Spectrophotometric standardisation of ZTF type Ia Supernovae

Constance GANOT, supervised by Yannick COPIN and Mickael RIGAULT

PhD Days - April 17, 2025

Summary

- Introduction to cosmology with SNe Ia
- Spectro-photometric standardisation methods
- ZTF spectra sample
- Testing standardisation on ZTF
- Conclusion

Type Ia supernovae

SN 1994D in galaxy NGC 4526
Hubble Space Telescope

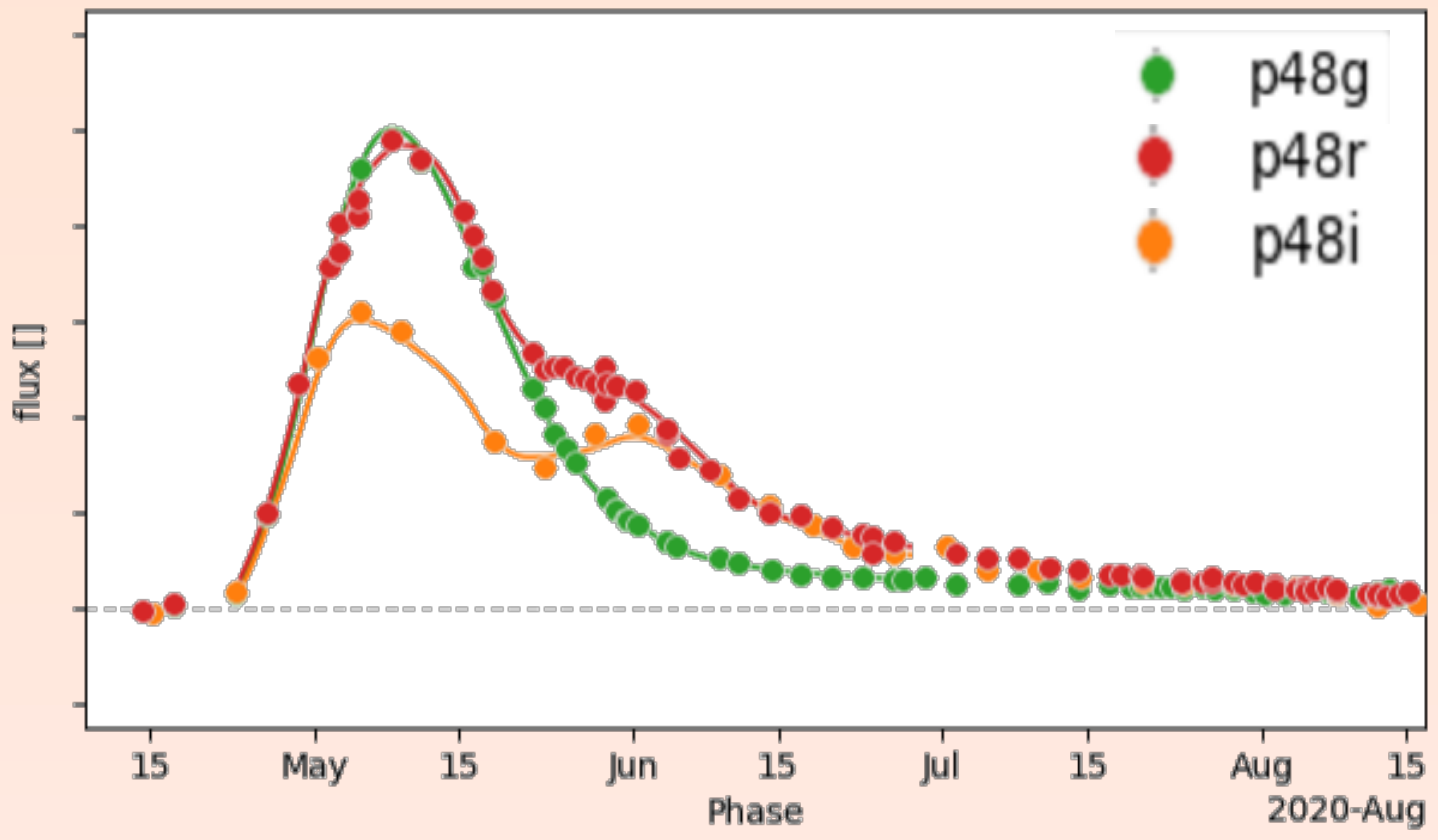
Luminosity ~constant

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

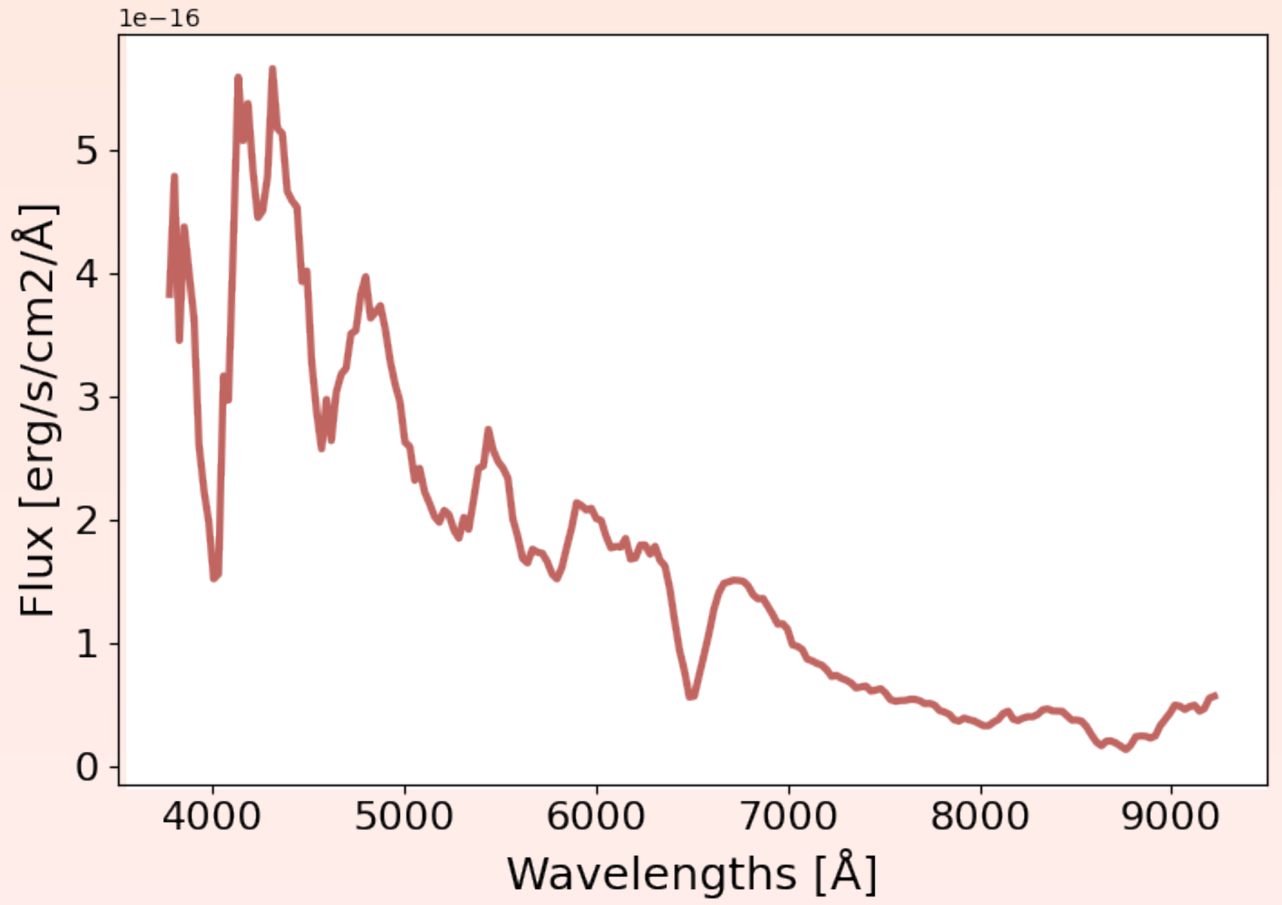
Distance modulus

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

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



Lighcurves of ZTF20abxzrqw



Spectrum of ZTF20abeqsrm
at phase -5.73

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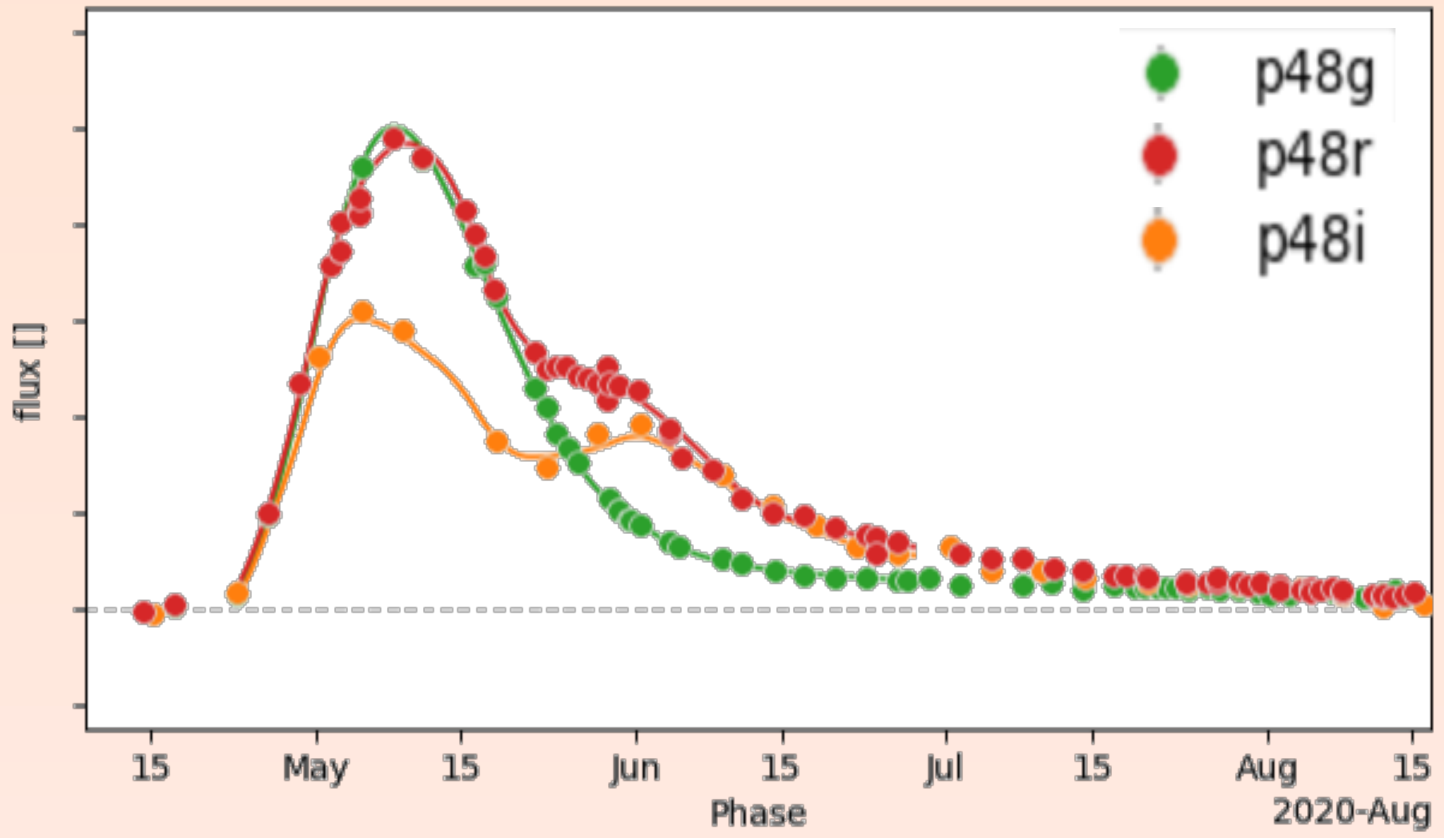

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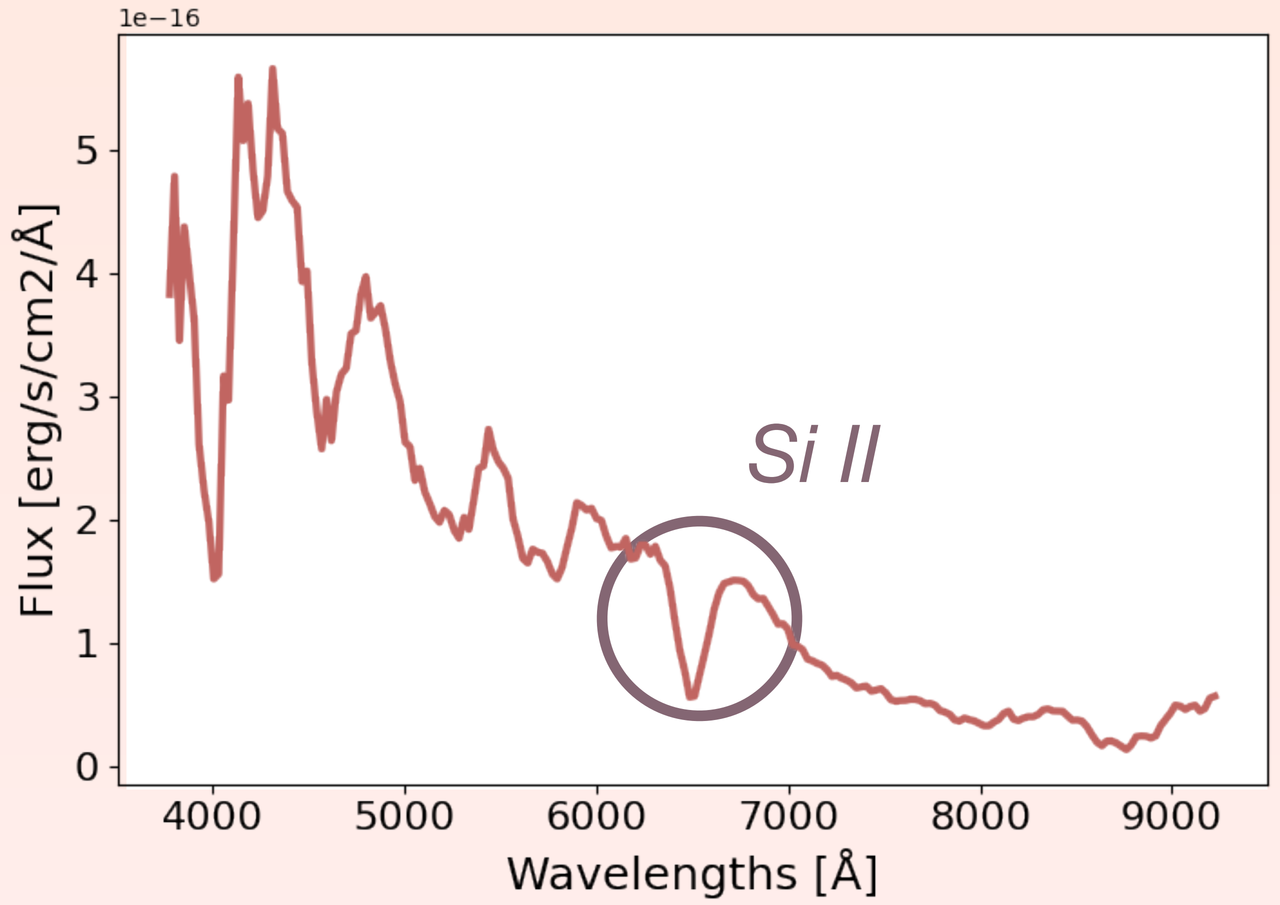
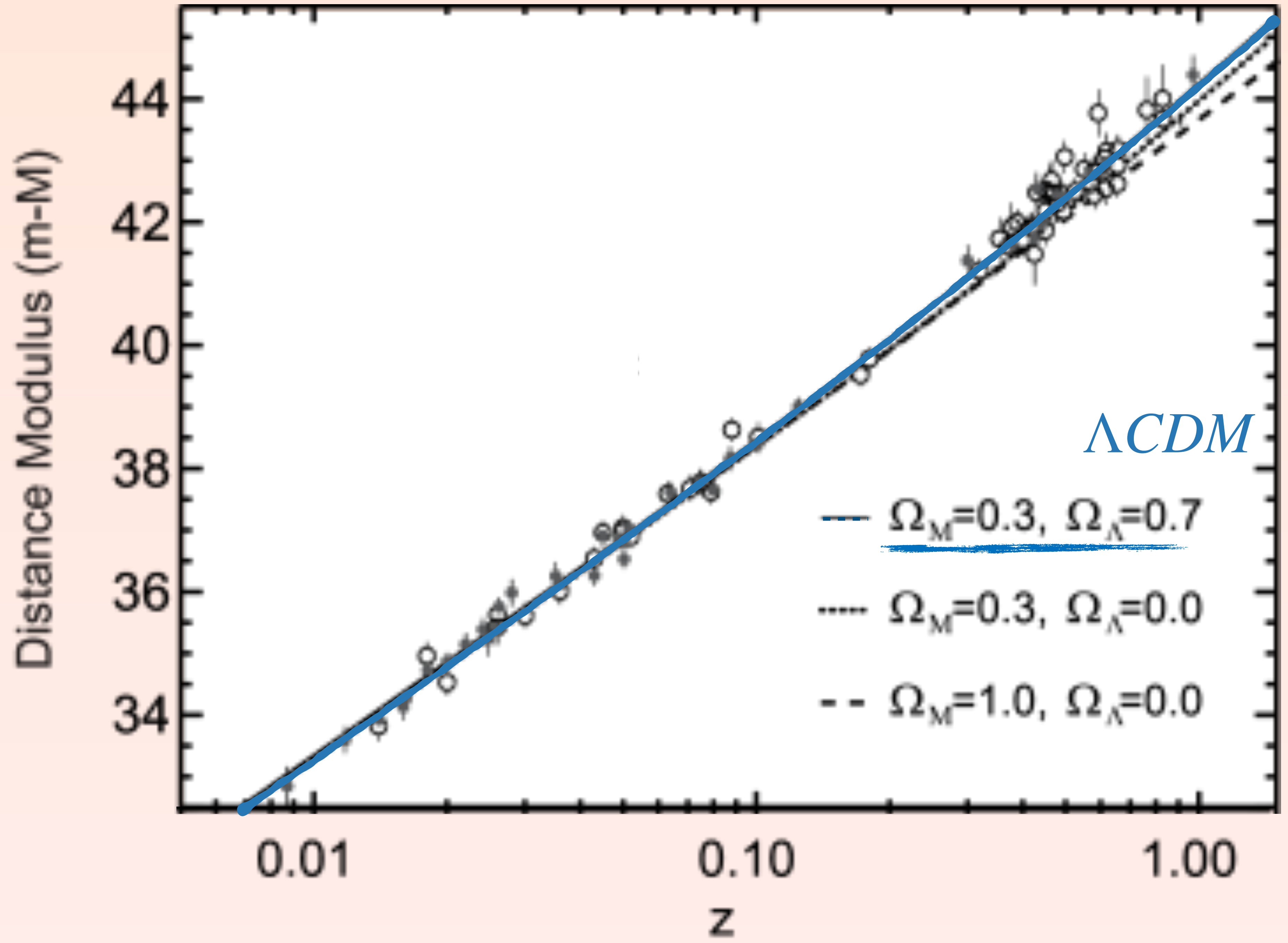


Spectrum of ZTF20abeqsrm
at phase -5.73

Goals | *Cosmology*

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



Hubble Diagram - Frieman 2008

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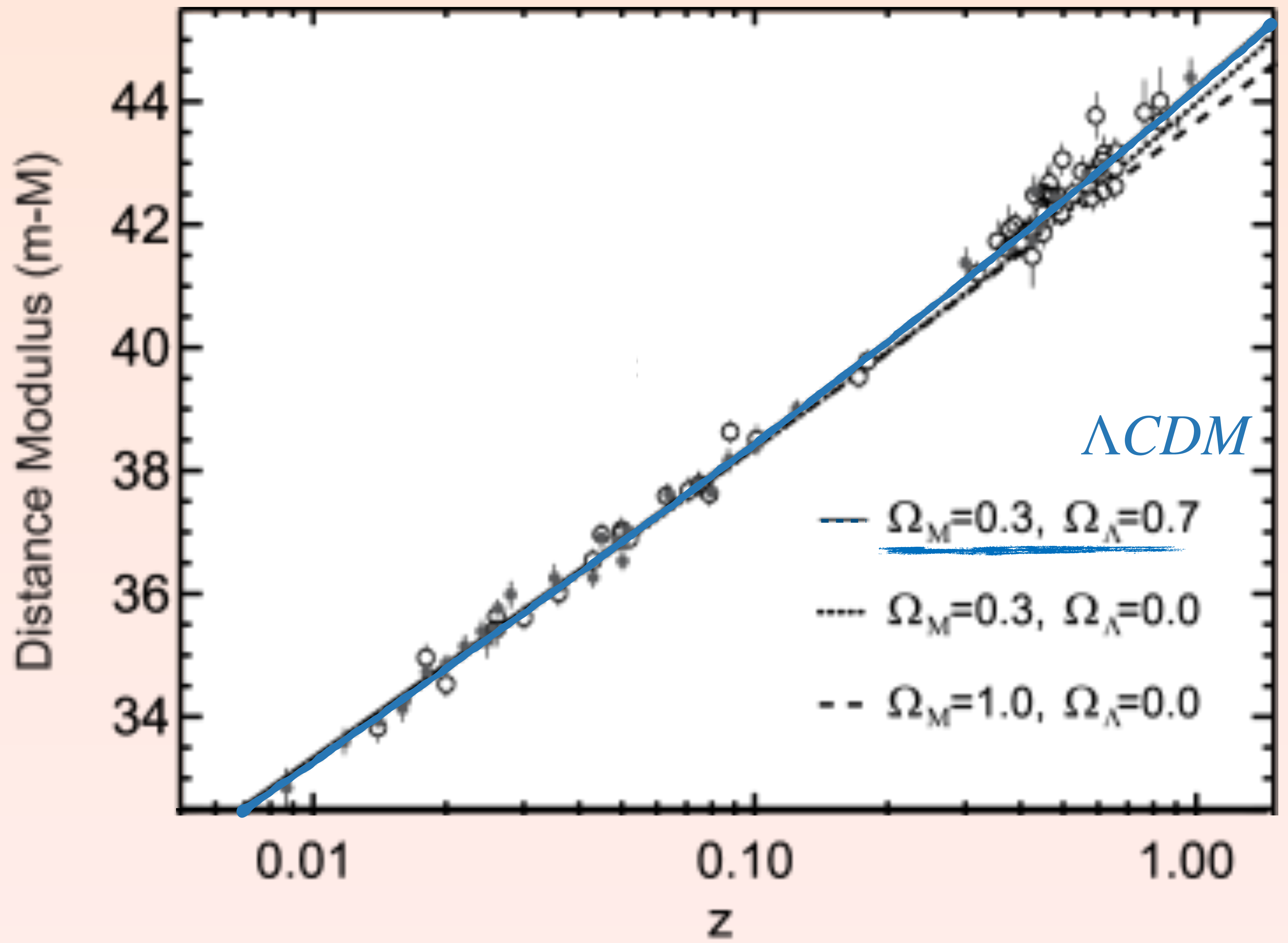


Hubble Diagram - Frieman 2008

Matter density — *Dark Energy density* — *parameter of the dark energy equation of state*

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

Equation of ωCDM model

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

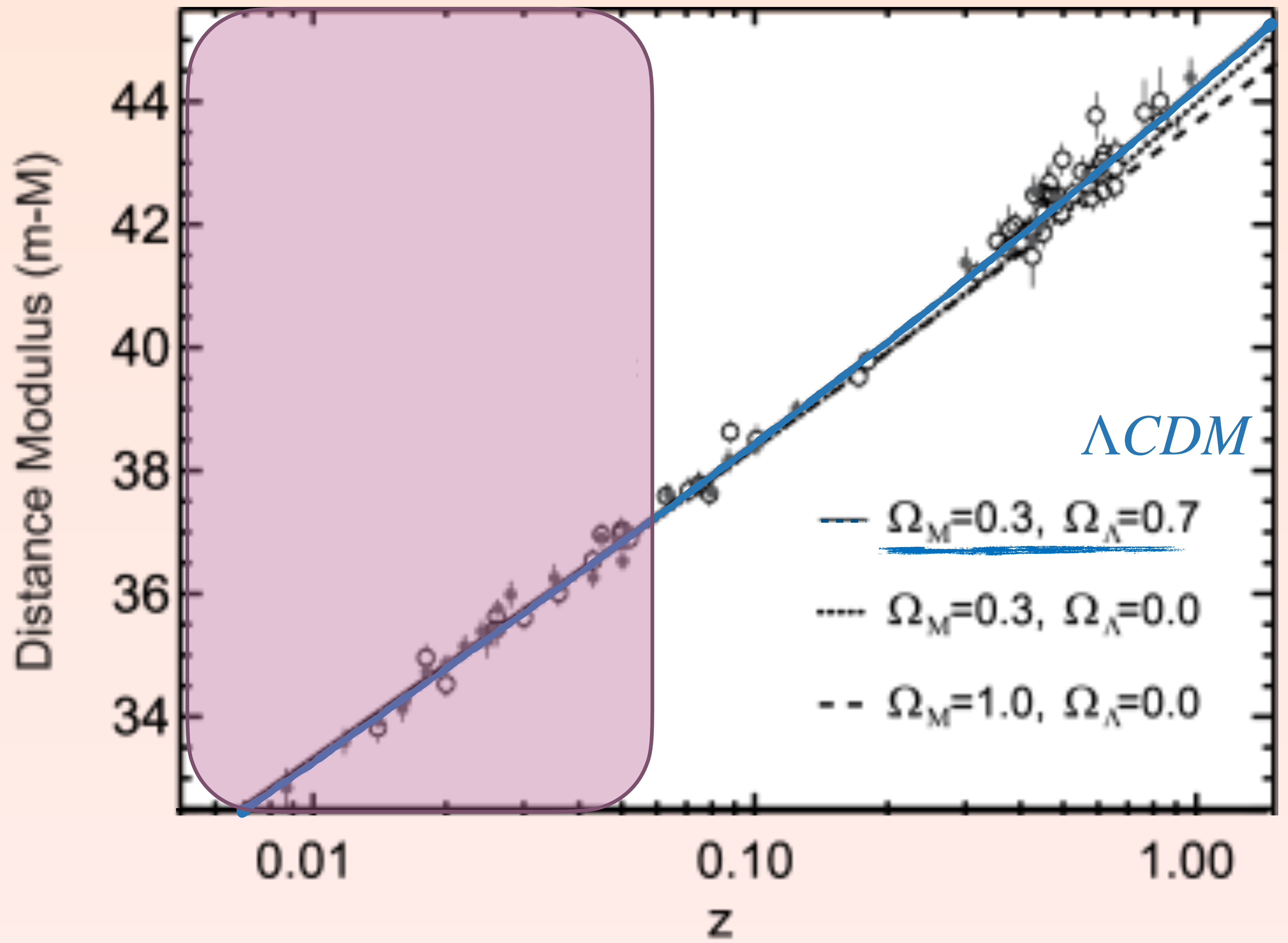
Latest Combined result

DESI+CMB+Panth.

