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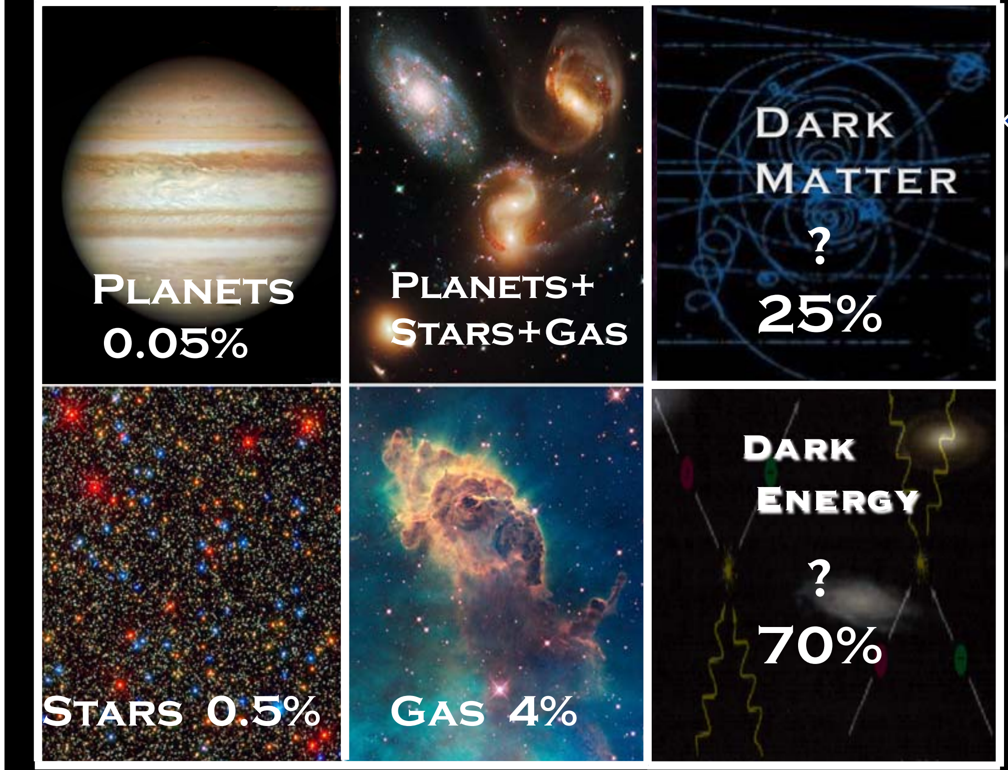
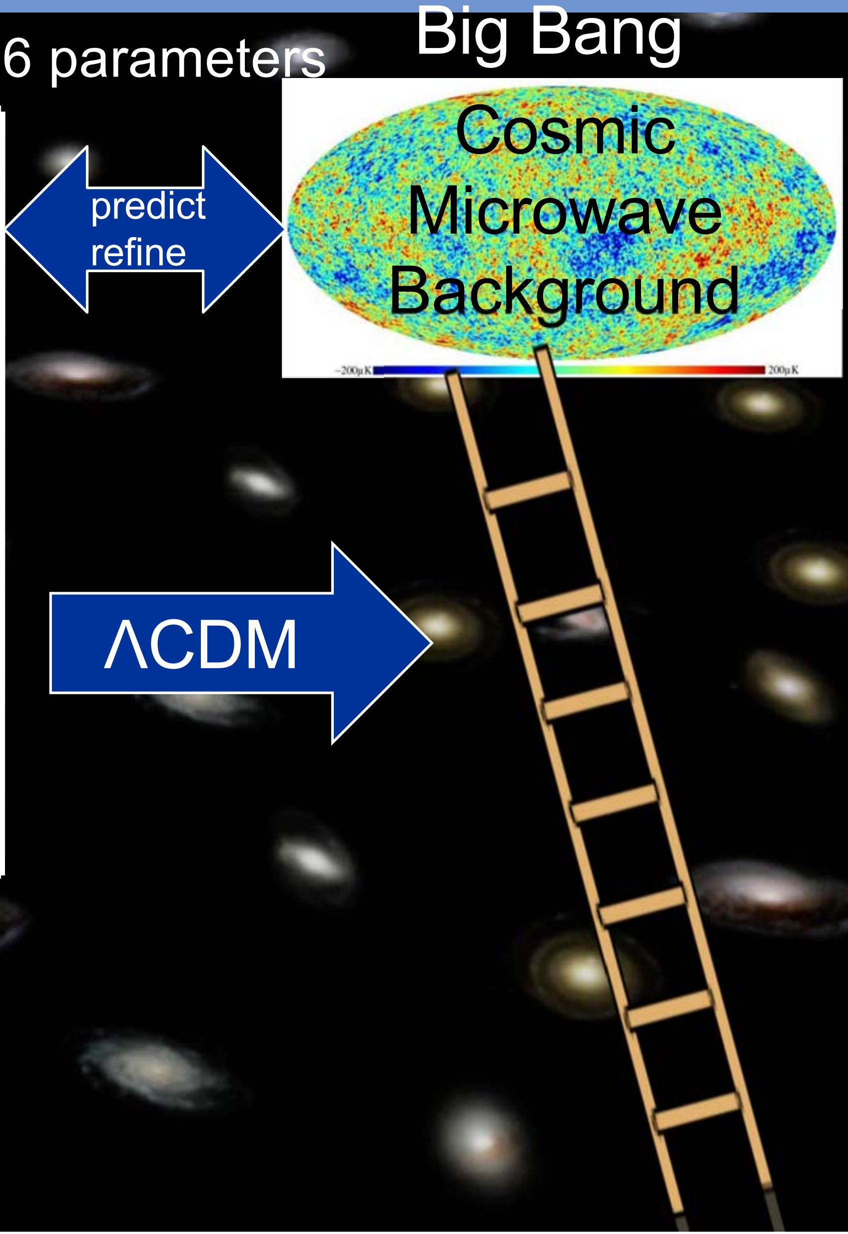
A New Measurement of the Expansion Rate of the Universe, Hints of New Physics?

SH$_0$ES Team

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

Standard Model of Cosmology, ΛCDM, 6 parameters





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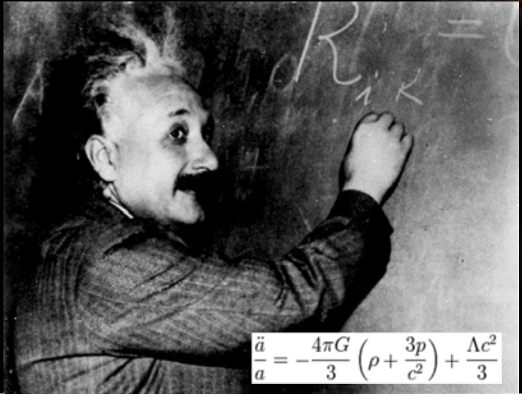


$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}\left(\rho+\frac{3p}{c^2}\right)+\frac{\Lambda c^2}{3}$$

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

A Direct, Local Measurement of H_0 to percent precision

The SH_0ES Project (2005)

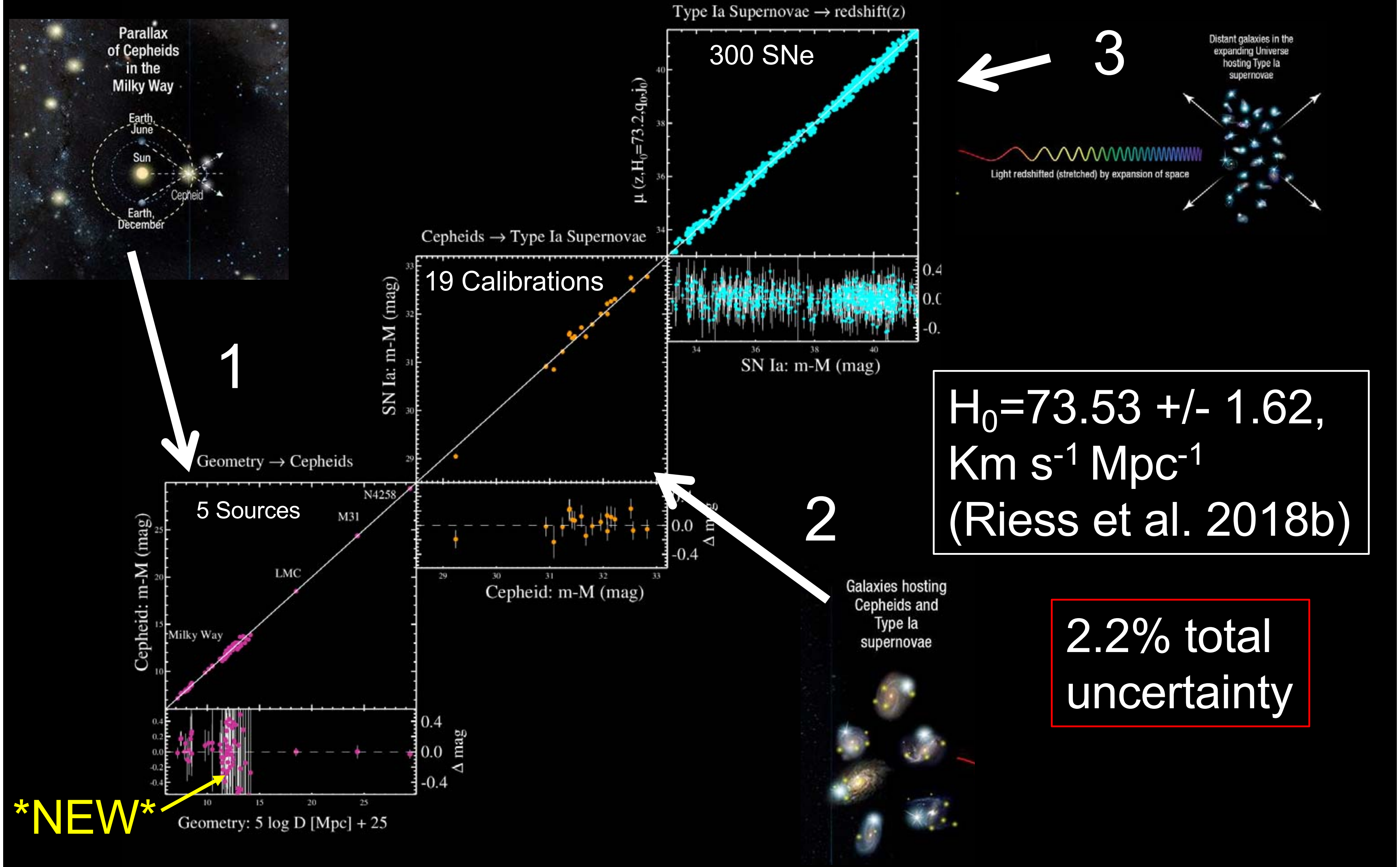
(Supernovae, H_0 for the dark energy Equation of State)

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

Measure H_0 to ~1% percent precision empirically by:

- A clean, simple ladder: Geometry → Cepheids → SNe Ia
- Reducing systematic error with better data, better collection
- Thorough propagation of statistical and systematic errors

