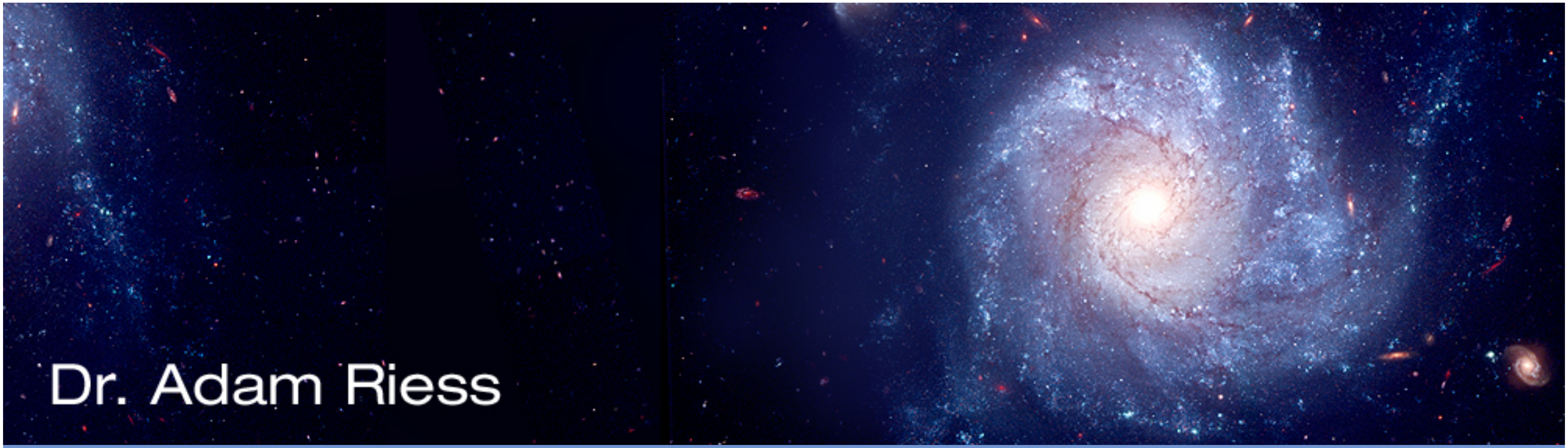


Dr. Adam Riess

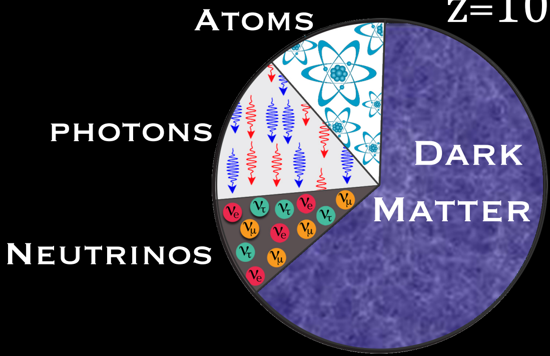
Johns Hopkins University
Space Telescope Science Institute

The Expansion of the Universe, Faster Than We Thought

Riess et al. 2019, ApJ, arXiv:1903.07603

Ultimate “End-to-end” test for ΛCDM, Predict and Measure H_0

Standard Model: (Vanilla) ΛCDM, 6 parameters + ansatz (w, N_{eff}, Ω_K, etc)



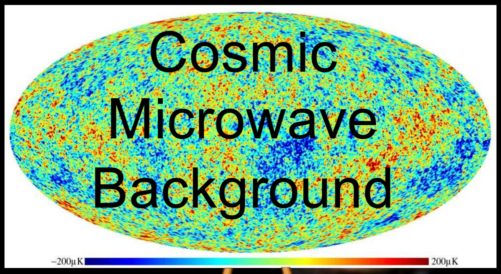
z=1000

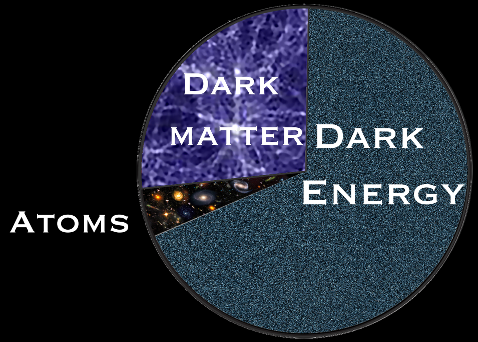
Predict physical size fluctuations, r_s, Ω_B

Measure angular fluctuations (or Ω_B)

Calibrate ΛCDM …

Big Bang

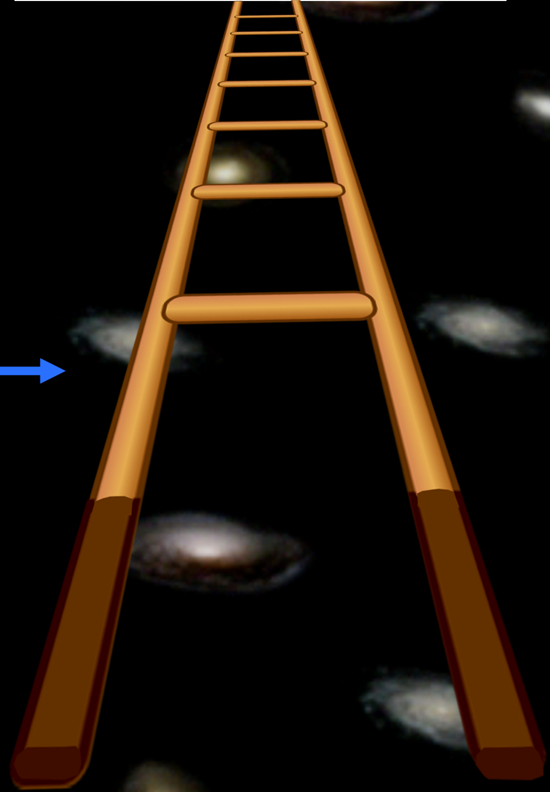


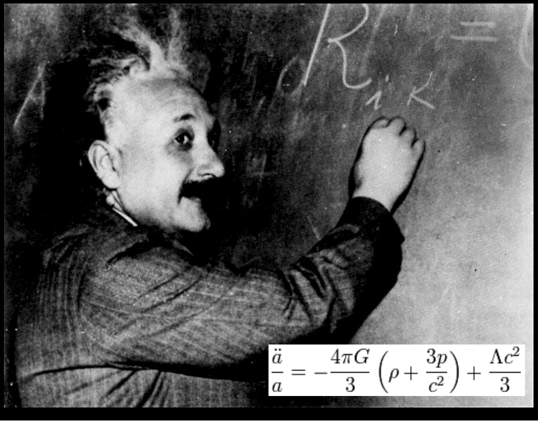


Now

Expansion history predicted

(“guard rails”, BAO, SNe)





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

Planck Predicted, H_0=67.4+/-0.5 km/s/Mpc

A Direct, Local Measurement of H_0 to percent precision

The SH_0ES Project (2005)

(Supernovae, H_0 for the dark energy Equation of State)

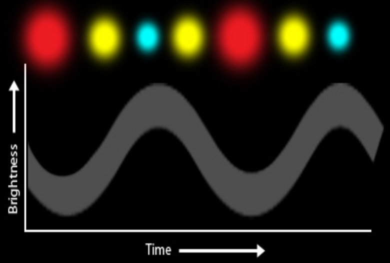
A. Riess, L. Macri, S. Casertano, D. Scolnic, A. Filippenko, W. Yuan, S. Hoffman, et al

Measure H_0 to percent precision empirically by:

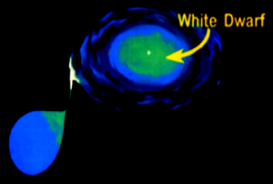
- A strong, simple ladder: Geometry → Cepheids → SNe Ia

Multiple ways

Pulsating Stars,
$10^5 L_\odot$, P-L relation



Exploding Stars,
$10^9 L_\odot$, $\sigma \sim 5\%$

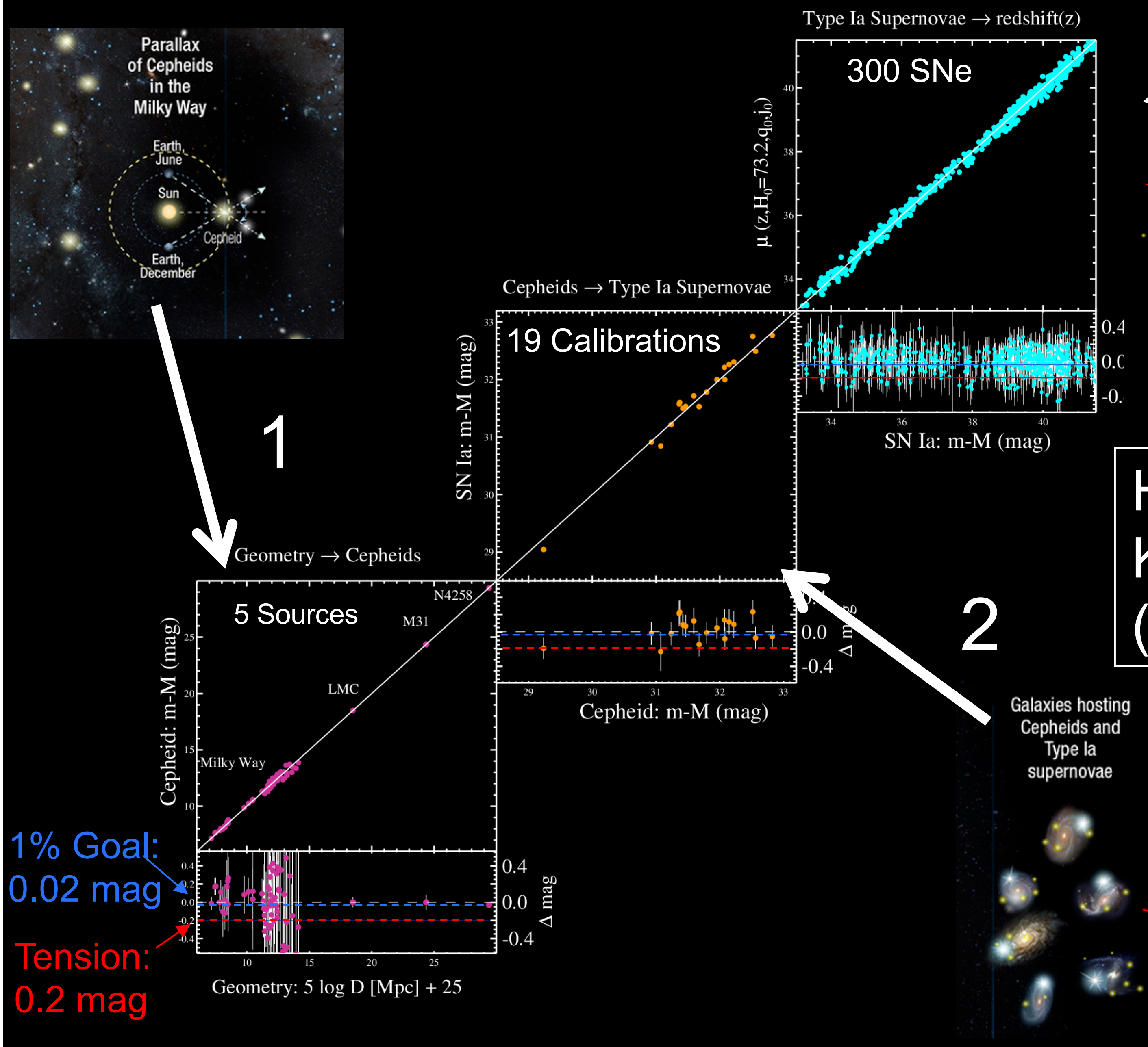


An explosion resulting from the thermonuclear detonation of a White Dwarf Star.

