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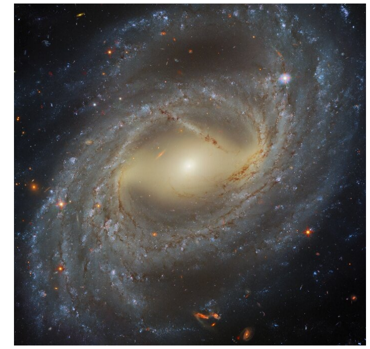


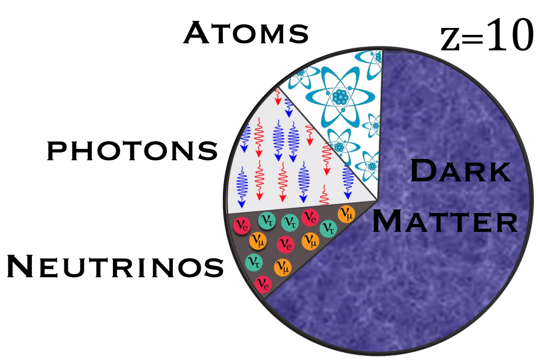
A Comprehensive Measurement of Local H_0 to 1 km/sec/Mpc Uncertainty from HST, SH0ES, Pantheon+

Cheat Sheet: 1 km/Mpc/sec=0.031 mag "Tension"=0.18 mag

SH_0ES Team
Riess, Yuan, Macri, Scolnic, Brout, Casertano, Jones, Murakami,Breuval,Brink,Filippenko,Hoffmann,Kenworthy,Mackenty,Stahl,Zheng 2021, arxiv (12/9) 2021arXiv211204510 (ApJ, in press), github: https://pantheonplussh0es.github.io

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)

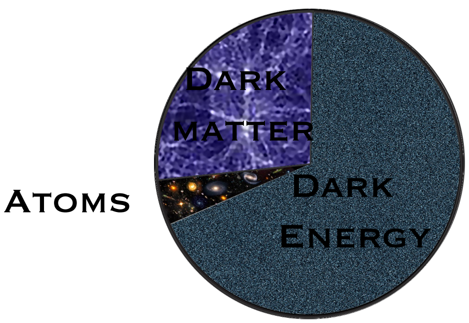


z=1000

Predict physical size fluctuations, r_s, Ω_B →

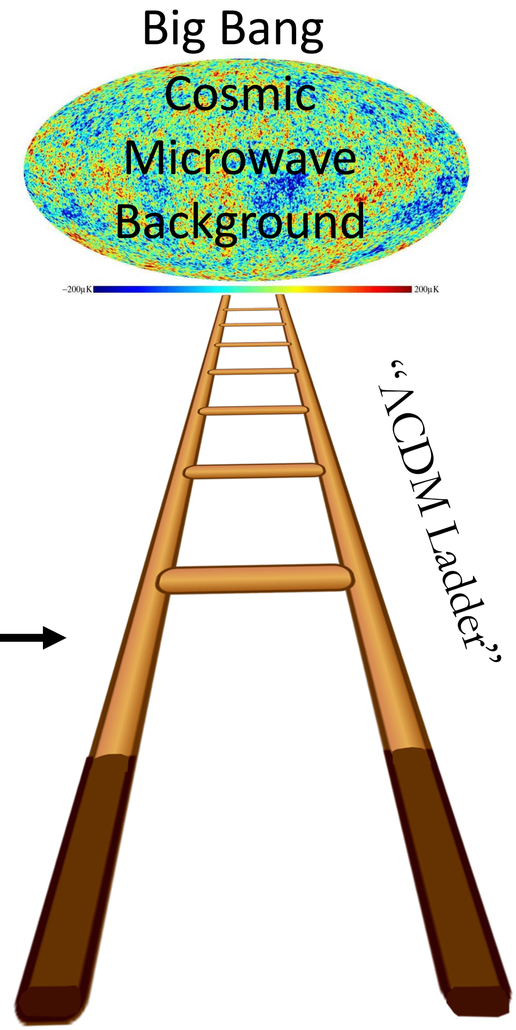
← Measure angular fluctuations (or Ω_B)

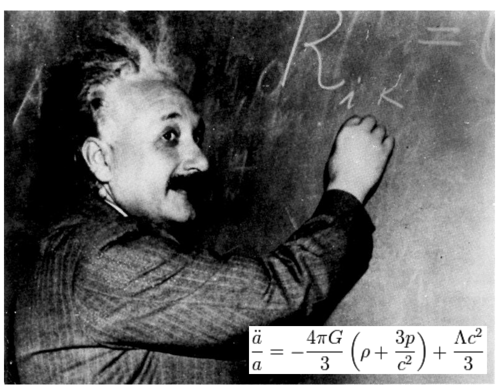
Calibrate ΛCDM …



Now

Expansion history predicted ("guard rails", BAO, SNe) →





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

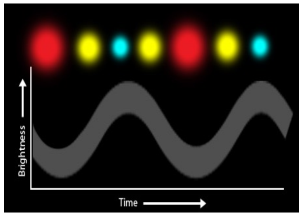
A Direct, Local Measurement of H_0, percent precision w/ HST

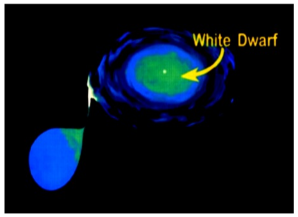
The SH0ES Project (since 2005)

$$D = \frac{c}{H_0}\left[z - \frac{1}{2}(1+q_0)\,z^2\right] + O(z^3)$$

Measure H_0 to percent precision empirically by:

