Mega-SHoES: H_0 to 2% and beyond

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A 3% SOLUTION: DETERMINATION OF THE HUBBLE CONSTANT WITH THE *HUBBLE SPACE TELESCOPE* AND WIDE FIELD CAMERA 3*

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- New Co-Is in MEGA-SH0ES:
  - Jay Anderson (STScI)
  - John MacKenty (STScI)
  - Peter Nugent (LBNL)
  - Mohan Ganeshalingam (Berkeley)
  - Fritz Benedict (UT Austin)

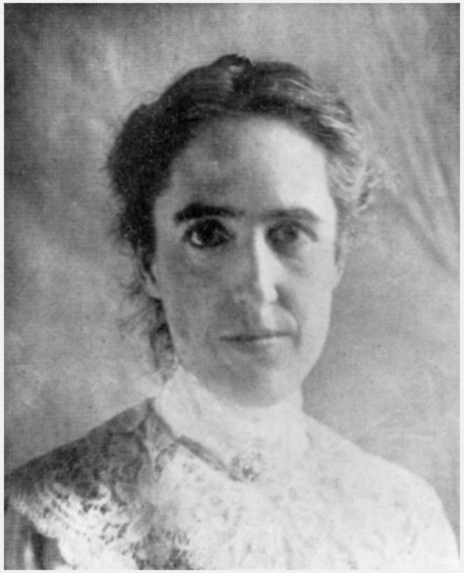
Summary

- A precise and accurate measurement of H_0 imposes needed additional constraints on the equation of state of dark energy
- SH$_0$ES project: calibration of recent SNe Ia using Cepheids in the near-infrared
  - $H_0 = 73.8 \pm 2.4$ km/s Mpc $\rightarrow \sigma(H_0) = 3.3\%$
- Long-term goal: $\sigma(H_0) = 1\%$
  - *HST* & *Gaia* parallaxes to Milky Way & LMC Cepheids
  - Calibration of additional local SNe Ia
  - Better characterization of systematic uncertainties

Outline

- Introduction & motivation
- The SH0ES project
- Under way: Mega-SH0ES
- The future…

One hundred years ago…



Henrietta Leavitt

Vesto Slipher

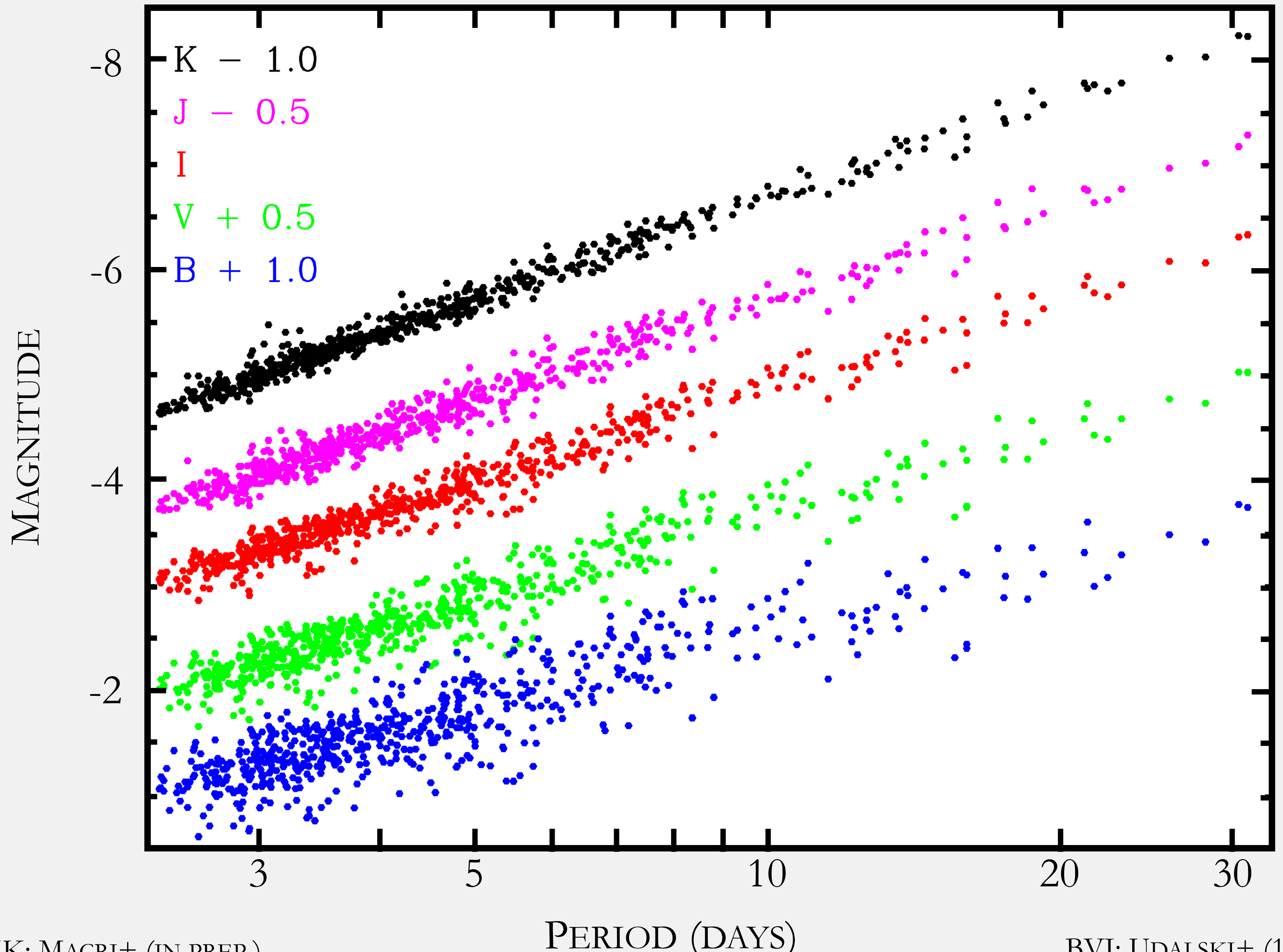
Cepheid Period-Luminosity relation
(the Leavitt Law)

Harvard College Observatory (1912)

First measurements of
galaxy radial velocities

Lowell Observatory (1912)

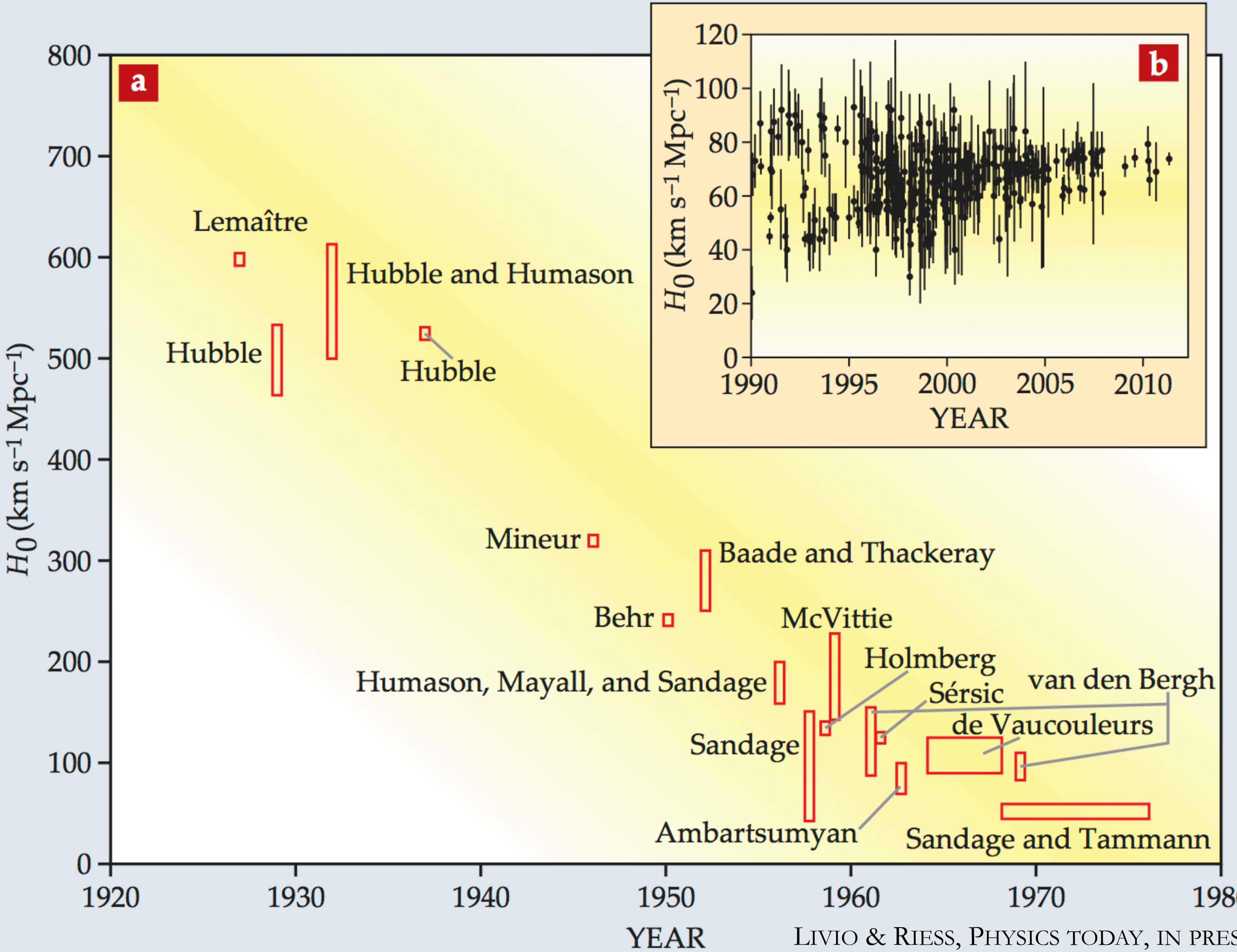
The Leavitt law (P-L relation)



JK: Macri+ (in prep.)

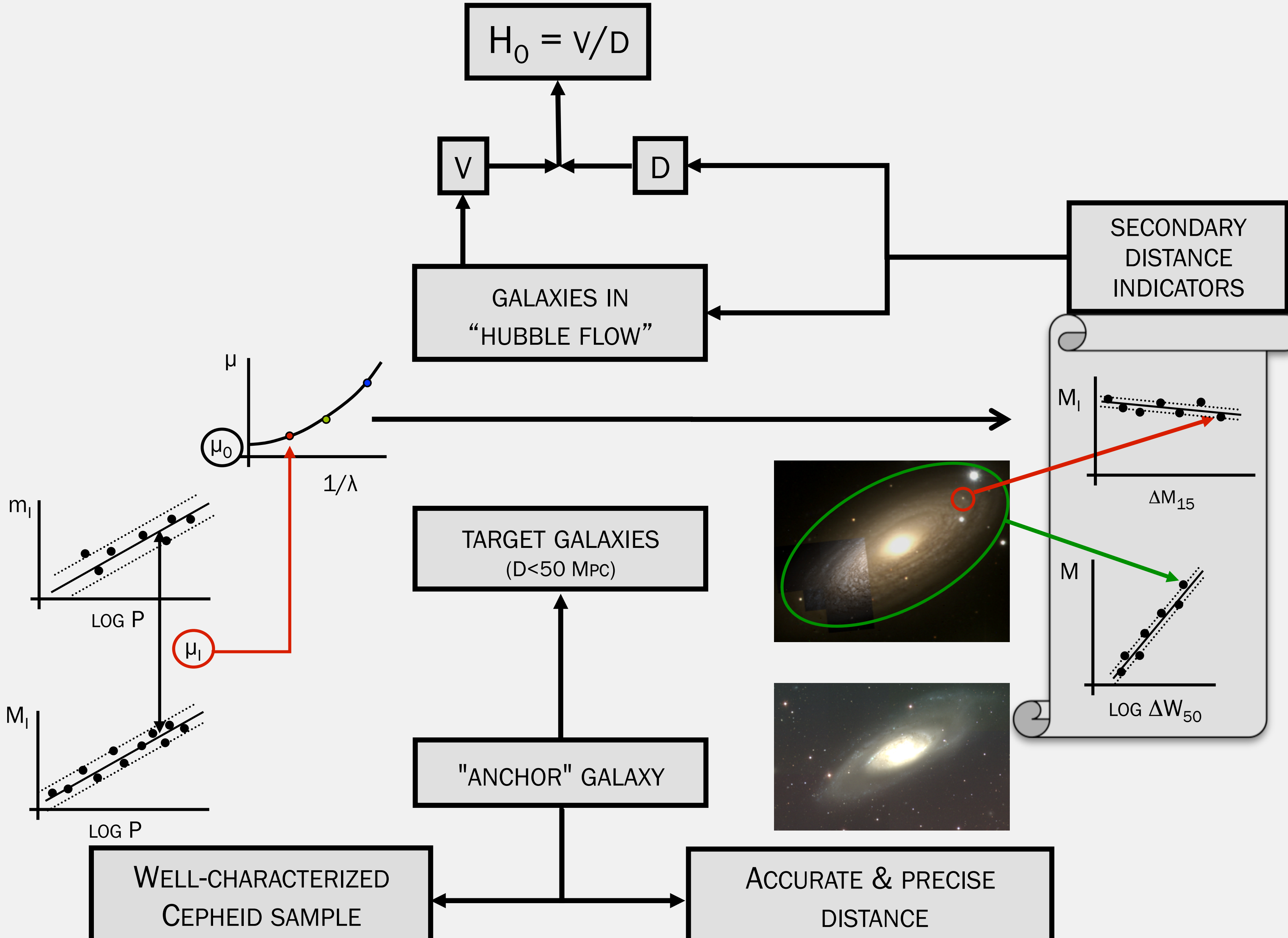
BVI: Udalski+ (1999)

