Class 1: Introduction | Observable universe & Dark energy

Class 2: Details on Type Ia Supernova cosmology

Class 3: The Hubble Constant tension

$$v_H = H_0 d_L$$

Recessional velocity

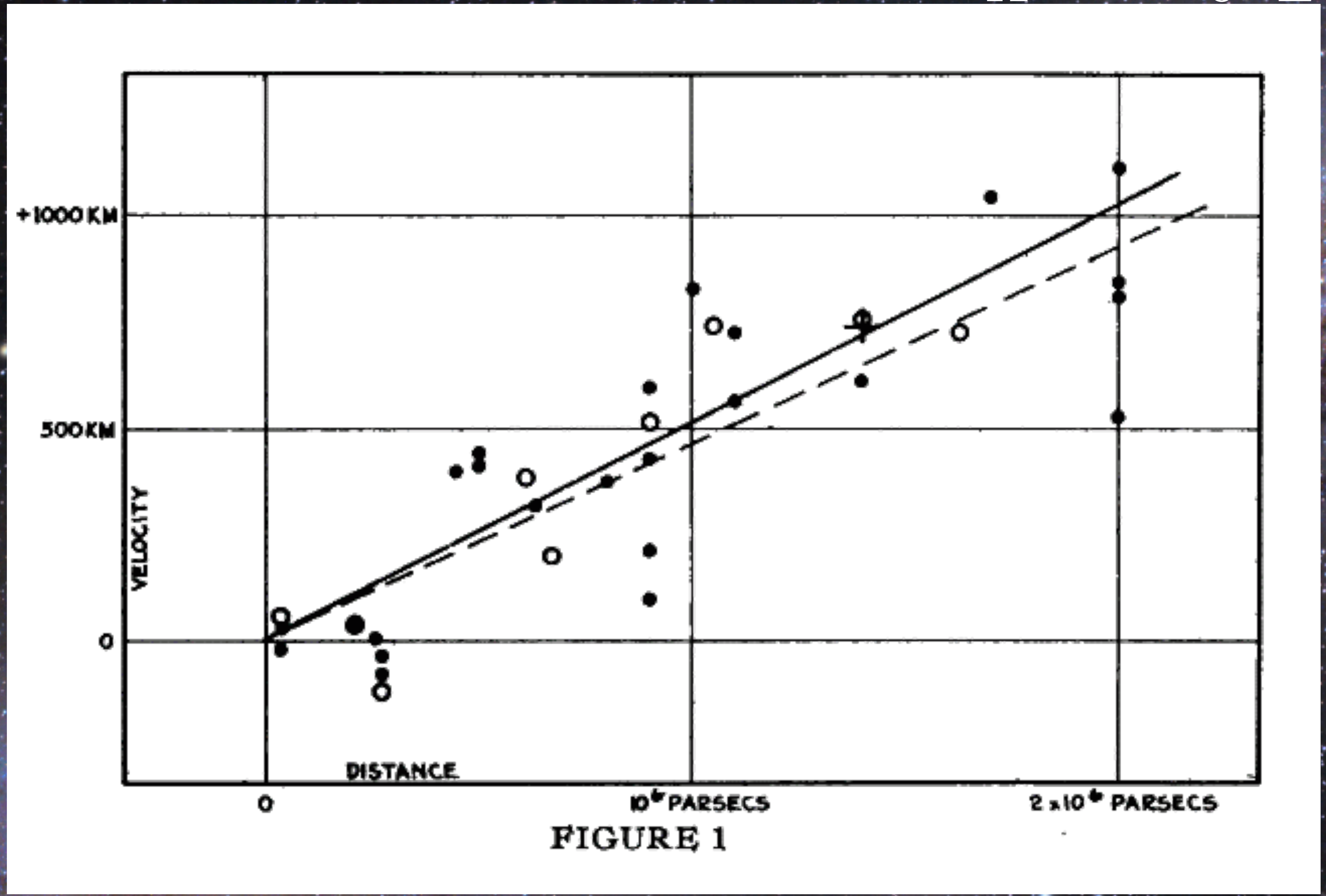
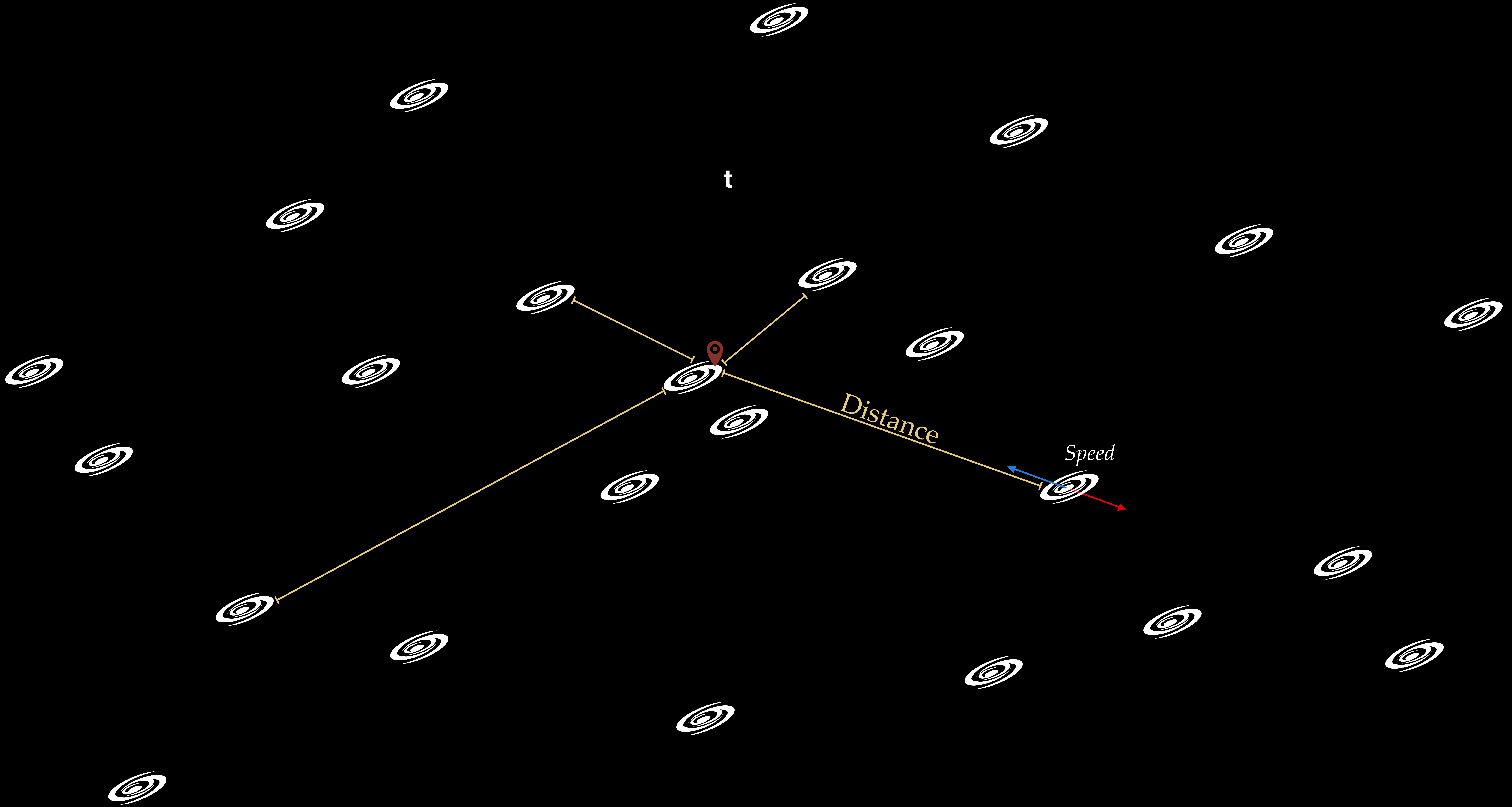
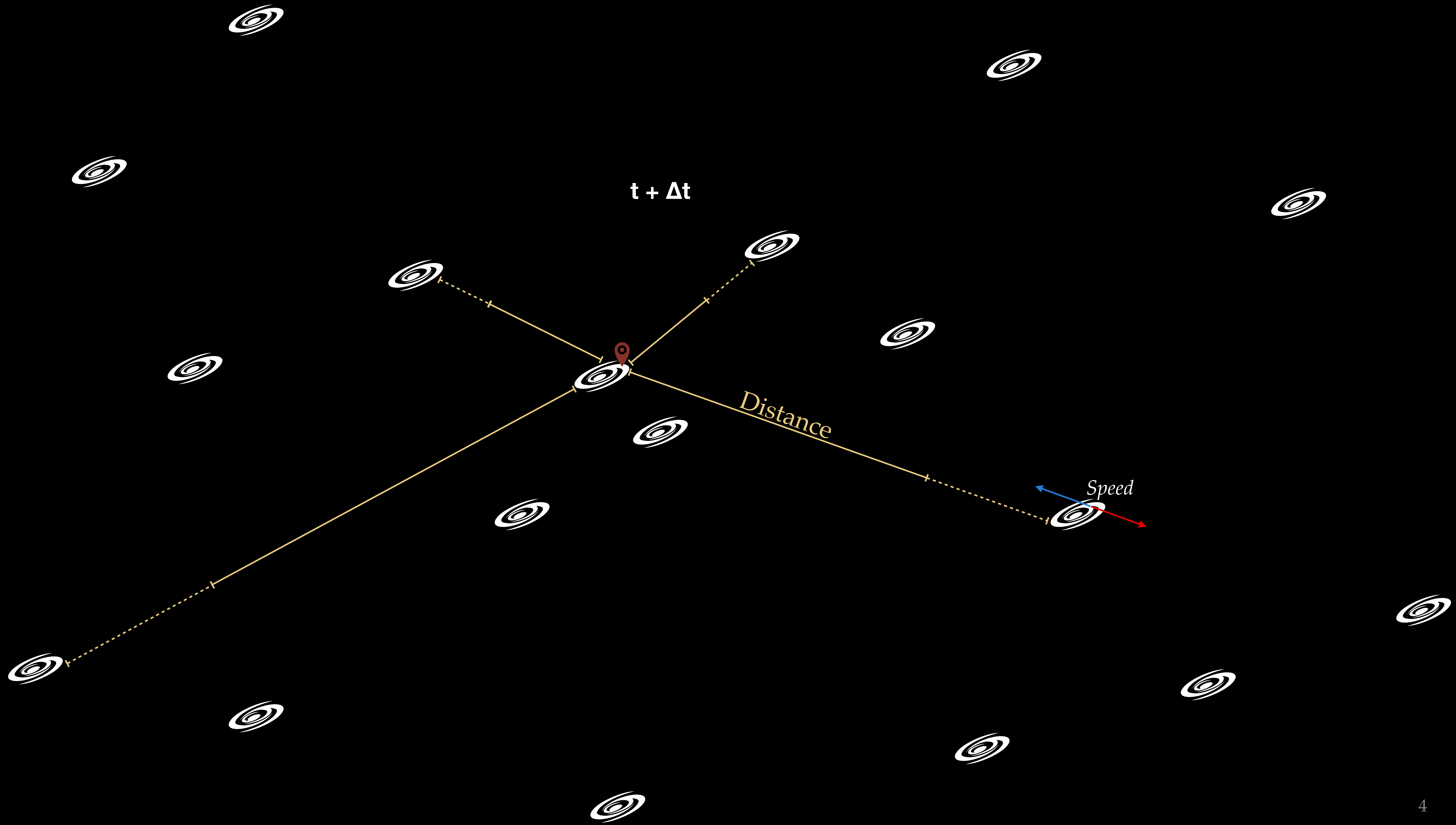


FIGURE 1

Distance from us

The Hubble Constant *H_0*: How fast the Universe is currently expanding


t
Distance
Speed



t + Δt
Distance
Speed

Modern Cosmology | *H_0 Direct vs. Indirect Measurements*

$$H_0 = d_l / v_h$$

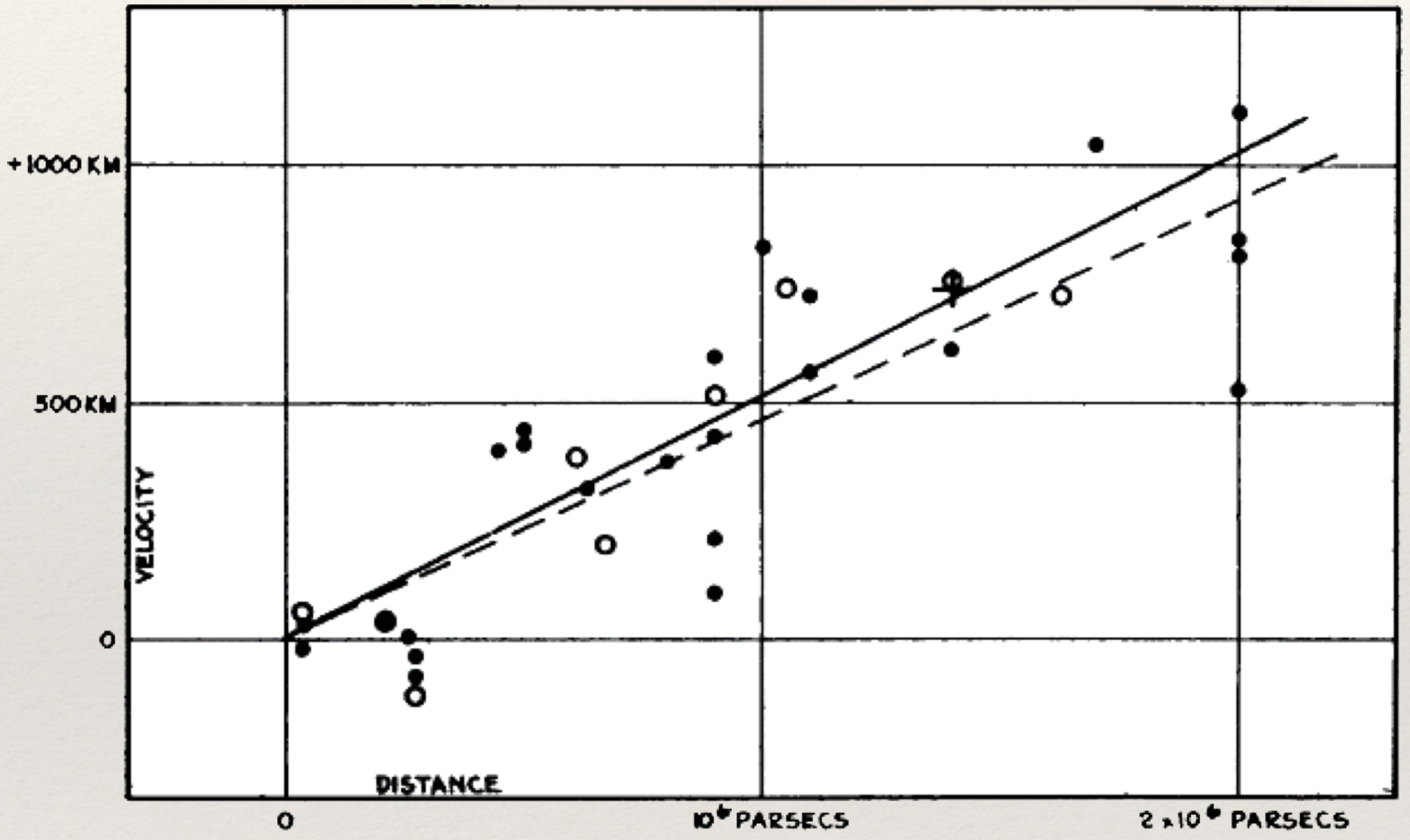
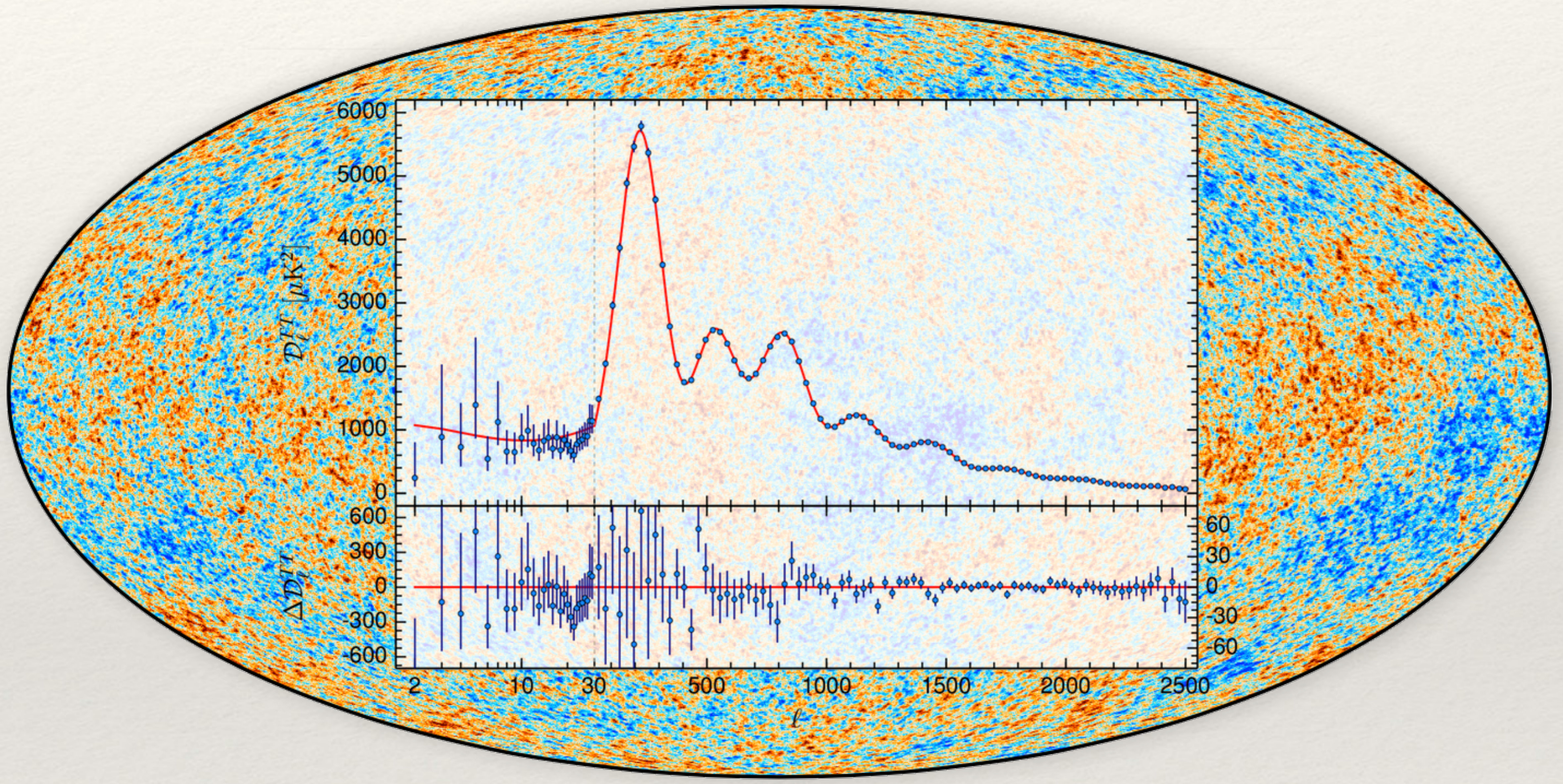


FIGURE 1

Careful with peculiar velocities

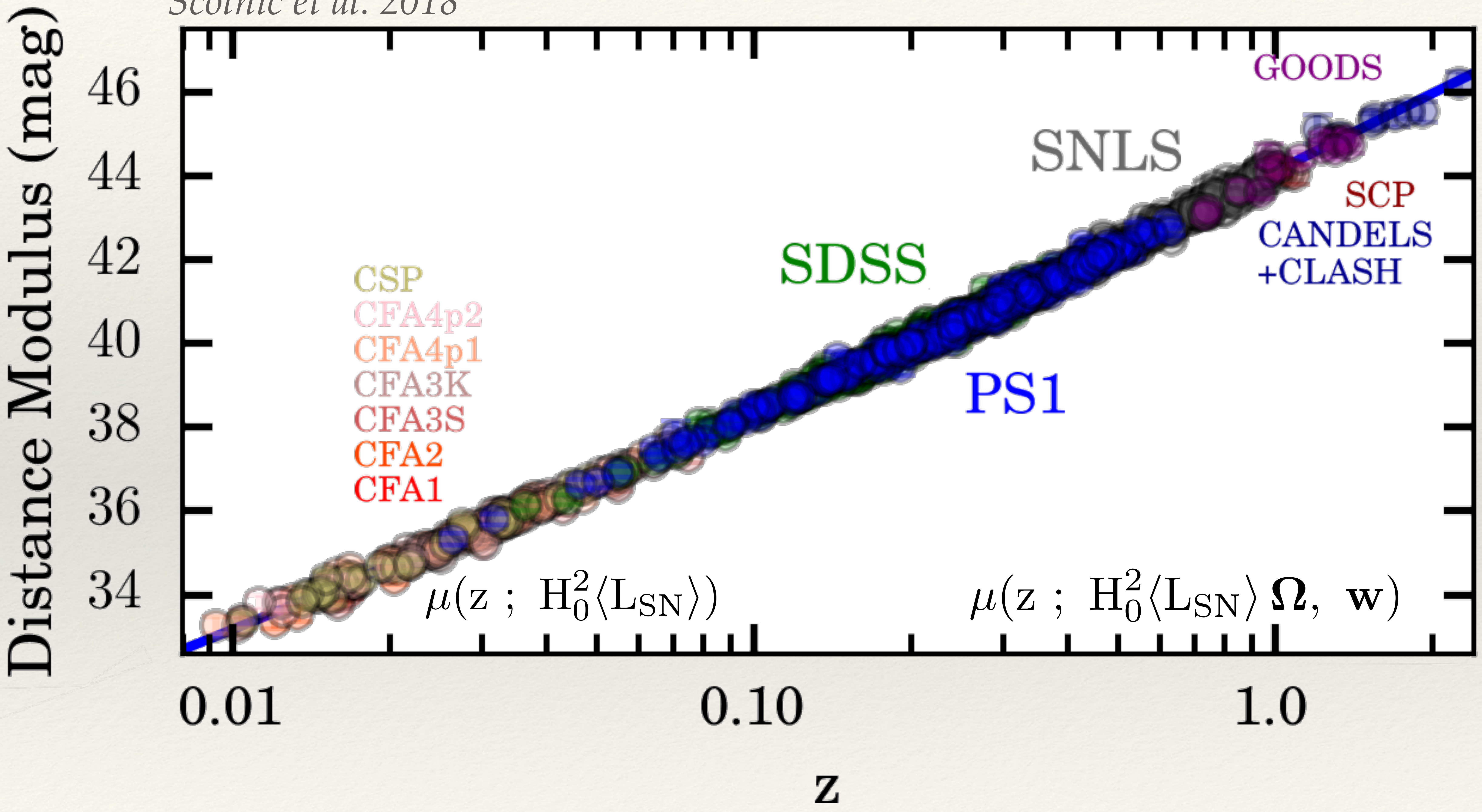
$$H(z) = H_0 \times \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}$$



Model dependent

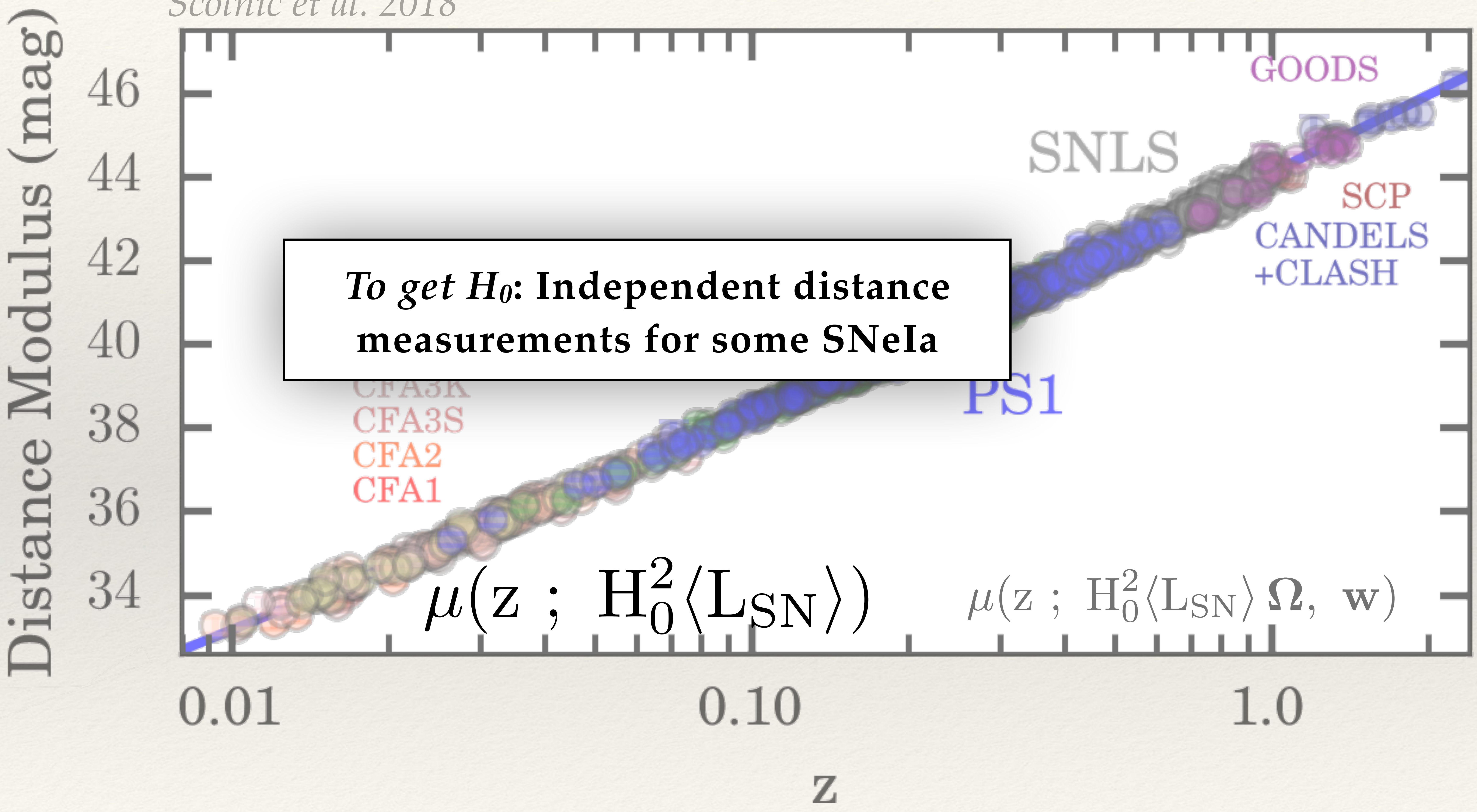
Type Ia Cosmology

Scolnic et al. 2018



Type Ia Cosmology | Measuring H_0

Scolnic et al. 2018



To get H_0: **Independent distance measurements for some SNeIa**

Direct Distance Ladder | *SH0ES*

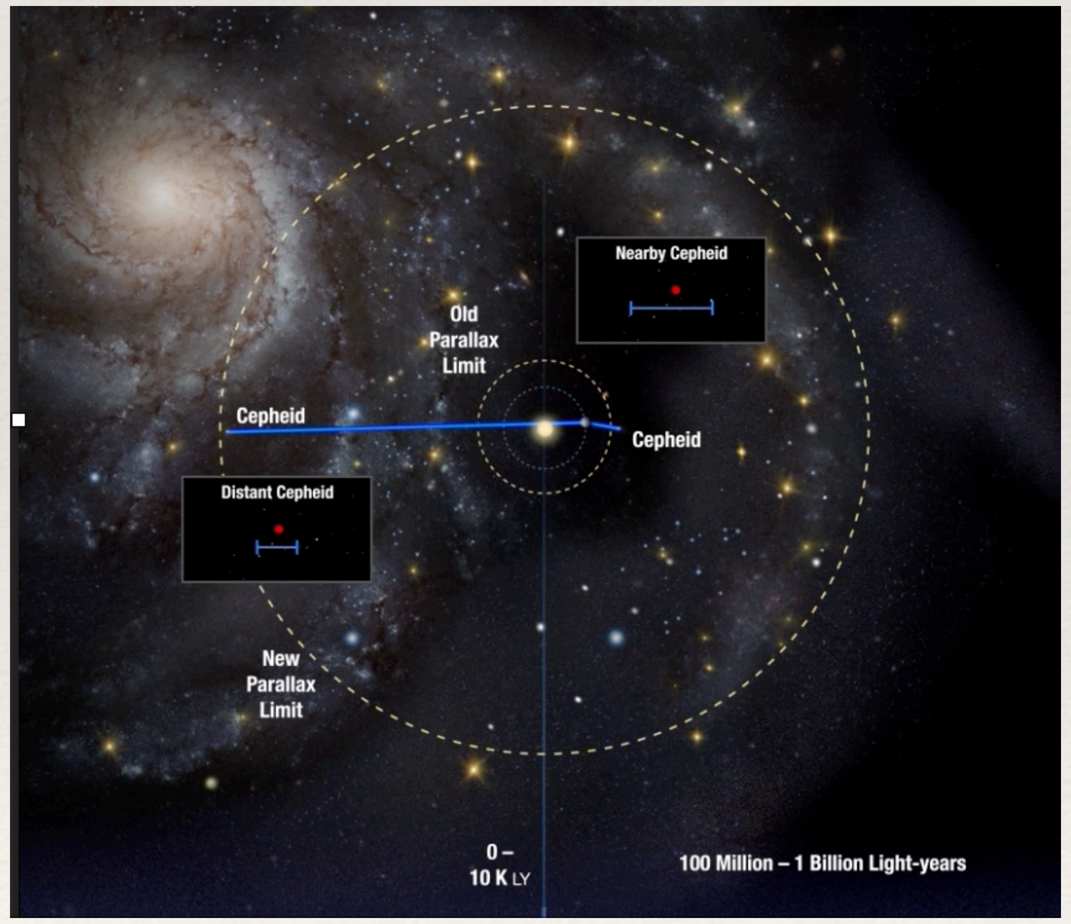
Get independent distances for SNe Ia

Calibrate the "Period-Luminosity" relation — *Measure "L_{SN}"* — *Get "H_0"* → **distance**

"Geometry"

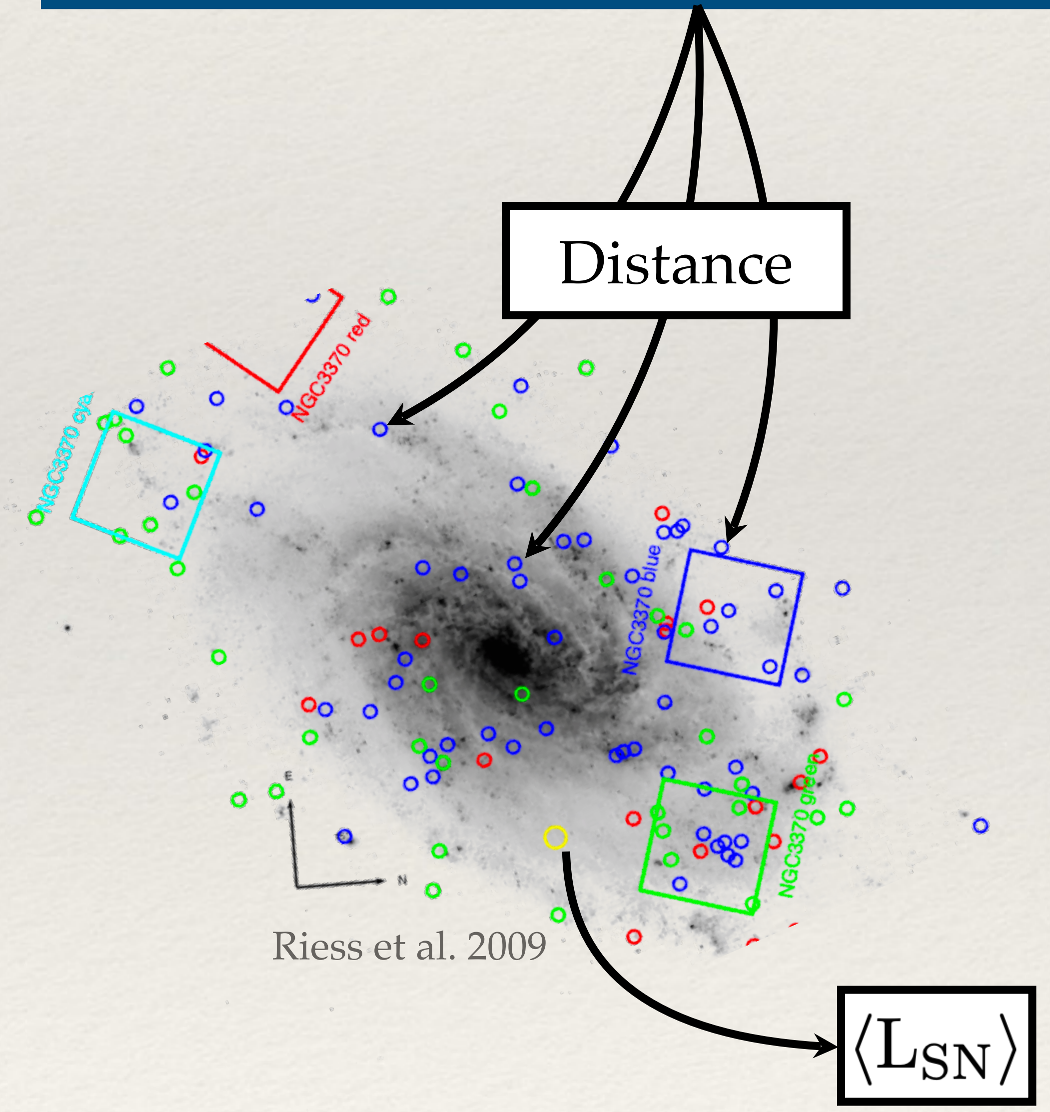
Parallaxes | D.E.B. | Maser

Source: eso



"Calibrators"

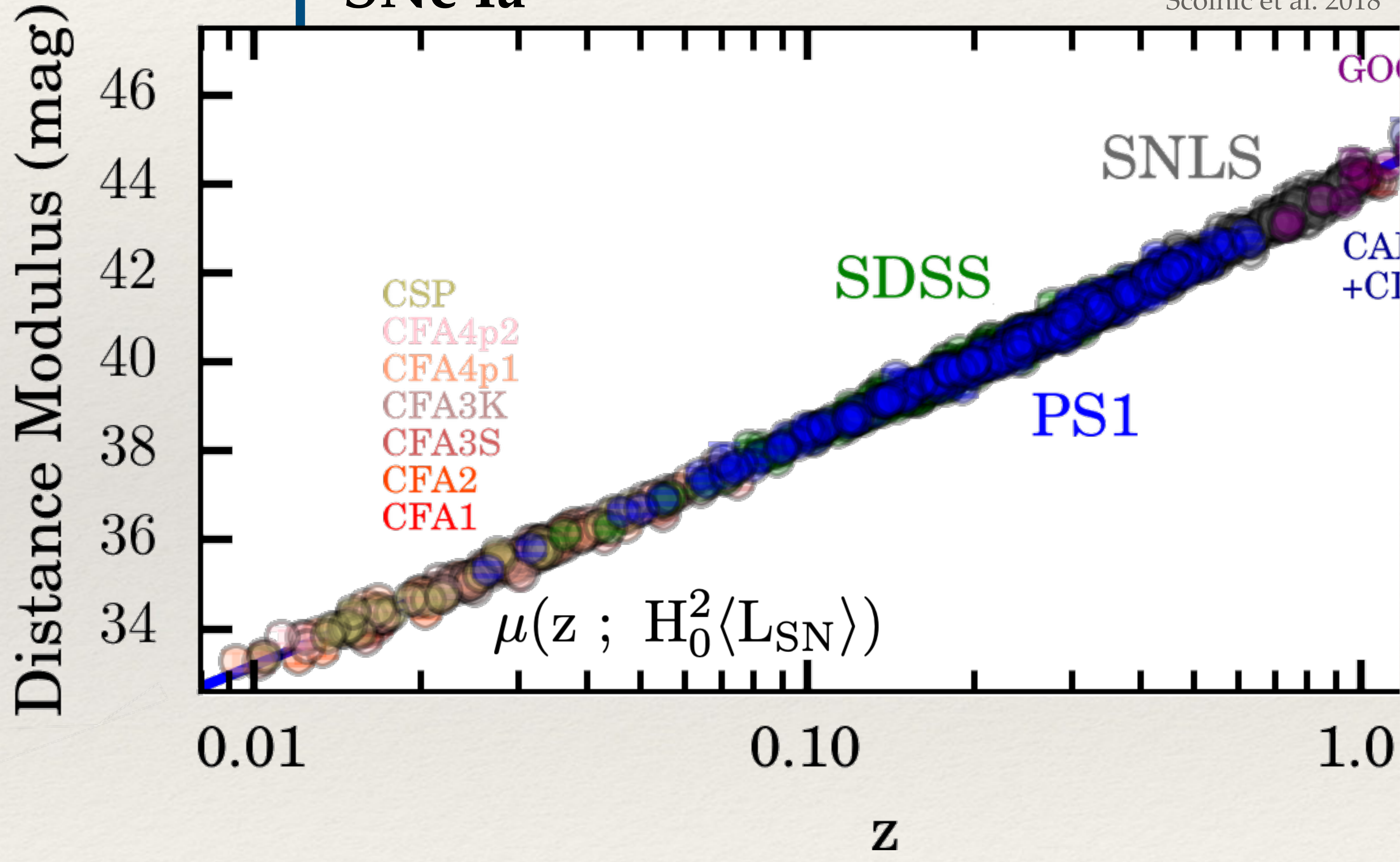
Cepheids



Riess et al. 2009

"SNe Ia"

Scolnic et al. 2018



SH0ES

Geometrical Distances

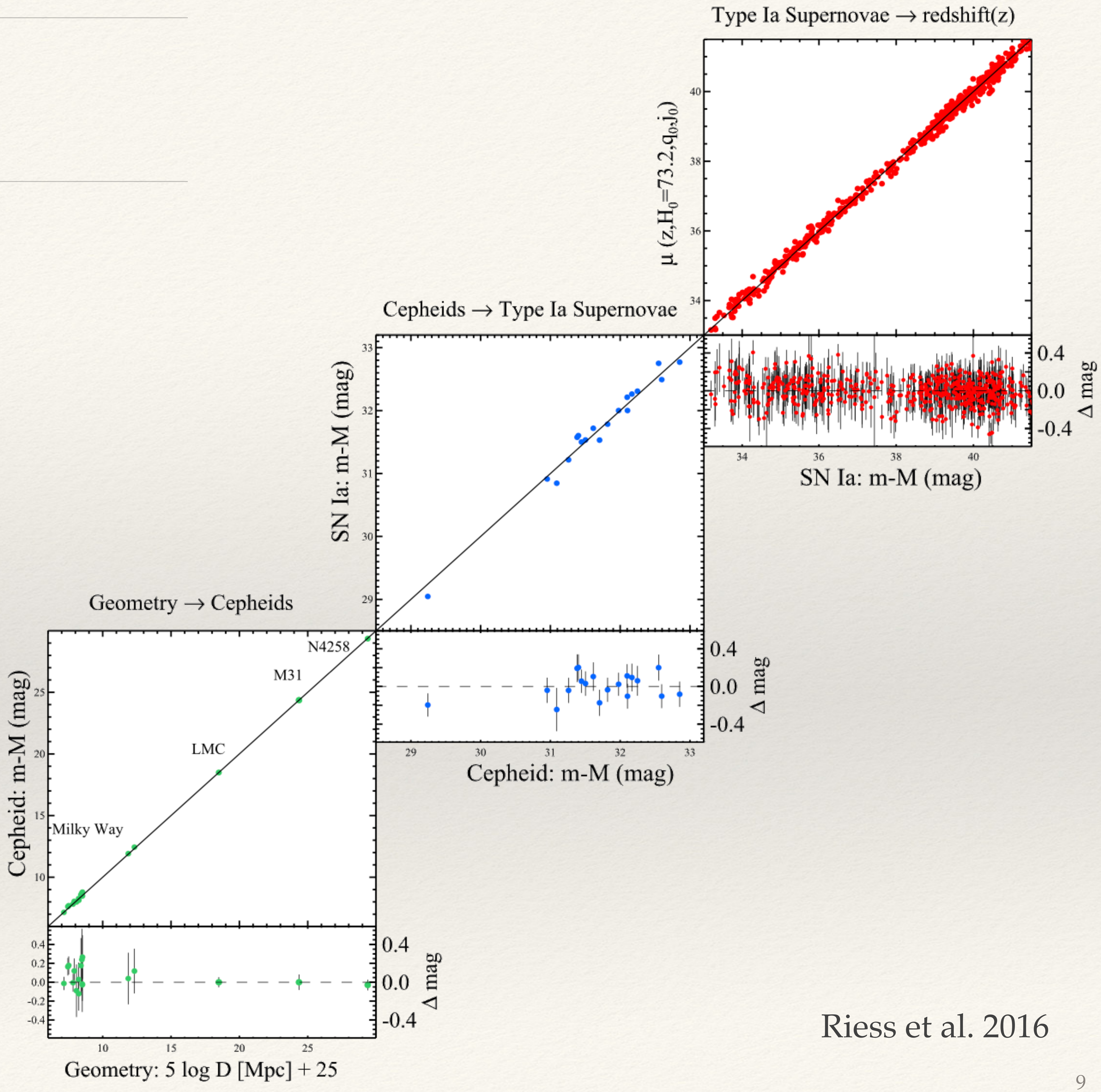
Cepheids

Type Ia Supernovae

10 Mpc

100 Mpc

1 Gpc



Riess et al. 2016

SH0ES

Geometrical Distances

10 Mpc

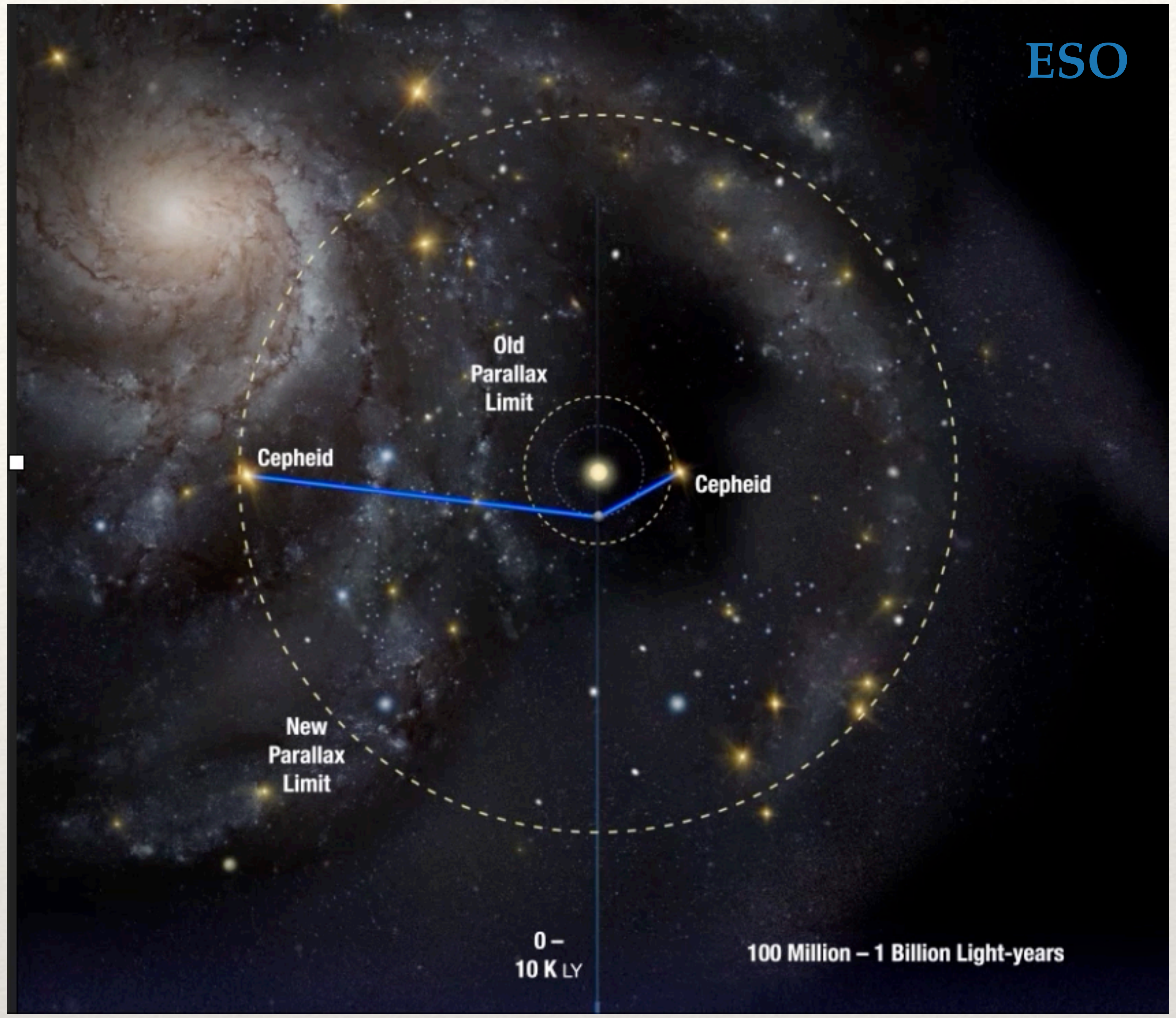
Cepheids

100 Mpc

Type Ia Supernovae

1 Gpc

Parallaxes *(Milky Way)*



Detached Eclipsing Binaries
(LMC & M31)