H_0	67.74 ± 0.71 km s^{-1} Mpc^{-1}
Ω_M	0.3095 ± 0.0069
ω	–0.997 ± 0.025

Goals | *Cosmology*

Low-redshift ($z<0.15$)
Constrains H_0



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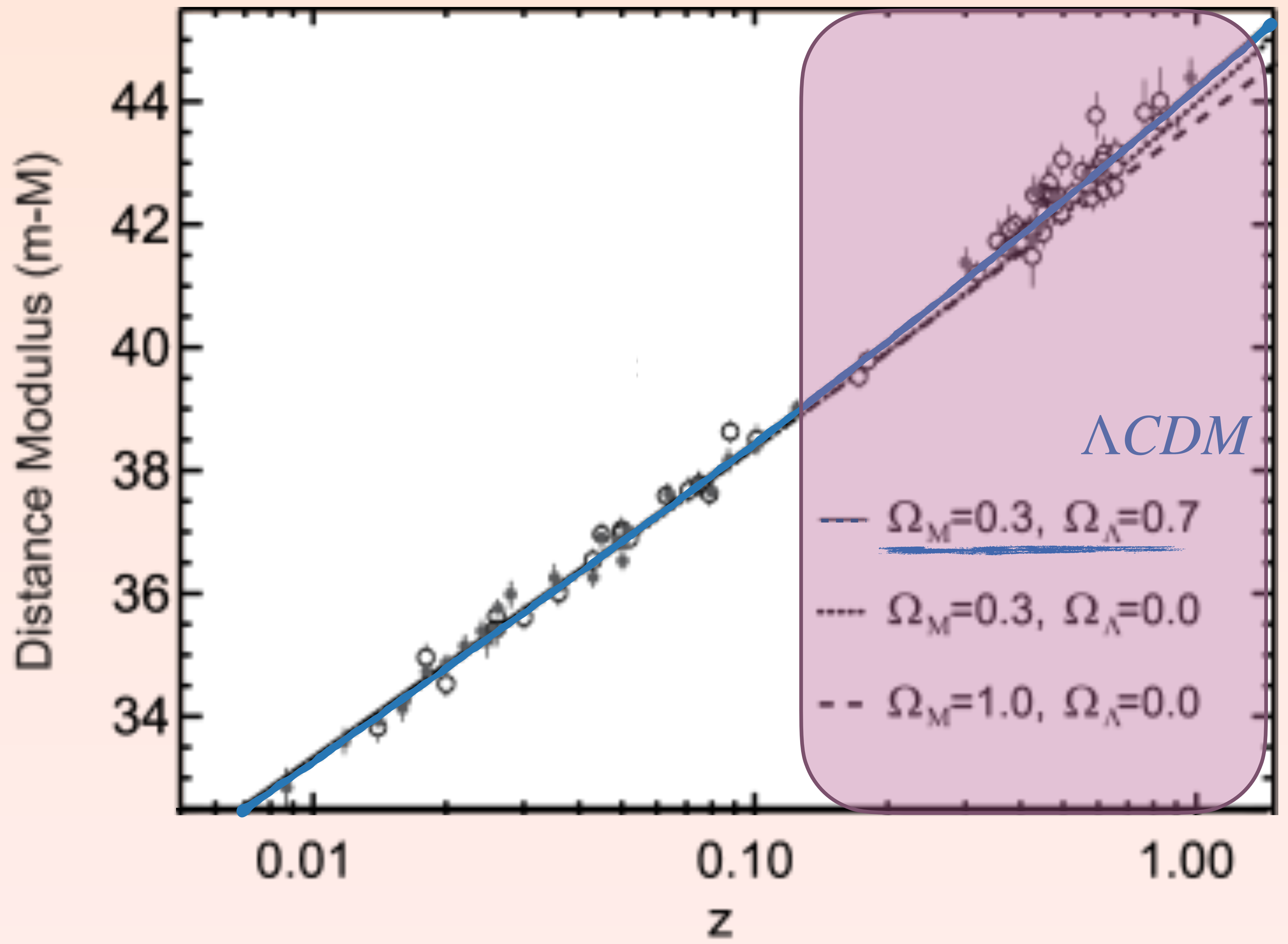
High-redshift (z>0.15)
Constrains $(\Omega_M, \Omega_\Lambda)$



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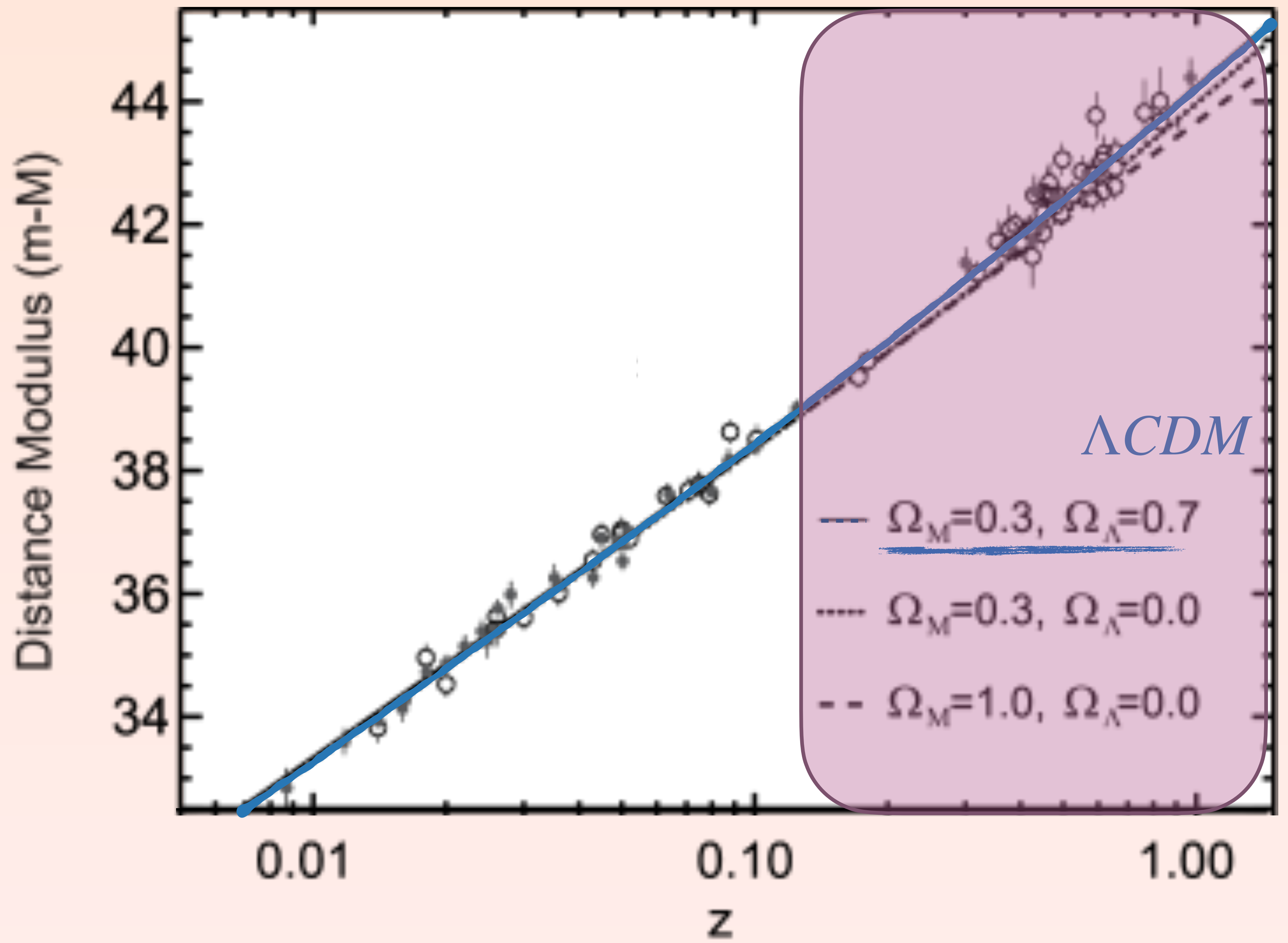

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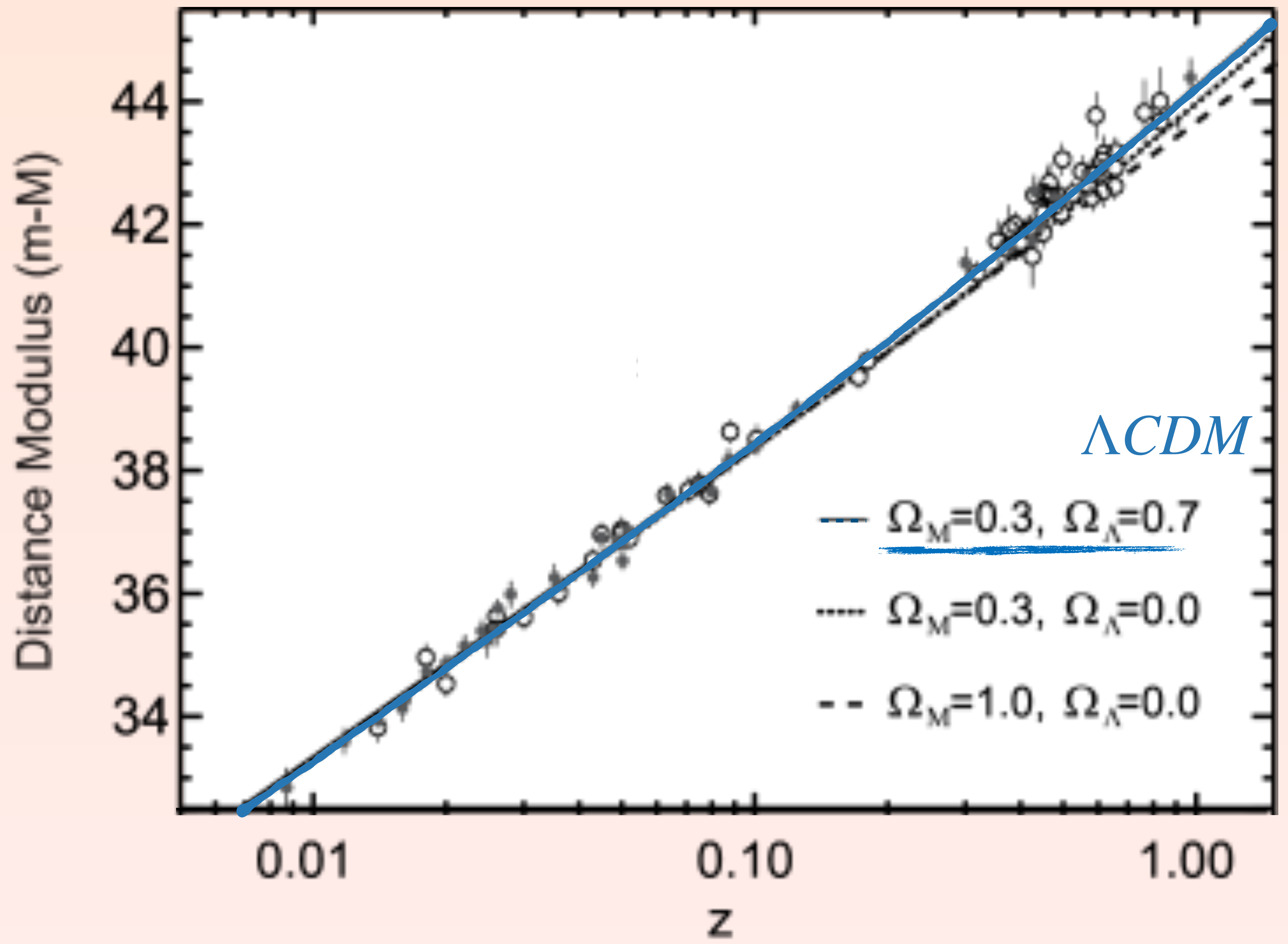
Goals | *Cosmology*

w variations are in the thickness of the line :
we compute $\mu - \mu_{\Lambda CDM}$ to see it



Hubble Diagram - Frieman 2008

Matter density *Dark Energy density* *parameter of the dark energy equation of state*

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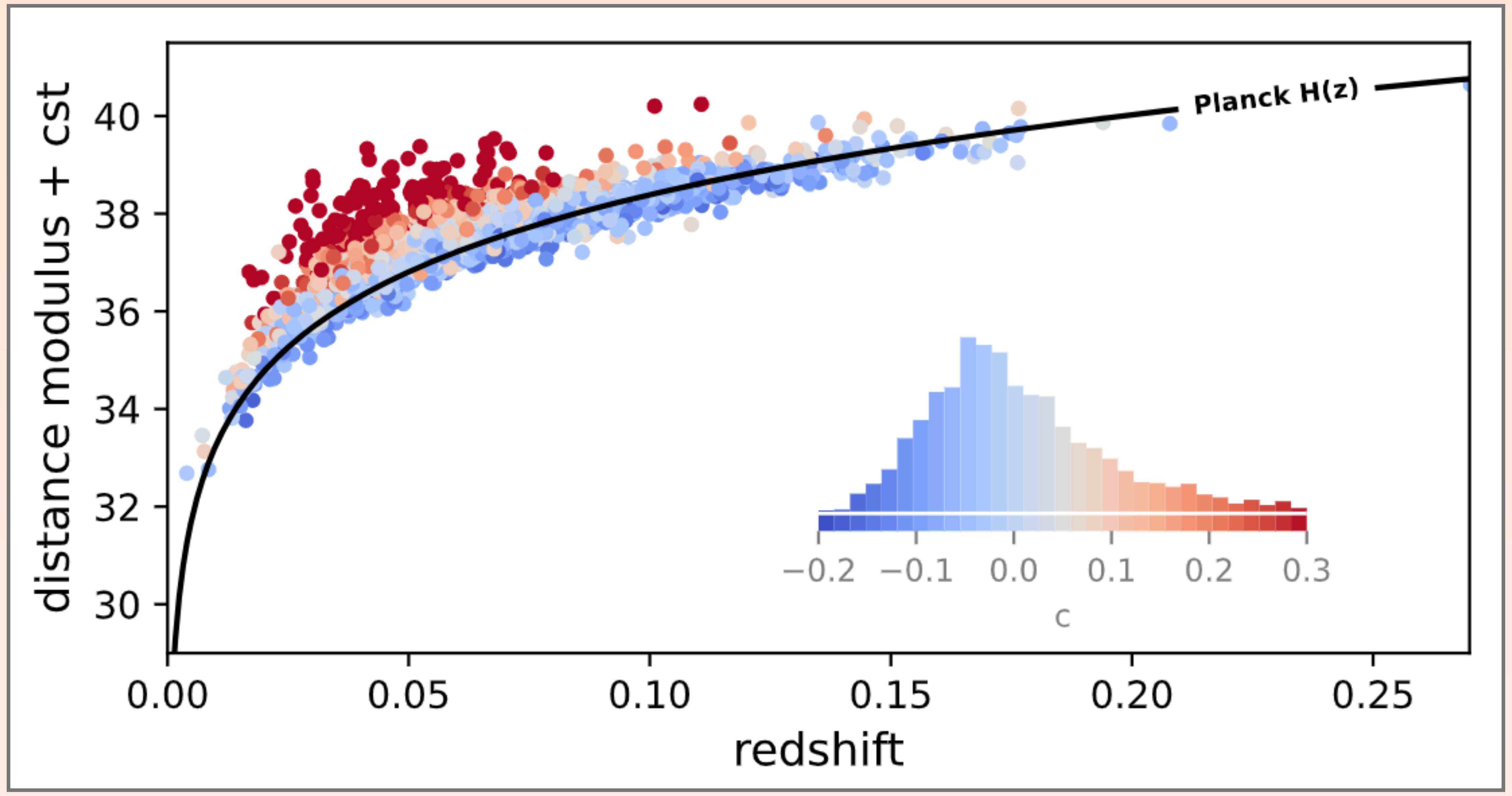
Photometric standardisation

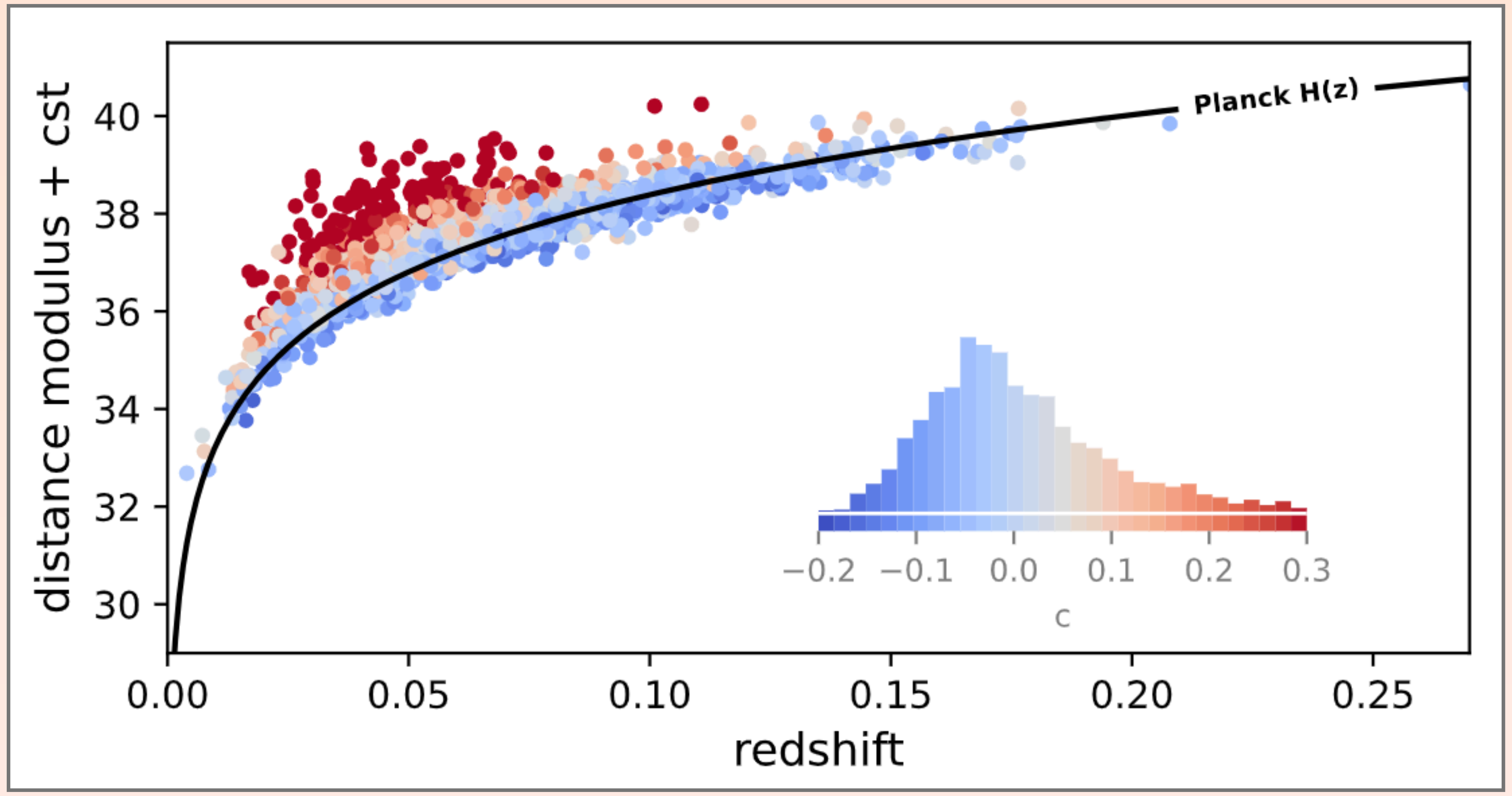


Hubble Diagram photometric standardisation
Credit : in prep. ZTF “DR2” Data paper, Smith et al.

