The extinction law of Type Ia Supernovae

The Nearby Supernovae Factory

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Outlook

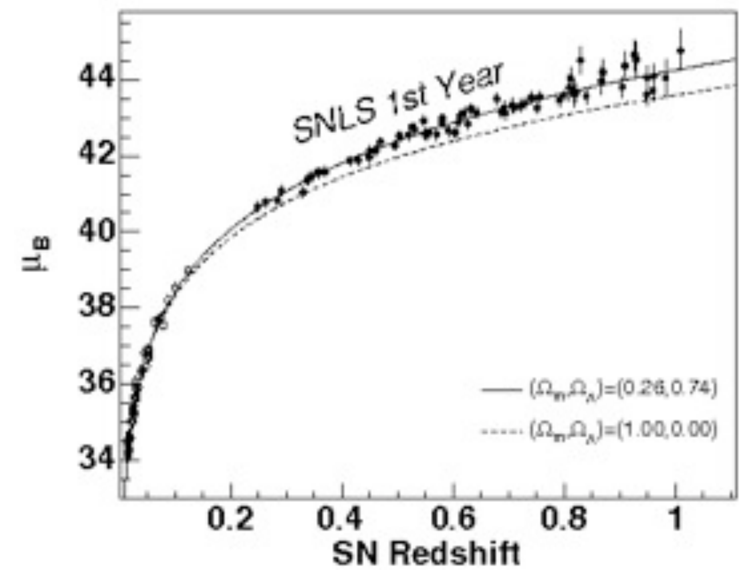
Introduction

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

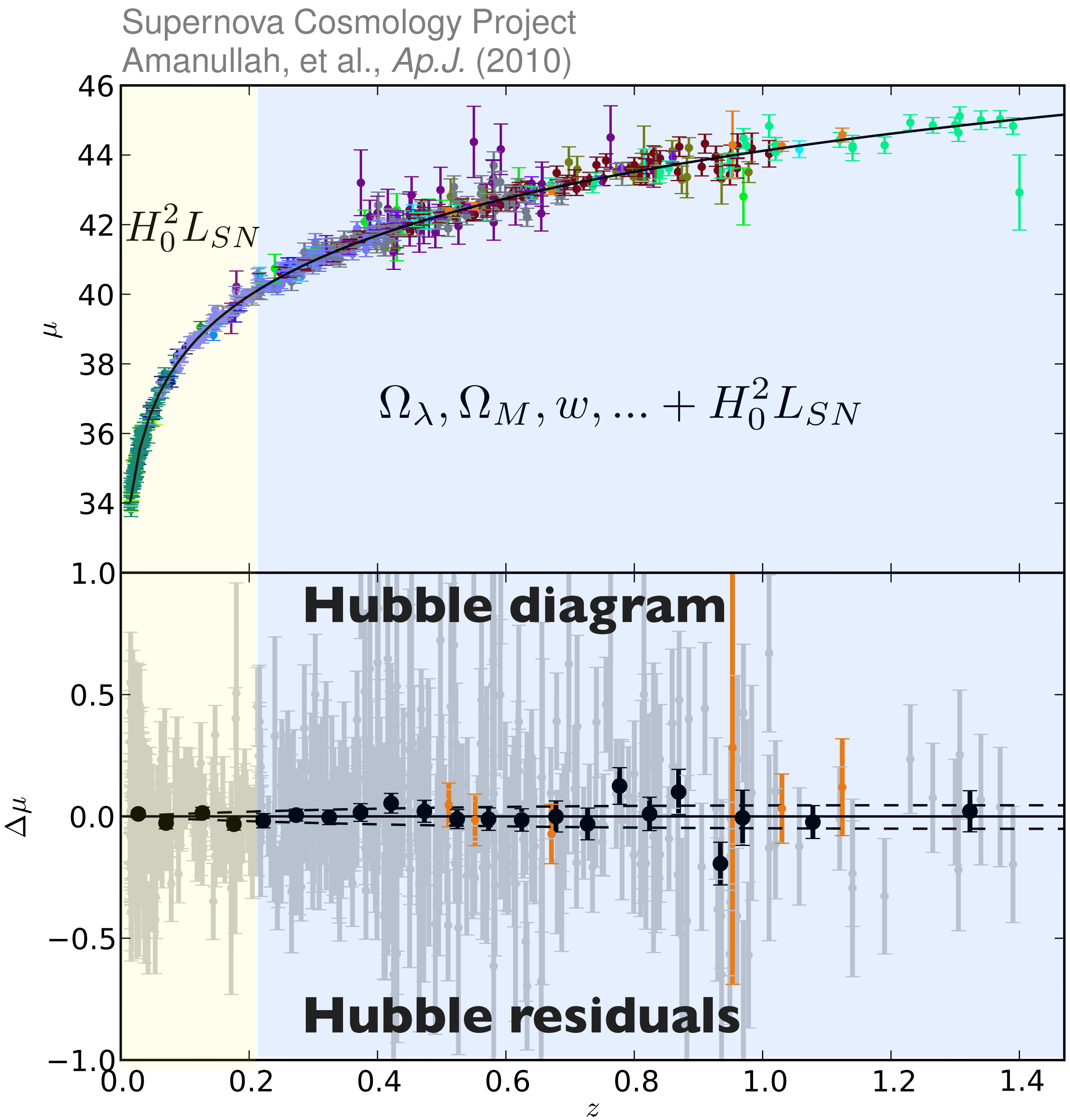
SNe Ia variability

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

Conclusion



Observational cosmology with SNe Ia



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:** expansion and 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