Mega Maser *(NGC4258)*

SH0ES

Geometrical Distances

10 Mpc

Cepheids

100 Mpc

Type Ia Supernovae

1 Gpc

Parallaxes *(Milky Way)*

Detached Eclipsing Binaries
(LMC & M31)

Mega Maser *(NGC4258)*

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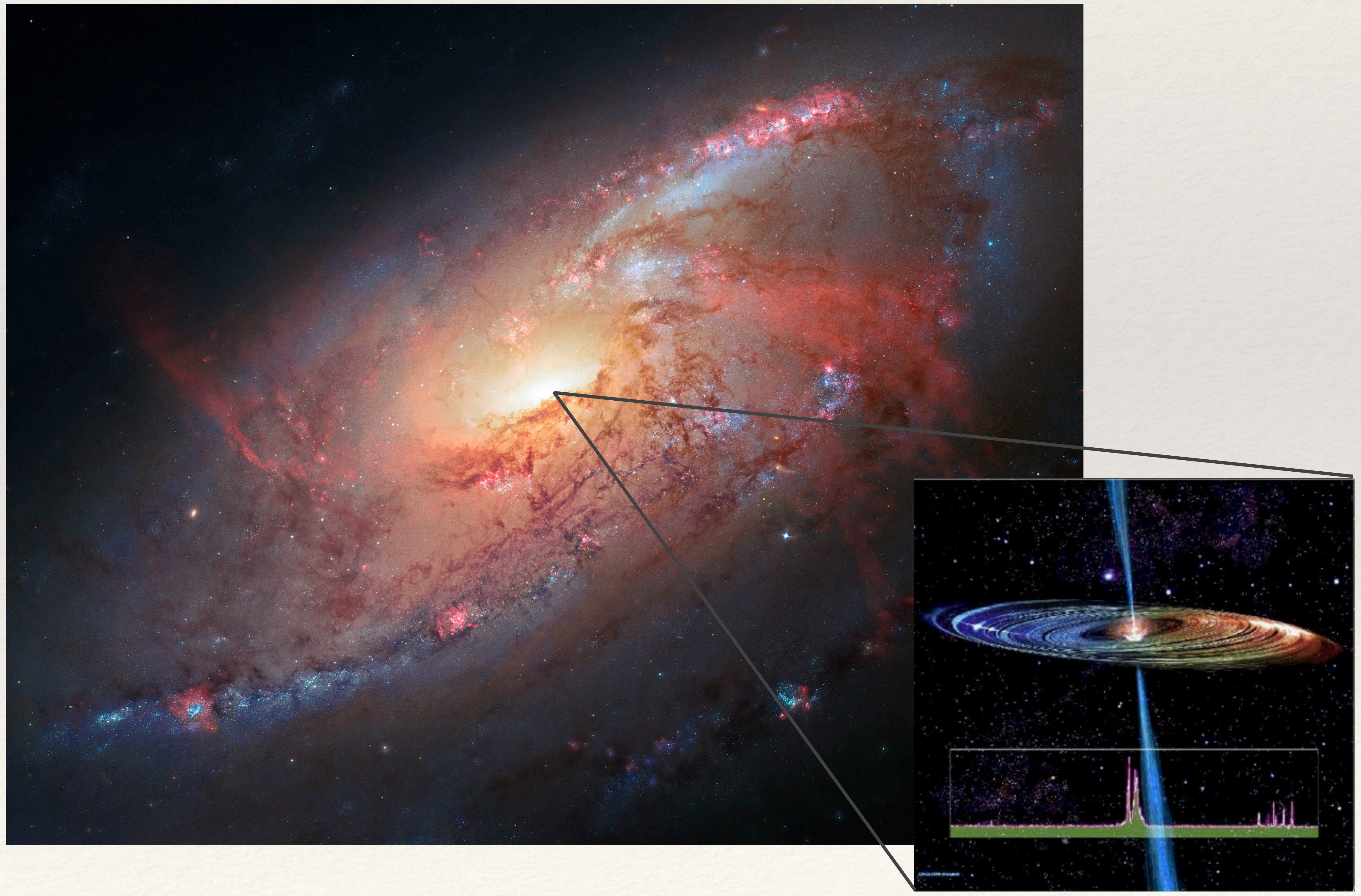
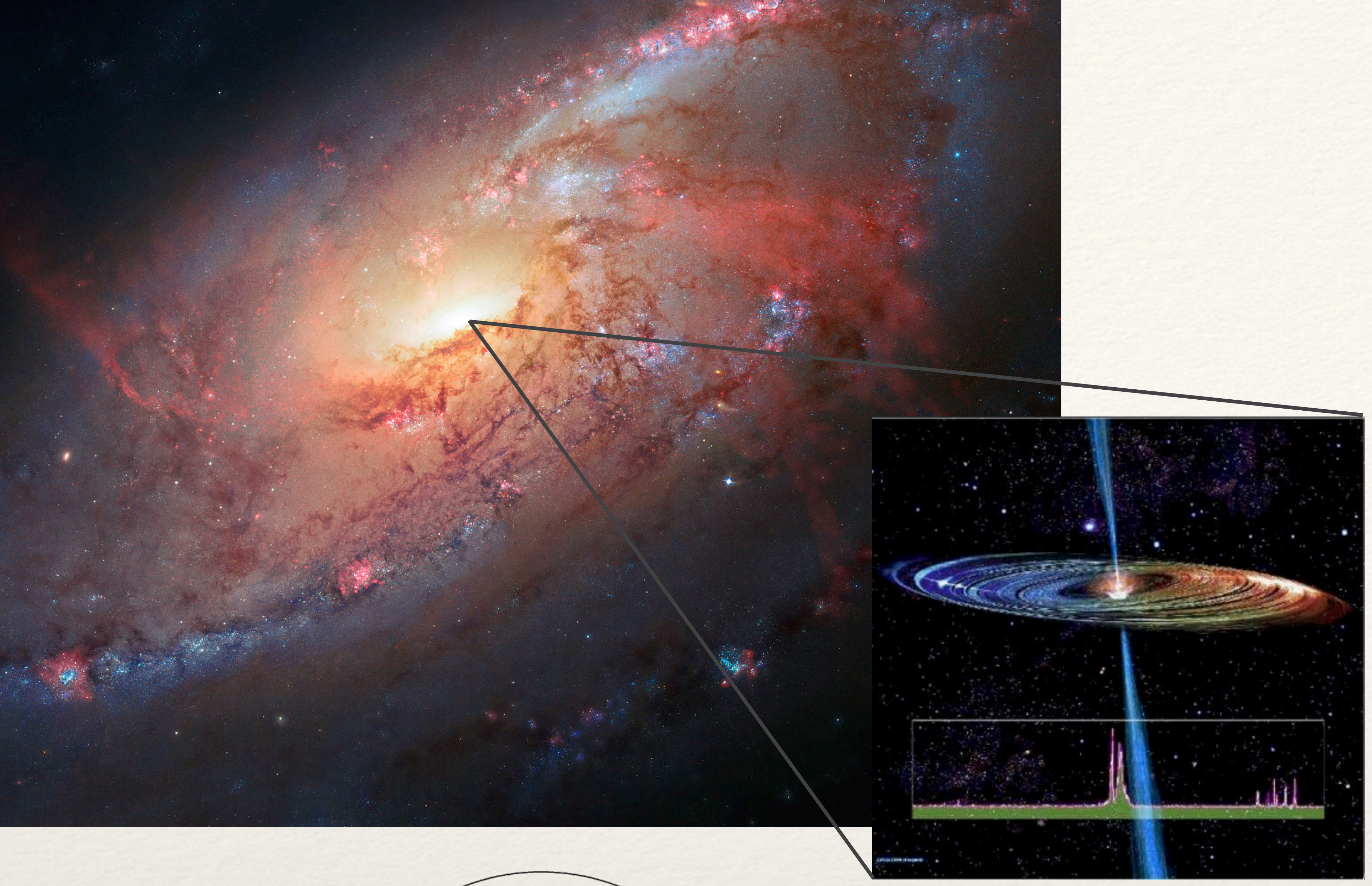
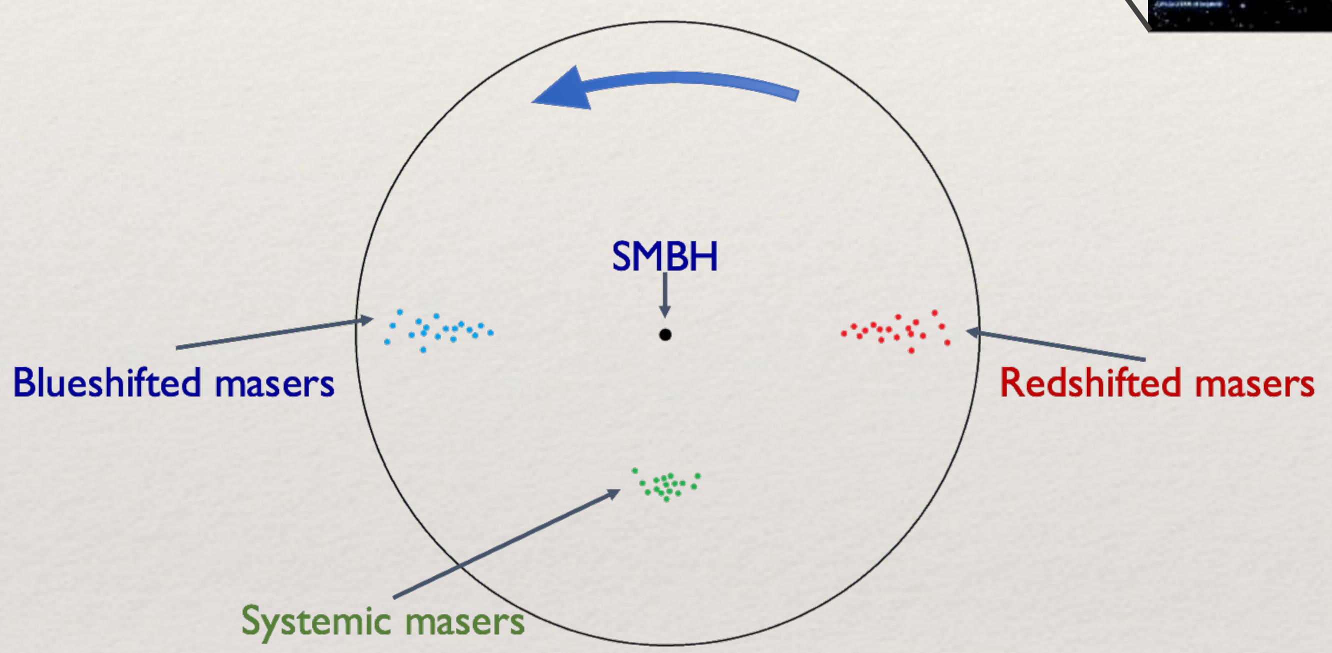
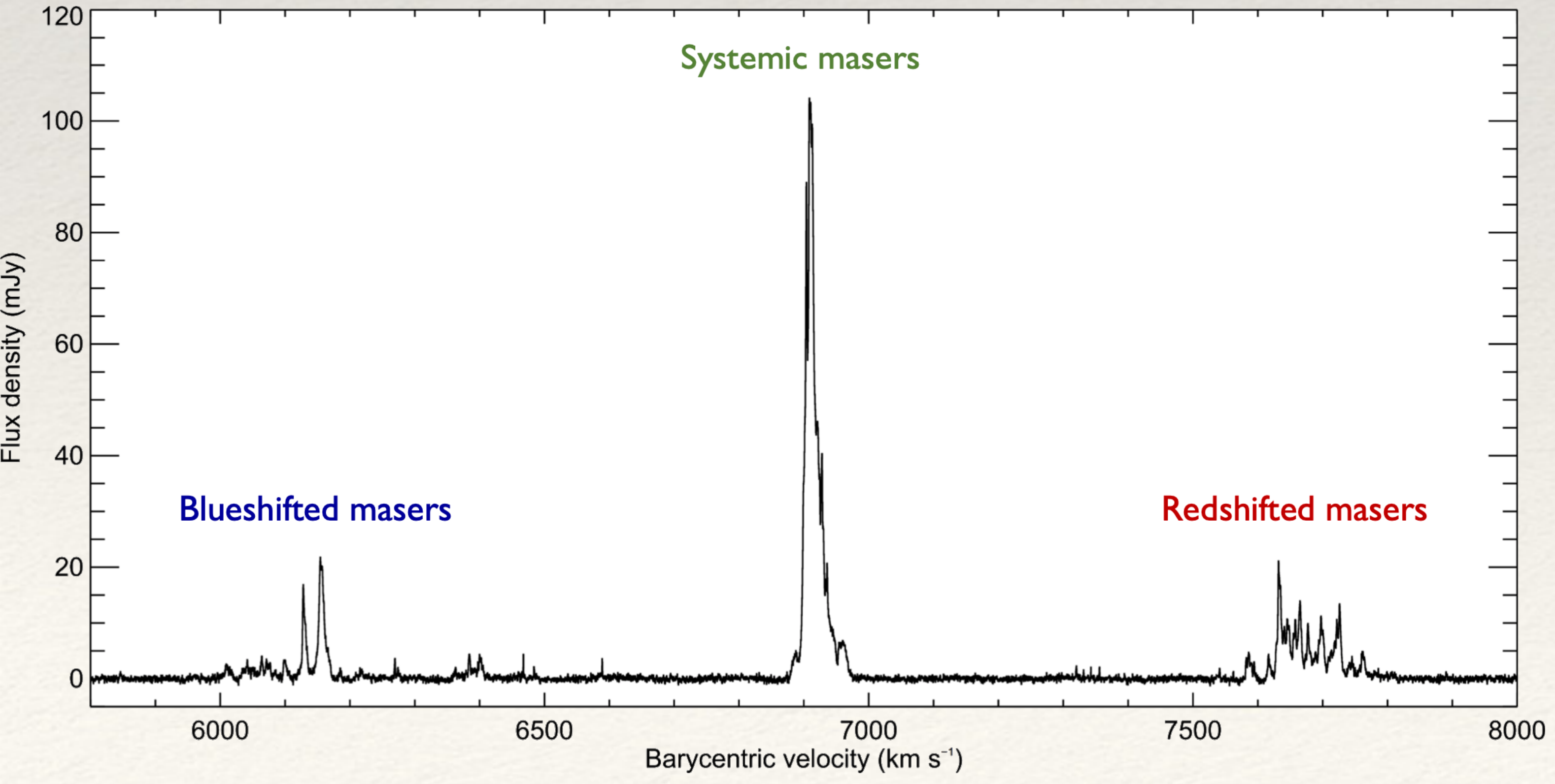


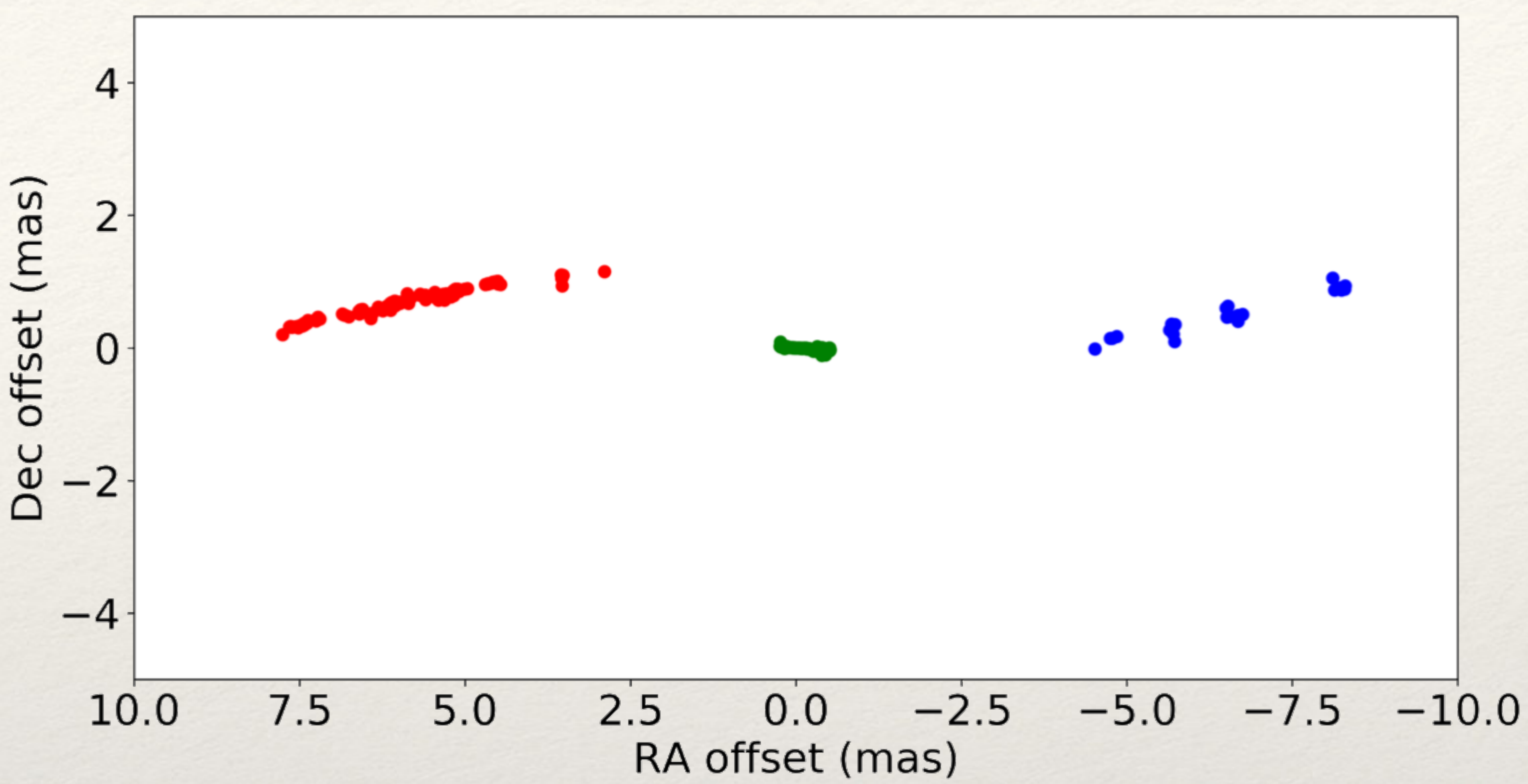
Maser

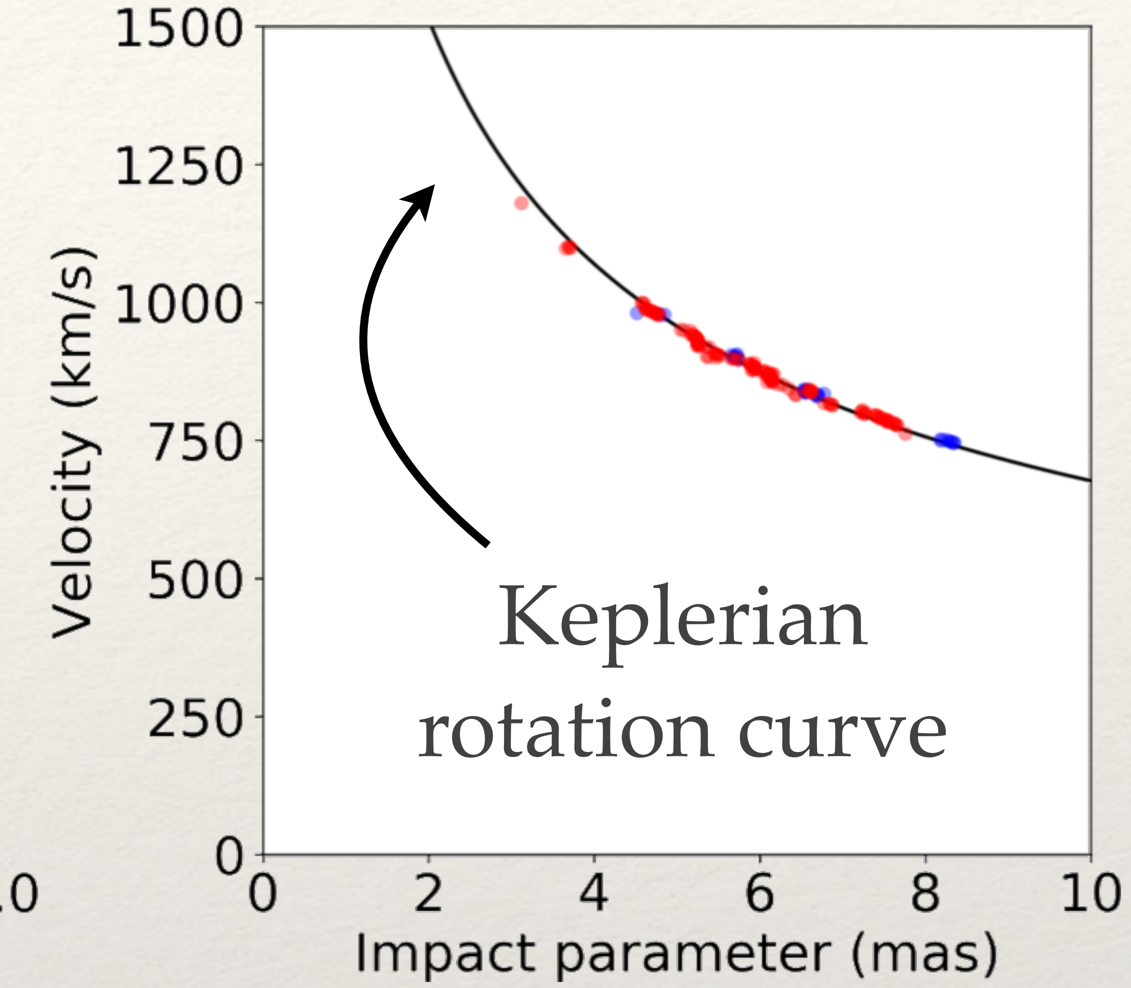
credit: Dom Pesce











Consider a masing cloud on a circular orbit at (angular) radius θ_r around a central SMBH of mass M and situated at an azimuthal angle φ with respect to the line of sight

Observed (on-sky) position: $\theta = \theta_r \sin(\varphi)$

Observed (line-of-sight) velocity: $v = v_r \sin(\varphi)$

Observed (line-of-sight) acceleration: $a = a_r \cos(\varphi)$

$$v_r = \sqrt{\frac{GM}{\theta_r D}} \qquad a_r = \frac{v_r^2}{\theta_r D} = \frac{GM}{\theta_r^2 D^2}$$

○ = measured ○ = fit

SH0ES

10 Mpc

100 Mpc

1 Gpc

Geometrical Distances

Cepheids

Type Ia Supernovae

Parallaxes *(Milky Way)*

Detached Eclipsing Binaries *(LMC & M31)*

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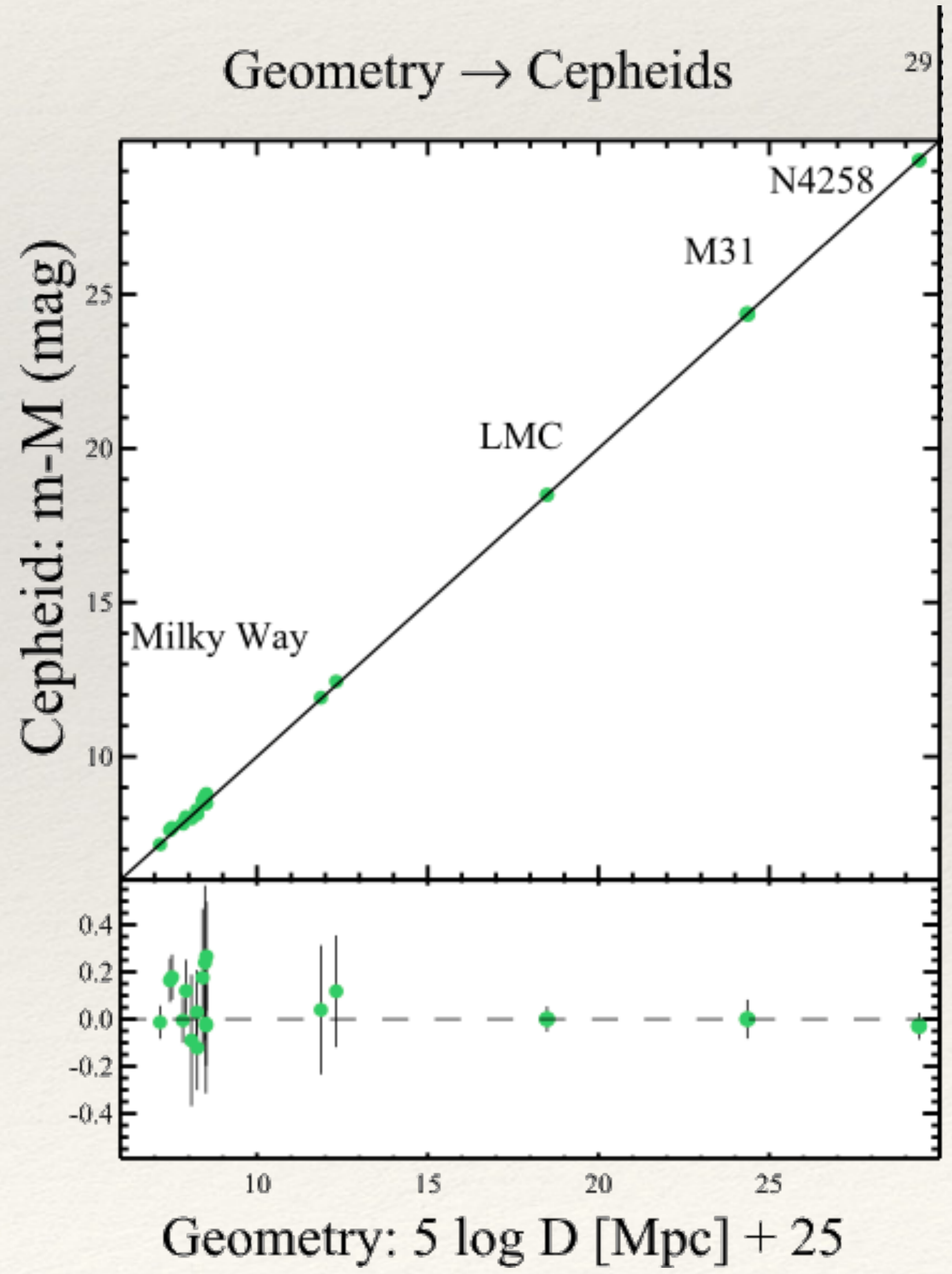


SH0ES

Geometrical Distances

10 Mpc

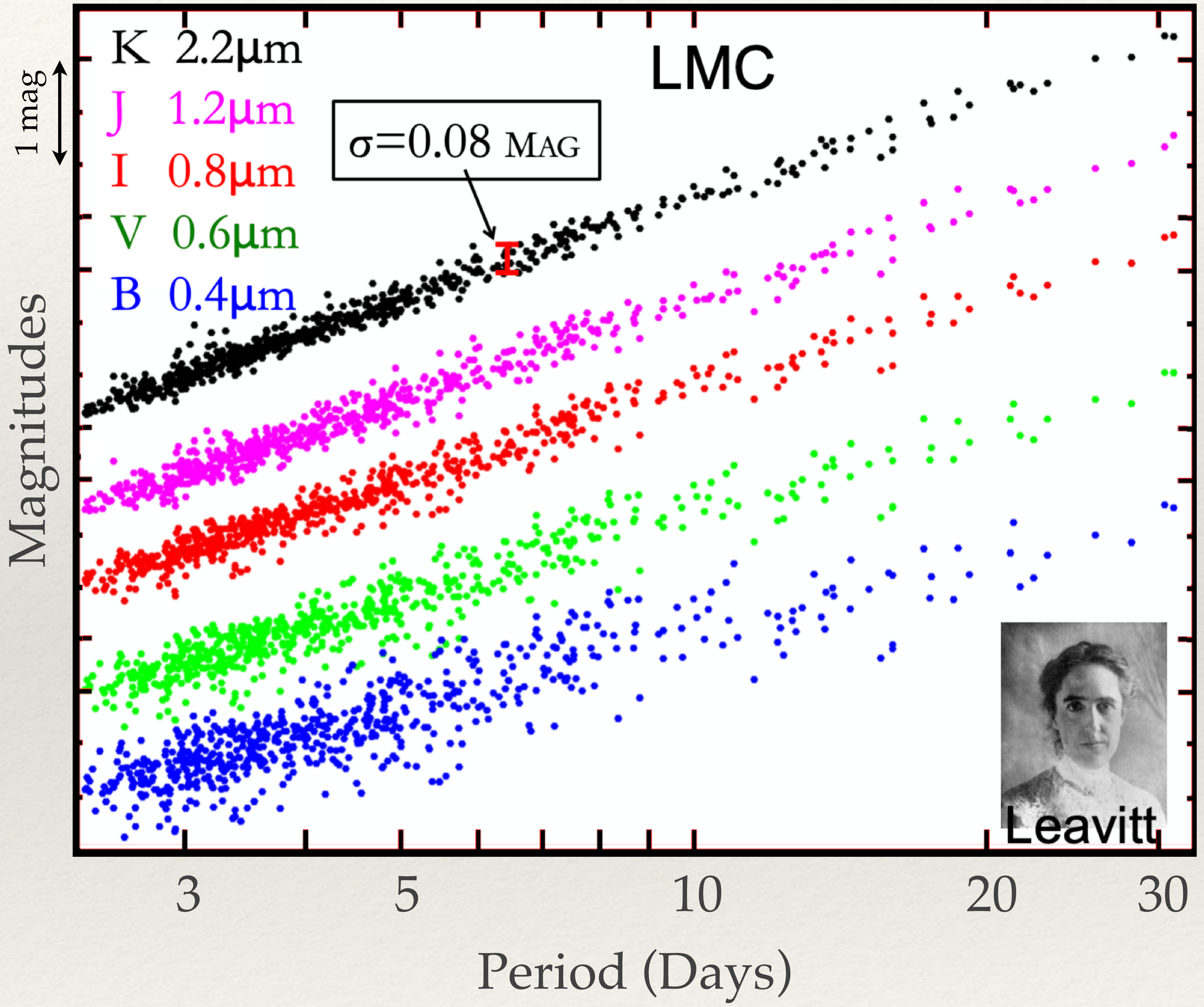
Cepheids

100 Mpc

Type Ia Supernovae

1 Gpc

Macri et al. 2015 | *SH0ES collaboration*



SH0ES

10 Mpc

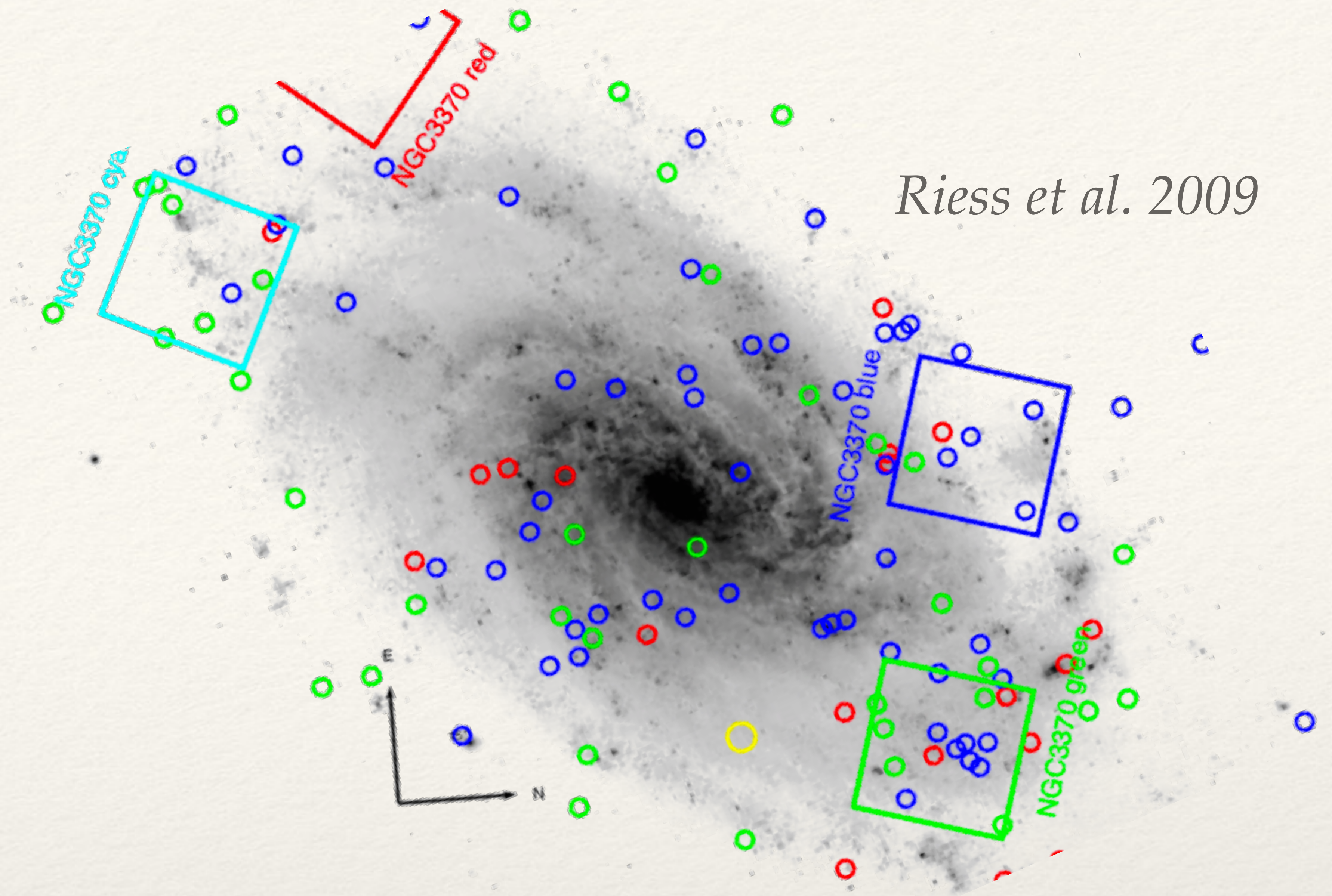
100 Mpc

1 Gpc

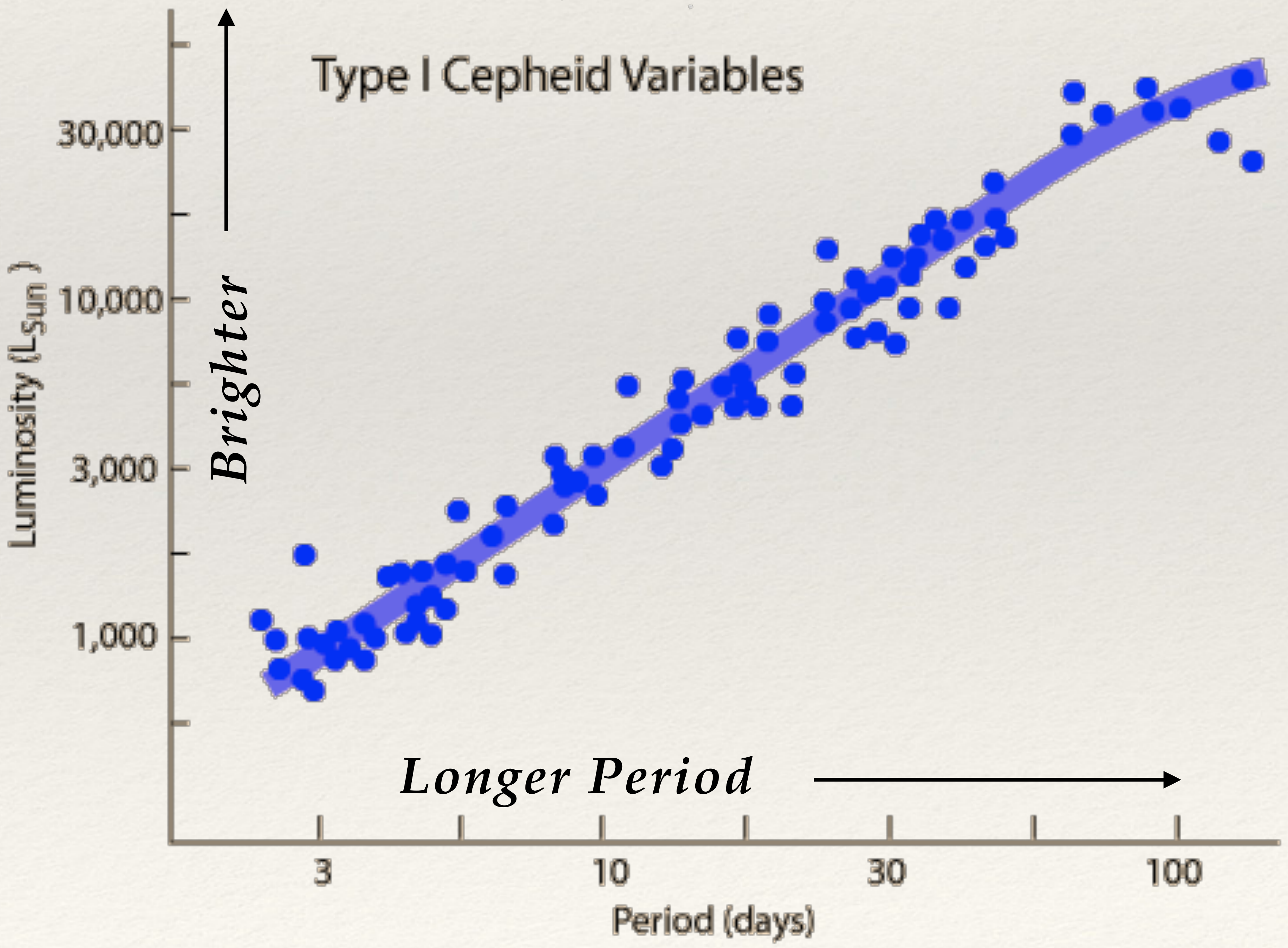
Geometrical Distances

Cepheids

Type Ia Supernovae



Riess et al. 2009



SH0ES

Geometrical Distances

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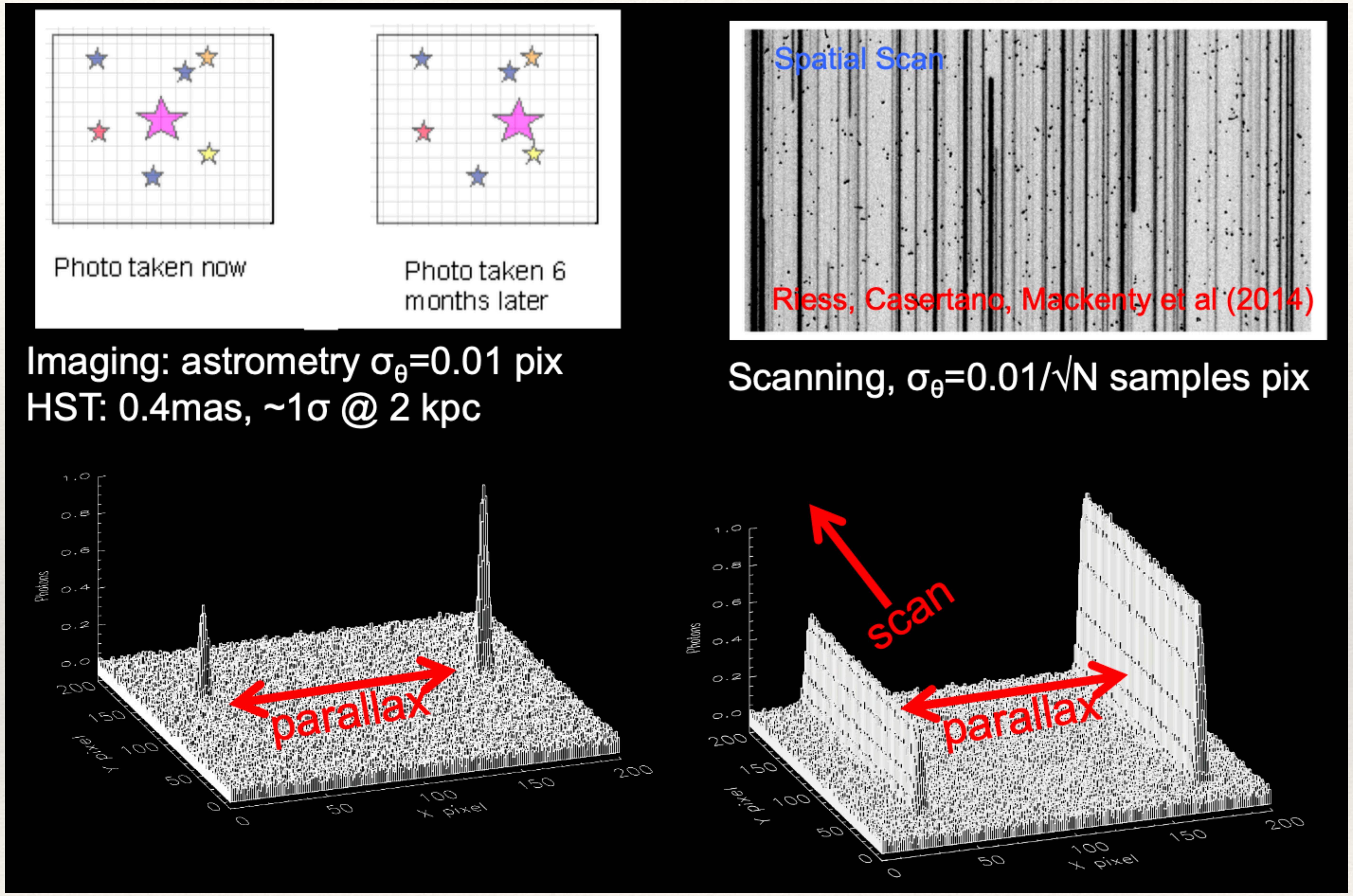
Cepheids

