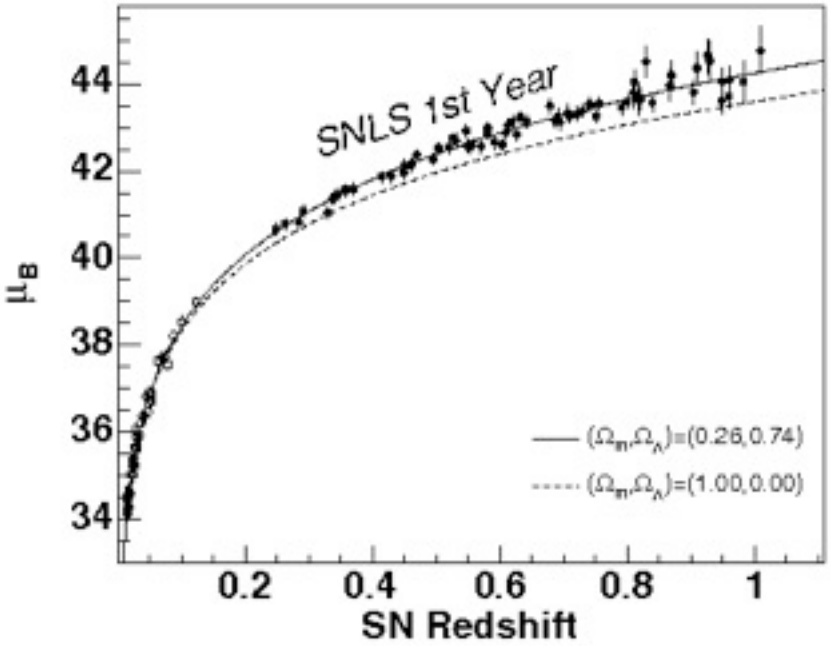
The extinction law of Type Ia Supernovae

The Nearby Supernovae Factory

CHOTARD Nicolas
HEP 2011
22 / 07

Outlook



Introduction

- ✴Observational cosmology with SNe Ia
- ✴The Nearby Supernova Factory

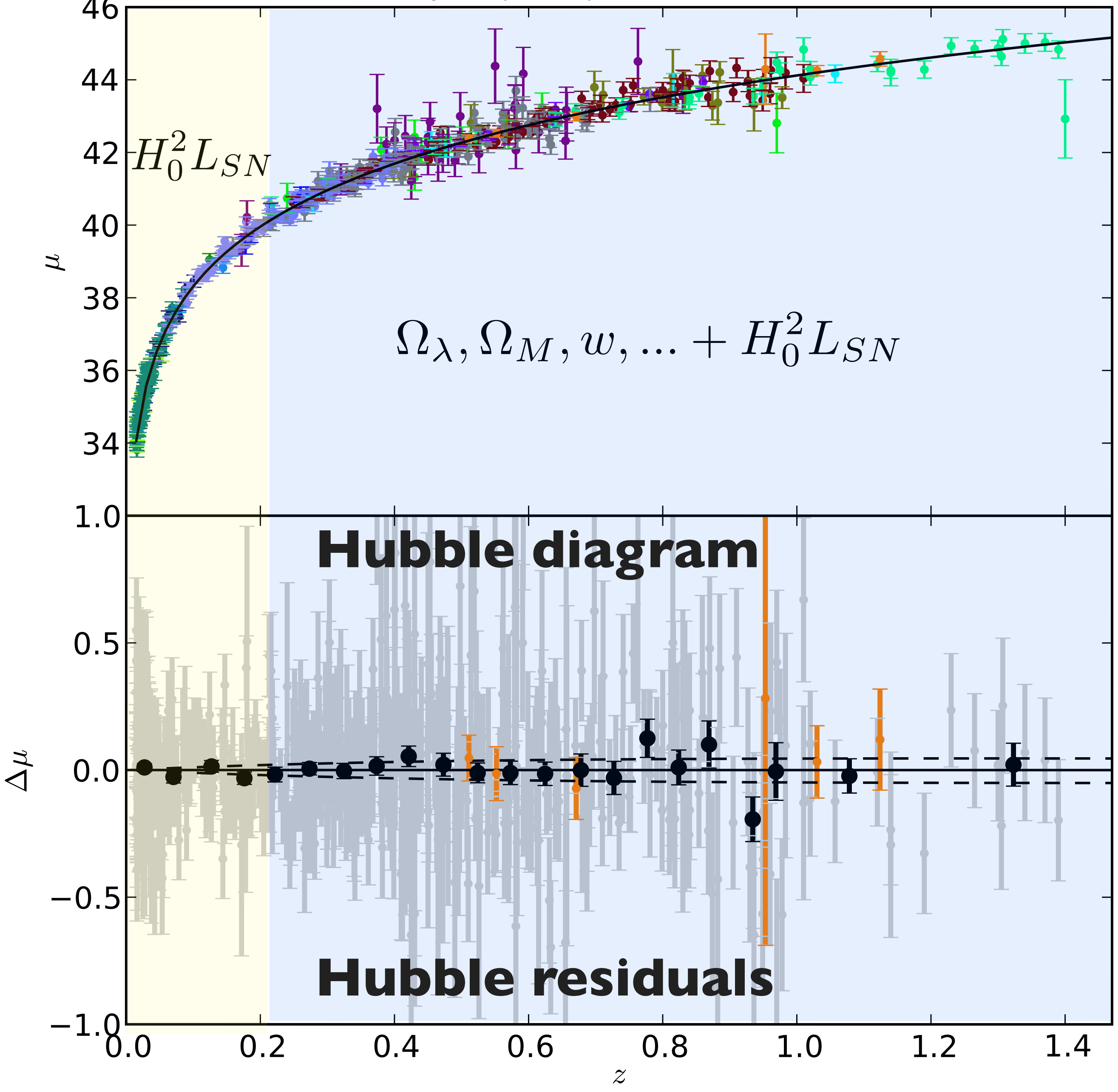
SNe Ia variability

- ✴SNe Ia and extinction law
- ✴Spectral analysis
- ✴Empirical extinction law construction

Chotard, et al., A&A. (2011)

Observational cosmology with SNe Ia

Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)



Amanullah, et al., Ap.J. (2010)

- **Hubble diagram :** distance modulus vs. redshift

$$\mu_B = m_B - M_B = 5log(d_L) - 5$$

- **High-z SNe:** cosmological parameters (in d_L)
- **Nearby SNe:** constrain the degeneracy between cosmology and SNe Ia luminosity

- **High quality data** of low redshift SNe Ia needed to reduce systematics
- **Optimal redshift** centered around 0.05 : **Hubble flow** (Linder 06)

↓

SNFactory

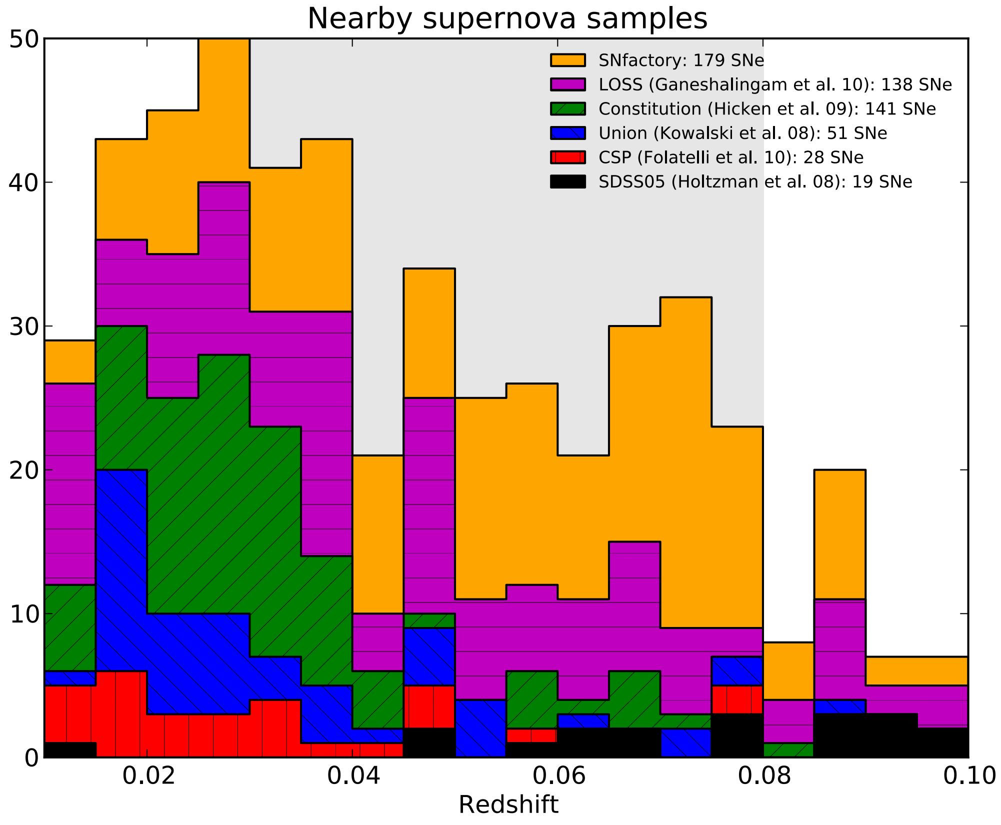
The Nearby Supernovae Factory

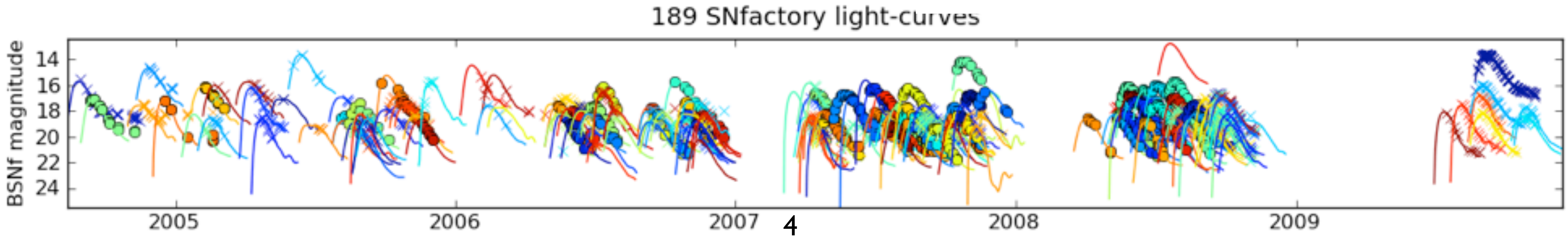
Main Goals

- Increase the nearby SNe Ia sample ($0.03 < z < 0.08$)
- Large sample of flux calibrated spectral time series: control of systematic and standardization
- **SNe Ia physics:**
  - constrain the models with high quality spectra at multiple phases,
  - **spectral properties, extinction study**, host analysis,...

