

2405.20965

2406.02072



# Cosmology with Type Ia Supernovae and the ZTF SN Ia DR2 sample

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LPCA - 24<sup>th</sup> January 2025



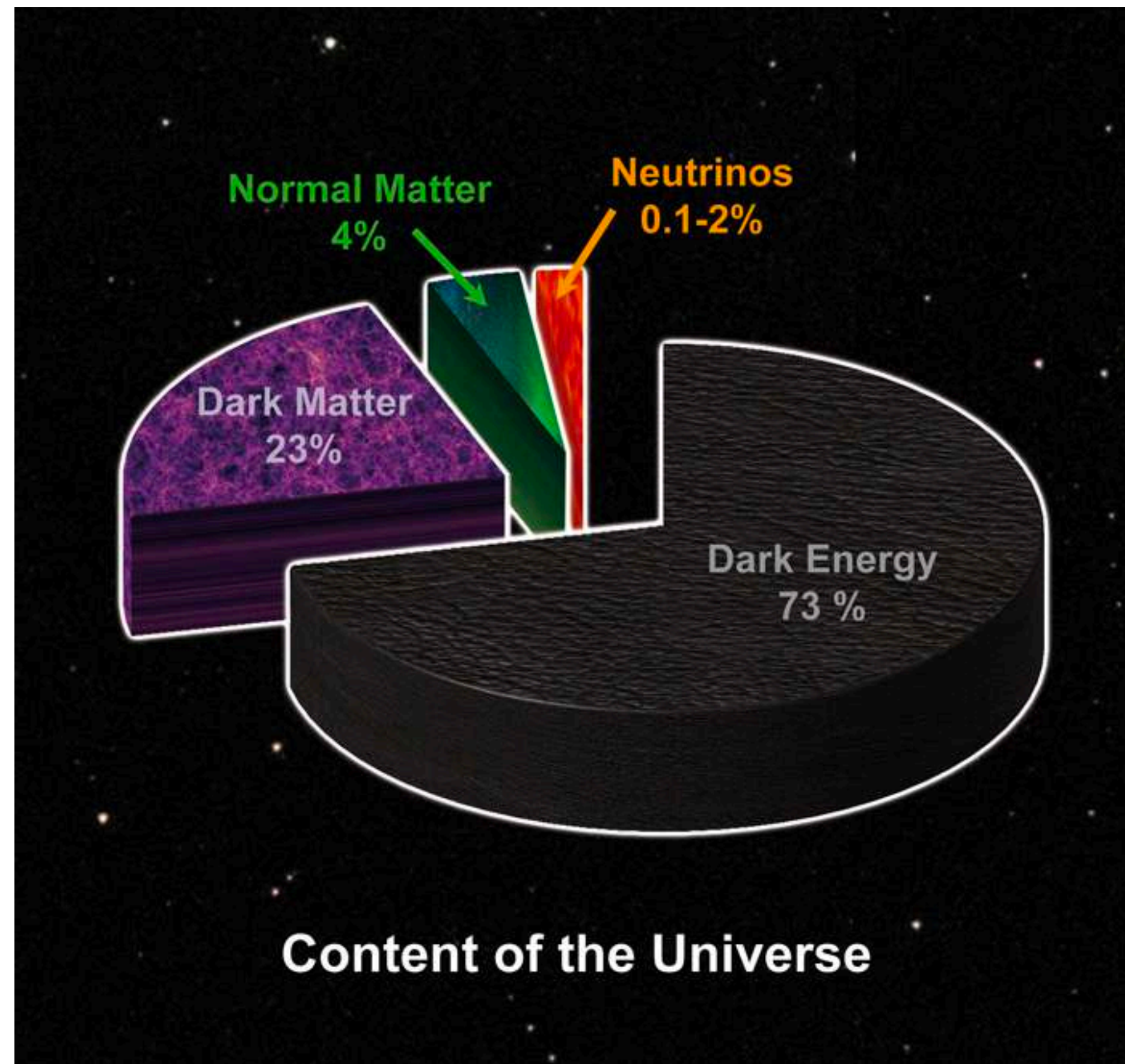
# Outline

- I. Cosmology with Type Ia supernovae
- II. ZTF SN Ia DR2
- III. SNe Ia standardisation with the ZTF DR2
- IV. Next steps

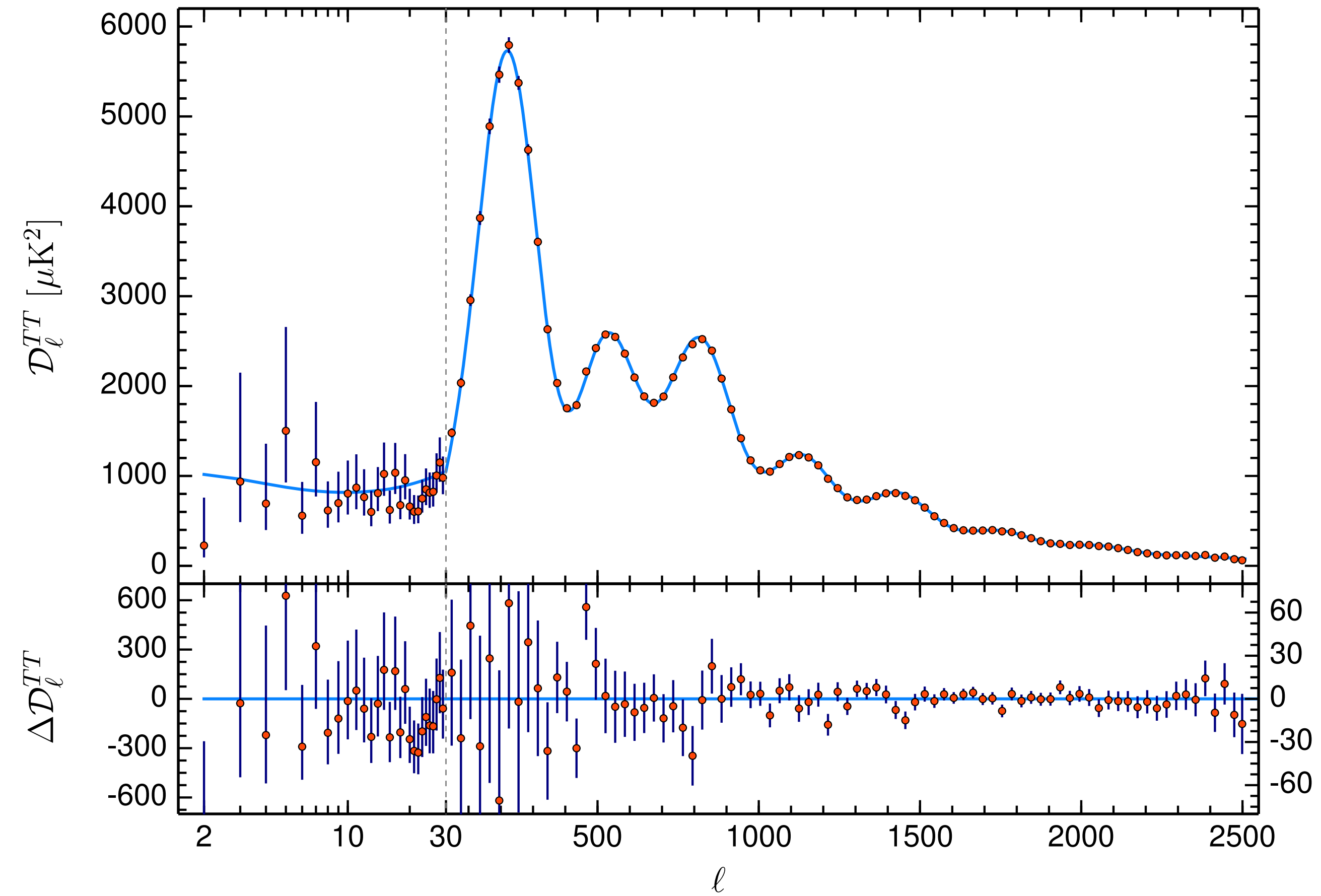
# I. Cosmology with Type Ia Supernovae

# Cosmology

## $\Lambda$ CDM model



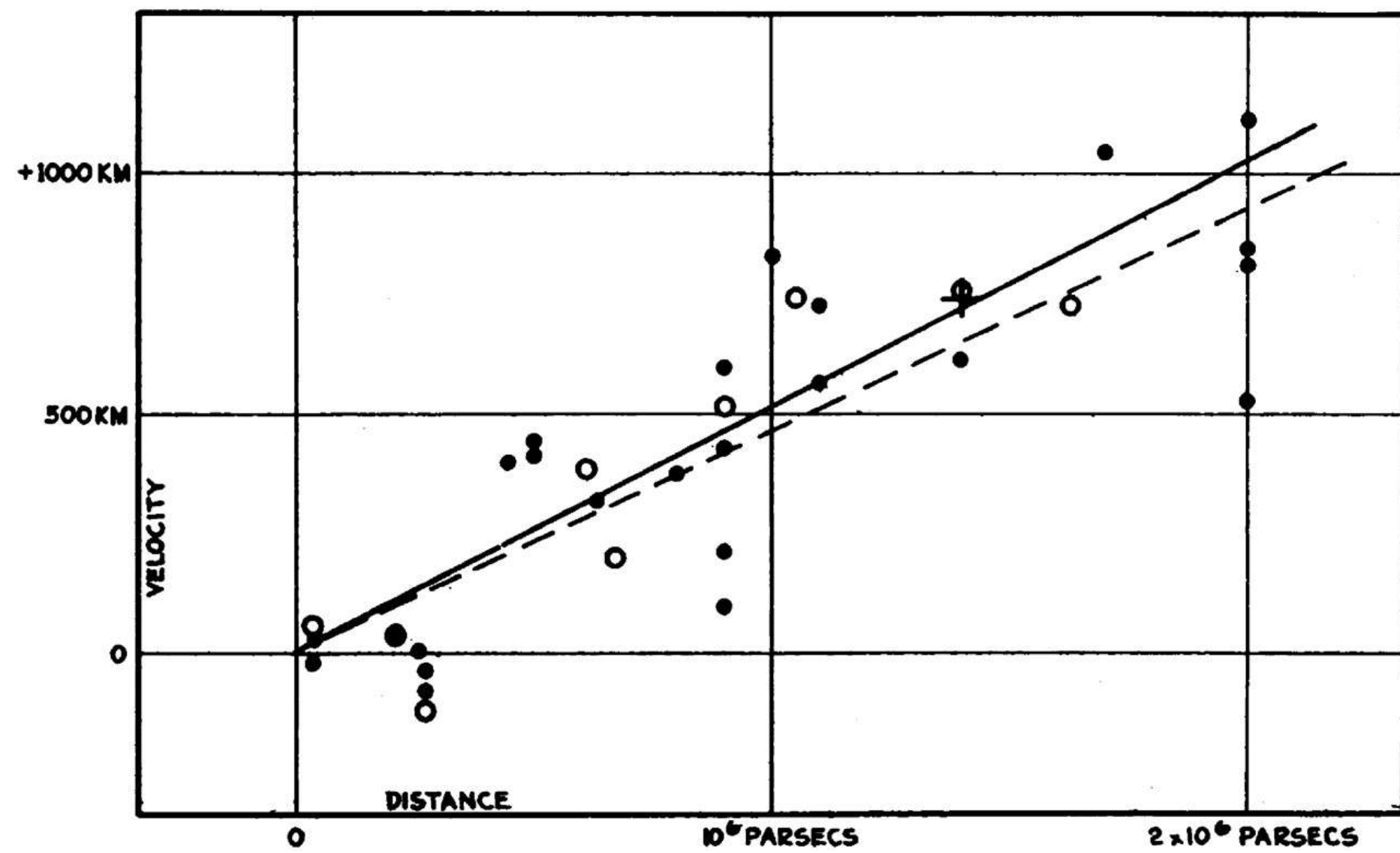
Credits: HAP / A. Chantelauze



Planck 2018

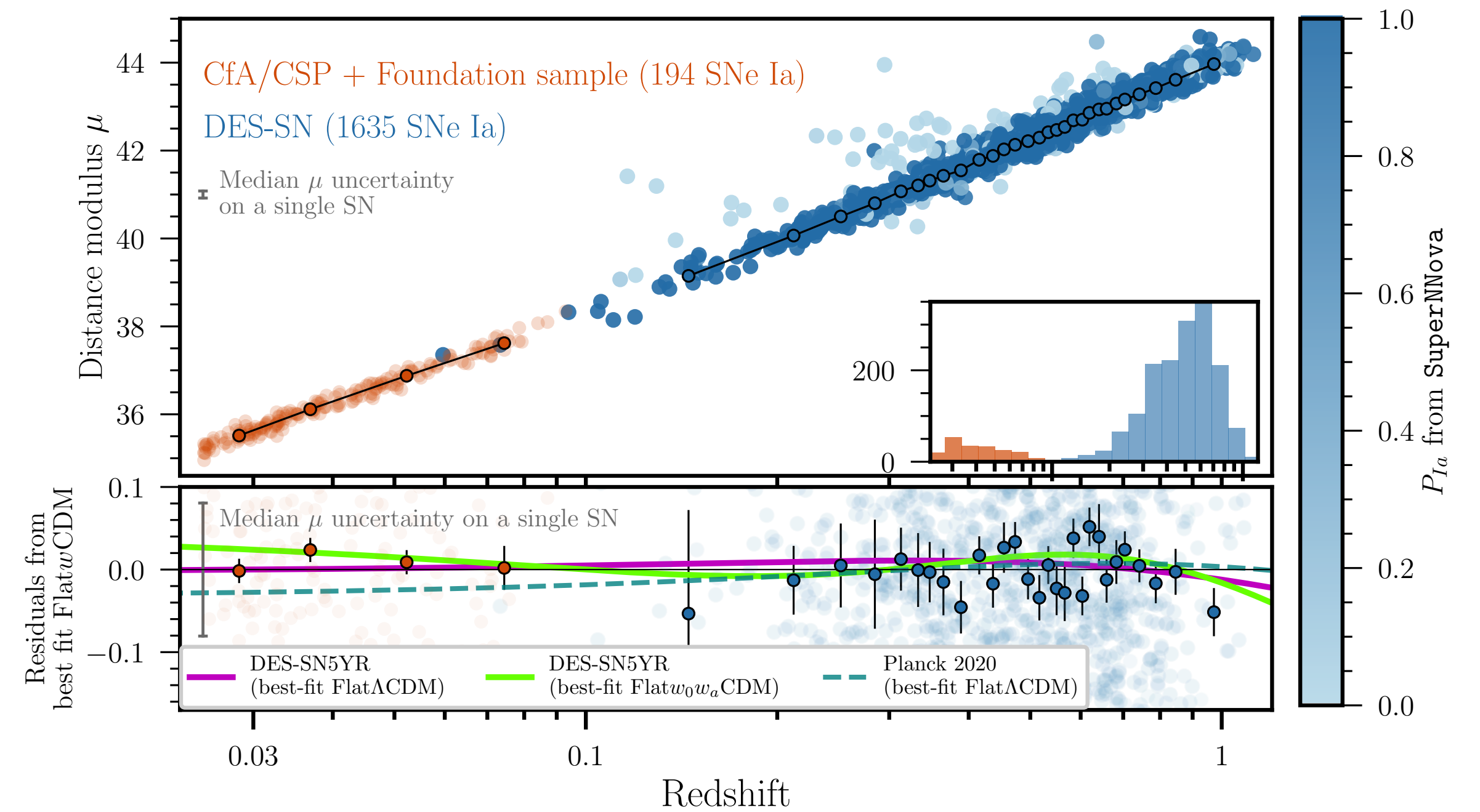
# Cosmology

## Hubble diagram



Hubble (1929)

$$H_0$$

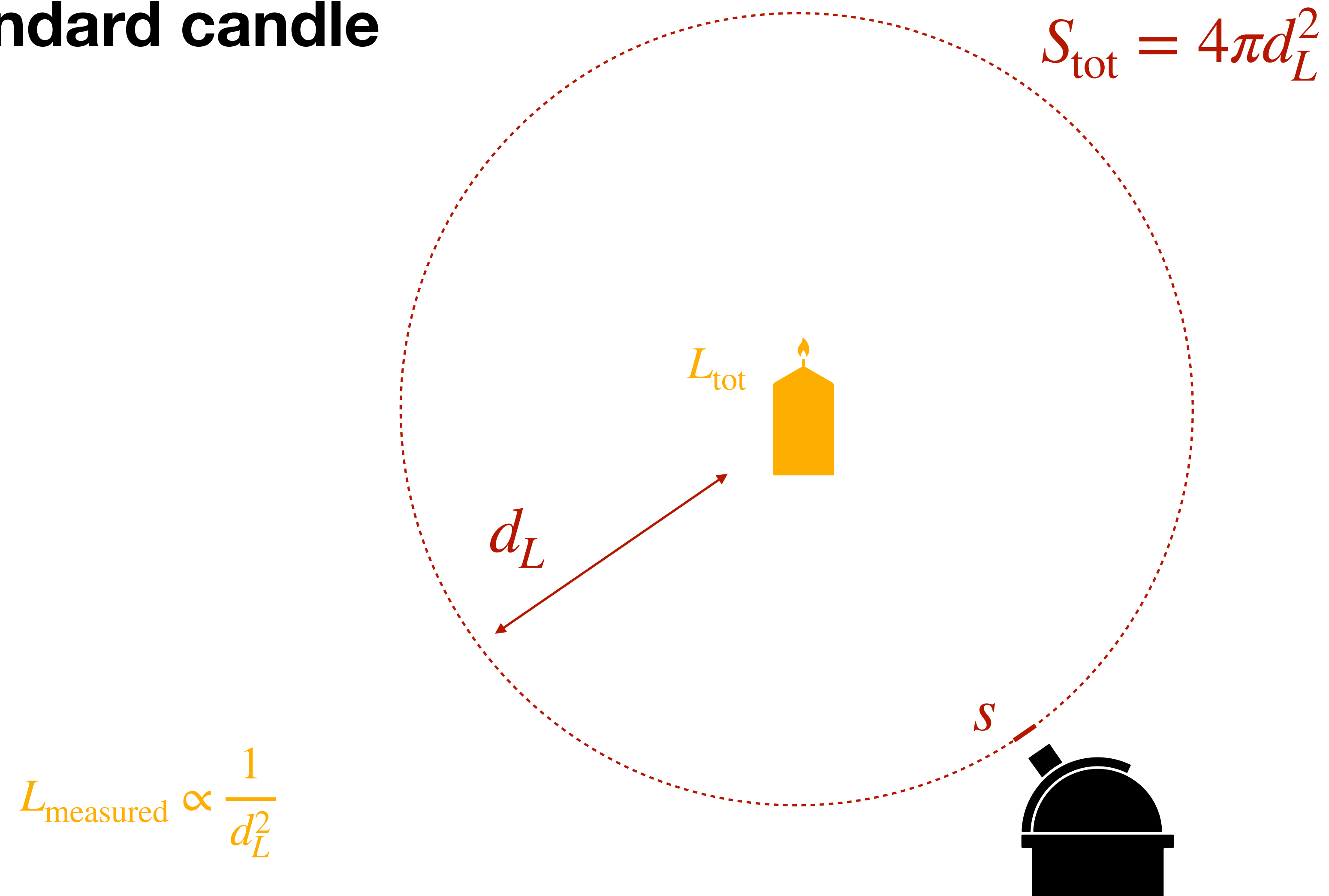


DES-SN5YR

$$H_0, w, \Omega_m$$

# Cosmology

## Standard candle

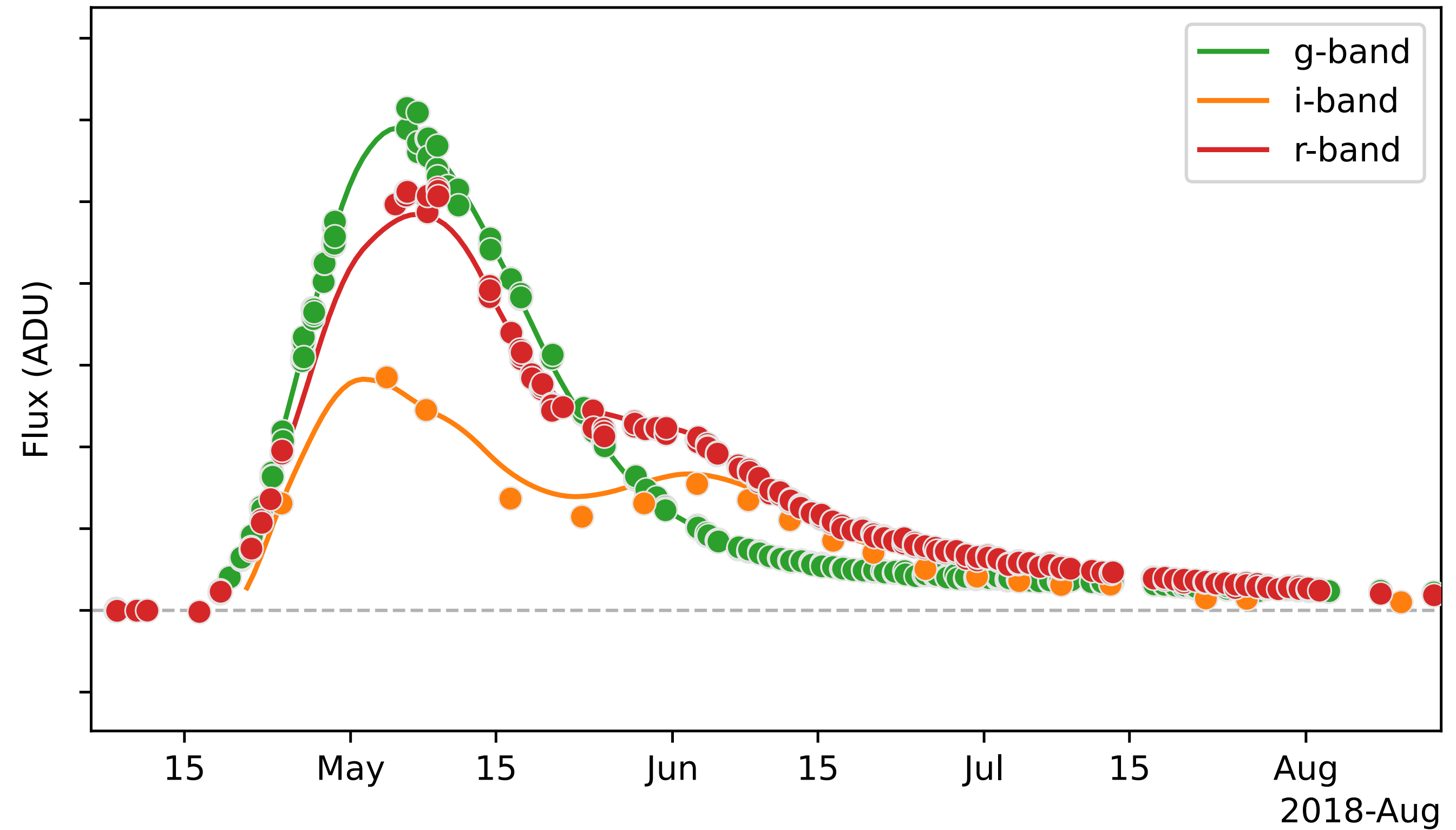


# Type Ia Supernovae (SNe Ia)

## Lightcurve



Credits: B.J. Fulton/  
LCOGT/Caltech



# Type Ia Supernovae (SNe Ia)

## Lightcurve fitting

Flux of the SN:

