# Intrinsic tension in the supernova sector of the local Hubble constant measurement and its implications

**CosmoVerse@Lisbon**

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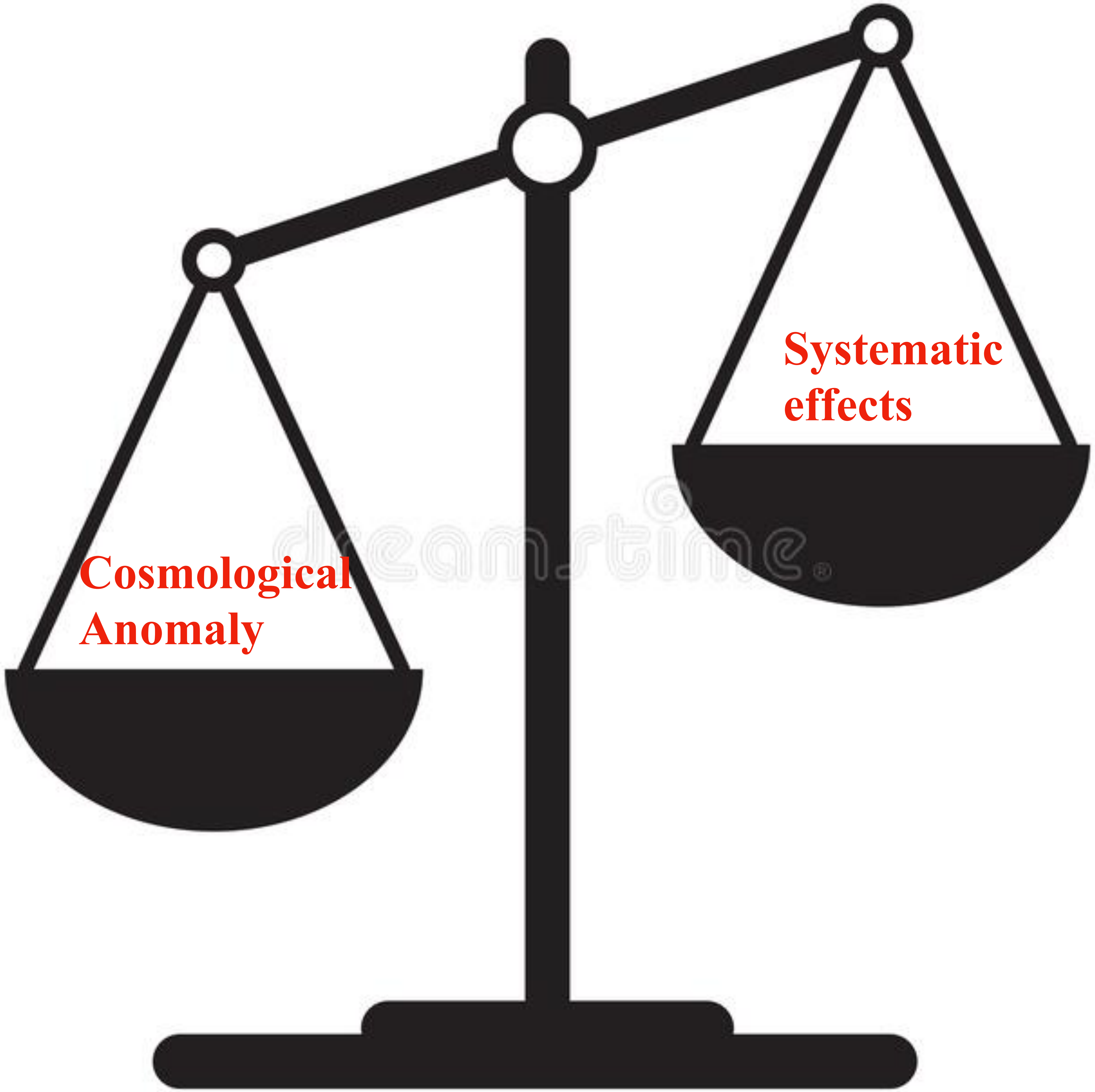
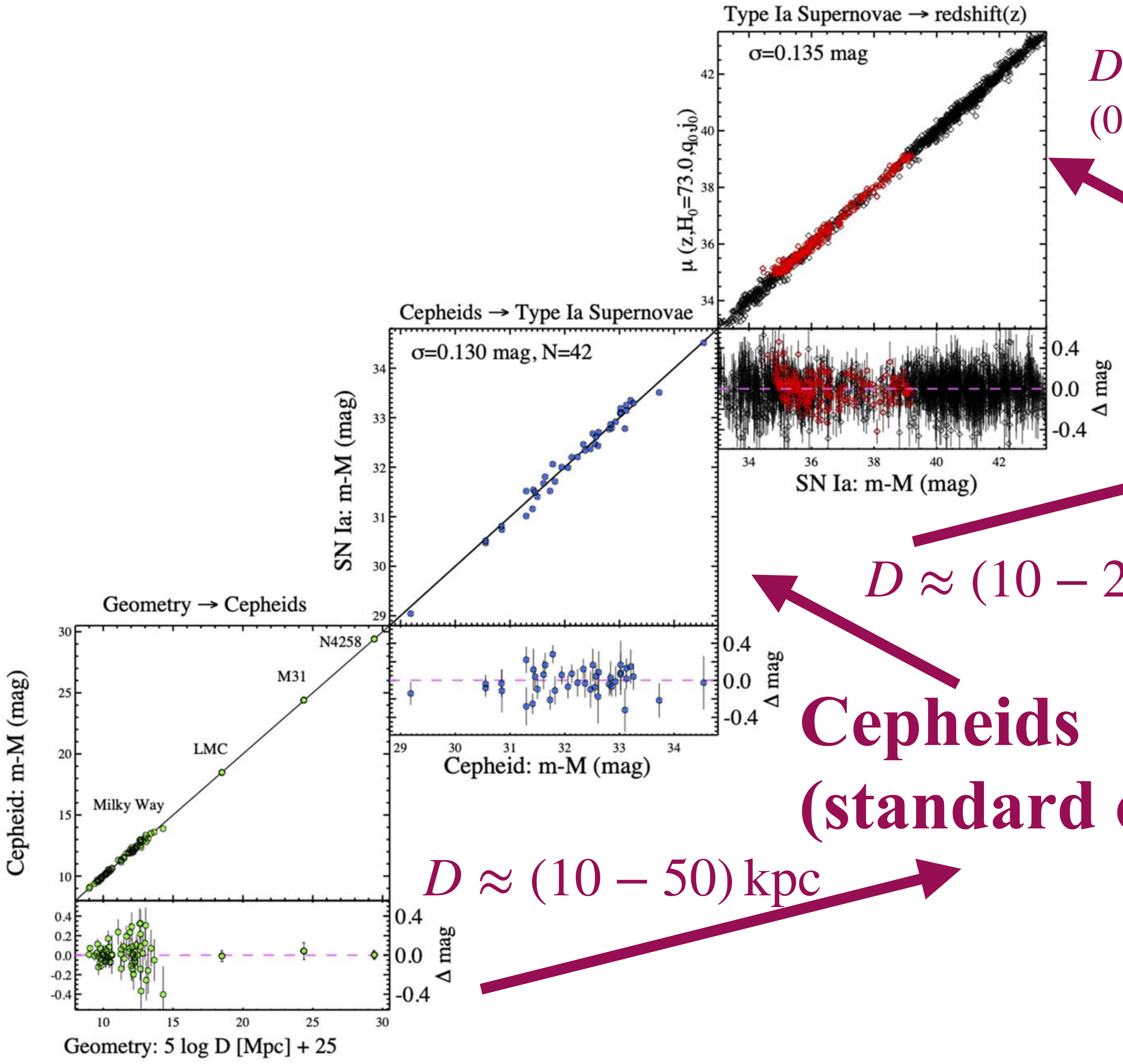
# The $H_0$ tension: 8% rel. difference, 5$\sigma$ significance

SH0ES: $H_0 = 73.04 \pm 1.04\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

Planck(+flat $\Lambda$CDM): $H_0 = 67.4 \pm 0.5\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

