# The expansion history of the Universe

Lucas Macri – Texas A&M University

&

Adam Riess – Johns Hopkins University / STScI

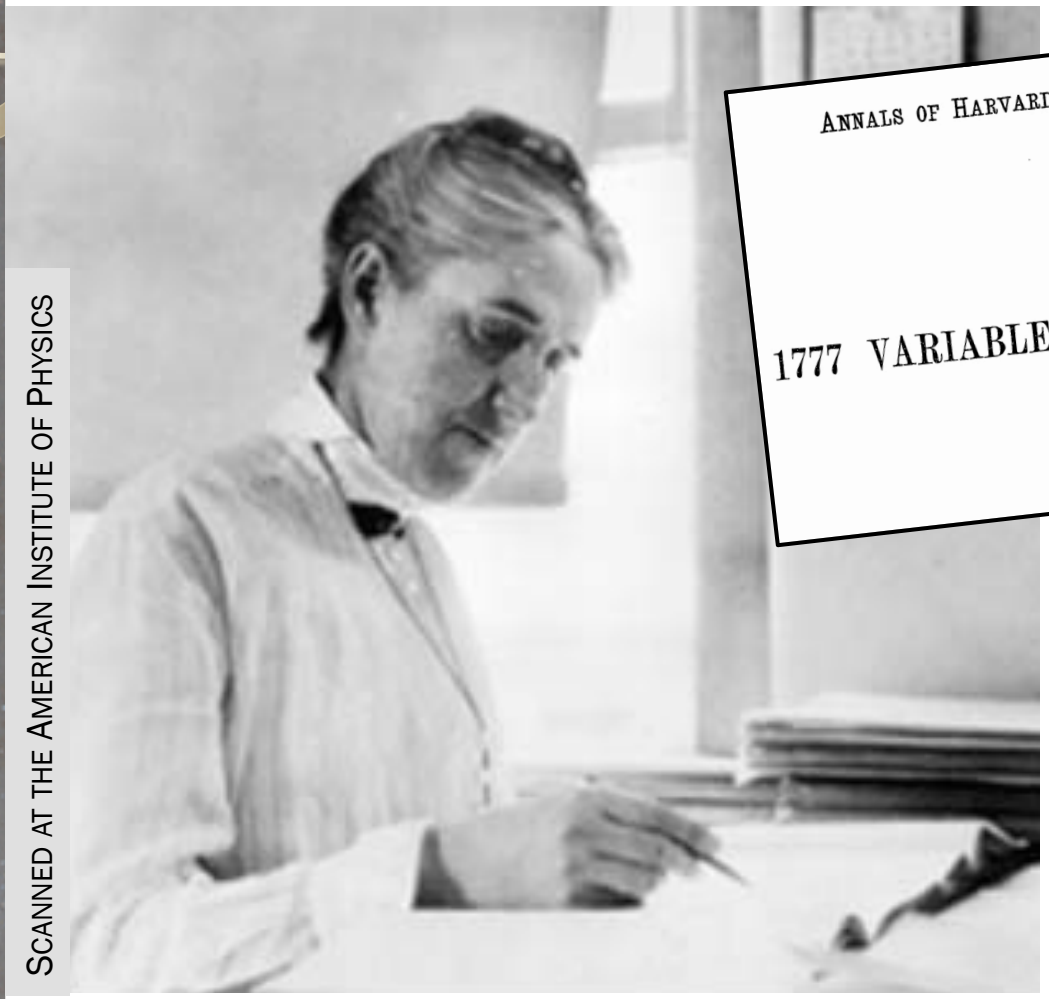
*Science with the Hubble Space Telescope - III*

*two decades and counting*

# OUTLINE

- IN THE BEGINNING…
  - WFPC2-BASED SURVEYS: $H_0$ TO 10%
  - HST & DARK ENERGY
  - $SH_0ES$: $H_0$ TO 5%
  - LATEST RESULTS FROM WFC3

# Henrietta Swan Leavitt



Scanned at the American Institute of Physics

ANNALS OF HARVARD COLLEGE OBSERVATORY. VOL. LX. No. IV.

1777 VARIABLES IN THE MAGELLANIC CLOUDS.

BY HENRIETTA S. LEAVITT.

Leavitt (1908)

# The Leavitt Law (Cepheid P-L rel)

HARVARD COLLEGE OBSERVATORY.

CIRCULAR 173.

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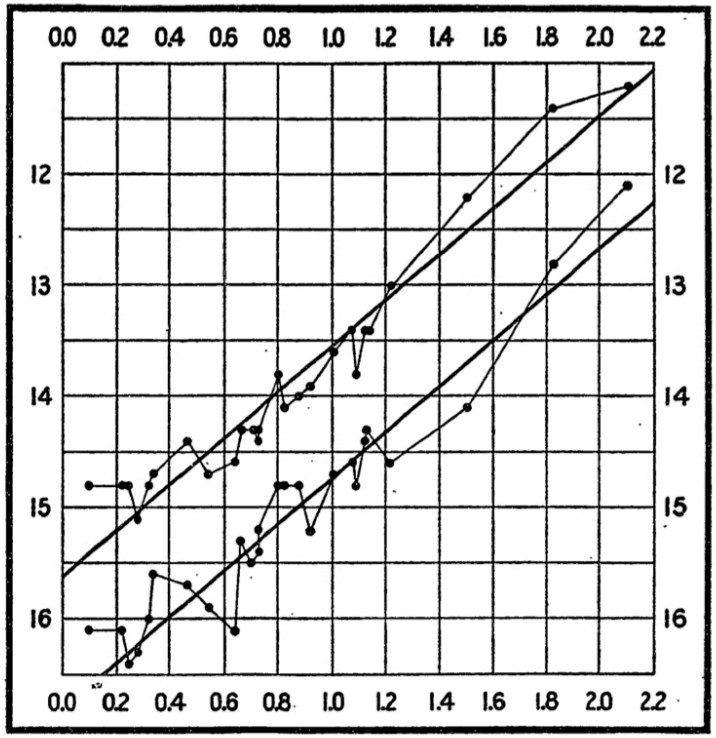
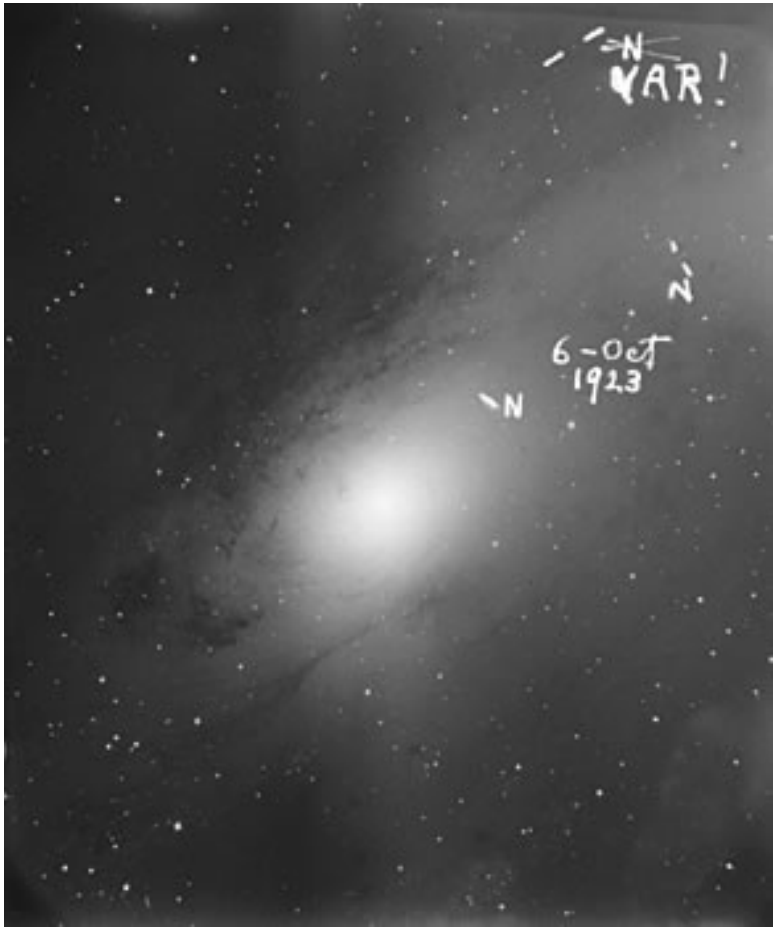
PERIODS OF 25 VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

It is to be hoped, also, that the parallaxes of some variables of this type may be measured.




Leavitt & Pickering (1912)

# Hubble & Cepheids

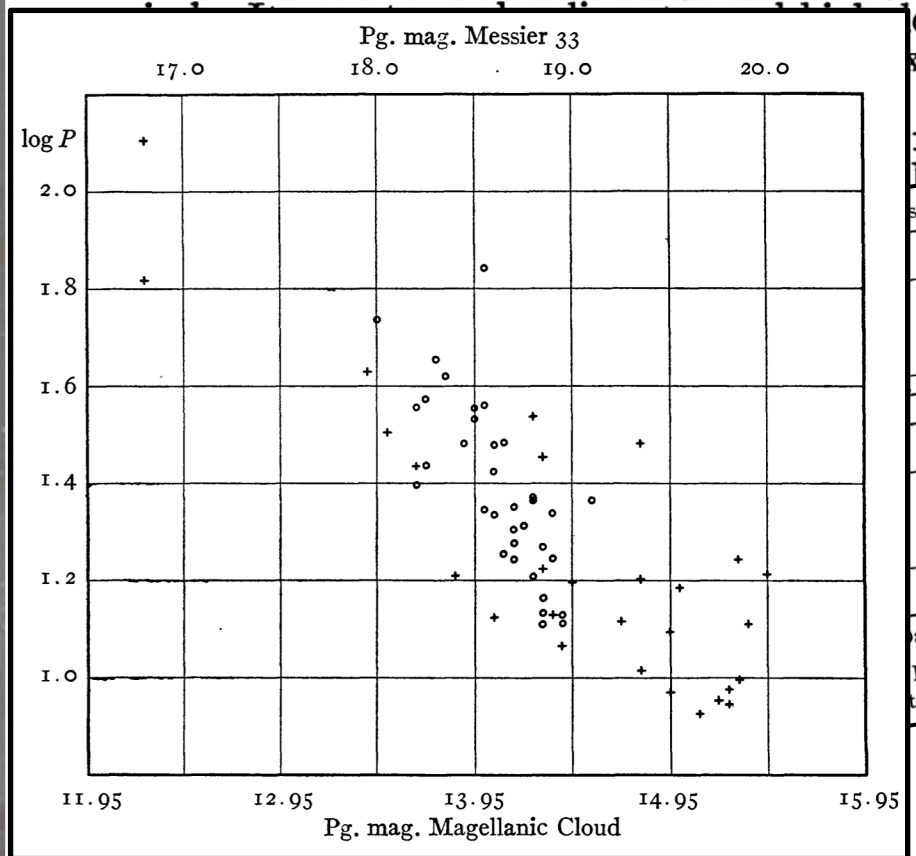
# HUBBLE & CEPHEIDS

## A SPIRAL NEBULA AS A STELLAR SYSTEM MESSIER 33[1]

By EDWIN HUBBLE

ABSTRACT

*The spiral nebula Messier 33.*—This object is the fainter of the two naked-eye
egree of resolution, suggesting that it is
xceptional opportunities for detailed in-
100-inch reflector
he



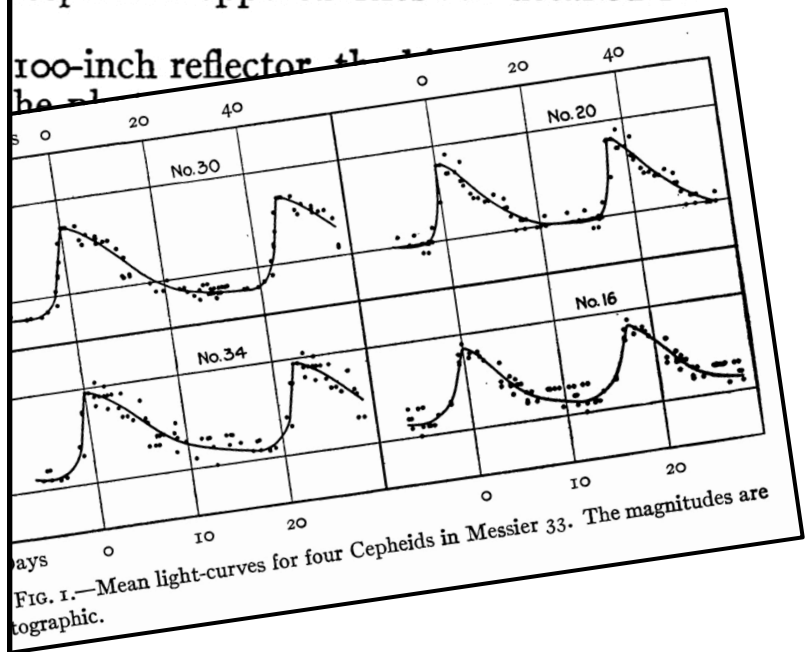




FIG. 1.—Mean light-curves for four Cepheids in Messier 33. The magnitudes are
tographic.

HUBBLE (1926)

# THE FIRST EXTRAGALACTIC DISTANCE SCALE

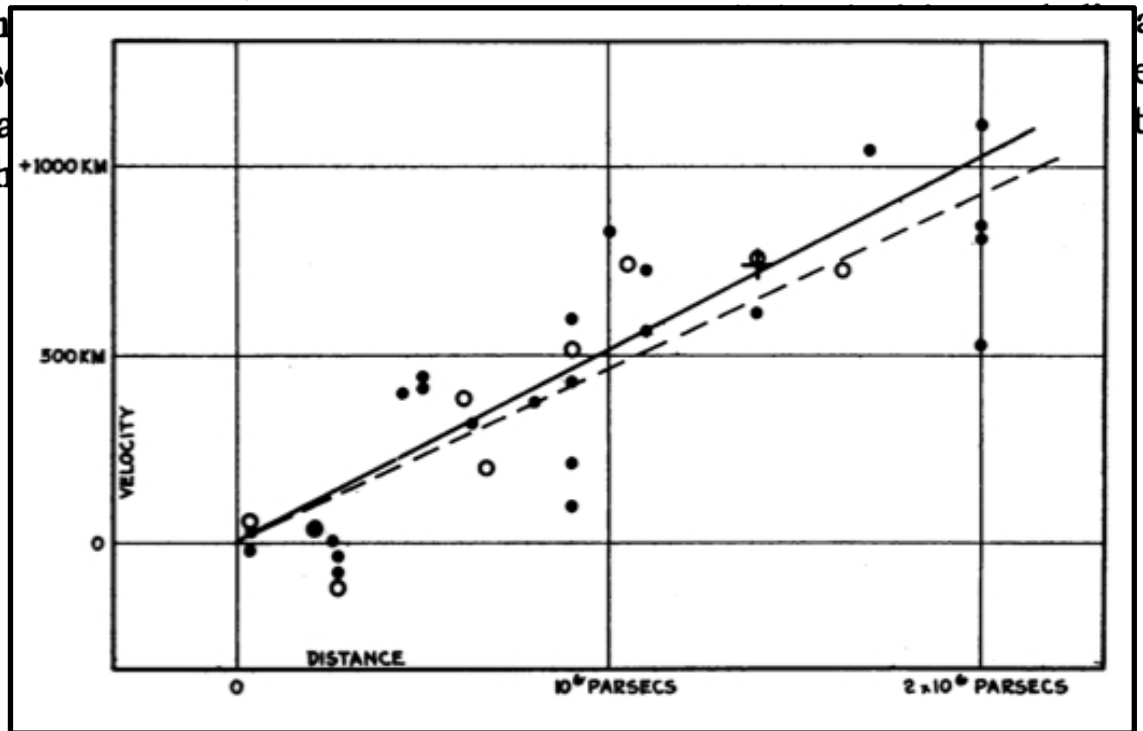
*A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE*

By Edwin Hubble

Mount Wilson Observatory, Carnegie Institution of Washington

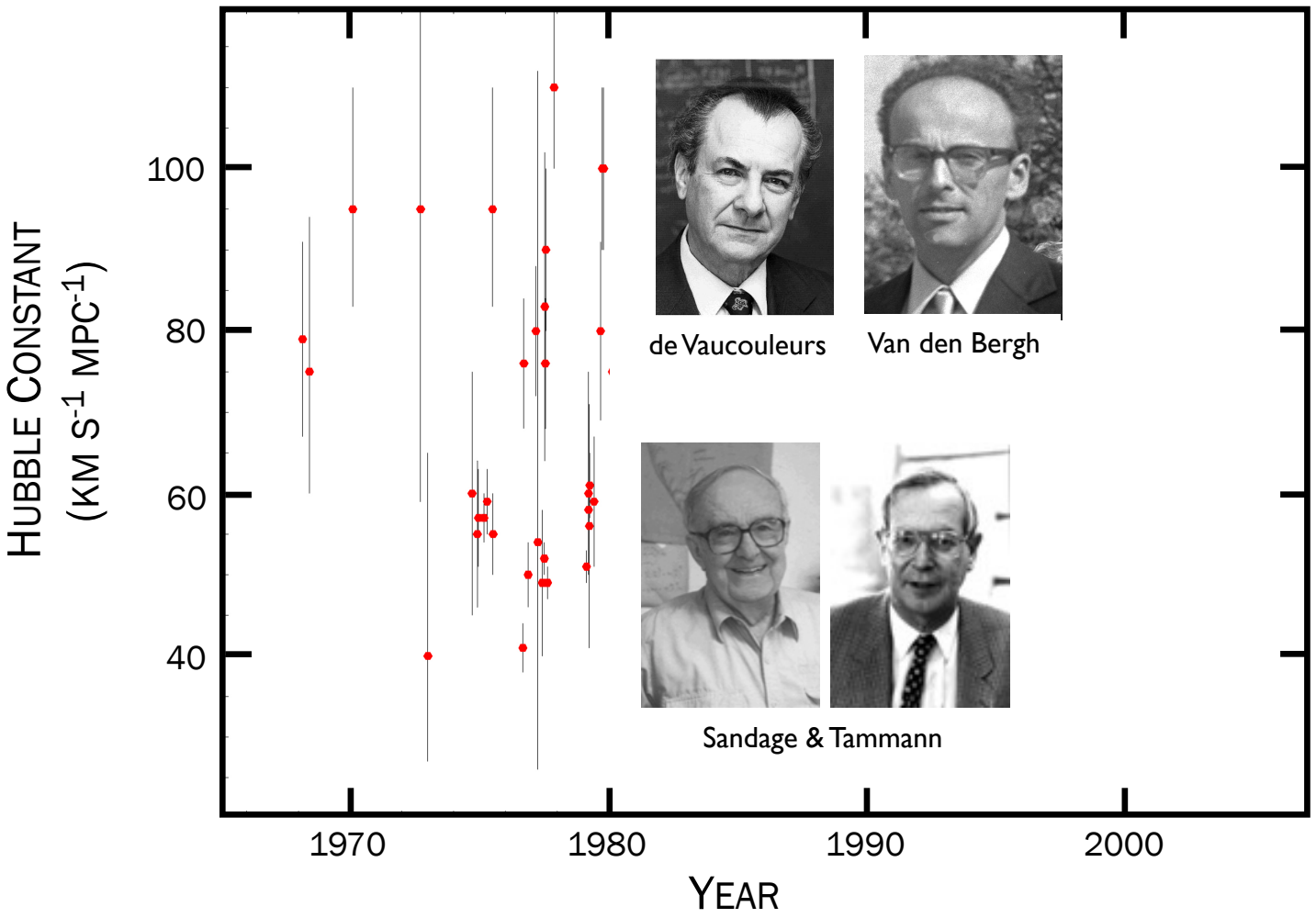
Communicated January 17, 1929

Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a $K$ term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sough ances, but s er is a re-exa tances which