The Hubble Constant in 3 Steps: Present Data

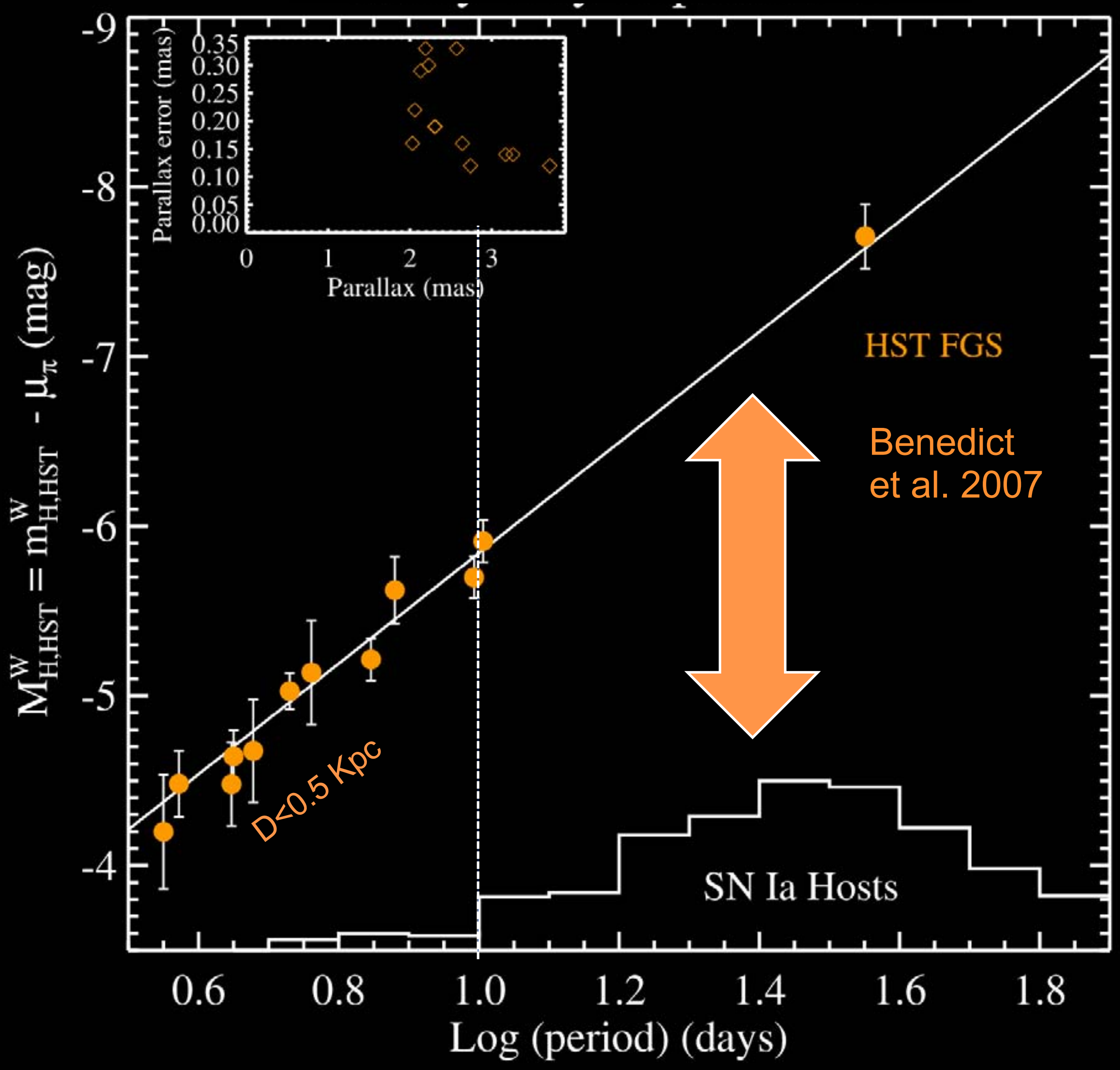


H_0=73.53 +/- 1.62, Km s^{-1} Mpc^{-1} (Riess et al. 2018b)

2.2% total uncertainty

Step 1: The Milky Way Cepheid P-L Relation

Milky Way PL Relation

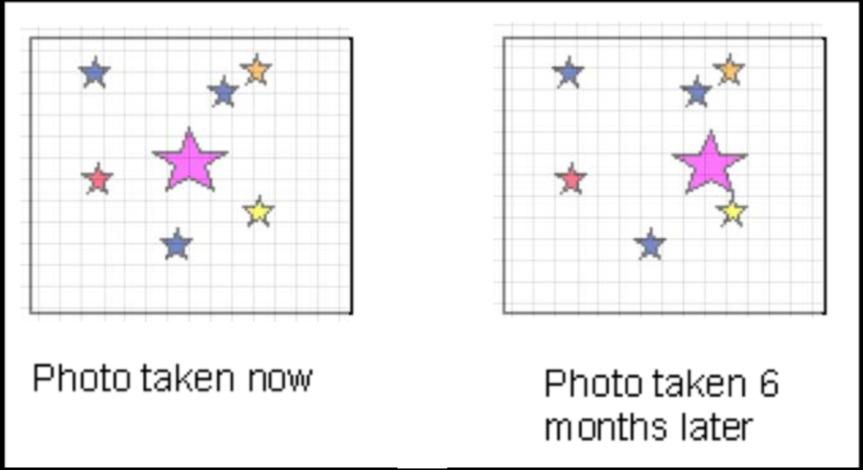


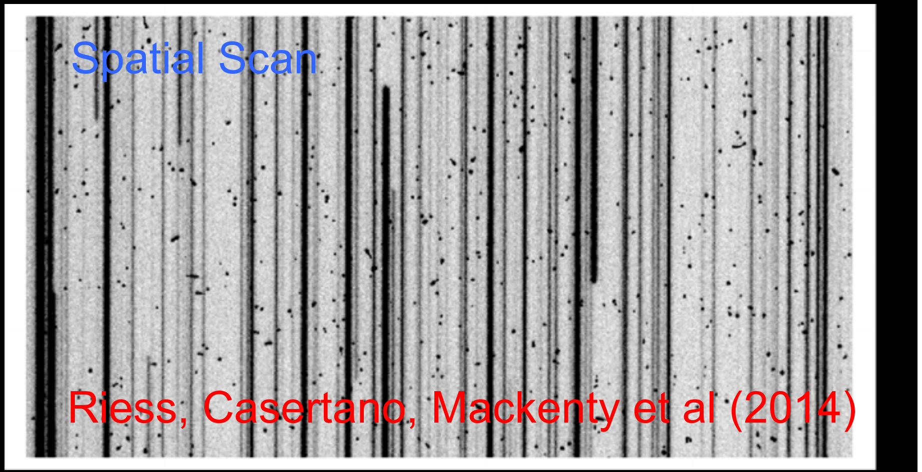
Two Potential Systematics:

- Difference in mean period, MW vs SN Ia hosts
- Inhomogeneous Cepheid photometry, MW vs SN Ia hosts

Most long period Cepheids D>2 Kpc requires higher precision parallaxes

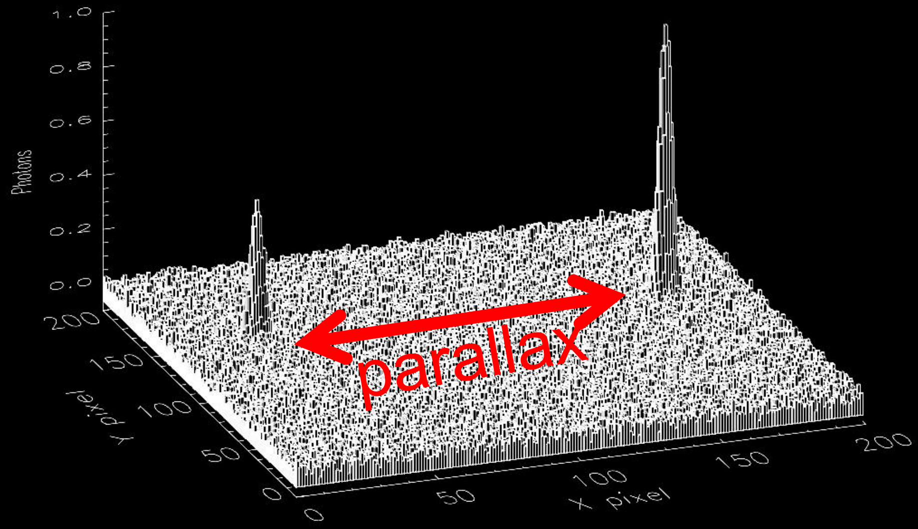
Extending Parallax with HST WFC3 Spatial Scanning

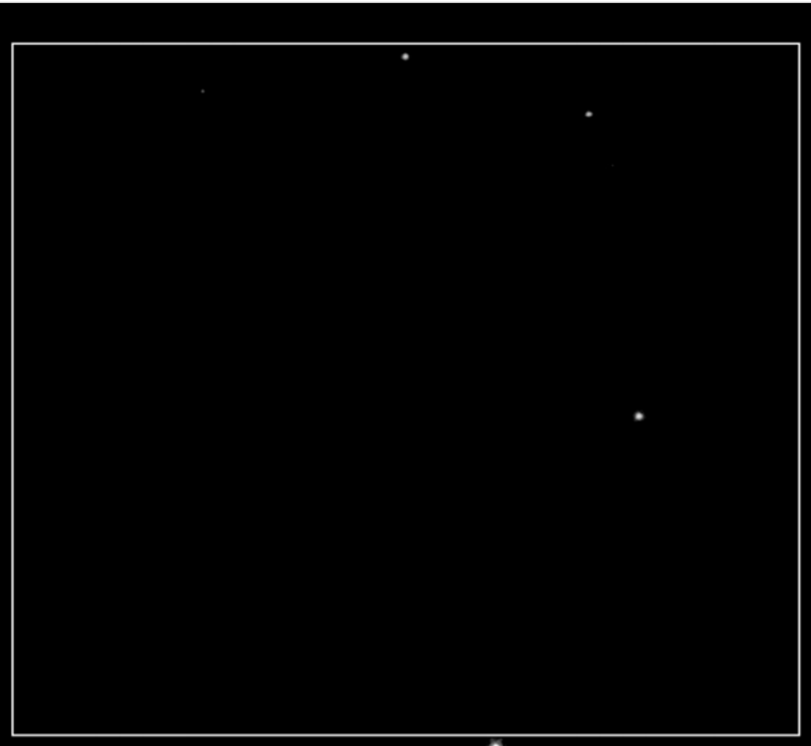




Riess, Casertano, Mackenty et al (2014)