Data sample

- **~200 SNe** with more than 5 spectra
- **~3000 spectra** from -15 to +40 days / max
- redshift coverage from 0.01 to 0.1, median is 0.06
- median phase of 1st spec: -2
- mean cadence of observation: ~3 days
- spectral coverage 3000 - 9000 Å





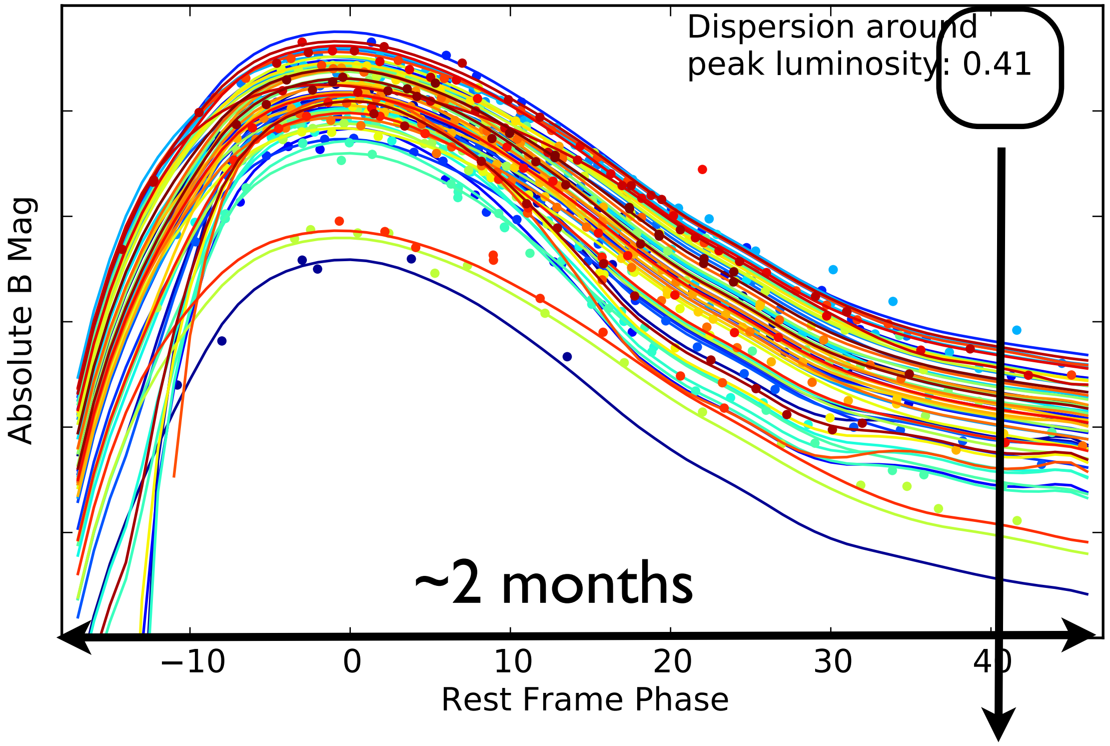
SNe Ia : quasi-standard candles

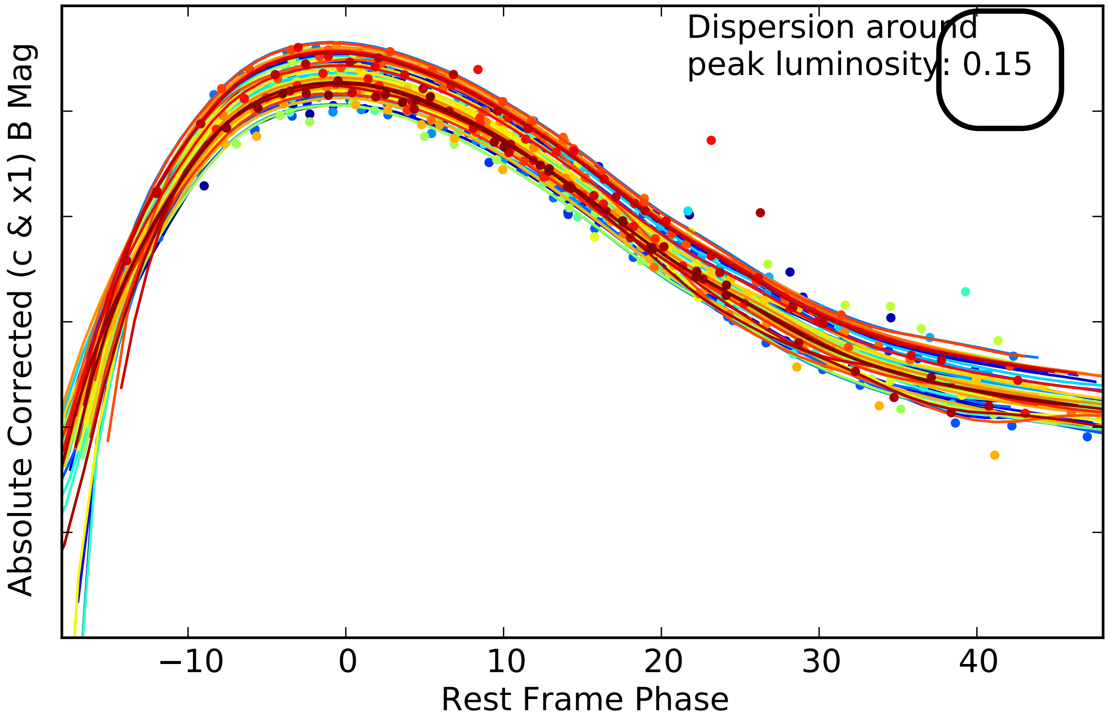
Homogeneity

- similar progenitor (white dwarf)
- similar mass - similar luminosity (Chandrasekhar mass)
- but dispersion **~0.4 mag without any correction**

Variability

- intrinsic:
  - *progenitor composition (metallicity),*
  - *progenitor explosion (^{56}Ni mass, viewing angle)*
- extrinsic: *mainly driven by the host ISM extinction*
- evolution effects: *galaxy properties*





Empirical corrections to reduce the dispersion:

- *light curve width : Δm15, stretch, x1* *BRIGHTER - SLOWER*
- *color: B-V at max, salt2 color* *BRIGHTER - BLUER*

In the SALT2 formalism: $\mu_B = m_B - M_B + \alpha x_1 - \beta c$

Guy, et al., A&A. (2007)

➡ dispersion reduced to 0.15 mag

Dust extinction

- **Dust** in the ISM responsable for an **extinction**, **function of the wavelength**

- A **2 parameters law**:
  - dust properties: $\mathbf{R_V}$
  - amount of dust: **E(B-V)**

$$\boxed{R_V = \frac{A_V}{E(B-V)}}$$

- **Cardelli extinction law:**

  Cardelli, Clayton, Mathis, ApJ. (1989)

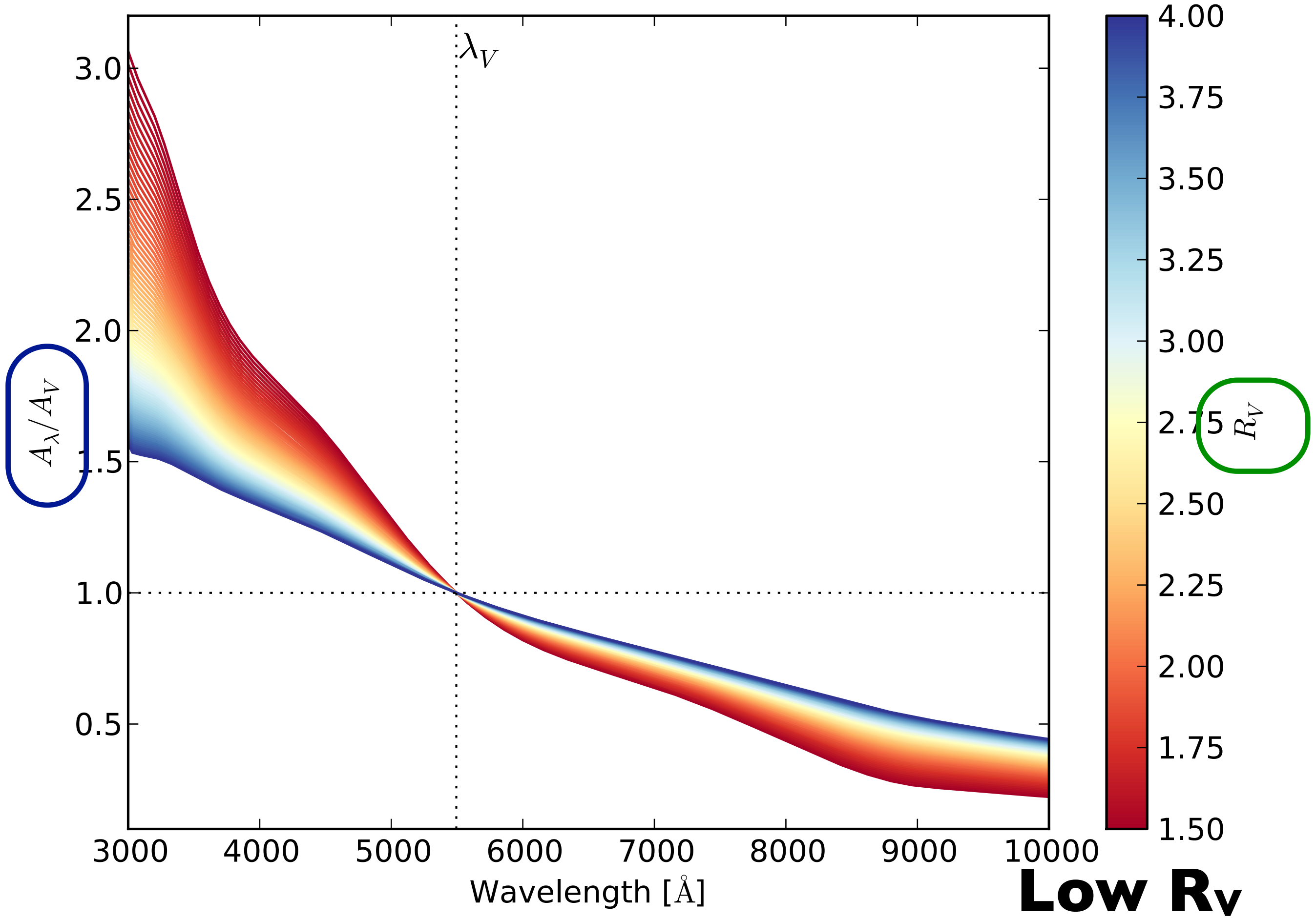
$$A_\lambda = E(B-V) \times (R_V \times a_\lambda + b_\lambda)$$