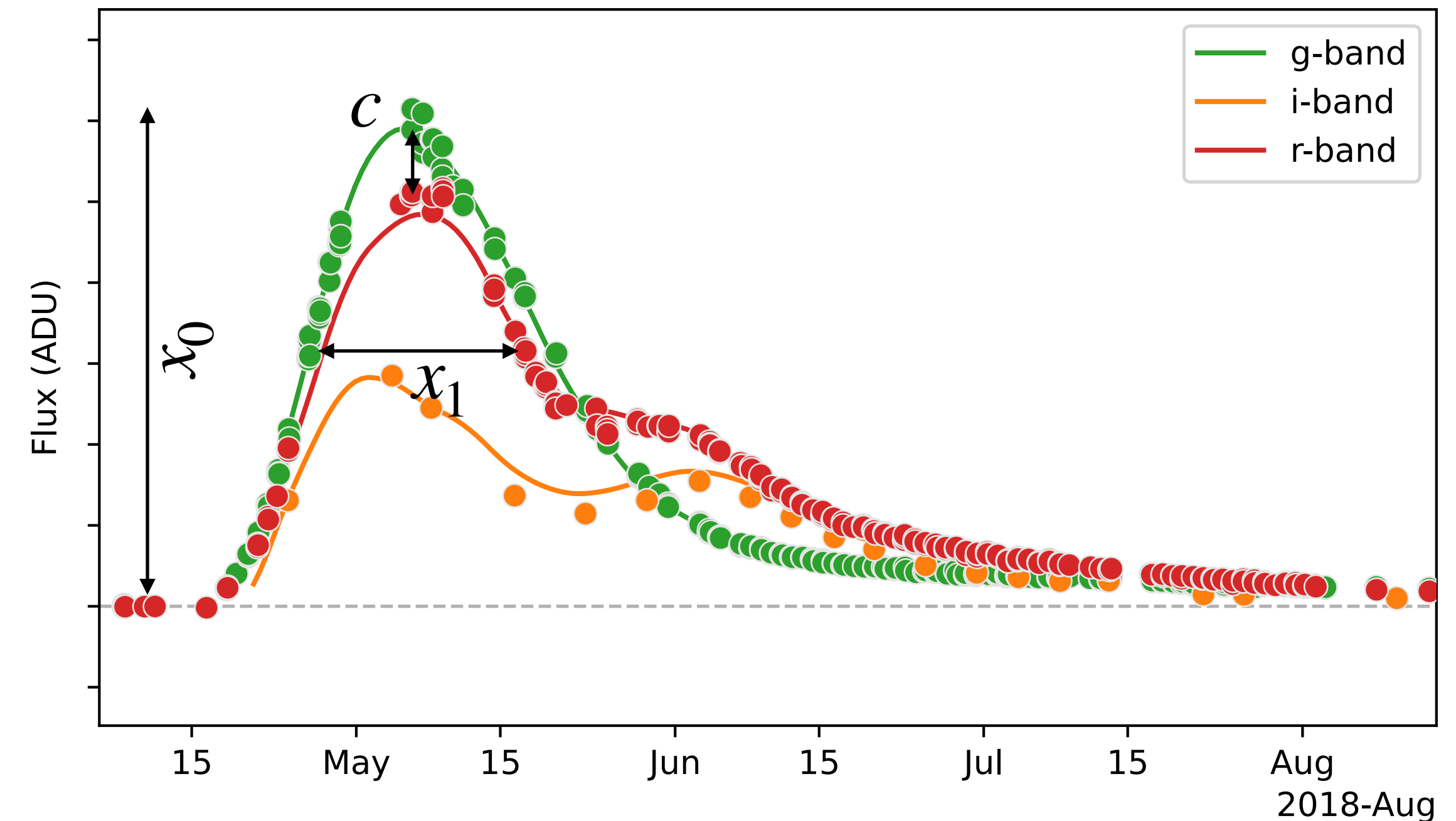
$$F(SN, p, \lambda) = x_0 [M_0(p, \lambda) + x_1 M_1(p, \lambda)] \exp(c CL(\lambda))$$

Parameters relative to the observation

$p$ : phase of the observation  
 $\lambda$ : wavelength

Parameters relative to the SN

$x_0$ : amplitude  
 $x_1$ : stretch  
 $c$ : colour  
 $t_0$ : time of the peak

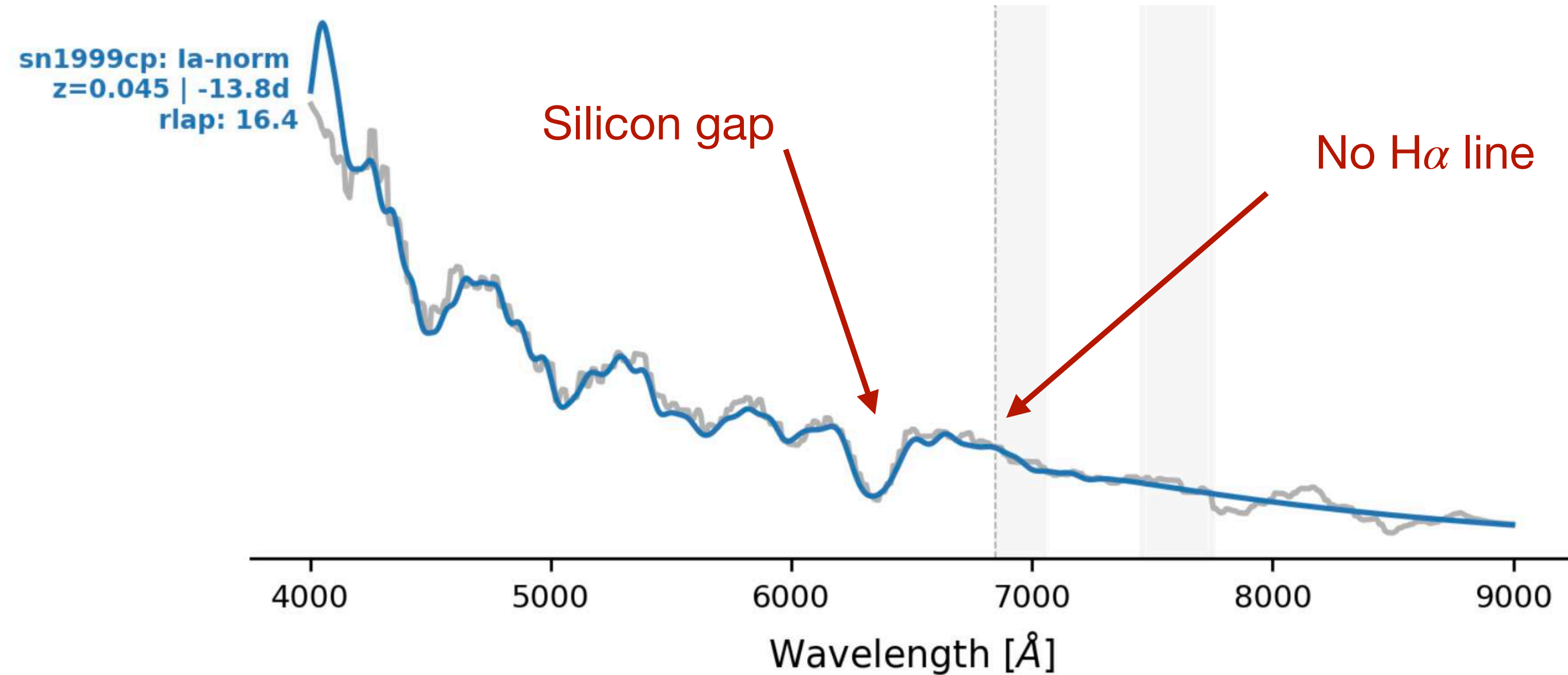


SALT2.4 - Guy et al (2007)  
SALT3 - Kenworthy et al (2021)

# Type Ia Supernovae (SNe Ia) Spectrum

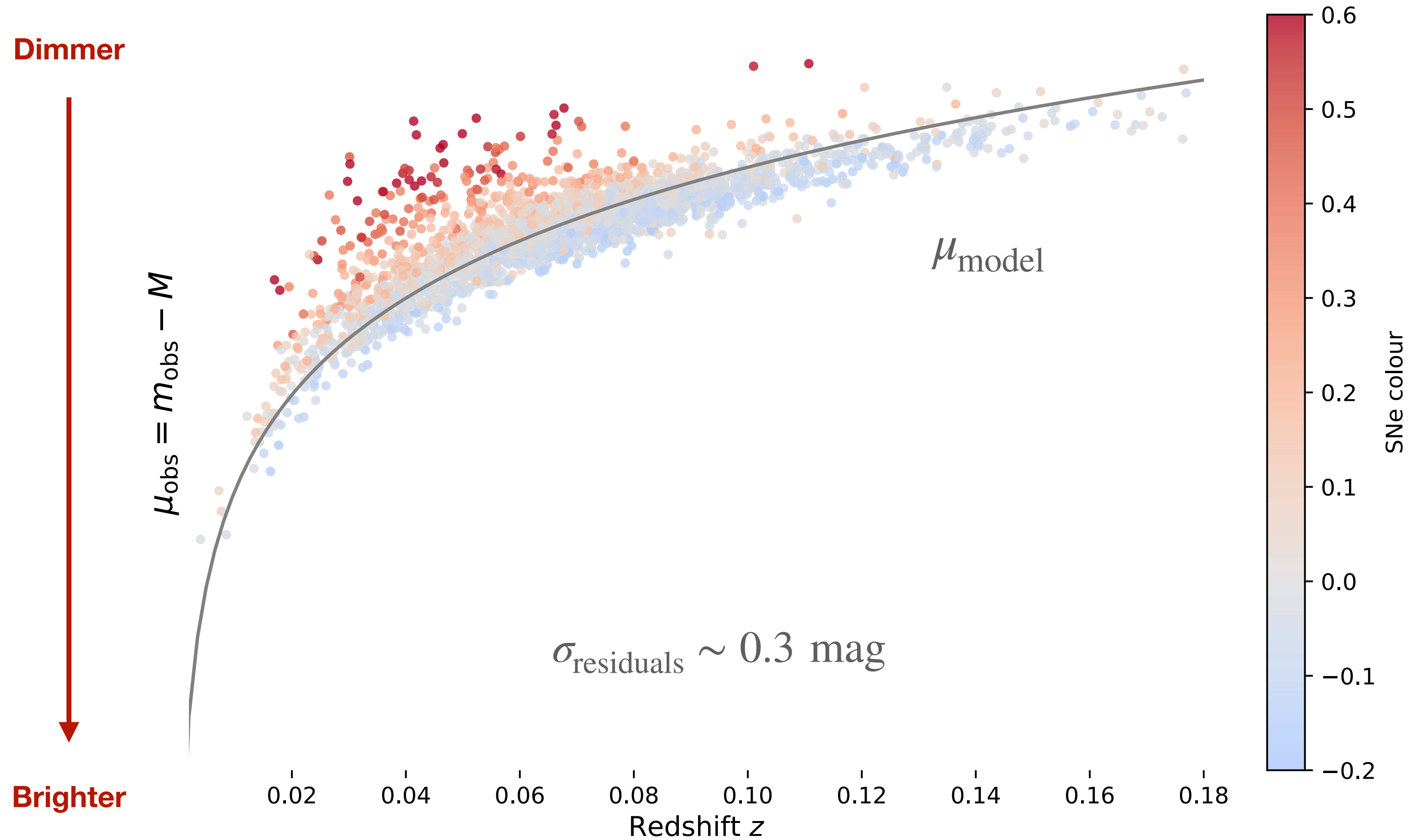
Spectroscopic  
typing

Redshift  
information



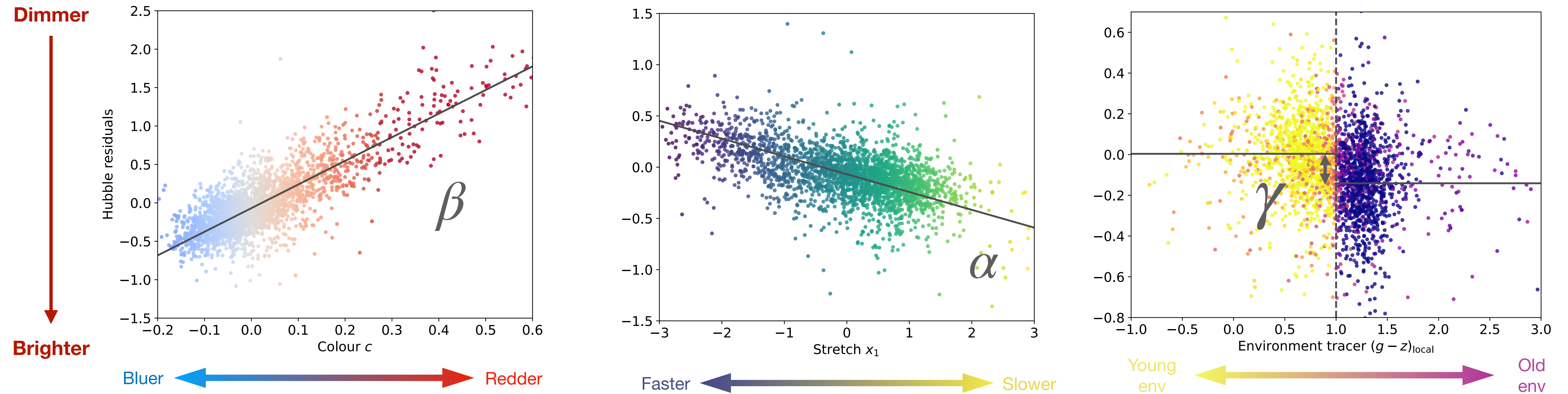
# Cosmology with SNe Ia

## Supernovae standardisation



# Cosmology with SNe Ia

## Standardisation



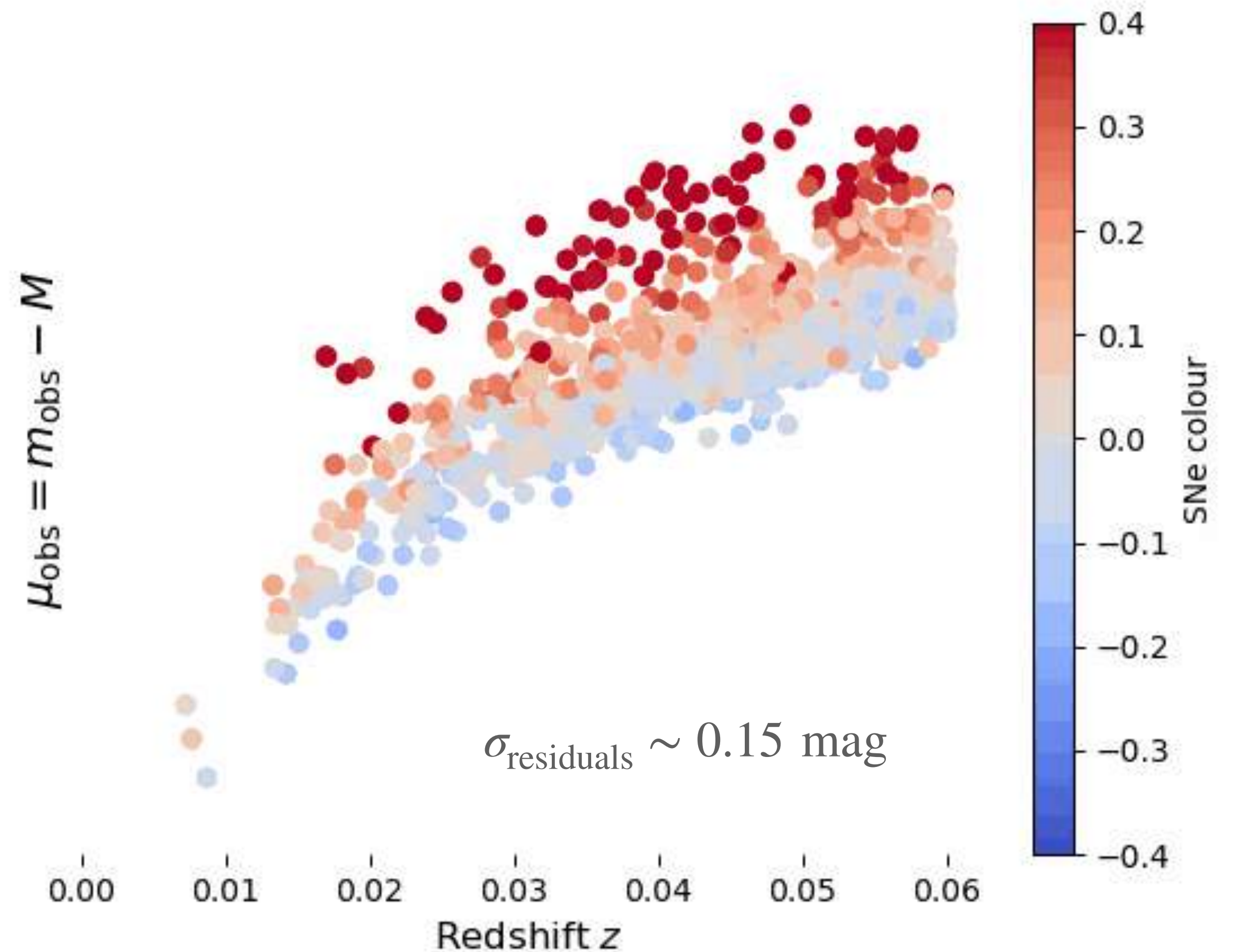
$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$

# Cosmology with SNe Ia

## Standardisation

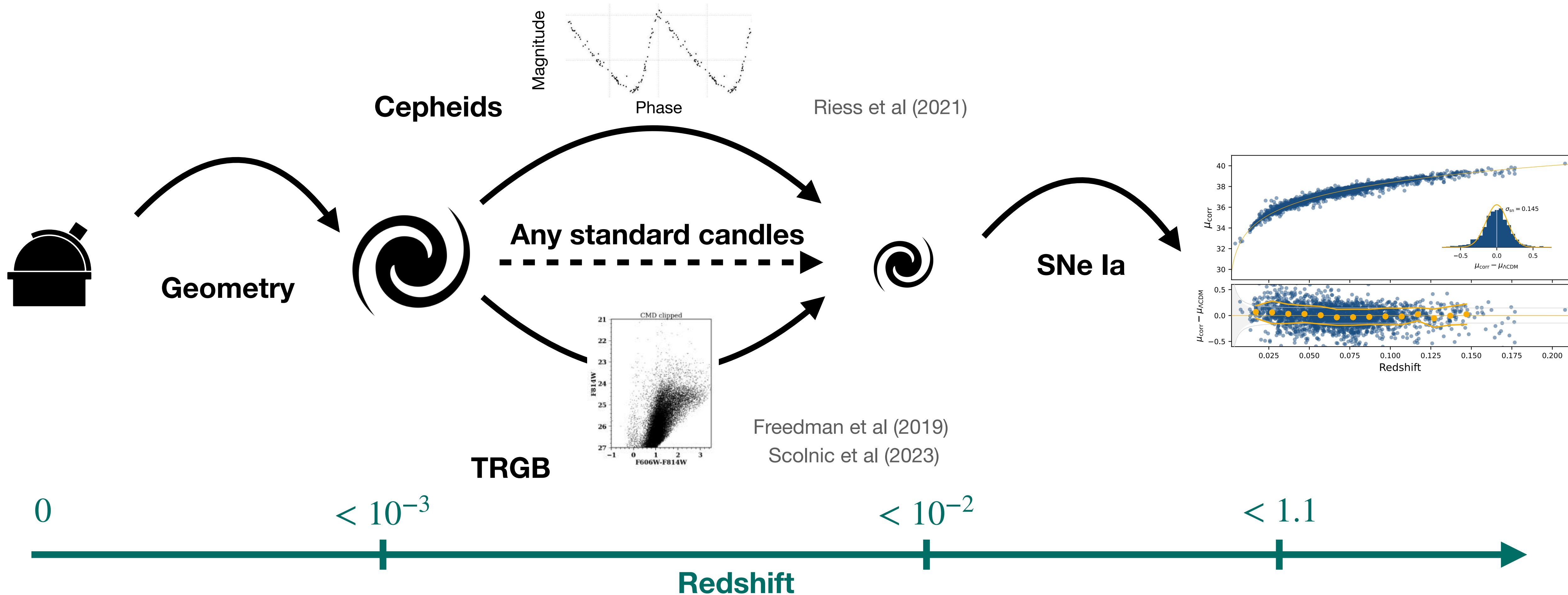
$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$

(Tripp 1998)

