Spectrophotometric standardisation of type Ia Supernovae

Constance GANOT, supervised by Yannick COPIN and Mickael RIGAULT

JRJC - nov. 2024 - at St-Jacut-de-la-mer

Summary

- Introduction about 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

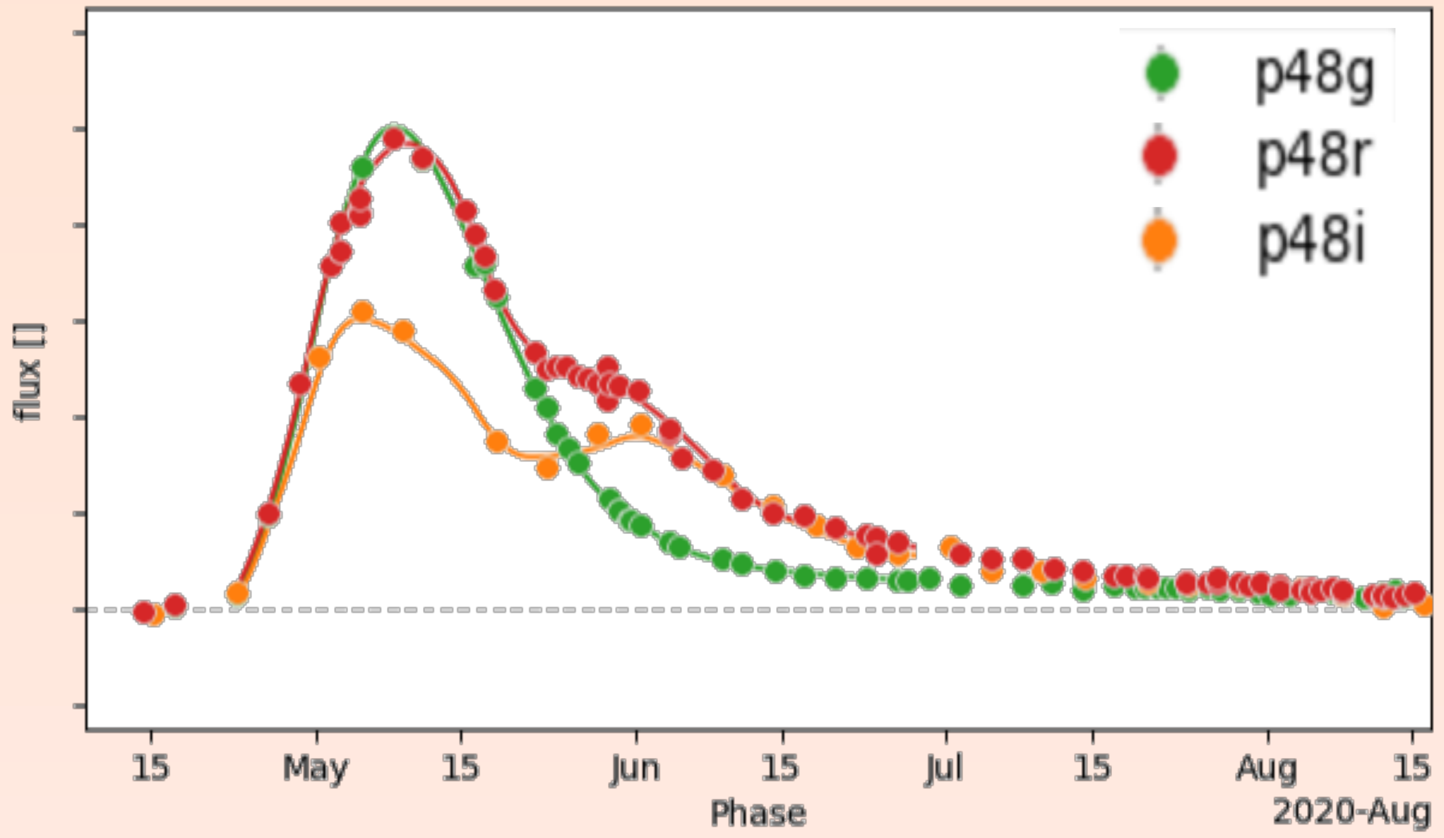
Luminosity ~constant

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

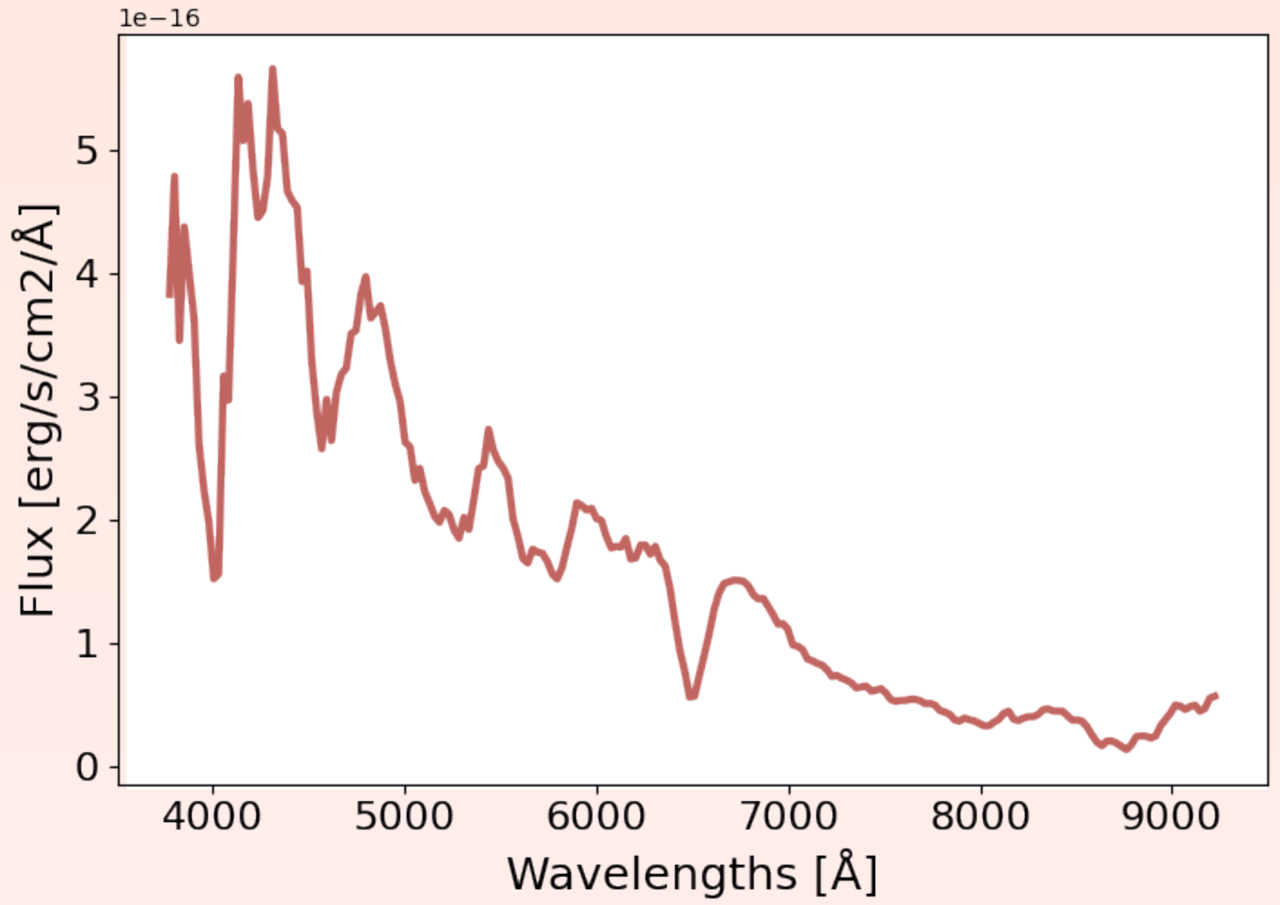
Distance modulus

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

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



Lighcurves of ZTF20abxzrqw



Spectra of ZTF20abeqsrm
at phase -5.73

Type Ia supernovae

SN 1994D in galaxy NGC 4526
Hubble Space Telescope

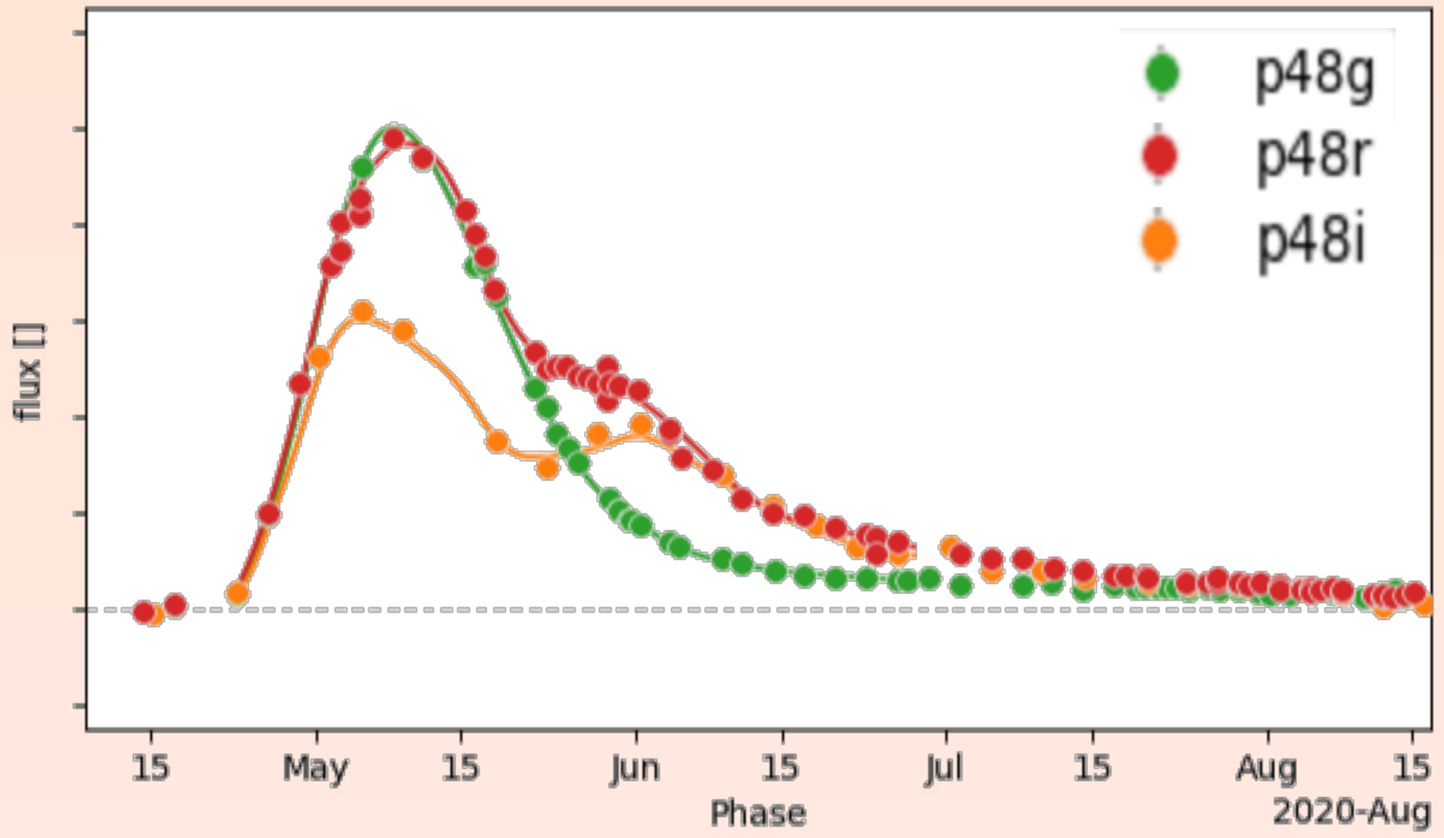
Luminosity ~constant

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

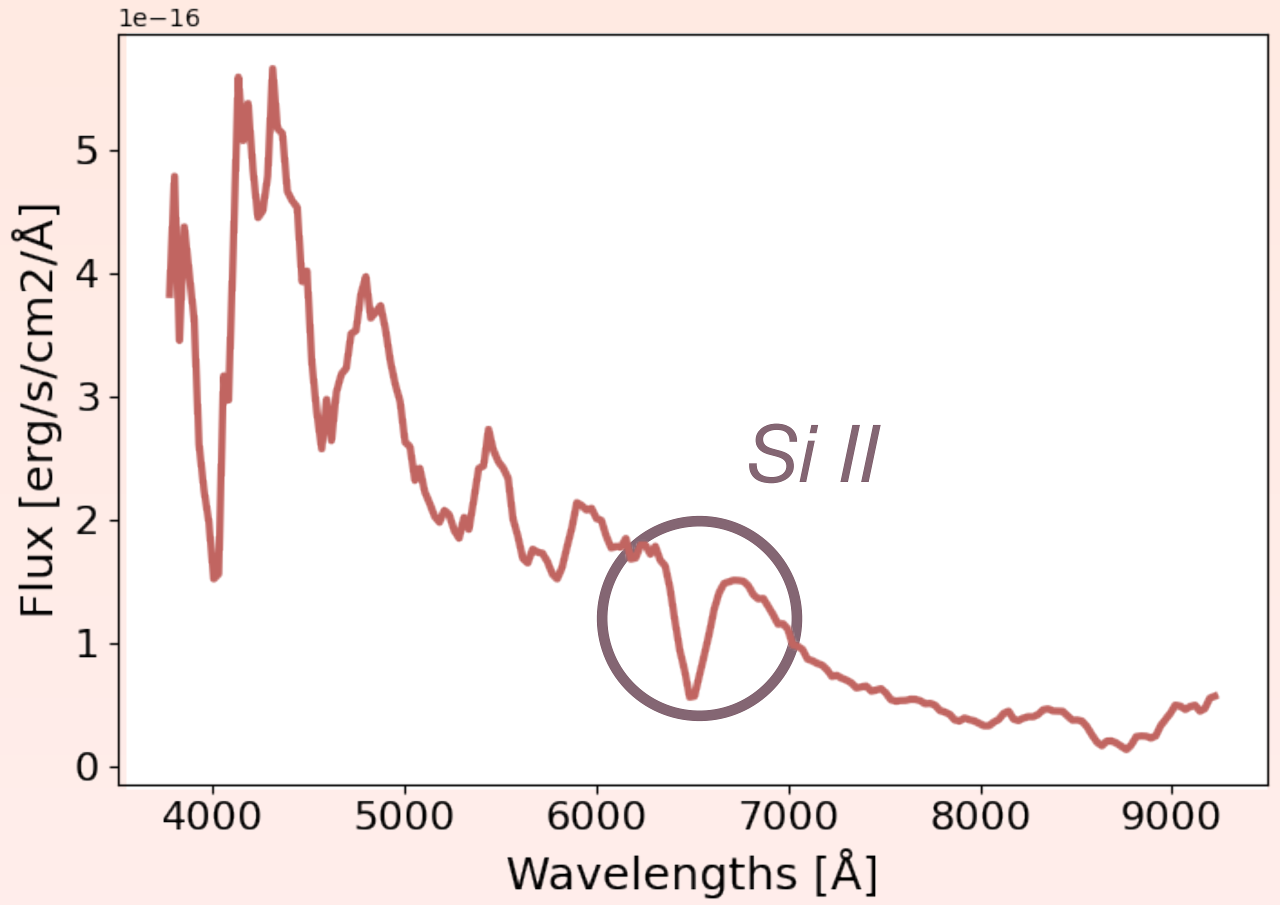
Distance modulus

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

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



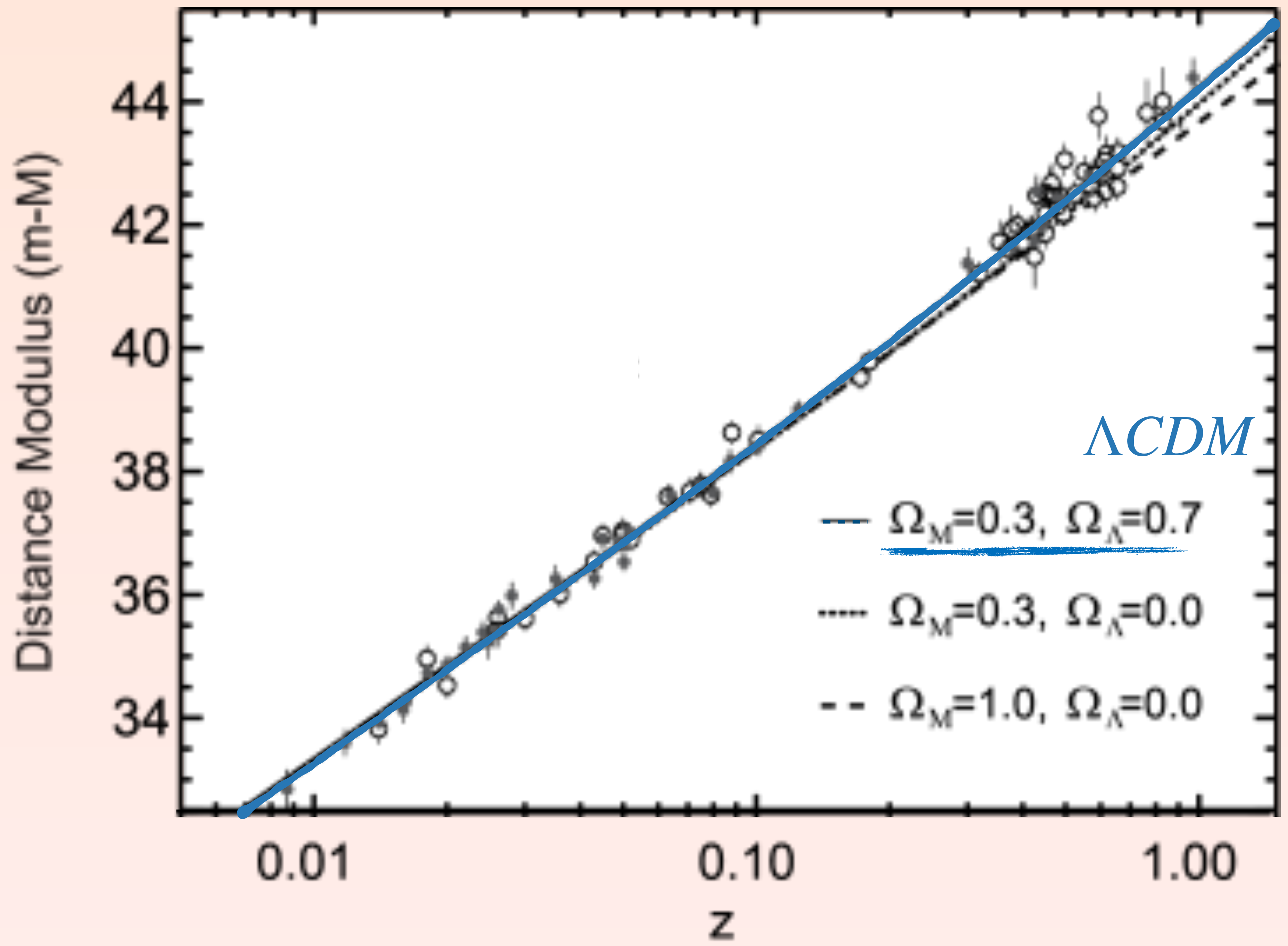
Lighcurves of ZTF20abxzrqw



Spectra of ZTF20abeqsrm at phase -5.73

Goals | *Cosmology*

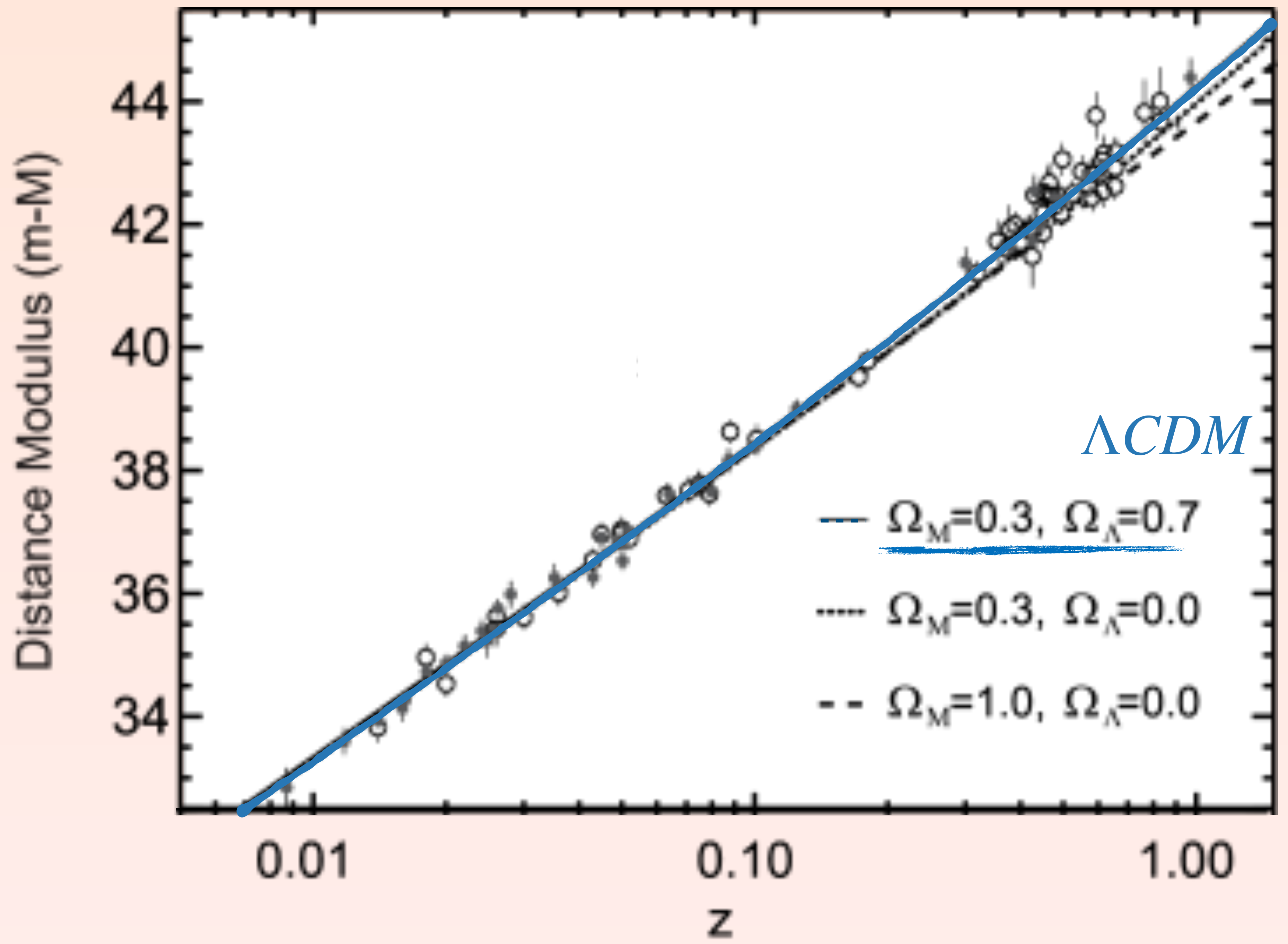
Distance modulus can be measured on lightcurves
Redshift can be measured on spectrum



Hubble Diagram - Frieman 2008

Goals | *Cosmology*

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



Hubble Diagram - Frieman 2008

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

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

Equation of $wCDM$ model

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

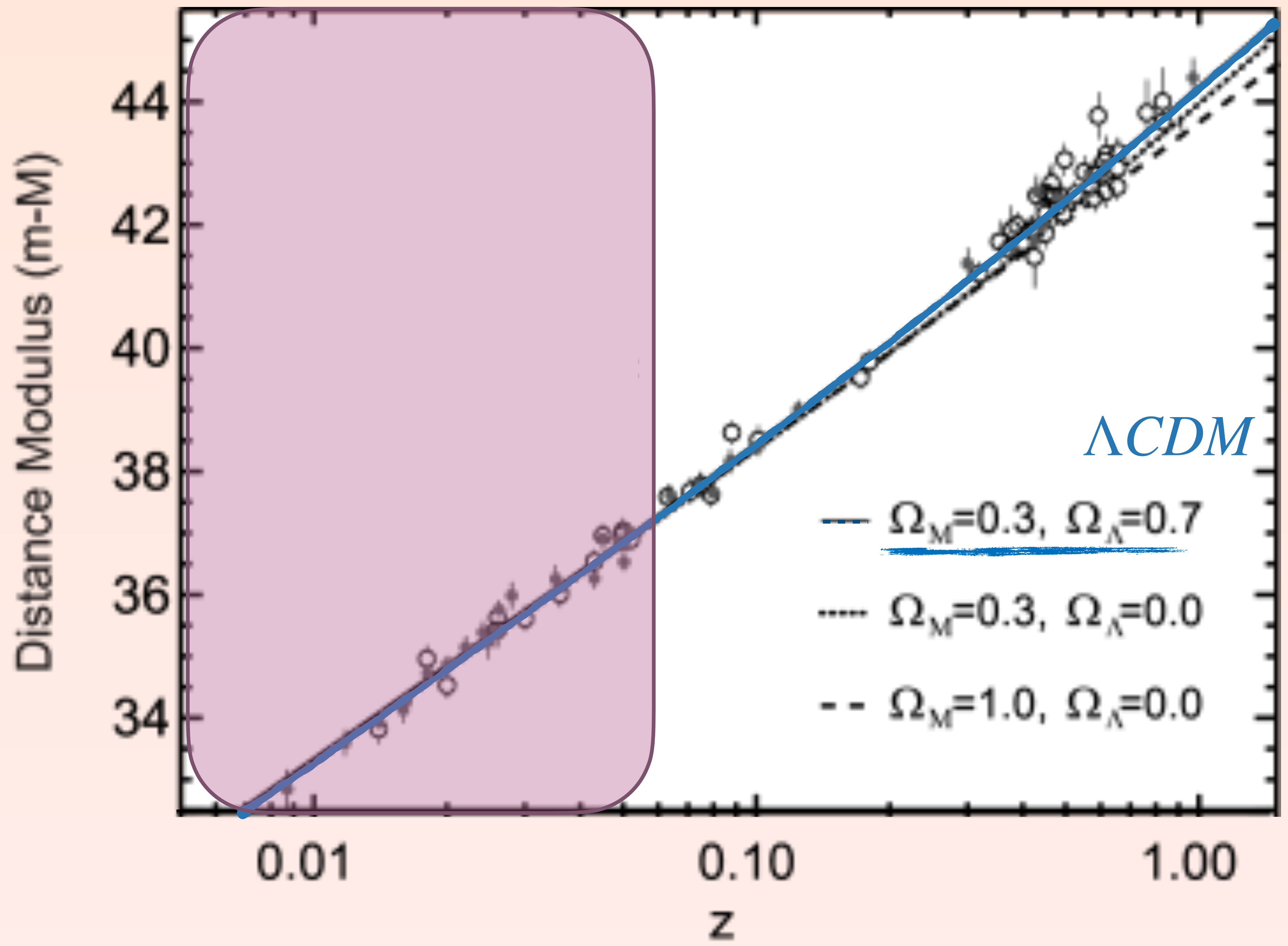
Lastest Combined result

DESI+CMB+Panth.