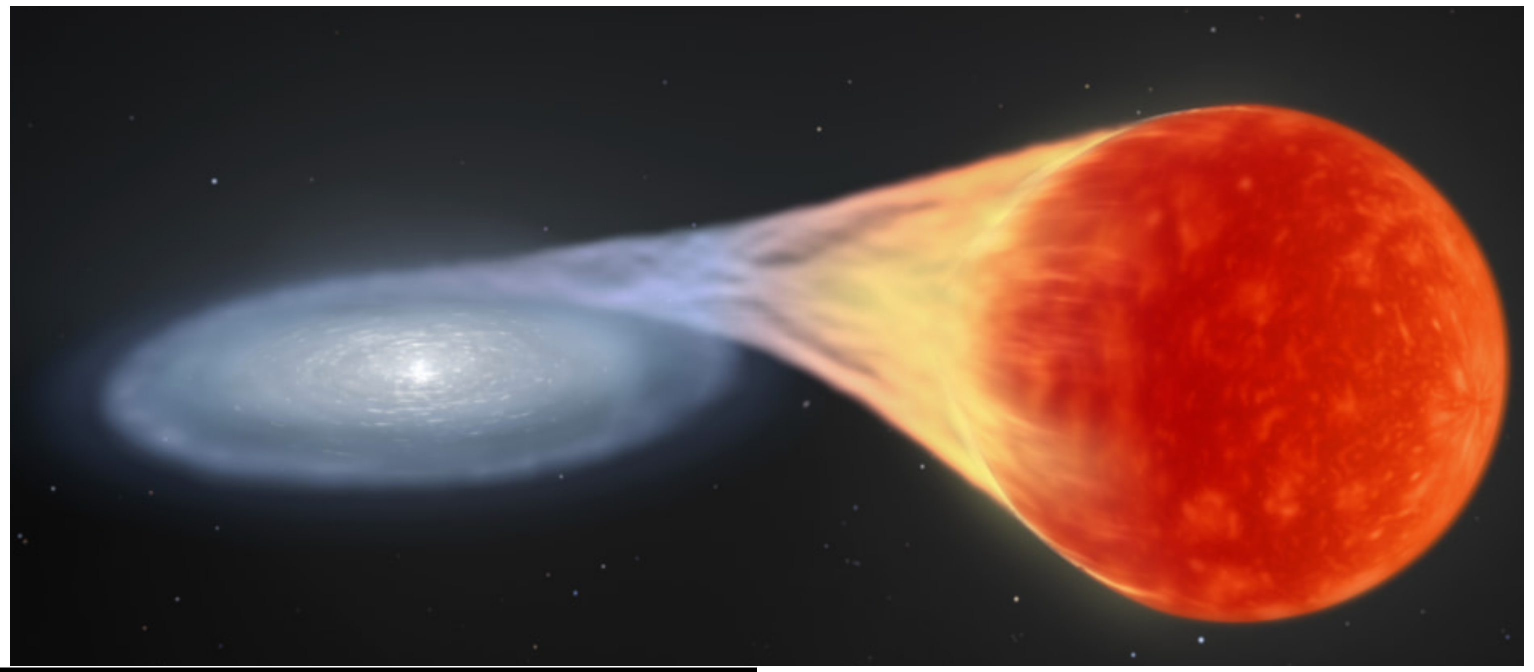

Systematic effects
Cosmological Anomaly

# Direct/local $H_0$: distance ladder



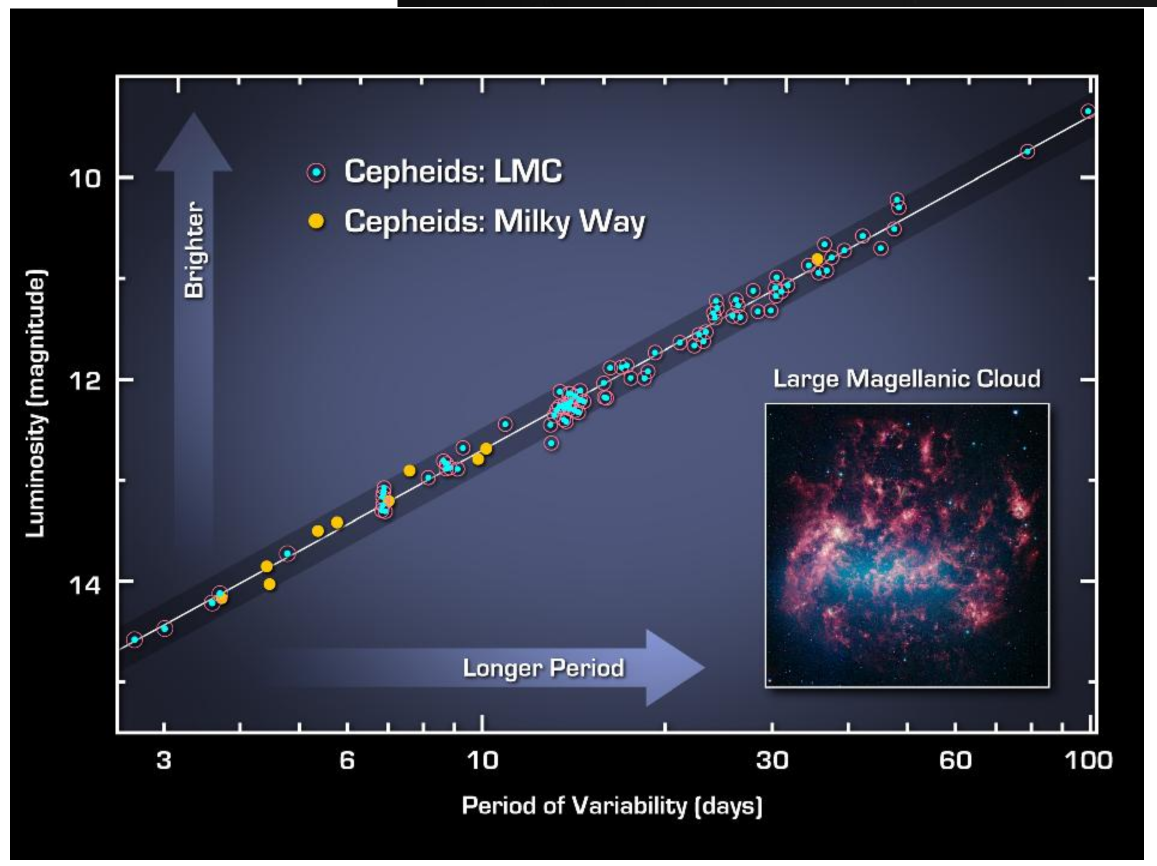

$D \approx (100 - 500)$ Mpc
$(0.023 < z < 0.13)$

**Type Ia supernovae (Standardisable candles)**



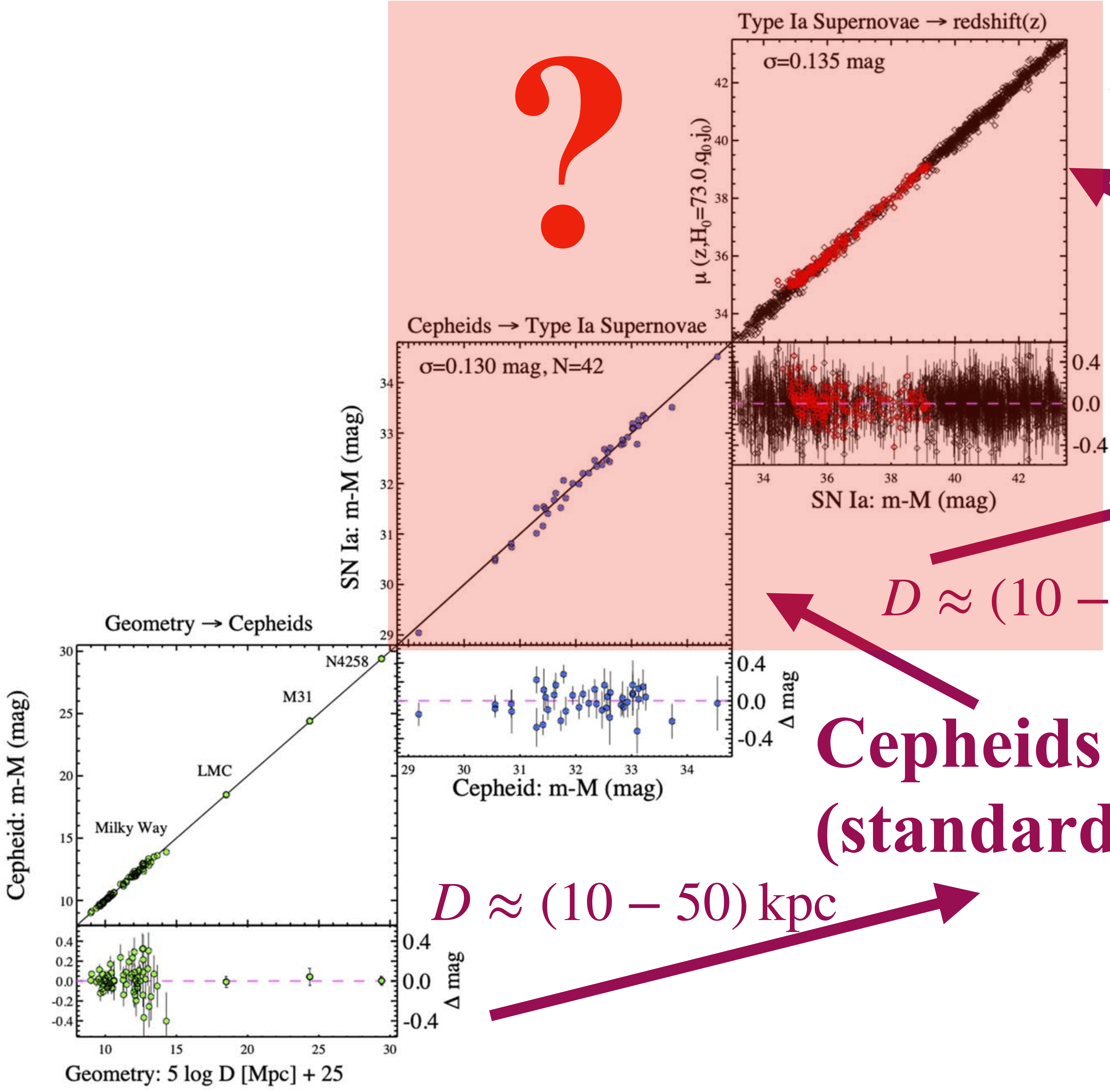
$D \approx (10 - 20)$ Mpc

**Cepheids (standard candles)**




$D \approx (10 - 50)$ kpc

# Direct/local $H_0$: distance ladder

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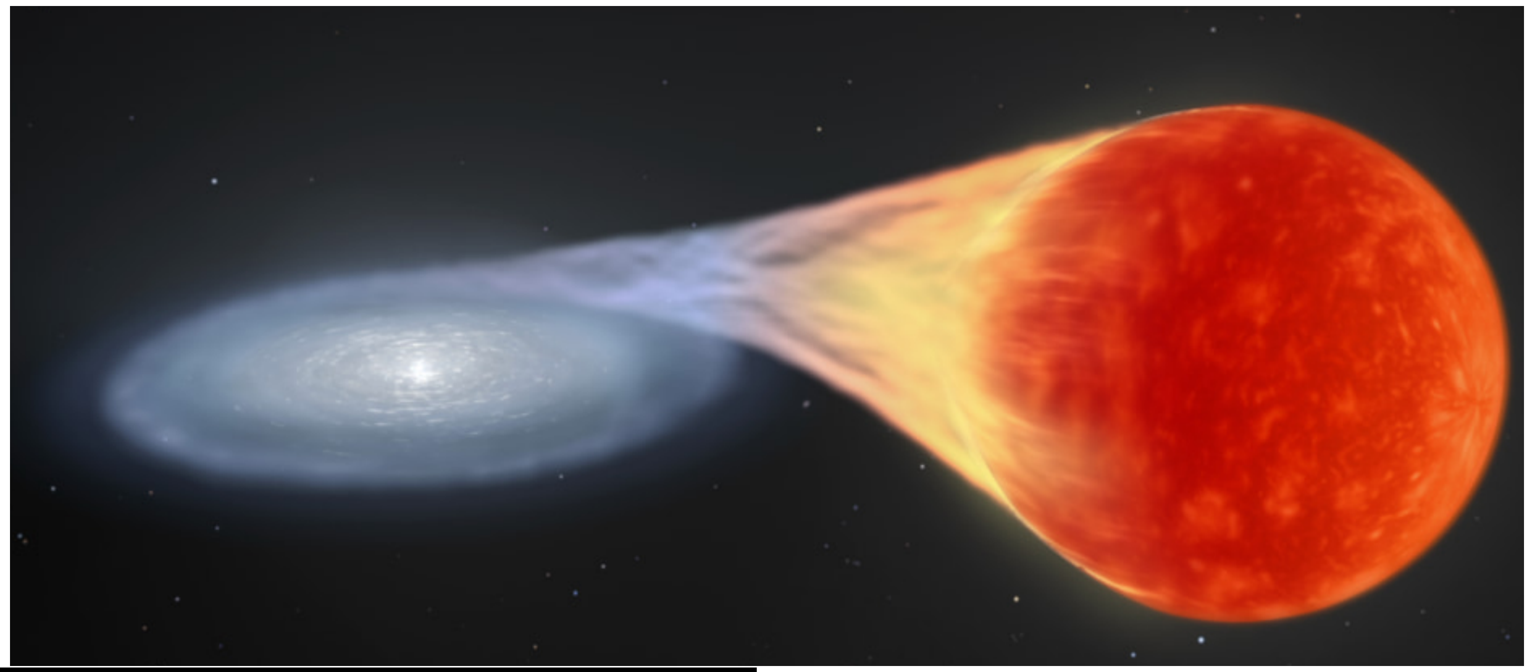

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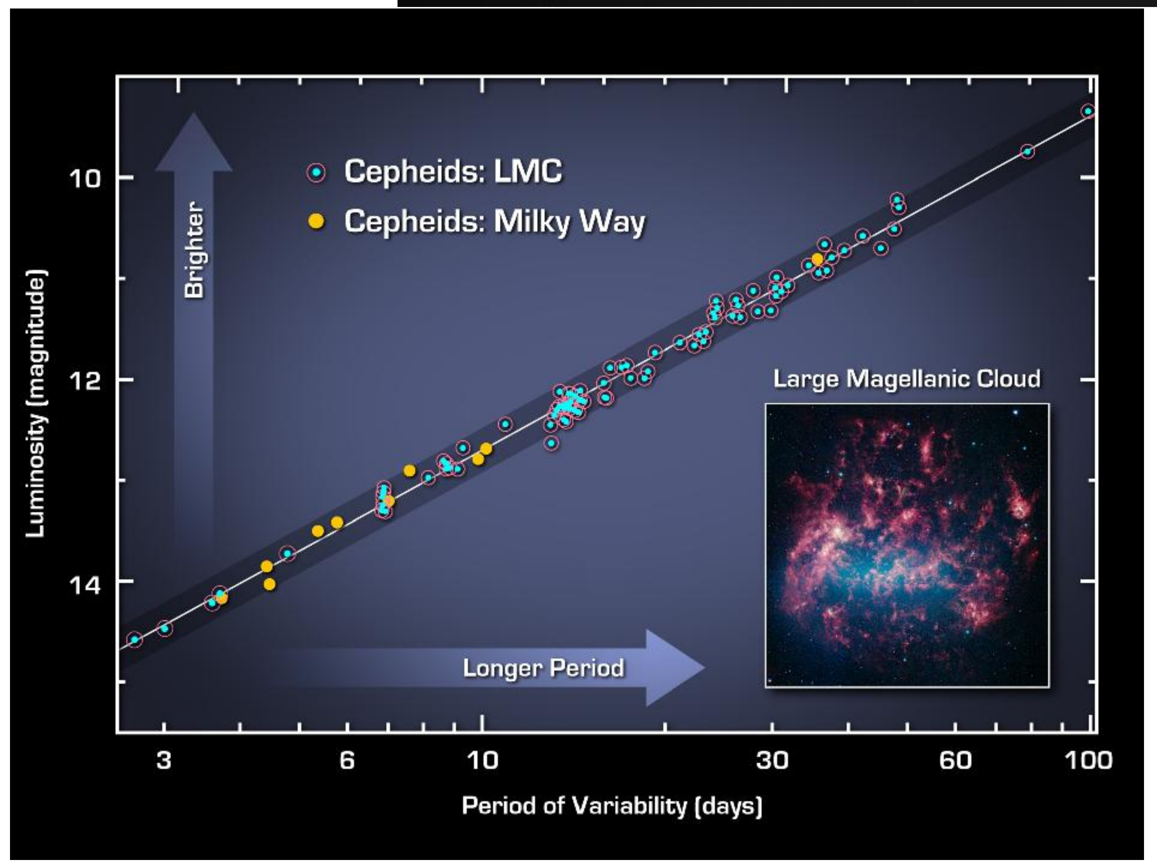
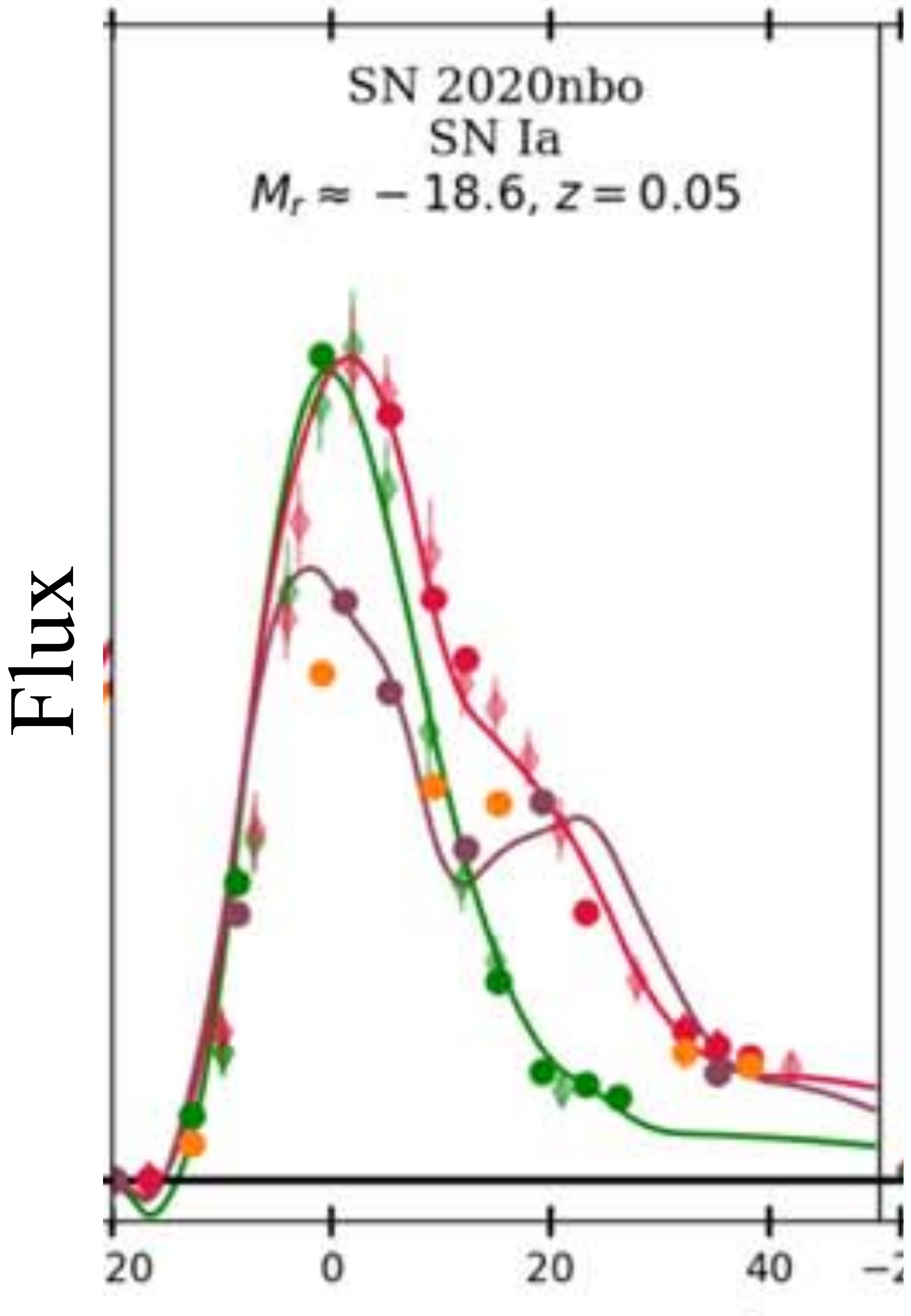


# Type Ia SN: light curve parameters

Light curves




Empirical models
Based on observed SEDs(t)

Light Curve Fitting

Light curve parameters:

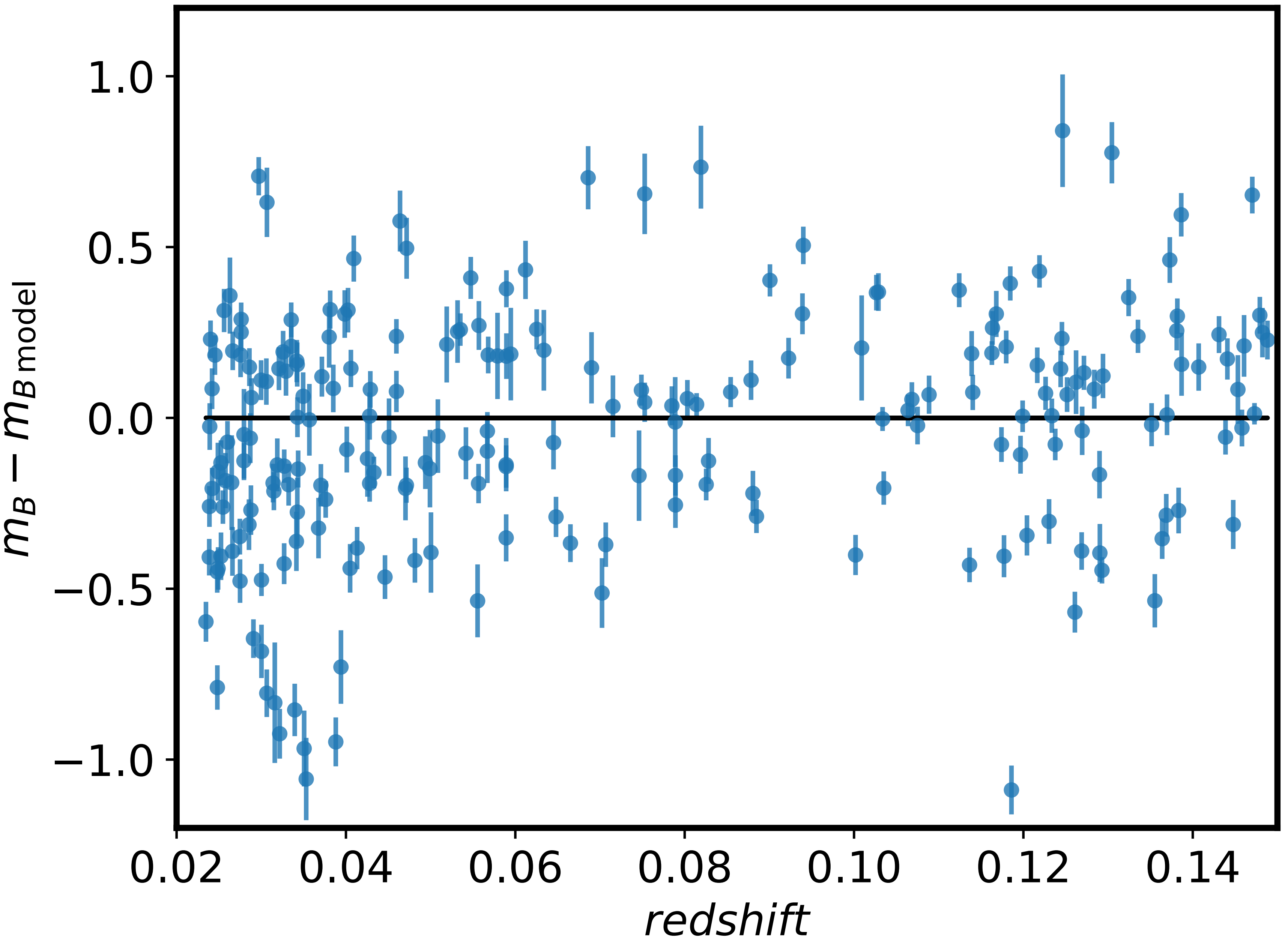
Peak mag (B band): $m_B$

Shape parameter (width/rate decline): $x_1$

Observed colour (B-V): $c$

# Type Ia SN: standardisation

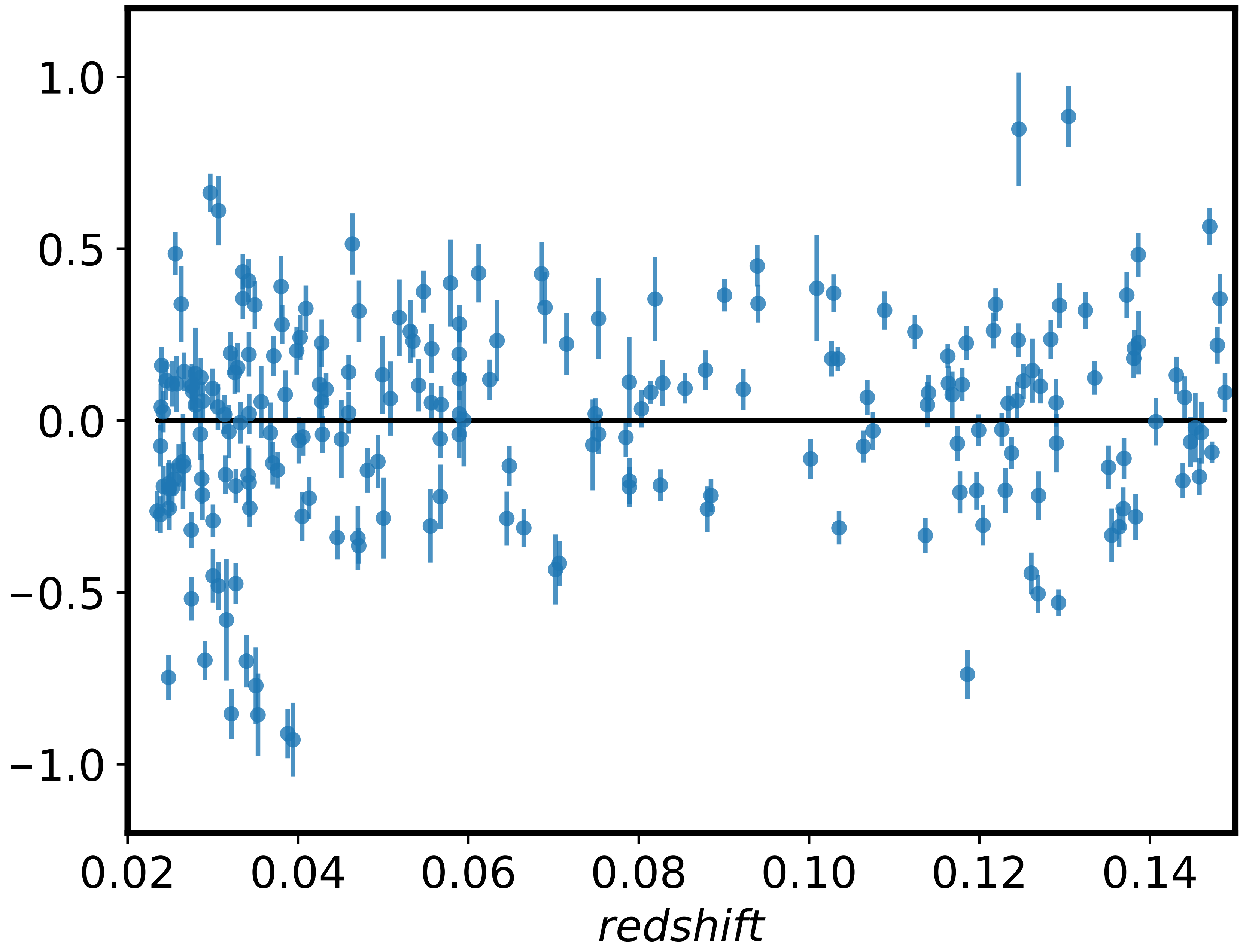
$$m_{\text{model}} = M_{\text{B}} + \mu(z)$$