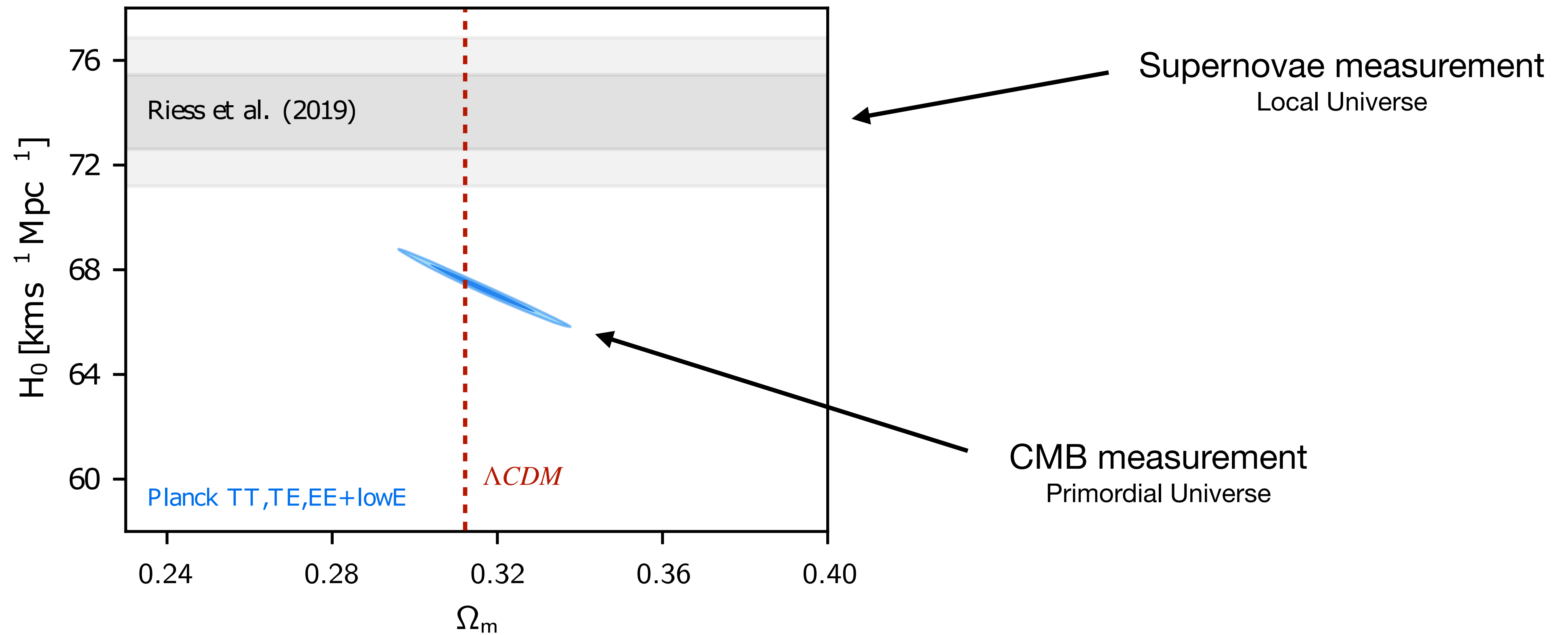


# Cosmology with SNe Ia

## Anchoring the Hubble diagram

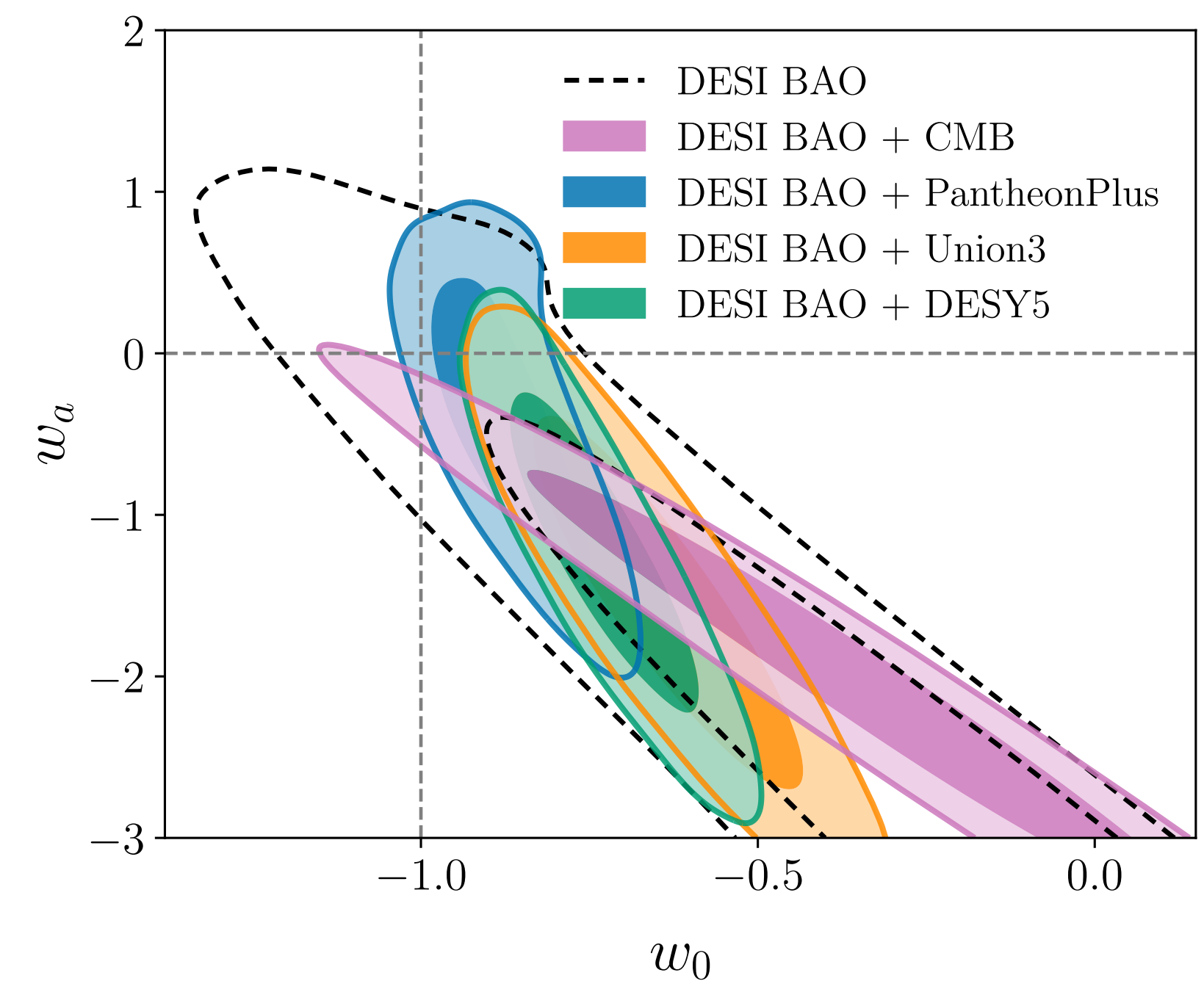
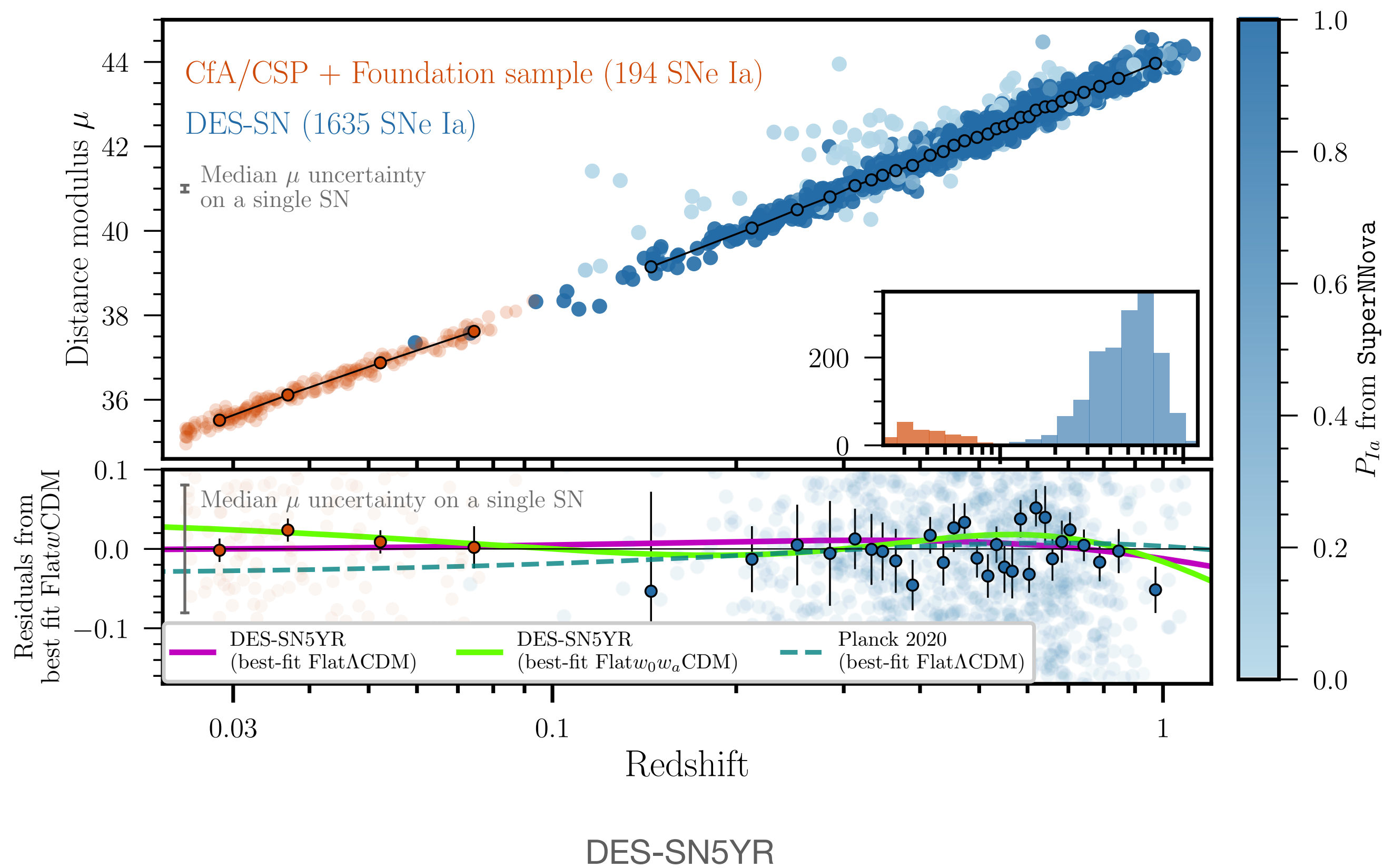


# Hubble tension



Adapted from Planck collaboration (2020)

# Evolving dark energy?



DESI 2024

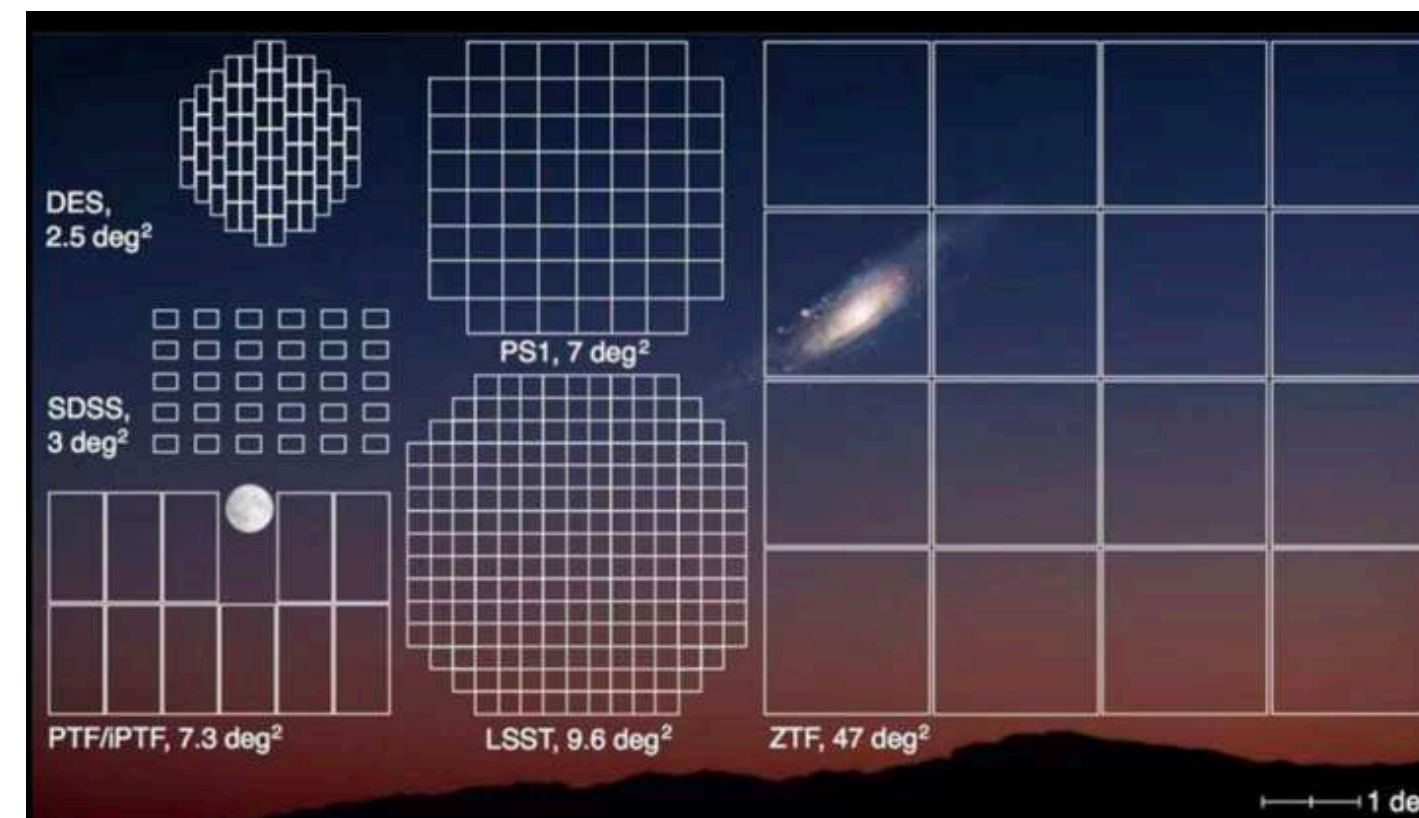
## **II. ZTF SN Ia DR2**

# ZTF



## Zwicky Transient Facility

- Large FoV
- Short exposures
- 3 bands (g, r, i)
- Depth of 20.5 mag in r
- (SNe Ia at  $z \sim 0.1$ )

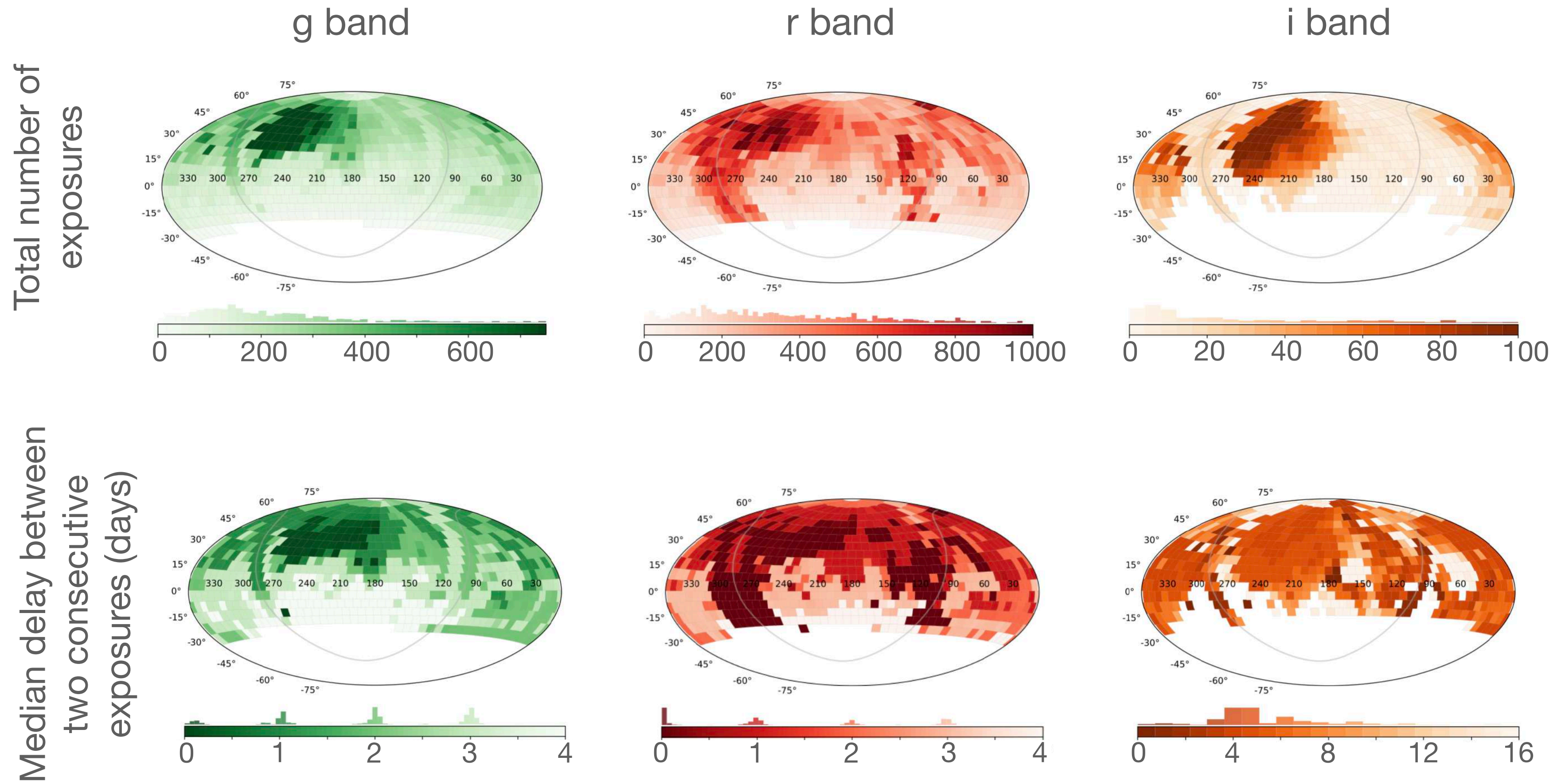


## SEDmachine

- Low resolution
- ~1h exposures

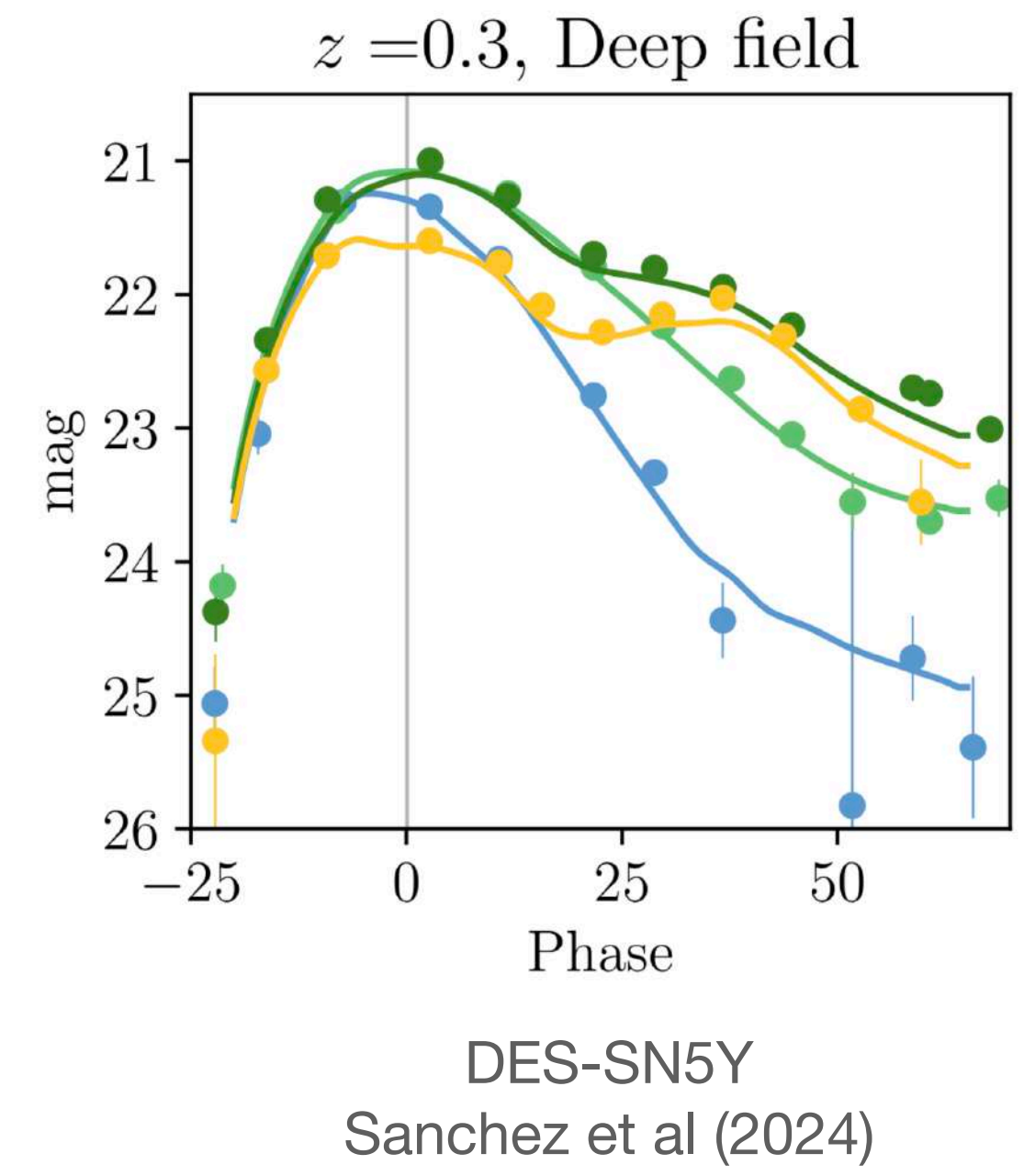
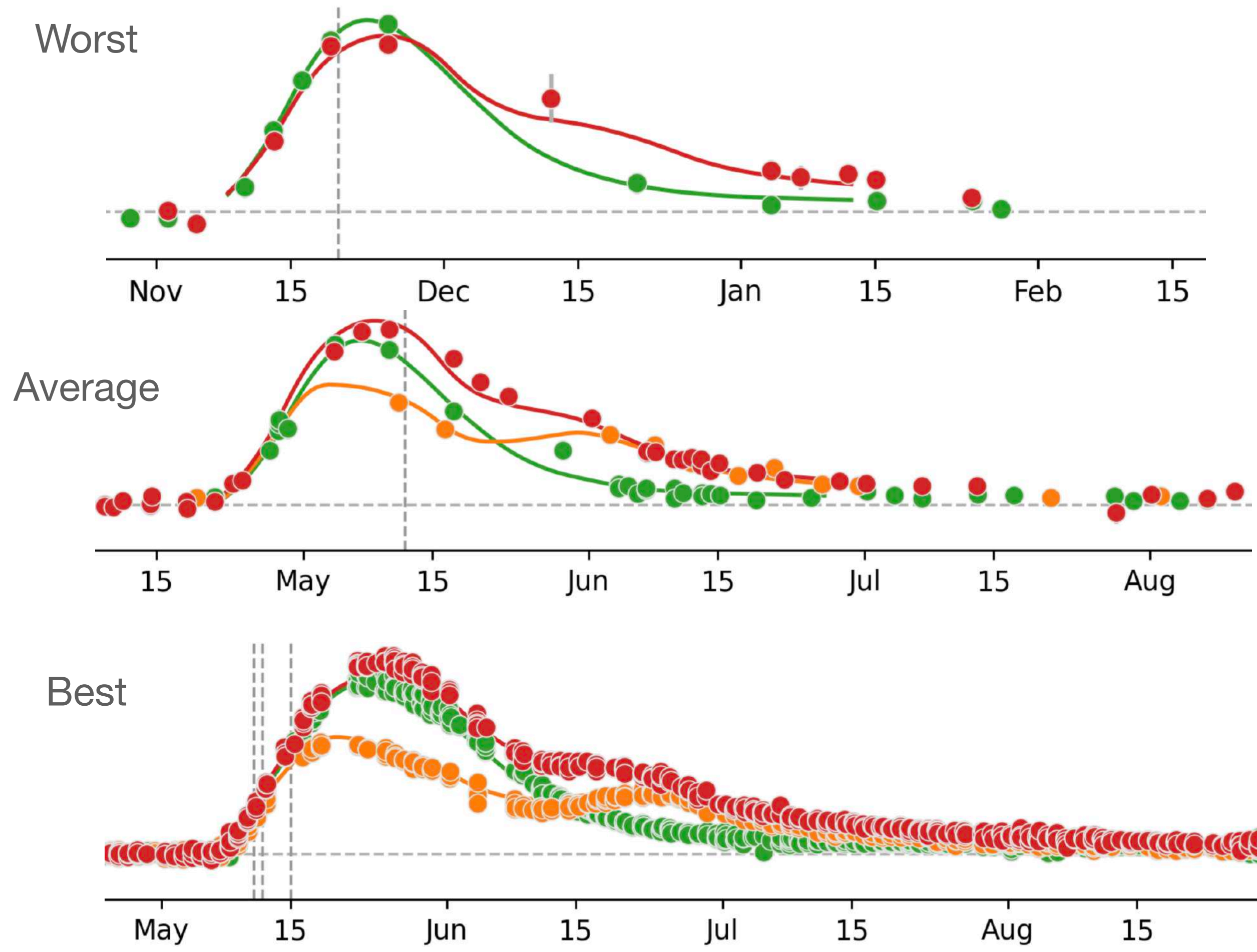
# ZTF SN Ia DR2

