Spectro-standardisation of ZTF Sne Ia

Constance GANOT - IP2I (Lyon)
Under supervision of Yannick COPIN & Mickael RIGAULT

Twins Embedding

ZTF spectra calibration

Standardisation

January 2024

Summary

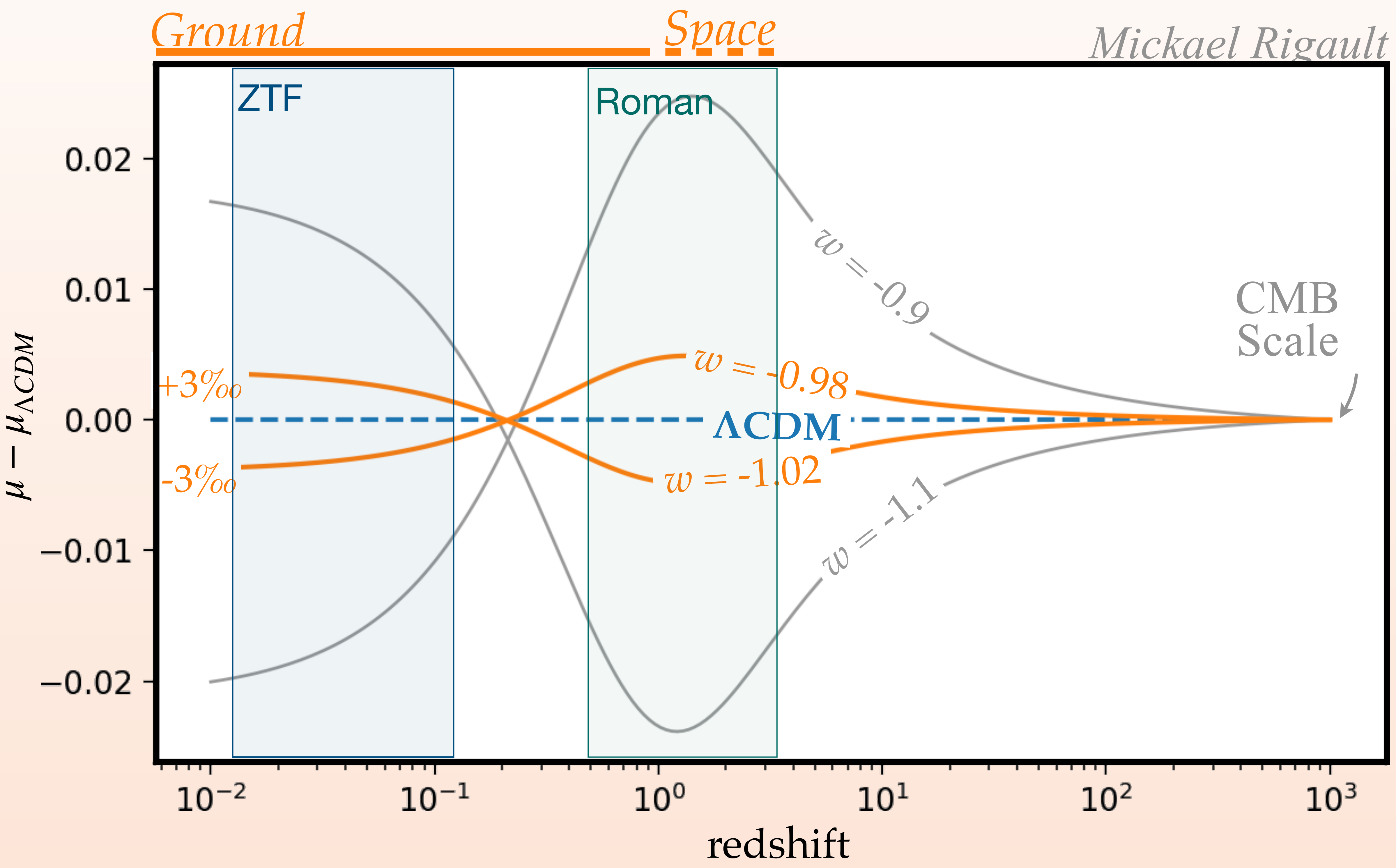
Part I

- Twins
- Twins Embedding

Part II

- Flux calibration of ZTF spectra
- Standardisation with SALT on ZTF spectra

Context



$$\mu = m_B - \{M_B - \alpha \cdot x_1 - \beta c\}$$

$$\mu_{\Lambda CDM}(z) = +2.5 \cdot log_{10}(\left[\frac{d_L(z)}{10pc}\right]^2)$$

—> New standardisation of distance modulus, using spectral information

Sample passing requirements:

SNFactory :	ZTF :
173 Sne Ia	985 Sne Ia
~500 spectra	1075 spectra

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

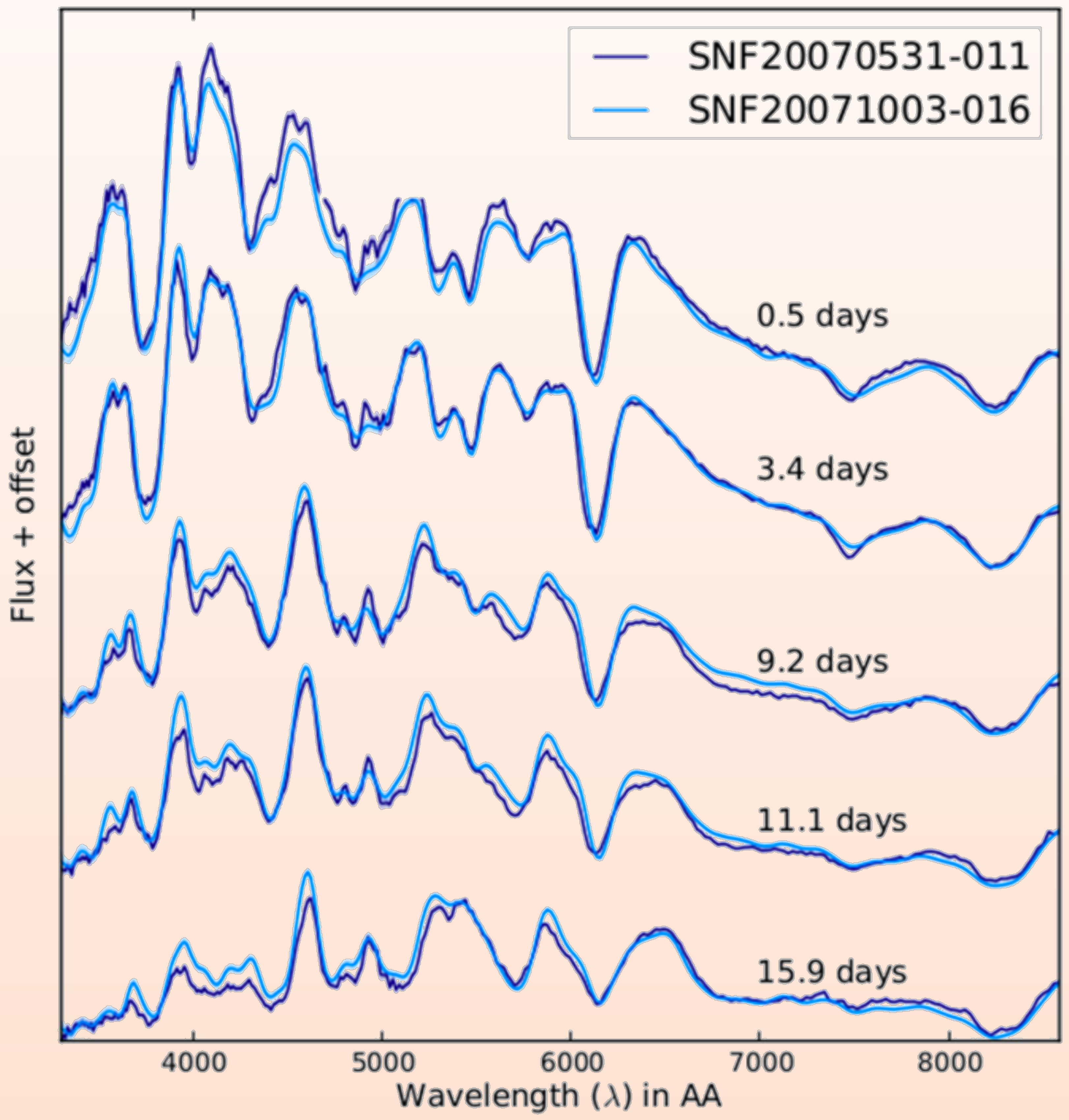
Photometry :
$\sigma_{mag} = 0.15\text{mag}$

With SNFactory

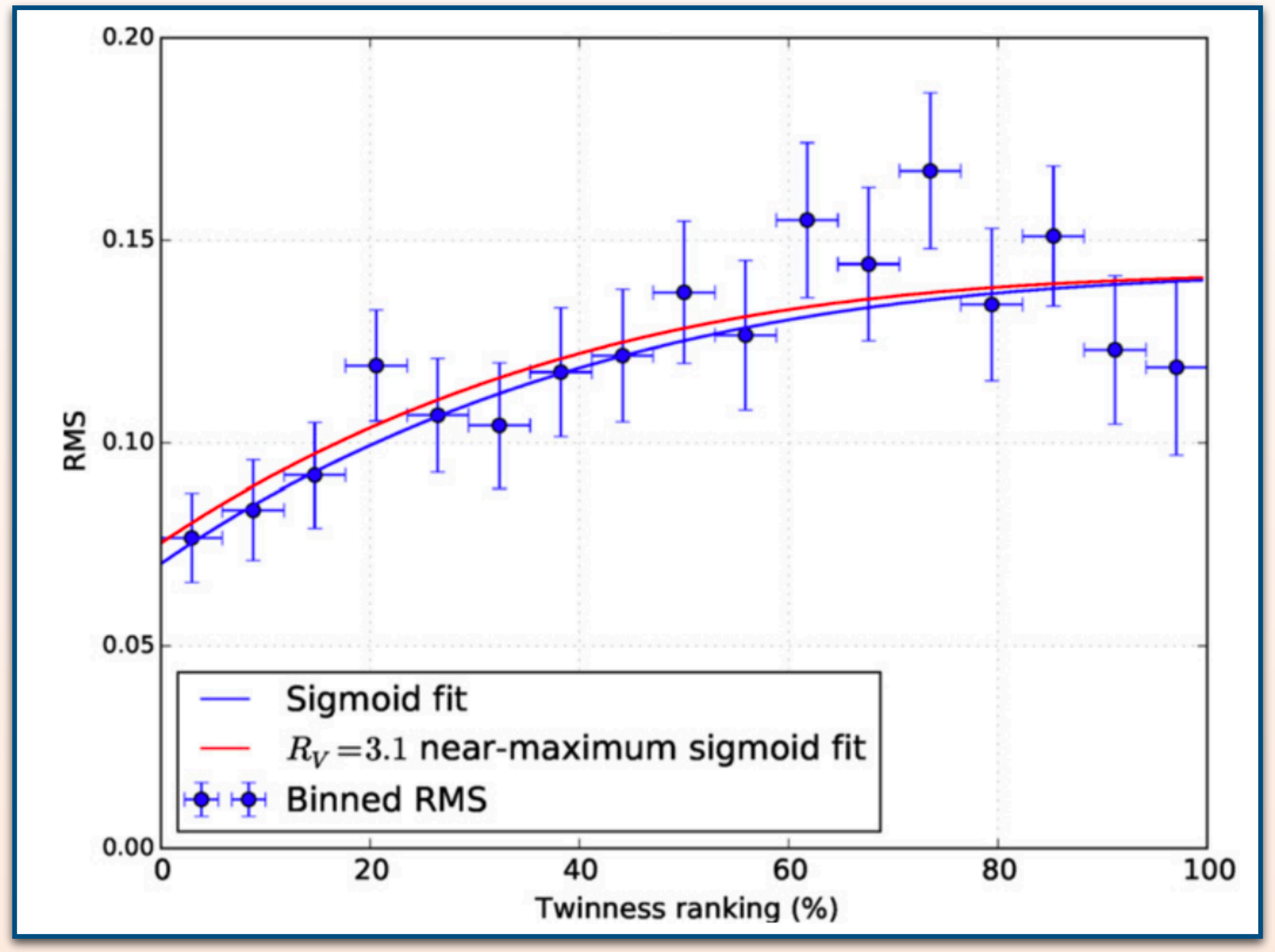
Twins Embedding :
$\sigma_{mag} = 0.07\text{mag}$

Twins

Twins supernovae have matching spectral time-series



Spectral time-series of two 'Twins' Sne
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