$\sigma_{\text{int}} \approx 0.32$ mag

$$m_{\text{model}} = M_{\text{B}} + \mu(z) + \alpha x_1$$

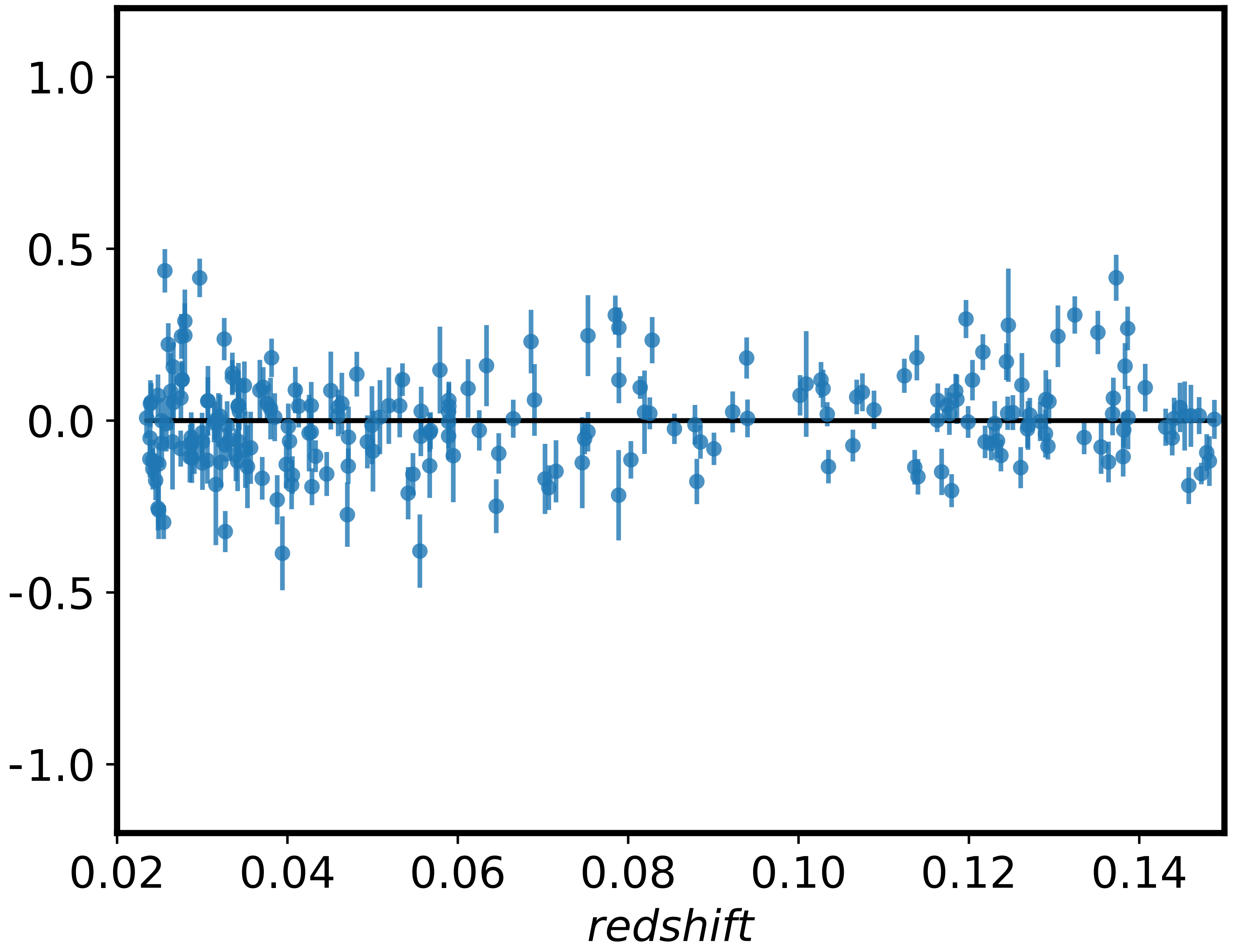
**Phillips relation (Phillips 1995)**




$\sigma_{\text{int}} \approx 0.27$ mag

$$m_{\text{model}} = M_{\text{B}} + \mu(z) + \alpha x_1 + \beta c$$

**Tripp calibration (Tripp 1998)**



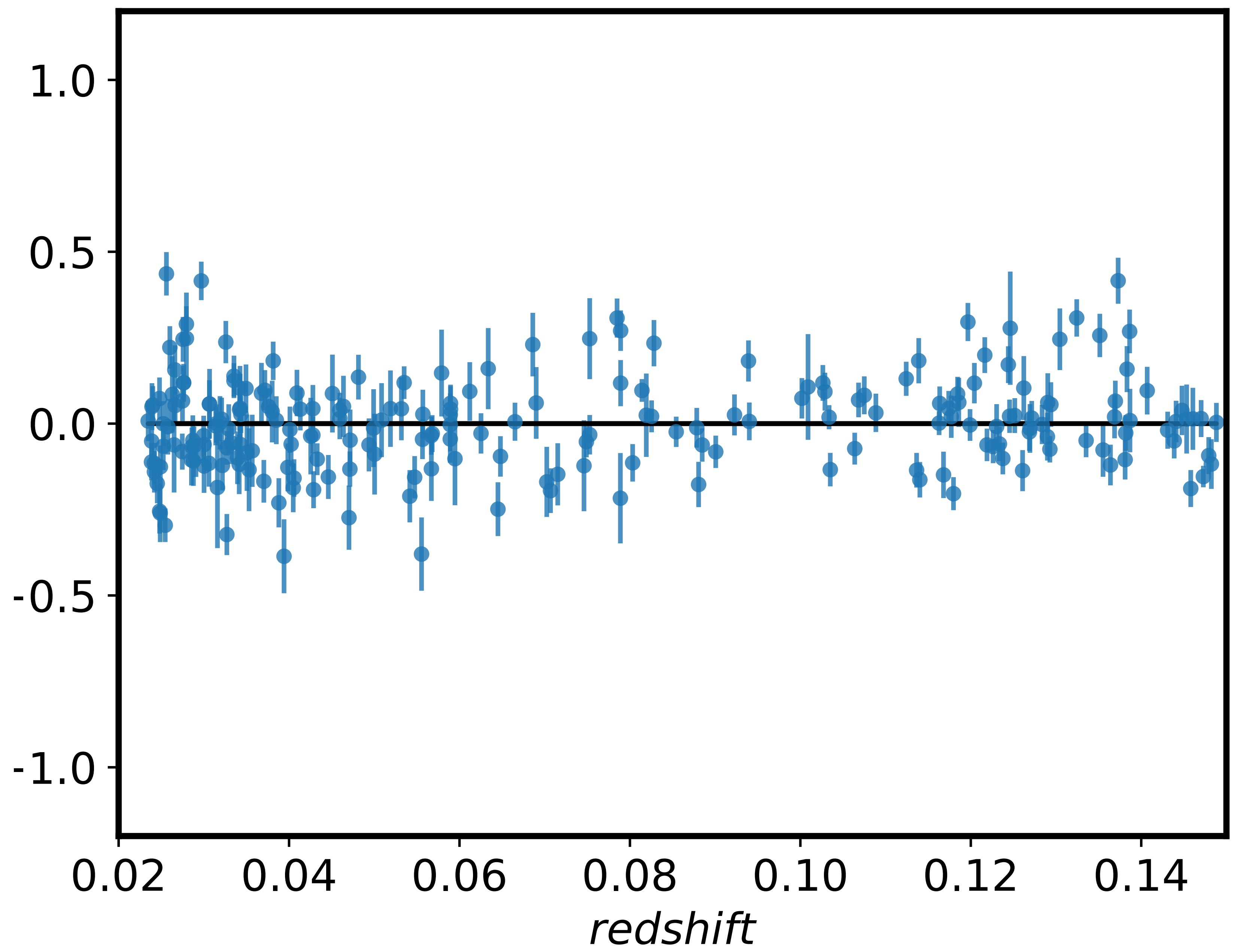

Irreducible intrinsic scatter:
$\sigma_{\text{int}} = 0.12$ mag

# Type Ia SN: “standard” standardisation

**Fitting strategy: cosmology + Tripp calibration +$\sigma_{\rm int}$**

$$m_{\rm model} = M_{\rm B} + \mu(z) + \alpha x_1 + \beta c$$

**Tripp calibration (Tripp 1998)**




Irreducible intrinsic scatter:
$\sigma_{\rm int} = 0.12$ mag

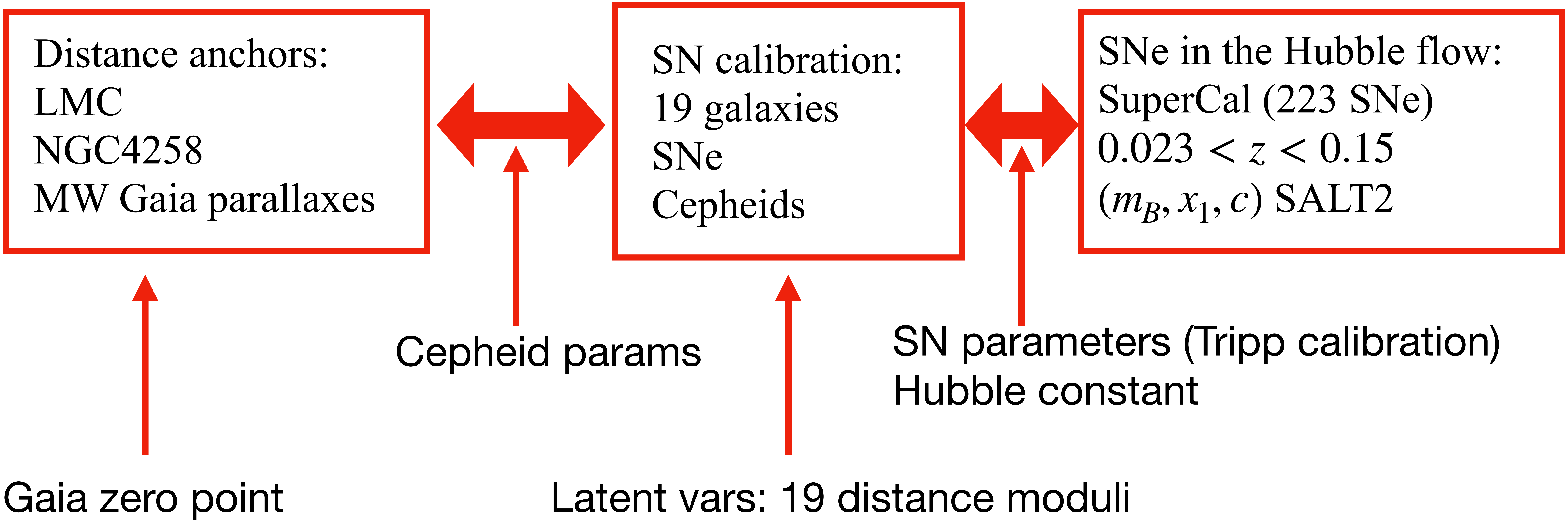
**(Implicit) assumptions:**

- **Tripp calibration is universal across redshift and SN samples (calibration vs Hubble flow)**
- **Distribution of latent variable(s) behind intrinsic scatter is universal across redshift and SN samples: we can effectively decrease error in distance as $\sigma_{\rm int}/N^{1/2}$**

**Unresolved problems:**

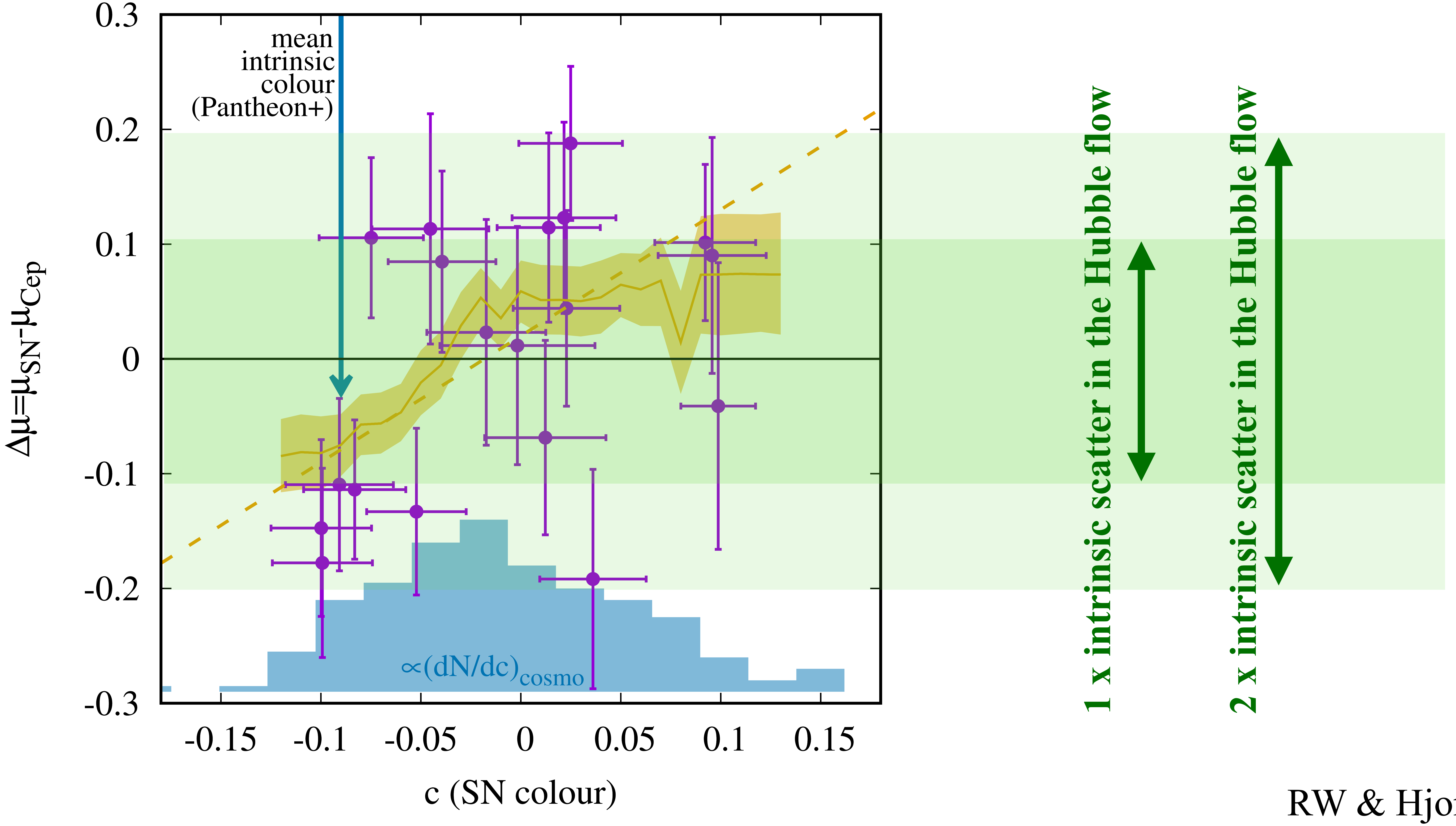
- **Physical origin of intrinsic scatter**
- **Physical origin of the colour correction: extinction in SN host galaxy vs intrinsic colour**
- **The role of basic physical properties, e.g. two progenitor channels**

# (Pre 2022) SH0ES data and global likelihood




$$L \propto L_{\rm LMC} \times L_{\rm MW} \times L_{\rm cal} \times L_{4258} \times L_{\rm LMC\,dist} \times L_{\rm SN\,cal} \times L_{\rm SN}$$

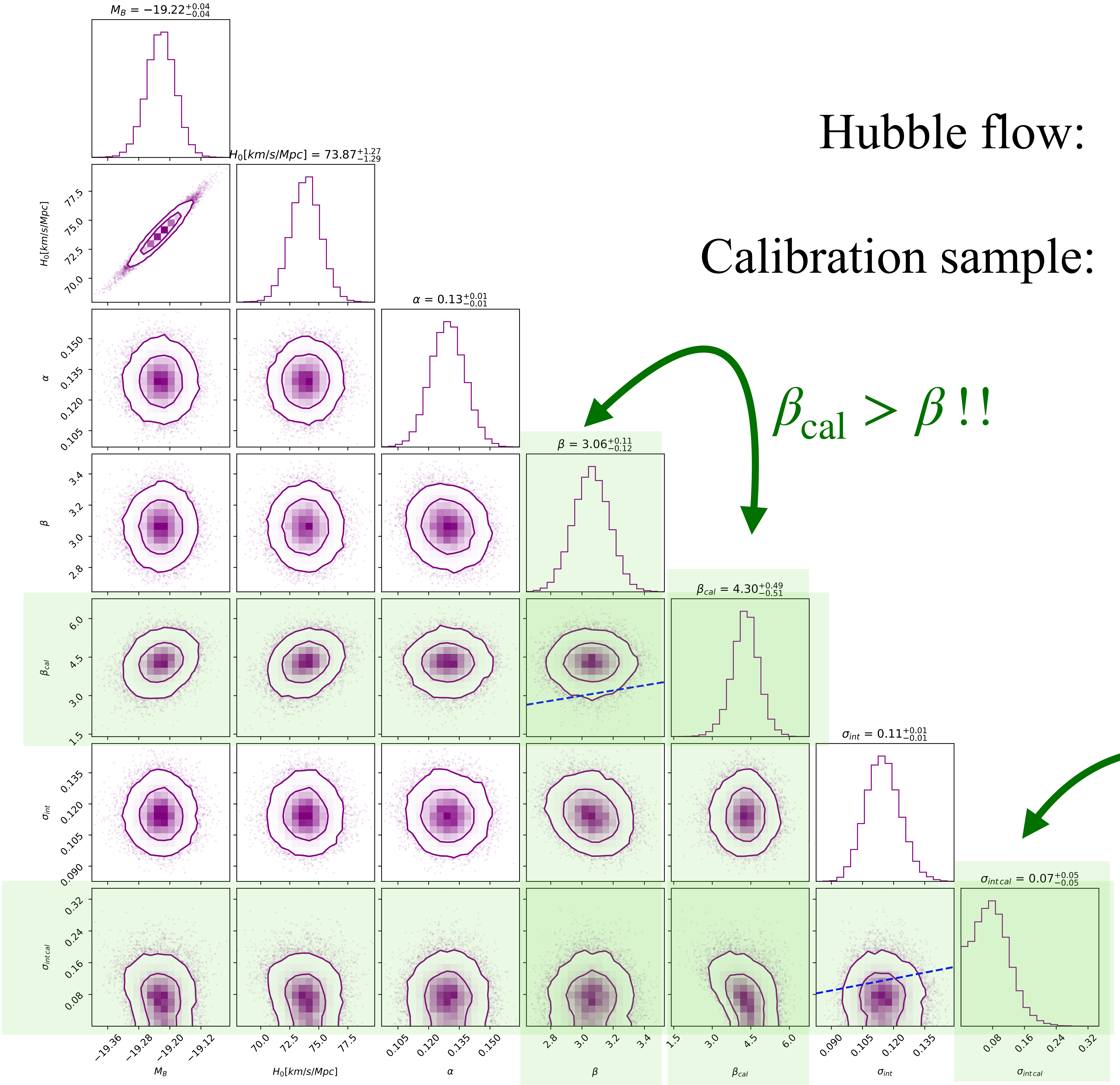
# Anomaly in the calibration sample




RW & Hjorth (2022)

Hubble flow: $m_B = M_B - \alpha x_1 + \beta c$

Calibration sample: $m_B = M_B - \alpha x_1 + \beta_{\rm cal} c$




$\beta_{\rm cal} > \beta$ !!