H_0	67.74 ± 0.71 km s⁻¹ Mpc⁻¹
Ω_M	0.3095 ± 0.0069
w	−0.997 ± 0.025

Goals | *Cosmology*

Low-redshift (z<0.15)
Constrains H_0



Hubble Diagram - Frieman 2008

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

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

Equation of $wCDM$ model

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

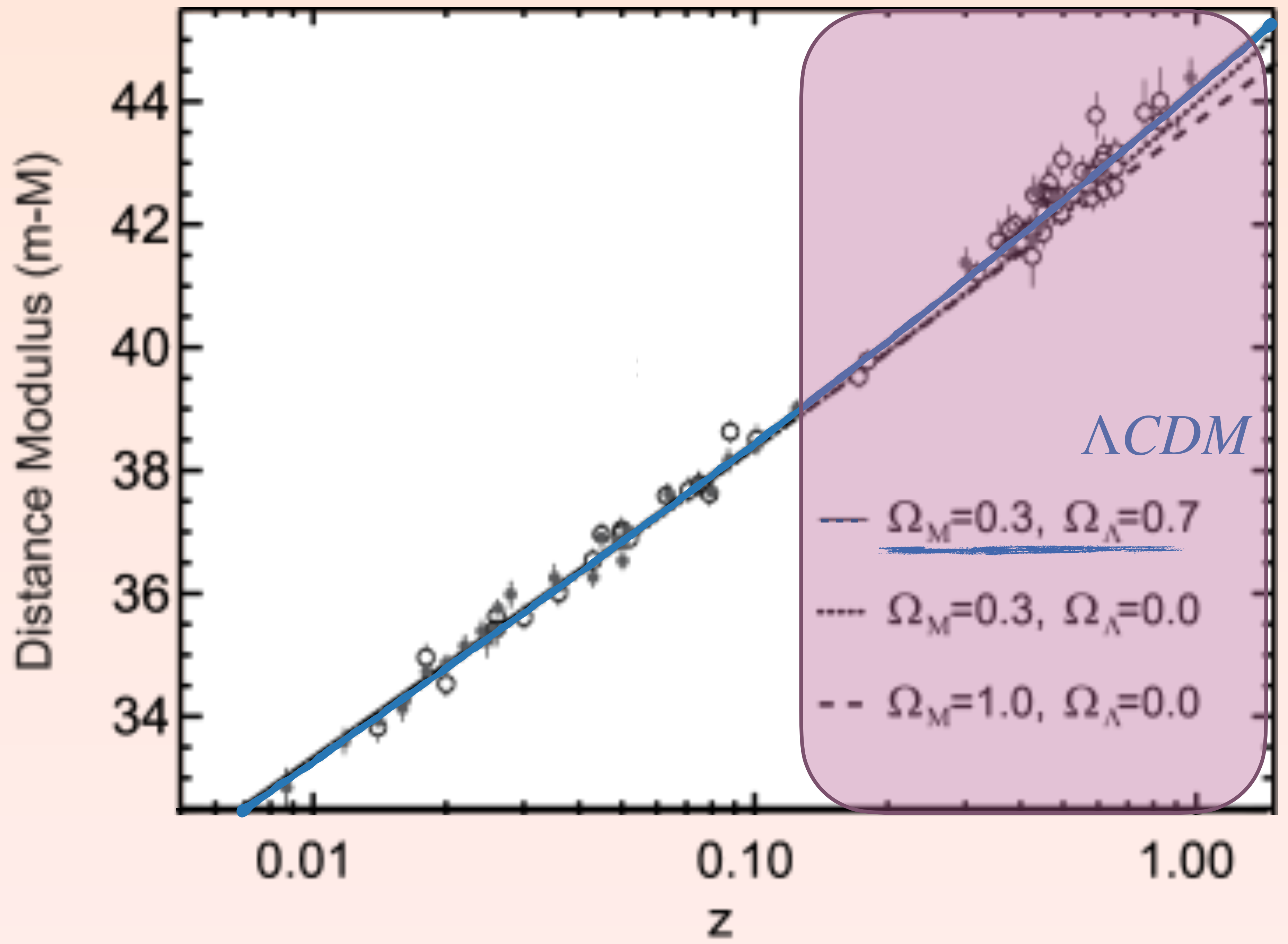
Lastest Combined result

DESI+CMB+Panth.

H_0	67.74 ± 0.71 km s⁻¹ Mpc⁻¹
Ω_M	0.3095 ± 0.0069
w	–0.997 ± 0.025

Goals | *Cosmology*

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



Hubble Diagram - Frieman 2008

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

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

Equation of $wCDM$ **model**

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

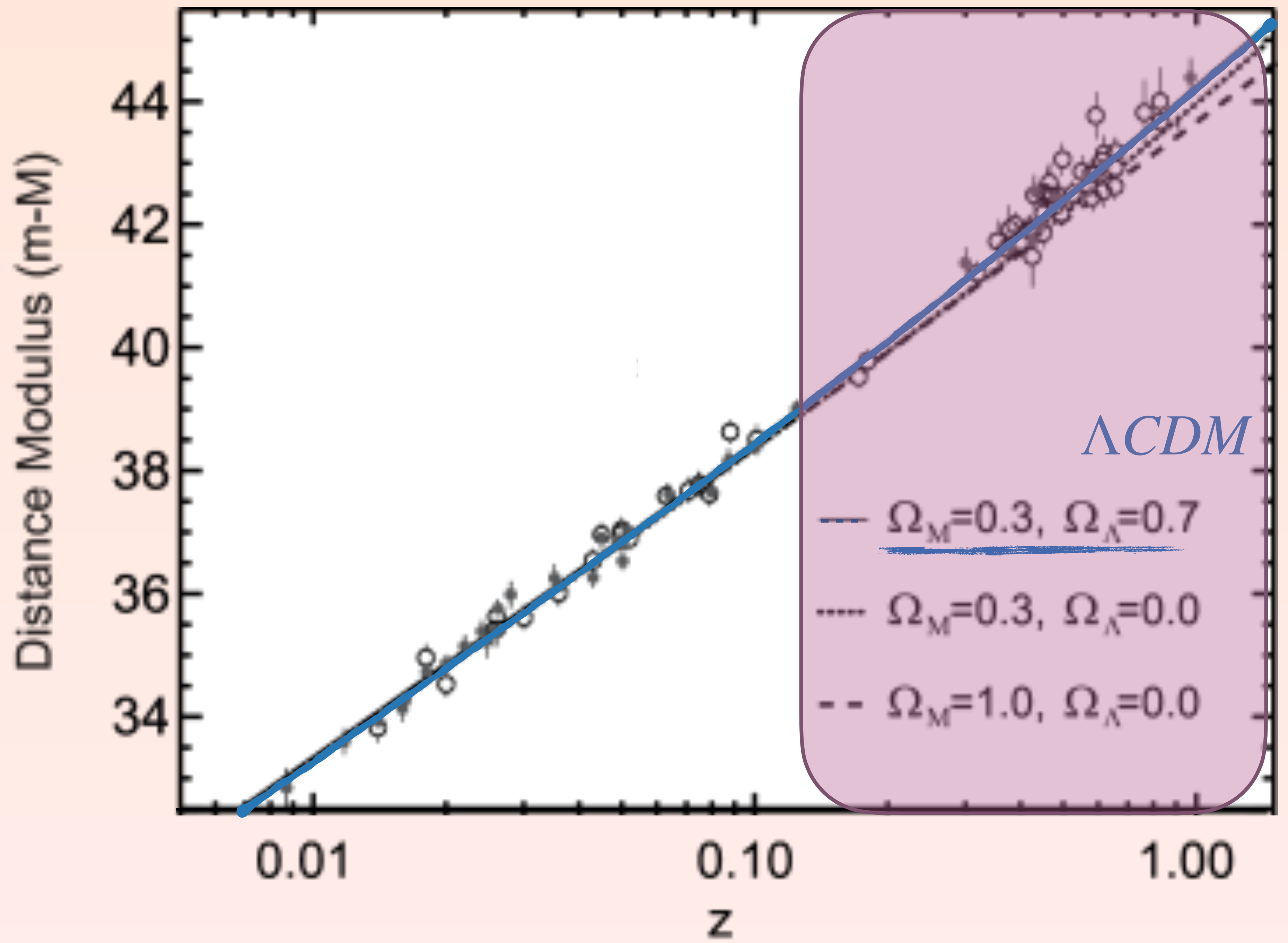
Lastest Combined result

DESI+CMB+Panth.

H_0	67.74 ± 0.71 km s⁻¹ Mpc⁻¹
Ω_M	0.3095 ± 0.0069
w	−0.997 ± 0.025

Goals | *Cosmology*

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



Hubble Diagram - Frieman 2008

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

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

Equation of $wCDM$ model

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

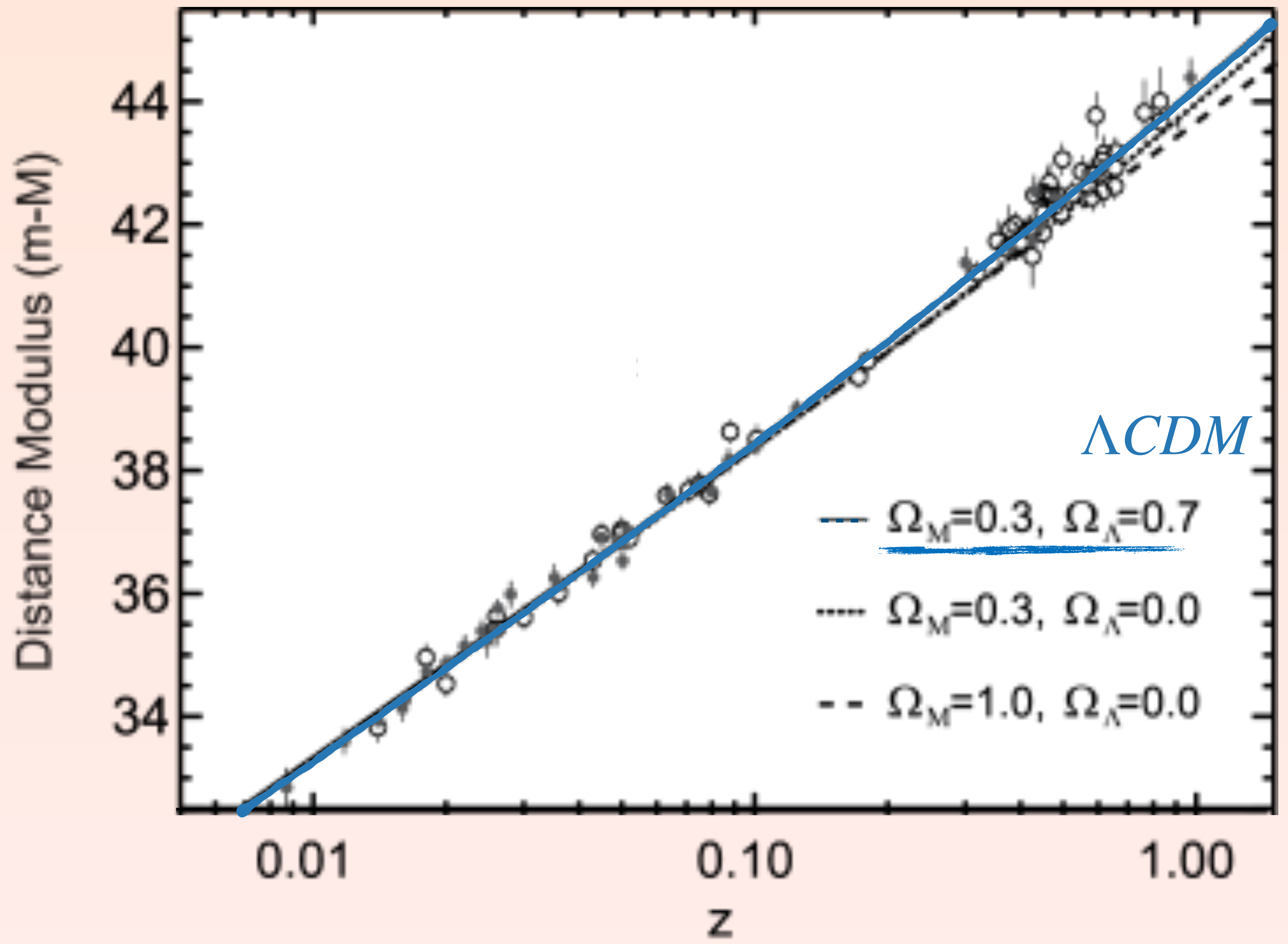
Lastest Combined result

DESI+CMB+Panth.

H_0	67.74 ± 0.71 km s⁻¹ Mpc⁻¹
Ω_M	0.3095 ± 0.0069
w	−0.997 ± 0.025

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*

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

Equation of $wCDM$ model

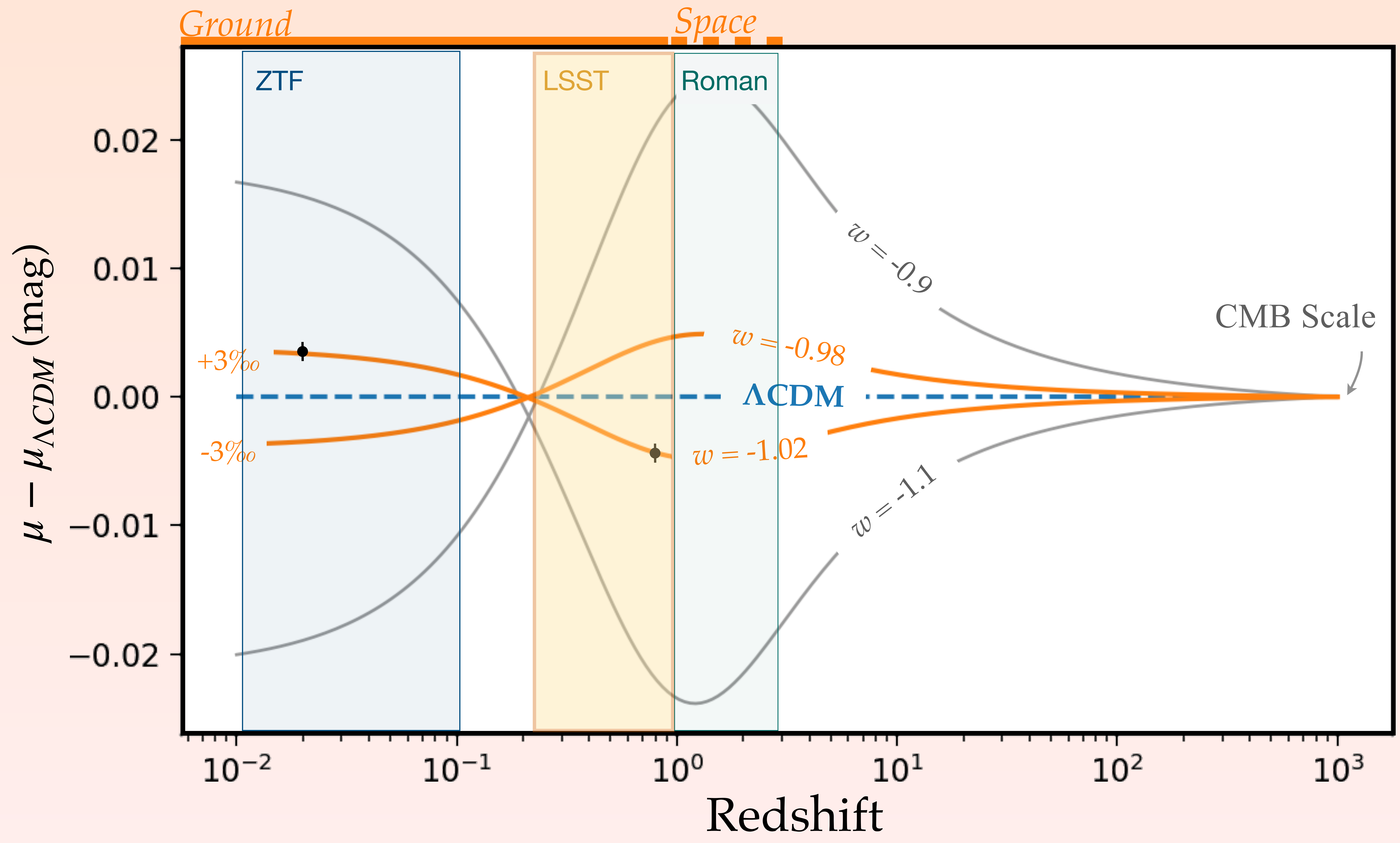
- Flat Universe
- $\Omega_M + \Omega_\Lambda = 1$

Lastest Combined result

DESI+CMB+Panth.

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

Goals | *Dark Energy*



Precision required (Systematics)

Calibration :

δmag = 0.001

Astrophysical bias:

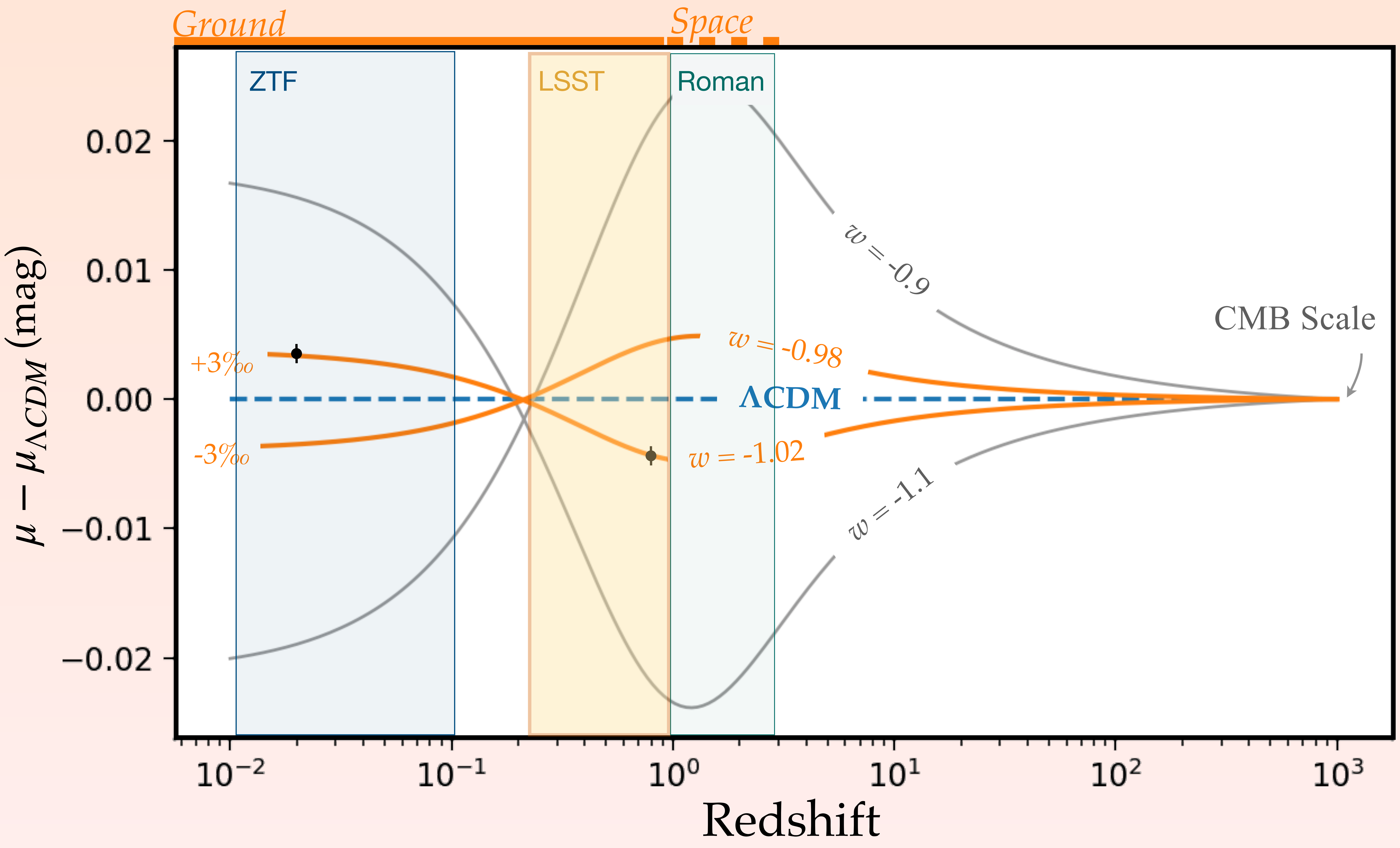
δmag = 0.001

Dispersion (Statistics)

SNe Ia dispersion :

$\sigma_{mag} = 0.40$

Goals | *Dark Energy*



Precision required (Systematics)

Calibration :

δmag = 0.001

Astrophysical bias:

δmag = 0.001

Dispersion (Statistics)

SNe Ia dispersion :

$\sigma_{mag} = 0.40$

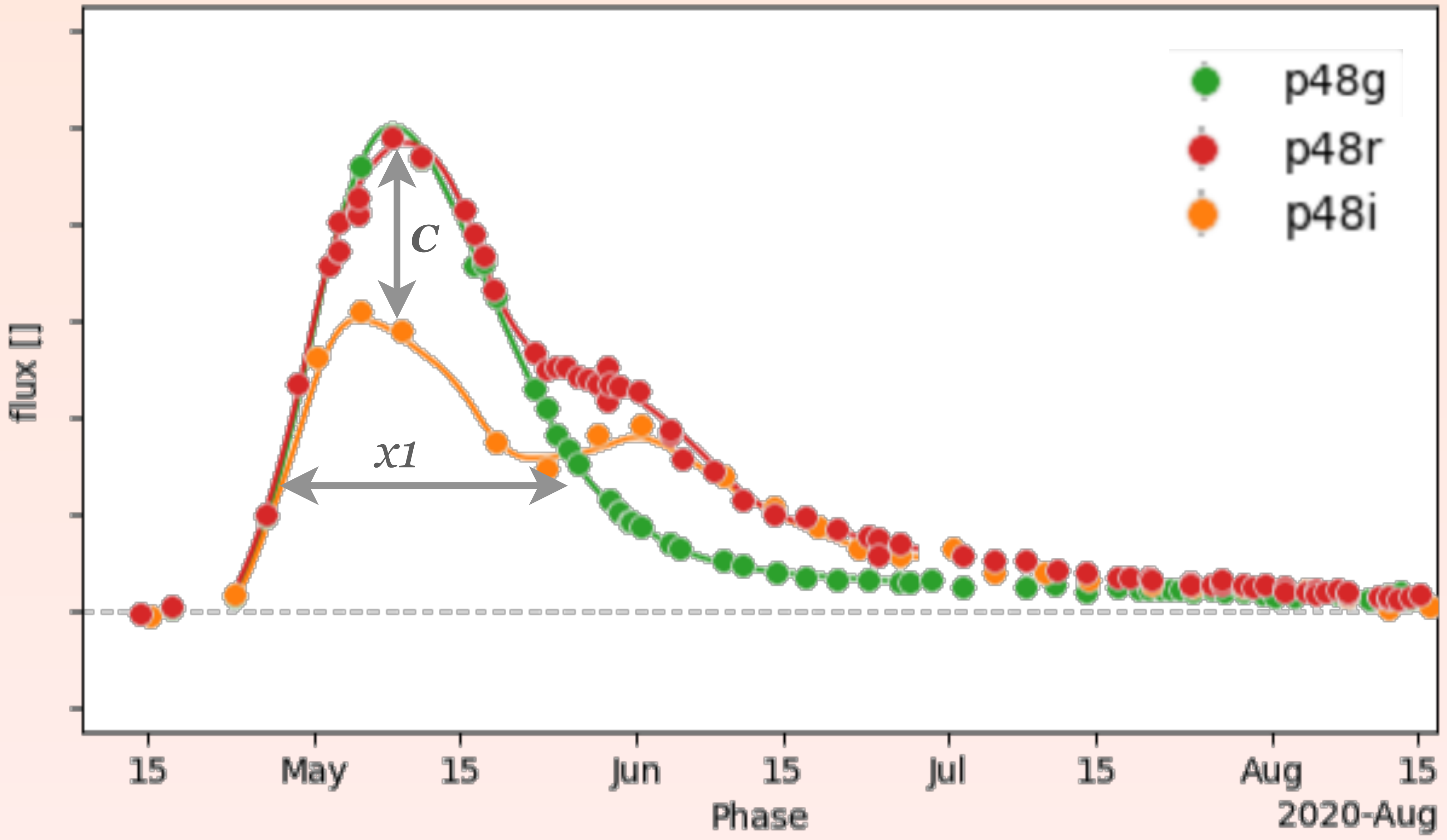
SNe Ia are not standard candles !

