Spectrophotometric standardisation of SNe Ia

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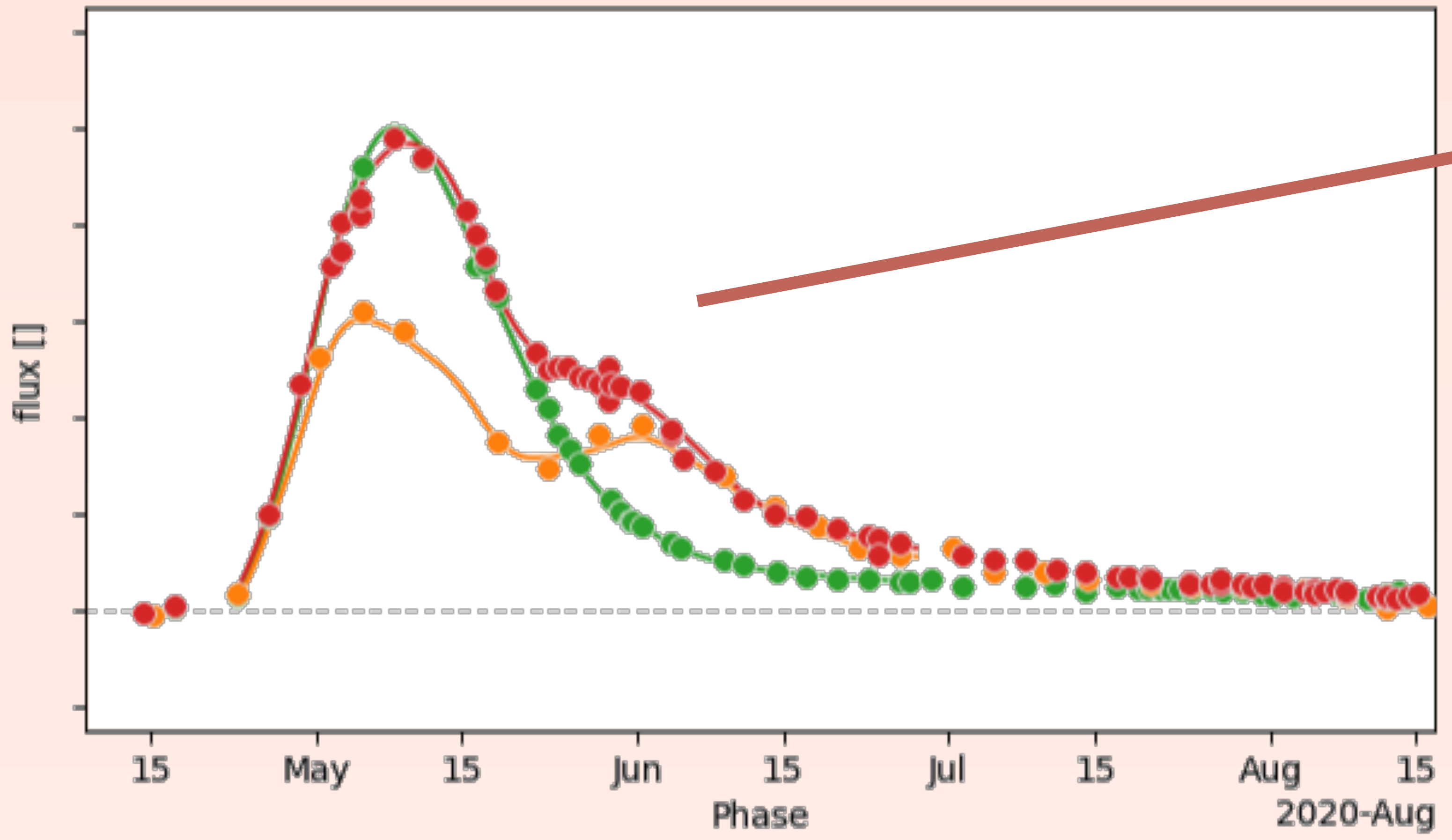
Summary

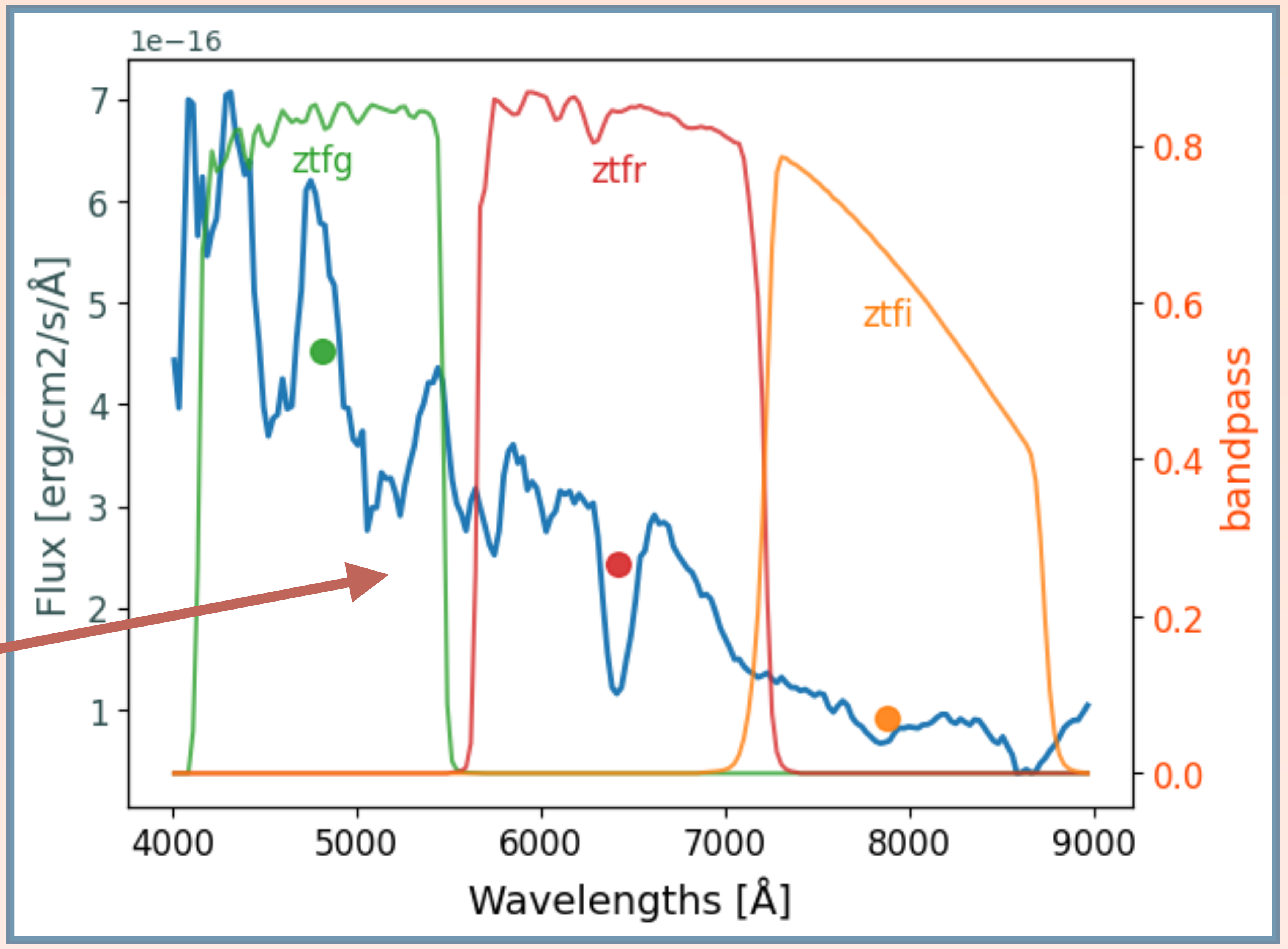
- Spectro-photometric standardisation
- ZTF spectra sample
- Twins Embedding on ZTF
- SNLS spectra sample
- Conclusion

Spectro-photometry

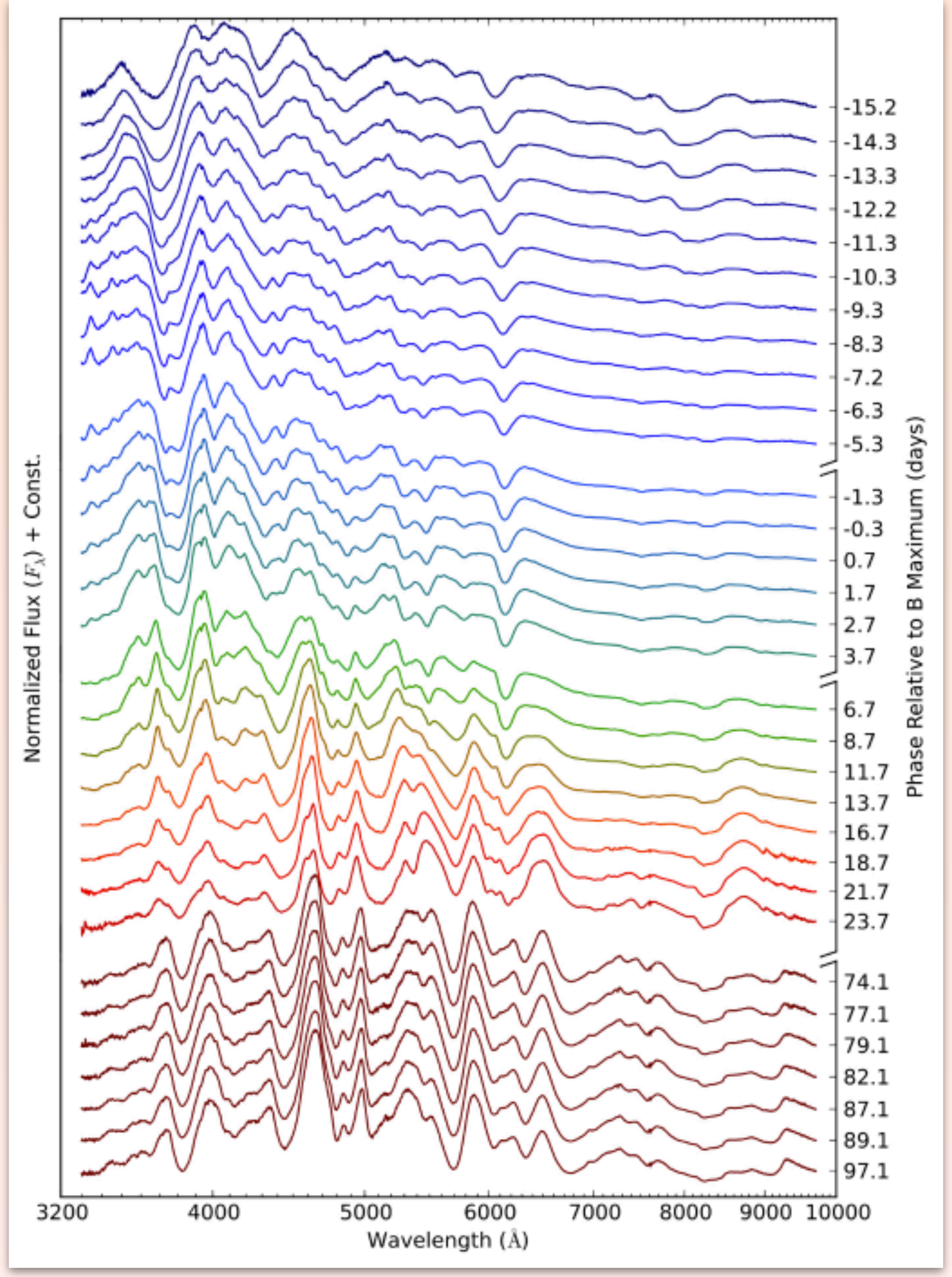
A lightcurve datapoint corresponds to the spectrum integrated in the bandpass



