The H_0 tension

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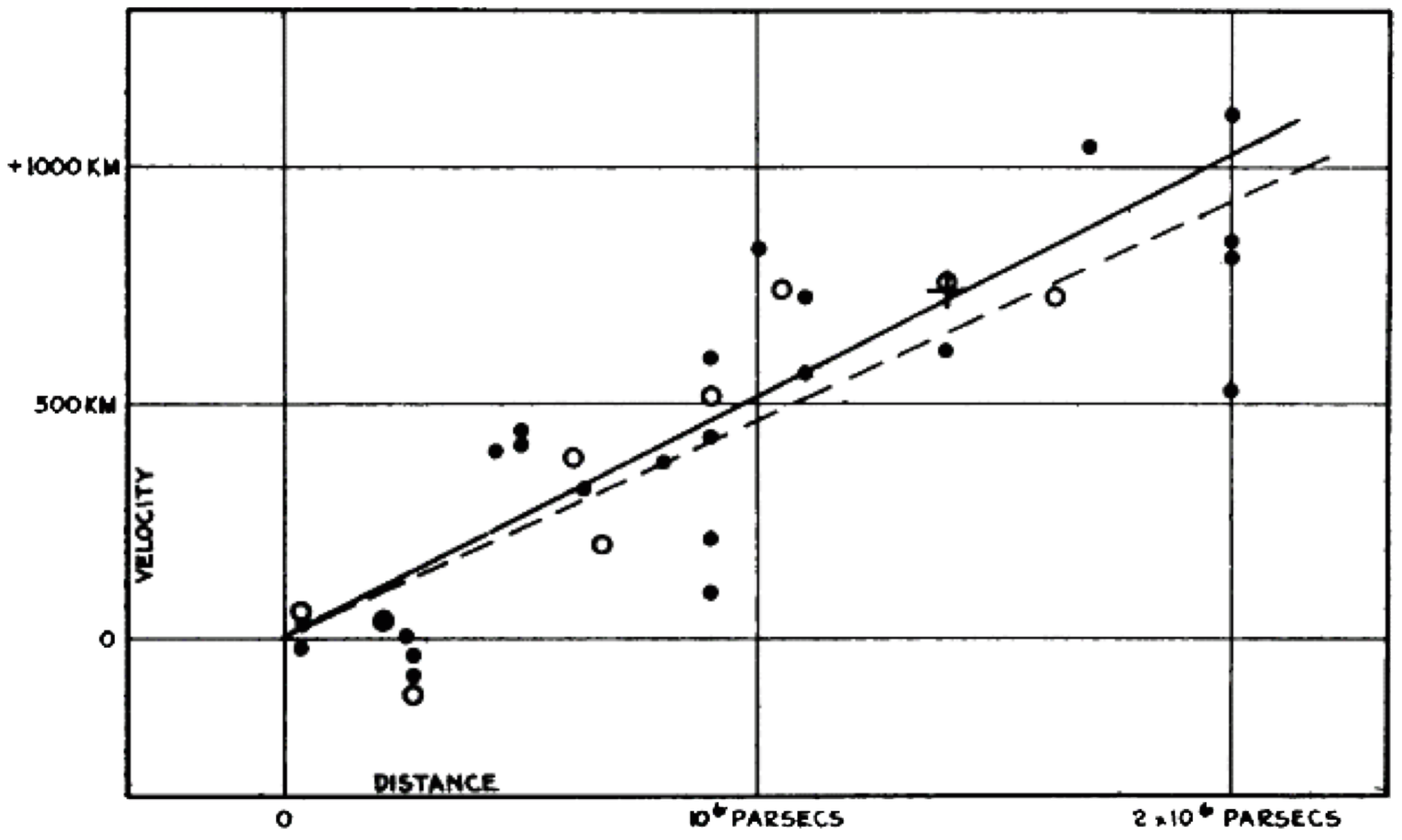
This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement n°759194 - USNAC)

Two approaches | H_0

Direct Method

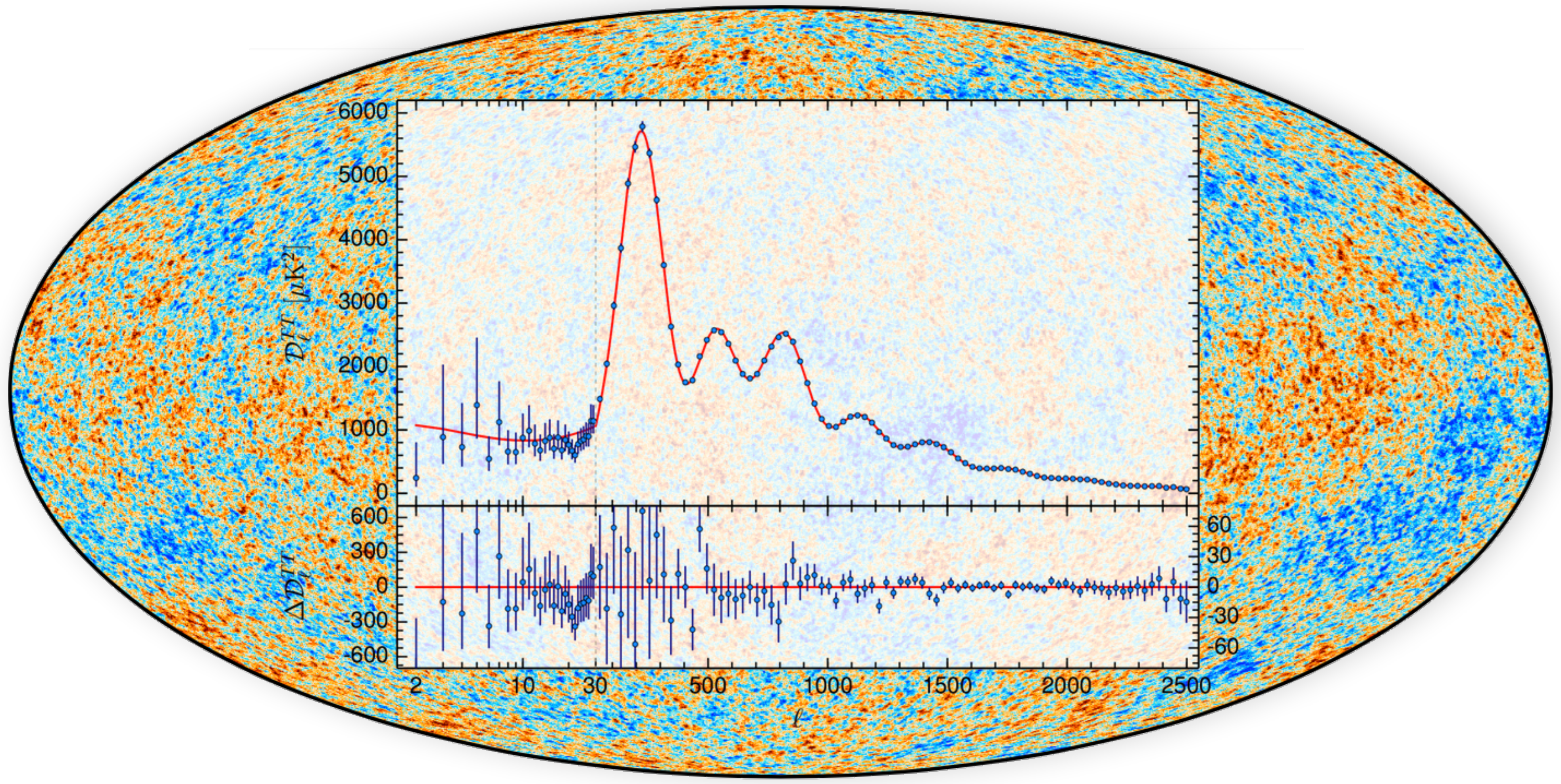
$$H_0 \sim d_l / v_h$$



Redshifts & Distances

Indirect Method

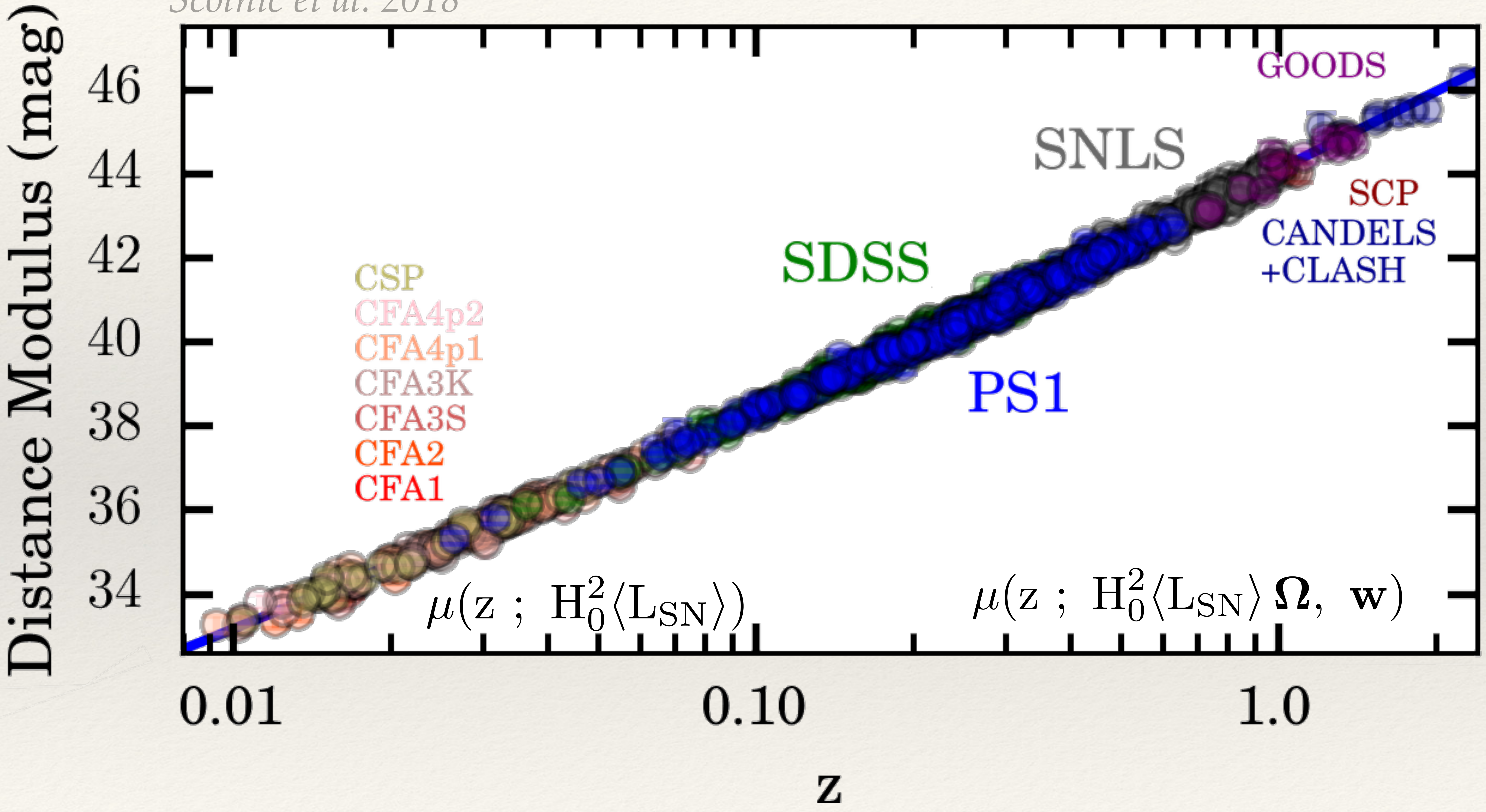
$$H(z) = H_0 \times \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}$$



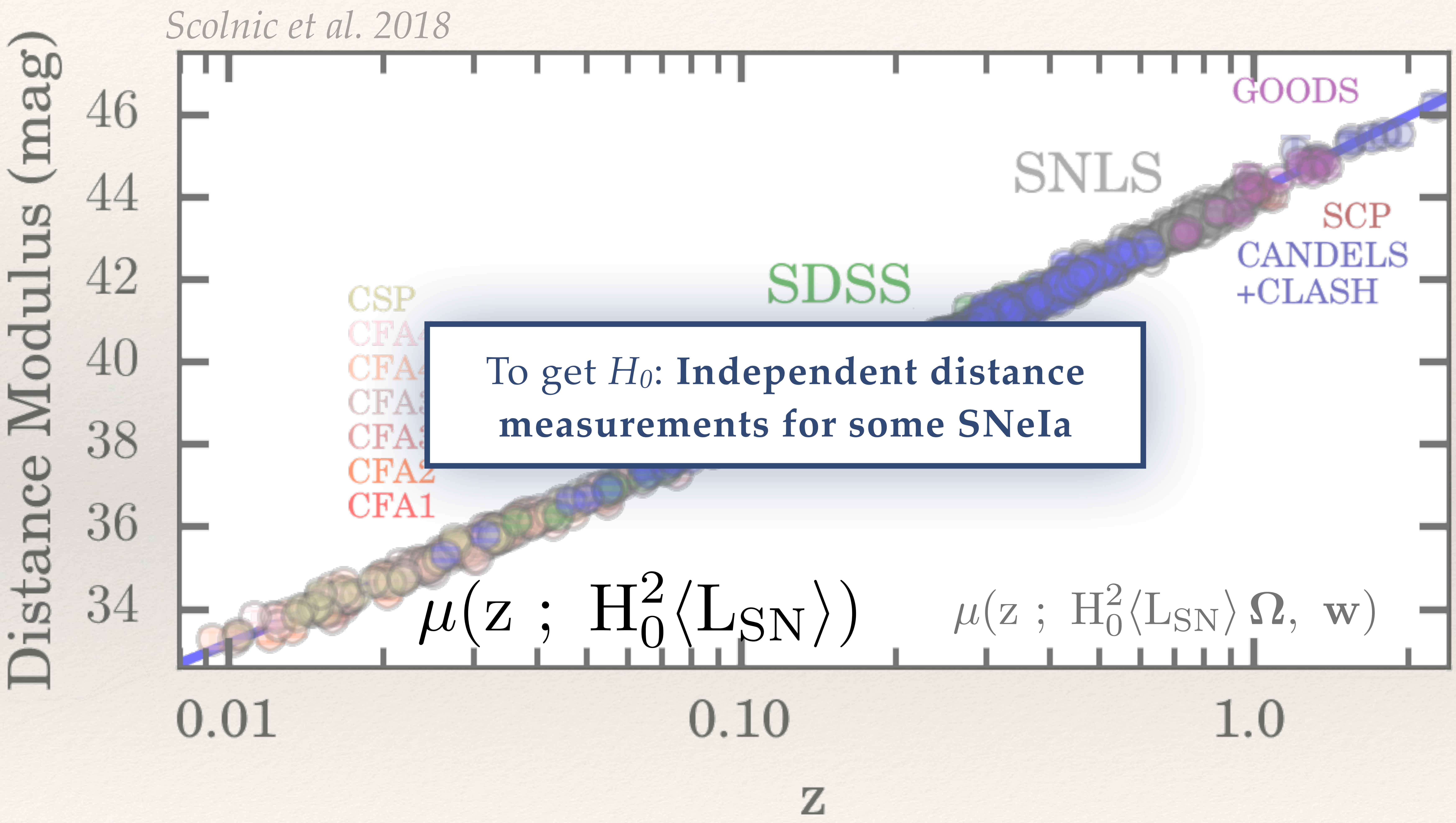
Model & High redshift anchoring

Type Ia Supernova Cosmology

Scolnic et al. 2018



Type Ia Supernova Cosmology | H_0



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

Direct Distance Ladder | *SH0ES*

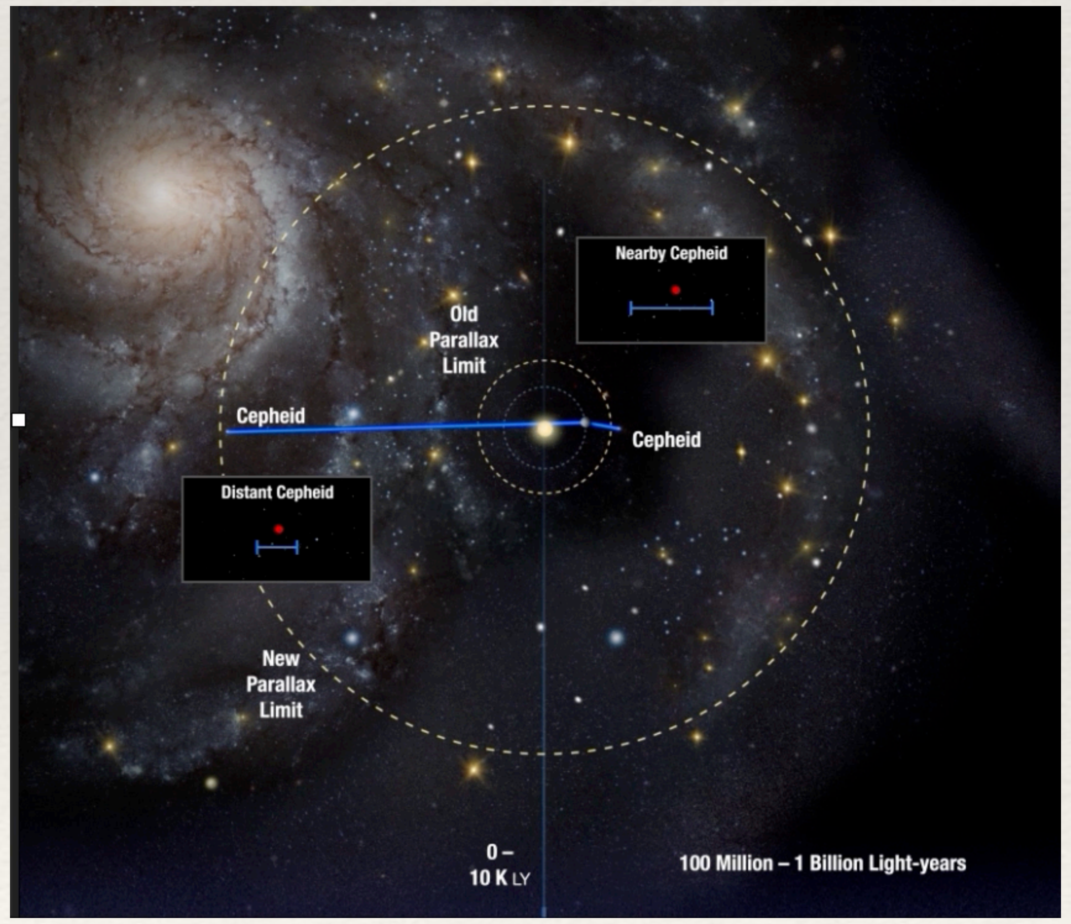
Get independent distances for SNe Ia

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

"Geometry"

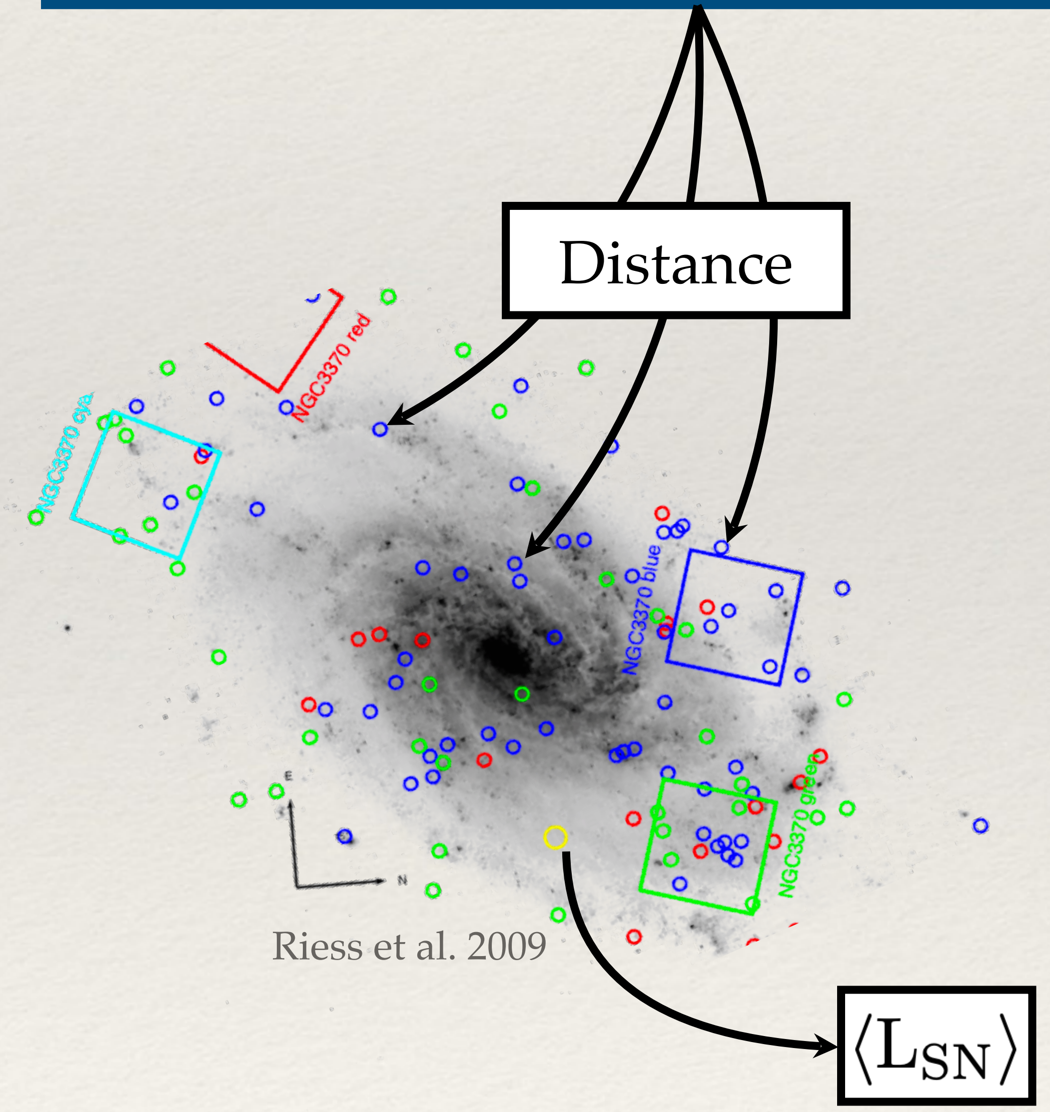
Parallaxes | D.E.B. | Maser

Source: eso



"Calibrators"

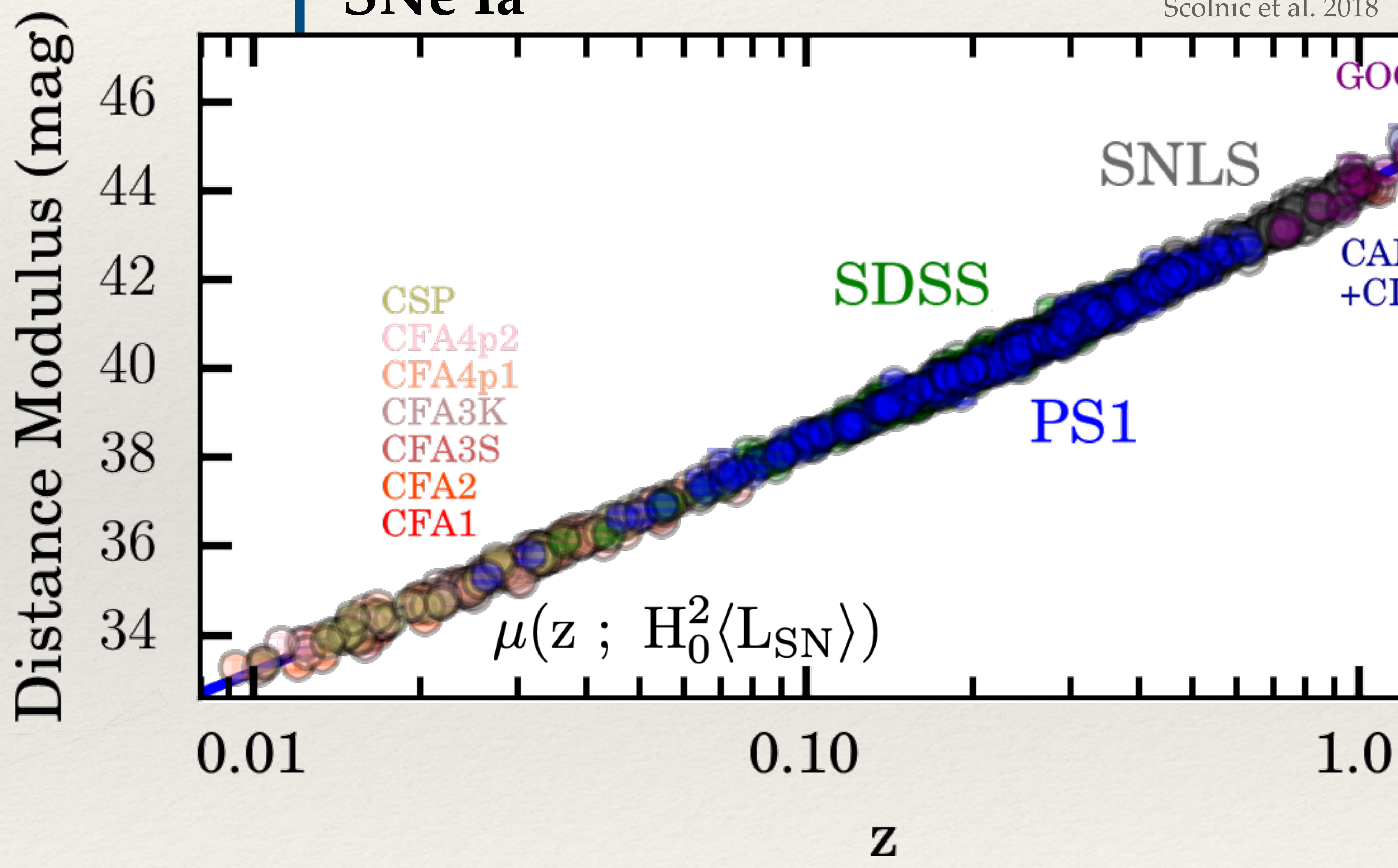
Cepheids



Riess et al. 2009

"SNe Ia"