Photometric standardisation

Tripp relation (1998) :

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

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



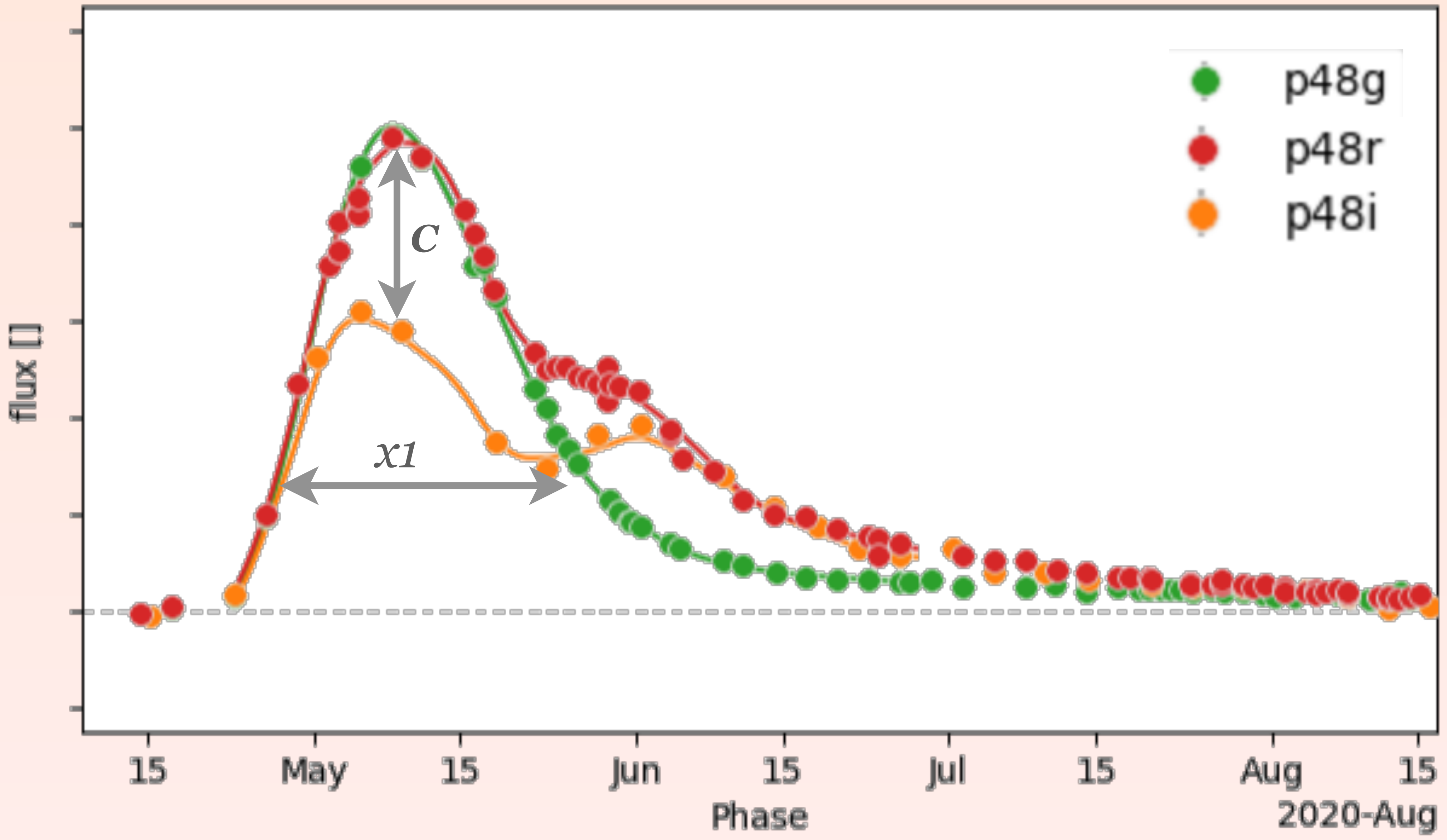
Lightcurves of ZTF20abxzrqw

Photometric standardisation

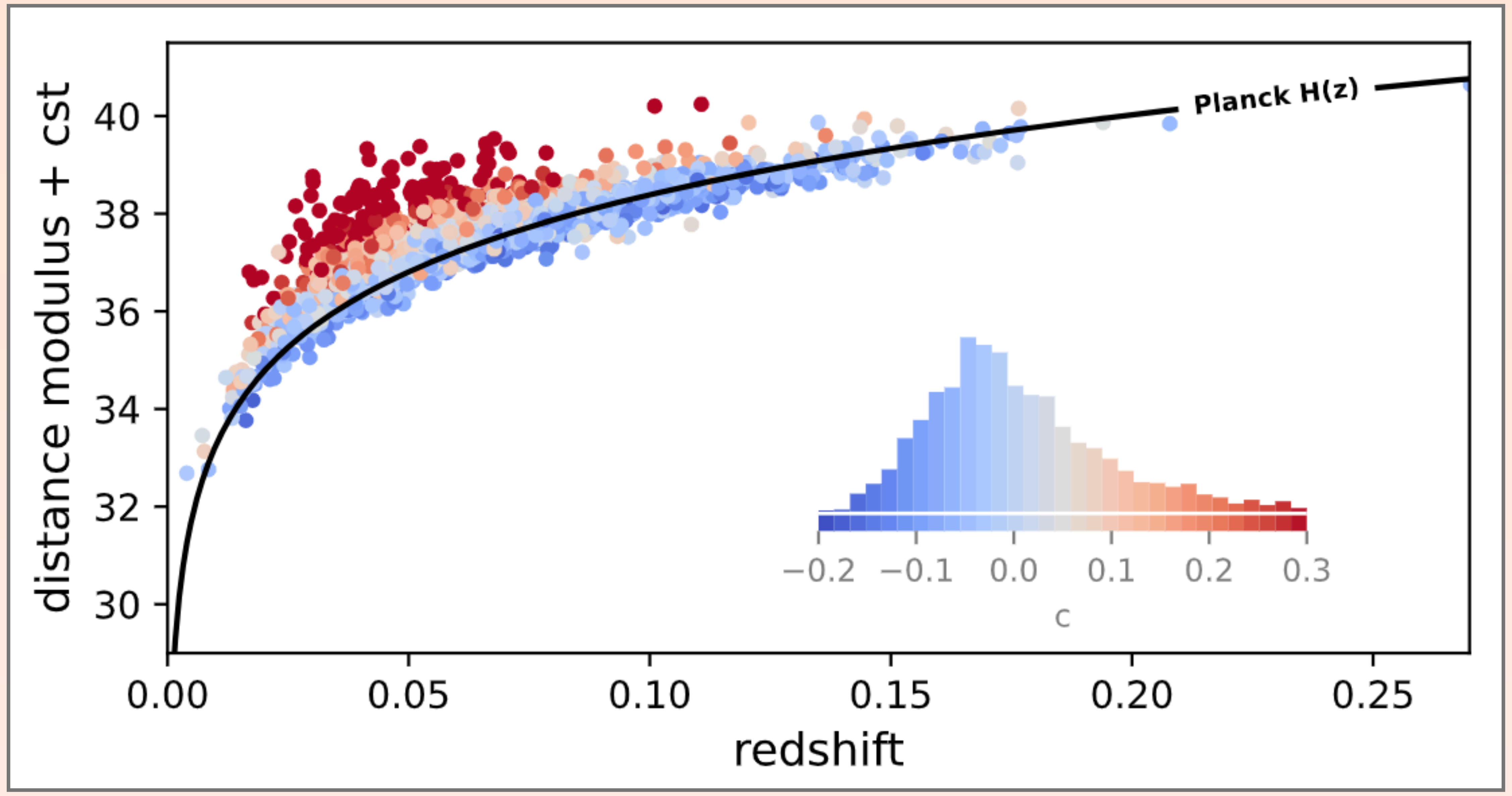
Tripp relation (1998) :

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

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



Lightcurves of ZTF20abxzrqw



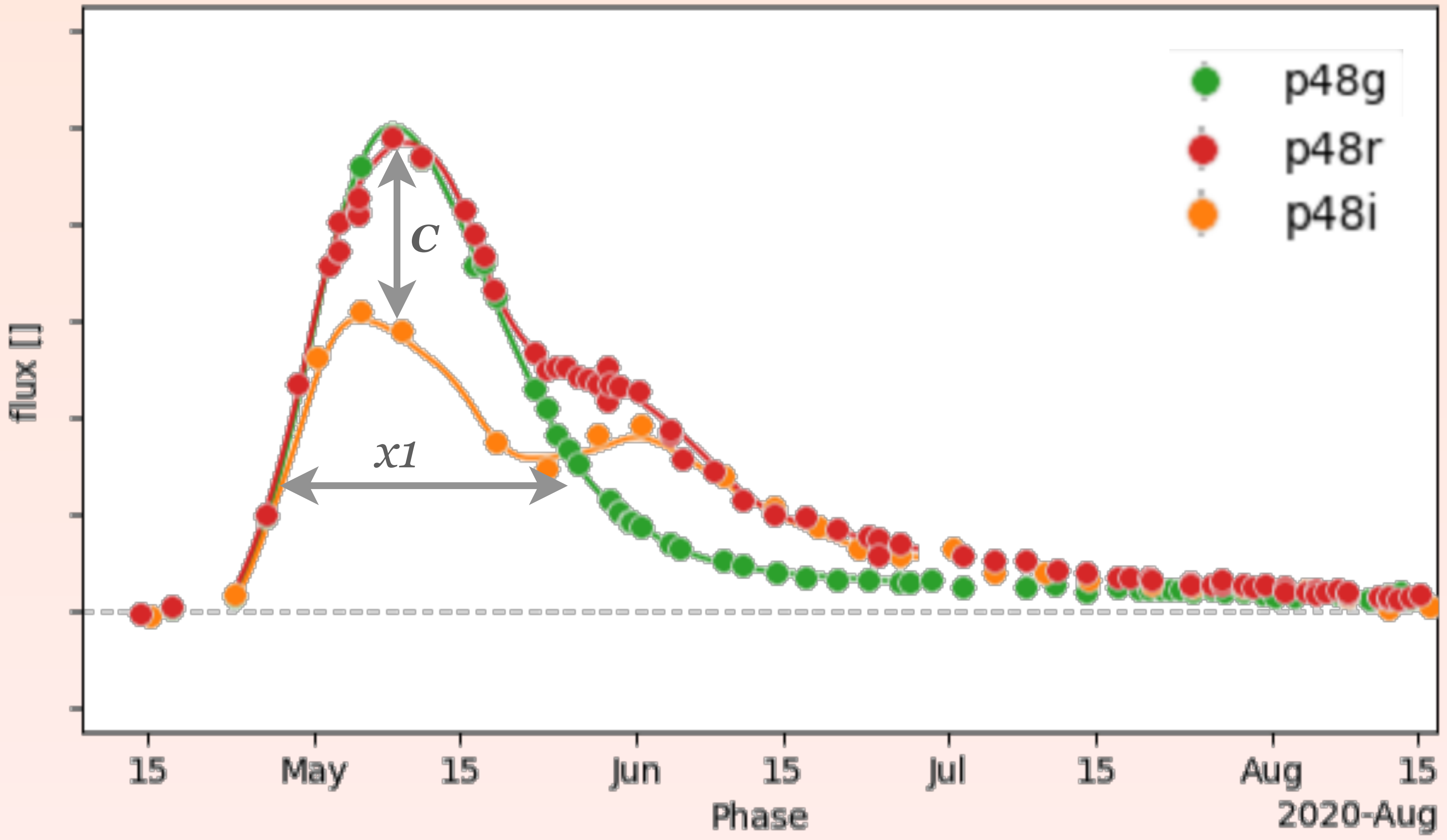
Hubble Diagram photometric standardisation
Credit : in prep. ZTF "DR2" Data paper, Smith et al.

Photometric standardisation

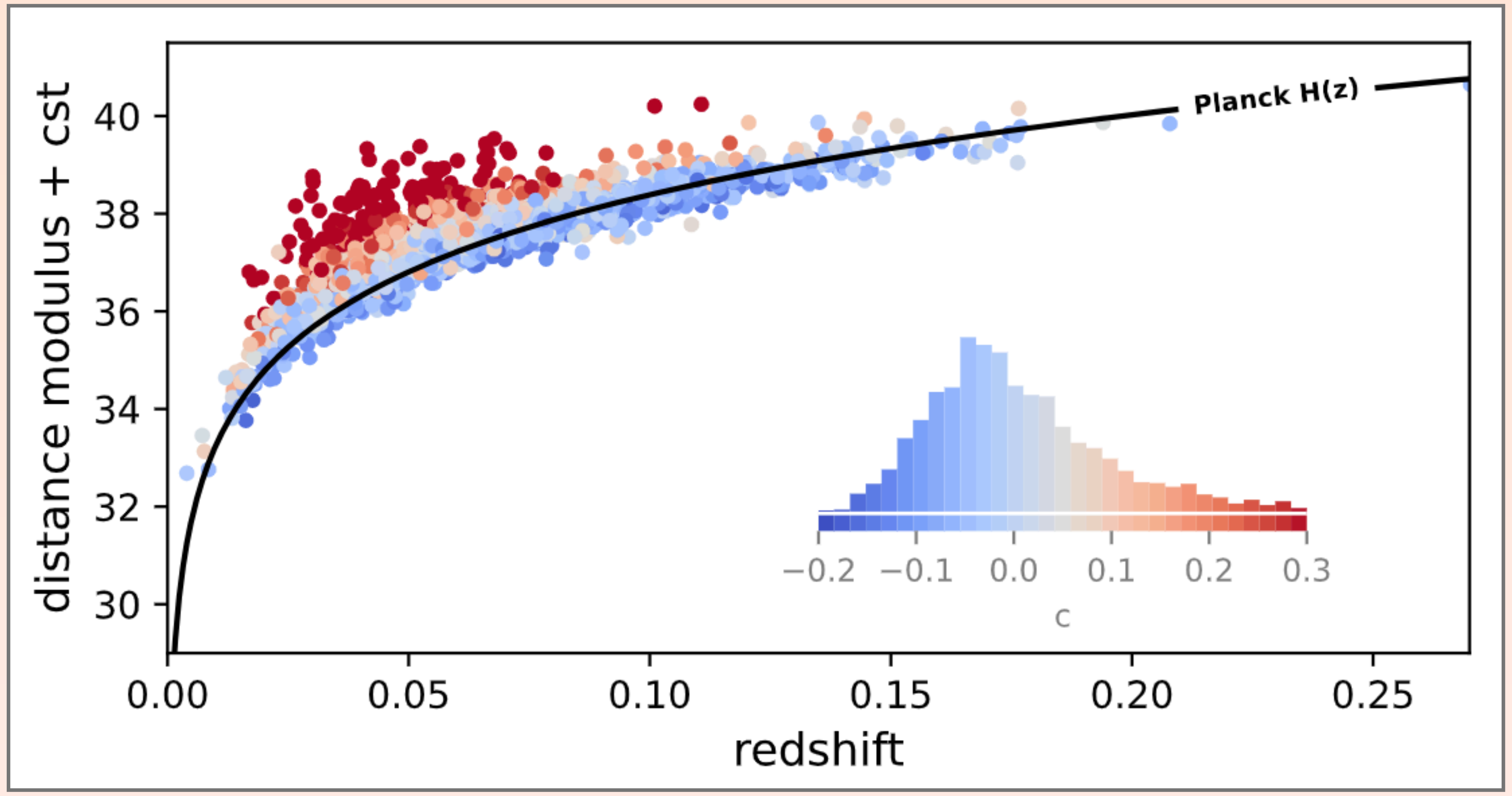
Tripp relation (1998) :

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

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



Lightcurves of ZTF20abxzrqw



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

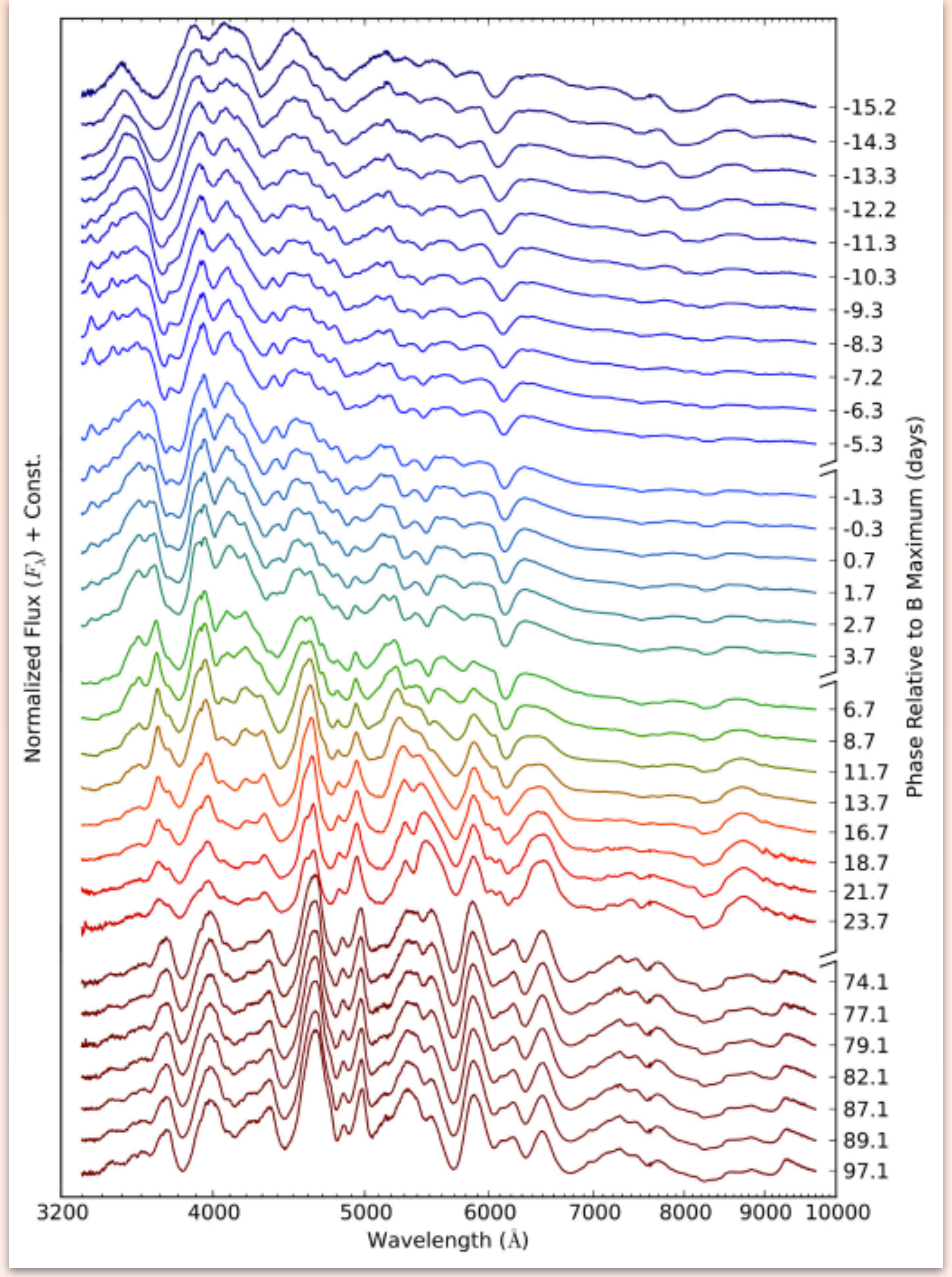
SNe Ia dispersion :

σ_{mag} = ~~0.40~~ $= 0.15$

with Photometric standardisation

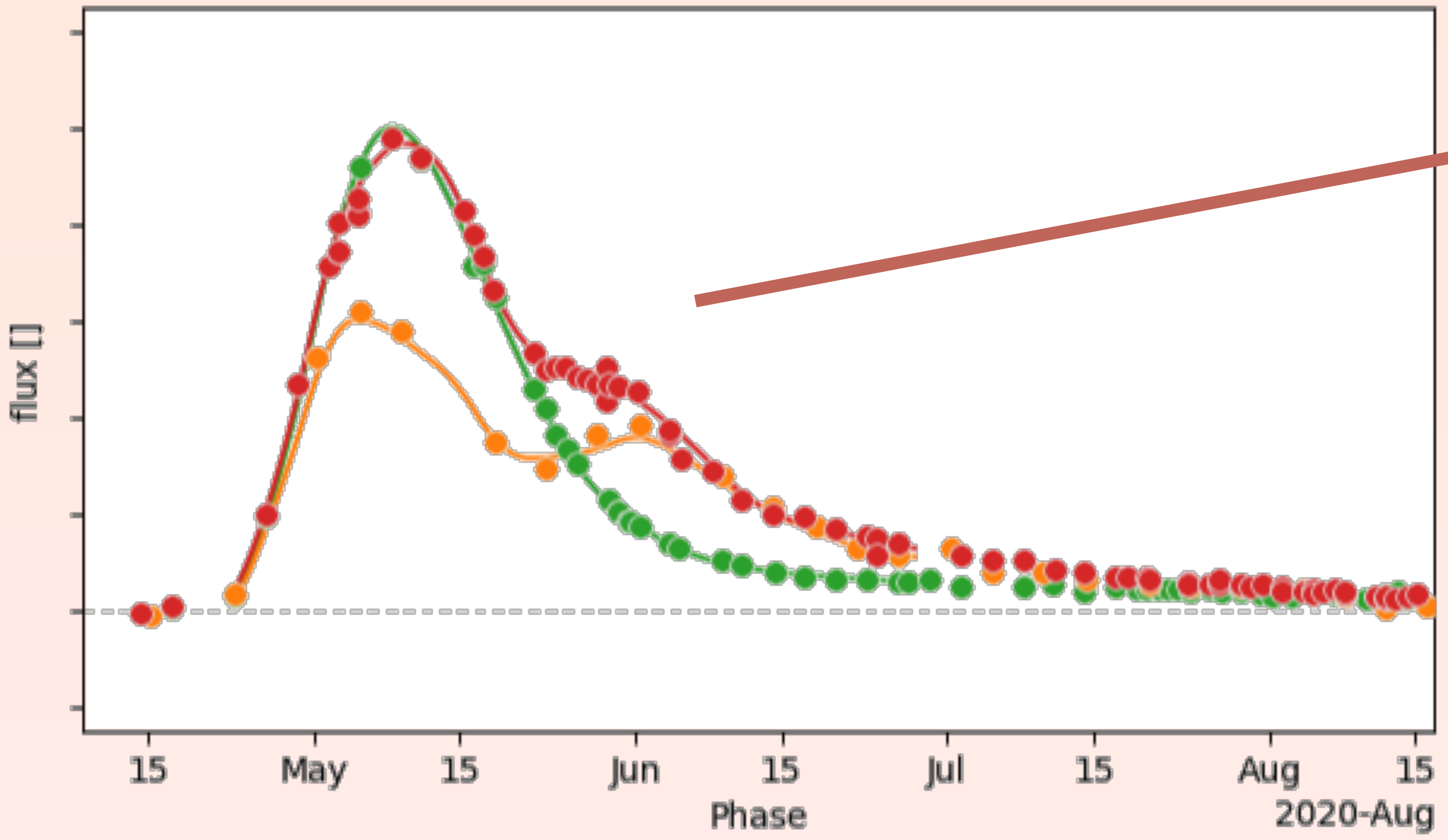
***Problem :** The origin of the dispersion of 0.15 mag is unknown*

Spectro-photometry

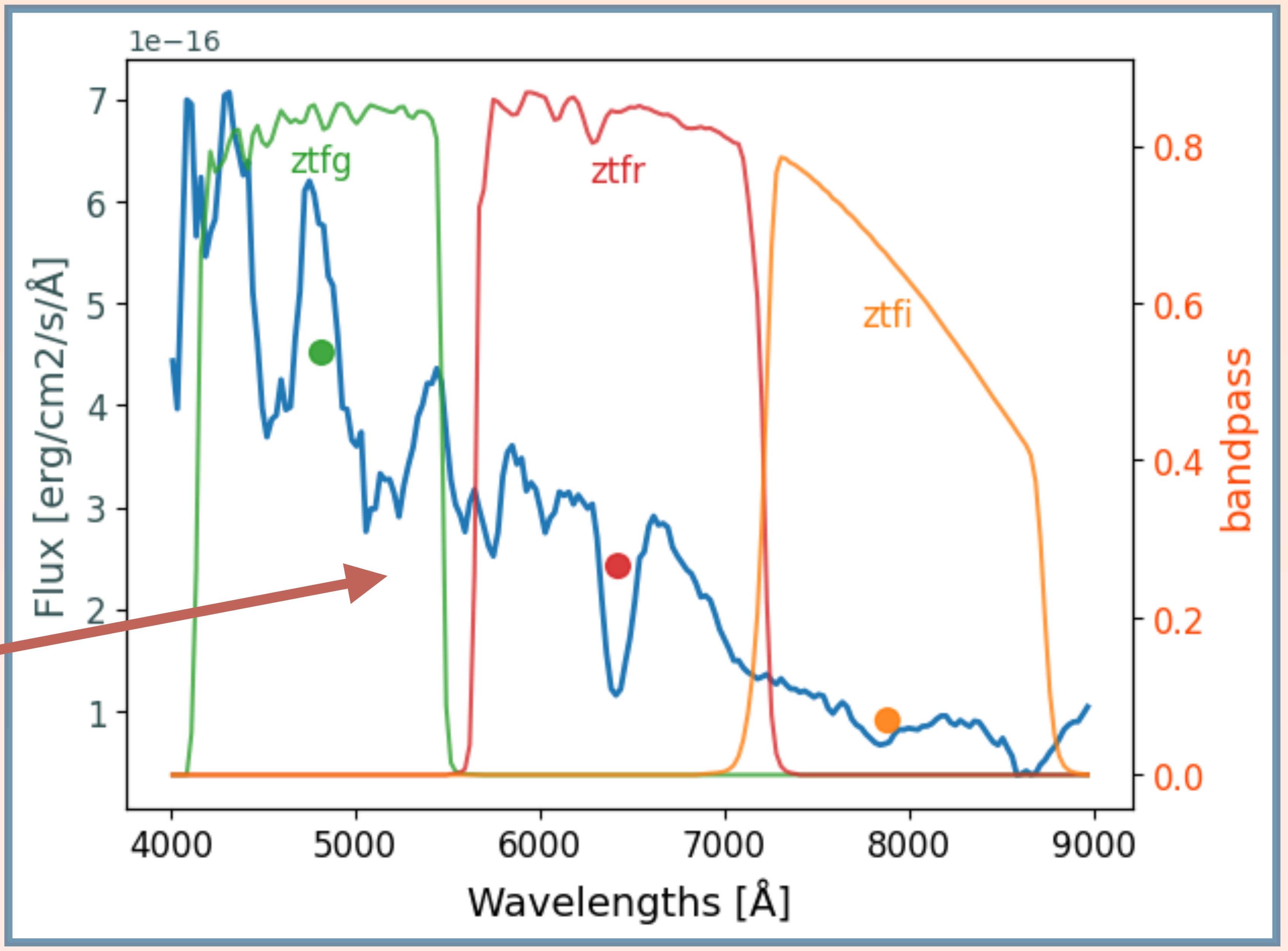


Time series of SN2011fe
between **-15** to **+100** days
Credit: Pereira et al. 2013

