Spectrophotometric standardisation of ZTF type Ia supernovae

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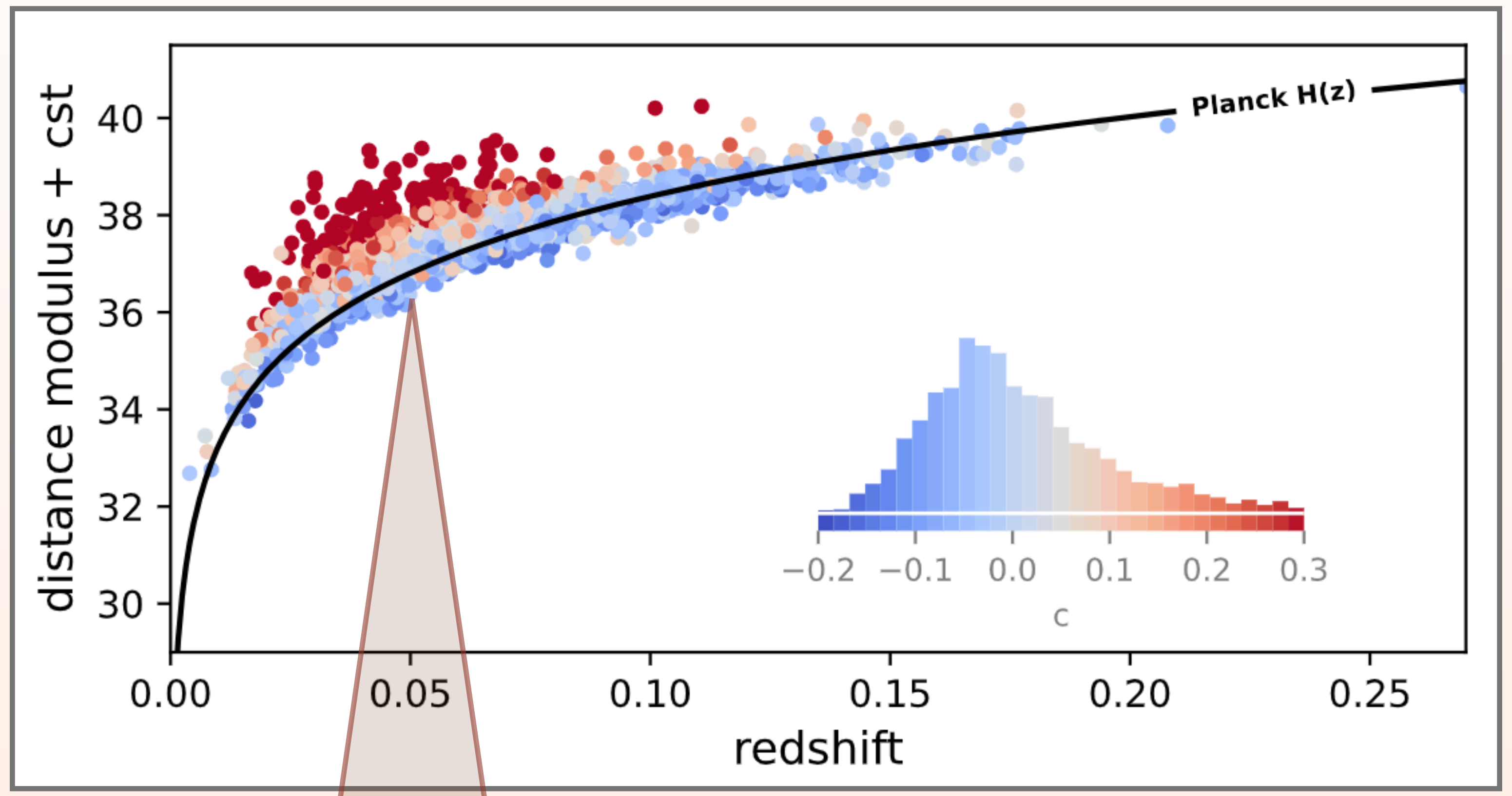
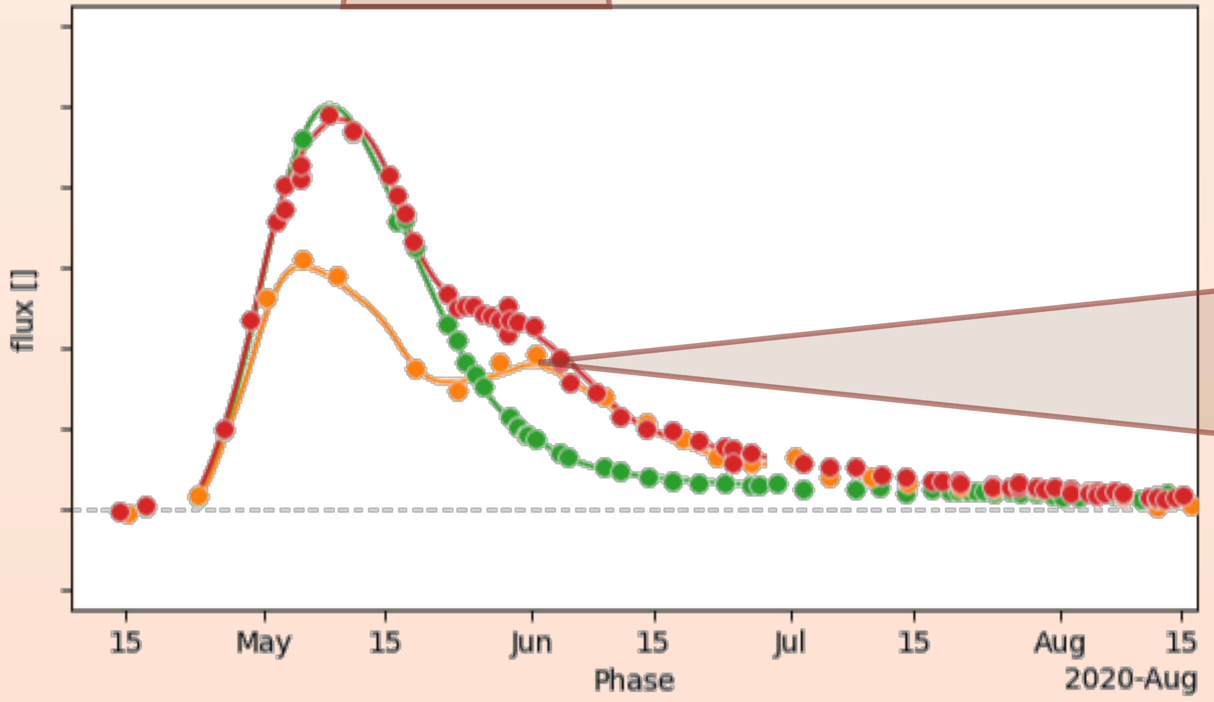
Summary

- Spectrophotometric standardisation context
- Presentation of Twins Embedding
- Presentation of ZTF spectra sample (and flux calibration)
- Twins Embedding method applied on ZTF spectra
- ZTF standardisation result

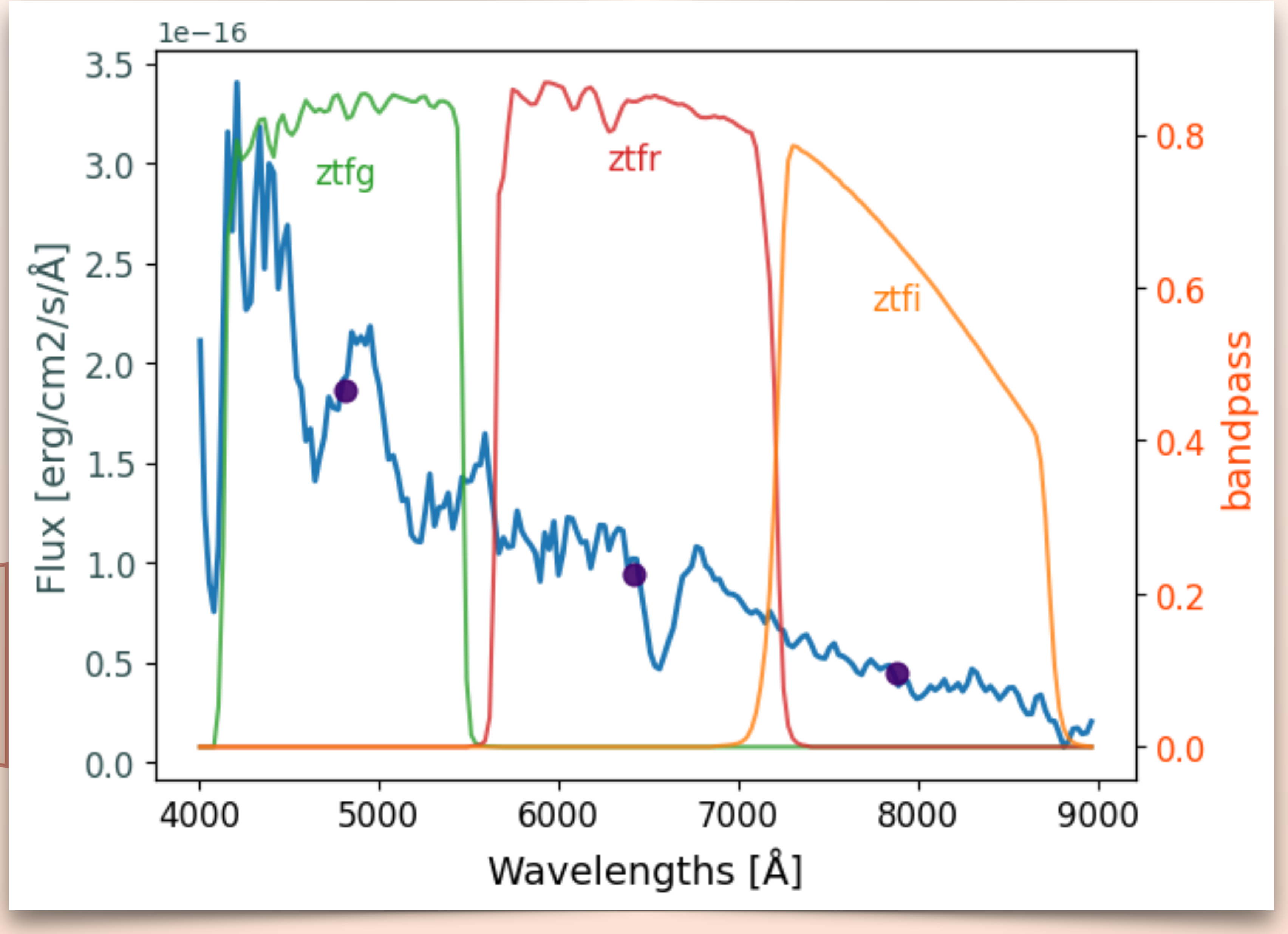
Spectro-photometric standardisation



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



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



Spectro-photometry of ZTF20aboyujf
at phase -3.73days

—> New standardisation of distance modulus, using spectral information

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

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

With SNFactory

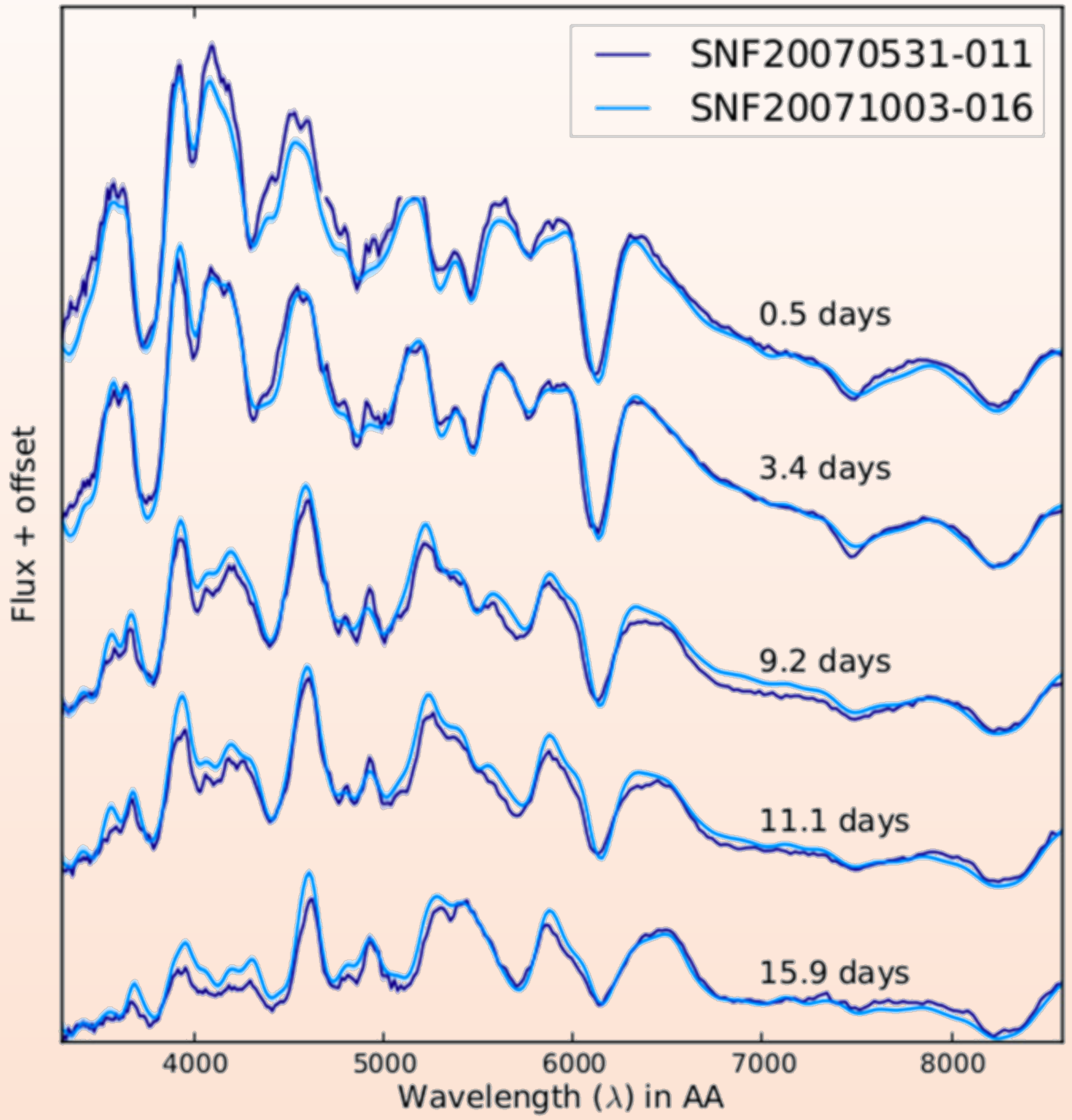
Twins Embedding :
$\sigma_{mag} = 0.07\text{mag}$

