Spectrophotometric standardisation of type Ia supernovae

Constance Ganot, PhD student at IP2I, Lyon
supervised by Y. Copin and M. Rigault

Seminar at LPNHE, December 2025

Outline

- Cosmology with SNe, Hubble diagram, Dark energy, Tensions
- Traditional photometric standardisation
- Spectrophotometric standardisation
- Building the ZTF spectrophotometric SN Ia sample
- Twins Embedding application to ZTF

Type Ia supernovae

SN 1994D in galaxy NGC 4526
Hubble Space Telescope

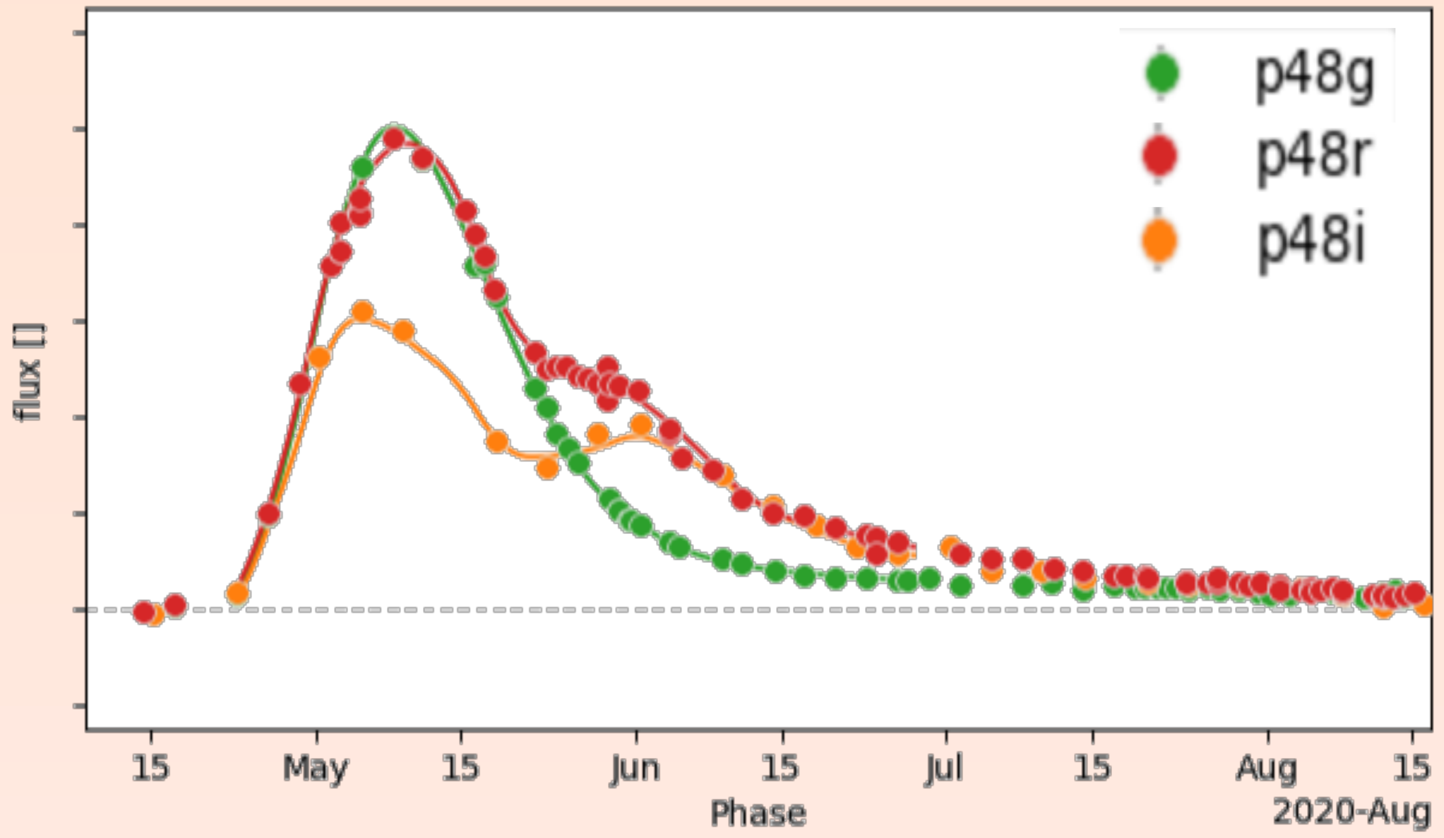
Luminosity ~constant

Standard candles : $f = \dfrac{L}{4\pi d_L^2}$

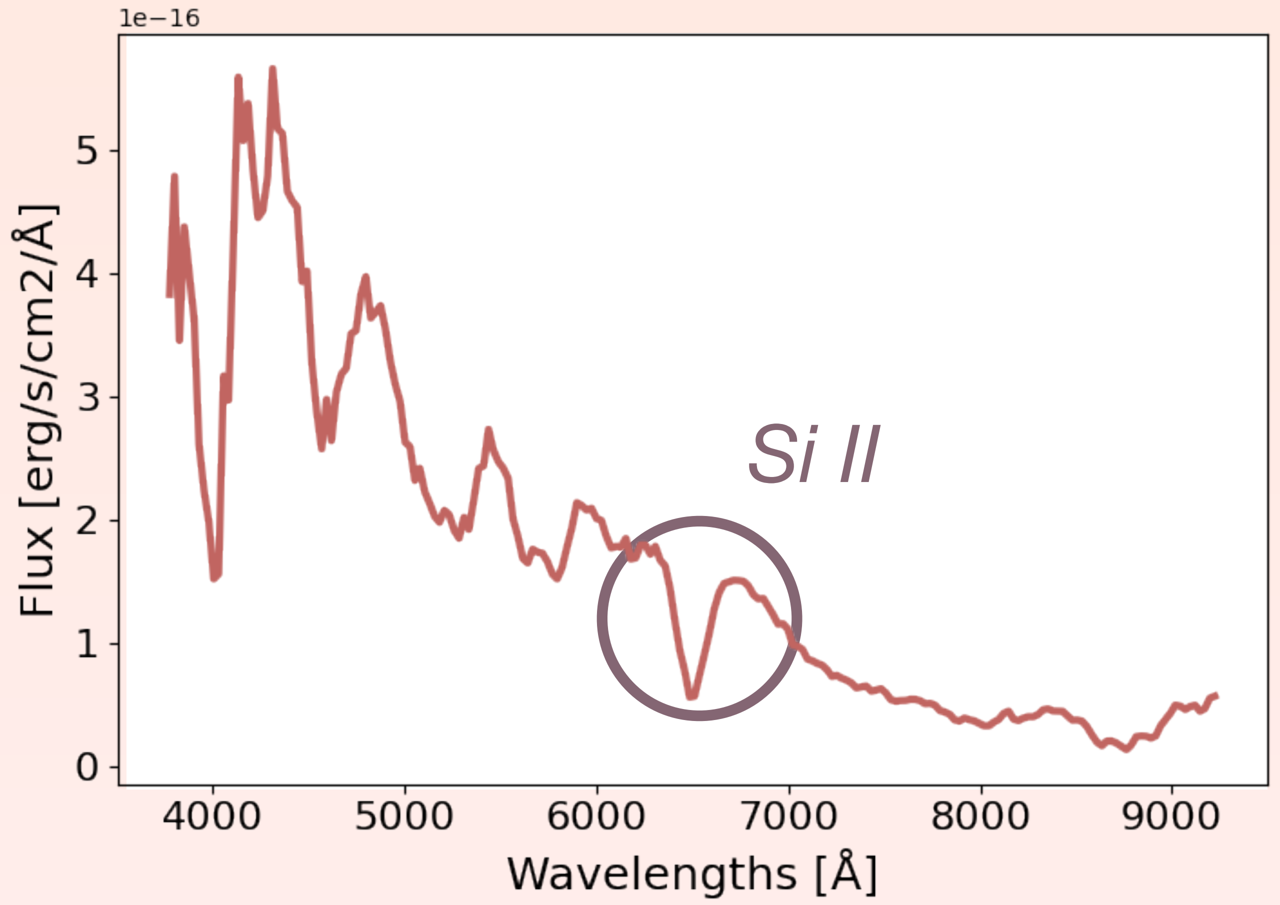
Distance modulus

$$\mu = m_B^{max} - M_B^{max}$$

$$\mu = 5log\left(\frac{d_L}{10pc}\right)$$



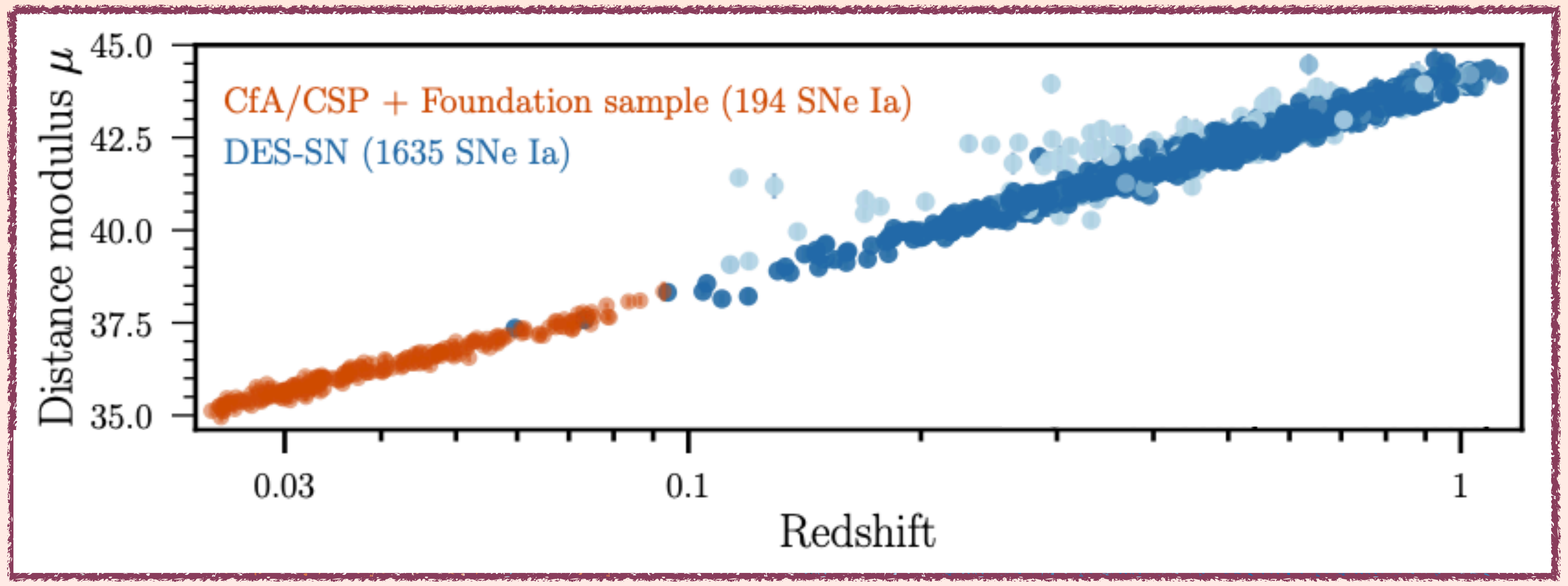
Lighcurves of ZTF20abxzrqw



Spectrum of ZTF20abeqsrm
at phase -5.73

Goals | *Cosmology*

Distance modulus can be measured on lightcurves
Redshift can be measured with a spectrum



Hubble Diagram of DES-SN (Vincenzi 2024)

Goals | *Cosmology*

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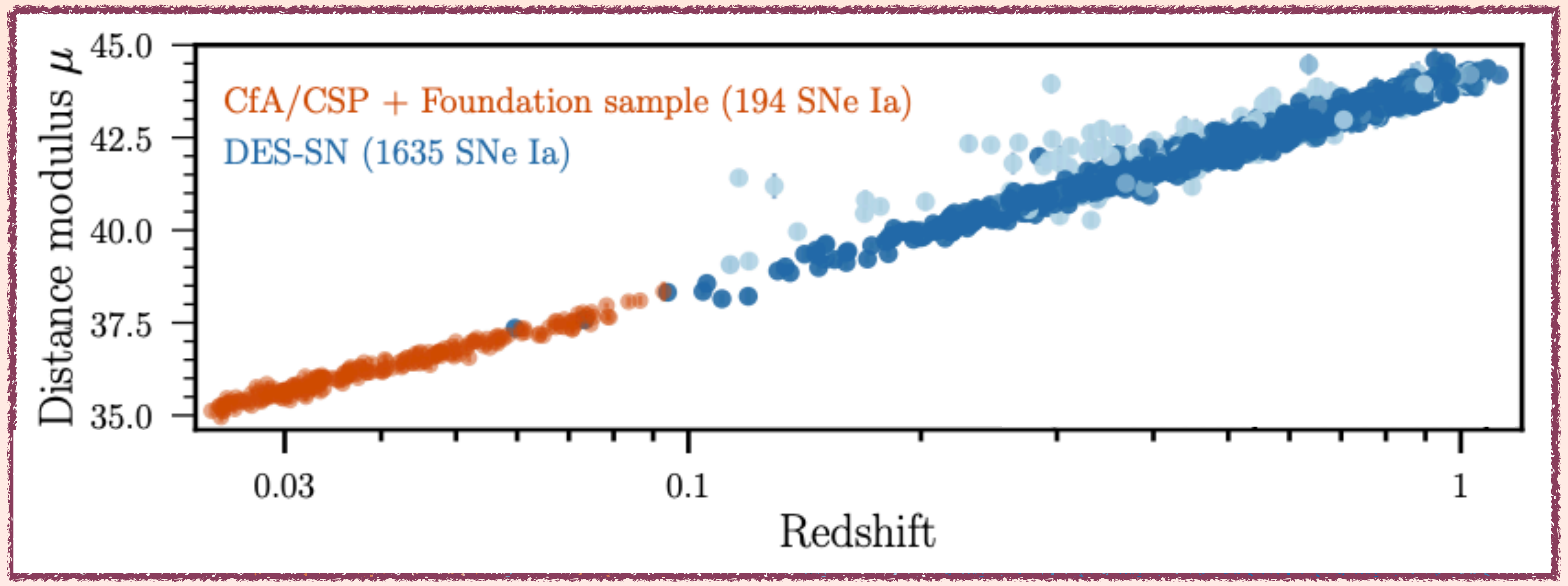


Hubble Diagram of DES-SN (Vincenzi 2024)

Standard model of cosmology: ΛCDM

Cosmological constant Λ

Cold dark matter CDM

$$H(z) = H_0 \times \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$$

Matter density

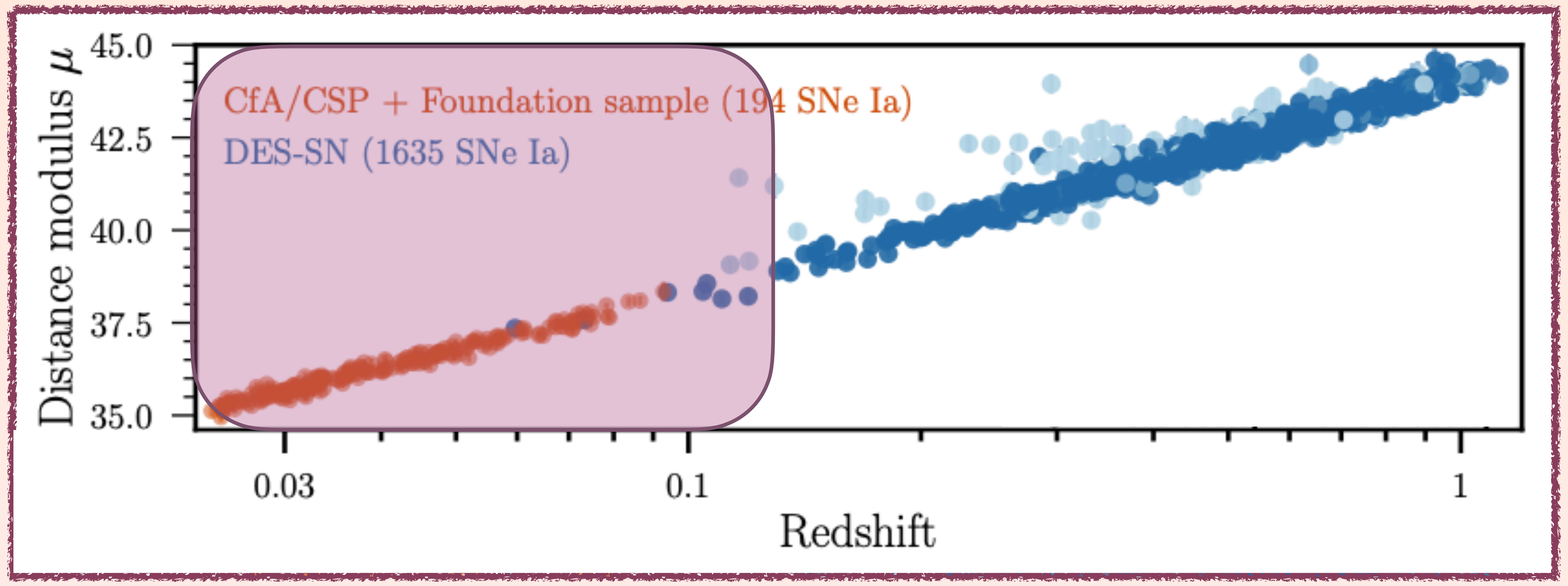
Dark Energy density

Equation of ΛCDM model

- Flat Universe
- $\Omega_M + \Omega_\Lambda = 1$

Goals | *Cosmology*

Low-redshift (z<0.1)
Constrains H_0



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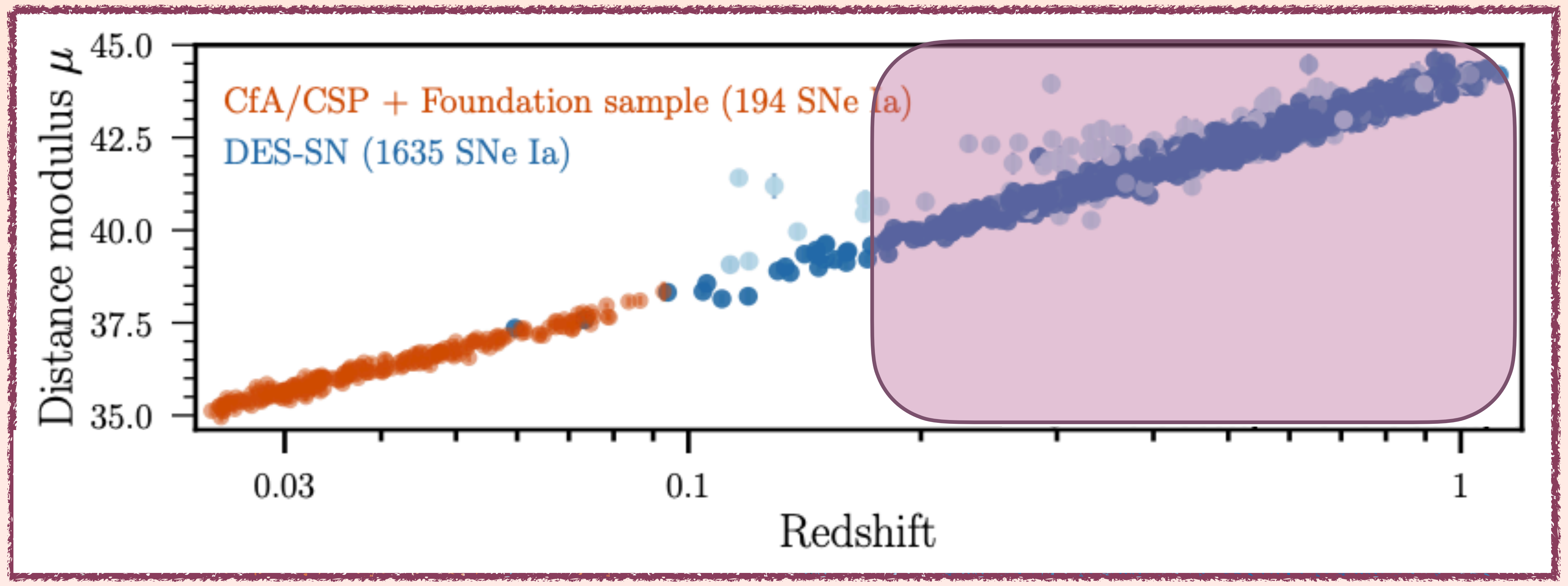
Goals | *Cosmology*

High-redshift (z>0.1)
Constrains (Ω_M, Ω_Λ)



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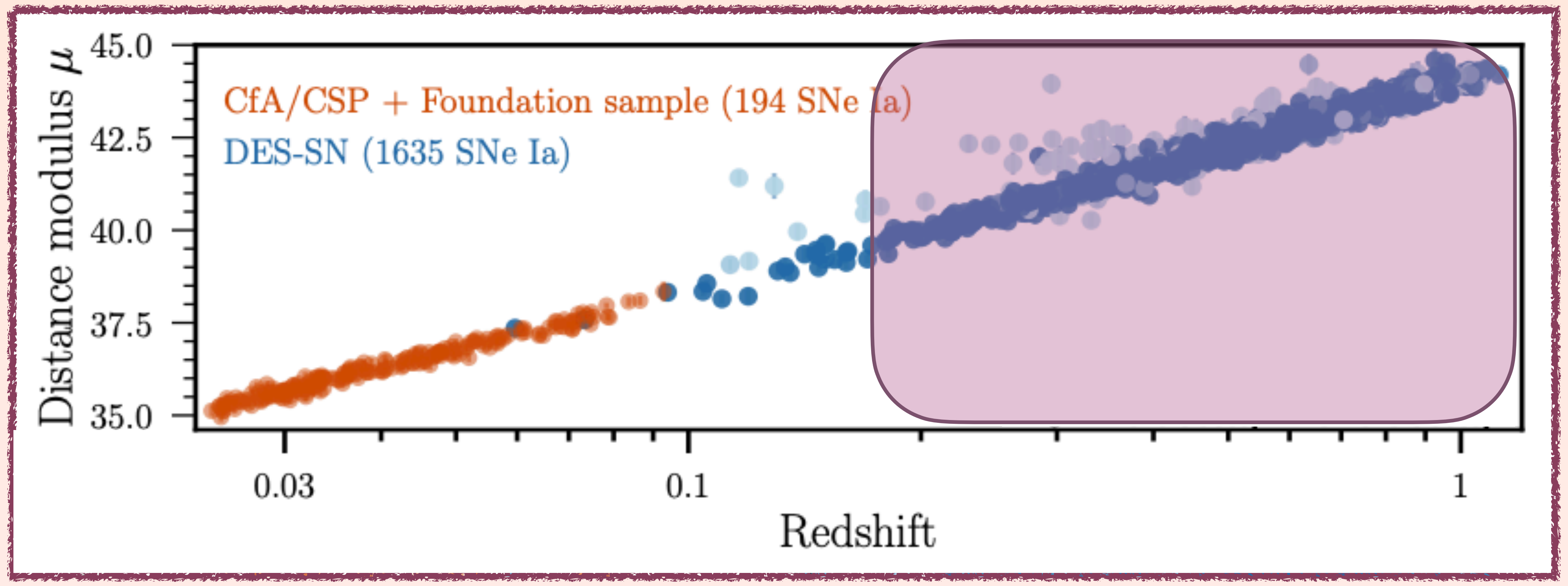

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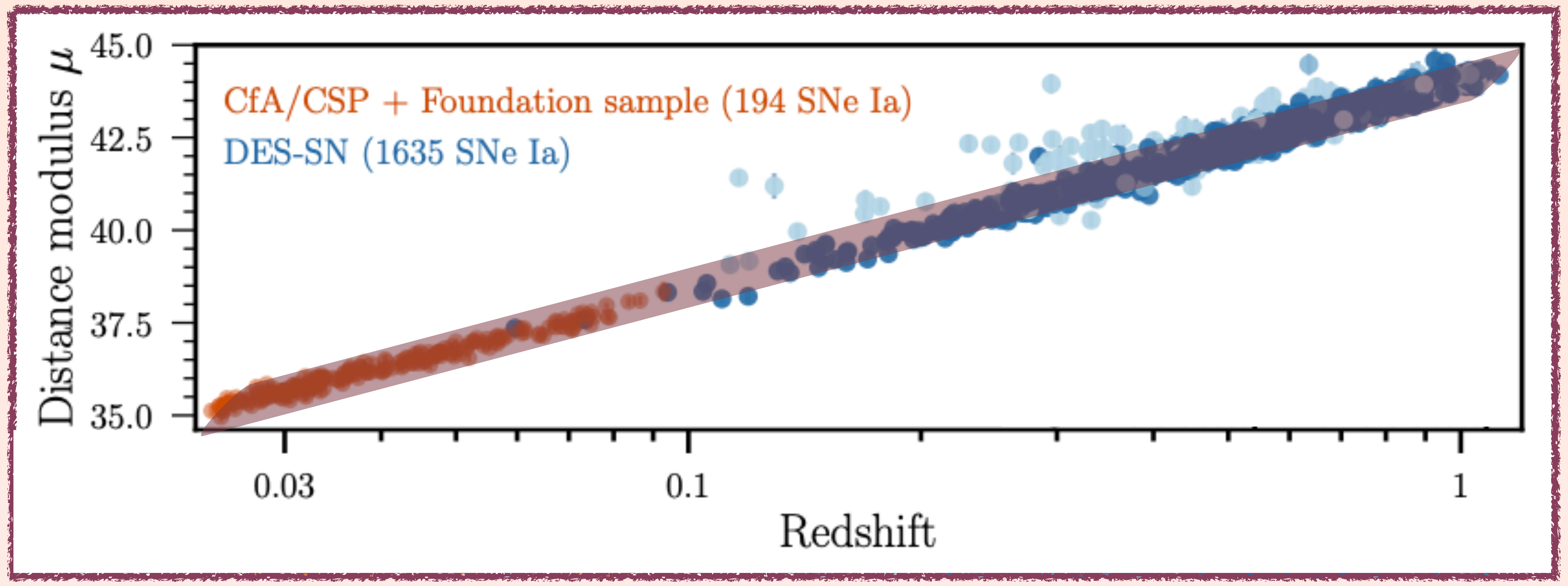
Goals | *Cosmology*

Dynamical Dark Energy

w variations are in the thickness of the line :

we compute $\mu - \mu_{model}$ to see it



Hubble Diagram of DES-SN (Vincenzi 2024)

Extensions of the ΛCDM model:

parameter of the dark energy equation of state

$wCDM$ model:

$$H(z) = H_0 \times \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}$$

Present value *Rate of change*

$w_0 w_a CDM$ model: $w(a) = \boxed{w_0} + \boxed{w_a}(1-a)$

$\Lambda CDM : w = -1$

$\Lambda CDM : w_0 = -1; w_a = 0$

Goals | *Cosmology*

Dynamical Dark Energy

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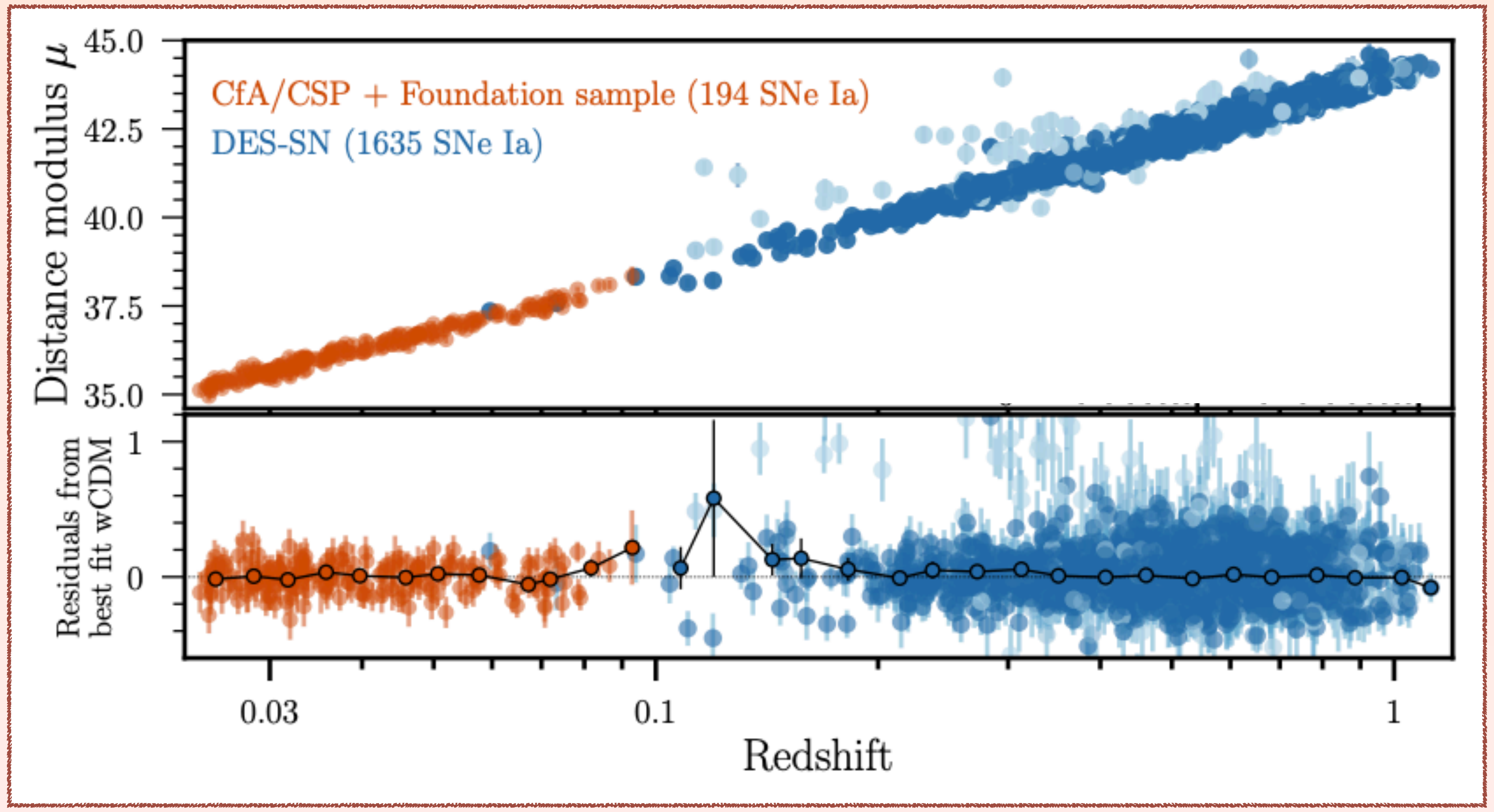

Hubble Diagram of DES-SN (Vincenzi 2024)
Hubble **residuals** from best-fit wCDM

Extensions of the ΛCDM model:

parameter of the dark energy equation of state

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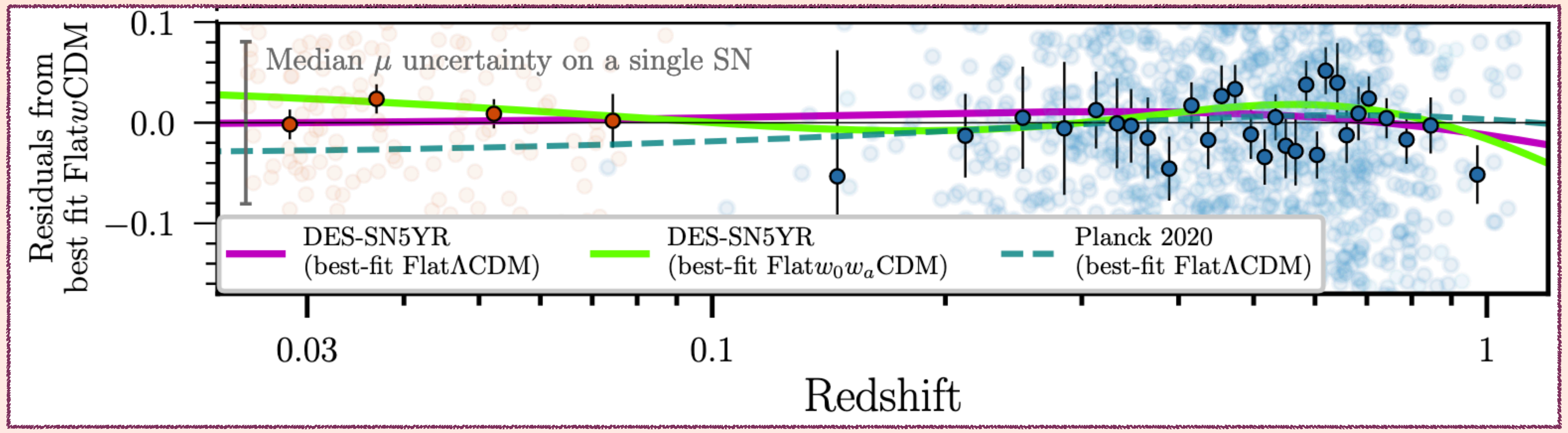
Goals | *Cosmology*

