Supernovae, Host Galaxies, and the Hubble Tension

Speaker:
Gonçalo Martins

Supervisors :
Ana Mourão (DF/CENTRA)
João Duarte (DF/CENTRA)
Santiago González-Gaitan (ESO/IA)

centra

TÉCNICO LISBOA

1 - What is the Hubble Constant and the Hubble Tension?

Hubble's Law:

$v = H_0 \times d$

v = velocity of the galaxy H_0 = Hubble constant d = distance of the galaxy

CMB Measurements

H0 = 67.36 ± 0.54 $\mathbf{km\ s^{-1} Mpc^{-1}}$
(Planck Collaboration et al. 2020)

Local Distance Ladder

H0 = 73.04 ± 1.04 $\mathbf{km\ s^{-1} Mpc^{-1}}$
(Riess et al. 2022)

~ 5σ difference!

Can indicate the need for new physics, or unexpectedly large systematic errors in the measurements.

1 - Introduction: Type Ia Supernovae

A SNe Ia result from the thermonuclear explosion of a **carbon-oxygen white dwarf star in a binary system**.

Occurs when the **WD mass approaches the Chandrasehkar limit** ~1.44 M⊙

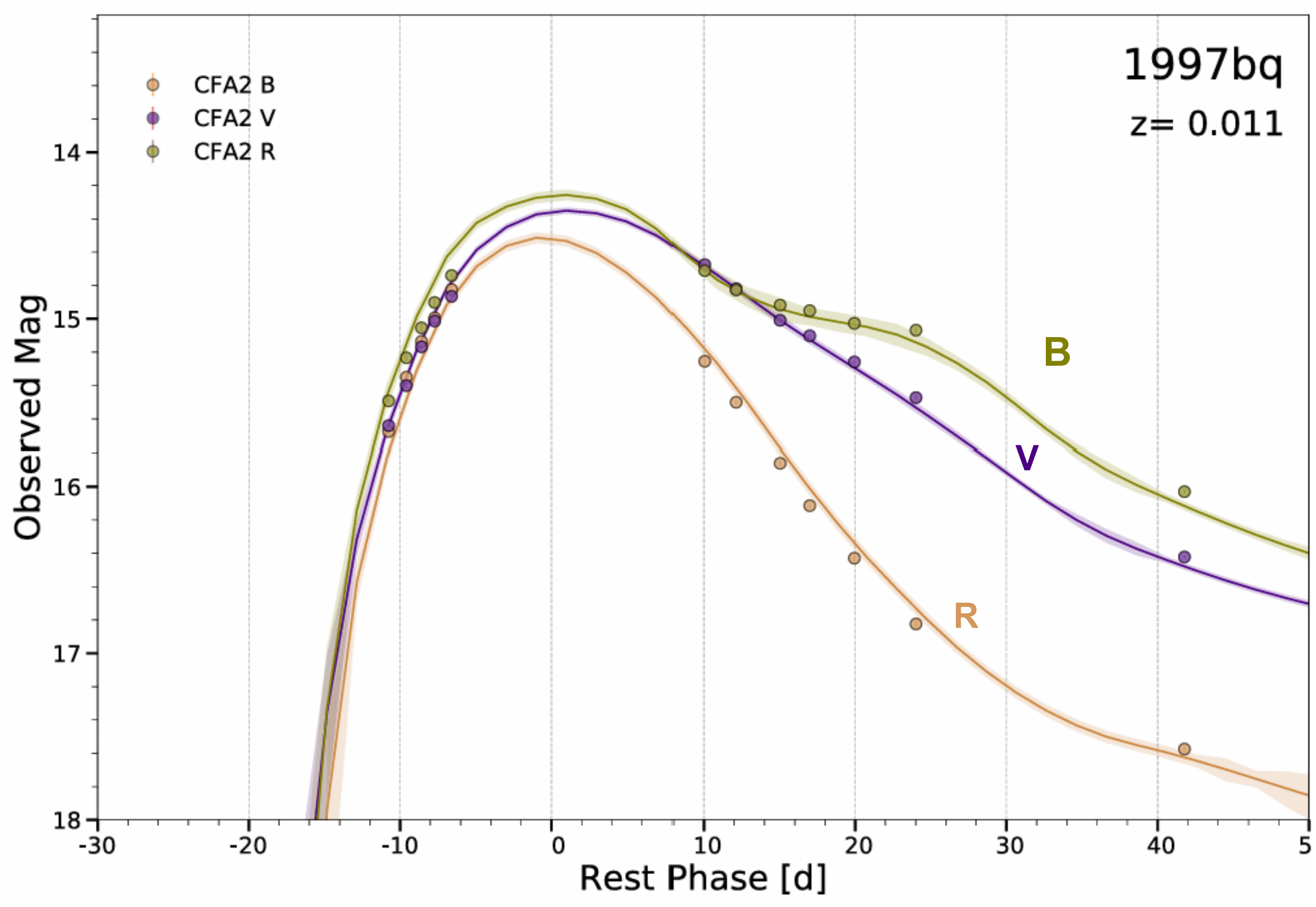
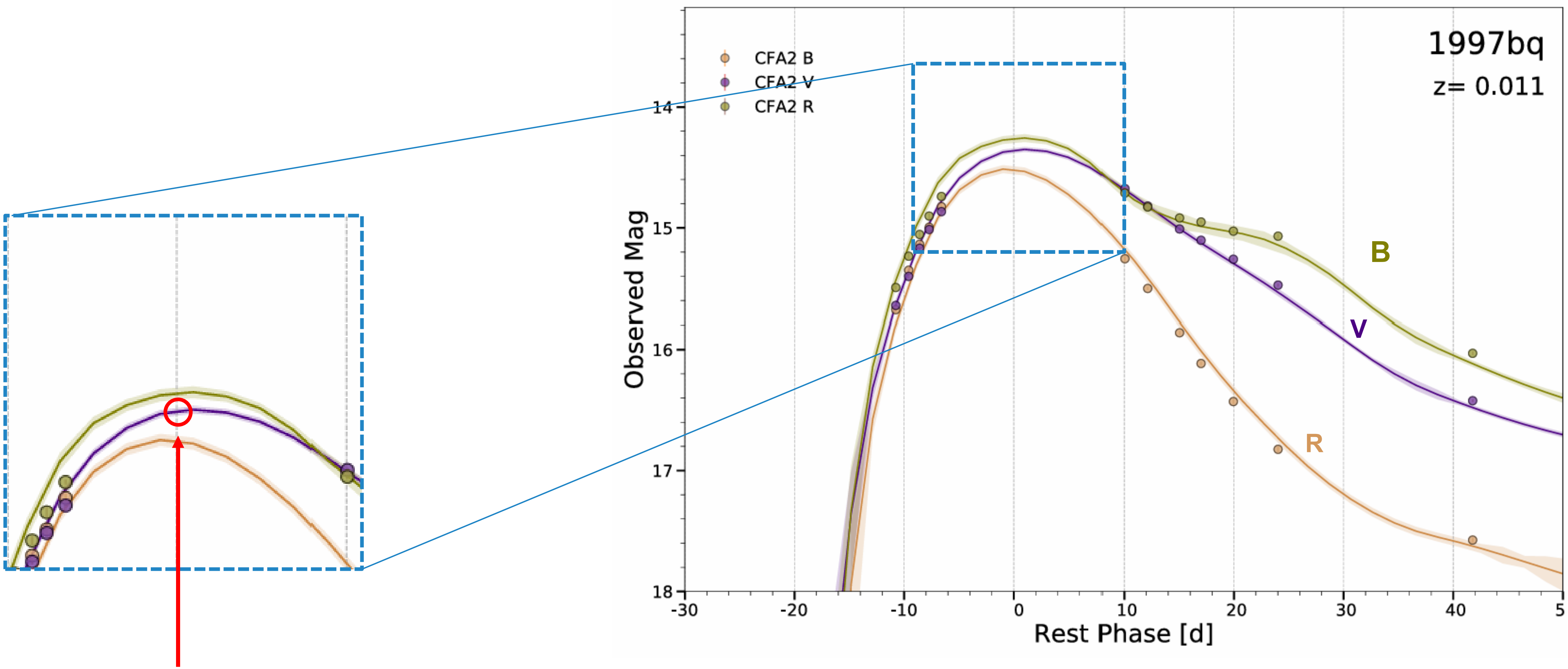


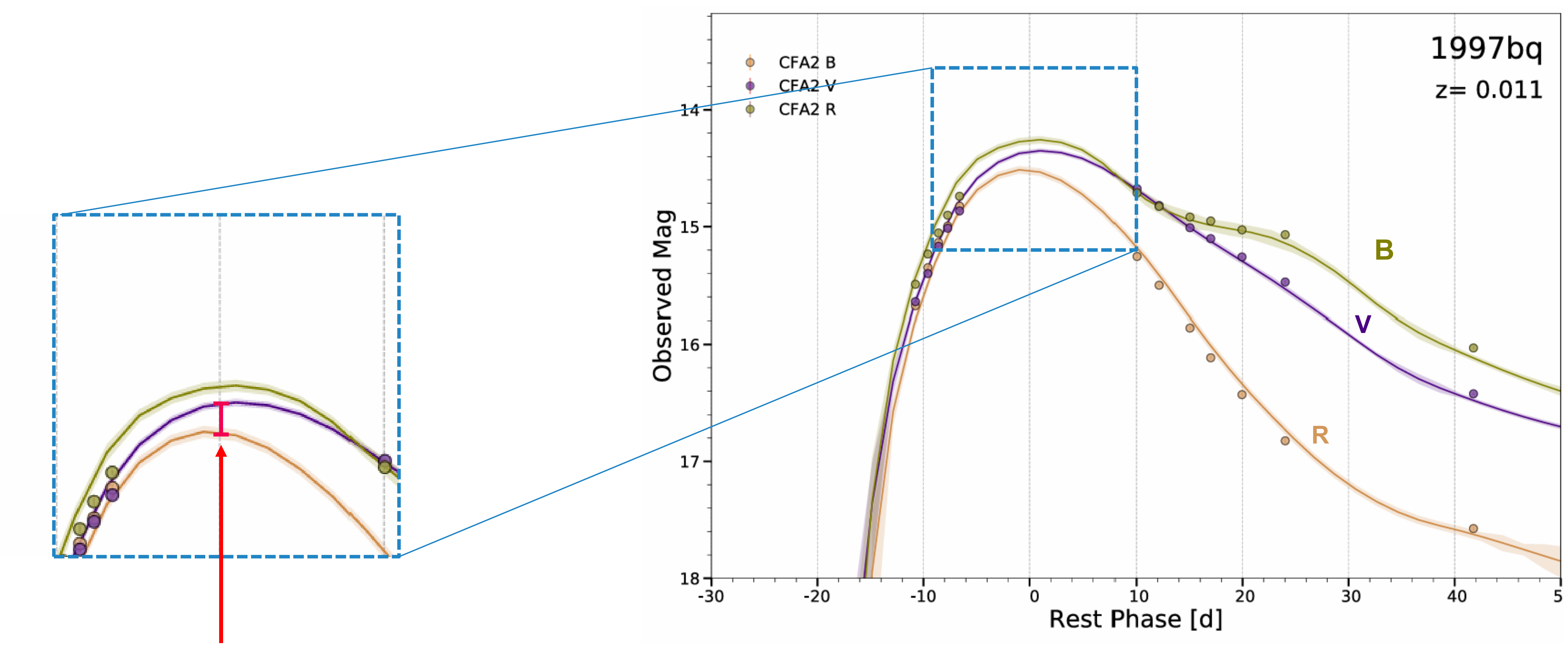
Fig. 1 - Light curve of SN1997bq for different filters (Scolnic et al., 2022)

