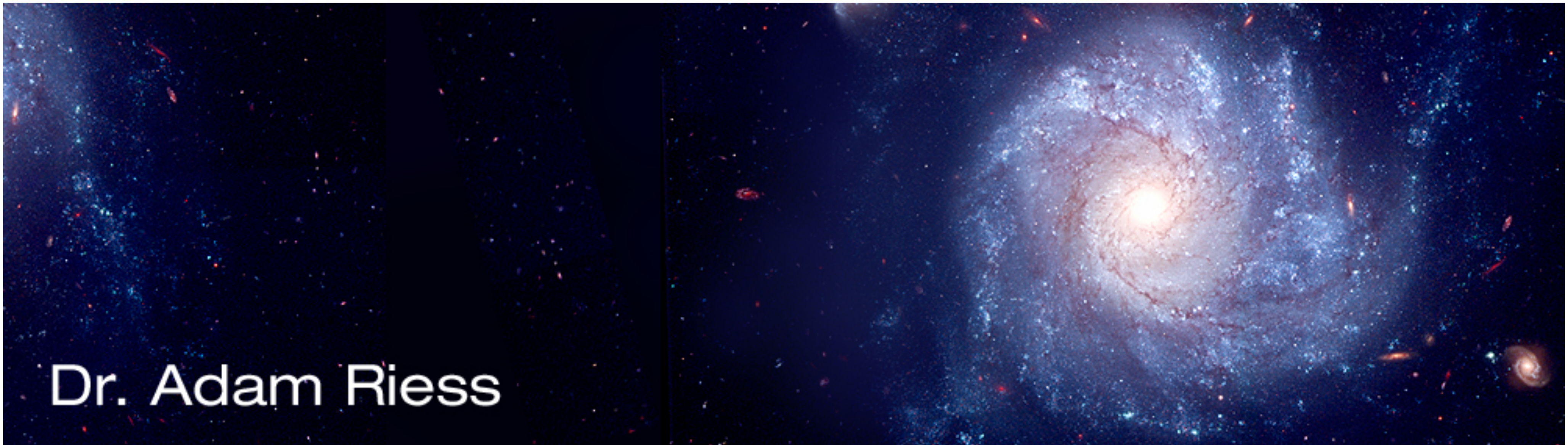


Johns Hopkins University
Space Telescope Science Institute

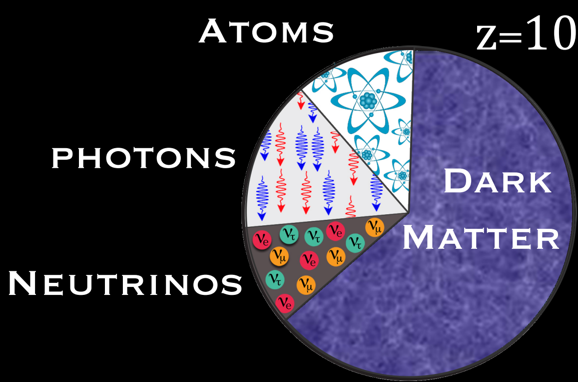
New Measurements of the Expansion Rate of the Universe, Hints of New Physics?

SH_0ES Team

Review: Verde, Treu, Riess 2019, NatAs,3,891
SH_0ES Team: Riess+2019, ApJ, 876, 85

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)



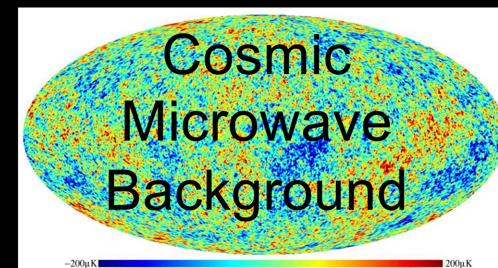
z=1000

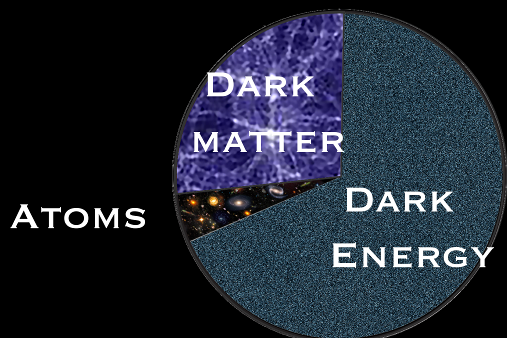
Predict physical size fluctuations, r_s, Ω_B →

← Measure angular fluctuations (or Ω_B)

Calibrate ΛCDM …

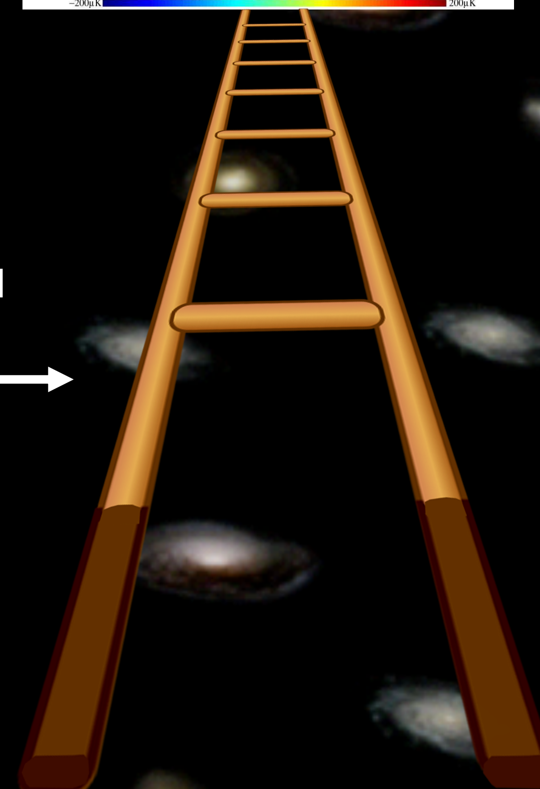
Big Bang



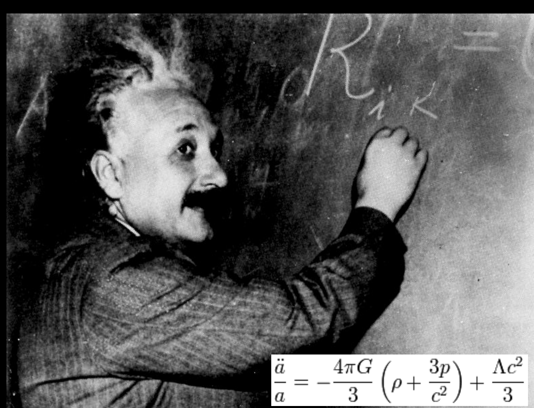


Now

Expansion history predicted
(“guard rails”, BAO, SNe) →



+



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

The SH_0ES Project (2005)

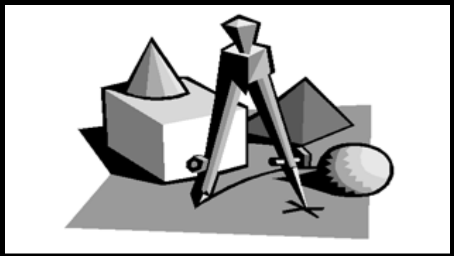
(Supernovae, H_0 for the dark energy Equation of State)

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

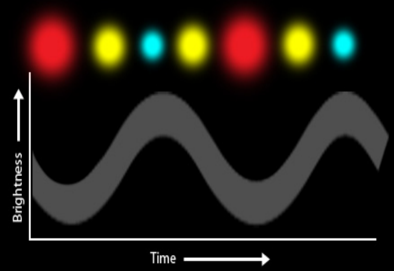
Measure H_0 to percent precision empirically by:

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

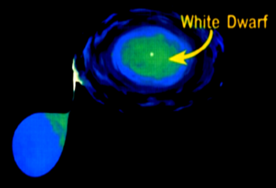
Multiple ways



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



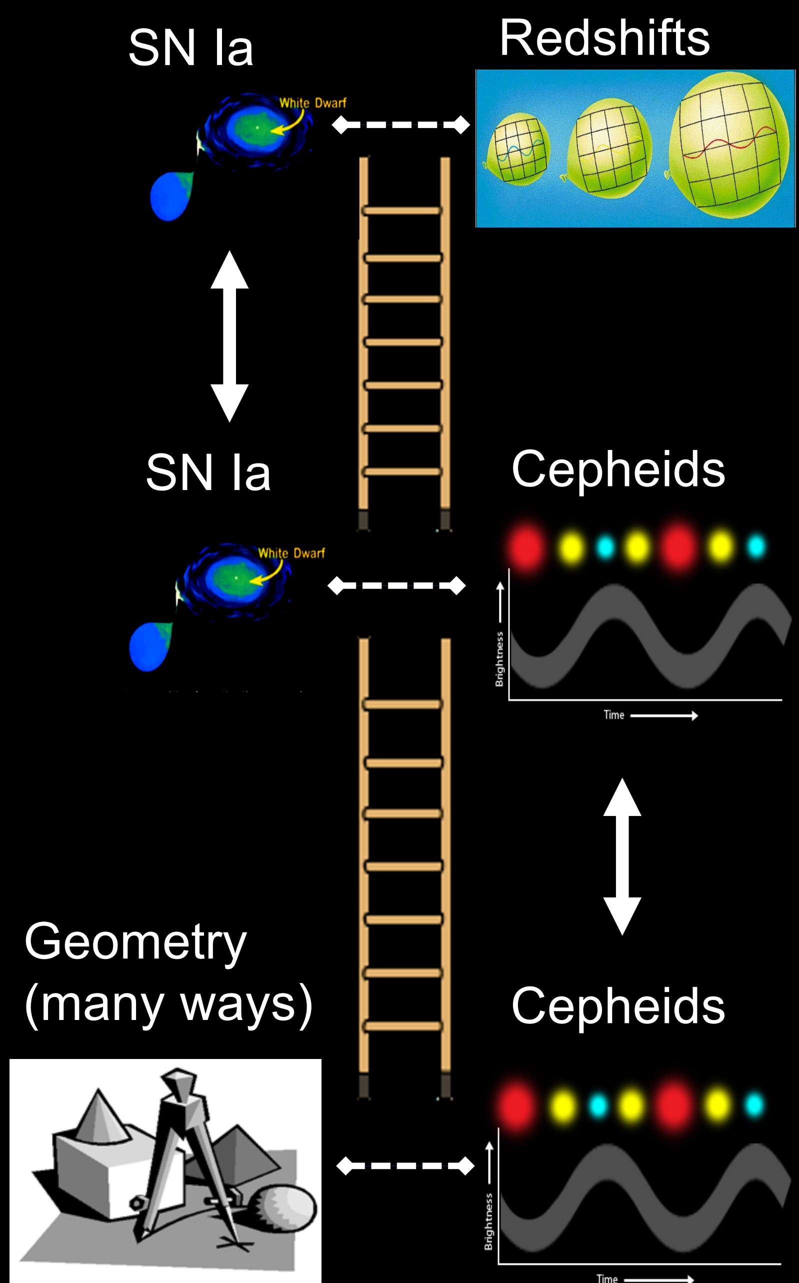
Exploding Stars, 10^9 $L_\odot$, σ~ 5%



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

Distance Ladders: Simple & Empirical, Must be Consistent



Hubble Flow:
D~Gpc, z~0.1

Cross-calibrate:
D~10-40 Mpc

Anchors:
D~Kpc or Mpc

Nutrition Facts

Serving size 1 potato (148g/5.2oz)

