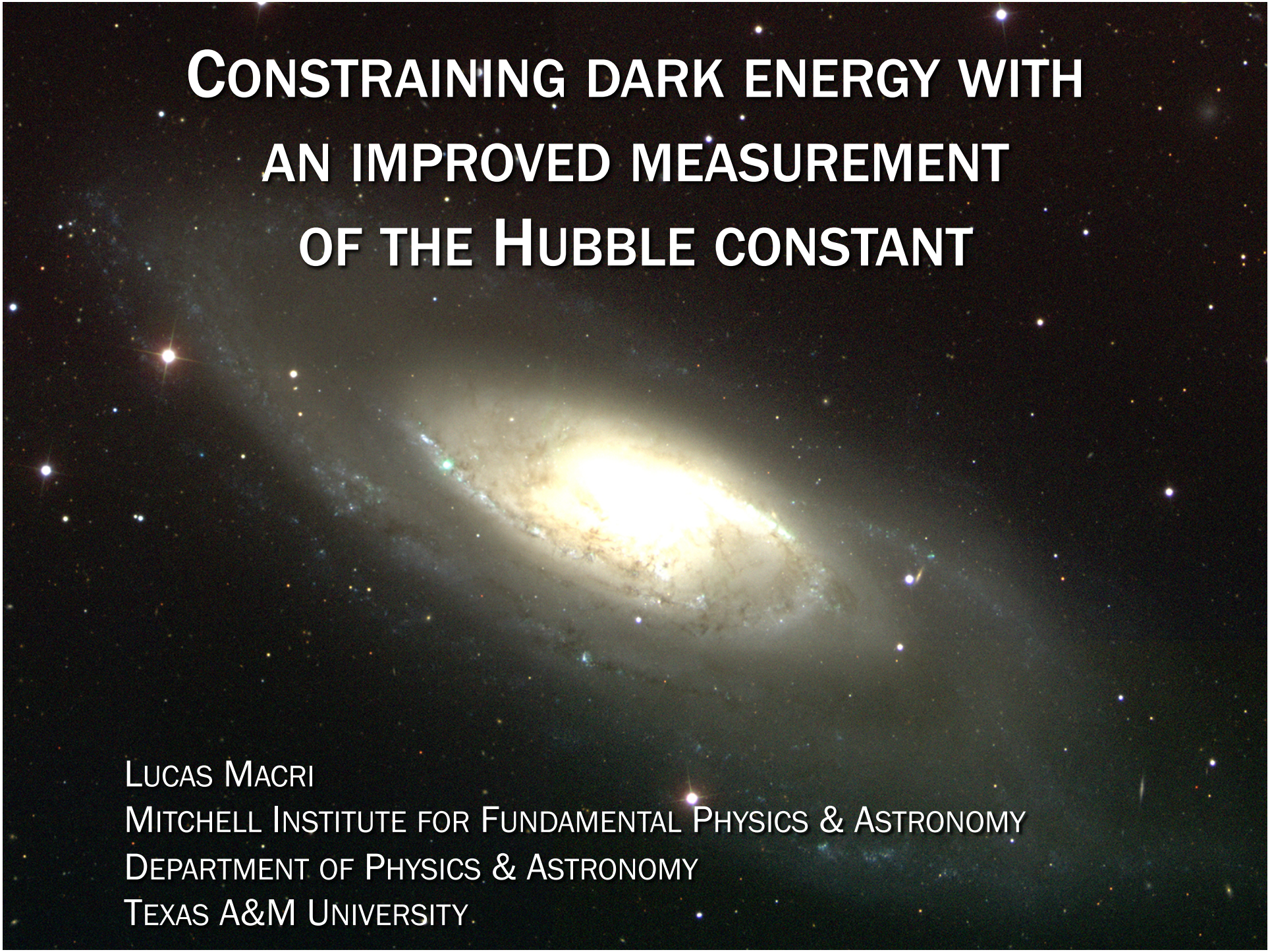


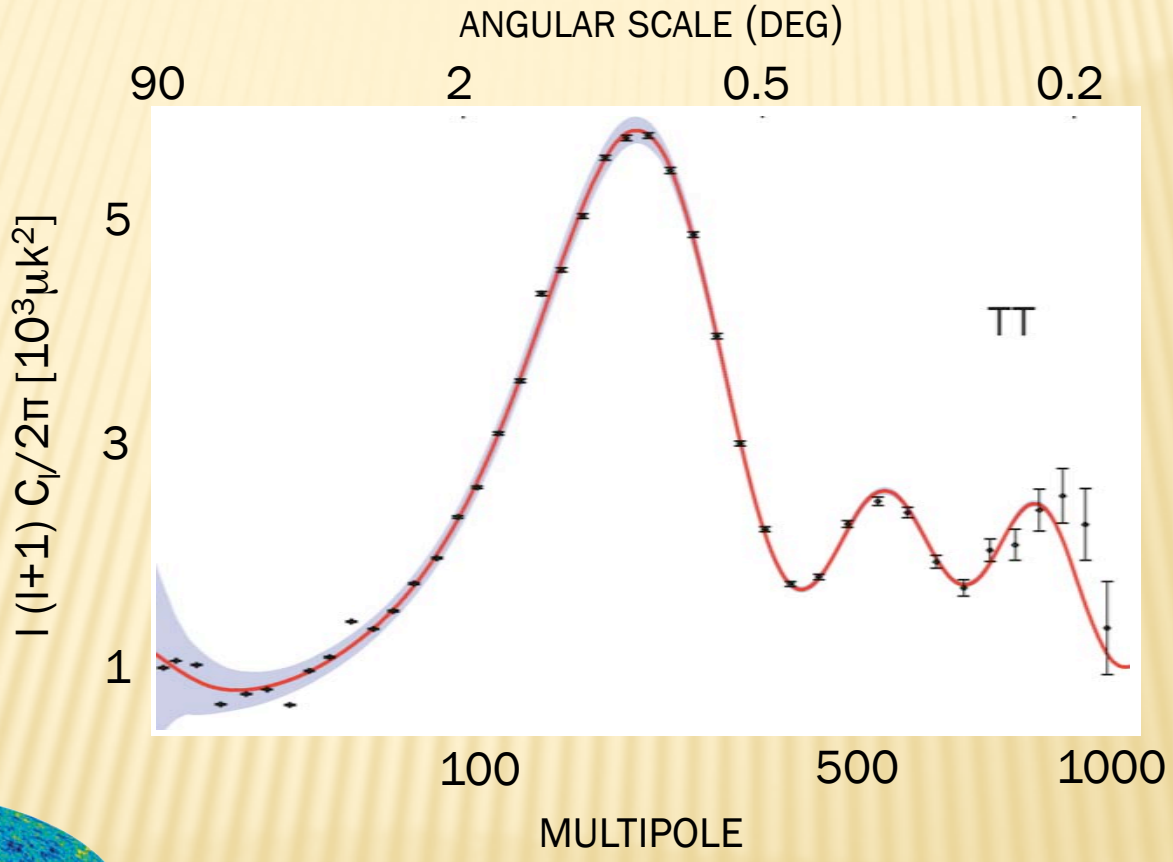
Constraining dark energy with an improved measurement of the Hubble constant

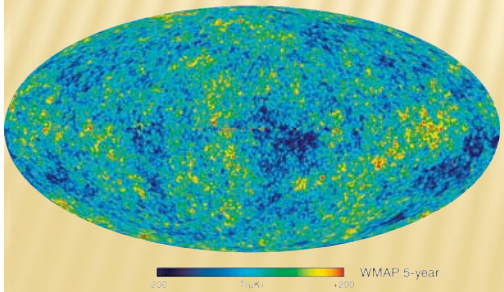
Lucas Macri
Mitchell Institute for Fundamental Physics & Astronomy
Department of Physics & Astronomy
Texas A&M University

Conclusions

- HST observations of 240 Cepheid variables in:
  - NGC 4258 / M106 (aka “the maser galaxy”)
  - Six hosts of “modern & ideal” type Ia SNe
- were used to construct a “sturdier” distance ladder and determine $H_0 = 74.2 \pm 3.6$ km s^{-1} Mpc^{-1}
  - (Riess, Macri, et al. 2009, ApJ 699, 539)
- Combined with WMAP 5-year results *alone* (Komatsu et al. 2009), they yield $w = -1.12 \pm 0.12$
  - add BAO, high-z SNe for further constraints on *w*