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



Synthetic photometry in ZTF filters
ZTF20abxzrqw at phase +1.29



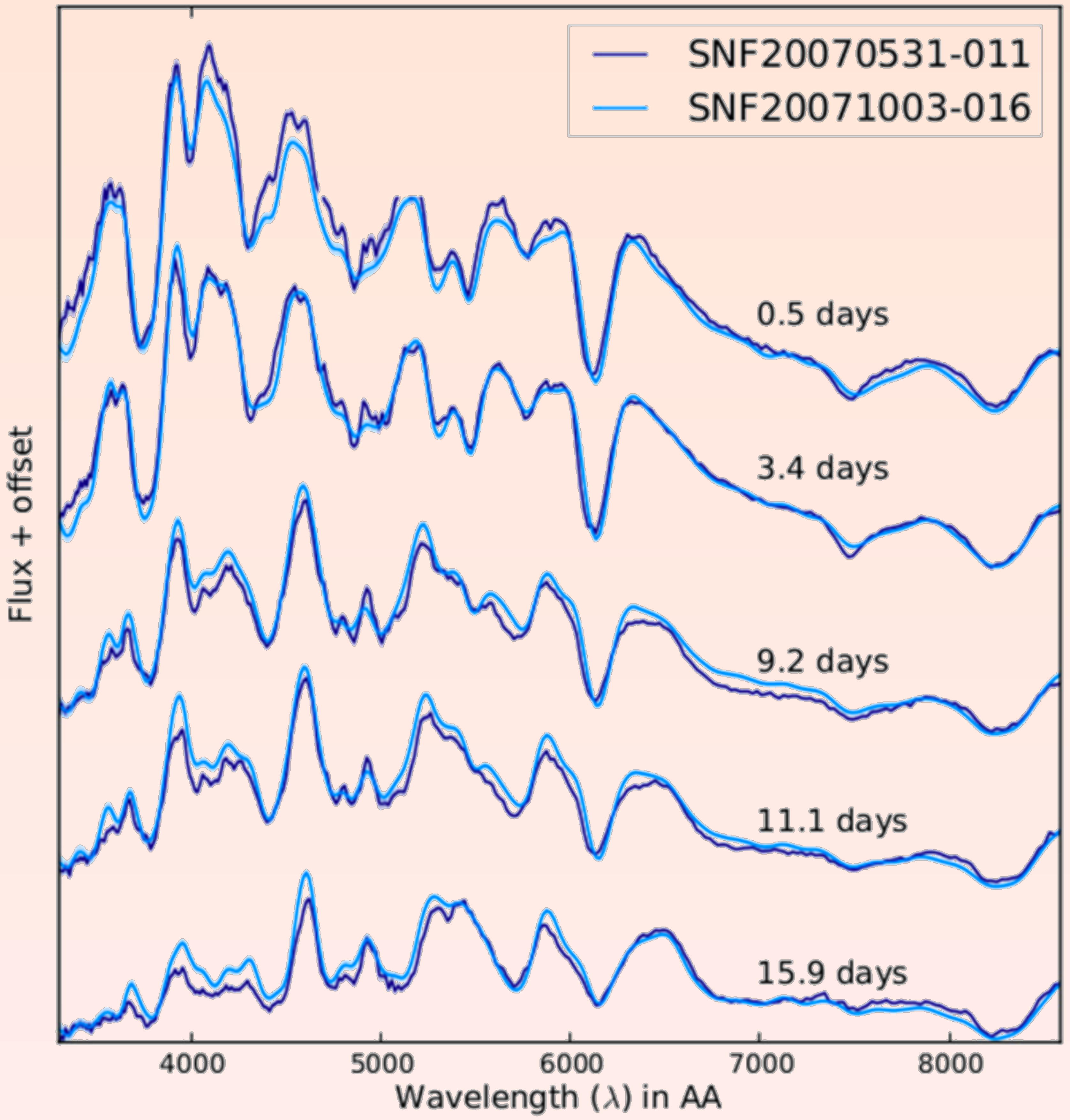
Time series of SN2011fe
between **-15** to **+100** days
Credit: Pereira et al. 2013

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

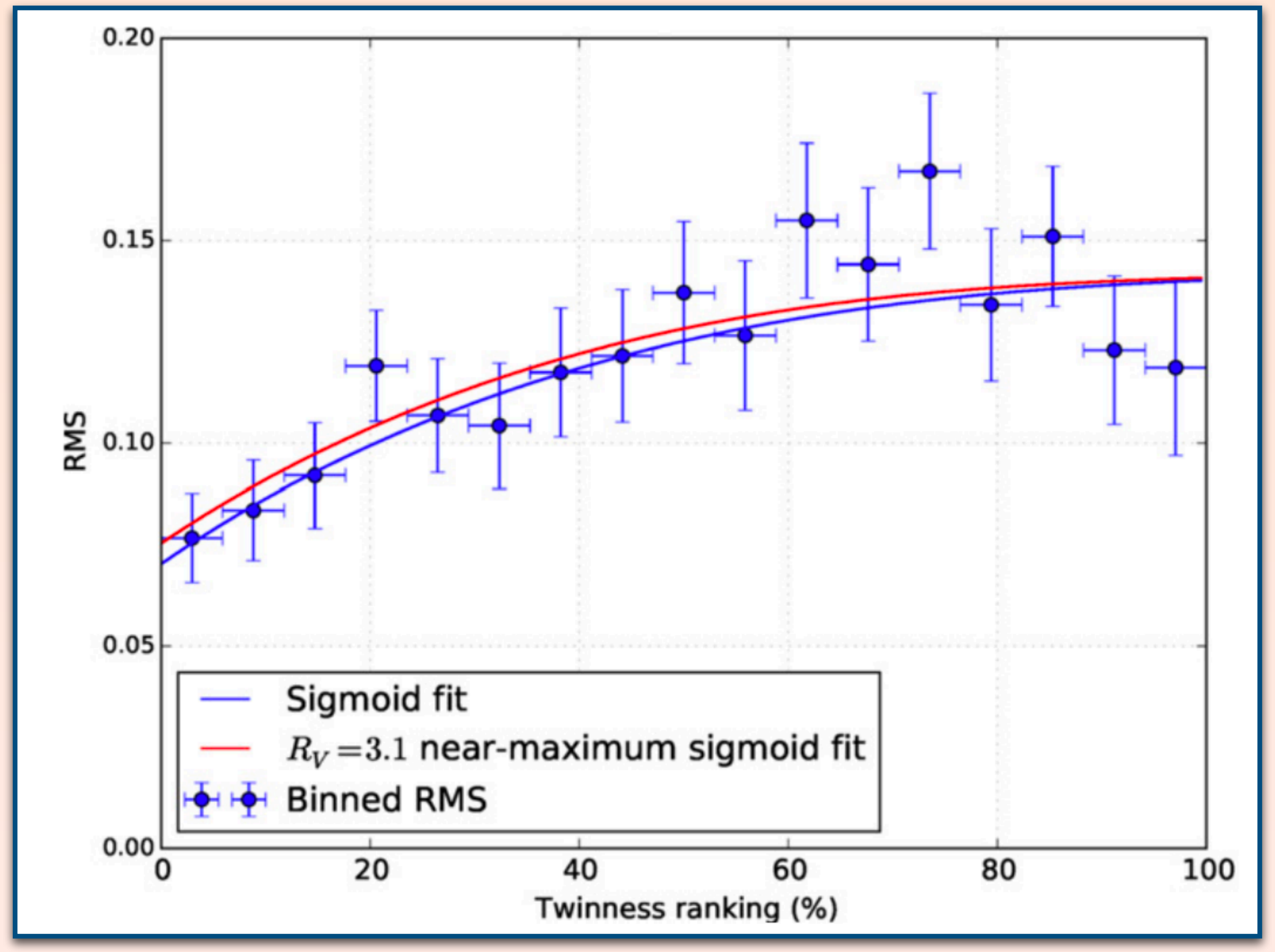
Spectro-photometric standardisation

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

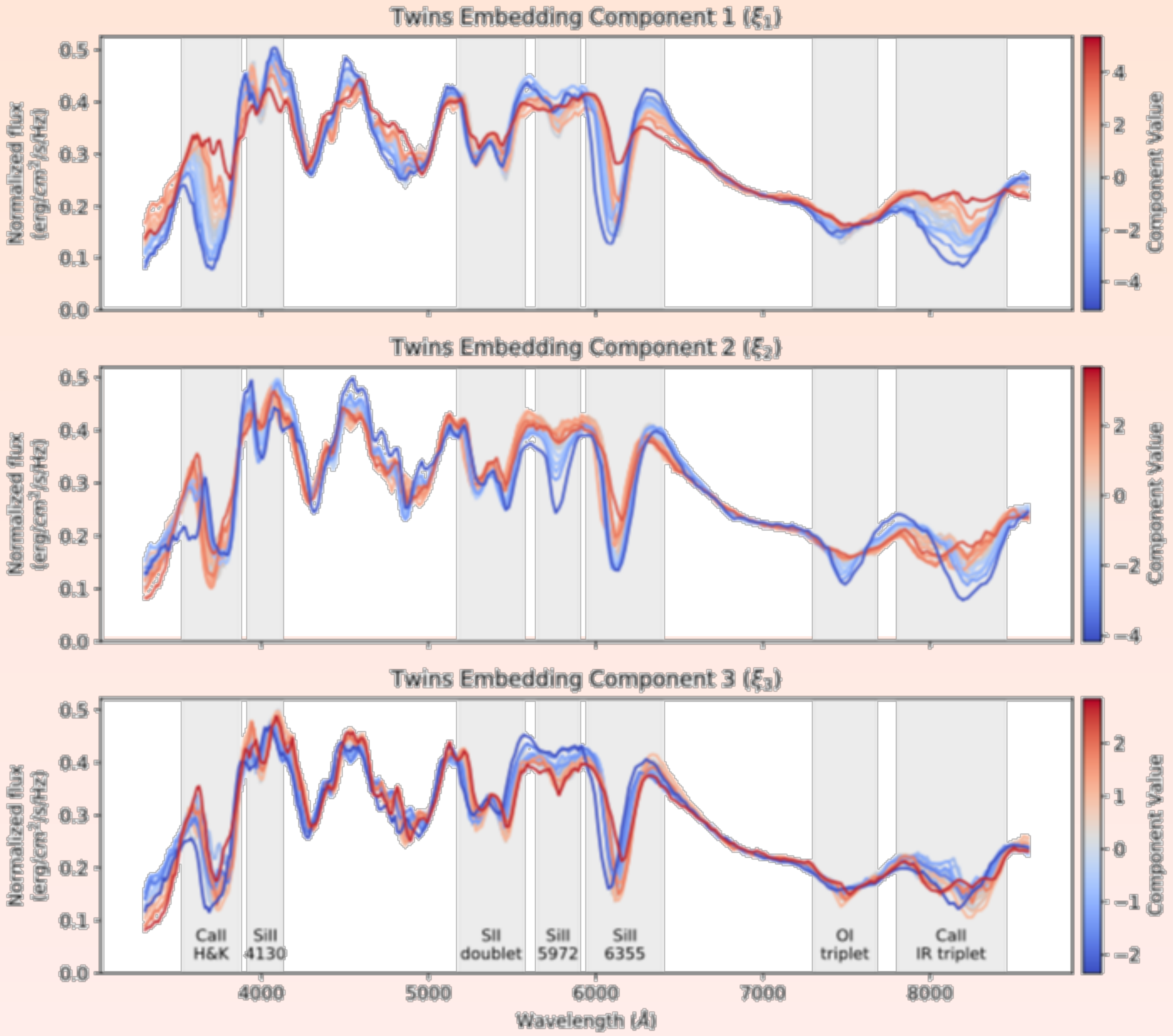
—> magnitude dispersion is smaller for the lowest 'twinness' parameters

—> Only one spectrum at maximum per SN Ia 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*

—> New standardisation of distance modulus, using spectral information

-> Describe the spectral variation at phase=0

Before standardisation :
$\sigma_{mag} = 0.40\text{mag}$

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

With SNFactory

Twins Embedding :
$\sigma_{mag} = 0.07\text{mag}$

SNFactory : ~250 SNe

↓

ZTF : ~700 SNe (for now)