Scolnic et al. 2018

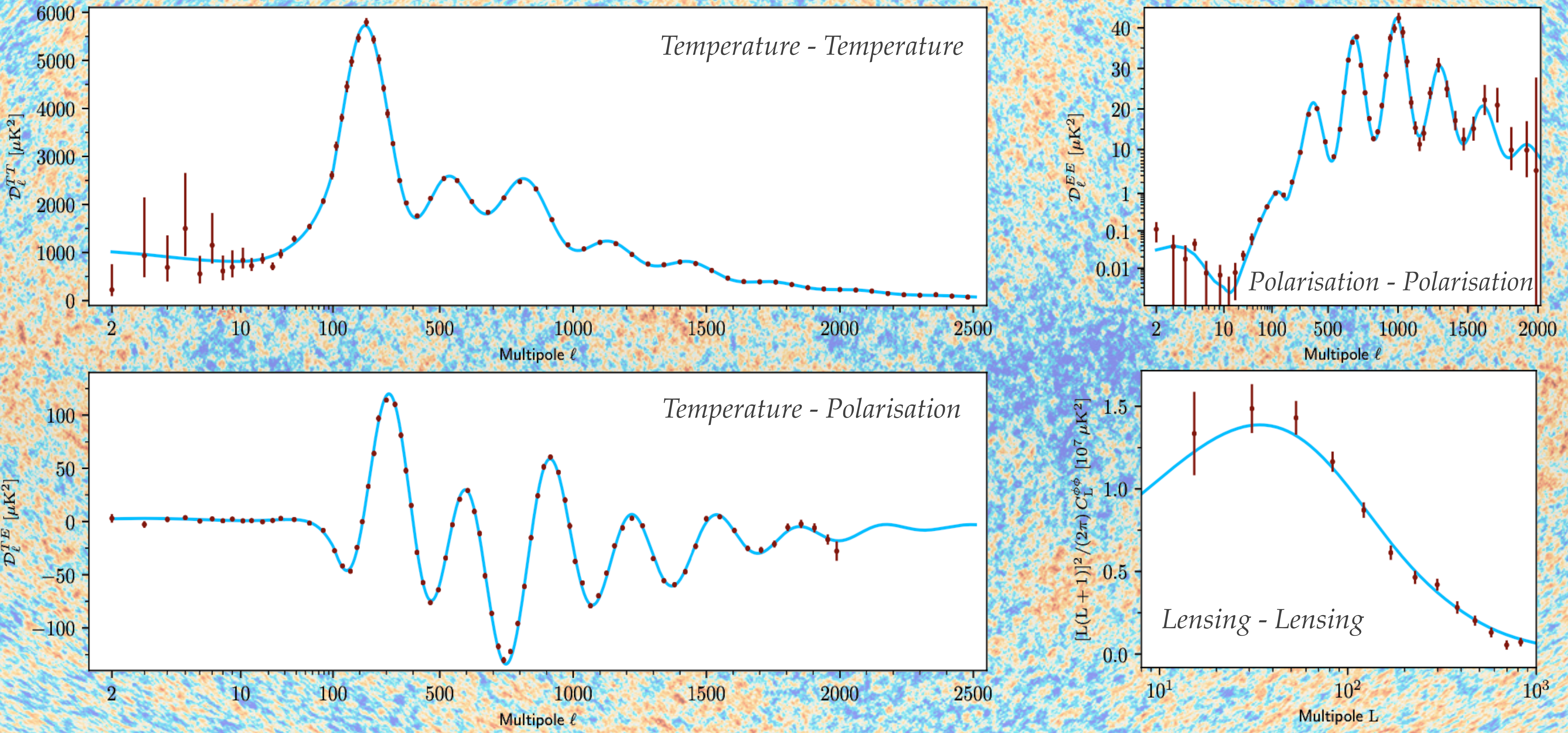


Riess et al. *2022*

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

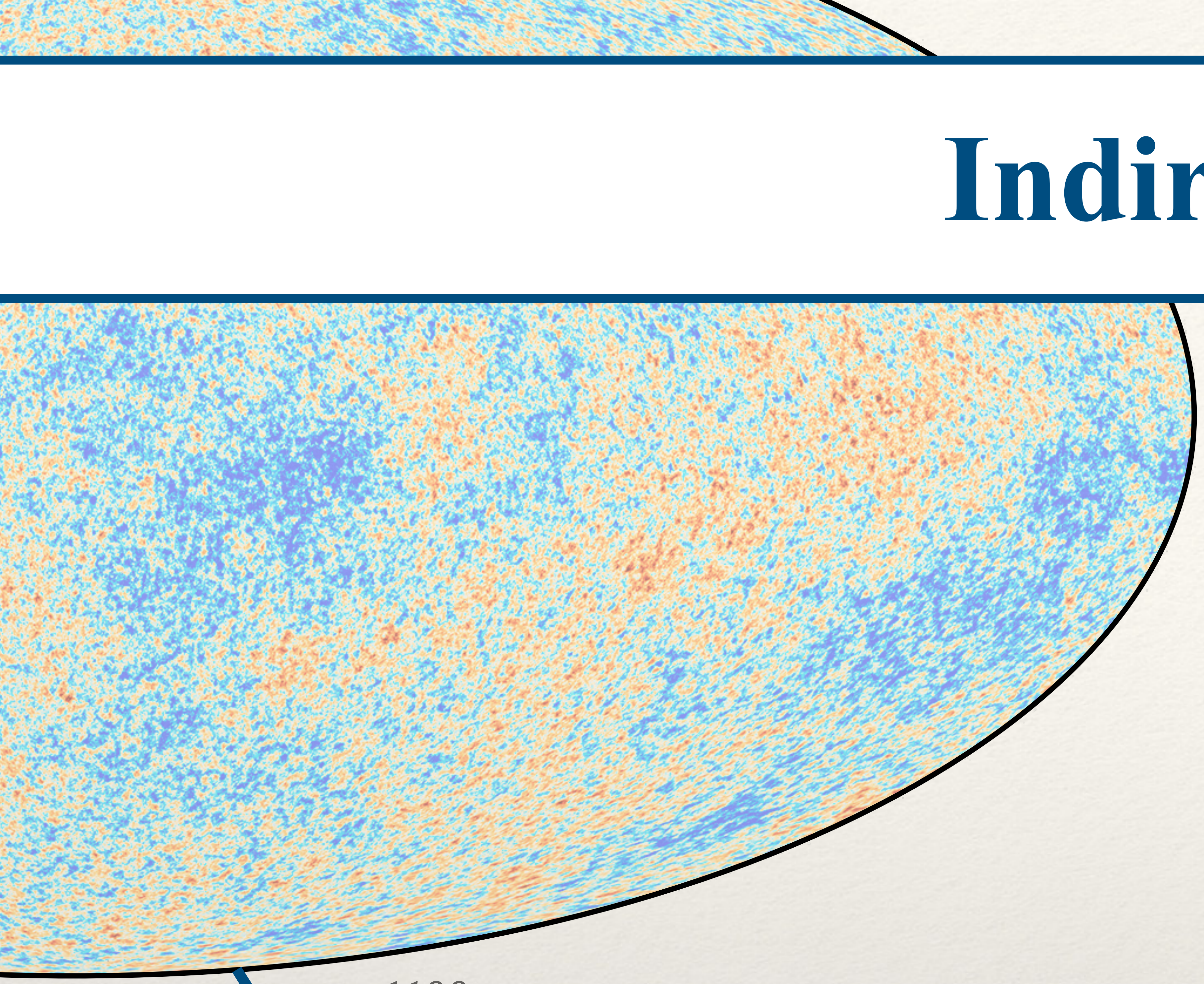
Planck Data | *6 free parameters*

Planck et al. 2020



Indirect determination of H_0

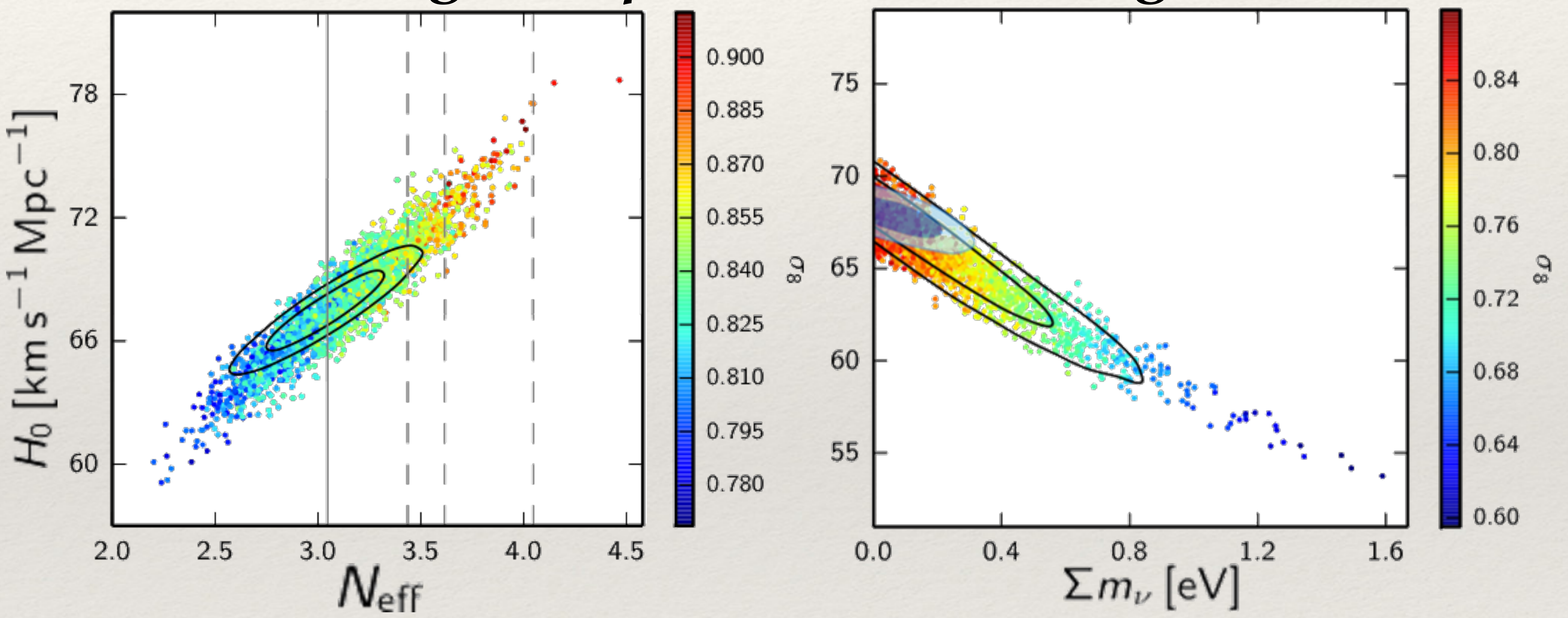
Planck et al. 2020



z~1100

Test the concordance model ΛCDM

Change the parameters, change H_0



Illustrative plots from Planck 2015

THE MODEL CONTRAINS H_0

z~0

Planck et al. *2020*

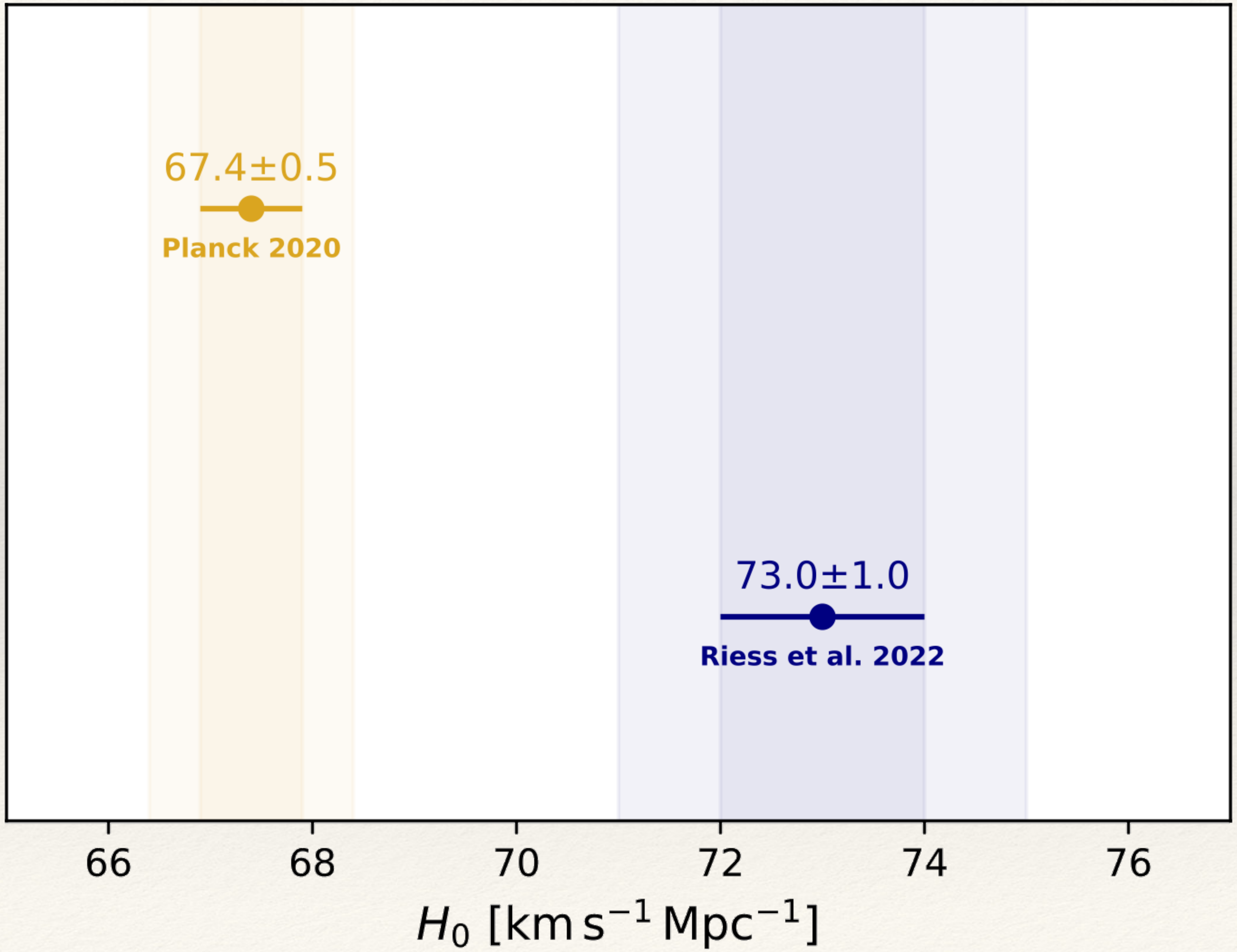
$$H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

— based on ΛCDM —

H_0 Tension | *SH0ES vs. Planck*

ΛCDM

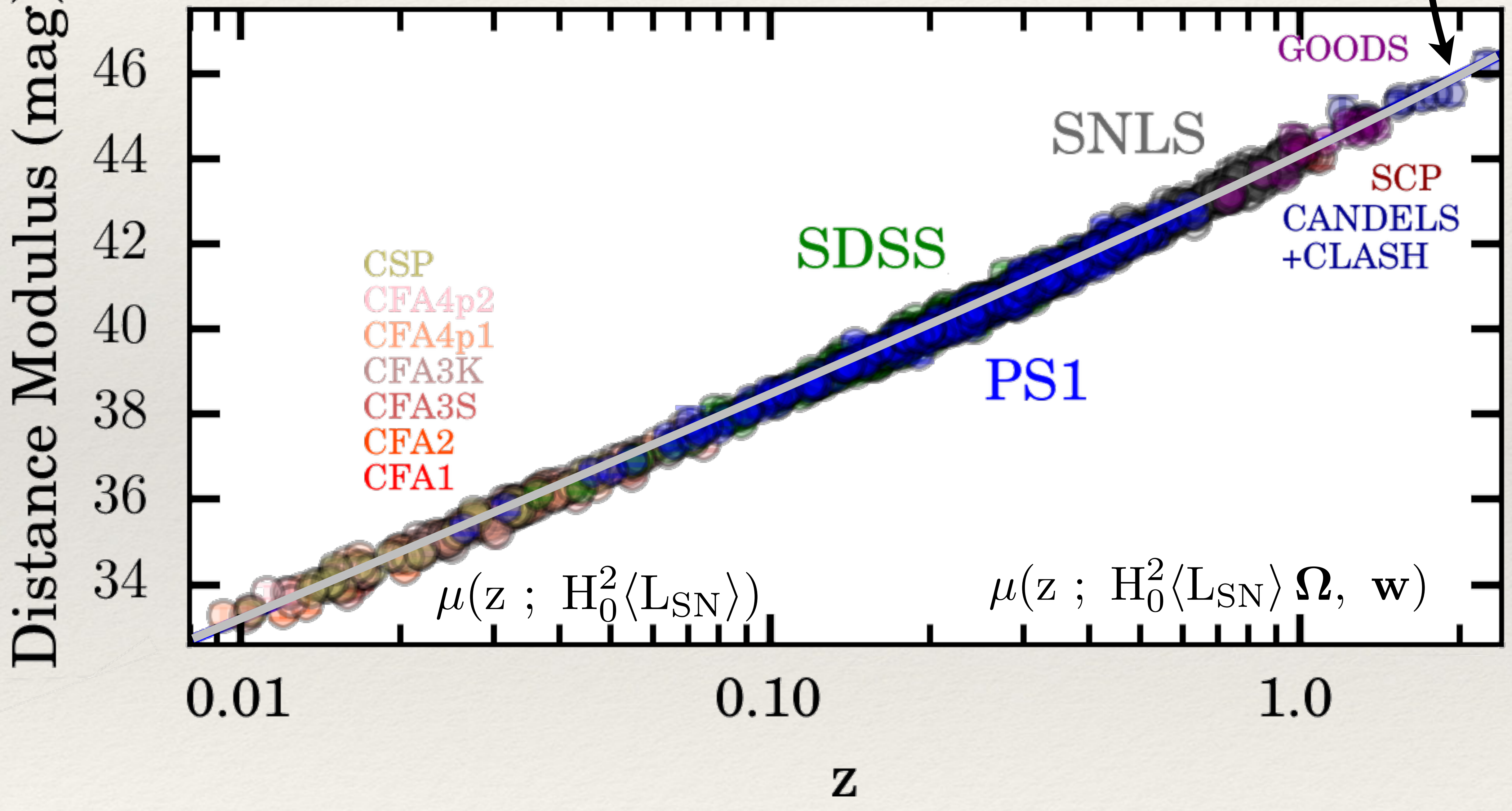
direct



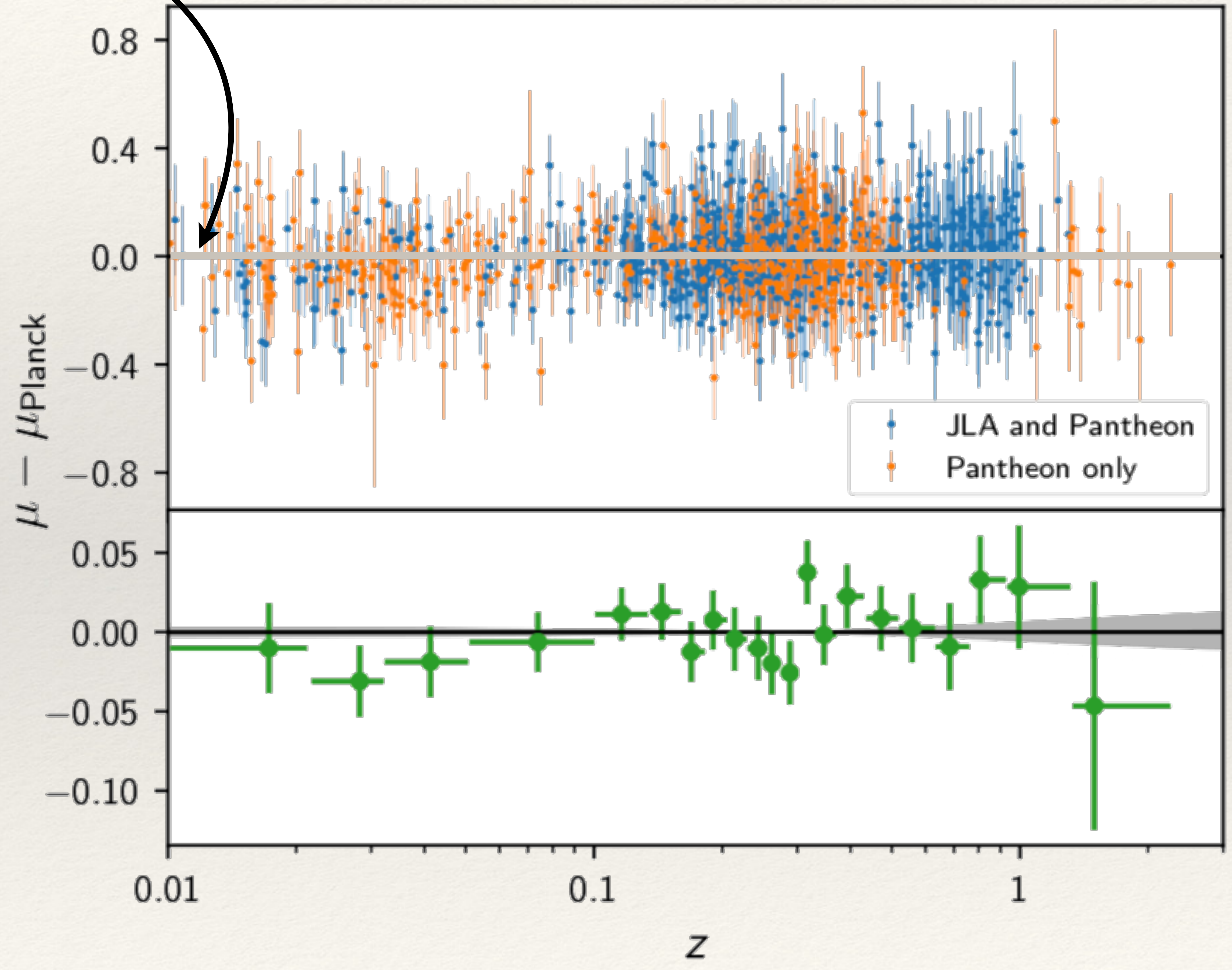
Are Supernovae & CMB in tension ? *No!*

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*

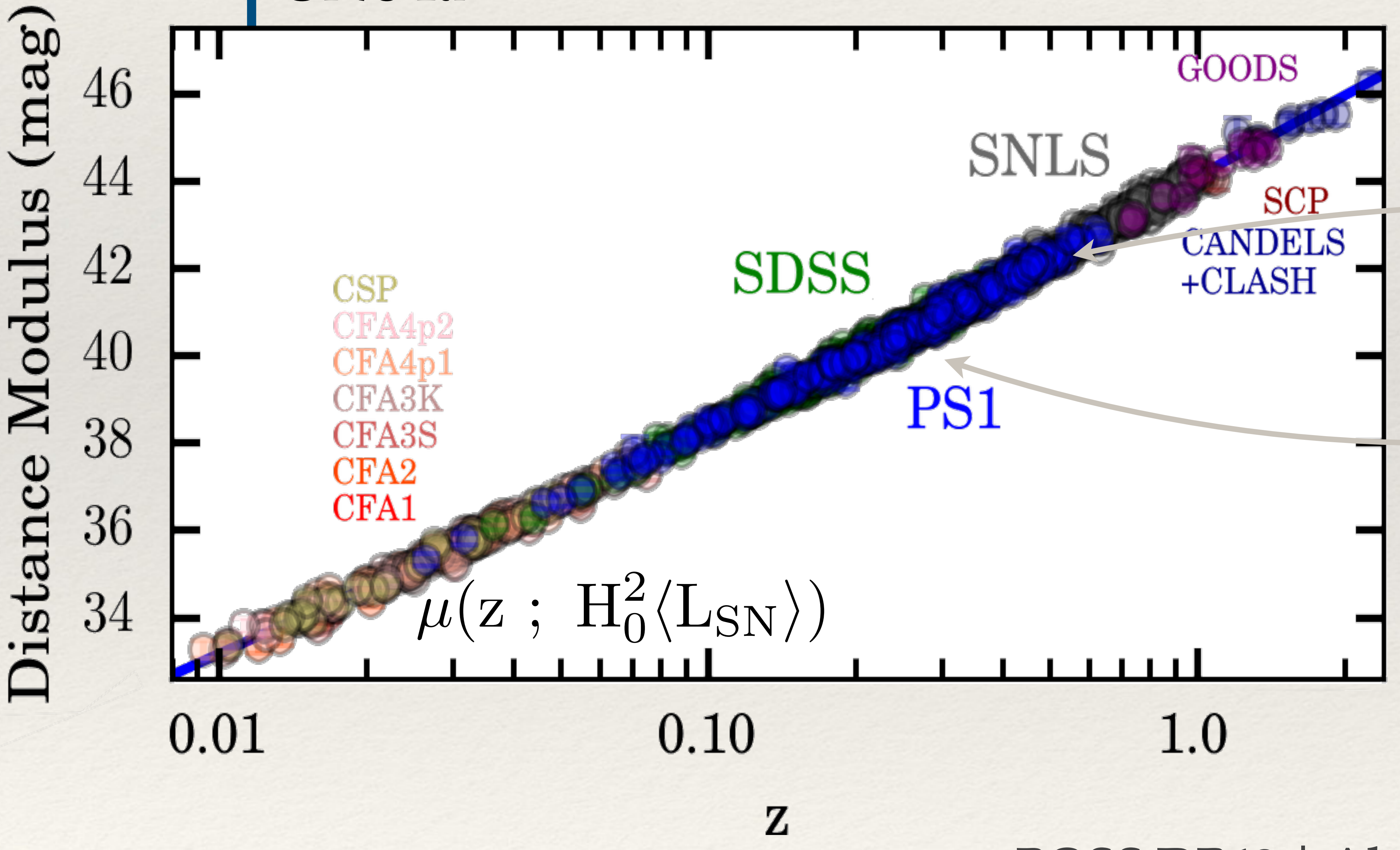
Get independent distances for SNe Ia

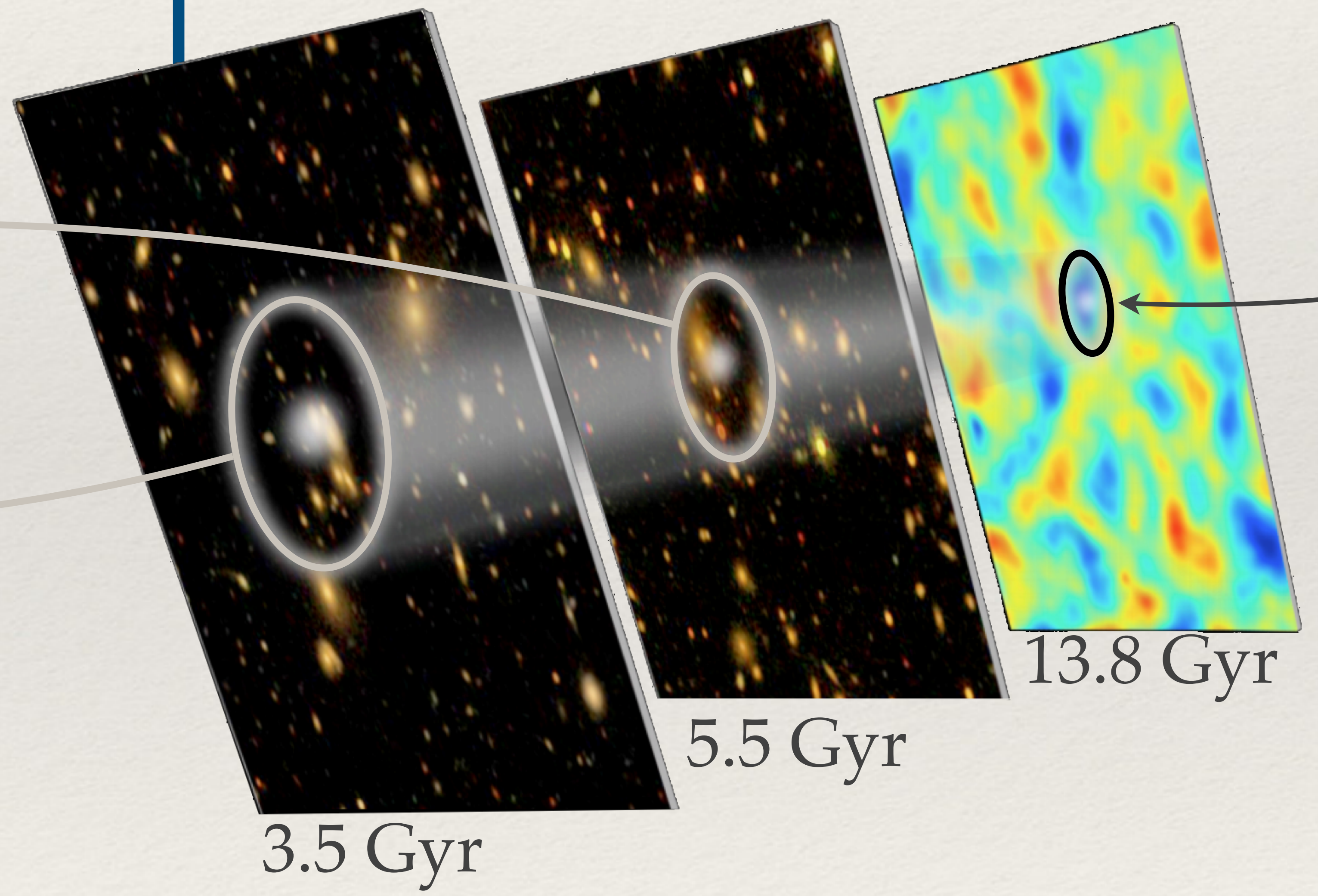
"Transfert"
H(z=1) → H(z=0)

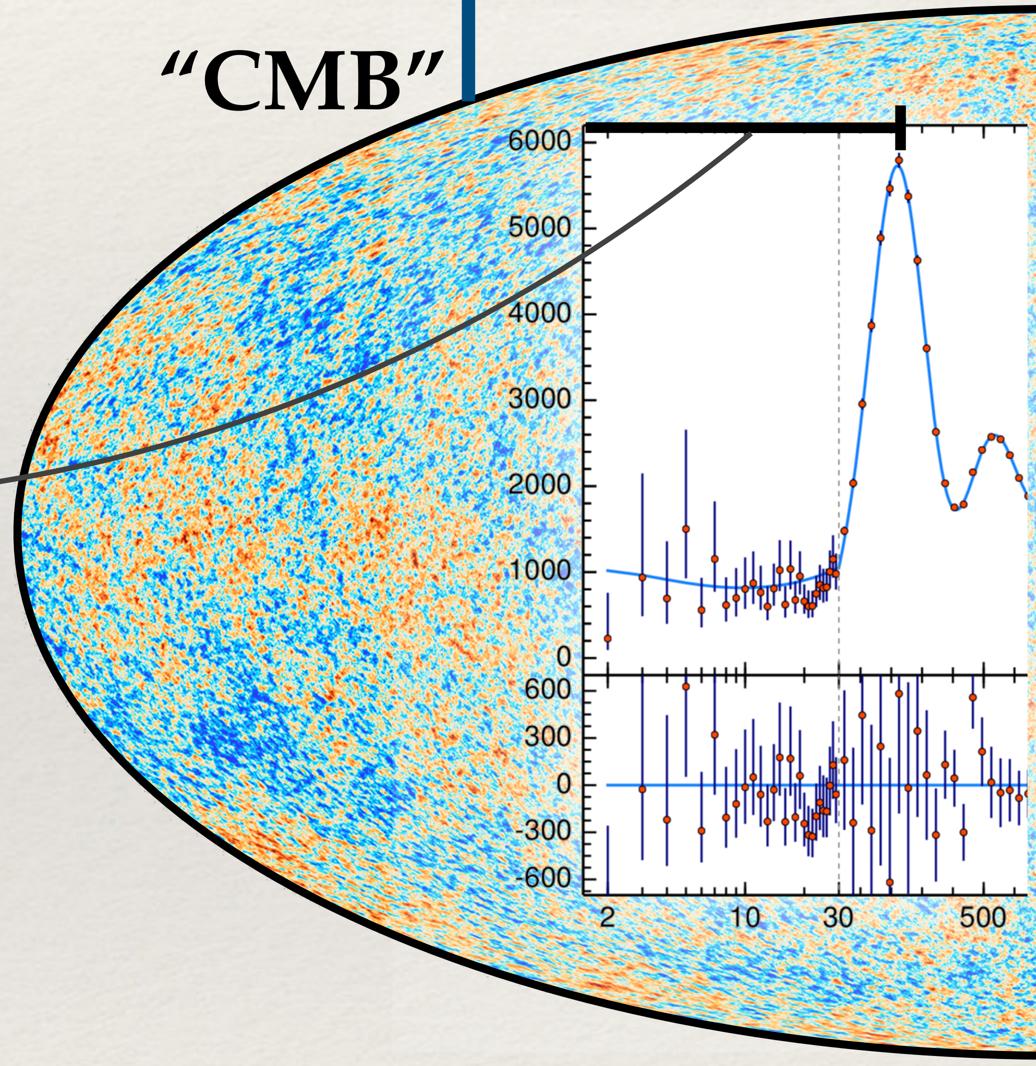
Sets the scale of the Universe at z~1

distance

"SNe Ia" **"BAO."** **"CMB"**







BOSS DR12 | Alam et al. *2017*

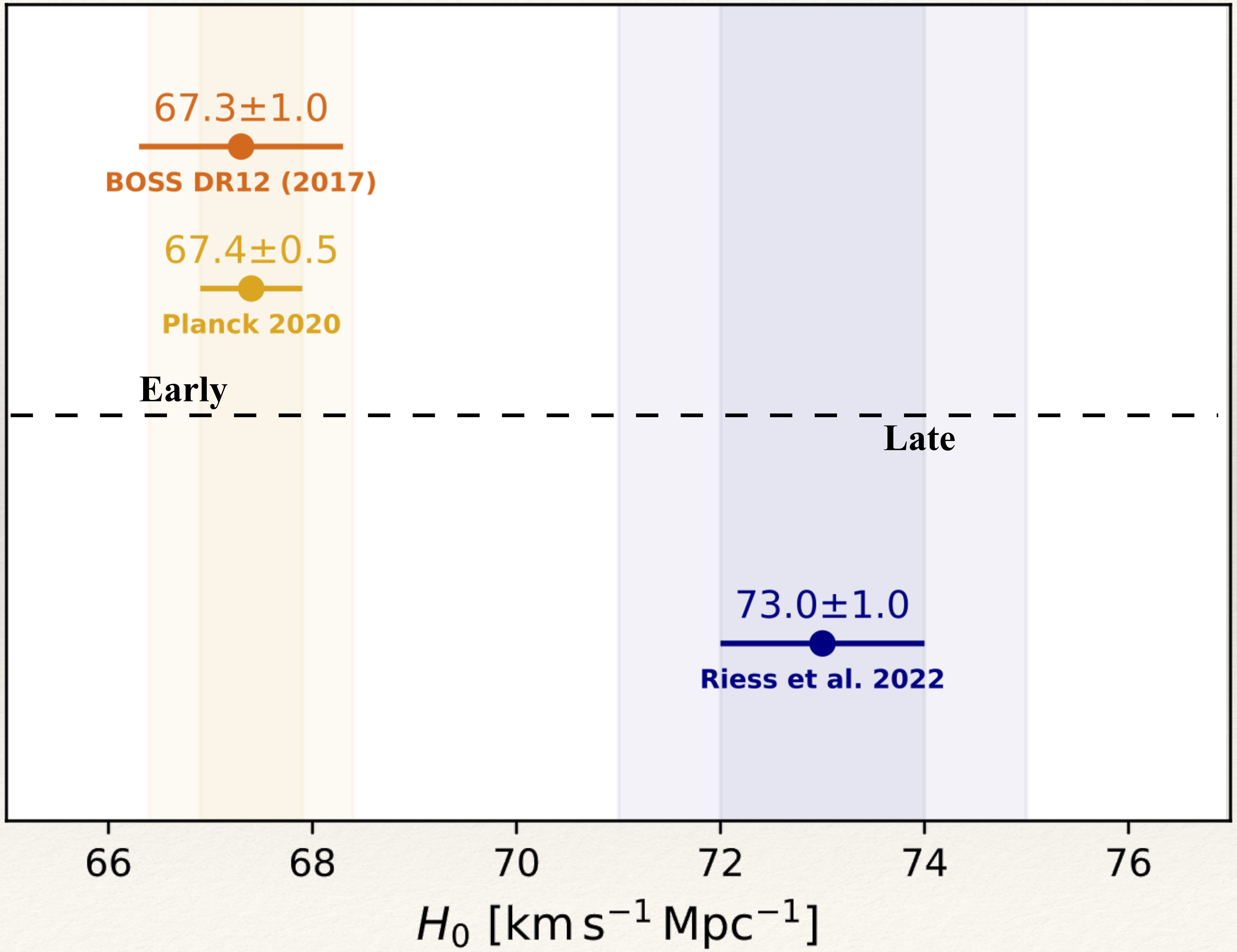
***H_0* = 67.3 ± 1.0 km s^{-1} Mpc^{-1}**

H_0 Tension | *Early vs. Late*

“~ΛCDM”

