Recent Cosmological Results from Type Ia Supernovae in Pantheon+ and SH0ES

Dan Scolnic (presenting work from Pantheon+SH0ES teams: Dillon Brout ea., Adam Riess ea.)

Duke University

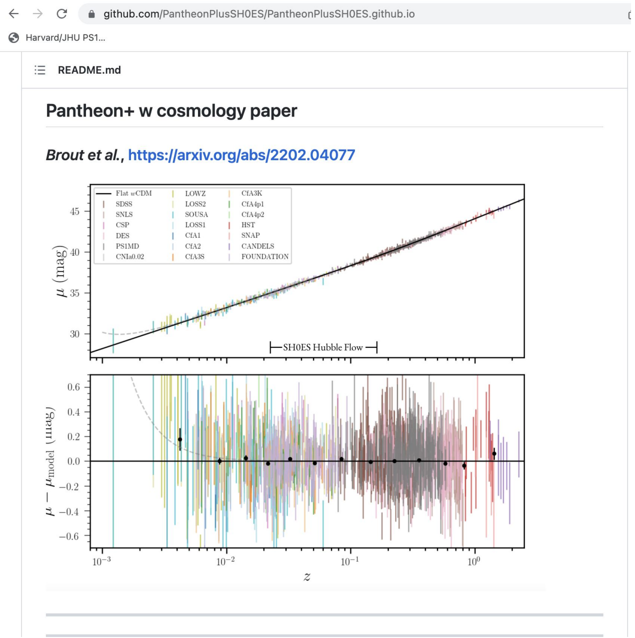
Tensions in Cosmology , Sep 8th, 2022

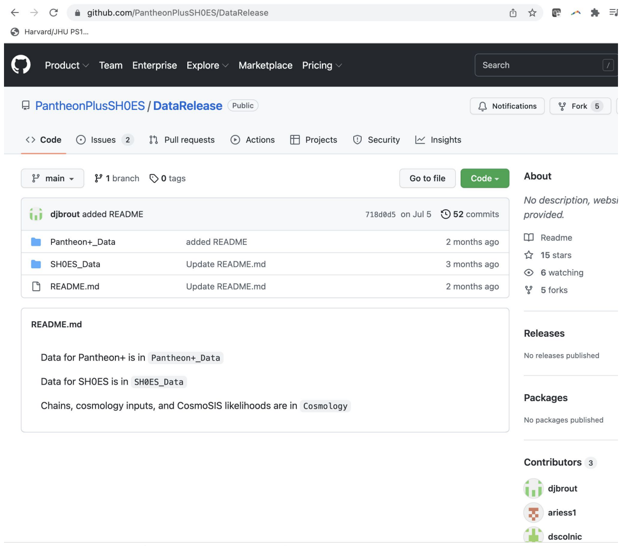
Some takeaways:

- Pantheon+SH0ES data is public. Please reach out (especially in person).
- SH0ES 2022 and Pantheon+ are *major* updates, largest since 2016
- We tried very hard on Cepheid and Supernova side to allow H0 to move, but not moving.
- Ideas to move H0 becoming more ‘non-Aristarchusan’.
- Pantheon+ measurement of w and OmegaM harder, it moves, but still big improvement over Pantheon

Aristarchus of Samos was an ancient Greek astronomer and mathematician who presented the first known heliocentric model that placed the Sun at the center of the known universe, with the Earth revolving around the Sun once a year and rotating about its axis once a day.

P+SH0ES papers accepted, data on Github page. Same landing page for Pantheon+ and SH0ES data.





https://github.com/PantheonPlusSH0ES. Email Dillon Brout djbrout@gmail.com, Dan Scolnic daniel.scolnic@duke.edu (P+); Adam Riess ariess@stsci.edu (SH0ES)

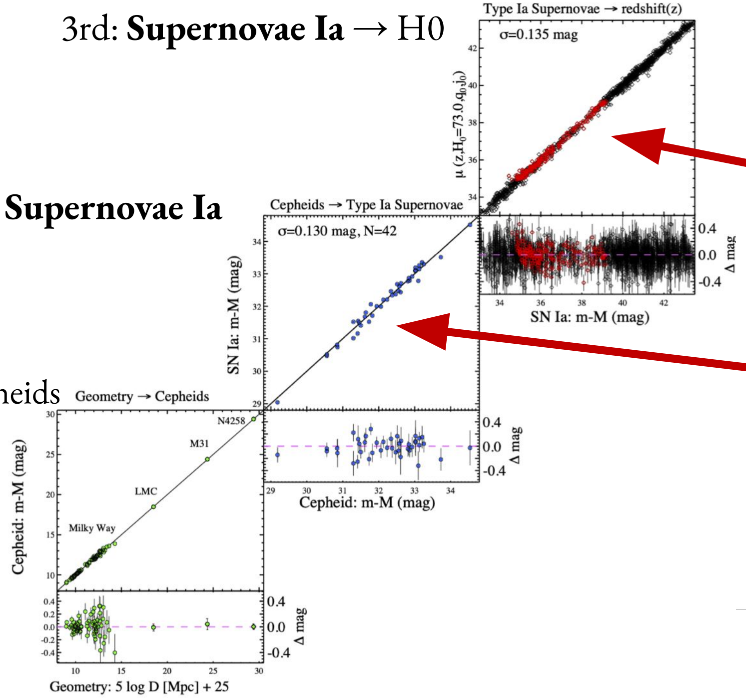
Recent work is the marriage of two teams - SH0ES and Pantheon+

SH0ES

3rd: **Supernovae Ia** → H0

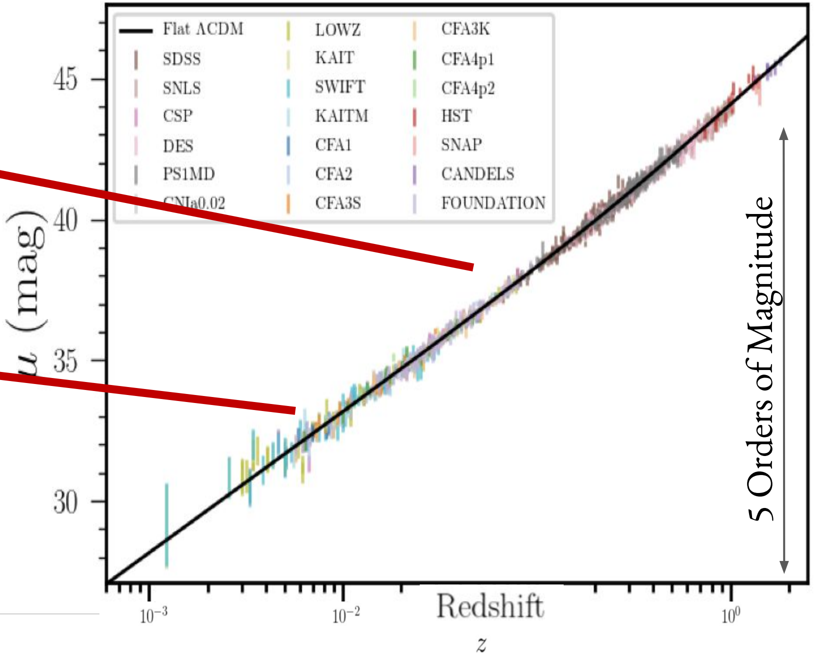
2nd: Cepheids → **Supernovae Ia**

1st: Geometry → Cepheids



Riess, Yuan, Macri, Scolnic, Brout+21

Pantheon+



Brout, Scolnic+2022

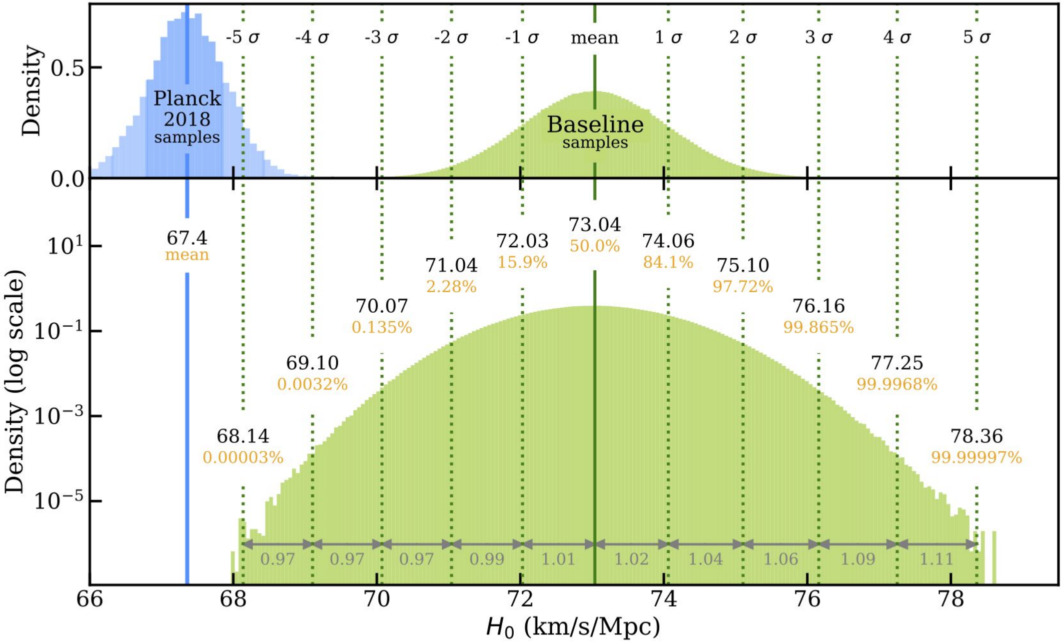
Cepheid calibrator SNe are analyzed simultaneously with Hubble flow SNe

Pantheon+SH0ES allows exploration of tensions in Flat ΛCDM and Beyond

Planck
67+-0.5

SH0ES & Pantheon+
73+-1

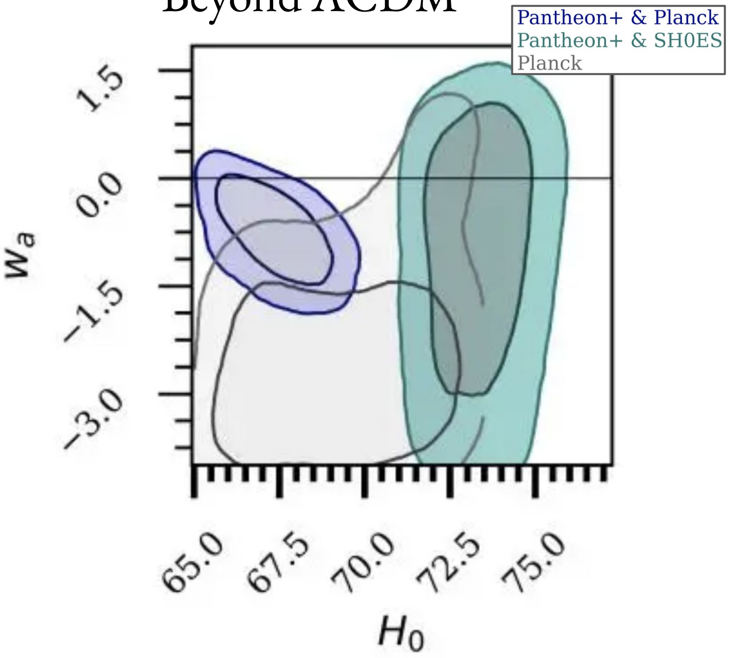
In Flat ΛCDM



5.0 sigma difference !

