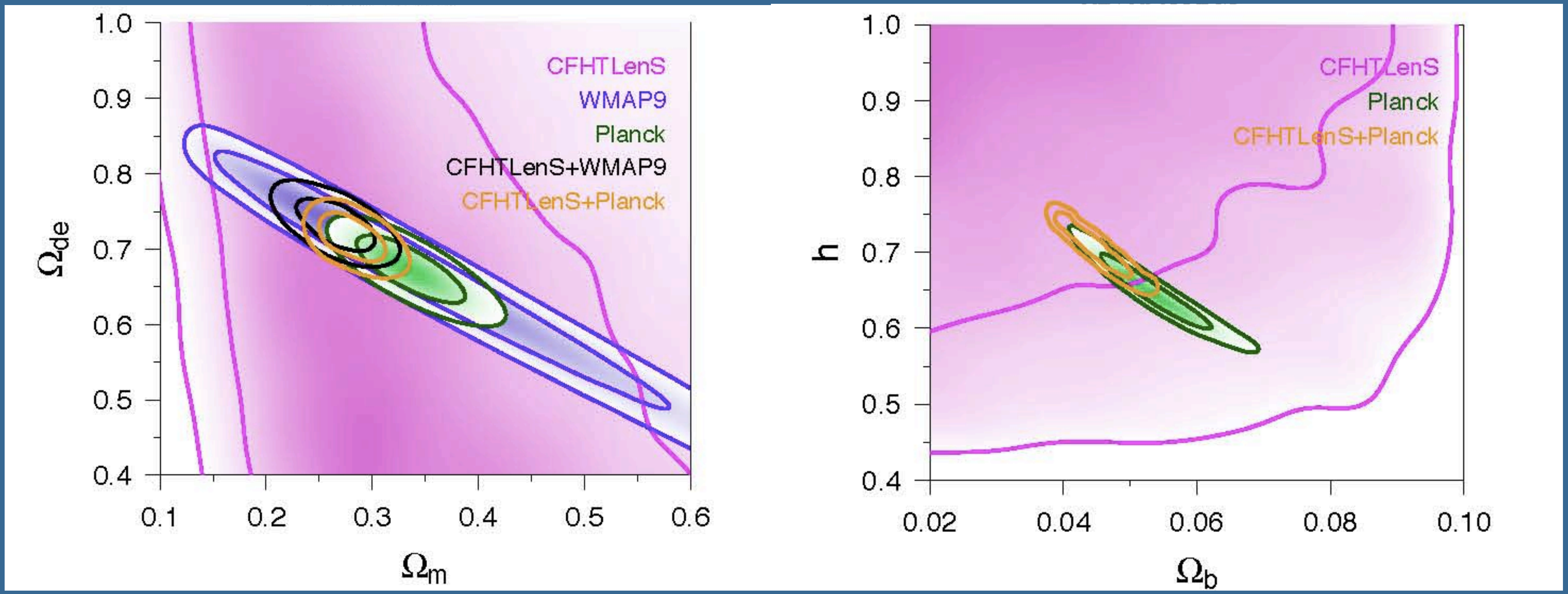




Dark Energy Measurement Methods

- **Weak Lensing**
  - g(z) to z ~ 1.5
  - Ongoing and future ground-based and space projects
  - Need hundreds of thousands of galaxies for statistical accuracy in shear measurements
  - The signal from any single galaxy is very small, but there are a lot of galaxies.
  - Key challenges: calibration, corrections for intrinsic shapes and alignments of galaxies, anisotropy of the point spread function, detector stability, understanding of the optics, accuracy of photometric redshifts, correction for the atmosphere (for ground-based measurements)

CFHTLenS Results



Fu et al 2014

Galaxy Clusters

Dark Energy Measurement Methods

- **Cluster Surveys**
  - **Measure both D(z) and g(z)**
  - **Ground and space (x-ray) observations**
  - **Sunyaev-Zeldovich, X-ray observations**
  - **Key challenges: constraining the relationship between observed quantities and cluster mass, uncertainties in photo-redshifts, understanding cluster selection effects, better understanding of numerical simulations of structure formation**

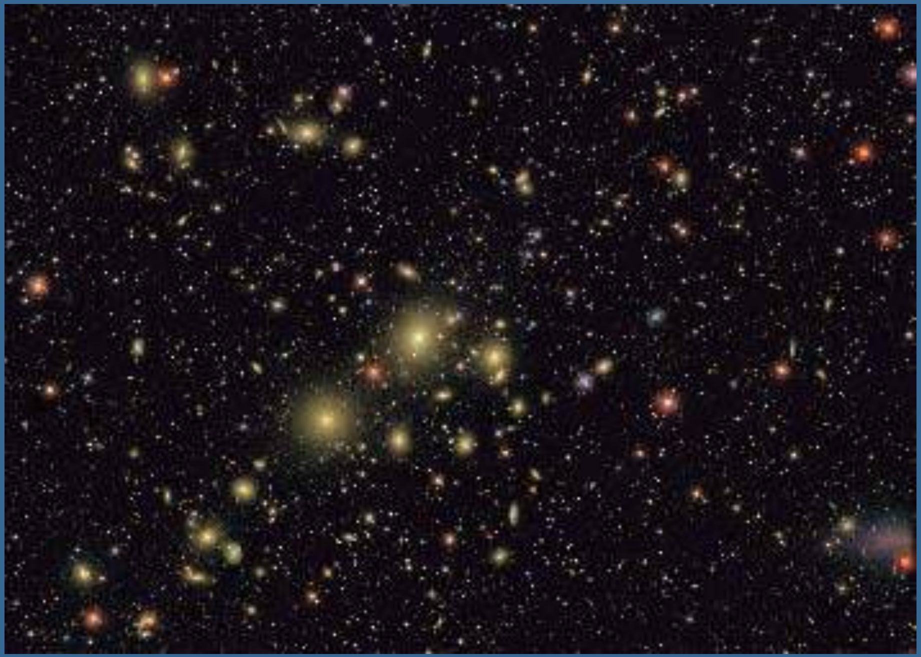
Galaxy Clusters

- Two methods:

1) Co-moving volume element depends on dark energy; therefore counts depend on expansion history

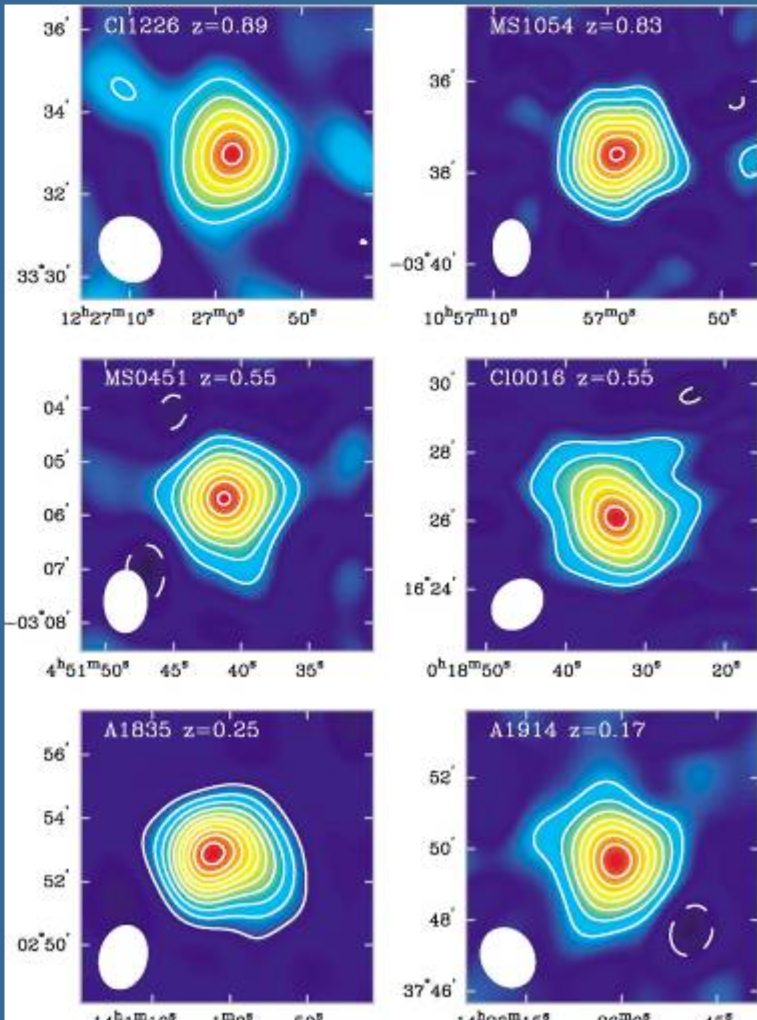
2) The mass function is sensitive to the growth function, g(z)

- Theory predicts the *mass function*
- Observers measure *luminosities and number counts*
- Calibration of observables to mass is critical



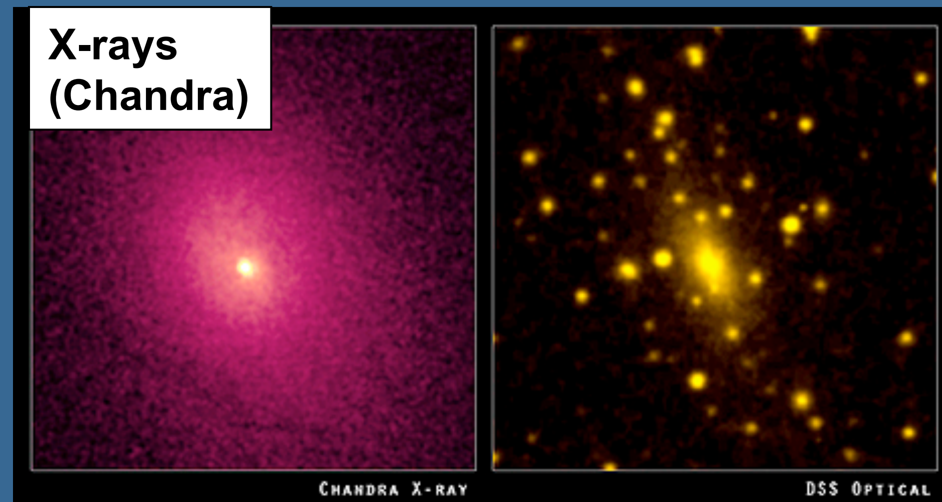
Cluster method probes both D(z) and g(z)