ΛCDM

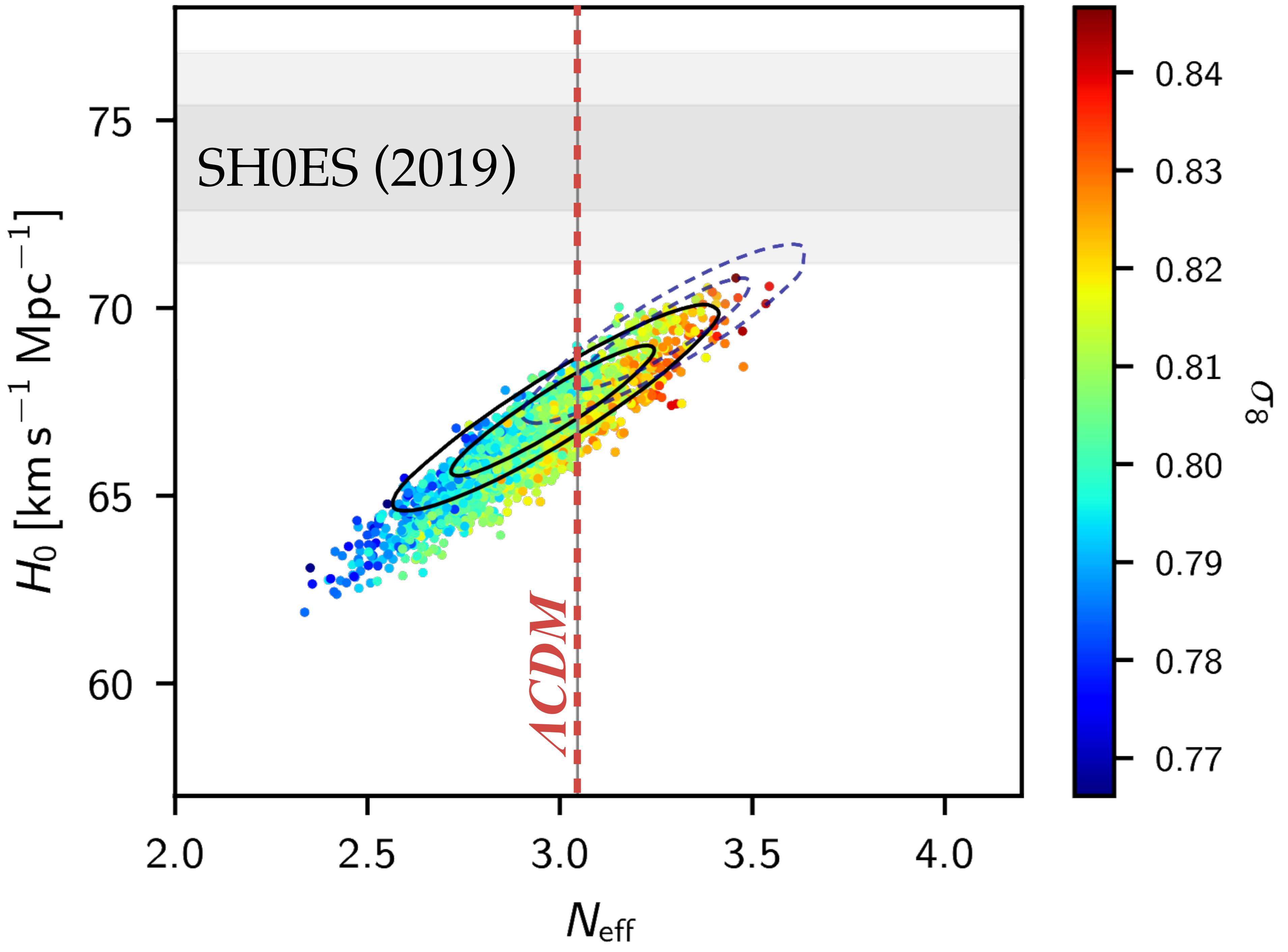
Direct



H_0 Tension | *Change the model ?*

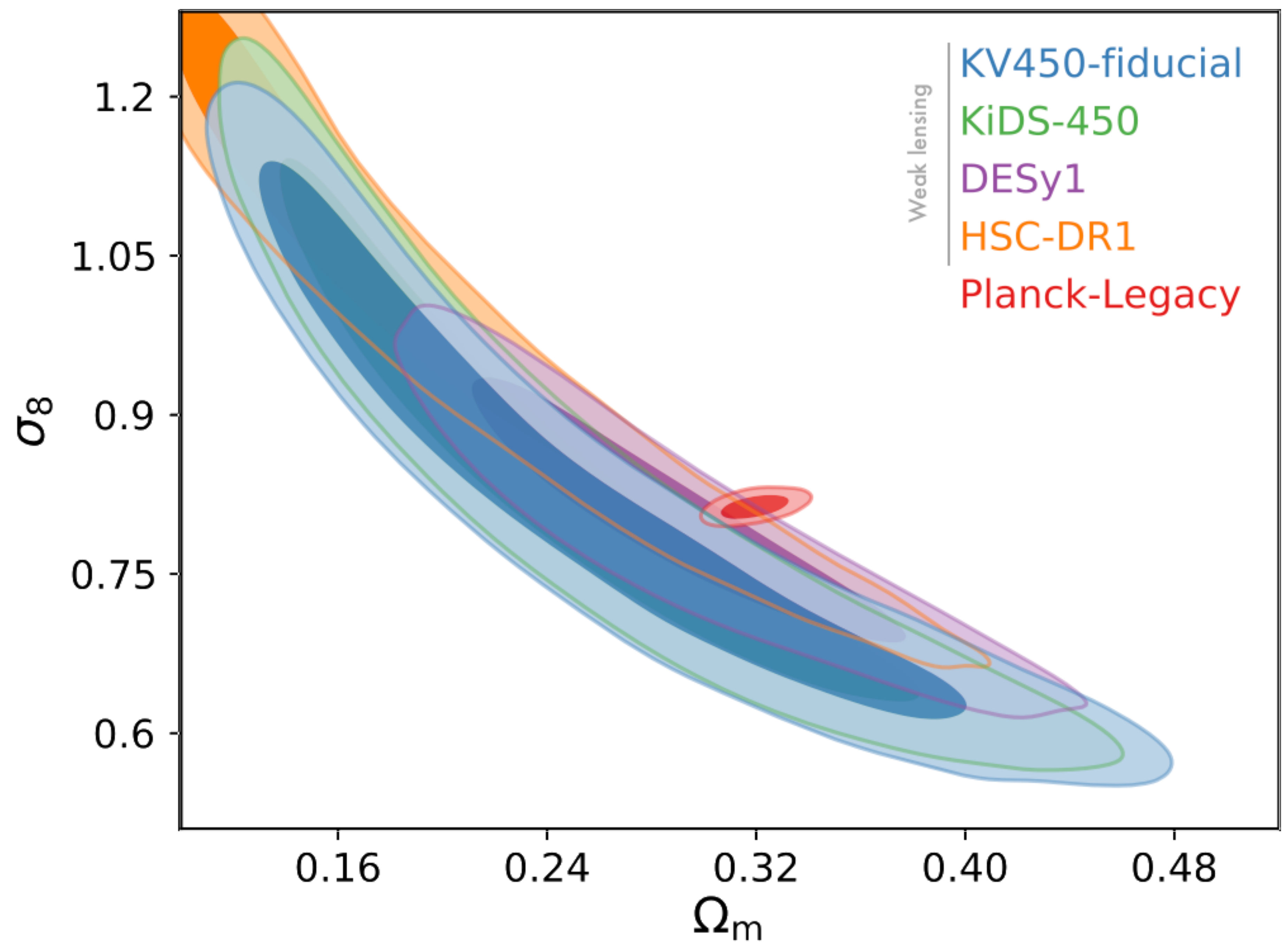
H_0 Tension | 5 σ

Universe's expansion is too fast



σ_8 Tension | 2.5 σ

Structures are too small

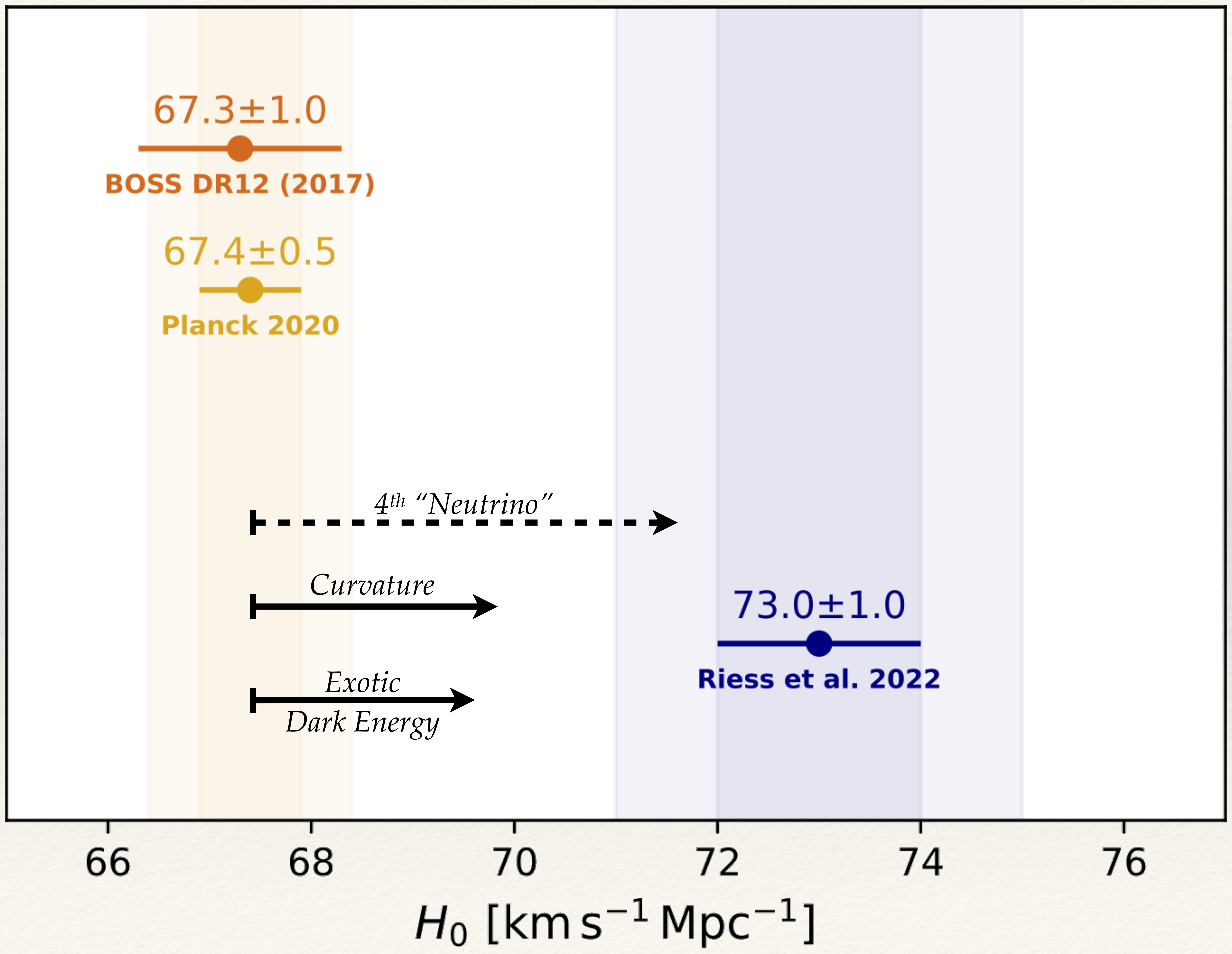


Extending the Standard Model of Cosmology

ΛCDM

ΛCDM

Directe



Time Delay Cosmology

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

H_0 Tension | *Systematics in strong lensing*

See also e.g.:
Etherington et al. submitted

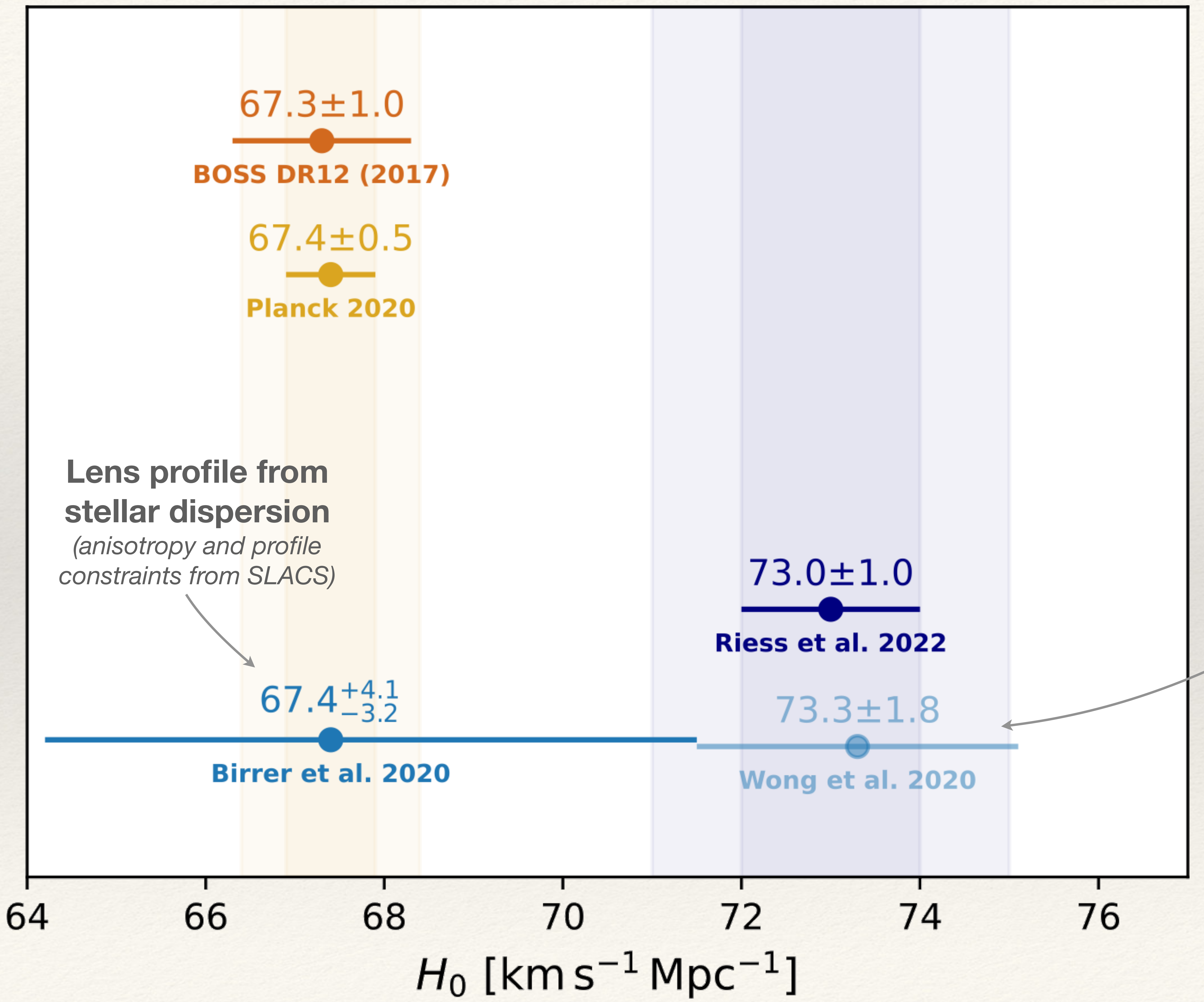
"~ΛCDM"
Inverse distance ladder

ΛCDM
CMB

DIRECT:

SNeIa & Cepheids

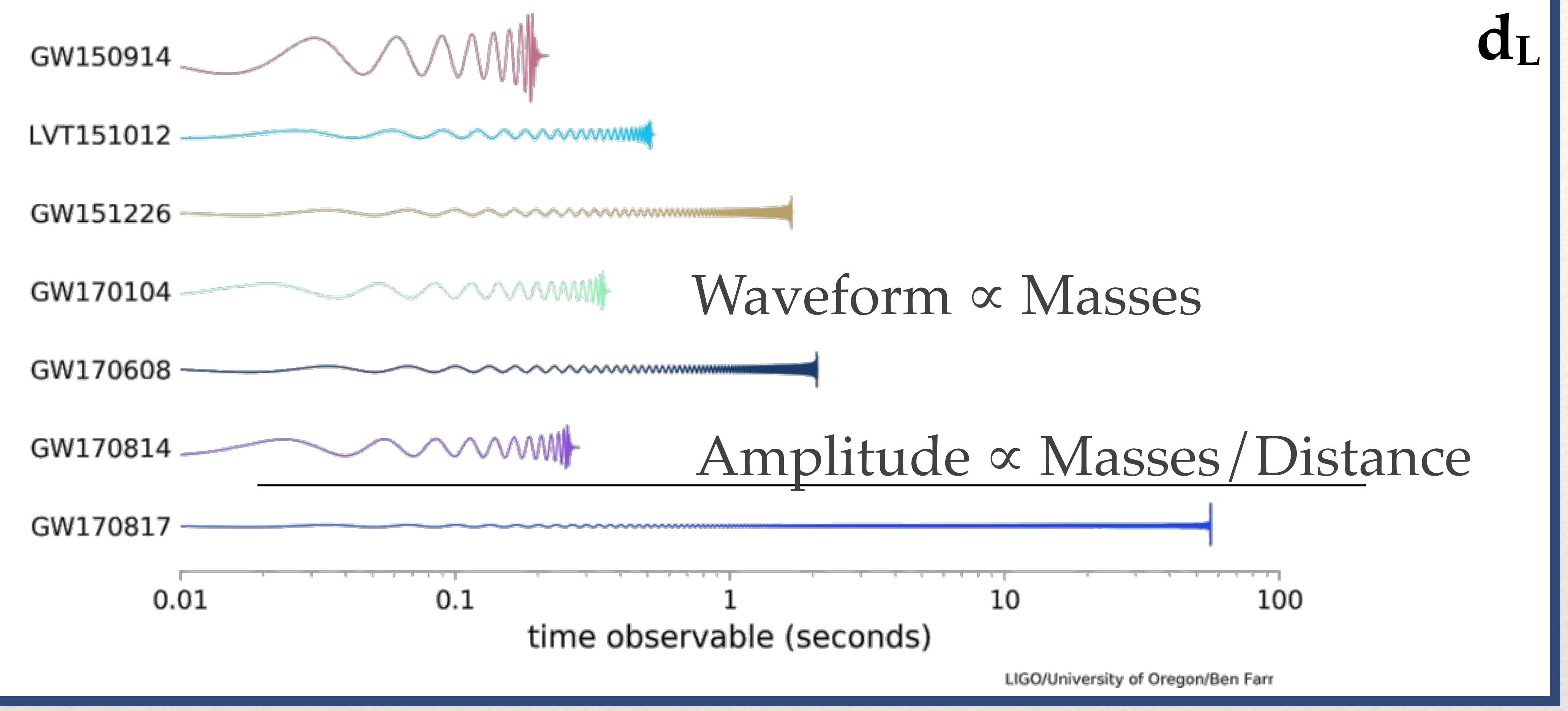
Strong Lensing



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

Gravitational Waves & ElectroMagnetism | H_0

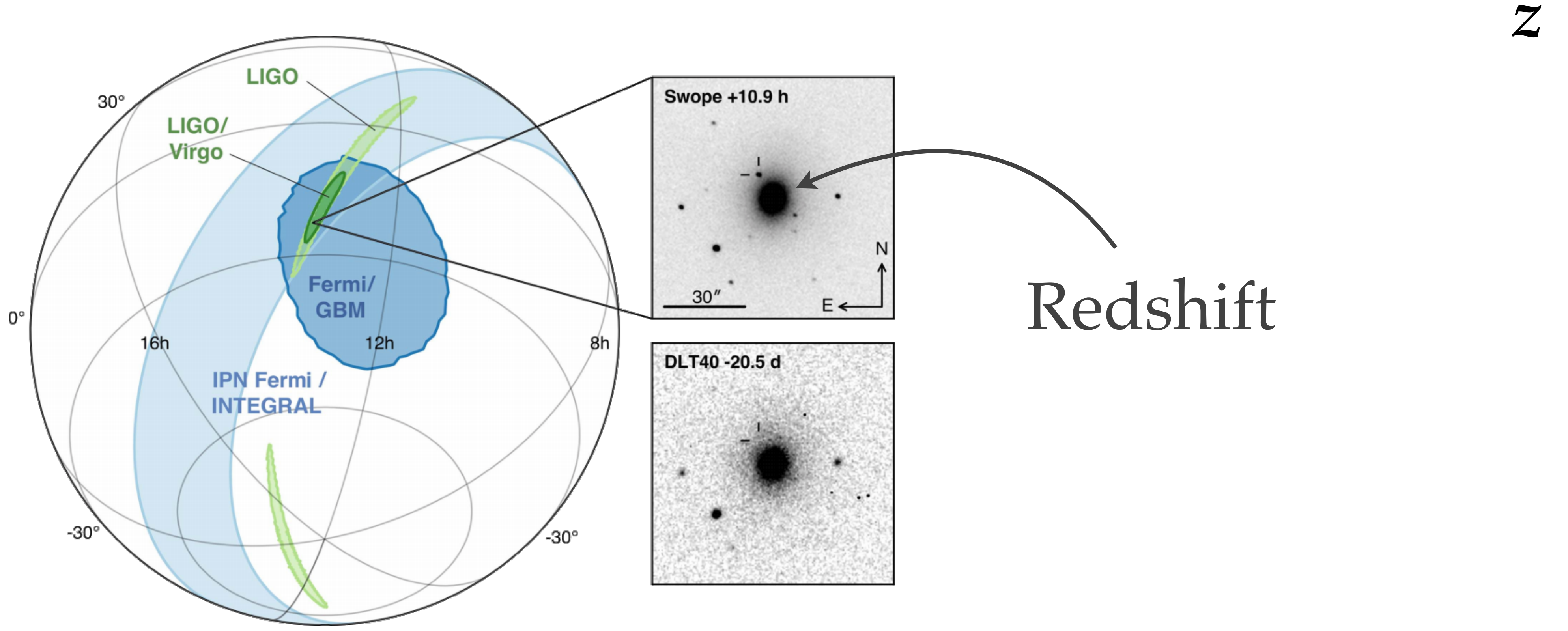
Gravitational Waves



Waveform ∝ Masses

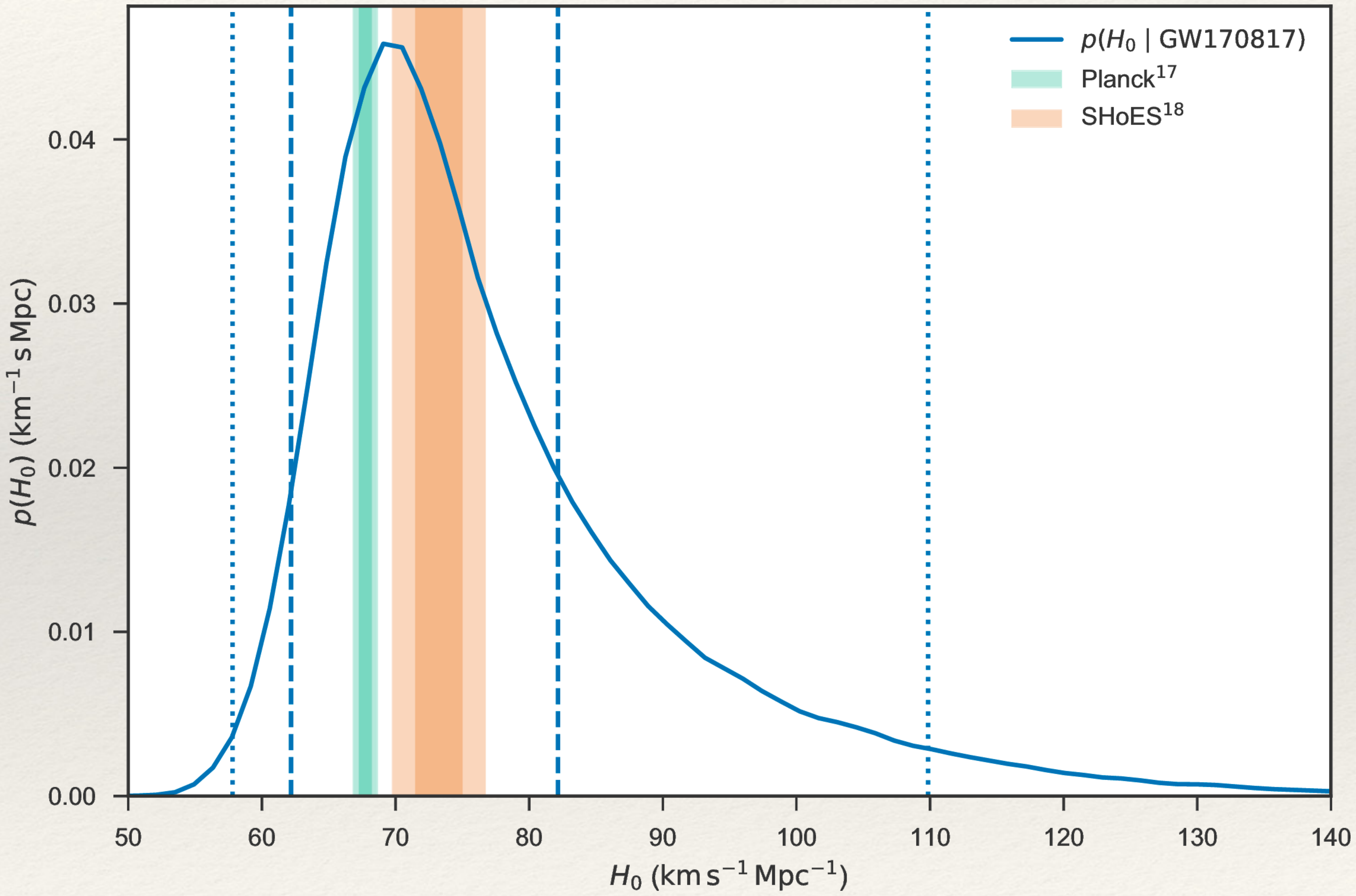
Amplitude ∝ Masses / Distance

Optical Counterpart

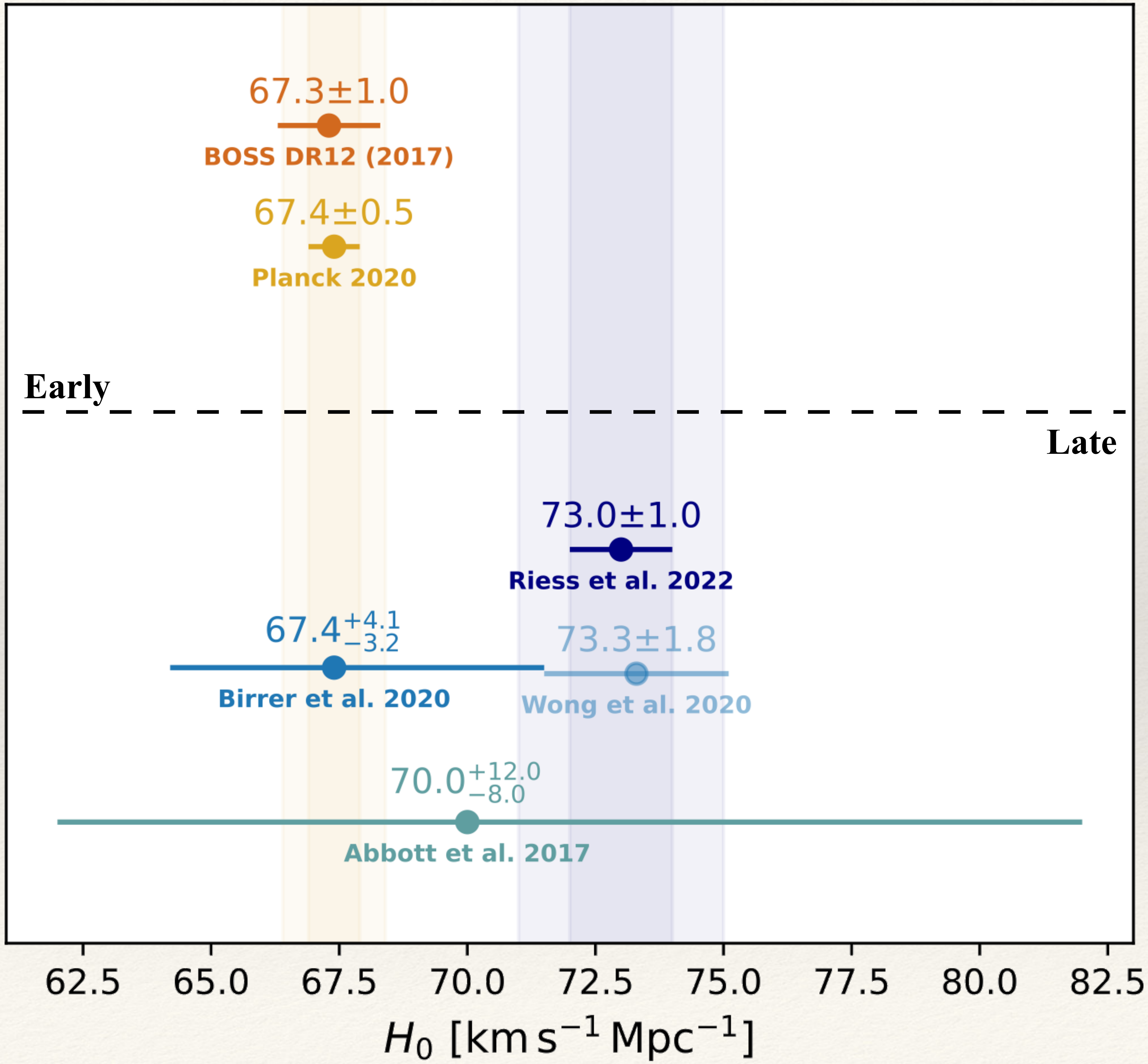


Redshift

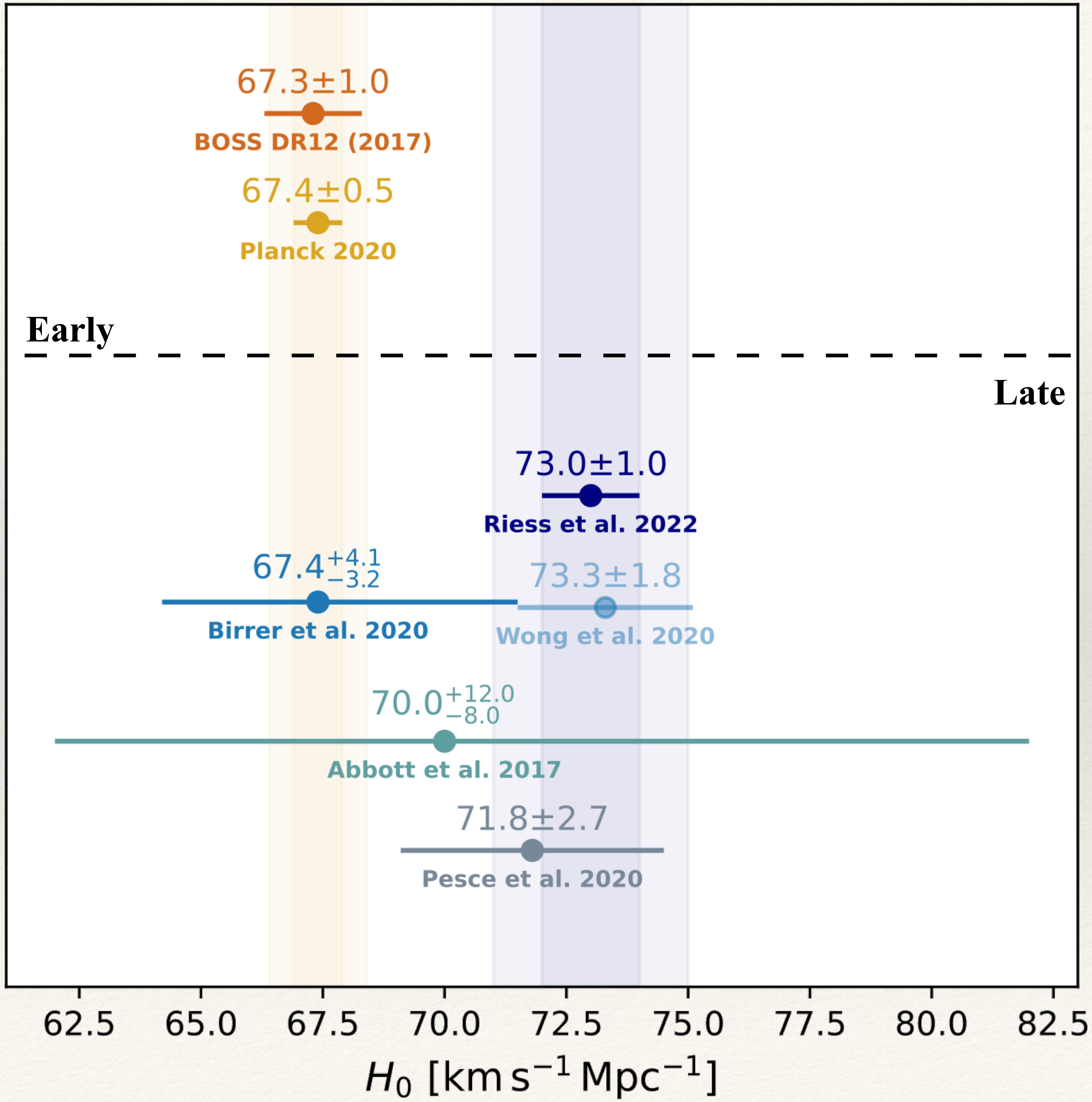
$$v_H = H_0 d_L$$



H_0 Tension | *Systematics in strong lensing*



H_0 Tension | *Mega maser: absolute Hubble Diagram*



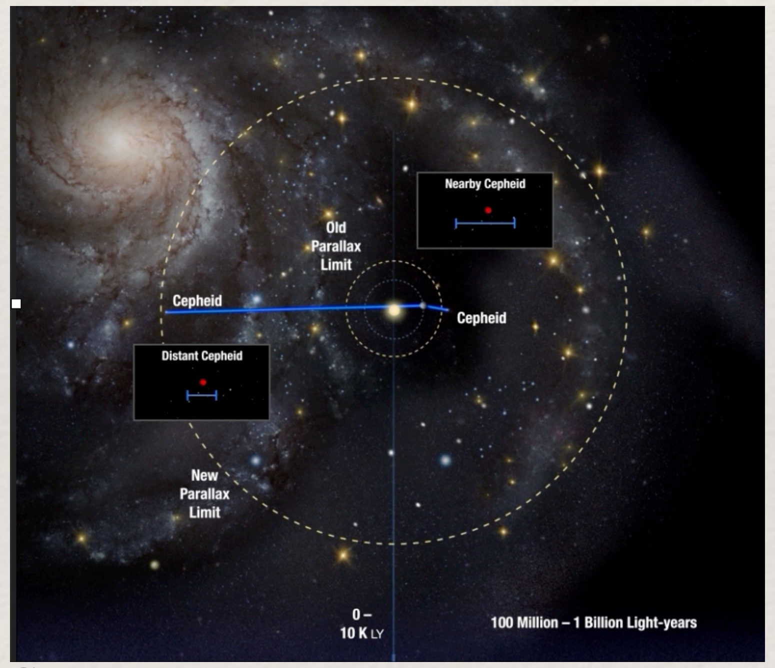
Direct Distance Ladder | *TRGB*

Get independent distances for SNe Ia

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

"Geometry"