ZTF spectra sample

March 2018 to December 2020

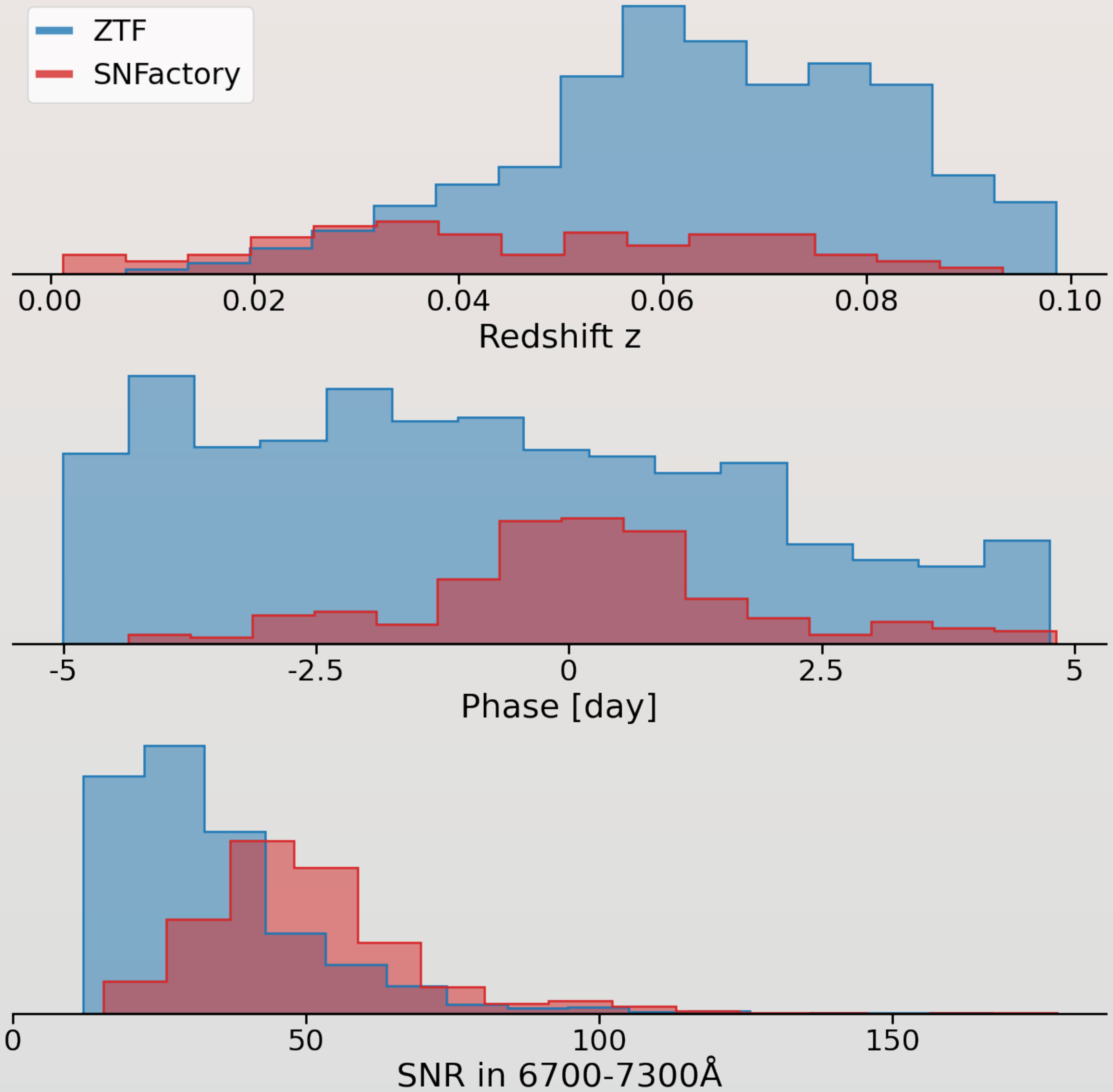
SEDm (P60)
Integral field Spectrograph

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

Optical window: 3,650 - 10,000 Å

Cut	Interval	Quantity removed
from SEDm		40 %
Quality		20 %
z	<0.1	around 7/8%
phase	[-5,+5] days	**around 50%**
cosmo		around 15%