## Cadence



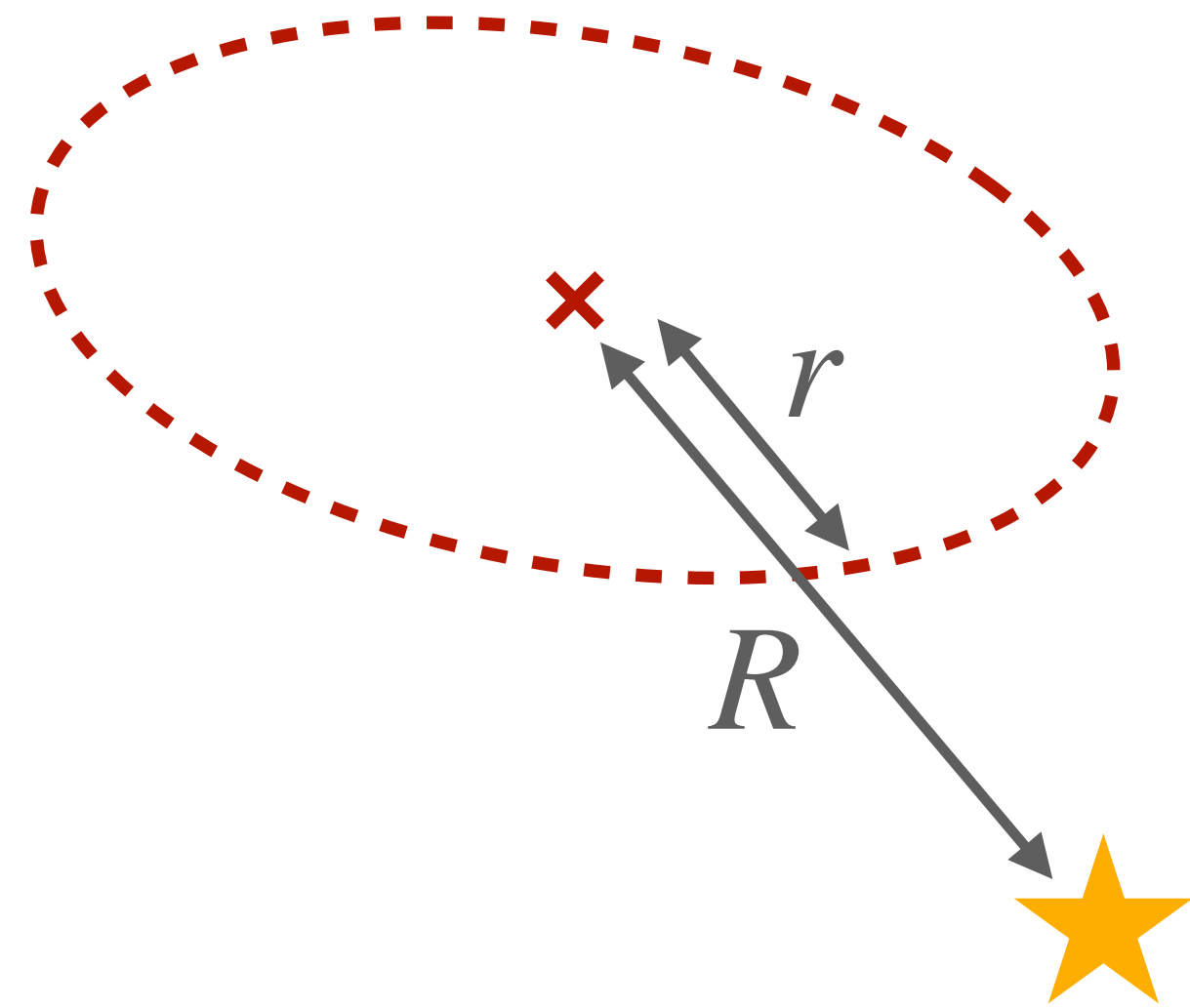
# ZTF SN Ia DR2

## Lightcurves



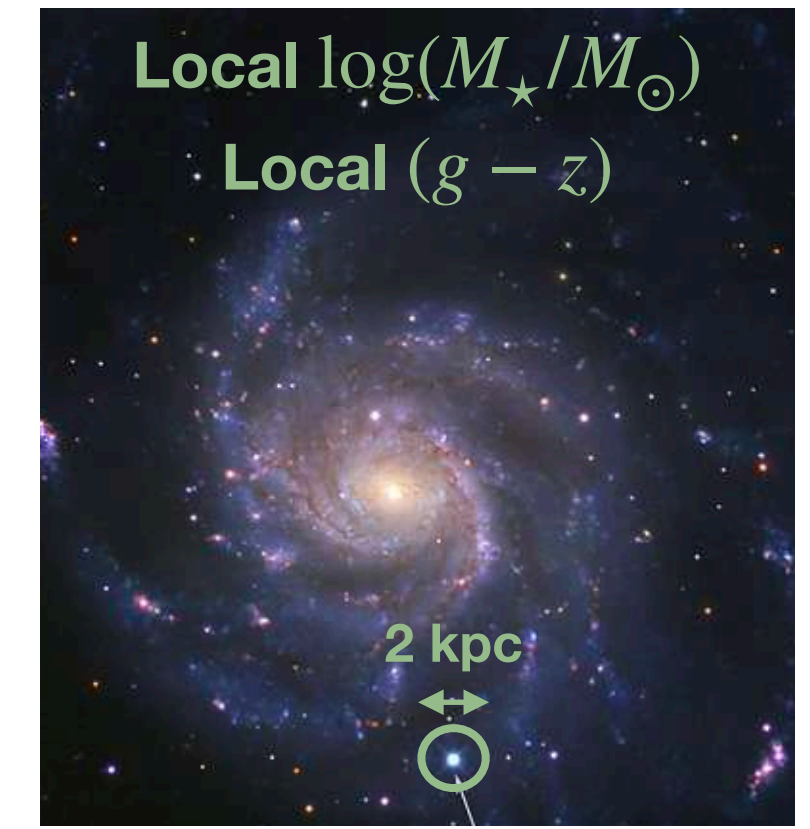
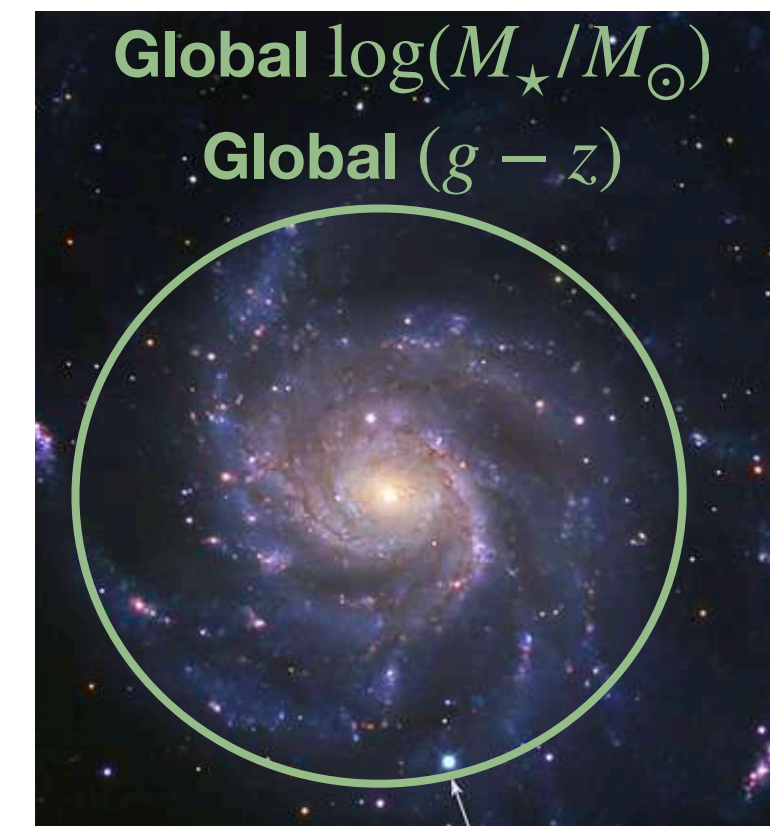
# ZTF SN Ia DR2

## Environmental properties

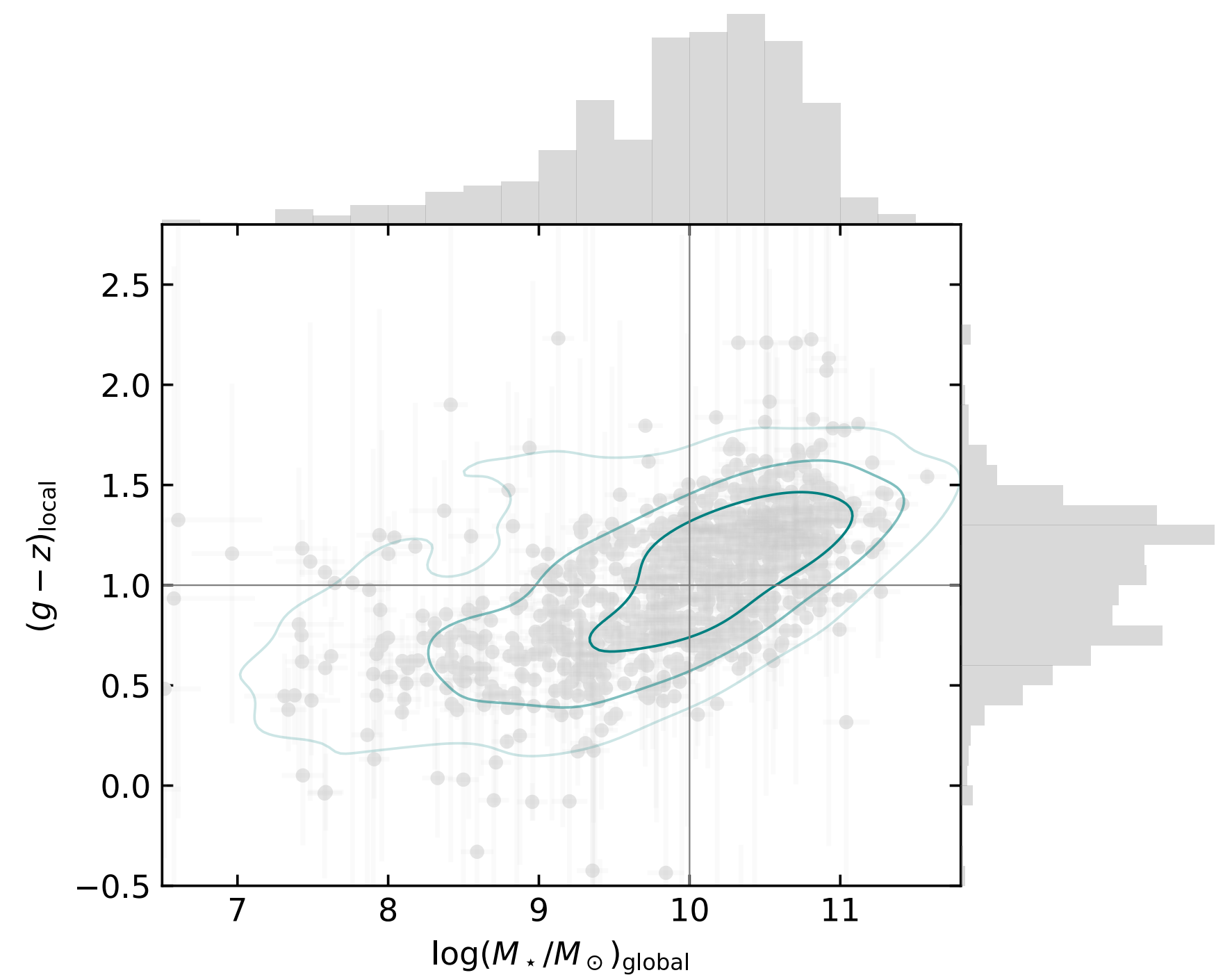


$$dDLR = \frac{R}{r}$$

Sullivan et al 2006, Gupta et al 2016



Credits: B.J. Fulton/LCOGT/Caltech



# ZTF SN Ia DR2

## Numbers

2.5 years of data

3628 SNe

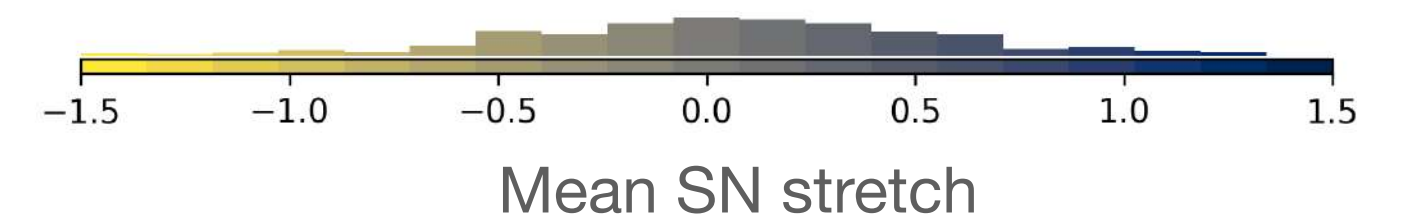
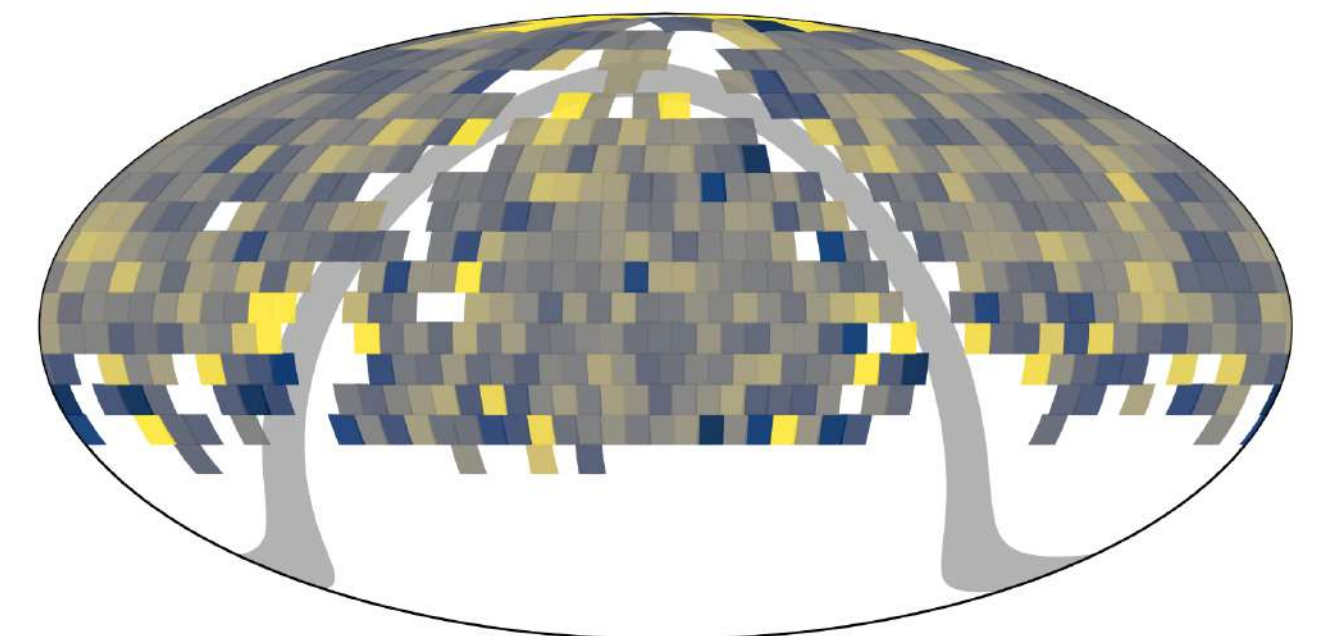
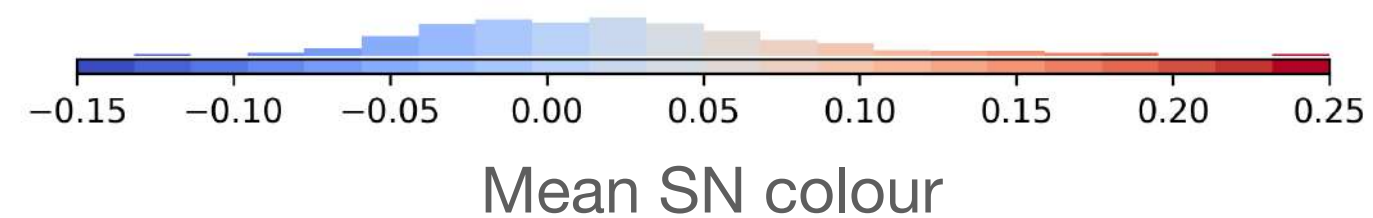
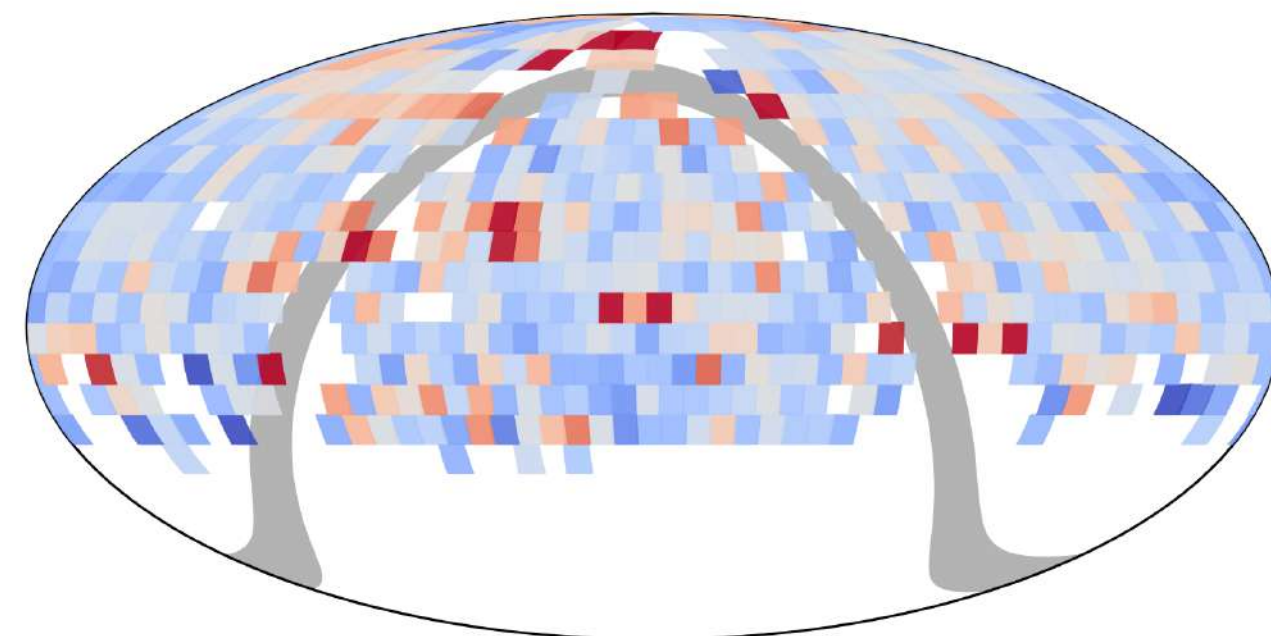
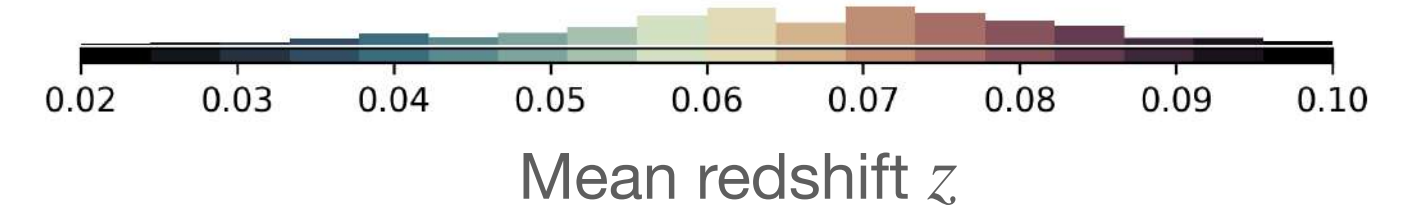
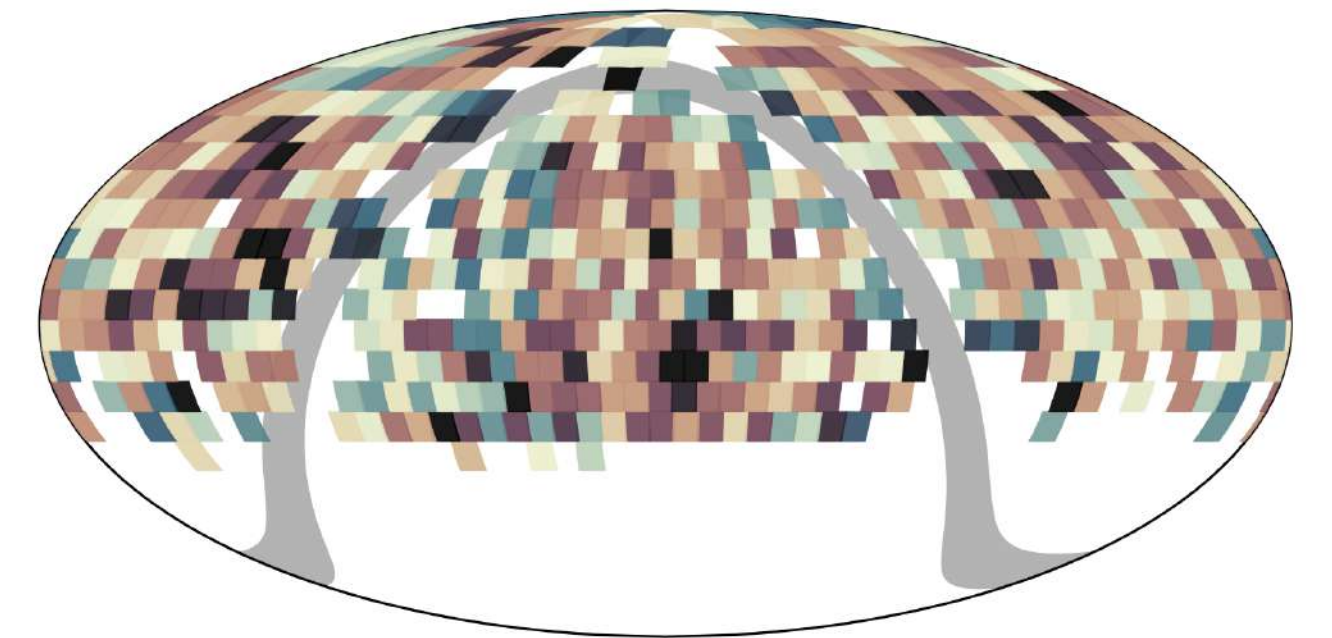
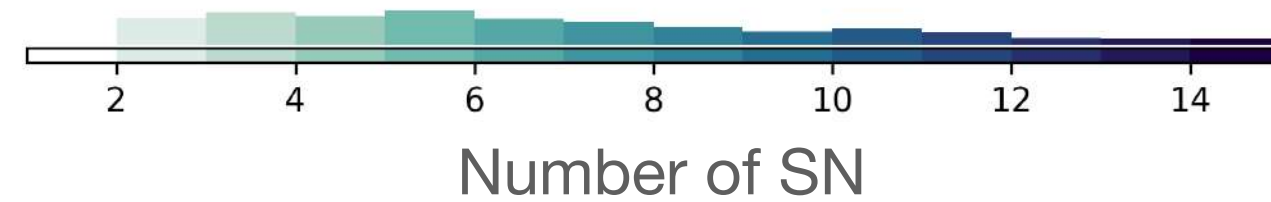
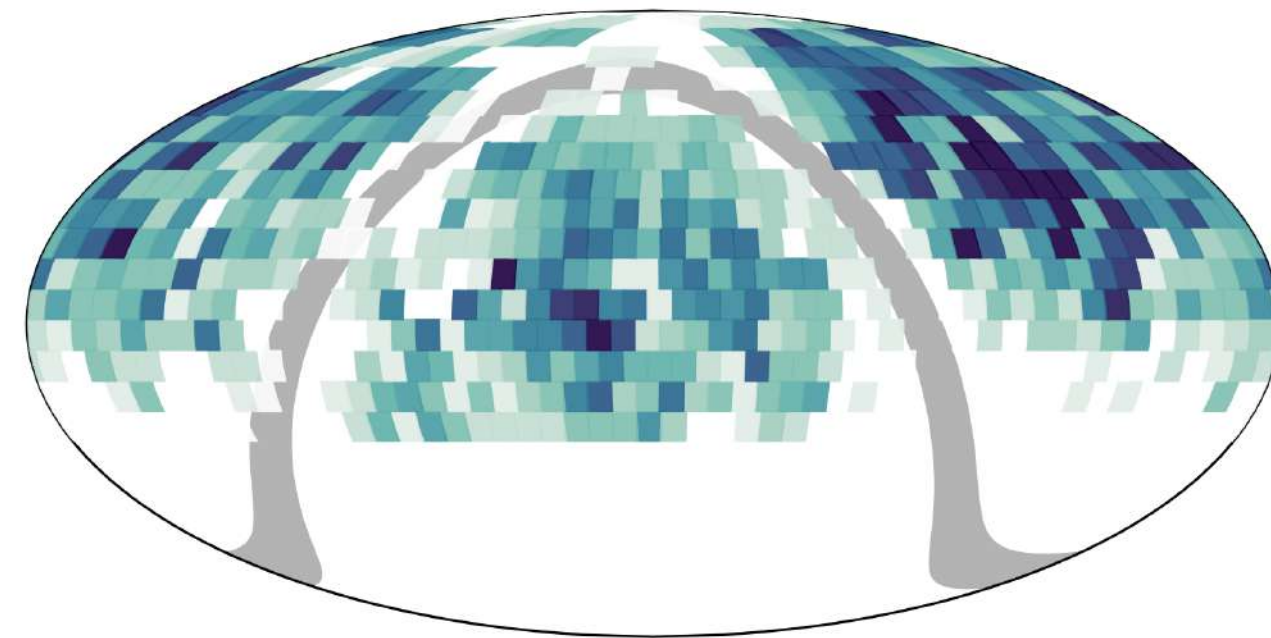
Confirmed SNe Ia