SNe Ia dispersion :

$\sigma = 0.40 \text{ mag}$

Photometric standardisation



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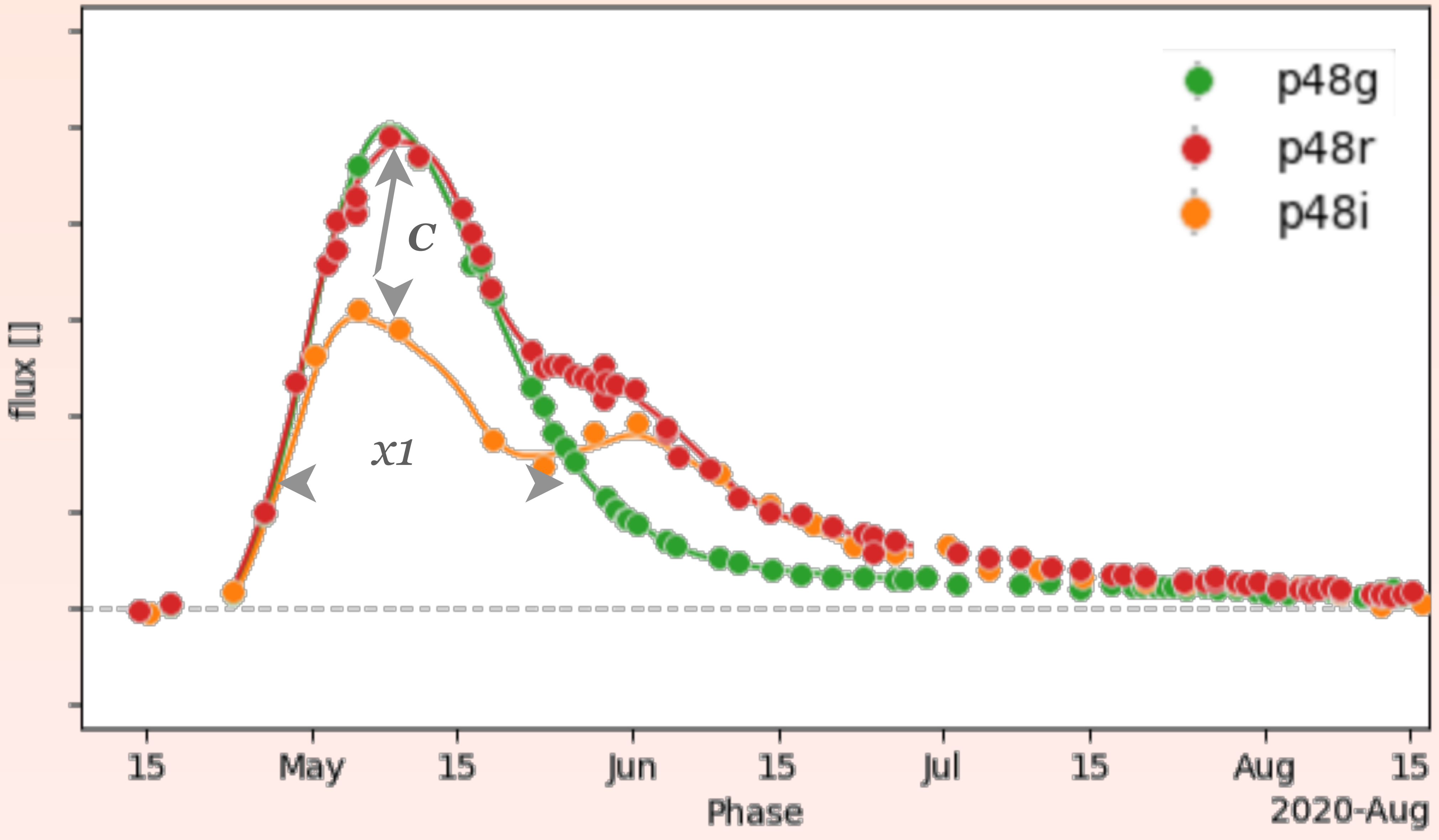
Tripp relation (1998) :

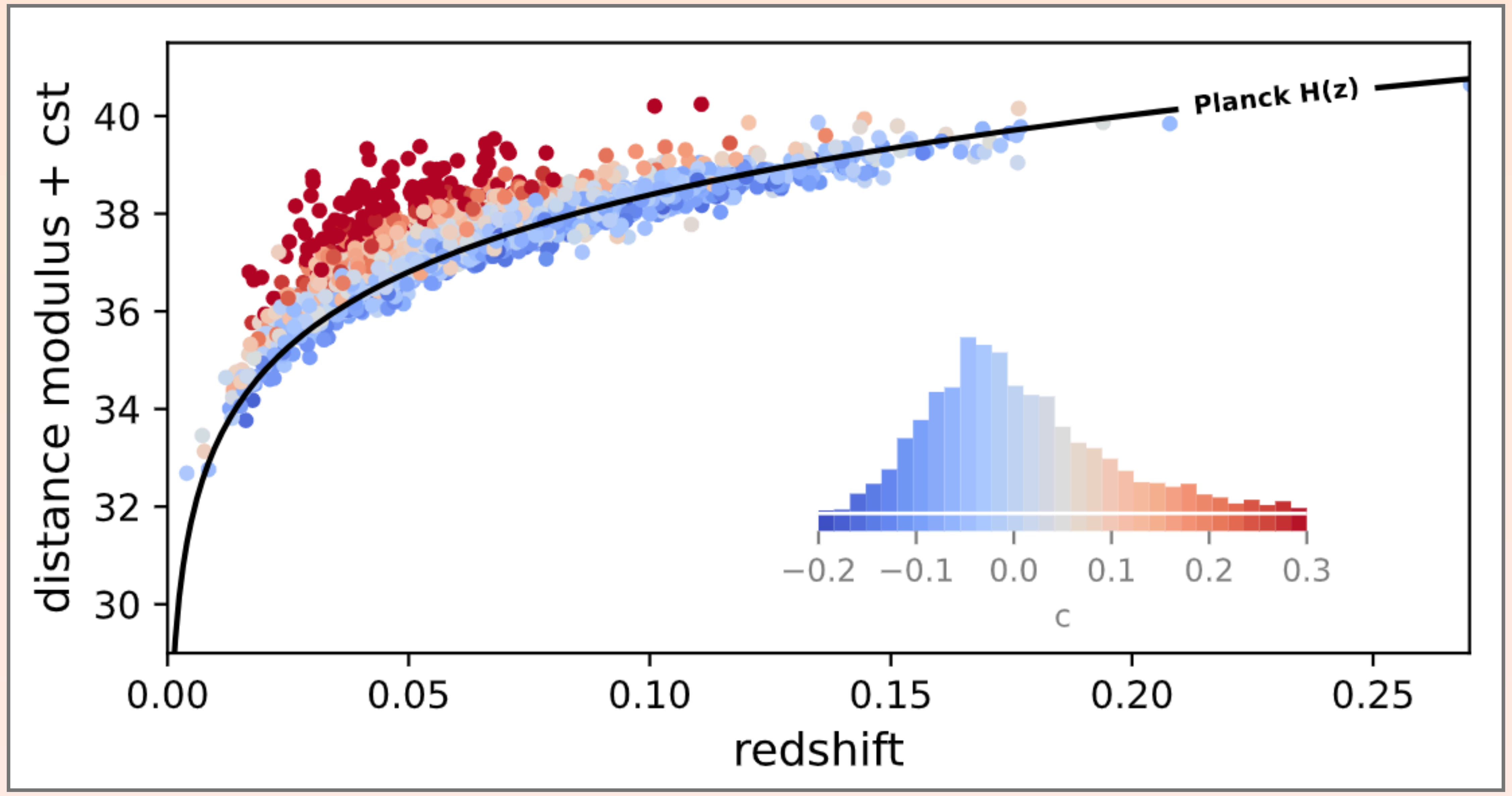
Corrections
'Slower-brighter' : x_1
'Brighter-bluer' : c

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



Lightcurves of ZTF20abxzrqw

Photometric standardisation



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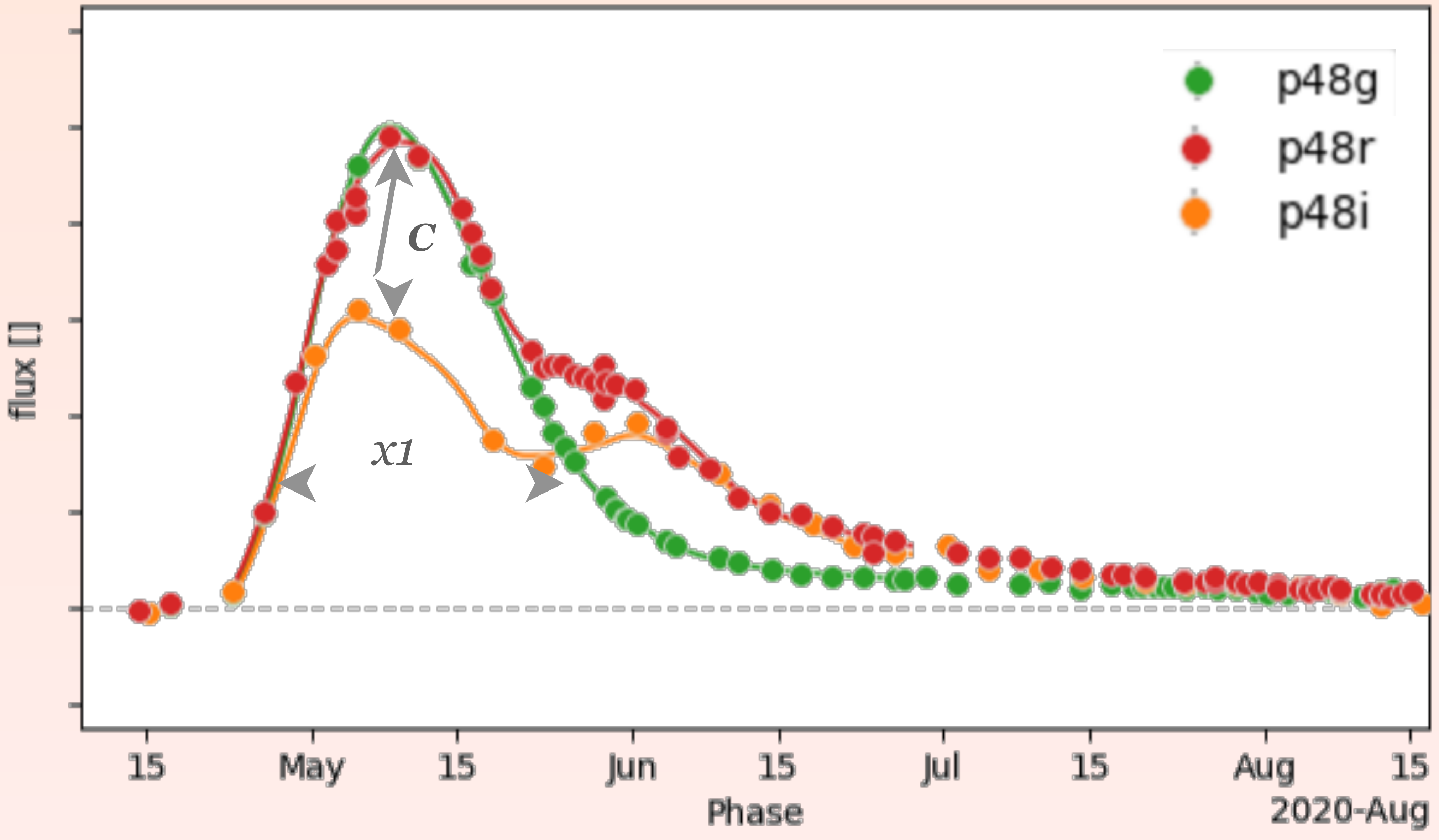


Lightcurves of ZTF20abxzrqw

SNe Ia dispersion :

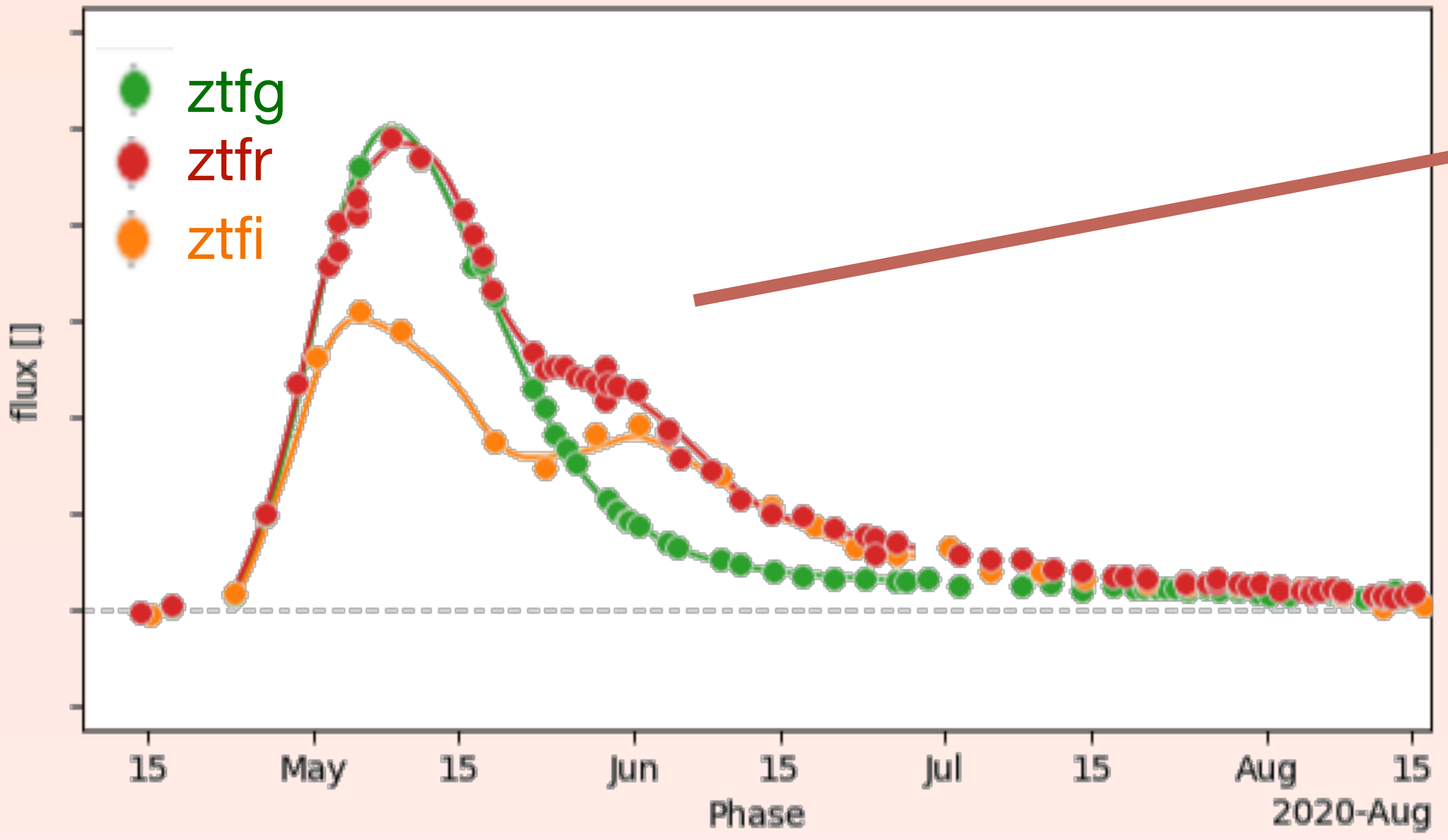
$\sigma_{corr} = \cancel{0.40} = 0.15$

with Photometric standardisation

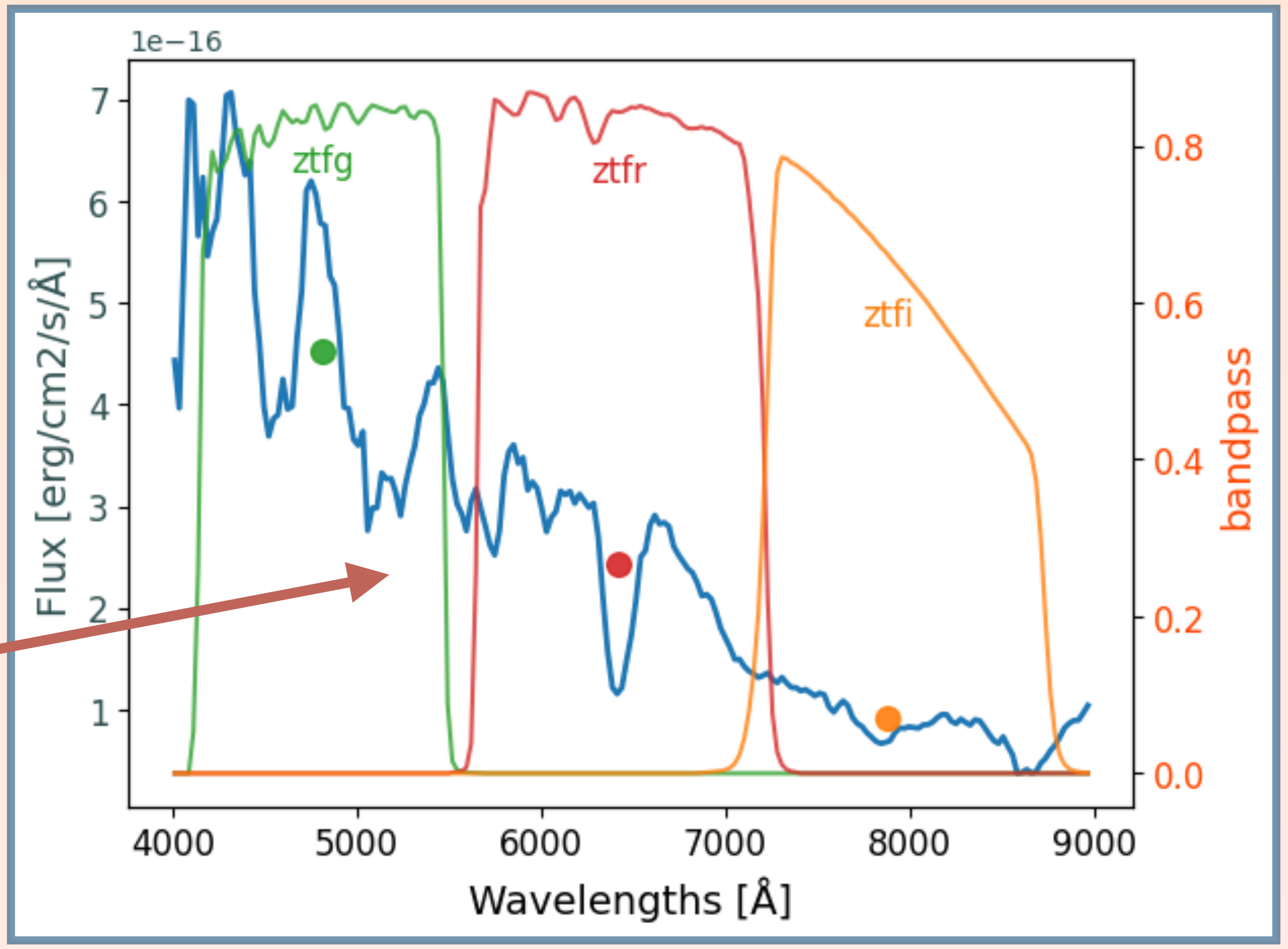
***Problem** : The origin of the dispersion of 0.15 mag is unknown*

Spectro-photometry

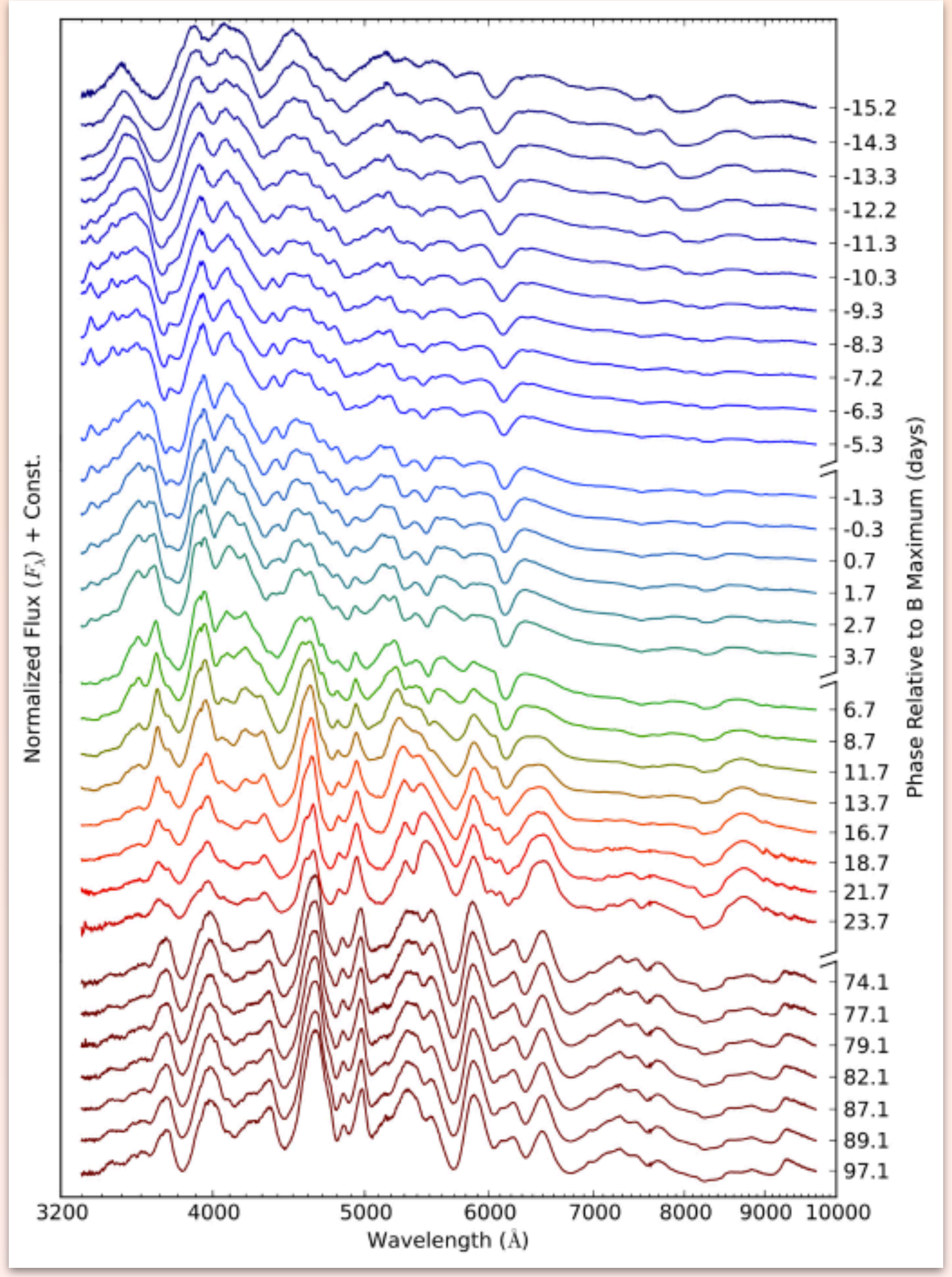
A lightcurve datapoint corresponds to the spectrum integrated in the bandpass



