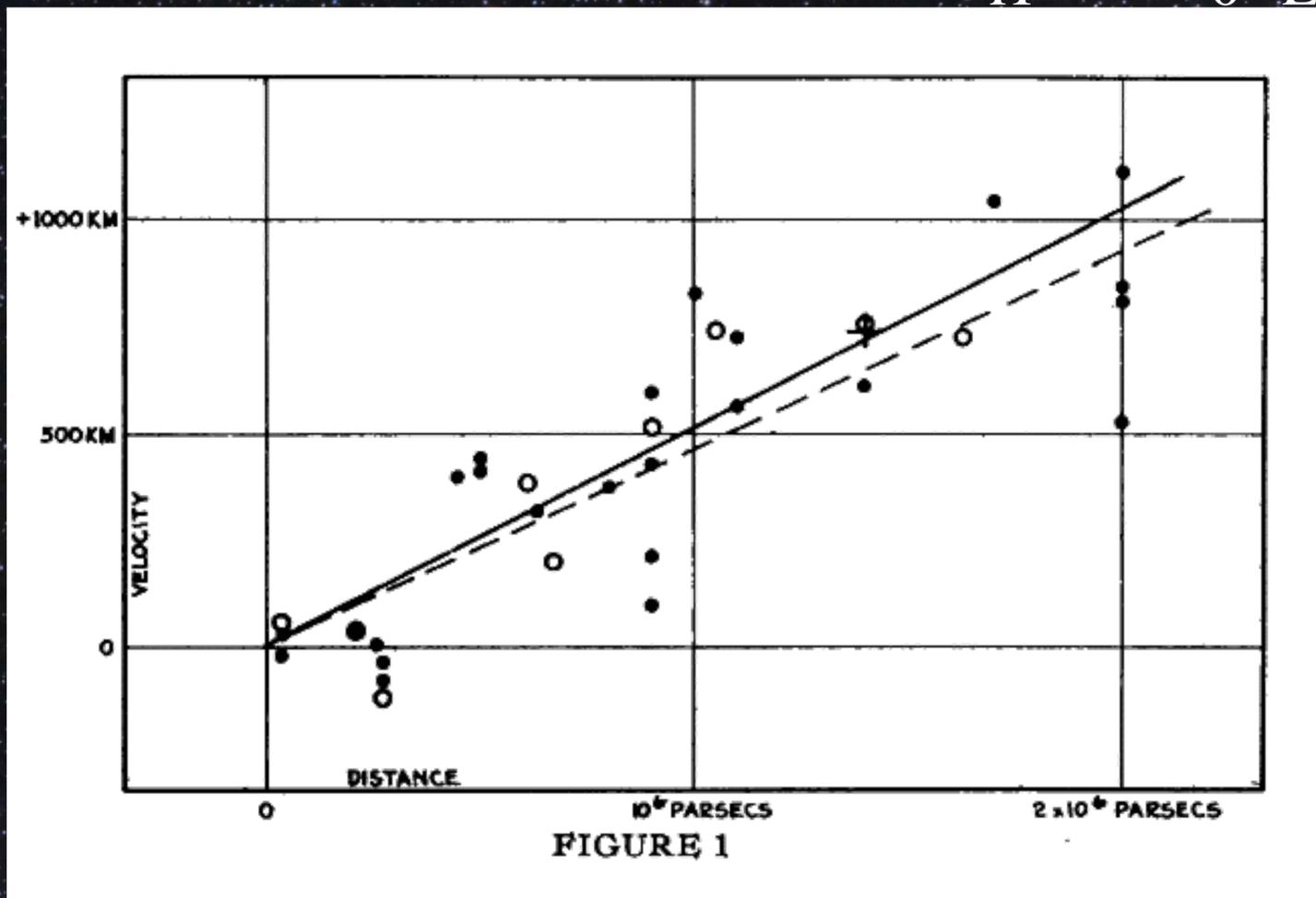




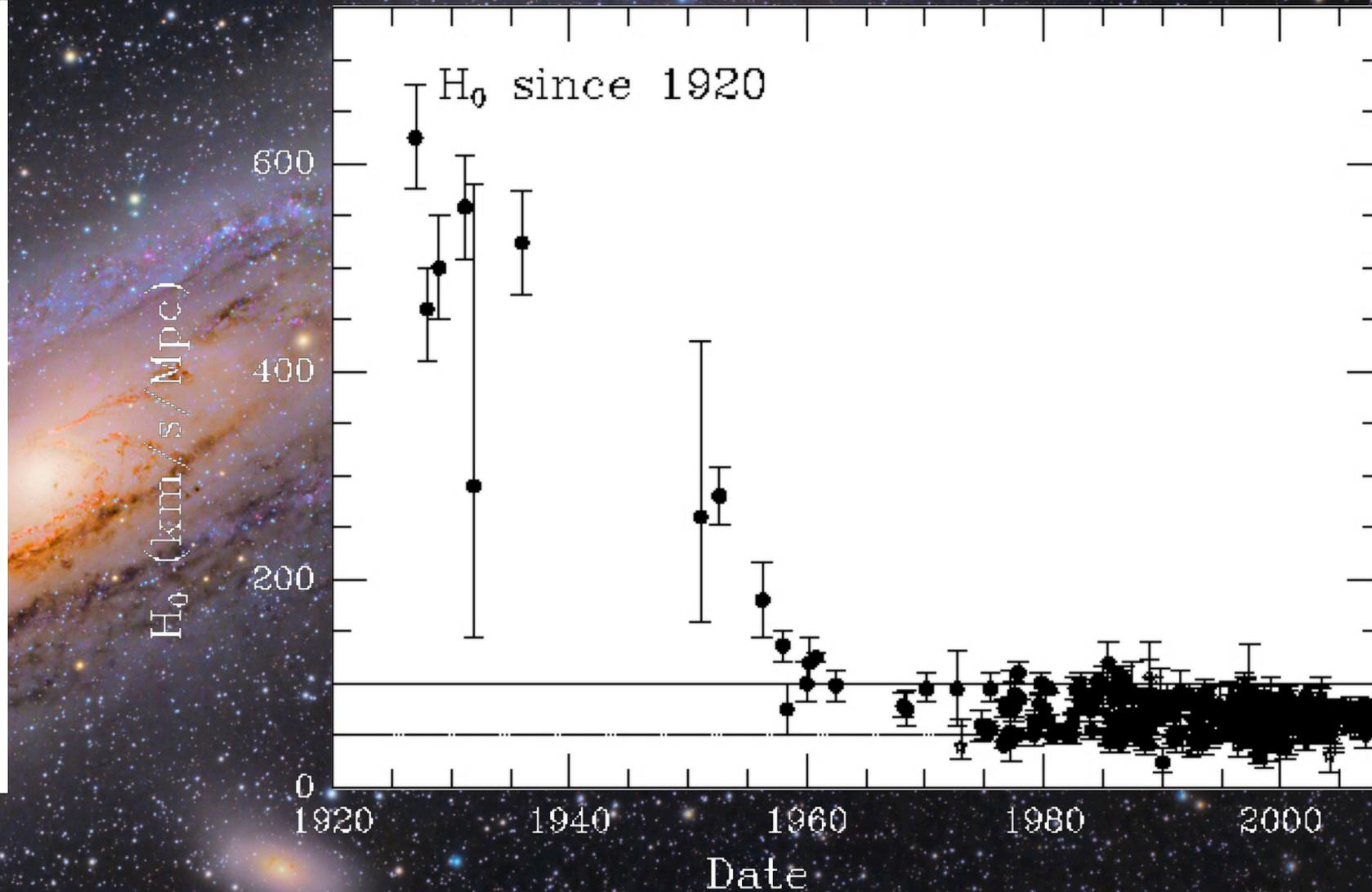
# *The Hubble Constant*

$$v_H = H_0 d_L$$

Recessional velocity



Distance from us



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

# Modern Cosmology | $H_0$ Direct vs. Indirect Measurements

$$H_0 = d_l / v_h$$

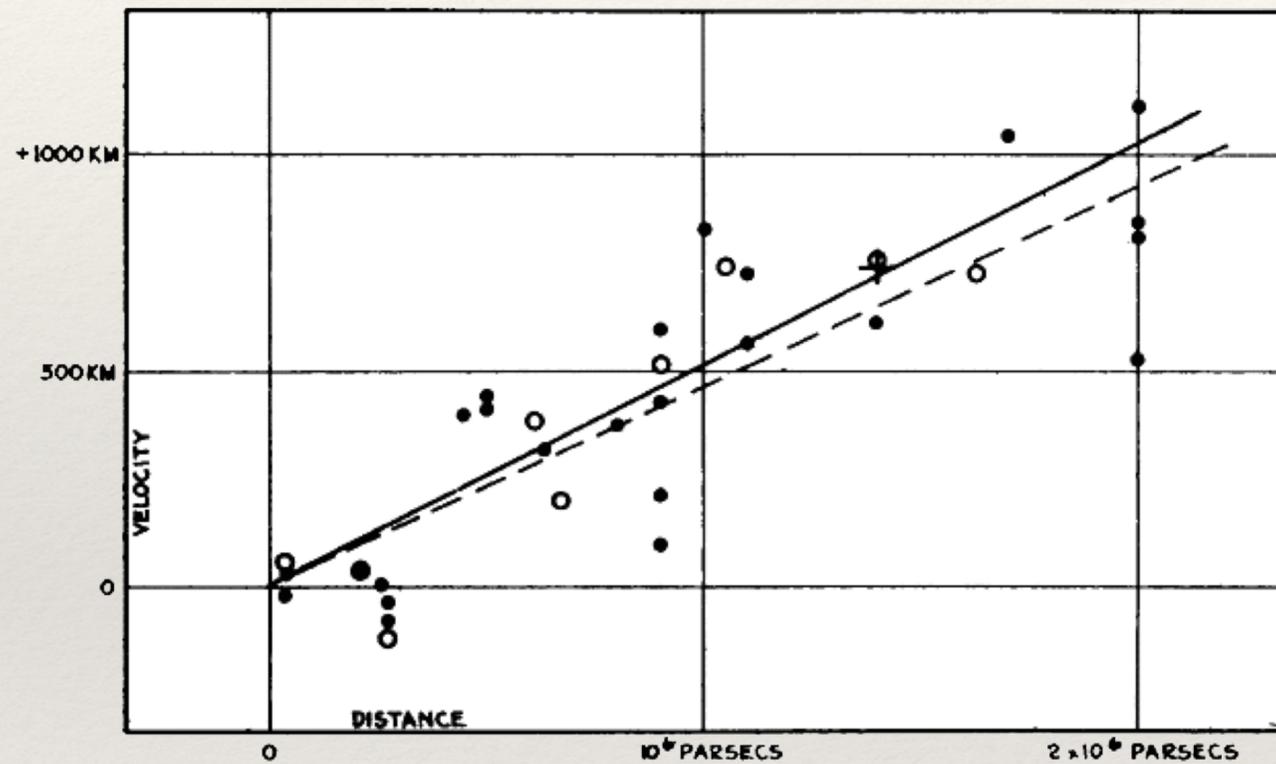
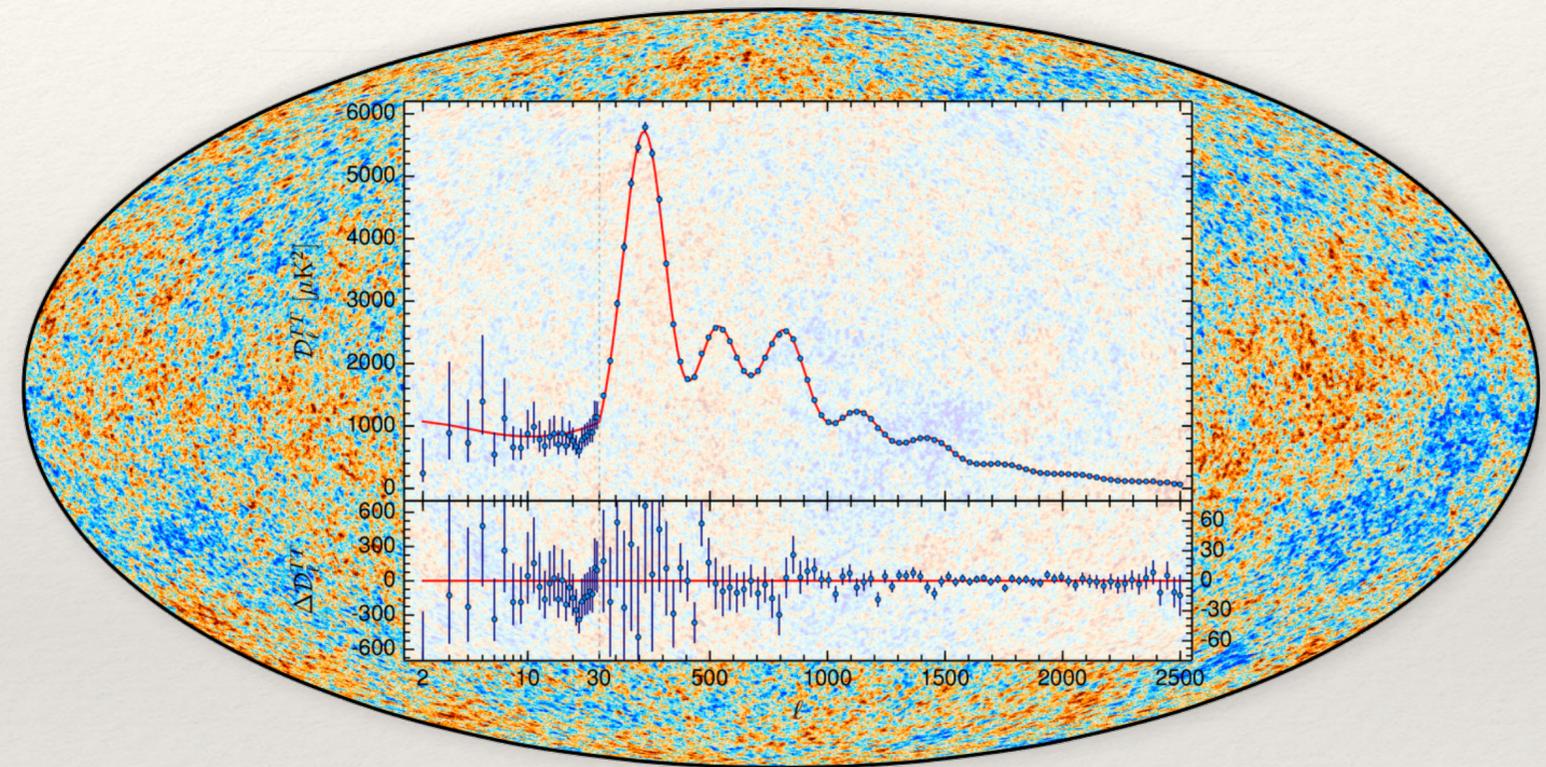