90 YEARS OF H_0 MEASUREMENTS

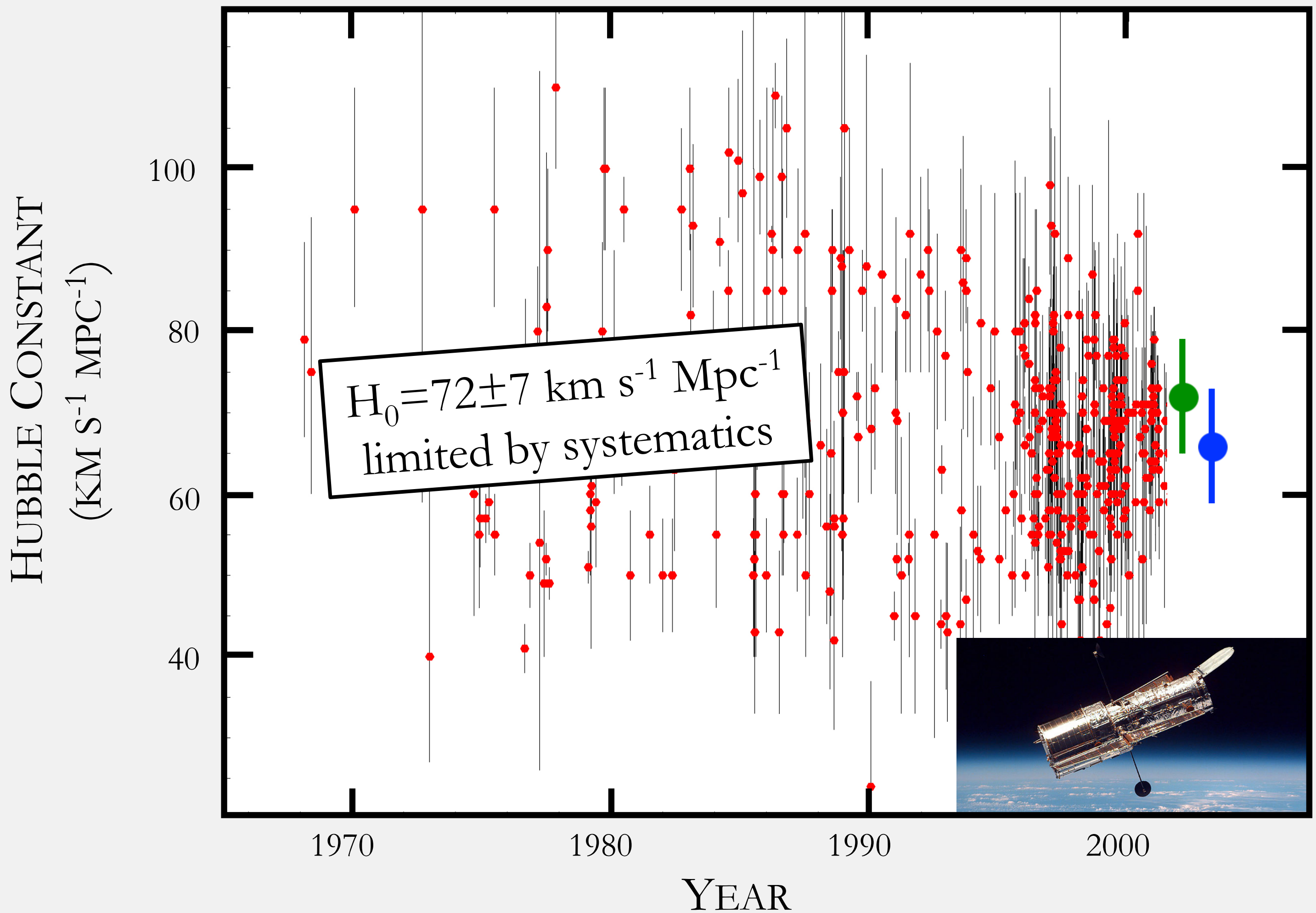


LIVIO & RIESS, PHYSICS TODAY, IN PRESS

The Hubble constant



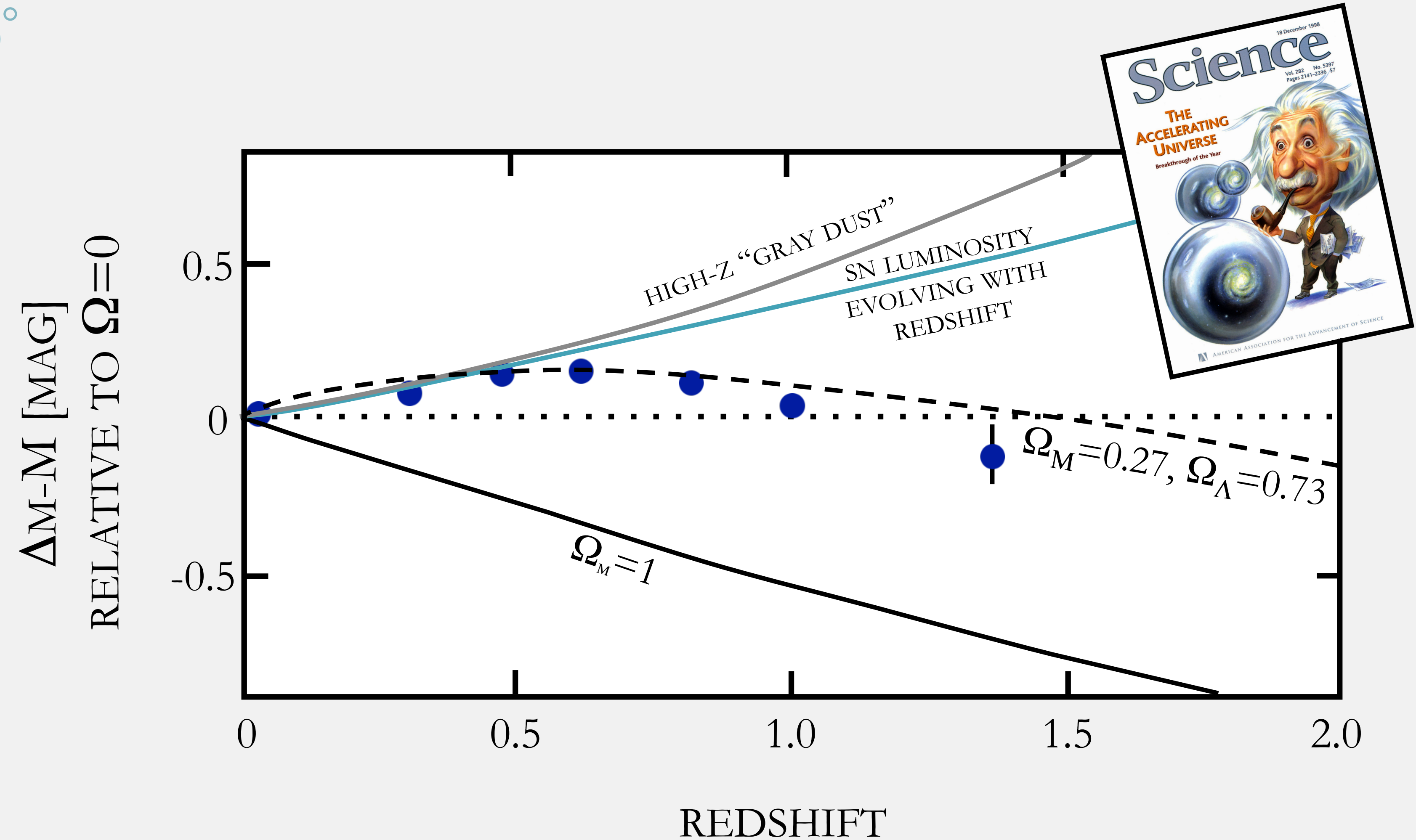
The Hubble constant vs. time



Freedman+ (2001)
Sandage+ (2006)

Compilation by John Huchra

SNe Ia: the Universe is dominated by dark energy & dark matter



Riess+ (1998); Perlmutter+ (1999)

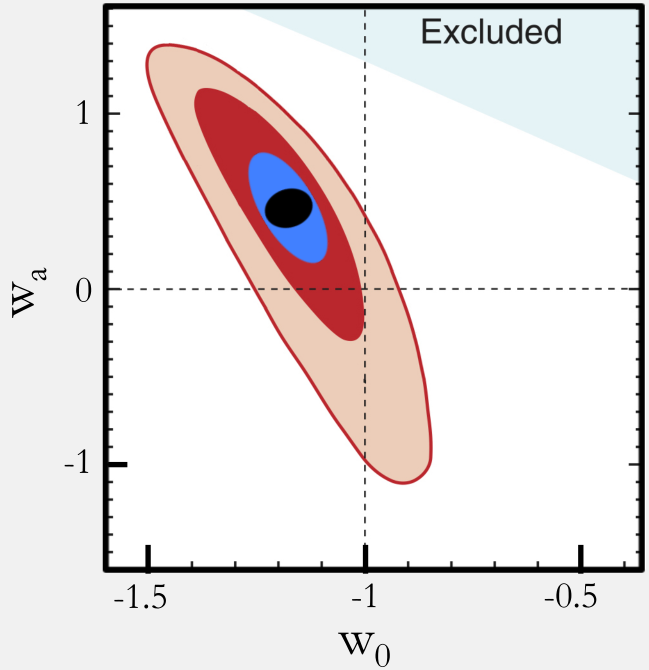
Riess+ (2007)

Combining the constraints

- Equation of state of dark energy:

$$\boxed{w = P/\rho c^2}$$

$$\boxed{w(a)=w_0+w_a(1-a)}$$

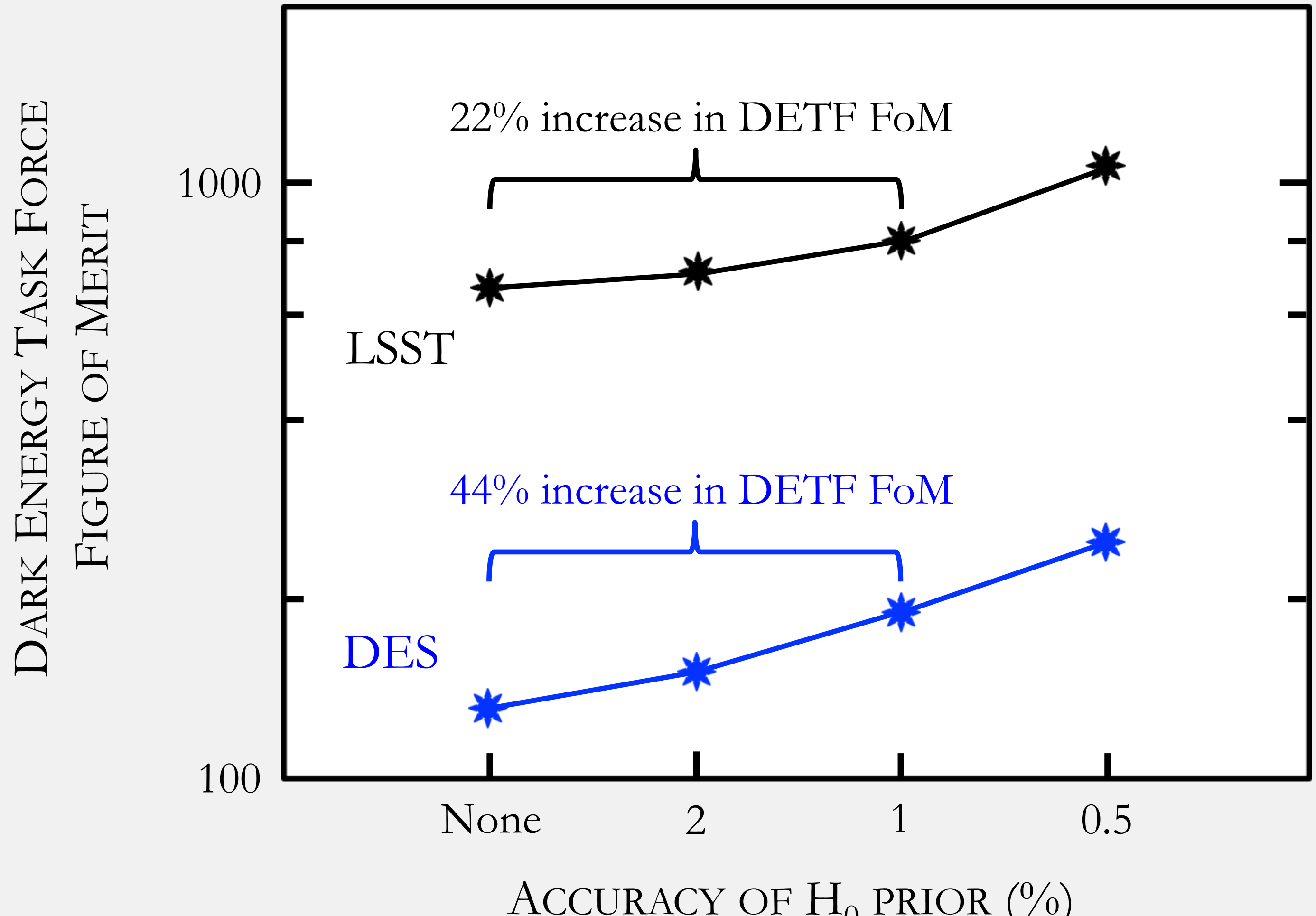


Coupled with additional priors (such as H_0)

- H12: w_0 ±0.13; w_a ±0.5
- DES: w_0 ±0.08; w_a ±0.3
- LSST: w_0 ±0.05; w_a ±0.1

Bennett+ (2012); Hinshaw+ (2012)

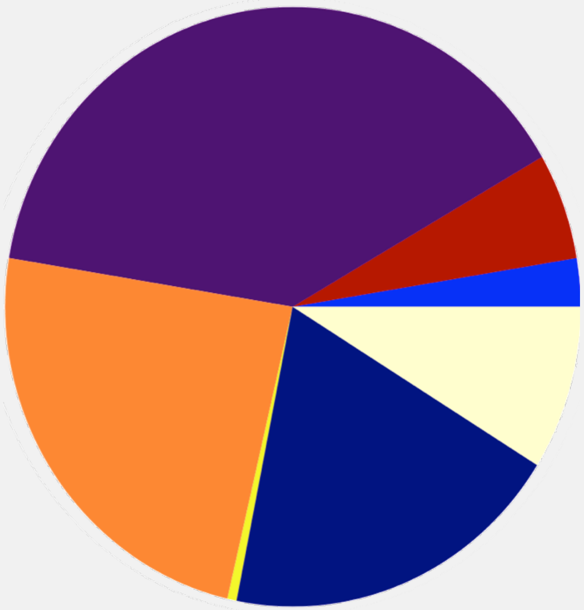
Motivation for further improvement in H_0



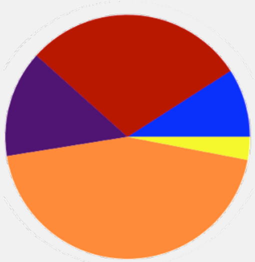
After Weinberg+ (2012)

WFPC2 PROJECTS → SHOES '09, '11

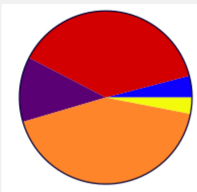
$\sigma(H_0) \approx 10\%$



Term	KP %	'09 %	'11 %
Anchor distance	5.0	3.0	1.3
Cepheid reddening, zeropoints (anchor-to-hosts)	4.5	0.3	1.4
P-L slope, d log P (anchor-to-hosts)	4.0	0.5	0.6
Cepheid metallicity dependence (anchor-to-hosts)	3.0	0.8	1.0
WFPC2 CTE, long-vs-short zeropoints	3.0	--	--
Mean of SN Ia calibrators	2.5	2.5	1.9
Mean of P-L in anchor	2.5	1.5	0.7
Mean of P-L in SN hosts	1.5	1.5	0.6
SN Ia m-z relation	1.0	0.5	0.5
Analysis systematics	--	1.3	1.0
Total	**10**	**4.8**	**3.3**



