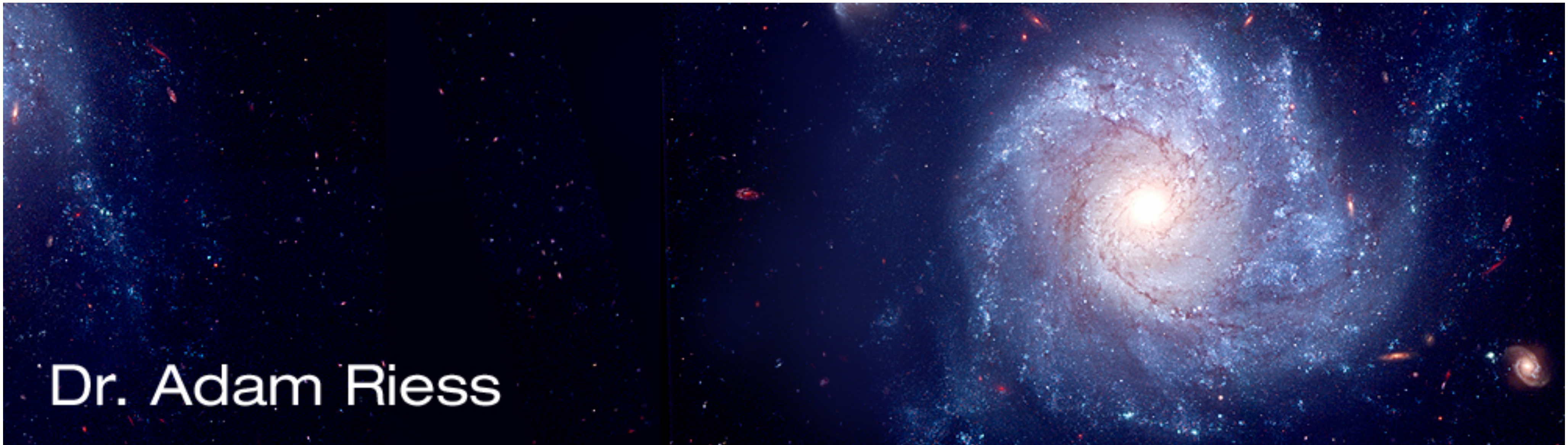
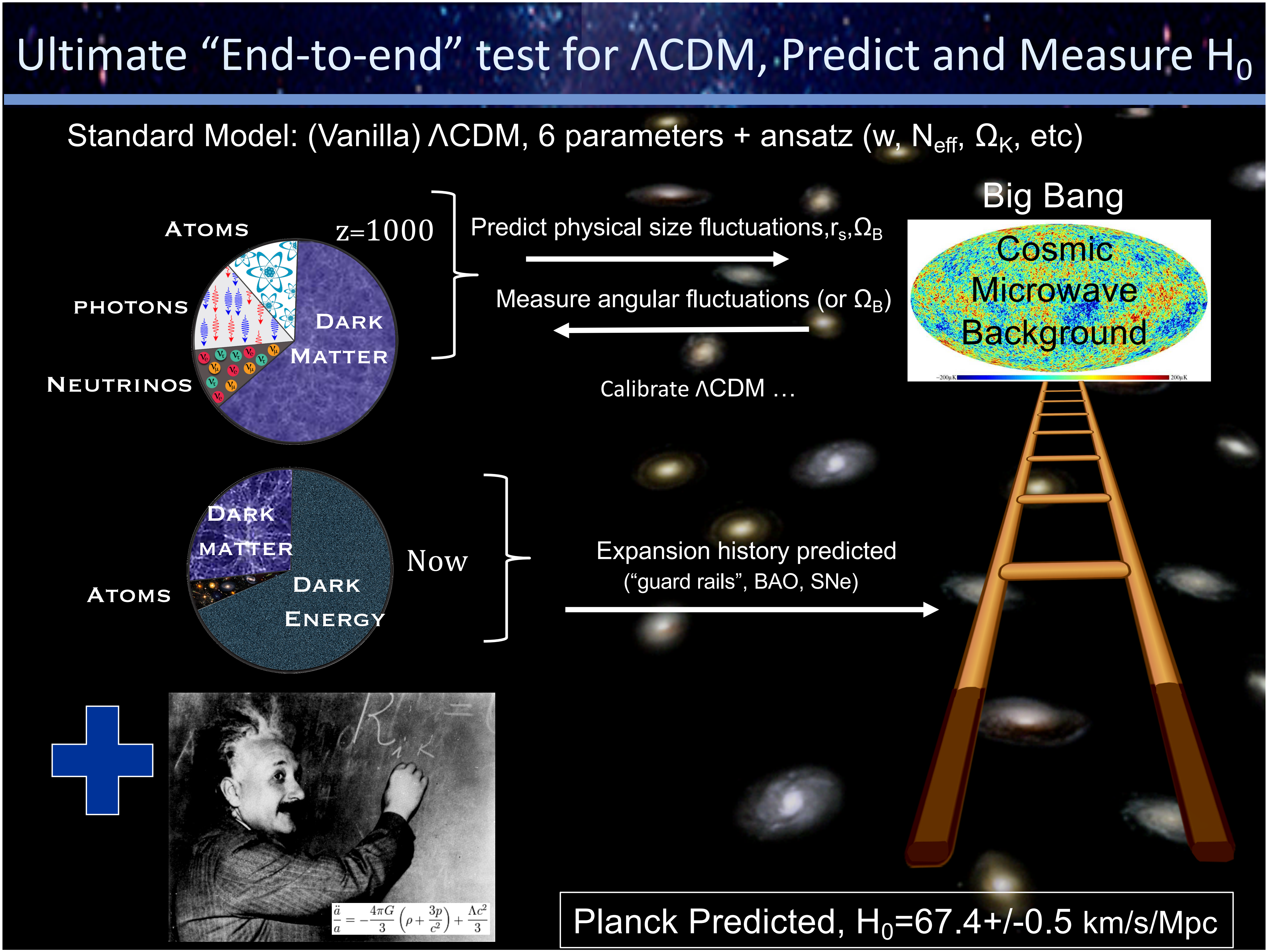


Johns Hopkins University
Space Telescope Science Institute

New Determination of the Hubble constant with Gaia EDR3, Further evidence of excess expansion

SH_0ES Team

Riess et al. 2020, arXiv: 2012.08534


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)
Atoms
Photons
Neutrinos
Dark Matter
z=1000
Predict physical size fluctuations, r_s, Ω_B
Measure angular fluctuations (or Ω_B)
Calibrate ΛCDM ...
Big Bang
Cosmic Microwave Background
Dark Matter
Atoms
Dark Energy
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

The SH_0ES Project (2005)

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

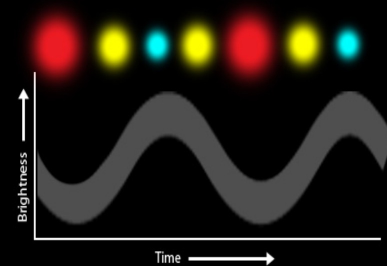
A. Riess, L. Macri, D. Scolnic, S. Casertano, A. Filippenko, W. Yuan, S. Hoffman, +

Measure H_0 to percent precision <u>empirically</u> by:

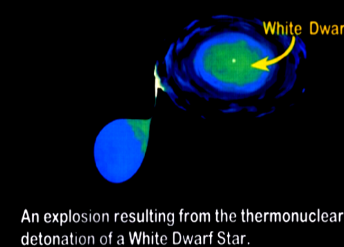
- A strong, simple ladder: Geometry→Cepheids→ SNe Ia

Multiple ways

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

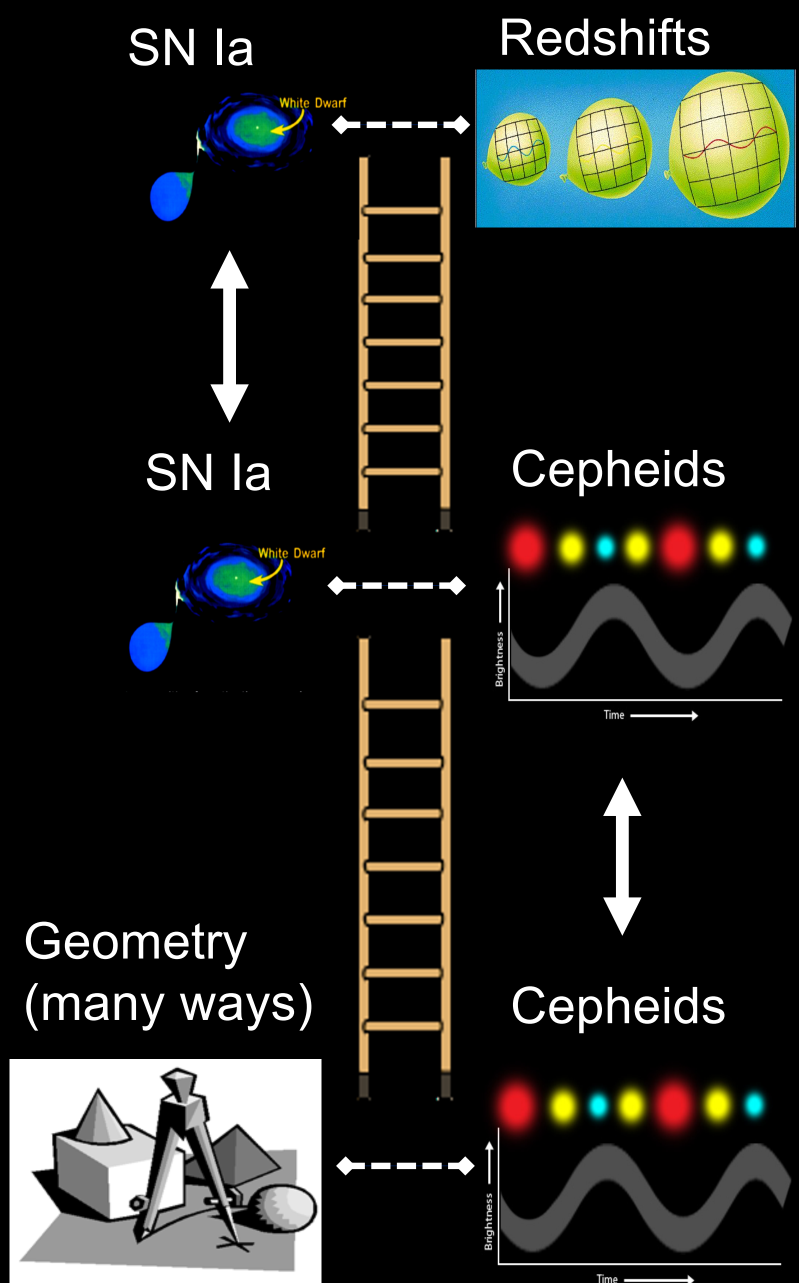


<u>Exploding Stars</u>,
10^9 $L_\odot$, σ~ 5%



--Reduce systematics w/ consistent data along ladder and NIR
--Thorough propagation of statistical and systematic
--HST Cycle 11-28, 17 competed GO proposals,~1000 orbits

Distance Ladders: Empirical & Model-free, 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*

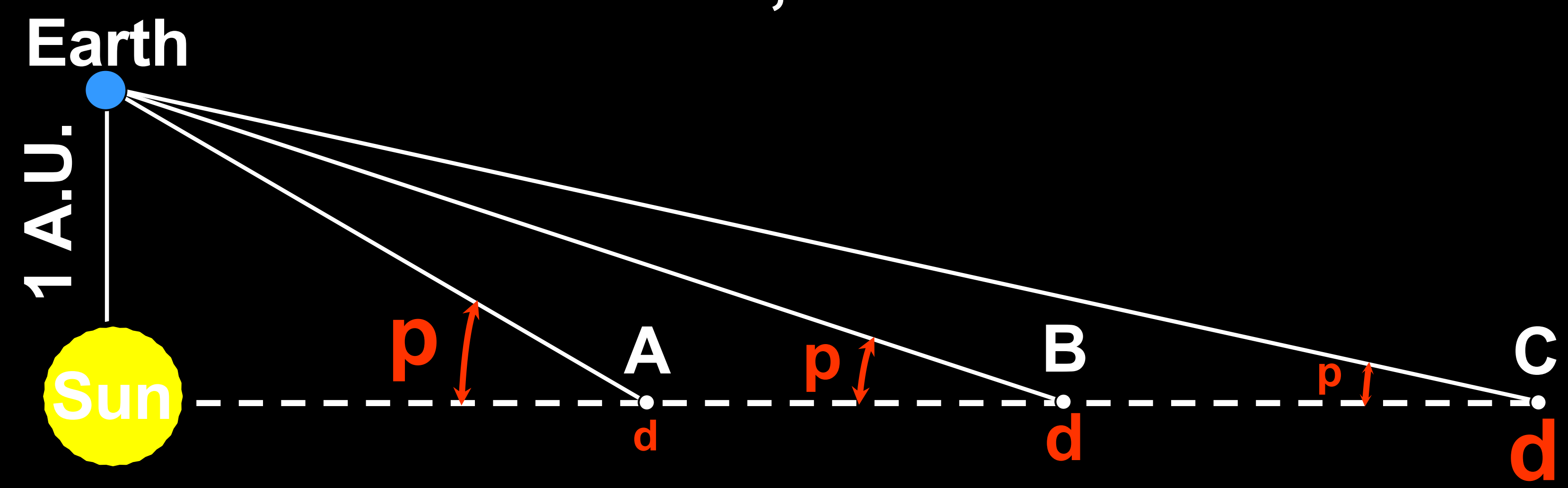
Astrophysical modeling	0%
General Relativity	<1%
LCDM	<1%

WARNING

Same object types on different rungs must be standardized and measured consistently!