100 Mpc

Type Ia Supernovae

1 Gpc

SH0ES collaboration



SH0ES

10 Mpc

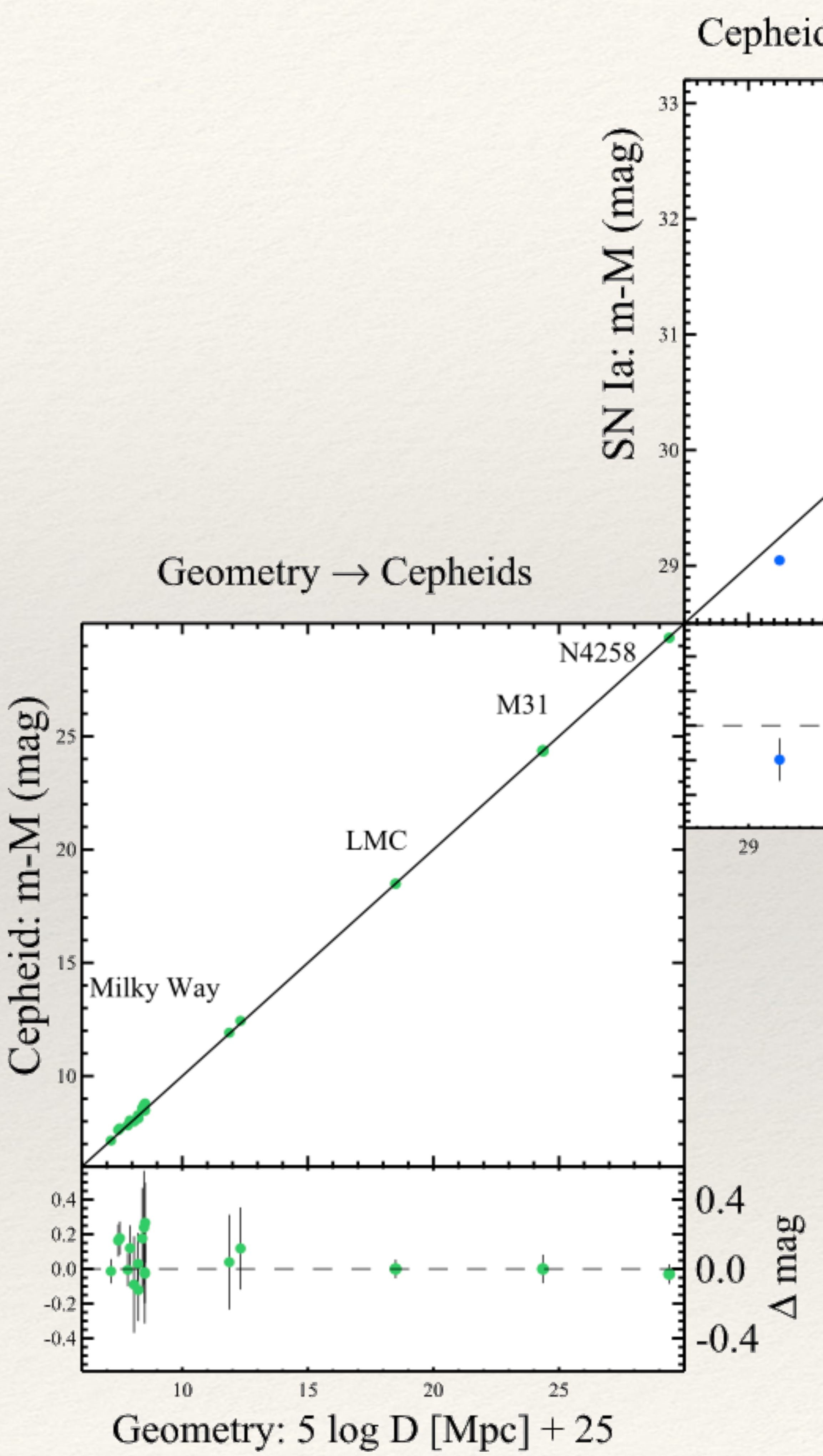
100 Mpc

1 Gpc

Geometrical Distances

Cepheids

Type Ia Supernovae



SH0ES

cf. **Supernova Cosmology Class**

10 Mpc

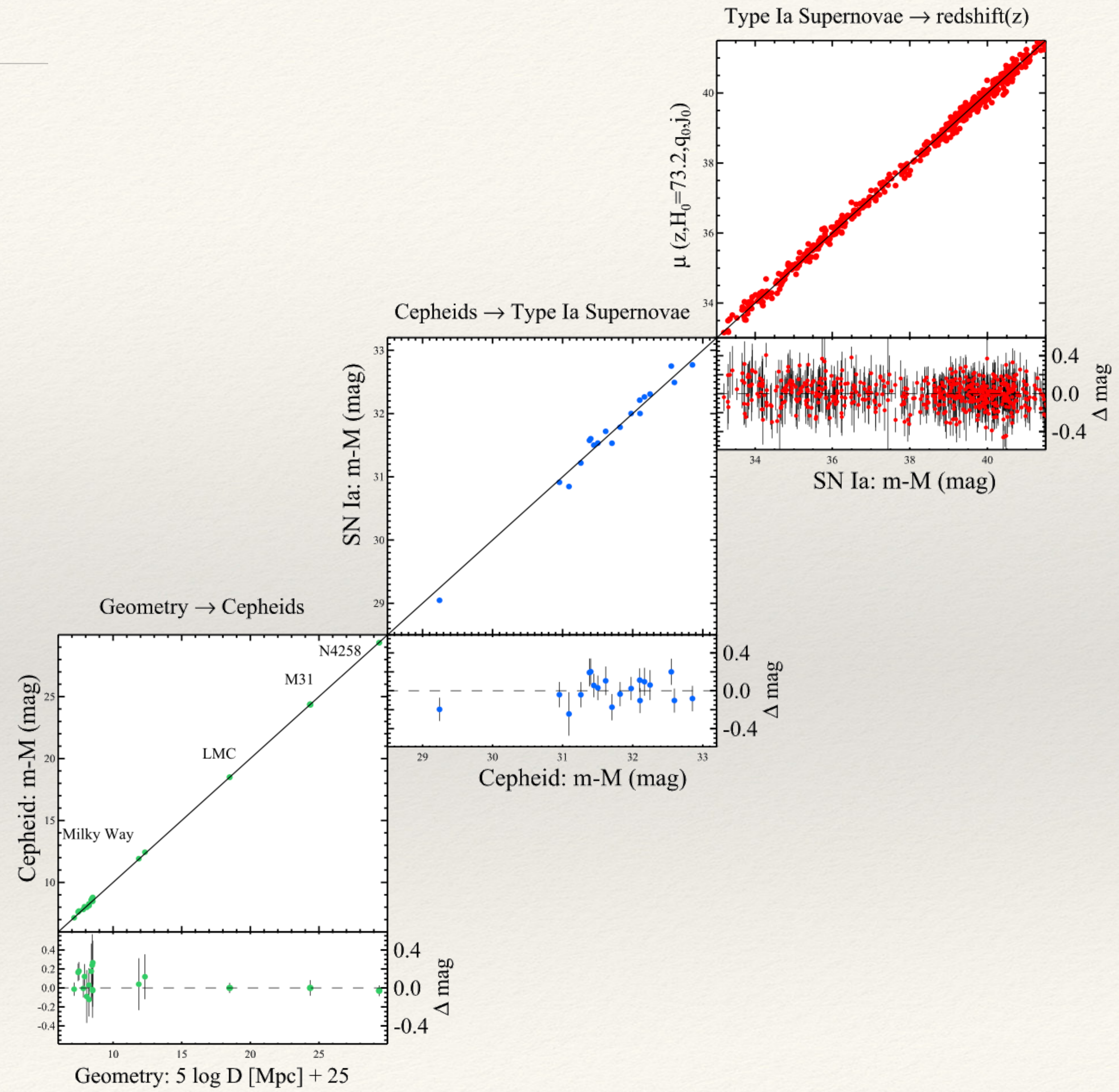
Geometrical Distances

Cepheids

100 Mpc

Type Ia Supernovae

1 Gpc



Direct Distance Ladder | *SH0ES*

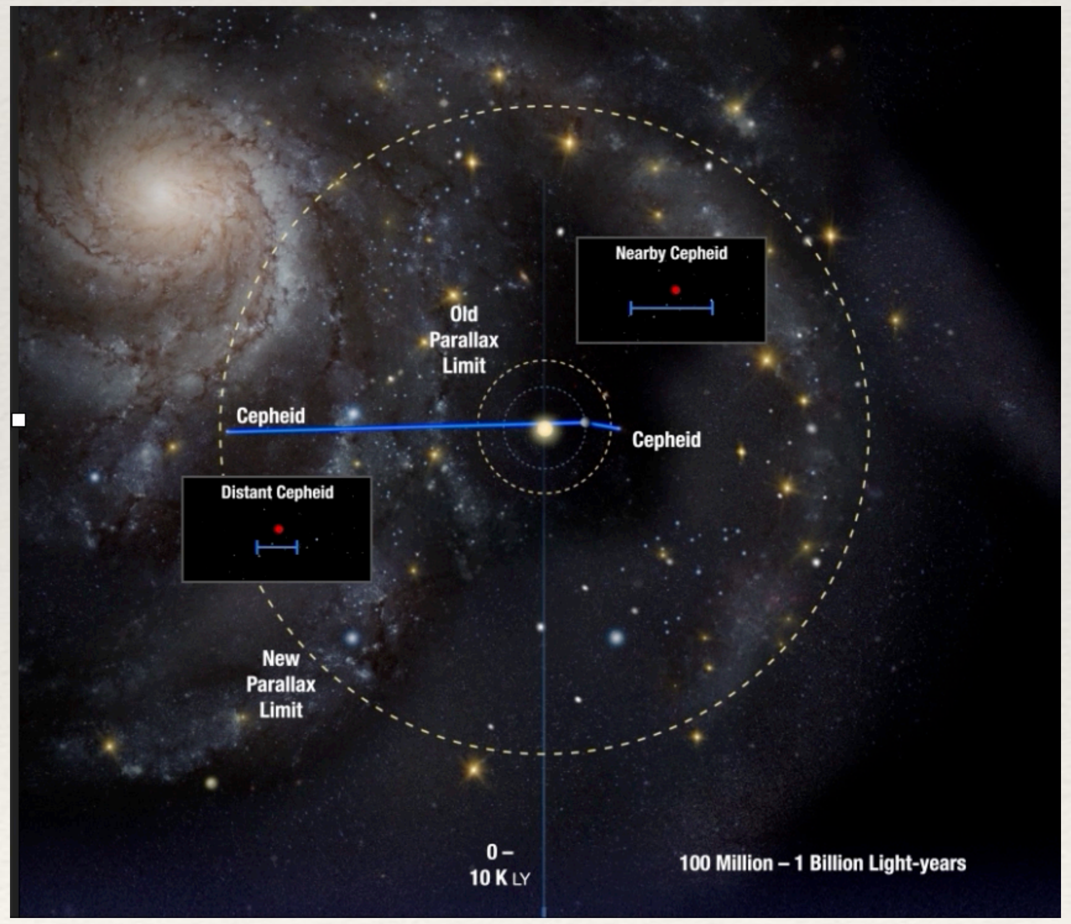
Get independent distances for SNe Ia

Calibrate the "Period-Luminosity" relation — *Measure "L_{SN}"* — *Get "H_0"* → **distance**

"Geometry"

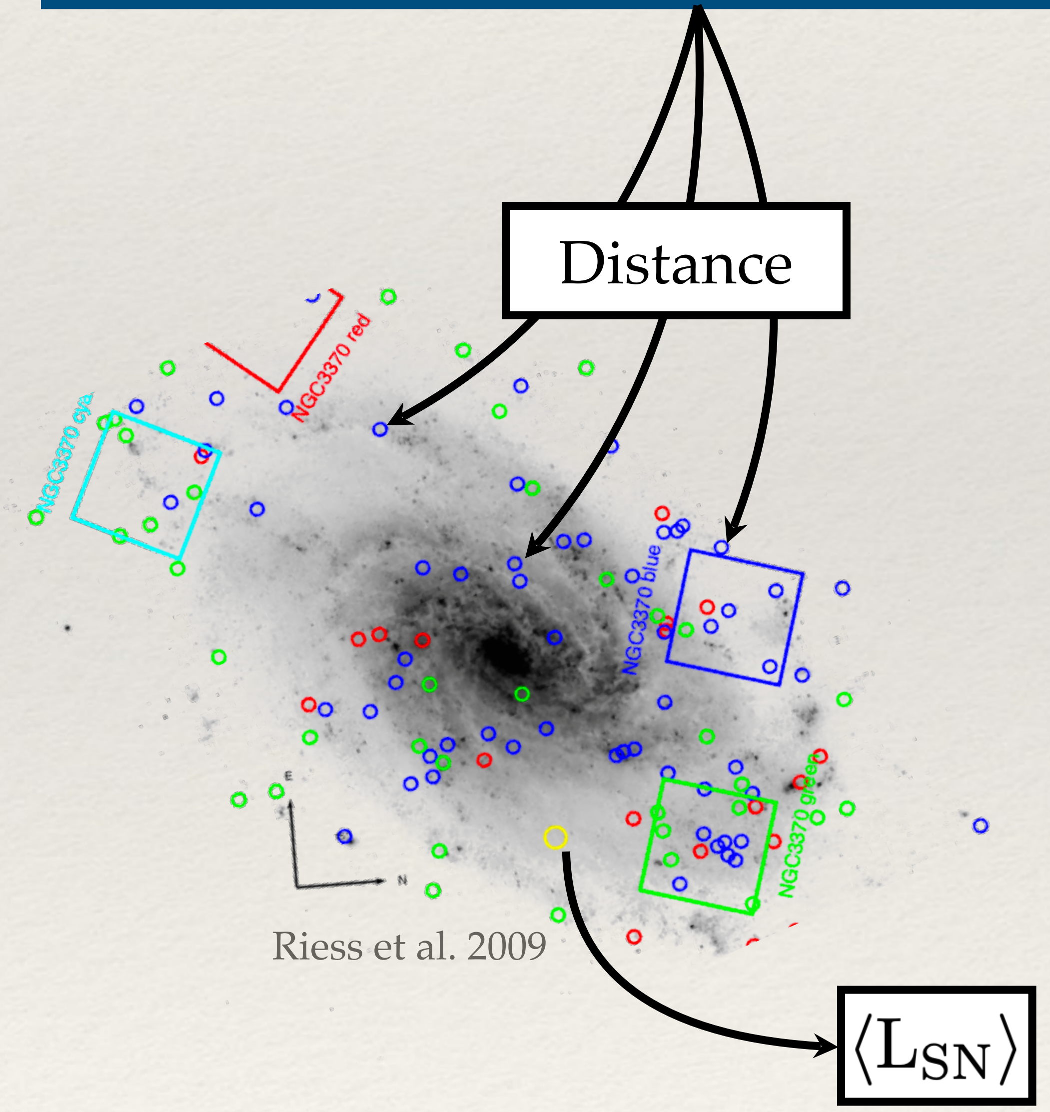
Parallaxes | D.E.B. | Maser

Source: eso



"Calibrators"

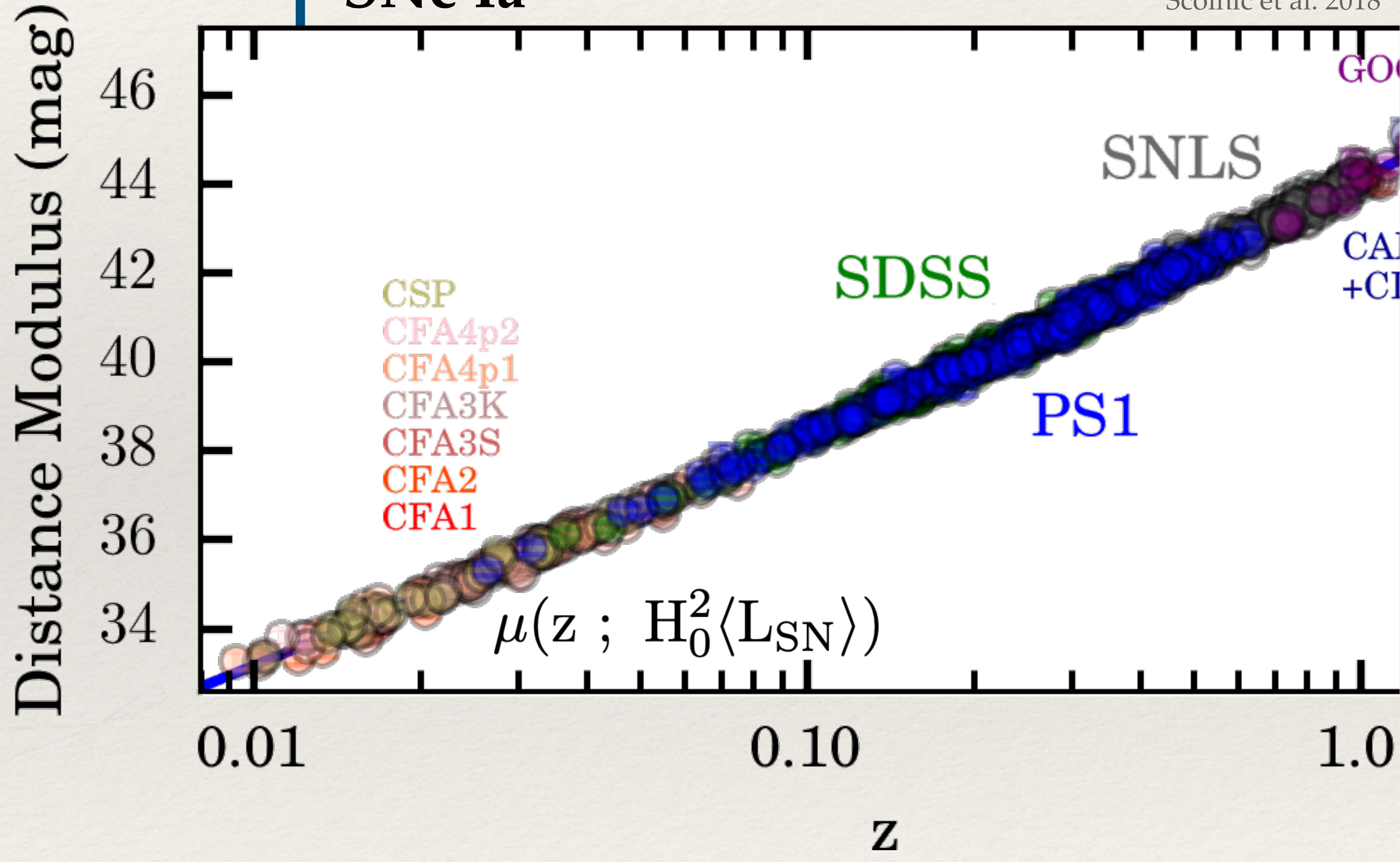
Cepheids



Riess et al. 2009

"SNe Ia"

Scolnic et al. 2018



Riess et al. *2022*

***H_0* = 73.0 ± 1.0 km s^{-1} Mpc^{-1}**

Modern Cosmology | *H_0 Direct vs. Indirect Measurements*

$H_0 = d_l / v_h$

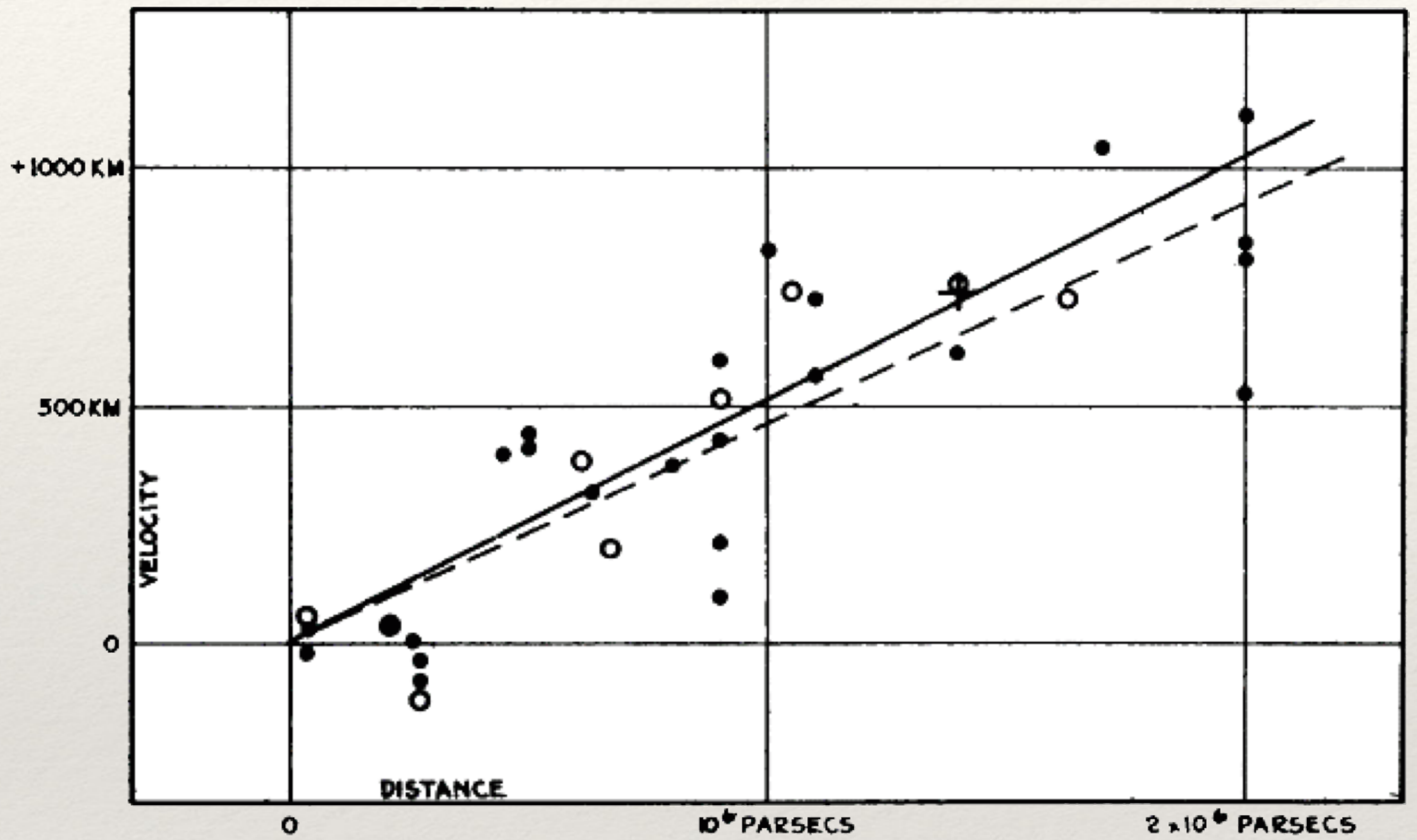
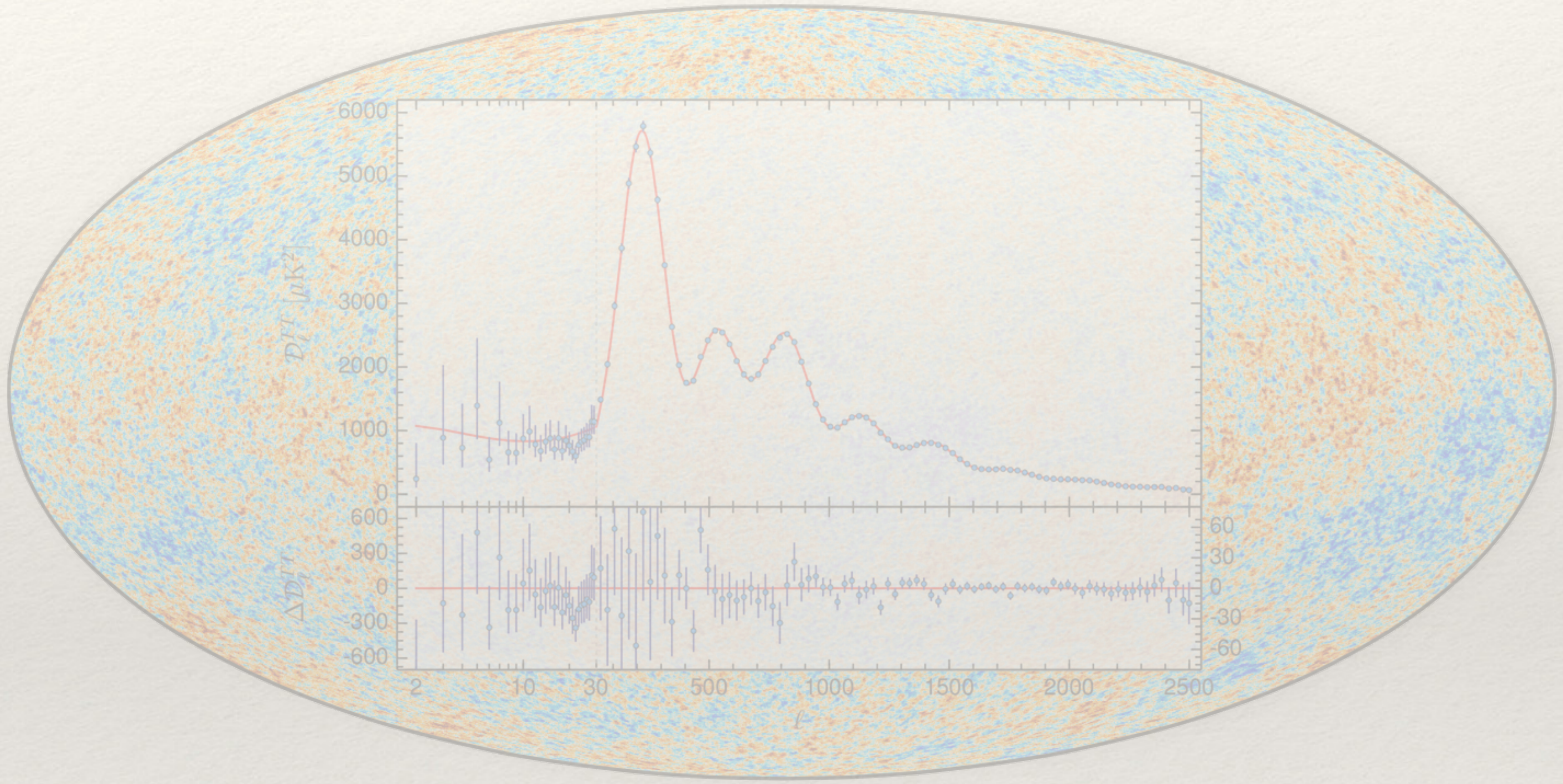


FIGURE 1

Geometry → Cepheids → SNe Ia

$H_0 = 73.0 \pm 1.0$ km s^{-1} Mpc^{-1}

$H(z) = H_0 \times \sqrt{\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_\Lambda (1+z)^{3(1+w)}}$



Model dependent

Planck 2020

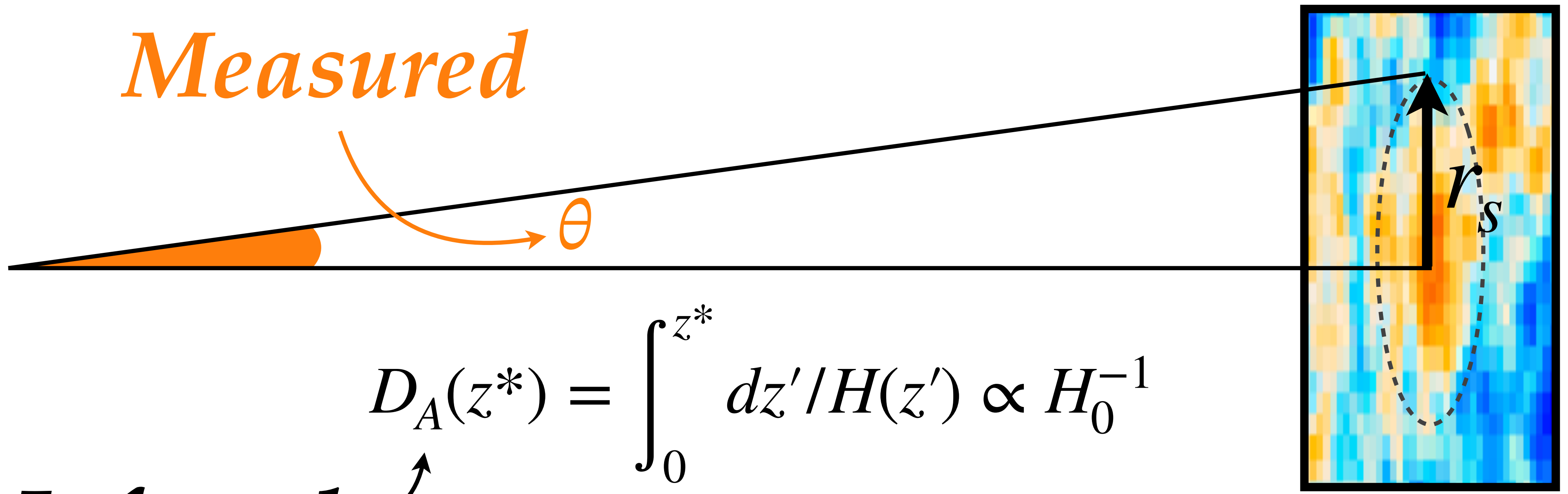
Intensity
Model
Data
6000
5000
4000
3000
2000
1000
0
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
l
Angular Size

Planck 2020

Deriving H_0

$$H(z) = H_0 \times \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}$$

H_0 from CMB



$$D_A(z^*) = \int_0^{z^*} dz'/H(z') \propto H_0^{-1}$$

Inferred

r_s « *the sound horizon* »

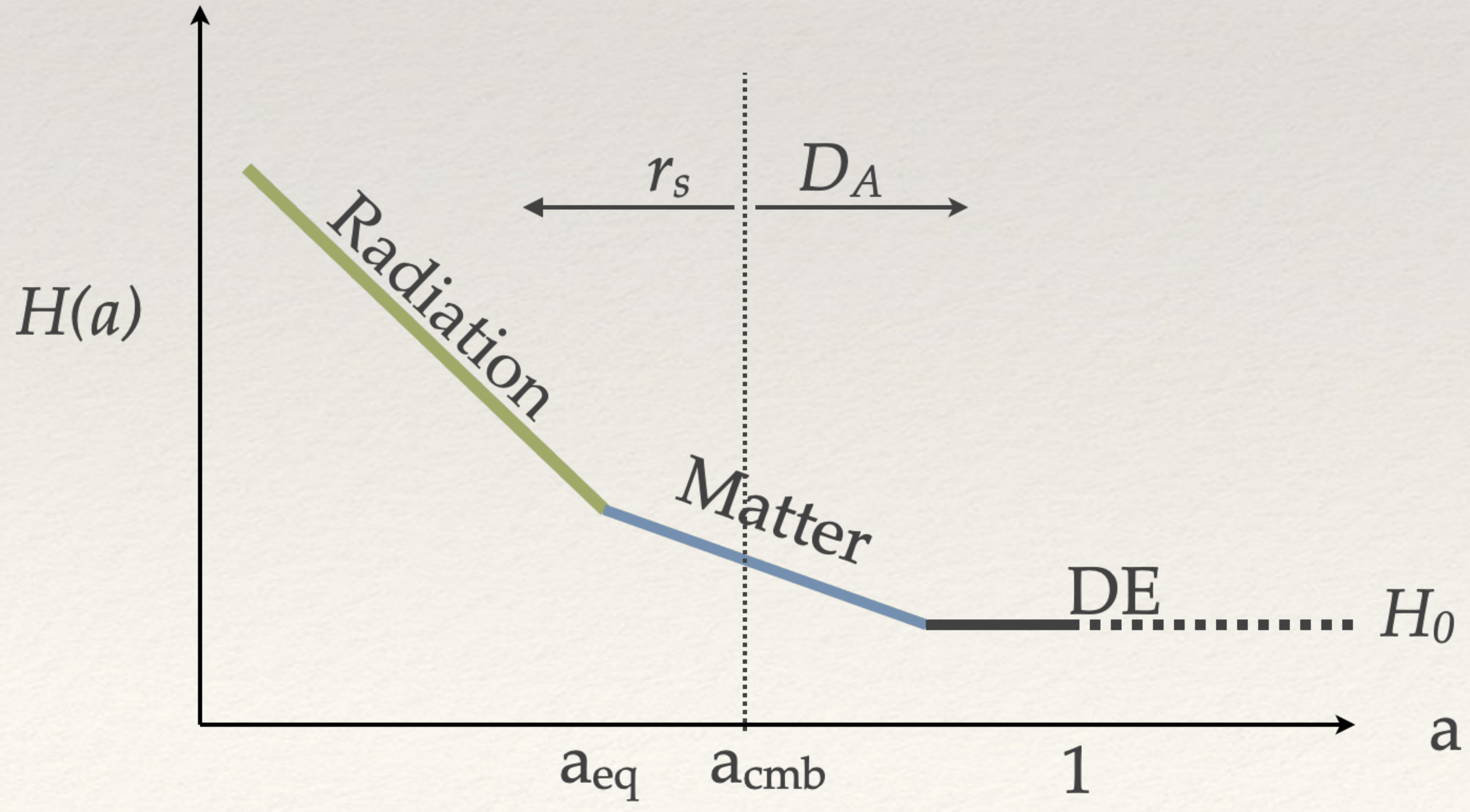
Calculated

$$r_s = \int_{z_s}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Radiation driven

$$H^2(z) = \frac{8\pi G}{3}\left(\rho_\gamma + \rho_\nu + \rho_m\right)$$

r_s from baryon and matter density (radiation) • θ from observation • H(z) from $D_A = r_s/\theta$



We can think of the estimation of H_0 from CMB data as proceeding in three steps:

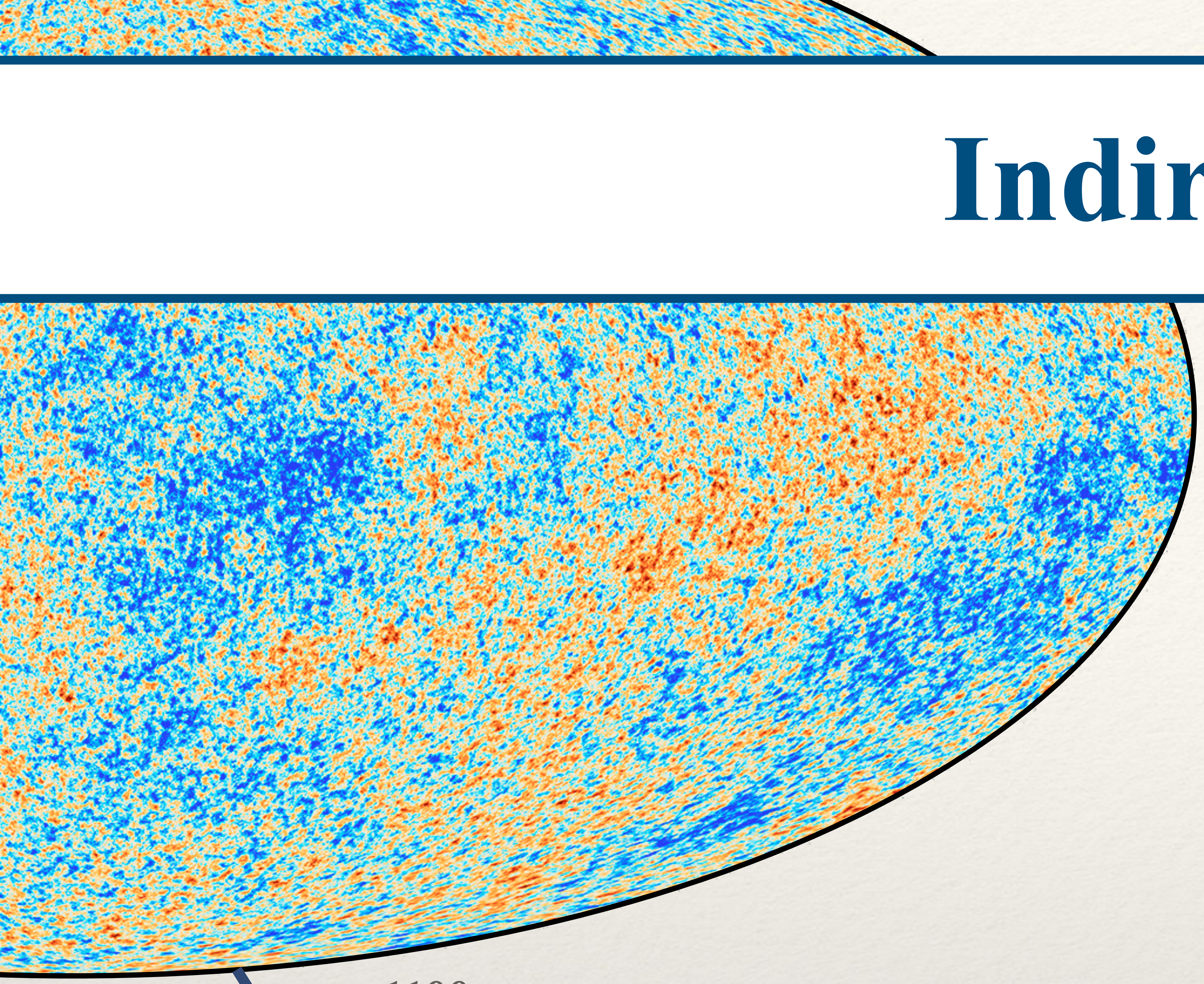
1) determine the baryon density and matter density to allow for calculation of r_s ,
2) infer θ_s from the spacing between the acoustic peaks to determine the comoving angular diameter distance to last scattering $D_A = r_s / \theta_s$,
3) adjust the only remaining free density parameter in the model so that D_A gives this inferred distance.

With this last step complete we now have H(z) determined for all z, including z = 0.