Riess, Yuan, Macri, Scolnic +21

Beyond ΛCDM

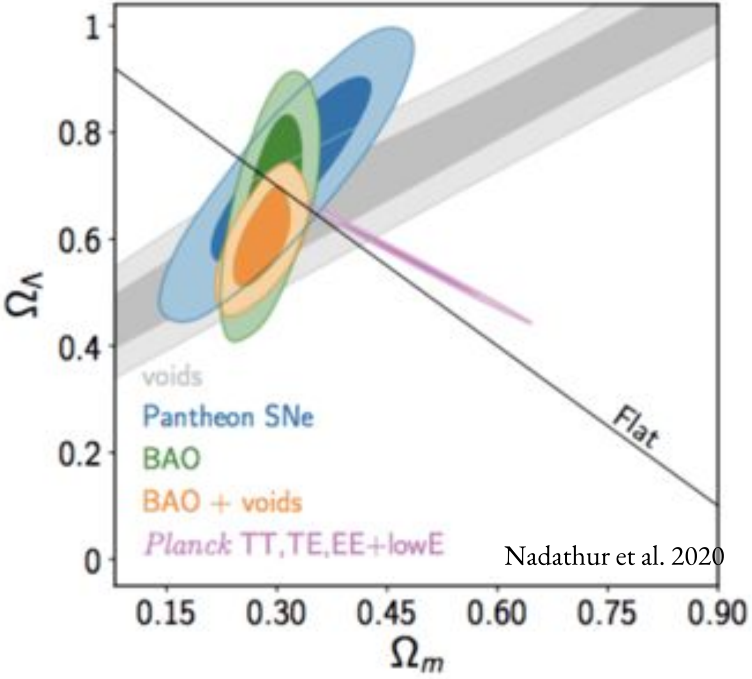


Brout, Scolnic+22

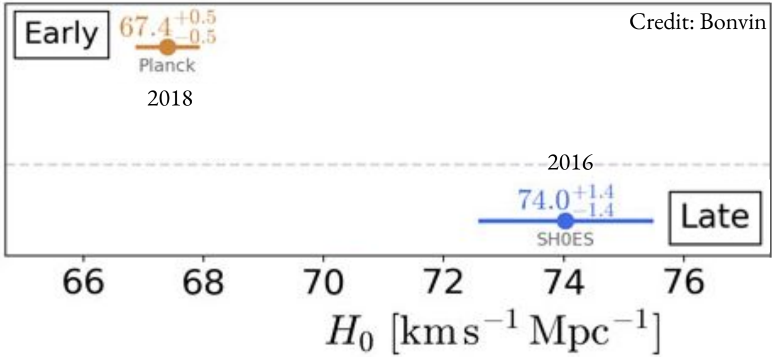
This talk focuses more on SNe Ia, as they play a unique role in both

<u>ΛCDM 'concordance cosmology'</u> and <u>the observed H0 tension</u>

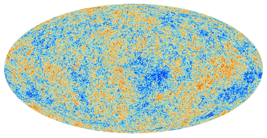
Dark Energy Density



Matter Density

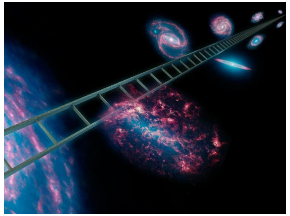


Planck



Early Universe H0 (CMB)

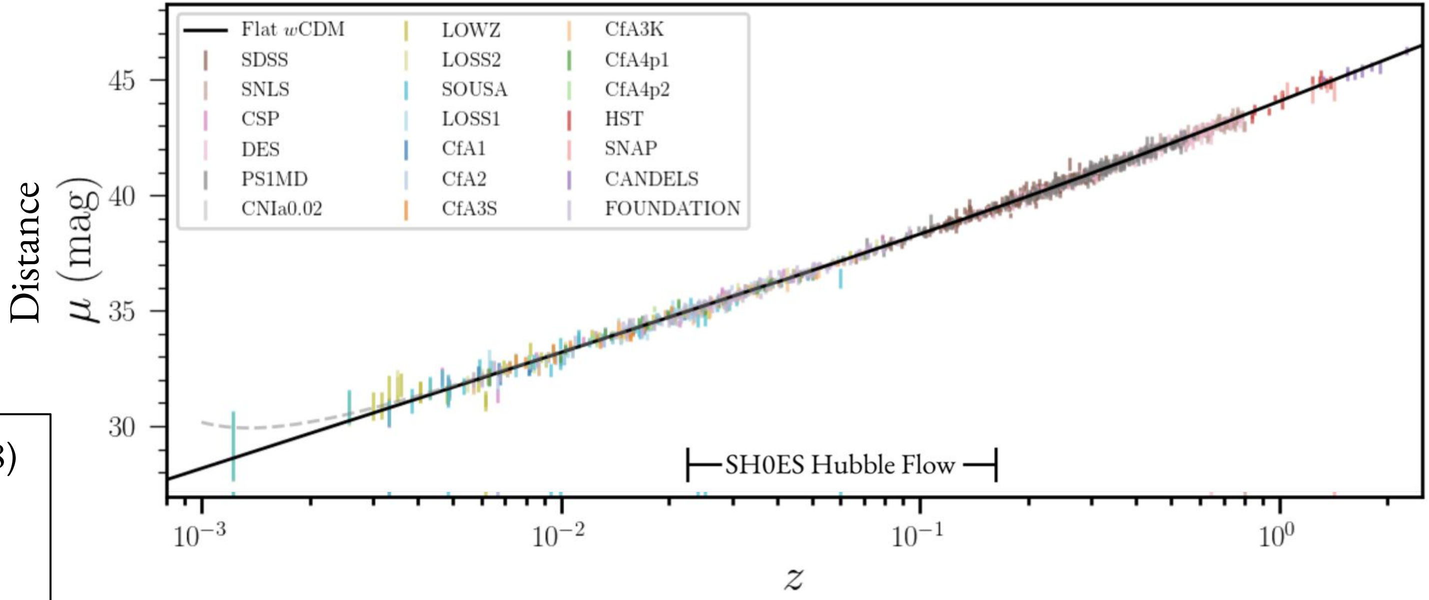
SH0ES



Local/Late Univ./Direct H0

(Geometry → Cepheids → Pantheon SNe)

Pantheon+



Successor to Pantheon (2018)

Largest compilation of the high quality and best calibrated SNe over the last 30 years..

STARTS WITH A BANG — FEBRUARY 15, 2022

Record-breaking Pantheon+ supernova study reveals what makes up our Universe

Ethan Siegel

"With 1550 individual type Ia supernovae that span 10.7 billion years of cosmic history, the latest Pantheon+ results are a feast for the cosmically curious."

"[I]t's arguable that the most impressive of all the "heavy lifting" done by the Pantheon+ team is the remarkably tiny errors and uncertainties that exist when you look at the data.."

The core of Pantheon+ is a group of ~10 scientists, largely led by early career scientists.

1) https://arxiv.org/absf/2202.0407

The Pantheon+ Analysis: Cosmological Constraints

Dillon Brout,[1,2] Dan Scolnic,[3] Brodie Popovic,[3] Adam G. Riess,[4,5] Joe Zuntz,[6] Rick Kessler,[7,8] Anthony Carr,[9] Tamara M. Davis,[9] Samuel Hinton,[9] David Jones,[10,2] W. D'Arcy Kenworthy,[5] Erik R. Peterson,[3] Khaled Said,[9] Georgie Taylor,[11] Noor Ali,[12] Patrick Armstrong,[13] Pranav Charvu,[3] Arianna Dwomoh,[3] Antonella Palmese,[14] Helen Qu,[15] Benjamin M. Rose,[3] Christopher W. Stubbs,[16,1] Maria Vincenzi,[3] Charlotte M. Wood,[17] Peter J. Brown,[18,19] Rebecca Chen,[3] Ken Chambers,[20] David A. Coulter,[10] Mi Dai,[5] Georgios Dimitriadis,[21] Alexei V. Filippenko,[22] Ryan J. Foley,[10] Saurabh W. Jha,[23] Lisa Kelsey,[24] Robert P. Kirshner,[25,1] Anais Möller,[26,27] Jessie Muir,[28] Seshadri Nadathur,[29] Yen-Chen Pan,[30] Armin Rest,[4] Cesar Rojas-Bravo,[10] Masao Sako,[15] Matthew R. Siebert,[10] Mat Smith,[31] Benjamin E. Stahl,[22] and Phil Wiseman[32]