Spectrophotometric standardisation method Using Machine Learning

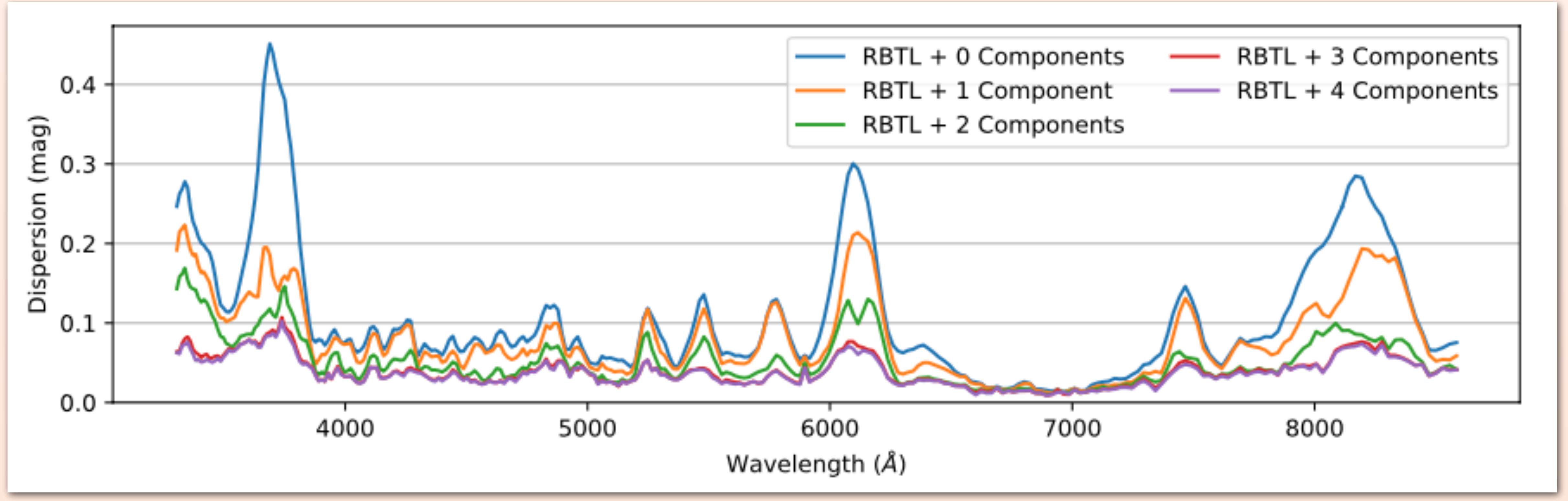
Twins Embedding - Boone et al. 2021

Pre-processing data :
Adjust relative brighness of the Sne to a common redshift

1. Differential time evolution model

2. RBTL - remove grey scatter and extinction

3. Manifold Learning - parameters reduction



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

STEP 1

Differential time evolution model

=> *Spectra @ max*

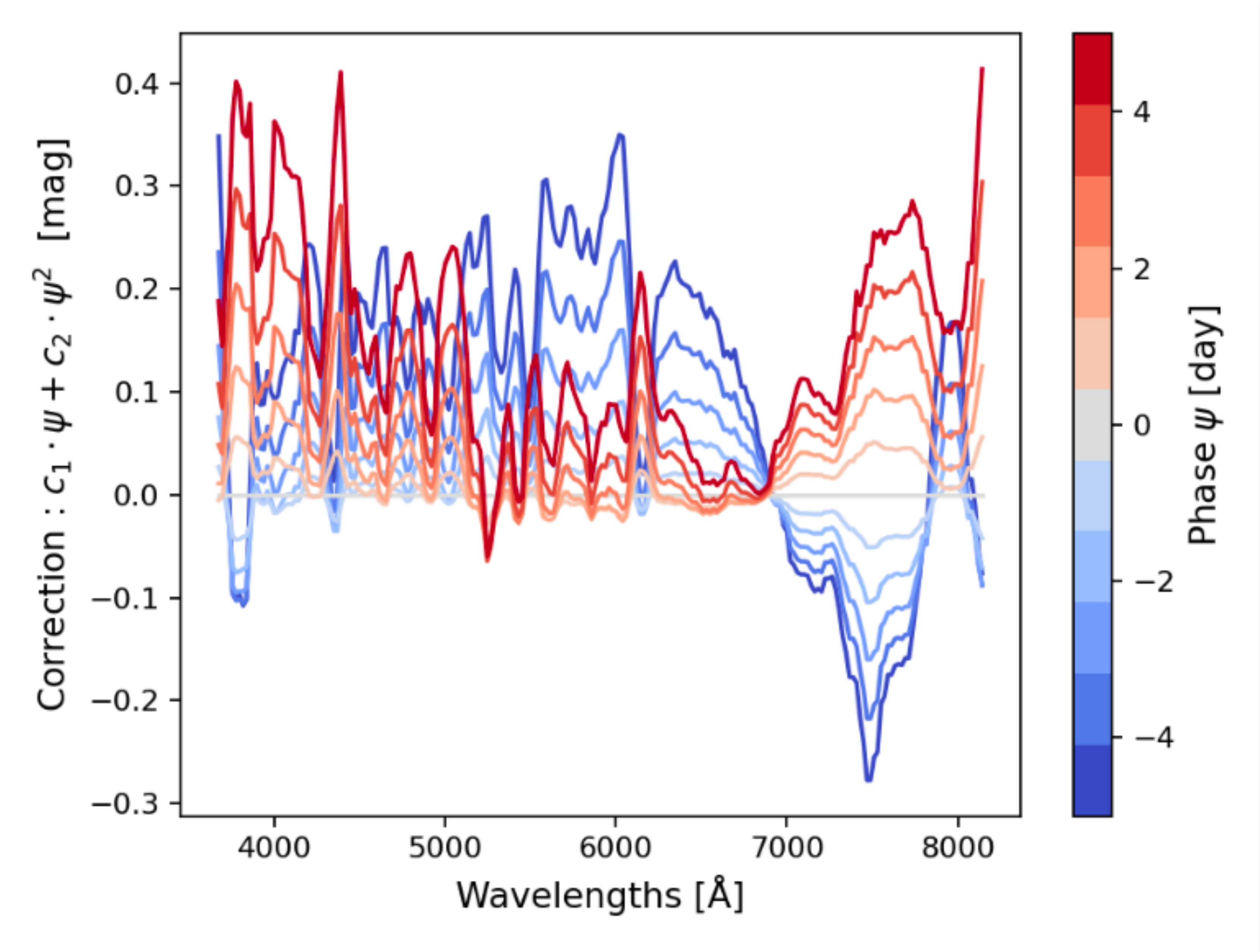
Formula of quadratic evolution in phase :

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

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

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

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

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

<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

=> *Spectra @ max*

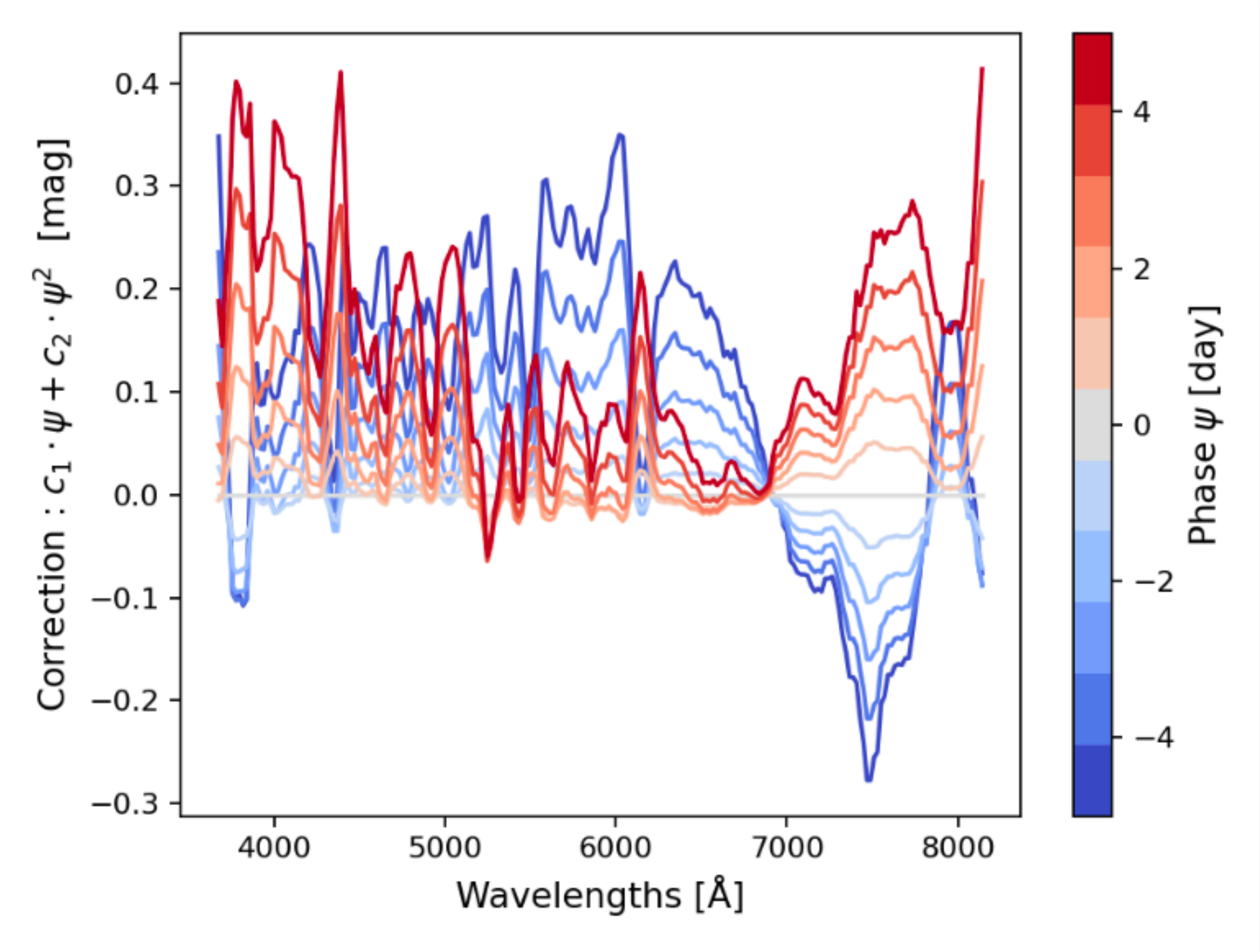
Formula of quadratic evolution in phase :

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

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 :

$\epsilon(p,\lambda_k)$ 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 1

Differential time evolution model

=> *Spectra @ max*

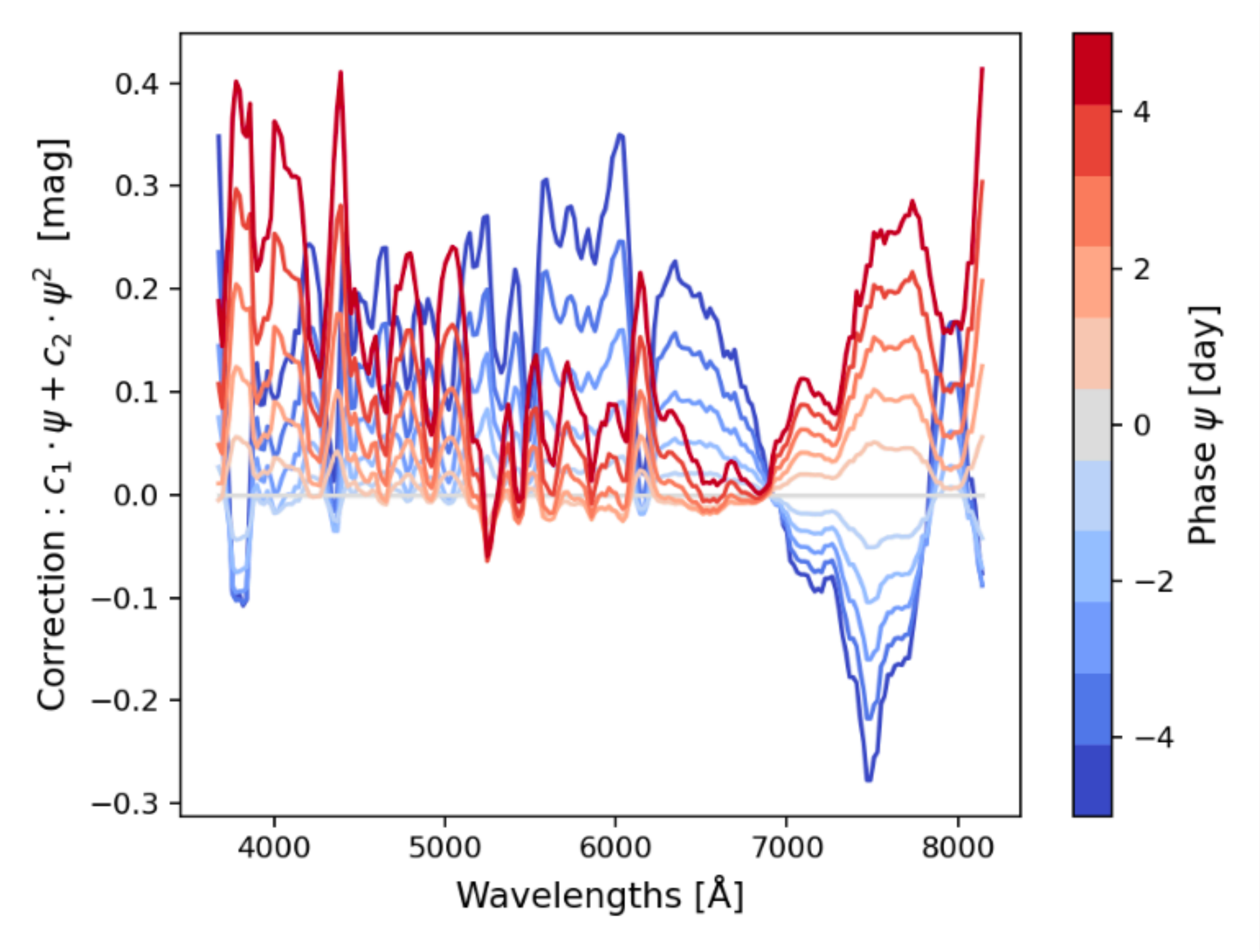
Formula of quadratic evolution in phase :