- 3-Rung Distance Ladder of "gold-standards": Geometry → Cepheids → SNe Ia



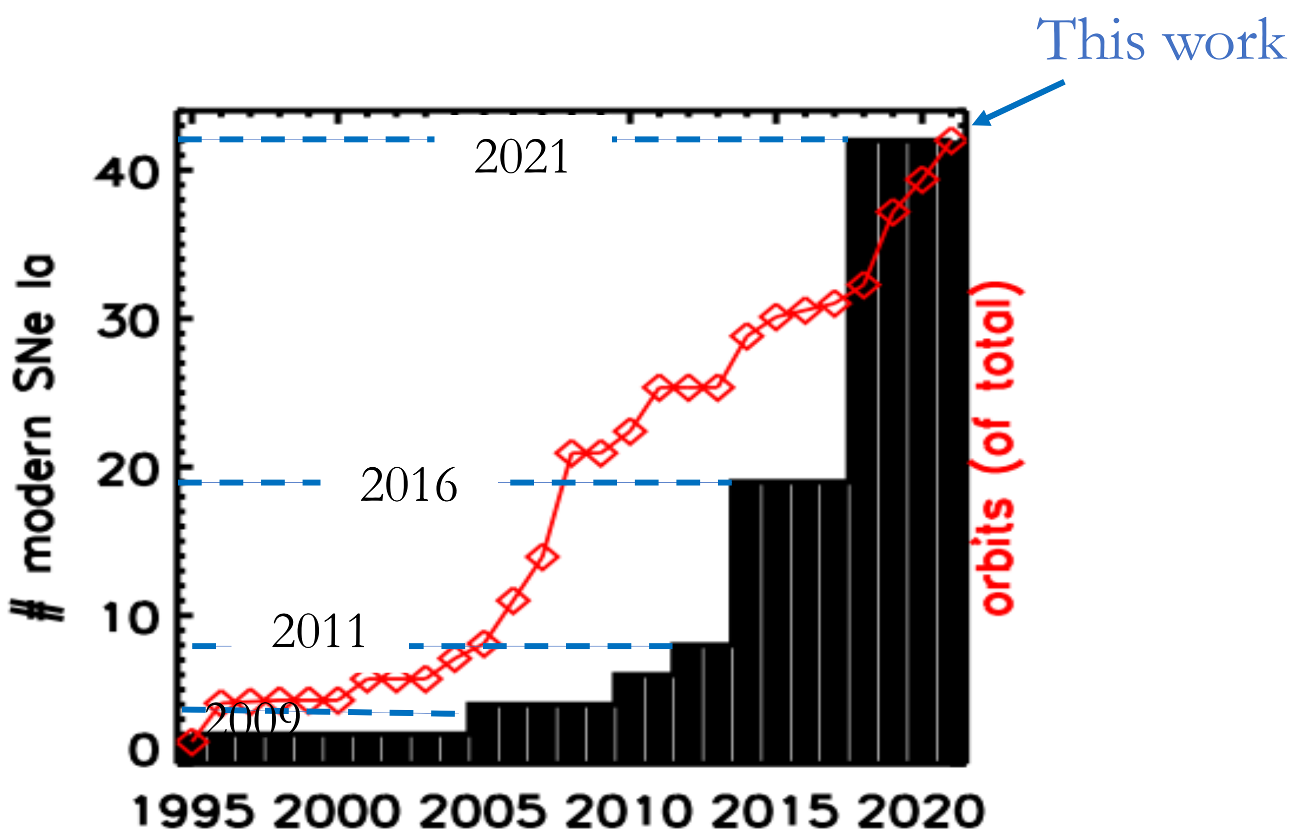


- Reduce systematics w/ differential measurements along ladder and NIR

- "Gen 2": HST Cycle 11-29, 18 competed proposals,~1000 orbits

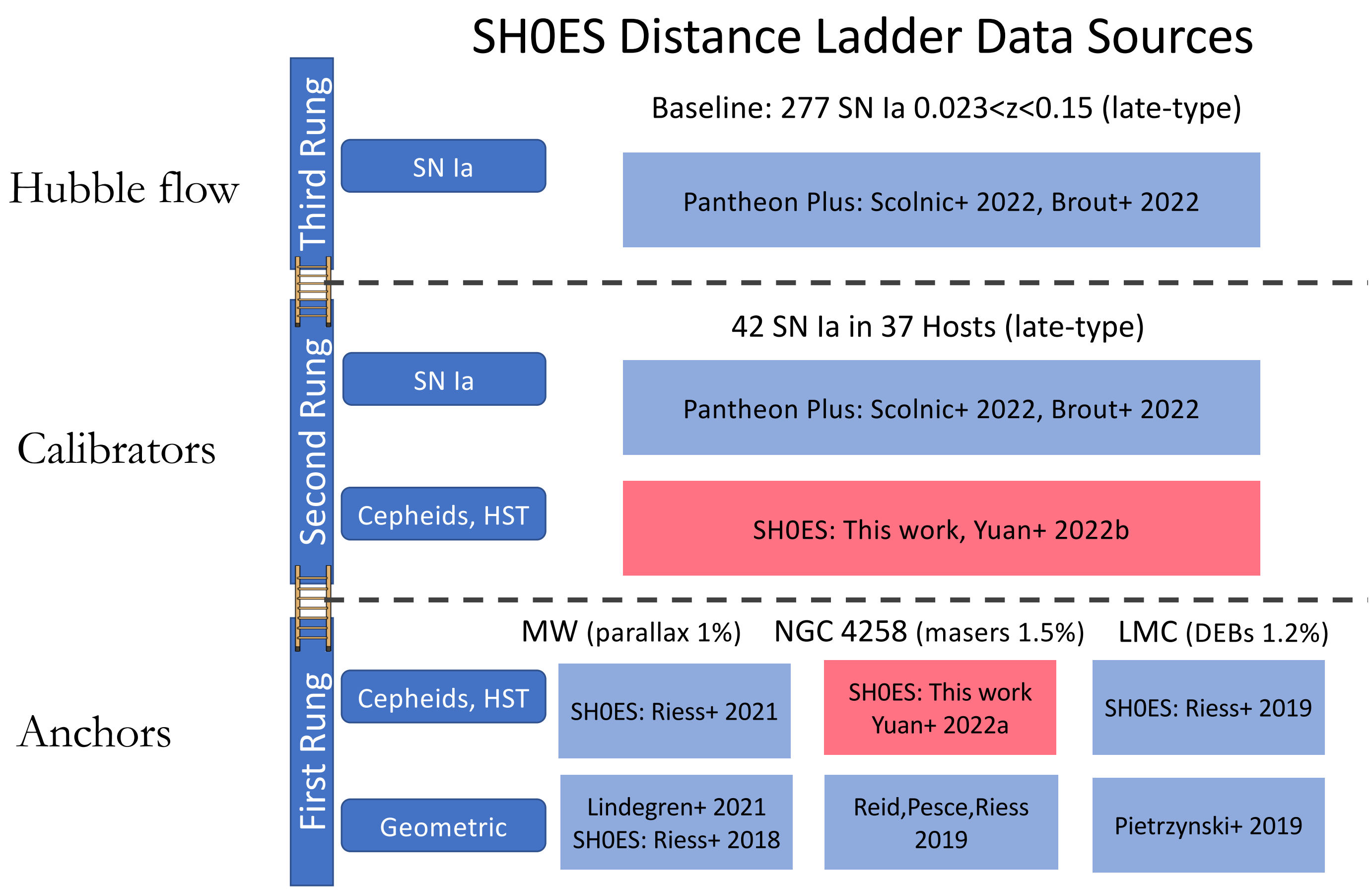
SH_0ES 2022, First Major Update Since 2016 (>1000 orbits HST)

- More than doubles SN calibrators from 19→42, (1/yr), all at z≤0.01, HST milestone!
- More than triples Cepheid calibrators in geometric Maser host NGC 4258
- Data reprocessed with improved pipeline and new STScI reference files



SH_0ES 2022: The 3-Rung Distance Ladder

- Three Independent Geometric Anchors: MW Gaia EDR3, N4258 Masers, LMC DEBs
- Uses Pantheon+ SN (Scolnic+22, Brout+22), SN and Cepheid covariance modeled
- Exhaustive tests, comprehensive analyses of systematics, 67 variants
- Full Release: 10^7 data #s, please read paper, ask if you have questions!



New Cepheid Measurements

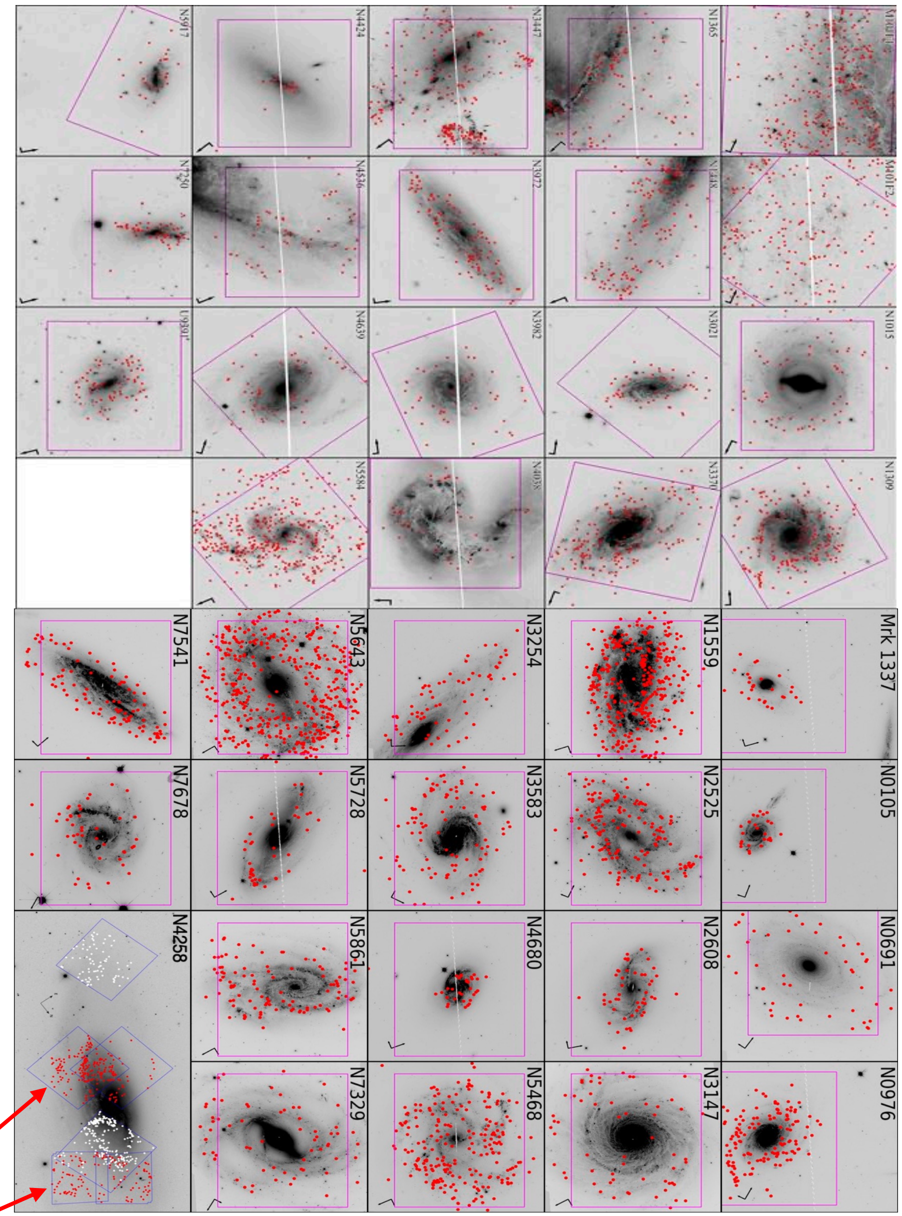
All Cepheids measured *same HST instrument* (WFC3), 3 filters (F555W ,F814W ,F160W) between rungs

→ Nullify zeropoint errors

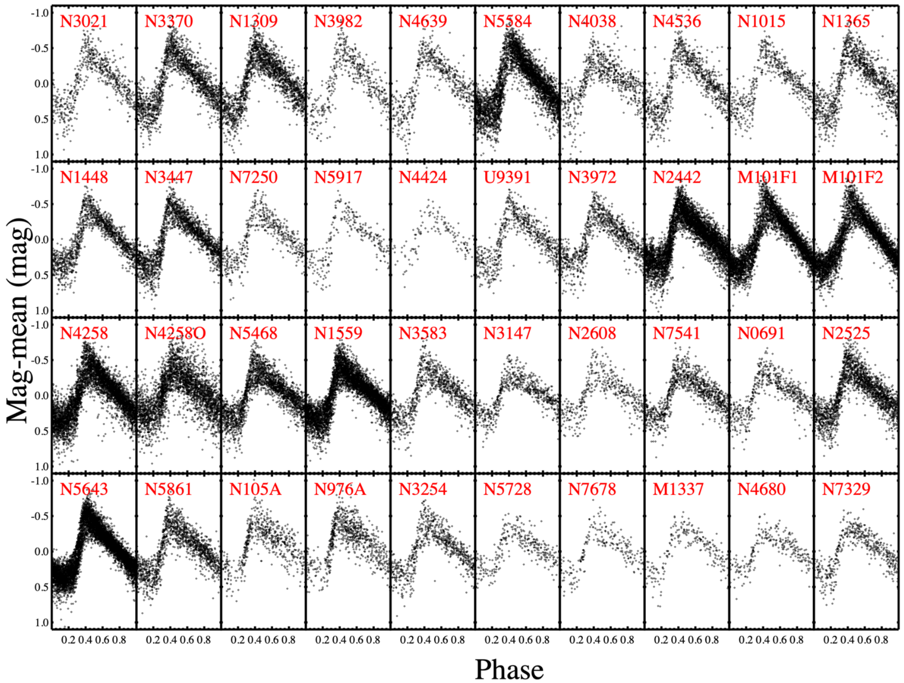
Hosts of 42 New SN Ia

(red pts Cepheids)

