The Hubble Constant Tension Problem: An Overview

Dillon Brout
Einstein Fellow @ University of Pennsylvania

dbrout@physics.upenn.edu

3rd World Summit Meeting on
Exploring the Dark Side of the Universe

Guadeloupe Islands
March 12th 2020

Penn UNIVERSITY of PENNSYLVANIA

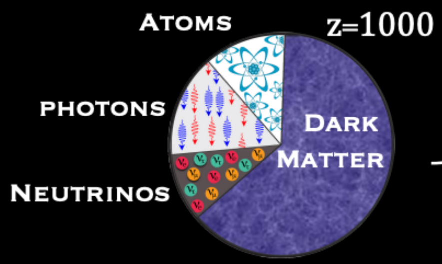
NASA

Fermilab

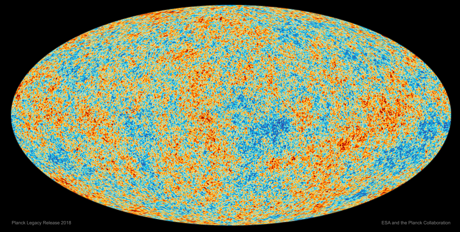
Outline

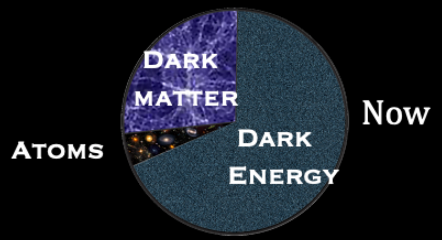
- Overview of the Tension
- Systematic Uncertainties
- Complementary and Independent Probes
- Hint of new physics?

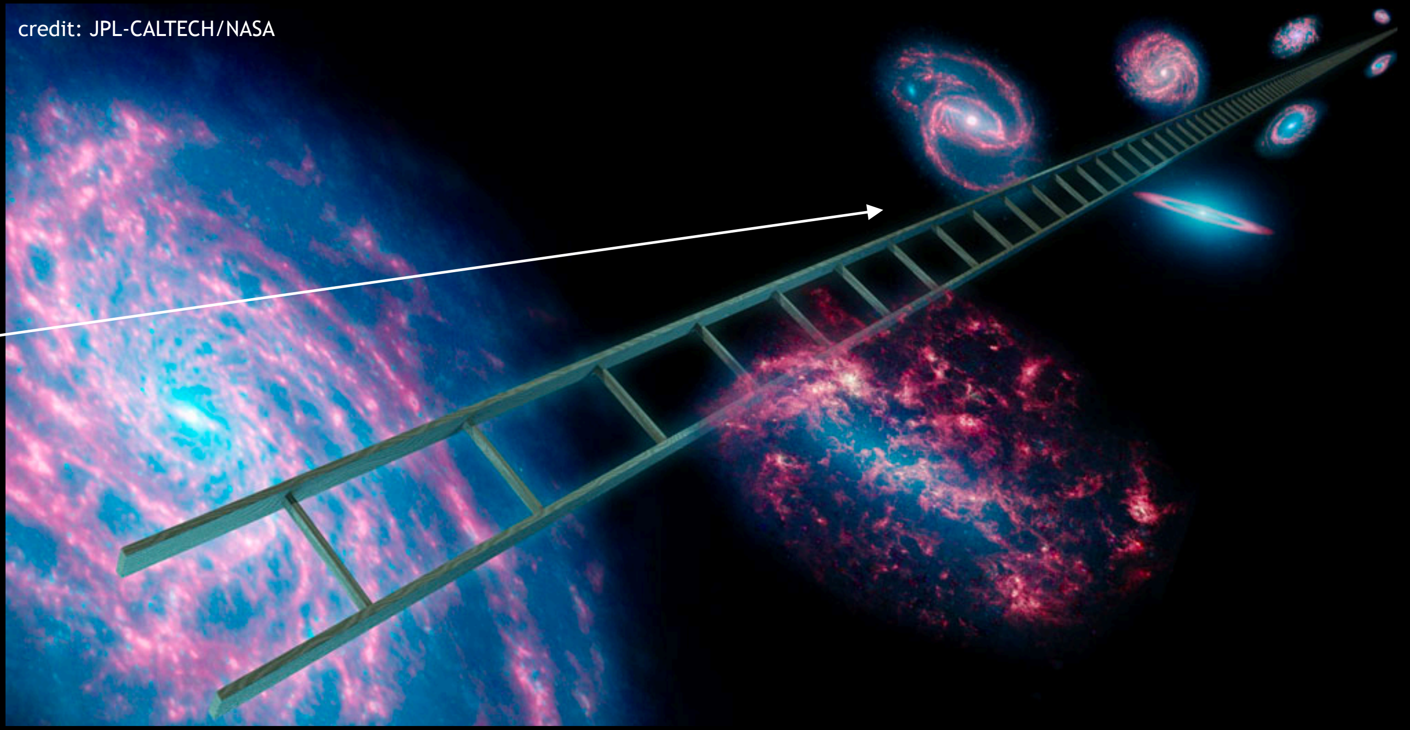
Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM



Infer expansion rate. Primary peak sets angular scale.
Physical scale is set by sound horizion + redshift —> h



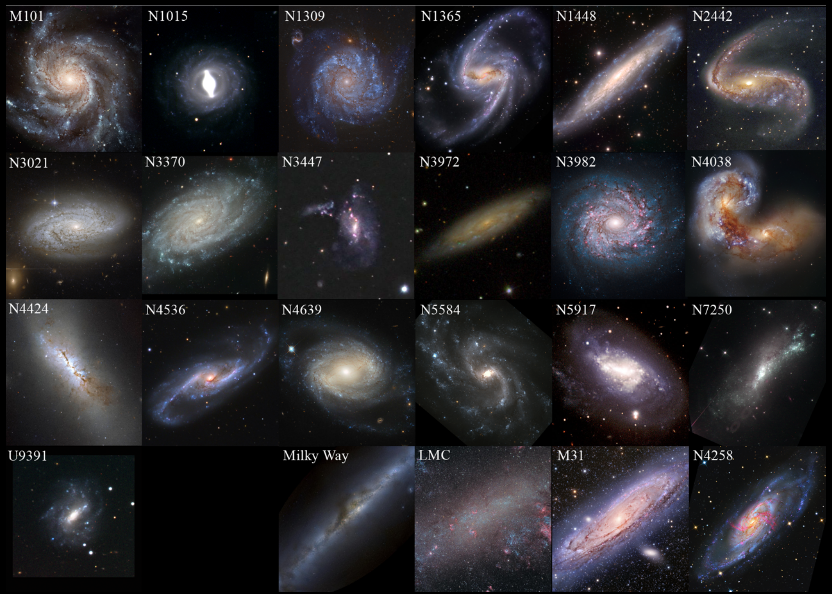


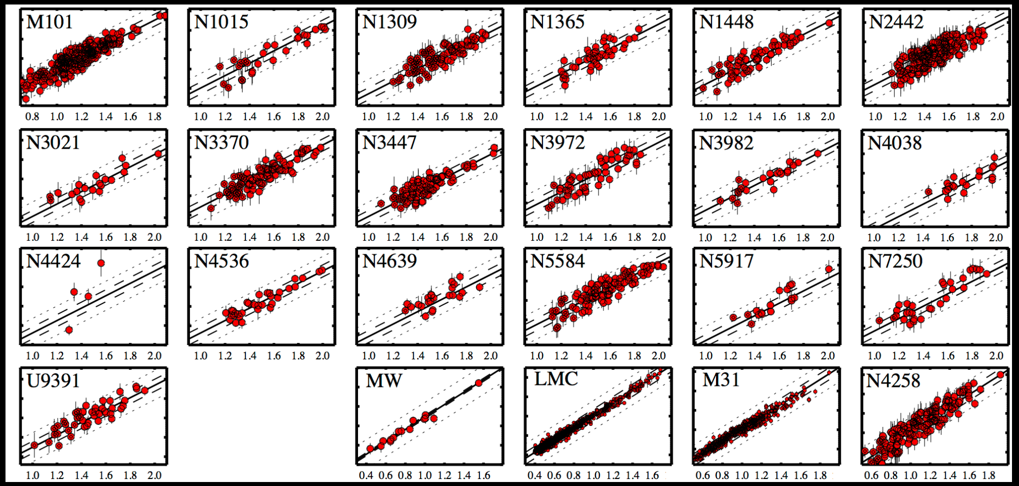


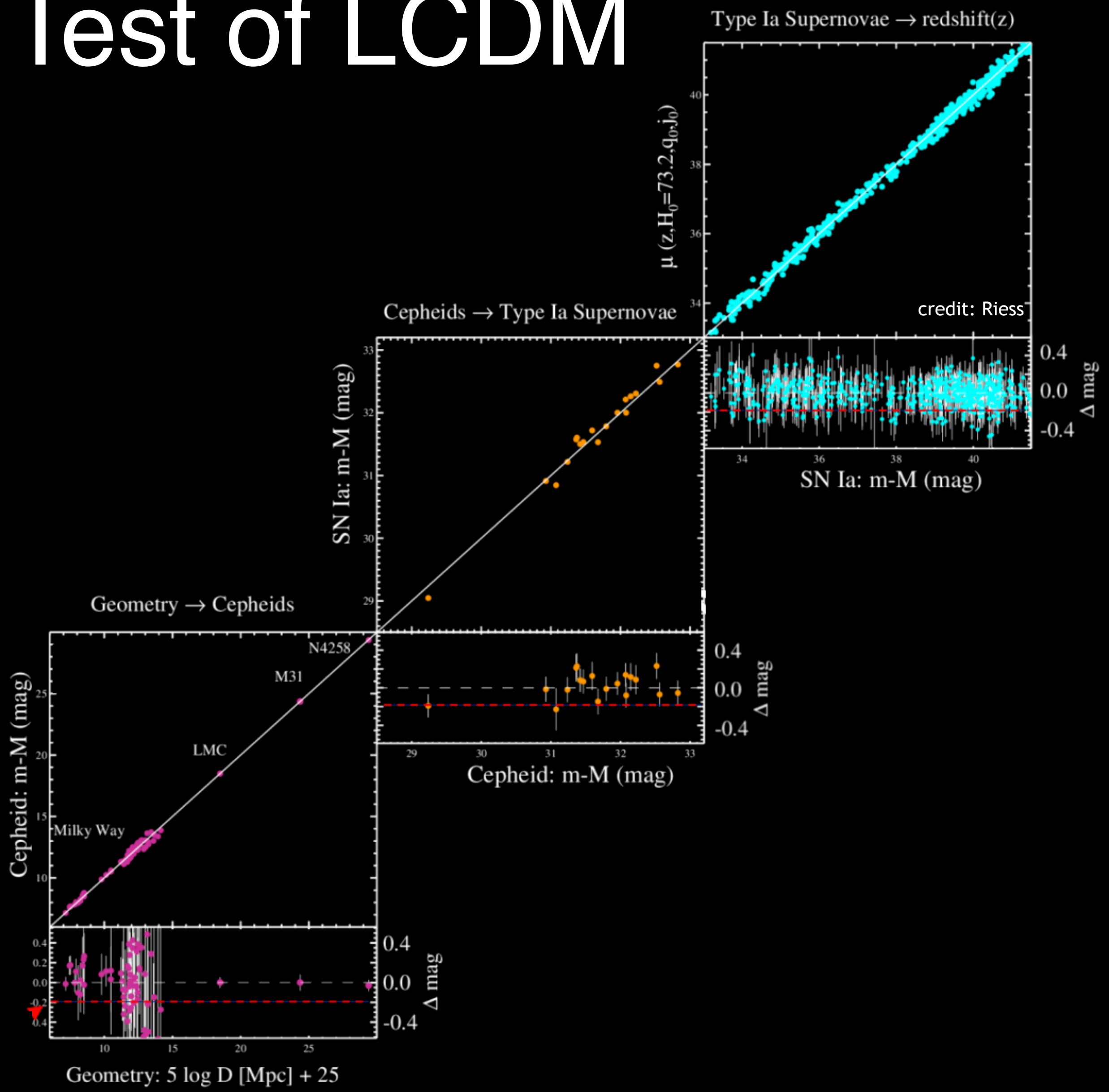
~14B years of cosmic Expansion History (guard rails provided by SNe, BAO, LCDM…)

Planck Predicts H0=67.4 +/- 0.5 km/s/Mpc

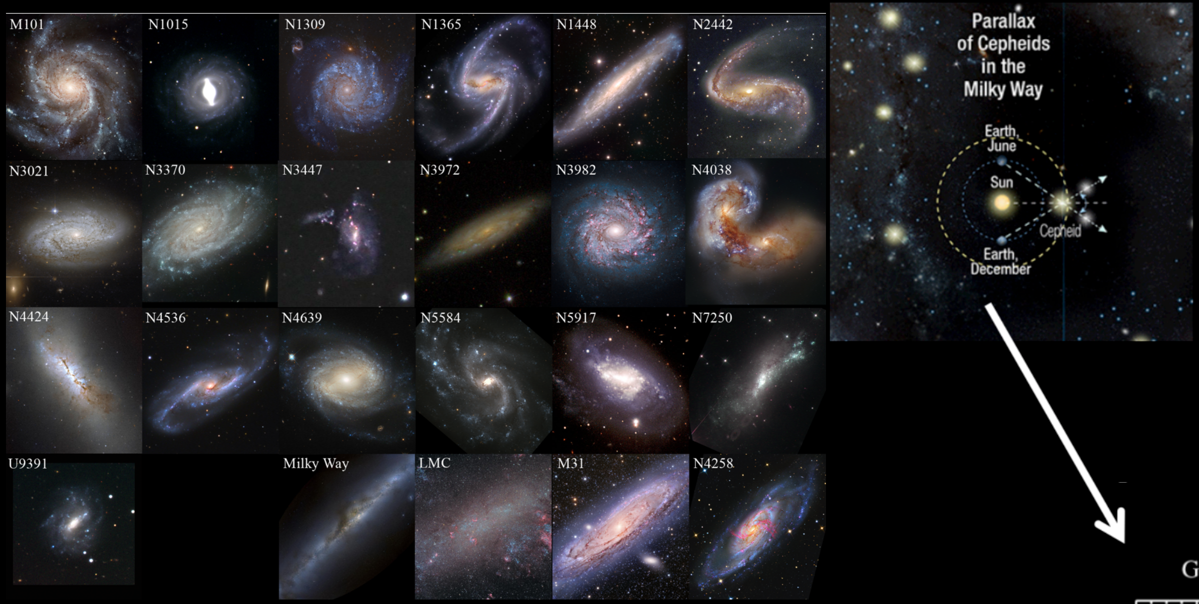
Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM