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

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 :

$\epsilon(p,\lambda_k)$ 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)*

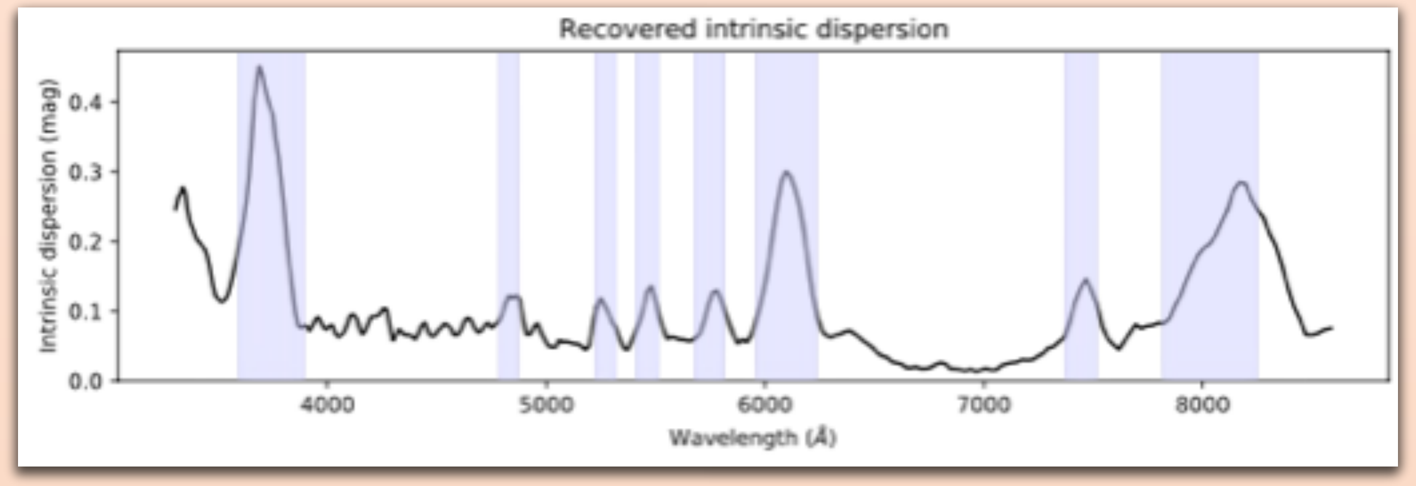
Fit all together with bayesian inference :

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

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

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

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



STEP 2

Read between the lines (RBTL)

=> Explain Scatter Between the lines

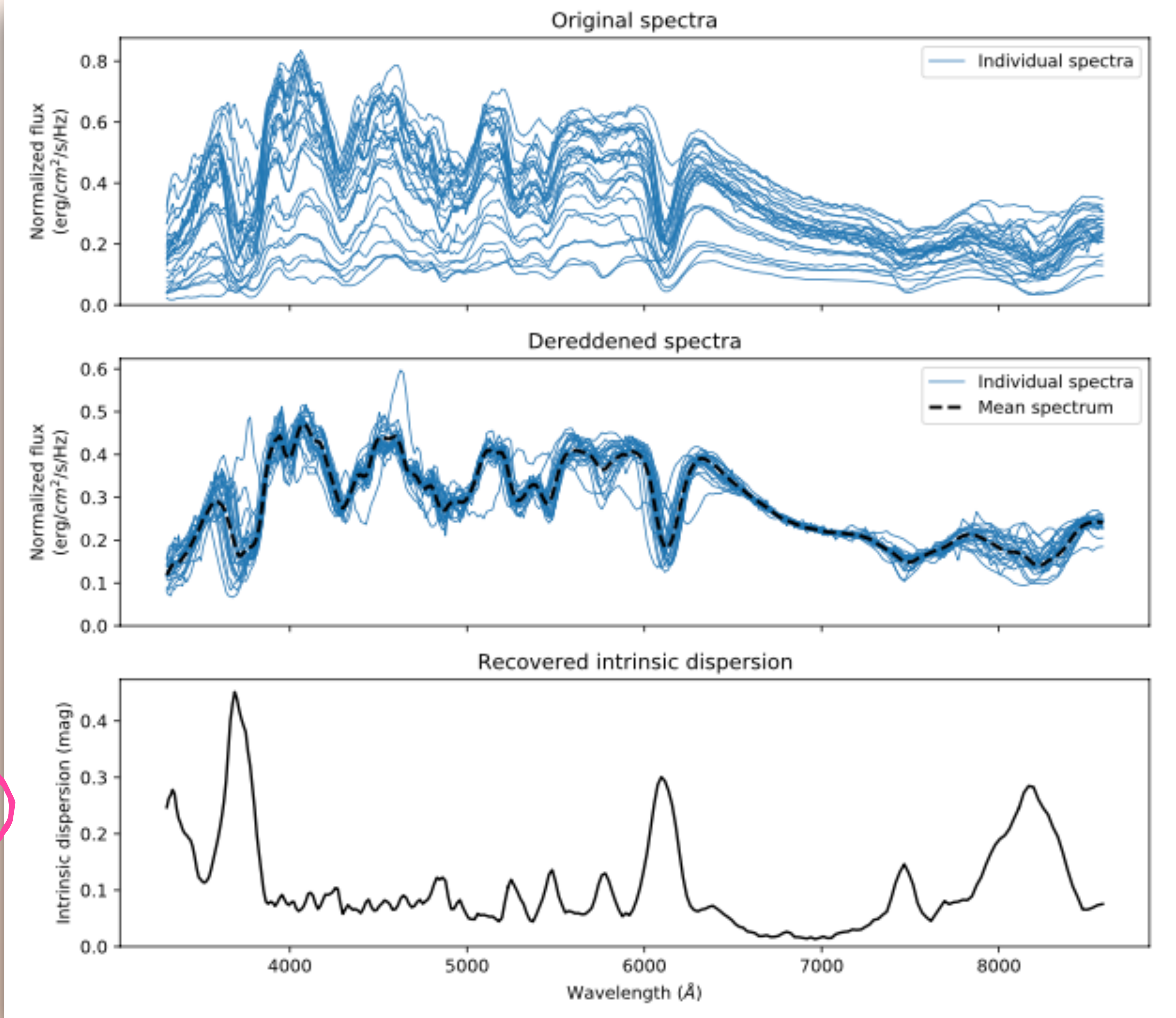
Capture Grey scatter + Extinction

Remove variability:

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

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

$\eta(\lambda_k)$



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

Read between the lines (RBTL)