New Cepheids in geom. calibrator
4 new fields in NGC 4258

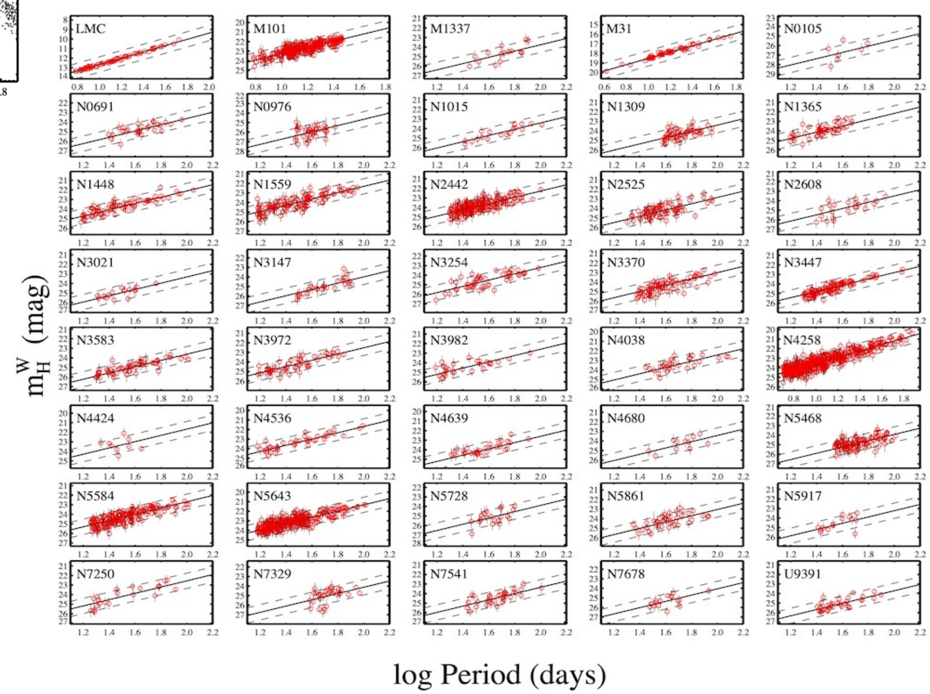


New Cepheid Measurements

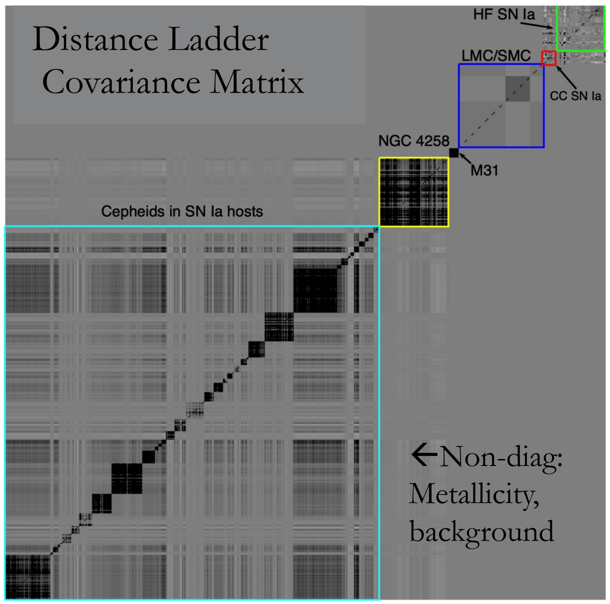


Composite Cepheid Light Curves per host, <u>all periods→ identify</u>

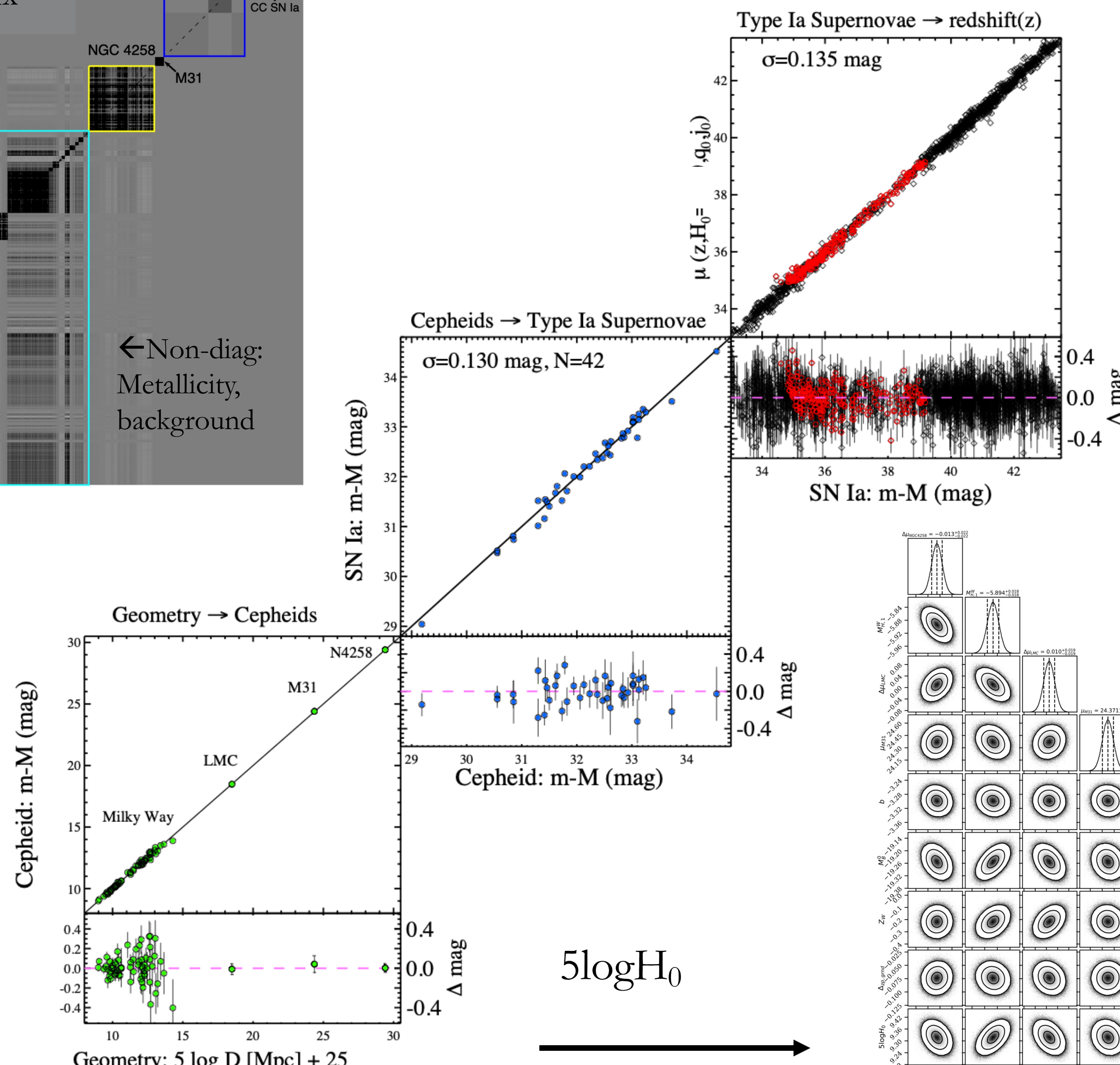
Host Period-Luminosity relations, reddening-free 3 bands→distance



Baseline Fit: ~3200 Cepheids, ~300 SN, non-diagonal covariance

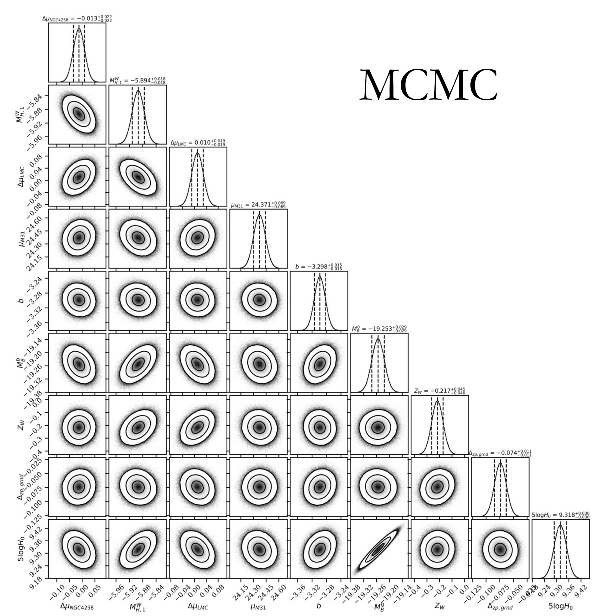


5 free params: [SN Ia, Lum., Cepheid slope, Z, $5\log H_0$]