—> 752 spectra from 695 SNe Ia

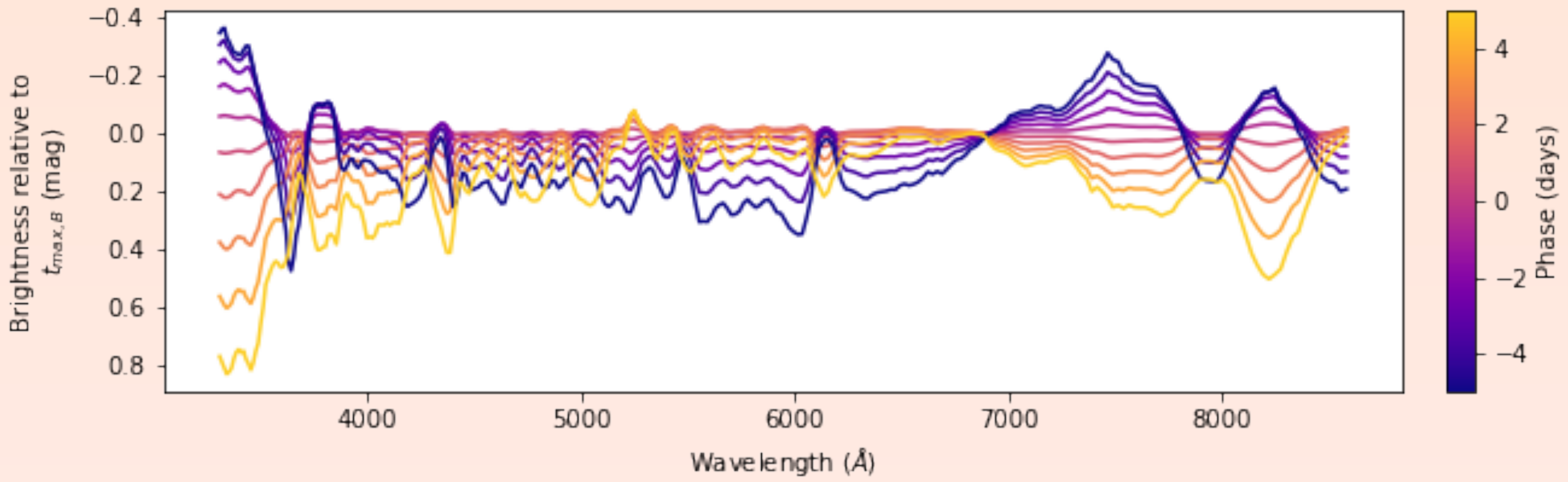


Twins Embedding - *Boone et al. 2021*

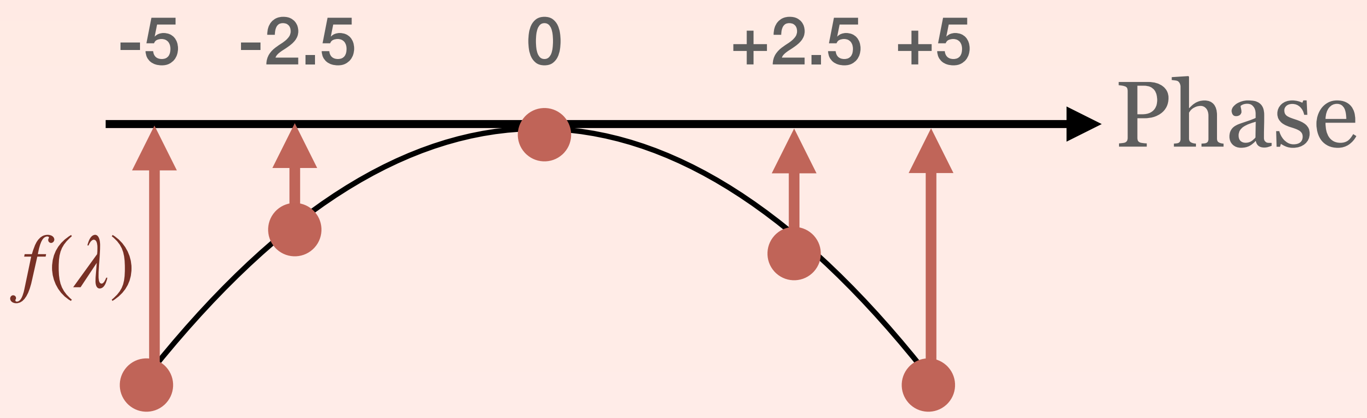
3 steps

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

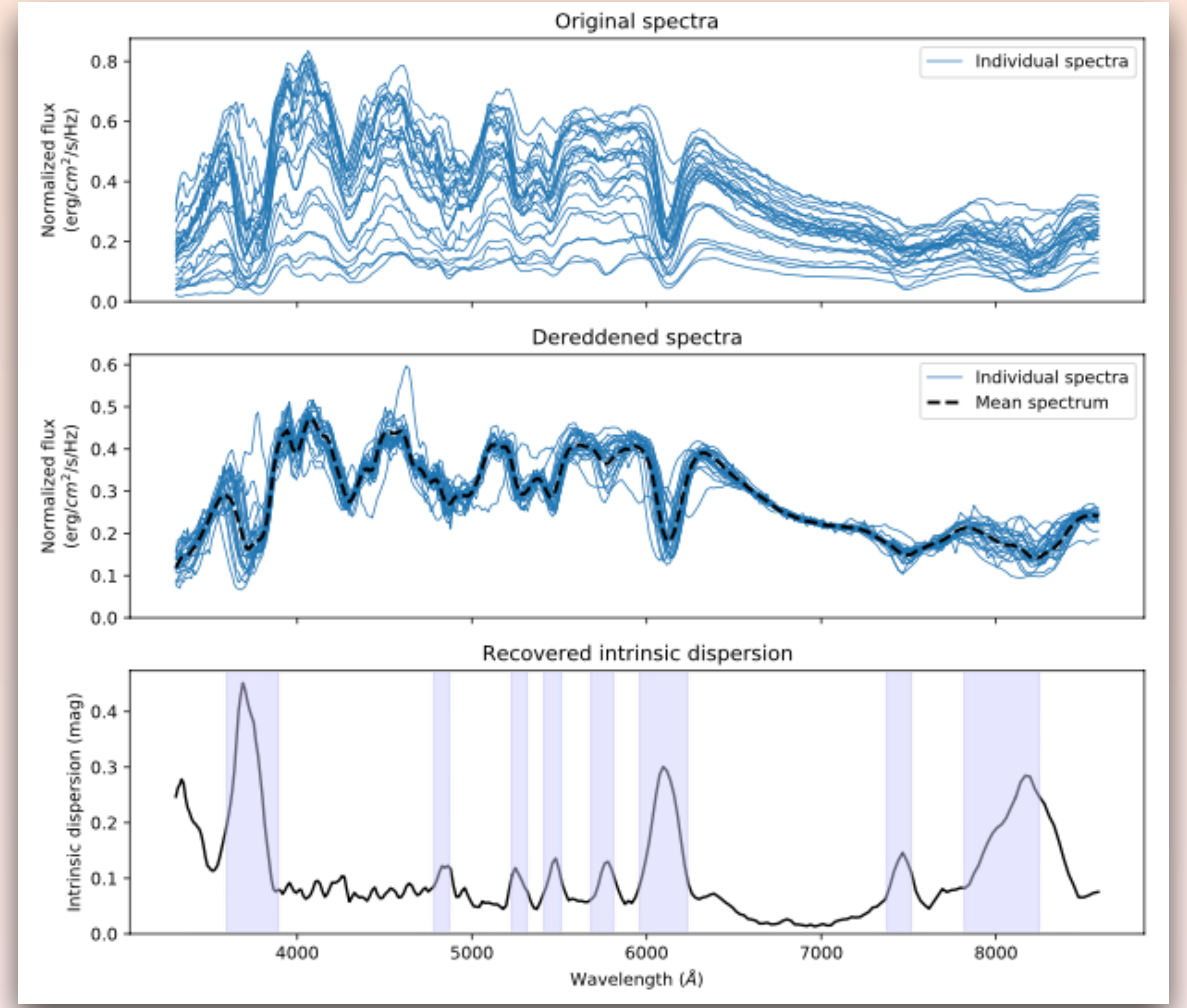


On bessell-b Lightcurve

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

2. RBTL - fit one offset and a color outside the lines

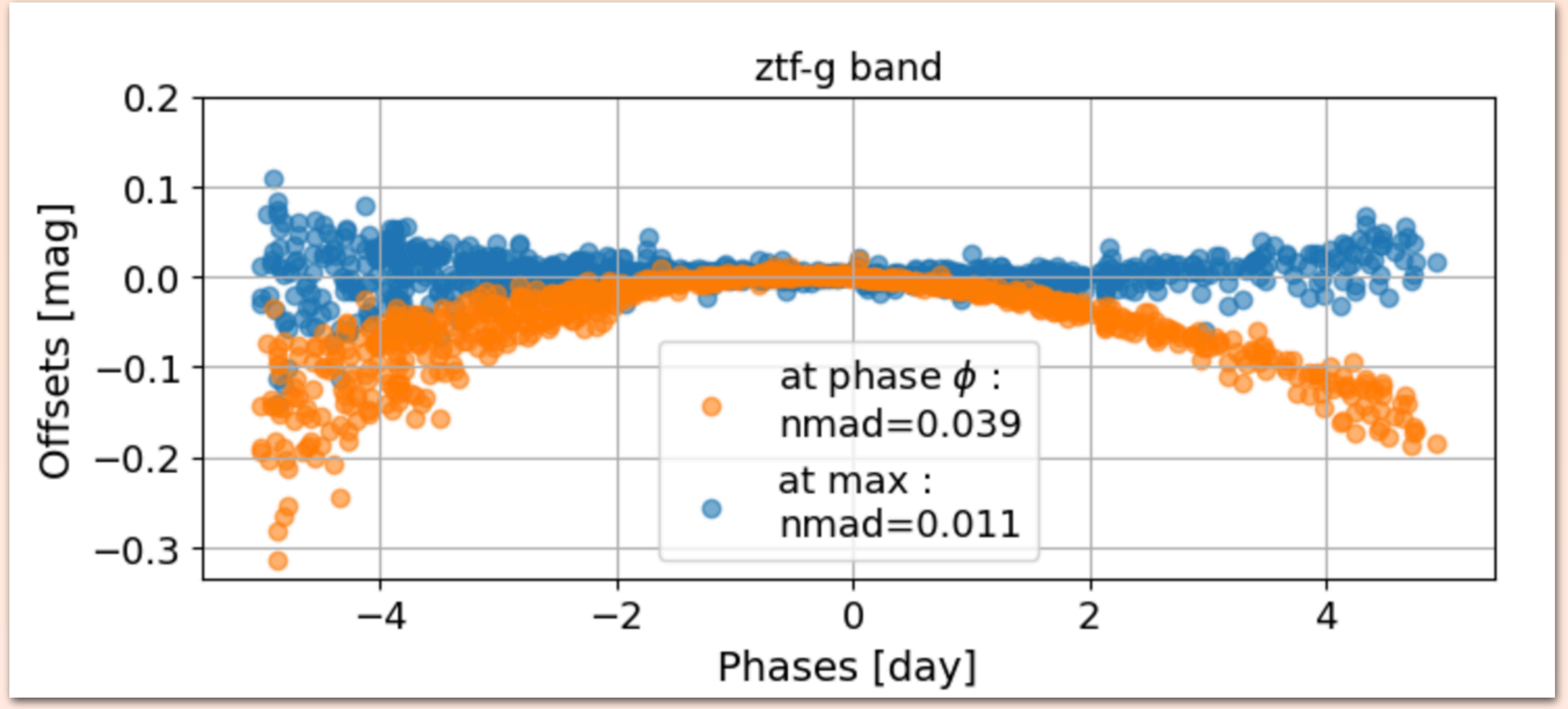
- Δm_i a magnitude offset compared to reference spectrum
- $\Delta \tilde{A}_{V,i}$ a color coefficient compared to reference spectrum



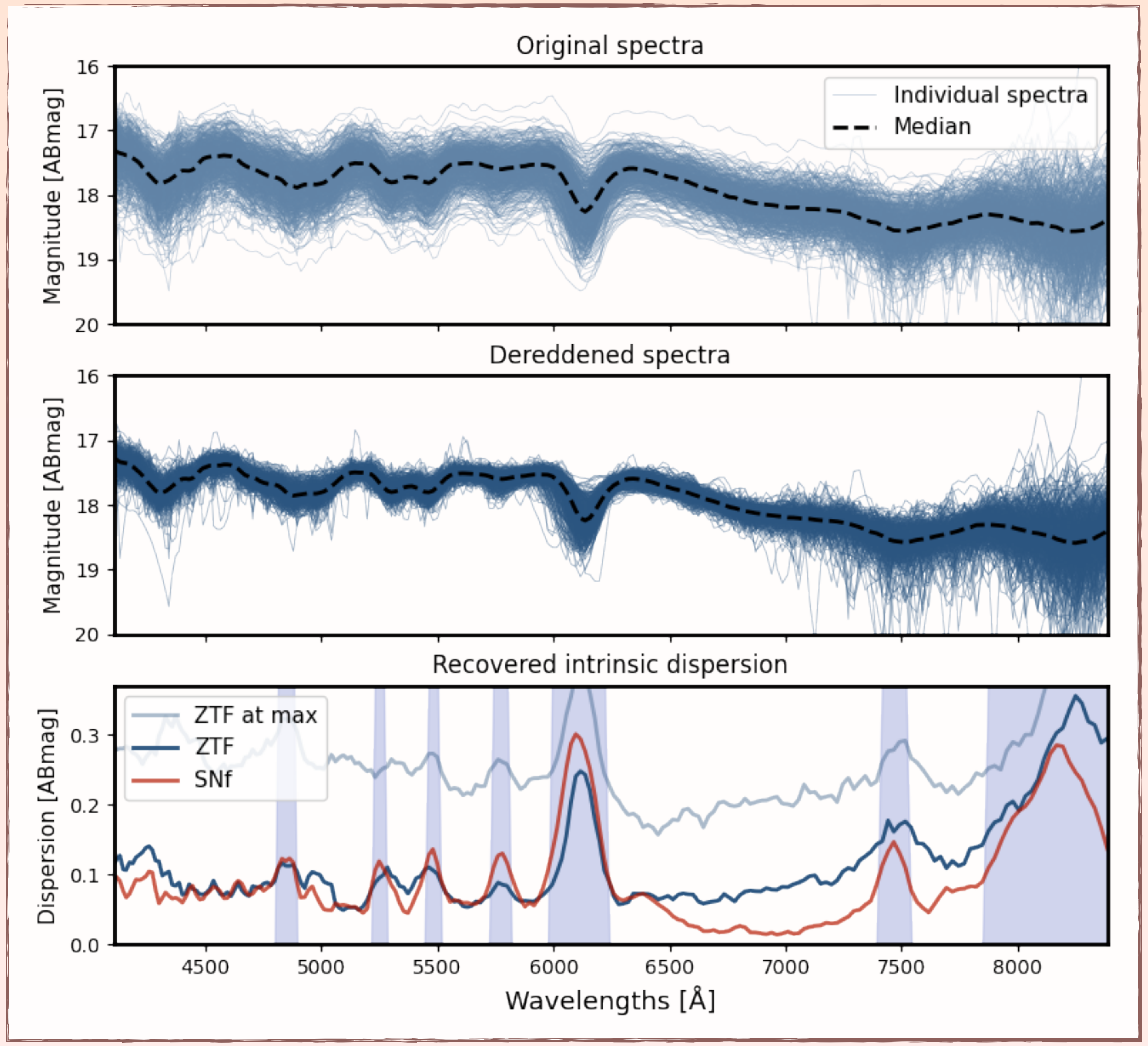
SNFactory spectra before/after dereddening, and residuals intrinsic dispersion (std) *Credit : Boone et al. 2021*

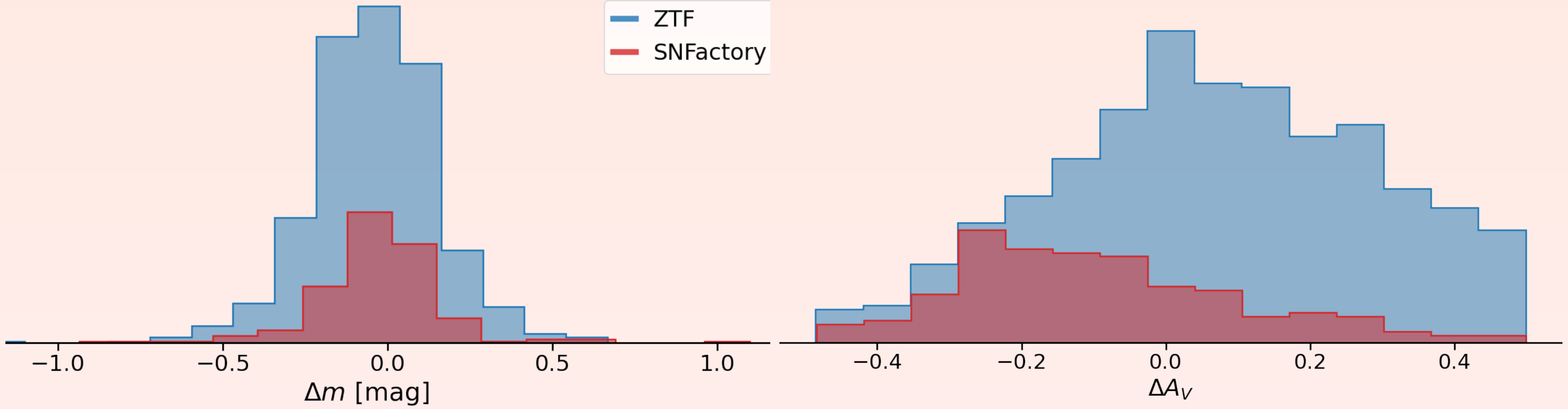
Twins Embedding on ZTF

- ☑ Flux calibration
- ☑ Milky Way correction
- ☑ Shift spectra to z=0.05
- ☑ Put at phase=0



Photometric evolution in phase for **ZTF** sample, in g-band (closest to besselb)





More red SNe in **ZTF** sample, same distribution in magnitude

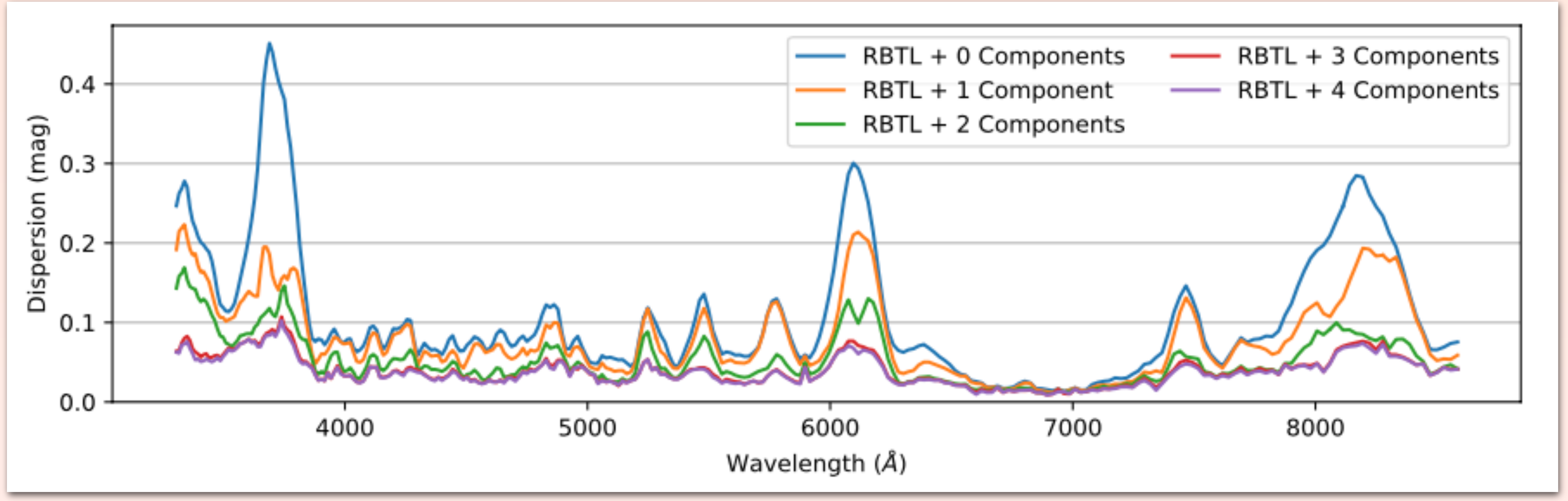
ZTF spectra before/after dereddening, and Spectral dispersion (nMAD) after RBTL correction for **SNf** and **ZTF**