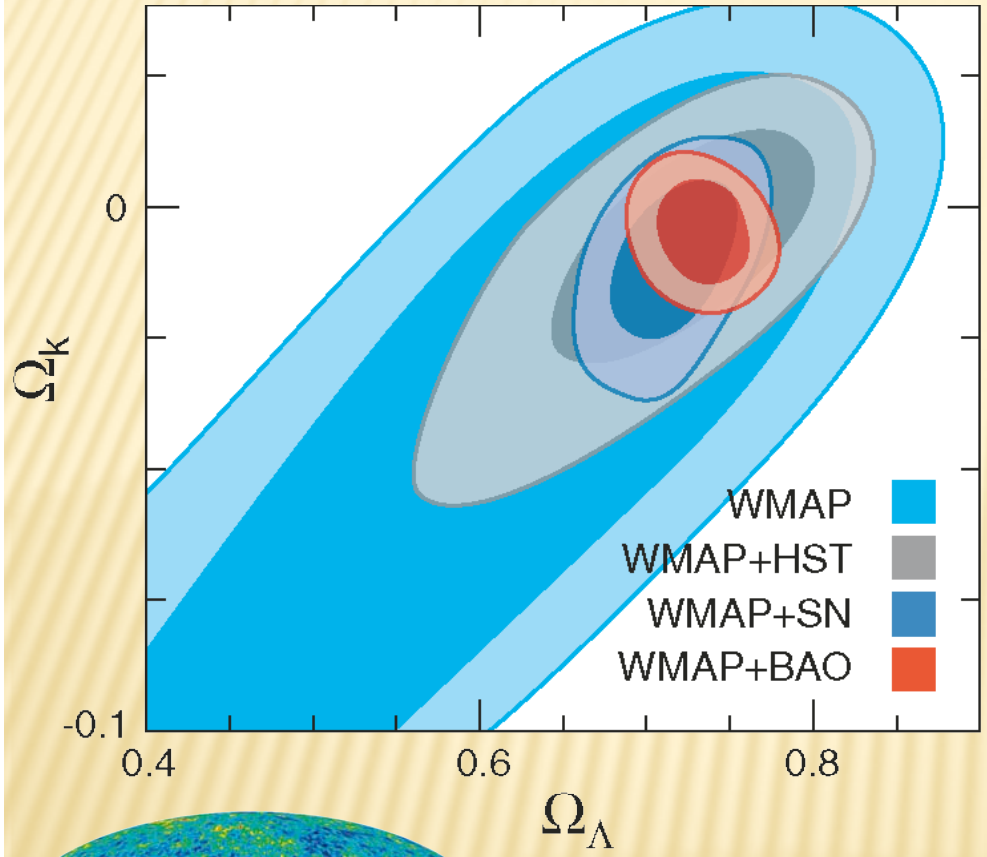
PRECISION COSMOLOGY

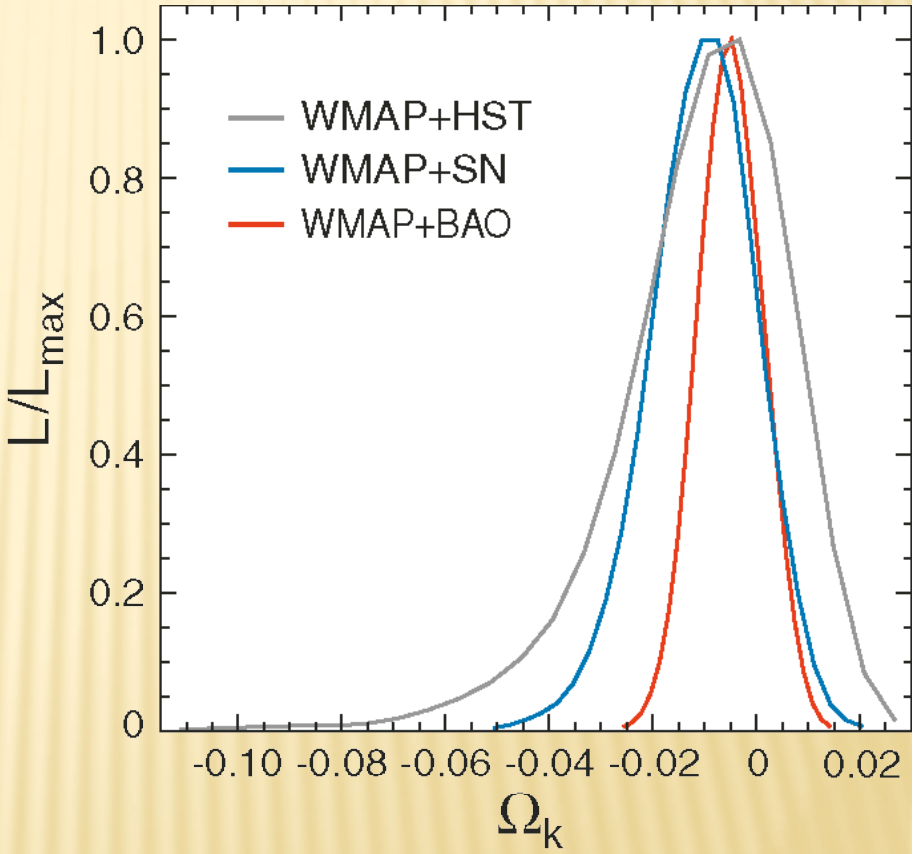


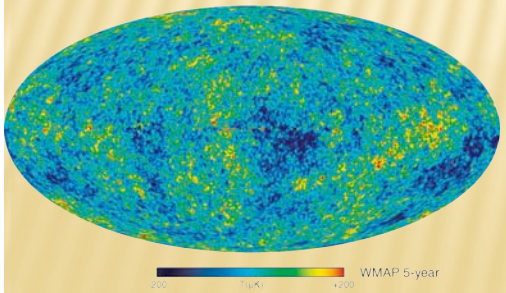


HINSHAW+ (2009)

PRECISION COSMOLOGY

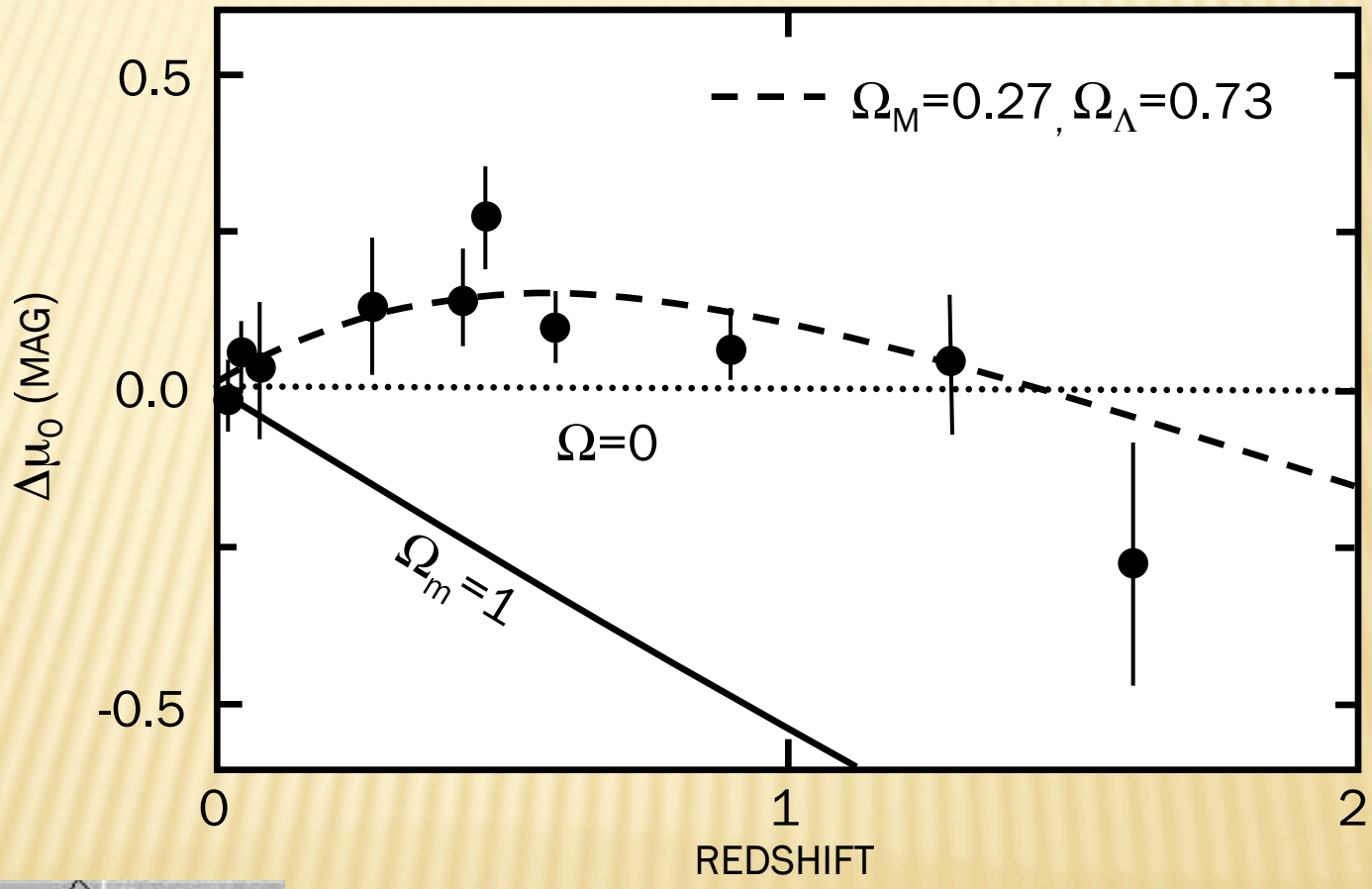


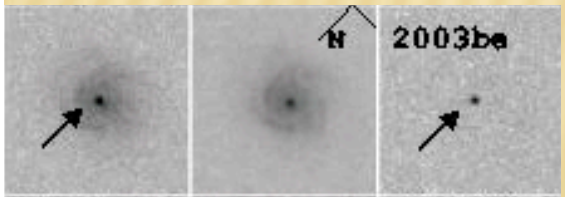




KOMATSU+ (2009)