SNFactory : ~250 Sne

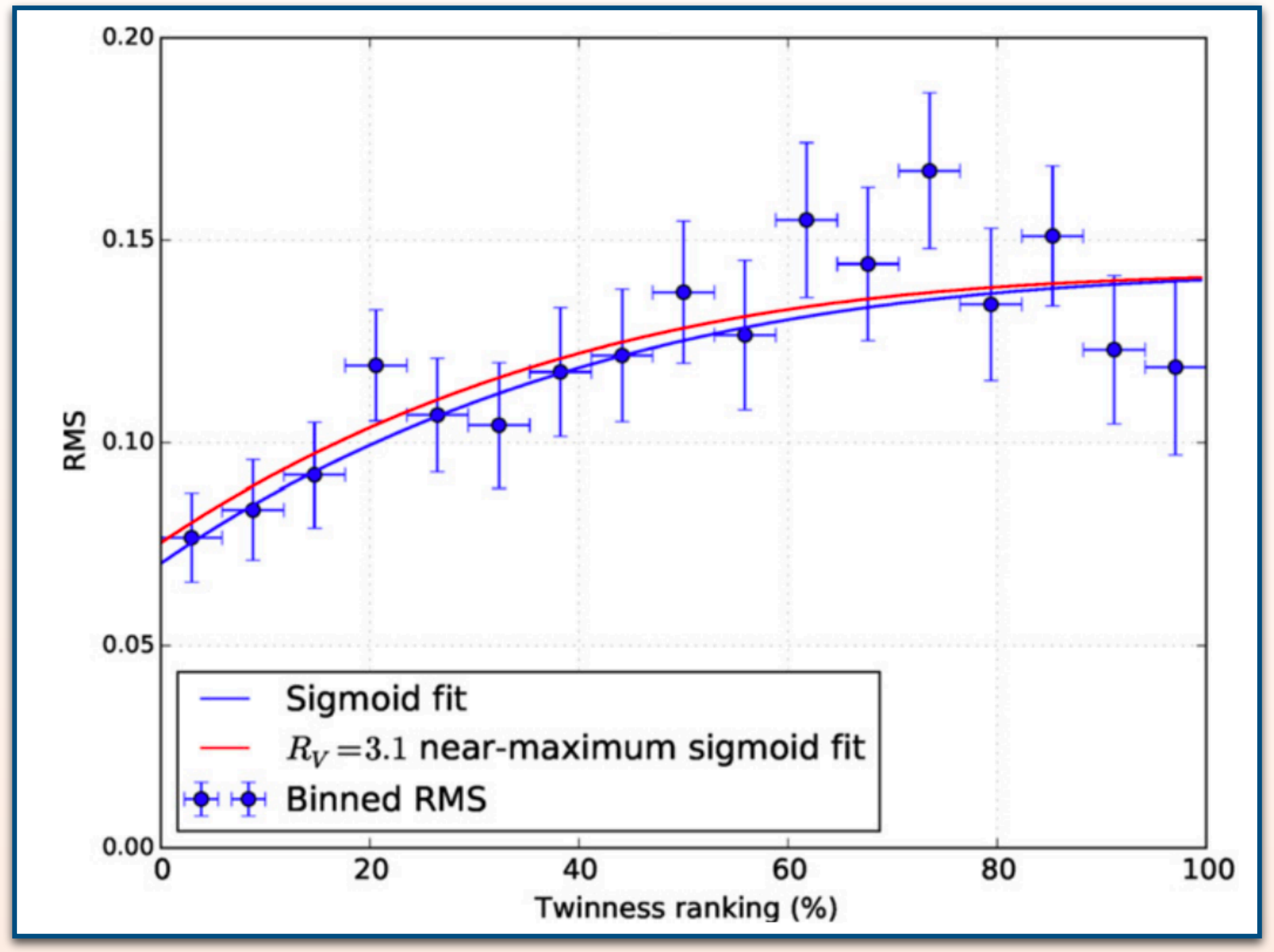
↓

ZTF : ~700 Sne
(for now)

Twins - *Fakhouri et al. 2015*



Spectral time-series of two 'Twins' SNe - SNfactory
Figure from Fakhouri 2015



Twins have lower dispersion in luminosity than spectroscopically dissimilar SNe
Figure from Fakhouri 2015

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

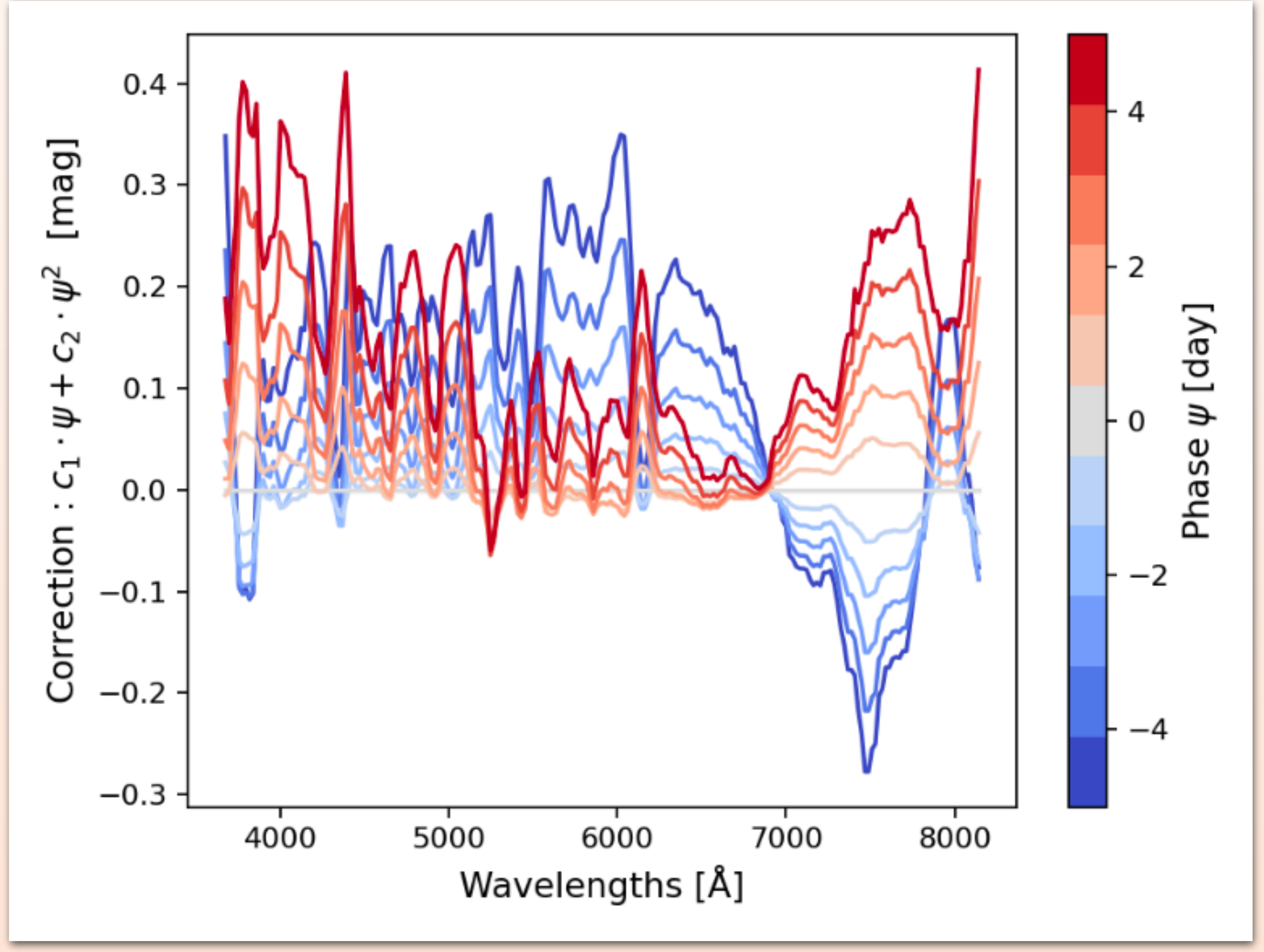
—> Only one spectrum at maximum per SN Ia is sufficient to have the variation information

Twins Embedding - *Boone et al. 2021*

3 steps

1. Generate at maximum luminosity

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

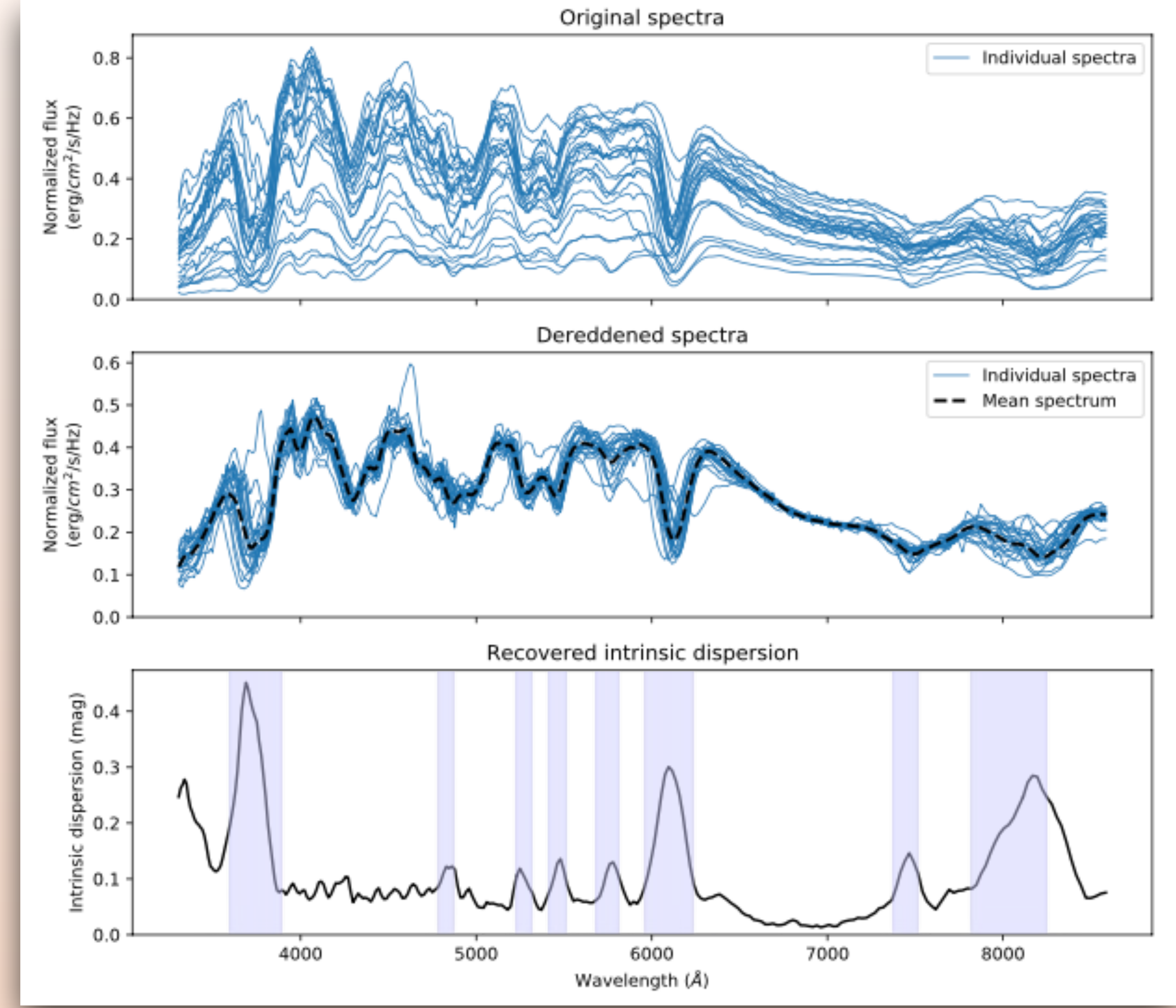


Quadratic evolution in phase of SN Ia spectra

Capture 84.6% of the spectral 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



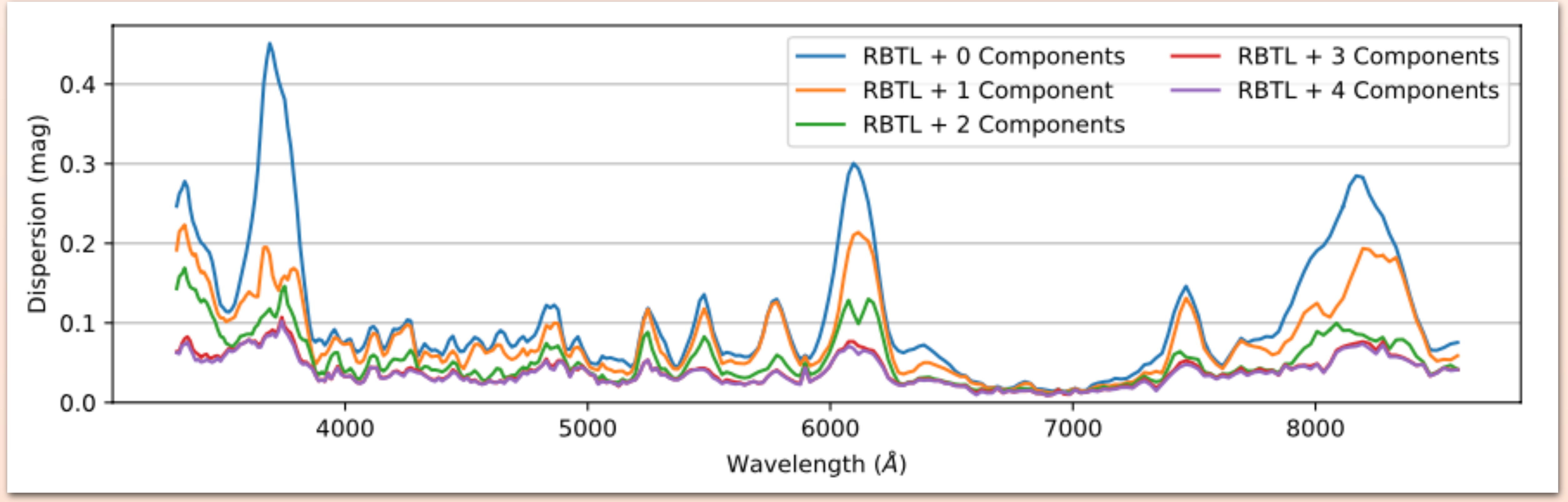
SNFactory spectra before/after dereddening, and residuals intrinsic dispersion (std)
Credit : Boone et al. 2021