Amount per serving
Calories **73**

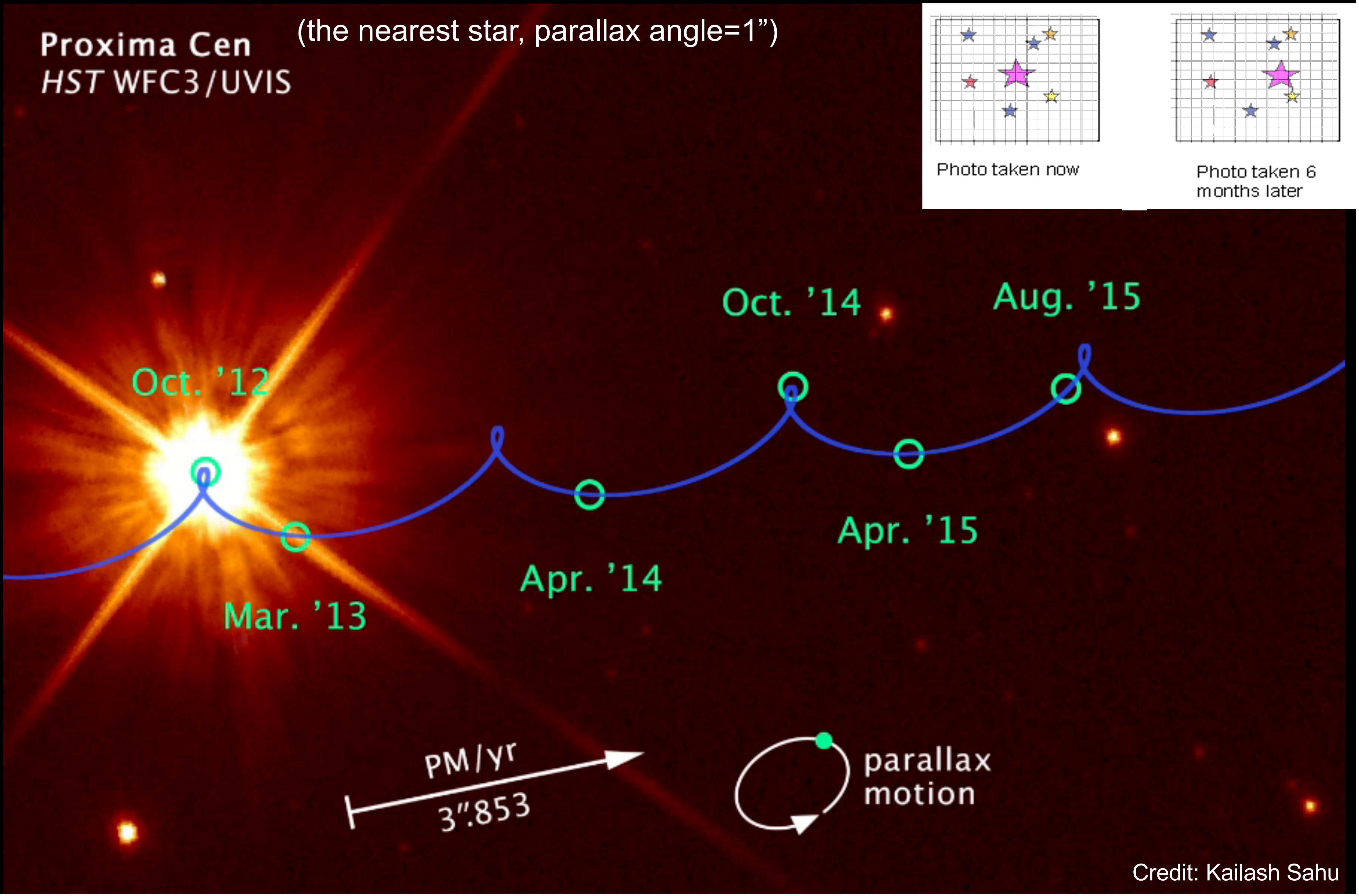
% Daily Value*

Astrophysical modeling	0%
General Relativity	<1%
LCDM	<1%

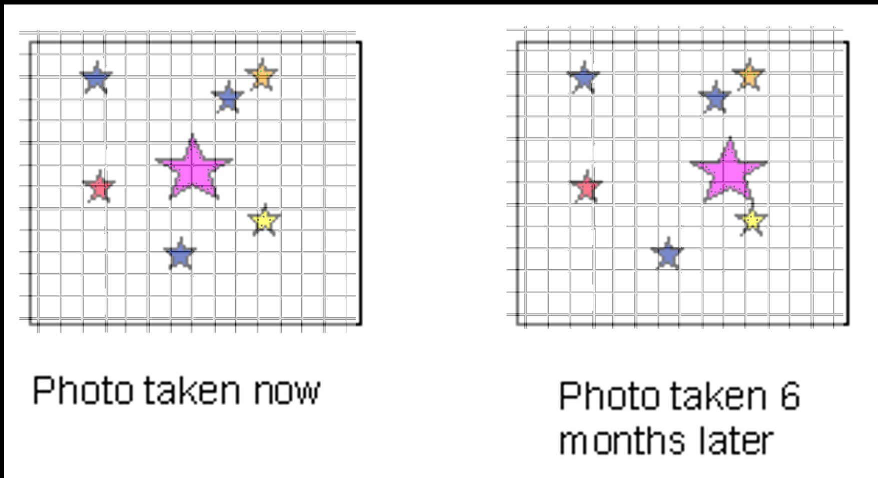
⚠ WARNING

Same object types on different rungs must be standardized and measured <u>consistently</u>!

Stars are far, Parallax is small !

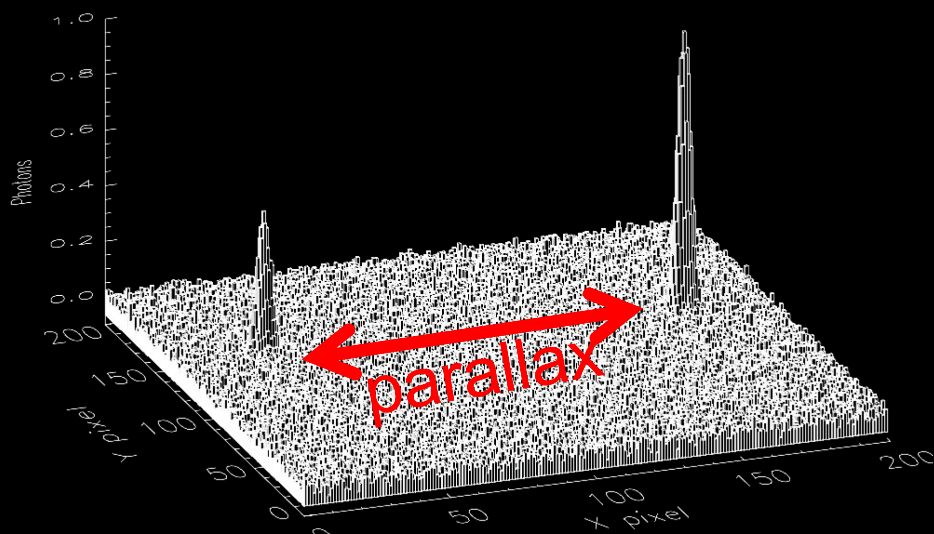


Extending Parallax with WFC3 Spatial Scanning



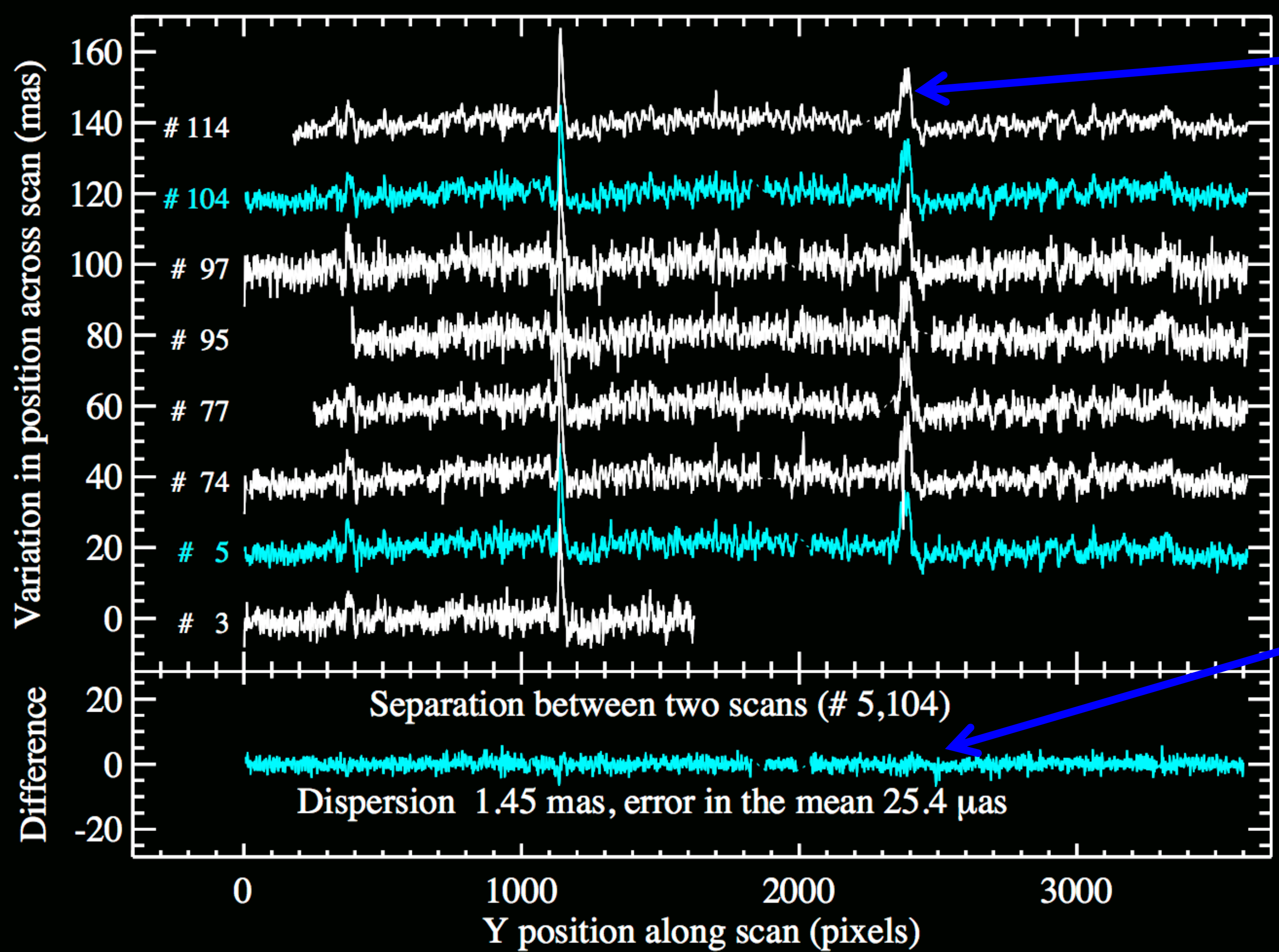
Imaging, precision=0.01 pix
WFC3: ~1σ @ 3 kpc

Sc



Two Features of Spatial Scans: Sampling and Jitter Removal

Extracted scan lines of stars from a single scan



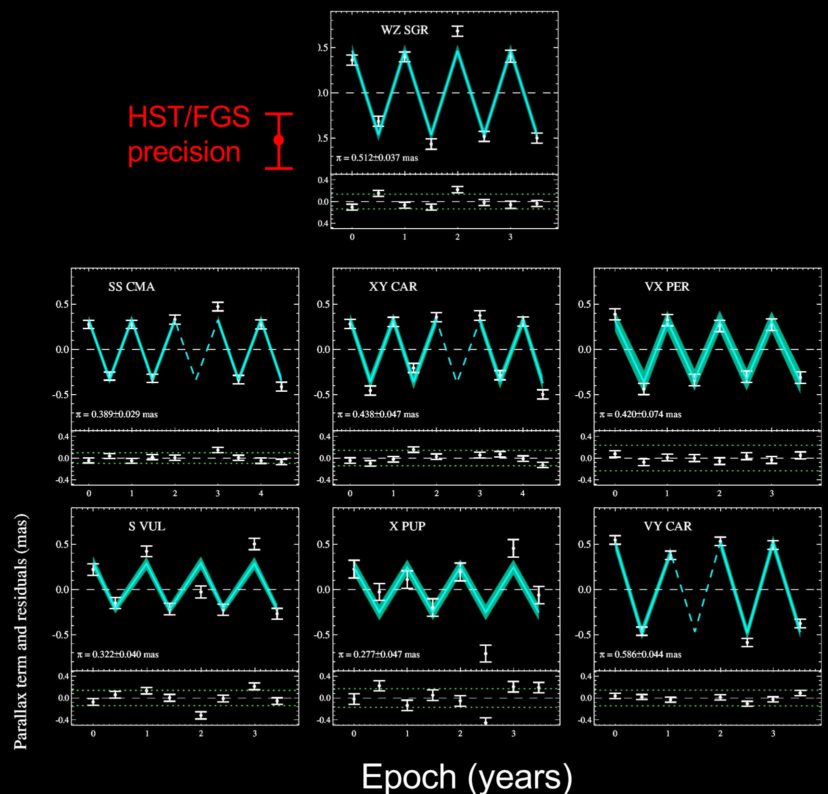
Jitter between lines is *coherent*, subtracted in line separations (vs time)