$\sigma(H_0) = 4.8\%$



$\sigma(H_0) = 3.3\%$

Riess+ (2009, 2011)

OUTLINE

- ✓ Introduction & motivation
- ➢ The SH0ES project
- Under way: Mega-SH0ES
- Next steps

The SH$_0$ES project

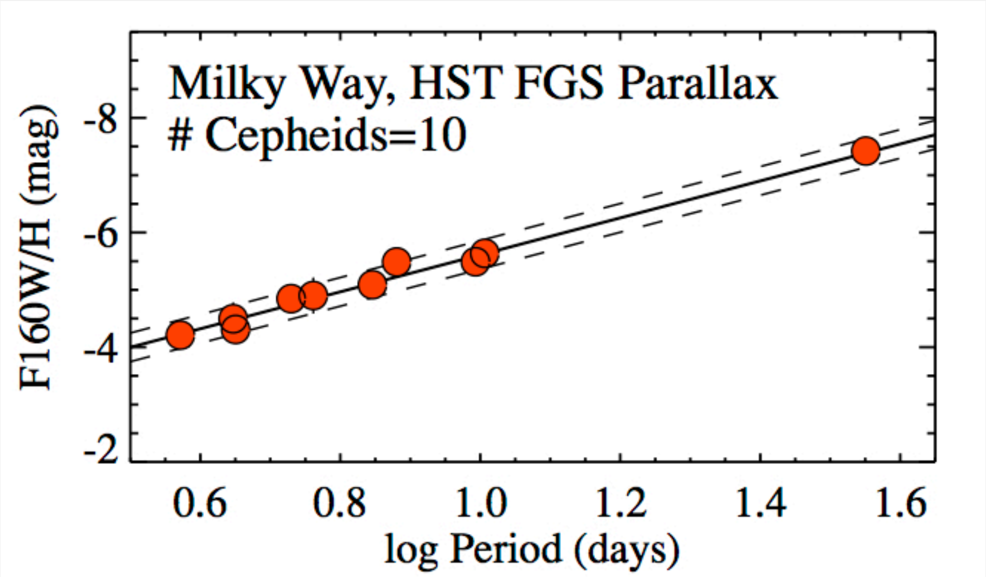
- Started in 2005 by Riess, Macri & collaborators to reduce systematic uncertainty in H_0:
  - Adopt Messier 106 as anchor
    - D=7.6 Mpc ± 3% (Humphreys+ 2008 & 2013)
    - Cepheids with similar abundance as spirals that host SNe Ia
    - Large sample with P>20d, observable with HST
  - Use <u>only</u> modern & ideal SNe Ia (N = 2 → 6)
    - Photoelectric or CCD photometry; low reddening; pre-max
  - Observe whole Cepheid sample with same telescope, cameras
    - Optical: HST, WFPC2+ACS → ACS+WFC3
    - NIR (reduce sensitivity to dust, metallicity): HST, NIC2 → WFC3 (IR)

The SH$_0$ES project

- First result: $\sigma(H_0)=4.8\%$ (Riess+ 2009)
- Improvements in second iteration:
  - "Basket of anchors"
    - MW parallaxes, LMC DEBs, Maser in Messier 106
  - Increase number of SN hosts ($N = 6 \rightarrow 8$)
  - More homogeneous photometry + 2.5× Cepheids
    - ACS+WFC3/UVIS (V, I) ; WFC3/IR (H)
- Latest result: $\sigma(H_0)=3.3\%$ (Riess+ 2011)
  - Fully propagated random + systematic uncertainties
  - Only ongoing program with all observations @ same λs

Milky Way Cepheid P-L in H

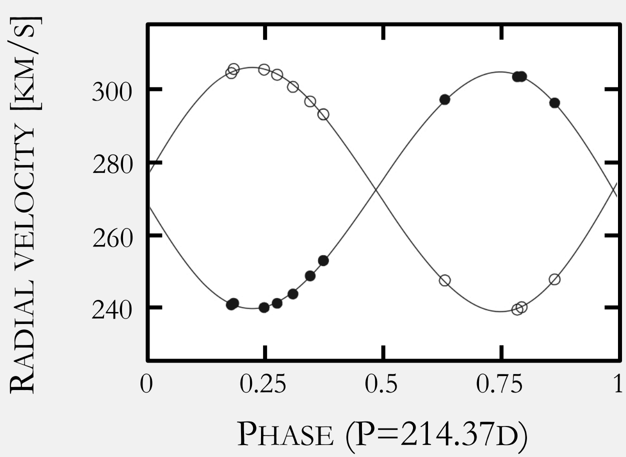
- One of three P-Ls used by SH_0ES project (Riess+ 2011)
  - 10 Cepheids with 8% HST/FGS parallaxes (Benedict+ 2007)
    - 3 of these also have Hipparcos parallaxes (van Leeuwen 2007)
  - Ground-based H-band magnitudes (Groenewegen 1999)
  - Fully-propagated uncertainties: σ(zpt)=2.8%

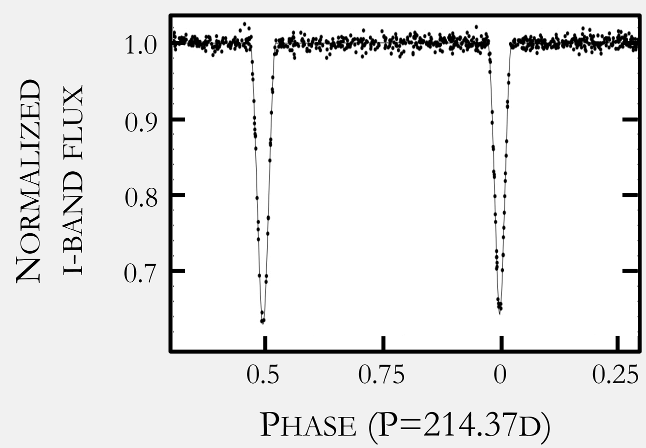


Riess+ (2009, 2011)

LMC Cepheids+eclipsing binaries

- LMC Cepheids: H-band observations by Persson+ (2004)
- Detached eclipsing binary distances
  - Photometry + spectroscopy: fluxes, radii & temperatures
  - Calculate luminosities using stellar atmosphere *models*
  - $D=\sqrt{L/4\pi f}$; uncertainties from 3-6% depending on system
  - Pietrzynski+ 2013: D(LMC)=50.0 kpc ±2.2% based on 8 DEBs

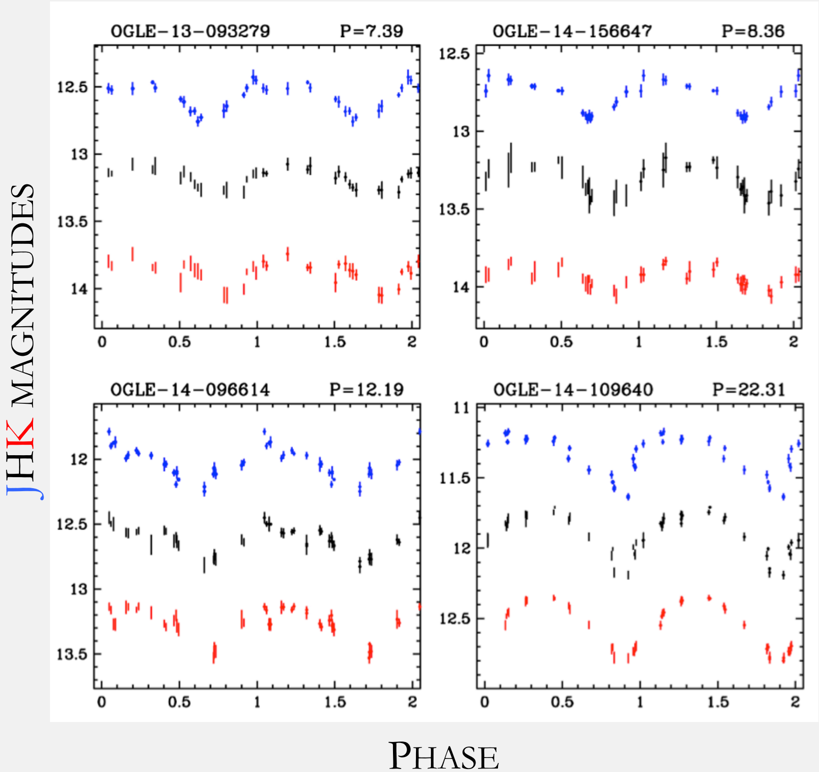


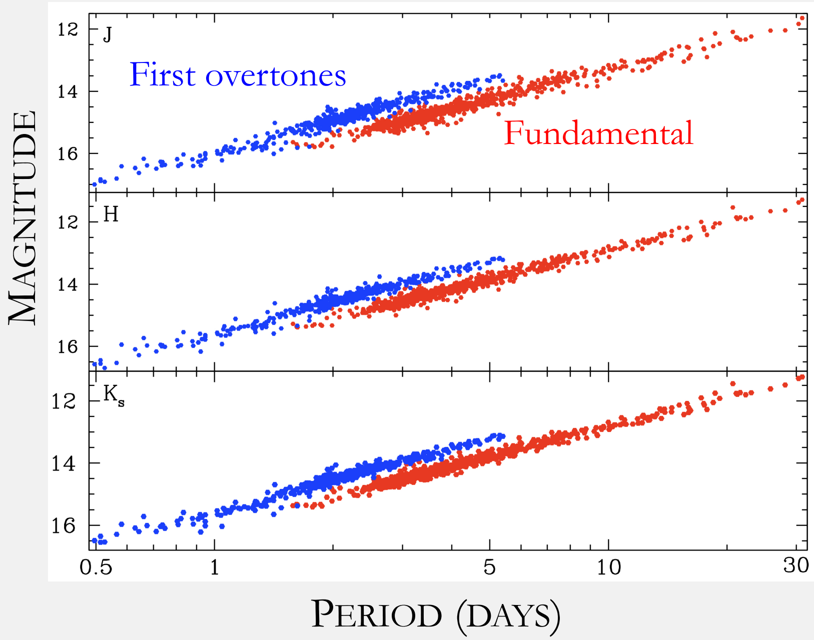


Pietrzynski+ (2009)

LMC JHK P-L RELATIONS

- CTIO 1.5-m CPAPIR survey, 49 fields across LMC
  - >1,100 Cepheids & 5.3 million point sources
  - σ(P-L slopes) reduced by 2× relative to Persson+ (2004)



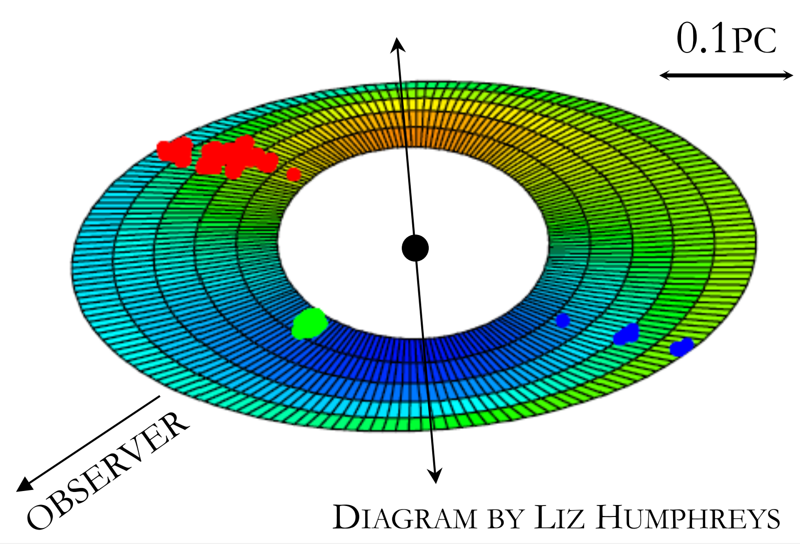


MACRI, KANBUR, NGEOW+ (IN PREP.)

Maser distance to M106

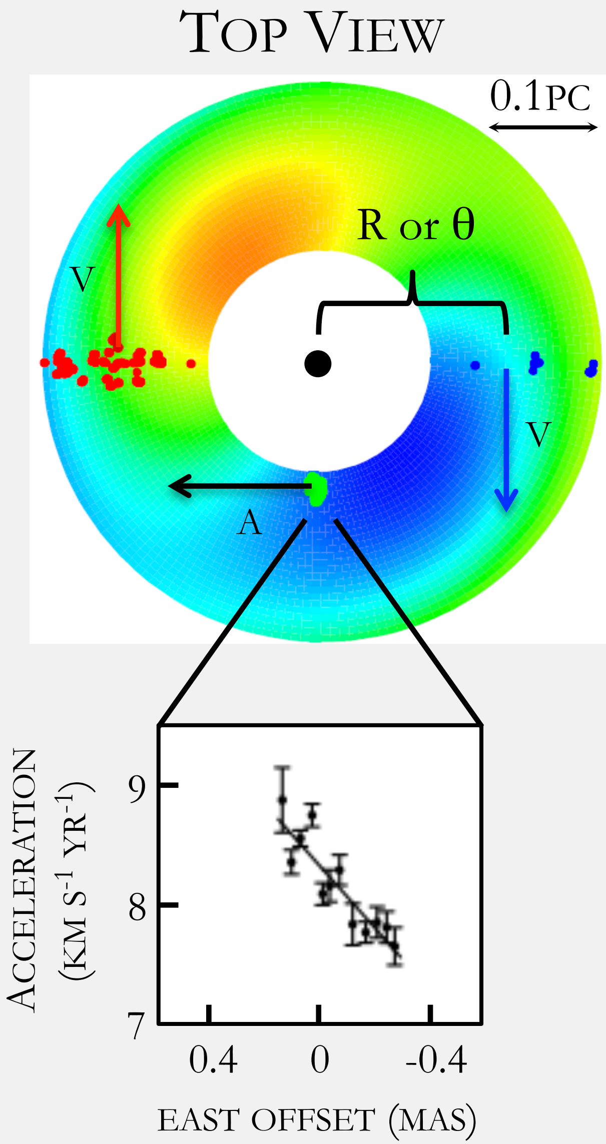
- Distance based on 10+ years of VLBI observations of water masers orbiting central black hole
- D = 7.6 Mpc ± 3%

  (Humphreys+ 2008, 2013)