=> Explain Scatter Between the lines

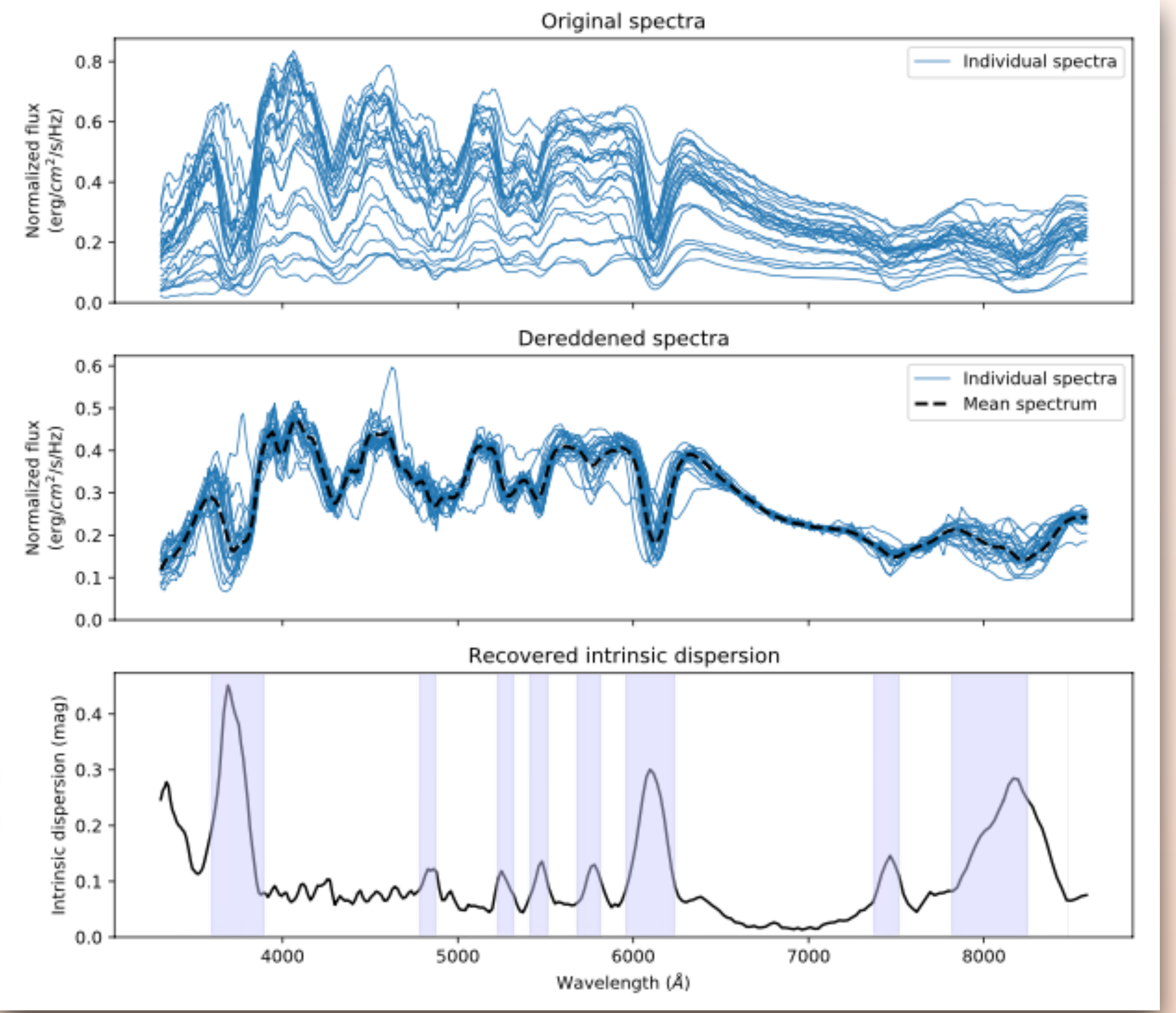
Capture Grey scatter + Extinction

<u>Remove variability:</u>

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

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

$\eta(\lambda_k)$



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

STEP 3

The Twins Embedding parameters space

=> Explain $\eta(\lambda_k)$

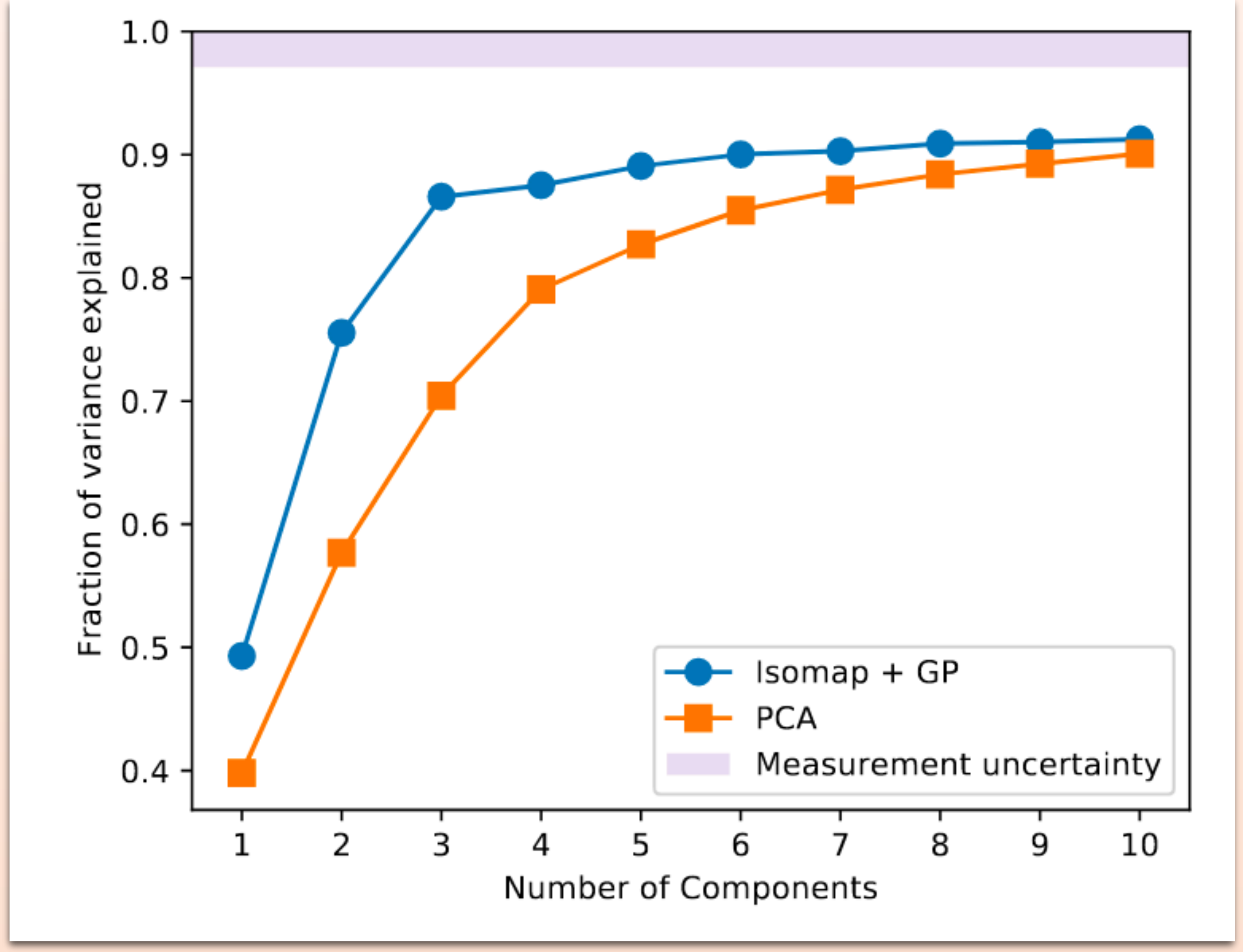
Spectral distance between two Sne I and j :

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

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

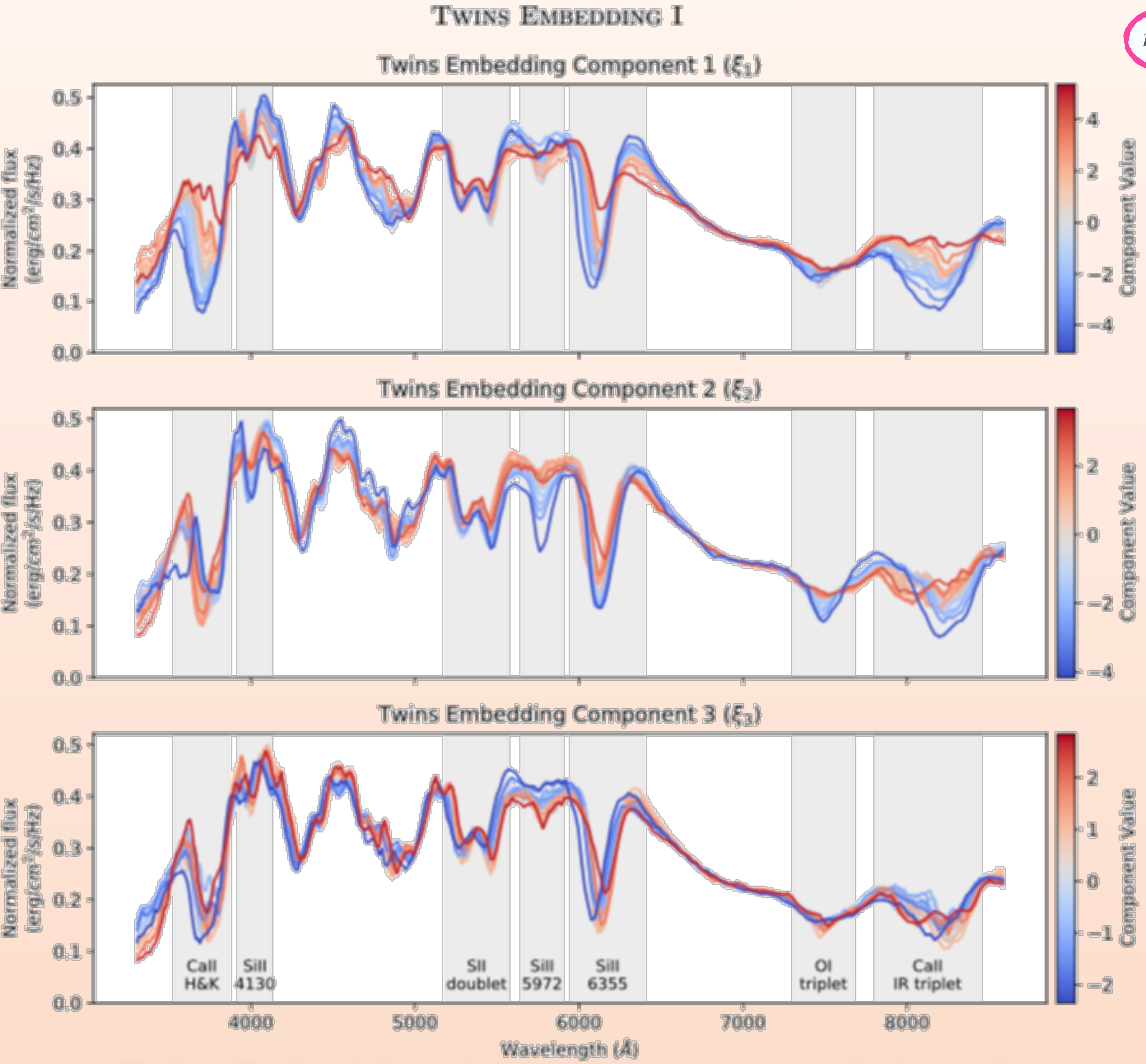


Fraction of the variance explained for different models - from Boone 2021

STEP 3

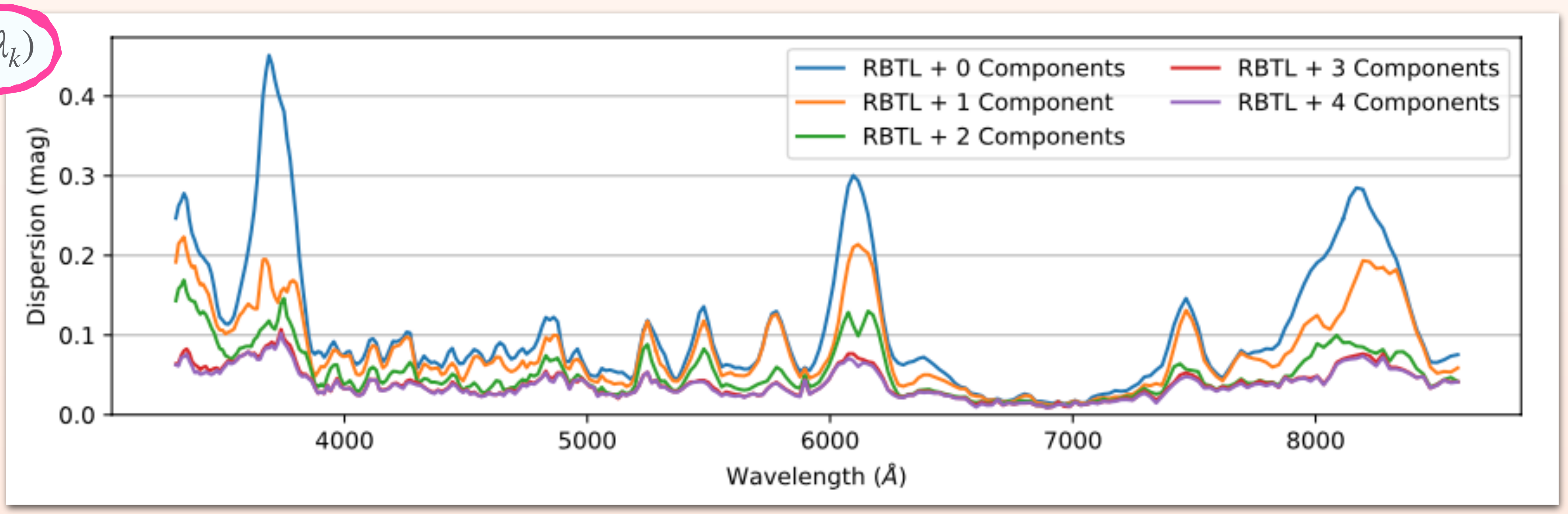
The Twins Embedding parameters space

=> *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)*

	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

(Colour scale: Fraction of Variance Explained, 0.5–1.0)

Dependancy of the variance explained with S/N and binning

With ZTF Spectra

Steps :

- ☑ Flux calibration of the spectra
- ☑ Correct from the Milky Way
- ☑ Put each spectrum at same z
- ☐ Convert the flux in magnitude and put to phase=0

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

- ☐ Correction of RBTL variability by fitting the Δm_i and $\Delta \tilde{A}_{V,i}$