A lightcurve datapoint corresponds to the spectrum integrated in the bandpass



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



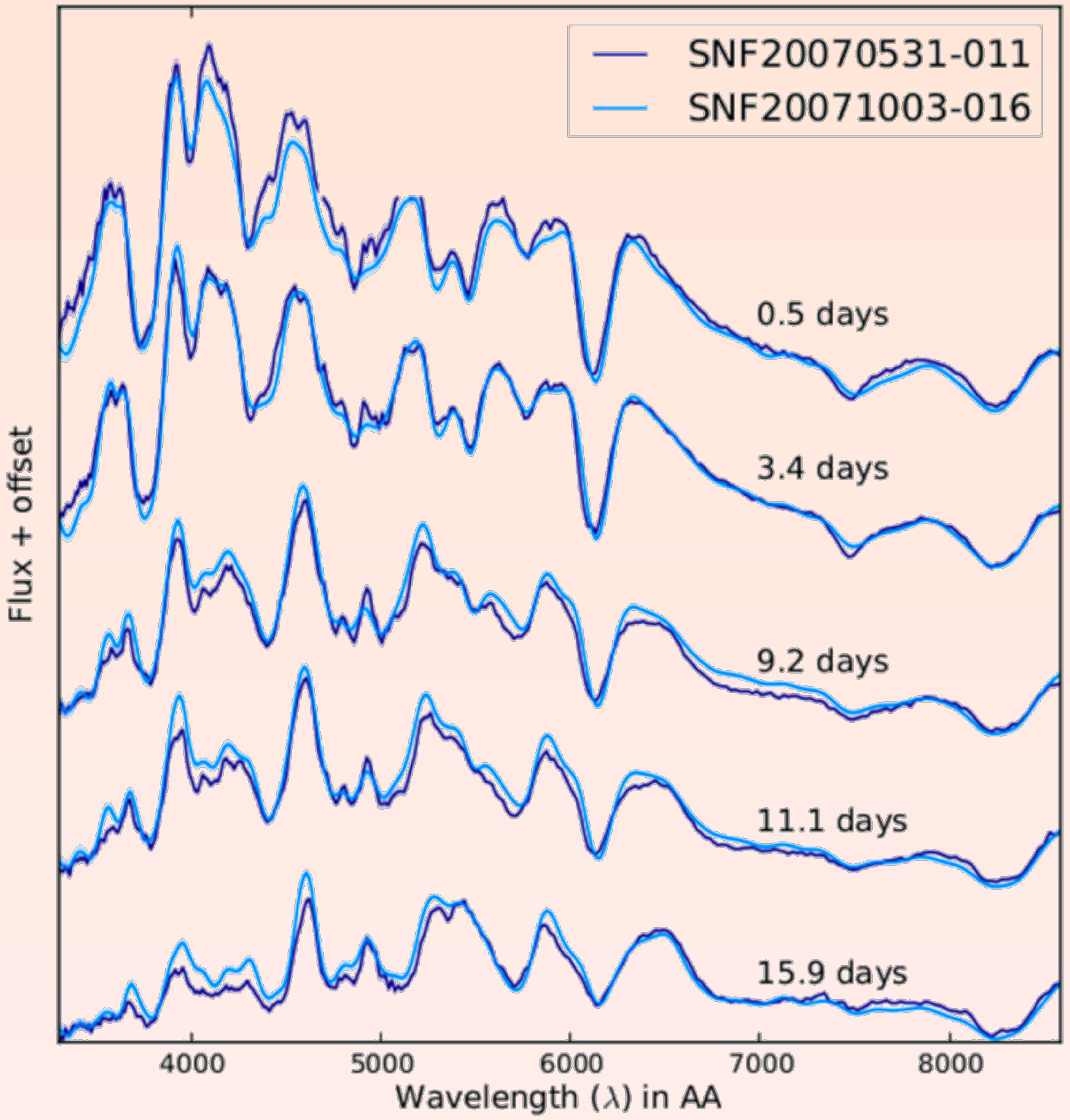
Synthetic photometry in ZTF filters
ZTF20abxzrqw at phase +1.29

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

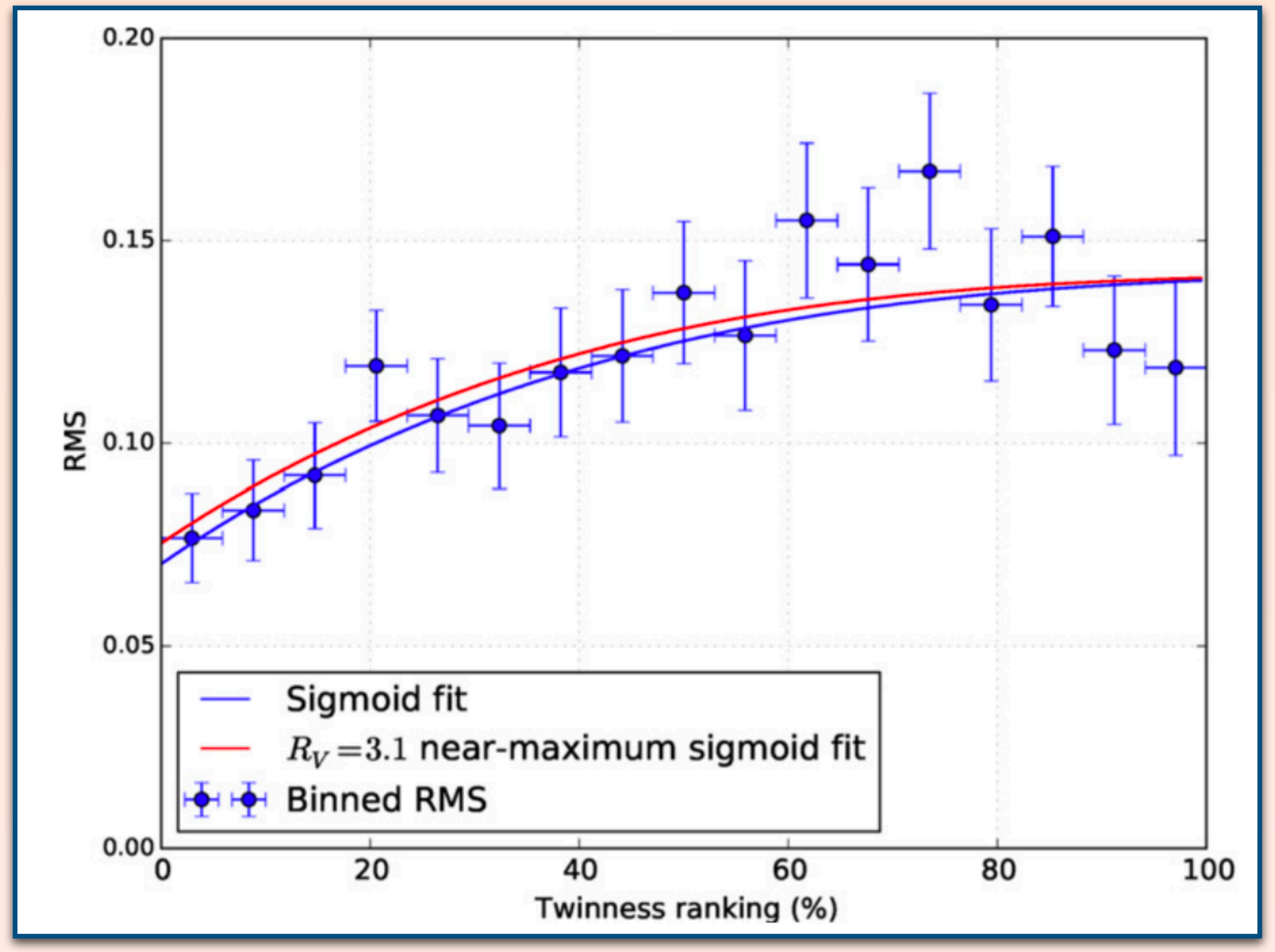
Spectro-photometric standardisation

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

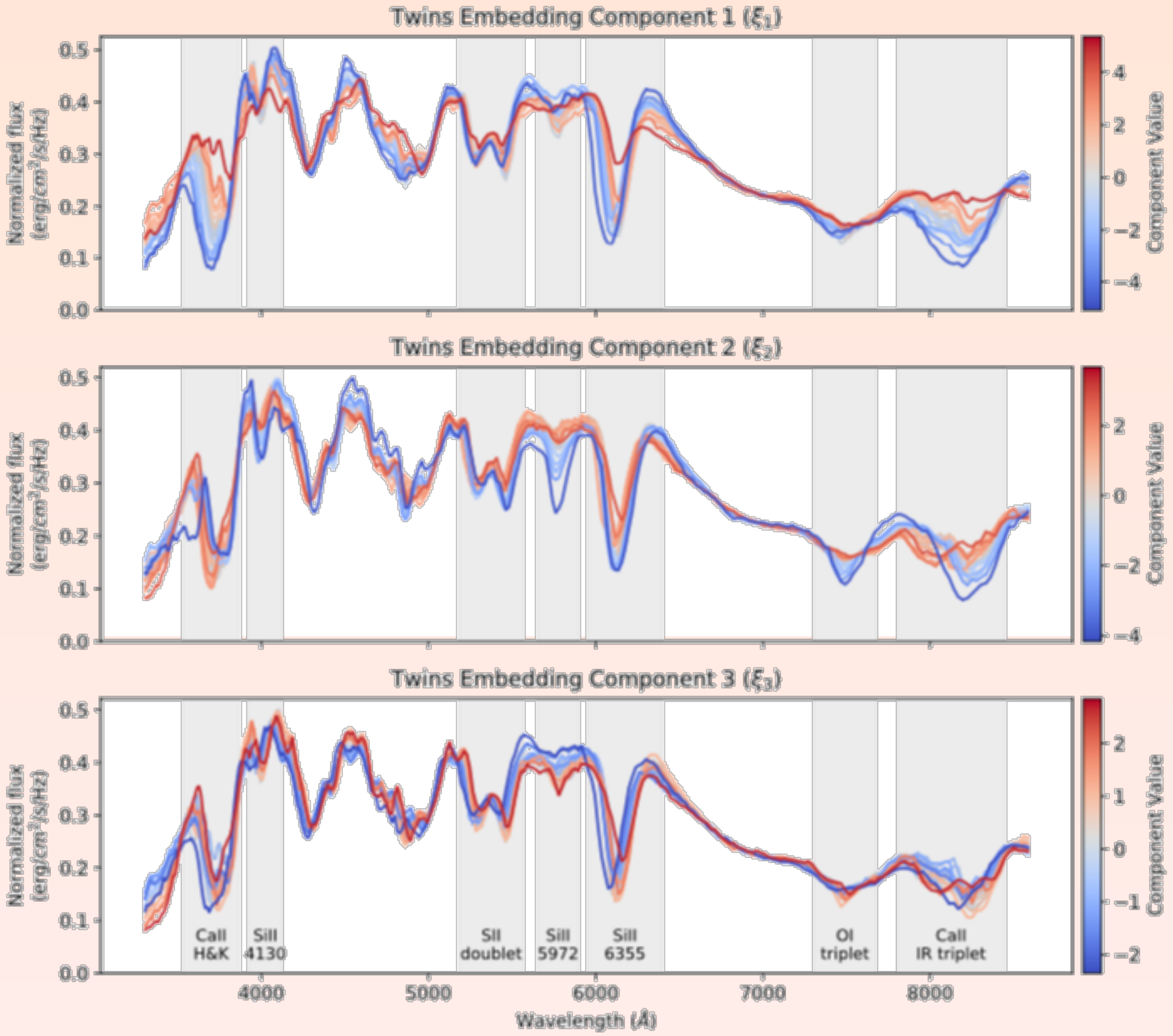
—> magnitude dispersion is smaller for the lowest 'twinness' parameters

—> 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)

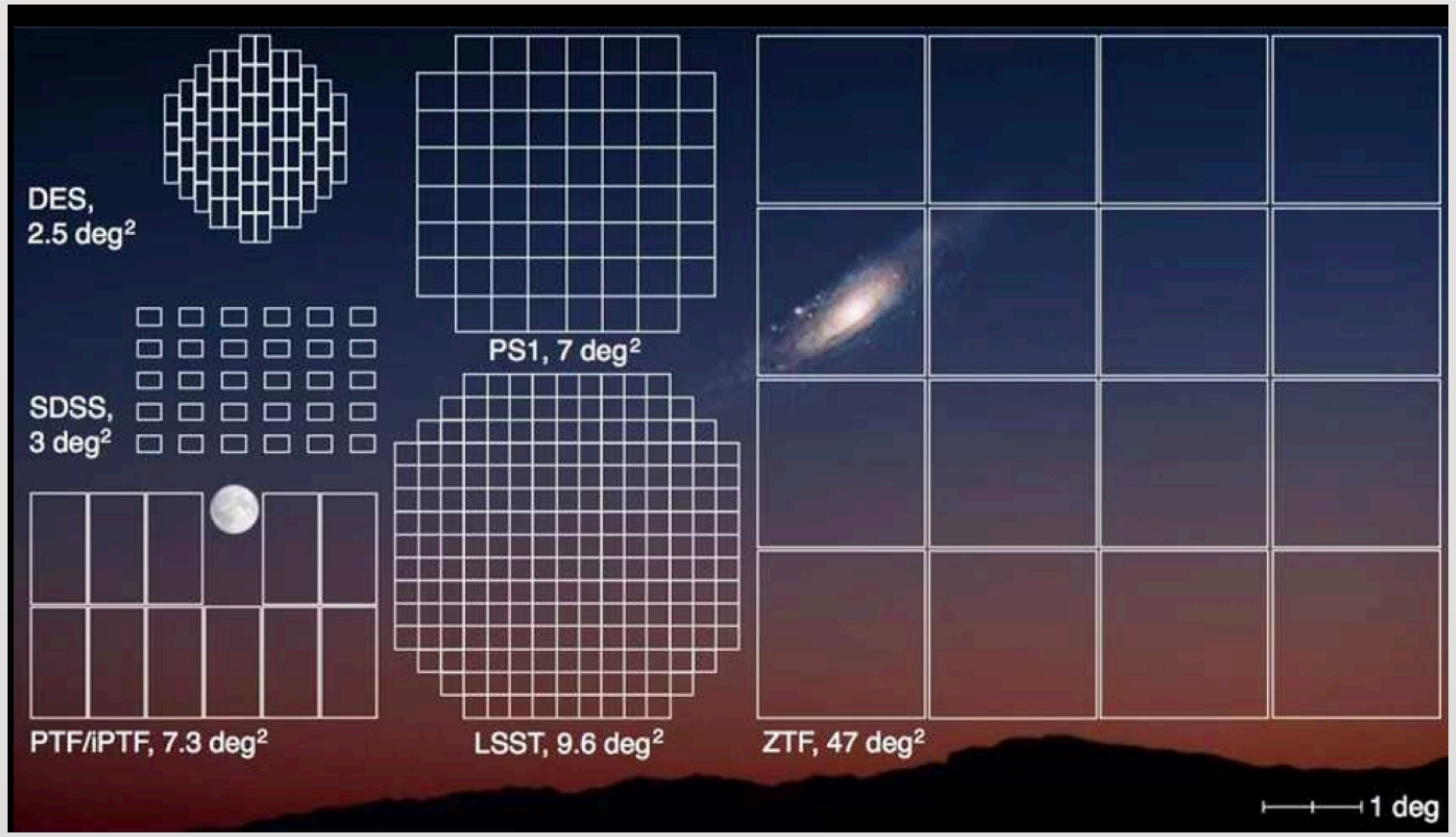
Zwicky Transient Facility

March 2018 to 2027

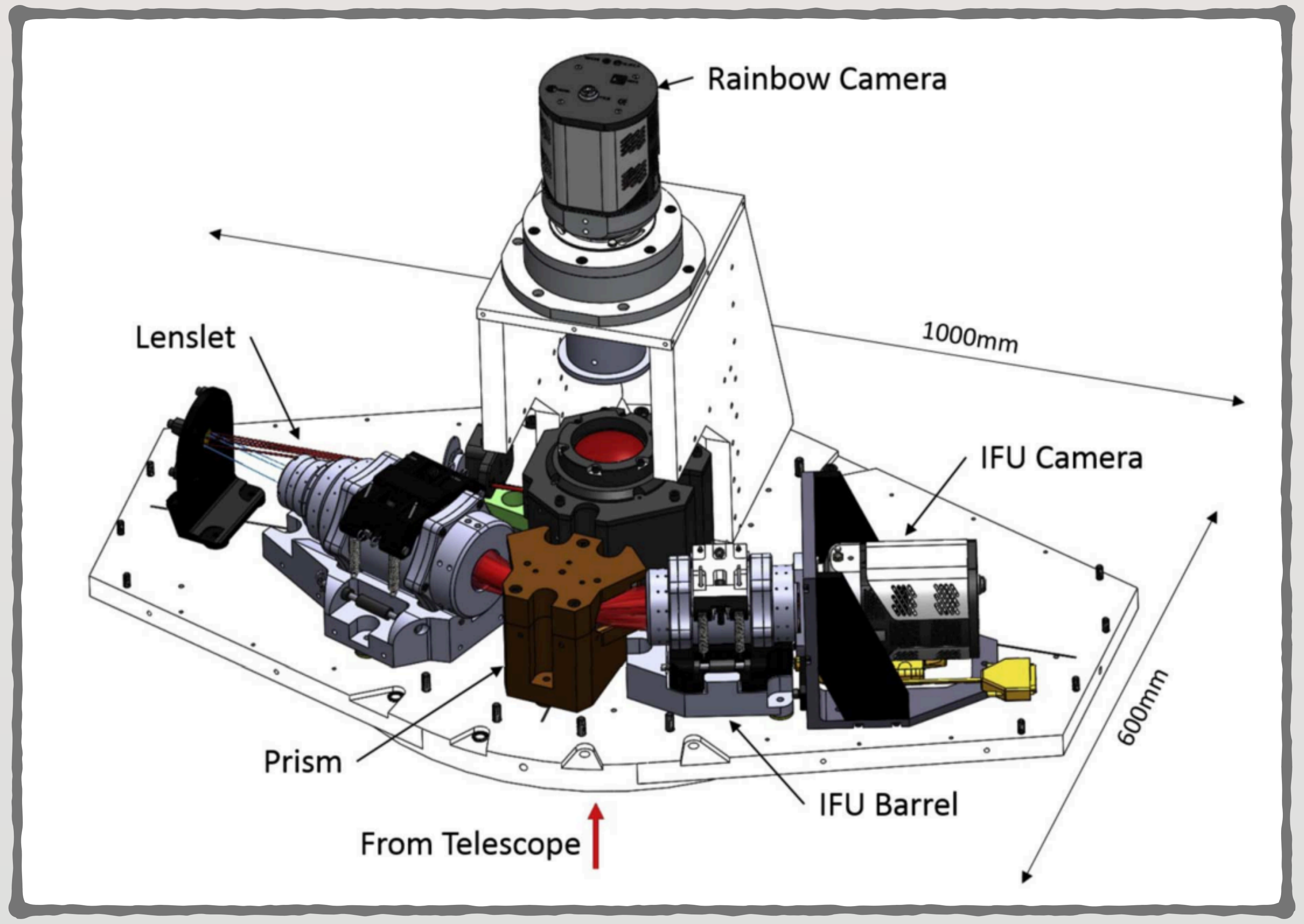
Low-redshift z<0.15
Northern sky
3 filters : g, r, i
Limits in magnitude of ~20mag

Two instruments :

- P48 camera
- P60 spectrograph



ZTF Camera P48 FoV
Source : Joel Johansson



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

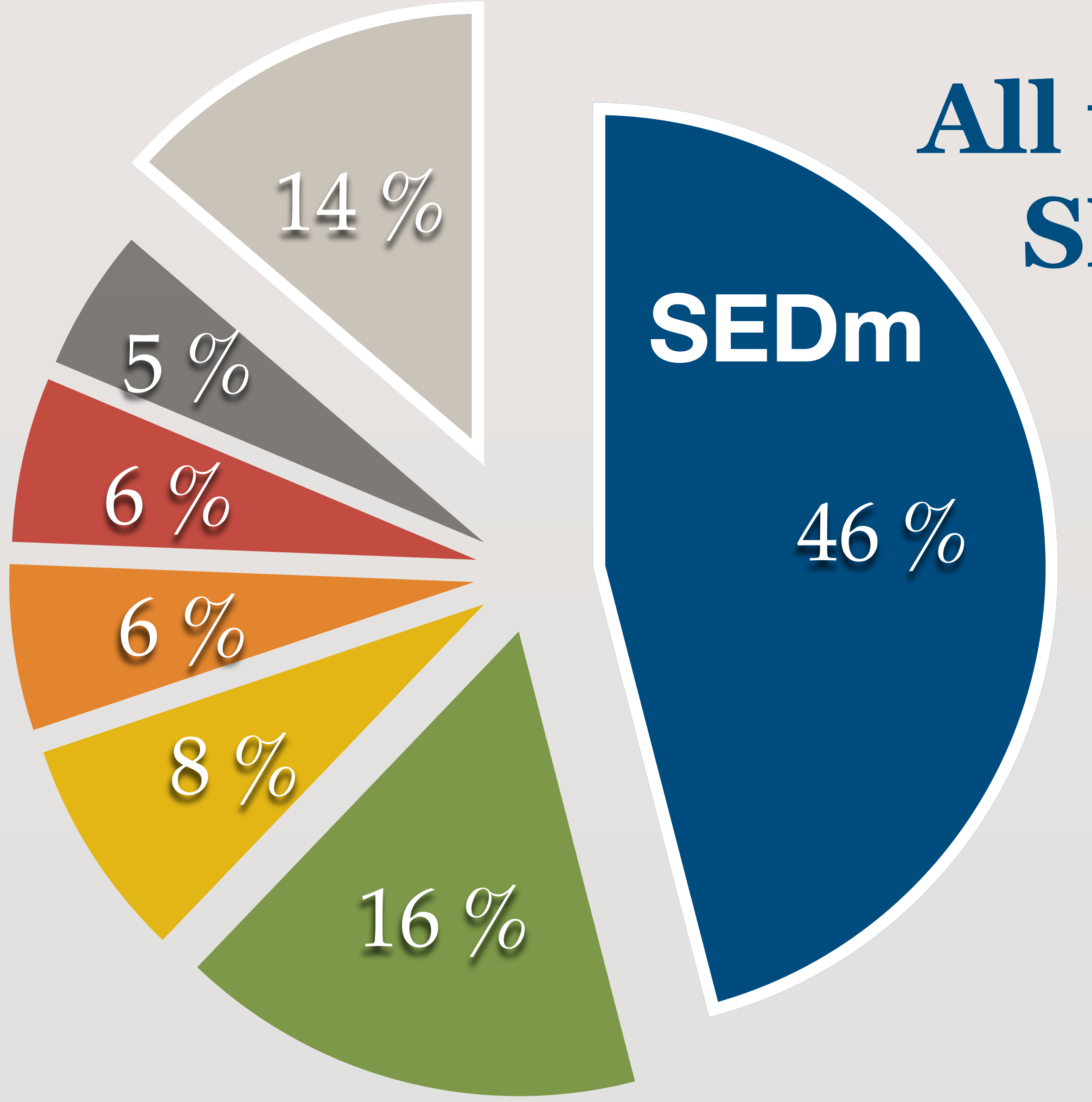
Located in Mount Palomar in California

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

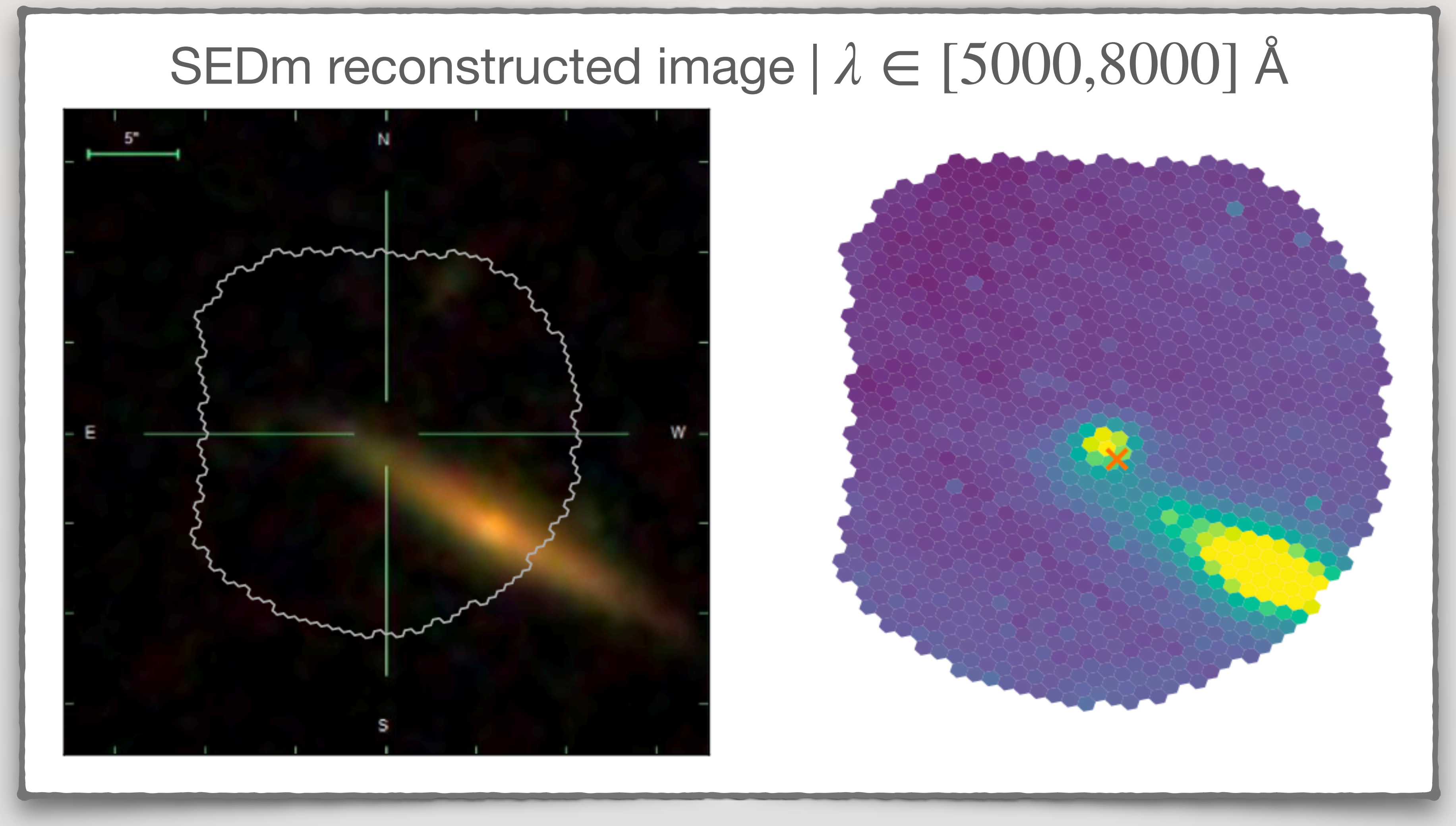
Source: Transient Name Server
wis-tns.org/stats-maps