FIGURE 1

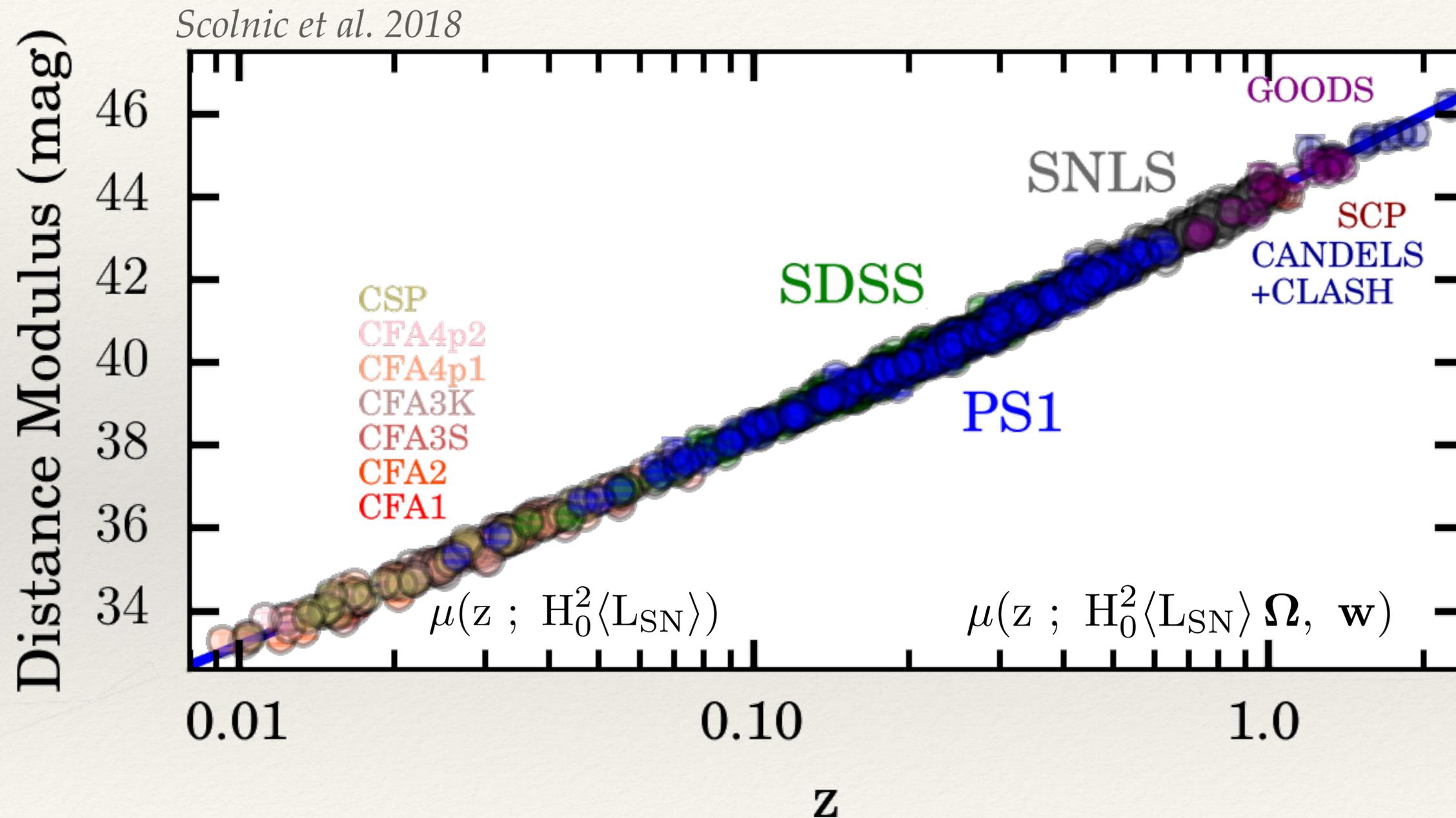
*Careful with peculiar velocities*

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

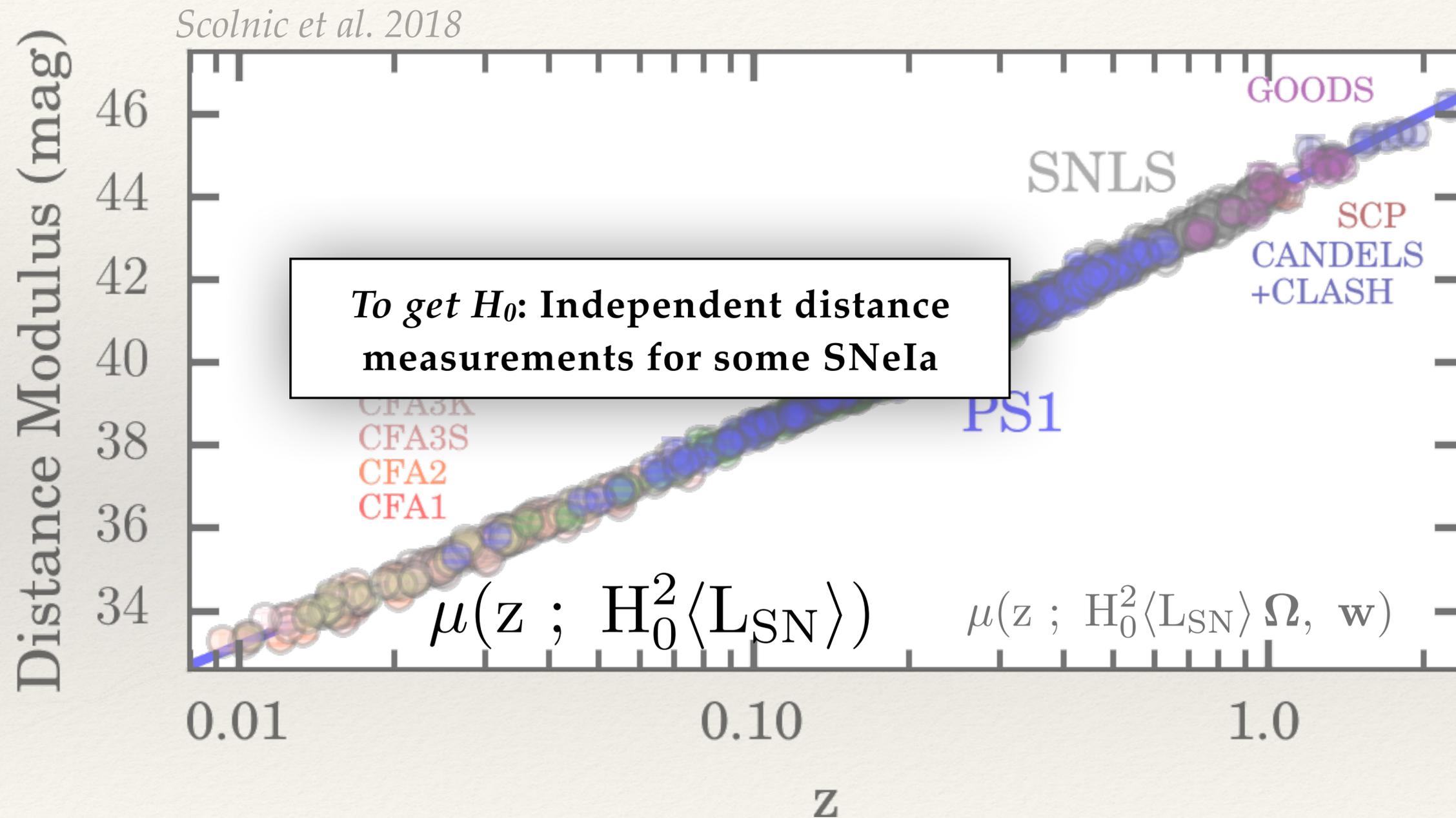


*Model dependent*

# Type Ia Cosmology



# Type Ia Cosmology | Measuring $H_0$



# SHOES

Geometrical Distances

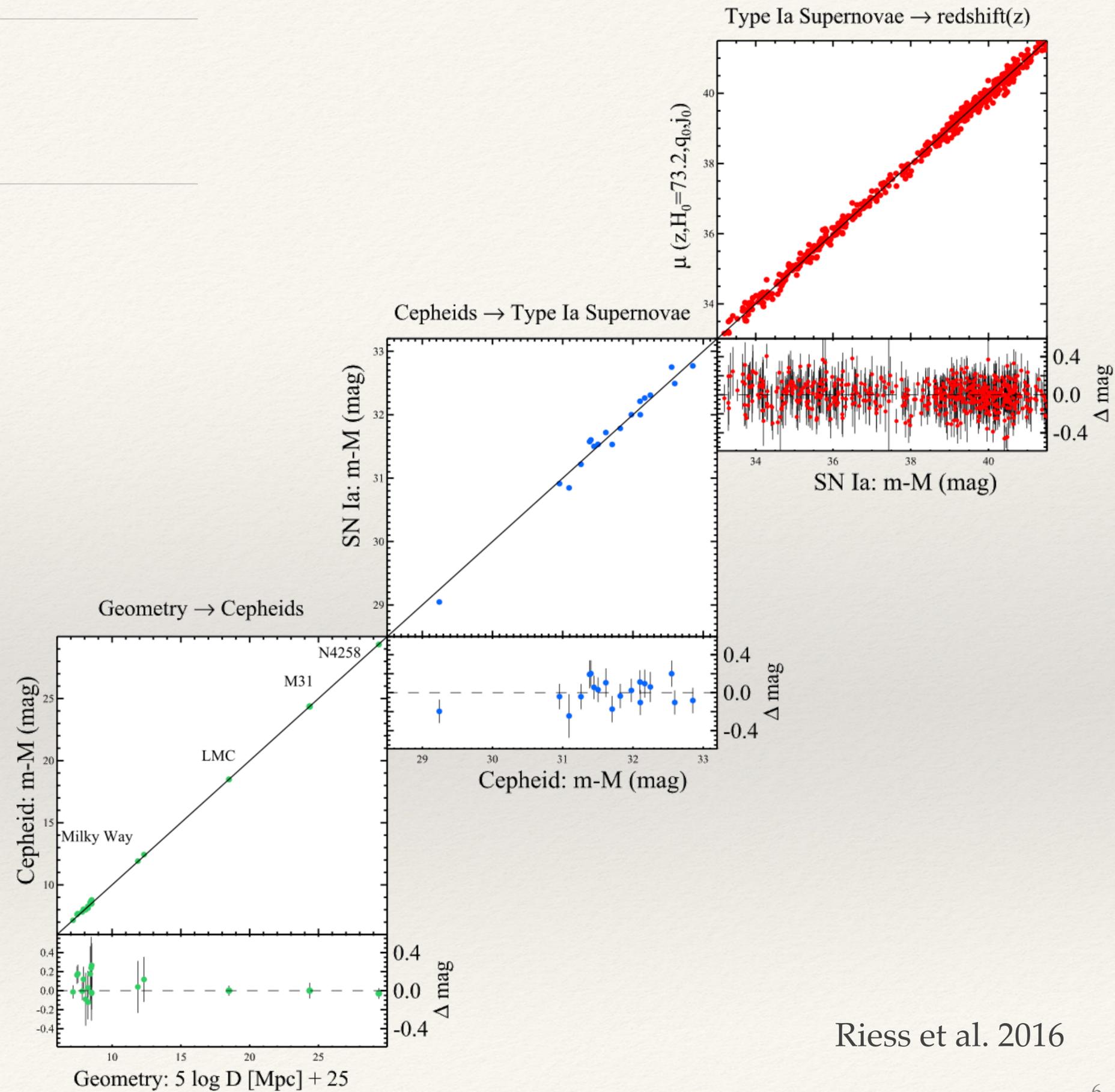
Cepheids

Type Ia Supernovae

10 Mpc

100 Mpc

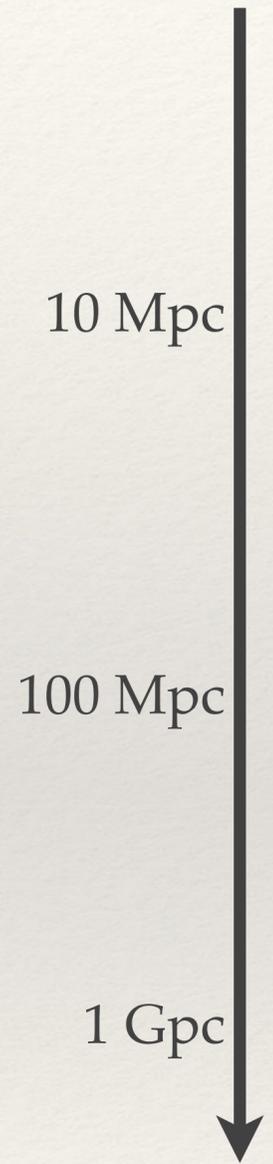
1 Gpc



Riess et al. 2016

# SHOES

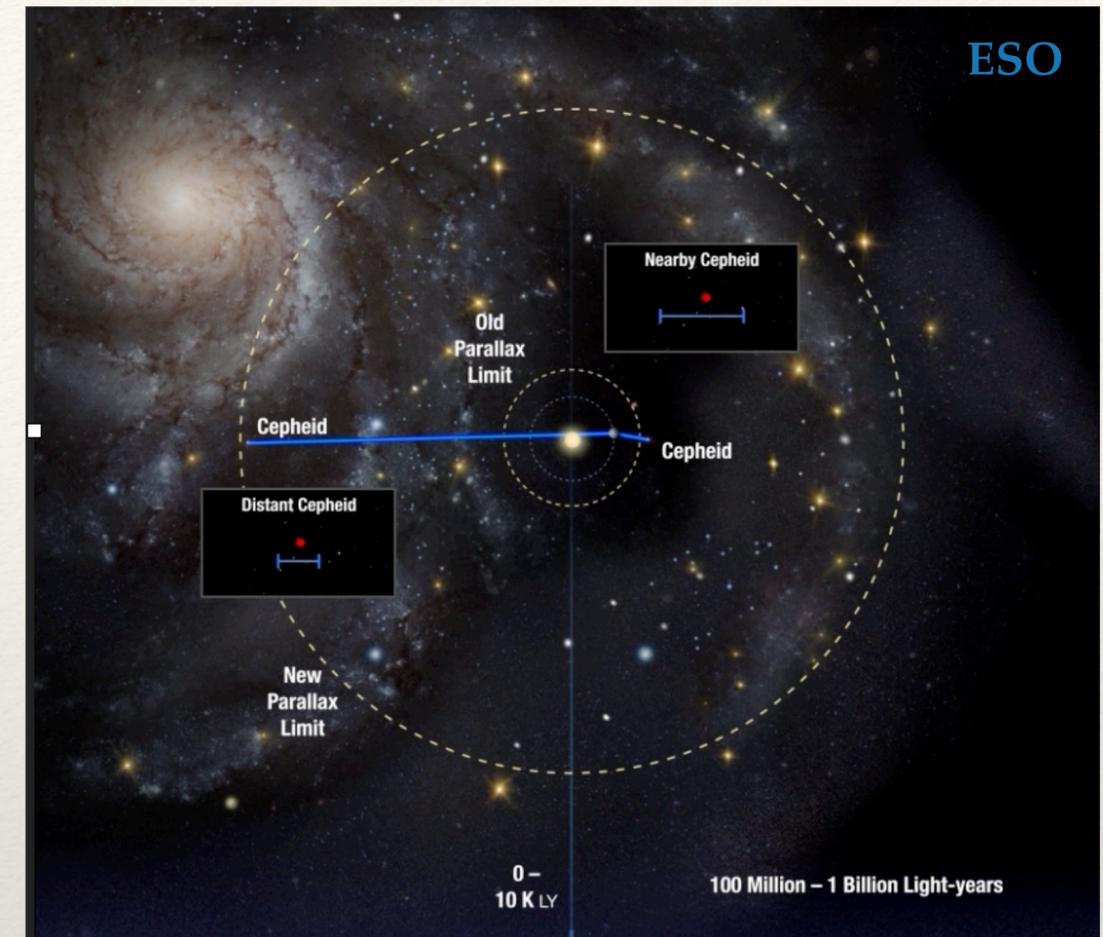
## Geometrical Distances



Cepheids

Type Ia Supernovae

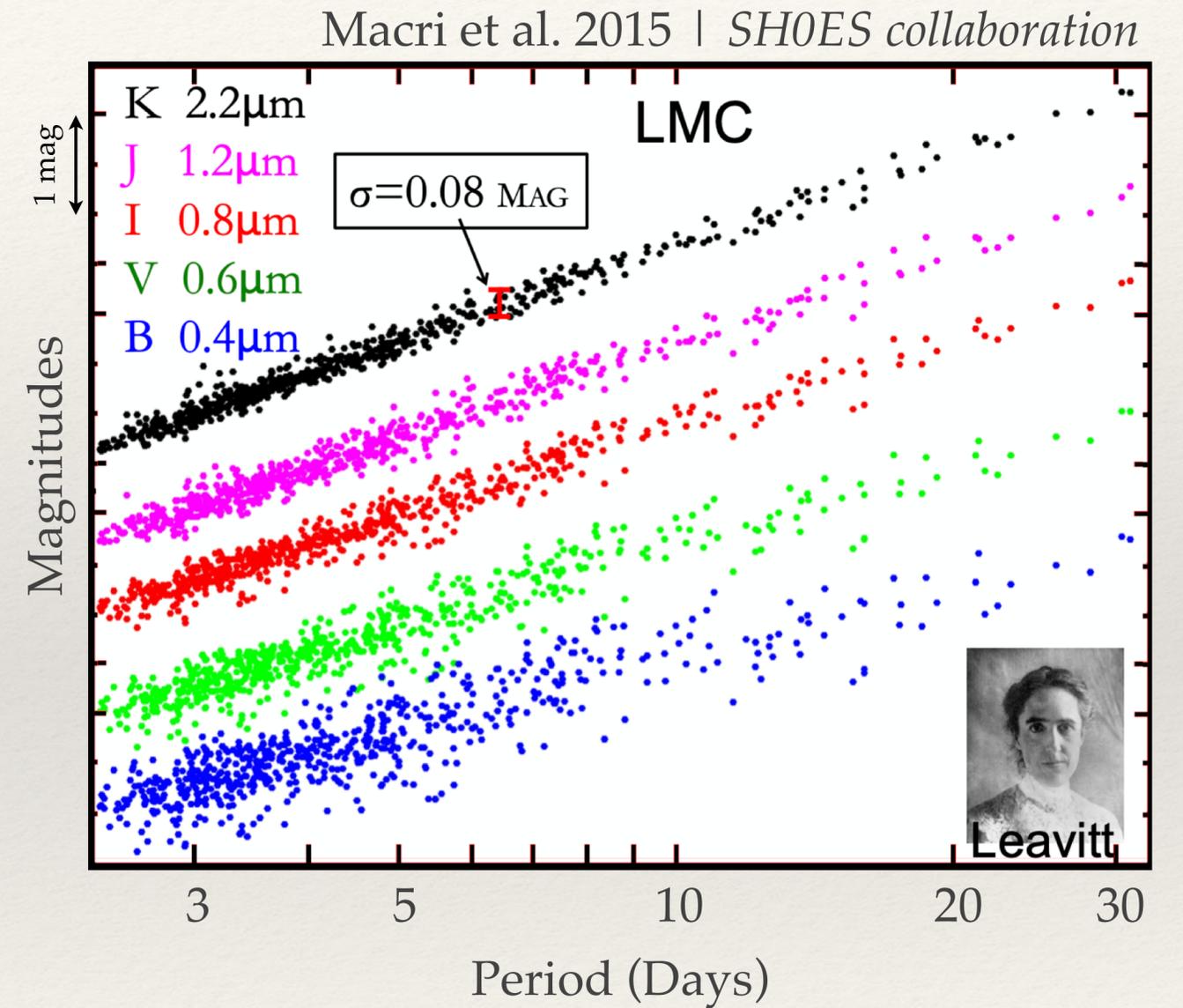
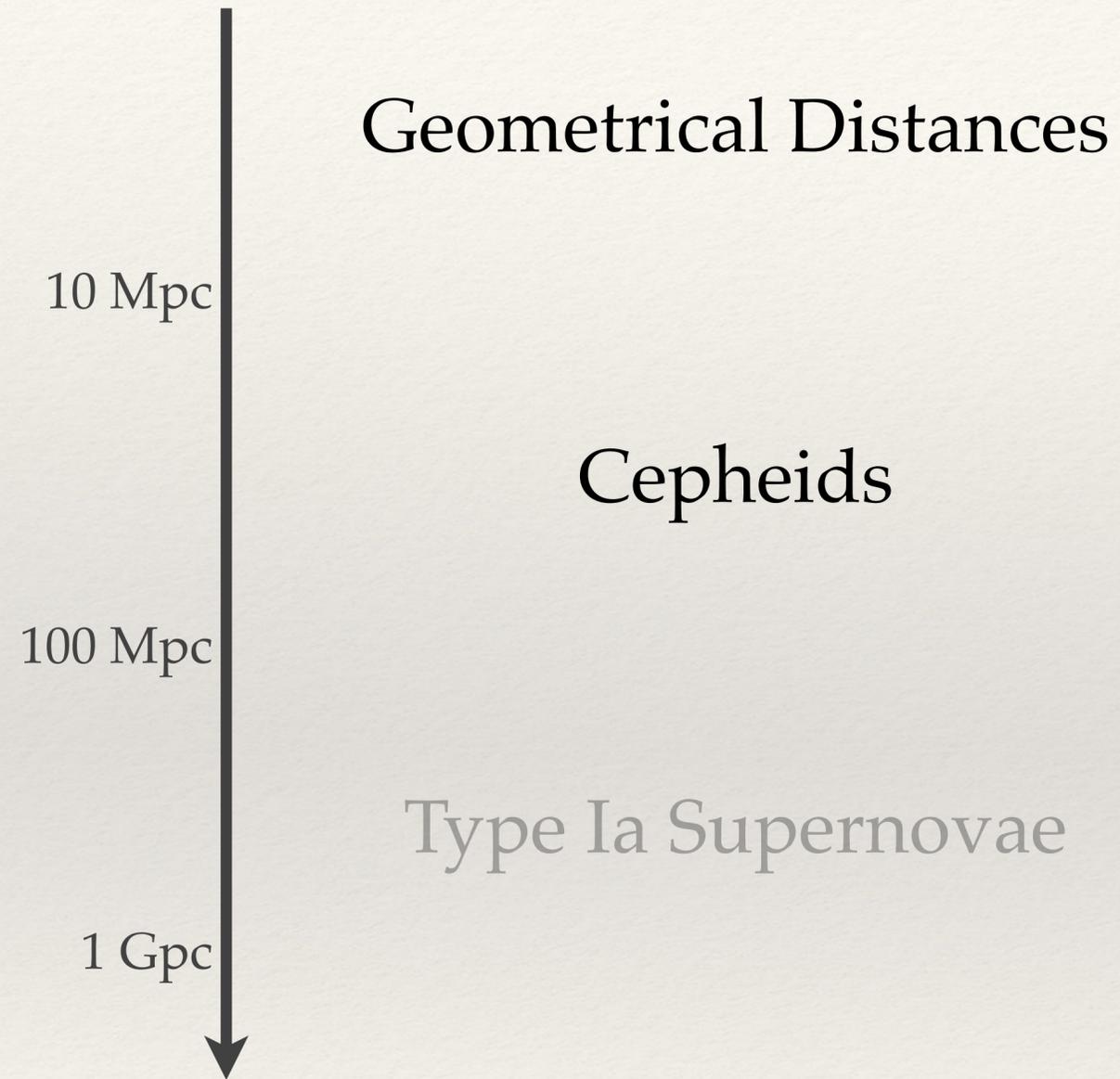
## Parallaxes (*Milky Way*)



## Detached Eclipsing Binaries (*LMC & M31*)

## Mega Maser (*NGC4258*)

# SHOES



# SHOES

Geometrical Distances

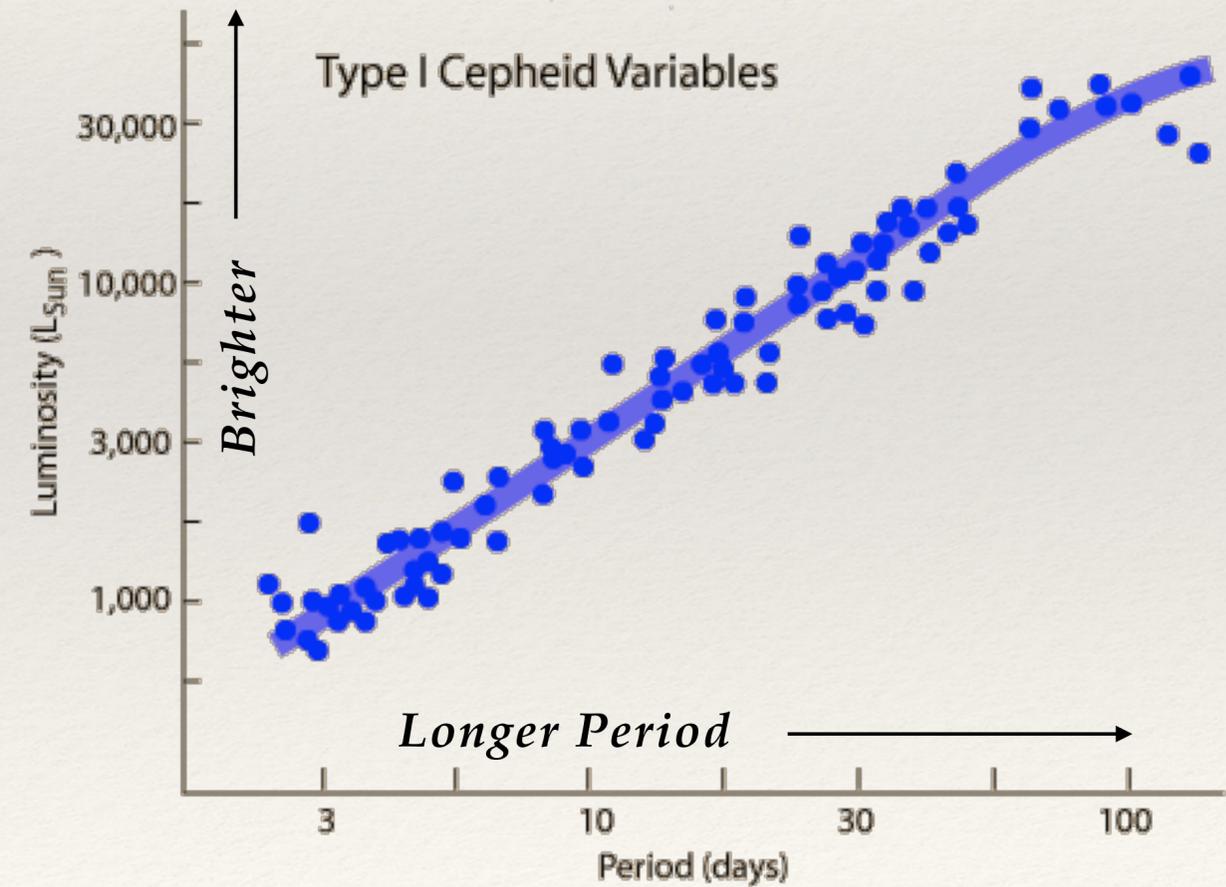
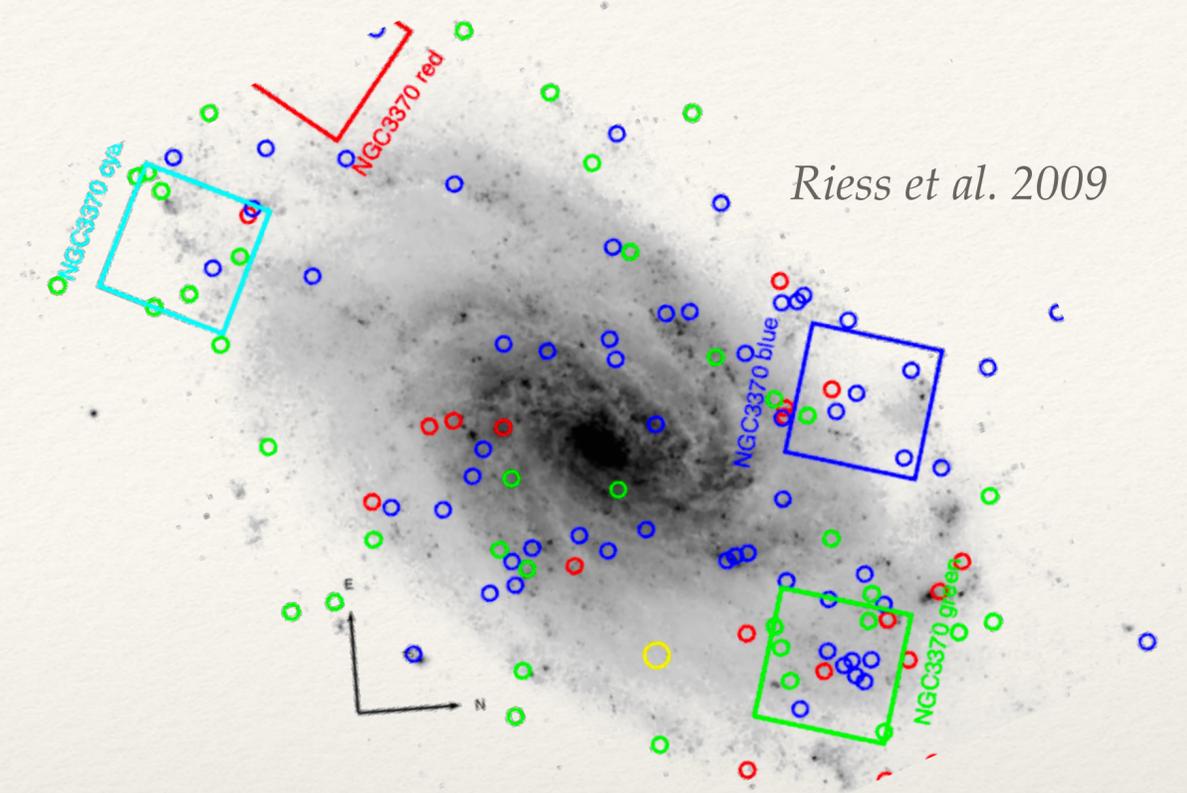
10 Mpc

Cepheids

100 Mpc

Type Ia Supernovae

1 Gpc



# SHOES

Geometrical Distances

10 Mpc

Cepheids

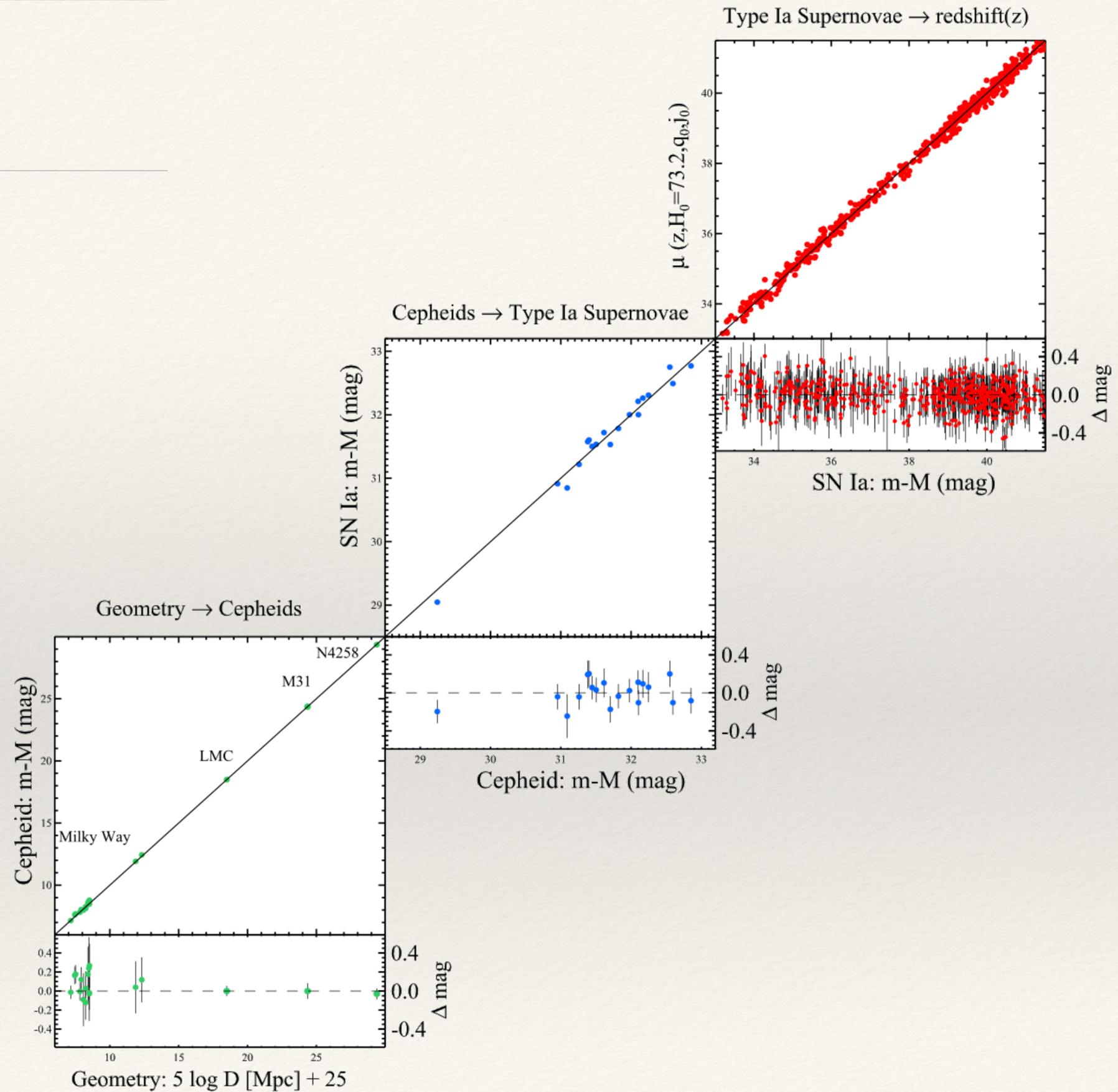
100 Mpc

Type Ia Supernovae

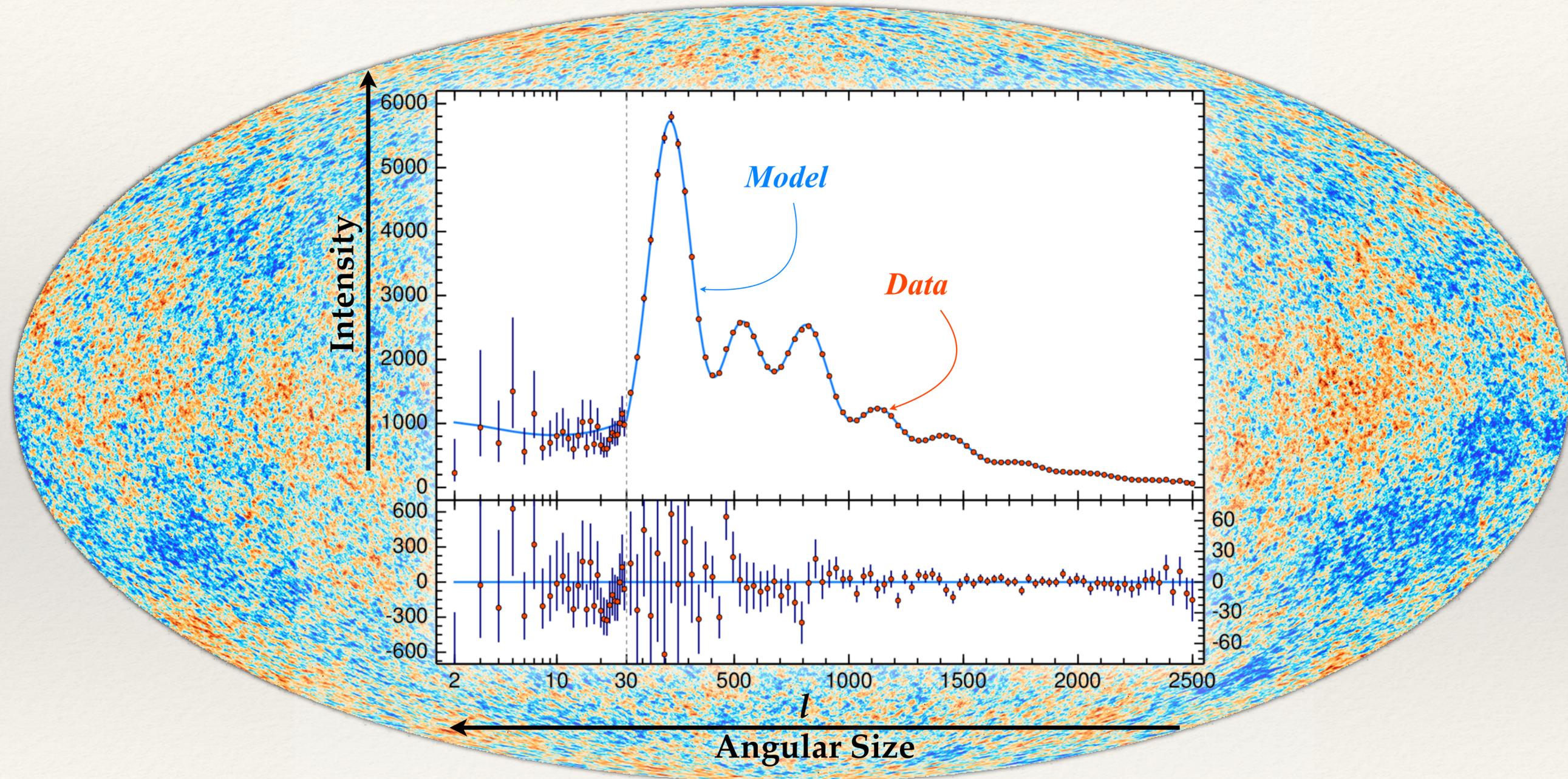
1 Gpc

$$H_0 = 73.5 \pm 1.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

(Ried et al. 2019, Riess et al. 2019)