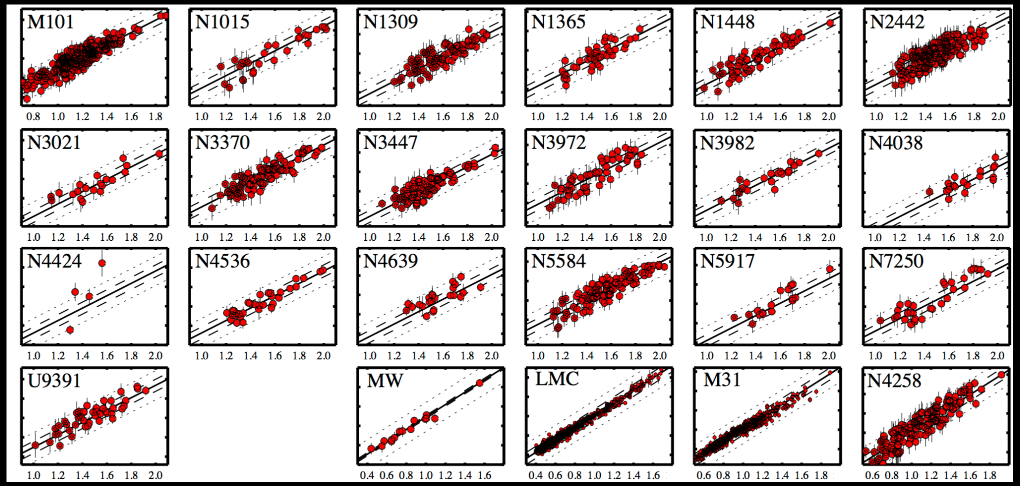


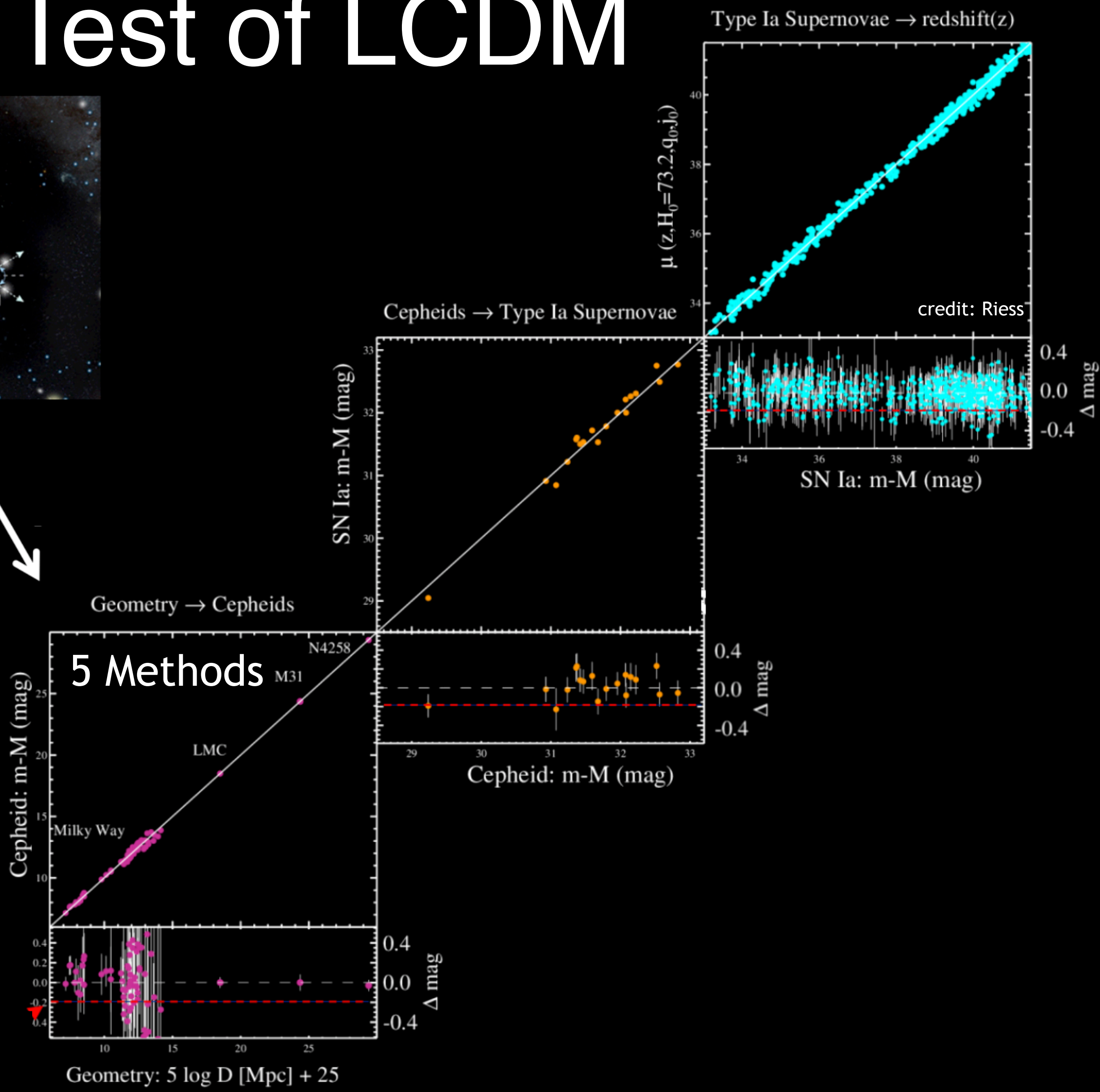




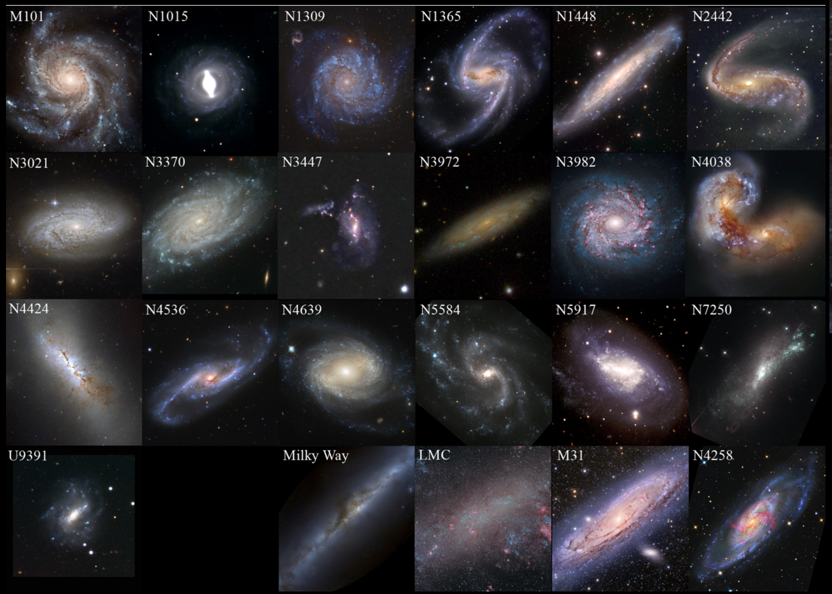
Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM

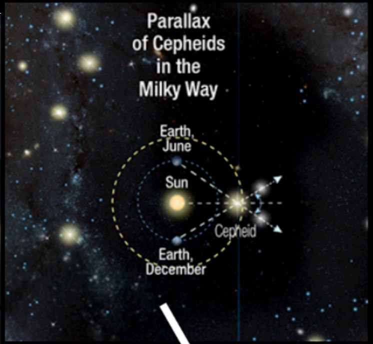


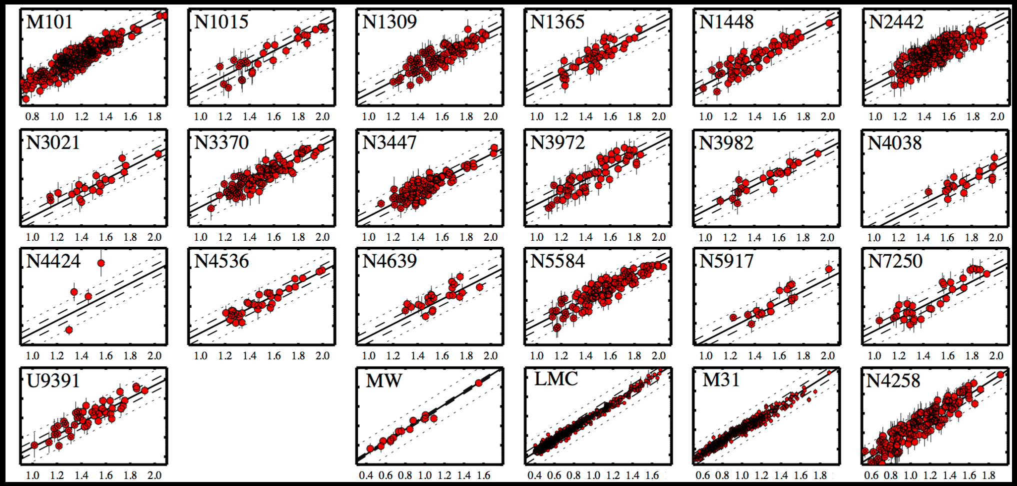


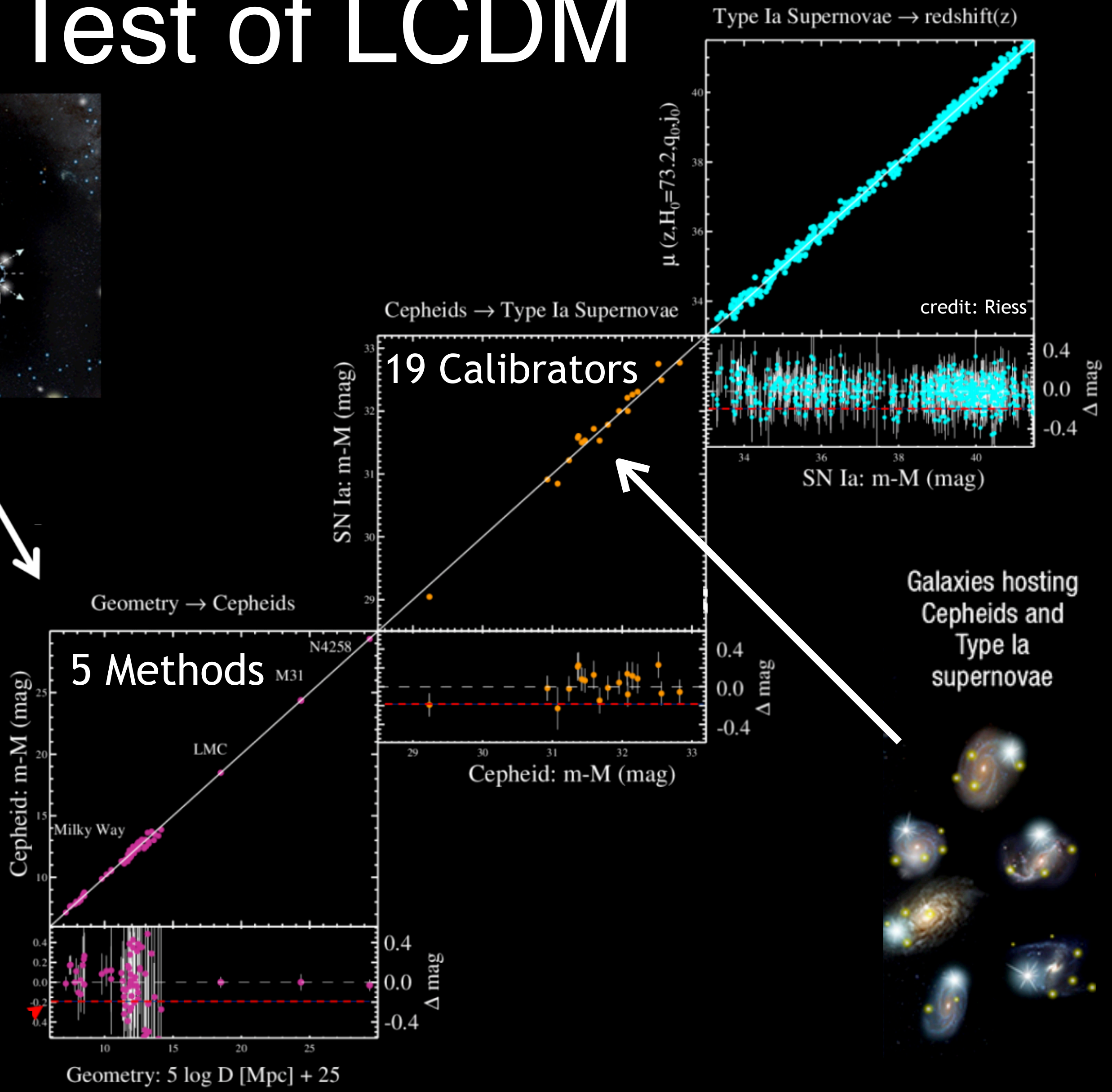


Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM

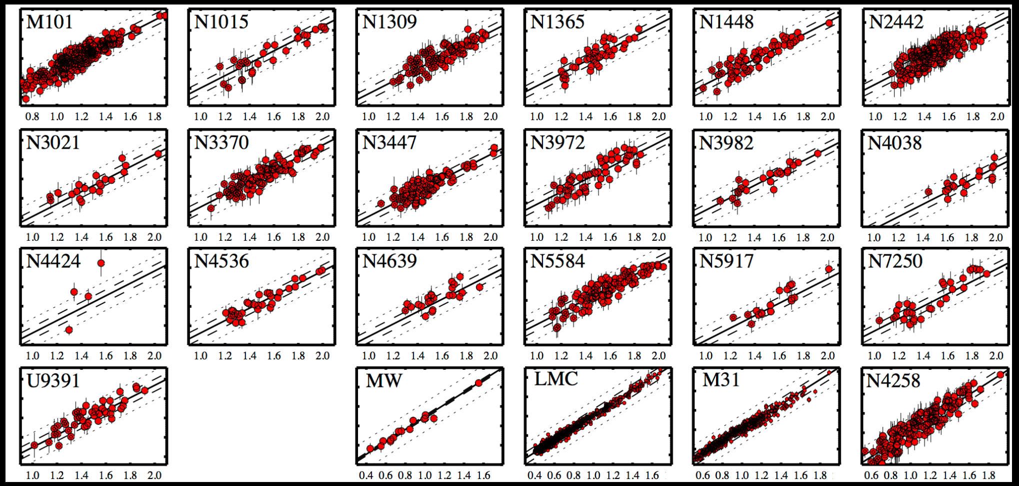


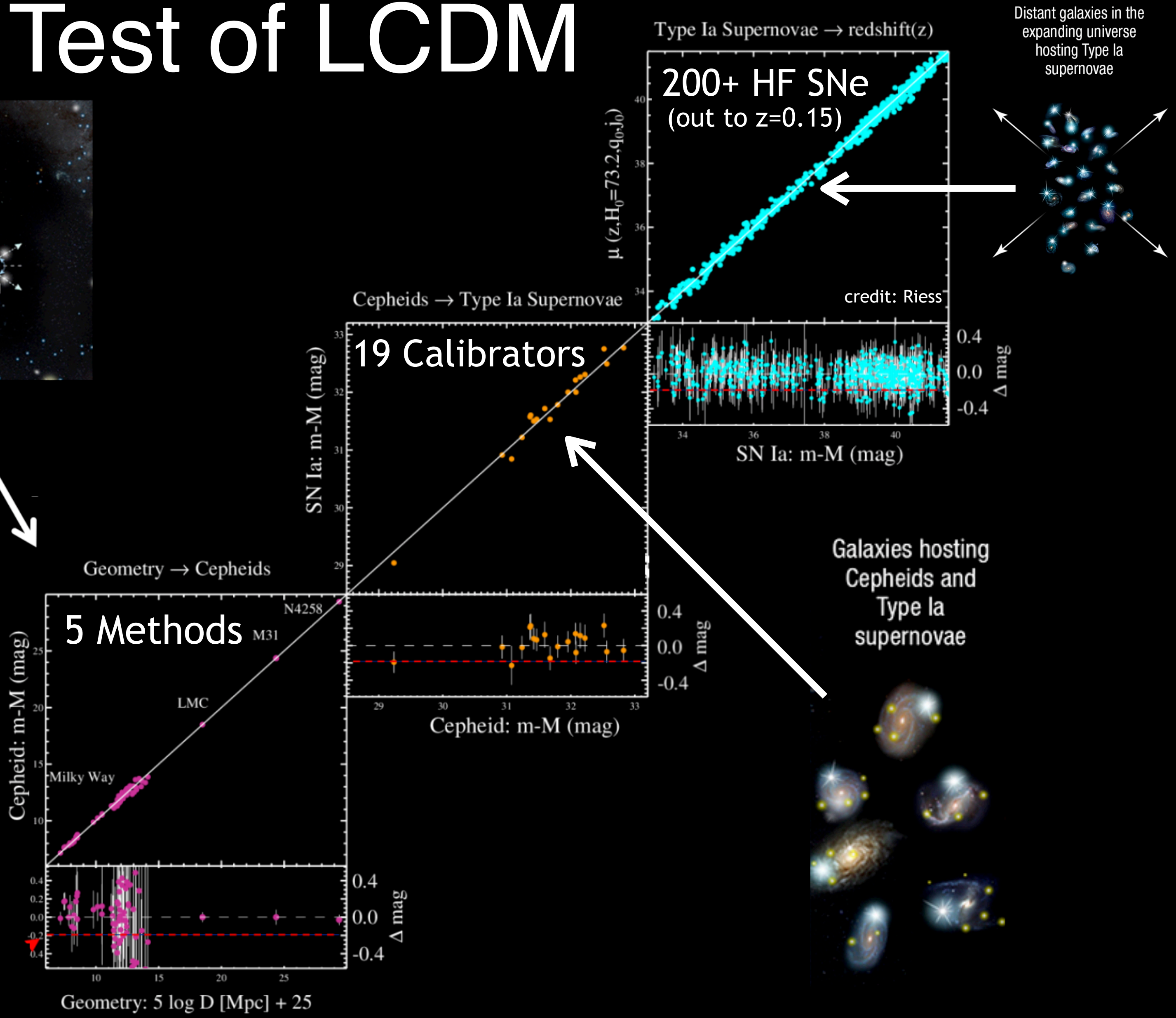






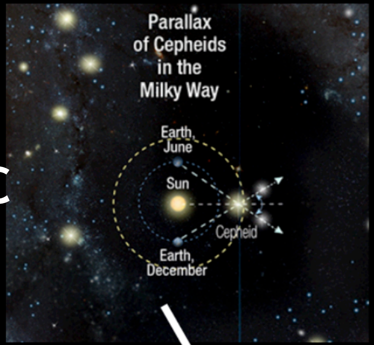
Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM

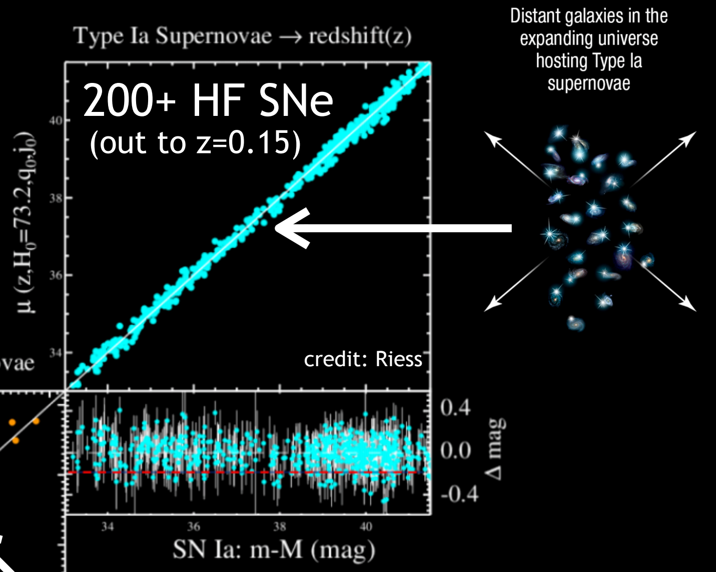


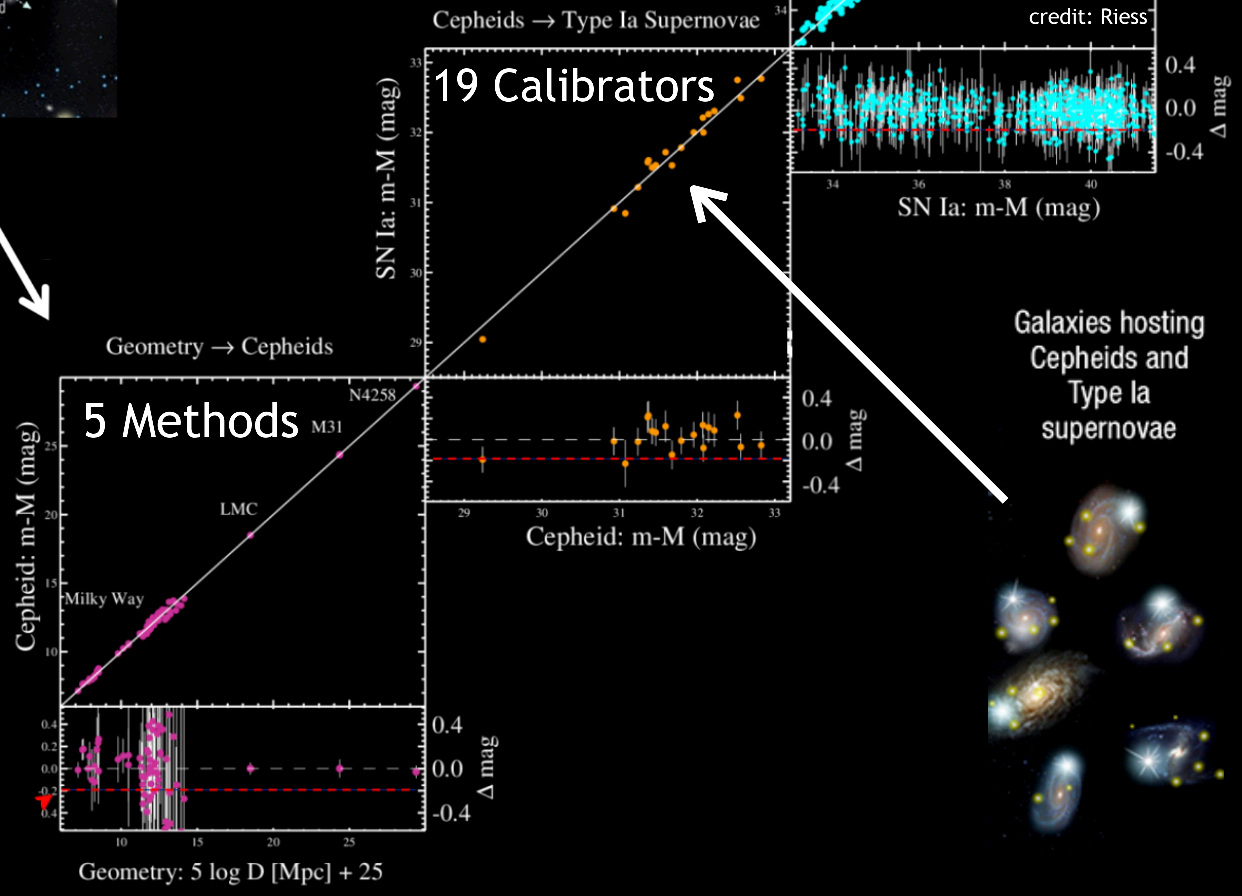


Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM

Planck Predicts
H0=67.4 +/- 0.5 km/s/Mpc



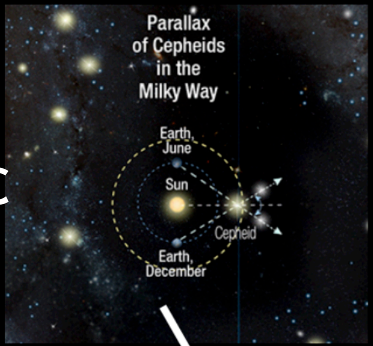


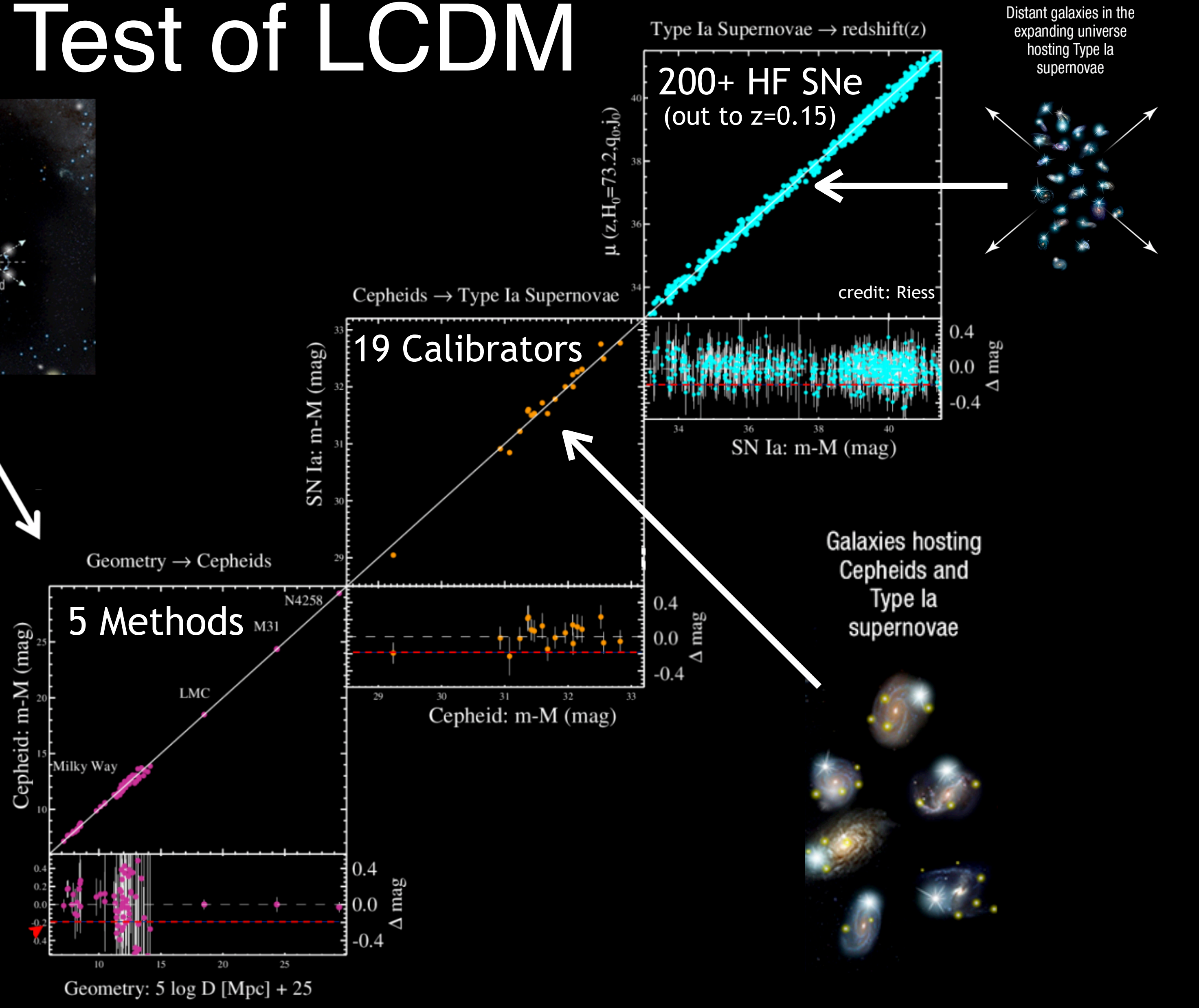


Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM

Planck Predicts
H0=67.4 +/- 0.5 km/s/Mpc

SH0ES Measures
H0=73.5 +/- 1.4 km/s/Mpc



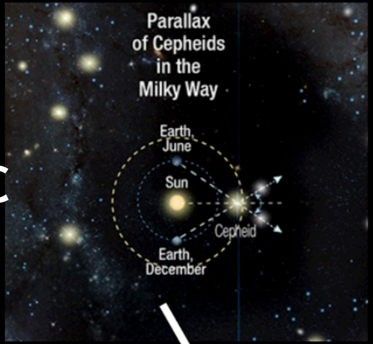


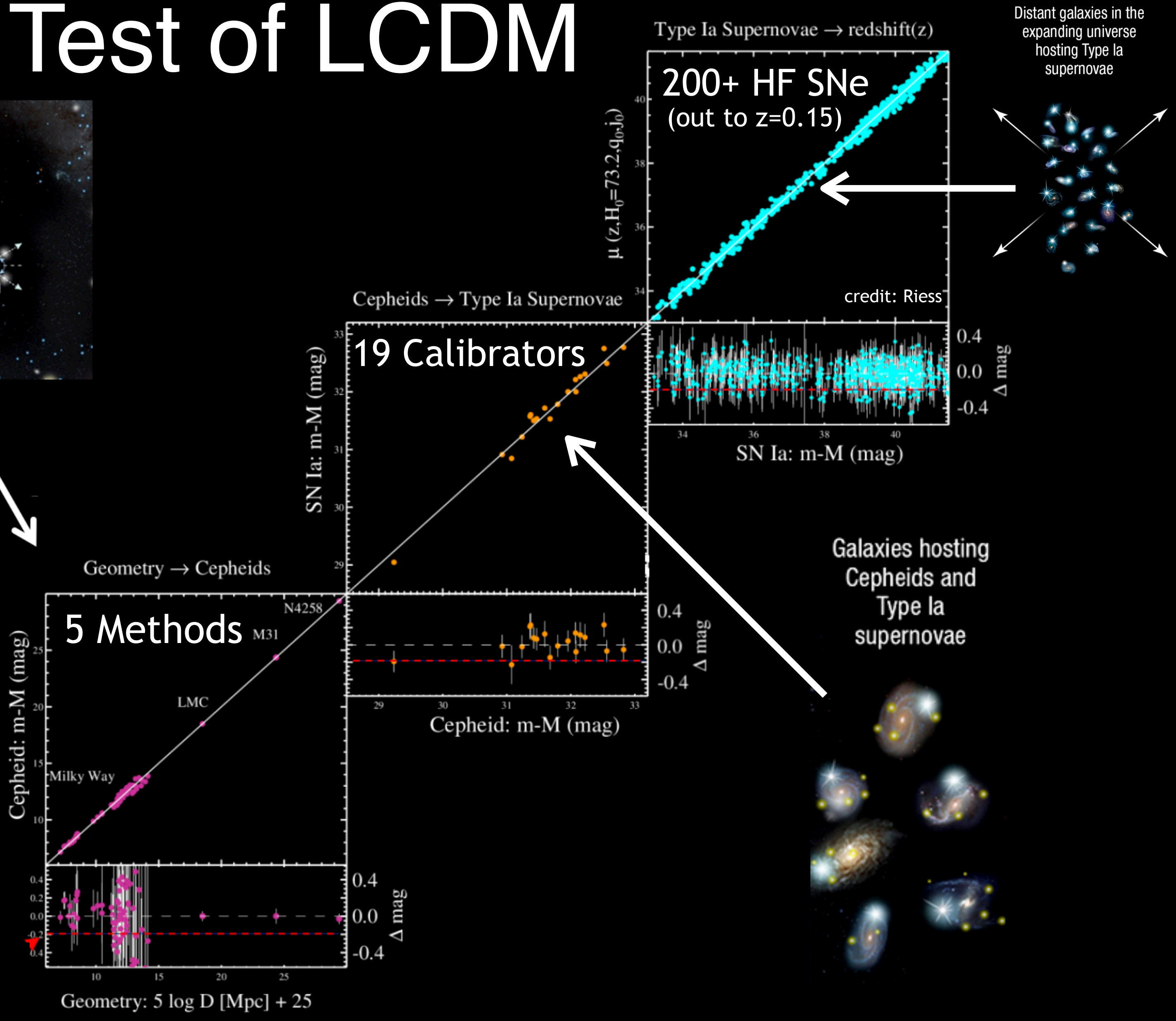
Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM

Planck Predicts
H0=67.4 +/- 0.5 km/s/Mpc

SH0ES Measures
H0=73.5 +/- 1.4 km/s/Mpc

—> 4.1 Sigma from CMB (67.4)



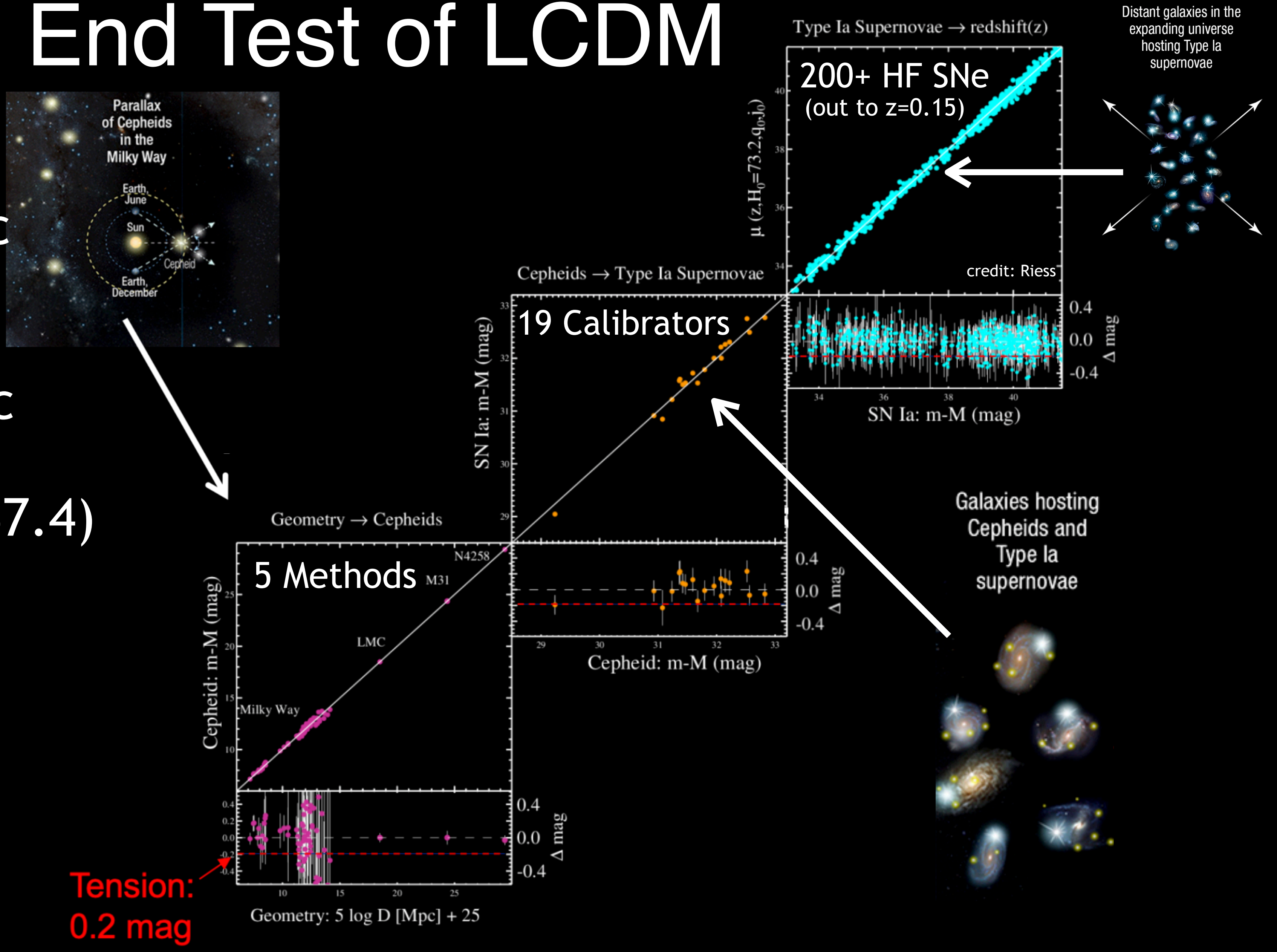


Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM

Planck Predicts
H0=67.4 +/- 0.5 km/s/Mpc

SH0ES Measures
H0=73.5 +/- 1.4 km/s/Mpc

—> 4.1 Sigma from CMB (67.4)



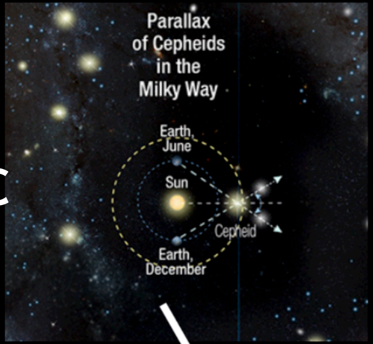
Prediction and Measurement of H0 Provides the Ultimate End to End Test of LCDM