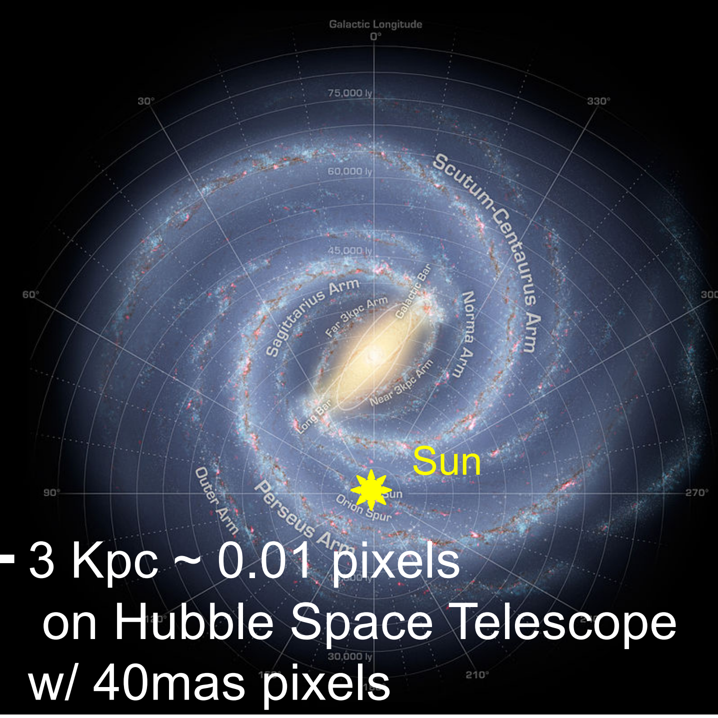
Step 1: Parallax in the Milky Way at Kiloparsec Distances

Stars are far, Parallax is small !



$$d\ (\text{kpc}) = \frac{1}{p\ (\text{milliarcsec})}$$

Nearly all long-period (P>10 days)
MW Cepheids D > kpc (p<mas)



— 3 Kpc ~ 0.01 pixels
on Hubble Space Telescope
w/ 40mas pixels

Extending Parallax with WFC3 Spatial Scanning (~2014)

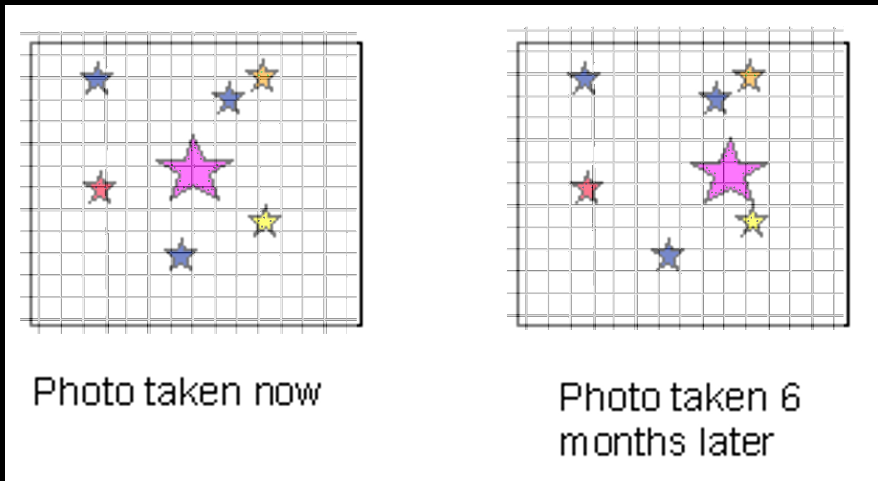
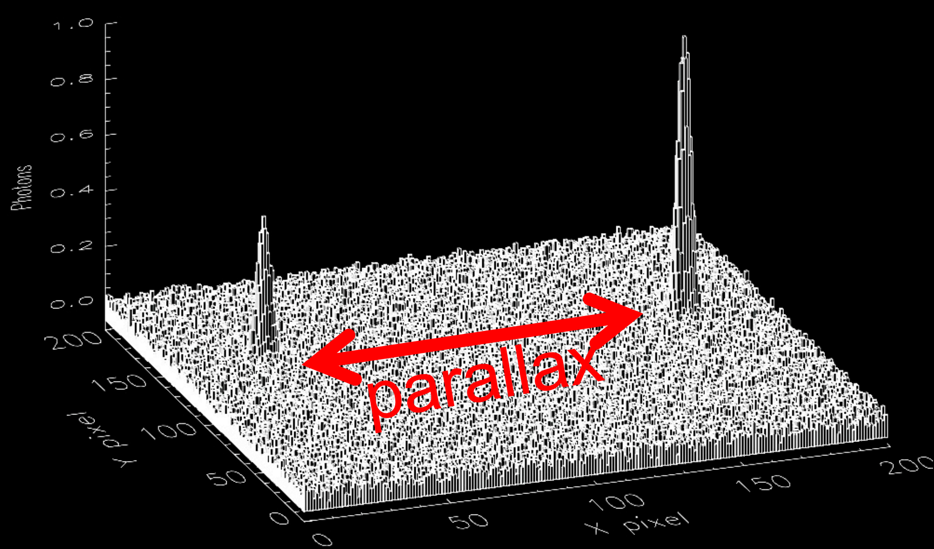
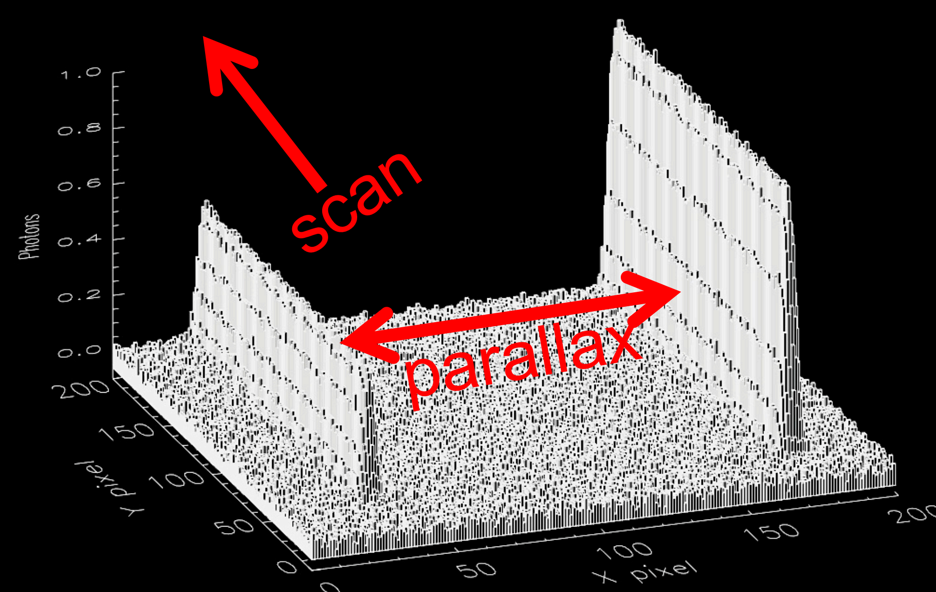


Image centroiding precision:
~0.01 pix WFC3: ~1σ @ 3 kpc

Scanning, $\sigma_\theta = 0.01/\sqrt{N}$ samples pix
20-40 μas parallax precision!

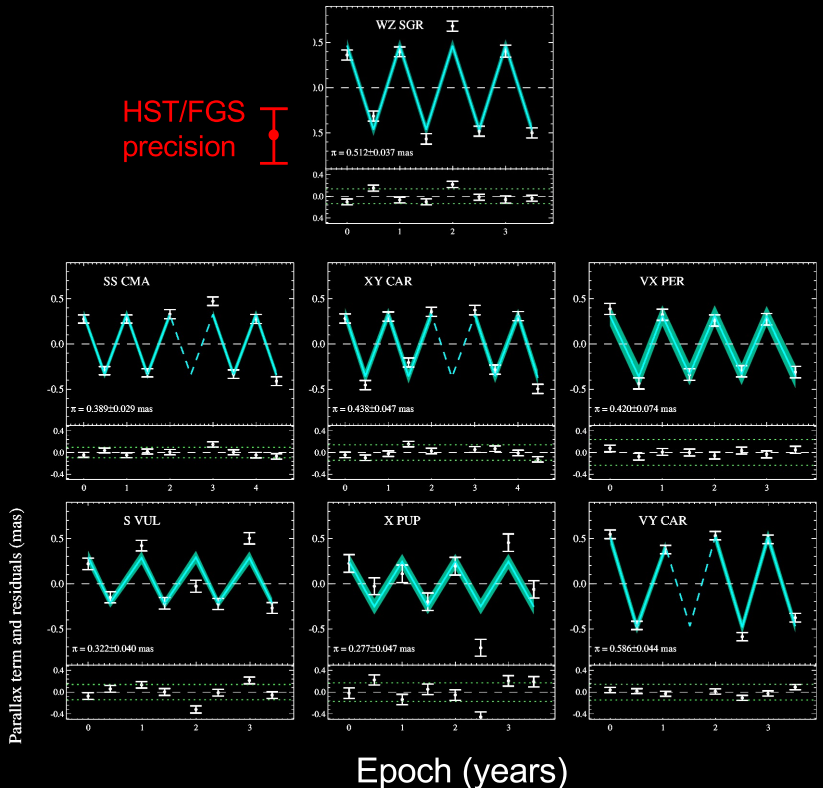




New Tool: WFC3 Spatial scanning for long range parallaxes, photometry

Approach 1: HST Spatial Scanning

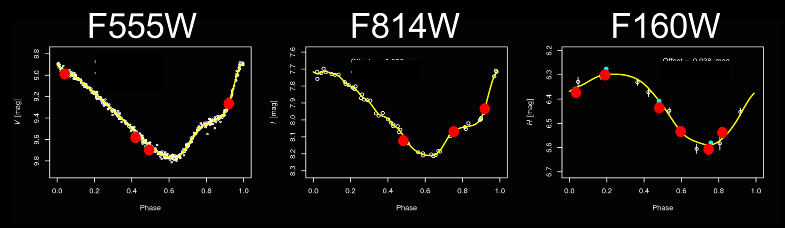
4 Years Later, 8 MW long-P Cepheid Parallaxes, 20-40 μas precision, 1.7<D<3.6 Kpc, error in mean=3.3%