- Reduce systematics w/ consistent data along ladder and NIR

- Thorough propagation of statistical and systematic errors

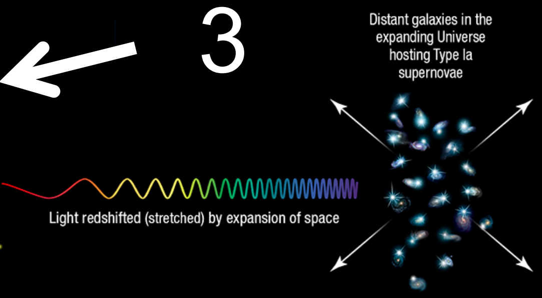
The Hubble Constant in 3 Steps: Present Data



1% Goal: 0.02 mag

Tension: 0.2 mag

3



$$5\log H_0 = M_B^0 + 5a_B + 25$$

$H_0 = 74.0 \pm 1.4$, Km s^{-1} Mpc^{-1} (Riess et al. 2019)

1.9% total uncertainty

4.4σ from CMB + ΛCDM !

Step 1: Geometric Distances to Cepheid Luminosities

1) Geometric distances and 2) *Consistent* Cepheid Measurements

Geometric Distances-5 Sources at <3%-
  MW Parallaxes: 3 types HST FGS, Scanning, Gaia
  LMC DEBs and Masers in NGC 4258
  See Talks by Brown, Reid, Pietrynzski, Casertano, Chan

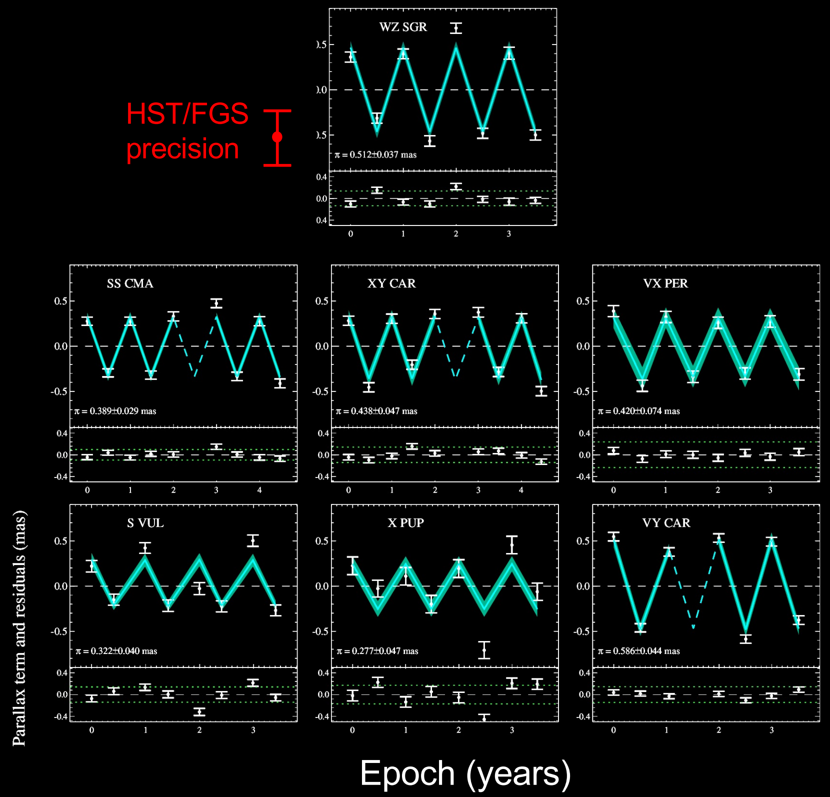
Consistent (along the distance ladder) Cepheid Measurements—

Measuring Cepheid Photometry between magnitudes:
6-8 (MW), 13 (LMC), 23 (NGC 4258) and 24-26 (SN Hosts)

Linearly, same photometric system (WFC3 V,I,H), same range of periods and metallicities

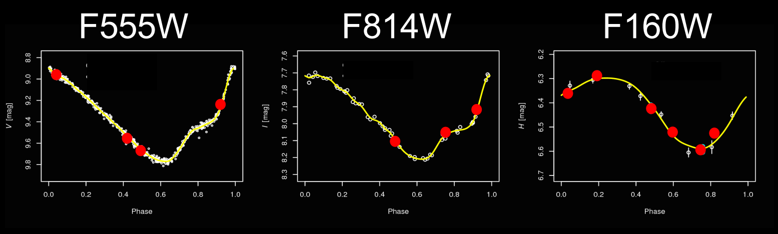
New Tool: WFC3 Spatial scanning for long range parallaxes, photometry

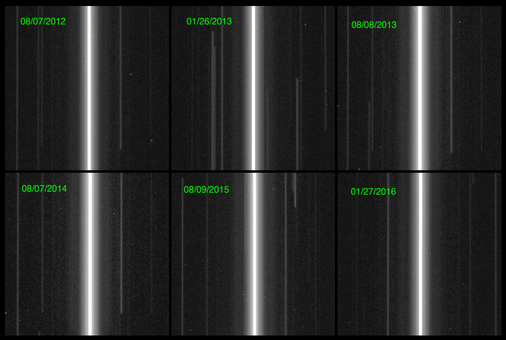
WFC3 Spatial Scanning→ 20-40 μas
4 Years Later: Proper Motion subtracted,
8 MW long-P Cepheid Parallaxes
1.7<D<3.6 Kpc, error in mean=3.3%



Riess et al. (2018a), ApJ, 855,136

50 *Benchmark* MW Cepheids all w/
HST Photometry, Long-Periods
A “photometric bridge” for Gaia



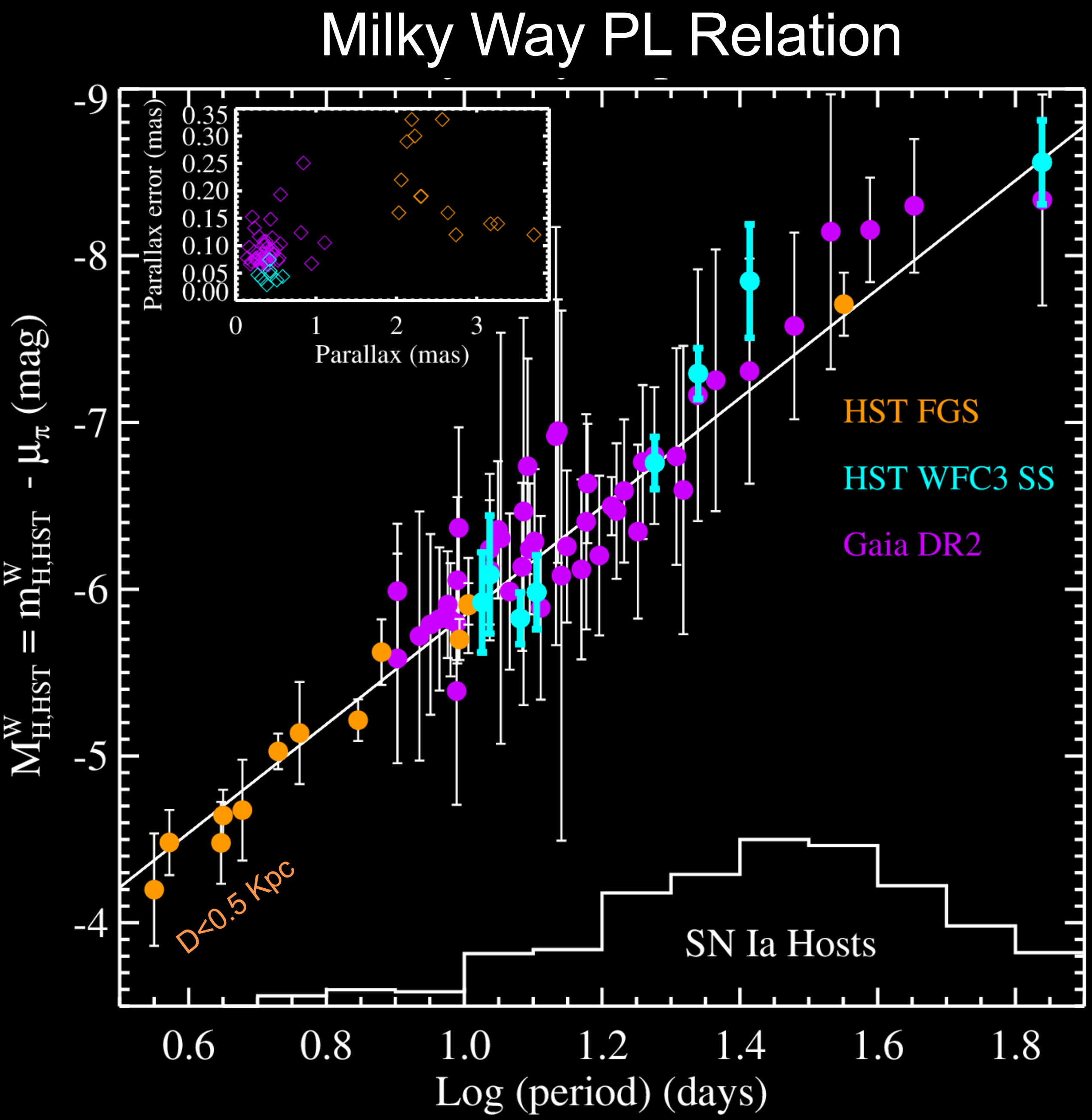


Fast Scans 7.5”/s exp time~0.01 sec
Error individual Cepheid mean D<1%

w/ Gaia DR2, error in mean=3.3%
Riess et al. (2018b), ApJ, 861, 126

More in Cycle 27 to help resolve Gaia
zeropoint, reach 1% distance calibration

Milky Way Cepheid P-L Relation, Now w/ HST photometry, Long Periods



Final Gaia Parallaxes + HST Photometry→ H_0~0.4%!