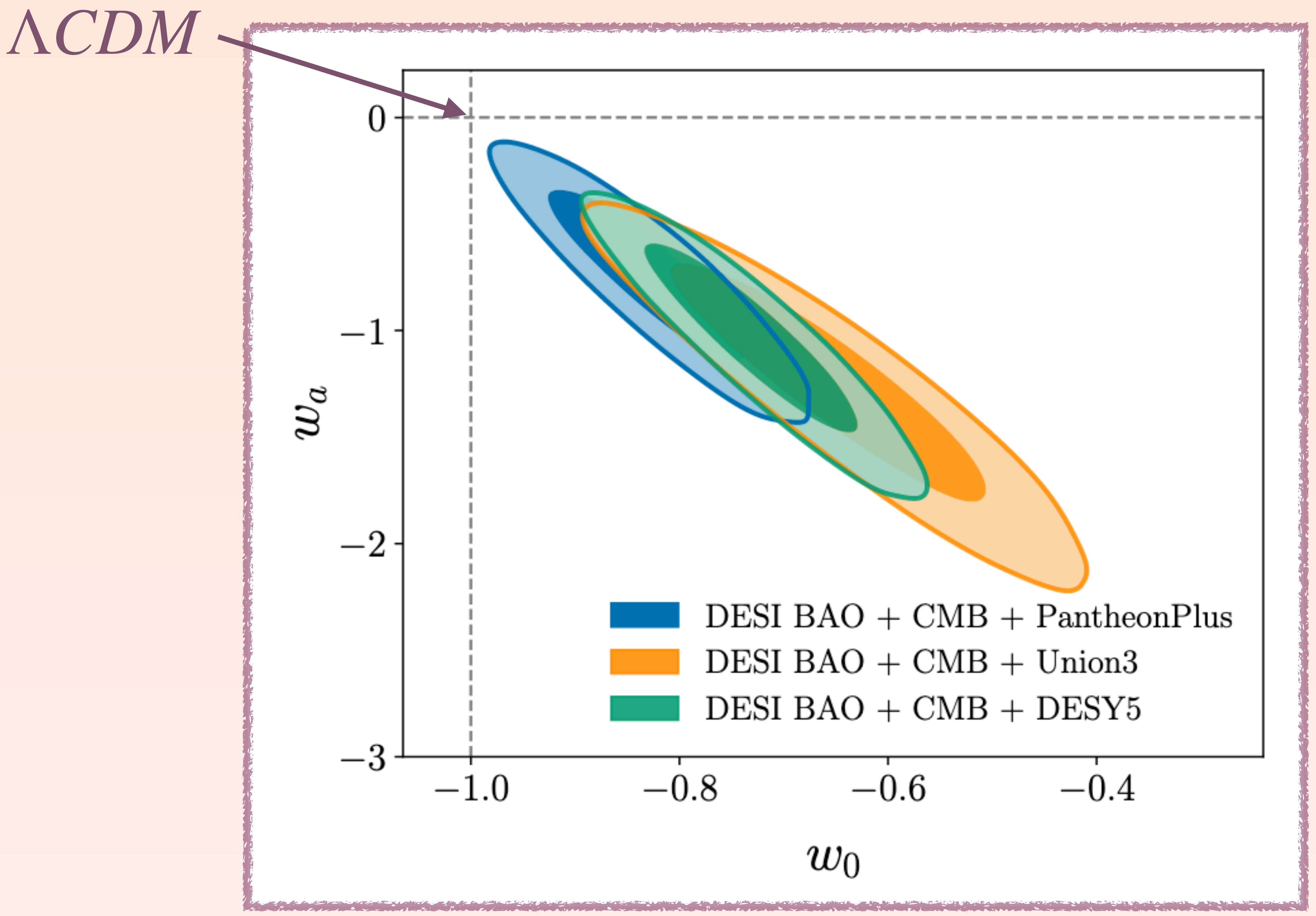
Dynamical dark energy detected

2.5σ, 3.5σ and 3.9σ with ΛCDM (DESI 2024 VI)



Hubble **residuals** of DES-SN5YR (DES collaboration 2024)

Best-fit: *ΛCDM*, $w_0w_a CDM$

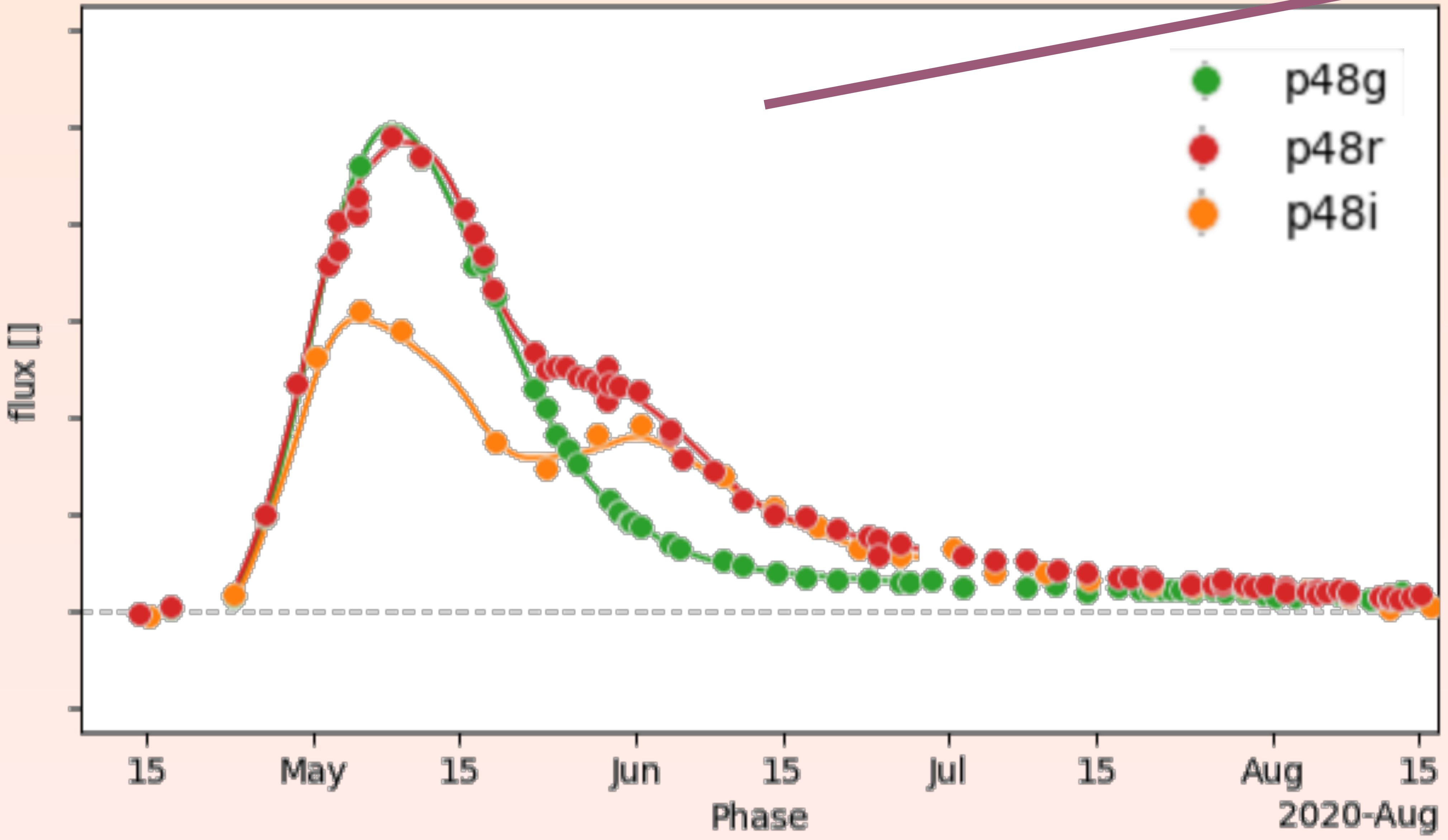


Driven by the choice of the SN Ia sample / the cosmological inference pipeline

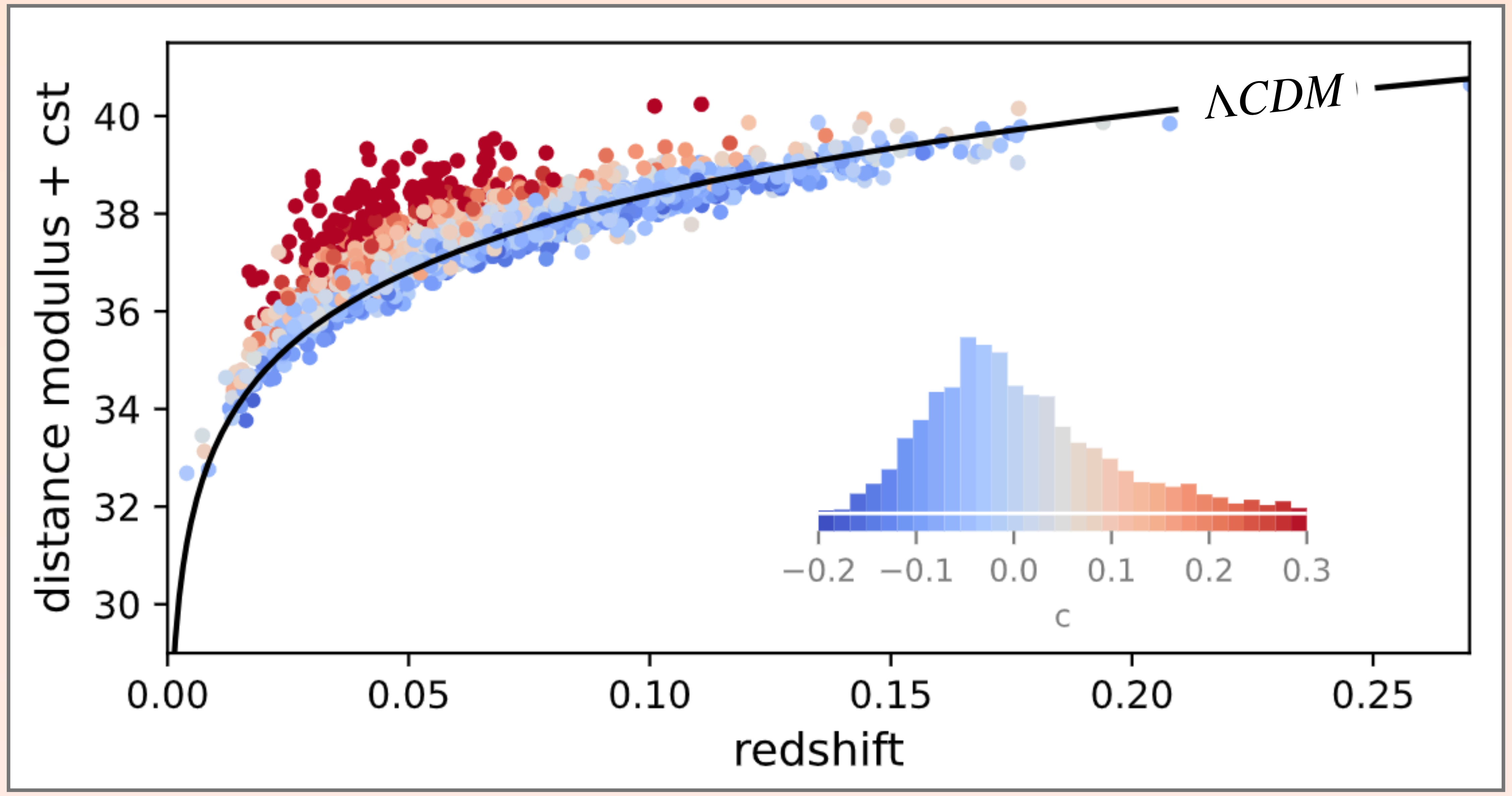
Photometric standardisation

Derive m_B^{max}

Compute $\mu = m_B^{max} - M_B^{max}$



Lightcurves of ZTF20abxzrqw



Hubble Diagram photometric standardisation
Credit : in prep. ZTF "DR2" Data paper, Smith et al.

SNe Ia dispersion :

$\sigma = 0.40$ mag

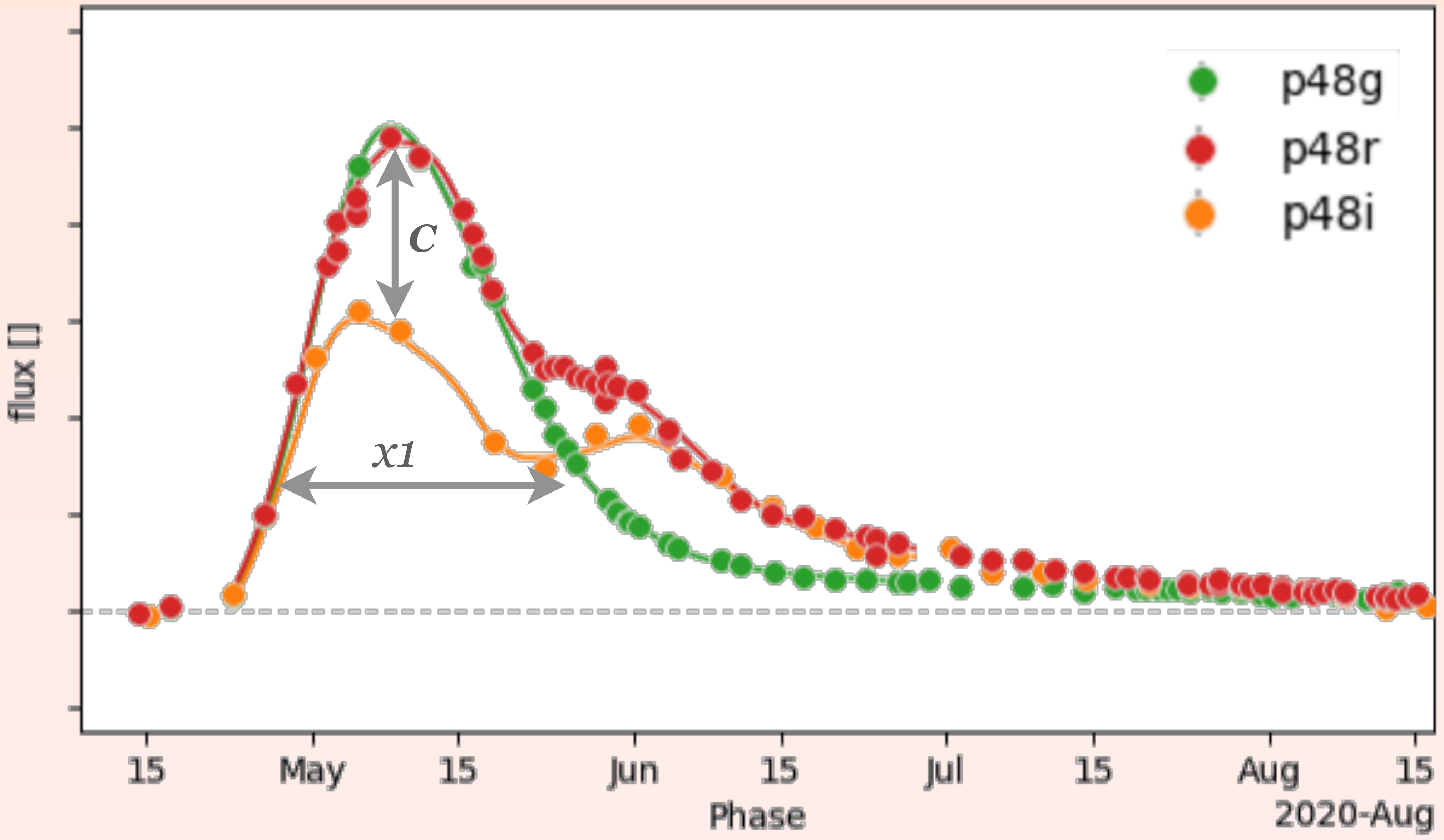
Photometric standardisation

Tripp 1998
Guy 2010

Empirical standardisation:

Corrections
'Brighter-bluer' : c
'Slower-brighter' : x_1

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



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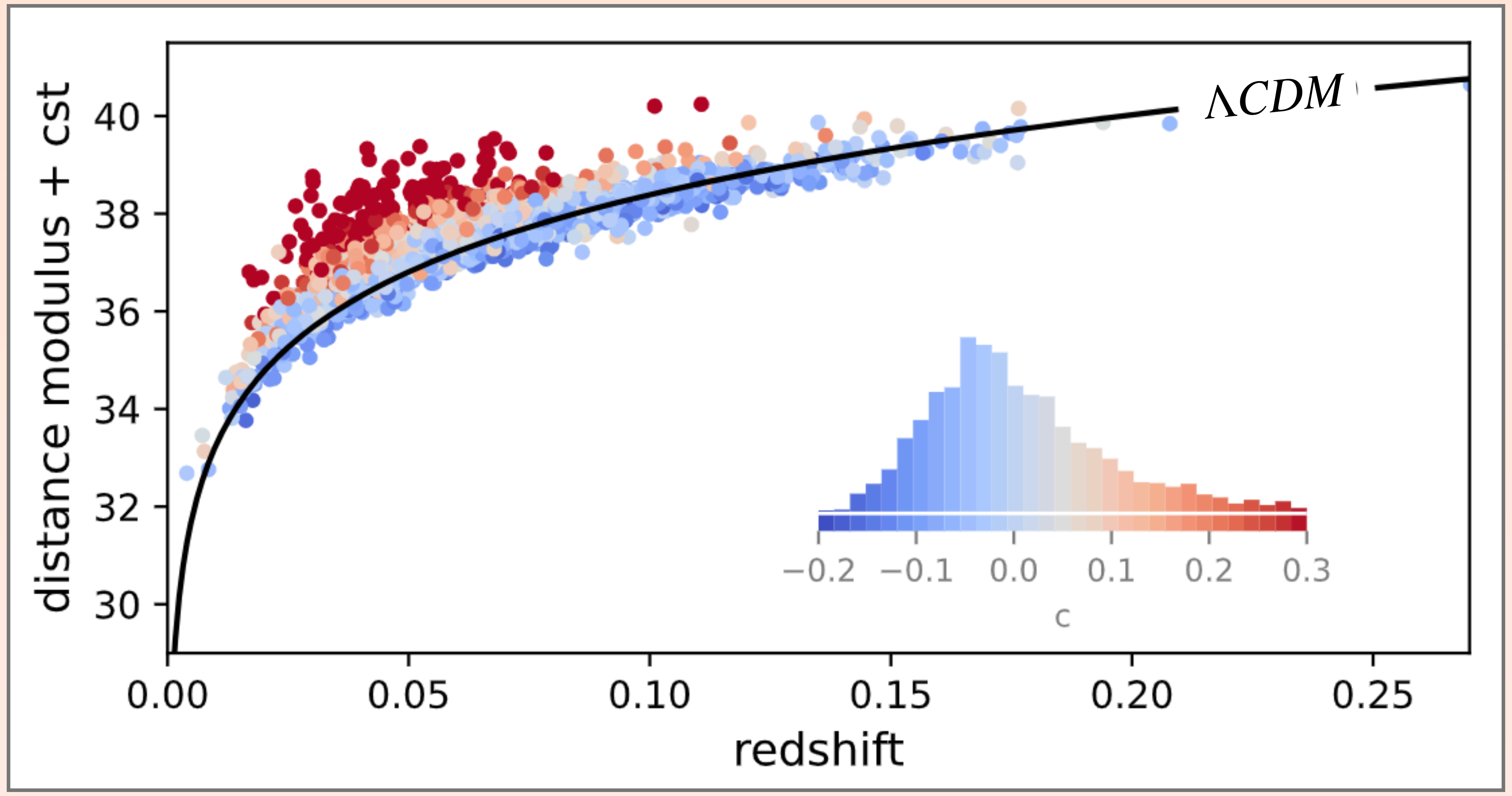

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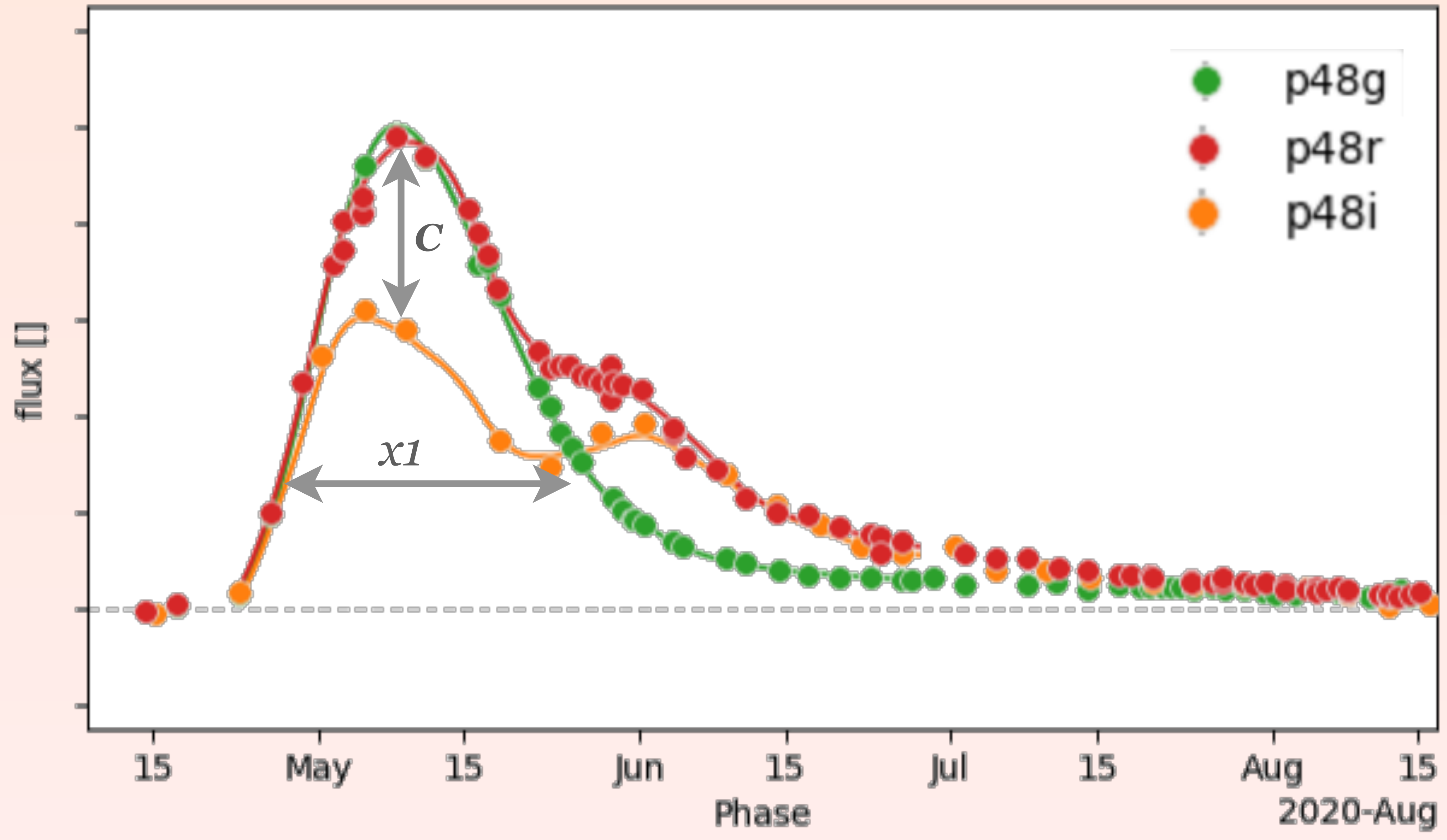
Empirical standardisation:

Correction for host galaxy property G_{host}: 'mass step' or 'color step'

$$\mu_{corr} = m_B^{max} - M_B^{max} - \beta c + \alpha x_1 + \gamma G_{host}$$



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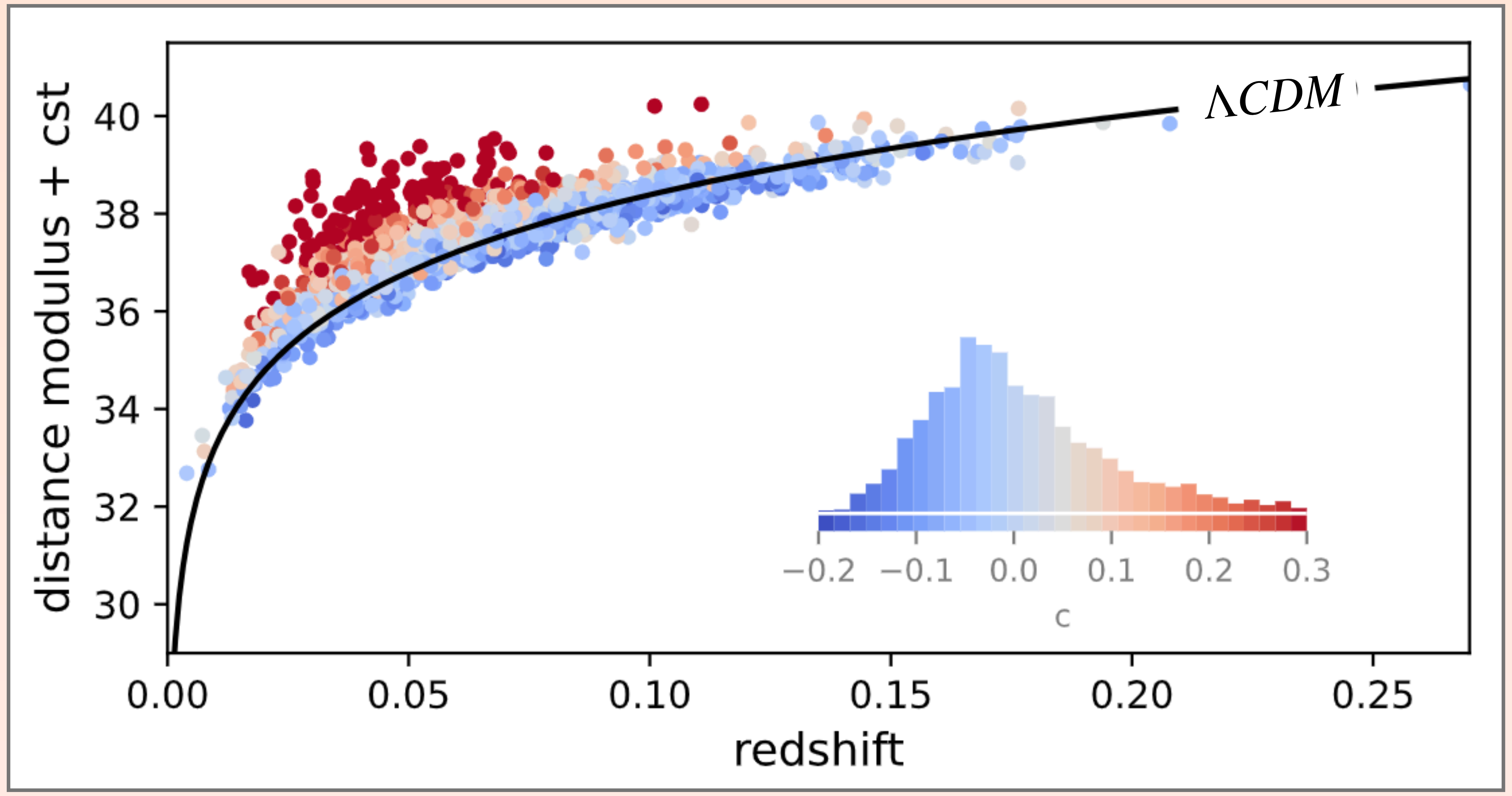

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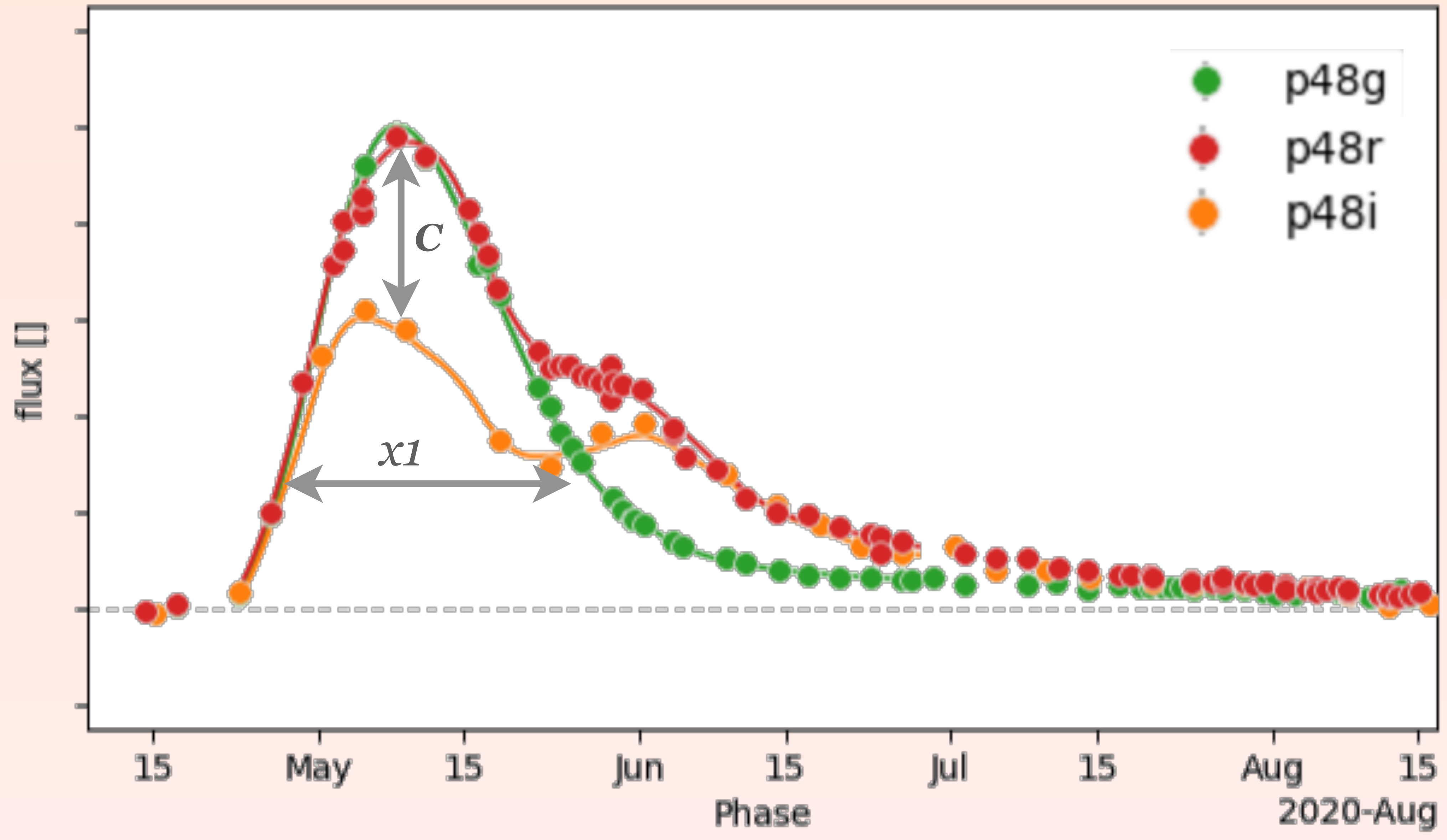

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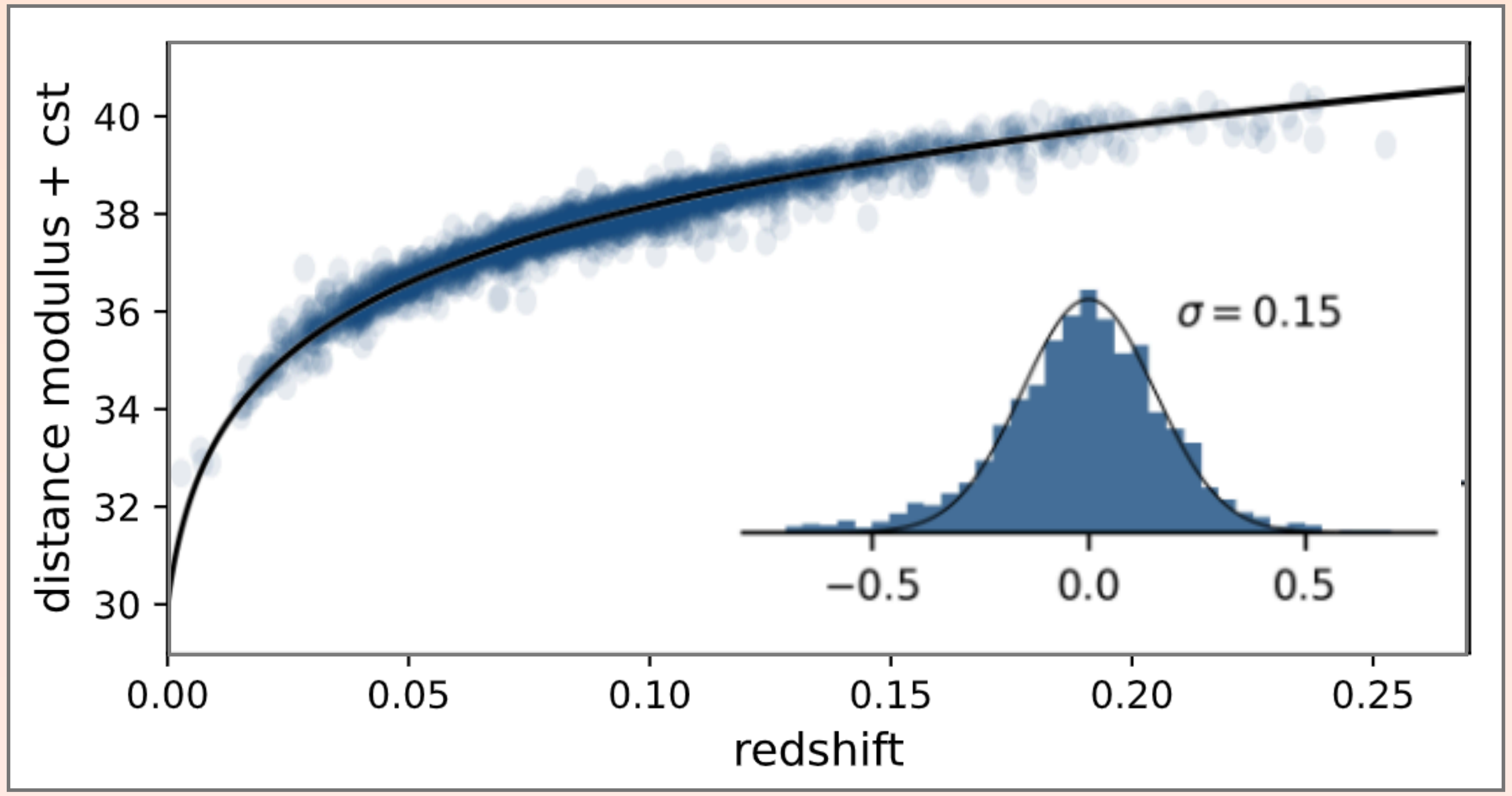

Hubble Diagram photometric standardisation
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SNe Ia dispersion :

