# *The $H_0$ tension*

## *new fundamental physics or astrophysical bias*

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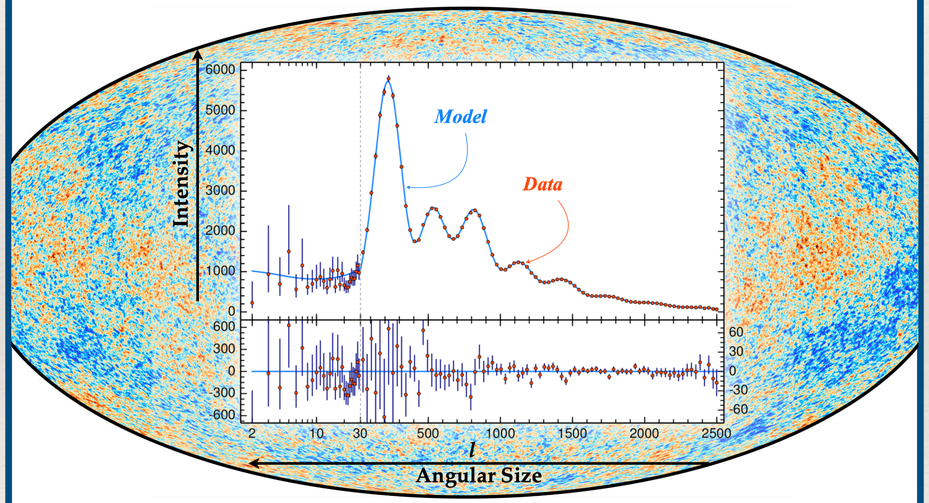
*This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement n°759194 - USNAC)*