— Hubble Hunter's Guide *L. Knox & M. Millea 2019*

Indirect determination of H_0

Planck et al. 2020



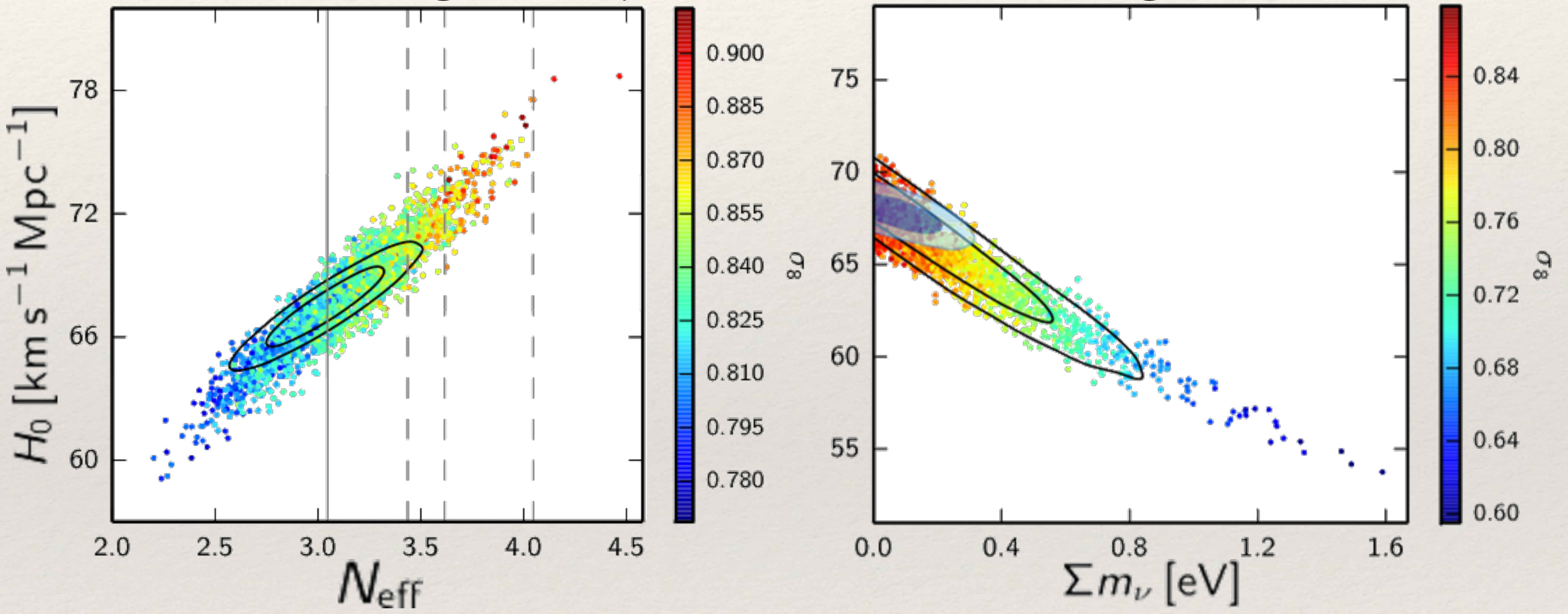
z~1100

THE MODEL CONTRAINS H_0

z~0

Test the concordance model ΛCDM

Change the parameters, change H_0

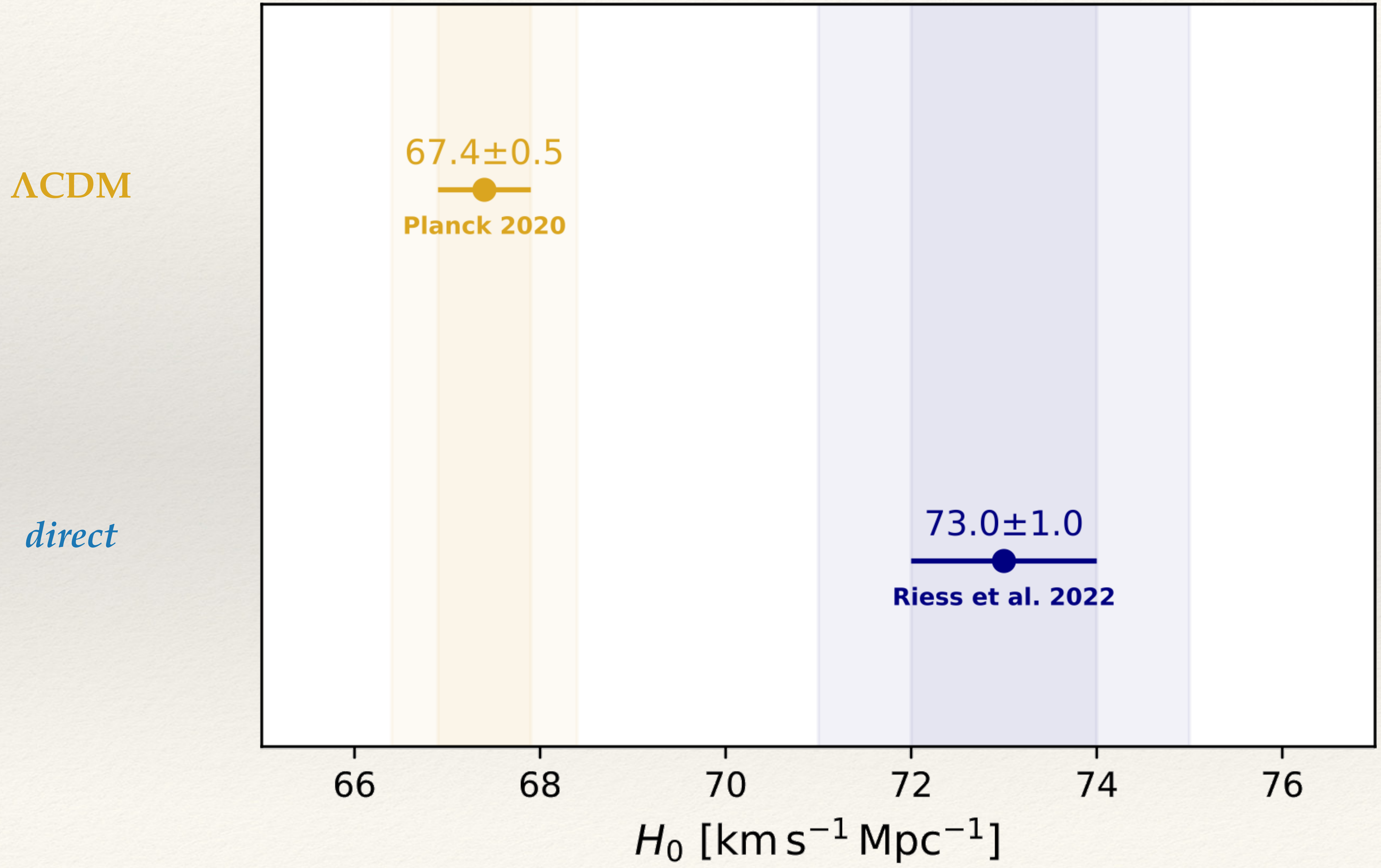


Illustrative plots from Planck 2015

$$H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

— based on ΛCDM —

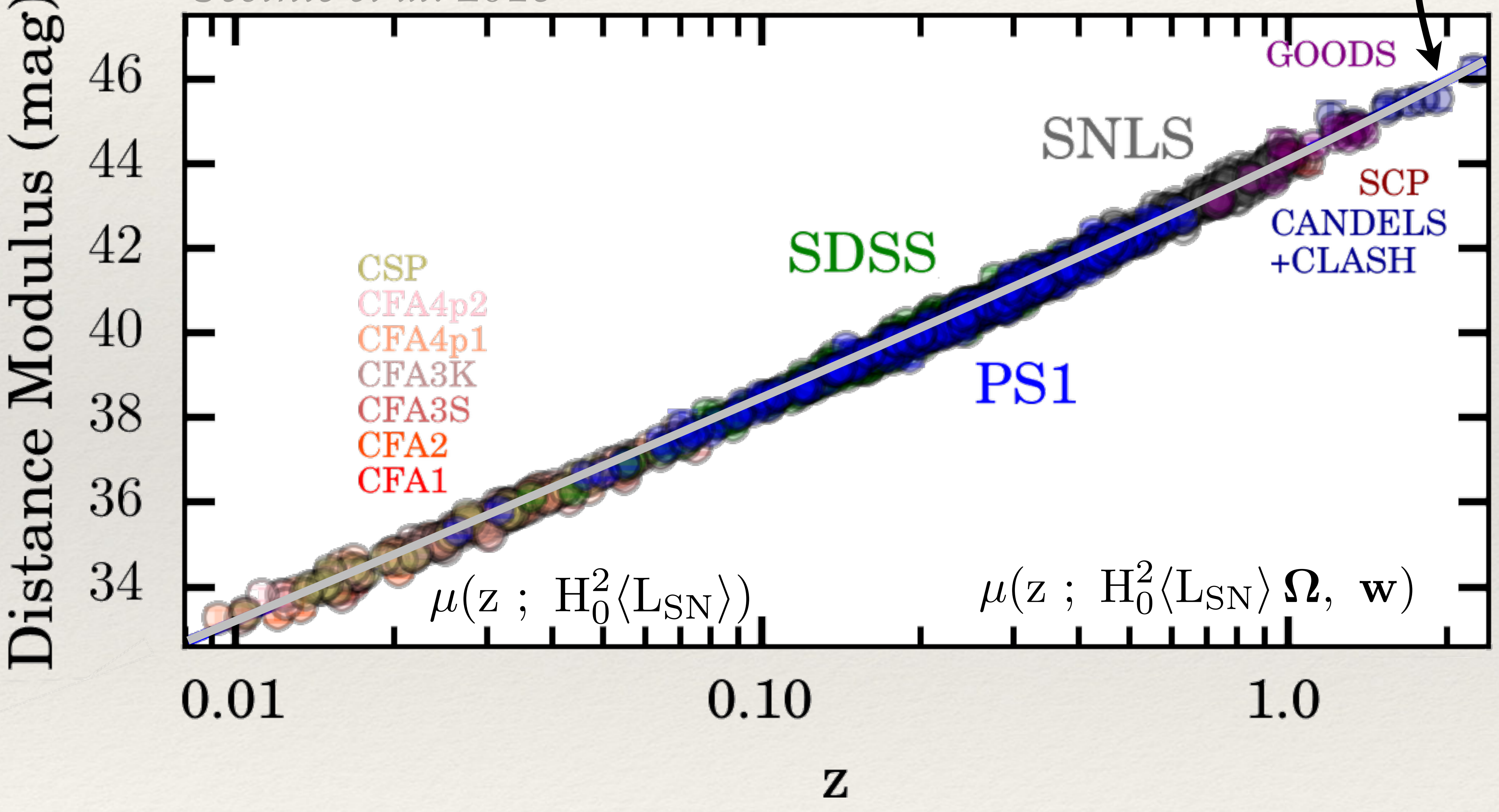
H_0 Tension | *SH0ES vs. Planck*



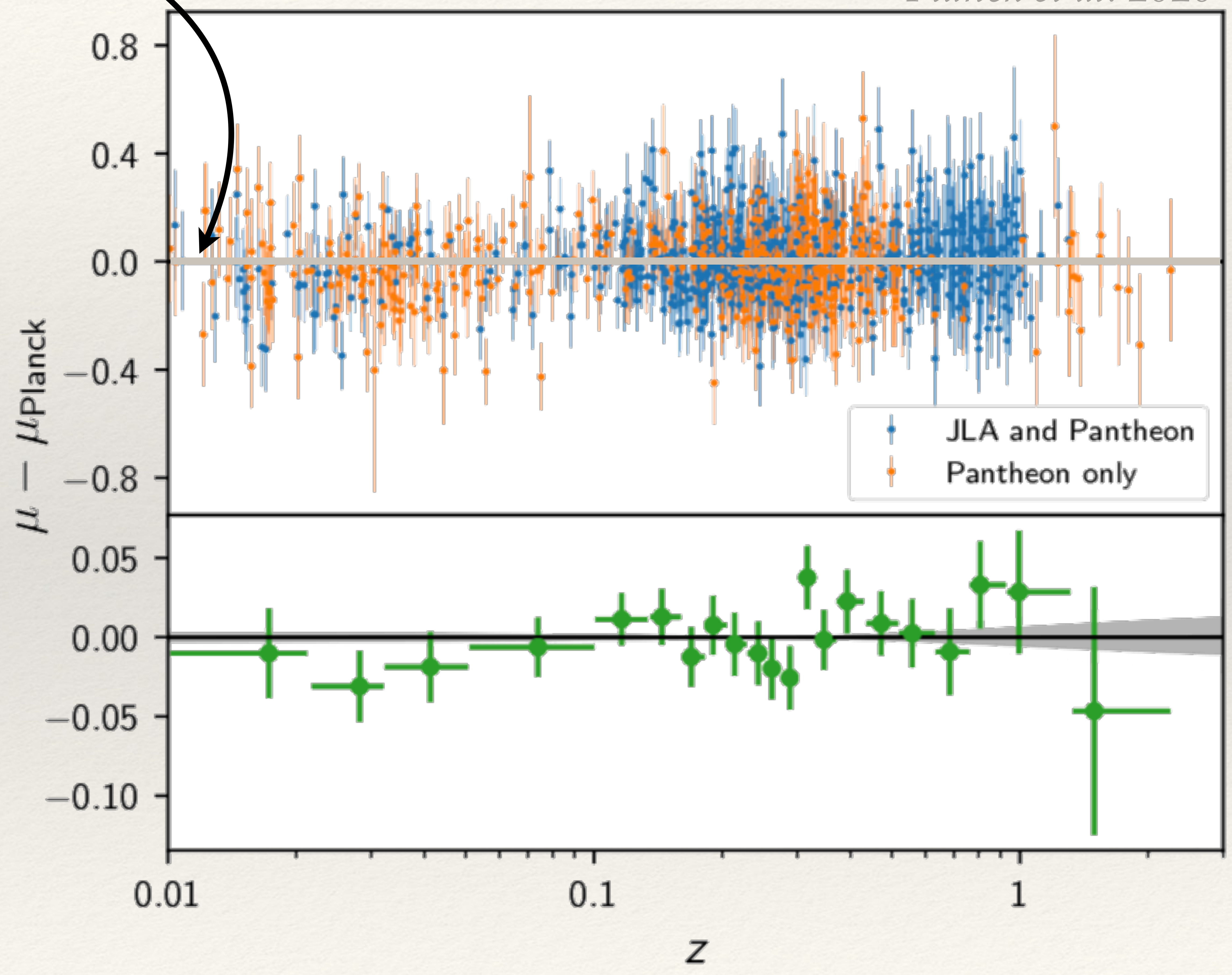
Are Supernovae & CMB in tension ? *No!*

H(z) from Planck

Scolnic et al. 2018



Planck et al. 2020



Inverse Distance Ladder

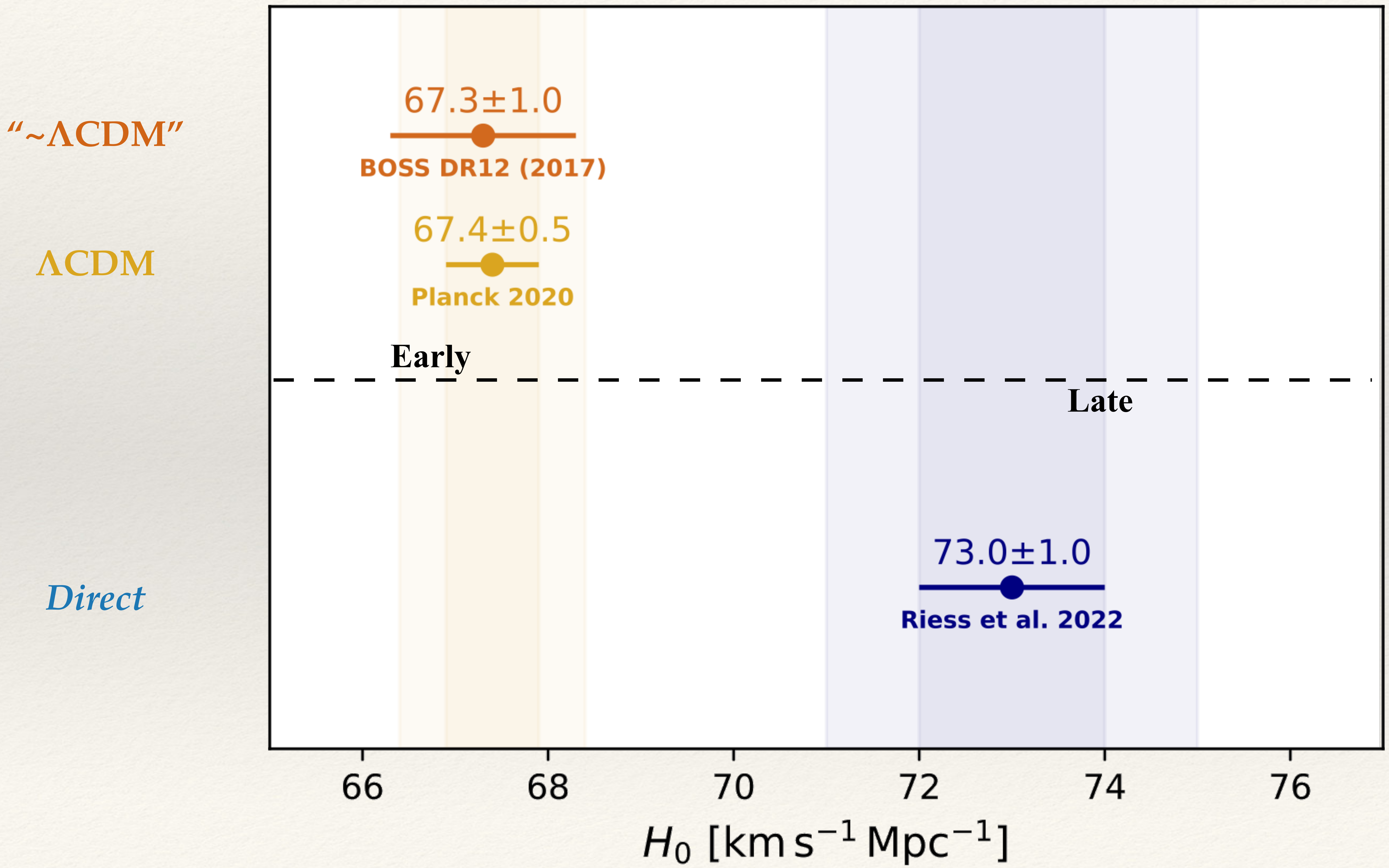
See also e.g.:
Aubourg et al. 2015 • *Macaulay et al. 2018*

Get independent distances for SNe Ia

BOSS DR12 | Alam et al. *2017*

$H_0 = 67.3 \pm 1.0$ km s^{-1} Mpc^{-1}

H_0 Tension | *Early vs. Late physics*



Time Delay Cosmology

$$t(\theta, \beta) = \frac{(1+z_d)}{c}\frac{D_d D_s}{D_{ds}}\left[\frac{(\theta-\beta)^2}{2} - \psi(\theta)\right]$$

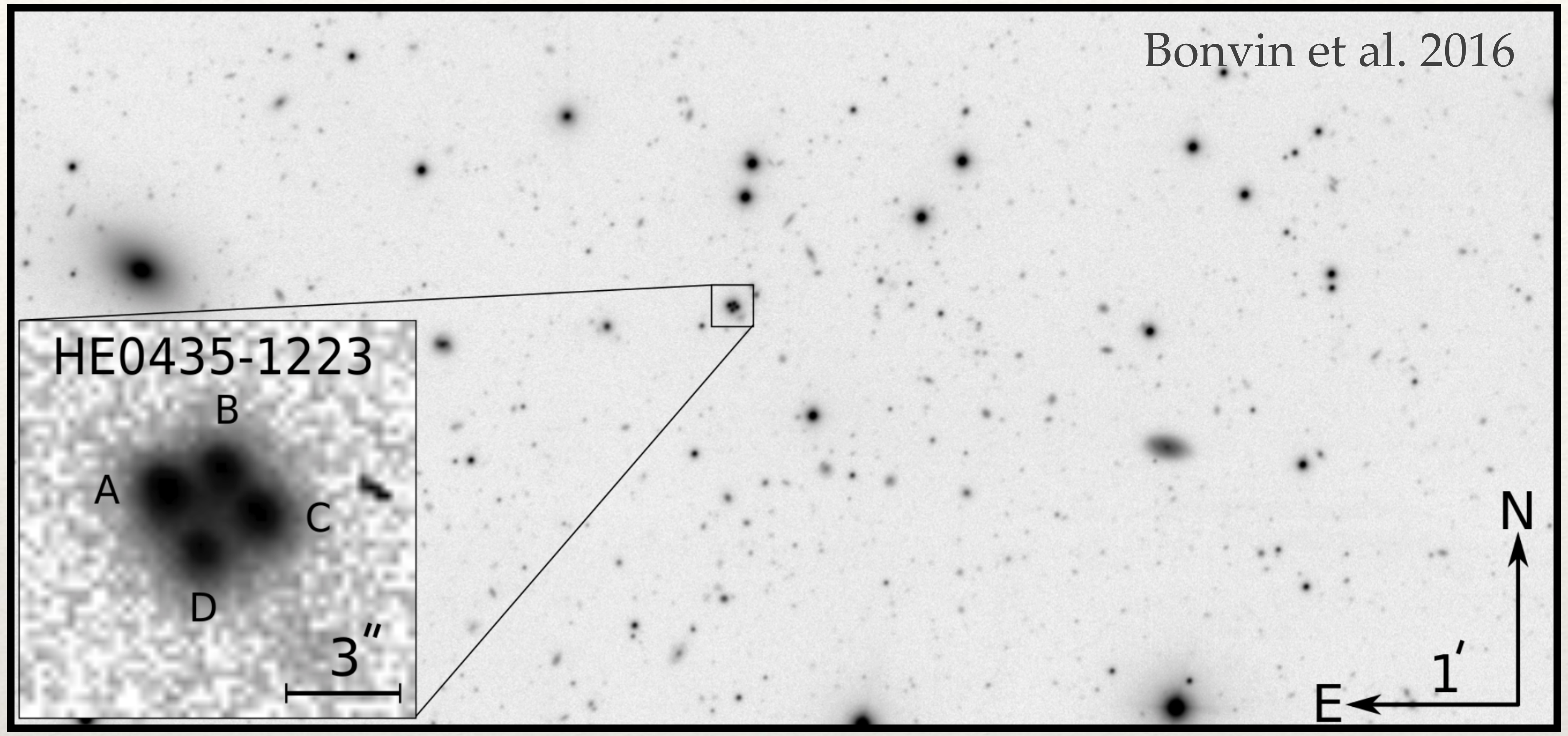
measured

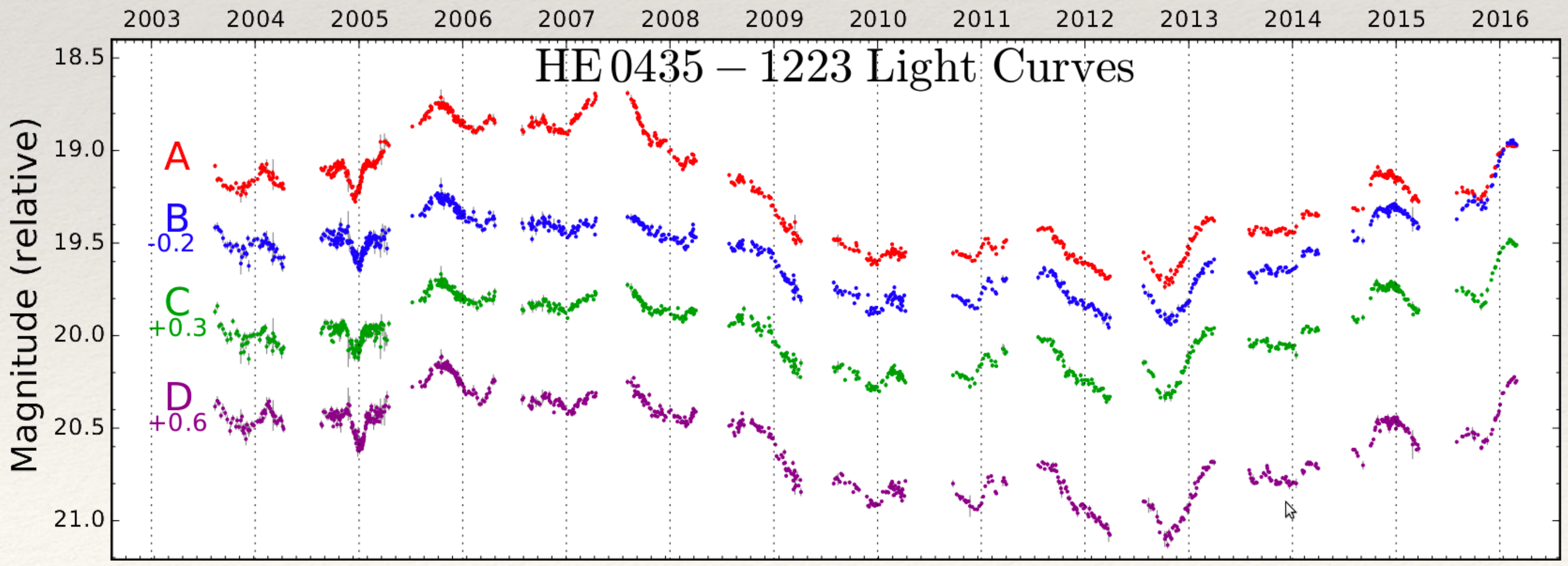
H_0^{-1}

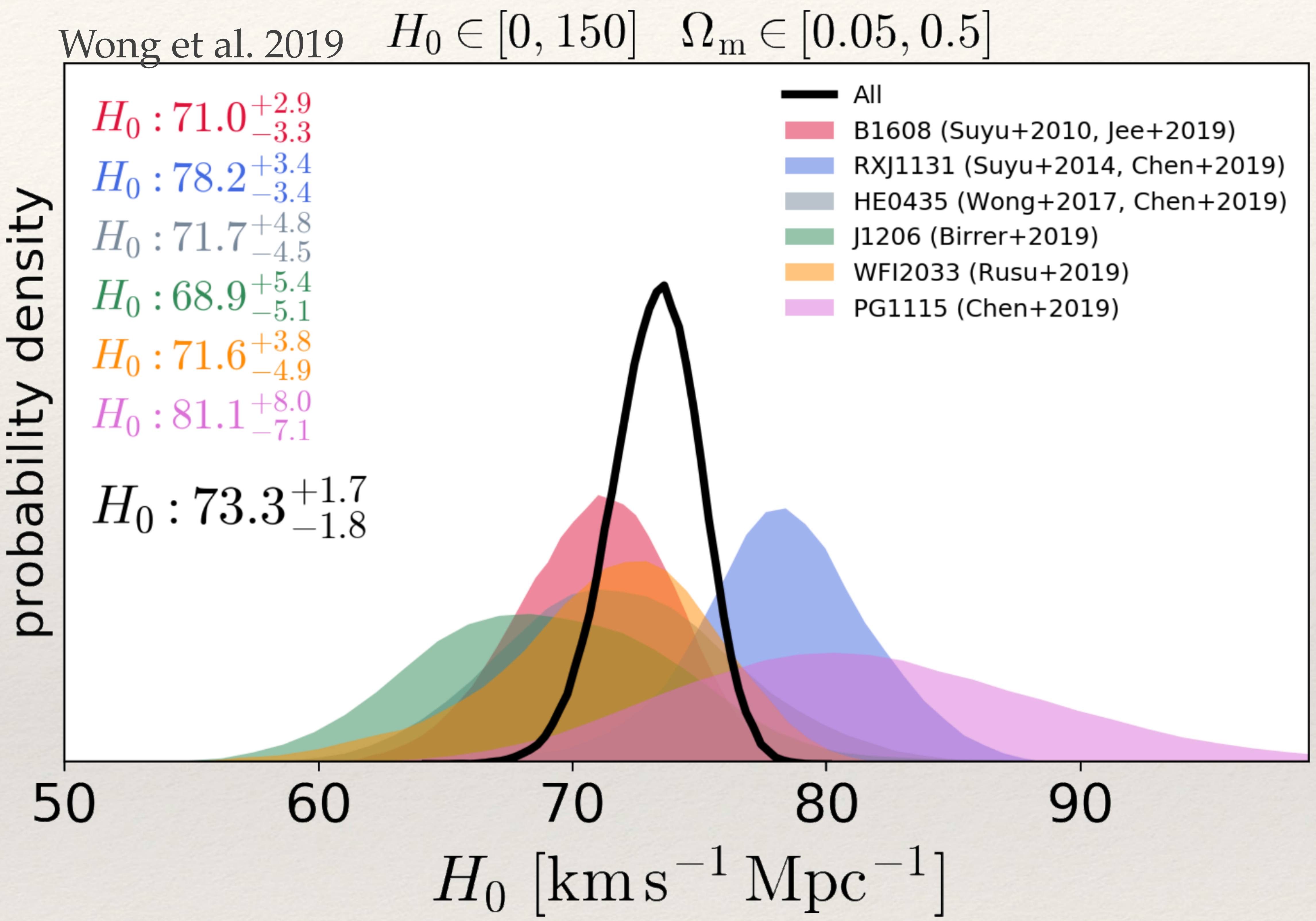
Light path

Lensing potential

H_0 from Strong Lensing





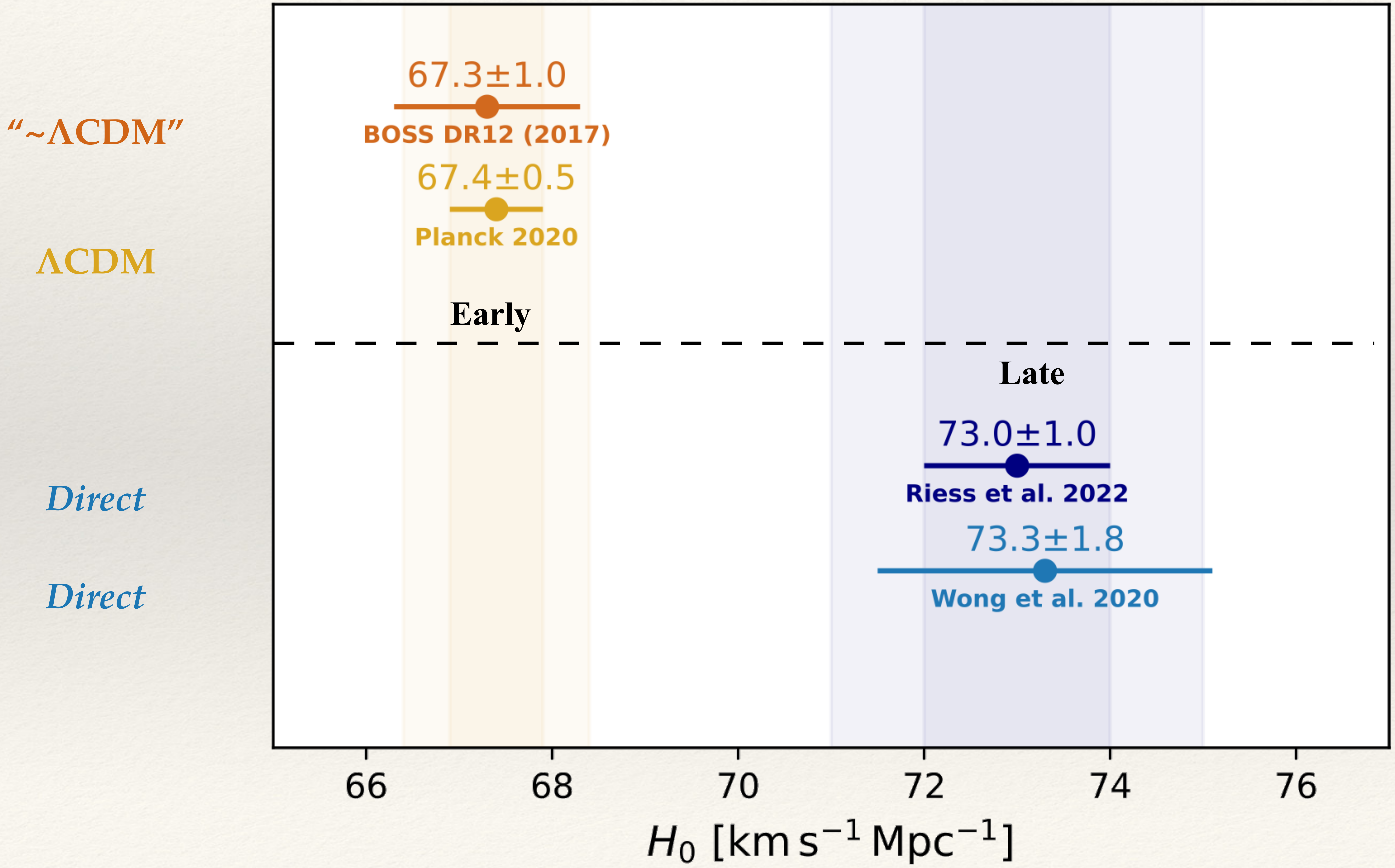


$$\Delta t = \frac{1}{c} D_{\Delta t} \phi_{lens}$$

$\propto H_0^{-1}$

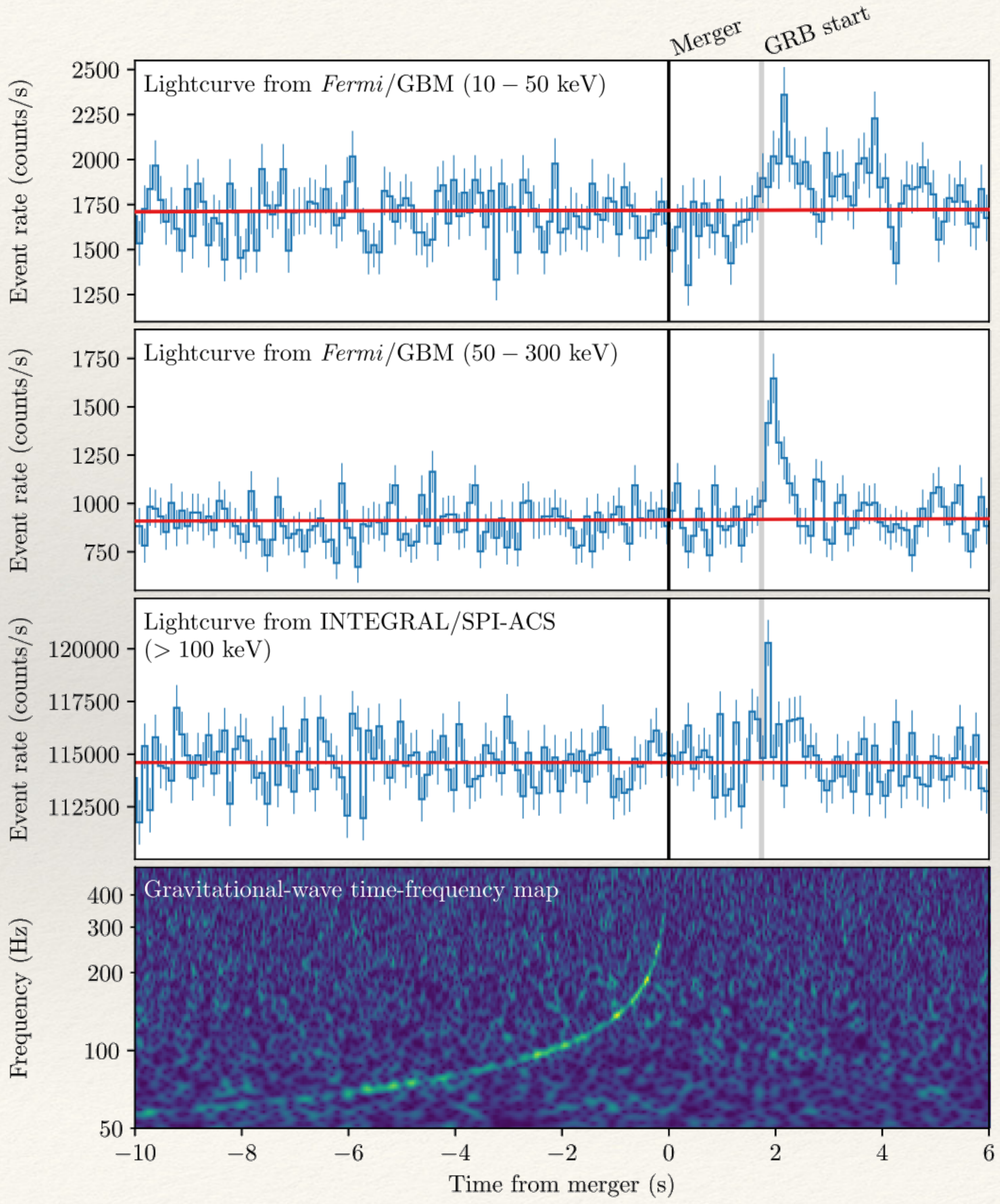
Obtained from lensing mass model

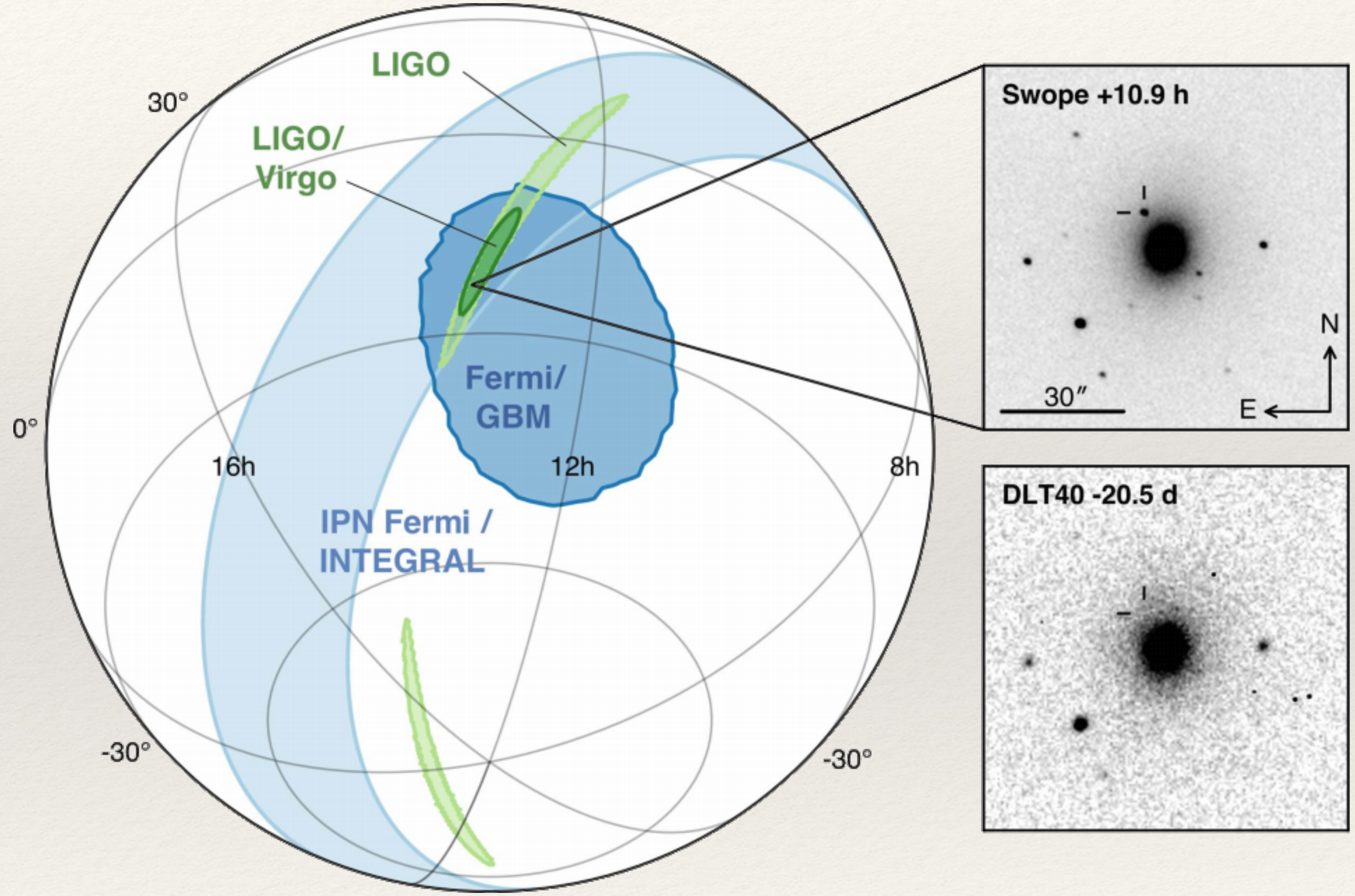
H_0 Tension | *At least 2 independent systematics*