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

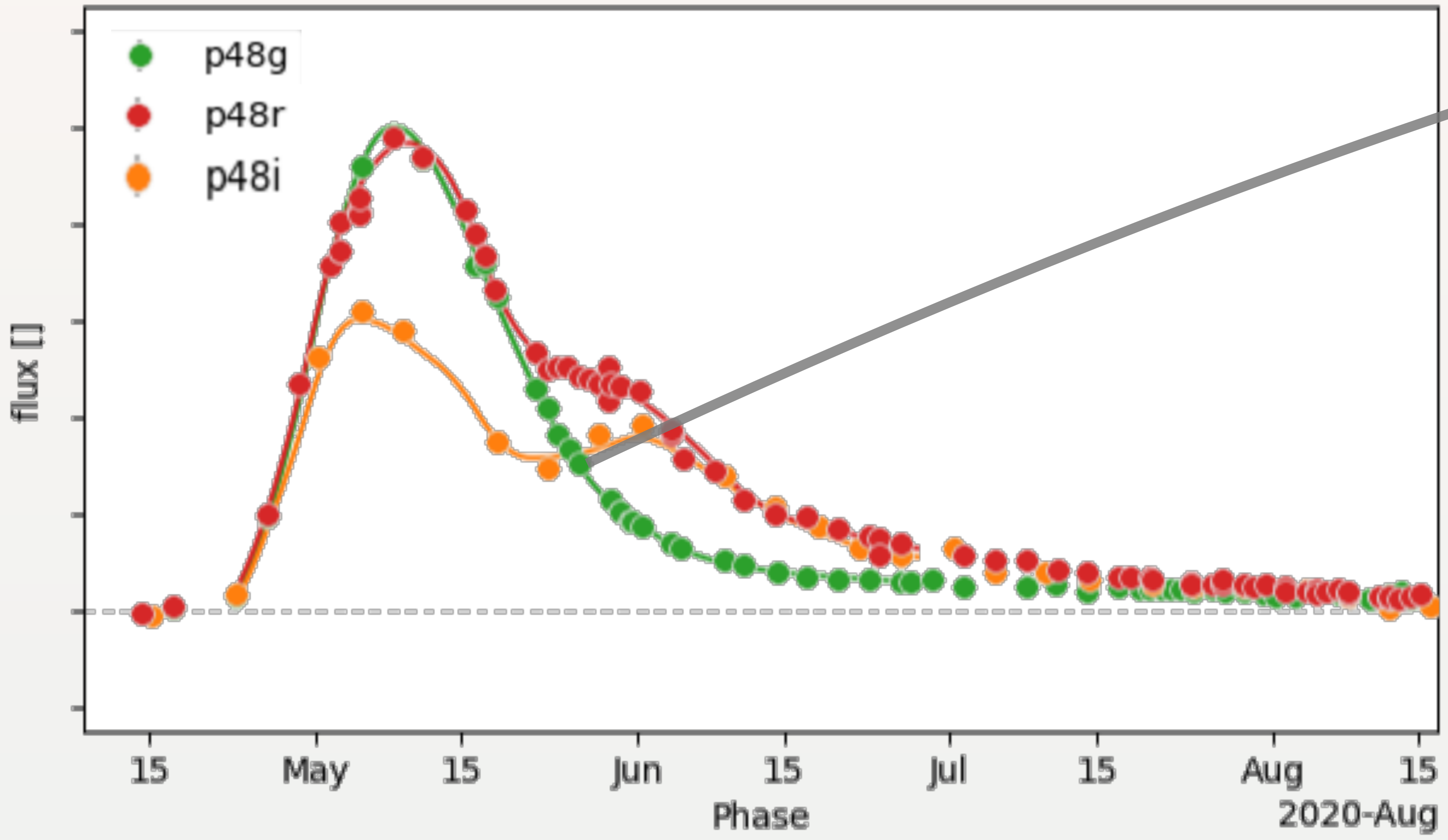
- ☐ Projection on the 3 components space to get $\overrightarrow{\xi}$
- ☐ Standardisation of the magnitude residuals …

ZTF Data - Plan

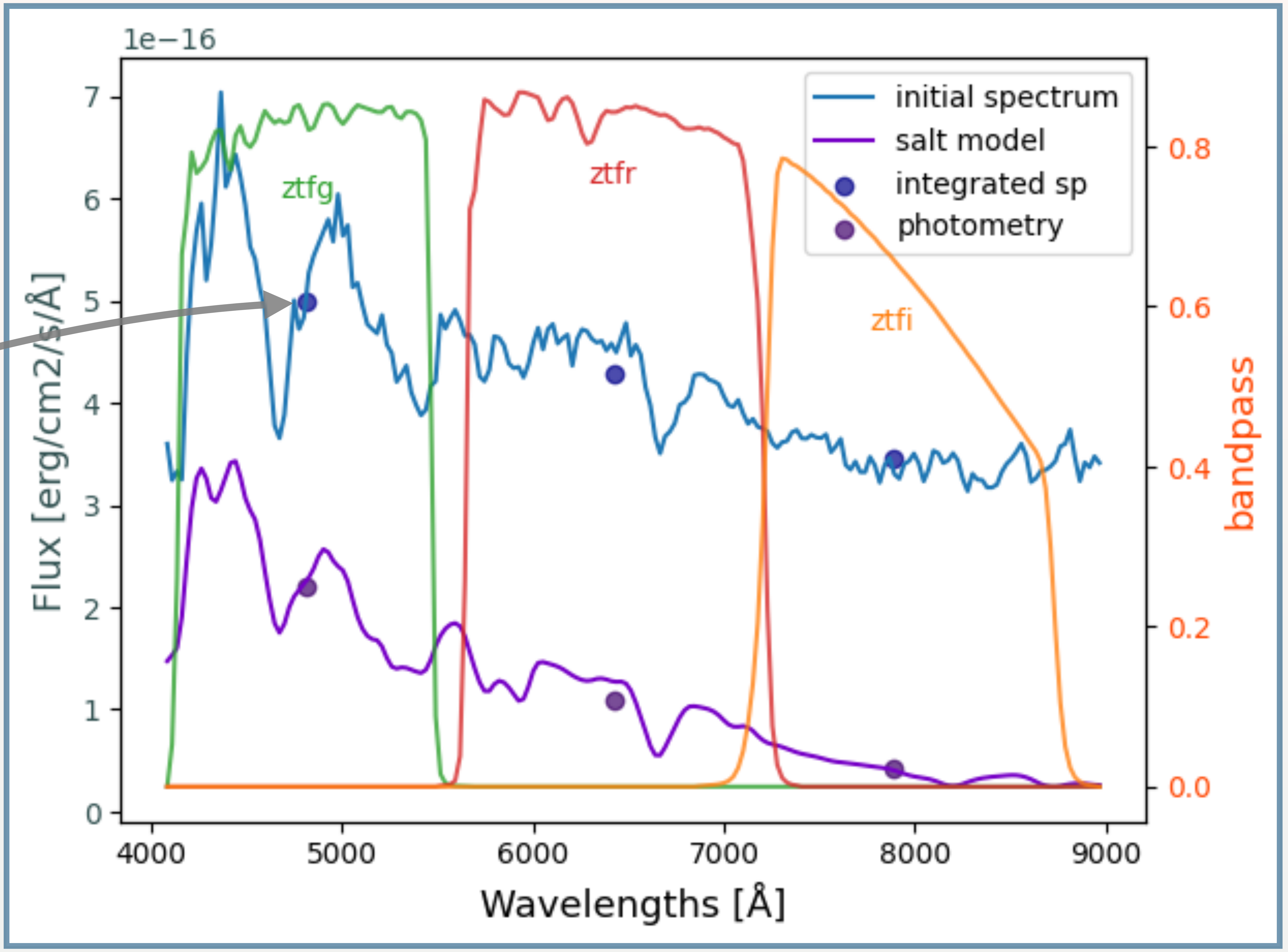
- Flux calibration of ZTF spectra
- Correction of the MW and the redshift
- Standardisation of the spectra with SALT

Synthetic Photometry

A point on the lightcurve corresponds to the spectrum integrated on the band



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



Synthetic photometry with ZTF filters For ZTF18abjijwk at phase 0.45

Spectrophotometric Calibration

2nd order polynomial :

$$poly \sim c_2 \cdot \lambda_{norm}^2 + c_1 \cdot \lambda_{norm} + c_0$$

Legendre Polynomials :

We normalise wavelengths between -1 and 1

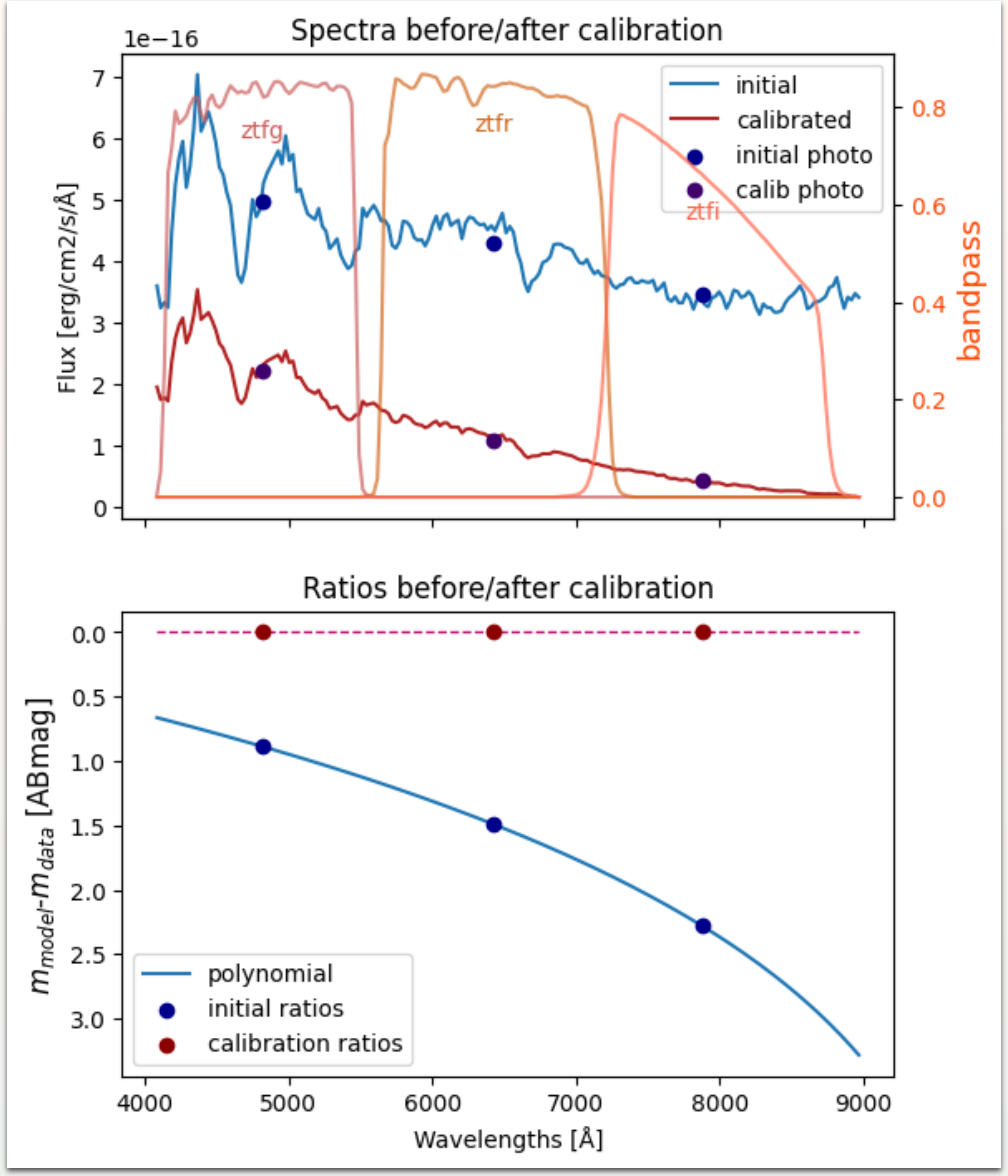
$$\lambda_{norm} = 2 \cdot \frac{\lambda - \lambda_{min}}{\lambda_{max} - \lambda_{min}} - 1$$

Minimisation function :

$$\chi^2 = \sum_N \left(\int_{3filters} f_{obs}(\lambda) \cdot poly(\lambda) \cdot d\lambda - F_{photo}^{g,r,i} \right)^2$$

Polynomial converted in magnitude :

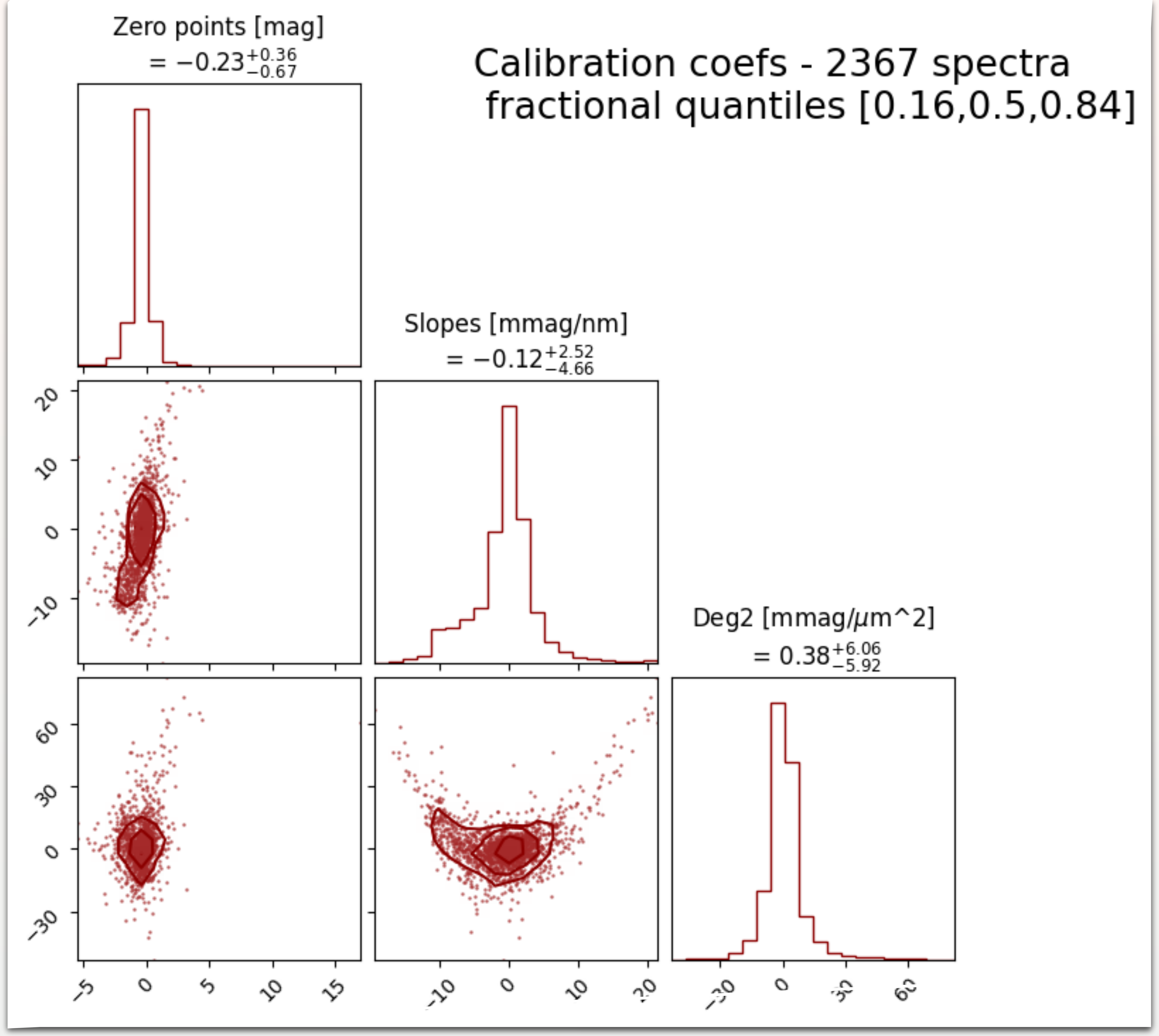
$$m_{model} - m_{init} = -2.5 \cdot \log_{10}\left(\frac{f_{model}}{f_{init}}\right)$$