Twins Embedding - *Boone et al. 2021*

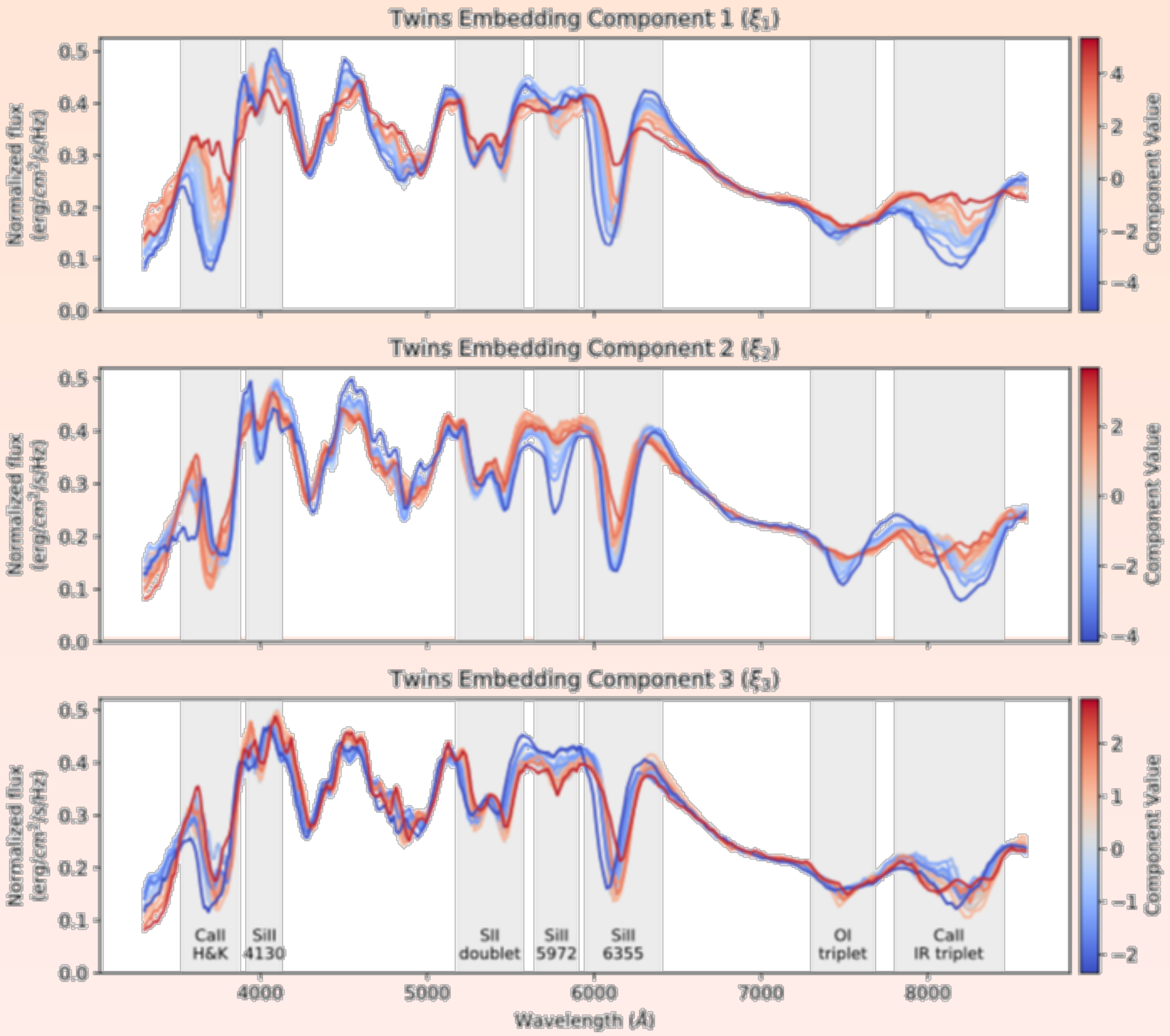
3 steps

1. **Generate at maximum luminosity**
2. **RBTL - *fit one offset and a color outside the lines***
3. **Manifold Learning - *parameters reduction***

87% of remaining variance explained with 3 components



SNFactory spectra fluxes STD, in function of wavelengths, for different numbers of Manifold Learning components : **parameter reduction**. *Credit : Boone et al. 2021*



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

Twins Embedding - *Boone et al. 2021*

3 steps

1. **Generate at maximum luminosity**
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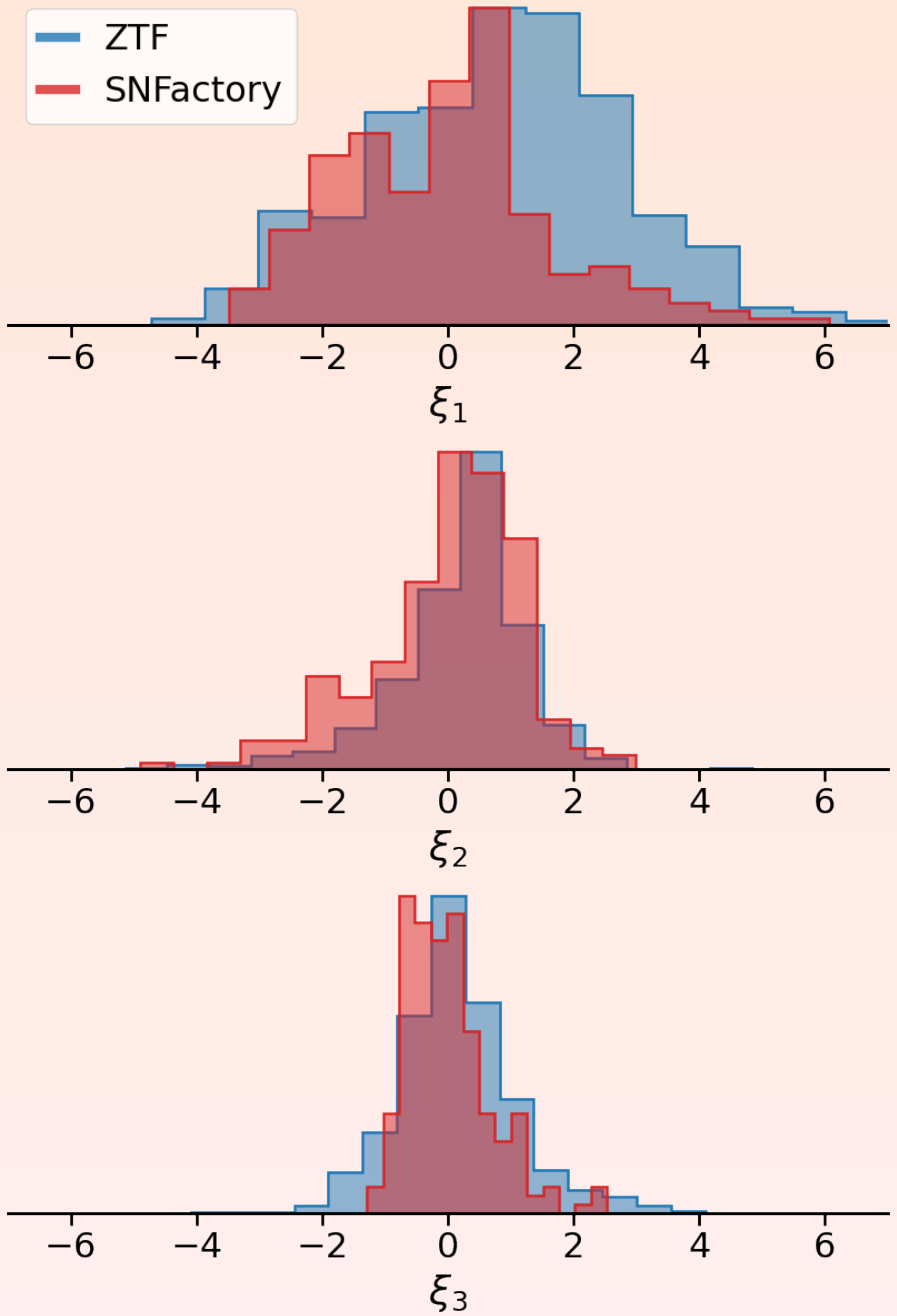
3. **Manifold Learning - *parameters reduction***

*Normalised distributions of Manifold components for both **ZTF** and **SNf***



- ξ_2 matching
- Differences for ξ_1 and ξ_3, and outlyers have been removed

RBTL standardisation

linear correction

$$\mu = m^{max} - M^{max} - \alpha \cdot \Delta A_V$$

Manifold standardisation

Gaussian process

$$\mu = m^{max} - M^{max} - GP(\vec{\xi}\,)$$

With SNFactory

Twins Embedding :

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

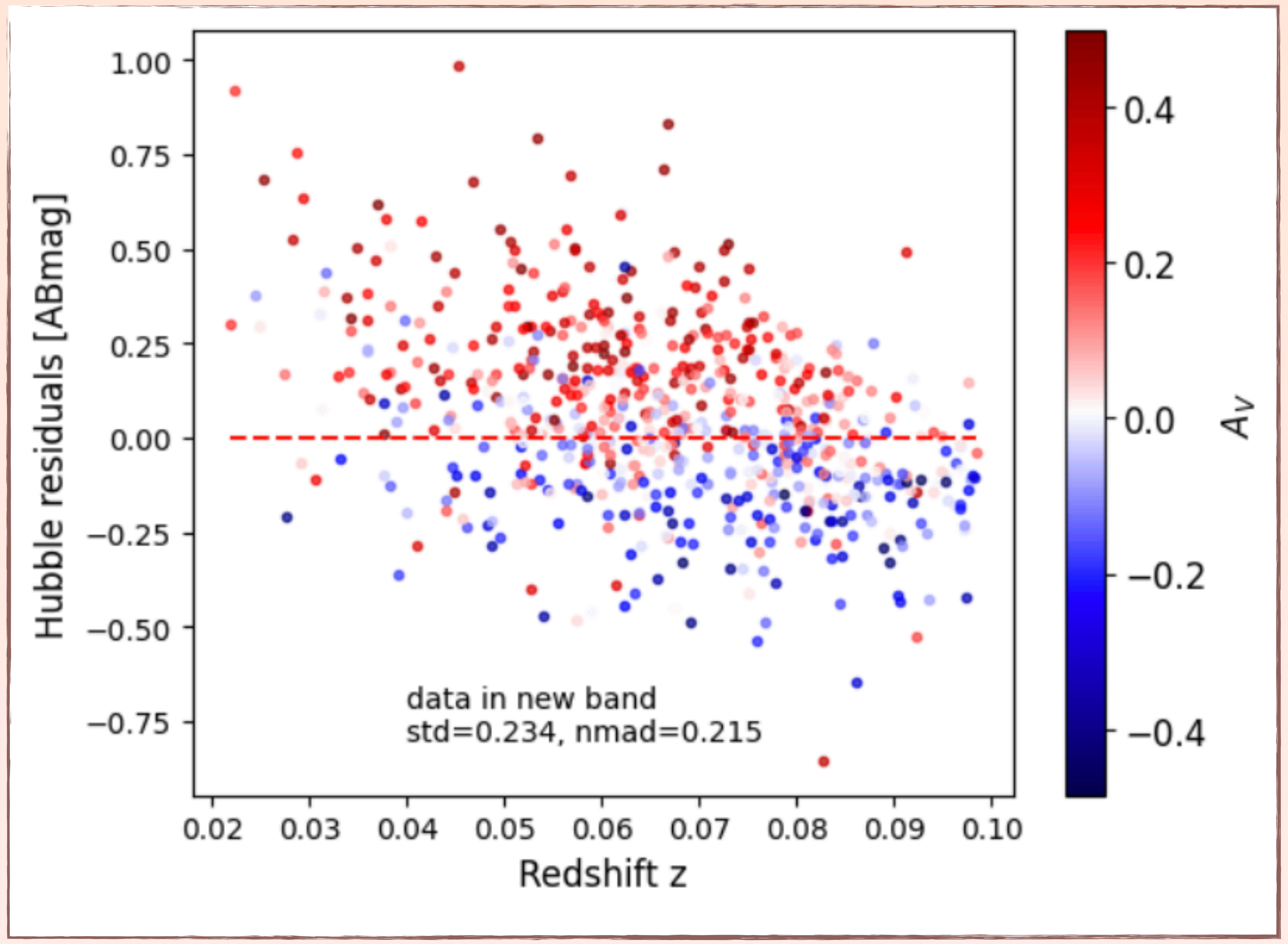
—> what with ZTF ?