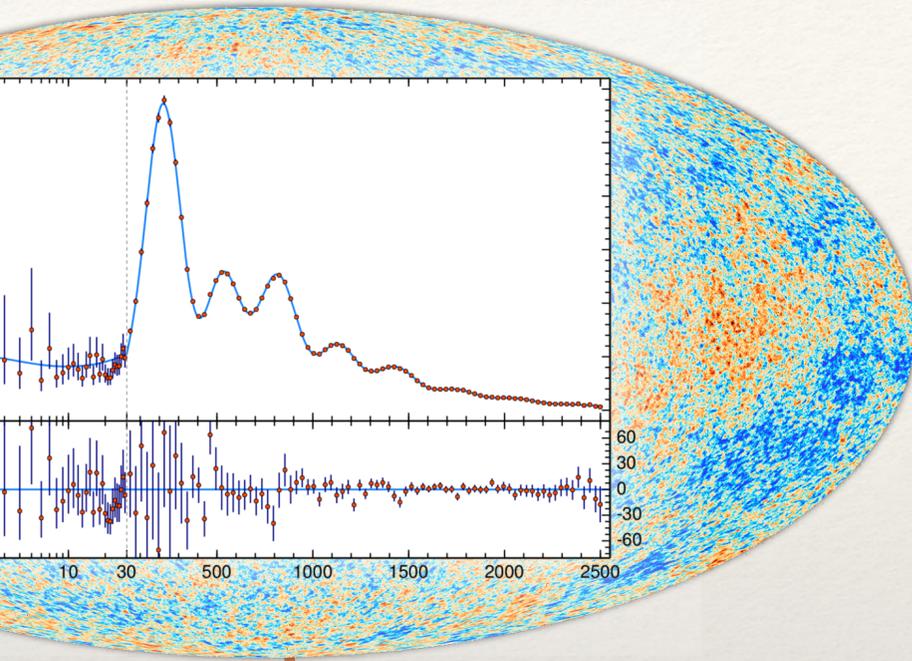


# Planck Results



# Indirect determination of $H_0$

Planck 2018



$z \sim 1000$

**THE MODEL  
CONSTRAINS  $H_0$**

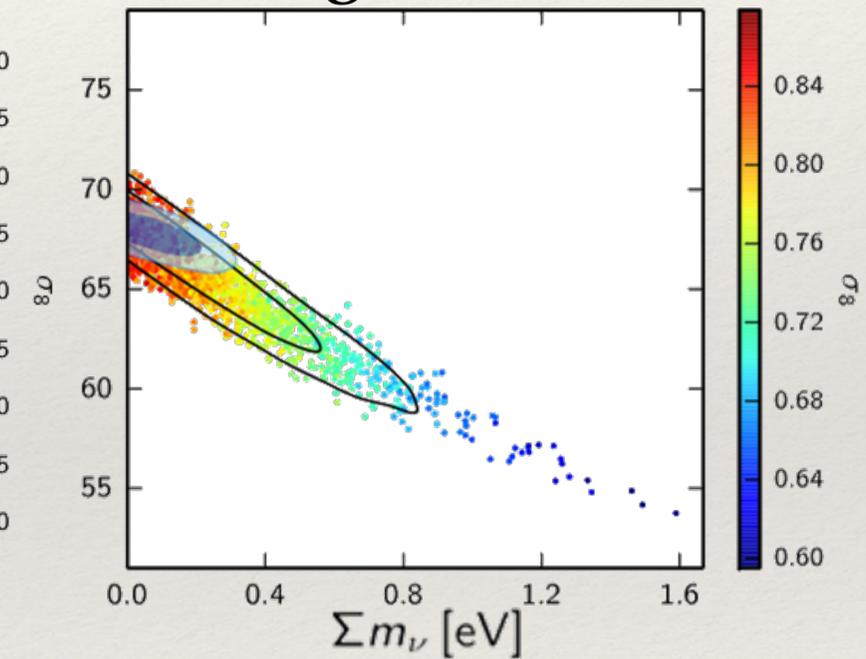
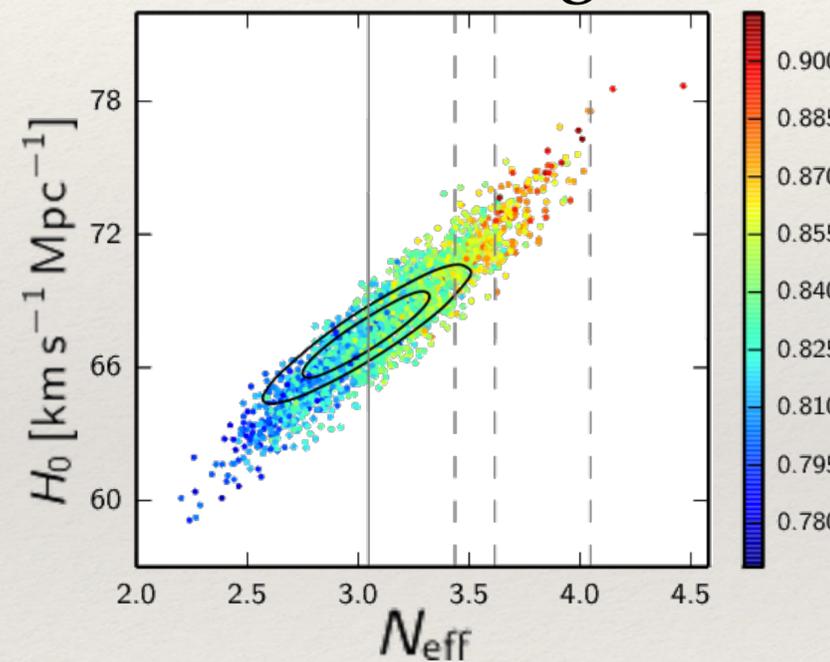
$z \sim 0$

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

— based on  $\Lambda$ CDM —

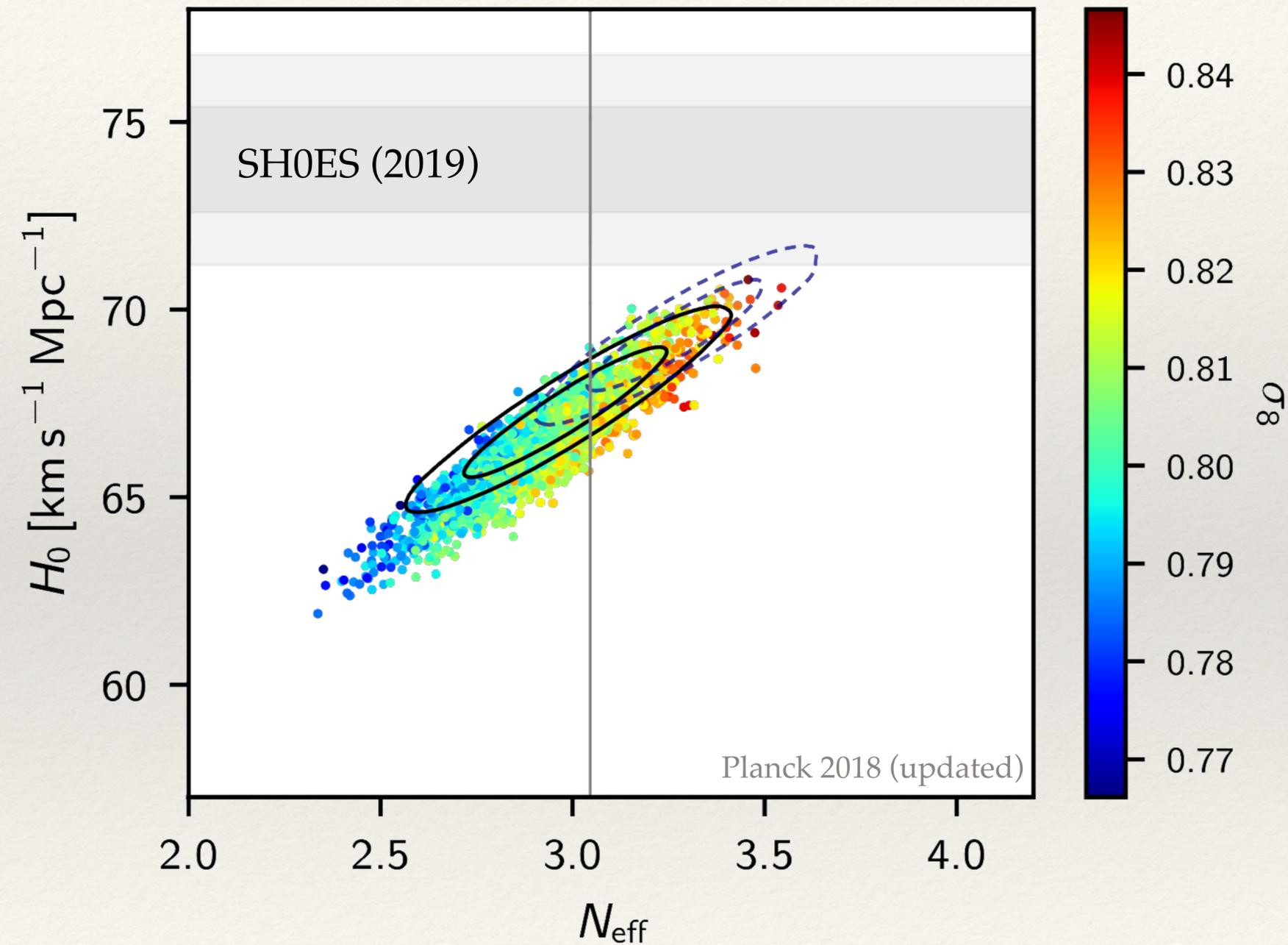
*Test the concordance  
model  $\Lambda$ CDM*

*Change the model, change  $H_0$*



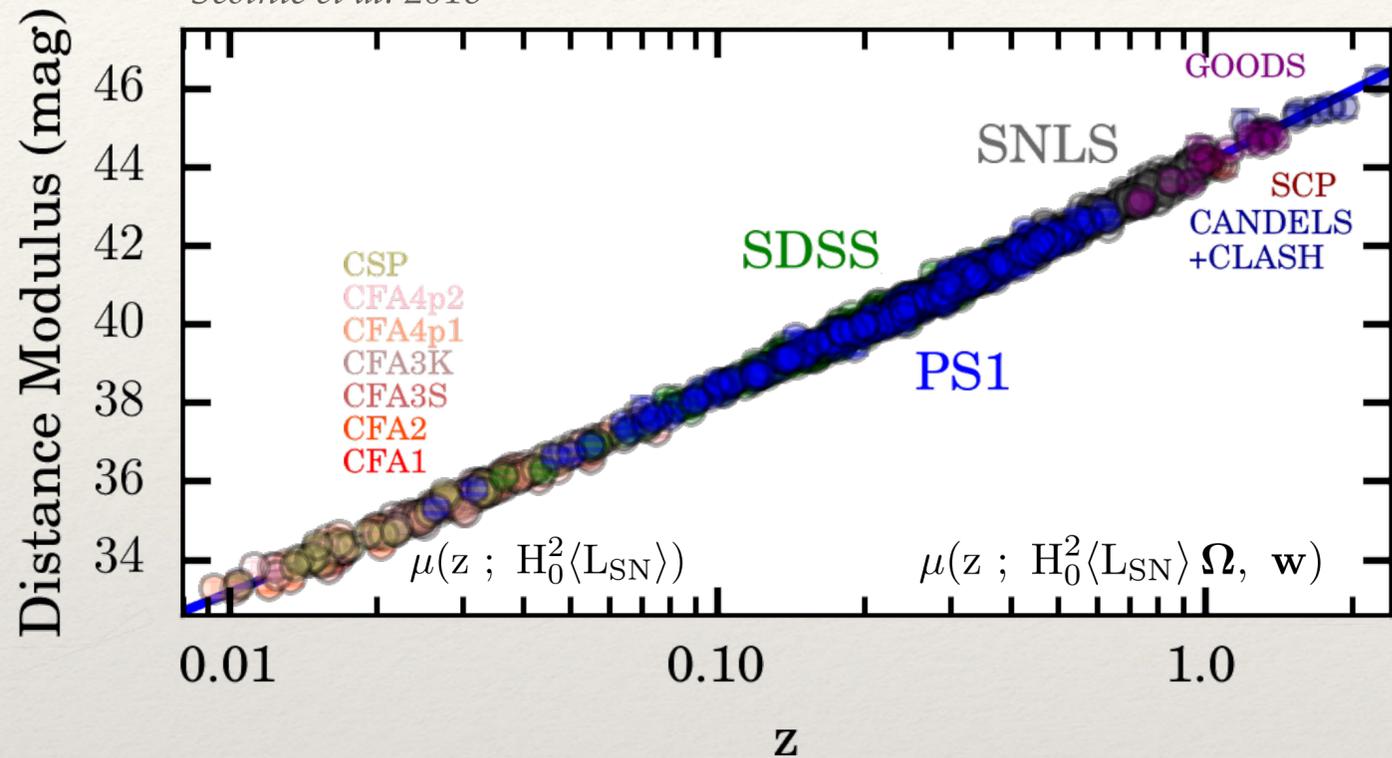
*Illustrative plots from Planck 2015*

# The $H_0$ Tension



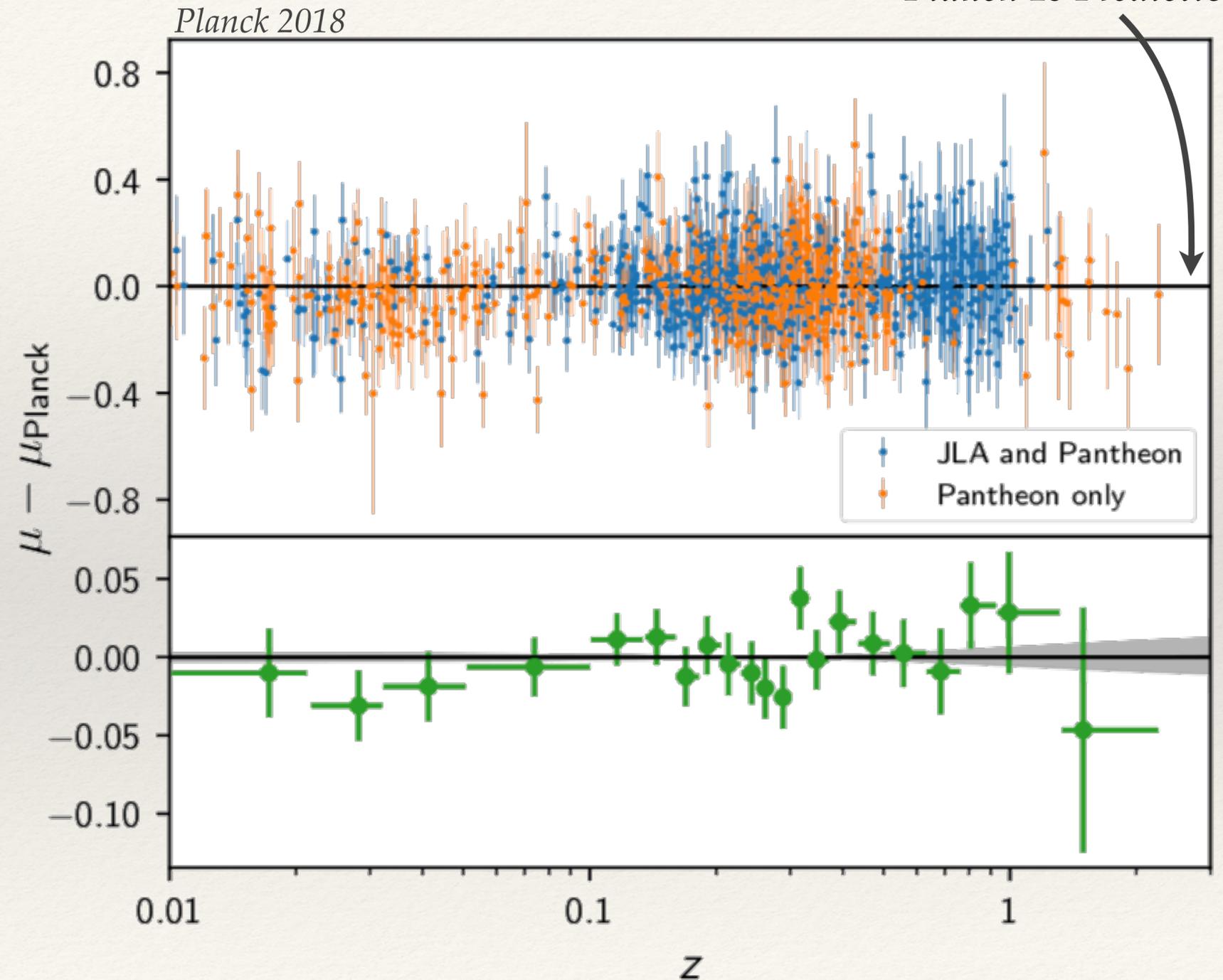
# CMB & SNeIa in disagreement ? *No!*

Scolnic et al. 2018

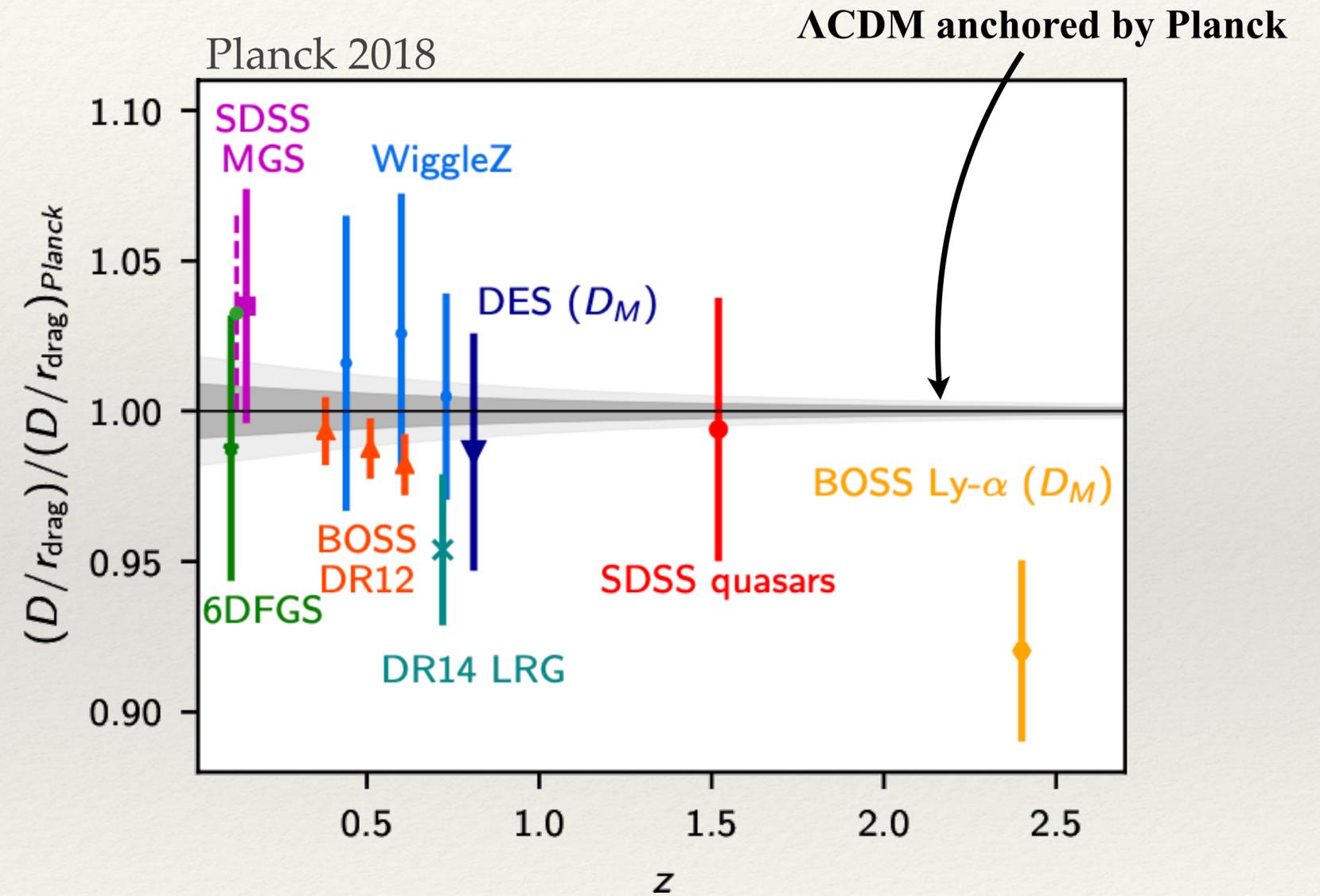
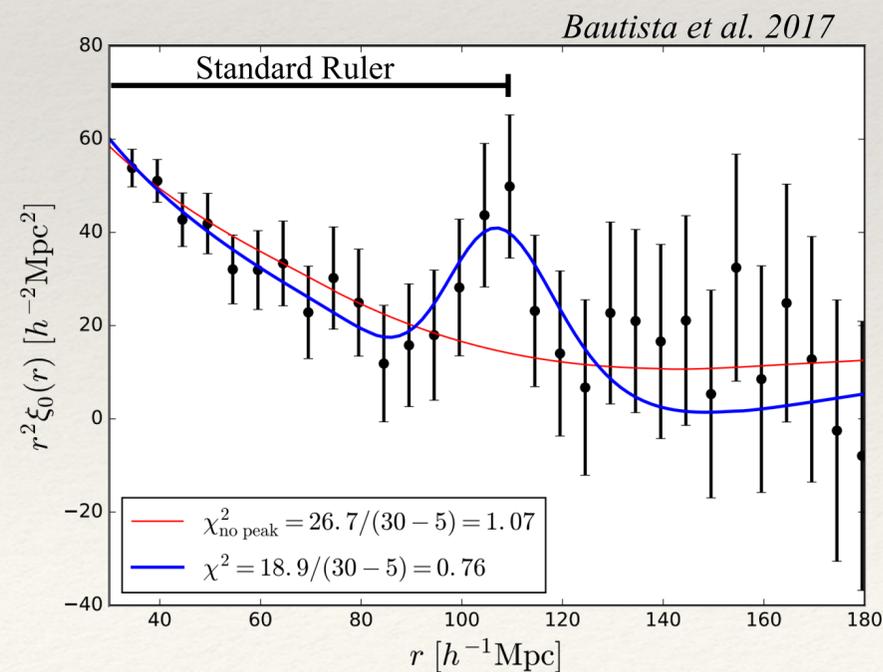
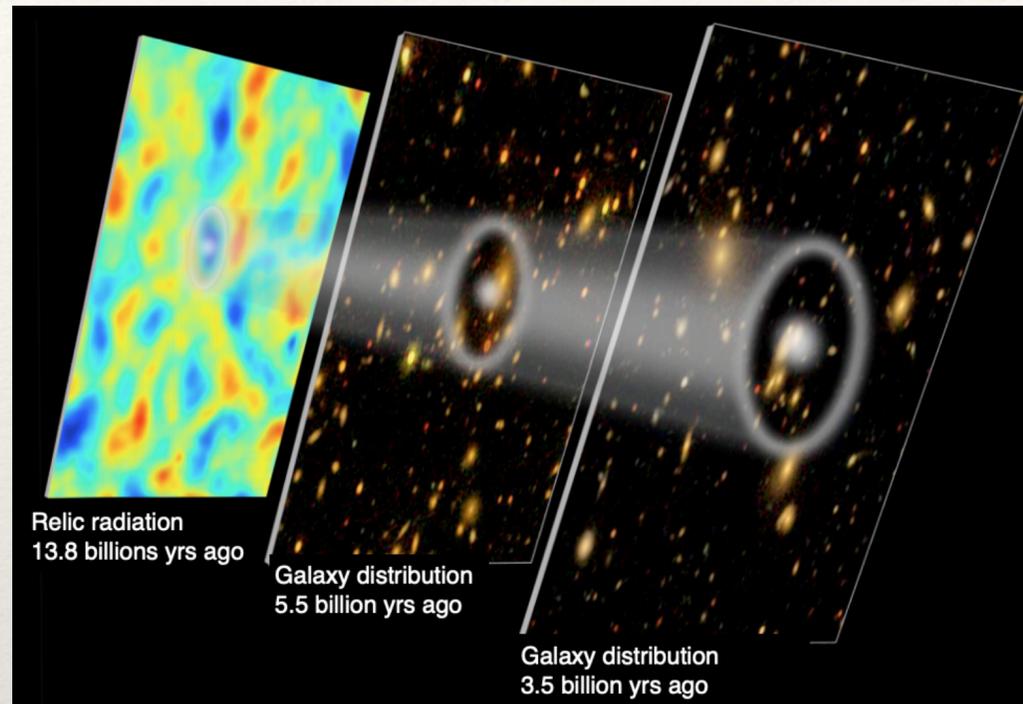