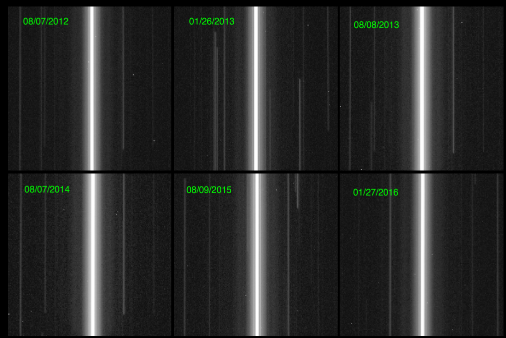


Riess et al. (2018a), ApJ, 855,136

Approach 2: Gaia + HST

75 MW Cepheids w/ Gaia parallaxes and HST fluxes *directly* from scans a "photometric bridge" for Gaia



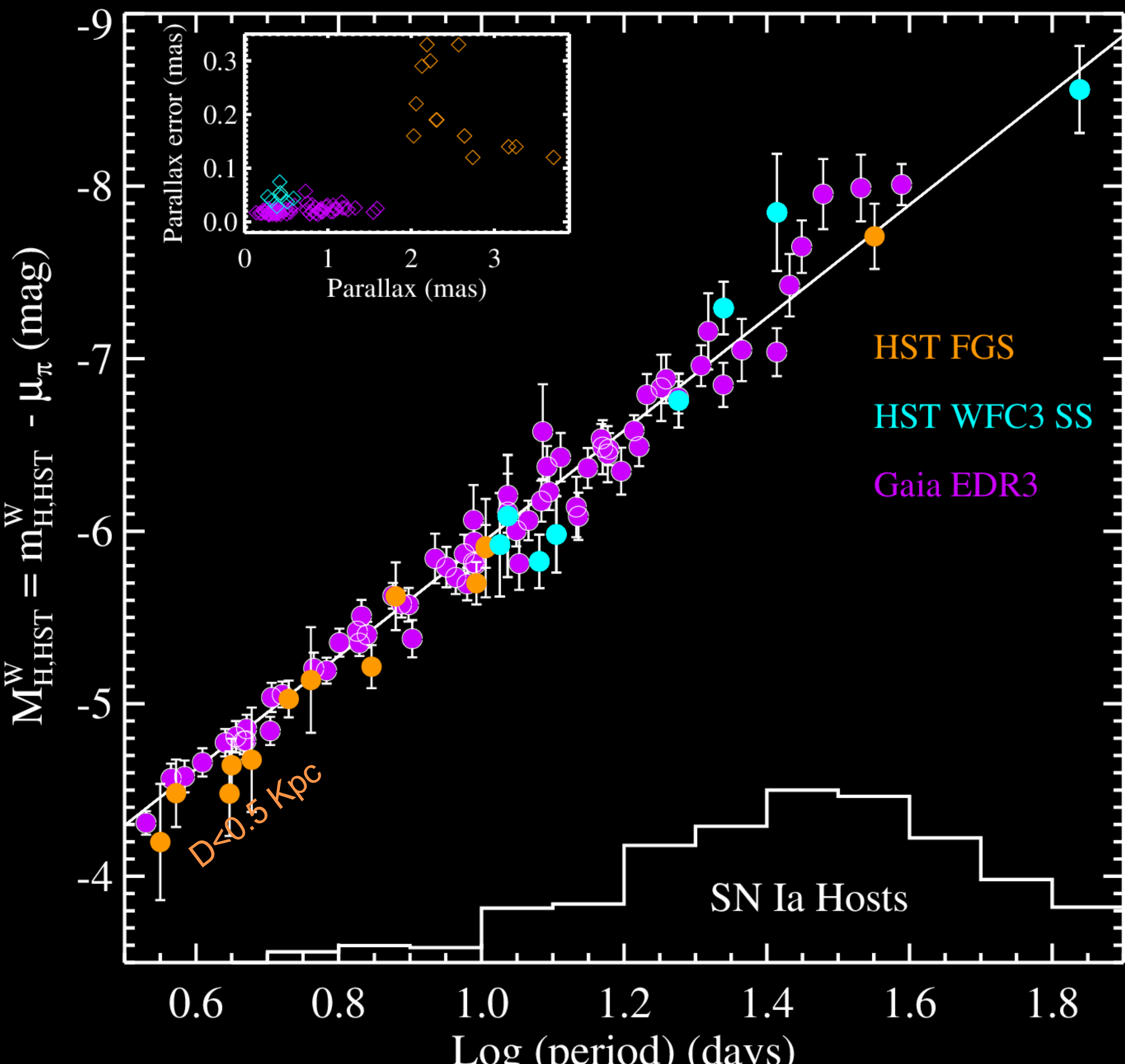


Fast Scans 7.5"/s exp time~0.01 sec
Error individual Cepheid phot., D<1%

w/ Gaia EDR3, error in mean=1.0%
Riess et al. (2021), ApJ, arxiv: 2012.08534

Milky Way Cepheid P-L Relation, Now w/ HST photometry, Gaia EDR3!

Milky Way Cepheid Period-Luminosity Relation



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

Two advantages over old HST FGS parallaxes (Benedict+2007)

1) Periods > 10 days
2) HST photometry

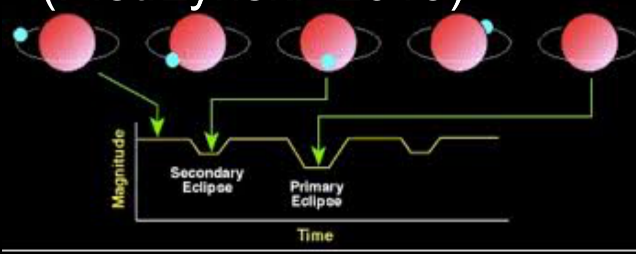
Three Sources of Geometric Distances to Calibrate Cepheids

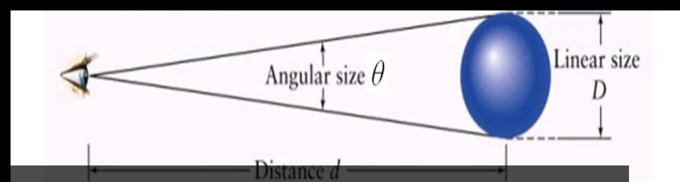
Parallax in Milky Way (WFC3 SS, HST FGS, Gaia)

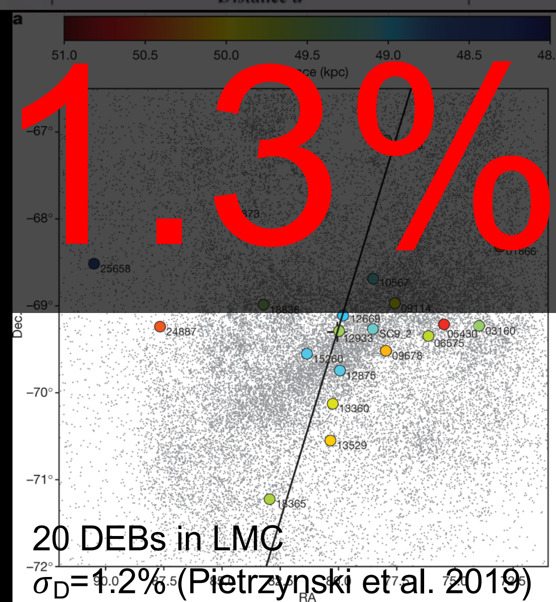
1.0%

Detached Eclipsing Binaries in LMC

(Pietrzynski+2019)



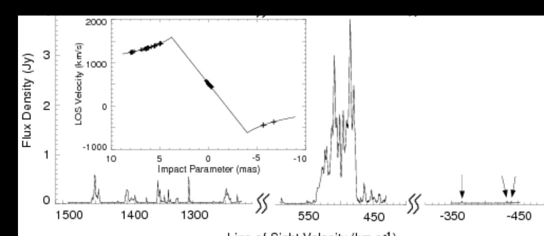




1.3%

Masers in NGC 4258, Keplerian Motion

(Reid+2019)



1.5%

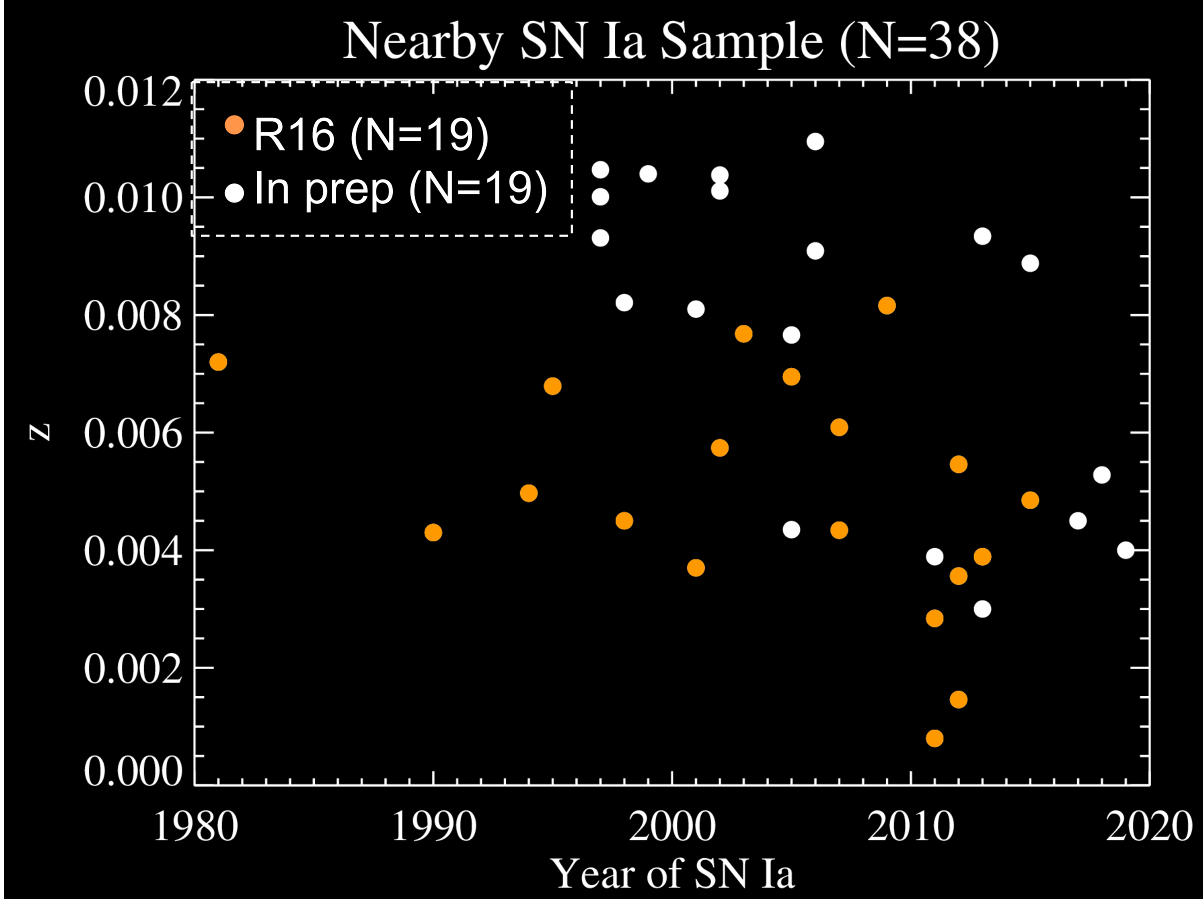
Step 2: Cepheids to Type Ia Supernovae

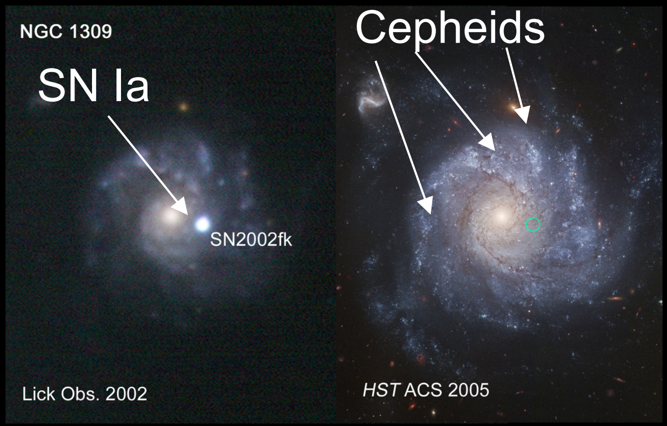
Number nearby SN Ia limits H_0 precision, $\sigma = \frac{6\%}{\sqrt{N}}$