1 - Introduction: Sne Ia lightcurves



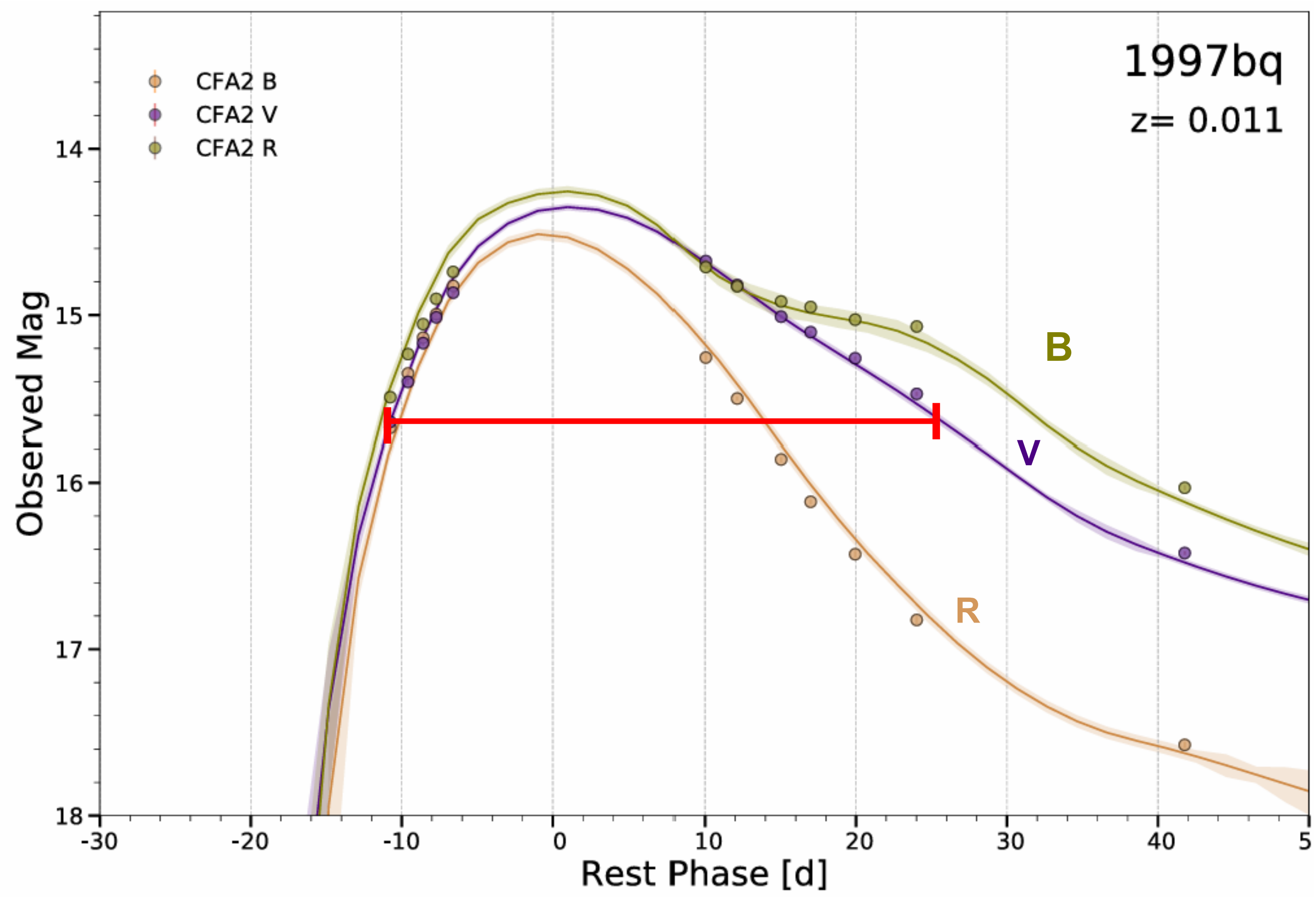
Peak magnitude in the B band (m_B)

1 - Introduction: Sne Ia lightcurves



Color (c) : The difference between the magnitude in the B and V bands at the fitted epoch of peak brightness

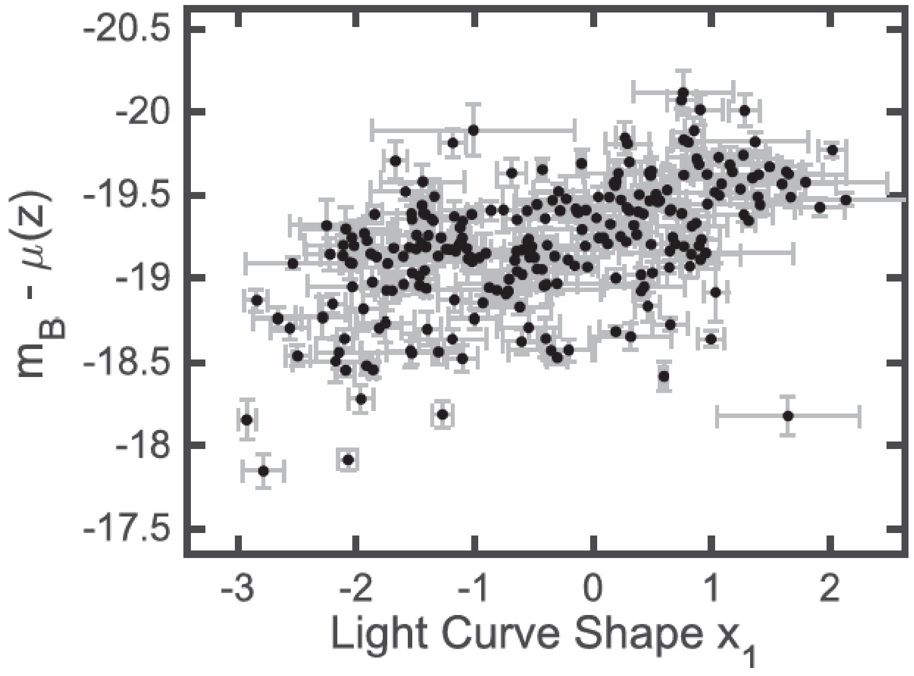
1 - Introduction: Sne Ia lightcurves



Stretch (x_1) : Dimensionless parameter that quantifies the width of the light curve

1 - Introduction: SNe Ia luminosities can be standardized!

Distance modulus: $\mu = m_B^{corr} - M_B$



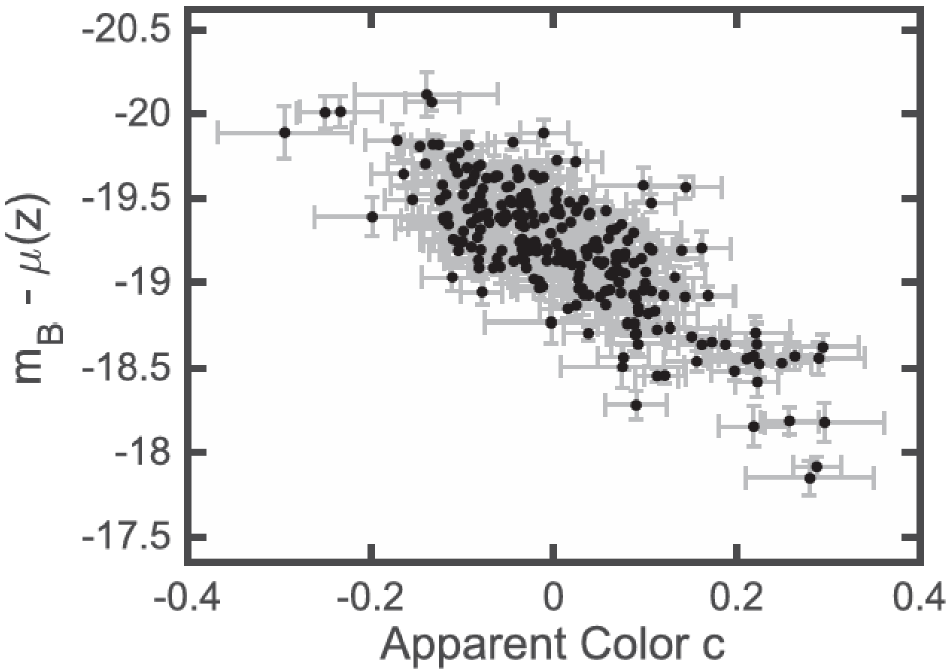
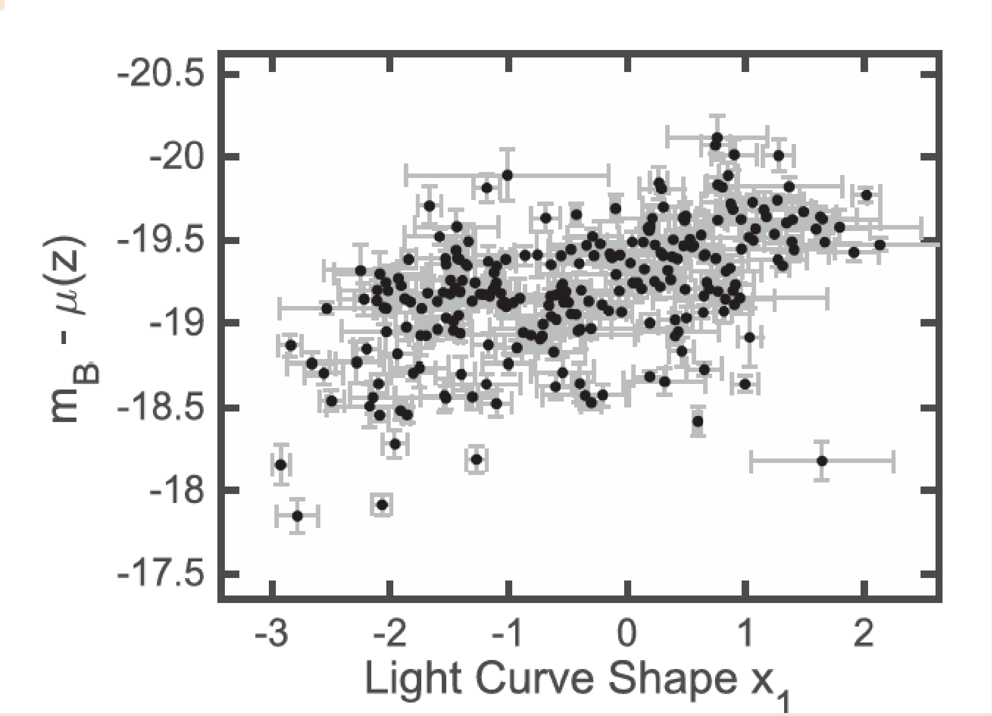


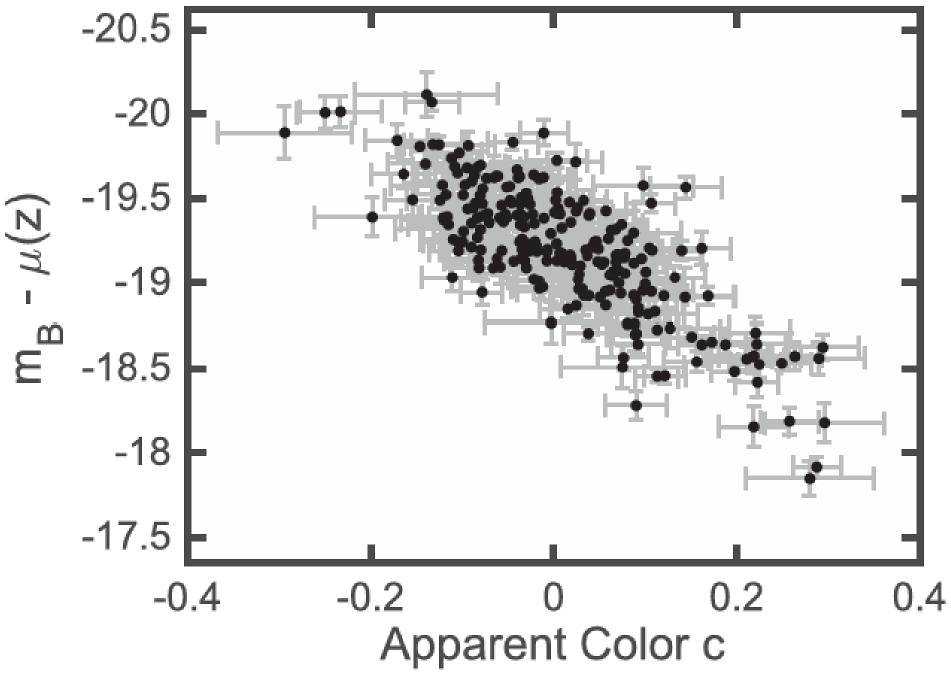
Fig. 2 and 3 – Diference between the μ and m_B as a function of color ($c \sim m_V - m_B$) and stretch (x_1) (Mandel K. et al., 2017)

The **SNe Ia luminosities** and **light curves** can be **standardized using empirical relations**!