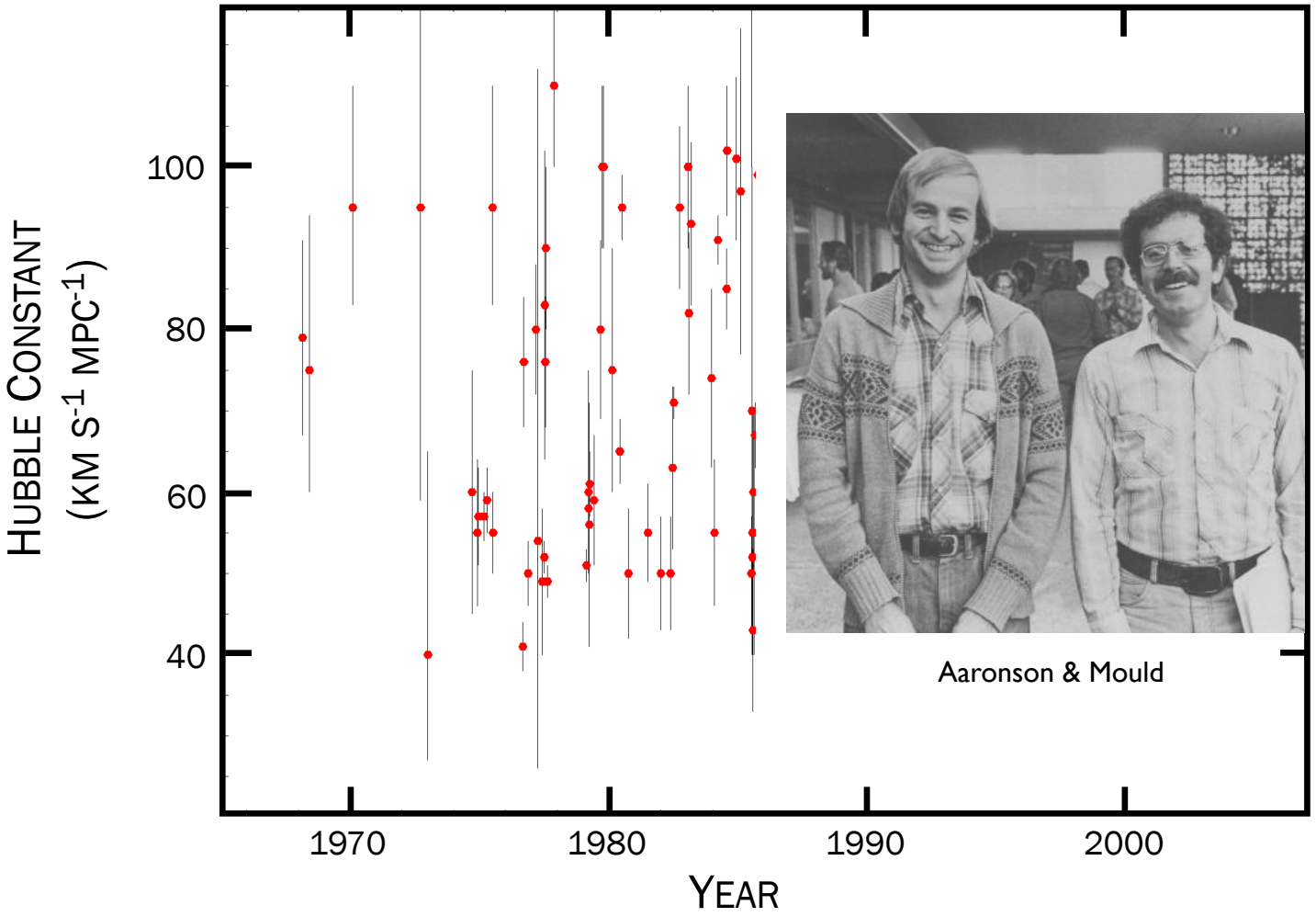

HUBBLE (1929)

# The Hubble constant vs. time



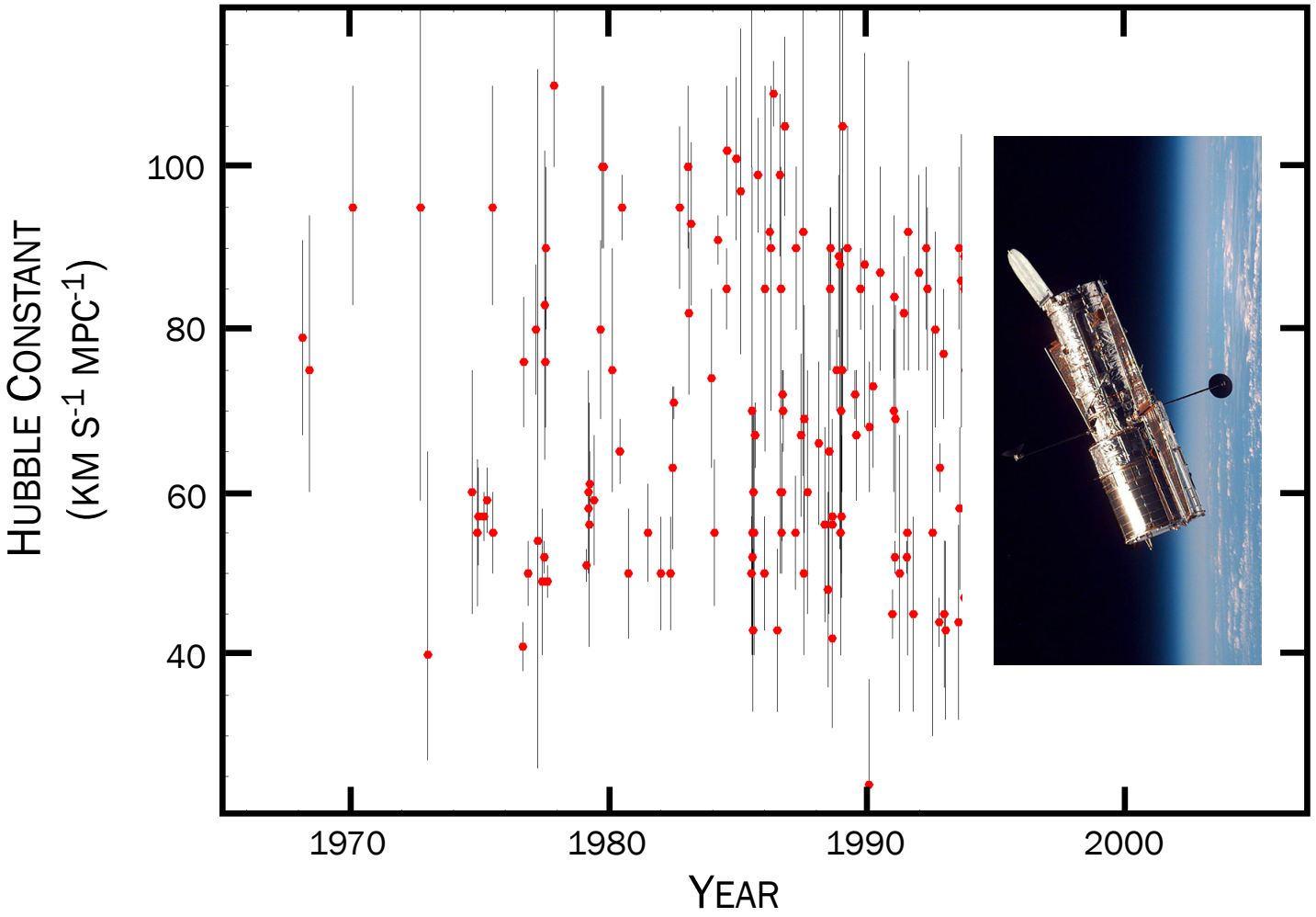

Compilation by John Huchra

# The Hubble constant vs. time




Compilation by John Huchra

# The Hubble constant vs. time




Compilation by John Huchra

# Outline

- ✔ In the beginning…
- ➔ WFPC2-based surveys: $H_0$ to 10%
- HST & dark energy
- $SH_0ES$: $H_0$ to 5%
- Latest results from WFC3

# WFPC2: $H_0$ to 10%

**DETERMINATION OF THE EXTRAGALACTIC DISTANCE SCALE: I. M81**
**HST Proposal 2227**

**Jeremy Mould**
**National Optical Astronomy Observatories, AURA**

**Cycle:** 1
**Category:**
**Proposal type:** GO
**Status:**

HST Proposal Information:
about this proposal
about other proposals by this PI

## Proposal Abstract

Many fundamental problems in cosmology and astrophysics remain undetermined becau
expansion rate is uncertain to a factor of two. HST will provide the opportunity to break th
program which in combination with other GTO and GO work should lead to a measureme
Our main goal is the observation of Cepheids in two dozen fields in nearby galaxies, for t
calibrating the infrared Tully-Fisher relation. The accumulated data will also allow investig
distance indicators, including the brightest resolved stars, supernovae, and calibration of
Measurement of Cepheids in the Virgo and Fornax clusters will also be attempted. A nec
our proposal is strengthening the calibration of the Cepheid PL relation itself, largely via
clusters in the LMC, M31, and M33. ;

HST Key Project on the Extragalactic Distance Scale: Infrared Tully-Fisher + other secondary distance indicators

**CALIBRATION OF SUPERNOVAE OF TYPE I AS STANDARD CANDLES**
**HST Proposal 2547**

**Allan Sandage**
**Carnegie Institution of Washington**

**Cycle:** 1
**Category:**
**Proposal type:** GO
**Status:**

HST Proposal Information:
about this proposal
about other proposals by this PI

## Proposal Abstract

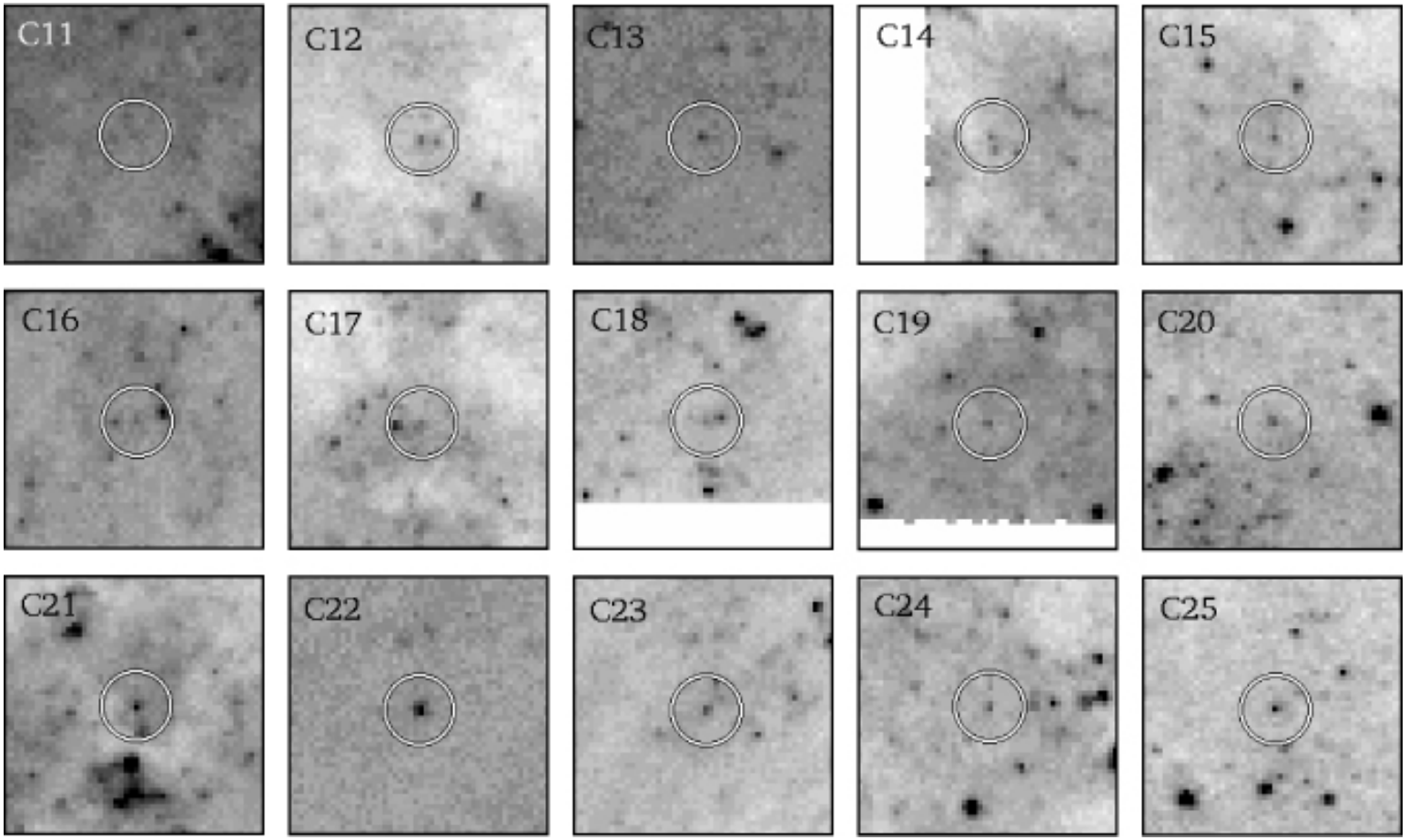
We propose to determine Cepheid distances to nearby, highly resolved, late type galaxies, which have produced type I supernovae (SNeI). The purpose is to determine how good such SNe are as standard candles in the V band. The distances to these nearby galaxies and the galaxy groups of which they are members will also be directly important in mapping the very local Hubble expansion field. The present program is for IC 4182. We propose to determine the corrected distances using observations of a selected field in the program galaxy in the V, as well as in the I bands, so as to determine the internal absorption of each Cepheid by Freedman's method. Optimized periods and accurate mean magnitude determinations of the Cepheids are the main requirements. Color-magnitude diagrams of the brightest resolved stars will also be obtained and will improve our knowledge of this secondary calibrator. The ultimate purpose is to calibrate the SNeI, freed of absorption effects, for the determination of H_o. We do not propose to begin again the many steps required for the fundamental calibration of the P-L relation.Our more restricted program, which is a necessary complement to the more extensive Key "Hubble Constant" Project is complete within itself for the stated purpose. ;

Cepheid calibration of Peak Brightness of Type Ia Supernovae

# NGC 2841

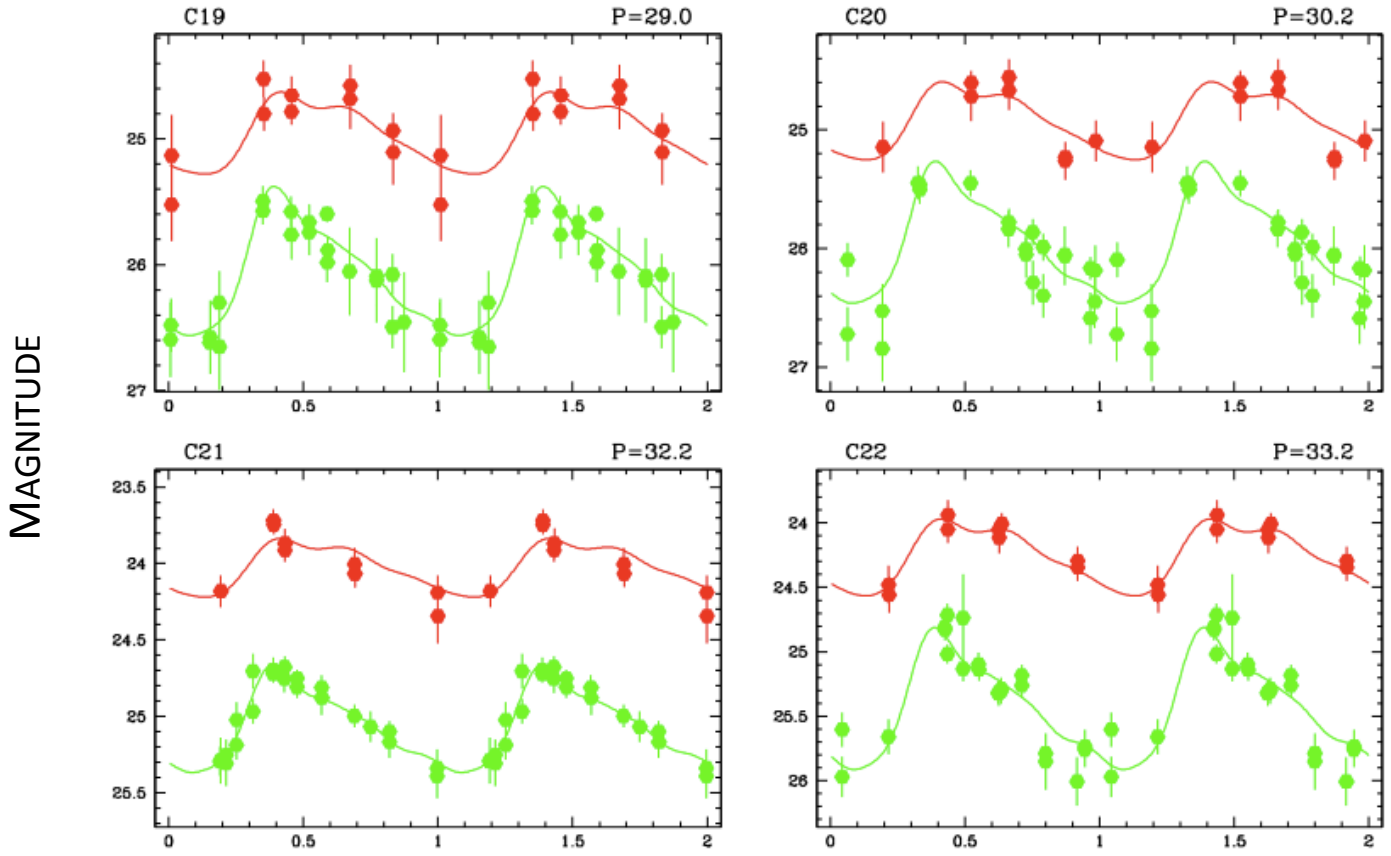
MACRI+ (2001)

