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

CosmoVerse@Lisbon

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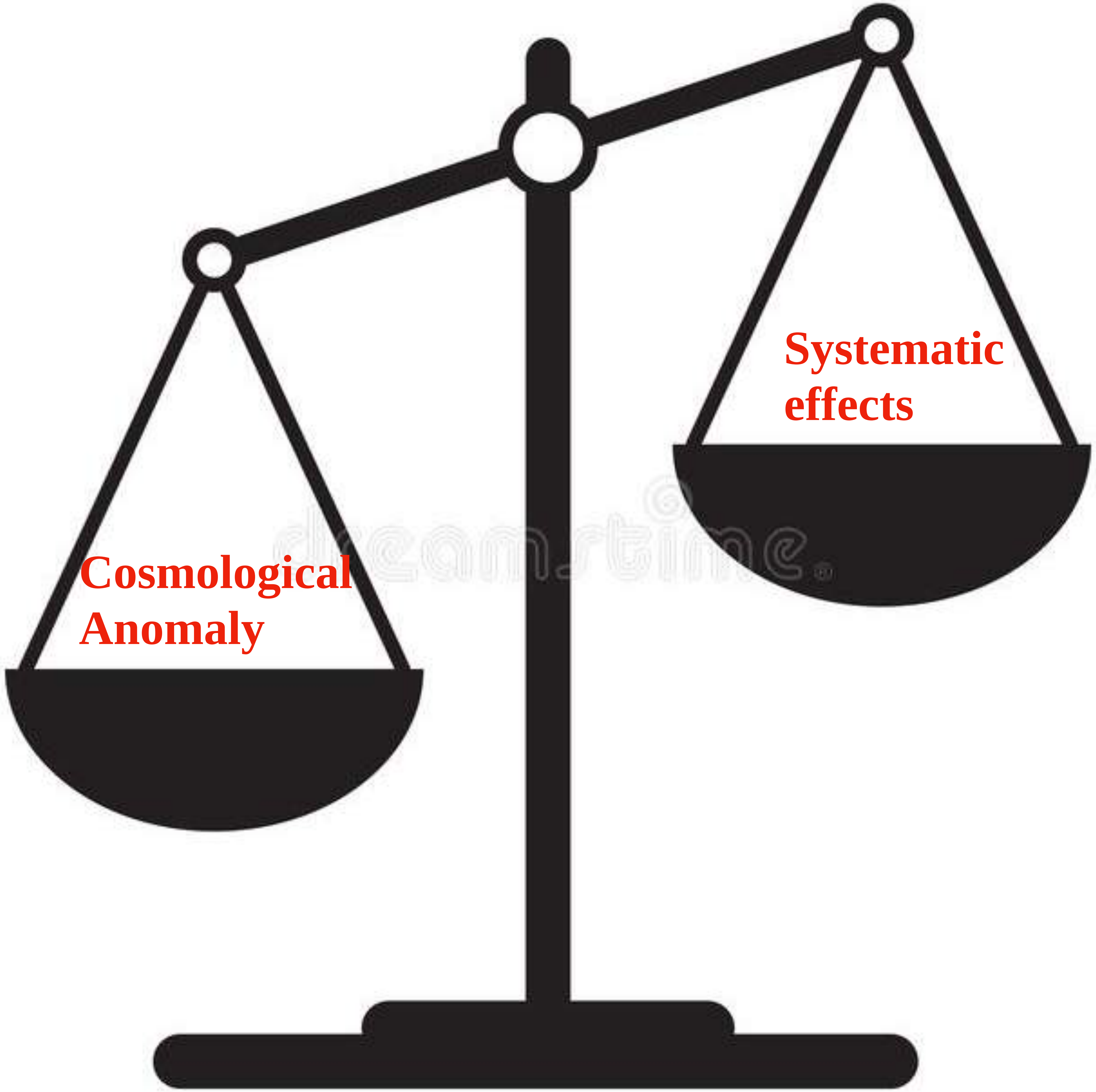
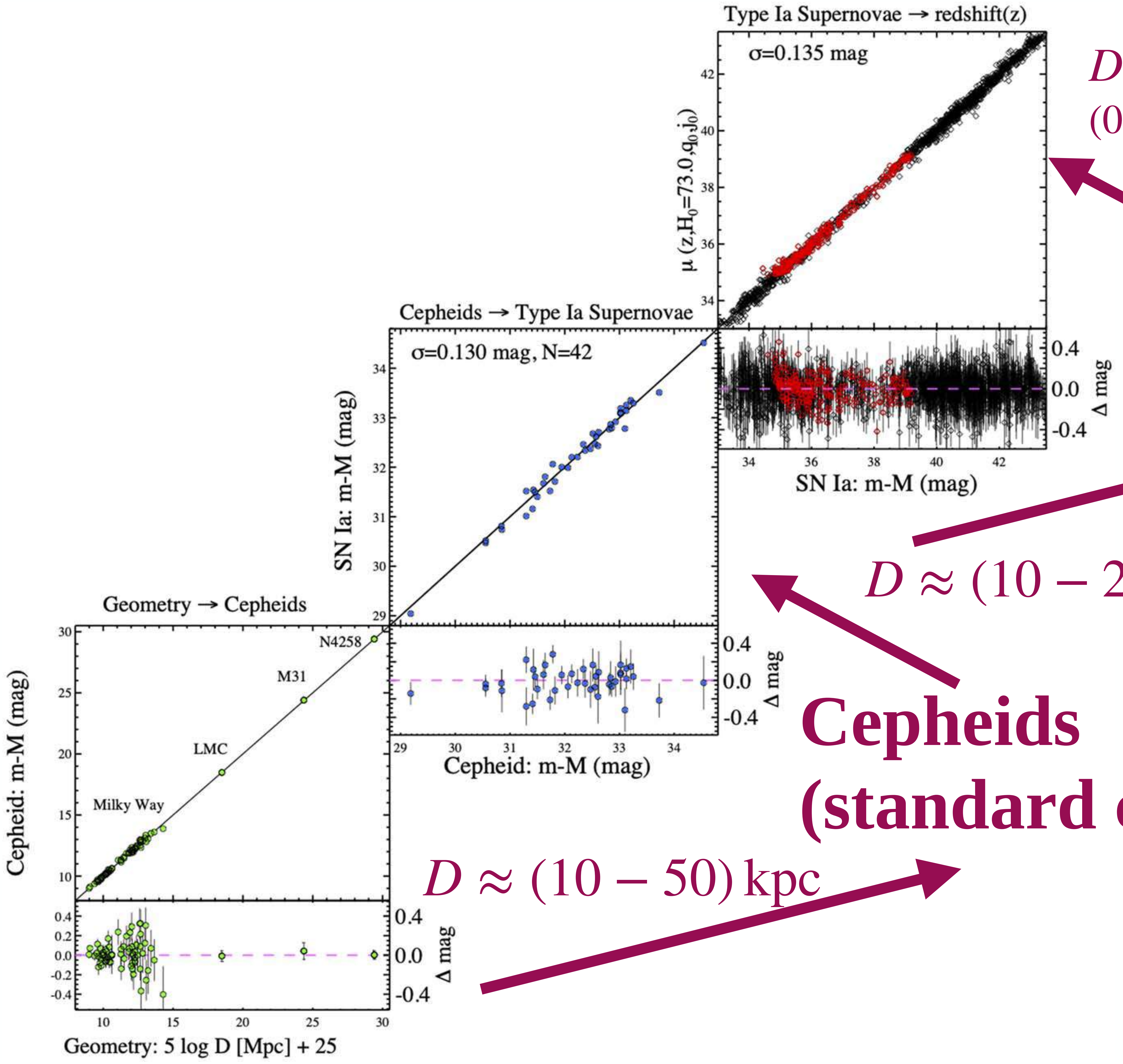
The H_0 tension: 8% rel. difference, 5σ significance

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

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


Cosmological
Anomaly
Systematic
effects

Direct/local H_0: distance ladder



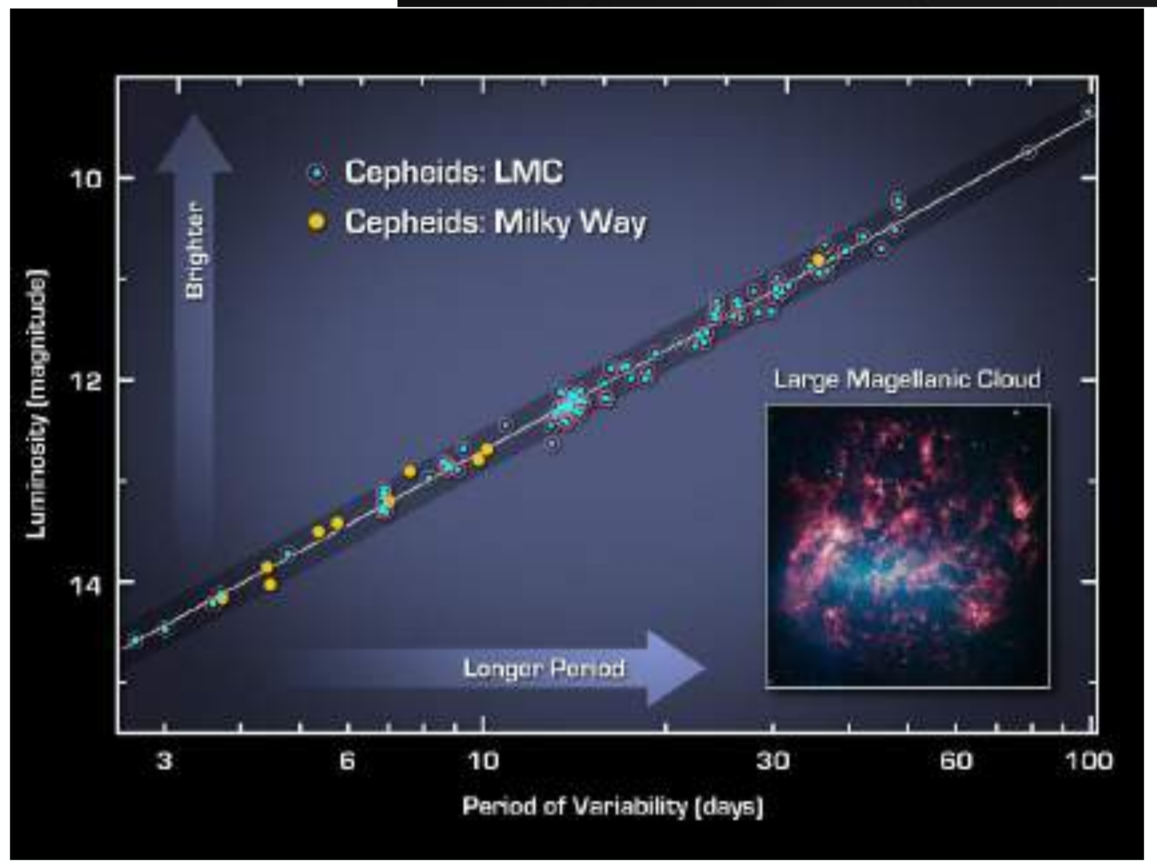
$D \approx (100 - 500)$ Mpc
$(0.023 < z < 0.13)$

Type Ia supernovae (Standardisable candles)

$D \approx (10 - 20)$ Mpc

Cepheids (standard candles)

$D \approx (10 - 50)$ kpc



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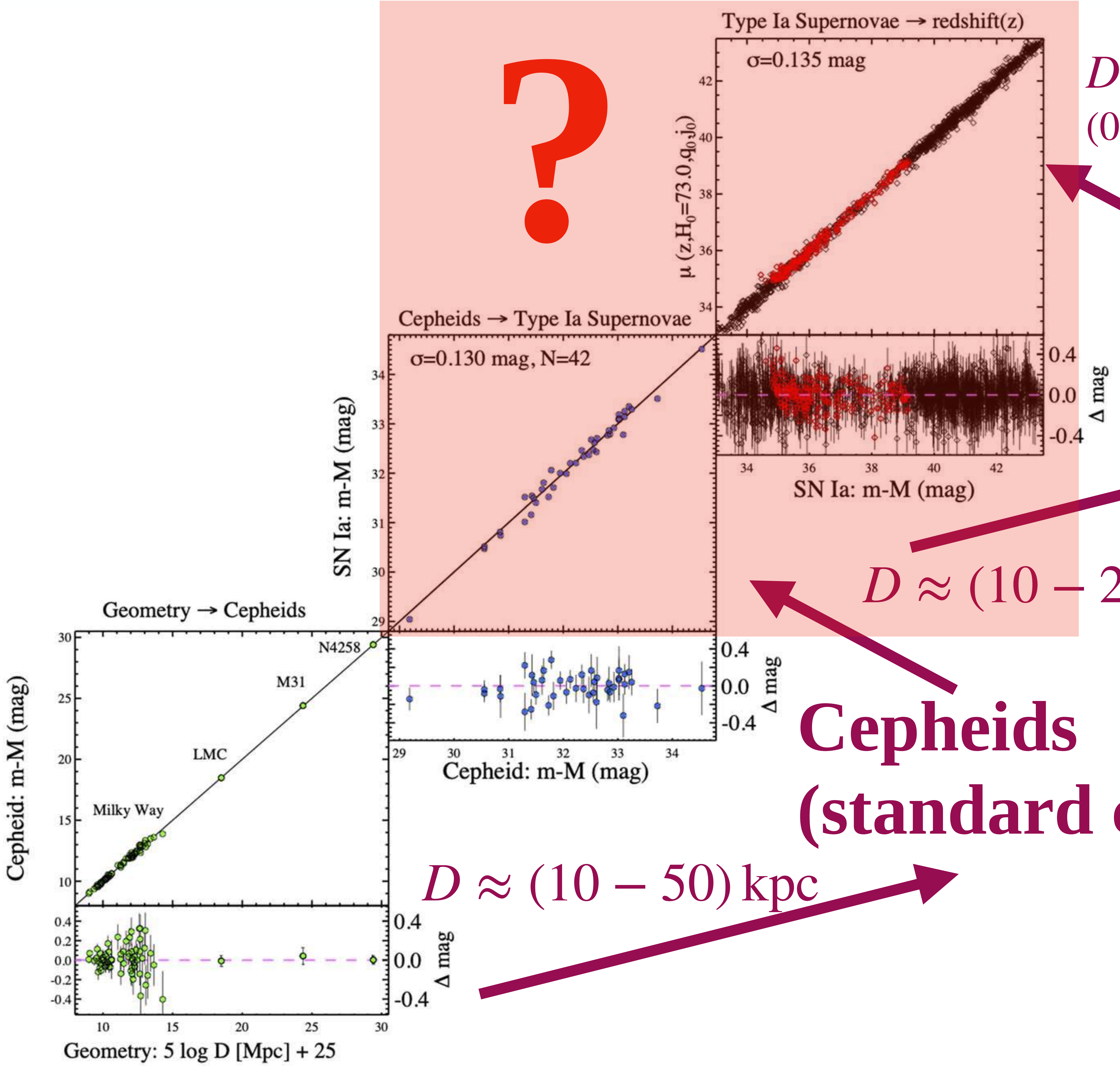