Standard Sirens

Ligo& Virgo ApJ 848, 12L

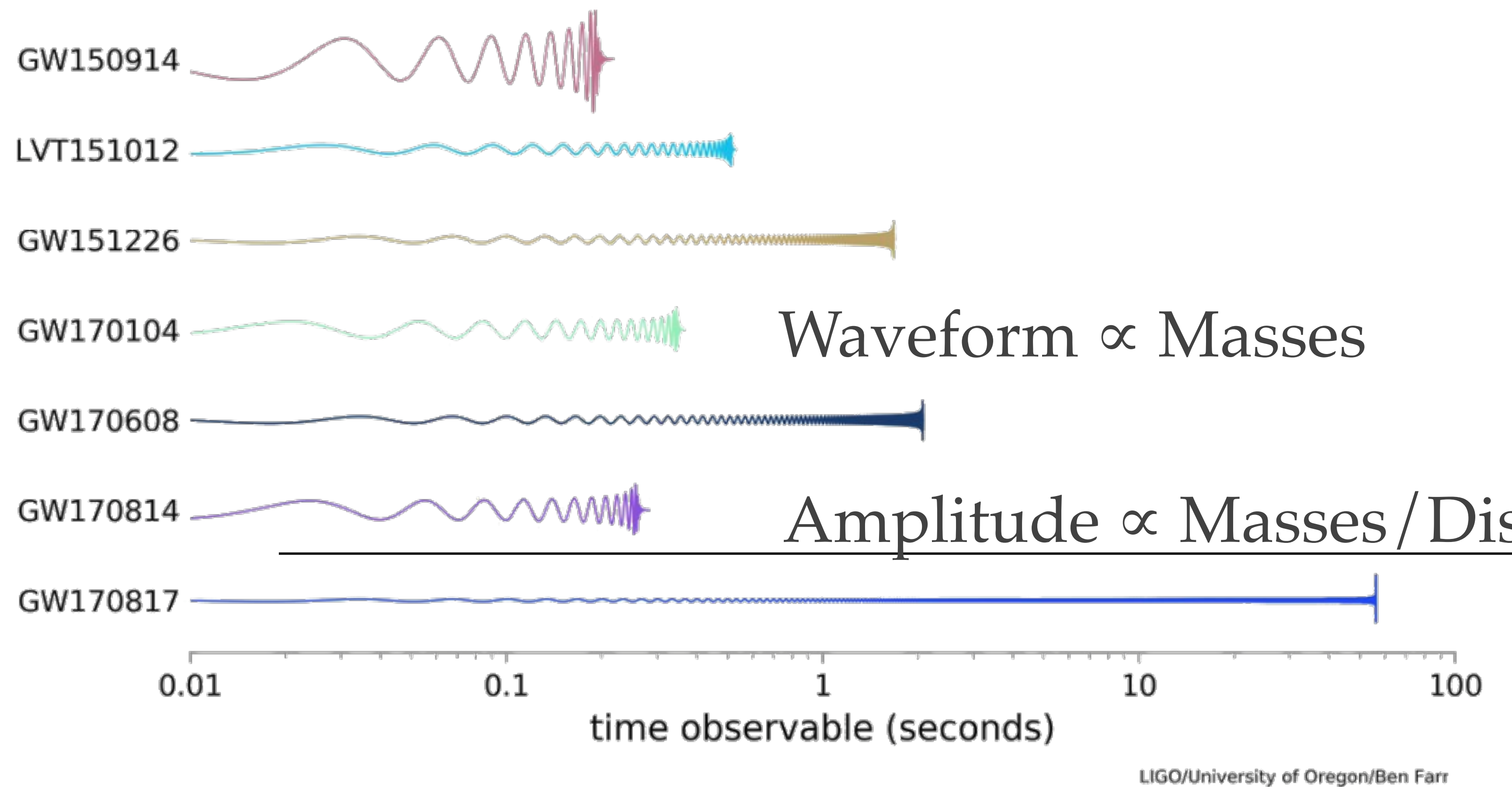




Gravitational Waves & ElectroMagnetism | H_0

Gravitational Waves

$\mathbf{d_L}$

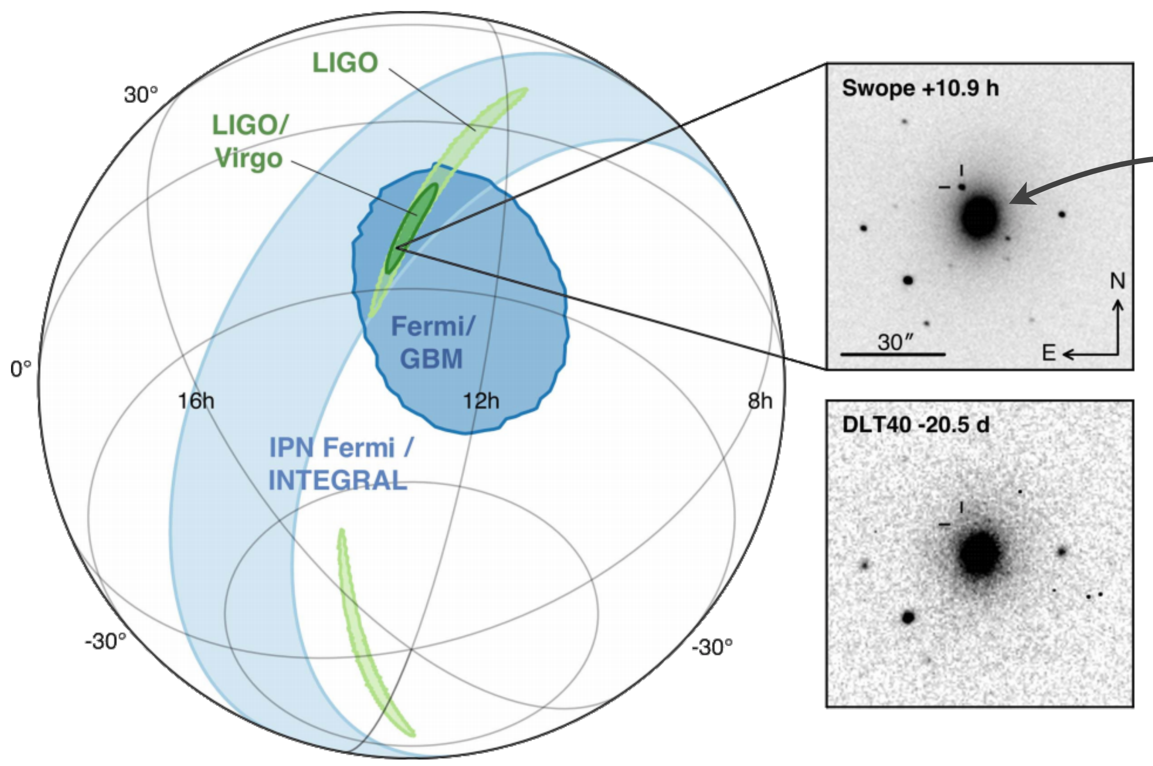


Waveform ∝ Masses

Amplitude ∝ Masses / Distance

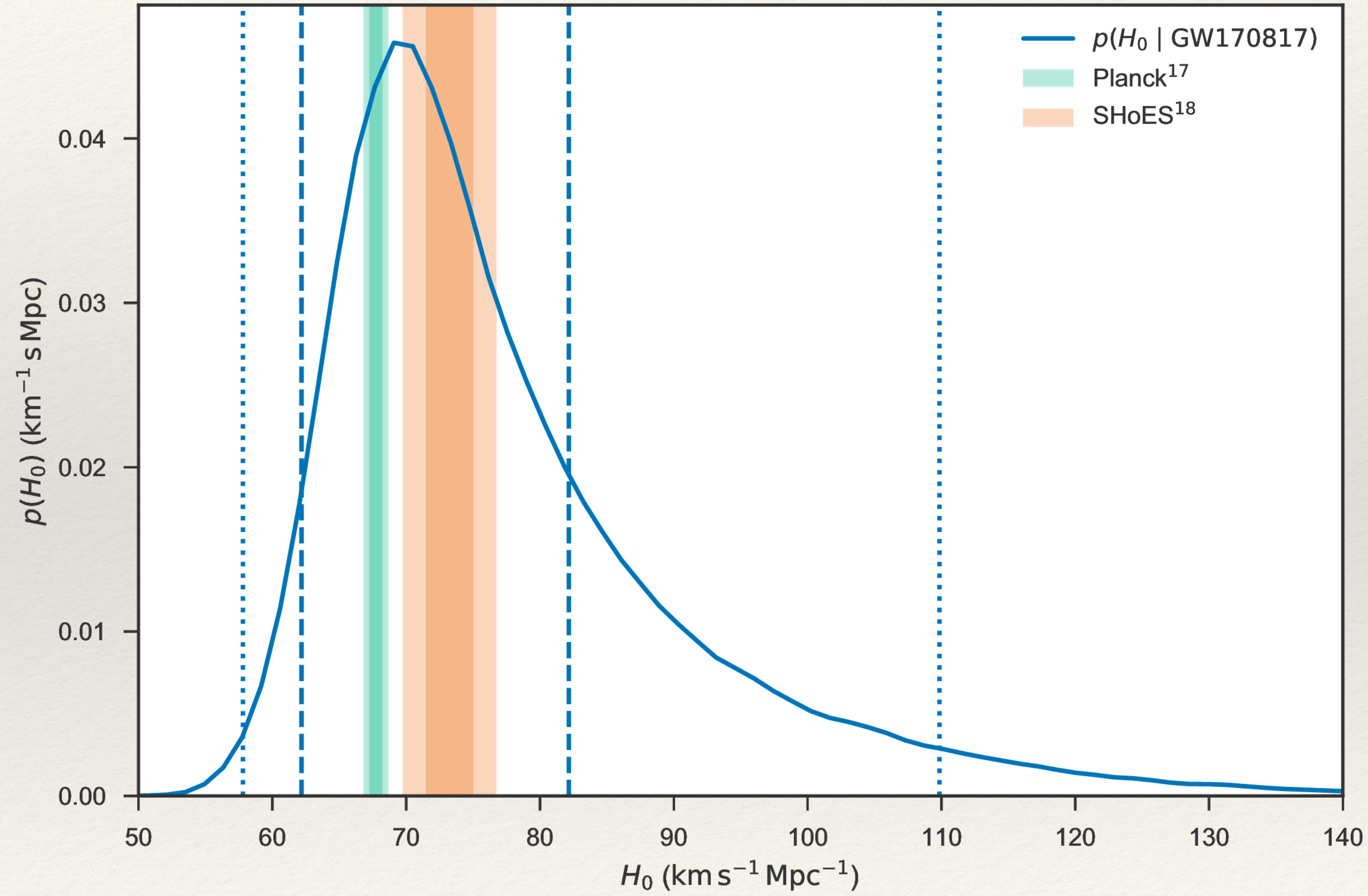
Optical Counterpart

z

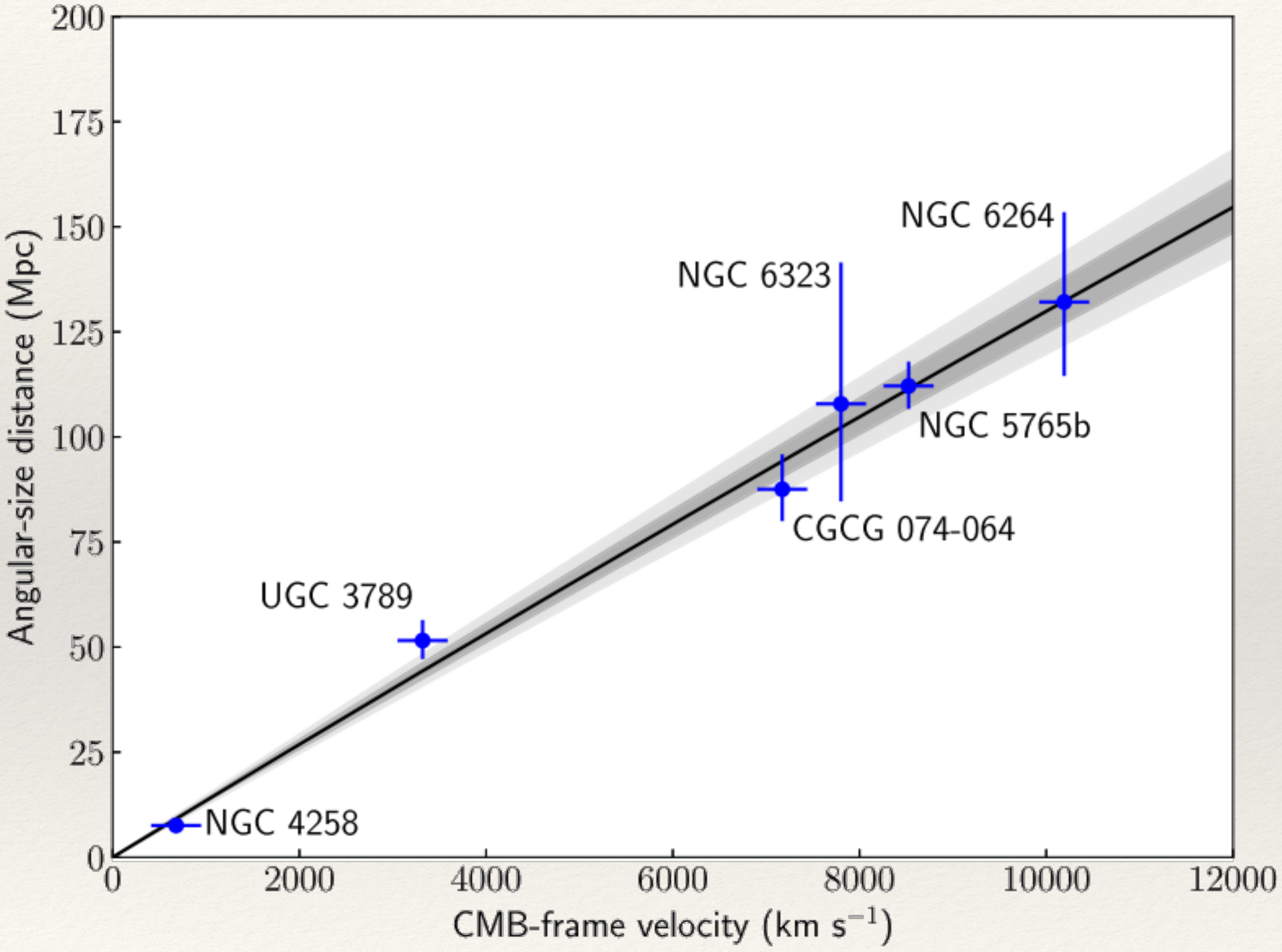


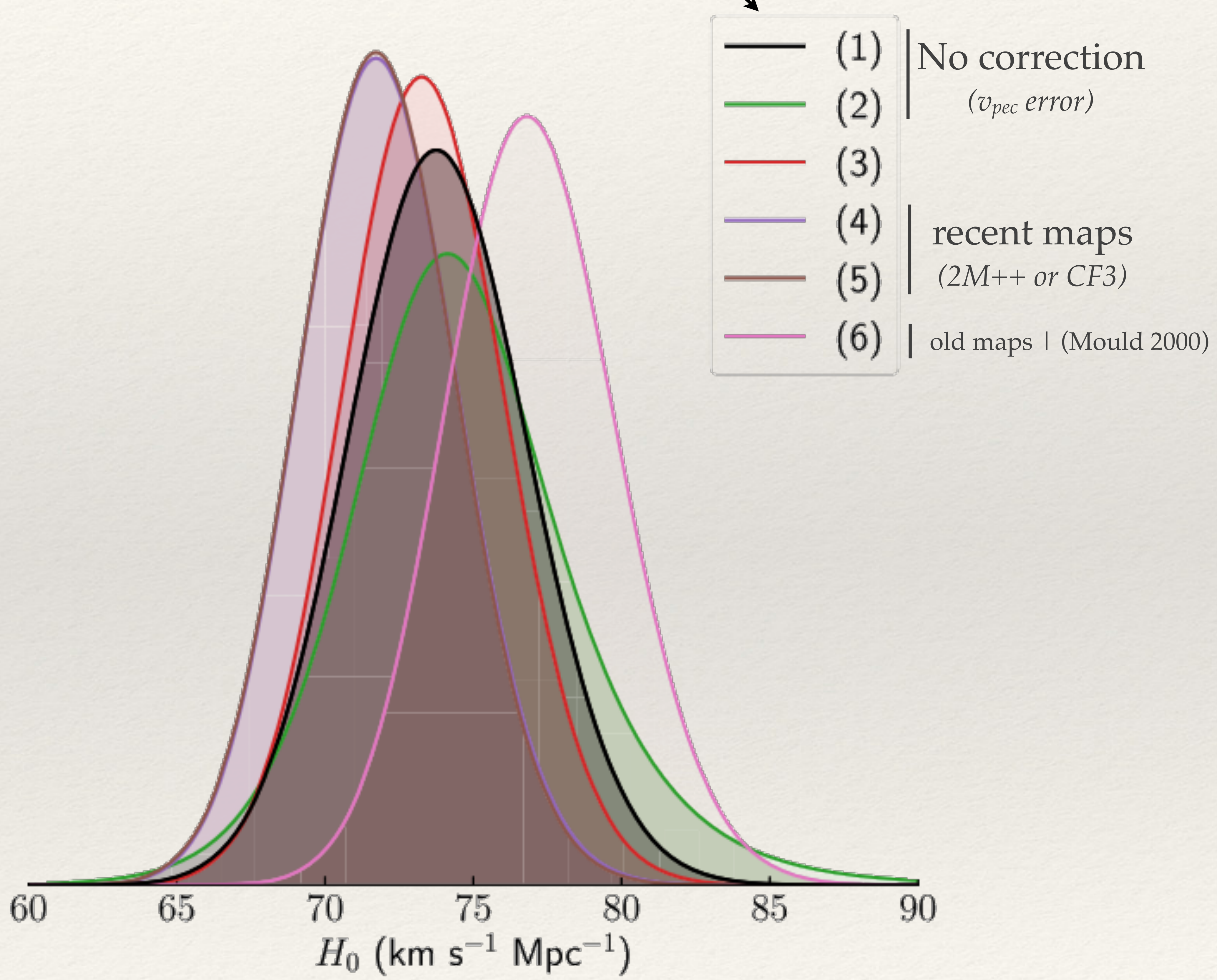
Redshift

$$v_H = H_0 d_L$$

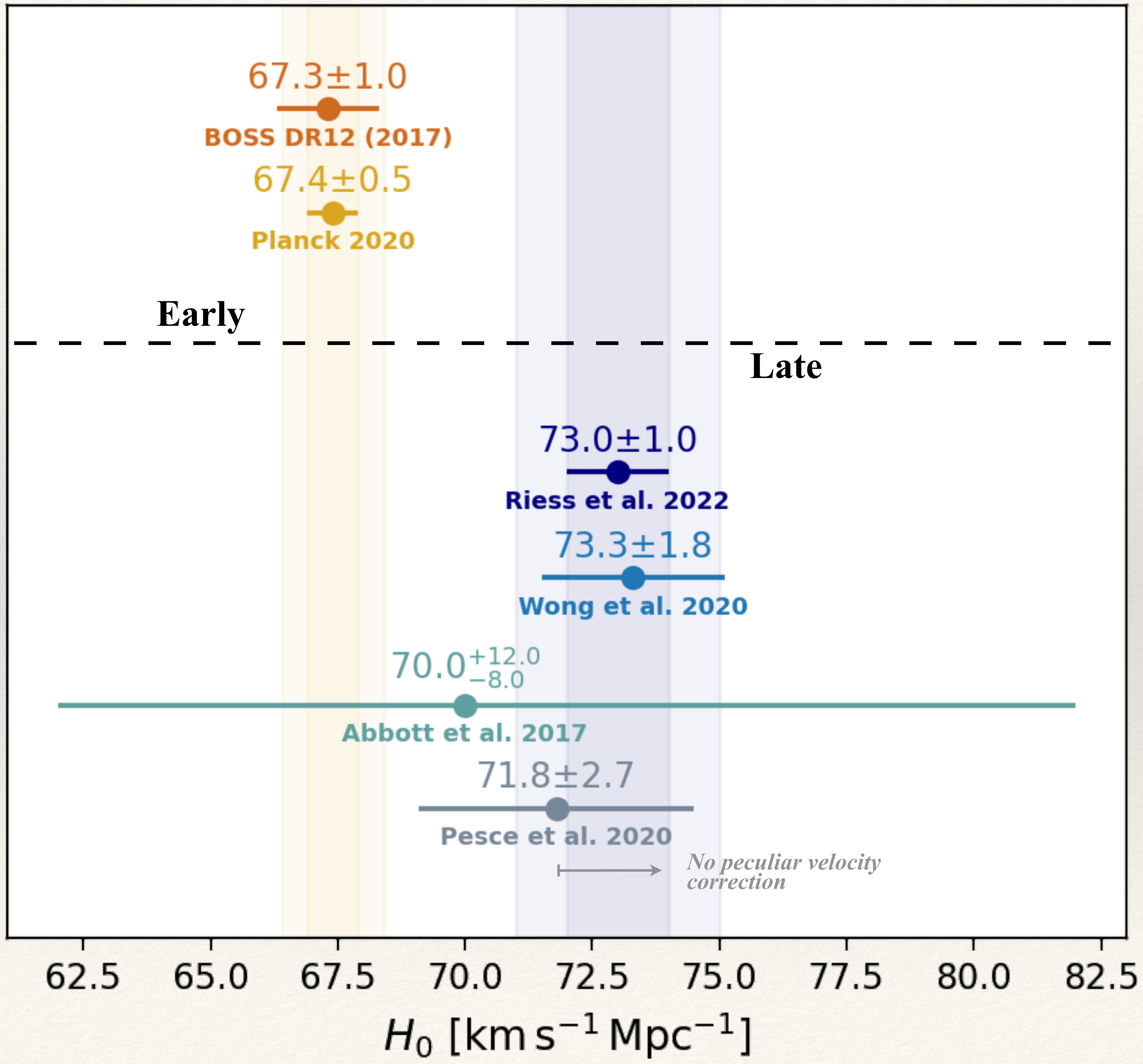


Mega Maser cosmology project



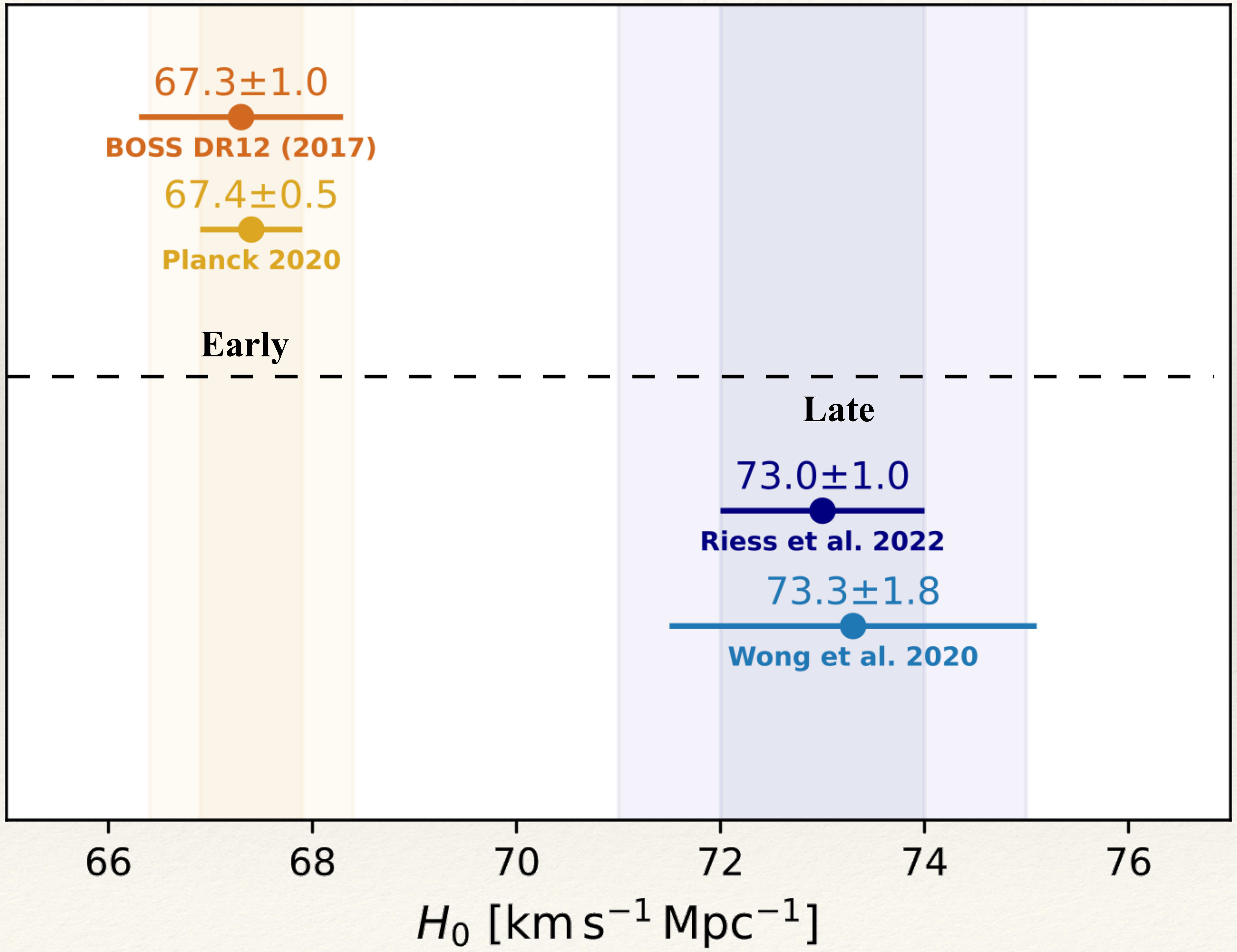


H_0 Tension | *alternative probes are still quite far*

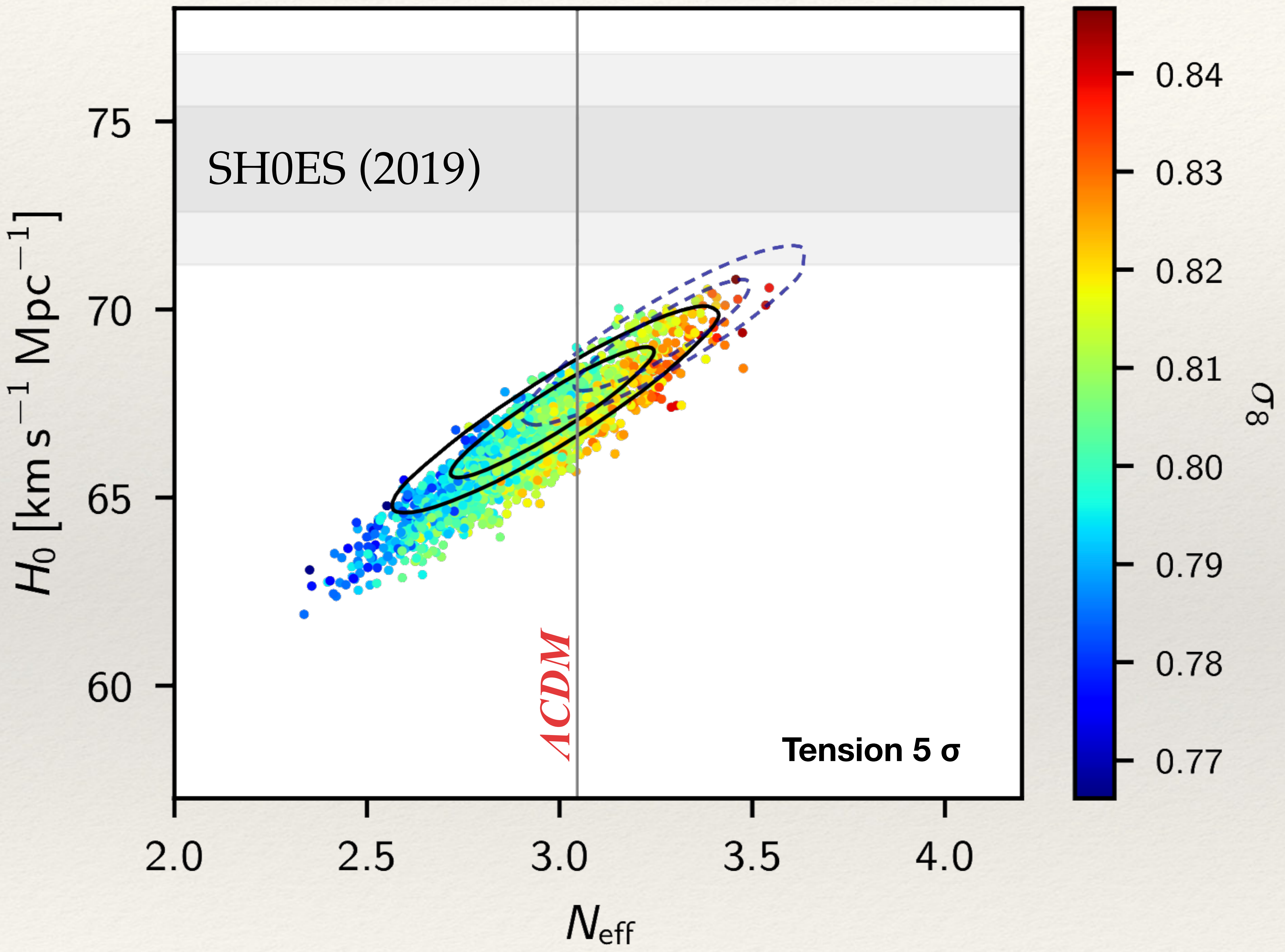


Sensitive to peculiar velocity correction

H_0 Tension | *At least 2 independent systematics*

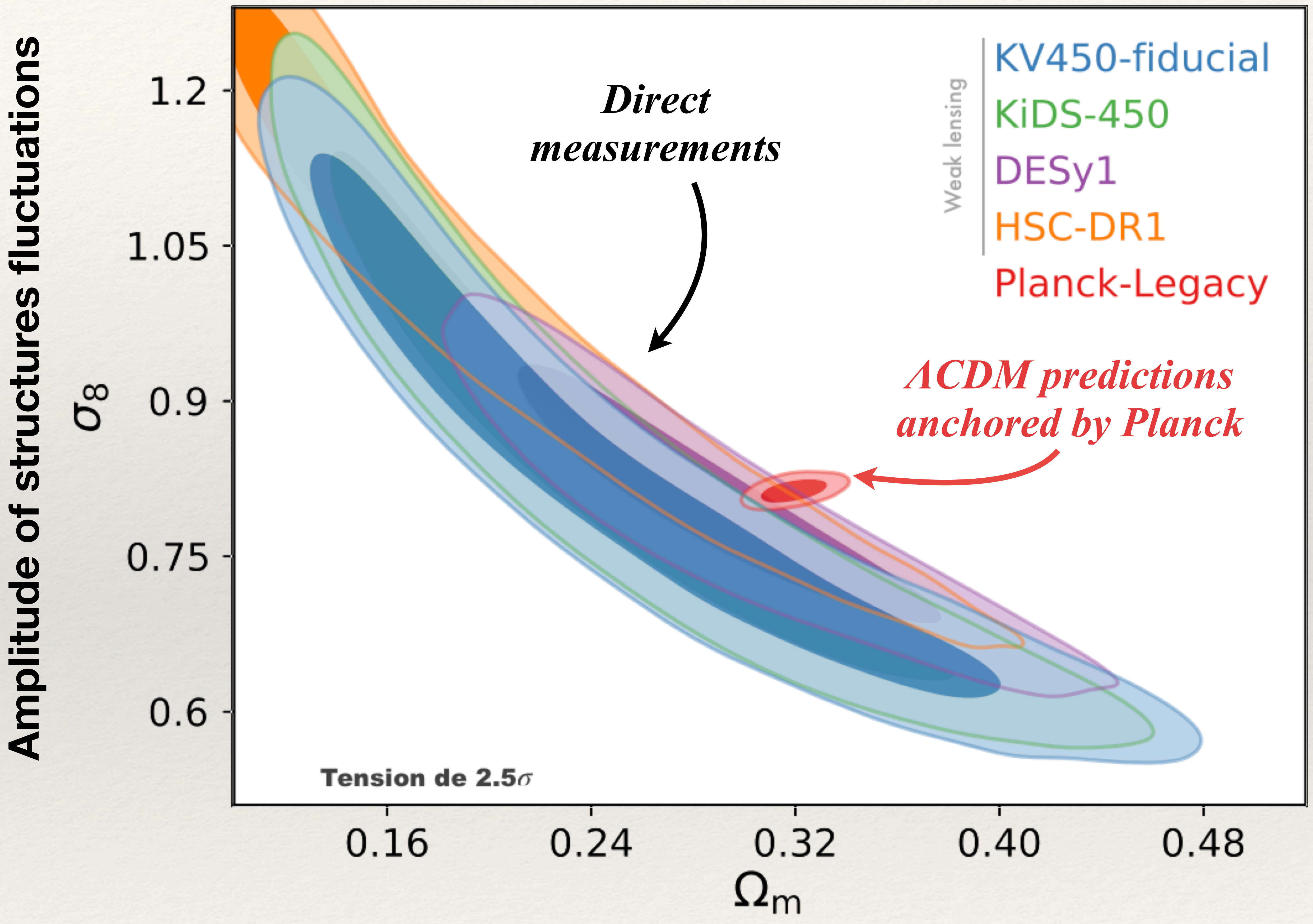


Tensions In Cosmology | *Changing the model*



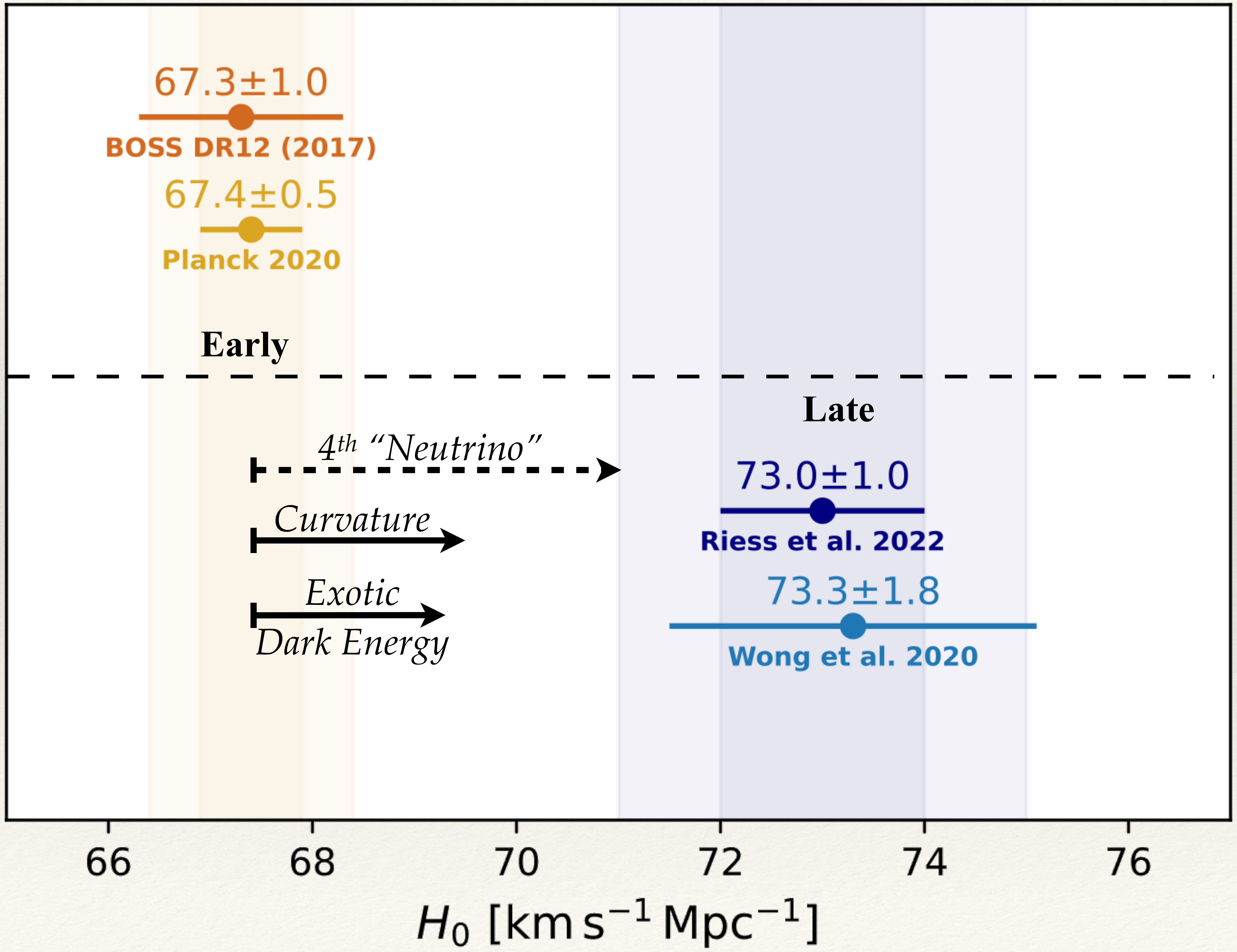
Effective number of « neutrino“

Planck 2018



Density of Matter

H_0 Tension | *At least 2 independent systematics*



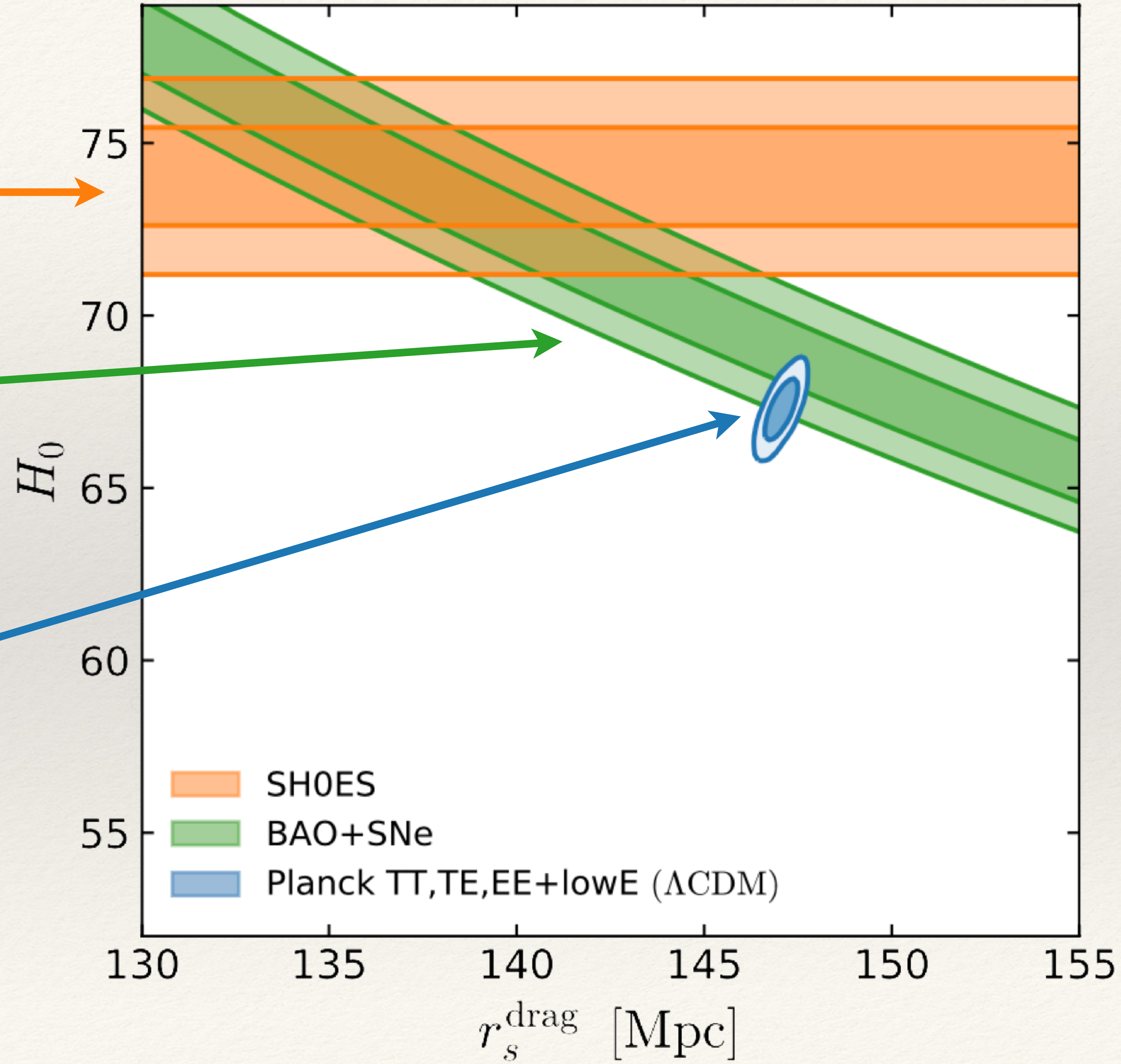
H_0 tension or r_s tension ?

Knox & Millea et al. 2019

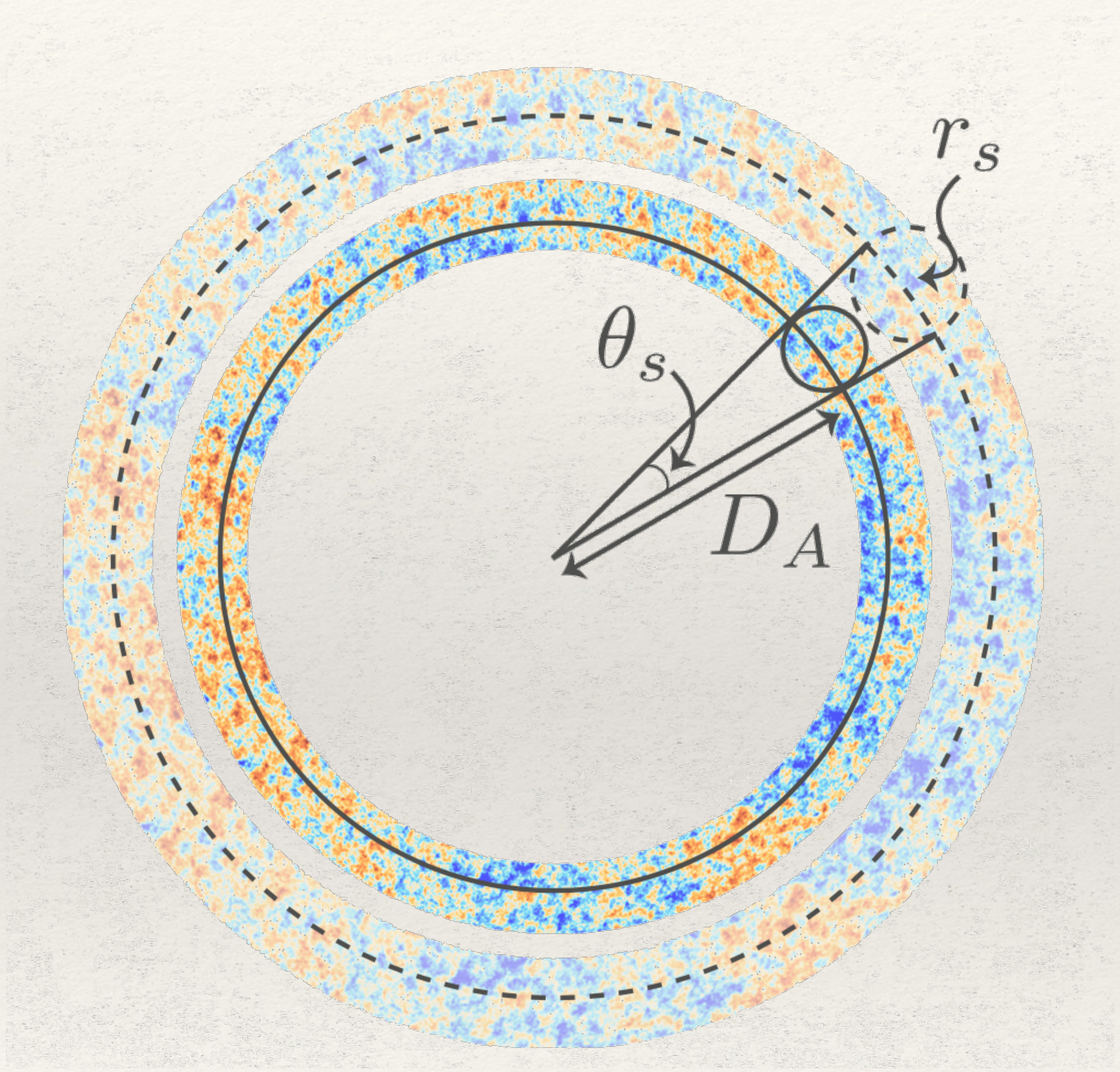
SH0ES 2019 (Cepheids & SNe Ia)
(No assumption of ΛCDM)

BAO + SNe Ia
(No assumption of ΛCDM | 5d spline)

Planck
(Assumes ΛCDM)

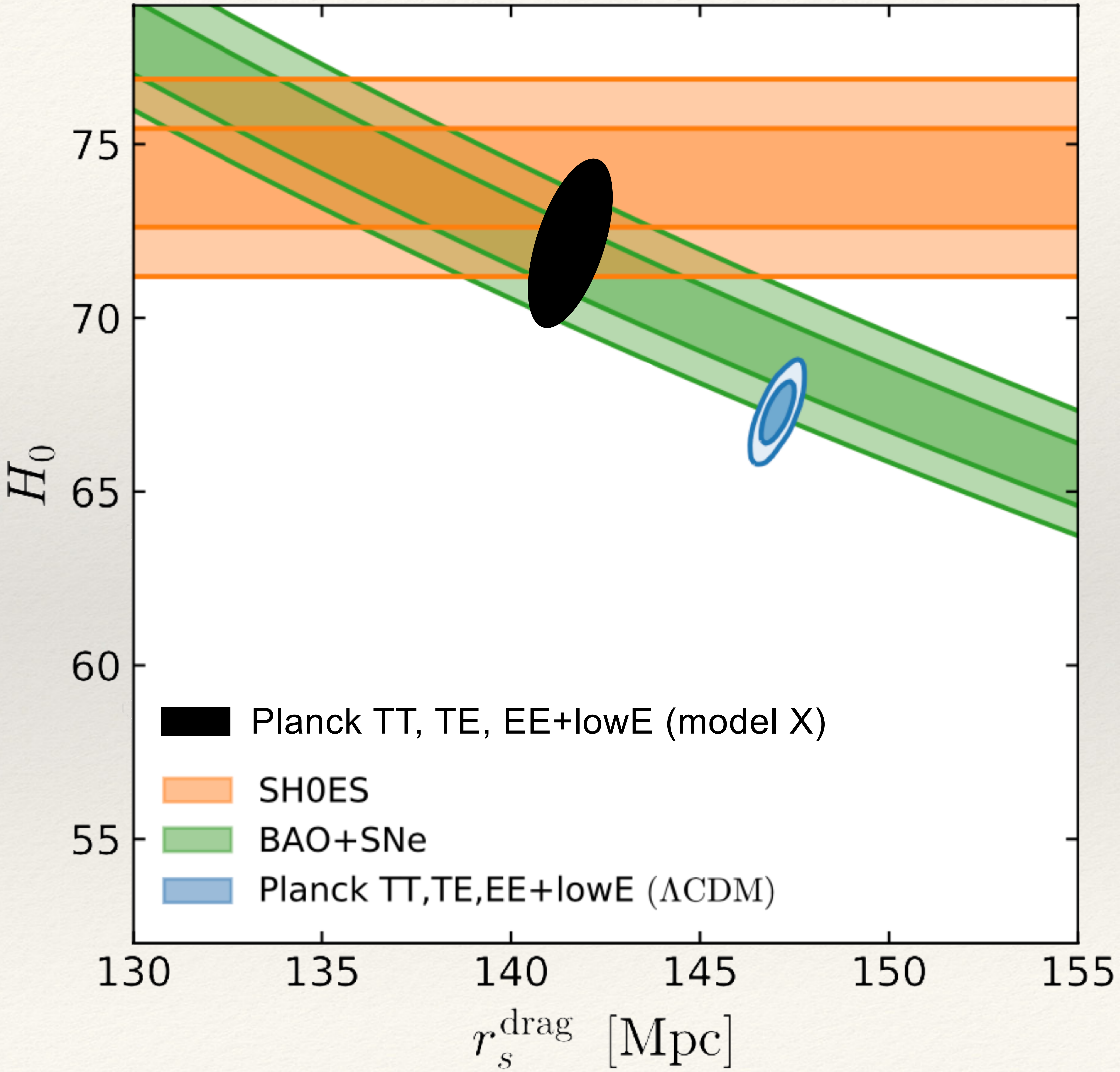


Then what about New Fundamental Physics ?



T. Smith | V. Poulin

Knox & Millea et al. 2019



…or it’s systematics

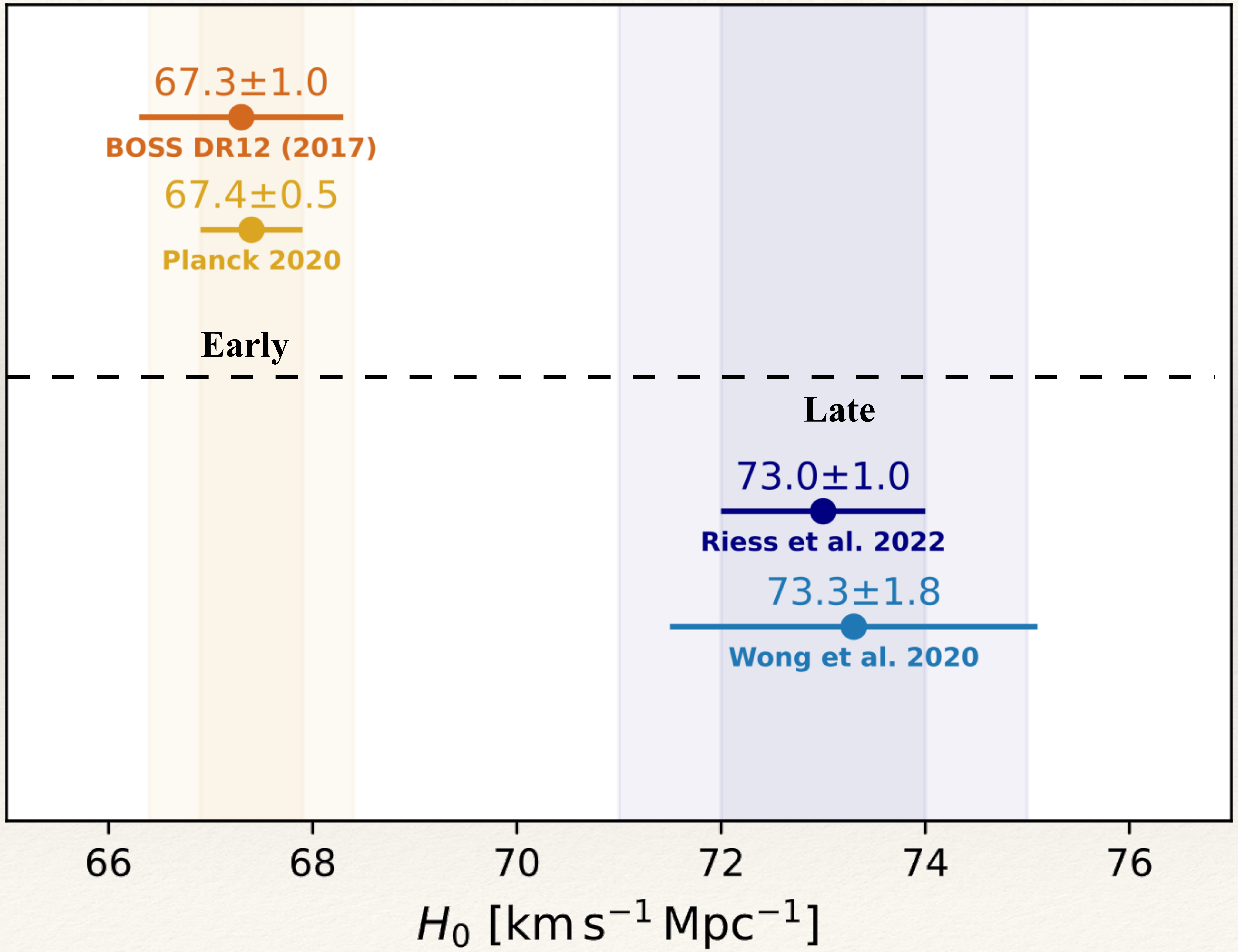
H_0 Tension | *At least 2 independent systematics*

"~ΛCDM"