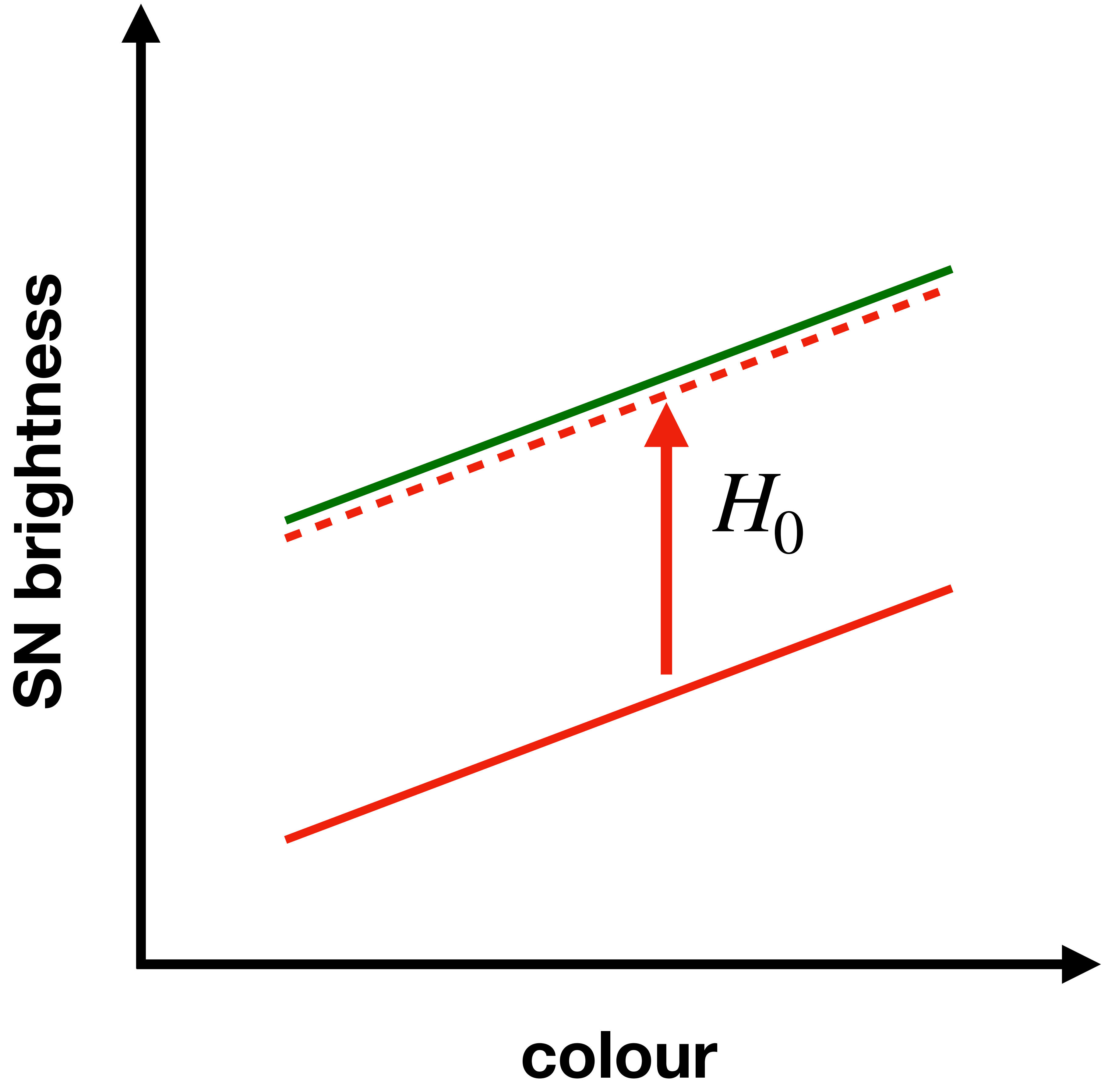
$\sigma_{\rm int,cal} = 0$ !!

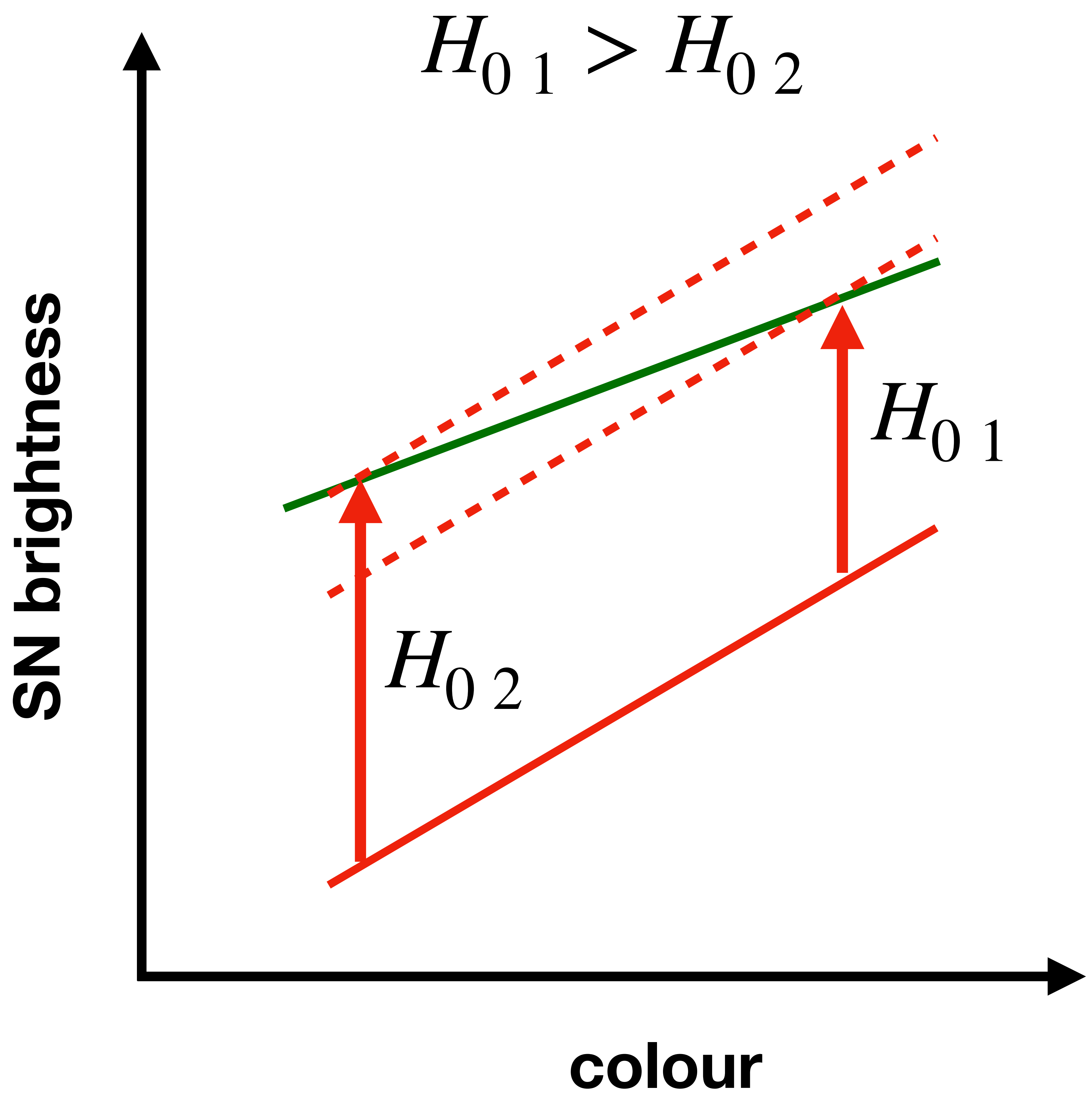
RW & Hjorth (2022)

4.2$\sigma$ (19 cals) Hubble constant tension
goes together with
3.8$\sigma$ intrinsic anomaly
of the SN standardisation.

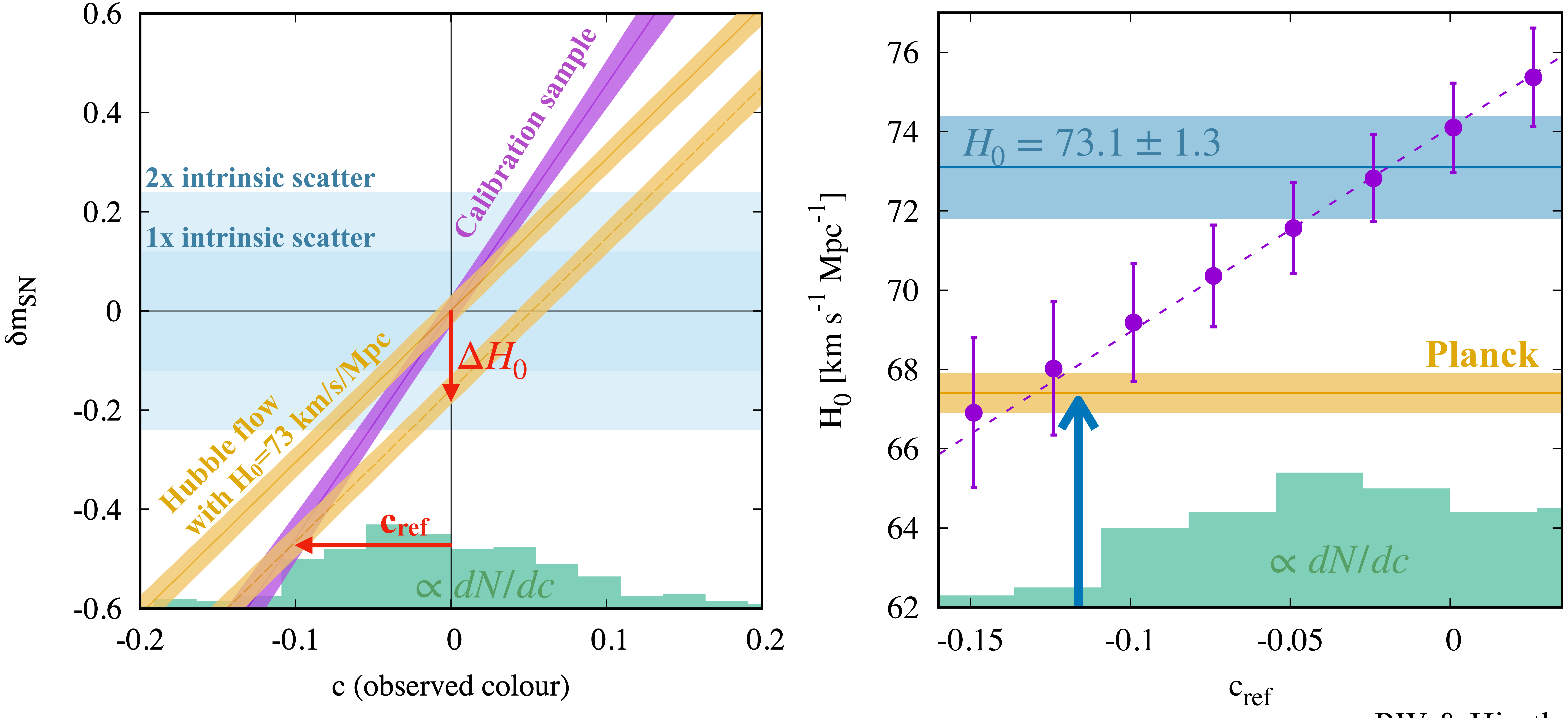
RW & Hjorth (2022)