Target scanned over ~4000 pix, Improves SNR by factor of 10

Reaching 20-40 μas

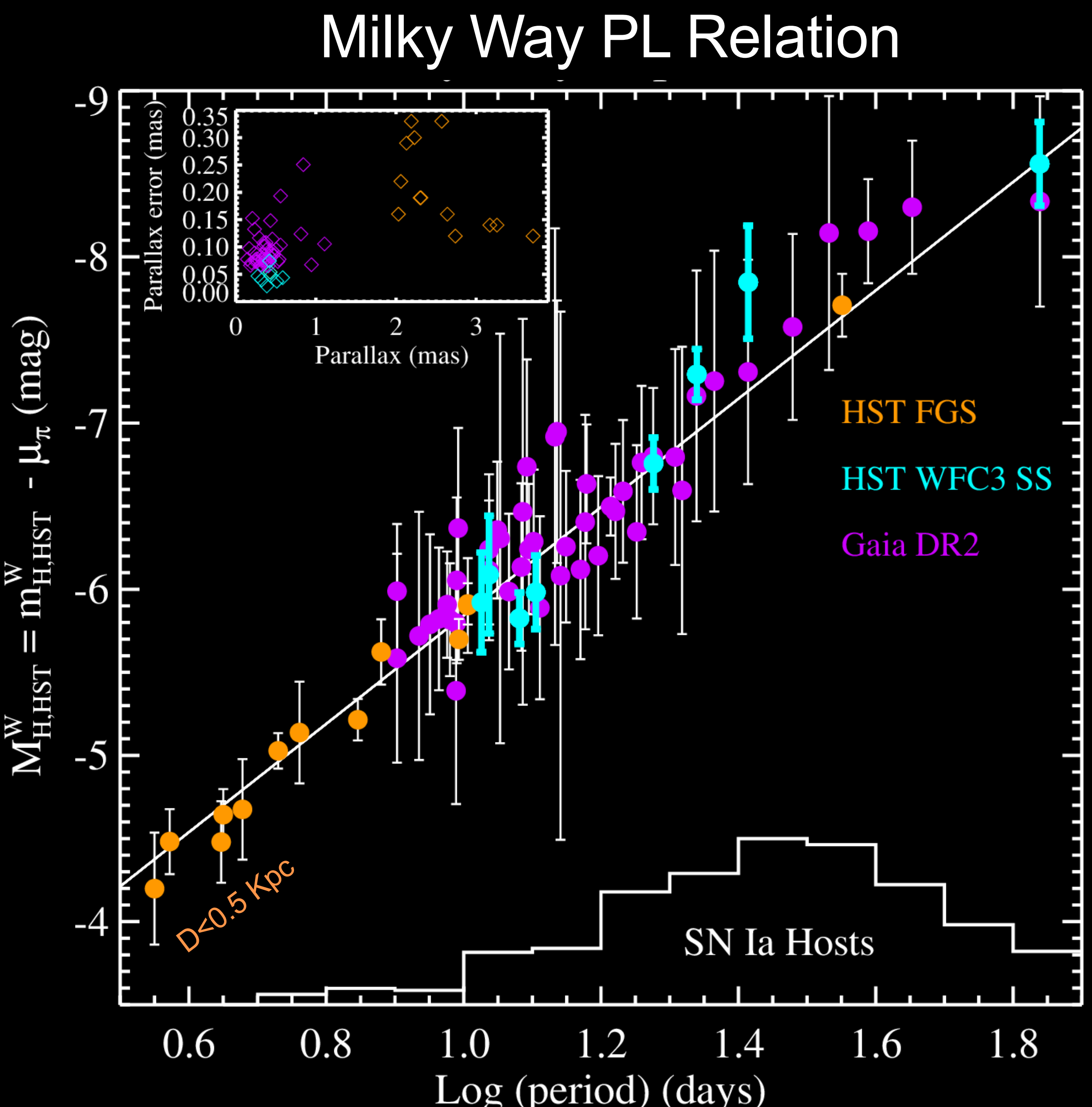
New Tool: WFC3 Spatial scanning for long range parallaxes, photometry

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

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



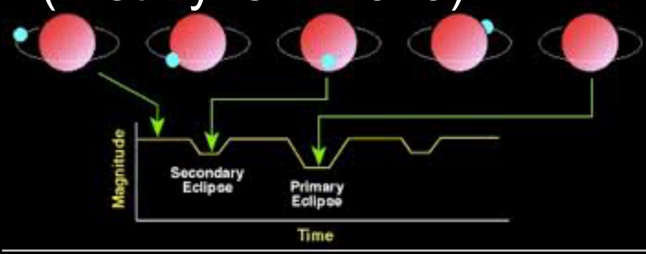
Final Gaia Parallaxes + HST Photometry→ H_0~0.4%!

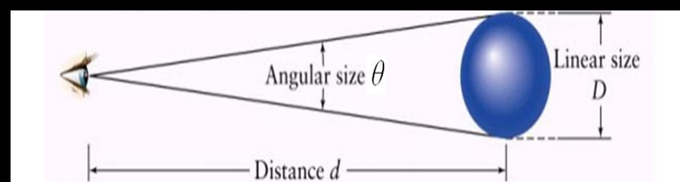
Periods > 10 days matching Cepheids HST sees in SN Ia hosts

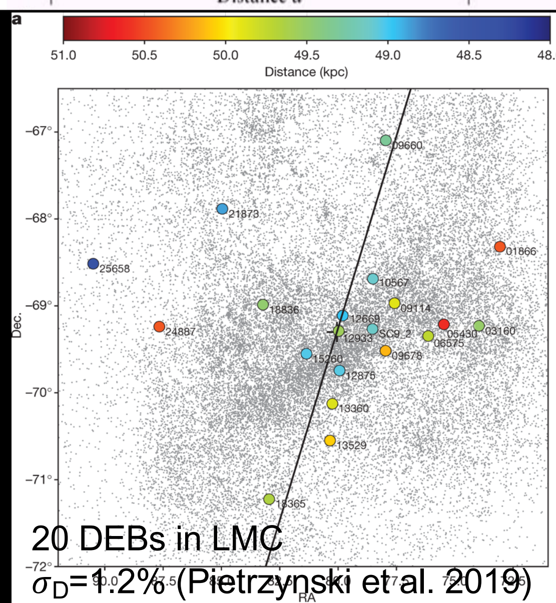
Three Sources of Geometric Distances to Calibrate Cepheids

Parallax in Milky Way (WFC3 SS, HST FGS, Gaia)

Detached Eclipsing Binaries in LMC
(Pietrzynski+2019)

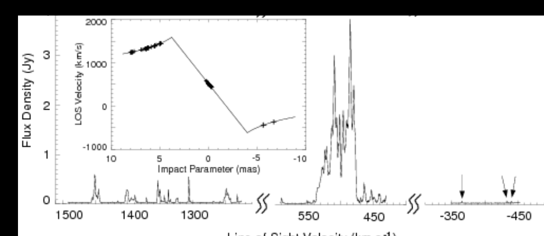






20 DEBs in LMC
σ_D=1.2% (Pietrzynski et al. 2019)

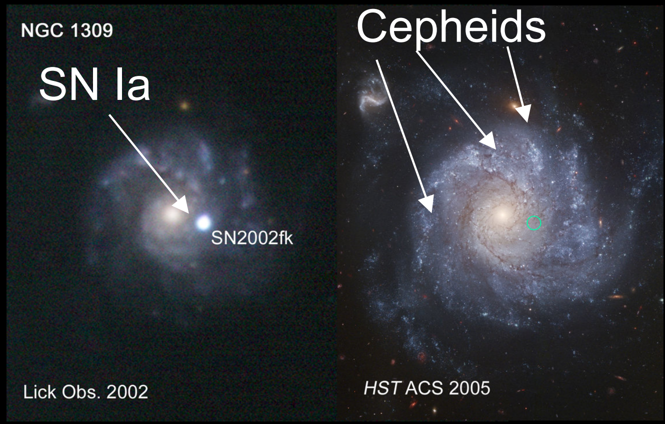
Masers in NGC 4258, Keplerian Motion
(Reid+2019)



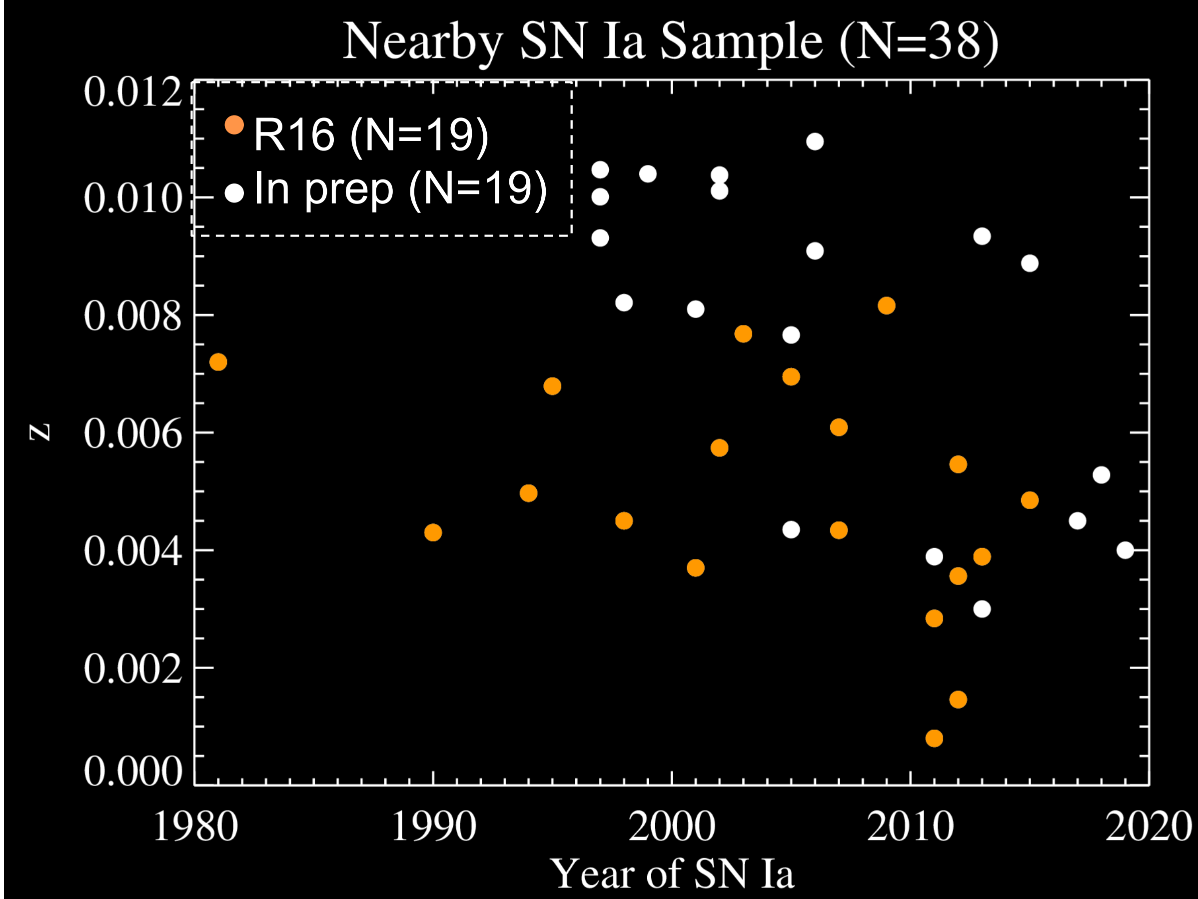
Step 2: Cepheids to Type Ia Supernovae

Number nearby SN Ia limits H_0 precision, $\sigma = \frac{6\%}{\sqrt{N}}$

SN Ia Requirements: A_V<0.5, normal, pre-max, digital
Host Requirements: Late-type, z≤0.01, not-edge on