ΛCDM

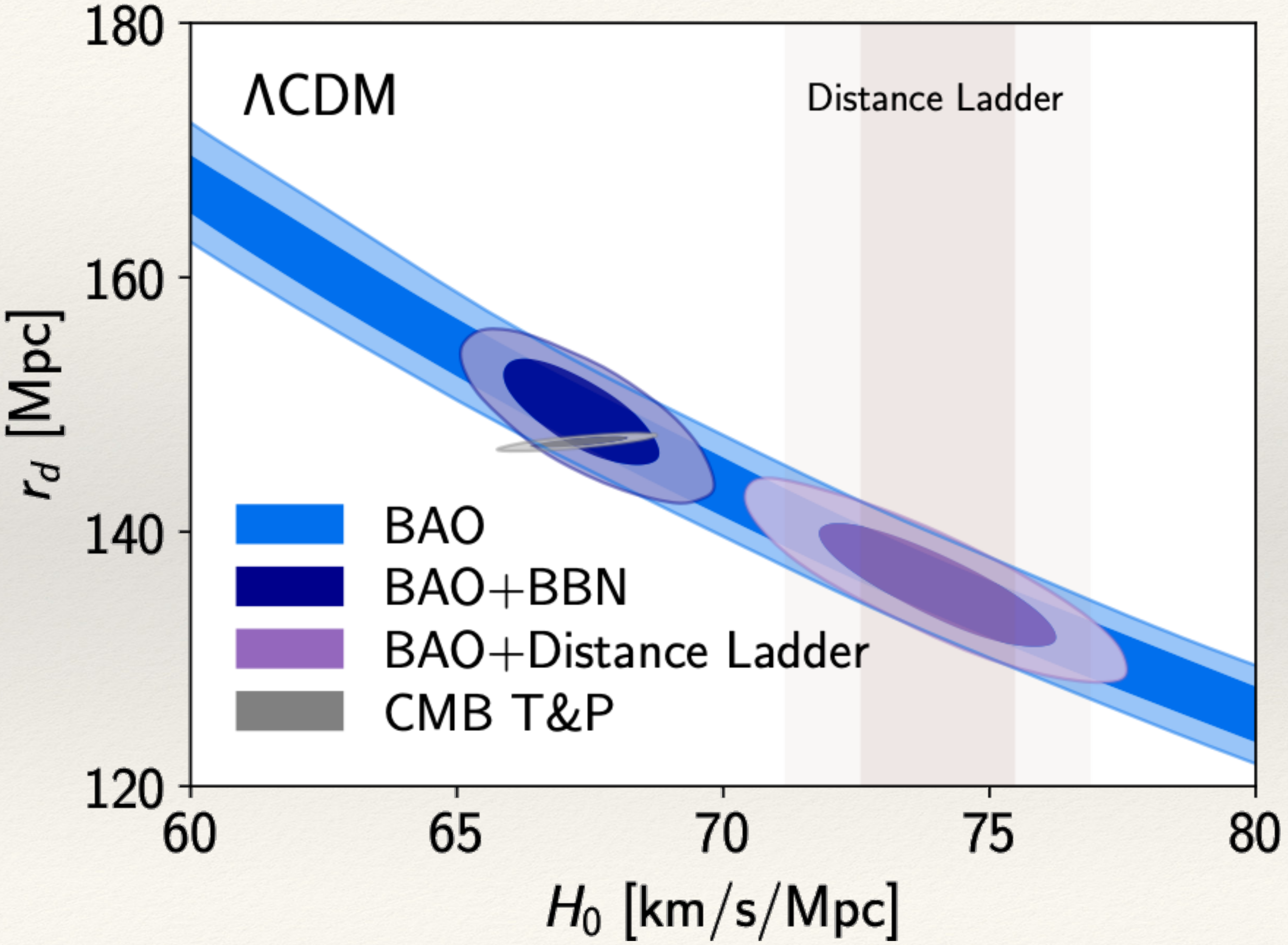
Direct

Direct



No CMB Data | *Big Band Nucleosynthesis*

eBOSS collab. 2020

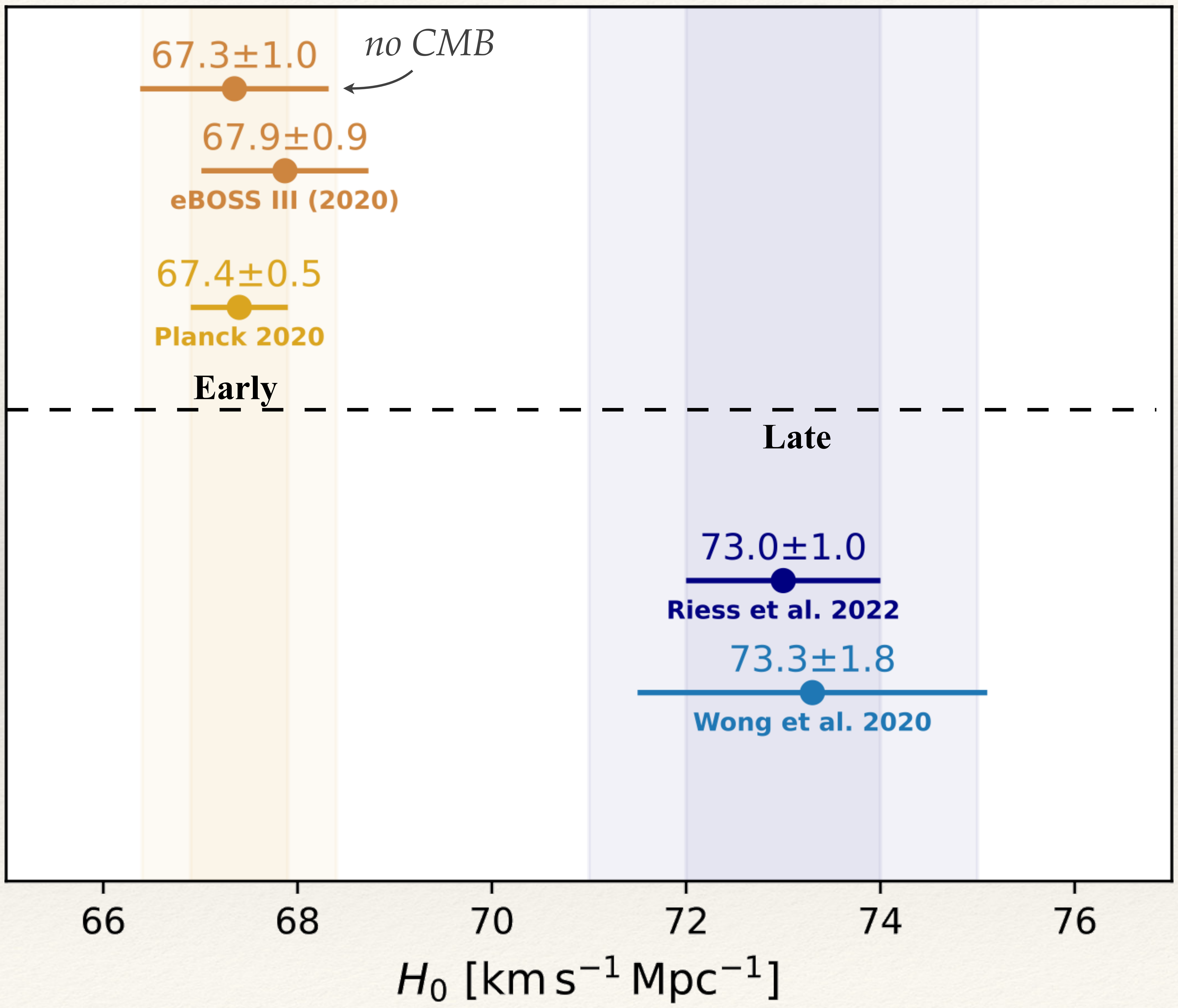


H_0 Tension | *At least 2 independent (late) systematics*

ΛCDM: BAO & BBN

*ow_ow_a***CDM:**
CMB P&T & BAO & SN

ΛCDM: CMB P&T



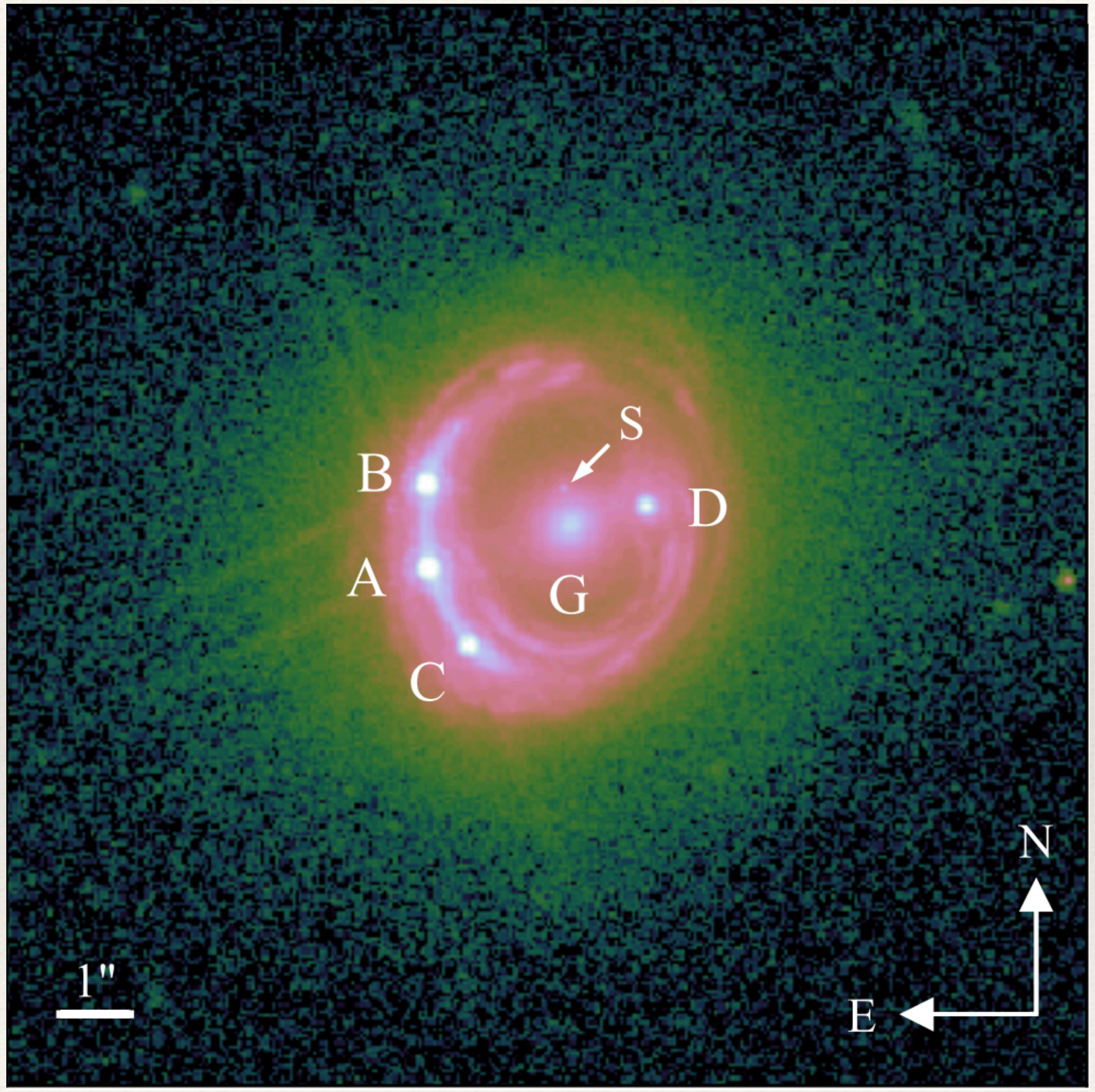
Direct: Geom+Cepheids+SNeIa

Direct~: Strong Lensing

Strong Lensing | *systematics in density profile*

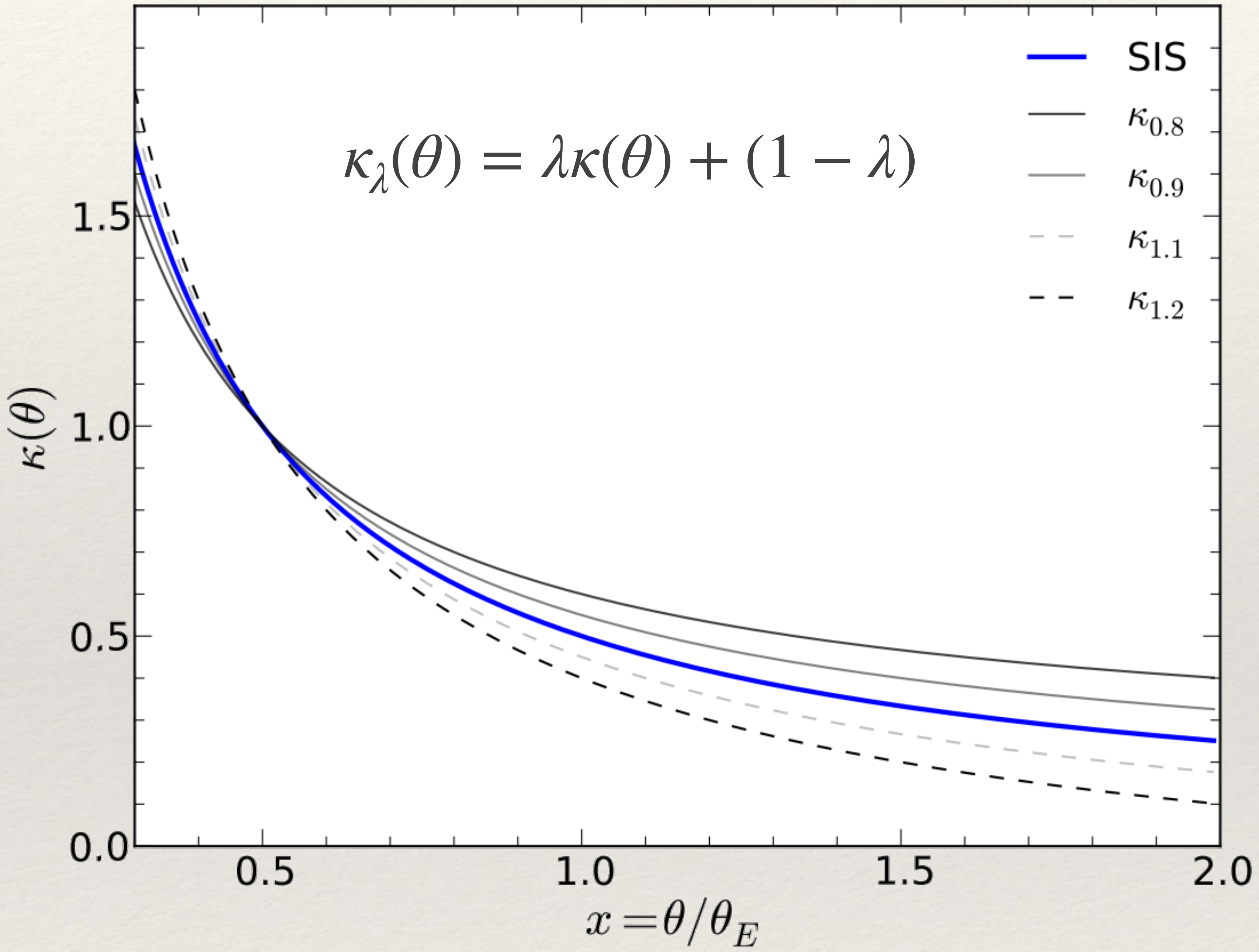
The mass-sheet degeneracy:

from the observed image positions and flux ratios, one cannot distinguish between the original κ and any κ_λ



RXJ1131−1231 | HST | Shajib et al. 2023

Schneider & Sluse 2013



"if the SIS density profile provides a good fit to the lensing data, an equally good fit is obtained by all the κ_λ."

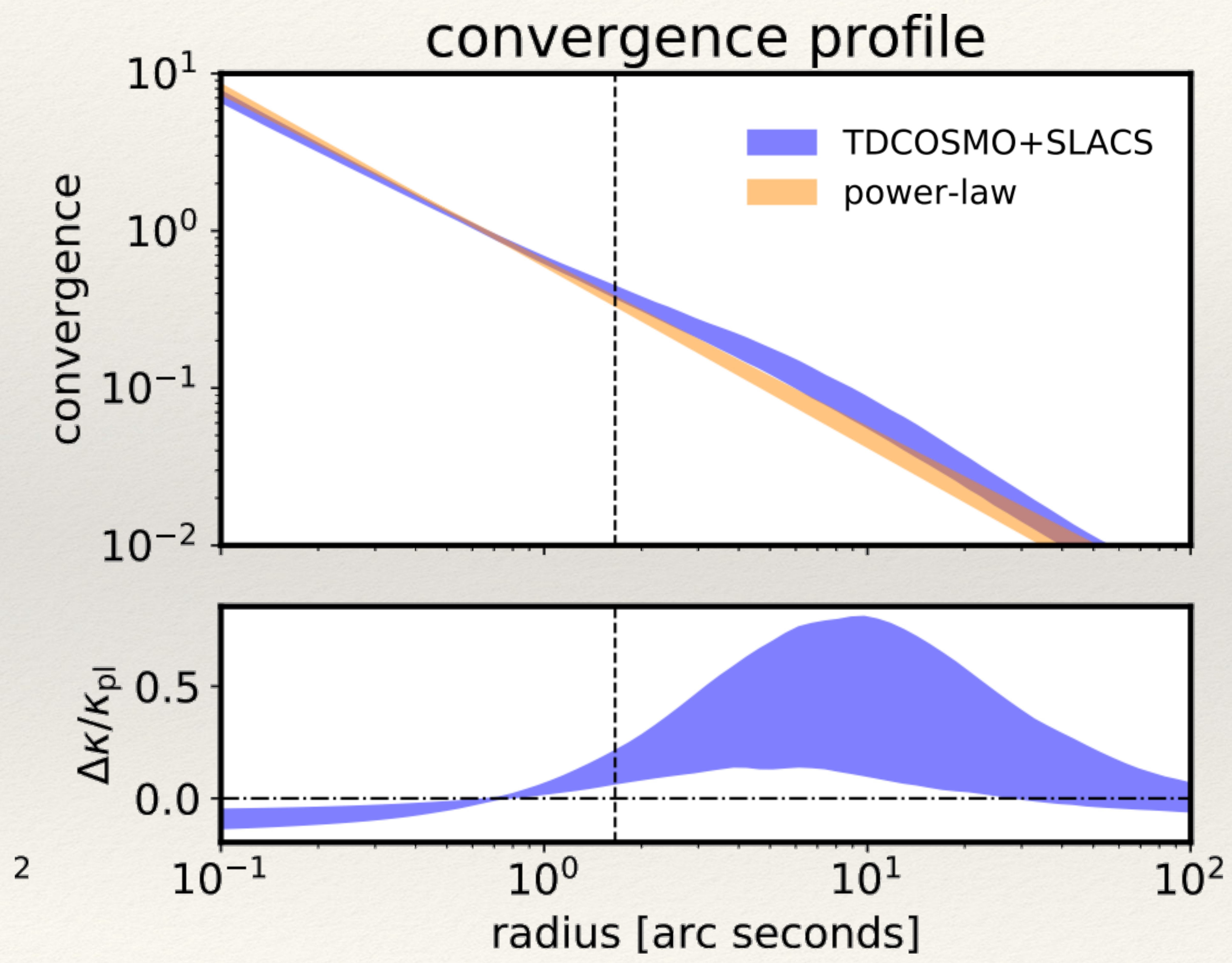
But:

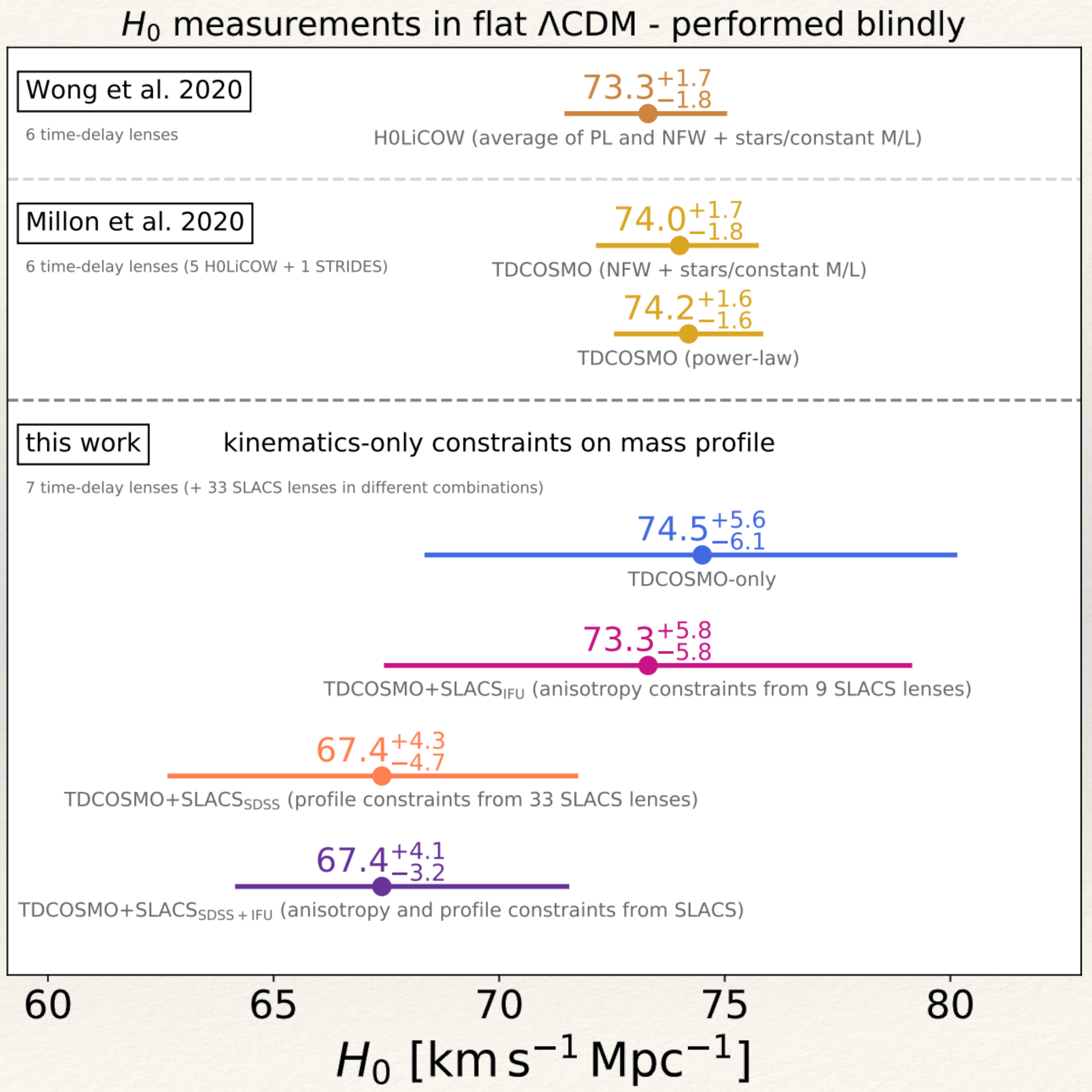
$$H_0\Delta t \rightarrow \lambda H_0\Delta t$$

Good news:
The mass sheet degeneracy can be broken by spatially resolved velocity dispersion measurements

Strong Lensing | *systematics in density profile*

Birrer et al. 2020



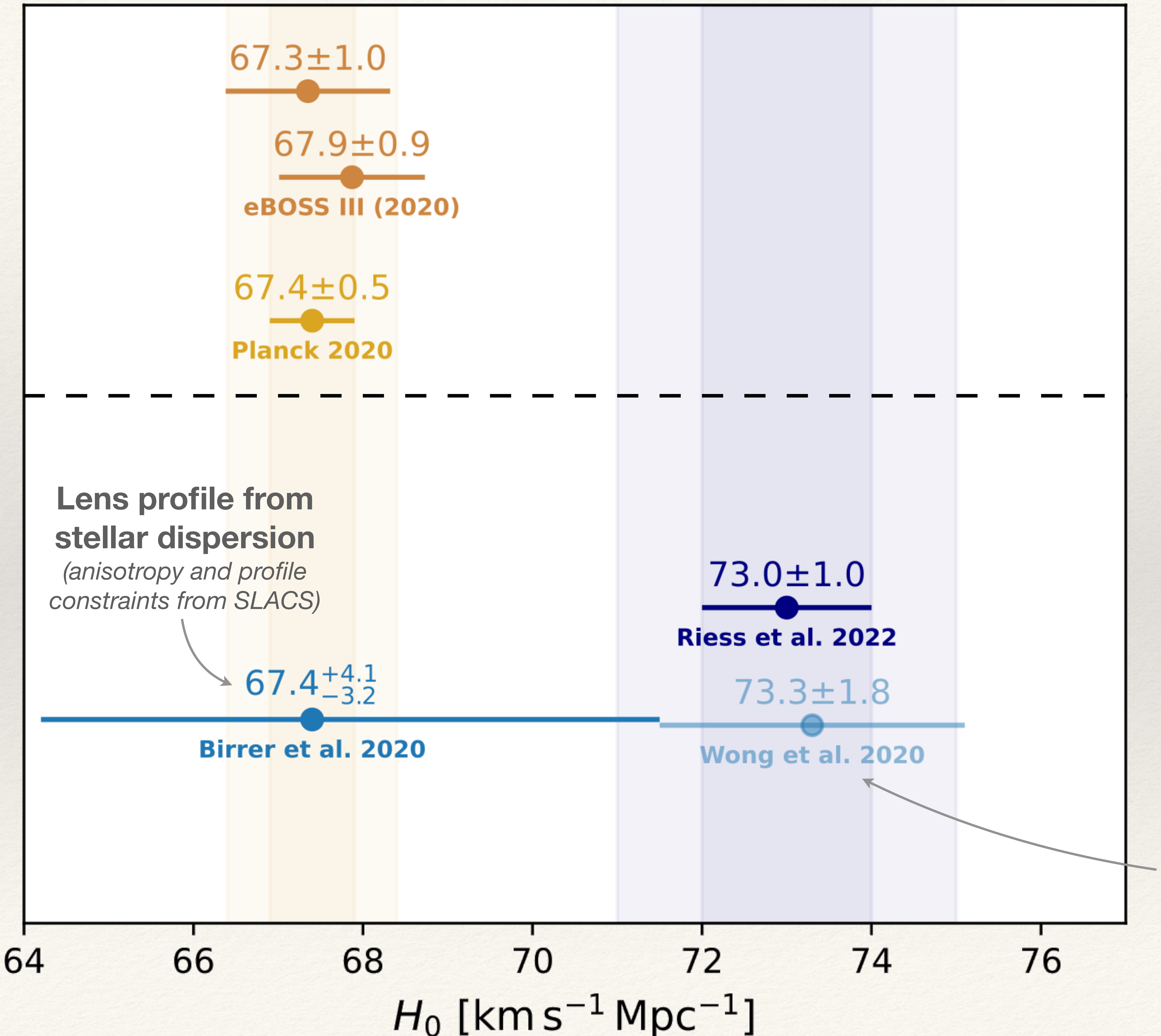


H_0 Tension | *Highly debated systematics in strong lensing*

ΛCDM: BAO & BBN

ow_0w_a**CDM:**
CMB P&T & BAO & SN

ΛCDM: CMB P&T



Direct: Geom+Cepheids+SNeIa

Direct~: Strong Lensing

Power-law & star constant M/L & Dark matter halo
(See Suyu 2009)

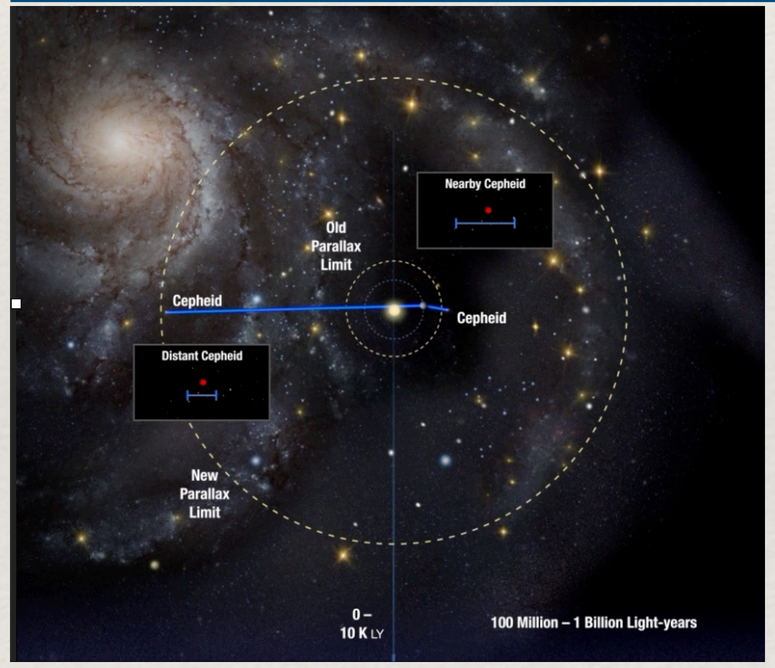
Direct Distance Ladder | *TRGB*

Get independent distances for SNe Ia

Calibrate the "Period-Luminosity" relation — *Measure "L_{SN}"* — *Get "H_0"* → **distance**

"Geometry"

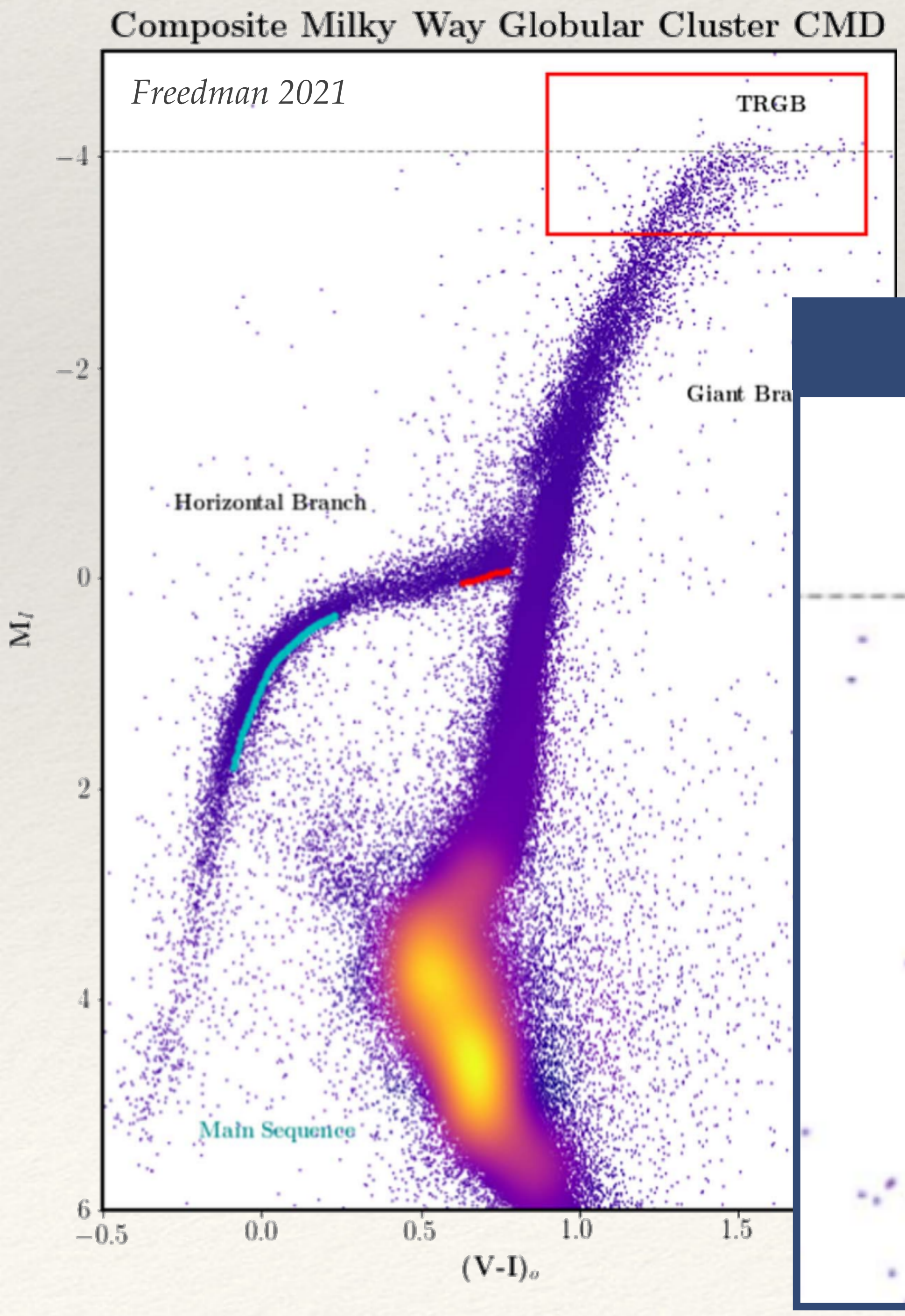
Parallaxes | D.E.B. | Maser

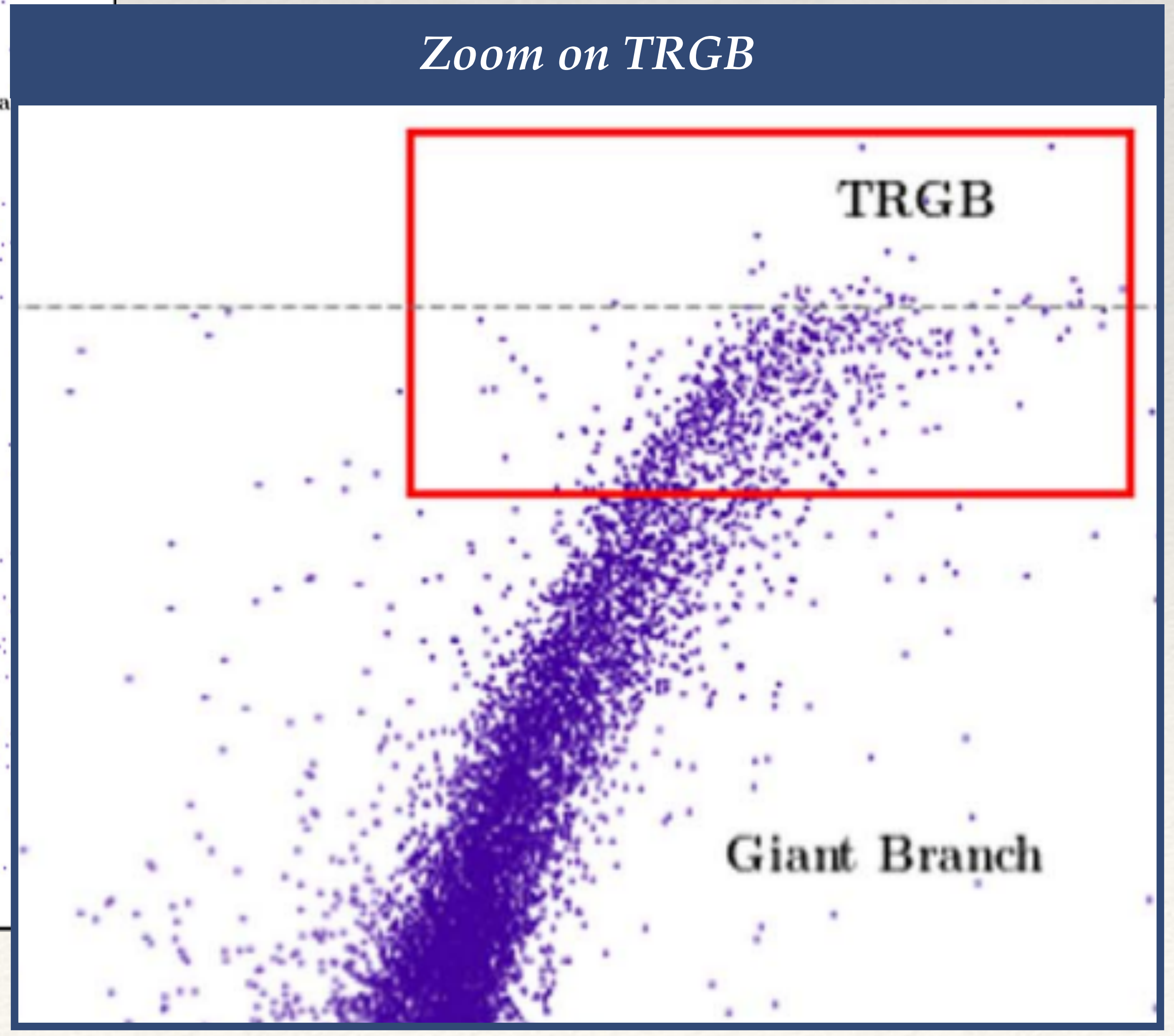


Source: eso

"Calibrators"

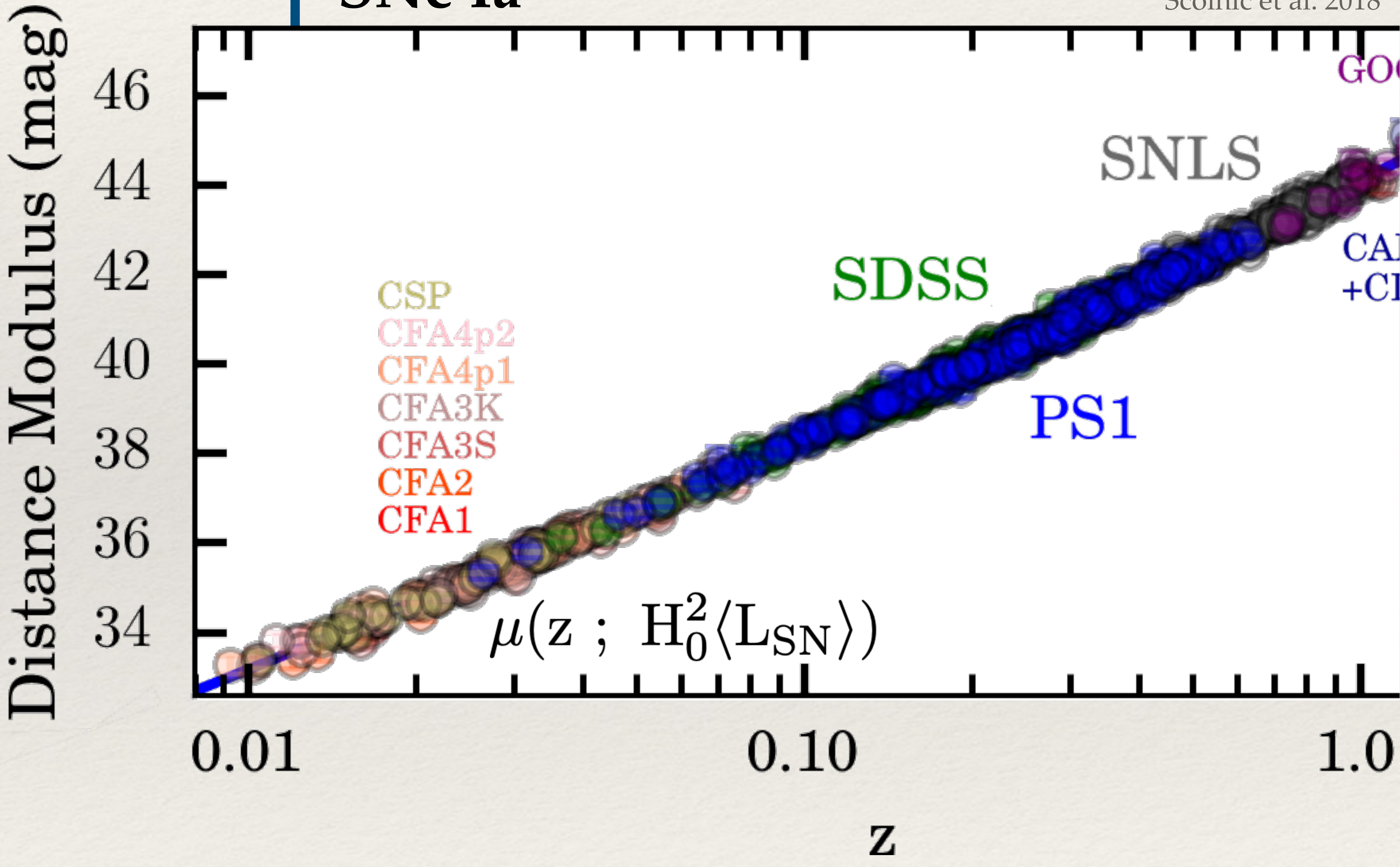
TRGB





"SNe Ia"

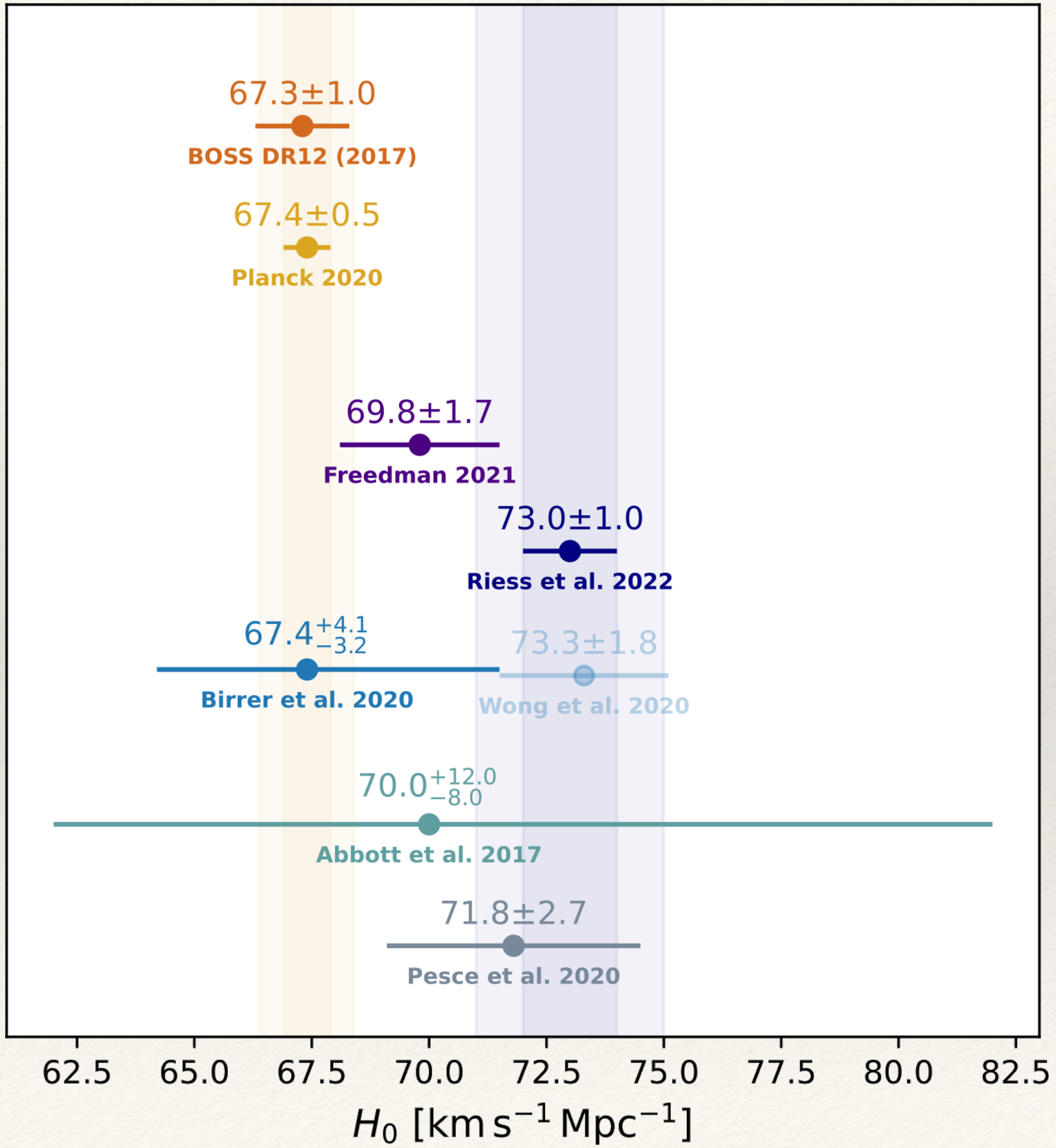
Scolnic et al. 2018

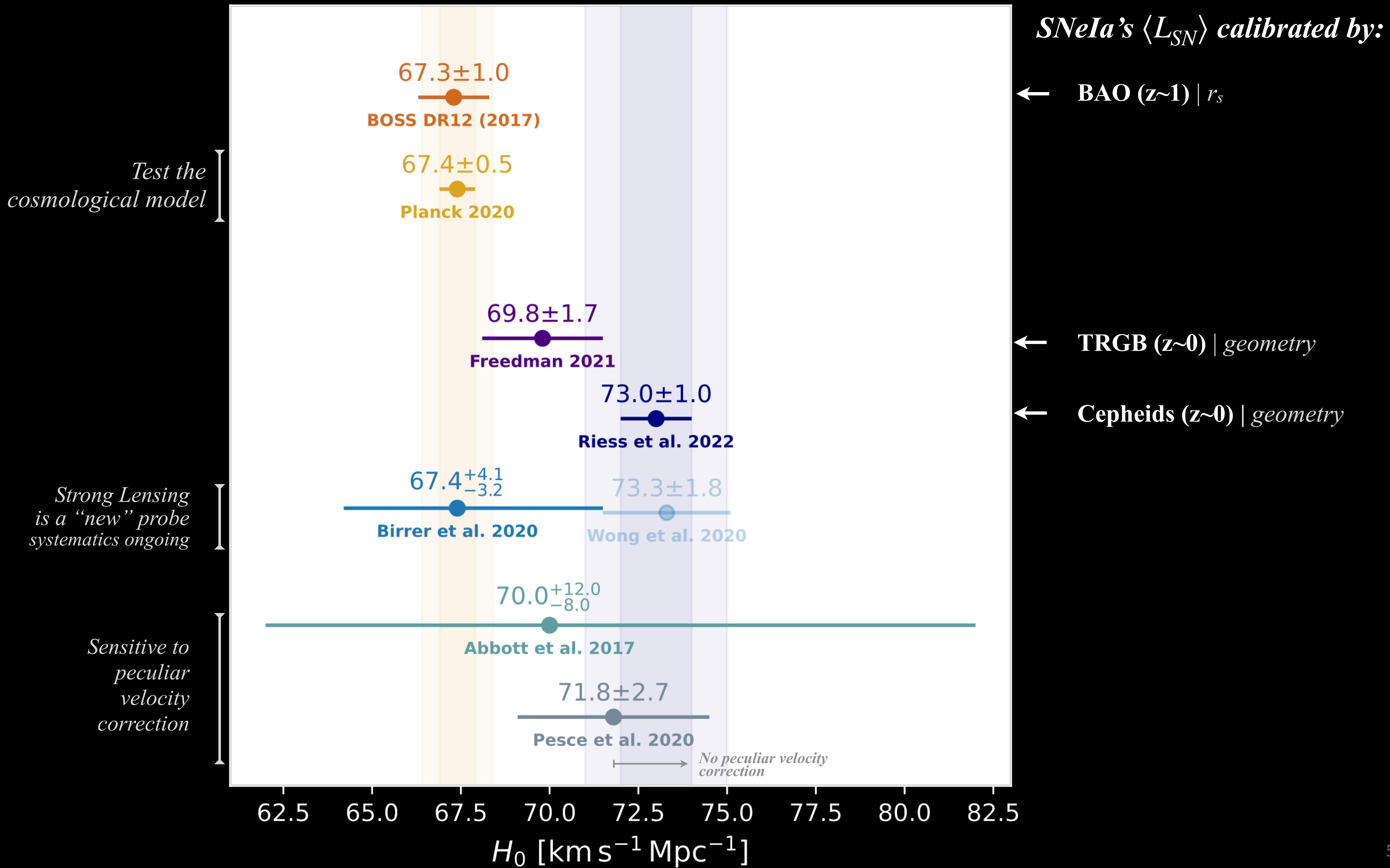


Freedman et al. *2021*

***H_0* = 69.8 ± 0.6** (stat) **± 1.6** (sys) **km s^{-1} Mpc^{-1}**

H_0 Tension | *TRGB vs. Cepheid*



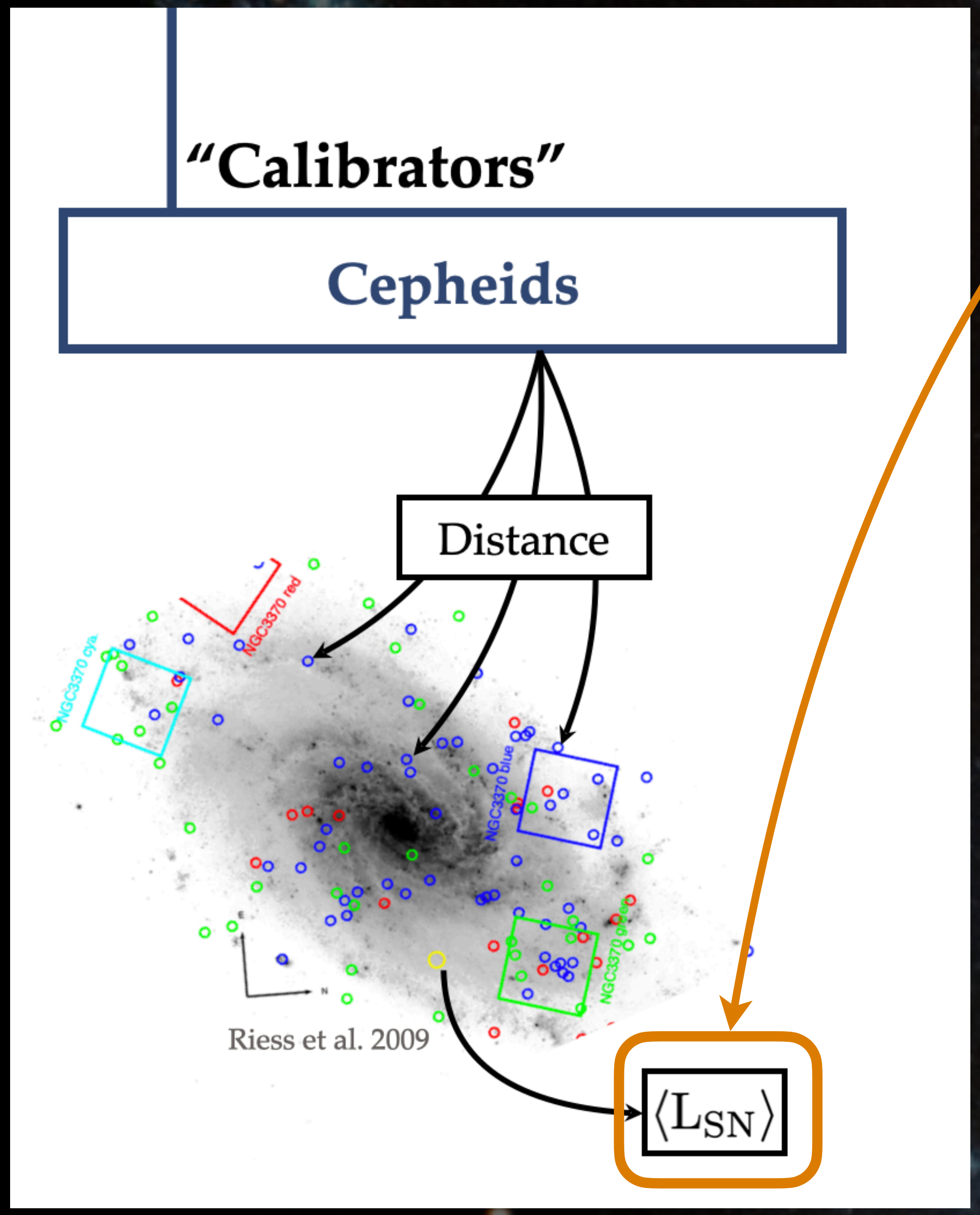


67.3±1.0
BOSS DR12 (2017)
67.4±0.5
Planck 2020
69.8±1.7
Freedman 2021
73.0±1.0
Riess et al. 2022
$67.4^{+4.1}_{-3.2}$
Birrer et al. 2020
73.3±1.8
Wong et al. 2020
$70.0^{+12.0}_{-8.0}$
Abbott et al. 2017
71.8±2.7
Pesce et al. 2020
No peculiar velocity correction
62.5 65.0 67.5 70.0 72.5 75.0 77.5 80.0 82.5
H_0 [km s^{-1} Mpc^{-1}]
Test the cosmological model
Strong Lensing is a "new" probe systematics ongoing
Sensitive to peculiar velocity correction
SNeIa's $\langle L_{SN} \rangle$ calibrated by:
BAO (z~1) | r_s
TRGB (z~0) | geometry
Cepheids (z~0) | geometry