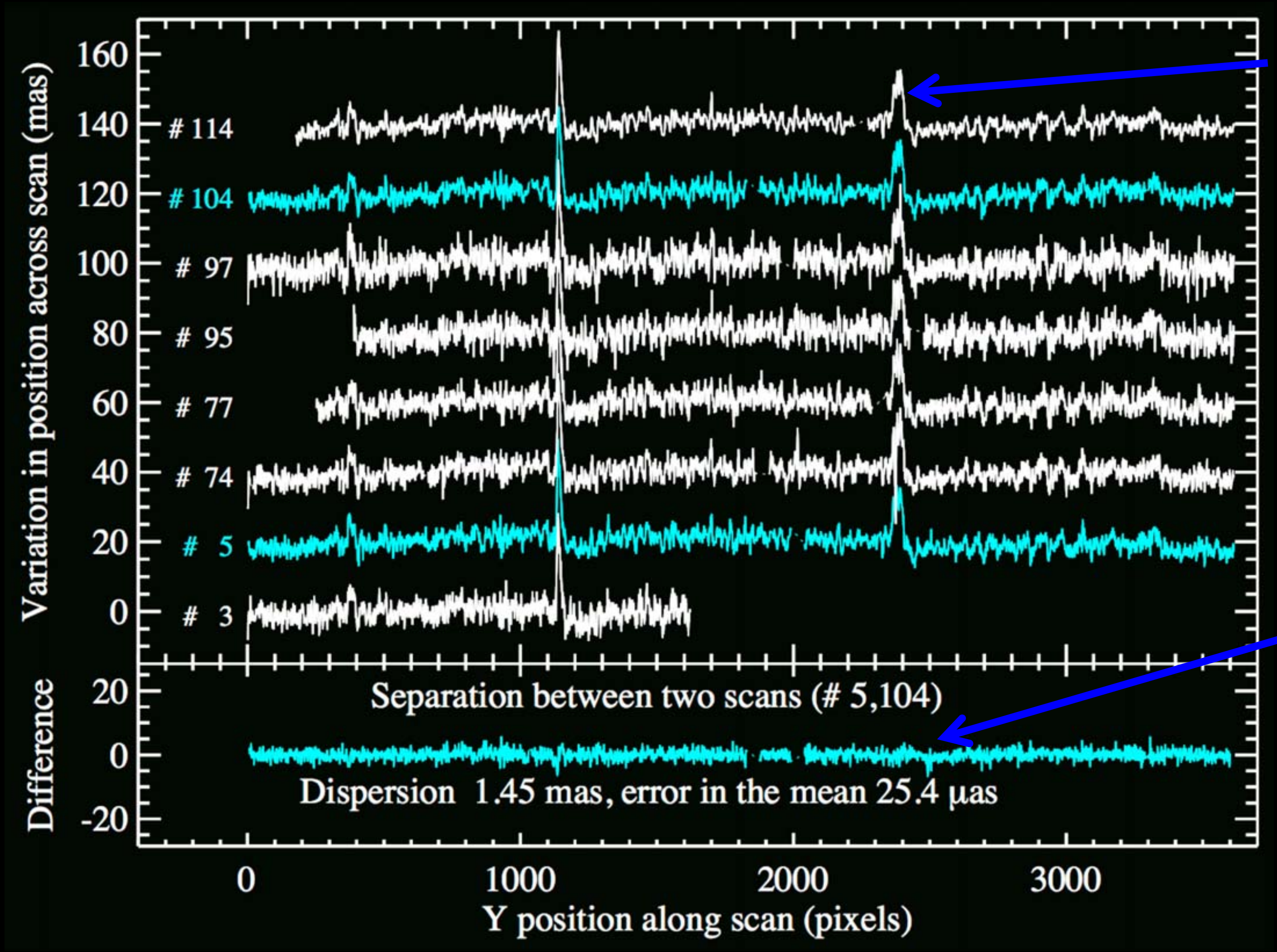
Imaging: astrometry σ_θ=0.01 pix
HST: 0.4mas, ~1σ @ 2 kpc





Two Features of Spatial Scans: Sampling and Jitter Removal

Extracted scan lines of stars from a single scan



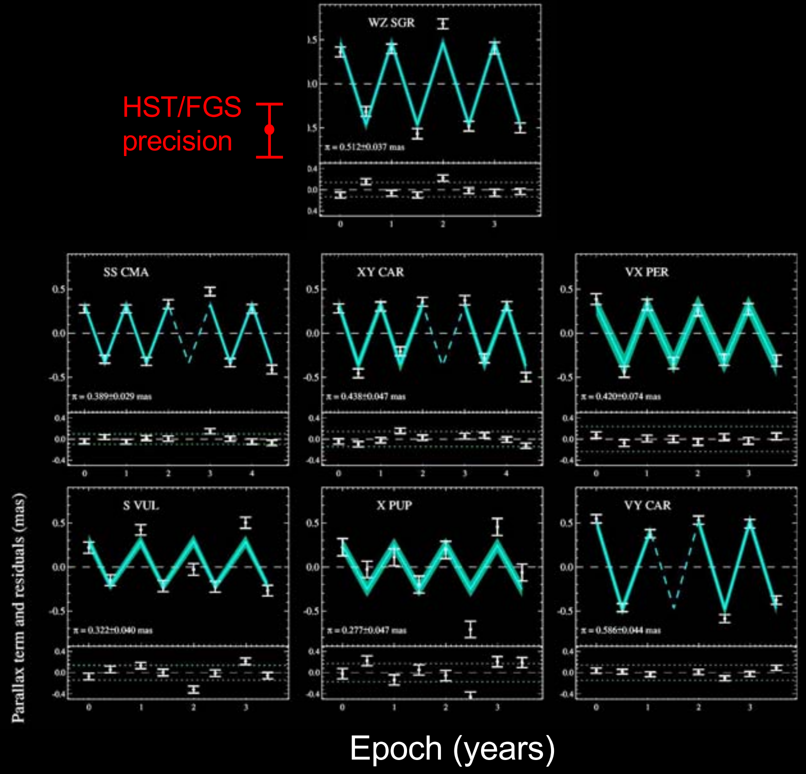
Jitter between lines is *coherent*, subtracted in line separations (vs time)

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

Reaching 20-40 μas

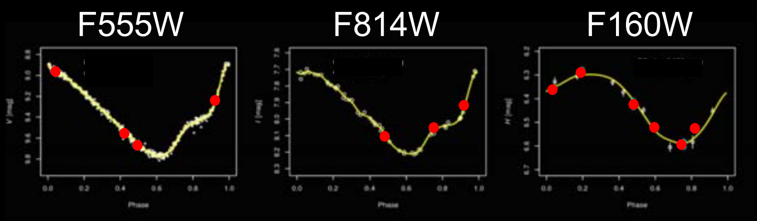
4 Years Later, New Parallaxes 8 Milky Way Cepheids, 3% Error in Mean

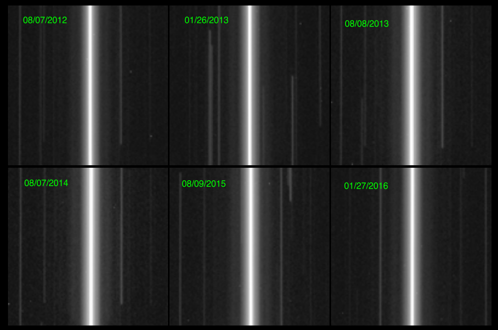
4 Years Later: Proper Motion subtracted,
8 MW Cepheid Parallax measurements
1.7<D<3.6 Kpc, error in mean=3.3%



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

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



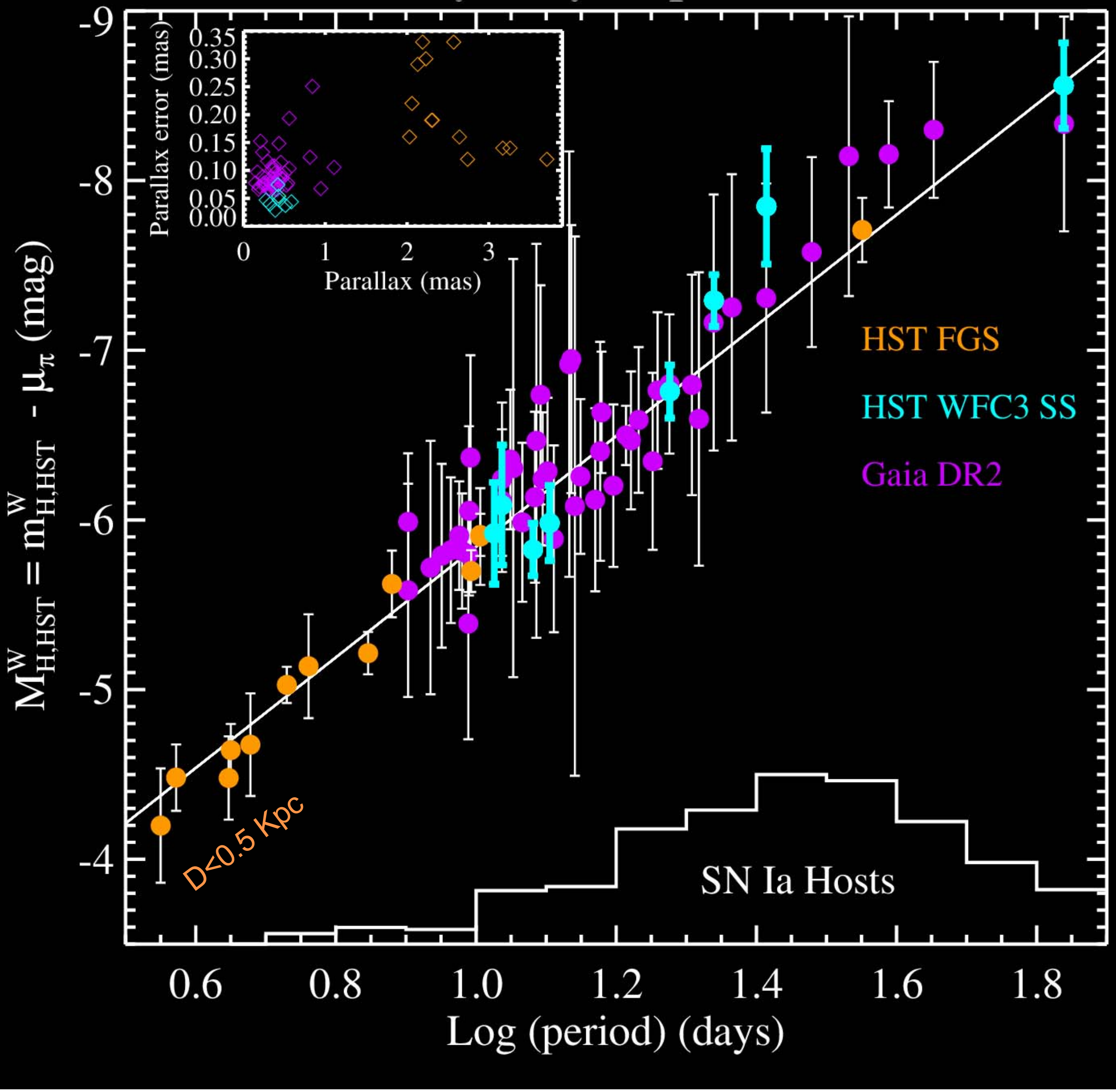


Fast Scans 7.5”/s exp time~0.01 sec
Error individual Cepheid mean D<1%

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

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

Milky Way PL Relation



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

} with 3 band HST photometry
and
Periods > 10 days both matching Cepheids HST sees in SN Ia hosts