Using  $H(z)$  from Planck best fit  $\Lambda$ CDM

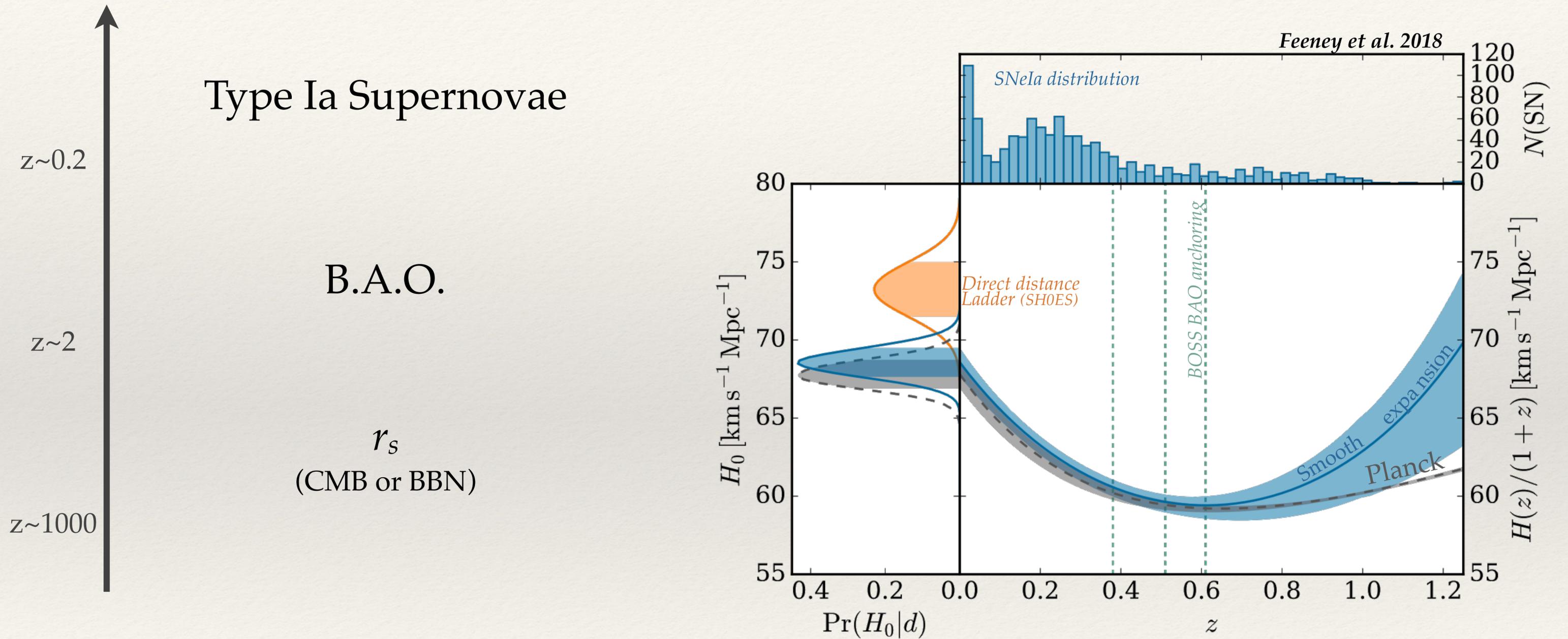
Planck 18 Prediction



# Baryonic Acoustic Oscillation | *In perfect agreement with CMB*



# Inversed Distance Ladder

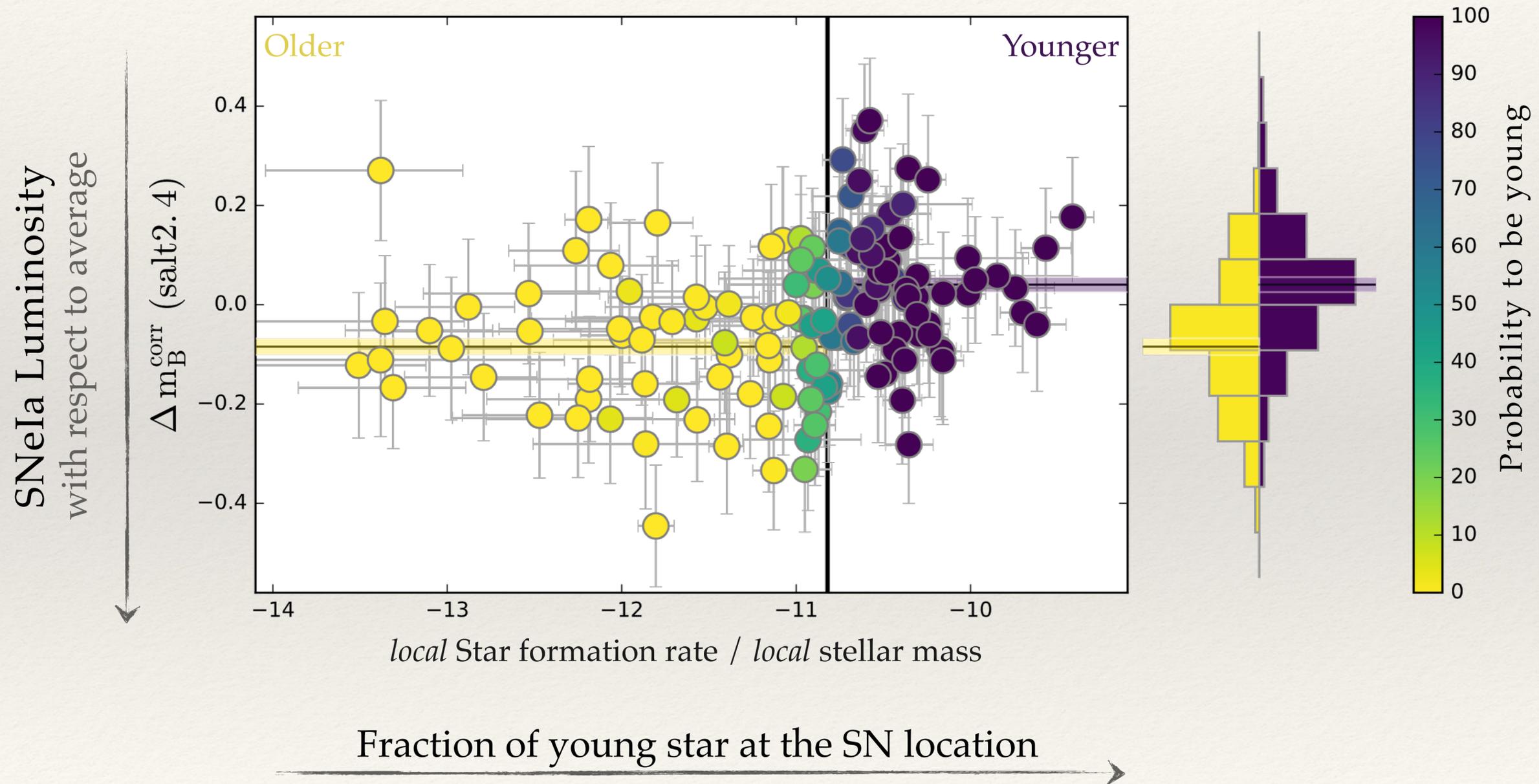




# Host Issue in SHOES

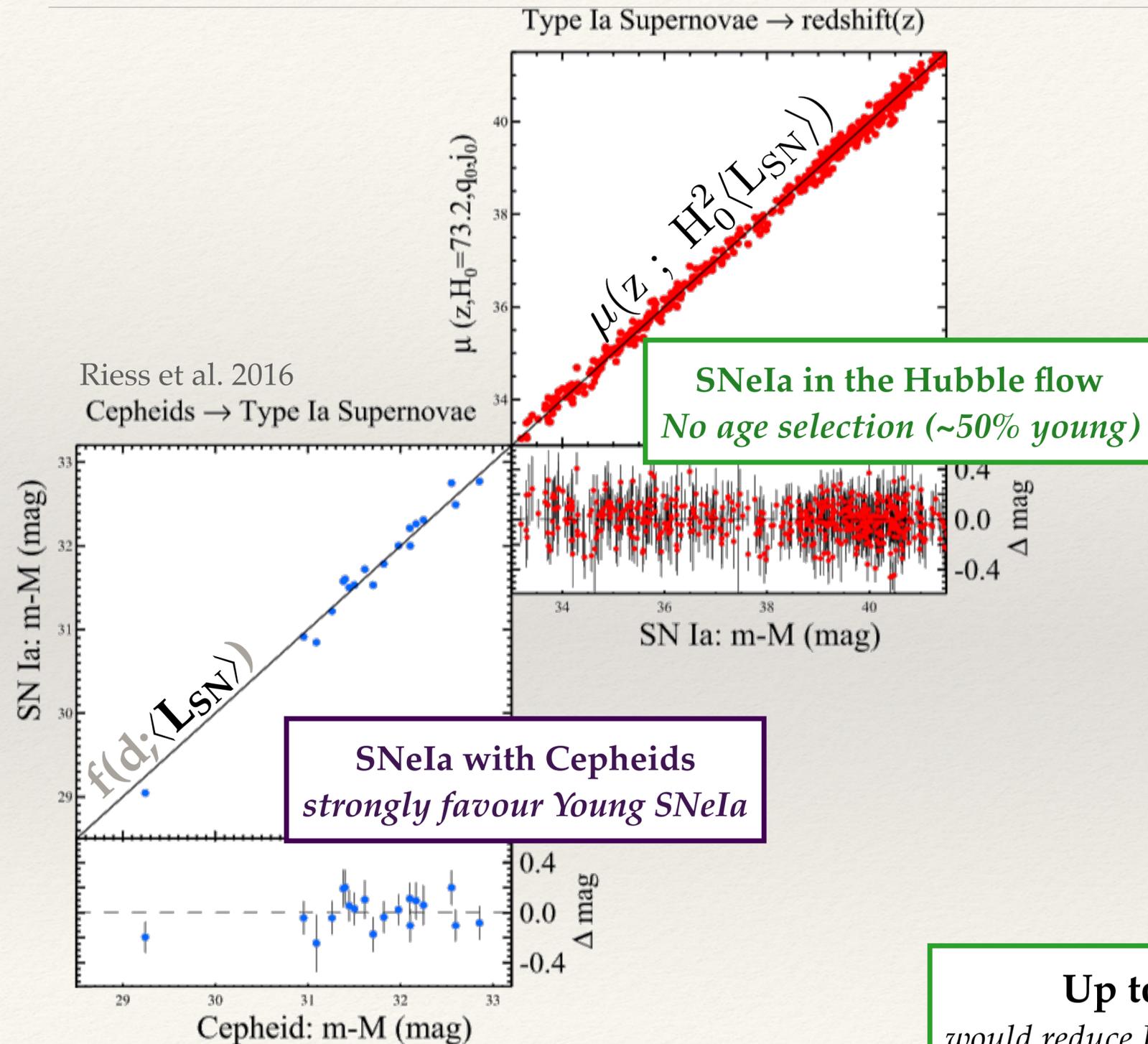
Rigault et al. 2018

non-zero at  $\sim 6\sigma$  level |  $\Delta_Y = 0.16 \pm 0.03$

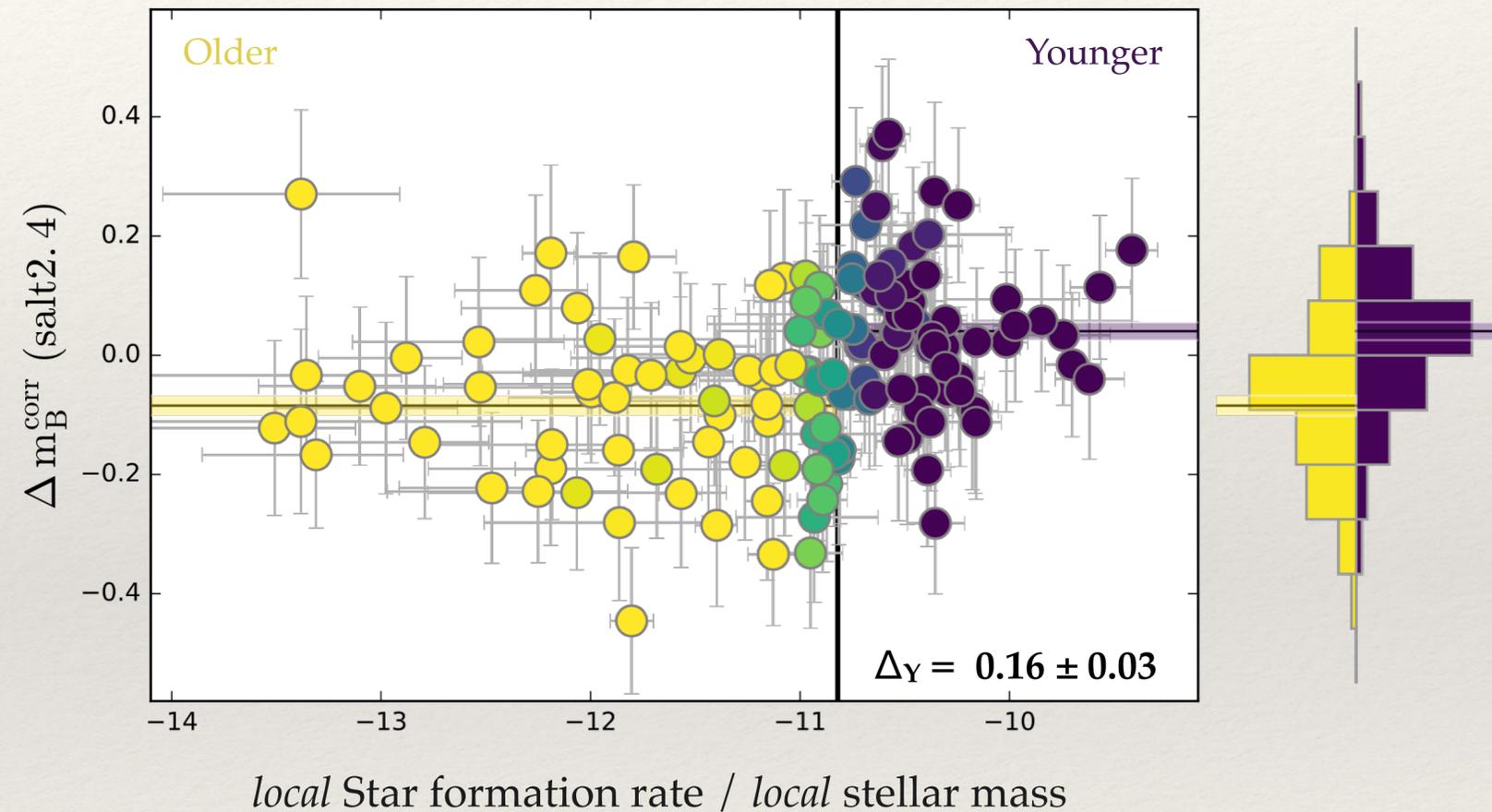


# Astrophysical SN bias & the $H_0$ tension

Rigault et al. 2015, 2018, in prep



non-zero at  $\sim 6\sigma$  level | **Young SNe Ia are 0.16 fainter**



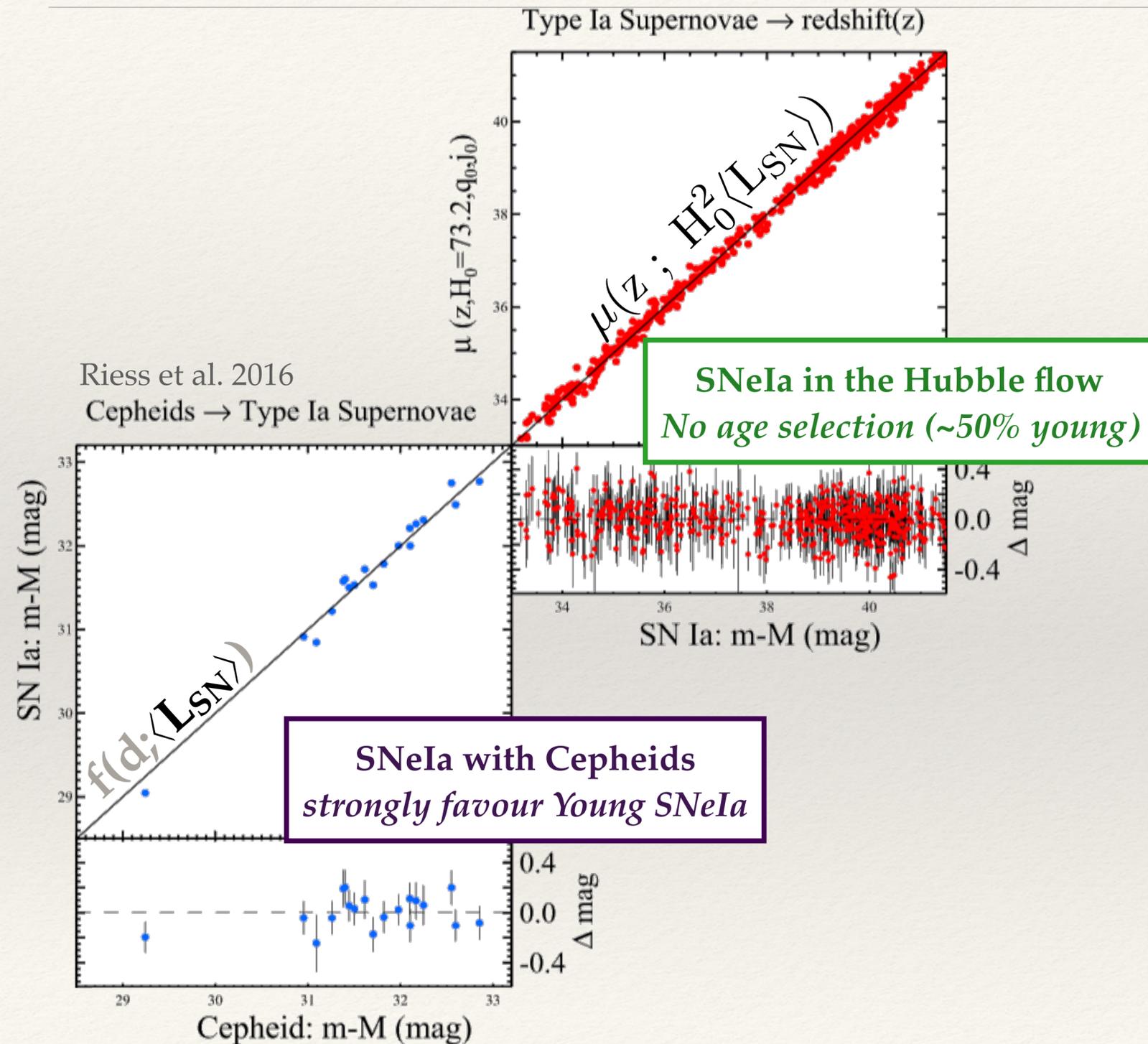
See also SNLS+SDSS  $7\sigma$  step in Roman2018

**Up to 3% bias on  $H_0$**   
would reduce  $H_0$  down to  $\sim 71.5 \text{ km/s/Mpc}$

# Astrophysical SN bias & the $H_0$ tension

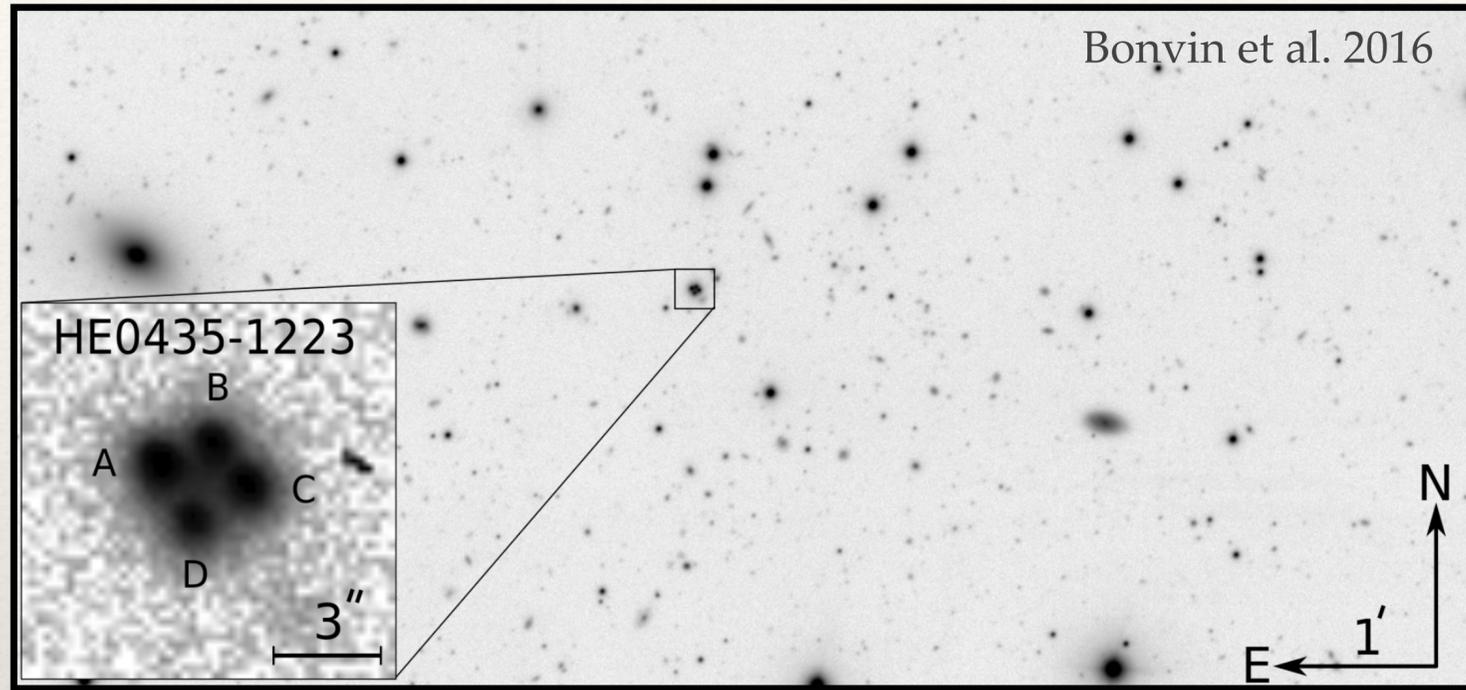
Rigault et al. 2015, 2018, in prep

Riess et al. 2016

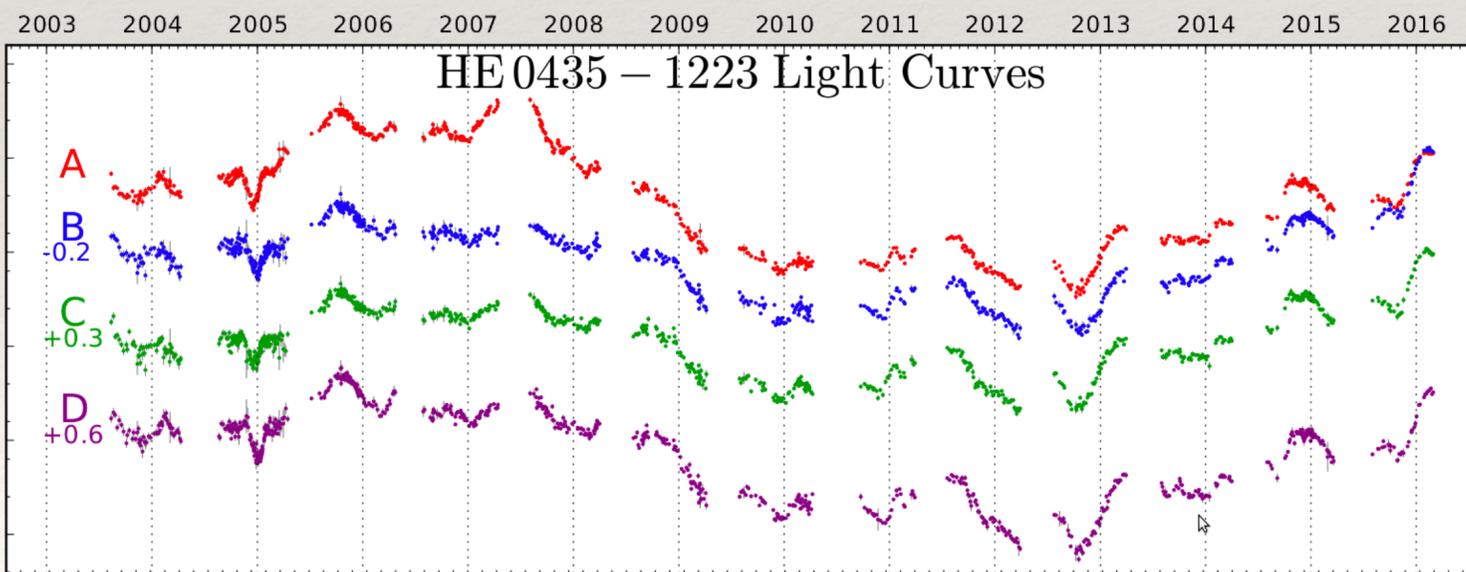
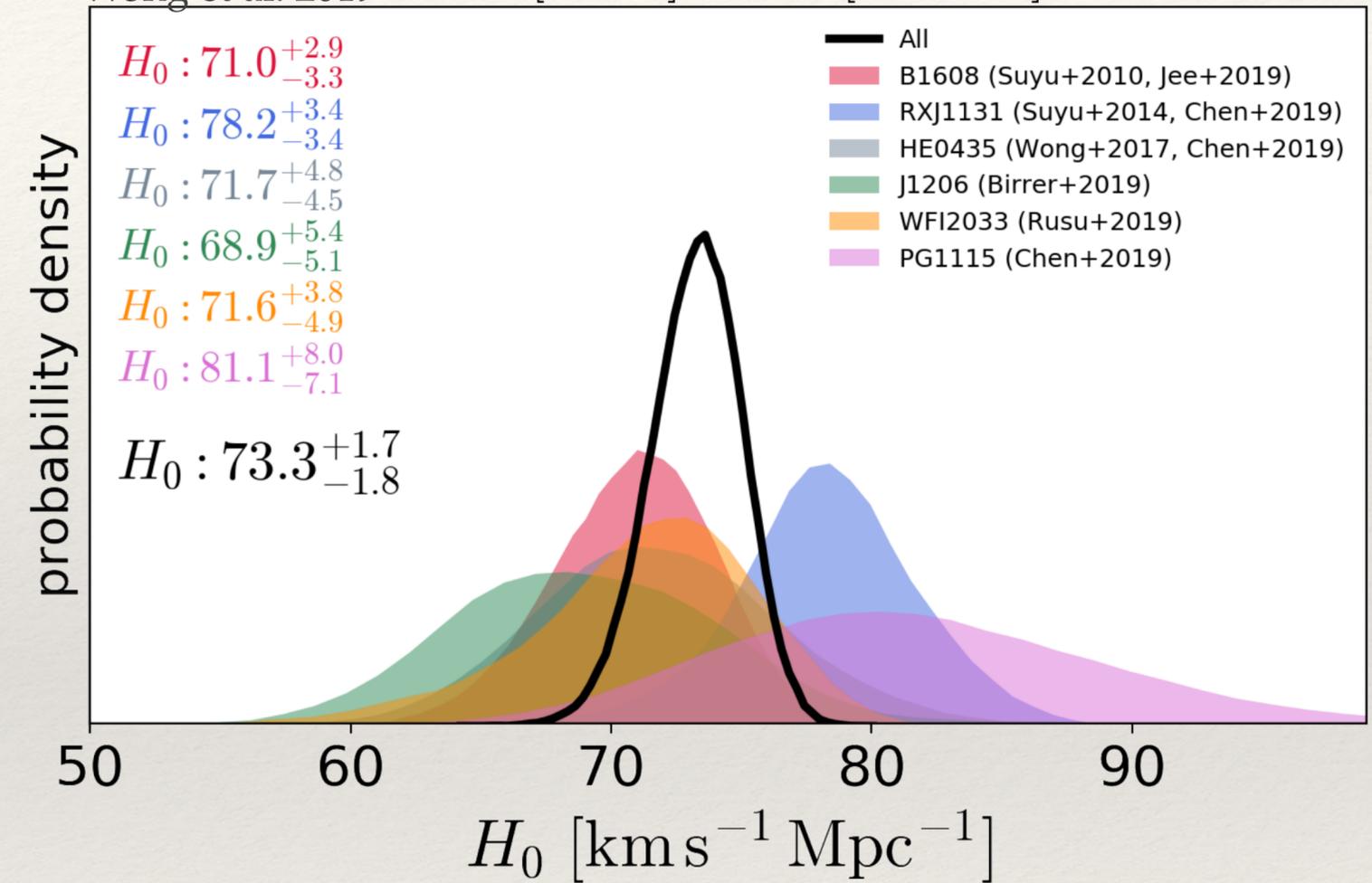