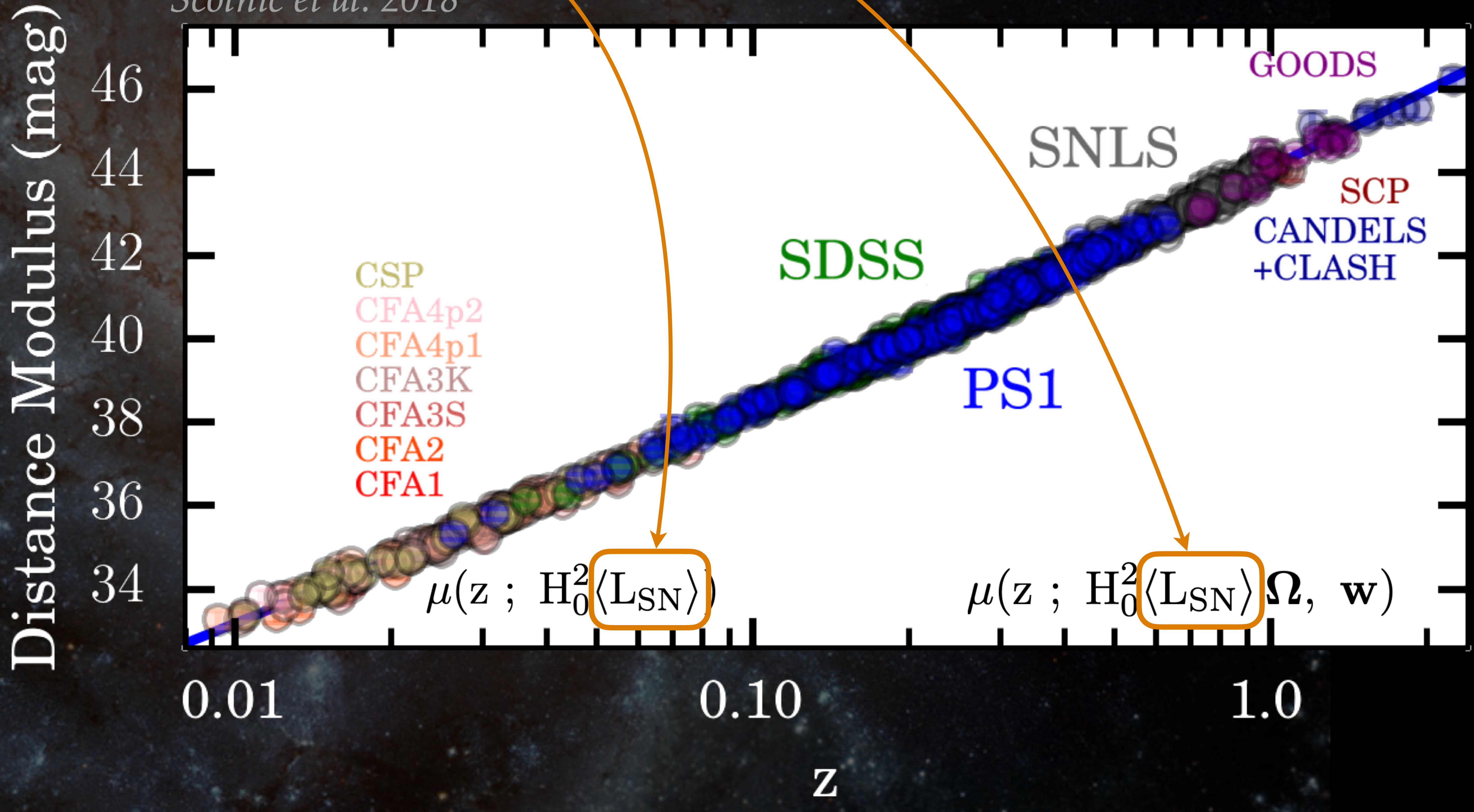

SN2011fe

The Progenitor issue | *Astrophysical biases*

Constant ?



Scolnic et al. 2018



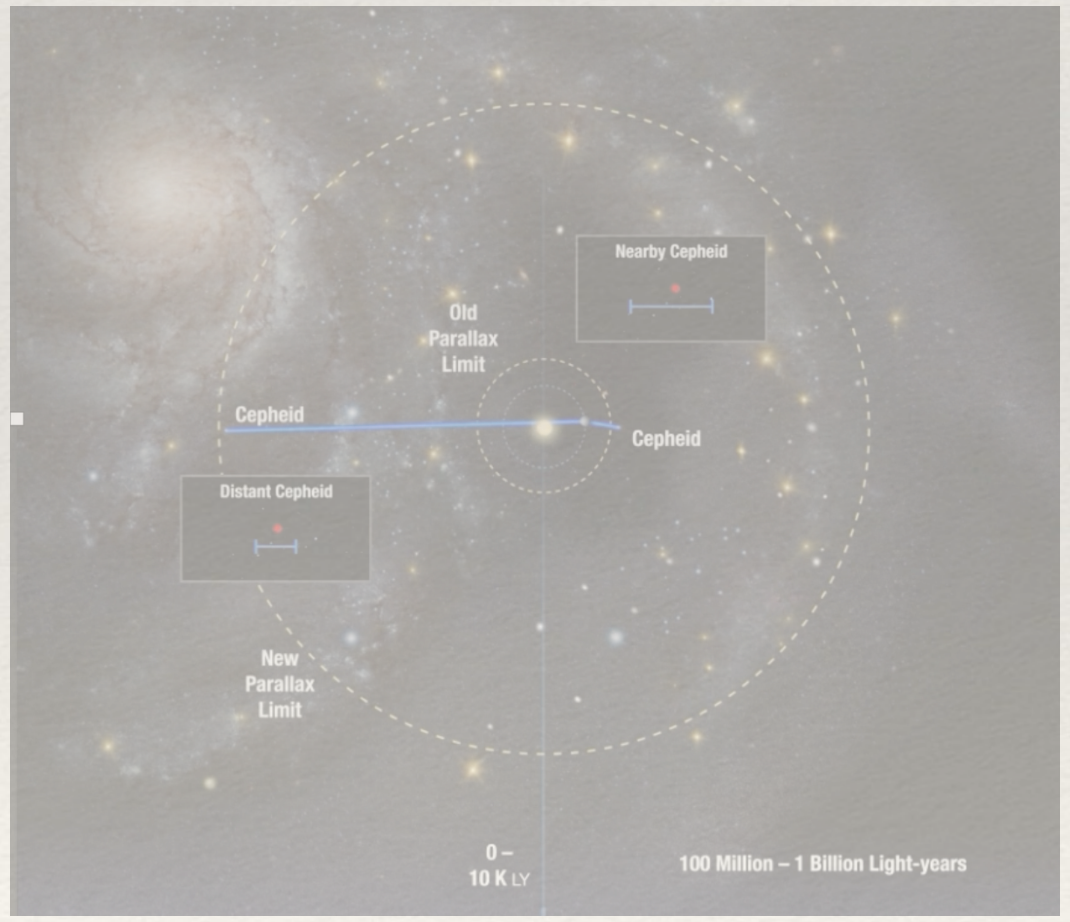
SN2011fe

Direct Distance Ladder | *SH0ES*

Calibrate the "Period-Luminosity" relation

"Geometry"

Parallaxes | D.E.B. | Maser



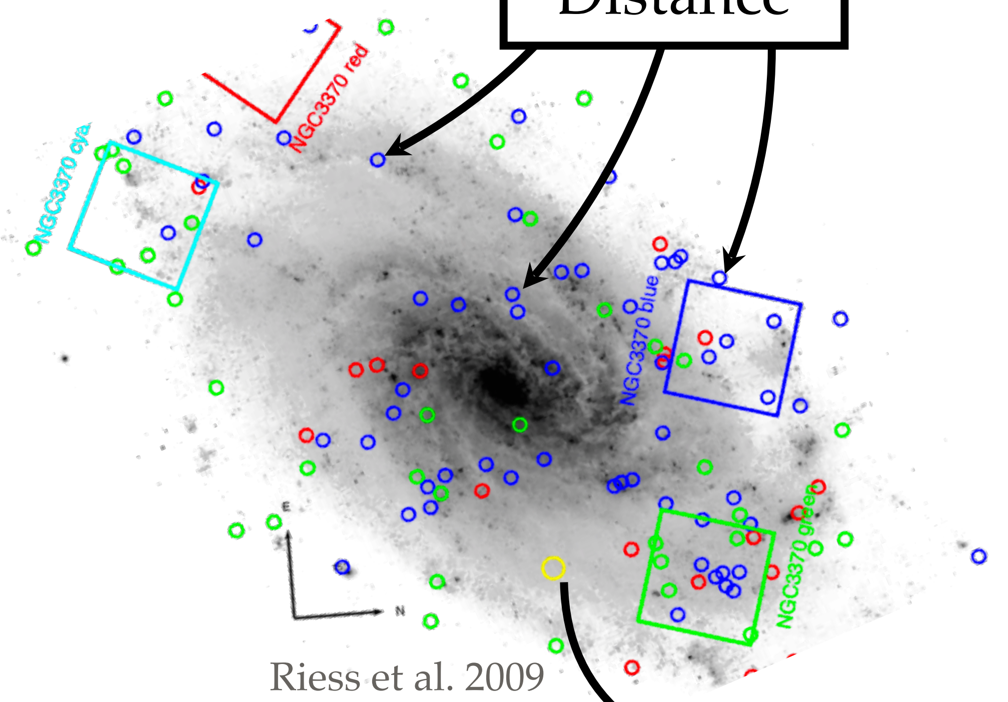
The SNe Ia "matching" problem

Measure "L_{SN}" — *Get "H_0"* → **distance**

"Calibrators"

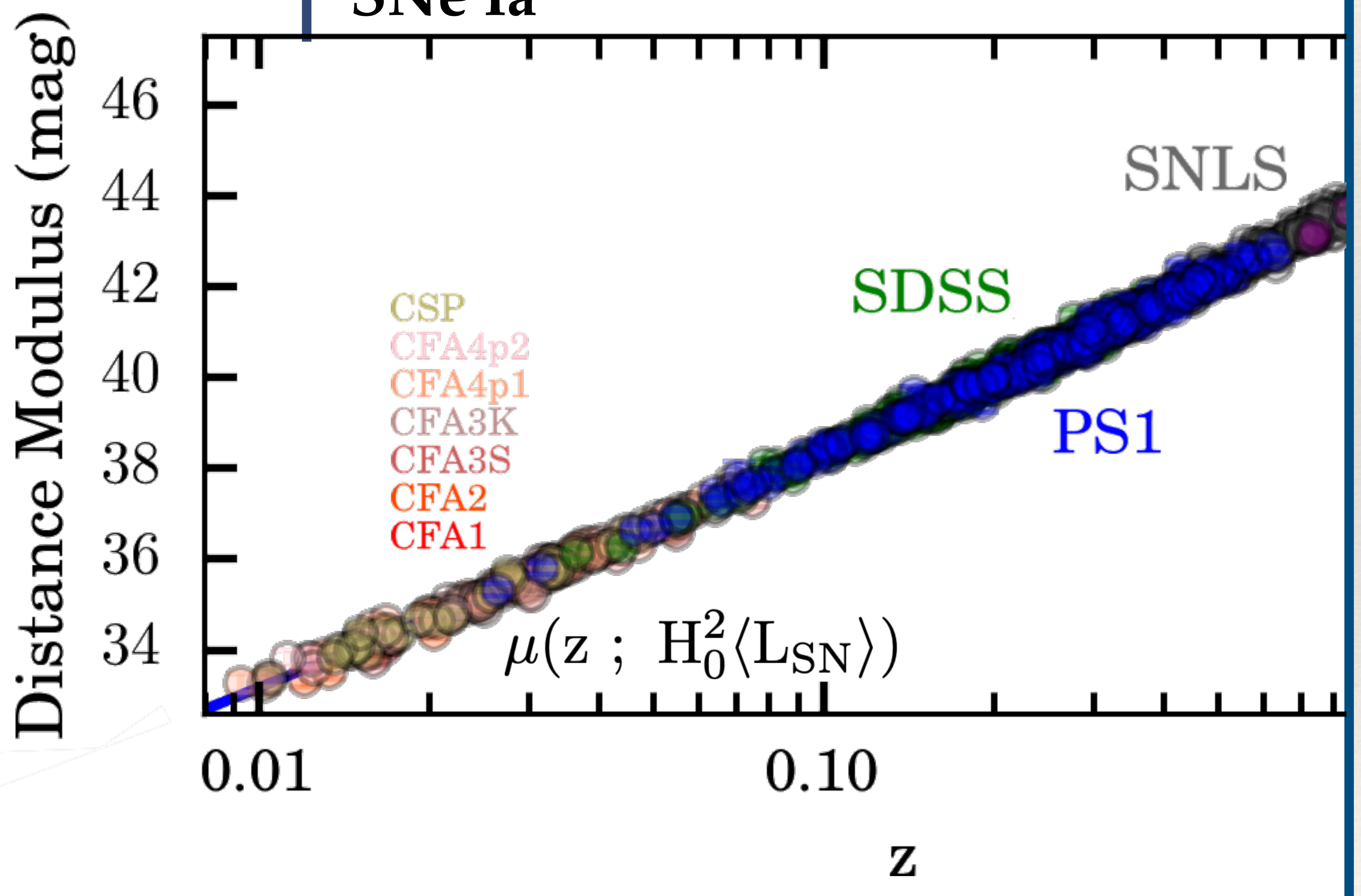
Cepheids

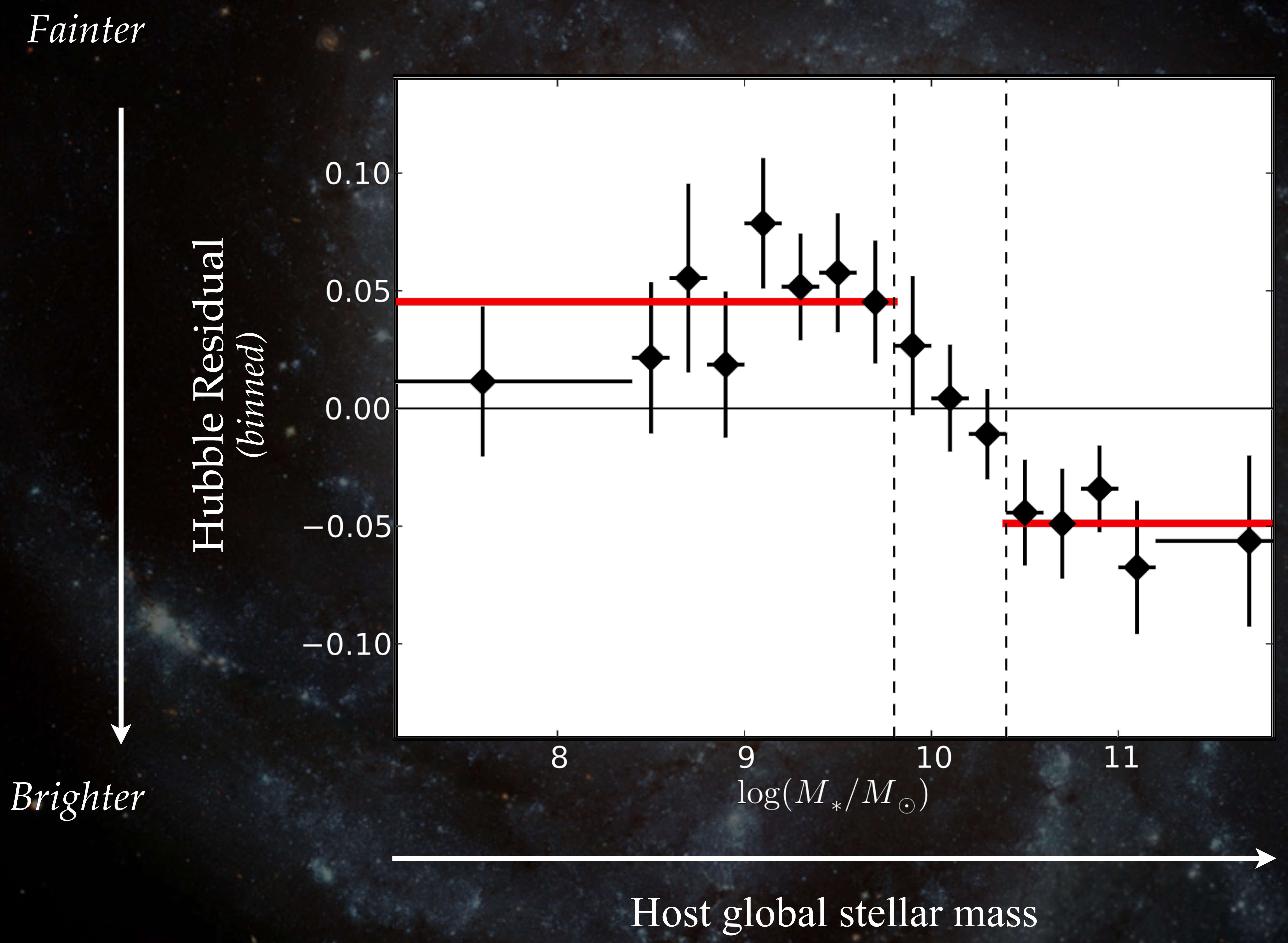
Distance


Riess et al. 2009

$\langle L_{SN} \rangle$

"SNe Ia"




Fainter
Brighter
Hubble Residual
(binned)
0.10
0.05
0.00
−0.05
−0.10
8
9
10
11
$\log(M_*/M_\odot)$
Host global stellar mass

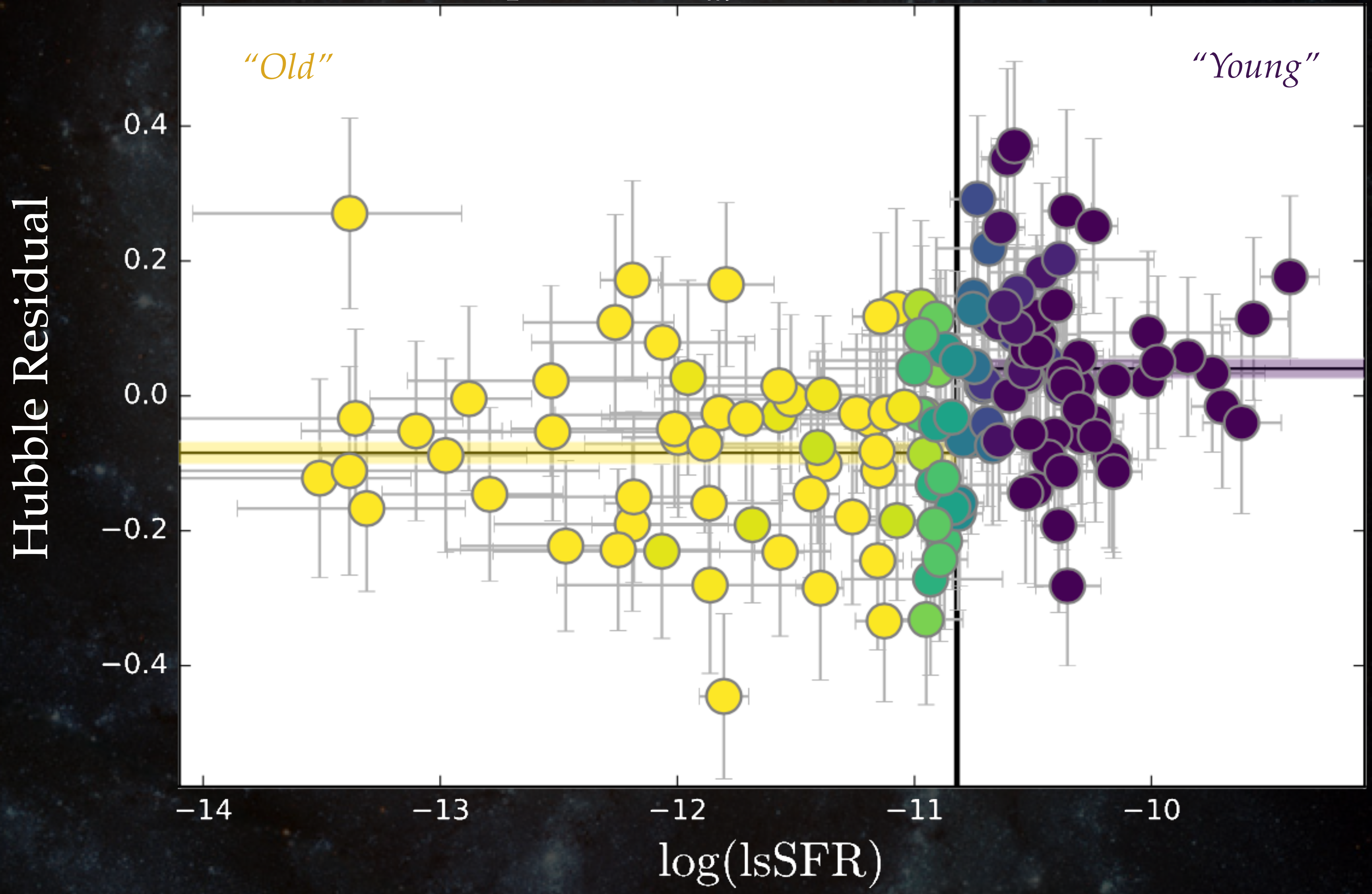
Rigault et al. 2020
Nicolas et al. 2021
Briday et al. 2022

"No" young stars → *High fraction of young stars*

Fainter

Brighter

Amplitude: $\Delta_m = 0.16 \pm 0.03$ mag

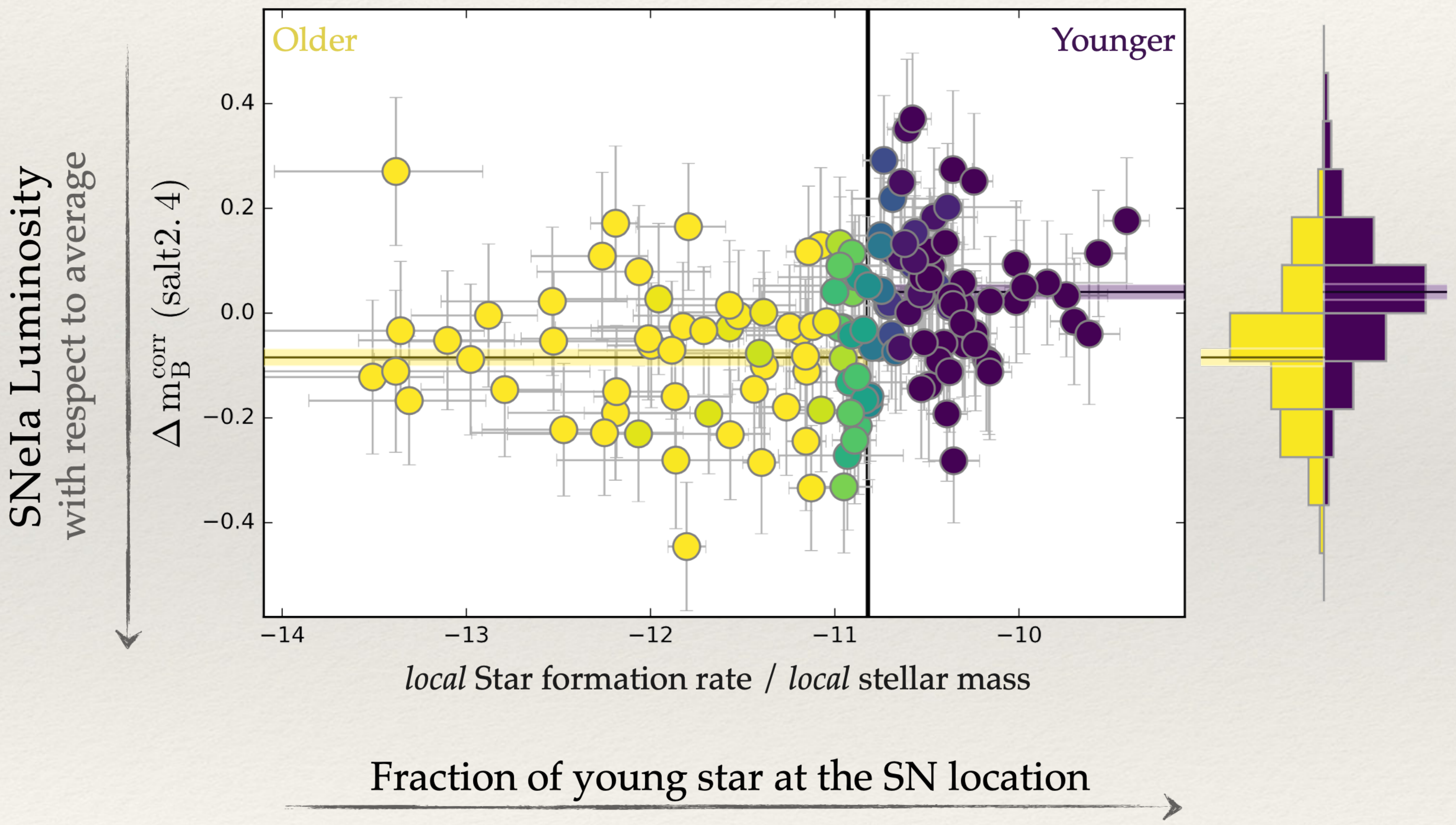


$$\text{lsSFR} \propto \frac{\#\ \text{Young Stars}}{\#\ \text{Old Stars}}$$

The Age Step & H_0

Rigault et al. 2015, 2020

non-zero at ~6σ level | Δ_Y = 0.16 ± 0.03



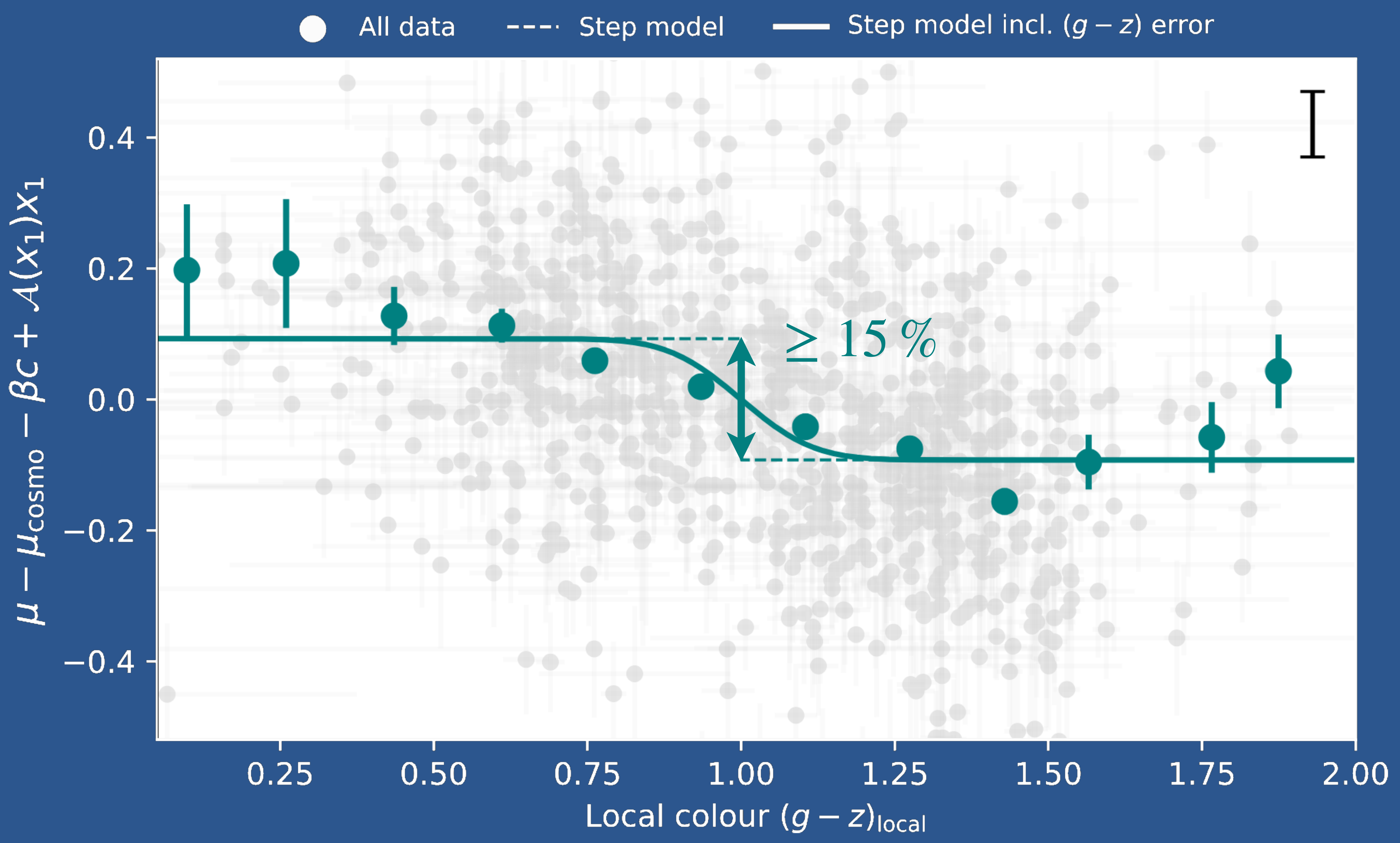
Impact on H0 of difference in SN Population

$$\log(H_0^{\mathrm{corr}}) = \log(H_0) - \frac{1}{5}\Delta f_y \times \Delta_\gamma$$

Magnitude offset between the two SNe Ia populations

Relative fraction of Young SNeIa between the Cepheid and HubbleFlow samples

~0.15mag

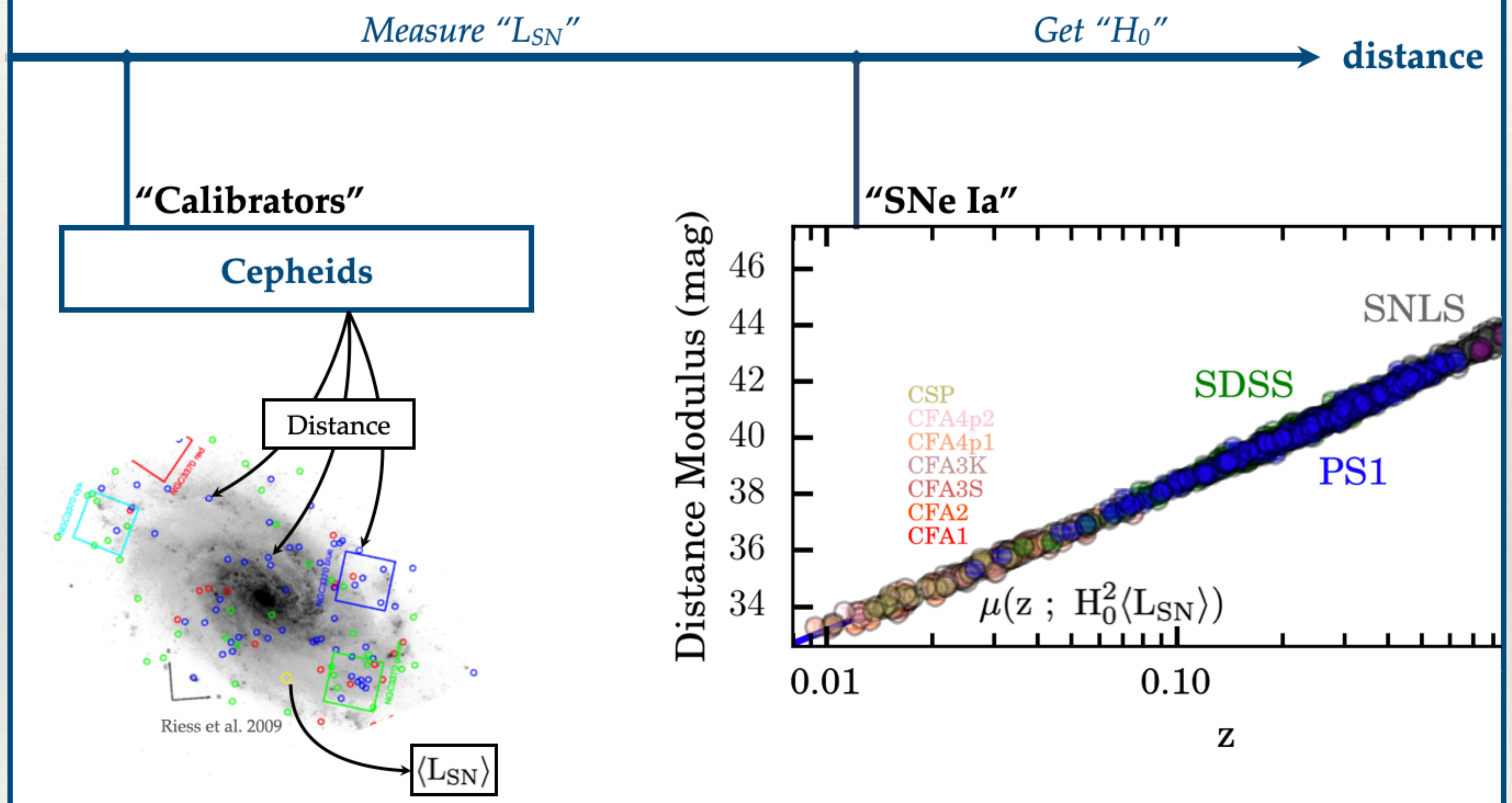


Ginolin et al. 2024 (a)

Astrophysical Bias affecting H_0

Rigault et al. 2015

The SNe Ia "matching" problem



SNeIa with Cepheids
strongly favour Young SNeIa

SNeIa In Hubble Flow
All kinds of SNe Ia

3% bias on H_0

So a **2 km s^{-1} Mpc^{-1}** shift

Total current SH0ES error budget
1.04 km s^{-1} Mpc^{-1}

SH0ES "corrected"
~71 ± 1.5 km s^{-1} Mpc^{-1}

Rigault et al. in prep. | Rigault et al. 2015, 2020

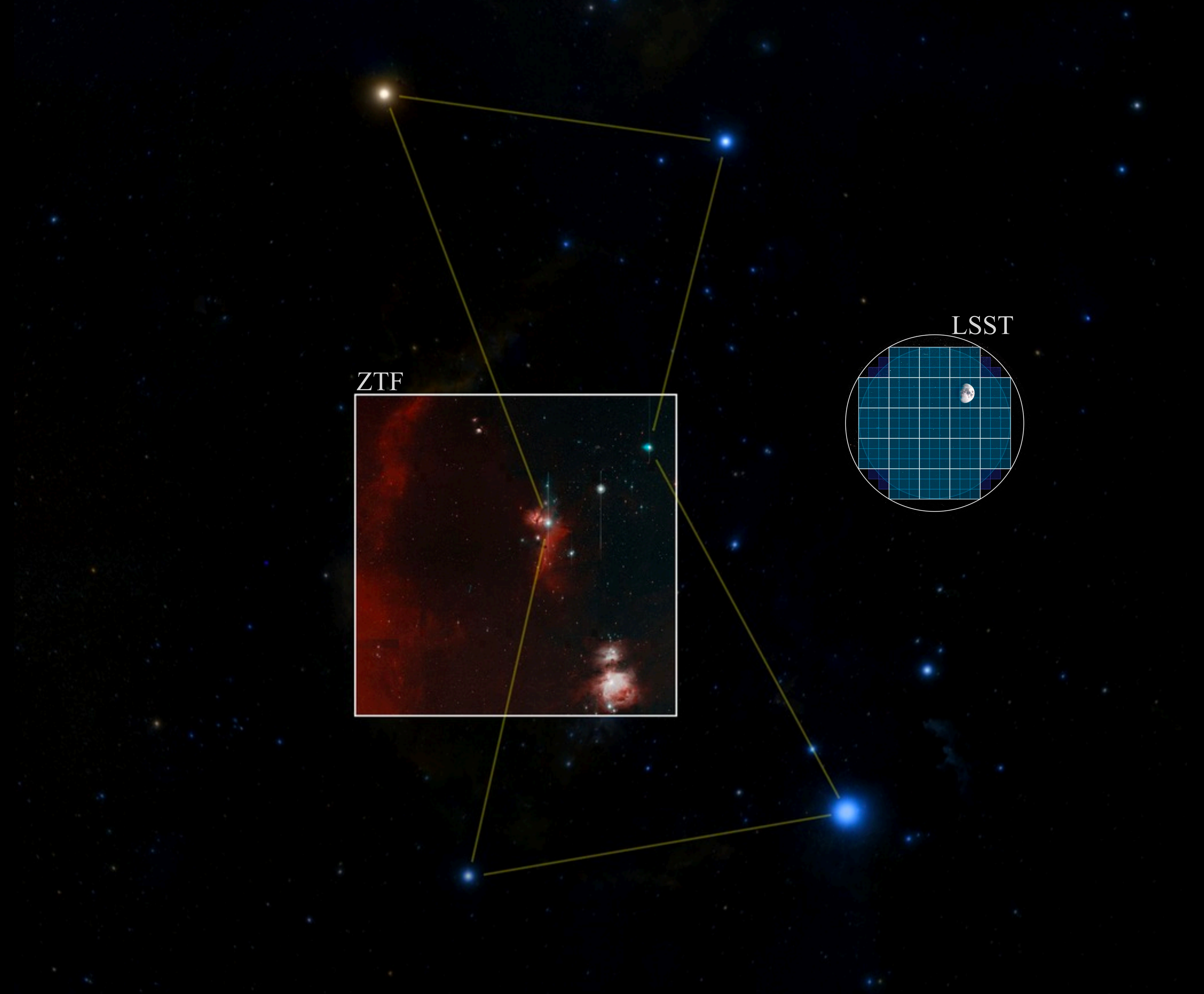
SH0ES rebuttal

"If we mimic the Cepheids selection function and only take Hubble flow SNe Ia from *Spiral* hosts, H_0 reduces by 0.5%"

Riess et al. 2022 | Riess et al. 2016, 2019

What’s next ?