Color mosaic based on SDSS images

Maser distance to M106



Angular diameter distance

- V from high-velocity masers
- A from systemic masers
- θ from VLBI map

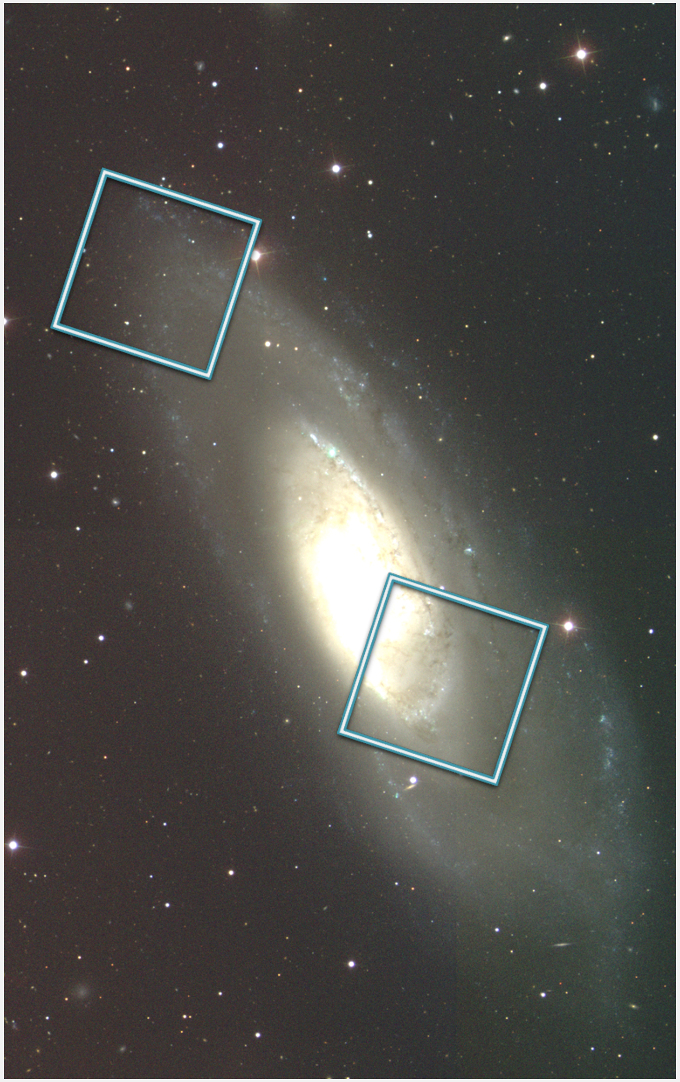
- $A = V^2/R$
- $R = D\,\theta$

$$\boxed{D = V^2/A\theta}$$

Herrnstein+ (1999);
Humphreys+ (2008, 2013)

CEPHEIDS IN MESSIER 106

- HST/ACS: ~300 Cepheids with 4d<P<45d (Macri+ '06)
- HST re-visit + 4 years of Gemini observations: longer-period Cepheids (Samantha Hoffmann, Texas A&M PhD Thesis)
- HST H-band imaging as part of SH_0ES project



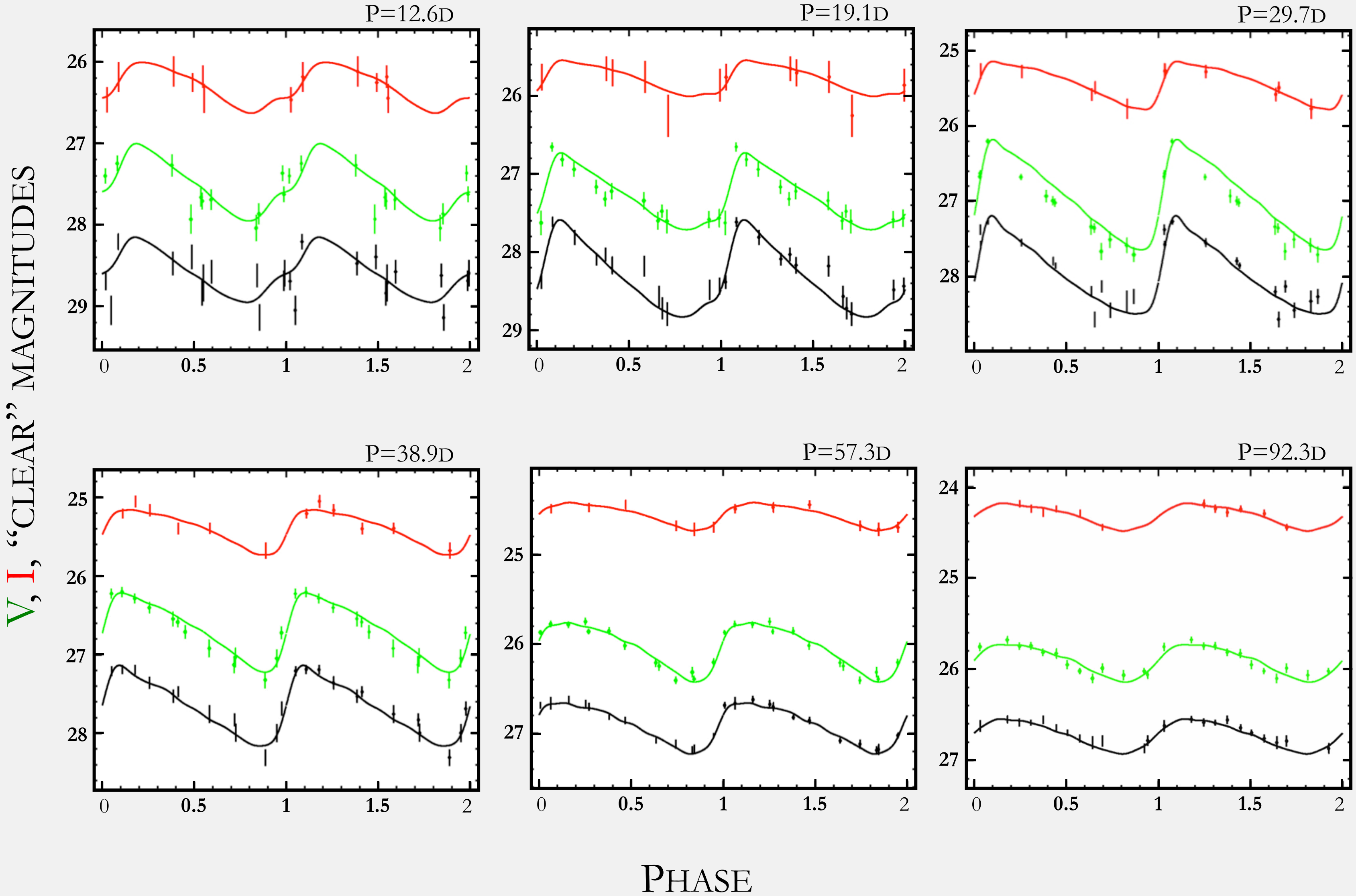
COLOR MOSAIC BASED ON SDSS IMAGES

NGC 5584: WFC3/UVIS

- Observed in Cycle 15 as part of SH0ES-II
- "Standard" HST search (12 V + 6 I epochs)
- Also tested feasibility of "clear filter" search
  - Reduce # orbits for future HST targets
- >300 Cepheids discovered

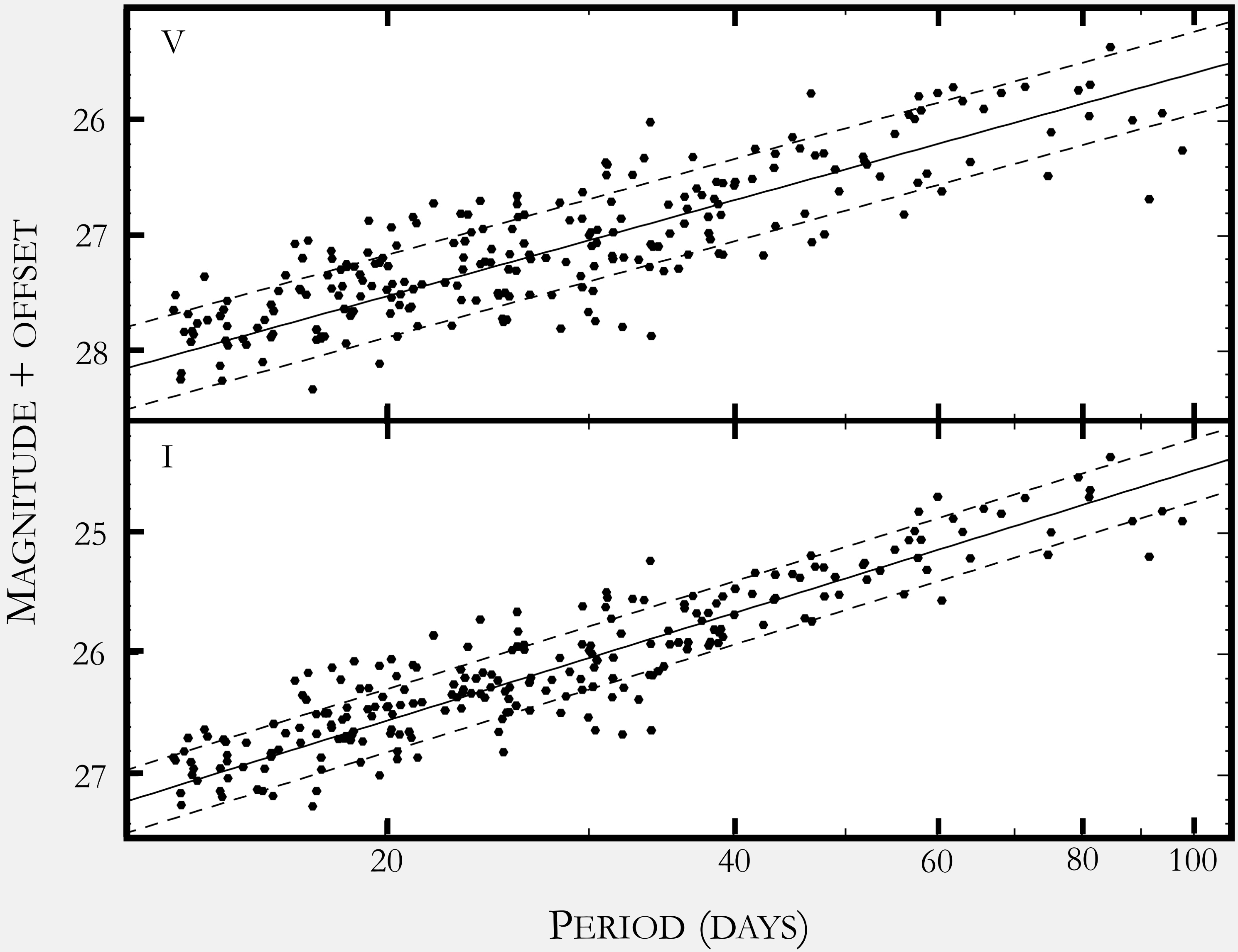
N5584: HOST OF SN 2007AF

N5584 WFC3 CEPHEID LIGHT CURVES



MACRI, RIESS+ (IN PREP.)

N5584: P-L relations from WFC3



Macri, Riess+ (in prep.)

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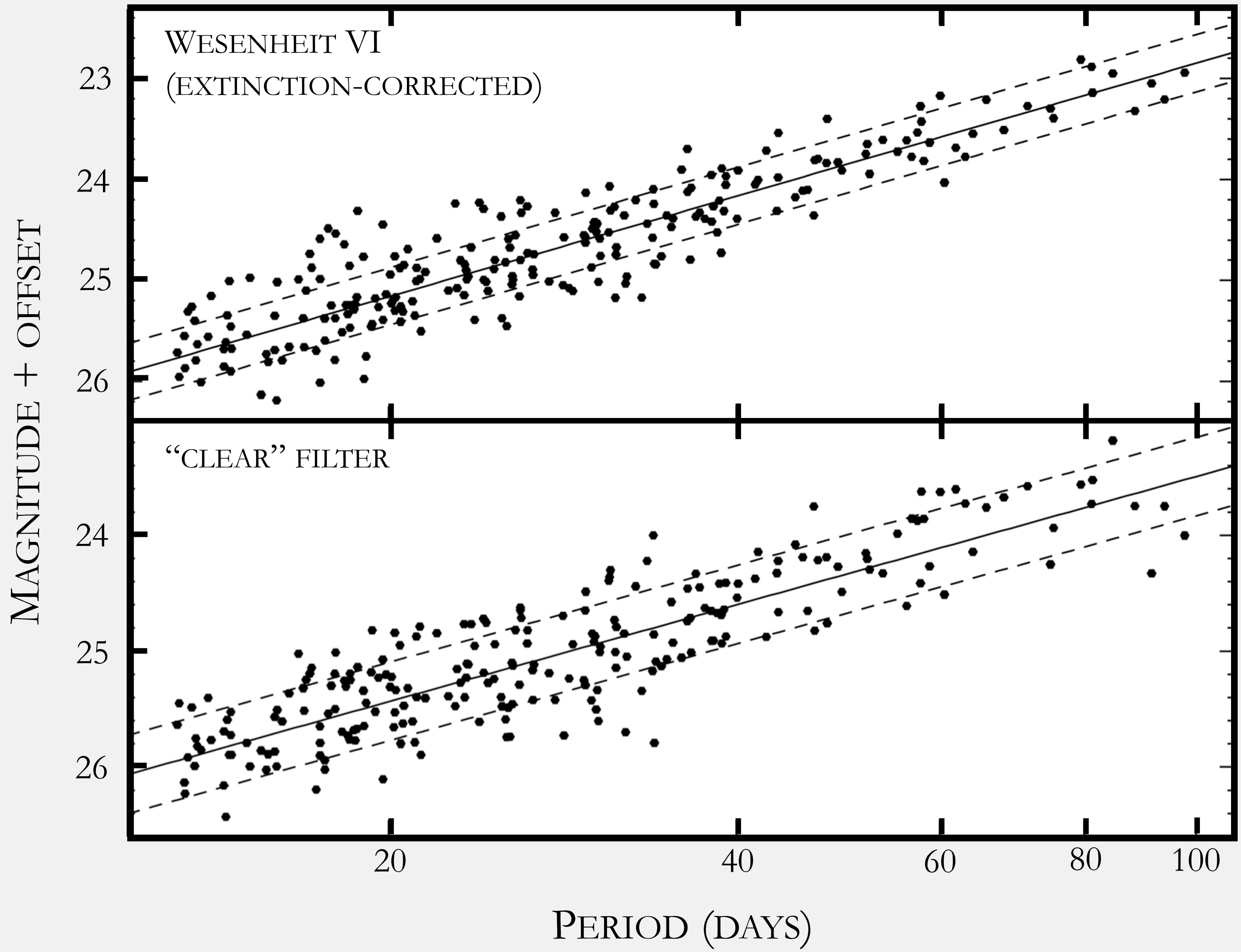
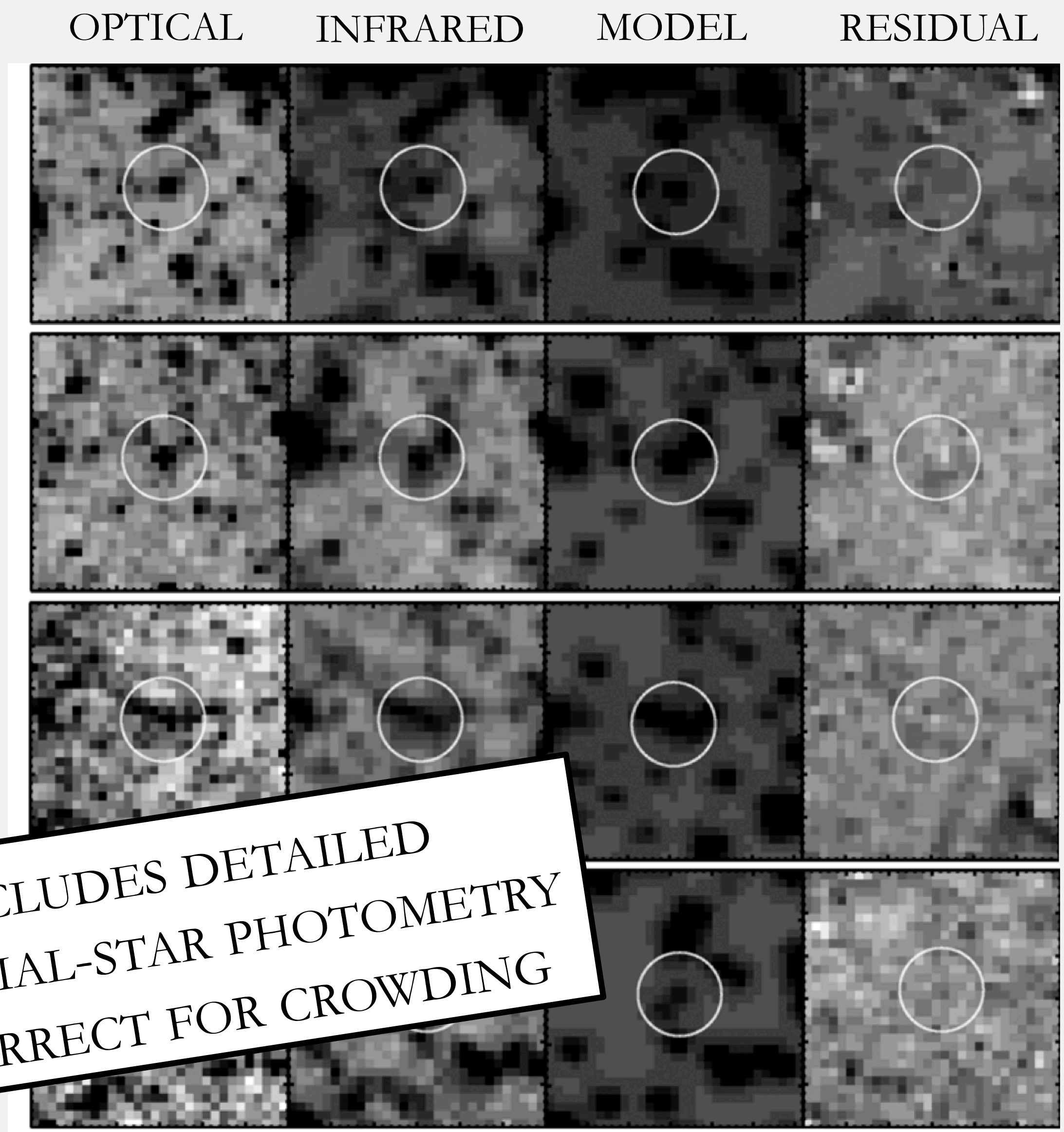