# Context of Research | *ΛCDM Works*

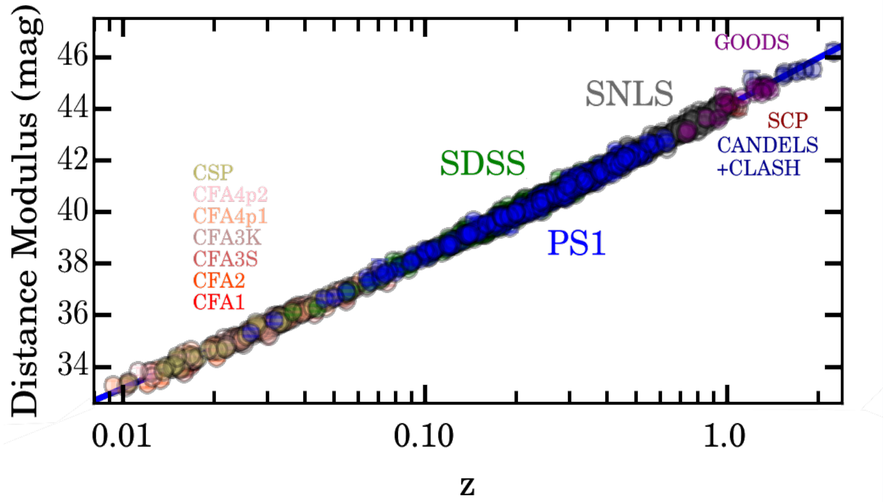
Only 6 free parameters

## Cosmic MicroWave Data




*z~1100*

## Type Ia Supernovae




*z<1*

**Baryon Acoustic Oscillation**

**Clusters**

**Weak Lensing**

**Baryon Nucleosynthesis**

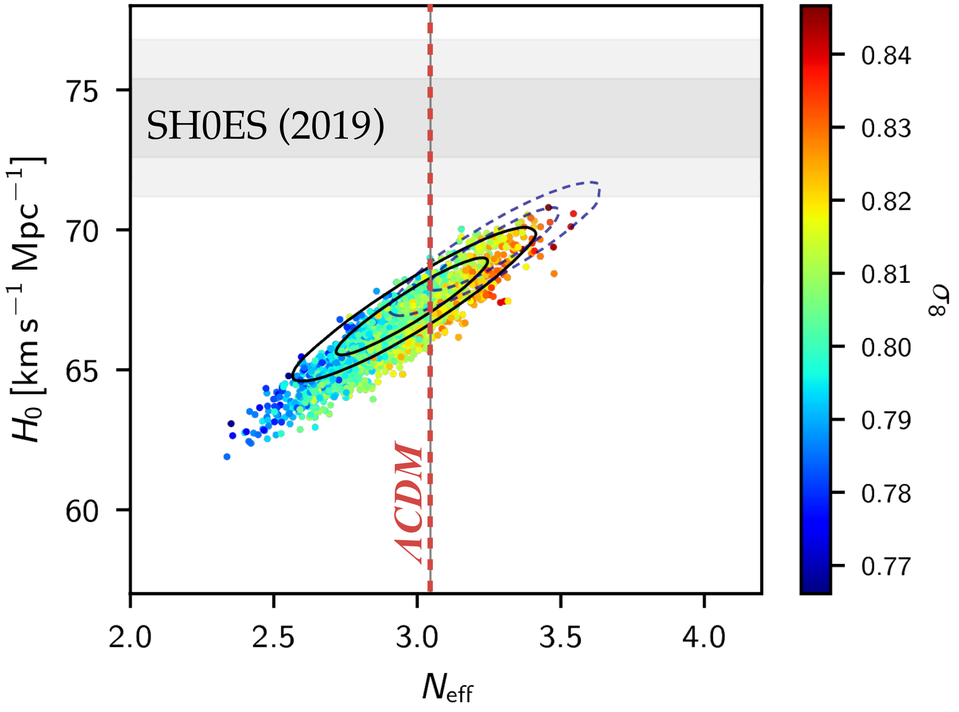
**…**

# Context of Research | *ΛCDM Works,* ***except when it doesn't !***

Only 6 free parameters | ***but "Λ" and "CDM"***

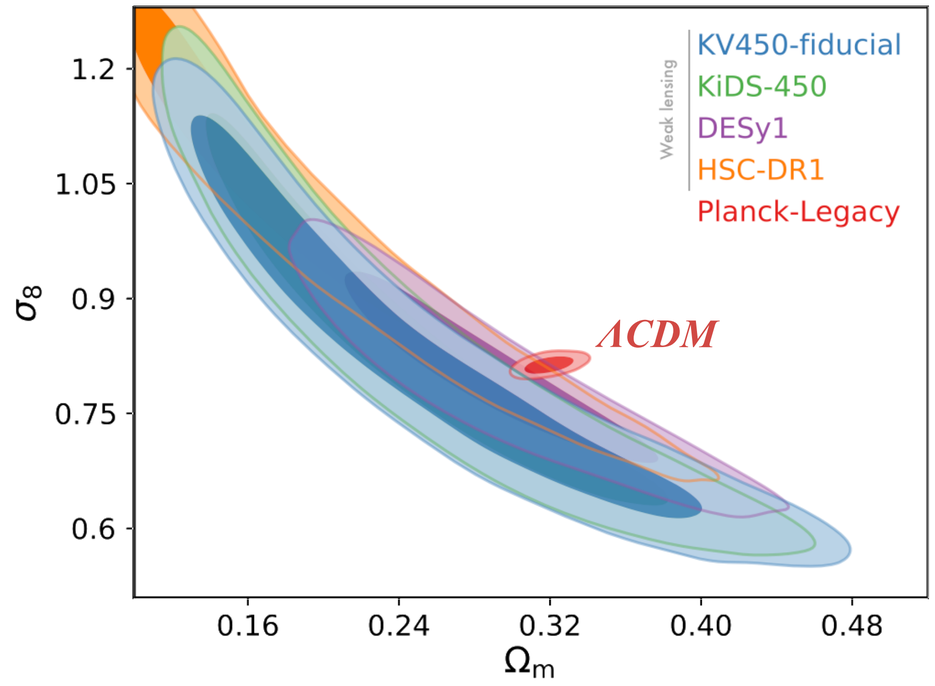
## $H_0$ Tension | 5 σ

*Universe's expansion is too fast*



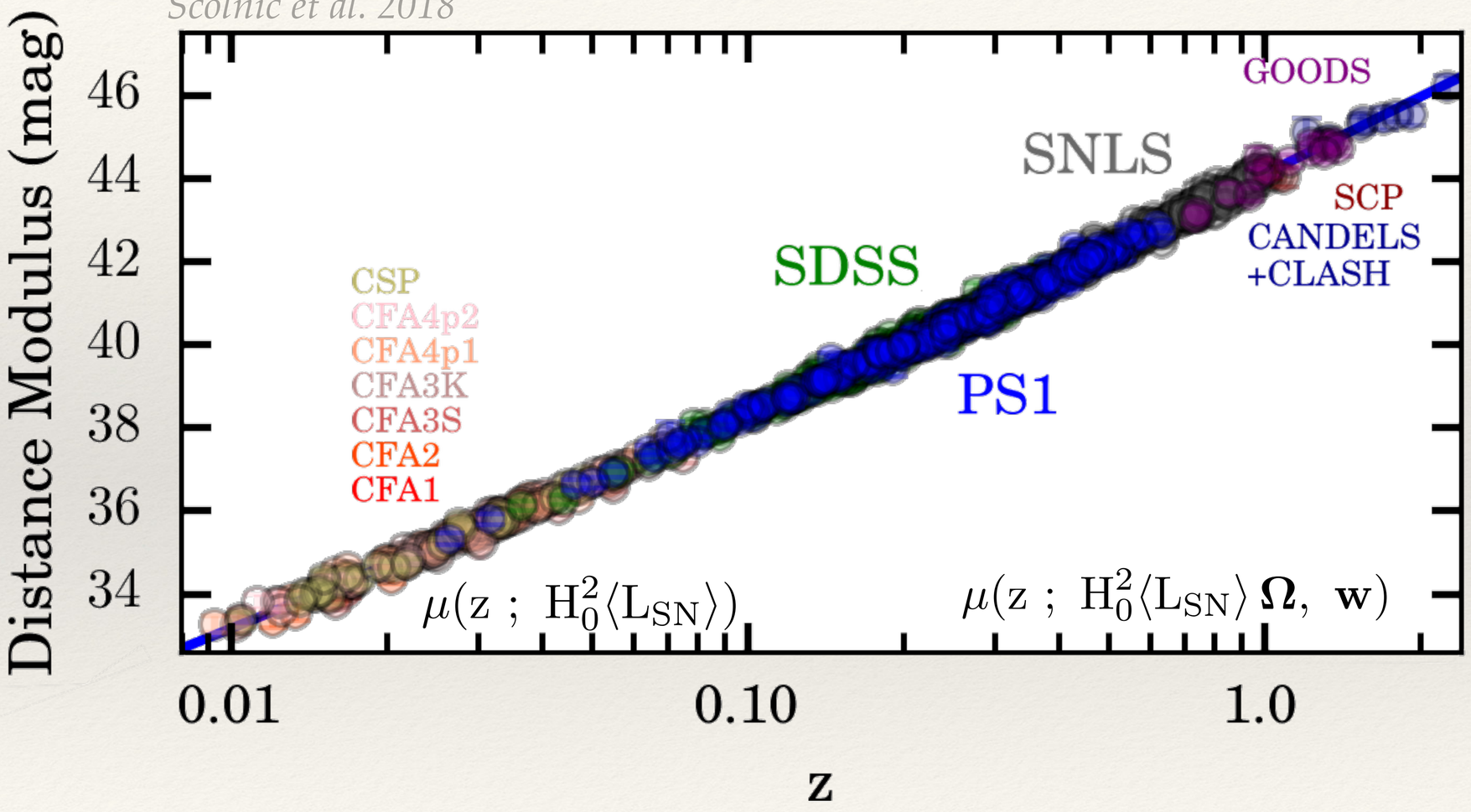

## $\sigma_8$ Tension | 2.5 σ

*Structures are too small*

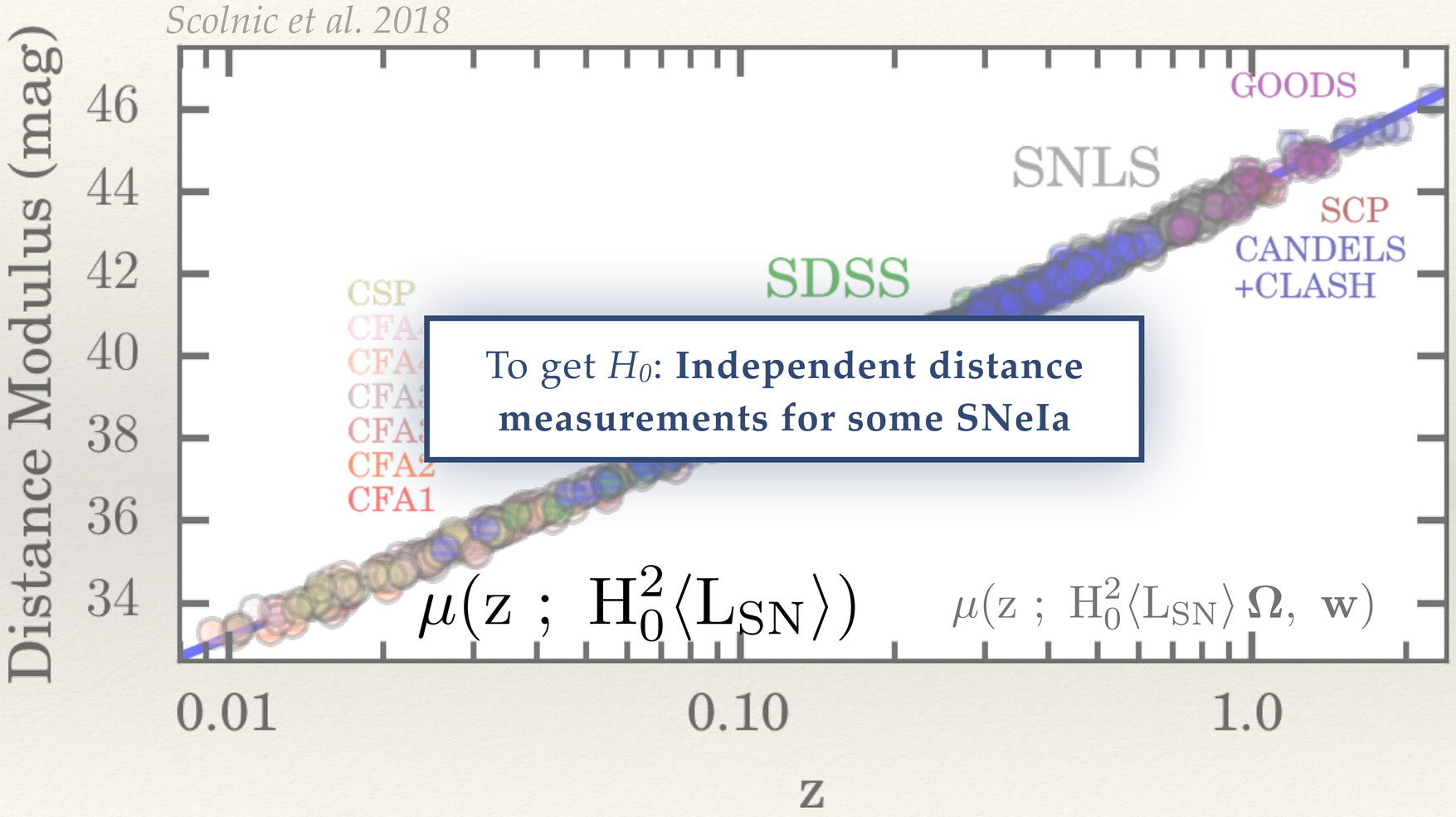


# Type Ia Supernova Cosmology

*Scolnic et al. 2018*



# Type Ia Supernova Cosmology | $H_0$



# Direct Distance Ladder | *SH0ES*

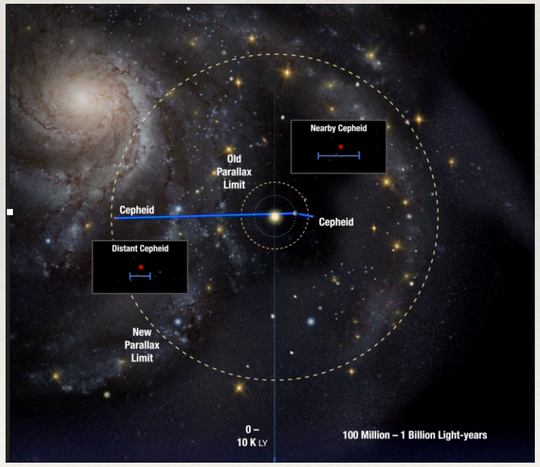
Get independent distances for SNe Ia

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

**"Geometry"**

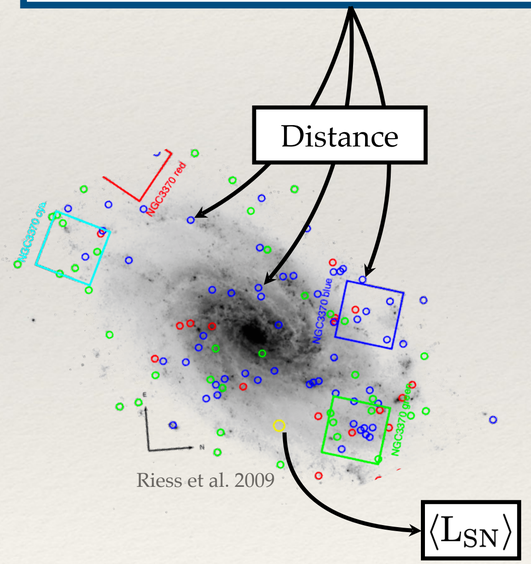
**Parallaxes | D.E.B. | Maser**

Source: eso




**"Calibrators"**

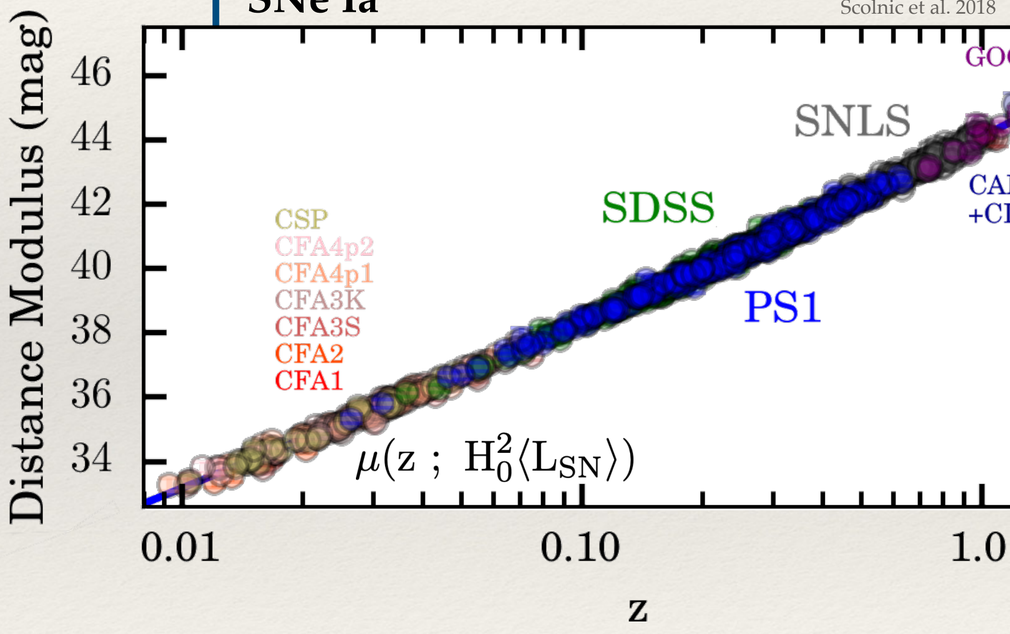
**Cepheids**




Riess et al. 2009

**"SNe Ia"**

Scolnic et al. 2018

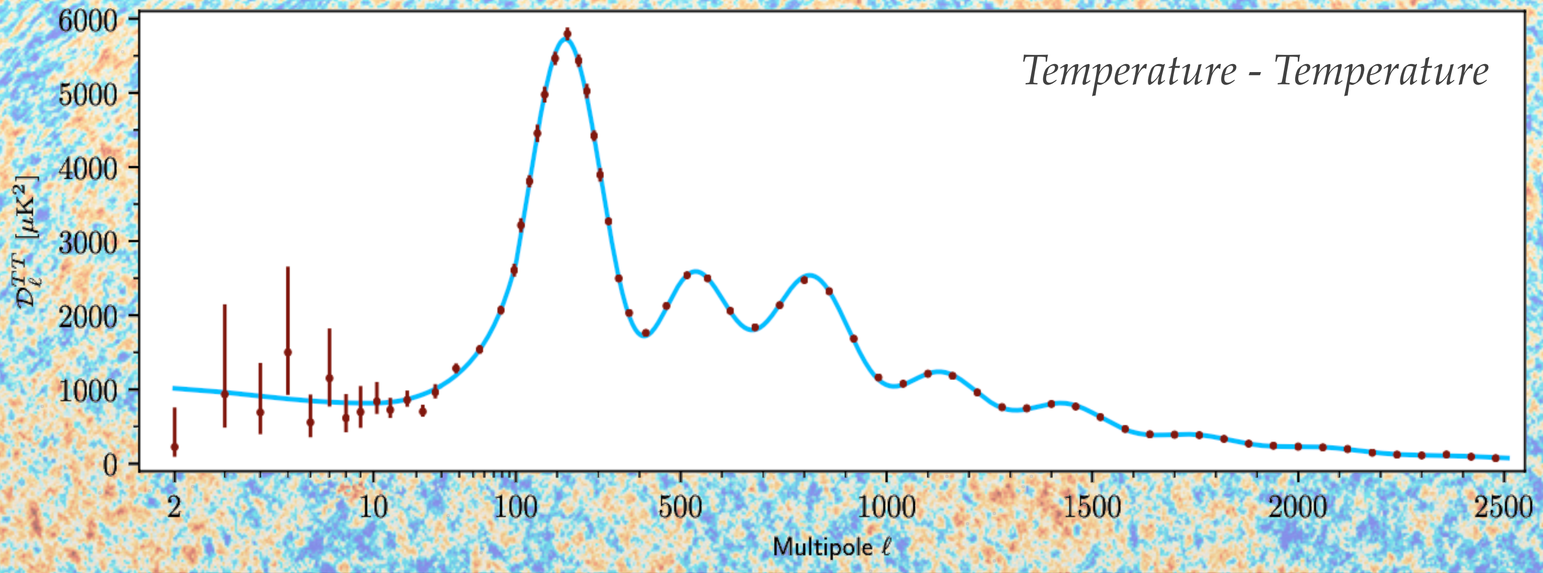


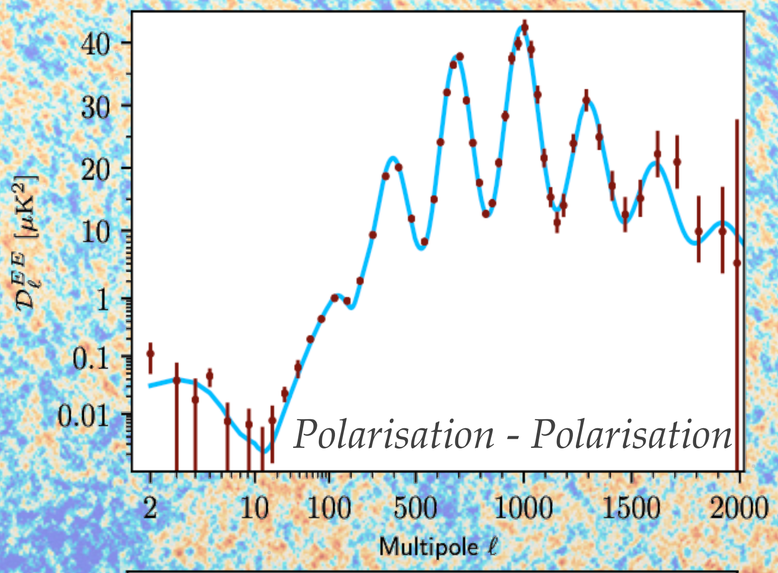

**Riess et al.** *2022*

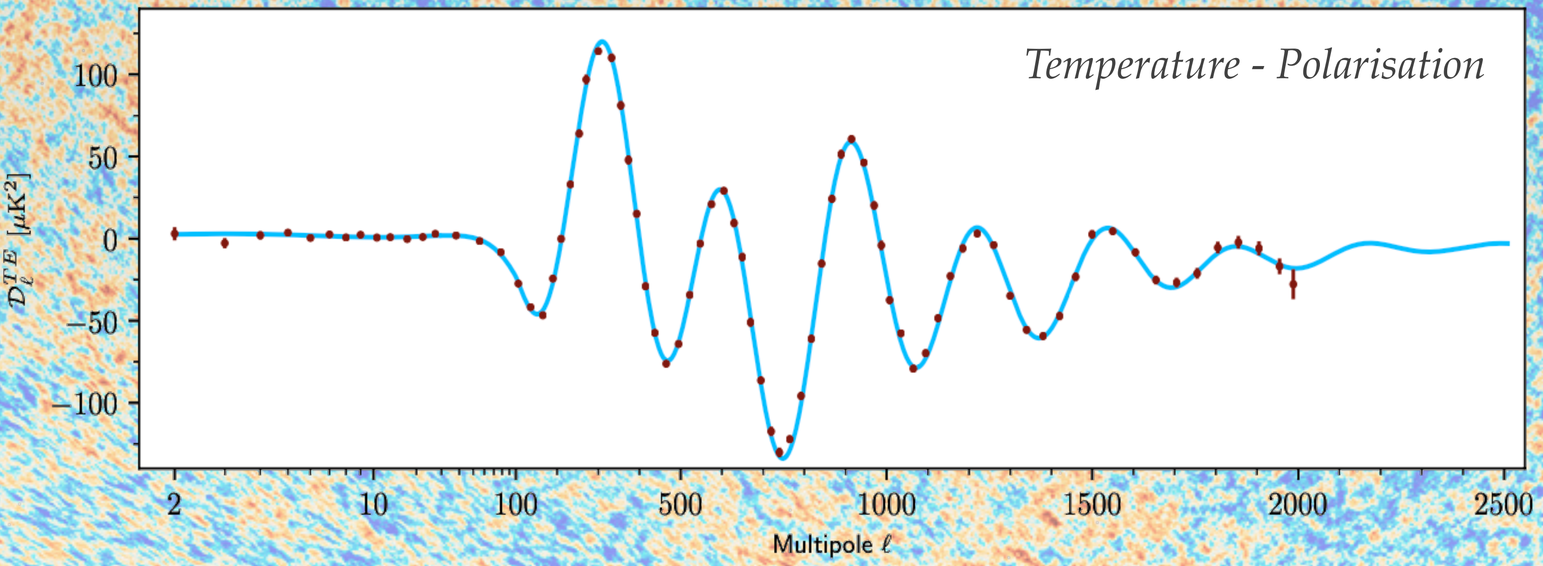
$H_0 = 73.0 \pm 1.0$ km s$^{-1}$ Mpc$^{-1}$