Twins Embedding

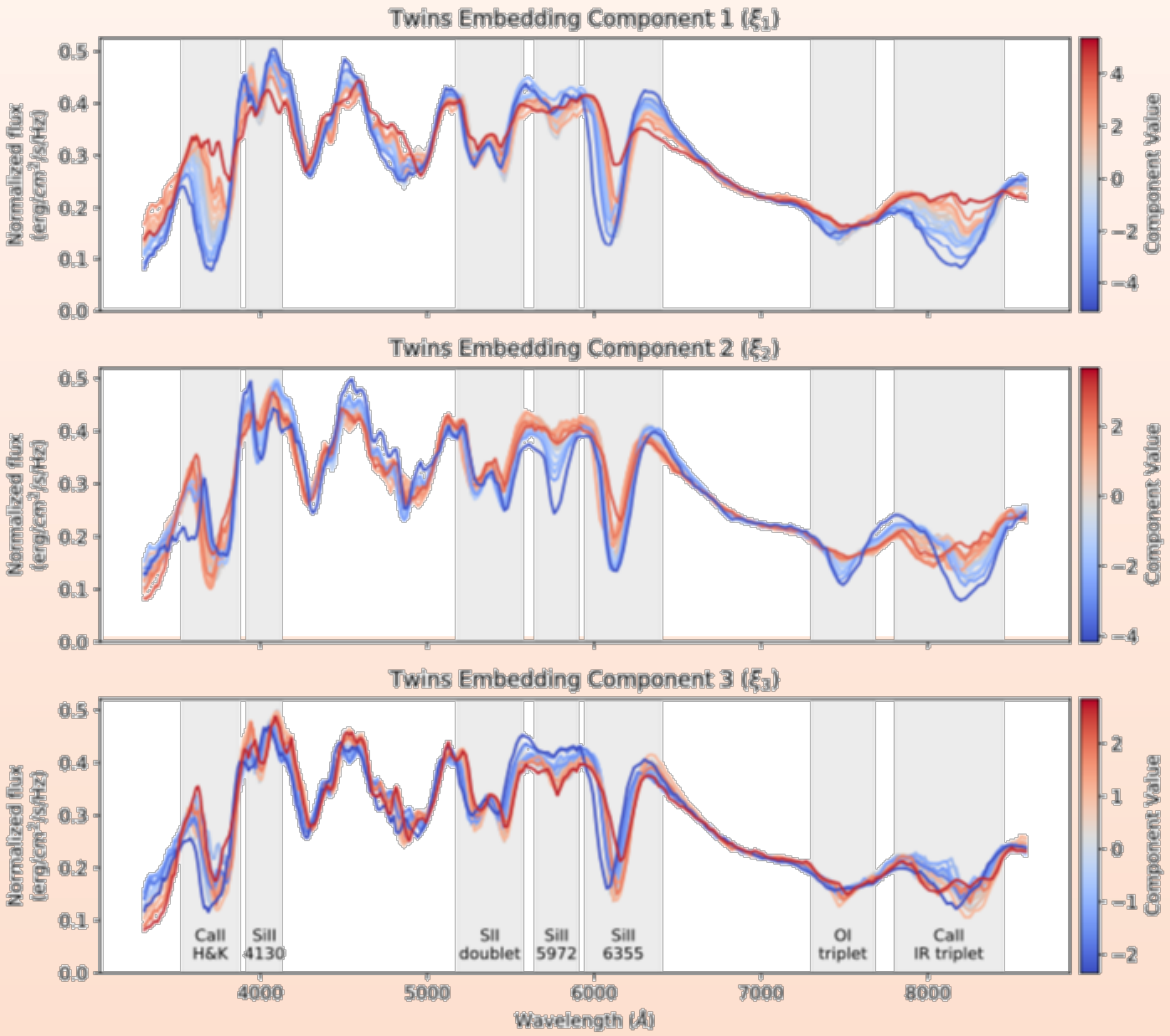
3 steps

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

86.6% of variance explained with 3 components



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



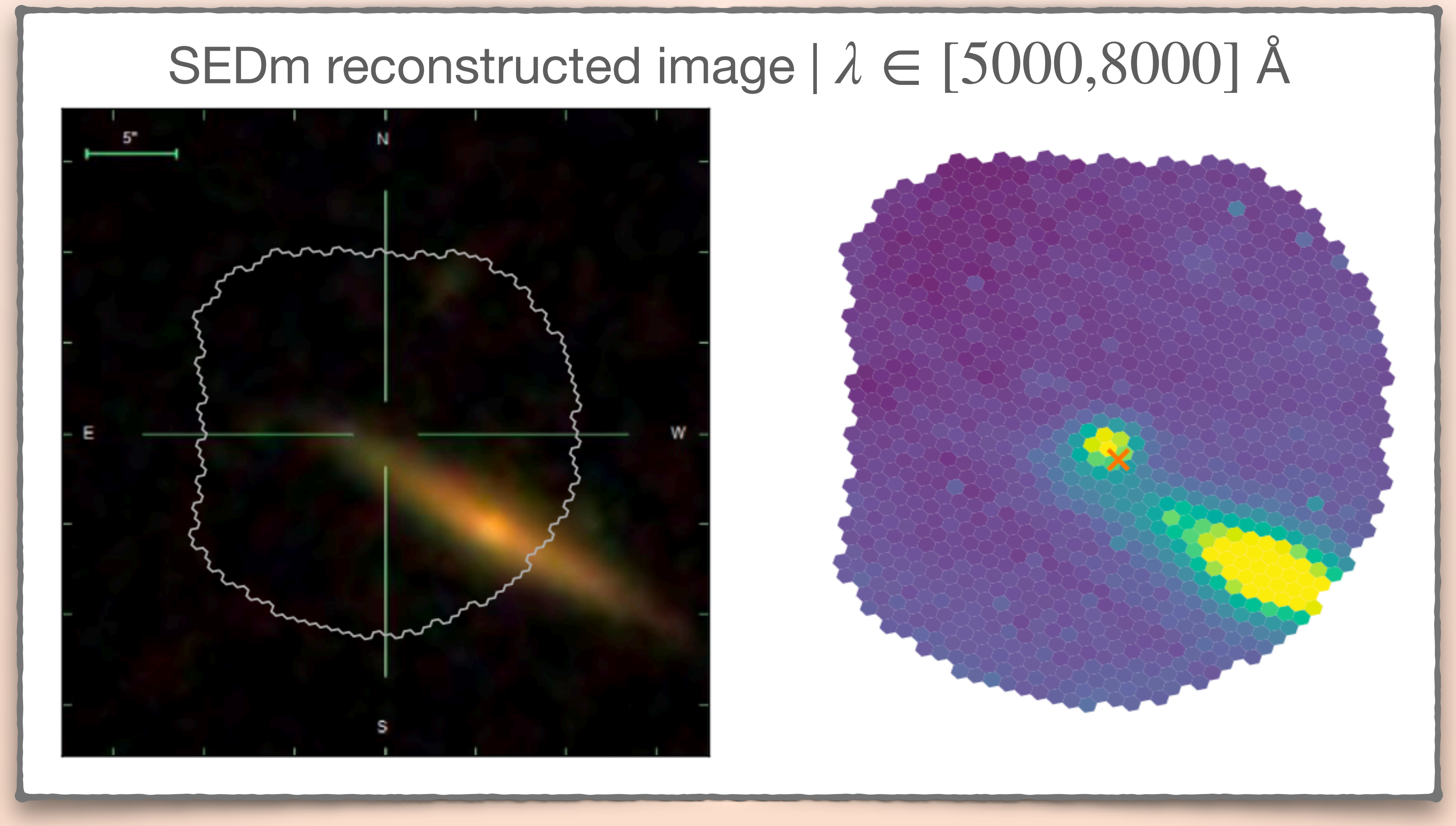
Twins Embedding components variation effects on spectra. *Credit : Boone et al. 2021*

Zwicky Transient Facility - spectra sample

Purpose : typing and redshift
3628 Supernovae Ia - 4114 spectra (until 2020)
2594 spectra from the SEDm

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

Optical window: 3,650 - 10,000 Å
spectral extraction by pysedm
Correction of host galaxy by Hypergal

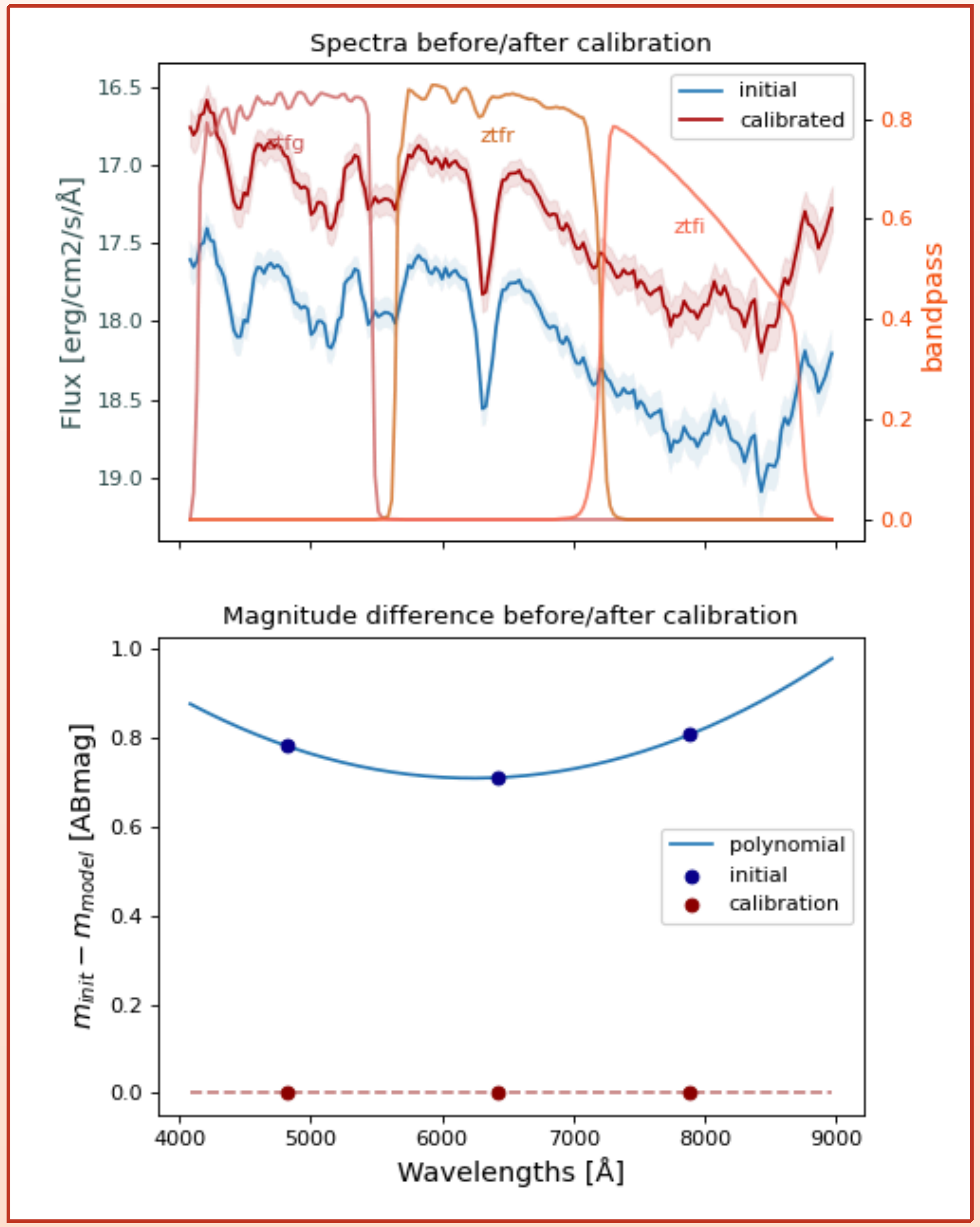


SEDm (P60)- Integral field Spectrograph
field of view of ZTF18abqlpgq
Source : pysedm - Rigault, Neill

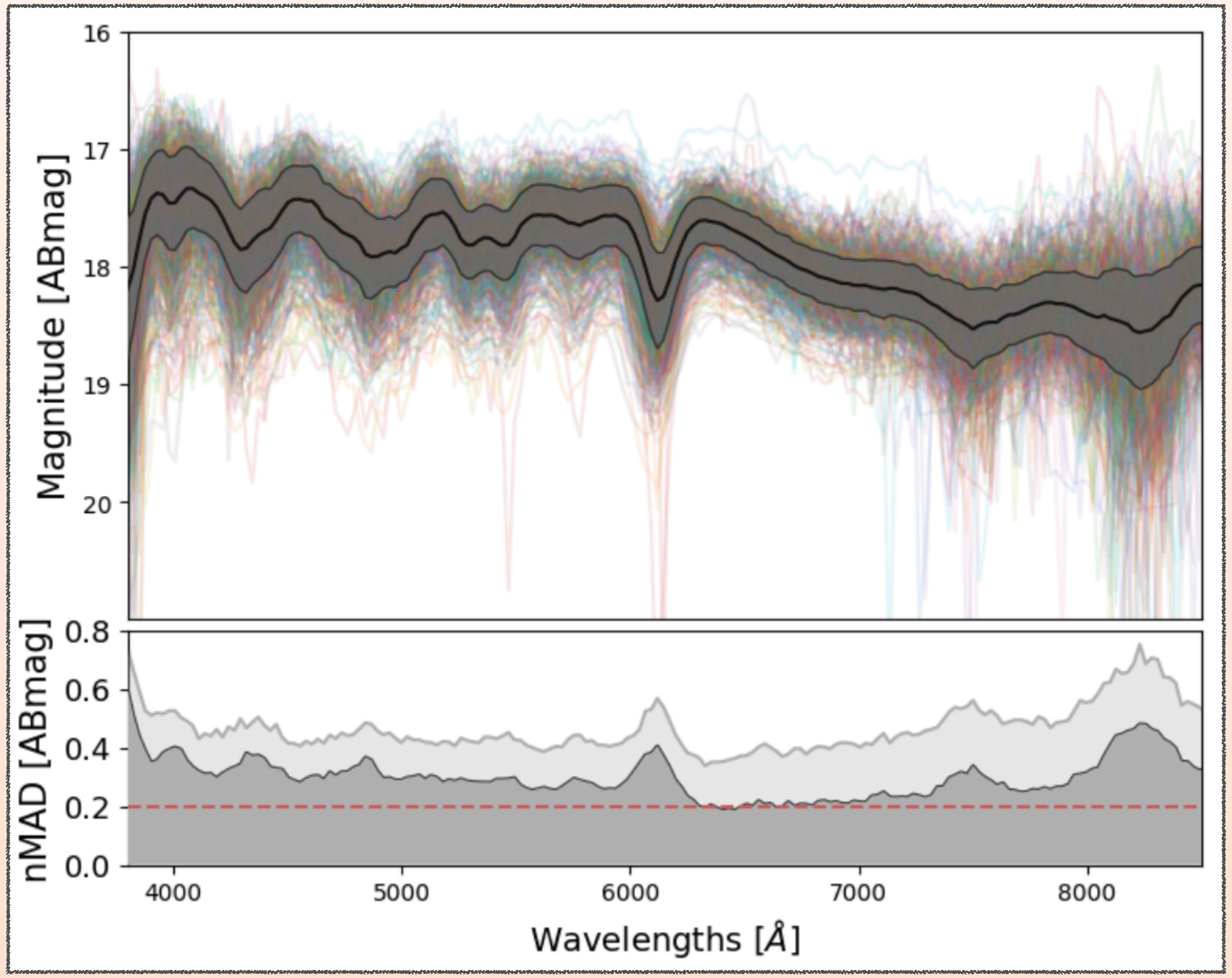
Cut	Interval	Quantity removed
from SEDm		40 %
Quality		20 %
z	<0.1	around 7/8%
phase	[-5,+5] days	**around 50%**
cosmo		around 15%