2) https://arxiv.org/abs/2112.03863

The Pantheon+ Type Ia Supernova Sample: The Full Dataset and Light-Curve Release

Dan Scolnic,[1] Dillon Brout,[2,3] Anthony Carr,[4] Adam G. Riess,[5,6] Tamara M. Davis,[4] Arianna Dwomoh,[1] David O. Jones,[3,7] Noor Ali,[8] Pranav Charvu,[1] Rebecca Chen,[1] Erik R. Peterson,[1] Brodie Popovic,[1] Benjamin M. Rose,[1] Charlotte M. Wood,[9] Peter J. Brown,[10,11] David A. Coulter,[7] Kyle G. Dettman,[12] Georgios Dimitriadis,[13] Alexei V. Filippenko,[14,15] Ryan J. Foley,[7] Saurabh W. Jha,[12] Charles D. Kilpatrick,[16] Robert P. Kirshner,[2,17] Yen-Chen Pan,[18] Armin Rest,[19] Cesar Rojas-Bravo,[7] Matthew R. Siebert,[7] Benjamin E. Stahl,[14] and WeiKang Zheng[14]

3) https://arxiv.org/abs/2112.04510

A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s^{-1} Mpc^{-1} Uncertainty from the *Hubble Space Telescope* and the SH0ES Team

Adam G. Riess,[1,2] Wenlong Yuan,[2] Lucas M. Macri,[3] Dan Scolnic,[4] Dillon Brout,[5] Stefano Casertano,[1] David O. Jones,[6] Yukei Murakami,[2] Gagandeep S. Anand,[1] Louise Breuval,[2] Thomas G. Brink,[7] Alexei V. Filippenko,[7,8] Samantha Hoffmann,[1] Saurabh W. Jha,[9] W. D'Arcy Kenworthy,[2] John Mackenty,[1] Benjamin E. Stahl,[7] and Weikang Zheng[7]

4) https://arxiv.org/abs/2112.03864

The Pantheon+ Analysis: SuperCal-Fragilistic Cross Calibration, Retrained SALT2 Light Curve Model, and Calibration Systematic Uncertainty

Dillon Brout,[1,2] Georgie Taylor,[3] Dan Scolnic,[4] Charlotte M. Wood,[5] Benjamin M. Rose,[4] Maria Vincenzi,[4] Arianna Dwomoh,[6] Christopher Lidman,[7,8] Adam Riess,[9] Noor Ali,[10] Helen Qu,[11] Mi Dai,[9] and Christopher Stubbs[12]

5) https://arxiv.org/abs/2112.04456

The Pantheon+ Analysis: Forward-Modeling the Dust and Intrinsic Colour Distributions of Type Ia Supernovae, and Quantifying their Impact on Cosmological Inferences

Brodie Popovic[1], Dillon Brout[2,3], Richard Kessler[4], Daniel Scolnic[1]

6) https://arxiv.org/abs/2112.01471

The Pantheon+ Analysis: Improving the Redshifts and Peculiar Velocities of Type Ia Supernovae Used in Cosmological Analyses

Anthony Carr,[1] Tamara M. Davis,[1] Dan Scolnic,[2] Khaled Said,[1] Dillon Brout,[3,4] Erik R. Peterson,[2] and Richard Kessler[5]

7) https://arxiv.org/abs/2110.03487

The Pantheon+ Analysis: Evaluating Peculiar Velocity Corrections in Cosmological Analyses with Nearby Type Ia Supernovae

Erik R. Peterson,[1] W. D'Arcy Kenworthy,[2] Daniel Scolnic,[1] Adam G. Riess,[2,3] Dillon Brout,[4,5] Anthony Carr,[6] Hélène Courtois,[7] Tamara Davis,[6] Arianna Dwomoh,[1] David O. Jones,[8,5] Brodie Popovic,[1] Benjamin M. Rose,[1] and Khaled Said[6]

8) https://arxiv.org/abs/2110.03486

The Pantheon+ Analysis: Dependence of Cosmological Constraints on Photometric-Zeropoint Uncertainties of Supernova Surveys

Sasha Brownsberger,[1] Dillon Brout,[1,2] Daniel Scolnic,[3] Christopher W. Stubbs,[1,2] and

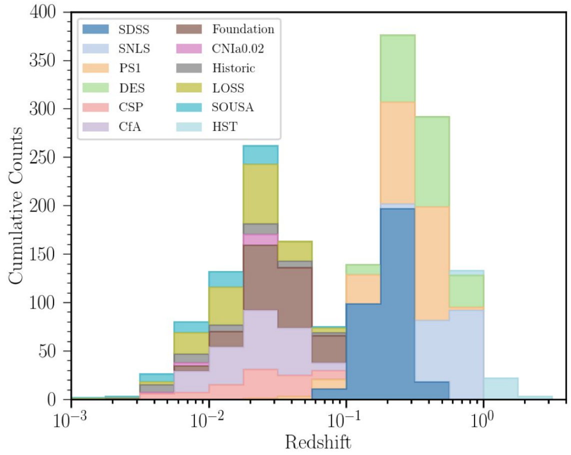
The Pantheon+ Compilation of SNe (Scolnic, Brout+2021)

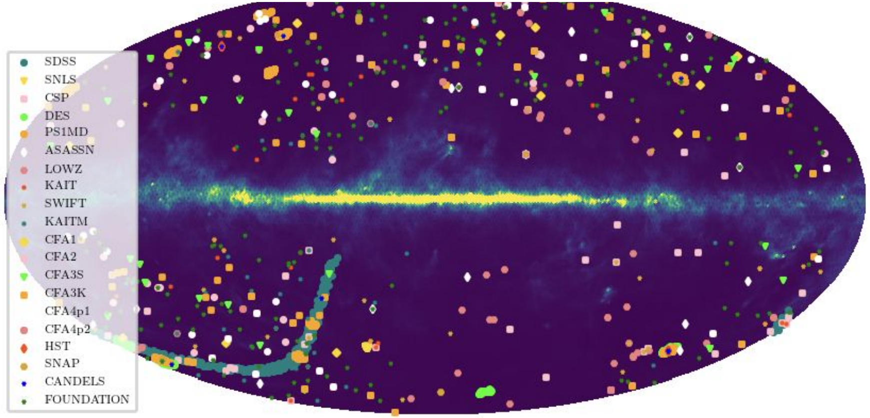
- 1701 Light-Curves of 1550 individual SNe Ia (0.001<z<2.3)
  - compared to original Pantheon of 1048 Light-Curves (0.02<z<2.3)

- 18 surveys, 25 systems, 105 filters

- More than doubled Cepheid Calibrated SNe, 19→42 (>1000 HST orbits, cannot double in HST lifetime)

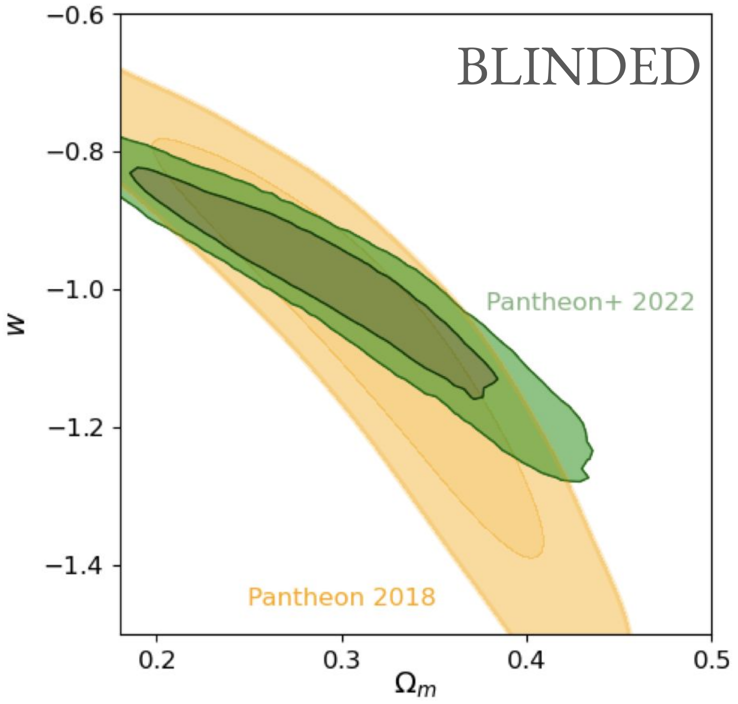
- Now have an average of 2 photometric systems for each SN that is in a cepheid host (80 light curves in 42 hosts)





Improvements in Pantheon+ Fall in 5 Main Categories

Factor of 2 improvement in FoM!



1. Statistical (only a factor of 1.4x comes from statistics)
2. Analysis Methodology
3. Improvements to Survey Calibration
4. Improvements in redshifts and peculiar velocities
5. Improvements in modeling SNIa intrinsic variations and dust

Georgie Taylor

arXiv:2112.03864

Anthony Carr

arXiv:2112.01471

Erik Peterson

arXiv:2110.03487

Brodie Popovic

arXiv:2102.01776

arXiv:2112.04456

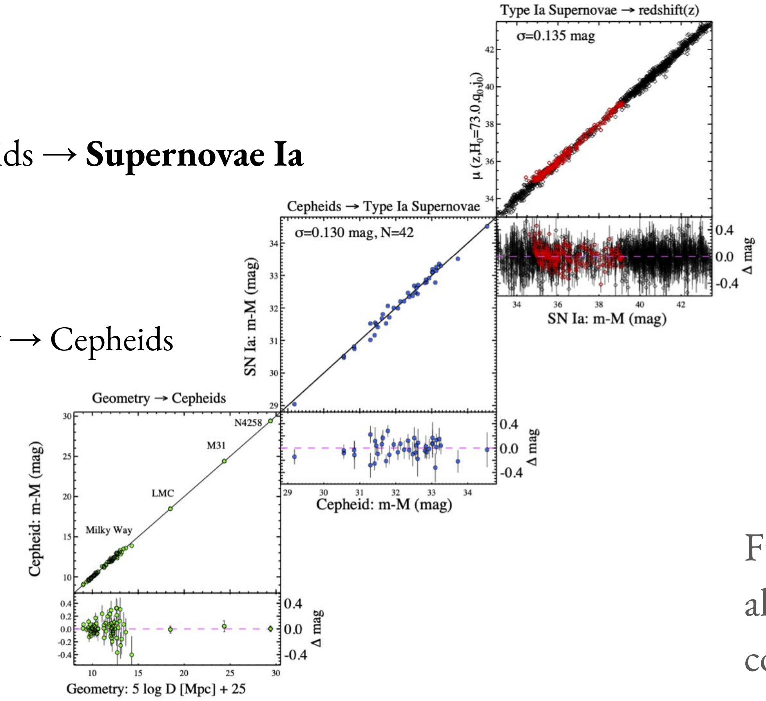
Pantheon+ pushed down the error floor, and tied covariance to SH0ES for first time.