# CEPHEIDS WITH WFPC2



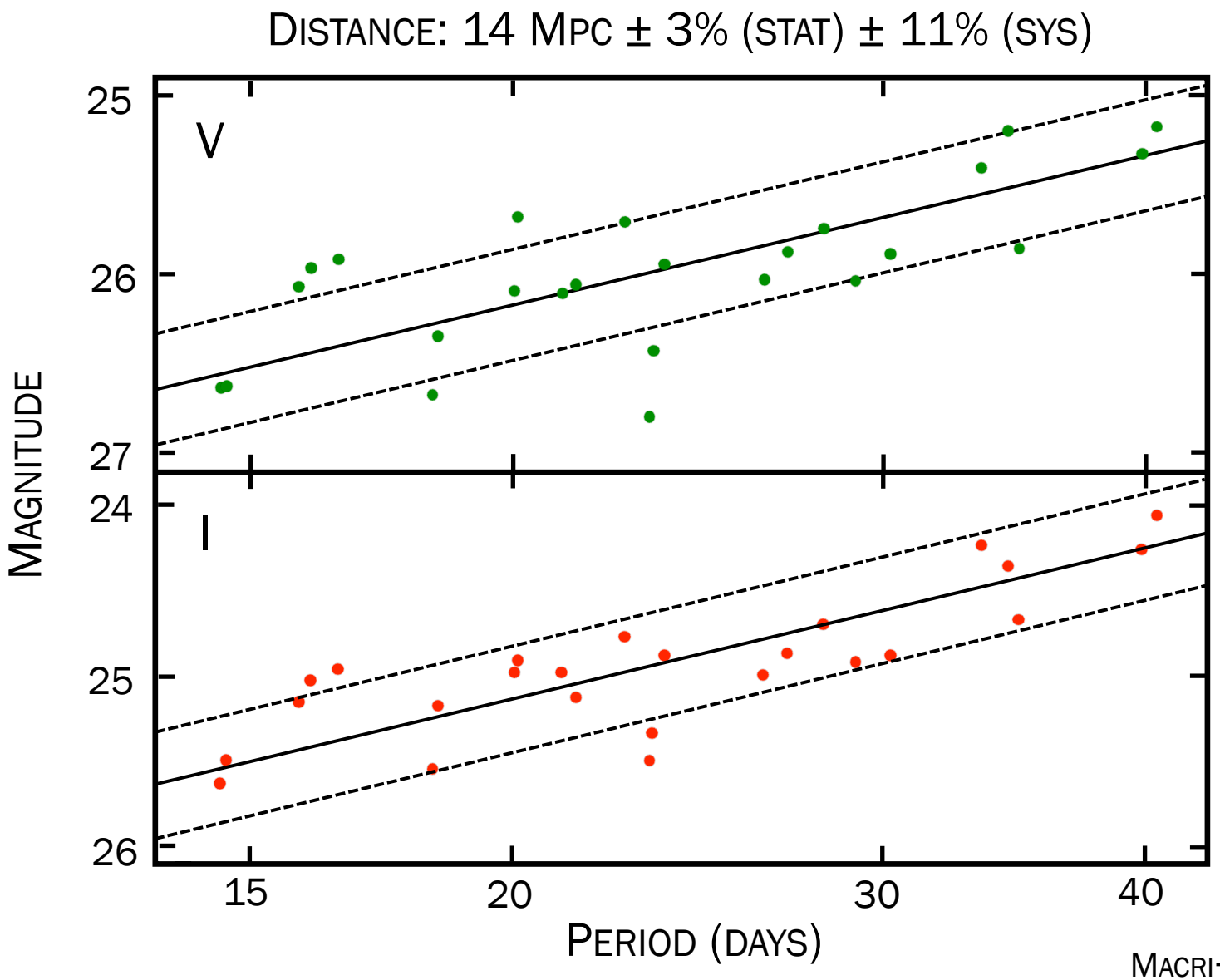

MACRI+ (2001)

# CEPHEIDS WITH WFPC2



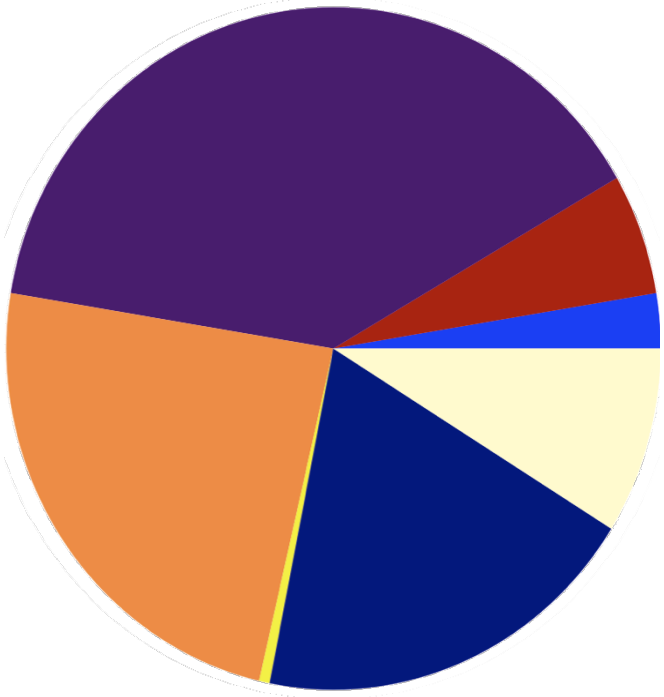

MACRI+ (2001)

# CEPHEIDS WITH WFPC2




MACRI+ (2001)

# WFPC2 PROJECTS – ERROR BUDGET



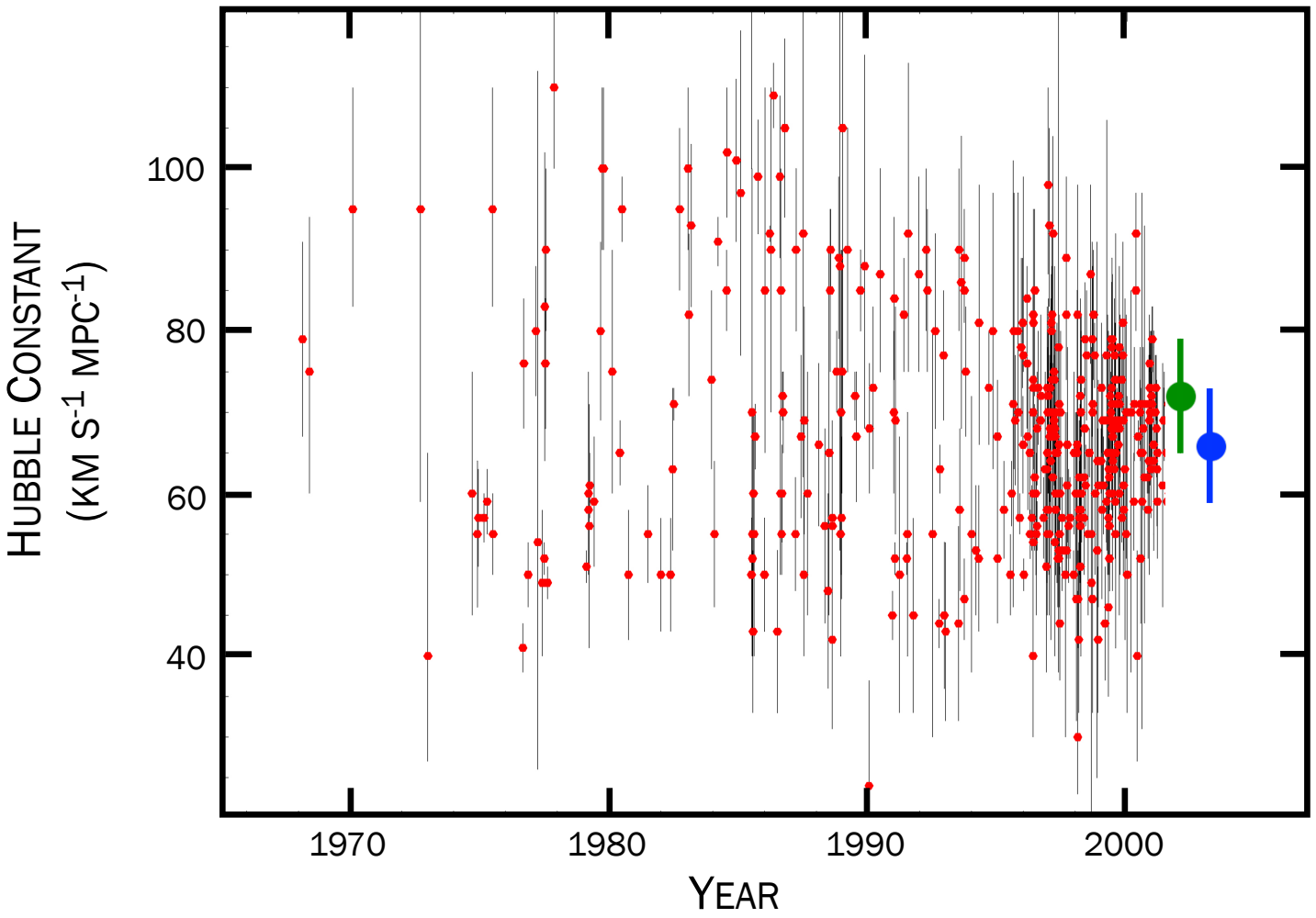
$\sigma(H_0)\approx 11\%$

| Term | % |
|---|---|
| Anchor distance | 5.0 |
| Cepheid reddening, zeropoints (anchor-to-hosts) | 4.5 |
| P-L slope, d log P (anchor-to-hosts) | 4.0 |
| Cepheid metallicity dependence (anchor-to-hosts) | 3.0 |
| WFPC2 CTE, long-vs-short zeropoints | 3.0 |
| Mean of SN Ia calibrators | 2.5 |
| Mean of P-L in anchor | 2.5 |
| Mean of P-L in SN hosts | 1.5 |
| SN Ia m-z relation | 1.0 |

Freedman+ (2001)
Sandage+ (2006)

Riess, Macri+ (2009)

# The Hubble constant vs. time




Freedman+ (2001)
Sandage+ (2006)

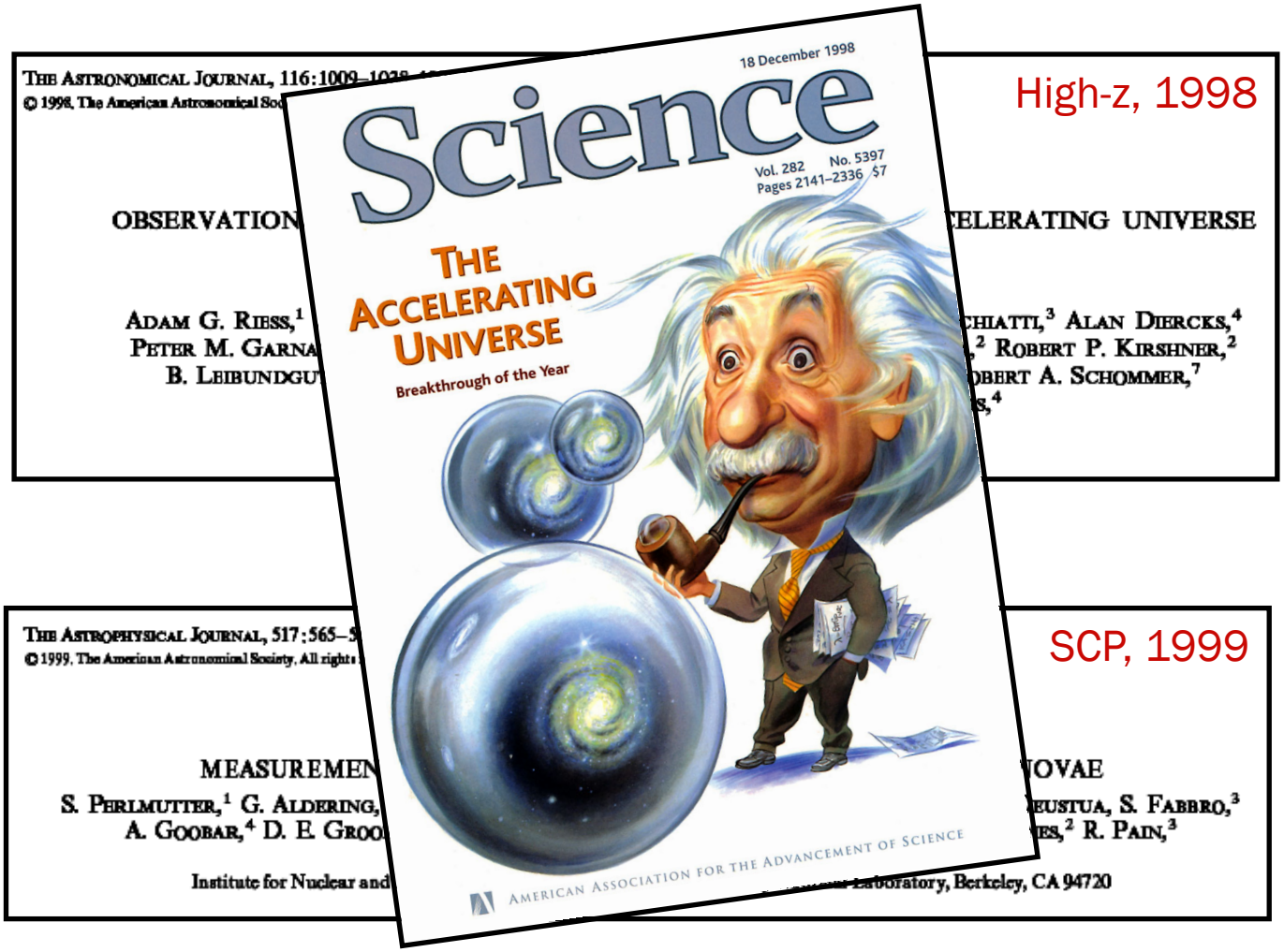
Compilation by John Huchra

# OUTLINE

- ✔ IN THE BEGINNING…
- ✔ WFPC2-BASED SURVEYS: $H_0$ TO 10%
- ➔ HST & DARK ENERGY
  - $SH_0ES$: $H_0$ TO 5%
  - LATEST RESULTS FROM WFC3

# The Accelerating Universe – two teams

Faintness of SNe Ia at z~0.5 give first *observational* evidence for acceleration & dark energy

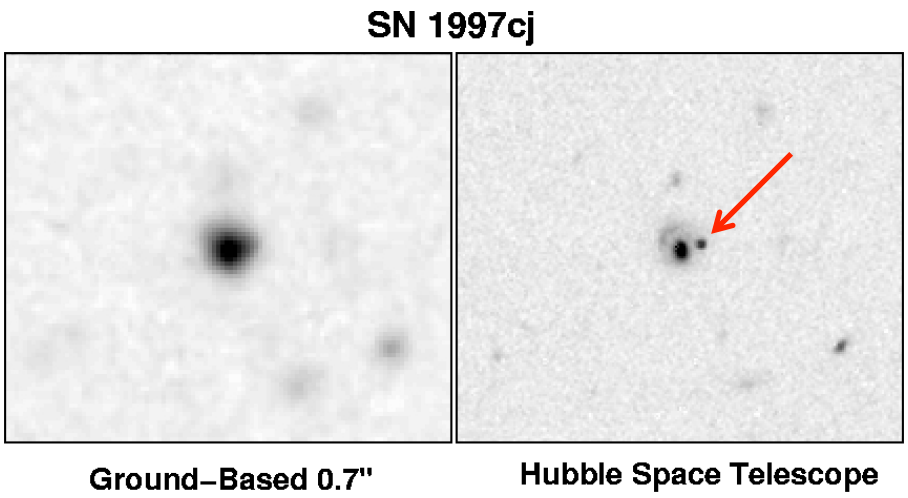


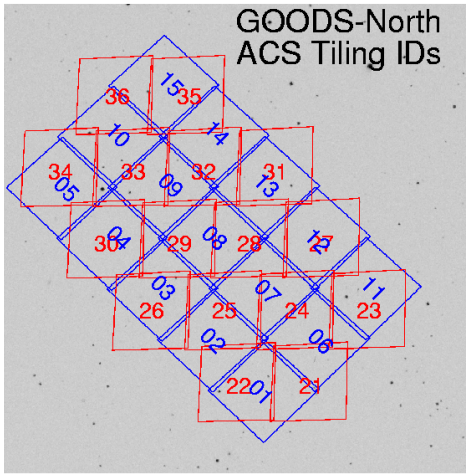
# Discovering SNe Ia at z>1 with HST

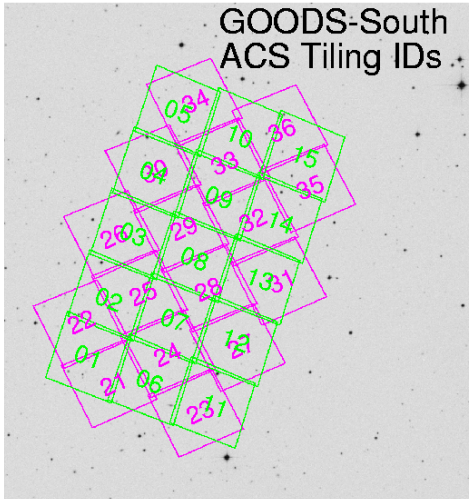

**Higher-z Team and GOODS Treasury Team**

Riess, Ferguson, Strolger (STScI), Tonry (UH), Filippenko, Jha, Li (UCB), Kirshner, Challis (CfA), Casertano, Dickinson, Giavalisco, Livio, Mobasher (STScI), Foley, Chornock (UCB), Lampeitl (STScI)