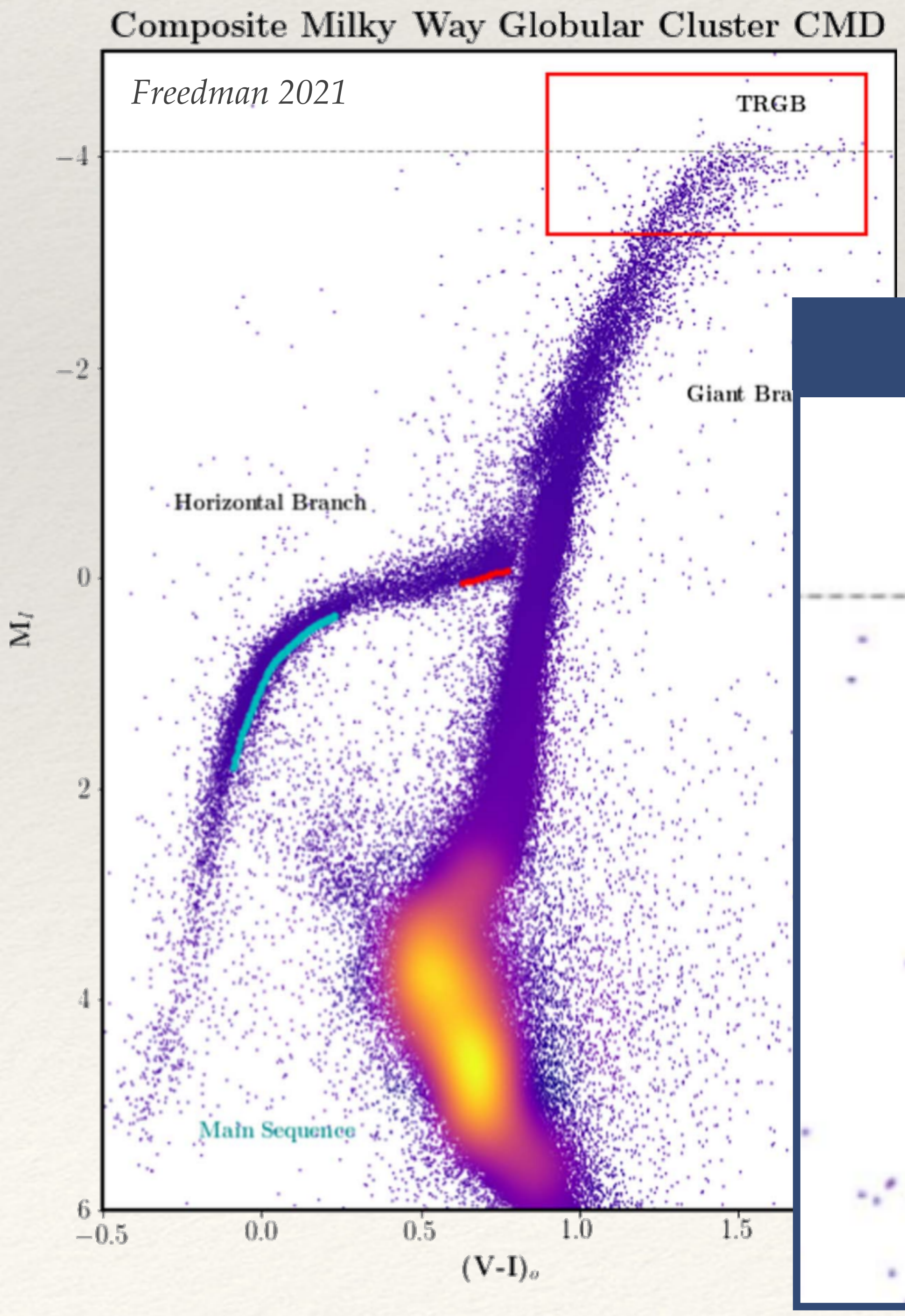
Parallaxes | D.E.B. | Maser

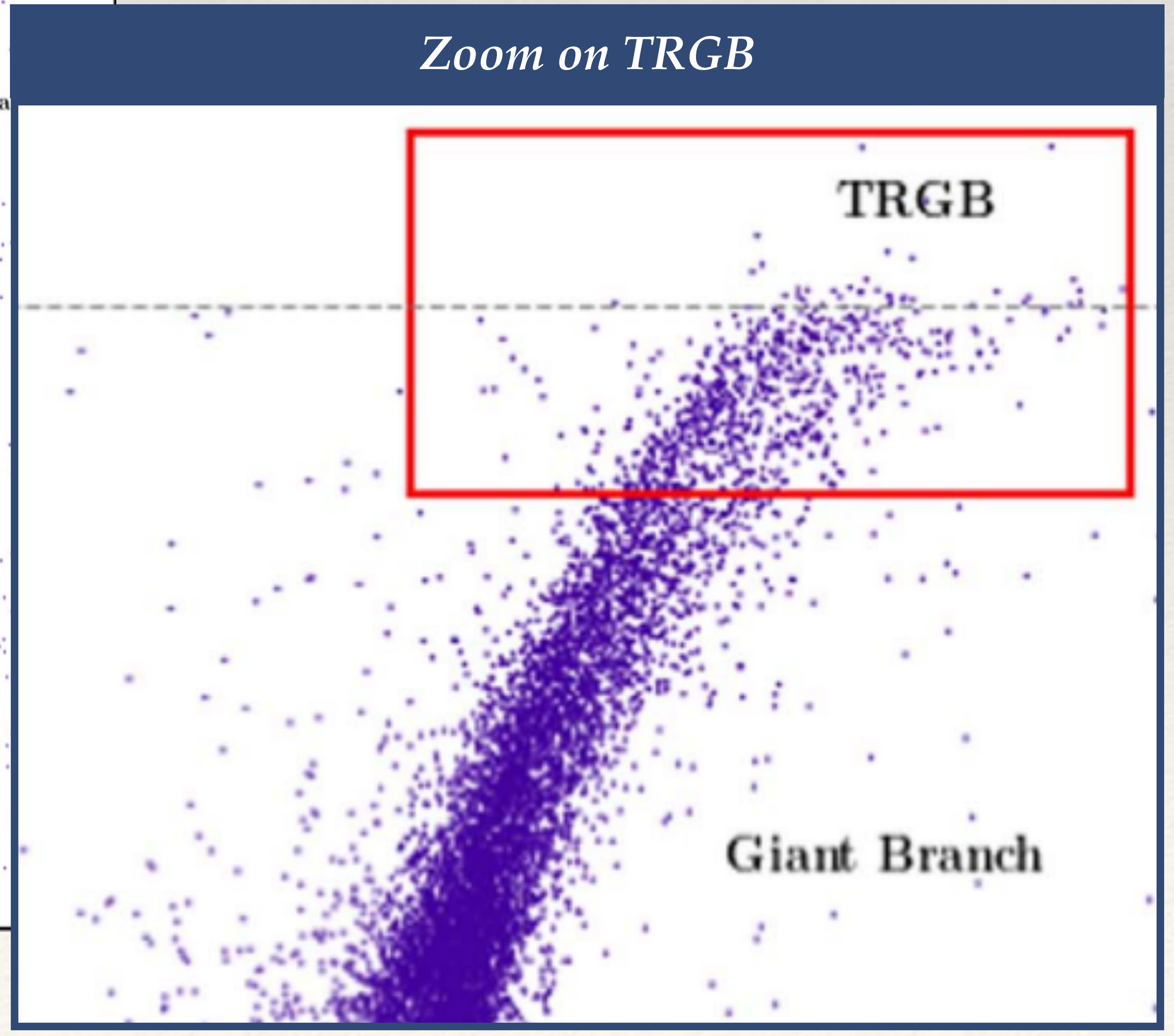


Source: eso

"Calibrators"

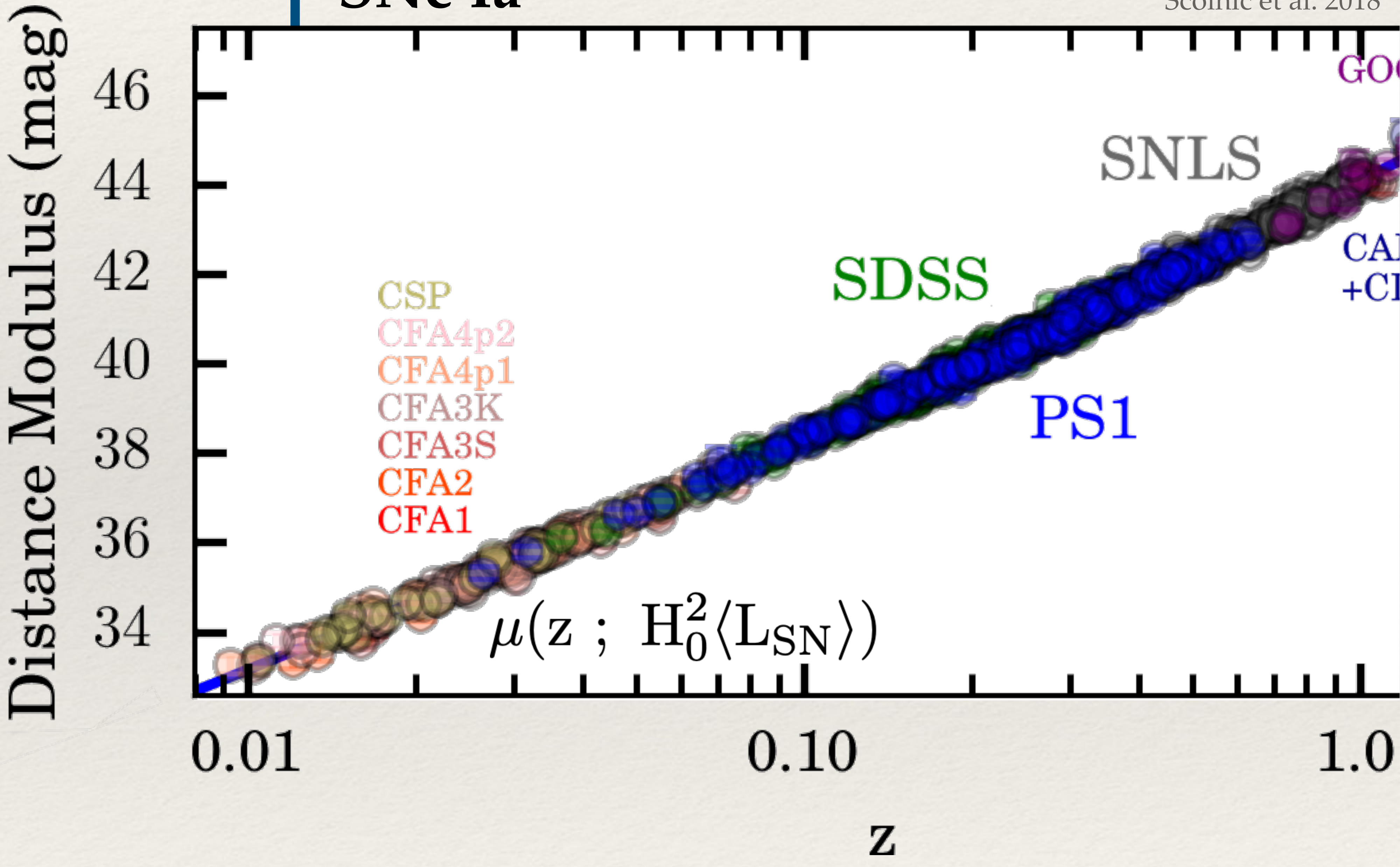
TRGB





"SNe Ia"

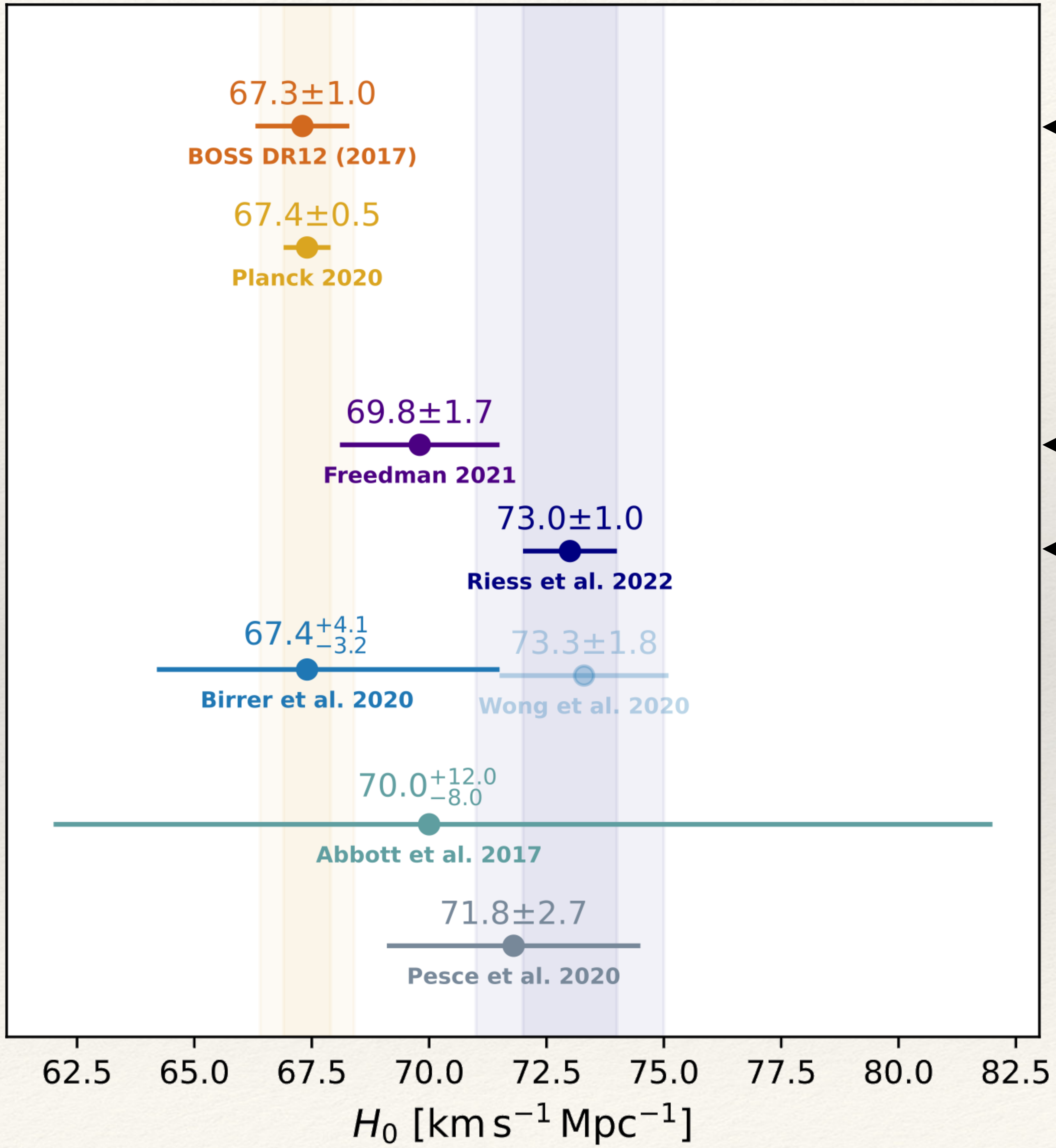
Scolnic et al. 2018



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*



SNeIa's $\langle L_{SN} \rangle$ calibrated by:

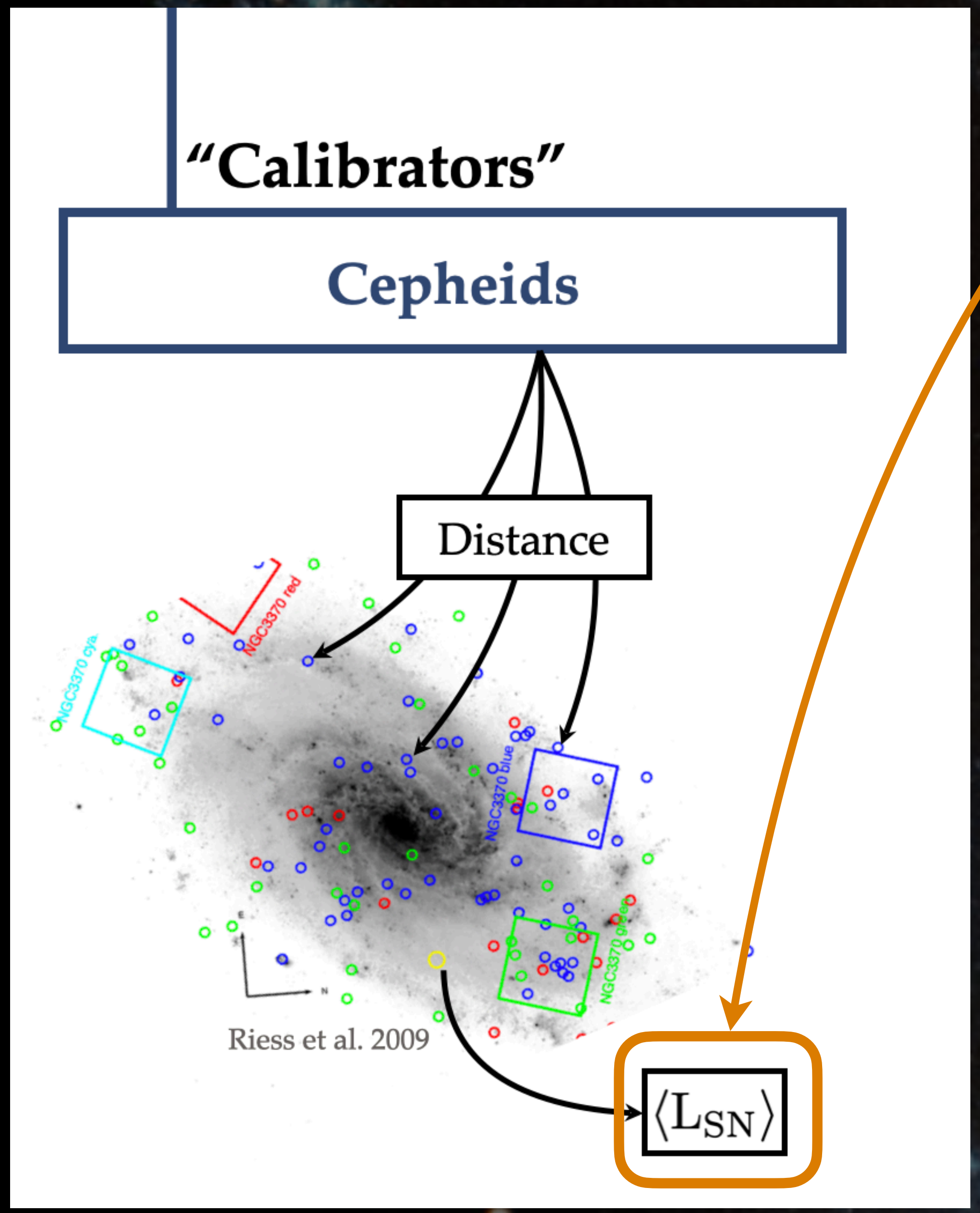
← **BAO (z~1)** | r_s

← **TRGB (z~0)** | *geometry*

← **Cepheids (z~0)** | *geometry*

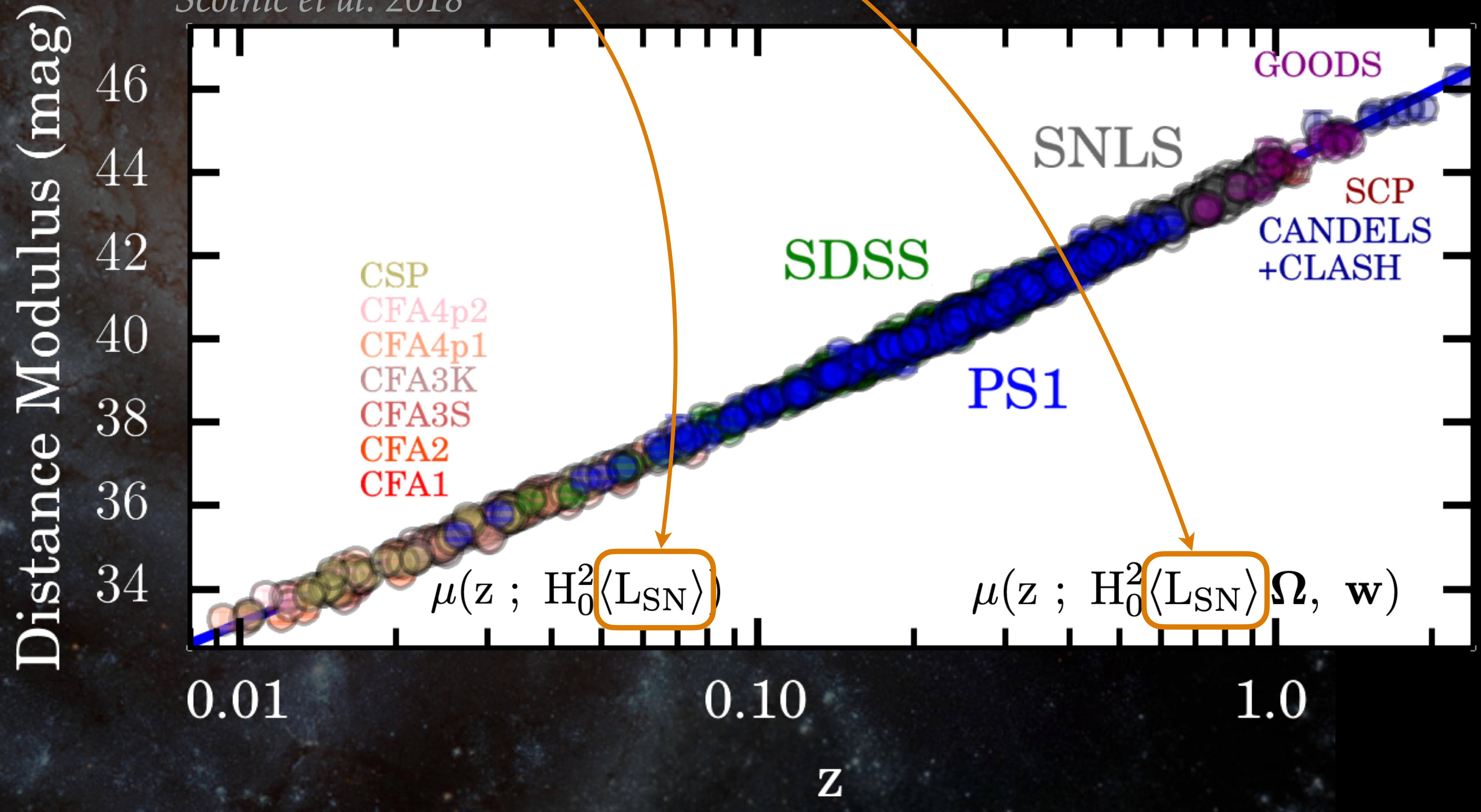

SN2011fe

The Progenitor issue | *Astrophysical biases*



Constant ?

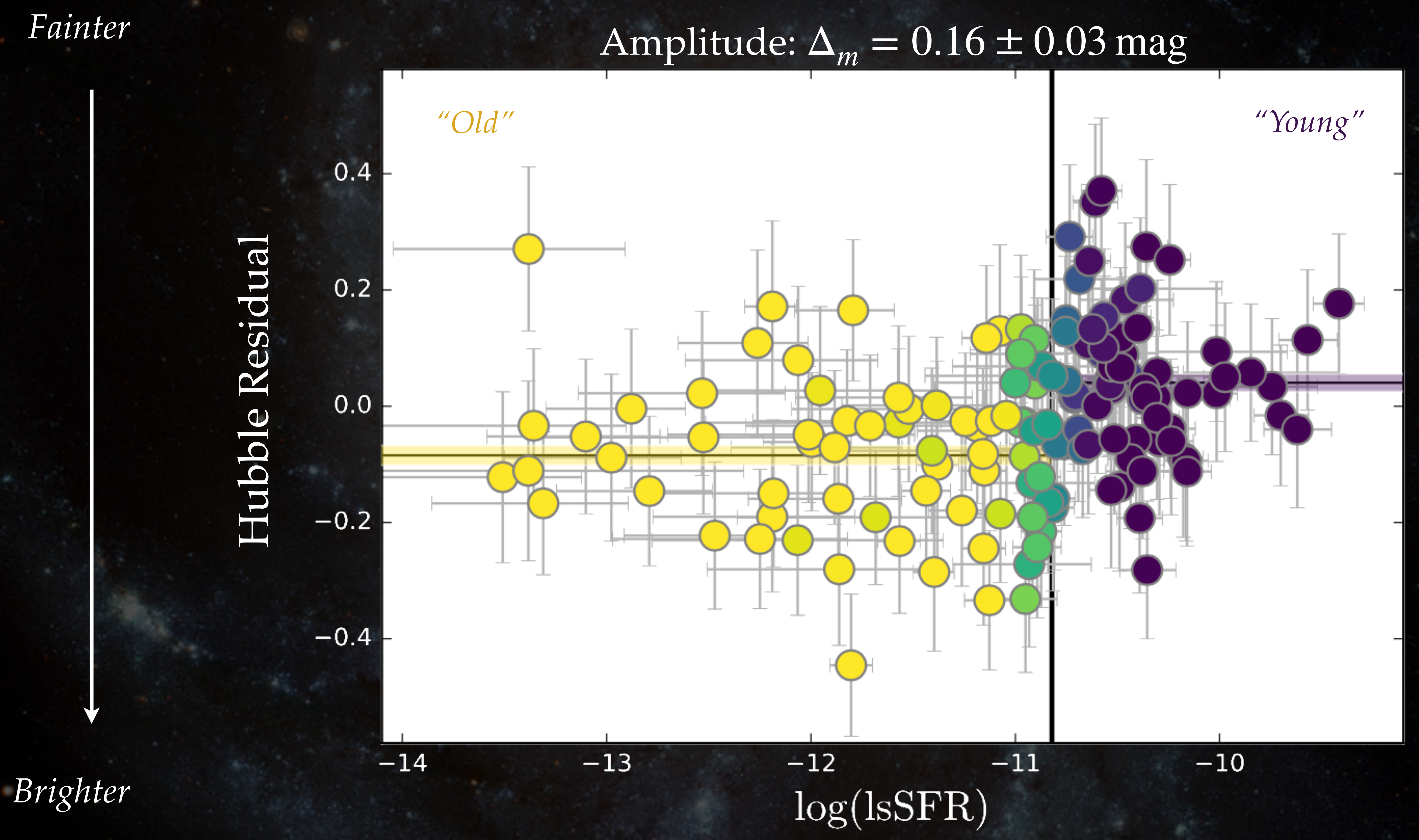
Scolnic et al. 2018



SN2011fe

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

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



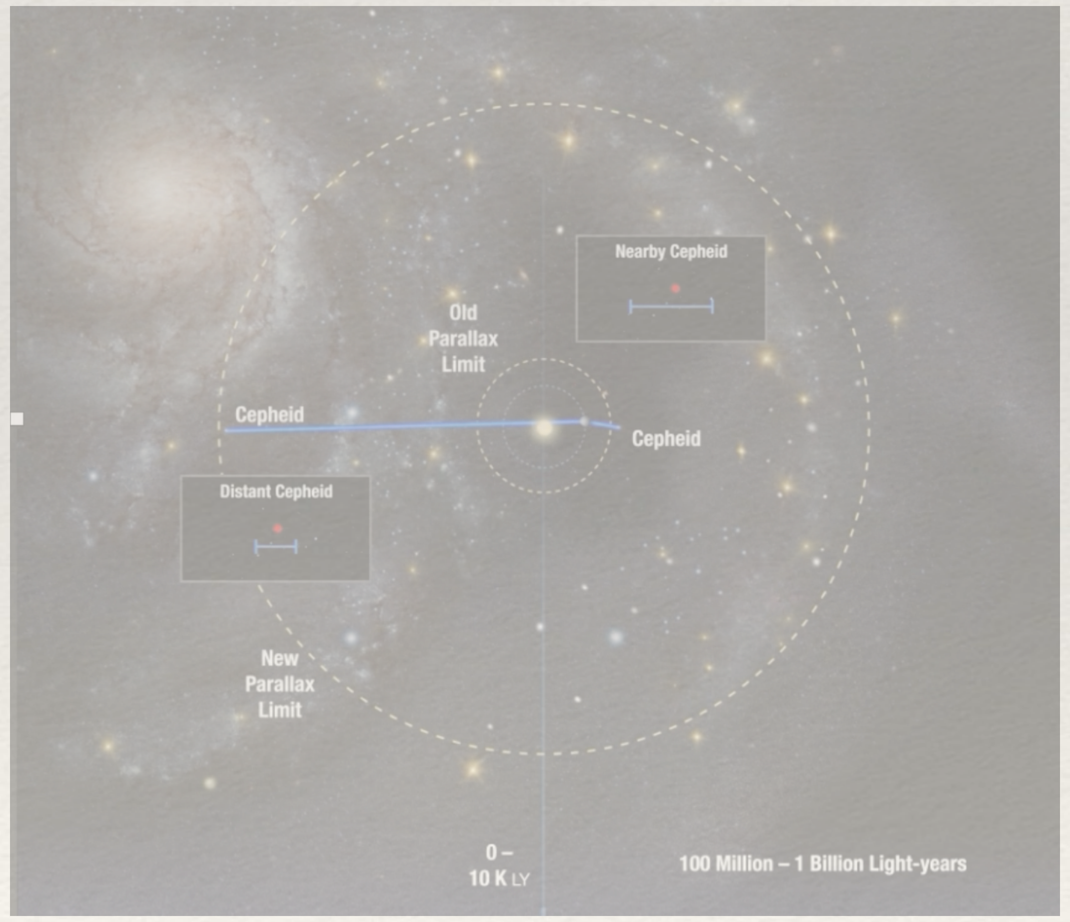
$$\text{lsSFR} \propto \frac{\#\ \text{Young Stars}}{\#\ \text{Old Stars}}$$

Direct Distance Ladder | *SH0ES*

Calibrate the "Period-Luminosity" relation

"Geometry"

Parallaxes | D.E.B. | Maser



The SNe Ia "matching" problem

Measure "L_{SN}"

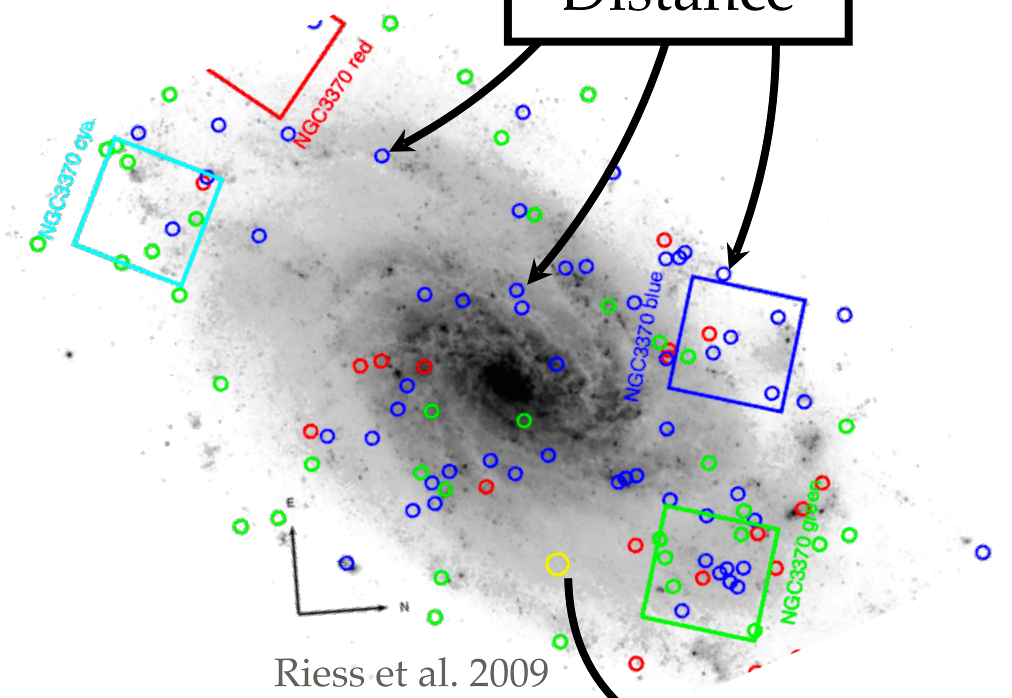
Get "H_0"

distance

"Calibrators"