SN Ia Requirements: A_V<0.5, normal, pre-max, digital

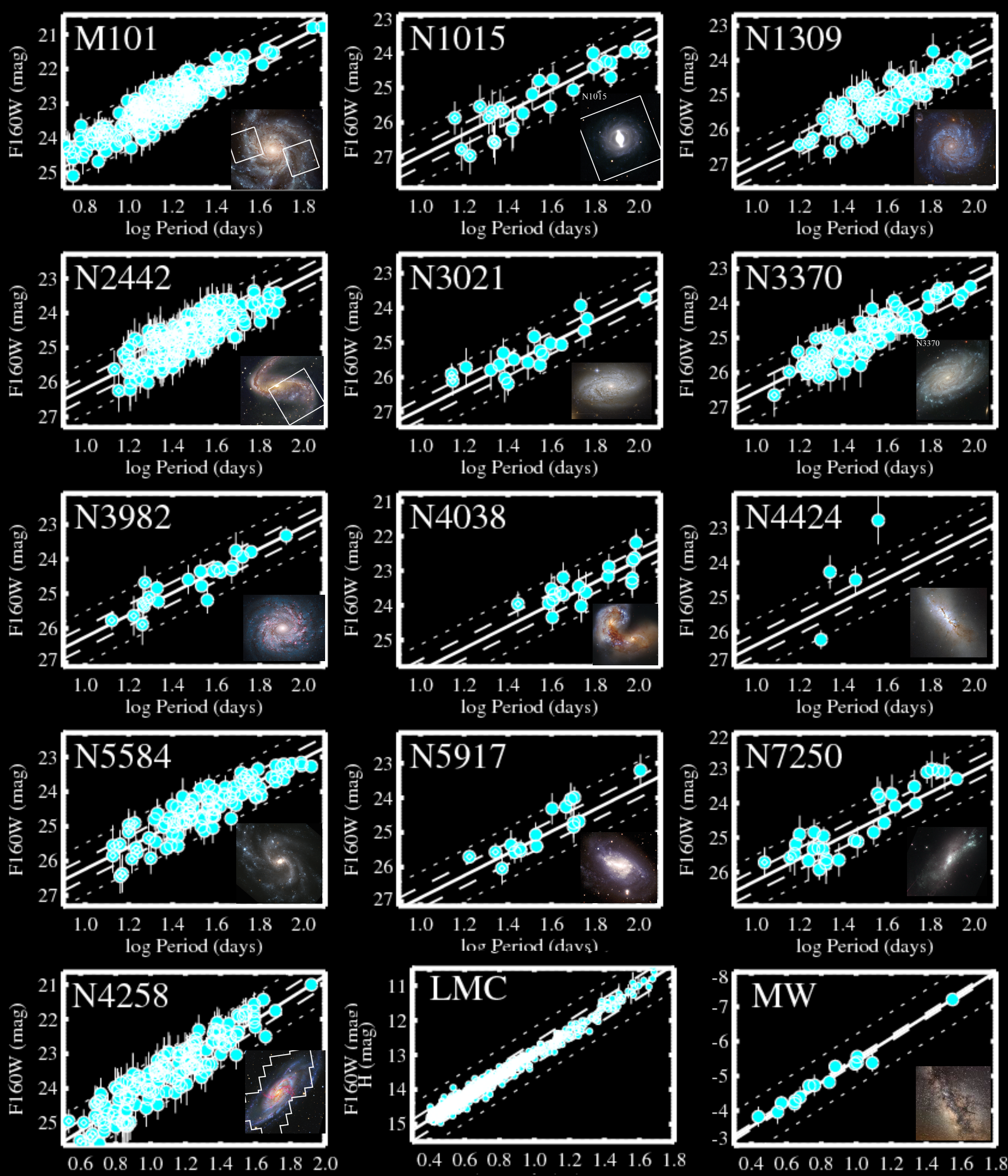
Host Requirements: Late-type, z≤0.01, not-edge on

2020 Complete sample (new ones @ 1.5/yr)





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

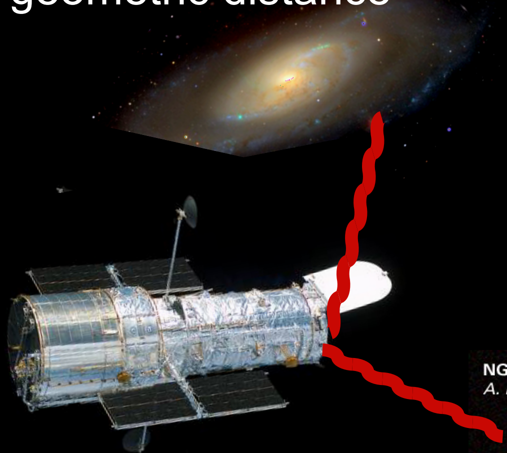


3 Anchors

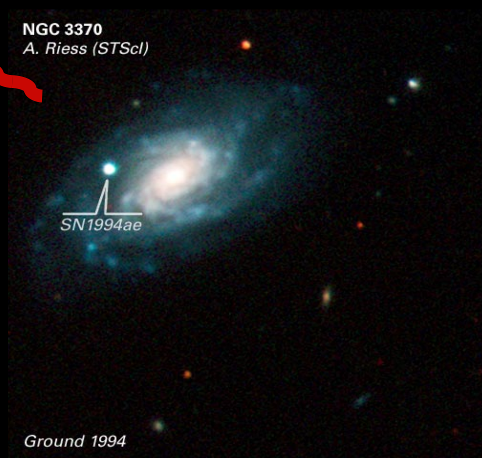
Lower Systematics from *Differential* Flux Measurements

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

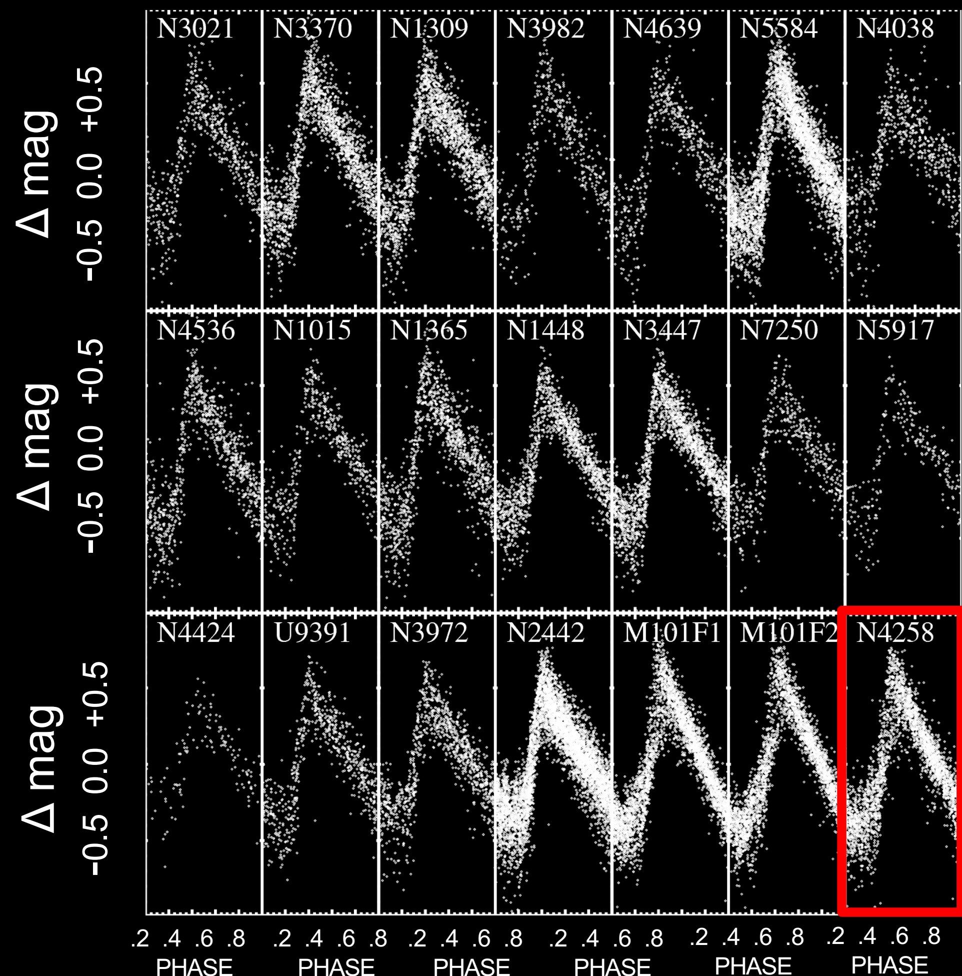
ANCHORS: NGC 4258, MW, & LMC geometric distance



19 SN Ia Hosts



Cepheid composite LC's, >2400



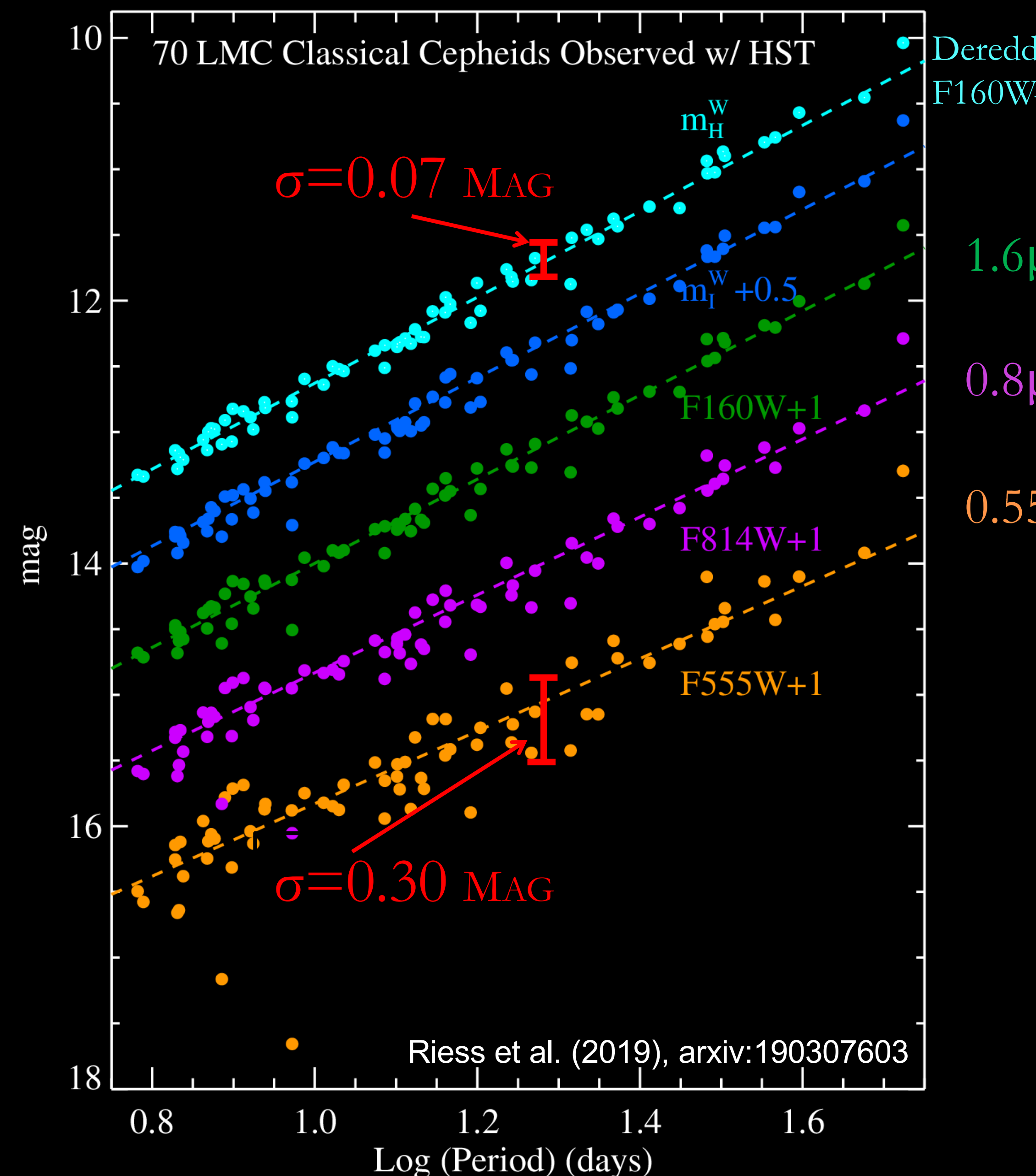
Lowering Systematics: Near-IR Cepheid Observations + HST, Now in LMC!