## Method: Subtract ACS images from 45 day interval campaigns

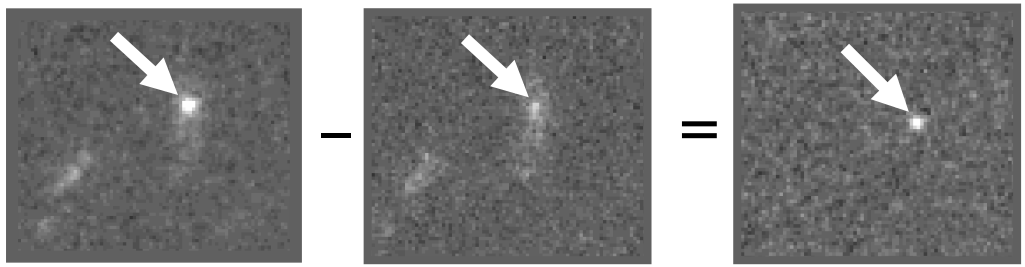


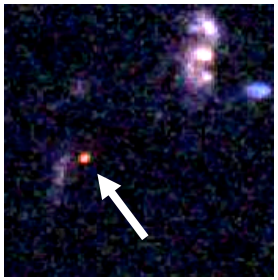



# Discovering SNe Ia at z>1 with HST

## Step 1: Detection at $m_I$>25 with ACS

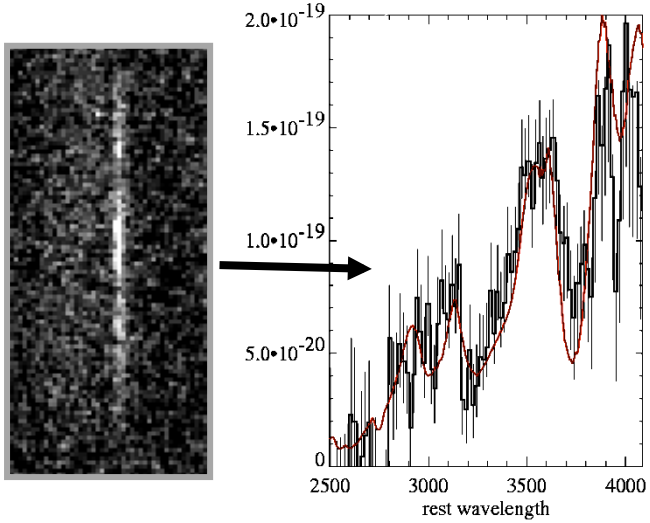


## Step 2: Winnowing



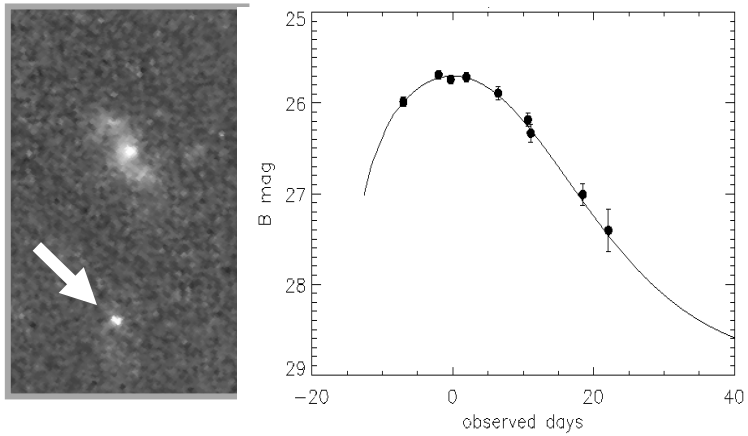
SN Ia are red in UV

## Step 3: Identification & redshift with ACS grism spectrum



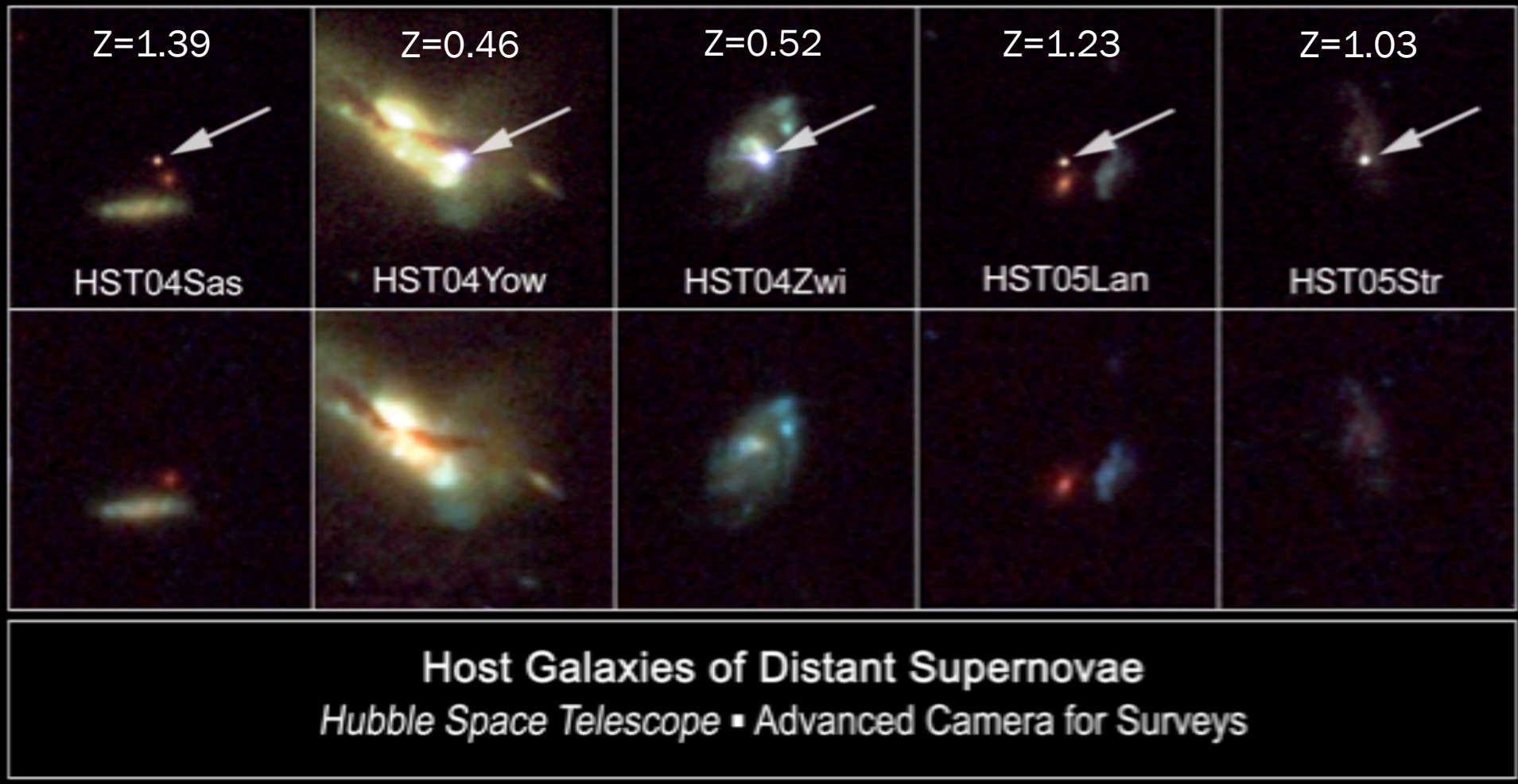

Ground has never measured redshift this high

## Step 4: Follow-up near-IR light curve with NICMOS

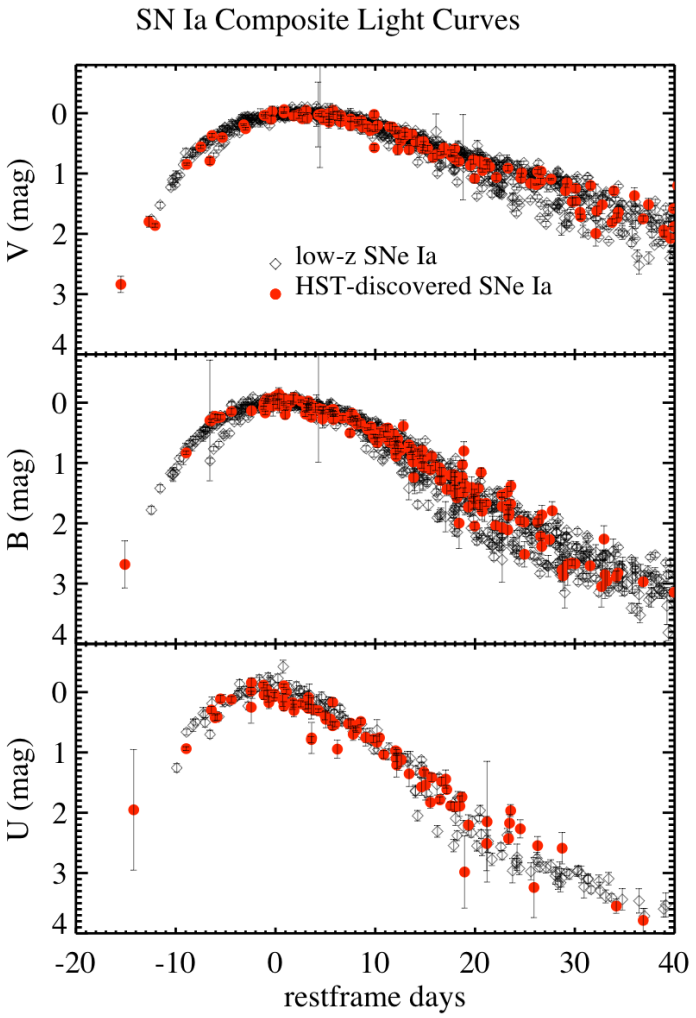


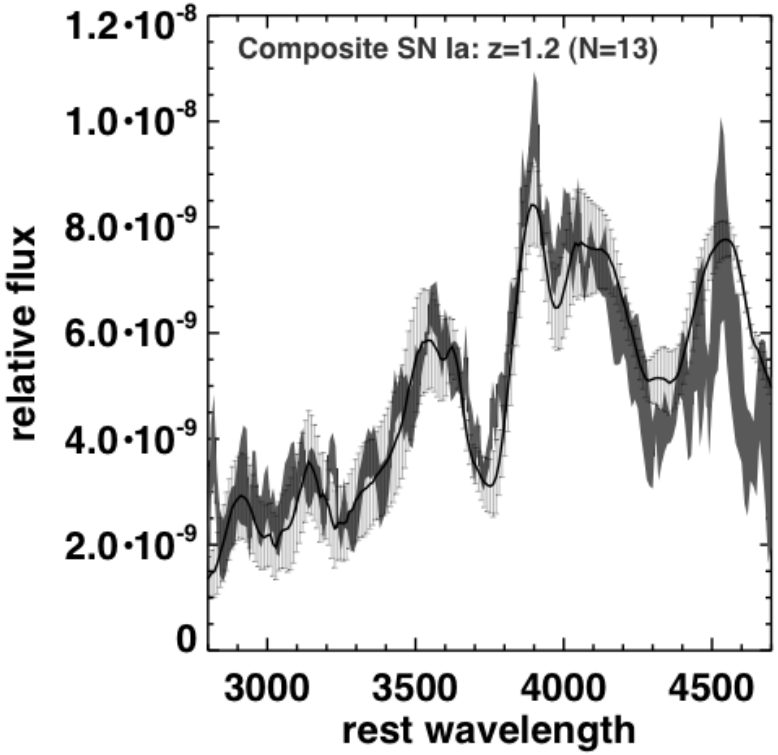

Peak and shape yields distance

# HIGHER-Z SNE IA WITH HST

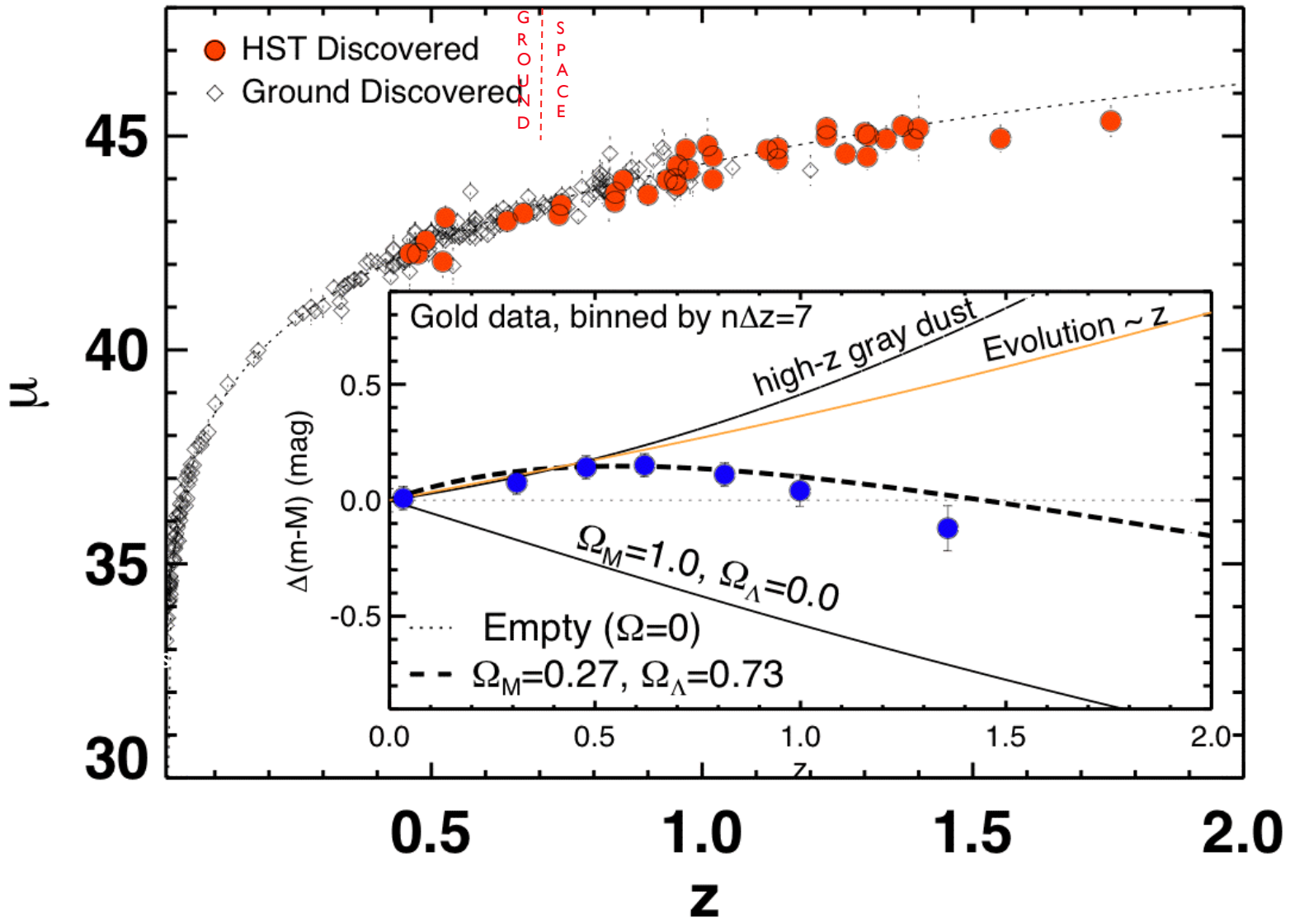


# The Higher-z Team, ACS 2002-2007: 135 SNe, 50 SNe Ia, 25 SNIa at z>1



# HST: SNe Ia at z >1 find past deceleration, confirming dark energy + dark matter model



# Equation of State of Dark Energy

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

- What is the present value of *w* ?
- Was it different in the past? (d*w*/dz)

- The answers will help distinguish among different models of dark energy
  - w = -1 and dw/dz = 0 → "cosmological constant"
  - w ≠ -1 or dw/dz ≠ 0 → "inflation-like scalar field"

(Linder astro-ph/1004.4646)

# Equation of State of Dark Energy

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

- What is the present value of *w* ?
- Was it different in the past? (d*w*/dz)

- We can measure w and dw/dz using…
  - "standard candle" (type Ia SNe)
  - "standard ruler" (baryon-acoustic oscillations)
  - peaks in CMB power spectrum [w only]

# Equation of State of Dark Energy

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

- What is the present value of *w* ?
- Was it different in the past? (d*w*/dz)

- Regardless of the technique used, an accurate and precise measurement of $H_0$ significantly narrows the allowed range in *w*:

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

# OUTLINE

- ✔ IN THE BEGINNING…
- ✔ WFPC2-BASED SURVEYS: $H_0$ TO 10%
- ✔ HST & DARK ENERGY
- ➔ $SH_0ES$: $H_0$ TO 5%
  - LATEST RESULTS FROM WFC3

# THE $SH_0ES$ PROJECT

- Aim: determine the value of $H_0$ with a total uncertainty below 5% through a "sturdier" distance ladder
- Approach: minimize sources of systematic uncertainty

# The $SH_0ES$ Project

- Minimize sources of systematic uncertainty:
  - Use same telescope & instruments
    - Optical: ACS/WFC; Near-infrared: NICMOS/NIC2
    - Work at H-band to minimize impact of extinction
  - Target Cepheids with …
    - Similar abundances
      - Based on published gradients + new Keck observations
    - Same period range
      - 10d < P < 100d, to minimize impact of non-universal slope
    - Similar background stellar densities
      - Exhaustive crowding simulations; median correction 0.15 mag