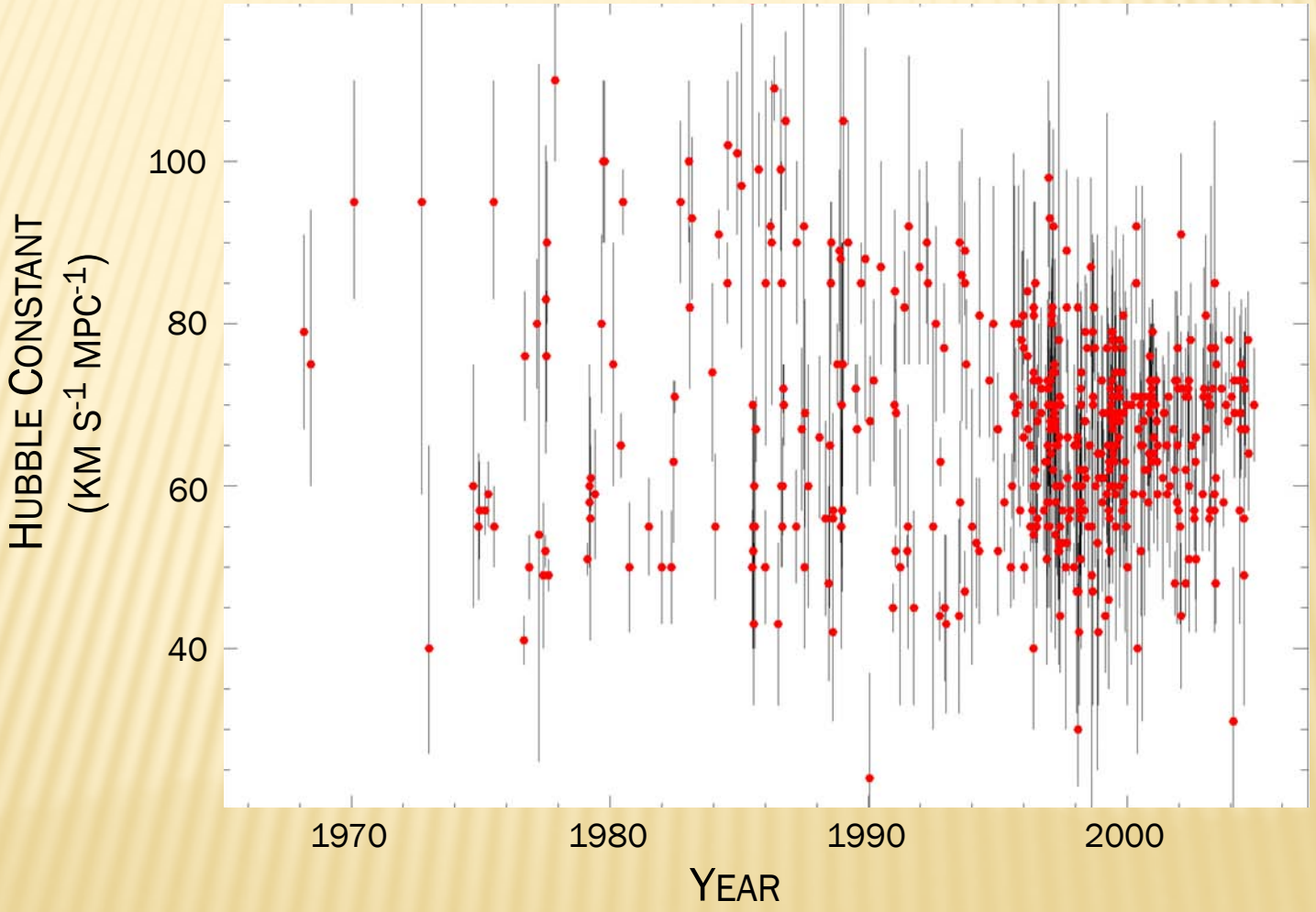
PRECISION COSMOLOGY





RIESS+ (2004)

PRECISION COSMOLOGY???



COMPILATION BY JOHN HUCHRA

THE LONG ROAD TO H_0

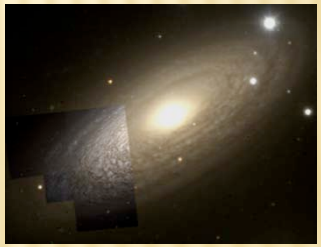
$H_0 = V/D$

V

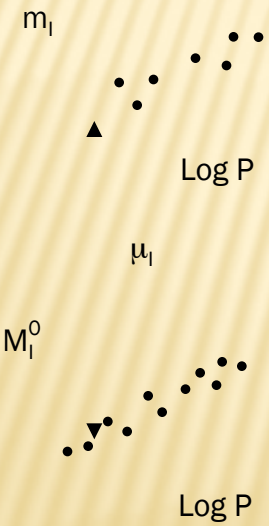
D

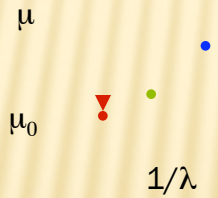
GALAXIES IN HUBBLE FLOW

SECONDARY DISTANCE INDICATORS (IA, TF, SBF)

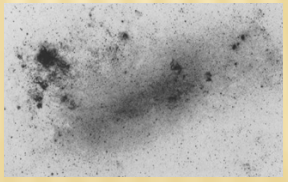


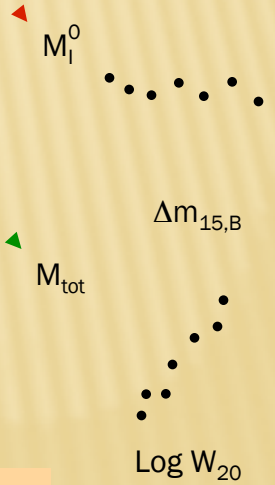
TARGET GALAXIES (D<30 MPC)





"ANCHOR" GALAXY

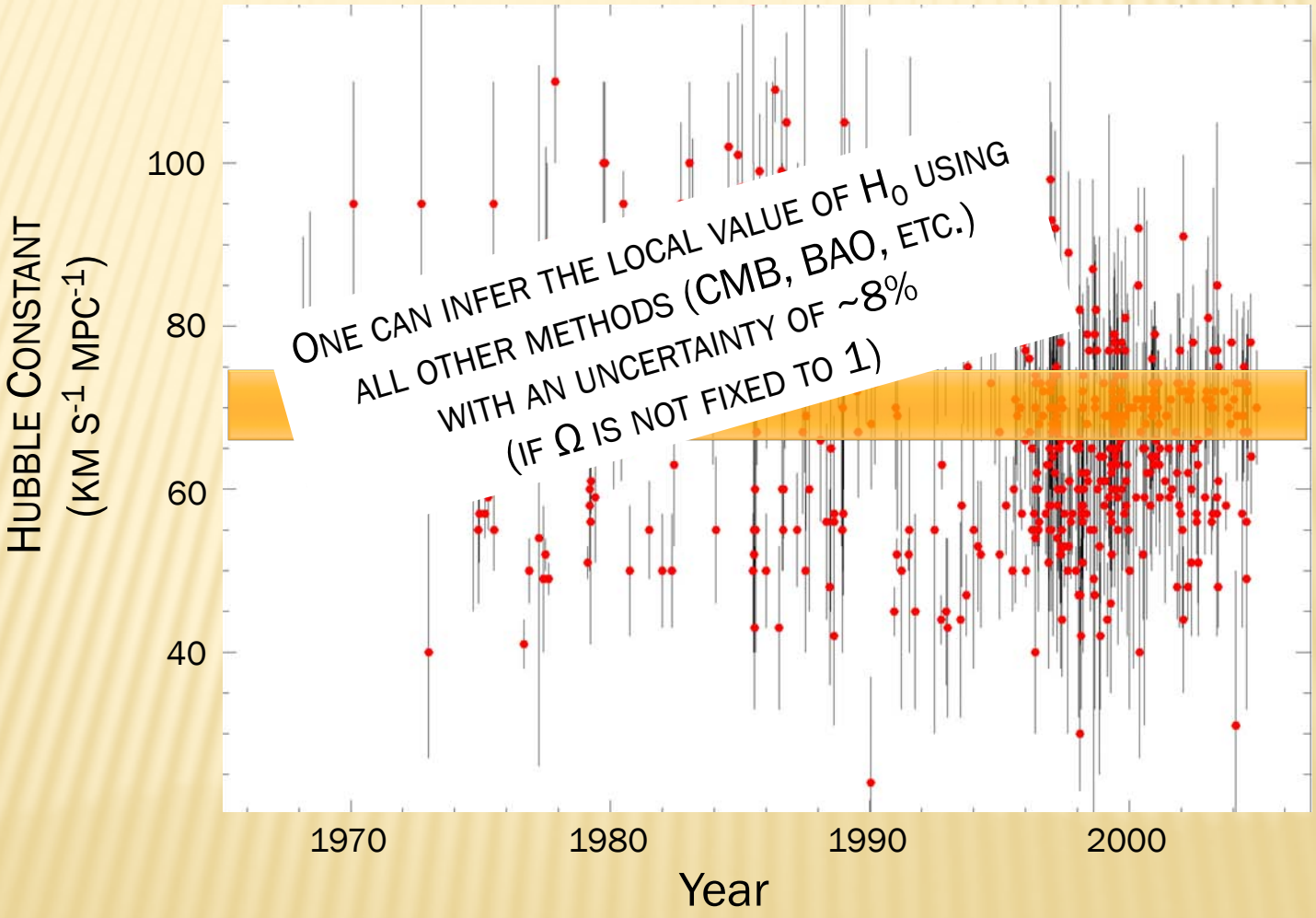




WELL-STUDIED CEPHEID SAMPLE (ABUNDANCES, EXTINCTION)

ACCURATE & PRECISE ABSOLUTE DISTANCE

PRECISION COSMOLOGY???