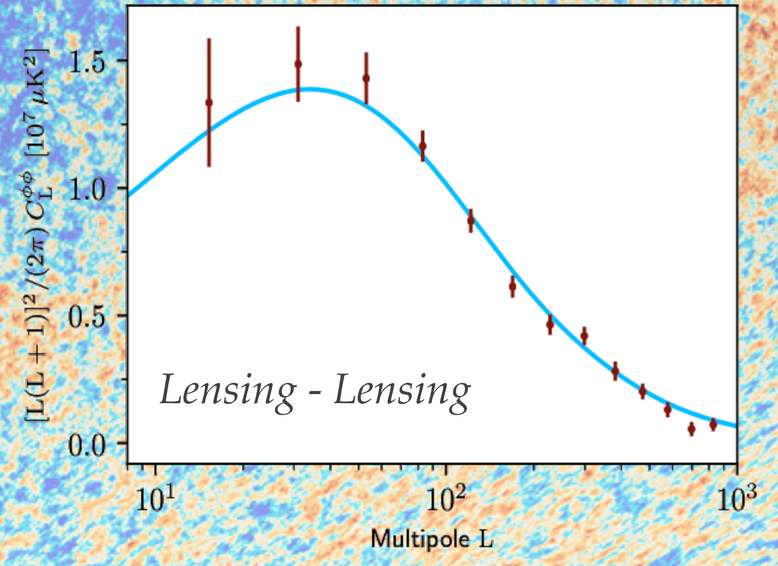
# Planck Data | *6 free parameters*

*Planck et al. 2020*



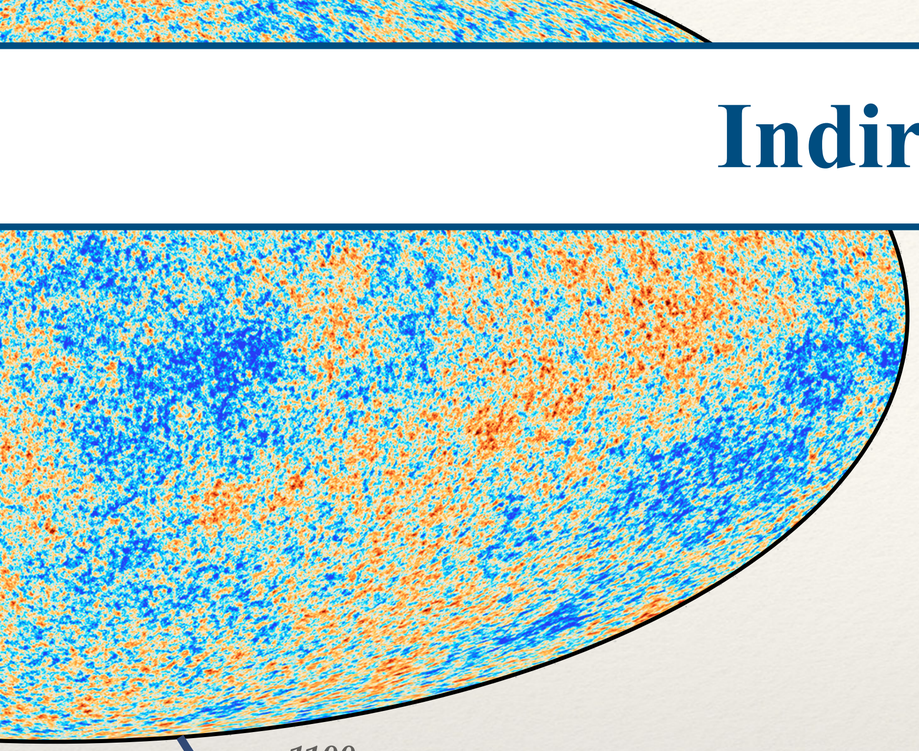



# Indirect determination of $H_0$

*Planck et al. 2020*



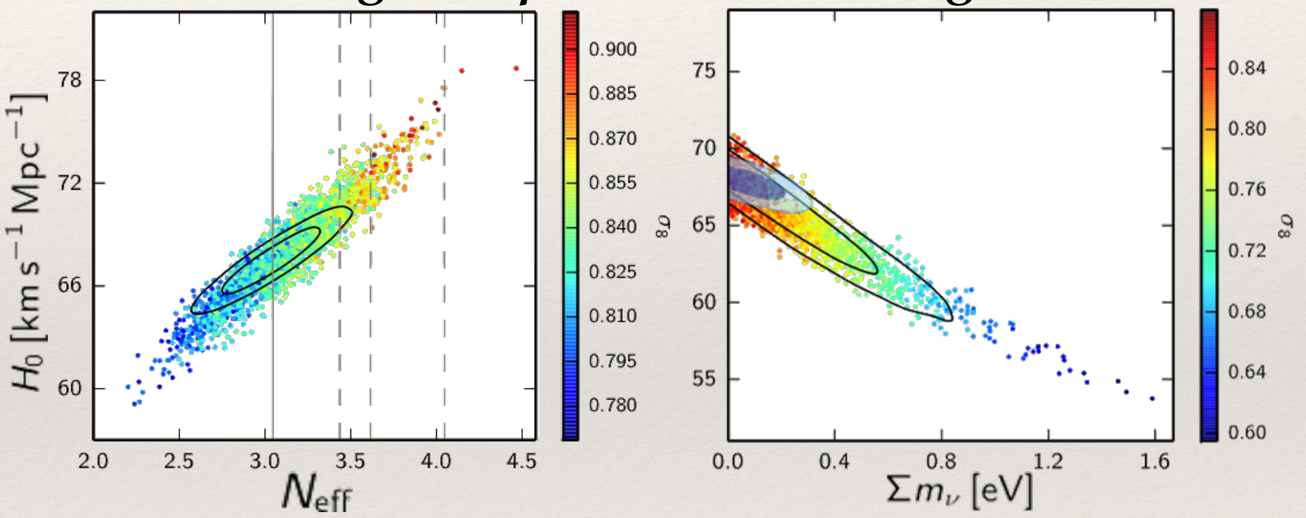
*z~1100*

THE MODEL CONTRAINS $H_0$

*z~0*

*Test the concordance model ΛCDM*

***Change the parameters, change $H_0$***




*Illustrative plots from Planck 2015*

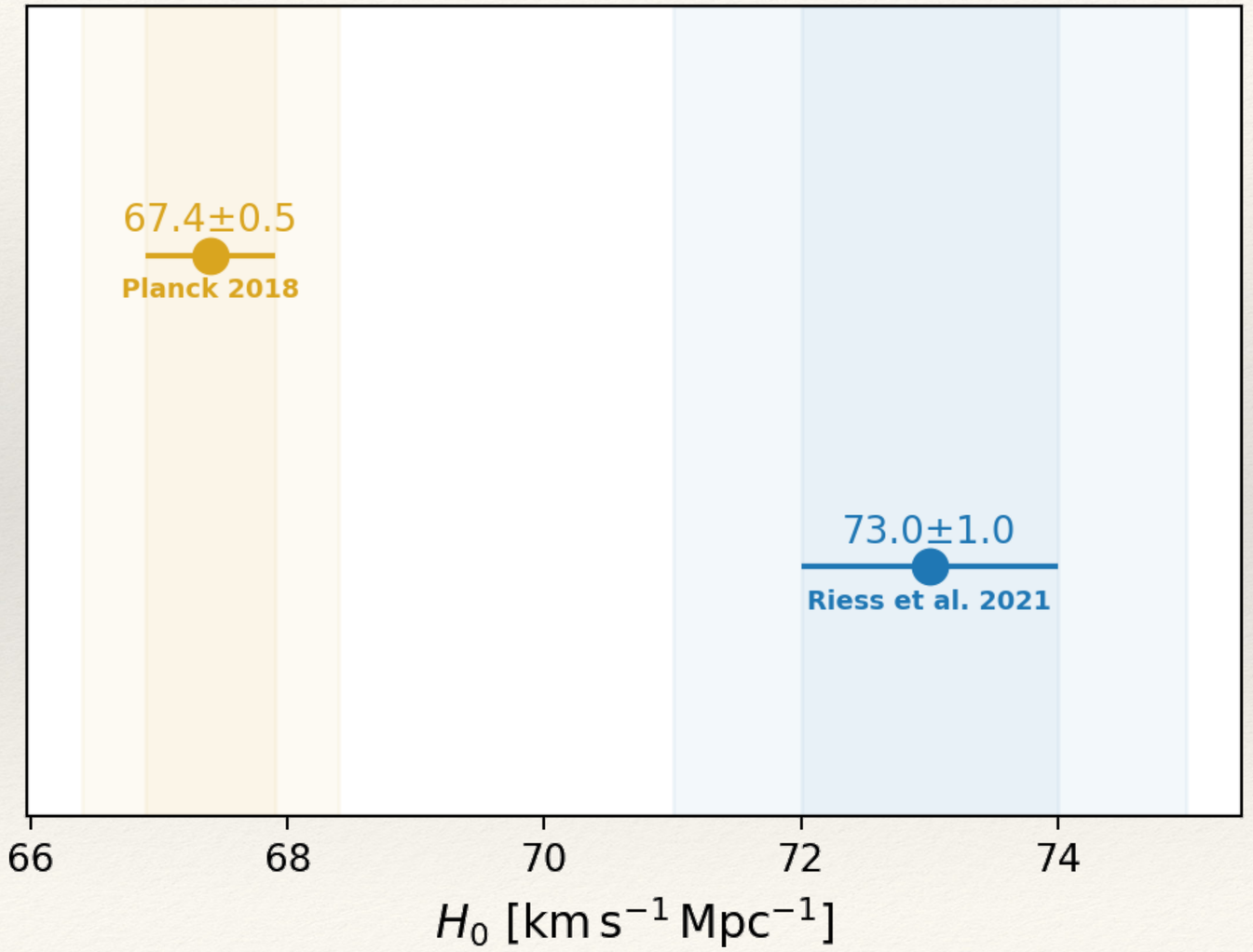
$H_0 = 67.4 \pm 0.5$ km s$^{-1}$ Mpc$^{-1}$