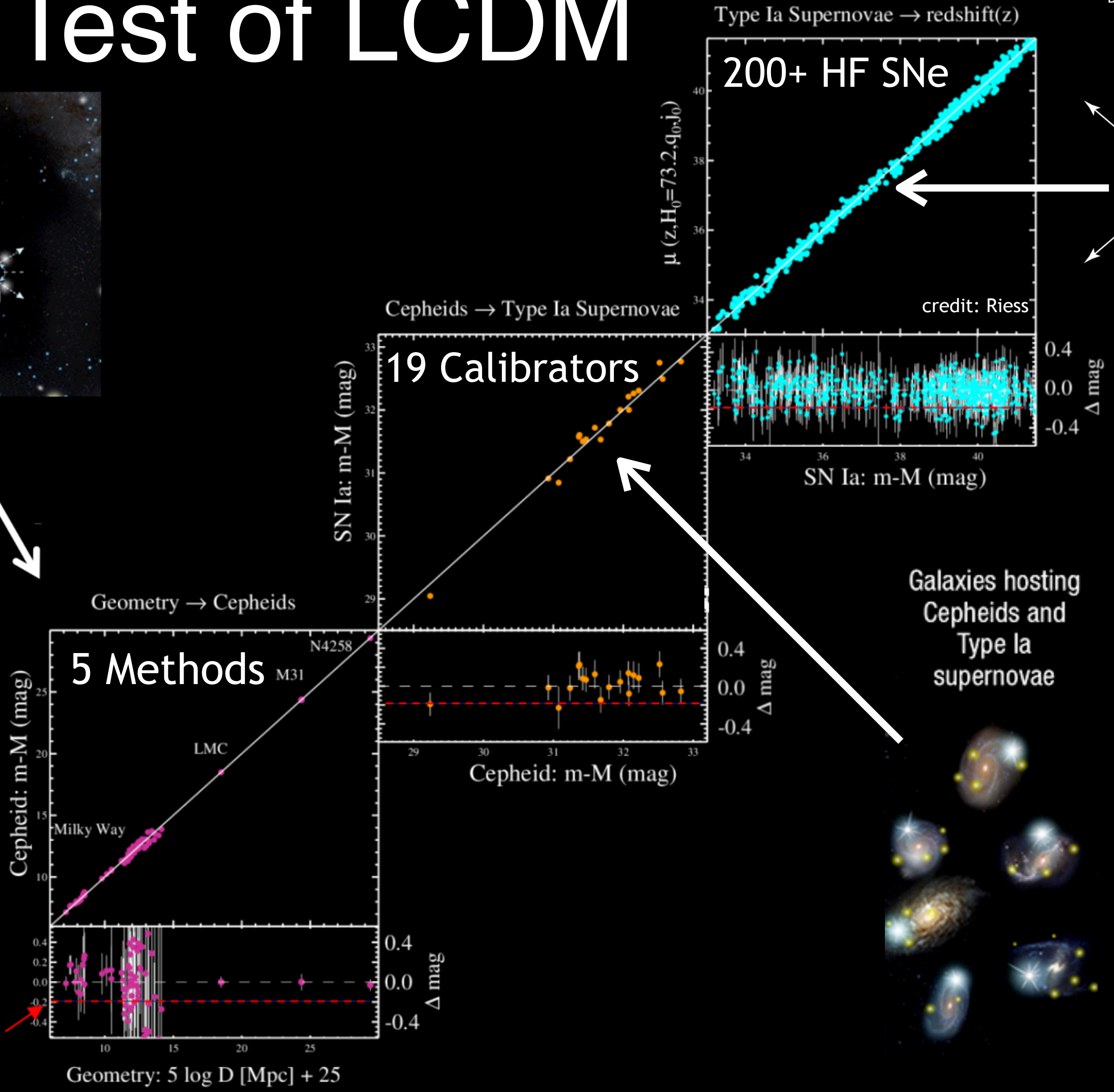
Planck Predicts
H0=67.4 +/- 0.5 km/s/Mpc

SH0ES Measures
H0=73.5 +/- 1.4 km/s/Mpc

—> 4.1 Sigma from CMB (67.4)

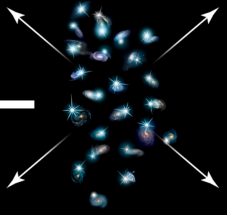
Cepheids and SNe each appear in two rungs. If demographics are the same, systematics cancel.





Tension:
0.2 mag

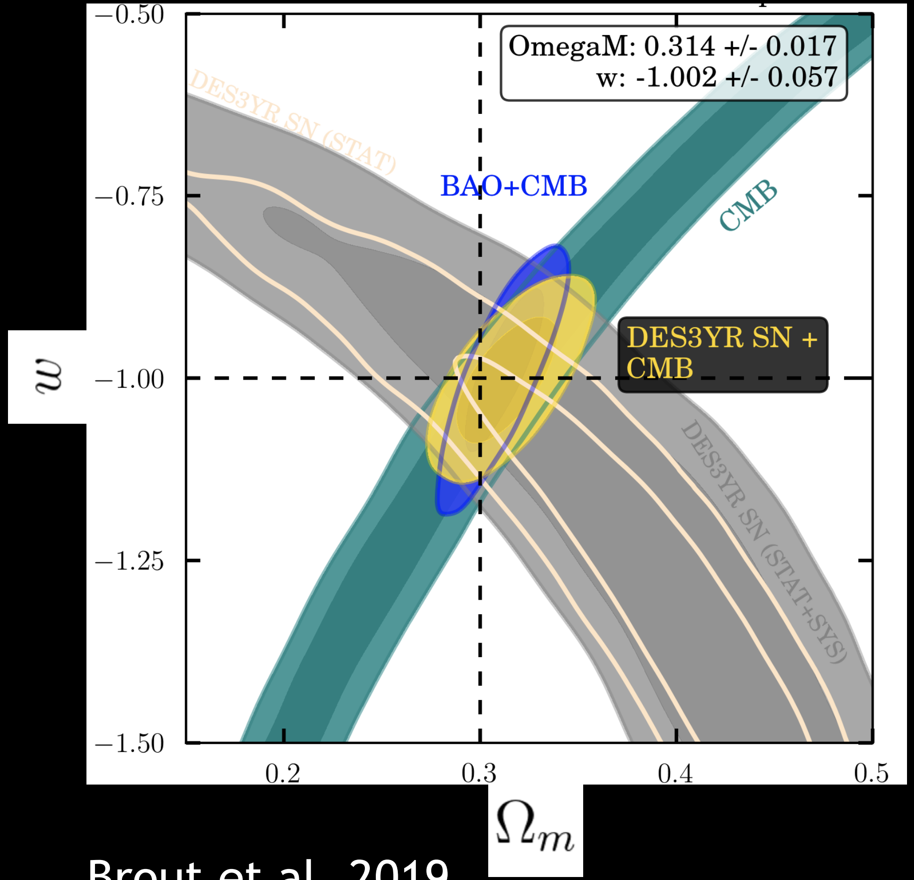
Distant galaxies in the expanding universe hosting Type Ia supernovae



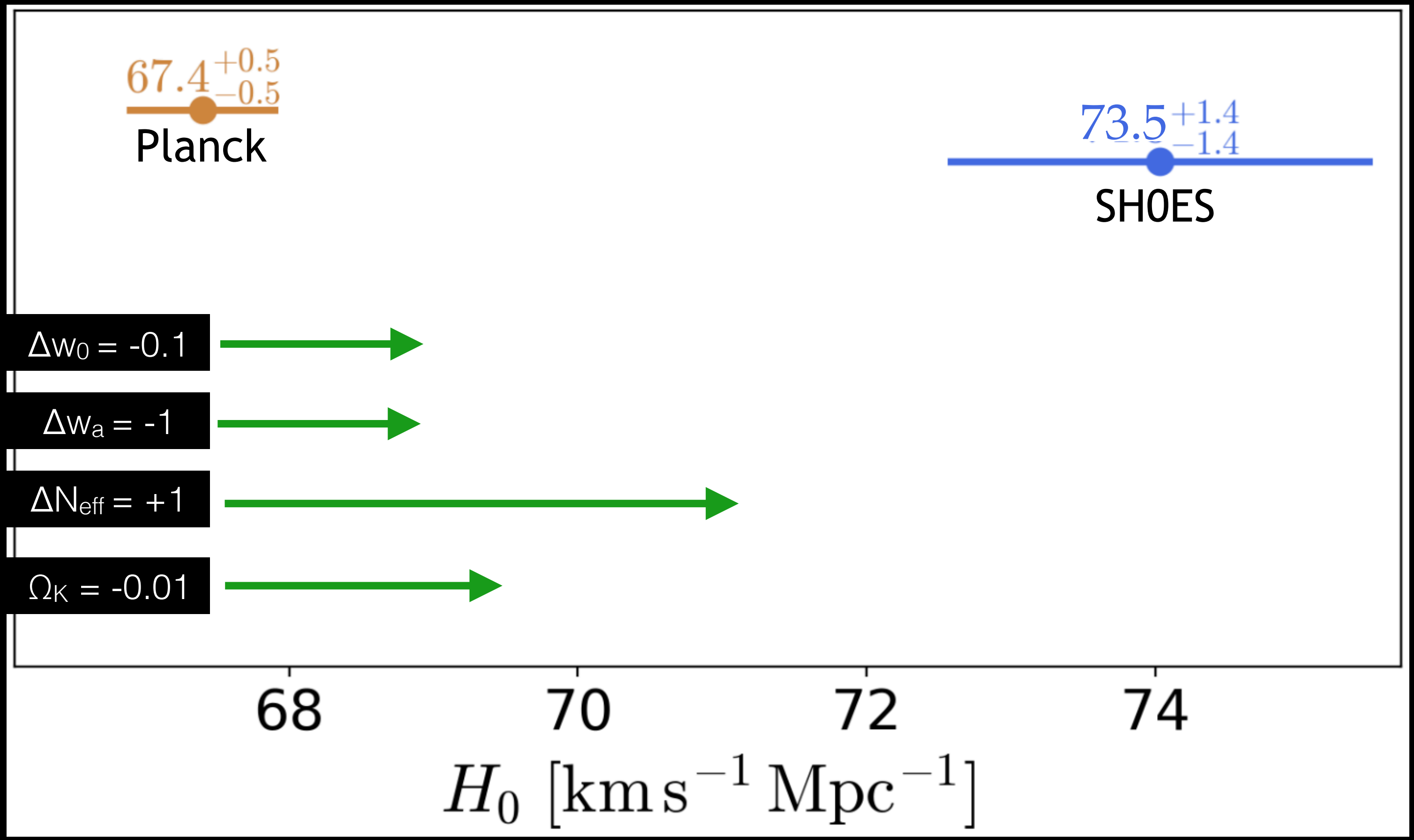
Galaxies hosting Cepheids and Type Ia supernovae

We already have restrictions on possibilities for resolving this tension

No immediately obvious way to get there…

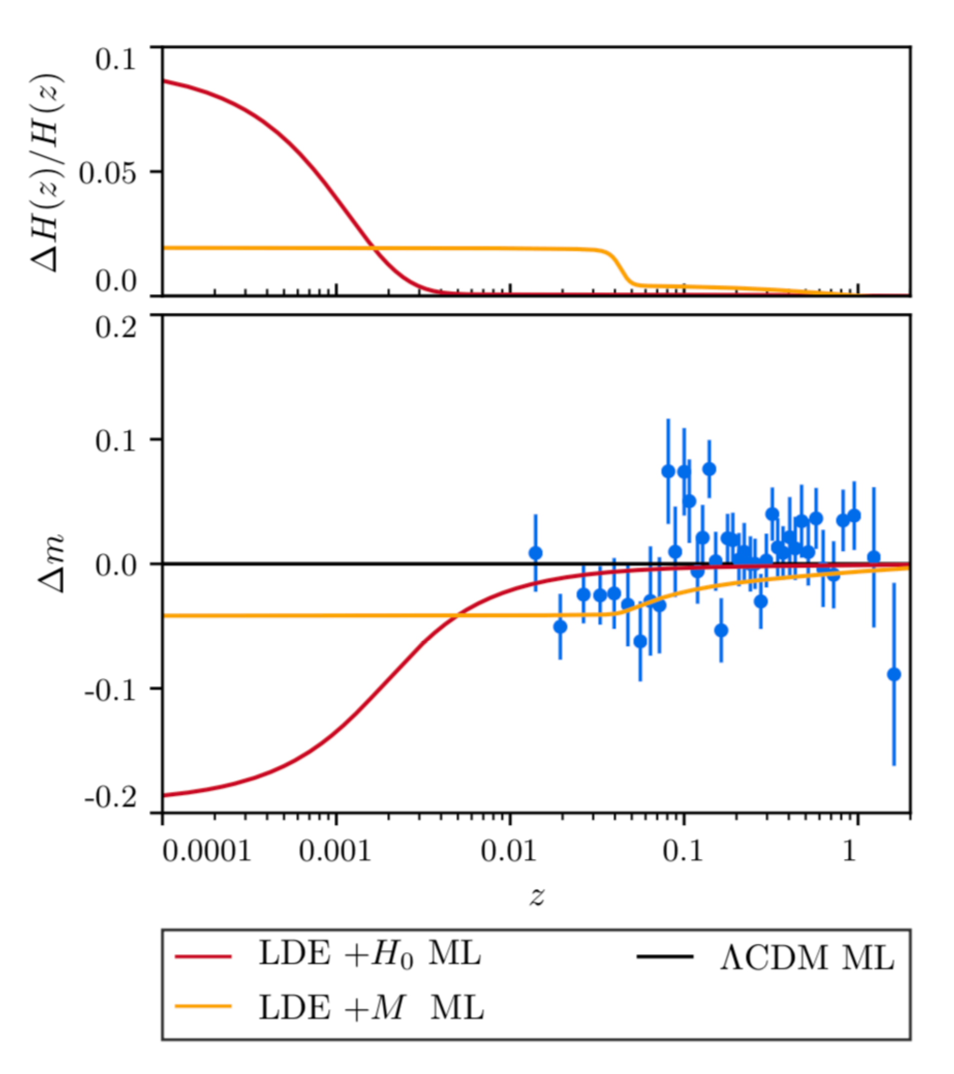


Brout et al. 2019

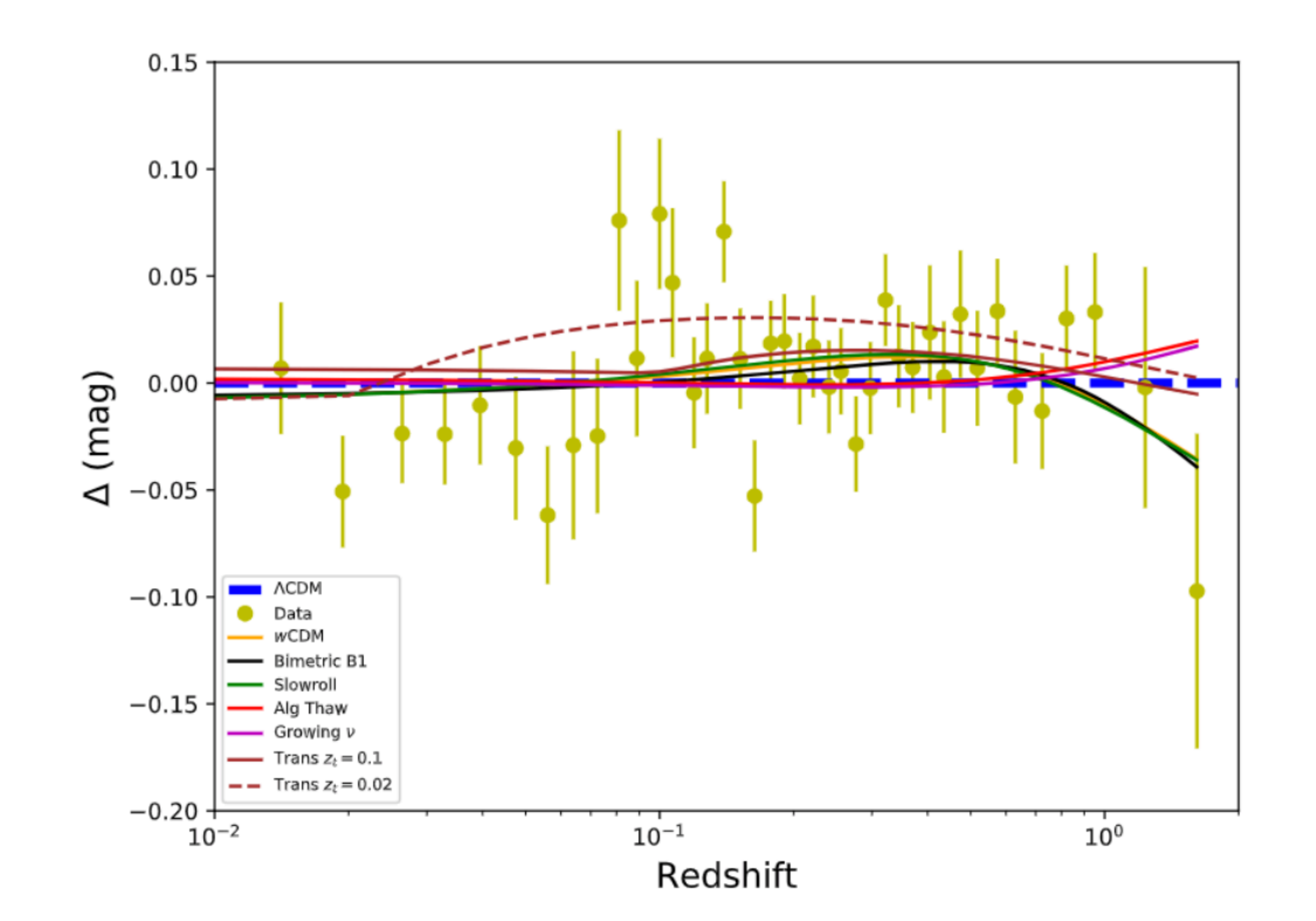


Its difficult to find a late universe model to explain the tension.