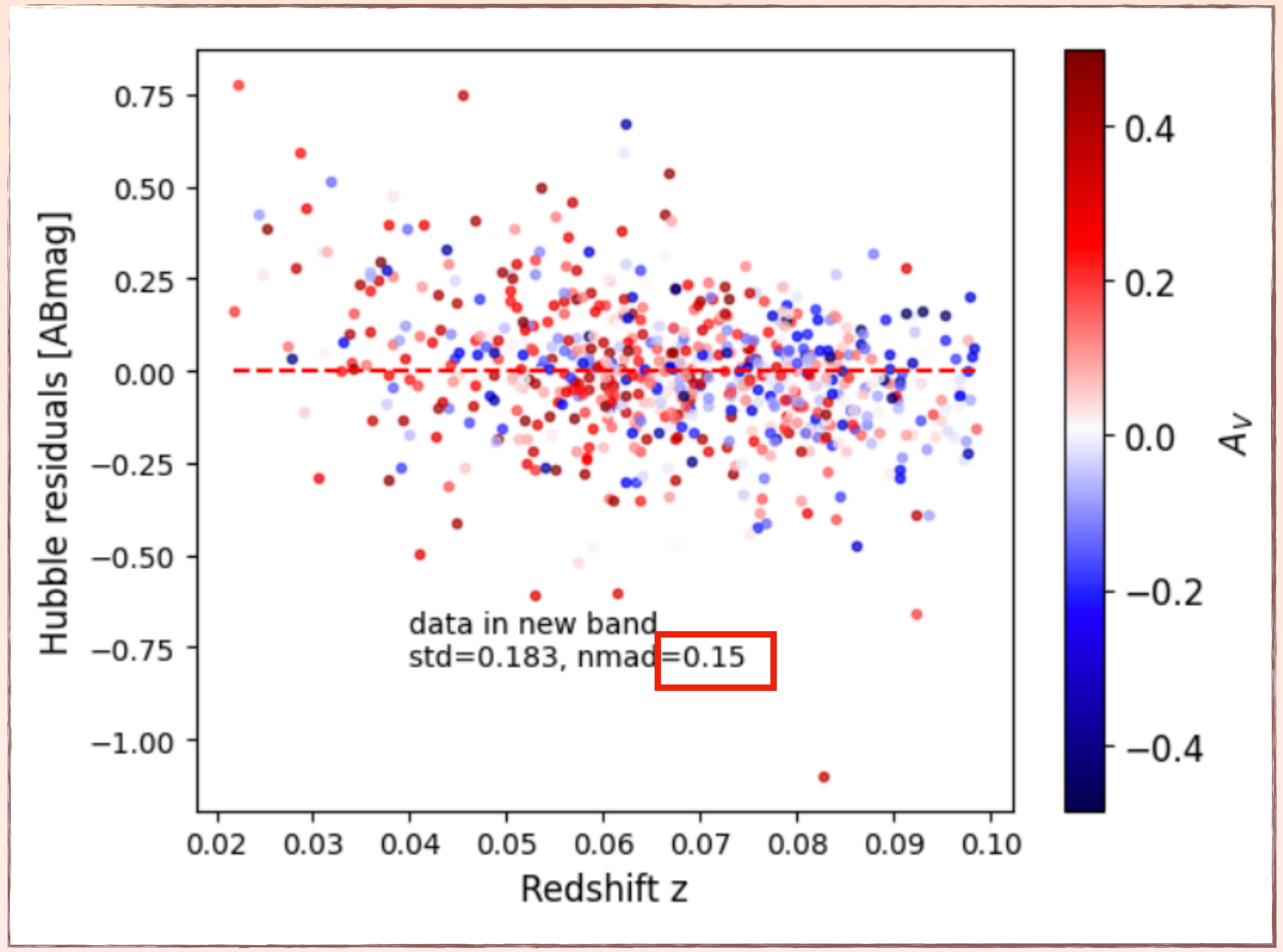
(work in progress)

RBTL linear standardisation

$$\Delta\mu = \mu_{z=0.05} - (m_{band} - M_{offset})$$

$$-\alpha \cdot \Delta A_V$$





For ZTF sample

647 SNe Ia before/after standardisation
after a cut on DAv < 0.5 (remove around 7% SNe)

Comparable dispersion that photometric standardisation with only 1 parameter

SuperNova Legacy Survey

2003 to 2008

High-redshift $0.2 < z < 1$
Equatorial sky
4 bands : g, r, i/i2, z
$1deg^2$

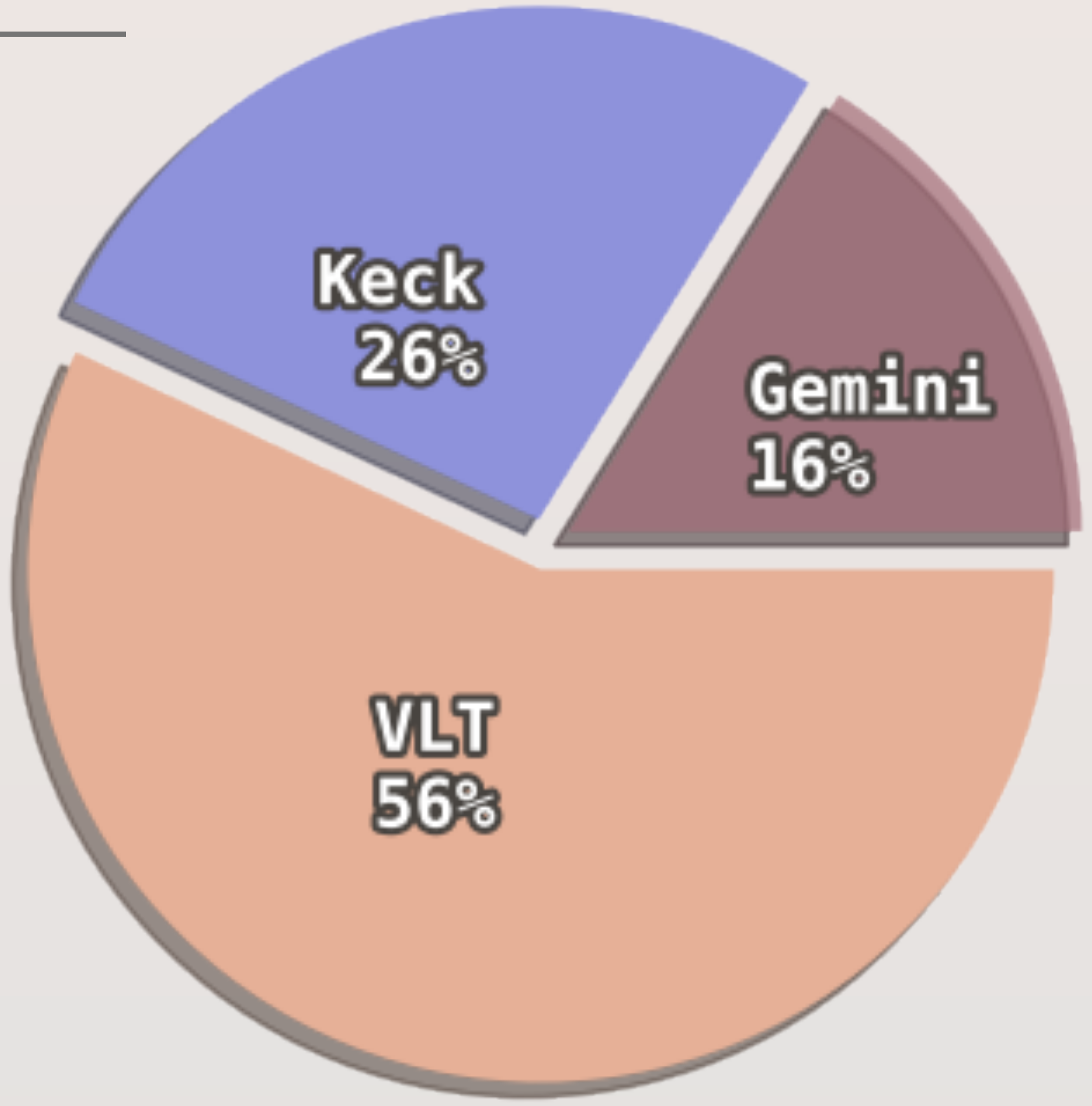
—> 133 spectra from 127 SNe Ia ***after cuts***

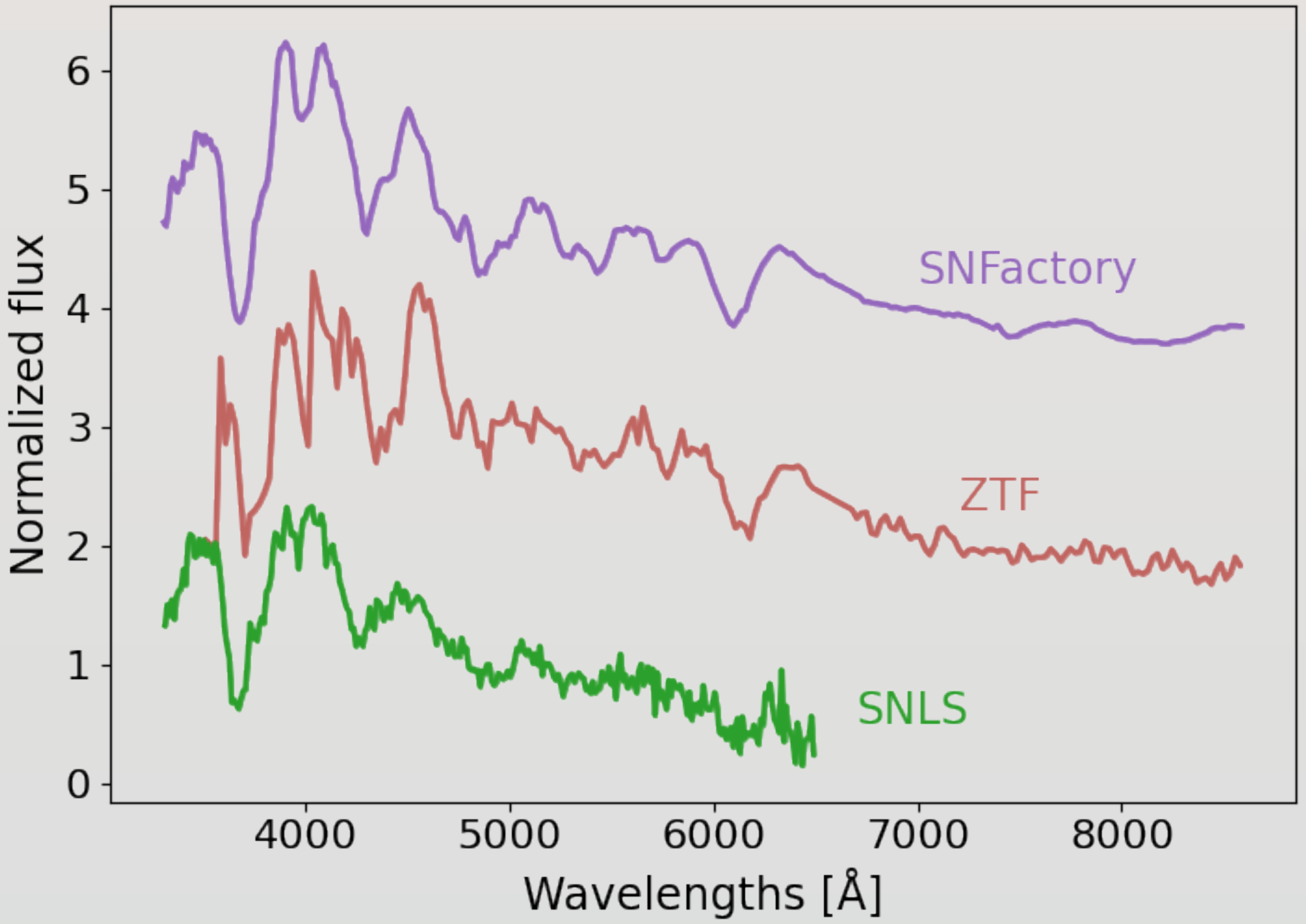
- ☑ Flux calibration
- ☑ Milky Way correction
- ☑ Shift spectra to z=0.05
- ☑ Put at phase=0

Instruments :