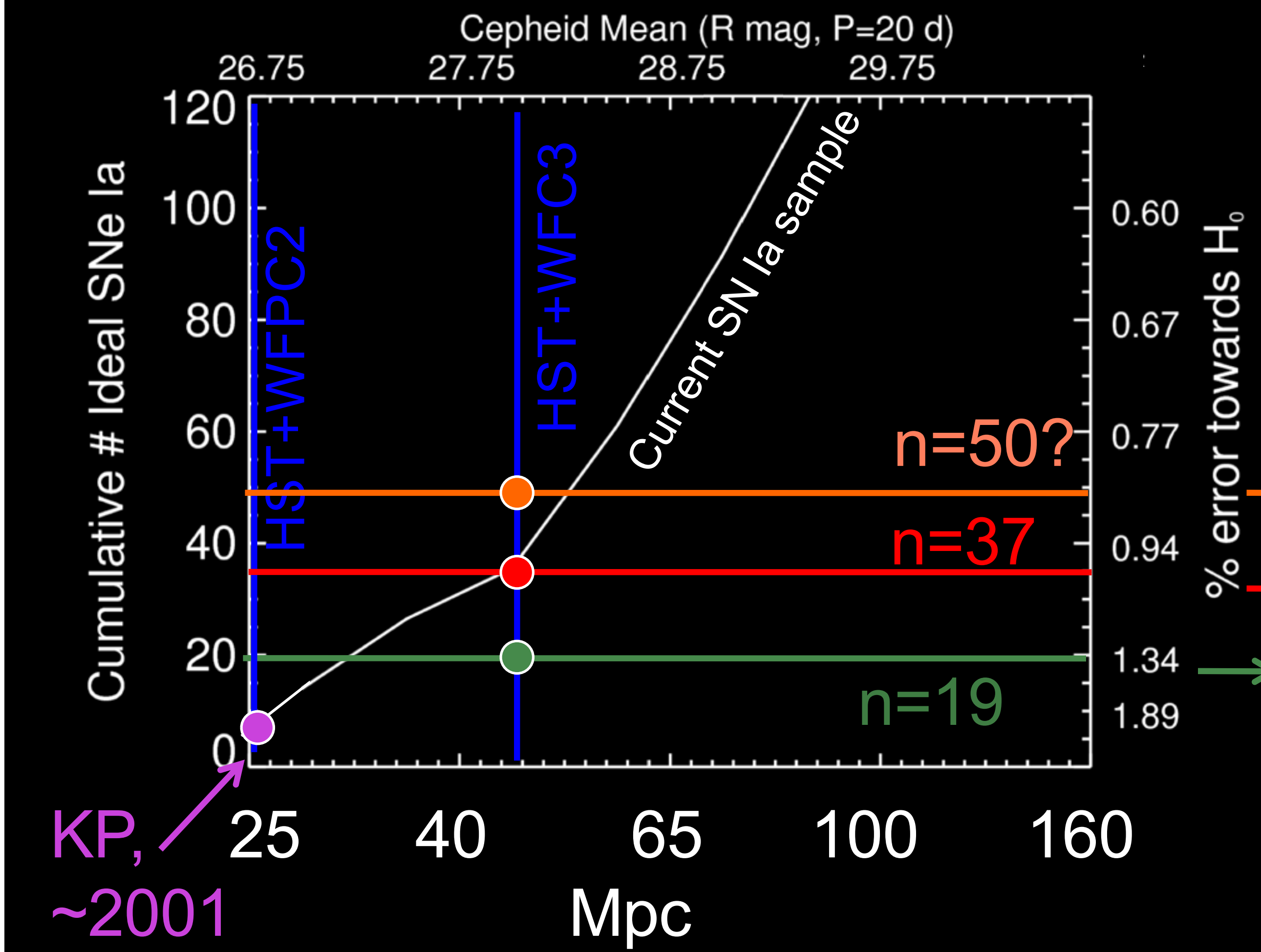
Step 1: Five Sources Geometric Cepheid Calibrations

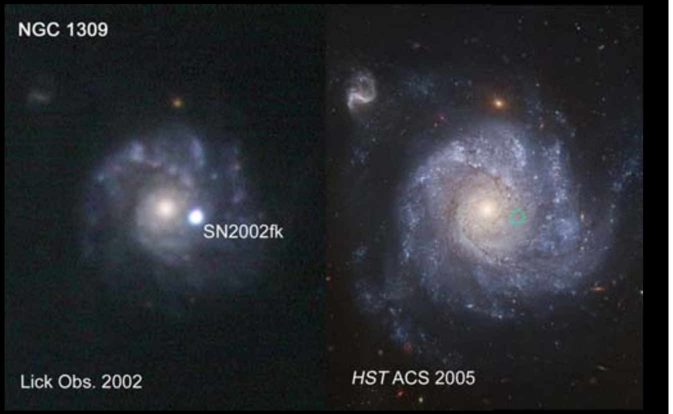
	Independent Geometric Source	σ	H_0
	NGC 4258 H_20 Masers: Humphreys et al 2013, Riess et al 2016	2.6%	72.3
	LMC 8 Late Detached Eclipsing Binaries: Pietzrynski et al. 2013	2.5%	72.0
	Milky Way 10 HST FGS Short P Parallaxes: Benedict et al. 2007 --also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2
NEW	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, *Independent Systematics*

Step 2: Cepheids to Type Ia Supernovae

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



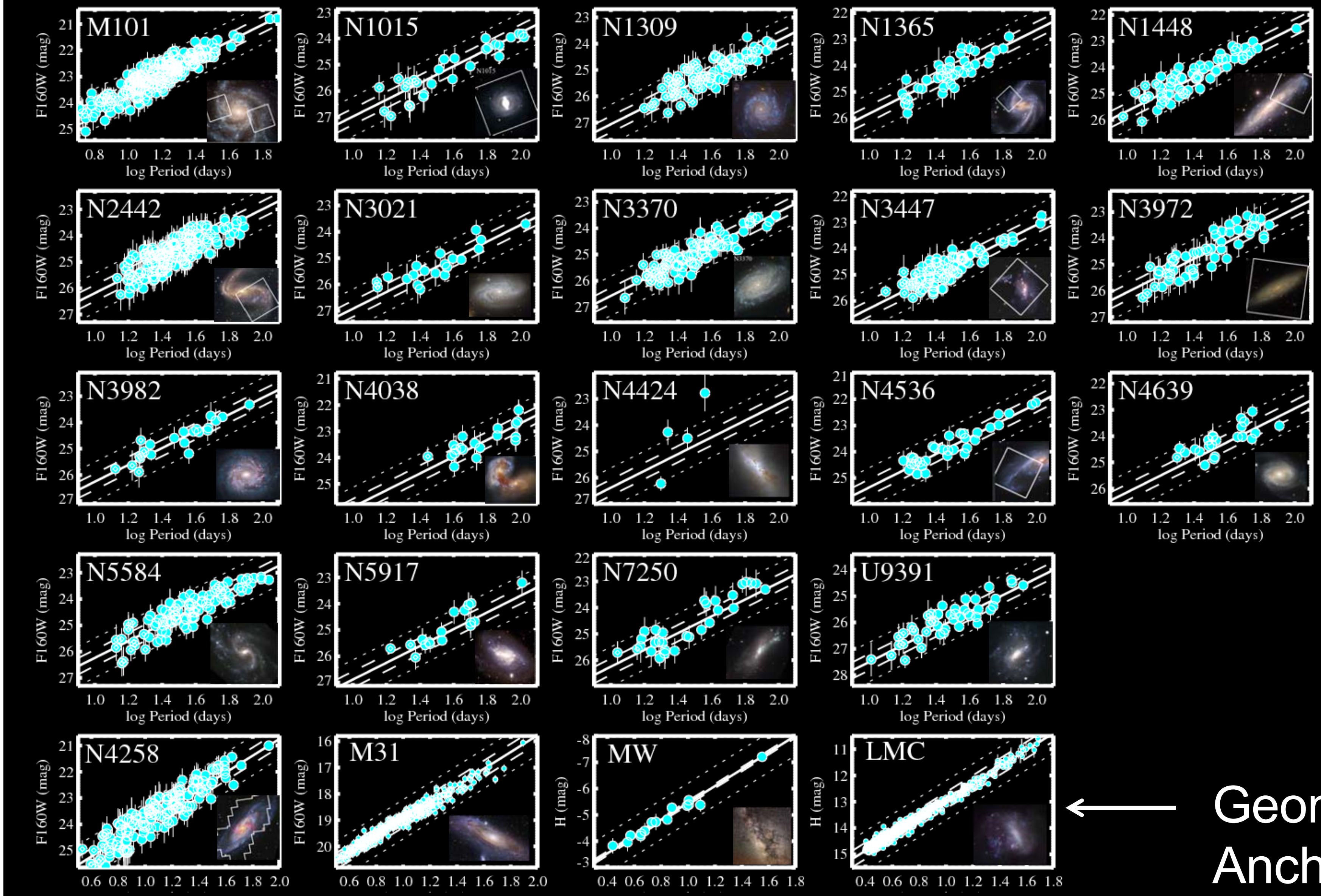


→ **HST Final? (0.8%)**

→ Next (Cycle 25/26, 0.9%)

→ Now (Cycle 20 R16,1.3%)

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



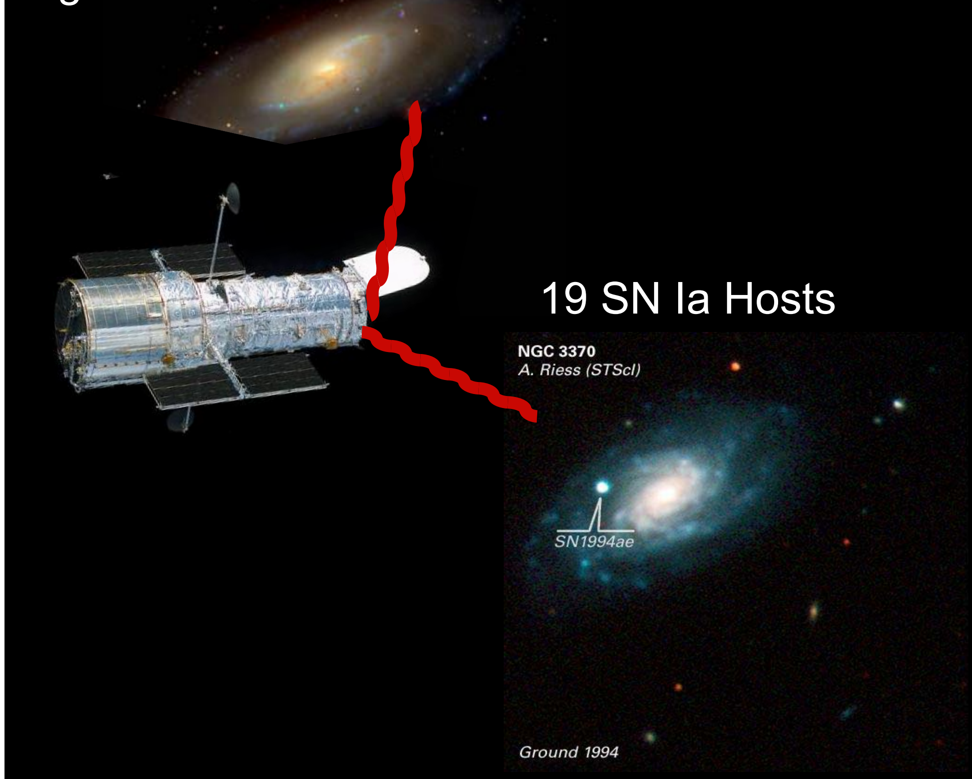
SN HOSTS

Geometric Anchors

Lower Systematics from *Differential* Flux Measurements

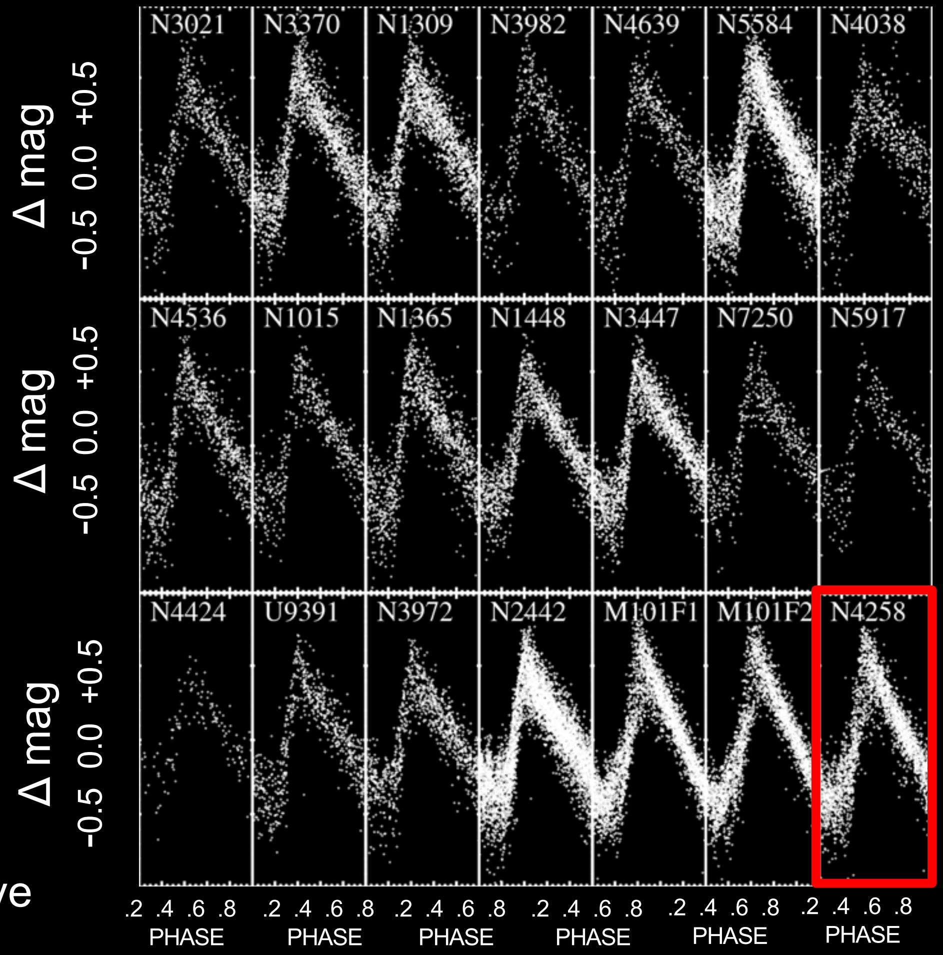
We reduce systematic errors by measuring all Cepheids with
same instrument, filters, similar metallicity, period range,
we correct for crowding and dust statistically