Benevento, Hu, Raveri 2020



Dahwan, Brout, et al 2020

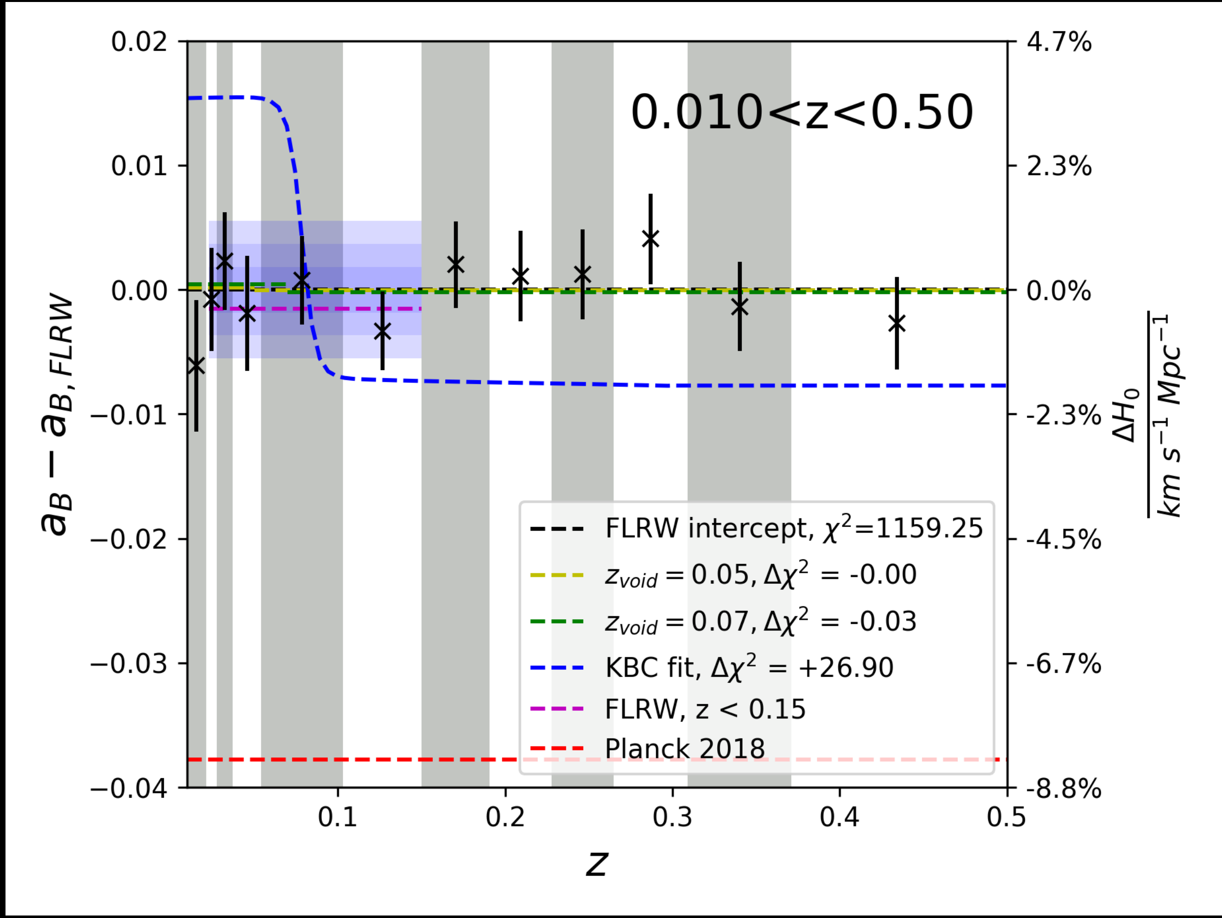


Re-Analyses of SH0ES 2016

SH0ES 2016		H0 = 73.2 ± 1.7
Zhang et al 2017	Blind analysis. Caveat, didn’t treat systematics simultaneously	H0 = 72.5 ± 3.1
Dhawan et al 2018	Use NIR data for SNeIa	H0 = 72.8 ± 2.8
Burns et al 2018	Different Supernovae. Optical and NIR sample.	H0 = 73.2 ± 2.3
Cardona et al 2017 https://arxiv.org/pdf/1611.06088.pdf	Bayesian hyper-parameters and no Cepheid period cut.	H0 = 73.8 ± 2.1
Feeney et al 2017 https://arxiv.org/pdf/1707.00007.pdf	Bayesian hierarchical model	H0 = 73.2 ± 1.8
Follin and Knox 2017 https://arxiv.org/pdf/1707.00007.pdf	Cepheid systematics.	H0 = 73.3 ± 1.7

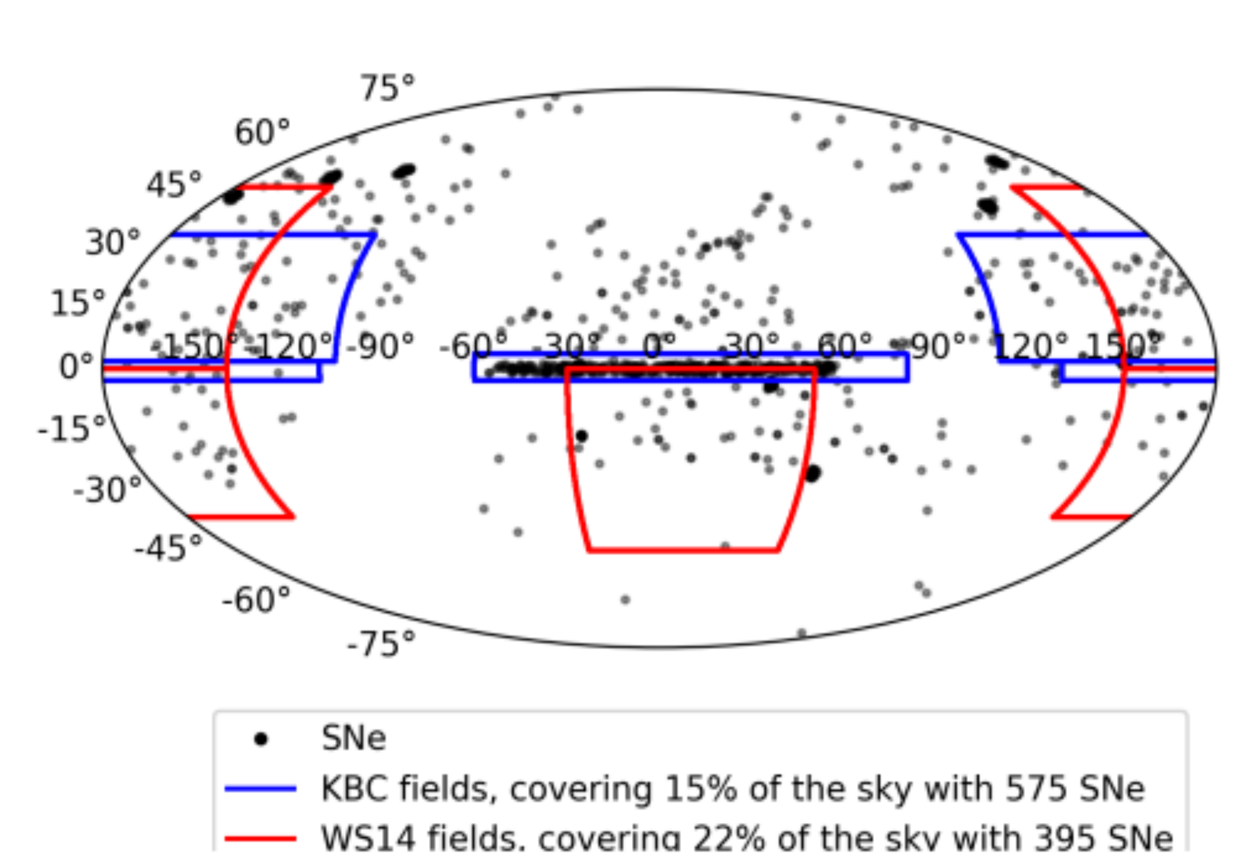
Tension doesn't appear to be due to a local void.

Kenworthy, Scolnic & Riess 2019



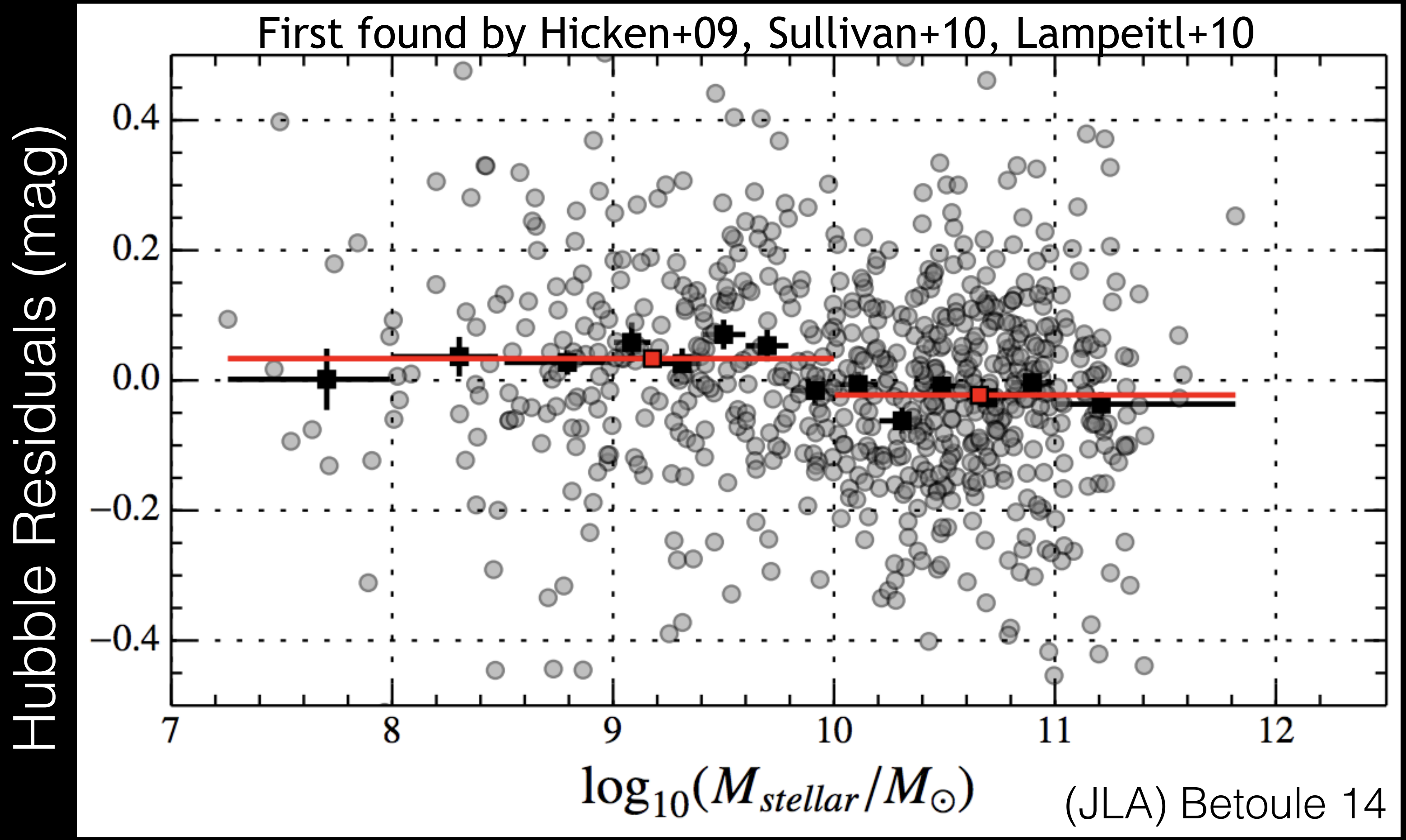
No evidence for kink in SN Hubble Diagram.

Kenworthy, Scolnic & Riess 2019



Wu+Huterer 2017 show cosmic variance effect on H0 is <0.5%

There is evidence for a fourth standardization parameter that is related to host galaxy properties

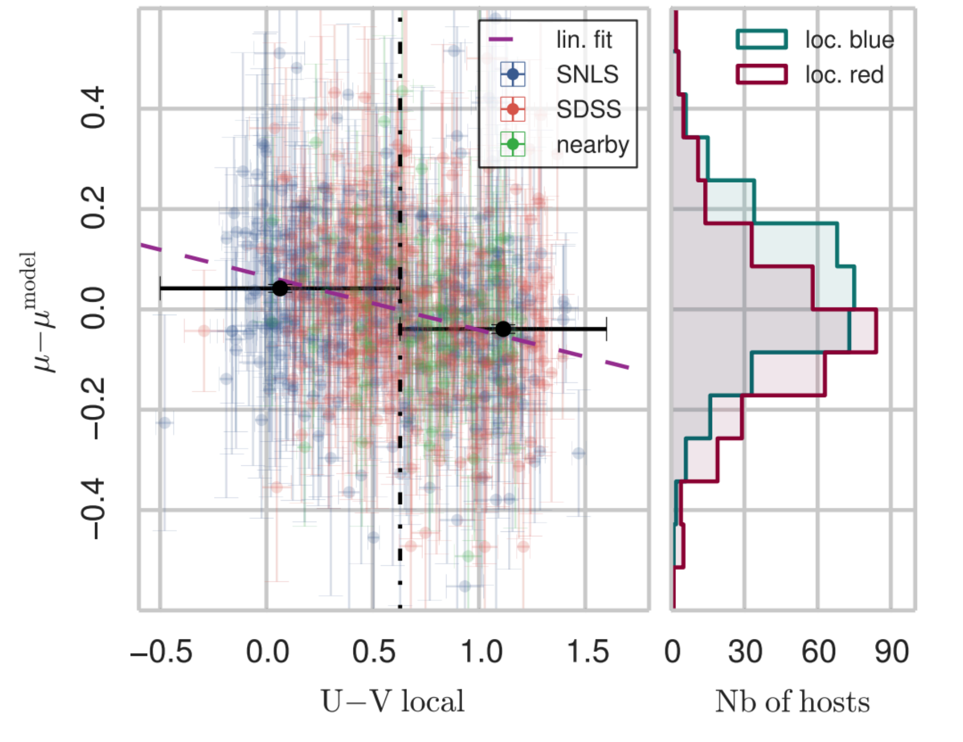


Host galaxy mass.

SH0ES+16 correct for this effect, which is small.
But there is not consensus on strongest host galaxy property.

Its not clear yet what parameter best describes this additional correlation.