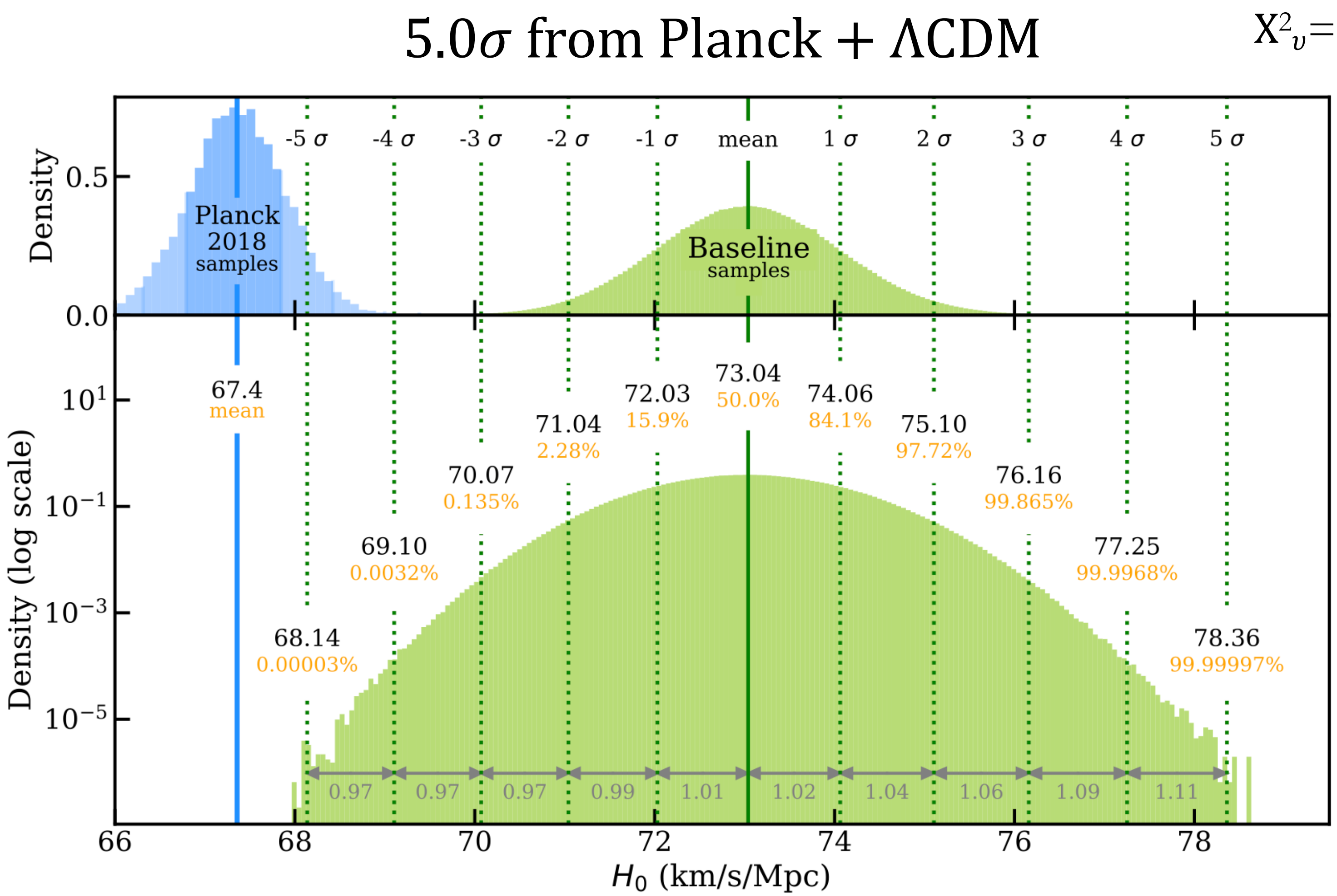
MCMC

$5\log H_0$ →

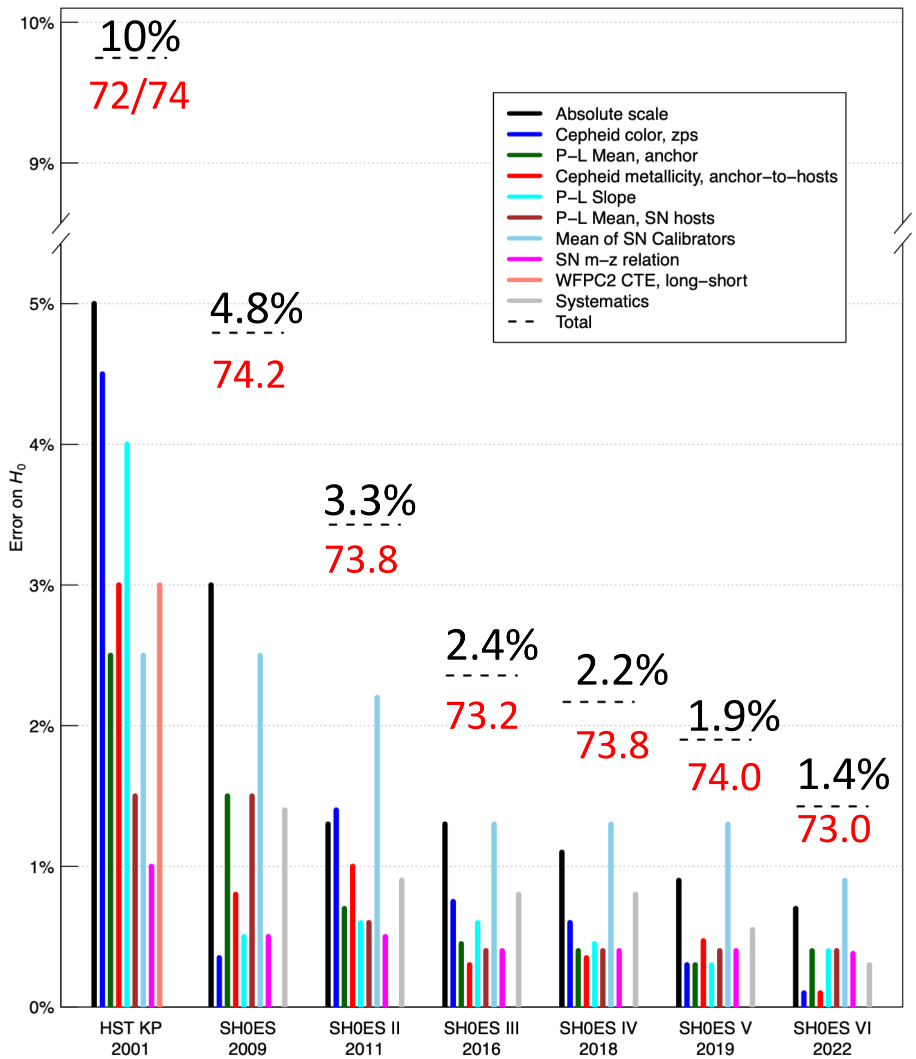


Baseline Fit: $\mathbf{H_0}$**=73.04 +/- 1.04**, km s^{-1} Mpc^{-1}, w/ systematics

X^2_{υ}=1.03, N=3500



SH_0ES Error Budget



- Biggest improvement Since 2011→2016, factor of 8 since HST-Key Project

- All terms now <1%

- With N=42 local SN and ~1/yr, this sample unlikely to be doubled again

Systematics and FAQs

(Not enough time for all, please ask if I miss yours)