- Megacam 3.6m camera
- 3 follow-up spectrograph

8m telescopes : Gemini N&S, VLT, Keck





Located on the Mauna Kea mountain in Hawaii

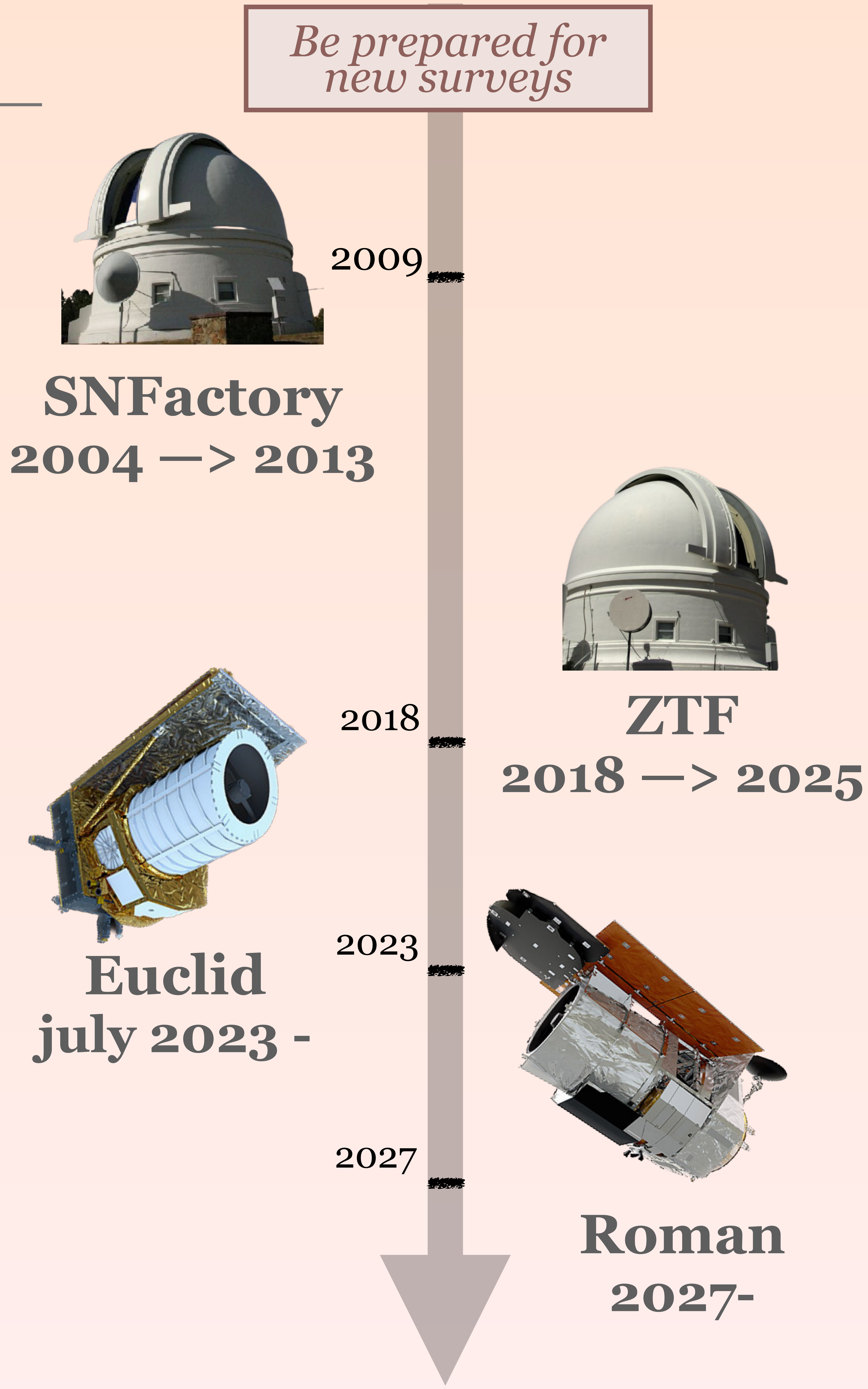
Conclusion

First TE application results :

- RBTL standardisation is working well
- Manifold standardisation still in progress

Goals

- paper on ZTF + TE (around January)
- build a first Hubble Diagram with ZTF + SNLS using spectrophotometric standardisation



STEP 1

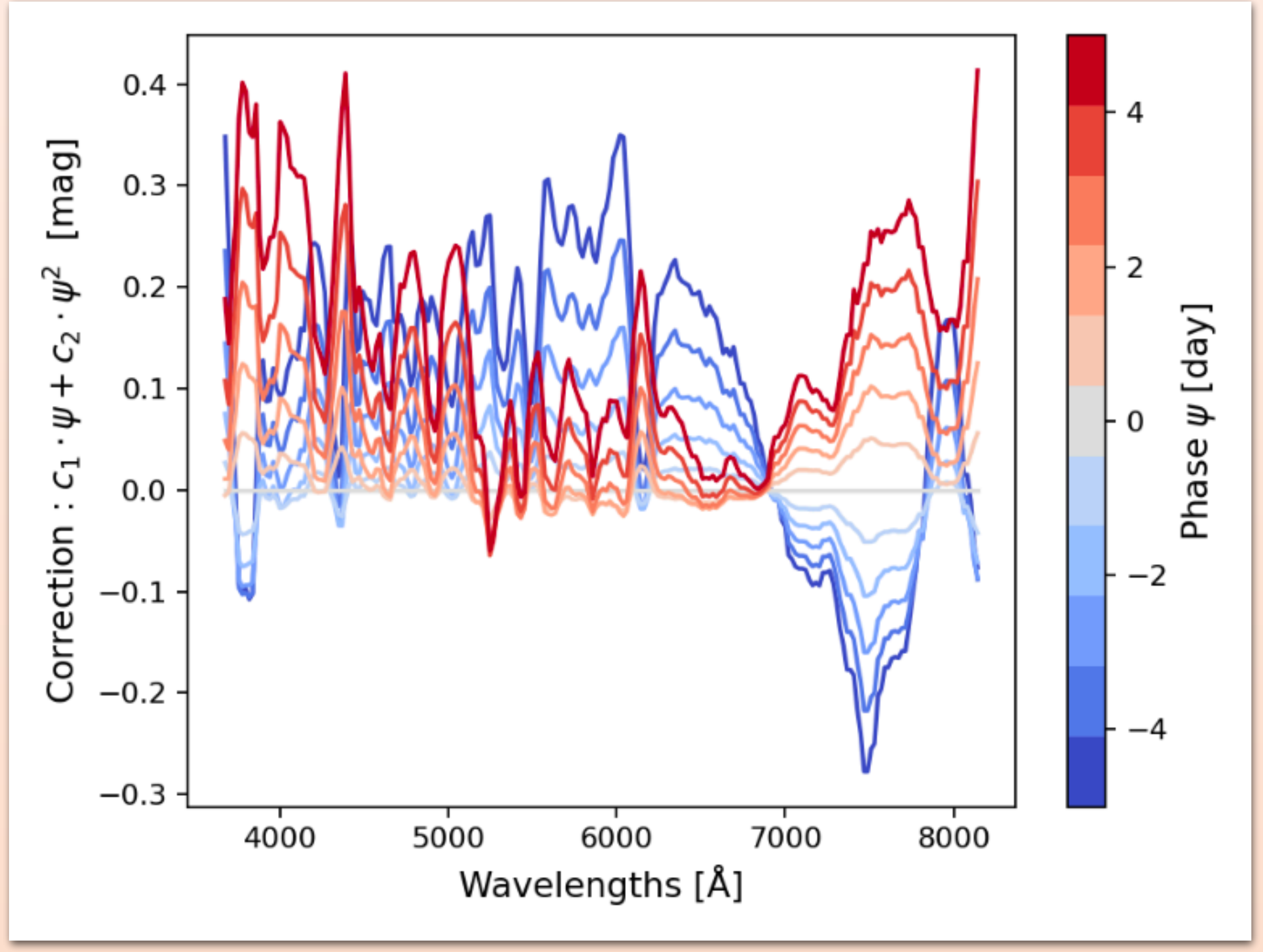
Differential time evolution model

=> ***Spectra @ max***

Formula of quadratic evolution in phase :

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

with p the phase,
$c_{1,2}(\lambda_k)$ the coefficients common to all Sne
$m_i(p,\lambda_k)$ the magnitude of the SN i



Quadratic evolution in phase of SN Ia spectra

$$f_{meas.,\,s}(p;\lambda_k) \sim N(f_s(p;\lambda_k); \sigma^2_{tot.,\,s}(p;\lambda_k))$$

$$f_s(p;\lambda_k) = 10^{-0.4(m_i(p;\lambda_k)+m_{\mathrm{gray},s})}$$

$$\sigma^2_{tot.,\,s}(p;\lambda_k) = \sigma^2_{\mathrm{meas.},s}(\lambda_k) + (\epsilon(p;\lambda_k)\cdot f_s(p;\lambda_k))^2$$

<u>Fitted parameters :</u>
$f_s(p,\lambda_k)$ the model flux of spectrum s
$\epsilon(p,\lambda_k)$ the model uncertainties common to all Sne,
$m_{gray,s}$ the gray offset of the spectrum s
$c_{1,2}(\lambda_k)$ the coefficients common to all Sne

<u>Known:</u>
$f_{obs}(p,\lambda_k)$ the observed flux of spectrum s

Capture 84.6% of the spectral evolution variance common to every Sne between -5 and 5 days

STEP 1

Differential time evolution model

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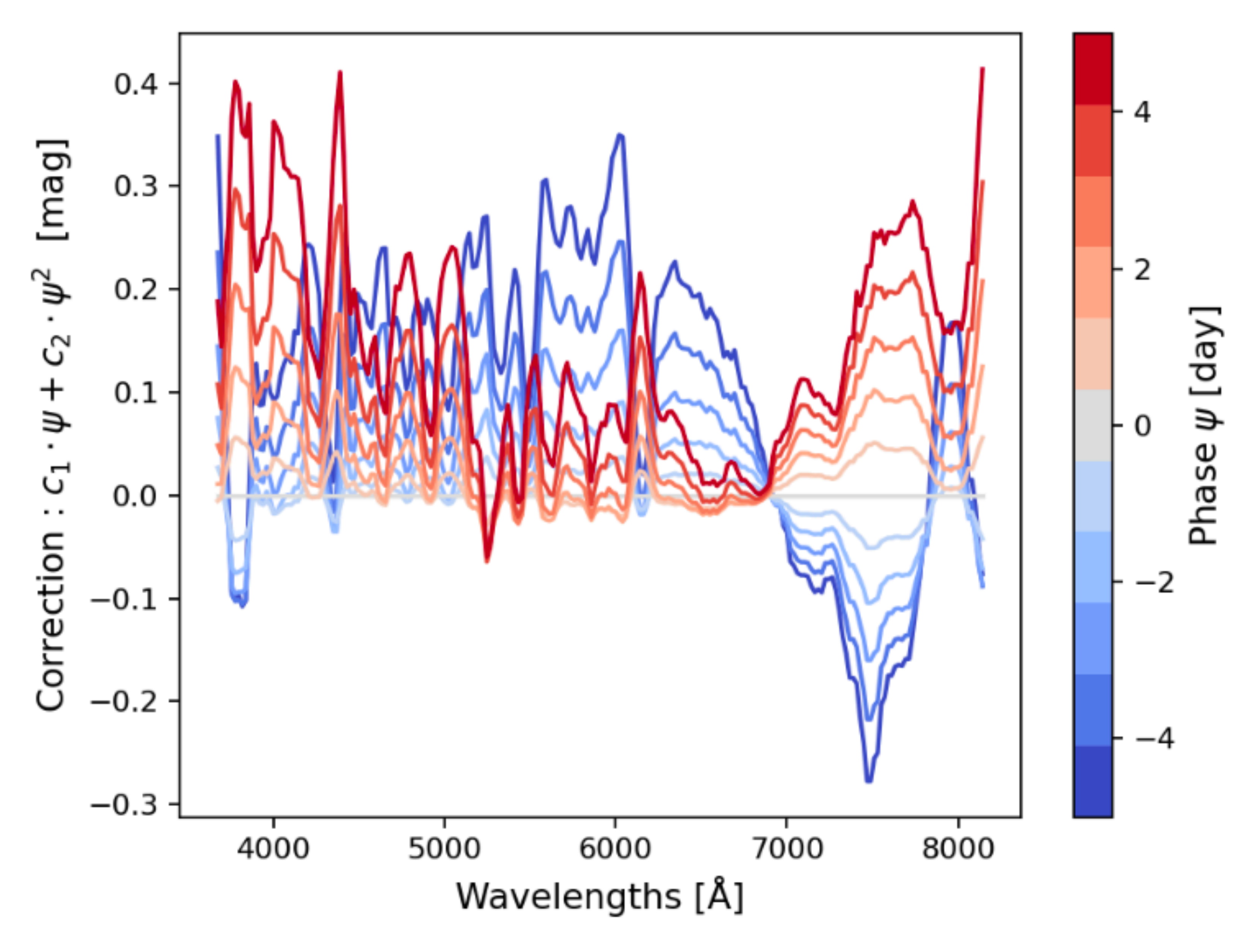