1 - Introduction: SNe Ia luminosities can be standardized!



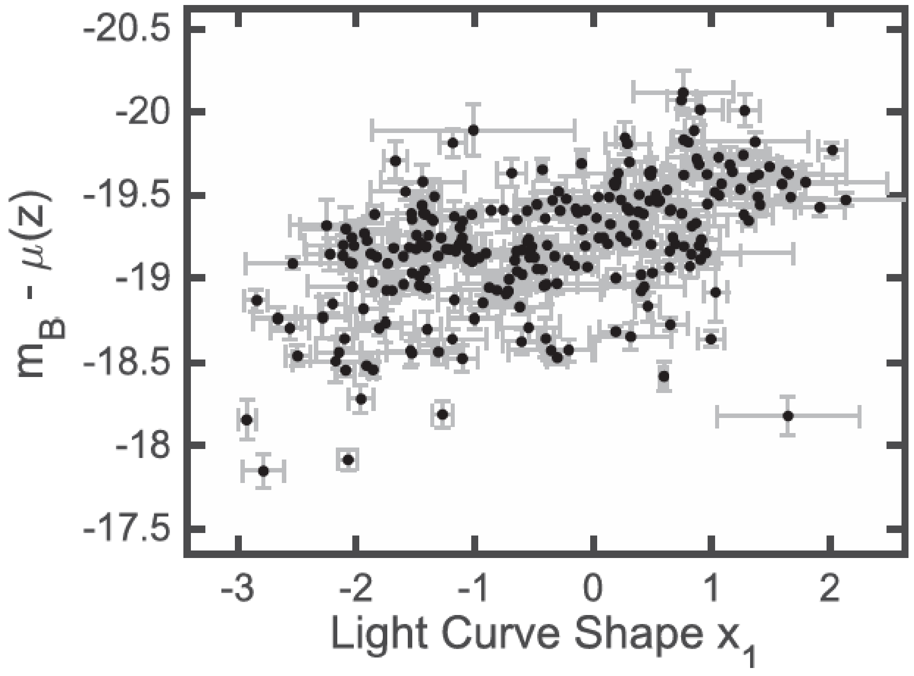
Shape-luminosity relation (Philipps 1993)

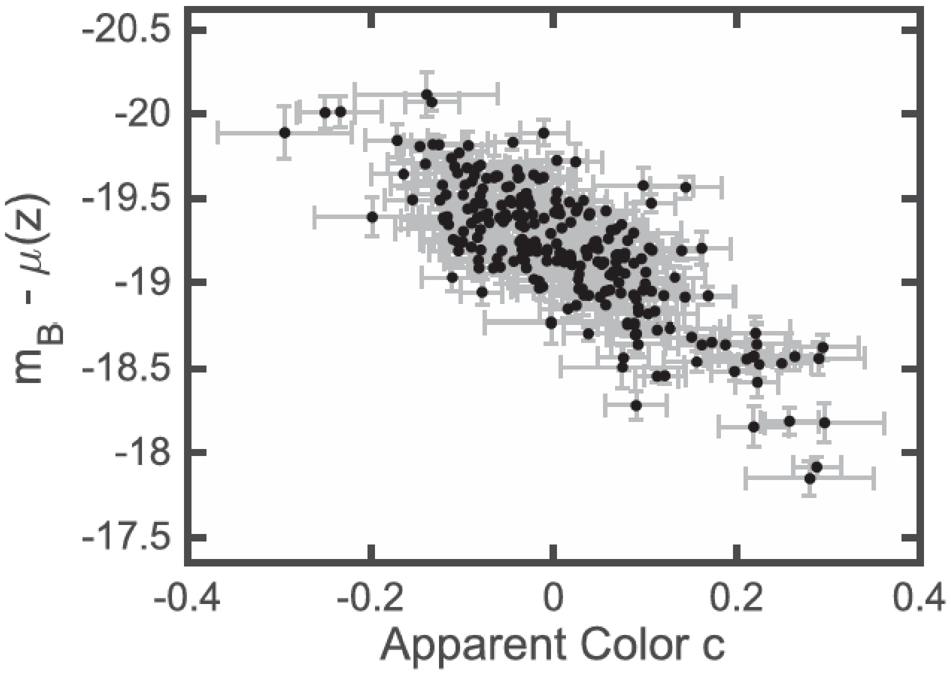


Tripp correction formula:

$$m_B^{corr} = m_B + \alpha x_1$$

1 - Introduction: SNe Ia luminosities can be standardized!





Color-luminosity relation (Tripp 1998)

Tripp correction formula:

$$m_B^{corr} = m_B + \alpha x_1 - \beta c$$

1 - Introduction: SNe Ia luminosities can be standardized!

Light curve of several Sne after the standarization stretch and colour corrections!

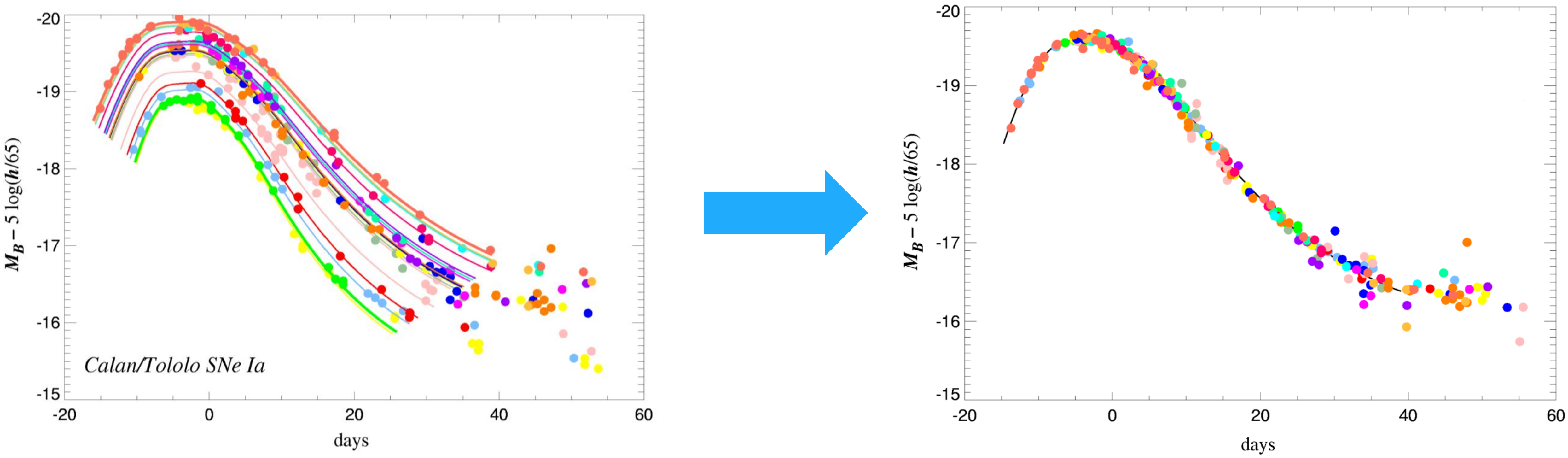


Fig. 4 and 5 – Different SNe Lightcurves before and after applying the Tripp standarization (Miao Li. et al., 2011)

Tripp correction formula:

$$m_B^{corr} = m_B + \alpha x_1 - \beta c$$

1 - Introduction: Mass step

There's a dependence of Type Ia Sne luminosities on their host galaxies!

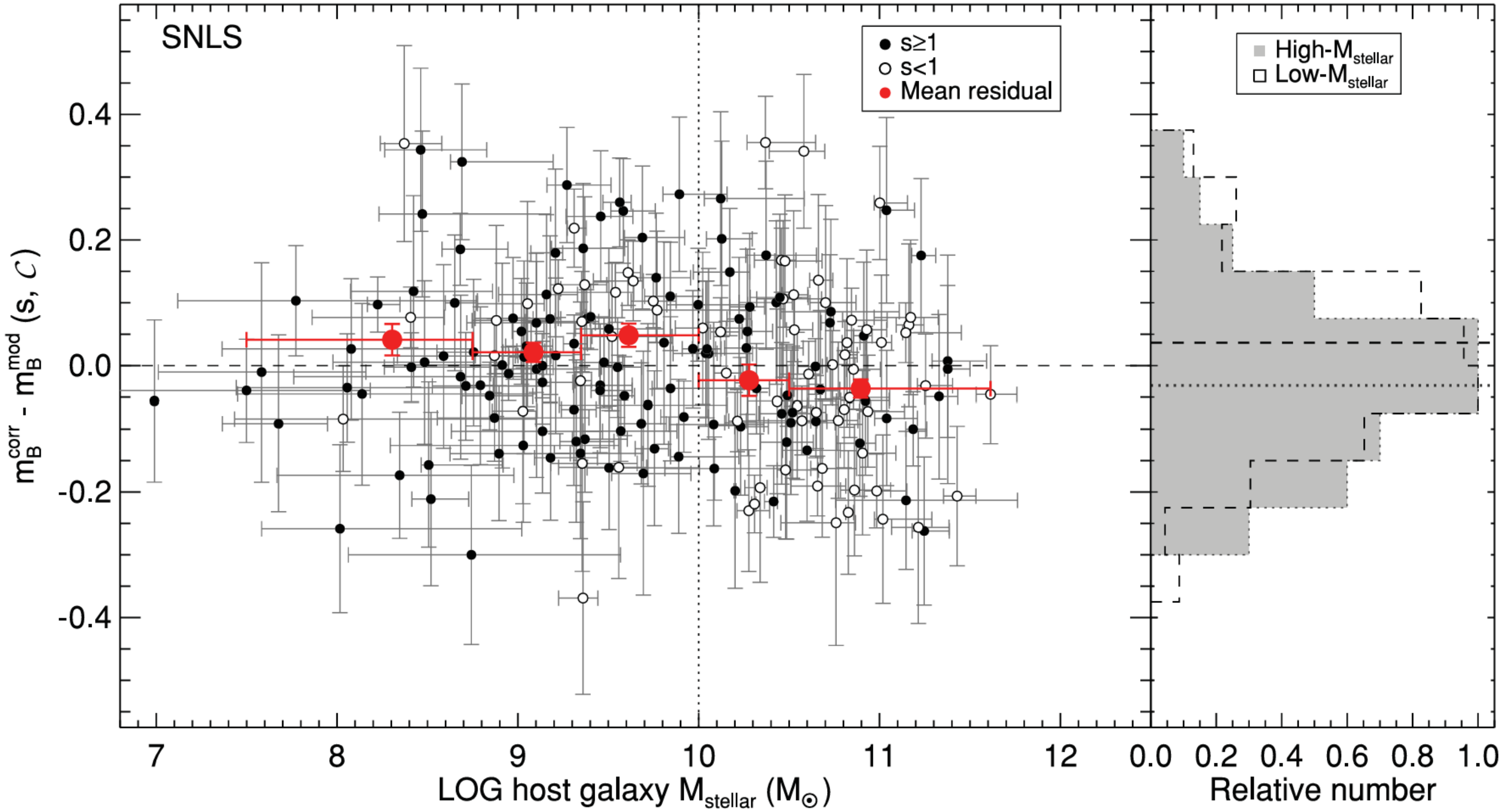


Fig. 6 – Mass step from Sullivan et al. 2010

Tripp correction formula:

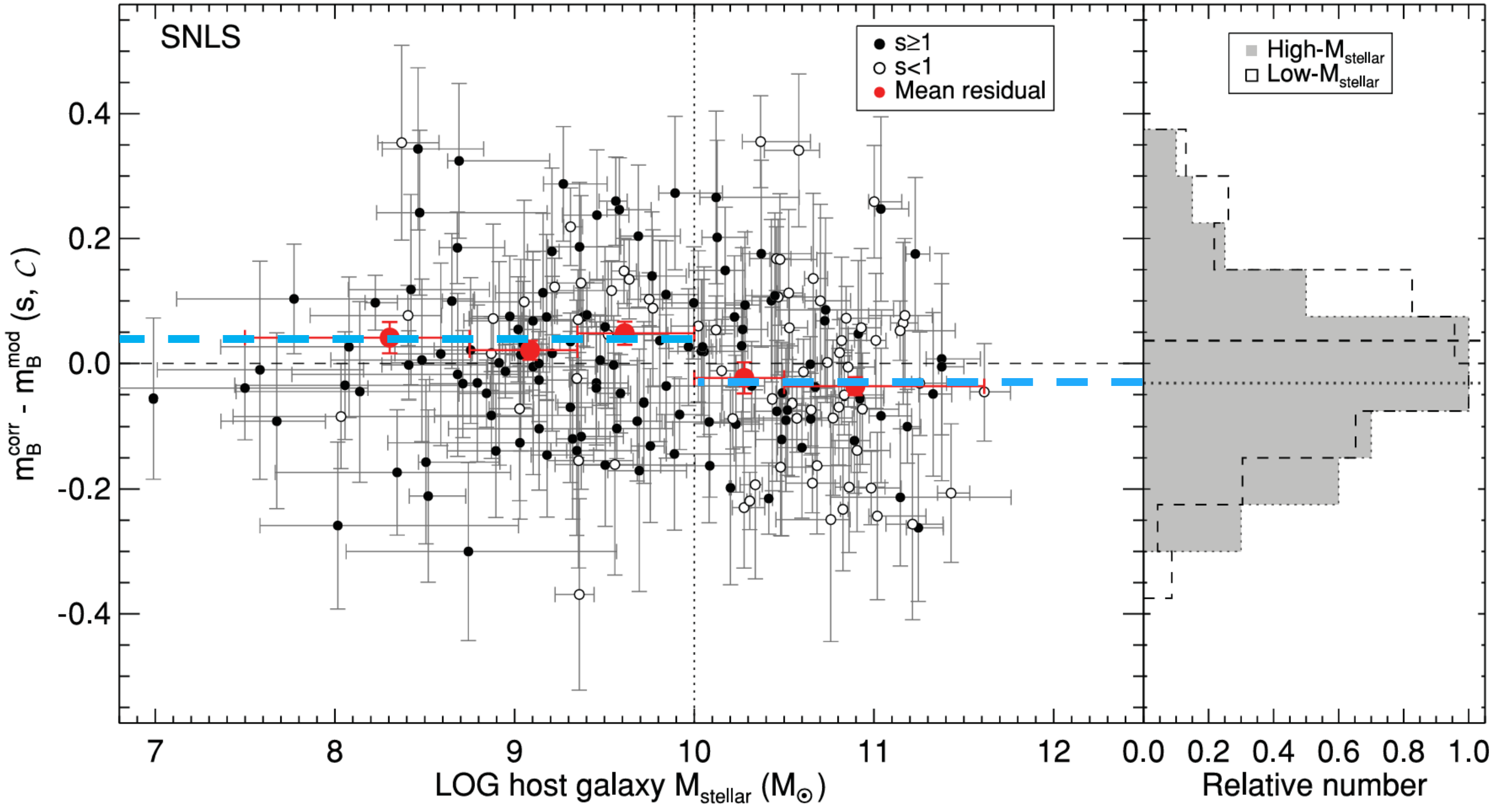
$$m_B^{corr} = m_B + \alpha x_1 - \beta c$$

with

$$\delta_{host} = \begin{cases} \Delta_{host} \text{ if } \log(M/M_\odot) < \log(M_{step}/M_\odot) \\ -\Delta_{host} \text{ if } \log(M/M_\odot) > \log(M_{step}/M_\odot) \end{cases}$$

1 - Introduction: Mass step

SNe in more massive galaxies are brighter after corrections!



Tripp modified correction formula:

$$m_B^{corr} = m_B + \alpha x_1 - \beta c + \delta_{host}$$

with

$$\delta_{host} = \begin{cases} \Delta_{host} \text{ if } \log(M/M_\odot) < \log(M_{step}/M_\odot) \\ -\Delta_{host} \text{ if } \log(M/M_\odot) > \log(M_{step}/M_\odot) \end{cases}$$

Fig. 6 – Mass step from Sullivan et al. 2010

1 – Introduction: How does the Cosmic Distance Ladder works?

For **Cepheids**:

$$M_\lambda = m_\lambda - \mu = \alpha_\lambda(\log P - \log P_0) + \gamma_\lambda[\mathrm{Fe/H}] + \delta_\lambda$$

Period-Luminosity-Metallicity Relation
(Breuval et al. 2022)

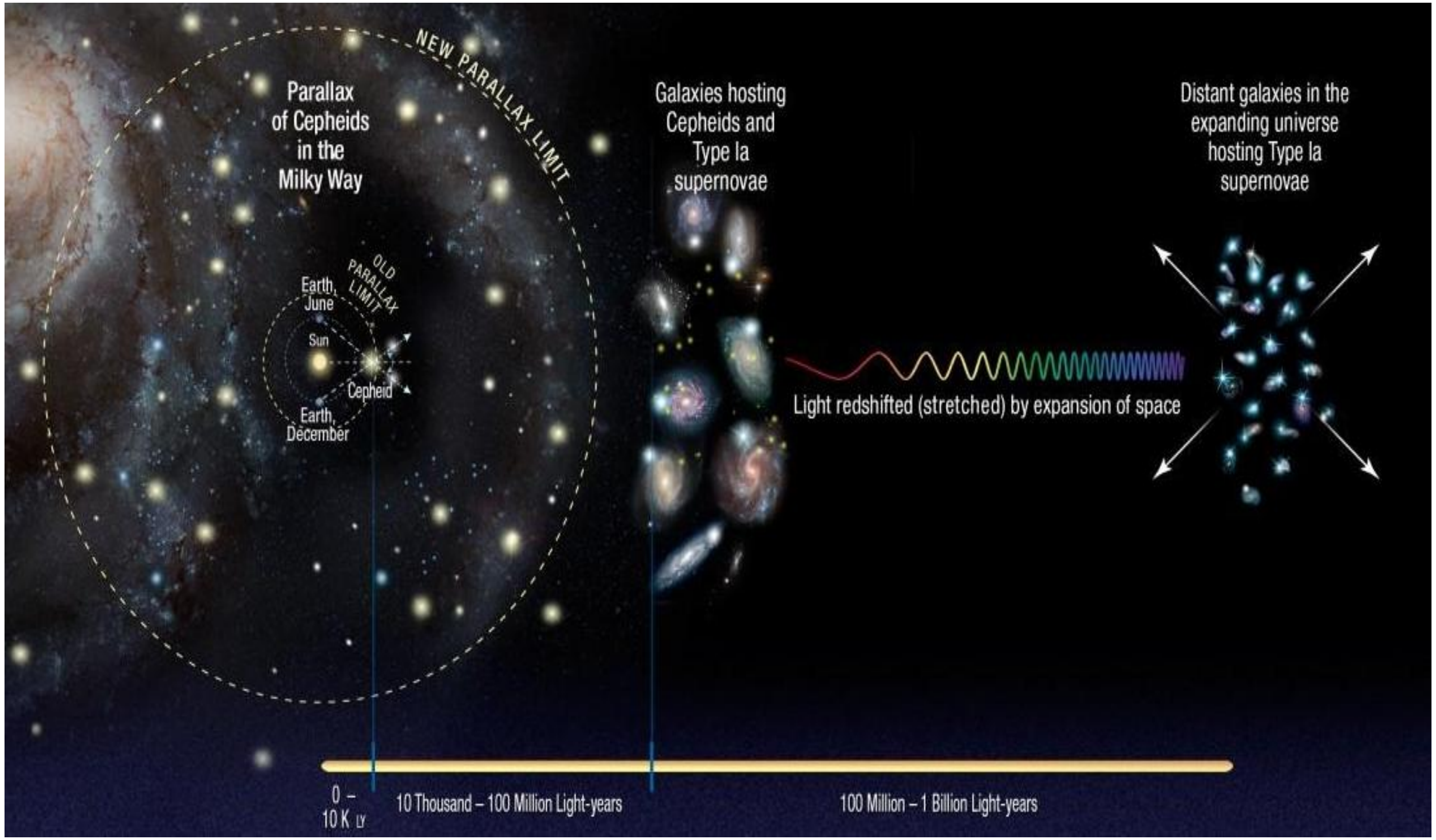


Fig. 7 - Cosmic Distance Ladder [NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)] .

1 – Introduction: How does the Cosmic Distance Ladder works?

For **SNe Ia**:

Tripp modified correction formula

$$\mu = m_B^{corr} - M_B = m_B - M_B + \alpha x_1 - \beta c + \delta_{host}$$

with

$$\delta_{host} = \begin{cases} \Delta_{host} \text{ if } \log(M/M_\odot) < \log(M_{step}/M_\odot) \\ -\Delta_{host} \text{ if } \log(M/M_\odot) > \log(M_{step}/M_\odot) \end{cases}$$

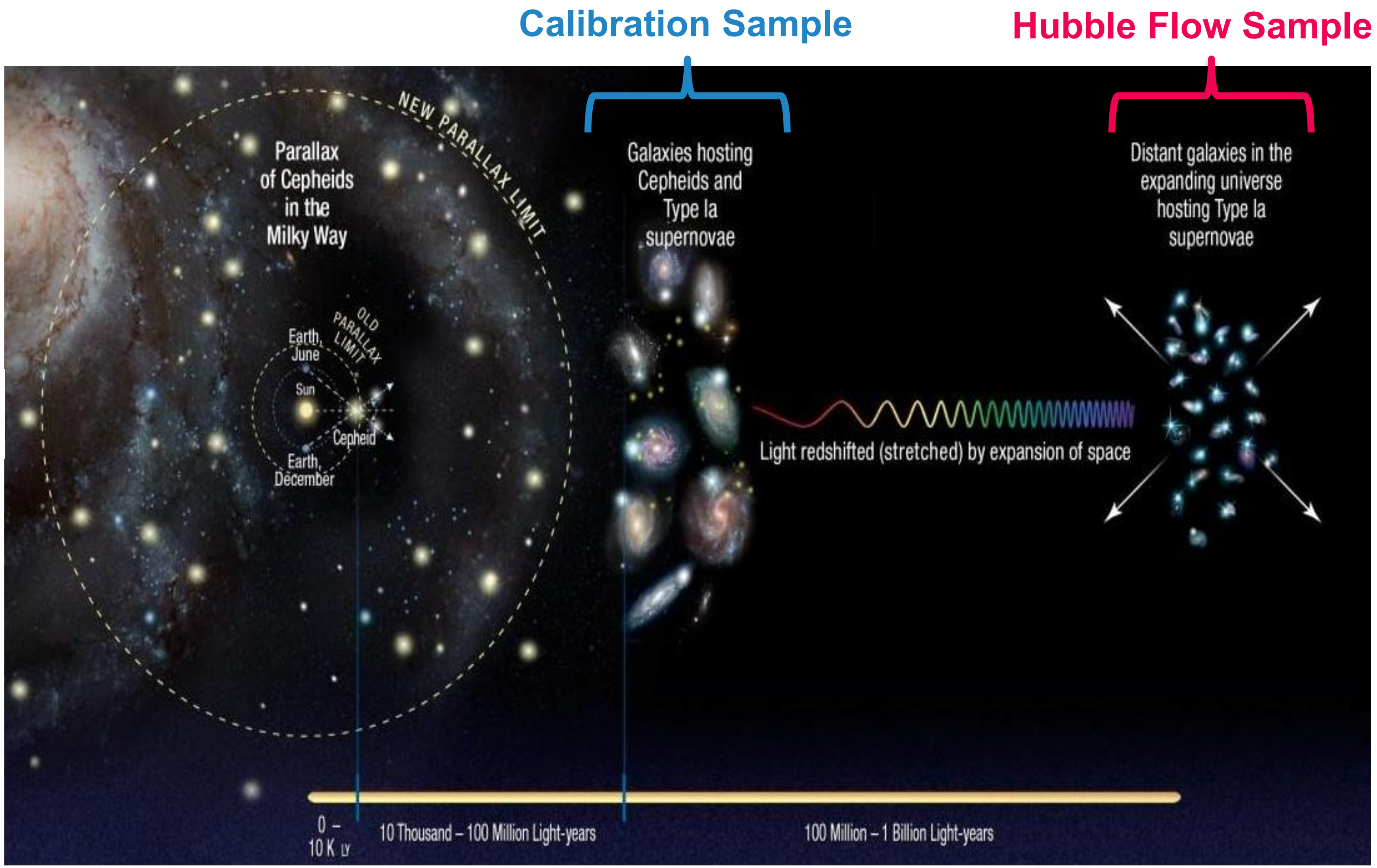


Fig. 7 - Cosmic Distance Ladder [NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)] .