—> 752 spectra from 695 Sne Ia

ZTF flux-calibrated spectra



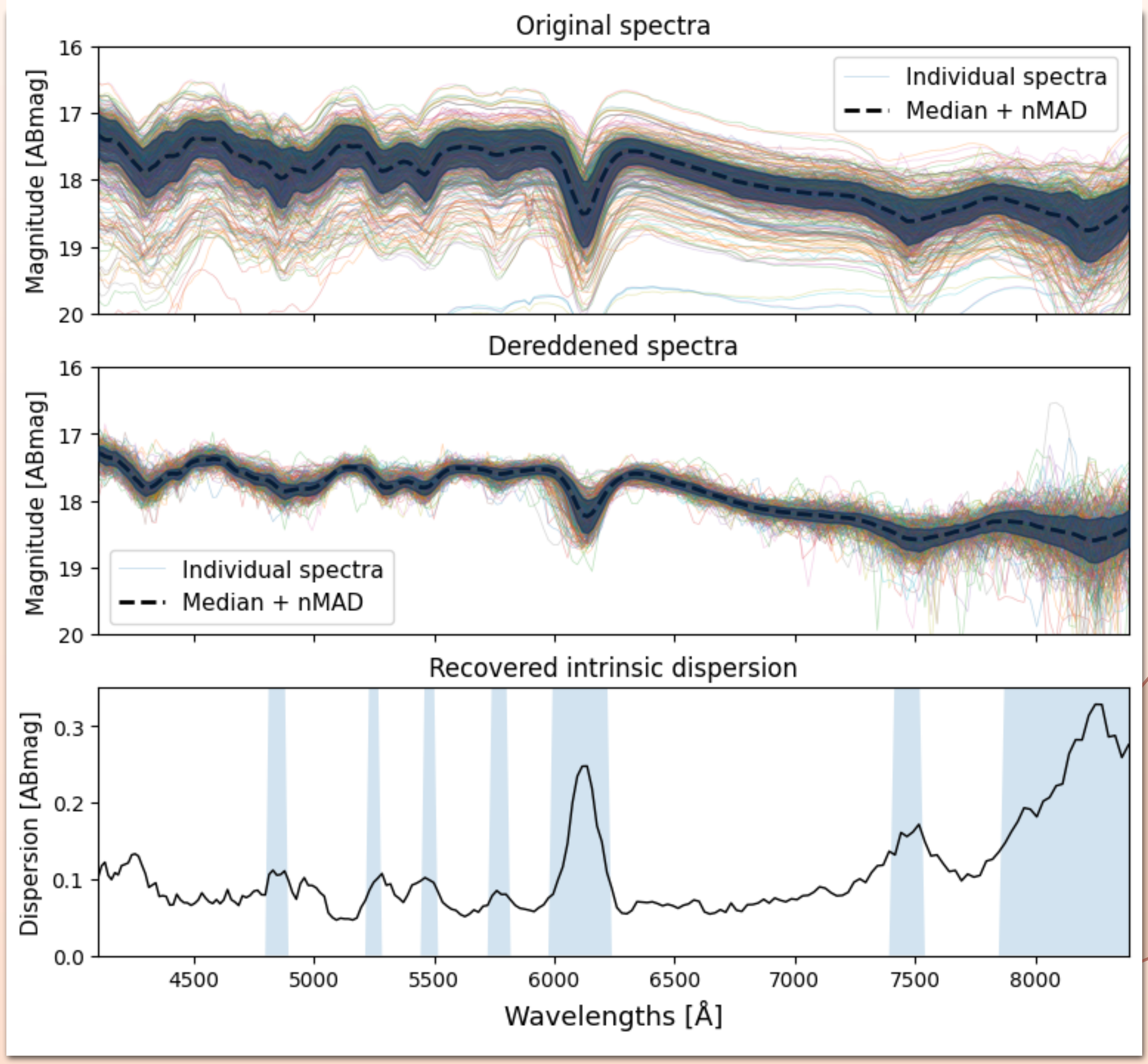
Example of flux calibration
with ZTF20aayvubx_20200524_SEDm_0

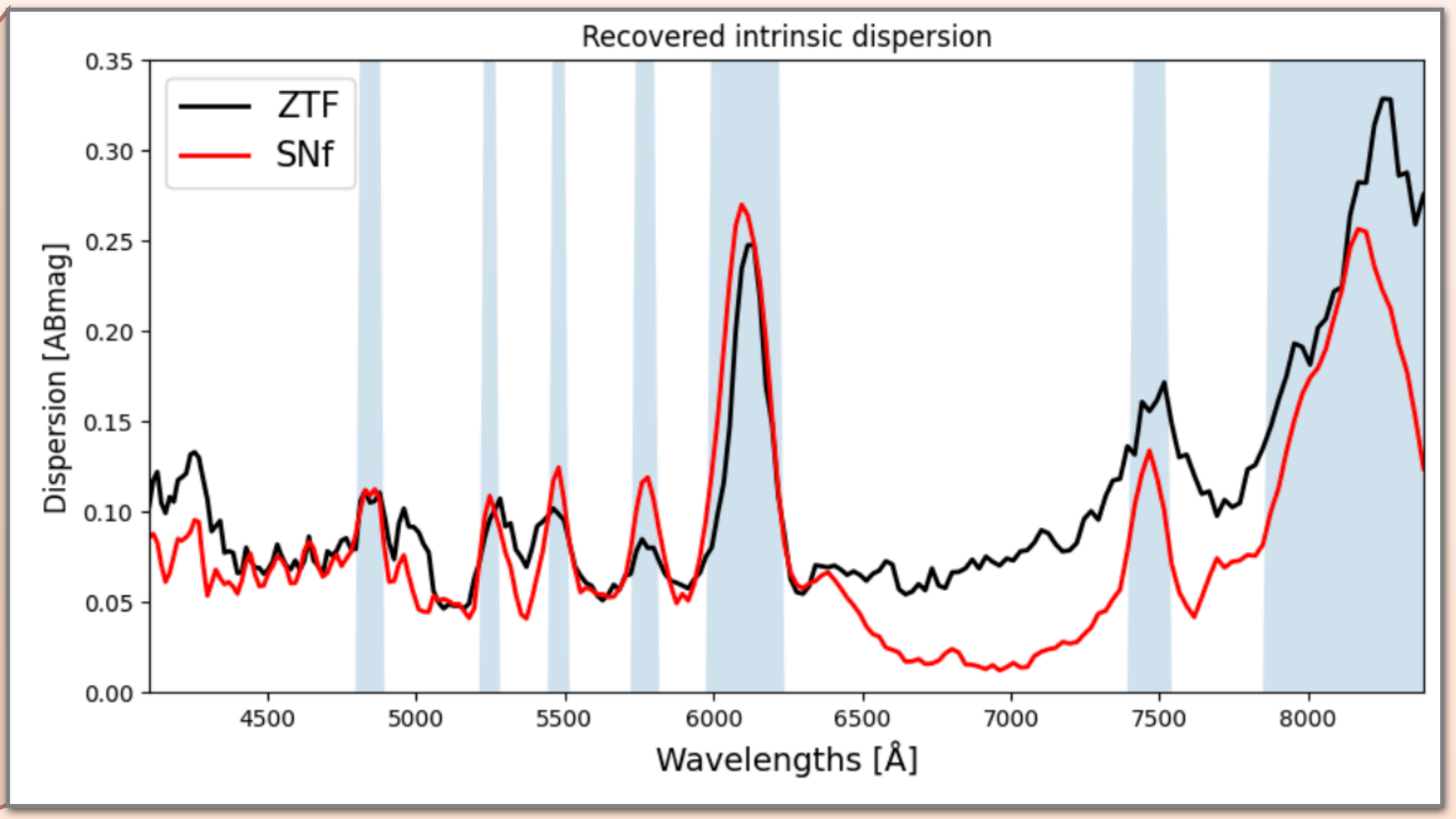


Median+nMAD of **752** ZTF flux-calibrated spectra
at z=0.05
For phases in [-5,5], and cosmo cuts

- ☑ Flux-calibrated
- ☑ Corrected from the Milky Way
- ☑ Shift spectra at same z=0.05
- ☑ Shift spectra at phase=0 (step1 of the Twins Embedding)

RBTL applicated to ZTF





Spectral dispersion (nMAD) after RBTL correction for **SNf** and **ZTF**

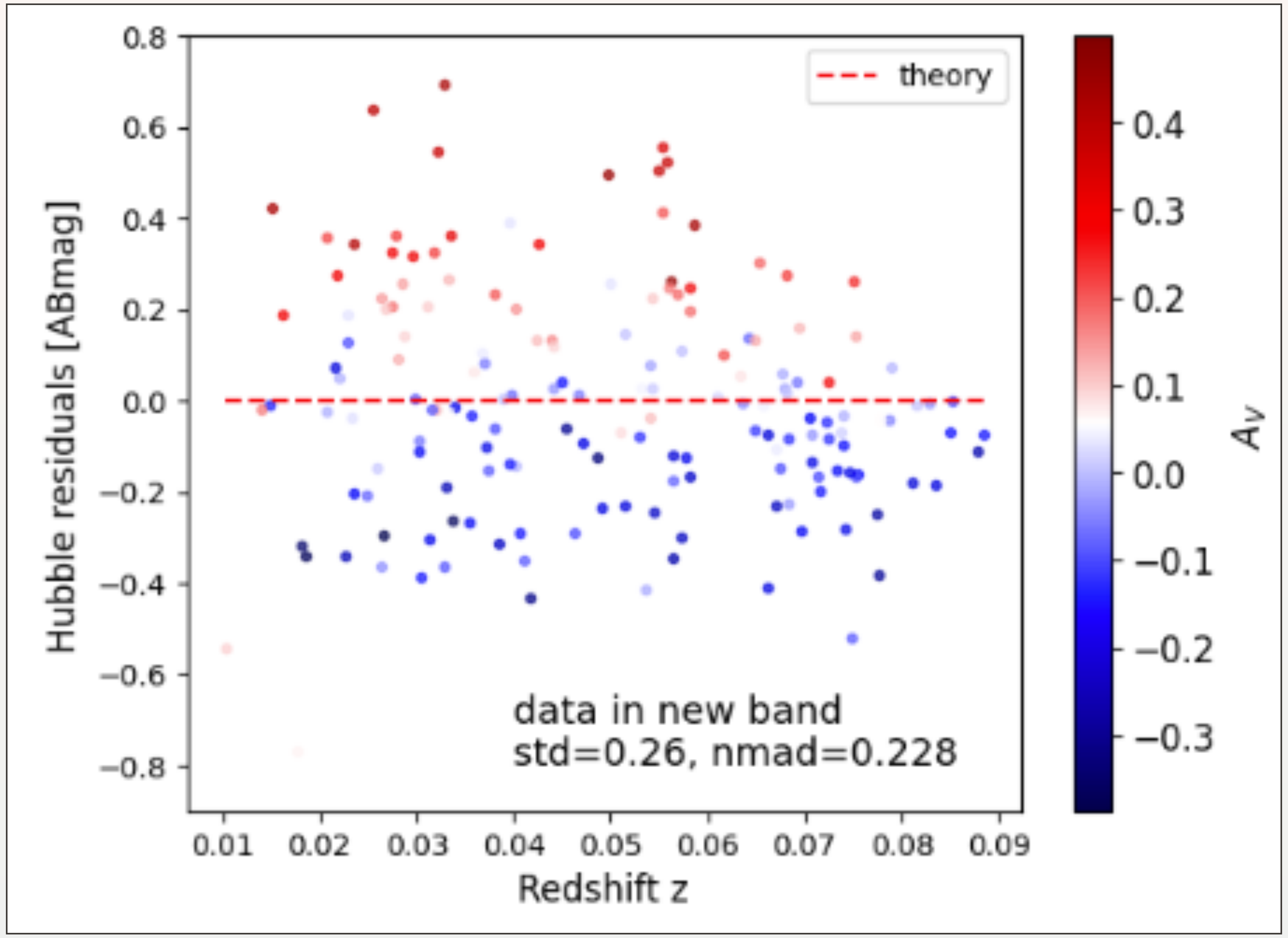
ZTF spectra before/after dereddening, and residuals intrinsic dispersion (nMAD)