}

Periods > 10 days matching Cepheids HST sees in SN Ia hosts

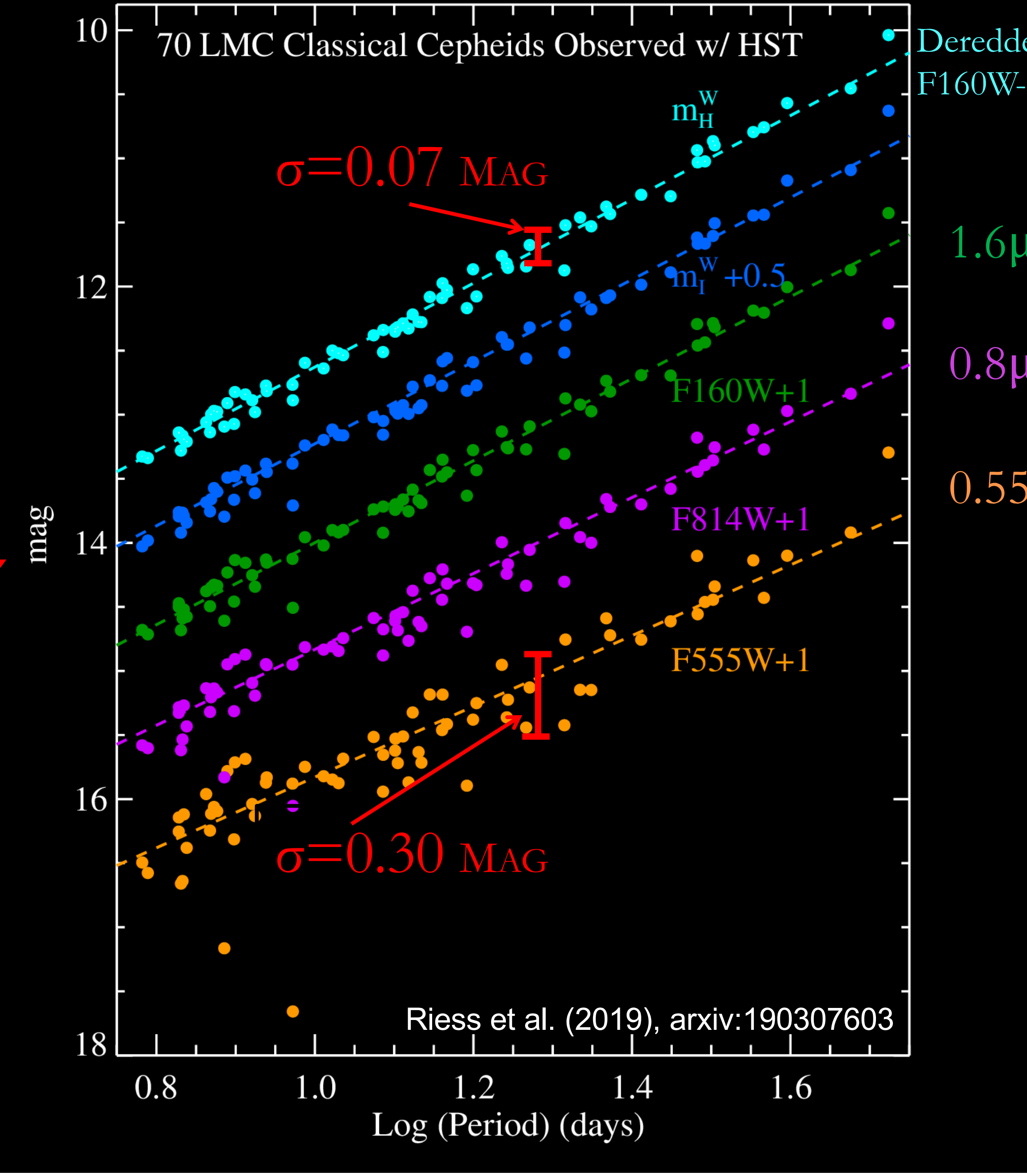
Observing 70 long P Cepheids *Directly* with HST WFC3 in LMC (w/ 1.2% DEB Distance)

-Negligible sensitivity to metallicity in NIR (F160W)

-Dependence on reddening laws 6x smaller than optical

We use F160W-band as primary +F555W,F814W

Key Project used F555W and F814W

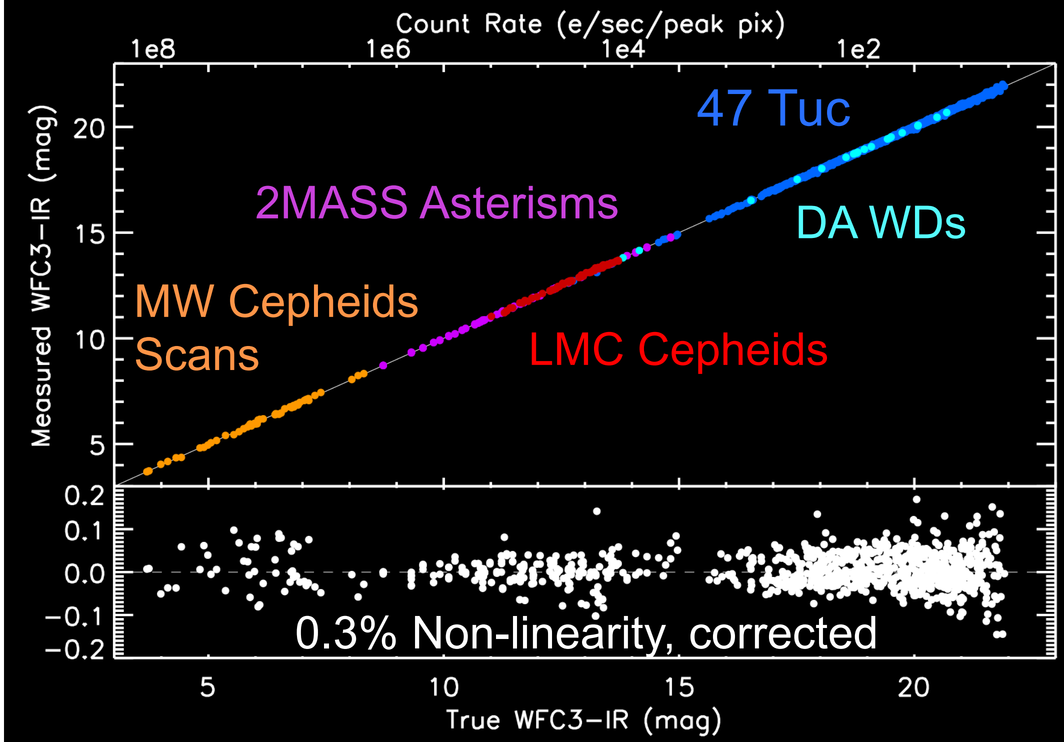


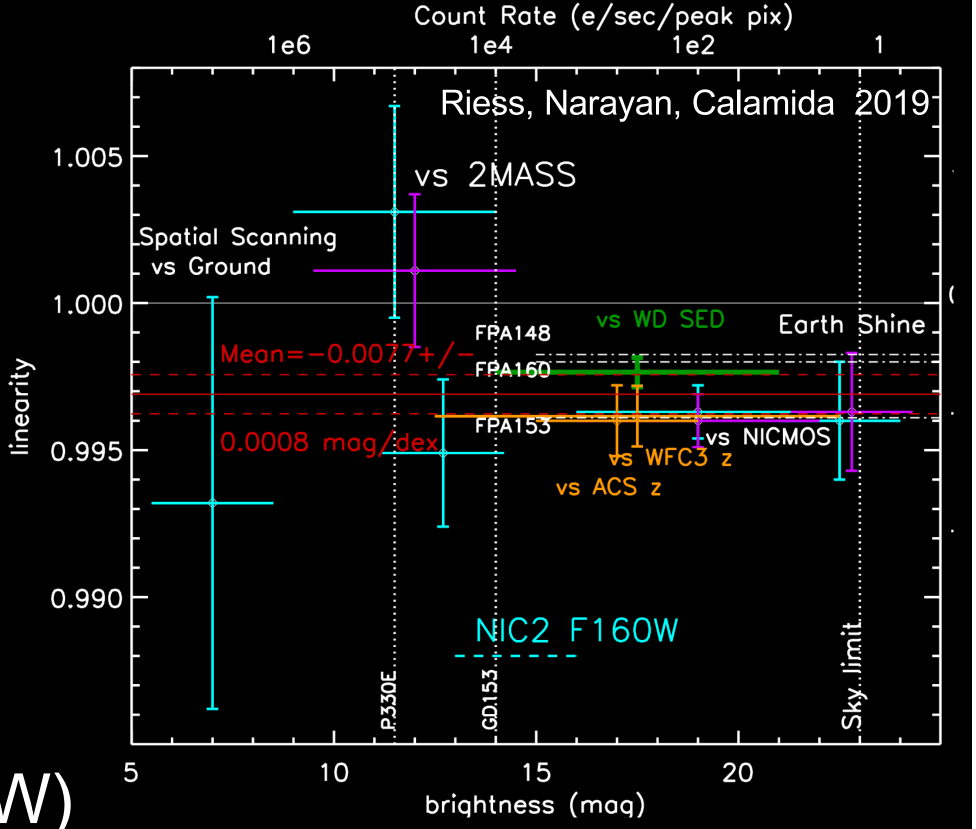
Riess et al. (2019), arxiv:190307603

Leavitt

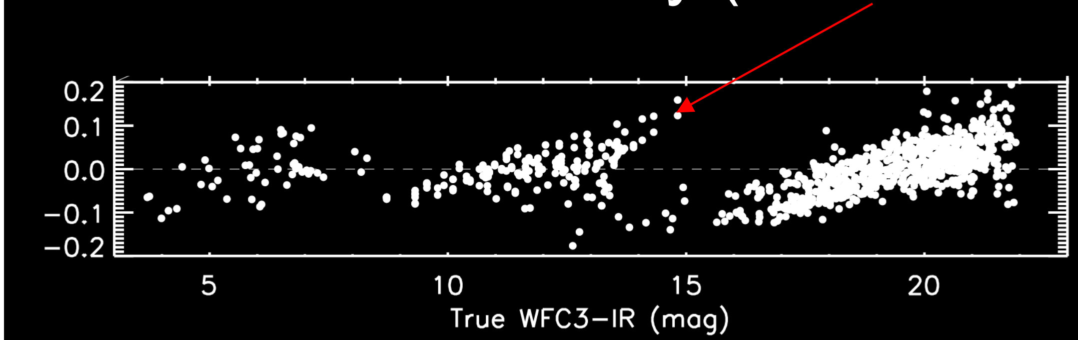
New: HST WFC3-IR Flux Scale calibrated to support 1% H_0

“Flux Calibration Ladder”





if 3.0% Non-linearity (NIC2 F110W)