1 - Introduction: SNe Ia subpopulations

There's a **bimodal behavior in the stretch distribution**
(two SNe populations?)

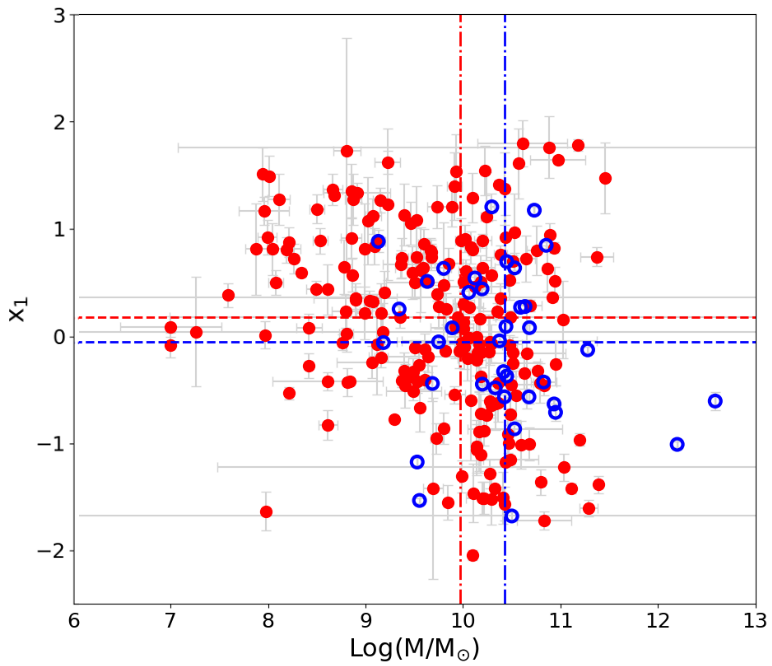


Fig. 8 – Stretch (x_1) as a function of the log(M/ M⊙)

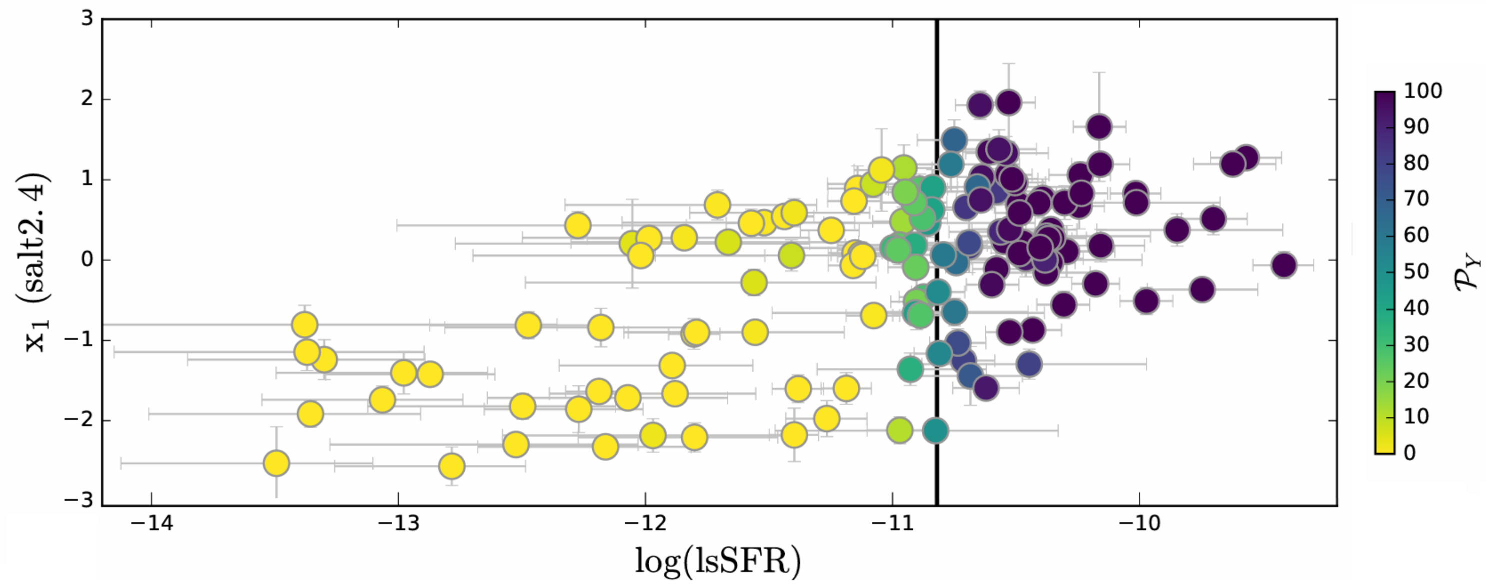


Fig. 9 – Stretch (x_1) as a function of local sSFR (Rigault et al. 2020).

1 - Introduction: Our proposal to decrease the Hubble tension

SNe Ia in very nearby galaxies hosting Cepheids that constitute the

Calibration sample may not be representative of the full Hubble Flow sample.

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Is it valid to **apply a universal correction** to all SNe Ia luminosities**, regardless of subpopulation?**

1 - Introduction: Our proposal to decrease the Hubble tension

SNe Ia in very nearby galaxies hosting Cepheids that constitute the

Calibration sample may not be representative of the full Hubble Flow sample.

Is it valid to **apply a universal correction** to all SNe Ia luminosities**, regardless of subpopulation?**

↓

Investigate the supernova and the host galaxy properties of the distance ladder samples (with and without Cepheids);

Try to get a subsamples from the Calibration and HF sample that match to understand the impact in the Hubble parameter estimation.

Derive a more accurate correction for SNe Ia luminosities.

2 - Analysis

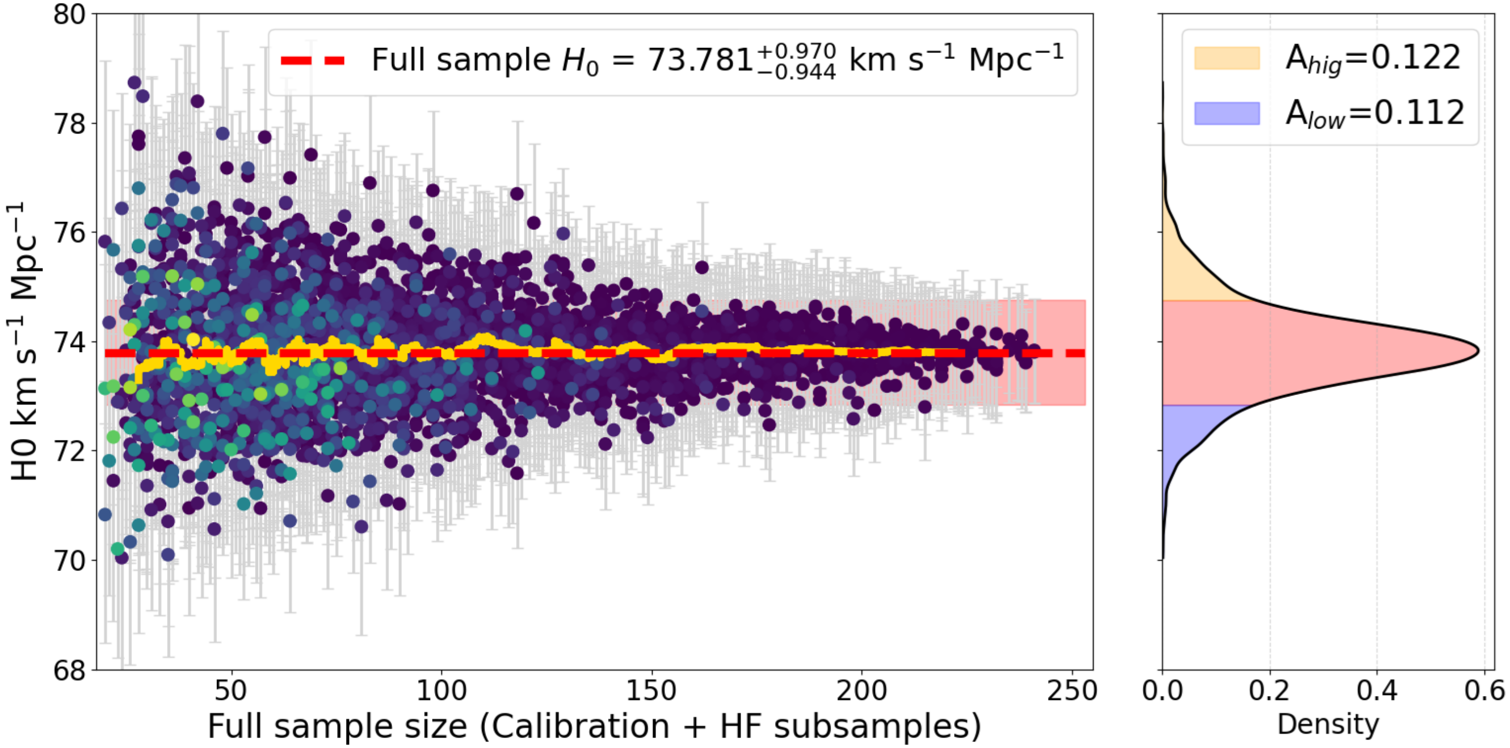


Fig. 10 - H0 as a function of the subsamples size.

Reducing intrinsic discrepancies
and
acessing SN subpopulations

The uncertainty in H0 might be underestimated!