— based on ΛCDM —

# $H_0$ Tension | *SH0ES vs. Planck*

ΛCDM

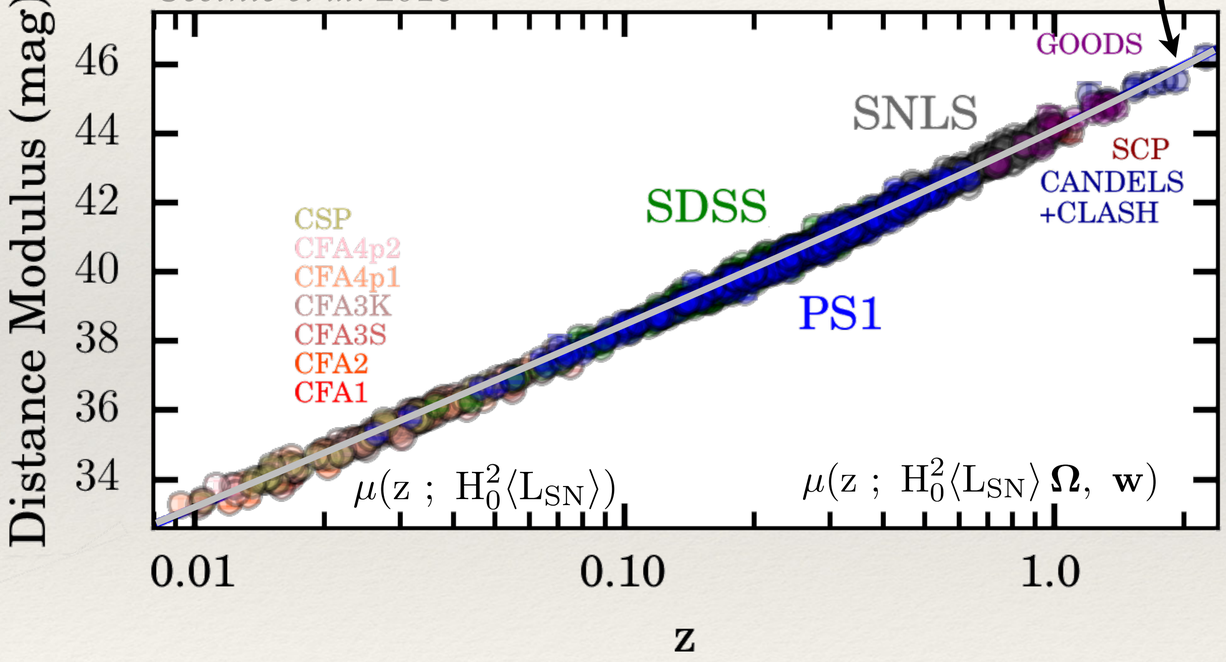
*direct*



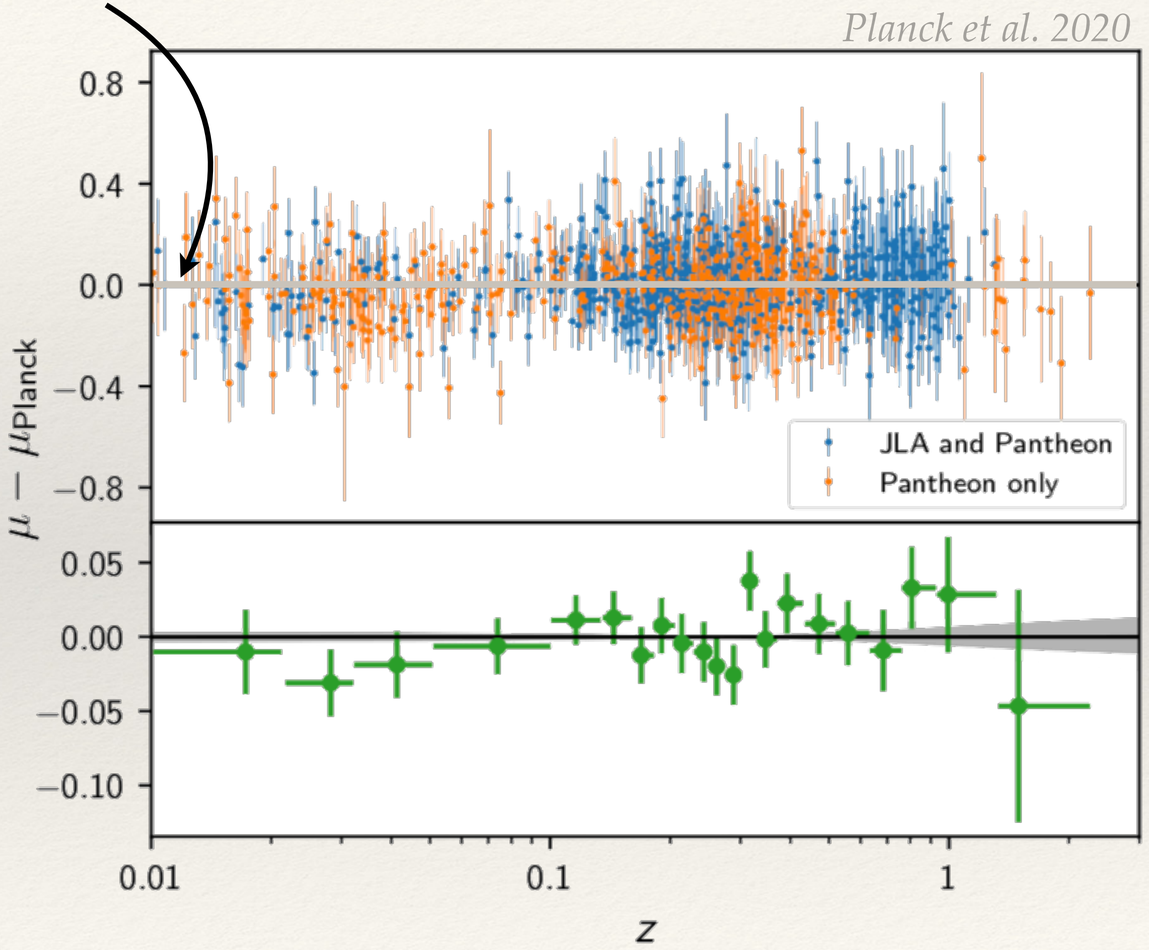
# Are Supernovae & CMB in tension ? *No!*

H(z) from Planck

*Scolnic et al. 2018*




*Planck et al. 2020*



# Inverse Distance Ladder

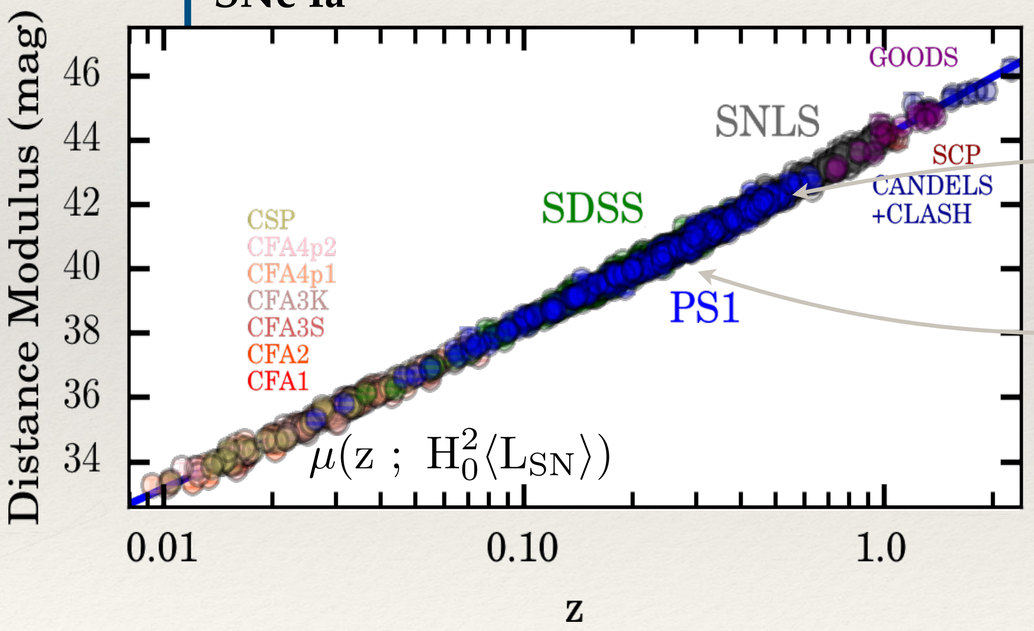
Get independent distances for SNe Ia

*"Transfert"*
*H(z=1) → H(z=0)*

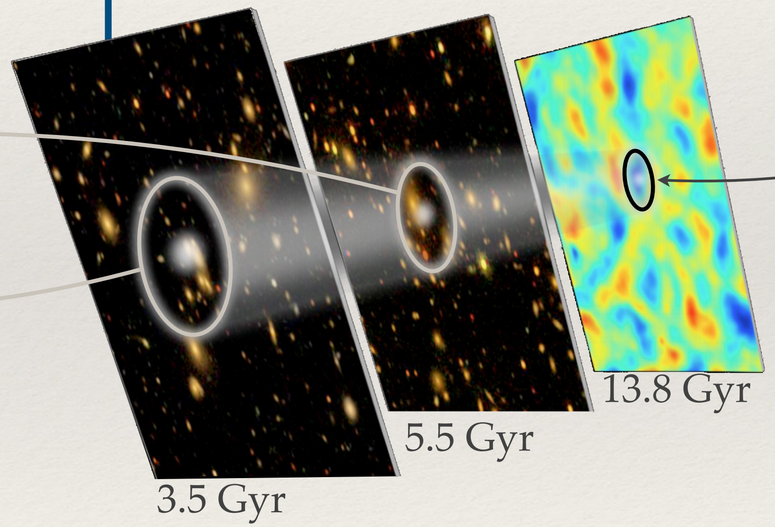
*Sets the scale of the Universe at z~1*

**distance**

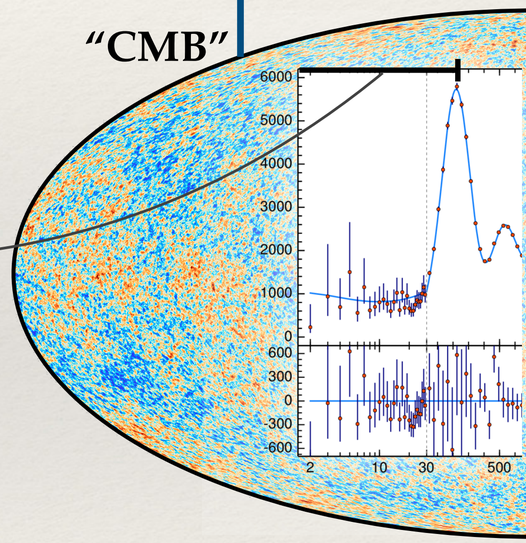
**"SNe Ia"**




**"BAO."**




**"CMB"**




$H_0 = 67.4 \pm 1.1$ km s$^{-1}$ Mpc$^{-1}$

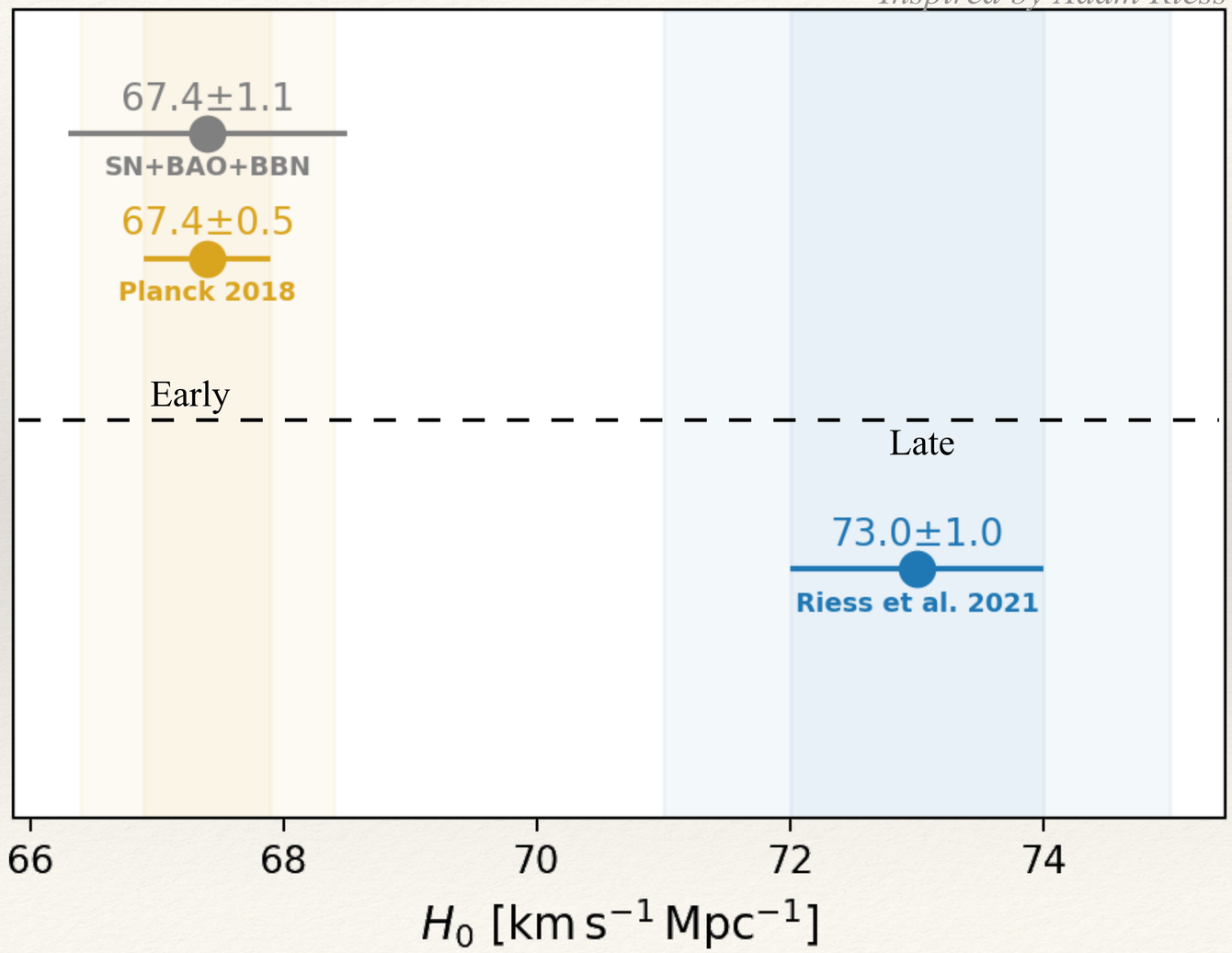
# Extending the Standard Model of Cosmology