Galaxy Clusters



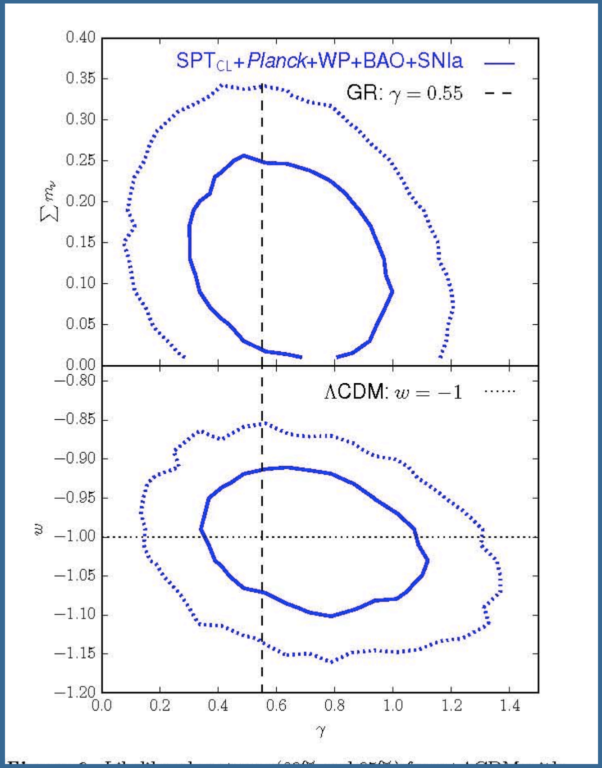
30 GHz maps
(Carlstrom et al)
Sunyaev-Zeldovich effect

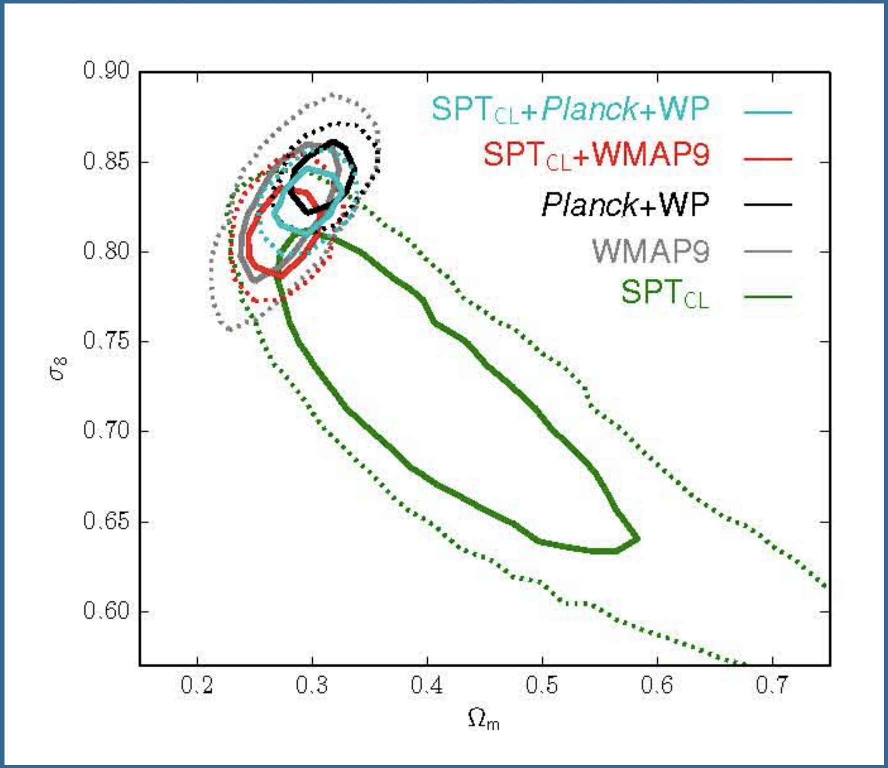
Future X-ray, SZ, lensing surveys: several tens of thousands detections.



- **Estimate mass from:**
  - **Galaxy count/luminosity**
  - **Weak lensing**
  - **Sunyaev-Zeldovich**
    - **South Pole Telescope**
    - **Dark Energy Survey**
    - **DES and SPT cover the same area of sky**
    - **LSST**

Constraints from SZ (SPT) and X-ray Measurements

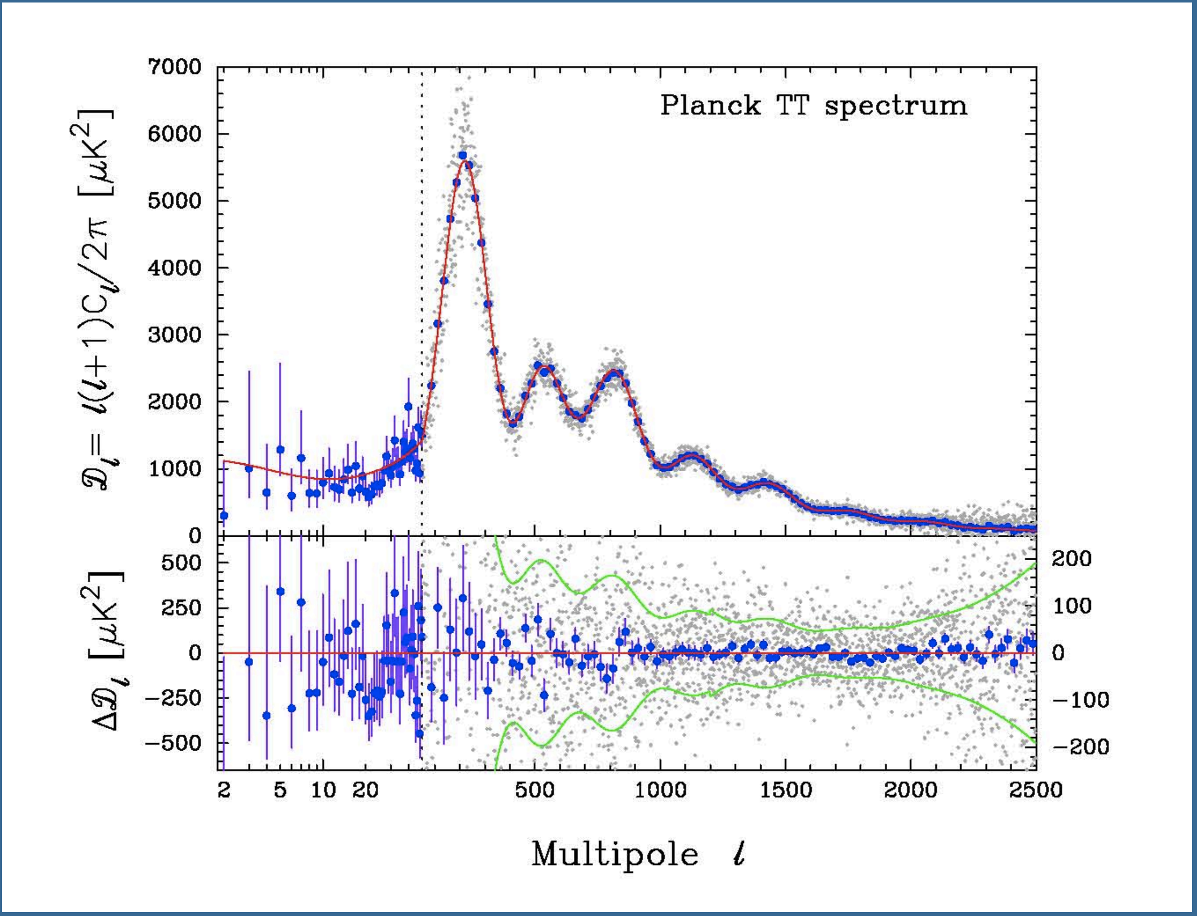




Bocquet et al. 2014

CMB + Higher Accuracy in H_0

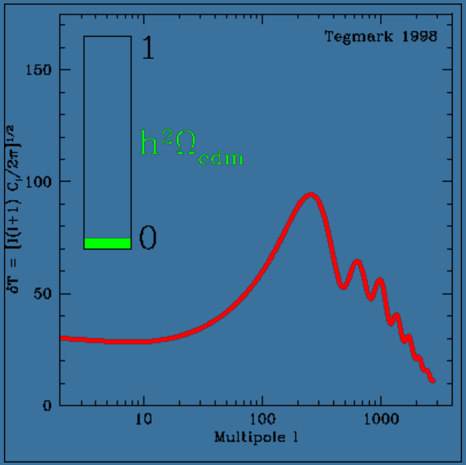
Planck Results Paper XVI



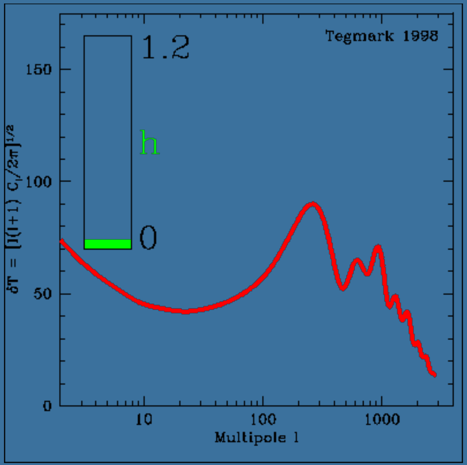
Planck Collaboration XVI arXiv:1303.5076