2977 SNe

with well-sampled lightcurves

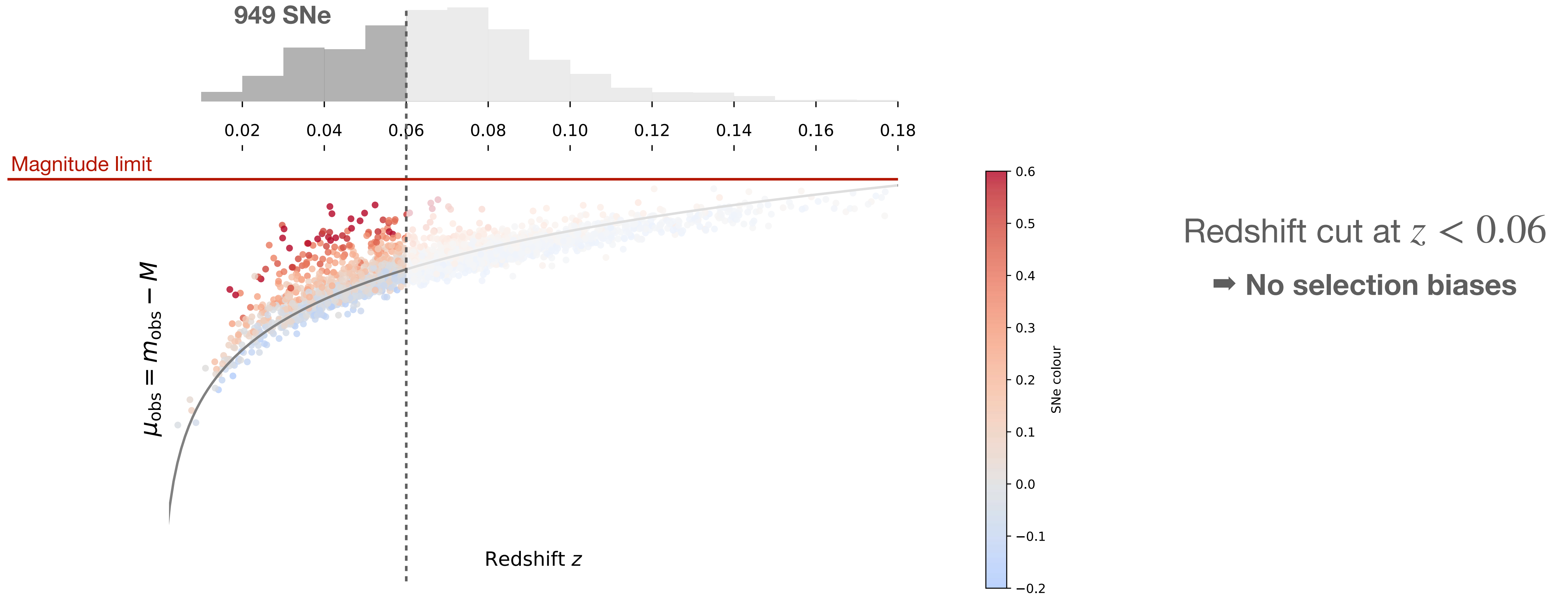
2628 SNe

usable for cosmology



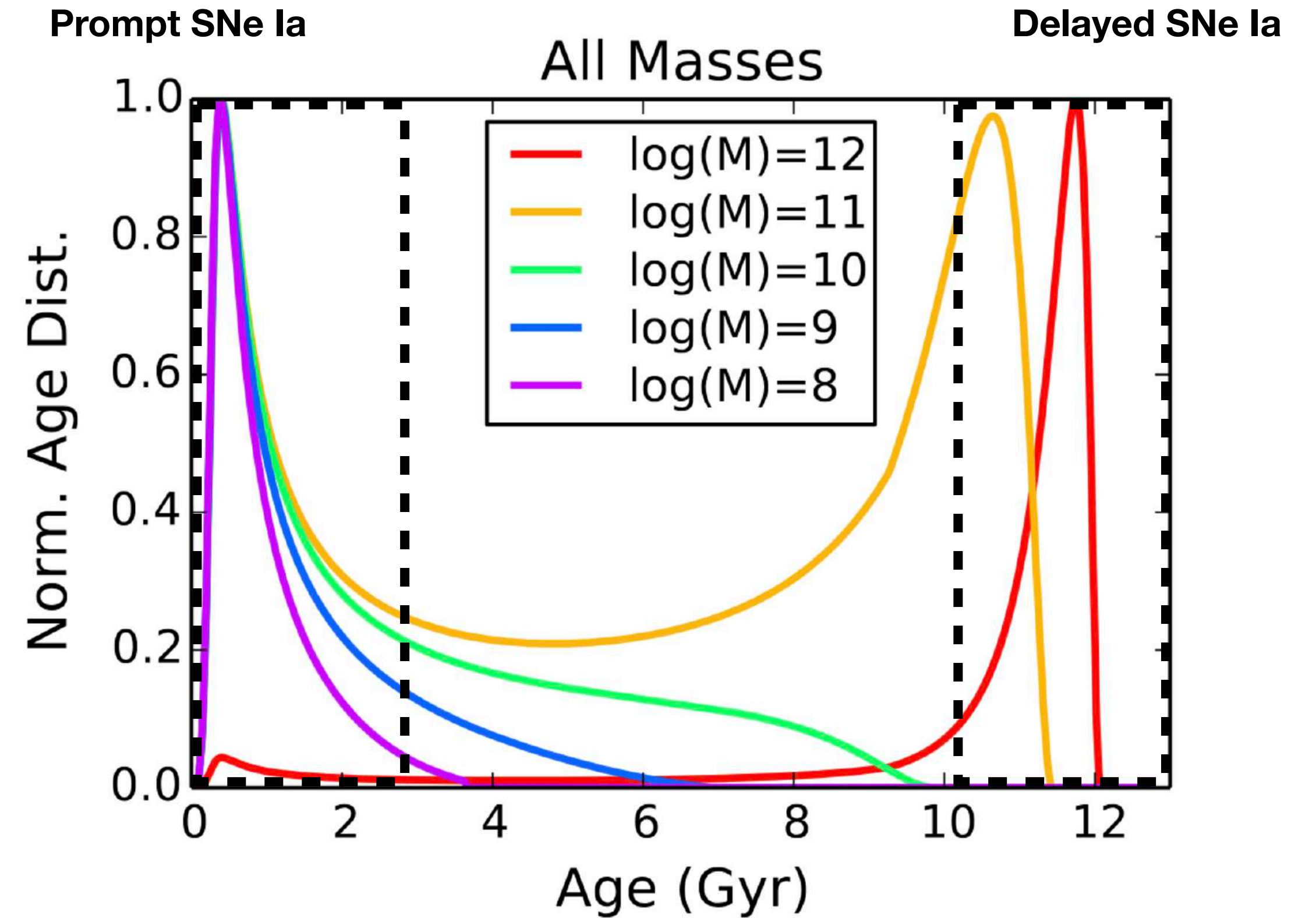
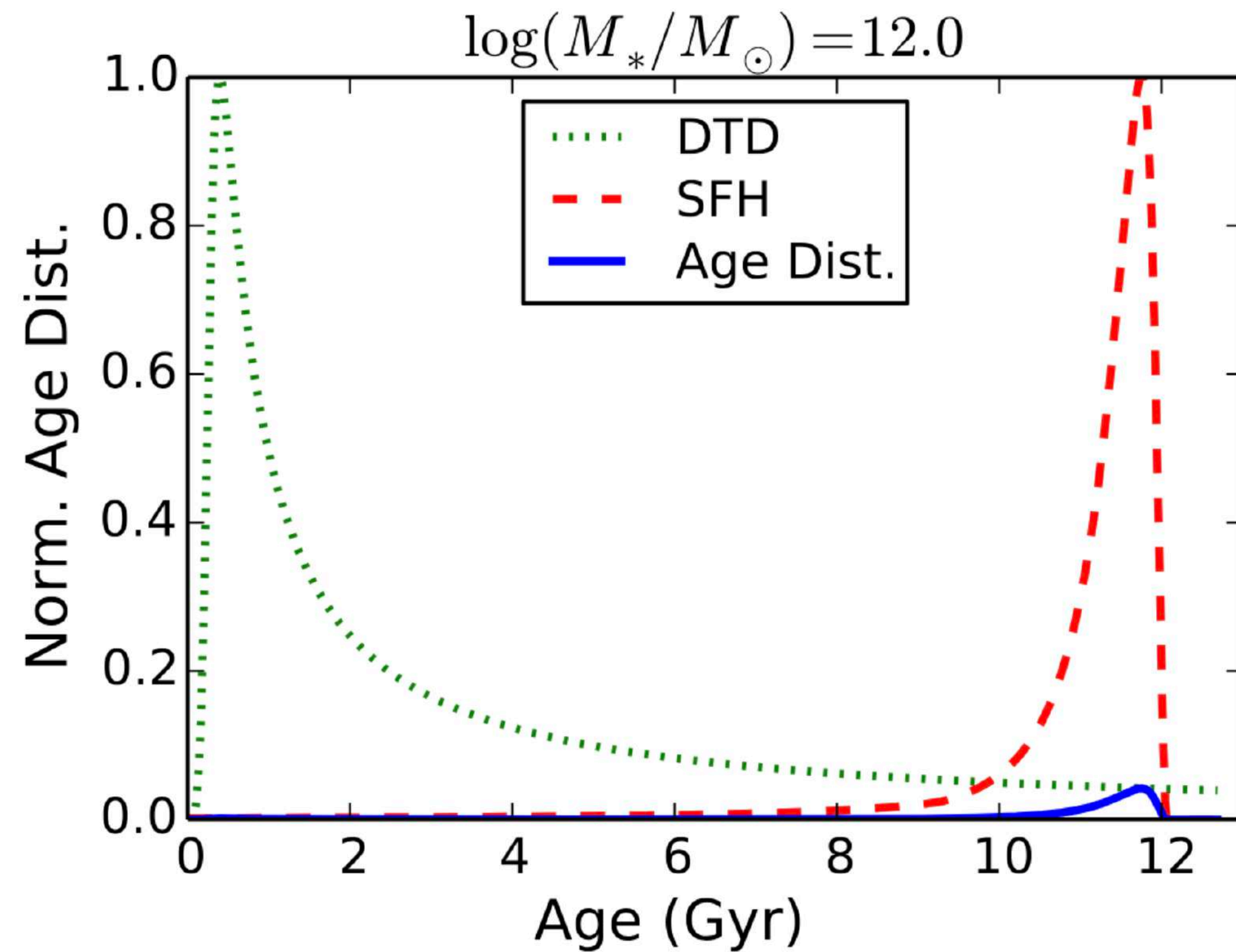
# ZTF SN Ia DR2

## Volume limited sample



# **III. SNe Ia standardisation with the ZTF DR2 volume-limited sample**

# Two population model



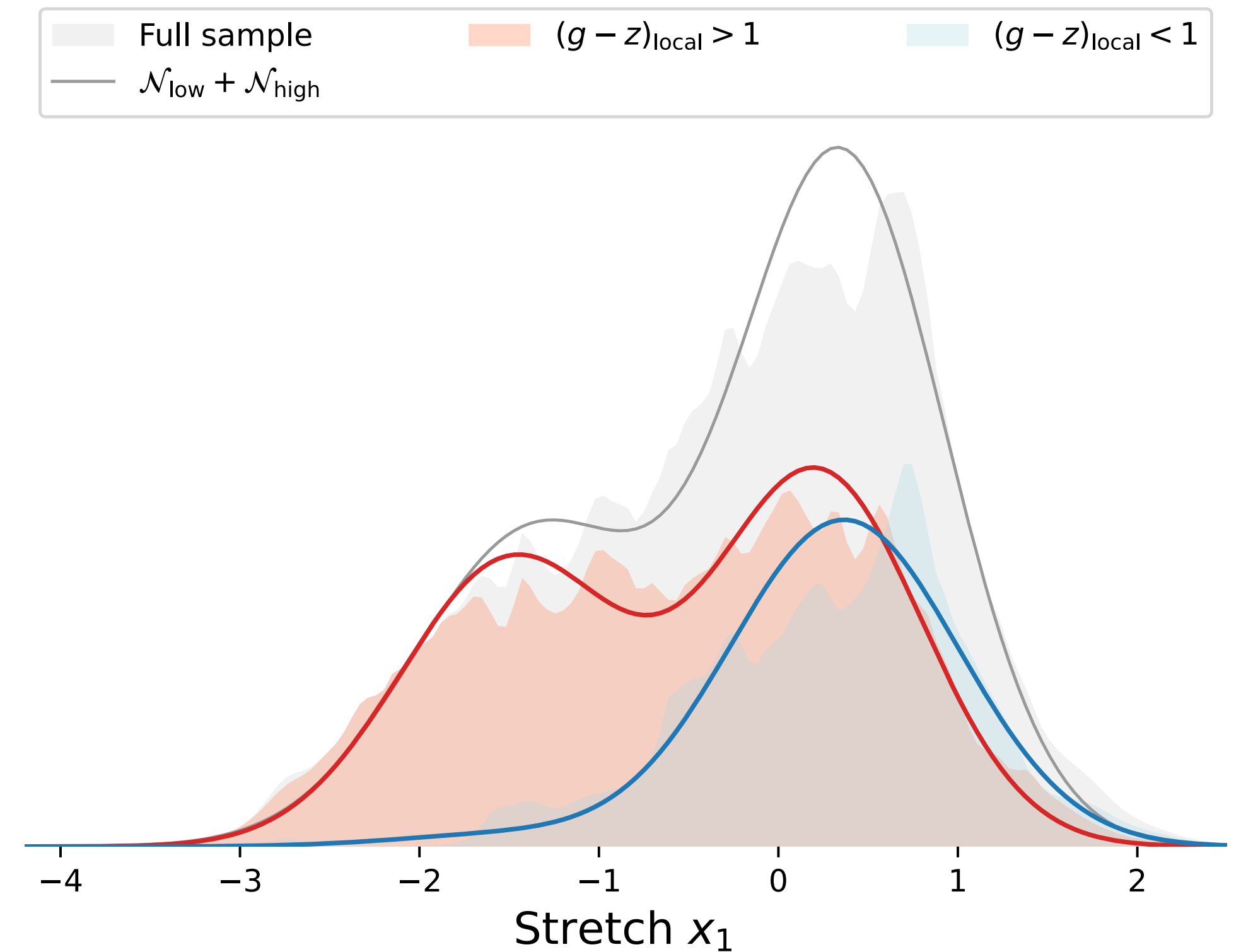
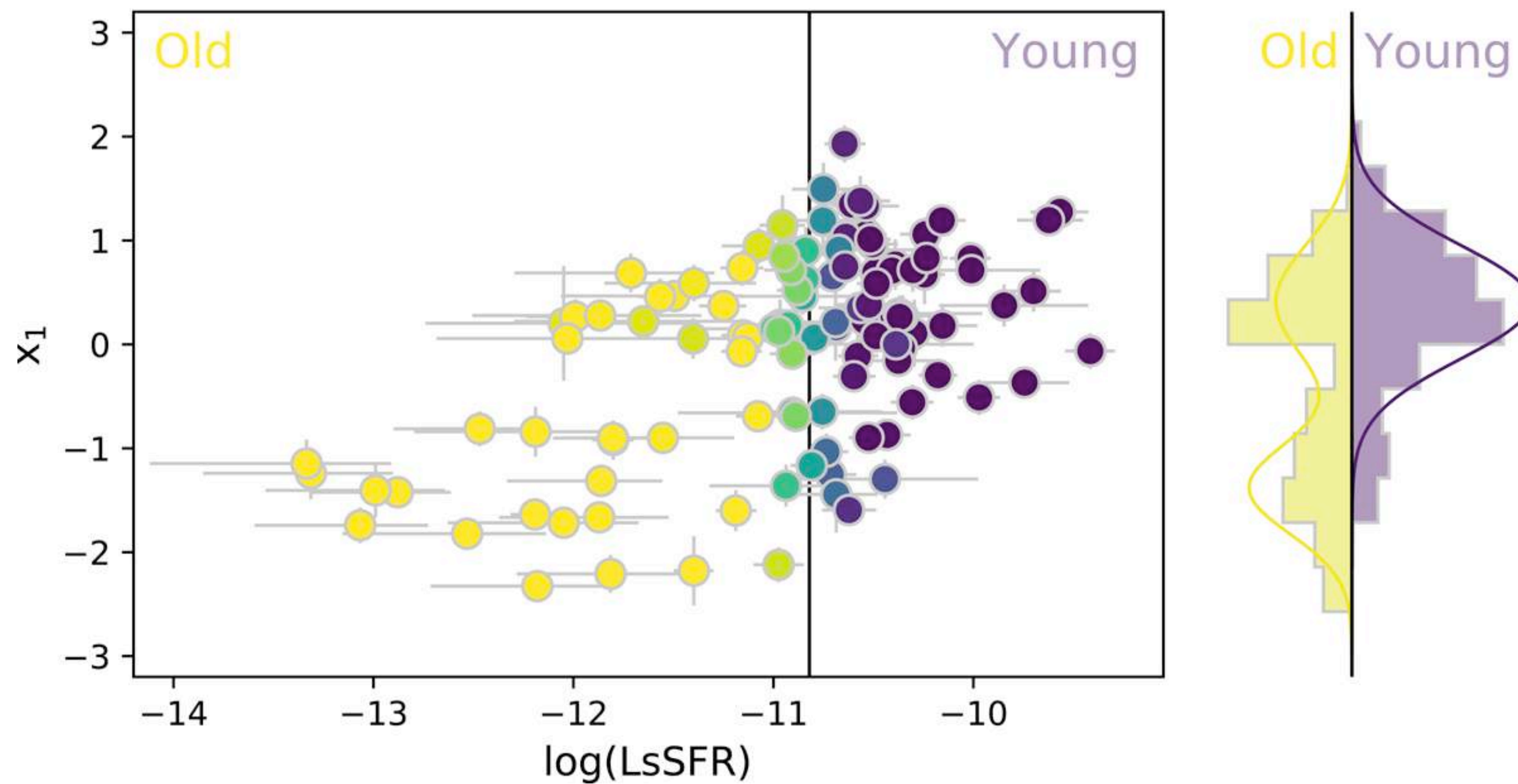
Childress et al (2014)

Mannucci et al (2005)

# Stretch

## Stretch distribution

$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$

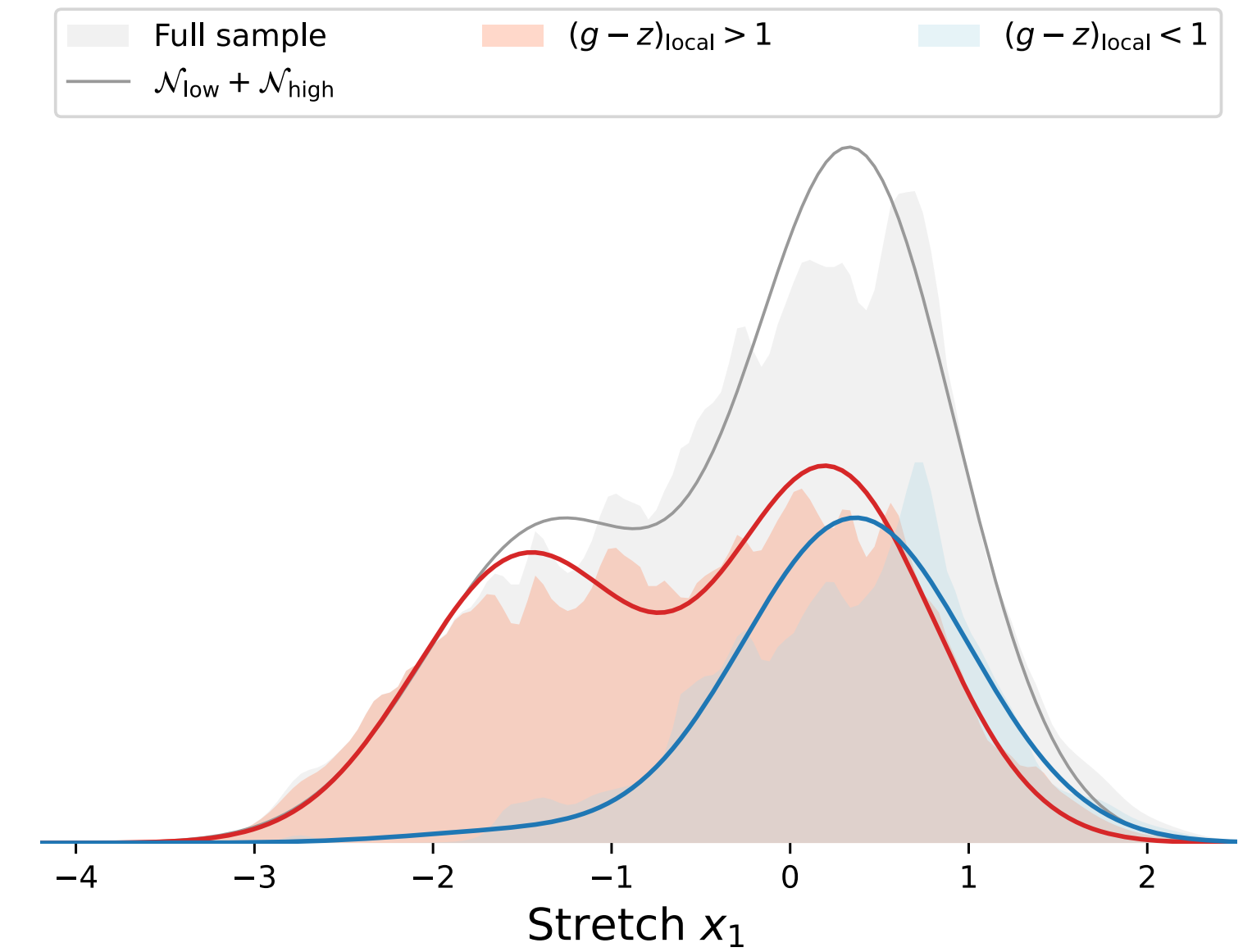
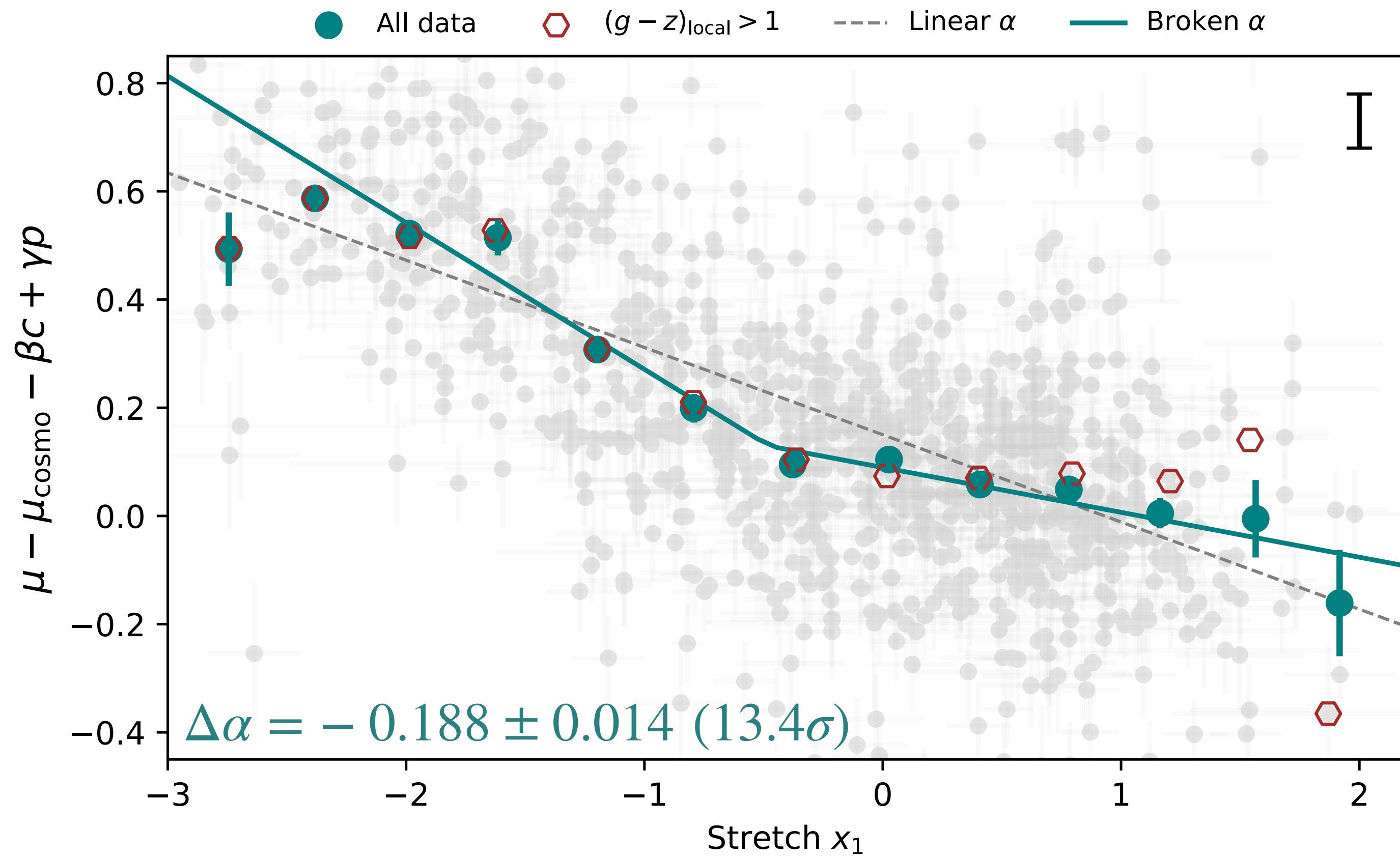