Purpose : typing and redshift

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

Optical window: 3,650 - 10,000 Å

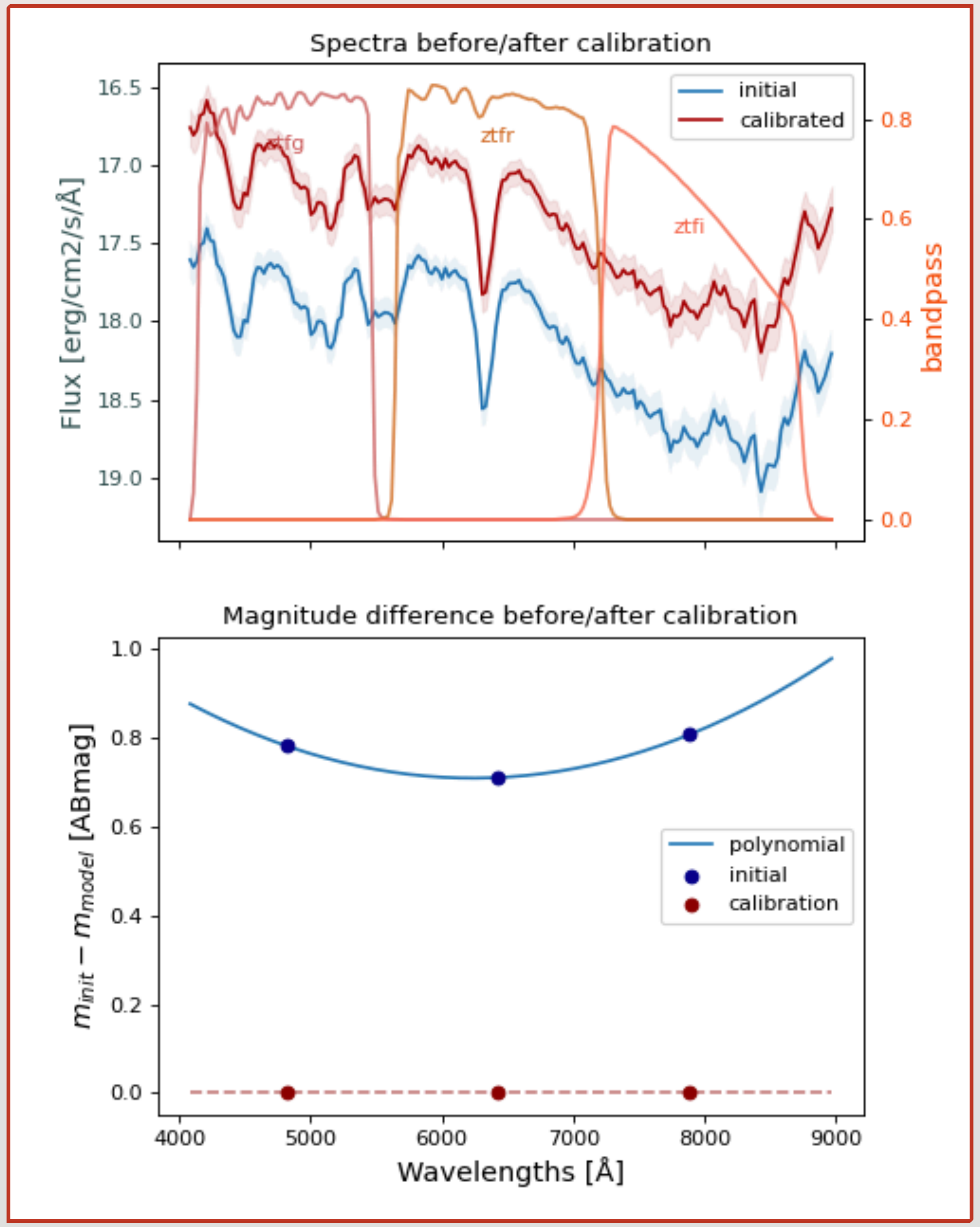
Acquisition of ~1 hour



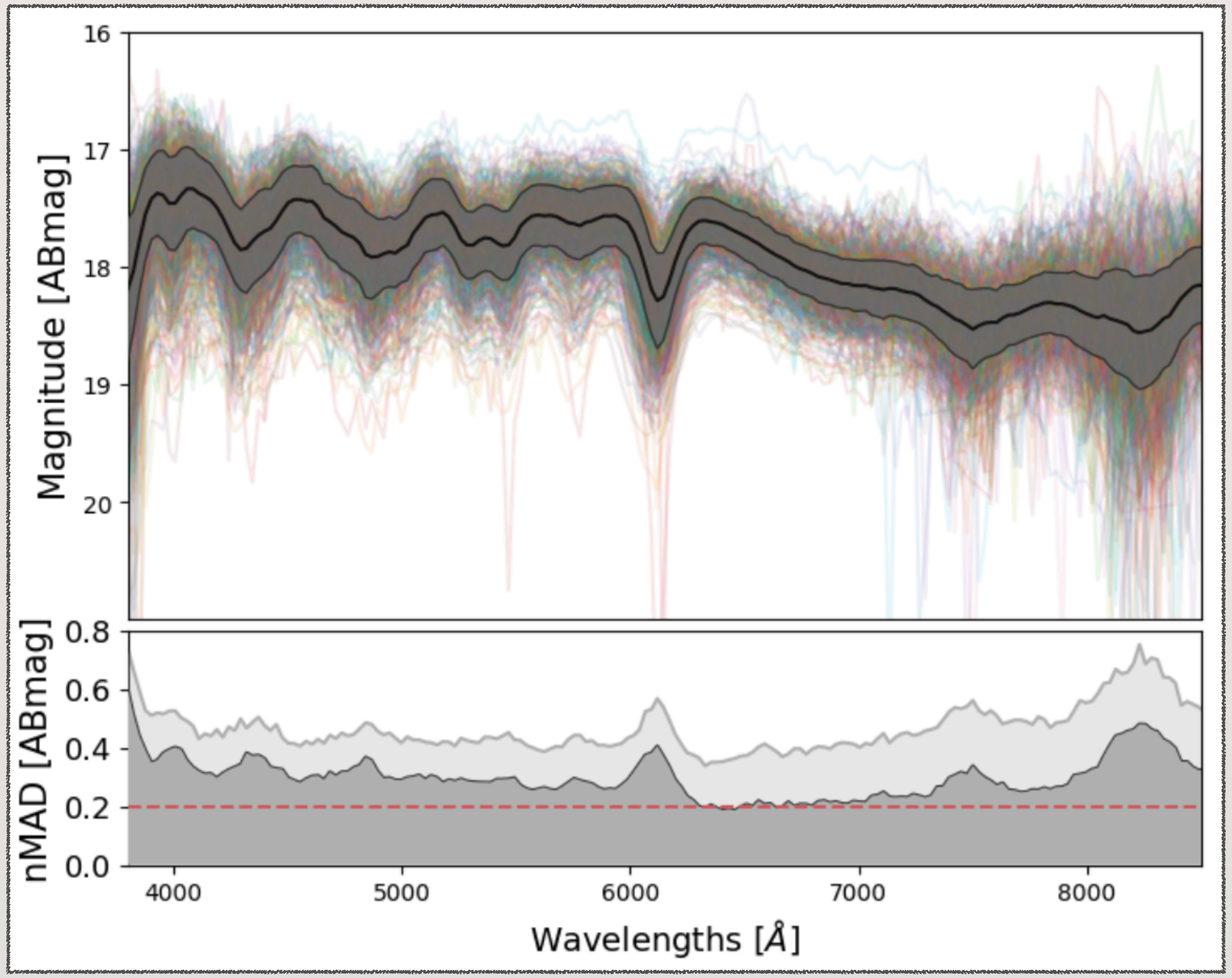
SEDm (P60)- Integral field Spectrograph field of view of ZTF18abqlpgq
Source : pysedm - Rigault, Neill

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

ZTF spectra flux-calibration



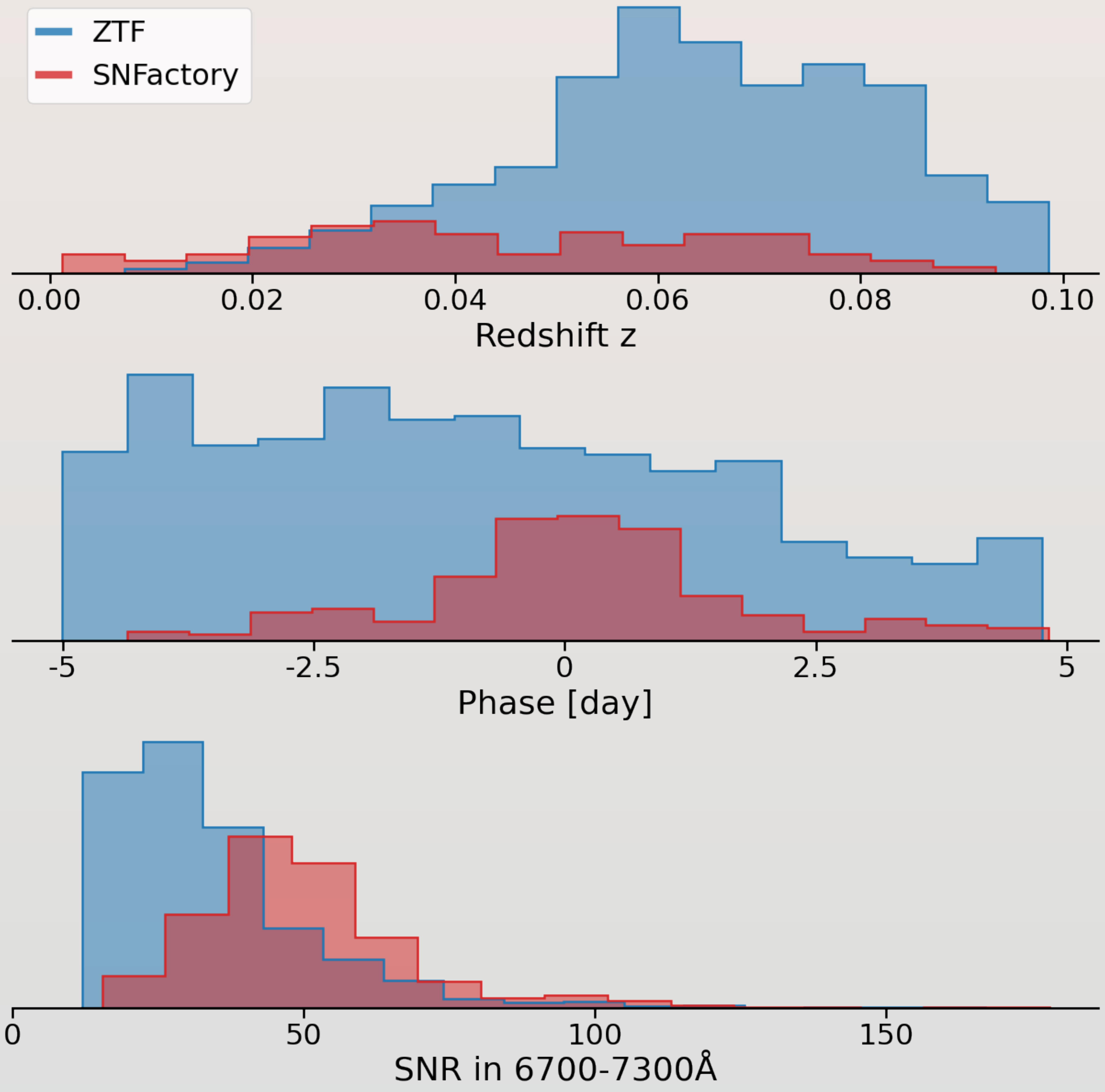
Exemple of flux calibration
with ZTF20aayvubx_20200524_SEDm_0



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

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

ZTF spectra sample



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

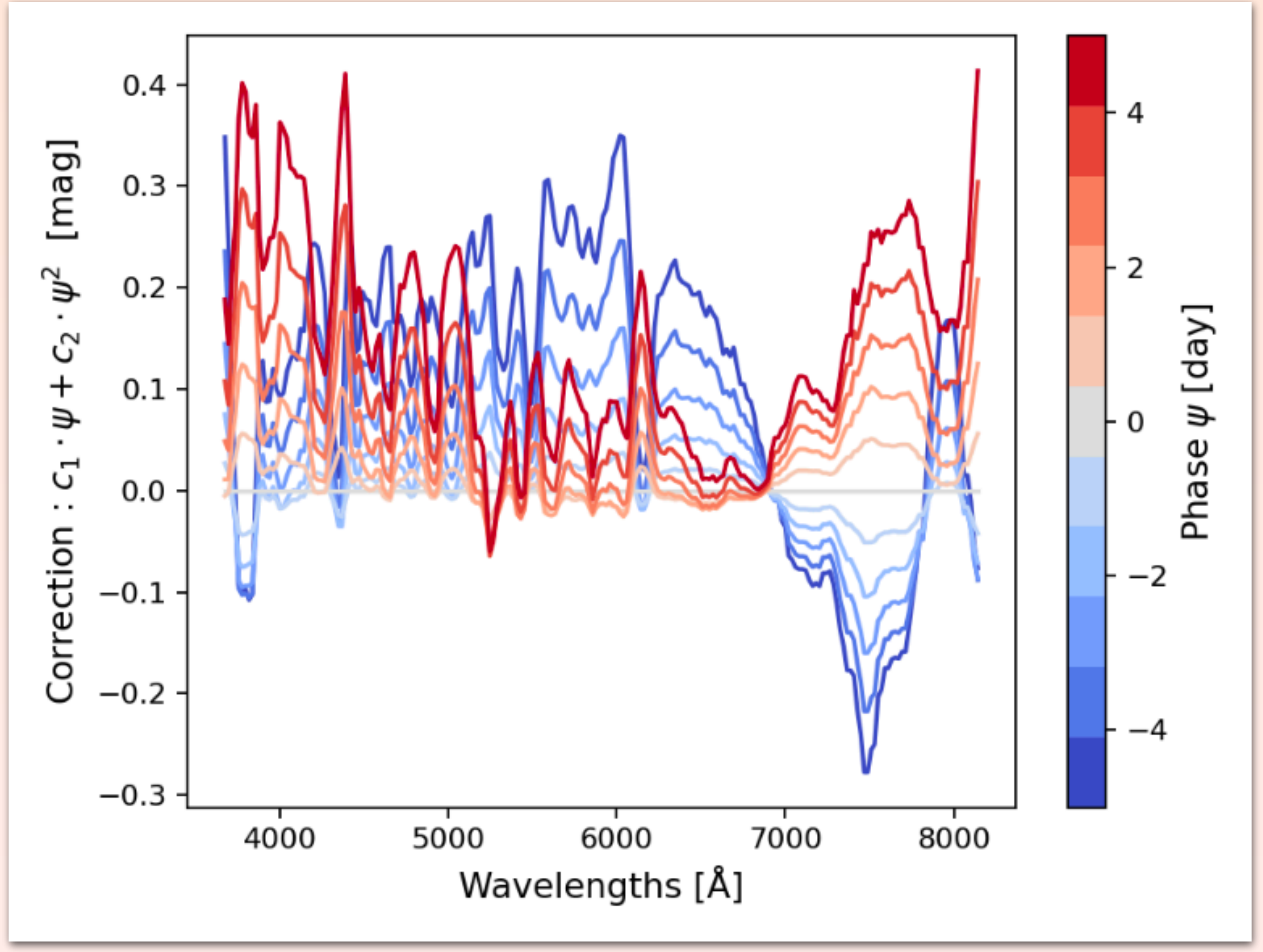
—> The spectra sample is ready to test the standardisation

Twins Embedding - *Boone et al. 2021*

3 steps

1. Generate at maximum luminosity

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

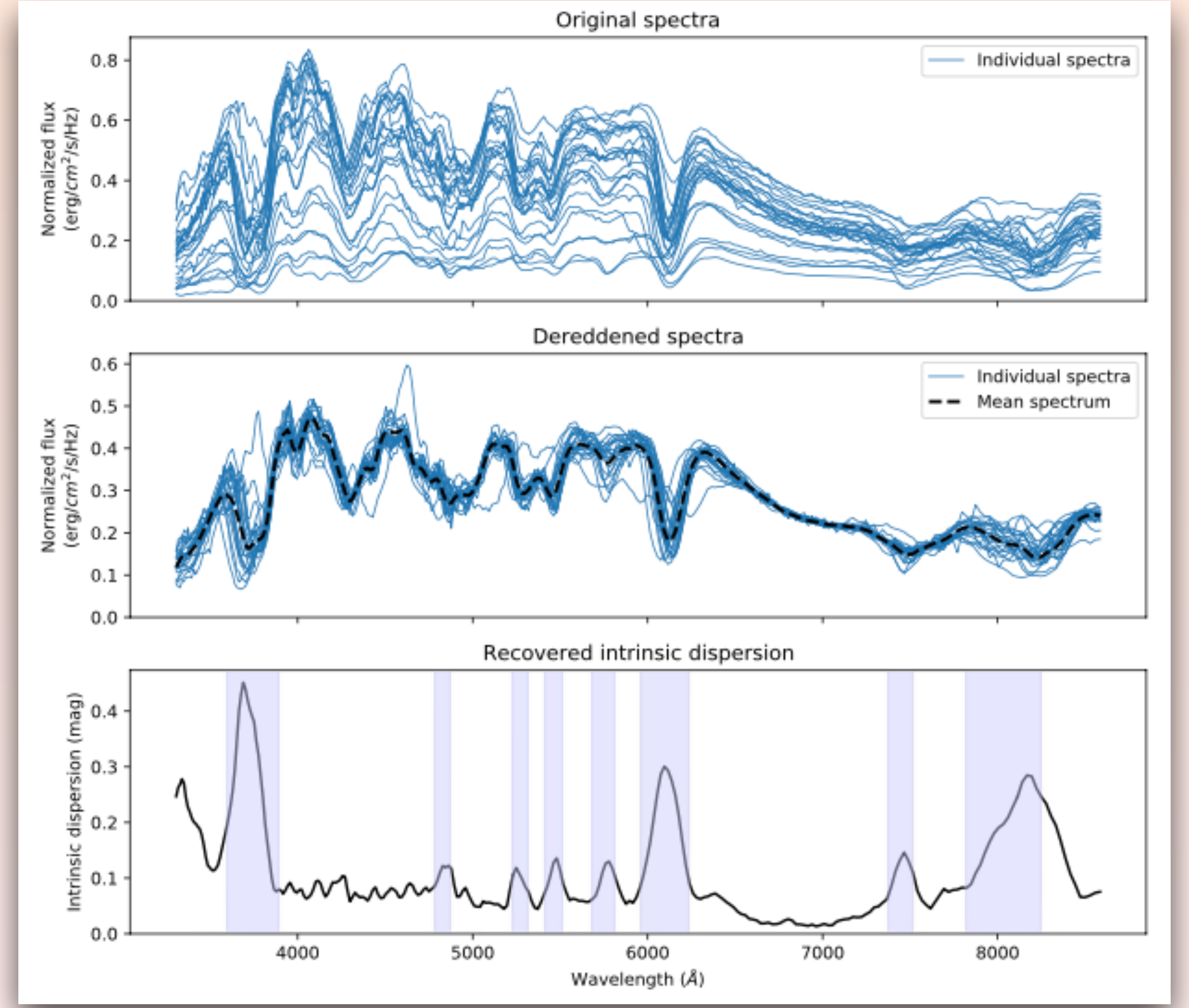


Quadratic evolution in phase of SN Ia spectra

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

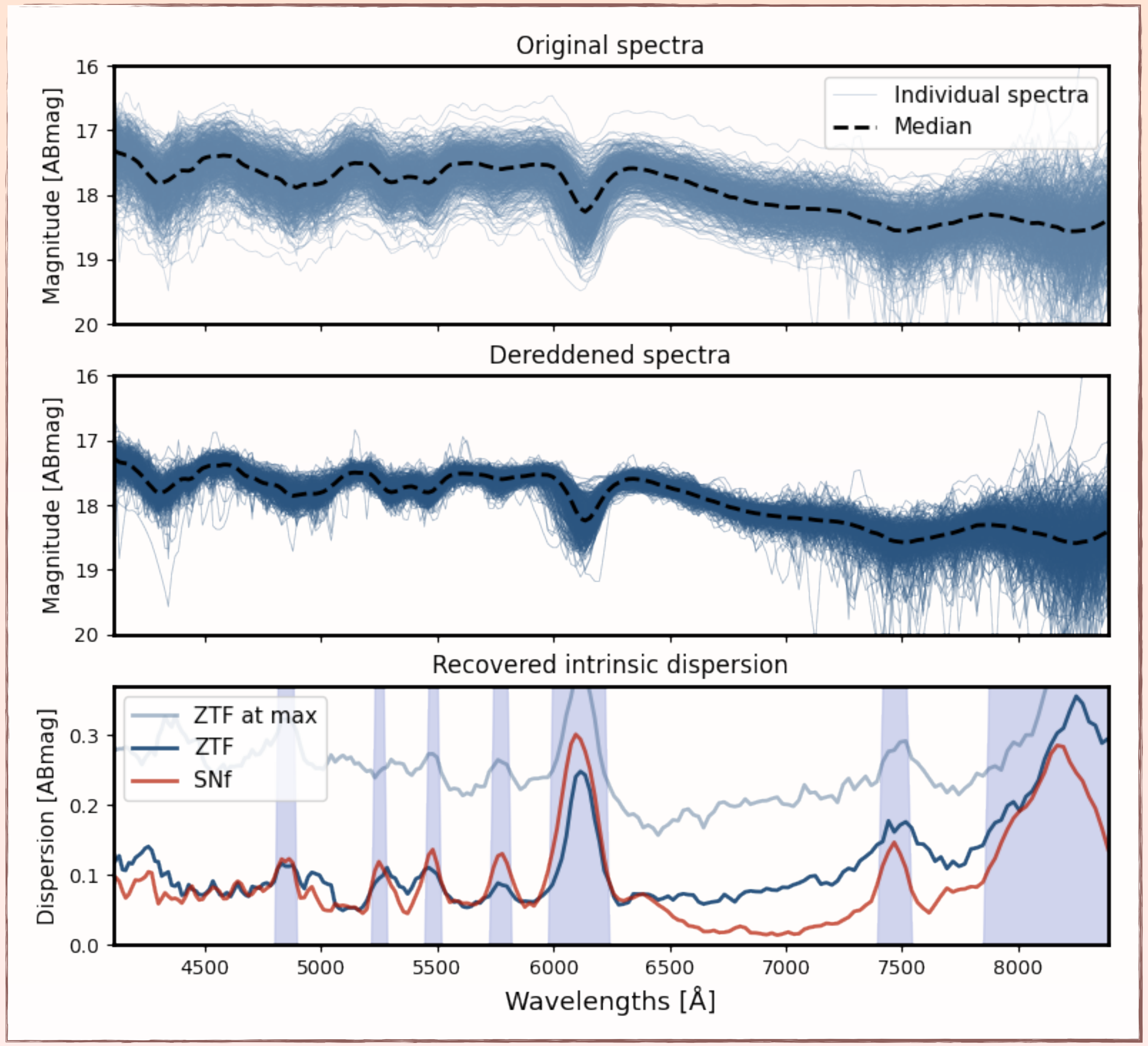
2. RBTL - fit one offset and a color outside the lines

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

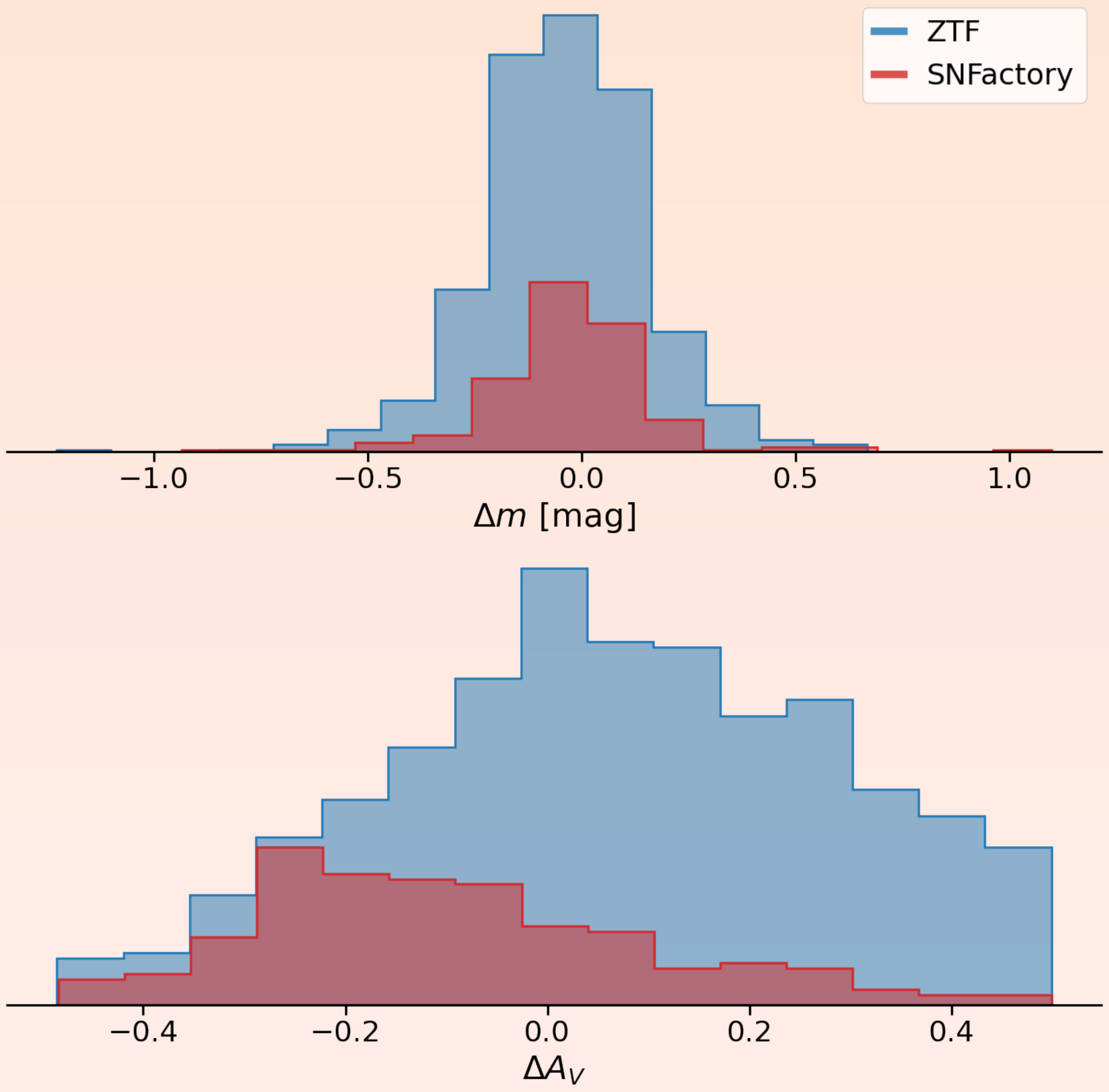


SNFactory spectra before/after dereddening, and residuals intrinsic dispersion (std) *Credit : Boone et al. 2021*