ANCHORS: NGC 4258 (and now MW, LMC)
geometric distance



19 SN Ia Hosts

Cepheid composite LC's, >2400



All photometry in R16, all images in MAST archive

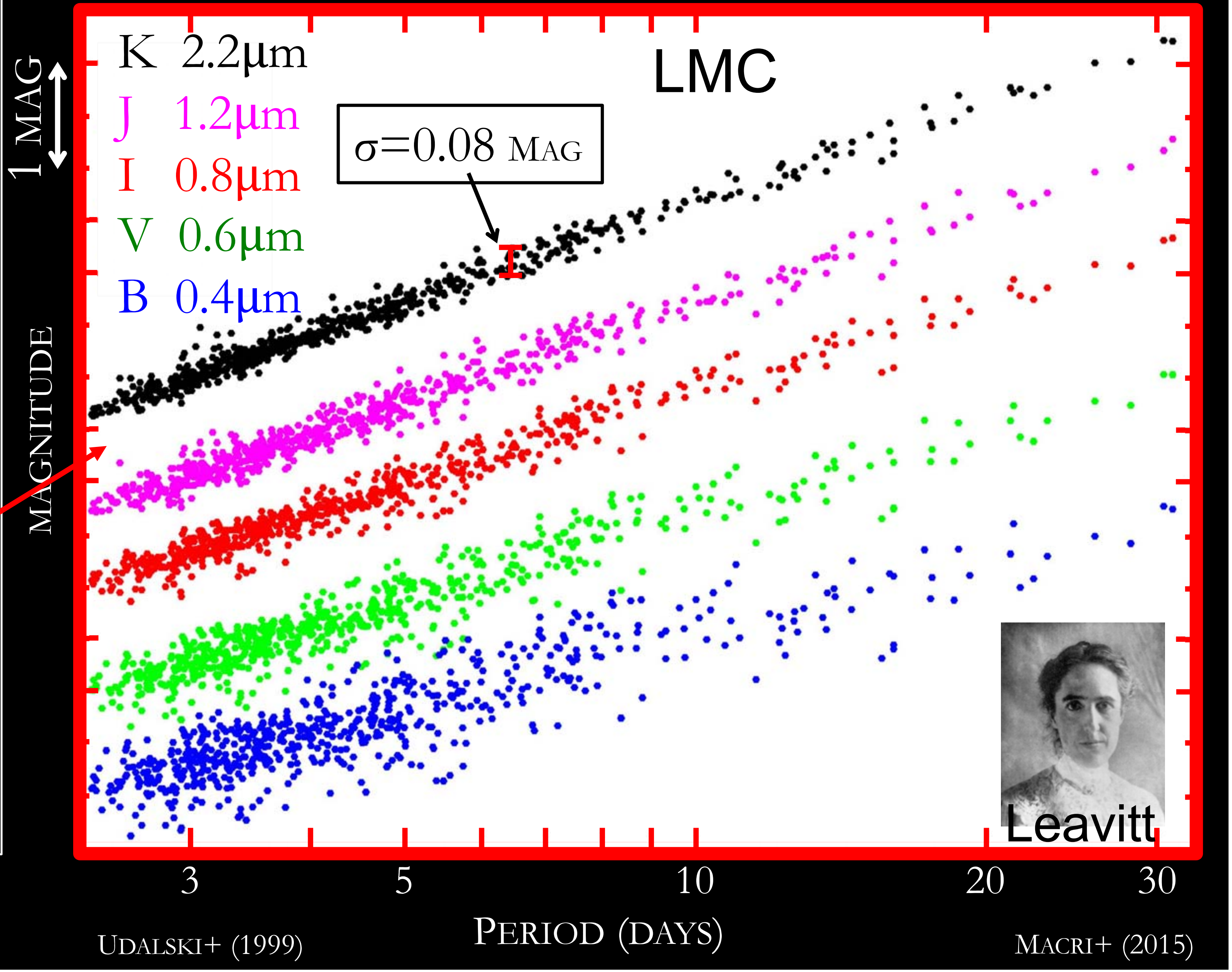
Lowering *Systematics* with Near-IR Cepheid Observations

-Negligible sensitivity to metallicity in NIR

-Dependence on reddening laws 6x smaller than optical

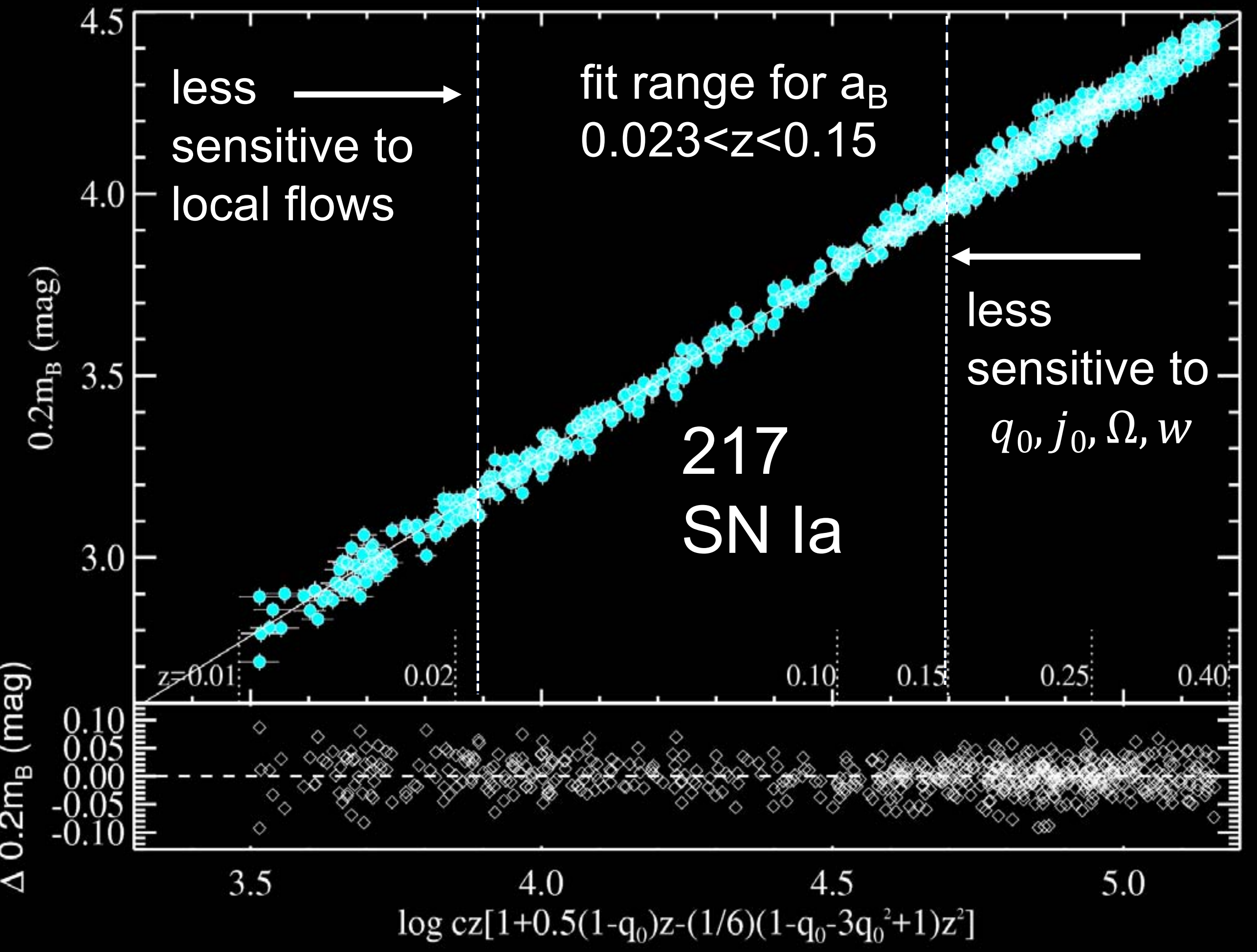
We use H-band as primary +V,I

Key Project used V and I



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



less → sensitive to local flows

fit range for a_B 0.023<z<0.15

217 SN Ia

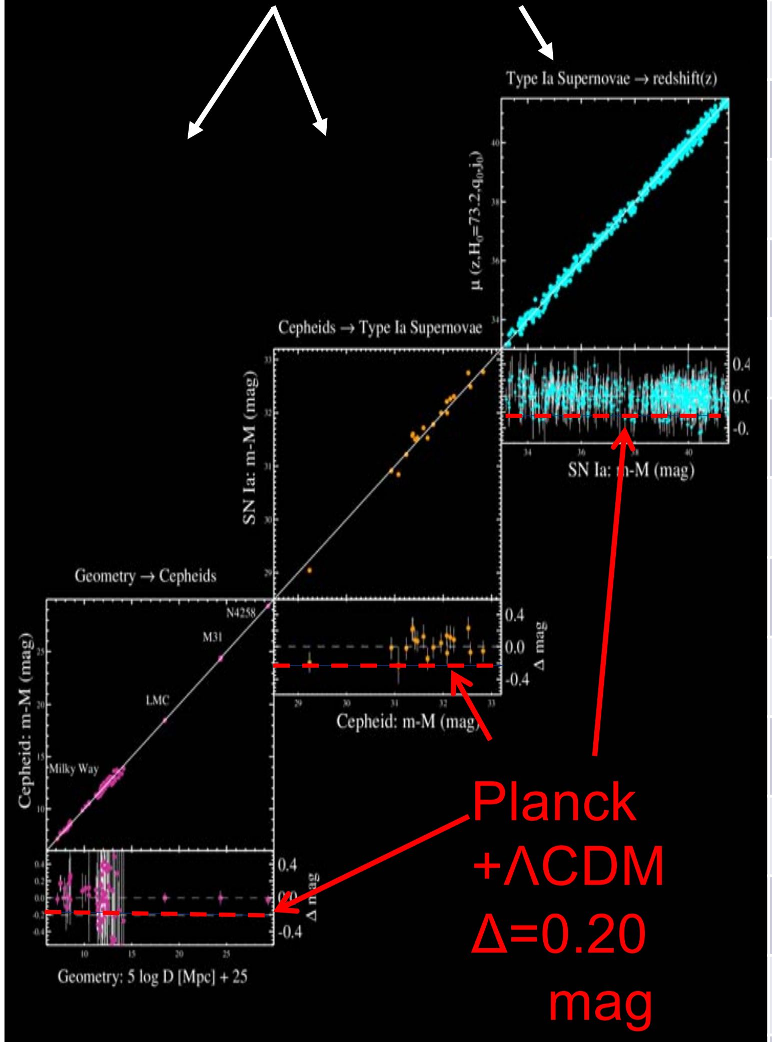
← less sensitive to q_0, j_0, Ω, w

a_B=0.71273 +/- 0.00176 (units log H_0), 217 SNe Ia 0.023<z<0.15, q_0=-0.55, j_0=1
(see Burns et al. 2018-similar results with CSP SN sample, different SN fitter)