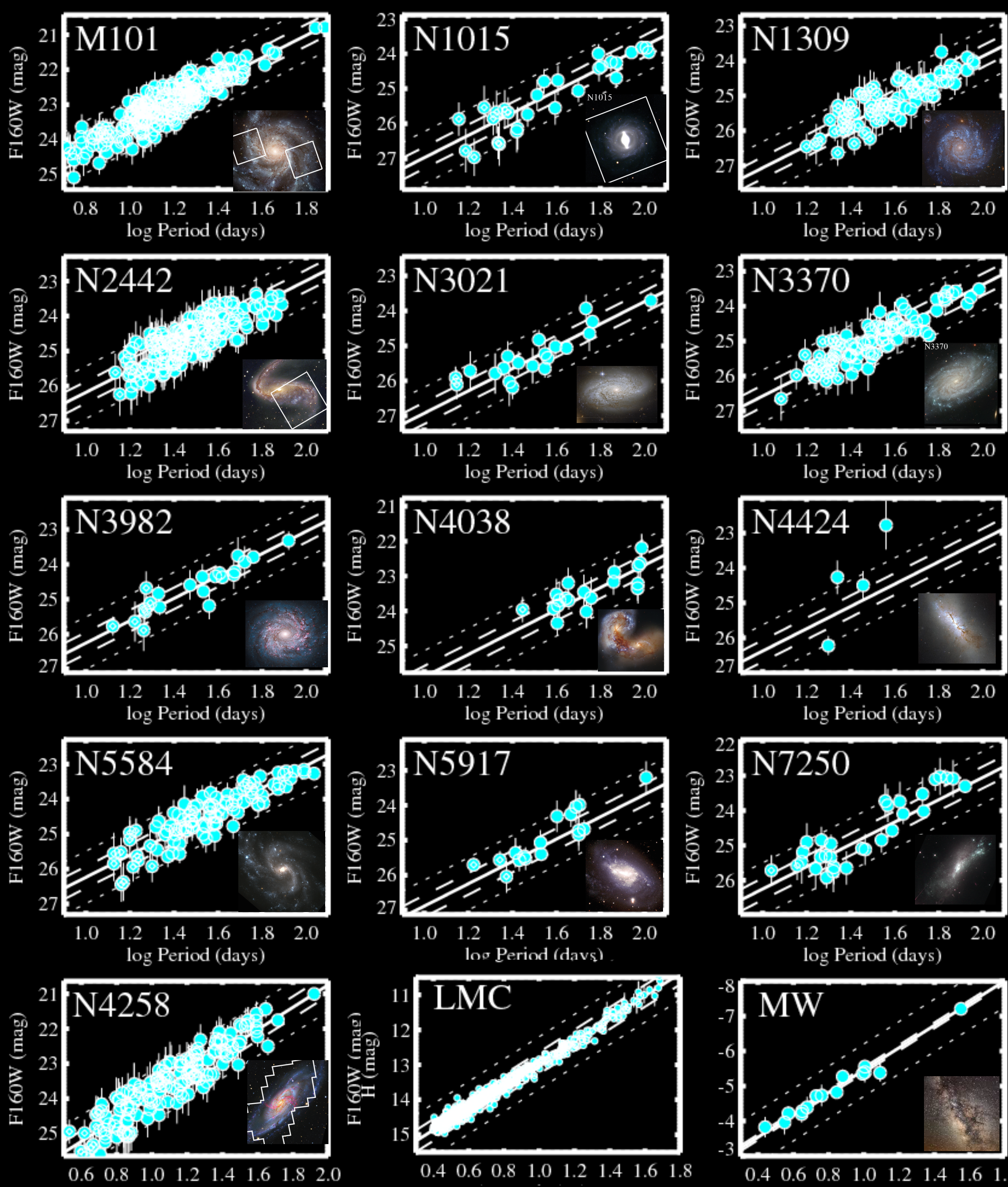


2019 Complete sample (new ones @ 1.5/yr)



Measured by same surveys as SN Ia in Hubble flow

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

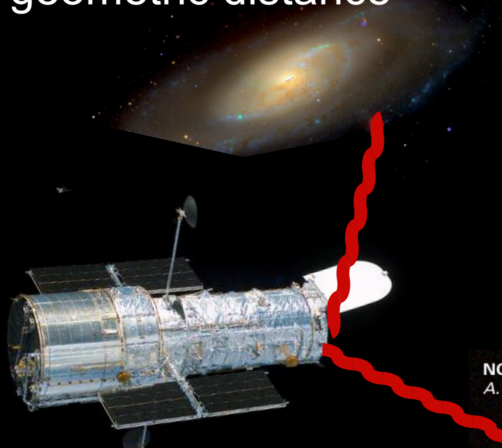


3 Anchors

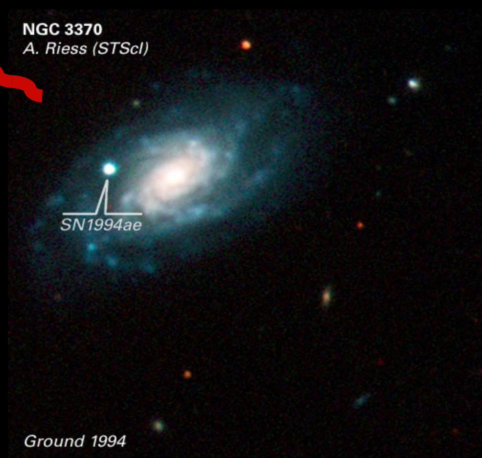
Lower Systematics from *Differential* Flux Measurements

To reduce systematic errors: measure all Cepheids with same instrument, filters, similar metallicity, period range

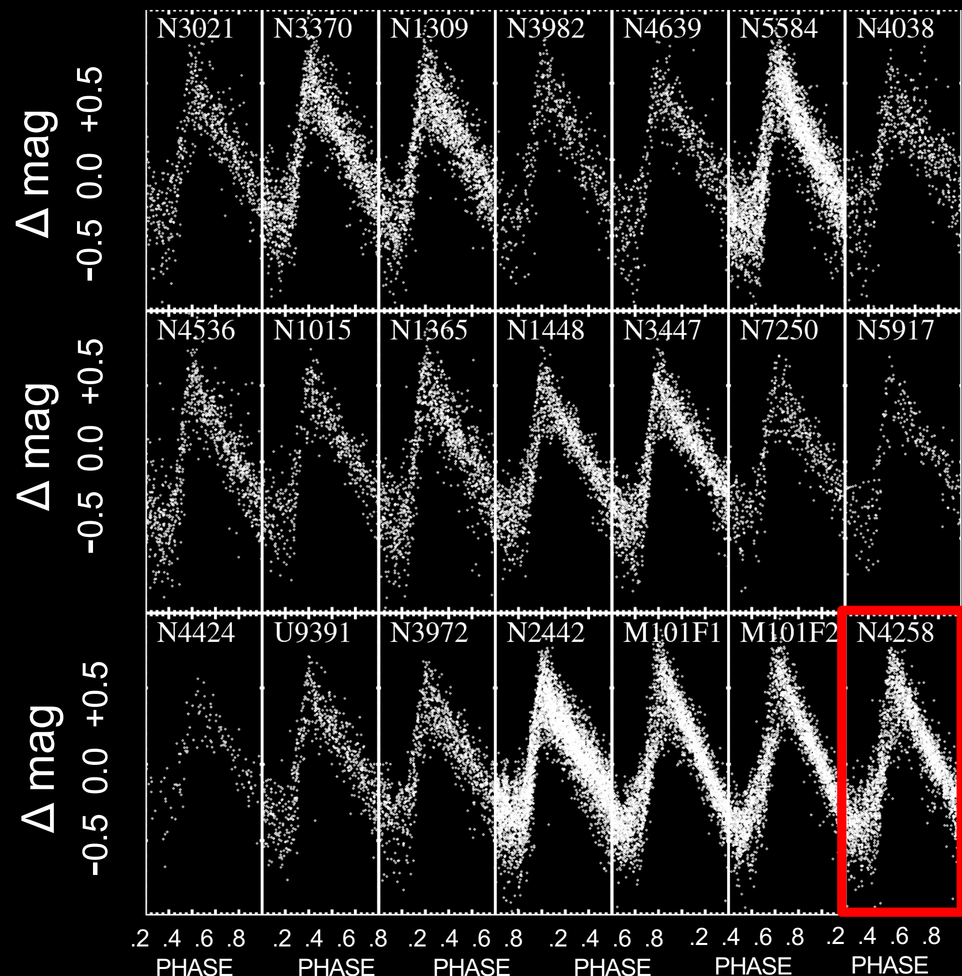
ANCHORS: NGC 4258, MW, & LMC
geometric distance



19 SN Ia Hosts



Cepheid composite LC's, >2400



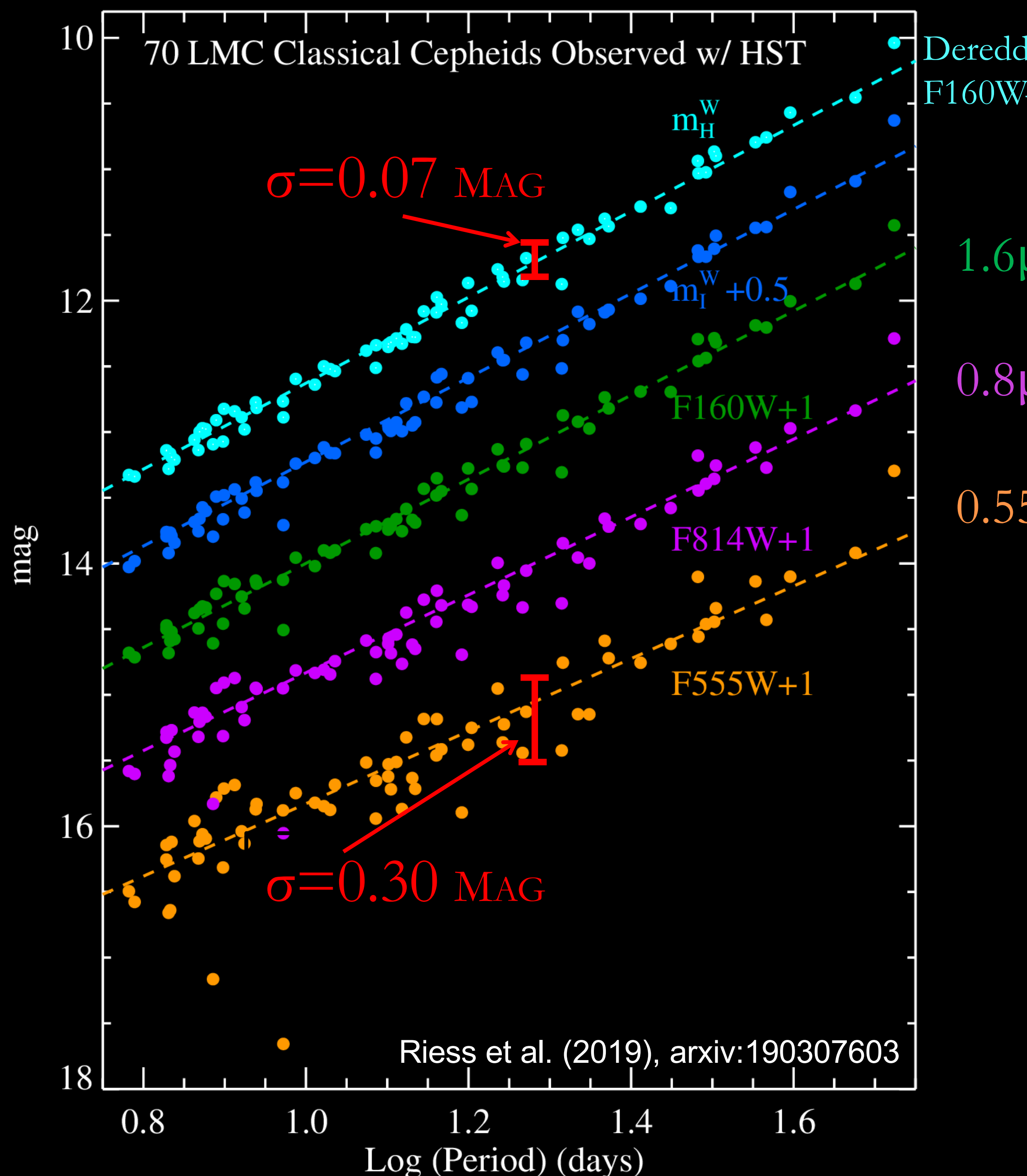
Lowering Systematics: Near-IR Cepheid Observations + HST, Now in LMC!