Analysis Variant (R16)	$H_0$
Best Fit (R16, w/ HST, Gaia, R18=73.53)	73.24
Reddening Law: LMC-like ( $R_V=2.5$ , not 3.3)	73.15
Reddening Law: Bulge-like (N15)	73.39
No Cepheid Outlier Rejection (normally 2%)	73.49
No Correction for Extinction	74.79
No Truncation for Incomplete Period Range	74.39
Metallicity Gradient: None (normally fit)	73.30
Period-Luminosity: Single Slope	73.26
Period-Luminosity: Restrict to $P > 10$ days	71.64
Period-Luminosity: Restrict to $P < 60$ days	73.06
Supernovae $z > 0.01$ (normally $z > 0.023$ )	73.38
Supernova Fitter: MLCS (normally SALT)	74.39
Supernova Hosts: Spiral (usually all types)	73.37
Supernova Hosts: Locally Star Forming	73.54
Cepheid Measurements: Optical Only	71.74

# $H_0$ from Strong Lensing



Wong et al. 2019  $H_0 \in [0, 150]$   $\Omega_m \in [0.05, 0.5]$



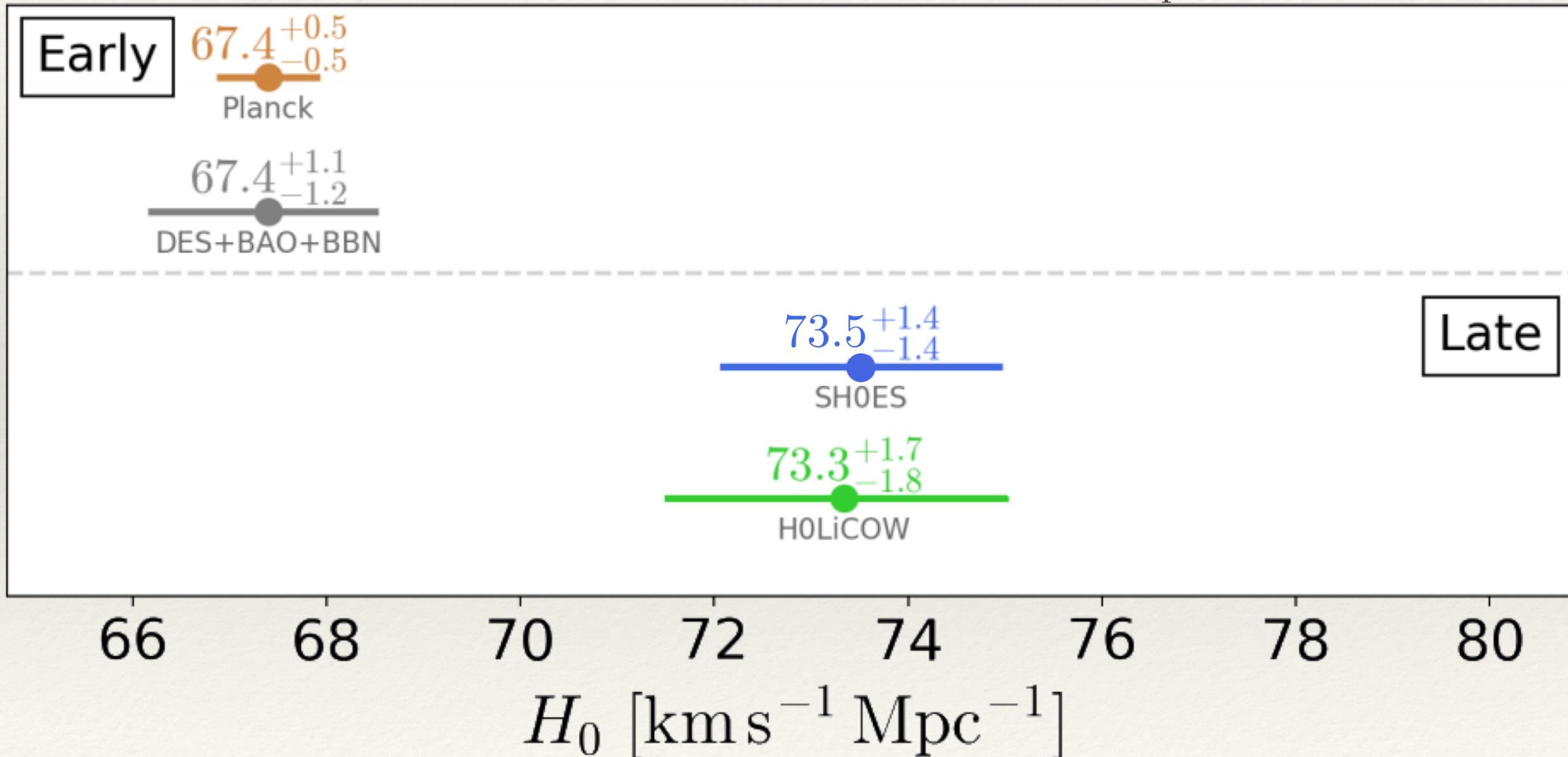
$$\Delta t = \frac{1}{c} D_{\Delta t} \phi_{lens} \propto H_0^{-1}$$

Obtained from lensing mass model

# $H_0$ Controversy | $5\sigma$ “crisis”

flat –  $\Lambda$ CDM

Adapted from Verde et al. 2019



# Tip of the Red Giant Branch

Beaton et al. 2018

Friedman et al. 2019

Geometrical  
Distances

10 Mpc

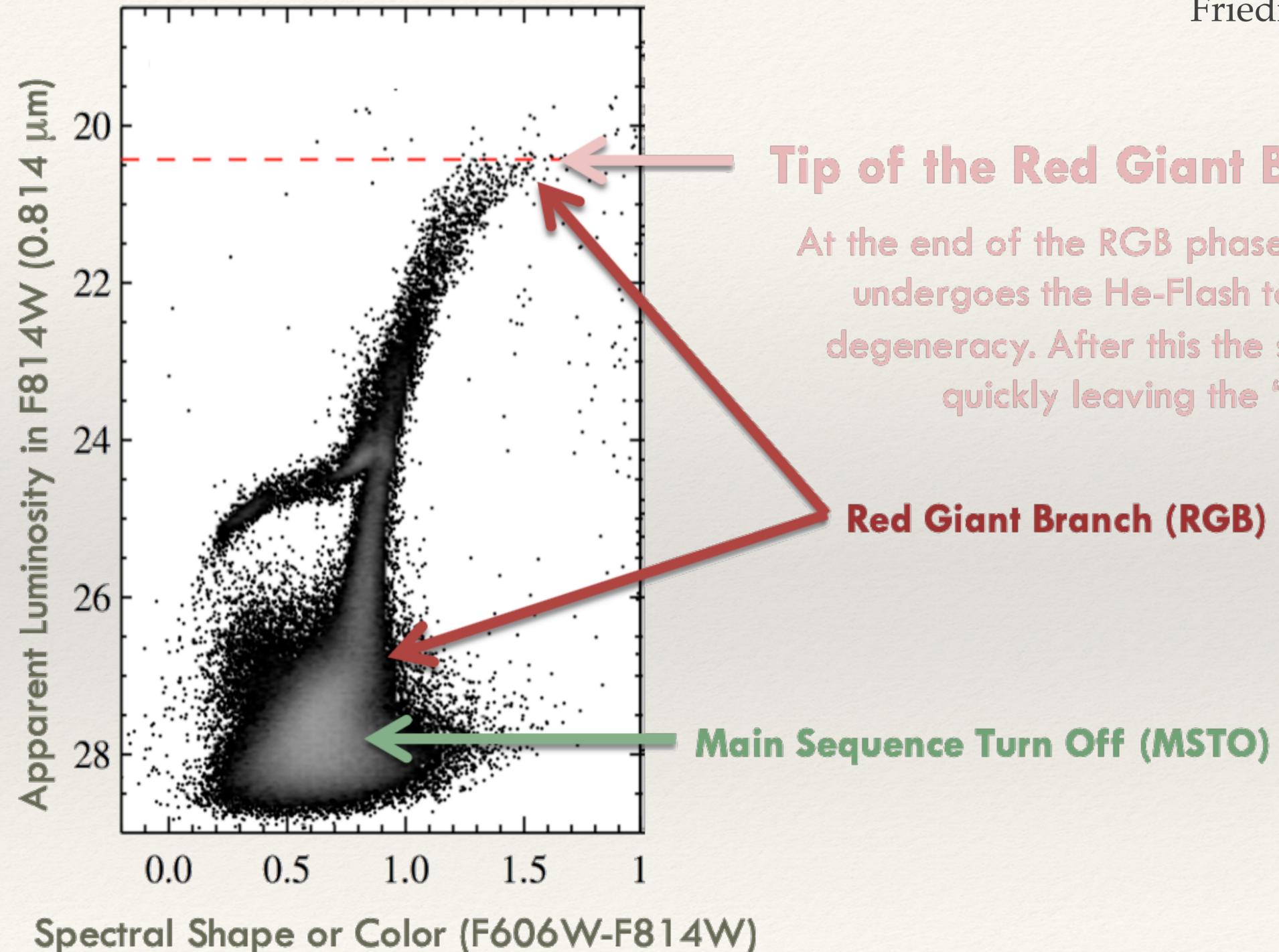
Cepheids

T.R.G.B.