2 - Analysis

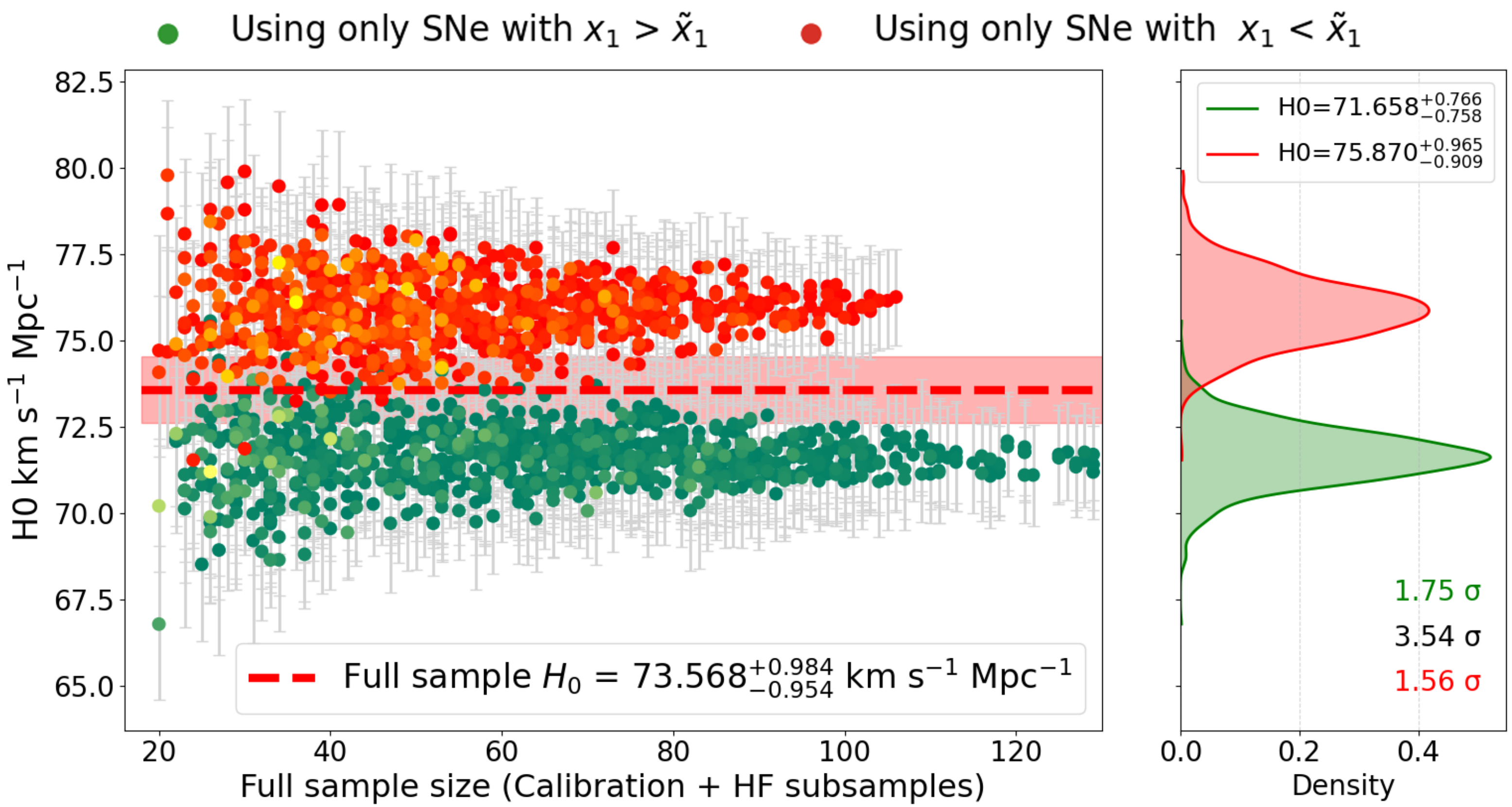
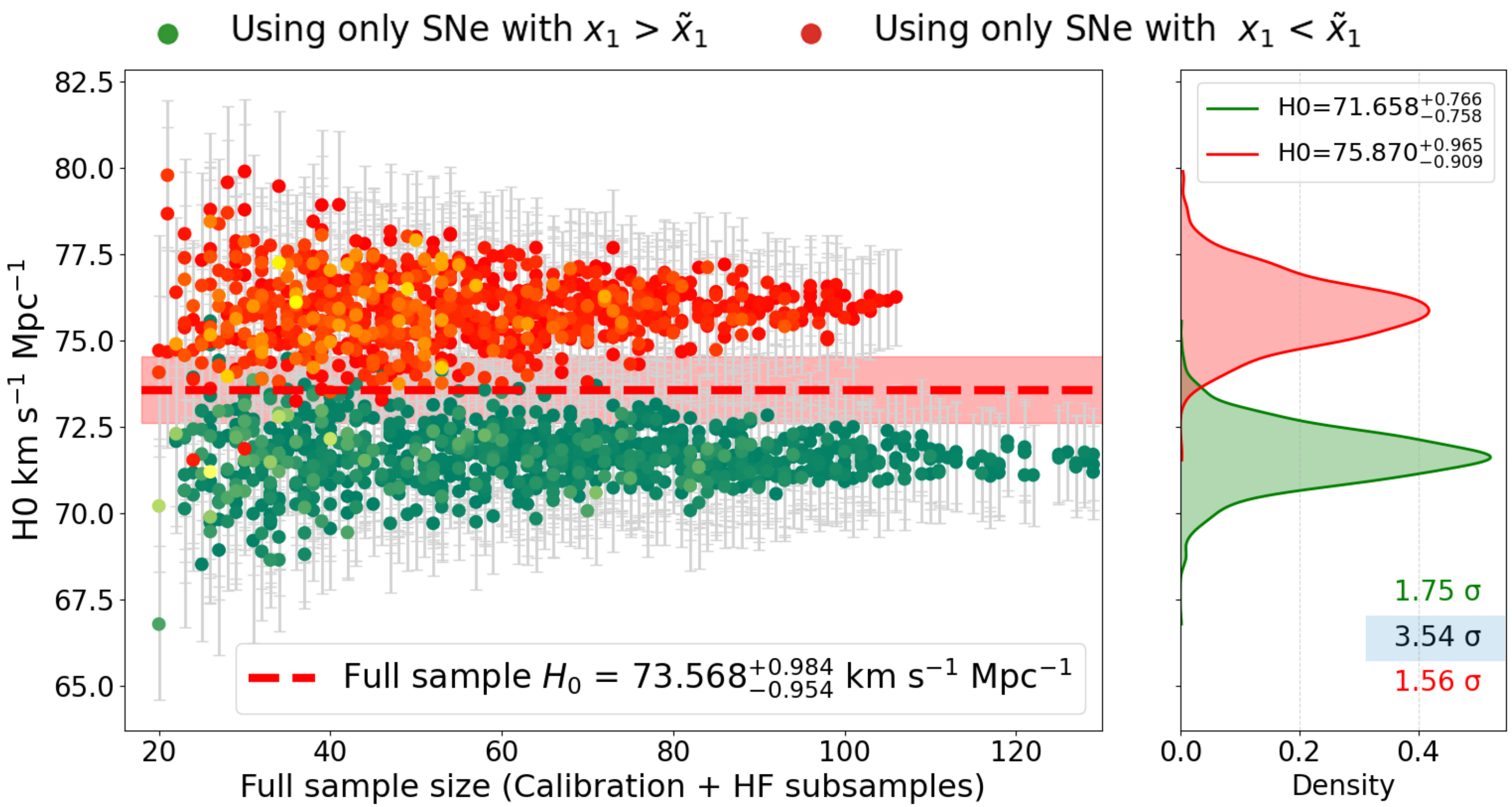


Fig. 11 - Median values distributions of H0 and respective differences to the 16th and 84th percentiles estimated using subsamples of SNe in diferent bins divided by the median stretch.

Median stretch $\tilde{x_1} = 0.087$

2 - Analysis



We can observe **a significant discrepancy** between the values of **H_0** estimated using **SNe with higher stretch** compared to those obtained from the **lower stretch bin**!

Δ_{host} consistent with 0!

3 - Summary

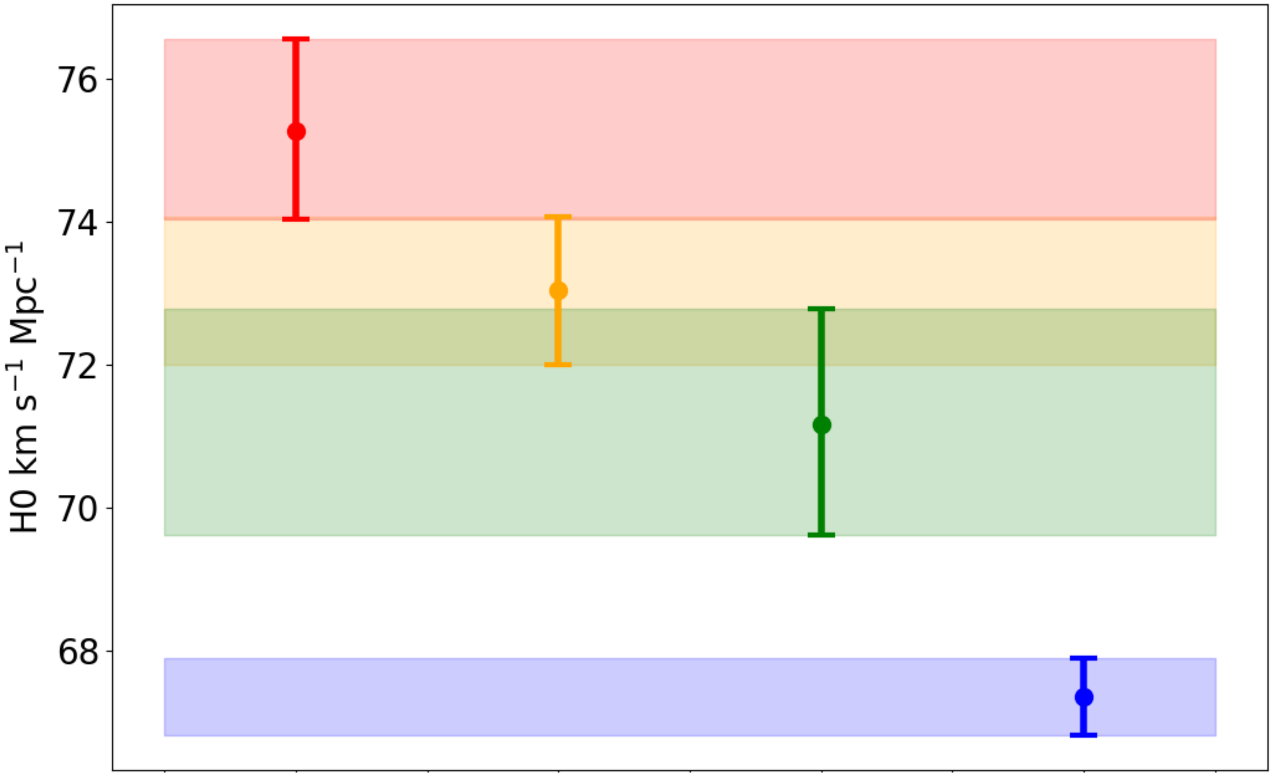
- A subsample of the Hubble Flow sample capable of independently **resolving the Hubble tension does not seem to exist**.

- The uncertainty on H_0 may be underestimated.

- There is **a clear discrepancy between the values of H_0** estimated from **high-stretch SNe Ia** and those obtained from the **low-stretch mode SNe Ia**.

- The **mass step may result from the mixing of these SN subpopulations**.

Decreasing Tension!



Using SNe with lower stretch (5.85σ)

Riess et al. 2019, 2021 a,b (4.84σ)

Using SNe with higher stretch (2.32σ)

Planck Collaboration et al. 2020

Thank You!

Extra slides (Hubble Tension)

There are more ways of estimate the H0 ...

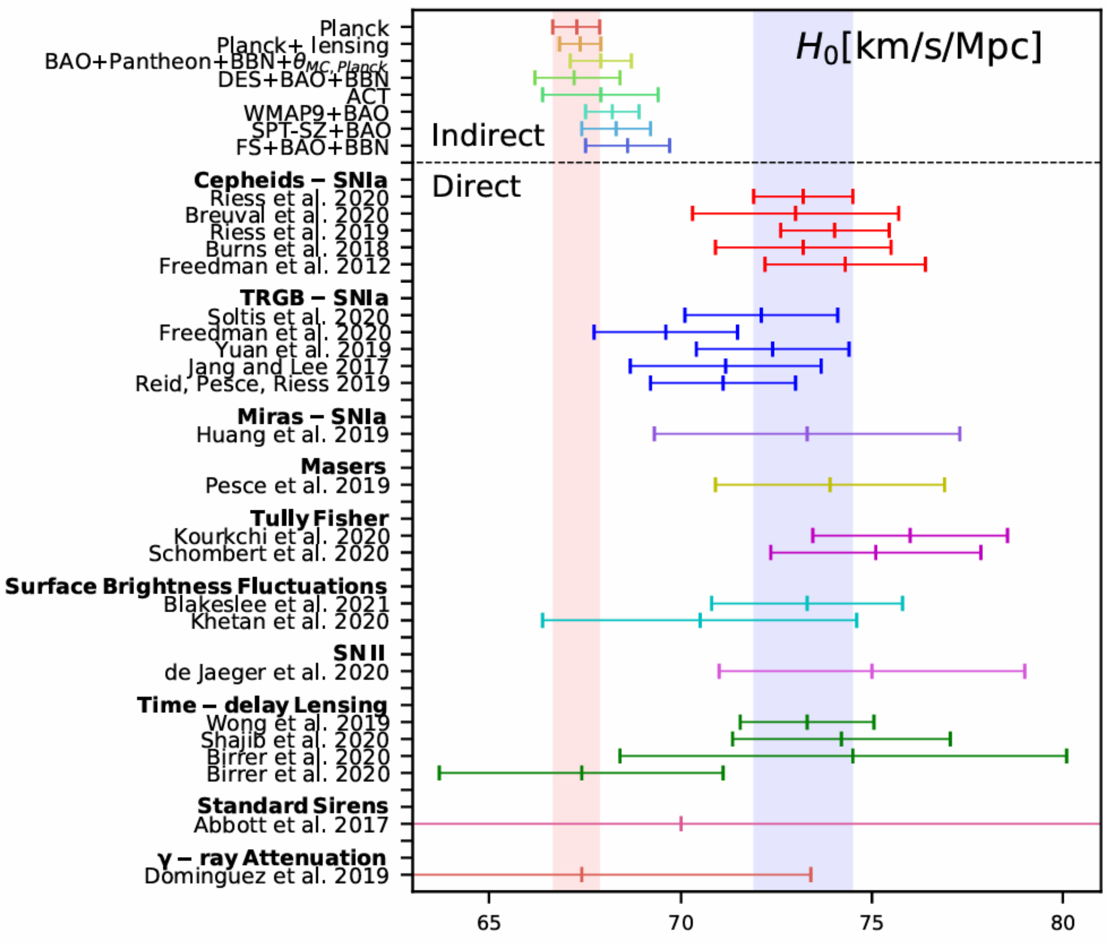


Fig . 13 - Estimations of H0 from different methods (Di Valentino 20221)