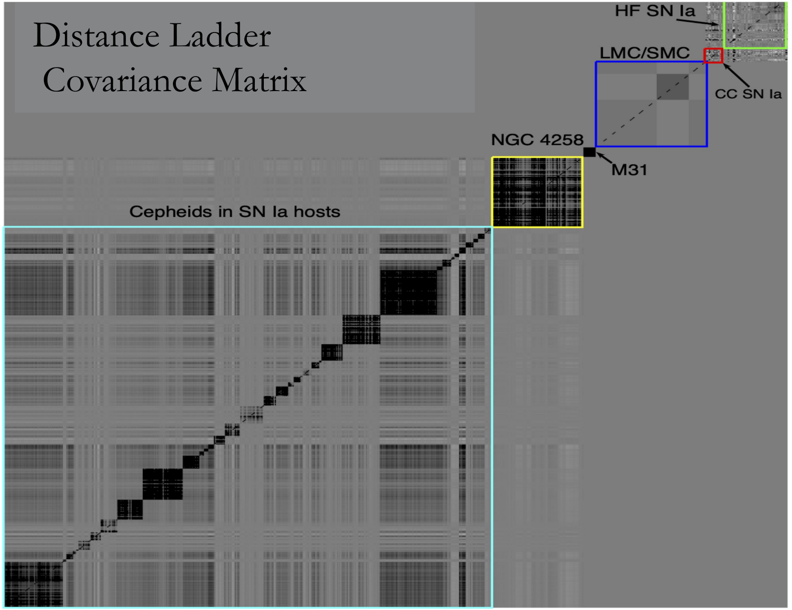
Incorporated over 115 sources of systematic uncertainty into a 1701x1701 systematic covariance matrix

3rd: **Supernovae Ia** → H0

2nd: Cepheids → **Supernovae Ia**

1st: Geometry → Cepheids



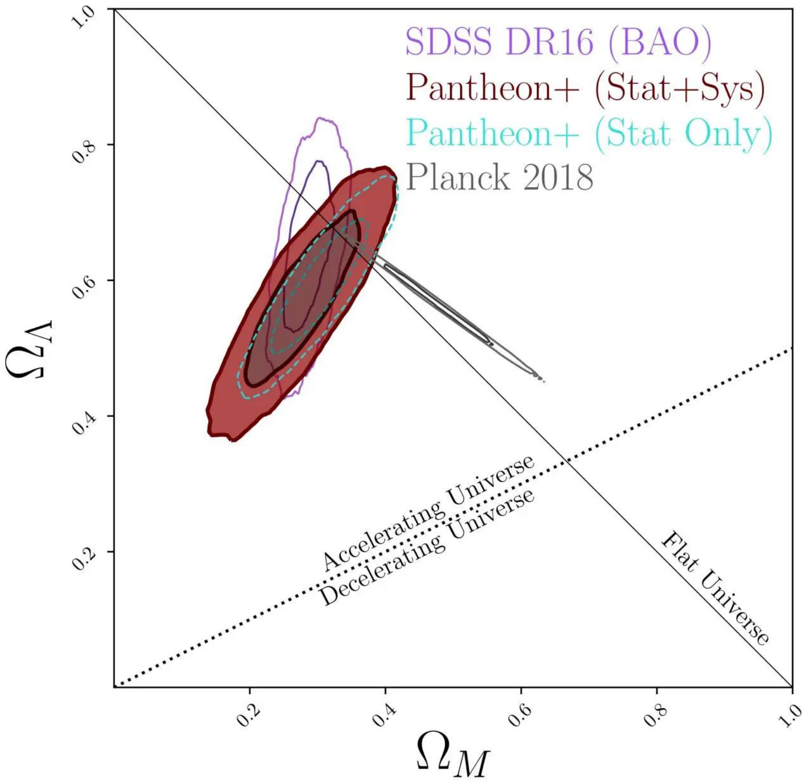


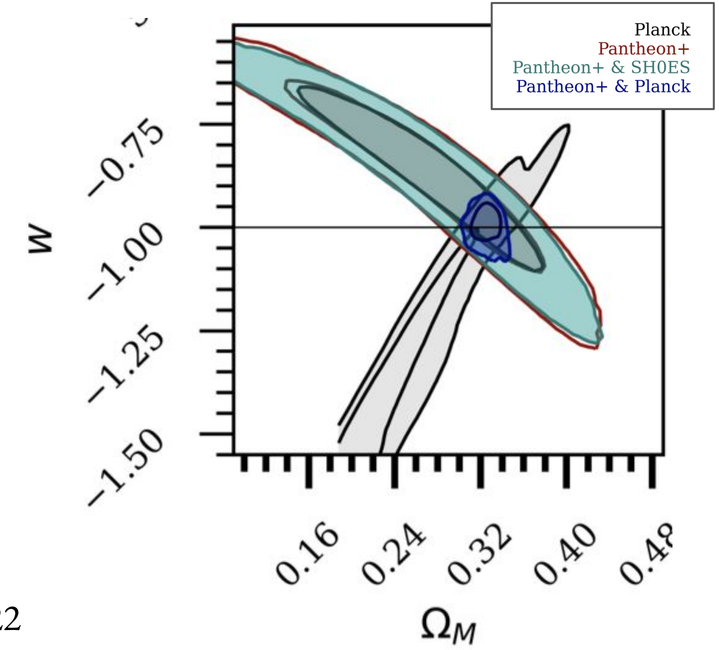
Full systematic covariance of each rung and out to z~2.3 allows for simultaneous measurements of H0 with cosmological expansion history models

Pantheon+ Constraints on Dark Matter and Dark Energy

Flat ΛCDM $\Omega_m = 0.338 \pm 0.018$

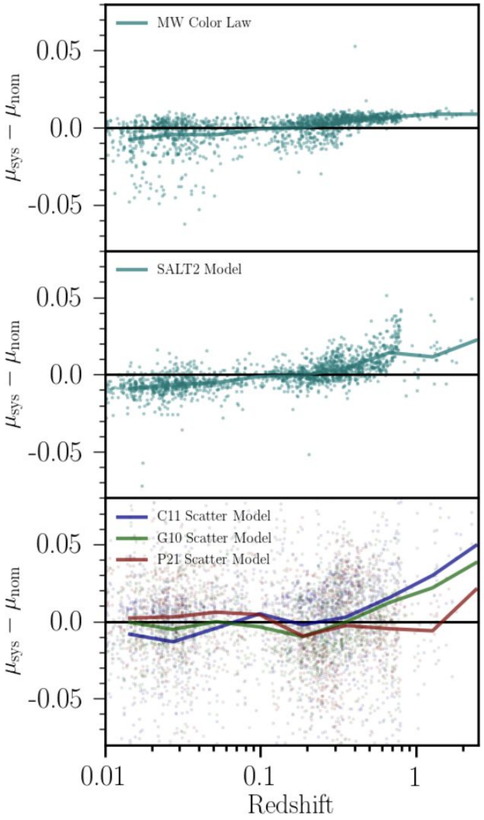
Flat wCDM $w = -0.89 \pm 0.13$





Brout+22

What changed between Pantheon and Pantheon+?



Flat ΛCDM $\Omega_{\rm m} = 0.338 \pm 0.018$

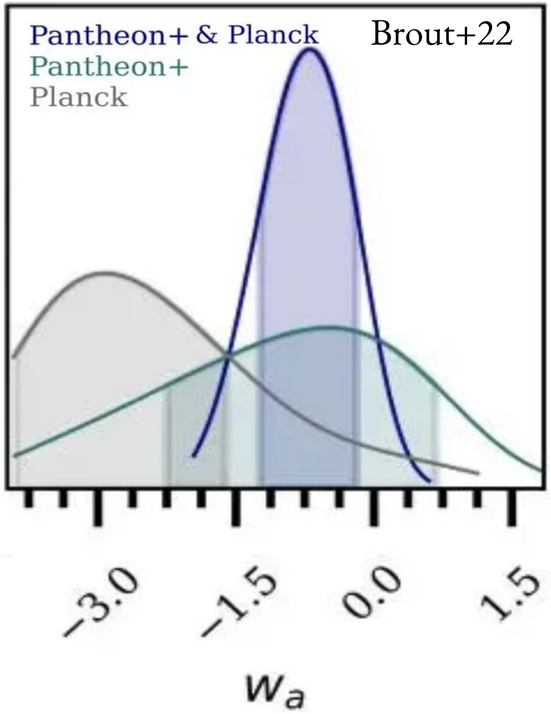
Flat wCDM $w = -0.89 \pm 0.13$

- Pantheon (Scolnic+ 18) found $\Omega_{\rm m}$ = 0.30 +-0.022 . Part is statistics.
- Three large-sized systematics all moved in same direction.
- Note size of this is ~0.01 mag, which is ~nothing for H0, big for $\Omega_{\rm m}$