CMB Anisotropies

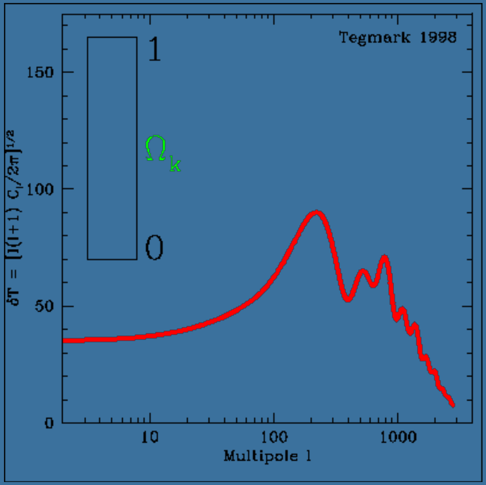
❖ Ω_{CDM}



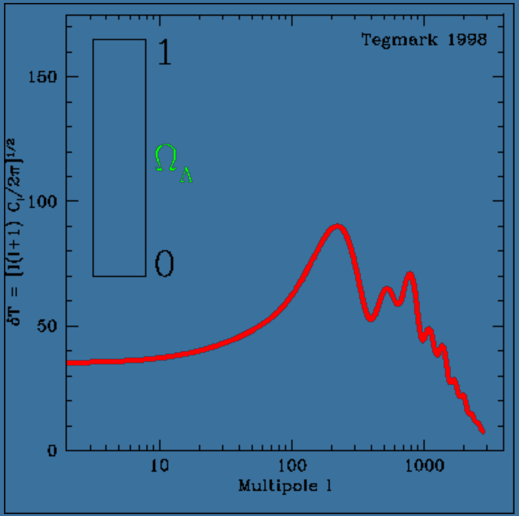
❖ H_0



❖ Ω_k

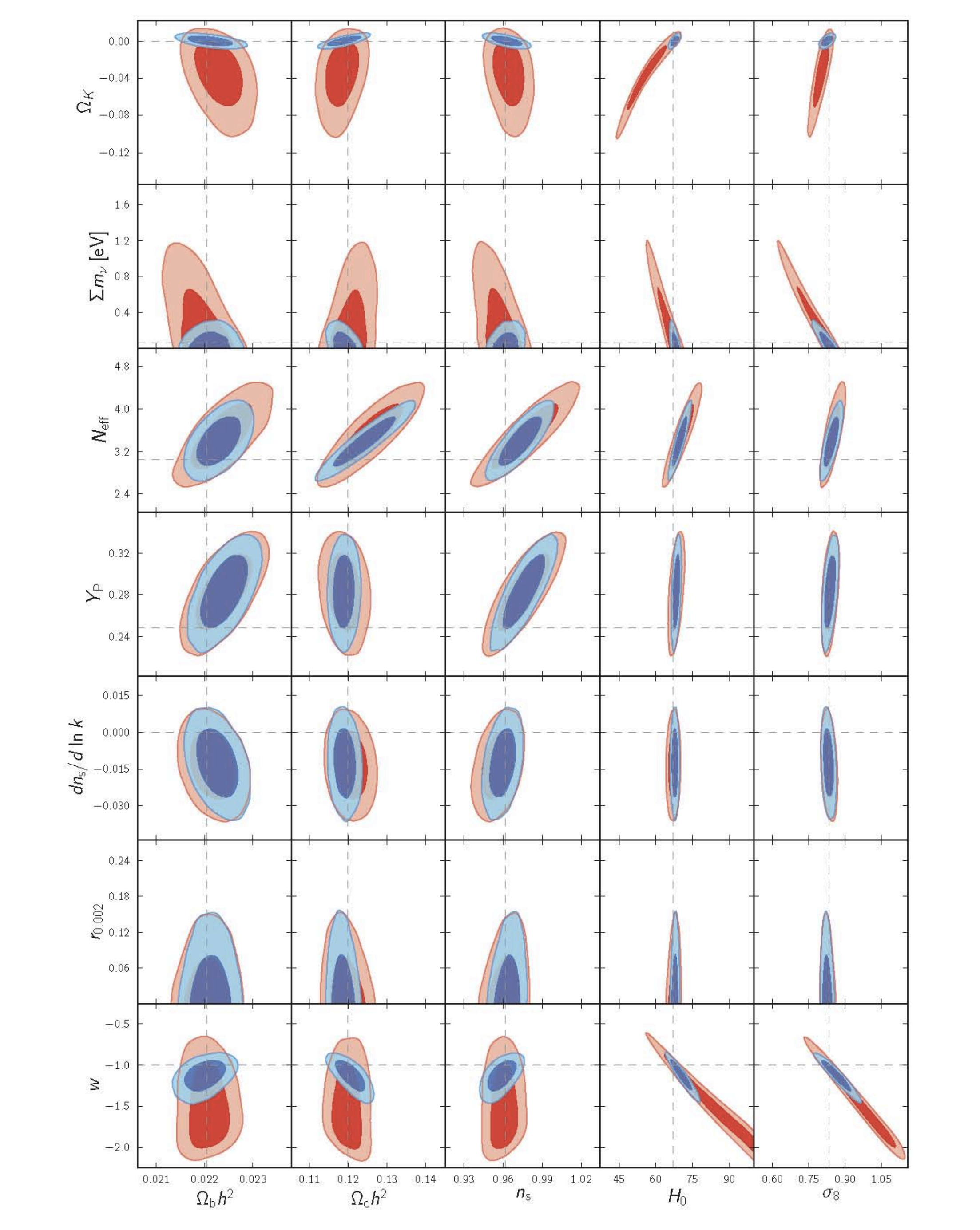


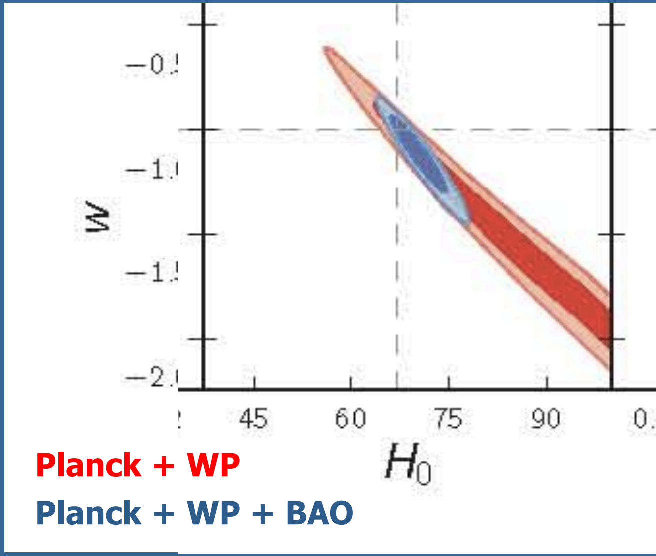
❖ Ω_Λ



M. Tegmark

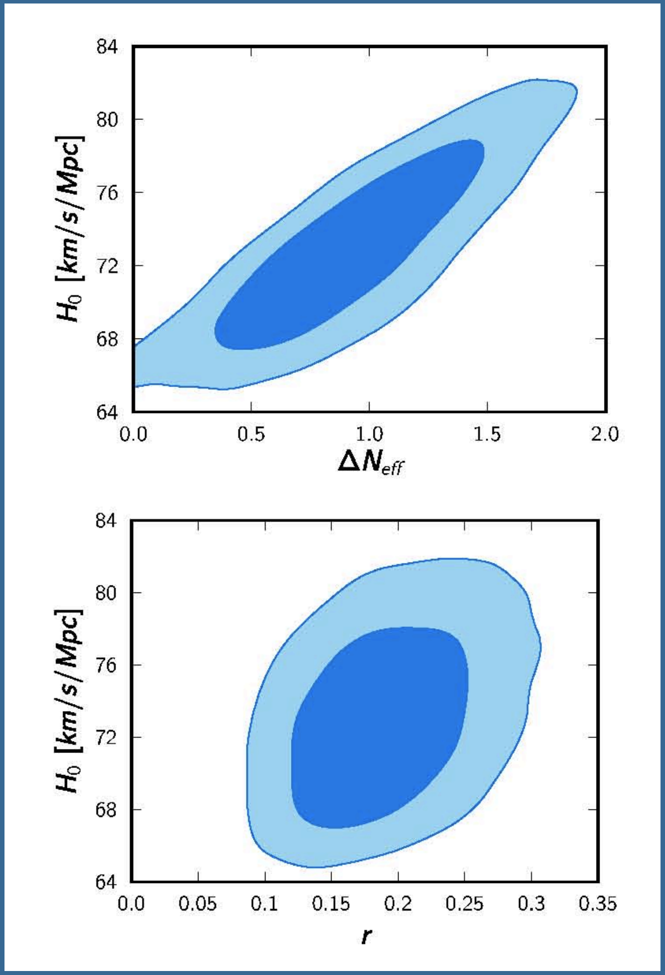
Planck Results Paper XVI





CMB alone only weak constraints on w and H_0

Extra Relativistic Species (Λ_{CDM} + r + ν_s)

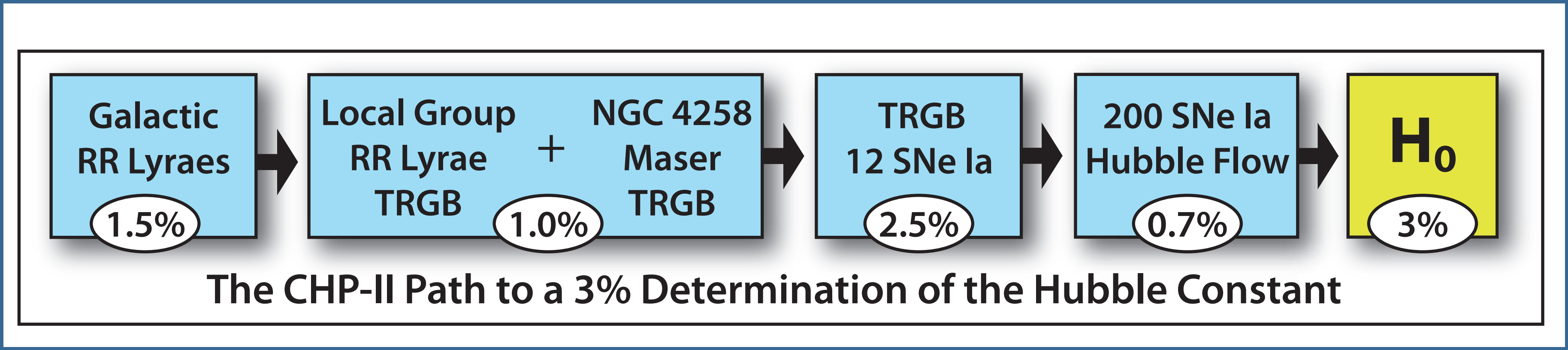


Dvorkin et al 2014

If allow for higher r and an extra neutrino species a higher value of H_0 is favored.

Also Zhang et al 2014 Reconciles tension with Planck and $H_{0,}$ WL, and SZ cluster counts

An Independent Route to H_0 (Carnegie Hubble Project: CHP II)



- The dispersion in the RR Lyrae period-luminosity relation is <0.05 mag; half that of Cepheids
- Measurement of H0 to 3% + Planck
- One of most accurate measurements of w!