$\sigma_{corr} = \cancel{0.40} = 0.15$

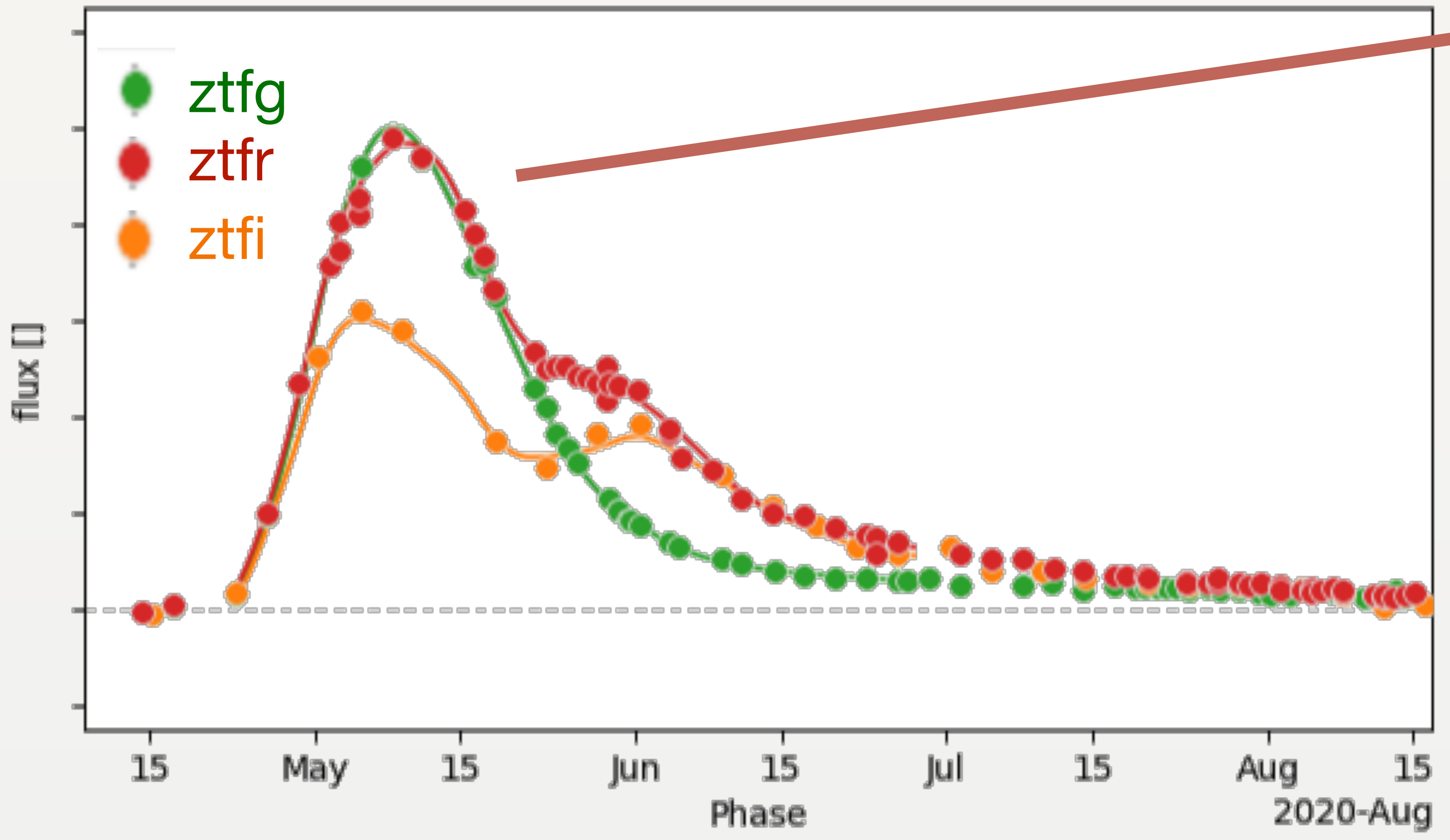
with Photometric standardisation

Problem : Reducing the 0.15 mag dispersion

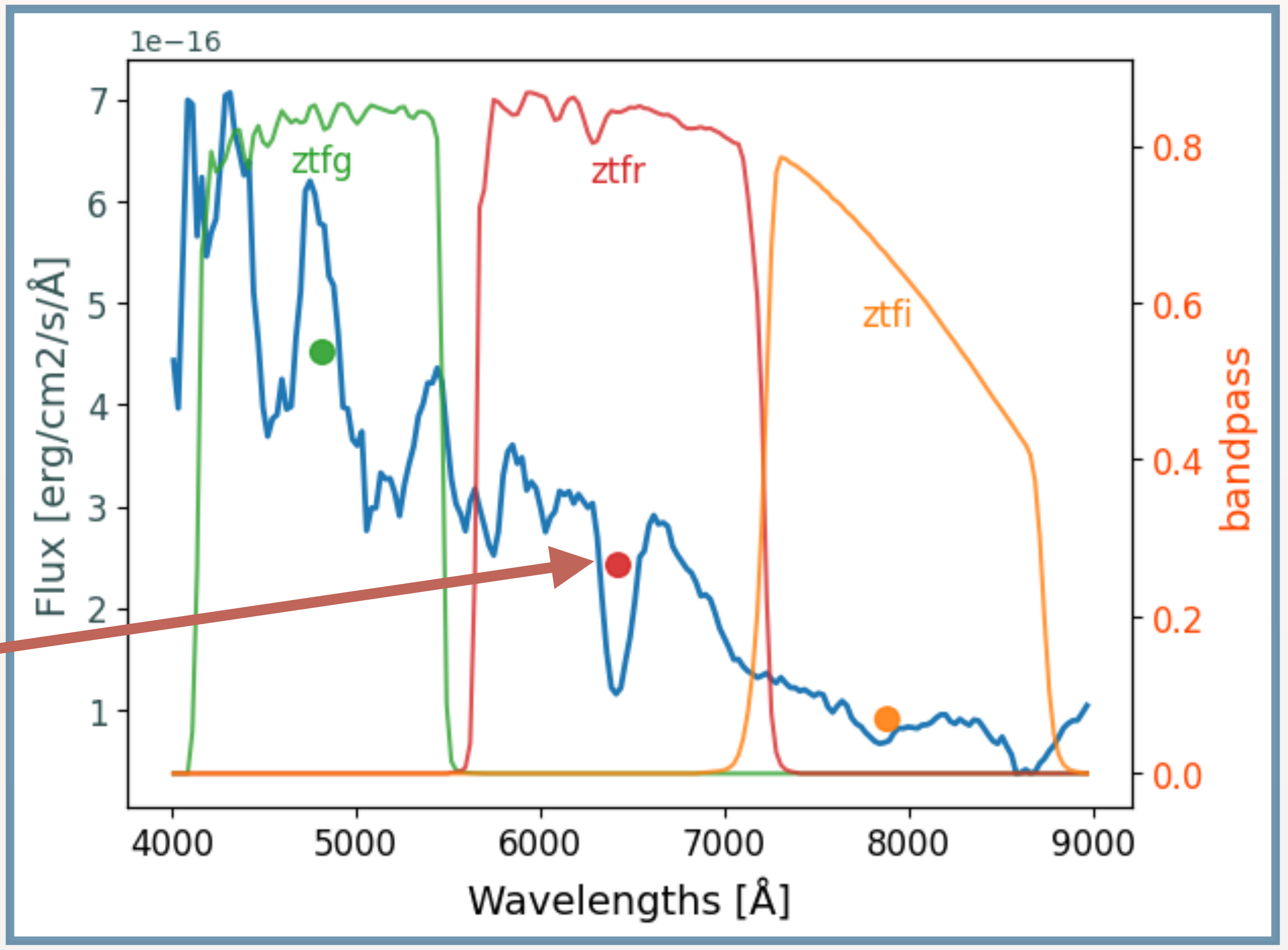
SN Ia standardisation

Problem : Reducing the 0.15 mag dispersion

A lightcurve datapoint corresponds to the spectrum integrated in the bandpass



Lightcurves of ZTF20abxzrqw
In ztf-g, ztf-r, ztf-i filters



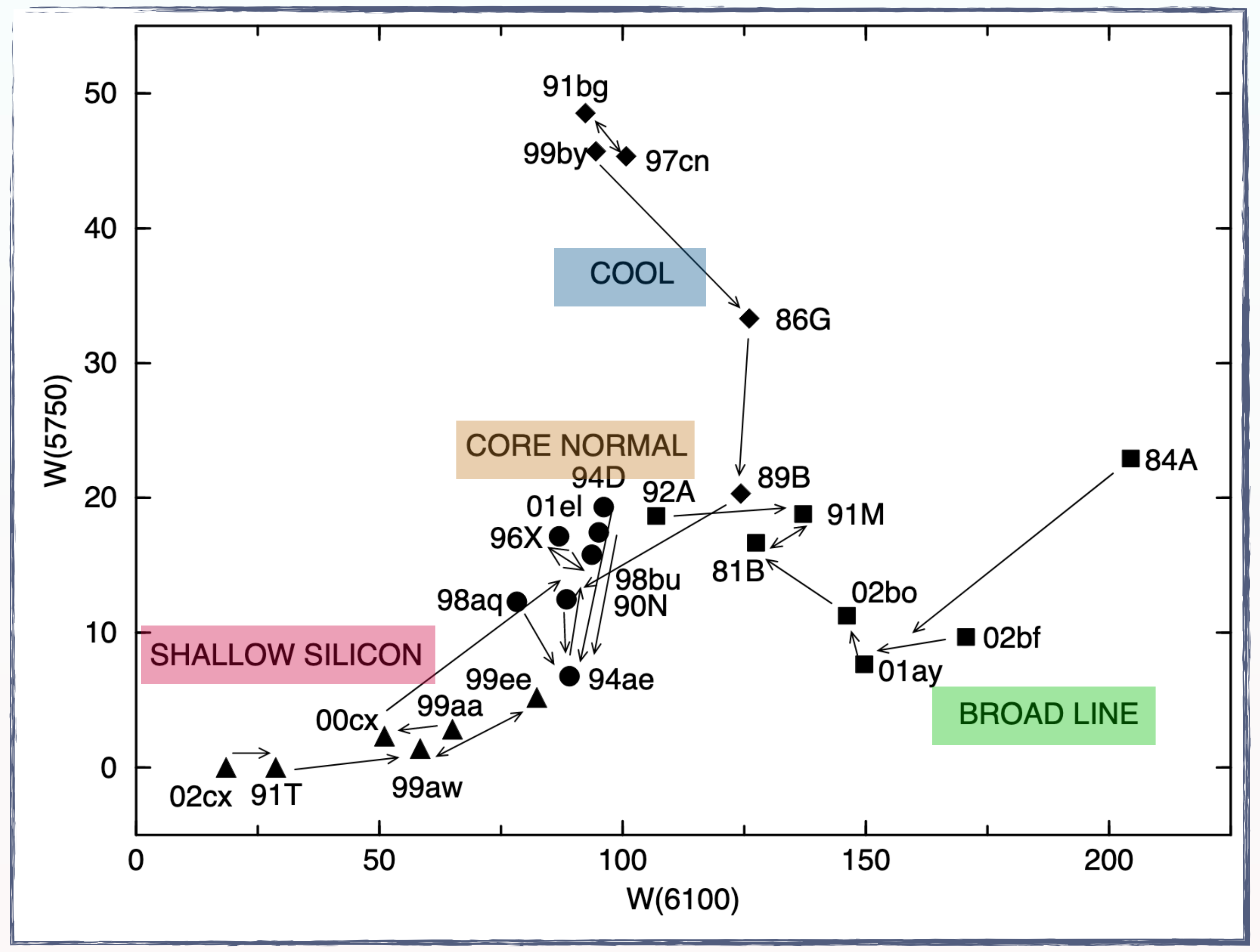
Synthetic photometry in ZTF filters
ZTF20abxzrqw at phase +1.29

- *Loose the spectral information*
- *Integrate at obs-frame*

—> New standardisation of distance modulus, using spectral information?

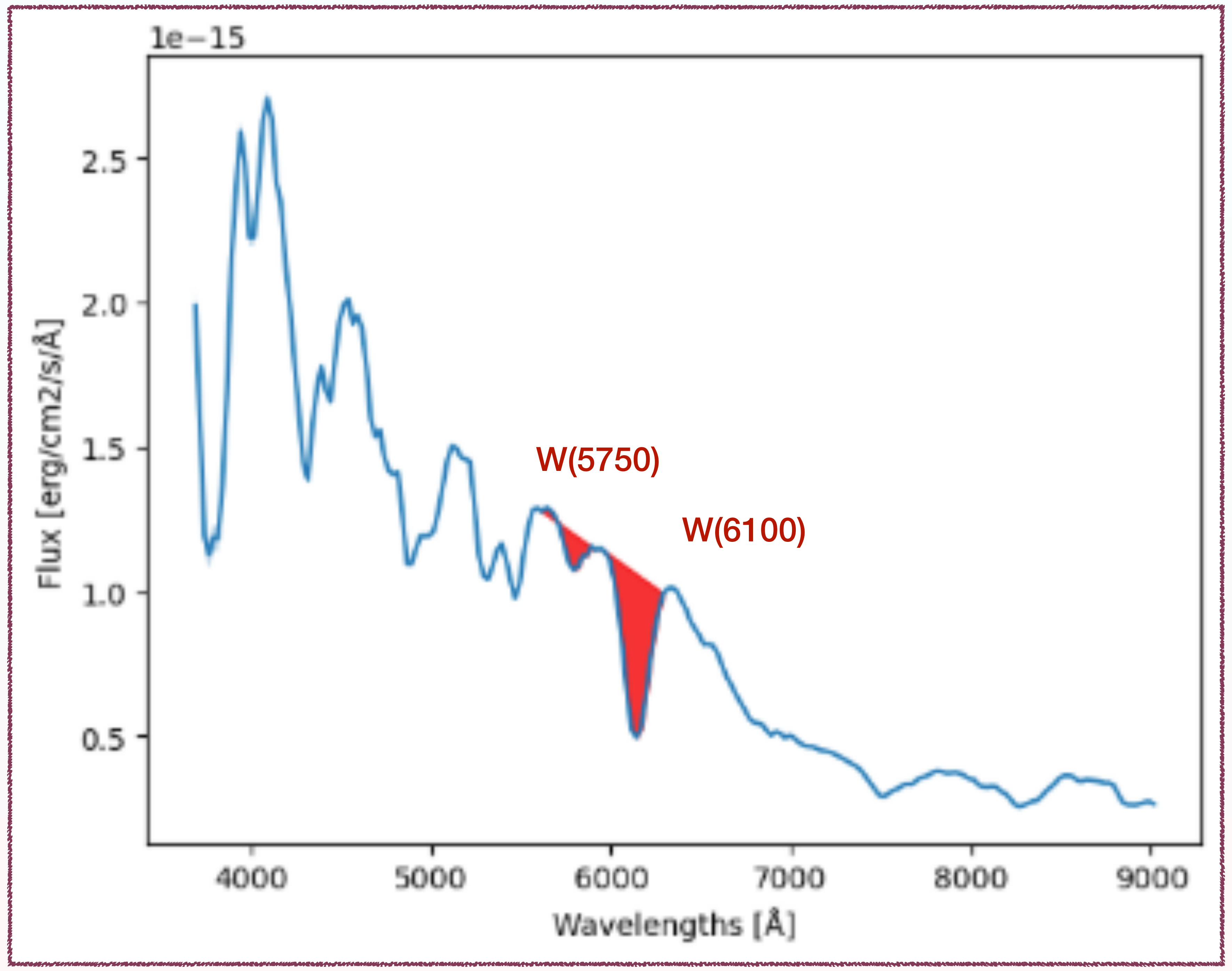
Branch classification

Branch 2006



Core Normal (CN)
Broad-Line (BL)
Cool (CL)
Shallow-Silicon (SS)

2 dimensions to explain the SN Ia diversity



- Equivalent width W

—> New standardisation of distance modulus, using spectral information?

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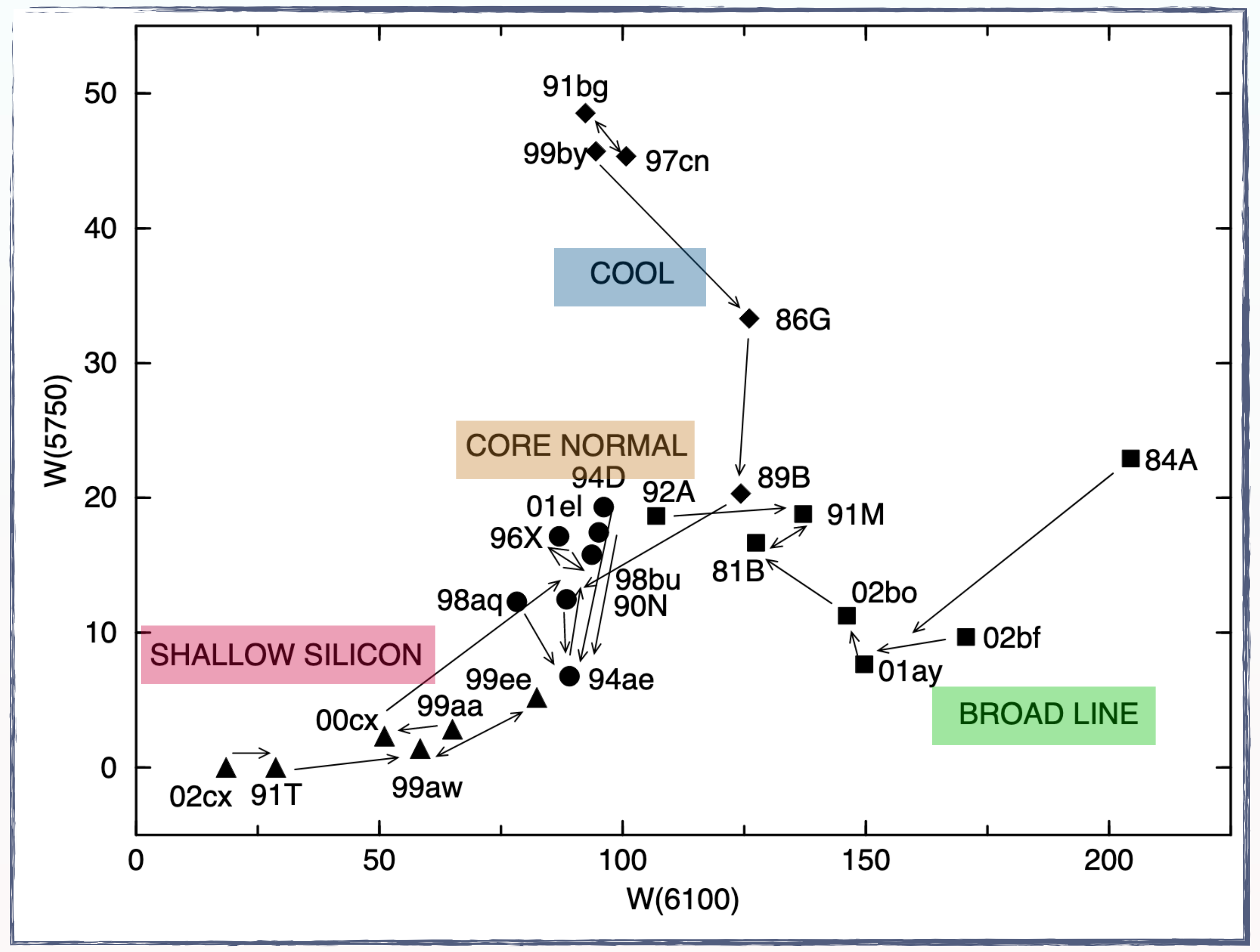

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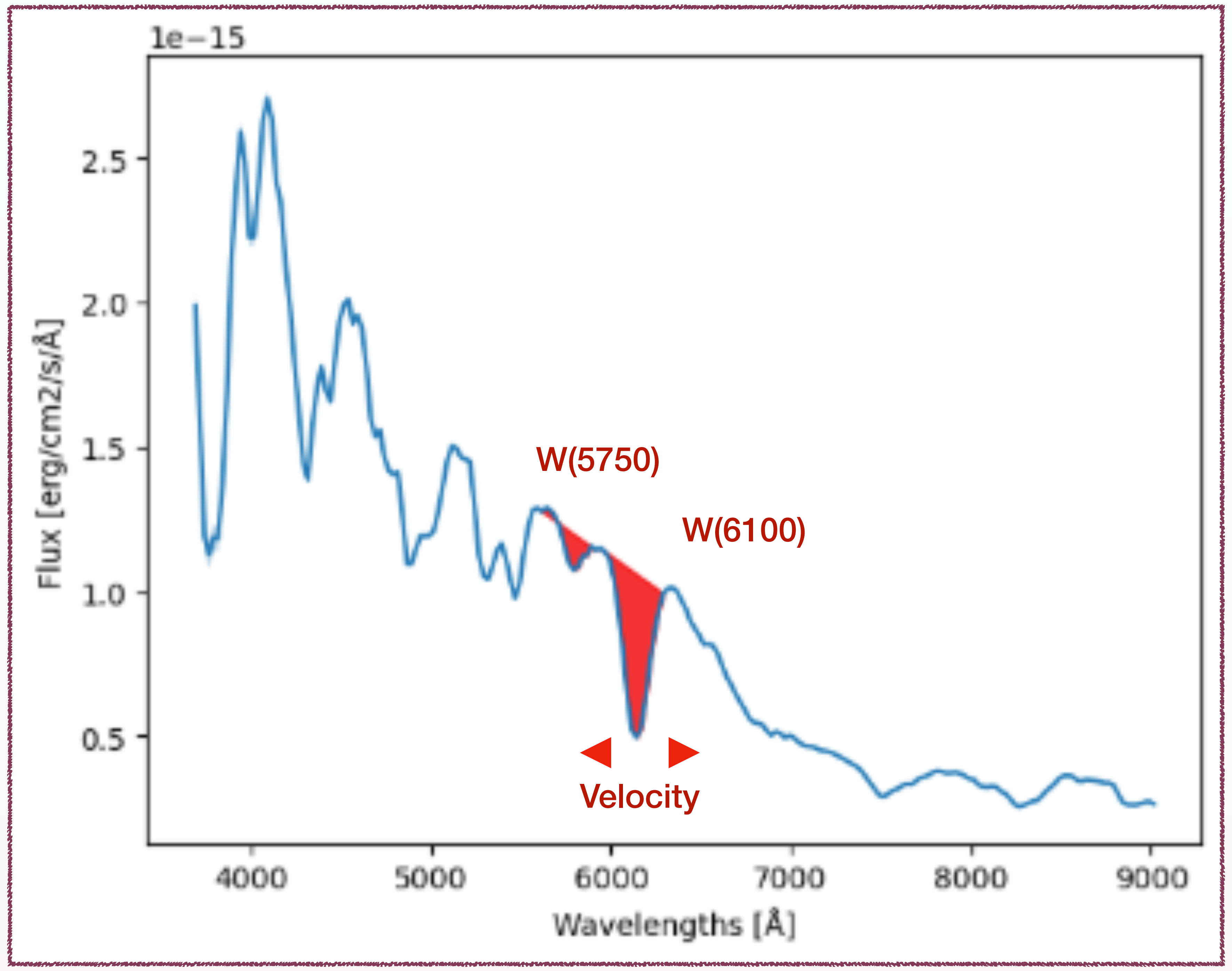
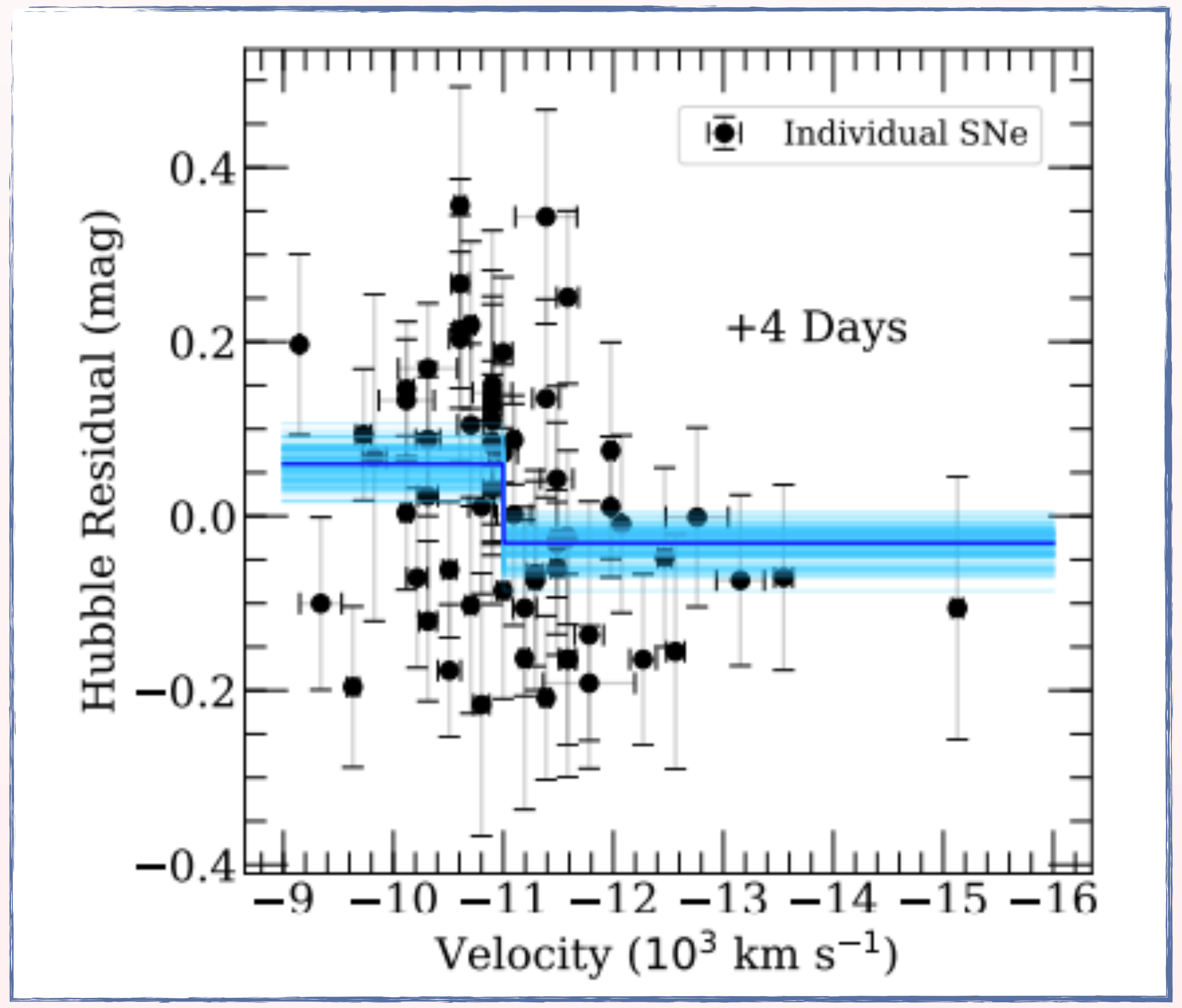


Si II velocity

Siebert 2020



Normal / High-Velocity (N / HV)
called velocity-HR effect

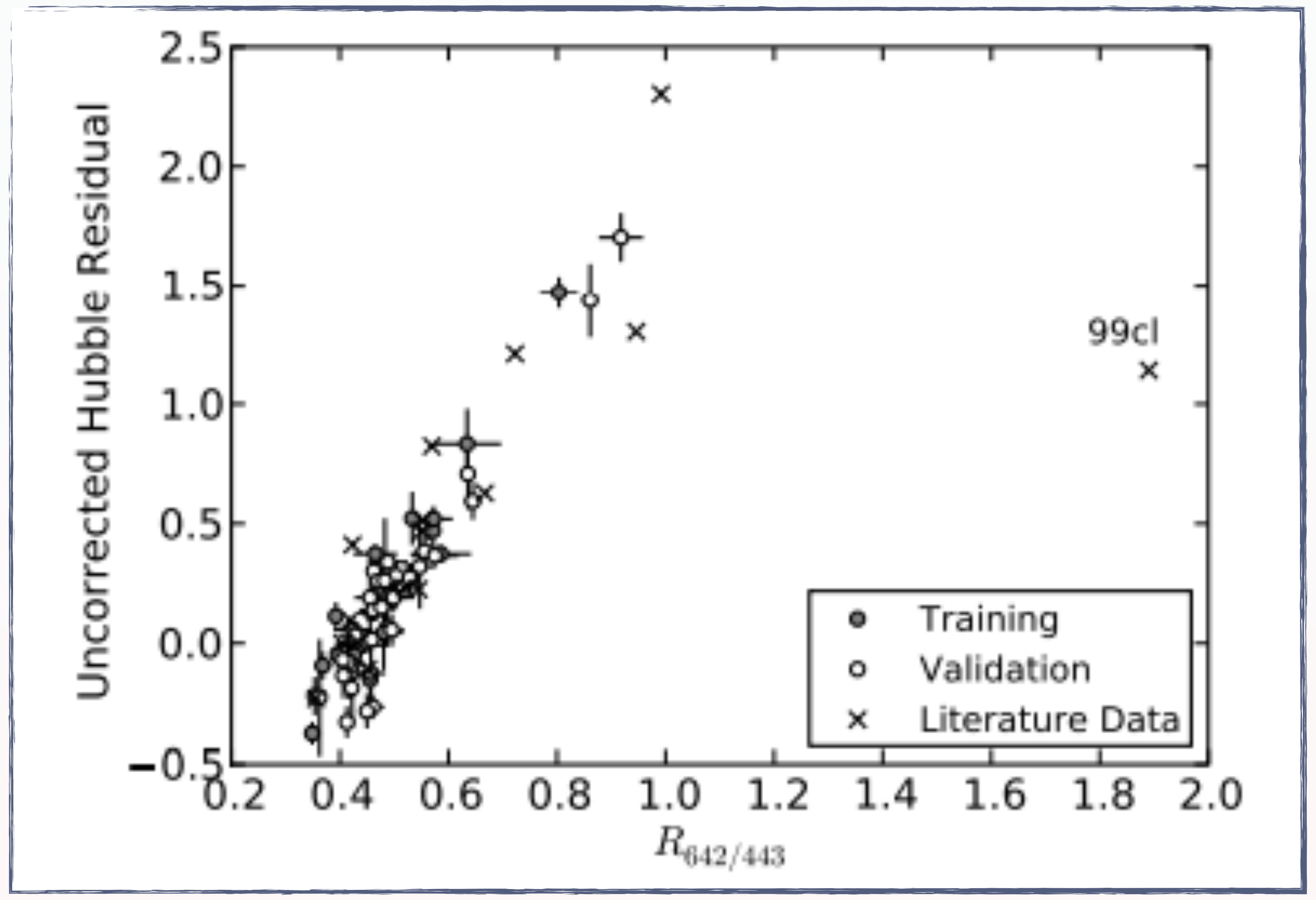
Wang 2009 (158 SNe)
Foley&Kasen 2010 (121 SNe)
Siebert 2020 (700 SNe)

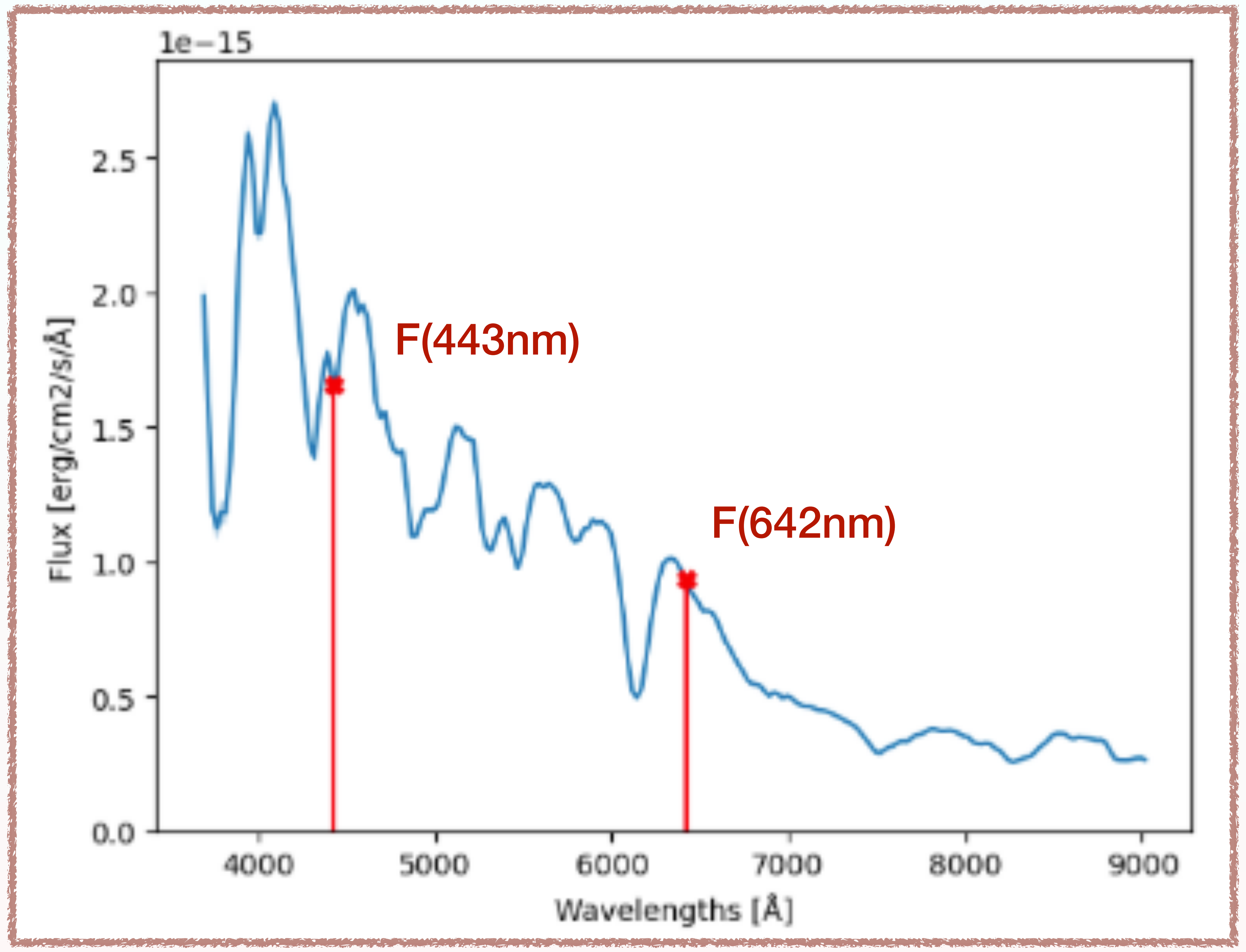
- Equivalent width W
- Line velocity

—> New standardisation of distance modulus, using spectral information?