Pantheon+ Cosmological Constraints on Evolving Dark Energy

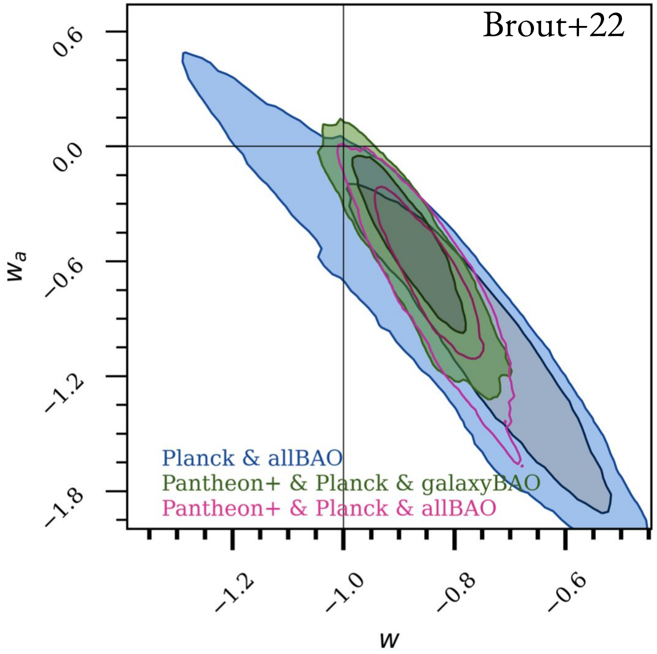
Pantheon+ SNe provide the single best constraint on dark energy evolution: w_a

$$w_a = -0.4^{+1.0}_{-1.8}$$



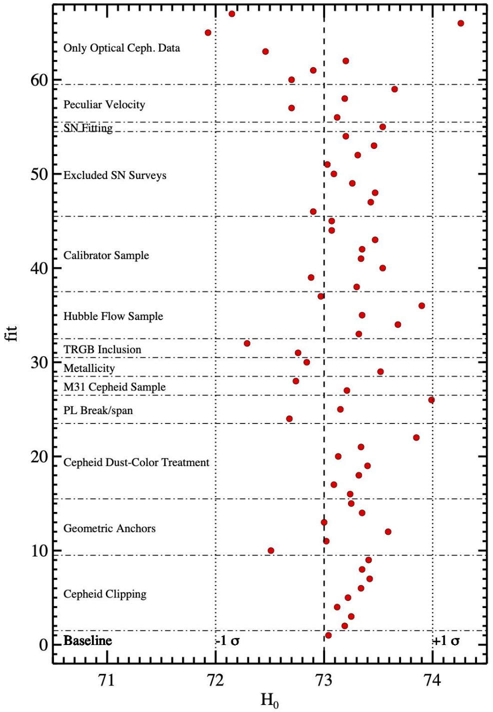
When combined with BAO and Planck

$$w_a = -0.65^{+0.28}_{-0.32}$$

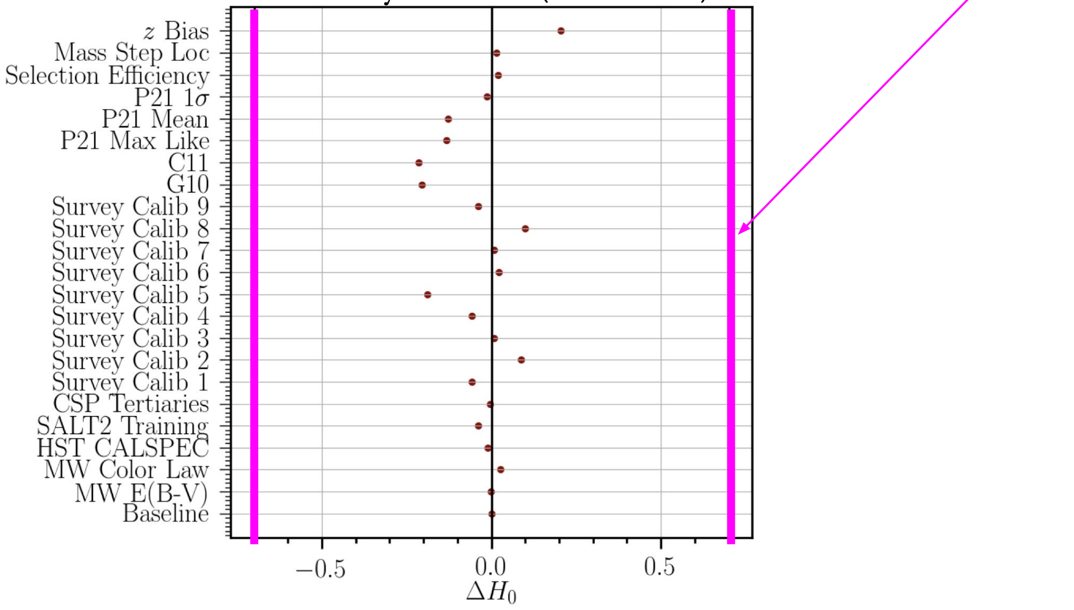


SNe comprise less than ⅓ of the H0 error budget.

All Analysis Variants (Riess+21)



SN H0 Systematics (**Brout**+22)



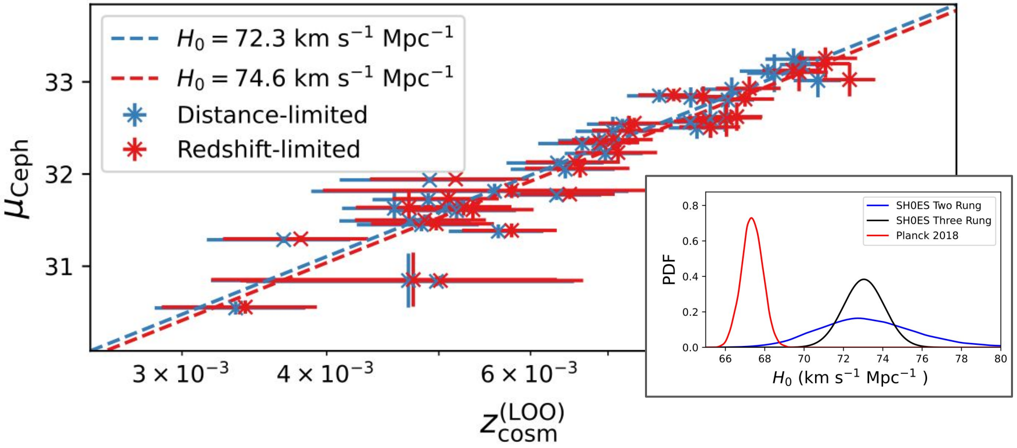
<u>Bottom line</u>: With ~70 analysis variants motivated by community requests, it's very hard to get below 72.5 without throwing out data or adding new tensions…

The Robustness of SNe in the Distance ladder

2-Rung Distance Ladder

(*Kenworthy ea*) arXiv:2204.10866

$$H_0 = 73.1^{+2.6}_{-2.3}$$



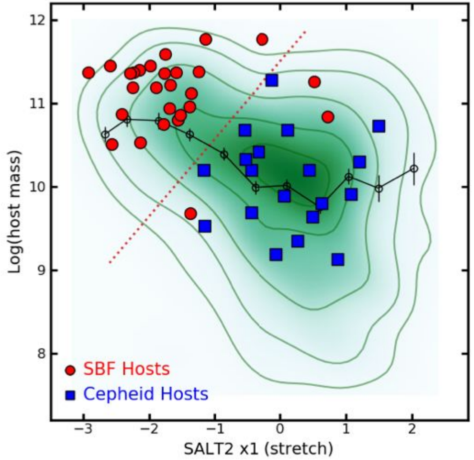
Geometry→Cepheids

Dominated by peculiar velocities and Cepheid host-z selection but still come up with a decent constraint…

4-Rung Distance Ladder

(*Garnavich ea*) arXiv:2204.12060

$$H_0 = 74.6 \pm 0.9(\text{stat}) \pm 2.7(\text{syst})$$



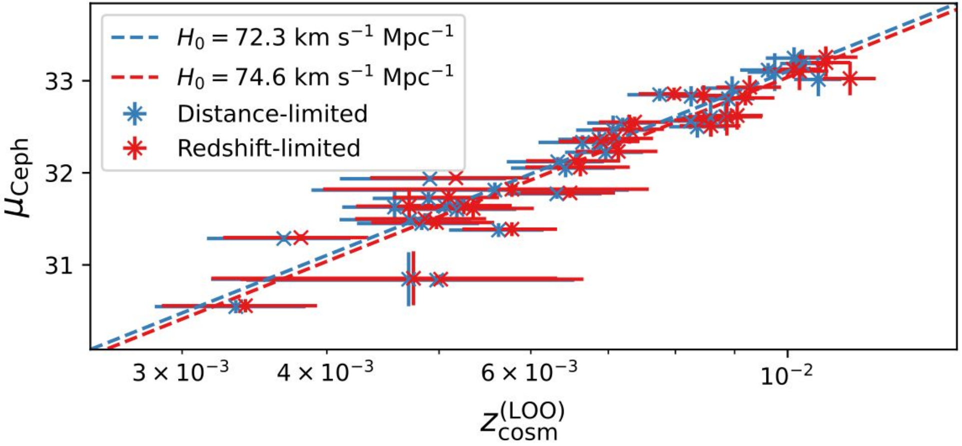
Geometry→Cepheids or TRGB→SBF→Pantheon+ SNeIa

SBF hosts are different and so are their SNe.

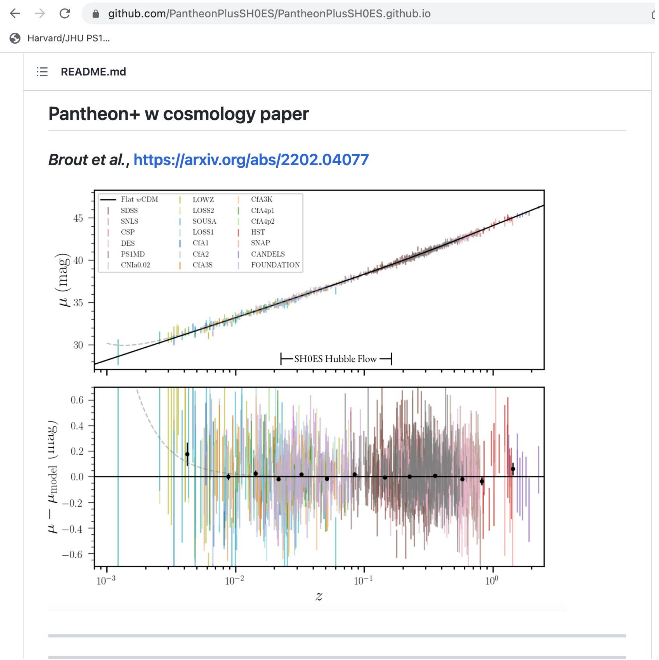
This allows for a systematic test on SN calibration.