COMPILATION BY JOHN HUCHRA

THE SH_0ES PROJECT (PI: A. RIESS)

- Aim: determine the value of H_0 with a total uncertainty (random + systematic) below 5% through a "sturdier" distance ladder
- Motivation: a precise and accurate measurement of H_0 can impose useful constraints on the equation of state of dark energy

$$w=P/\rho c^2$$

$$\sigma(w) \approx 2 \times \sigma(H_0)$$

THE ASTROPHYSICAL JOURNAL, 652:1133–1149, 2006 December 1

A NEW CEPHEID DISTANCE TO THE MASER-HOST GALAXY NGC 4258
AND ITS IMPLICATIONS FOR THE HUBBLE CONSTANT[1]

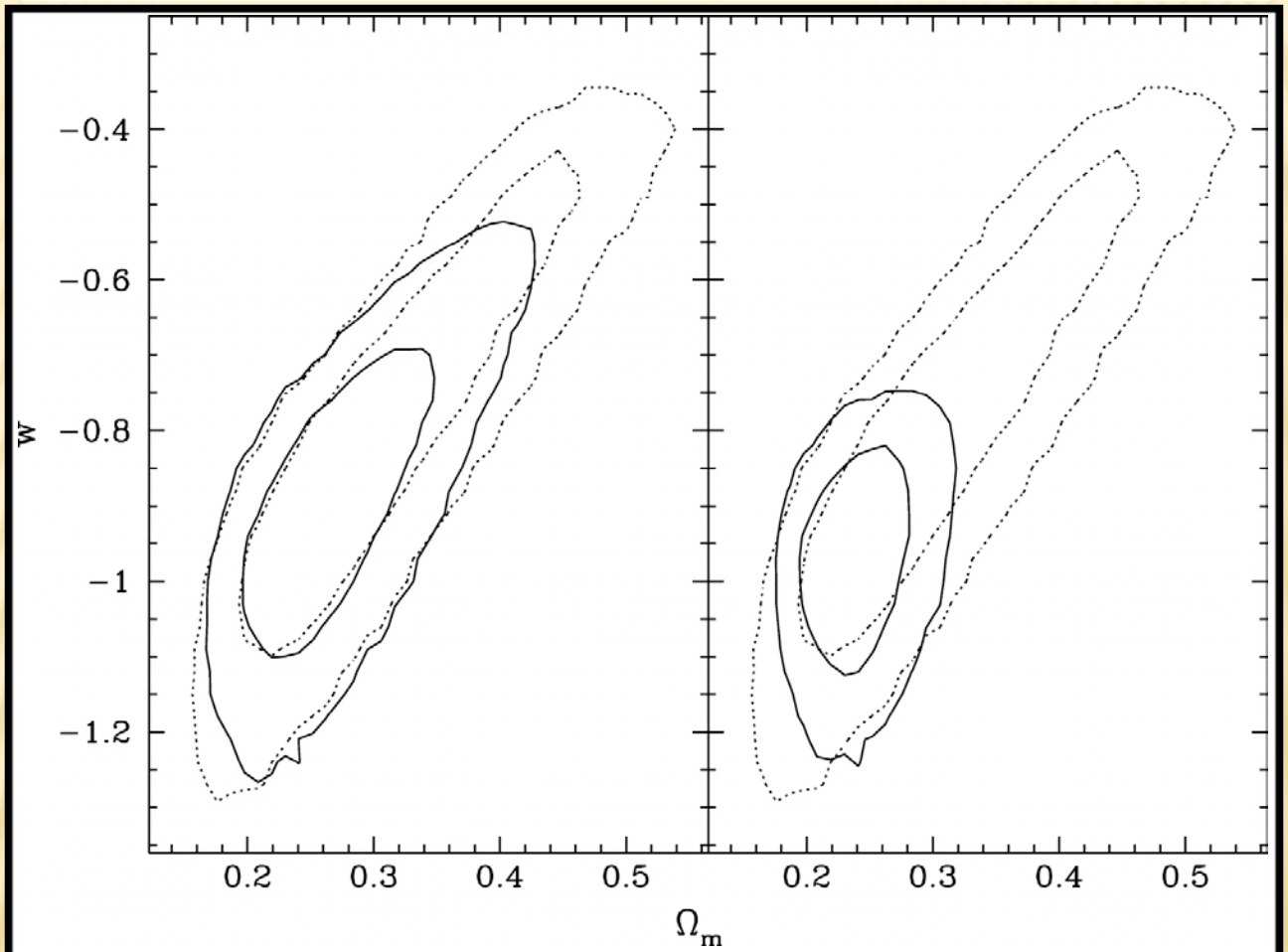
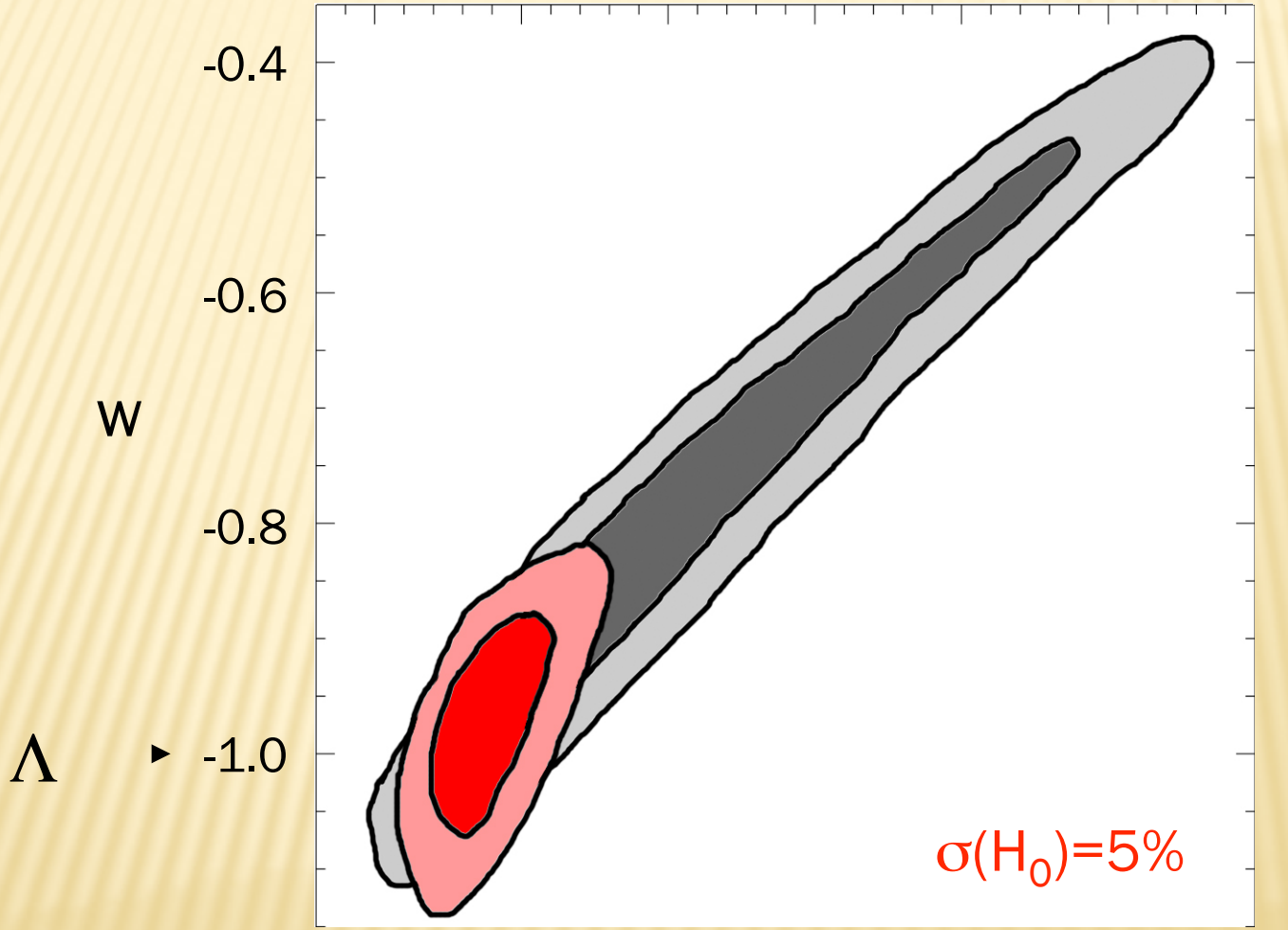


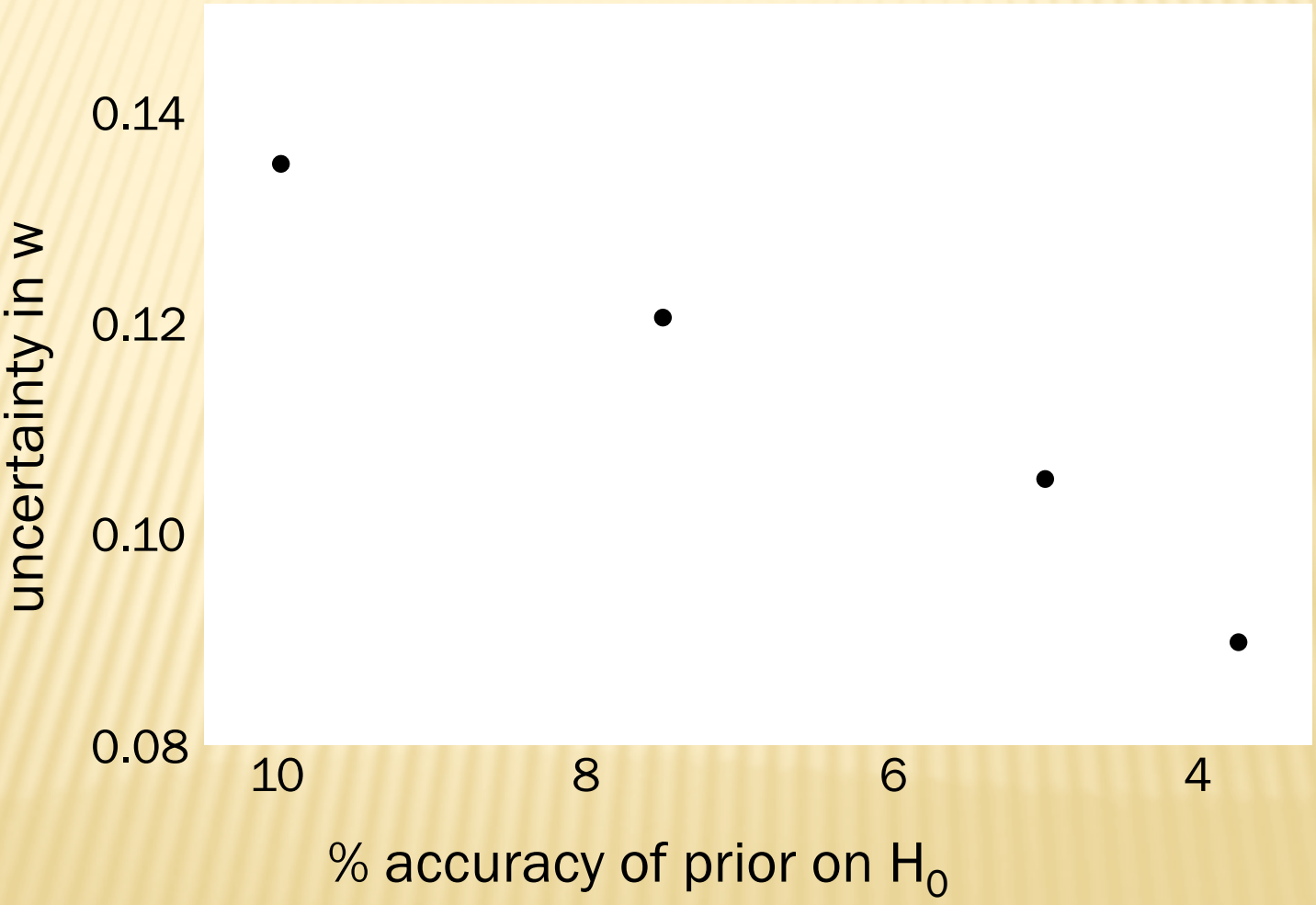
FIG. 23.—*WMAP* 3 yr 1 and 2 σ error contours (*dashed lines*) in the Ω_M-w plane, for the `wcdm+nopert` model of Spergel et al. (2006). The solid contours represent the improvement obtained by using priors on H_0. *Left*: Prior of $H_0 = 72 \pm 7$ km s^{-1} Mpc^{-1} (Freedman et al. 2001). *Right*: Prior of hypothetical future measurement of $H_0 = 74 \pm 3.5$ km s^{-1} Mpc^{-1}.