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



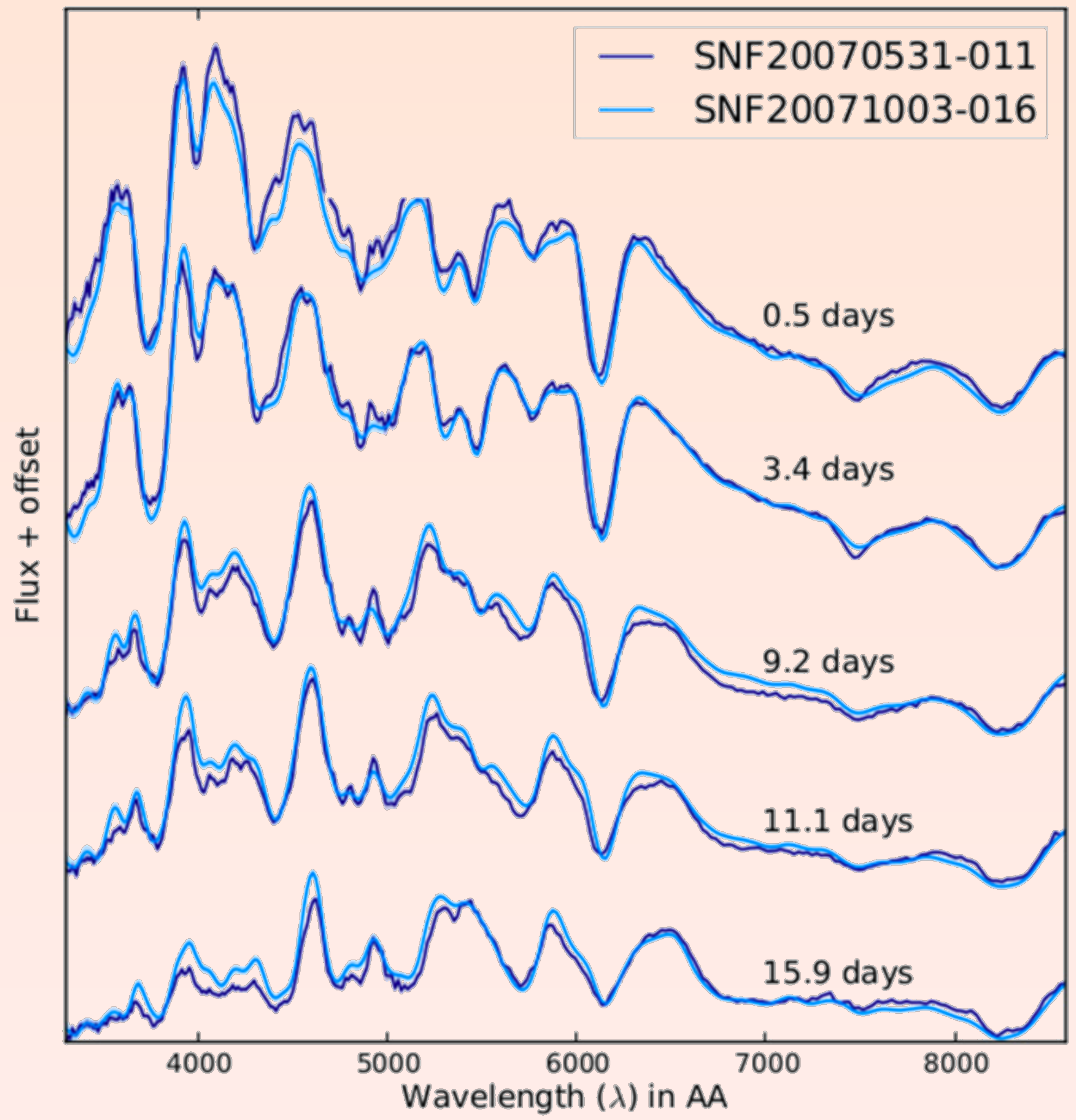
Synthetic photometry in ZTF filters
ZTF20abxzrqw at phase +1.29



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



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

Initial discovery :

Twins - Fakhouri 2015

- Magnitude dispersion is smaller for similar time-series
- One spectrum at maximum is sufficient to have the variation information

Full method :

Twins Embedding - Boone 2021

- Parameterization of the spectral variation of spectra 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 :
$\sigma_{mag} = 0.07\text{mag}$

SNFactory : ~200 SNe

↓

ZTF : ~750 SNe (for now)

Zwicky Transient Facility

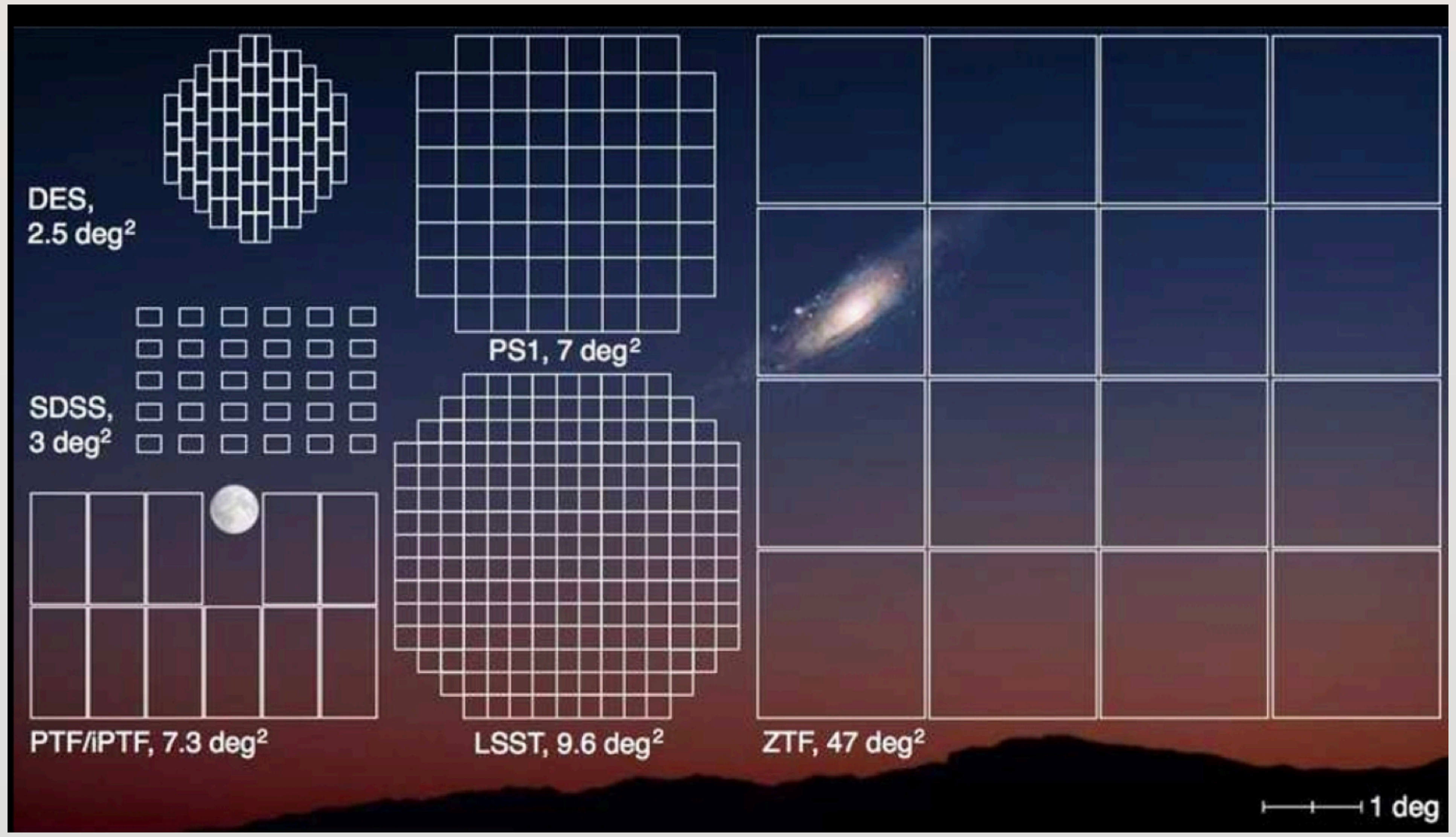
March 2018 to 2026

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

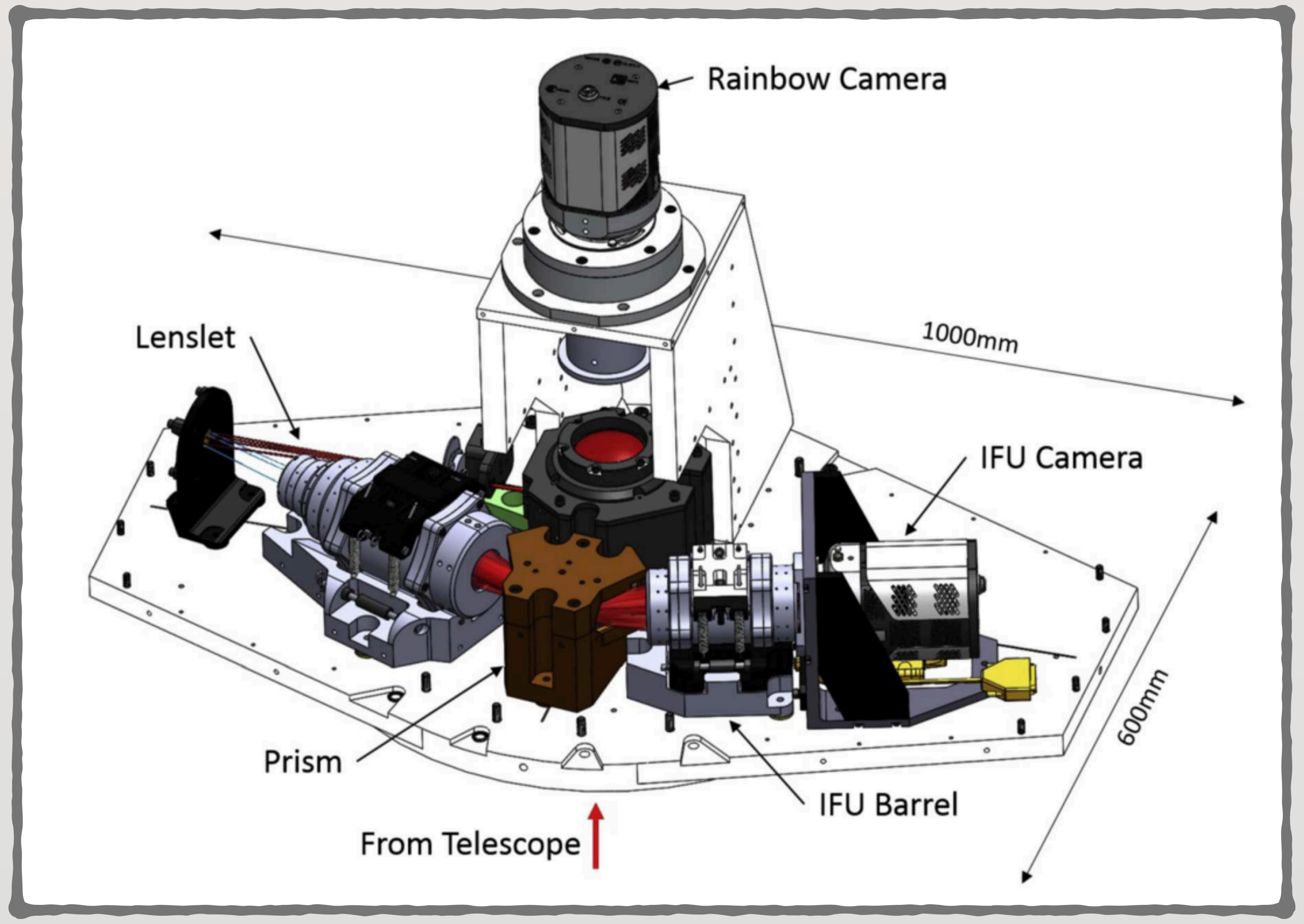
Two instruments :

- P48 camera
- P60 spectrograph

Located in Mount Palomar in California



ZTF Camera P48 FoV
Source : Joel Johansson



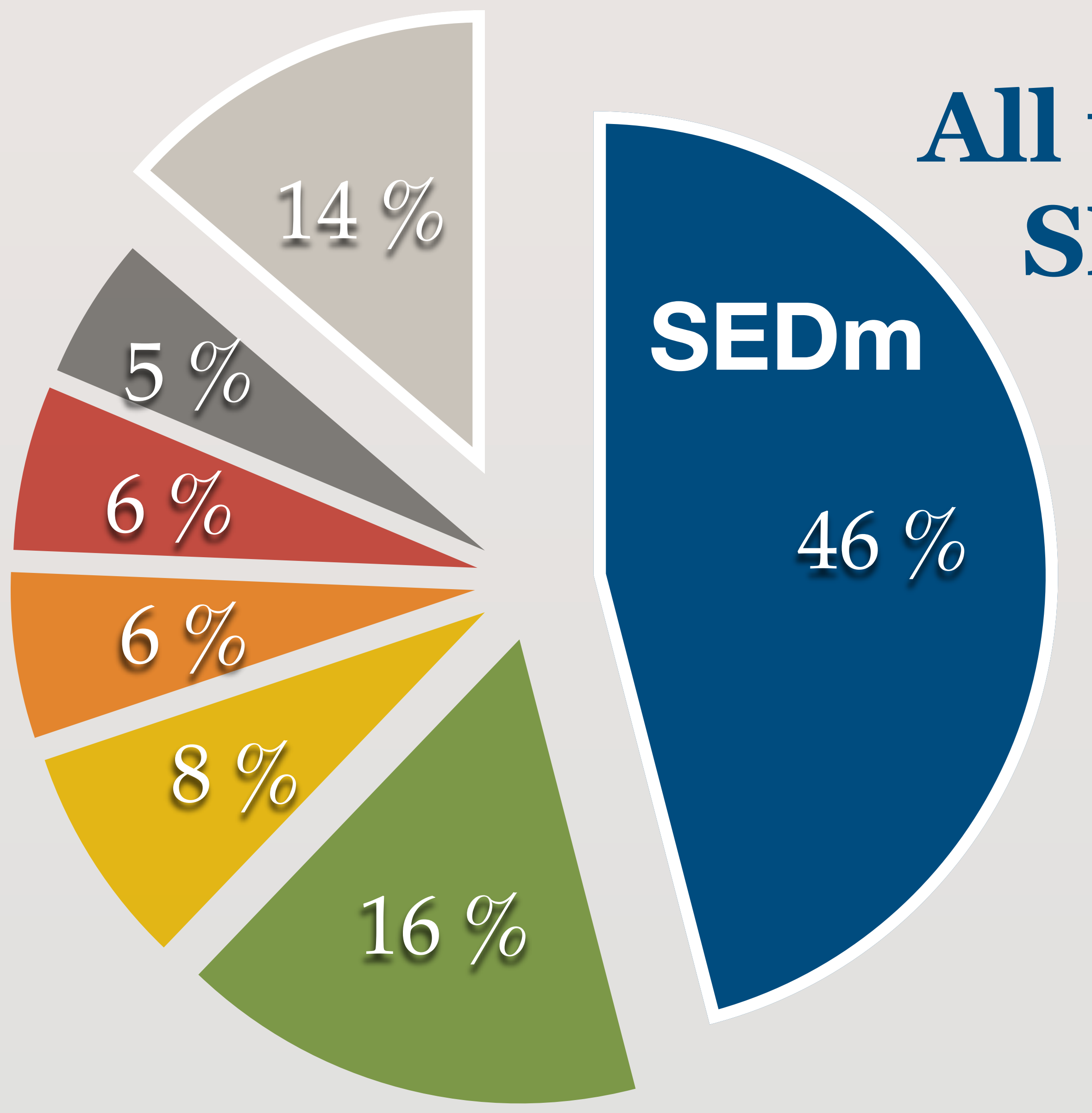
SEDm (P60)- Integral field Spectrograph
Source : N. Blagorodnova et al. 2018

SEDmachine

March 2018 to December 2020

$o(3600)$ Supernovae Ia
$o(4000)$ spectra

60% SNe Ia spectra from the SEDm



All the classified SNe spectra in the world

Source: Transient Name Server
wis-tns.org/stats-maps

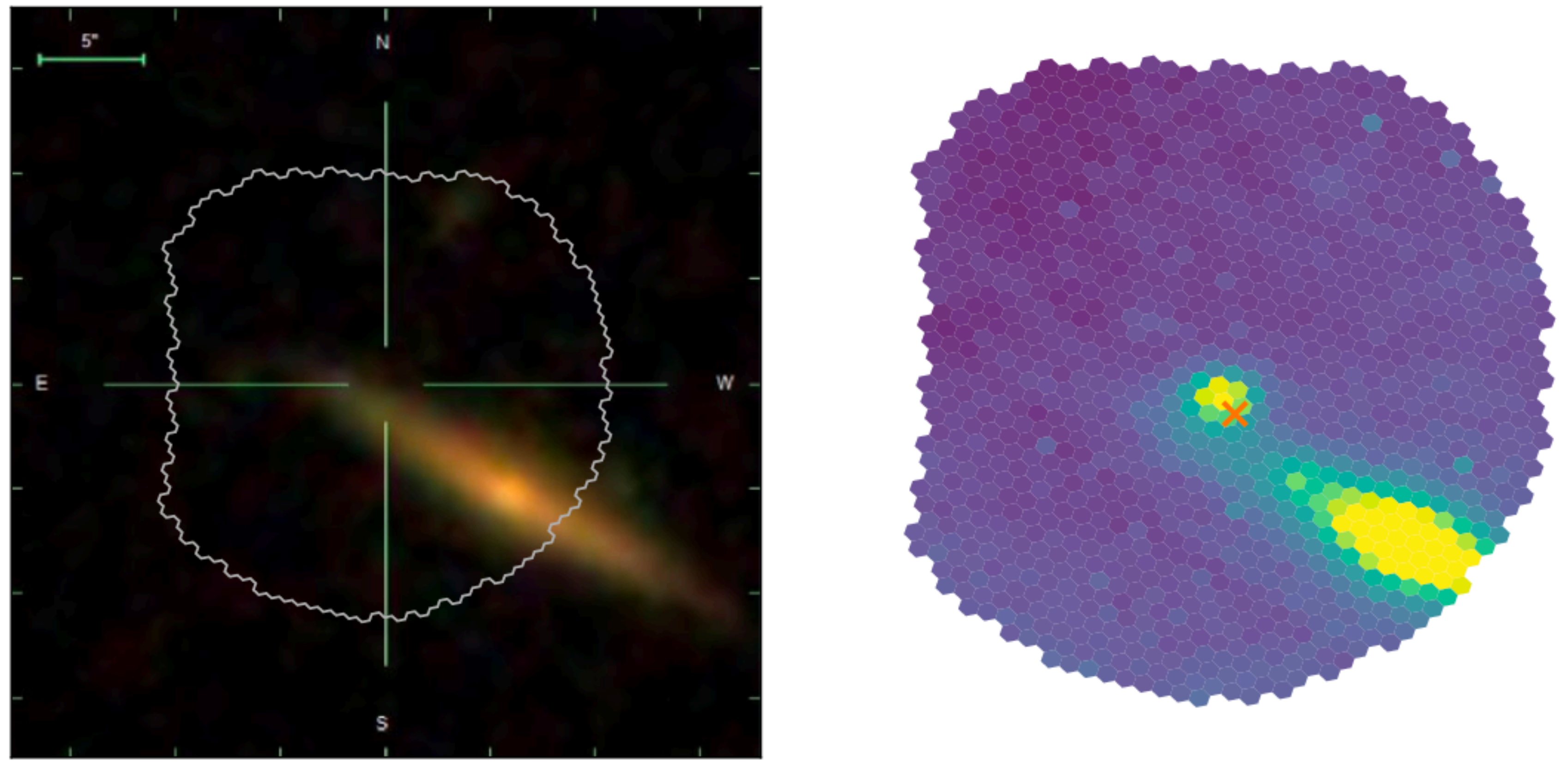
Purpose : typing

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

Optical window: 3,650 - 10,000 Å

Acquisition of ~1 hour

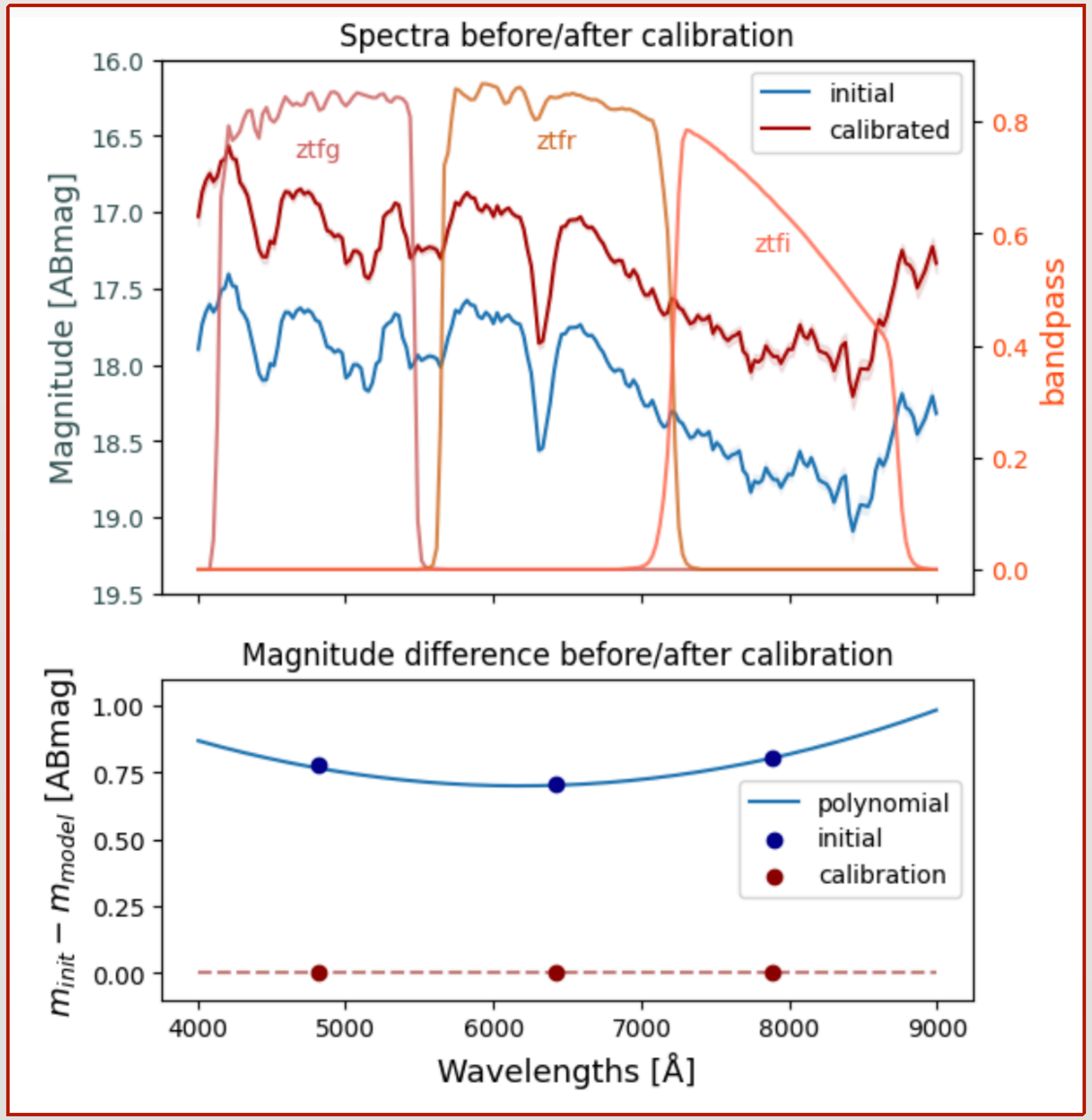
SEDm reconstructed image | $\lambda \in [5000,8000]$ Å



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

- spectral extraction by pysedm. (Rigault 2019)
- Correction of host galaxy by Hypergal (Lezmy 2022)