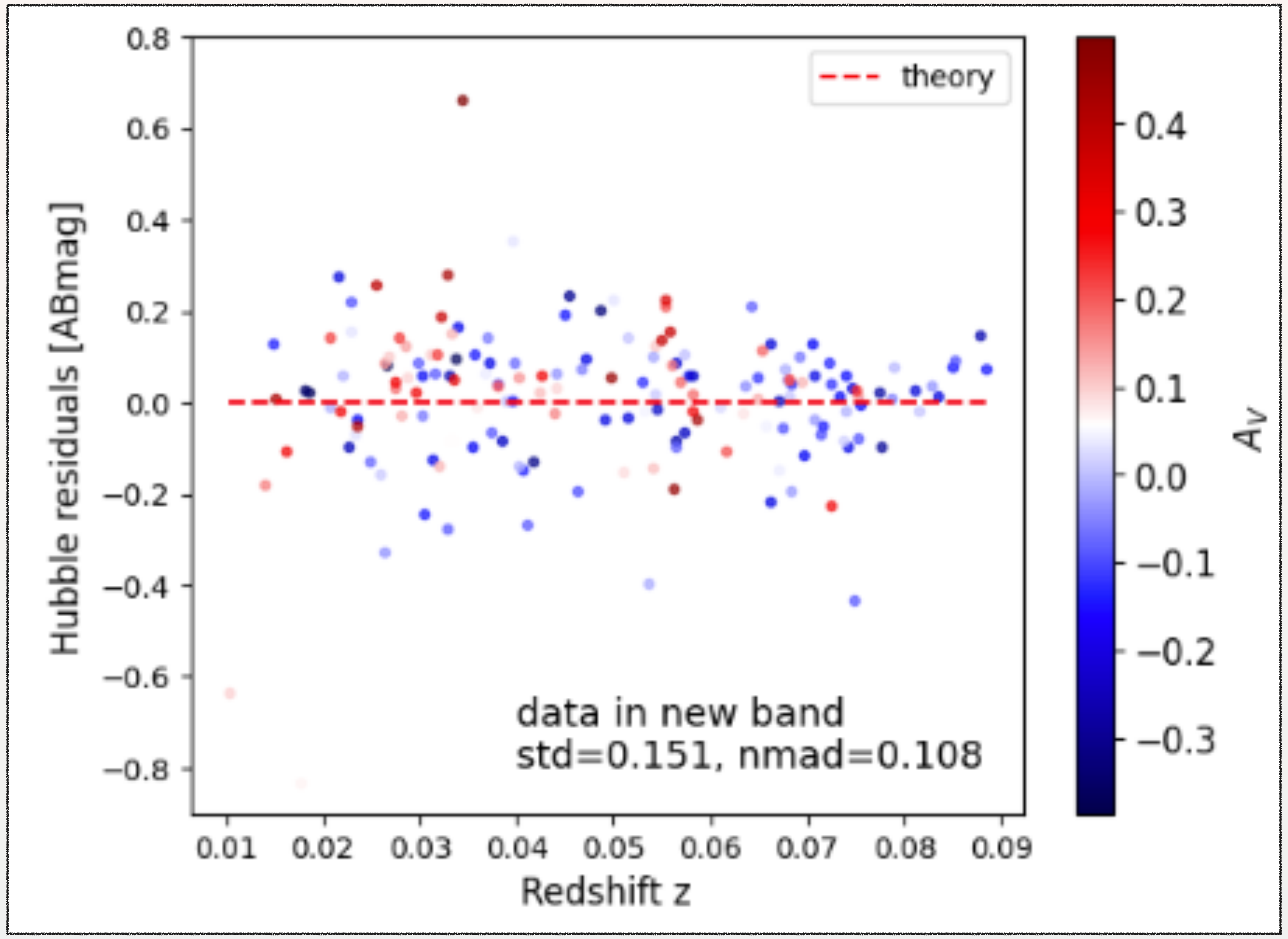
RBTL linear standardisation

For SNFactory sample

$-\alpha \cdot \Delta A_V$

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





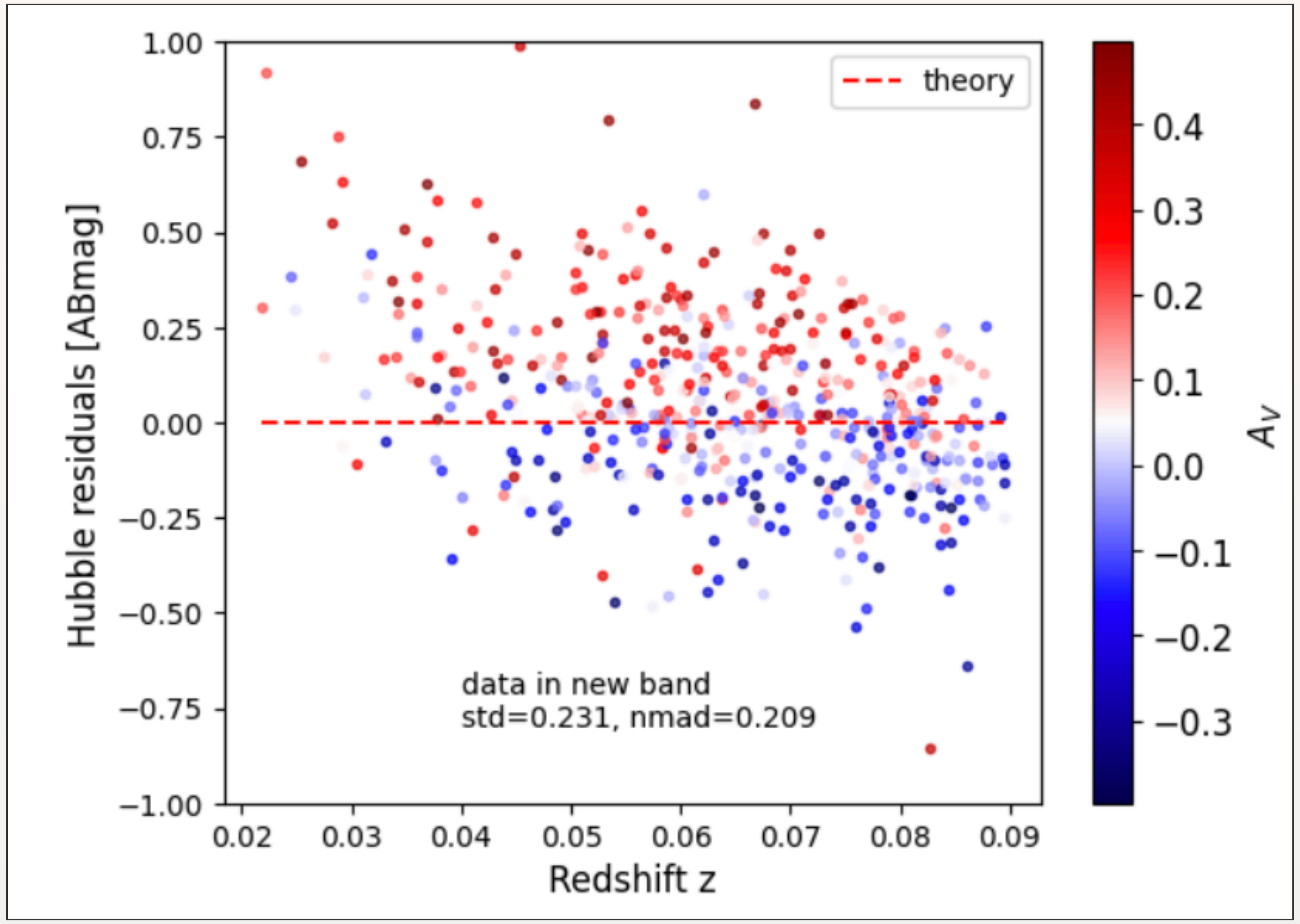
168 SNe Ia before/after standardisation
after a cut on DAv < 0.5

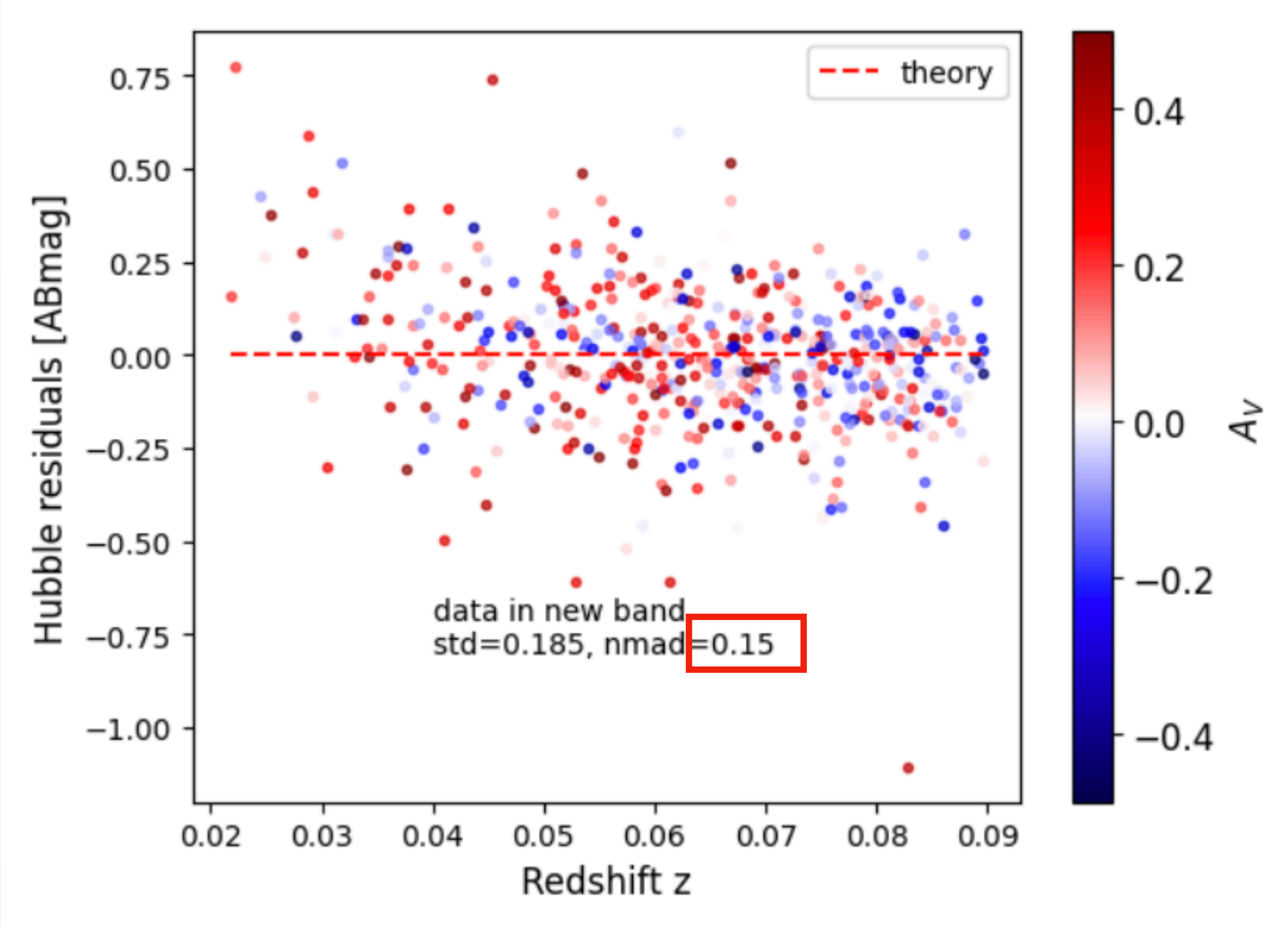
RBTL linear standardisation

For ZTF sample

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

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



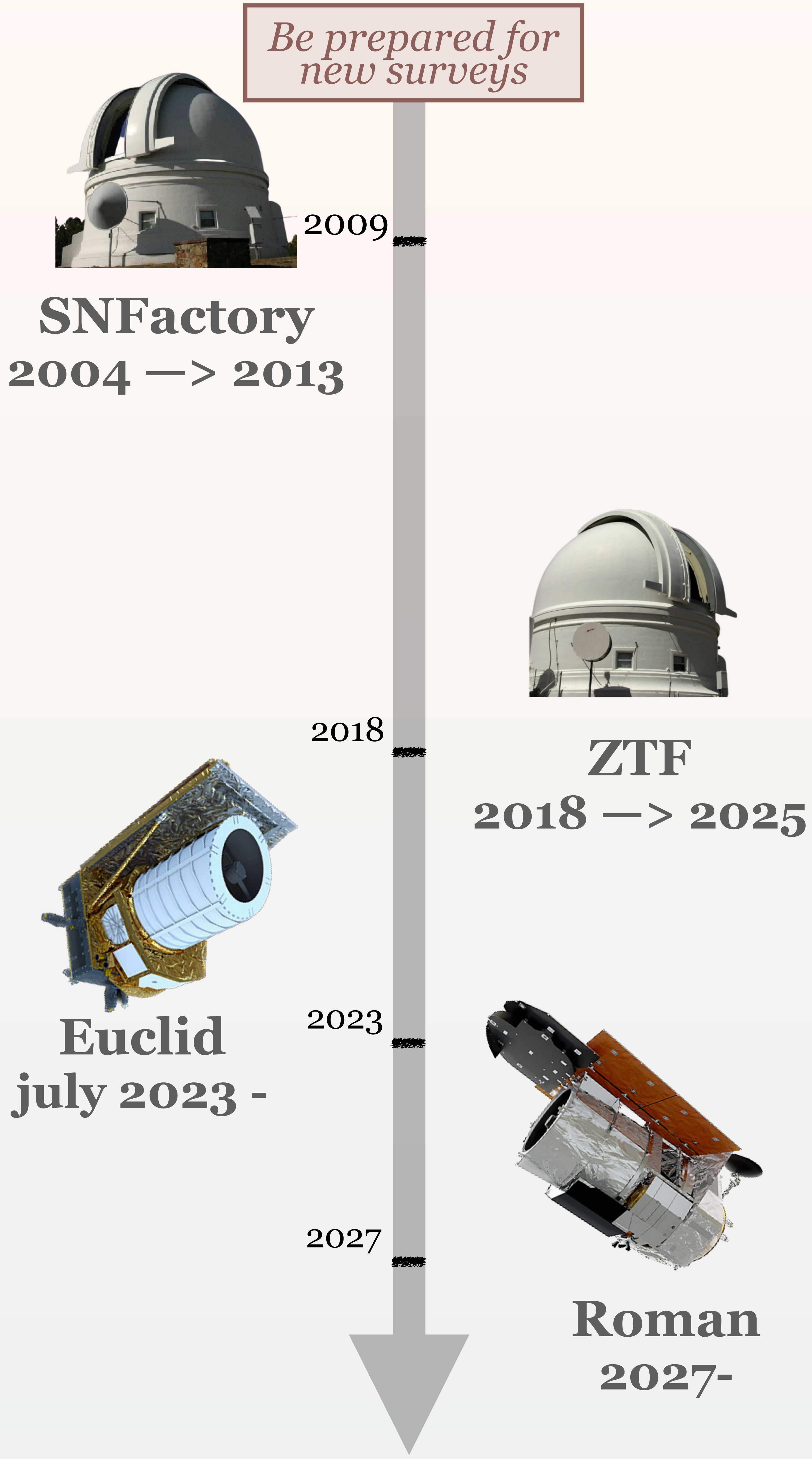


647 SNe Ia before/after standardisation
after a cut on DAv < 0.5 (remove around 7% SNe)

Comparable dispersion that photometric standardisation with only 1 parameter

Conclusion

- RBTL step is working well
- Standardisation with Manifold still in prep
- A paper to come on a whole study TE+ZTF