Note very different from Khetan et al. result.

The agreement of two-rung and three-rung ladder, and continuity of Hubble diagram from z~0 to z~2, disproves anything 'non-Aristarchusan'. No change in SN physics at z=0.01.

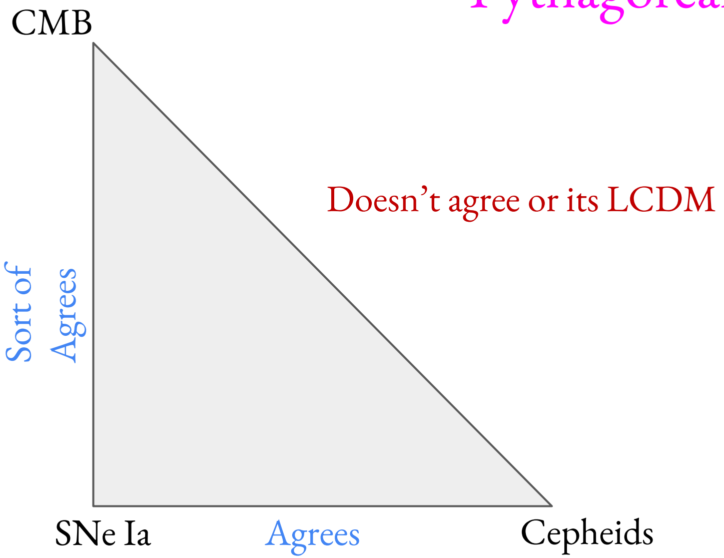


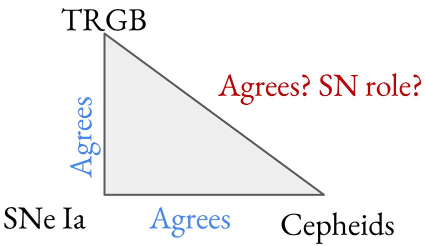
Kenworthy et al. 2021

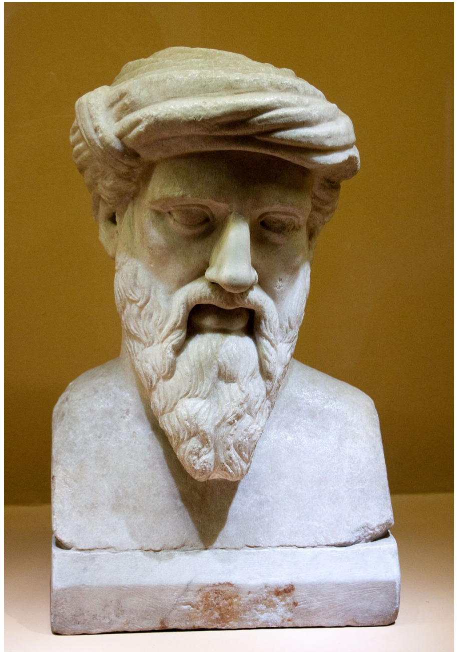


How do we improve H0 to 1%?

“Pythagorean Tension”







Pythagoras, also of Samos, Greece!

How do we improve H0 to 1%? Supernovae.

- Some difference between H0 from Cepheids-SN and TRGB-SN. [Conference note: Please no more Cepheids/TRGB good/bad]

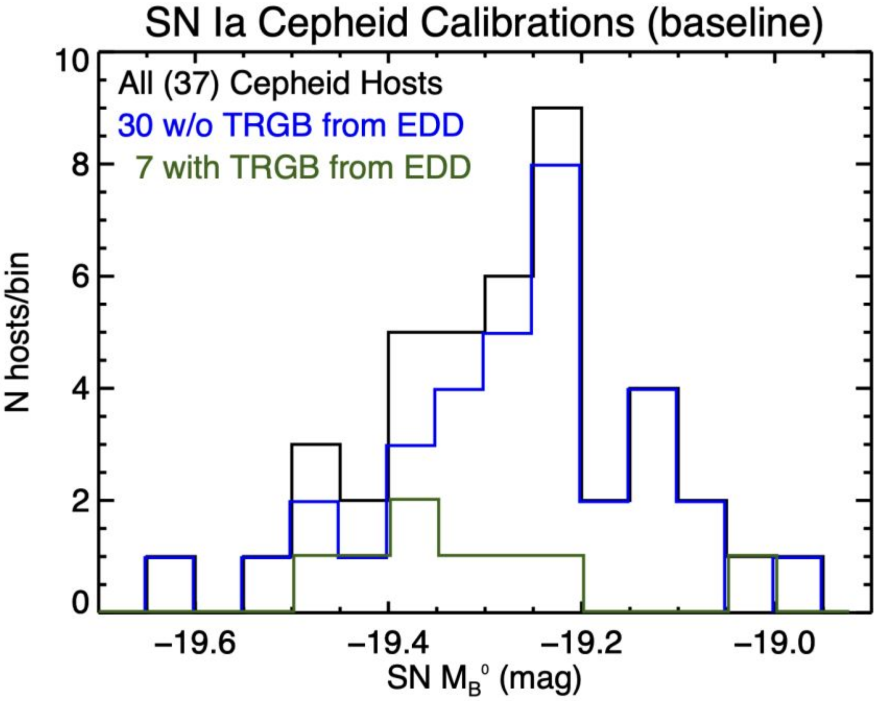
- My previous stance 'Leave SNe Ia out of it' not quite right.

- ~Half of difference can be explained by SNIa treatment. Different statistics and some things not in some TRGB+SNIa analyses (e.g., CCHP):

  Peculiar velocity corrections, should raise TRGB H0 1%

  Measuring SN survey offsets, should raise TRGB H0 1%

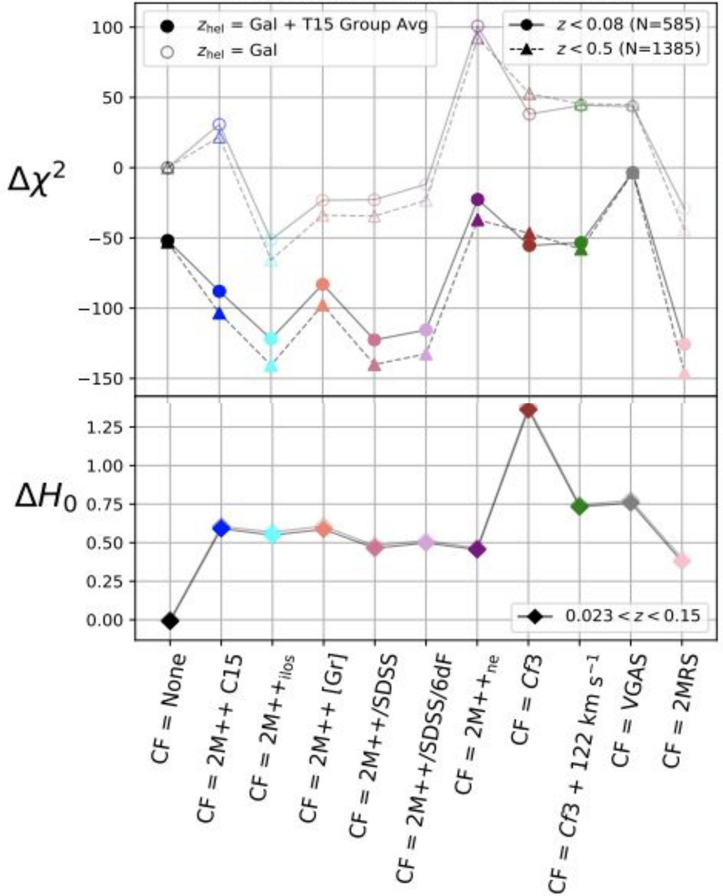
  Different treatments of host-galaxy correlations with large mass range (unclear impact)



How do we improve H0 to 1%? Supernovae (Peculiar Velocities).

1) Comparison of multiple different peculiar velocity maps
2) Comparison of different catalogs of group redshifts/assignments

- Extremely strong evidence to correct for bulk flows and group corrections
- Accuracy of corrections is ~0.1 km/s/Mpc.
- Not correcting* shifts H0 down by 0.6 km/s/Mpc.



Peterson, Kenworthy, Scolnic ea.

How do we improve H0 to 1%? Supernovae (Common surveys).

Pantheon+ strongly helped by having measurements from same survey in calibrator set and Hubble flow set -> survey systematics cancel out.

- "Specifically, we find that miscalibrated inter-survey systematics could represent a source of uncertainty in the measured value of H0 that is **no larger than 0.2 km/s/Mpc**."

- CSP only for Hubble flow set shifts H0 down by ~0.6 km/s/Mpc, increases sensitivity to calibration systematics.