Cepheids: MW→ SN hosts,
σ =7 dex * 0.0008 mag/dex
=0.006 mag → 0.3% in H_0

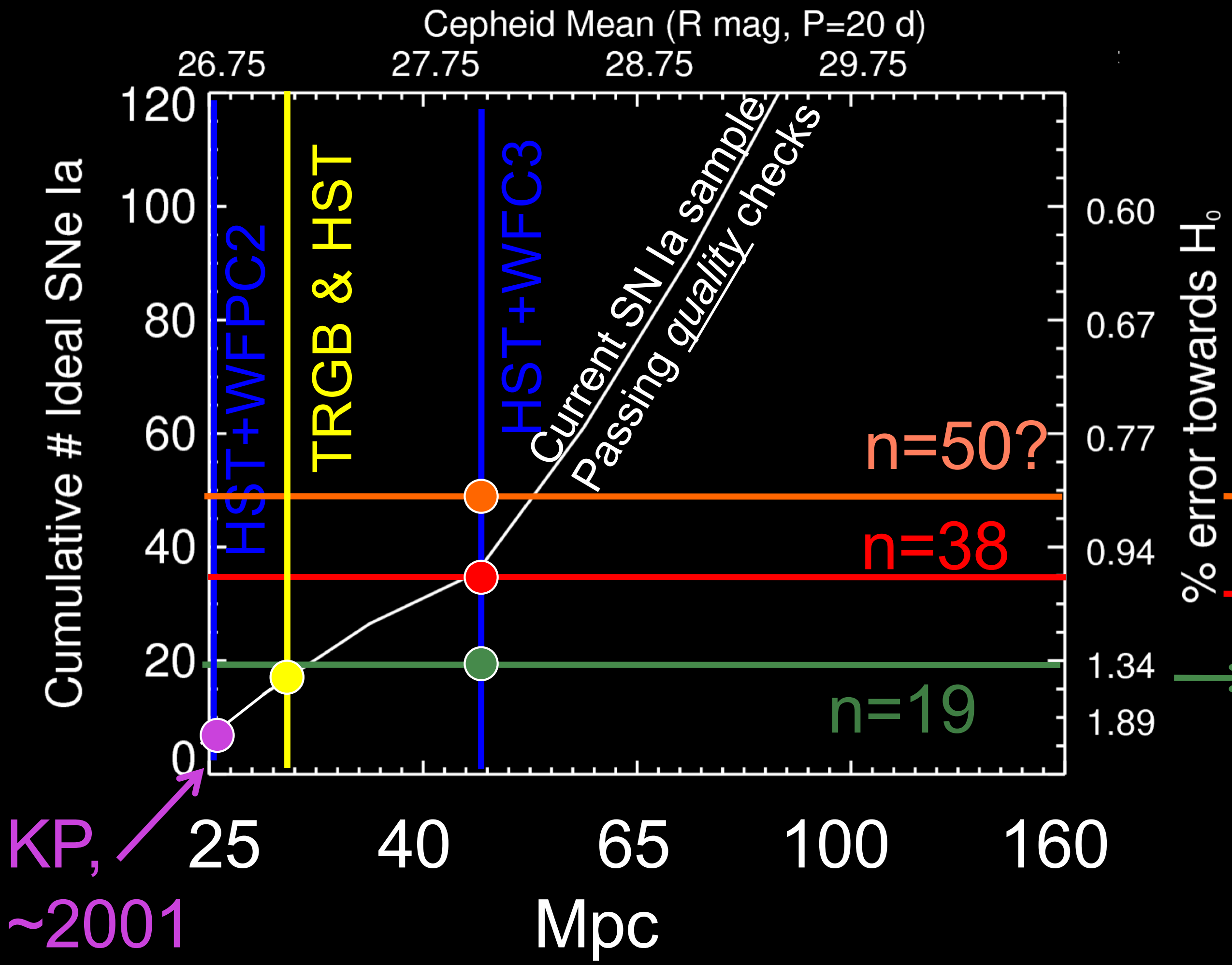
Robust? Five Sources of Cepheid Geometric Calibration

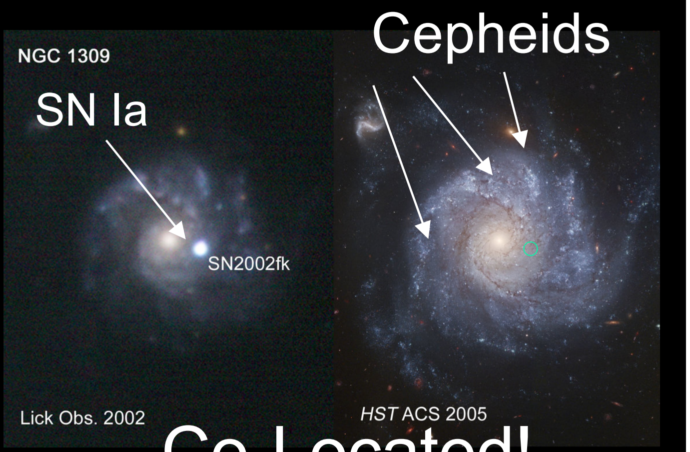
	Independent Geometric Source	**σ**	**H_0**
	NGC 4258 H_20 Masers: Humphreys et al 2013, Riess et al 2016 Reid et al. (2019) in prep	~~2.6%~~ 1.5%	~~72.3~~ ~72.0
NEWER	LMC 20 Late Detached Eclipsing Binaries: Pietzrynski et al. 2019 +70 HST LMC Cepheids Riess et al (2019)	1.3%	74.2
	Milky Way 10 HST FGS Short P Parallaxes: Benedict et al. 2007 --also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2
NEW	Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess et al. 2018	3.3%	75.7
NEW	Milky Way 50 Gaia+HST, Long P Parallaxes: Riess et al. 2018	3.3%	73.7

Consistent Results (1.4σ), *Independent Systematics*

Step 2: Cepheids to Type Ia Supernovae

This is the H_0-Limiting Step: Number of SN Ia in Cepheid Range





Co-Located!

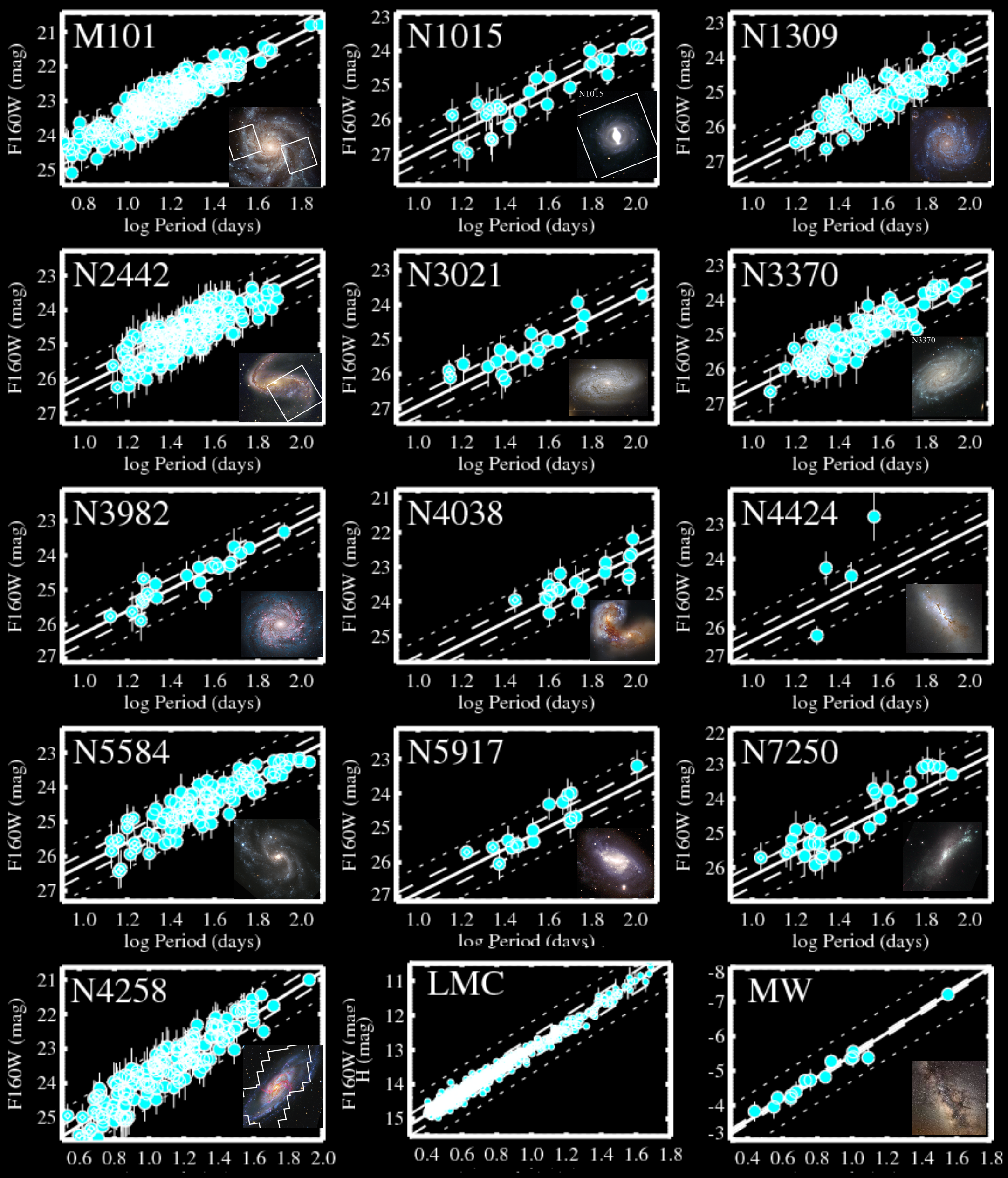
→ **HST Final? (0.8%)**

→ Next (2019-2020, 0.9%)

→ Now (Riess et al. 2016,1.3%)