CHP I : Spitzer as a Tool for Measuring Cepheid Distances

Advantage of Spitzer for the extragalactic distance scale:

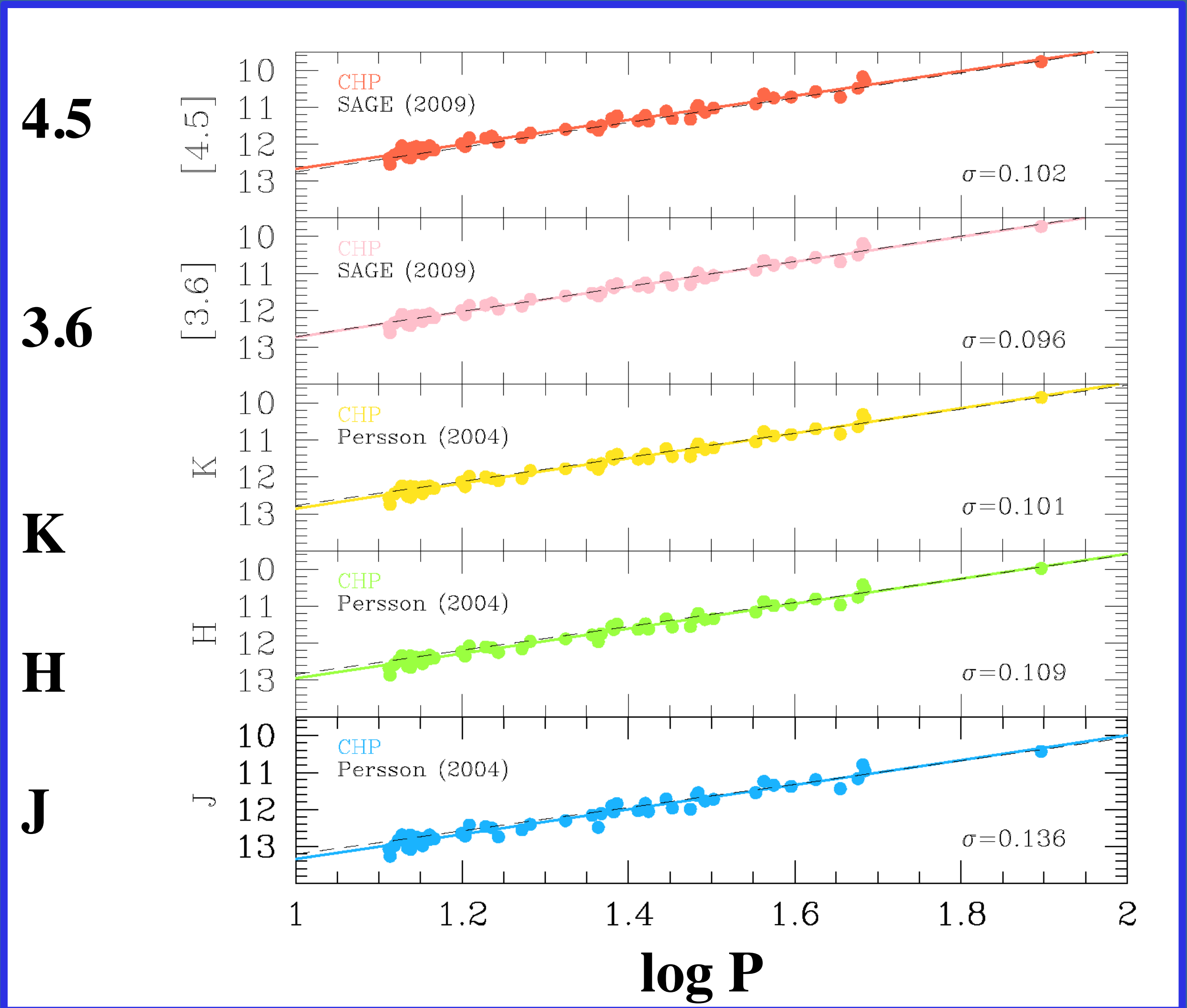
At 3.6 μm, A_λ is ~17 times smaller than at optical (V-band) wavelengths.

Dispersion in Cepheid PL relation a factor of two to three smaller than in optical.

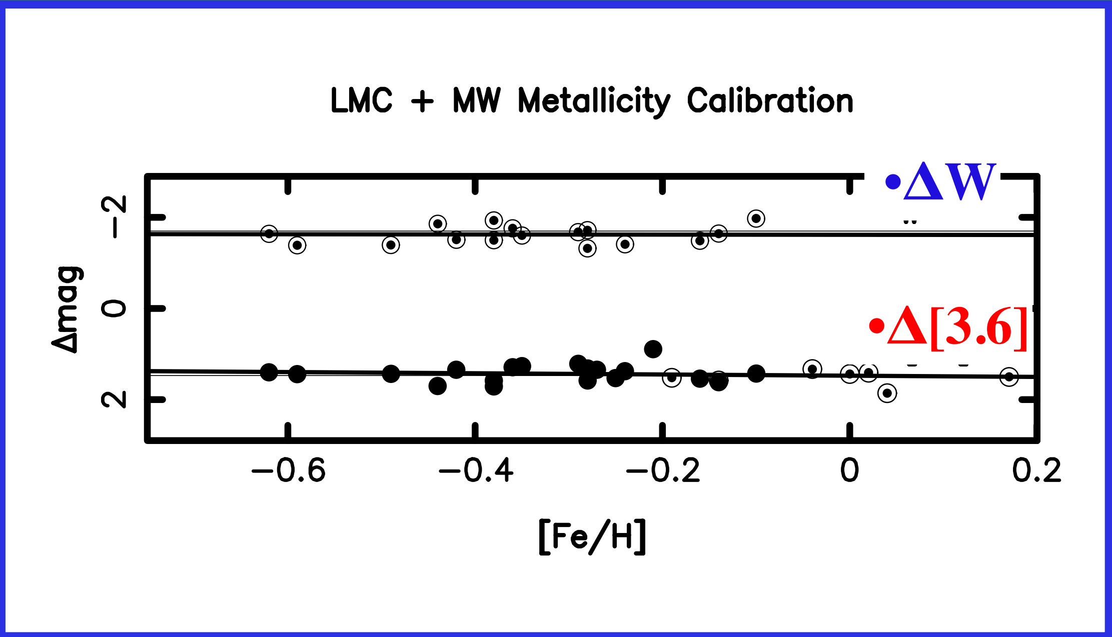
Metallicity effects predicted to be negligible.

Spitzer Infrared Telescope

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



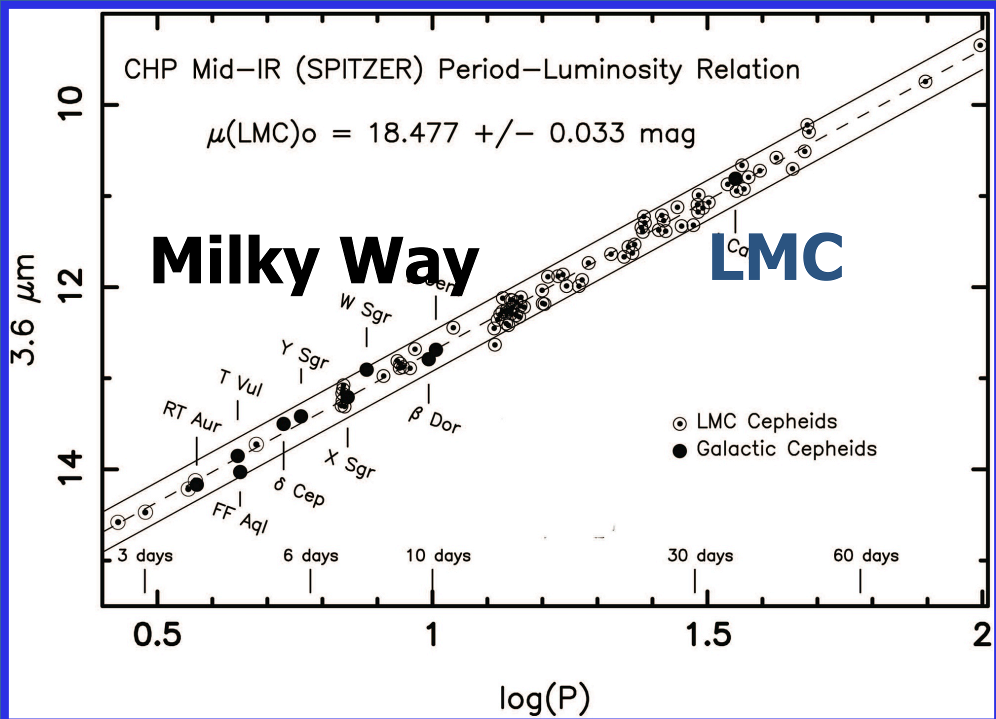
Sensitivity to [Fe/H]



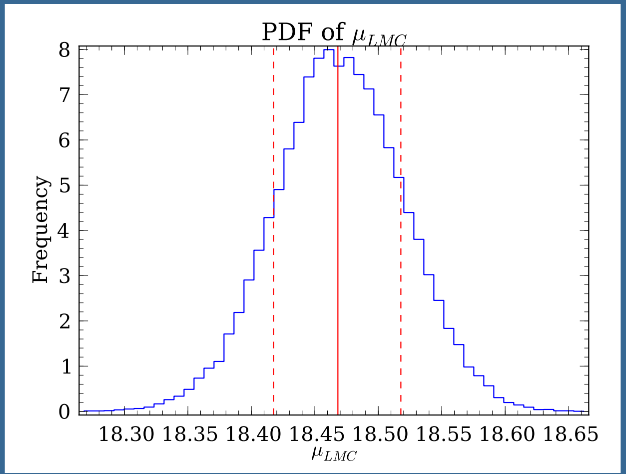
WLF *et al.* (2012)

- Spectroscopic [Fe/H] from Romanielli et al. (2008)
- Most sensitive and direct test yet of metallicity effects
- LMC and Milky Way Wesenheit function $W = V - R\,(V-I)$ also very insensitive to metallicity

Comparison of Spitzer LMC and Milky Way Leavitt Laws



WLF *et al.* (2012)



$\mu_{\mathrm{LMC}} = 18.48 \pm 0.01$ (stat)

± 0.03(sys)

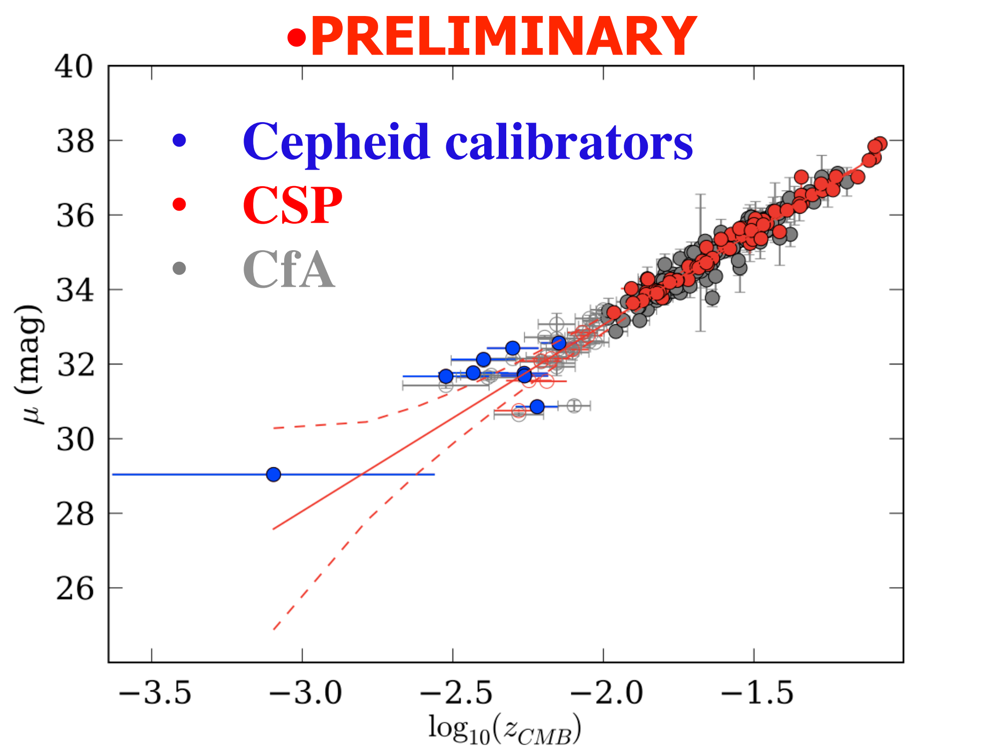
d = 49.6 ± 0.8 kpc

WLF *et ål.* (2014)