# N4258: NEW "ANCHOR GALAXY"

- 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

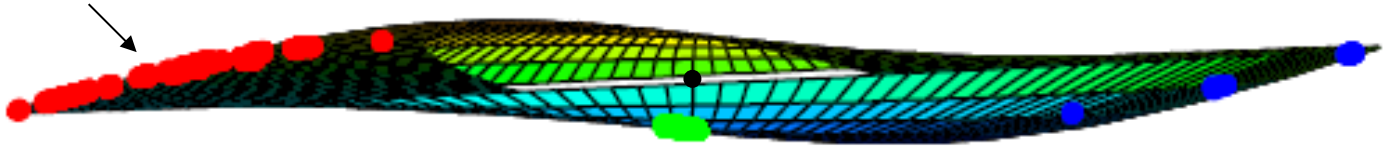
COLOR MOSAIC BASED ON SDSS IMAGES

# Maser distance to N4258

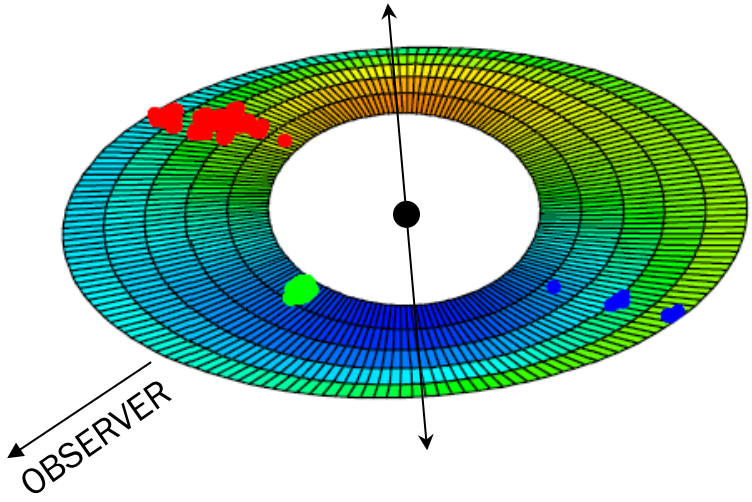
Observer's View

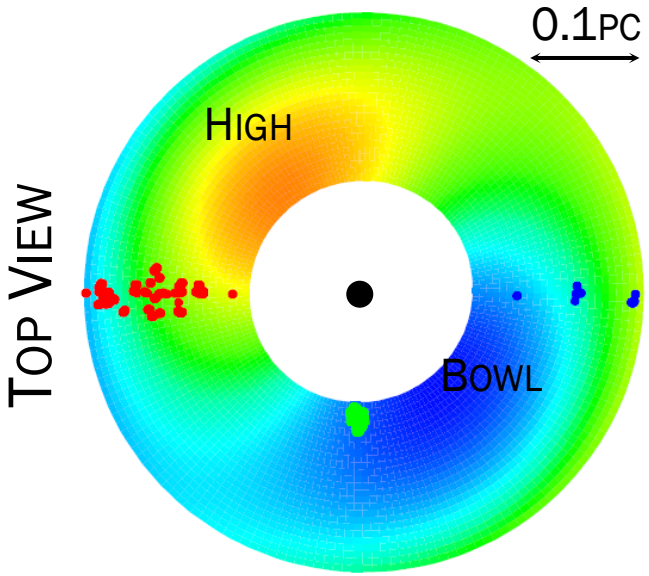
Incl. warp: 8°

P.A. warp: 9°




Accuracy: 7% ('99) → 3% ('08)

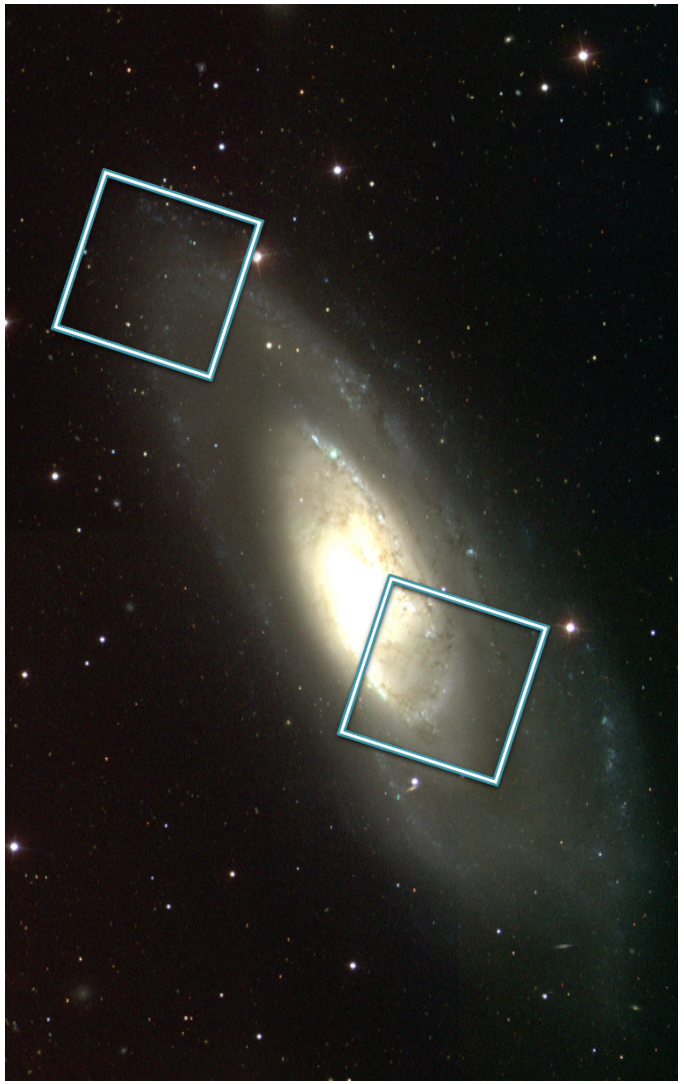



Humphreys+ (2008)

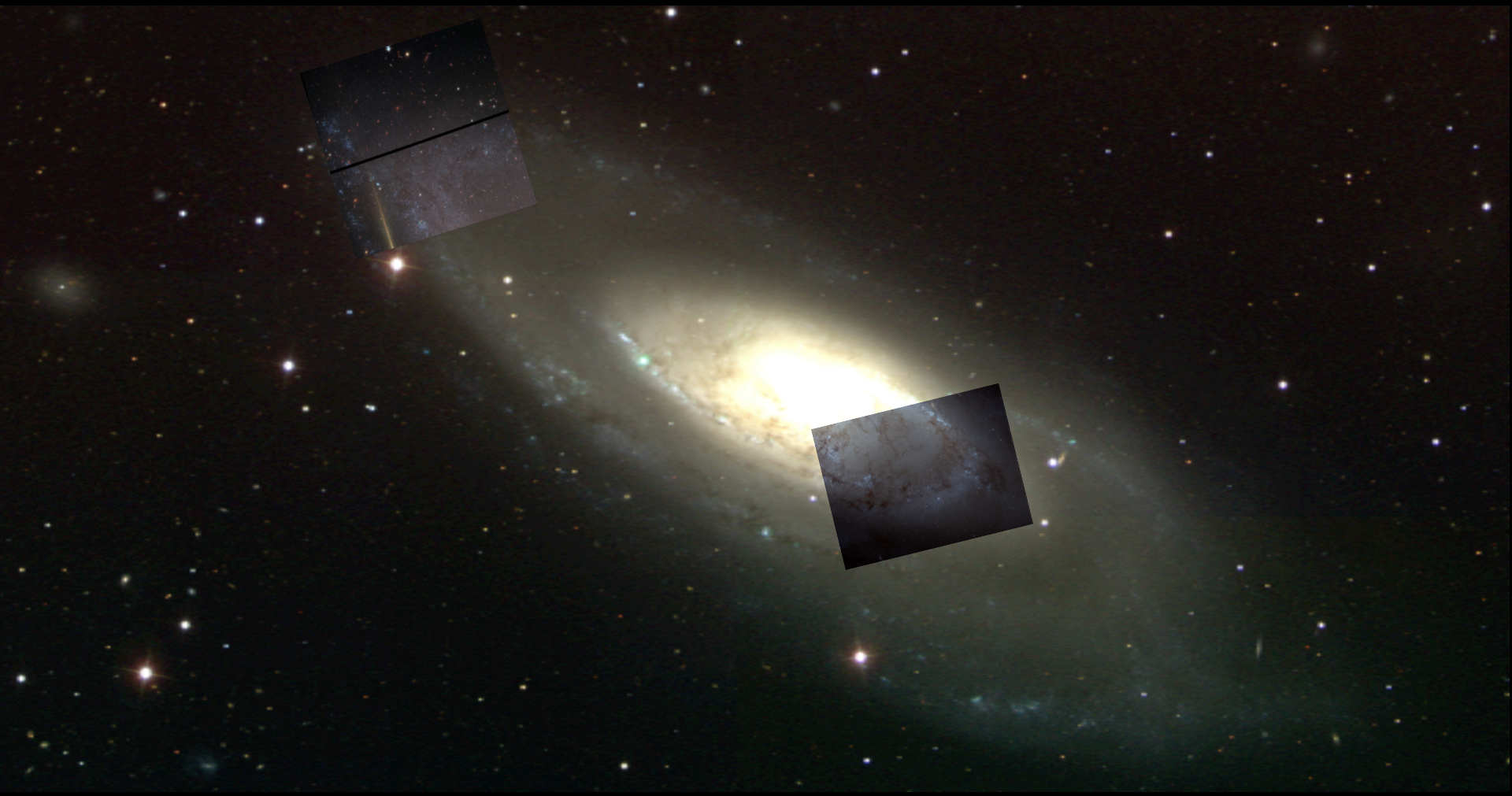
# N4258: NEW "ANCHOR GALAXY"

- 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



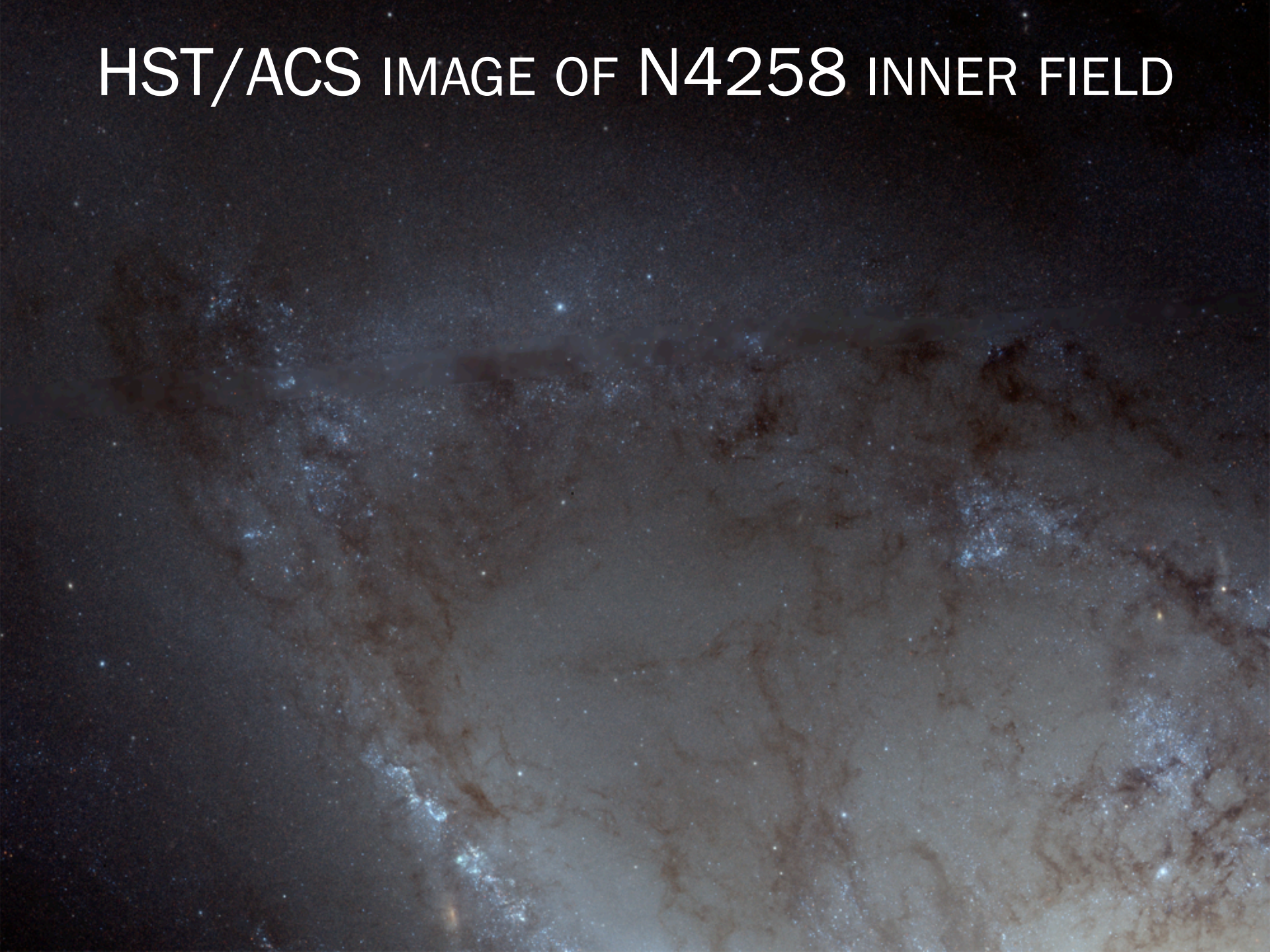
COLOR MOSAIC BASED ON SDSS IMAGES

# NGC 4258: SDSS+HST/ACS



# HST/ACS IMAGE OF N4258 OUTER FIELD

# HST/ACS IMAGE OF N4258 INNER FIELD

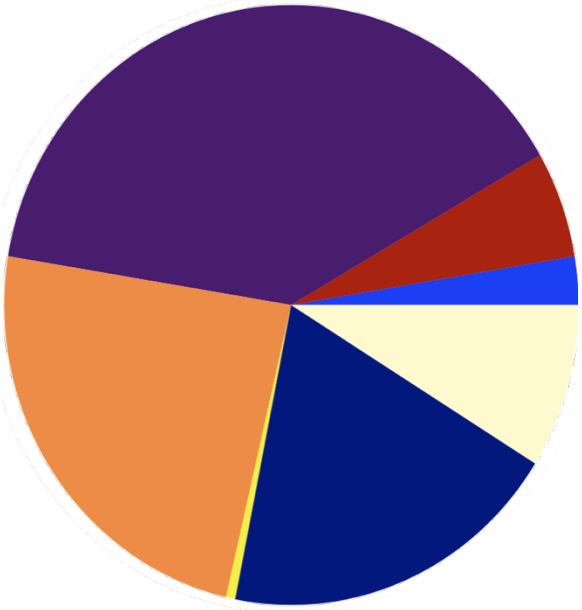


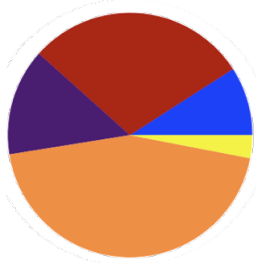
# The $SH_0ES$ Approach

- Minimize sources of systematic uncertainty:
  - Type Ia SNe limited to “modern” & “ideal”
    - CCD or photoelectric photometry (sorry, no plates!)
    - Observed before maximum
    - Low extinction
    - Decline rate in normal range (no sub-luminous)
  - 6 SNe met these criteria and were located within the reach of HST
    - 4 previously observed
    - 2 new Cepheid distances in HST Cycle 14
      - (Riess, Macri, et al. 2009, ApJS 183, 109)

# WFPC2 PROJECTS → $SH_0ES$

$\sigma(H_0)\approx 11\%$



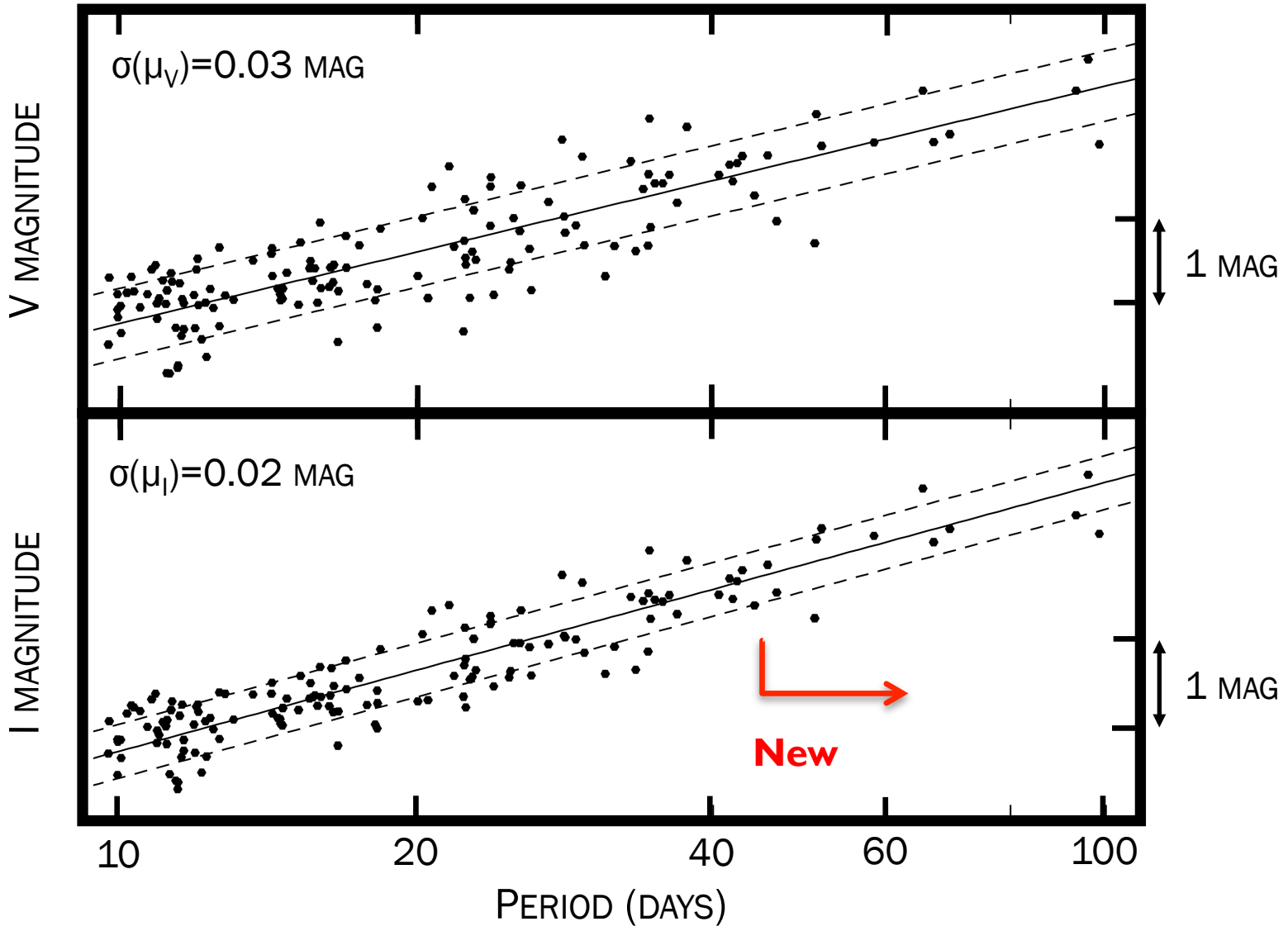


$\sigma(H_0)=4.8\%$

| Term | % | % |
|---|---|---|
| Anchor distance | 5.0 | 3.0 |
| Cepheid reddening, zeropoints (anchor-to-hosts) | 4.5 | 0.3 |
| P-L slope, d log P (anchor-to-hosts) | 4.0 | 0.5 |
| Cepheid metallicity dependence (anchor-to-hosts) | 3.0 | 0.8 |
| WFPC2 CTE, long-vs-short zeropoints | 3.0 | -- |
| Mean of SN Ia calibrators | 2.5 | 2.5 |
| Mean of P-L in anchor | 2.5 | 1.5 |
| Mean of P-L in SN hosts | 1.5 | 1.5 |
| SN Ia m-z relation | 1.0 | 0.5 |