Twins Embedding on ZTF



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



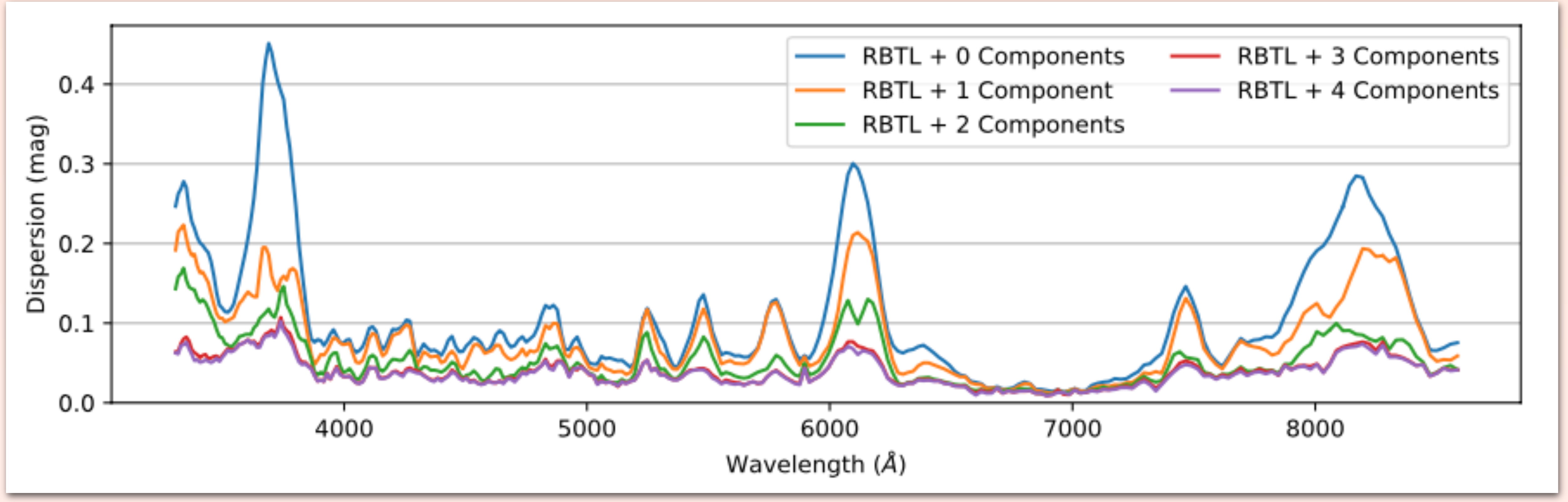
More red SNe in **ZTF** sample, same distribution shape in magnitude

Twins Embedding - *Boone et al. 2021*

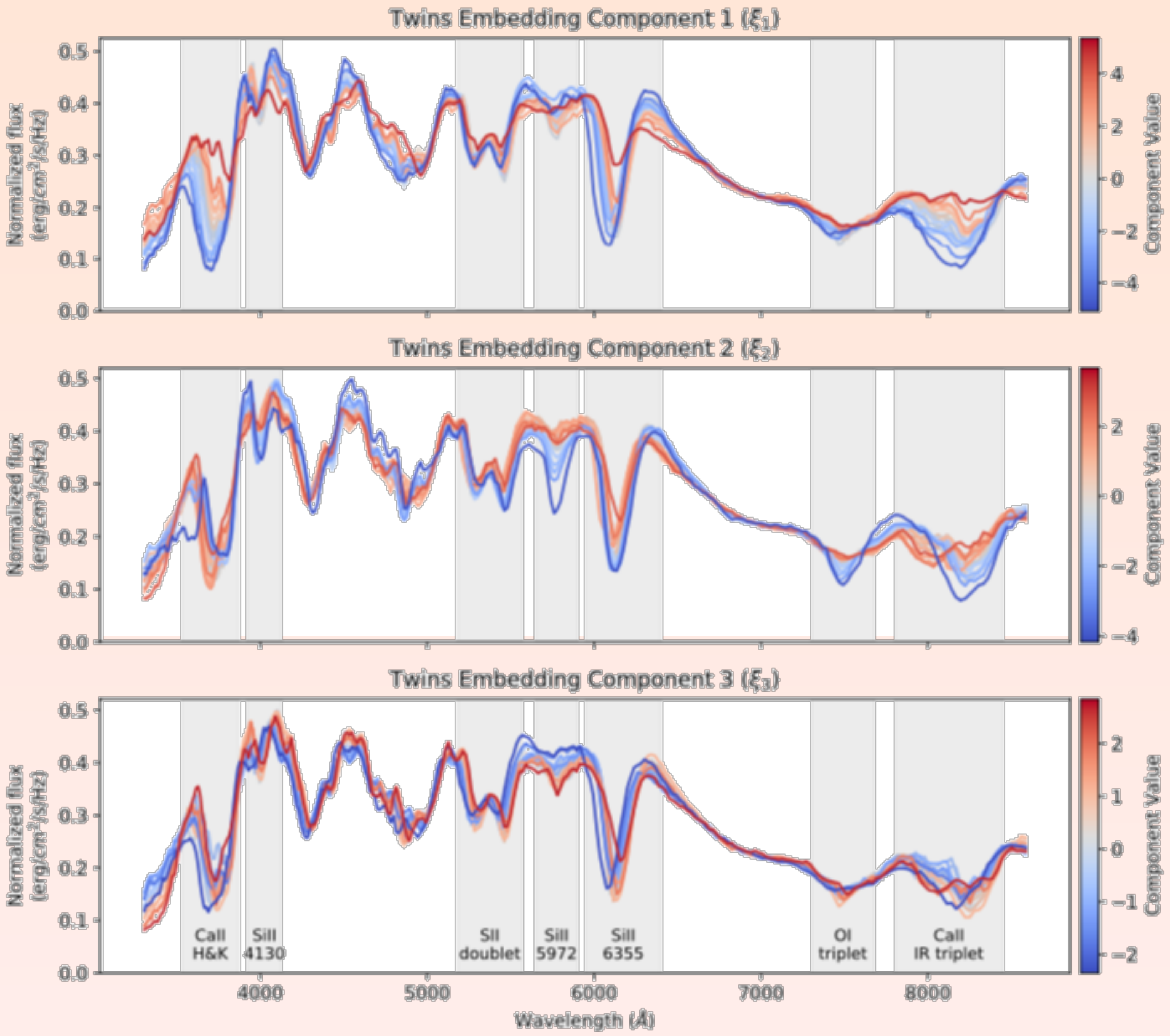
3 steps

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*



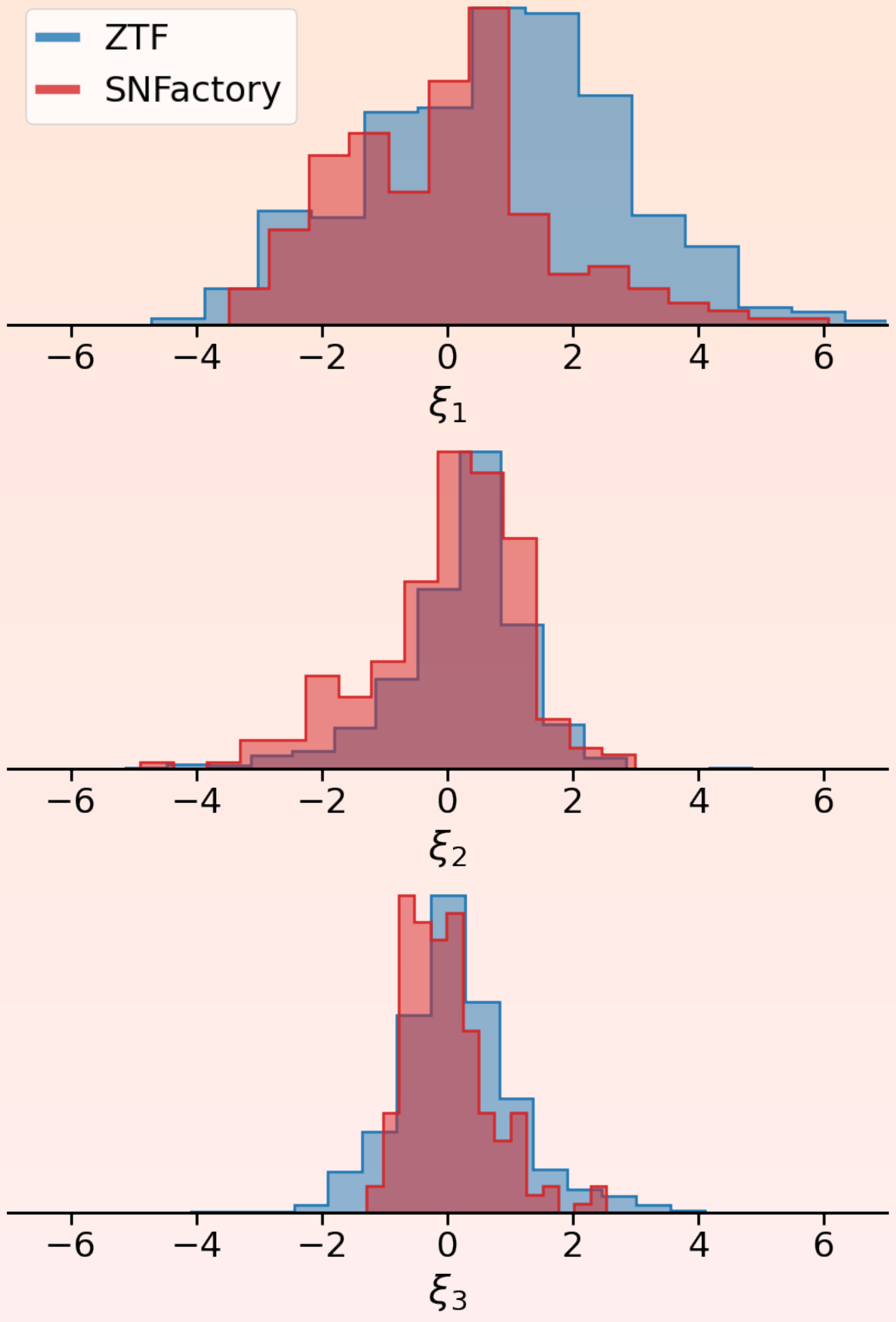
Twins Embedding components variation effects on spectra. *Credit : Boone et al. 2021*

Twins Embedding - *Boone et al. 2021*

3 steps

1. **Generate at maximum luminosity**
2. **RBTL - *fit one offset and a color outside the lines***
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

(work in progress)

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

With SNFactory

Twins Embedding :

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

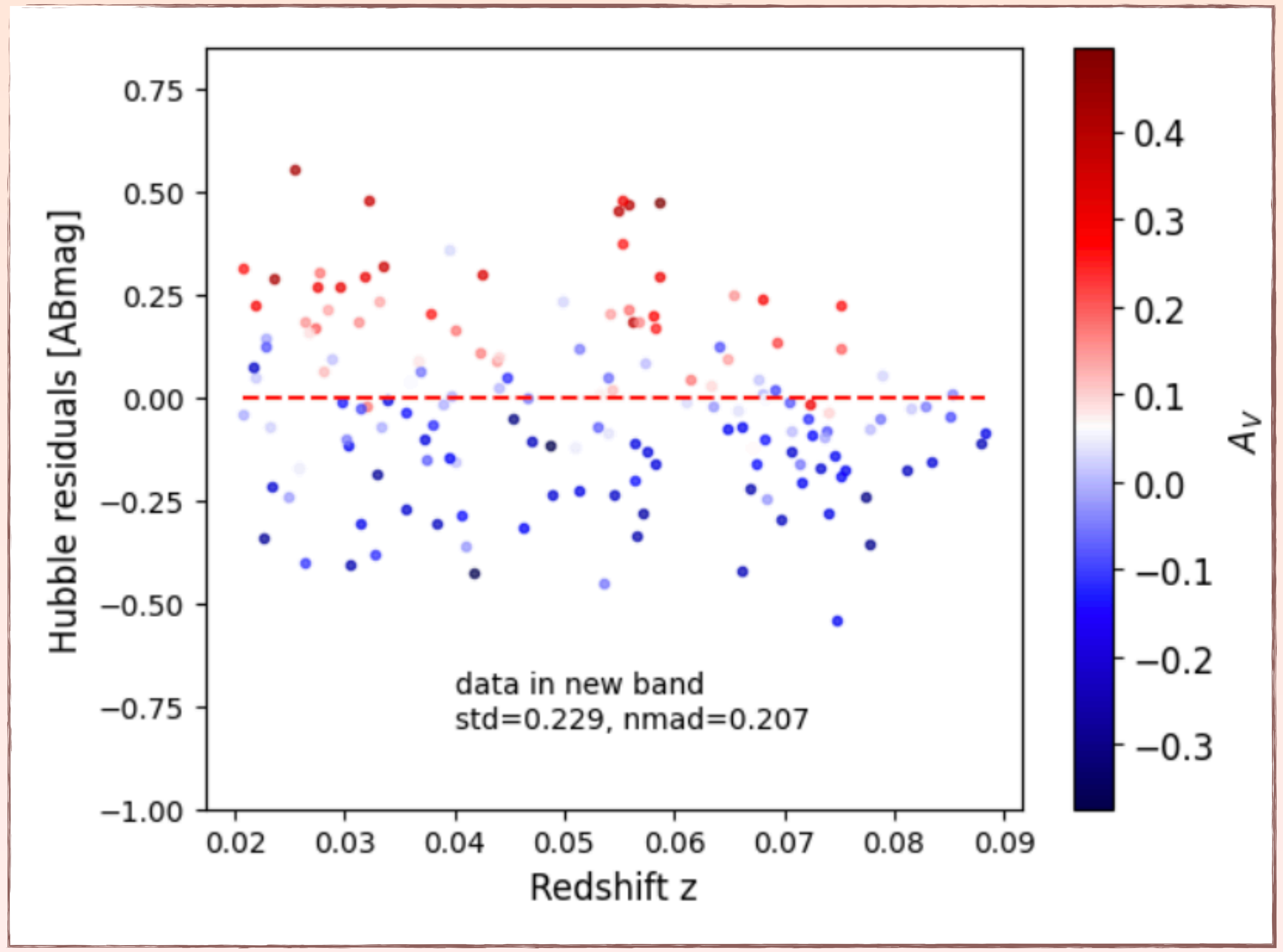
—> what with ZTF ?

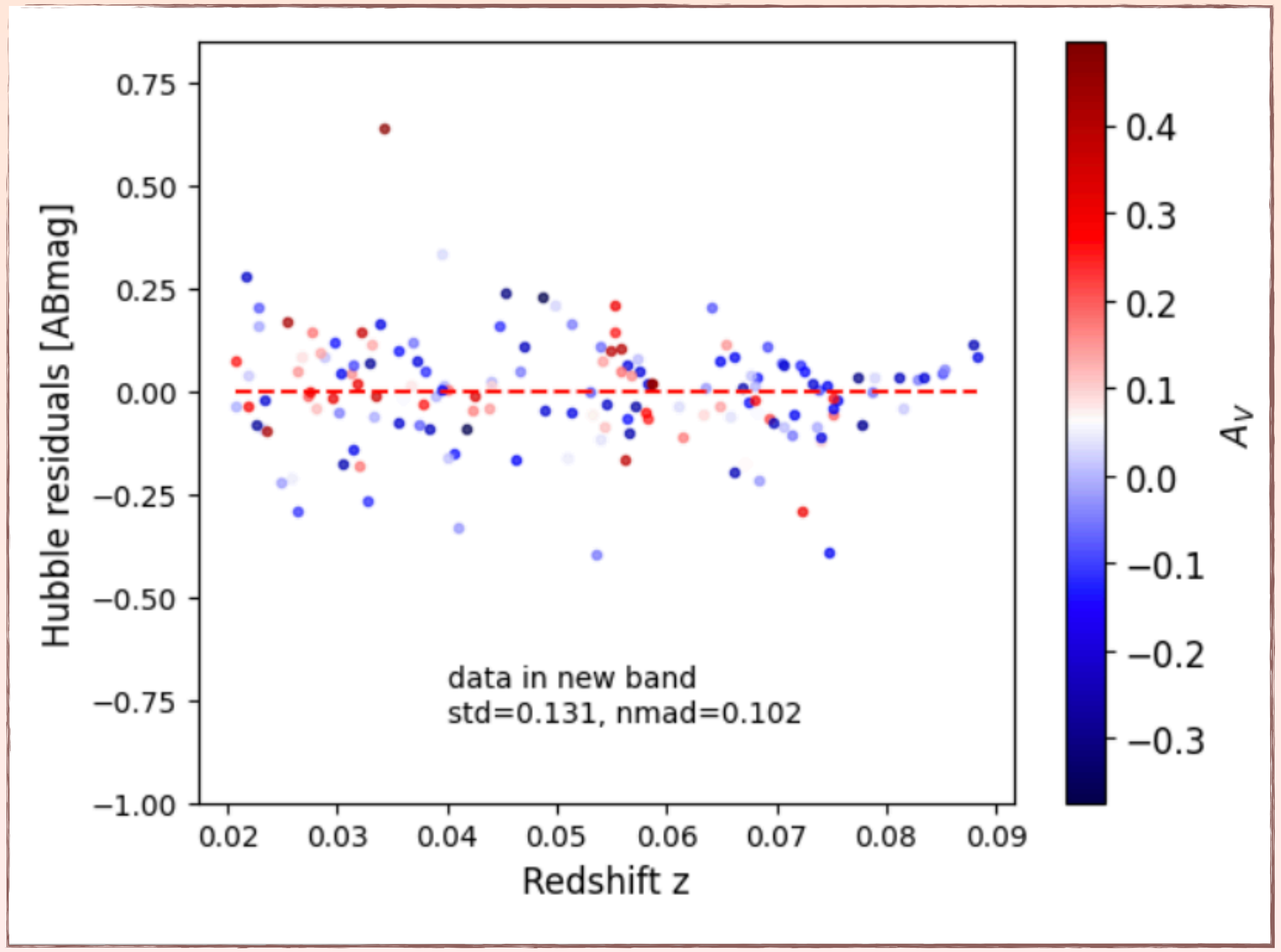
RBTL linear standardisation

For SNFactory sample

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

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





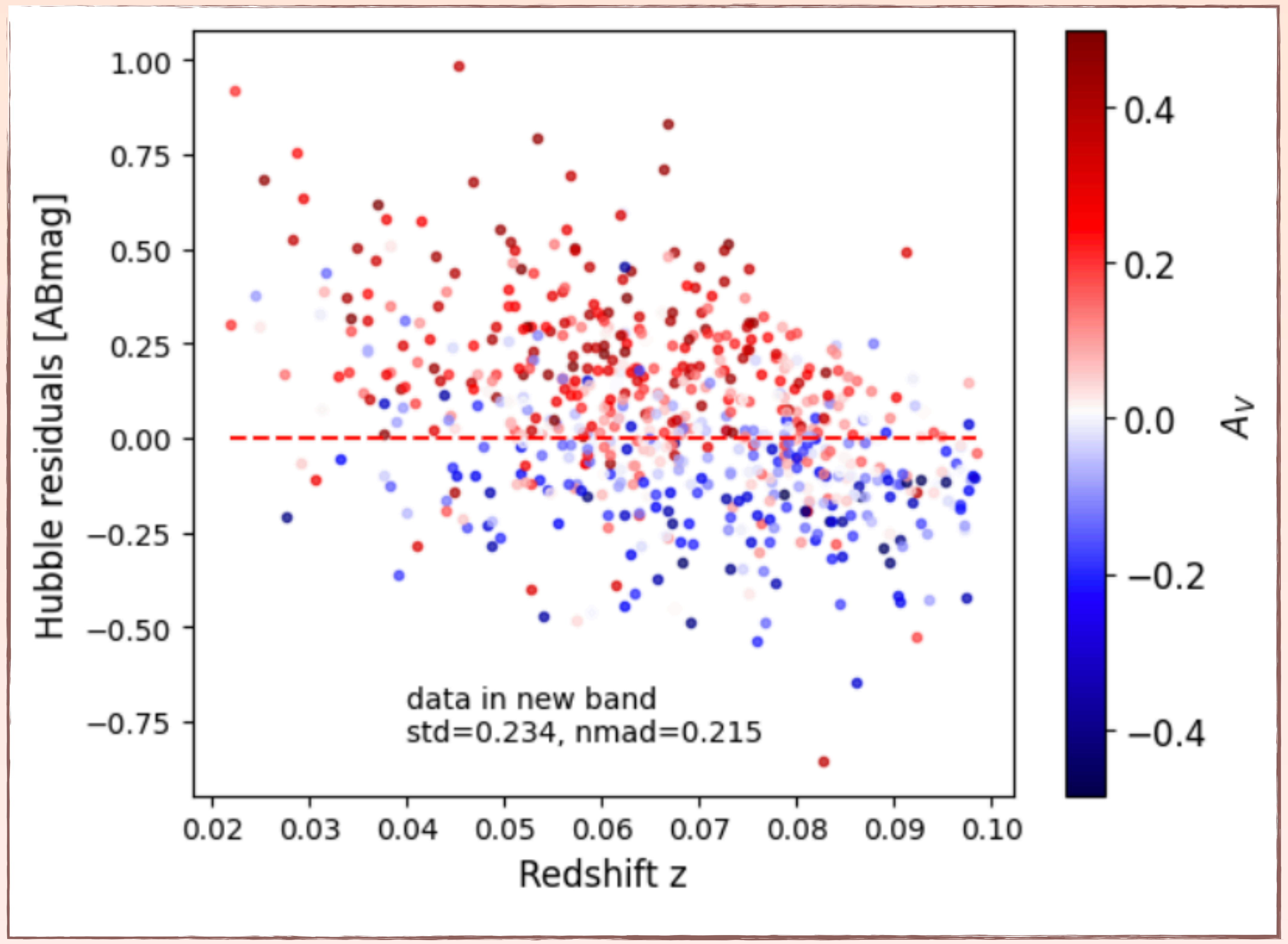
168 SNe Ia before/after standardisation after a cut on DAv < 0.5

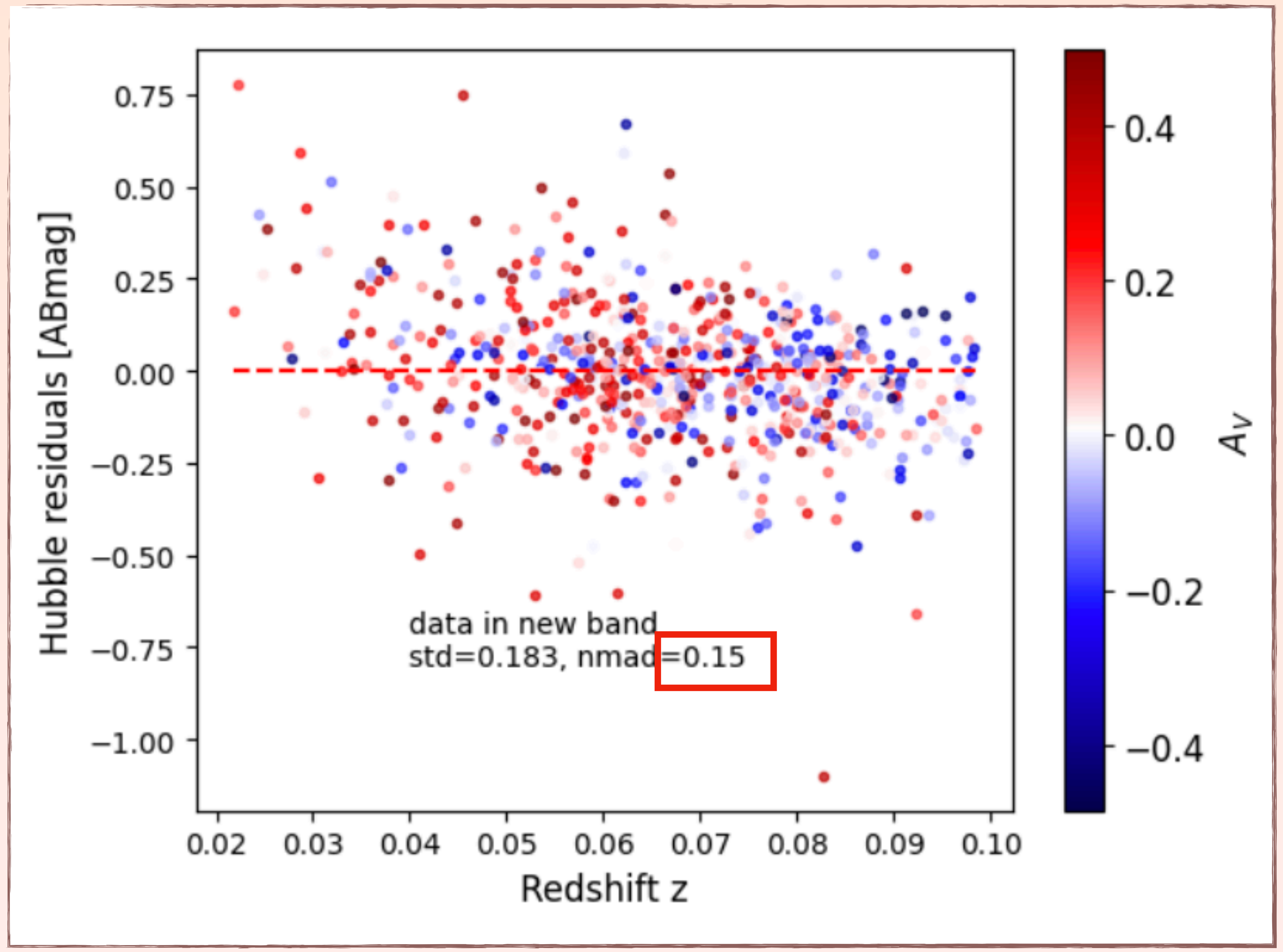
RBTL linear standardisation

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

First application results

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

PhD Calendar

1st year	Evaluation of Twins Embedding method on ZTF spectra
2nd year	1st paper on the results
	2nd paper on a Hubble Diagram using ZTF and SNLS spectra and Twins Embedding
3rd year	Cosmology with spectro-photometric standardisation