Distance modulus:

$$\mu_0 = \mathrm{m} - \mathrm{M} = 5\log \mathrm{d_L} + 25 \quad \text{where } \mathrm{d}_L \text{ is in Mpc}$$

H_0 From Enlarged Sample of Type Ia Supernovae



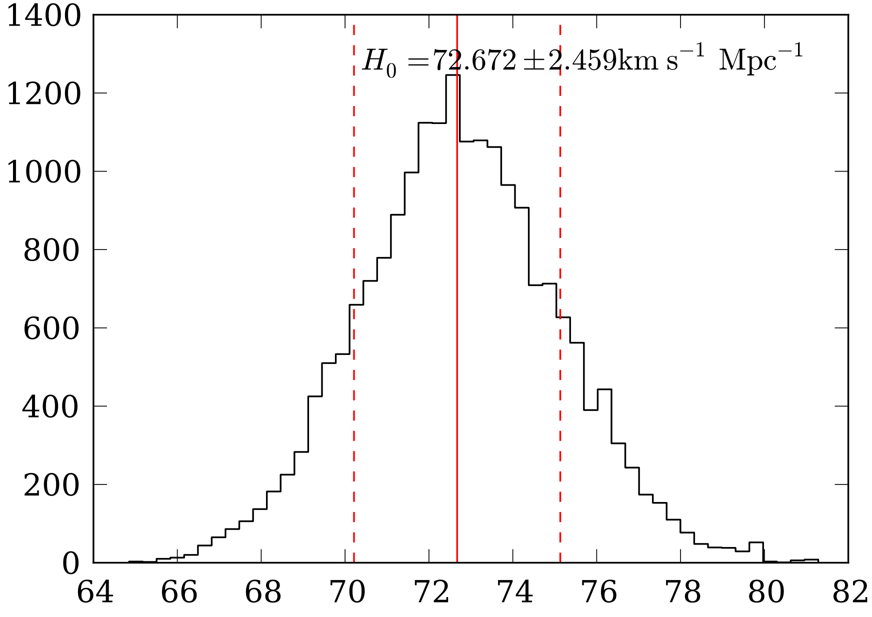
Data for H_0 analysis:

- 9 Cepheid SN Ia hosts *
- 61 CSP SNe Ia *
- 155 CfA + CTIO SNe Ia *
- Total: 215 objects with z>0.01

WLF et al. (2014)

H_0 From Enlarged Sample of Type Ia Supernovae

•PRELIMINARY



•MCMC analysis

•Solve for:

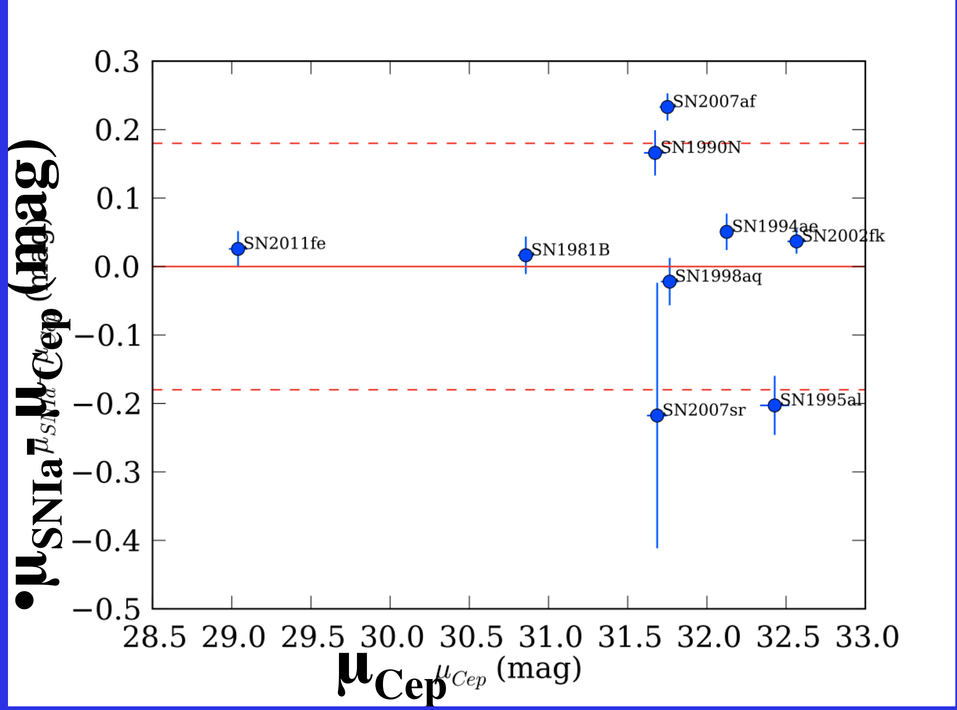
•H_0, LMC, NGC 4258 distances

•Cepheid PL parameters, reddenings, metallicity dependence

•Supernova light curve parameters, calibrator distances, z_{CMB}

H_0 = 72.7 ± 2.0 [stat] ± 0.5 [sys] km s $^{-1}$ Mpc

Uncertainty in Type Ia Supernovae Calibrators



- Largest uncertainty: small number of calibrators
- Dashed lines show ± 0.18 mag, the SNIa dispersion in the far sample.
- For the calibrators, σ ~ 0.14 mag
- Error on mean for the 9 calibrators is 0.046 mag or 2.3% in H_0

- **Challenge for 1% H_0 : only 9 calibrators
- Nature delivers new one only every 2-3 years!

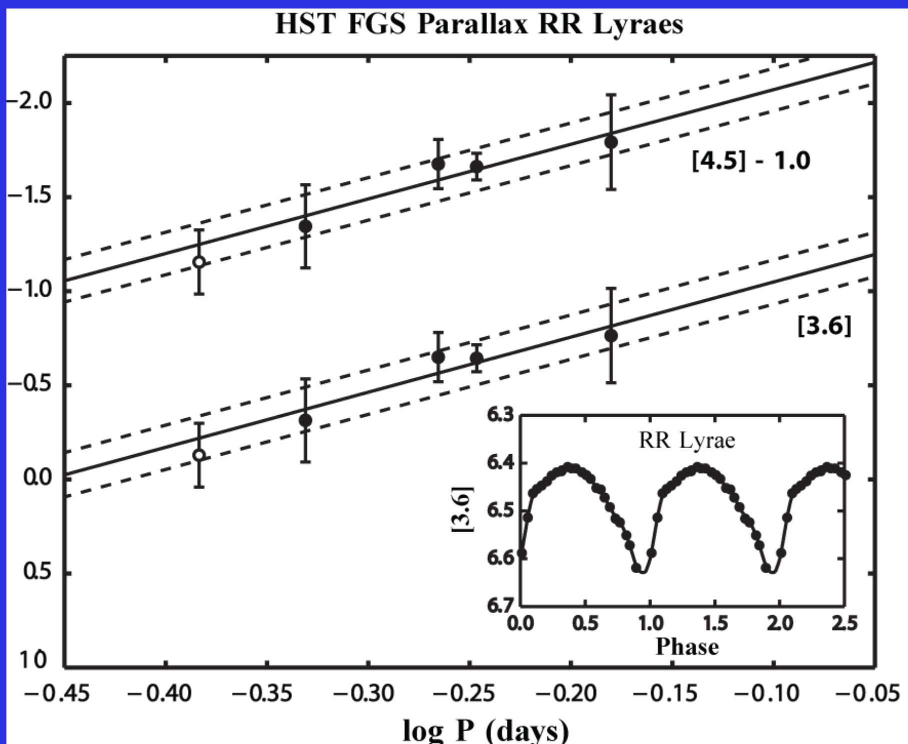
RR Lyrae Stars A Calibration Independent of Cepheids

NEW Carnegie Hubble Project (CHP) II

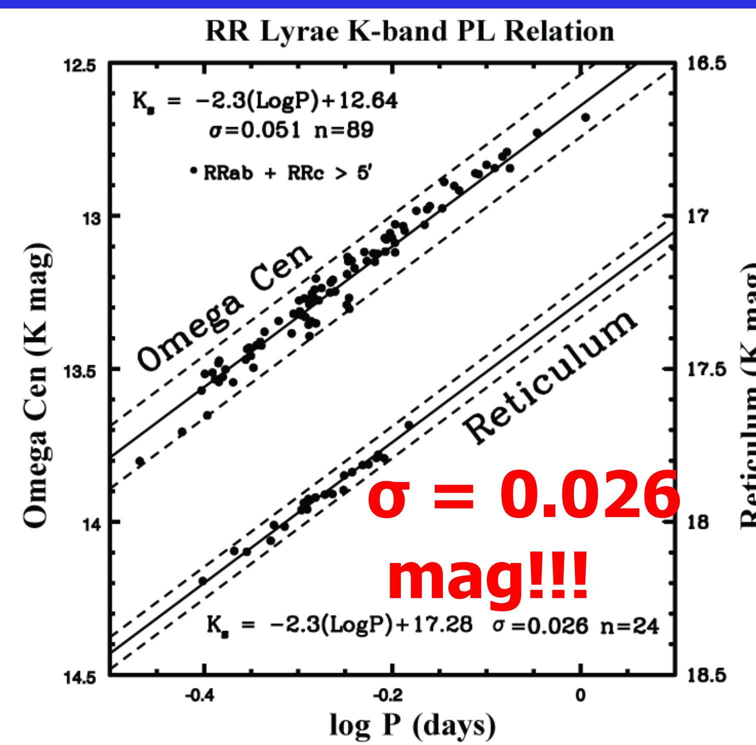
- HST Cycle 22
- 132 hours prime, 52 parallel
- WFC3, ACS
- RR Lyrae and TRGB distances
- Galactic and nearby galaxies
- Double the number of SNaIe calibrators
- Goal: H_0 to 3%

Recent RR Lyrae Distances (Spitzer, Magellan, TMT**)