Cepheid V,I,H band Period-Luminosity Relationships: 19 hosts, 3 anchors

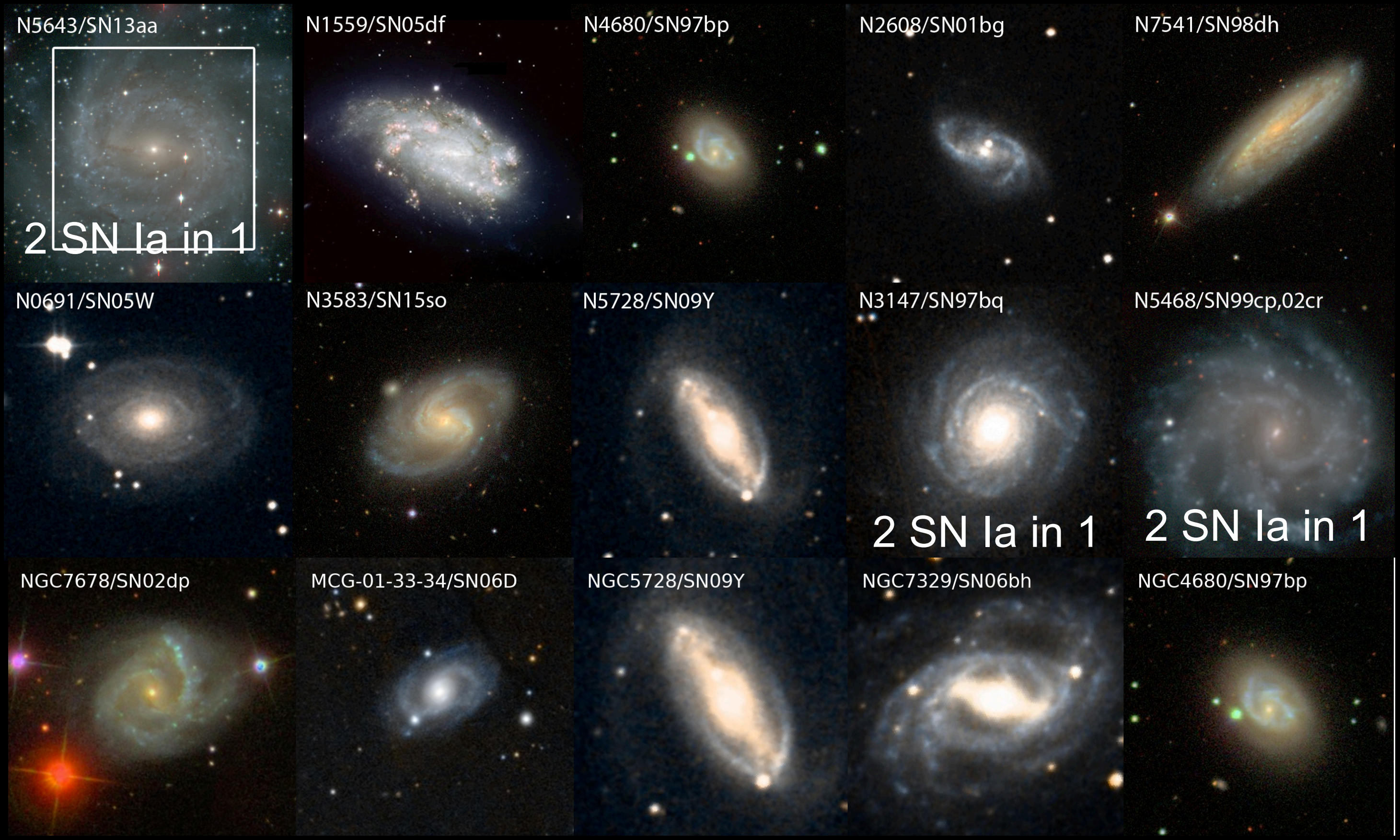
talk by Macri



3 Anchors

Next Steps: Increasing Number of SN-Cepheid Calibrations

NEW SHOES Large HST Programs, Cycles 25,26
19 more Cepheid-SN Ia Calibrators underway,
to reach total=38



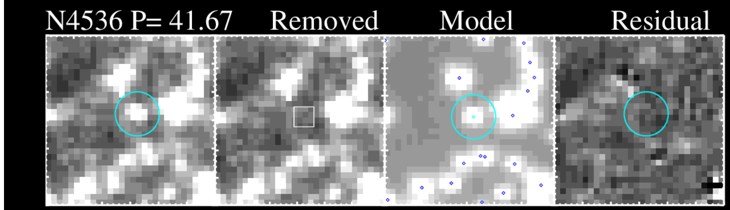
Measuring Extragalactic Cepheids with HST

All Cepheid photometry provided in R16, all pixels in MAST archive!

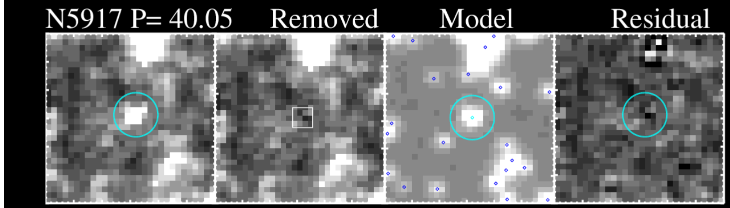
Standard Methods (DAO: Stetson 87) Fit Multi-source PSF, NIR Cepheid location known (“sky”, amp)

Measure background w/ <u>local fake stars,</u> remove bias (due to crowding/SBF), measure stat err. Fakes gaussian <u>log flux</u>

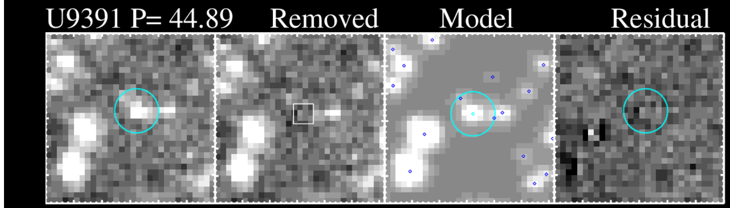
<u>Real PL scatter matches errors.</u>



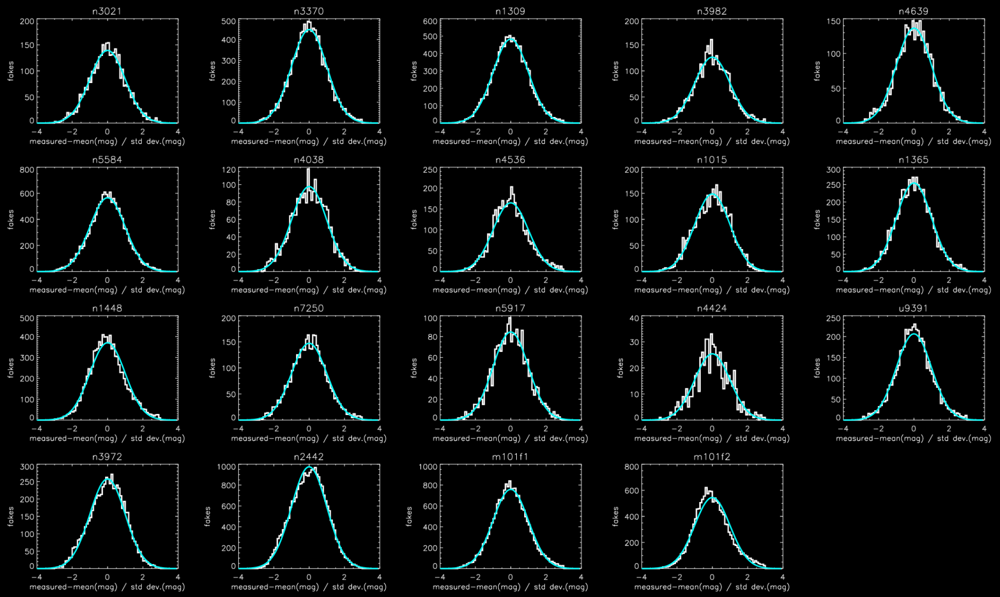
15 Mpc

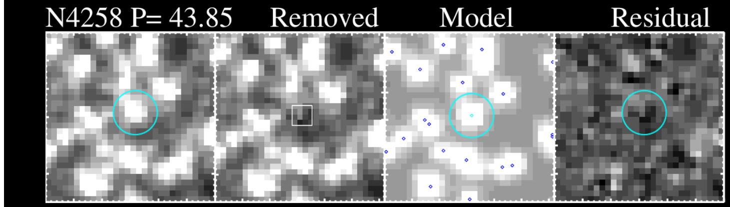


28 Mpc

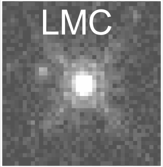


38 Mpc





7.5 Mpc (anchor)

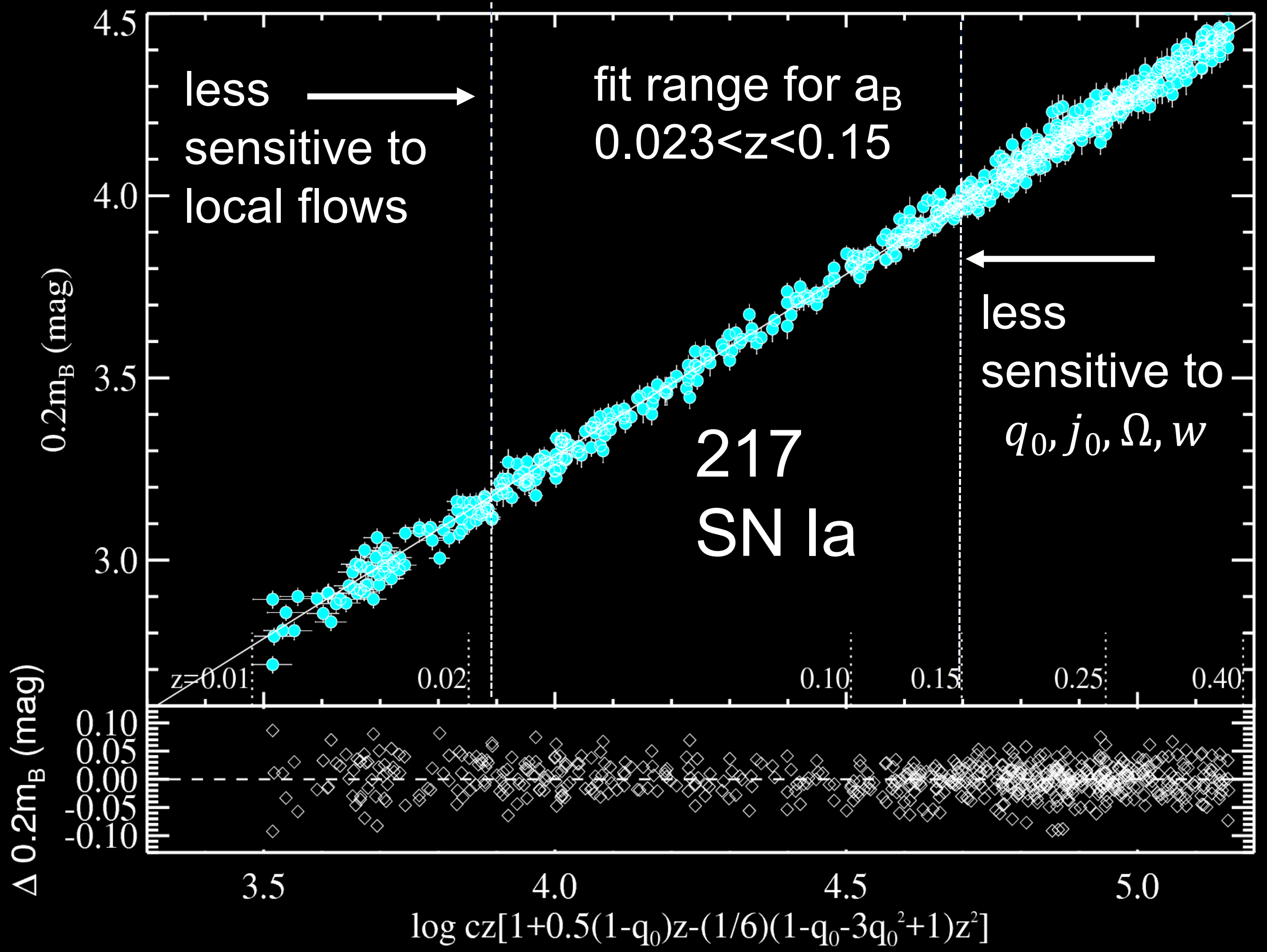


*associated stars are negligible, too dim (binaries) or too rare (open clusters; 3%); Anderson and Riess 2018

Step 3: Intercept of SN Ia Hubble Diagram: Distance vs Redshift
Talks by Scolnic, Jones, Rodney, Broudt!