BACK-UP SLIDE

STEP 1

Differential time evolution model

=> Spectra @ max

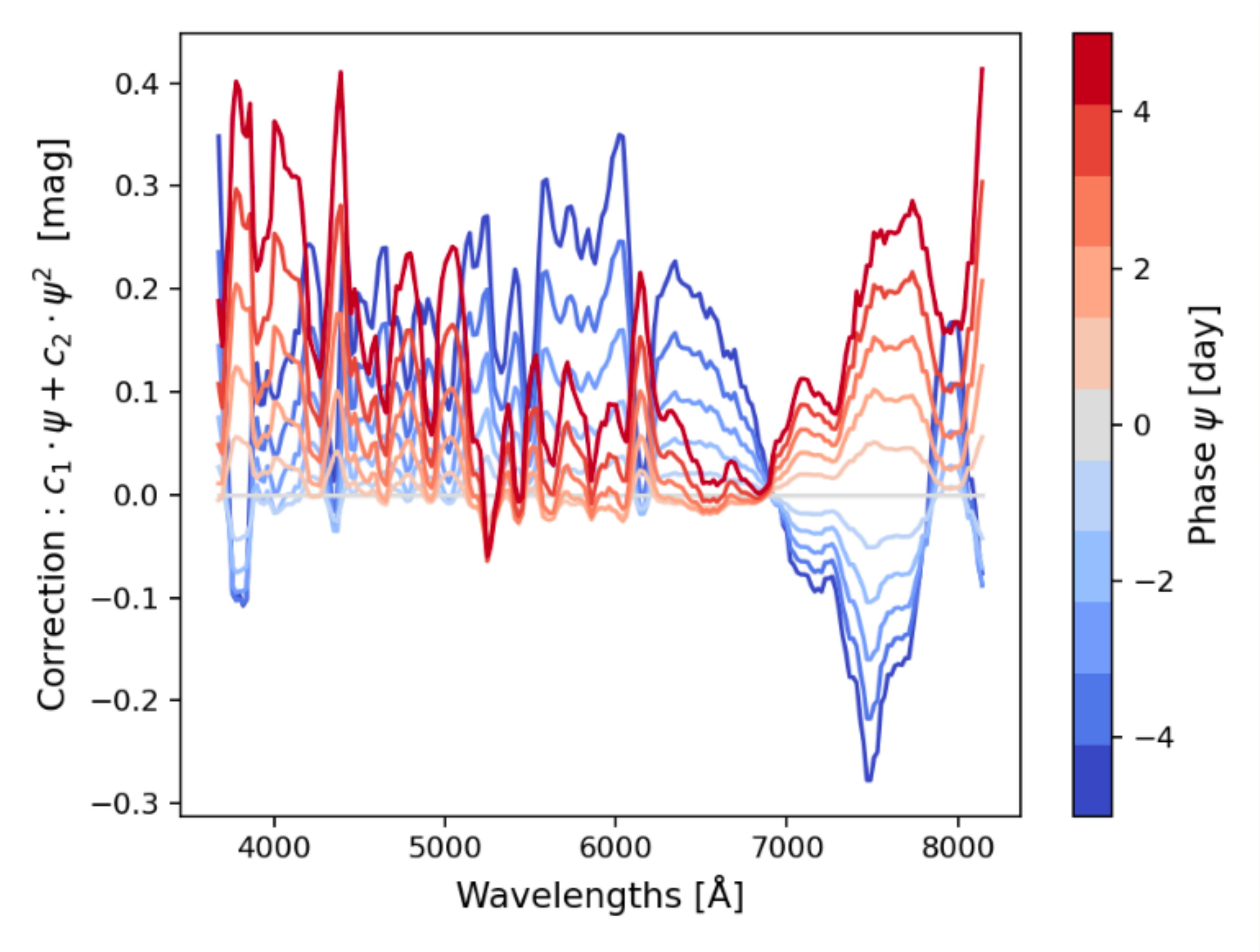
Formula of quadratic evolution in phase :

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

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

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

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

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

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

Differential time evolution model

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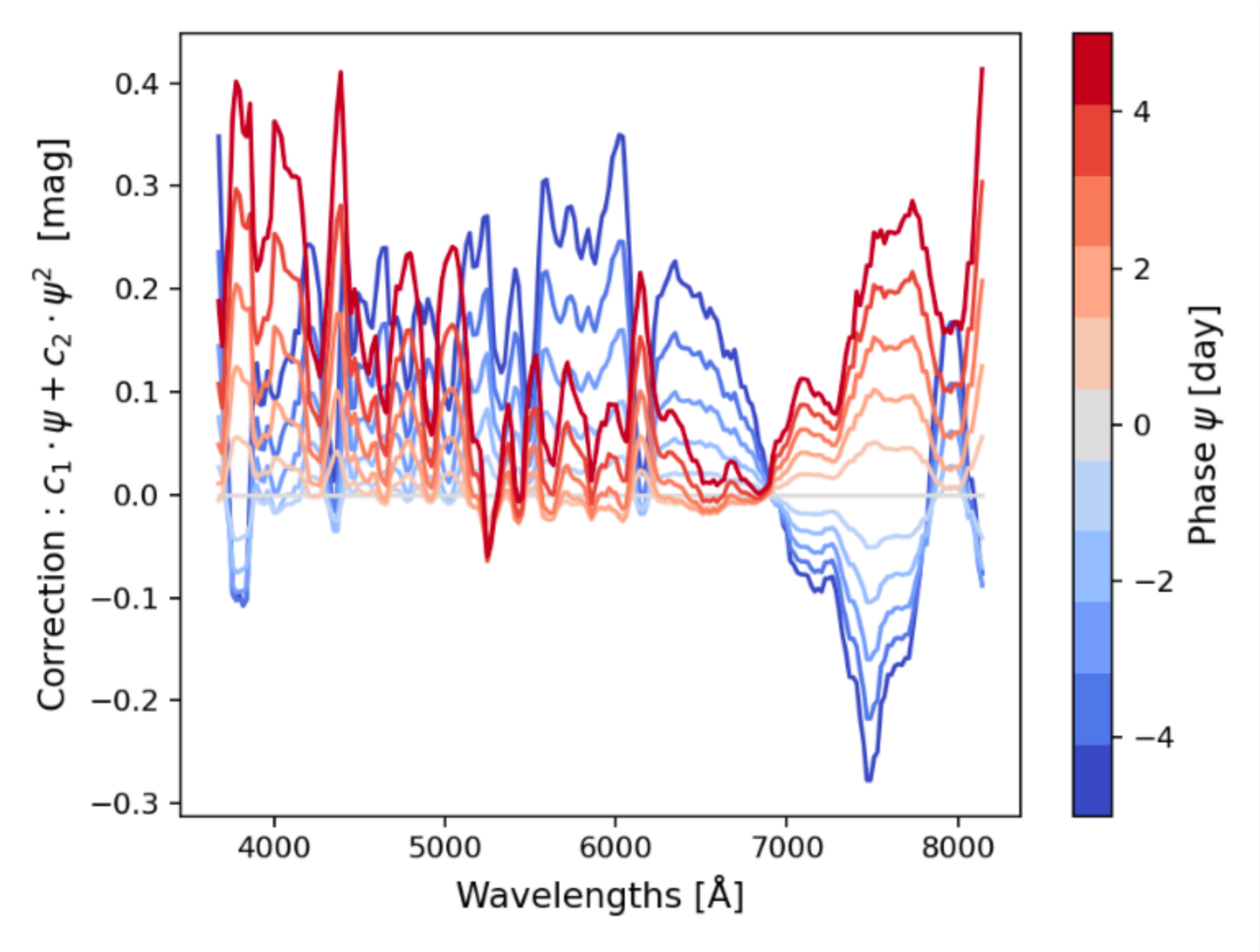

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$m_{gray,s}$ the gray offset of the spectrum s

$c_{1,2}(\lambda_k)$ 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

BACK-UP SLIDE

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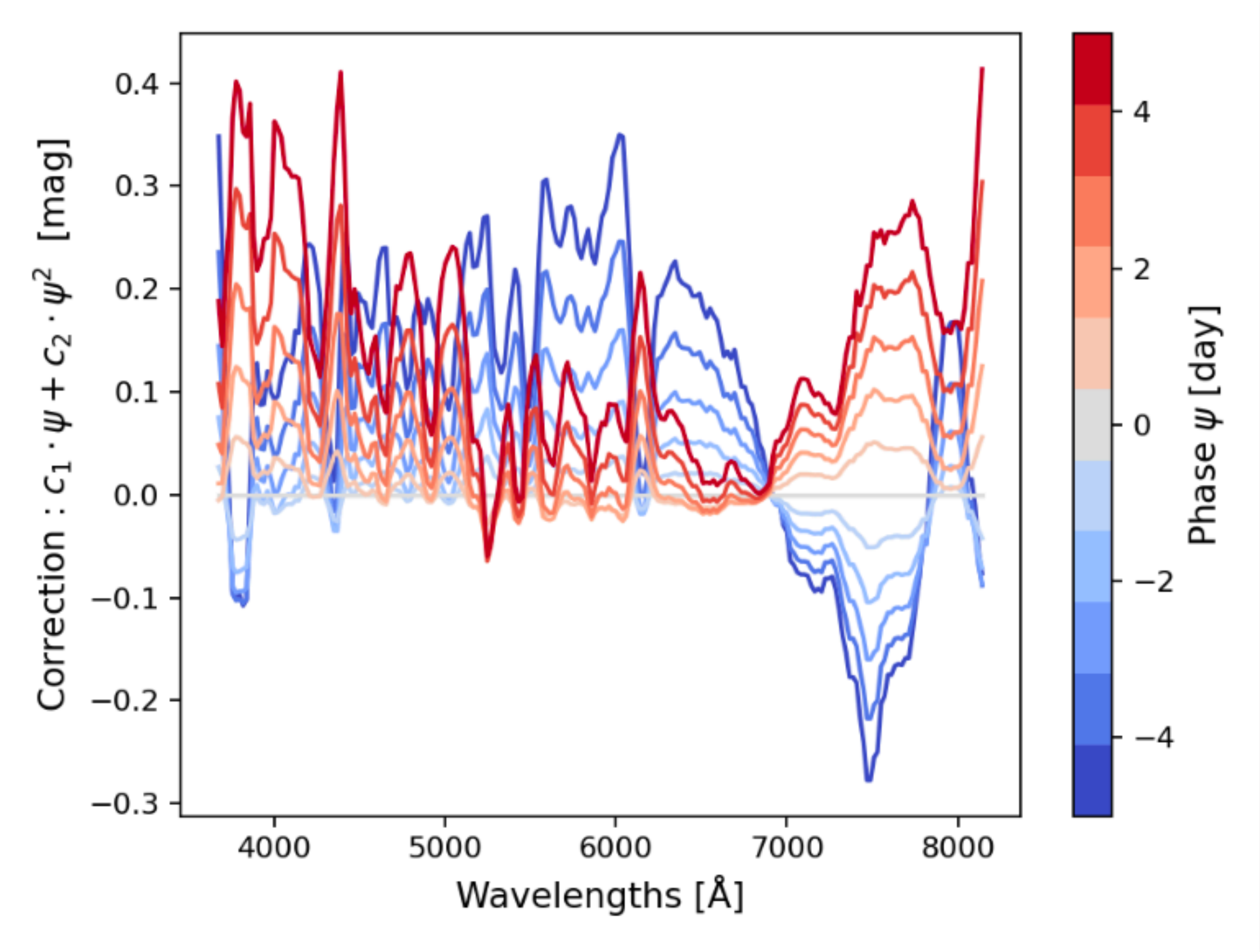

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Capture 84.6% of the spectral evolution variance common to every Sne between -5 and 5 days

BACK-UP SLIDE

STEP 2

Read between the lines (RBTL)

=> *Explain Scatter Between the lines*

Capture Grey scatter + Extinction

Fit all together with bayesian inference :

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

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

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

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)*

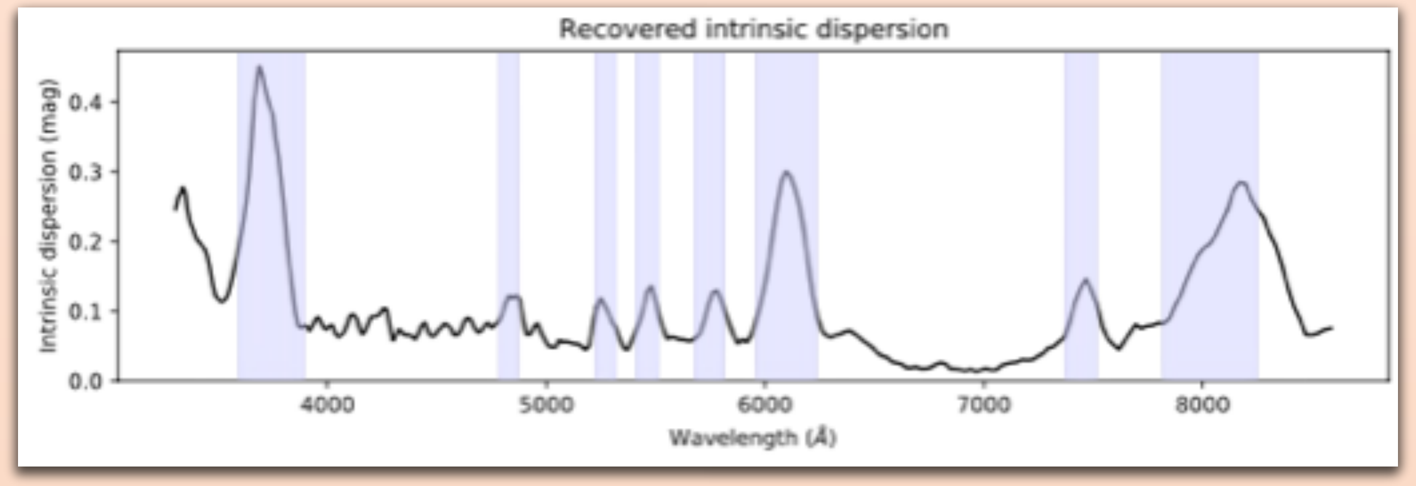
Known:

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

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



BACK-UP SLIDE

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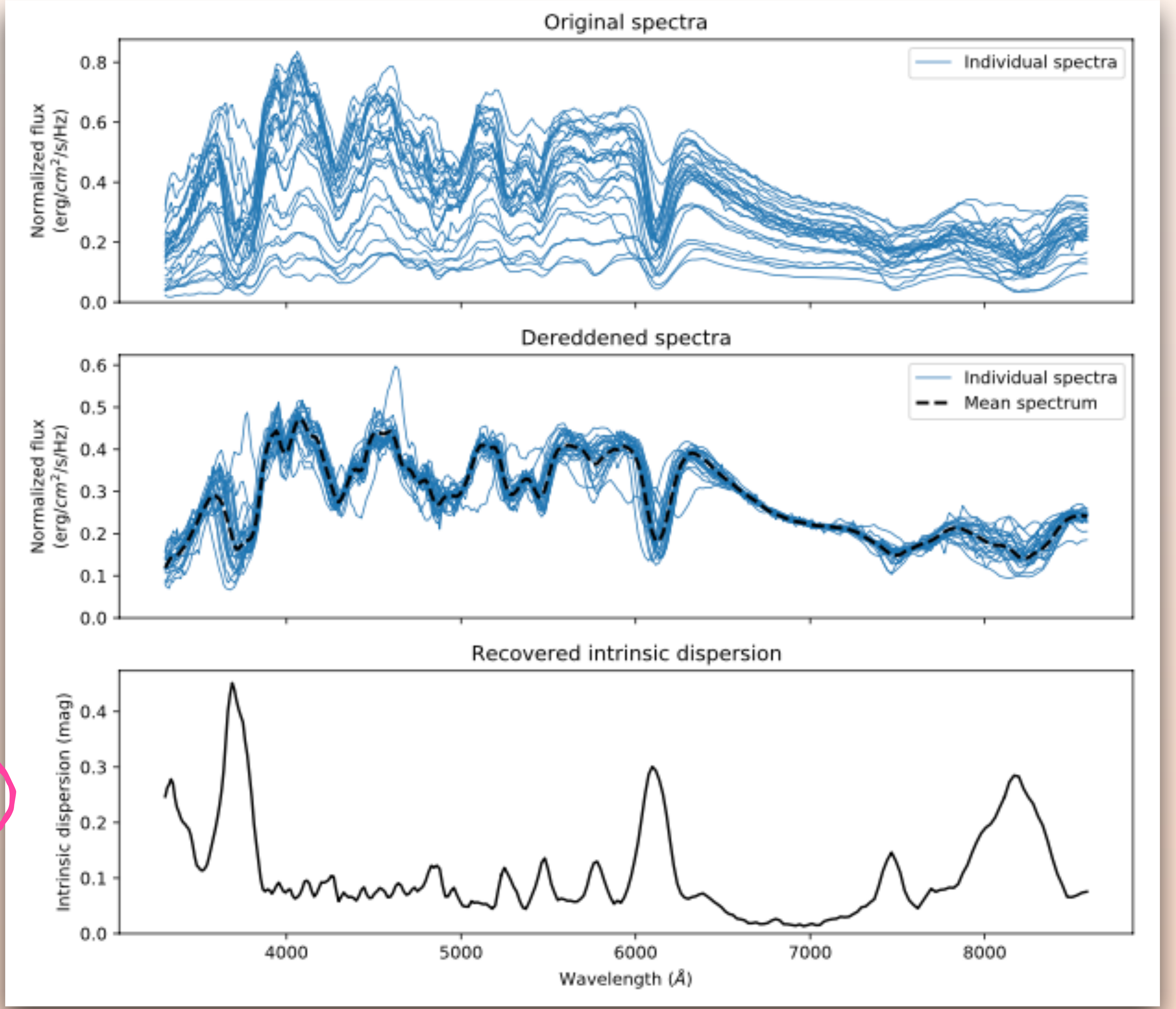
$$f_{\mathrm{dered.},i}(\lambda_k) = f_{\mathrm{max.},i}(\lambda_k) \times 10^{+0.4(\Delta m_i + \Delta \tilde{A}_{V,i} C(\lambda_k))}$$

$\eta(\lambda_k)$



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 2

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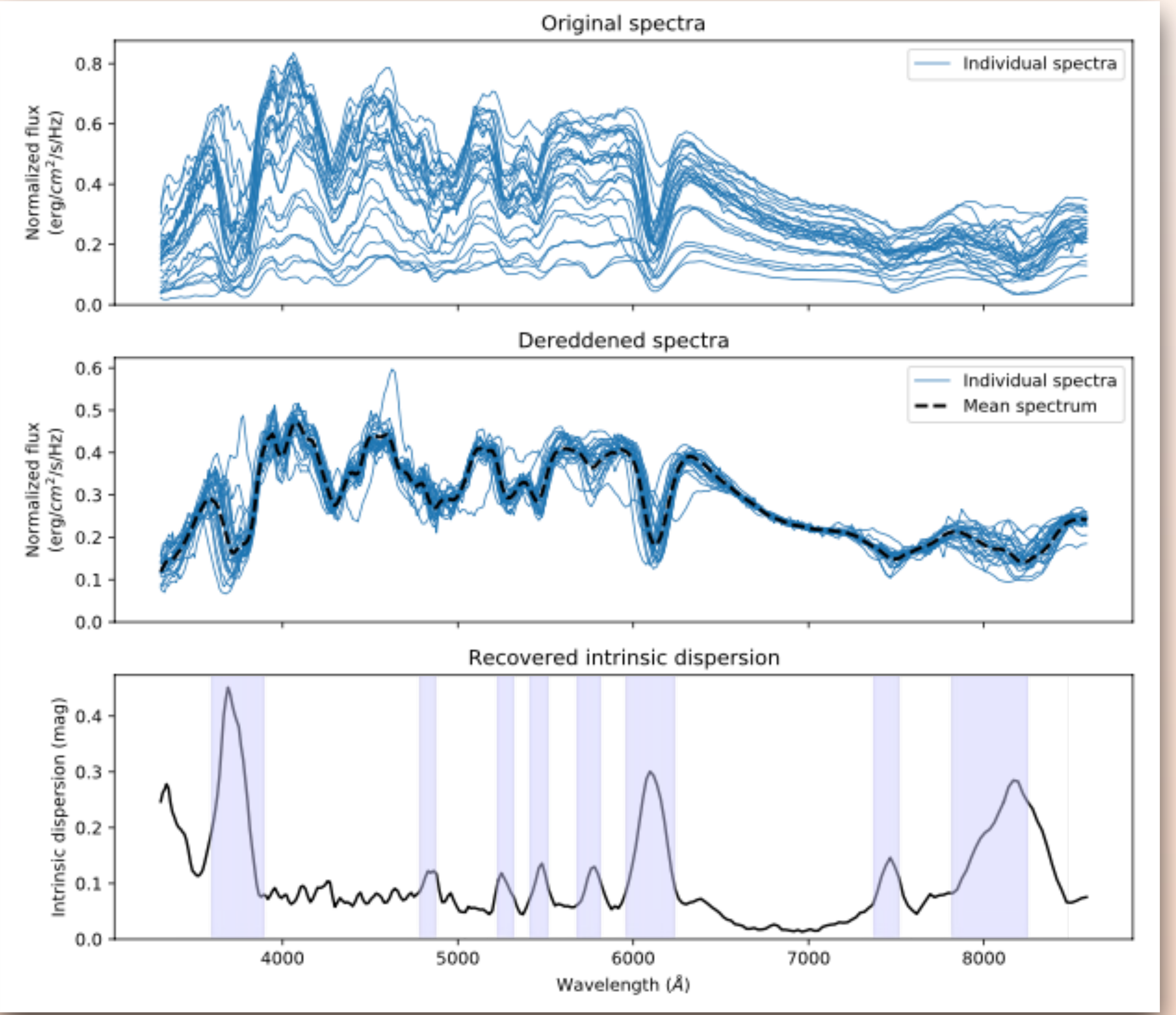
$\eta(\lambda_k)$



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

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

BACK-UP SLIDE

STEP 3

The Twins Embedding parameters space

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

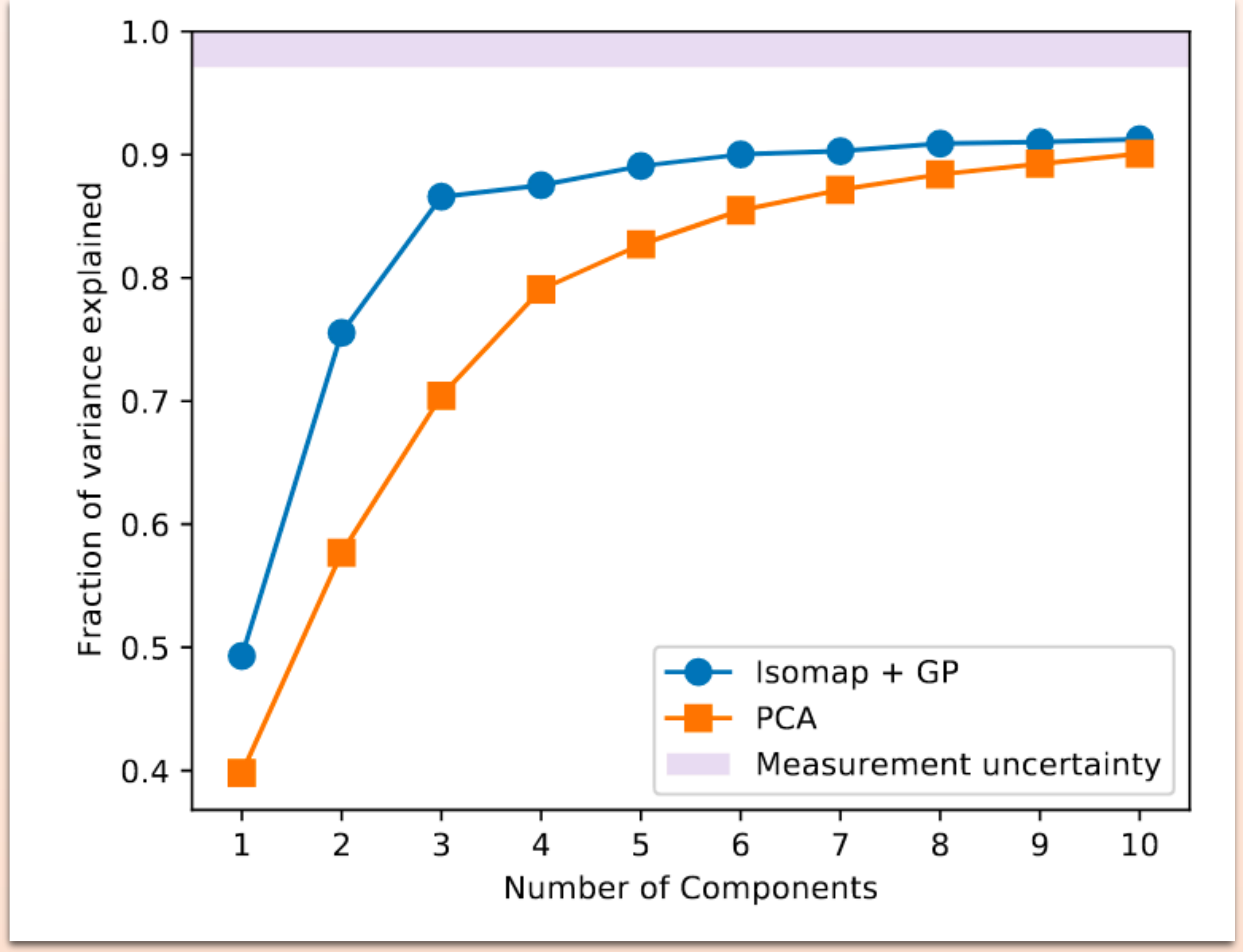
Spectral distance between two Sne I and j :

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

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

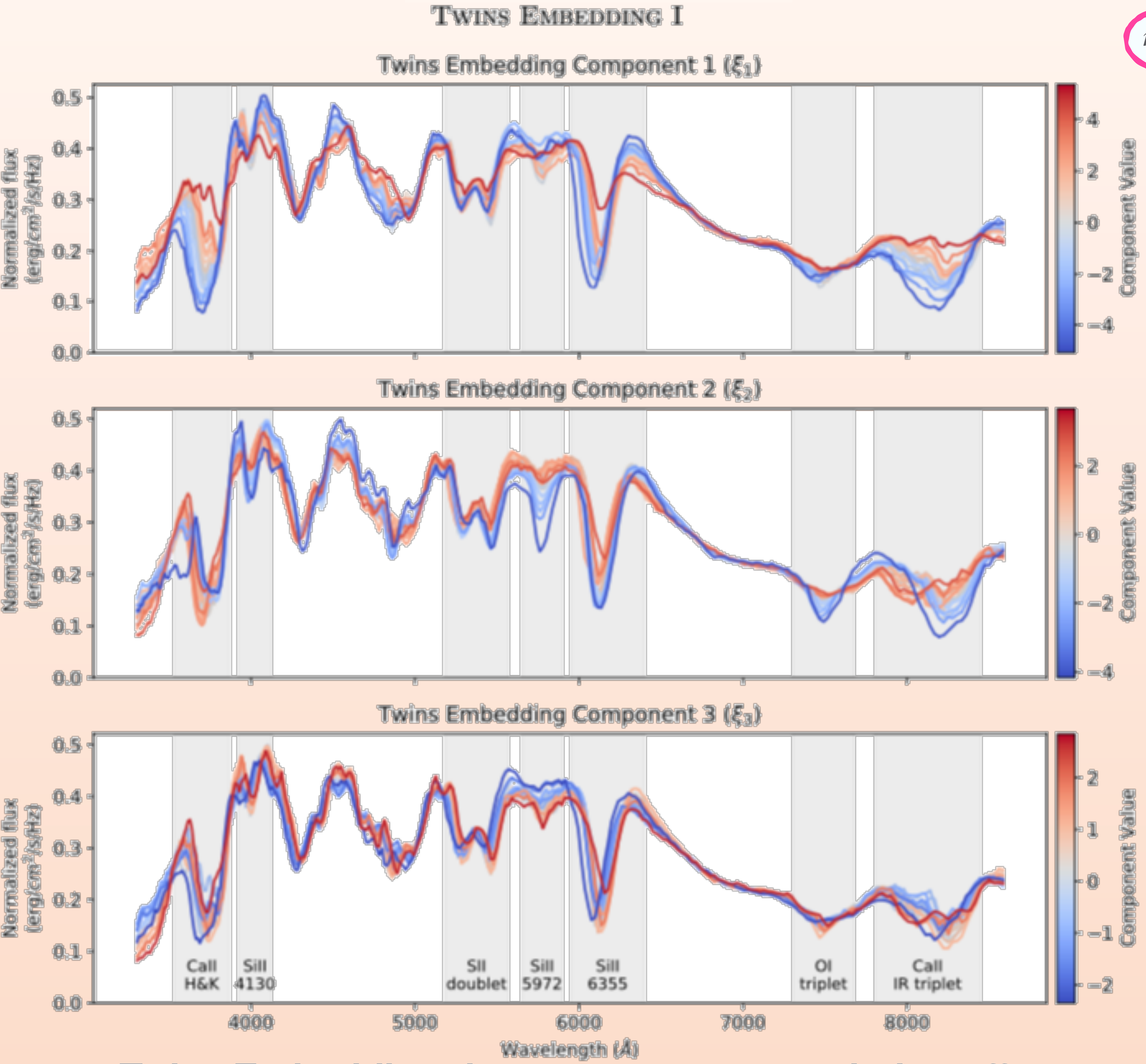
86.6% of variance explained with 3 components