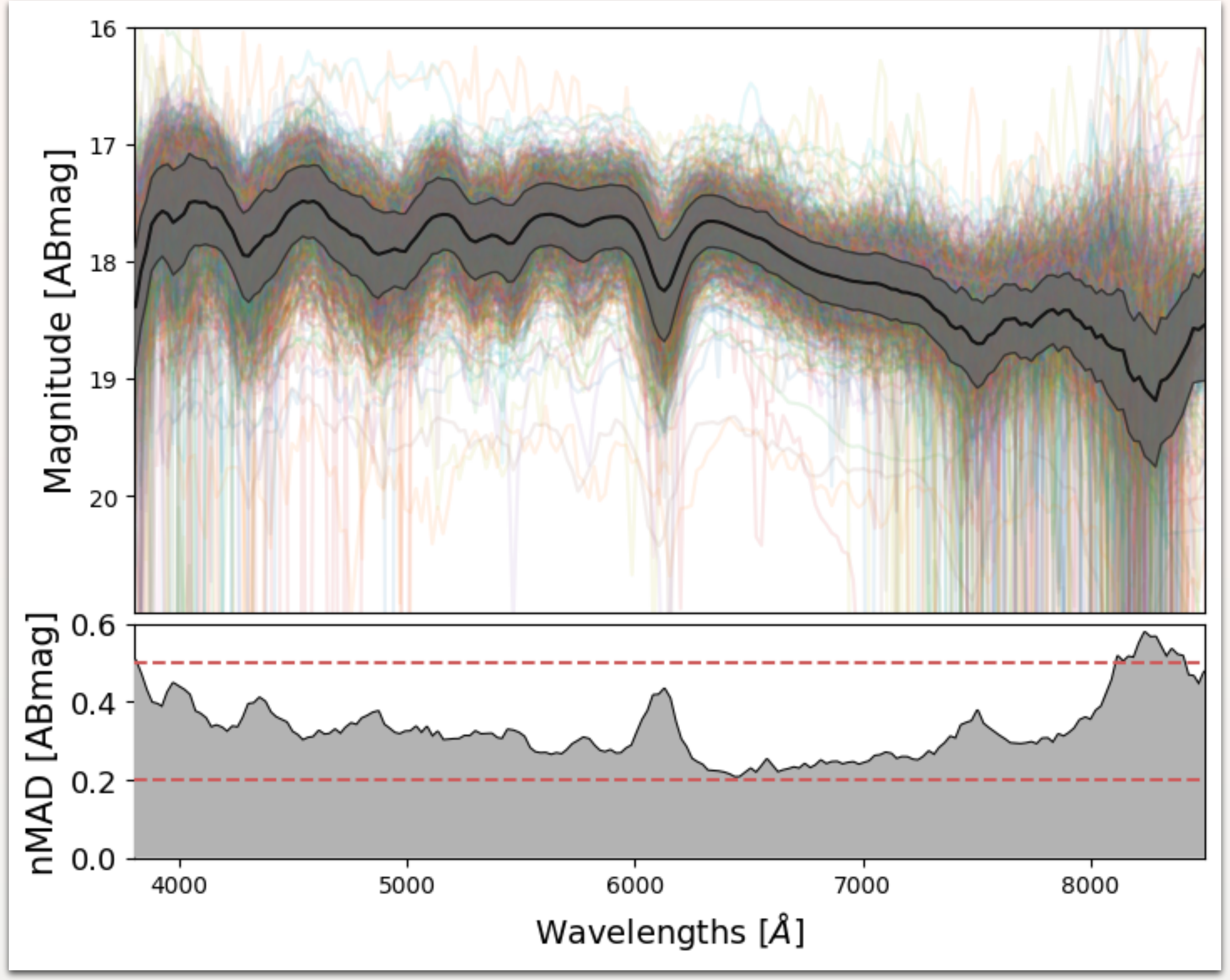


Example of calibration with ZTF18abjijwk

Spectrophotometric Flux Calibration

For 2367 spectra





Calibrated, corrected of MW and redshift at 0.05, for 1075 spectra of 985 Sne Ia (cosmology cuts + phase bewteen +/-5 days)

Standardisation with SALT - applied to ZTF spectra

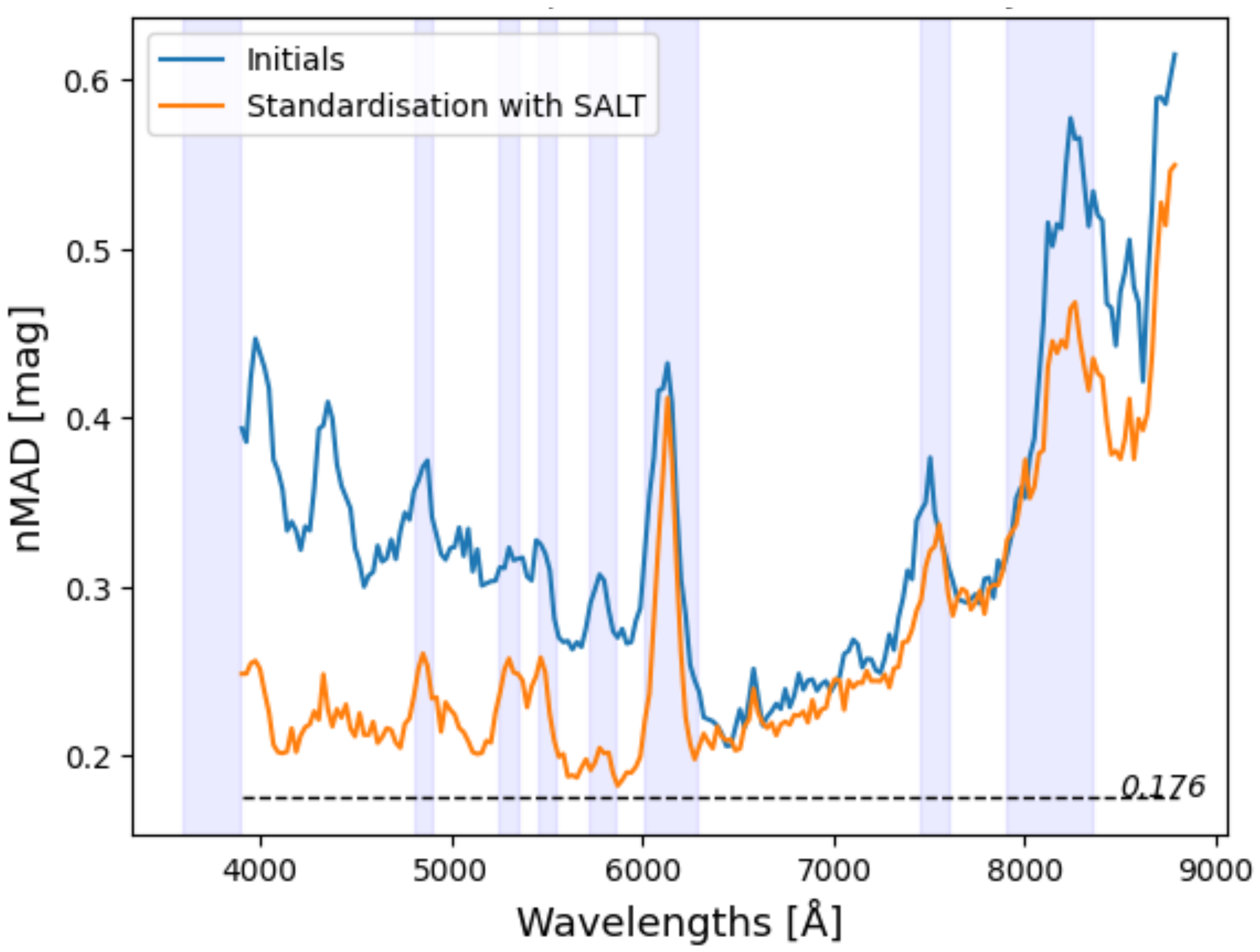
Method :

Correct the fluxes from SALT parameters and redshift

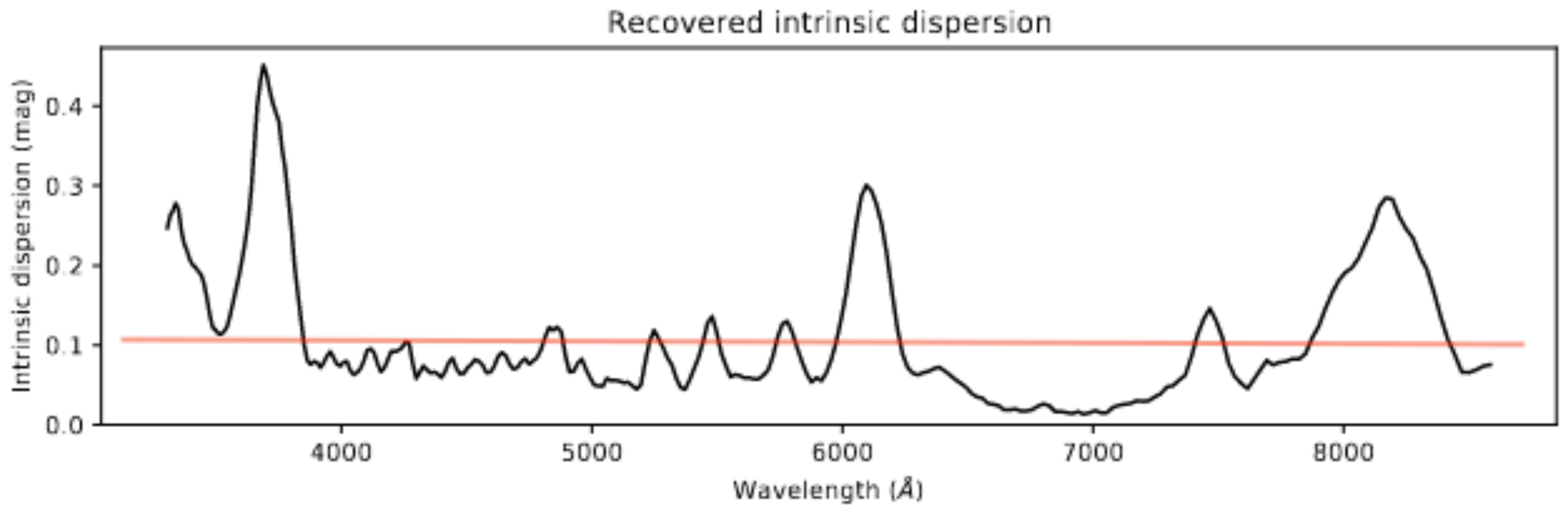
Convert the fluxes in ABmag, and apply Tripp standardisation