Nicolas et al (2021)  
SnFactory - 114 SNe

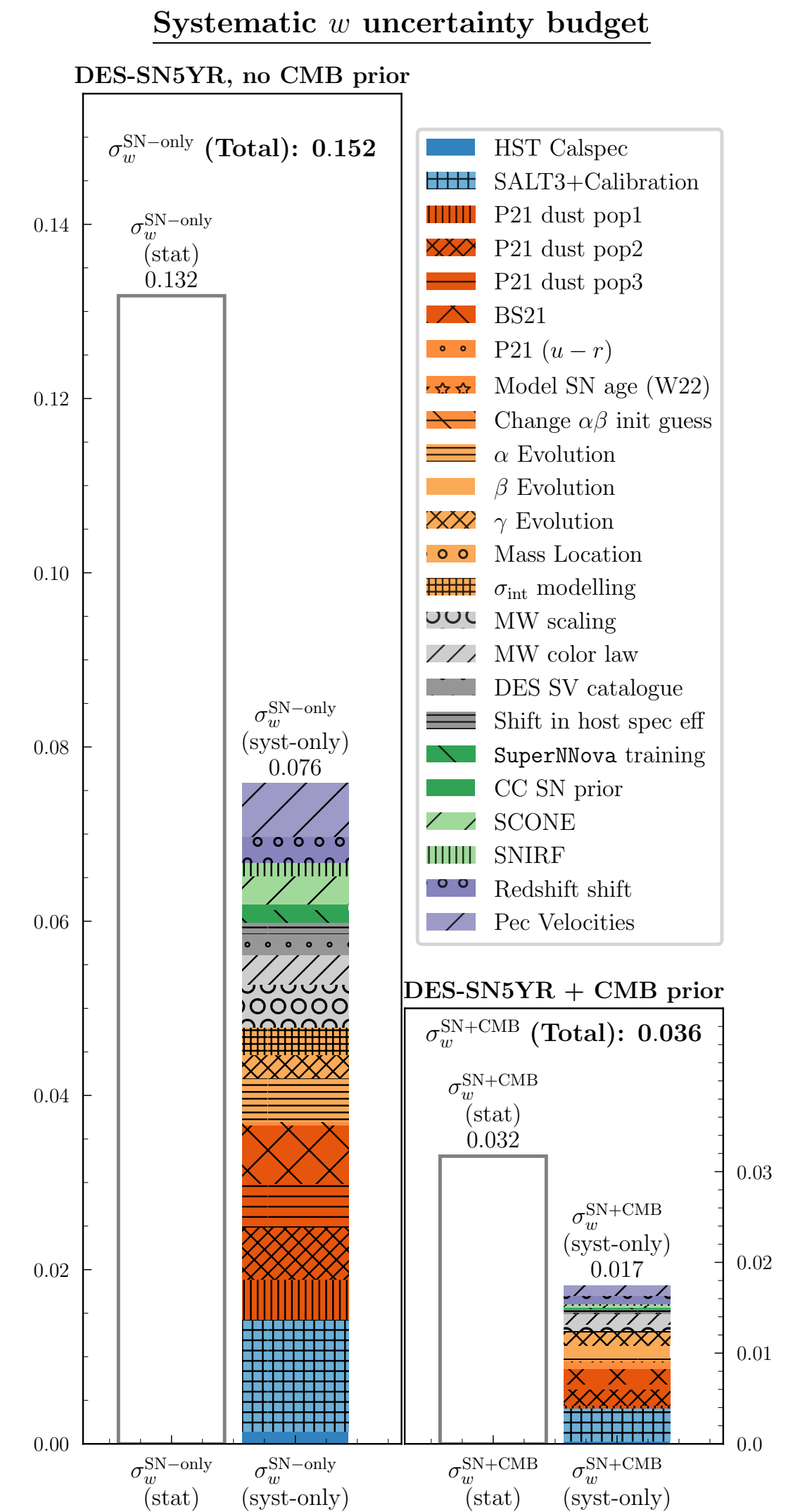
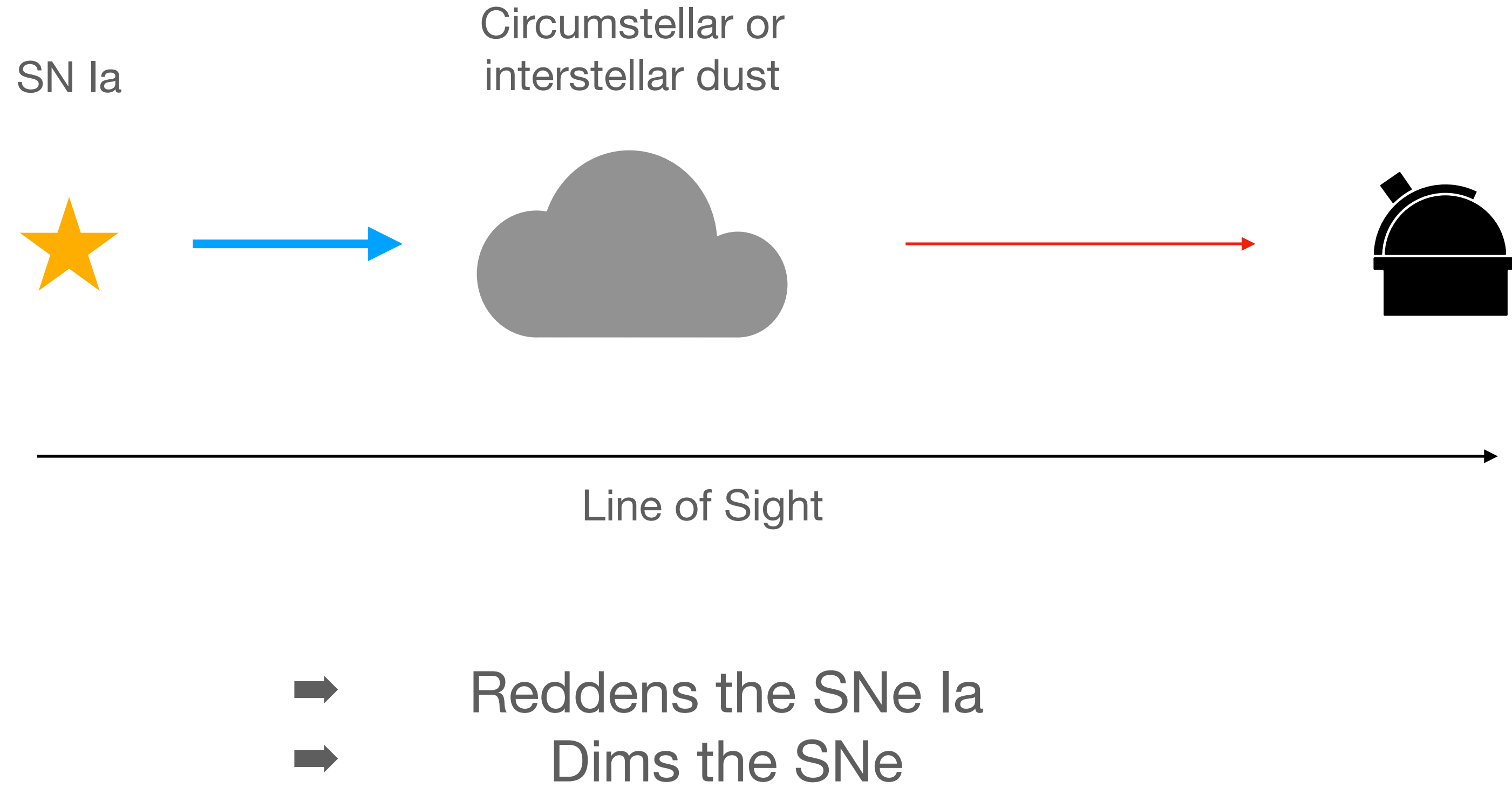
# Stretch

## Non linearity of the stretch-residuals relation

$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$



# Dust



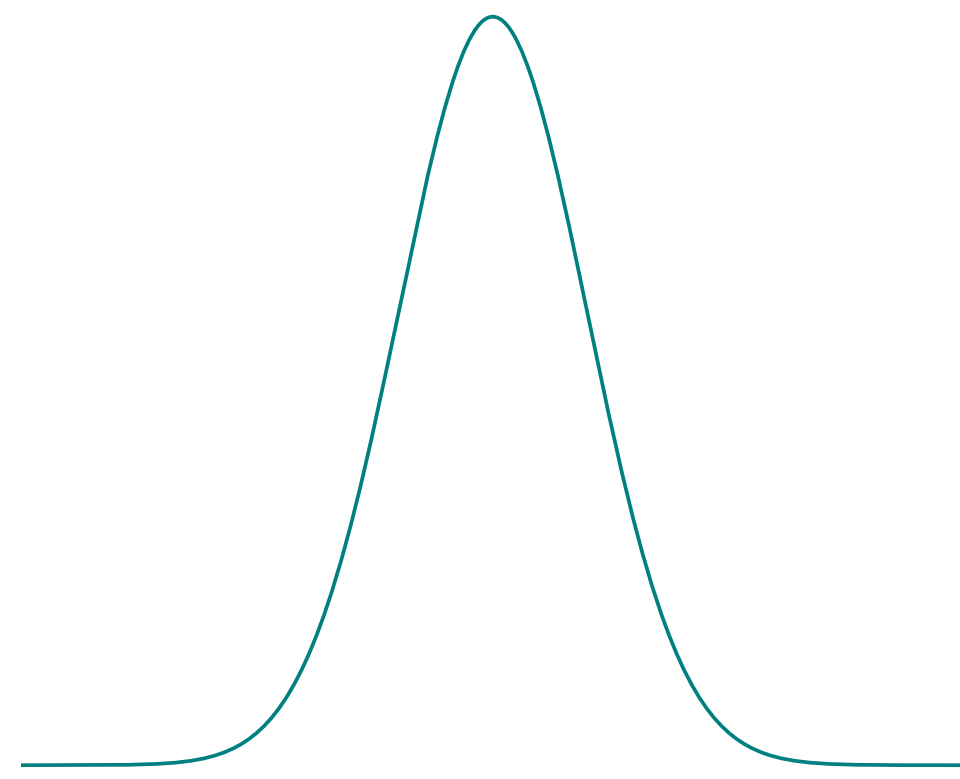
Vincenzi et al (2024)

# Colour

## Colour distribution

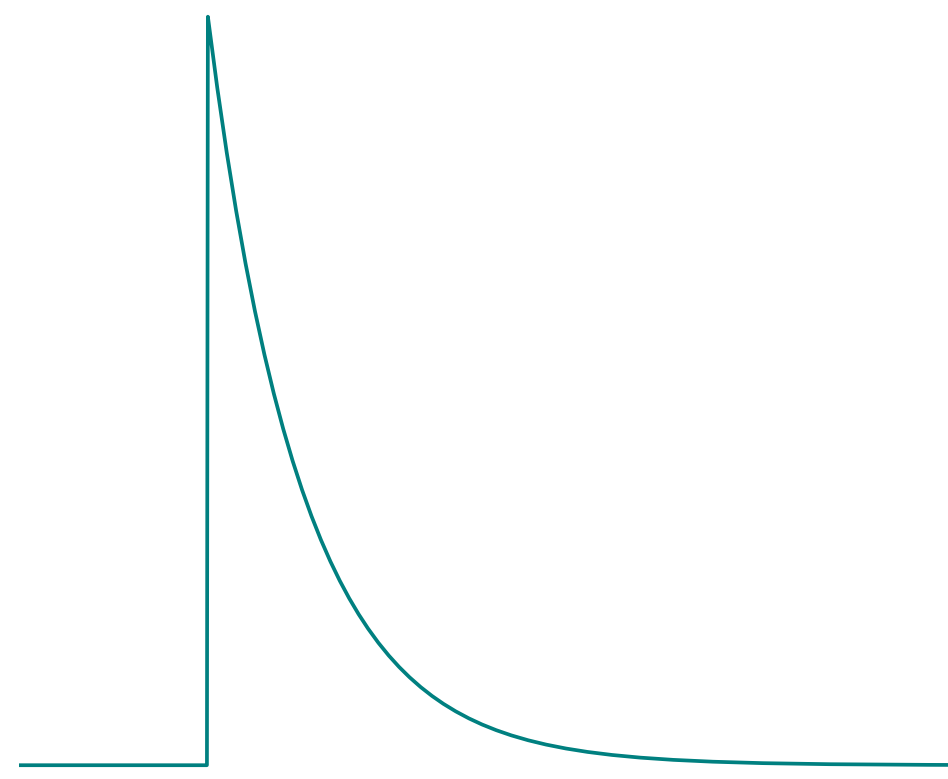
$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$

Intrinsic colour

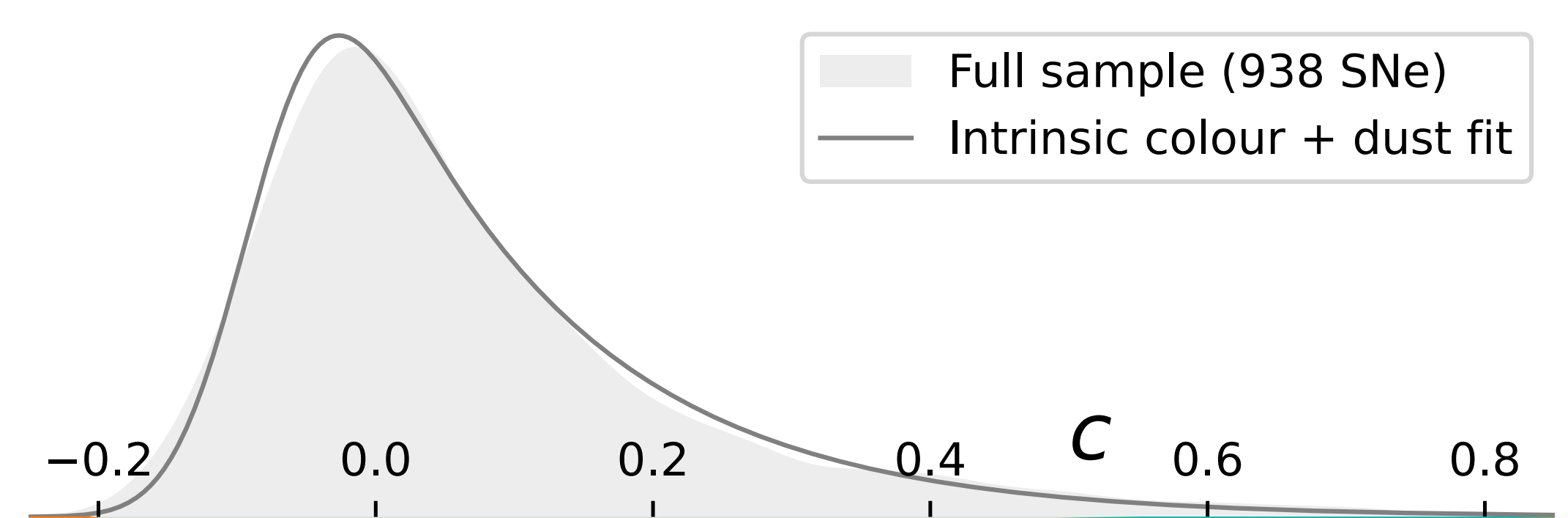


$$\mathcal{N}(c, c_{\text{int}}, \sigma_c)$$

Dust reddening



$$e^{-c\tau}$$

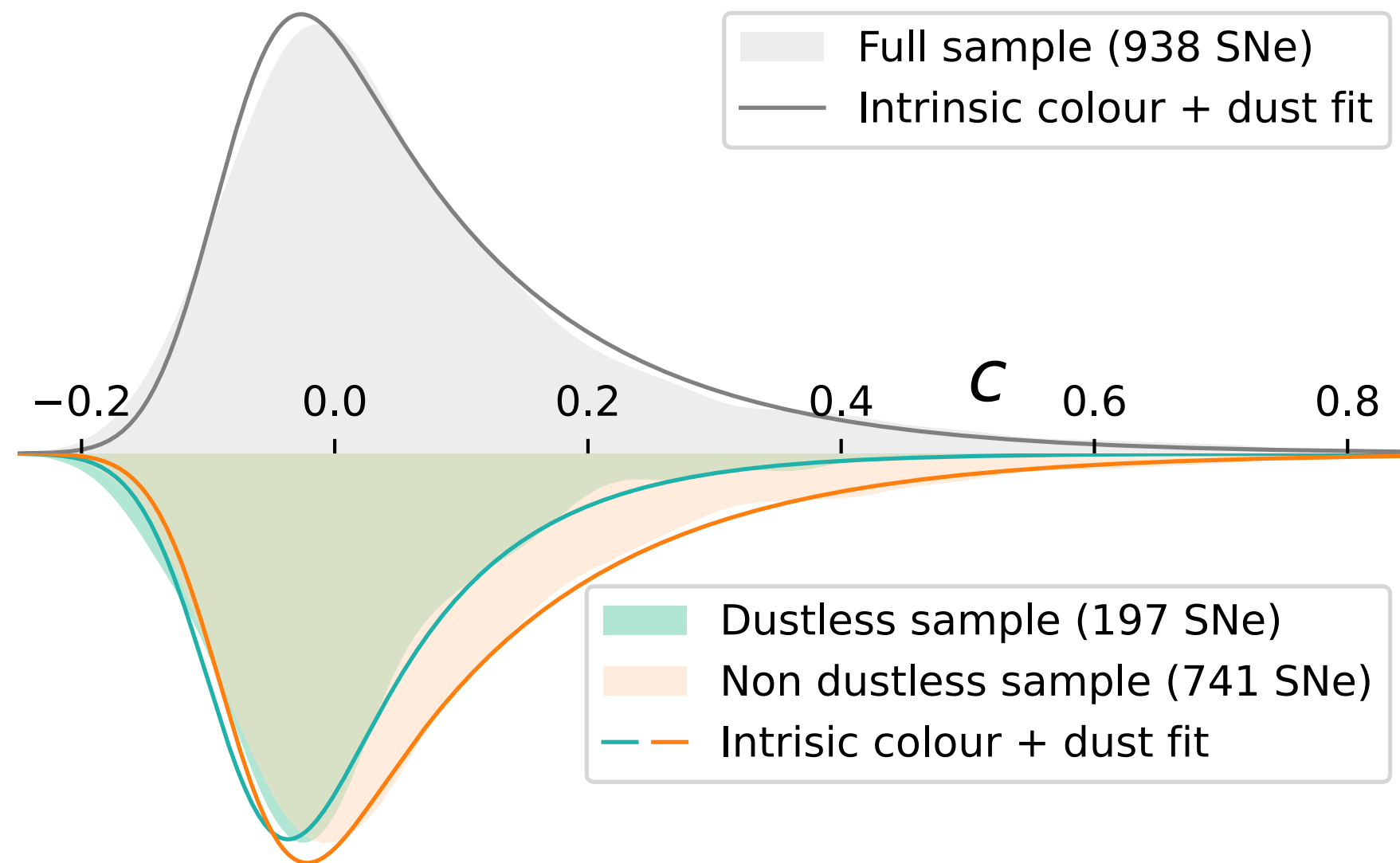


Jha et al. (2007)  
Mandel et al. (2011)  
Brout & Scolnic (2021)

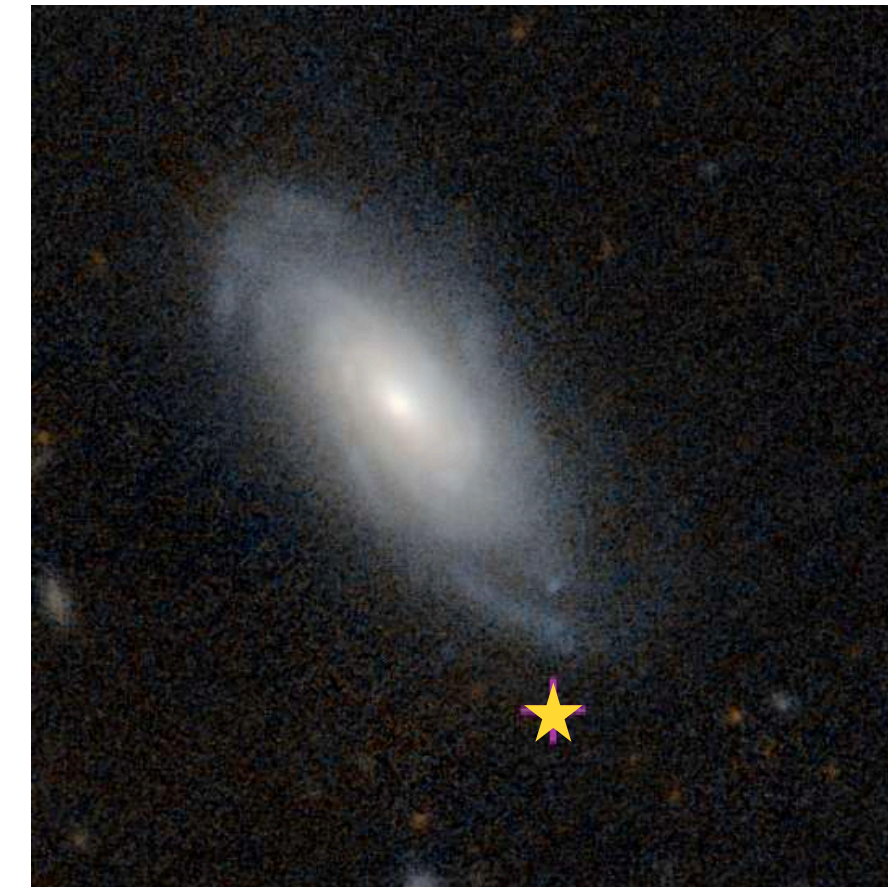
# Colour

## Dependence on environment

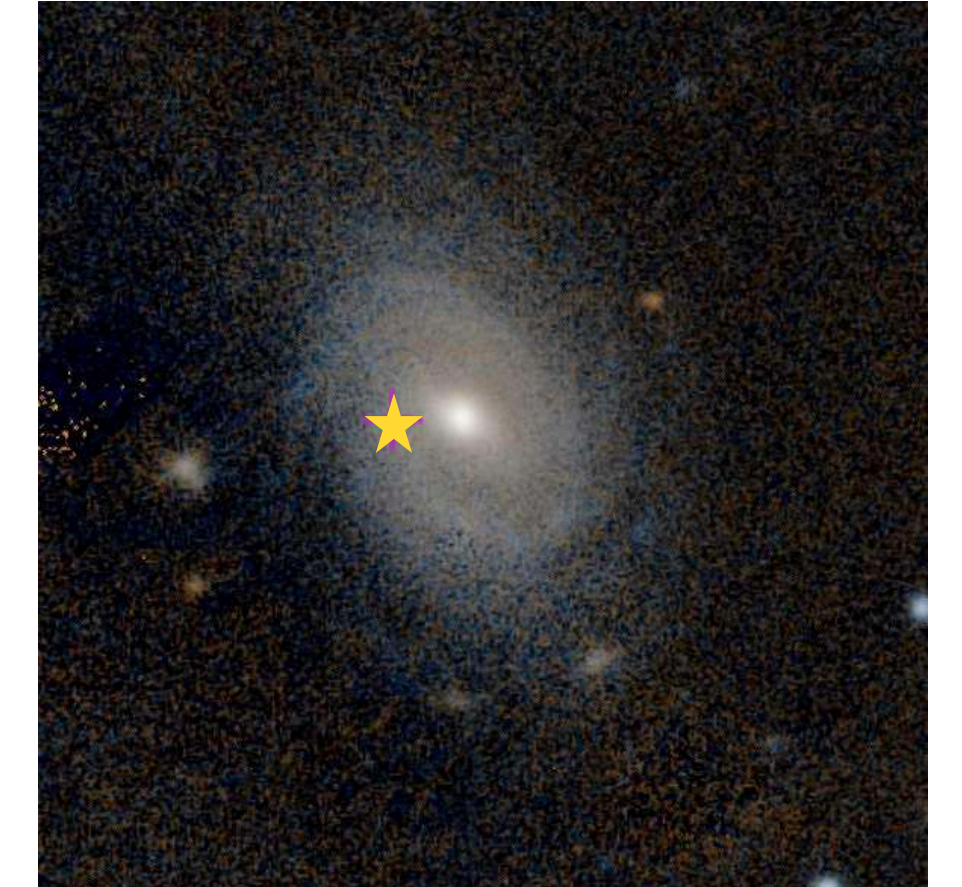
$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$