Systematics R16: 23 Analysis Variants

Best Fit:

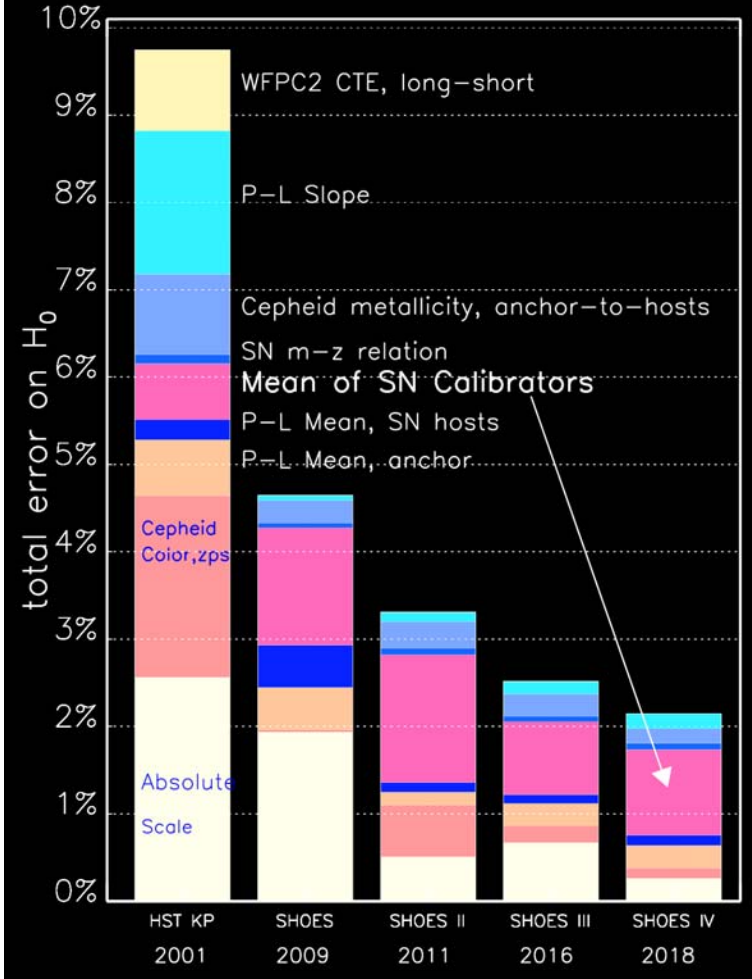
$5\log H_0 = M_B^0 + 5a_B + 25$



Planck +ΛCDM Δ=0.20 mag

Analysis Variants	H_0
Best Fit (R16, w/ HST,Gaia , R18=73.53)	73.24
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.15
Reddening Law: Bulge-like (N15)	73.39
No Cepheid Outlier Rejection (normally 2%)	73.49
No Correction for Cepheid Extinction	74.79
No Truncation for Incomplete Period Range	74.39
Metallicity Gradient: None (normally fit)	73.30
Period-Luminosity: Single Slope	73.26
Period-Luminosity: Restrict to P>10 days	71.64
Period-Luminosity: Restrict to P<60 days	73.06
Supernovae z>0.01 (normally z>0.023)	73.38
Supernova Fitter: MLCS (normally SALT)	74.39
Supernova Hosts: Spiral (usually all types)	73.37
Supernova Hosts: Locally Star Forming	73.54
Cepheid Measurements: Optical Only	71.74

Error Budget for H_0 from 2016; 2.4% uncertainty, 2018: 2.2%



2.2% Total Uncertainty

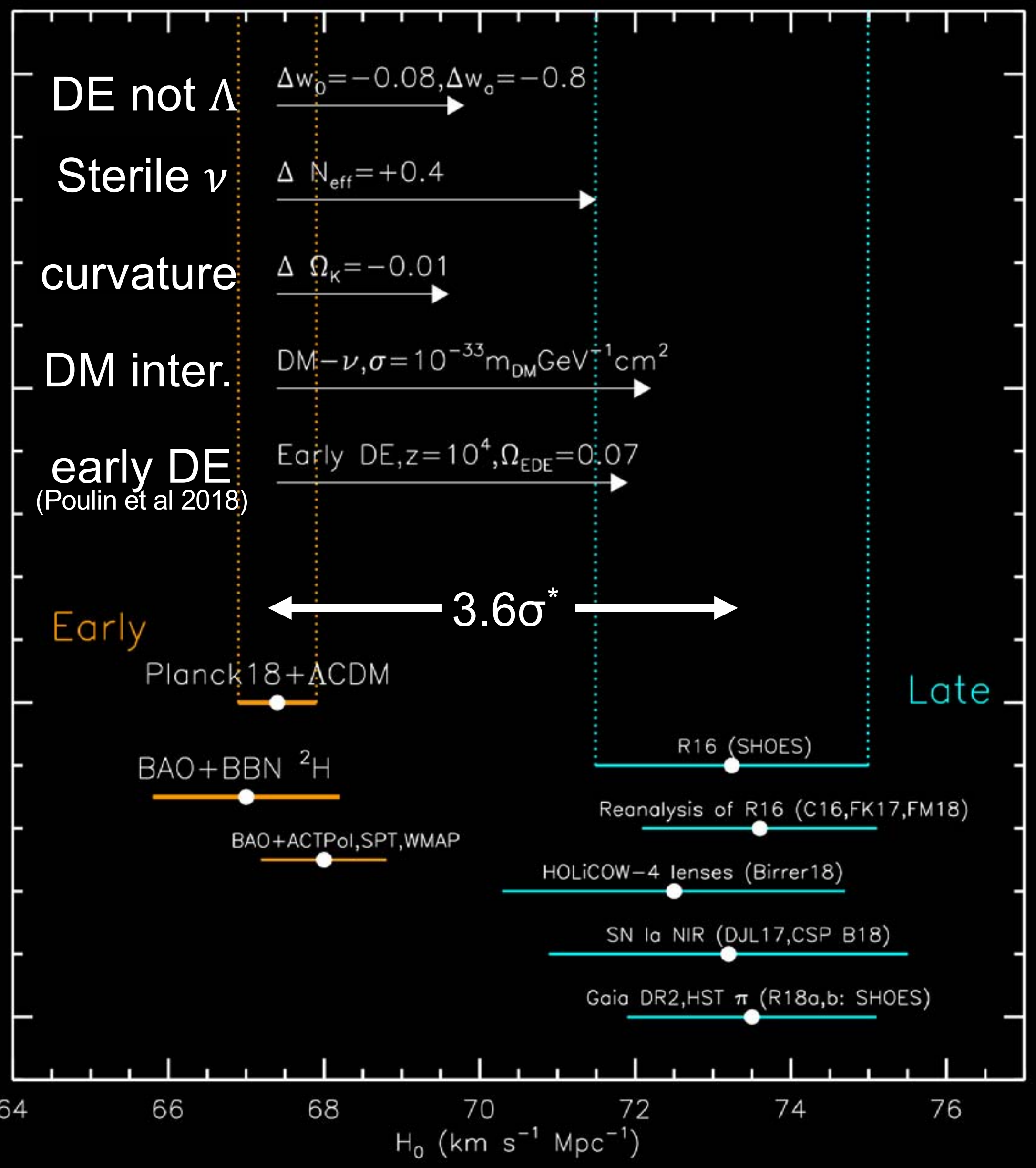
TERM		KP LMC %	R09 4258 %	R11 ALL %	R16 ALL3* %	R18 ALL3* %
ANCHOR DISTANCE	🟨	5.0	3.0	1.3	1.3	1.3
CEPHEID REDDENING, ZPTS (ANCHOR-TO-HOSTS)	🟧	4.5	0.3	1.4	0.3	0.3
P-L SLOPE, D LOG P (ANCHOR-TO-HOSTS)	🟦	4.0	0.5	0.6	0.5	0.5
CEPHEID METALLICITY (ANCHOR-TO-HOSTS)	🟦	3.0	1.1	1.0	0.5	0.5
WFPC2 CTE, LONG-VS-SHORT ZEROPOINTS	🟨	3.0	--	--	--	–
MEAN OF SN IA CALIBRATORS	🟪	2.5	2.5	1.9	1.2	1.2
MEAN OF P-L IN ANCHOR	🟧	2.5	1.5	0.8	0.7	0.7
MEAN OF P-L IN SN HOSTS	🟦	1.5	1.5	0.6	0.4	0.4
SN IA M-Z RELATION	🟦	1.0	0.5	0.5	0.4	0.4
ANALYSIS SYSTEMATICS (FROM 23 VARIANTS)		NA	1.3	1.1	1.0	1.0
TOTAL, % ERROR H_0		**10**	**4.8**	**3.3**	**2.4**	**2.2**

SH_0ES, Riess et al 2005: 73.0 2009: 74.2 2011: 73.8 2016: 73.2 2018: 73.5
KP: (Freedman et al. 2001/12: 72.0/74.0)

How does this compare to the CMB measurements?

H_0 : Measured Late vs. Predicted from Early Universe

NEW PHYSICS



* >4 σ with constraint on Gaia DR2 zp offset

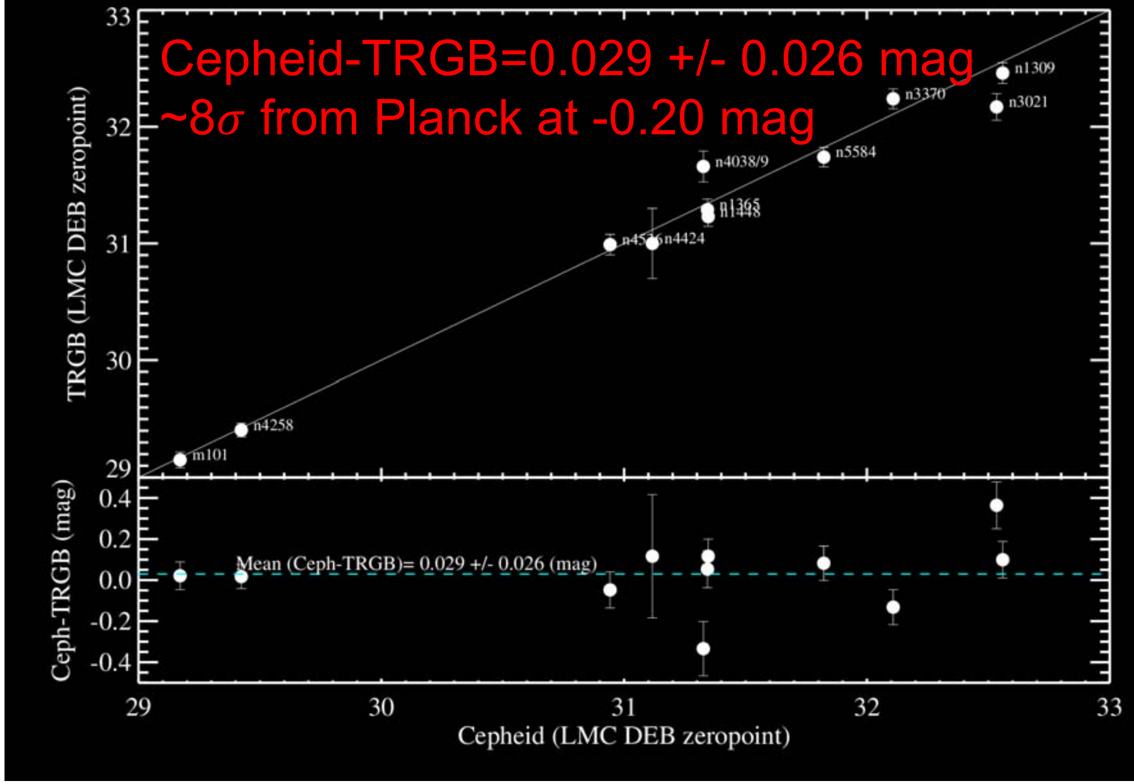
Cepheid Alternatives: VS. TRGB and VS O-rich Miras