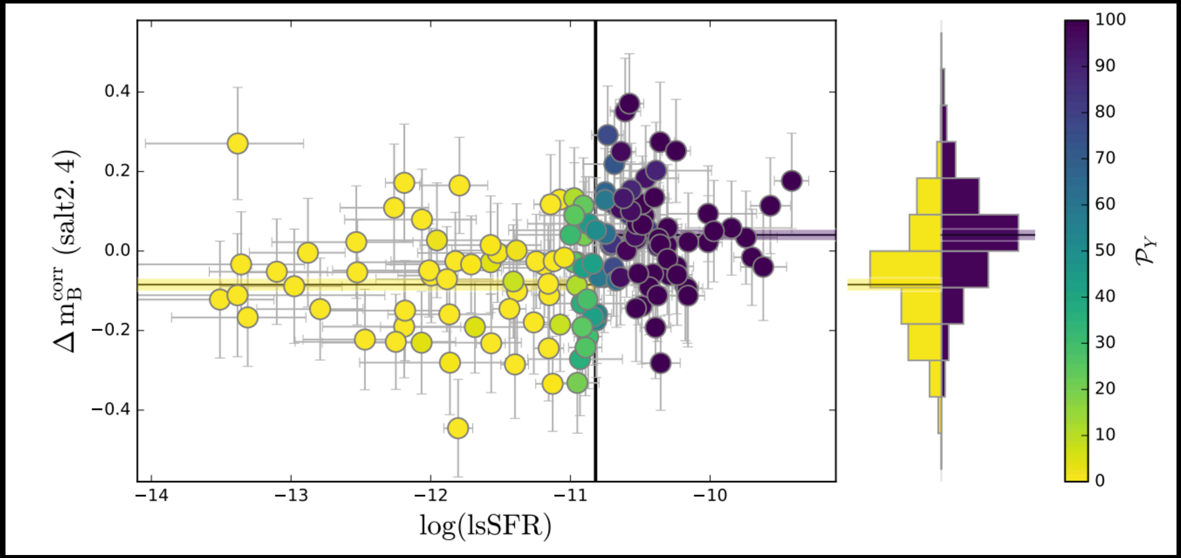
Roman 2018 looks at U-V local, similar tracer but different. Local color (7σ), Mass (5.5σ)



Survey/z range	Nb of SNIa	ΔM_B Local color (mag)
Nearby	85	-0.0491 ± 0.0462 (1.1σ)

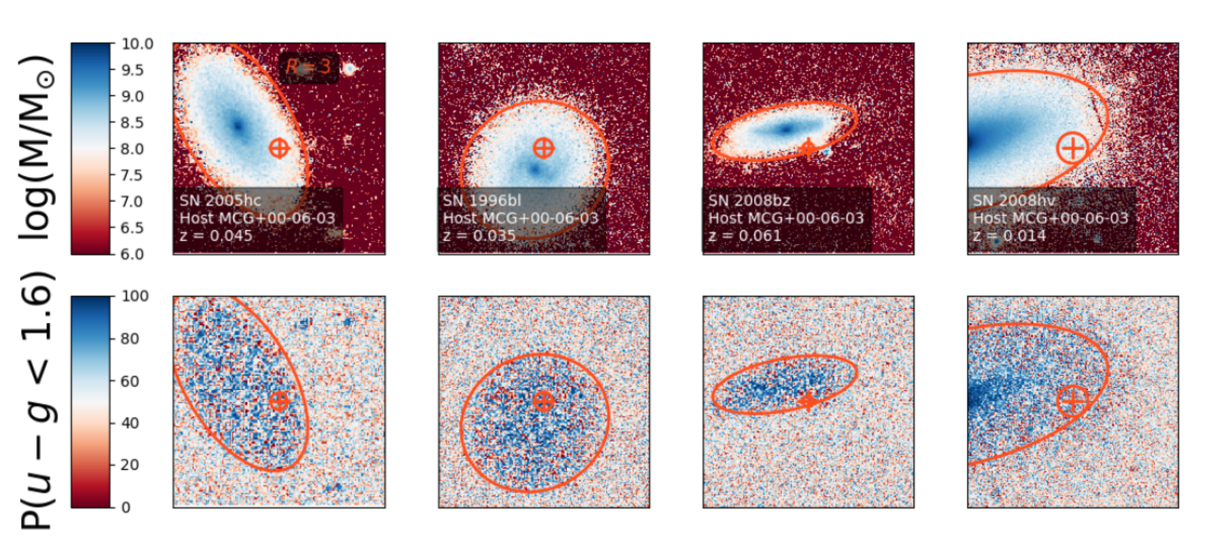
Rigault and Roman 2.5σ away at low-z. Final effect is still 0.07 mag lower than Rigault 2018 and driven by high-z. H0 measurement at low-z.

Rigault+17



Fraction of galaxies with local sfr changes with redshift.

Jones+17

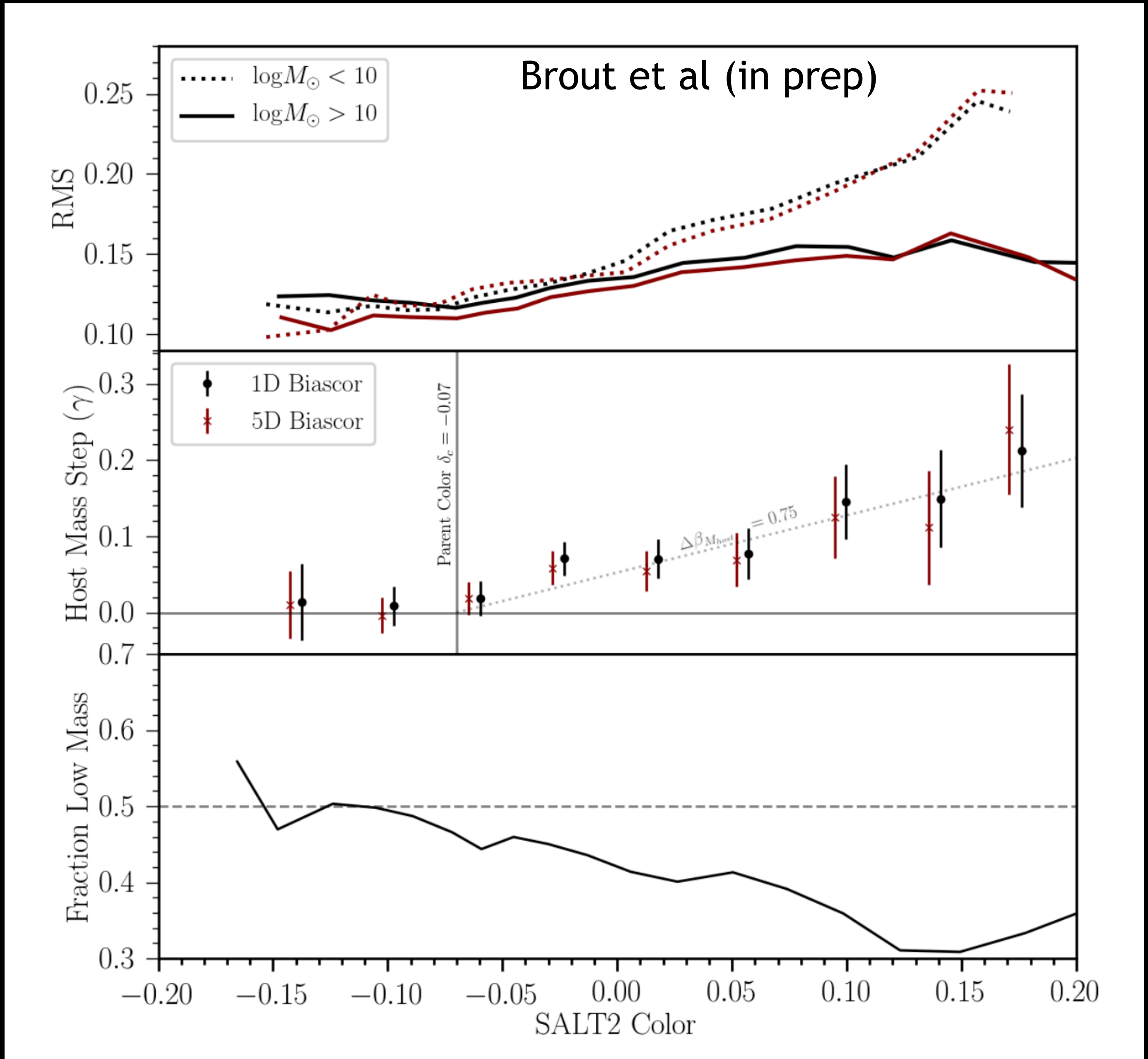


Underlying cause of host correlations...

SN Colors and Hubble diagram scatter is driven by dust.

It also appears that host galaxy correlations are also driven by dust. The correlation between SNIa luminosity and host mass is only significant the SNe affected by dust.

We need to understand this before we can attribute the host steps to progenitor scenarios, rather than simply dust.



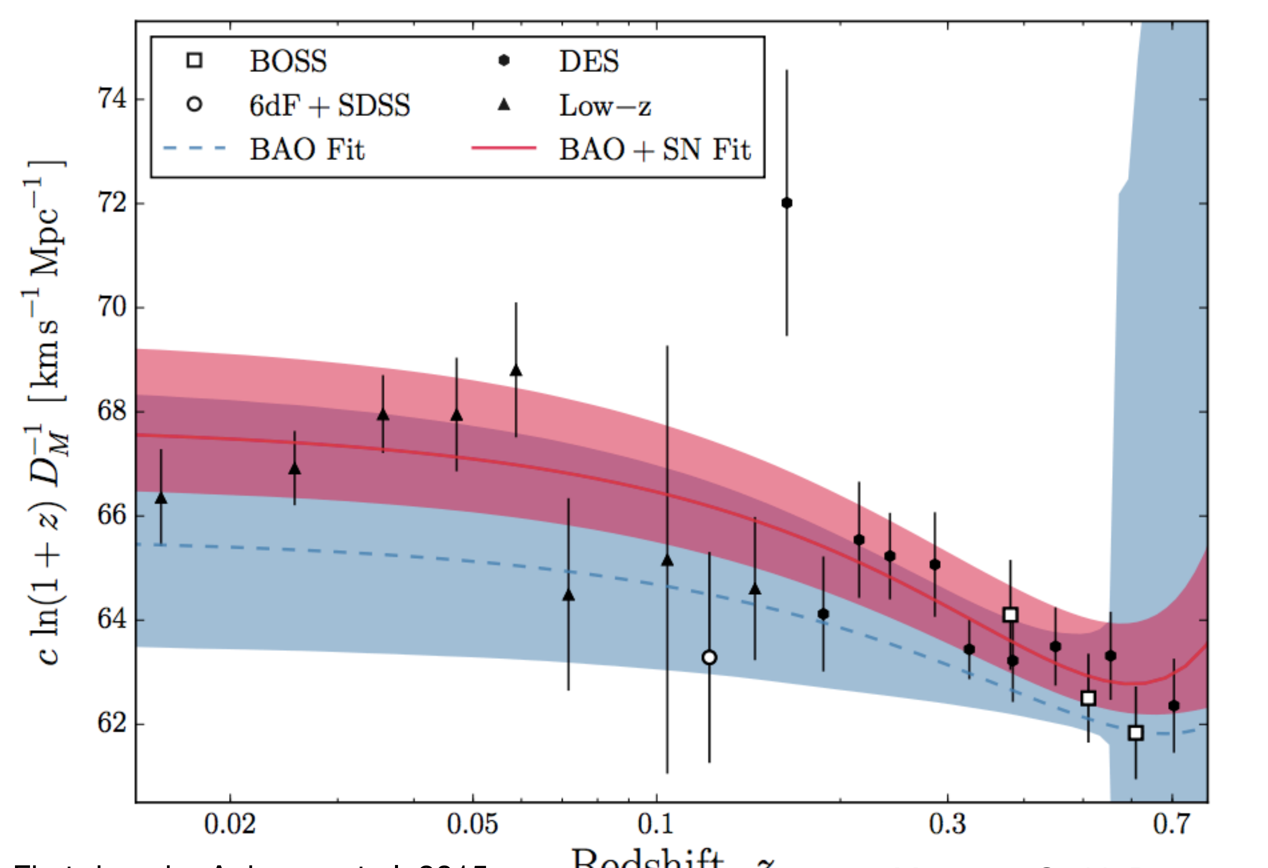
Overall impact from Host Galaxy properties systematic appears to be small for H0.

SN Host Property	Step Size	Step Significance	% HF-CC R16 Demographics	Delta H_0 R16 (km/s/Mpc)
Local mass > 8.3 dex	0.055 +/- 0.17	3.2	15.3%	-0.28
Global mass > 10 dex	-0.002 +/- 0.018	0.1	22.6%	0.02
Local u-g > 1.3	0.033 +/- 0.020	1.7	39.5%	-0.44
Global u-g>1.3	0.035 +/- 0.020	1.8	20.2%	-0.24
Local sSFR < -10.6	0.035 +/- 0.021	1.7	30.9%	-0.37
Global sSFR < -10.6	0.029 +/- 0.020	1.4	21.1%	-0.21

All these differences are >10x smaller than tension with CMB H0!!!

SNe are the middle person here: Depends on where are you getting your absolute scale from…