*Inspired by Adam Riess*

ΛCDM

ΛCDM

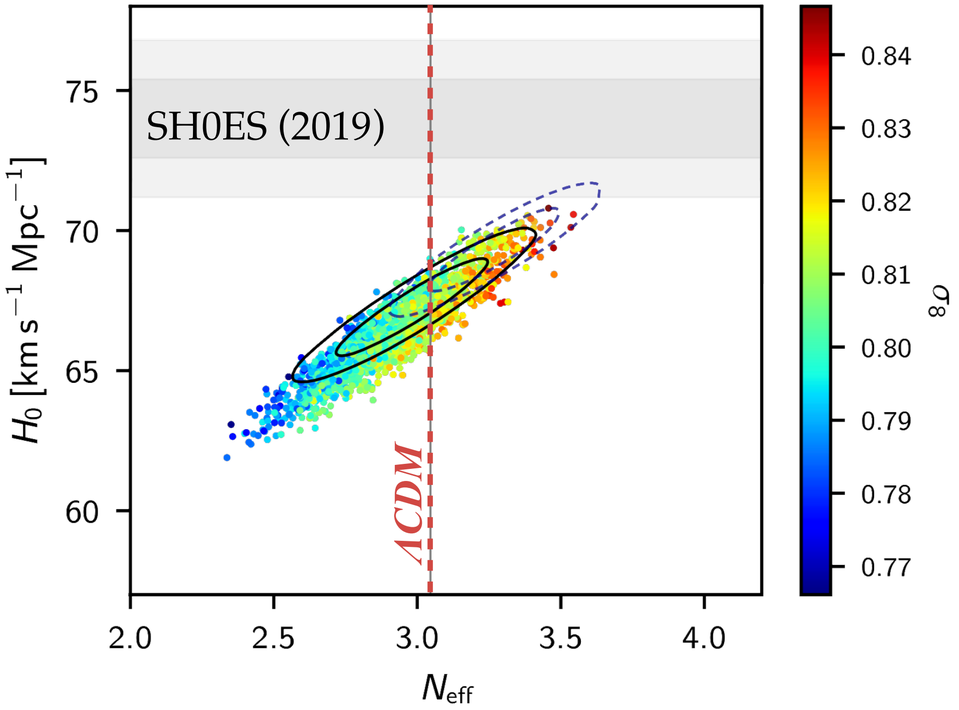
*Directe*



# $H_0$ Tension | *Change the model ?*

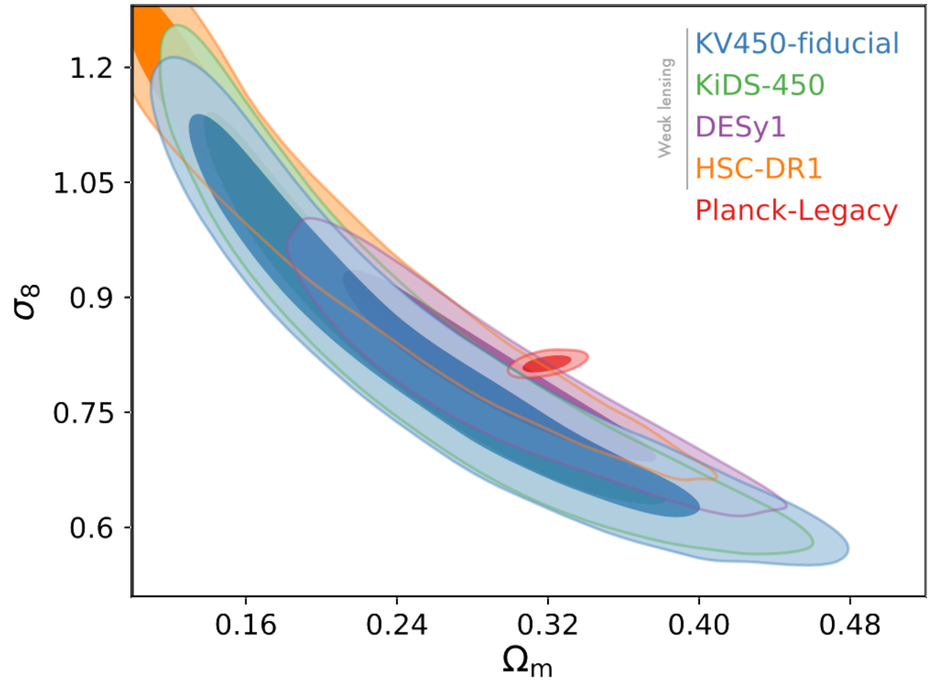
## $H_0$ Tension | 5 σ

*Universe's expansion is too fast*




## $\sigma_8$ Tension | 2.5 σ

*Structures are too small*



# Extending the Standard Model of Cosmology

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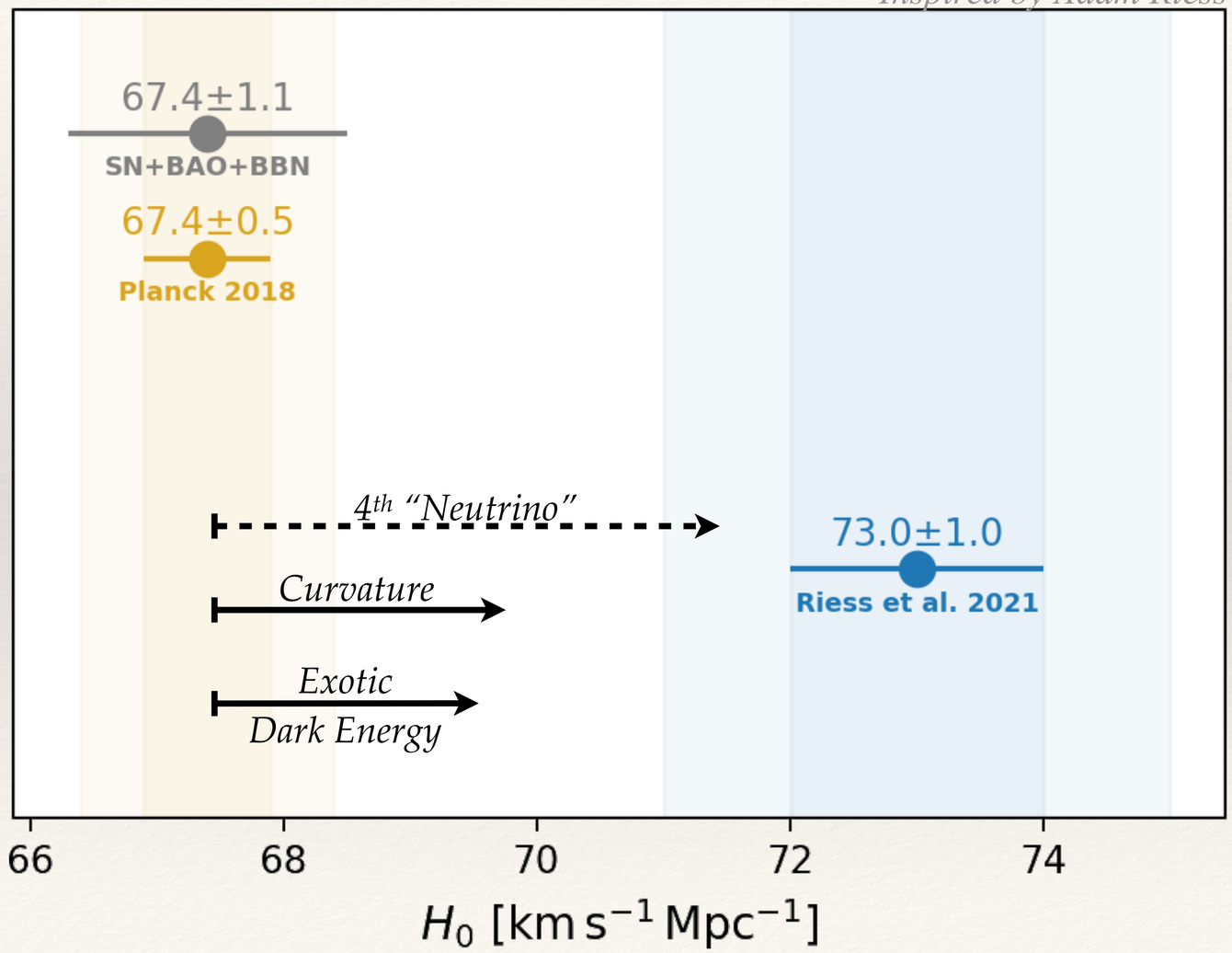
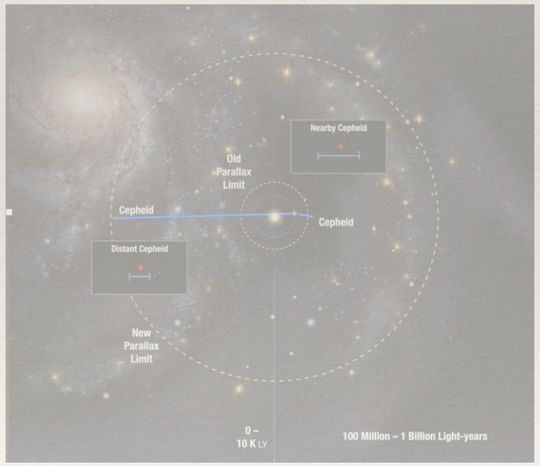


# Direct Distance Ladder | *SH0ES*

*Calibrate the "Period-Luminosity" relation*

"Geometry"

Parallaxes | D.E.B. | Maser



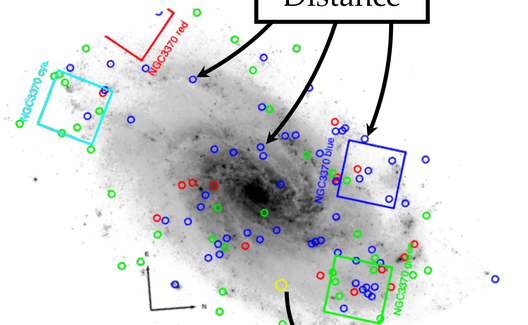

## The SNe Ia "matching" problem

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

"Calibrators"

**Cepheids**

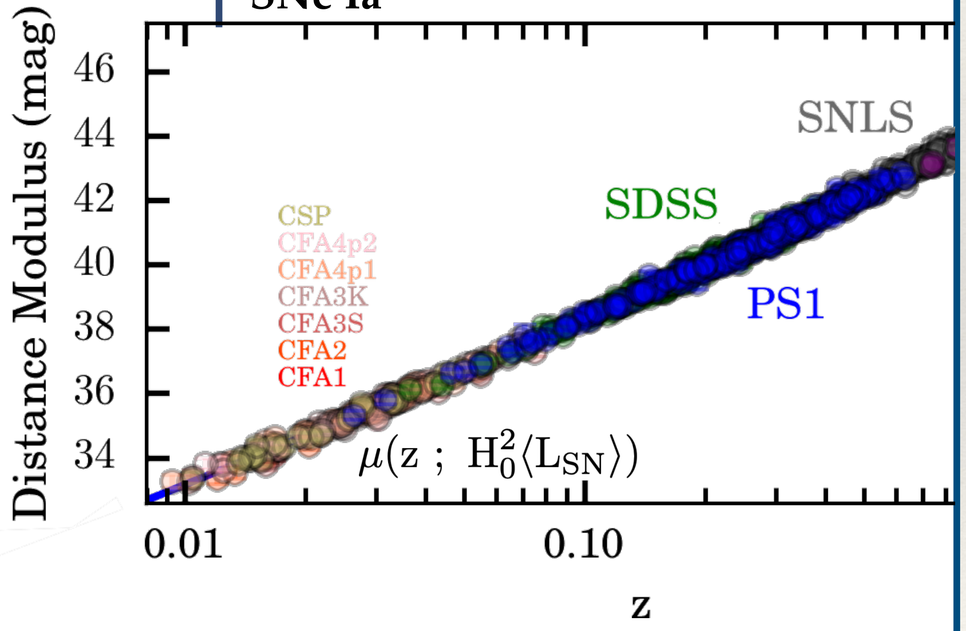
Distance




Riess et al. 2009

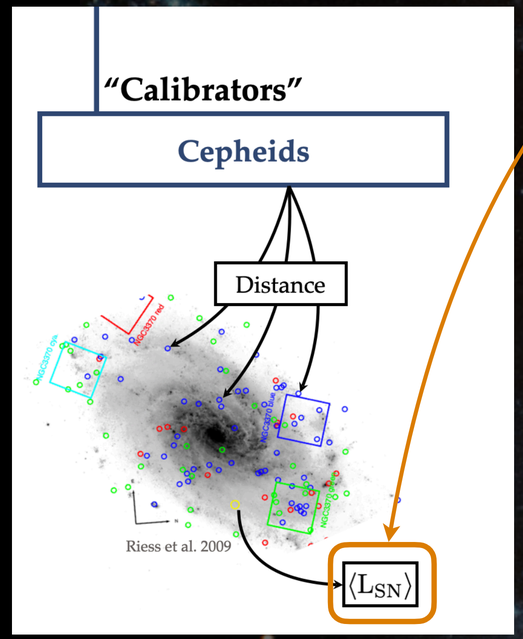
$\langle L_{SN} \rangle$

"SNe Ia"