Macri, Riess+ (in prep)

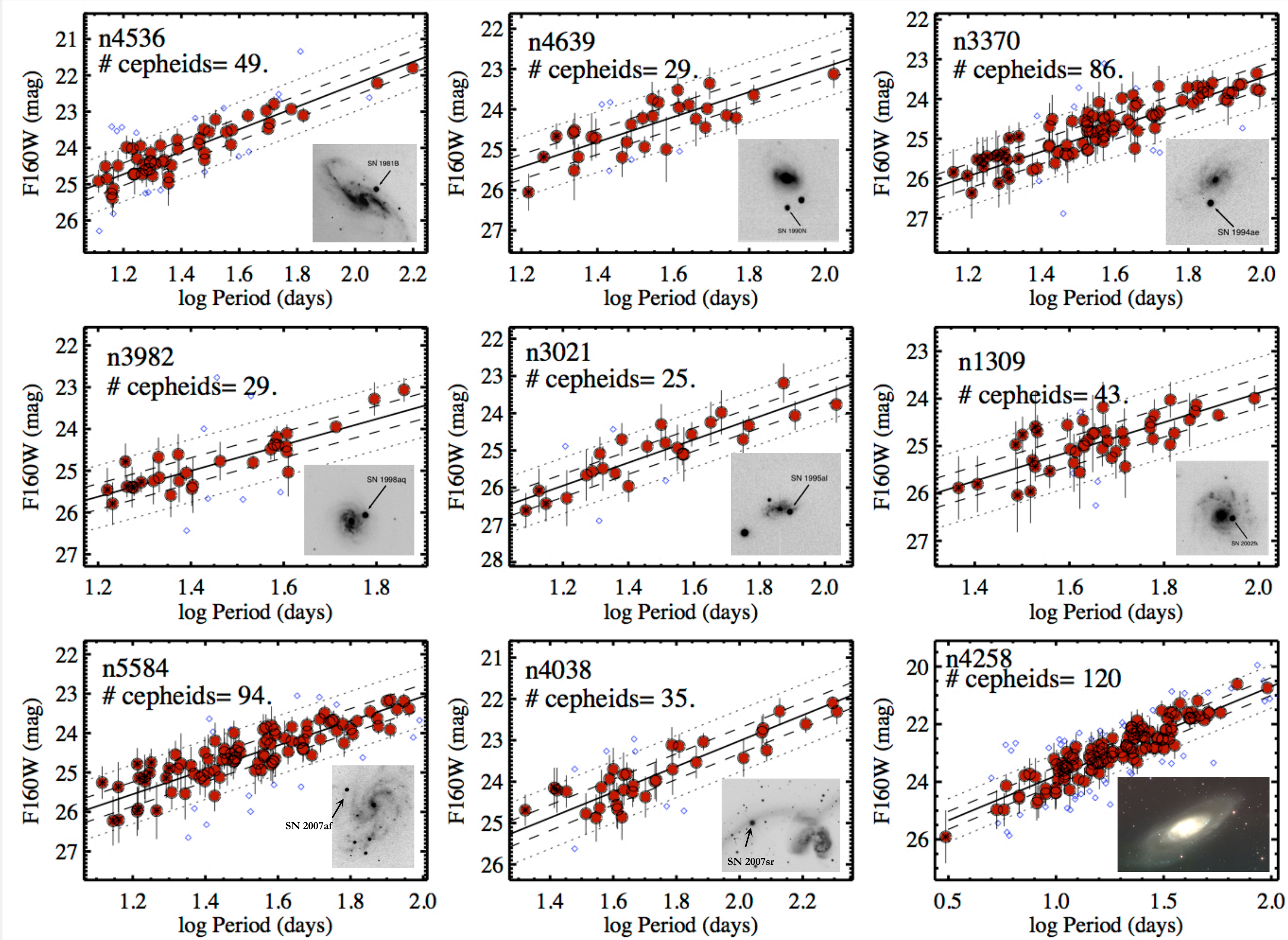
N5584: WFC3/IR PHOTOMETRY



INCLUDES DETAILED ARTIFICIAL-STAR PHOTOMETRY TO CORRECT FOR CROWDING

RIESS+ (2011)

SHOES WFC3 H-BAND P-L RELATIONS



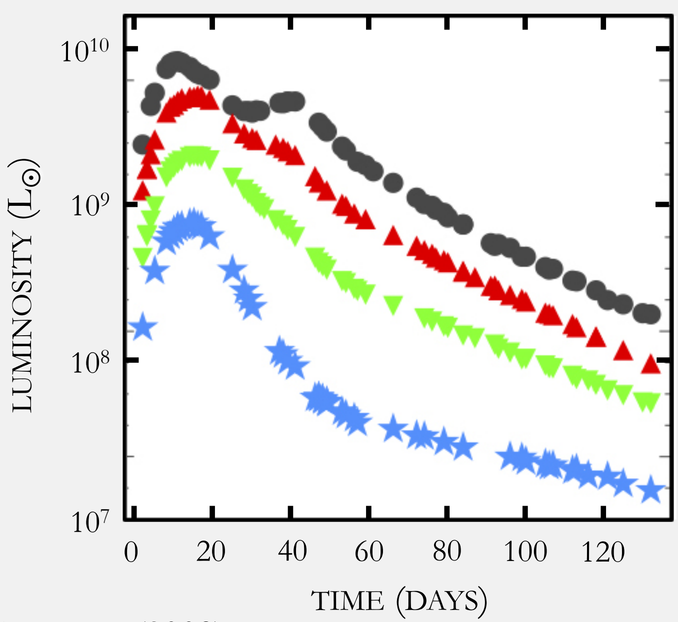
H MAGNITUDE

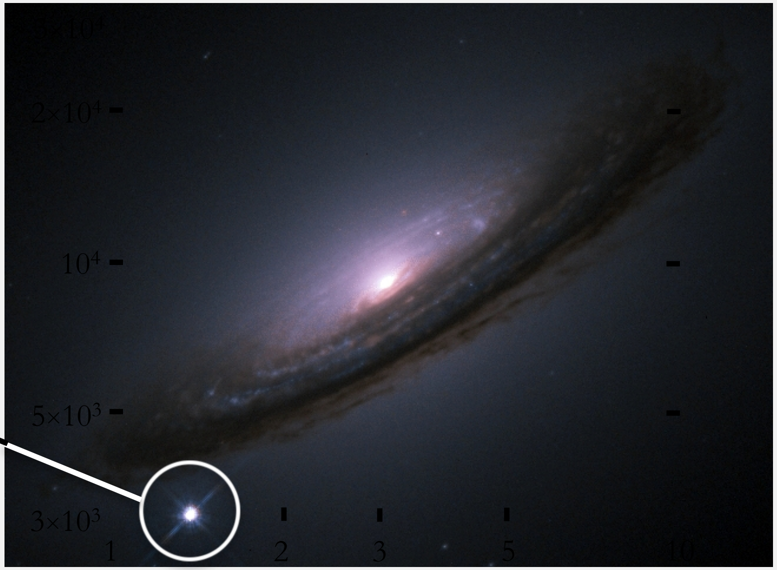
PERIOD (DAYS)

RIESS+ (2011)

SNe Ia

- Modern SNe Ia are excellent standardizable candles (Phillips 1993, Hamuy+ 1996, Riess+ 1996)
  - Hubble flow sample of 250 SNe with distance uncertainties of 8% in optical, 5% in near-IR (Hicken+ 2009, Mandel+ 2011)
  - Local & Hubble-flow samples observed with same telescopes
  - Minimize systematic uncertainties from photometry





HICKEN+ (2009)

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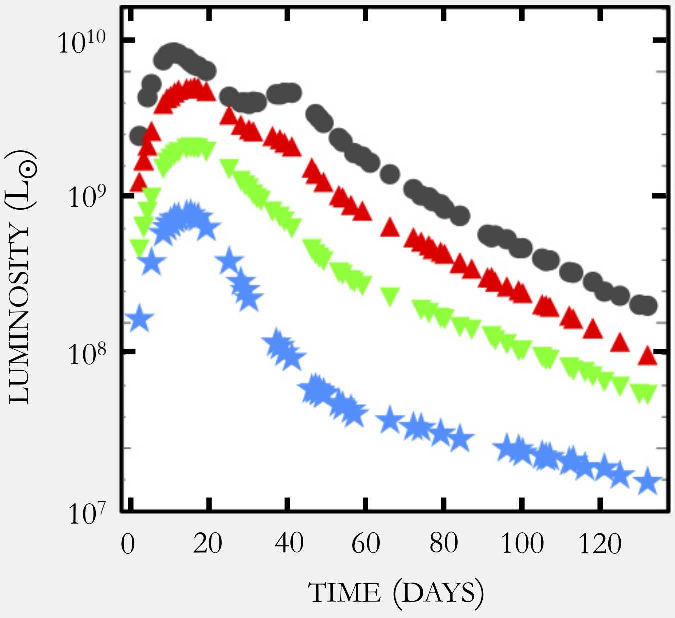
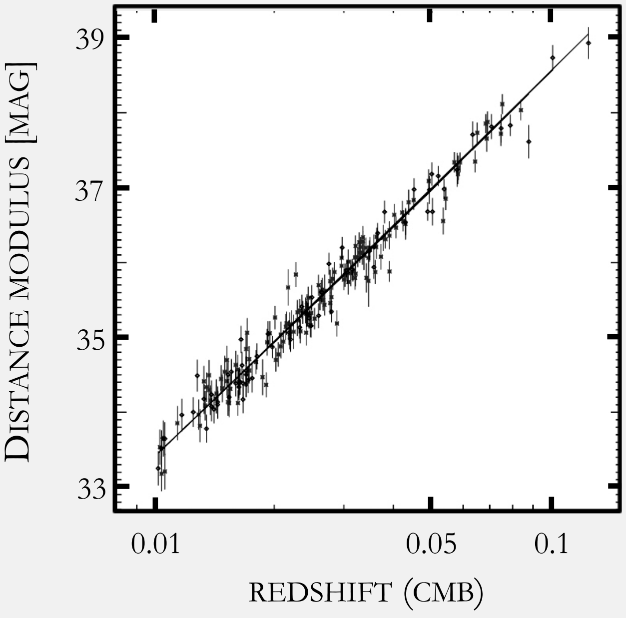
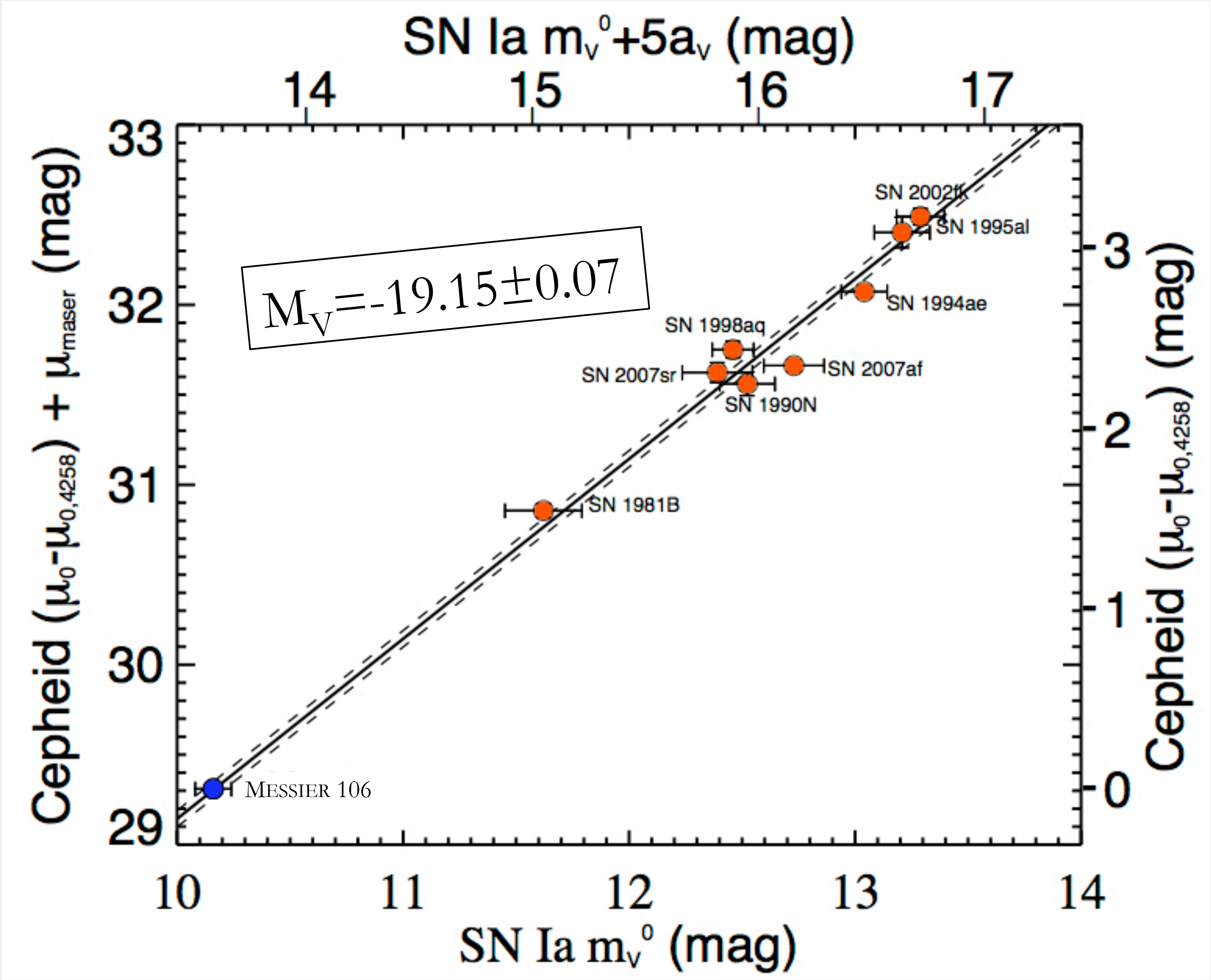