100 Mpc

SNe Ia

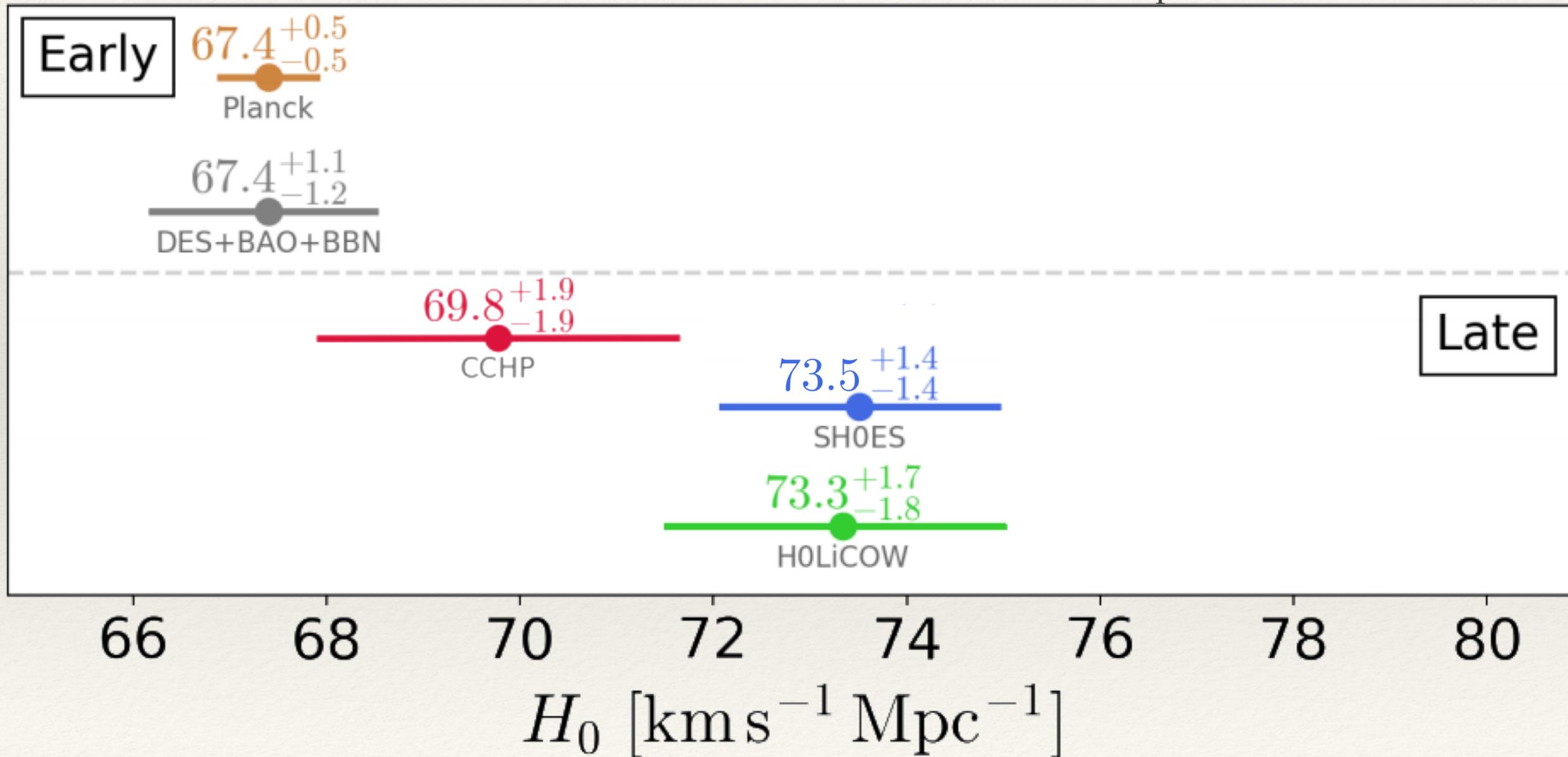
1 Gpc



# The $H_0$ Crisis

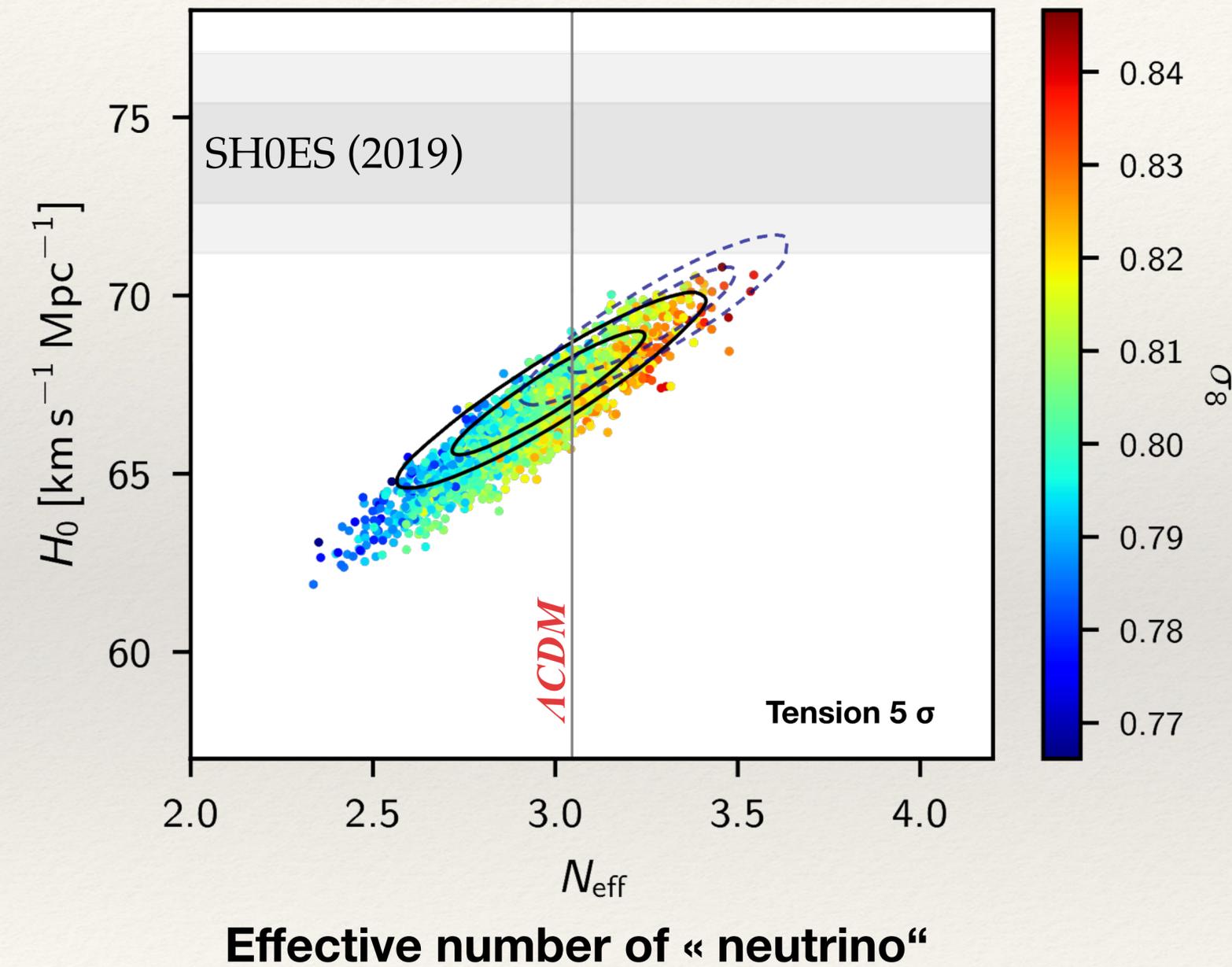
flat  $-\Lambda$ CDM

Adapted from Verde et al. 2019

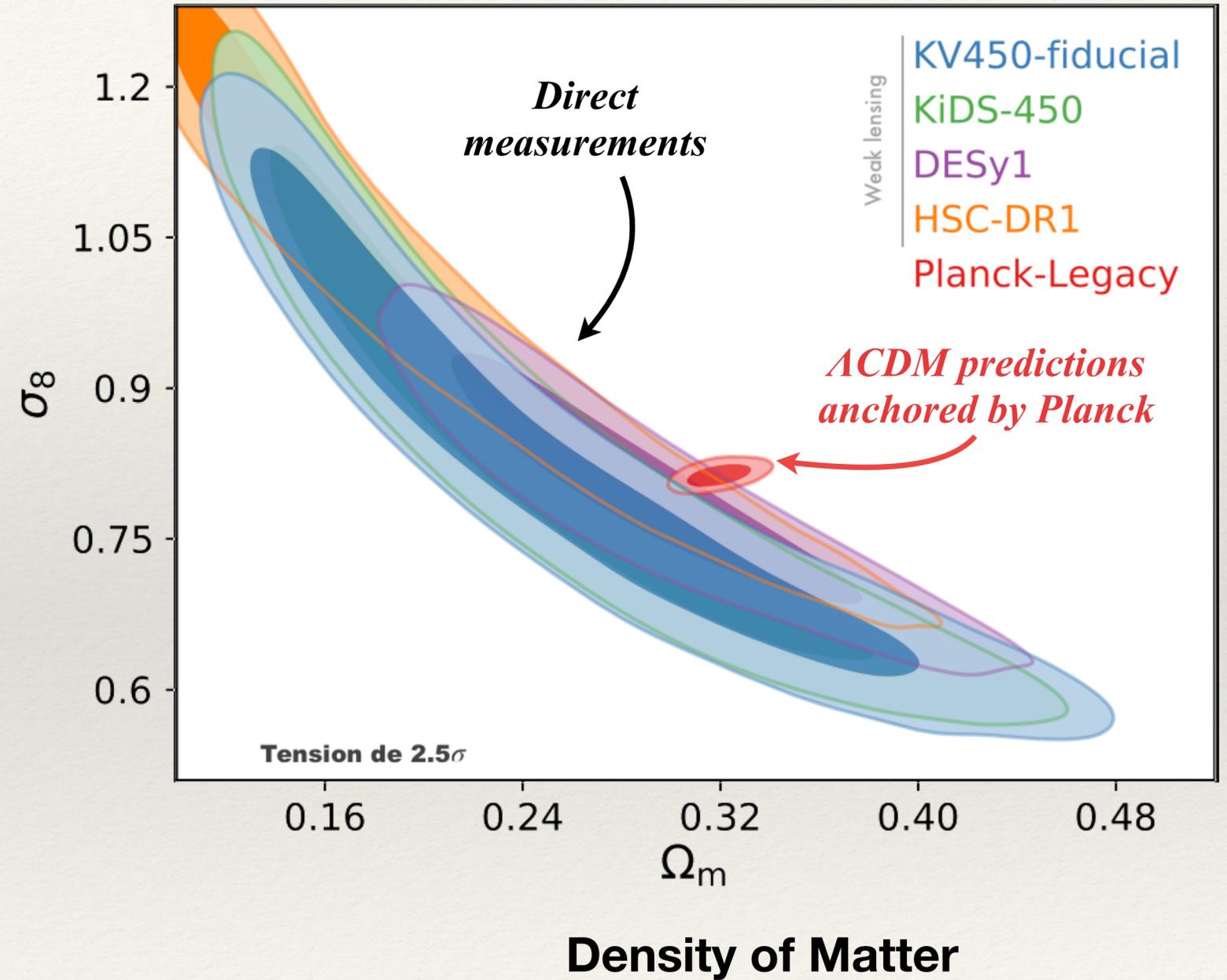


# Tensions In Cosmology | *Late vs. Early Universe*

Planck 2018

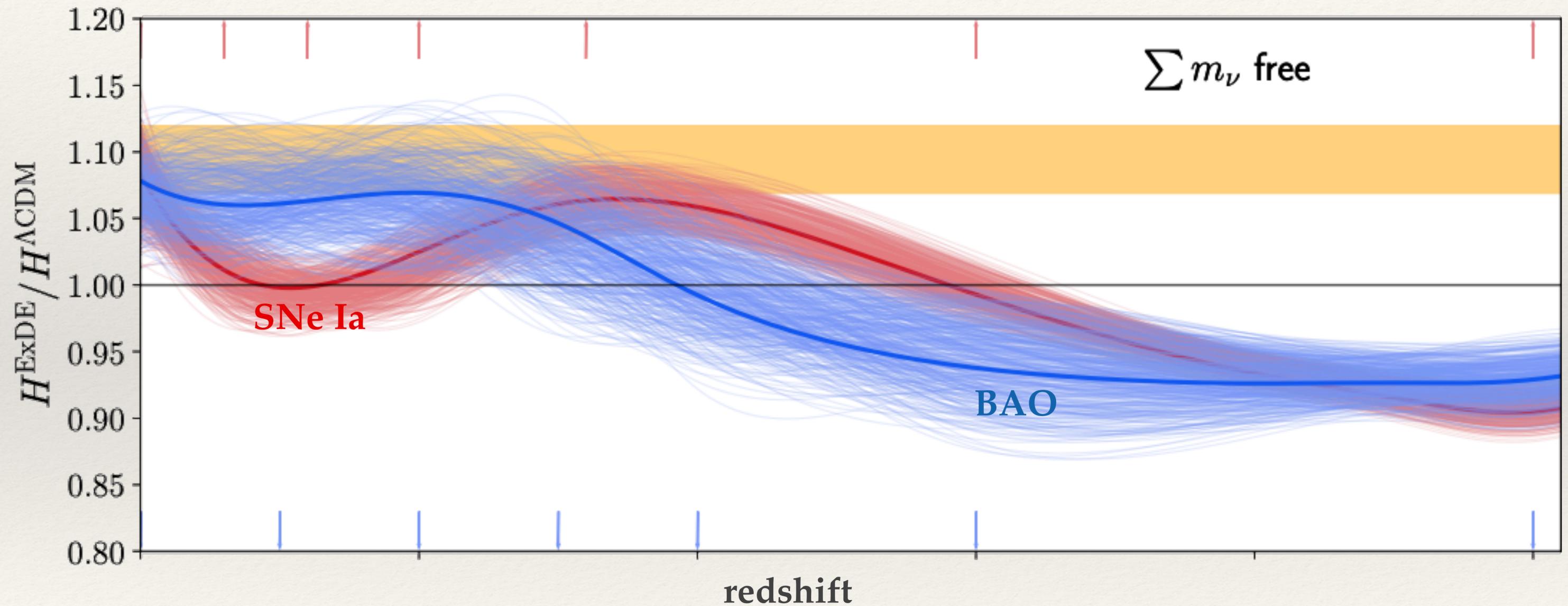


Amplitude of structures fluctuations



# Exotic Dark Energy + Neutrinos

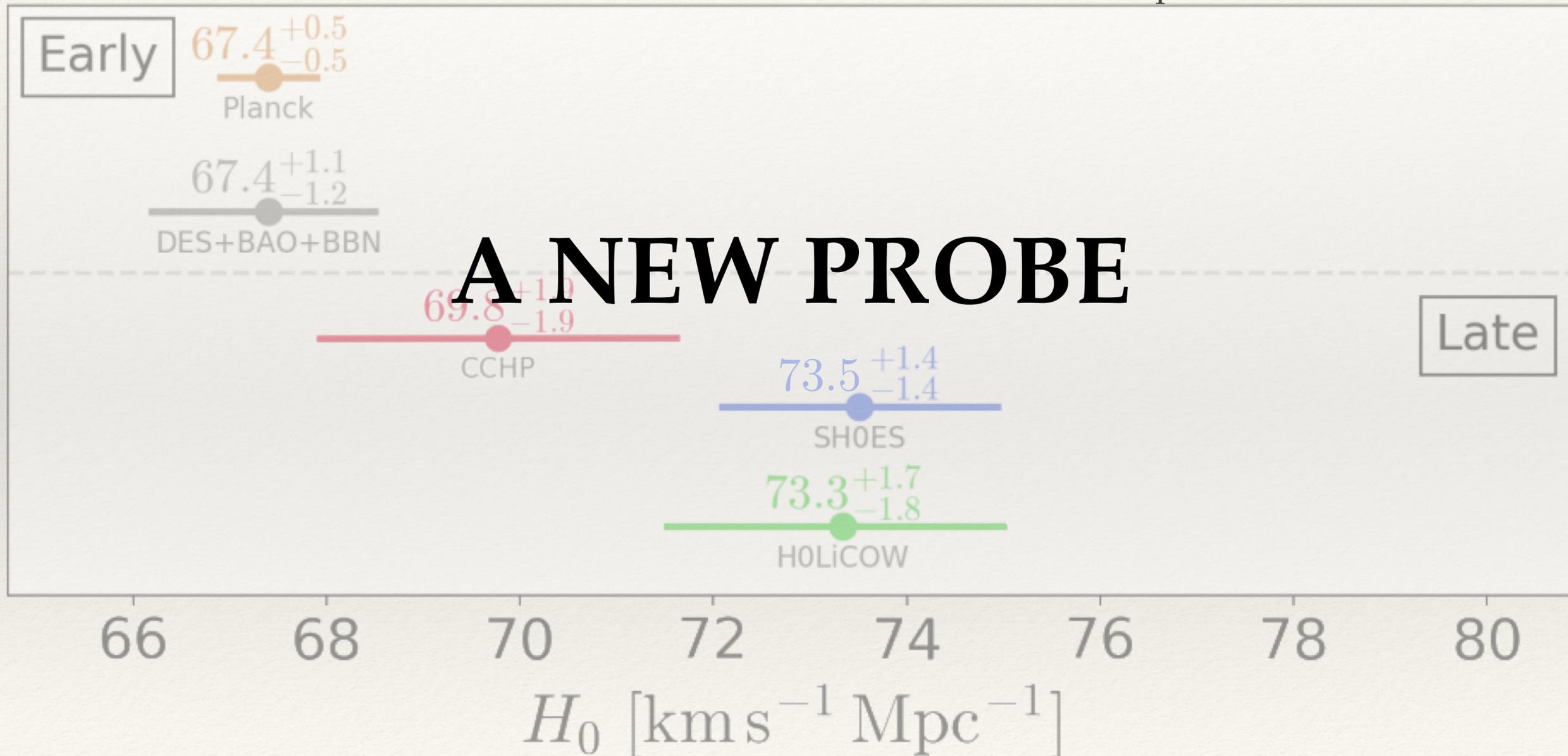
Poulin et al. 2018



# The $H_0$ Crisis

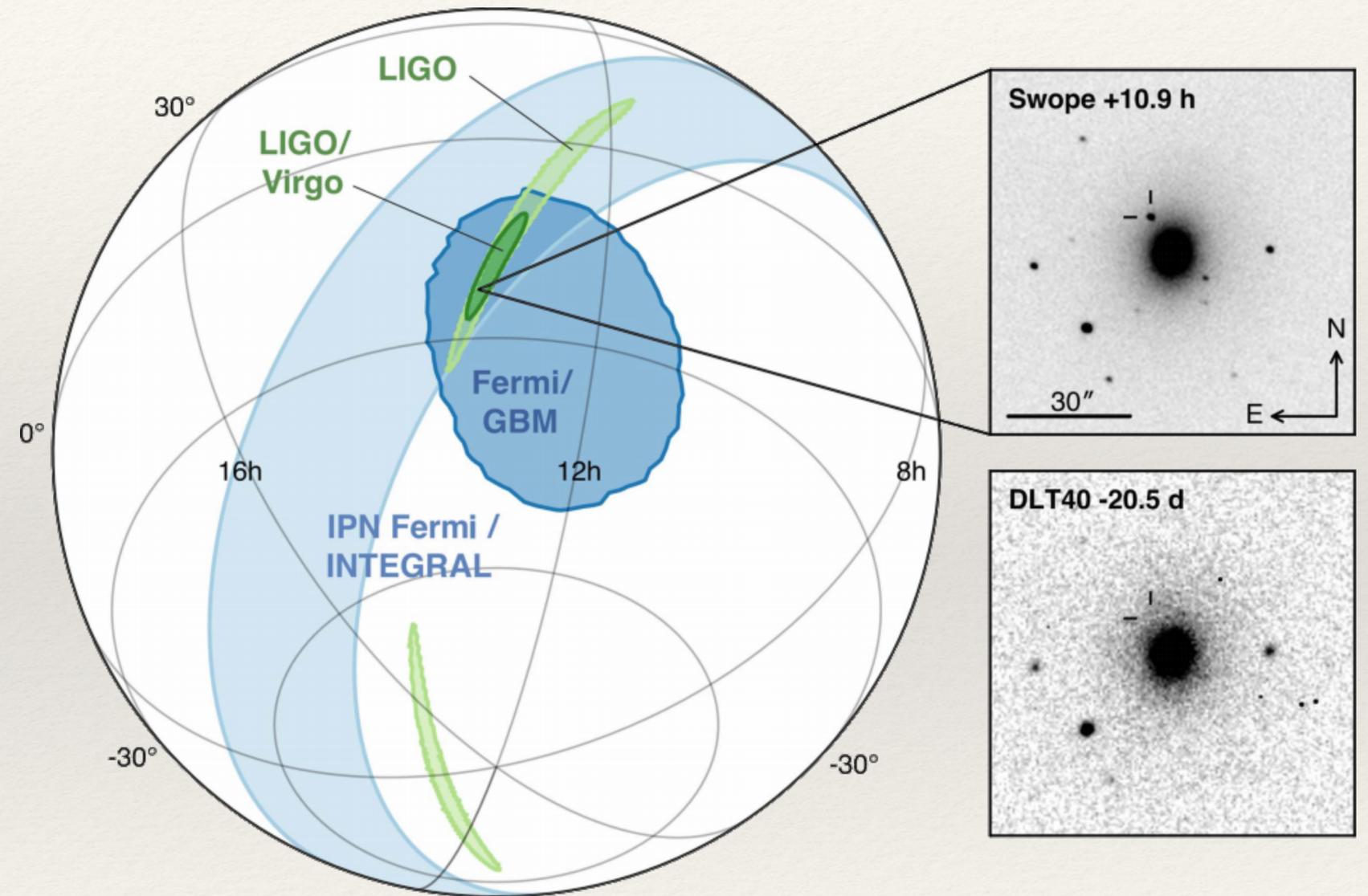
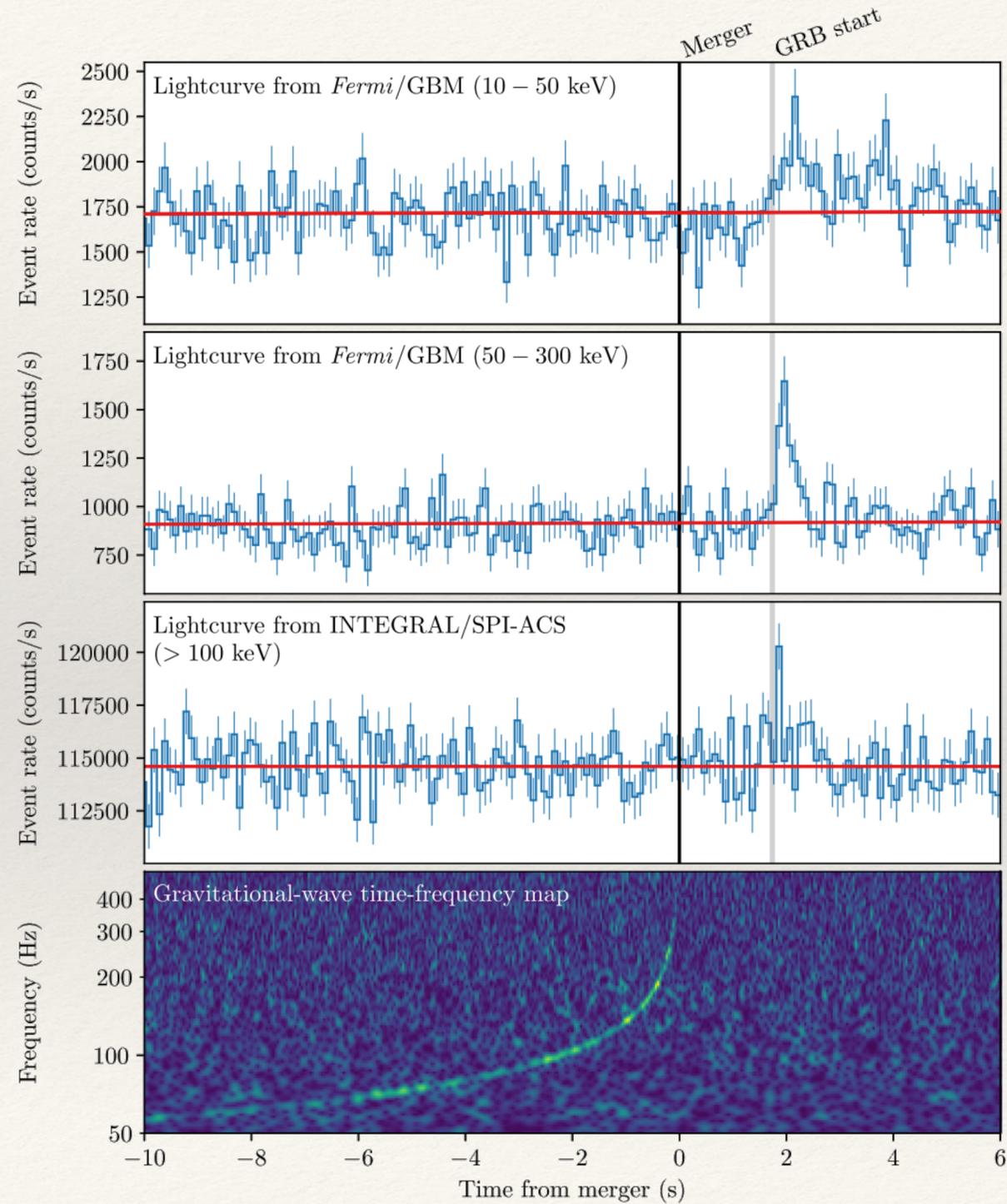
flat  $\Lambda$ CDM

Adapted from Verde et al. 2019

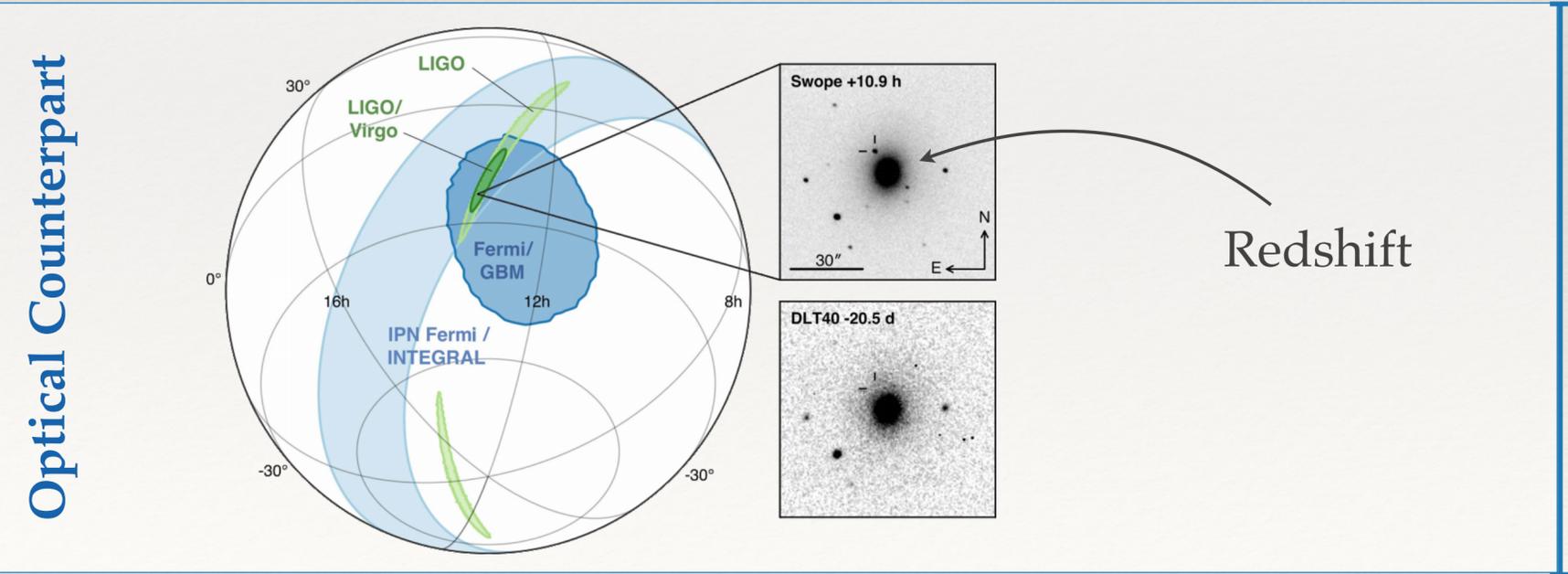
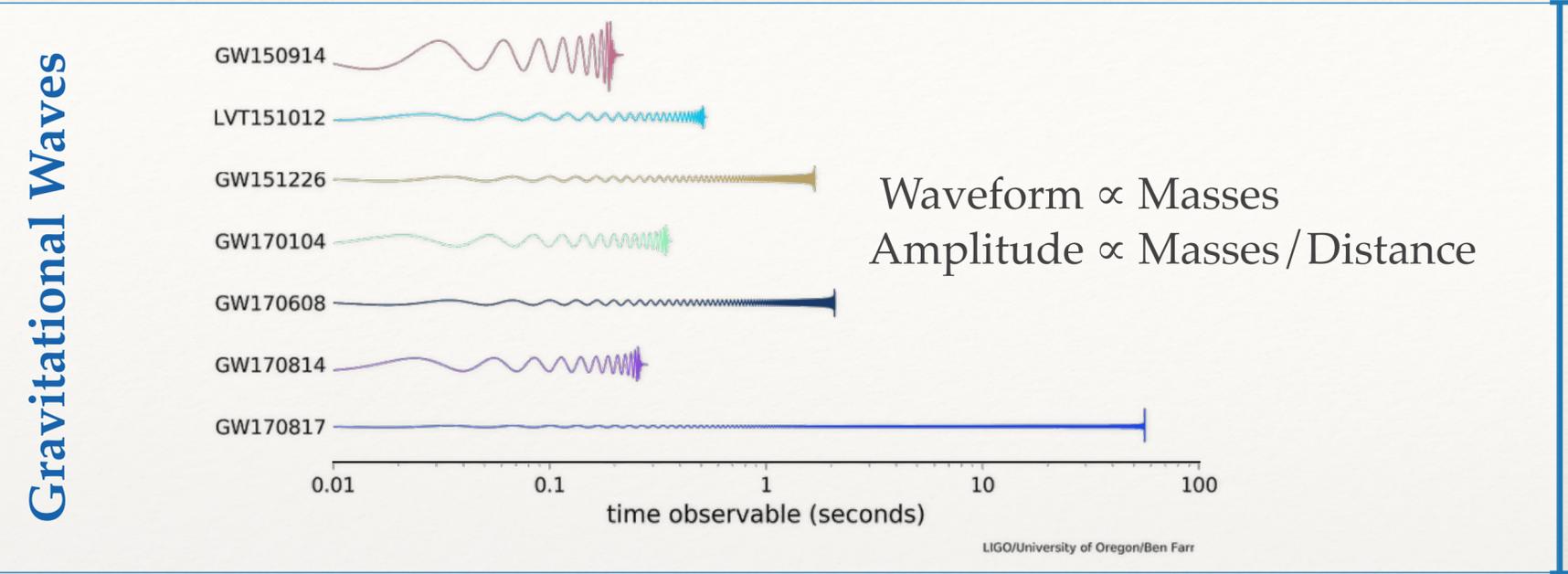