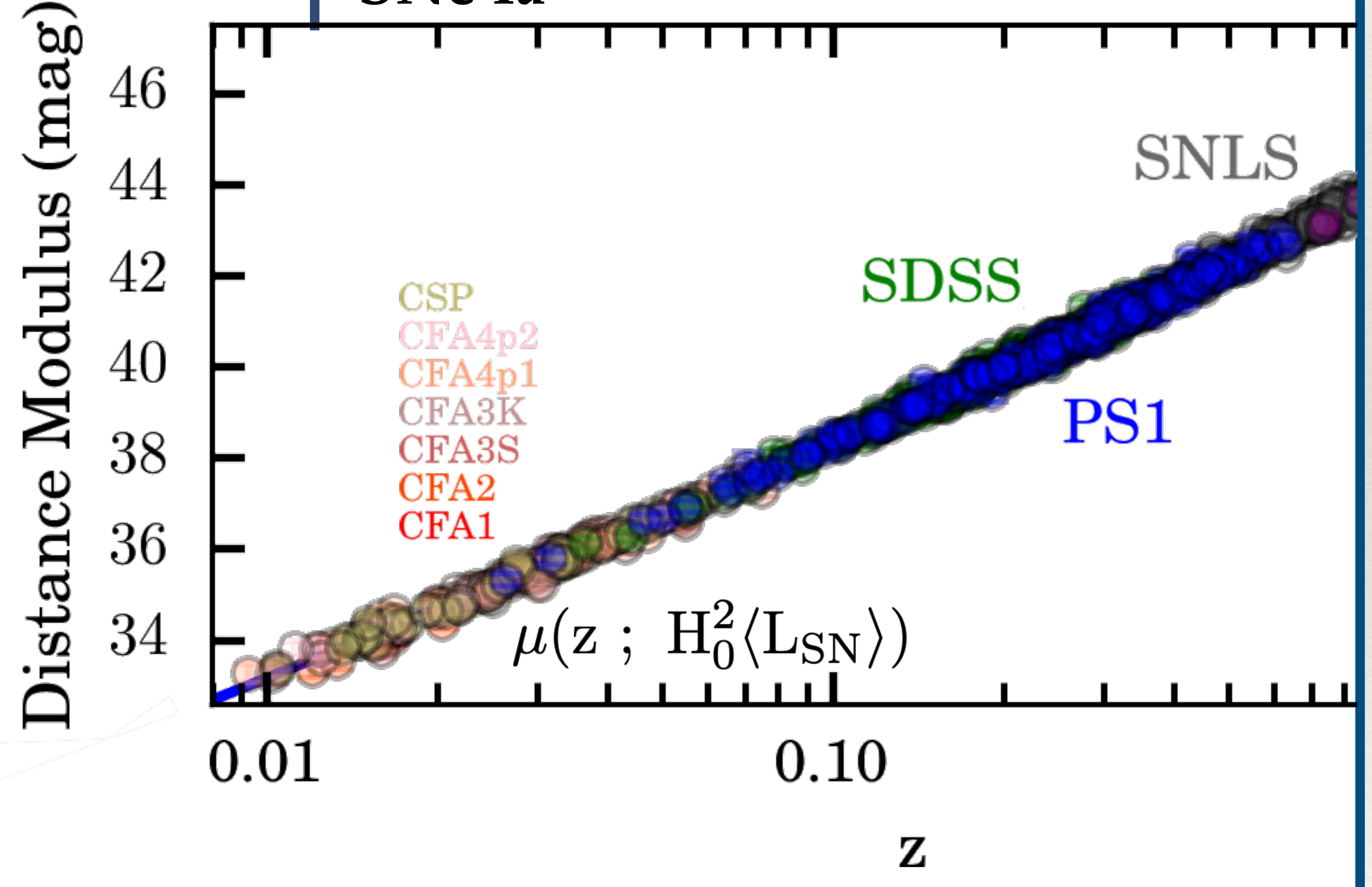
Cepheids

Distance



$\langle L_{SN} \rangle$

"SNe Ia"



Astrophysical Bias affecting H_0

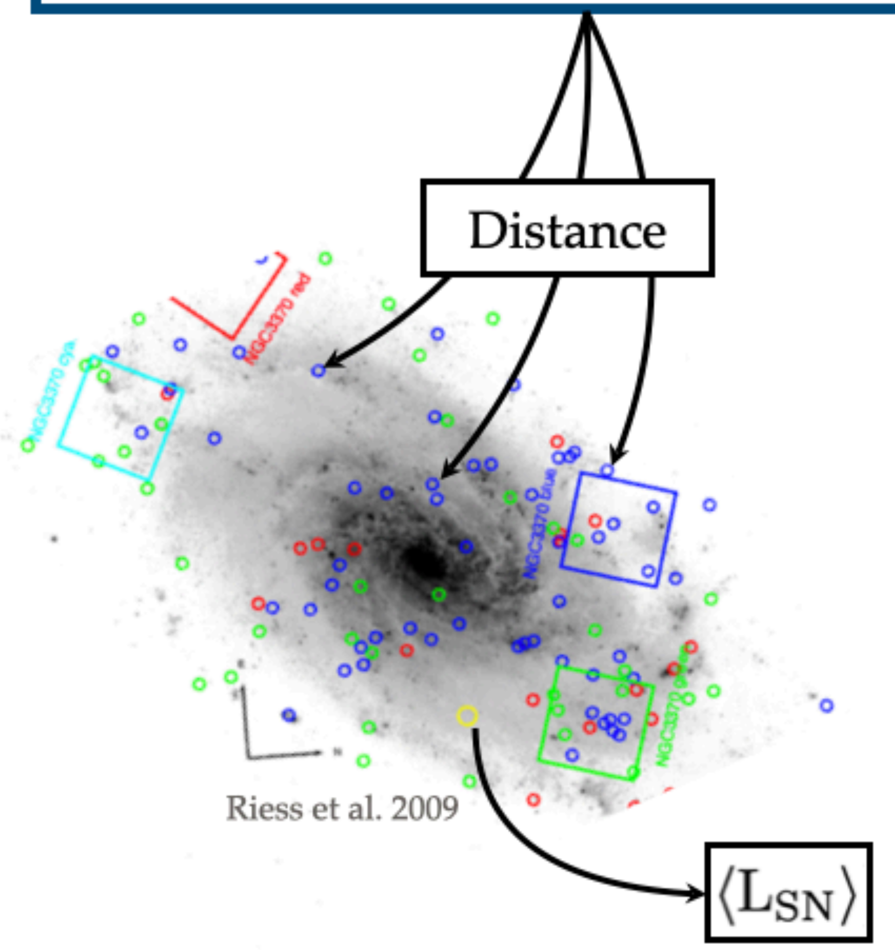
Rigault et al. 2015

The SNe Ia "matching" problem

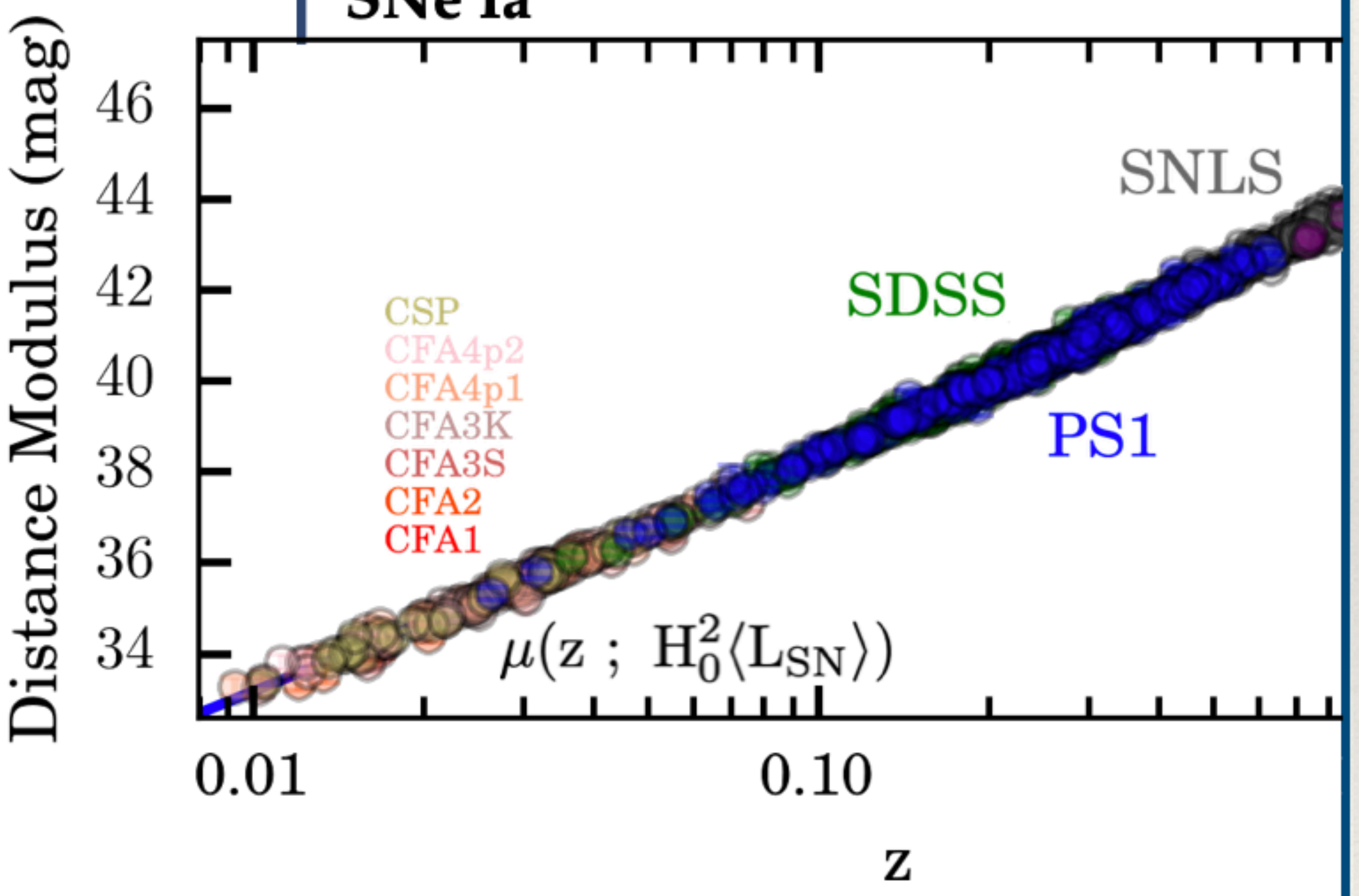
Measure "L_{SN}" — *Get "H_0"* → **distance**

"Calibrators"

Cepheids



"SNe Ia"



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}

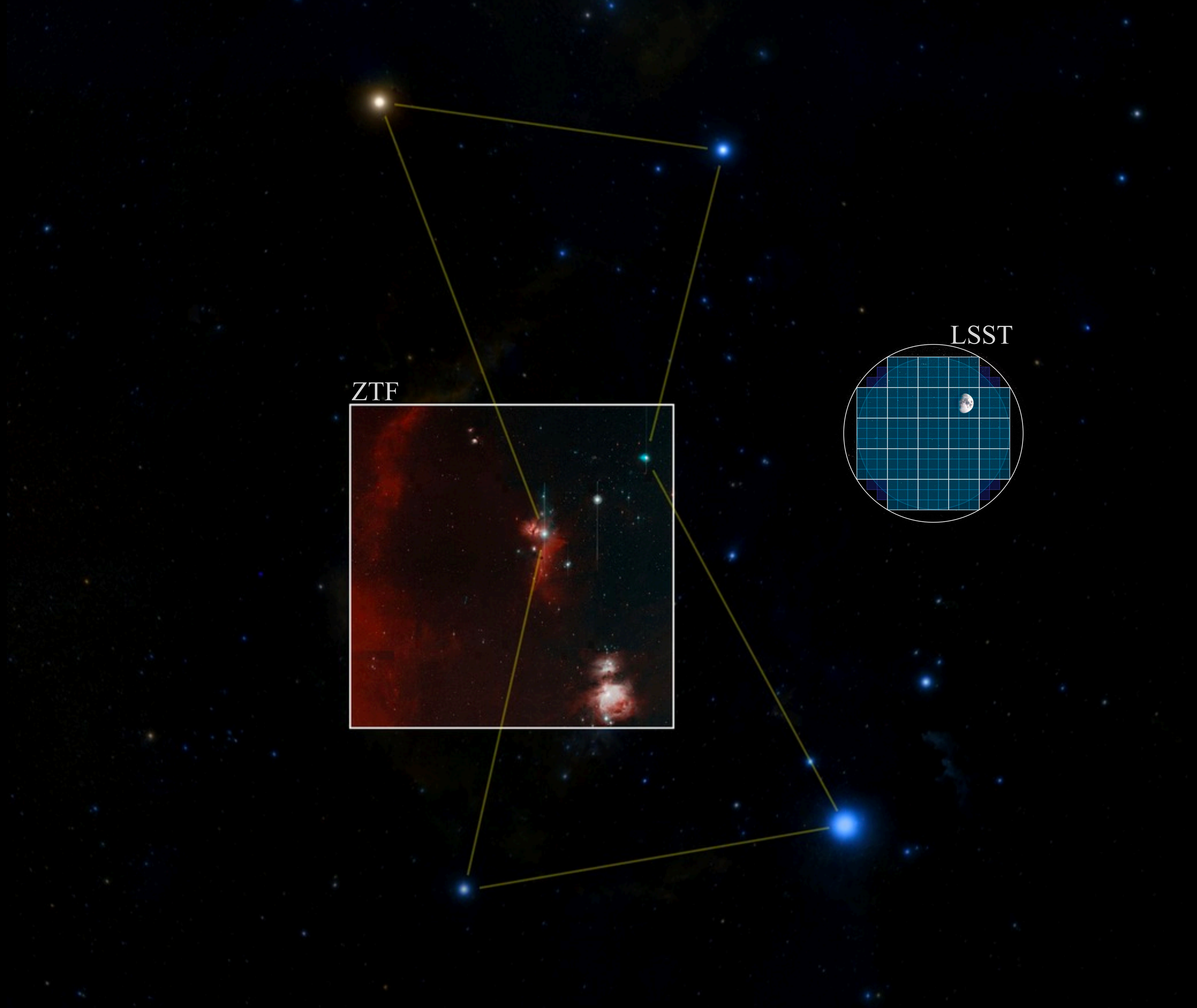
Rigault et al. in prep. | Rigault et al. 2015, 2020

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%"

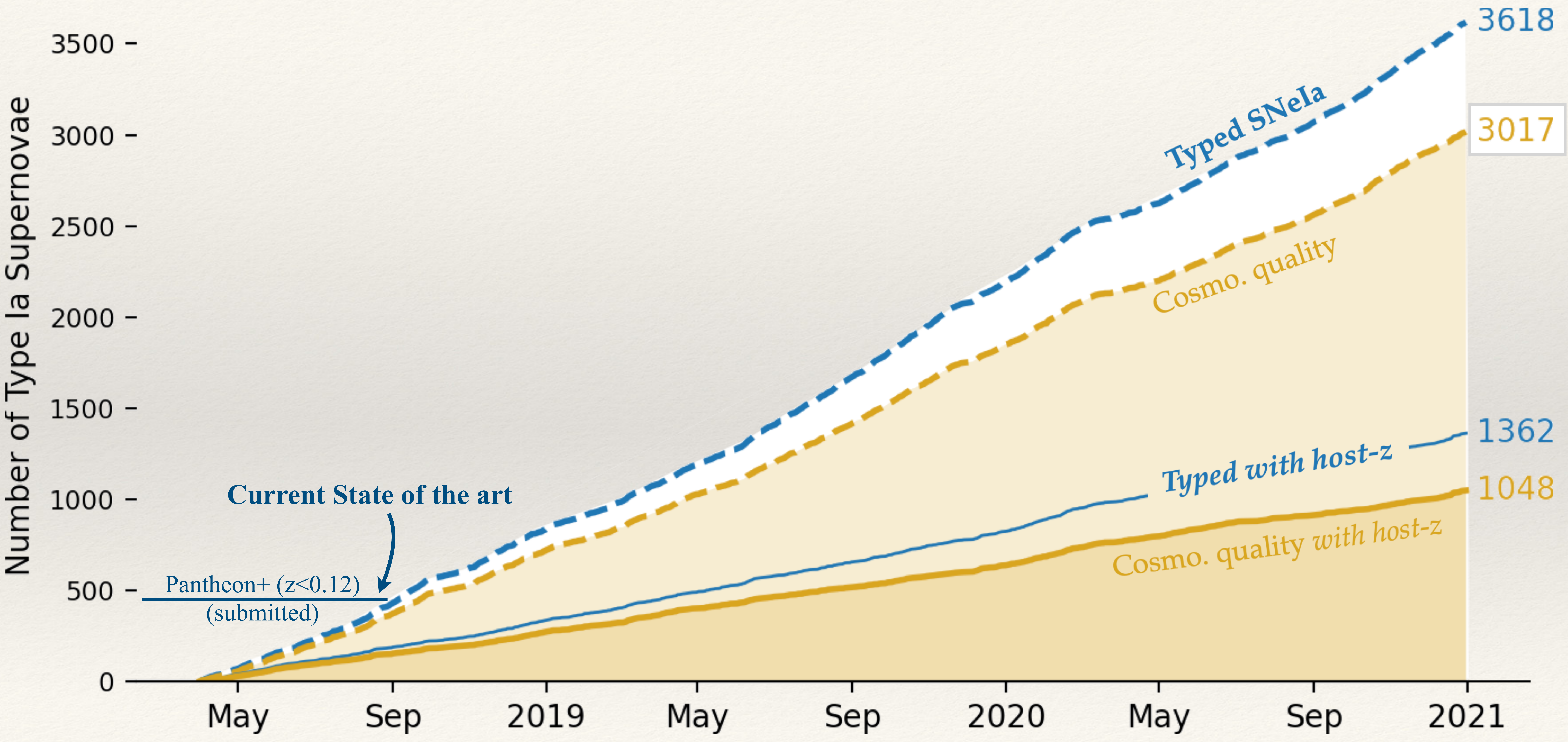
Riess et al. 2022 | Riess et al. 2016, 2019

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



ZTF | *Changing the scale of SN Cosmology*

Smith et al. *in prep*

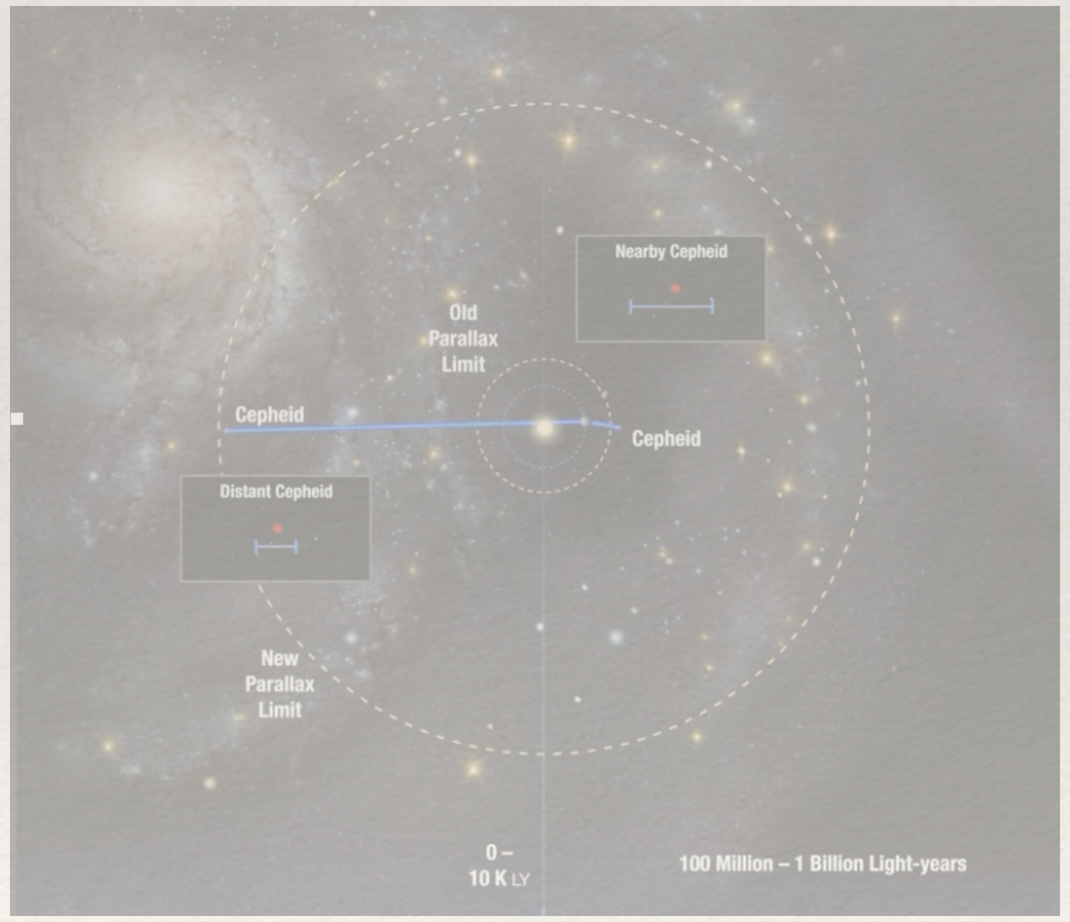


Direct Distance Ladder | *SH0ES*

Calibrate the "Period-Luminosity" relation

"Geometry"

Parallaxes | D.E.B. | Maser

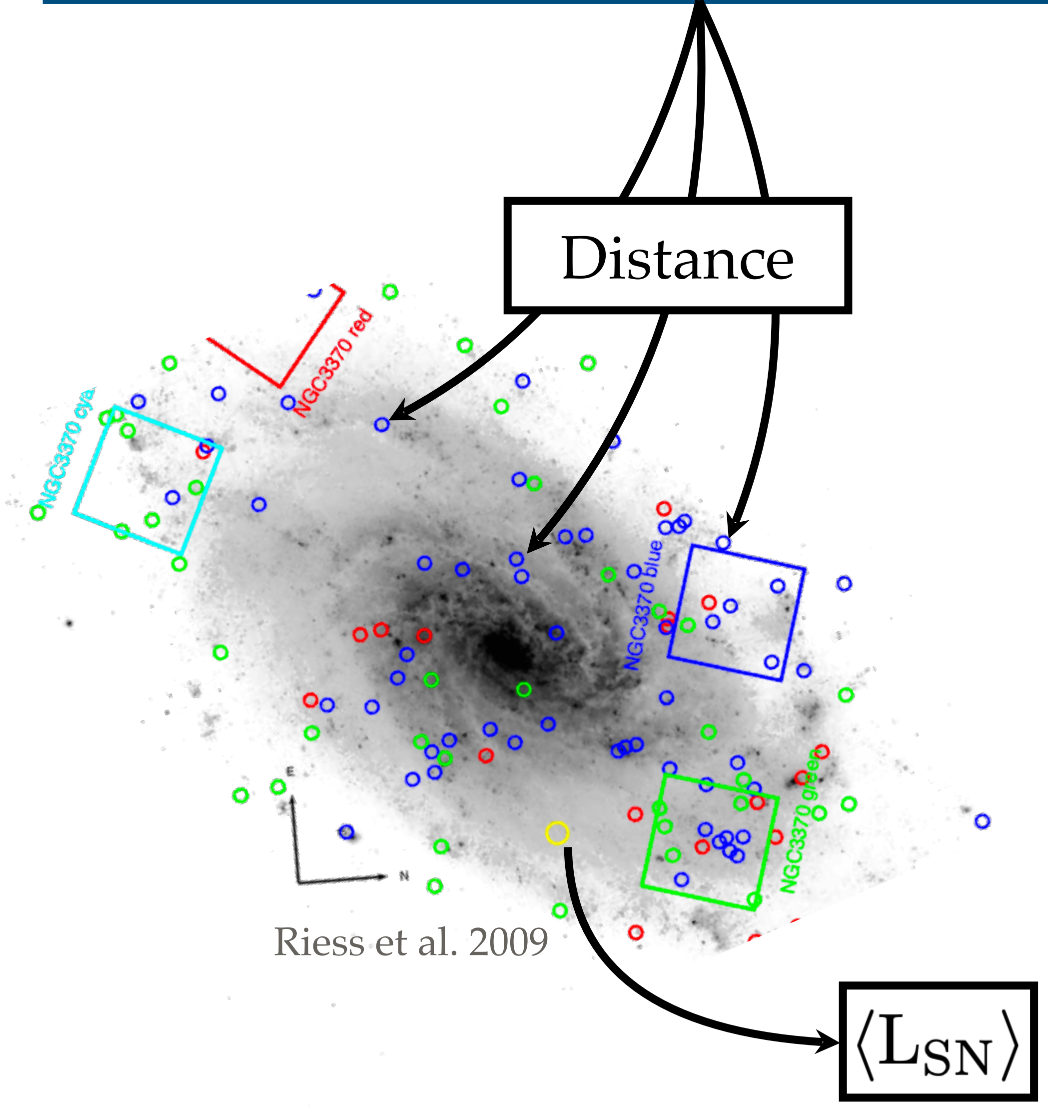


The SNe Ia "matching" problem

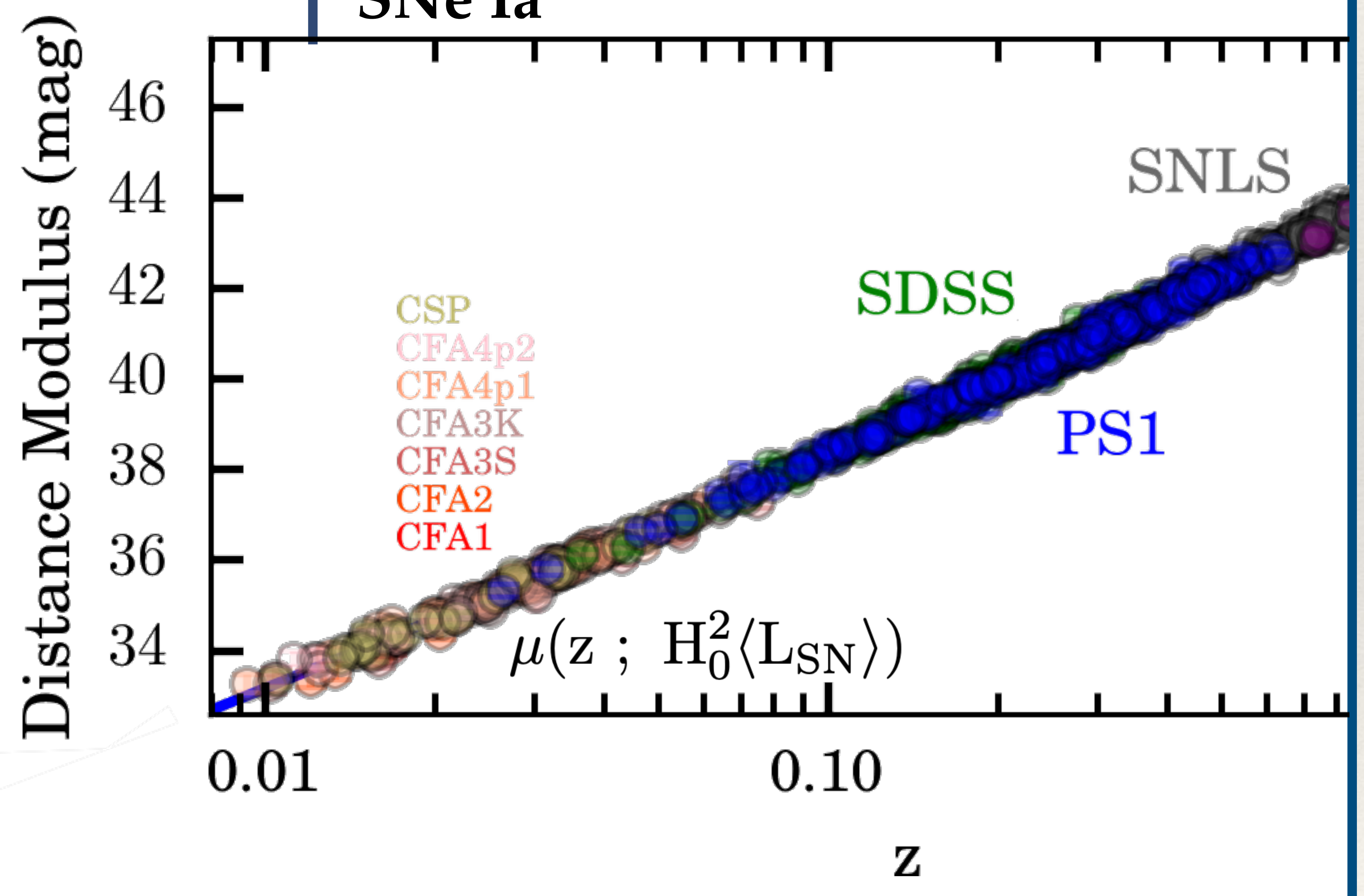
Measure "L_{SN}" *Get "H_0"* **distance**

"Calibrators"

Cepheids



"SNe Ia"



Direct Distance Ladder | *SH0ES*

SN steps | *Known Issues*

Selection Bias

Cepheids host favour young environments
Δmag (young, old) ~ 0.13 mag

Rigault et al. 2015

Photometric Calibration

Hubble Flow & Calibrator Samples are *compilations*
8 different surveys made | 15 different photometric

Selection Function Correction

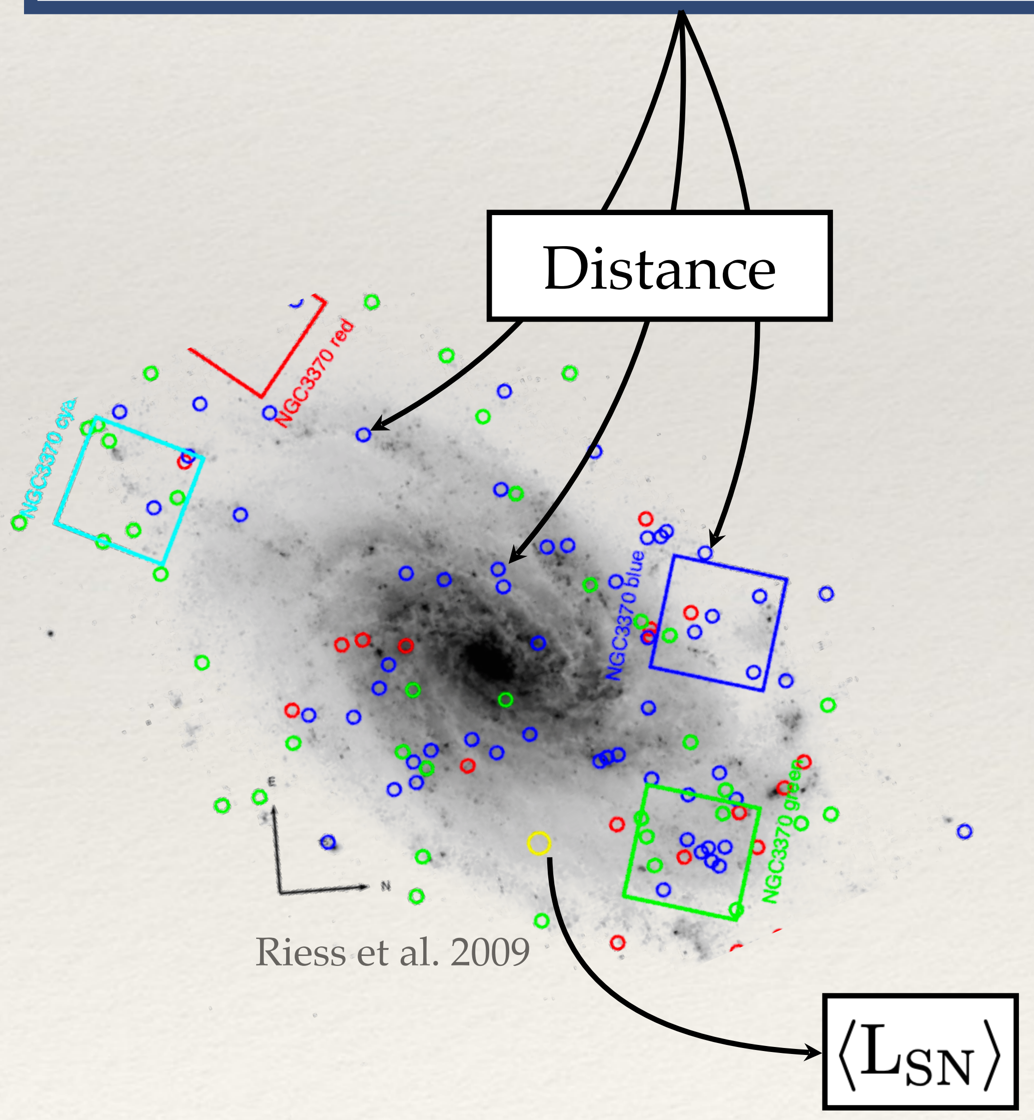
Some surveys are targeted surveys & Observing windows varies
How to correctly account for Malmqvist bias