Internal consistency: 5 tests <u>absolute</u> vs geometry, 19 tests <u>relative</u> vs. SNe Ia

Cepheids VS TRGB

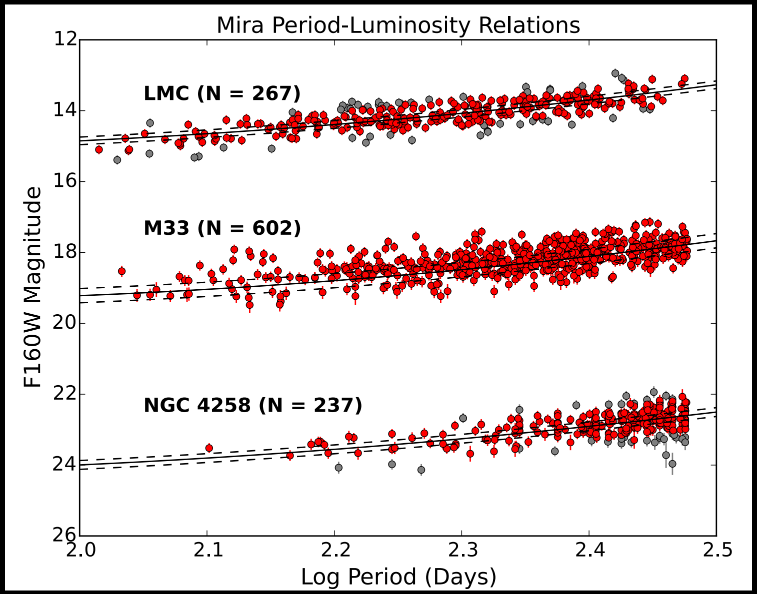
in 10 SN Ia Hosts + N4258

Cepheids: Riess et al. 2016,
TRGB: Hatt, WLF et al (2018),
Jang,Lee et al (2017/8), CCHP
using same zeropoint


Cepheid-TRGB=0.029 +/- 0.026 mag
~8σ from Planck at -0.20 mag

O-Rich Miras

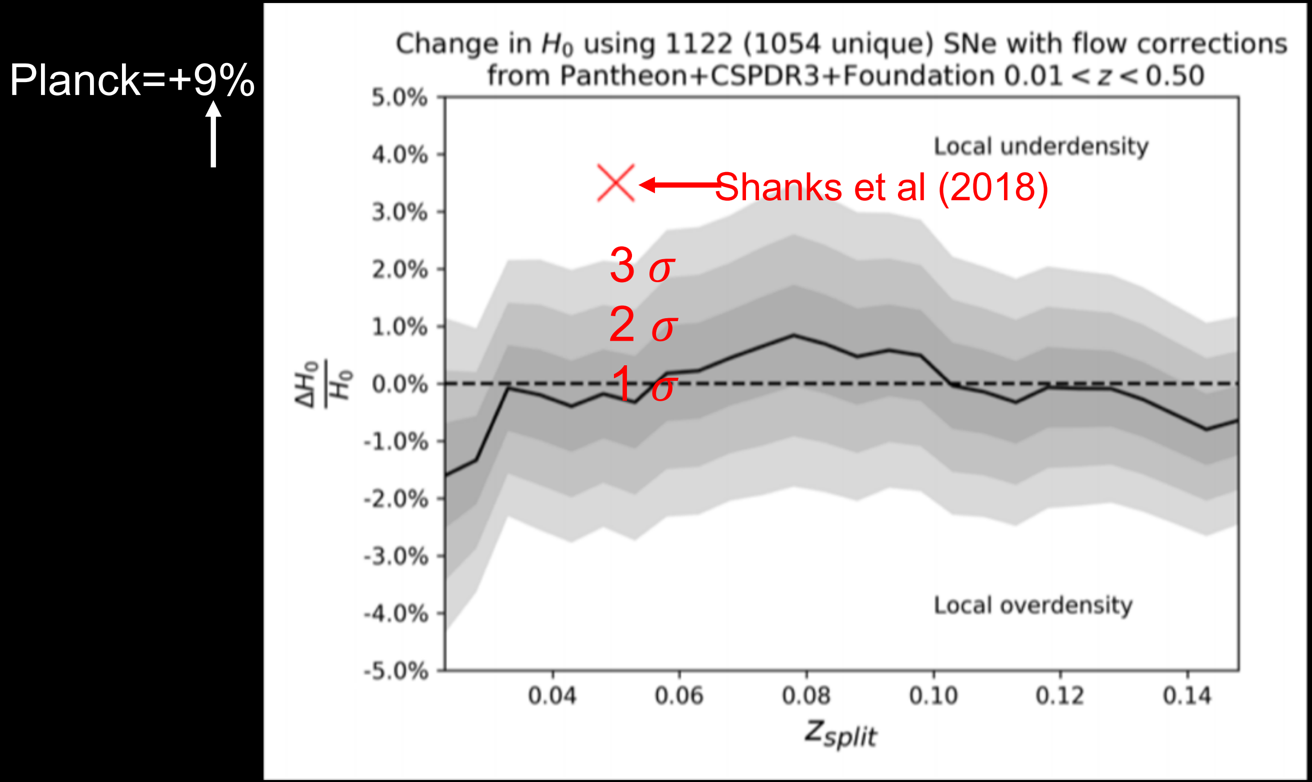
Variable AGB stars, large amplitudes, long periods



LMC to NGC 4258,
Consistent with Cepheids
Huang et al. (2018)
Miras in SN Ia hosts in prep

FAQ: Is local H_0 (0.0233<z<0.15) = global H_0? Yes to 0.5%

- We already correct for local (peculiar) flows derived from 2M++ density field
- Expect local-to-global ΔH_0 N-body sims in Gpc^3 box, SN, z → ΔH~0.3% Odderskov et al. (2016) and Wu & Huterer (2017)
- We can use SN Hubble diagram to look for change in H_0 with z