Riess, Macri+ (2009)

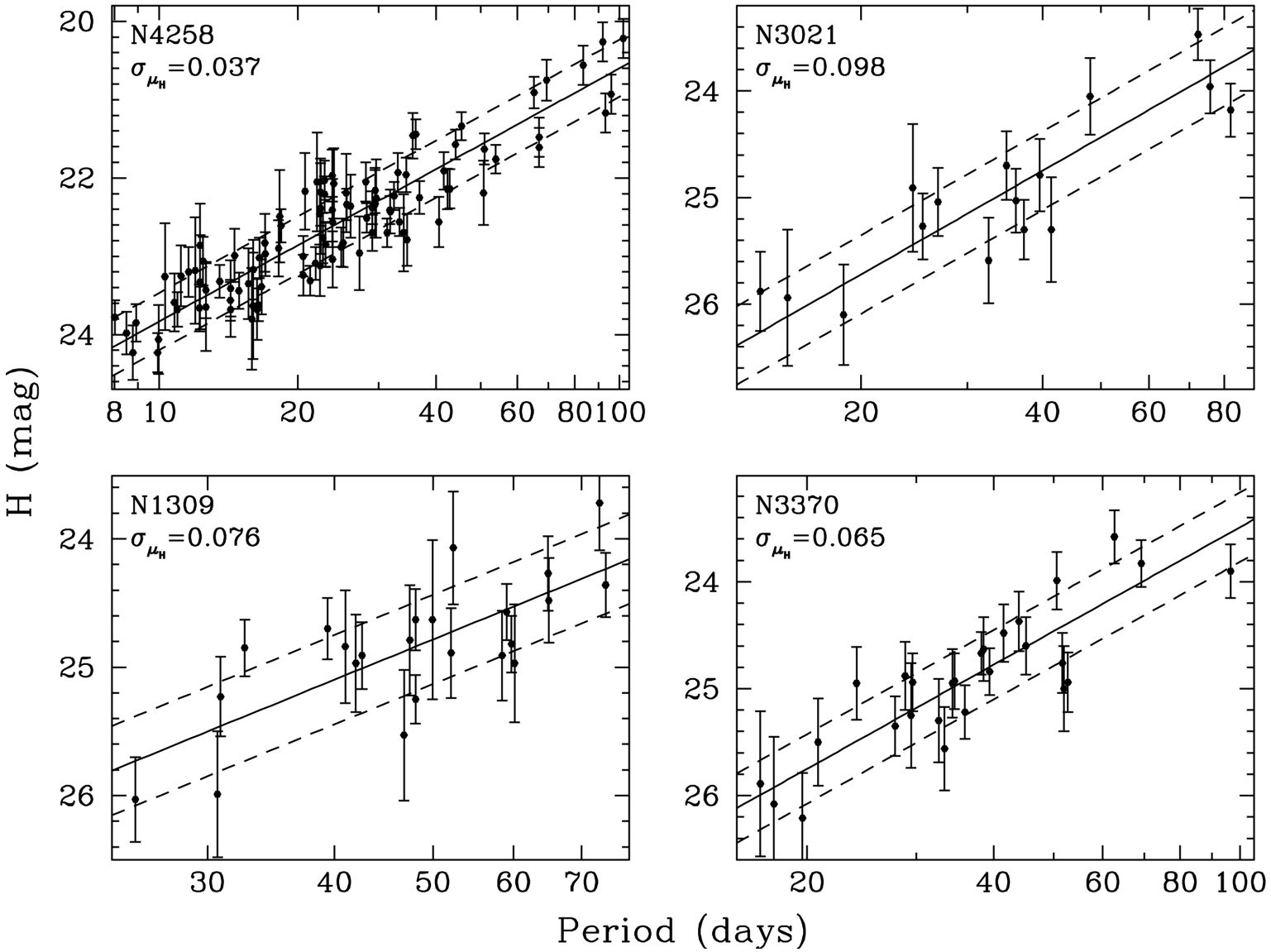
# New HST Cepheid P-Ls for N4258 (Inner)




Macri+ (2006)

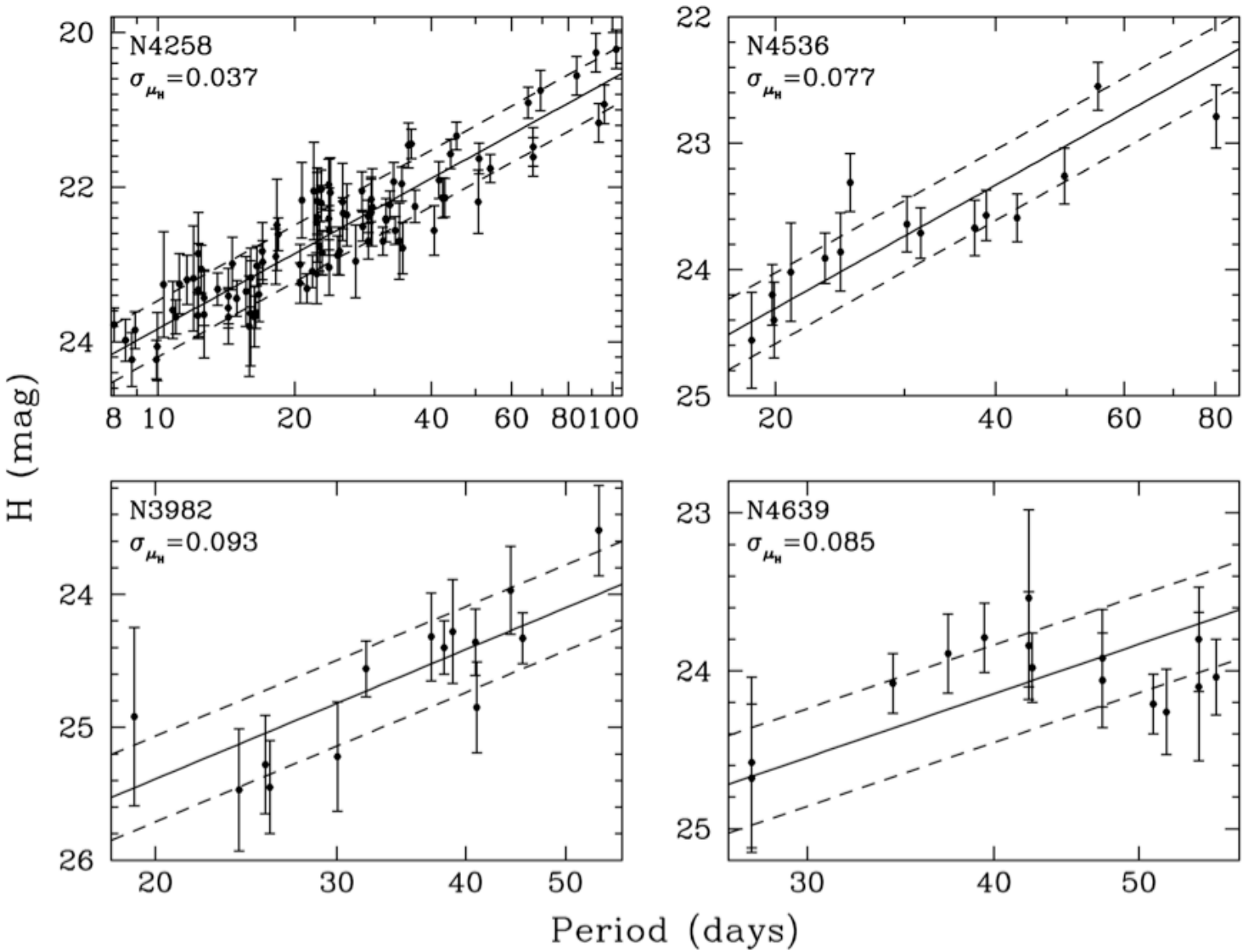
Macri, Riess+, in prep

# $SH_0ES$ H-BAND P-L RELATIONS




RIESS, MACRI+ (2009)

# $SH_0ES$ H-band P-L Relations




Riess, Macri+ (2009)

# $SH_0ES$: Analysis

- Global fit to Cepheid and SN data in matrix form
  - Solve for relative distances between galaxies
  - Calculate hypothetical peak magnitude of SNIa in N4258
    - Ties Cepheid & SN distance scales
    - Peak mag of SNIa in Hubble flow from Hicken+ ’09
  - Full propagation of errors through covariance matrix
    - Allows for full exploration of error budget
    - 22 scenarios considered

# $SH_0ES$: RESULTS

- HST/NICMOS H-band observations of 240 Cepheids in:
  - NGC 4258 / M106 (aka “the maser galaxy”)
  - Six hosts of “modern & ideal” type Ia SNe

were used to measure (Riess, Macri et al. 2009)

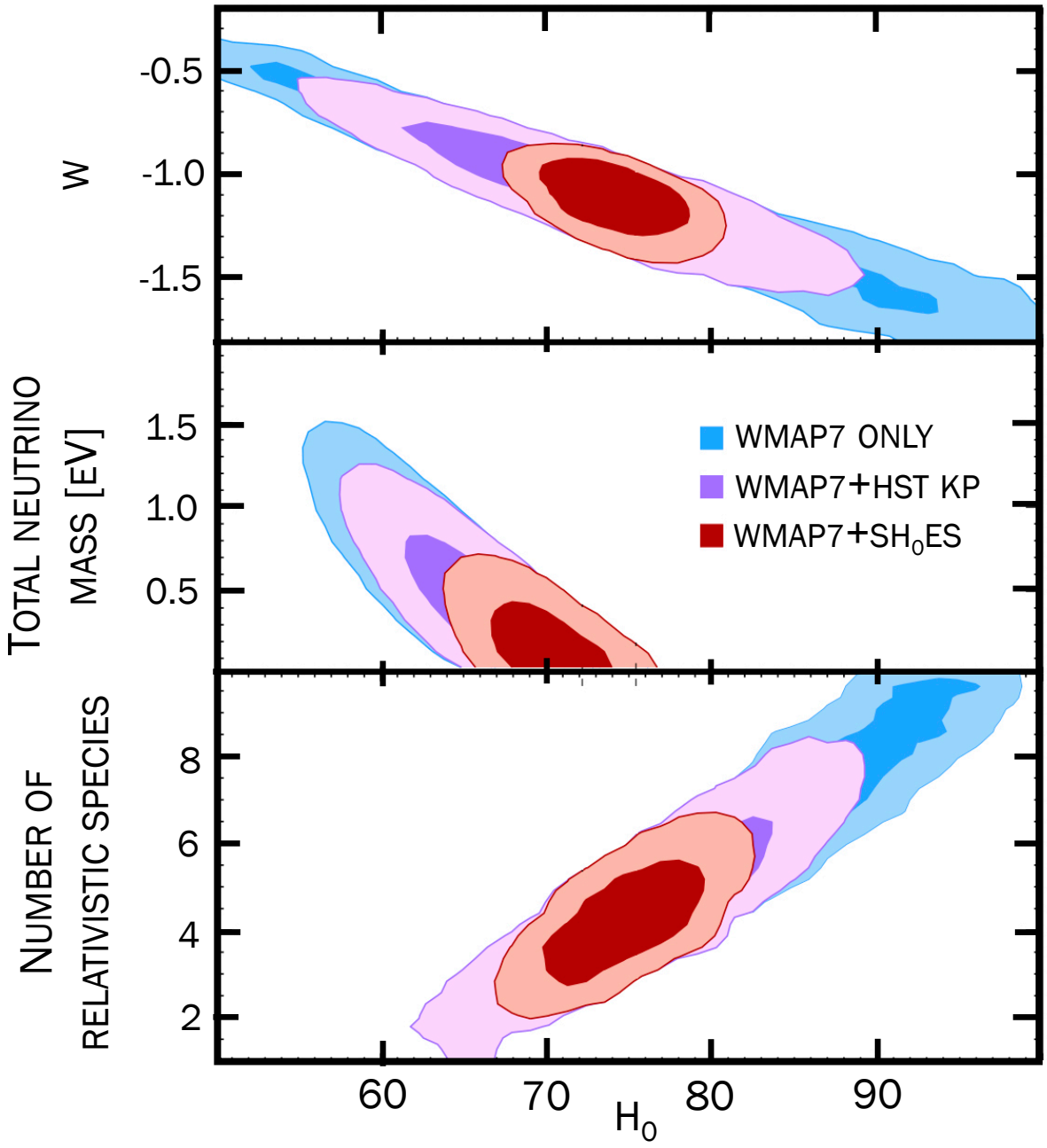
$$H_0 = 74.2 \pm 3.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

- Combined *only* with WMAP 5-year (Komatsu et al. 2009)

$$w = -1.12 \pm 0.12$$

  - add BAO and/or high-z SNe for further constraints on w

# $SH_0ES$ + WMAP

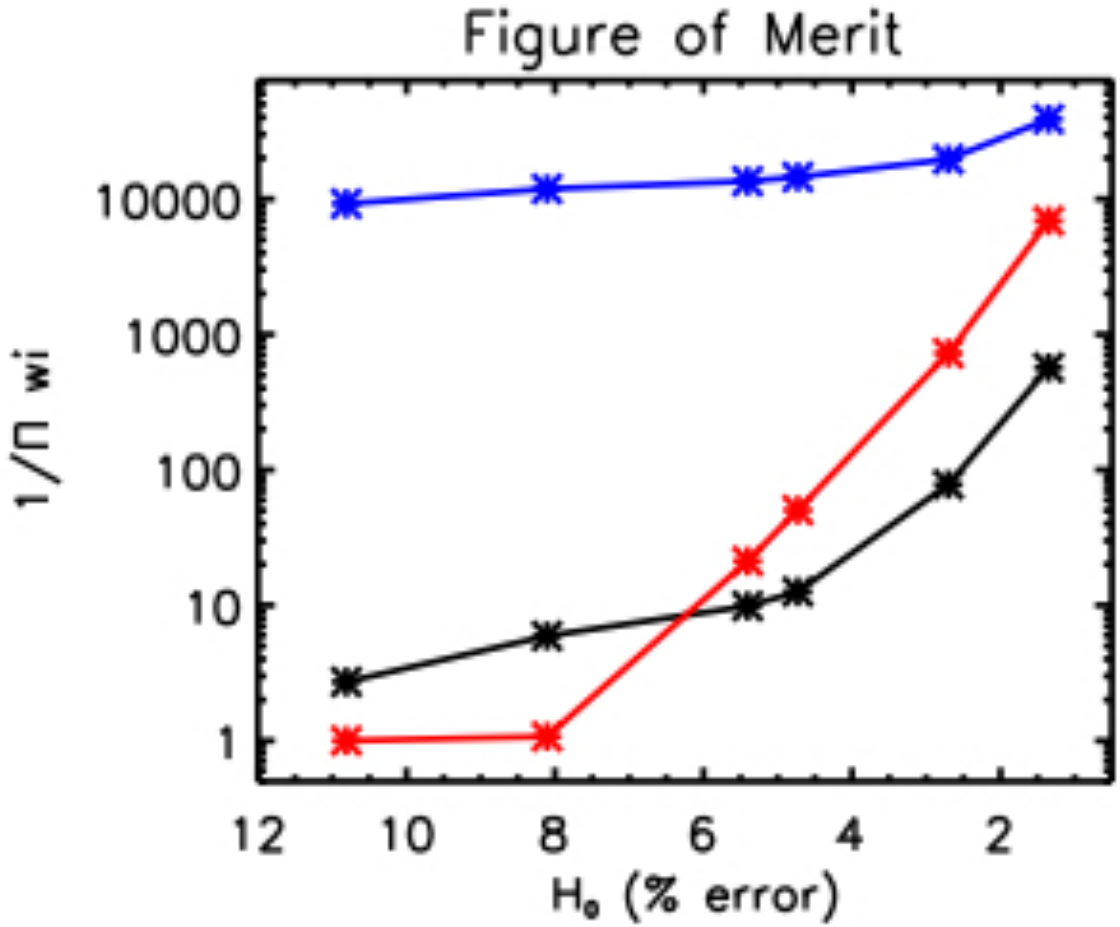



RIESS, MACRI+ (2009)

# Outline

- ✔ IN THE BEGINNING…
- ✔ WFPC2-BASED SURVEYS: $H_0$ TO 10%
- ✔ HST & DARK ENERGY
- ✔ $SH_0ES$: $H_0$ TO 5%
- ➔ LATEST RESULTS FROM WFC3