Get independent distances for SNe Ia

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

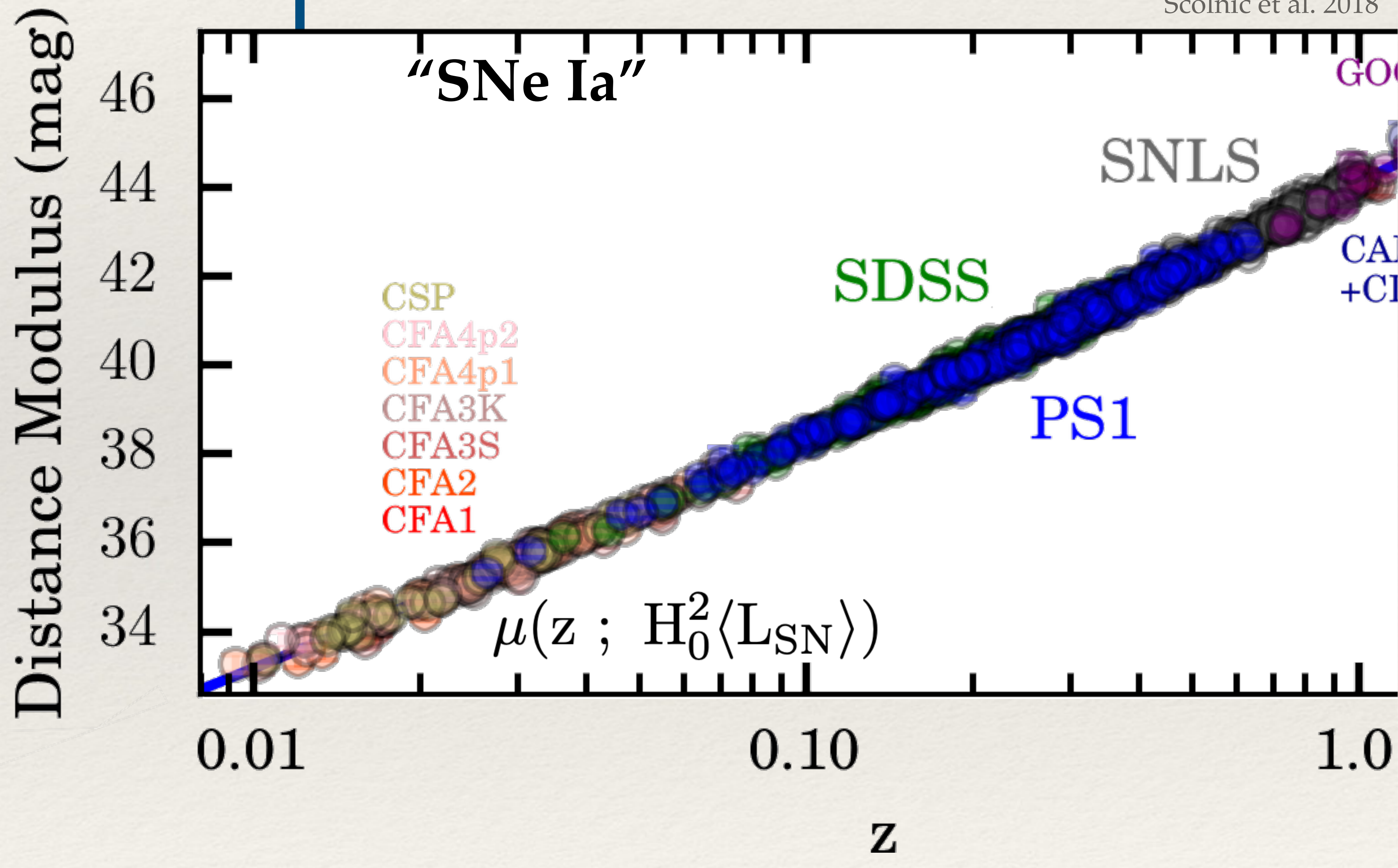
"Calibrators"

Cepheids



Riess et al. 2009

Scolnic et al. 2018



Riess et al. *2022*

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

ZTF Sample | *Toward a self-consistant H_0*

Ongoing Cycle 2 JWST proposal

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

Calibrator Sample

Volume limited ZTF-SNeIa < 60 Mpc

Technique
TRGB (doable in any galaxy)

Statistics: ~7 per year (~40 by end of ZTF)

Hubble Flow Sample

Volume limited ZTF-SNeIa z<0.06 Mpc

ZTF detects, follows and classifies *all* SNe Ia in the northern sky up to z~0.06

Statistics: Already >800 acquired

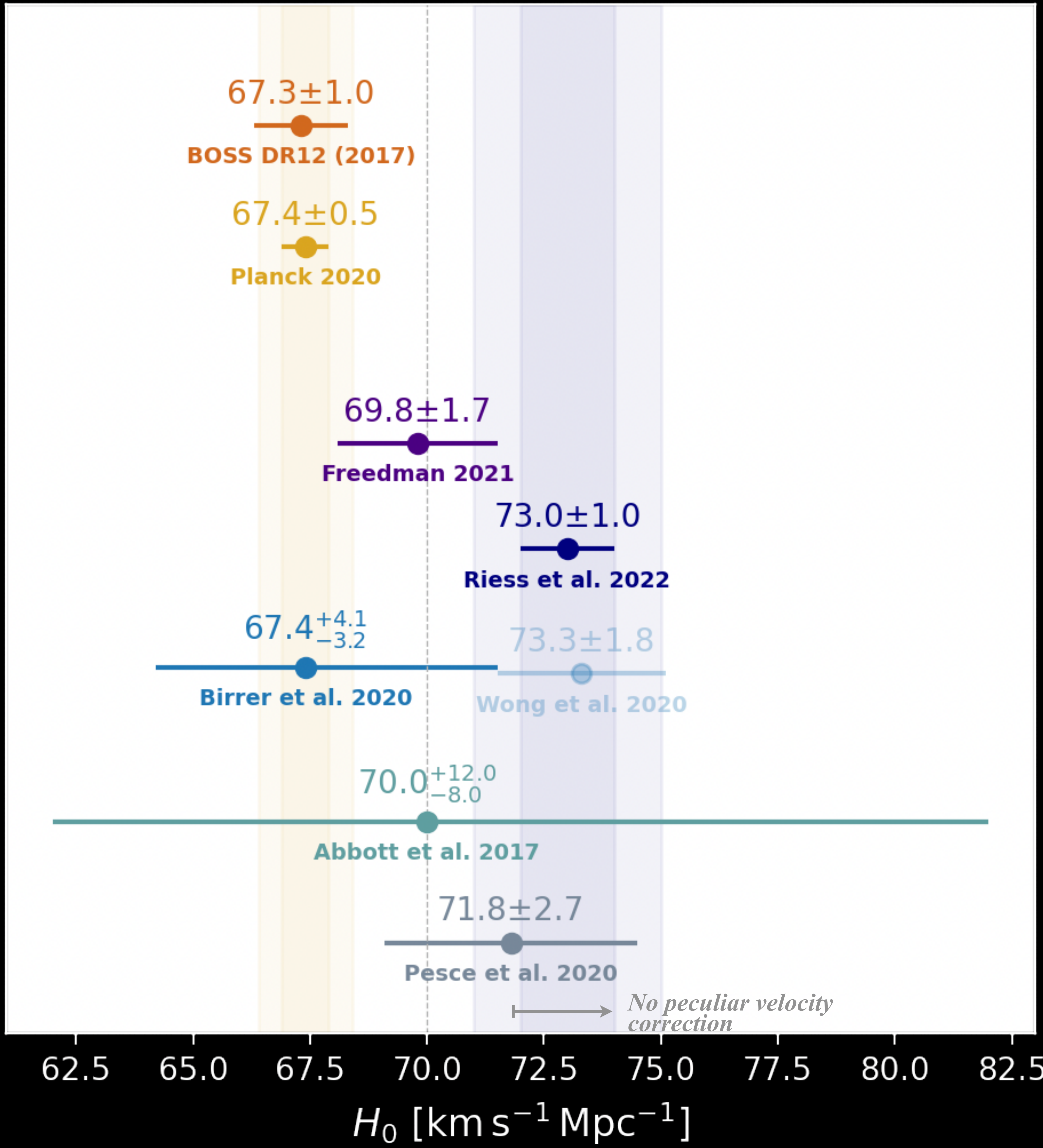
No selection function since both volume limited samples

Unique photometric system, no absolute photometric calibration issue
only relative, which is way easier

The Hubble Tension

Many more points (e.g. 2022)

- SNeIa->SNII: de Jaeger+2022 | 75±5%
- Geometry+Cepheids: Kenworthy+2022 | 73±4%
- BAO+BBN: Schöneberg+2022 | 68 ± 0.5%
- …



Strong Lensing
systematics actively studied

Sensitive to peculiar velocity correction

SNeIa calibrated by:

← **BAO (z~1)** | r_s

← **TRGB (z~0)** | *geometry*

← **Cepheids (z~0)** | *geometry*

ZTF is about to change the SNeIa field

The progenitor age model

	A two population model	
	Young *Prompt*	**Old** *delayed*
Rate	**Star Formation** O(100 Myr)	**Mass** O(5 Gyr)
Stretch	**Only** high stretch mode	**Both** low and high stretch modes
Color	*Could differ*	
Stardardisation	*No difference*	
Absolute Magnitude	**Fainter** by ~0.07 mag	**Brighter** by ~0.07 mag

Means evolution

"More star formation at higher redshifts"

Origin of biases

"Massive galaxies are redder, usually elliptical and less star forming"

Origin of biases

"Massive galaxies are redder, usually elliptical and less star forming"

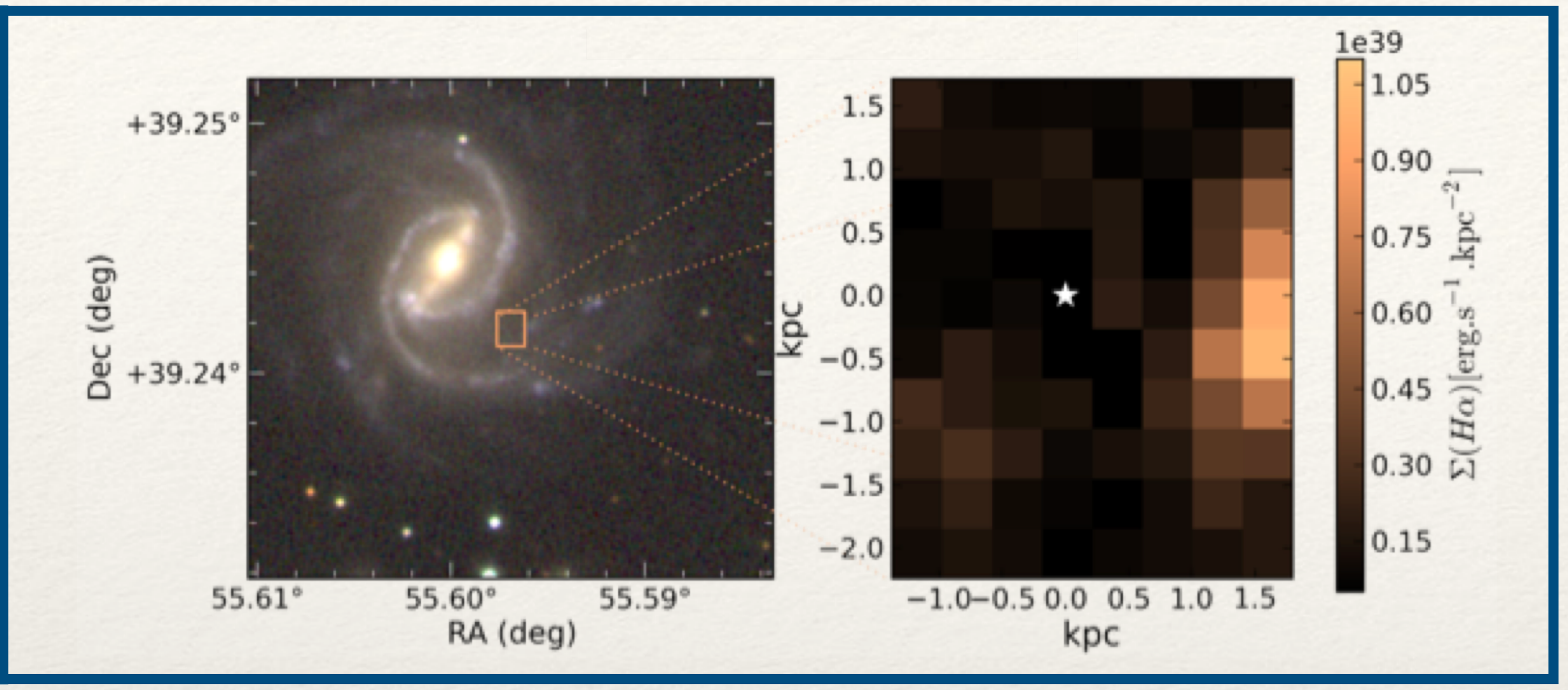
Observed Step & Tracer accuracy

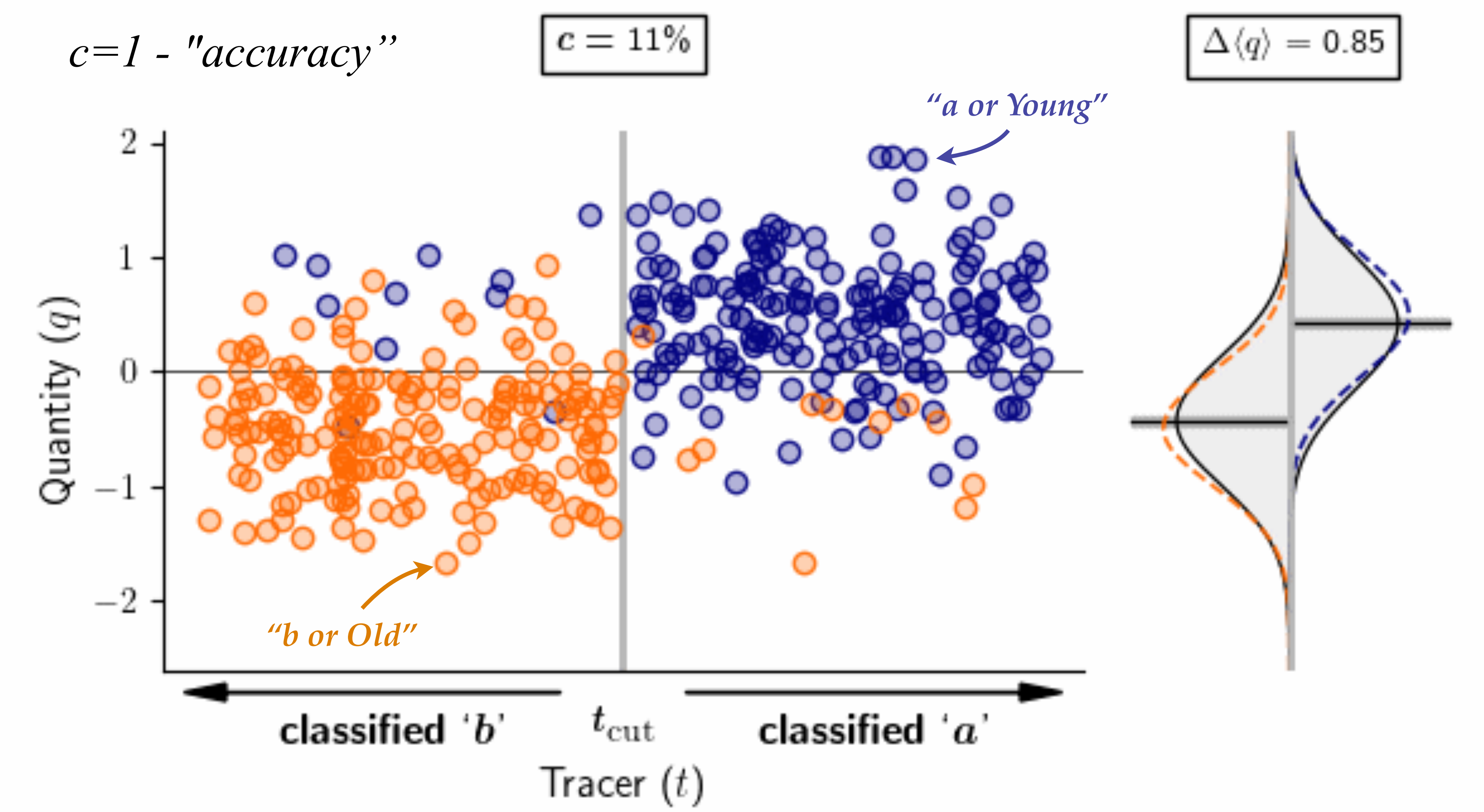
Briday, Rigault et al. 2022

erc | USNAC

"Spiral host means young progenitor"

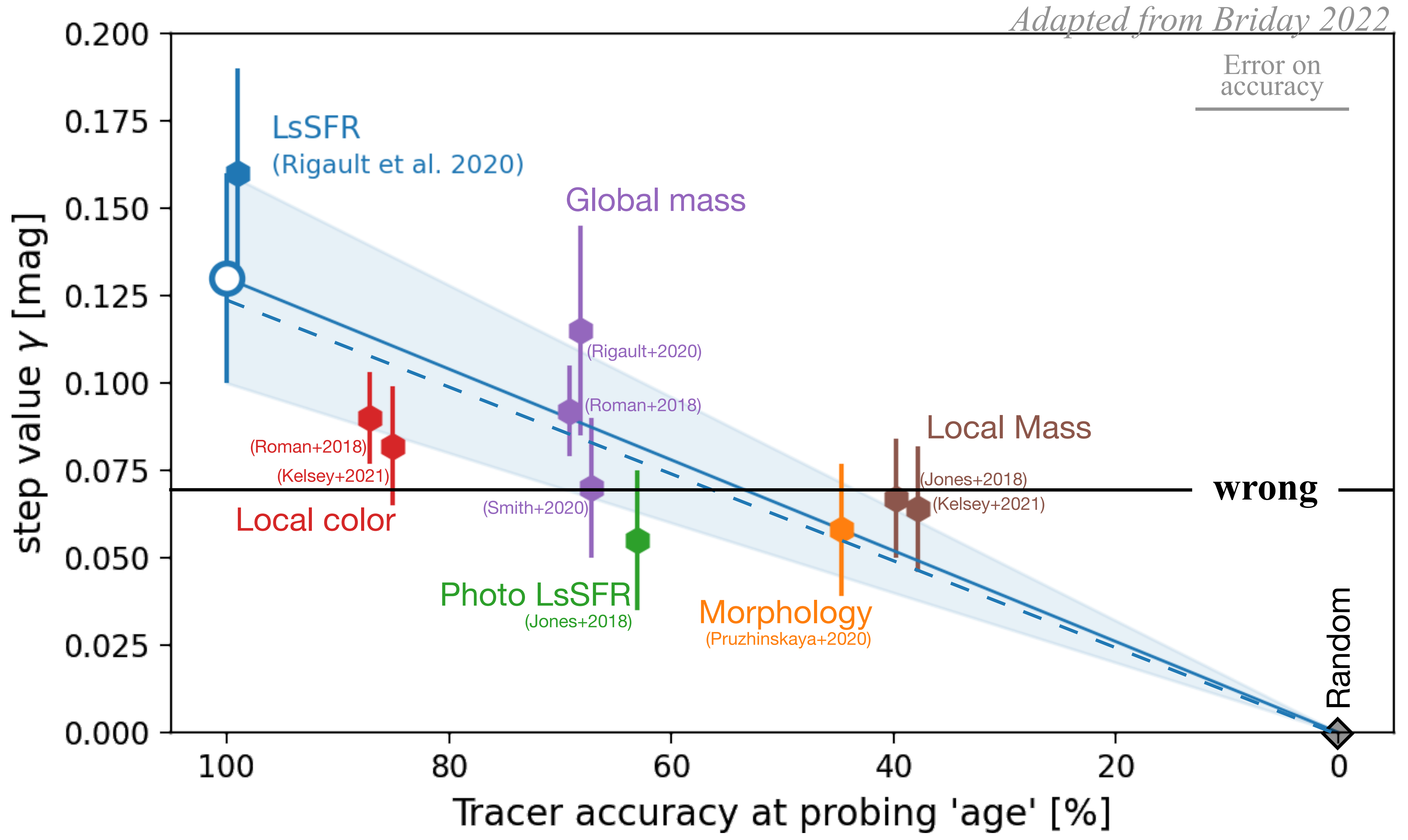
…nope…





The "steps" and how to measure them

Literature steps confirm the age model with a step of ~0.13 mag



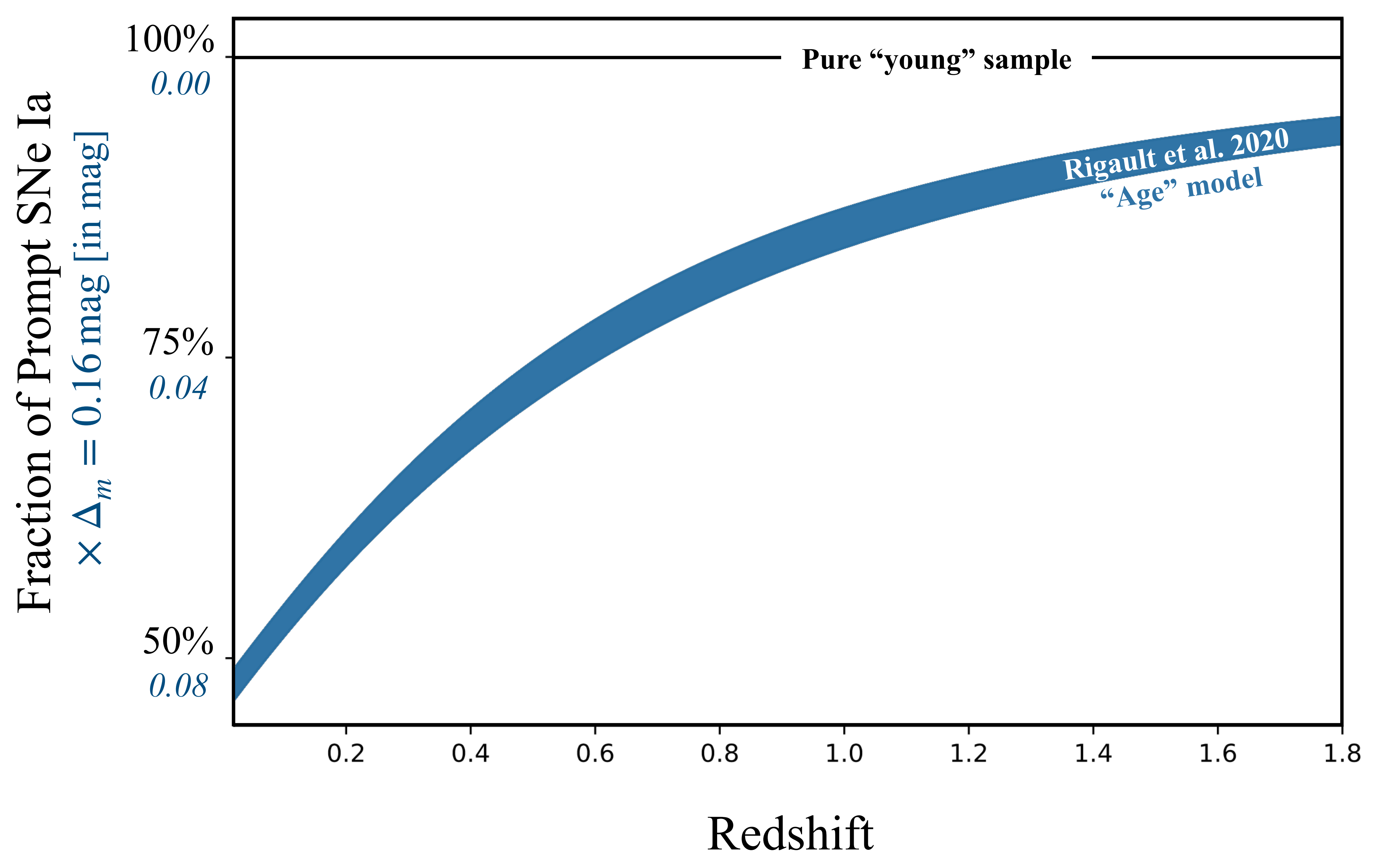
"More star formation at higher redshifts"

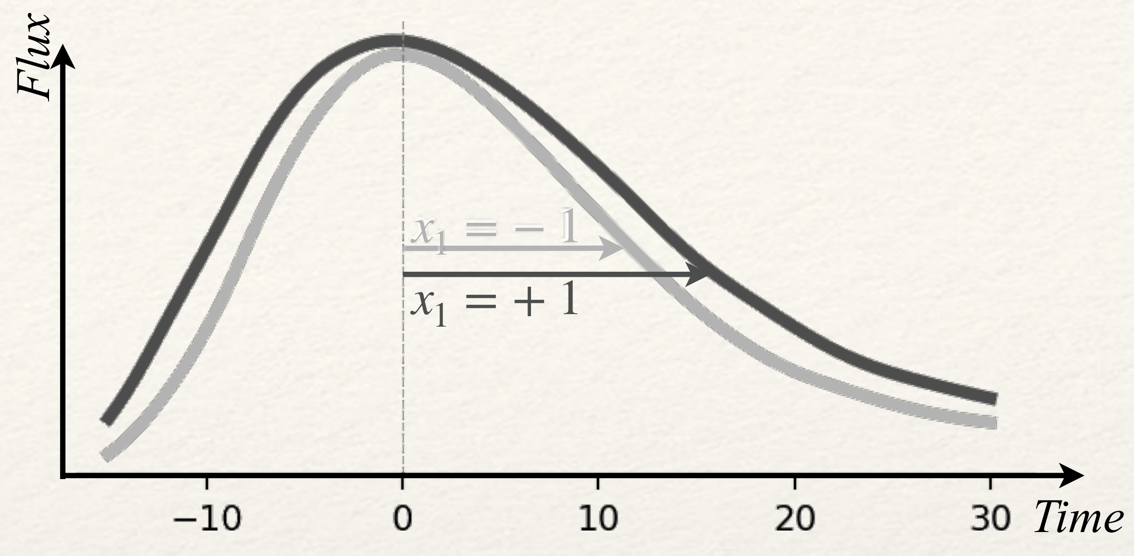
Probing the SNe Ia evolution

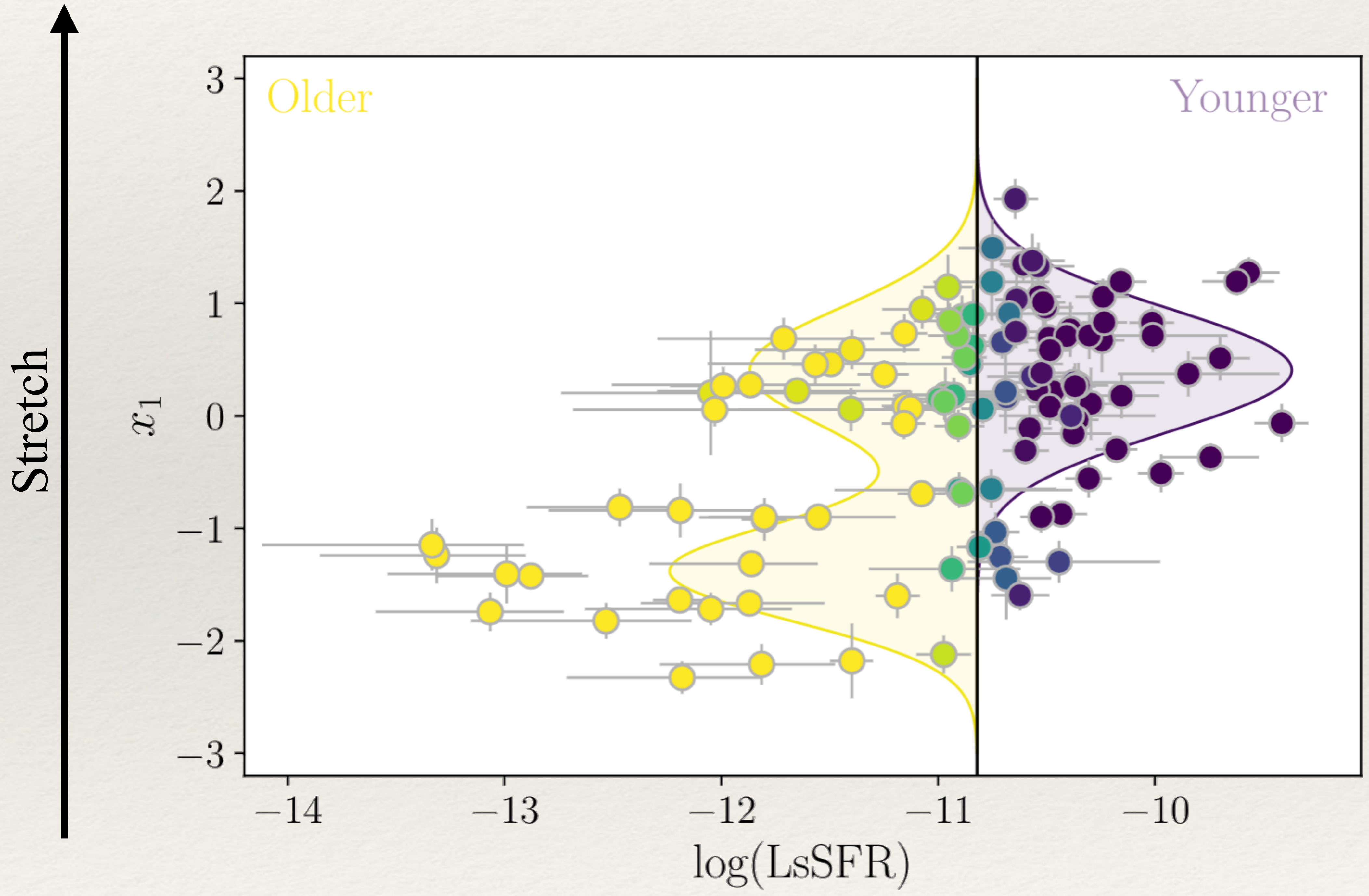
Nicolas, Rigault et al. 2021

erc | USNAC

Fraction of "young vs. old" SNe Ia







"More star formation at higher redshifts"