a_λ et b_λ, given parameters

$$\boxed{\frac{A_\lambda}{A_V}} = a_\lambda + \frac{b_\lambda}{\boxed{R_V}}$$

High $\mathbf{R_V}$

extinction more grey

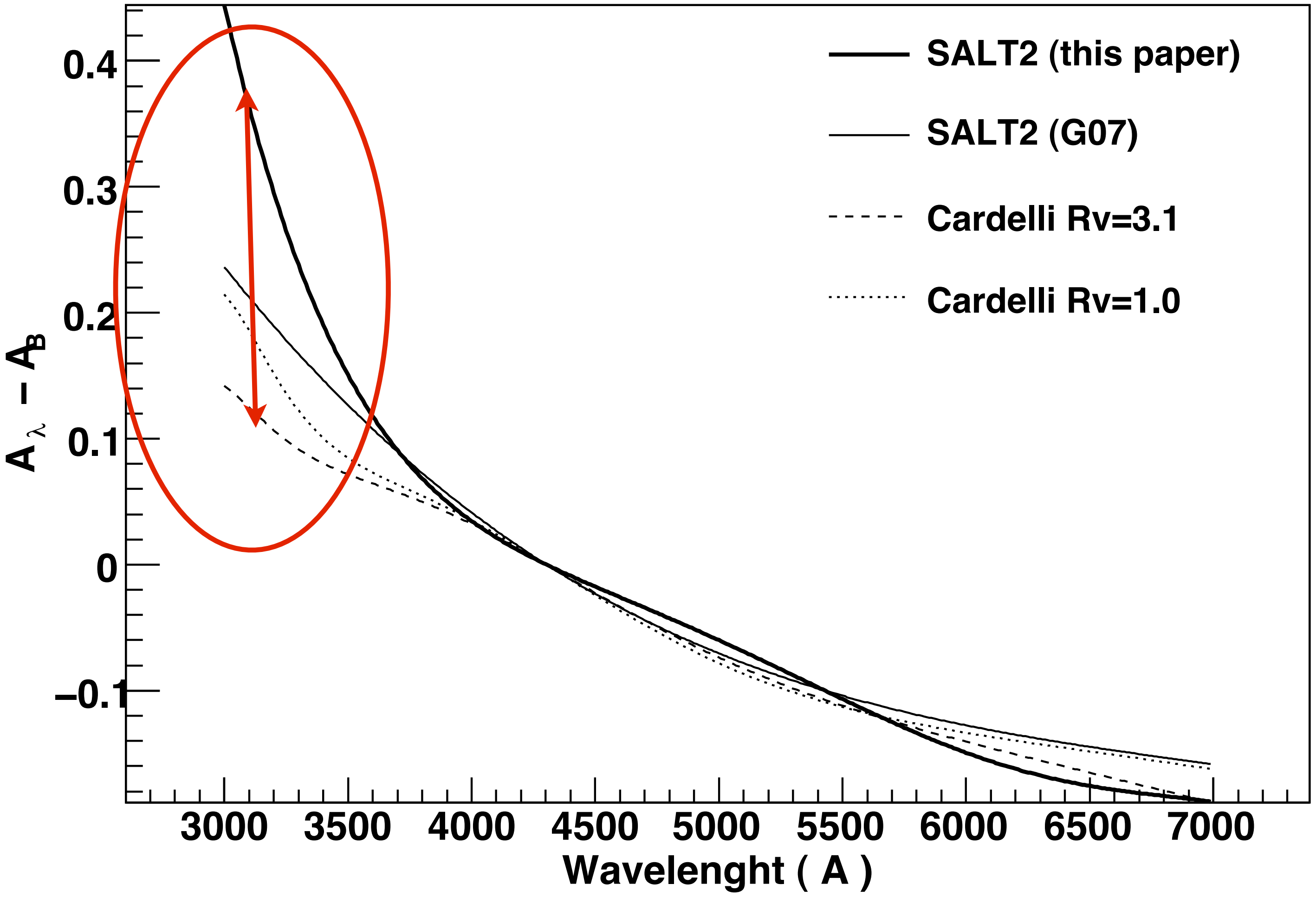


Low $\mathbf{R_V}$

UV extinction, **reddening**

Which extinction law for SNe Ia?

- **SNe Ia dispersion dominated by extinction variability**
- **Recurrent issue** in SNe Ia analysis: measurement of the **extinction law or 'Rv'**
- Nearby SNe independant from cosmology: direct estimate of the absorption



Guy, et al., A&A. (2010)

- SALT2 *(Guy07)* : β=1.8 ('Rv=0.8')
- MLCS2k2 *(Hicken09)* : Rv= 1.7
- SNLS 3 years *(Guy10)*: β=3.2 ('Rv=2.2')
- Some other analysis : 1.5 < Rv < 2.5
- Our galaxy : Rv = 3.1

Lower values than the Milky Way one usually found

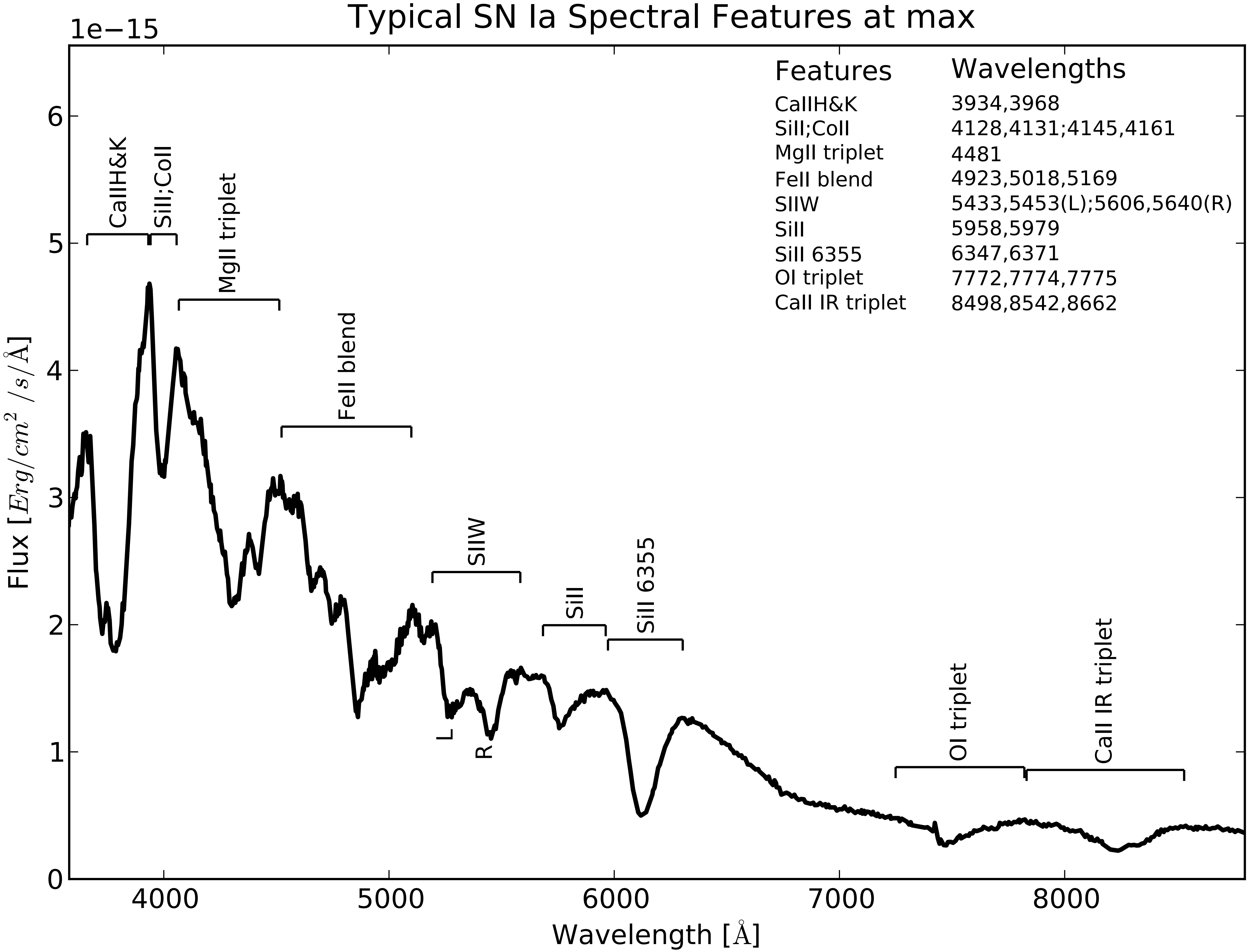
+

Large dispersion in these values

Difficulty: SNe Ia variability is a **mix of intrinsic + extrinsic** components

Our Solution : Measure the **intrinsic variability** with **spectral indicators**