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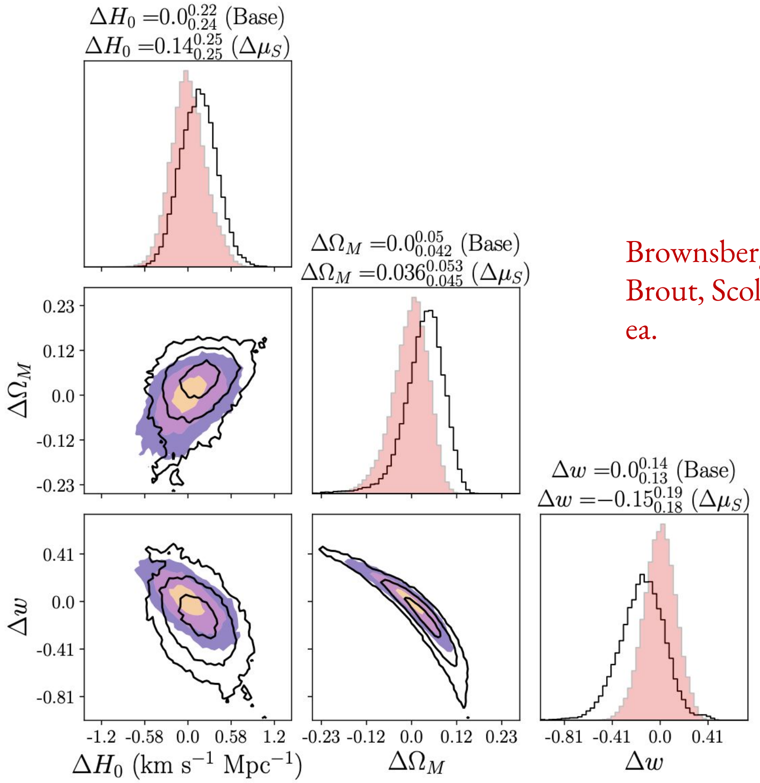
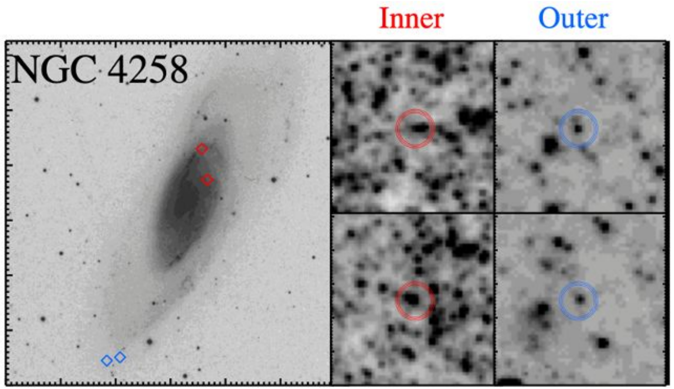
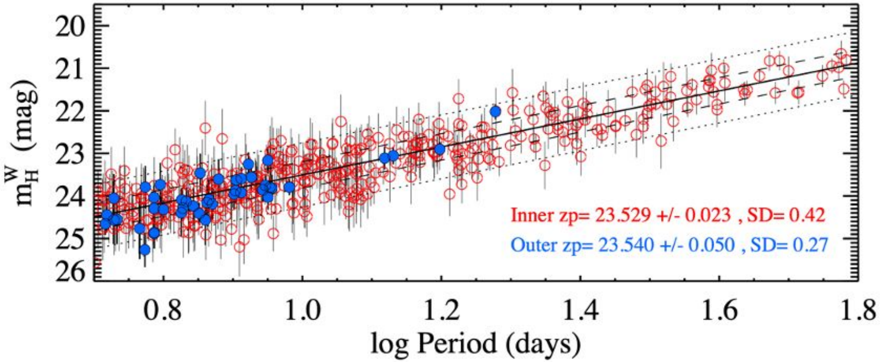


Brownsberger, Brout, Scolnic ea.

How do we improve H0 to 1%? Cepheids.

Crowded Uncrowded



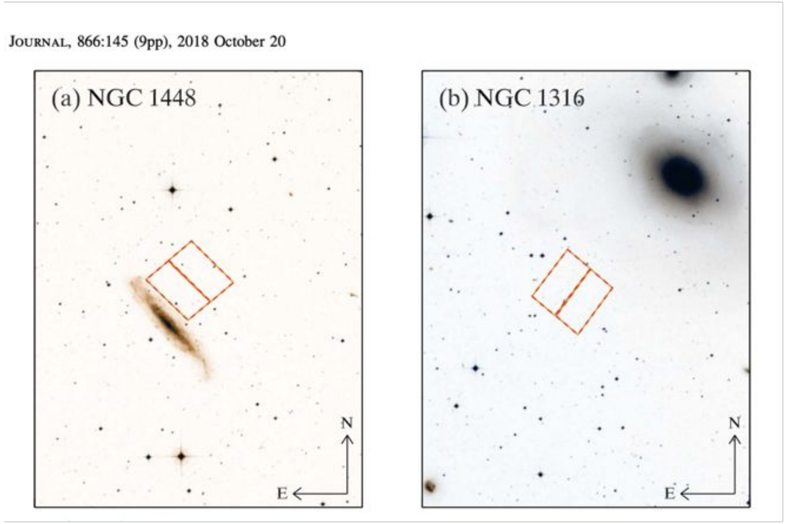


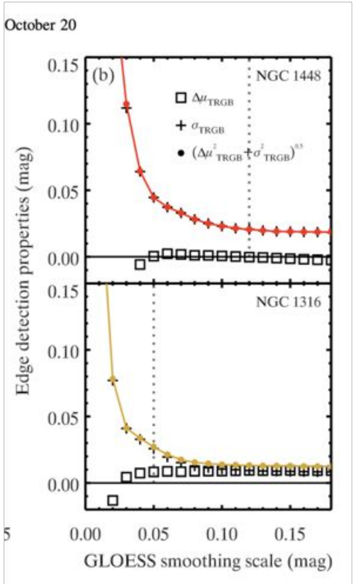
No evidence so far of biases due to Cepheid crowding (left, gives same result) or from Cepheid amplitude data; JWST resolution should be opportunity to reduce crowding, push to 1%.

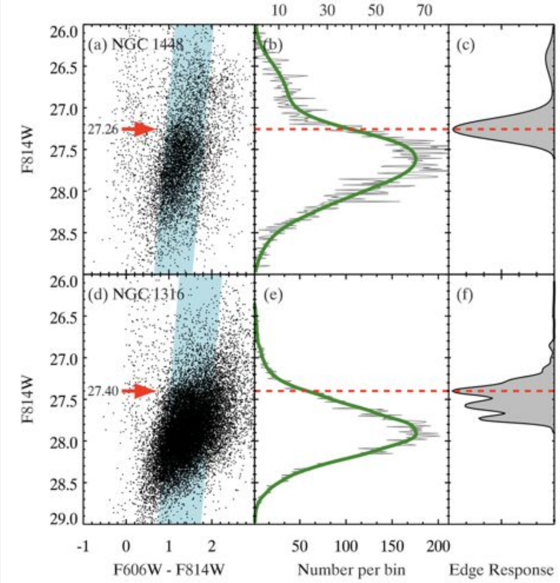
How do we improve H0 to 1%? TRGB.

-> Typically, each galaxy needs specific clipping/smoothing/ranges

How Can We Do Unsupervised Single Field Sobel Edge Detections of TRGB? (like SNIa world, single optimized, simulations, etc)

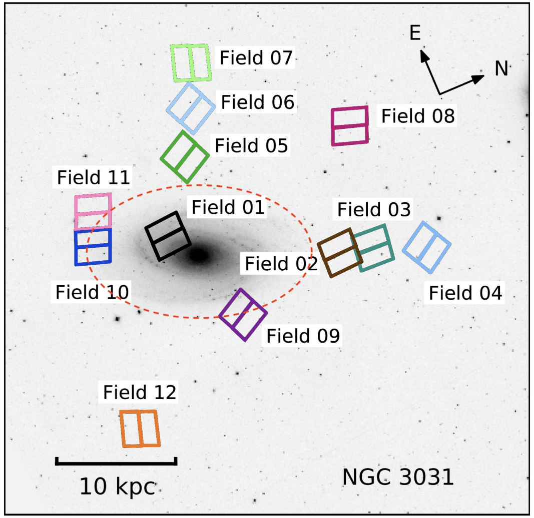






From Hatt et al. 2018

Dozen M81 pointings from GHOSTS

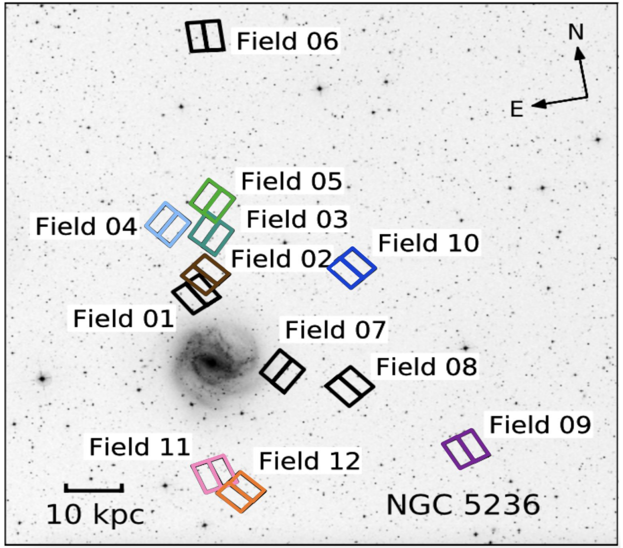


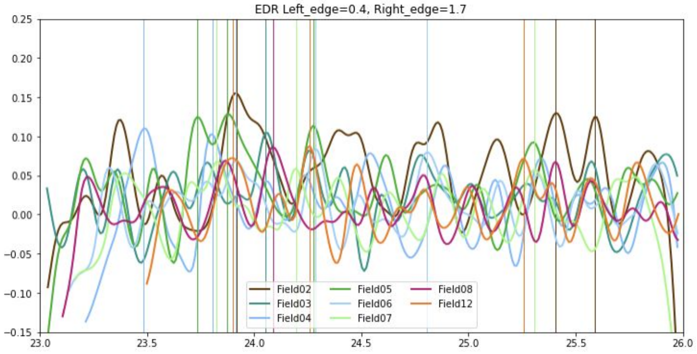
Test: Use *multiple* halo pointings around *same* host, apply "best practices", but *same analysis parameters for all pointings*

Data: GHOST Team, publicly available photometry, all nearby (3-8 Mpc) so optimal signal-to-noise, same exp time

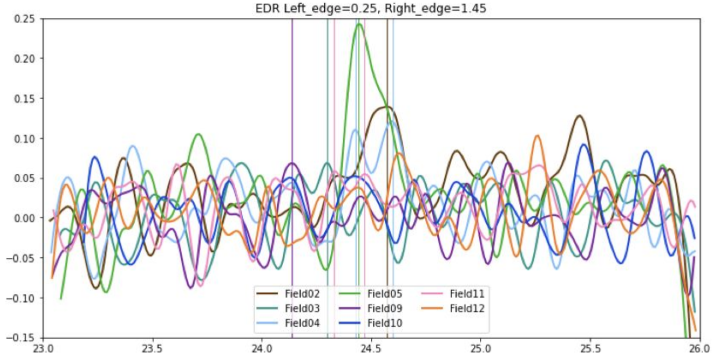
Early findings: we aren't seeing good consistency among different halo fields
(see edge response "wiggles" below)