Galactic Parallax Sample

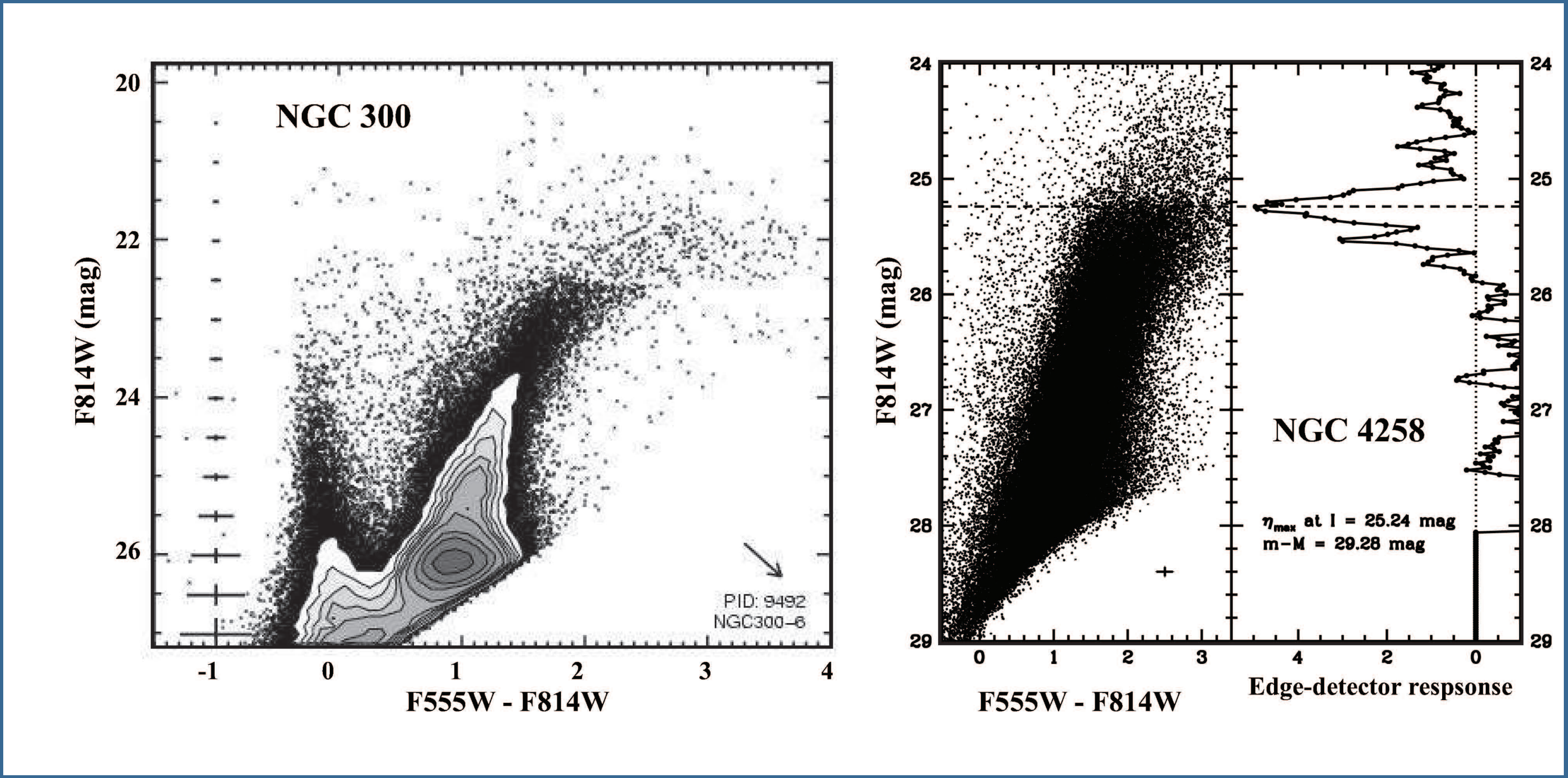


Omega Cen, Reticulum (LMC)



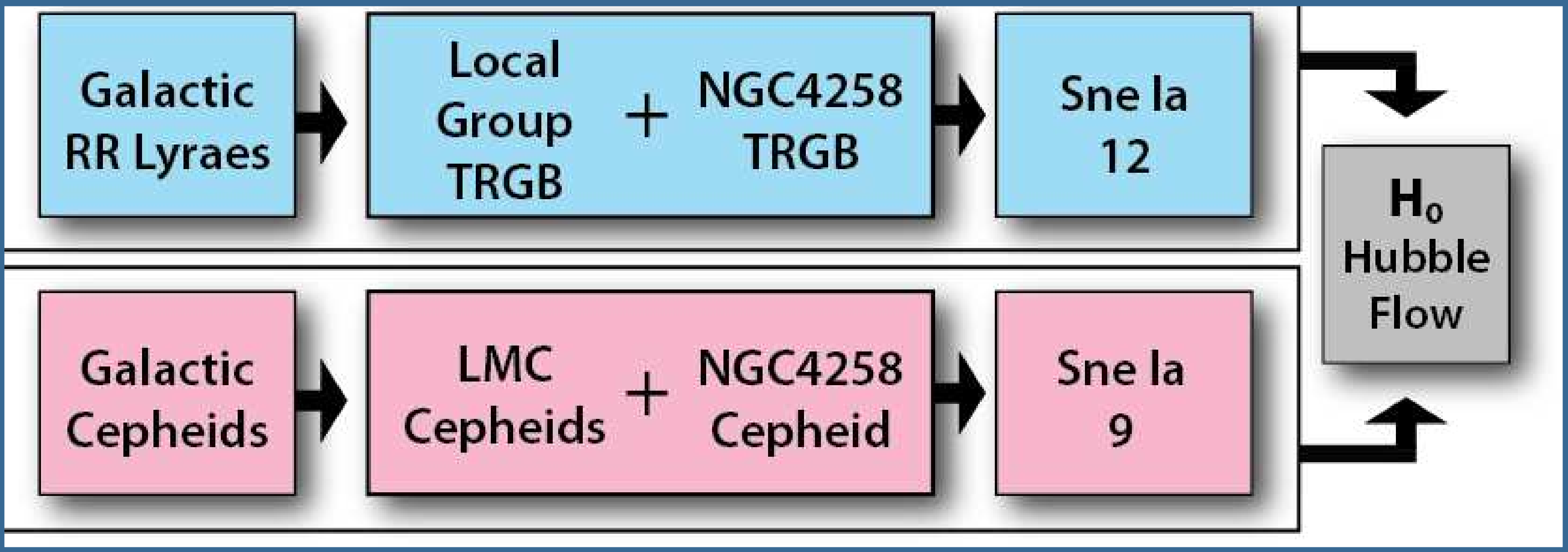
A. Monson, V. Scowcroft et al.

Tip of the Red Giant Branch (TRGB) Distances



NGC 300 NGC 4258

Carnegie Hubble Project: Independent Routes to H_0



Decreasing the Uncertainties in H_0

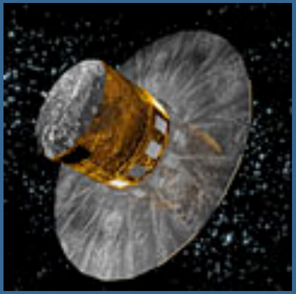
- **HST Key Project: [±10%]**
  - Several methods with independent checks
  - 5% statistical uncertainties
  - Robust tests of 10% final uncertainty
    - Cepheids (RR Lyraes, TRGB, PNLF)
    - SNeIa, TF, SBF, PNLF, SNII

- **Current H_0 Measurements: [±3-4%]**
  - Require additional tests to confirm Cepheid and SNeIa
  - distances at the 3-4% level.
  - Not yet available, but in progress.

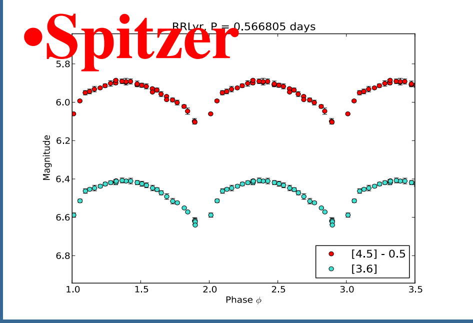
- **Future H_0 Measurements: [±2-3%]**
  - Spitzer RR Lyrae independent distances (2% level)**
  - Gaia parallaxes (<1%) for Cepheids and RR Lyraes.
  - IR measurements of SNeIa
  - Gravitational lensing, masers, Planck SZ clusters

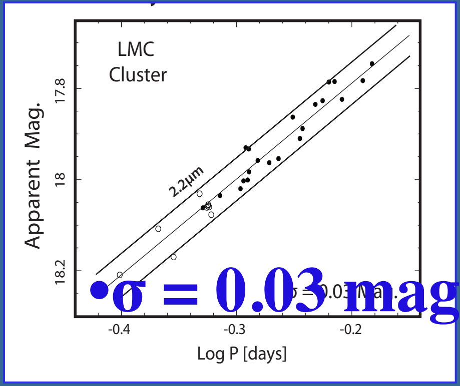
- **What is needed for H_0 to 1%?**
  - Several independent methods capable of 1%