# Deriving $H_0$: underdetermined problem



# Hubble constant determination : proof-of-concept

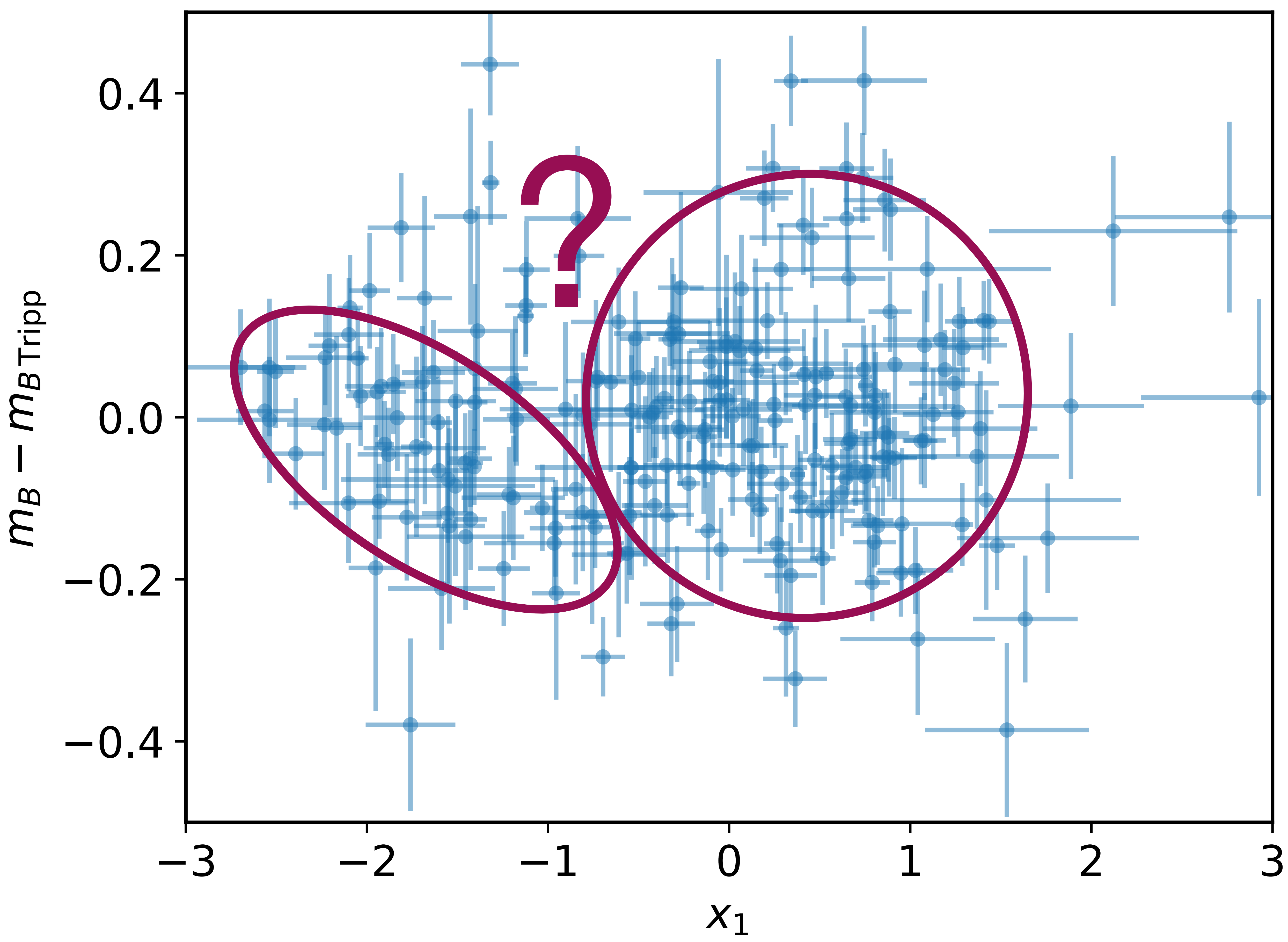


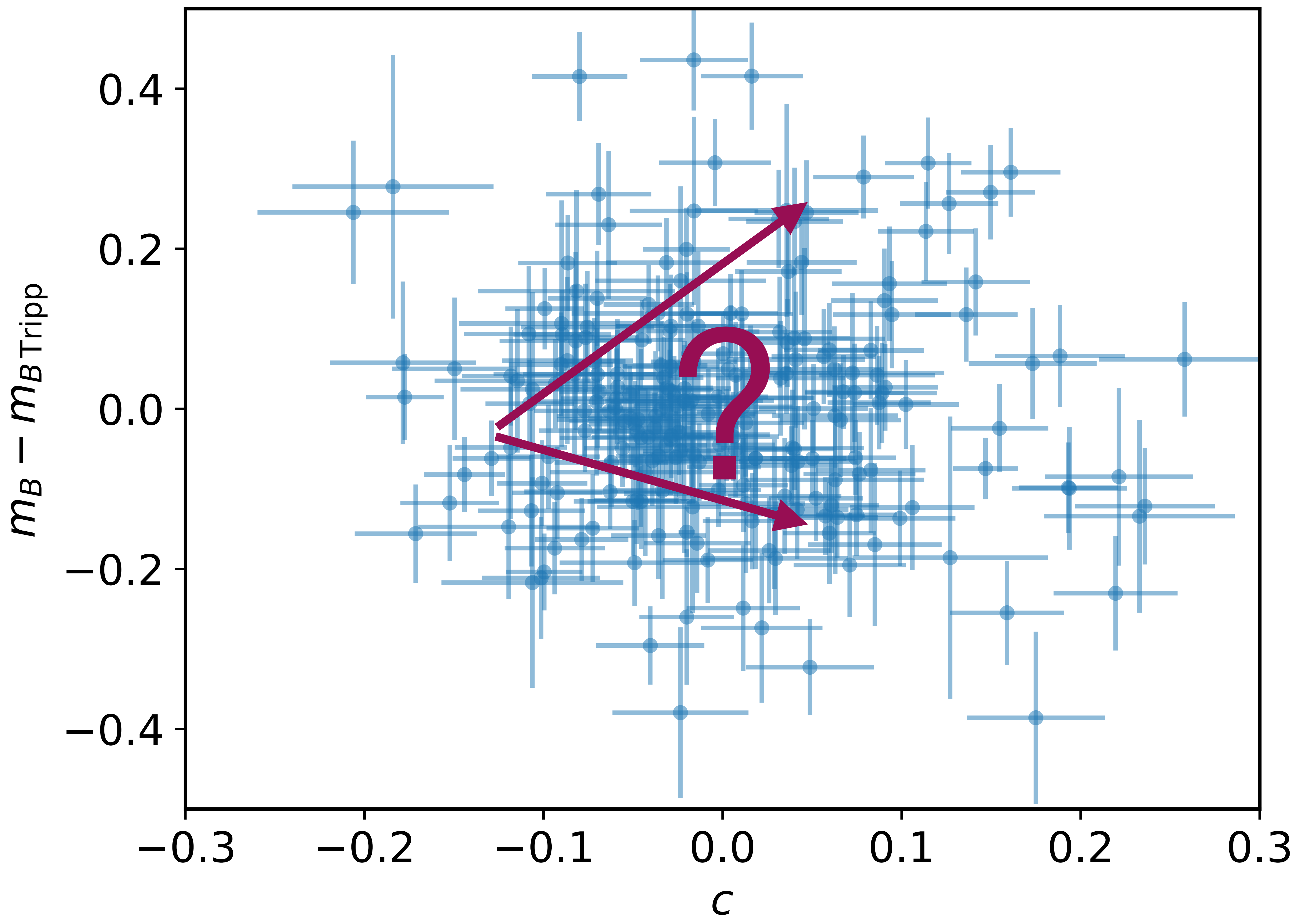

RW & Hjorth (2022)

The local Hubble constant measurement recovers the Planck value when SN mag-colour relations are matched at blue colours ($c \approx -0.12$).

RW & Hjorth (2022)

# The key is to understand Hubble residuals !



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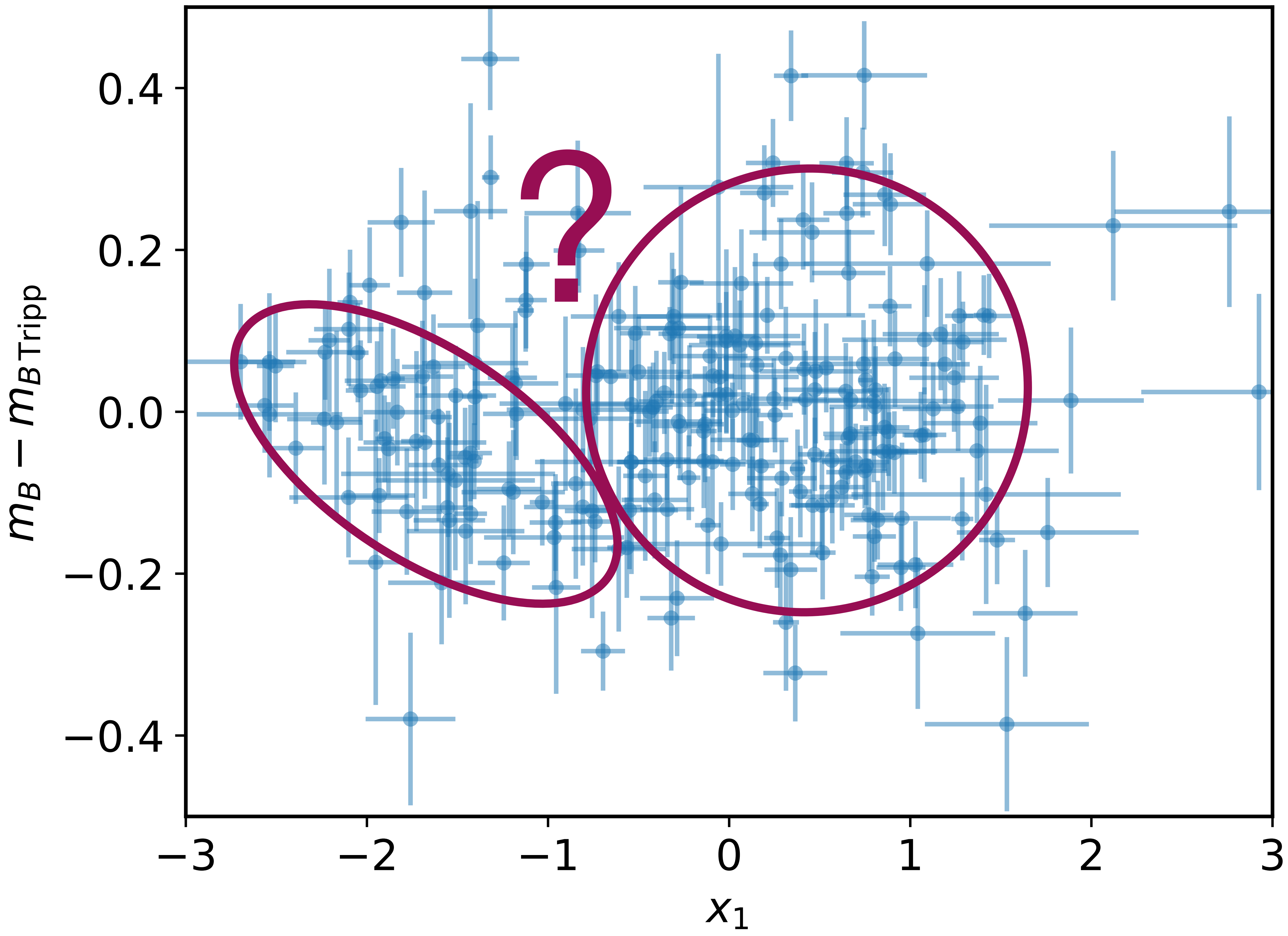
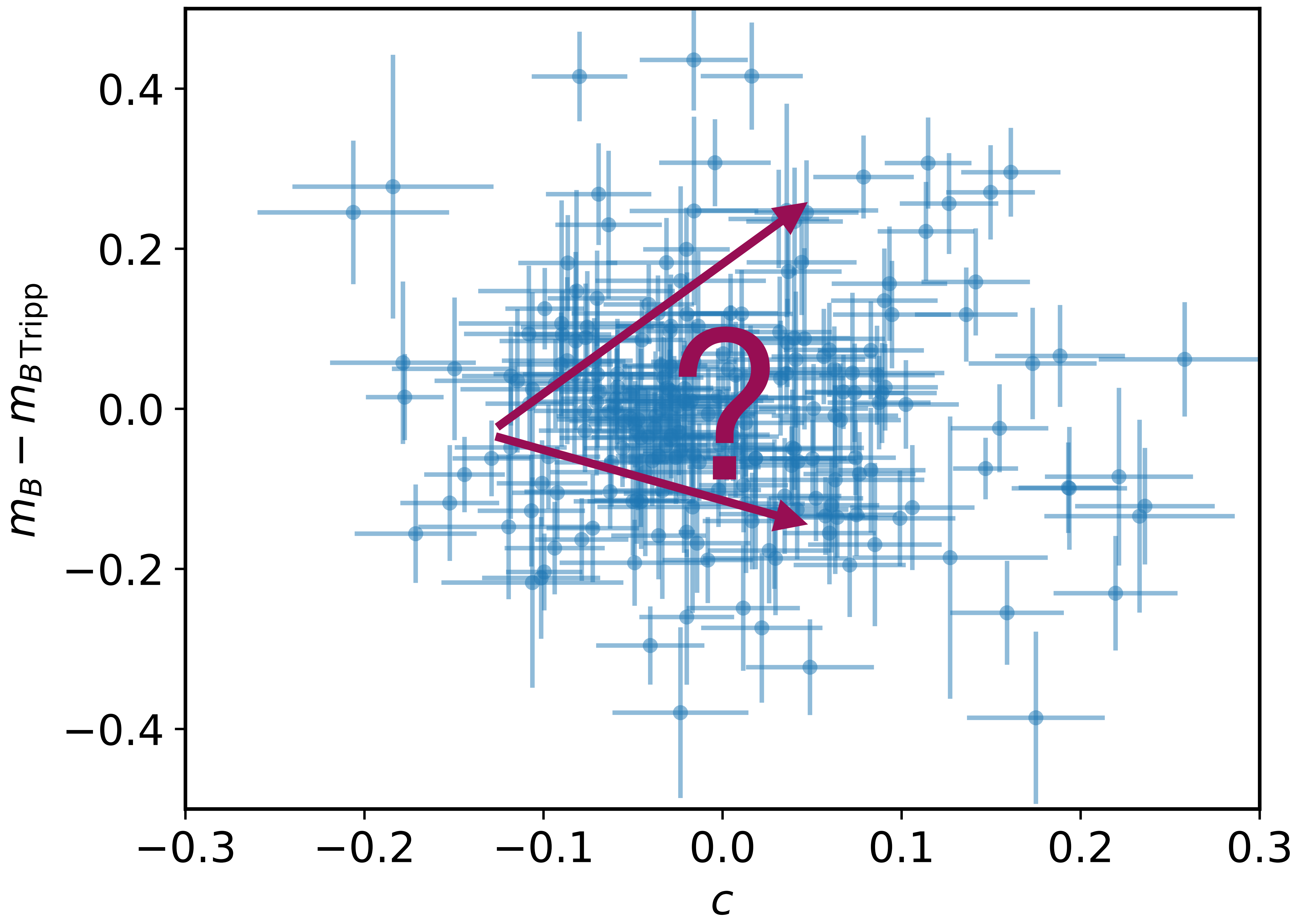


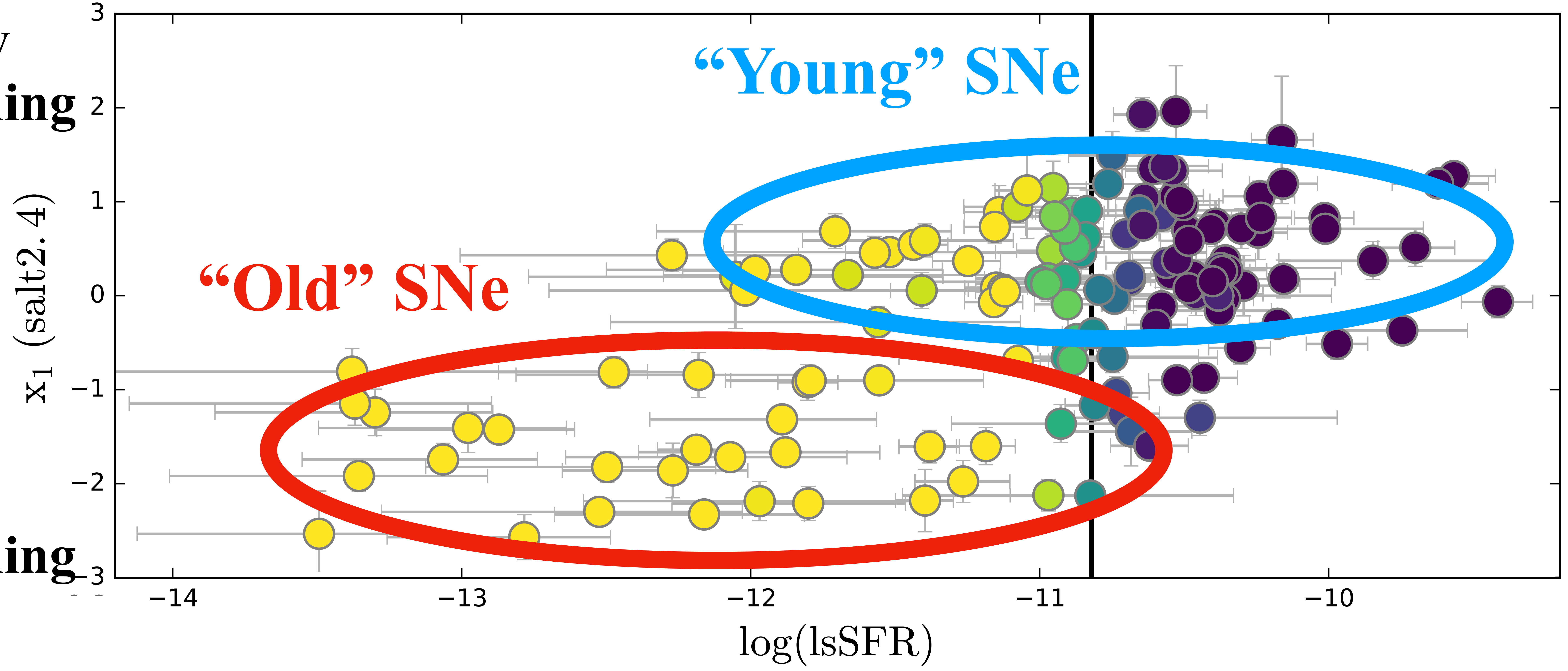




**Dust: reddening, extinction**

**Mandel et al. (2017), Thorp et al. (2021), Brout & Scolnic (2020)**

# SN populations

Slowly Declining

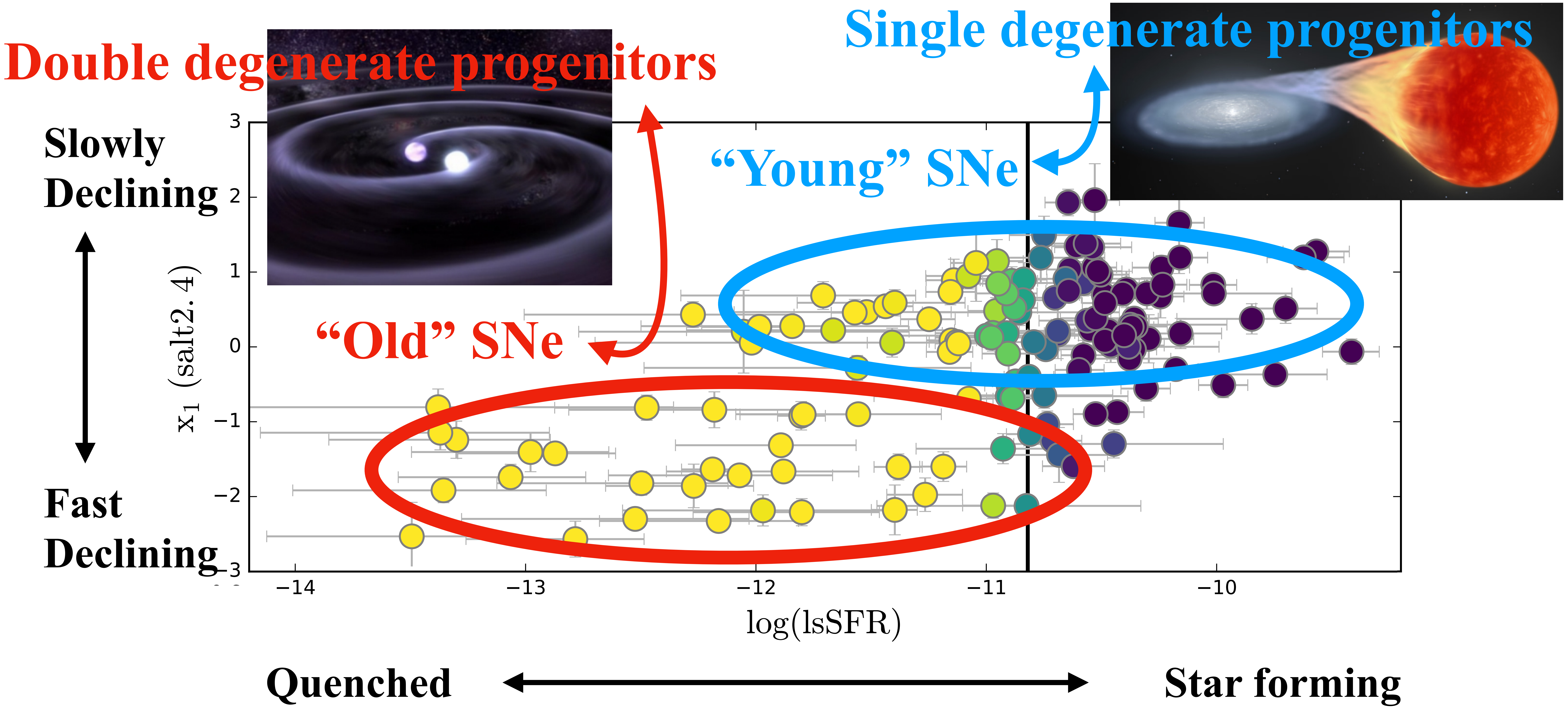



Fast Declining

Quenched ⟷ Star forming

Rigault et al. (2020)

# SN populations




Rigault et al. (2020)