Extra slides (Cepheids)

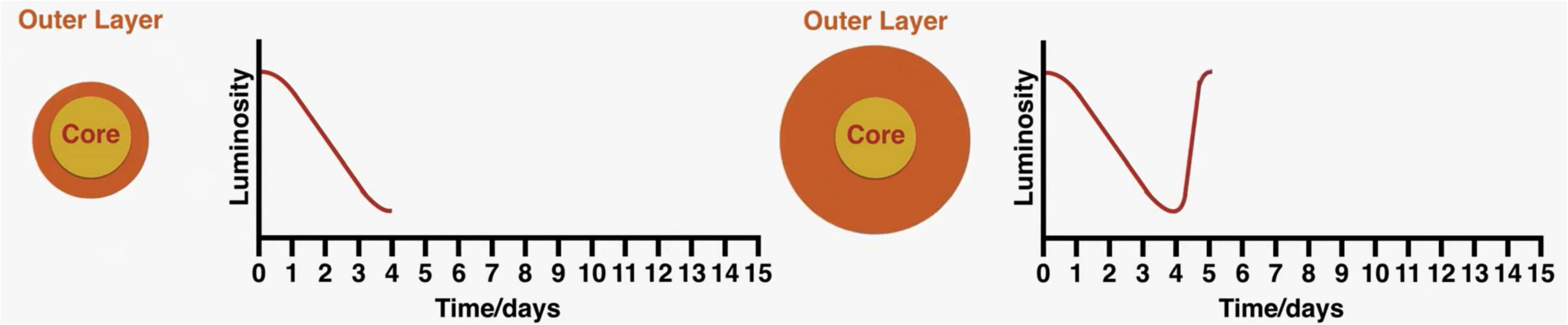


Fig . 14 –Illustration of the Cepheid light curve at different epochs (IB Physics - Andy Masley)

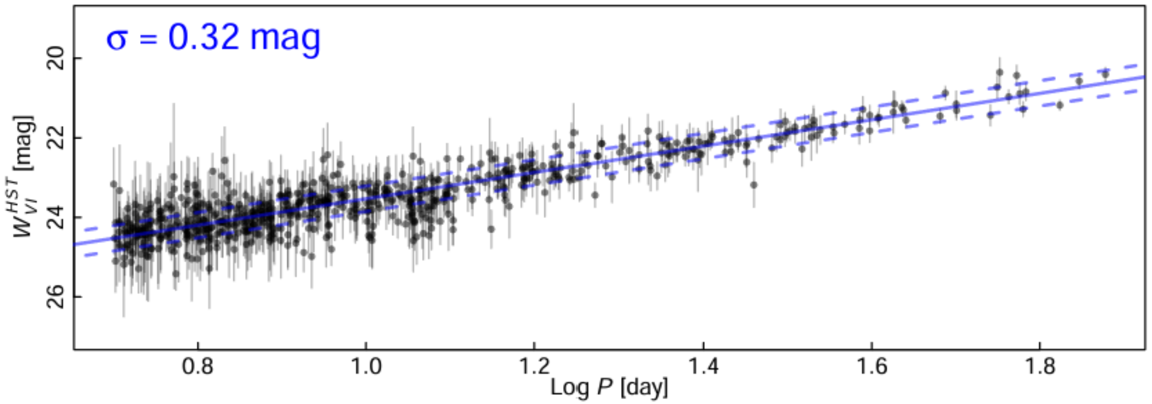
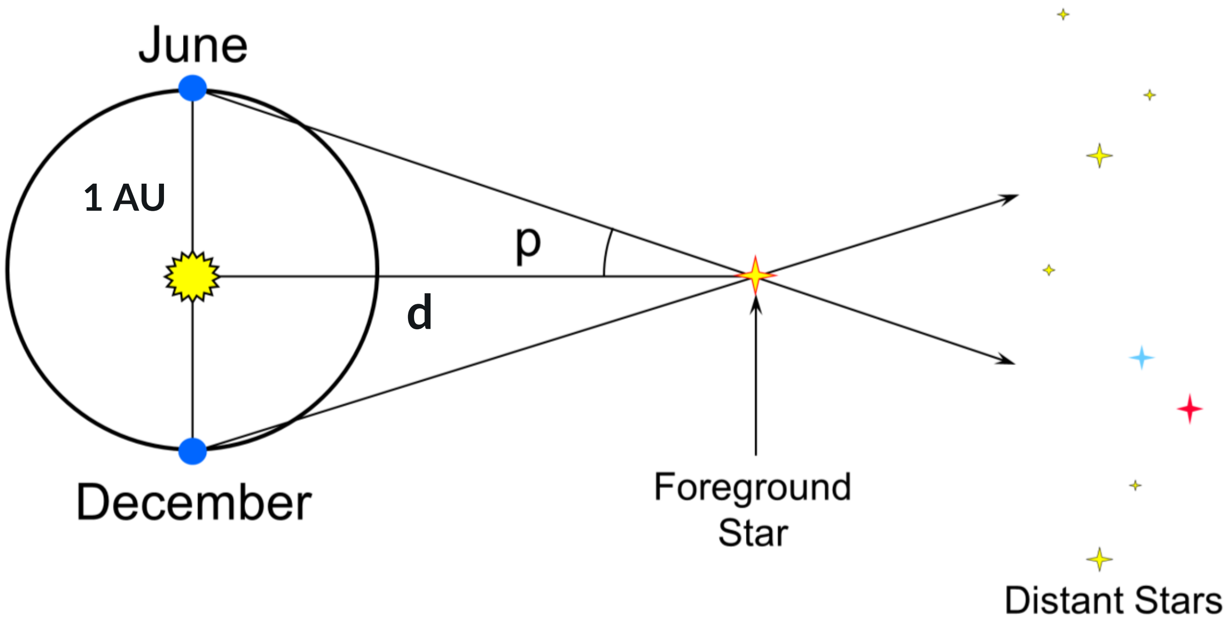


Fig. 15 – Period–Luminosity relation for brightness fluctuations (Yuan W. et al. 2022).

Extra slides (Parallax)



$$d = \frac{1}{p}$$

d = distance to star in parsecs

p = parallax angle of star in arcseconds

Fig. 16 – Parallax scheme (Pogge R., 2014)

Extra slides (Type Ia Supernovae)

SNe Ia result from the thermonuclear explosion of a **carbon-oxygen white dwarf** (C-O WD) **star in a binary system**.

Occurs when the **WD mass approaches the Chandrasehkar limit** ~1.44 M⊙

The accretion of material from another star (Single Degenerate)

Fig. 17 – From NASA's Goddard Space Flight Center Conceptual Image Lab

The merger with a secondary WD (Double Degenerate Channel)

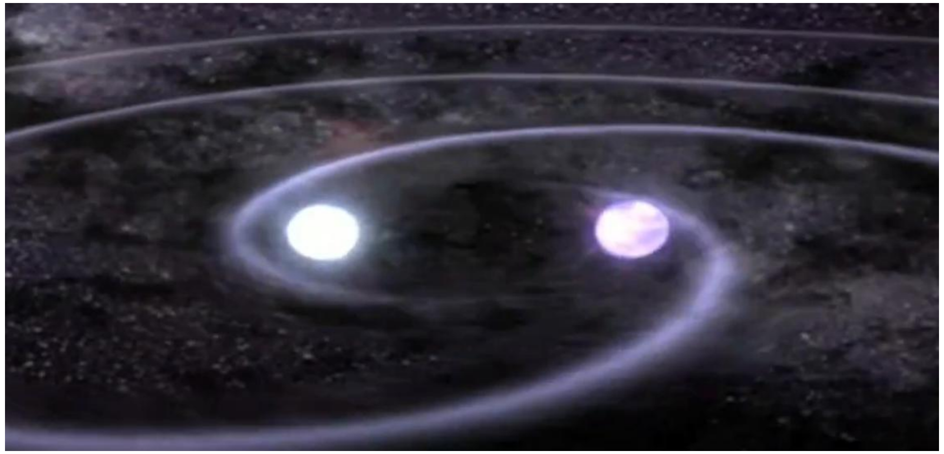
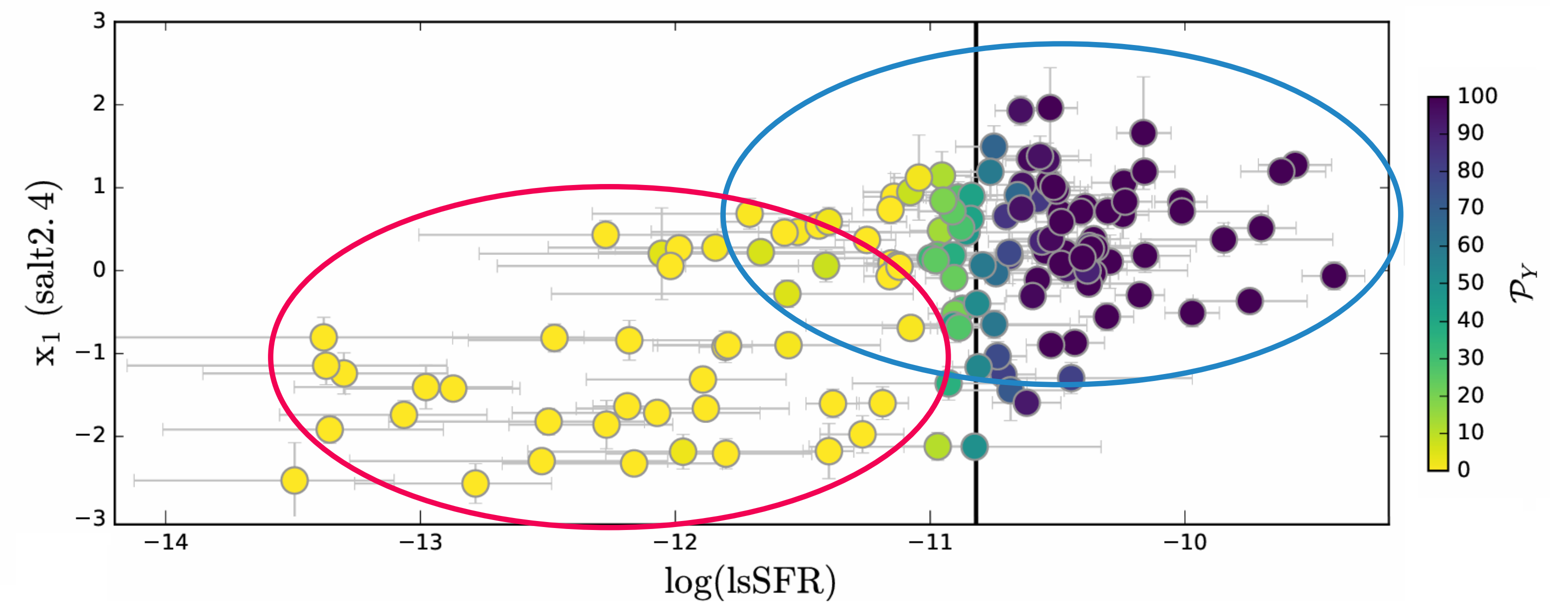


Fig. 18 – From NASA/Goddard Space Flight Center

Extra slides (Progenitors and stretch)

Single degenerated (younger)



Double degenerated (older)

Extra slides (Data)

This compilation includes **repeated SNe corresponding to the same event observed in different survey whose values we decided to unify.**

There are **7 SNe that present values of Log(sSFR) < - 15 yr^{-1}**, which seem to be outliers or upper limits on the true values of this parameter.