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

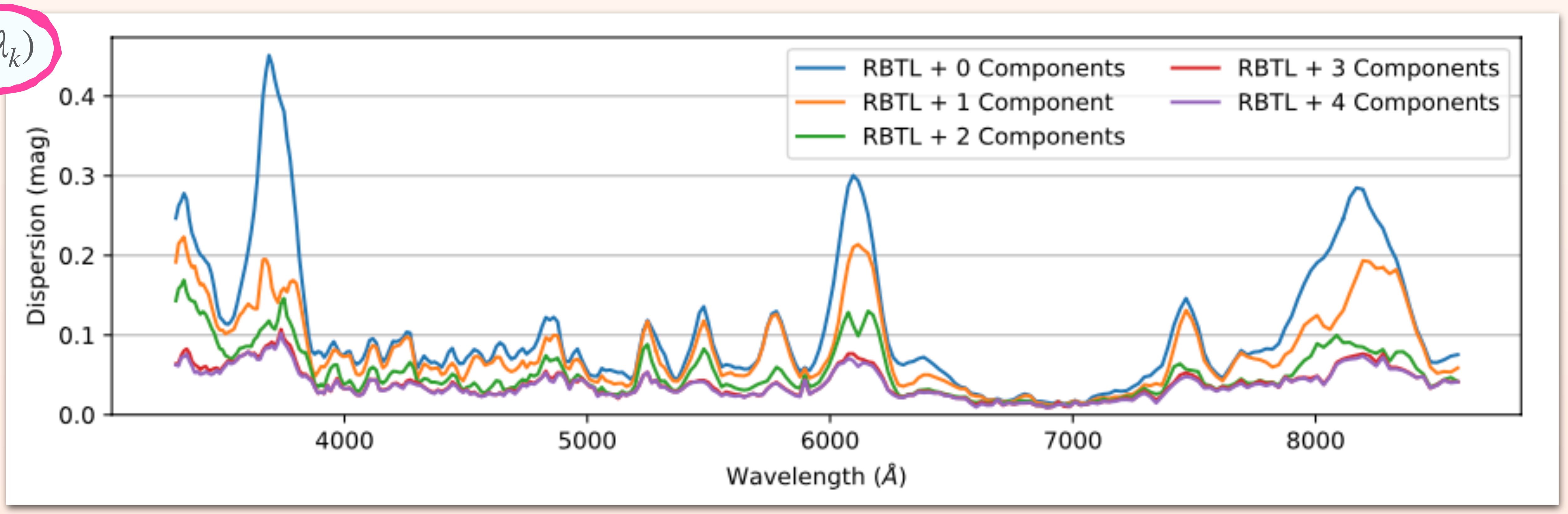
STEP 3

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)*

	ξ_1	ξ_2	ξ_3
Added noise, S/N = 20	0.99	0.98	0.96
Added noise, S/N = 10	0.97	0.96	0.89
Added noise, S/N = 5	0.94	0.88	0.79
Added noise, S/N = 2	0.68	0.12	0.22
Binning 2000 km/s	1.00	1.00	1.00
Binning 5000 km/s	1.00	0.99	0.97
Binning 10000 km/s	0.99	0.98	0.90

Fraction of Variance Explained

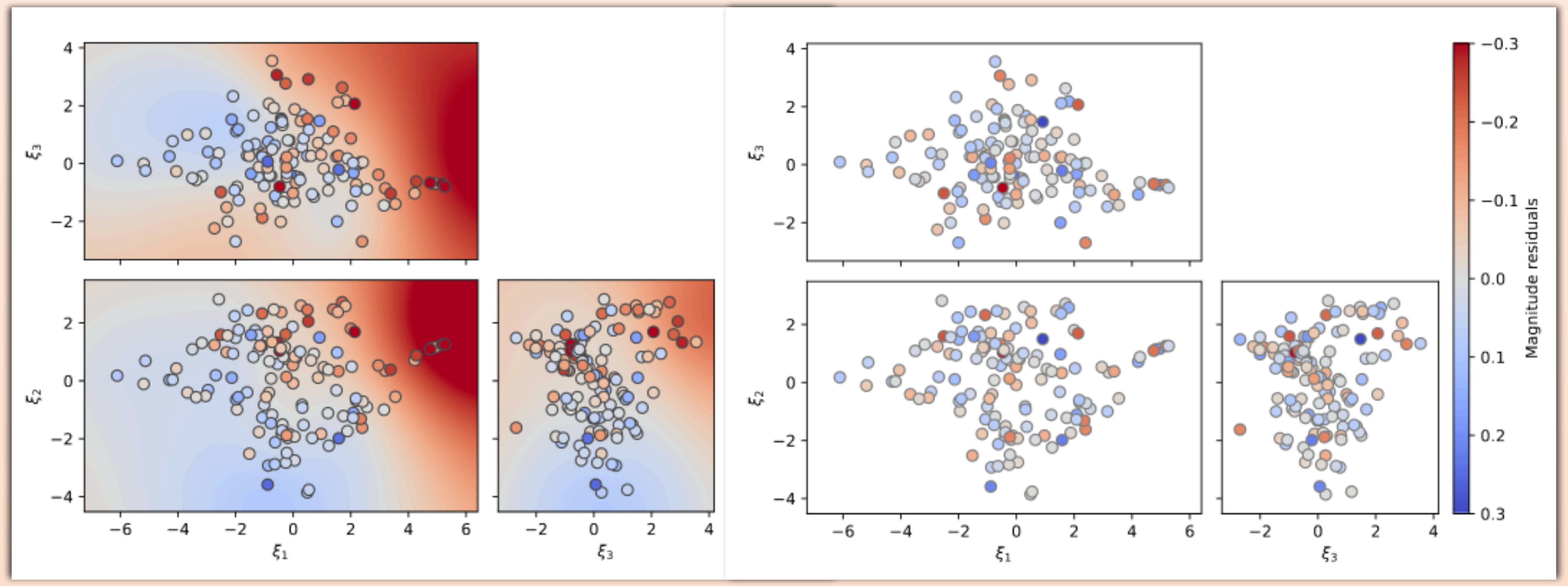
Dependancy of the variance explained with S/N and binning

BACK-UP SLIDE

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 :

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

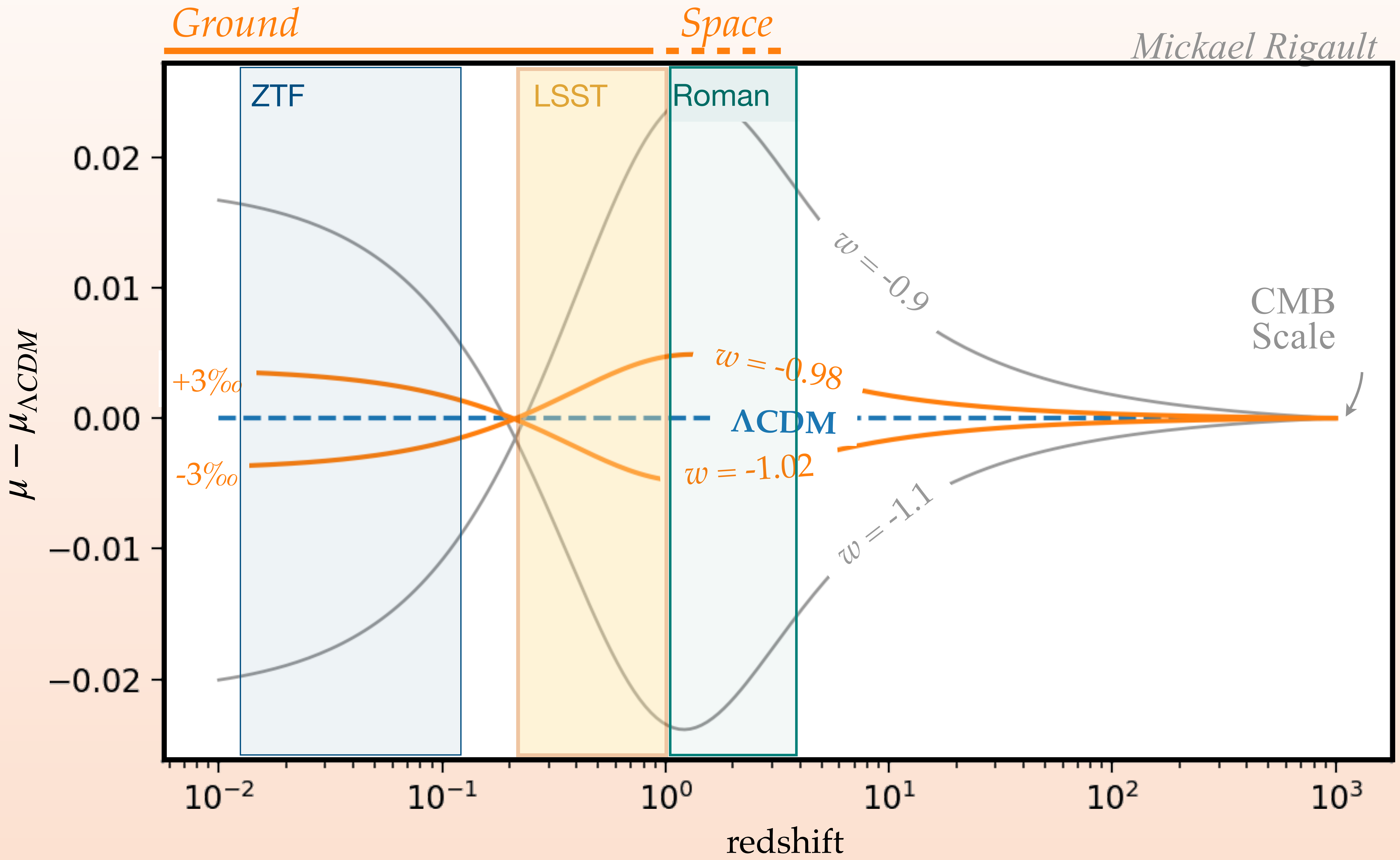
$\Delta \vec{A}_V$ *the reddening coefficients ,*

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

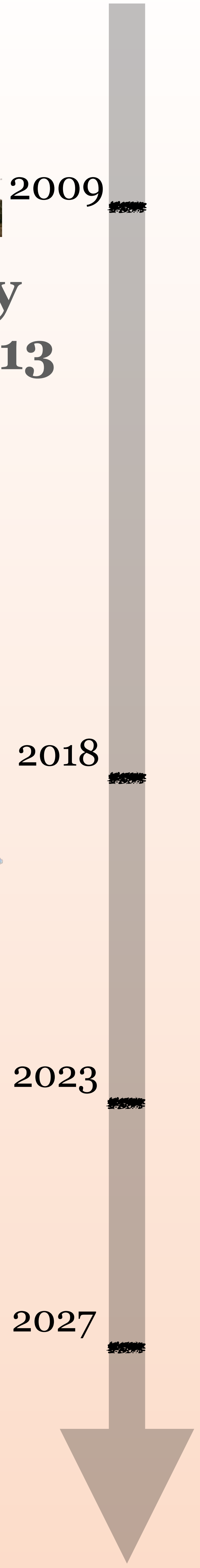
$\vec{\sigma}^2_{p.v.}$ *the host galaxy peculiar velocity variance*

BACK-UP SLIDE

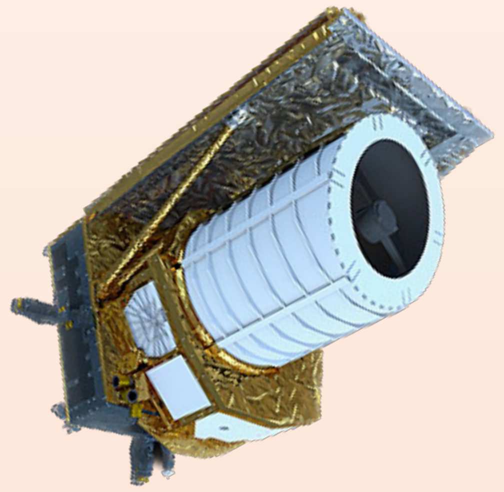
Standardisation context



SNFactory
2004 —> 2013



ZTF
2018 —> 2025



Euclid
july 2023 -

Roman
2027-

BACK-UP SLIDE

Coupures sur les parametres:

(in general, whatever other cut)

Parameter	Interval	Remains	Quantity removed
/	/	5136	
from SEDm		3069	40 %
goodcoverage			13 %
Offsets	2sigmas		19 %
deg2 coefs	abs<0.028		1 %
z	<0.1		around 7/8%
phase	[-5,+5] days		**around 50%**
sn_type	cosmo		around 15%
c, c_{err}	[-0.2,0.3] , <0.08		13.6% , 7%
x_1, $x_{1,err}$	[-3,3], <1		4.5% , 5.5%
$t_{0,err}$	<1 day	752	8.3%

—> 752 spectres de 695 Sne Ia