HICKEN+ (2009)

SHOES CALIBRATION OF SNE IA



RIESS+ (2011)

OUTLINE

- ✓ Introduction & motivation
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- ➢ Under way: Mega-SH0ES
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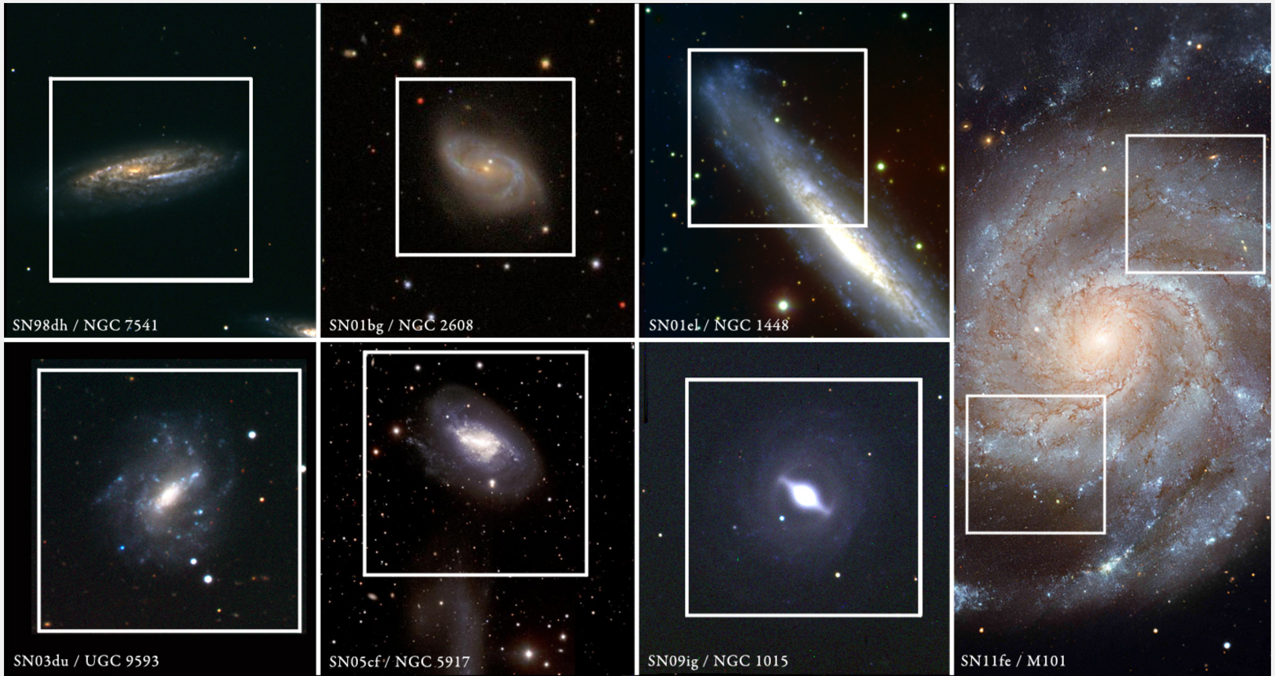
Under way: mega-SHOES

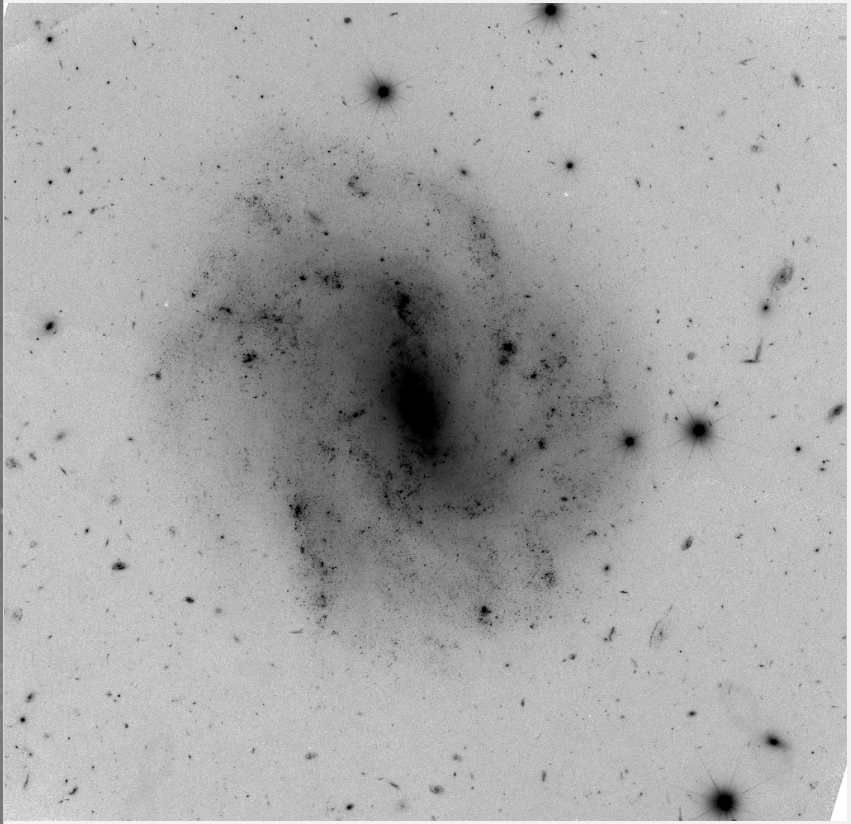
- Target 1.9% determination of H_0 based on:
  - HST parallaxes to an additional 18 Cepheids in Milky Way
  - Cepheid distances to 8 additional SNe Ia hosts
  - Use of SNe NIR light curves to reduce per-object error
  - 112 orbits in Cycle 20 + 18 in Cycle 21 + 7 in Cycle 22