-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

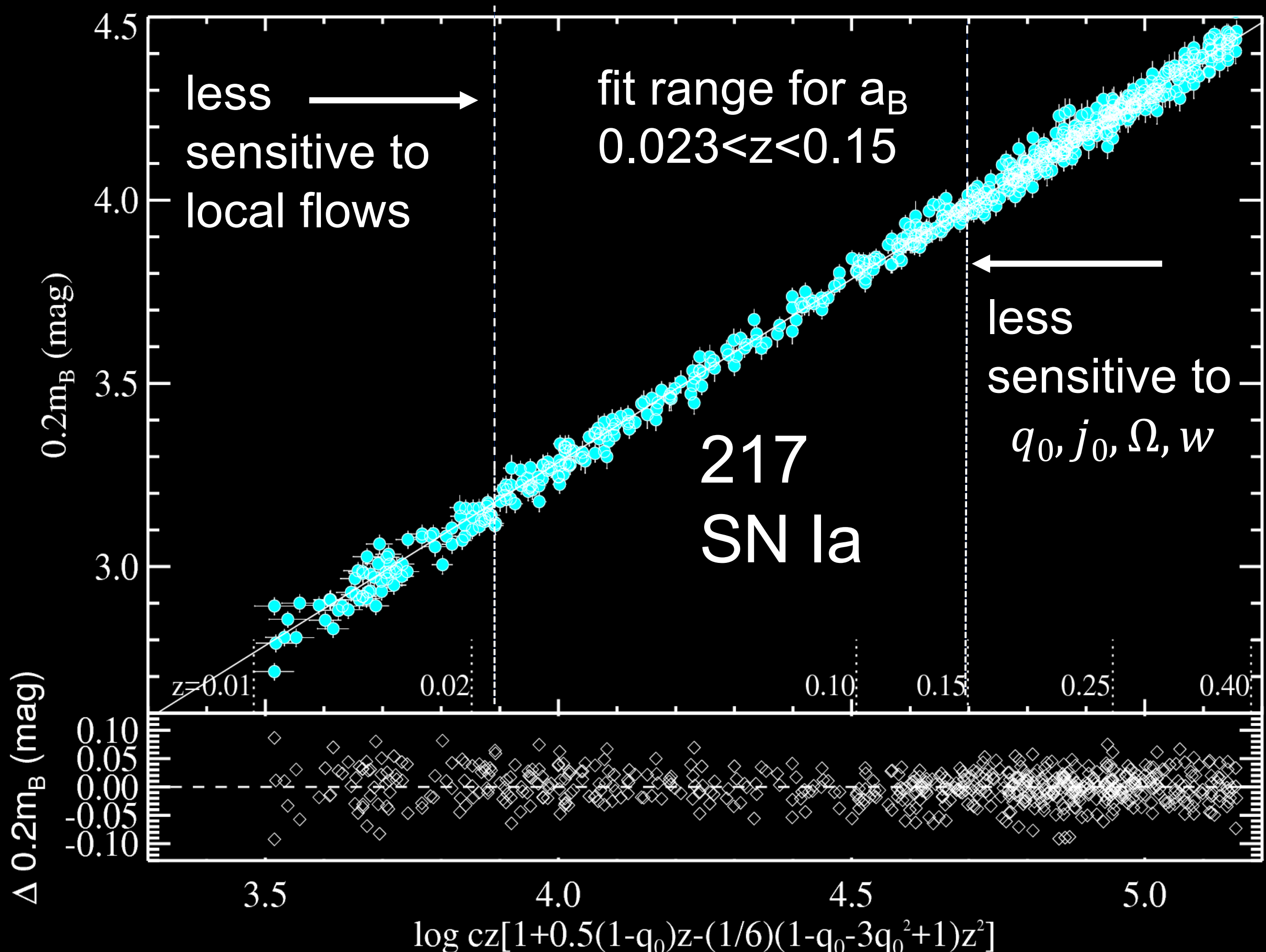


Leavitt

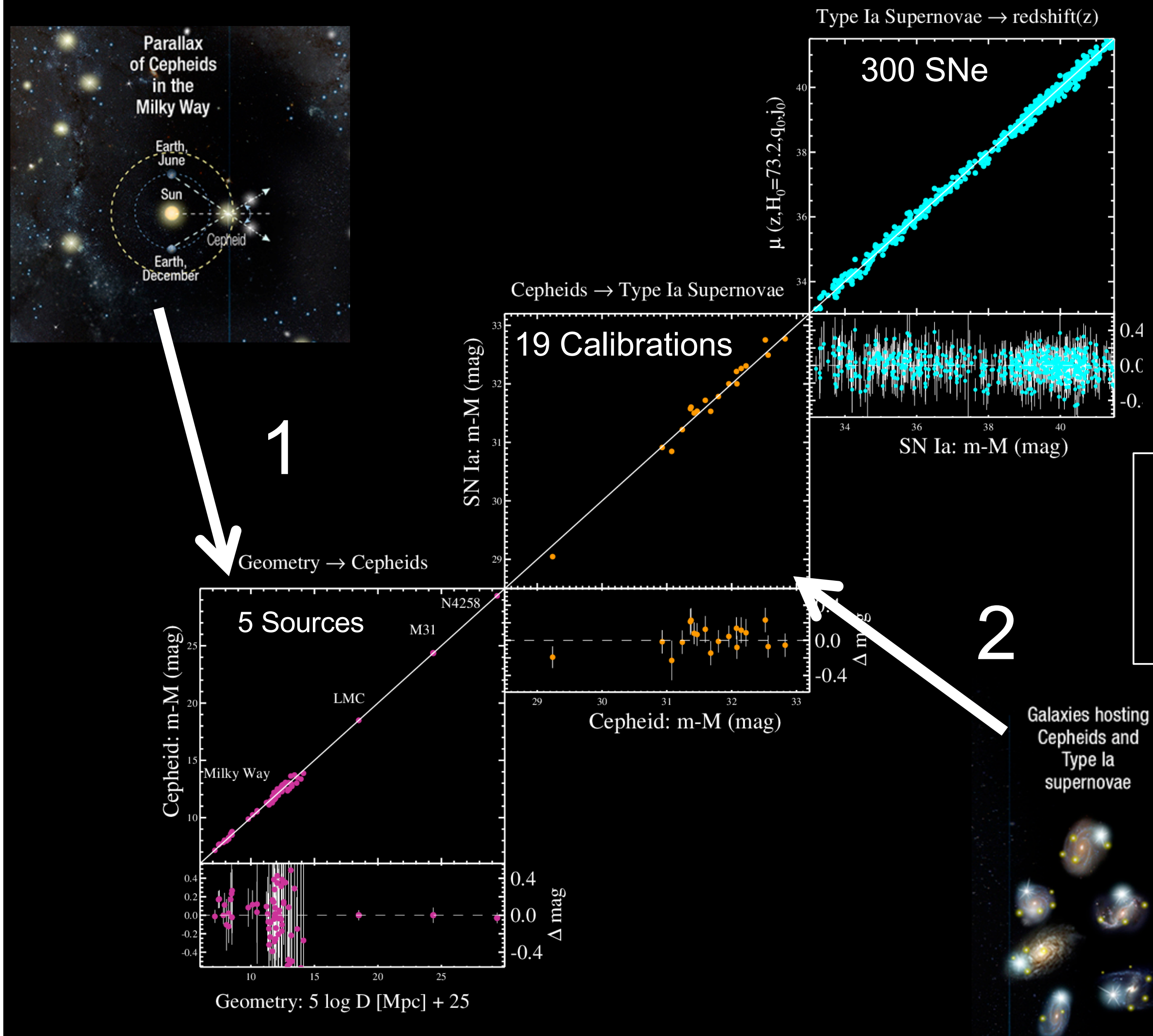
Step 3: Intercept of SN Ia Hubble Diagram: Distance vs Redshift

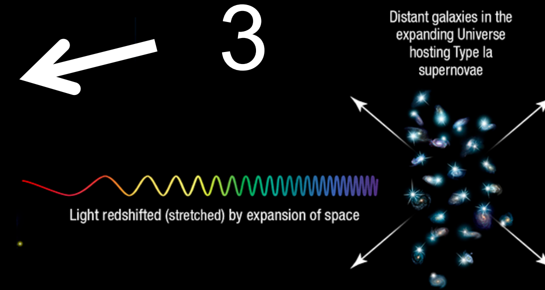
$$a_B = \log cz \left\{1 + \frac{1}{2}\left[1 - q_0\right] z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0\right] z^2 + O(z^3)\right\} - 0.2m^0_B$$

← Kinematic Intercept equation



The Hubble Constant in 3 Steps: Present Data





H_0=73.2 +/- 1.3, Km s^{-1} Mpc^{-1} (Riess et al. 2020)

1.8% total uncertainty

4.2σ from CMB + ΛCDM !

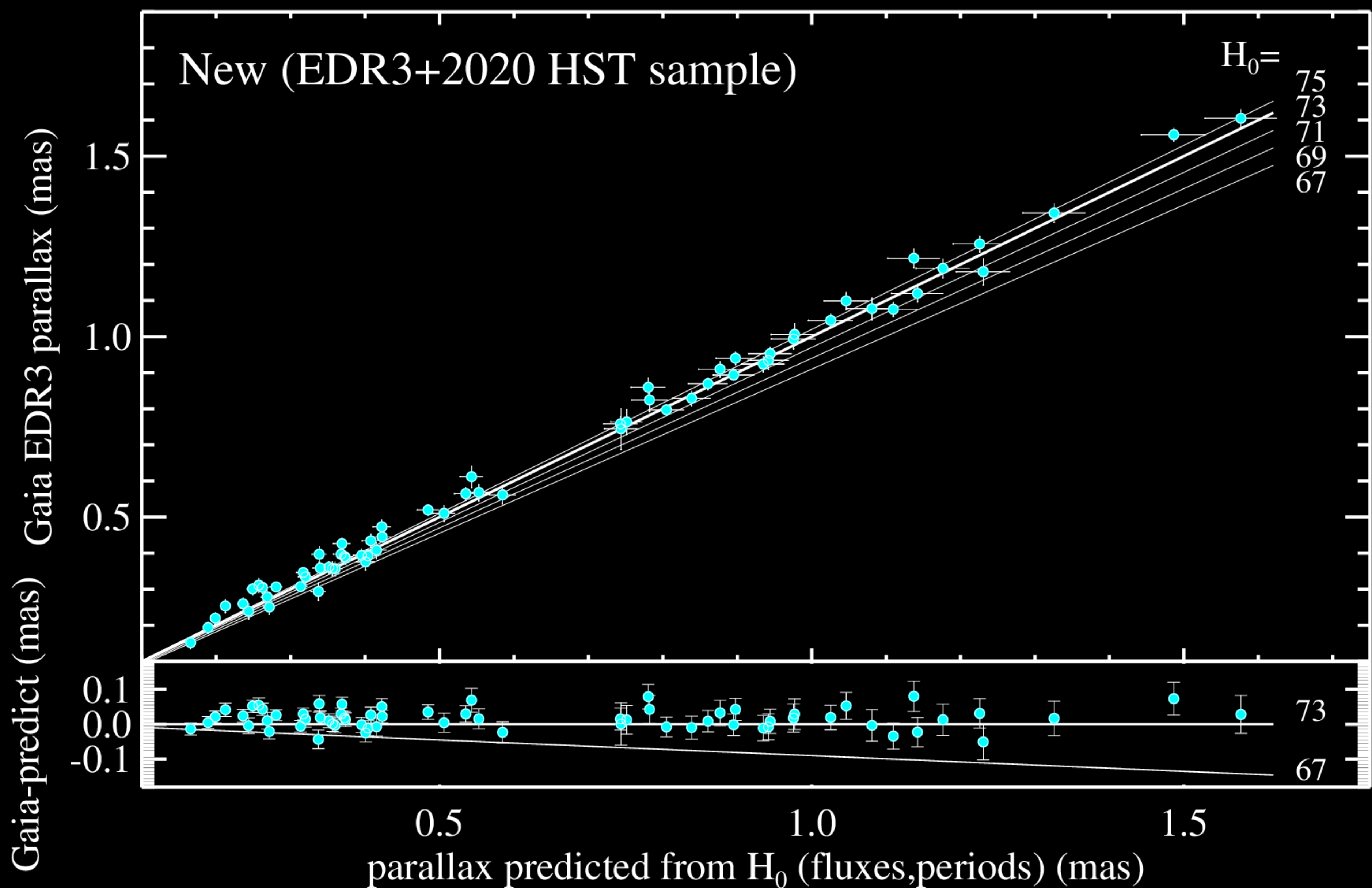
*Simultaneous Fit: Retain interdependence of data and parameters