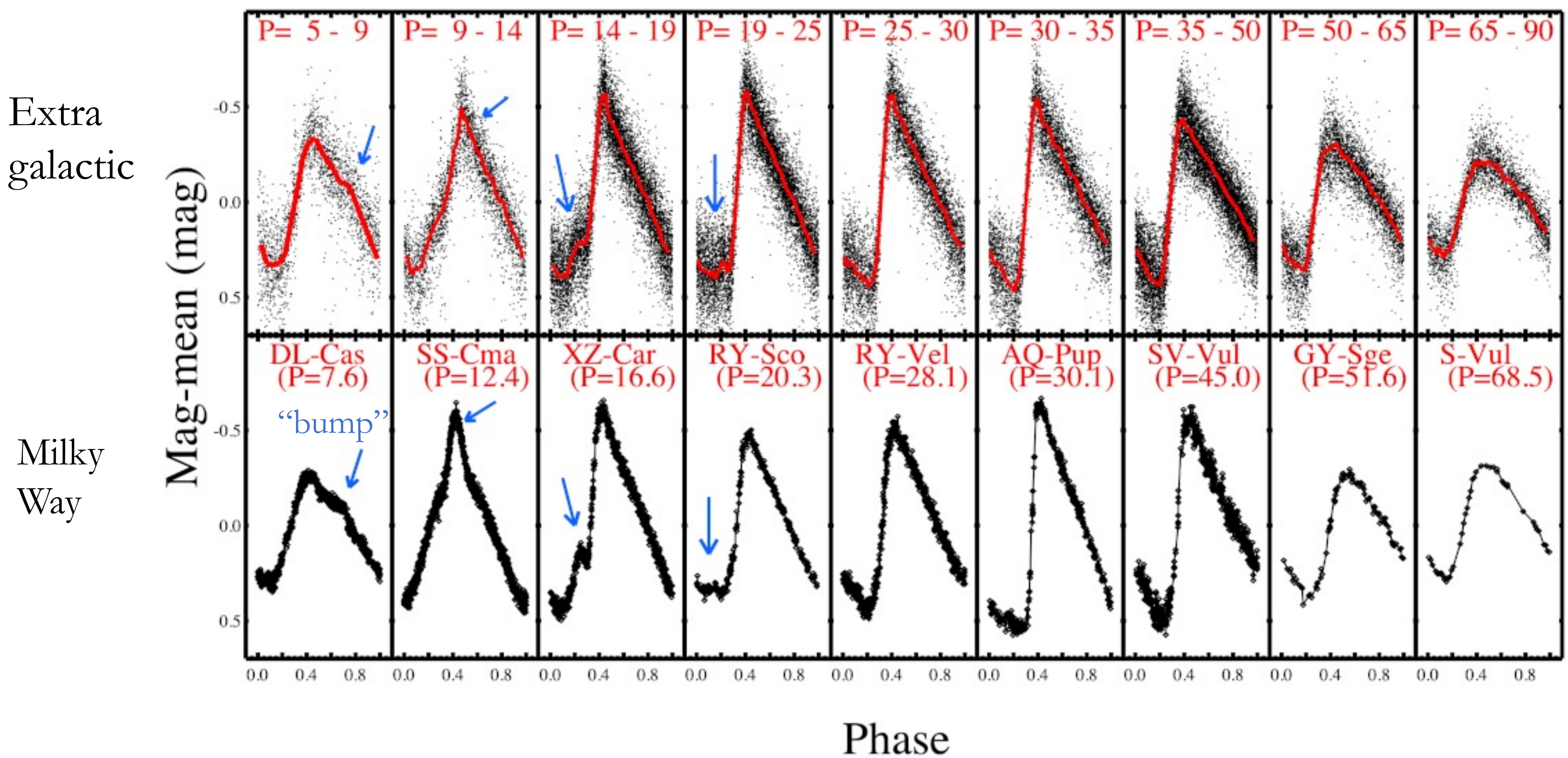
🤓

FAQ Frequently Asked Questions (hopefully includes yours!) Roadmap

- Are extragalactic Cepheids same as MW ?
- How Reliable (and Gaussian) is HST Cepheid Photometry?
- Do Cepheid crowded backgrounds compromise accuracy?
- Do differences in Cepheid metallicity compromise H_0 accuracy?
- Are different geometric anchors consistent?
- How does dust affect Cepheids, H_0 along distance ladder?
- Are Cepheid and TRGB distances consistent?
- Could a giant void (in which we live) solve tension?
- Is there a difference in SN Ia at ends of distance ladder?
- Is HST WFC3 instrument linear enough to measure H_0?
- What if you only include this SN/Cepheid subsample, this period range, this reddening law, only optical data, etc?
- What can we expect from JWST?
- How do I fit my new Cosmological model to the data?

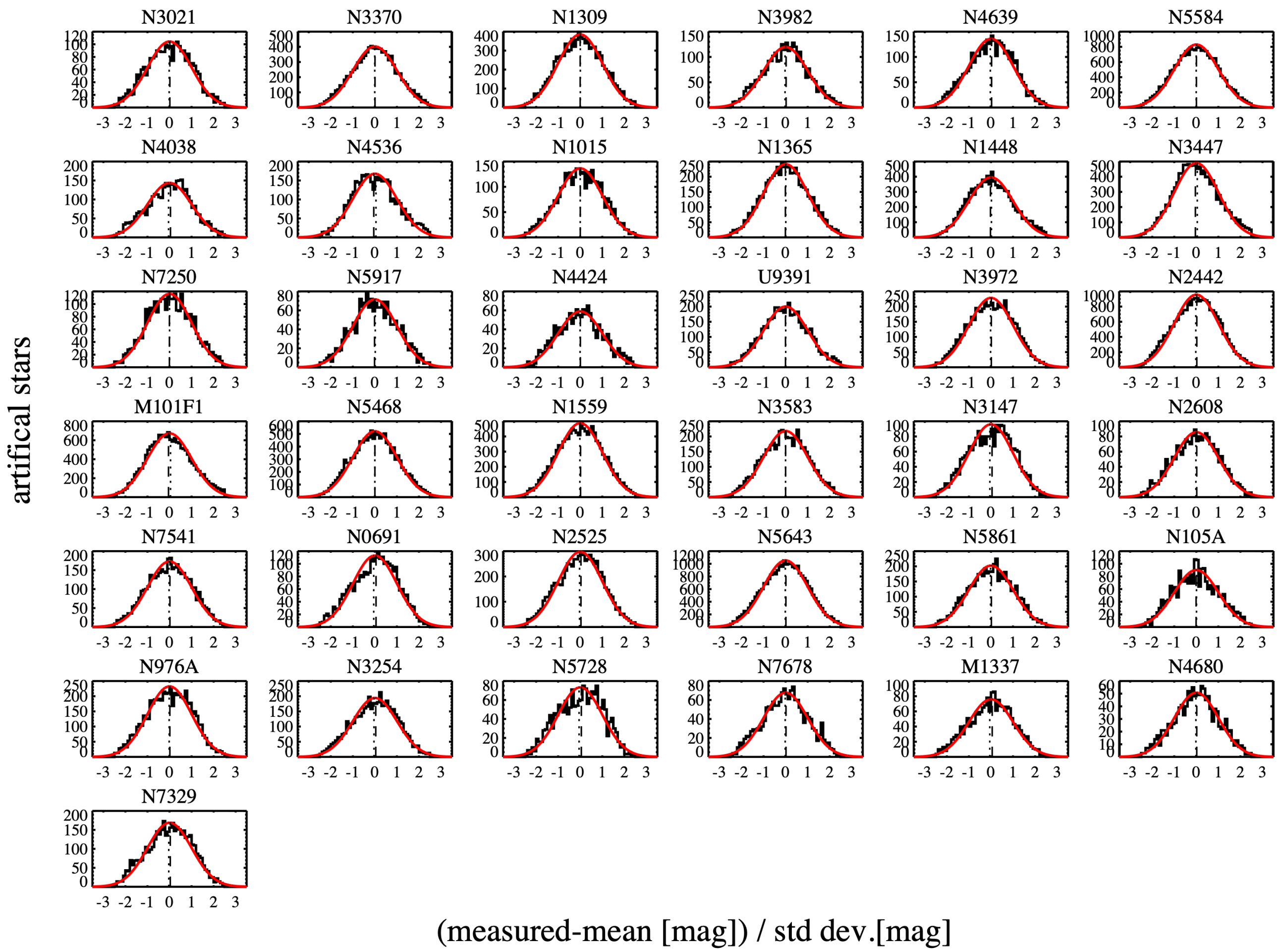
Are Extragalactic Cepheids Like in MW? Detailed Light Curves → Yes

MW Cepheids: light curves shape subtle changes with period
"Hertzsprung Progression" (1926) (Bono et al 2002)



How Reliable (Gaussian) is HST Cepheid Photometry?

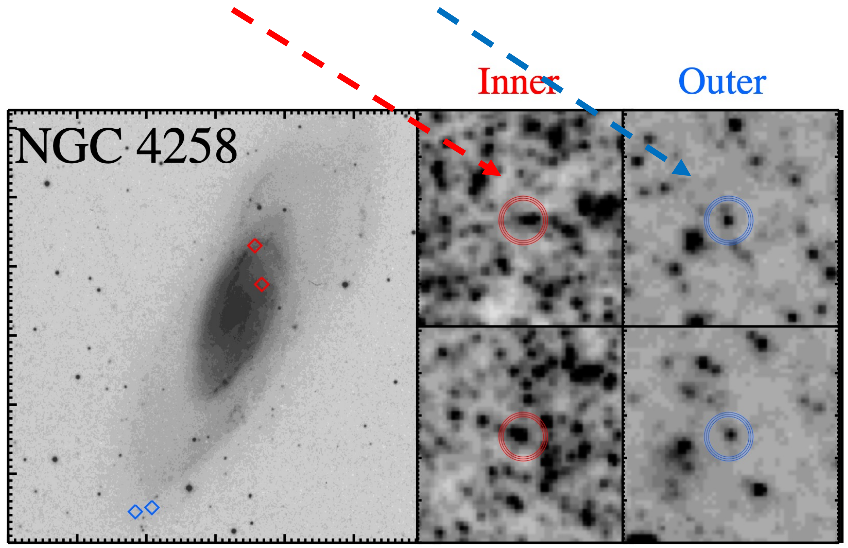
Artificial stars add to frames at known brightness, recovered w/ pipeline→ PSF fitting measurements (in magnitudes) Gaussian (to 3σ), "best practices"