« Dustless » example



« Non dustless » example

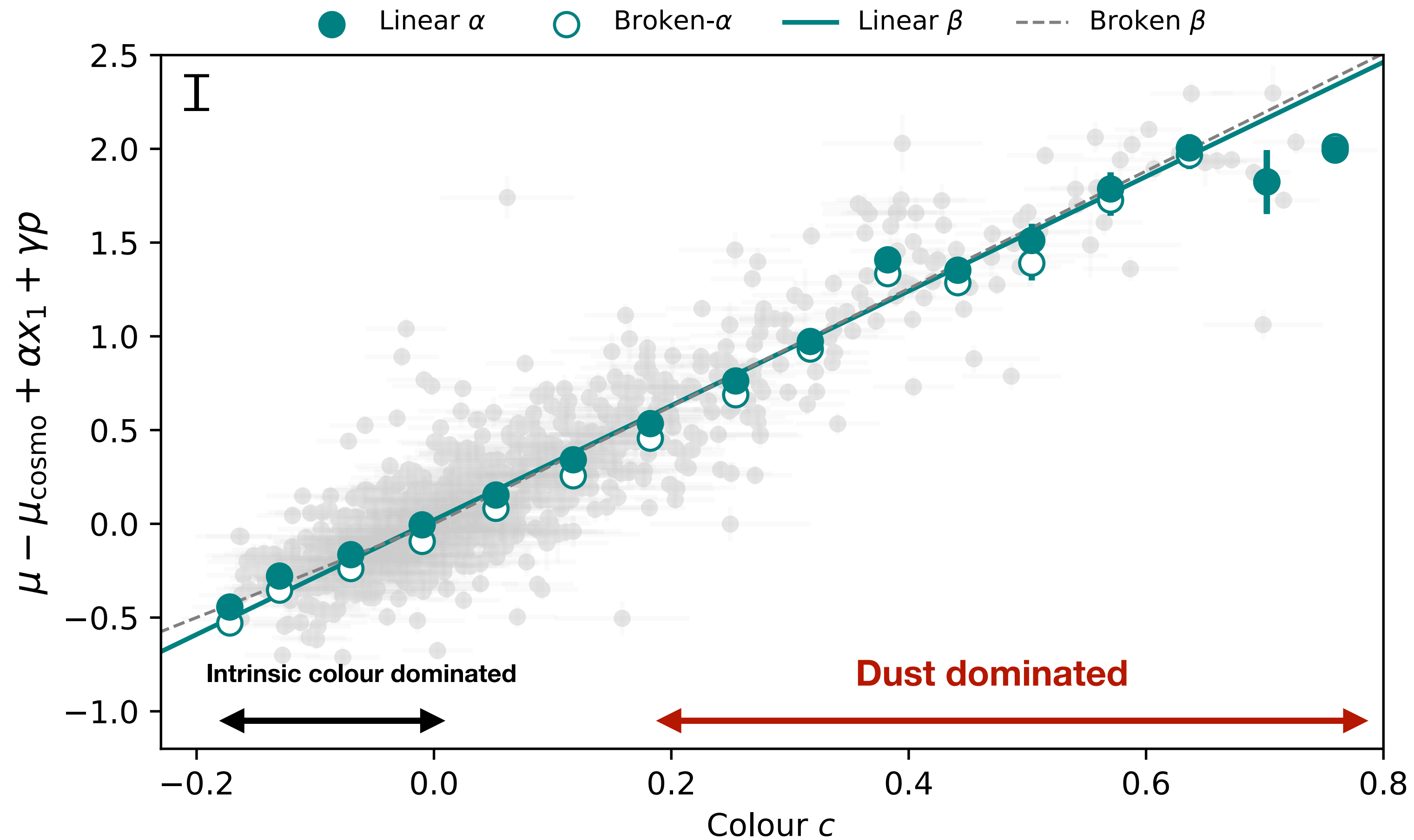


Sample	$c_{\text{int}}$	$\sigma_c$	$\tau$
Full sample	$-0.085 \pm 0.004$	$0.030 \pm 0.005$	$0.155 \pm 0.007$
Dustless* sample	$-0.087 \pm 0.008$	$0.033 \pm 0.008$	$0.102 \pm 0.010$
Non dustless sample	$-0.082 \pm 0.005$	$0.029 \pm 0.006$	$0.166 \pm 0.008$

# Colour

## Linearity of the colour-residuals relation

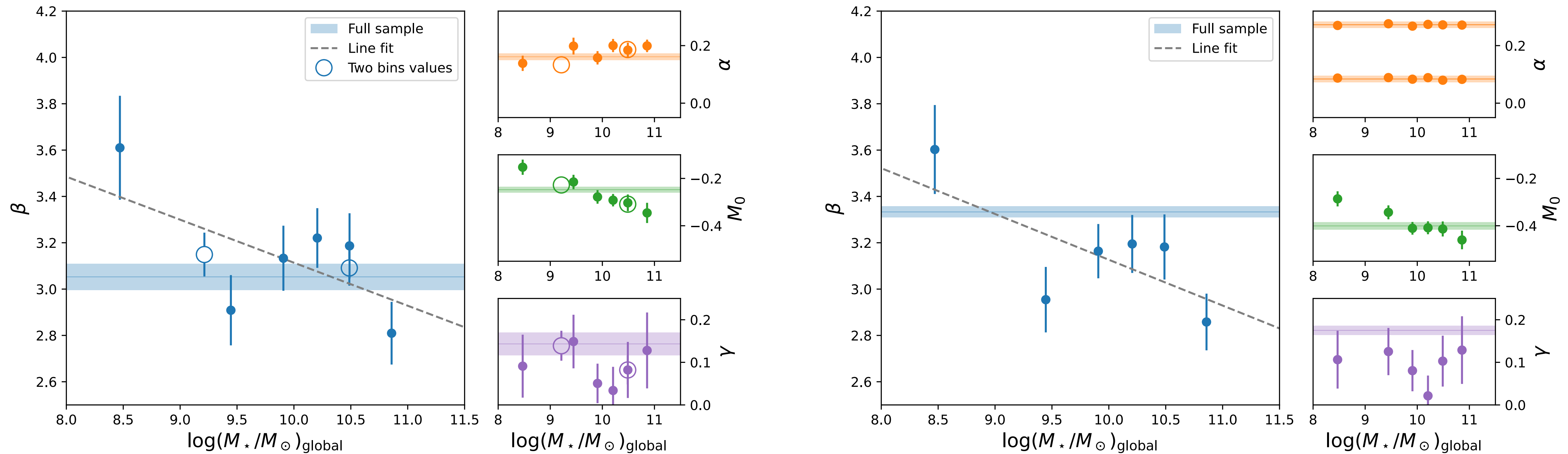
$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$



# Colour

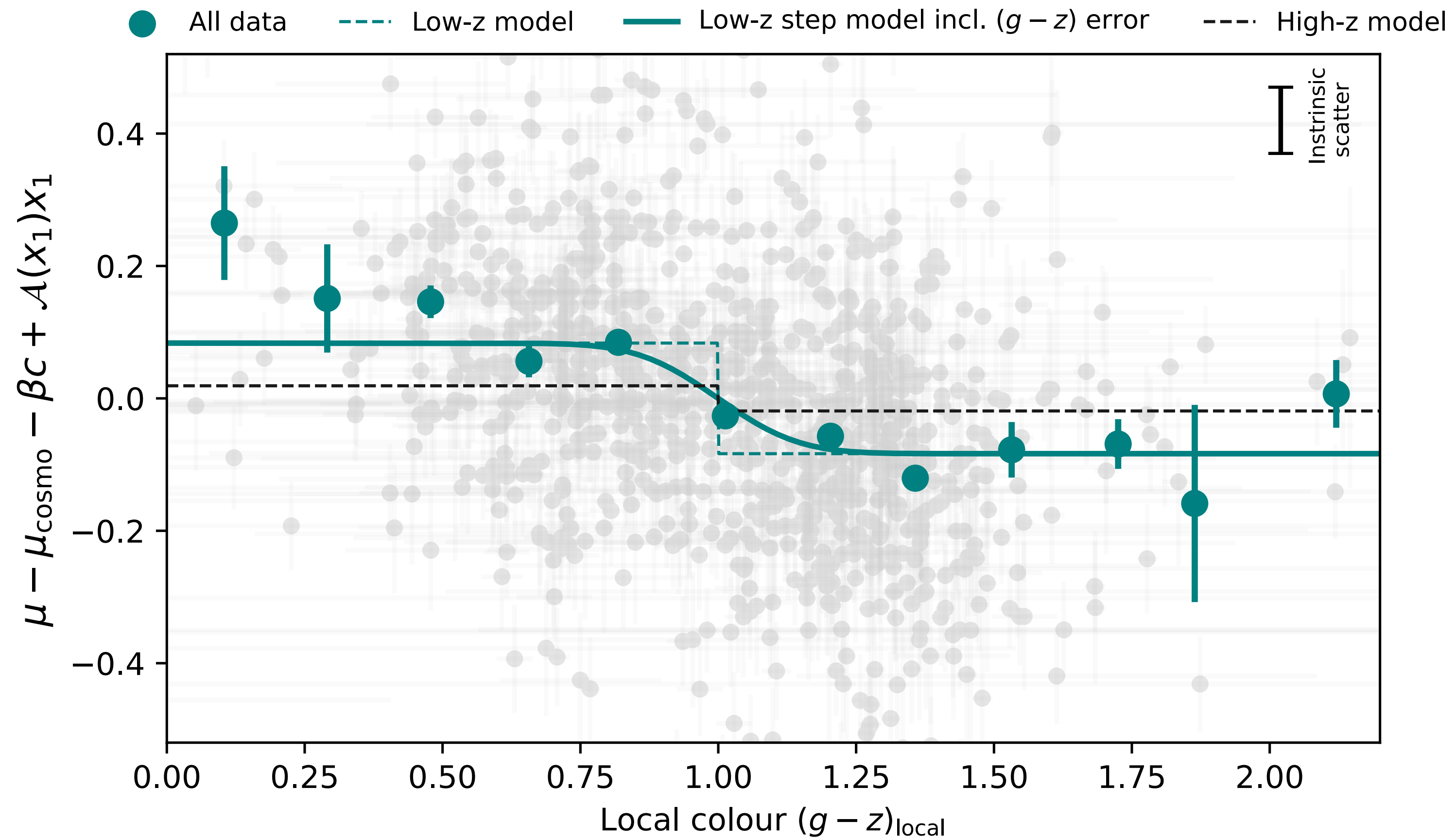
## $\beta$ evolution with environment

$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$



# Environmental step

$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$

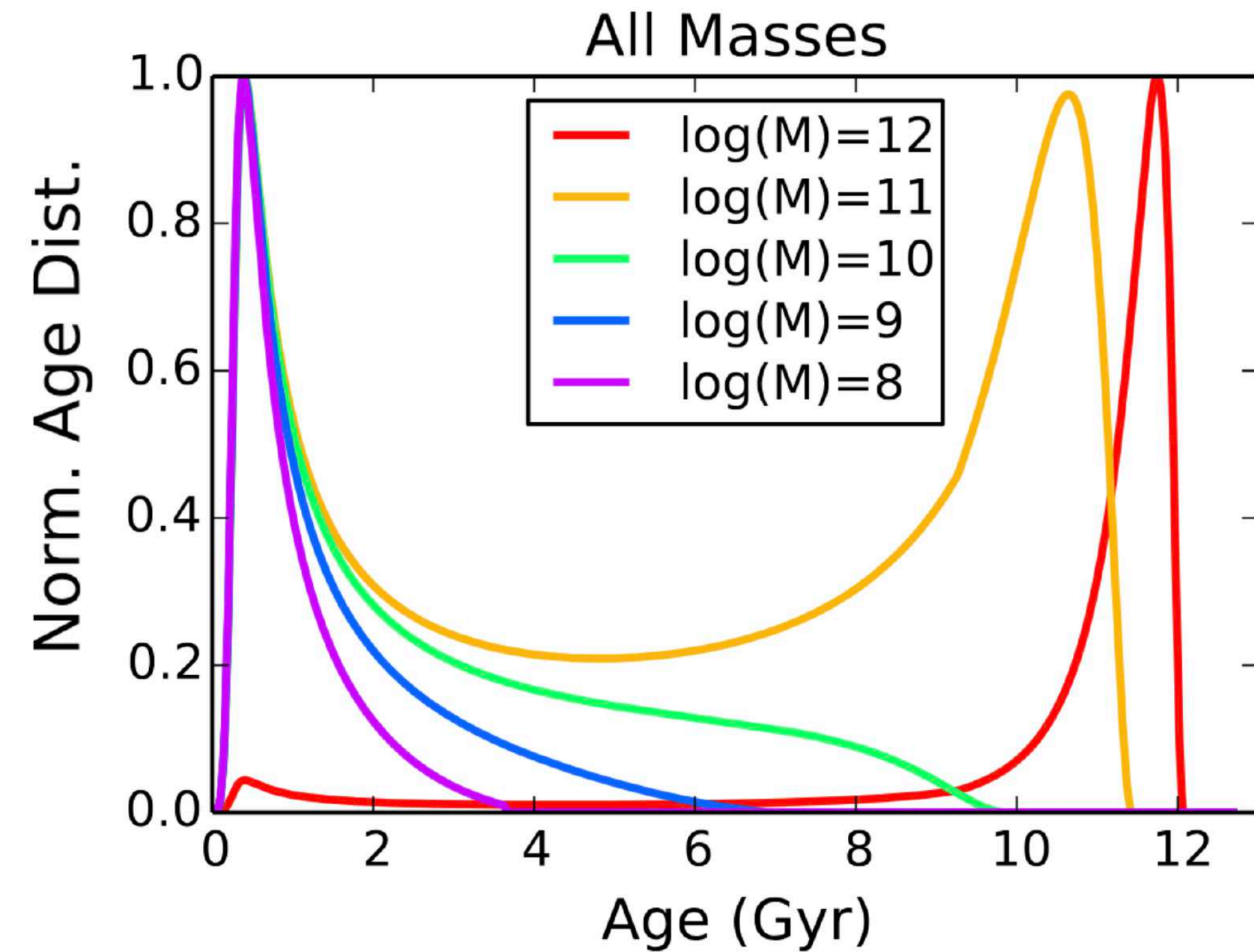


# Environmental step

## Origin of the step

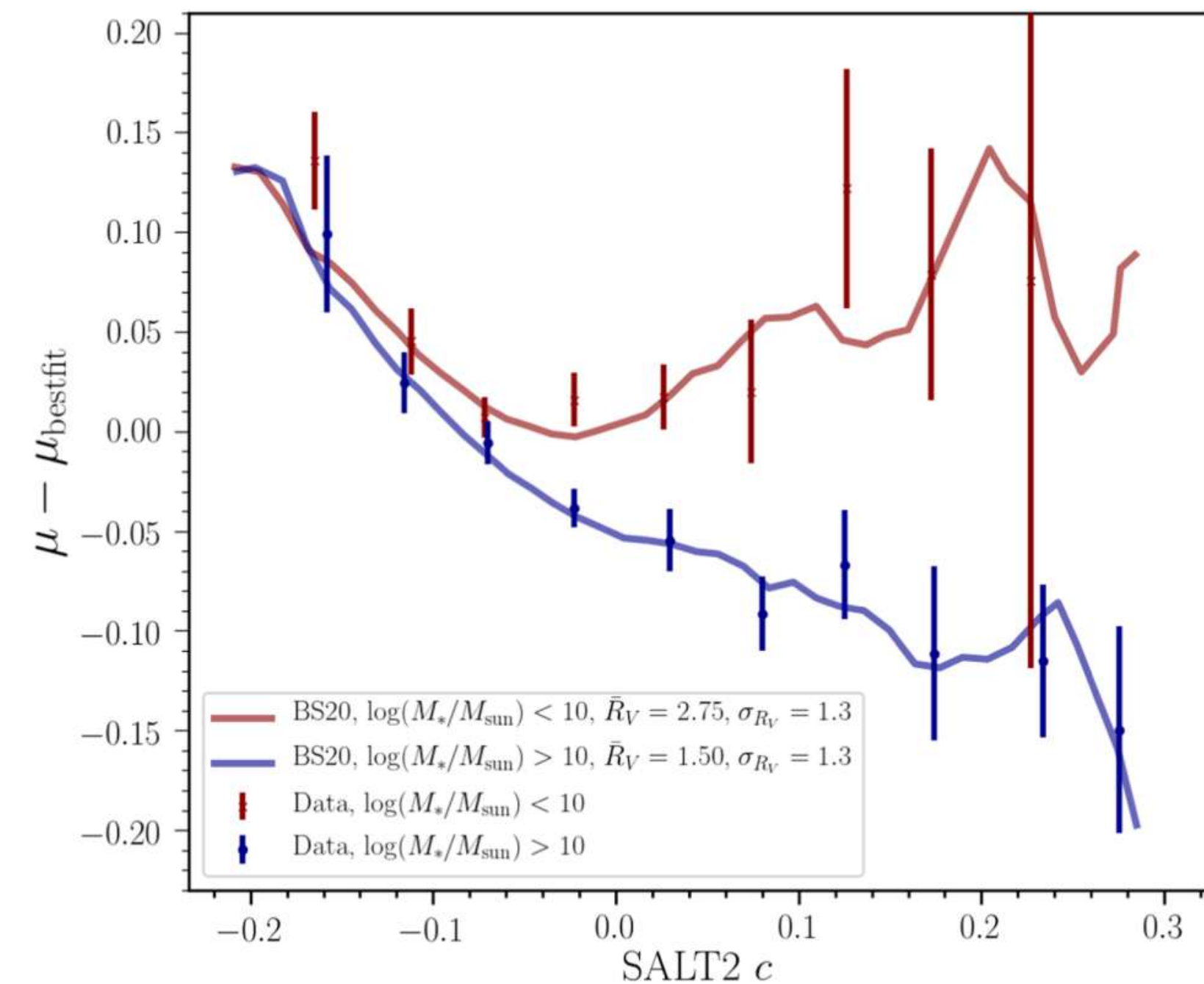
$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$

Two population interpretation



Childress et al (2014)

Dust interpretation

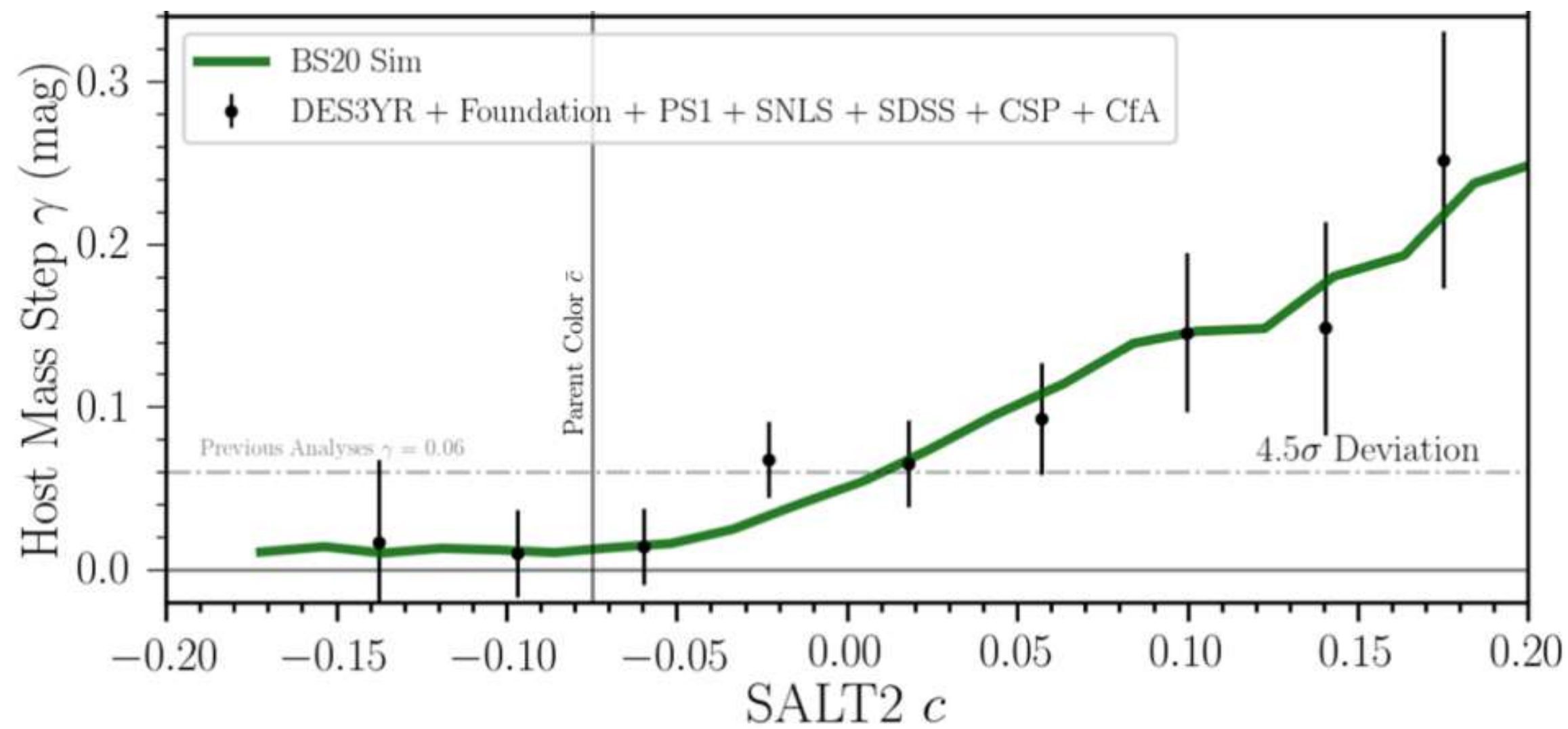


Brout & Scolnic (2021)

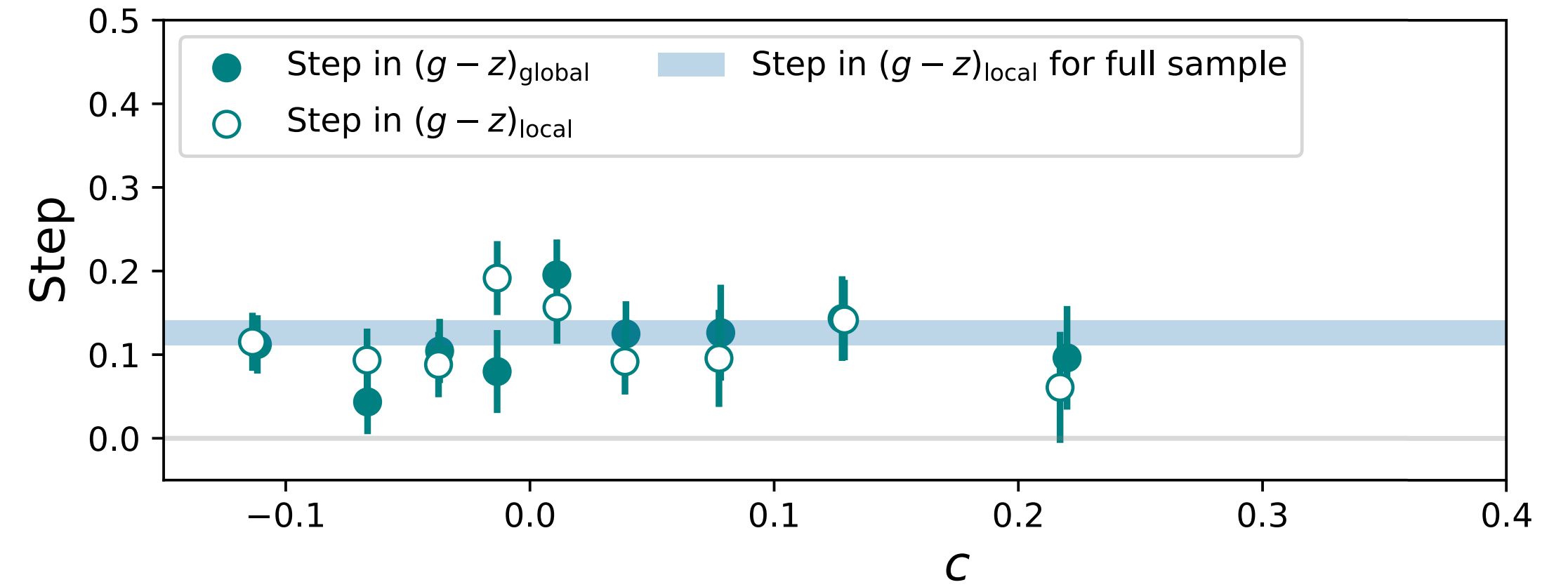
# Environmental step

## Colour-dependence of the step

$$\mu_{\text{obs}} + M = m_{\text{obs}} - \beta c + \alpha x_1 + p\gamma$$



Brout & Scolnic (2021)



**Table 3.** Parameters of the step evolution with SN colour: slope of the fit and  $\Delta\text{AIC}$  between an affine function and a constant.