Flux ratios

Bailey 2009





Developed on 58 SNe between +/-2.5 days :
Allows to decrease from to 0.118mag
when combined with color

Significance is hard to gauge given
the sample size (Blondin 2012)

- Equivalent width W
- Line velocity
- Flux ratios R

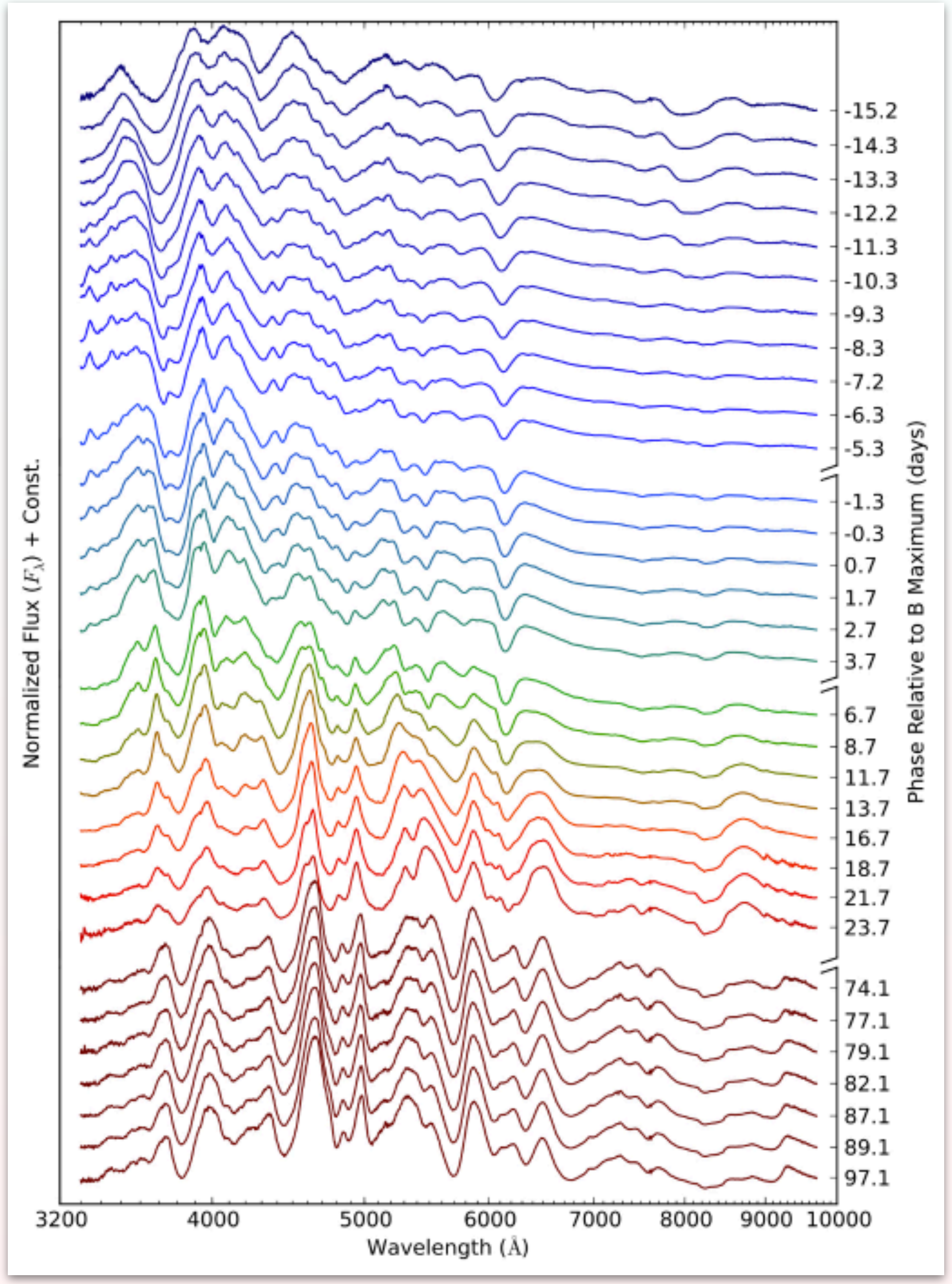
—> New standardisation of distance modulus, using spectral information?

Nearby Supernova Factory

2004-2014

- IFS : optical 3200-10000A, R=2000
- Temporal follow-up, every 3 days
- spectrophotometry : follow-up to remove sky extinction
- 427 SNe Ia : 3387 spectra
- Allows to compute stronger spectral analysis for standardisation

Located on the Mauna Kea mountain in Hawaii

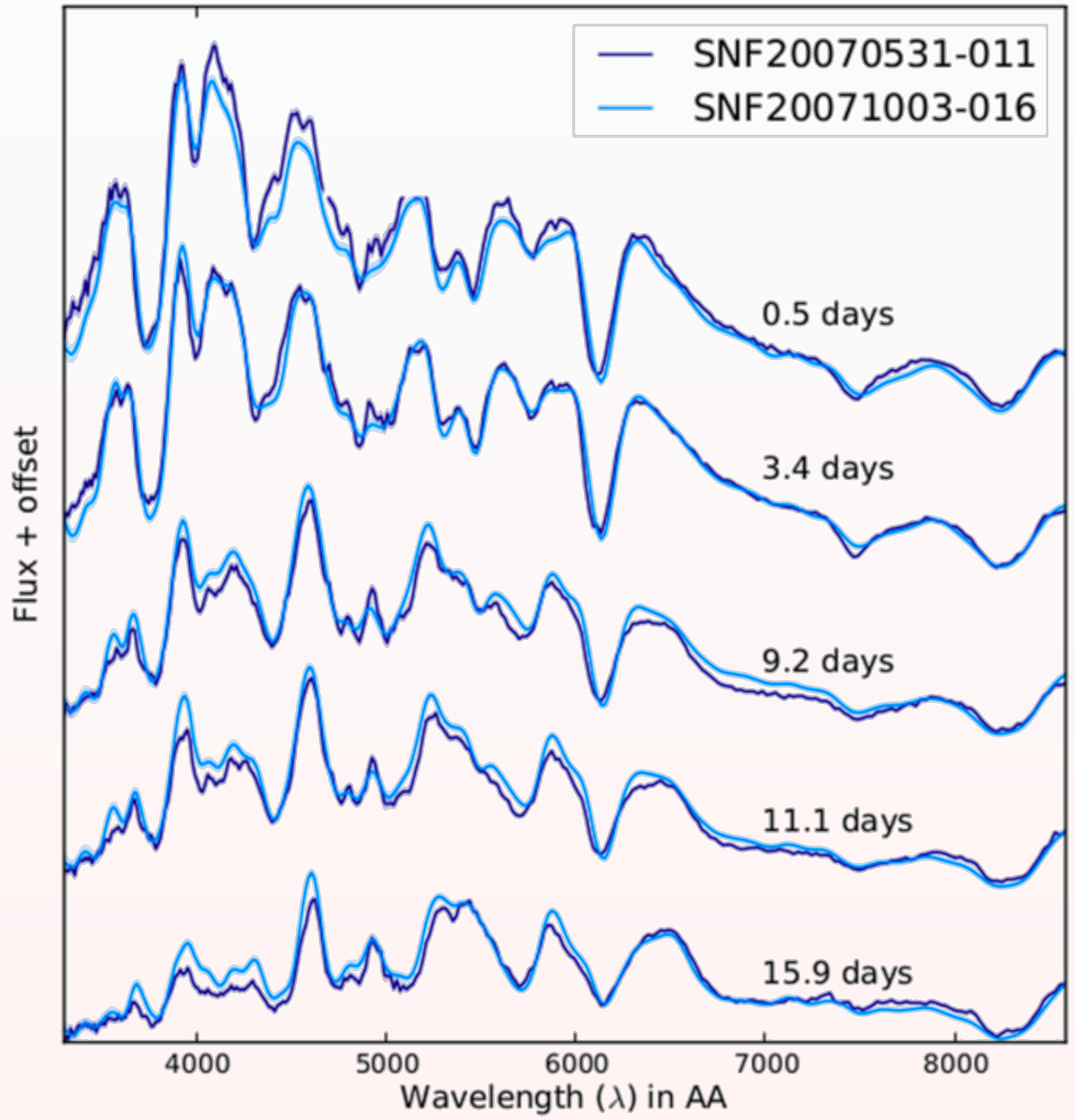


Time series of SN2011fe between **-15** to **+100** days
Credit: Pereira et al. 2013

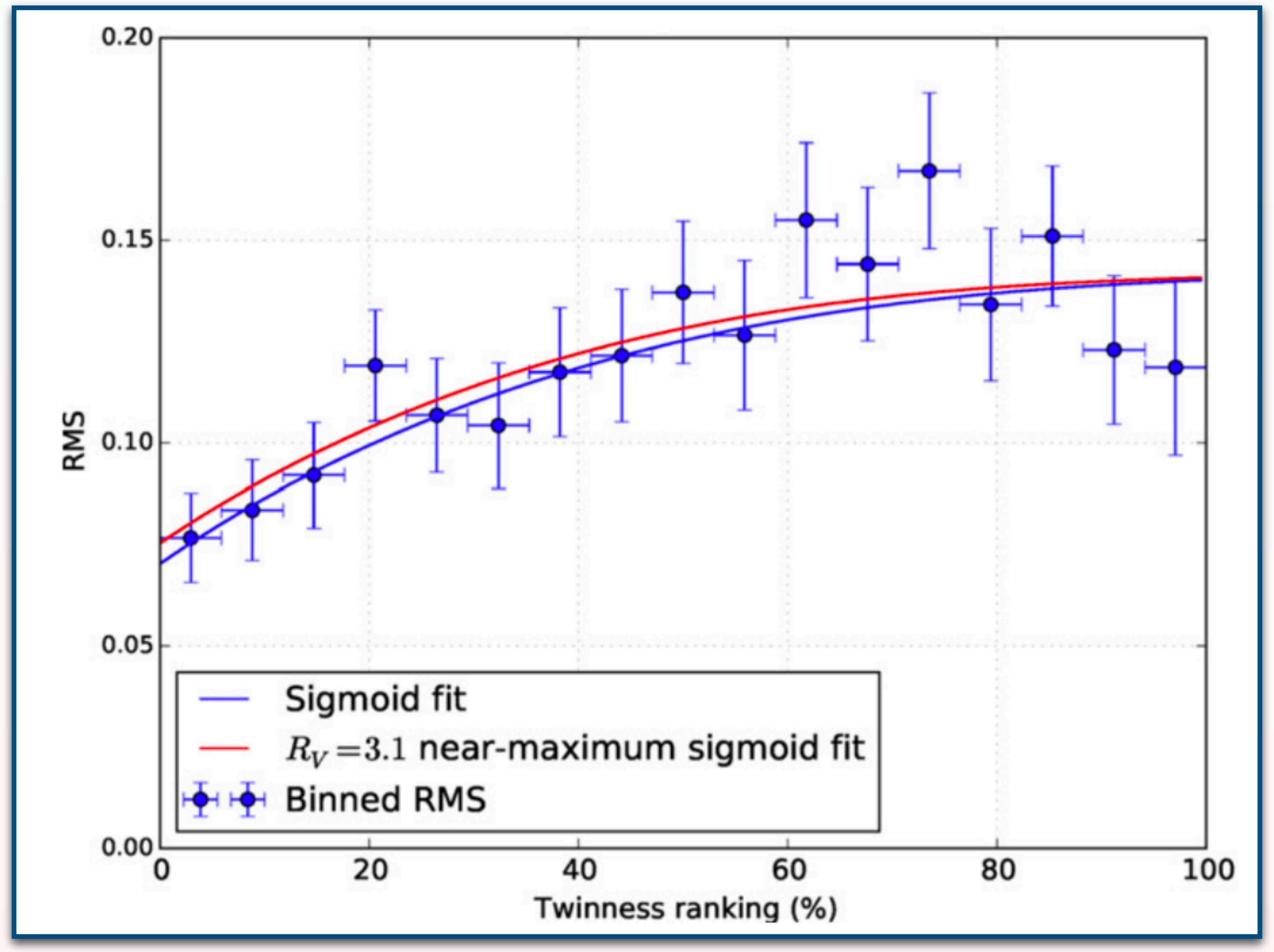
SN Ia spectral diversity

Initial discovery :

Twins - Fakhouri 2015



Spectral time-series of two 'Twins' SNe
Credit : Fakhouri et al. 2015



Luminosity RMS for different 'twinness' bins
Credit : Fakhouri et al. 2015

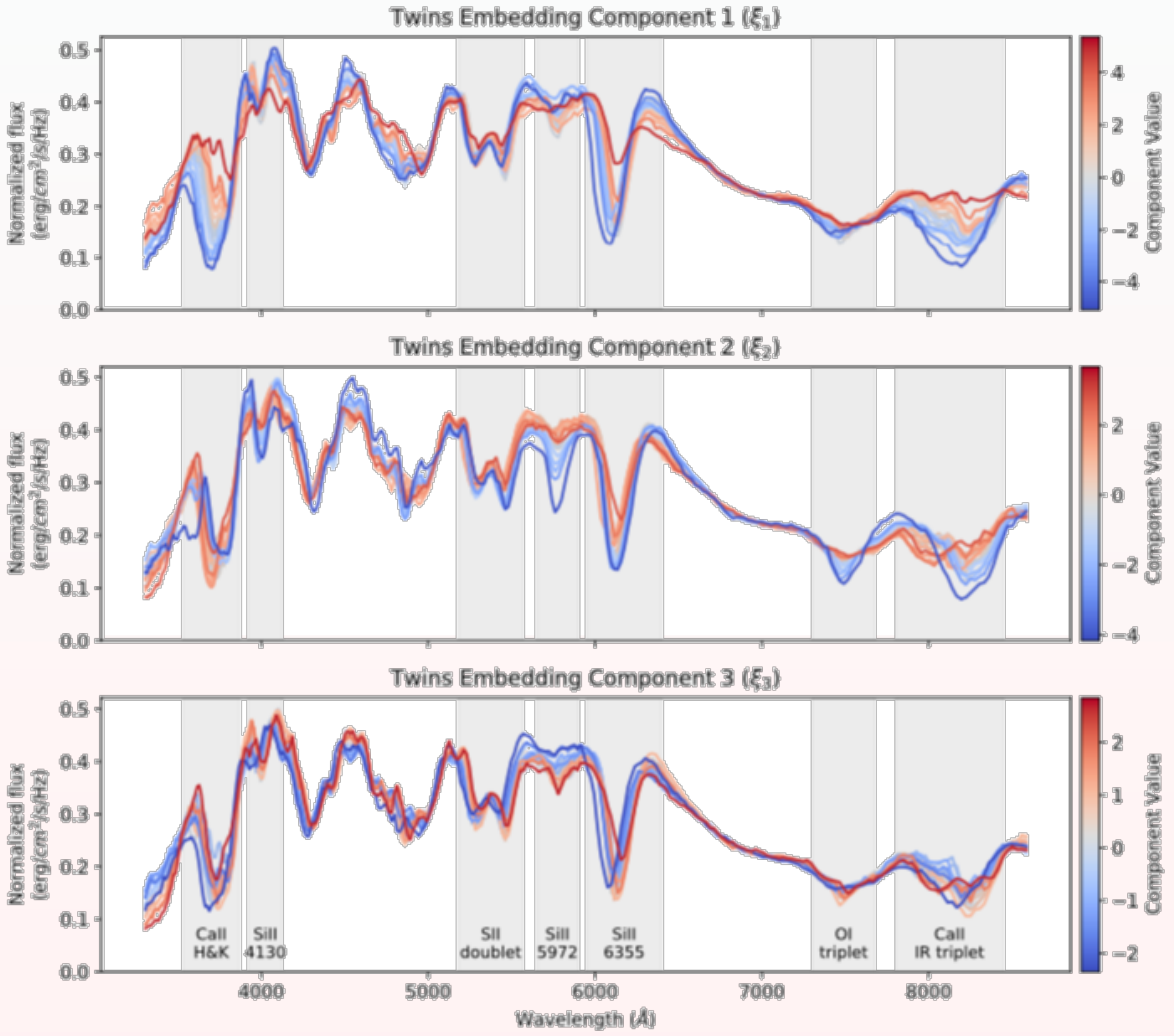
—> magnitude dispersion is smaller for the lowest 'twinness' parameters (similar time-series)

—> One spectrum at peak is sufficient to have the variation information

Spectro-photometric standardisation

Full method :

Twins Embedding - Boone 2021



Twins Embedding components variation effects on spectra. *Credit : Boone et al. 2021*

-> Parametrise the spectral variation at phase=0

—> New standardisation of SNe Ia, using spectral information

Before standardisation :

$\sigma_{mag} = 0.40\text{mag}$

Photometry :

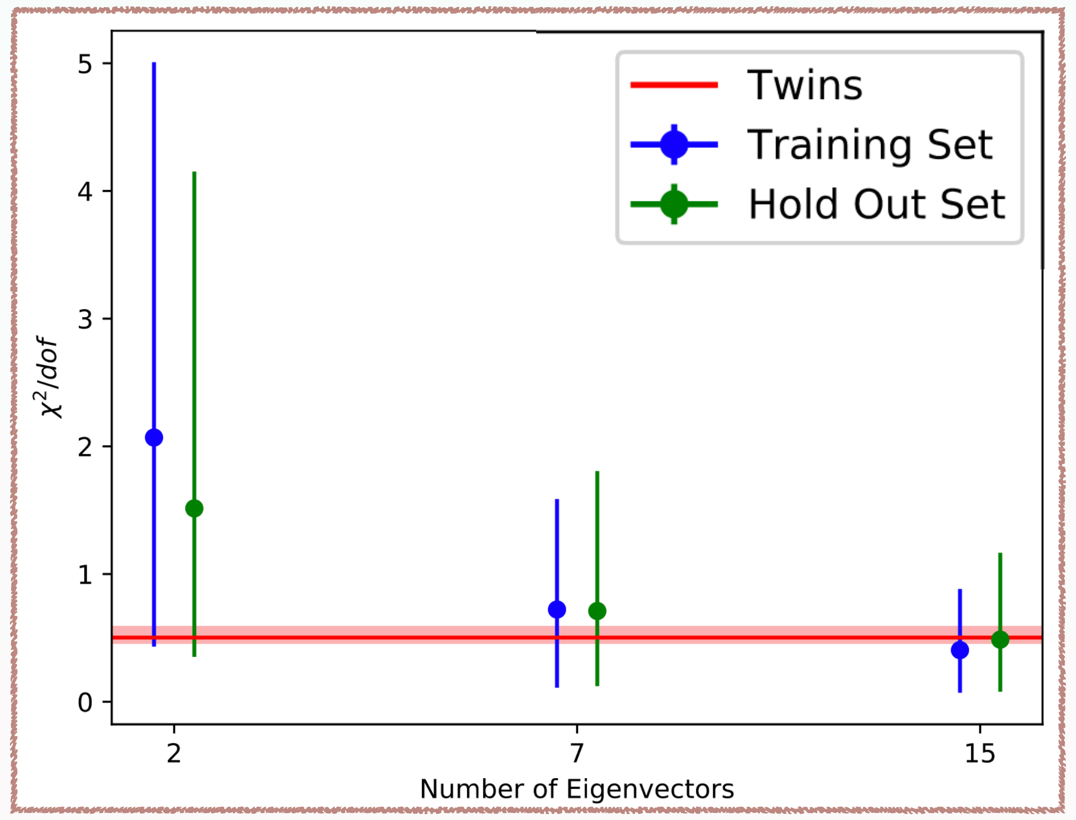
$\sigma_{mag} = 0.15\text{mag}$

With SNFactory

Twins Embedding :

$\sigma_{mag} = 0.07\text{mag}$

Twins Embedding standardisation



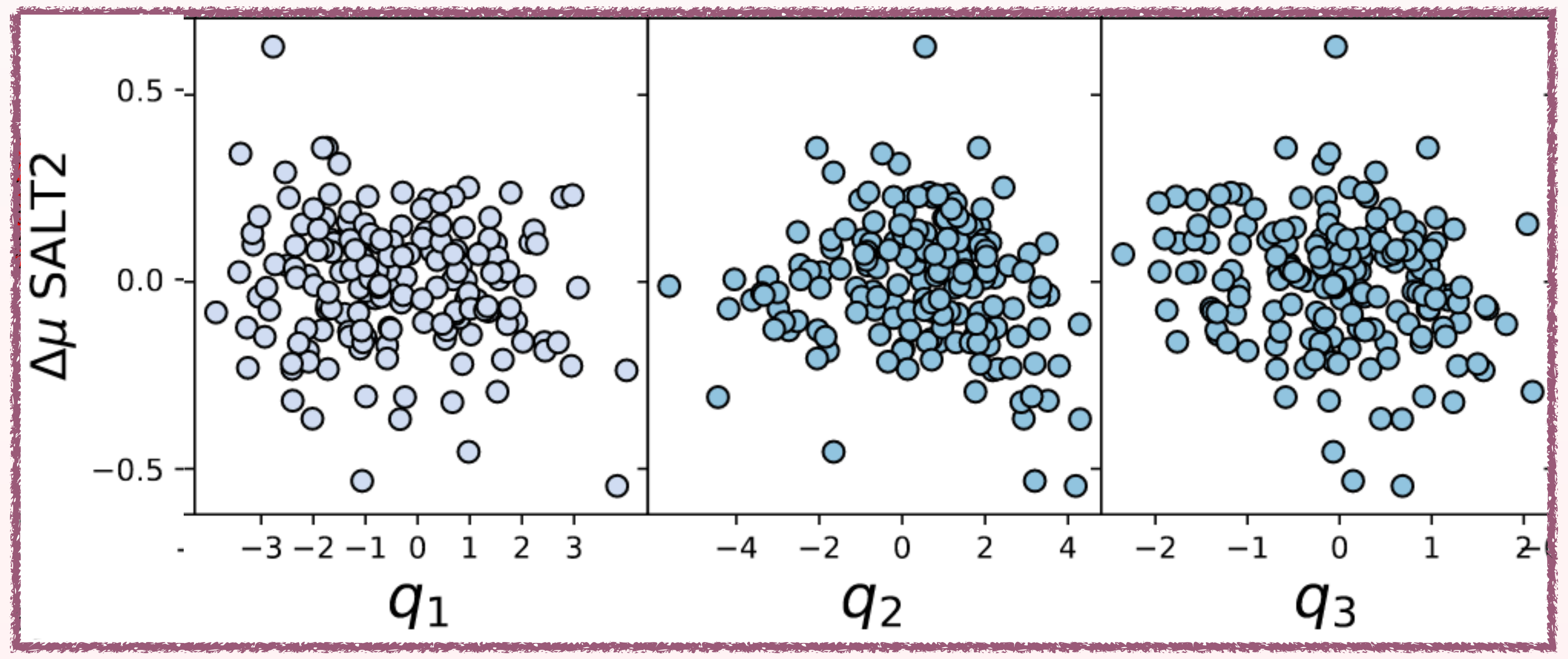
15-component linear SNEMO model

New method:

- *non-linear parameterisation*
- *Linked to HR*
- *Based solely on spectra*

No filter issues

- *PSF modelling: CCD calibration, chromaticity not taken into account*
- *Hard to characterise the filters: therefore hard to cross-calibrate the filters between dataset*



SUGAR is not correlated to HR

Need 4x less SNe

Photometry :

$$\sigma_{mag} = 0.15\text{mag}$$

With SNFactory

Twins Embedding :

$$\sigma_{mag} = 0.07\text{mag}$$

No template model

SNFactory : ~200 SNe

↓

ZTF : ~800 SNe

ZTF DR2 - SEDmachine

Low-redshift z<0.15
Northern sky
3 filters : g, r, i
Limits in magnitude of ~20mag

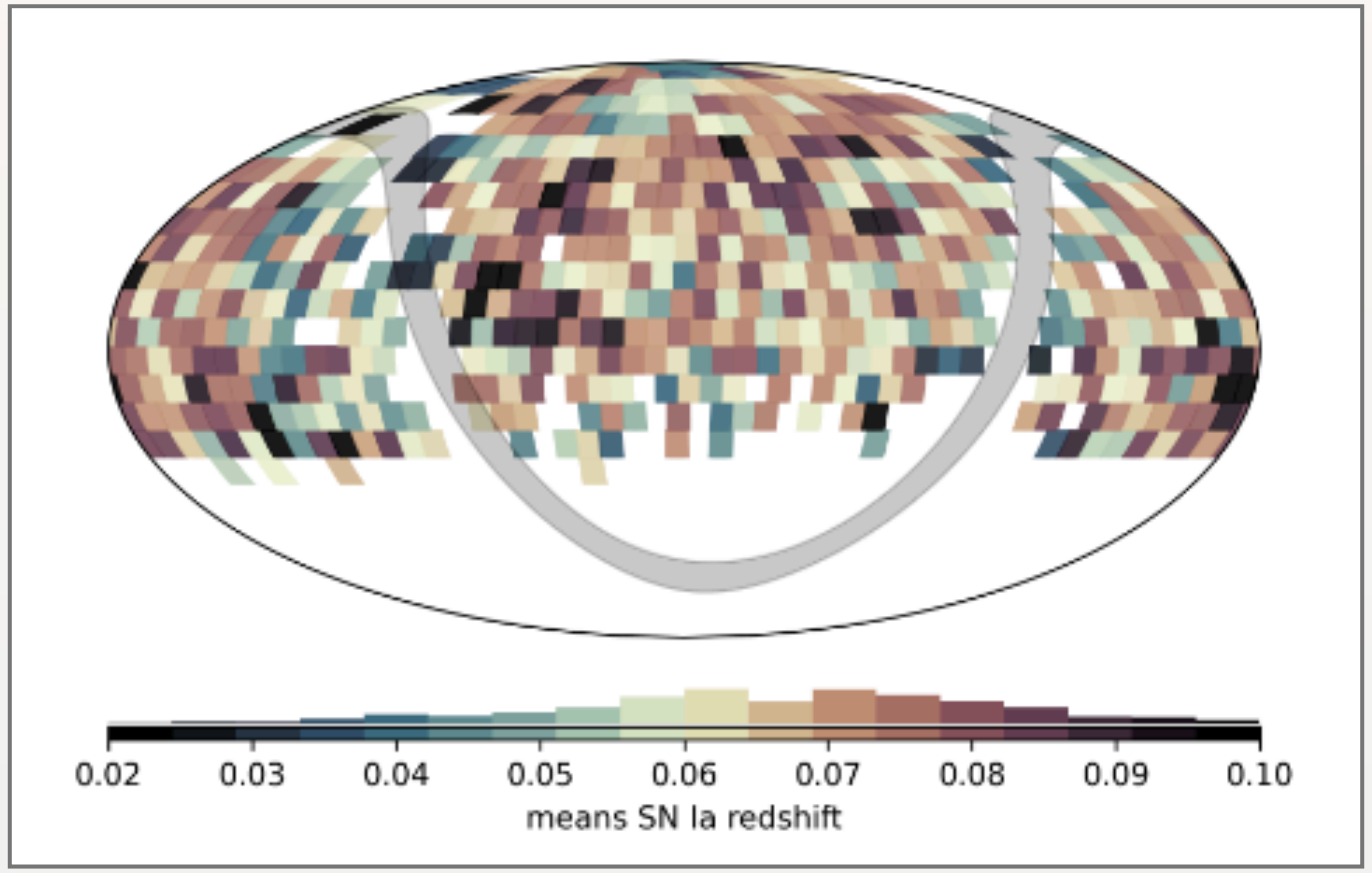
Two instruments :

- P48 camera
- P60 spectrograph

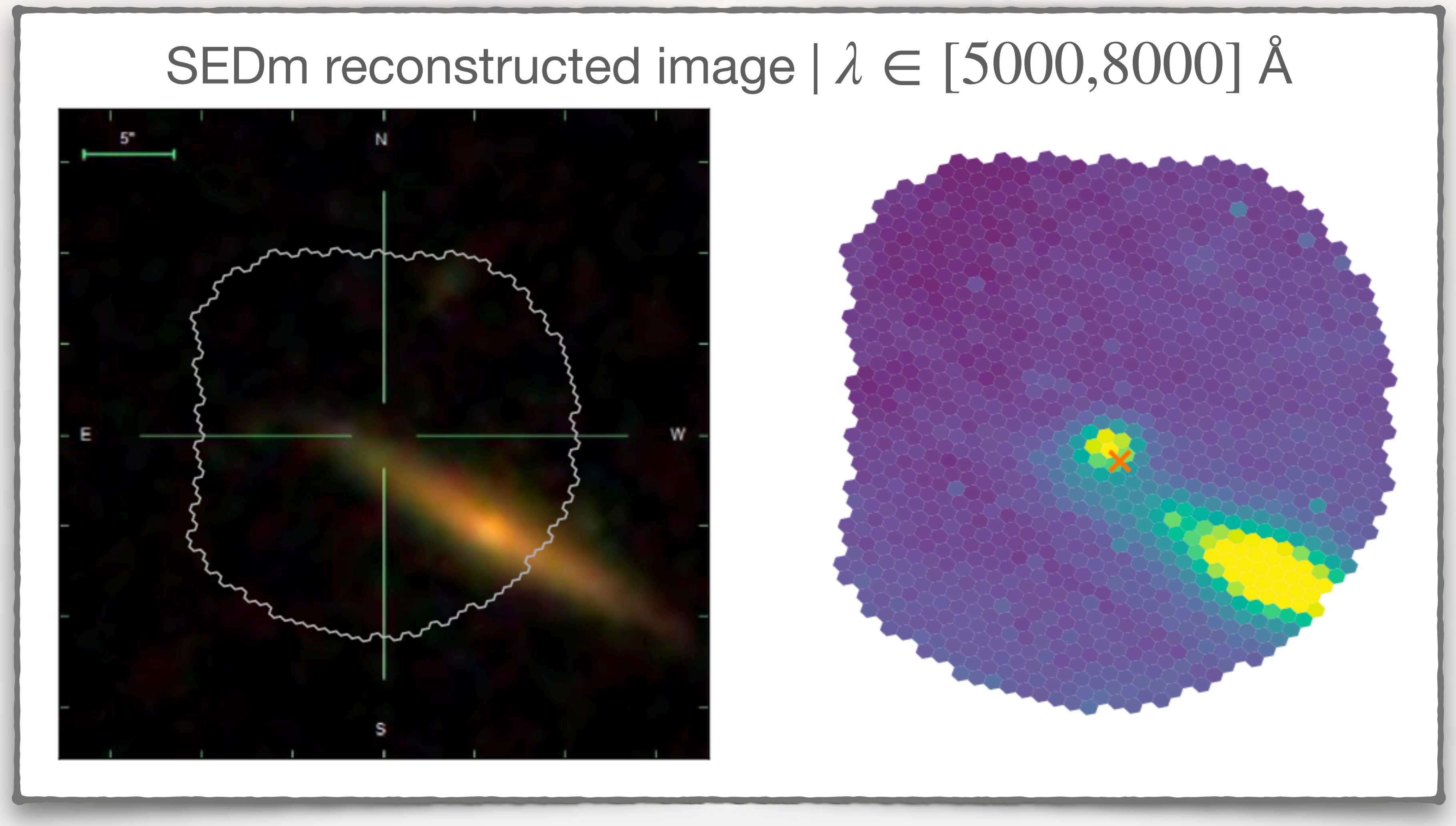
March 2018 to December 2020

o(3600) Supernovae Ia
o(4000) spectra

60% SNe Ia
spectra from the
SEDm



Sky map of **2663** redshifts of SNe Ia
Credit : in prep. ZTF "DR2" Data paper, Smith et al.