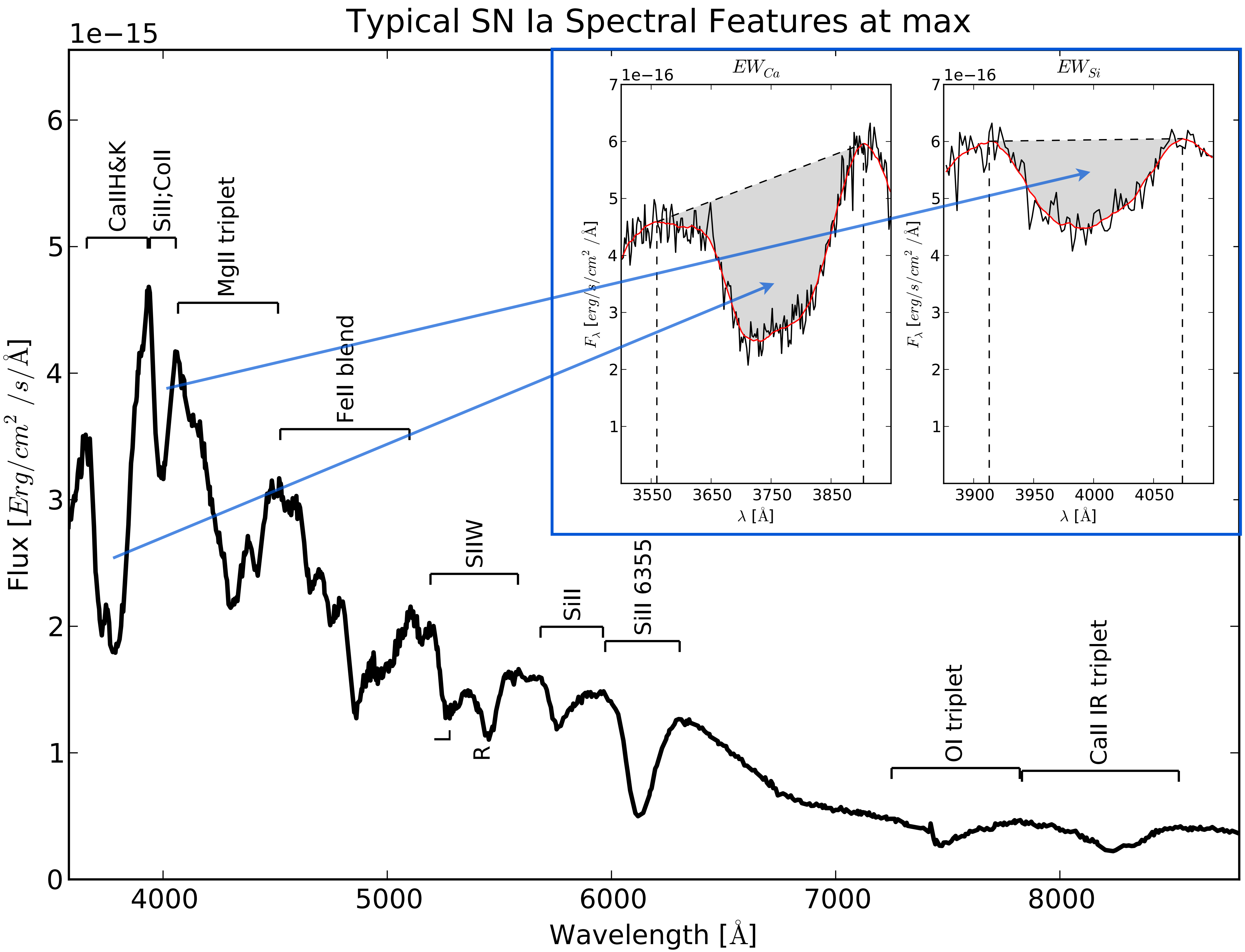
Spectral analysis at max



Typical SN Ia Spectral Features at max

Features	Wavelengths
CaIIH&K	3934,3968
SiII;CoII	4128,4131;4145,4161
MgII triplet	4481
FeII blend	4923,5018,5169
SIIW	5433,5453(L);5606,5640(R)
SiII	5958,5979
SiII 6355	6347,6371
OI triplet	7772,7774,7775
CaII IR triplet	8498,8542,8662

Spectral analysis at max



Spectral analysis at max

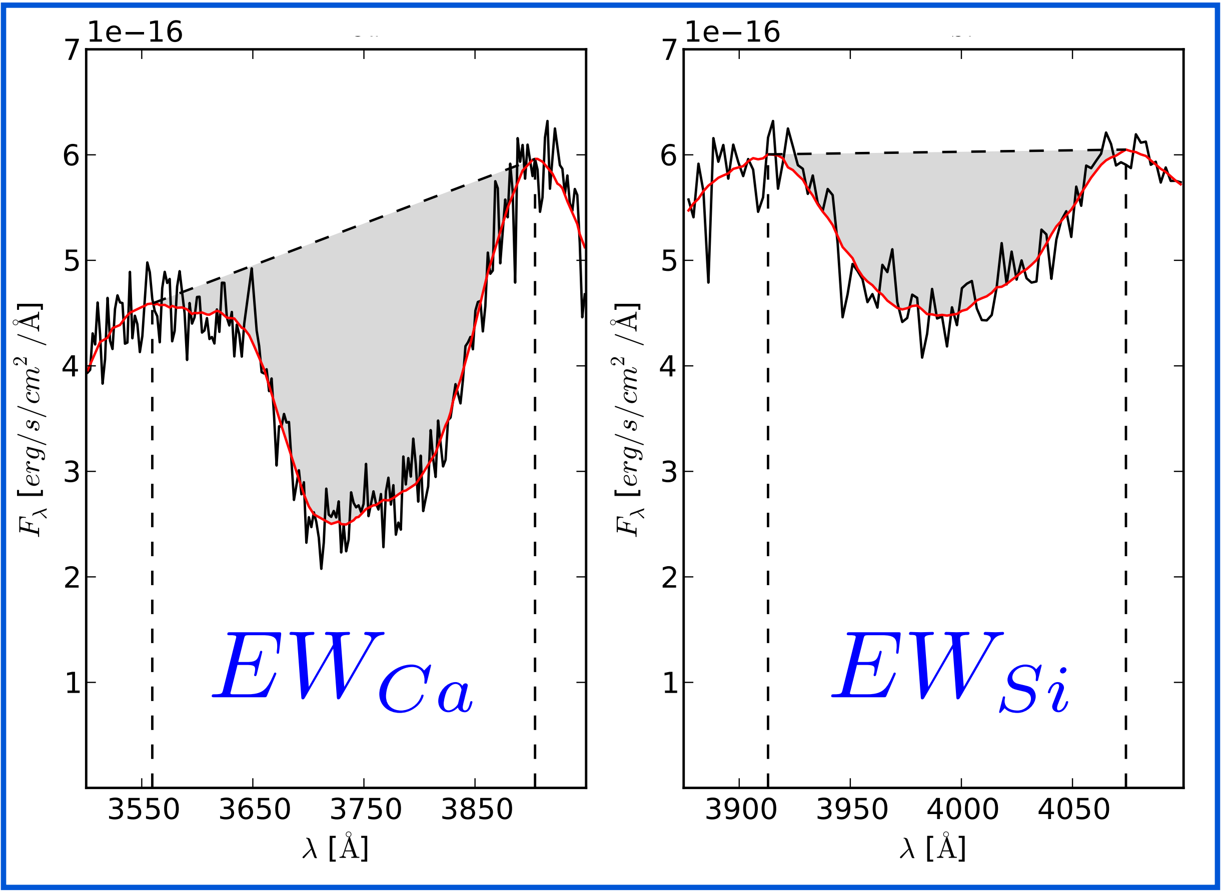
Equivalent widths:

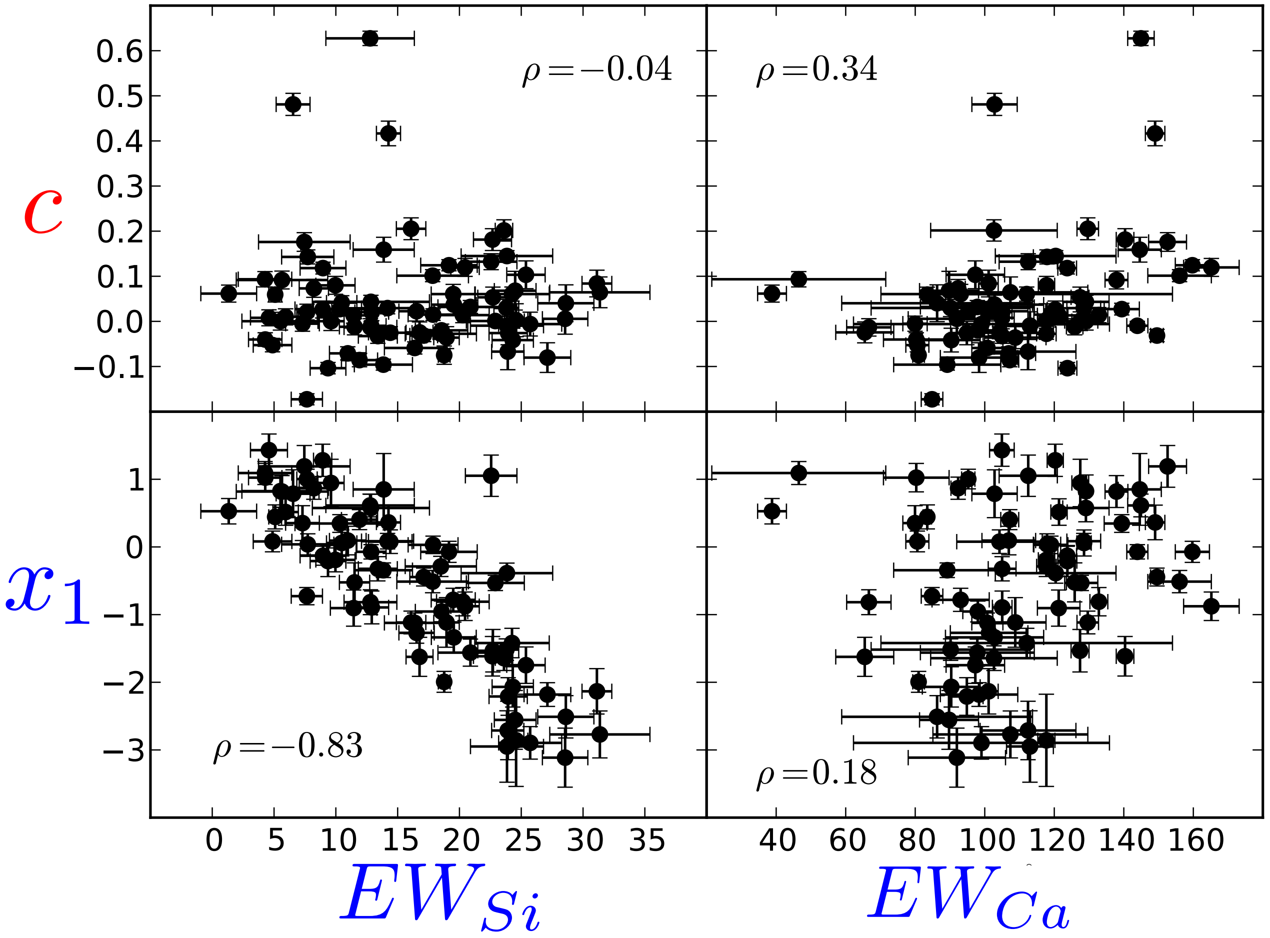
$$EW = \sum_{i=1}^{N} \left(1 - \frac{f_\lambda(\lambda_i)}{f_c(\lambda_i)}\right) \Delta\lambda_i$$