•Gaia



•Spitzer



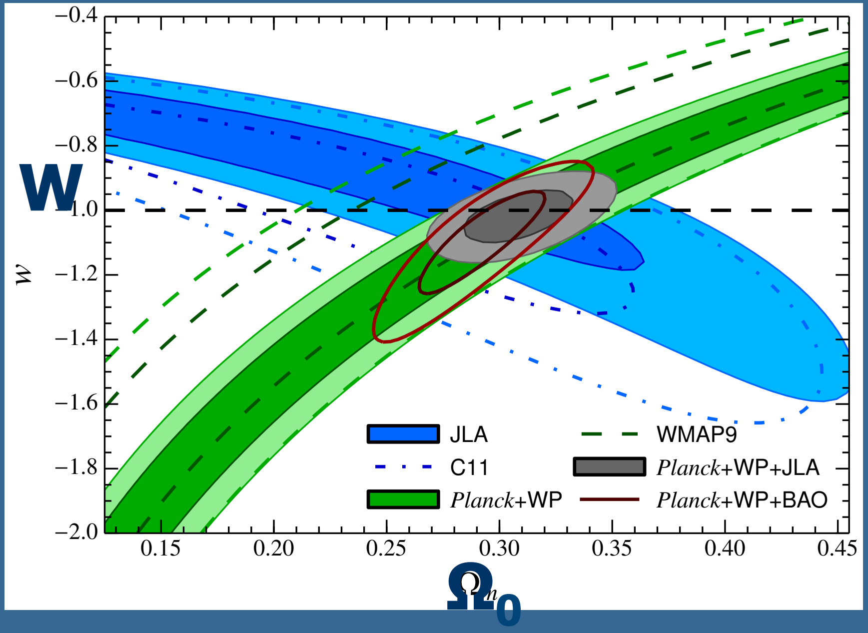


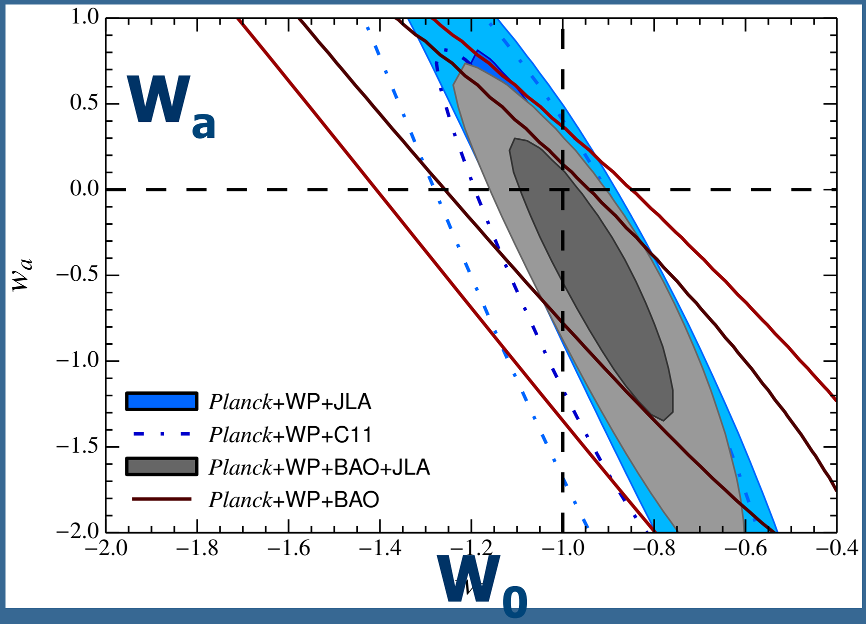
•σ = 0.03 mag

Looking Ahead

- **The Near Term:**
  - DES, PanStarrs, BOSS, HETDEX
  - Hyper Suprime-Cam (HSC) on Subaru
  - BigBOSS, DESI
  - SPT, ACT
  - Planck + H_0
- **Major New Facilities**
  - WFIRST / AFTA; Euclid (Dark Energy Missions)
  - LSST (Large Synoptic Survey Telescope)
  - GMT, TMT, E-ELT
  - JWST
  - SKA (BAO of HI in galaxies)
  - eRosita (ESA x-ray telescope – cluster survey)

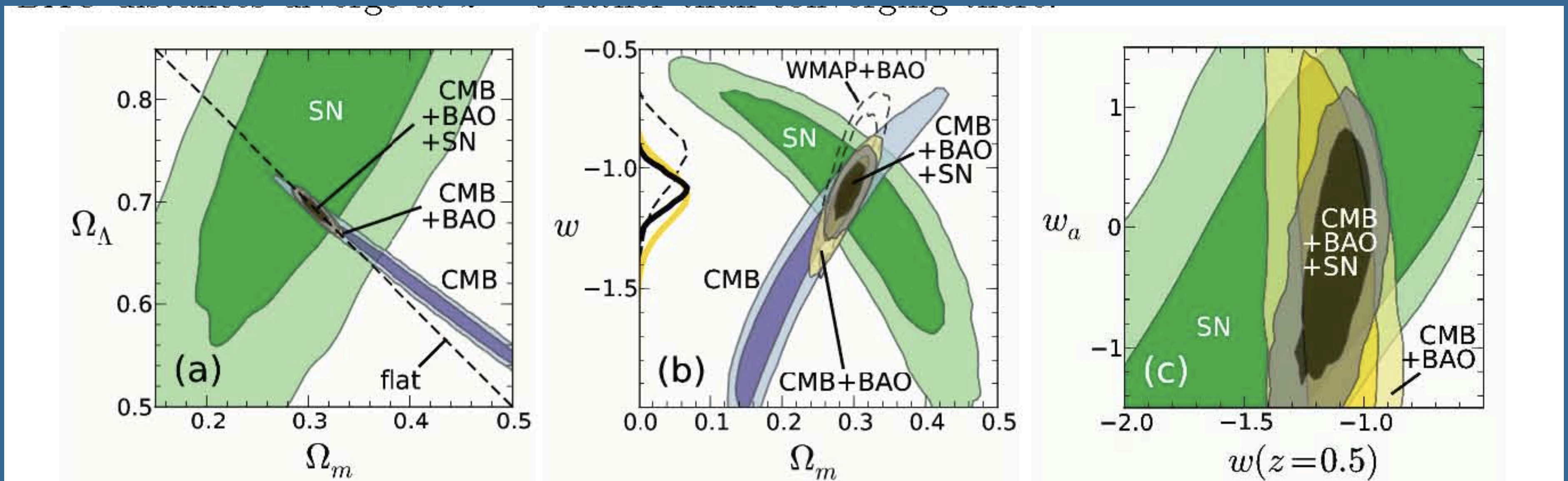
Combining Constraints





Betoule et al. 2014
Combining CMB, SN, BAO, WL, Clusters

Combining Constraints



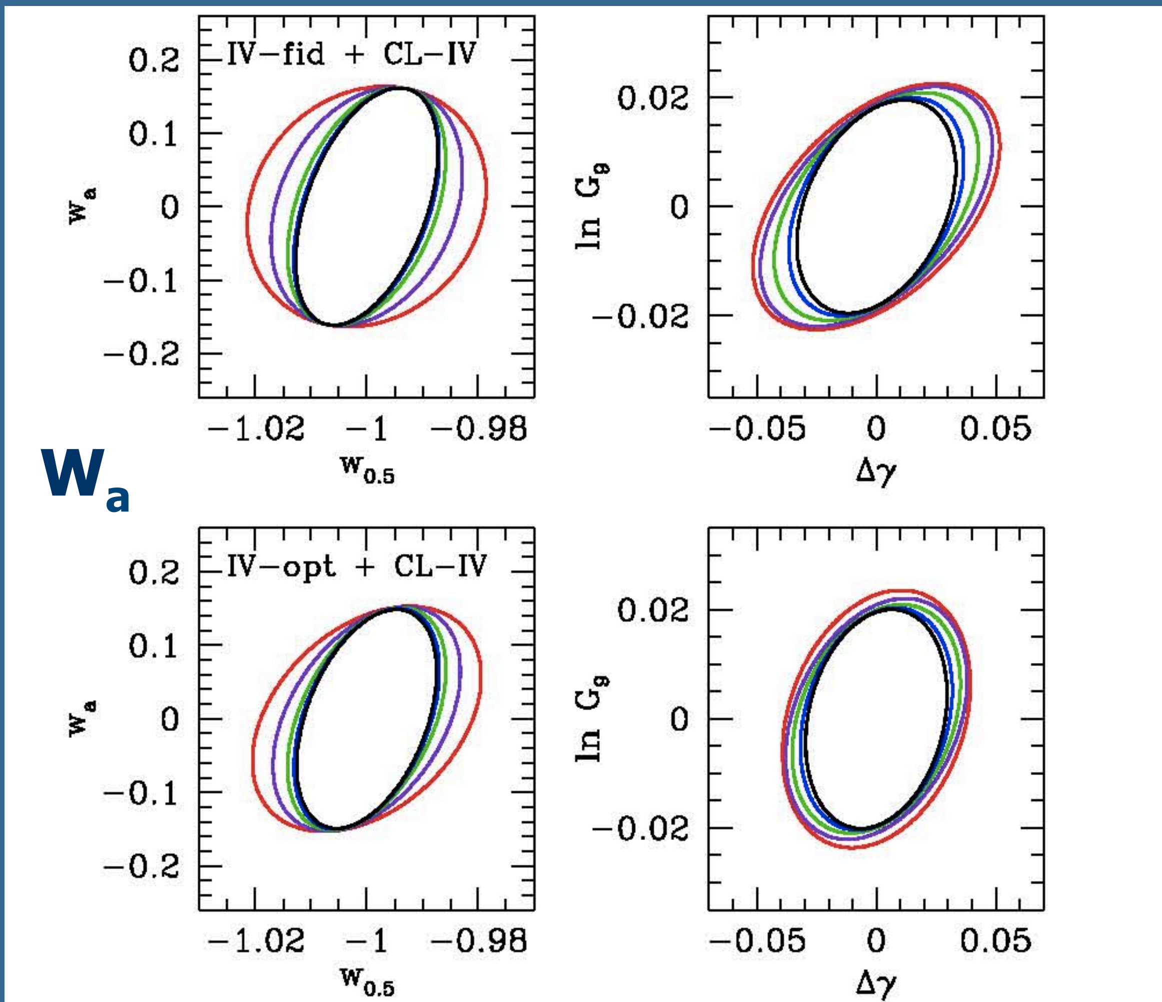
Assumptions:

flat universe, Λ_{CDM} **W = constant** **W_a = -dw/da**

Mortonson et al. 2013

The Future

Combining Constraints



$W_{0.5}$ = w (z=0.5)