# Physically motivated model: flow chart

# Two-population bayesian hierarchical model

**observables** **latent variables (LV) ⇒ priors ⇐ hyperparameters**

$$m_B = M_B + \mu + \alpha c_{int} + \beta X_1 + R_B E(B - V)$$

$$c = c_{int} + E(B - V)$$

$$x_1 = X_1$$

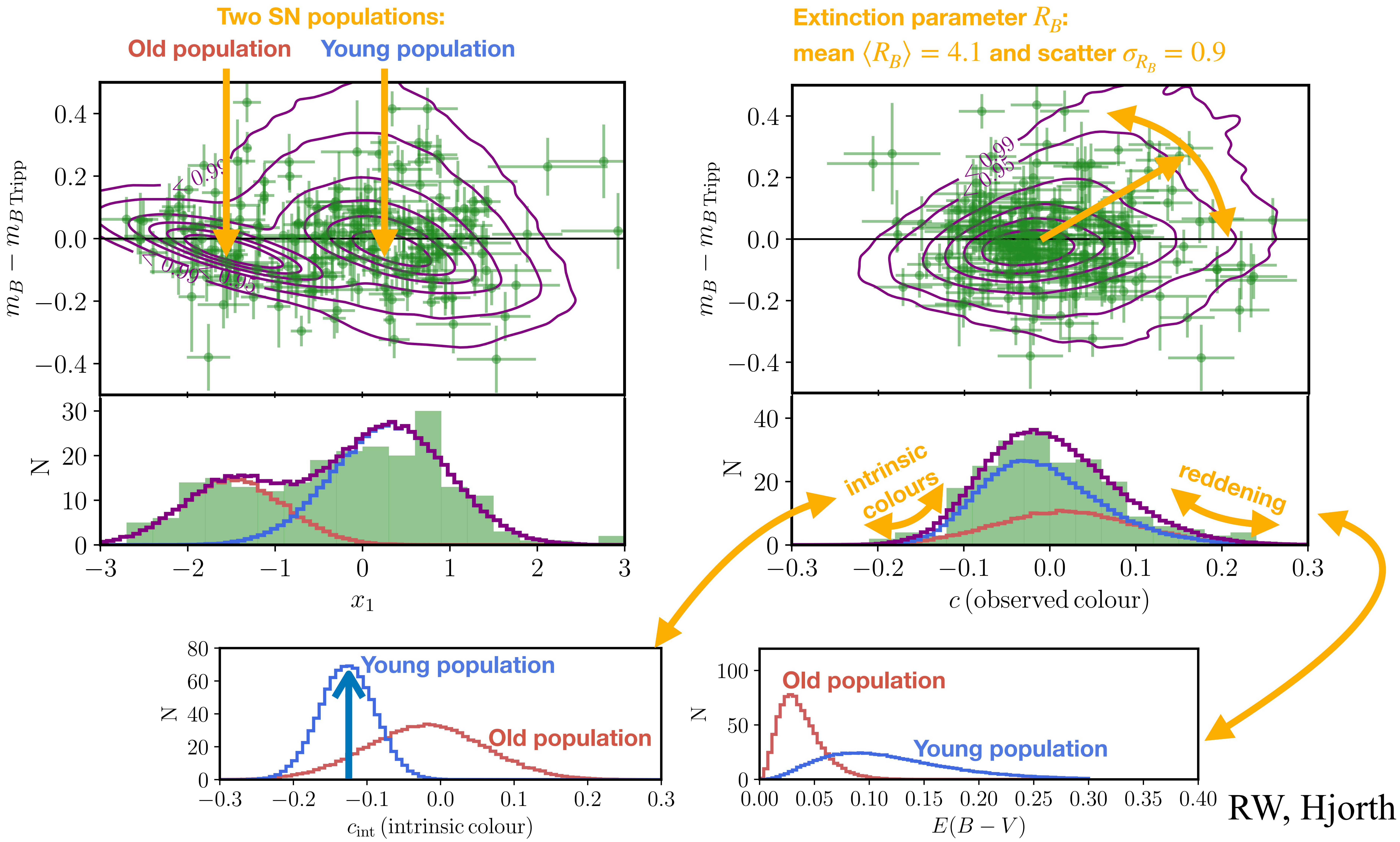
**Two sets of priors (hyperparameters)**

$$w_{SN} = \frac{N_{\text{old population}}}{N_{\text{young population}} + N_{\text{old population}}}$$

**Two SN populations**

RW, Hjorth , Hjortlund (2023)

# Forward modelling with 2-pop Bayesian hierarchical model: Complete description of SNe in the Hubble flow




RW, Hjorth , Hjortlund (2023)

# Extrinsic properties (↑):
# Are they different in the calibration sample ?

observables

latent variables (LV) ⇒ priors ⇐ hyperparameters

$$m_B = M_B + \mu + \alpha c_{int} + \beta X_1 + R_B E(B-V)$$

$$c = c_{int} + E(B-V)$$

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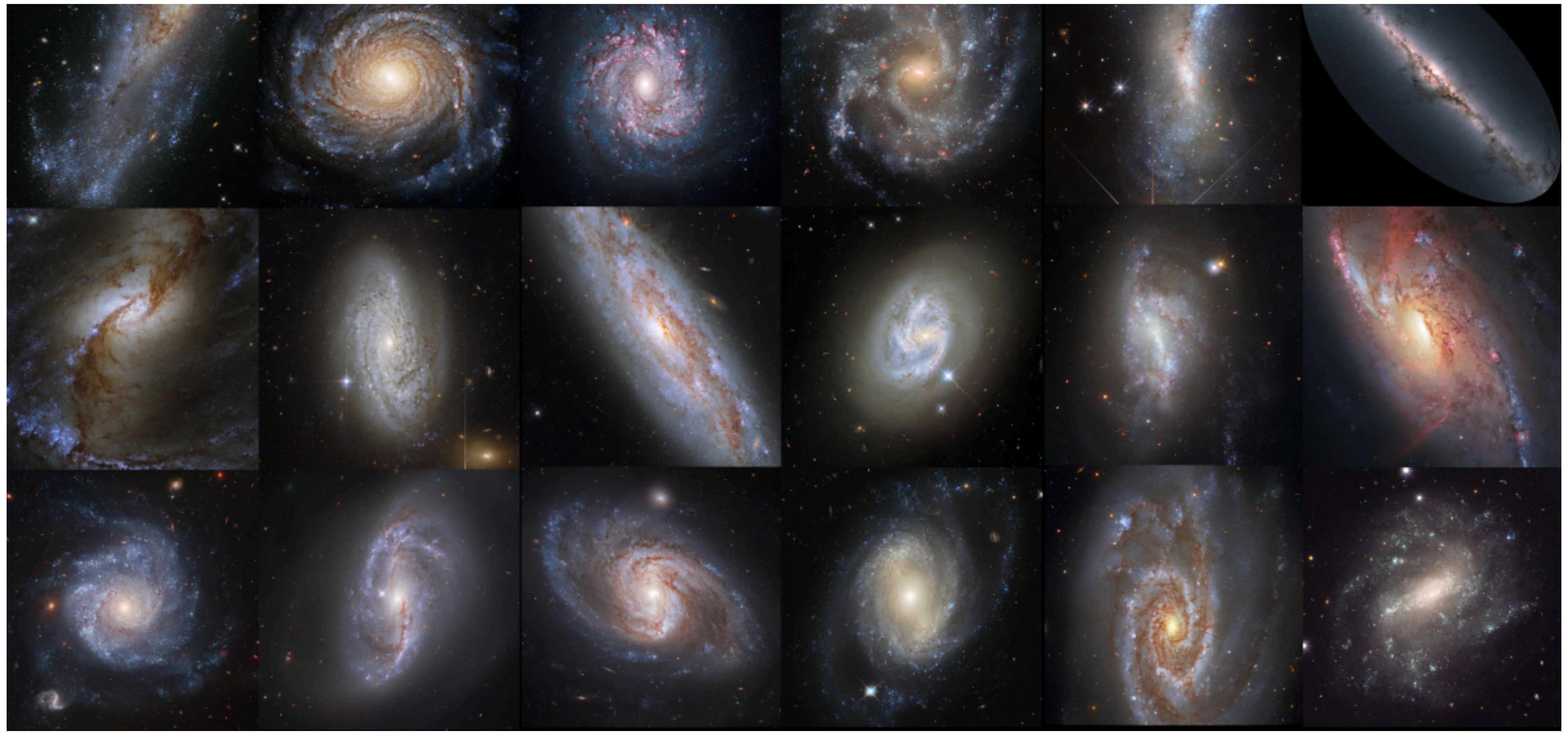
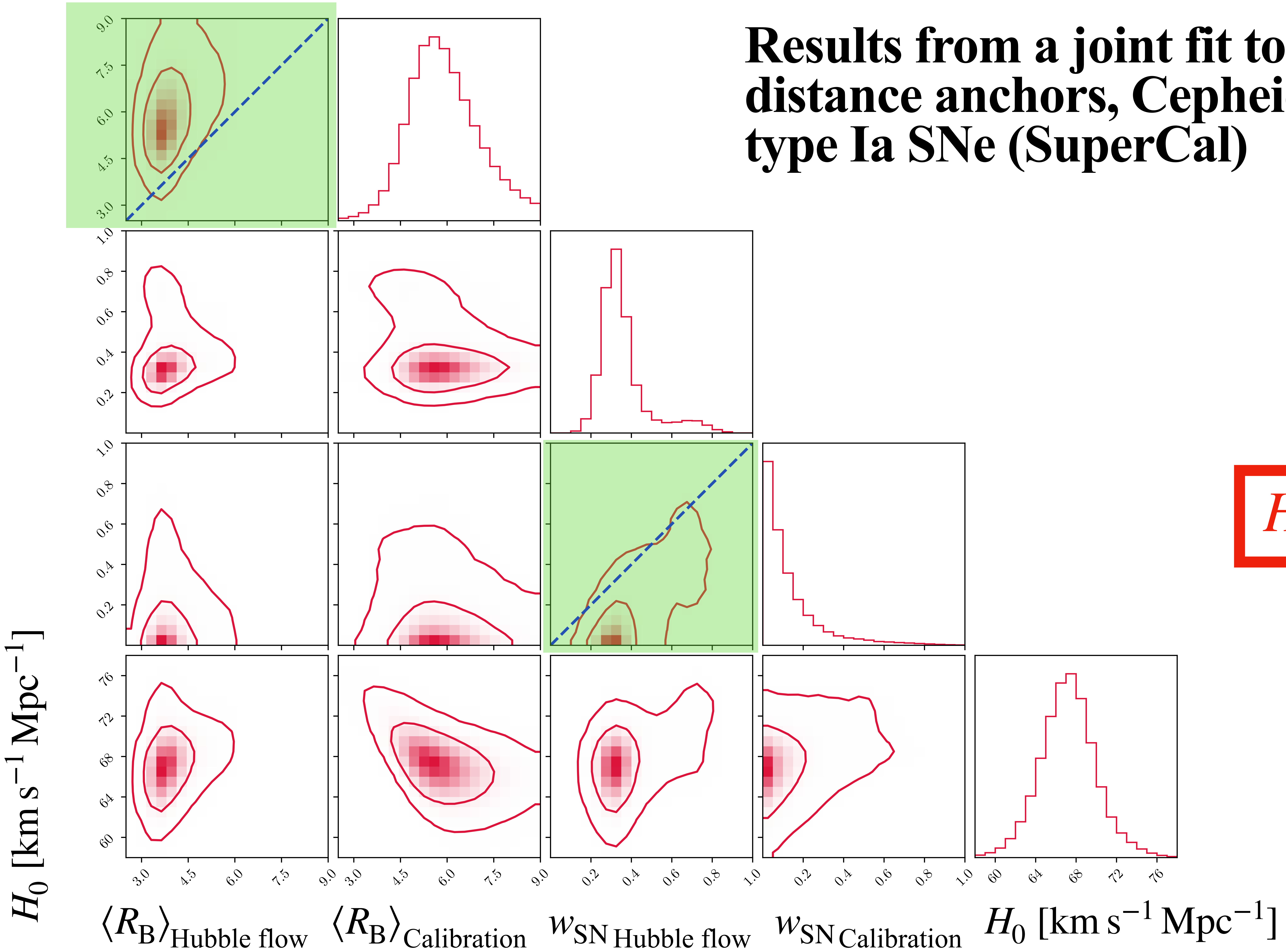


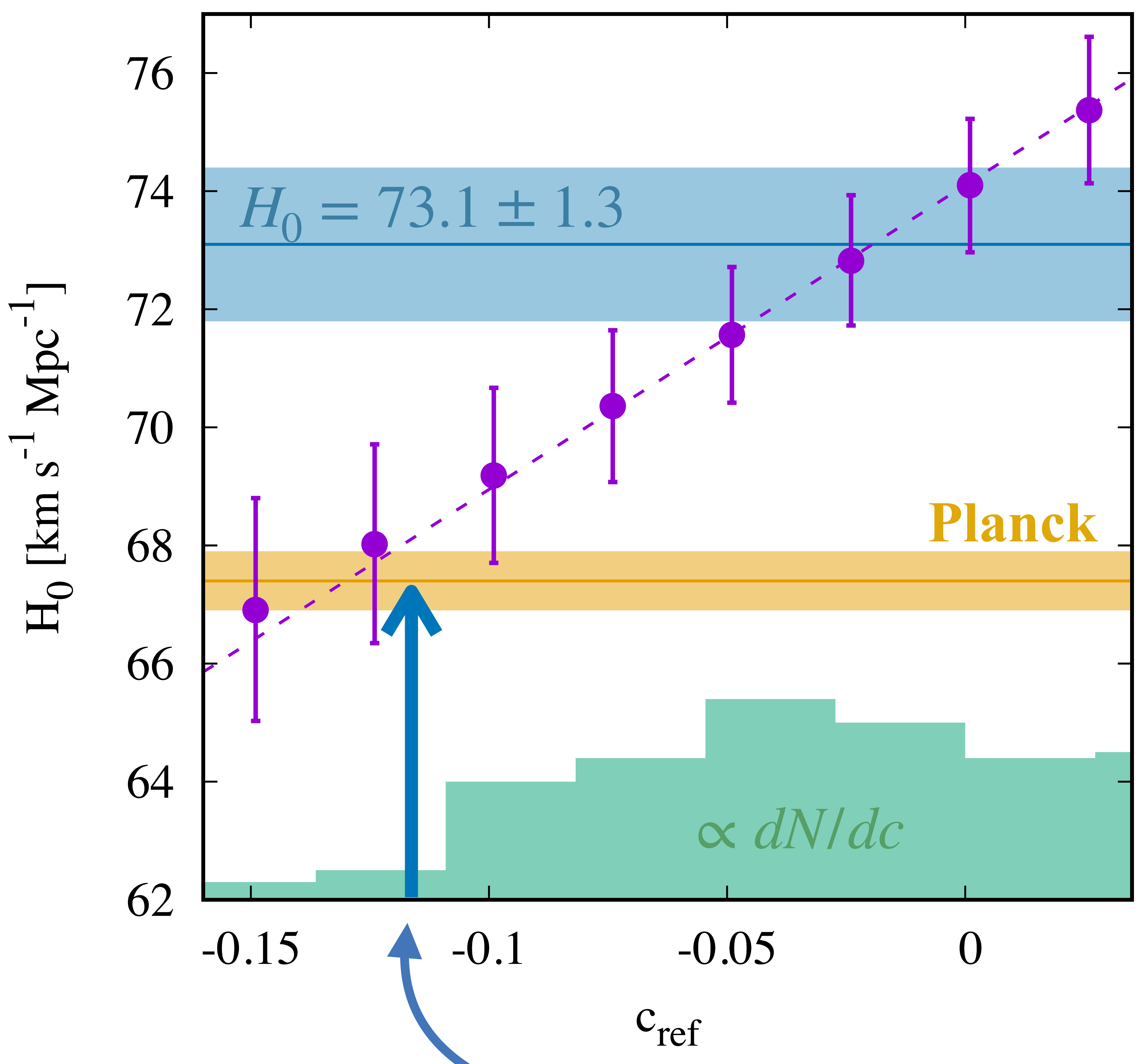
# Results from a joint fit to SH0ES data: distance anchors, Cepheids (19 calibrators), type Ia SNe (SuperCal)




$$H_0 = 67.2^{+2.6}_{-2.6}$$

RW, Hjorth (2023) TBS

# Intuitive interpretation




Higher (mean) extinction parameter in the calibration sample than in the Hubble flow

Intrinsic colours of young supernova population dominating in the calibration sample

# New Hubble constant

| | |
|---|---|
| Tripp calibration | $H_0 = 73.1^{+1.3}_{-1.3}$ |
| 2-pop model:<br>The same params in the calibration and Hubble flow | $H_0 = 72.4^{+1.2}_{-1.2}$ |
| 2-pop model:<br>independent $\langle R_B \rangle$, $\sigma_{\mathrm{R_B}}$, $\langle E(B-V) \rangle$, $w$ in the calibration and Hubble flow | $H_0 = 67.2^{+2.6}_{-2.6}$ |
| 2-pop model:<br>independent $\langle R_B \rangle$, $w$ (and $\sigma_{\mathrm{R_B}} = 0$) in the calibration and Hubble flow | $H_0 = 66.9^{+2.4}_{-2.4}$ |

RW, Hjorth (2023) TBS

# Physically motivated analysis of type Ia supernovae based on 2-population Bayesian hierarchical model resolves the Hubble constant tension.

RW, Hjorth (2023) TBS

# Summary

- $4.2\sigma$ Hubble constant tension goes together $3.8\sigma$ intrinsic anomaly of the SN standardisation (19 calibrators).

RW & Hjorth (2022)

- Understanding the physical origin of the anomaly requires complete understanding of supernova Hubble residuals. The new two-population Bayesian hierarchical model provides for the first time the necessary framework.

RW, Hjorth & Hjortlund (2023)

- The new modelling of type Ia supernovae shows that the colour anomaly is caused by (1) a higher extinction parameter and (2) a larger fraction of "young" SN population in the calibration sample than in the Hubble flow.