SEDm (P60)- Integral field Spectrograph
field of view of ZTF18abqlpgq
Credit : pysedm - Rigault, Neill

ZTF spectra flux-calibration

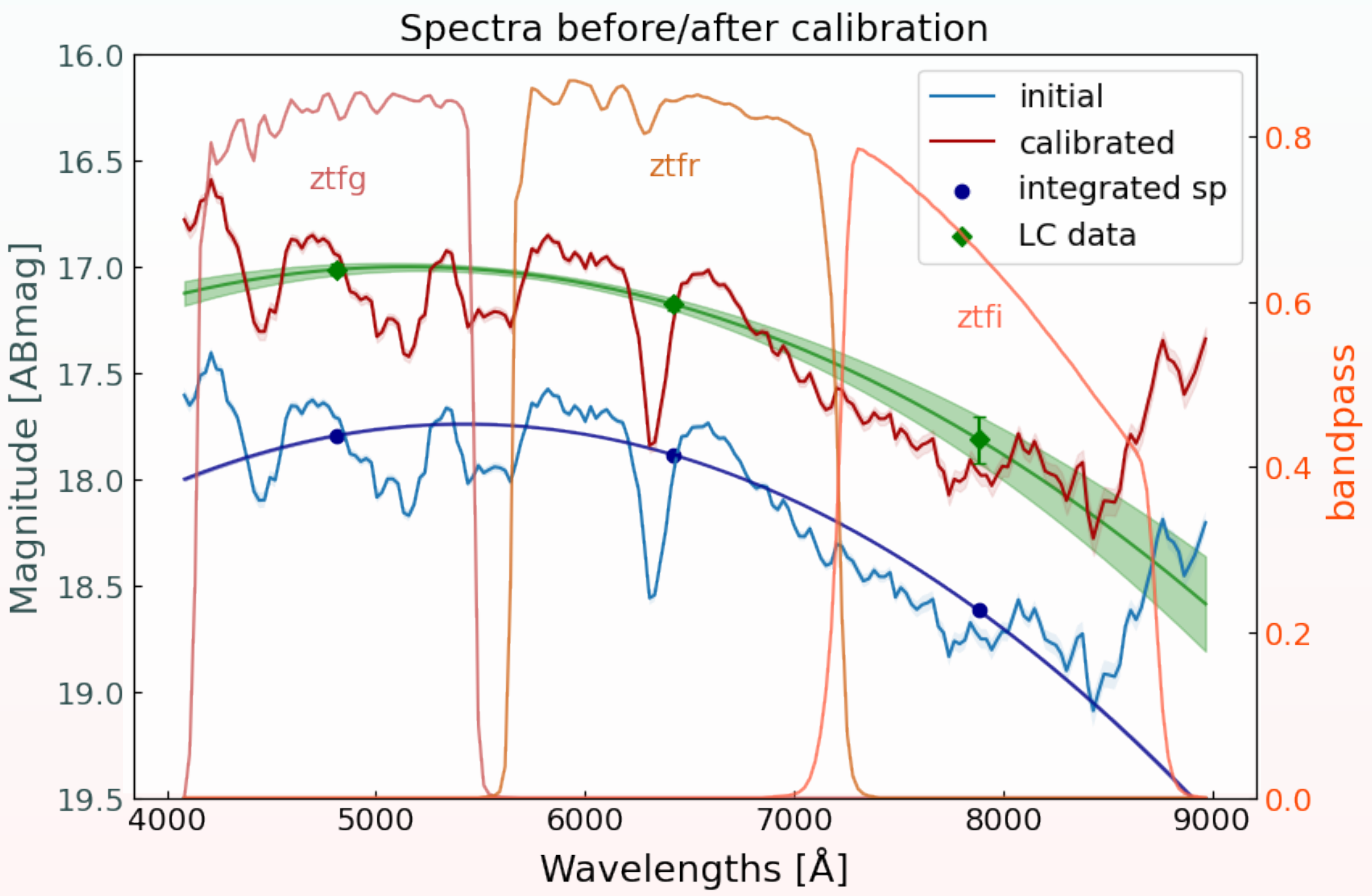
From DR2 : March 2018 to December 2020

Purpose : typing

Low resolution : $R = \dfrac{\lambda}{\Delta\lambda} \sim 100$

✓ Spectral extraction by pysedm (Rigault 2019)

✓ Correction of host galaxy by Hypergal (Lezmy 2022)



Located in Mount Palomar in California

—> 1607 flux-calibrated SNe Ia

The flux-calibrated sample will be published in Ganot et al. (in prep)

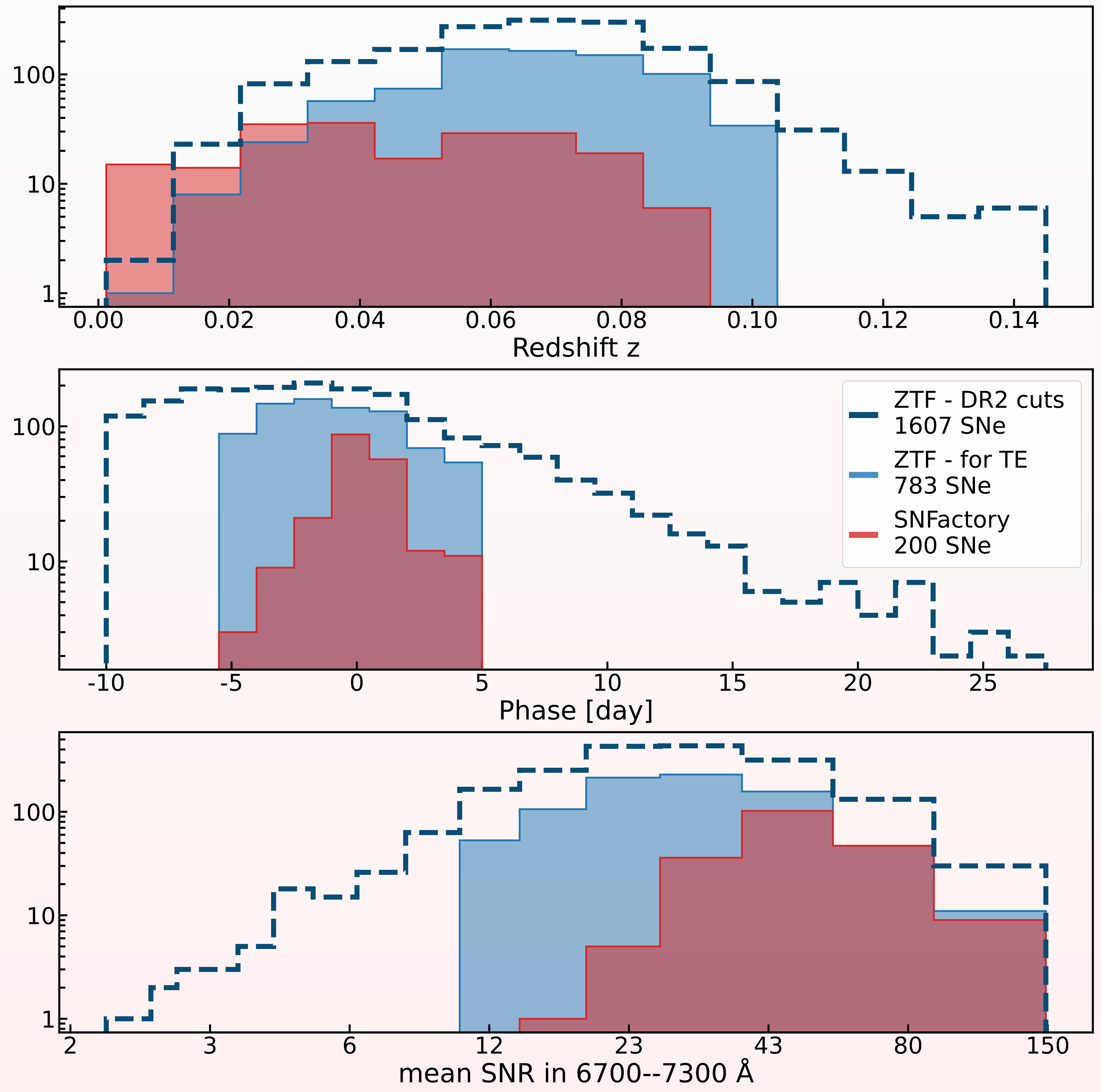
ZTF spectra sample for TE

✓ Flux calibration, precision of 0.07 mag

✓ Milky Way dust correction

✓ Shift spectra to z=0.05

—> 783 SNe Ia for TE application



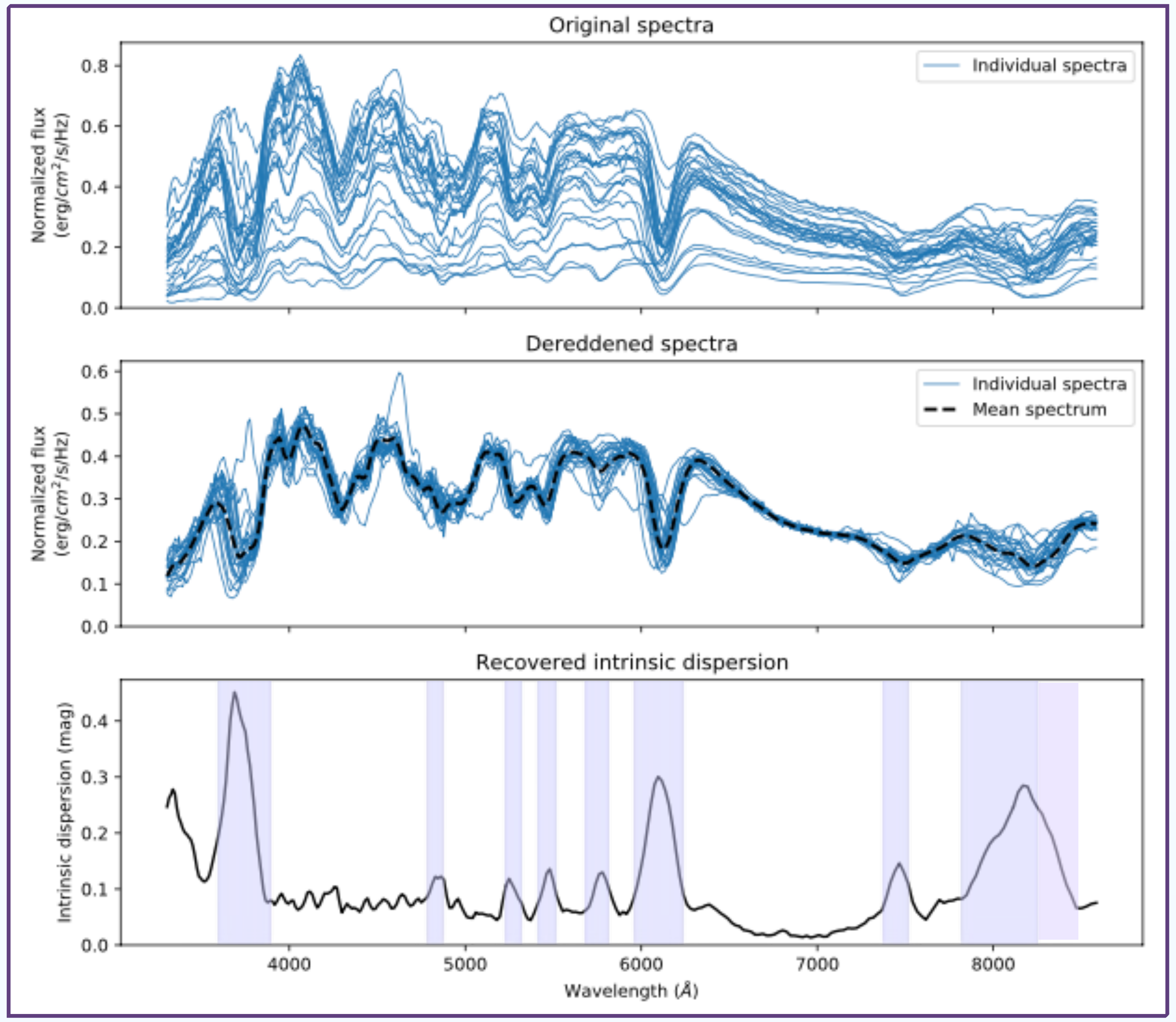
Cut	Interval	Quantity removed
Calibration quality		around 7%
z	<0.1	around 5%
phase	[-5,+5] days	**around 40%**
DR2 photo		around 7%

Twins Embedding - *Method*

3 steps

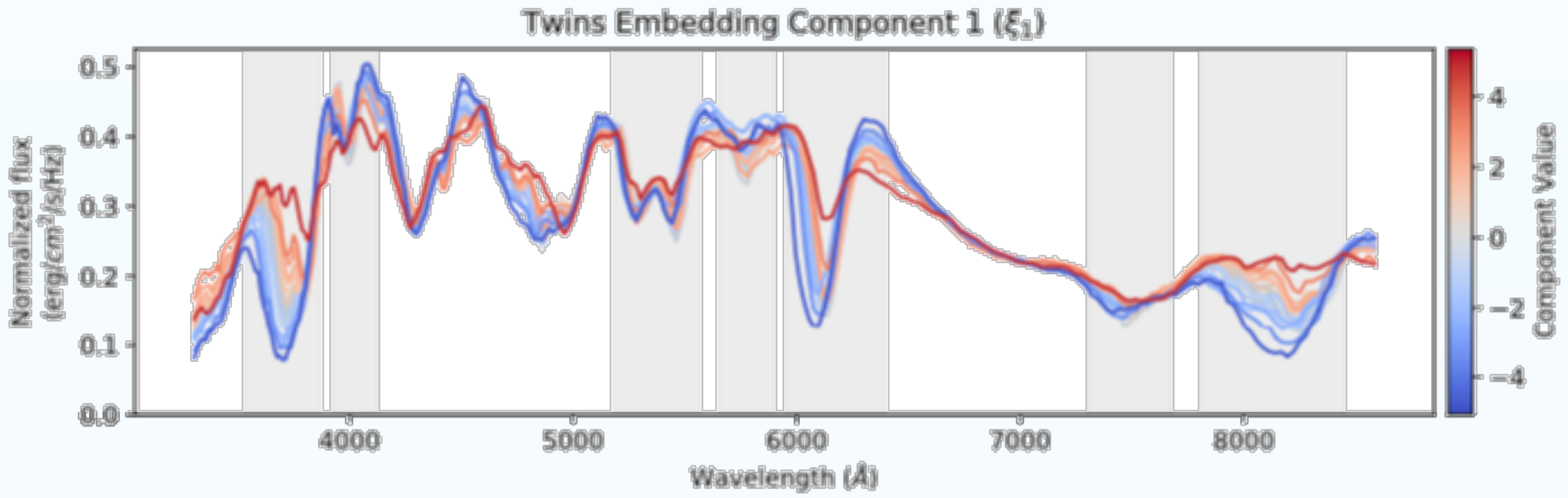
1. Shift spectra at phase=0
2. RBTL - fit one offset and a color outside the lines

only based on spectral data



SNFactory spectra before/after dereddening, and residuals intrinsic dispersion (std) *Credit : Boone et al. 2021*

3. Isomap : parameters reduction

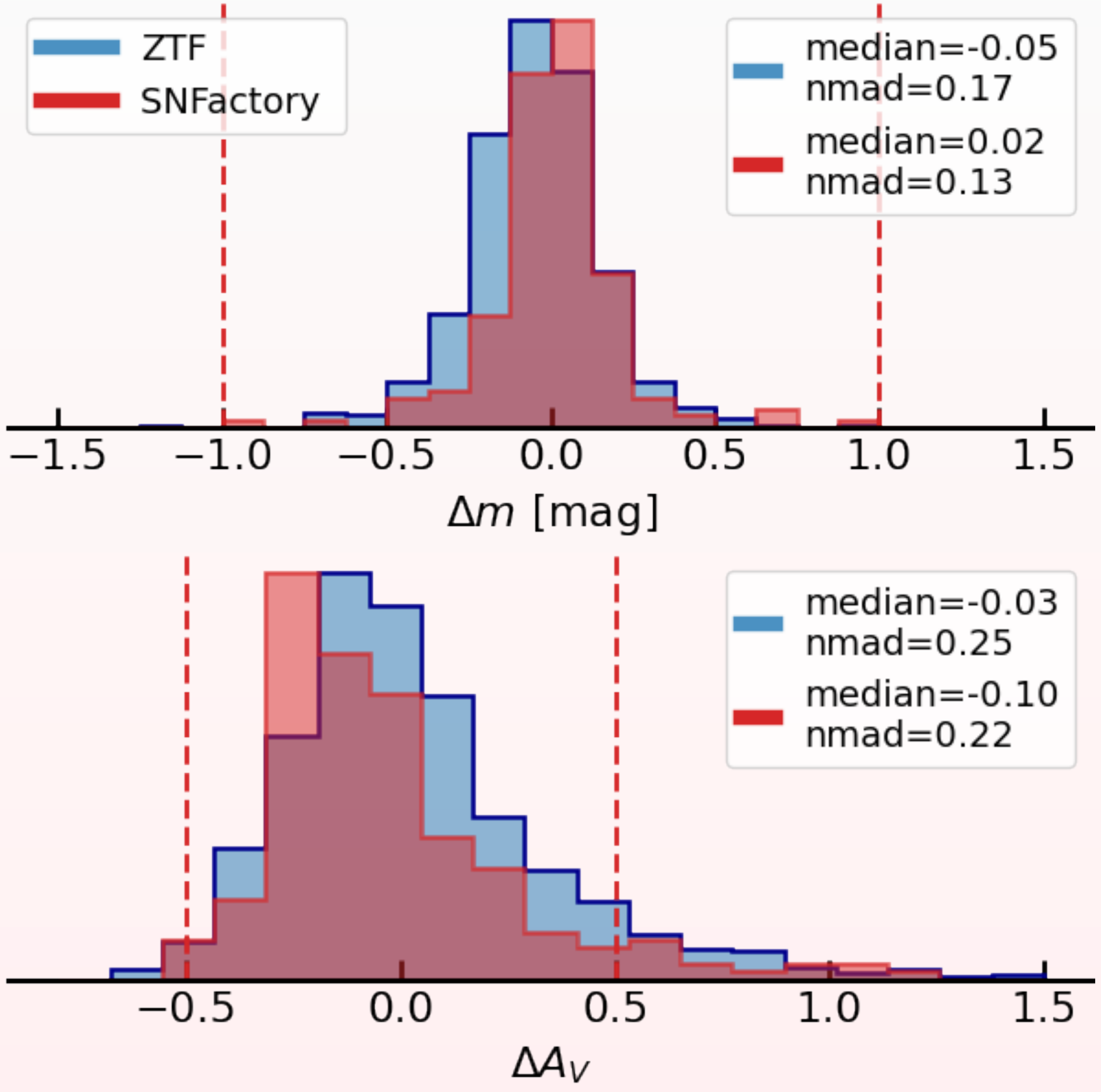


Twins Embedding components variation effects on spectra. *Credit : Boone et al. 2021*

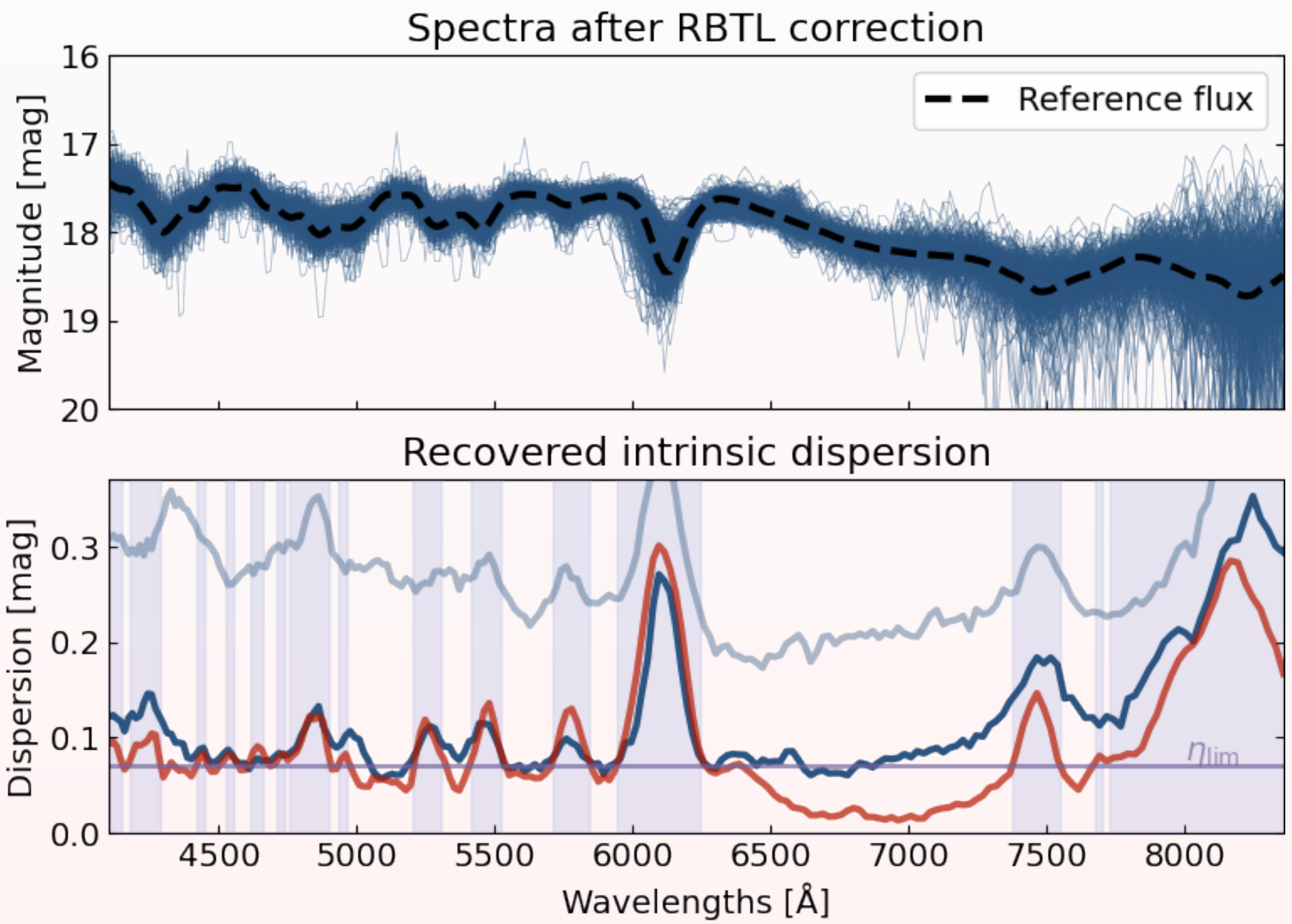
87% of the remaining variance is explained with 3 components

Twins Embedding - *Applied to ZTF*

1. **Shift spectra at phase=0**
2. **RBTL - fit one offset Δm_i *and a color* $\Delta A_{V,i}$ *outside the lines***



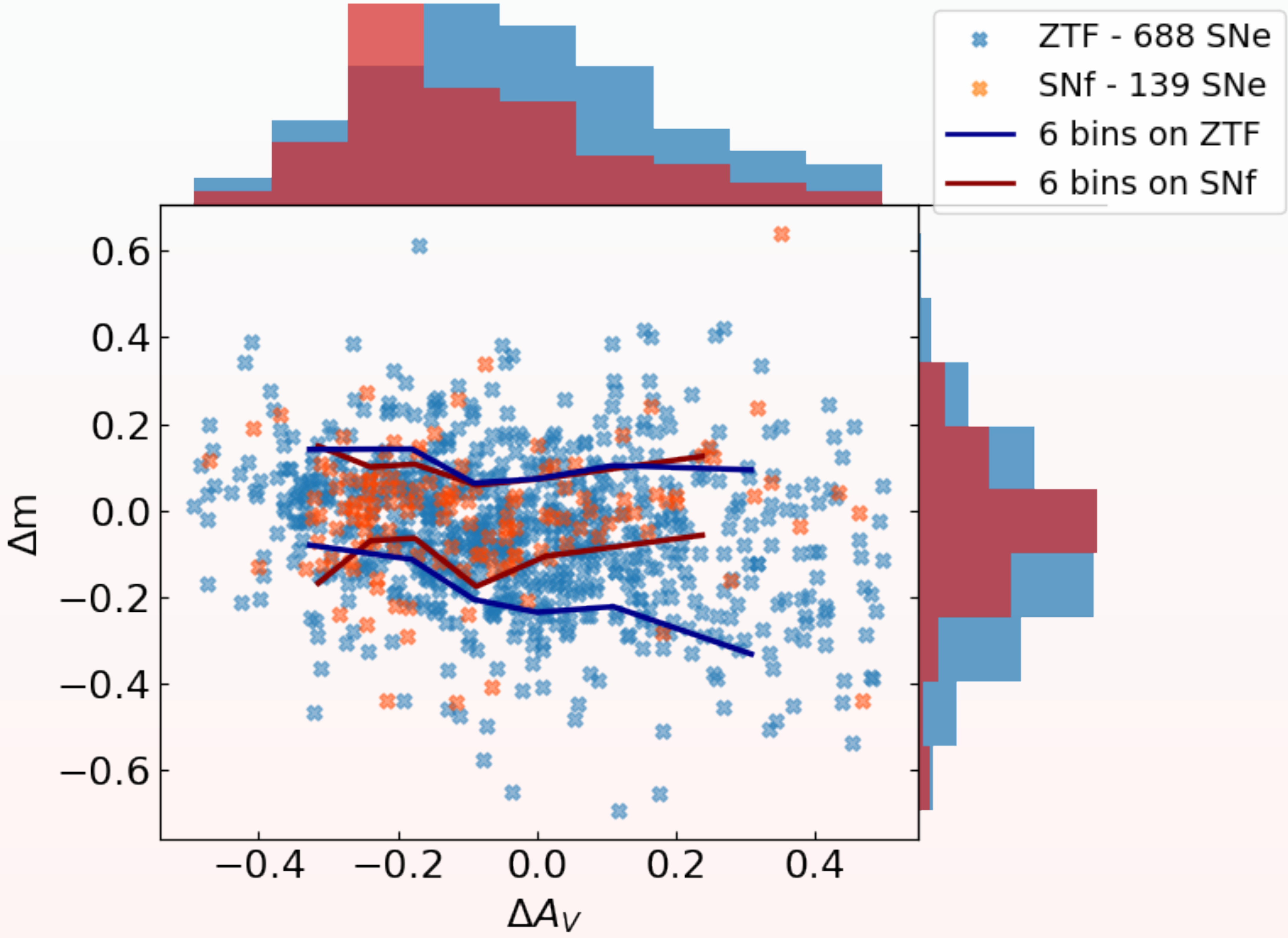
- More dispersion in Δm for ZTF
- More 'red' SNe in ZTF sample



783 **ZTF** SNe Ia RBTL spectral correction. Dispersion of the residuals, before/after correction compared with 200 SNe of **SNf**

Twins Embedding - *Standardisation in color*

- Remaining correlation between RBTL parameters for ZTF

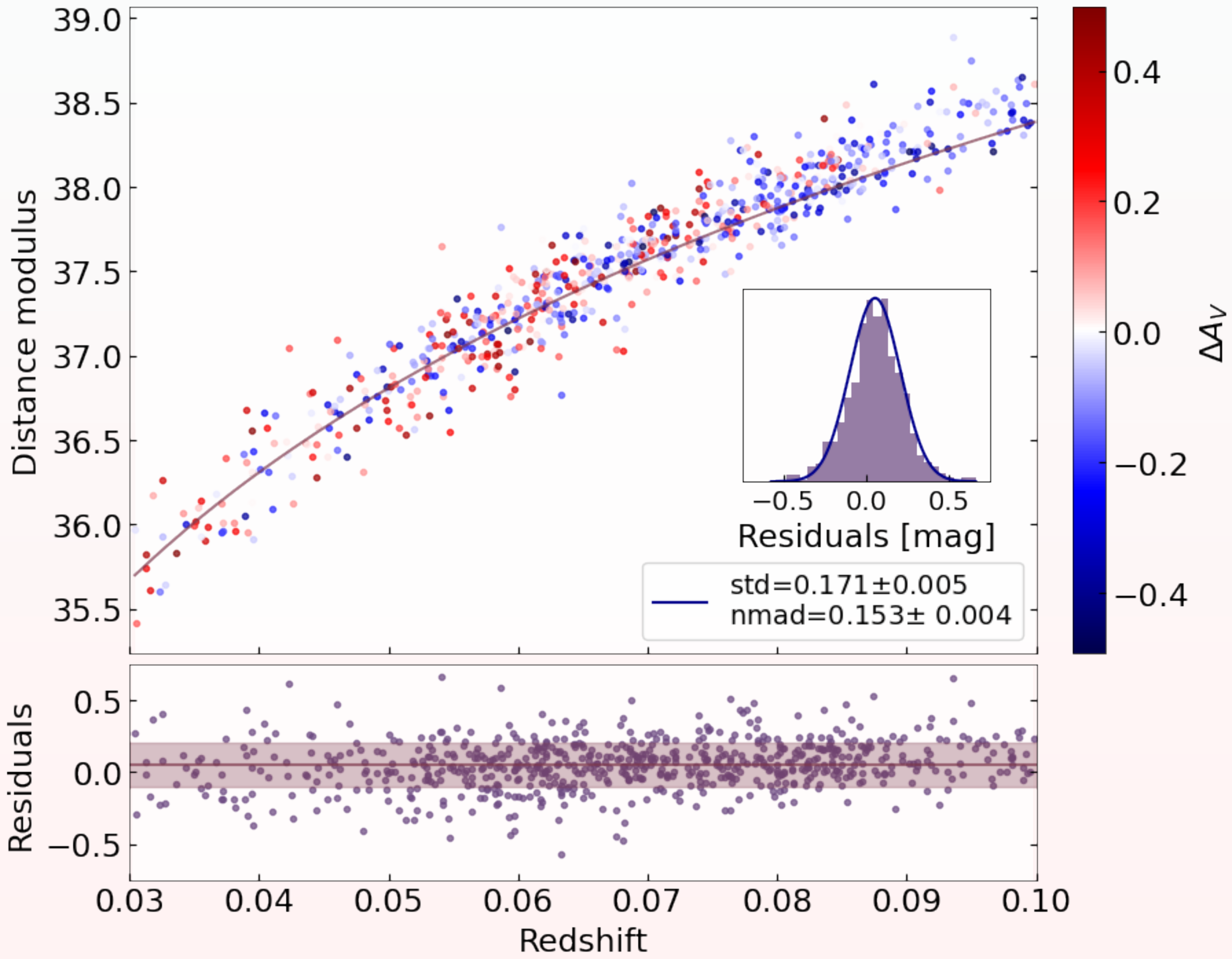


RBTL standardisation : linear color correction

$$\Delta\mu_{\mathrm{RBTL},i} = -\left[\Delta m_i - \beta_{\mathrm{RBTL}} \cdot \Delta A_{V,i}\right]$$

—> 0.153 mag for ZTF (0.164 SALT)

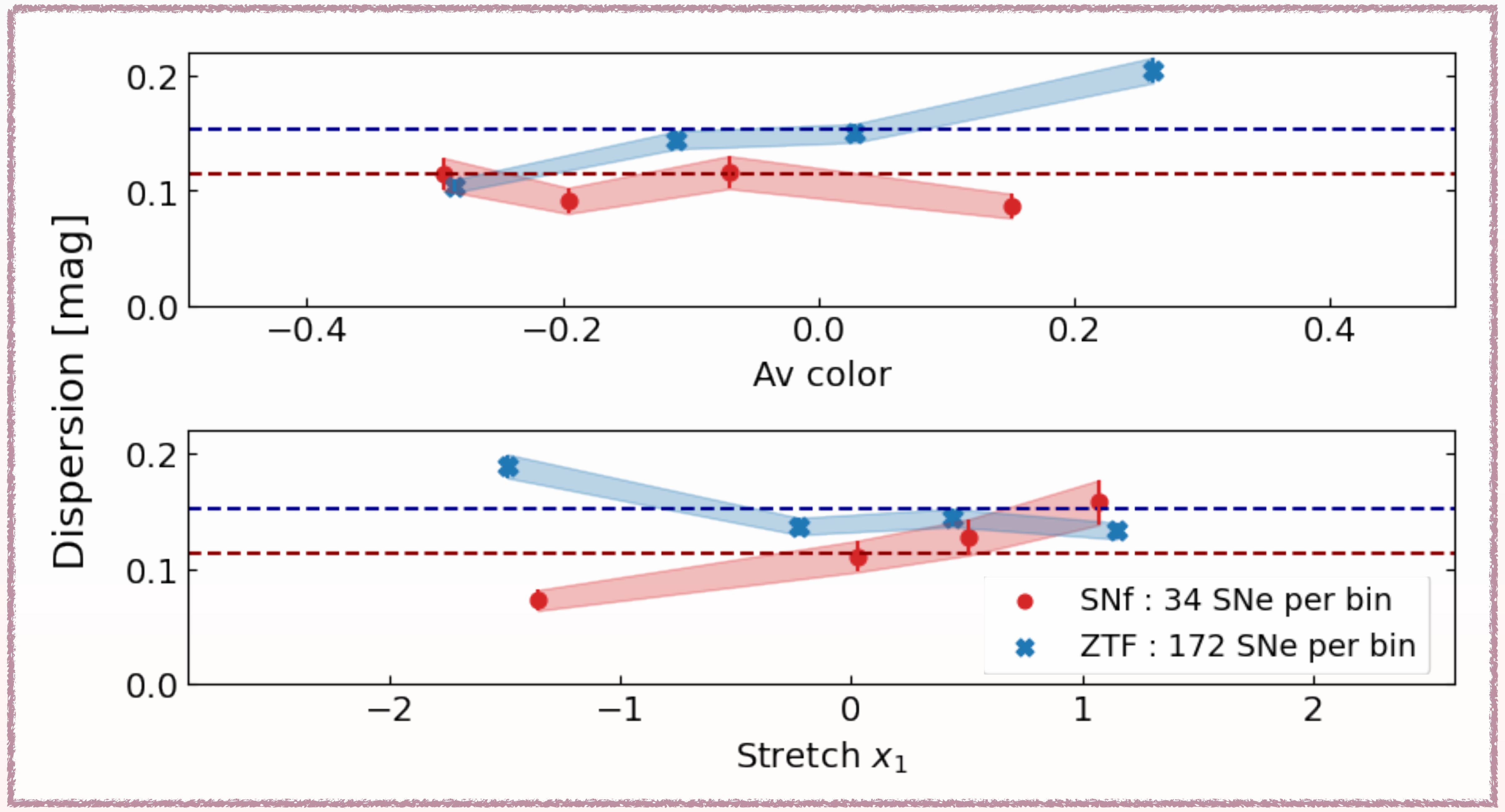
0.113 for SNf



Hubble Diagram after RBTL standardisation, for ZTF : 688 SNe

Twins Embedding - *Standardisation in color*

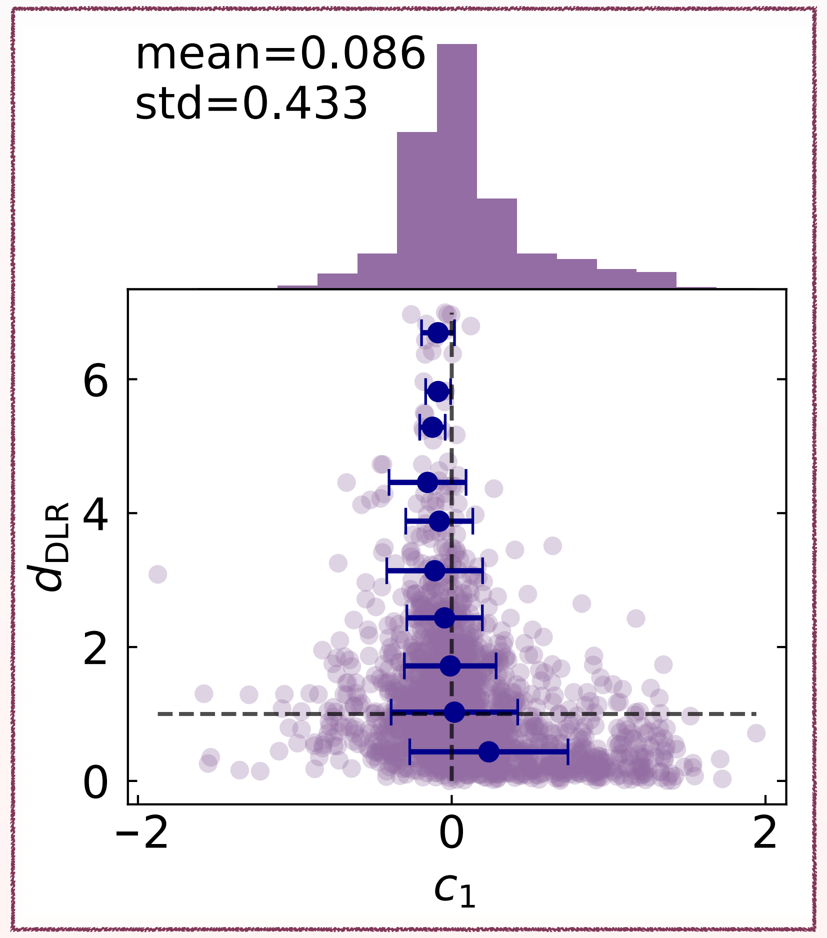
Test of the robustness

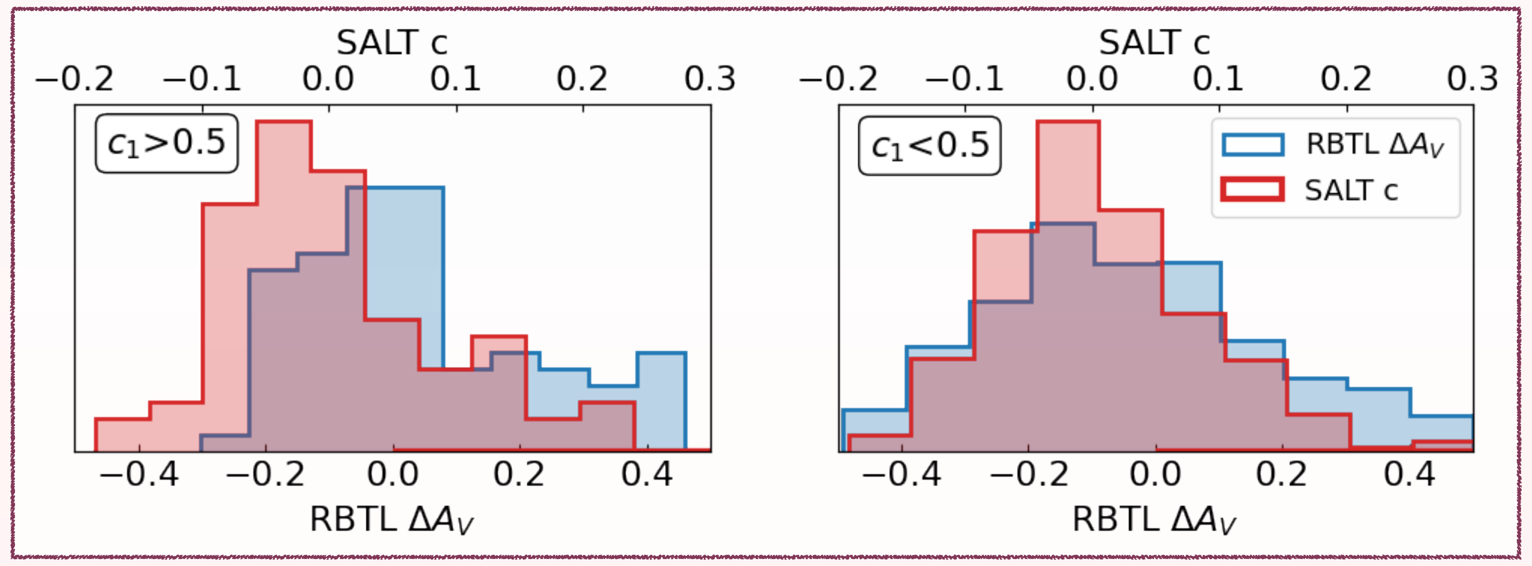


SNe with high color / low stretch are not well standardised in ZTF

- 0.04mag dispersion floor due to flux-calibration
- 0.07mag due to 40% of SNe with $\sigma_z \sim 10^{-3}$