Tracer	Slope	$\Delta\text{AIC}$
$(g-z)_{\text{local}}$	$0.05 \pm 0.11$ ( $0.5\sigma$ )	1.8
$(g-z)_{\text{global}}$	$0.02 \pm 0.12$ ( $0.2\sigma$ )	2.0
$\log(M_{\star}/M_{\odot})_{\text{local}}$	$-0.11 \pm 0.12$ ( $0.9\sigma$ )	1.2
$\log(M_{\star}/M_{\odot})_{\text{global}}$	$0.02 \pm 0.11$ ( $0.1\sigma$ )	2.0

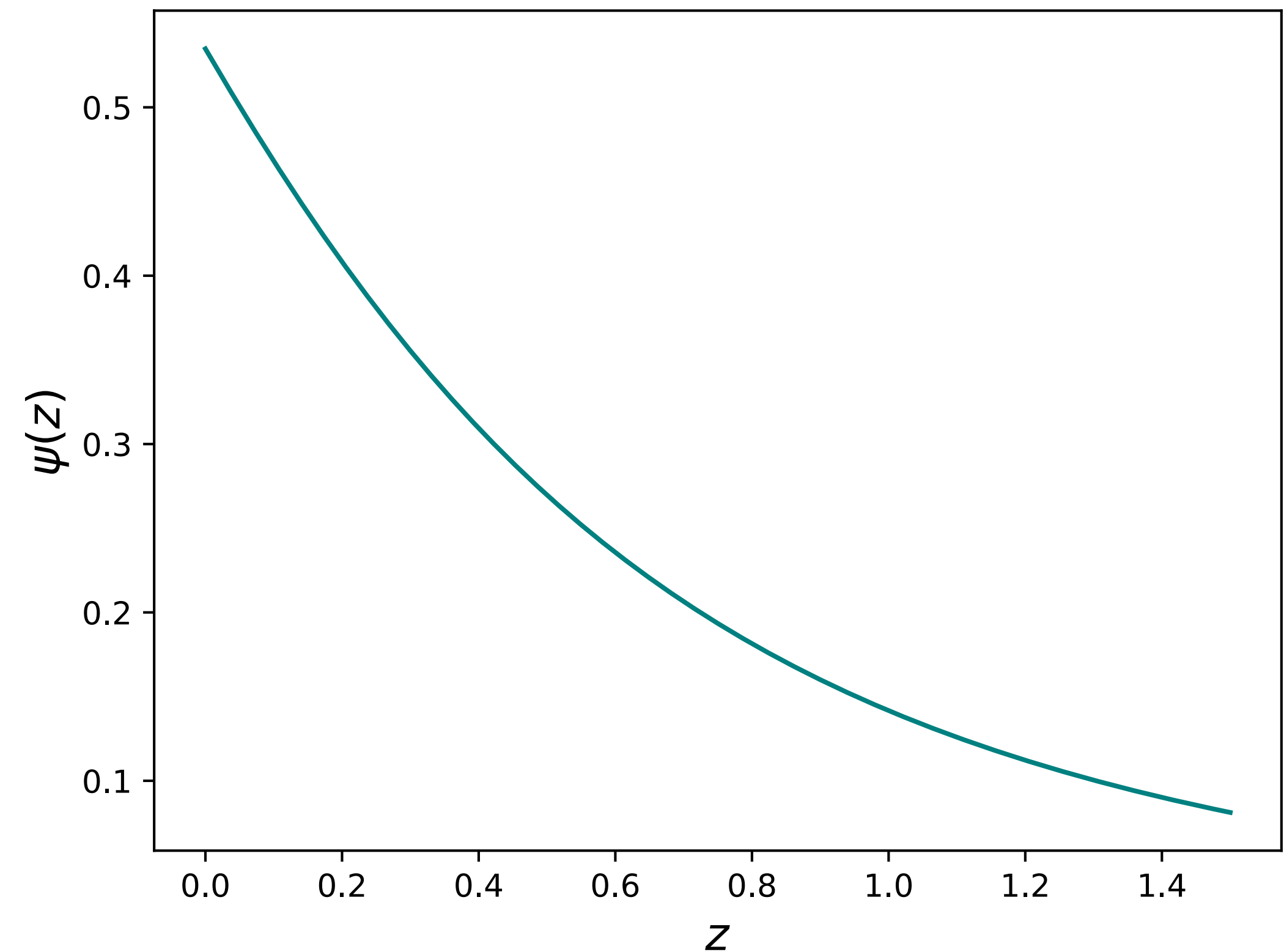
# IV. Next steps

# Redshift evolution

Fraction of old progenitor SNe Ia:

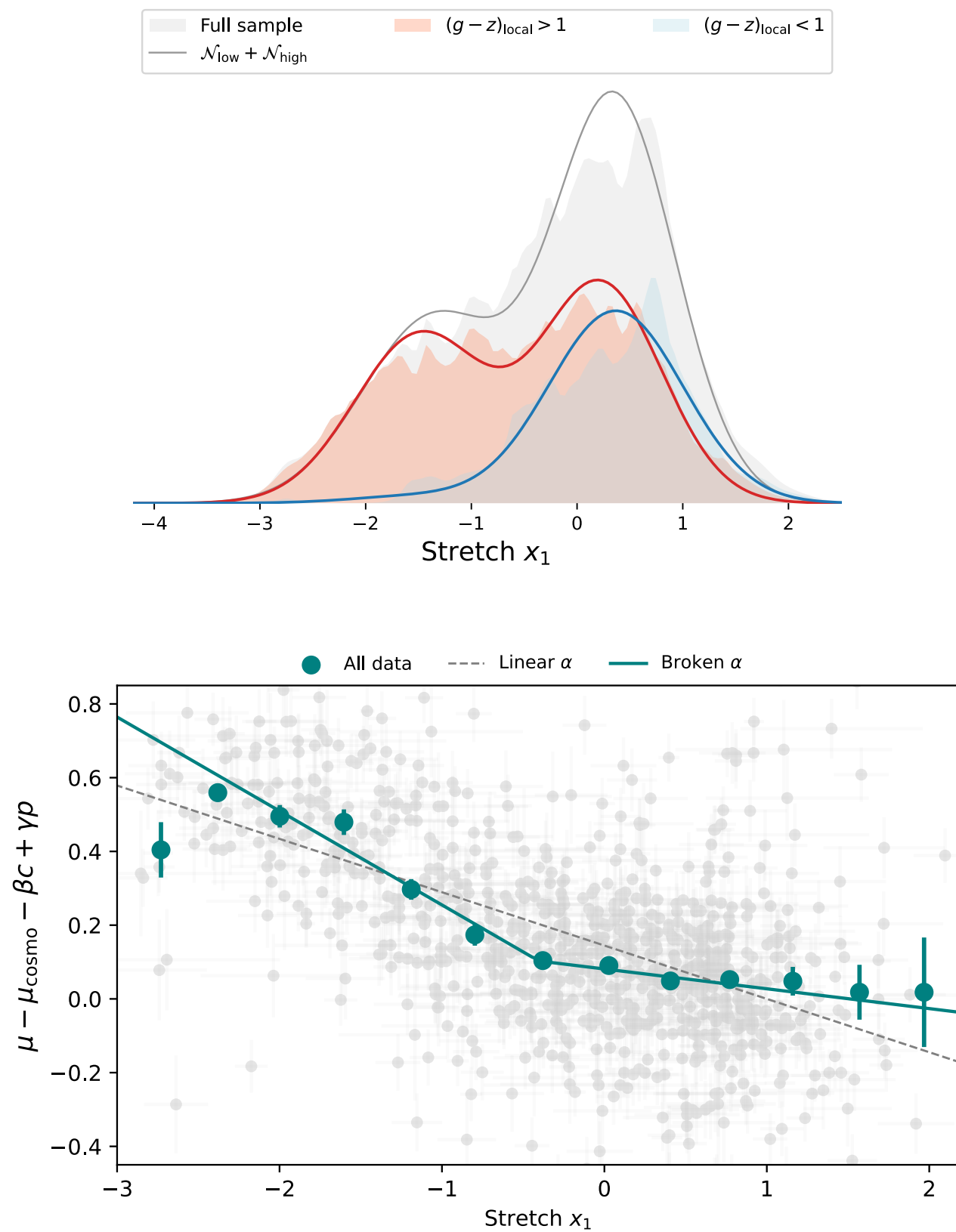
$$\psi(z) = \frac{1}{K(1+z)^\phi + 1}$$

Rigault et al (2020)  
Tasca et al (2015)  
Mannucci et al (2005)

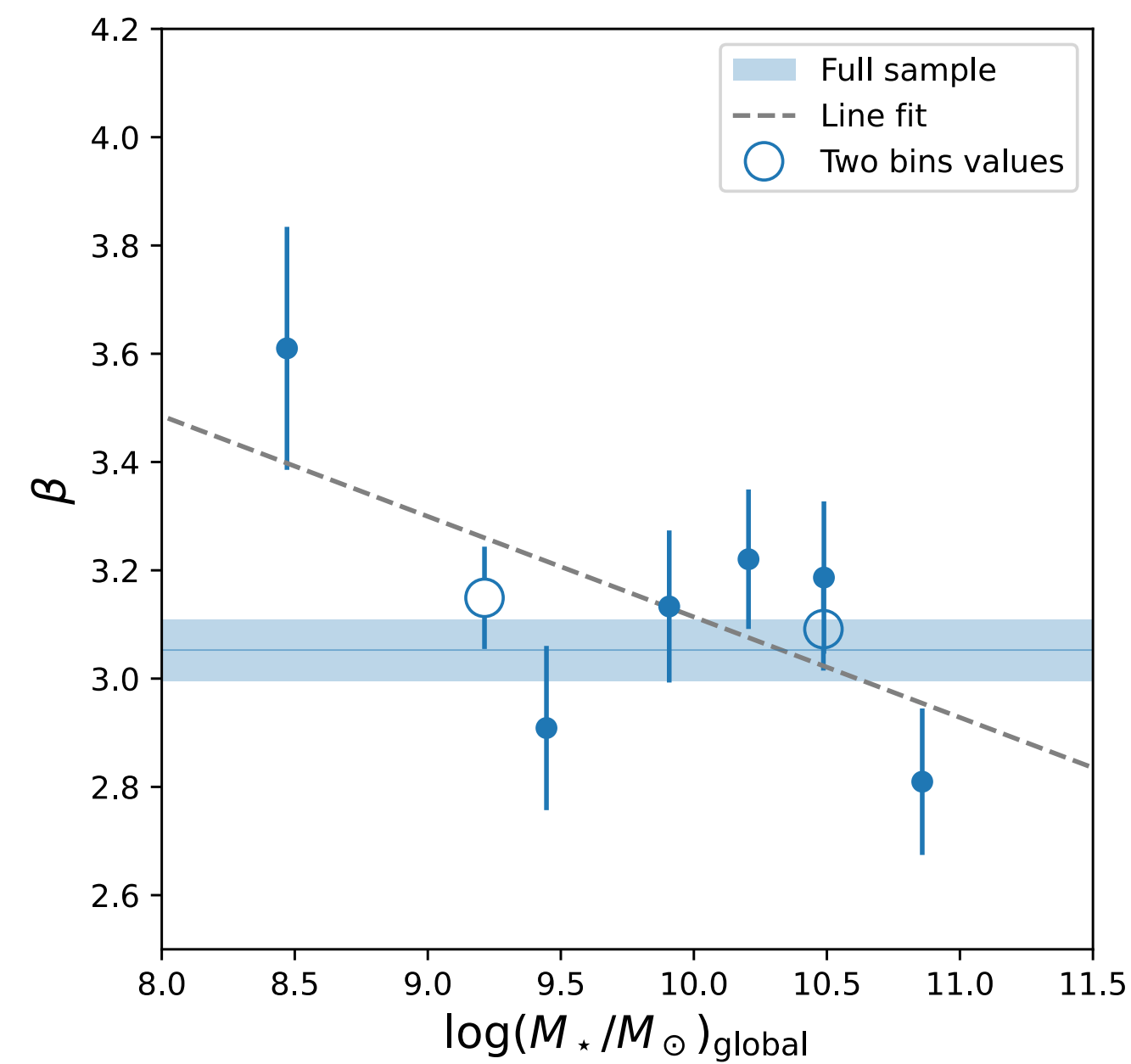


# Redshift evolution

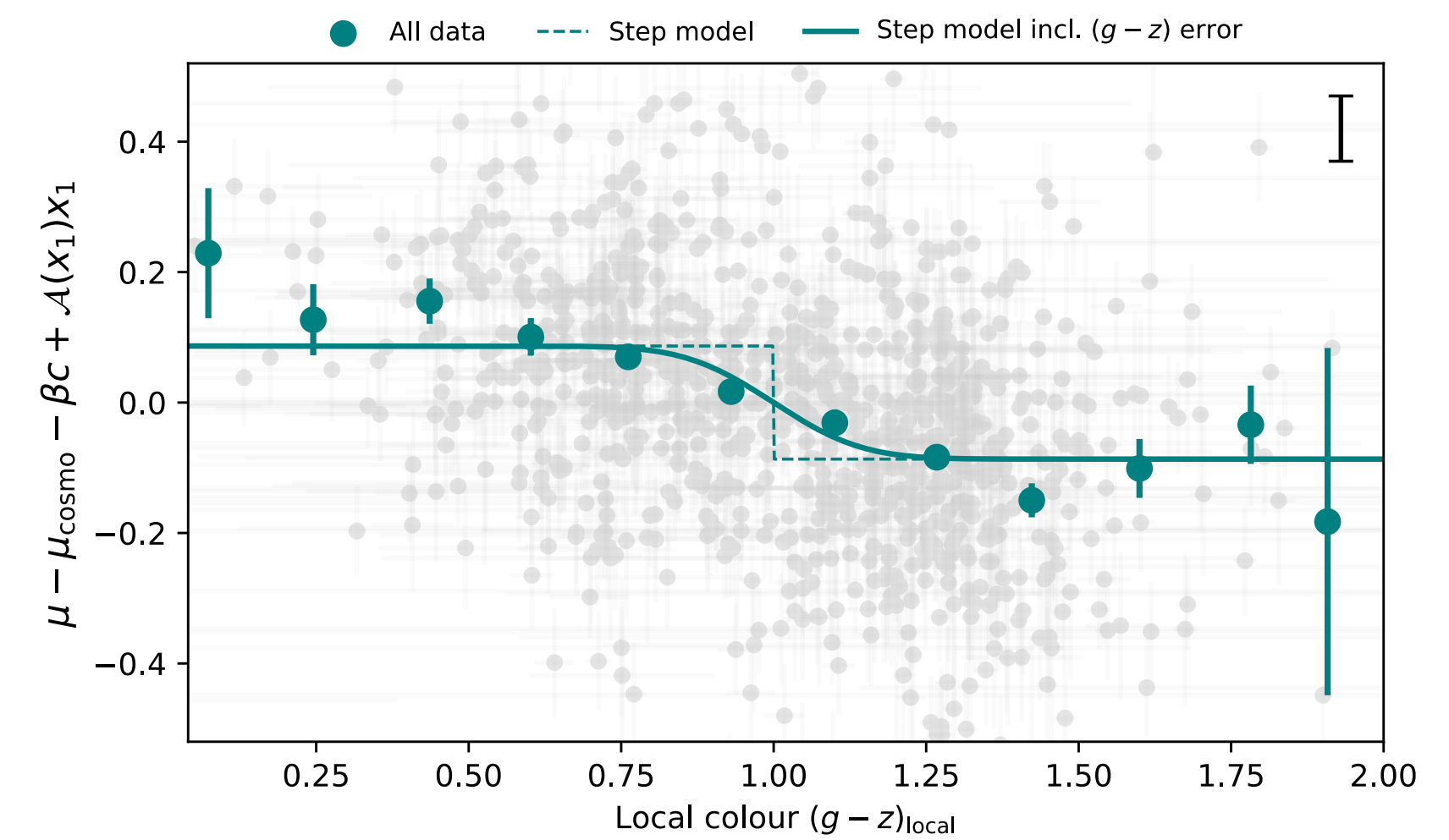
## $\alpha$ evolution



## $\beta$ evolution



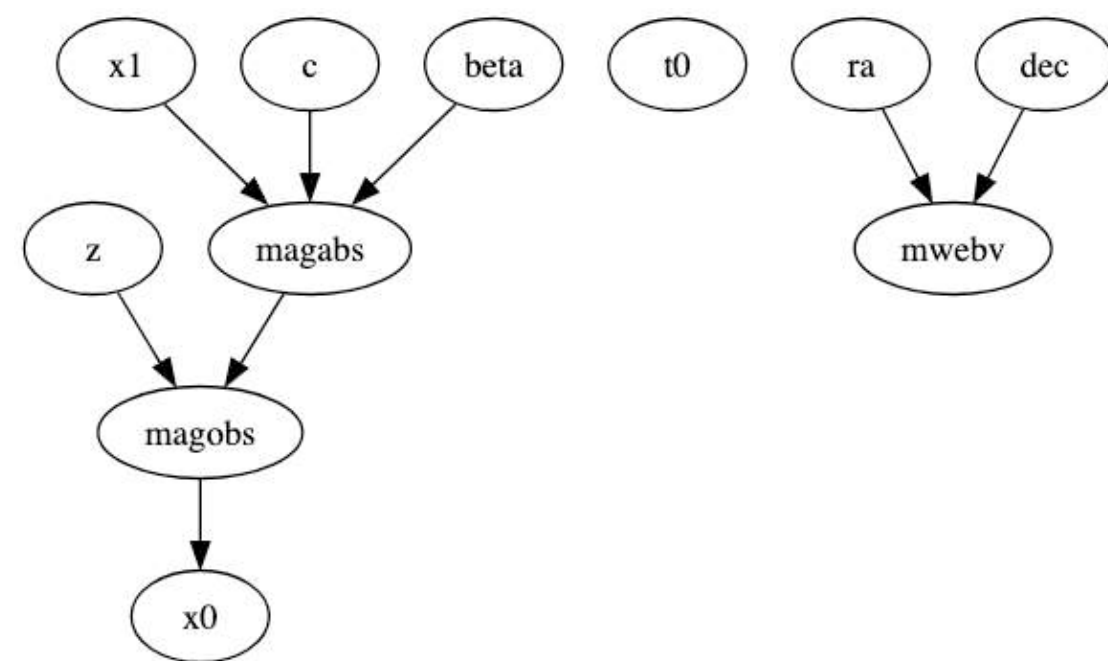
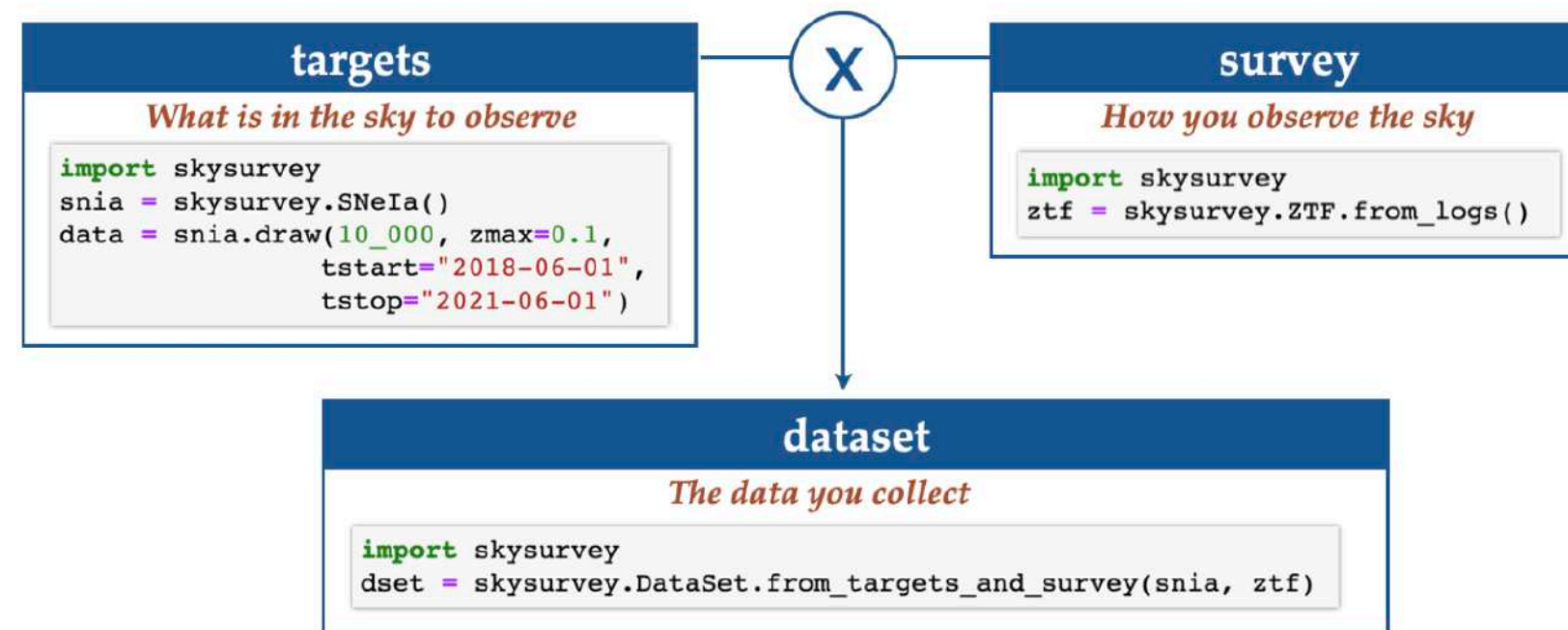
## Impact of the environmental step



# Next steps

## Include these effects in simulations skysurvey

[skysurvey.readthedocs.io](https://skysurvey.readthedocs.io)



## Investigate the redshift evolution with high-z data



### LSST @ Vera C. Rubin Observatory

1M SNe Ia over 10 years

Up to  $z \sim 1.1$

# Conclusion

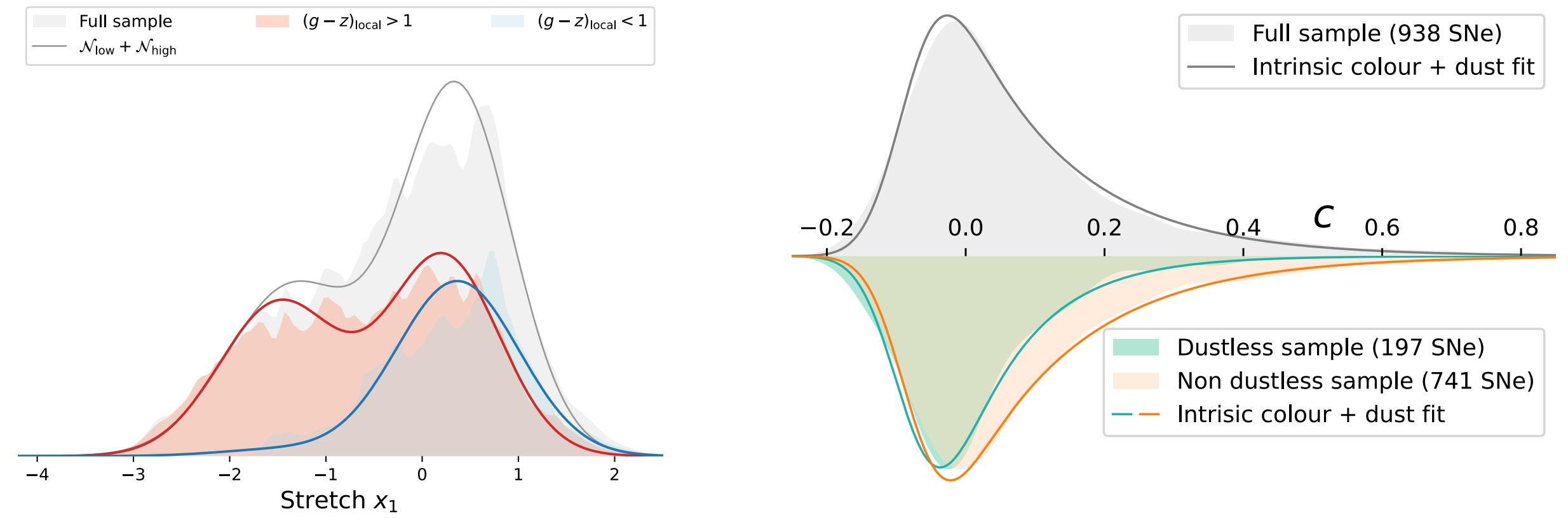
**ZTF SN Ia DR2**  
volume-limited sample

949 SNe Ia  
Homogenous  
High cadence + spectroscopic

2406.02072

2405.20965

## Type Ia Supernovae properties



## Standardisation dependency on environment