$$a_B = \log cz\left\{1+\frac{1}{2}\left[1-q_0\right]z-\frac{1}{6}\left[1-q_0-3q_0^2+j_0\right]z^2+O(z^3)\right\} - 0.2m^0_B$$

Kinematic Intercept equation



less sensitive to local flows

fit range for a_B
$0.023<z<0.15$

217
SN Ia

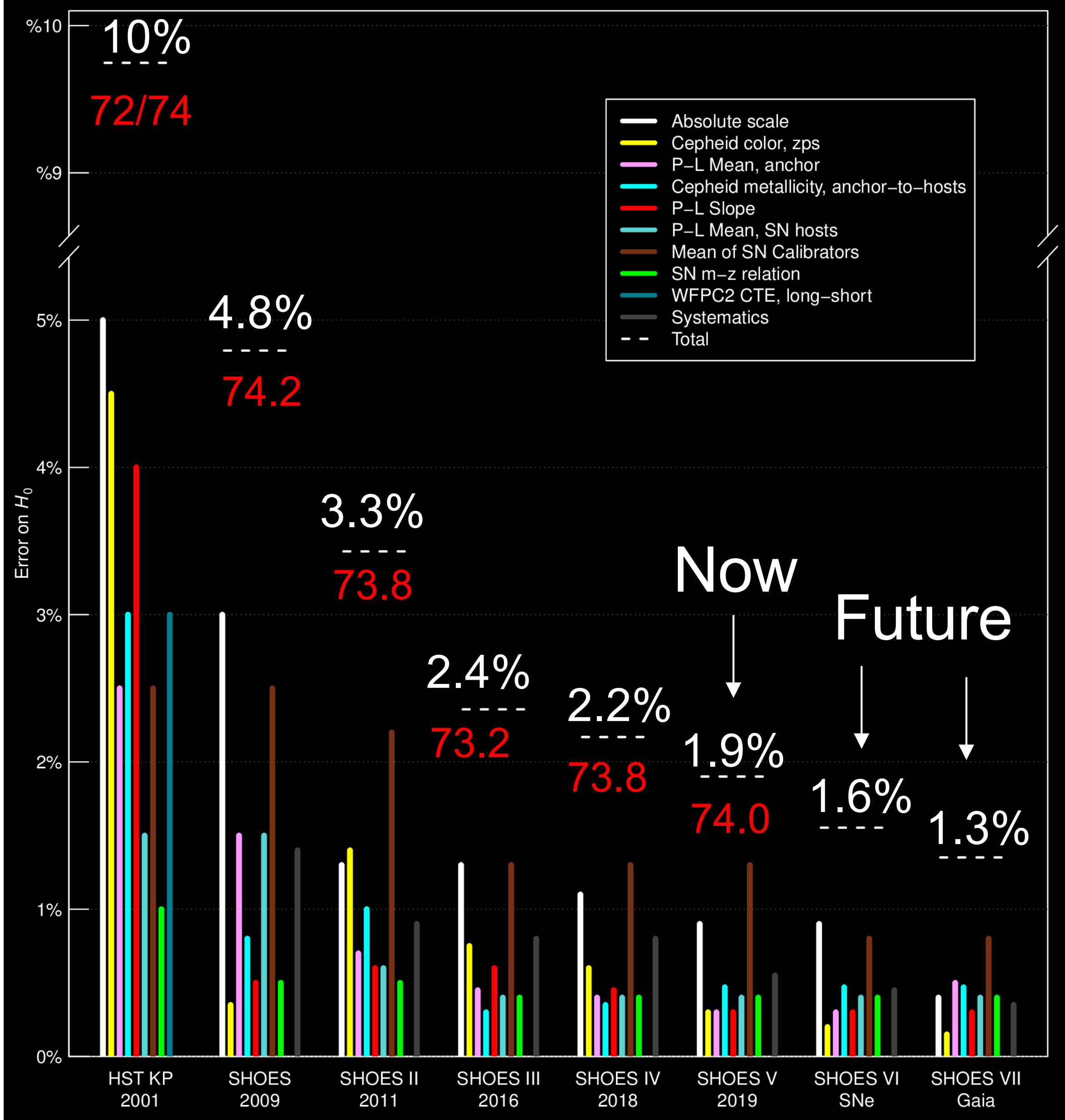
less sensitive to q_0, j_0, Ω, w

Systematics? 23 Analysis Variants—we propagate variation to error

Analysis Variants	**H_0**
Best Fit (R16, w/ HST,Gaia , R18=73.53)	74.03
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.89
Reddening Law: Bulge-like (N15)	74.40
No Cepheid Outlier Rejection (normally 2%)	74.32
No Correction for Cepheid Extinction	75.72
No Truncation for Incomplete Period Range	75.08
Metallicity Gradient: None (normally fit)	74.51
Period-Luminosity: Single Slope	74.34
Period-Luminosity: Restrict to P>10 days	74.24
Period-Luminosity: Restrict to P<60 days	74.60
Supernovae z>0.01 (normally z>0.023)	74.16
Supernova Fitter: MLCS (normally SALT)	75.91
Supernova Hosts: Spiral (usually all types)	74.14
Supernova Hosts: Locally Star Forming	74.32

Could a difference in SN calibrator & Hubble flow sample selection change H_0? No, (Jones et al. 2018) and talks by Scolnic, Jones

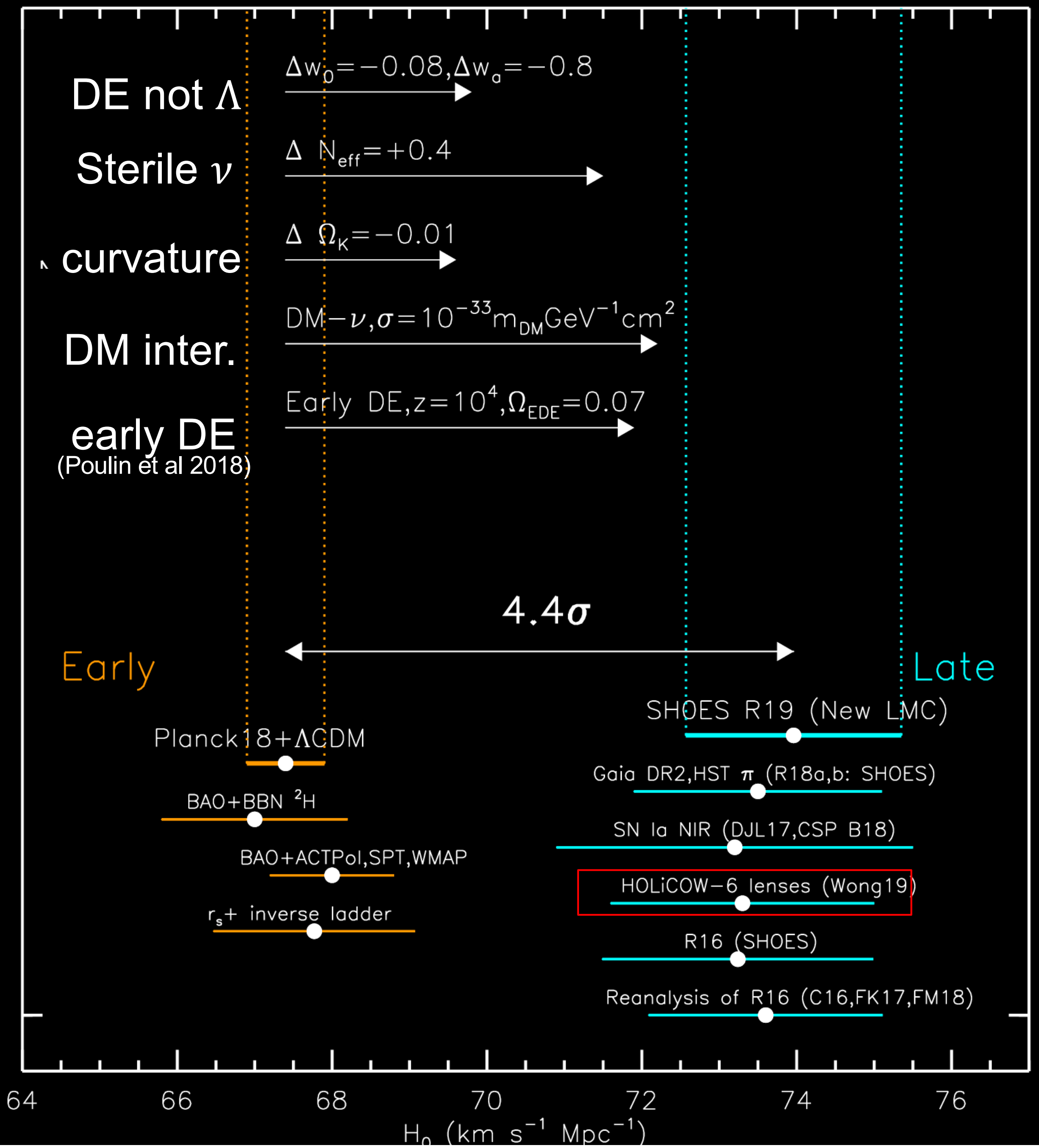
Holding Steady, Future Improvements



- **New low-z SN samples**
- **Doubling SN Calibrator sample, 19→38 (2019?)**
- **Gaia DR3 (2020?)**