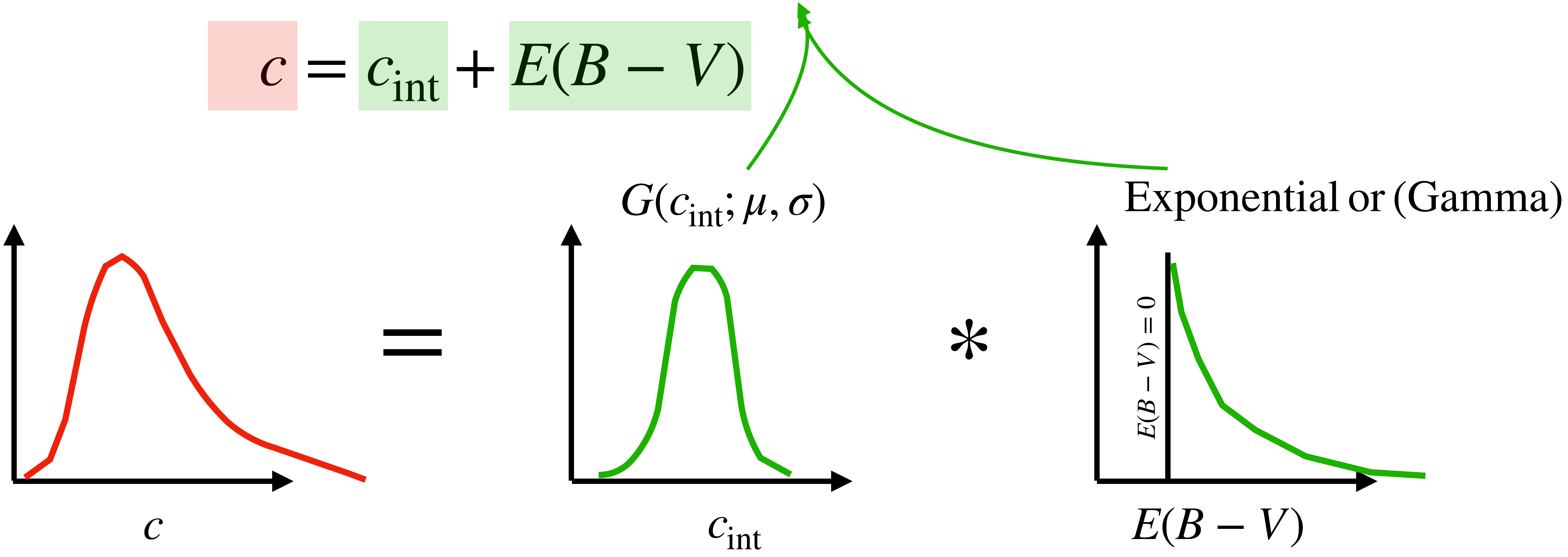
- Reanalysis of the SH0ES data using the new 2-population model yields the Hubble constant which is fully consistent with the Planck value.

RW & Hjorth (2023) TBS

# How does it work ?

observables latent variables (LV) ⇒ priors ⇐ hyperparameters

$$c = c_{\text{int}} + E(B-V)$$



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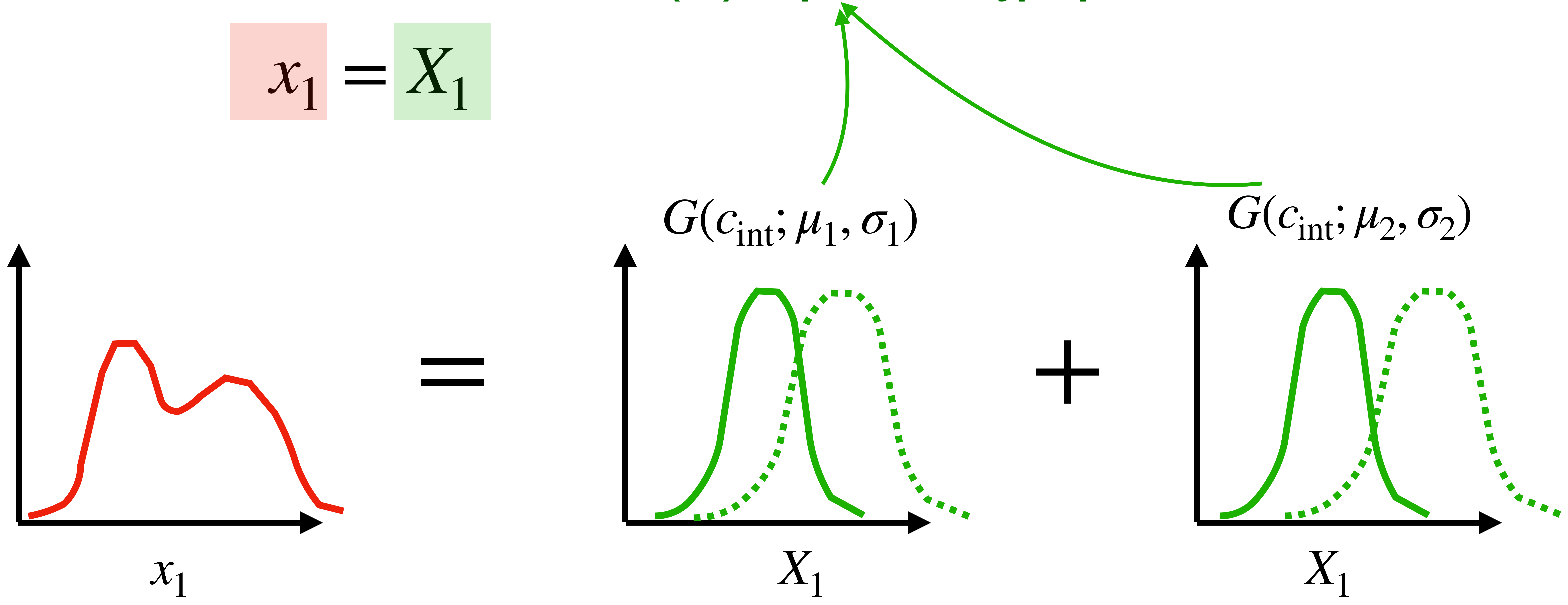
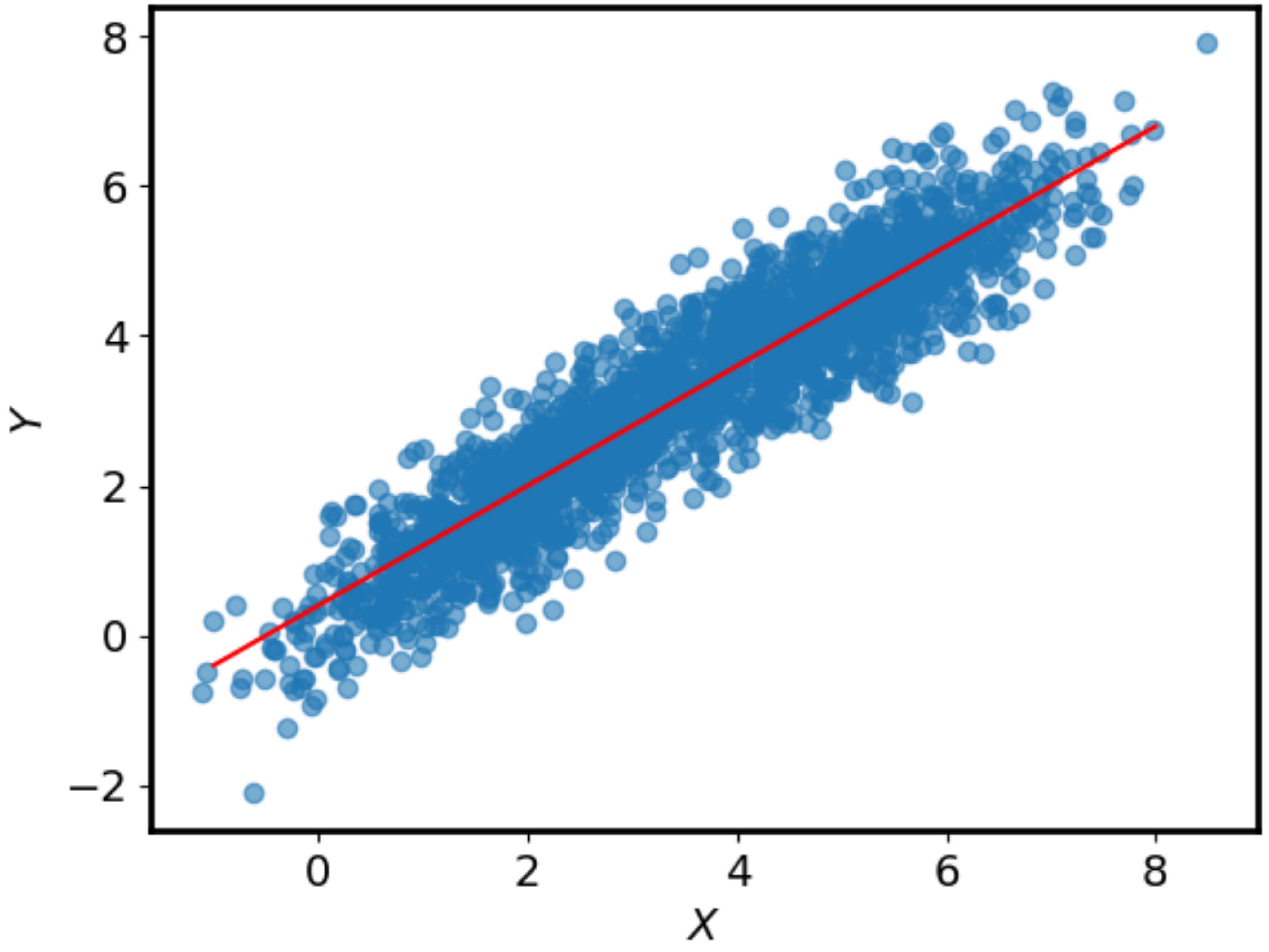


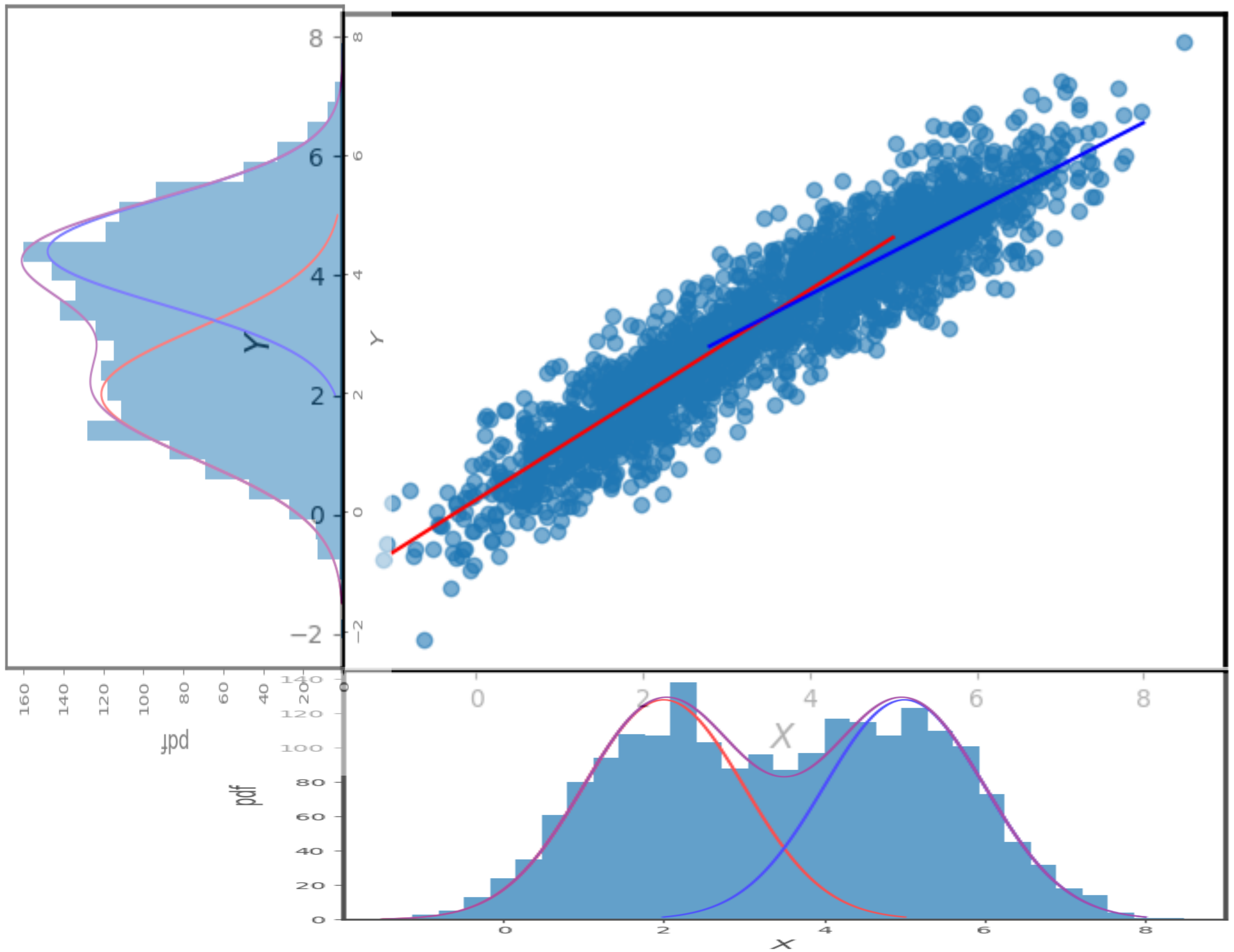
# Bayesian hierarchical modelling

## How does it work ?

Traditional modelling:
Relations between observables

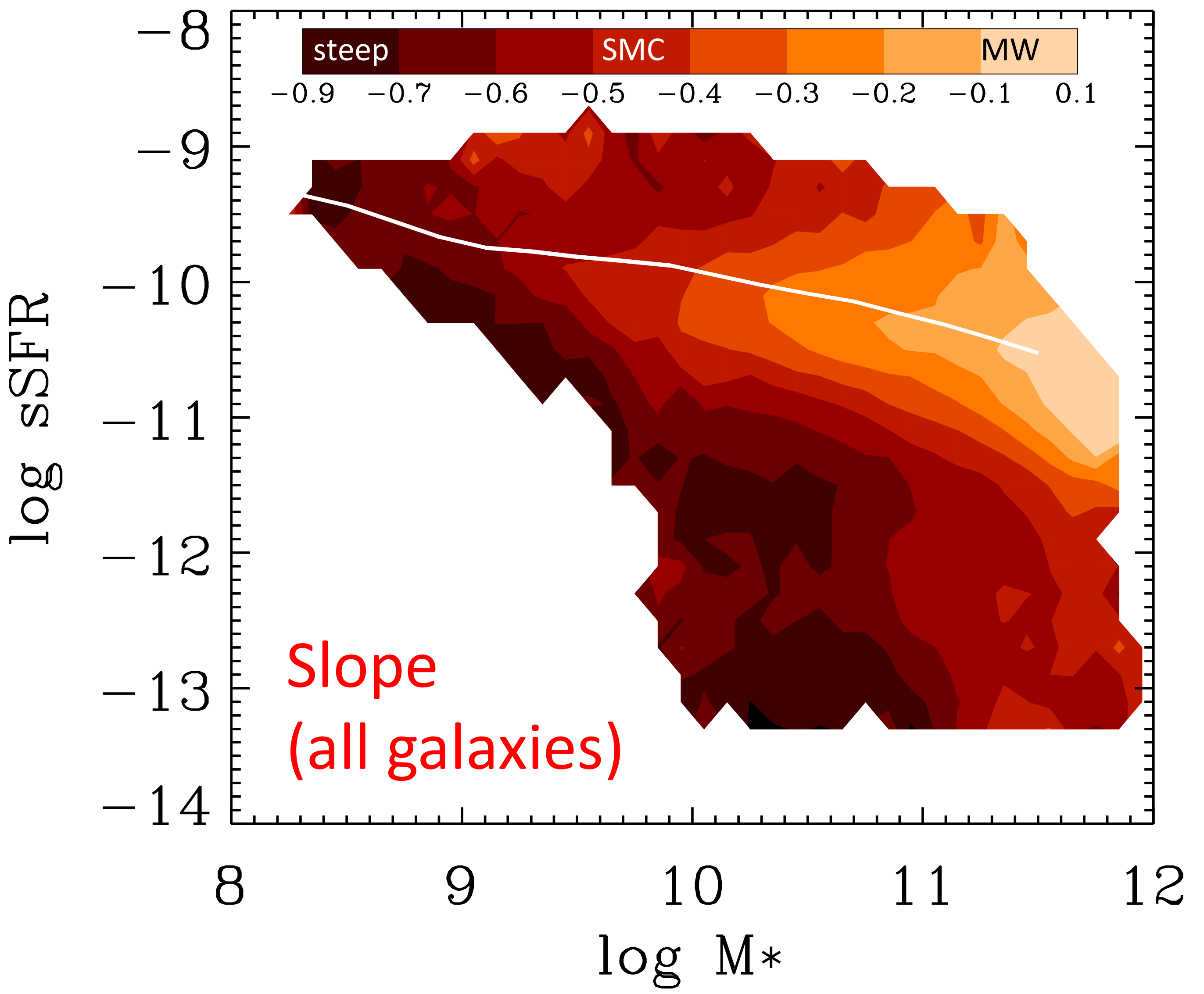
Bayesian hierarchical modelling:
Relations between observables+distribution of Observables