-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

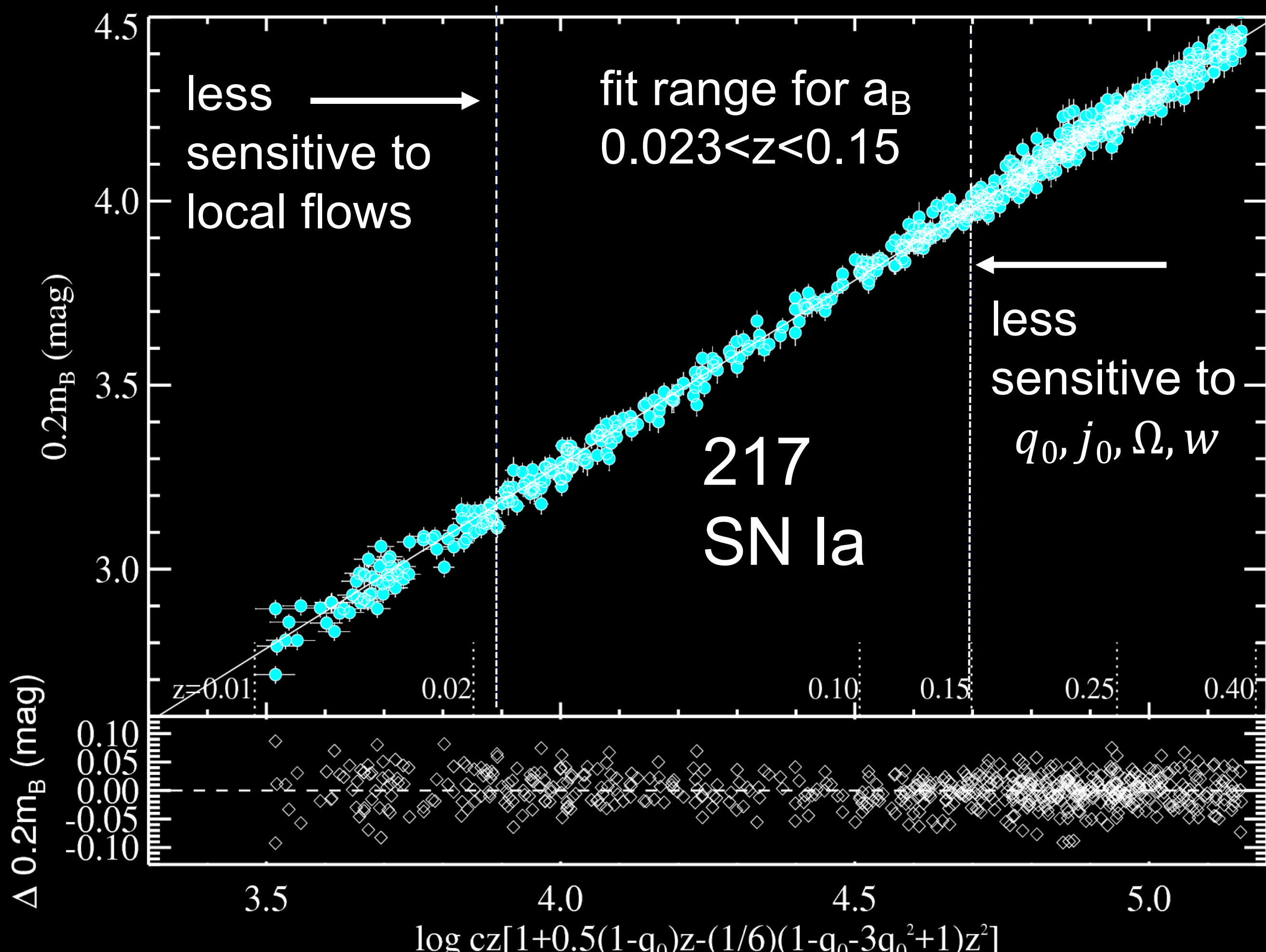


Leavitt

Step 3: Intercept of SN Ia Hubble Diagram: Distance vs Redshift

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

← Kinematic Intercept equation



Simultaneous Fit: Retain interdependence of data and parameters

Measurements

Cepheids in SN hosts; Cepheids in Anchors; SN Ia; Geometric Distance Priors

$$\begin{pmatrix} m^W_{H,1,j} \\ .. \\ m^W_{H,18,j} \\ m^W_{H,j,N4258} - \mu_{0,N4258} \\ m^W_{H,M31,j} \\ m^W_{H,MW,j} - \mu_{\pi,j} \\ m^W_{H,LMC,j} - \mu_{0,LMC} \\ m^0_{B,1} \\ .. \\ m^0_{B,18} \\ 0 \\ 0 \\ 0 \end{pmatrix} =$$

Regression Matrix

$$\begin{pmatrix}
1 & .. & 0 & 0 & 1 & 0 & 0 & \log P^h_{18,1}/0 & 0 & [O/H]_{18,1} & 0 & \log P^l_{18,1}/0 \\
.. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. \\
0 & .. & 1 & 0 & 1 & 0 & 0 & \log P^h_{18,j}/0 & 0 & [O/H]_{18,j} & 0 & \log P^l_{18,j}/0 \\
0 & .. & 0 & 1 & 1 & 0 & 0 & \log P^h_{N4258,j}/0 & 0 & [O/H]_{N4258,j} & 0 & \log P^l_{N4258,j}/0 \\
0 & .. & 0 & 0 & 1 & 0 & 1 & \log P^h_{M31,j}/0 & 0 & [O/H]_{M31,j} & 0 & \log P^l_{M31,j}/0 \\
0 & .. & 0 & 0 & 1 & 0 & 0 & \log P^h_{MW,j}/0 & 0 & [O/H]_{MW,j} & 1 & \log P^l_{MW,j}/0 \\
0 & .. & 0 & 0 & 1 & 1 & 0 & \log P^h_{LMC,j}/0 & 0 & [O/H]_{MW,j} & 1 & \log P^l_{LMC,j}/0 \\
1 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & .. & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & .. & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & .. & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

Free Parameters

$$* \begin{pmatrix} \mu_{0,1} \\ .. \\ \mu_{0,18} \\ \Delta\mu_{\rm N4258} \\ M^W_{H,1} \\ \Delta\mu_{\rm LMC} \\ \mu_{M31} \\ b \\ M^0_B \\ Z_W \\ \Delta zp \\ b_l \end{pmatrix}$$

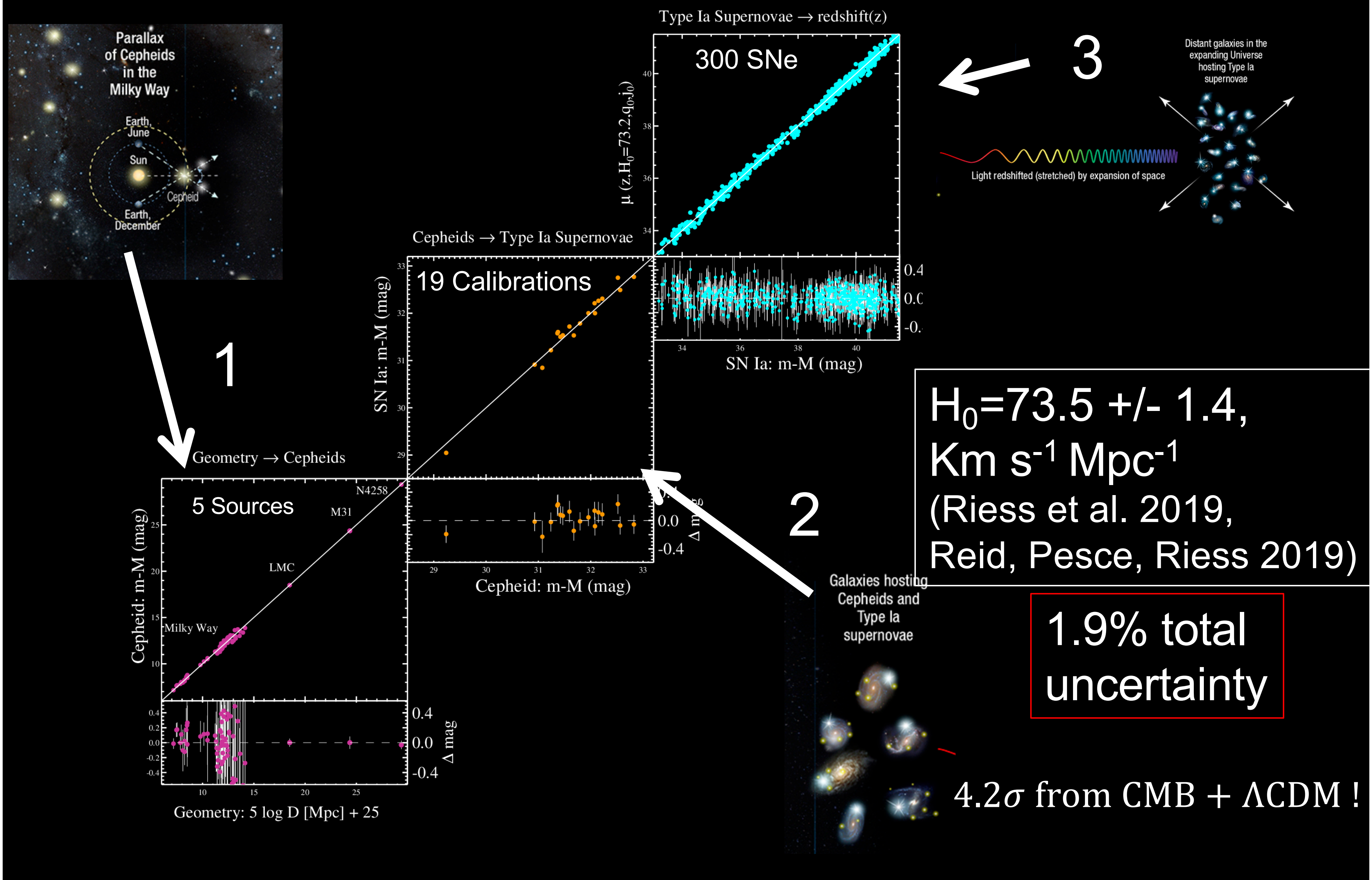
Absolute Host Distances
ΔD (N4258)
Cepheid Luminosity
ΔD(LMC)
ΔD(M31)
P-L slope (P>10 days)
SN Ia Luminosity
Metallicity, Cepheid
Zeropoint, LMC
P-L slope (P<10 days)

Error Matrix

[$\sigma^2_{tot,1,j}$,.. $\sigma^2_{tot,19,j}$, $\sigma^2_{tot,N4258,j}$, $\sigma^2_{tot,M31,j}$, $\sigma^2_{tot,MW,j}+\sigma^2_{\pi,j}$, $\sigma^2_{tot,LMC,j}$, $\sigma^2_{mB,1}$,.. $\sigma^2_{mB,19}$, σ^2_{zp}, $\sigma^2_{\mu,N4258}$,$\sigma^2_{\mu,LMC}$]

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

The Hubble Constant in 3 Steps: Present Data



Robust? Five Sources of Cepheid Geometric Calibration

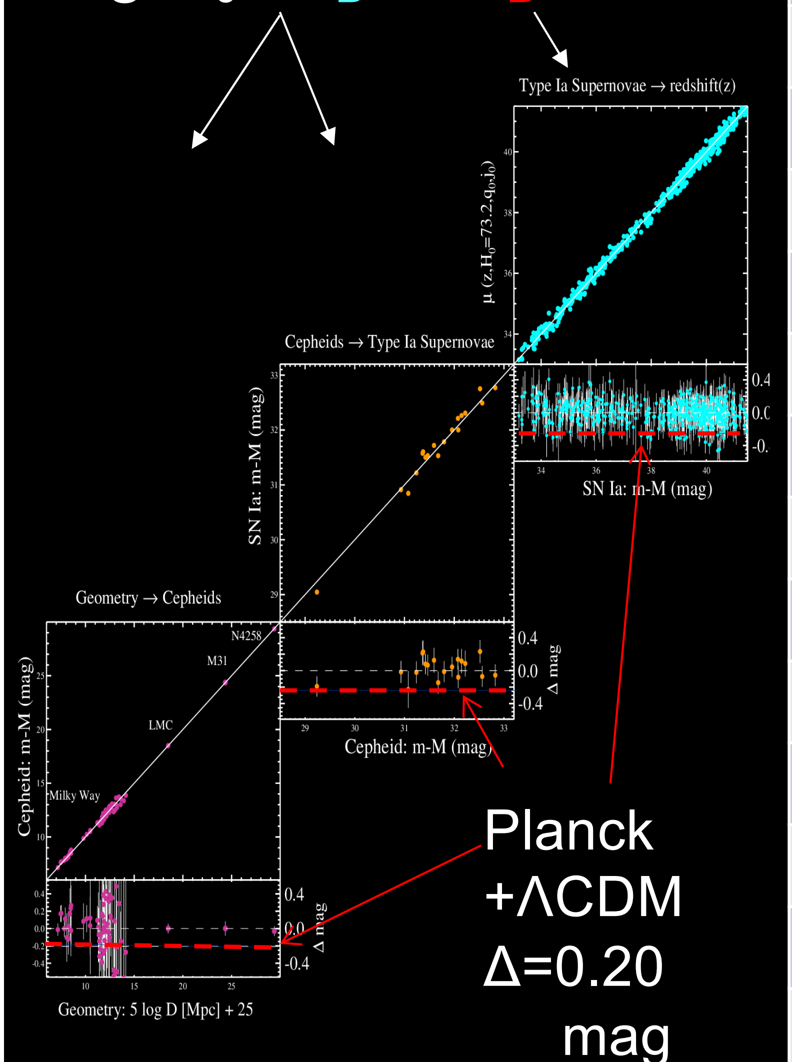
Independent Geometric Source	σ_D	H_0	Δ_{all}
NGC 4258 H_20 Masers: Reid, Pesce, Riess 2019	1.5%	72.0	-1.5±1.1
LMC 20 Detached Eclipsing Binaries: Pietzrynski+ 2019 + 70 HST LMC Cepheids: Riess+(2019)	1.3%	74.2	+0.7±1.0
Milky Way 10 HST FGS Short P Parallaxes: Benedict+2007 --also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2	+2.7±1.6
Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess+ 2018	3.3%	75.7	+2.2±2.4
Milky Way 50 Gaia+HST, Long P Parallaxes: Riess+ 2018	3.3%	73.7	+0.2±2.4