$$f_{corrected}(\lambda) = \left\{ \frac{f_{init}(\lambda) \cdot (1+z) \cdot d_L(z)^2}{10^{-0.4 \cdot CL(\lambda_{rest}) \cdot c}} - x0 \cdot x1 \cdot M_1(\phi, \lambda_{rest}) \right\} \times \frac{M_0(\lambda_{rest}, 0)}{M_0(\lambda_{rest}, \phi)} \cdot \frac{1}{(1+z_{ref}) \cdot d_L(z_{ref})^2}$$

$$\Delta\mu(\lambda) = m_{corrected}(\lambda) - (M_B - \alpha \cdot x_1 - \beta c)$$



nMAD of sample initially and after SALT correction+standardisation



Intrinsic variabilty after RBTL - from Boone 2021

Conclusion

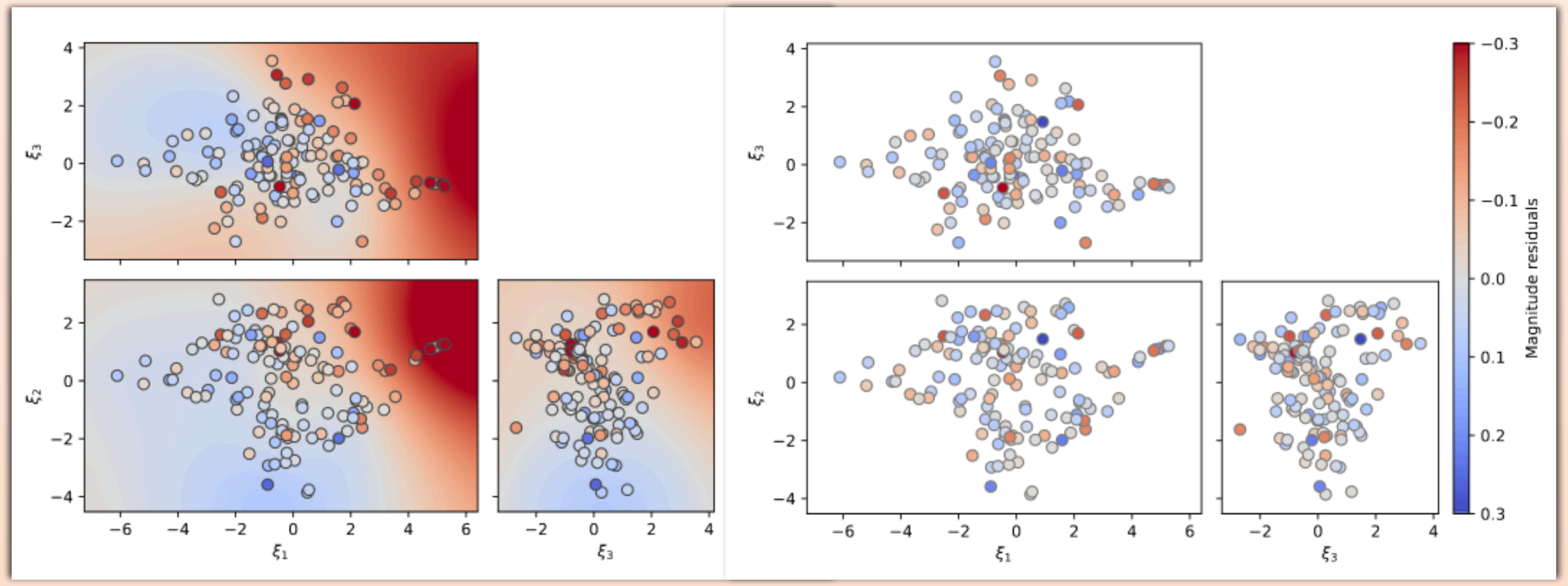
- ☑ Flux calibration of the spectra
- ☑ Preparation of the sample : correction of the MW and redshift
- ☑ SALT standardisation, SNEMO
- ☐ Test the *Twins Embedding* method with ZTF spectra
- ☐ More methods can be tested, like *PAE* by G.Stein

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 :

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



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

George GP regression python package is used for the fit

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 with SALT - applied to ZTF spectra

Flux modelled with SALT, in observed wavelengths :

$$F(\lambda, \phi) = x_0 \cdot \left[M_0(\lambda_{rest}, \phi) + x_1 \cdot M_1(\lambda_{rest}, \phi)\right] \cdot 10^{-0.4 \cdot c \cdot CL(\lambda_{rest})}/(1+z)$$

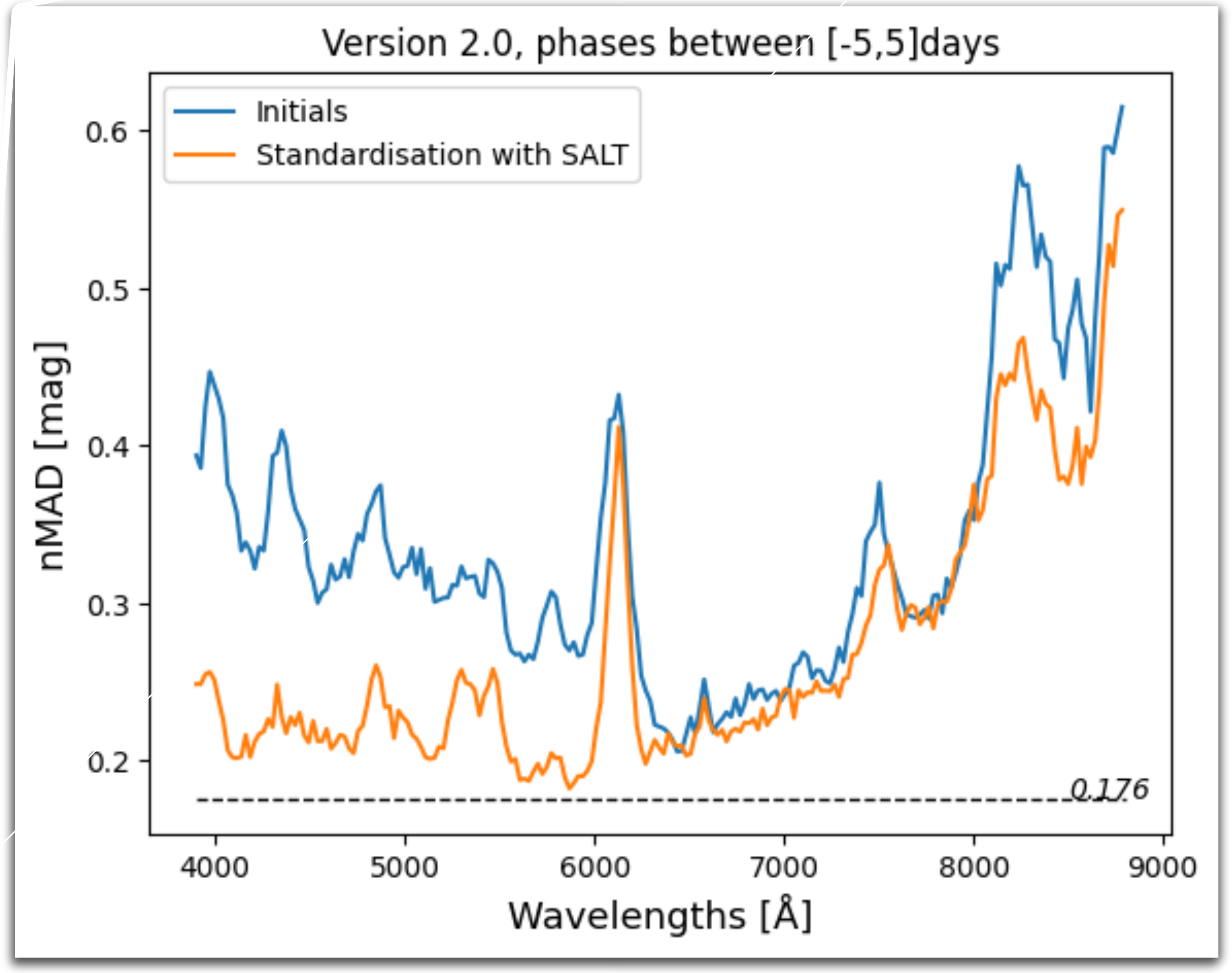
Method : Correct the fluxes from SALT parameters, convert the fluxes in ABmag, and apply Tripp standardisation

$$f_{Initials}(\lambda) = f_{meas}(\lambda) \cdot \frac{(1+z) \cdot d_L(z)^2}{(1+z_{ref}) \cdot d_L(z_{ref})^2}$$

$$\Delta\mu_{Initials}(\lambda) = F_{to}M\left(f_{Initials}(\lambda)\right)$$

$$f_{corrected}(\lambda) = \left\{ \frac{f_{init}(\lambda) \cdot (1+z) \cdot d_L(z)^2}{10^{-0.4 \cdot CL(\lambda_{rest}) \cdot c}} - x0 \cdot x1 \cdot M_1(\phi, \lambda_{rest}) \right\} \cdot \frac{M_0(\lambda_{rest}, 0)}{M_0(\lambda_{rest}, \phi)} \cdot \frac{1}{(1+z_{ref}) \cdot d_L(z_{ref})^2}$$

$$\Delta\mu_{stand}(\lambda) = F_{to}M\left(f_{corrected}(\lambda)\right) - (M_B - \alpha \cdot x_1 - \beta c)$$



nMAD of sample initially and after SALT correction+standardisation

Hubble diagram analogy:

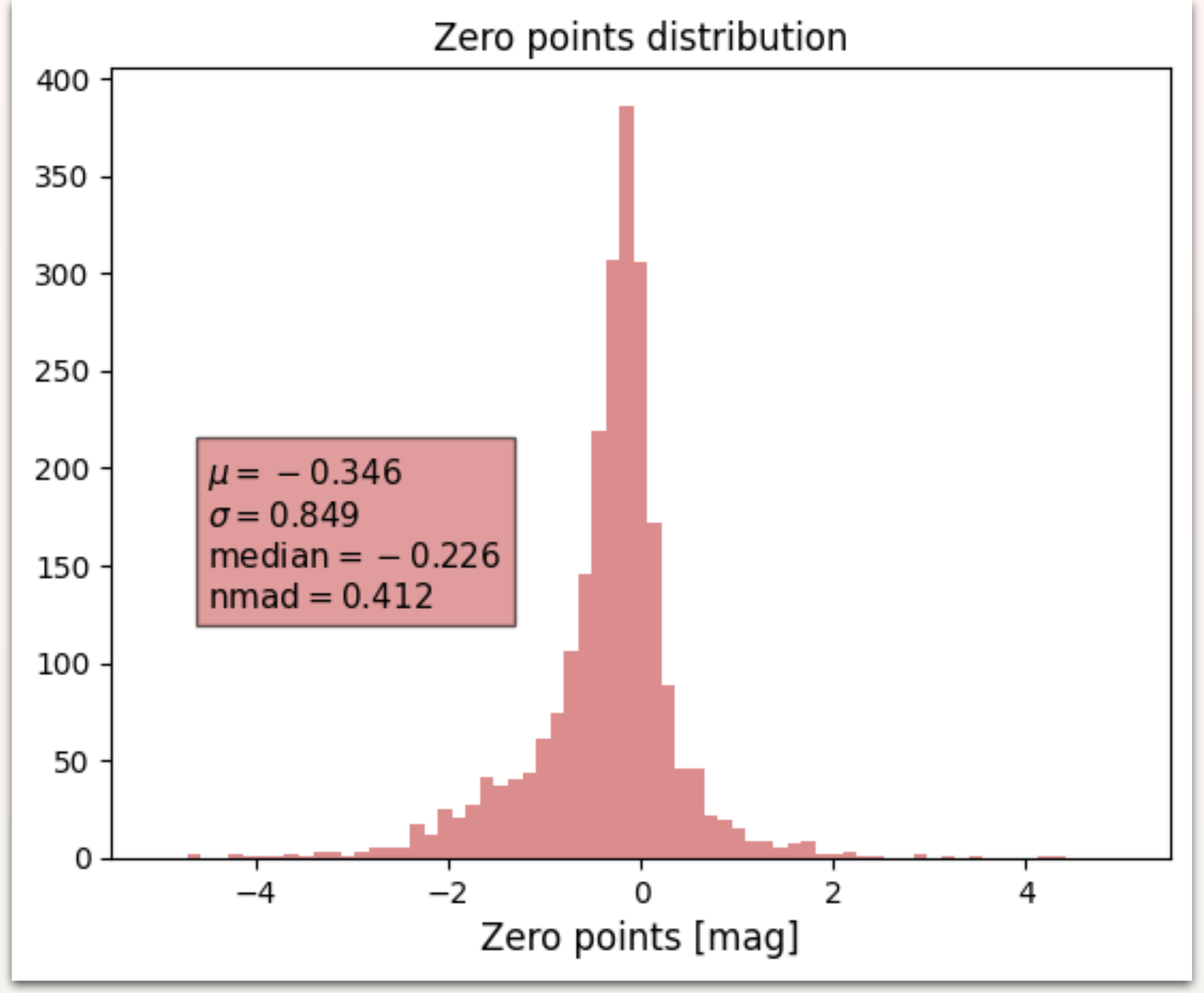
$$\mu = m_B - (M_B - \alpha \cdot x_1 - \beta c)$$