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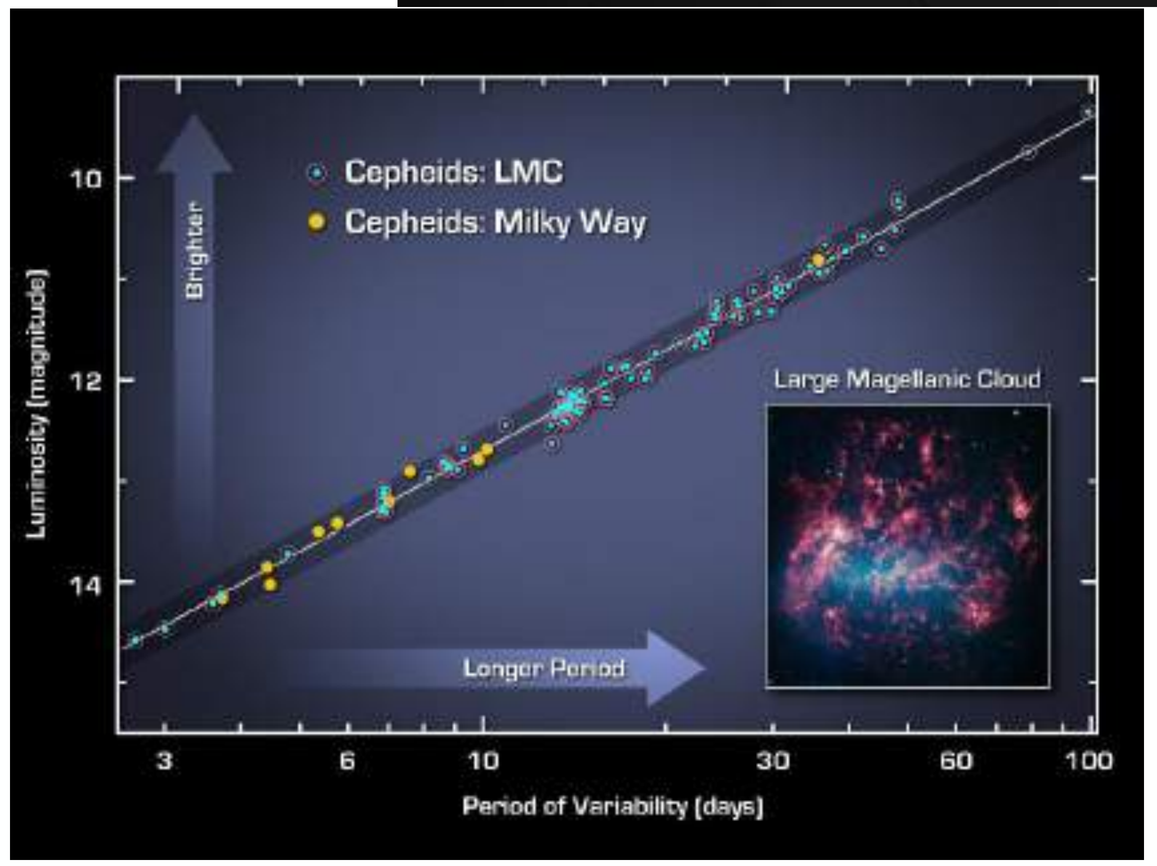
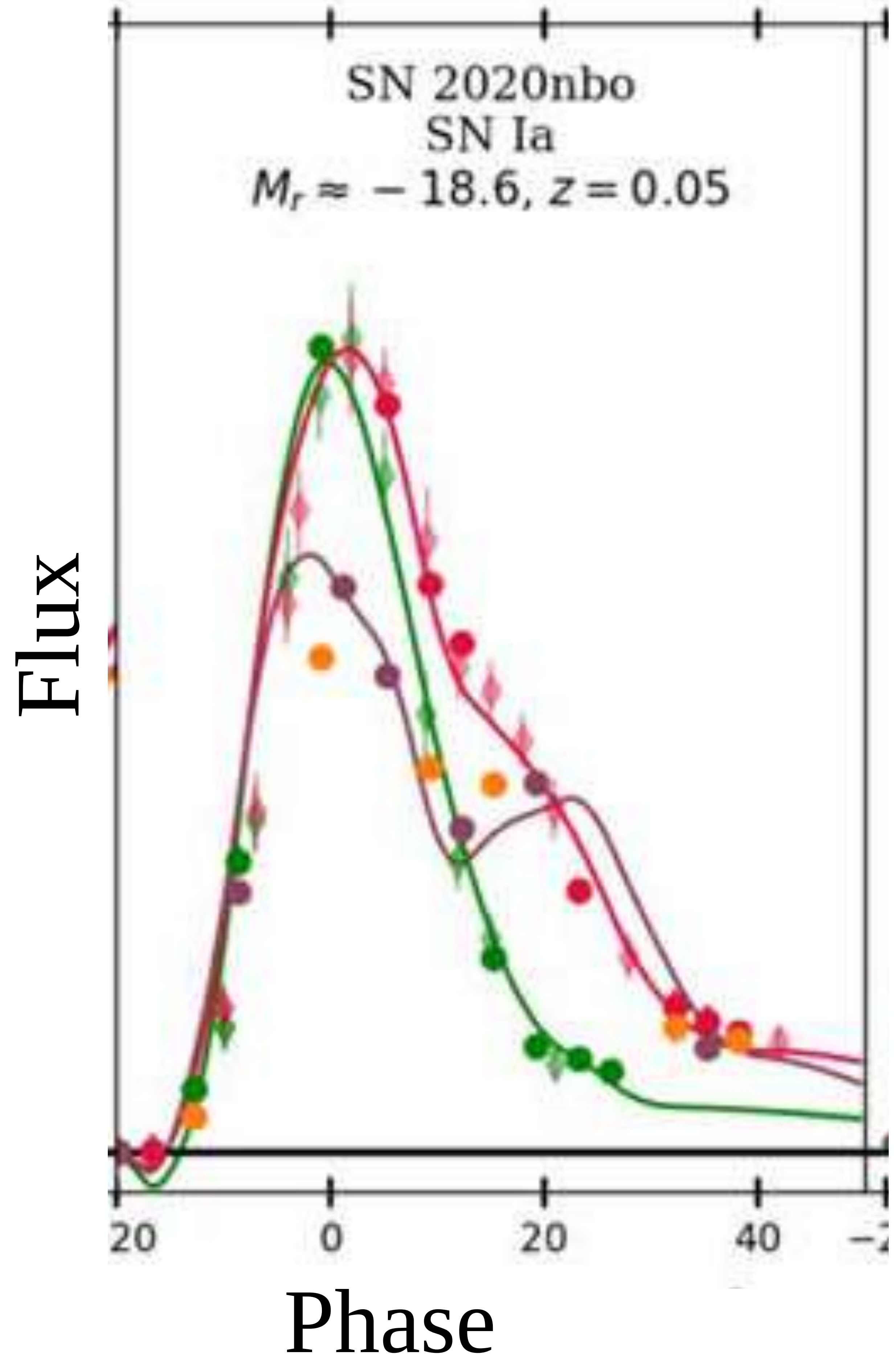


Type Ia SN: light curve parameters

Light curves



Empirical models
Based on observed SEDs(t)