# Motivation for further improvement




17 BAO + $H_0$

2300 SNe + $H_0$

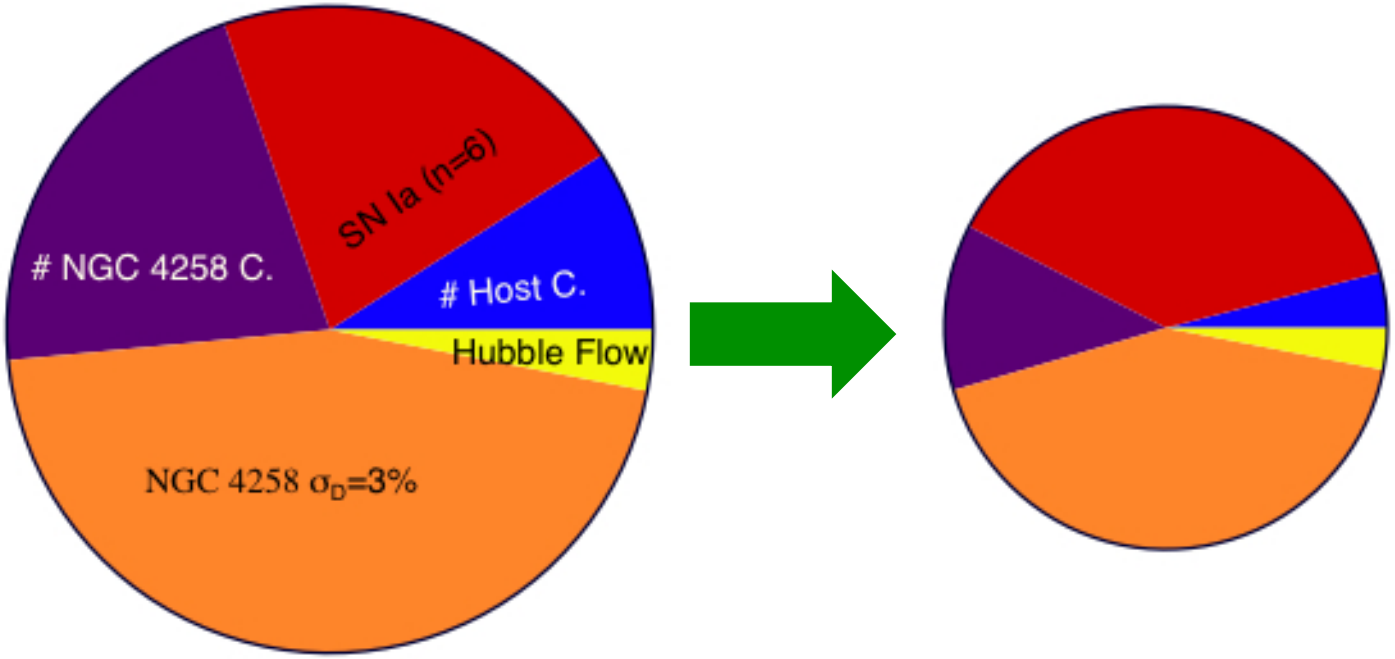
17 BAO + 2300 SNe + $H_0$

Figure of Merit:
2.5x increase from 5% to 1.3%

Simulations by Devdeep Sarkar

Riess, Macri+ '09

# Ongoing Improvements



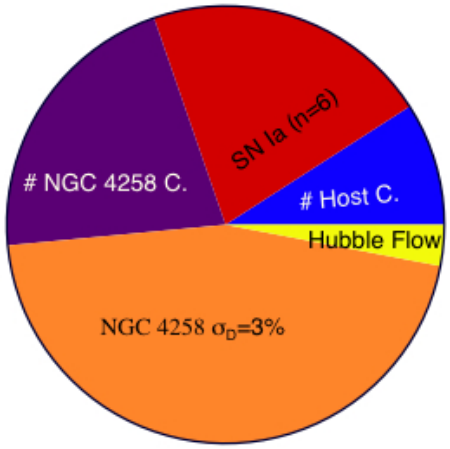

$\sigma(H_0)$=4.8%
(published)

$\sigma(H_0)$~3-4%
(in progress)

# THE CURRENT SITUATION

- What are the largest contributions to the error budget?

1) Single anchor: NGC 4258 with σ(D)=3%
2) Number of Cepheids in anchor(s)
3) Number of SN hosts




$\sigma(H_0)$=4.8%
(published)

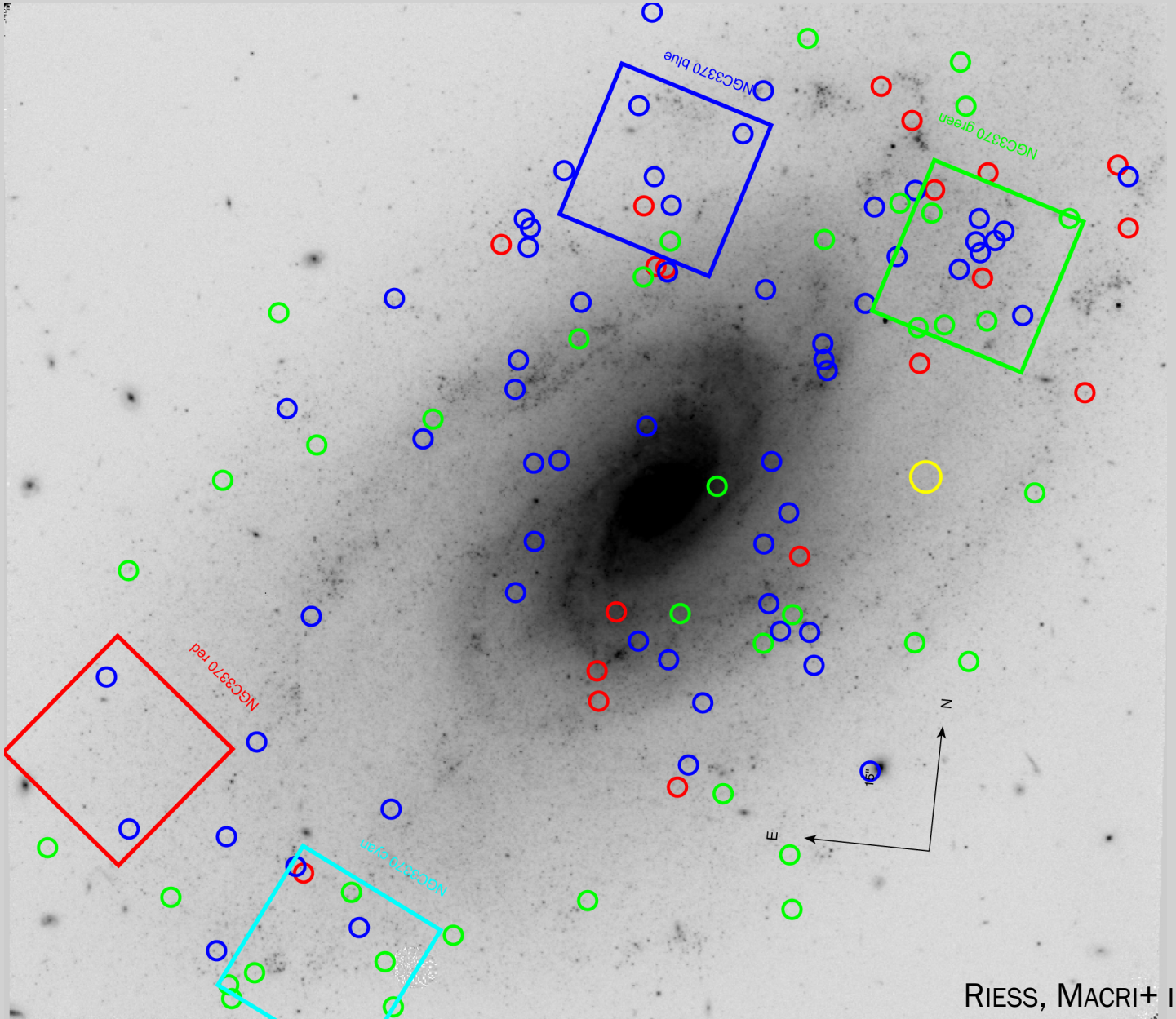
# Ongoing Improvements

- Single anchor: N4258 with σ(D)=3%
  - Add Milky Way Cepheids
    - HST-based parallaxes from Benedict et al. (2007)
    - *GAIA* parallaxes in a few years!!
  - Add LMC, M31, M33, [M81]
    - GAIA parallaxes + DEB distances
      - Systematics?
    - Need large, homogeneous samples @ NIR

# Ongoing Improvements

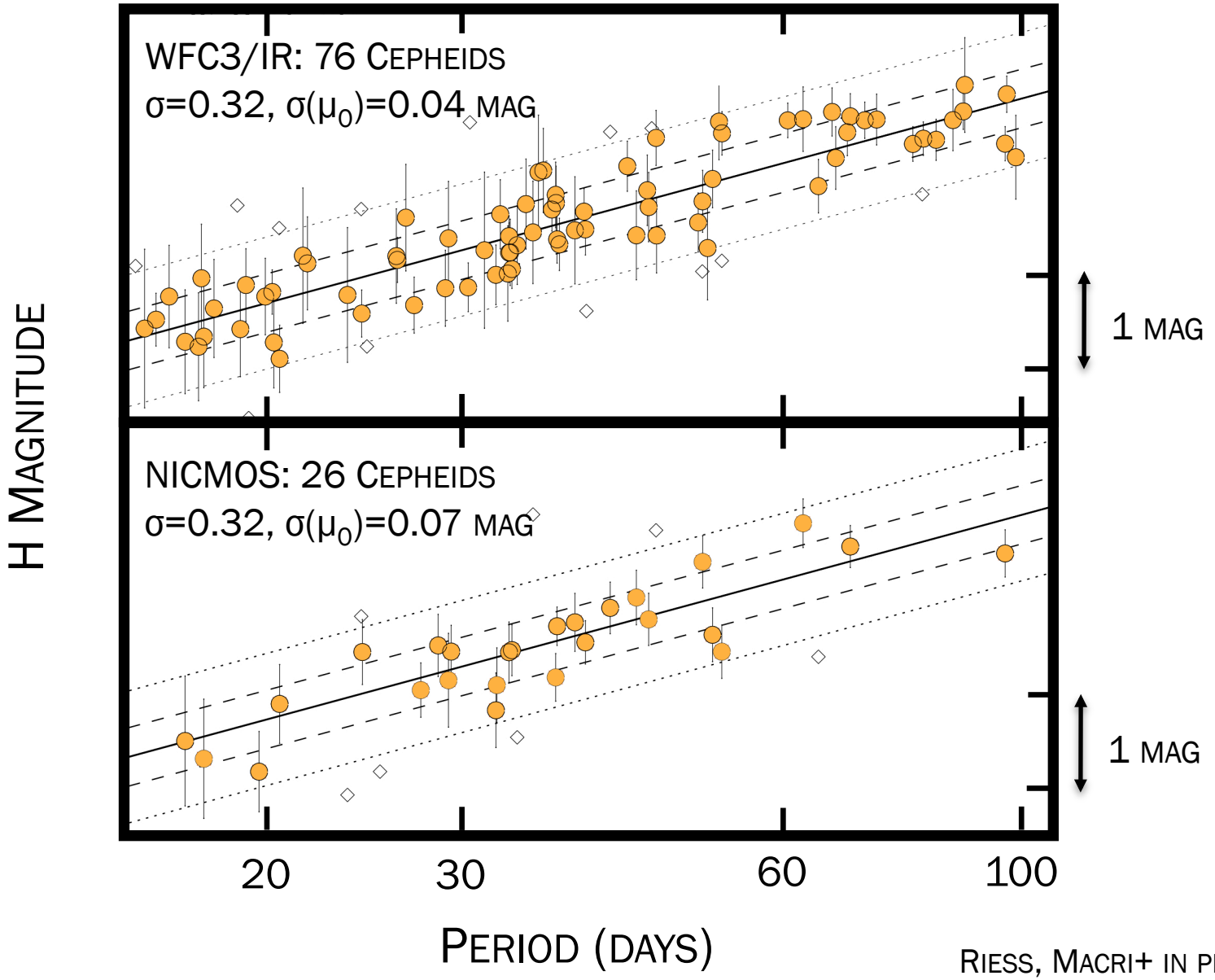
- Number of Cepheids in hosts + anchor
  - Obtain H-band data for all hosts with WFC3/IR
  - Tie to whole-disk survey of NGC 4258

# N3370: WFC3/IR vs NICMOS/NIC2




RIESS, MACRI+ IN PREP

# N3370: WFC3/IR vs NICMOS/NIC2

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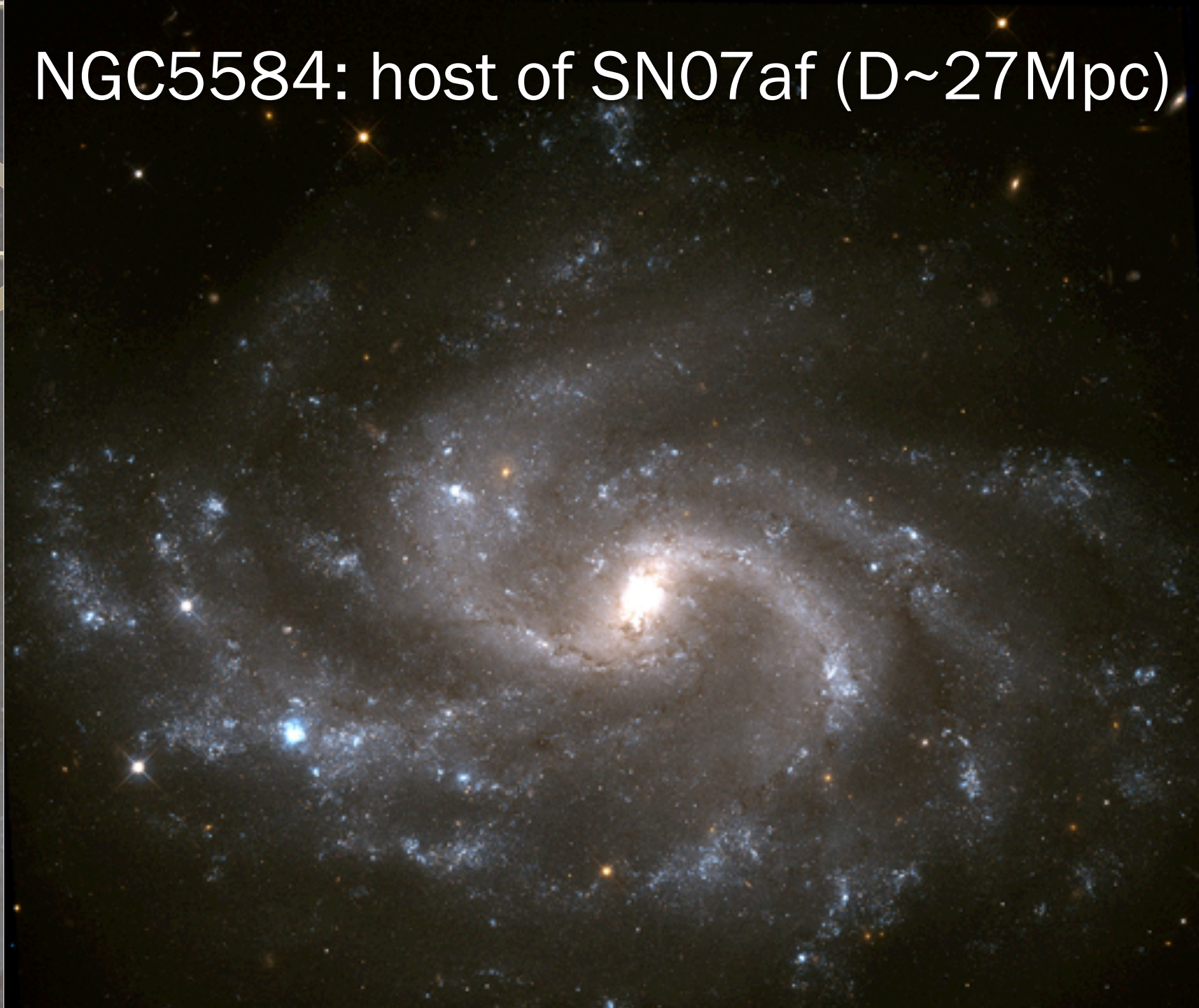
# Ongoing Improvements

- Current # SN hosts: N=6 with σ(D)=3-5% each
- Solution: pursue new SNe within HST volume
  - SN2007sr in NGC 4038/9 (Antennae): Cycle 16 ECP
  - SN2007af in NGC 5584: Cycle 17 (completed)
- Obtain H-band data for all 8 hosts with WFC3/IR
  - Tie to whole-disk survey of NGC 4258