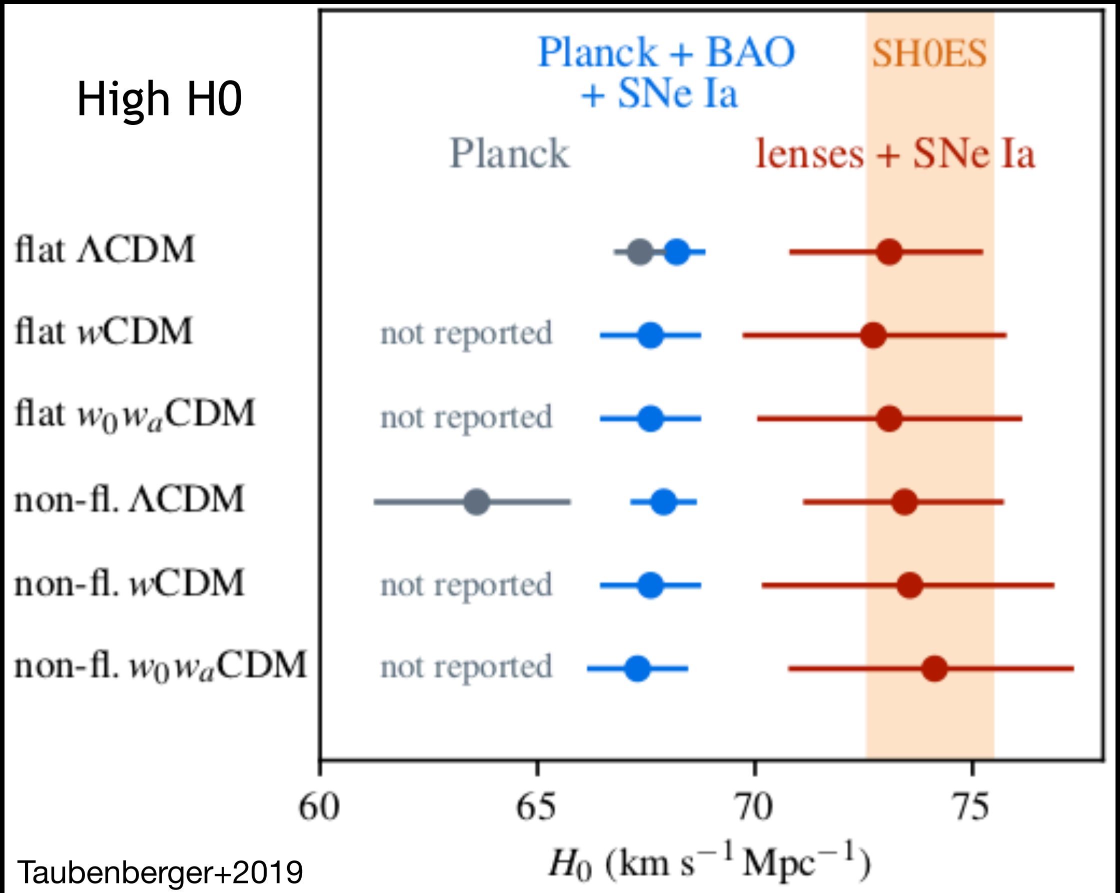
Calibrate to BAO —> Low H0



First done by Aubourg et al. 2015

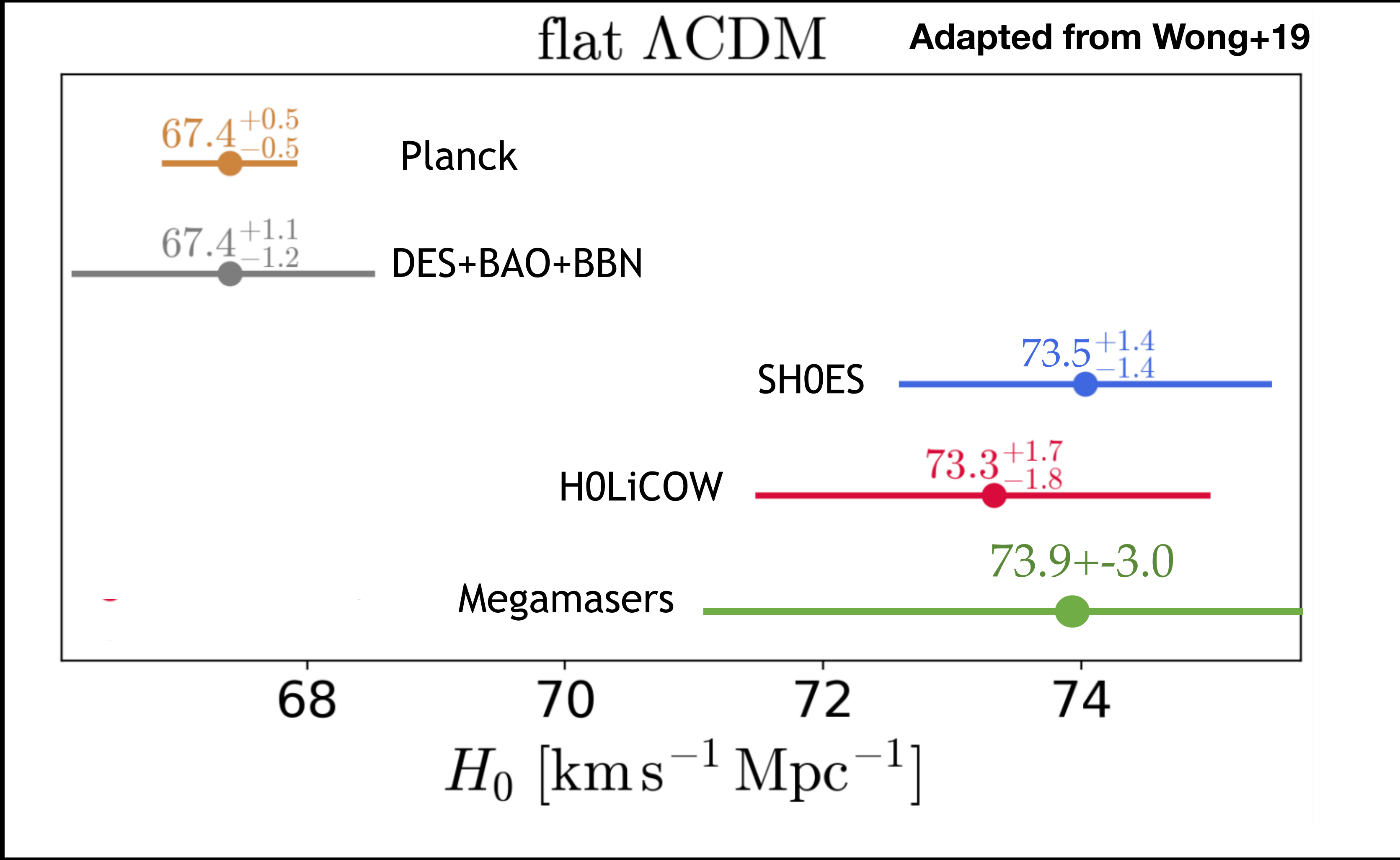
Macaulay,Smith,Brout+19

Calibrate to Strong Lenses —> High H0



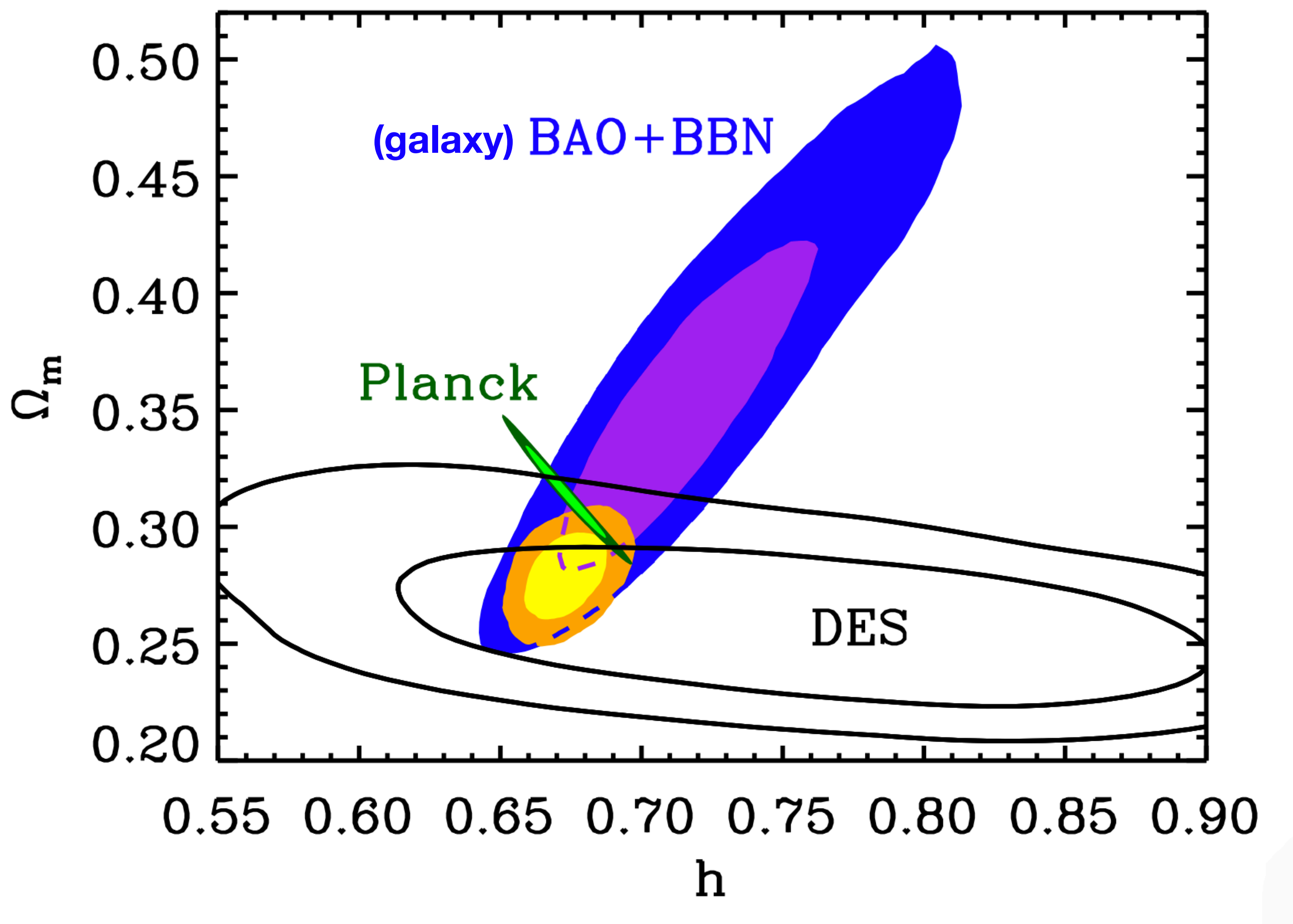
Taubenberger+2019

Probes split dramatically on early universe assumptions



Crosscheck on Low H0 with assumption of early universe physics.

DES Collaboration 2018



BAO observables:
D_M/r_s and c/(H*r_s)

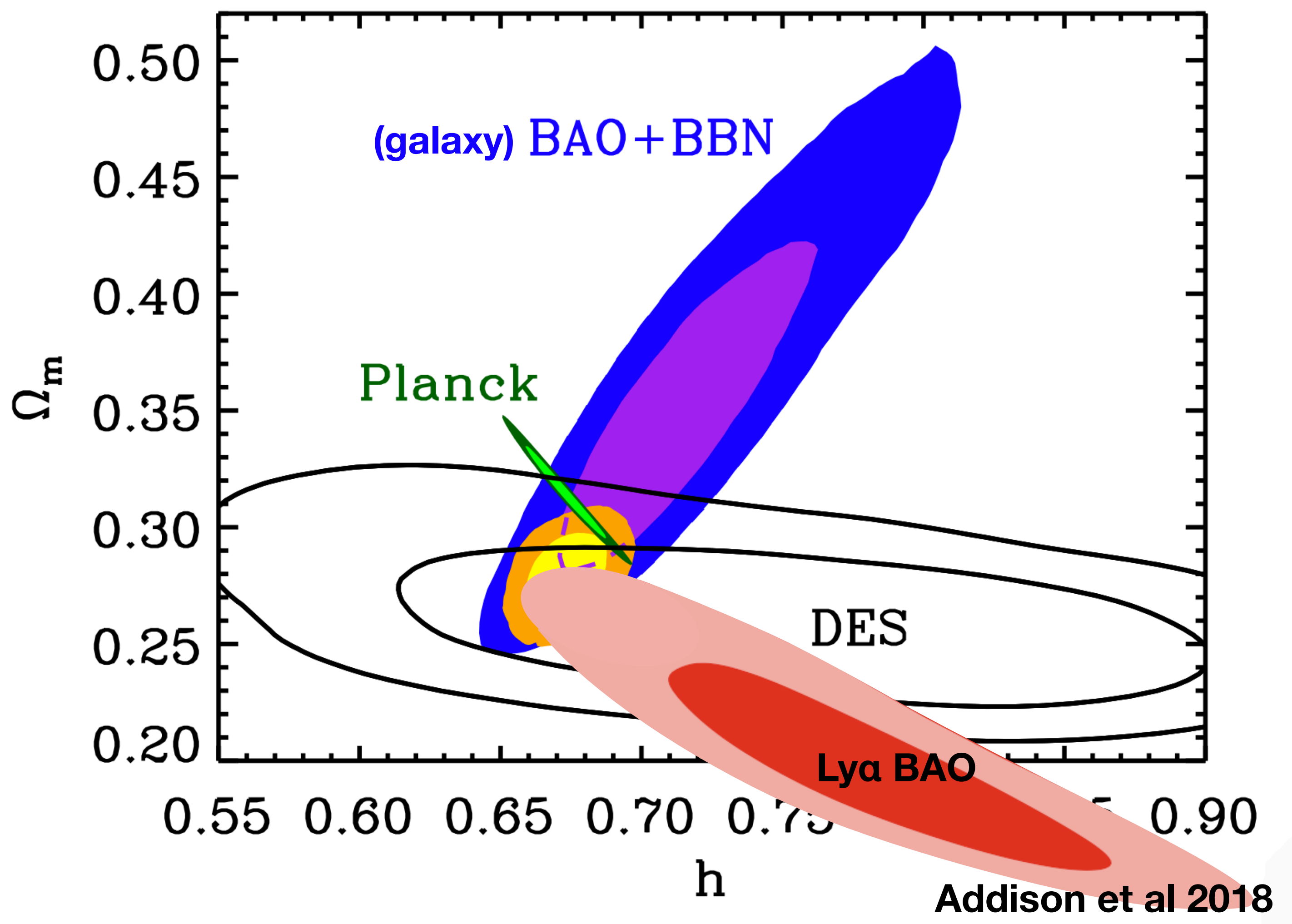
BAO Constraints:
Omega_M, Omega_b*h^2, h

BBN —> Omega_b*h^2

So you're left with a degeneracy between Omega_M and h, for which Omega_M can be constrained by DES Weak Lensing

Crosscheck on Low H0 with assumption of early universe physics.

DES Collaboration 2018



Addison et al 2018

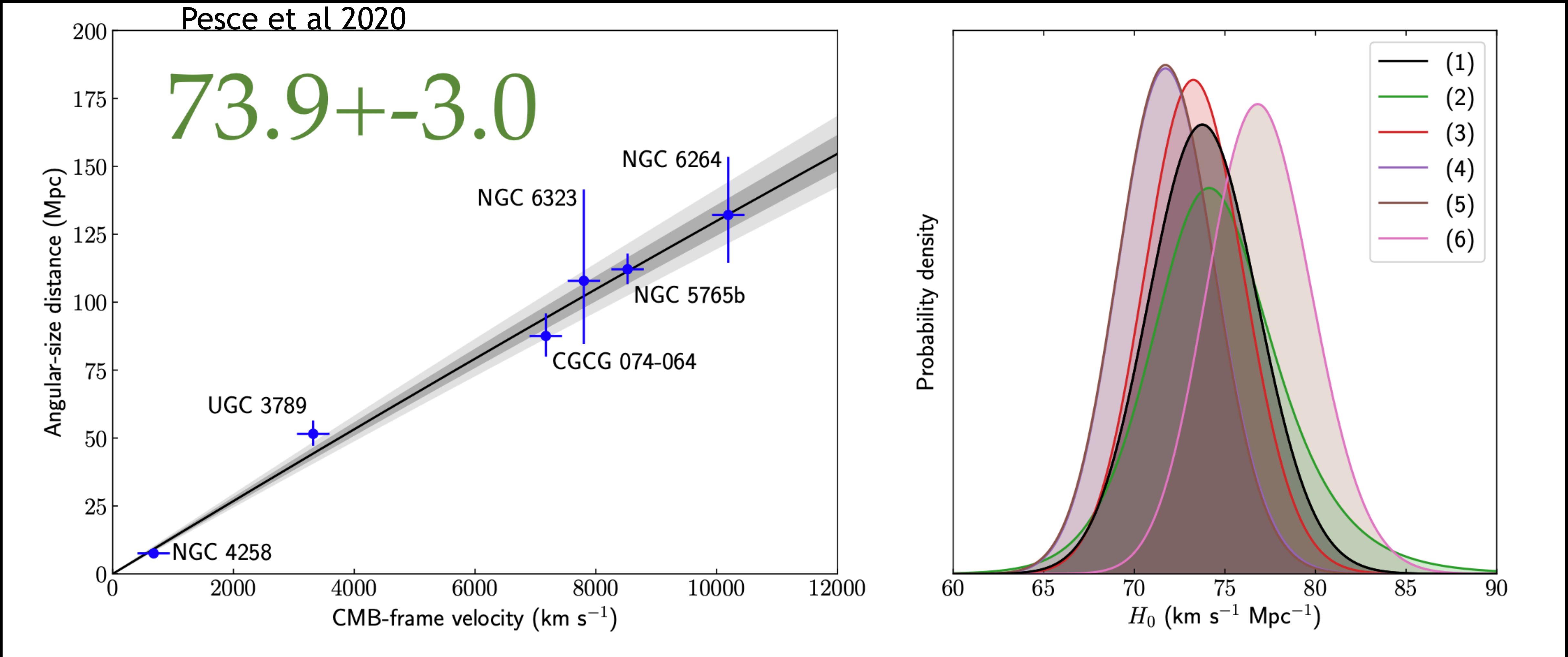
BAO observables:
D_M/r_s and c/(H*r_s)

BAO Constraints:
Omega_M, Omega_b*h^2, h

BBN —> Omega_b*h^2

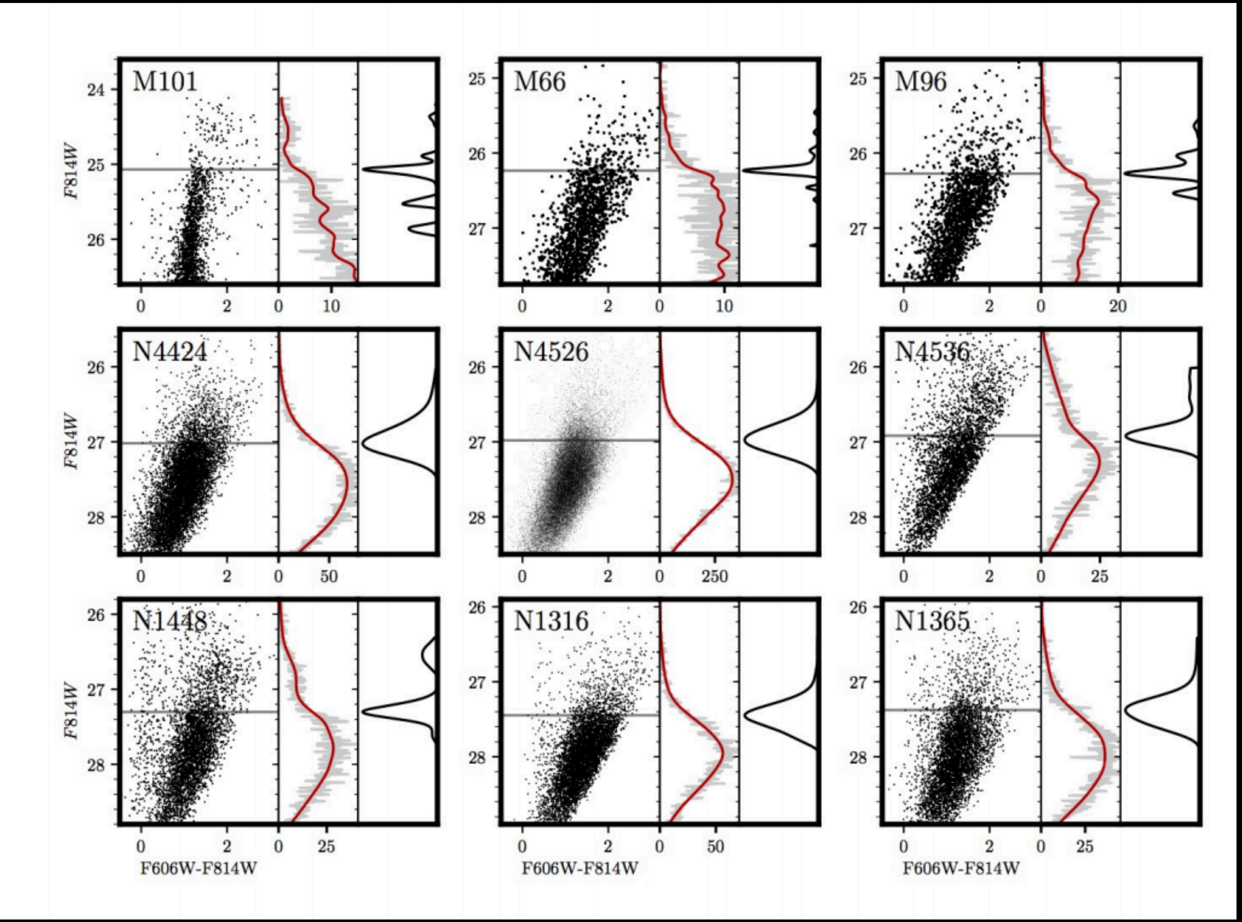
So you're left with a degeneracy between Omega_M and h, for which Omega_M can be constrained by DES Weak Lensing