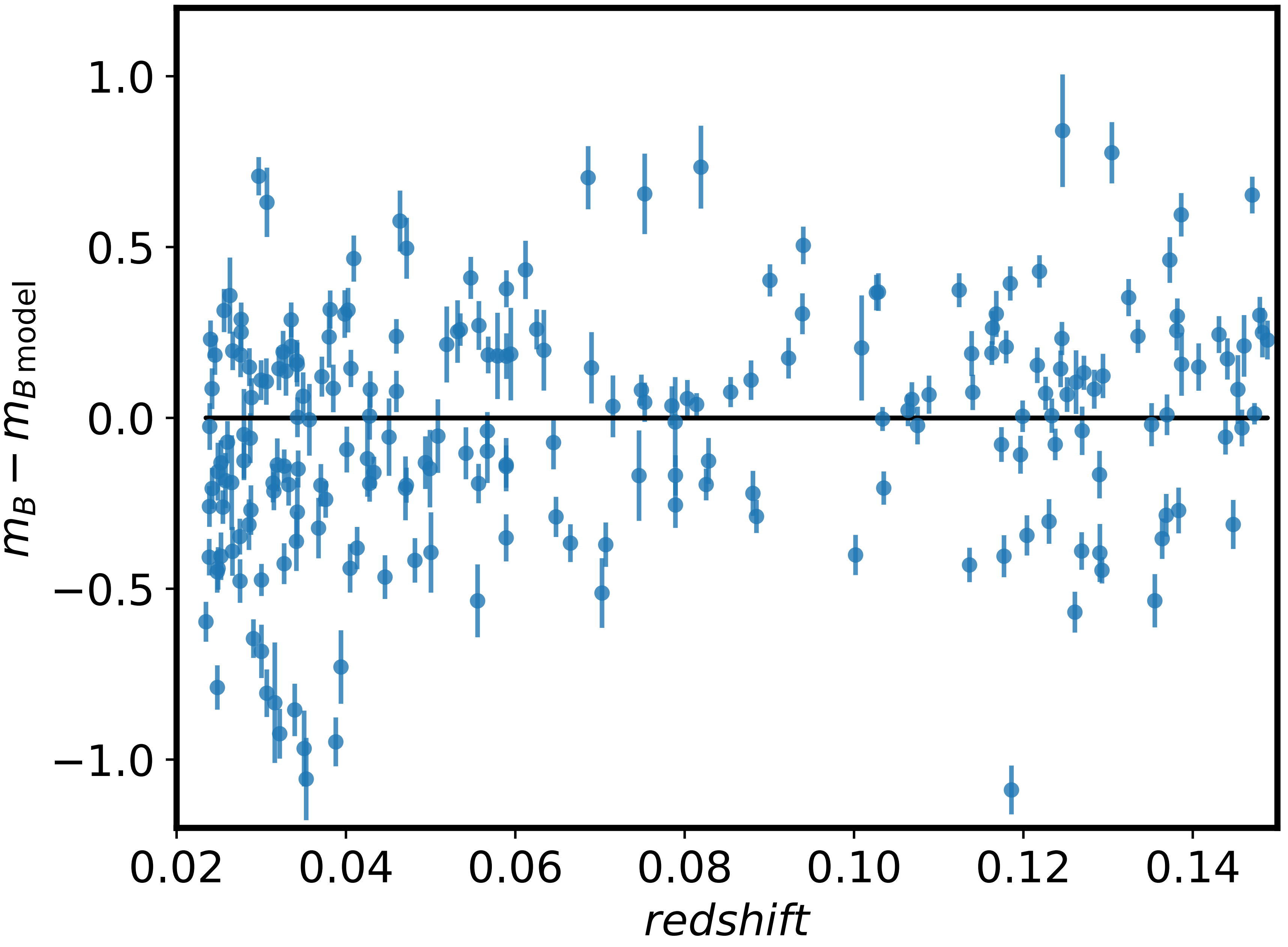
Light Curve Fitting

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

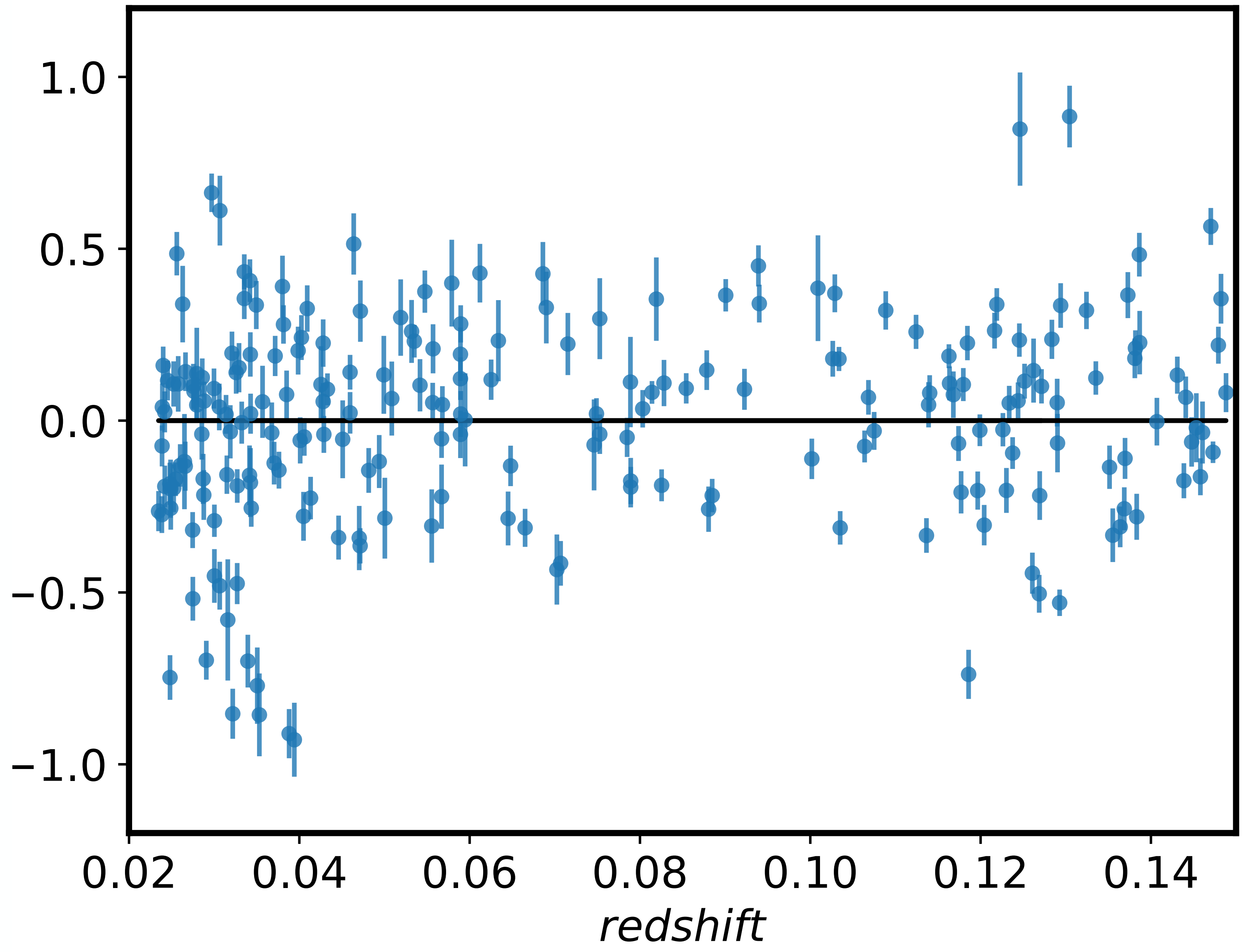
$$m_{\rm model} = M_{\rm B} + \mu(z)$$



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

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

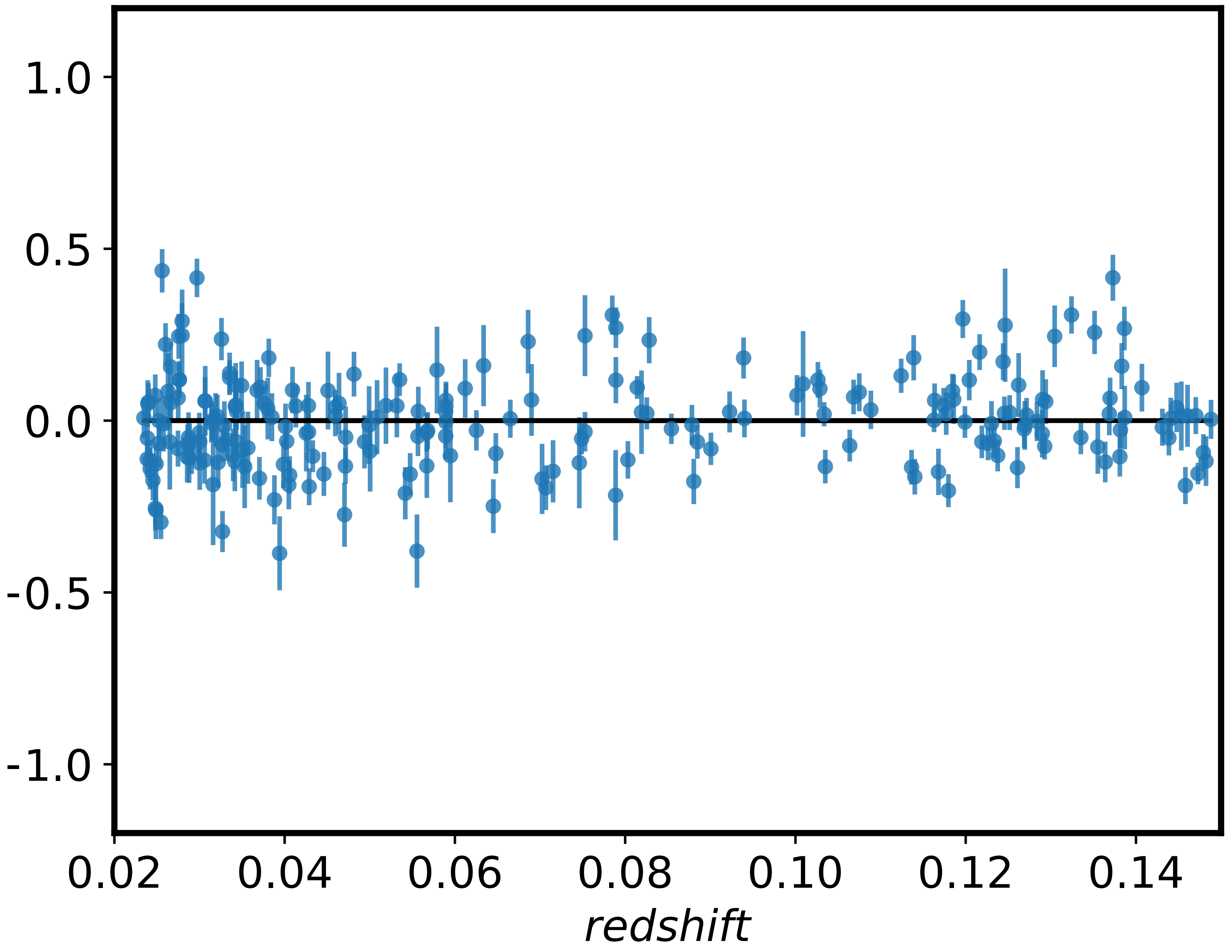
Phillips relation (Phillips 1995)



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

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

Tripp calibration (Tripp 1998)



Irreducible intrinsic scatter:

$\sigma_{\rm int} = 0.12$ mag

Type Ia SN: "standard" standardisation

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

(Implicit) assumptions:

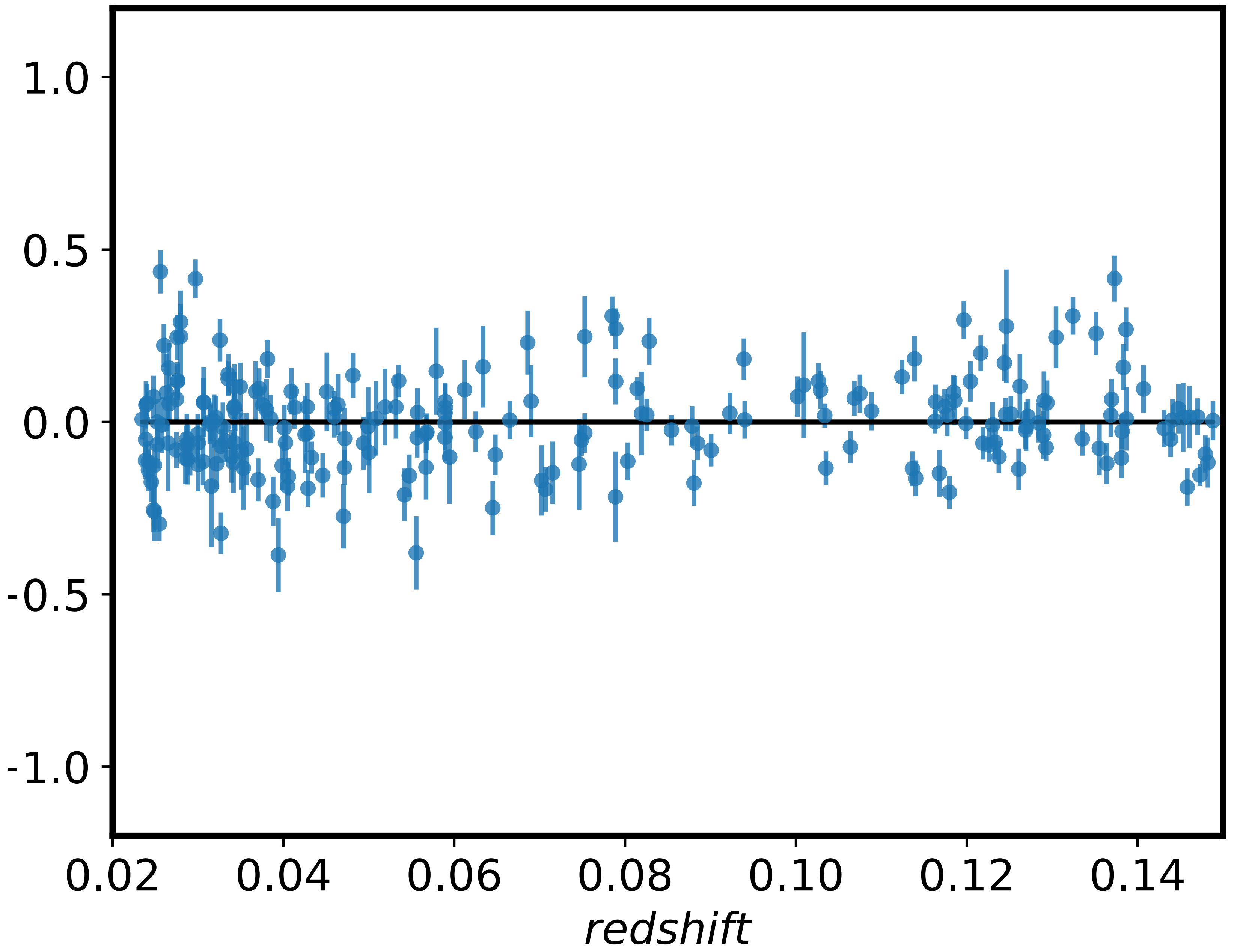
- **Tripp calibration is universal across redshift and SN samples (calibration vs Hubble flow)**
- **Distribution of latent variable(s) behind intrinsic scatter is universal across redshift and SN samples: we can effectively decrease error in distance as $\sigma_{\rm int}/N^{1/2}$**

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**

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

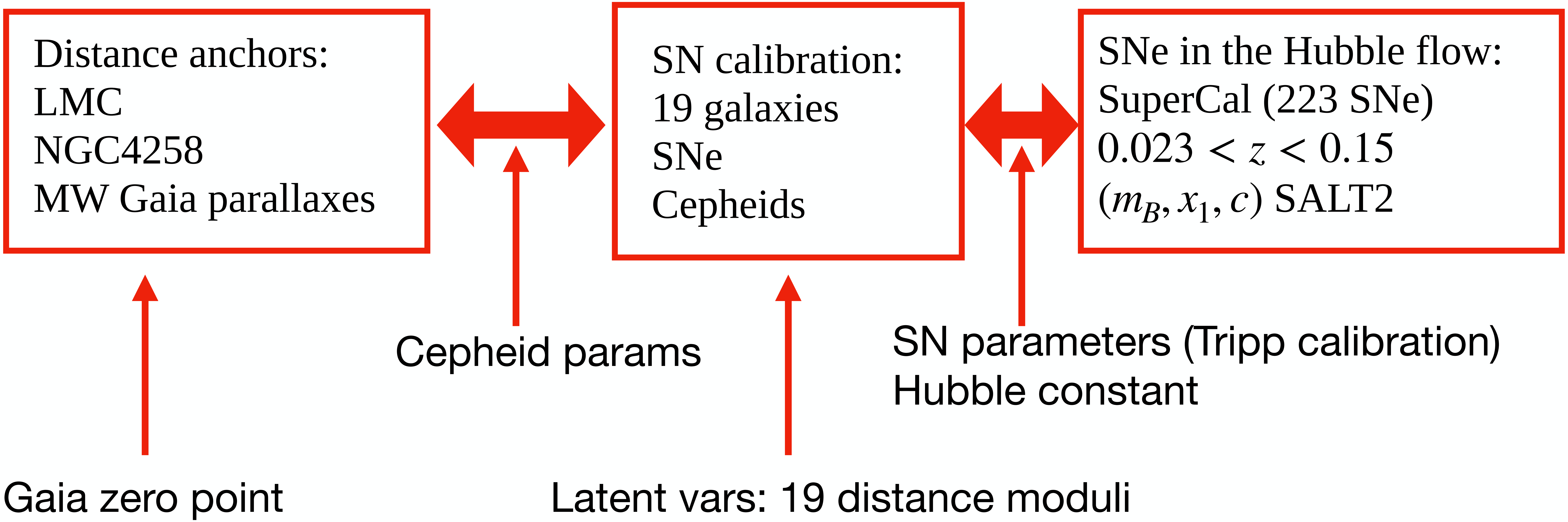
Tripp calibration (Tripp 1998)



Irreducible intrinsic scatter:

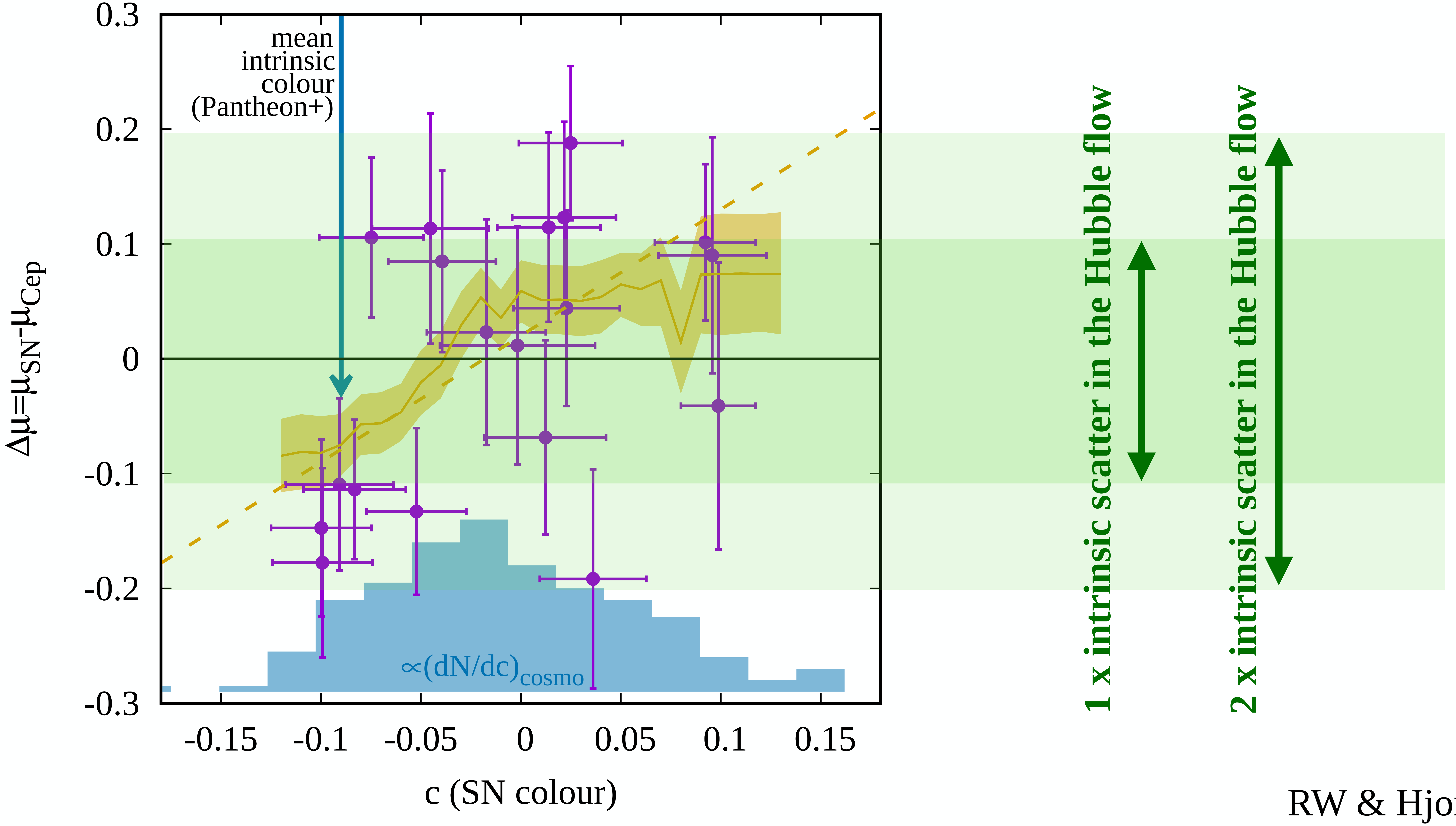
$\sigma_{\rm int} = 0.12$ mag

(Pre 2022) SH0ES data and global likelihood



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

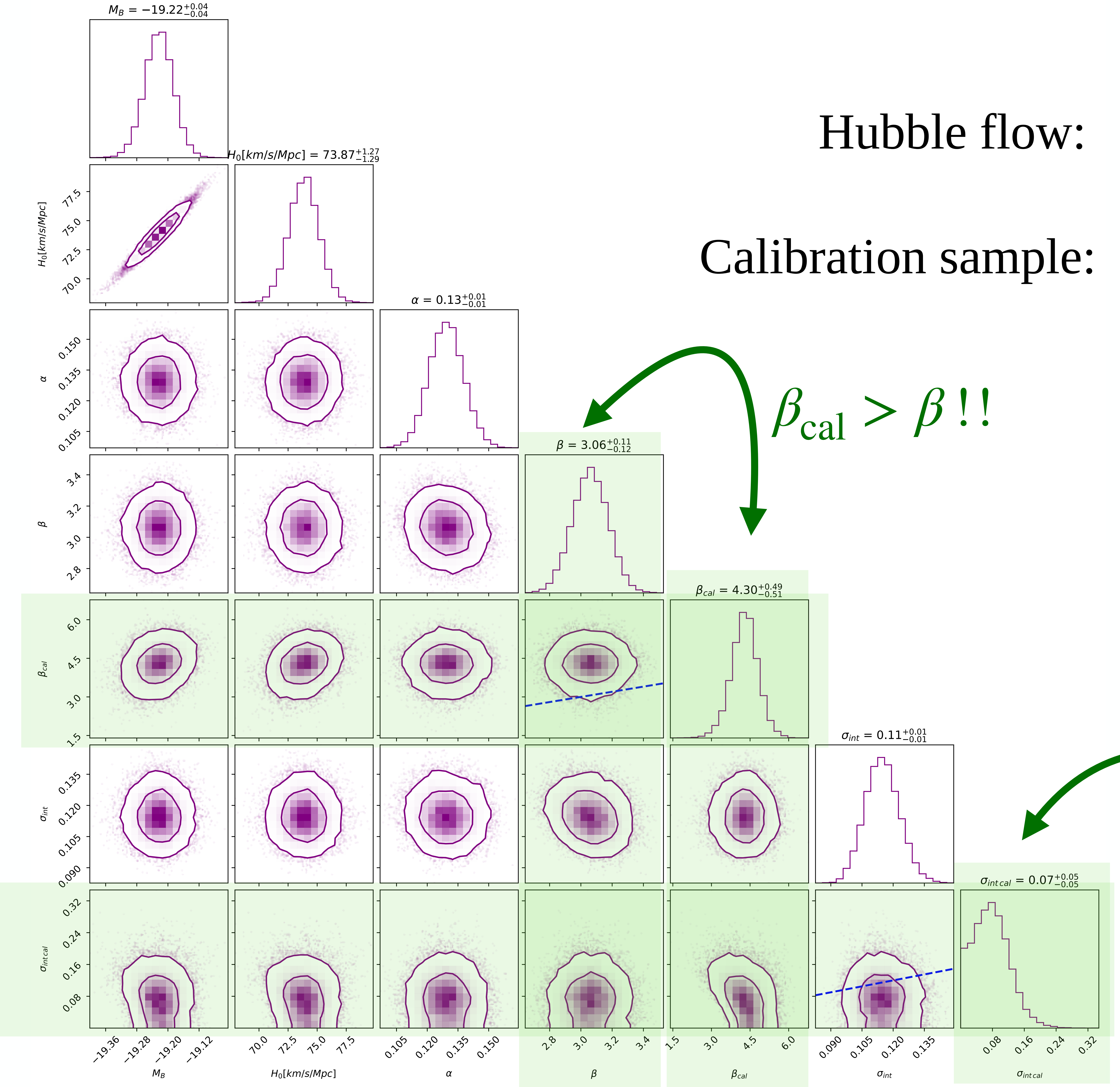
Anomaly in the calibration sample



RW & Hjorth (2022)

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

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



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

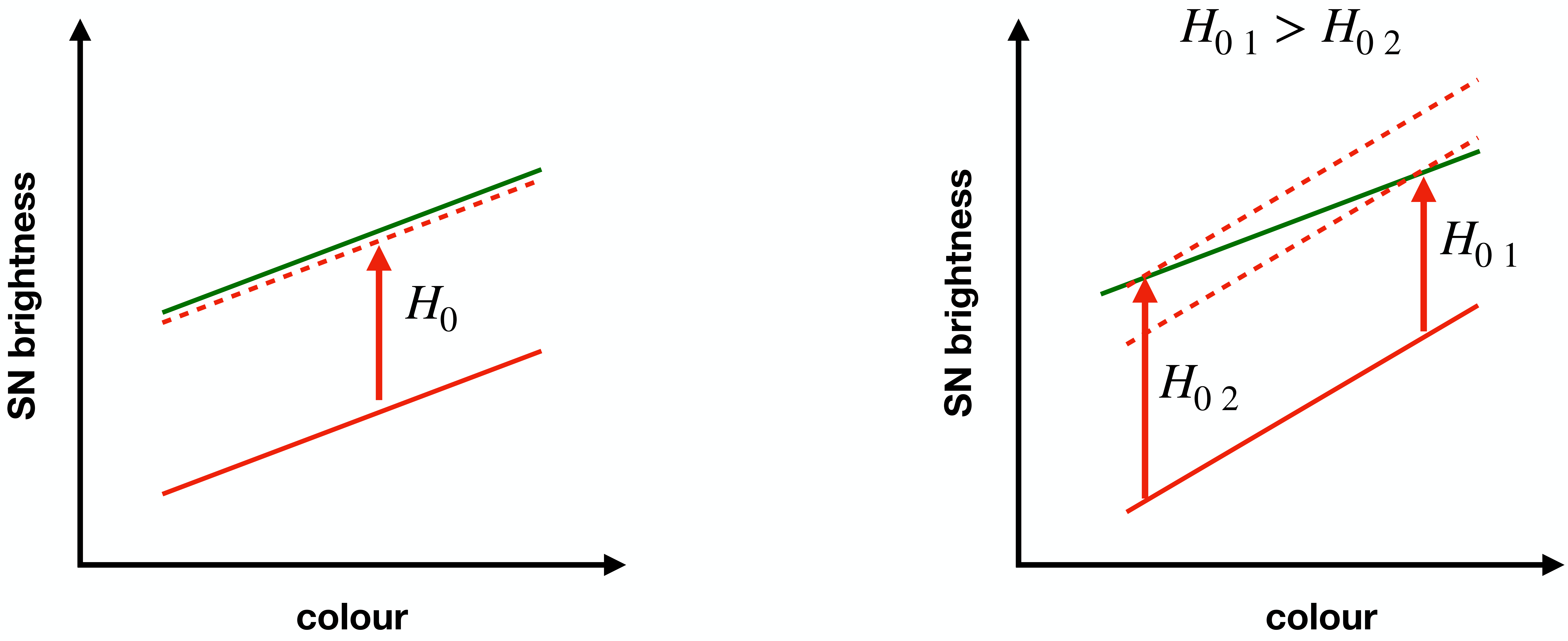
$\sigma_{\rm int,cal} = 0$!!

RW & Hjorth (2022)

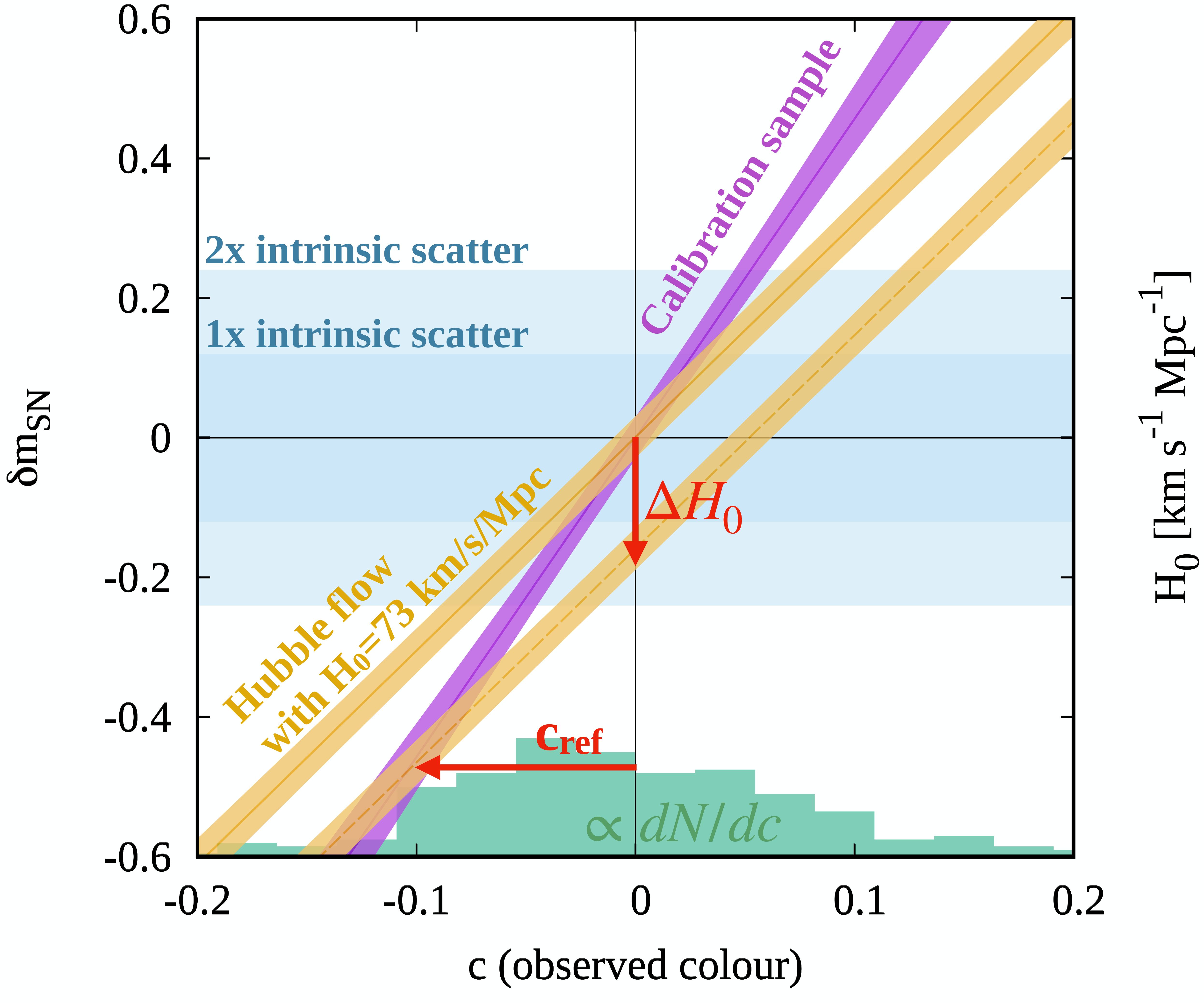
4.2σ (19 cals) Hubble constant tension
goes together with
3.8σ intrinsic anomaly
of the SN standardisation.