CMB Degeneracy



Macri+ (2006)

CONSTRAINTS ON *w* FROM CMB + PRIOR ON H_0



MACRI+ (2006)

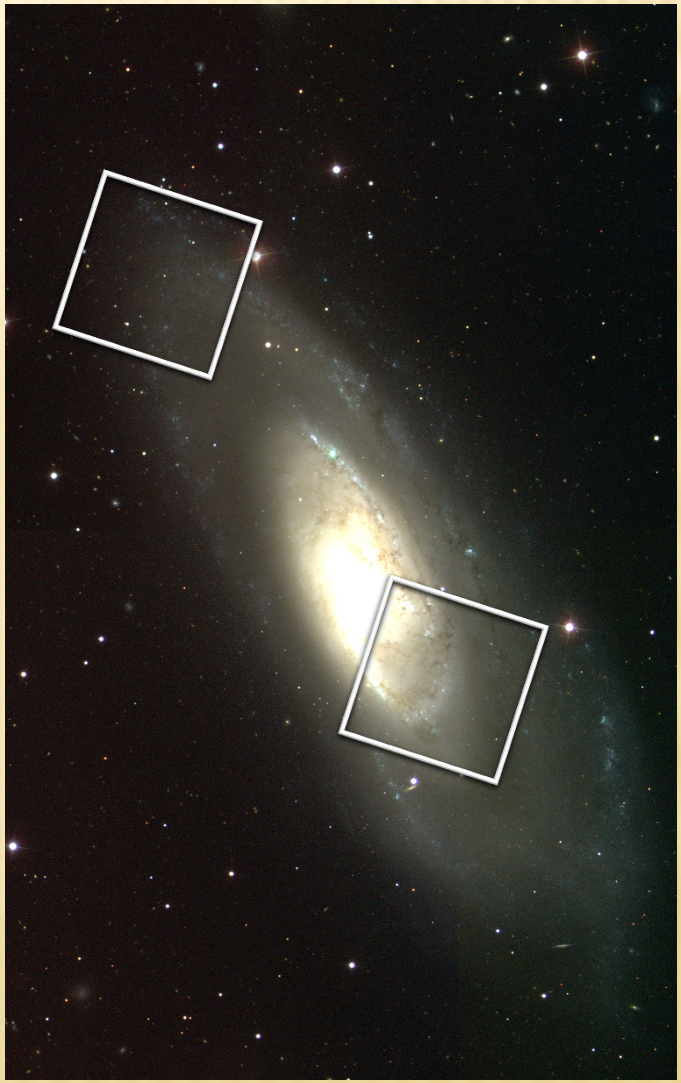
N4258: NEW "FIRST RUNG" OF DISTANCE LADDER

- Distance measurement based on 10+ years of VLBI observations of water masers orbiting central black hole
- D = 7.2 Mpc ± 3%
  - Herrnstein et al. 1999
  - Humphreys et al. 2008
  - Greenhill et al. 2009

COLOR MOSAIC BASED ON SDSS IMAGES

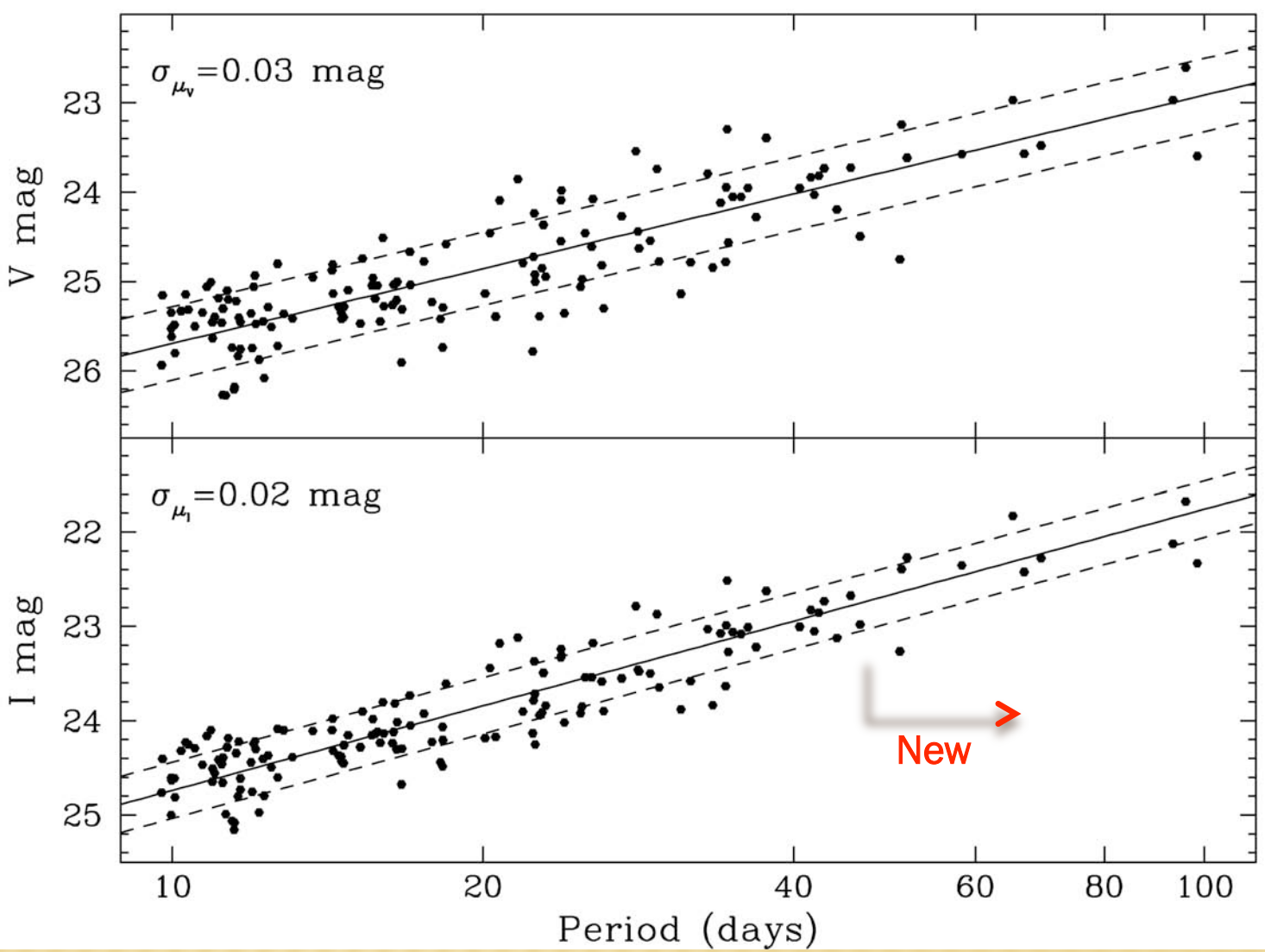
N4258: NEW "FIRST RUNG" OF DISTANCE LADDER

- HST/ACS survey of two fields discovered ~300 Cepheids with 4d<P<45d (Macri+ '06)
- SH_0ES project re-visited these fields 3 years later
- Revisits allowed discovery of longer period Cepheids