Consistent Results ($\leq 2\sigma$), *Independent Systematics*

Systematics? 23 Analysis Variants—we propagate variation to error

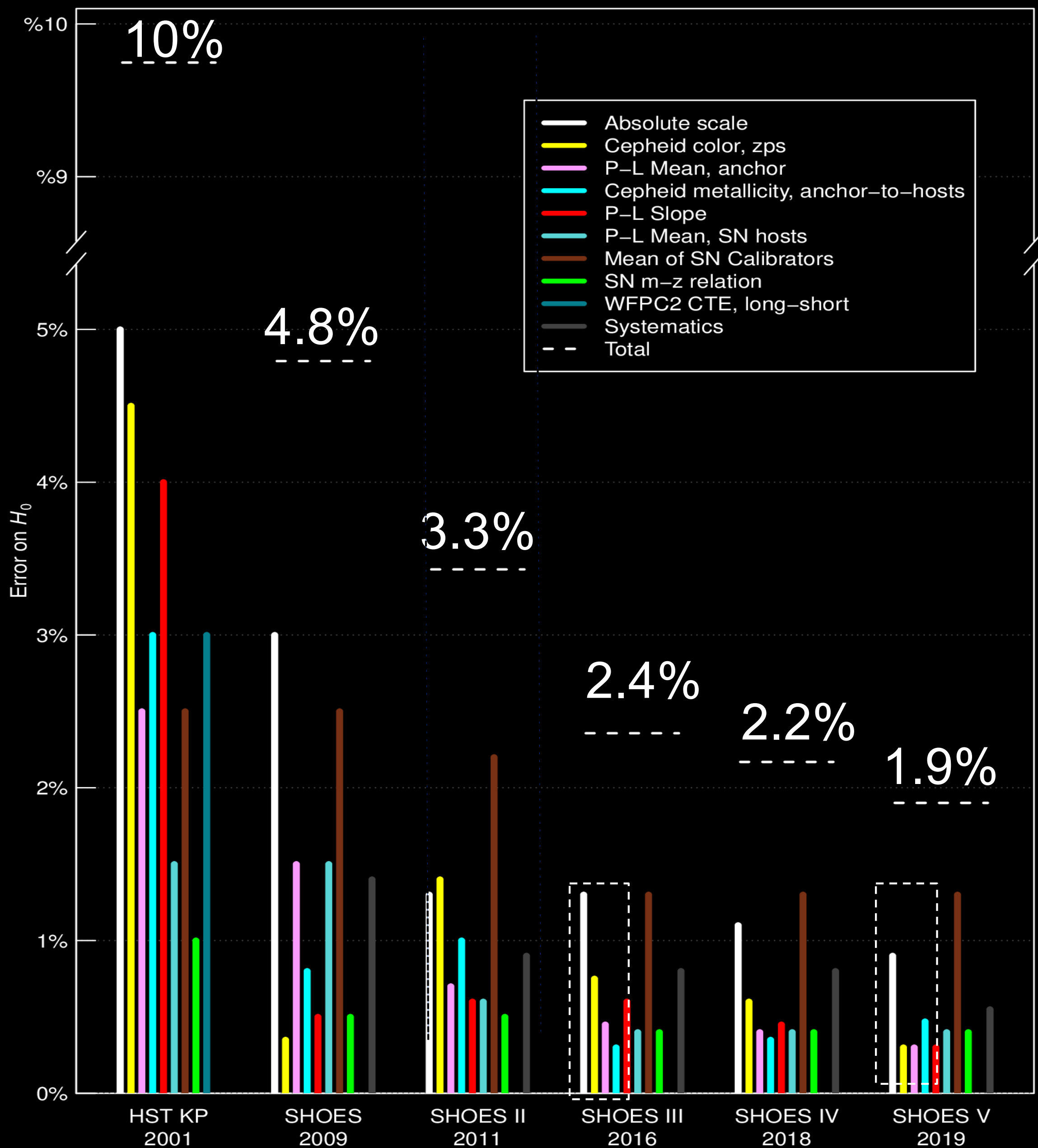
Best Fit:

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



Analysis Variants	H_0
Best Fit (2019)	73.5
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.4
Reddening Law: Bulge-like (N15)	73.9
No Cepheid Outlier Rejection (normally 2%)	73.8
No Correction for Cepheid Extinction	75.2
No Truncation for Incomplete Period Range	74.6
Metallicity Gradient: None (normally fit)	74.0
Period-Luminosity: Single Slope	73.8
Period-Luminosity: Restrict to P>10 days	73.7
Period-Luminosity: Restrict to P<60 days	74.1
Supernovae z>0.01 (normally z>0.023)	73.7
Supernova Fitter: MLCS (normally SALT)	75.4
Supernova Hosts: Spiral (usually all types)	73.6
Supernova Hosts: Locally Star Forming	73.8
Optical Cepheid Data only (no NIR)	72.0

Distance Ladder Error Budgets for H_0 (w/ SN+Cepheids) 2001-2019



2016-2019 Improvements:

Anchors

- MW parallax (HST & Gaia) & HST fluxes (Riess + 2018a,b)
- LMC DEBs & HST fluxes (Riess + 2019a)
- NGC 4258 masers (Reid, Pesce, Riess 2019)
- WFC3 CRNL (Riess + 2019b)

2020 Improvements:

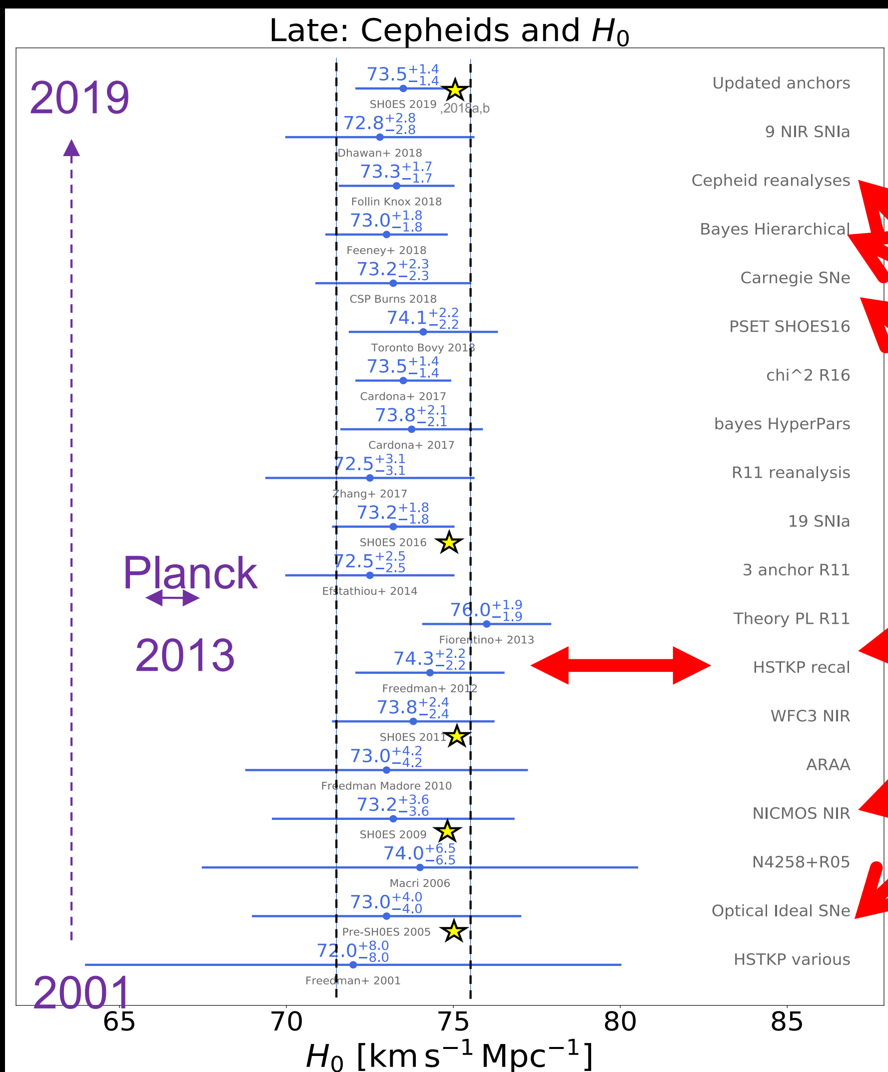
Cepheid-SN Ia Calibrators

- Doubling: 19→38

Gaia DR3

Distance Ladders with SN Ia and Cepheids 2001-2019

Why Cepheids? Advantages: 1) longest-range 2) most anchors 3) consistent photometry 4) most tested…



SH_0ES results (★) *cumulative* but compared to present… consistent

Different analyses

Different SNe

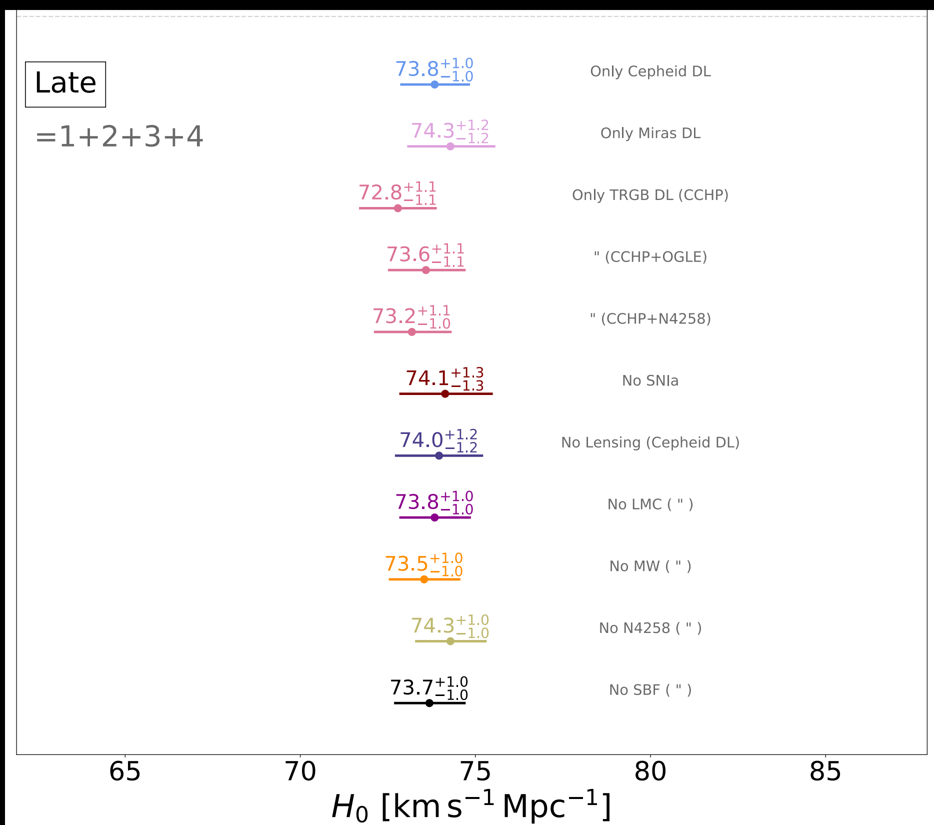
Different Cepheids, photometry, wavelengths

Different HST Instruments

Late Universe H_0 (KITP 2019)