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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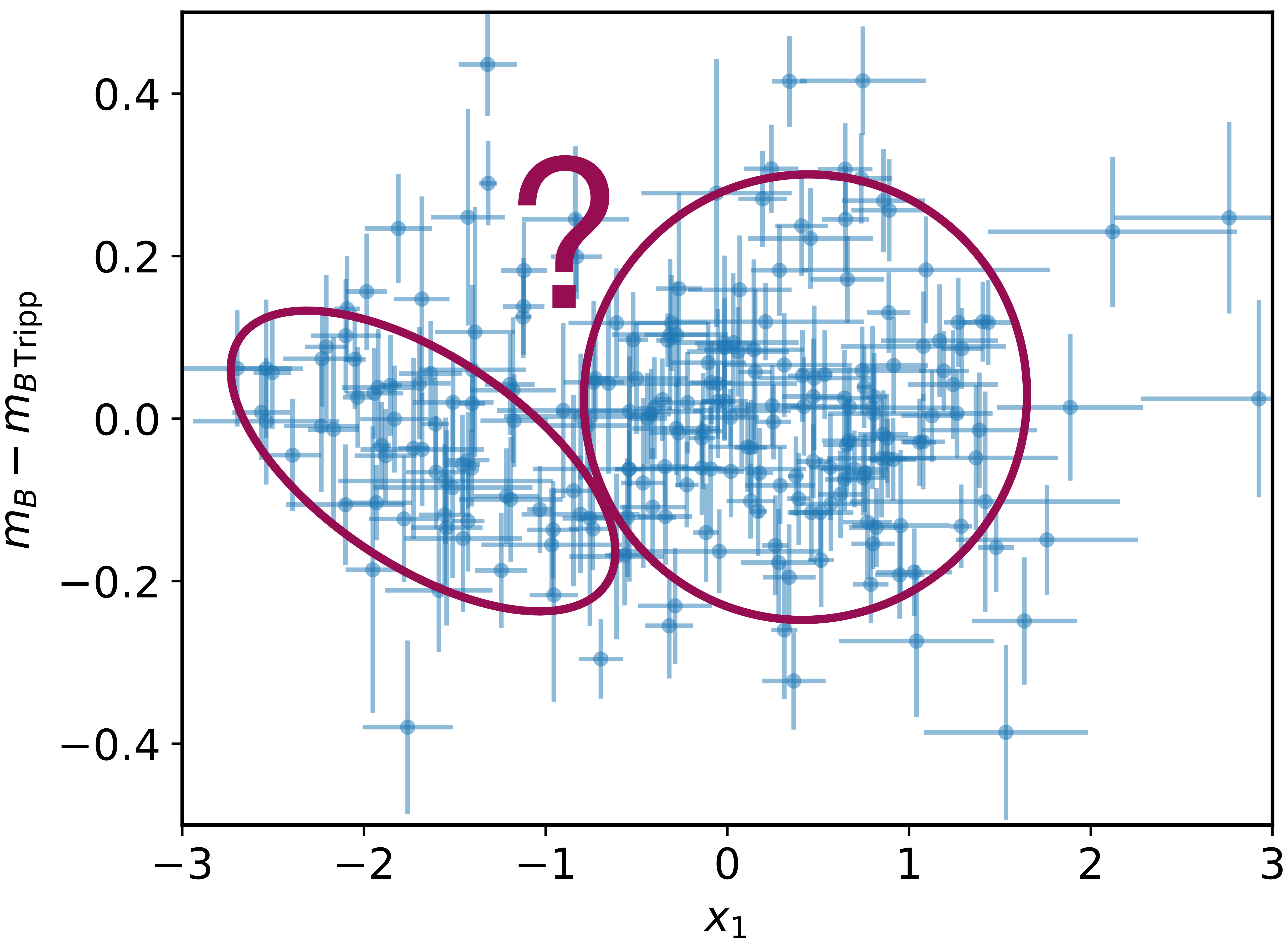
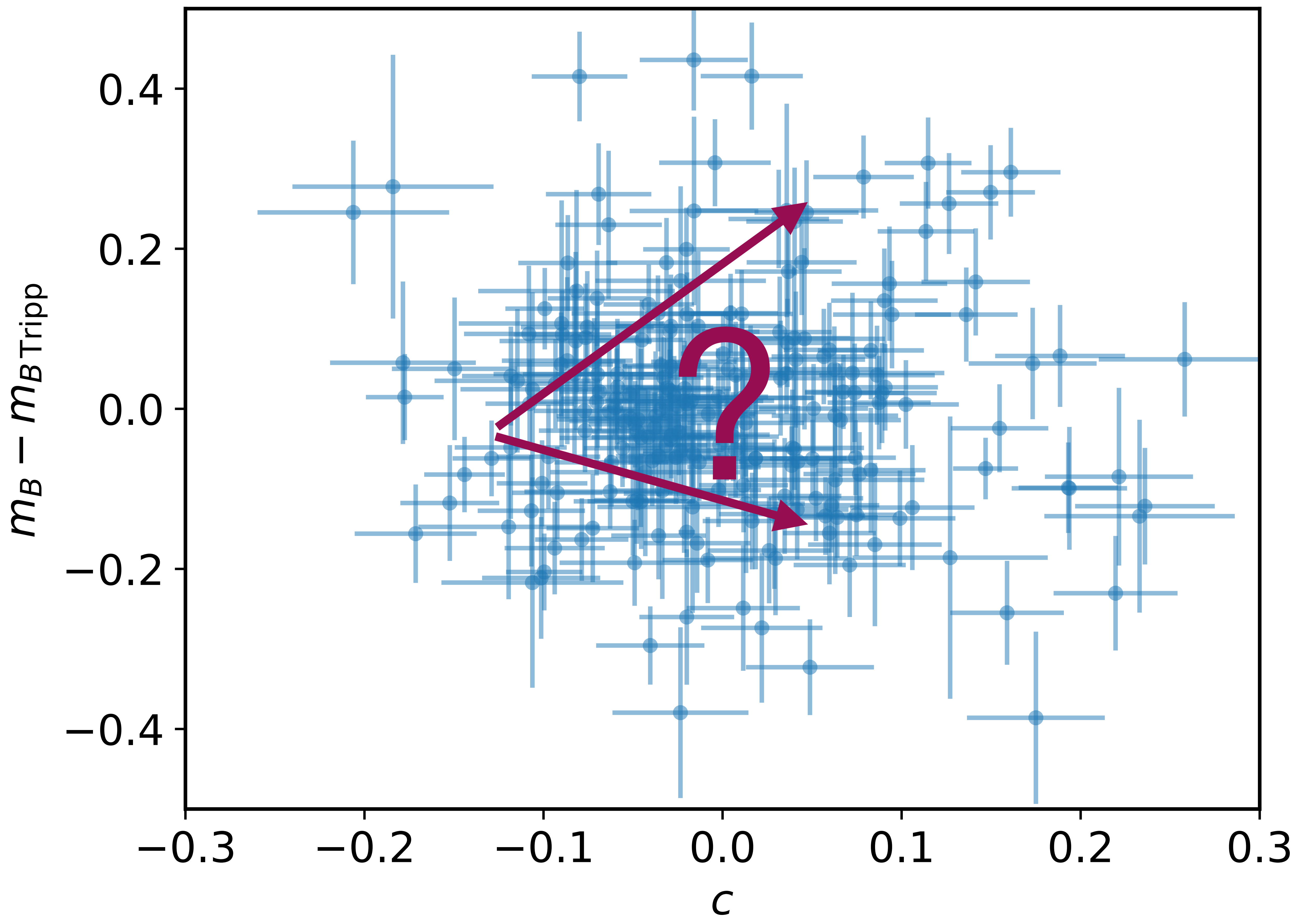
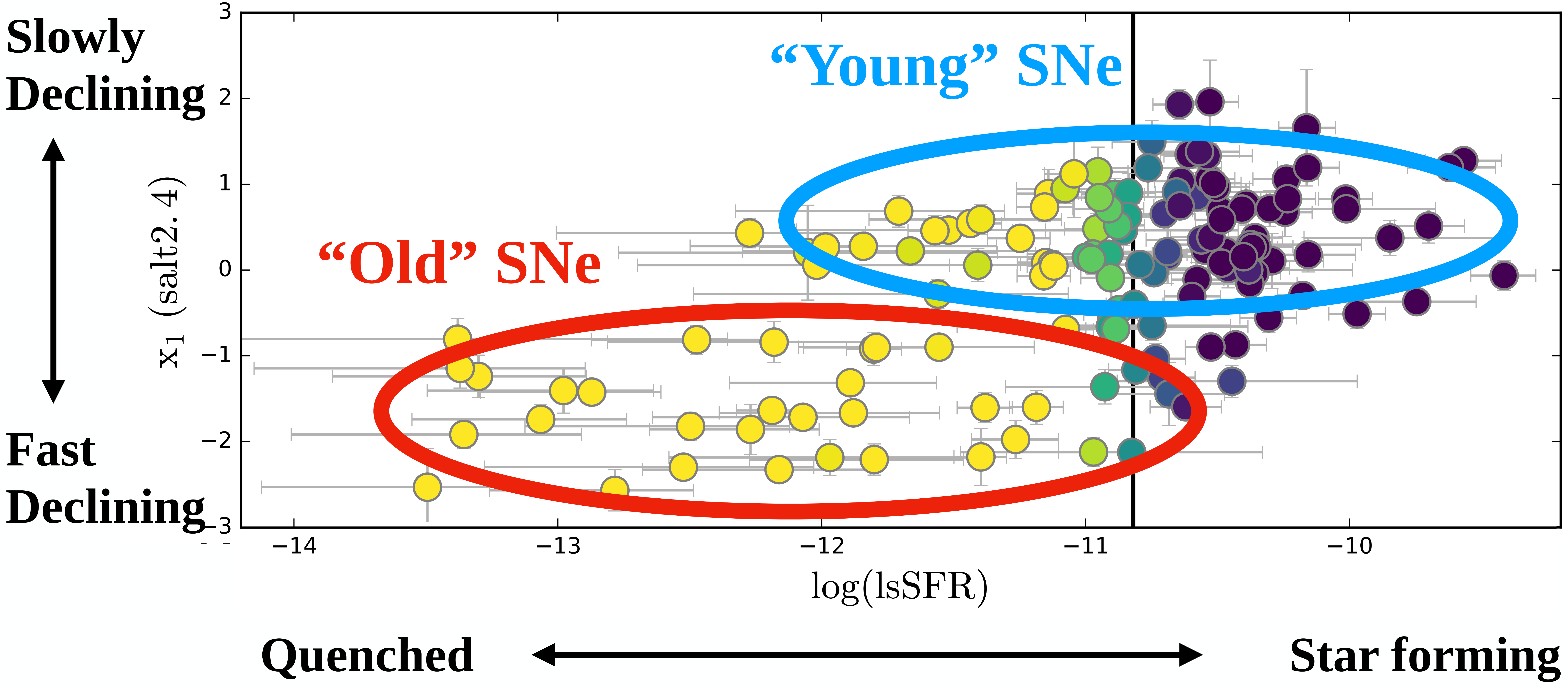




Dust: reddening, extinction

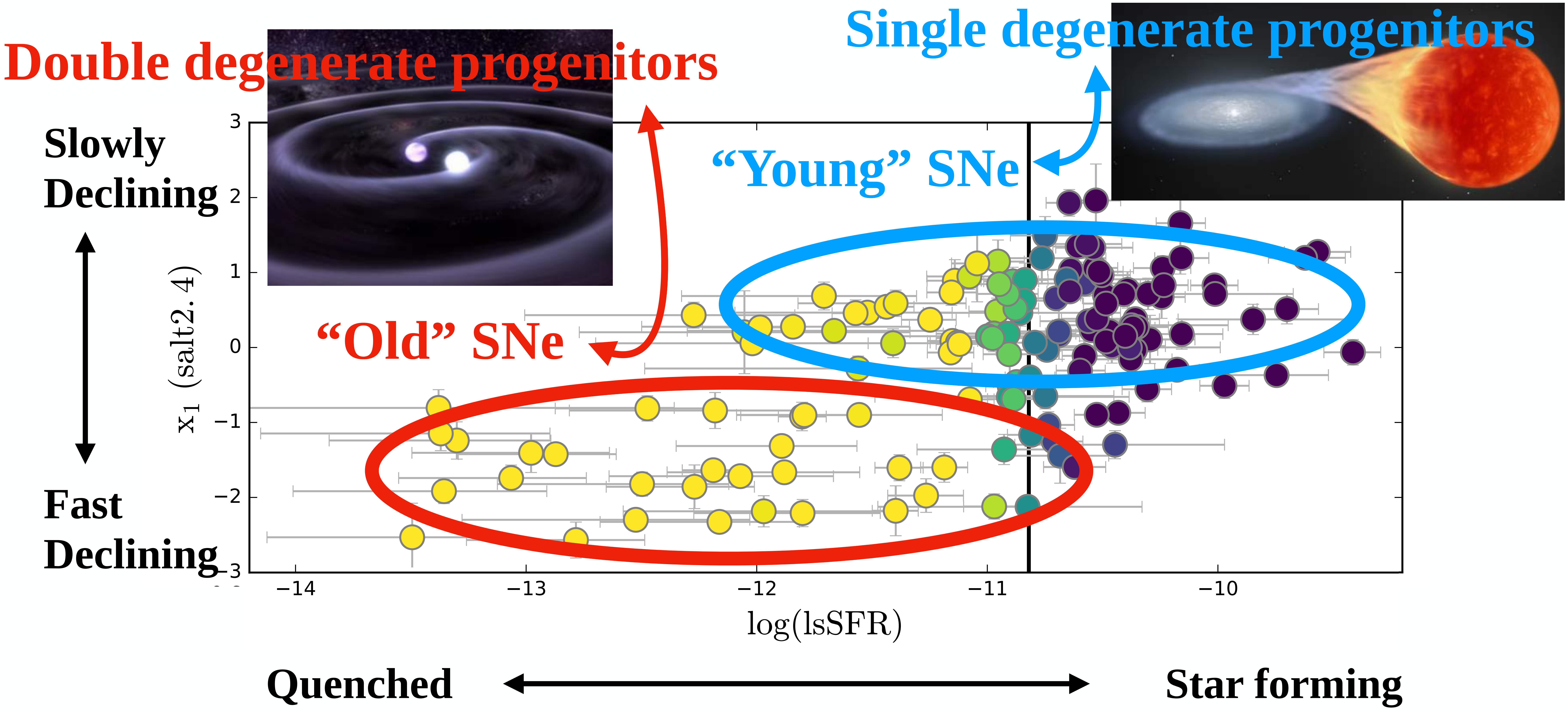
Mandel et al. (2017), Thorp et al. (2021), Brout & Scolnic (2020)

SN populations



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

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

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

$$x_1 = X_1$$

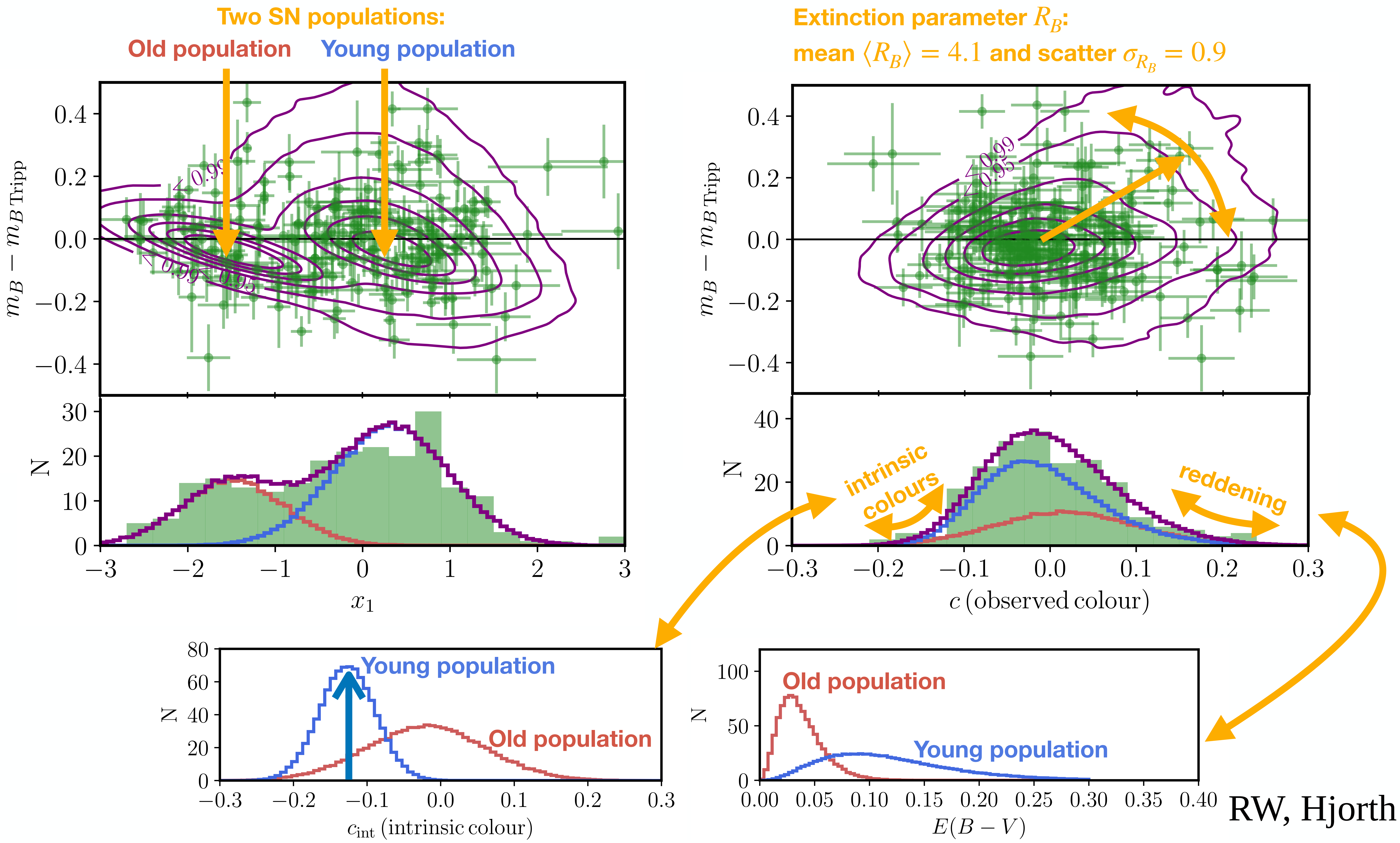
Two sets of priors (hyperparameters)