falls to 0.126 mag dispersion

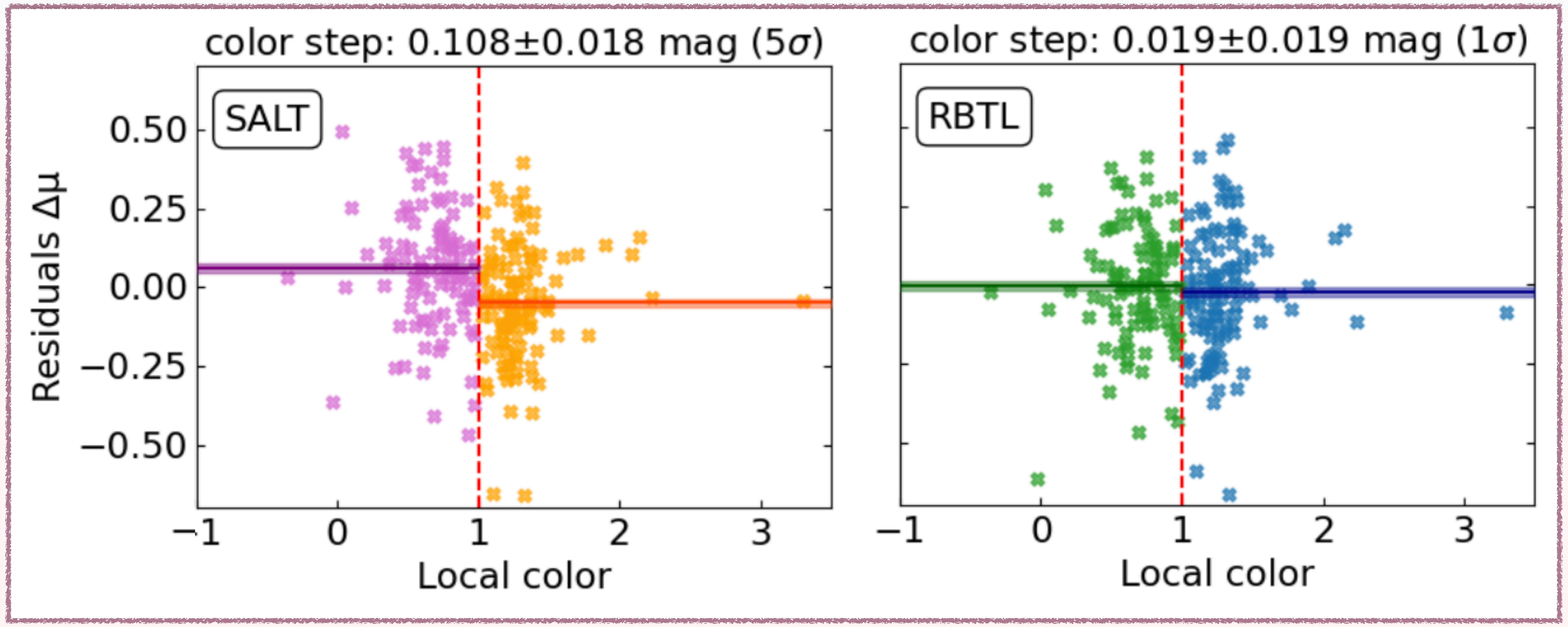




- Remaining host contamination on ZTF sample (unknown dispersion) : artificial reddening

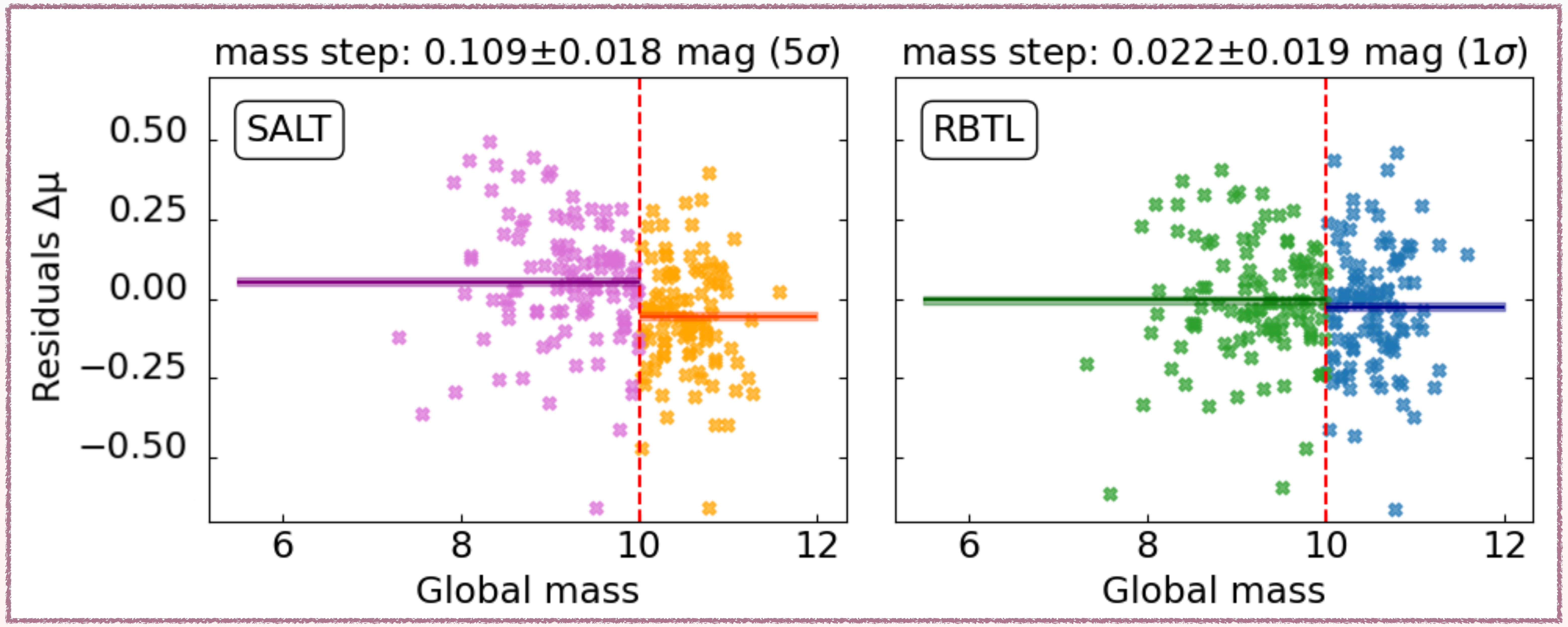
Twins Embedding - *Standardisation in color*

Less dependency in host galaxy properties:
Astrophysical biases mitigated



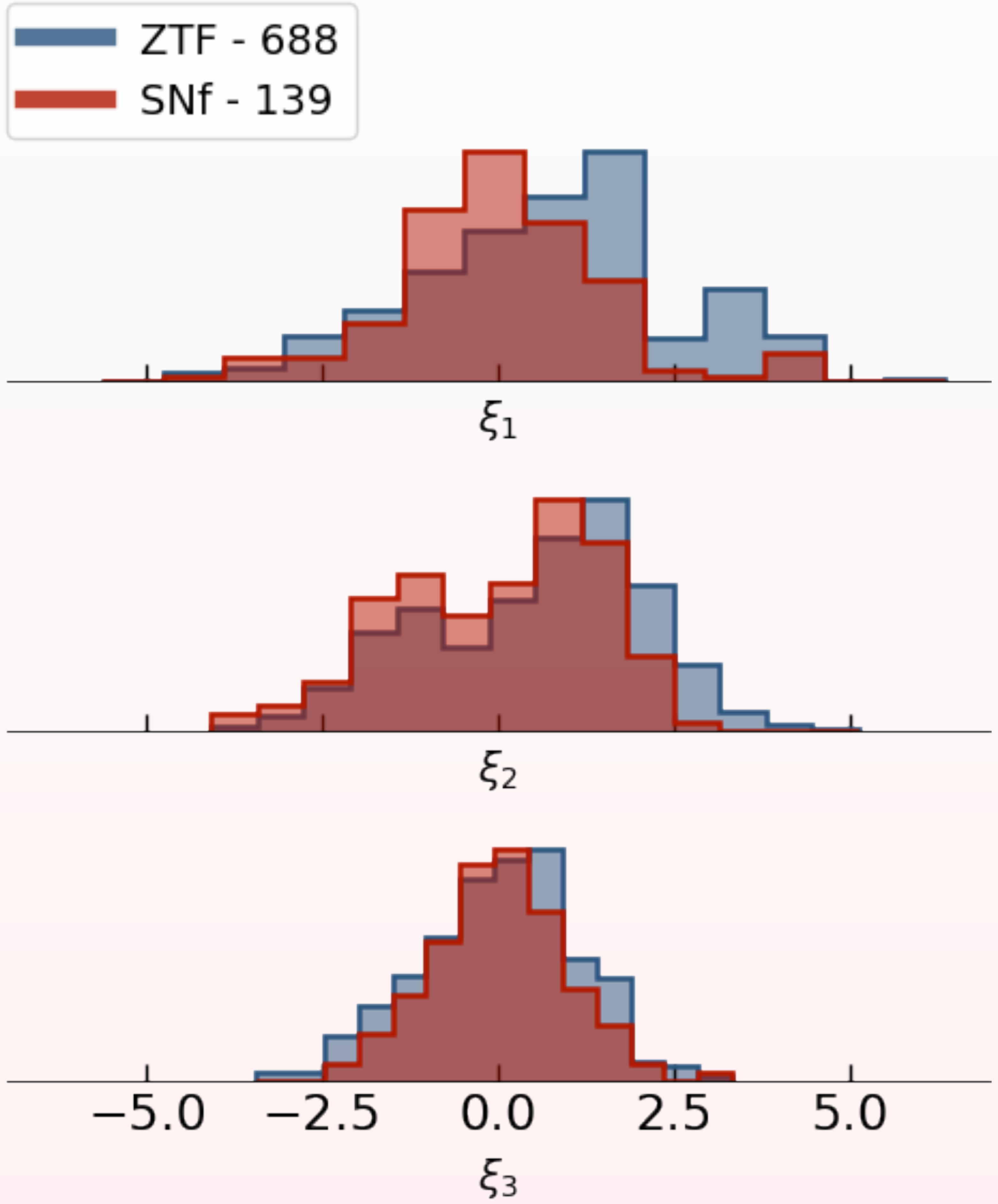
Twins Embedding - *Standardisation in color*

Less dependency in host galaxy properties:
Astrophysical biases mitigated

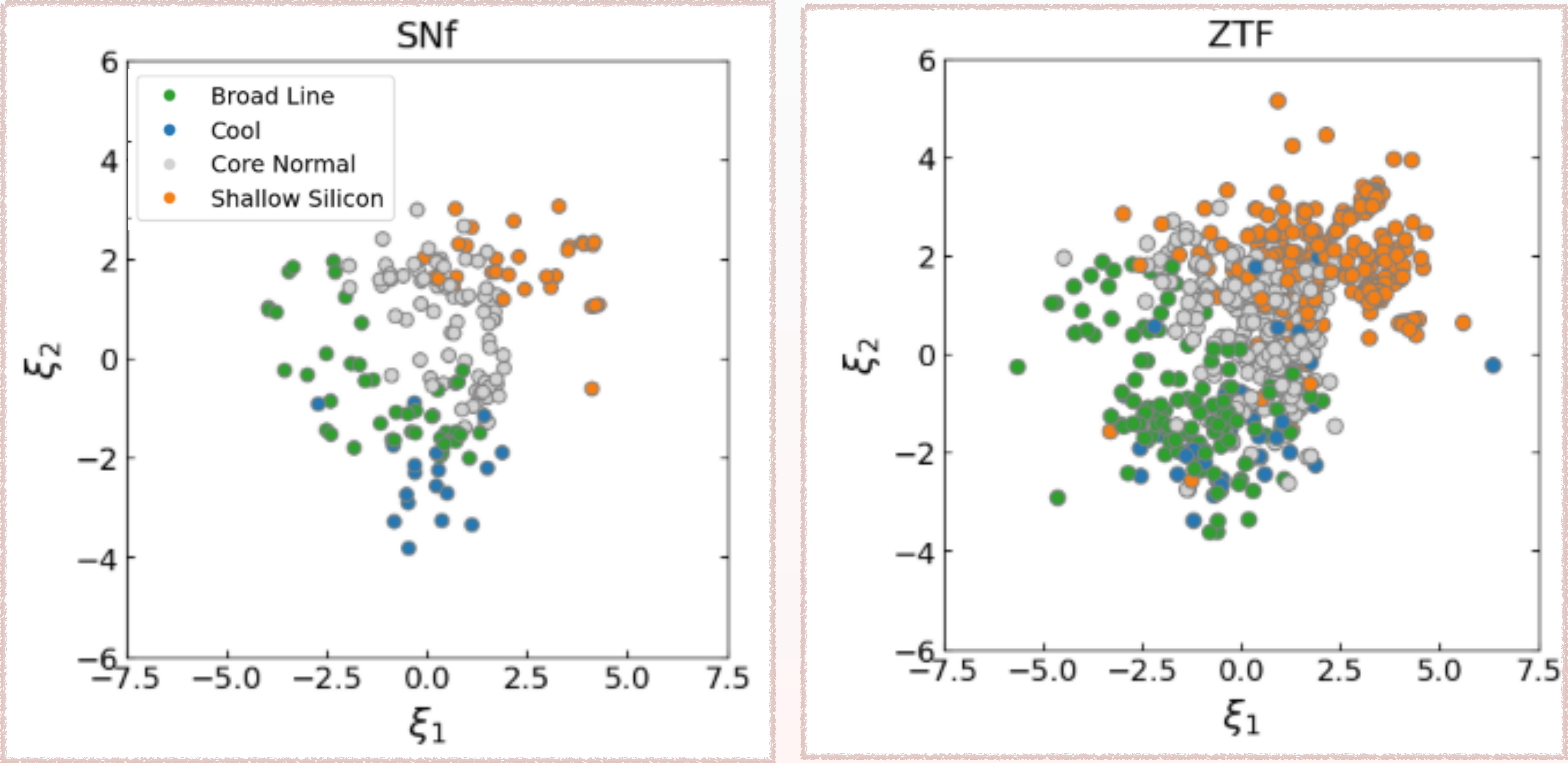


Twins Embedding - *Isomap parameters*

3. Fit three Isomap parameters $\vec{\xi}$ per SN



Normalised distributions of Isomap parameters

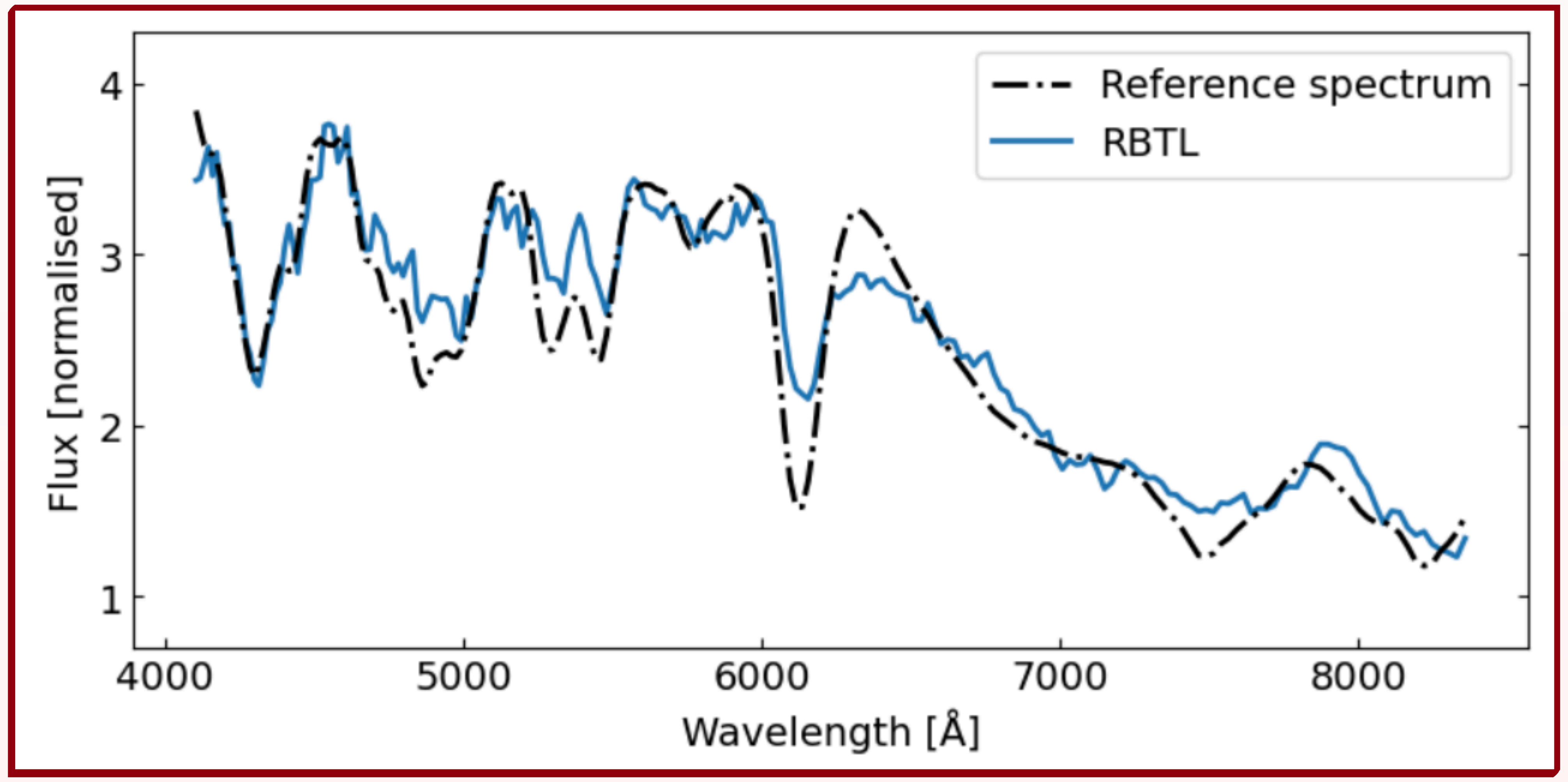


Recovered Branch classes

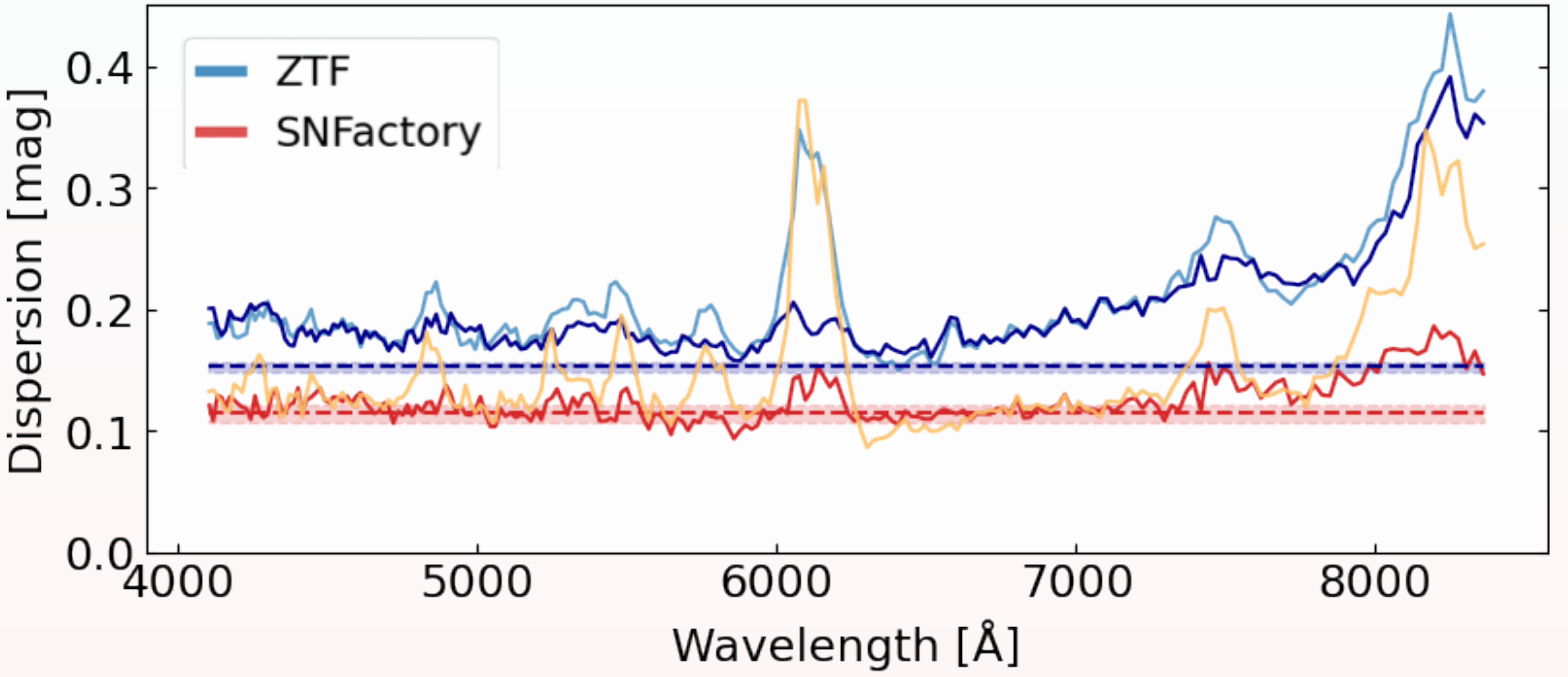
Twins Embedding - *Isomap parameters*

$GP(\lambda)(\overrightarrow{\xi}_i)$ modelling lines
(not a standardisation)

$$f_{\mathrm{RBTL},i}(\lambda) = f_{\max}(\lambda) \cdot 10^{+0.4(\Delta m_i + \Delta A_{V,i} \cdot CL(\lambda))} \cdot \frac{1}{1 + \mathrm{GP}(\lambda)(\overrightarrow{\xi}_i)}$$

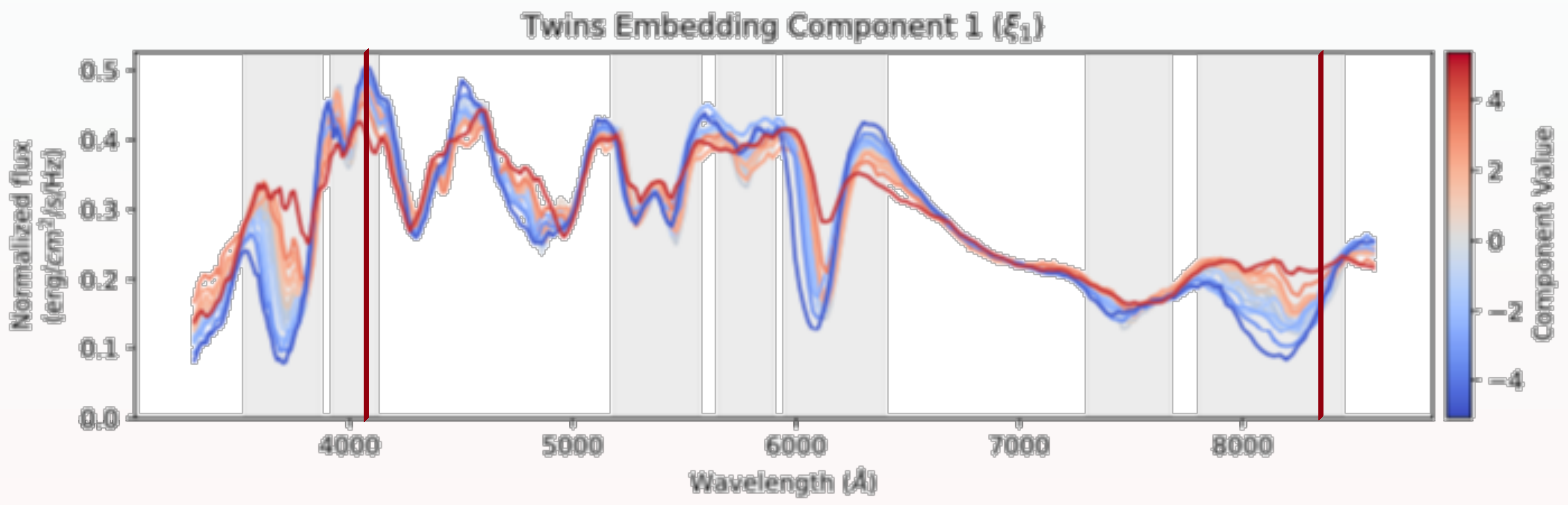


Spectral modelling using RBTL and Isomap parameters of SN ZTF18aaxvpsw

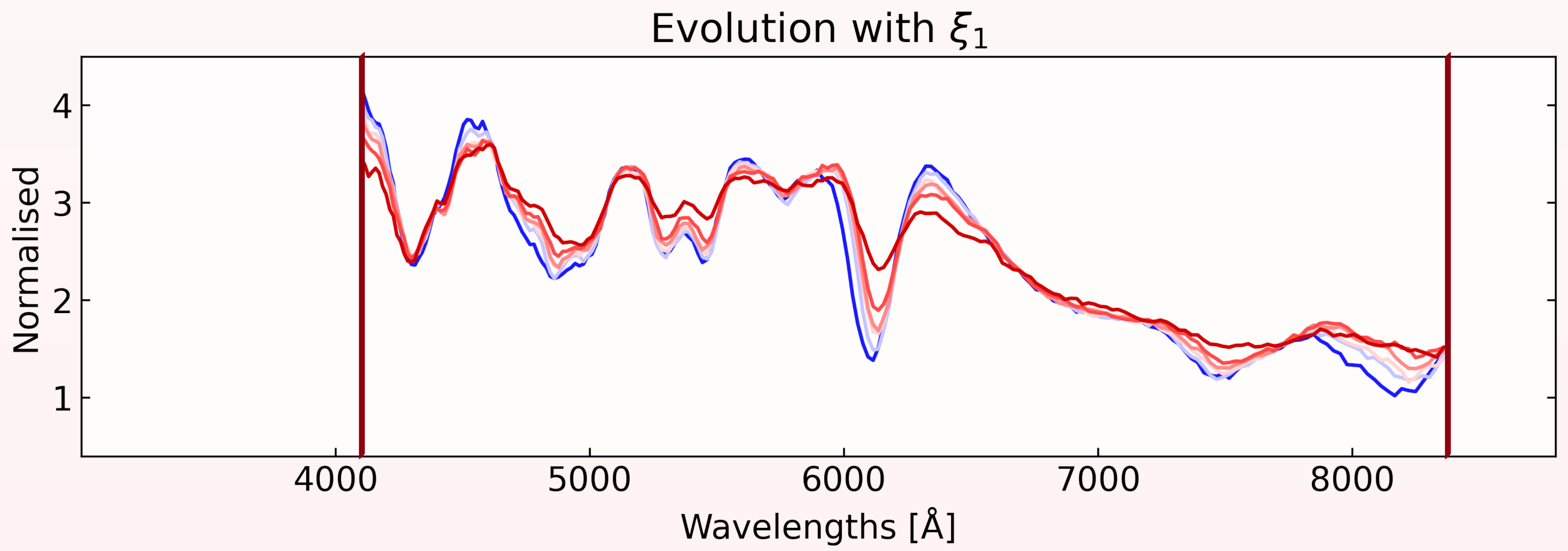


Spectral dispersion for 682 ZTF SNe and 139 SNf SNe after RBTL standardisation with/without line correction

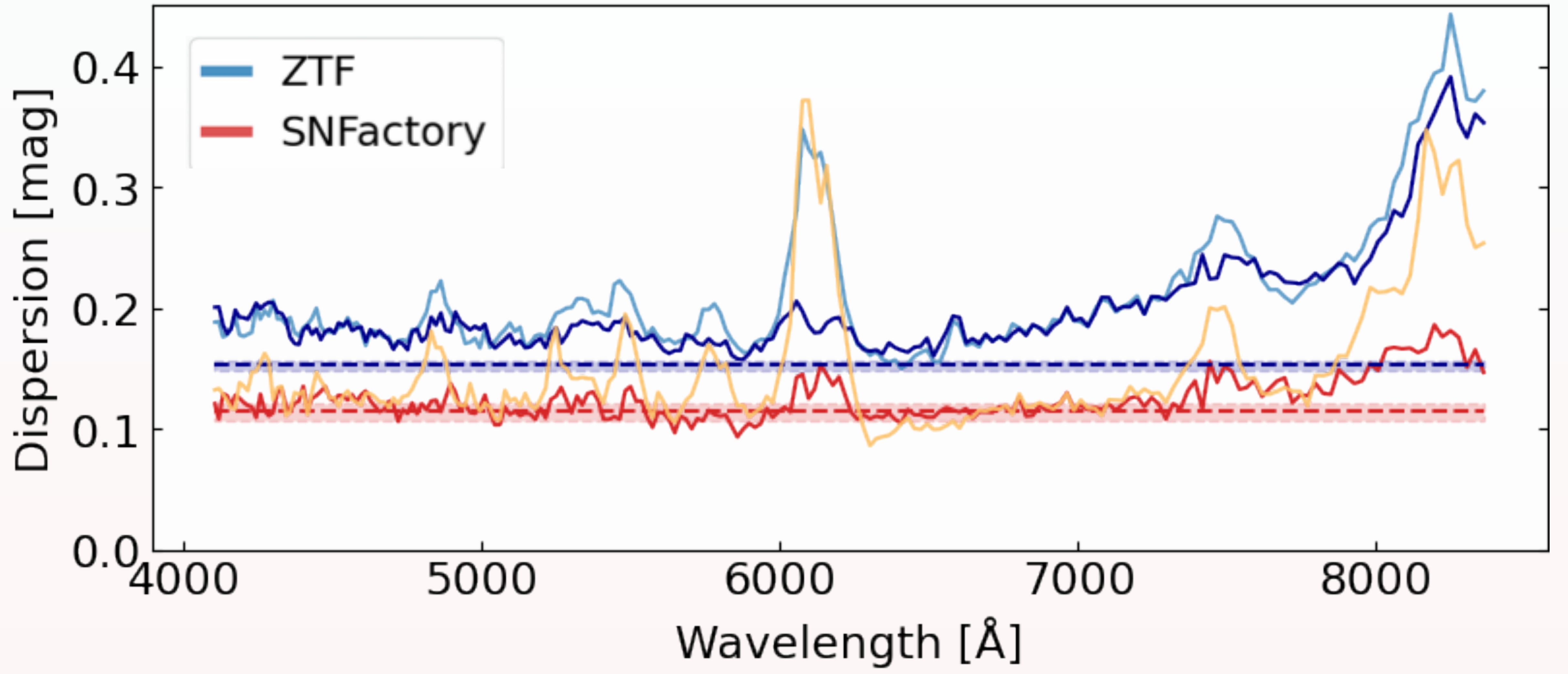
Twins Embedding - *Isomap parameters*



ξ_1 effects on SNf spectra



ξ_1 effects on ZTF spectra



Spectral dispersion for 682 ZTF SNe and 139 SNf SNe after RBTL standardisation with/without line correction