H_0 : Measured Late vs. Predicted from Early Universe

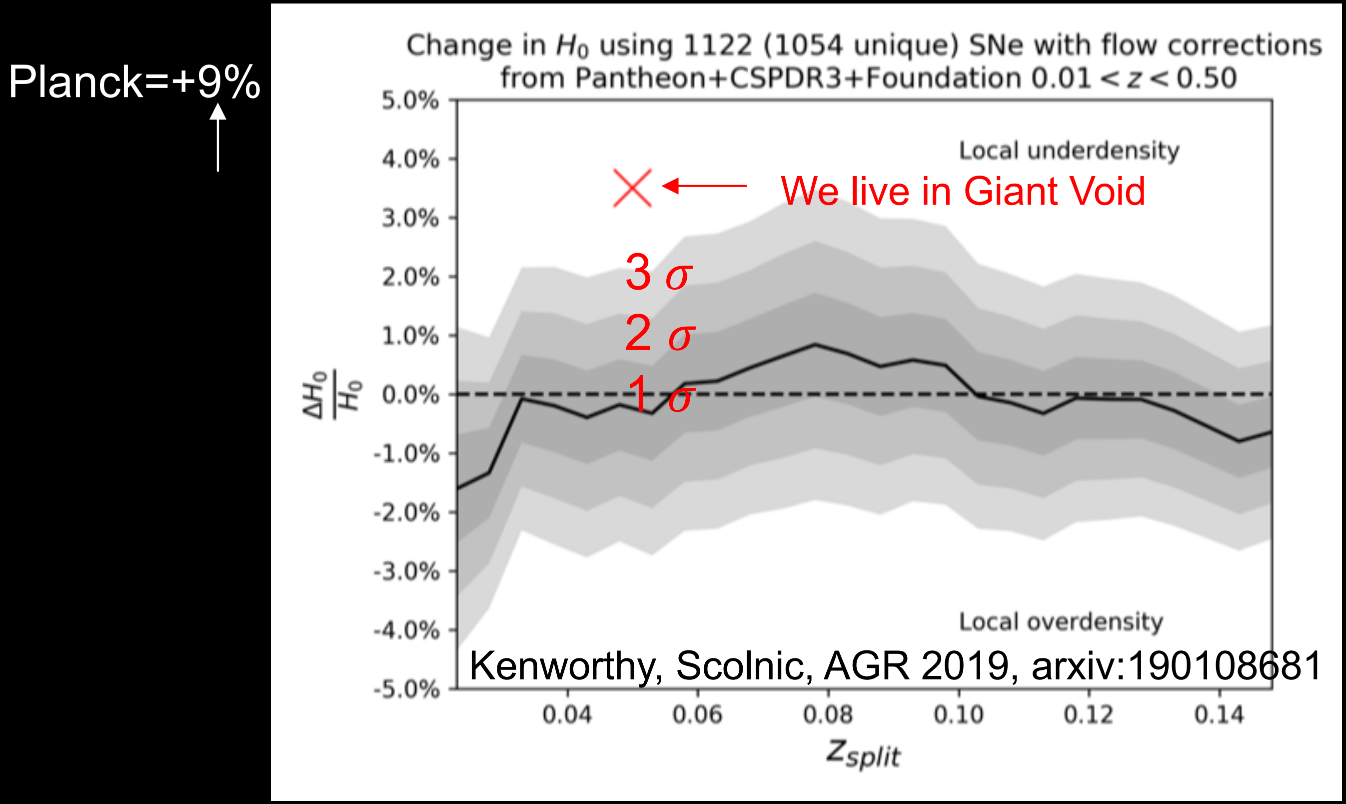
NEW PHYSICS



FAQ: Could we live in a giant (9% in H_0) void? No…to 0.6% in H_0

- We already correct for local motions from density field maps
- Theory: N-body sims in Gpc^3 box, SN, z → ΔH~0.4%

  Odderskov et al. (2016) and Wu & Huterer (2017)
- Empirical: limit on change z → ΔH~0.6% (Kenworthy, Scolnic, AGR 2019)



Kenworthy, Scolnic, AGR 2019, arxiv:190108681

Suggestion we live in 3.5% H_0 void (z<0.07; KBC 2013, Shanks et al. 2018), SN data rejects 4.5 σ

FAQ: Alternatives to Cepheids? Tip of Red Giant Branch (TRGB)

TRGB: Brightest luminosity of Red Giants before helium flash

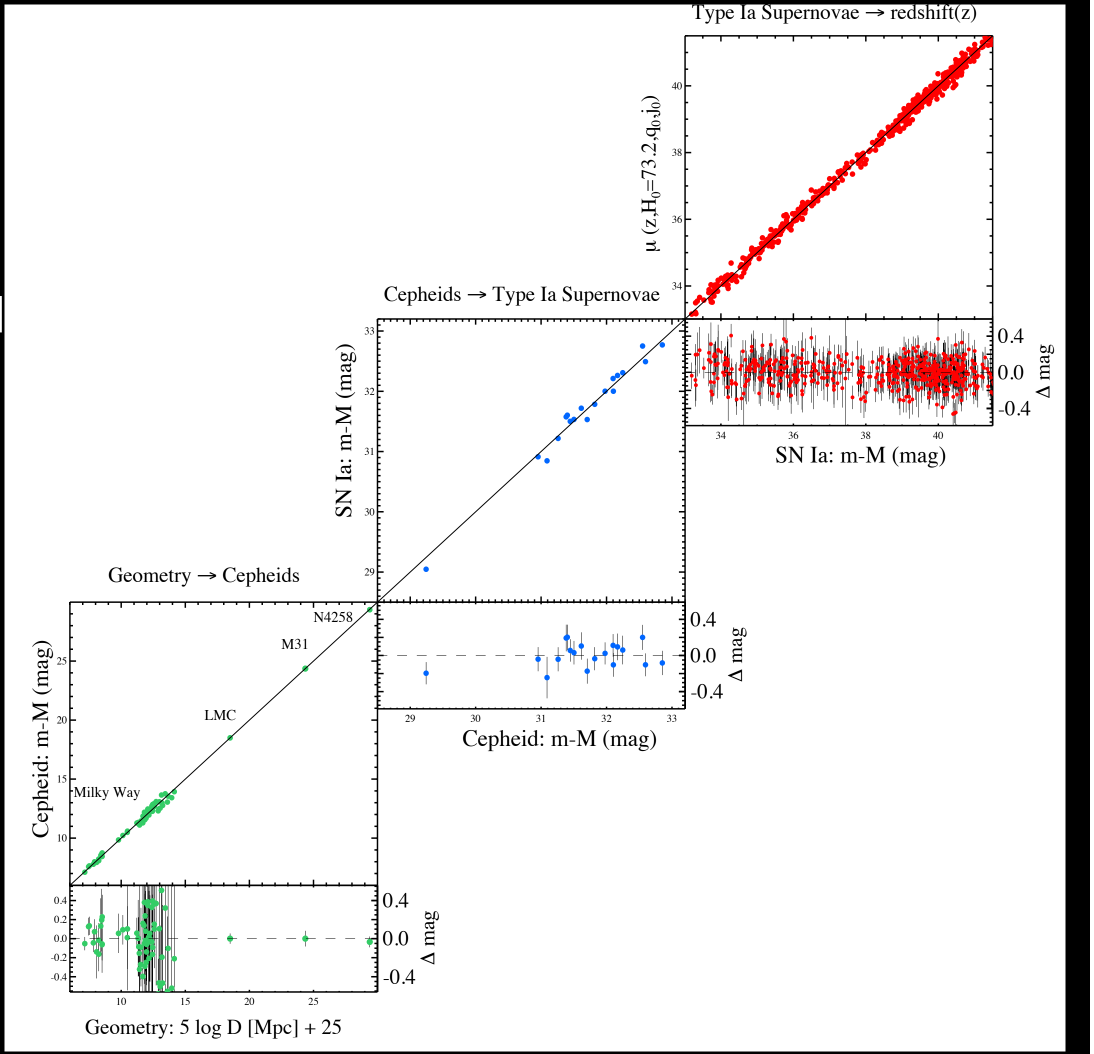
- Cross-check: Cepheid vs TRGB distances same 10 SN hosts, same LMC DEB D, same Supercal SNIa sample (R16)

- TRGB: HST/ACS F814W
  - SN hosts: Jang & Lee 2017, Hatt+201
  - LMC: I_0=14.52±0.04 (only ground)
  - A_I=0.10+/-0.03 mag (JL17, OGLE-III) P19 DEBs, yields M_{TRGB}=-3.97±0.05 mag OGLE→HST (Yuan+, in prep.)

- H_0=73.2±2.3 (TRGB)

vs 73.5±1.8 (Ceph)

Talks by Freedman, Jang

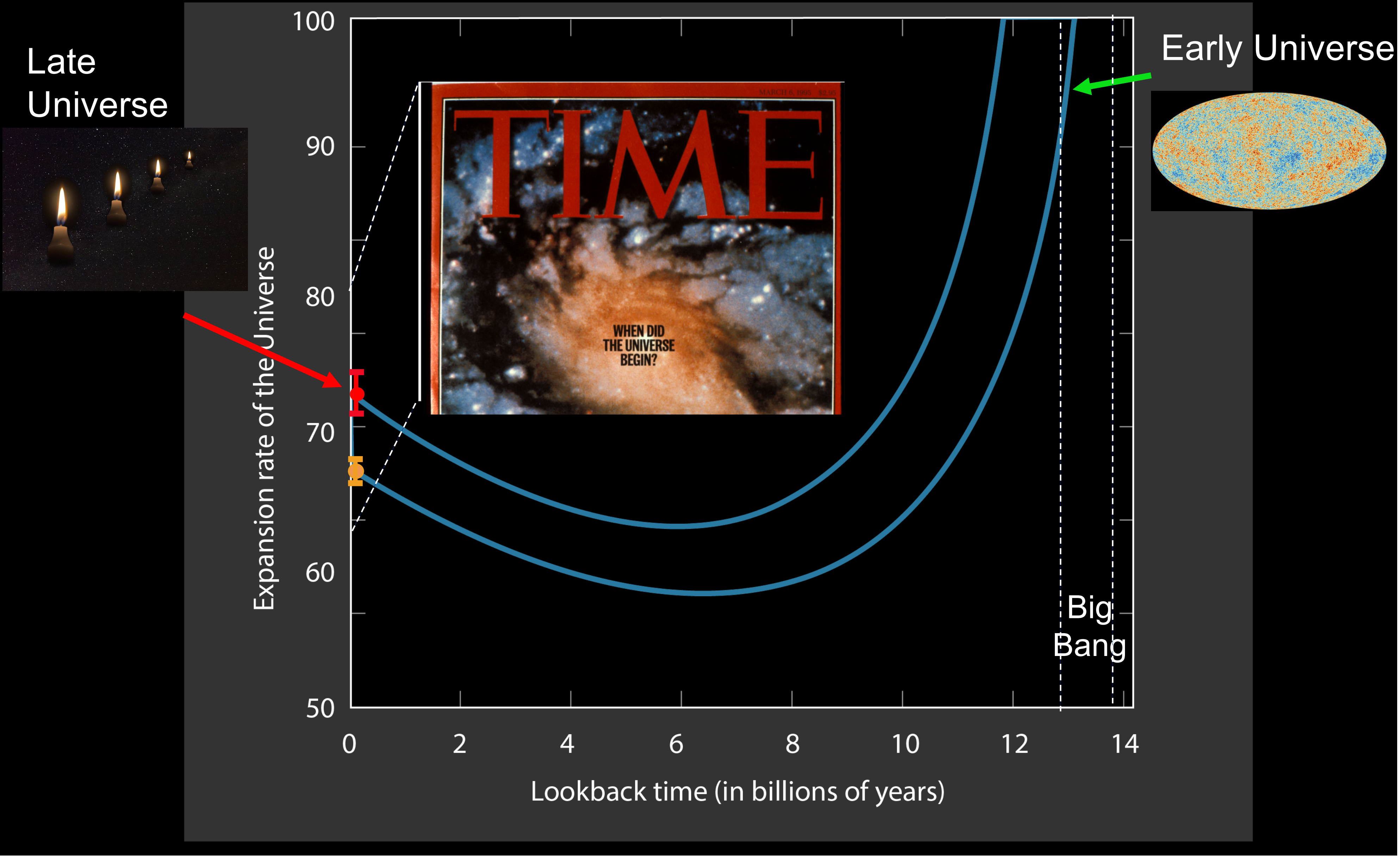


Good agreement with first Mira/SN Host, Huang et al in prep

Questions that keep me up at night.

How Old is the Universe?

CMB+LCDM=13.80 +/- 0.02 Gyr but $t_0 \sim 1/H_0$ may be 9% less, do we stop saying we know this?



TRGB Calibration: How well do we know extinction, in LMC?