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

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

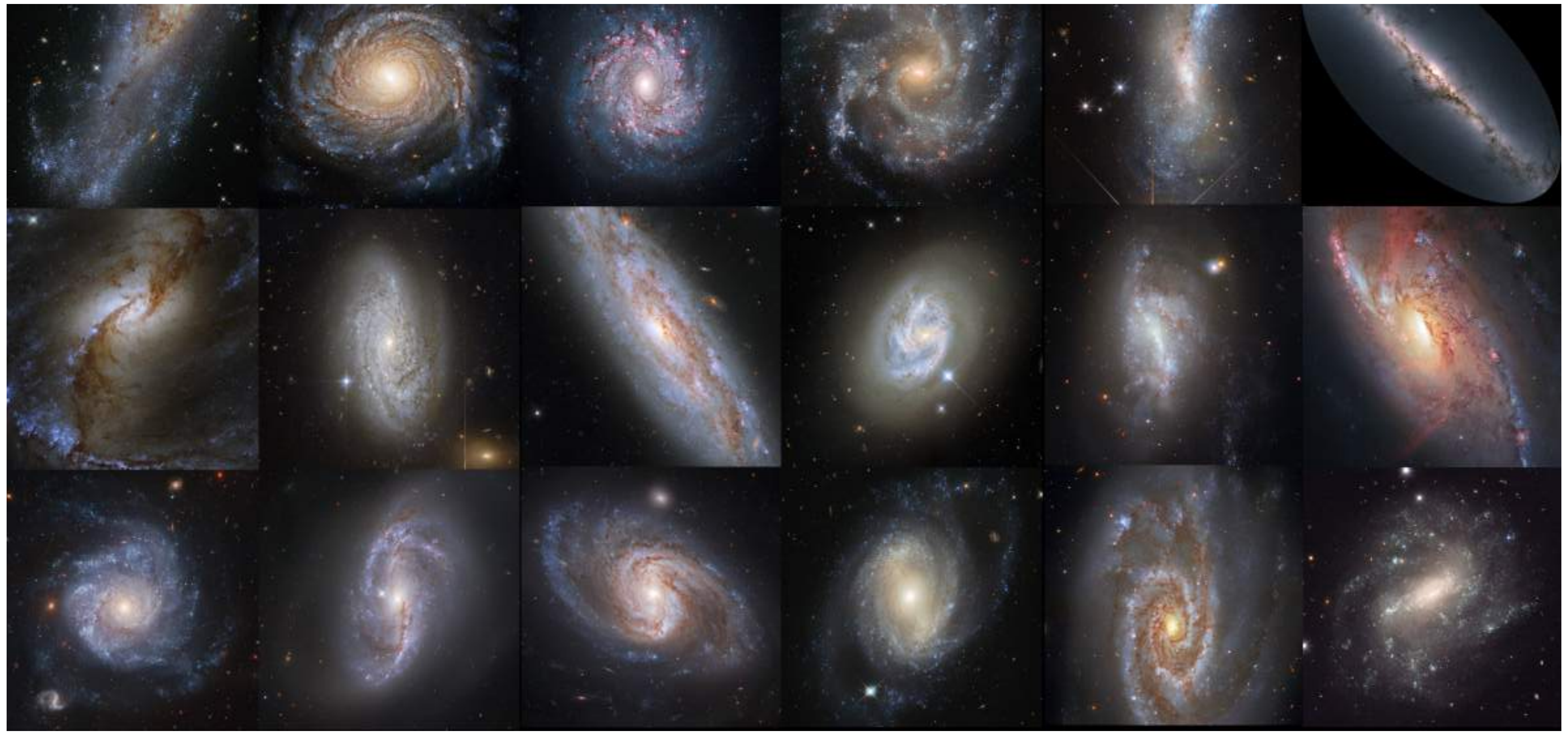
latent variables (LV) ⇒ priors ⇐ hyperparameters

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

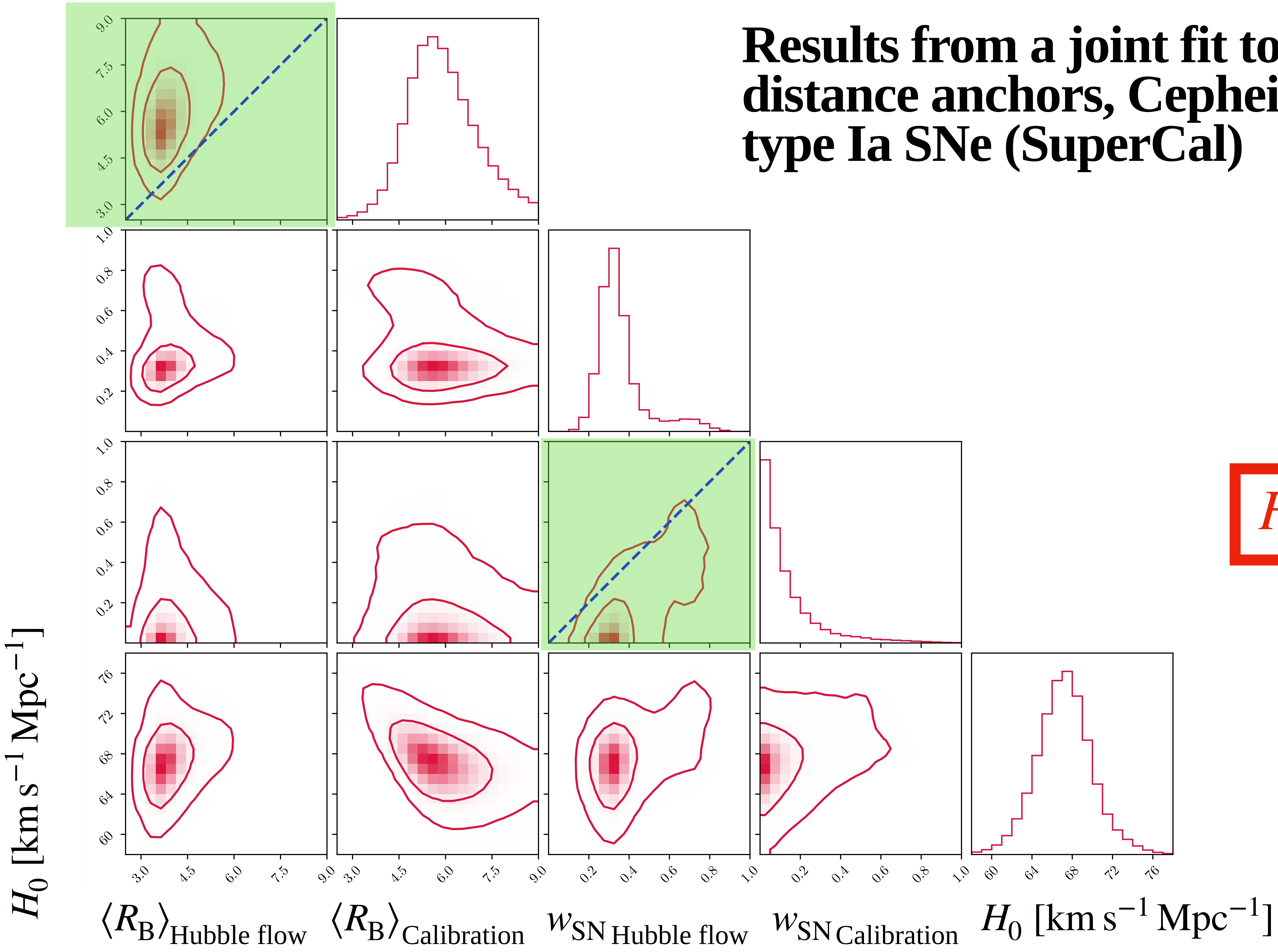
$$c = c_{int} + E(B-V)$$

$$x_1 = X_1$$

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



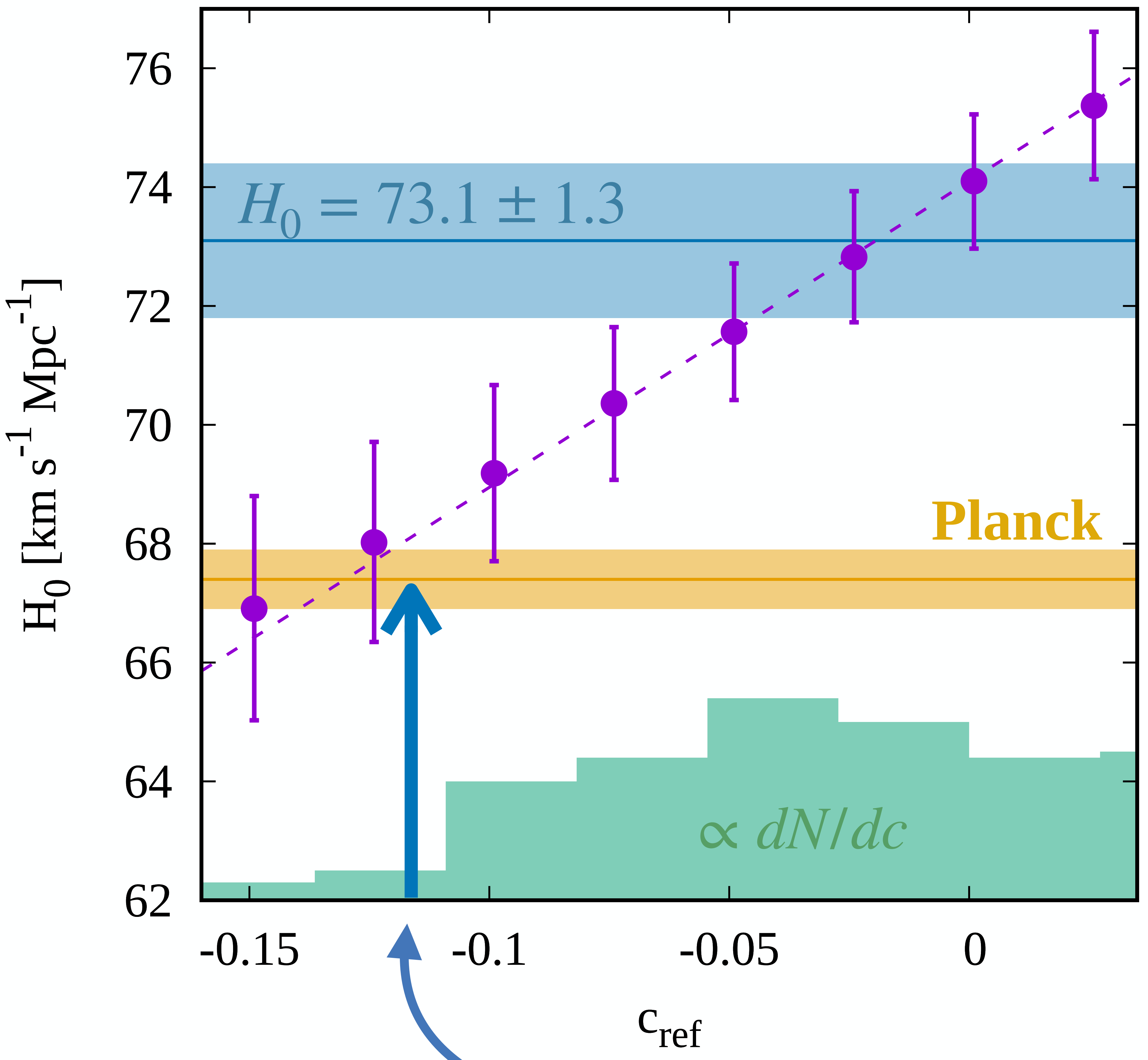
Results from a joint fit to SH0ES data: distance anchors, Cepheids (19 calibrators), type Ia SNe (SuperCal)



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

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: The same params in the calibration and Hubble flow	$H_0 = 72.4^{+1.2}_{-1.2}$
2-pop model: 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: 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

- 4.2σ Hubble constant tension goes together 3.8σ 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.

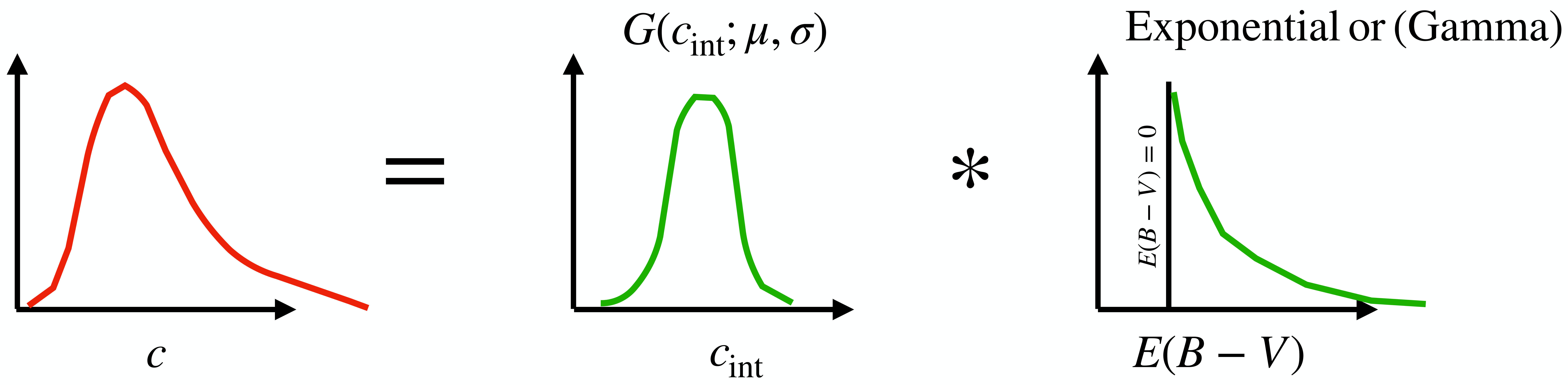
- Reanalysis of the SH0ES data using the new 2-population model yields the Hubble constant which is fully consistent with the Planck value.

RW & Hjorth (2023) TBS

How does it work ?

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

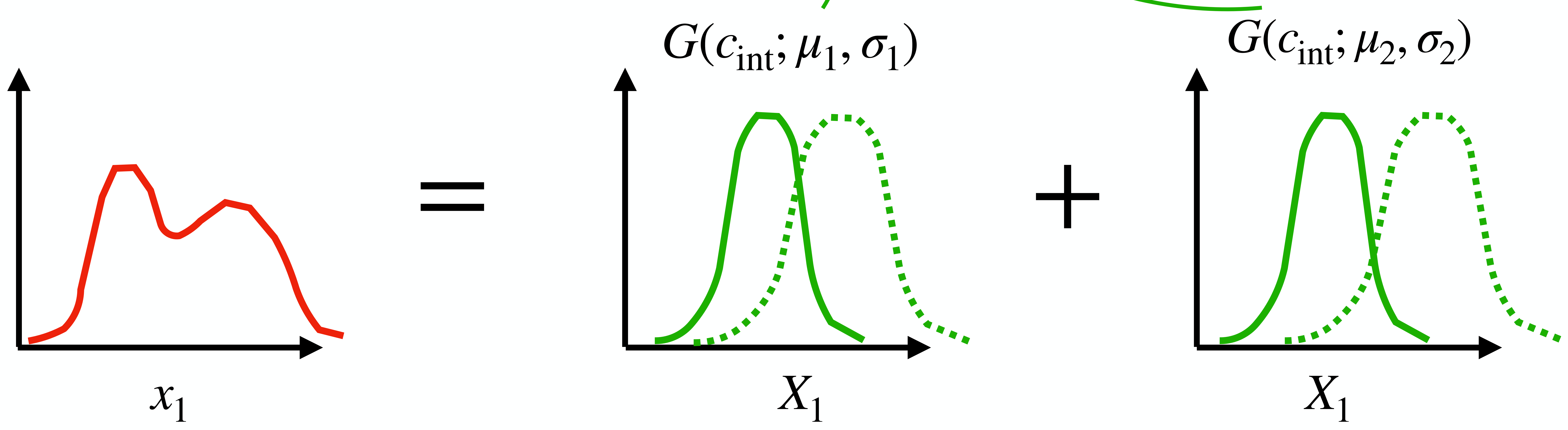
$$c = c_{\rm int} + E(B-V)$$



How does it work ?