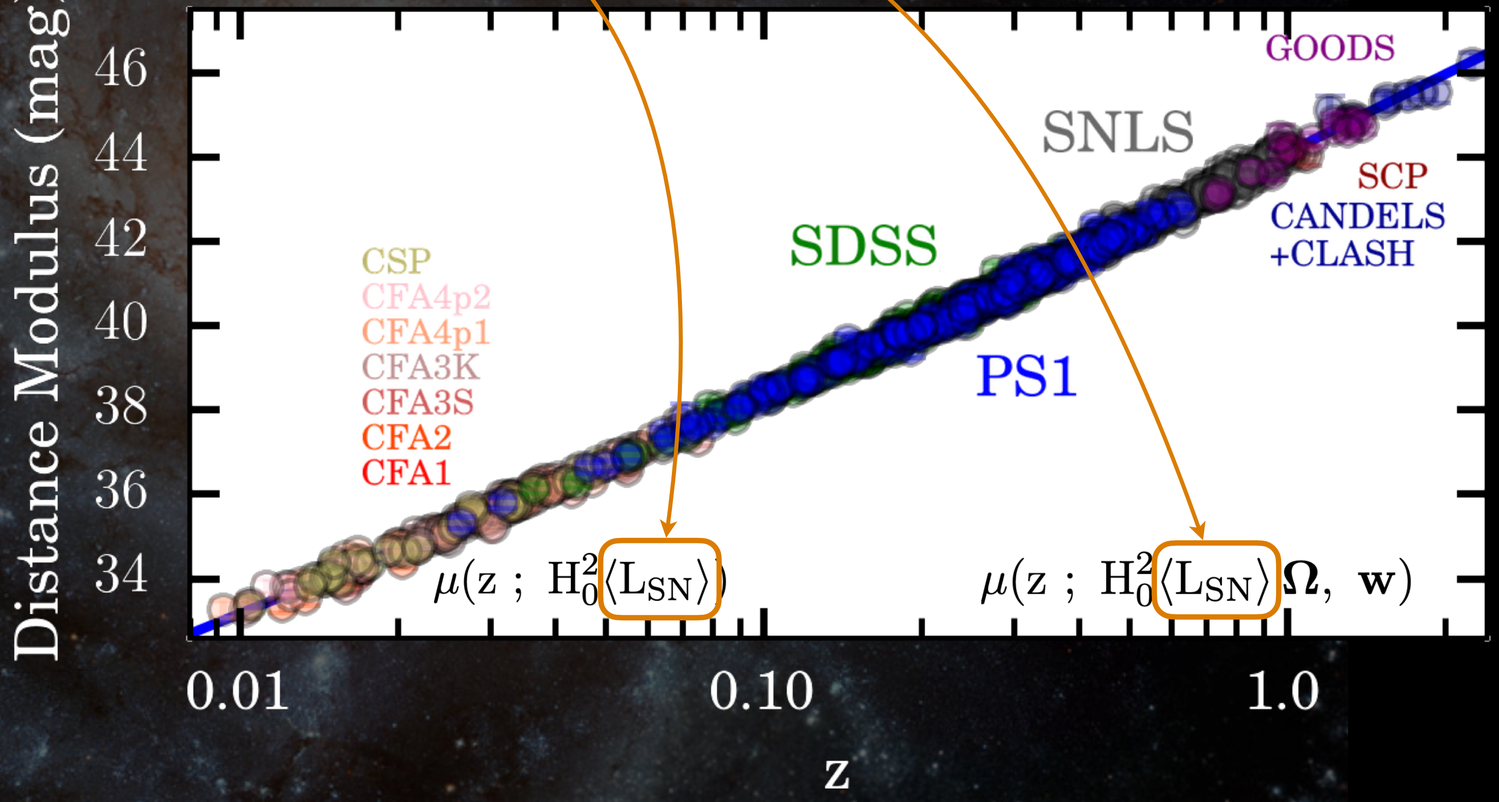

SN2011fe

# The Progenitor issue | *Astrophysical biases*



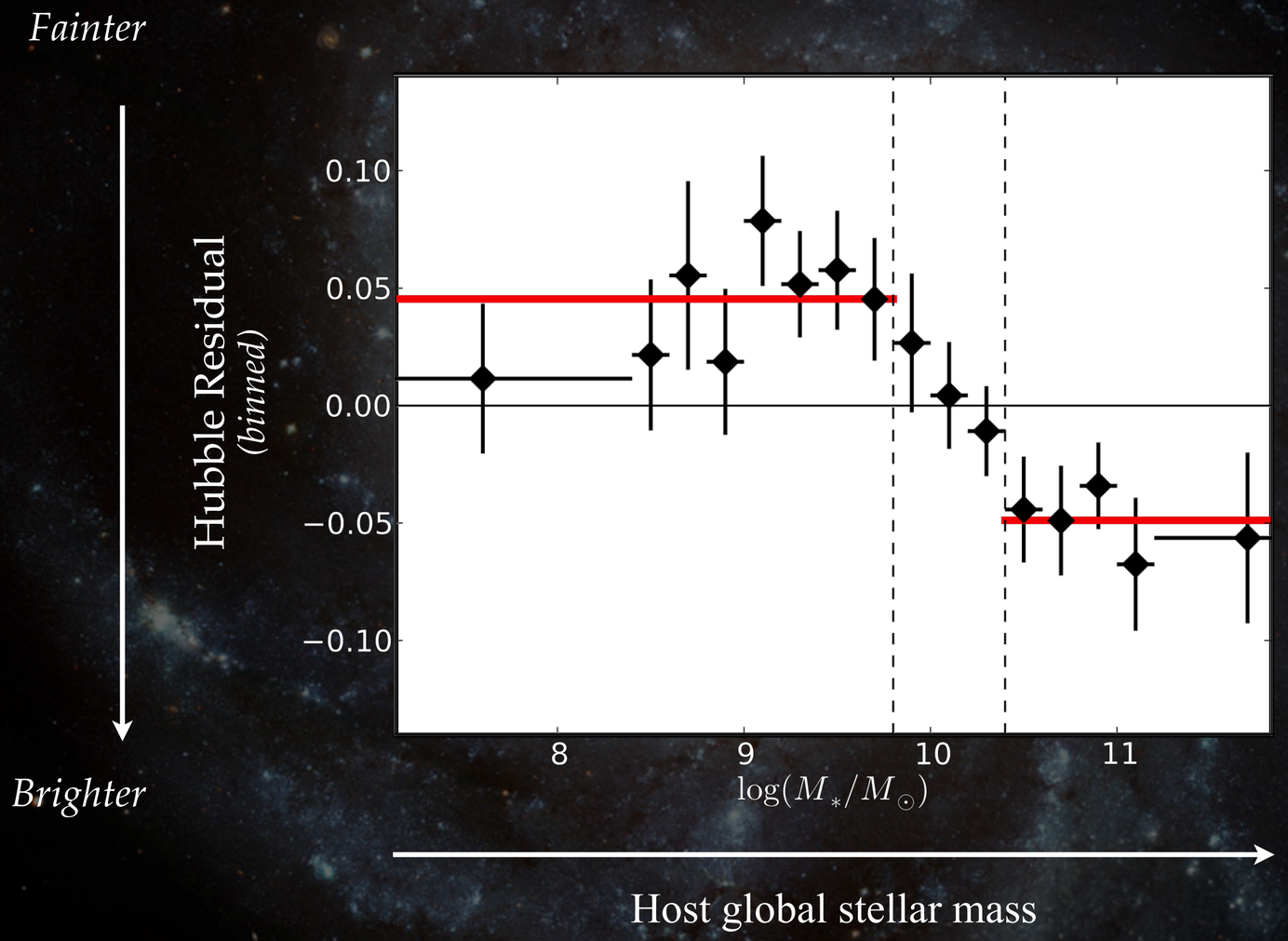

*Constant ?*

*Scolnic et al. 2018*



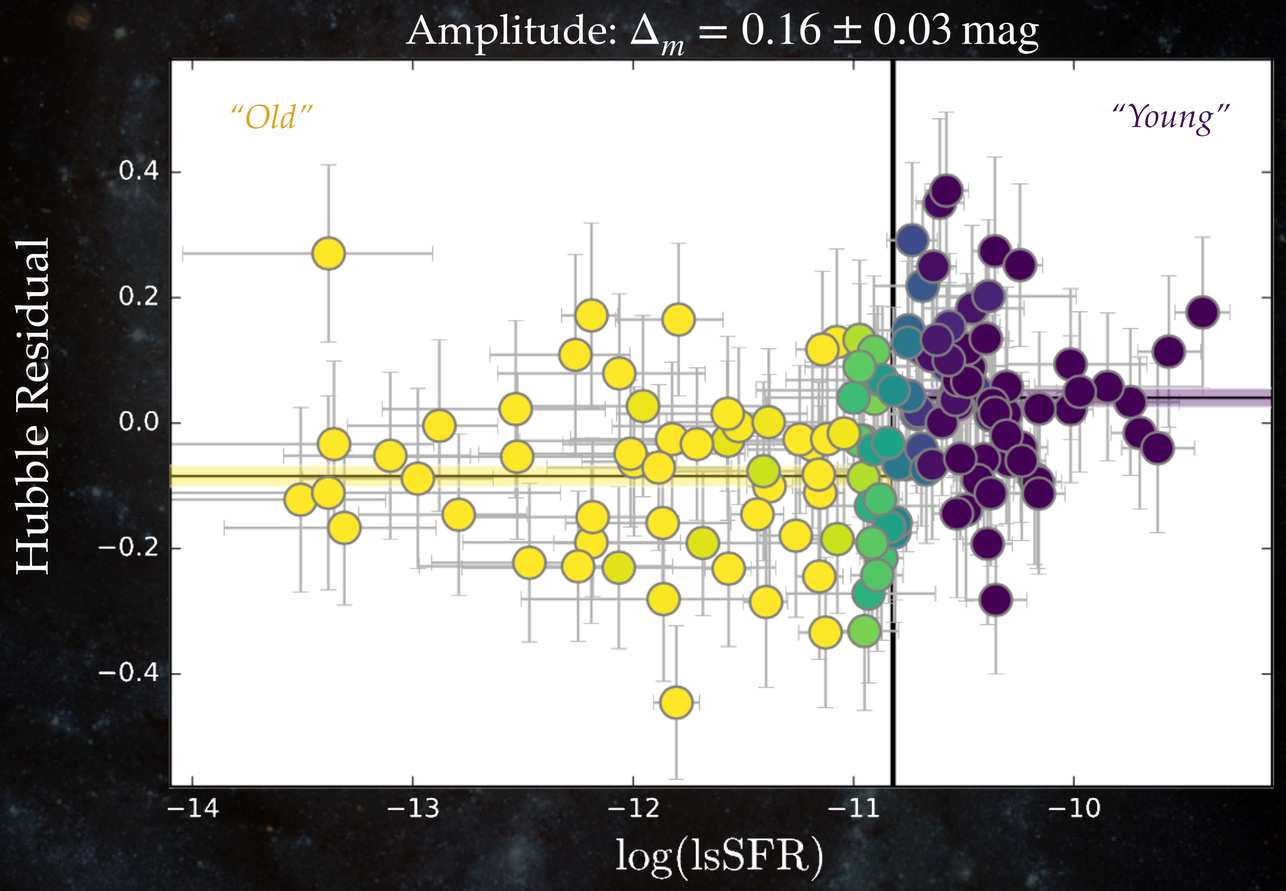

SN2011fe

Childress et al. 2013



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

*Fainter* ↓ *Brighter*

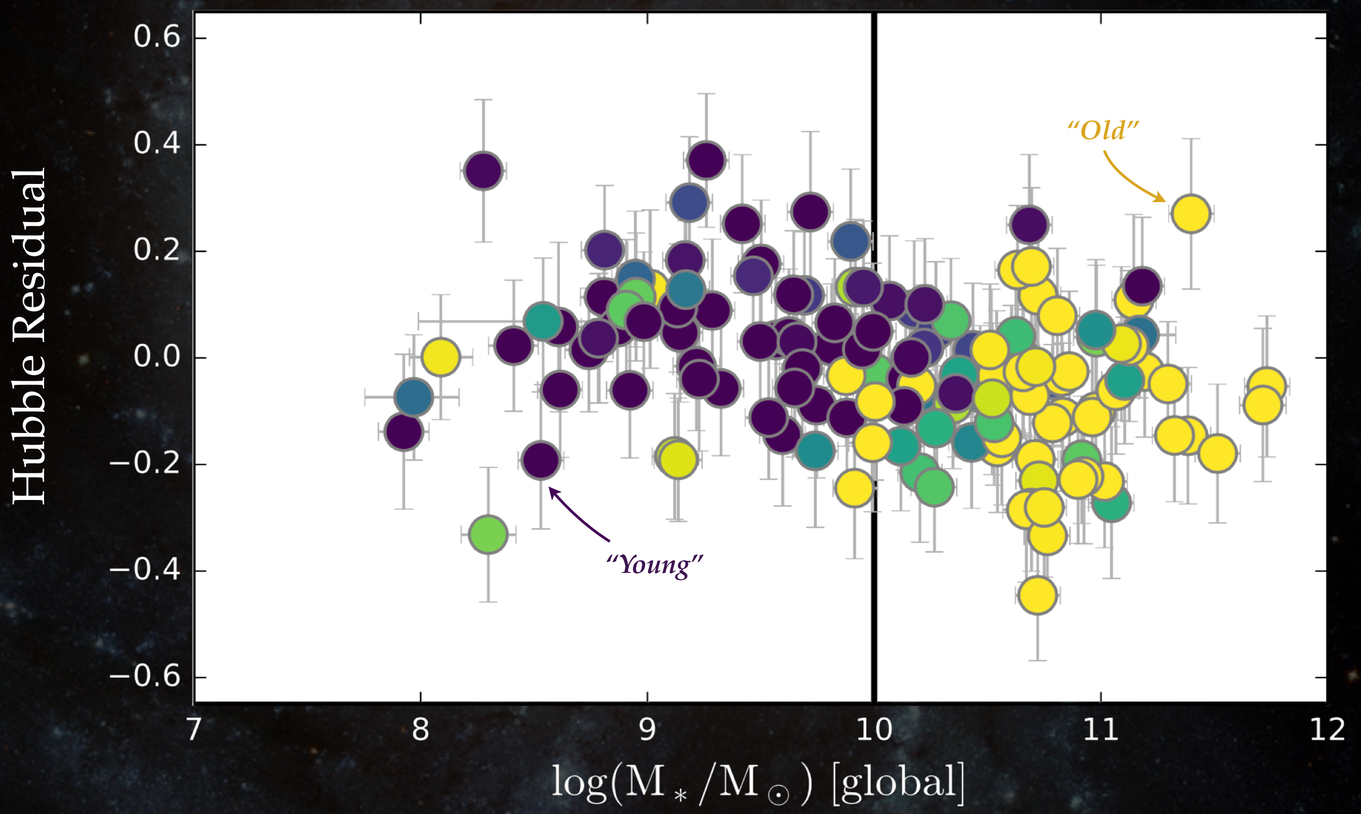



$$\text{lsSFR} \propto \frac{\#\ \text{Young Stars}}{\#\ \text{Old Stars}}$$

*Fainter*

*Brighter*

## *Explaining (fully?) the origin of the mass-step*




# Astrophysical Bias affecting $H_0$

*Rigault et al. 2015*

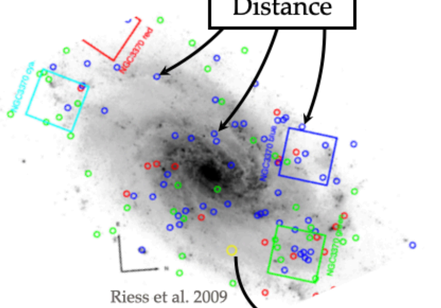
## The SNe Ia "matching" problem

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

**"Calibrators"**

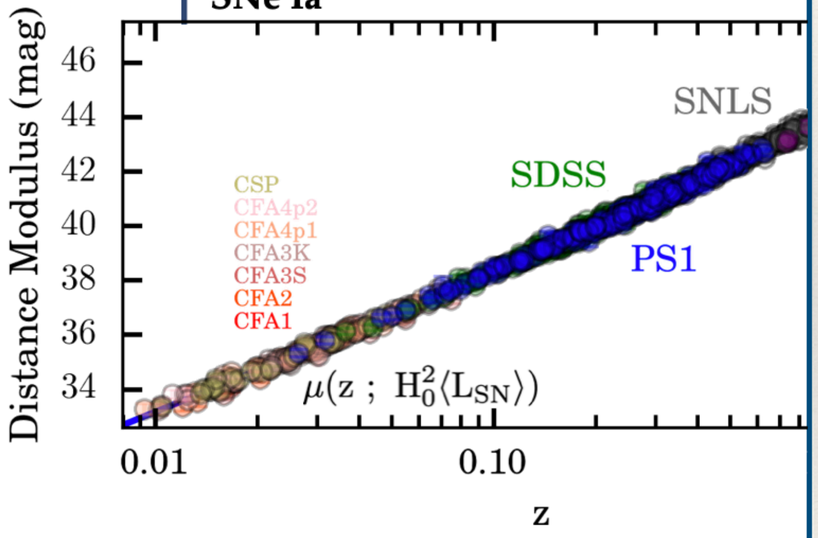
**Cepheids**

**Distance**




$\langle L_{SN} \rangle$

**"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

erc | USNAC

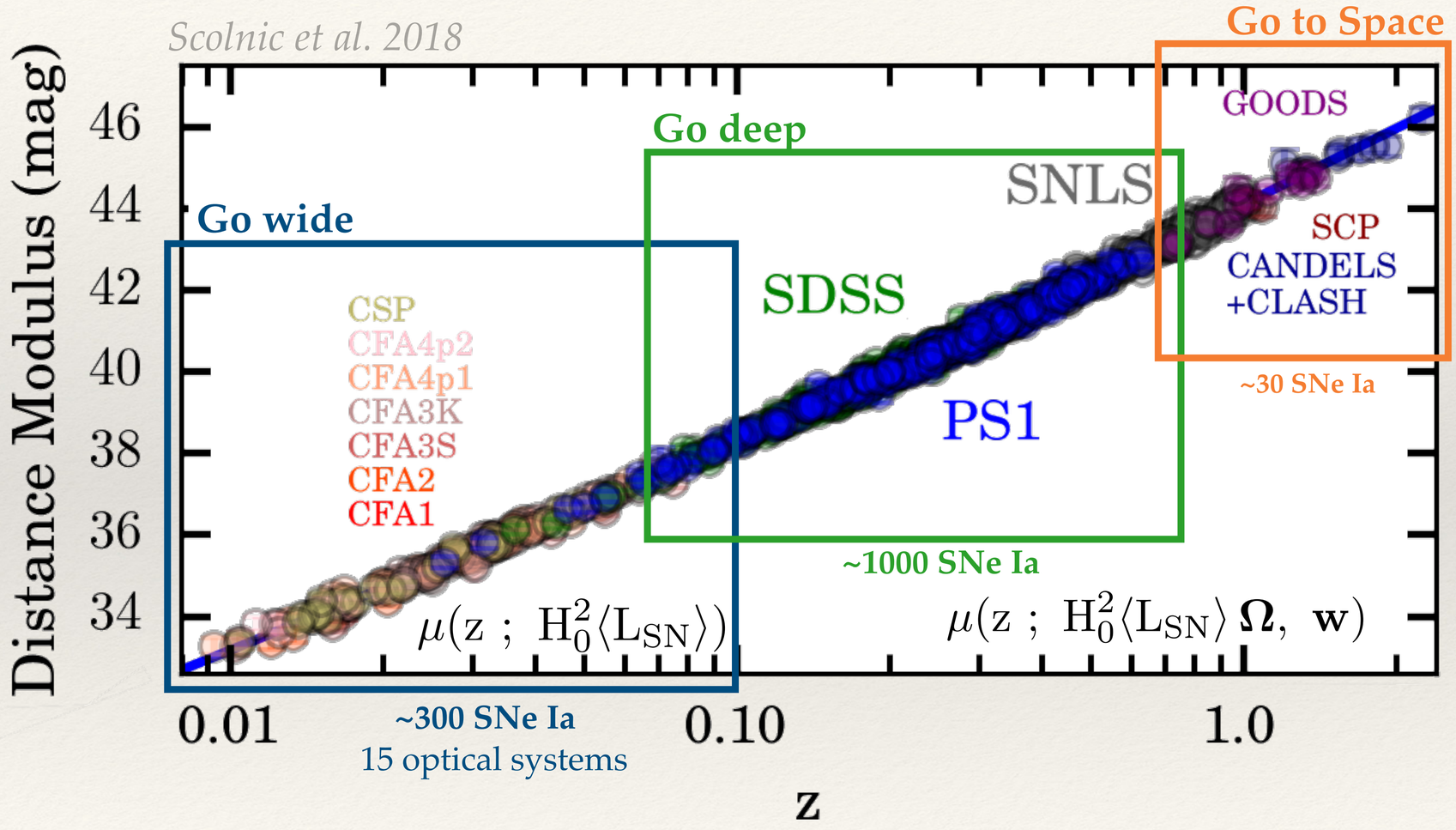