- ✴ Insensitive to dust extinction (less than 2%)

Ca and Si:

- ✴ Correlated to absolute magnitude (and stretch)
- ✴ Measurement of the **intrinsic** part of the **variability**





Sample: 76 SNe Ia which have

- ✴ a good phase sampling
- ✴ a spectrum at max (+/- 2.5 days around max)

Measurements (*on each spec at max*):

- ✴ EWs *(Si and Ca)*
- ✴ absolute magnitudes *(Hubble residuals)*

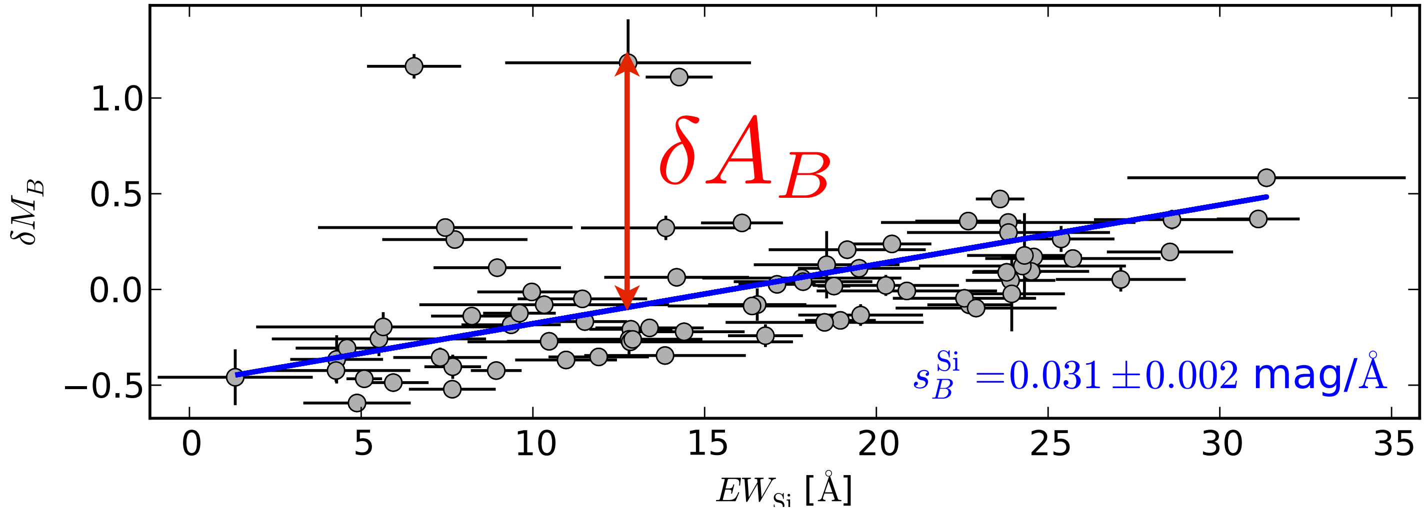
2 set of filters:

- ✴ 5 broad synthetic filters (UBVRI-like)
- ✴ 200 narrow synthetic filter («spectral»)

Separating the variabilities

GOAL : Construct a mean extinction law for SNe Ia

1st step : Decompose the Hubble residuals into intrinsic variabilities and relative absorptions δAλ (up to a constant term)



Three cases :

(a) SNe Ia are **perfect candles** : purely extrinsic variability

(b) Intrinsic variability described by a **«stretch-like» parameter** : EW^{Si}

(c) Intrinsic variability described by **two parameters**: EW^{Si} and EW^{Ca}

Hubble residuals

$$\delta M_\lambda = \begin{cases} \delta A_\lambda^0 & (a) \\ s_\lambda^{\rm Si}{\rm EW}^{\rm Si} + \delta A_\lambda^{\rm Si} & (b) \\ s_\lambda^{\rm Si}{\rm EW}^{\rm Si} + s_\lambda^{\rm Ca}{\rm EW}^{\rm Ca} + \delta A_\lambda^{\rm Si+Ca} & (c) \end{cases}$$

No correction

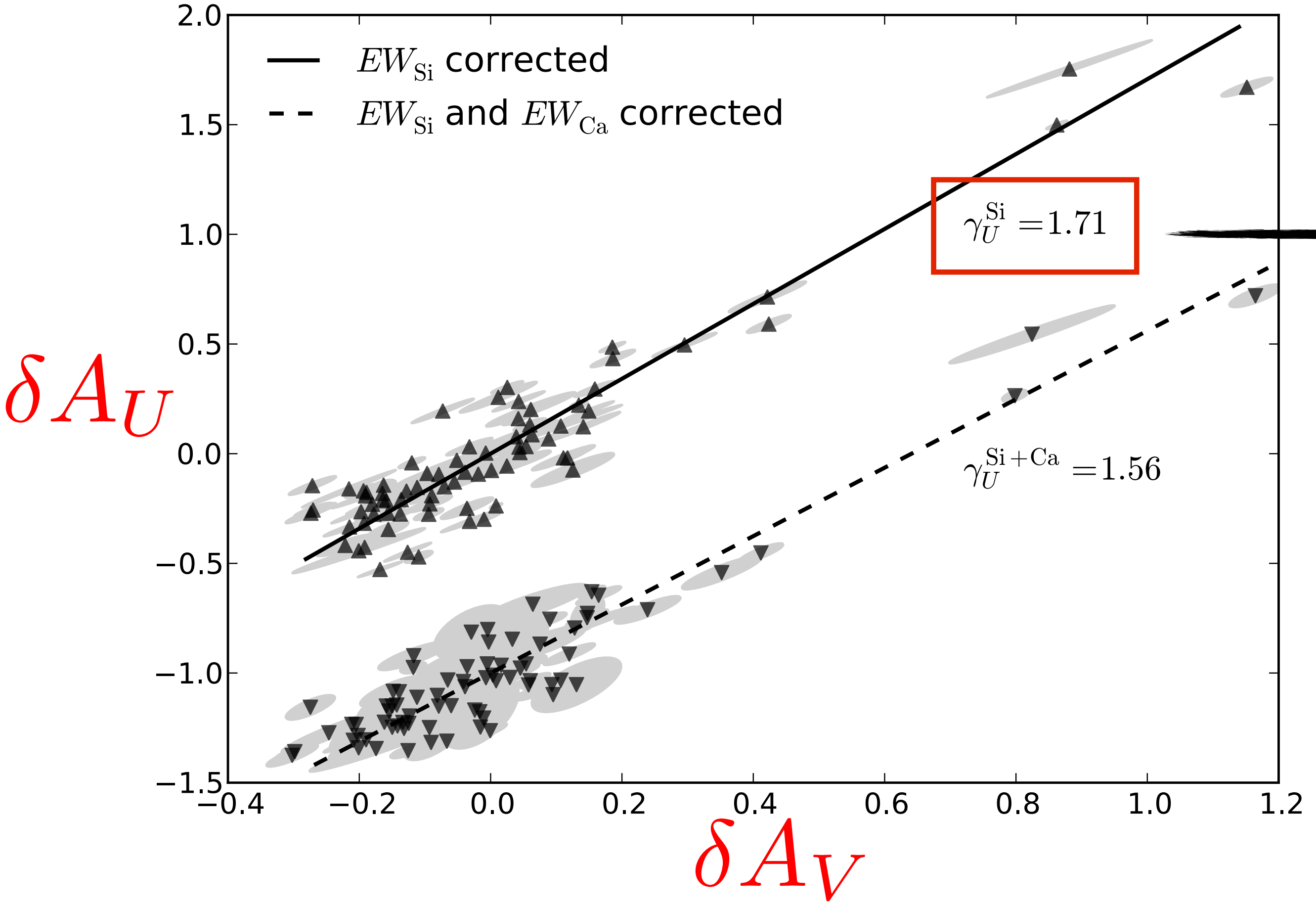
One intrinsic correction

Two intrinsic corrections

Construct the extinction law

GOAL : Construct a mean extinction law for SNe Ia

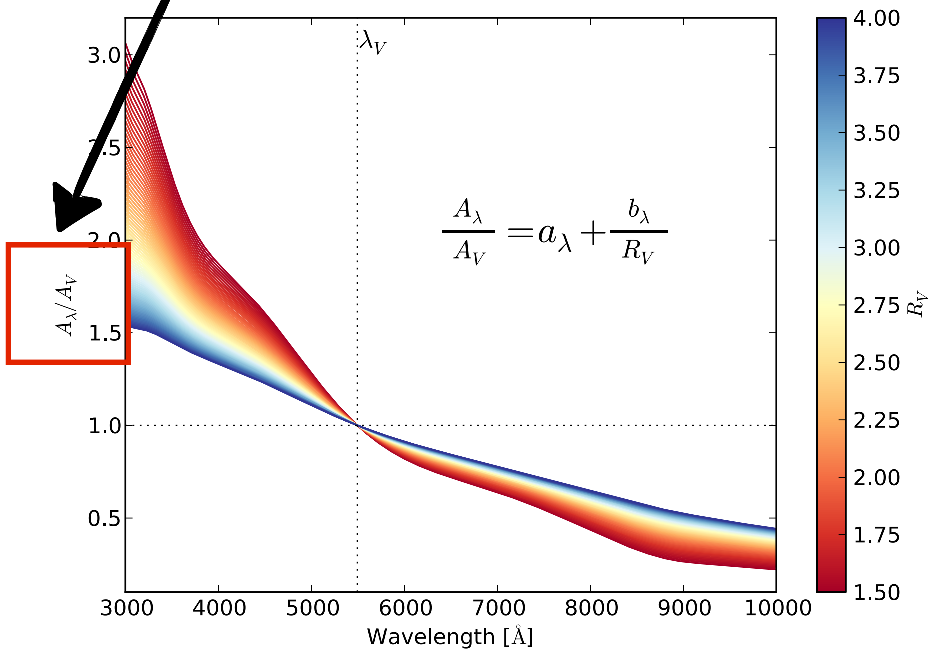
1st step : Decompose the Hubble residuals into intrinsic variabilities and relative absorptions δAλ (up to a constant term)
2nd step : Use the relation between the δAλ to construct the law