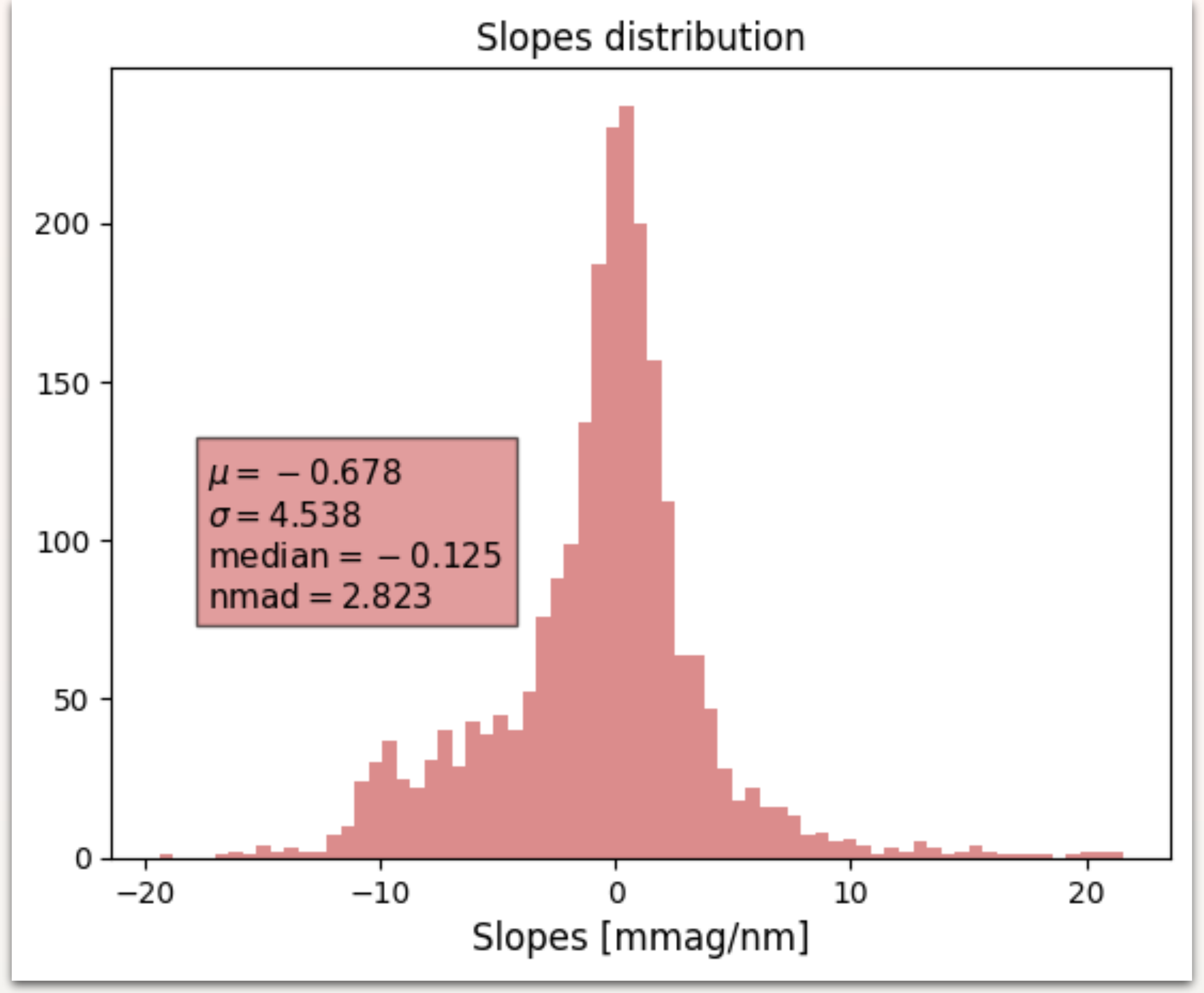
$$\mu(z) = +2.5 \cdot log_{10}(\left[\frac{d_L(z)}{10pc}\right]^2)$$

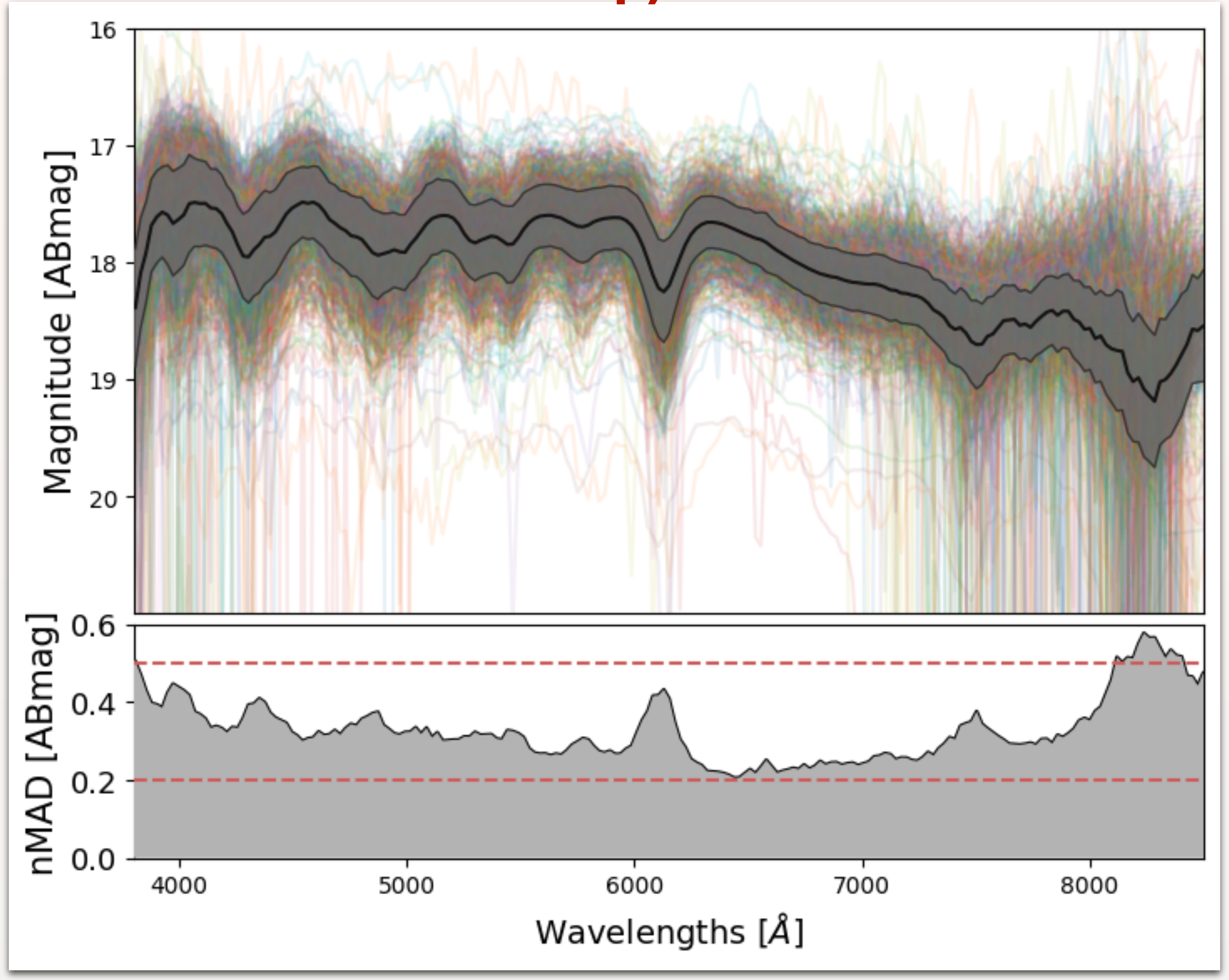
Spectrophotometric Flux Calibration

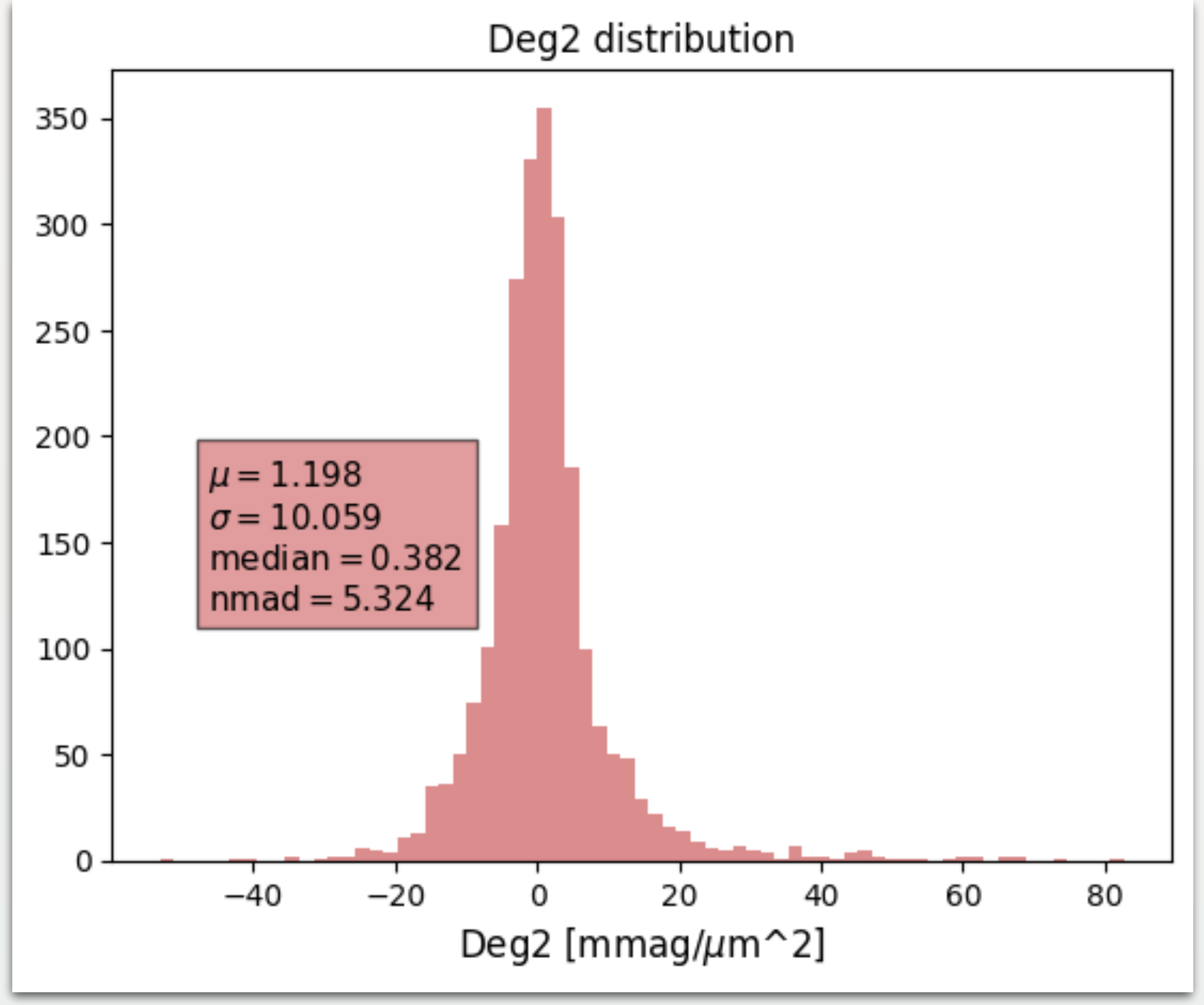
For 2367 spectra

Corner plot des 3 histogrammes (dire le nbr de sp, mettre tableau en backup)









Calibrated, corrected of MW and redshift at 0.05, for 1075 spectra of 985 Sne Ia (cosmology cuts + phase bewteen +/-5 days)