COLOR MOSAIC BASED ON SDSS IMAGES

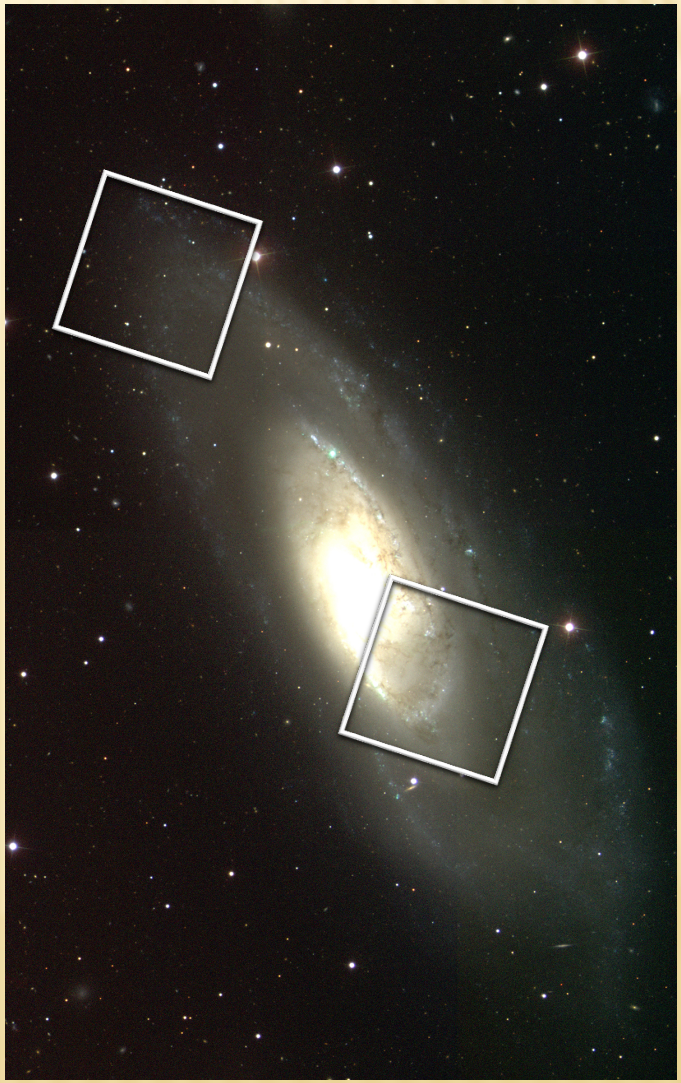
NEW HST CEPHEID P-LS FOR N4258 (INNER)



MACRI+, IN PREP

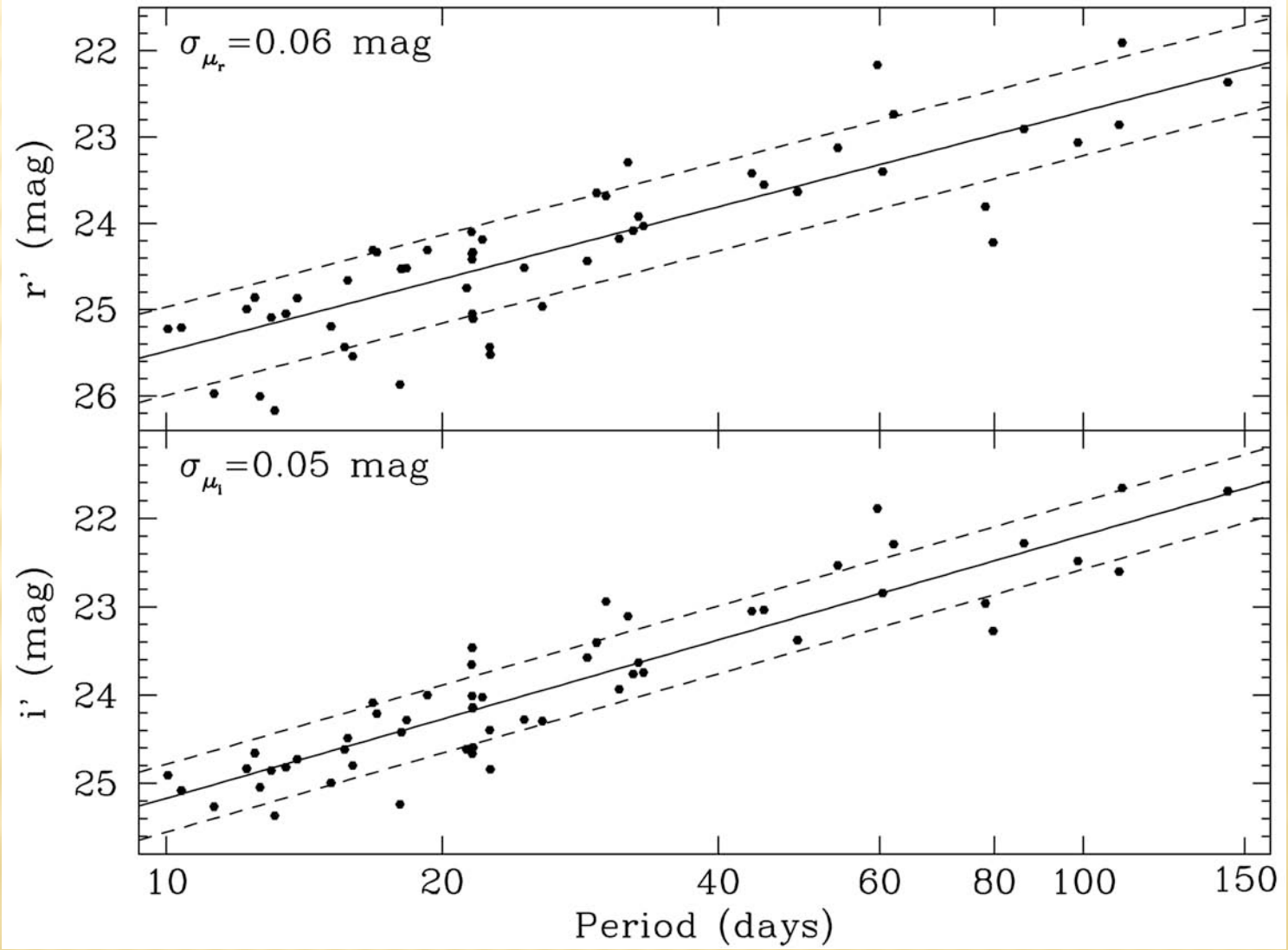
N4258: NEW "FIRST RUNG" OF DISTANCE LADDER

- Gemini North/GMOS survey of same fields:
  - 4 years, 22 epochs, ~0.5" seeing, *gri*
- Preliminary results for outer field in Samantha Hoffmann's poster:
  - 68 Cepheids with $P>10^d$
  - 12 with $45^d < P < 150^d$
  - lots of long-period variables (Miras, etc.)



COLOR MOSAIC BASED ON SDSS IMAGES

NEW GEMINI CEPHEID P-LS FOR N4258 (OUTER)



HOFFMANN+, IN PREP

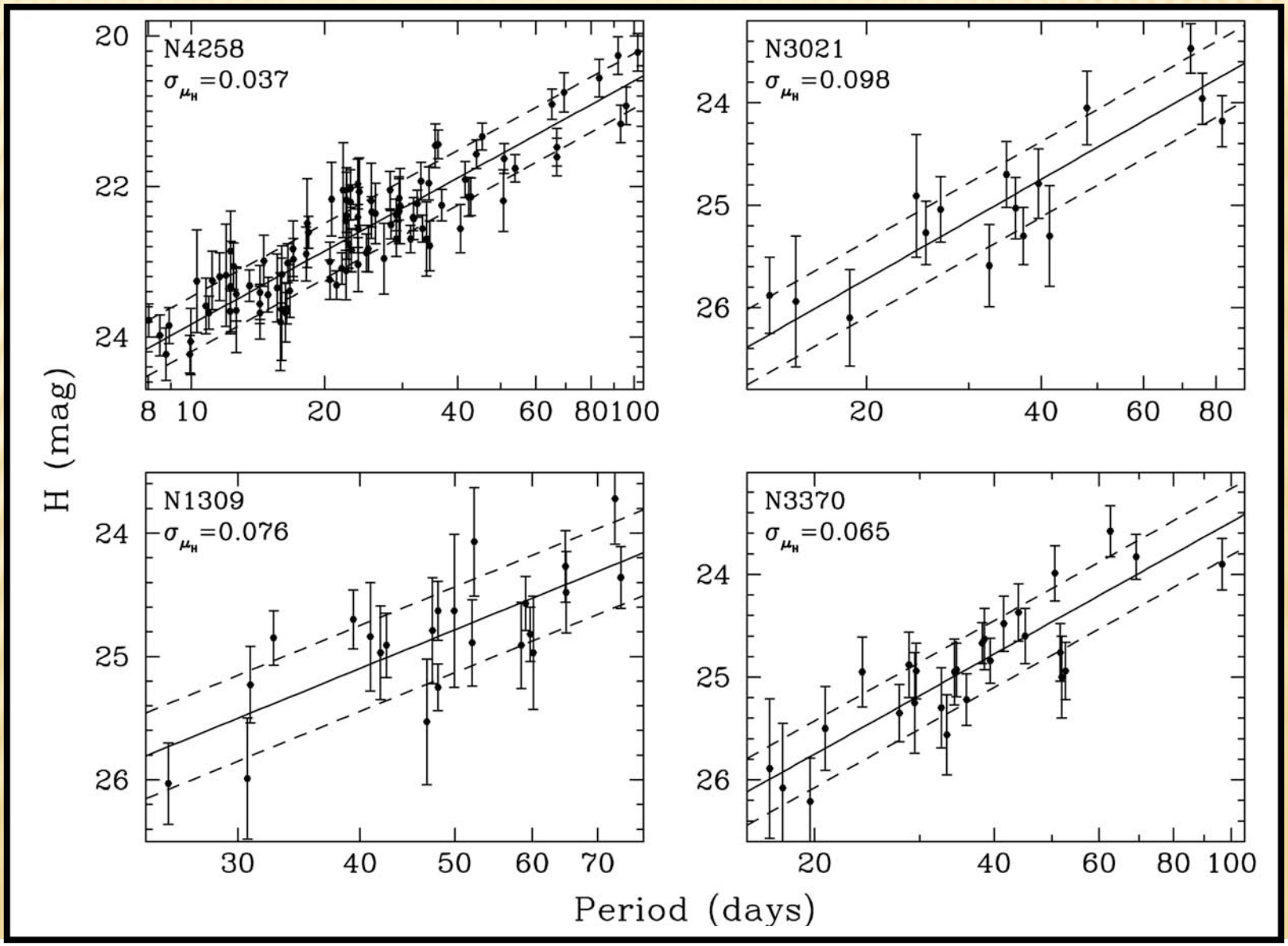
The SH_0ES Approach

- Minimize sources of systematic uncertainty:
  - All observations with same telescope & instrument
    - Optical: ACS/WFC; Near-infrared: NICMOS/NIC2
  - Cepheids with similar properties
    - Abundances (near solar)
    - Extinction (low)
    - Period range (10d < P < 100d)
    - Crowding/blending corrections (median 0.15 mag)