Linear model

Slopes

$$\delta A_\lambda(i) = \boxed{\gamma_\lambda}\, \delta A_V^*(i) + \eta_\lambda$$

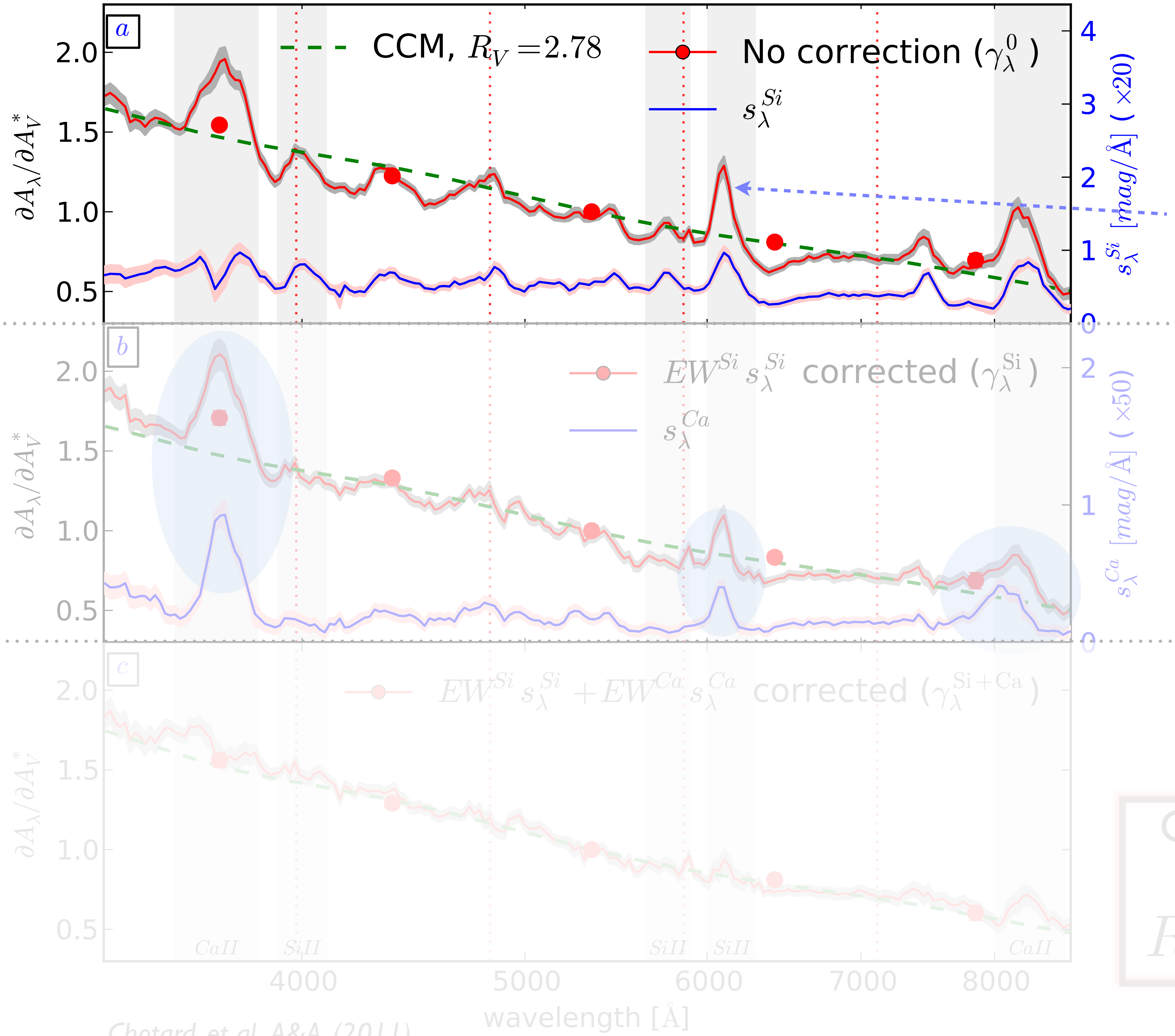


Estimation of Rv when forcing :

$$\boxed{\gamma_\lambda \equiv \frac{A_\lambda}{A_V} = a_\lambda + \frac{b_\lambda}{R_V}}$$

Cardelli extinction law

Results on the γ_λ



Chotard, et al., A&A. (2011)

«Perfect candles» **(a)**

$$\gamma_\lambda \equiv \frac{A_\lambda}{A_V}$$

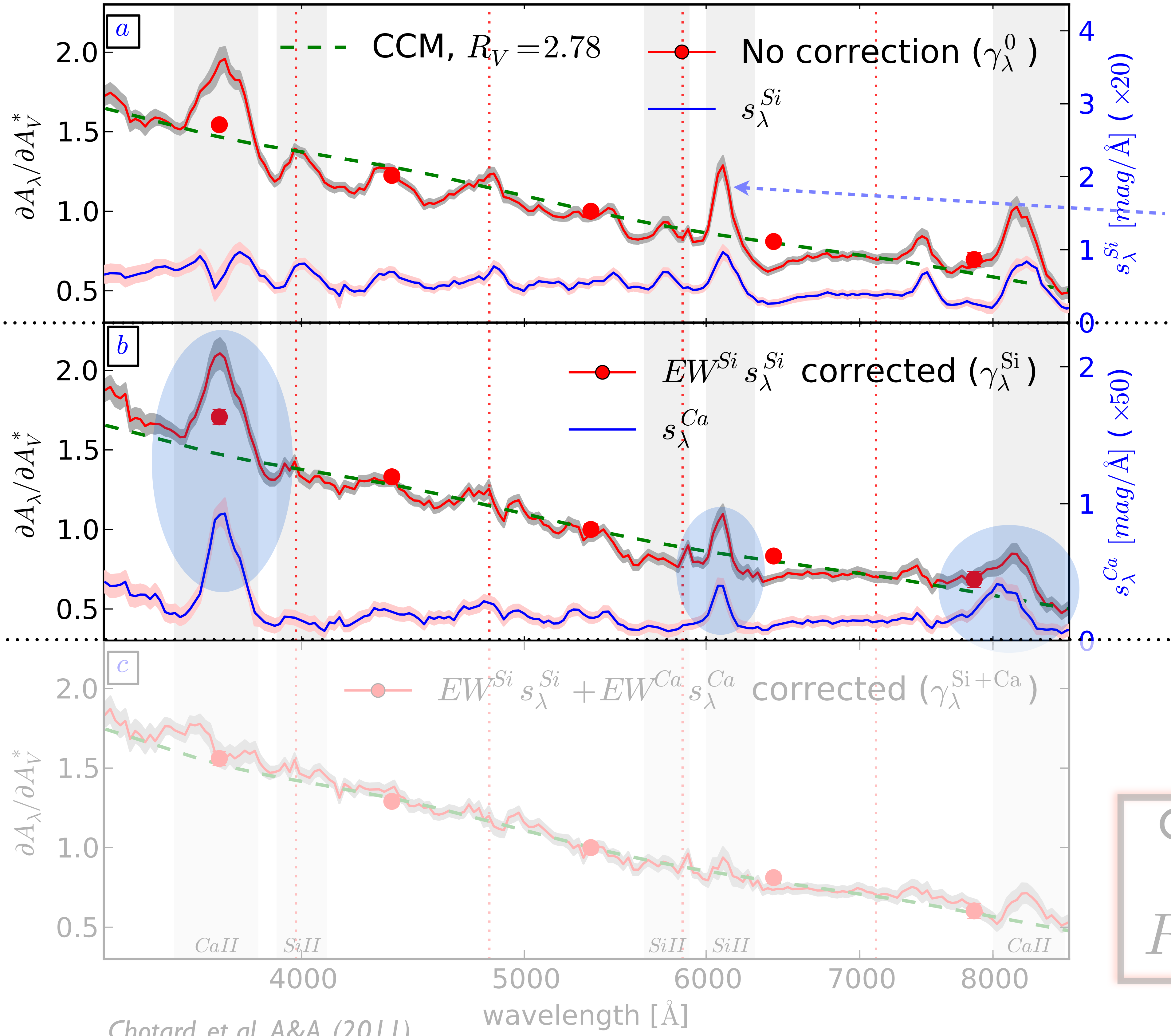
EW^{Si} correction («stretch-like») **(b)**

Residual intrinsic variability!

EW^{Si} and EW^{Ca} corrections **(c)**

Classic extinction law
+
$R_V = 2.8 \pm 0.4$

Results on the γ_λ



Chotard, et al., A&A. (2011)