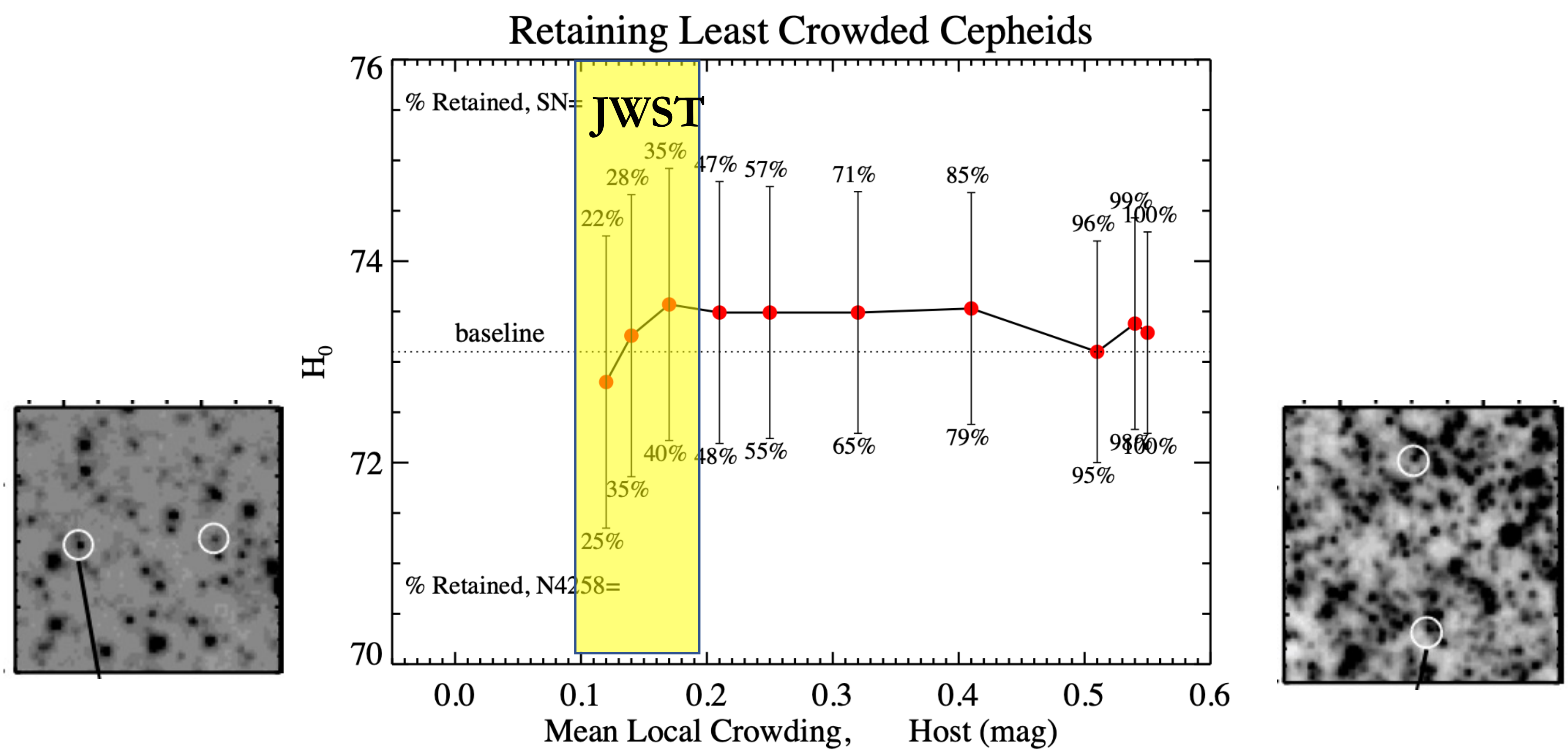
Do Cepheid crowded backgrounds compromise accuracy?

- Six validation tests of backgrounds/crowding, here is one:

Compare Cepheids in high and low background/crowding, same distance



Retaining Only the Least Crowded Data…JWST Preview

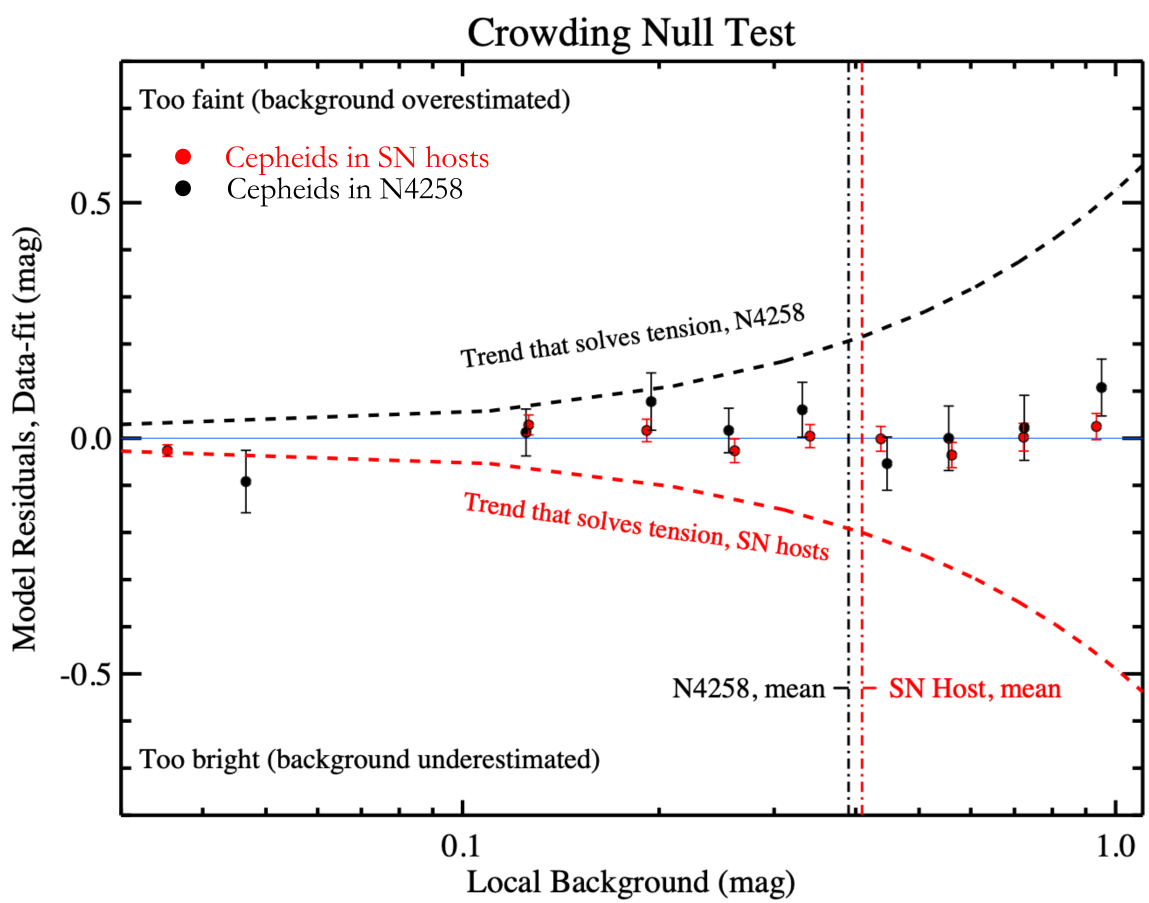


41	Use least crowded half	1.02	3446	73.34	1.16
42	Use most crowded half hosts	1.02	3445	73.35	1.37

Baseline Fit Residuals vs Background/Crowding

Compare fit residuals vs local Cepheid backgrounds
- -backgrounds are independent of fit, measured locally w/ artificial stars

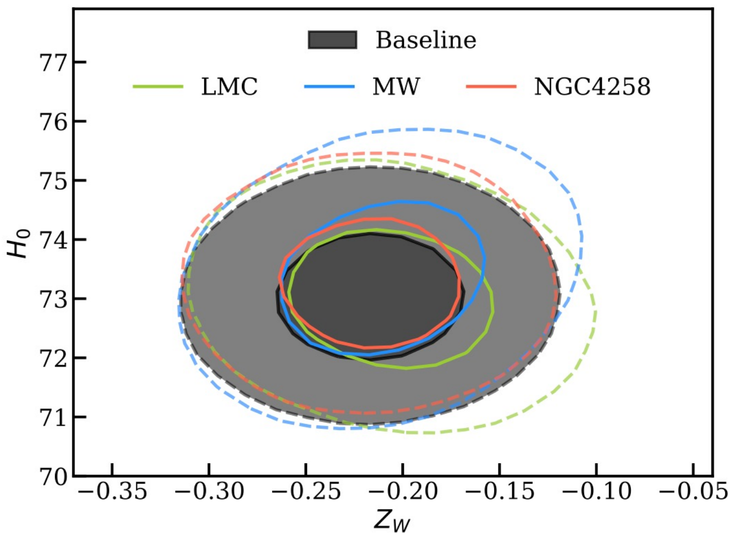
Would need to underestimate backgrounds in SN hosts (red line) and/or overestimate in NGC 4258 (black line) to match Planck+ΛCDM, strongly ruled out



Do differences in Cepheid metallicity compromise H_0 accuracy?

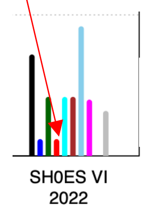
Metallicity measured in SN hosts, anchors (methods cross-calibrated in MW)

Luminosity-Metallicity relation, free parameter, ~-0.22+/-0.05 mag/dex



Marginalized posterior covariance vs H_0,

<u>H_0 insensitive to metallicity term</u>



	Metallicity Variants					
29	no metallity dependence	1.04	3446	73.52	1.01	-

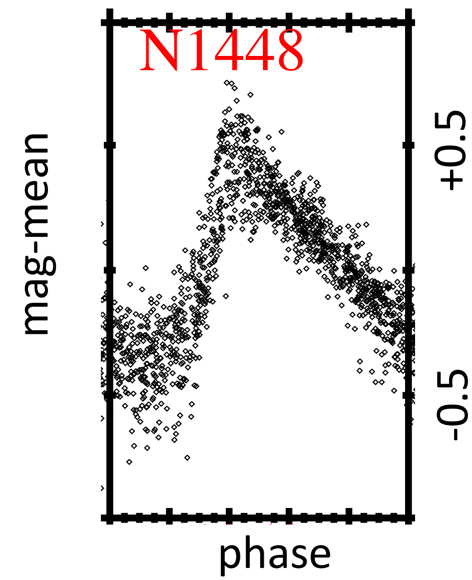
Cepheids in anchors and SN hosts have similar mean metallicity
→ no effect on H0

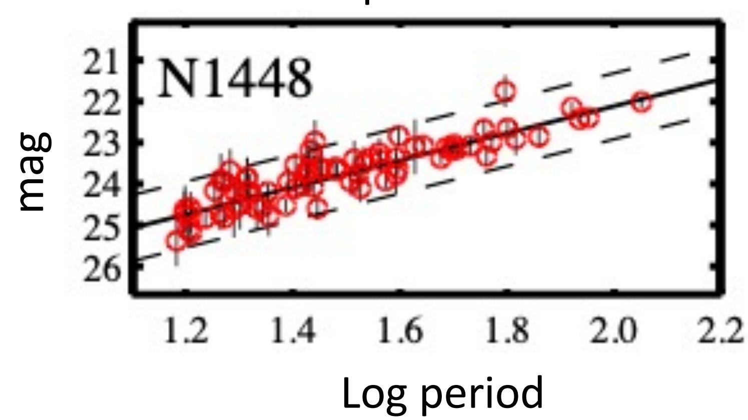
Are Cepheid and TRGB distances consistent?