Review by Verde, Treu, Riess (2019) Nature Astronomy *

Naïve Combo: 73 +/- <1 but some covariance so…



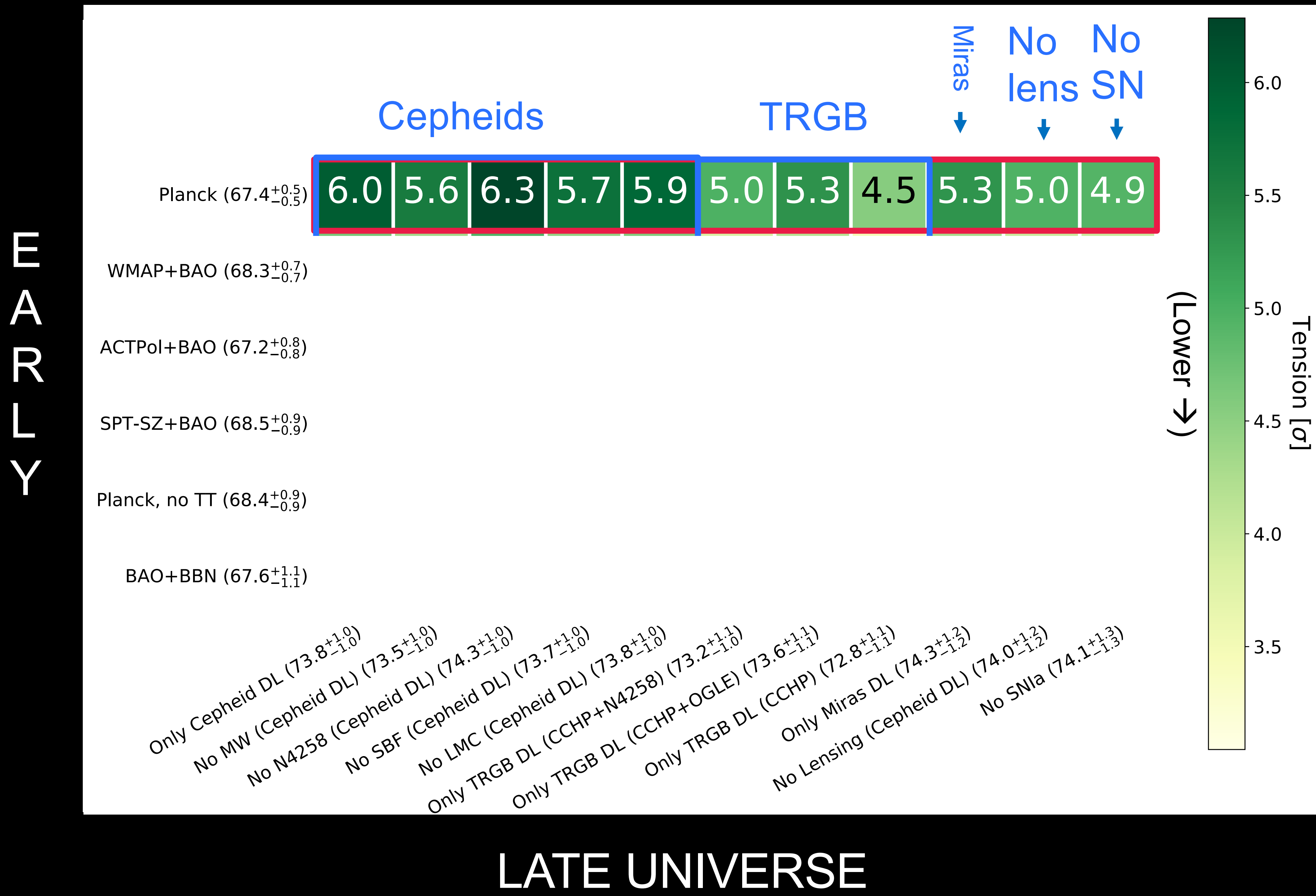
Late Universe
Prix Fixe Menu

One from 1
+ One from 2
+3
+4
- one peremptory challenge

*includes 7th lens from Shajib+2019

The Tension Matrix

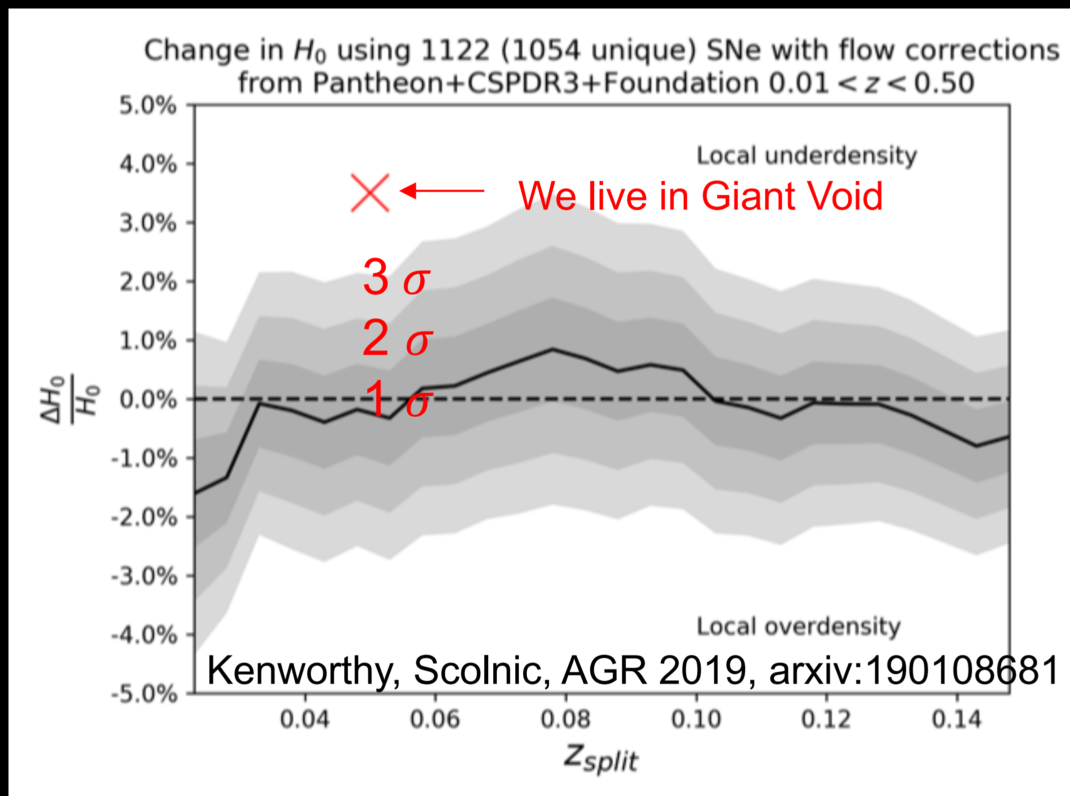
Review by Verde, Treu, Riess (2019)



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)

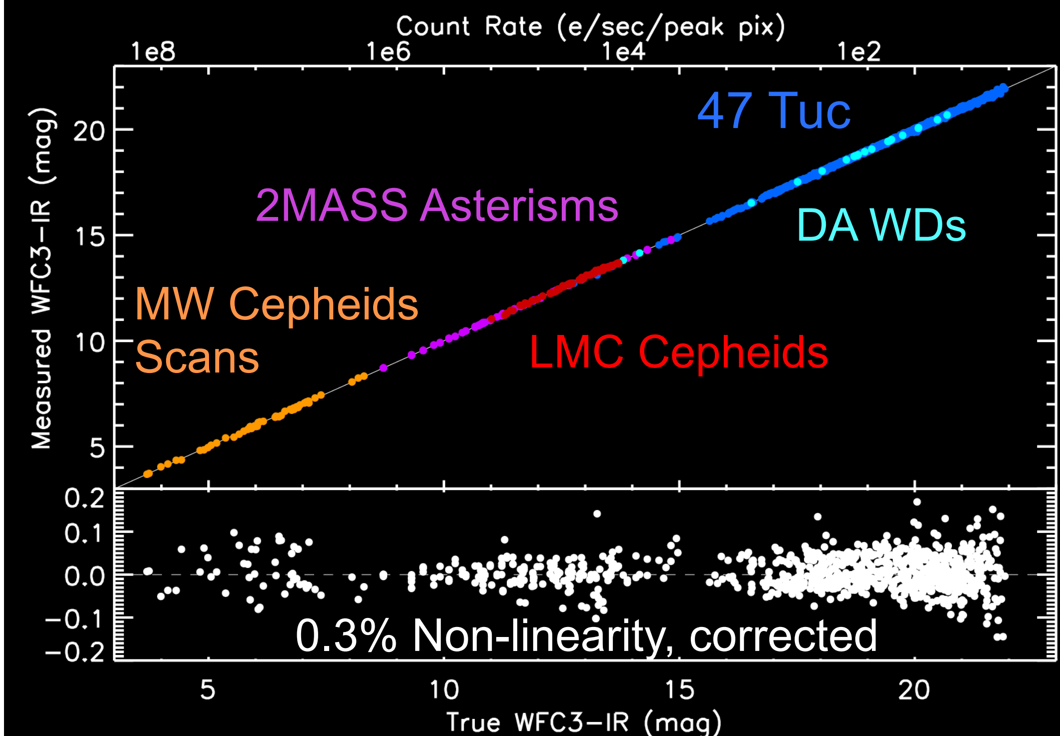
Planck=+9%

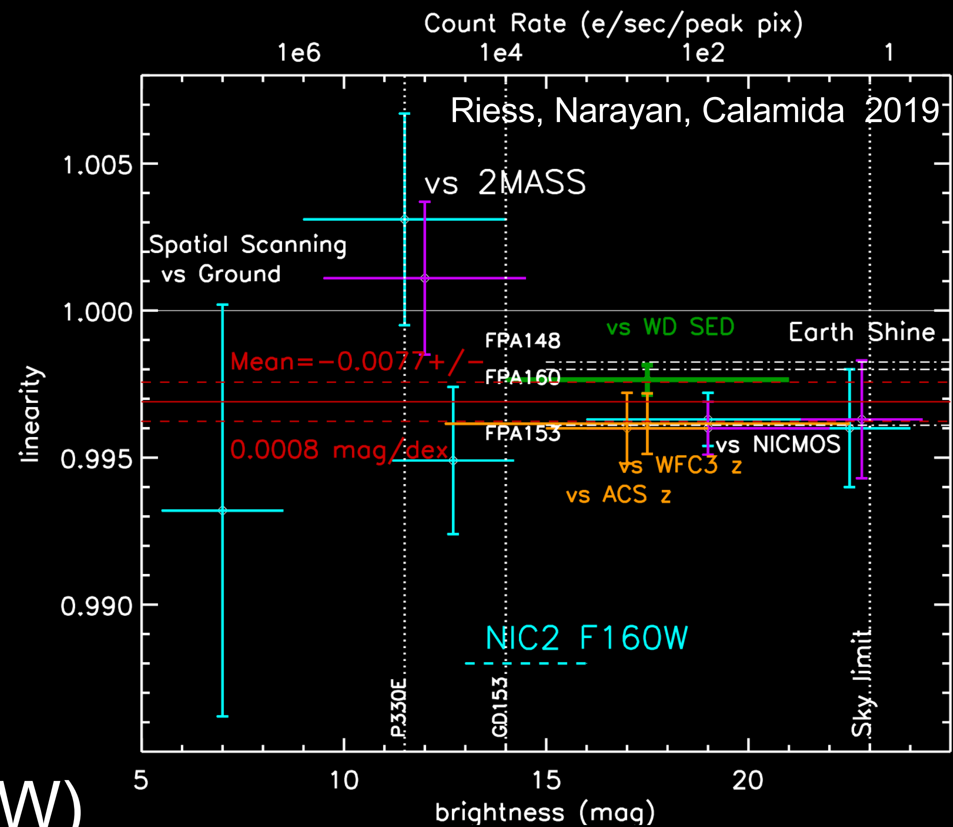


Suggestion we live in 3.5% H_0 void (z<0.07; KBC 2013, Shanks et al. 2018), SN data rejects 4.5 σ

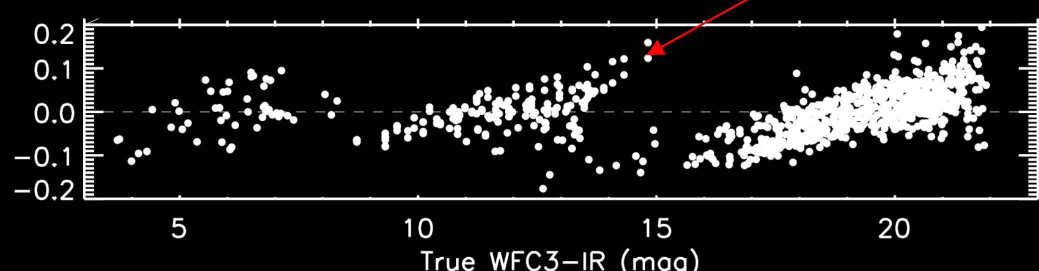
FAQ: Is HST WFC3-IR Flux Scale Linear to 1%?