observables   latent variables (LV) ⇒ priors ⇐ hyperparameters

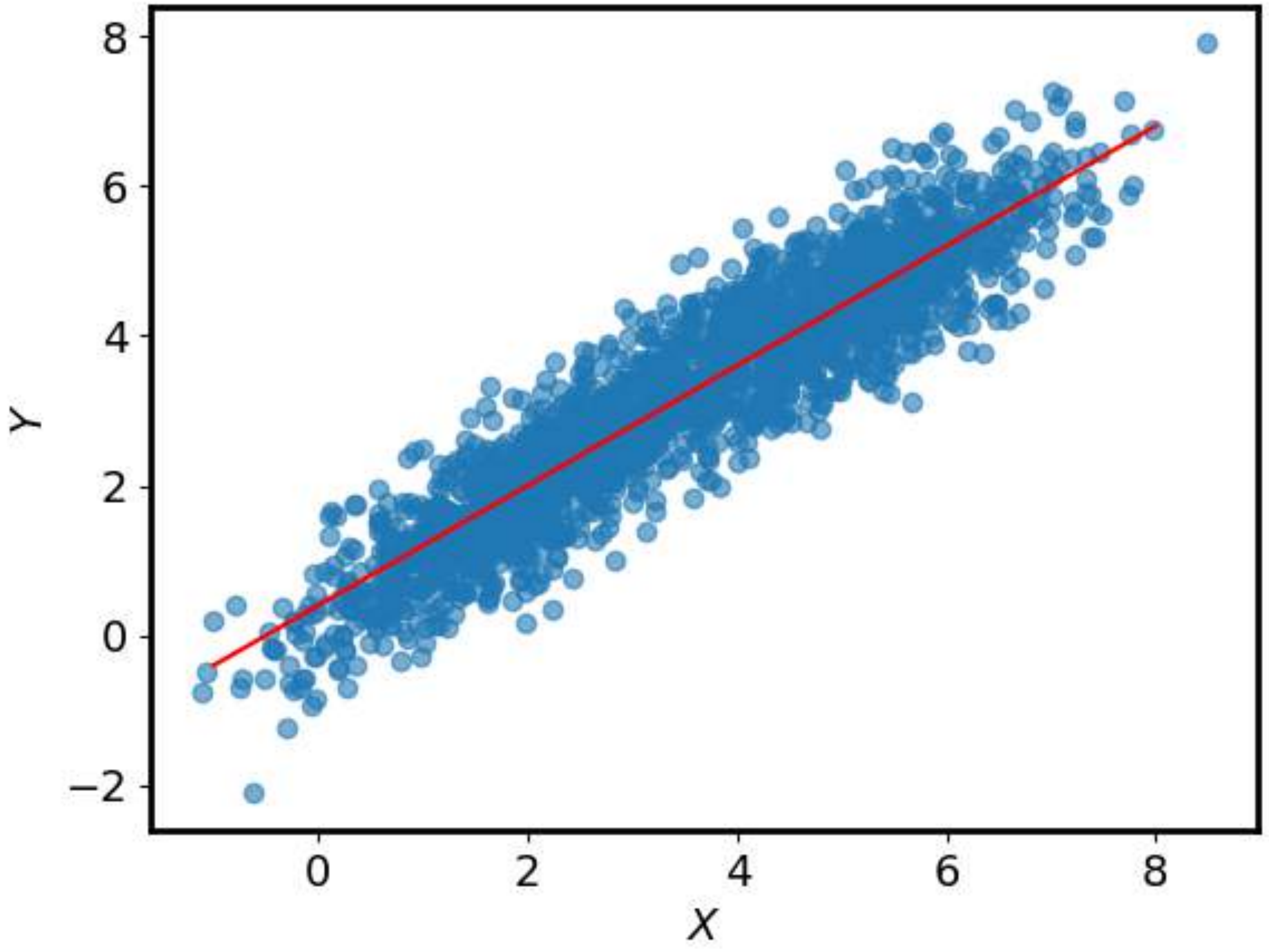
$$x_1 = X_1$$



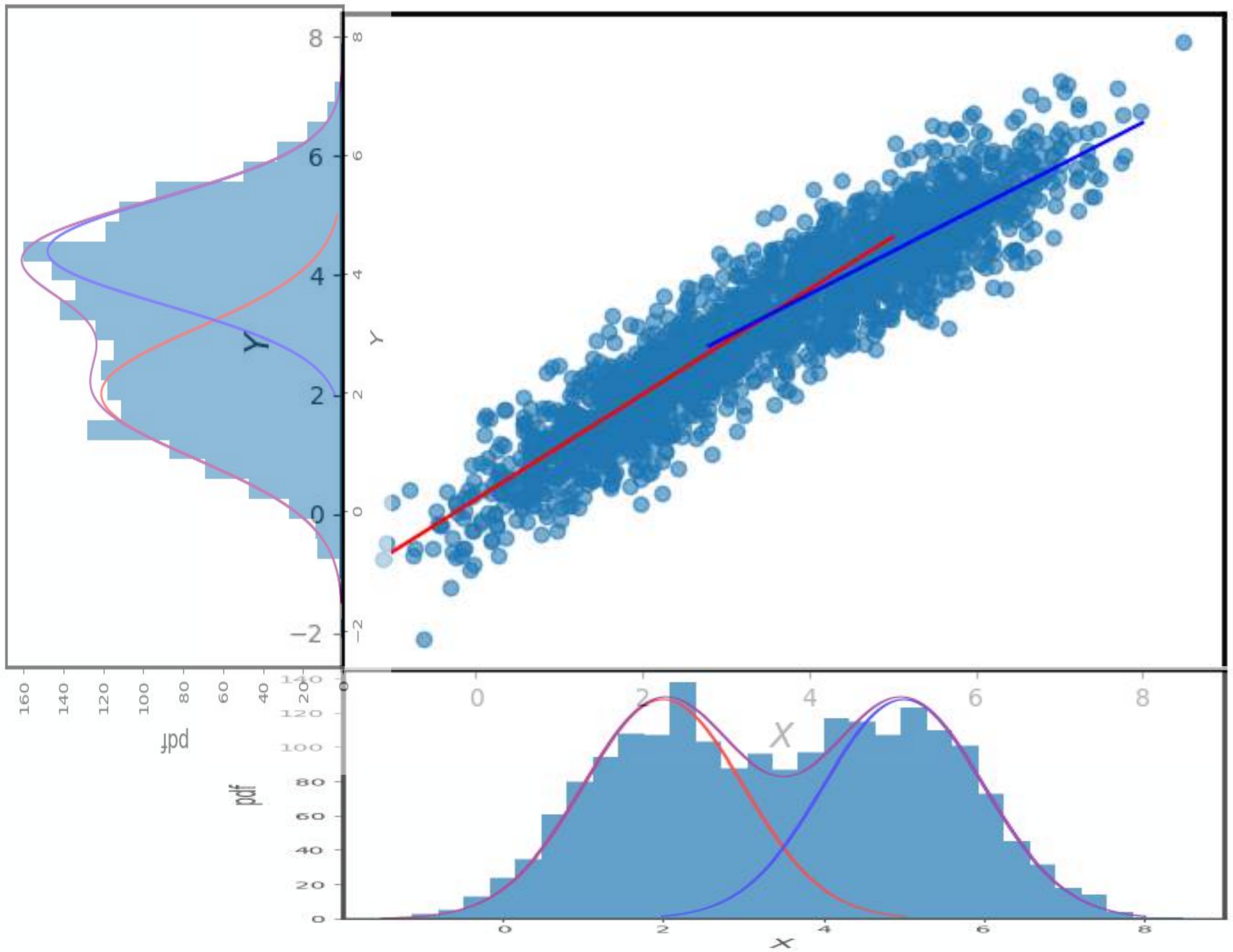
Bayesian hierarchical modelling

How does it work ?

Traditional modelling:
Relations between observables

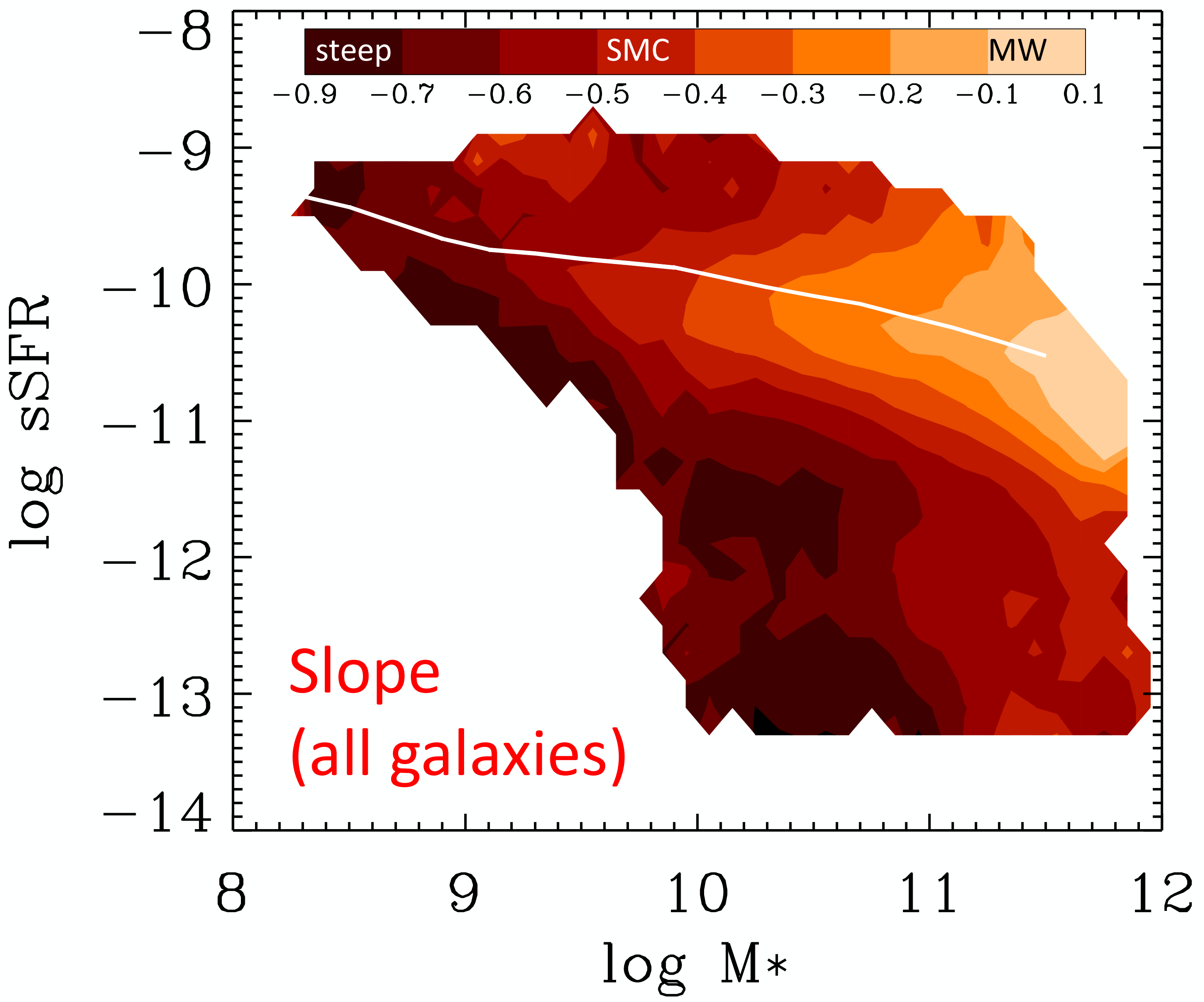


Bayesian hierarchical modelling:
Relations between observables+distribution of Observables