ZTF spectra flux calibration



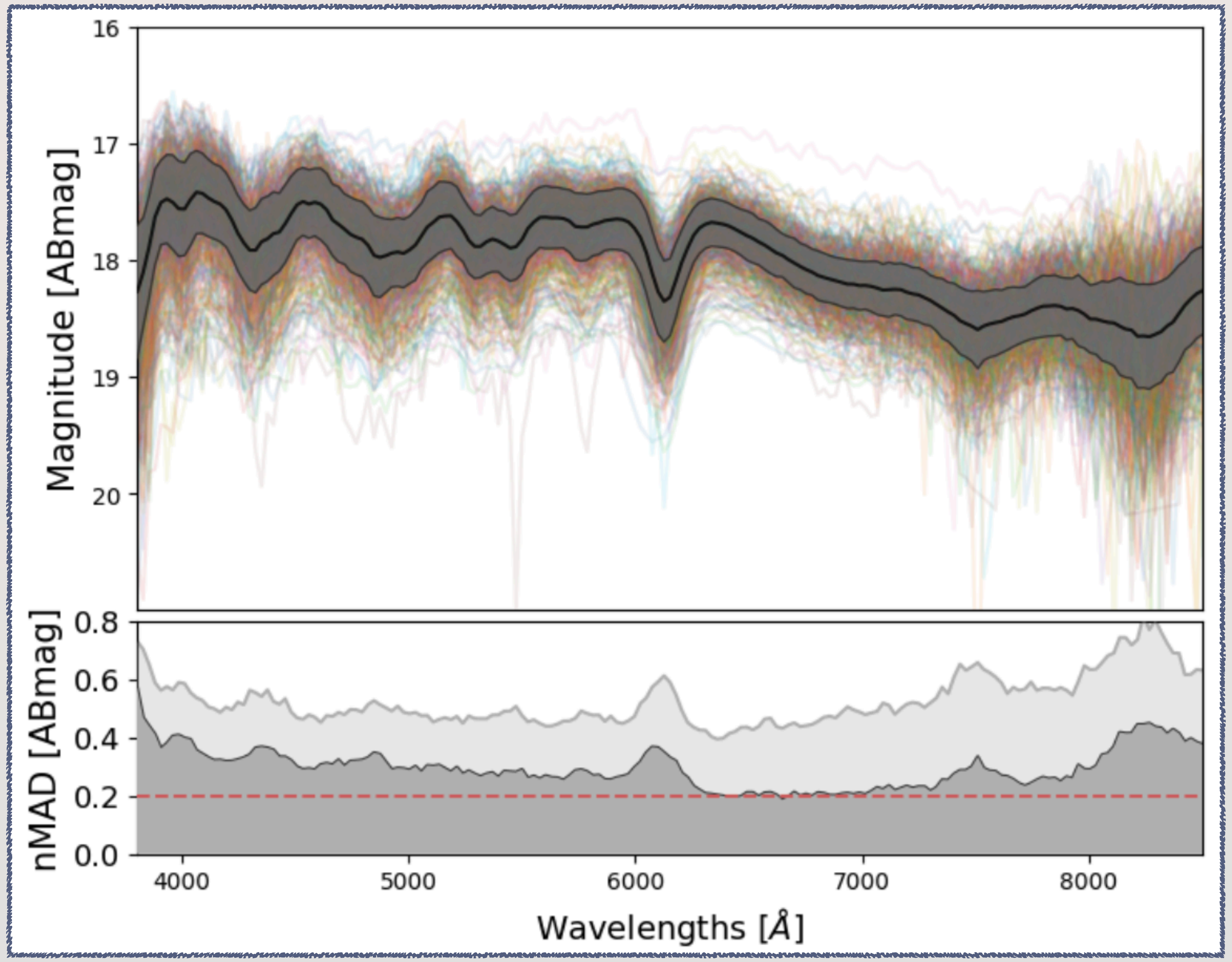
Example of flux calibration
with ZTF20aayvubx_20200524_SEDm_0

Parameter cut	Remains	Quantity removed
from SEDm	1749	40 %
phase in [-5,+5] days	1005	**around 40%**
z<0.1	992	around 6%
SNR>12	775	4 %

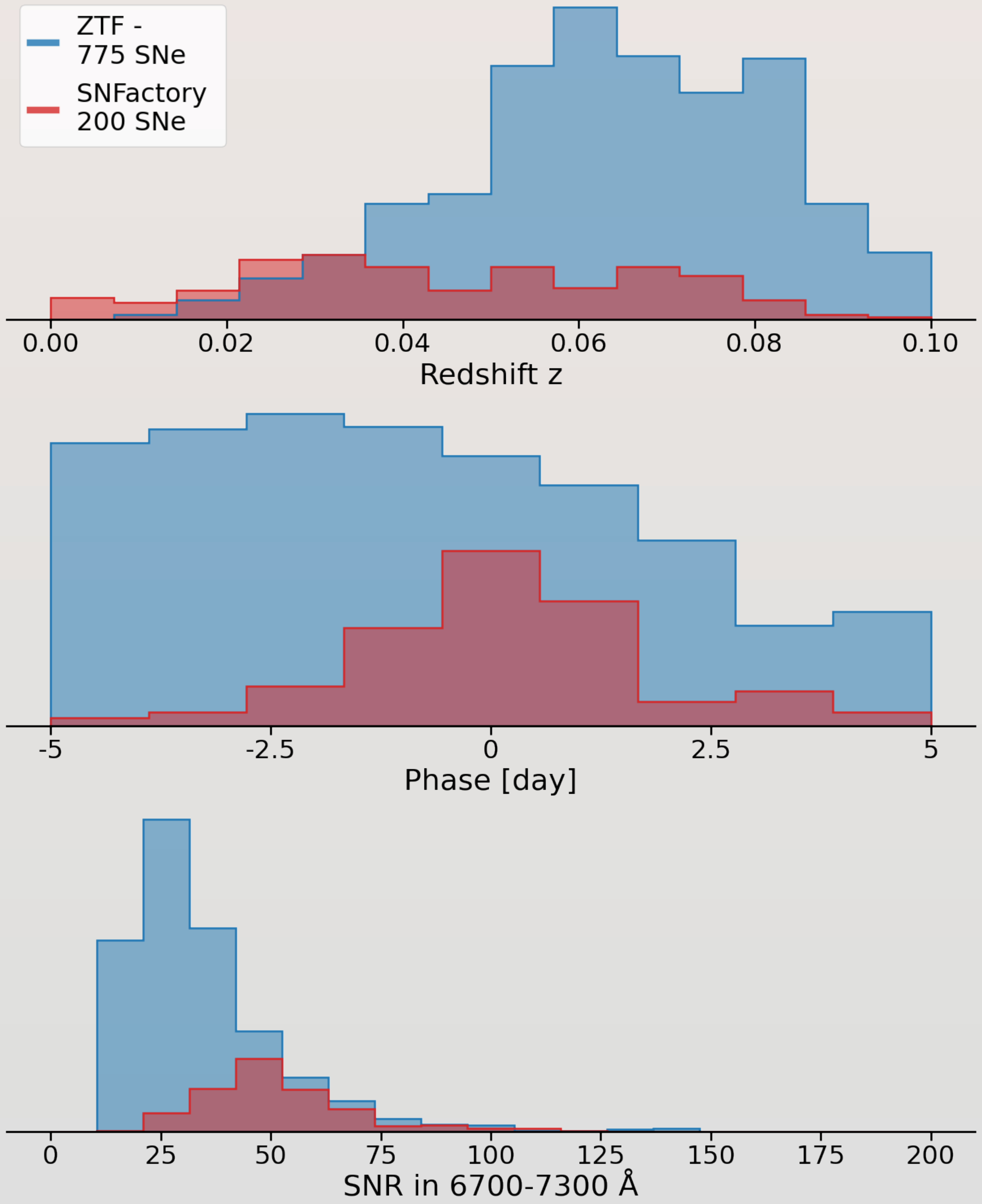
—> 846 spectra from 775 Sne Ia

ZTF spectra sample

- ☑ Flux calibration
- ☑ Milky Way correction
- ☑ Shift spectra to z=0.05



Median+nMAD of 667 ZTF flux-calibrated spectra with c<0.3
at z=0.05

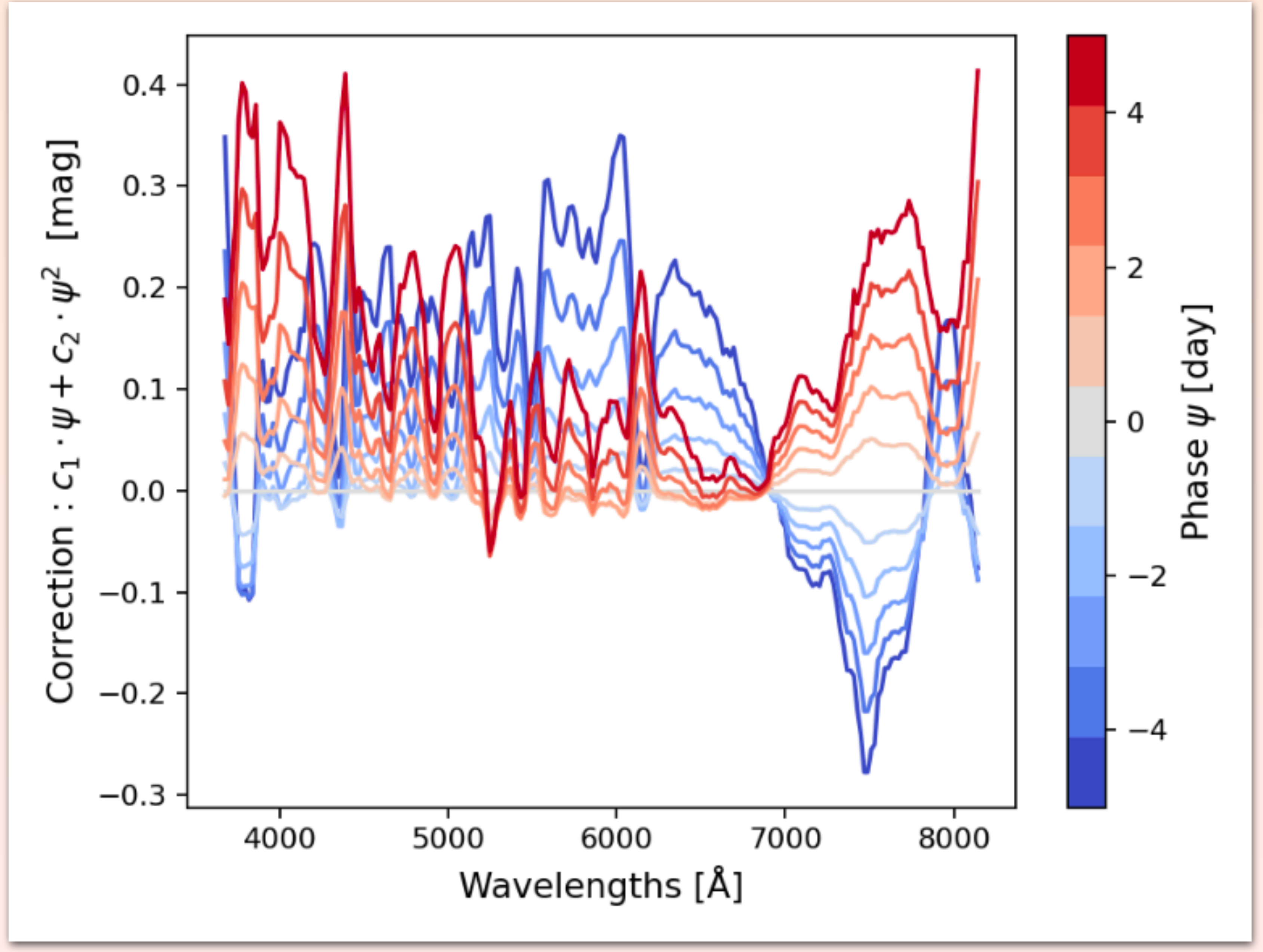


Twins Embedding - *Boone et al. 2021*

3 steps

1. Generate at maximum luminosity

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

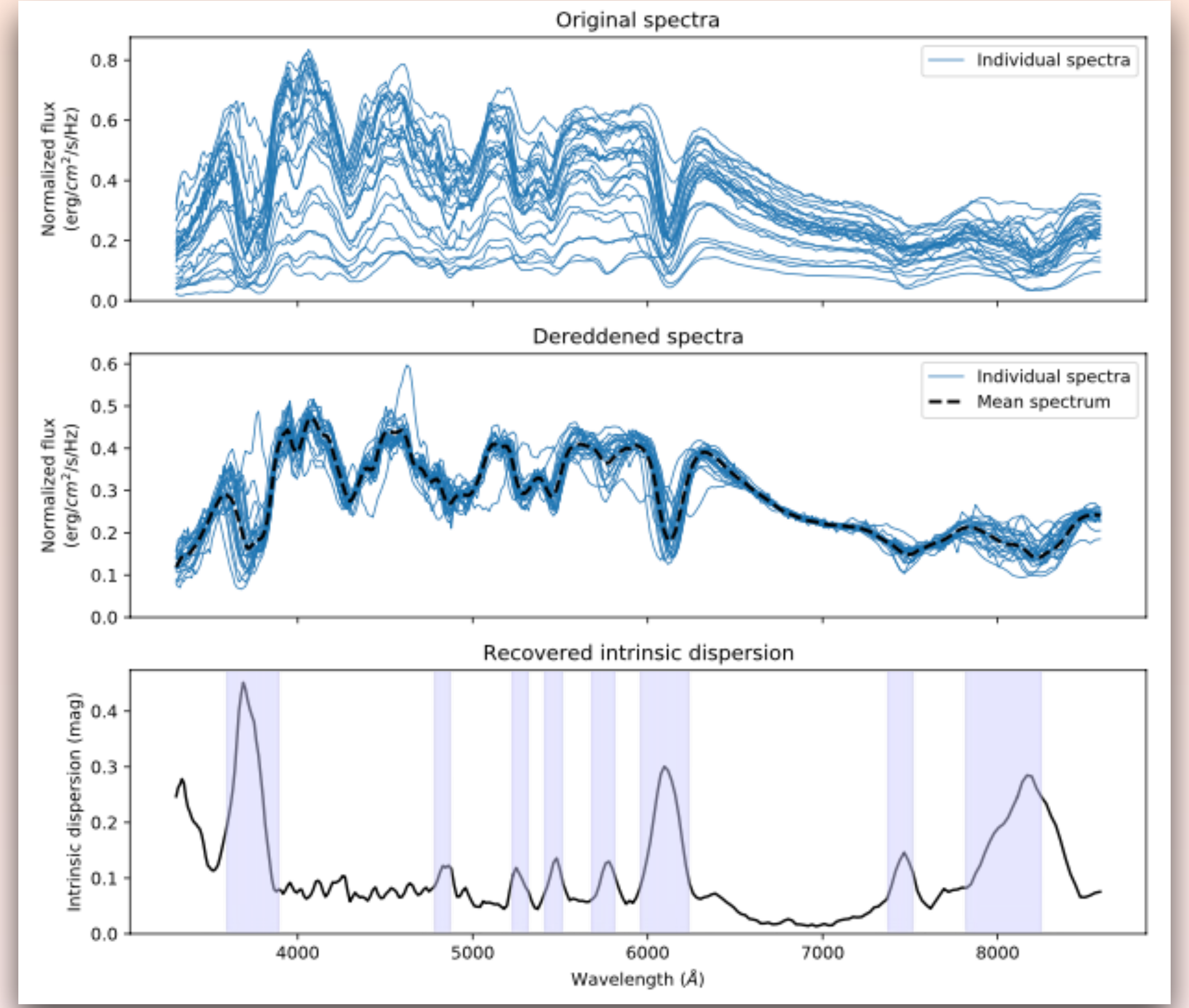


Quadratic evolution in phase of SN Ia spectra

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

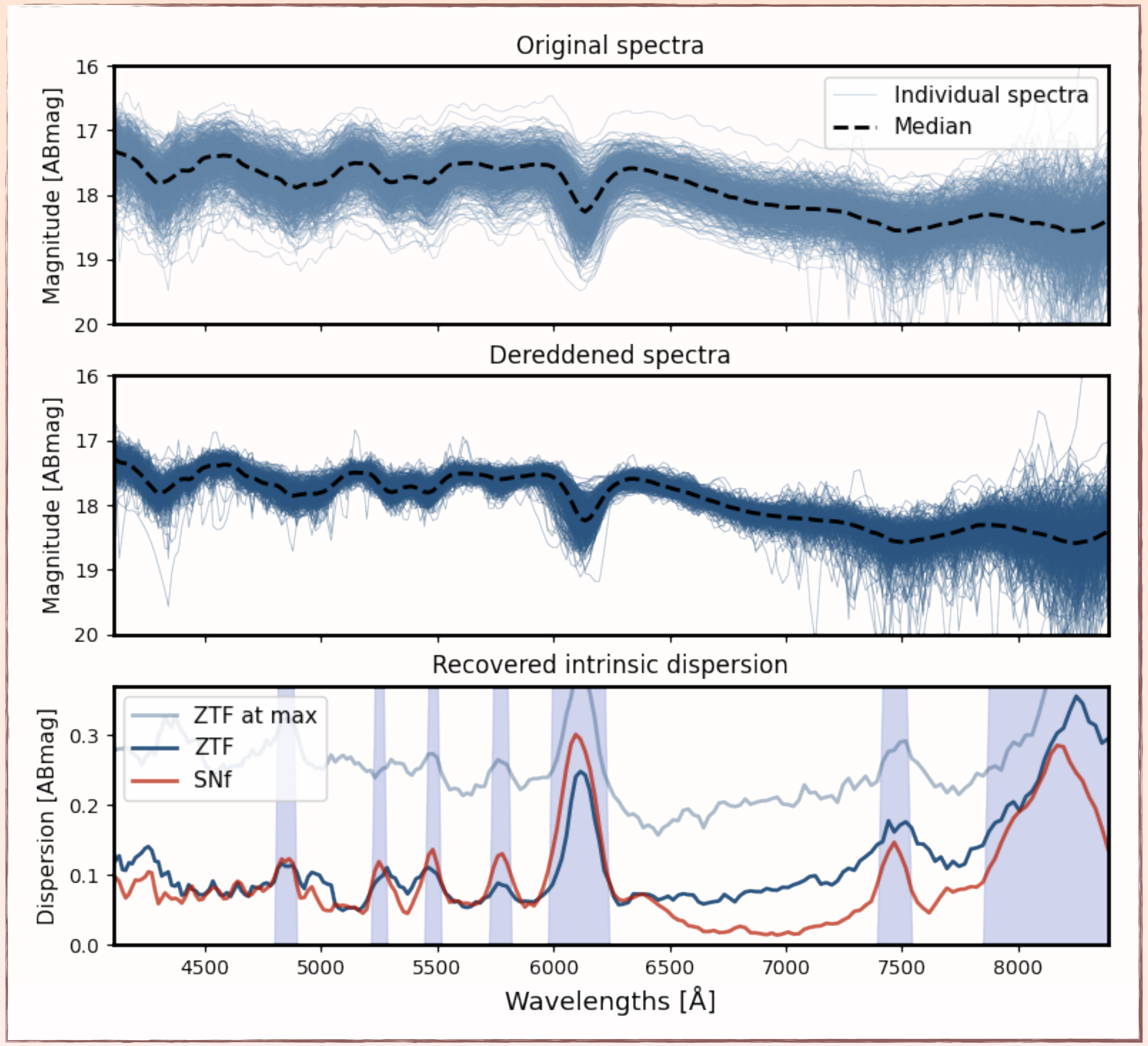
2. RBTL - fit one offset and a color outside the lines

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

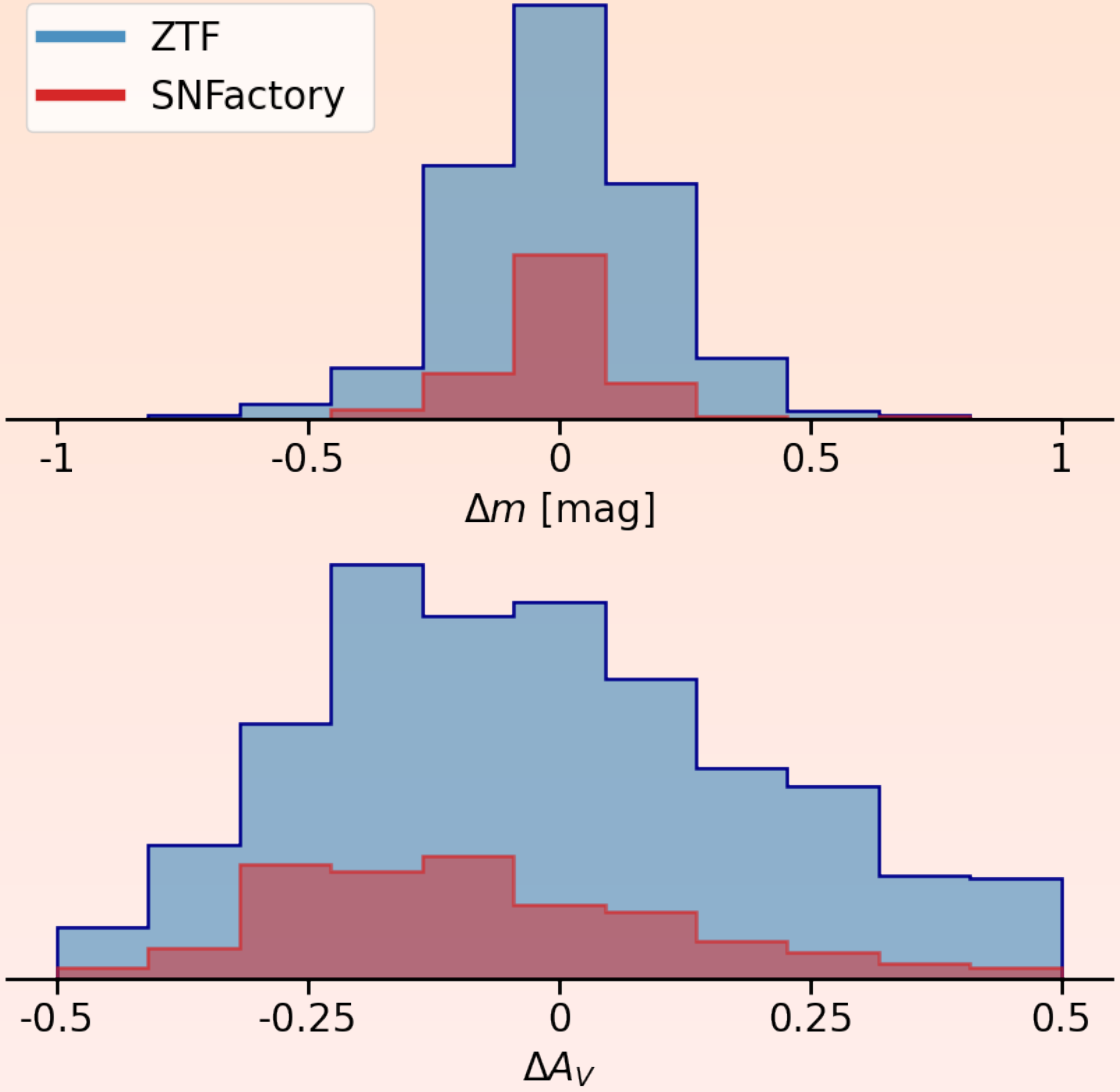


SNFactory spectra before/after dereddening, and residuals intrinsic dispersion (std) *Credit : Boone et al. 2021*

Twins Embedding on ZTF



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



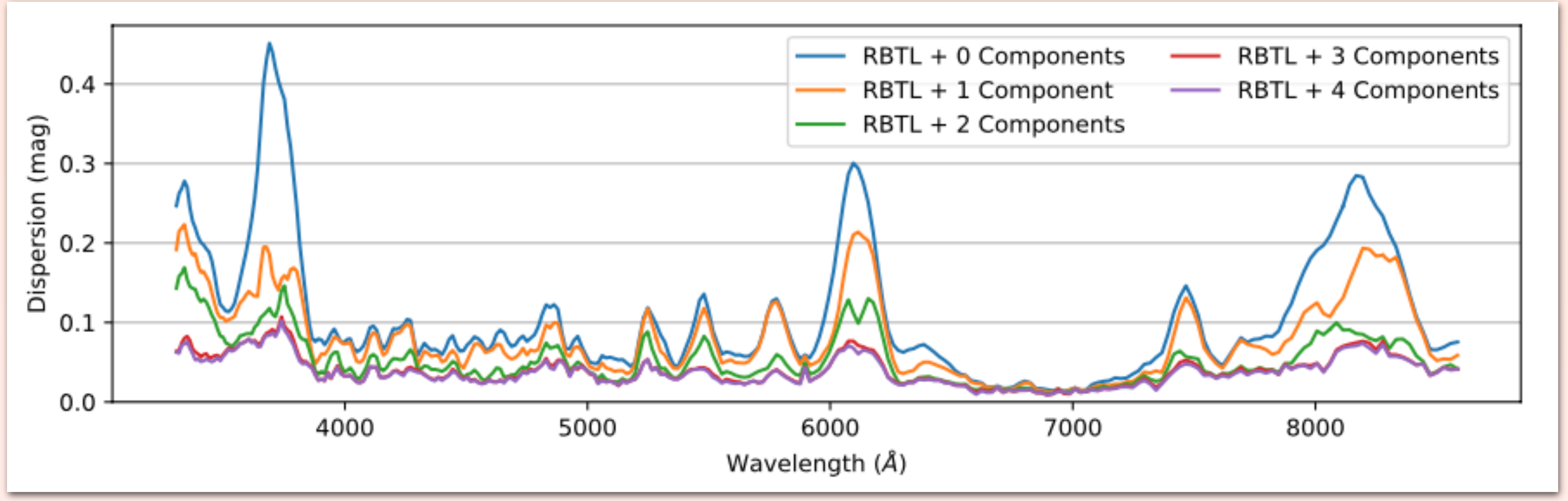
More red SNe in **ZTF** sample, same distribution shape in magnitude