Probing the SNe Ia evolution

Nicolas, Rigault et al. 2021

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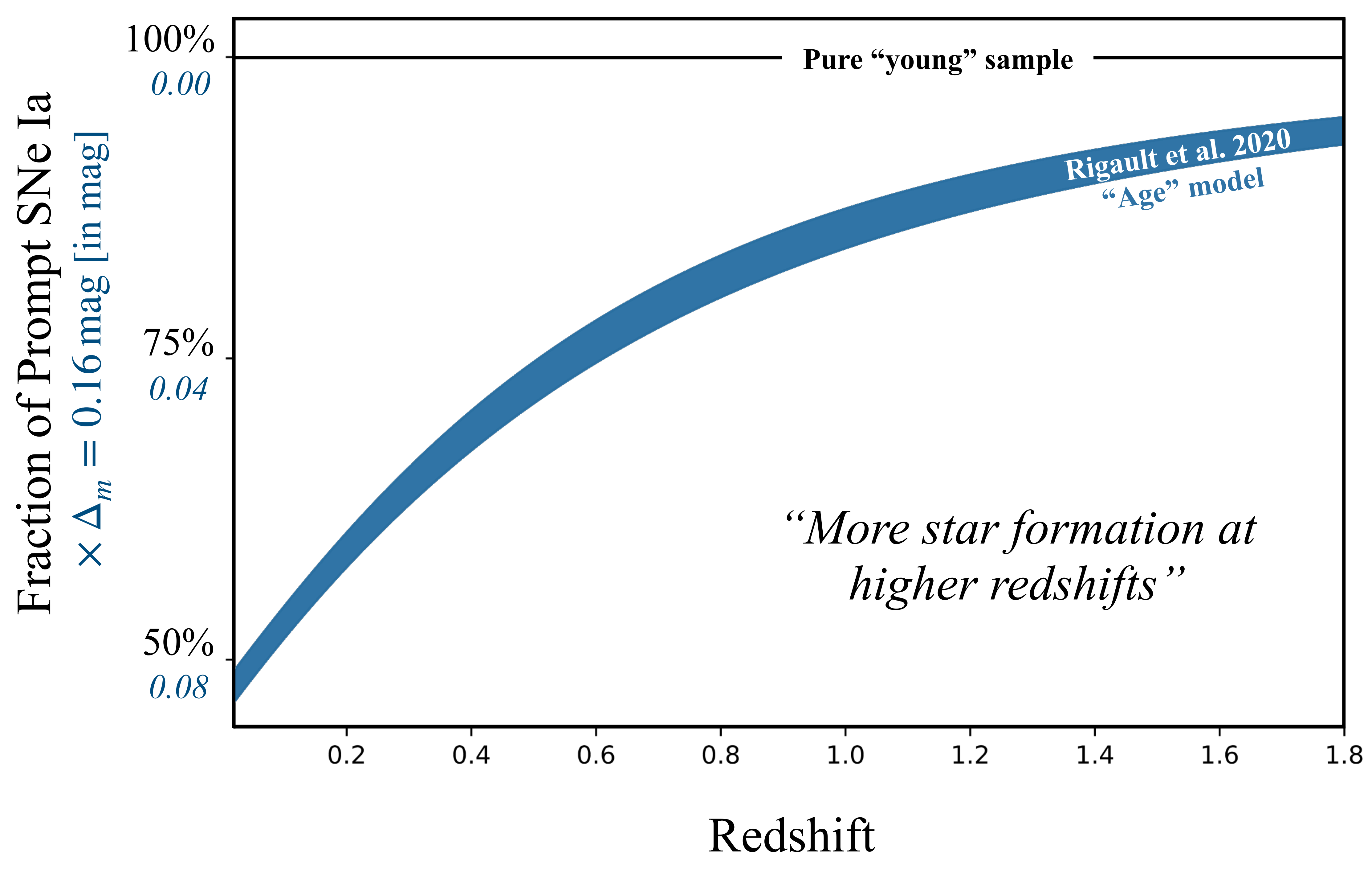
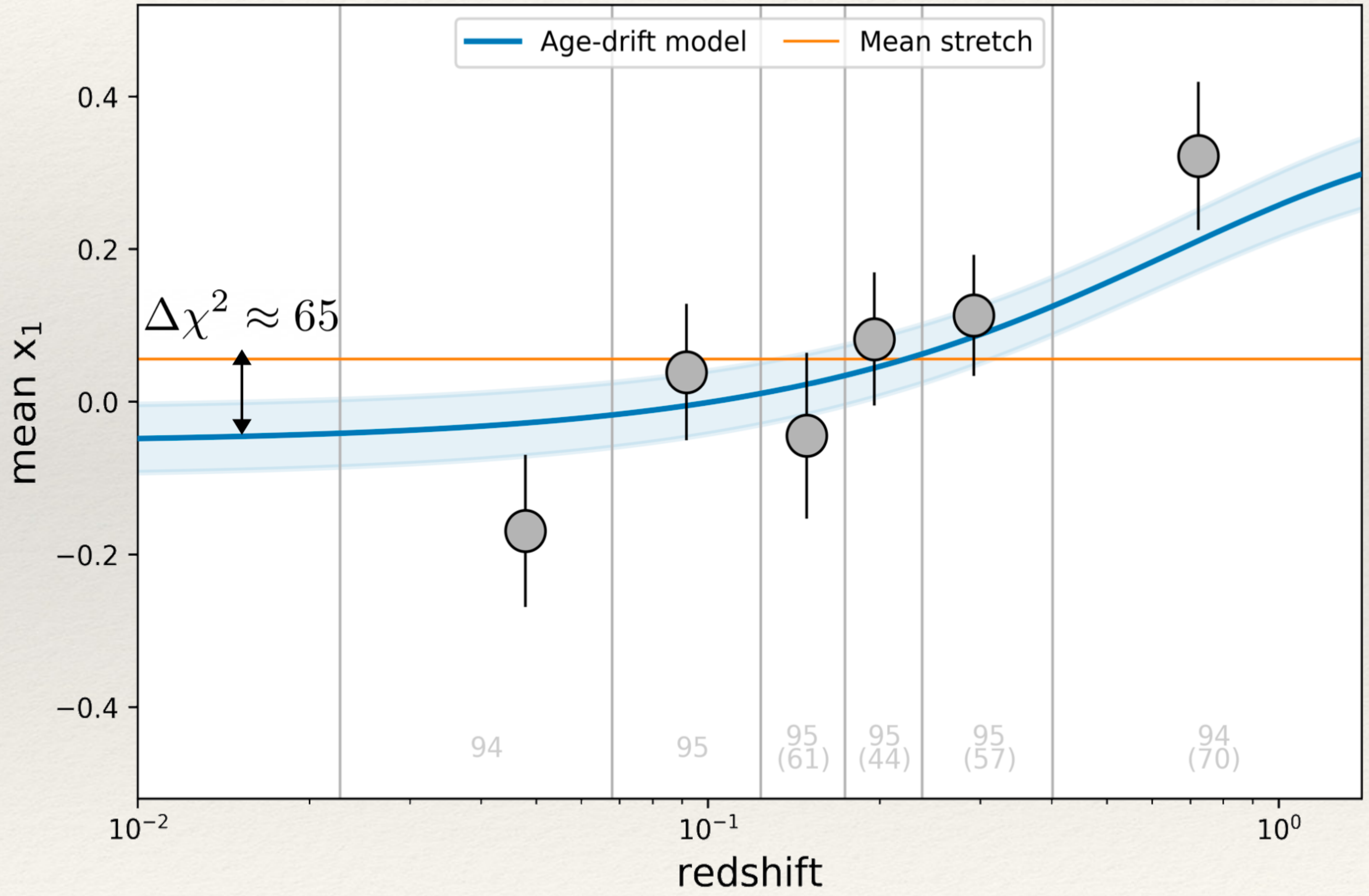
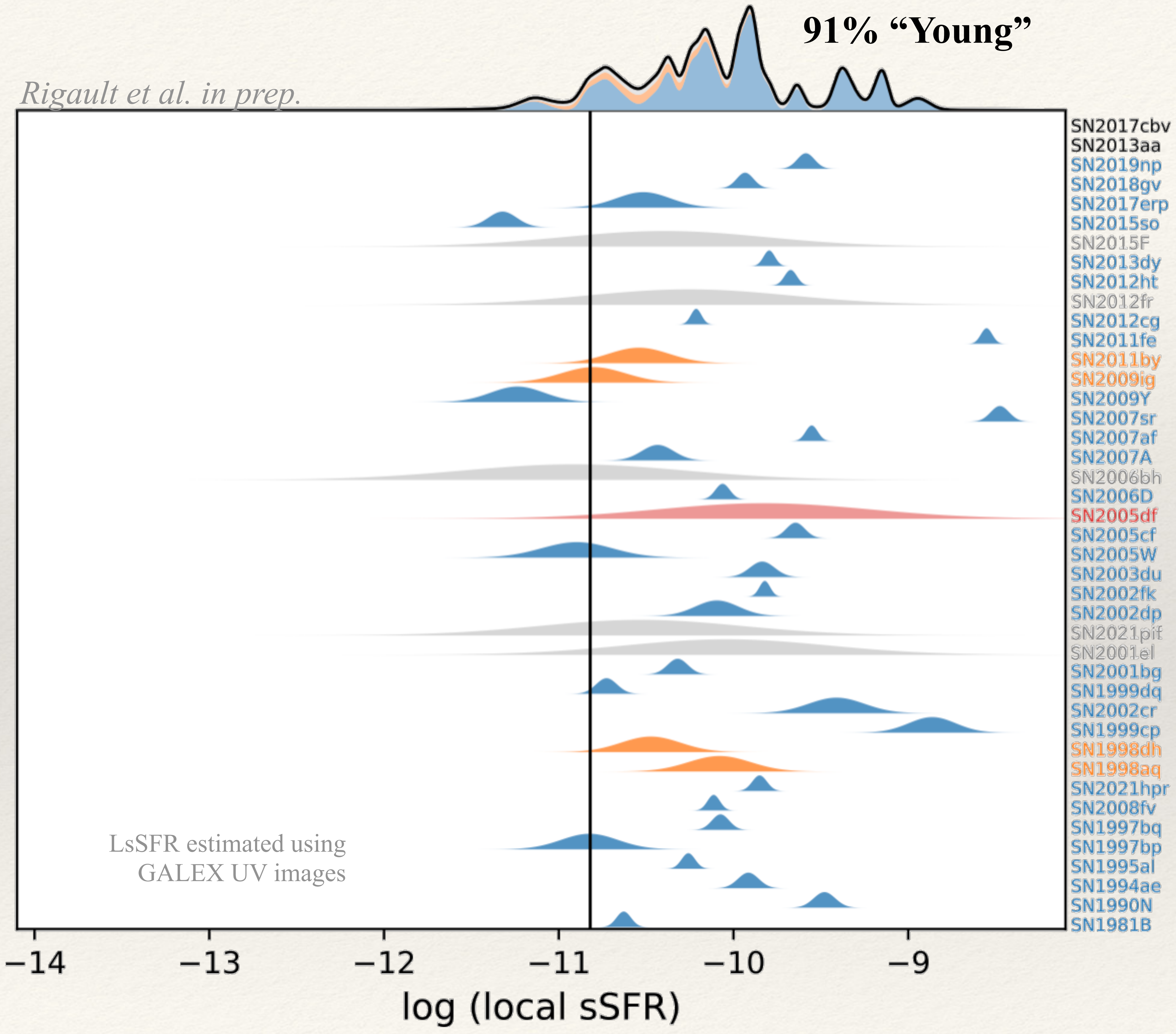
Fraction of "young vs. old" SNe Ia



SNe Ia do evolve, and do so as predicted by the age model !



Astrophysical bias affecting the measurement of H_0



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

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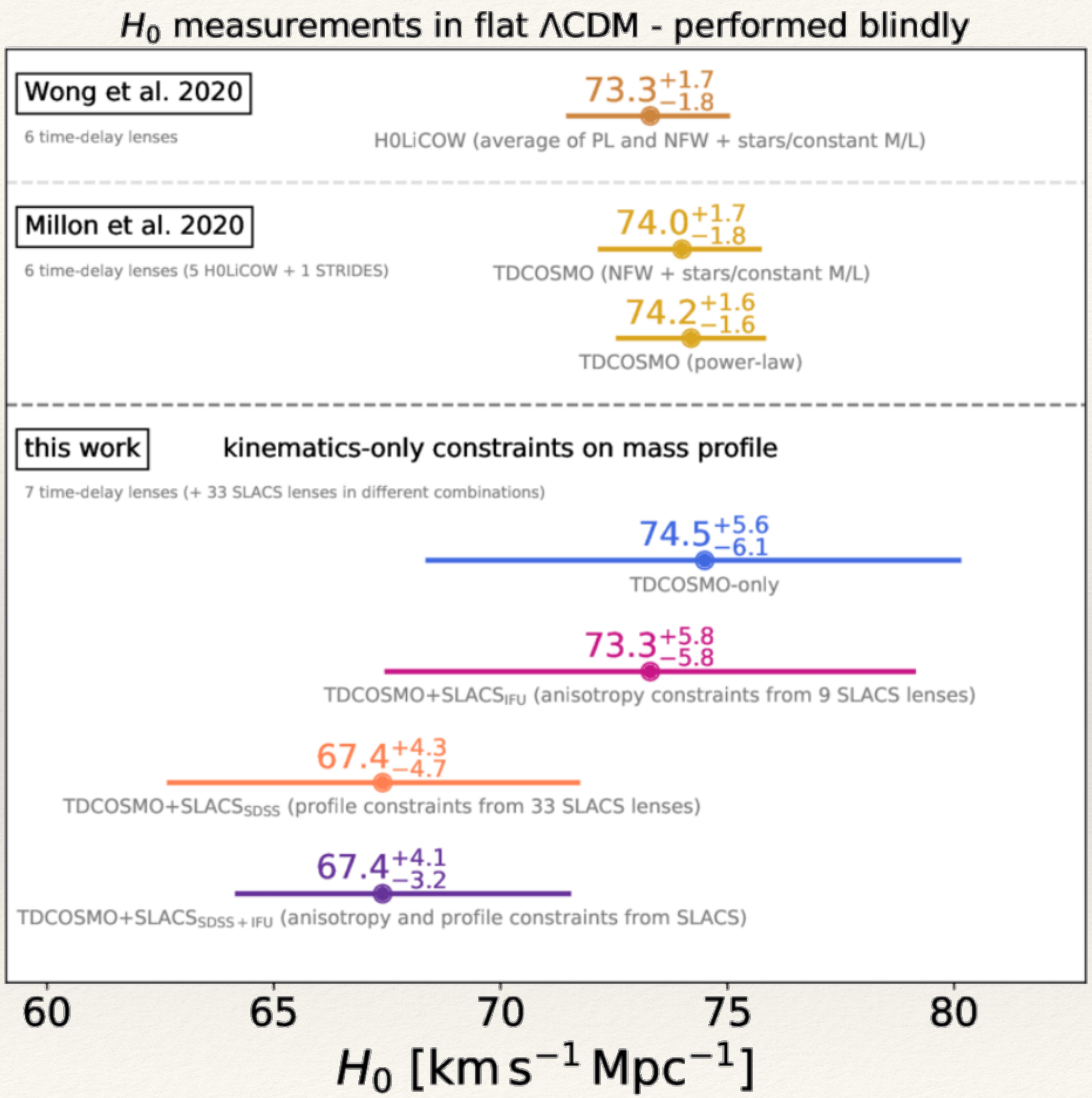
SH0ES rebuttal

"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

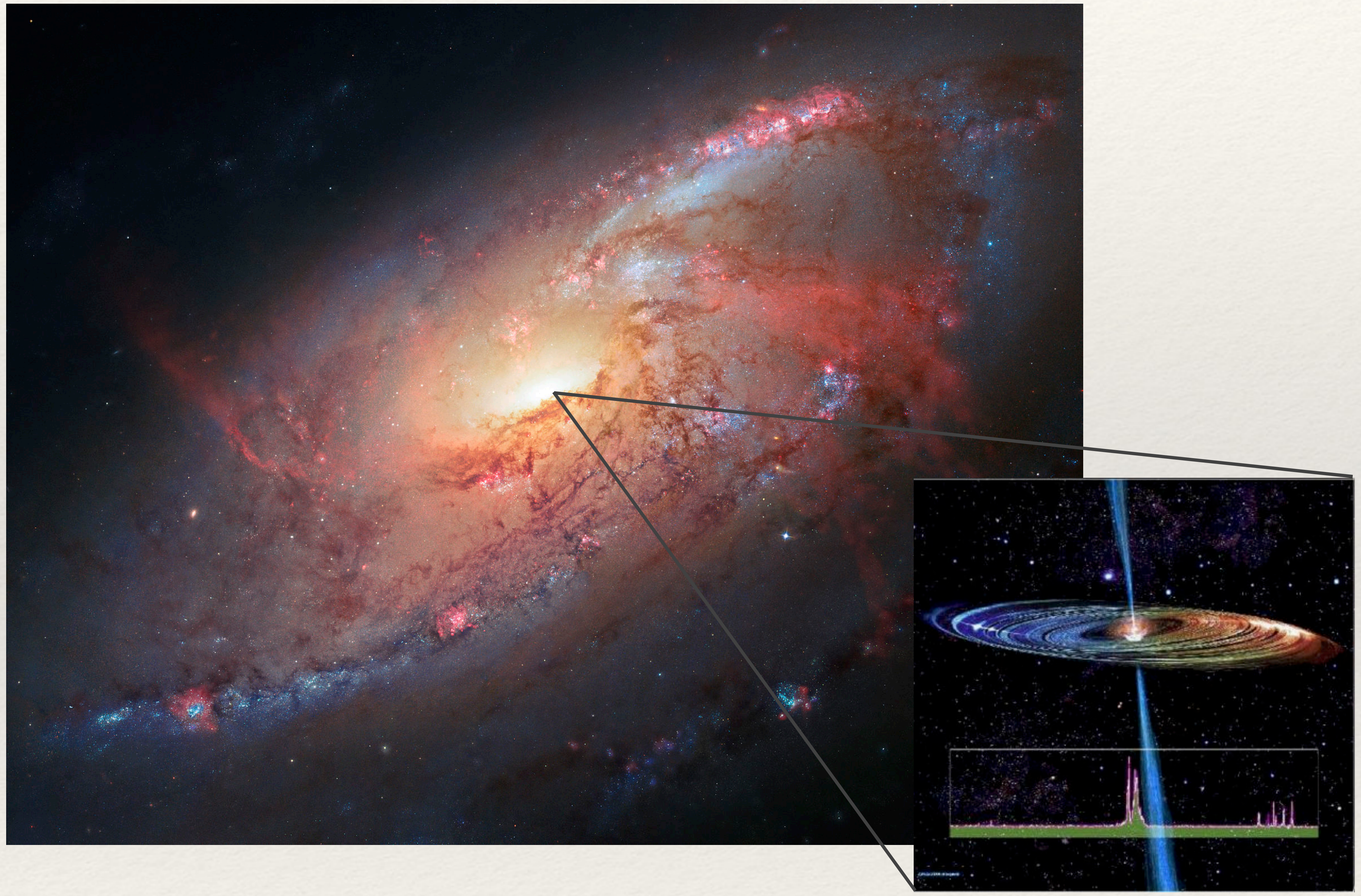
TDCOSMO

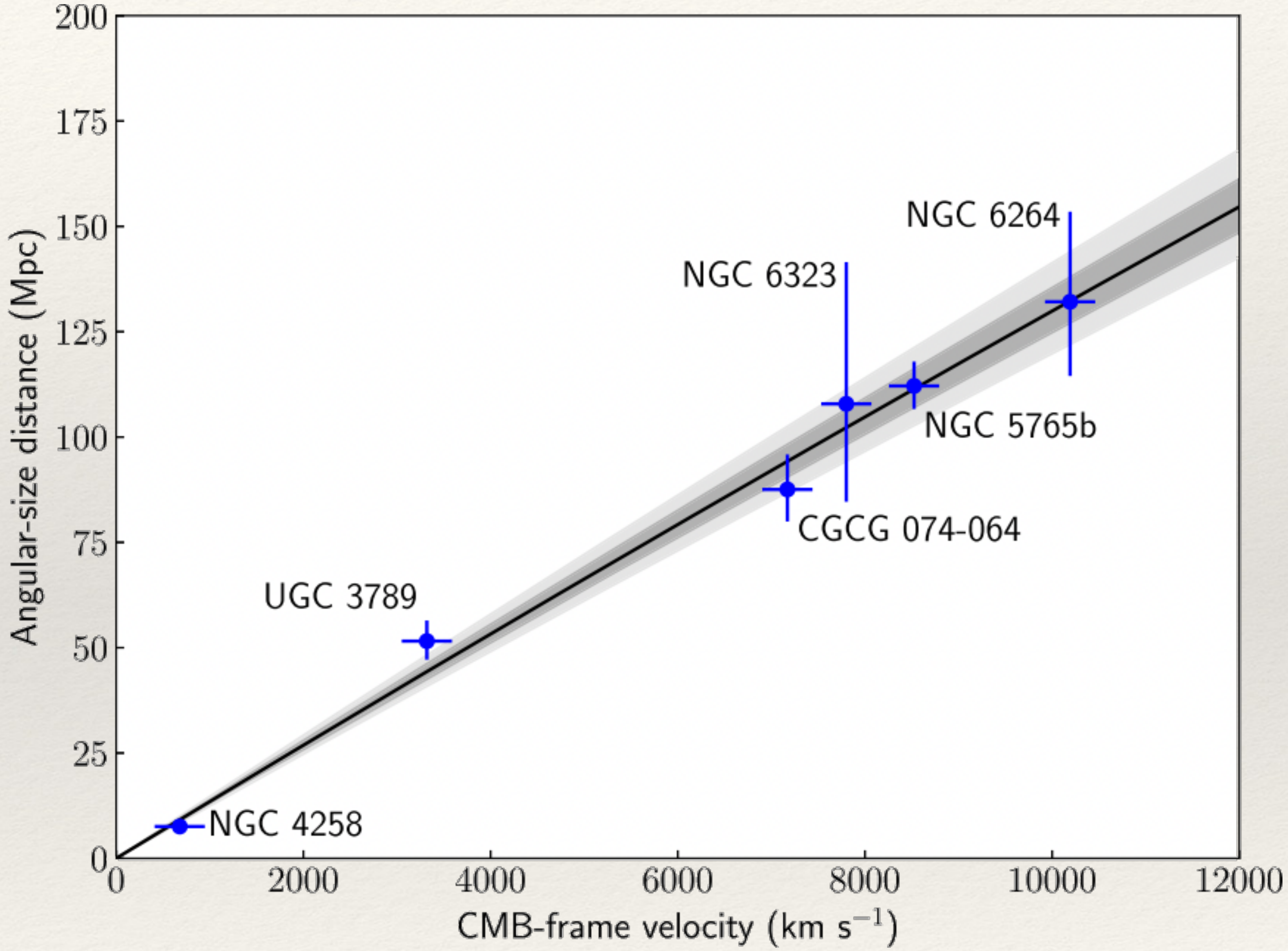
Birrer et al. 2020



Mega Maser | *Absolute Hubble Diagram H_0*

Pesce et al. 2020





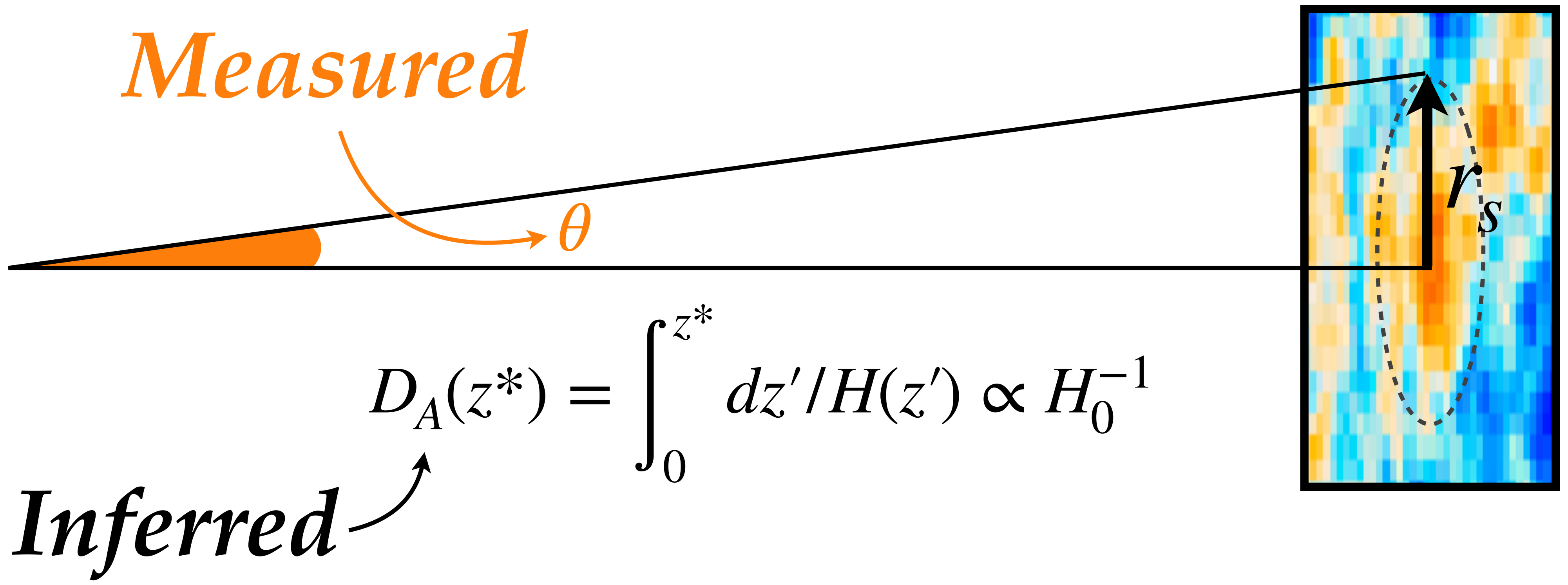
No peculiar velocity correction: **H_0 = 73.9 ± 3.0 km s^{-1} Mpc^{-1}**

peculiar velocity correction: **H_0 = 71.8 ± 2.7 km s^{-1} Mpc^{-1}**

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



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

r_s « *the sound horizon* »

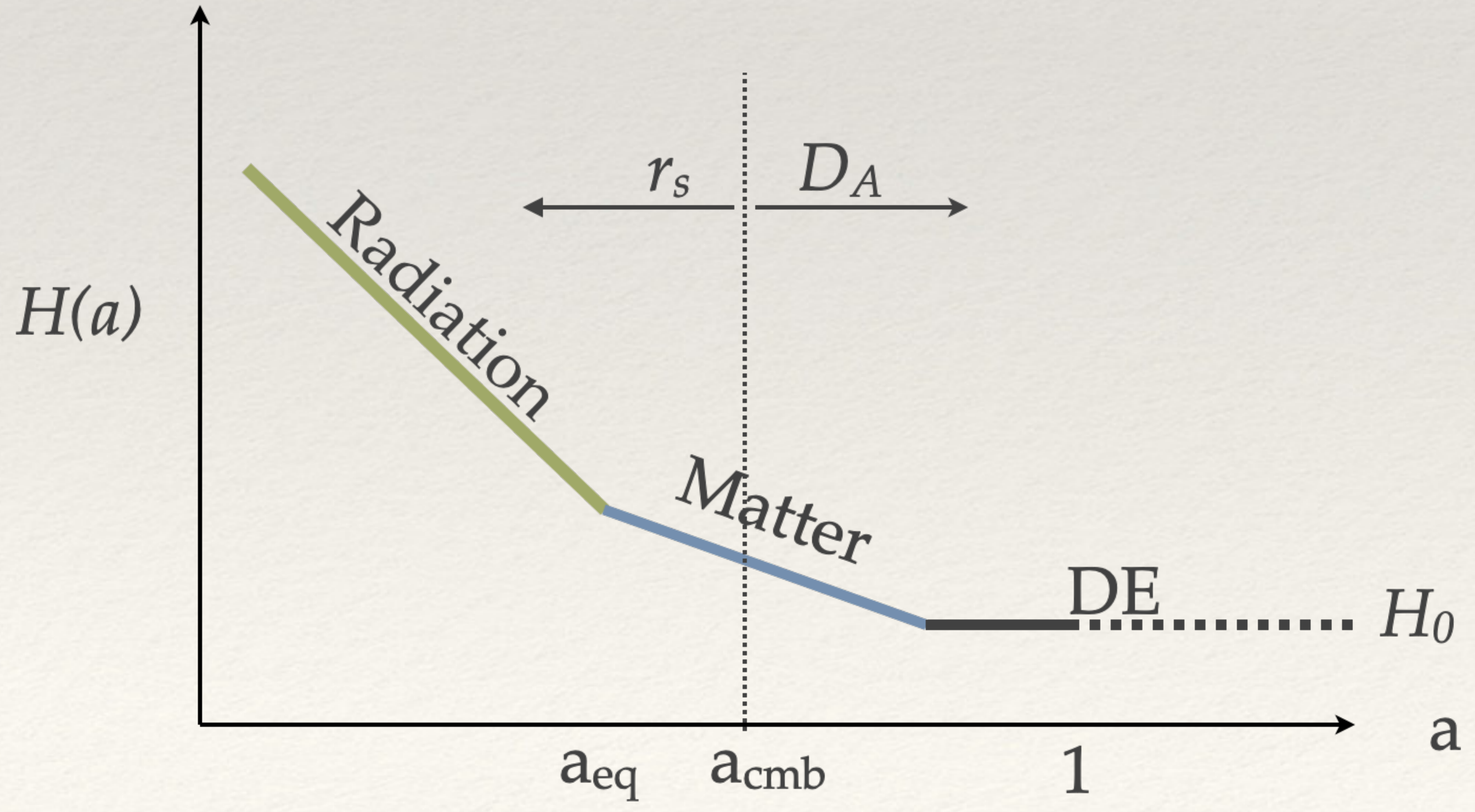
Calculated

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

Radiation driving

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

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:

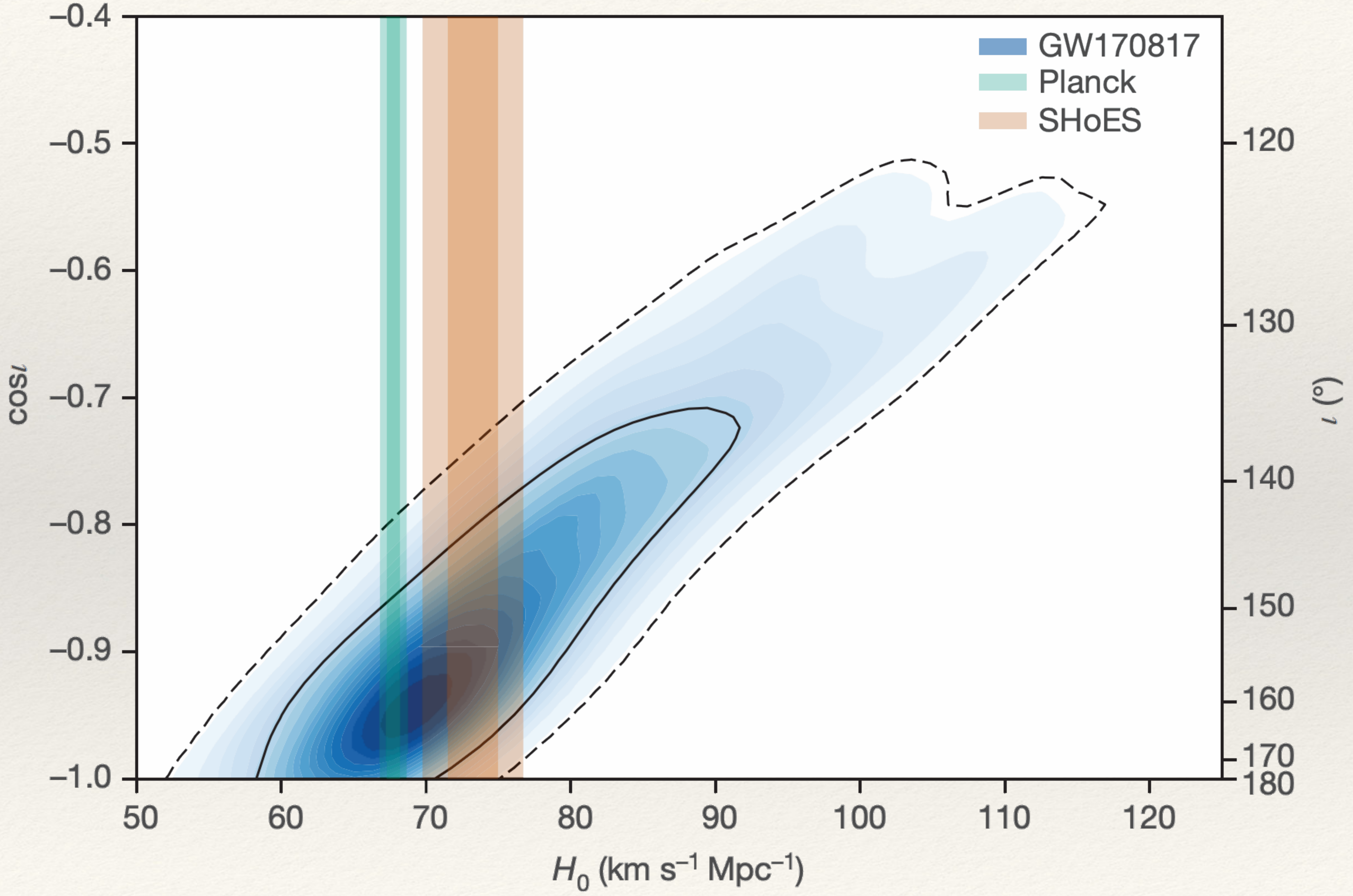
1) determine the baryon density and matter density to allow for calculation of r_s ,
2) infer θ_s from the spacing between the acoustic peaks to determine the comoving angular diameter distance to last scattering $D_A = r_s / \theta_s$,
3) adjust the only remaining free density parameter in the model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