Quadratic evolution in phase of SN Ia spectra

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$$f_s(p;\lambda_k) = 10^{-0.4(m_i(p;\lambda_k)+m_{\mathrm{gray},s})}$$

$$\sigma^2_{tot.,\,s}(p;\lambda_k) = \sigma^2_{\mathrm{meas.},s}(\lambda_k) + (\epsilon(p;\lambda_k) \cdot f_s(p;\lambda_k))^2$$

Fitted parameters :

$\epsilon(p,\lambda_k)$ the model uncertainties common to all Sne,
$m_{gray,s}$ the gray offset of the spectrum s
$c_{1,2}(\lambda_k)$ the coefficients common to all Sne

Known:

$f_{meas.,s}(p,\lambda_k)$ the observed flux of spectrum s
$\sigma_{meas.,s}(\lambda_k)$ the measured uncertainty of sp. s

Capture 84.6% of the spectral evolution variance common to every Sne between -5 and 5 days

STEP 2

Read between the lines (RBTL)

=> Explain Scatter Between the lines

Capture Grey scatter + Extinction

Remove variability:

- Magnitude offset (e.g peculiar velocity of host)
- Extinction (e.g Dust in the host)

Fitted parameters :

Δm_i *the offset with mean for SN i*

$\Delta \tilde{A}_{V,i}$ *the extinction coefficient for SN i*

$\eta(\lambda_k)$ *the intrinsic dispersion (common to all)*

Known:

$f_{max,i}(\lambda_k)/\sigma^2_{f_{max},i}(\lambda_k)$ *the spectrum flux/uncertainty at max for SN i*

$f_{mean}(\lambda_k)$ *the mean spectrum at max*

$C(\lambda_k)$ *the extinction law (Fitzpatrick 99)*

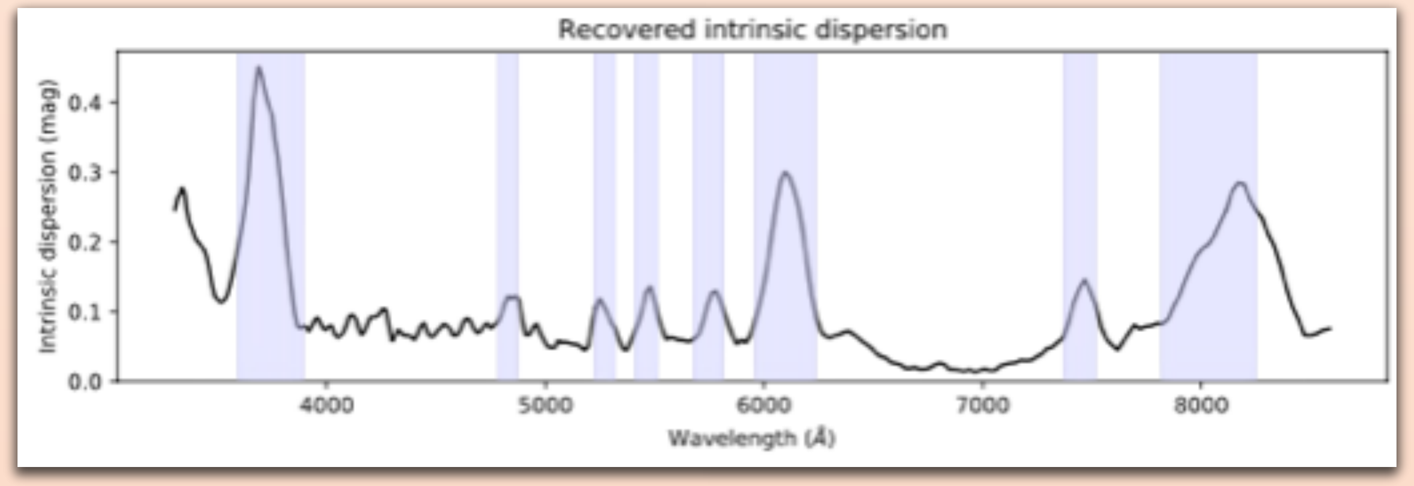
Fit all together with bayesian inference :

$$f_{\text{model},i}(\lambda_k) = f_{\text{mean}}(\lambda_k) \times 10^{-0.4(\Delta m_i + \Delta \tilde{A}_{V,i} C(\lambda_k))}$$

$$\sigma^2_{\text{total},i}(\lambda_k) = \sigma^2_{f_{\text{max.},i}}(\lambda_k) + (\eta(\lambda_k) f_{\text{model},i}(\lambda_k))^2$$

$$f_{\text{max.},i}(\lambda_k) \sim N(f_{\text{model},i}(\lambda_k); \sigma^2_{\text{total},i}(\lambda_k))$$

Areas with large intrinsic dispersion ($\eta(\lambda_k)$) are deweight during the fit :

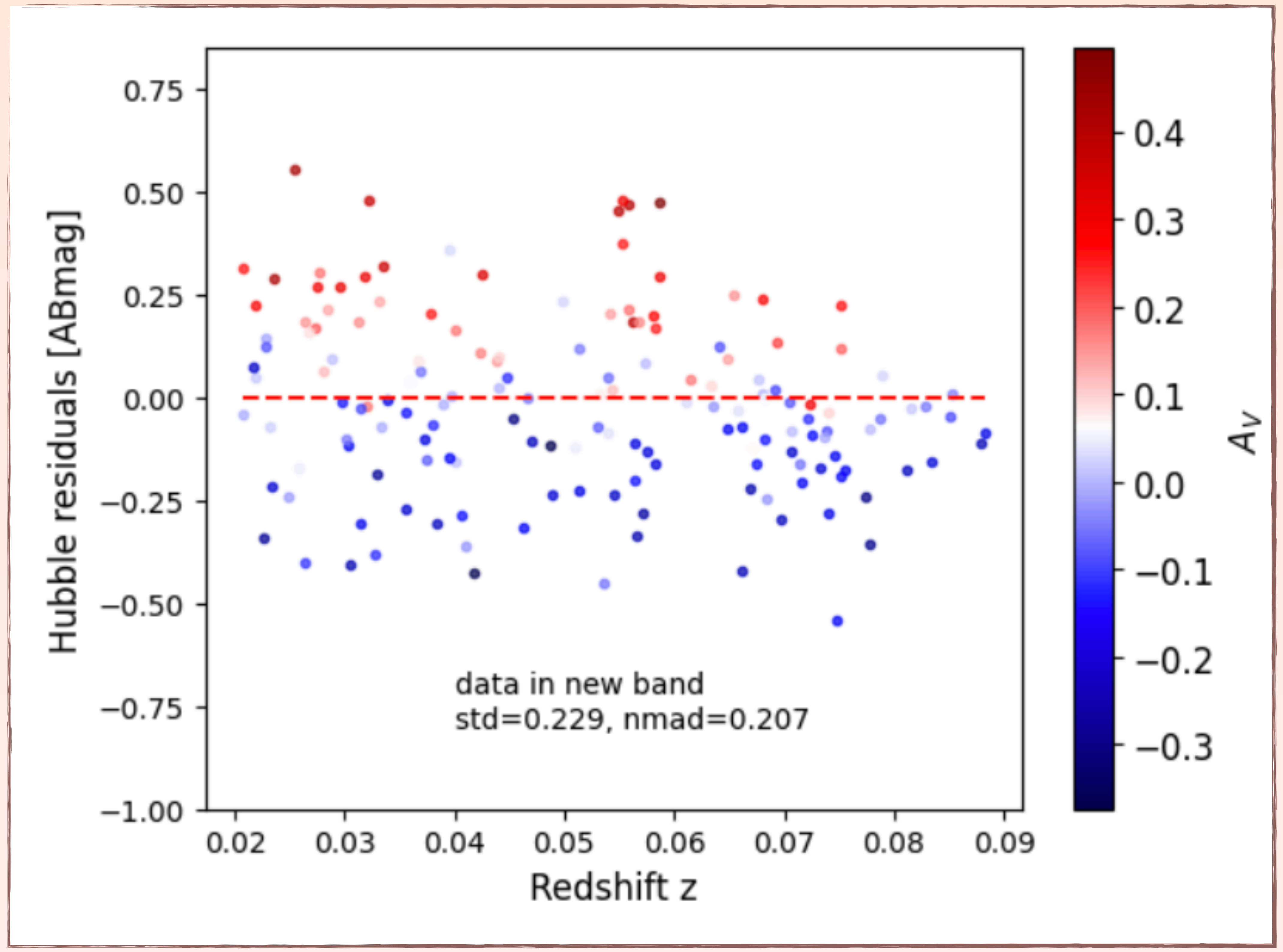


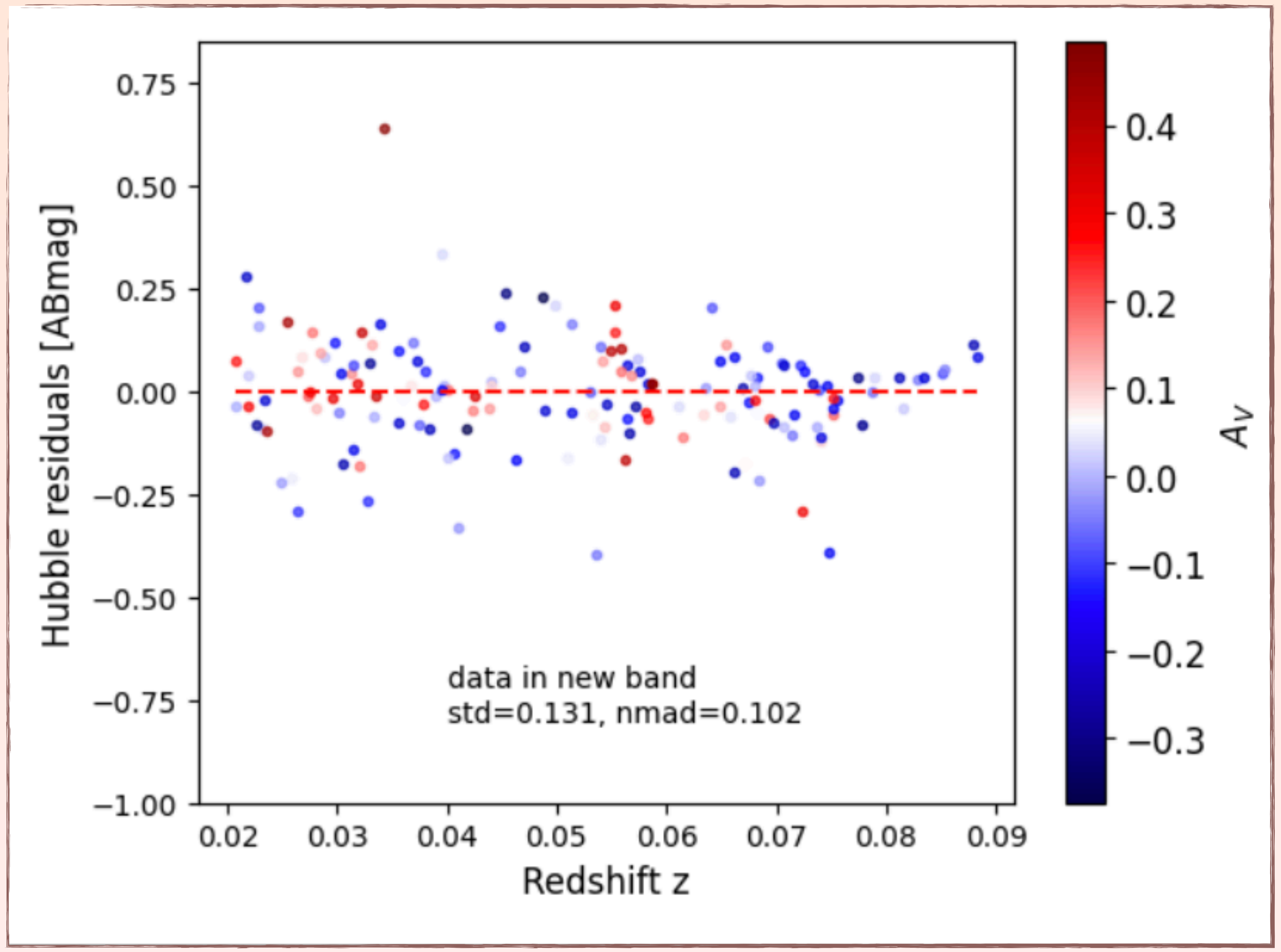
RBTL linear standardisation

For SNFactory sample

$-\alpha \cdot \Delta A_V$

$\Delta\mu = \mu_{z=0.05} - (m_{band} - M_{offset})$





168 SNe Ia before/after standardisation
after a cut on DAv < 0.5