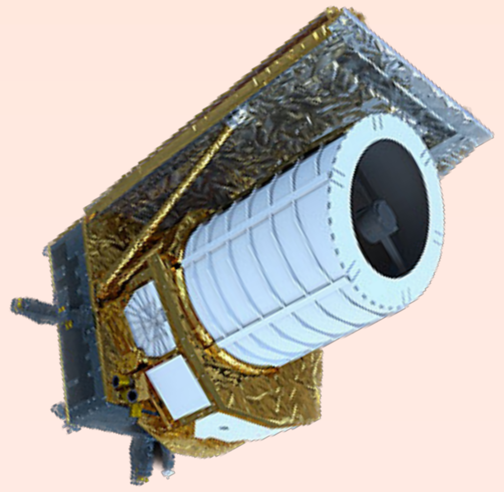
Be prepared for new surveys

2009

SNFactory
2004 —> 2013

2018

ZTF
2018 —> 2025



Euclid
july 2023 -

2023

2027

Roman
2027-

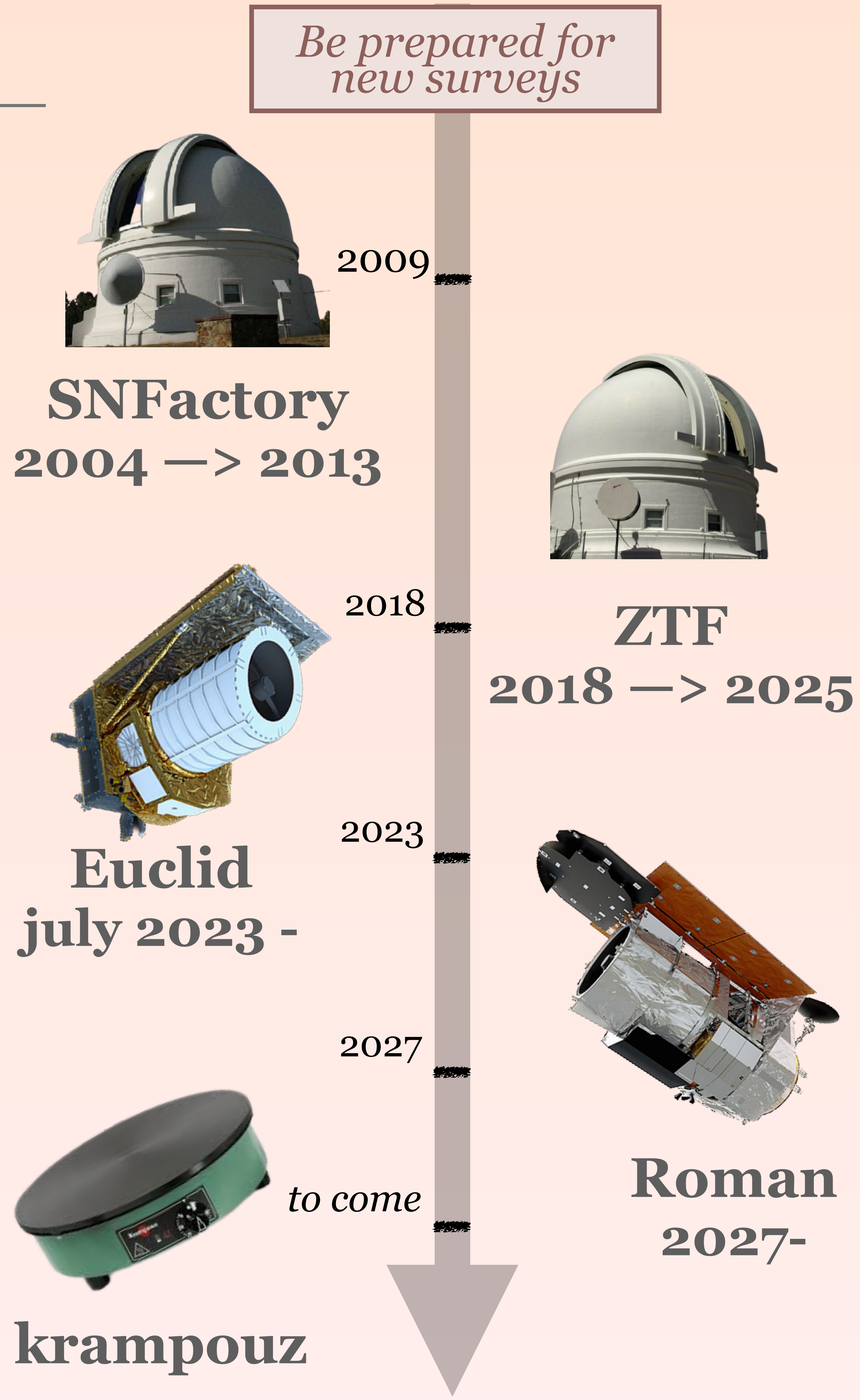
Conclusion

First application results

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

PhD Calendar

1st year	Evaluation of Twins Embedding method on ZTF spectra
2nd year	1st paper on the results
	2nd paper on a Hubble Diagram using ZTF and SNLS spectra and Twins Embedding
3rd year	Cosmology with spectro-photometric standardisation



STEP 1

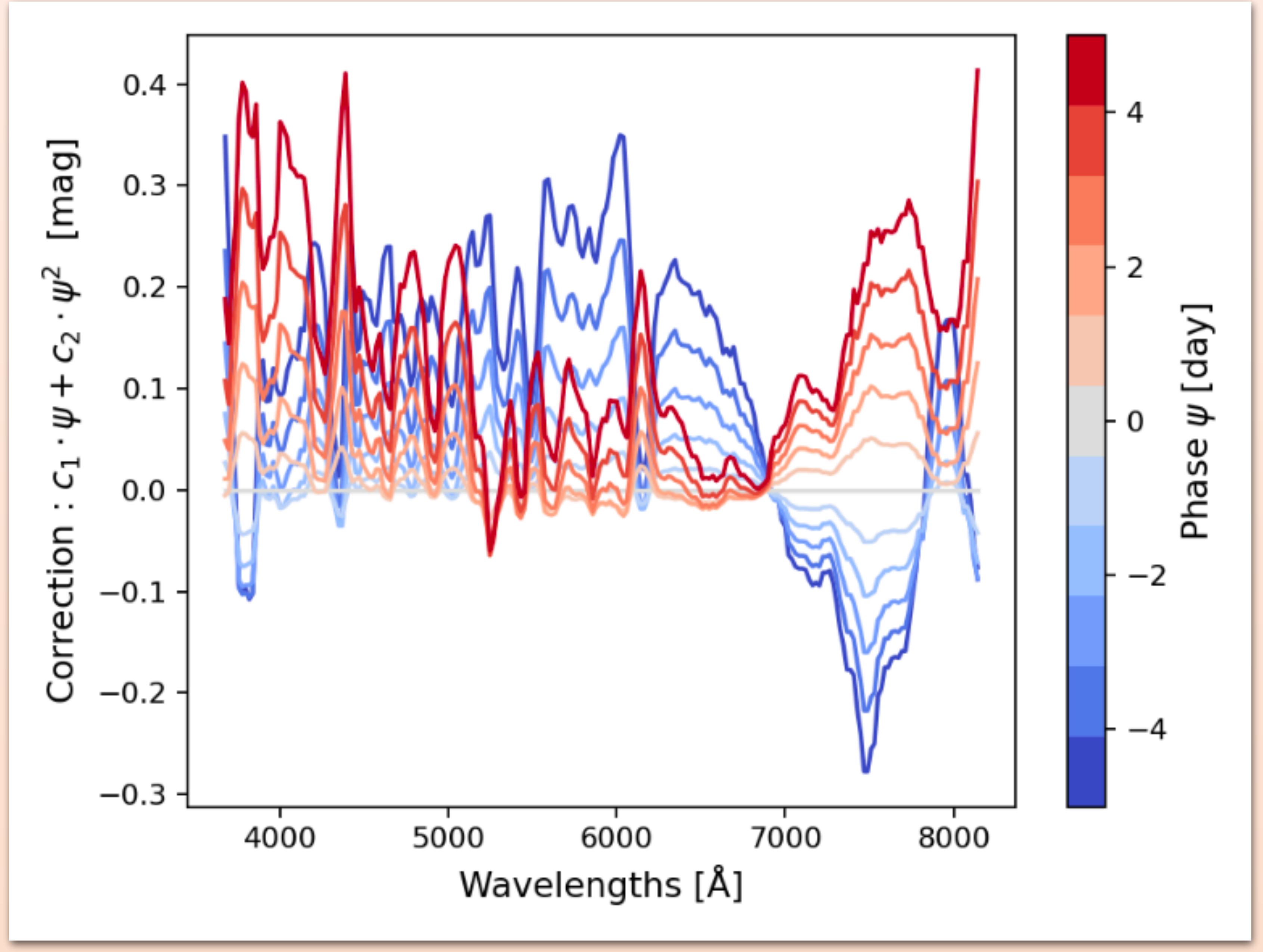
Differential time evolution model

=> ***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

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

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

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

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***

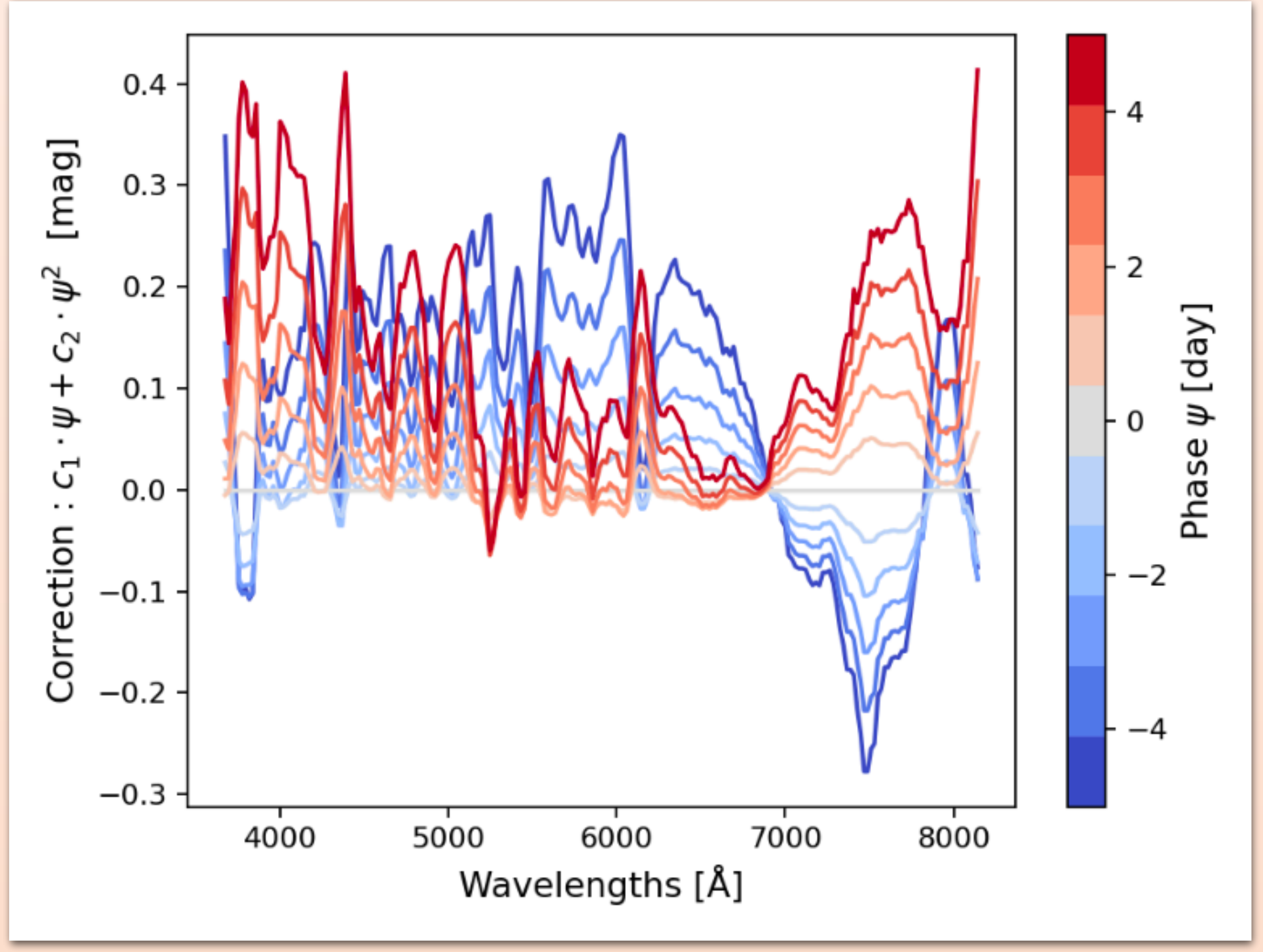
Formula of quadratic evolution in phase :

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

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

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

tot., s

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

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

Fitted parameters :

$\epsilon(p, \lambda_k)$ 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

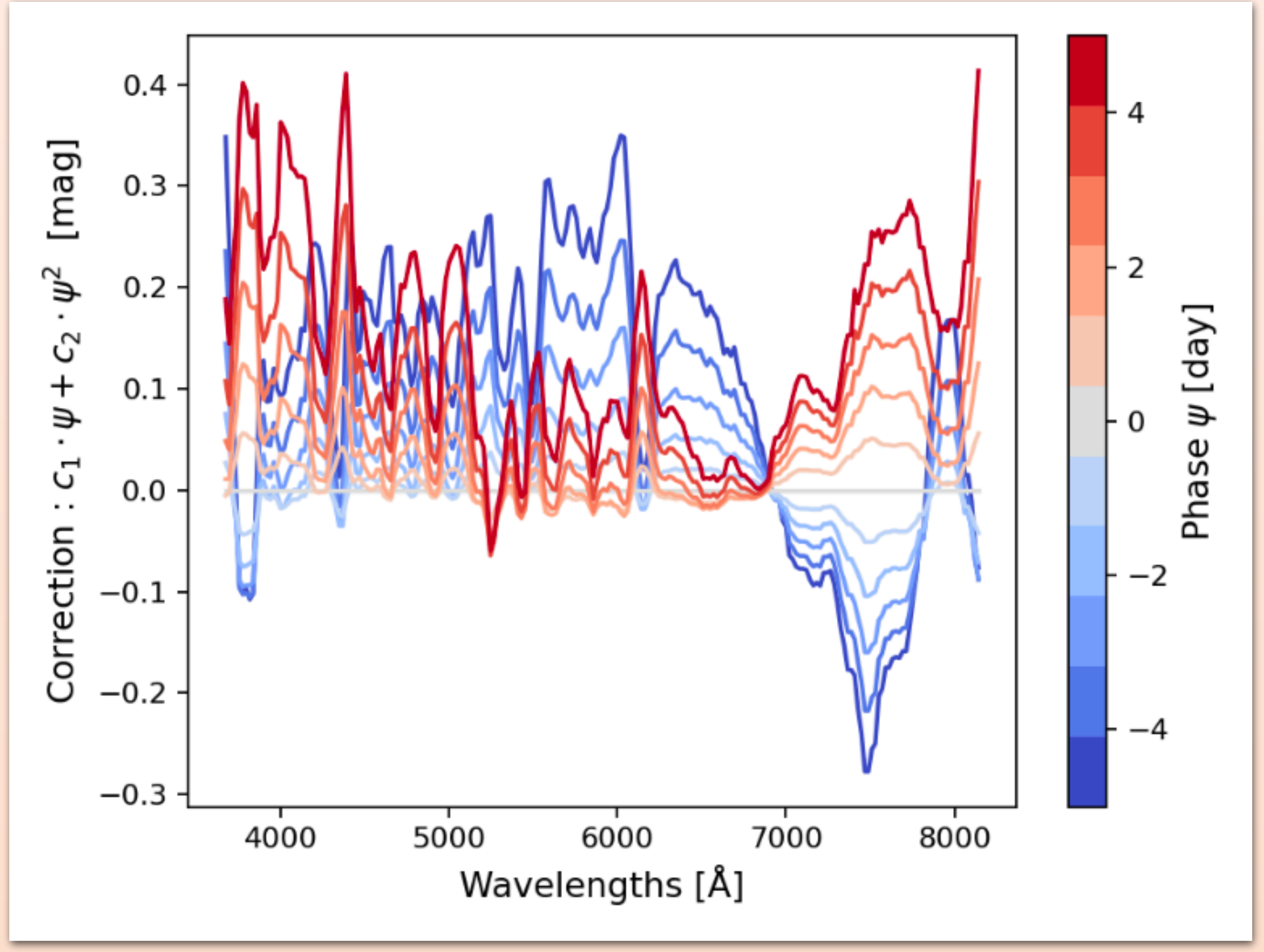
Formula of quadratic evolution in phase :

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

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)*

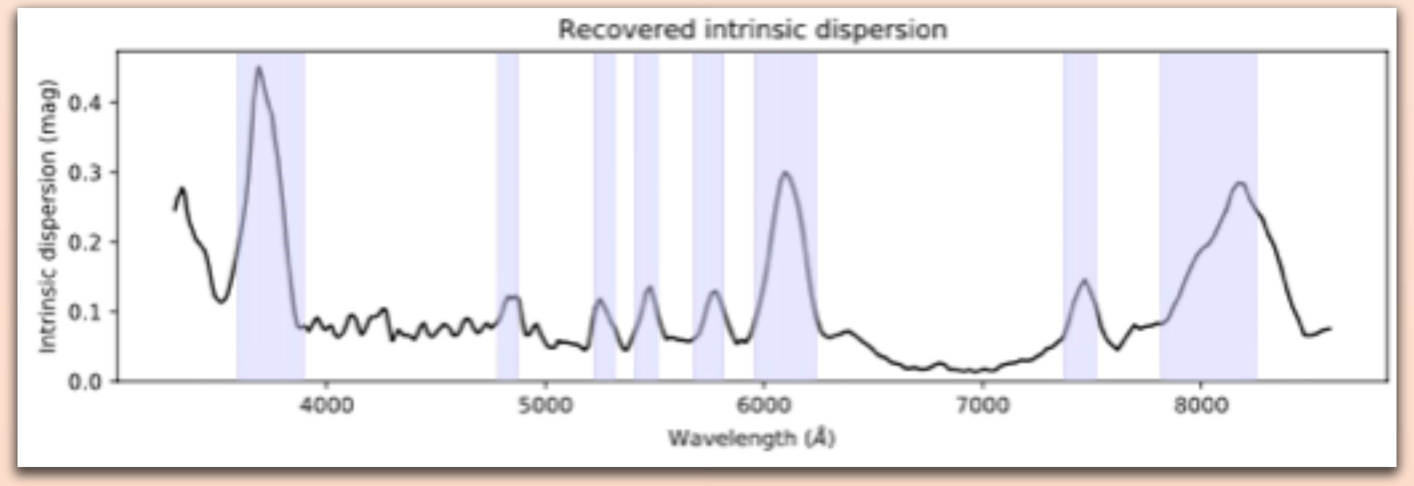
Fit all together with bayesian inference :

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

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

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

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



STEP 2

Read between the lines (RBTL)

=> Explain Scatter Between the lines

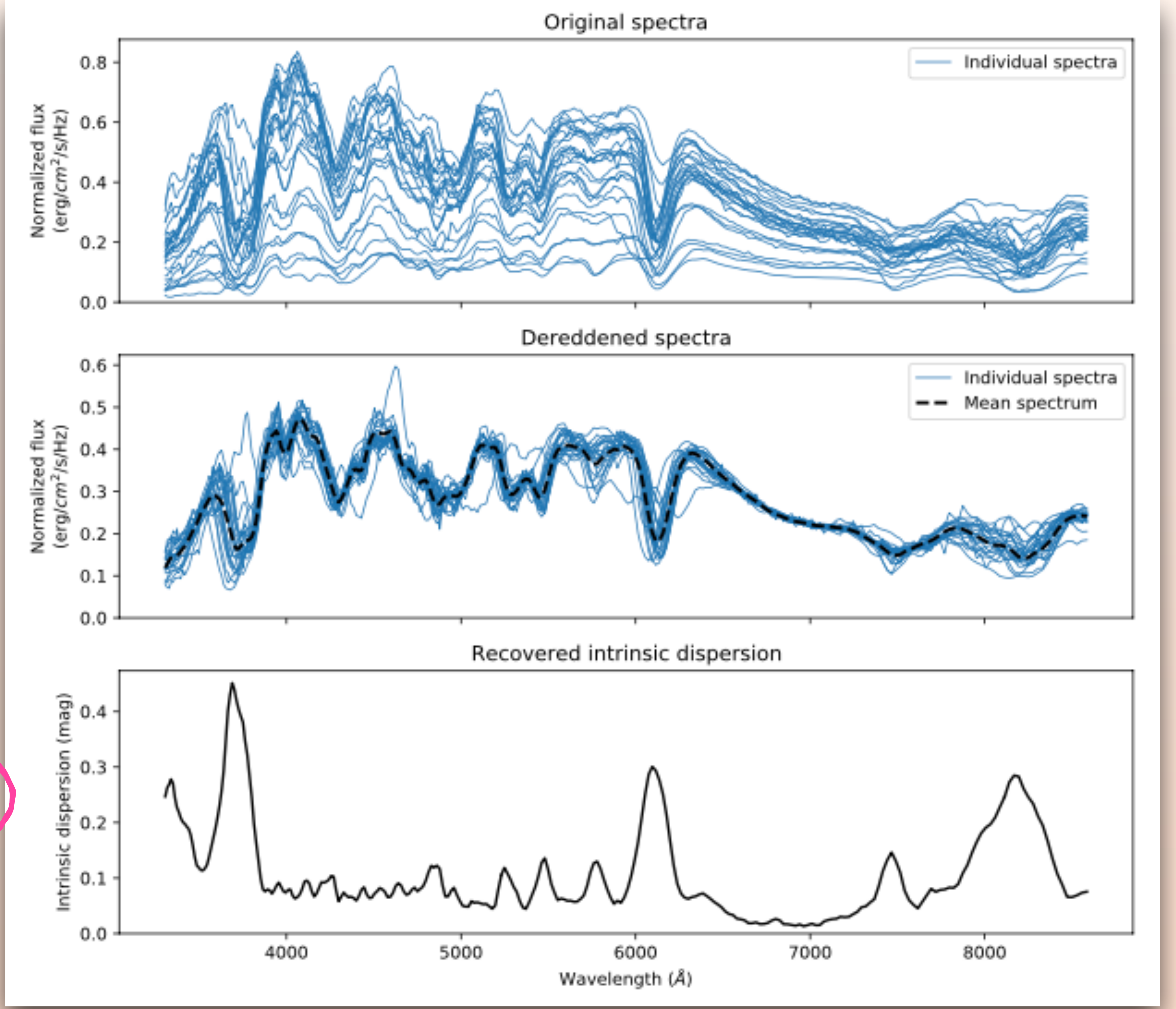
Capture Grey scatter + Extinction

Remove variability:

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

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

$\eta(\lambda_k)$



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

Read between the lines (RBTL)