The SH_0ES Approach

- Minimize sources of systematic uncertainty:
  - Type Ia SNe limited to “modern” & “ideal”
    - CCD or photoelectric photometry (no photog. plates)
    - Observed before maximum
    - Low extinction
    - Decline rate in normal range (no sub-luminous)
  - 6 SNe meet these criteria and are close enough for a HST-based Cepheid search
    - 4 previously observed
    - 2 new Cepheid distances in HST Cycle 14
      - (Riess, Macri, et al. 2009, ApJS 183, 109)

SH_0ES P-L Relations from HST/NICMOS



Riess, Macri+, ApJ 699 (2009)

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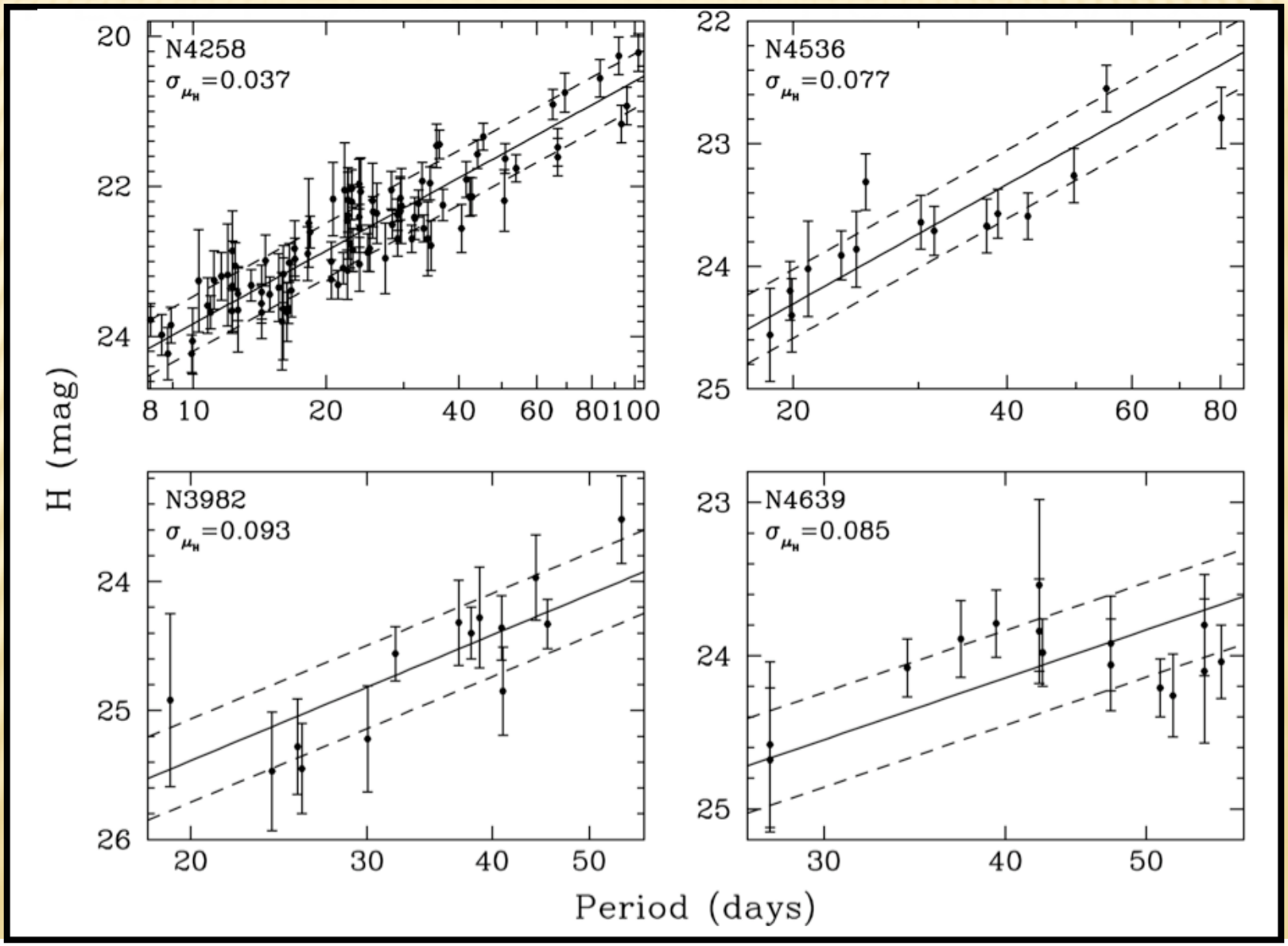


Riess, Macri+, ApJ 699 (2009)

The SH_0ES Approach

- Global fit to Cepheid and SN data in matrix form
  - Solve for relative distances between galaxies
  - Determine hypothetical peak magnitude of a type Ia SN in NGC 4258
    - Ties Cepheid & SN distance scales
    - Peak mag of type Ia SN in Hubble flow from Hicken+ ’09
  - Full propagation of errors through covariance matrix
    - Allows for full exploration of error budget
    - 22 scenarios considered

Results

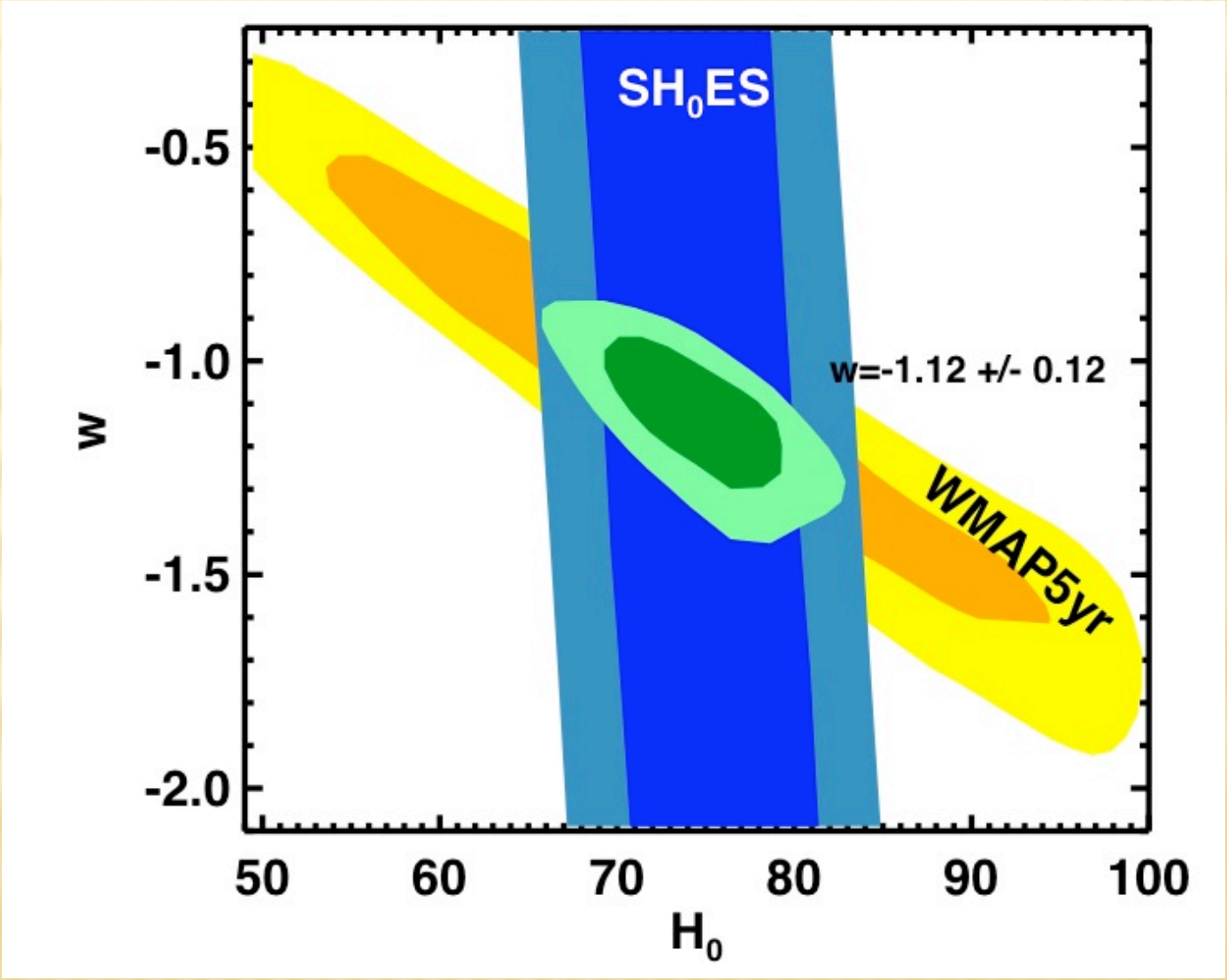
$$H_0 = 74.2 \pm 3.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

- What is the impact of a 5% measurement of H_0 on the allowed values of *w*?
- Combine our result with WMAP 5-year results (Komatsu et al. 2008) to obtain

$$w = -1.12 \pm 0.12$$

add BAO, high-z SNe for further constraints on w

Results



Riess, Macri+, ApJ 699 (2009)

Next step: H_0 to 3%

- What are the largest contributions to the current error budget?
  - Single anchor: N4258 with σ(D)=3%
  - Solution: add Milky Way Cepheids
    - HST-based parallaxes from Benedict et al. (2007)
    - Linearity of magnitude scale through 10^{11} in flux?
  - Solution: add LMC, M31, M33 (poster by Pellerin)
    - "Geometric" distances from detached eclipsing binaries
    - Metallicity dependence of Cepheids @ 1.6 μm?
    - Systematics of DEB distances? GAIA parallaxes?