Twins Embedding - *Boone et al. 2021*

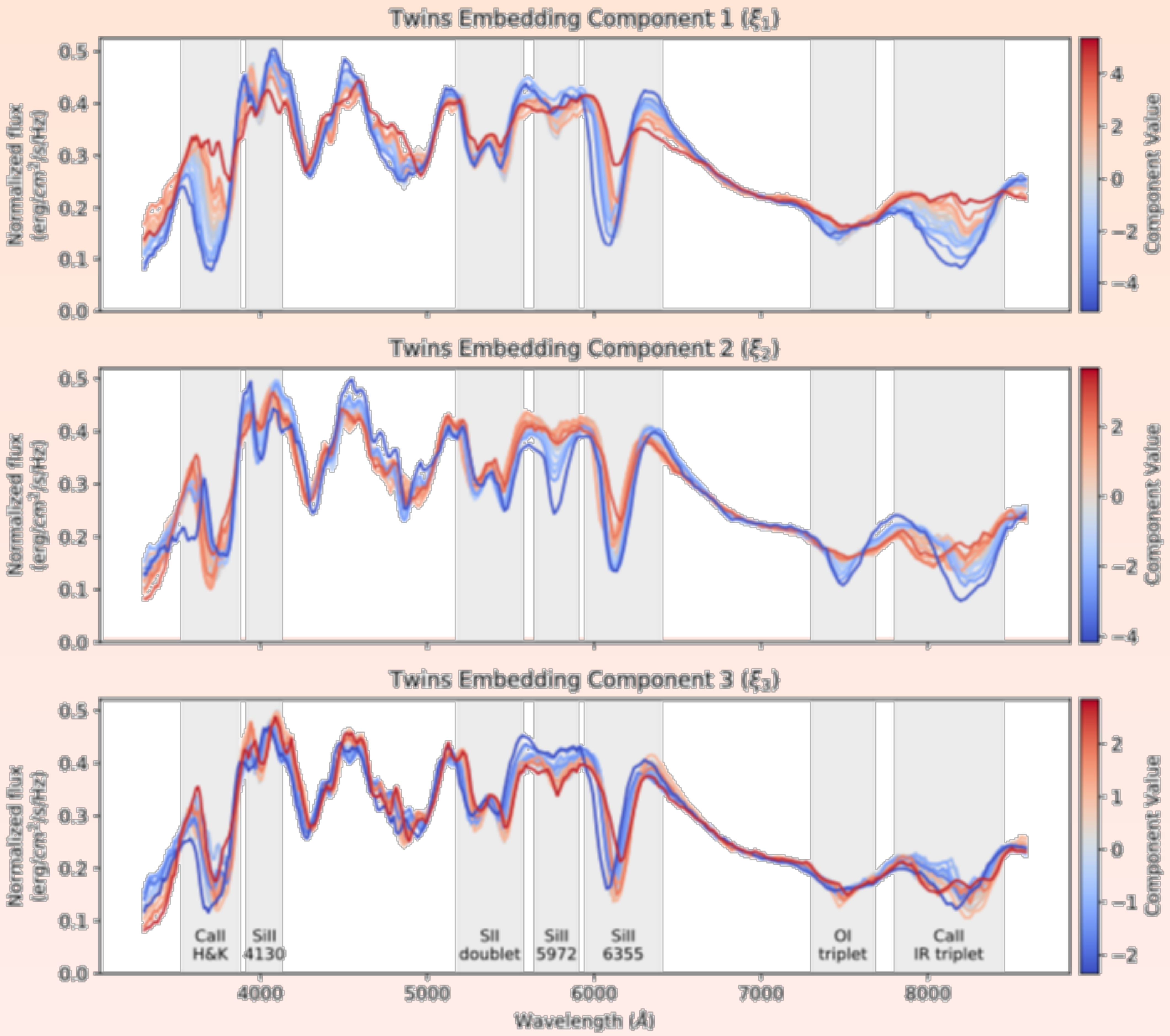
3 steps

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

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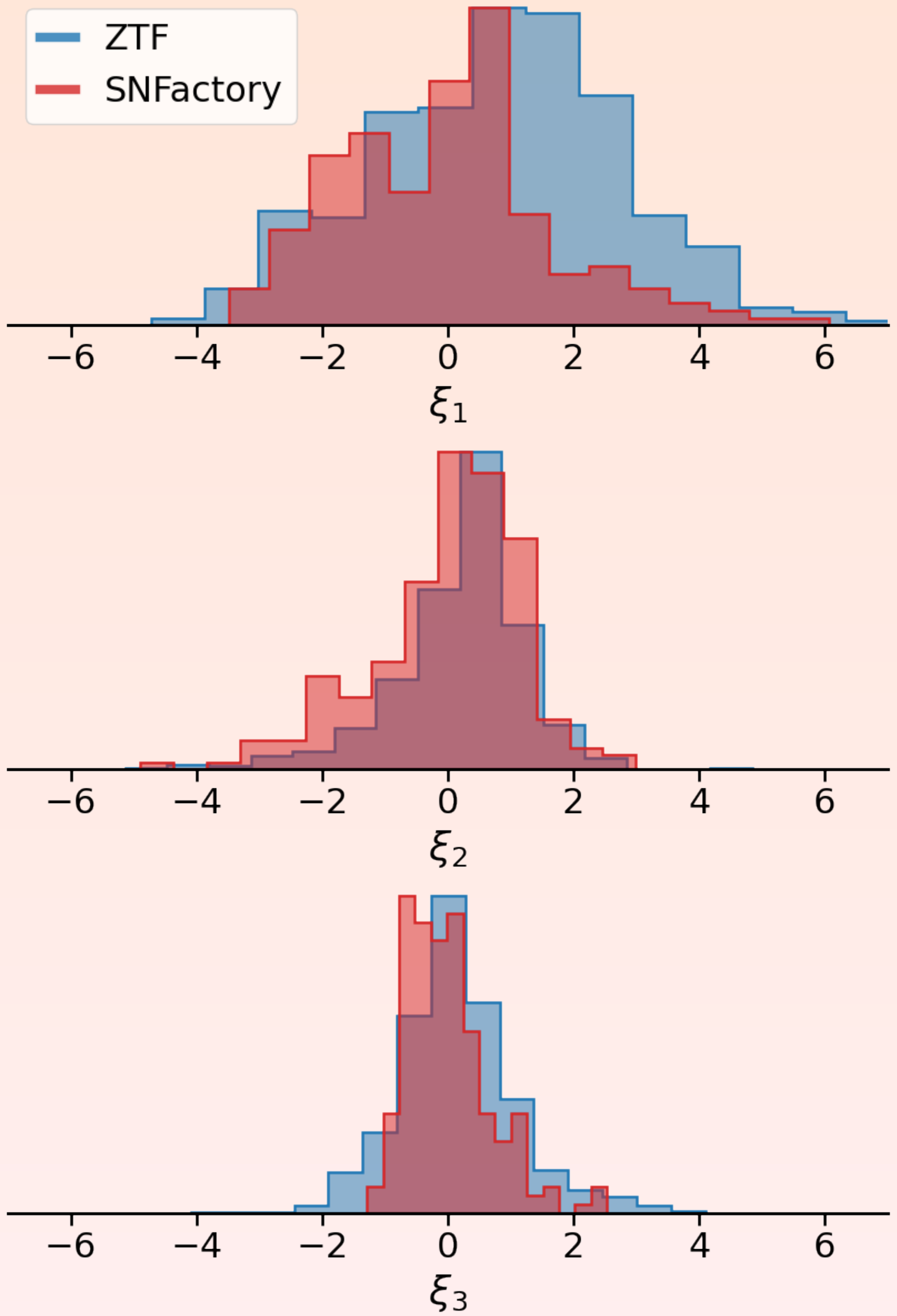


*Normalised distributions of Manifold components for both **ZTF** and **SNf***

RBTL standardisation

linear correction

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

Manifold standardisation

(work in progress)

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

With SNFactory

Twins Embedding :

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

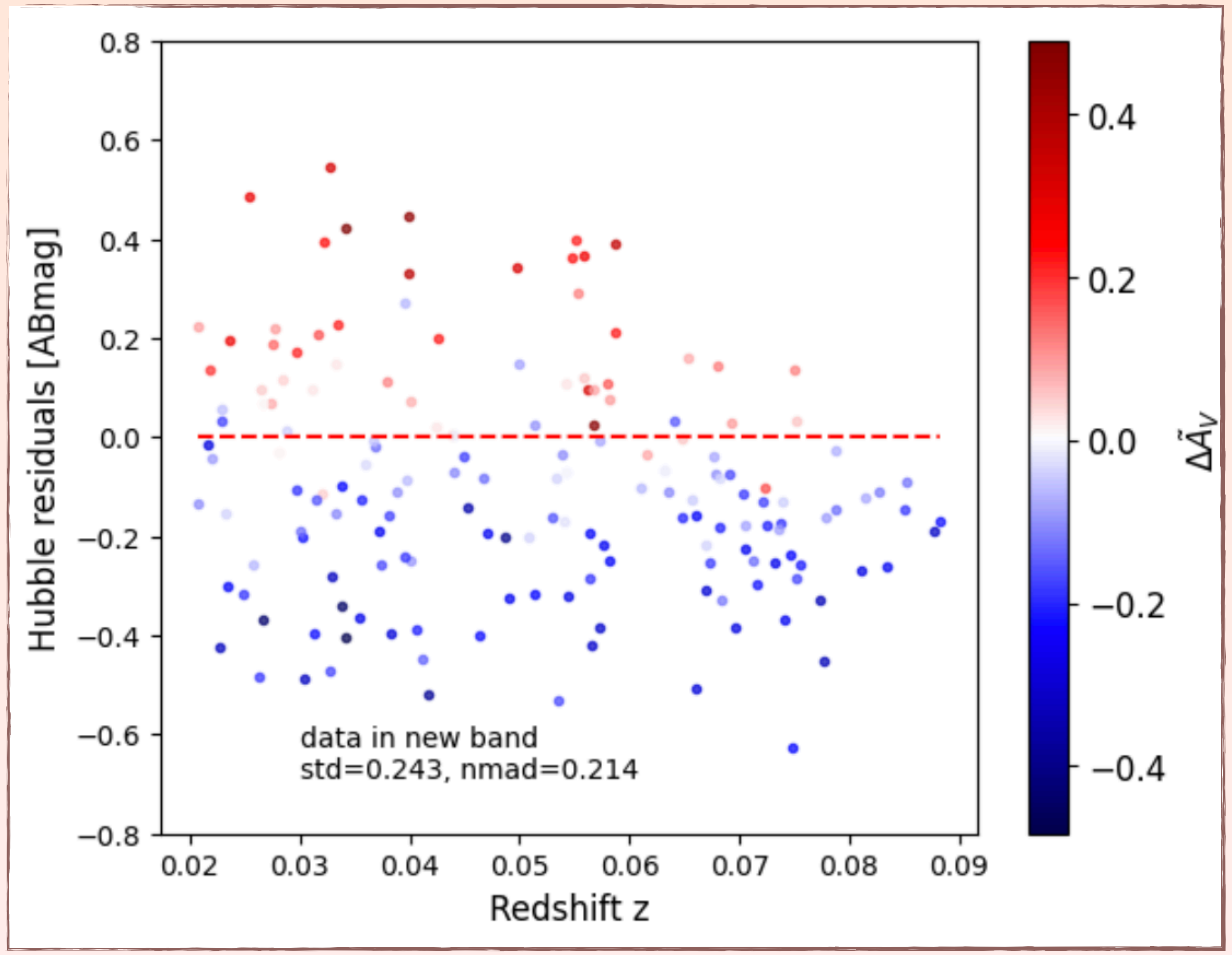
—> what with ZTF ?

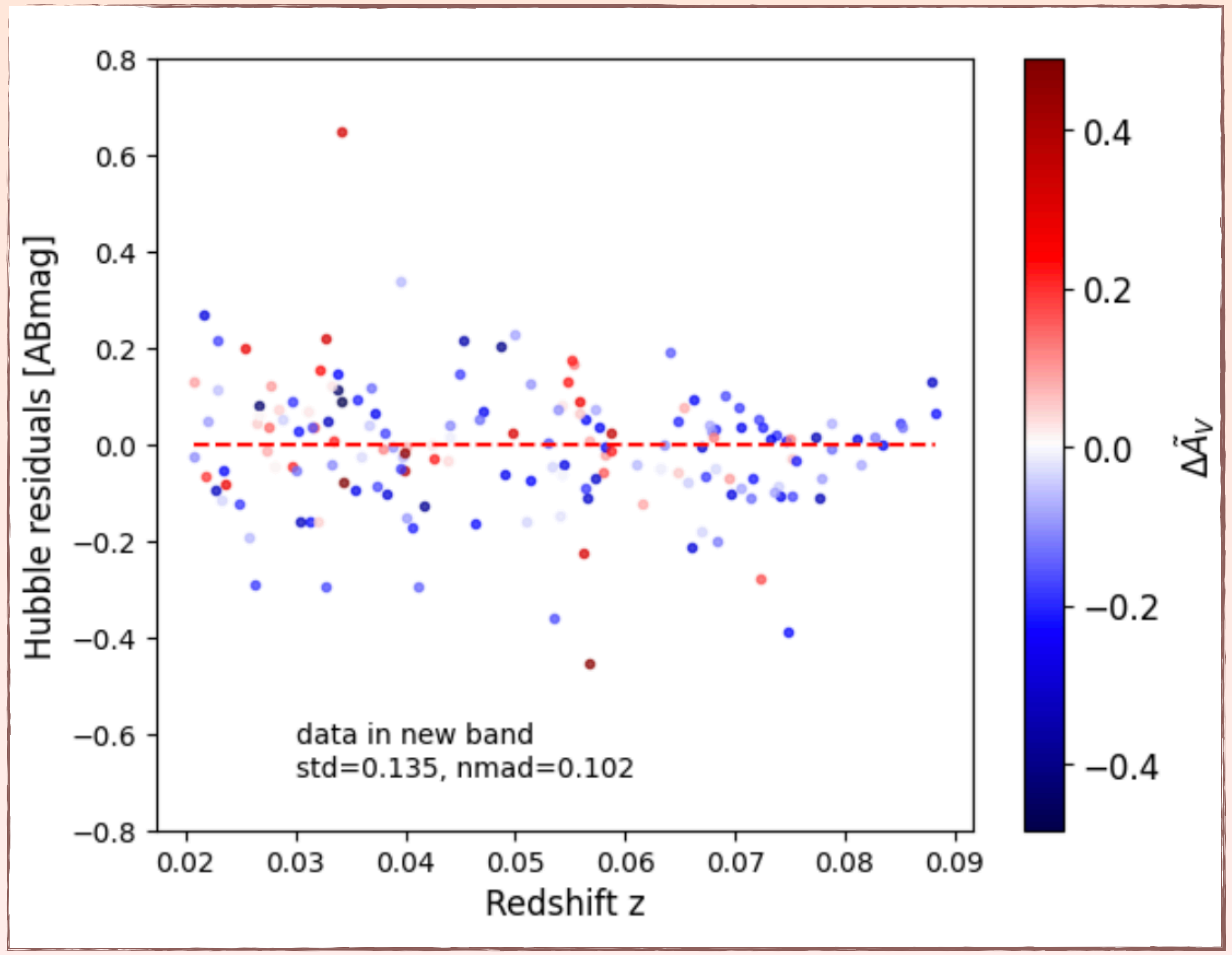
RBTL linear standardisation

For SNFactory sample

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

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



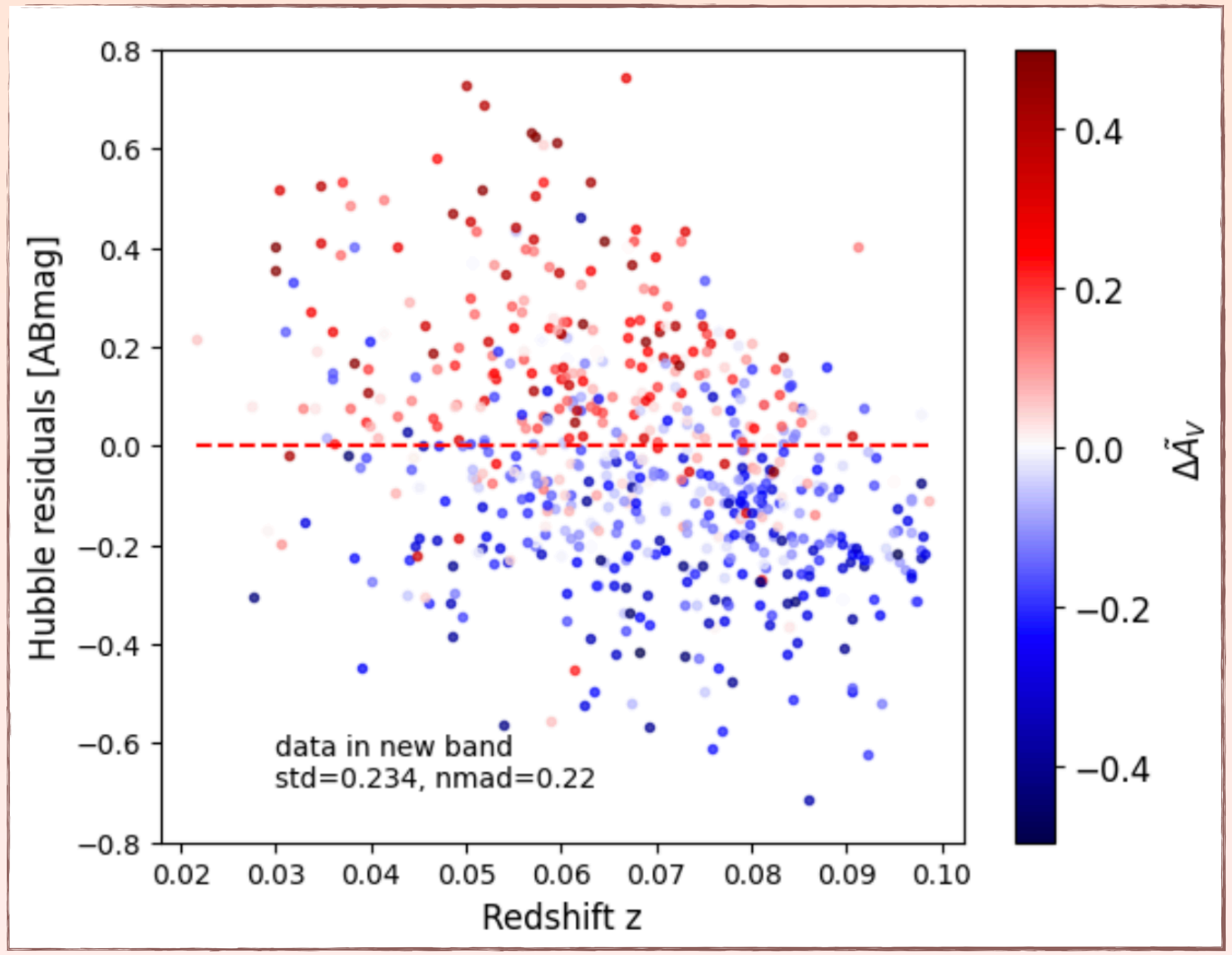


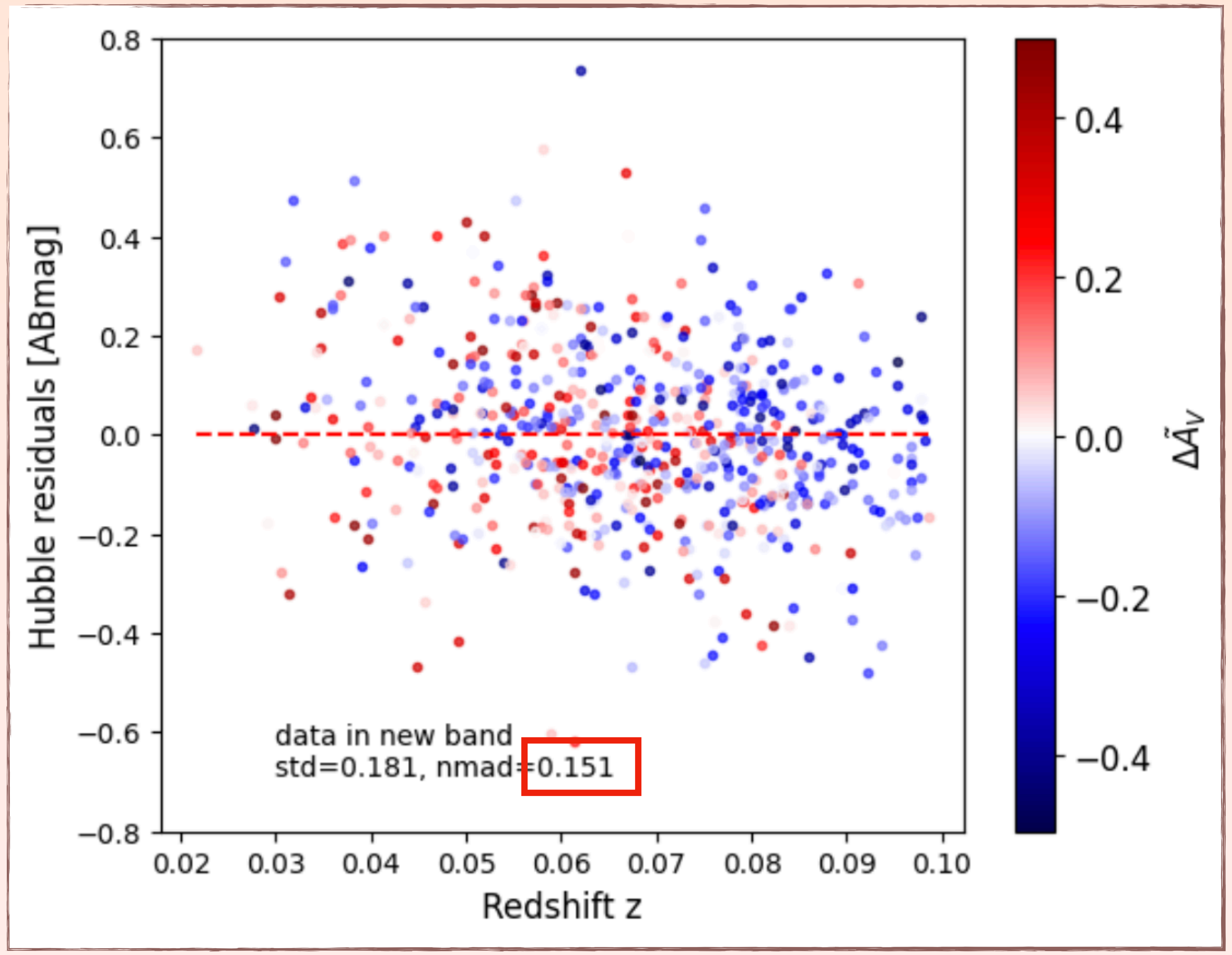
168 SNe Ia before/after standardisation after a cut on z, Av < 0.5 & RBTL uncertainties

RBTL linear standardisation

For ZTF sample

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





628 SNe Ia before/after standardisation after a cut on z, Av < 0.5 & RBTL uncertainties

Comparable dispersion to that of photometric standardisation, with only 1 parameter