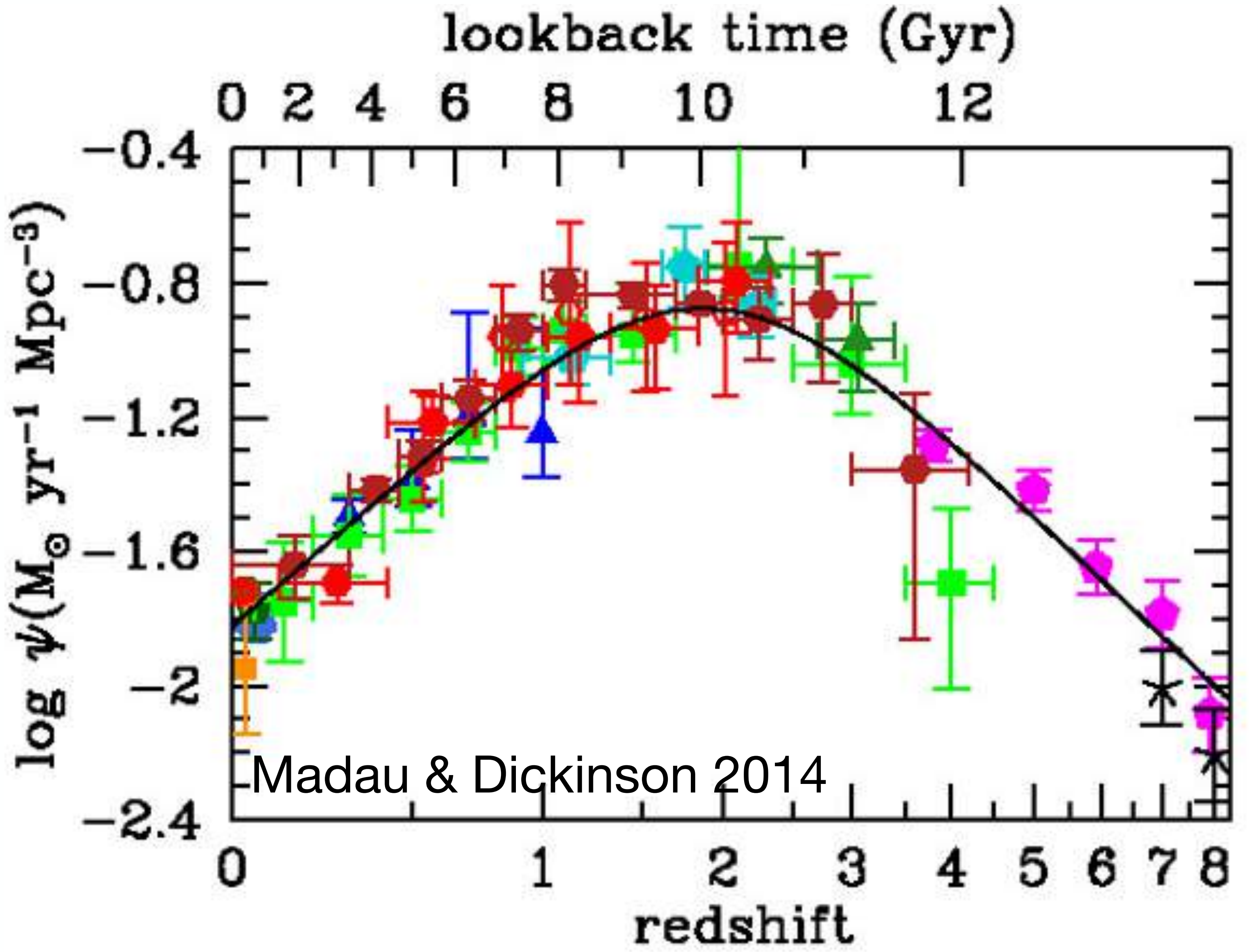
Testable implications/questions

Extinction properties/dust composition in different stellar environments



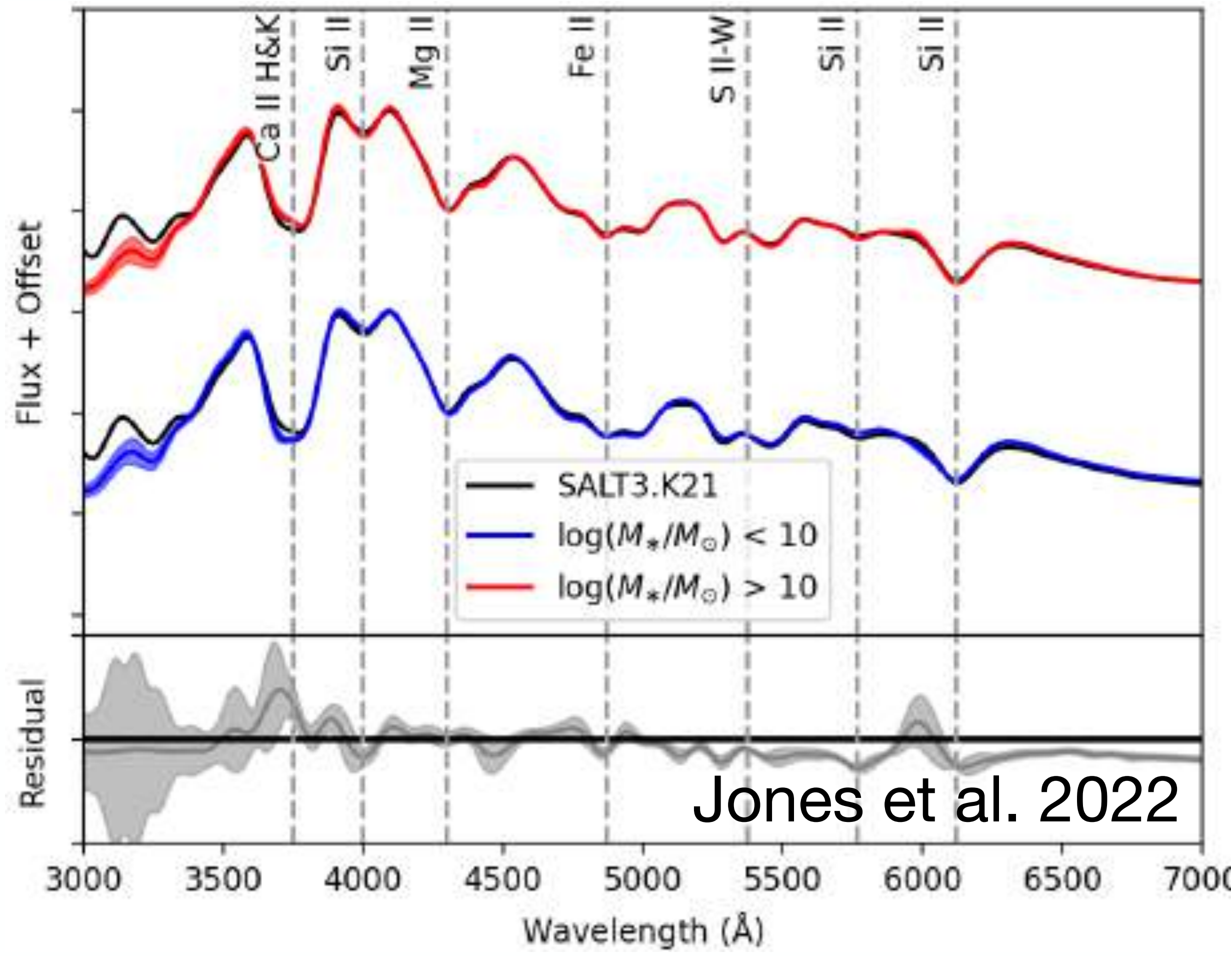
Salim et al. 2018

2-pops SN model

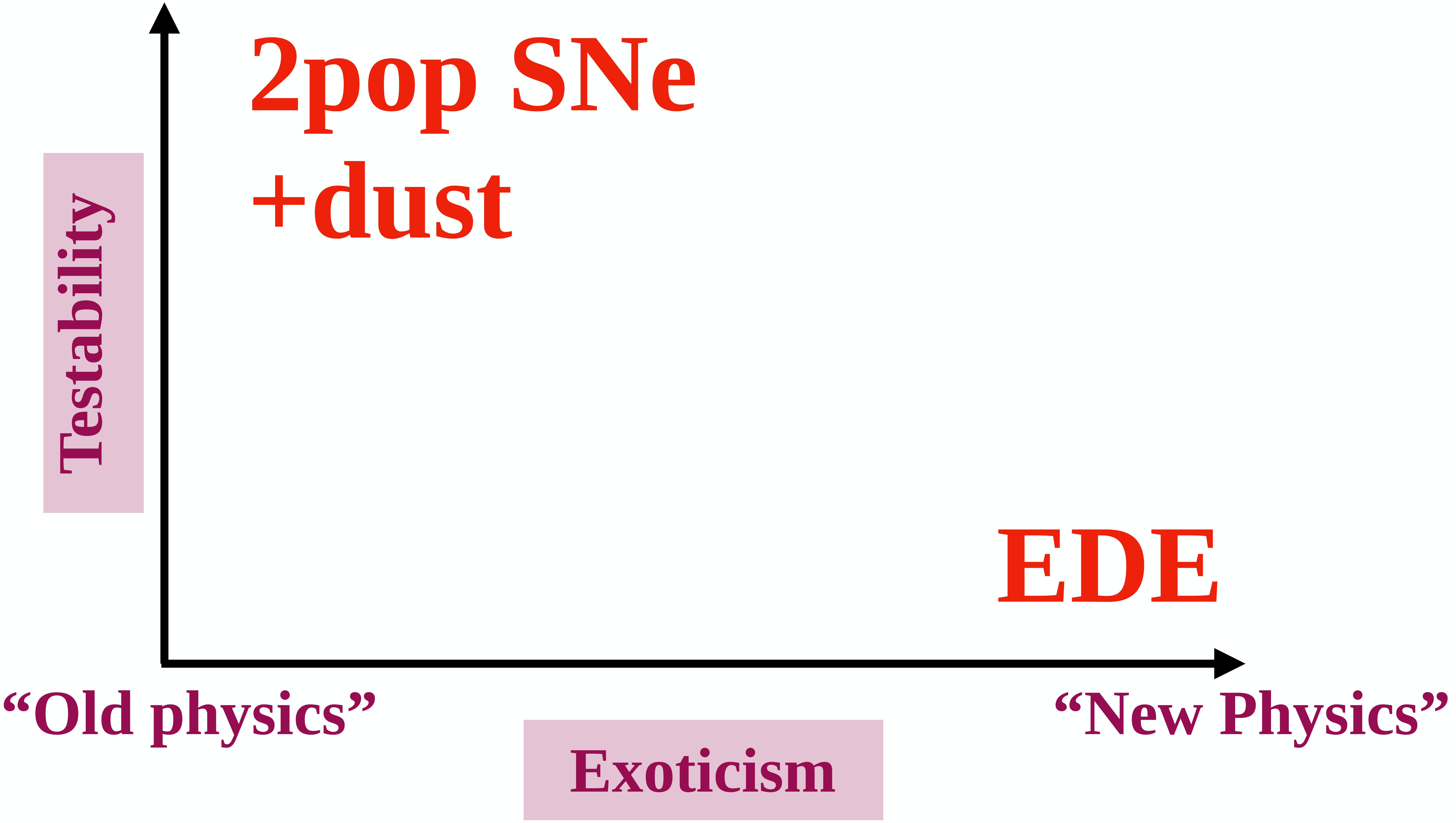


Relative fractions of SN populations should follow SFR

Spectroscopic differences between SN populations

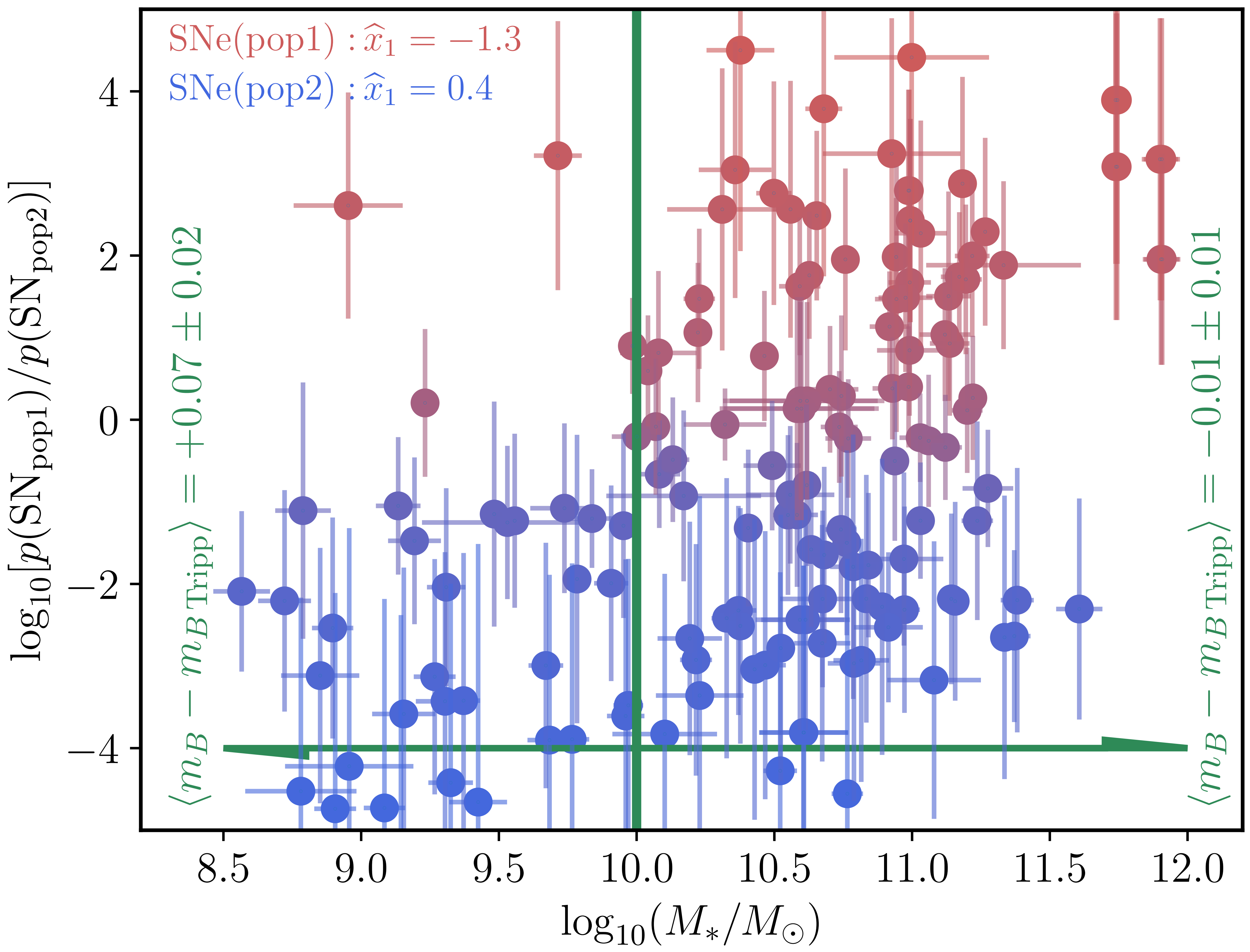


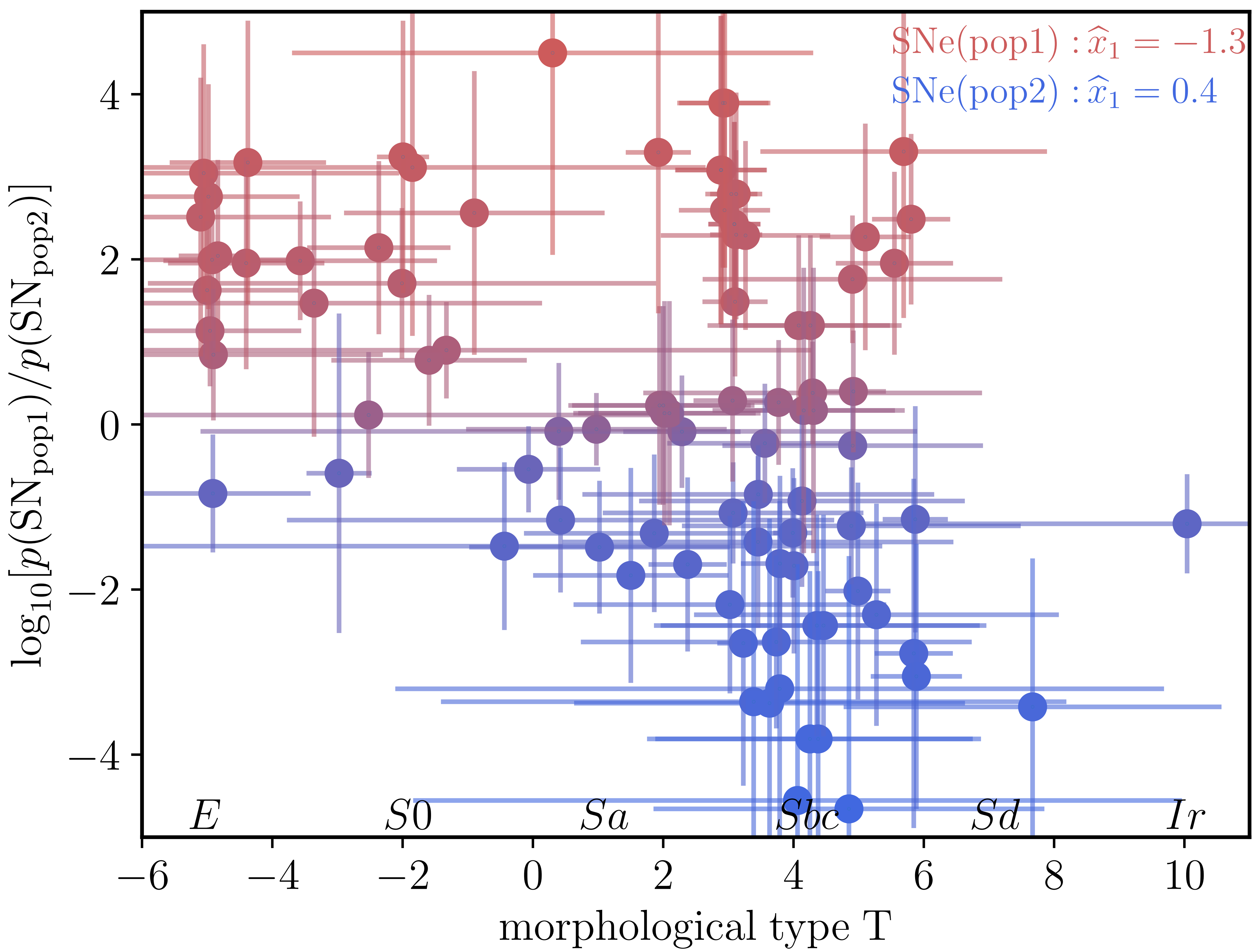
Hubble constant tension: SN physics vs EDE



“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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