- Compare distances to same SN Ia hosts, 8 in common (CCHP or EDD)

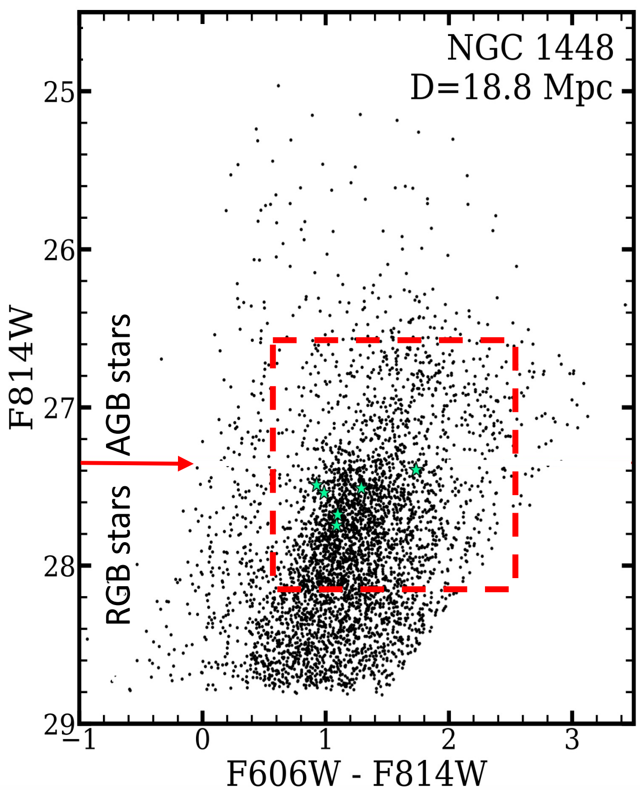
Example: NGC 1448, D~20 Mpc

Cepheids: find light curves, periods, measure Period-brightness relation





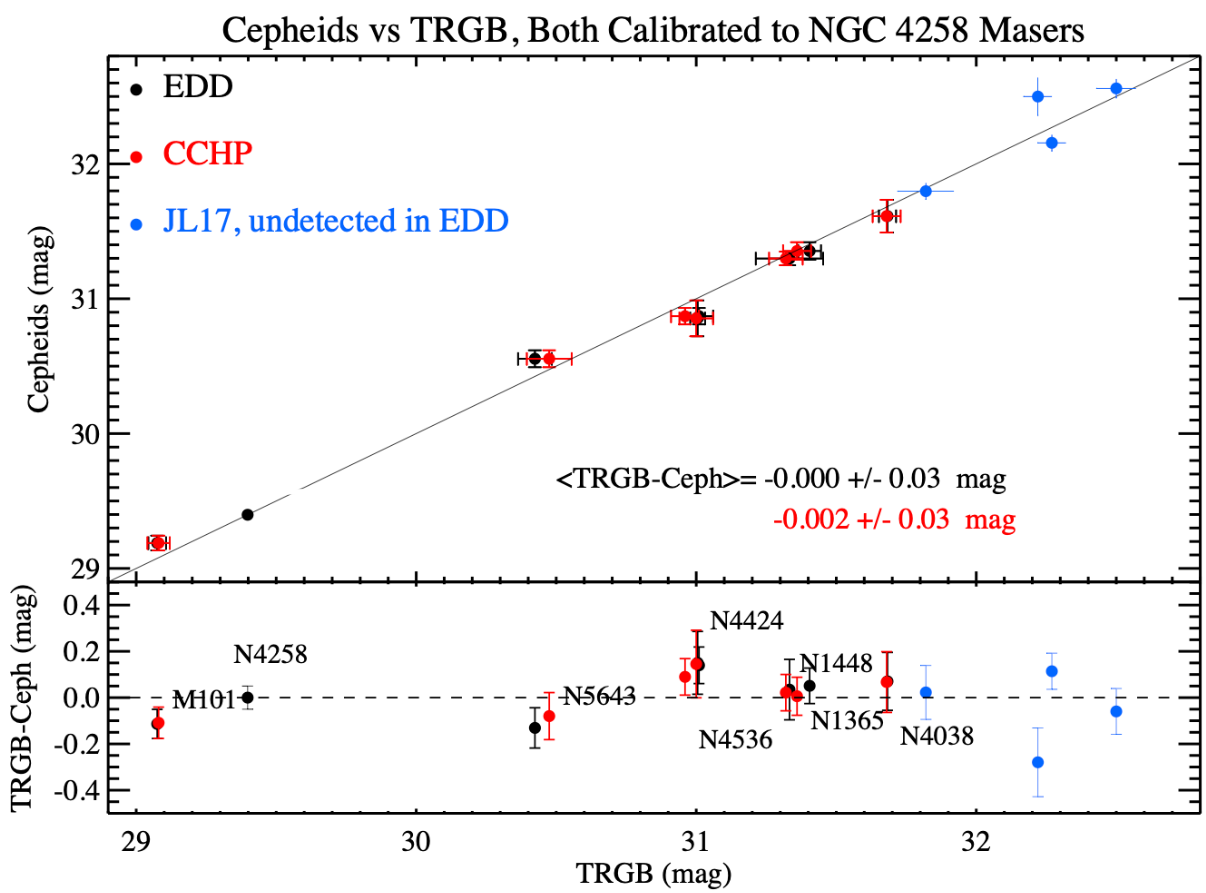
TRGB: find break between RGB/AGB



Are Cepheid and TRGB distances consistent?

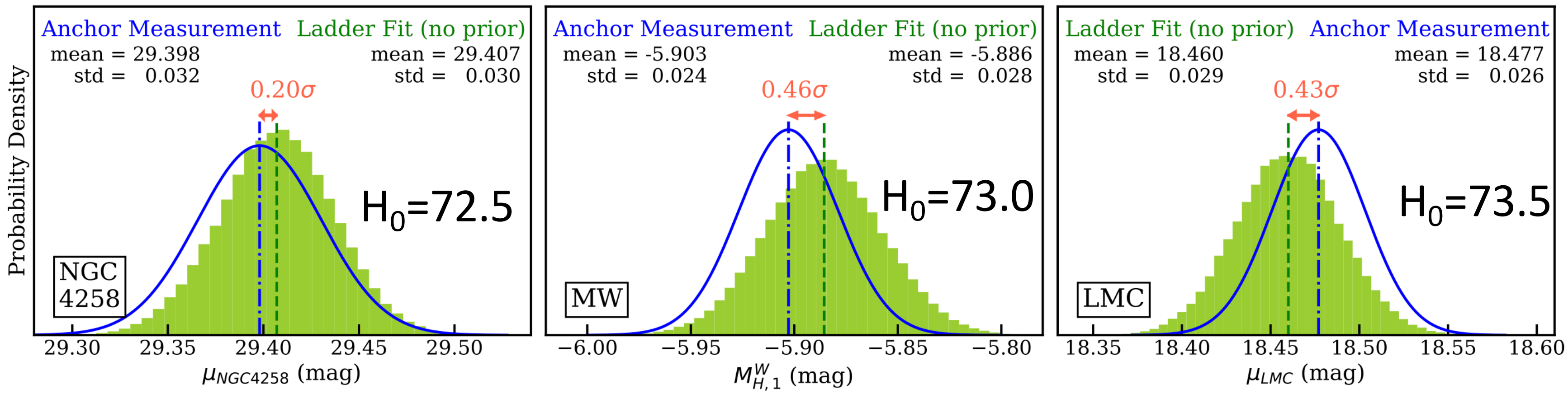
- Compare distances to same SN Ia hosts, 8 in common (CCHP or EDD)
- Both Cepheids and TRGB calibrated by same anchor, NGC 4258 (μ=29.398) (only w/ HST)

- No mean difference to σ =0.03 mag, simultaneous TRGB+Cepheids→ 72.53 +/- 0.99
- (ΔH_0 F21, w/F21: +1.3 from tip in N4258, +1.0 tripling SN sample, +0.5 z frame, backup slides)

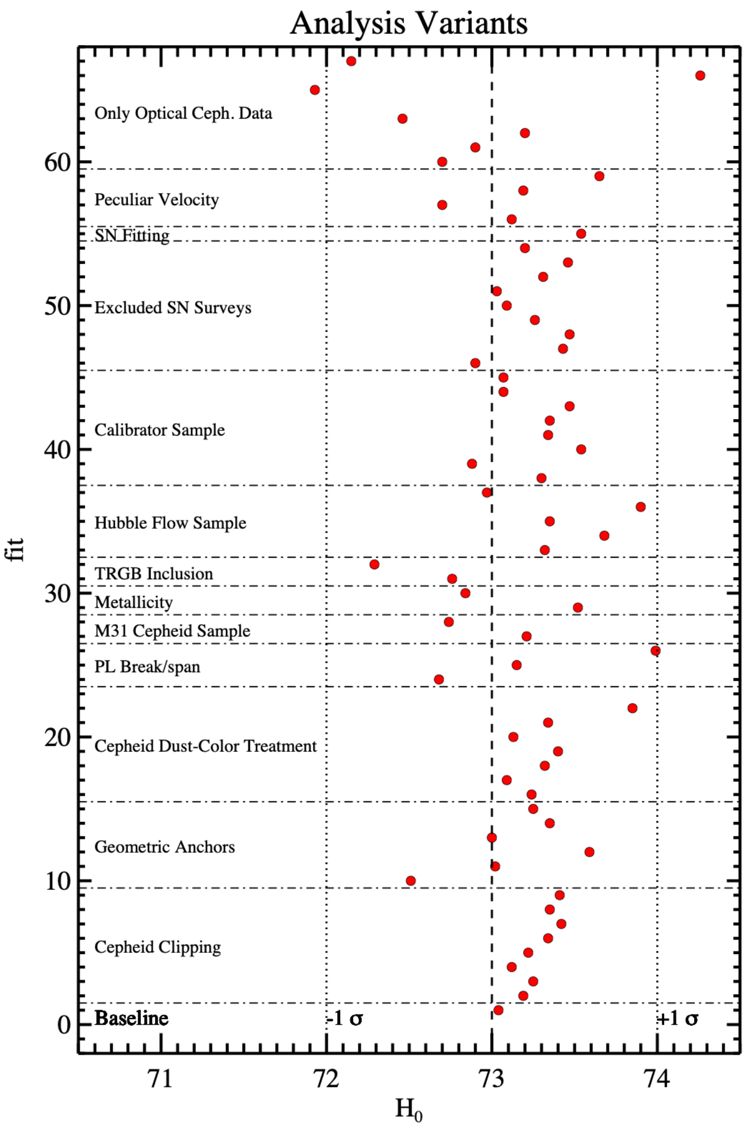


Are Different Anchors Consistent?