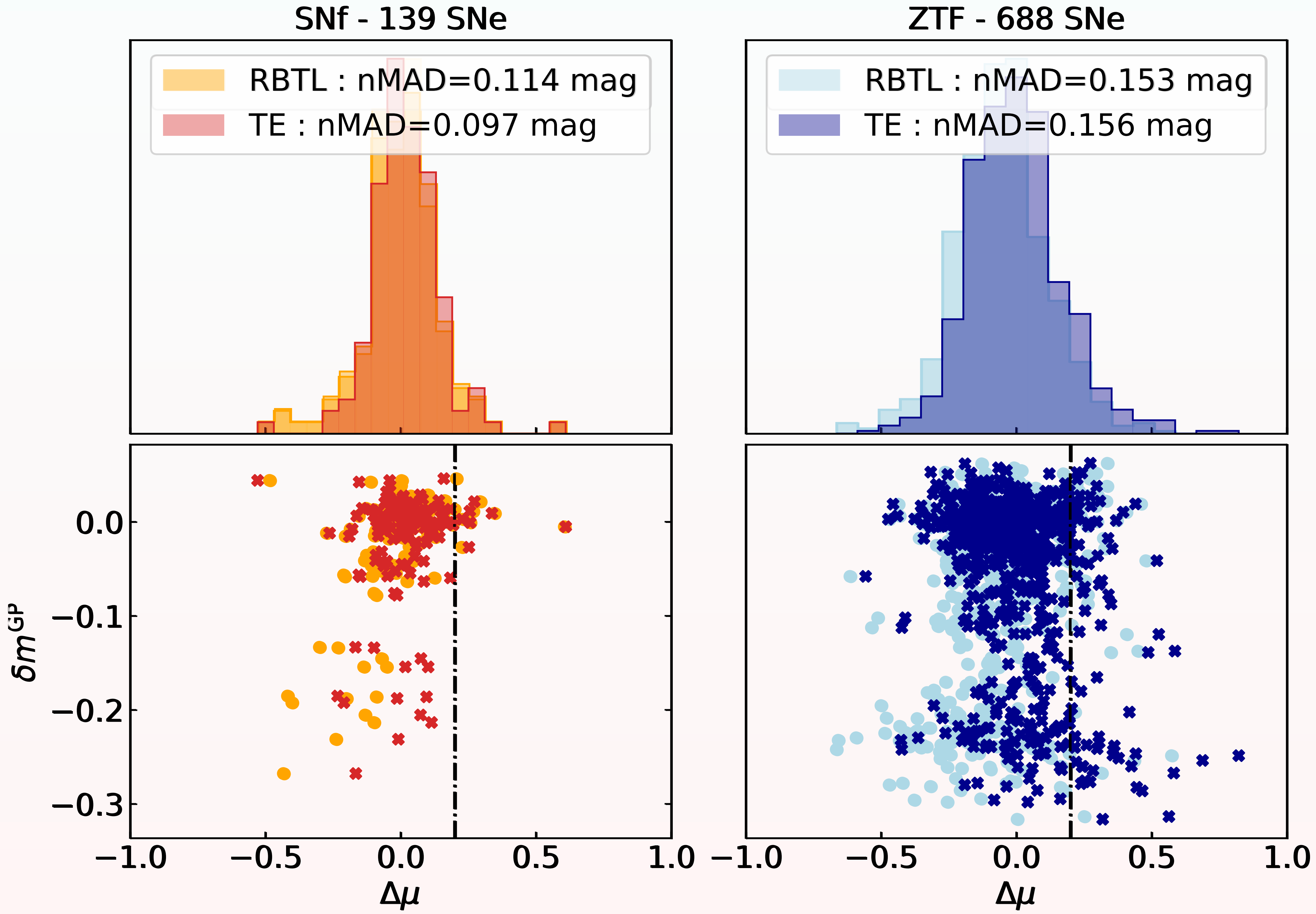
Twins Embedding - *Standardisation*

Manifold standardisation

color (#1)+ δm^{GP} (#3)

$$\Delta\mu_{\mathrm{TE},i} = -\left[\Delta m_i - \beta_{\mathrm{RBTL}} \cdot \Delta A_{V,i} - \delta m^{\mathrm{GP}}(\vec{\xi}_i)\right]$$

Residual prediction by GP



Residuals for 688 ZTF SNe and 139 SNf SNe

SNf results differences with Boone 2021:

- wavelength range
- no cut on data quality
- linear color correction

Gaussian Process δm^{GP} doesn't decrease the dispersion on ZTF

Conclusion

Ganot et al. (in prep)

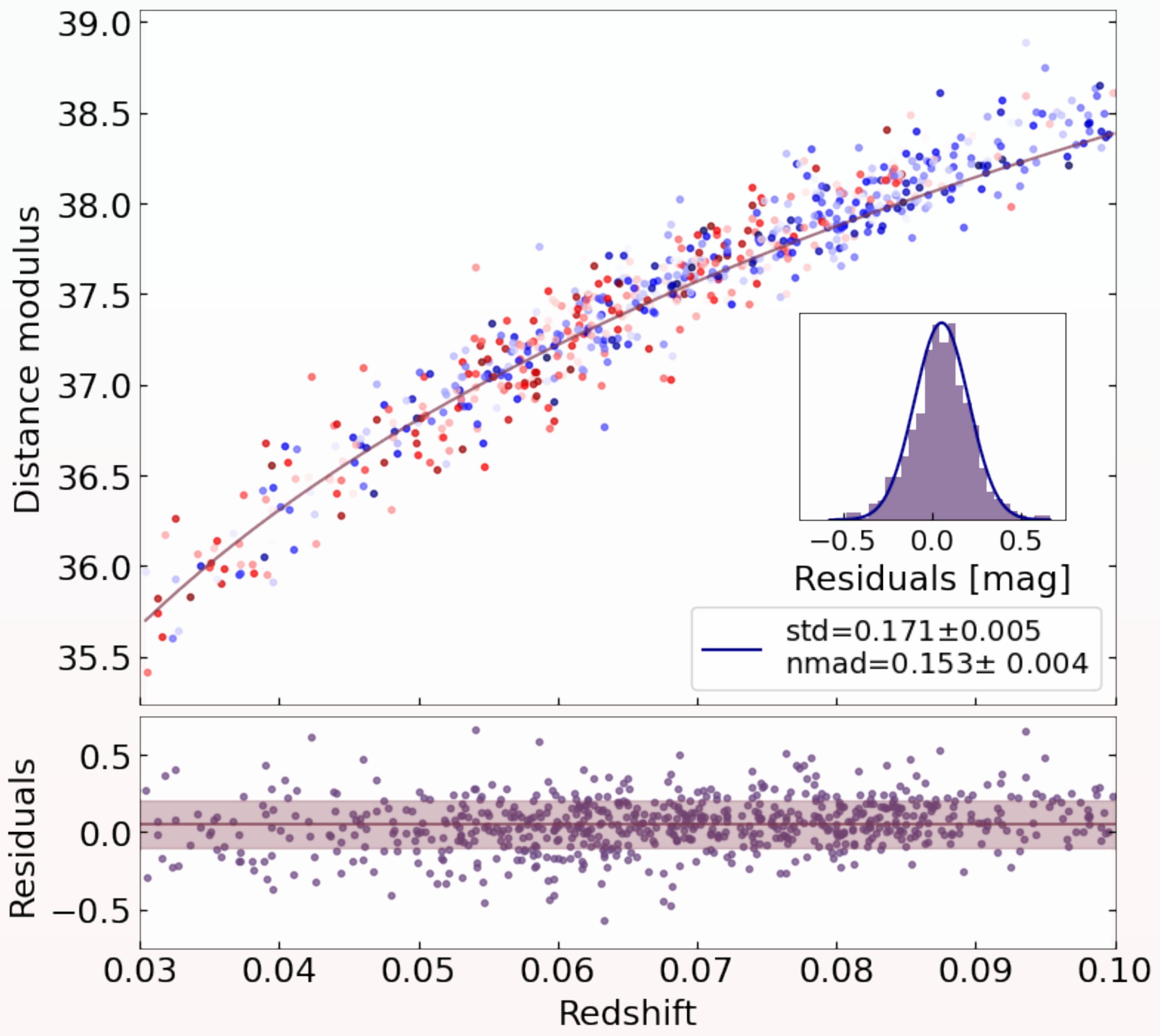
- 1607 ZTF spectra flux-calibrated at 0.07 mag

- ZTF TE sample has 4x more SNe than SNf
- RBTL standardisation efficiency is confirmed for ZTF

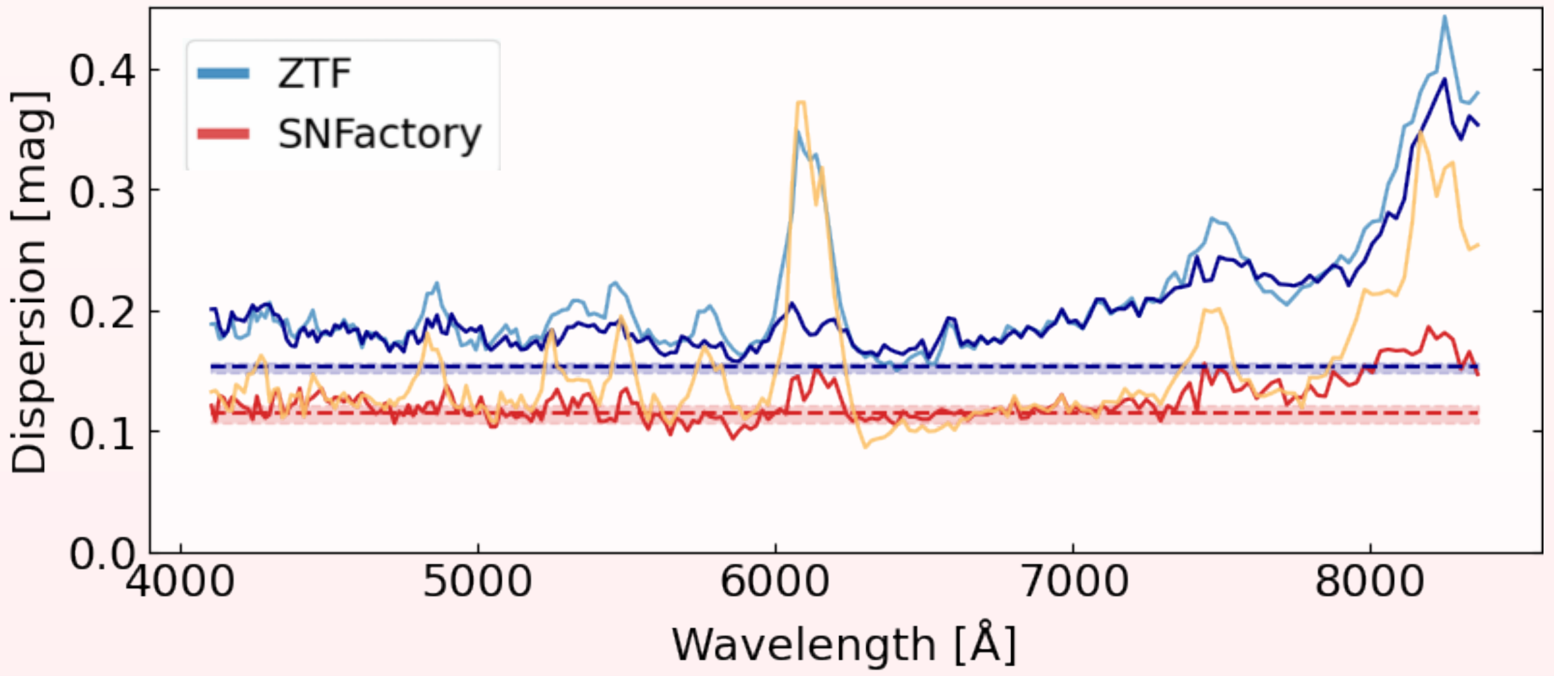
  —> 0.153 mag | 0.164 mag SALT c and x_1

  ~ 0.1 mag for the bluest

  Less dependency to environment



- Recover the line variabilities with GP(λ)($\vec{\xi}_i$)
- Manifold standardisation limited by spectral quality

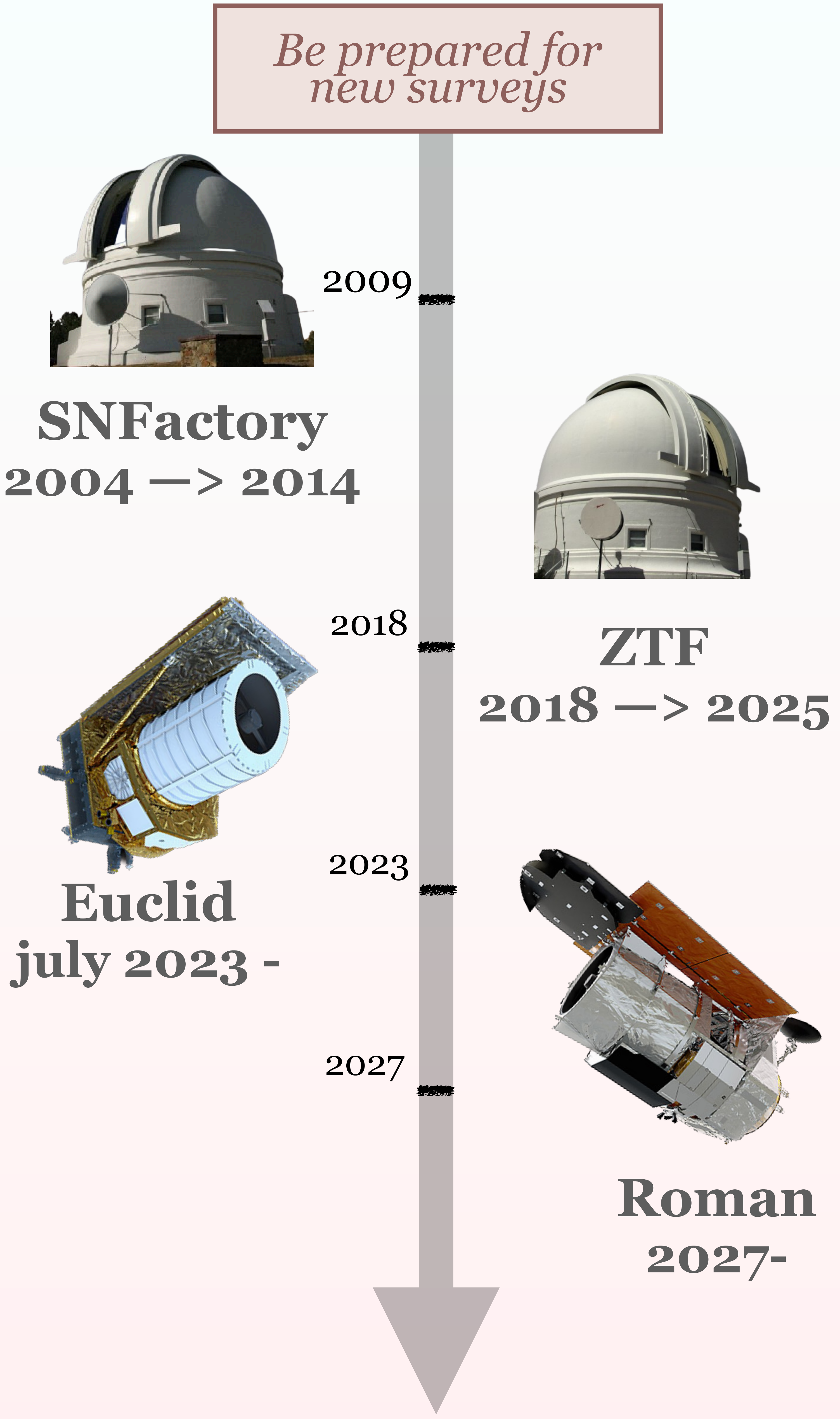


What's next

We need simulations to know what to focus on for future surveys

Ongoing work: *sntwin*

- Application of the TE to another surveys
- Dataset simulations: wavelength coverage, SNR, σ_z, resolution, revise the cuts…
- Improving the method: phase range, the colorlaw (dust evolution in z…)

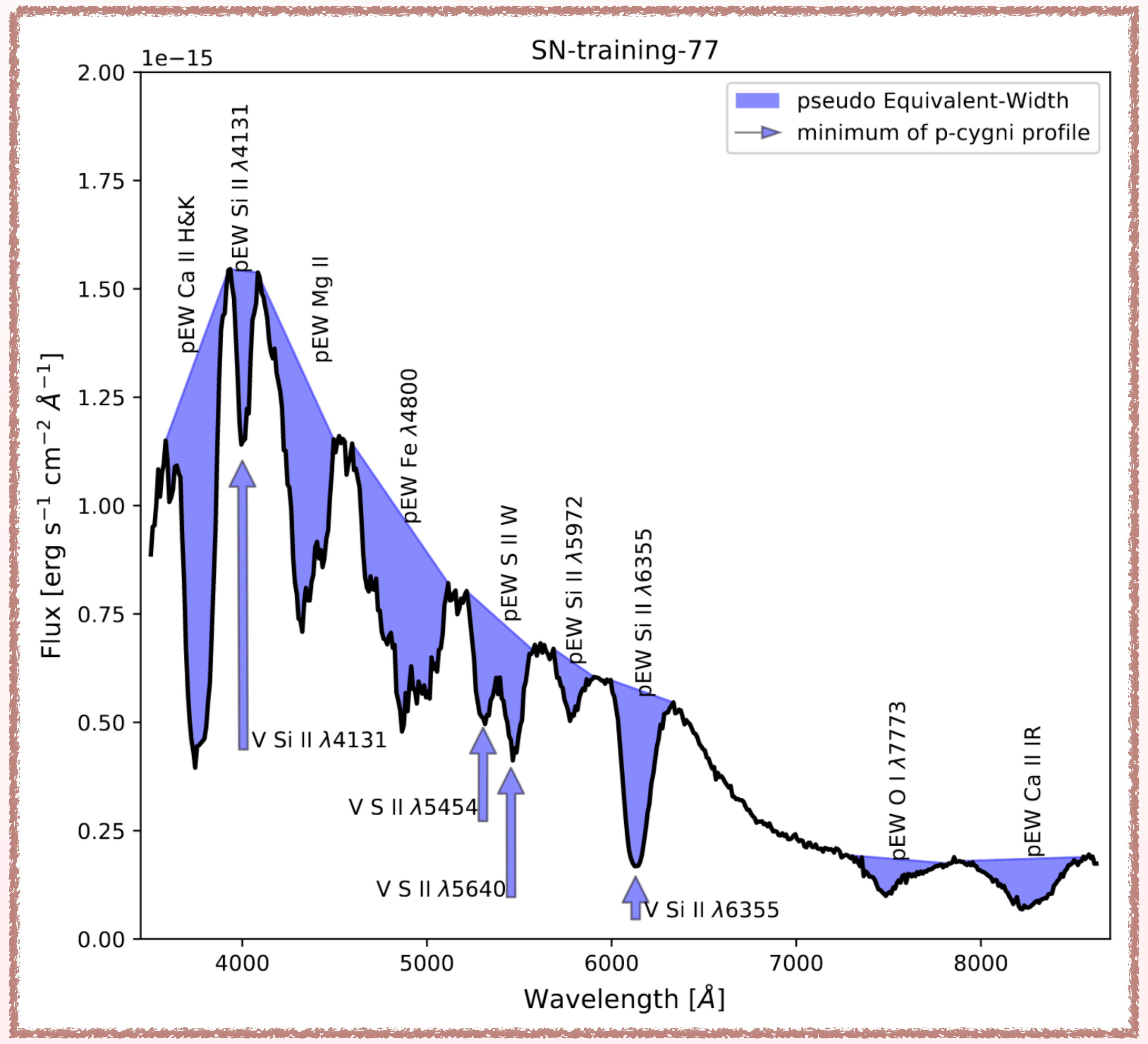


SUGAR

Léger 2019

features are highly correlated : SUGAR is combining the pEW and velocities
Linear combination of 13 spectral features

3 parameters q_i



SNEMO

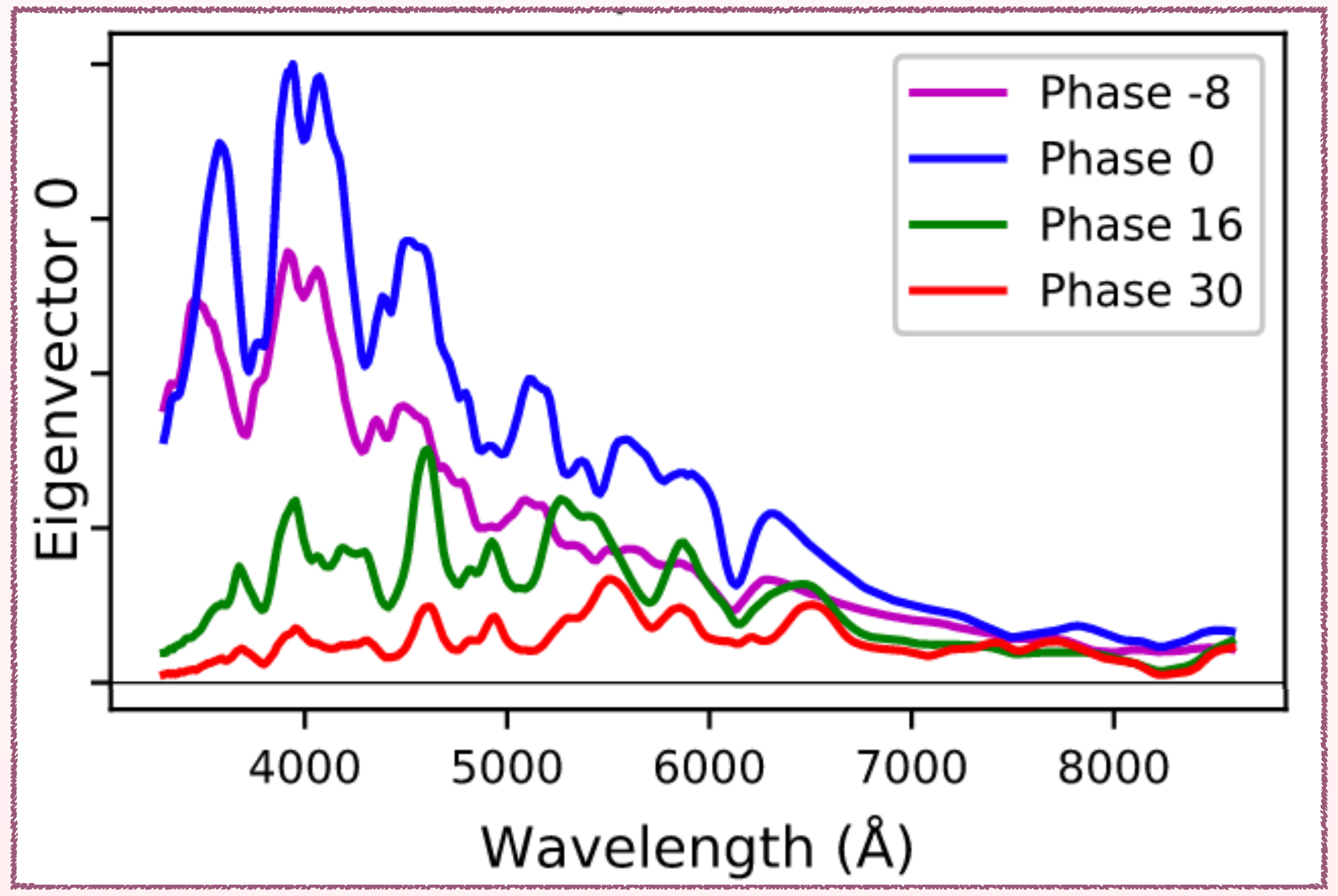
Saunders 2018

PCA describing the variations of SN Ia spectral time series

Eigenvectors $e_i(p, \lambda)$ + Eigenvalues $c'_{SN,i}$

2, 7 or 15 parameters

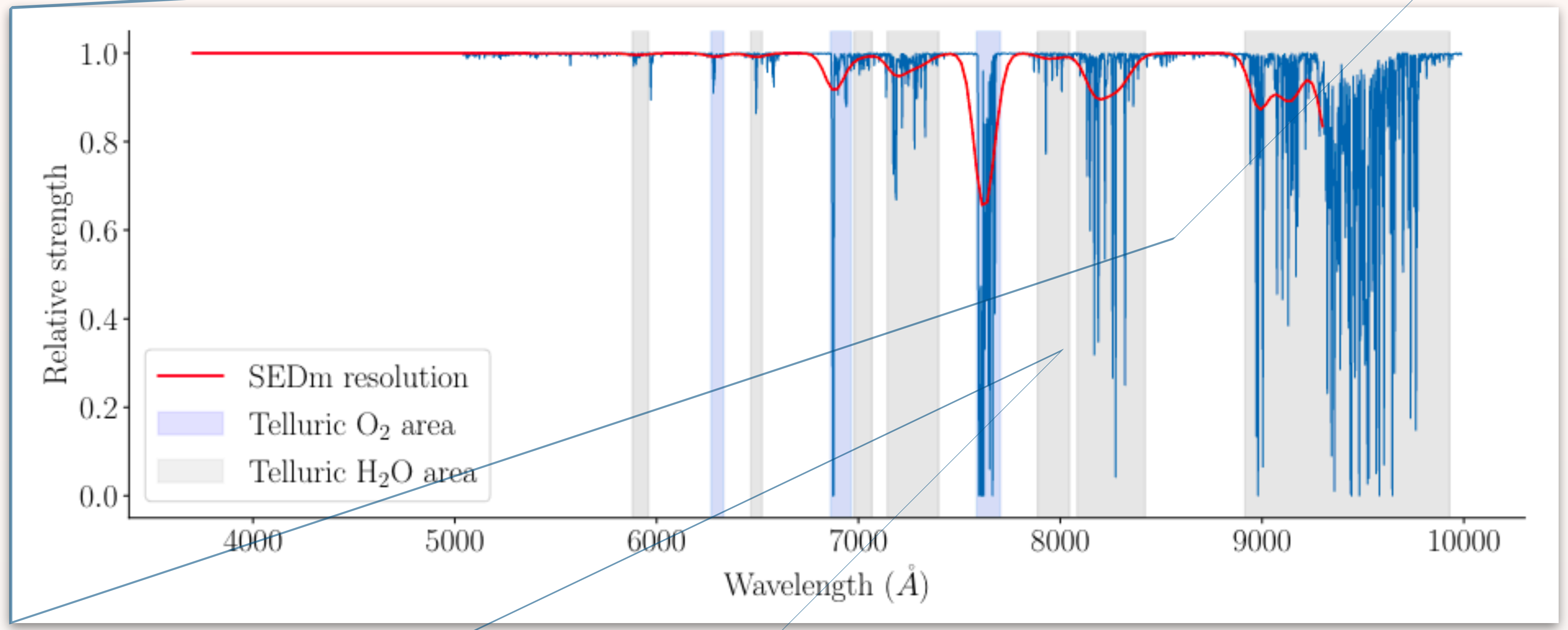
$$\boldsymbol{F}_{\rm SN}(p,\, \lambda) = c_{\rm SN,0}\left(e_0(p,\, \lambda) + \sum_{i=1}^{N} c'_{{\rm SN},i}\, e_i(p,\, \lambda)\right)$$



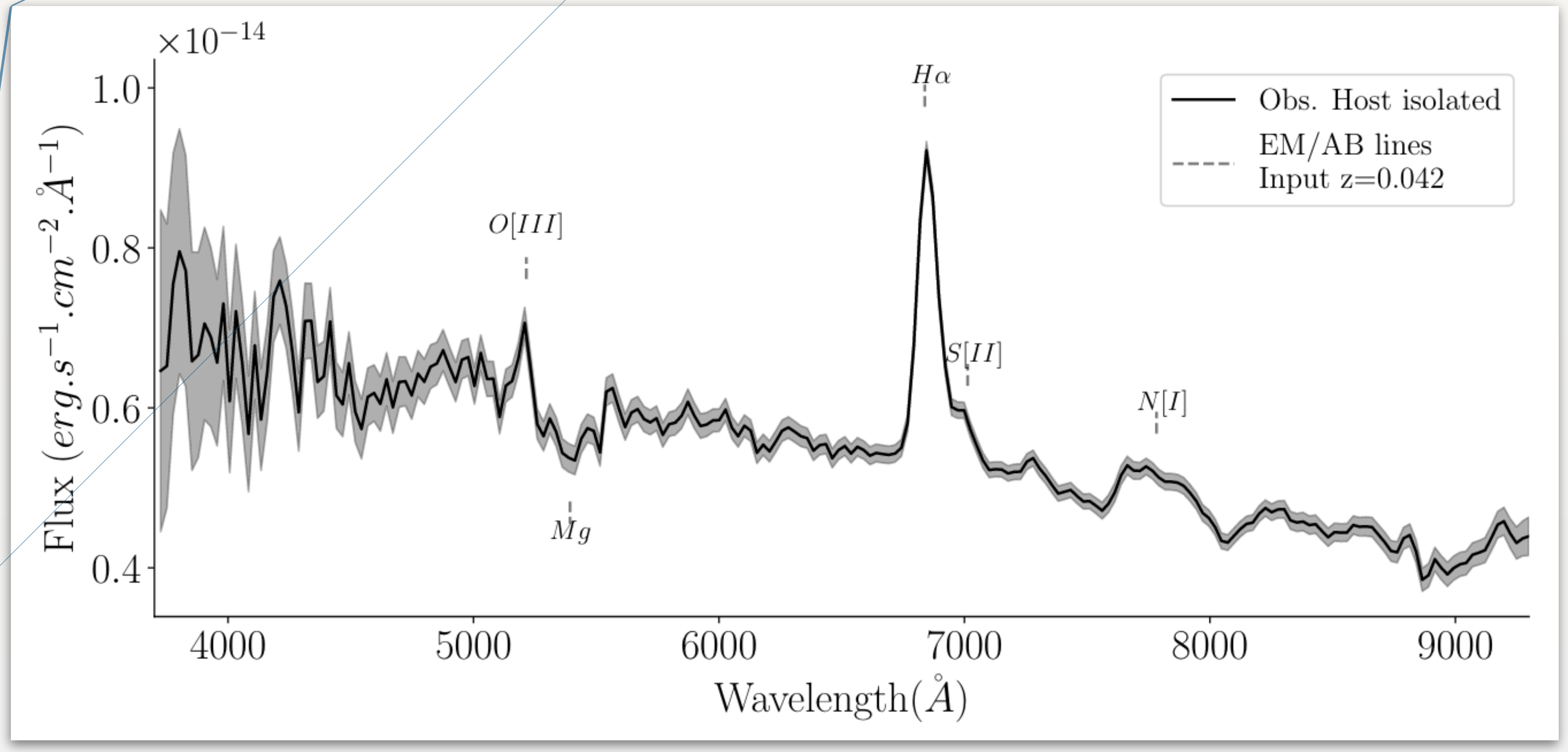
First eigenvector $e_0(p, \lambda)$ for several phase p

Data processing

- ☑ Extraction from data cude
- ☑ Wavelength calibration
- ☑ Correction atmospheric contamination
- ☑ Host galaxy contamination

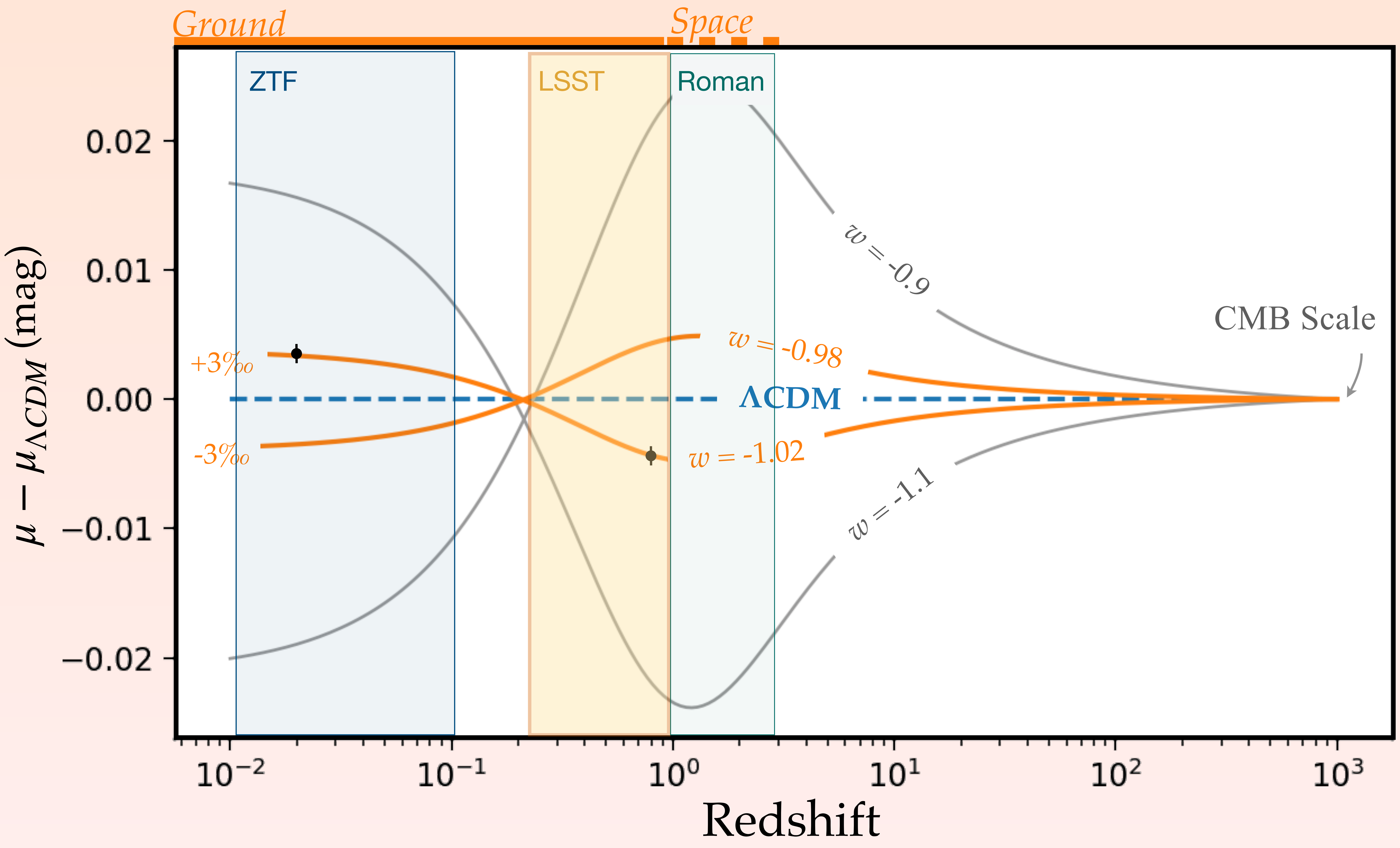


Telluric absorption lines from Kitt Peak Observatory
Credit: Hinkle et al., 2003



Spectrum of ZTF18accrorf host galaxy
Credit: Jeremy Lezmy thesis

Goals | *Dark Energy*



Precision required (Systematics)

Calibration :

δmag = 0.001

Astrophysical bias:

δmag = 0.001

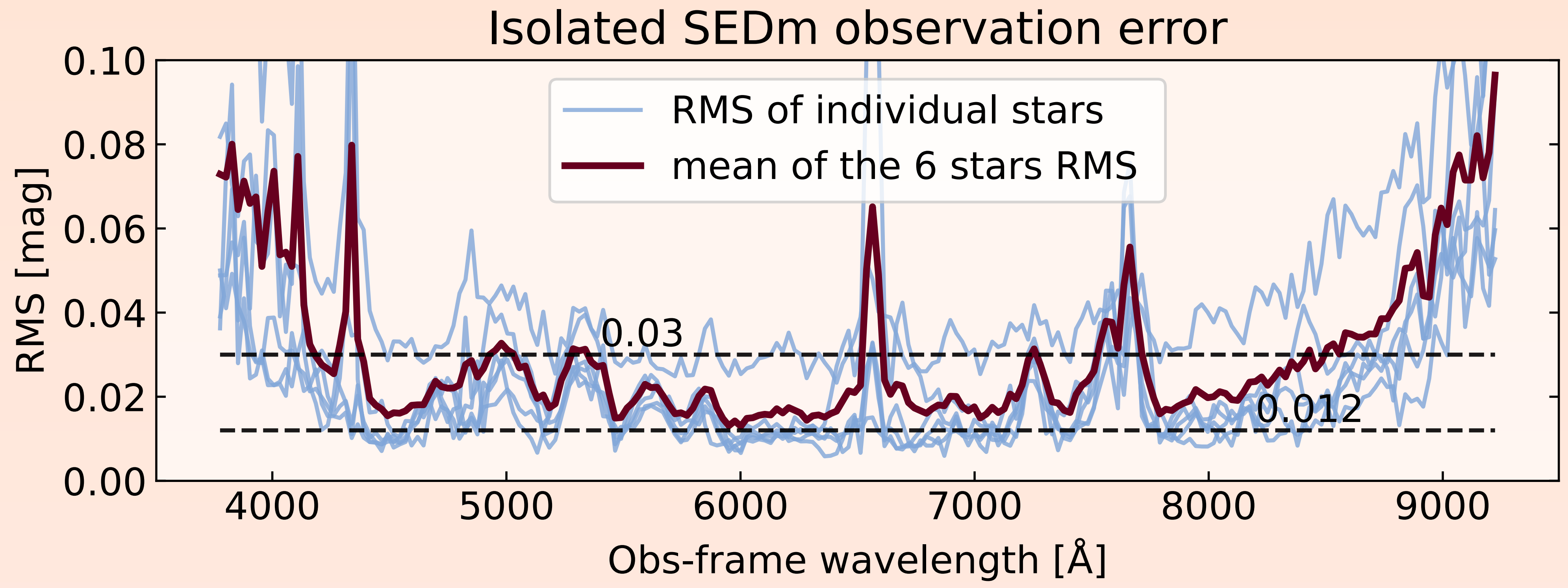
Dispersion (Statistics)

SNe Ia dispersion :

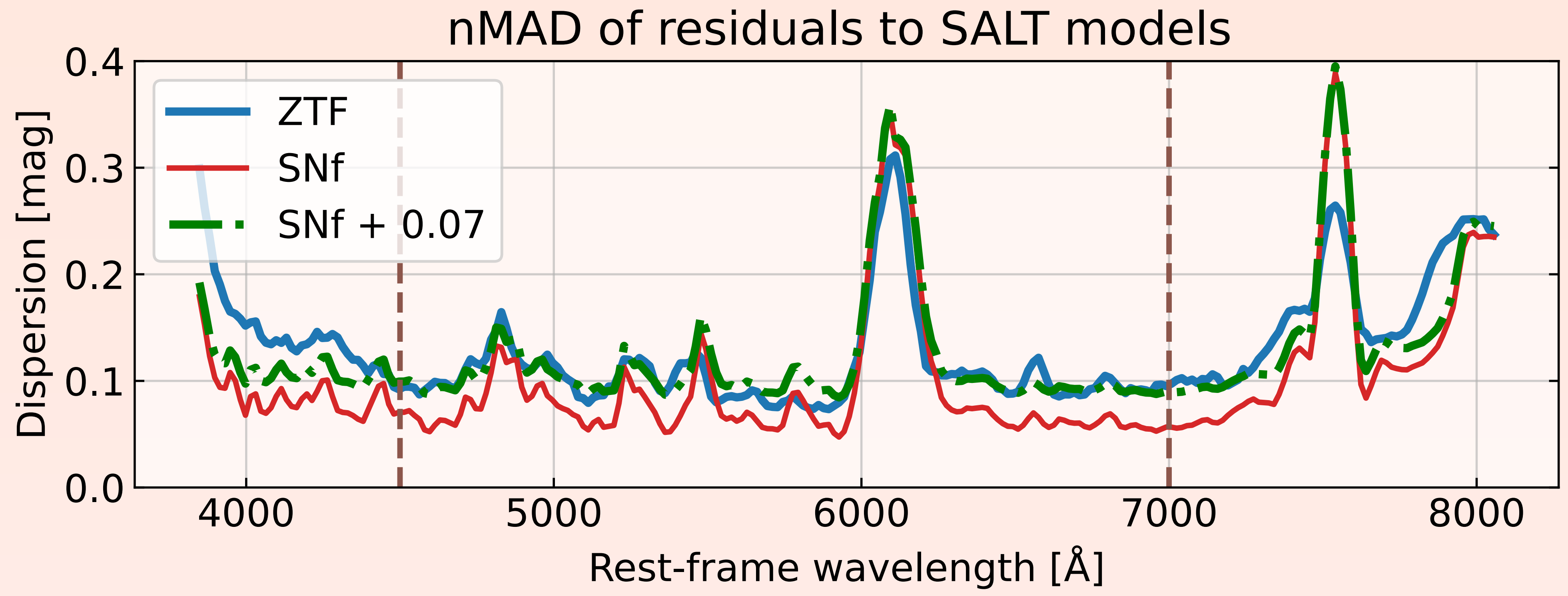
$\sigma_{mag} = 0.40$

SNe Ia are not standard candles !

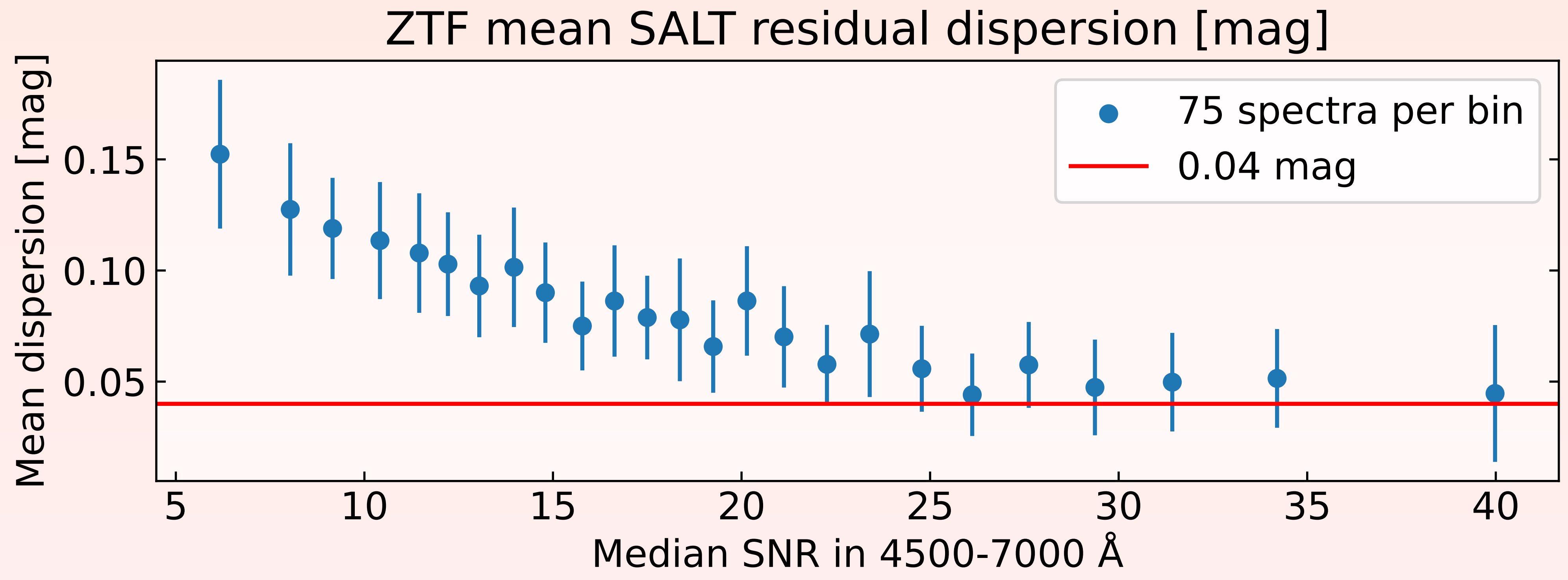
Flux calibration : precision estimates



Standard stars
Residuals of SEDm observations with CALSPEC reference spectra



SNe Ia
Dispersion error floor of ZTF compared to SNf

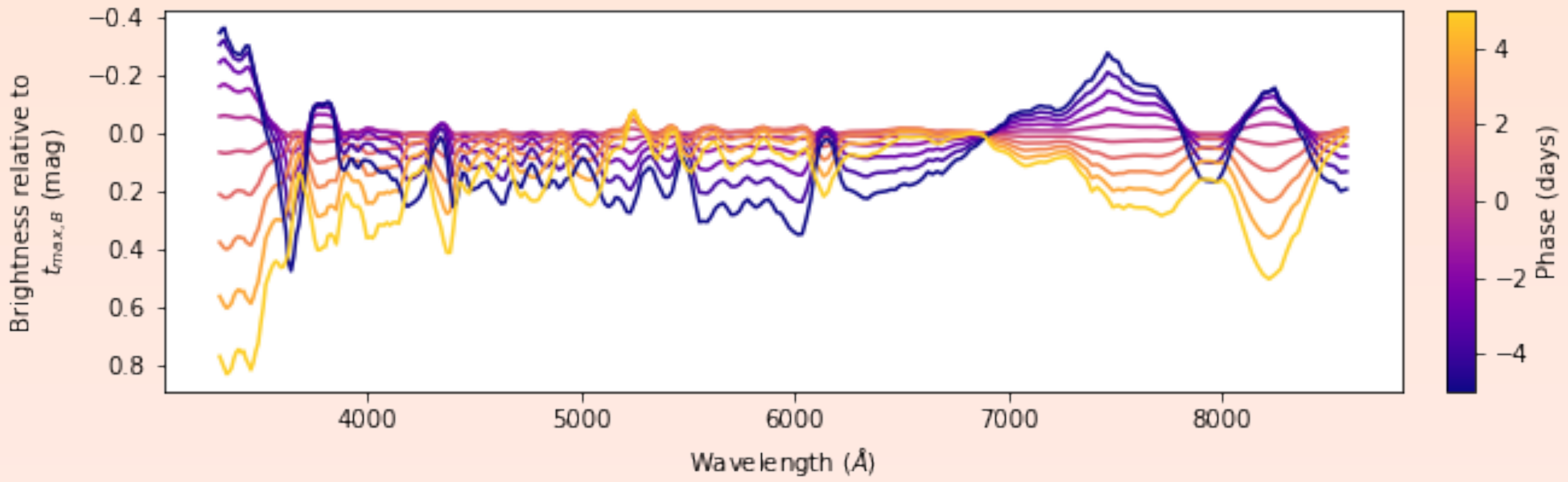


Isolated flux-calibration dispersion
Separate the contribution of SNR

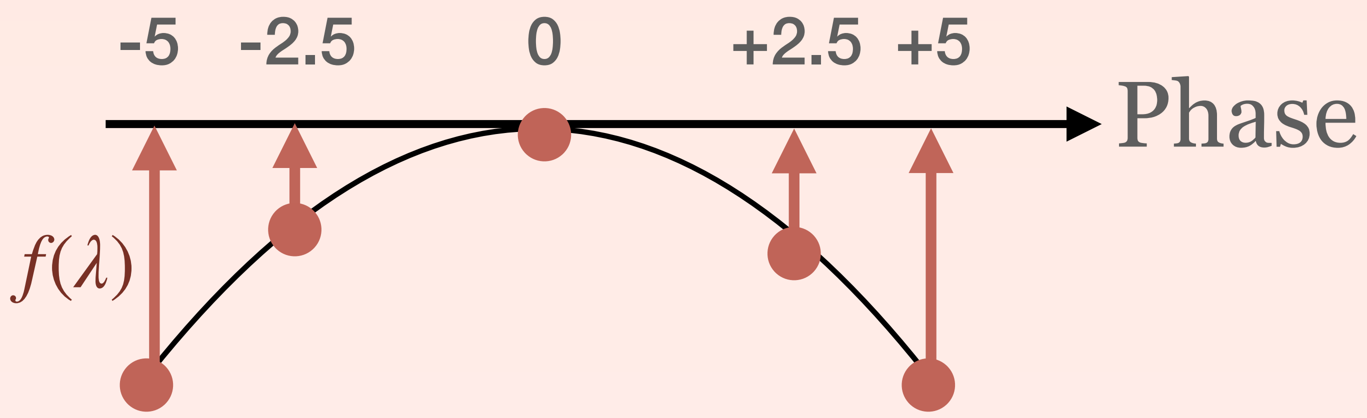
DTEM - phase correction

1. Generate at maximum luminosity

$$m_i(p;\lambda_k) - m_i(0;\lambda_k) = p \cdot c_1(\lambda_k) + p^2 \cdot c_2(\lambda_k)$$

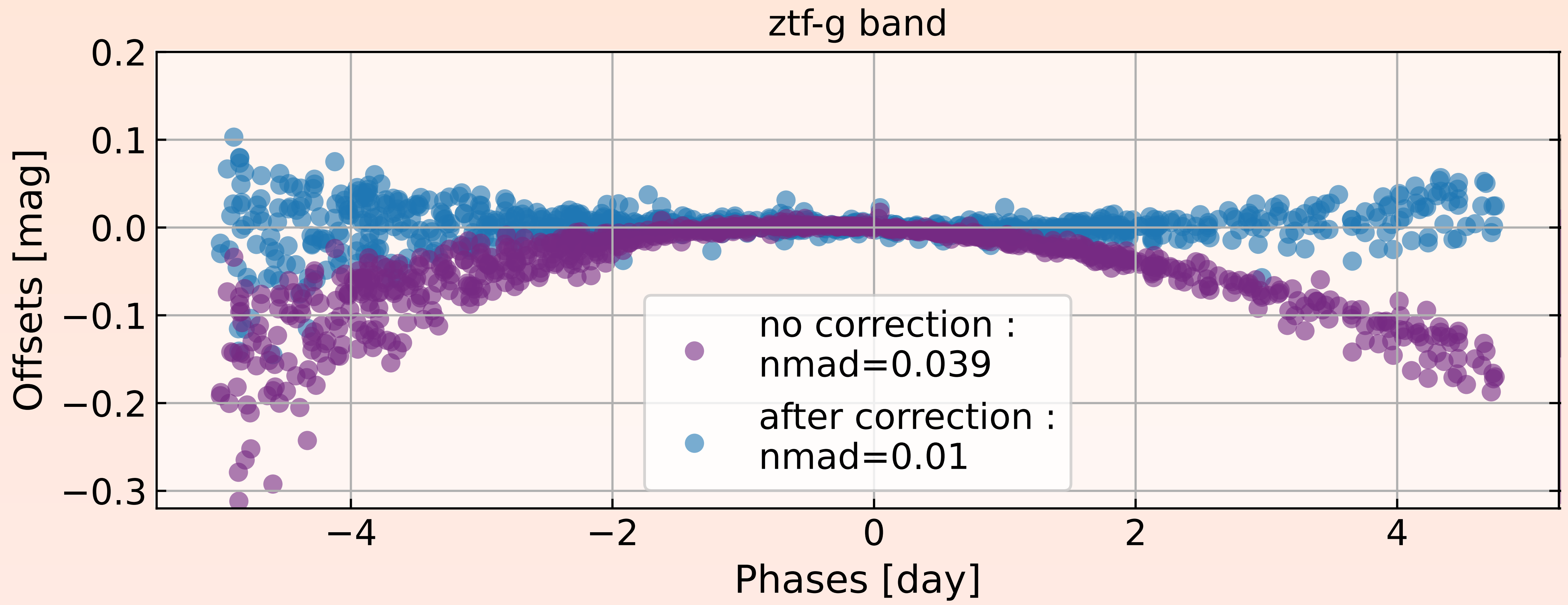


Quadratic evolution in phase of SN Ia spectra



On bessell-b Lightcurve

*Capture 85% of the spectral **time evolution** variance common to every Sne between -5 and 5 days*



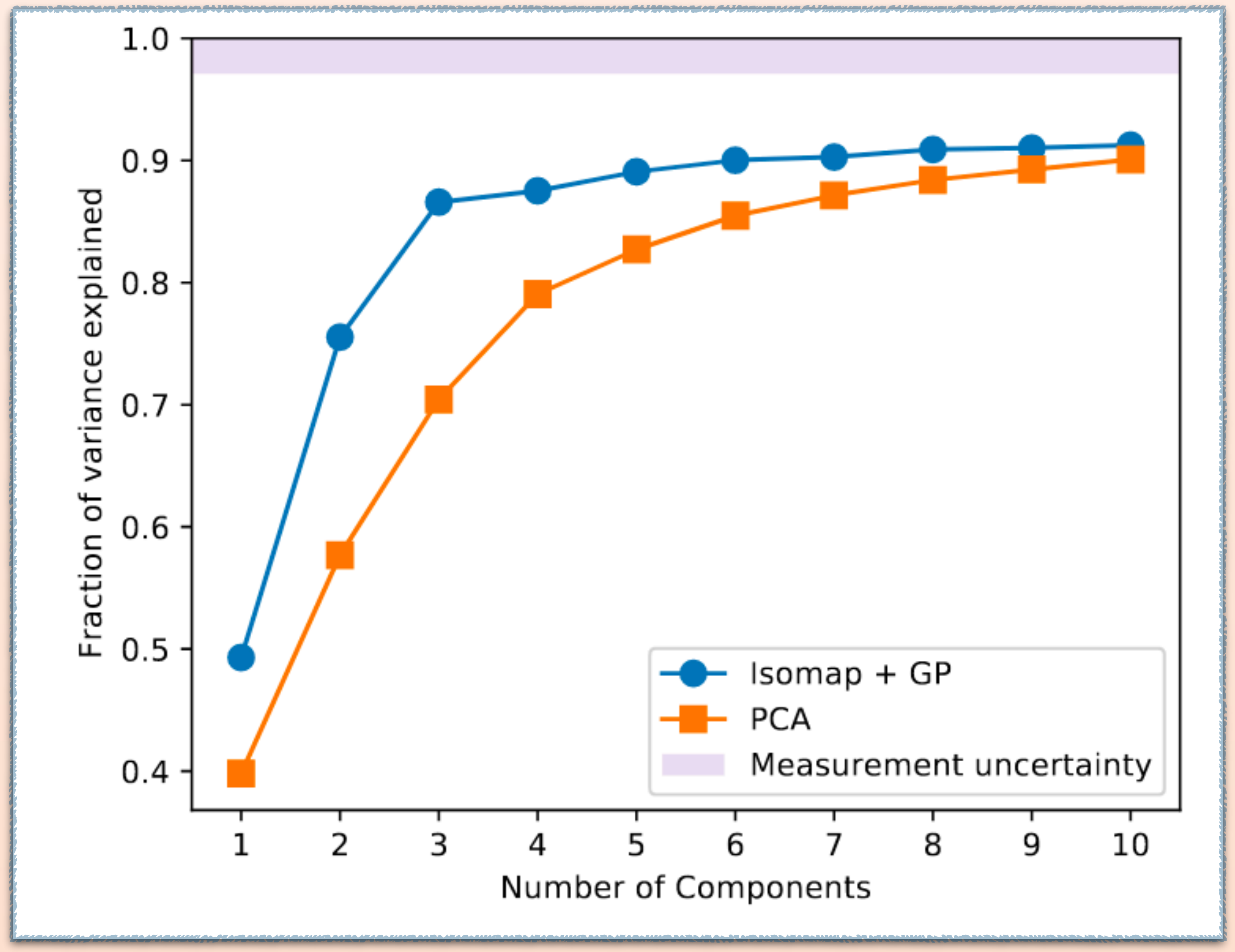
Synthetic photometry in g-band for 789 SNe of ZTF, compared to LC data at peak, before/after DTEM correction

—> estimated precision of 0.01 mag for ZTF in ztf-g band

The Twins Embedding parameters space

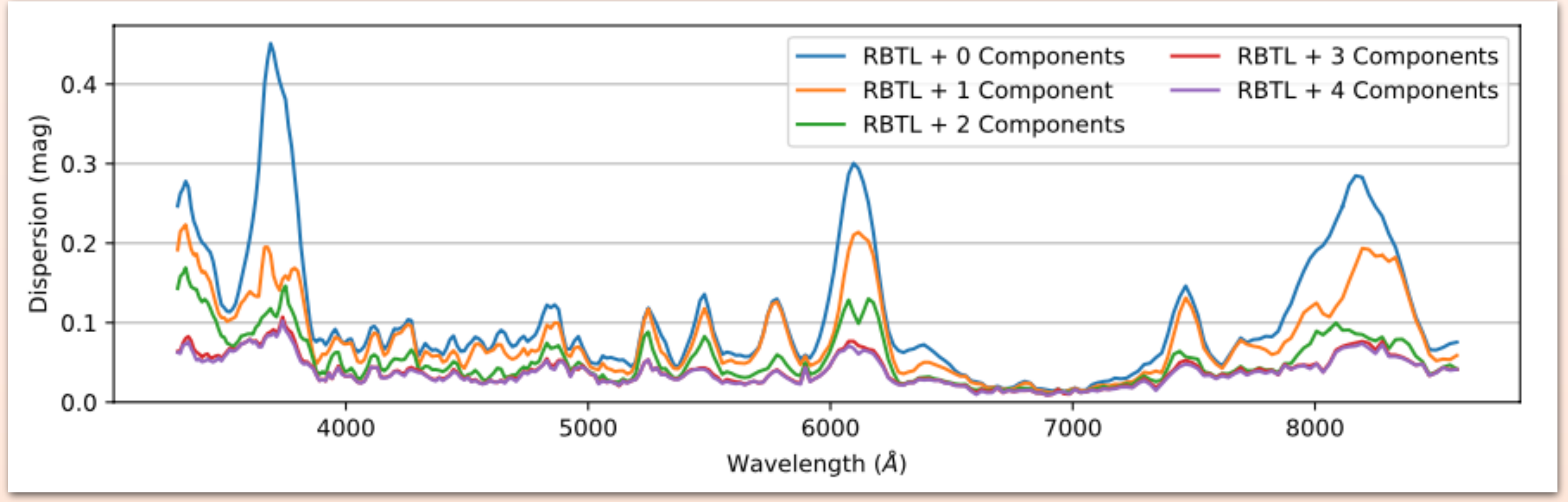
Spectral distance between two Sne I and j :

$$\gamma_{ij} = \sqrt{\sum_k \left(\frac{f_{\mathrm{dered.},i}(\lambda_k) - f_{\mathrm{dered.},j}(\lambda_k)}{f_{\mathrm{mean}}(\lambda_k)} \right)^2}$$



86.6% of variance explained with 3 components

Isomap algorithm embed high-dimensional space to low-dimentional while preserving distances



*From **K.Boone et al. 2021.** SN Factory spectra fluxes STD, in function of wavelengths, for different numbers of Manifold Learning components (parameters reduction)*

But it does not provide a model of a spectrum given its coordinates in the embedding : for that they use Gaussian Process

The standardisation using Twins Embedding

To map the magnitude residuals through the TE space : linear standardisation not sufficient, instead Gaussian Process regression :

$$\delta m_i^{\mathrm{GP}} = GP\left(\mu(m_{\mathrm{ref}}, \omega \cdot \Delta A_{V,i}); \sigma(\overrightarrow{\xi}_i, \overrightarrow{\sigma}^2_{p.v.,i}, \sigma_u^2)\right)$$

Fitted parameters :

m_{ref} *a common reference magnitude*

ω *a linear correction term*

σ_u *the unexplained residual dispersion*

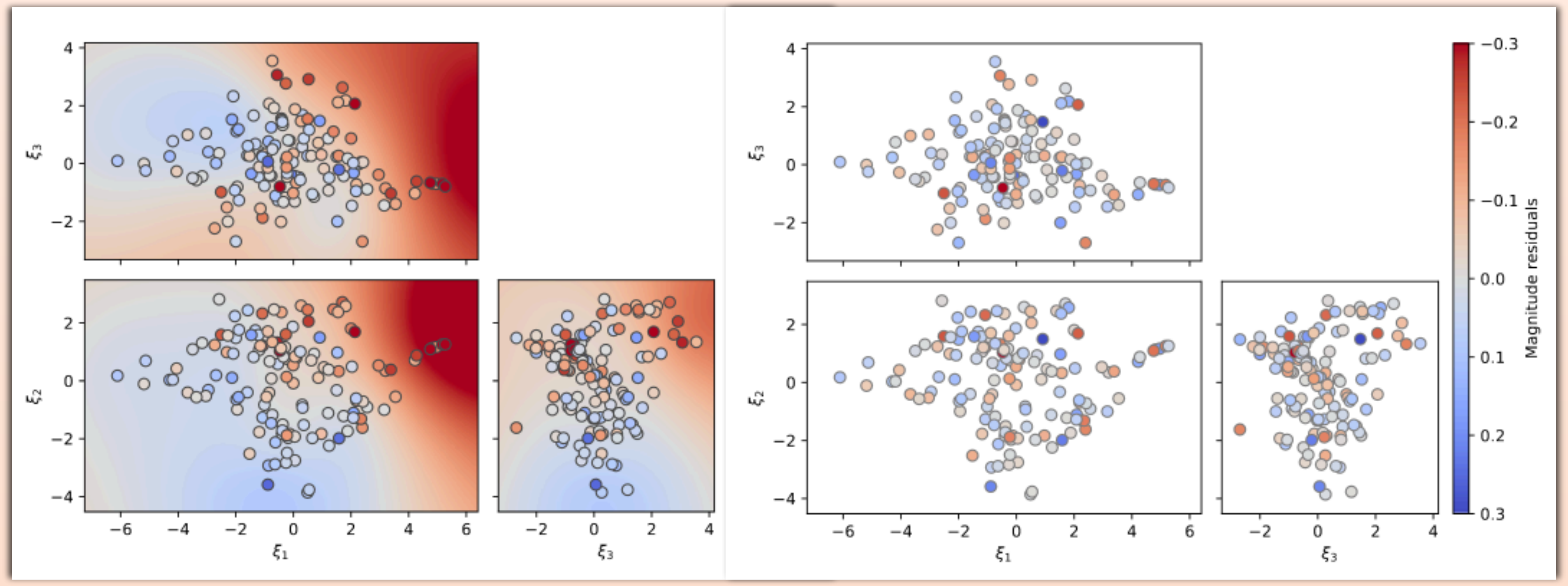
Known :

δm_i^{GP} *the RBTL magnitude residual*

$\Delta A_{V,i}$ *the RBTL color*

$\overrightarrow{\xi}_i$ *the Isomap coordinates*

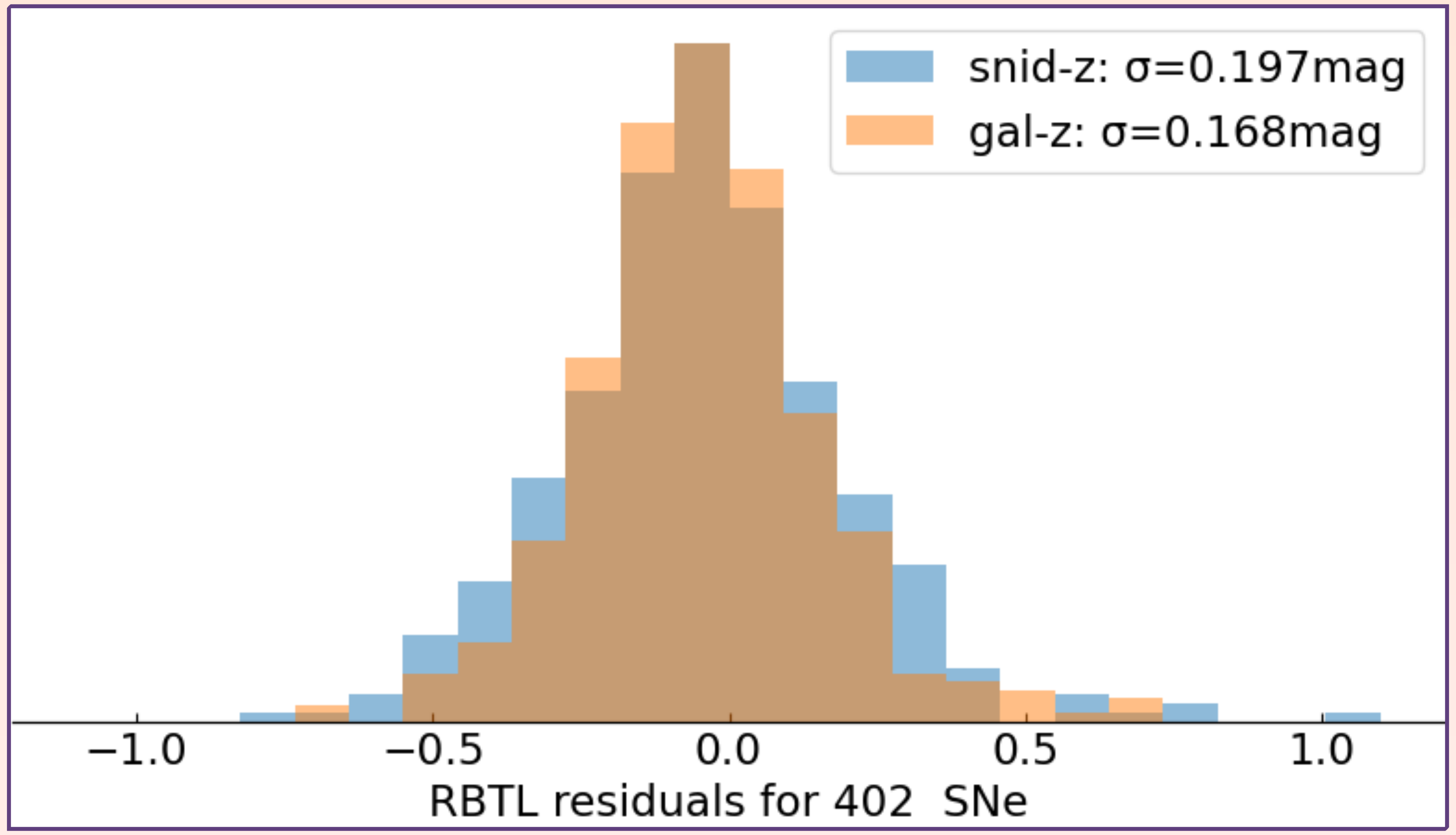
$\overrightarrow{\sigma}^2_{p.v.,i}$ *the host galaxy peculiar velocity variance*



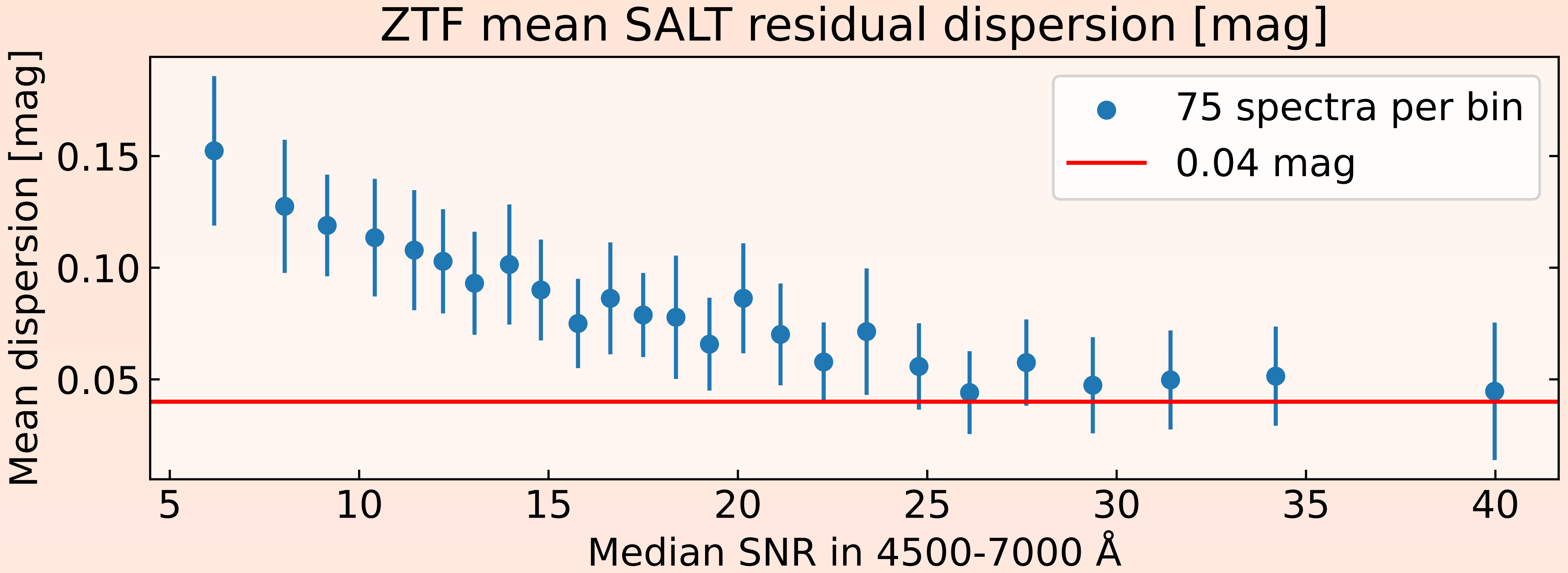
Before/after correction of magnitude residuals with GP from Boone 2021b

ZTF additional dispersion estimates

We run on 60% percent of the sample that have both SNID-z and gal-z: we found 0.07mag difference (in quadratic)



So we reduce the dispersion of 40% of the sample which have SNID-z only.



SNR should be absorbed by Δm

- **0.07mag due to 40% of SNe with $\sigma_z \sim 10^{-3}$**
- **0.04mag dispersion floor due to flux-calibration**

falls to 0.126 mag dispersion