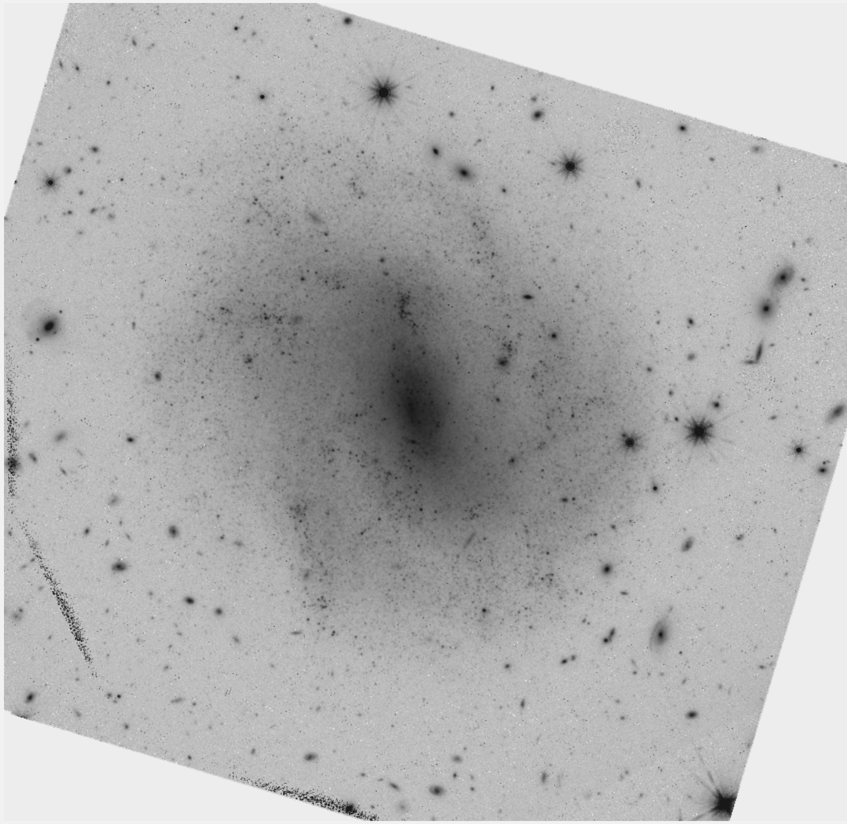
Under way: mega-SHOES

- First galaxy: UGC 9391, host of SN 2003du

WFC3/UVIS F350LP

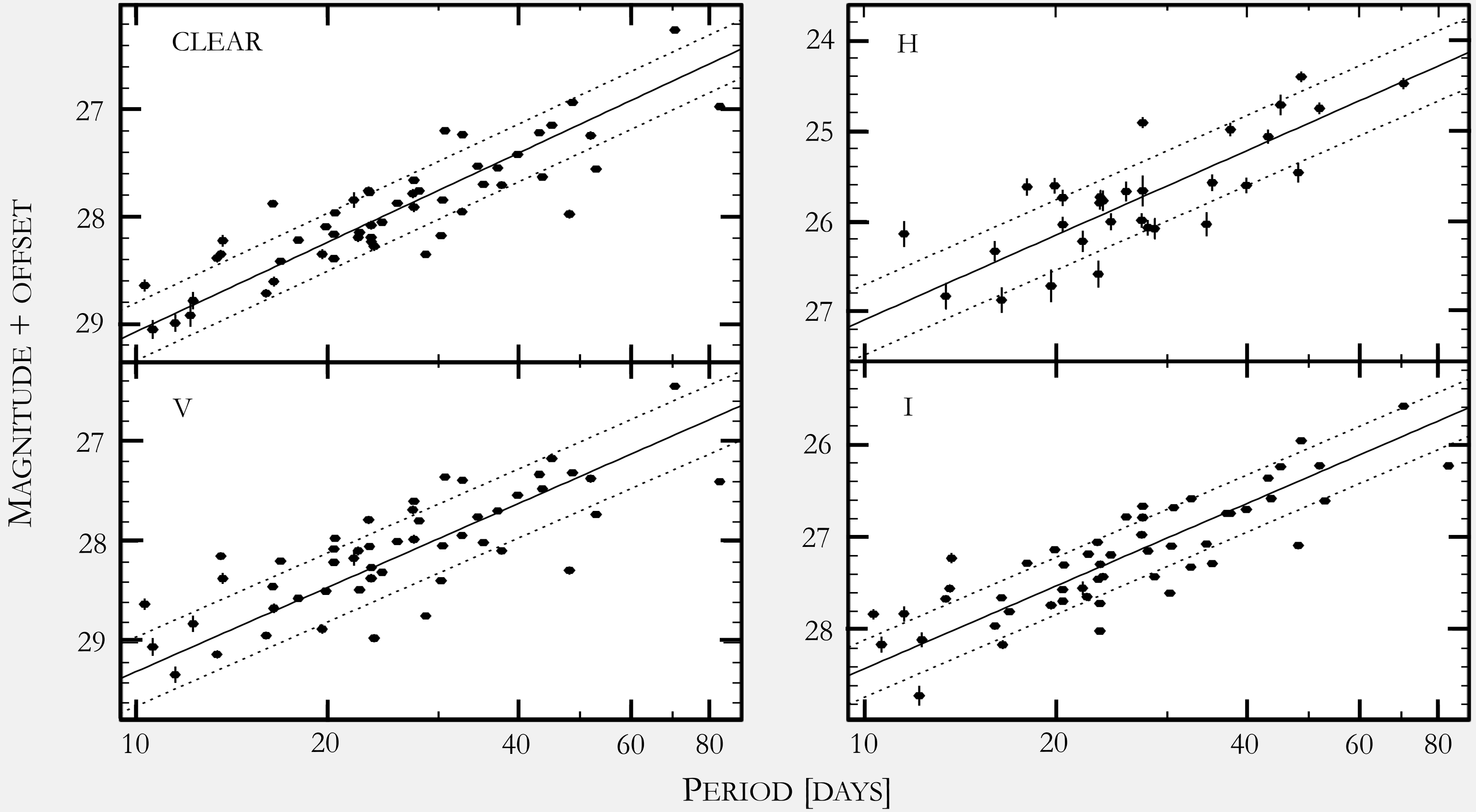


WFC3/IR F160W

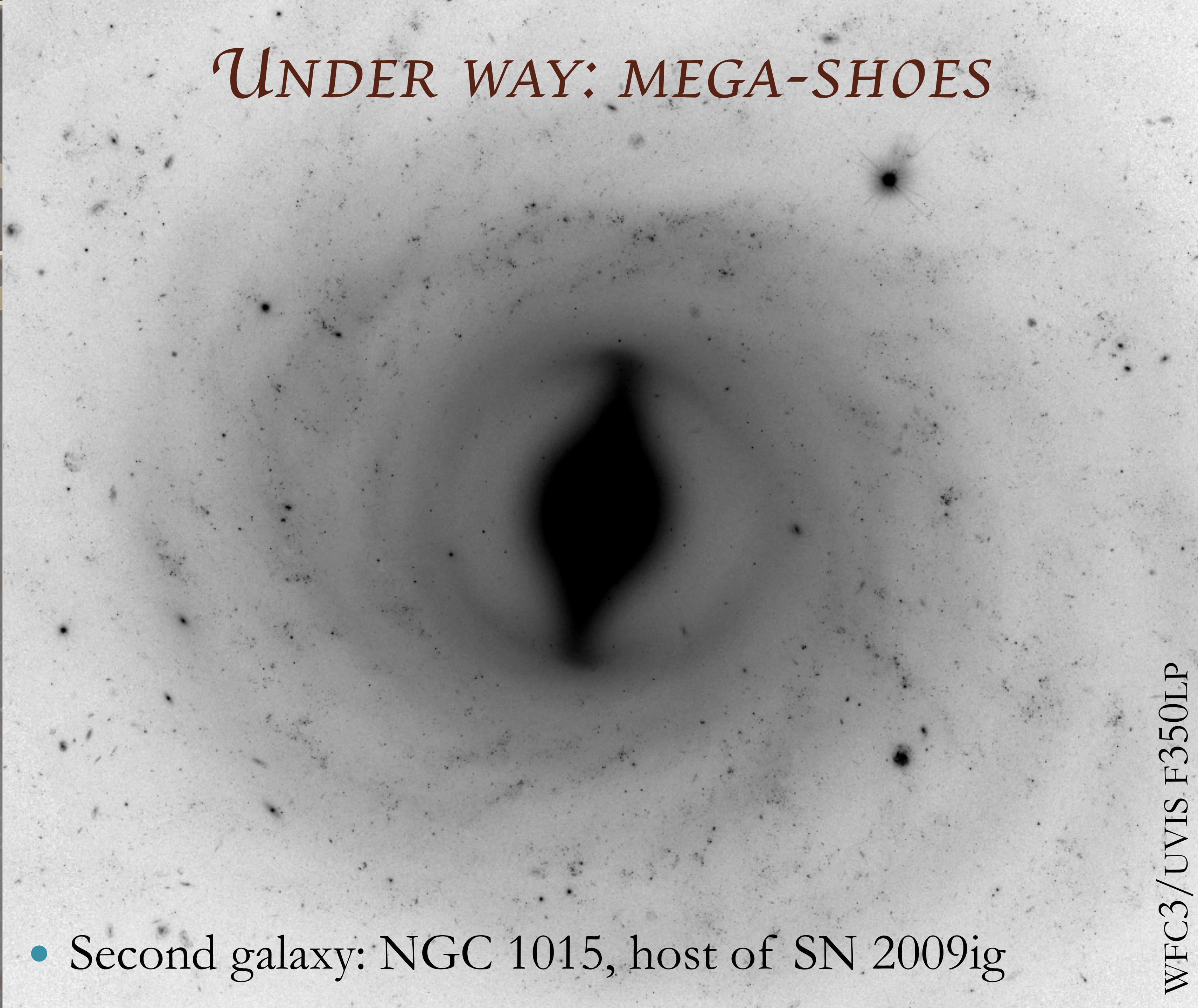


Under way: MEGA-SHOES

- Preliminary reduction of UGC 9391
  - ~30 Cepheids with 10≤P≤80; μ_0~33.2 mag (D~53 Mpc)
  - Most distant Cepheid P-L relation to date



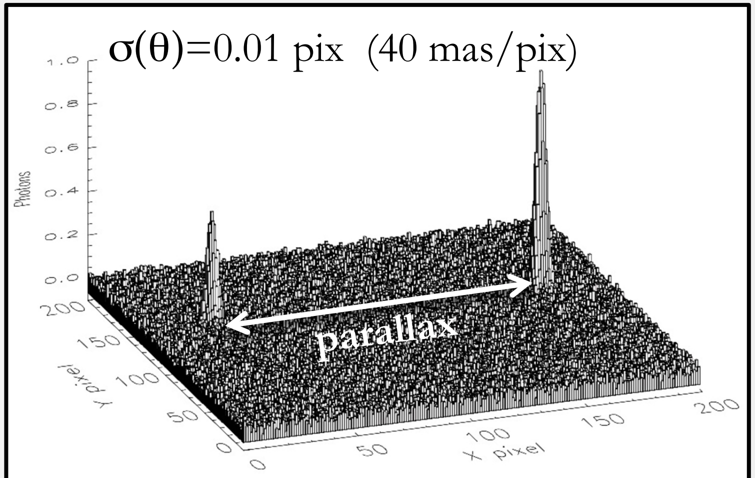
Under way: mega-SHOES

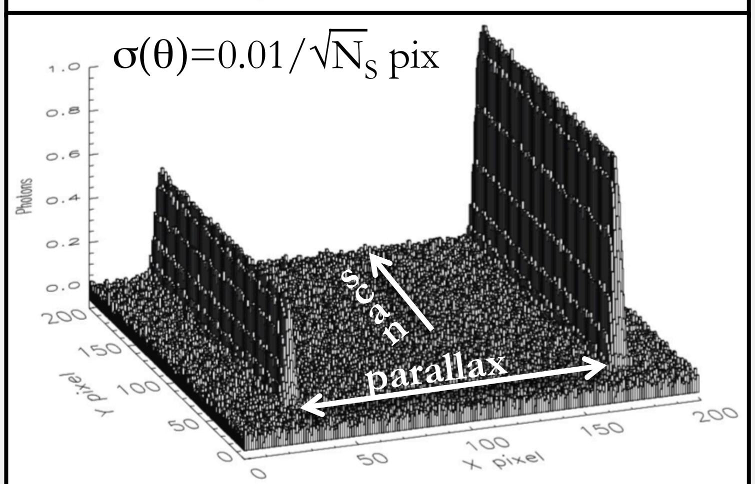


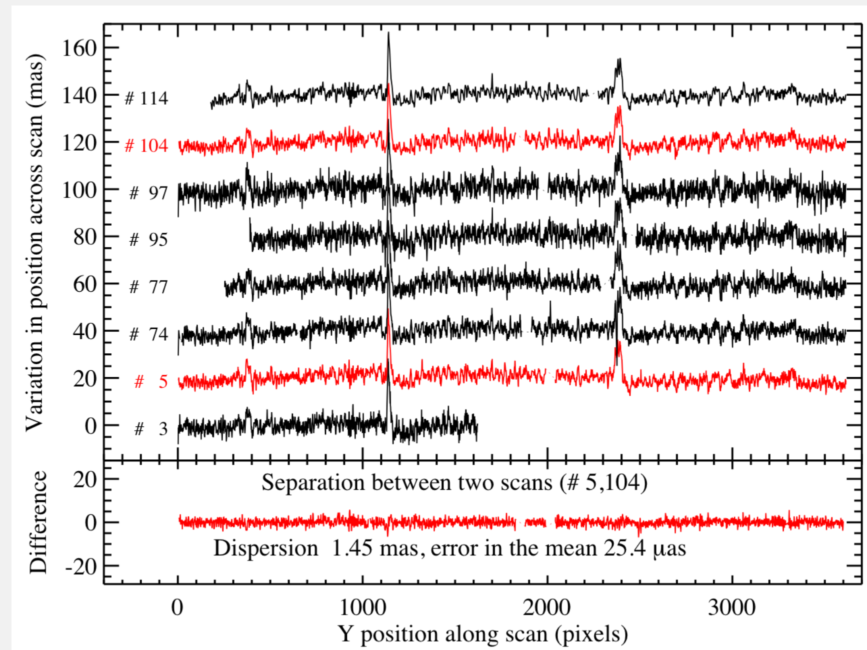
- Second galaxy: NGC 1015, host of SN 2009ig

Precision Astrometry with wfc3-uvis Spatial Scanning

Riess, Casertano, MacKenty & Anderson (STScI)







Jitter between lines is *coherent*,
subtracted in line separations

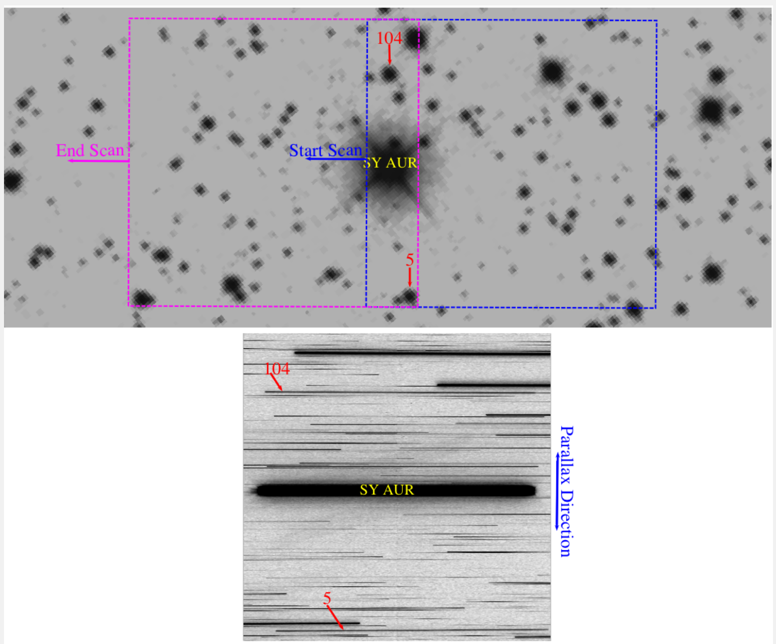
Astrometric precision of 30-80 µas

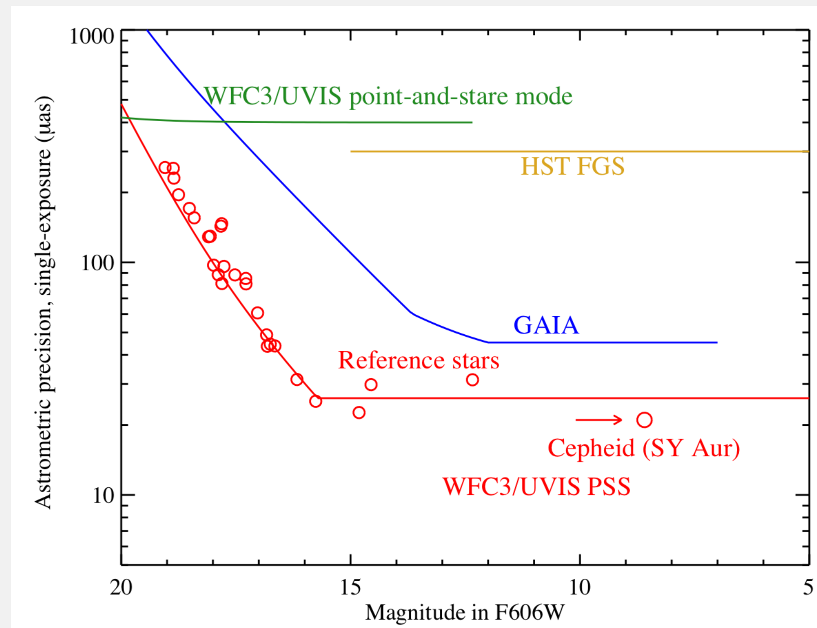
Material courtesy of Adam Riess

Precision Astrometry with WFC3-UVIS Spatial Scanning

Riess, Casertano, MacKenty & Anderson (STScI)

Cepheid SY Aur @ 2.3 kpc





Material courtesy of Adam Riess

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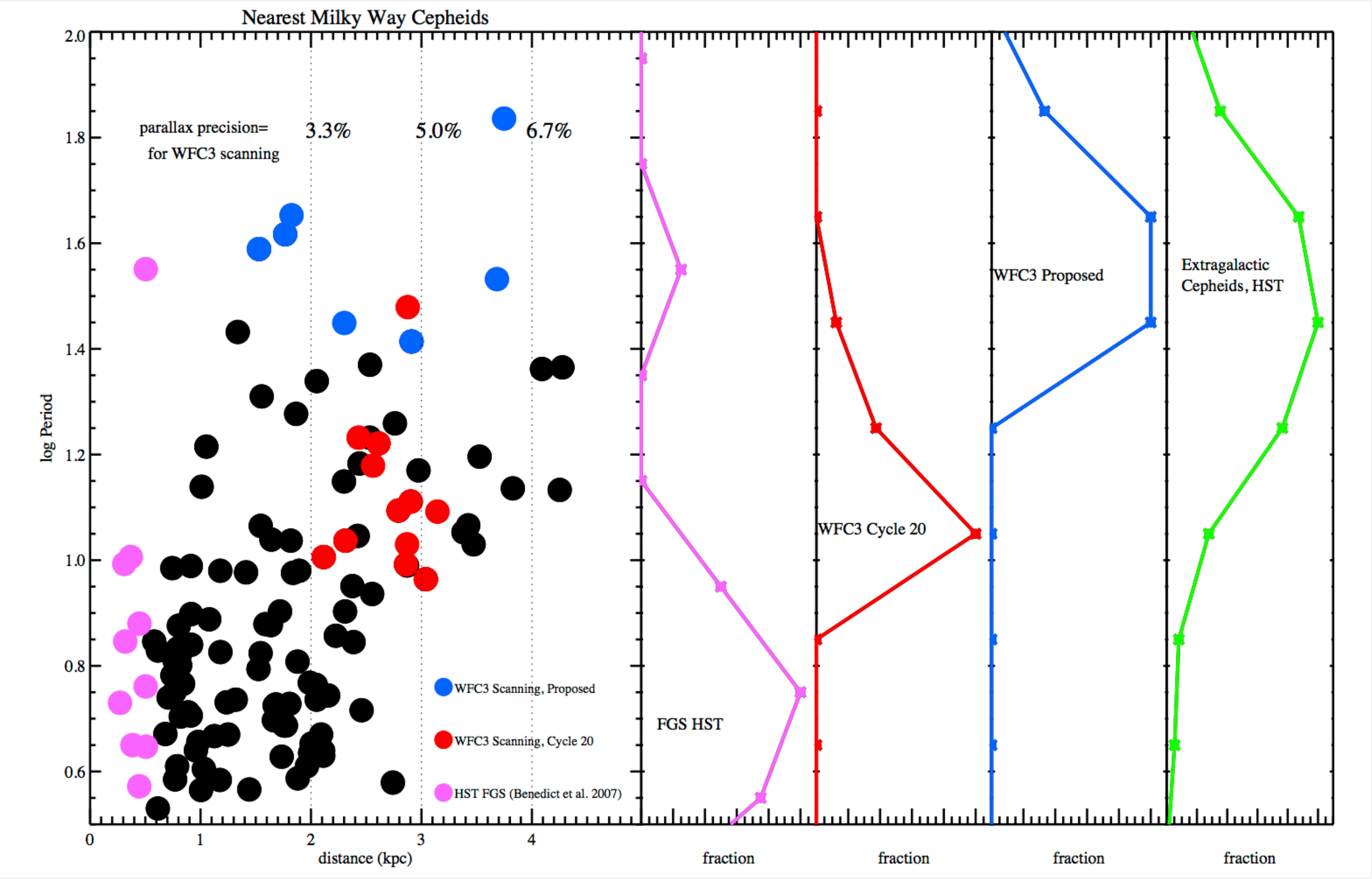