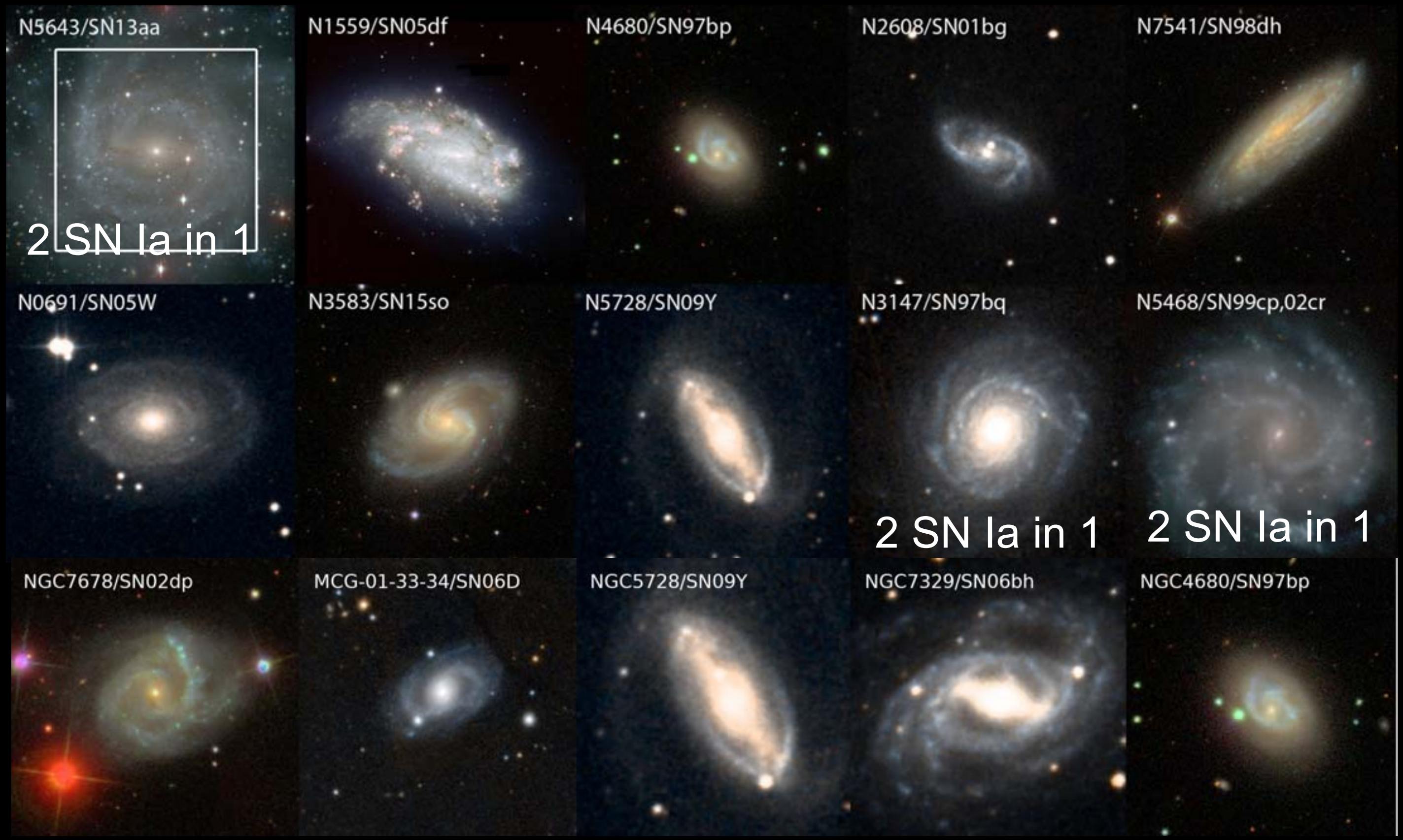


Kenworthy et al 2018,
In prep

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

Increasing Number of SN-Cepheid Calibrations

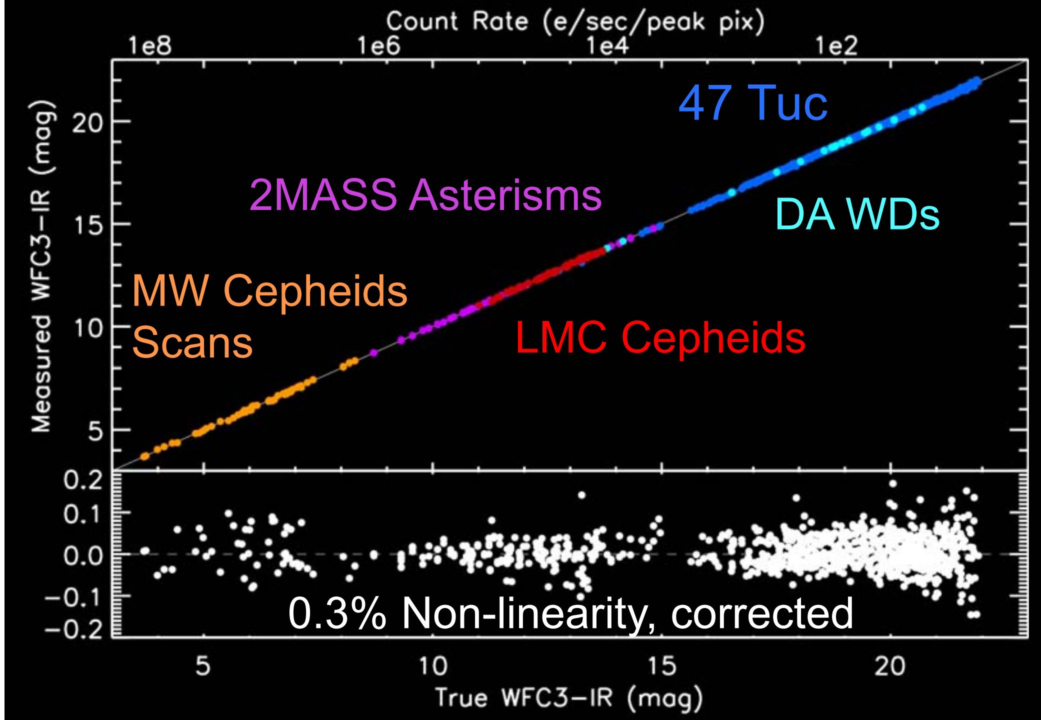
NEW SHOES Large HST Programs, Cycles 25,26
18 more Cepheid-SN Ia Calibrators underway,
to reach total=37

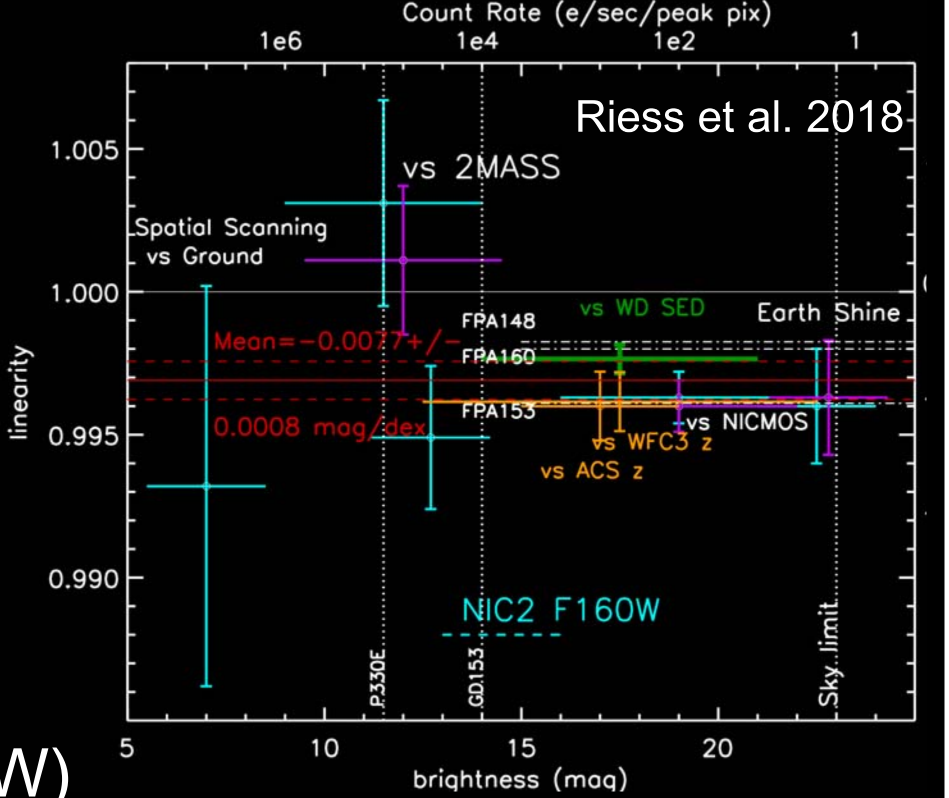


*Cepheids and Miras, Same data

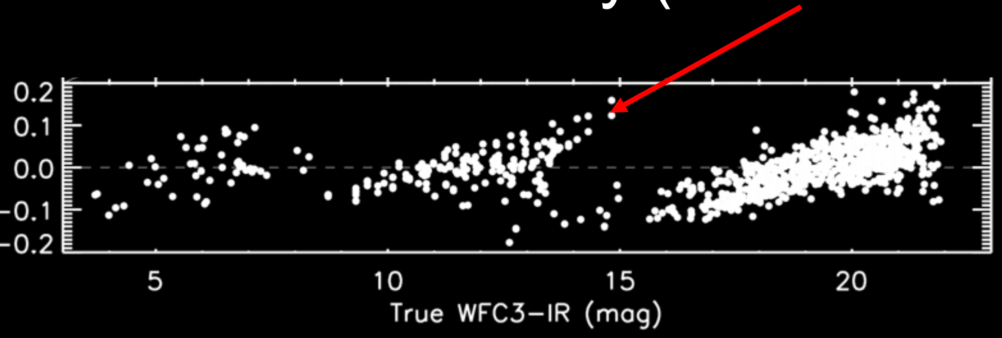
NEW Linearity: Can HST WFC3-IR Flux Scale Support 1%?

“Flux Calibration Ladder”





if 3.0% Non-linearity (NIC2 F110W)



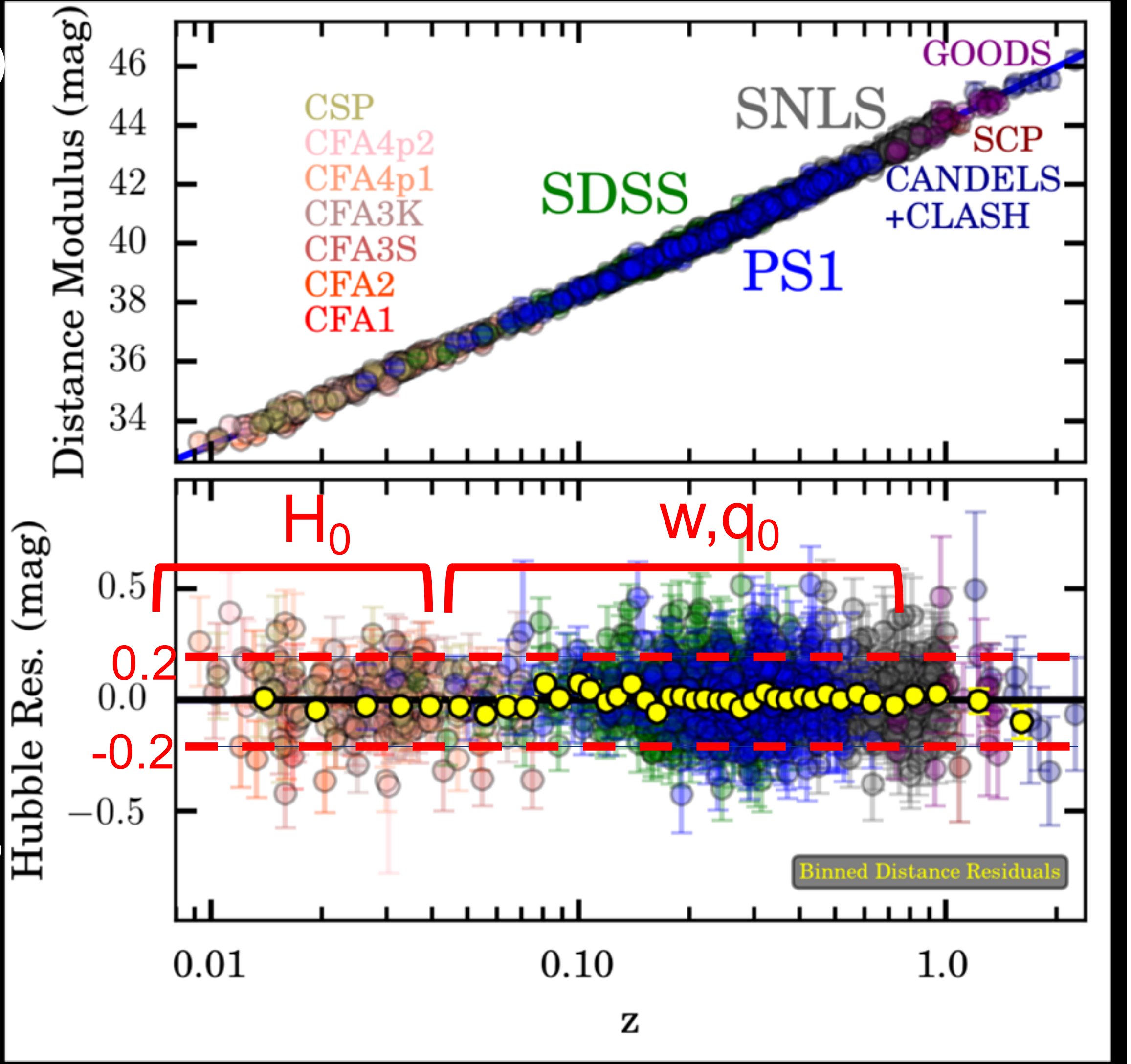
Cepheids: MW→ SN hosts,
σ =7 dex * 0.0008 mag/dex
=0.006 mag → 0.3% in H_0

H_0 is easier than q_0

SN Ia Hubble diagram
(Pantheon Set-Scolnic et al 2018)
0.01<z<2, 1100 Sne Ia
ΛCDM residuals <0.04 mag

Measuring w,q_0 requires
comparing z~0.05 to z~1.0
Sys: evolution, K-corrs, zps

Measuring H_0 requires
Comparing z~0 to z~0.05
Same surveys, no evolution,
negligible K-corrections,
no zeropoint changes.
Much easier!

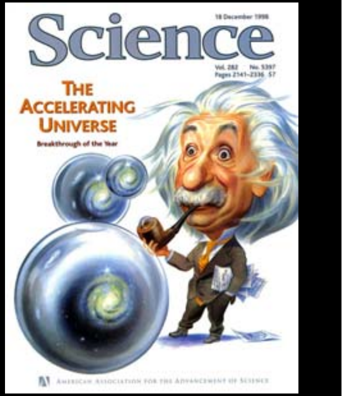


Breakthroughs When Local H_0 was too high. This time?

1930-1950:

H_0>300 km s^{-1} Mpc^{-1}→ t_0 ~Gyr << age of Earth

Why? Two populations of stars! Early and late, poor and rich.



1990's*:

$60<H_0<85 + \Omega_M=1 \rightarrow t_0$ (10 Gyr) << oldest stars (14 Gyr)

Why? Dark energy! $\Omega_M \sim 0.3$, $\Omega_\Lambda \sim 0.7$

2010's:

$H_0=73.5$ +/- 1.6→ 3.8σ higher than Planck CMB+ΛCDM

What will be discovered ?

* Internally inconsistent measures of H_0 indicated systematics not new features

Takeaways

- Universe now appears to be expanding ~9% (+/- 2.2%) faster -than-expected based ΛCDM+Planck CMB

- There are independent checks on each measurement so, either a *conspiracy* of errors or a new feature of LCDM

- We anticipate significant improvements in these measurements in just the next few years which may reveal the cause.

- With additional measurements HST and Gaia can enable a 1% measurement of H_0, a benchmark for constraining the cosmological model.

Ask me about host galaxy environmental effects (Backup Slides)