# GW170817

Ligo & Virgo ApJ 848, 12L



# Gravitational Waves & ElectroMagnetism | *Measuring H<sub>0</sub>*



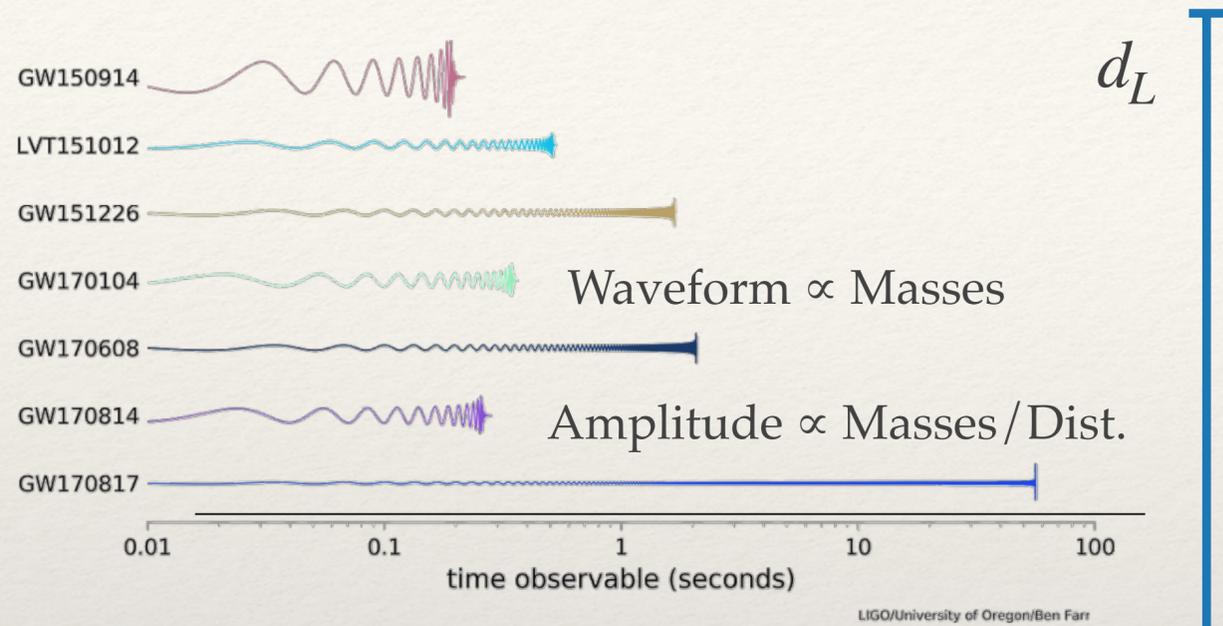
$d_L$

$$v_H = H_0 d_L$$

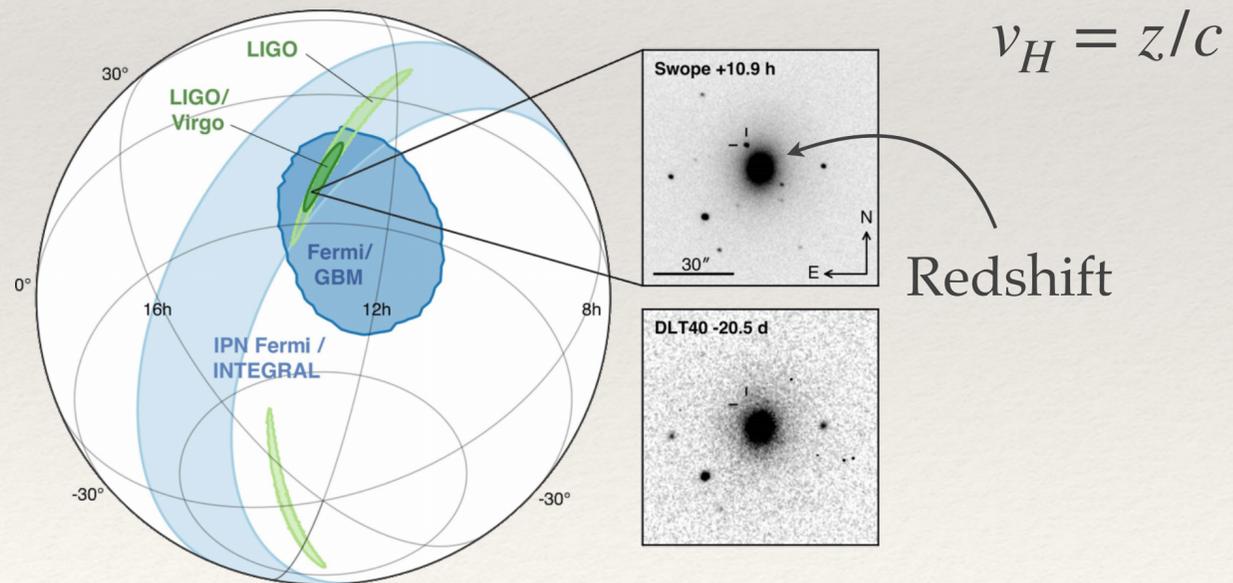
$v_H = z/c$

# Gravitational Waves & ElectroMagnetism | *Measuring $H_0$*

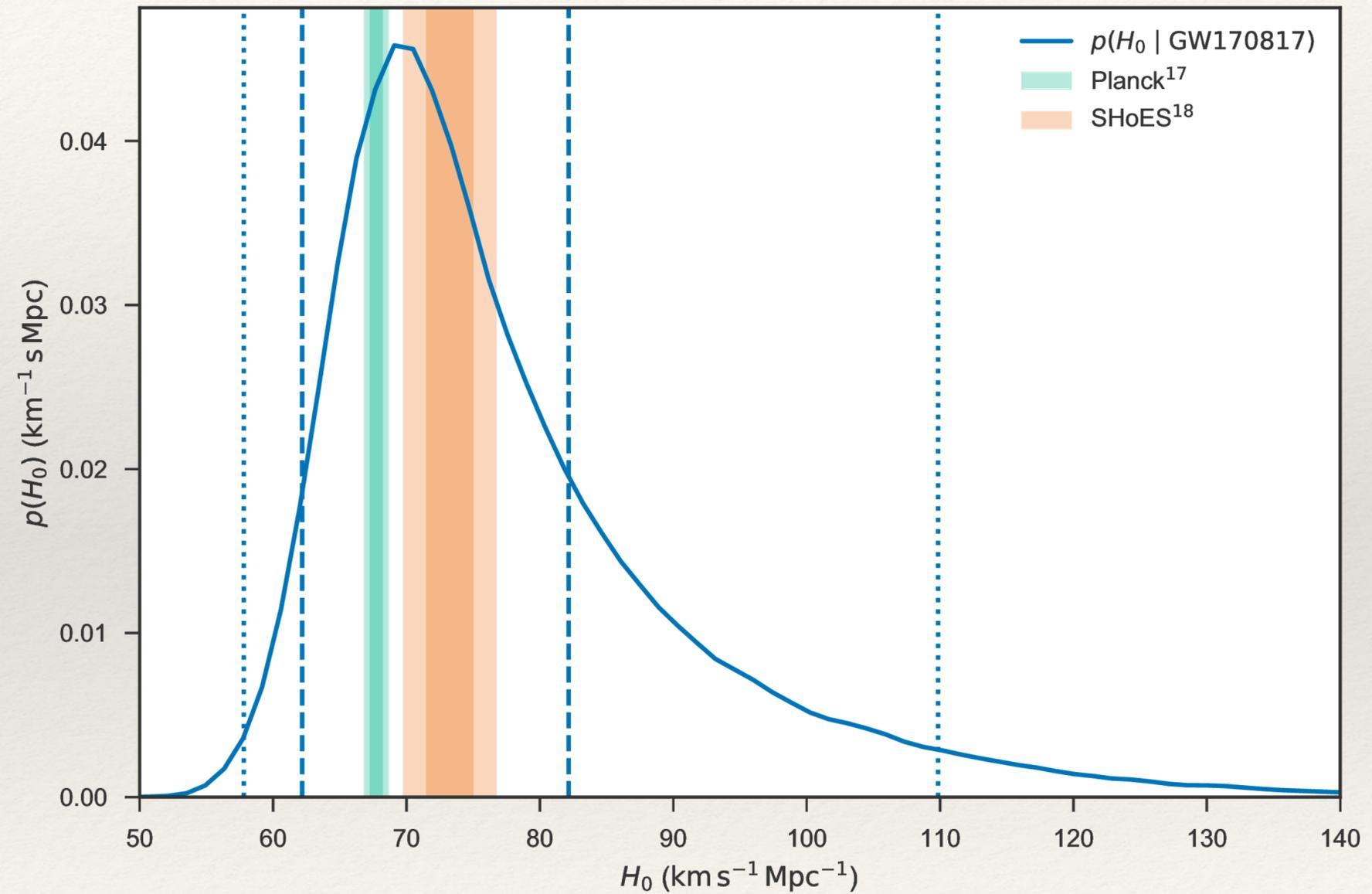
Gravitational Waves



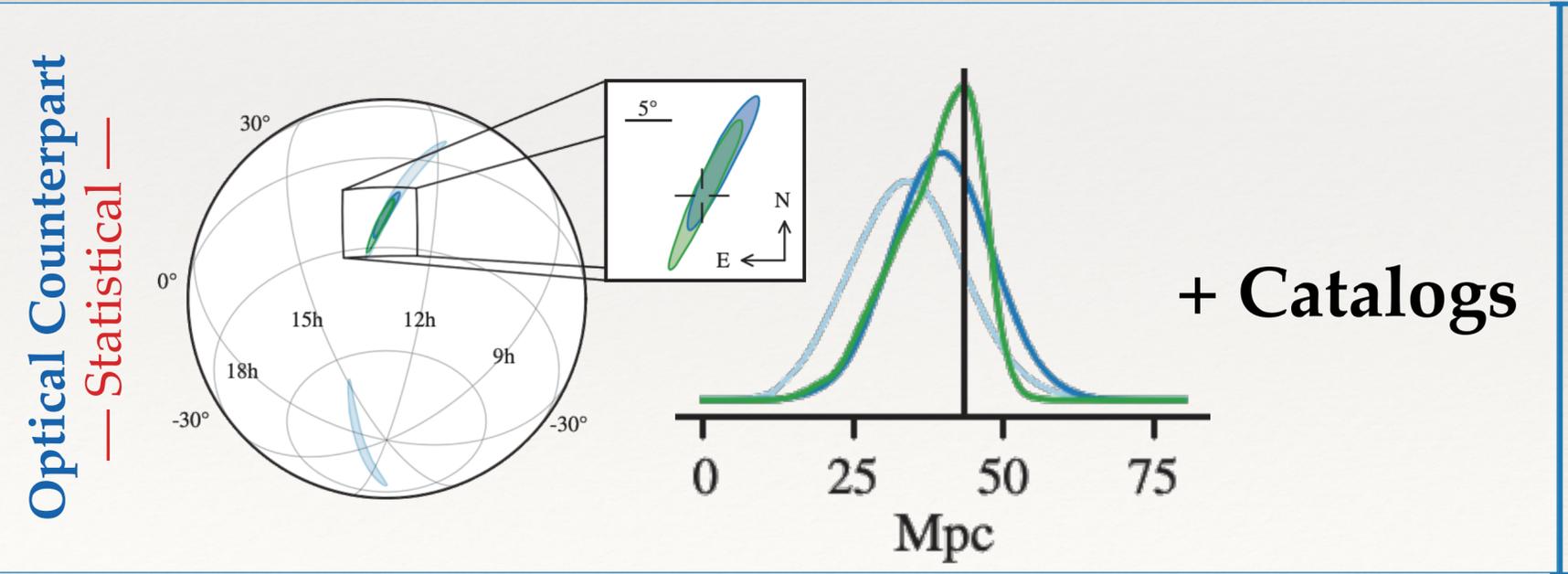
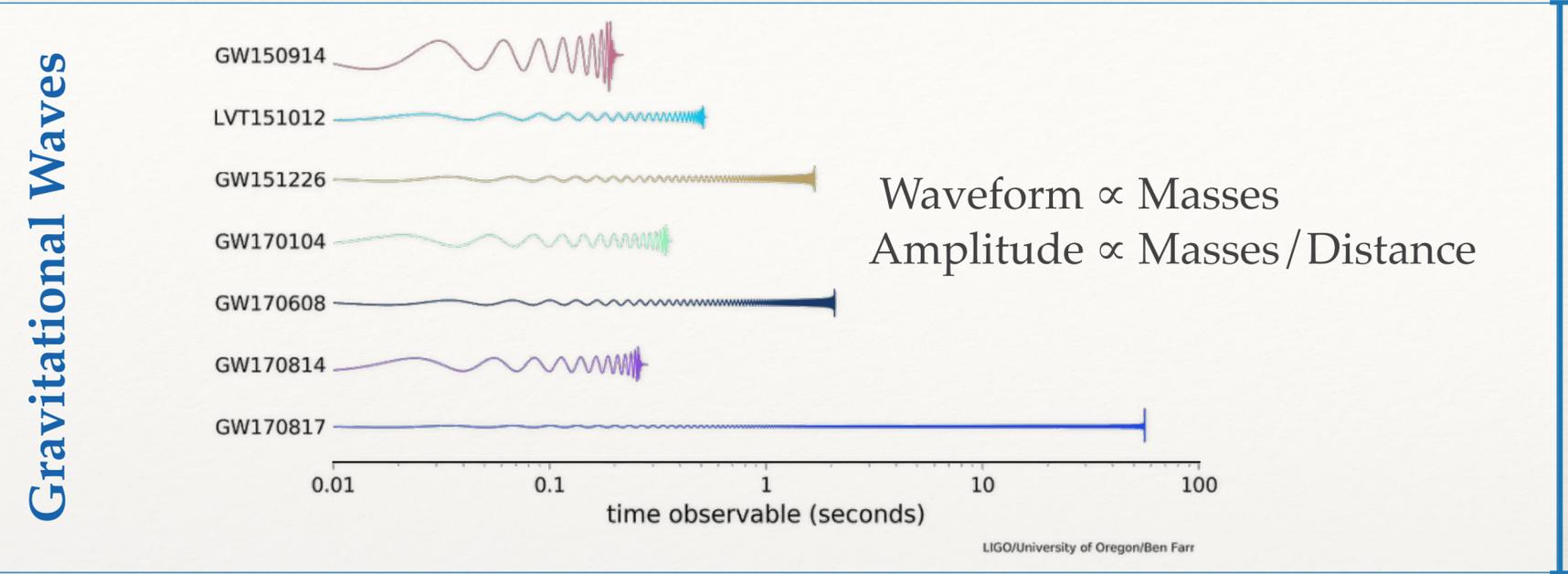
Optical Counterpart



$$v_H = H_0 d_L$$



# Gravitational Waves & ~~ElectroMagnetism~~ | *Measuring H<sub>0</sub>*

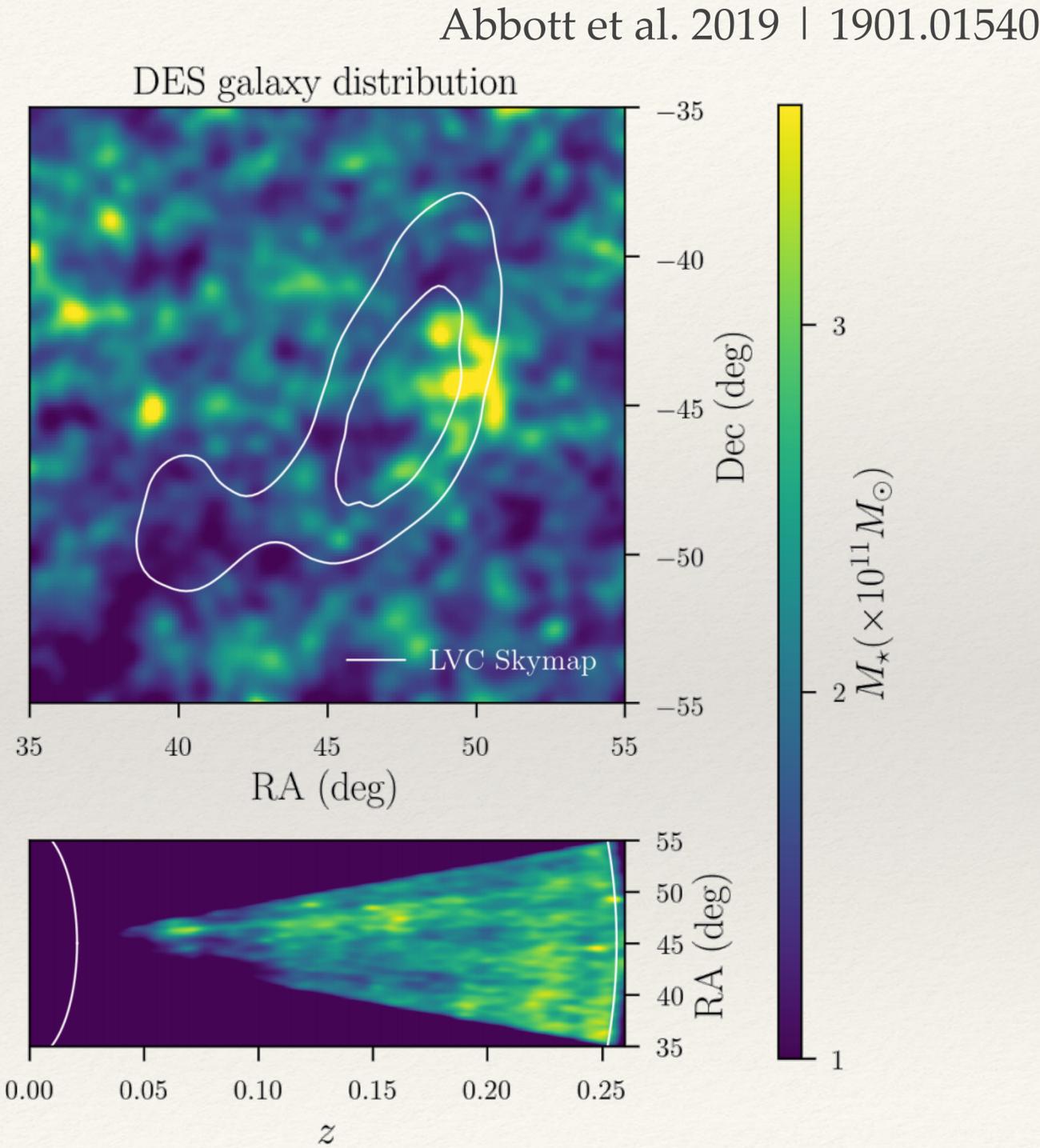
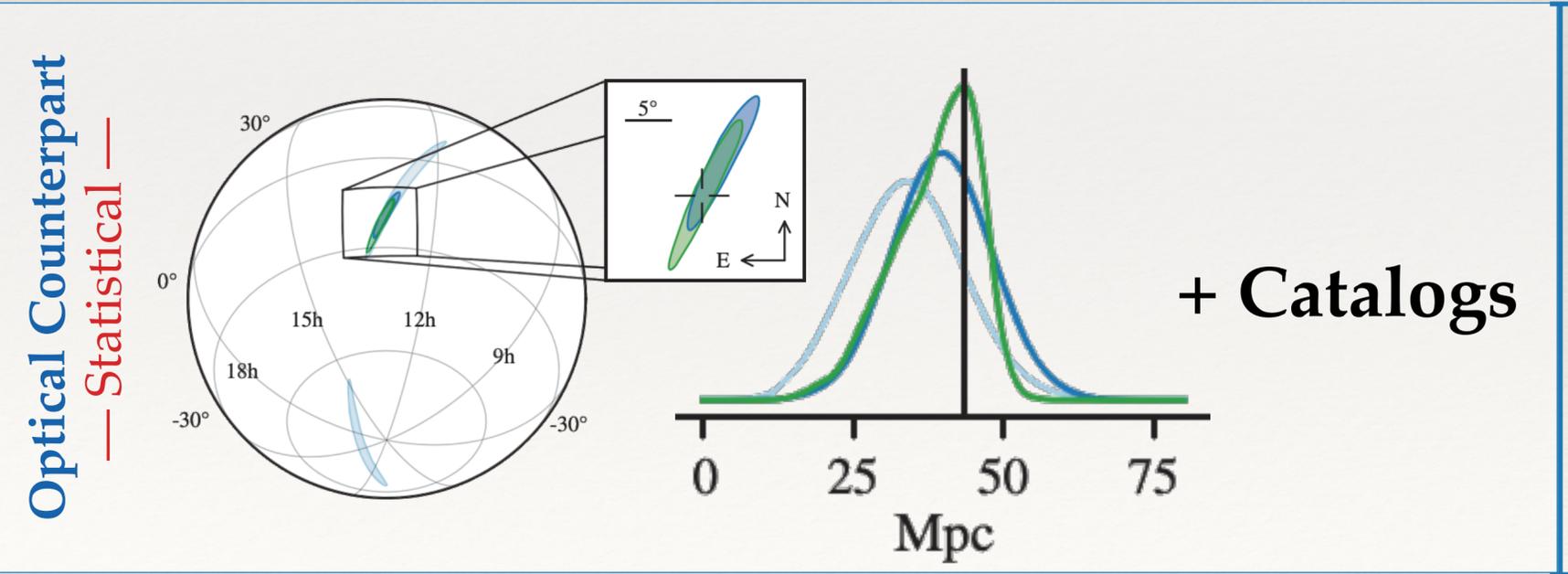
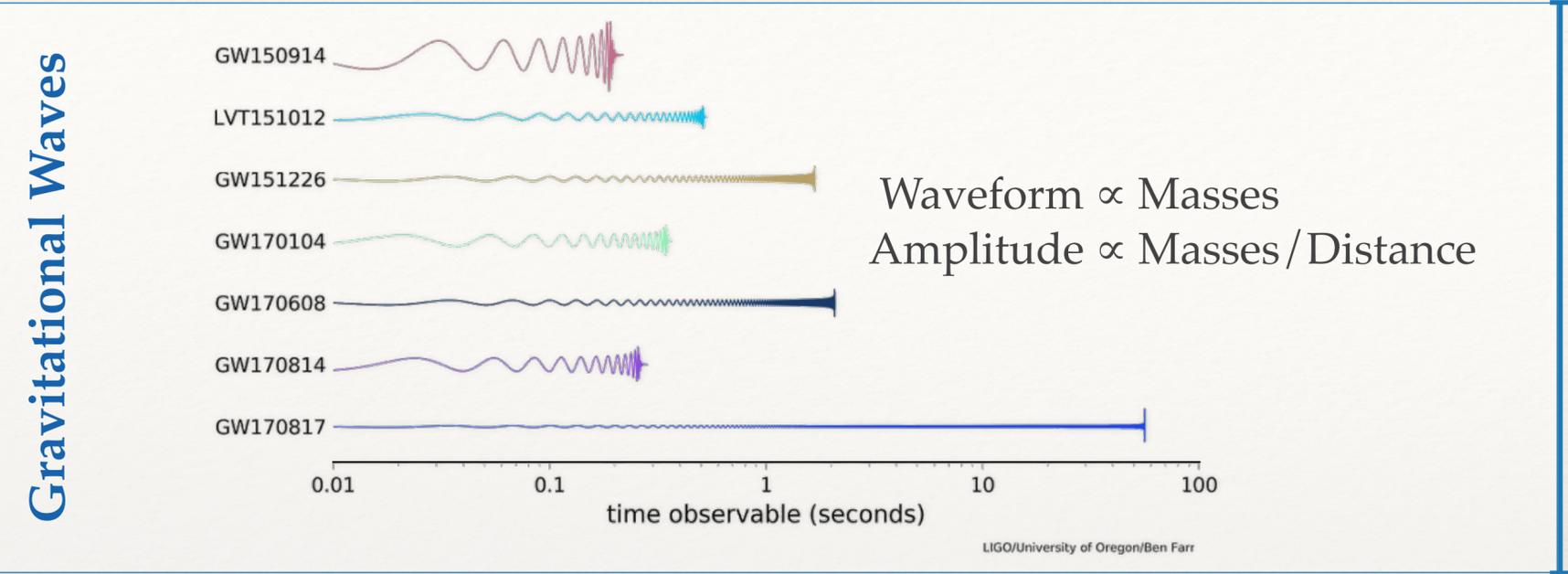


$d_L$

$$v_H = H_0 d_L$$

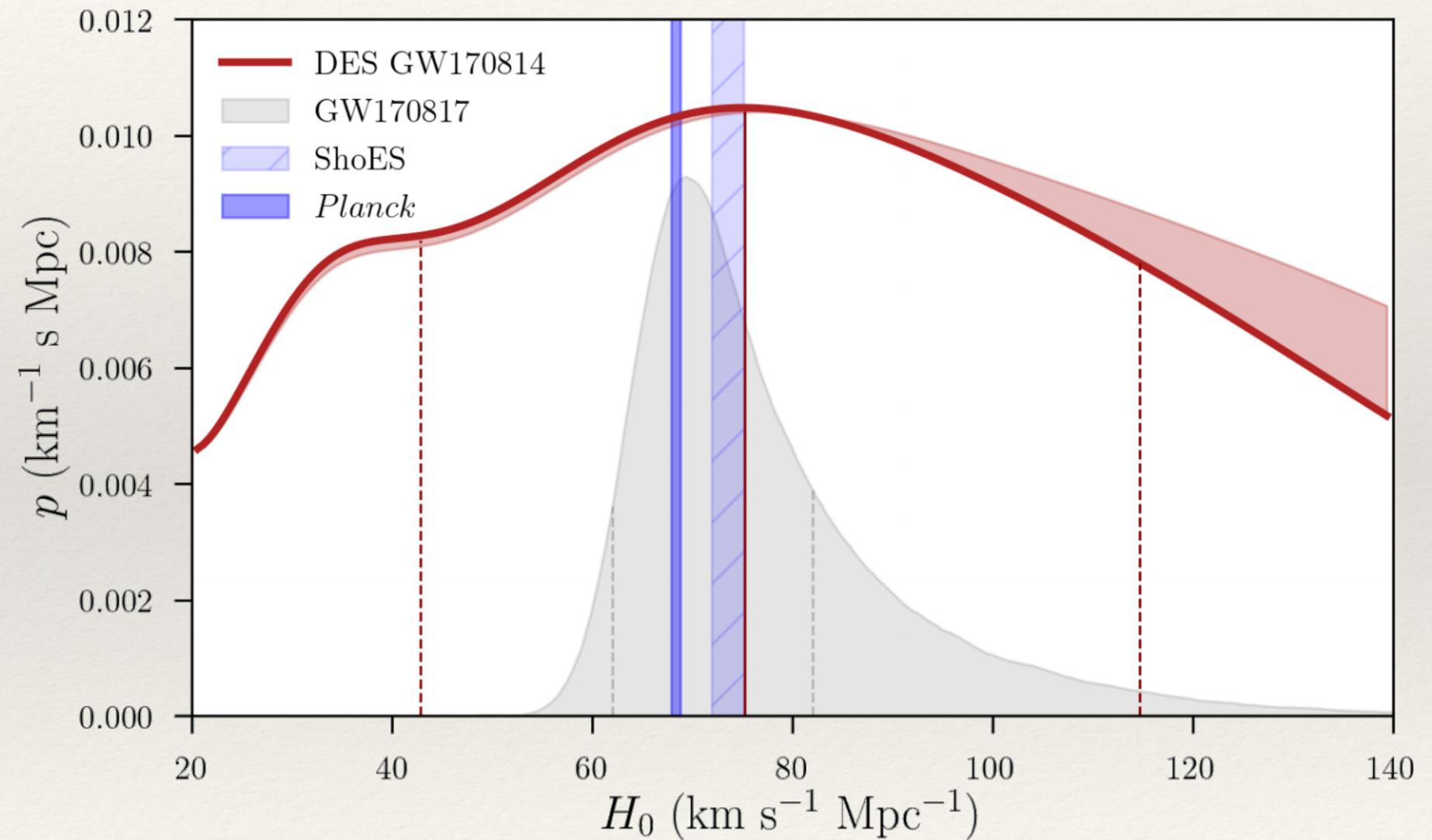
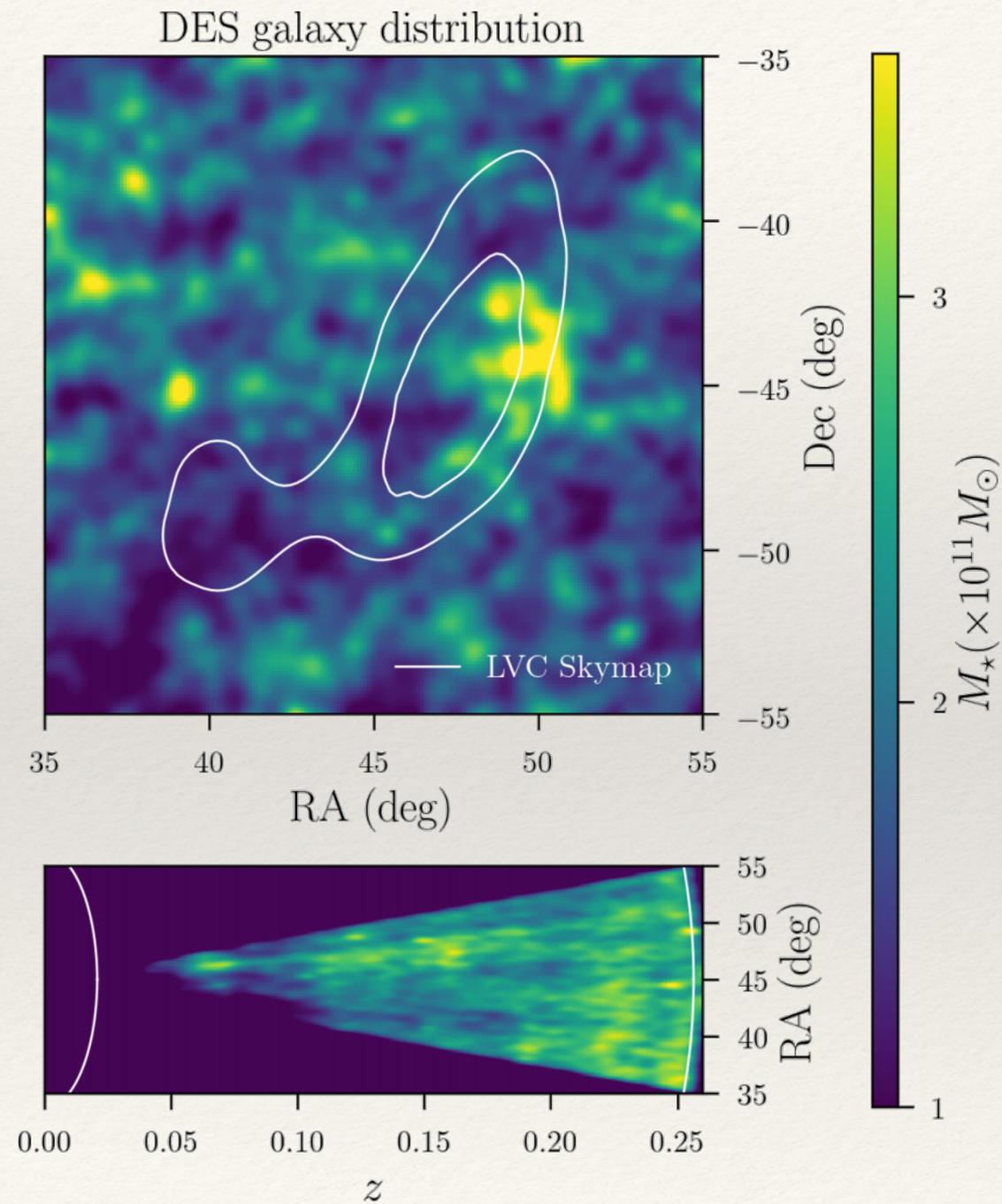
pdf( $v_H$ )