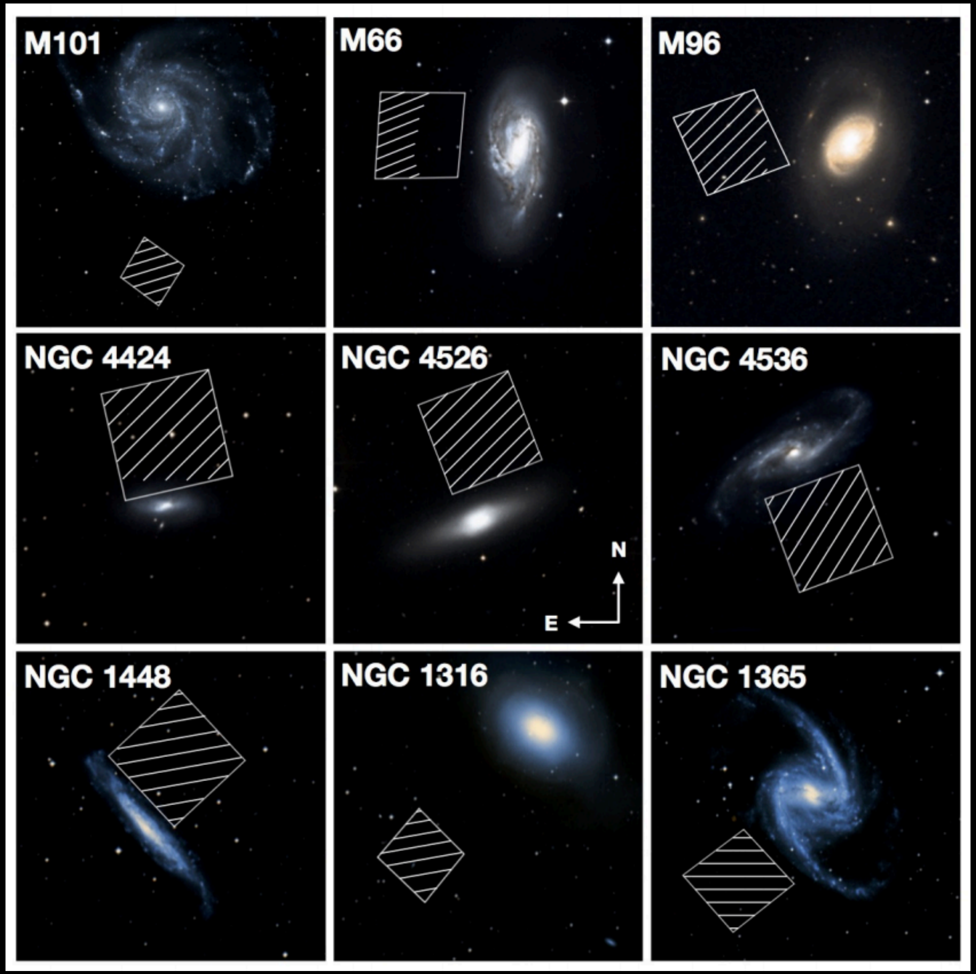
Late universe Crosscheck: Megamaser Cosmology Project



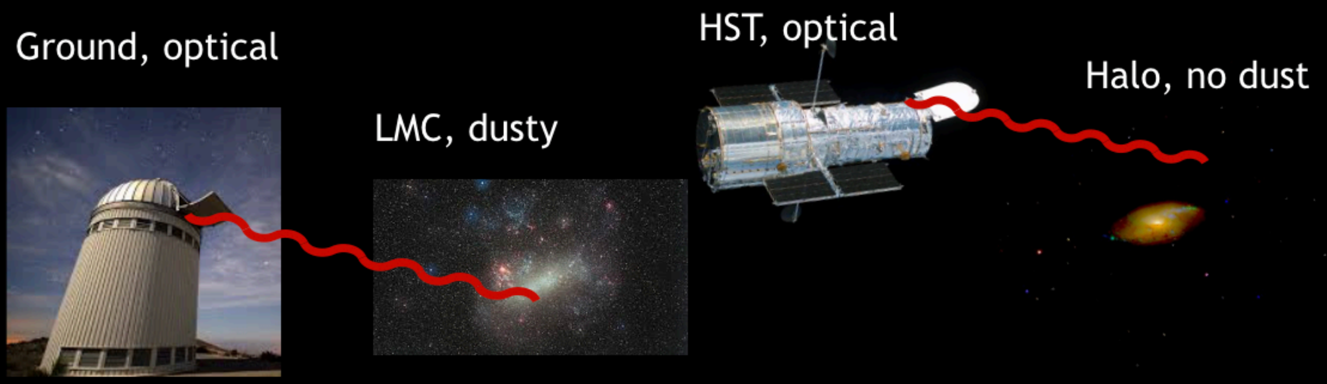
Tip of the Red Giant Branch

The peak brightness reached by red giant stars after they stop fusing hydrogen and begin fusing helium in their core



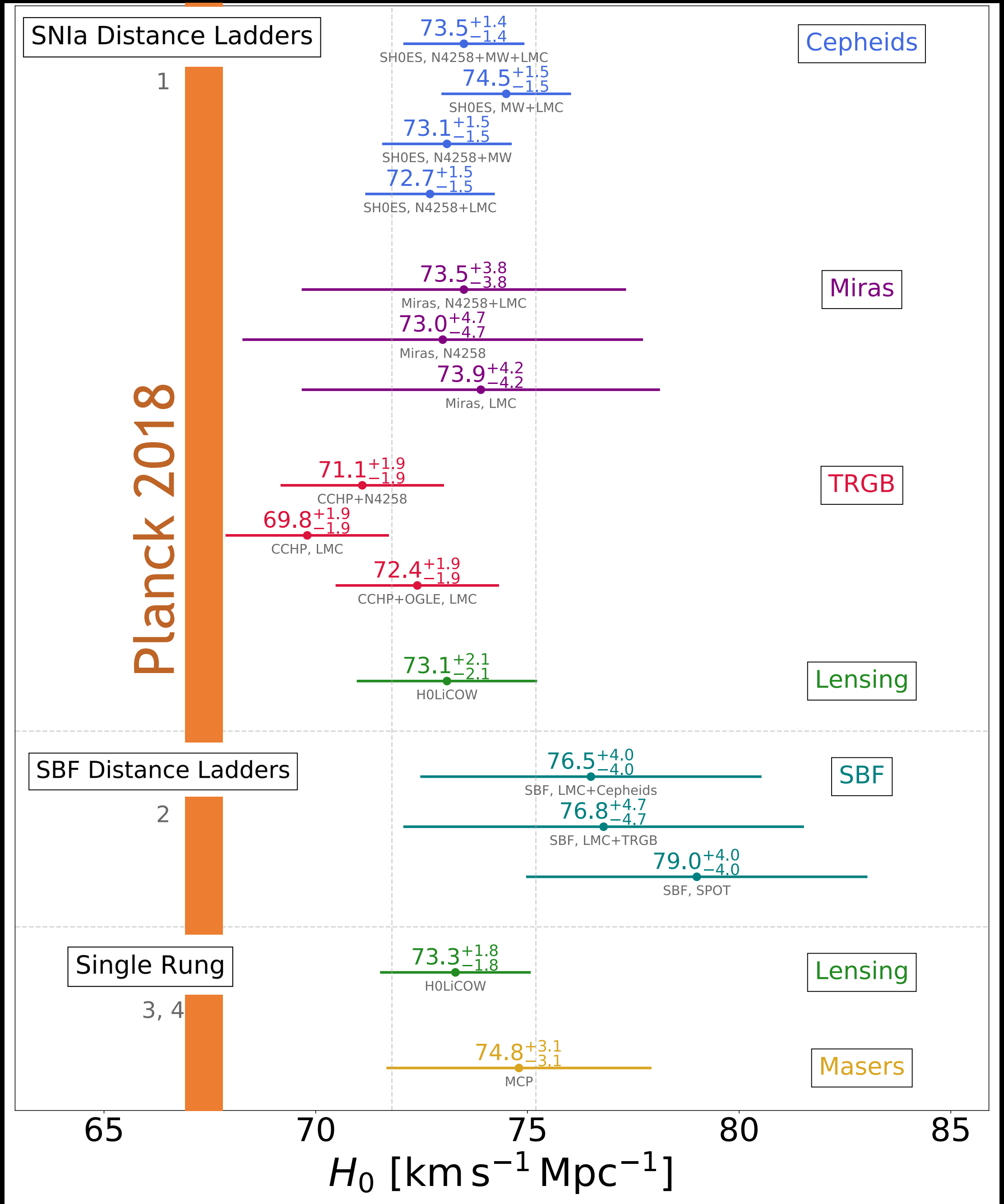


TRGB is a brightness that needs to be calibrated.

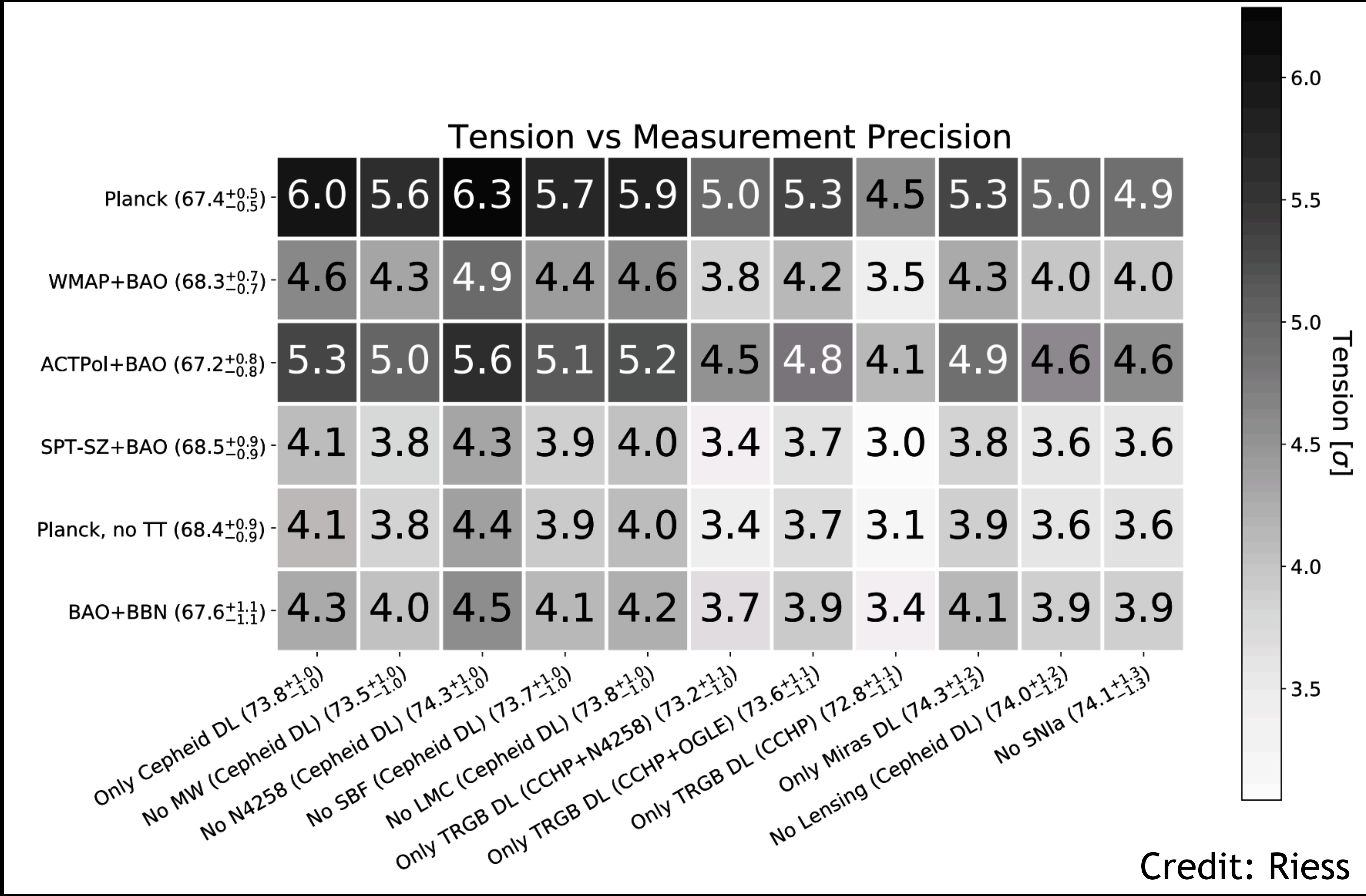


LMC Extinction Method	Extinction	TRGB M_I Calibration	Reference	Inferred H_0 (CHP/Pantheon)
OGLE RC LMC Maps	A=0.10 +/- 0.02	-3.97 +/- 0.03*	Jang and Lee 2017	72.4/73.2
NIR colors internal to LMC	A=0.05 +/- 0.05	-3.95 +/- 0.03	Hatt+2018, Hoyt+2017	73.1/73.9
Comparing colors in hosts (w/ different Fe/H)	A=0.165 +/- 0.02	-4.05 +/- 0.02	Freedman+2019	69.8/70.6
NGC4258	A=0	-4.01 +/-0.04	Ried, Pesce, Riess 2019	71.1/71.9

The Full Picture Of Late Universe Measurements



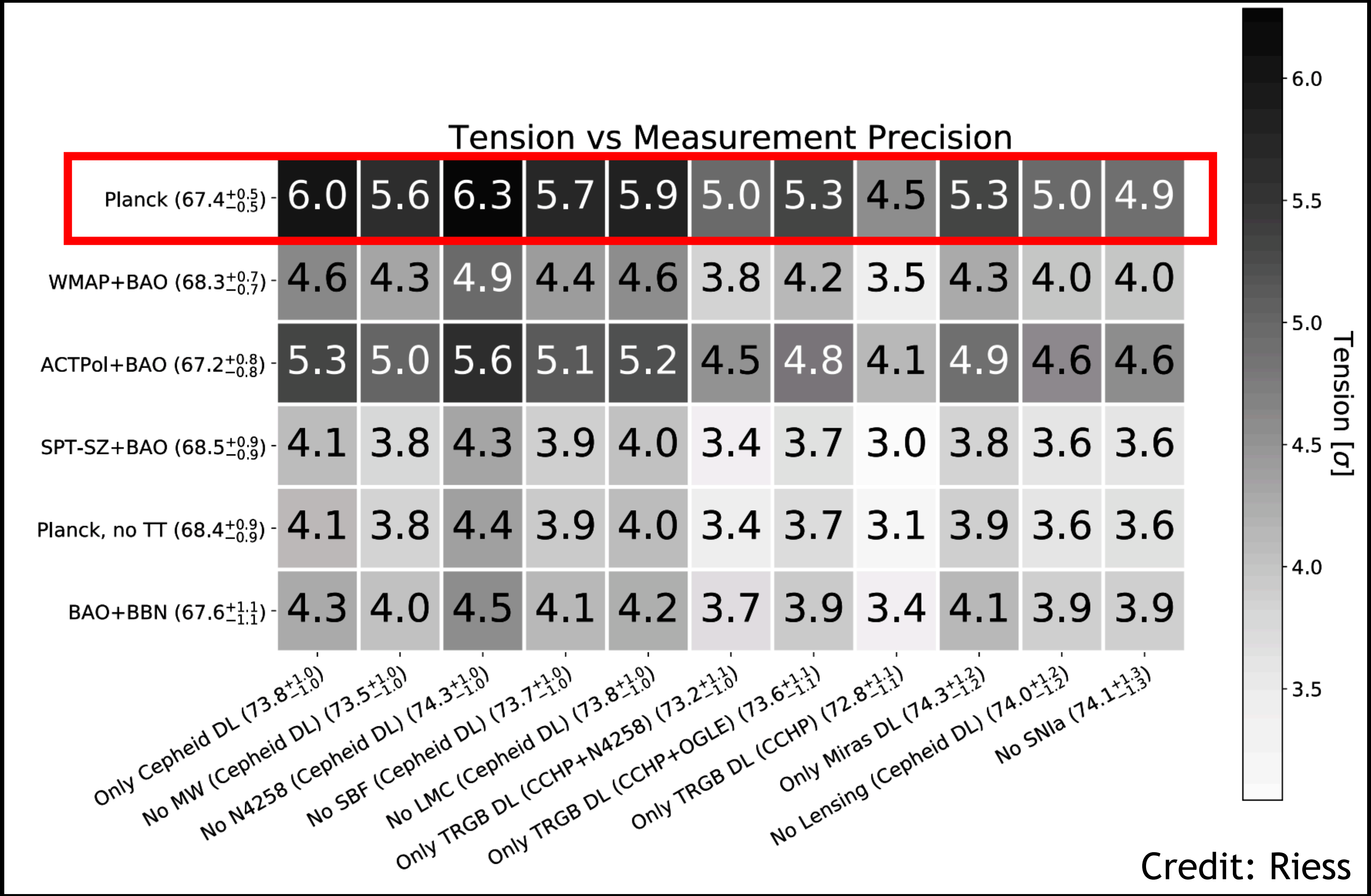
Tension no matter how you slice it



Dataset Assuming Early Universe Physics

Late Universe Dataset/Analysis

Tension no matter how you slice it



Dataset Assuming Early Universe Physics

Late Universe Dataset/Analysis

Conclusion

Numerous ways to achieve H0 tension. No single probe is driving tension.

SNIa are the middleperson - can achieve low or high H0.

Combining independent probes can achieve >5 sigma

Becoming more and more difficult to understand how systematics can resolve this.

SH0ES will be doubling its Cepheid sample in the coming year.

If the Universe fails this crucial end-to-end test (it surely hasn't yet passed), what might this tell us?