Robust? Seven Sources of Cepheid Geometric Calibration

	Independent Geometric Source	σ_D	H_0
primary	75 Milky Way Parallaxes Gaia EDR3 par. + HST fluxes Riess+ 2020	1.0%	73.0
primary	NGC 4258 H_20 Masers: Reid, Pesce, Riess 2019	1.5%	72.0
primary	LMC 20 Detached Eclipsing Binaries: Pietzrynski+ 2019 + 70 HST LMC Cepheids: Riess+(2019)	1.3%	74.2
checks	Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess+ 2018	3.3%	75.7
checks	Milky Way 10 HST FGS Short P Parallaxes: Benedict+2007 -- also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2
checks	Milky Way Short P Cepheid Binary Gaia DR2 Companion Parallax: Breuval+20	3.8%	72.7
checks	Milky Way Short P Cepheid Cluster Gaia DR2 Parallax: Breuval+20	3.2%	73.6

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

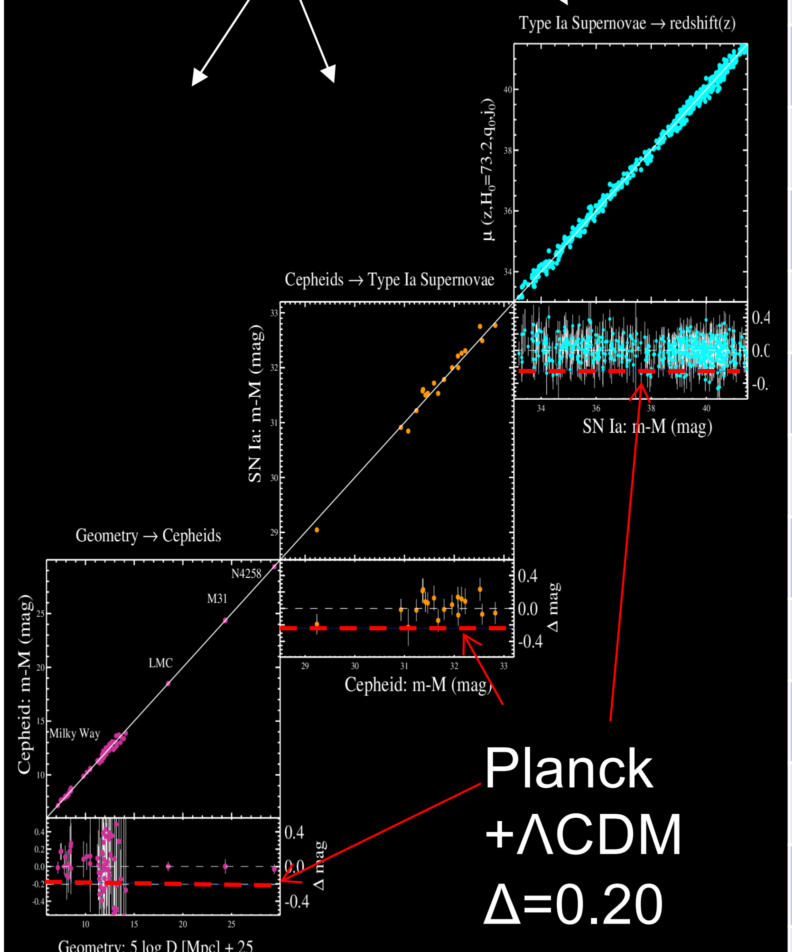
Gaia Improves: DR2 to DR3 plus more HST Photometry



Systematics? 23 Analysis Variants—we propagate variation to error

Best Fit:

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



Planck +ΛCDM Δ=0.20 mag

Analysis Variants	H_0
Best Fit (2020)	73.2
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.1
Reddening Law: Bulge-like (N15)	73.6
No Cepheid Outlier Rejection (normally 2%)	73.5
No Correction for Cepheid Extinction	74.9
No Truncation for Incomplete Period Range	74.2
Metallicity Gradient: None (normally fit)	73.7
Period-Luminosity: Single Slope	73.5
Period-Luminosity: Restrict to P>10 days	73.4
Period-Luminosity: Restrict to P<60 days	73.8
Supernovae z>0.01 (normally z>0.023)	73.3
Supernova Fitter: MLCS (normally SALT)	75.1
Supernova Hosts: Spiral (usually all types)	73.2
Supernova Hosts: Locally Star Forming	73.5
Optical Cepheid Data only (no NIR)	72.0

Frequently Asked Questions: technical, see backup slide

- Could we live in a giant void (9% in H_0)?
  No, LSS Theory and SN Ia mag-z limit σ~0.6% in H_0

  Odderskov et al. (2016) , Wu & Huterer (2017), Kenworthy, Scolnic, Riess 2019

- Is HST WFC3-IR flux scale linear to 1%?
  Yes, calibrated to σ=0.3% in H_0 across 15 mag

  Riess, Narayan, Calamida 2019

- Does Cepheid crowding compromise accuracy?
  No, amplitude data confirms accuracy of crowding estimates

  Riess, Yuan, Casertano, Macri, Scolnic 2020

- Is there a difference in SN Ia at ends of distance ladder?
  No, correlations of Hubble residuals < σ=0.3% in H_0

  Jones et al 2018

FAQ: Cepheid physics different *locally* vs bit more distant?

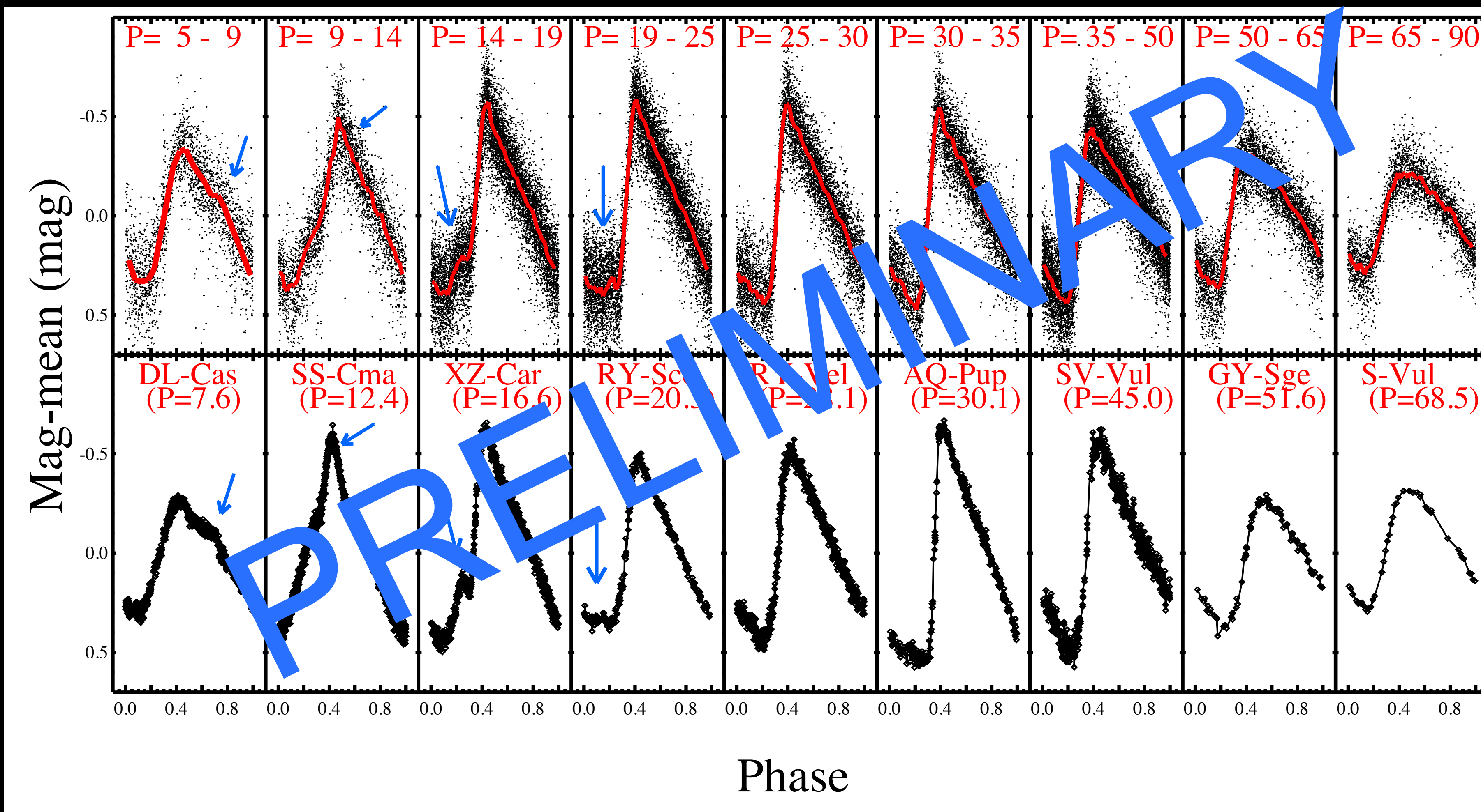
"Hertzsprung progression" (1926)—shape vs period (in prep)

- -asymmetry (Fund.), "bump", 2:1 resonance fundamental and 2[nd] overtone
- -high amplitude "saw-tooth", sinusoidal at P>40 days

Bono et al 2000/02

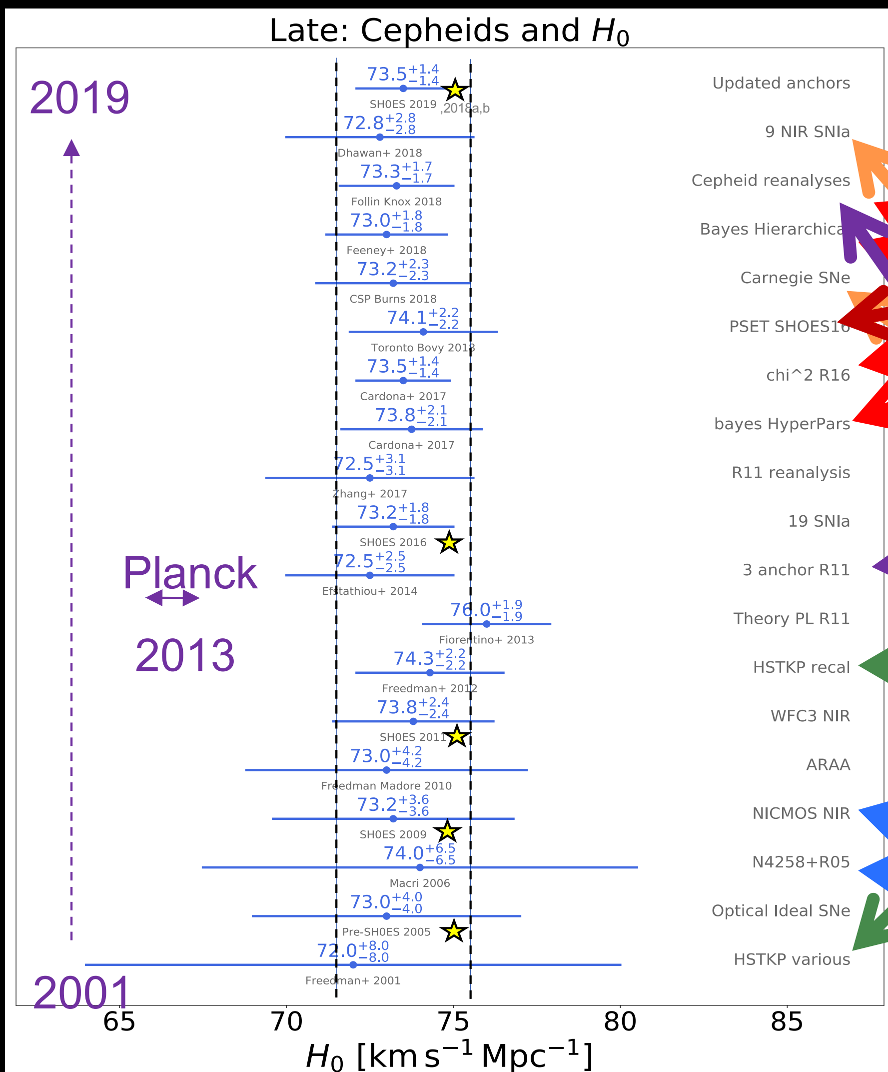
SN Ia Hosts

Milky Way



FAQ: Only us? No, Cepheids+SNIa, widely replicated: 2001-19

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



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

grad student problem set! (Toronto)