«Perfect candles» (a)

$$\gamma_\lambda \equiv \frac{A_\lambda}{A_V}$$

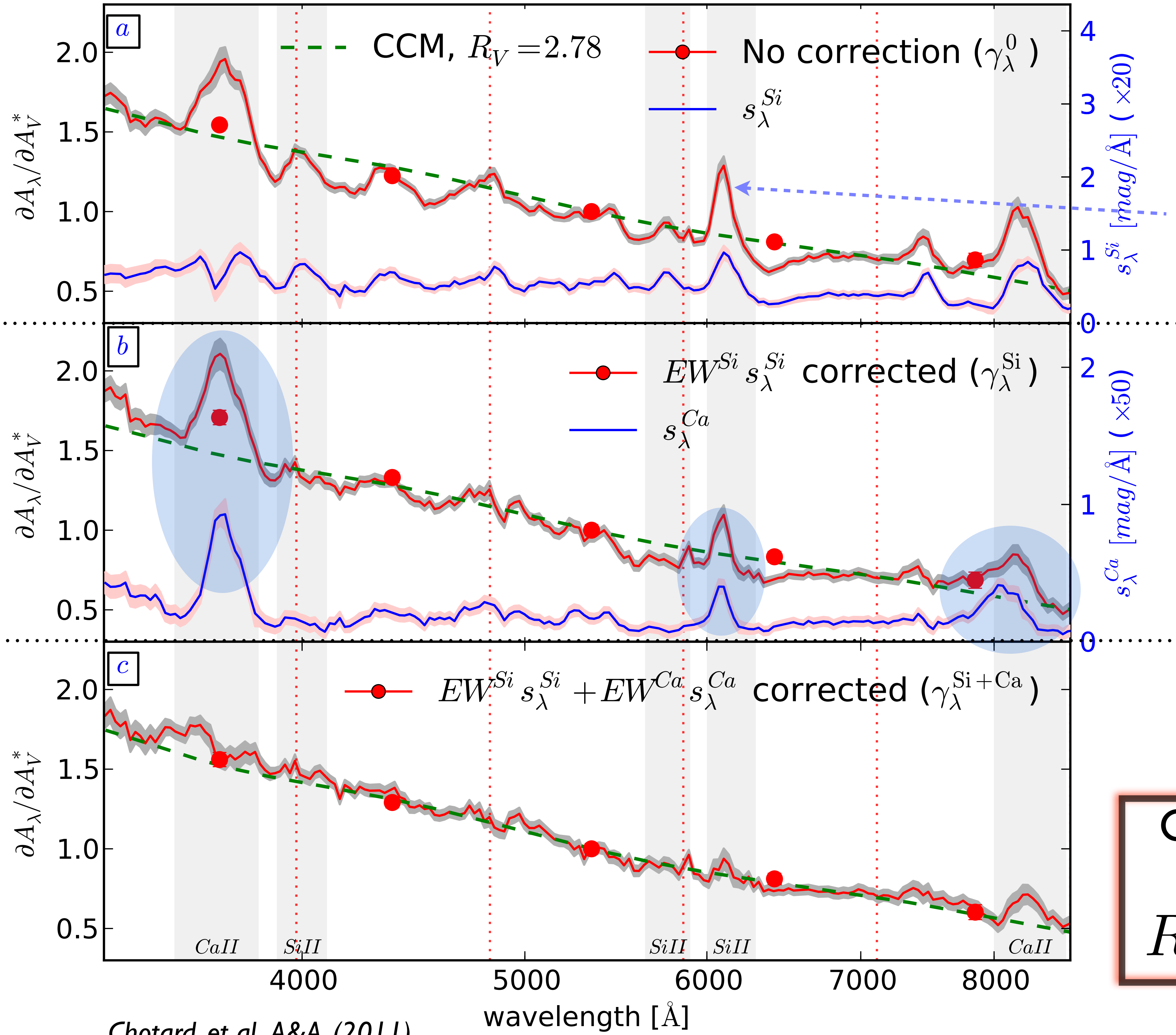
EW$^{\mathrm{Si}}$ correction («stretch-like») (b)

Residual intrinsic variability!

EW$^{\mathrm{Si}}$ and EW$^{\mathrm{Ca}}$ corrections (c)

Classic extinction law
+
$R_V = 2.8 \pm 0.4$

Results on the γ_λ



Chotard, et al., A&A. (2011)

«Perfect candles» (a)

$$\gamma_\lambda \equiv \frac{A_\lambda}{A_V}$$

EW$^{\mathrm{Si}}$ correction (b)
(«stretch-like»)

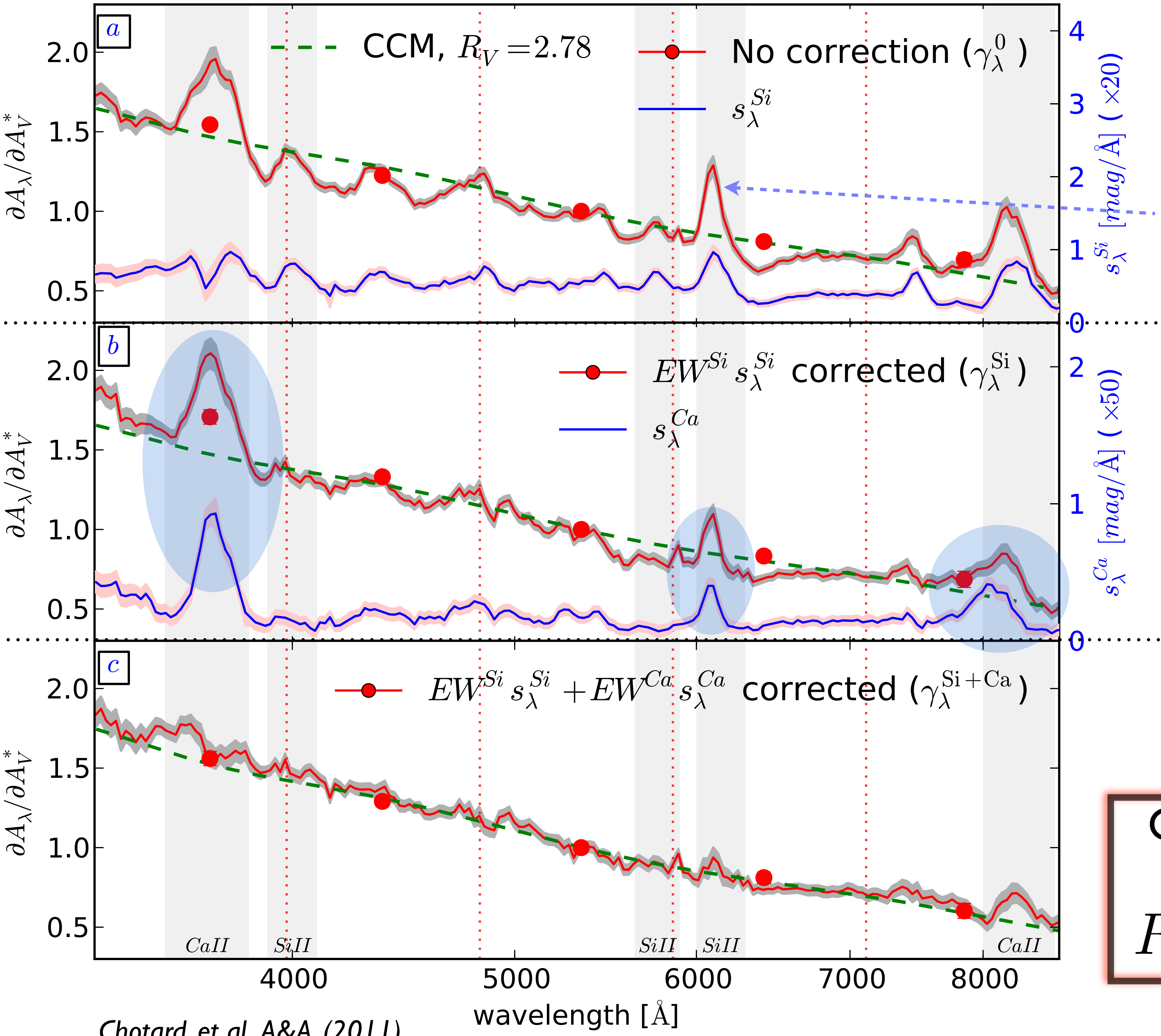
Residual intrinsic variability!

EW$^{\mathrm{Si}}$ and EW$^{\mathrm{Ca}}$ (c)
corrections

Classic extinction law
+

$$R_V = 2.8 \pm 0.4$$

Results on the γ_λ



Chotard, et al., A&A. (2011)

«Perfect candles» (a)

$$\gamma_\lambda \equiv \frac{A_\lambda}{A_V}$$

EW$^{\mathrm{Si}}$ correction («stretch-like») (b)

Residual intrinsic variability!

EW$^{\mathrm{Si}}$ and EW$^{\mathrm{Ca}}$ corrections (c)

Classic extinction law
+
$R_V = 2.8 \pm 0.4$

But need to introduce a dispersion into the fit...

Covariance matrix

Why? :

Using the measured covariance matrix only: $X^2 >> 1$

Extra dispersion matrix needed to set the X^2 to 1 (as in all cosmological fits with SNe Ia)

How? : Using the residual $r_\lambda(i)$ to the γ_λ fit to construct the additionnal covariance matrix

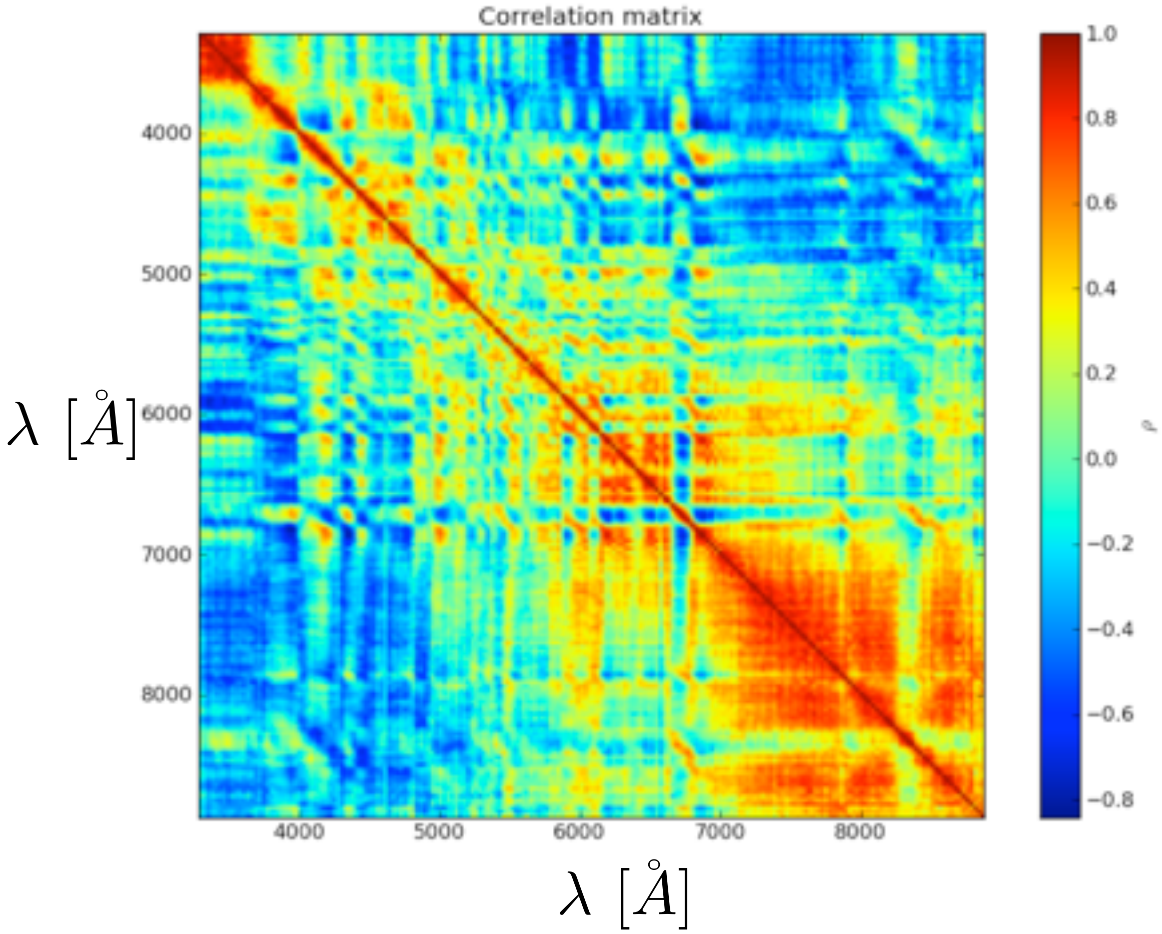
for each of the 3 cases (a,b,c)