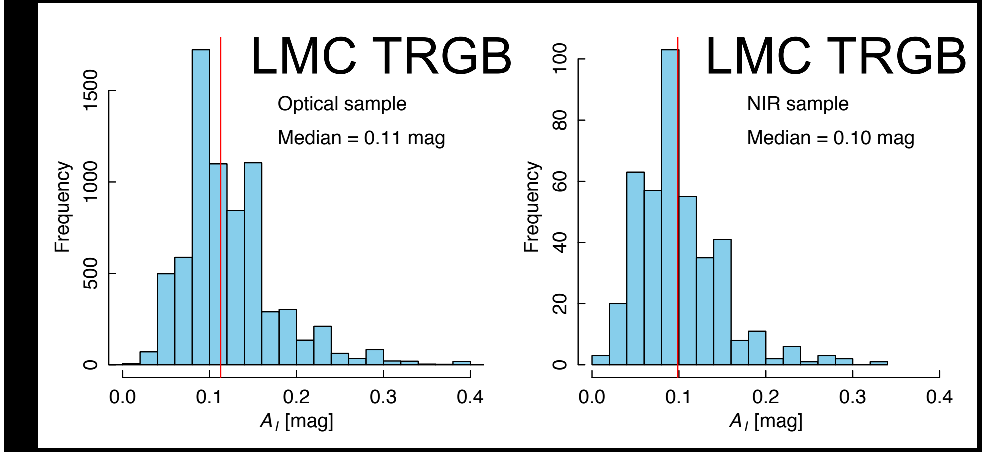
(one TRGB host in SH$_0$ES, NGC 5643, Yuan et al in prep)

TRGB in Halos assumed to have zero extinction

(But SDSS quasar reddening vs. separation, Menard et al. (2010), → A_I=0.01-0.02 mag)

LMC TRGB I-band extinction substantial, linear with H$_0$ & Cepheid comparison

Standard Approach: OGLE reddening maps: RC stars, RR Lyrae, vs z, Hascke et al 2011



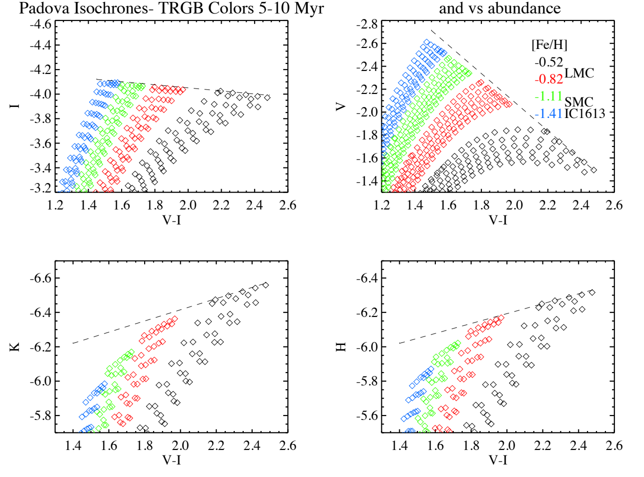
Same as Jang & Lee 2017, A_I=0.10 +/- ?
Used in our estimate

How uncertain? How can we check?

How Well Can LMC TRGB Colors Measure Extinction?

TRGB very *insensitive* to age (star formation history) and metallicity in I-band, not so in other bands, bias comparing galaxies like SMC with lower [Fe/H]

Linear color term corrects age



RGB [Fe/H]

LMC~-0.6

SMC~-1.2

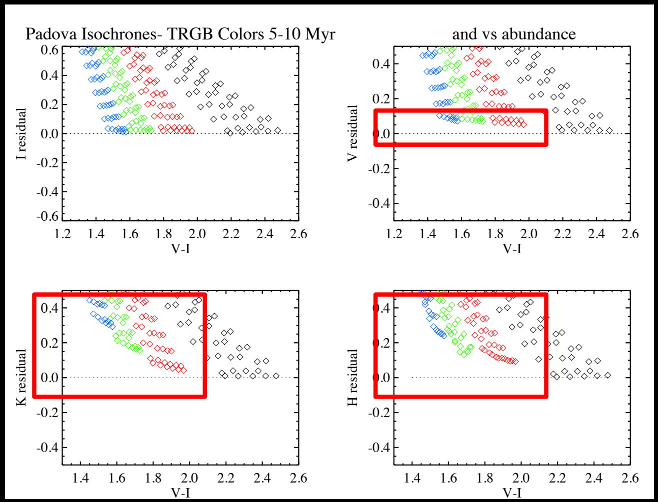
Nidever et al. 2019

IC 1613 ~-1.4

Sibbons et al. 2015

see also McQuinn et al (2019) for [Fe/H]=-1.5, -1.0, -2.0

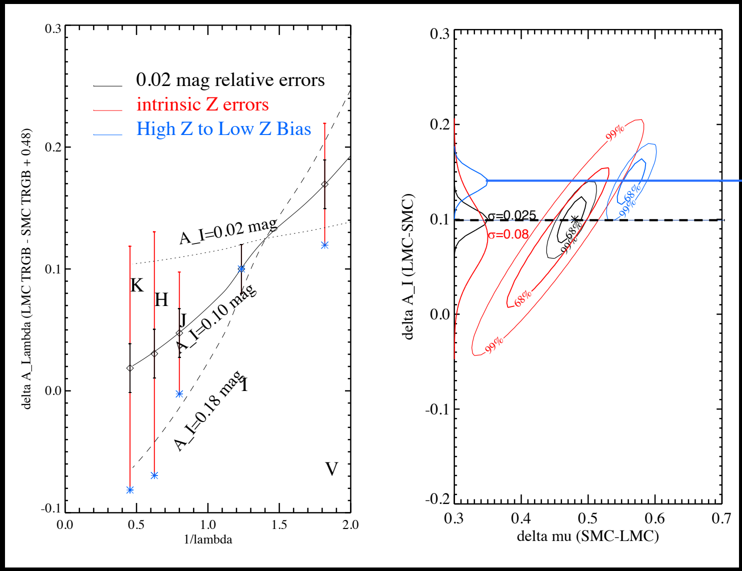
Residuals w/ linear color term from LMC



Two parameter fit:

$\Delta\mu, \Delta AI$

(Method similar to Freedman, Madore 1988)



Lower H0

would bias LMC A_I high by 0.05 mag because of different metallicity

Higher H0

Questioning SH$_0$ES Route: Can We Reach 1%?

Need ~50 SN Ia—lifetime of HST ?

Will Gaia solve zeropoint source dependence?

Can we measure Milky Way Cepheids same as distant hosts to ~0.02 mag ? 😰

Or can two independent approaches each reach 1.4%?

Maybe.

I think we can reach 1.3%. <1.0% is much harder

End

The Hubble Constant ~~Tension~~ *Problem* ?

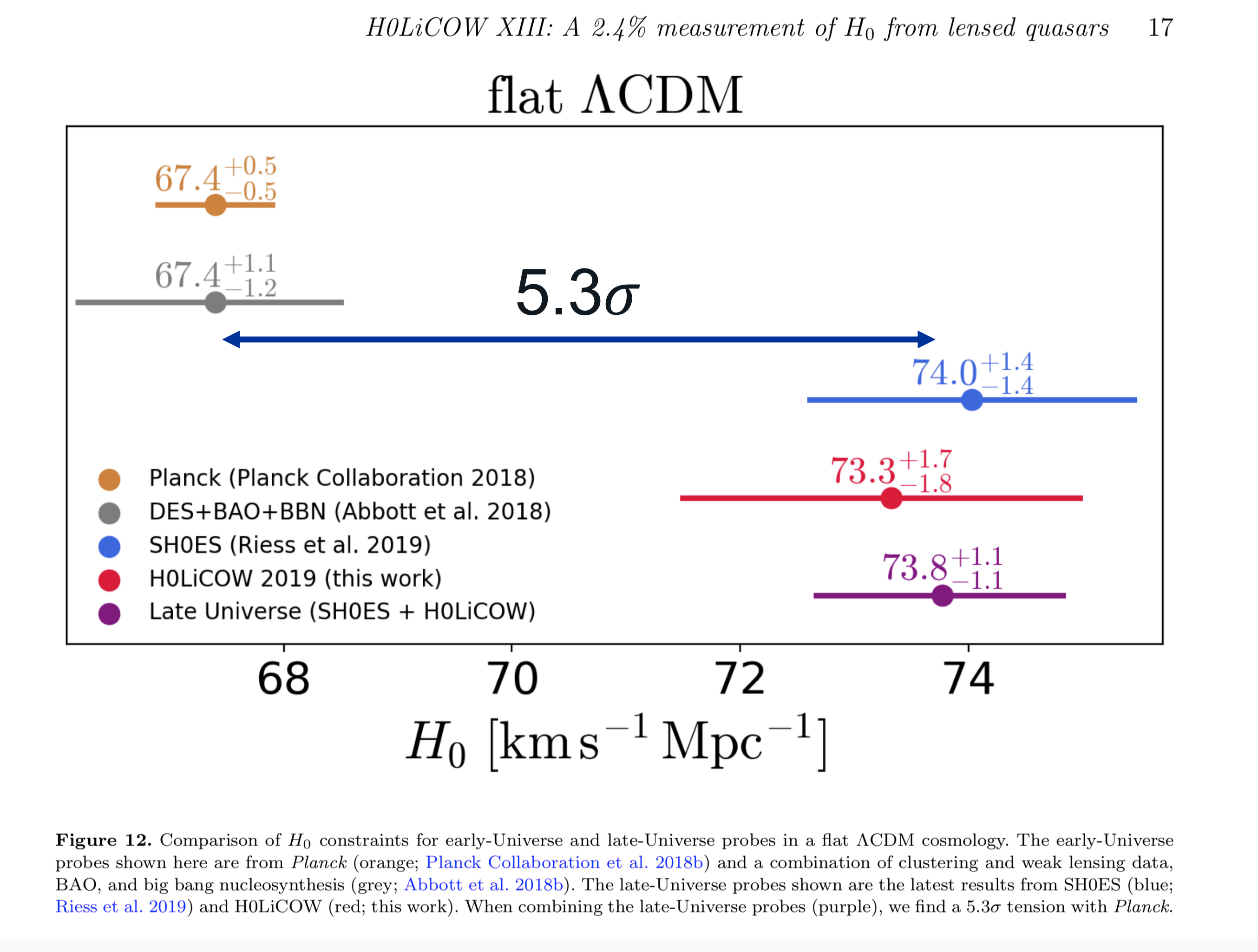


Figure 12. Comparison of H_0 constraints for early-Universe and late-Universe probes in a flat ΛCDM cosmology. The early-Universe probes shown here are from *Planck* (orange; Planck Collaboration et al. 2018b) and a combination of clustering and weak lensing data, BAO, and big bang nucleosynthesis (grey; Abbott et al. 2018b). The late-Universe probes shown are the latest results from SH0ES (blue; Riess et al. 2019) and H0LiCOW (red; this work). When combining the late-Universe probes (purple), we find a 5.3σ tension with *Planck*.

Wong et al 2019