=> Explain Scatter Between the lines

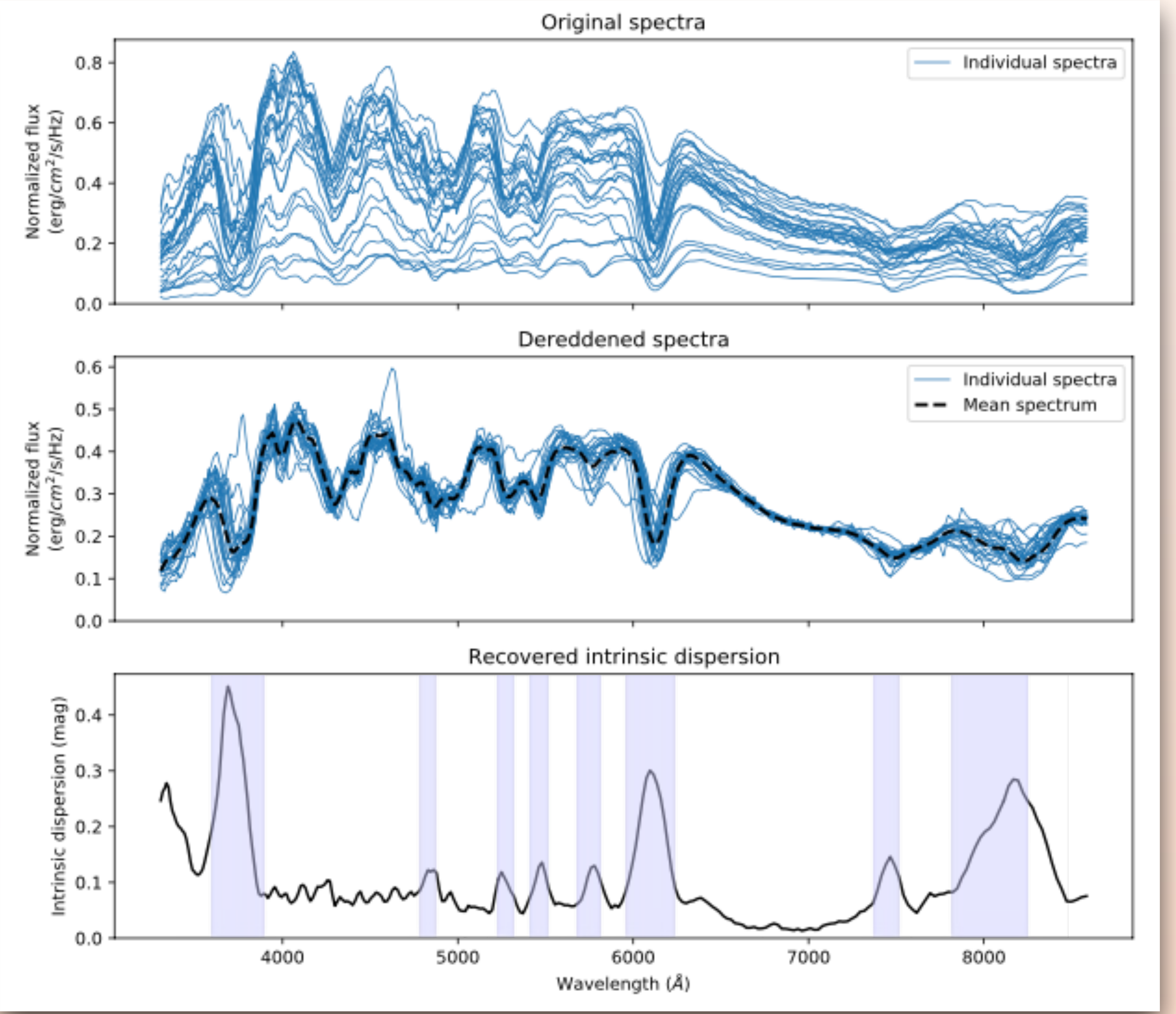
Capture Grey scatter + Extinction

<u>Remove variability:</u>

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

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

$\eta(\lambda_k)$



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 3

The Twins Embedding parameters space

=> Explain $\eta(\lambda_k)$

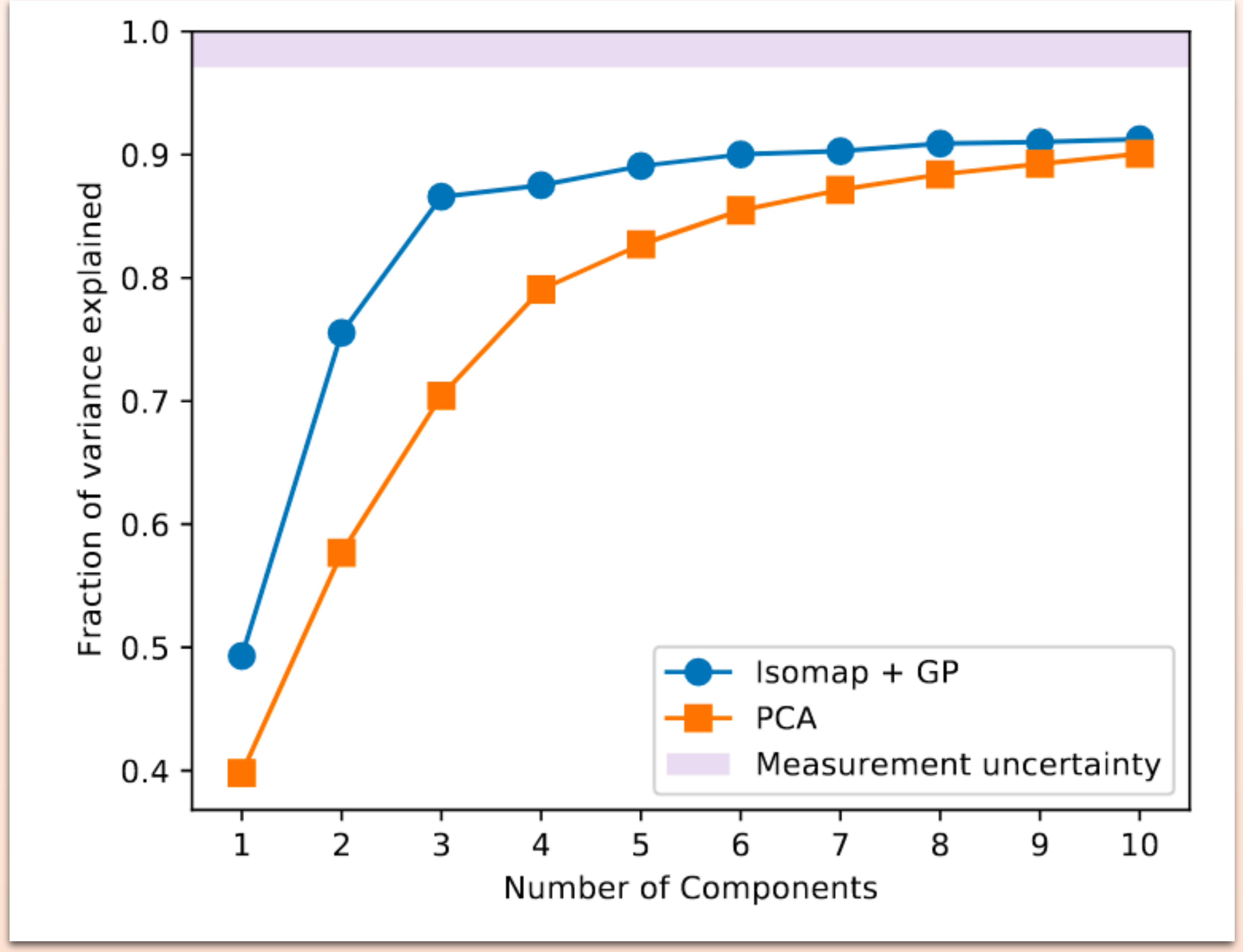
Spectral distance between two Sne I and j :

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

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

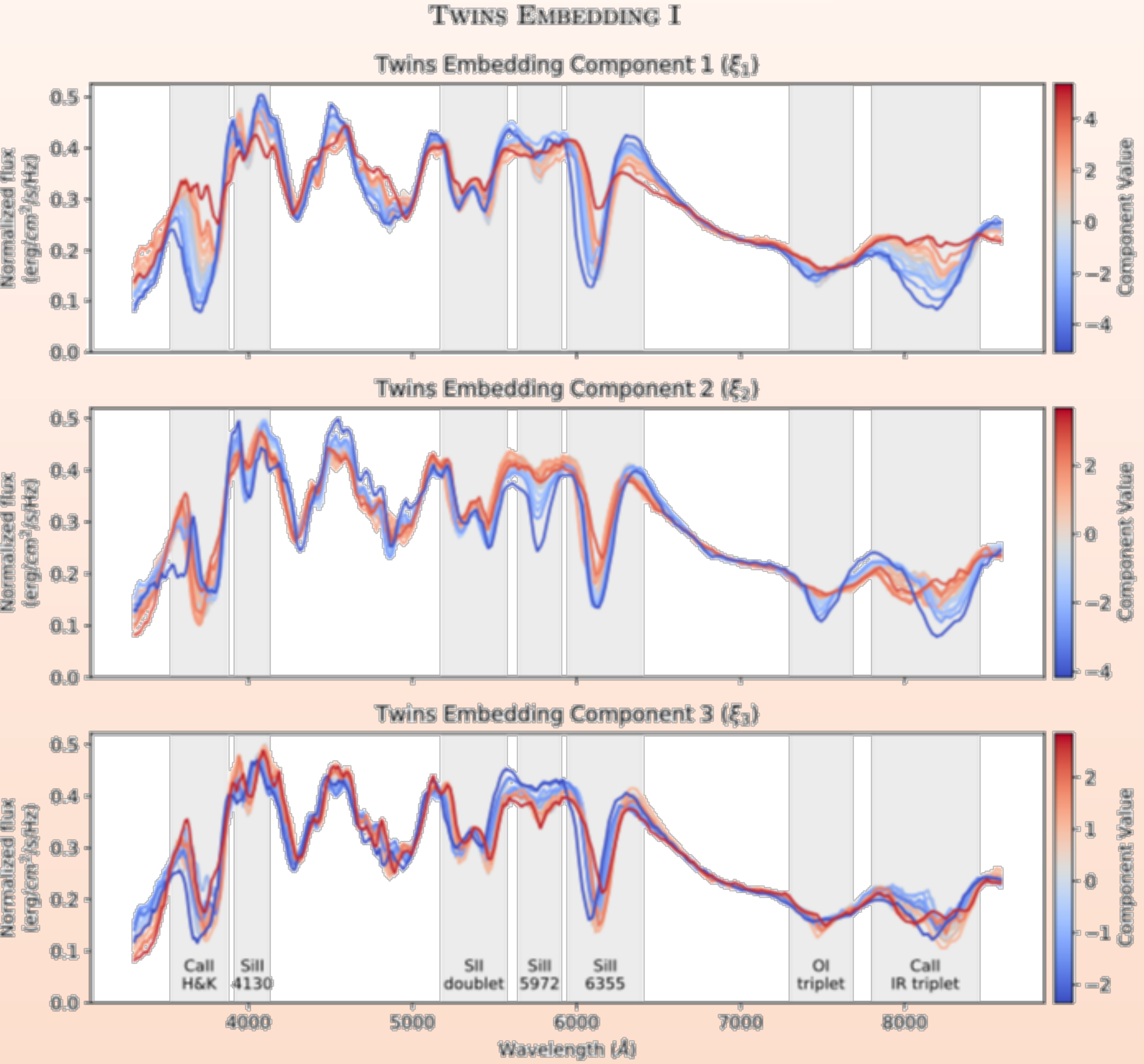


Fraction of the variance explained for different models - from Boone 2021

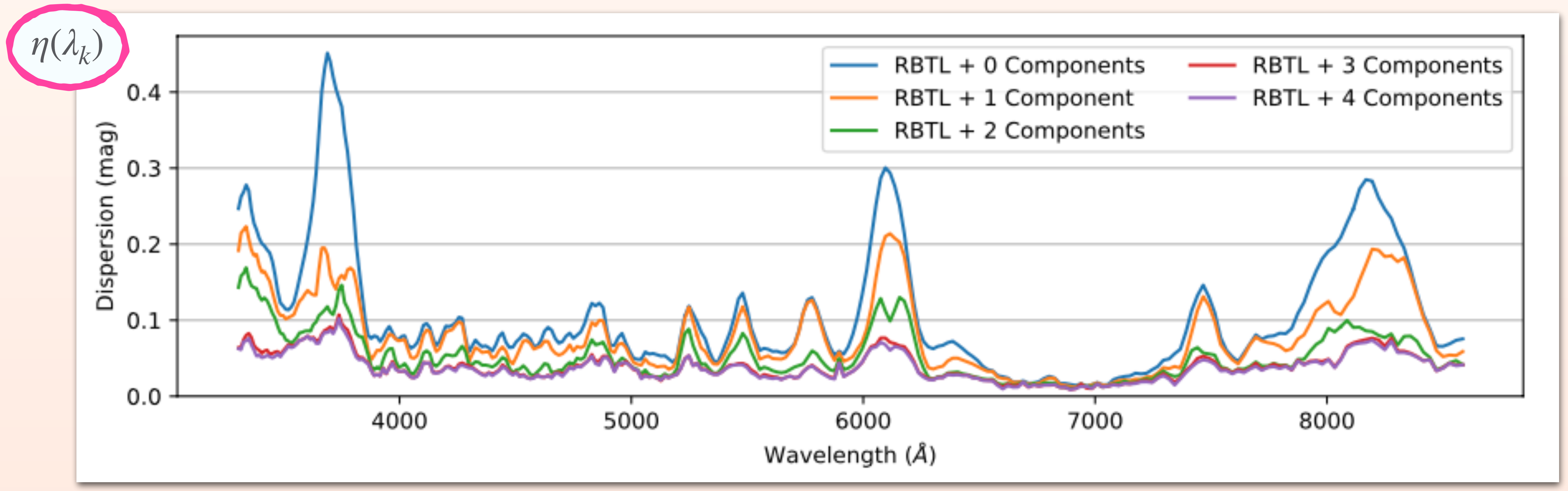
STEP 3

The Twins Embedding parameters space

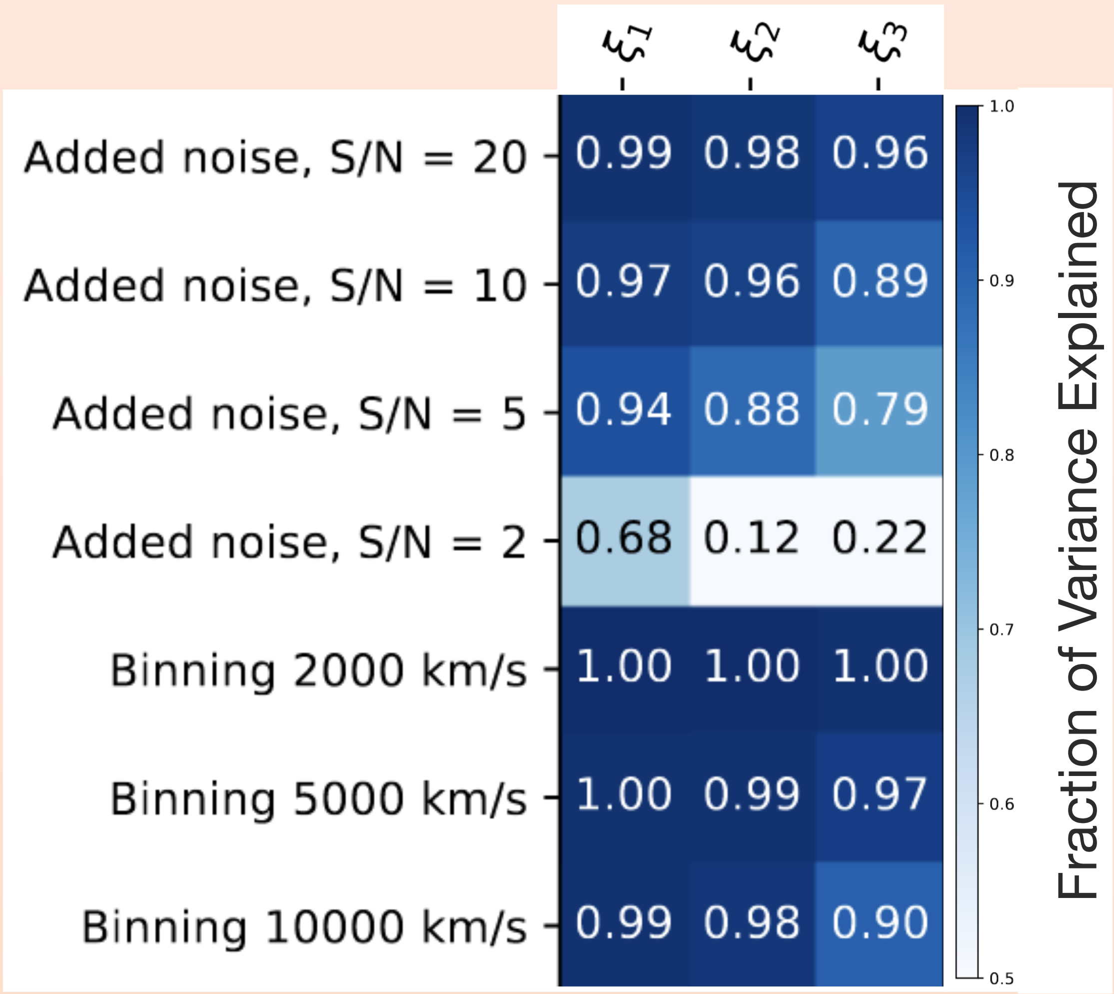
=> Explain $\eta(\lambda_k)$



Twins Embedding three components variation effects
Figure from Boone 2021



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

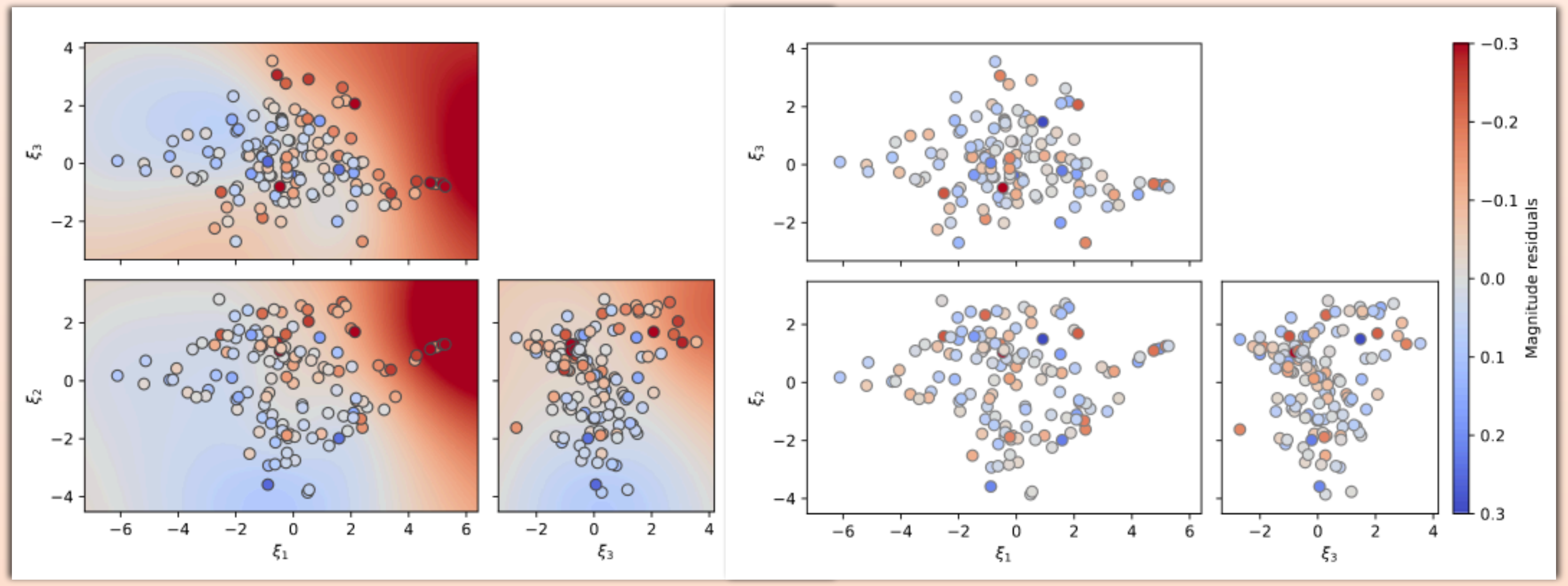


Dependancy of the variance explained with S/N and binning

The standardisation using Twins Embedding

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

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



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

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 ,*

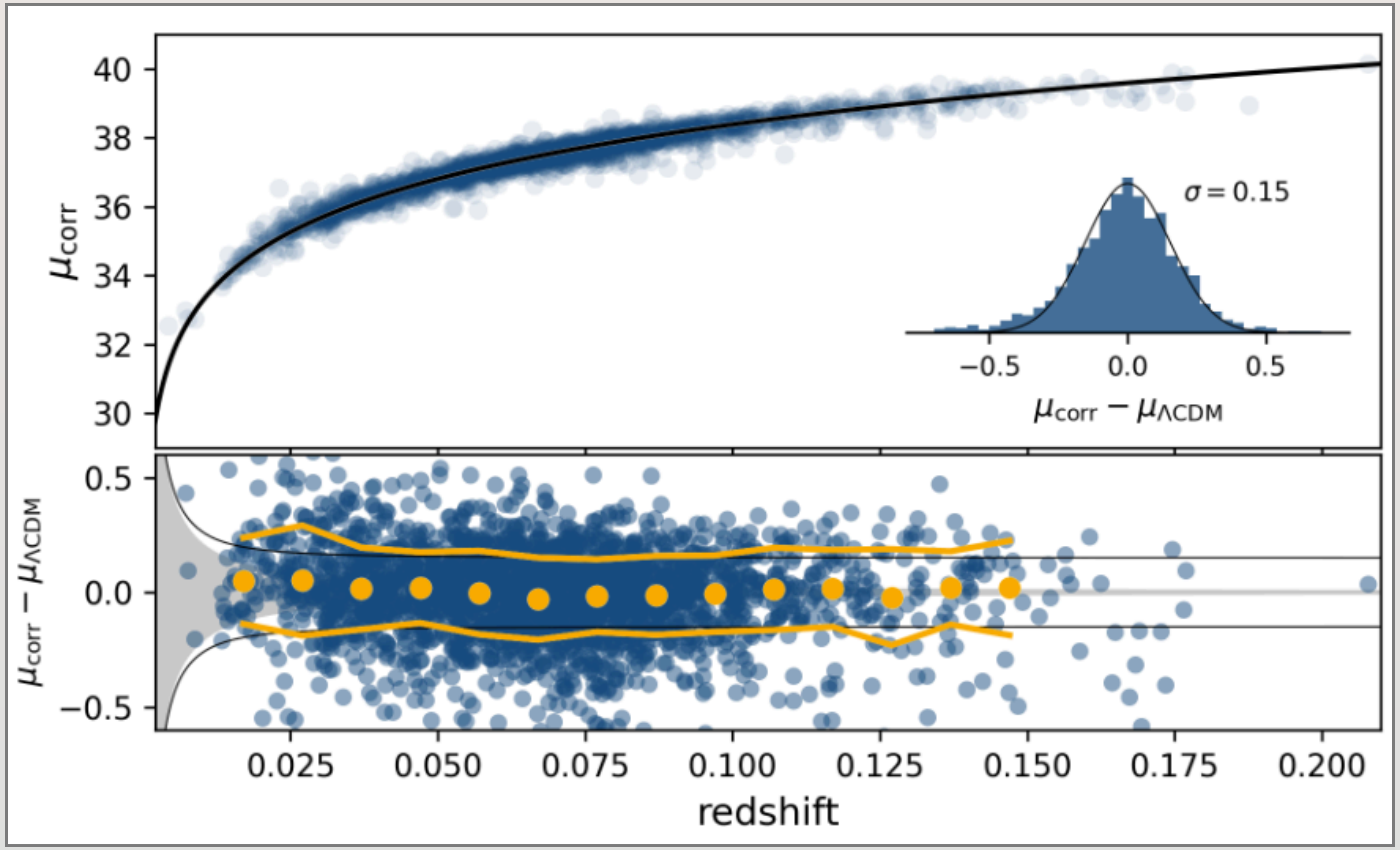
$\overrightarrow{\Delta A_V}$ *the reddening coefficients ,*

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

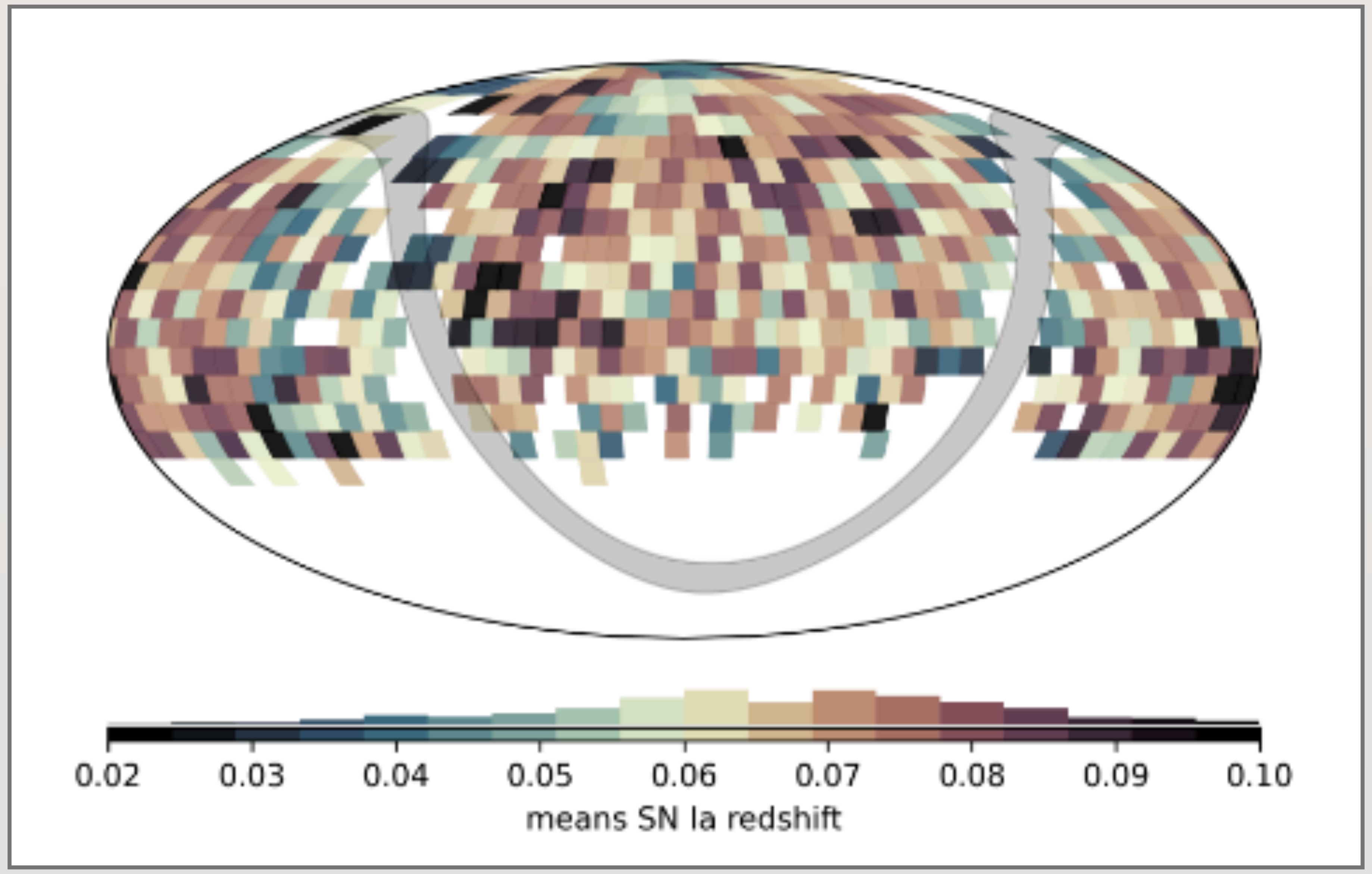
$\vec{\sigma}^2_{p.v.}$ *the host galaxy peculiar velocity variance*

ZTF - DR2

March 2018 to December 2020



2622 standardized SNe Ia, after minimal cuts
Credit : ZTF "DR2" Overview paper, Rigault et al.



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