2 – Extra slides (Data)

We used the Pantheon + SH0ES compilation of SNe Ia data that provide us:

Values for **SNe properties** such as:

- m_B (**apparent magnitude**) ;
- c (**colour**);
- x_1 (**stretch**);

Values for **host galaxies properties**:

- Log(M/ M⊙) (**stellar mass**);
- Log(sSFR) (**specific star formation rate**) ;

A covariance matrix (C) resulting from the **sum of the statistical and systematic covariance matrixes** including the uncertainties of supernova corrected magnitudes and distances moduli from Cepheids.

Extra slides (Singular measurements for each SNe)

Using the method described in section 8.1.8 of Petersen & Pedersen, "The Matrix Cookbook“ and knowing that the parameters m_B, x_1 and c are given by a Gaussian distribution $\mathcal{N}$ for each duplicated Sne, we have :

$$c\mathcal{N}(\mu, C) = \mathcal{N}(\mu_1, C_1) \cdot \mathcal{N}(\mu_2, C_2)$$

$$\mu = \begin{bmatrix} m_B \\ x_1 \\ c \end{bmatrix} \qquad C = \begin{bmatrix} \sigma^2_{m_B} & Cov(m_B, x_1) & Cov(m_B, c) \\ Cov(x_1, m_B) & \sigma^2_{x_1} & Cov(x_1, c) \\ Cov(c, m_B) & Cov(c, x_1) & \sigma^2_c \end{bmatrix}$$

For duplicated SNe:

$$C = (C_1^{-1} + C_2^{-1})^{-1}$$

$$\mu = (C_1^{-1} + C_2^{-1})^{-1}(C_1^{-1}\mu_1 + C_2^{-1}\mu_2)$$

For SNe repeated N times

$$C = (\sum_{i=1}^{N} C_i^{-1})^{-1} \qquad \mu = C(\sum_{i=1}^{N} C_i^{-1}\mu_i)$$

Extra slides (Repeated SNe)

Columns 0–1: 2011fe; columns 2–3: 2012cg
Rows 0–1: 2011fe; rows 2–3: 2012cg

	0	1	2	3	4	5
0	0.030799	0.005519	0.000516	0.000516	0.000000	0.000273
1	0.005519	0.031101	0.000516	0.000516	0.000000	0.000273
2	0.000516	0.000516	0.057606	0.052820	0.000000	0.000297
3	0.000516	0.000516	0.052820	0.068787	0.000000	0.000297
4	0.000000	0.000000	0.000000	0.000000	0.384772	0.000000
5	0.000273	0.000273	0.000297	0.000297	0.000000	0.022987

Extra slides (Methodology)

From Dhawan et al. 2018 and Duarte J. González-Gaitan S. et al., 2023, we can define the likelihood function as:

$$ln(\mathcal{L}) = -\frac{1}{2}\sum_{i=0}^{N}[\Delta\xi_i + ln(2\pi\sigma_i^2)]$$

With σ now being the diagonal of the systematical and statistical covariance matrix C from the Pantheon+SH0ES data without duplicated SNe and Δξ the solution of the following system of linear equations:

$$\Delta\mu = C\Delta\xi \Leftrightarrow \Delta\xi = C^{-1}\Delta\mu$$

and

$$\Delta\mu = m_B^{corr} - M - \mu \text{ with } \mu = \begin{cases} \mu_{Ceph} & \text{, for calibrators} \\ 5\log_{10}\left(\frac{c}{H_0}z\left[1+\frac{1}{2}(1-q_0)z - \frac{1}{6}(1-q_0-3q_0^2+j_0)z^2\right]\right) + 25 & \text{, for HF SNe} \end{cases}$$

With $q_0 = -0.51$ and $j_0 = 1$

Extra slides (Methodology)

We want to obtain our own α, β, Δhost and σ_{int} , as well as H_0 and M_B.

Tripp modified correction formula:

$$\mu = m_B^{corr} - M_B = m_B - M_B + \alpha x_1 - \beta c + \delta_{host}$$

$$\beta c \rightarrow \beta_{\text{int}} c_{\text{int}} \qquad (R_V + 1)E(B - V)$$

We do **not apply** any of the usual **bias correction** related to **the SNe intrinsic colour or dust reddening and extinction models** as we want to **reduce these effects naturally** with the **samples matching**!

The i-th term of the diagonal of the statistical covariance matrix C is given by :

$$\sigma_i^2 = \sigma_{m_B}^2 + (\alpha\sigma_{x_1})^2 + (\beta\sigma_c)^2 - 2\beta\sigma_{m_B,c} + 2\alpha\sigma_{m_B,x_1} - 2\alpha\beta\sigma_{x_1,c} - \sigma_{int}^2 + \sigma_{lens}^2 + \sigma_z^2 + \sigma_{vpec}^2$$

We need to subtract the α = 0.148 and β = 3.112 (Brout D. 2022) terms and define them as free parameters!

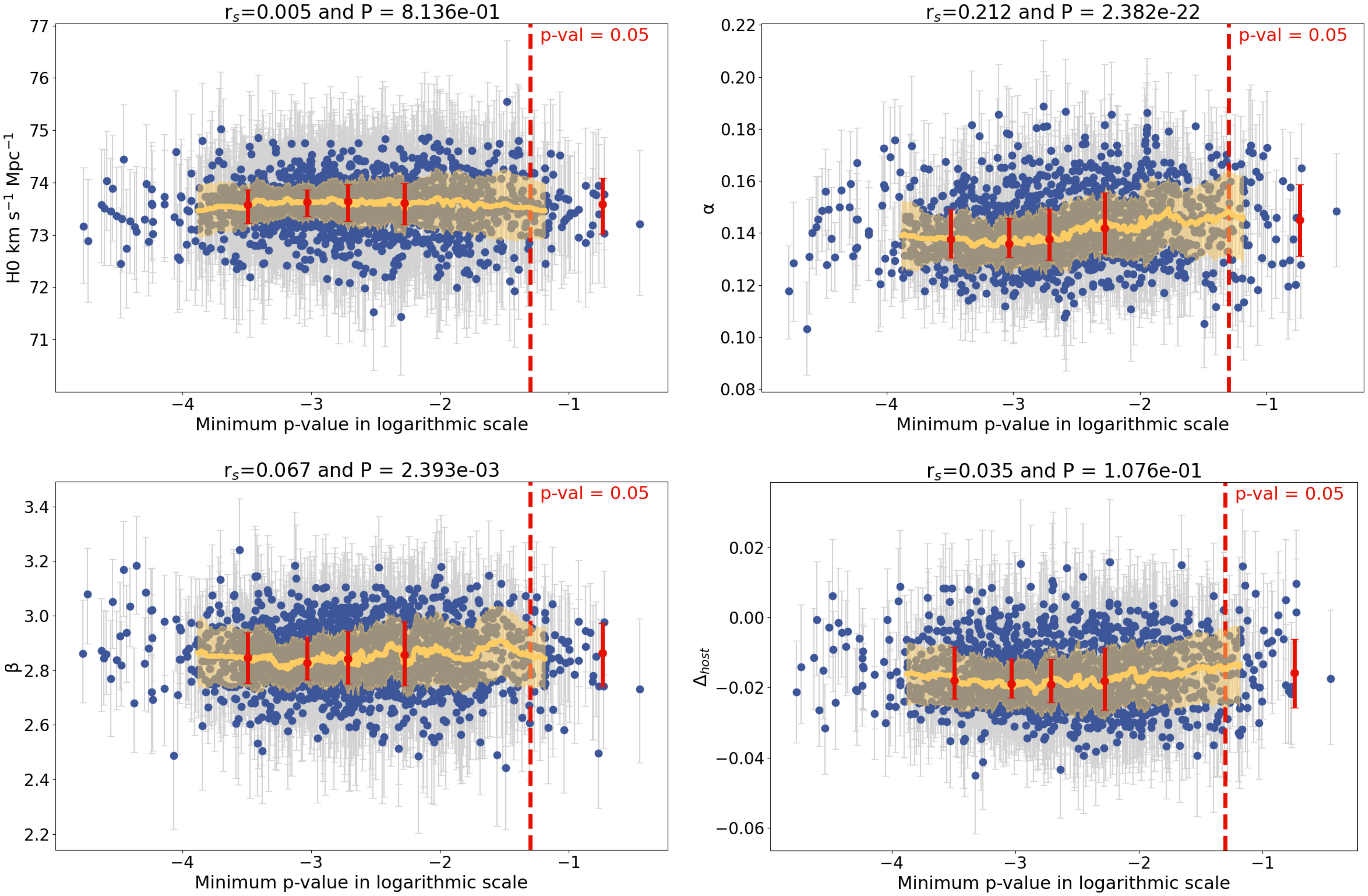


Fig. 19 - H0, α, β, and Δhost as a function of the minimum p-value obtained comparing each generated subsample with the full calibration sample.

Extra slides (Underestimating the H_0 Uncertainty)

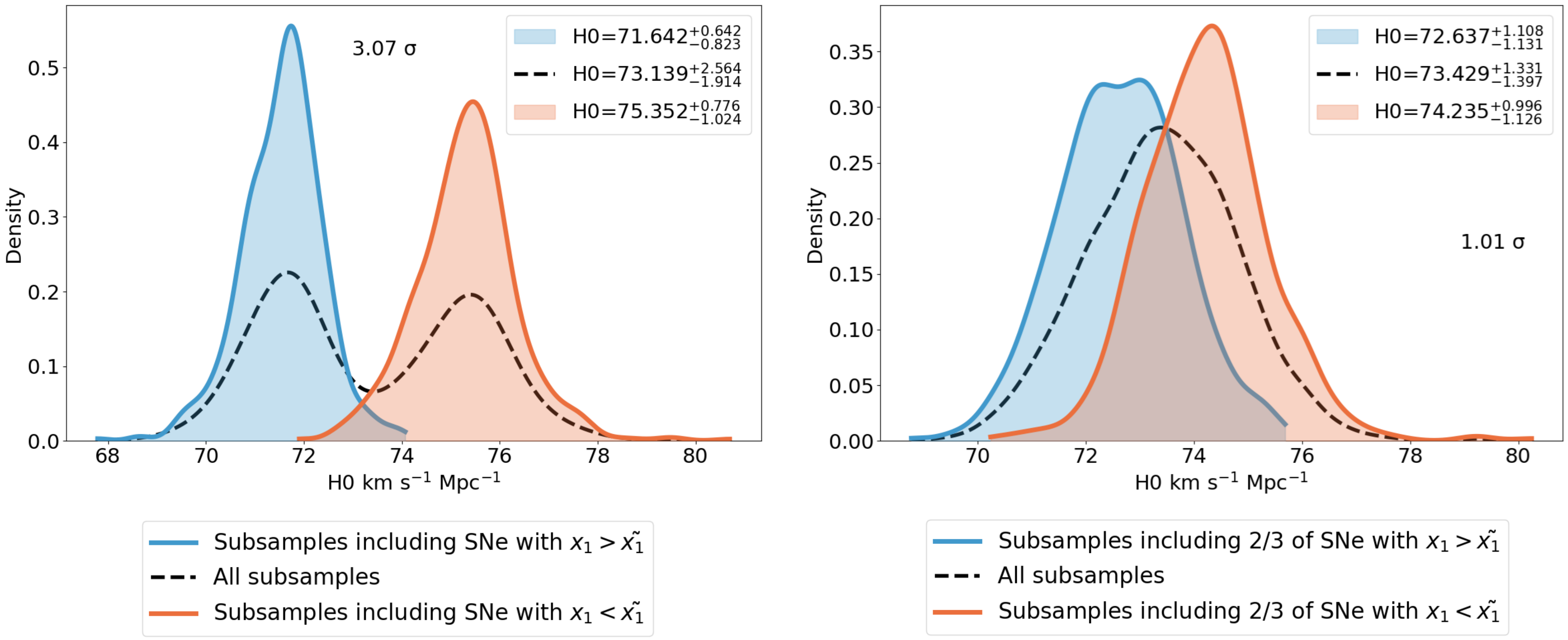


Fig 20 - Probability density function of the H_0 distribution from subsamples containing only SNe with x1 above or below the median stretch and subsamples including 2/3 of SNe from one stretch bin and 1/3 from the opposite bin.