# Gravitational Waves & ~~ElectroMagnetism~~ | *Measuring $H_0$*

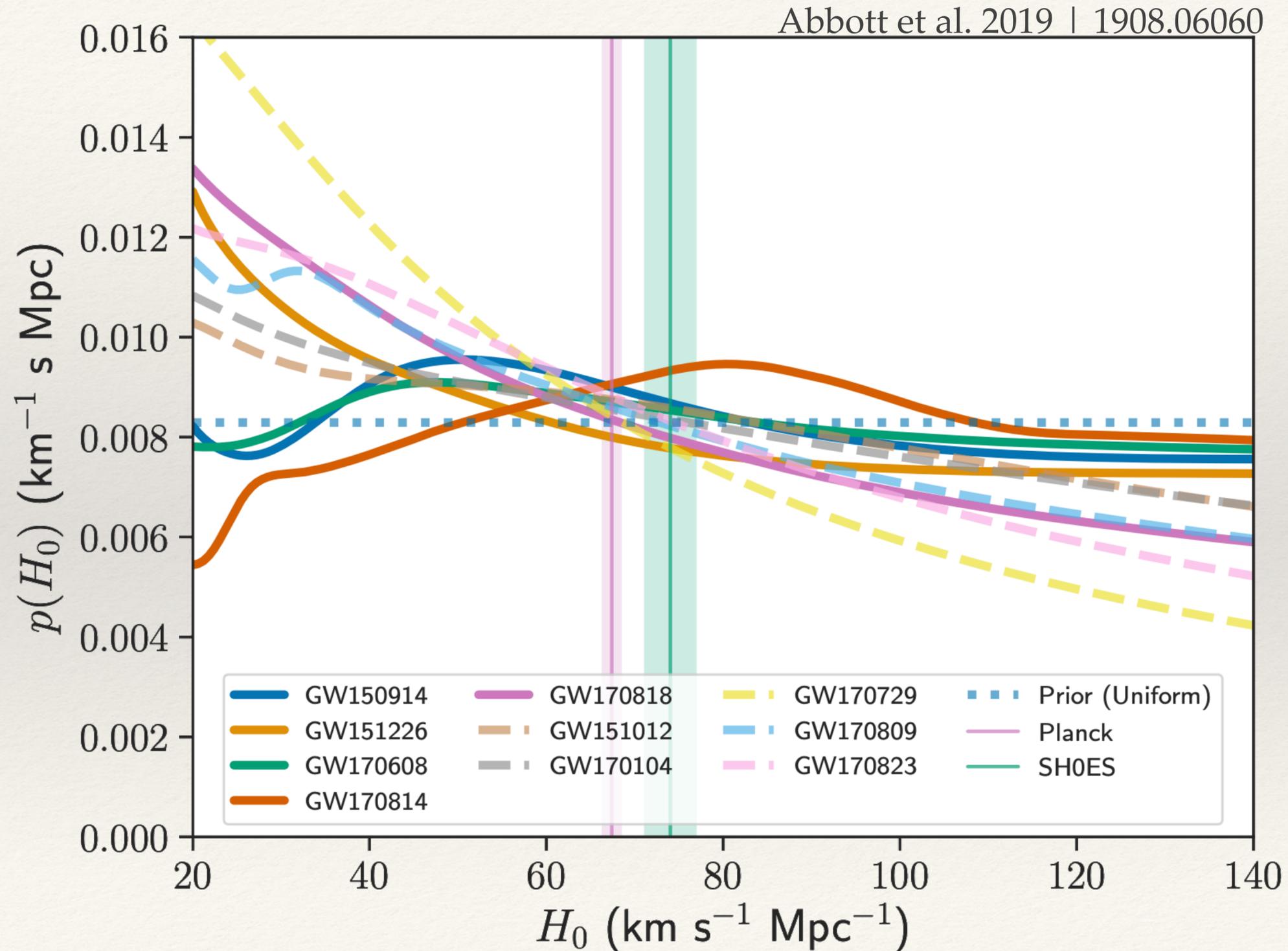


# Direct measurement of $H_0$ | *without counterpart*

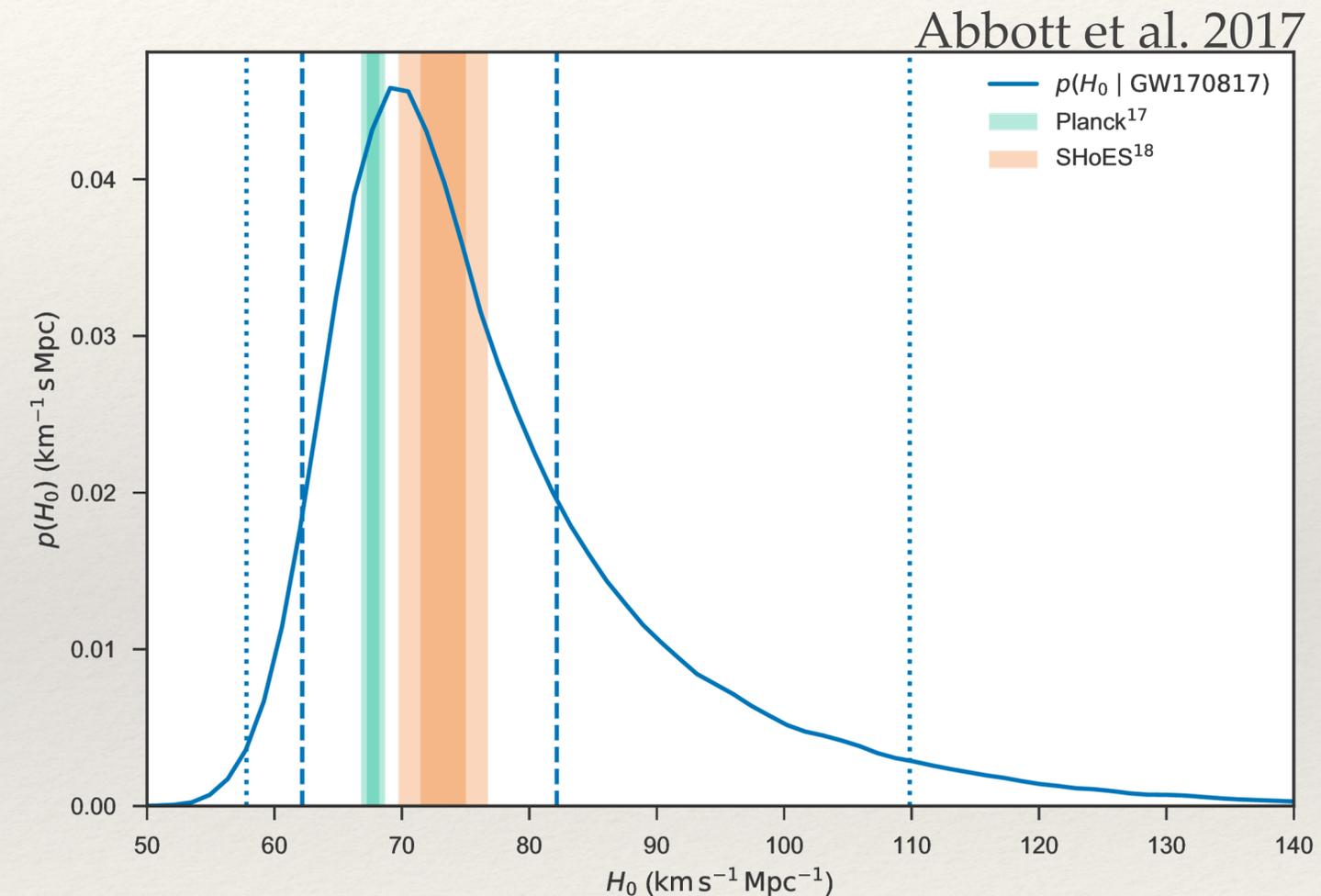
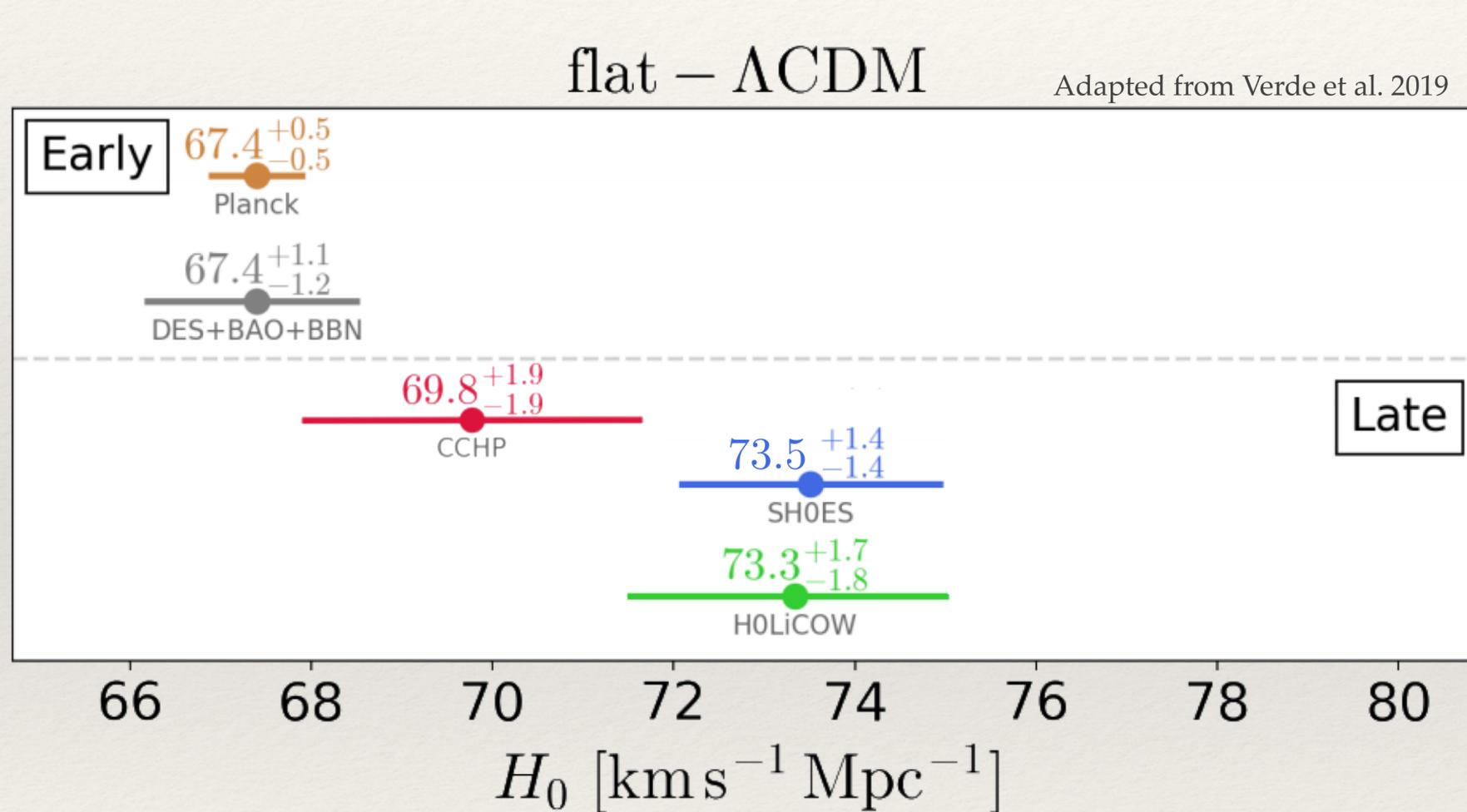
Abbott et al. 2019 | 1901.01540



# Direct measurement of $H_0$ | *without counterpart*



# The Hubble Constant



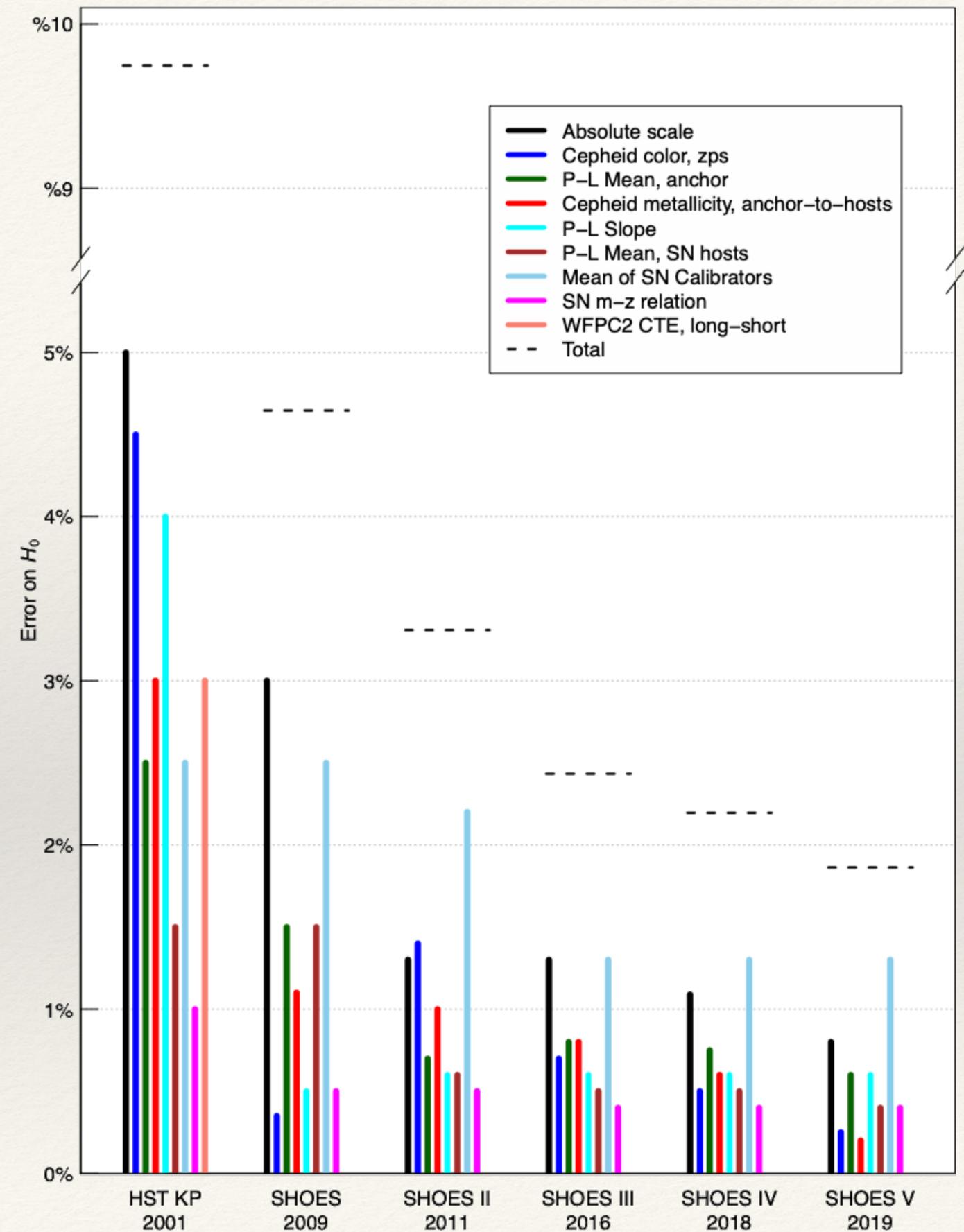


# Error Budget on $H_0$

Riess et al. 2019

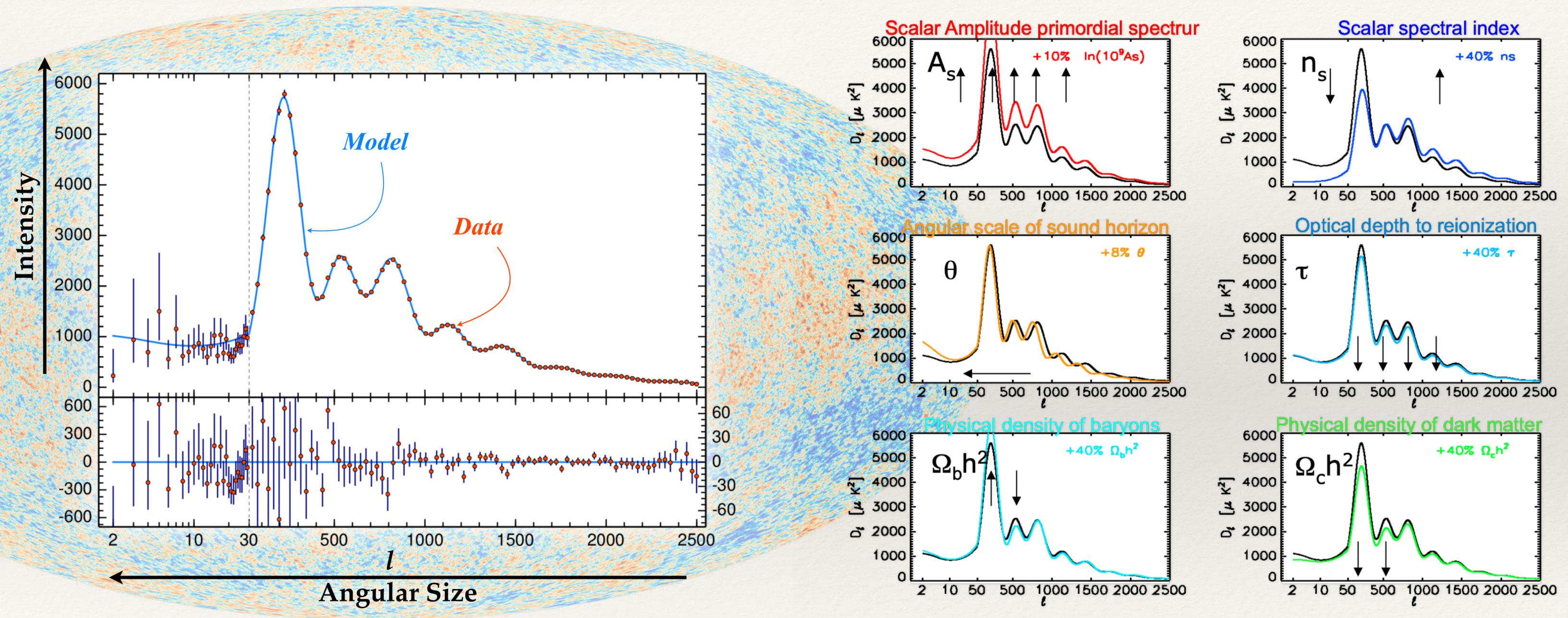
**More SNeIa in the Hubble flow is  
(almost) useless**

*More nearby is key ! But it takes time...*

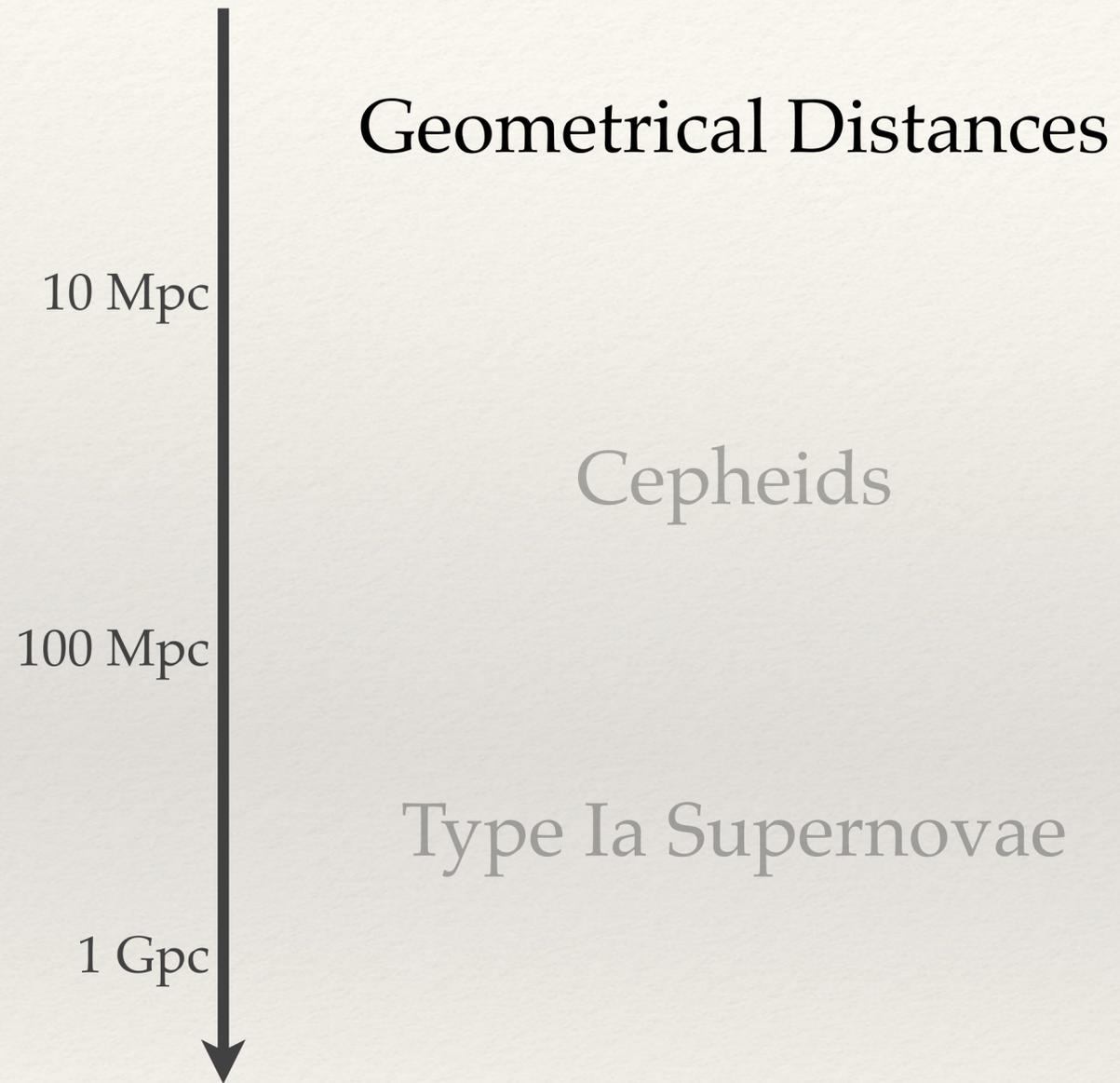


# Planck Results | 6 $\Lambda$ CDM Parameters

Credit: S. Galli | Planck Collaboration

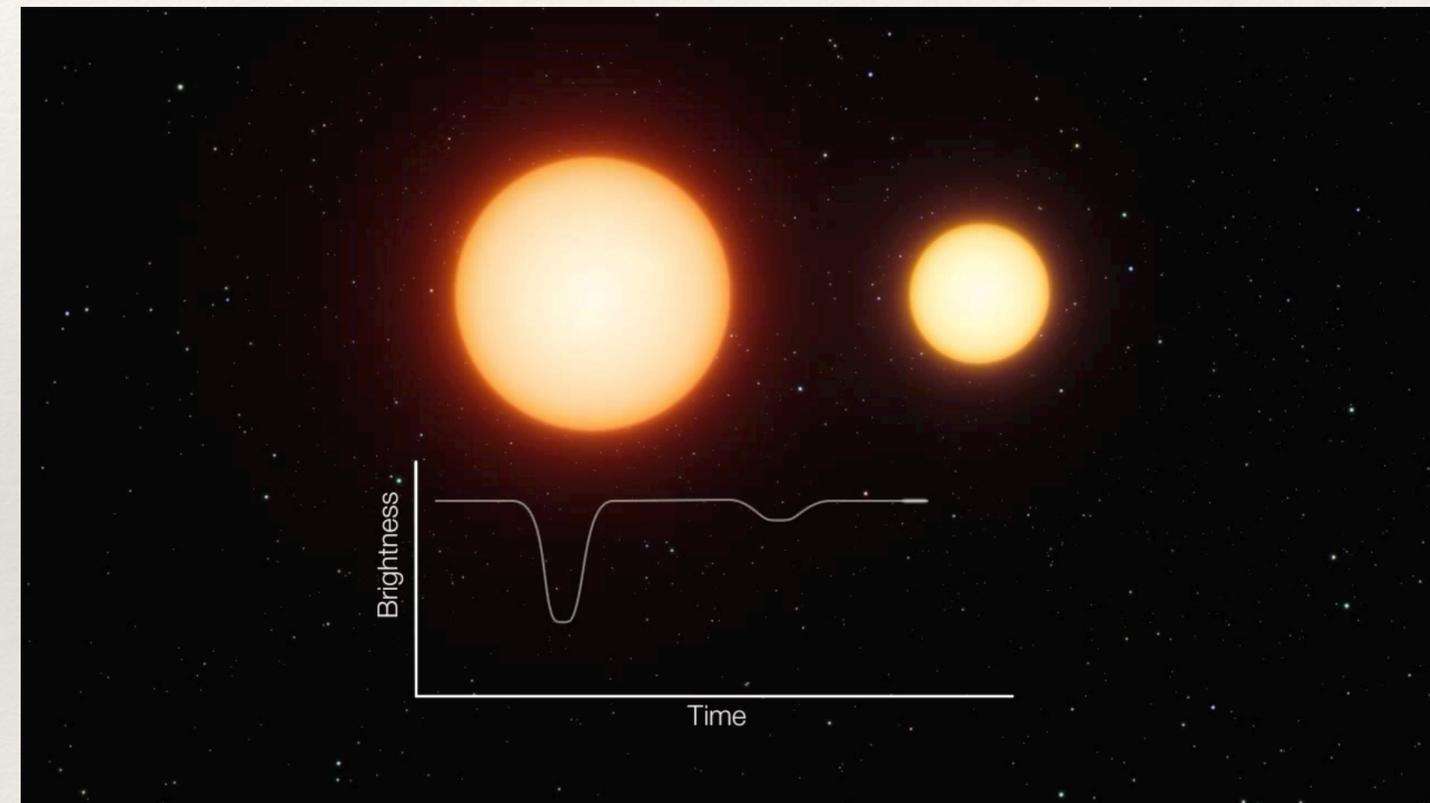


# SHOES



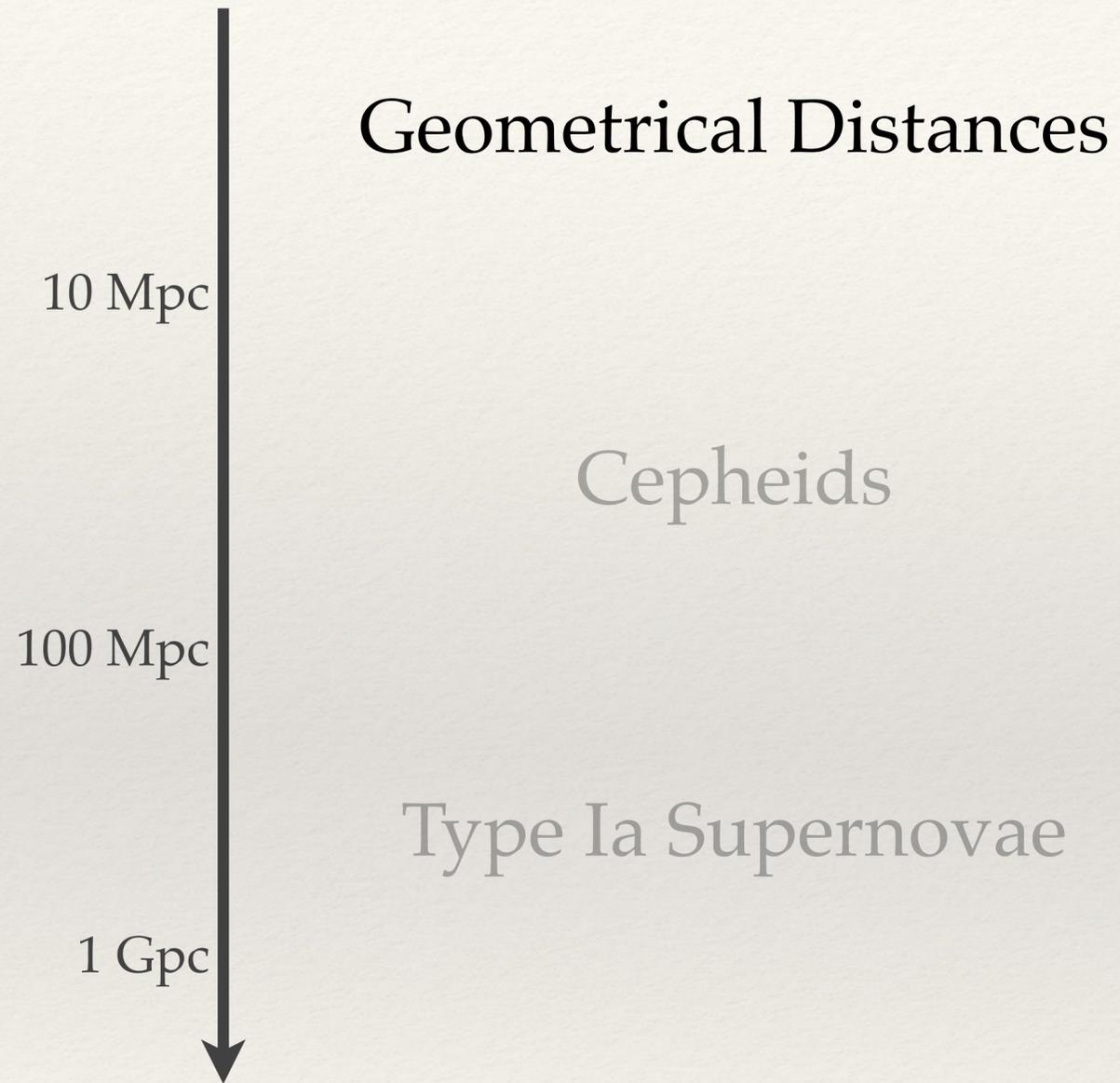
Parallaxes (*Milky Way*)

Detached Eclipsing Binaries  
(*LMC & M31*)



Mega Maser (*NGC4258*)

# SHOES



Parallaxes (*Milky Way*)

Detached Eclipsing Binaries  
(*LMC & M31*)

Mega Maser (*NGC4258*)