Different analyses

Different SNe, wavelength

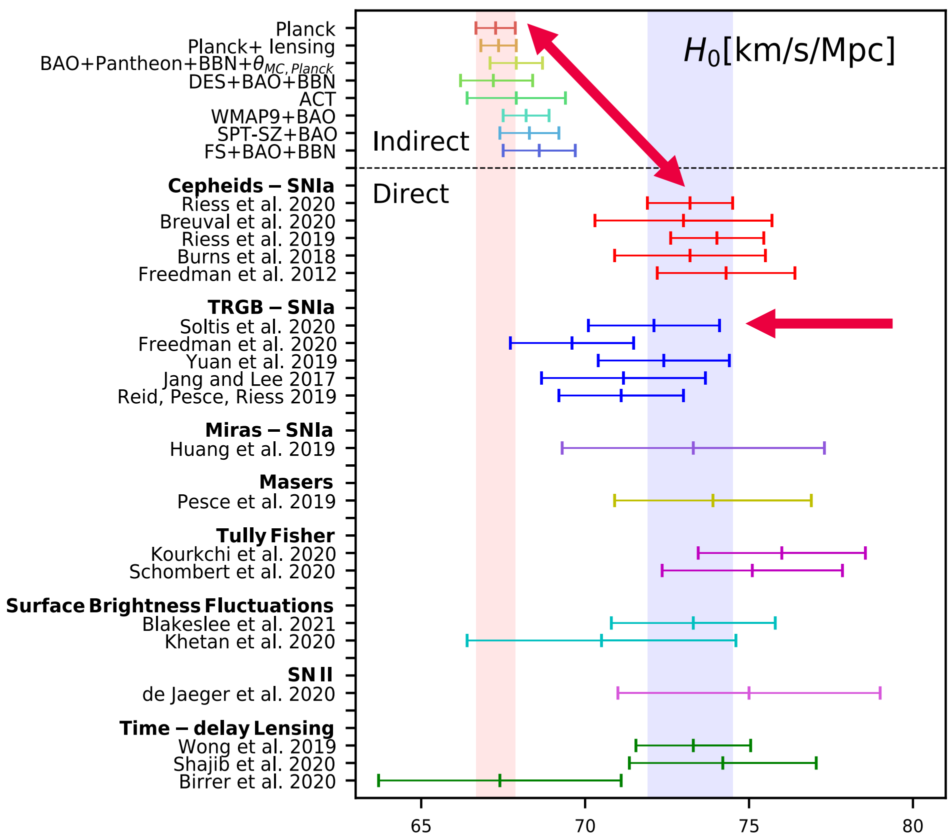
"Planck People"

Different Team (KP), photometry, Cepheids, wavelengths

Different HST Instruments

Others? The Hubble Constant ~~Tension~~, Discrepancy, ~~Problem~~, ~~Crisis~~

Present Status



Di Valentino 2020

Compilation from Di Valentino et al 2020

KITP 2019 (Verde, Treu, Riess 2019)

"does not appear to depend on the use of any one method, team or source"

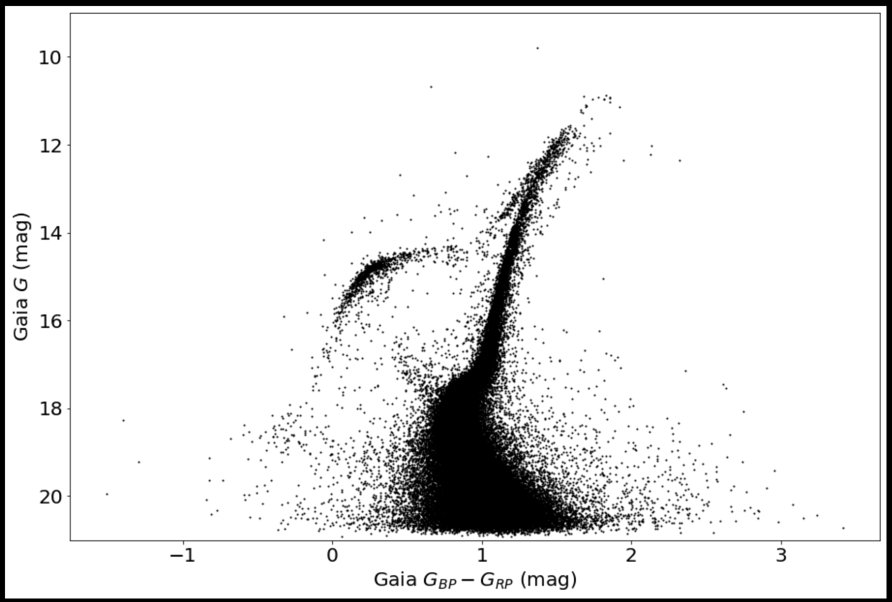
No Cepheids: 4.5-5.3σ
No TRGB: 5.7-6.3σ
No lens: 5.0σ
No SN Ia: 4.9σ
No Cepheids or TRGB: 5.3σ
No Planck: 4.4-4.9σ
No CMB: 4.0-4.5σ
(Riess 2019, Nature Reviews)

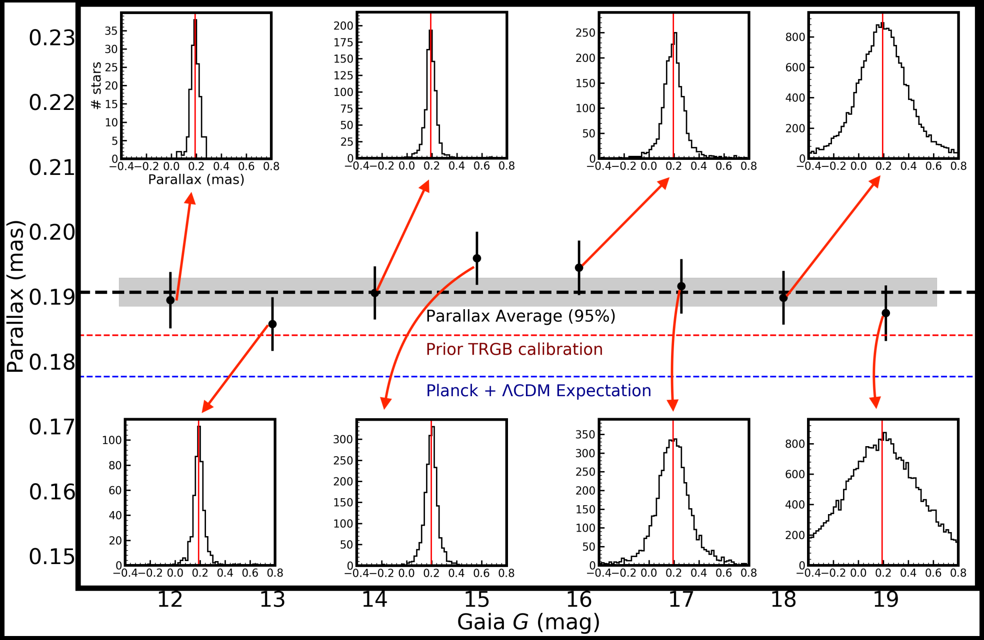
New: Gaia EDR3 also recalibrates TRGB w/ Parallax of Omega Centauri

ω Centauri: biggest globular cluster, best *direct* MW TRGB

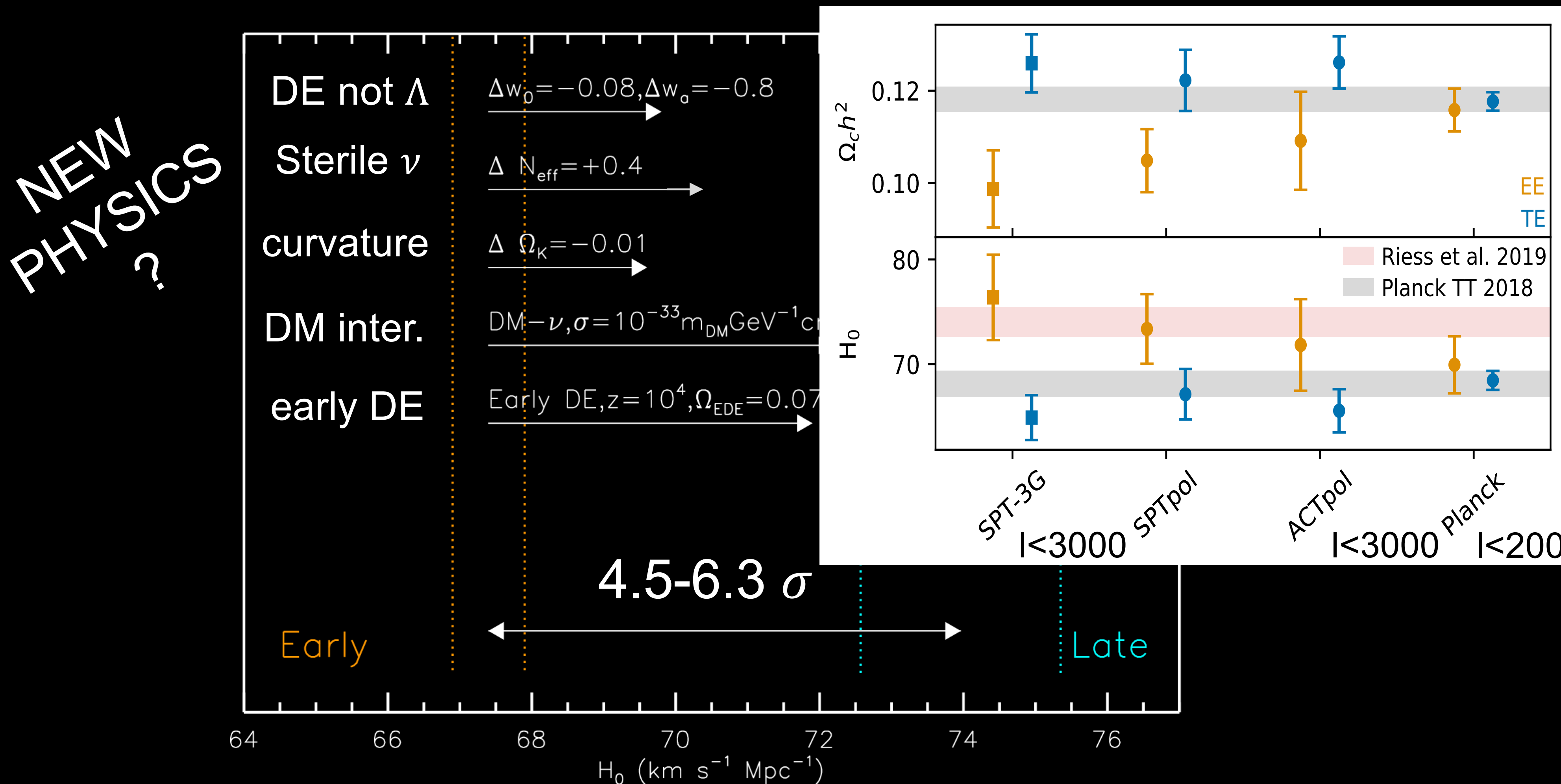
Soltis, Casertano, AGR 2020, ApJ, in press, arxiv:2012:09196

- 67,000 stars w/ tight position, motion locus in EDR3, sharp CMD, parallax independent of mag, color
- $\pi = 0.191 \pm 0.001 \pm 0.004,$ w/ known apparent tip and MW extinction→ M_I=-3.97 $\pm$ 0.06 mag, H_0=72.1+/- 2.0 km/s/Mpc