Next step: H_0 to 3%

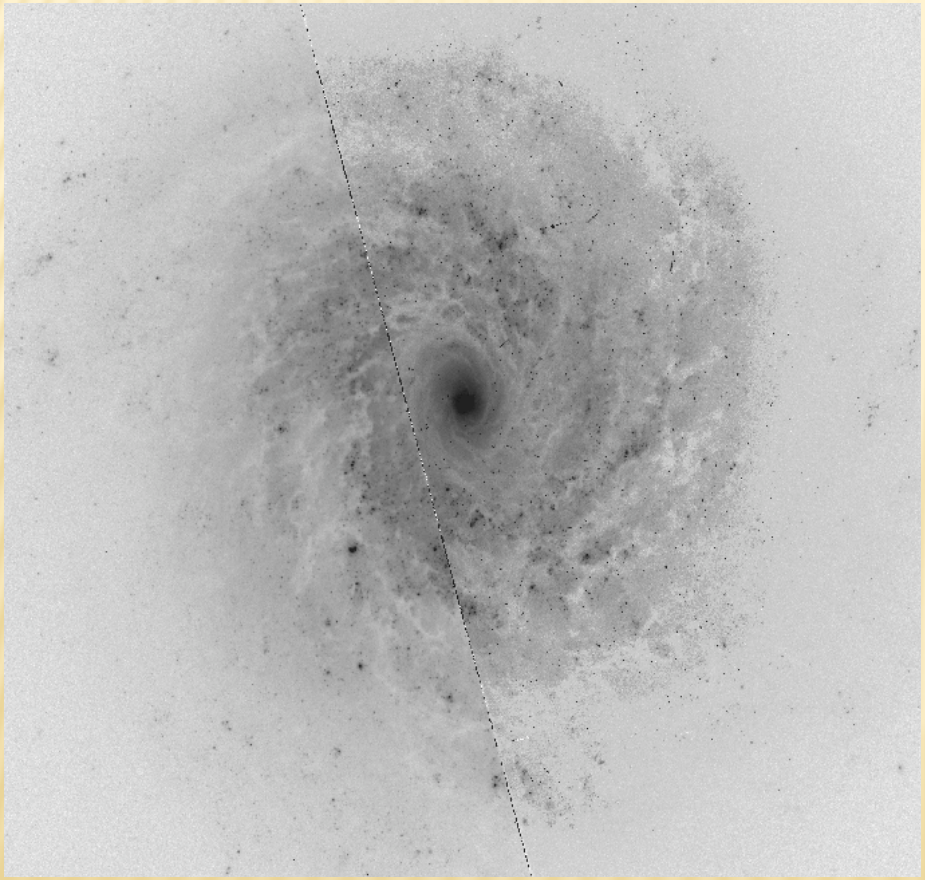
- What are the largest contributions to the current error budget?
  - # of Cepheids in anchor galaxy: N~100 with P>8d
  - Solution: ground-based surveys of N4258
    - Hoffmann et al (in prep): Gemini survey of HST fields
    - Ongoing LBT survey of entire disk (Kochanek et al.)
  - Will image entire disk of N4258 with WFC3/IR
    - Approved HST Cycle 17 program
    - Will revisit all SN hosts to tie WFC3/NICMOS mags

Next step: H_0 to 3%

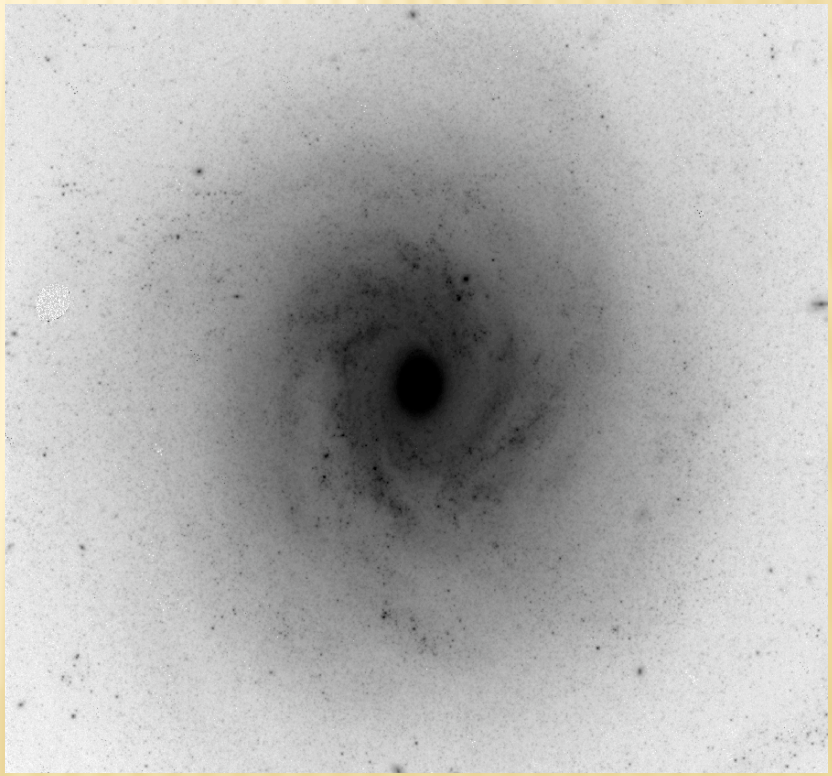
- What are the largest contributions to the current error budget?
  - # of SN hosts: N=6 with σ(D)=3-5% each
  - Solution: pursue new SNe within HST volume
    - NGC 4038/9 (Antennae): see poster by Chavez
    - One additional SN host in Cycle 17
  - Push the distance limit through difference imaging
    - Reliable detections, periods; might not get mean mags
    - Future follow-up with JWST NIRCam

First images from WFC3! ☺

NGC 3982: host of SN 1998aq ; D = 22 Mpc, z = 0.0037

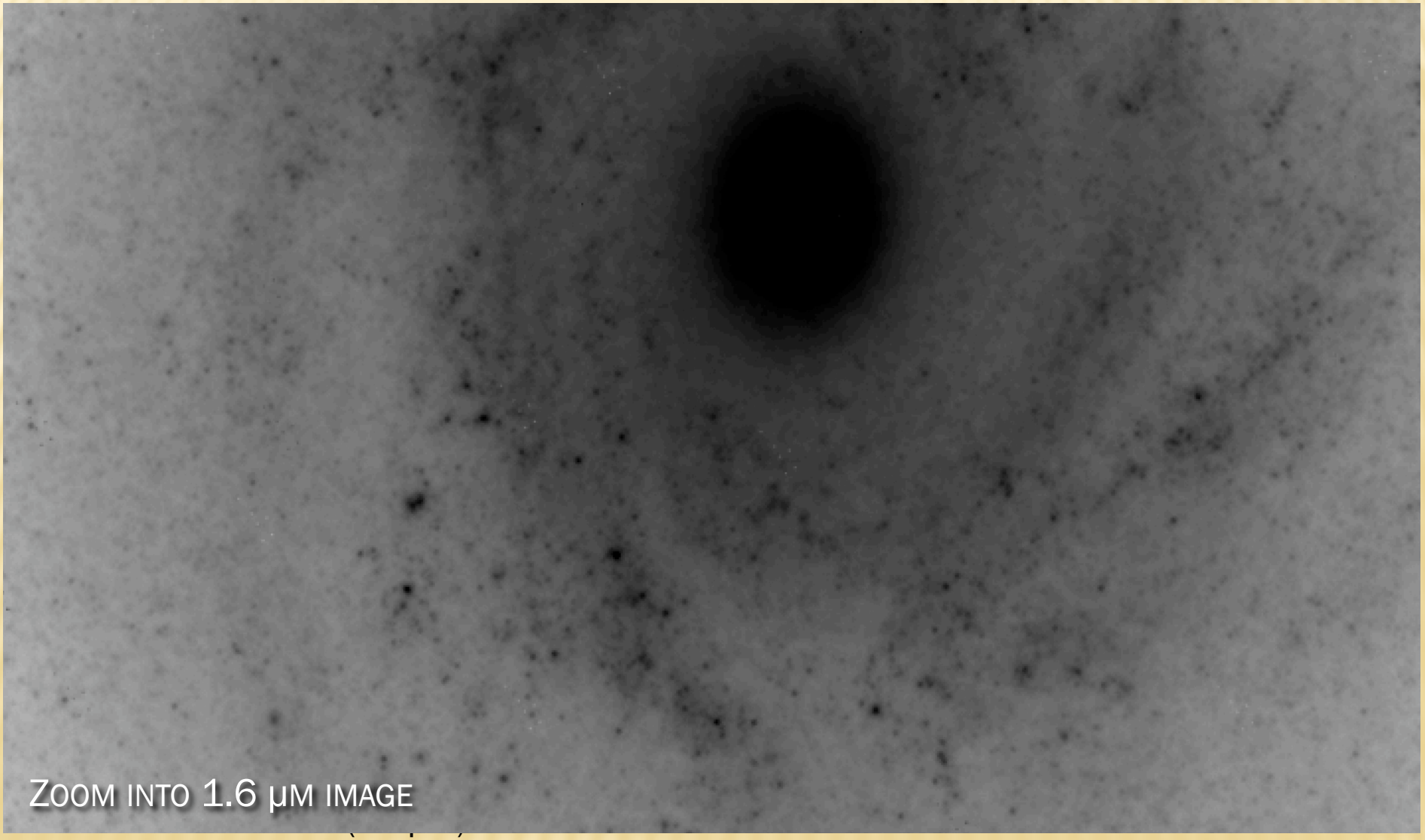


V-band (0.5μm)



H-band (1.6μm)

First images from WFC3! ☺



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  - add BAO, high-z SNe for further constraints on *w*