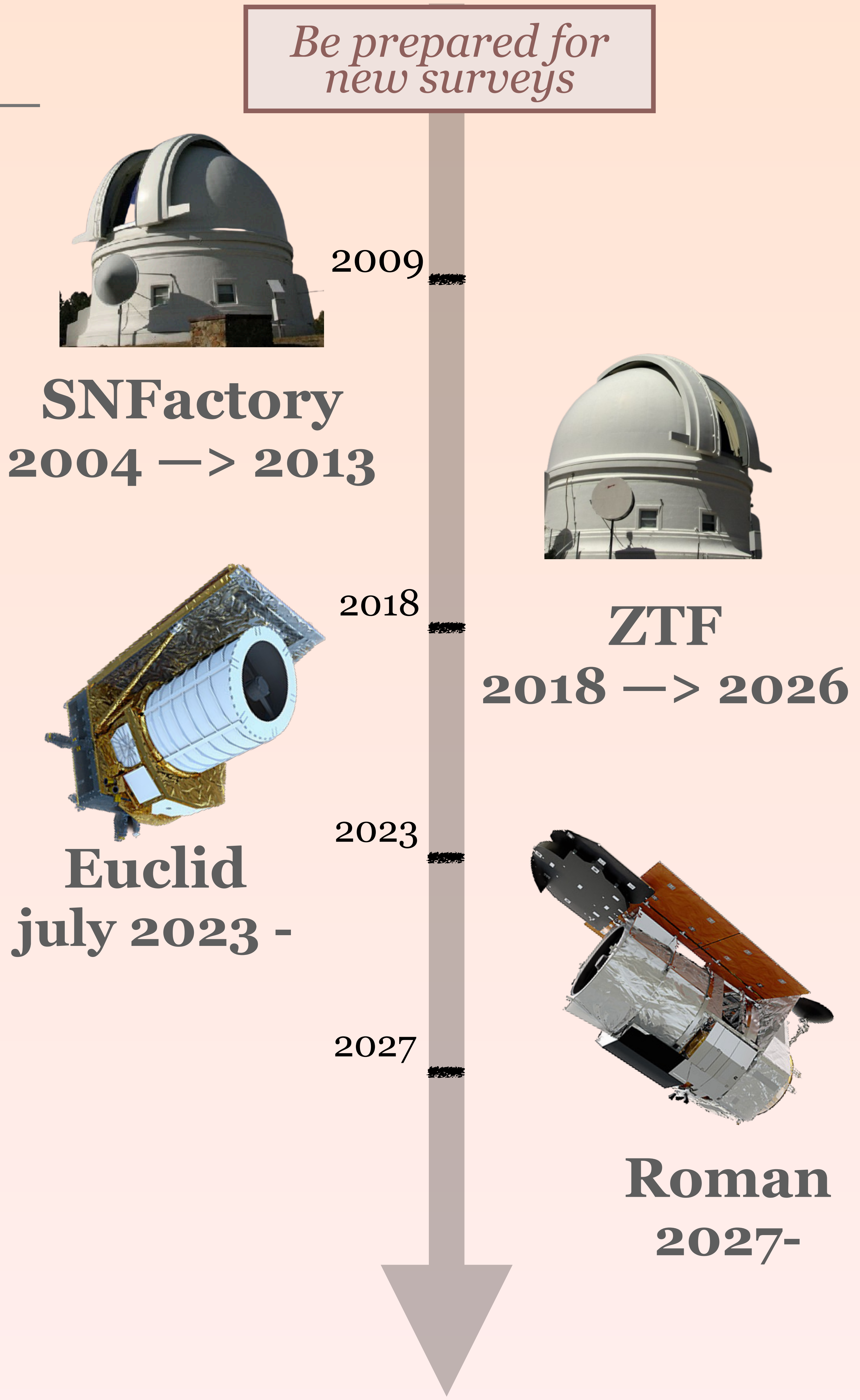
Conclusion

TE application results

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

What's next

- 1st paper on the results on the evaluation of Twins Embedding method on ZTF spectra
- Construct an Hubble Diagram using ZTF and SNLS spectra using Twins Embedding
- Cosmology with spectro-photometric standardisation



SNe parameters cuts

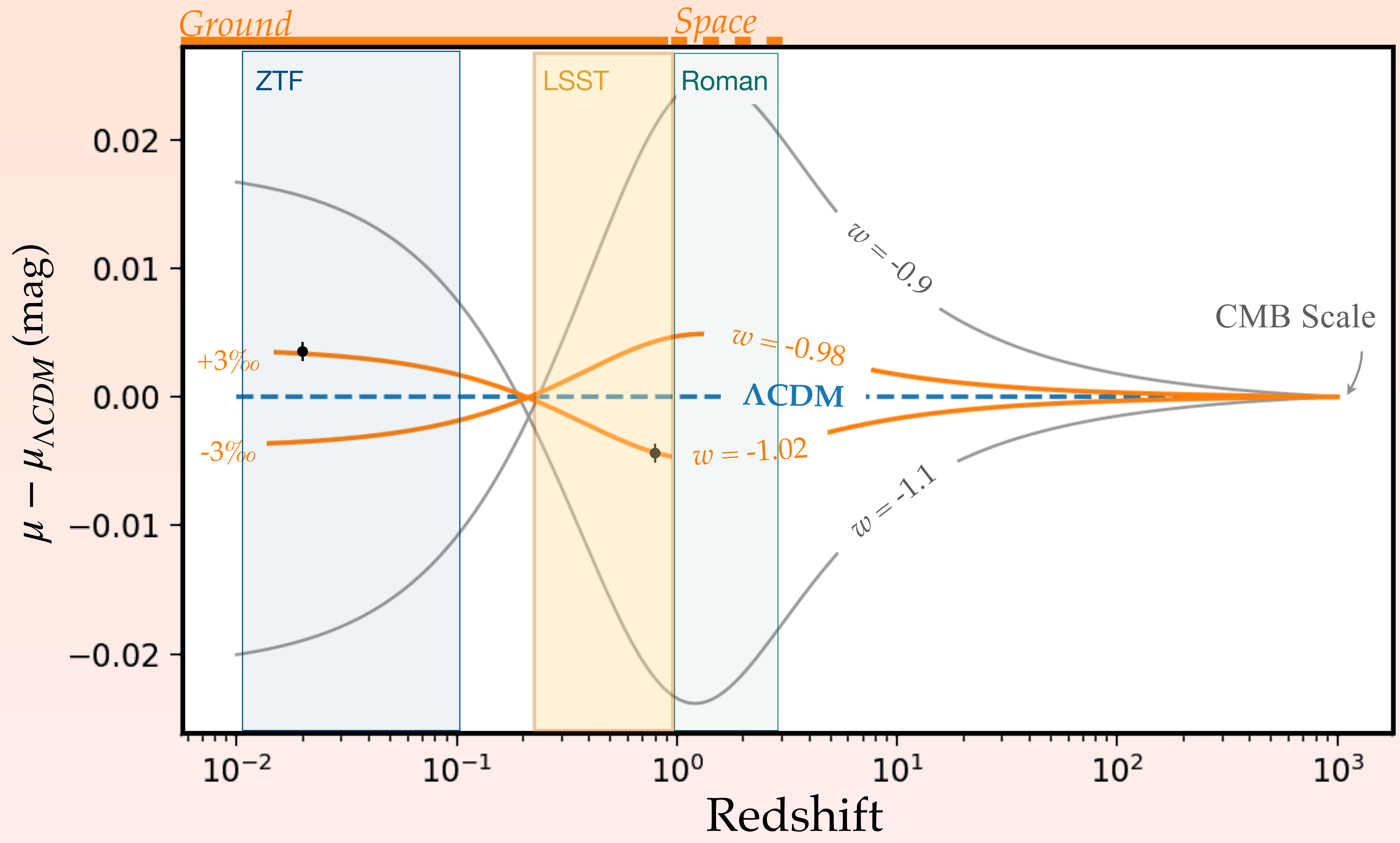
Parameter cut	Remains	Quantity removed
from SEDm	1749	40 %
calibration precision	1647	6 %
phase in [-5,+5] days	1005	**around 40%**
$z<0.1$	992	around 6%
cosmological params: c in [-0.2,0.8], $c_{err}<0.1$ x_1 in [-3,3], $x_{1,err}<1$ $t_{0,err}<1$ day	966	3 %
cosmo sn_type	830	around 14%
SNR>12	775	4 %

Cuts for RBTL standardisation

Parameter cut	Remains	Quantity removed
$z>0.02$	766	1 %
$A_V<0.5$ $A_{V,err}<0.2$ $Dm_{err}<0.2$	628	20 %

—> 767 spectra of 628 Sne Ia

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 !

STEP 1

Differential time evolution model

=> ***Spectra @ max***

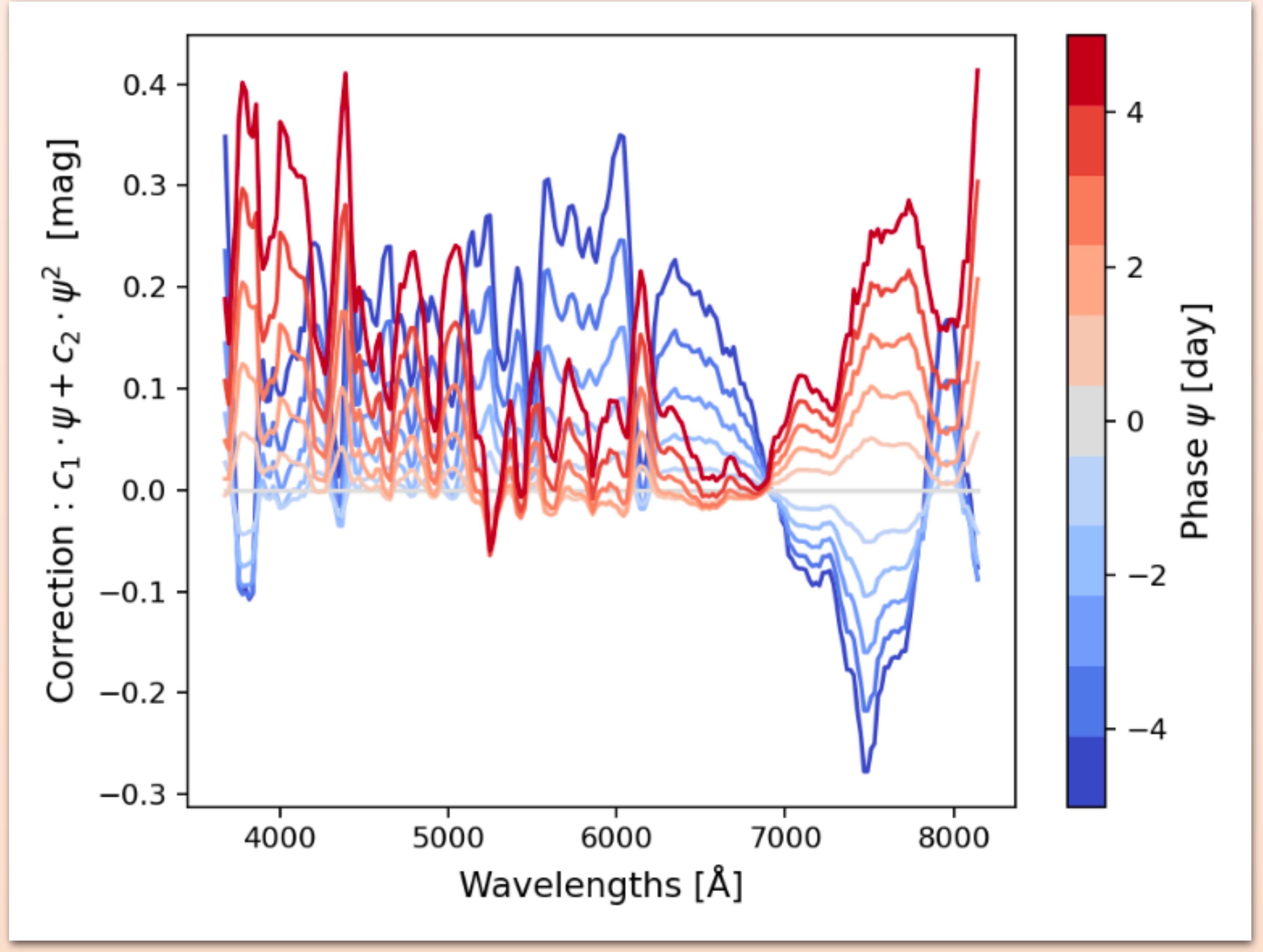
Formula of quadratic evolution in phase :

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

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

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

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

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

Fitted parameters :

$f_s(p,\lambda_k)$ 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

Known:

$f_{obs}(p,\lambda_k)$ 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

=> Spectra @ max

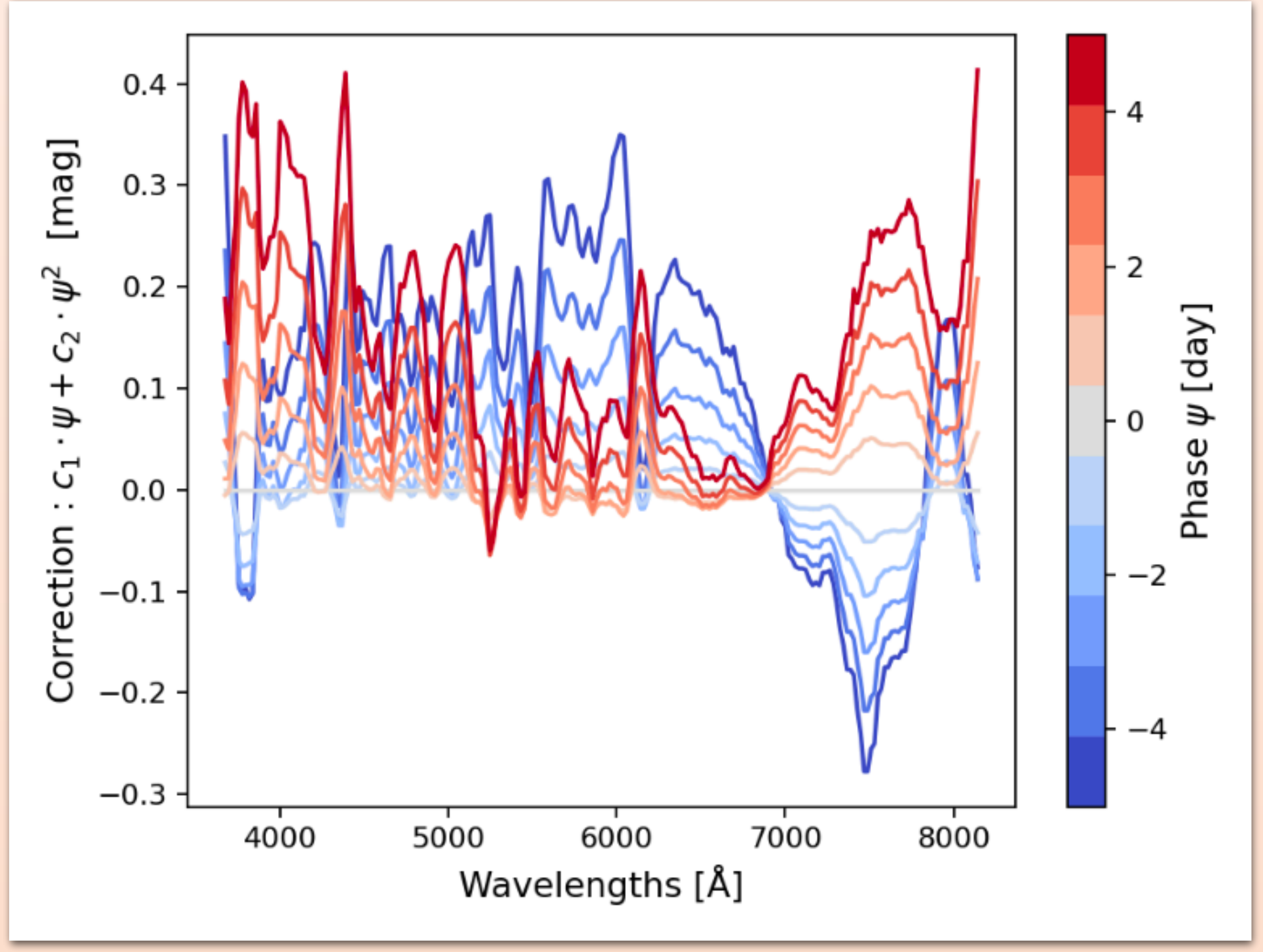
Formula of quadratic evolution in phase :

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

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

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tot., s

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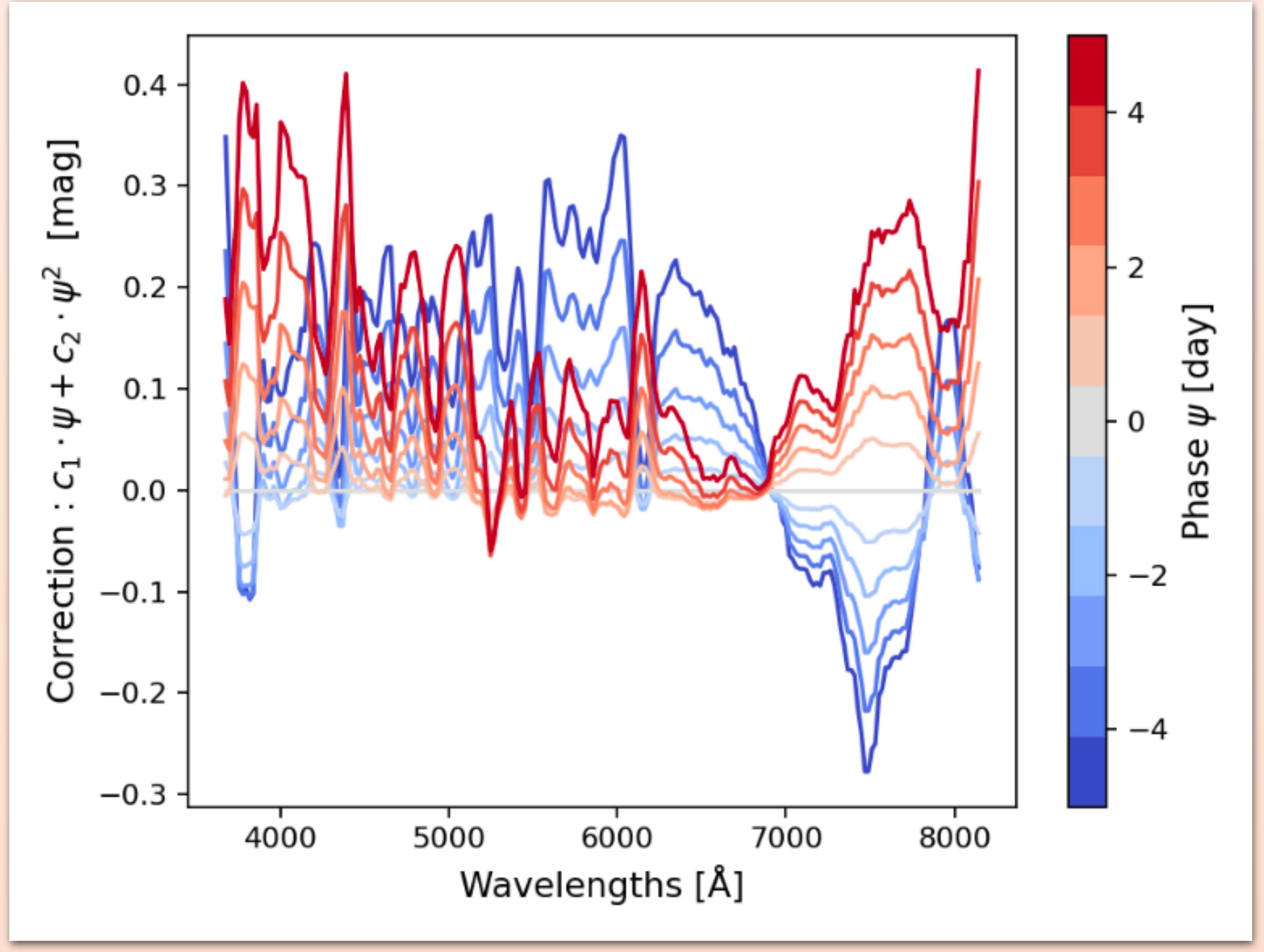

Quadratic evolution in phase of SN Ia spectra

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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

<u>Remove variability:</u>

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

<u>Fitted parameters :</u>

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)*

<u>Known:</u>

$f_{max,i}(\lambda_k)/\sigma^2_{f_{max},i}(\lambda_k)$ *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)*

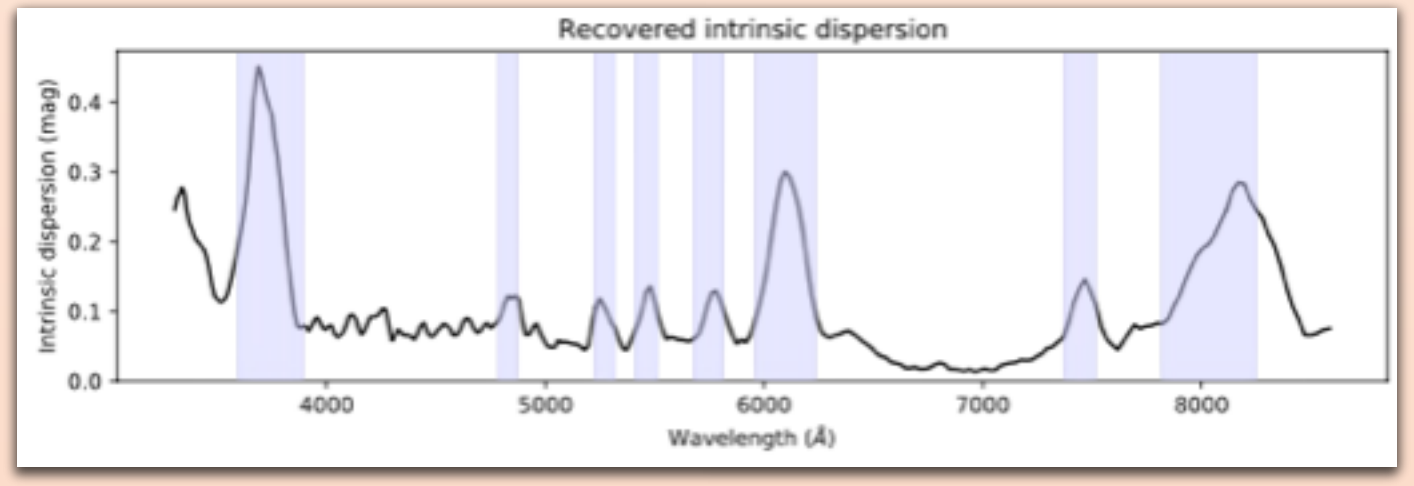
Fit all together with bayesian inference :

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

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

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

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



STEP 2

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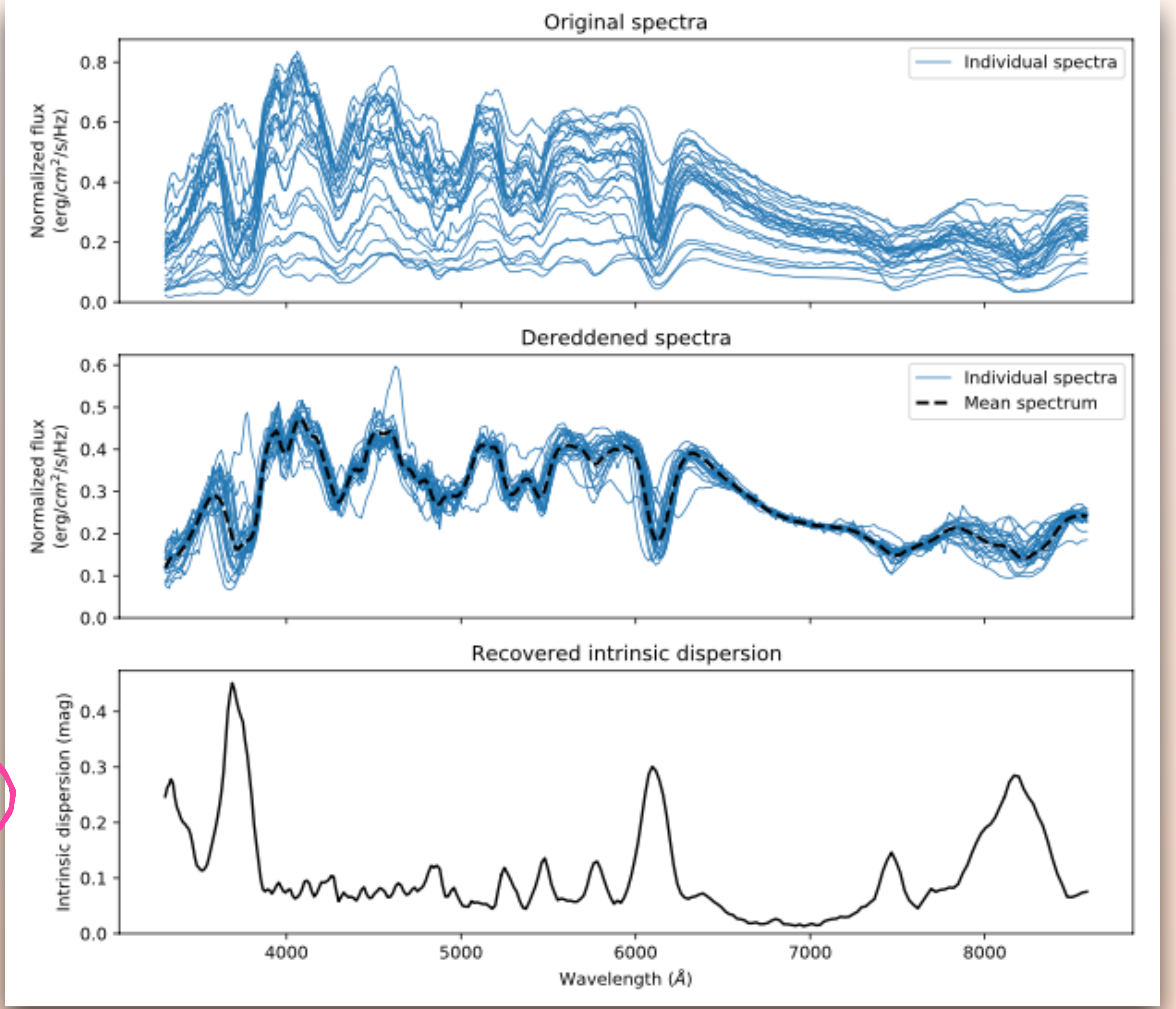
=> Explain Scatter Between the lines