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



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

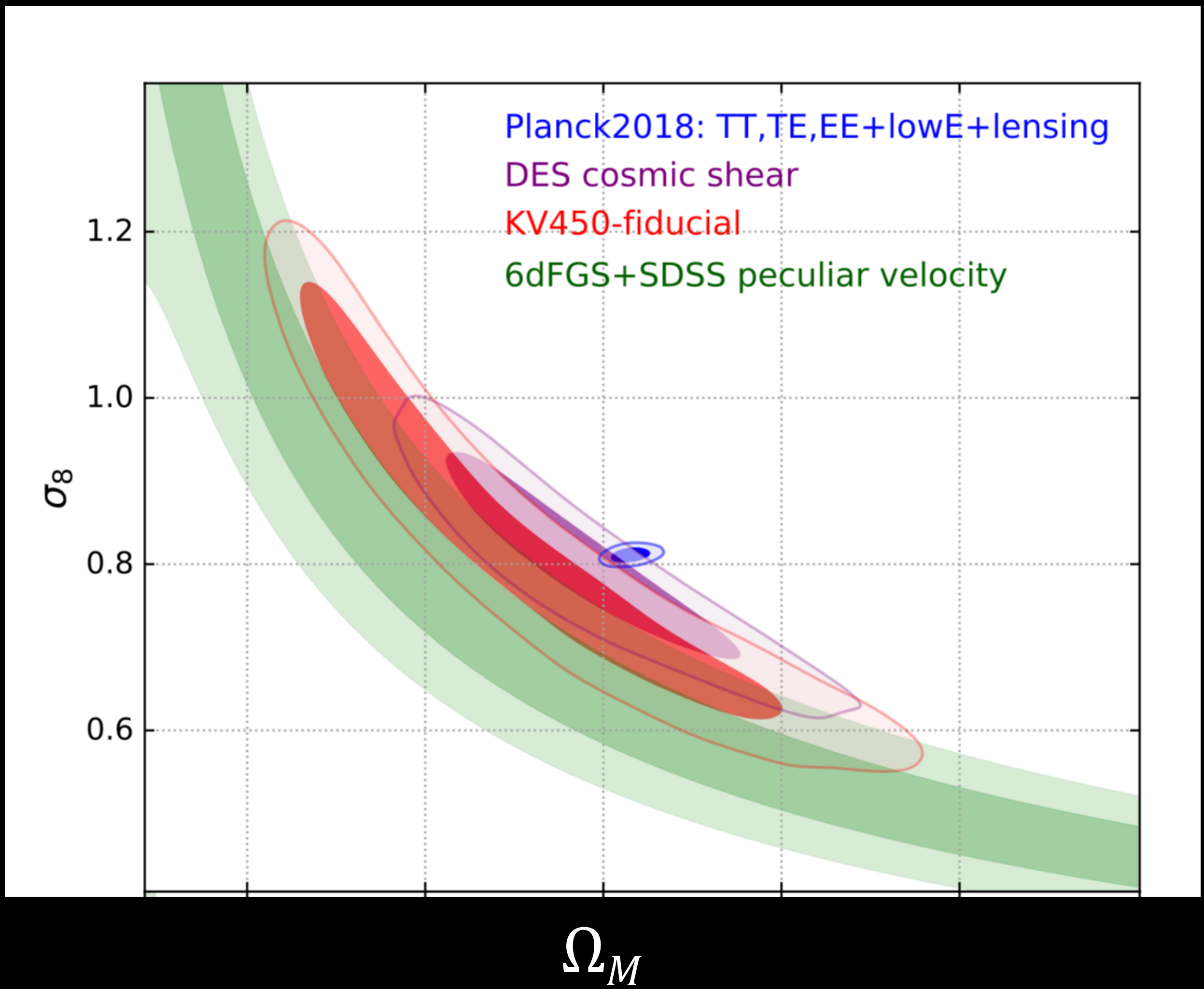
Mechanisms: Early DE or sterile (self-interacting) neutrinos

Claims: better fit to CMB, new CMB features, see also curiosities in high-el Between Temperature and Polarization (TE vs EE, Dutcher et al. 2021)

Another Early vs Late Tension? Matter clumpiness, σ_8

RMS matter fluctuation, σ_8 , (r=8 h^{-1} Mpc), 0.8 Early vs late divide

~3 σ from lensing and peculiar velocities, independently



6dFGS+SDSS

Said, K et al 2020, MNRAS,497, 1275

"…deviates by more than 3σ from the latest Planck CMB measurement. Our results favour … a Hubble constant H_0 > 70 km s^{-1} Mpc^{-1} or a fluctuation amplitude σ_8 < 0.8 or some combination of these. "

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?

Can We Believe Explanation without hypothesis (*how*)?

Present data provides formidable challenge!

"Its New Physics"—constrained precise H(z) data, CMB high-el

"Its Systematics"—many measures, many independent rungs, duplicate measurements, Copernican principle

I don't think so.

Reasons for optimism:

New data: LIGO, DESI, Roman, Rubin, Euclid, JWST, Simons, S4

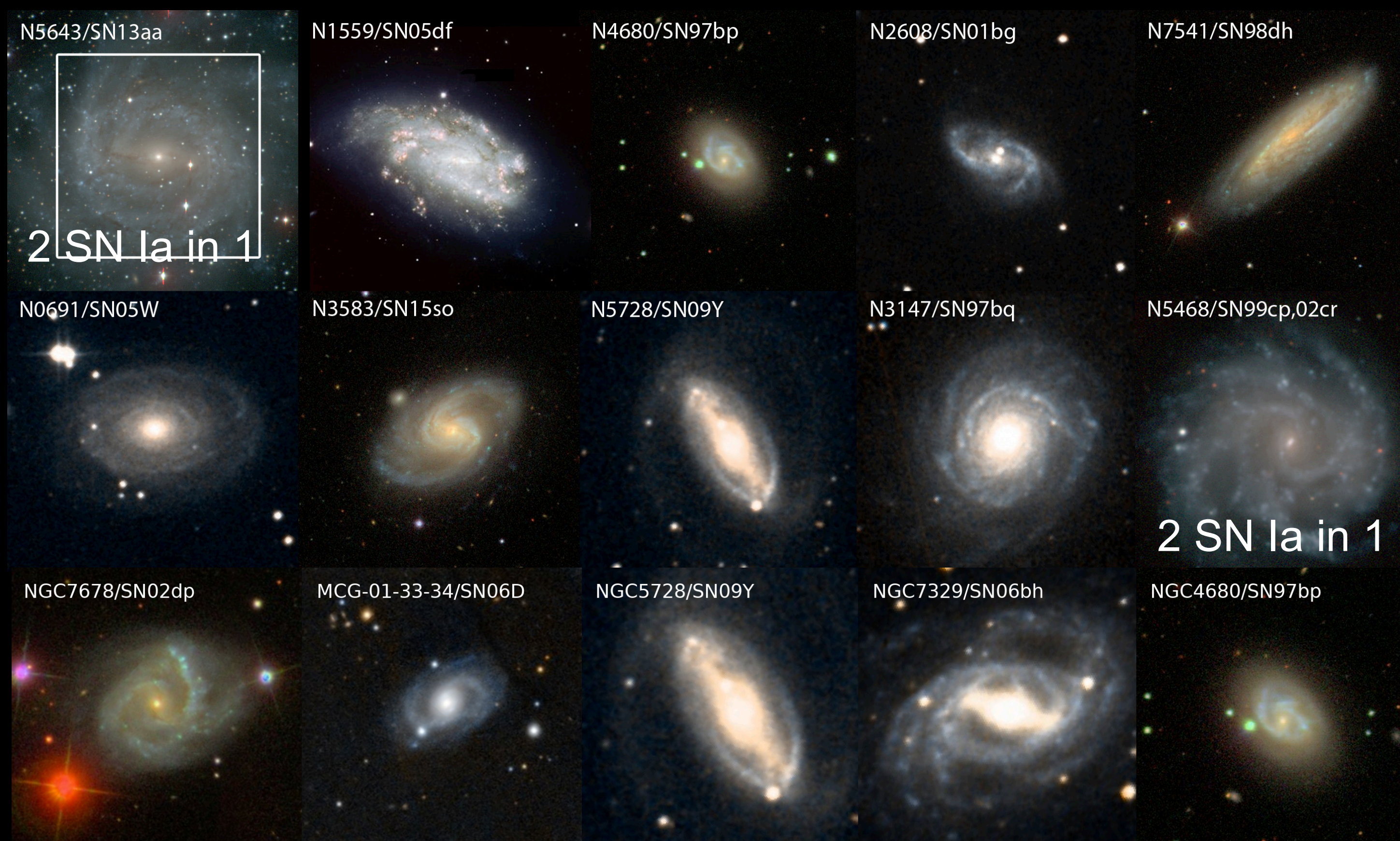
New clues: Early vs late σ_8, Cosmic Birefringence? high-el, BBN?

Big Playground: Lambda CDM is 95% dark, quantum gravity

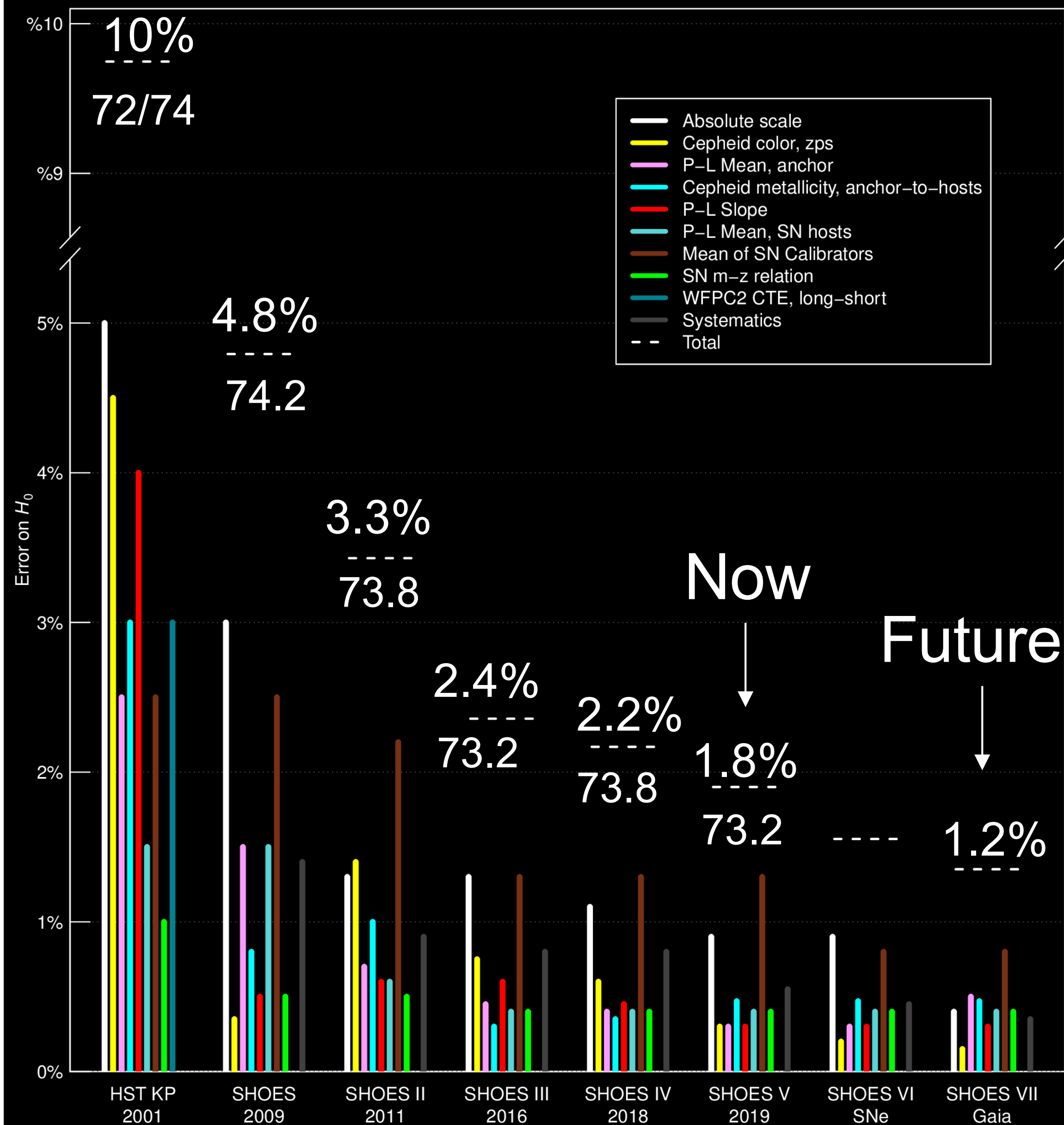
Next Steps: Increasing Number of SN-Cepheid Calibrations

NEW SHOES Large HST Programs, Cycles 25,26,28

24 more Cepheid-SN Ia Calibrators underway, to reach total=43, + Cepheids to Coma!



Future Prospects…



- **New low-z SN samples**
- **Doubling SN Calibrator sample, 19→40**
- 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 precise Late Universe measurements lower than any Early
- Appears robust, requires <u>multiple</u> catastrophic failures to avoid
- <u>Very interesting!</u> (unless your Bayesian prior on ΛCDM > 5 σ)
- Feign No Hypothesis, let's follow evidence, find the *how*
- Universe may be more clever than we are *now*