## SH0ES rebuttal

"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

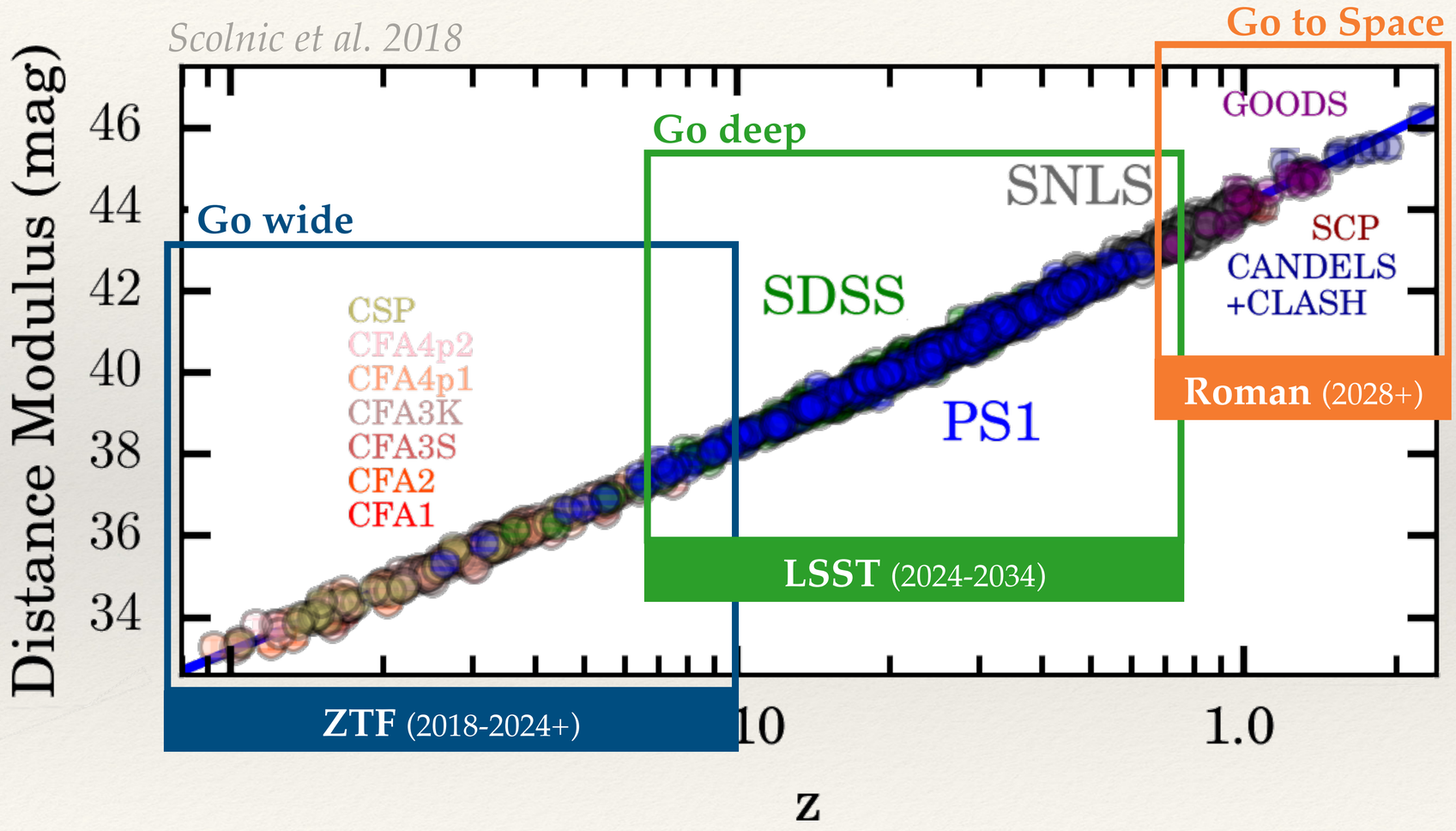
# Issue: SNe Ia are rare

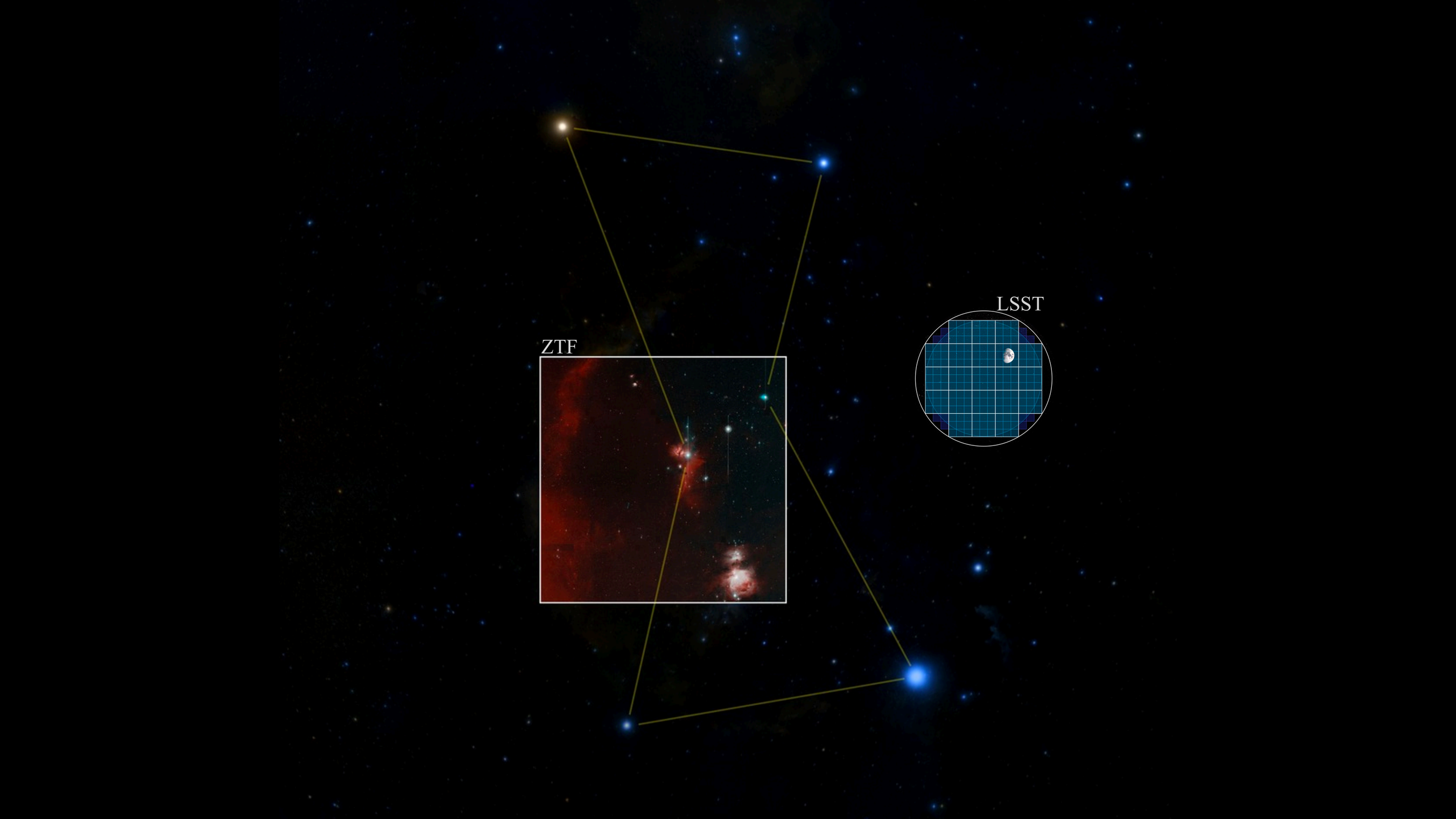
*O(10)* SNe Ia per day at $z < 0.1$



# New generation of SNe Ia surveys

*O(10)* SNe Ia per day at $z < 0.1$

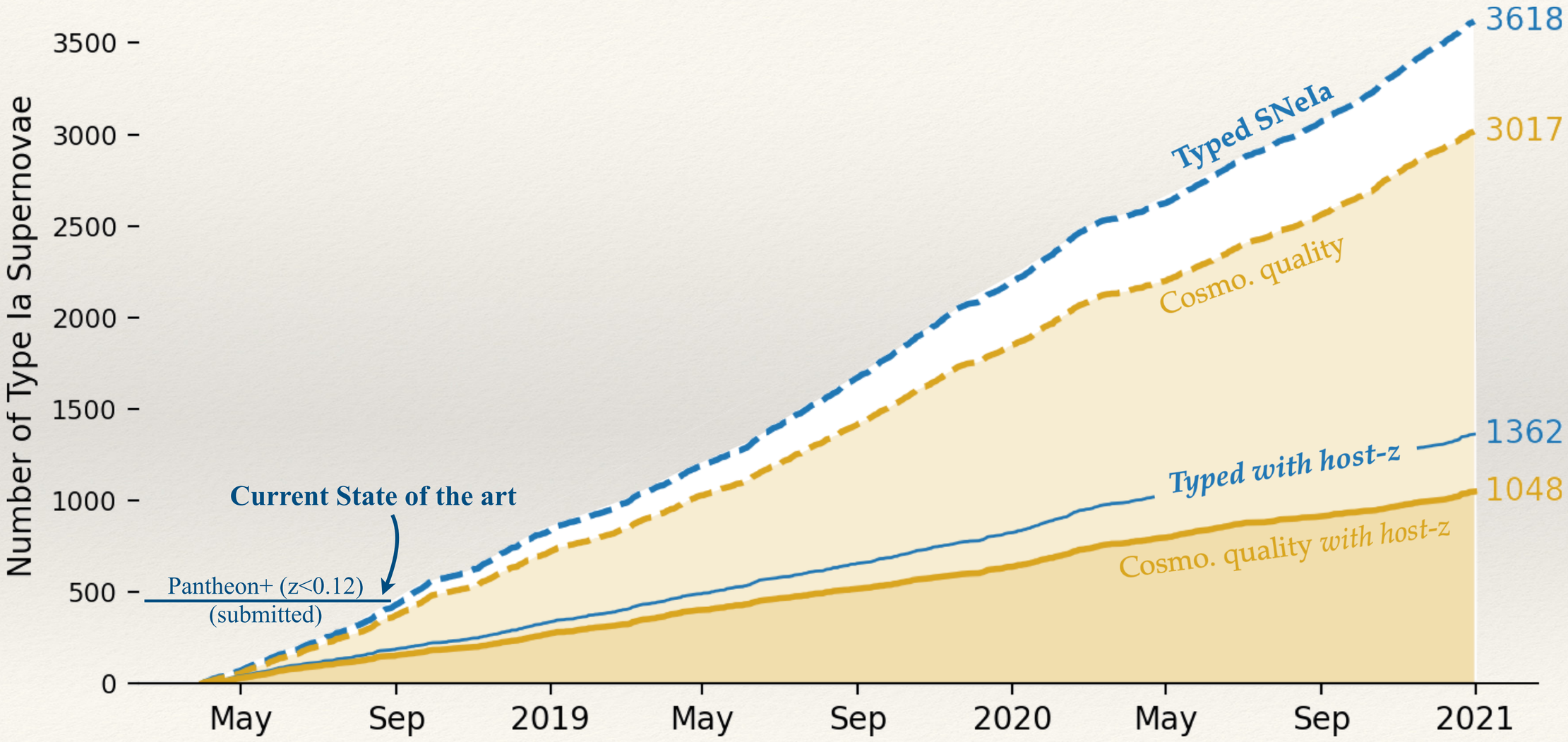



ZTF
LSST

# ZTF | *Changing the scale of SN Cosmology*

Rigault, **Smith** et al. in prep

erc | USNAC



# Direct Distance Ladder | *SH0ES*

Get independent distances for SNe Ia

## 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 photometry*

**Selection Function Correction**

Some surveys are targeted surveys & Observing windows varies

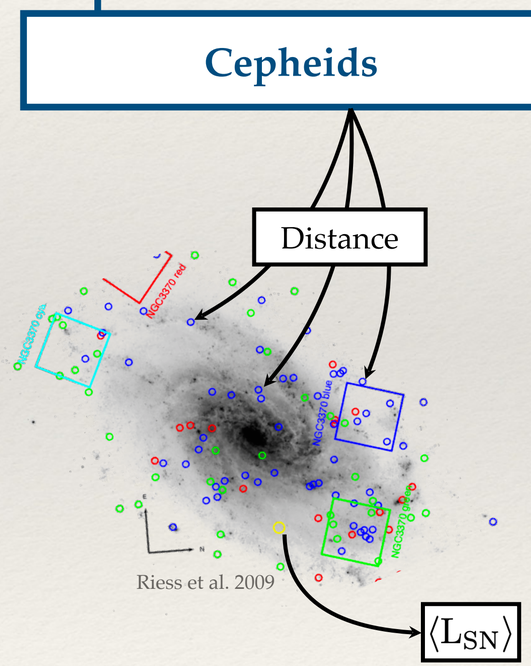
*How to correctly account for Malmqvist bias*

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

**"Calibrators"**

**Cepheids**

Distance

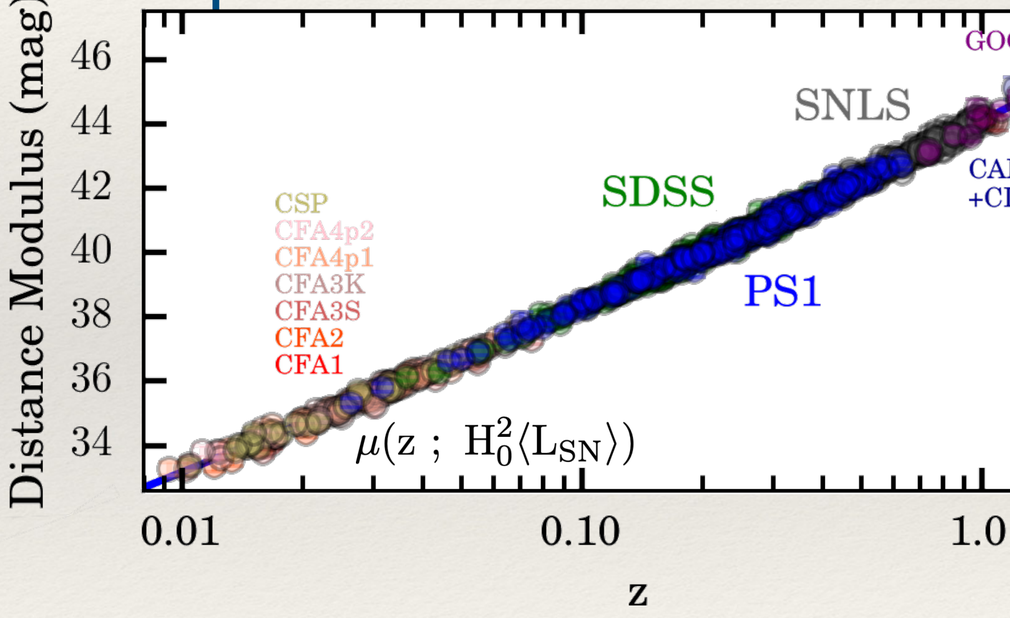



Riess et al. 2009

$\langle L_{SN} \rangle$

**"SNe Ia"**

Scolnic et al. 2018