Two anchors, predict 3rd. Consistent at the < 1 σ



Analysis Variants: 12 categories, 67 variants, bifurcations, extensions, etc



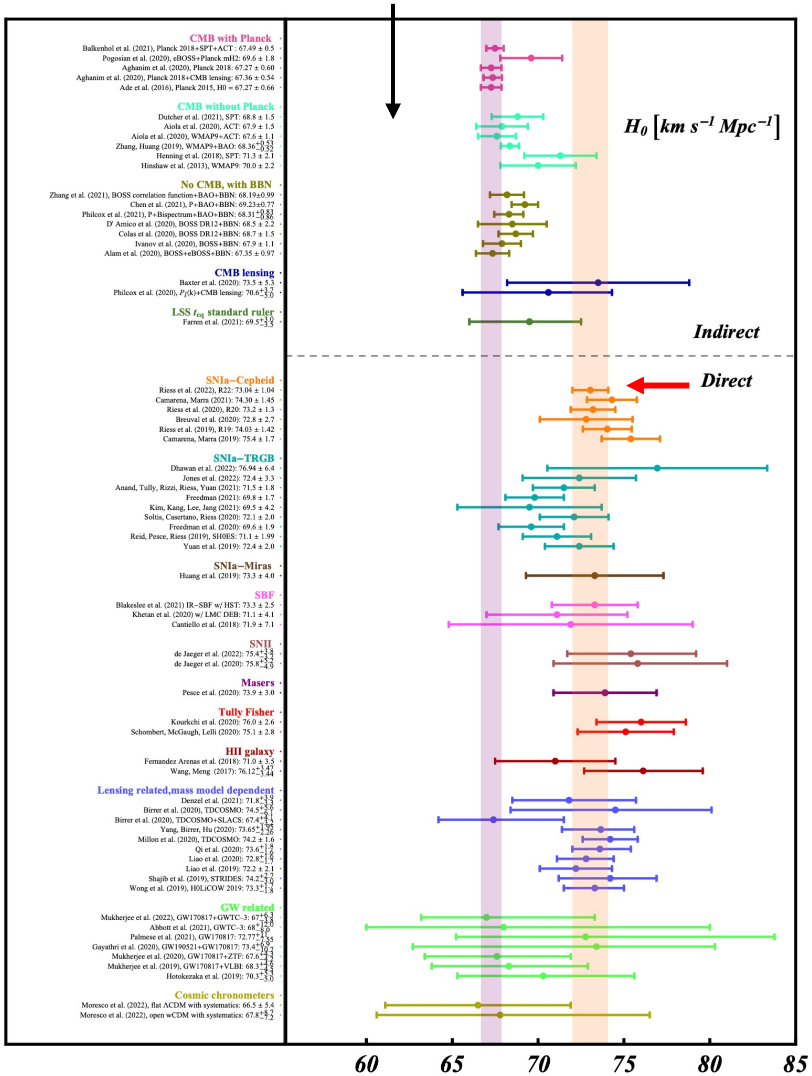
- Optical Cepheid data only (72.7)
- Different pec. vel map or none (73.1,72.7)
- SN scatter ind. wave+mass step (73.5)
- No pre-2000 SNe (73.2)
- closest half hosts (73.1)
- most crowded half (73.4)
- least crowded half (73.3)
- Skip "local hole" z>0.06 (73.4)
- All host types (73.3)
- include TRGB (consistent) jointly (72.5)
- No metallicity term (73.5)
- Break in PL at P=10 days (72.7)
- No dust correction (74.8)
- Individual host dust law (73.9)
- Free param dust law (73.3)
- Low R_V=2.5 dust law (73.2)
- Two of three anchors (73.0,73.4,73.2)
- No outlier rejection (73.4)

Bottom line: hard to get below 72.5, above 73.5, propagate dispersion as extra systematic

Tale of Two Tensions

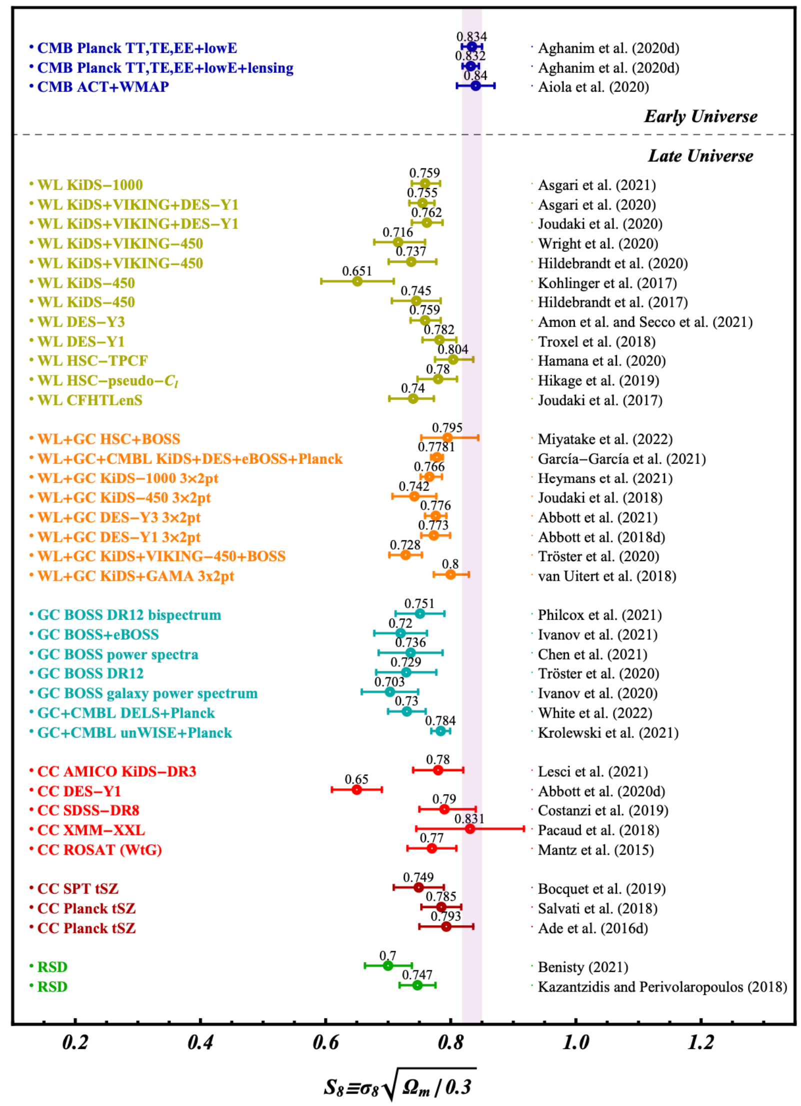
This is getting interesting! To take seriously…

Why no precise, local H_0<Planck?



Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Cosmology Intertwined:
A Review of the Particle Physics, Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies



Present data provides formidable challenge!

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

"Its Systematics"—mature (~10 yrs) measures, many independent rungs, duplicate measurements, Copernican principle

We have addressed known or posited systematics.

We need specific, new hypotheses that are not *already* tested.

Future progress:
Experiment: JWST, Gaia DR4,5, LIGO, R^2, Euclid...
Theory: Early Dark Energy, pre-recombination gravity, Neutrinos, decaying DM, primordial magnetic fields, etc.

Main Conclusions

- Baseline, SN=42, 73.04±1.04 km/s/Mpc with systematics
  joint: +TRGB 72.53±0.99, SN+Cepheids+TRGB+Masers+SBF=72.61±0.89(5.2 σ)
- Exceeds Planck+ΛCDM by 5.0σ (one in a million)
- Extragalactic Cepheids in detail look like MW
- Each geometric anchor consistent with other two at < 1σ, (consequence of Cepheid metallicity dependence)
- SNe on 2nd, 3rd rung matched: host types, properties, surveys
- Cepheid, TRGB consistent between same anchor-to-SN hosts
  (ΔH_0: +1.3 from tip in N4258, +1.0 tripling SN sample, +0.5 z frame)

- Exhaustive study of systematics, variations, no indications of internal inconsistencies, excess noise, unrecognized err.
  Tests inconsistent with dust, metallicity, crowding as explanations.

- Source of "Hubble Tension" unknown
  MUCH more detail in paper, on arxiv and github