Direct measurement of H_0

Abbott et al. 2017

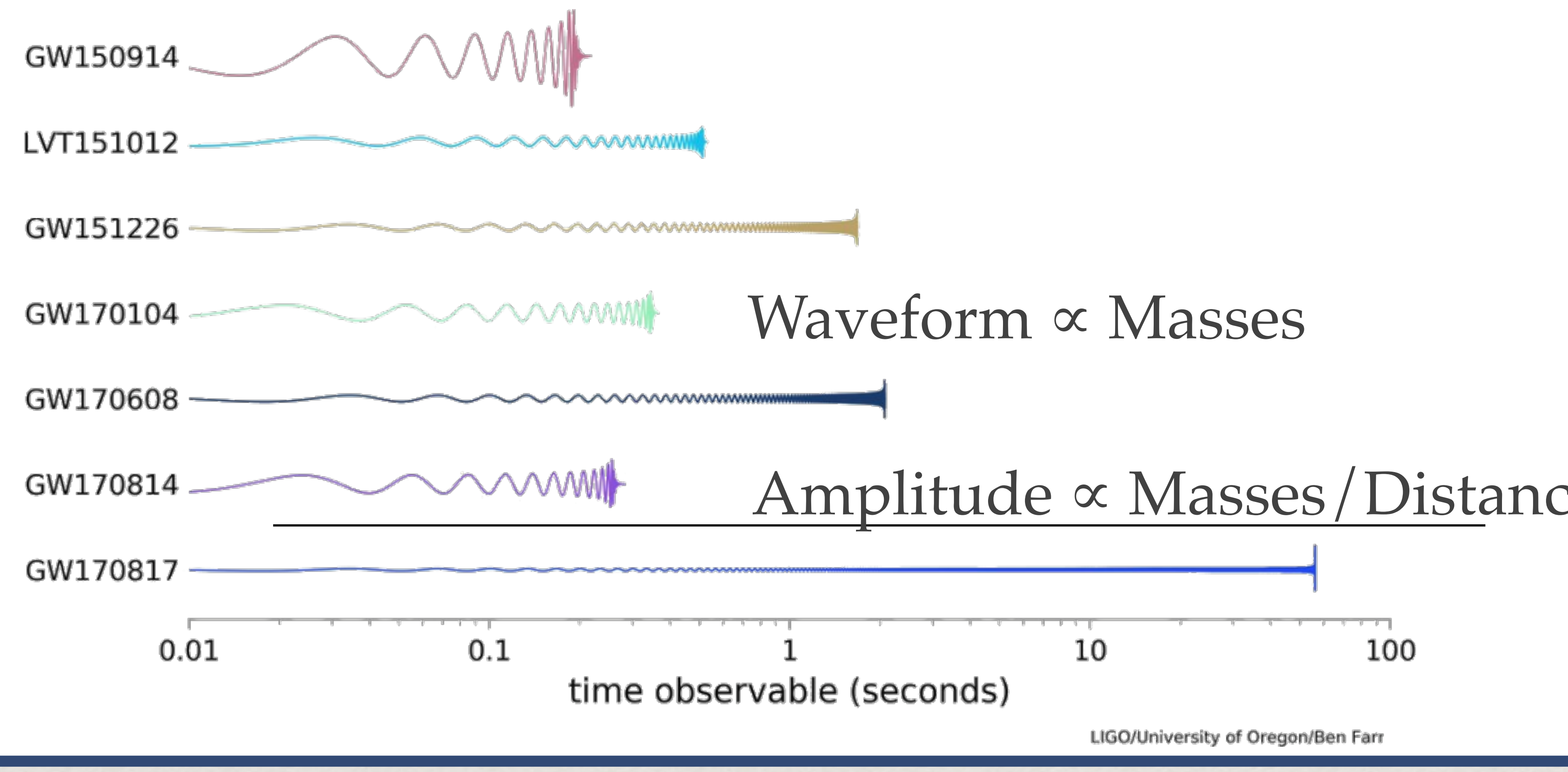


Gravitational Waves & ~~Electro~~Magnetism | H_0

Works with any Merger

Gravitational Waves

$\mathbf{d_L}$



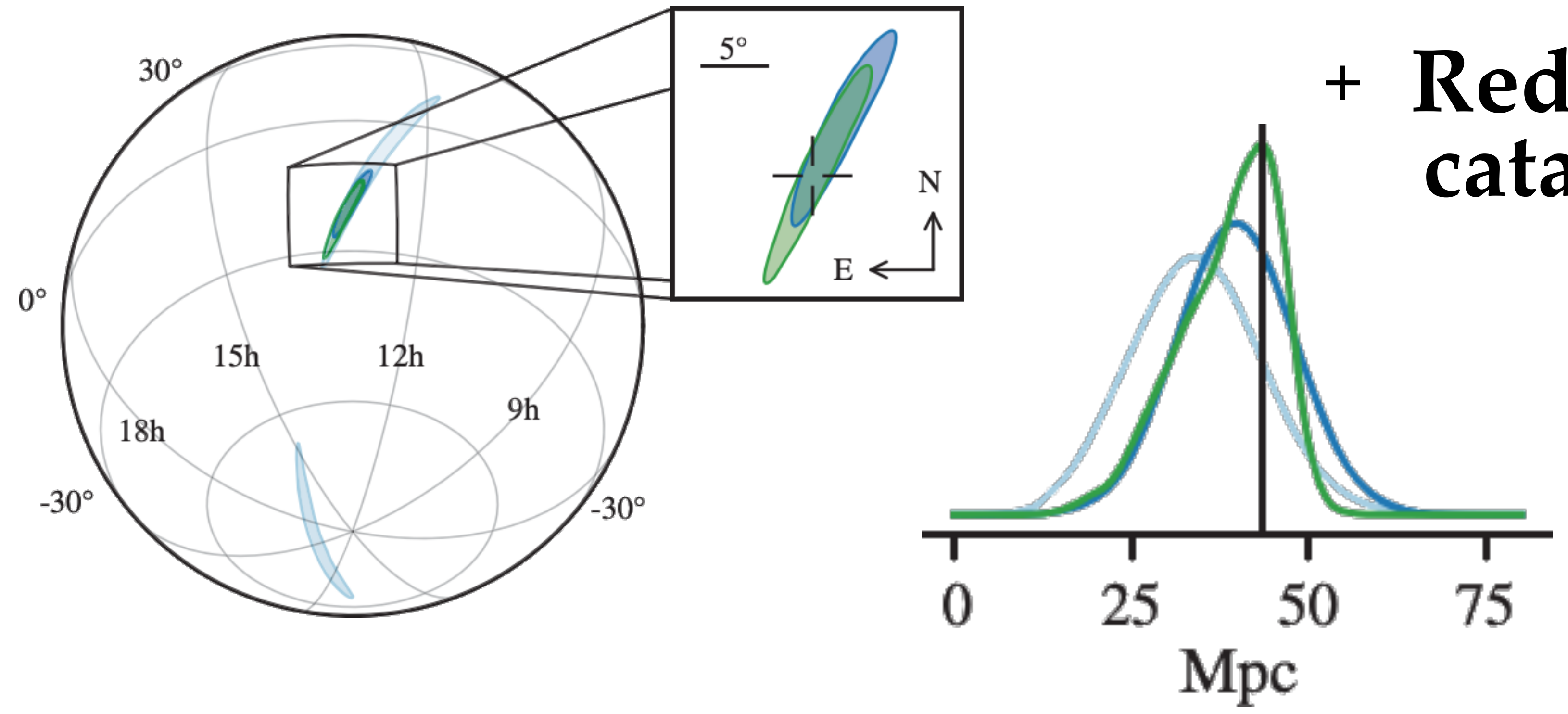
Waveform ∝ Masses

Amplitude ∝ Masses / Distance

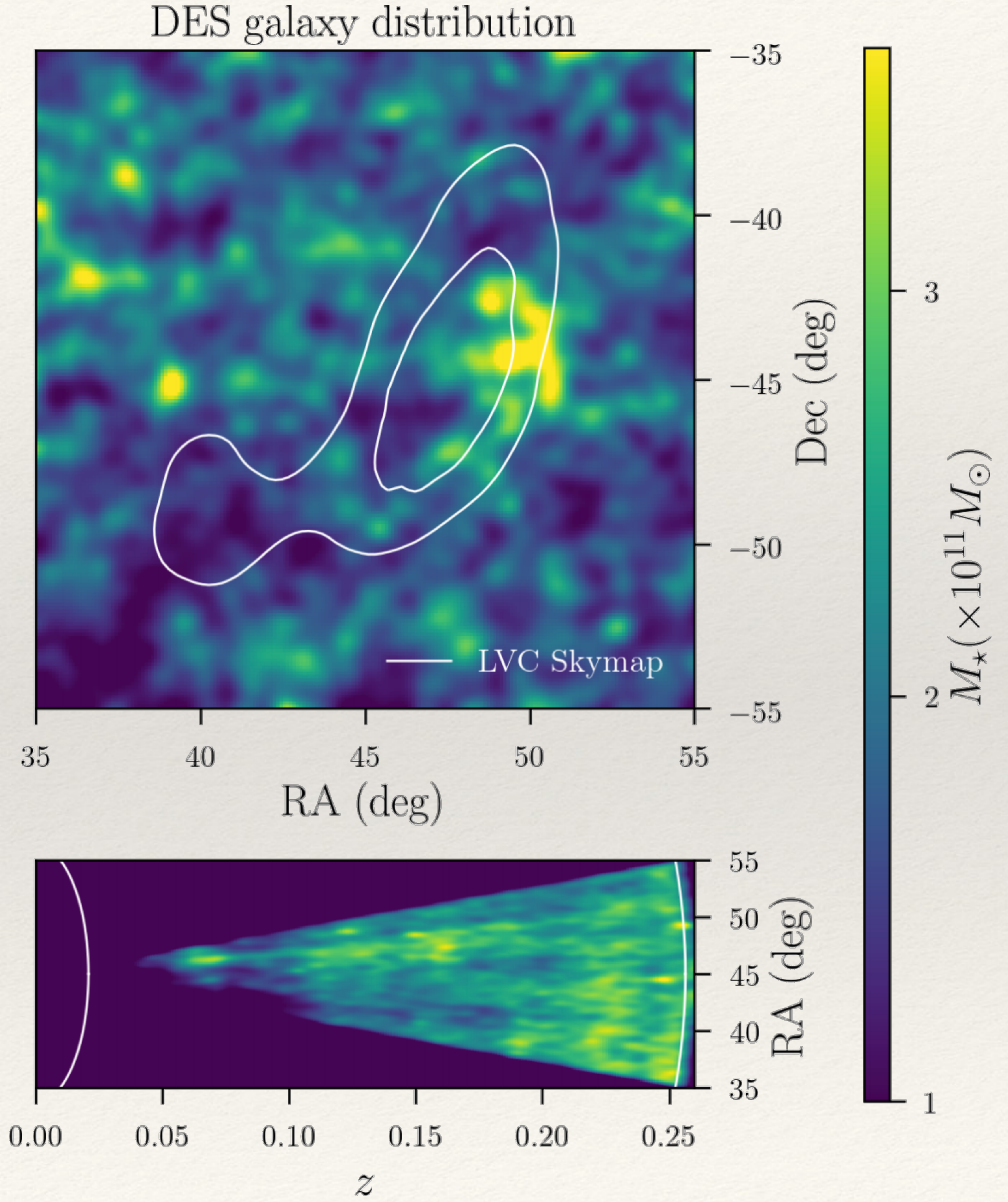
Optical Counterpart

— Statistical —

z

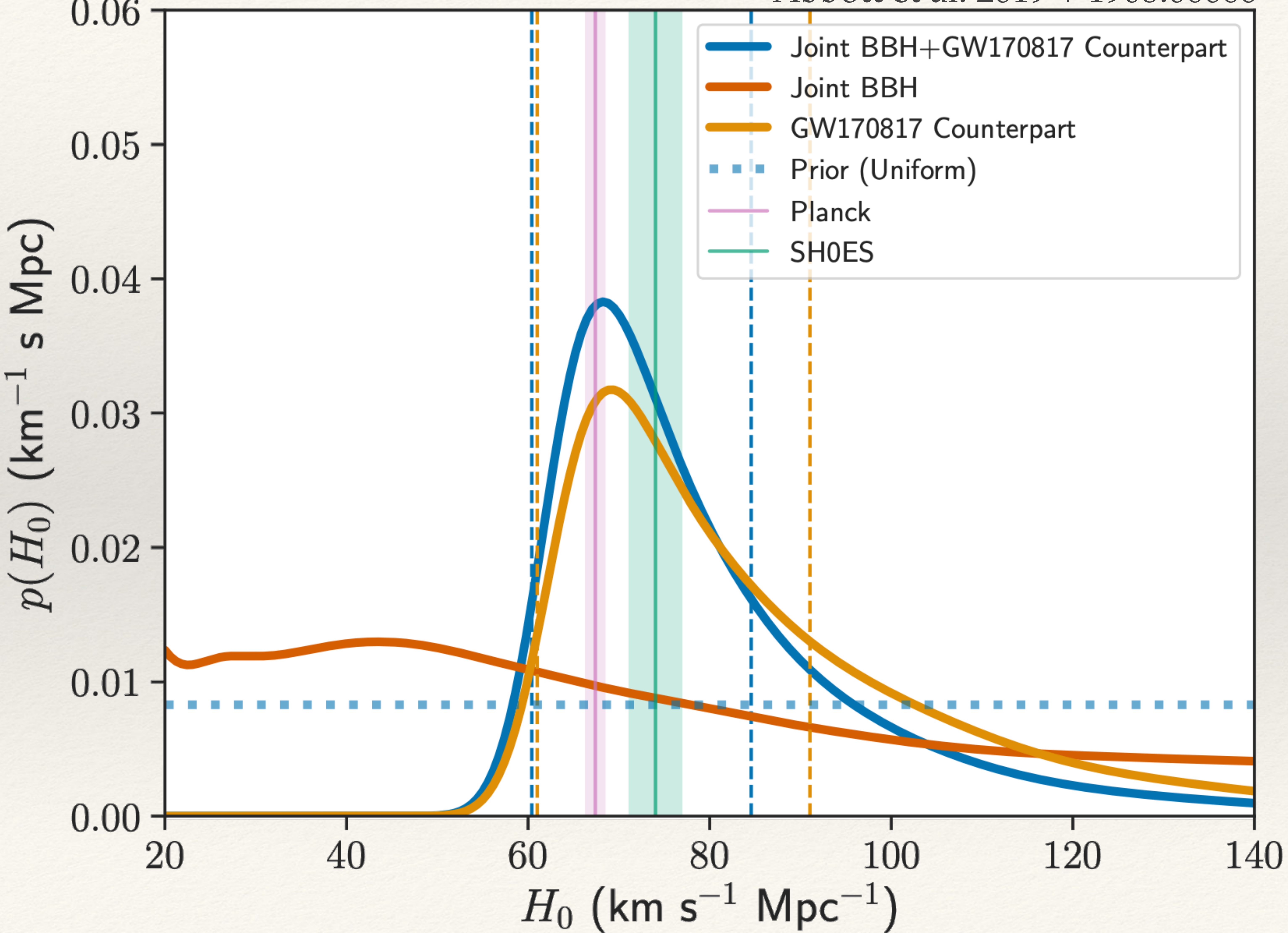


+ Redshift catalogs



Direct measurement of H_0 | *without counterpart*

Abbott et al. 2019 | 1908.06060

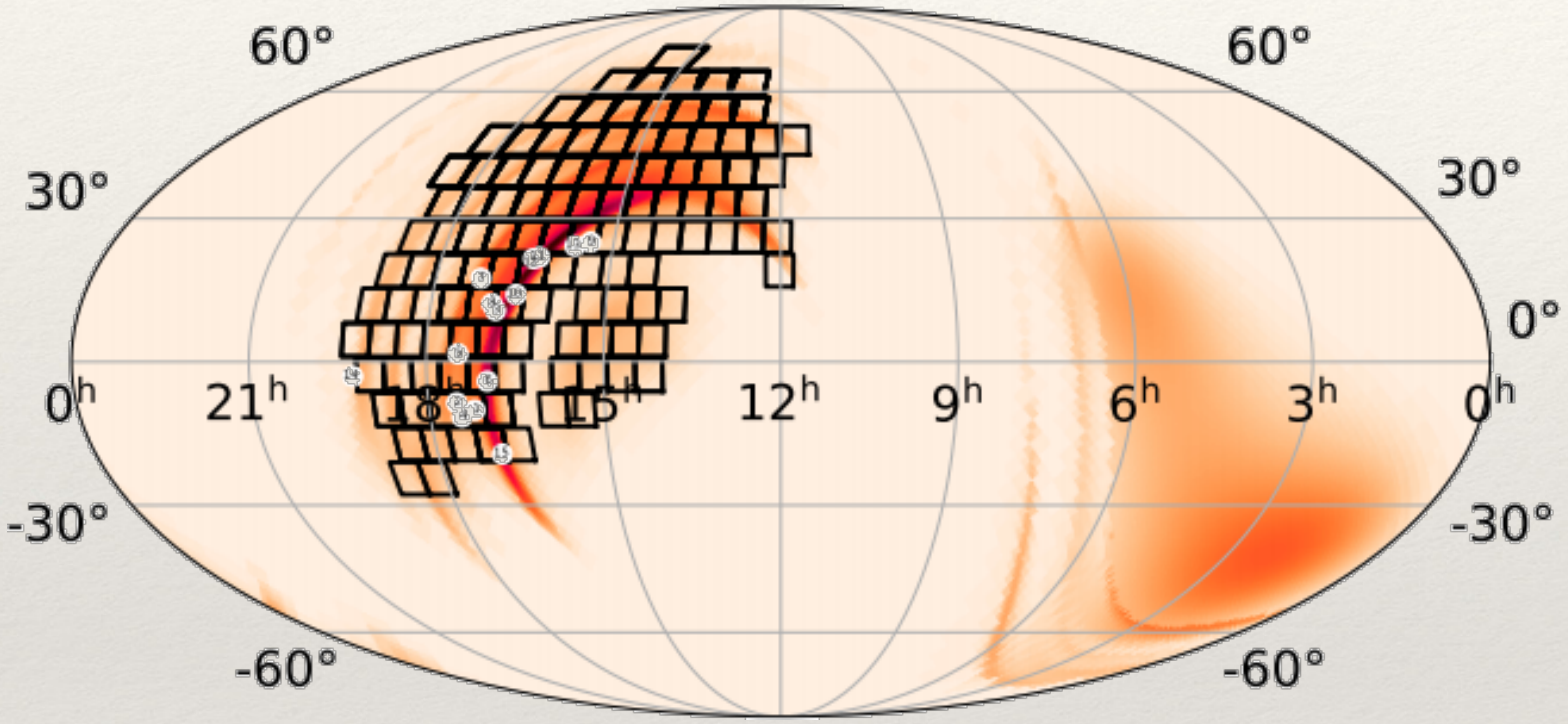


ZTF follow-up GW | *GW190425z (BBN)*

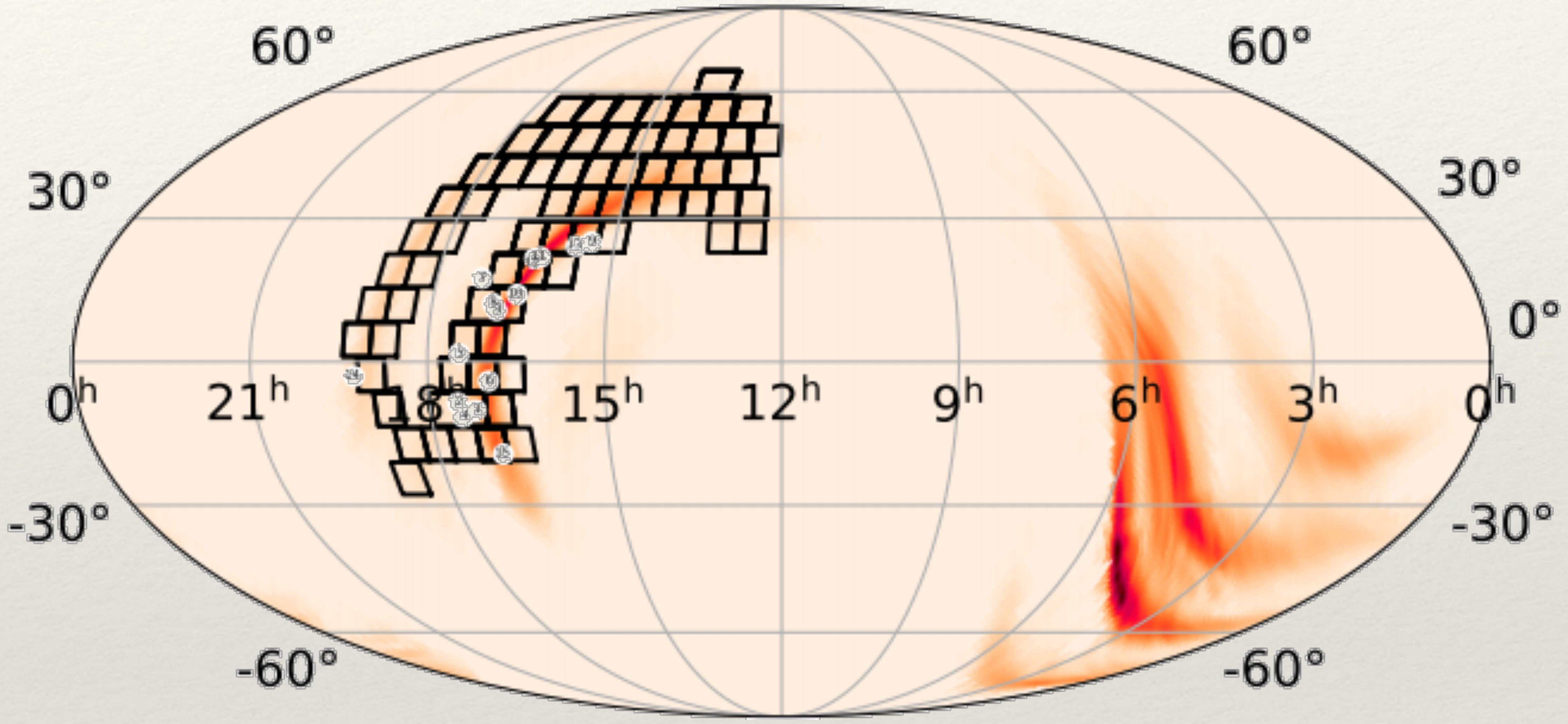
single detector event

Coughlin et al. 2019

Quick pipeline contours | **8000 deg²**



Final contours

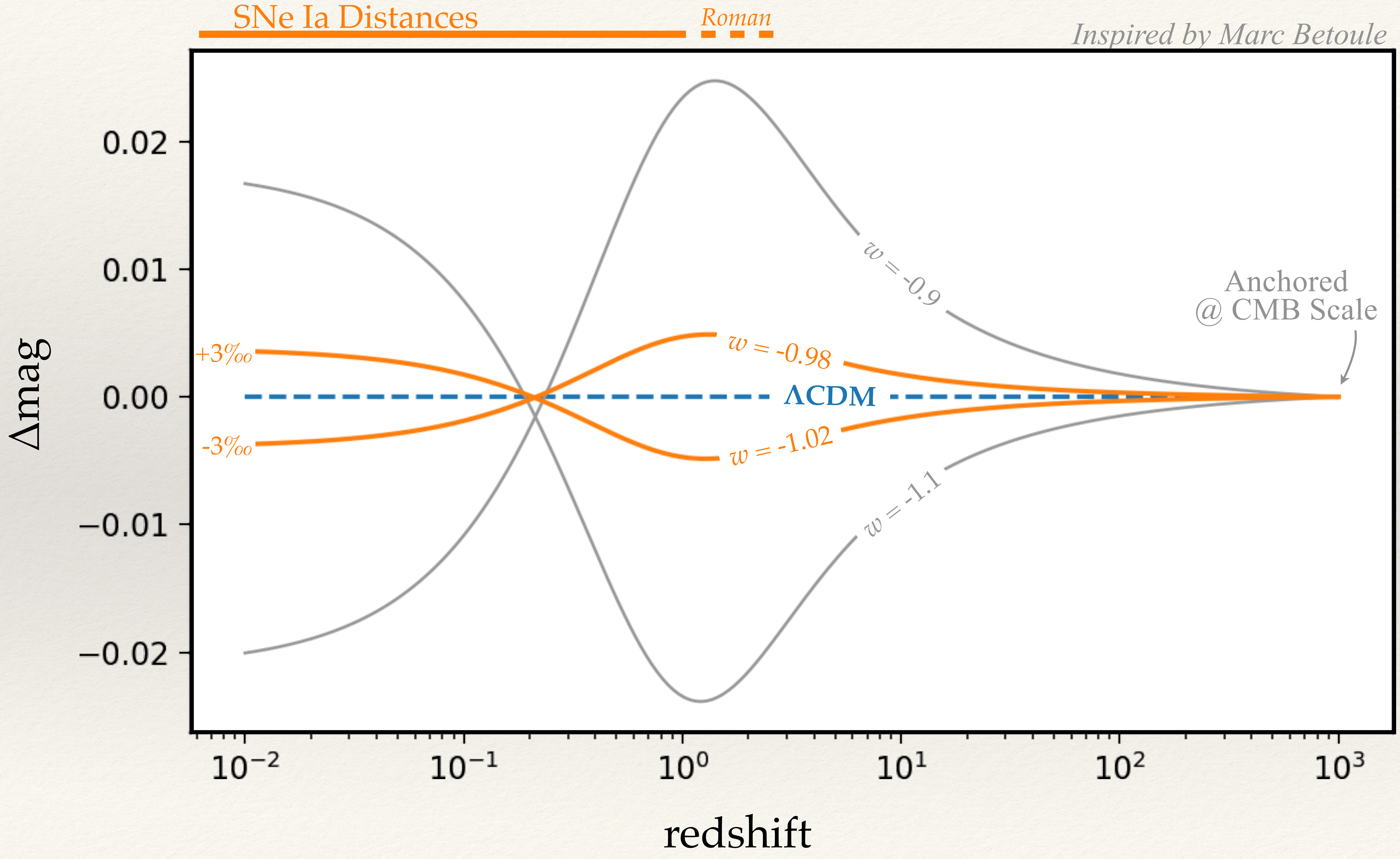


ZTF scanned 46% of confidence area in <u>*3 hours in 2 bands*</u> *(25% observing time used)*

338 646 alerts → **15 candidates counterparts** → **2 particularly interesting** → **All Supernovae…**

Type Ia Supernovae Cosmology | *w*

Stats & Precision



SNe Ia

→ Δmag=15%

O(5000) SNe Ia

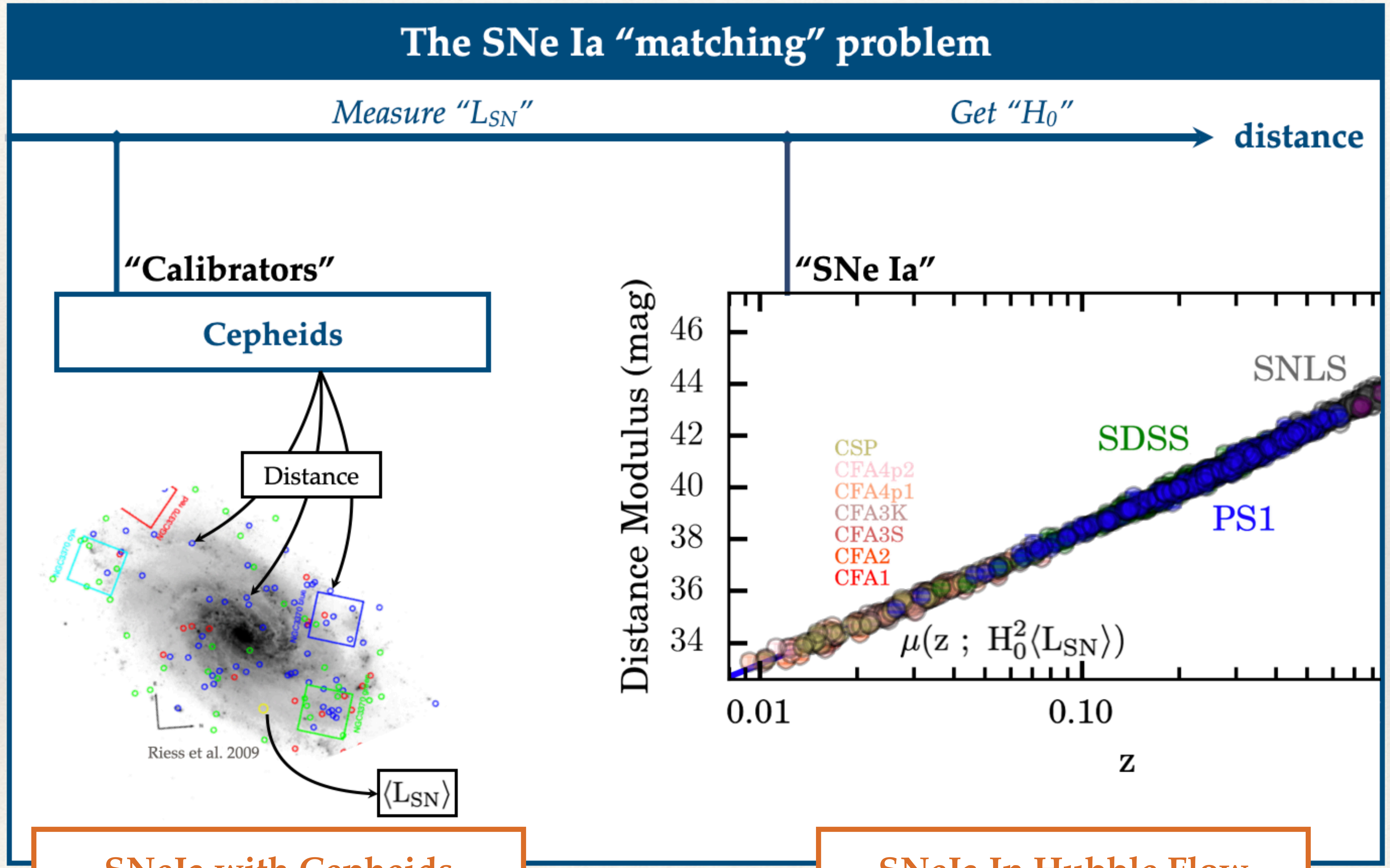
→ Δmag=0.2%

Photometric Accuracy

→ Δmag=0.1%

Astrophysical Bias affecting H_0

Rigault et al. 2015



SNeIa with Cepheids
strongly favour Young SNeIa

SNeIa In Hubble Flow
All kinds of SNe Ia

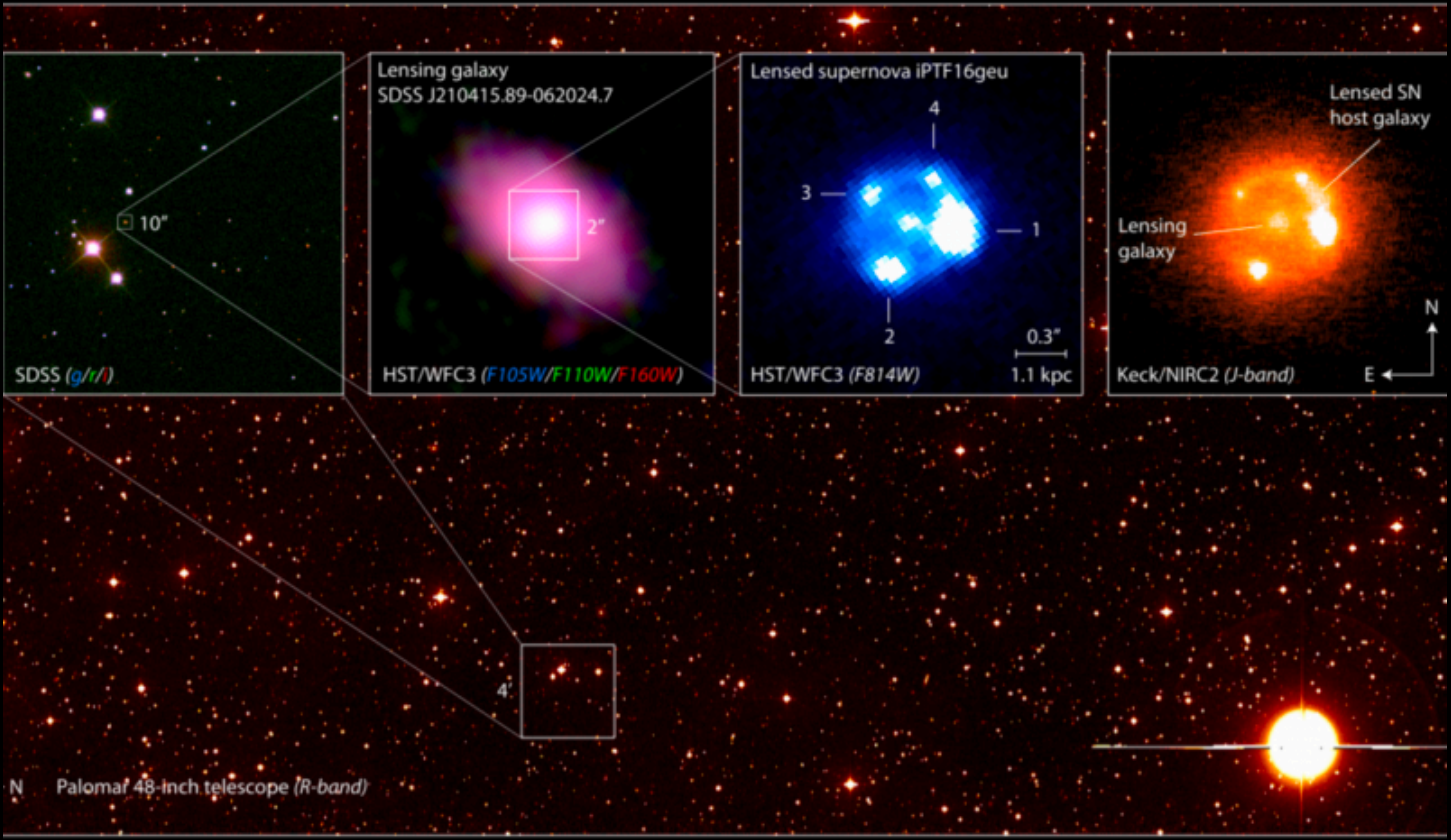
Difference in the fraction of *Young* SNeIa

Magnitude offset

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

~50%

~0.15mag



SDSS (g/r/i)
10″
Lensing galaxy
SDSS J210415.89-062024.7
2″
HST/WFC3 (F105W/F110W/F160W)
Lensed supernova iPTF16geu
4
3
1
2
0.3″
1.1 kpc
HST/WFC3 (F814W)
Lensed SN
host galaxy
Lensing
galaxy
N
E
Keck/NIRC2 (J-band)
4′
N
Palomar 48-inch telescope (R-band)