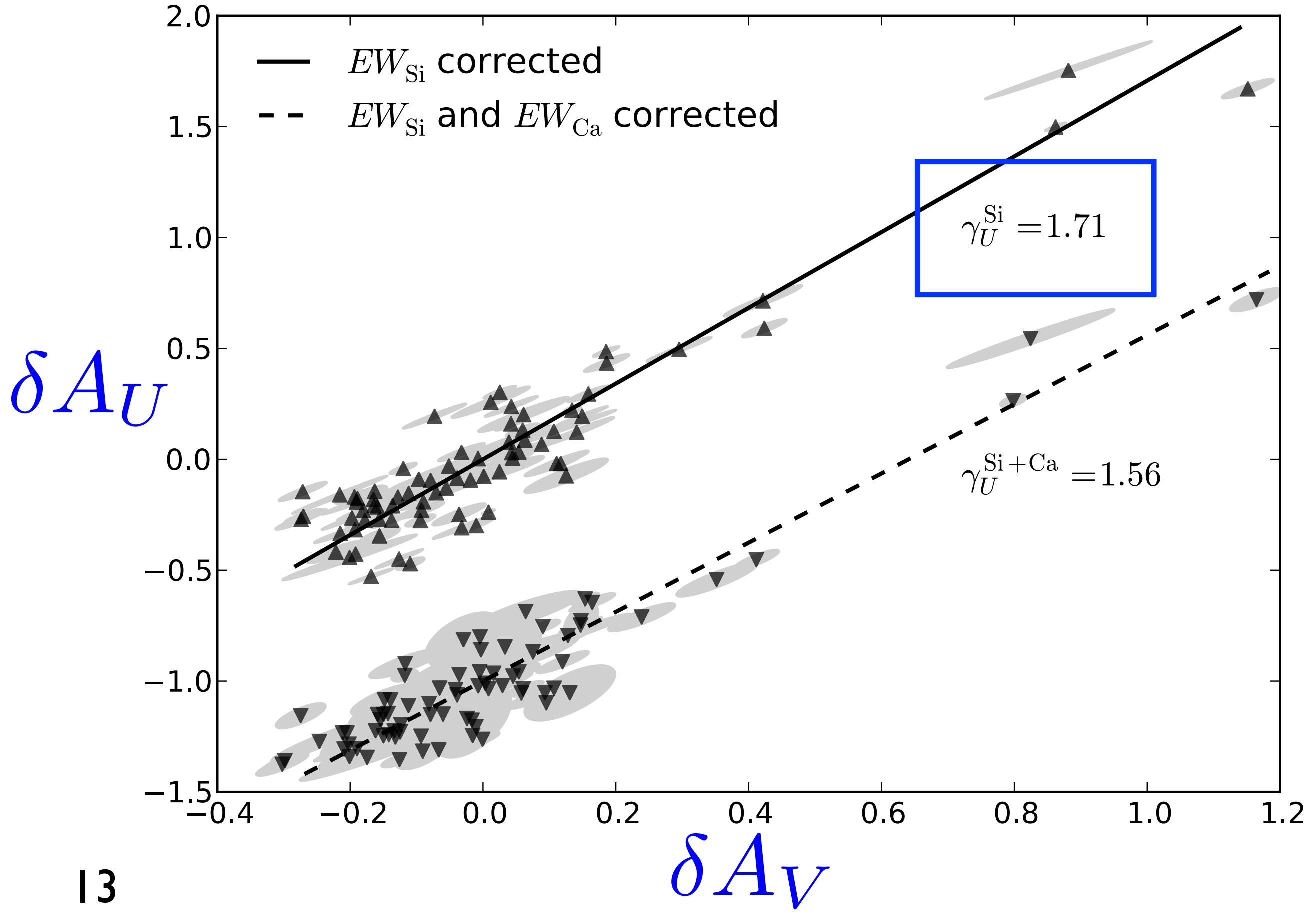
Introduction of a **color dispersion**, not usually used

- Anti-correlation mostly increases with the wavelength differences
- Same pattern for broad filters and narrow band (spectral) correlations

For the case (c): 2 intrinsic corrections

Reminder: $\delta A_\lambda(i) = \gamma_\lambda\ \delta A^*_V(i) + \eta_\lambda\ (+r_\lambda)$





Covariance matrix

Why? :

Using the measured covariance matrix only: $X^2 >> 1$

Extra dispersion matrix needed to set the X^2 to 1 (as in all cosmological fits with SNe Ia)

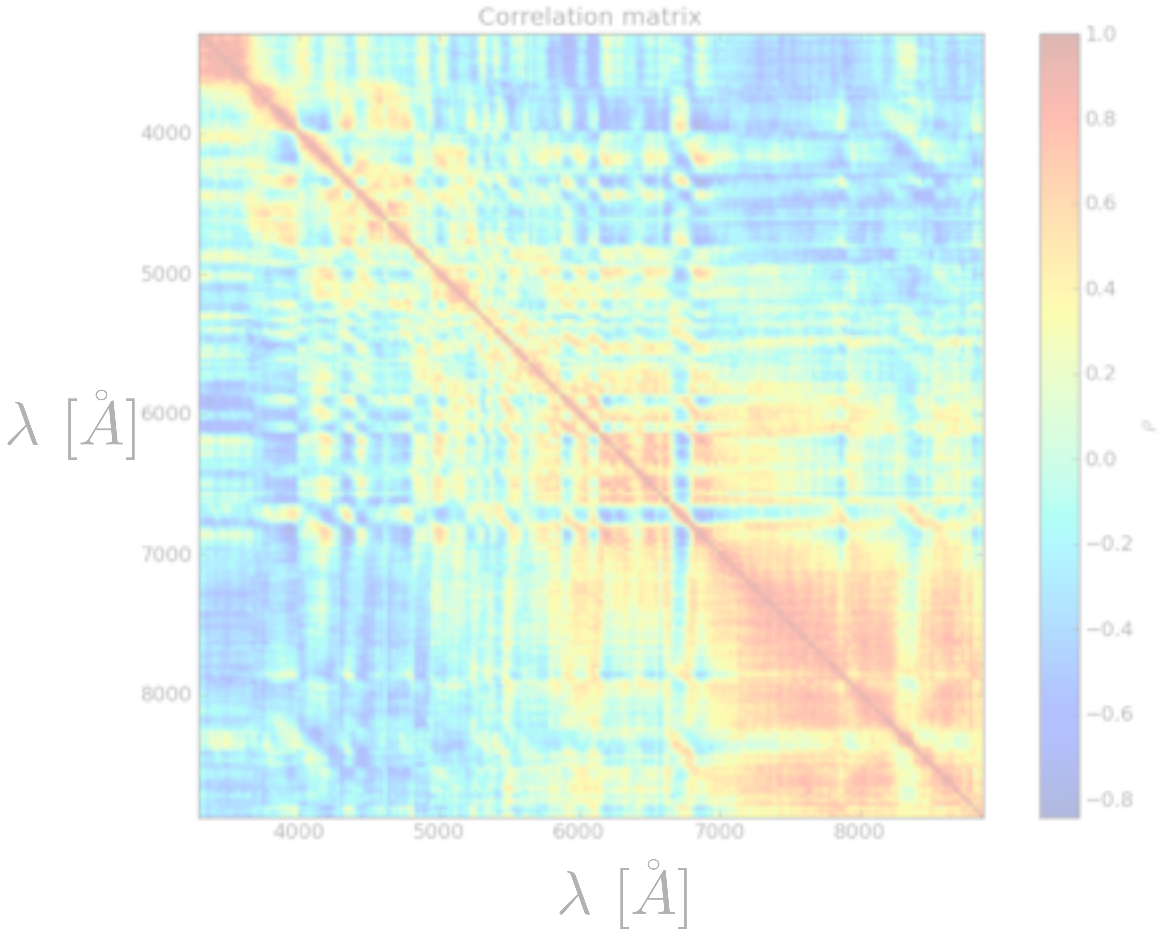
How? : Using the residual $r_\lambda(i)$ to the γ_λ fit to construct the additionnal covariance matrix

for each of the 3 cases (a,b,c)

Introduction of a **color dispersion**, not usually used

- Anti-correlation mostly increases with the wavelength differences
- Same pattern for broad filters and narrow band (spectral) correlations

For the case (c): 2 intrinsic corrections



Reminder: $\delta A_\lambda(i) = \gamma_\lambda\ \delta A_V^*(i) + \eta_\lambda\ (+r_\lambda)$

Intrinsic corrections

+

Dispersion in color

↓

Cardelli-like extinction law

and

Higher value of RV

Conclusion / What's next

Result:

See details in Chotard, et al., A&A. (2011)

- **Two variables** correlated to the **intrinsic variability**
- **Extinction law** compatible with a **Cardelli law**
- **Dispersion in color**
- **Rv value** compatible with the **Milky Way one**

Intrinsic corrections
+
Dispersion in color
↓
Cardelli-like extinction law
and
Higher value of RV

- Better understanding of the SNe Ia intrinsic dispersion and extinction is important to reduce systematic effects in cosmological analysis

Open questions:

- Dispersion: intrinsic or extrinsic residuals variabilities?
- Is the result the same at an other phase?
- Correlation of the matrix to other quantities (spectral variables, host quantities...)?
- ... A lot of further spectral analysis are in progress with the SNFactory spectral sample