Zwicky Transient Facility (ZTF) is acquiring ~1000 SNeIa per year at z<0.1 since 2018



ZTF H_0

Pure **ZTF**
Pure **Volume limited**

Get an independent measurement of L_{SN}

No selection effect

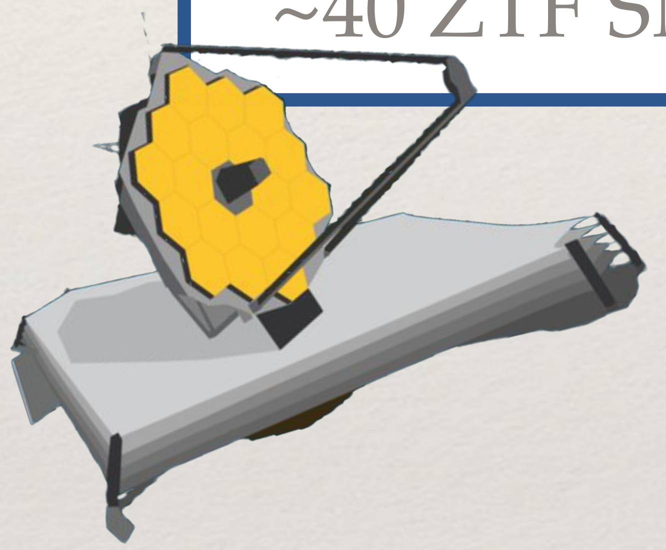
Self-consistent calibration

Measure L_{SN}

Volume limited
ZTF SNeIa < 60 Mpc

Tip Red Giant Branch
(doable in any galaxy)

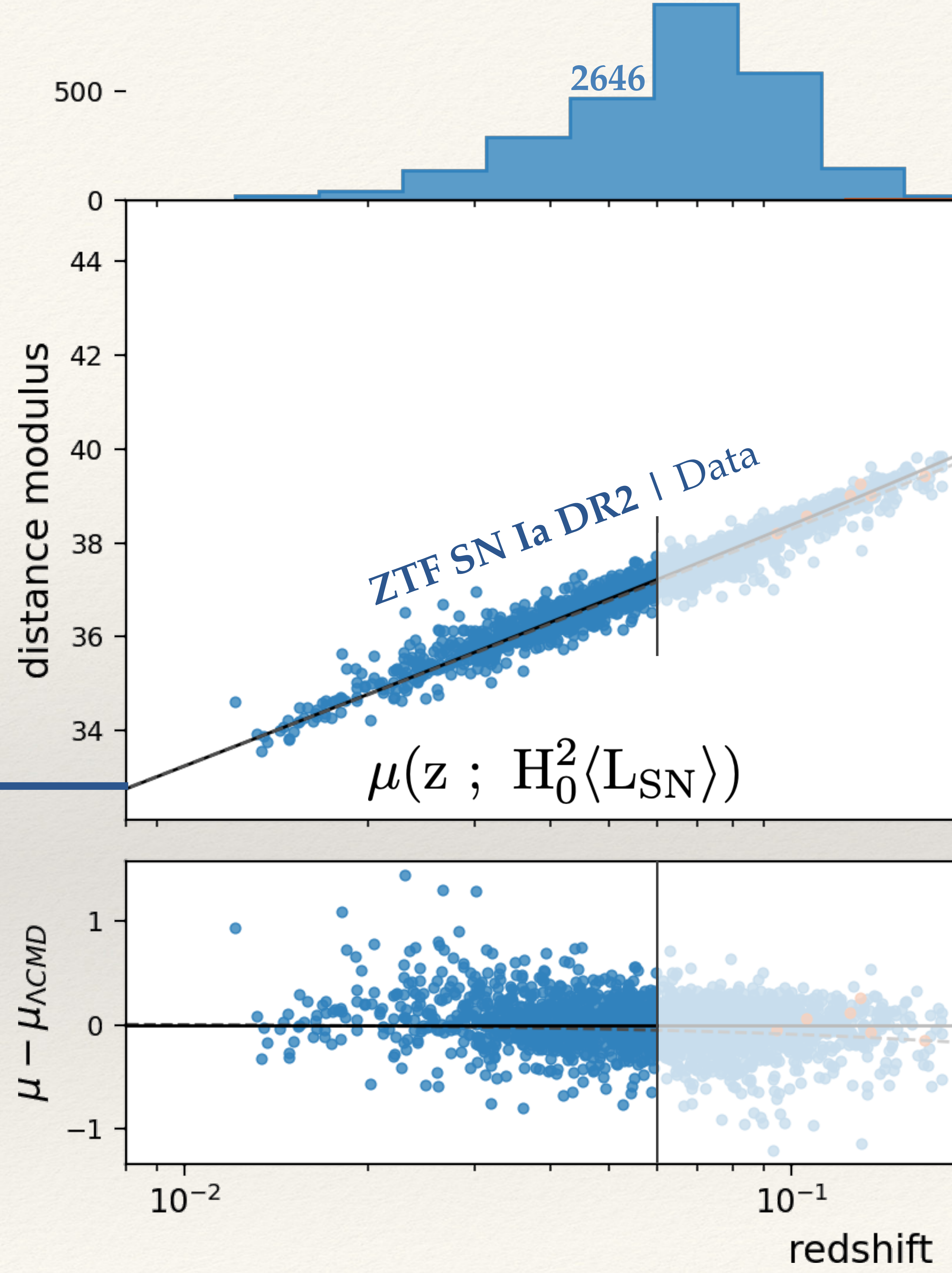
~40 ZTF SNe Ia | *need JWST*



Get H_0

Volume limited
ZTF SNeIa z < 0.06

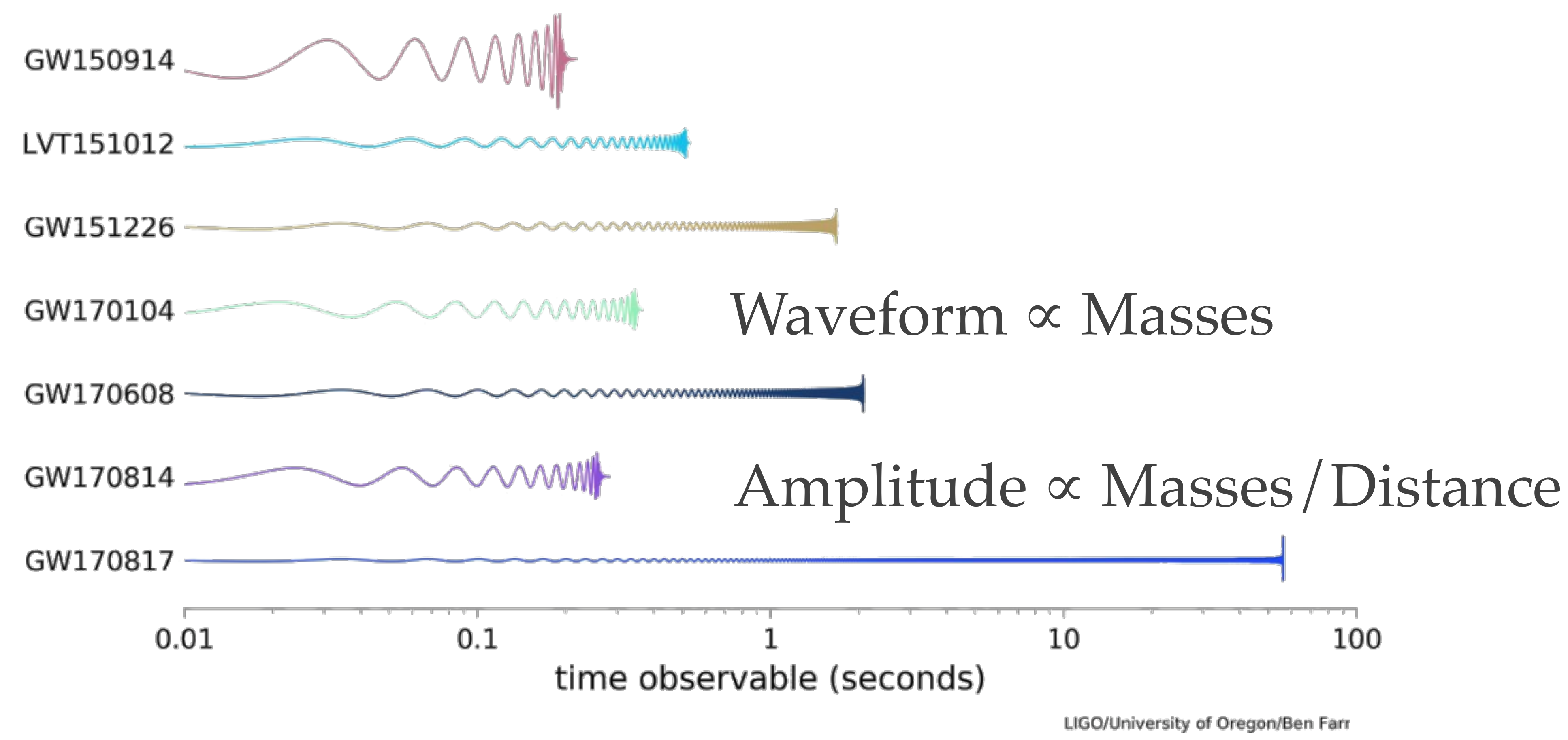
O(1000) ZTF SNe Ia | *ready*



Gravitational Waves & ElectroMagnetism | H_0

Gravitational Waves

$\mathbf{d_L}$

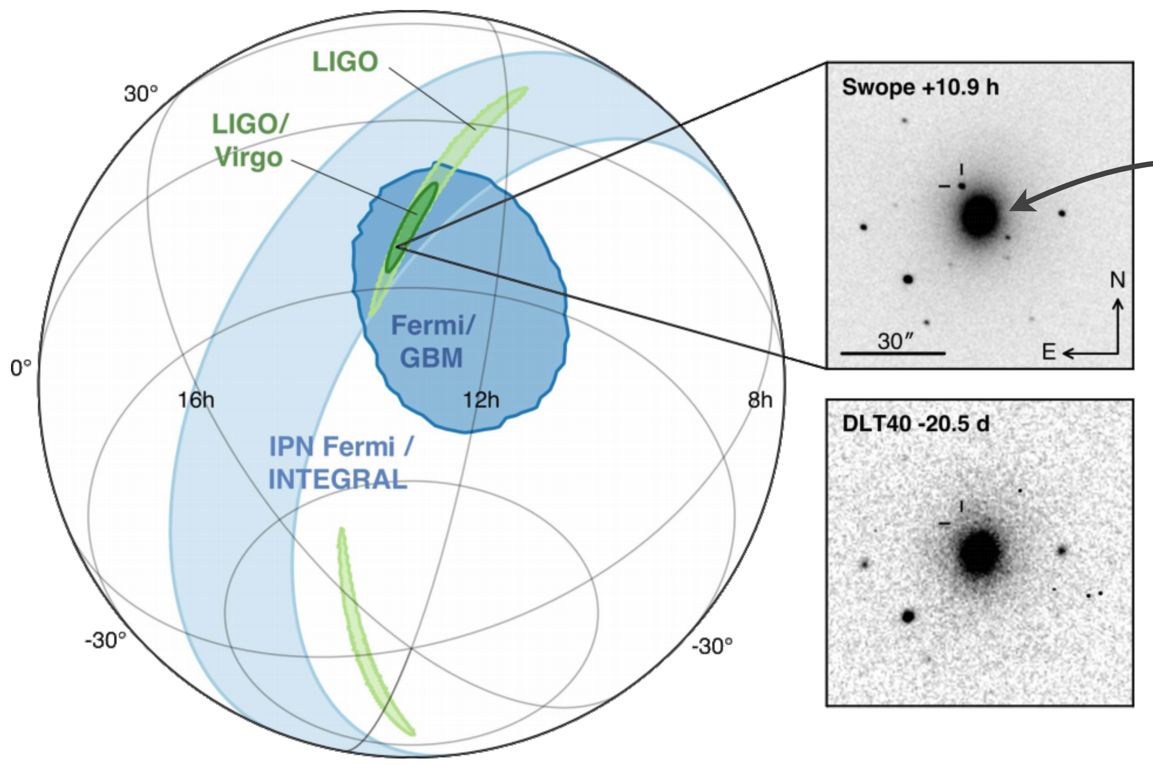


Waveform ∝ Masses

Amplitude ∝ Masses / Distance

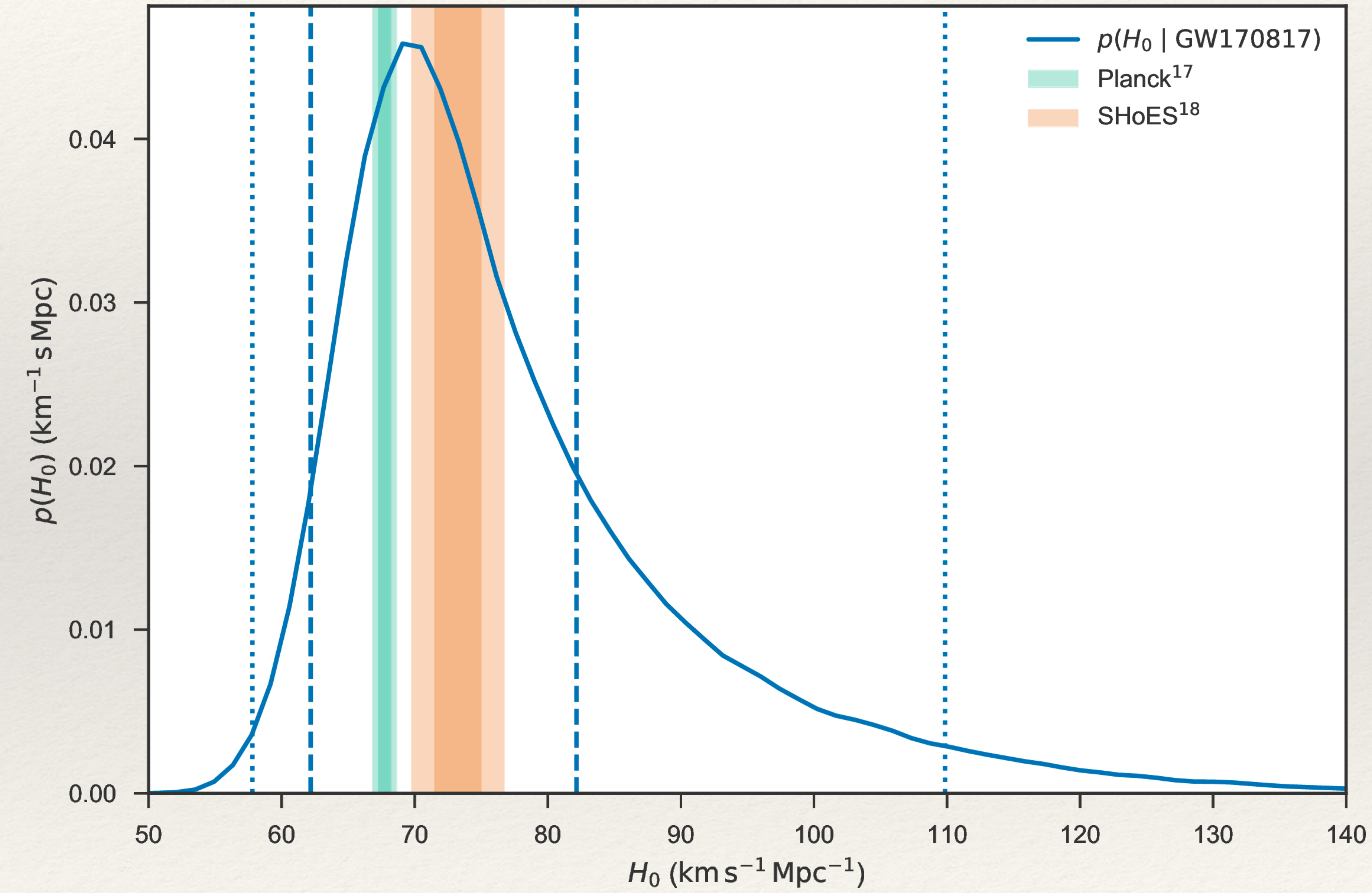
Optical Counterpart

z



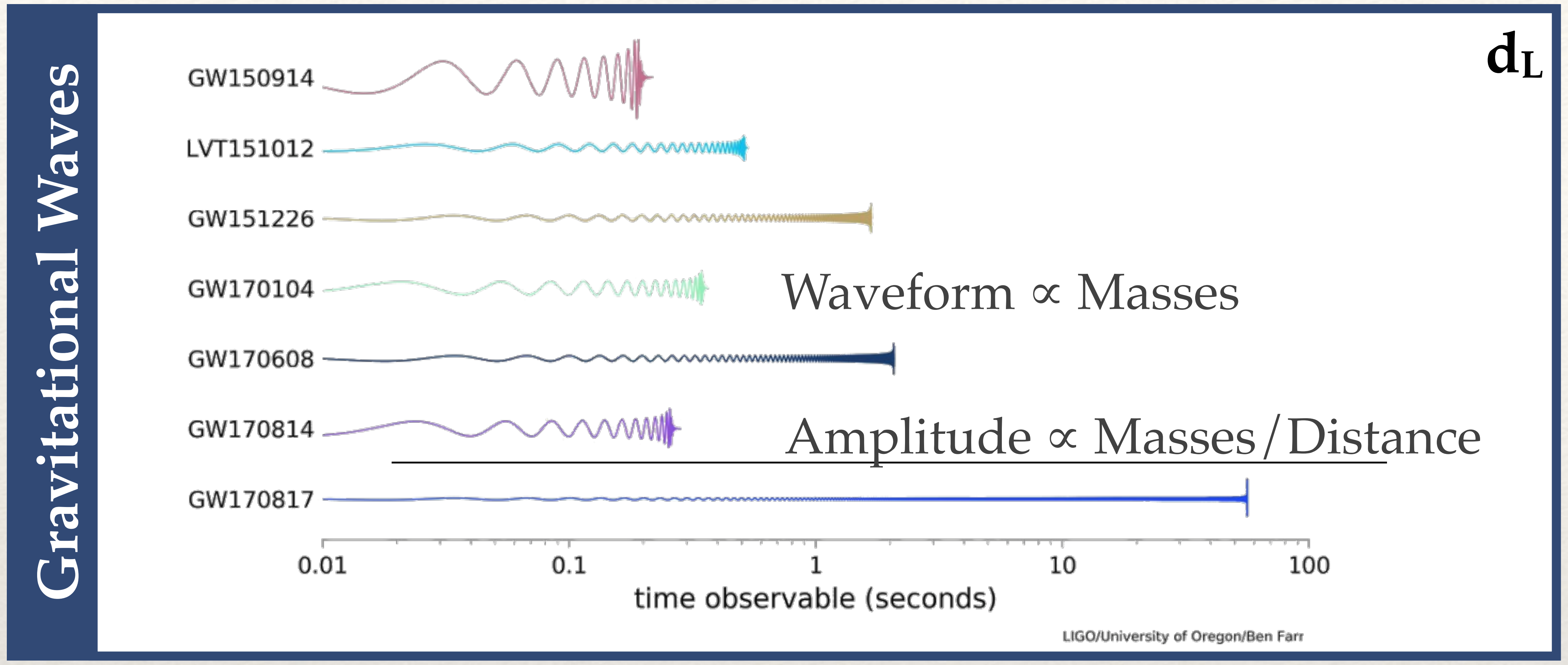
Redshift

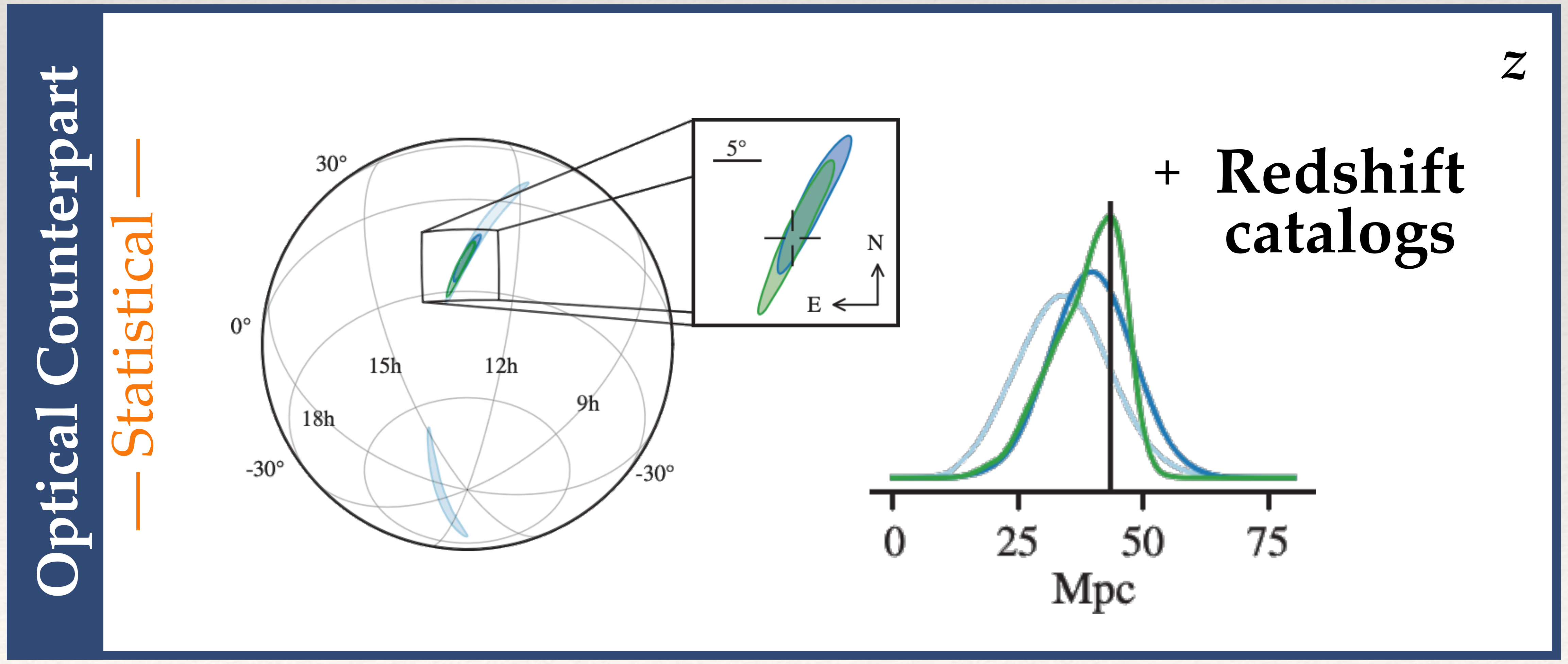
$$v_H = H_0 d_L$$

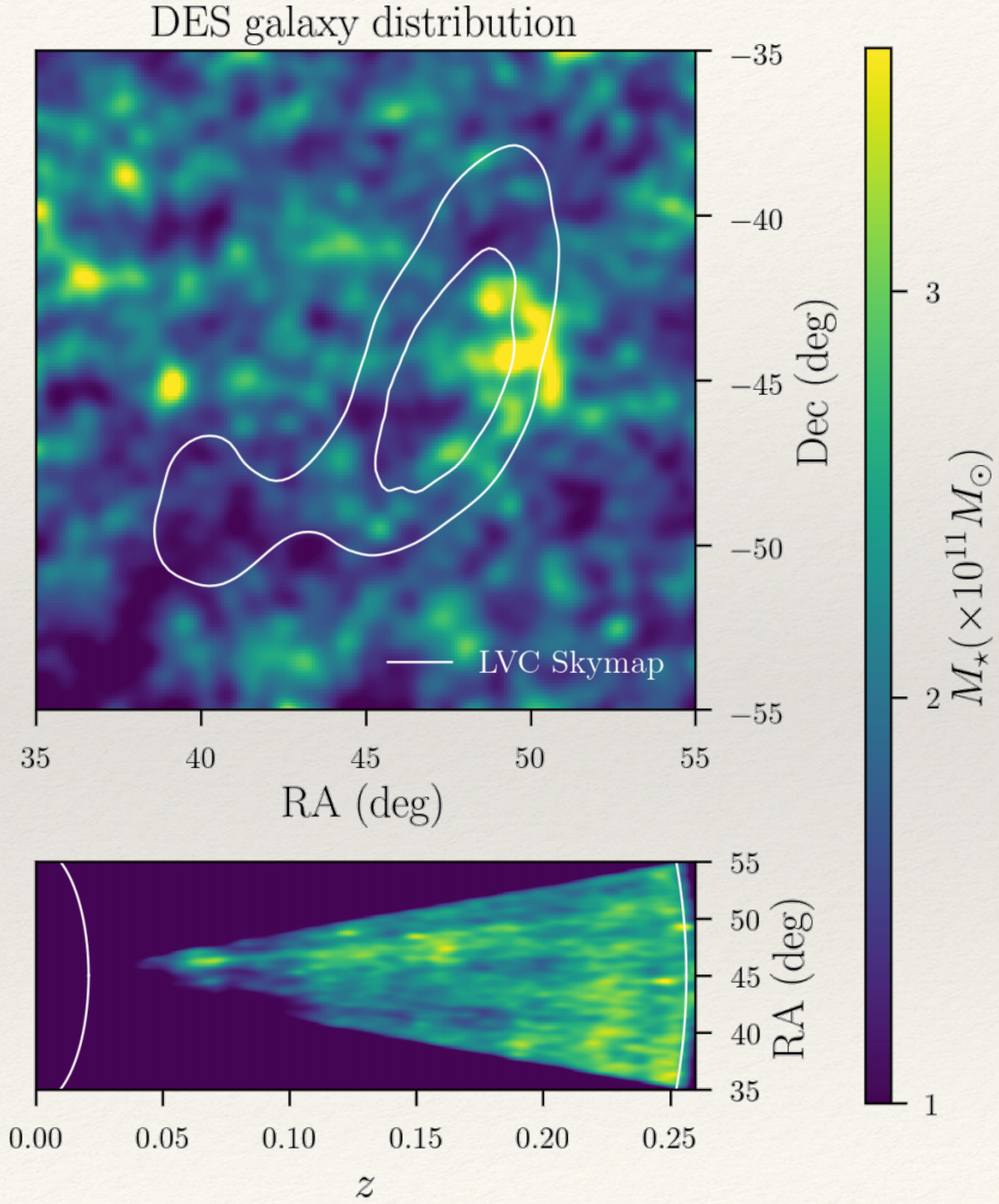


Gravitational Waves & ~~ElectroMagnetism~~ | H_0

Works with any Merger

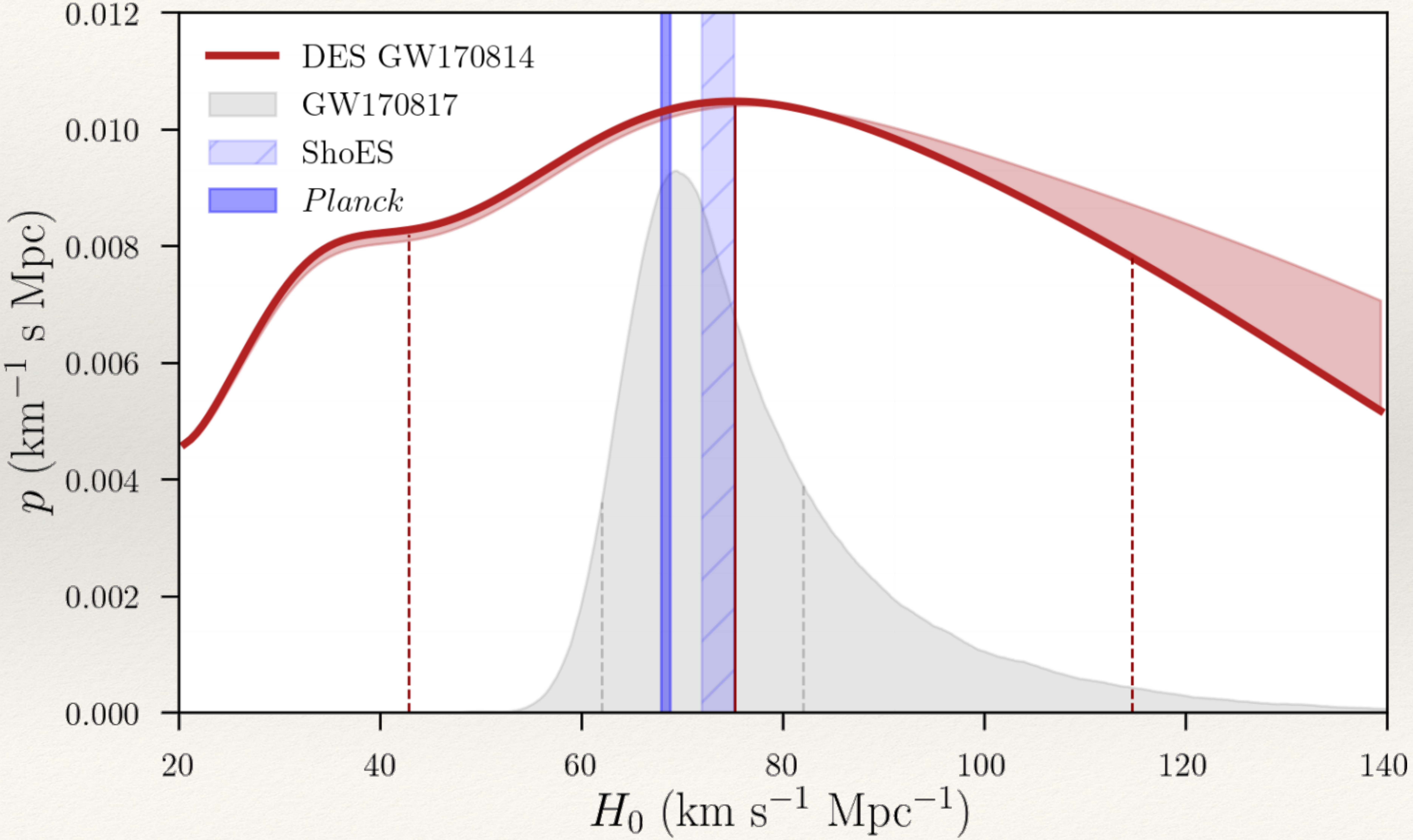






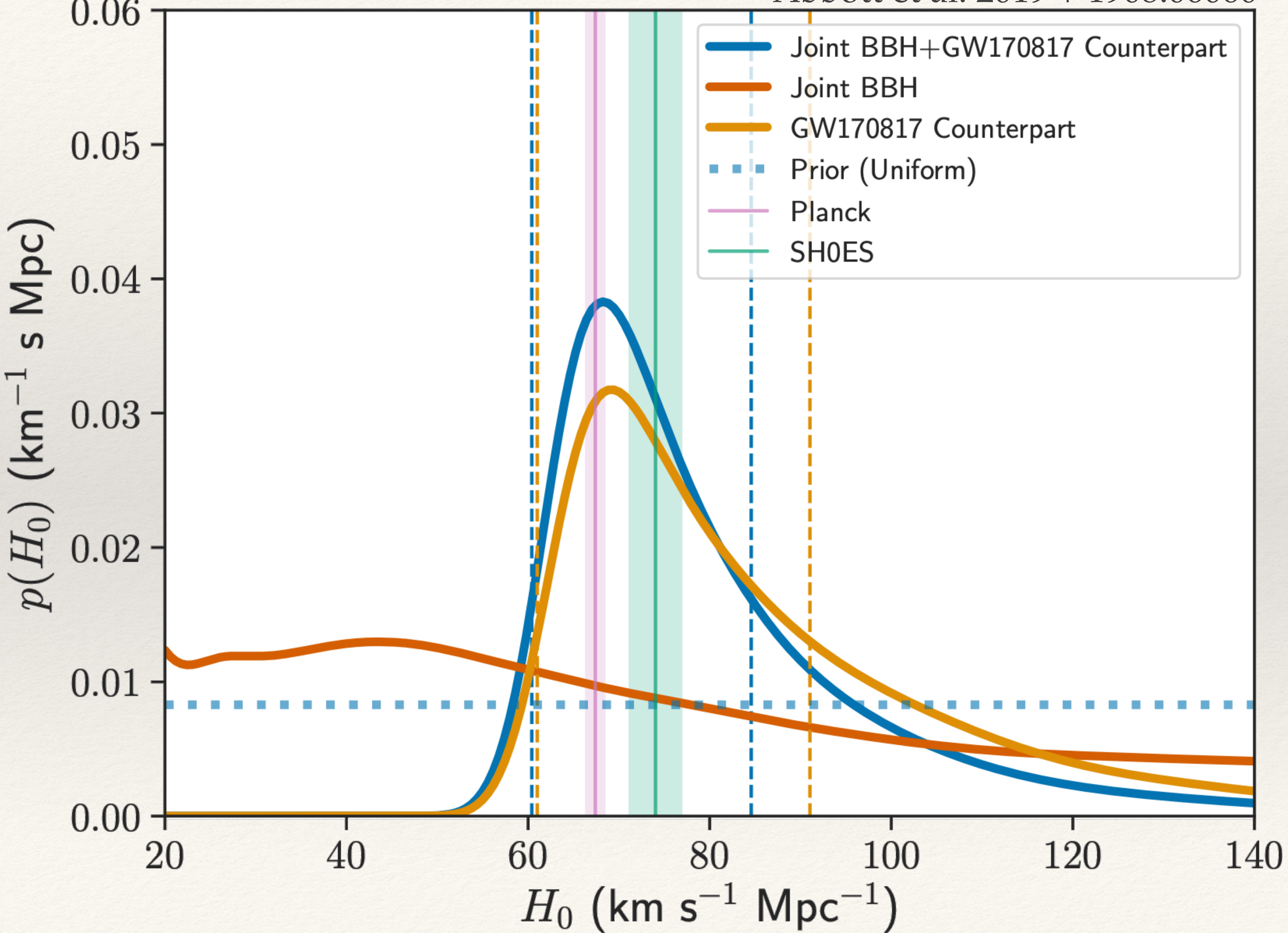
Direct measurement of H_0 | *without counterpart*

Abbott et al. 2019 | 1901.01540

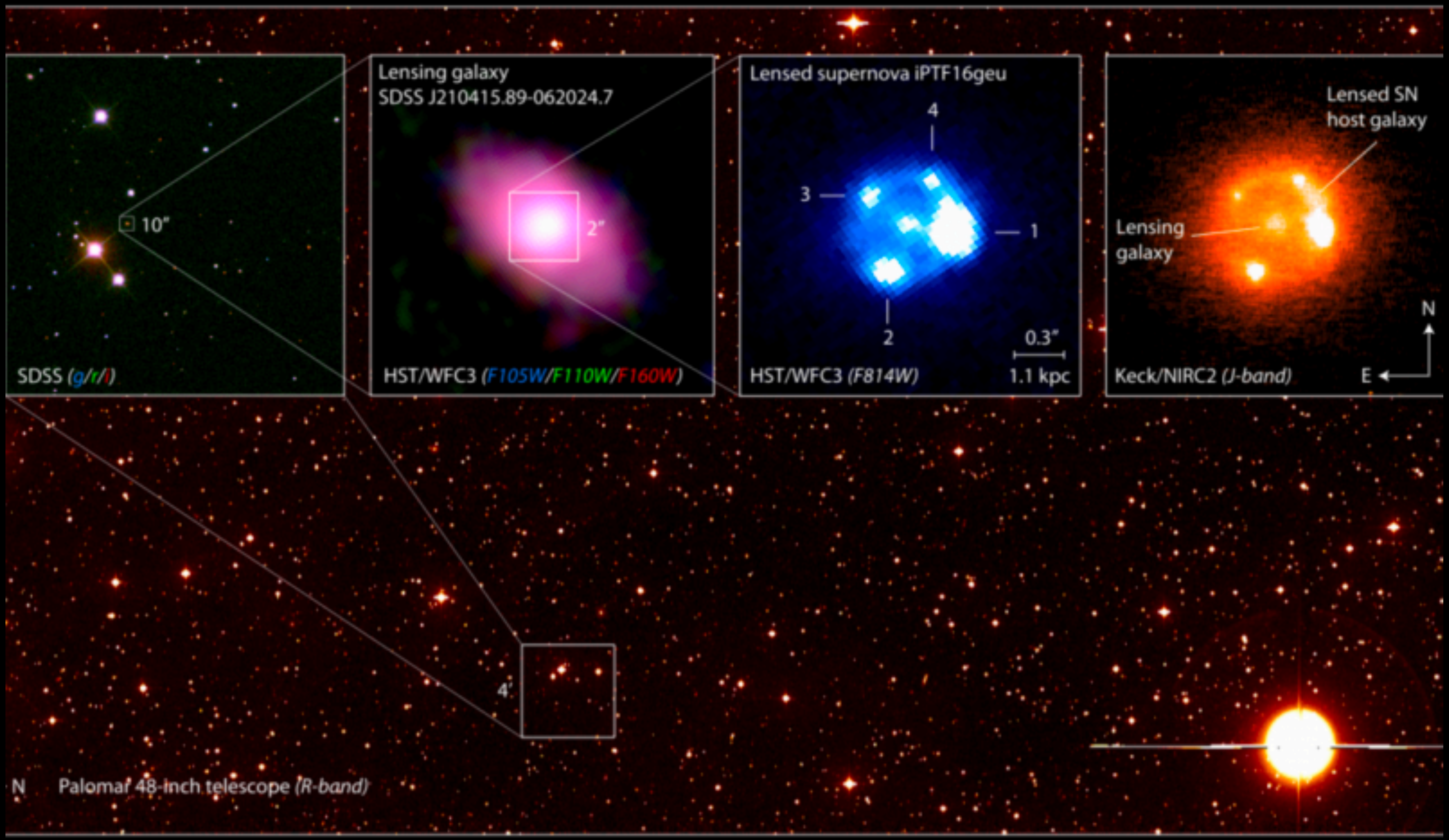


Direct measurement of H_0 | *without counterpart*

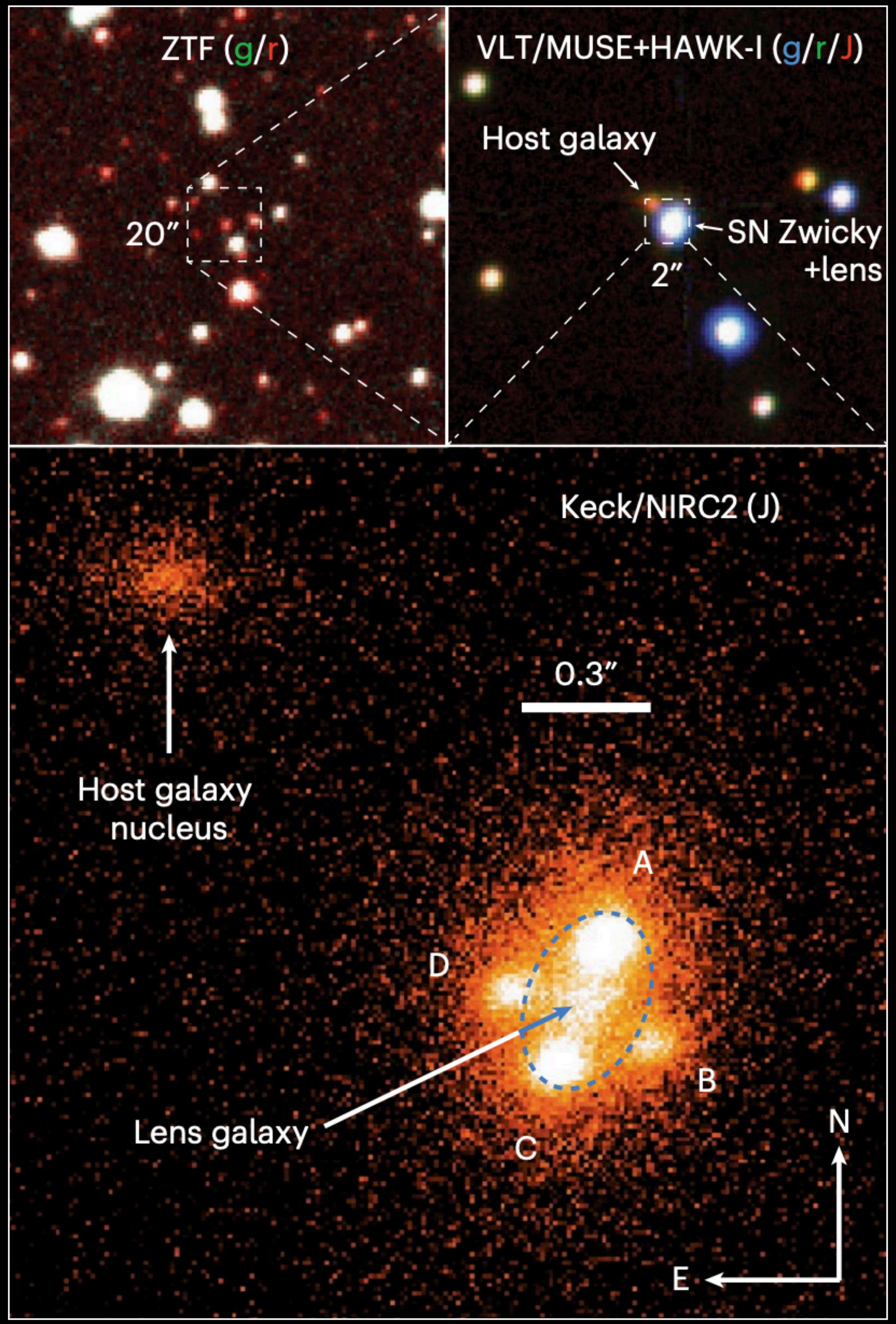
Abbott et al. 2019 | 1908.06060



iPTF16geu | Goobar et al. 2017

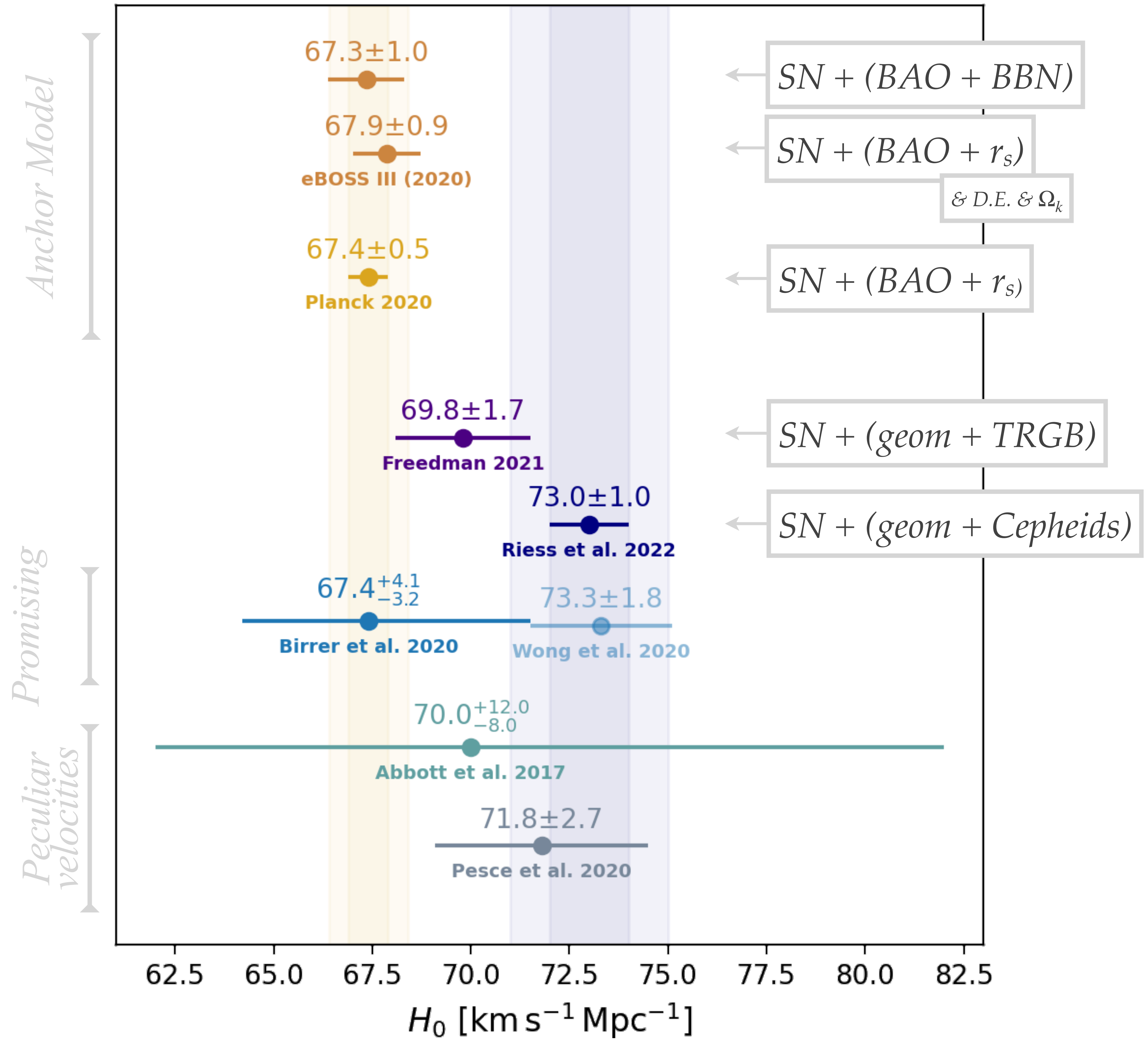


SN Zwicky | Goobar et al. 2023



Conclusion | *Hubble-Lemaître Constant*

H_0 Tension



— New fundamental Physics

No simple solutions so far

These solving H_0 break σ_8

— Type Ia Supernovae a key for H_0

Understanding their systematics is of paramount importance for cosmology

ZTF is about to change the game

— Systematic Uncertainties

Must be multiple sources

e.g. : age-bias for SNe Ia

& lensing modeling for strong lensing