**Riess et al.** *2022*

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

# ZTF Sample | *Toward a self-consistant $H_0$*

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

## Calibrator Sample

**Volume limited ZTF-SNeIa < 50 Mpc**

**Technique**
TRGB (doable in any galaxy)

**Statistics:** ~5 per year (~30 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**

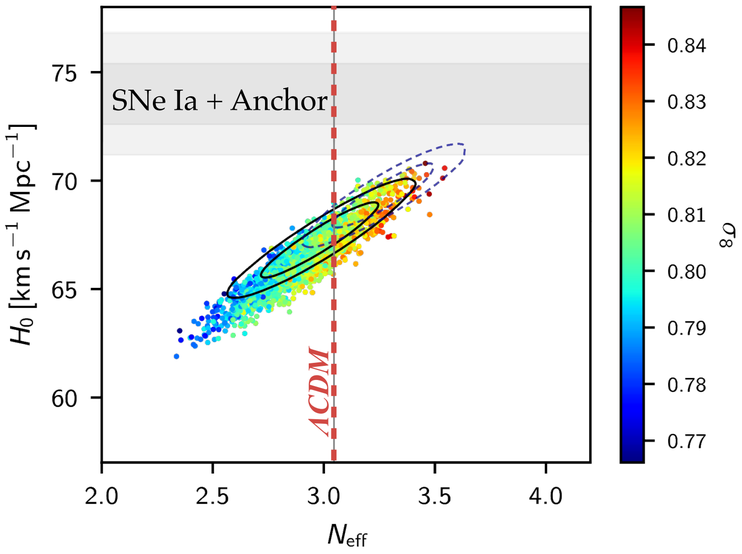
**Statistics:** Already >800 acquired

**No selection function since both volume limited samples**

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

# ZTF for Nearby Supernova Cosmology

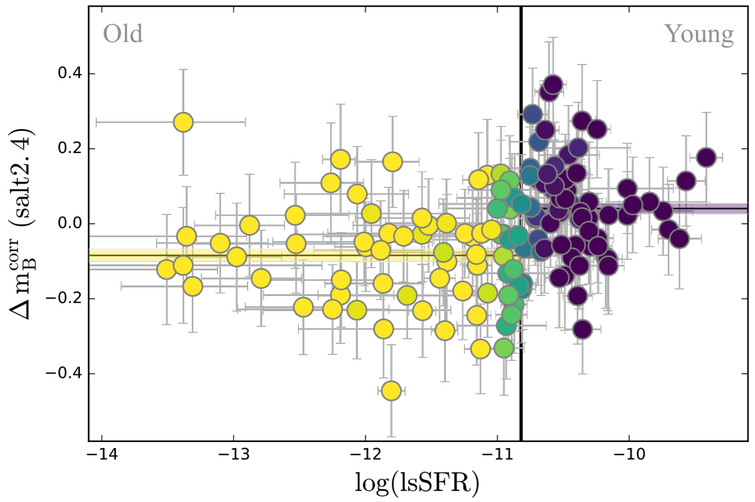
## $H_0$ | Hubble Constant




Hard to find model that can explain that without breaking something else.

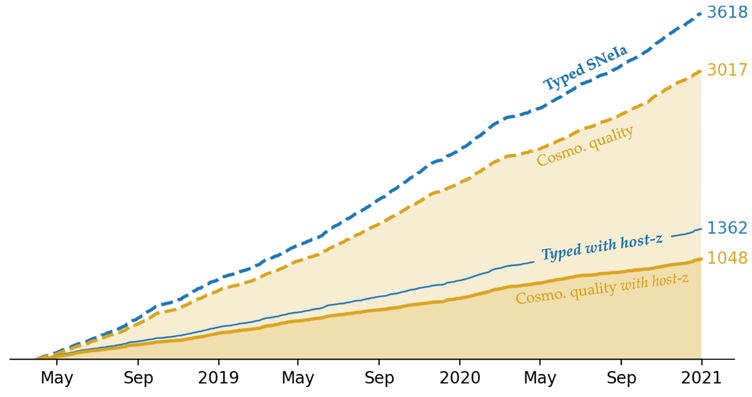
## $f\sigma_8$ | Growth rate of Structure

$\Delta_m \sim 0.15$ mag




Confirmed by: Roman+2018 (SNLS), Kim+2018 (Public), Kesley+2021(DES), Briday+2021, Nicolas+2022

## ZTF is changing the game




Let's get a pure-ZTF $H_0$