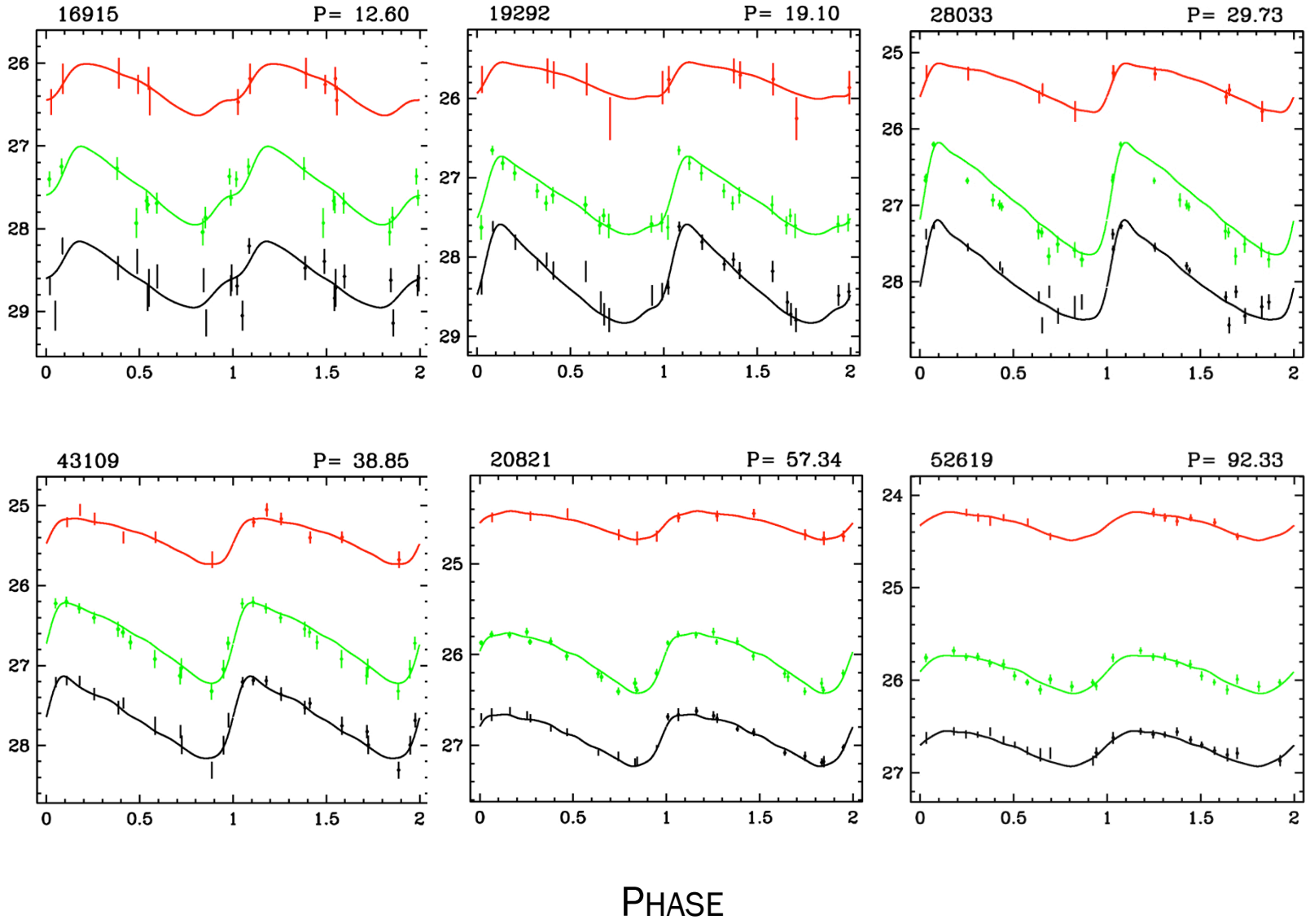
# NGC 5584: WFC3/UVIS

- Recently completed observations
- Standard HST search (12 V + 6 I epochs)
- Over 300 Cepheids discovered!
- Test feasibility of “white-light” search
  - Reduce # orbits for future HST targets

# NGC5584: host of SN07af (D~27Mpc)

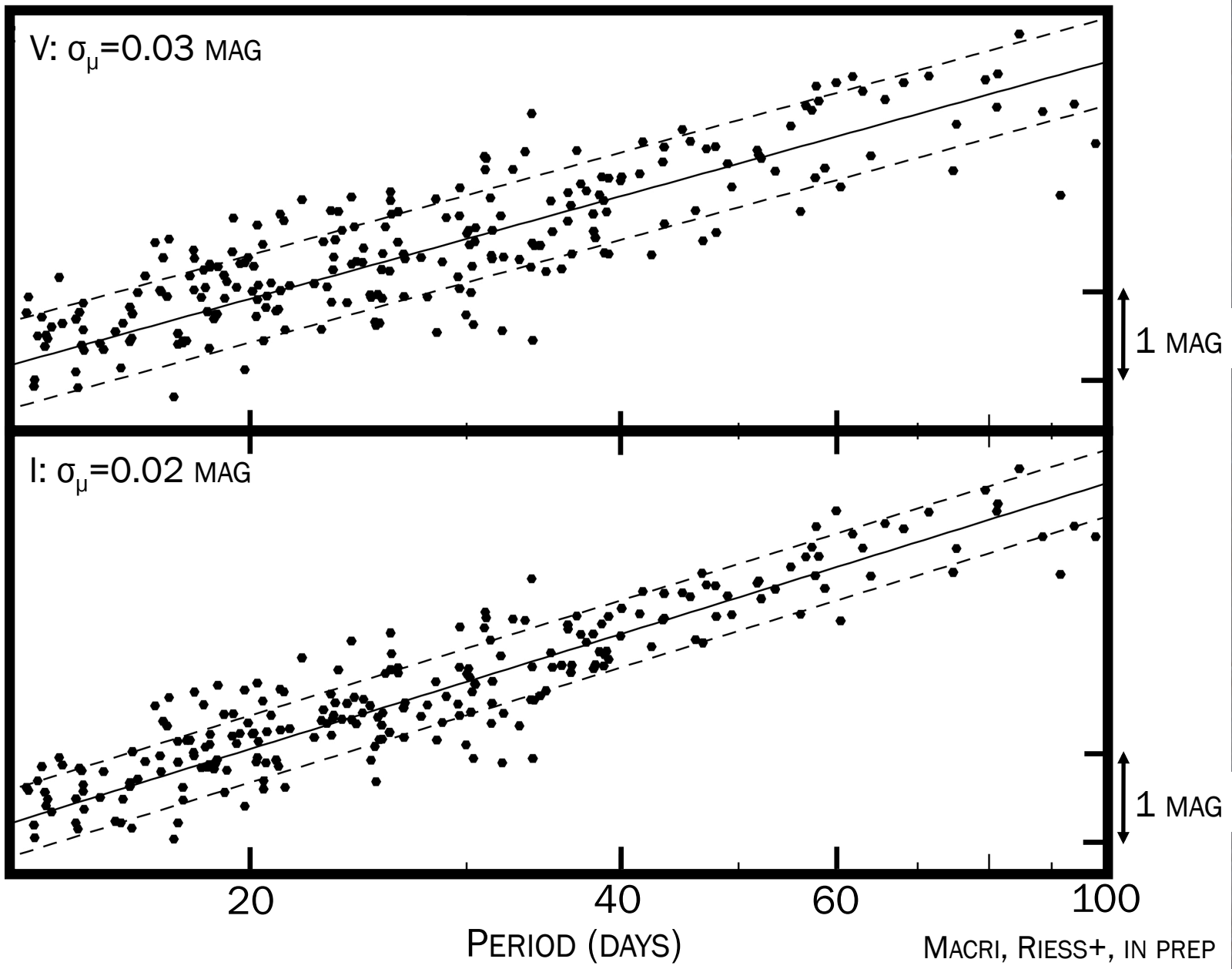


# N5584 WFC3 Cepheid light curves

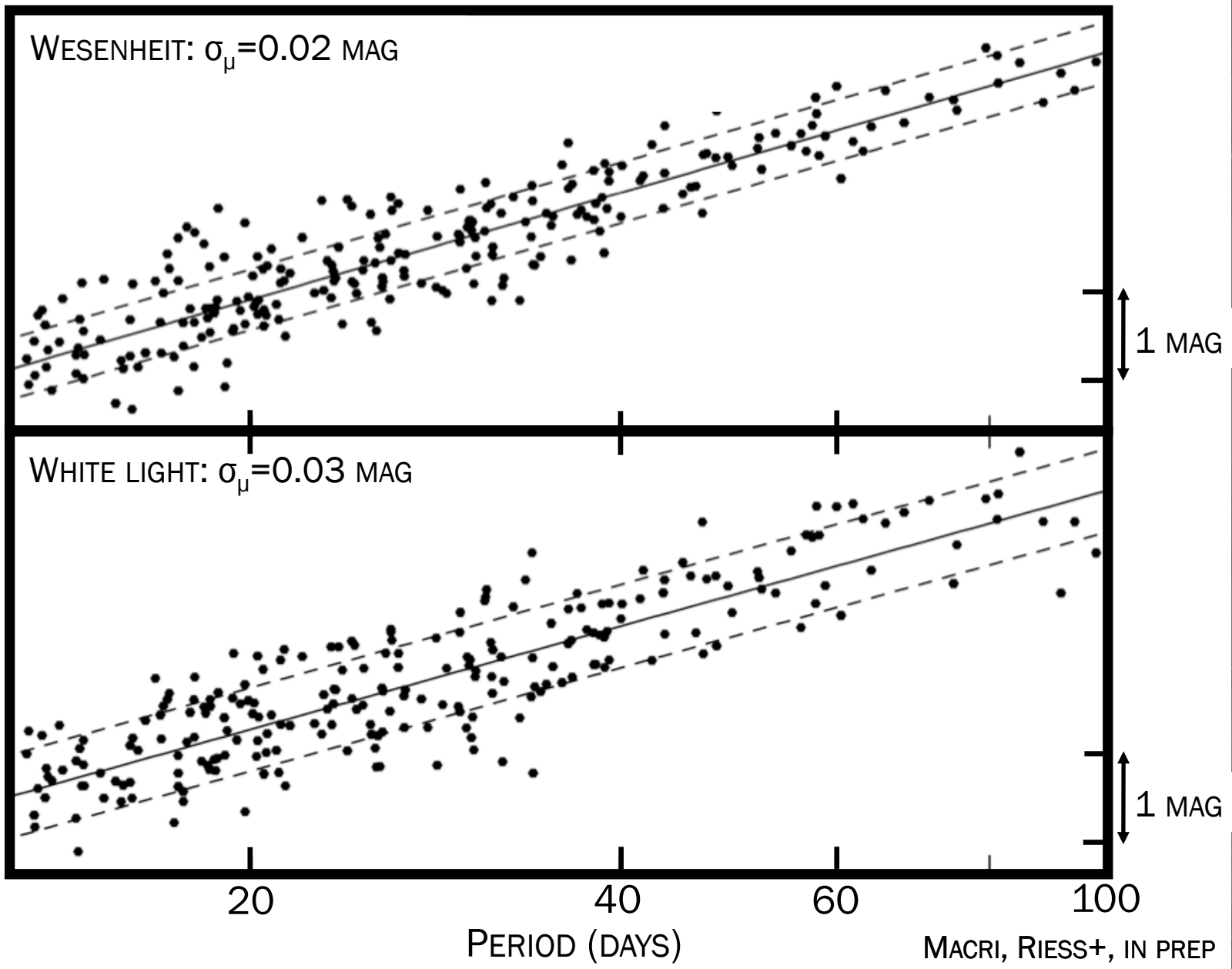


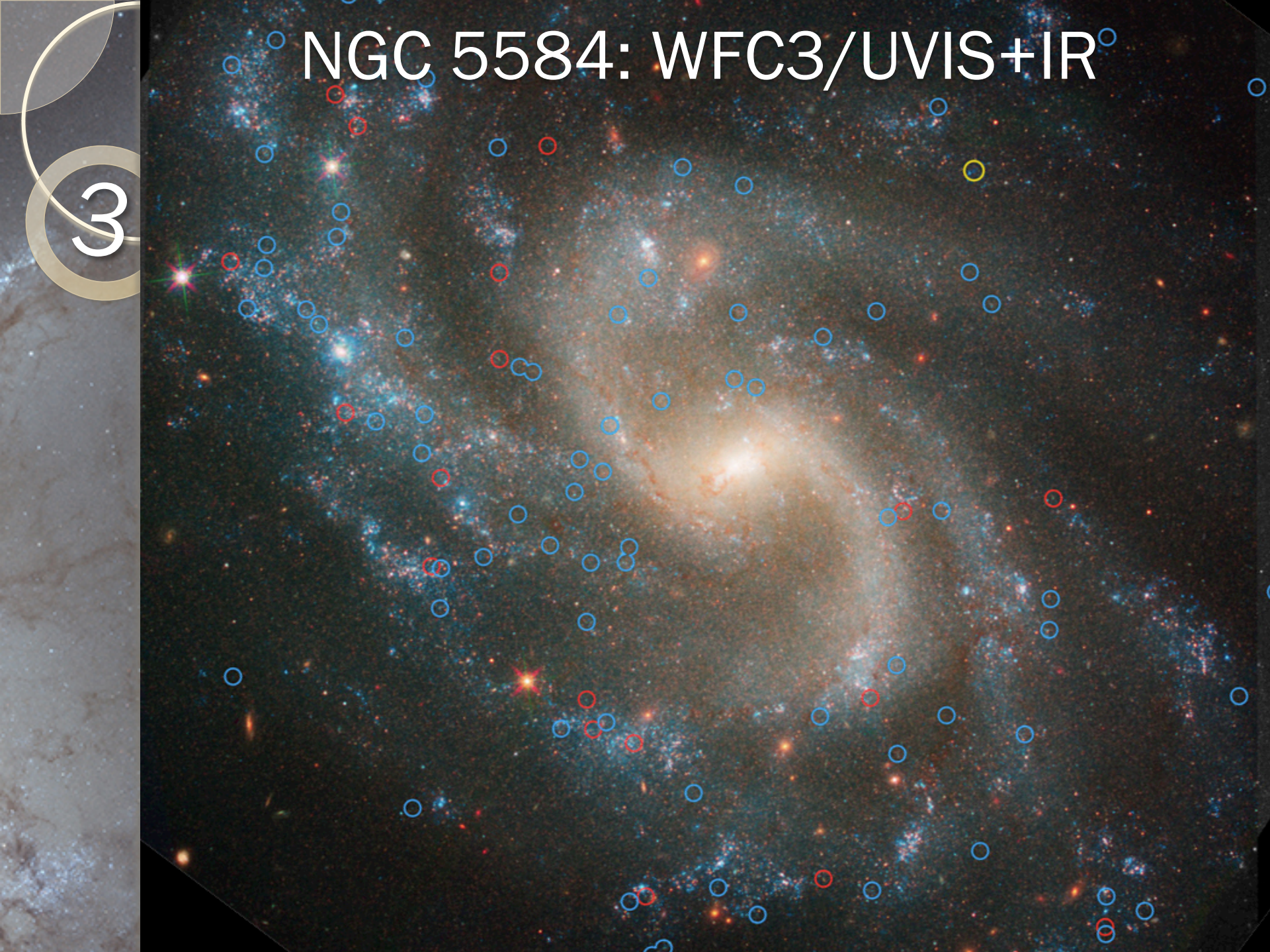

Macri, Riess+, in prep

# N5584 WFC3 P-L RELATIONS

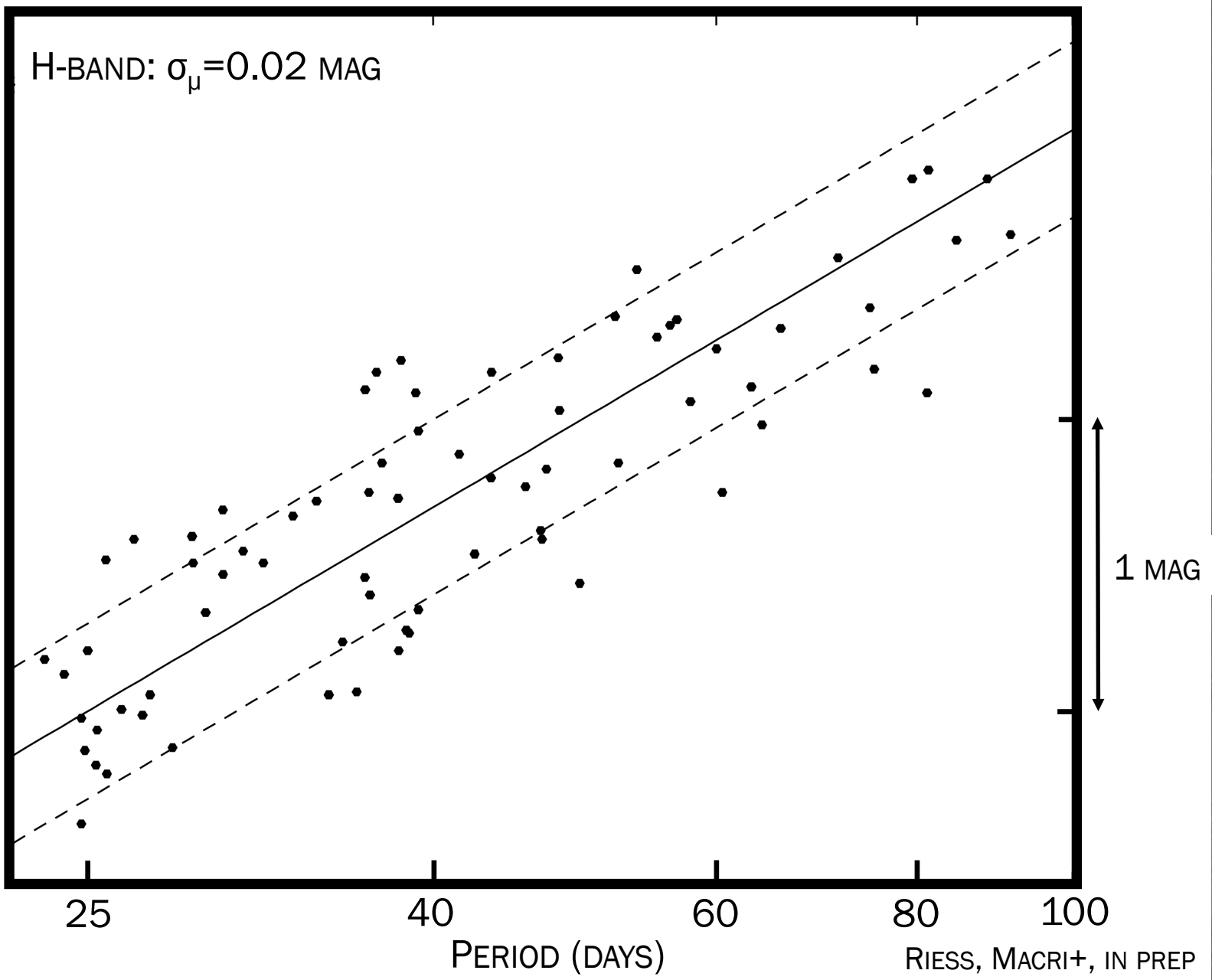


# N5584 WFC3 P-L RELATIONS




NGC 5584: WFC3/UVIS+IR
3

# N5584 WFC3 P-L RELATIONS



# Summary

- HST successfully fulfilled one of its original scientific objectives: $\sigma(H_0) \sim 10\%$
- As "usual" with HST, we have gone far beyond... SN Ia at $z>1$, $\sigma(H_0) < 5\%$
- Latest generation of instruments enabling important advances at modest "orbit cost"

# Goodbye John, we will miss you