"Flux Calibration Ladder"





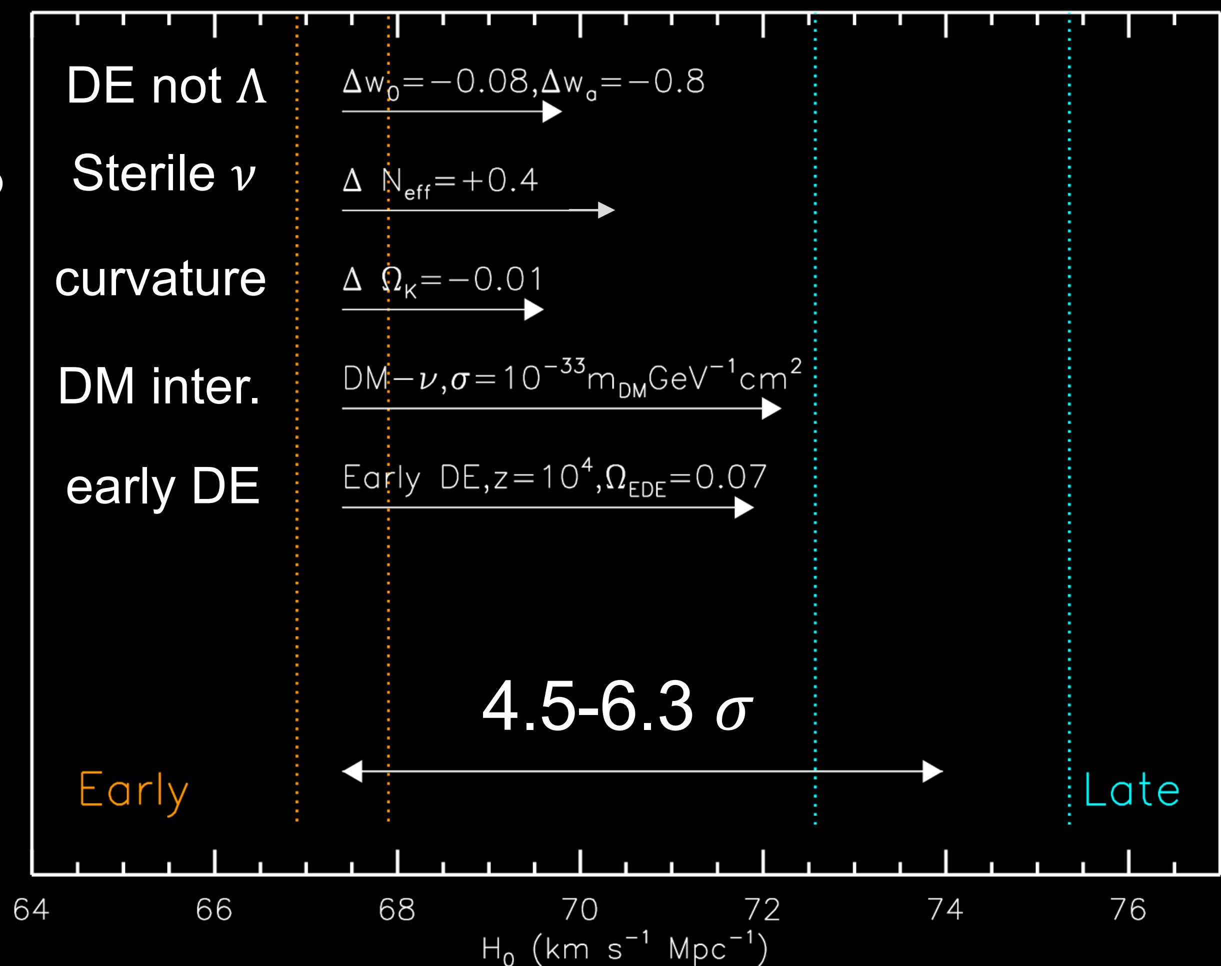
if 3.0% Non-linearity (NIC2 F110W)



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

Cause Early vs Late Difference? Newton: “Feign No Hypothesis”

NEW PHYSICS ?



“The Hubble Hunter’s Guide”, Knox and Millea, 2019: “Most Likely”: Increase Expansion Rate Pre-recombination->reduce sound horizon by 5-8%

Claims: better fit to CMB (not worse!), new CMB features

New idea 04/28/20: small-scale, mild non-linear inhomogeneities in the baryon density shortly before recombination, see arXiv:2004.09487

Can We Believe Measurements without Explanation?

Don't sweep "problems" under the rug

"Problems" are often clues!

~~Precession of Mercury~~ Solved!

~~Solar Neutrino Problem~~ Solved!

~~Missing Baryon Problem~~ Solved!

Lithium Problem

CMB Cold Spot

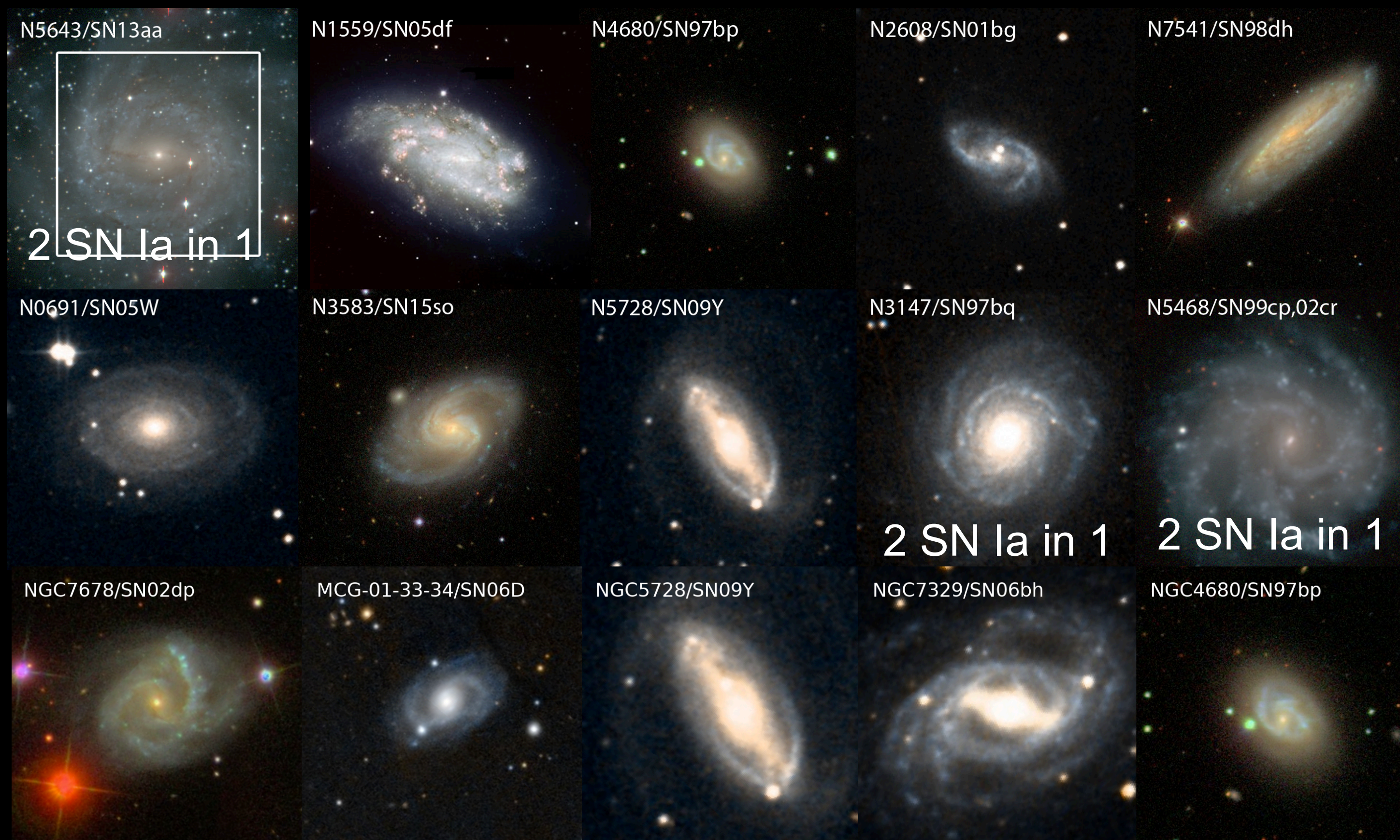
Flat rotation curves/
what/where is dark matter?

Accelerating Universe/
why Λ so small?

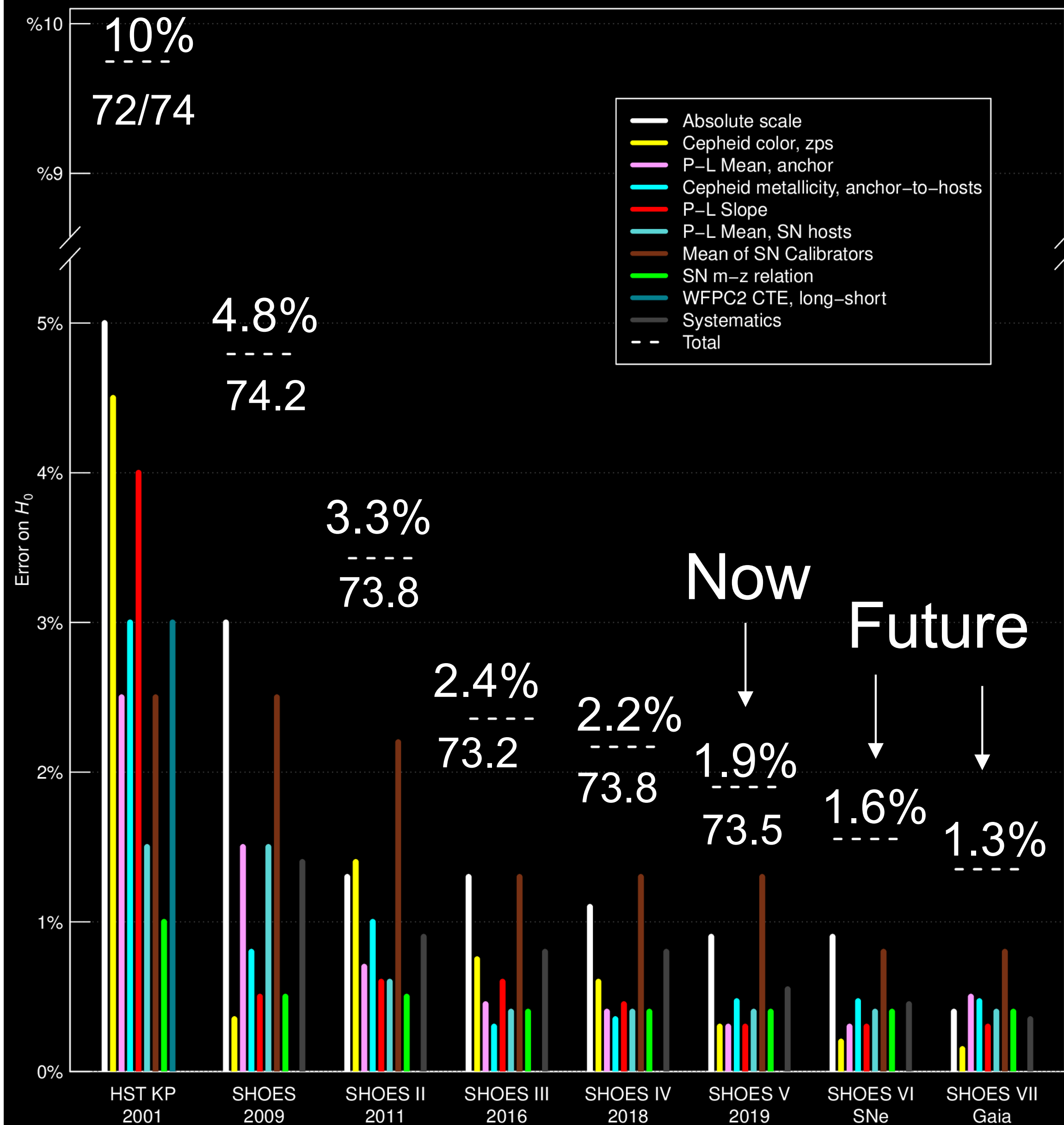
Next Steps: Increasing Number of SN-Cepheid Calibrations

NEW SHOES Large HST Programs, Cycles 25,26

19 more Cepheid-SN Ia Calibrators underway, to reach total=38



Future Prospects…



- **New low-z SN samples**
- **Doubling SN Calibrator sample, 19→38 (2020)**
- **Gaia DR3 (2020?)**
- LIGO H_0 (Late Universe)
- DESI,LSST,WFIRST,Euclid →better w(z)
- Next generation CMB: signatures (e.g., EDE)
- Stay tuned…

Final Thoughts

- Discrepancy is ~5σ (4-6) σ (depending on combination)
  No Late Universe measurements lower than any Early
- Its Robust, requires multiple catastrophic failures to avoid
- Very interesting! (unless your Bayesian prior on ΛCDM > 5 σ)
- Feign No Hypothesis, let's follow evidence!
- Universe may be more clever than we are *now*