Material courtesy of Adam Riess

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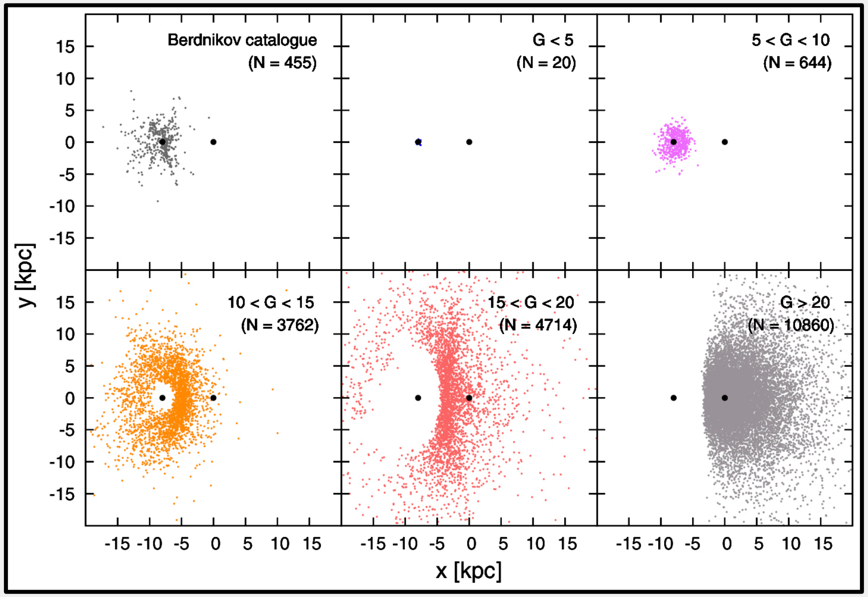
- ➢ The future…

Gaia parallaxes to MW Cepheids by end of mission (2020)

- Cepheid population of Milky Way:
  - $N_{TOT} \sim 20{,}000$; $N_{Gaia} \sim 9{,}000$
- Uncertainties in P-L parameters:
  - Slope: 0.1-0.2%
  - Zeropoint: 0.3-0.6%
    - High-end values for $\sigma\,(A_V)=0.05$ mag



Windmark, Lindegren & Hobbs (2011)

Gaia calibration of P-L relation by end of mission (2020)

- Milky Way: N~9000 Cepheids, <1% uncertainty
- LMC: ensemble parallax with 1% uncertainty
- Avoid systematic uncertainties in photometry
  - Observe from space (Spitzer, HST, WFIRST, JWST)
  - Approved HST Cycle 21 "snapshot" program: 60 Cepheids with P > 8d & D < 7 kpc

Regarding Planck's H_0

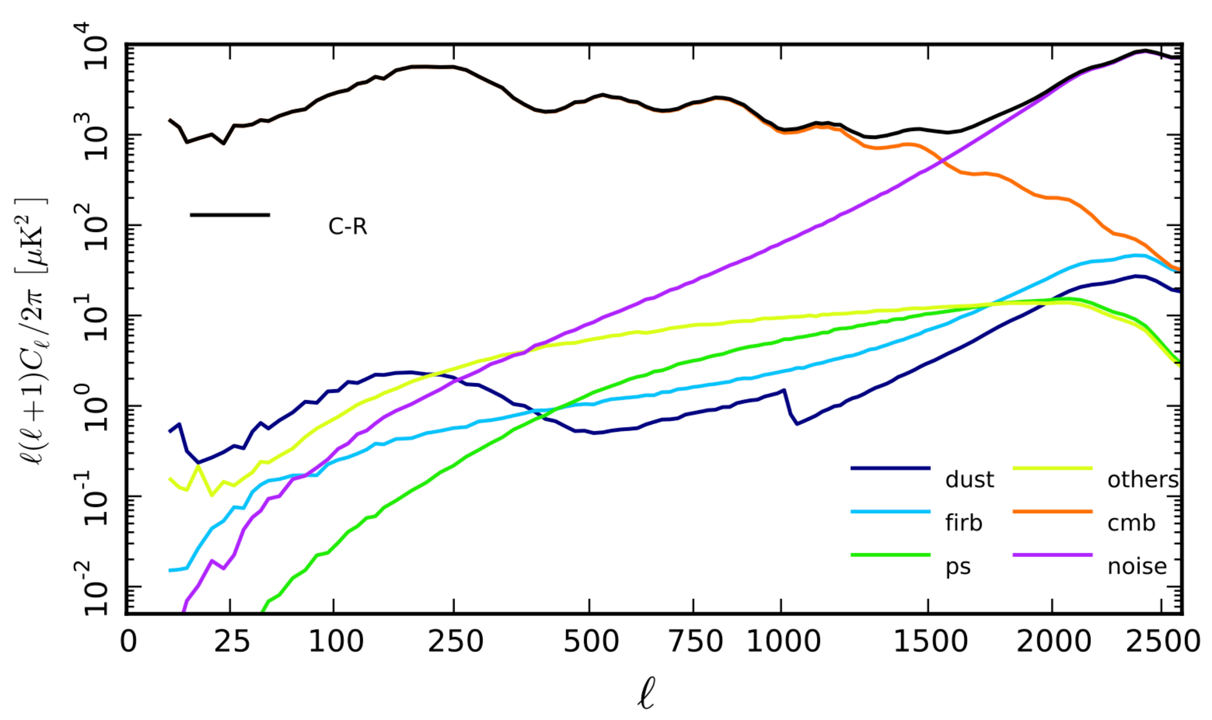
- From Planck collaboration, Paper XVI:

> We find the 2% constraint on H_0:
>
> $$H_0 = (67.4 \pm 1.4)\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \quad (68\%;\ \mathit{Planck}). \tag{13}$$
>
> [...]
>
> Note that these indirect constraints are highly model dependent. The data only measure accurately the acoustic scale, and the relation to underlying expansion parameters (e.g., via the angular-diameter distance) depends on the assumed cosmology, including the shape of the primordial fluctuation spectrum. Even small changes in model assumptions can change H_0 noticeably;

- Highly model dependent – not only on cosmological model but also on <u>foreground subtraction</u>

Regarding Planck's H_0

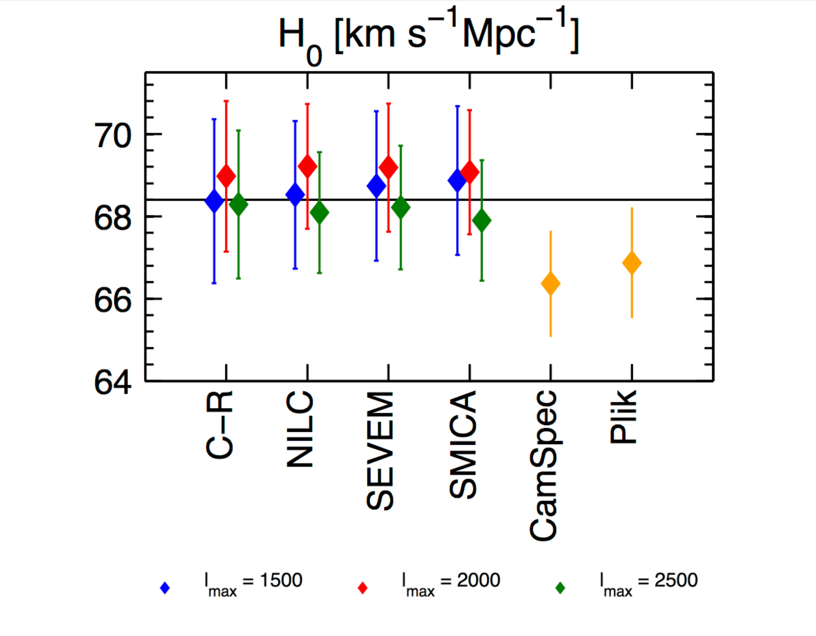
- From Planck collaboration, Paper XII, Figure E.3:



- Foreground at l>1500 very significant wrt CMB signal

Regarding Planck's H_0

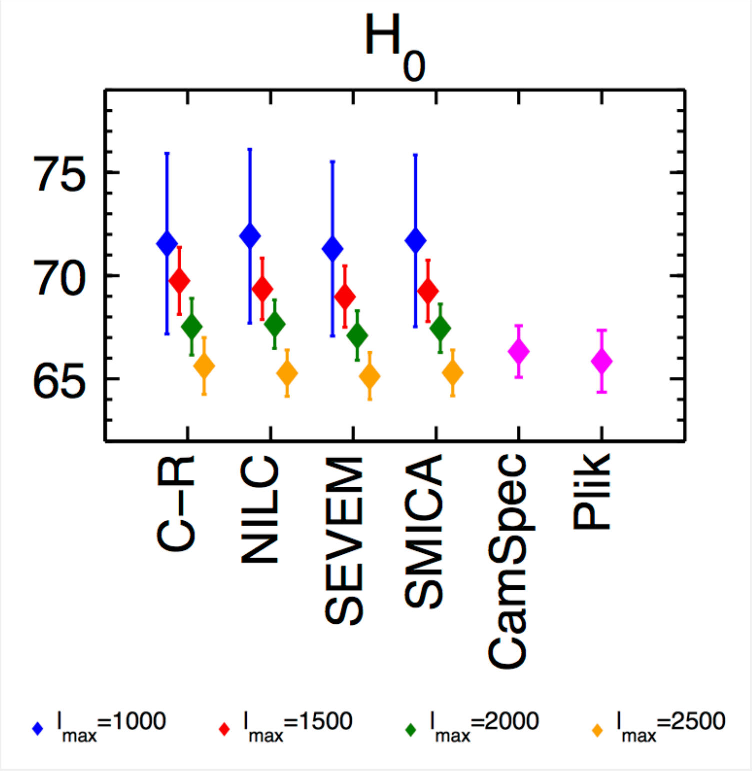
- Foreground correction should not bias the inferred value of H_0…



- Expectation from simulations (Planck XII, Fig E.5)

Regarding Planck's H_0

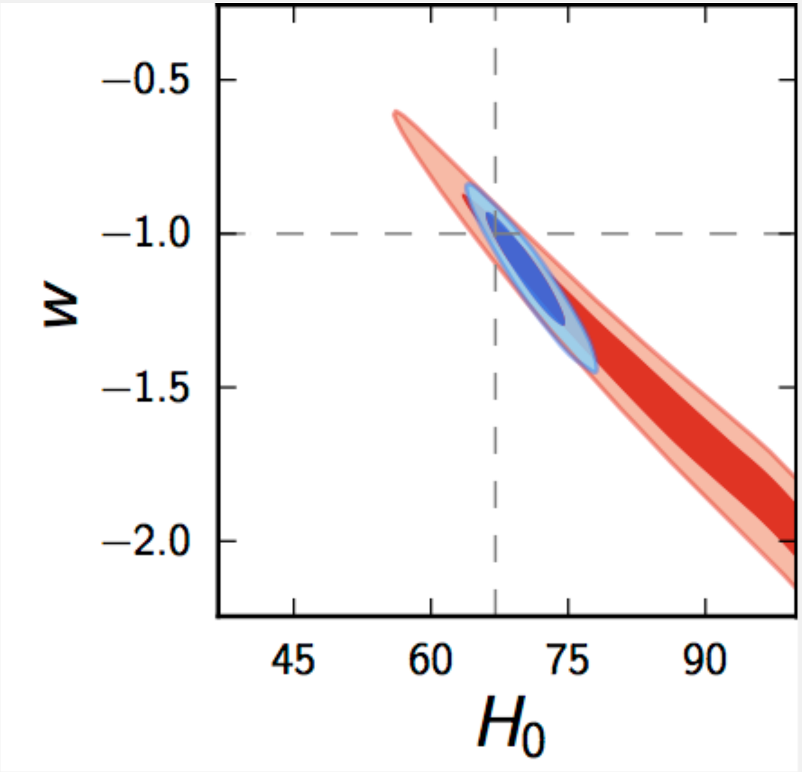
- But there is a clear correlation between the inferred value of H_0 and the maximum value of l considered



- Results of current analysis (Planck XV, Fig 30)

Regarding Planck's H_0

- Or perhaps the Universe is even more puzzling than we thought… w<-1?



- Cosmological parameters (Planck XVI, Fig 21)

Summary

- A precise and accurate measurement of H_0 imposes needed additional constraints on the equation of state of dark energy

- SH_0ES project: calibration of recent SNe Ia using Cepheids in the near-infrared
  - $H_0=73.8\pm2.4$ km/s Mpc $\rightarrow \sigma(H_0)=3.3\%$

- Long-term goal: $\sigma(H_0)=1\%$
  - *HST, Gaia* parallaxes to Milky Way & LMC Cepheids
  - Calibration of additional local SNe Ia
  - Better characterization of systematic uncertainties

Munich Institute for Astro- and Particle Physics

ABOUT MIAPP

The **Munich Institute for Astro- and Particle Physics (MIAPP)** hosts several topical workshops in astrophysics, cosmology, nuclear- and particle physics per year. Each workshop lasts up to four weeks and serves as a center for scientific exchange. MIAPP workshops include seminars, organized by the coordinators of the workshop, and provide a stimulating platform for informal discussions, collaborations and creative thinking. For every workshop about 30 international scientists will be invited to attend together with Munich-based researchers. A minimum stay of two weeks is required. External researchers receive financial support to participate in the workshops.

The institute is part of the Excellence Cluster „Universe" and is embedded in the academic environment of the physics departments of both Munich universities, the local Max Planck Institutes and the European Southern Observatory (ESO). It is located at Garching Research Campus.

WORKSHOPS

26 May – 20 June 2014
The Extragalactic Distance Scale
Registration

30 June – 25 July 2014
Neutrinos in Astro- and Particle Physics
Registration

28 July – 22 Aug. 2014
Challenges, Innovations and Developments in Precision Calculations for the LHC
Registration

25 Aug. – 19 Sep. 2014
Cosmology after Planck
Registration