Another example: NGC 5236



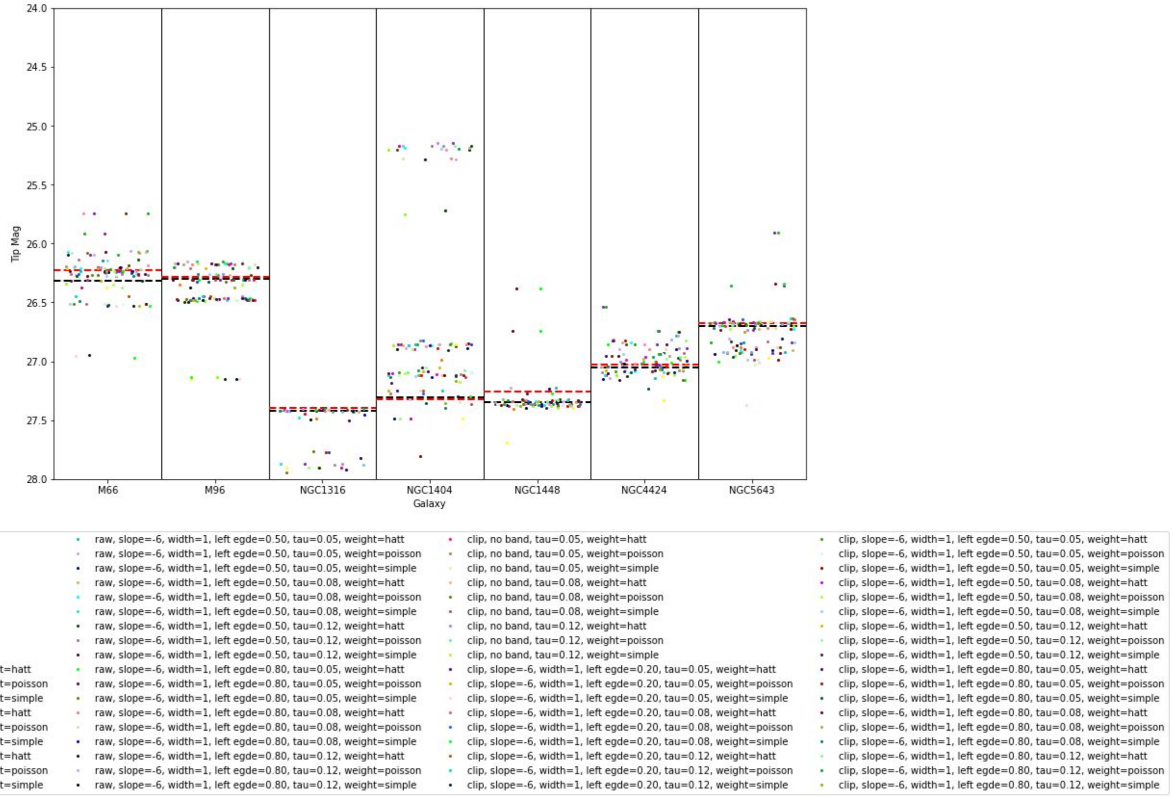


Jiaxi Wu,
applying to grad
school



Working on automating this, very interesting stats problem, happy to receive help.

Lines are from EDD and CCHP

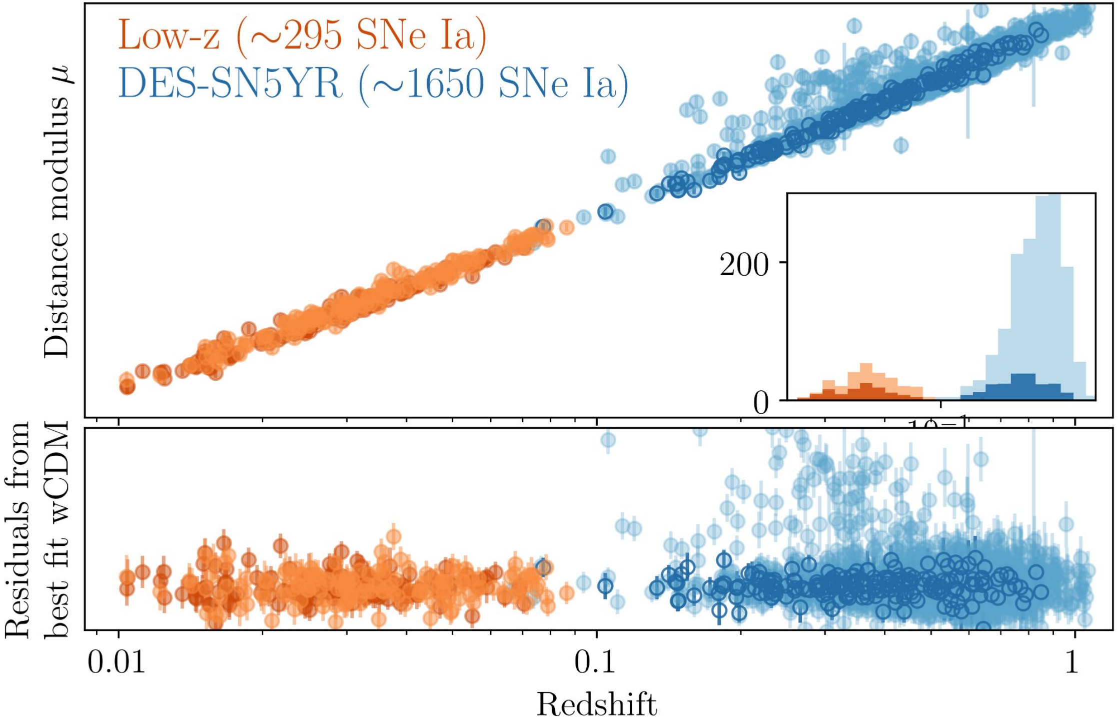


What's next? For constraining expansion history better with SNe Ia, huge samples coming this year.

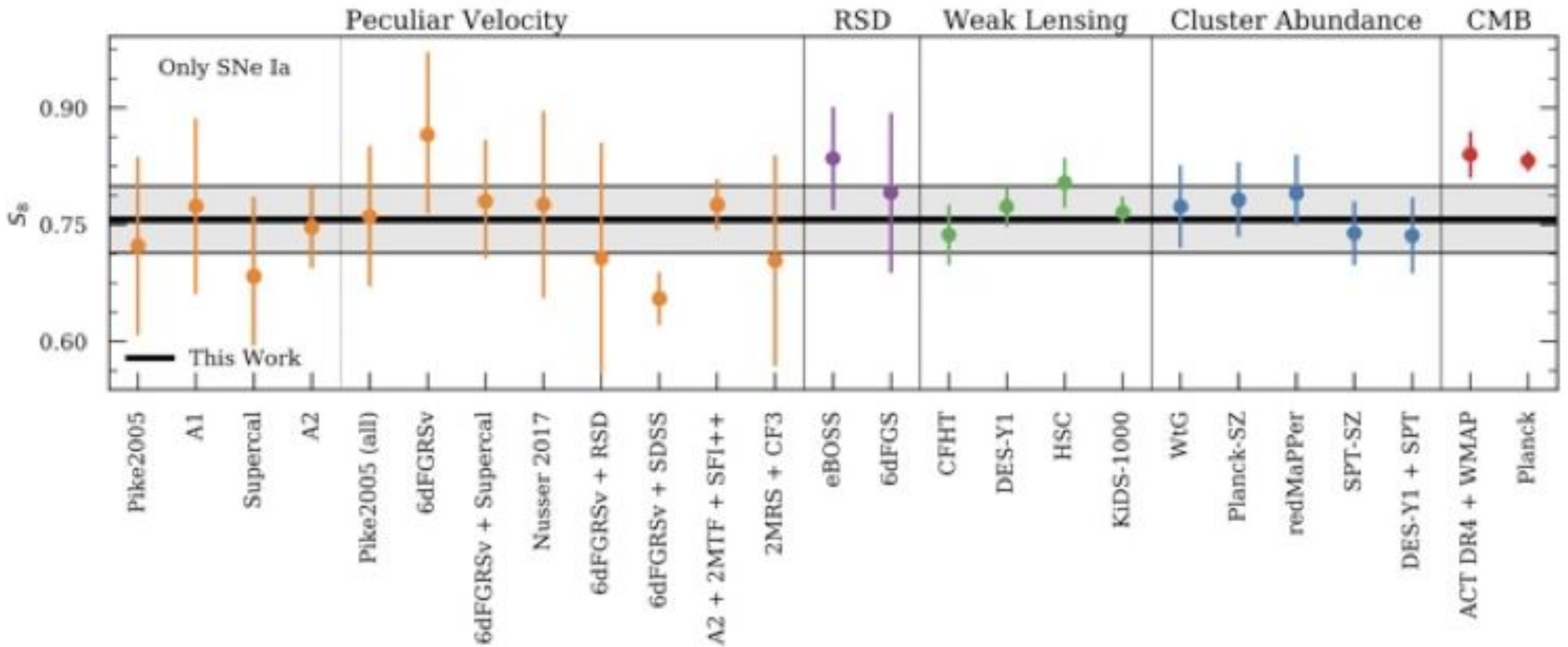
At low redshift:

- Gains on H0 limited as need calibrator data.
- Gains on w/OmegaM very large.

At high redshift: DES (Vincenzi et al. in prep.)



Lastly, want to mention that supernovae are being used to help with Sibling tension in S8.



Some (more) takeaways:

- Statistical gains on H0 from distance ladder will slow.
- Systematic ideas to resolve tension becoming non-Aristarchun, look worse than complicated theoretical models to explain tension.
- Expect large gains in supernova cosmology for constraining non-H0 parameters in next year, reach out about what model space would be interesting.

Thanks to the organizers!