Capture Grey scatter + Extinction



$\eta(\lambda_k)$

SNFactory spectra before/after dereddening, and residual intrinsic dispersion (std) - from Boone 2021

Remove variability:

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

$$f_{\mathrm{dered.},i}(\lambda_k) = f_{\mathrm{max.},i}(\lambda_k) \times 10^{+0.4(\Delta m_i + \Delta \tilde{A}_{V,i} C(\lambda_k))}$$

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

STEP 2

Read between the lines (RBTL)

=> *Explain Scatter Between the lines*

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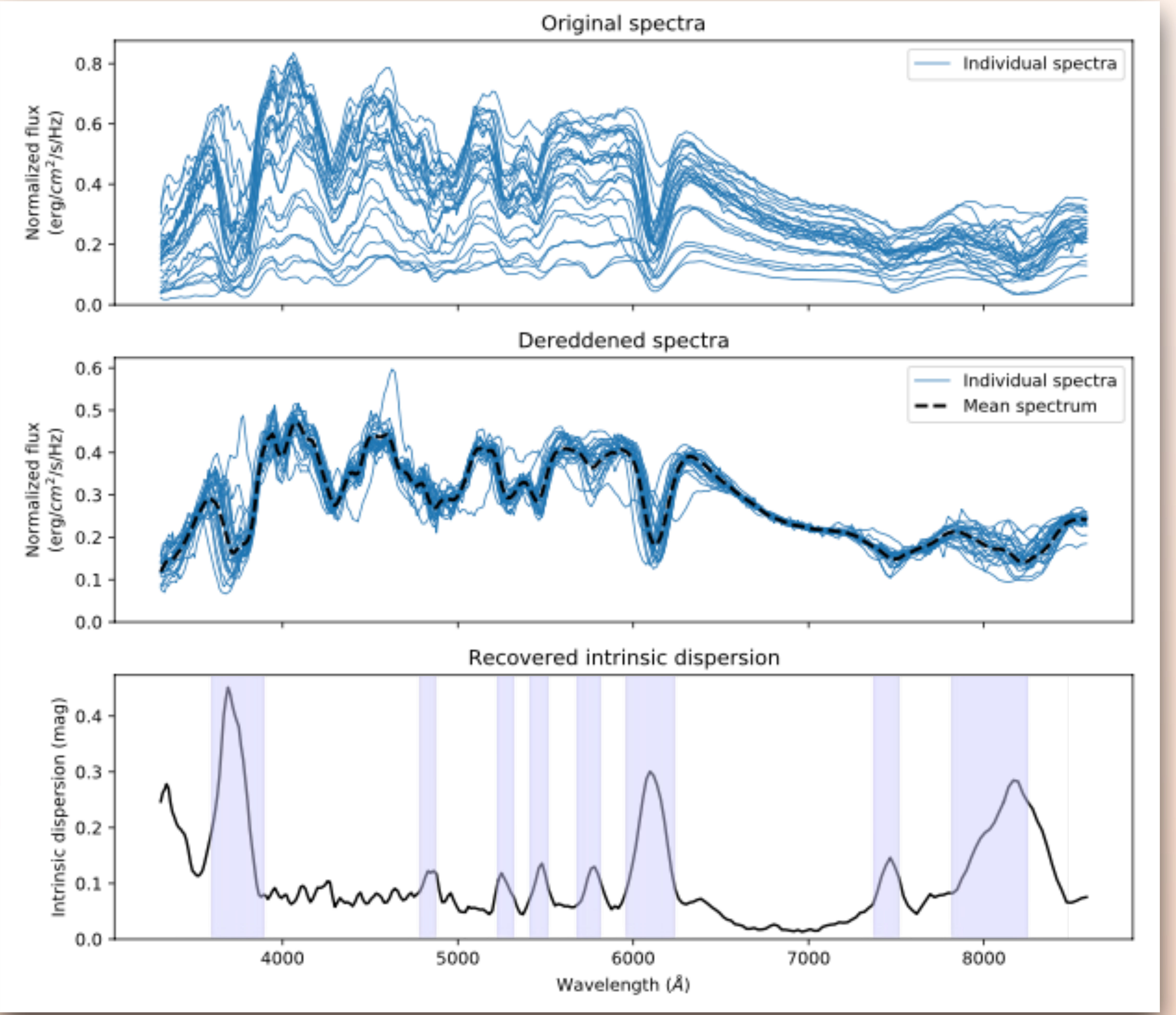
$\eta(\lambda_k)$



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

SNFactory spectra before/after dereddening, and residual intrinsic dispersion (std) - from Boone 2021

STEP 3

The Twins Embedding parameters space

=> *Explain* $\eta(\lambda_k)$

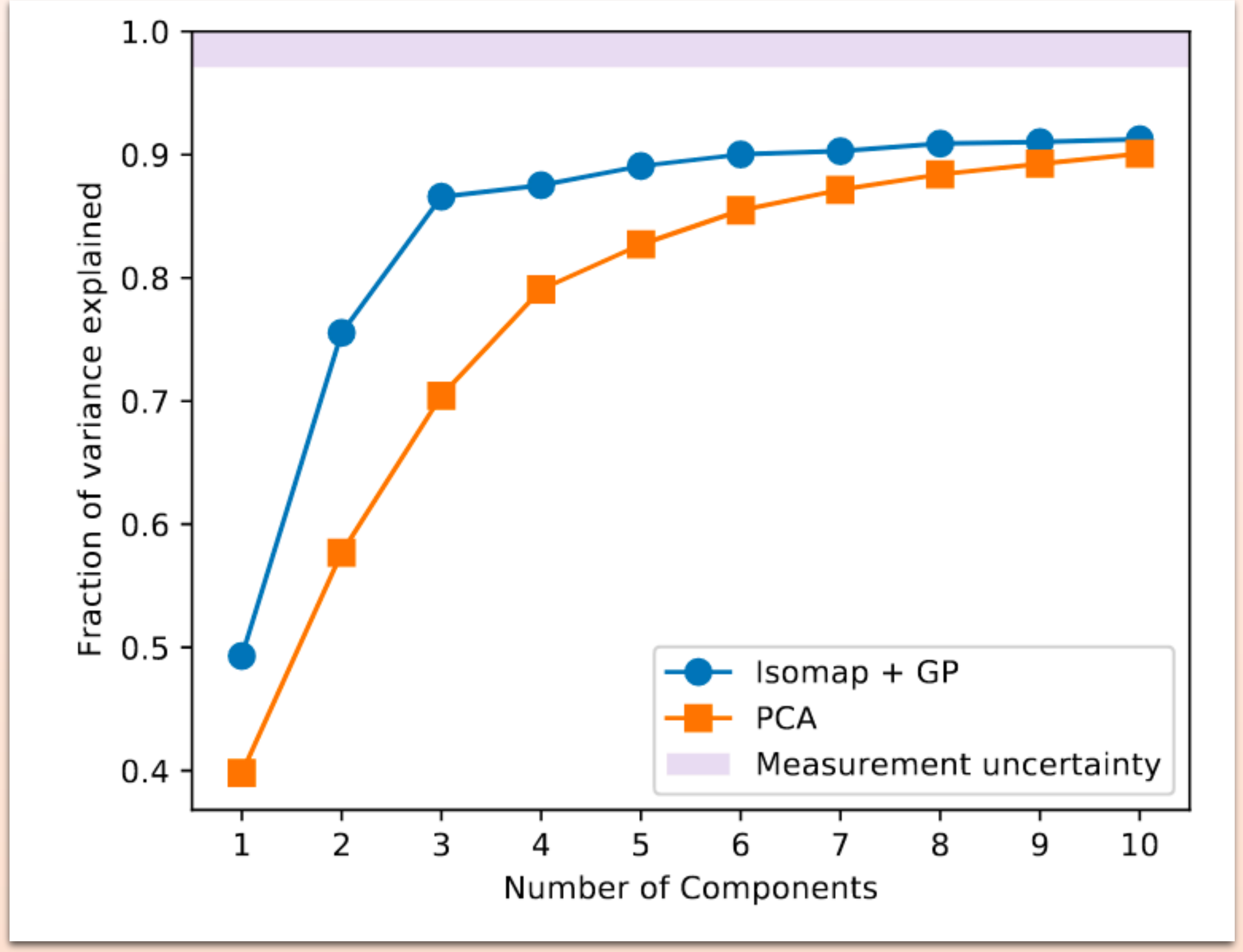
Spectral distance between two Sne I and j :

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

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

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

86.6% of variance explained with 3 components

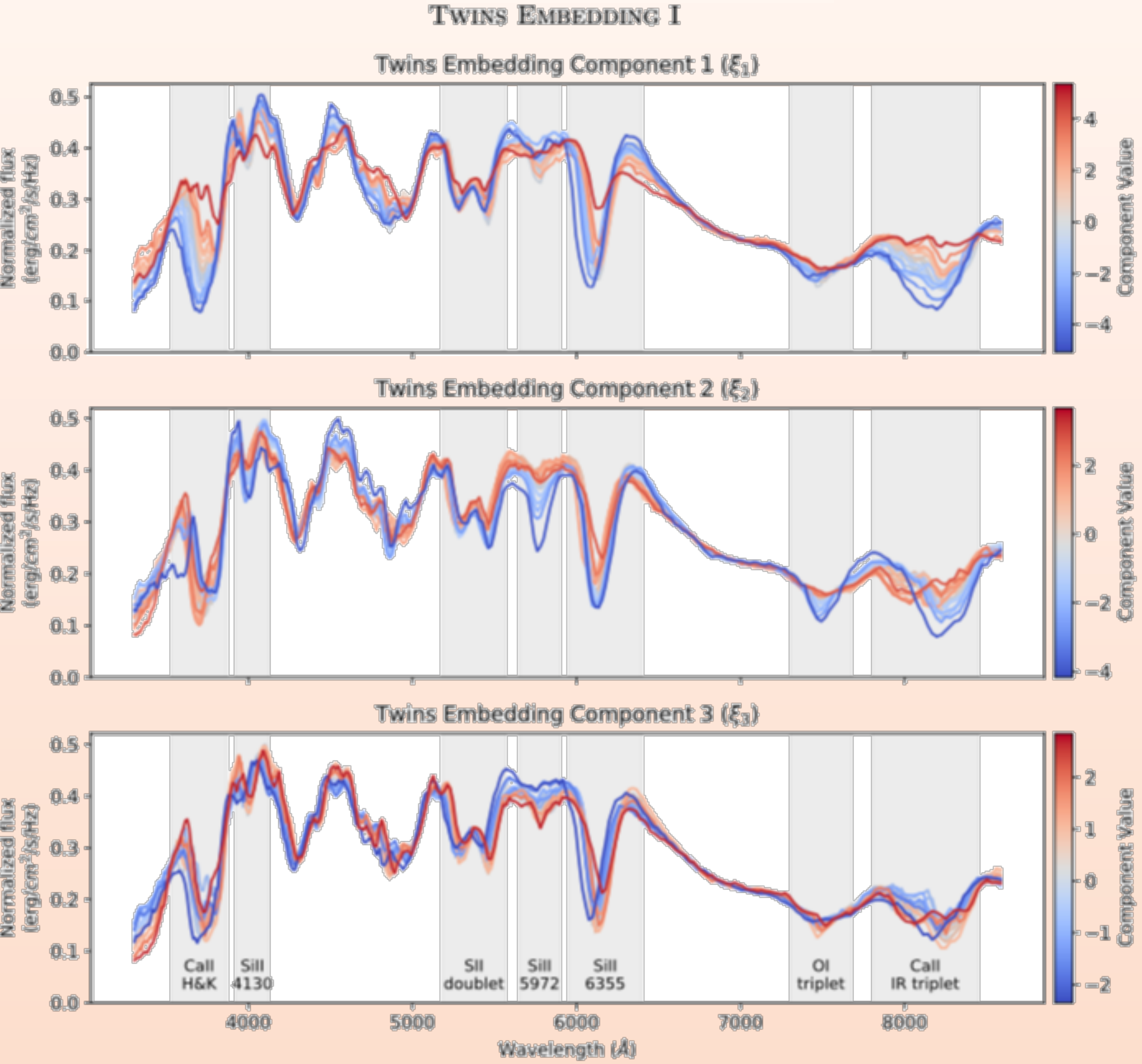


Fraction of the variance explained for different models - from Boone 2021

STEP 3

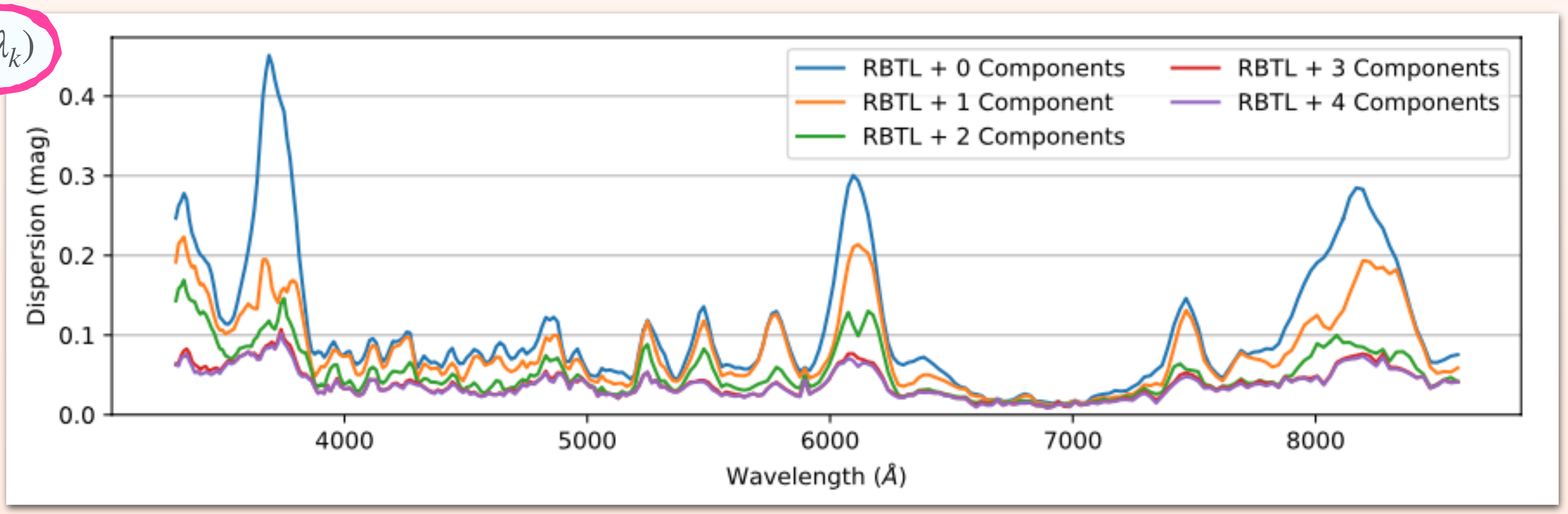
The Twins Embedding parameters space

=> ***Explain*** $\eta(\lambda_k)$

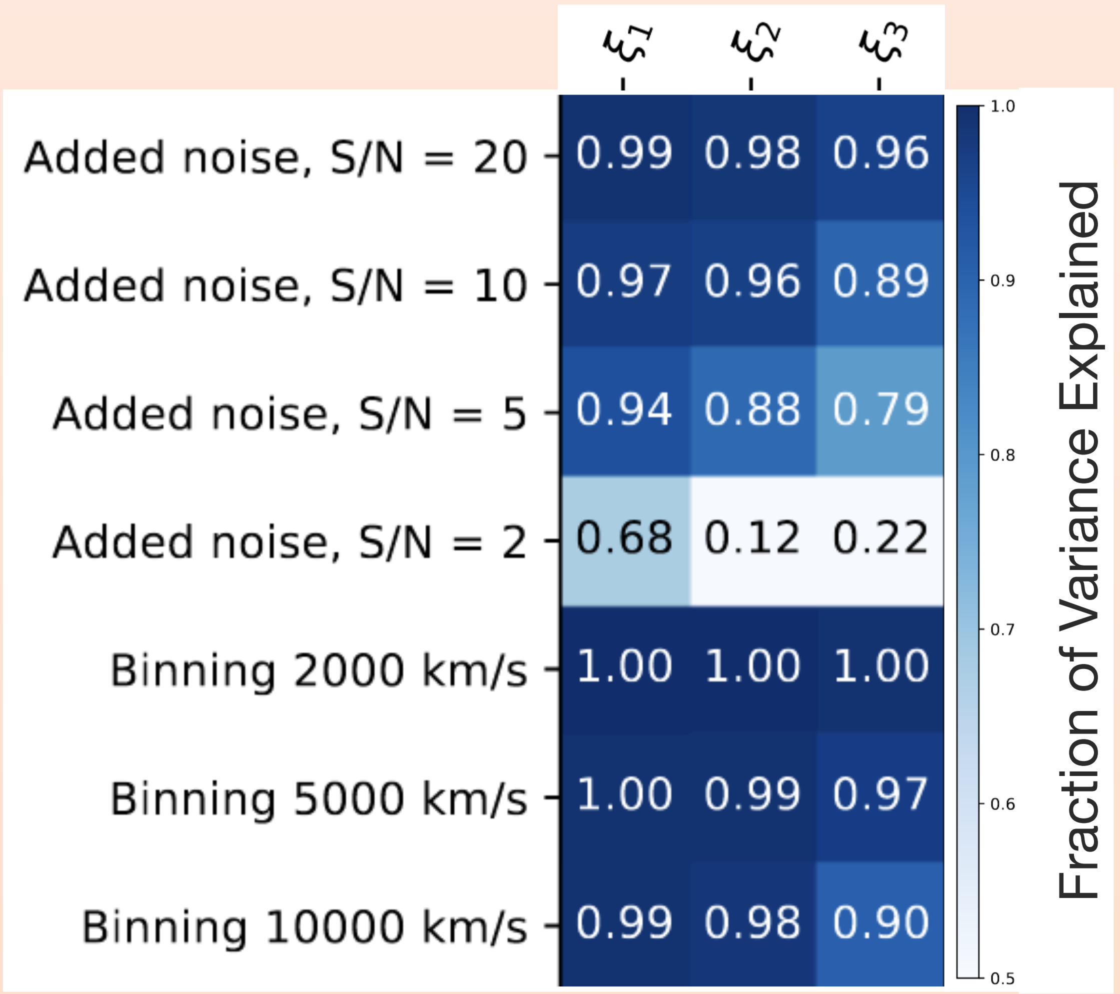


Twins Embedding three components variation effects
Figure from Boone 2021

$\eta(\lambda_k)$



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

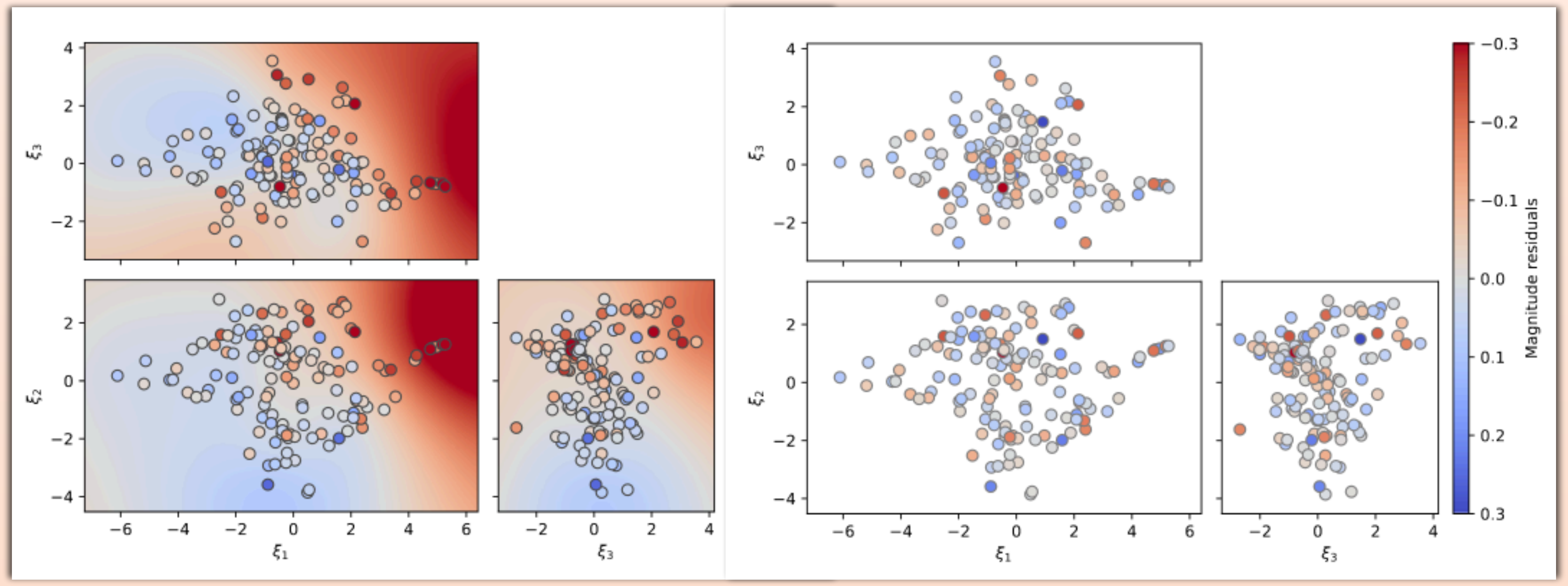


Dependancy of the variance explained with S/N and binning

The standardisation using Twins Embedding

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

$$\vec{m}_{\mathrm{RBTL}} \sim \mathcal{GP}\Big(m_{\mathrm{ref}} + \omega \Delta \vec{\tilde{A}}_V, \\ \mathbf{I} \cdot (\vec{\sigma}^2_{\mathrm{p.v.}} + \sigma_u^2) + K_{3/2}(\vec{\xi}, \vec{\xi}; A, l)\Big)$$



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

Fitted parameters :

m_{ref} *a common reference magnitude*

ω *a linear correction term*

σ_u *the unexplained residual dispersion*

A, l *the GP kernel parameters*

Known :

$\overrightarrow{m}_{RBTL}$ *the magnitudes residuals of the RBTL ,*

$\overrightarrow{\Delta A_V}$ *the reddening coefficients ,*

$\overrightarrow{\xi}$ *the coordinates in the TE space,*

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