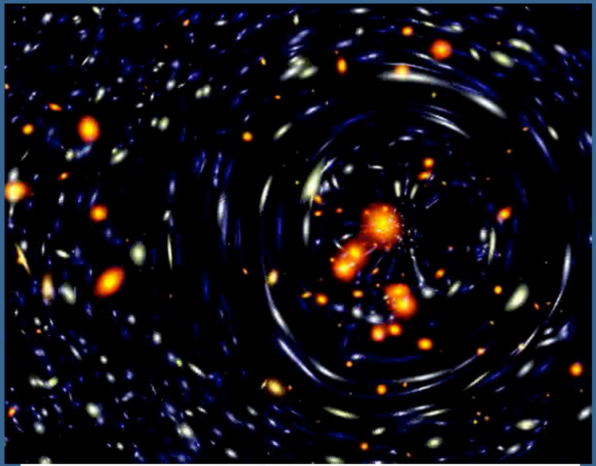
Weinberg et al. 2013

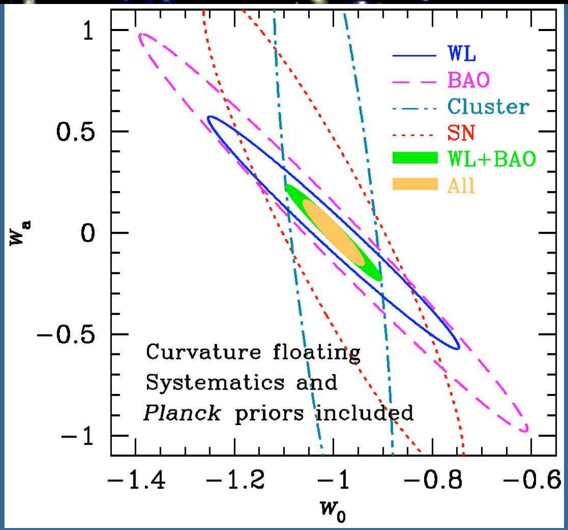
Combining CMB, SN, BAO, WL, Clusters

Stage IV forecast

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





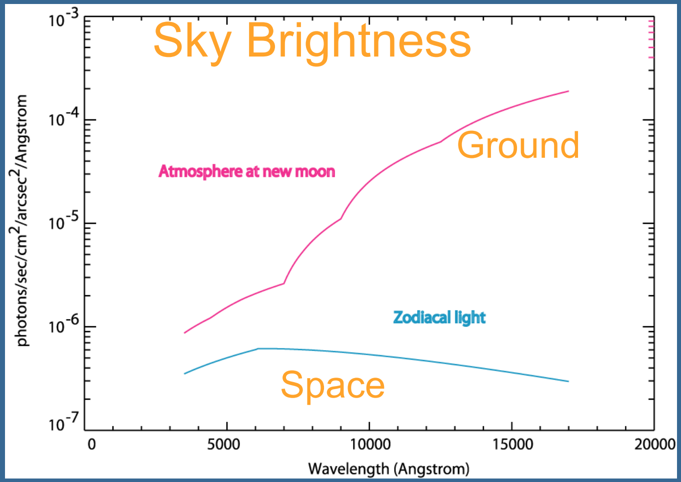
http://www.lsst.org/

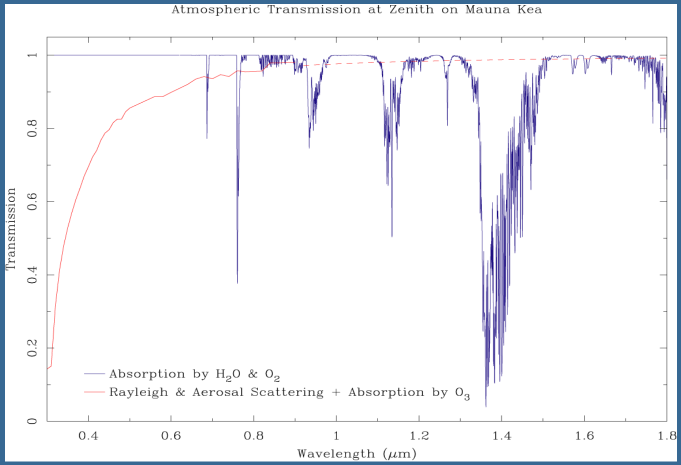
LSST Error forecast

Why go to space?

Near-infrared observations are impossible at very high redshifts from the ground

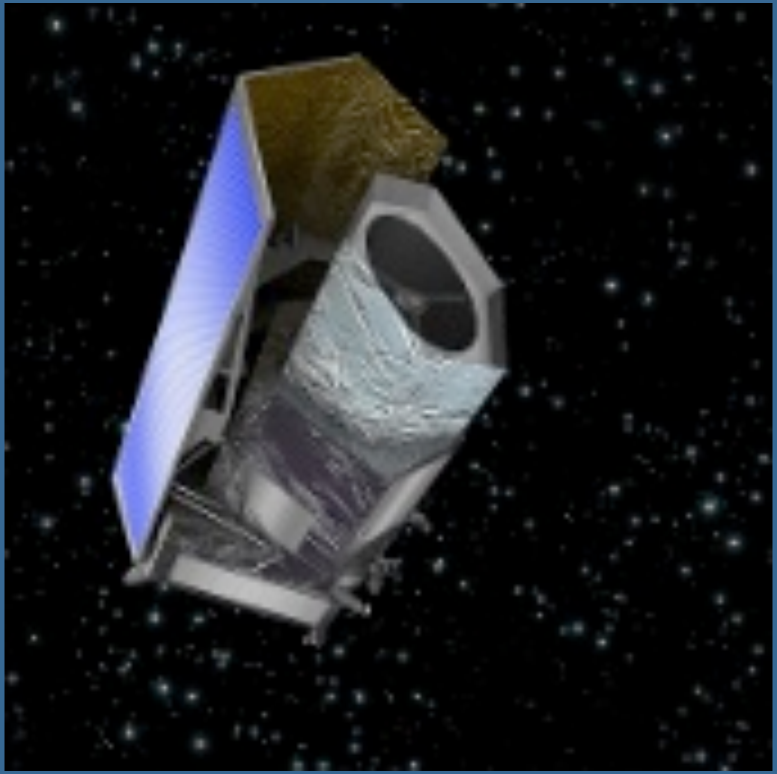
- Sky is very bright in NIR, (~500x brighter)
- Sky is not transparent in NIR, absorption due to H_2O molecular absorption bands is very strong and extremely variable





Dominic Benford

Future Dark Energy Missions

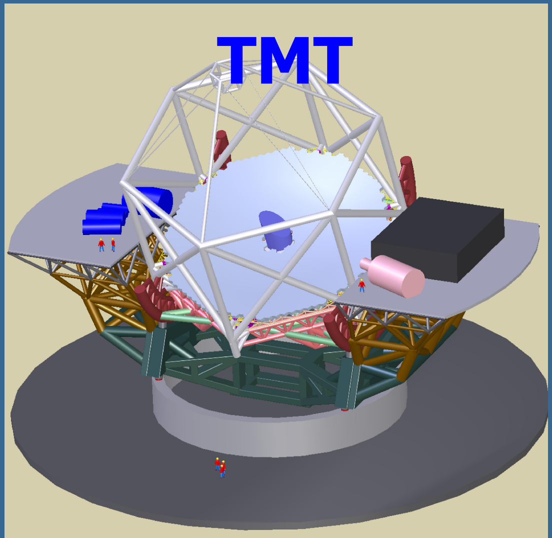


WFIRST-AFTA
Wide-Field Infrared Survey Telescope

Euclid

Extremely Large Telescopes: High Accuracy Requires Spectroscopy

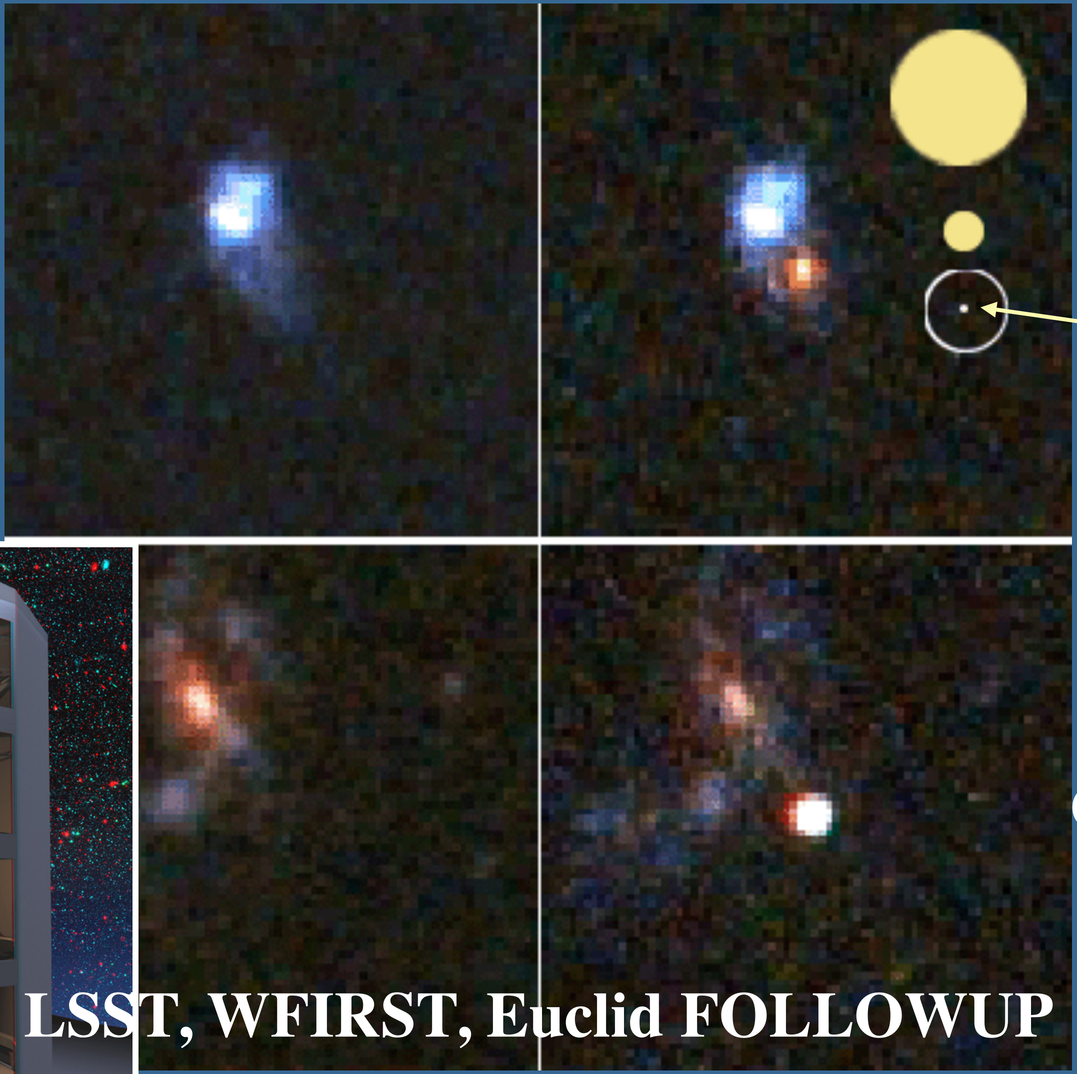
- Giant Magellan Telescope (GMT)
- Thirty-Meter Telescope (TMT)
- European Extremely Large Telescope (EELT)



The Future
SNe Ia & The GMT

SNe studies are limited by confusion

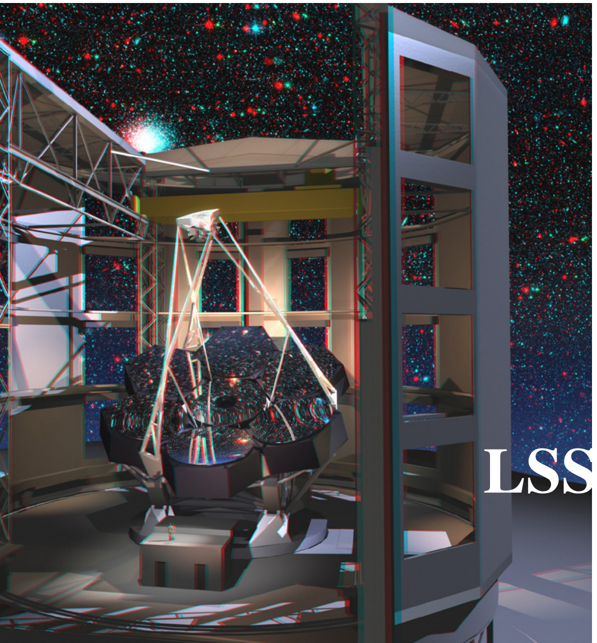
GMT AO



0.5″ seeing

HST 1.5μm

GMT AO



LSST, WFIRST, Euclid FOLLOWUP

GMT Science Working Group

The Giant Magellan Telescope

2021