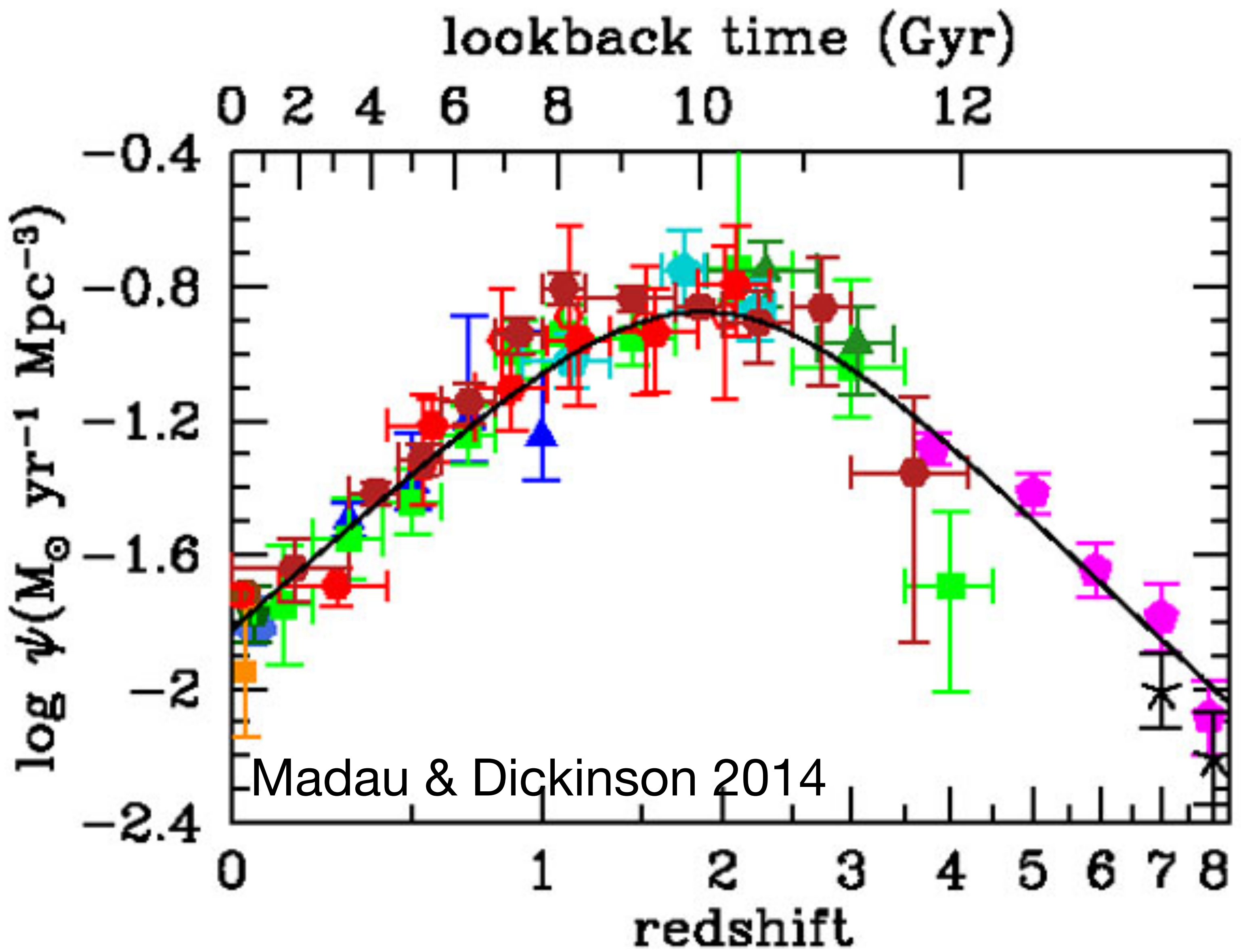
# Testable implications/questions

**Extinction properties/dust composition in different stellar environments**



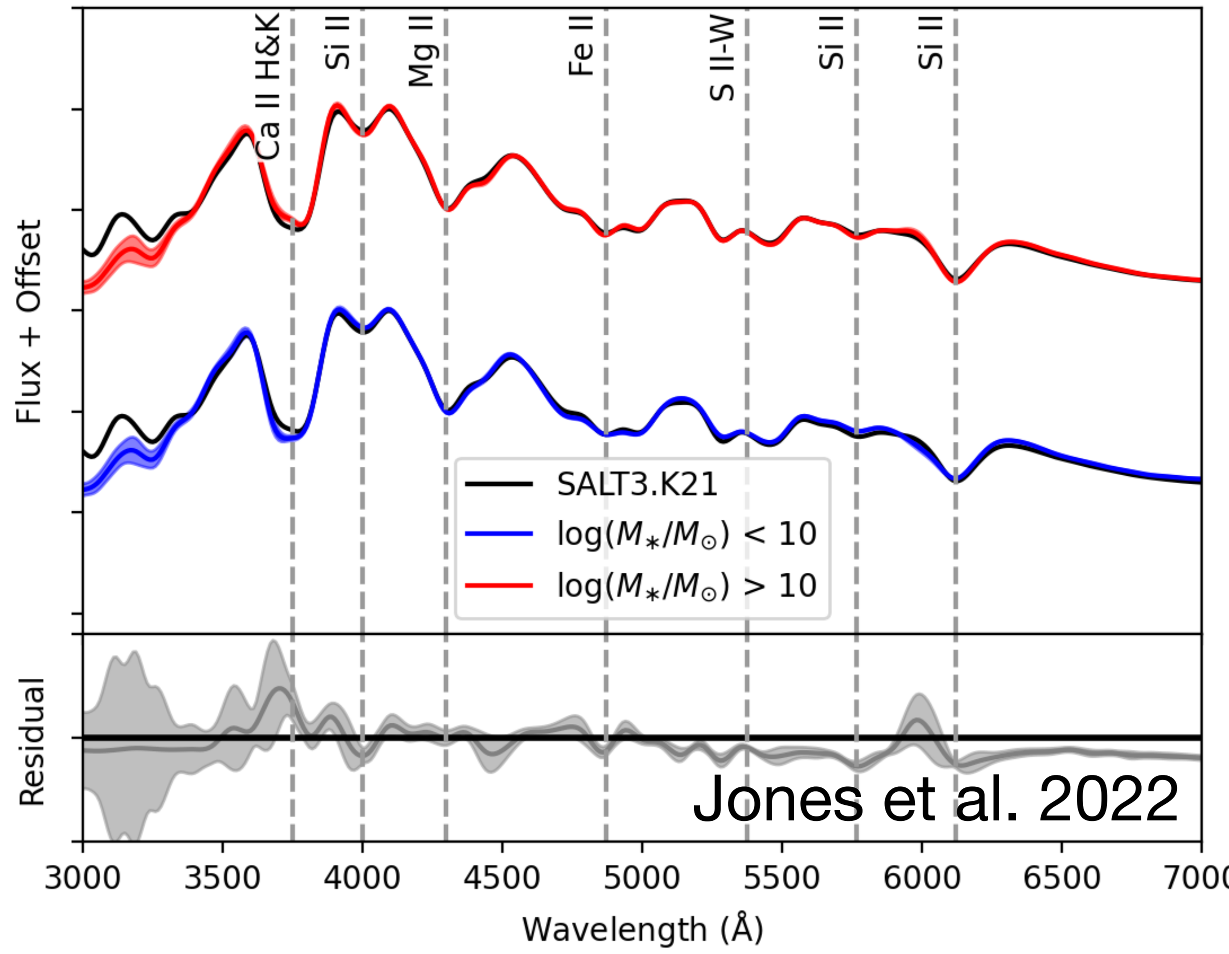

Salim et al. 2018

**2-pops SN model**

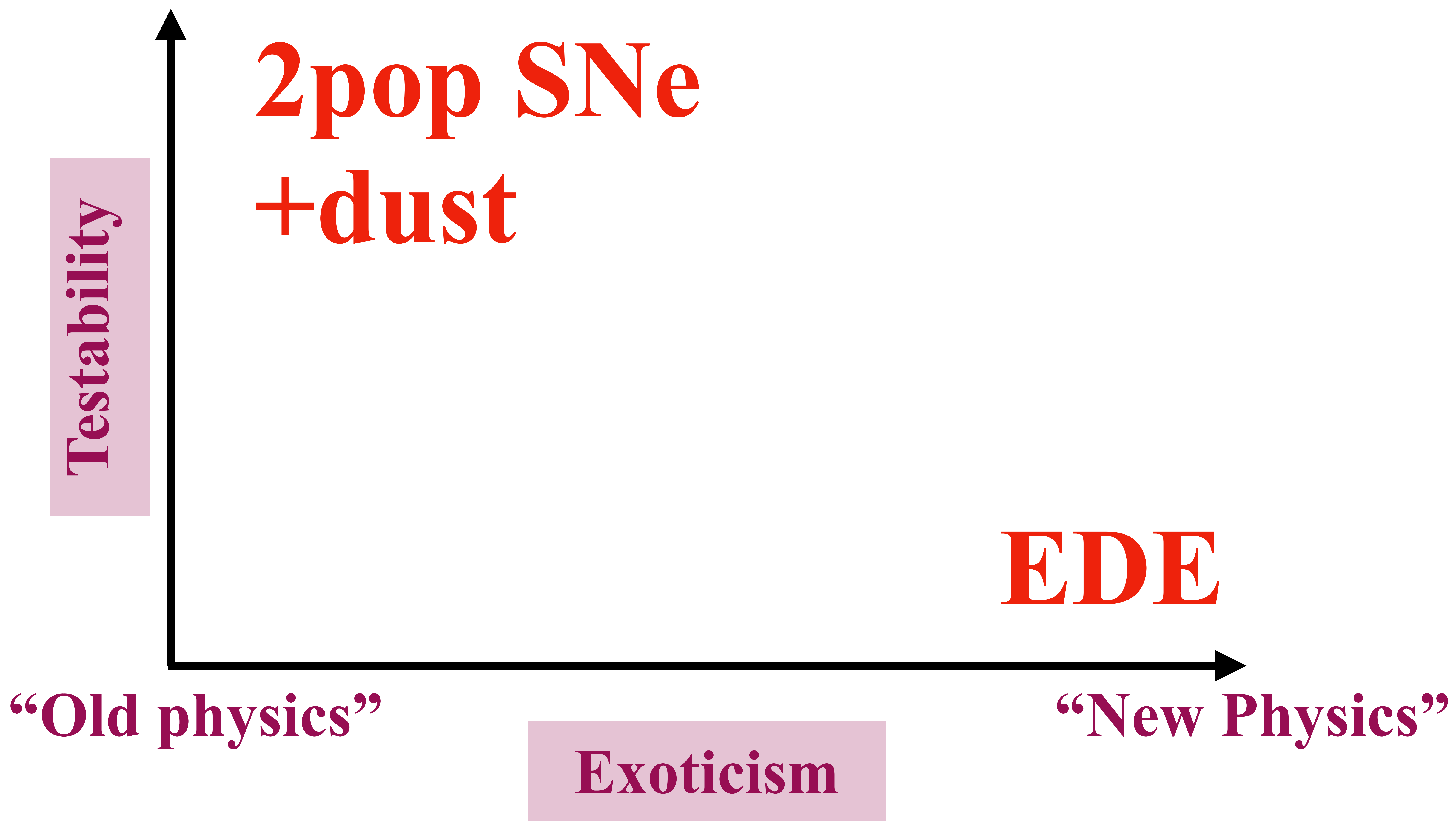



**Relative fractions of SN populations should follow SFR**

**Spectroscopic differences between SN populations**

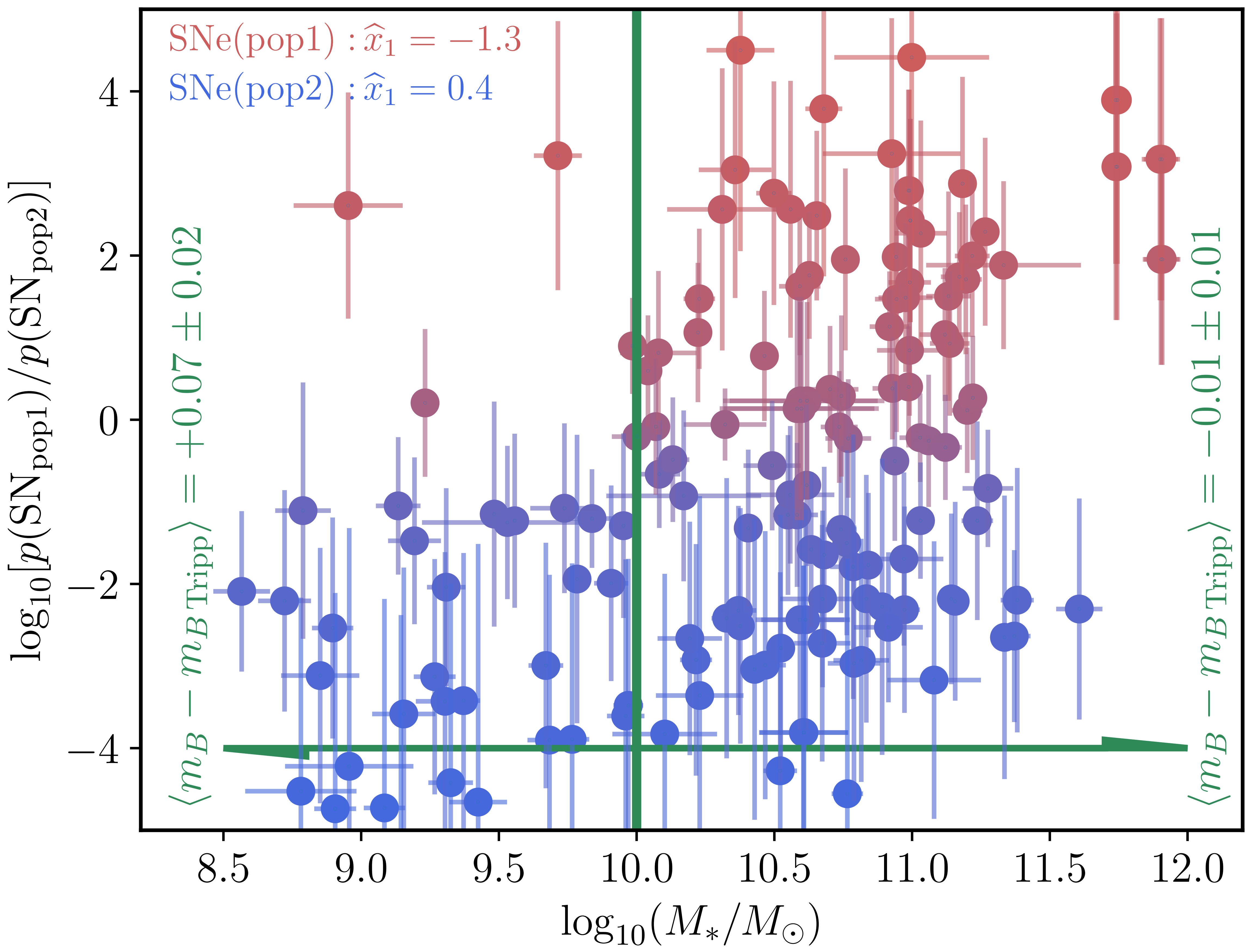


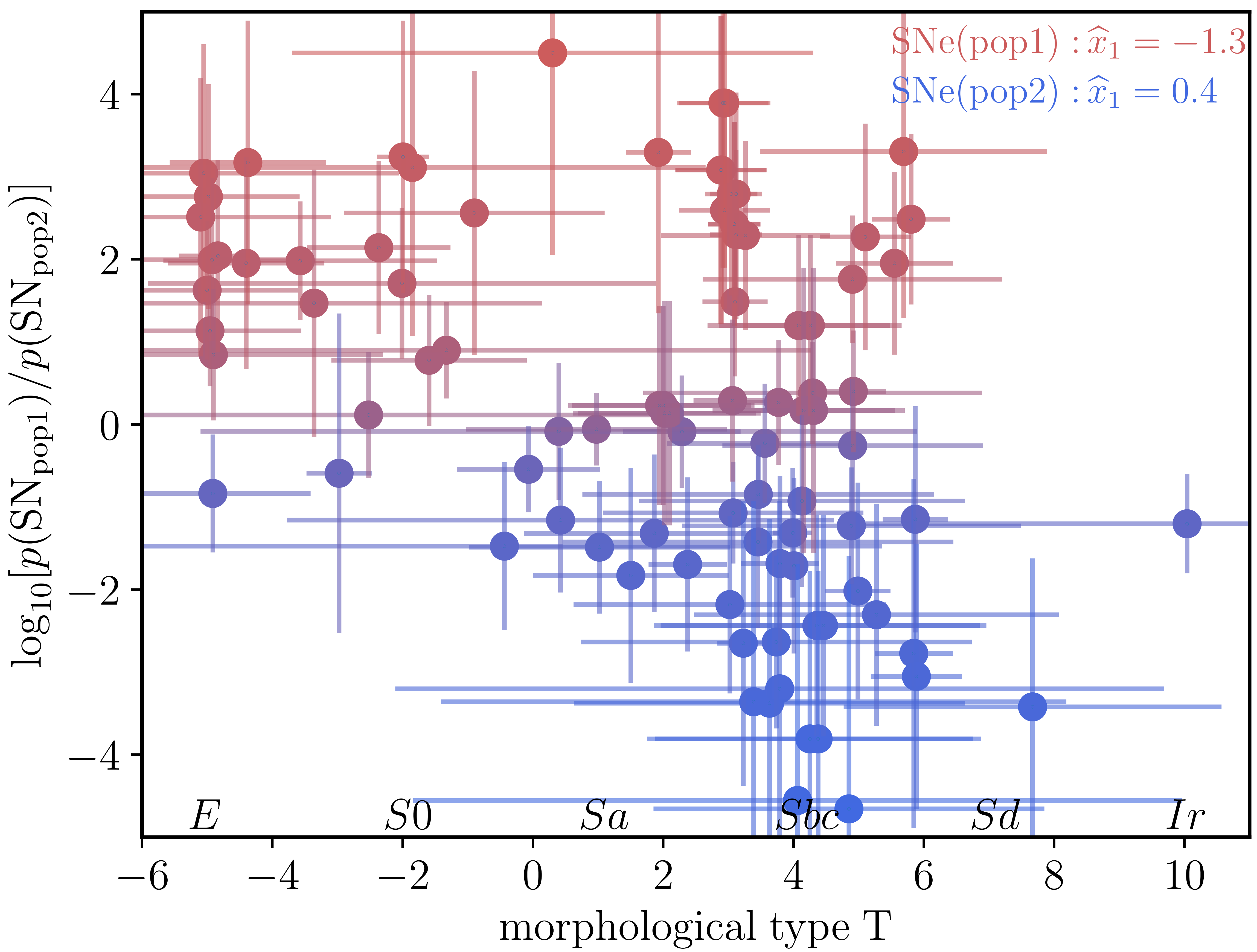
# Hubble constant tension: SN physics vs EDE



# “Step” correction is an emergent property

$$m_B = M_B - \alpha x_1 + \beta c + \gamma H(M_\star - M_0)$$



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