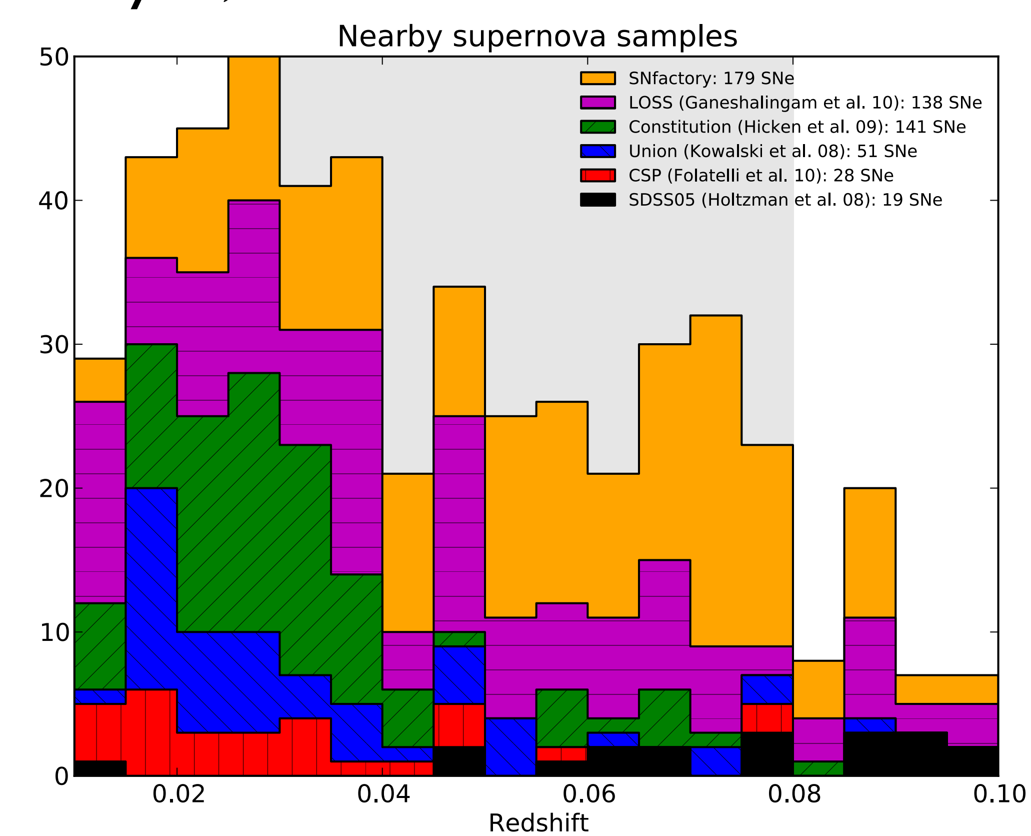
The Nearby Supernovae Factory

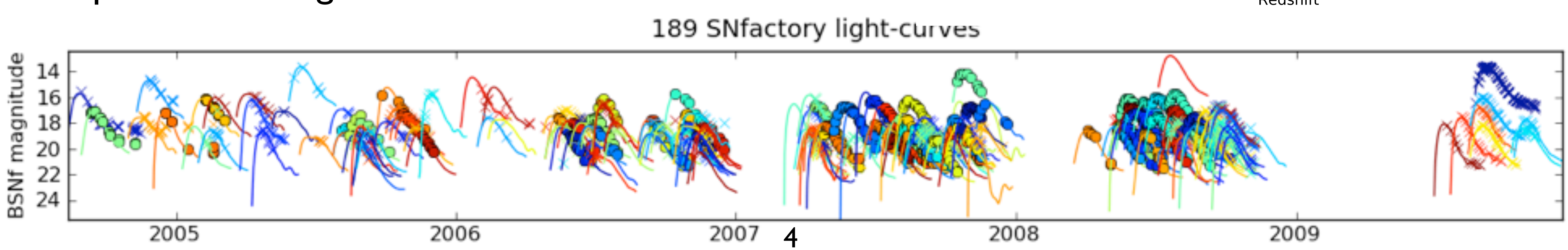
Main Goals

- 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,
  - **spectral properties, extinction study**, host analysis,...

Data sample

- 179 SNe with more than 10 spectra
- ~3000 spectra from -15 to +40 days / max
- redshift coverage from 0.01 to 0.1, median is 0.06
- median first phase: -2
- mean cadence of observation: ~3 days
- spectral coverage 3000 - 9000 Å

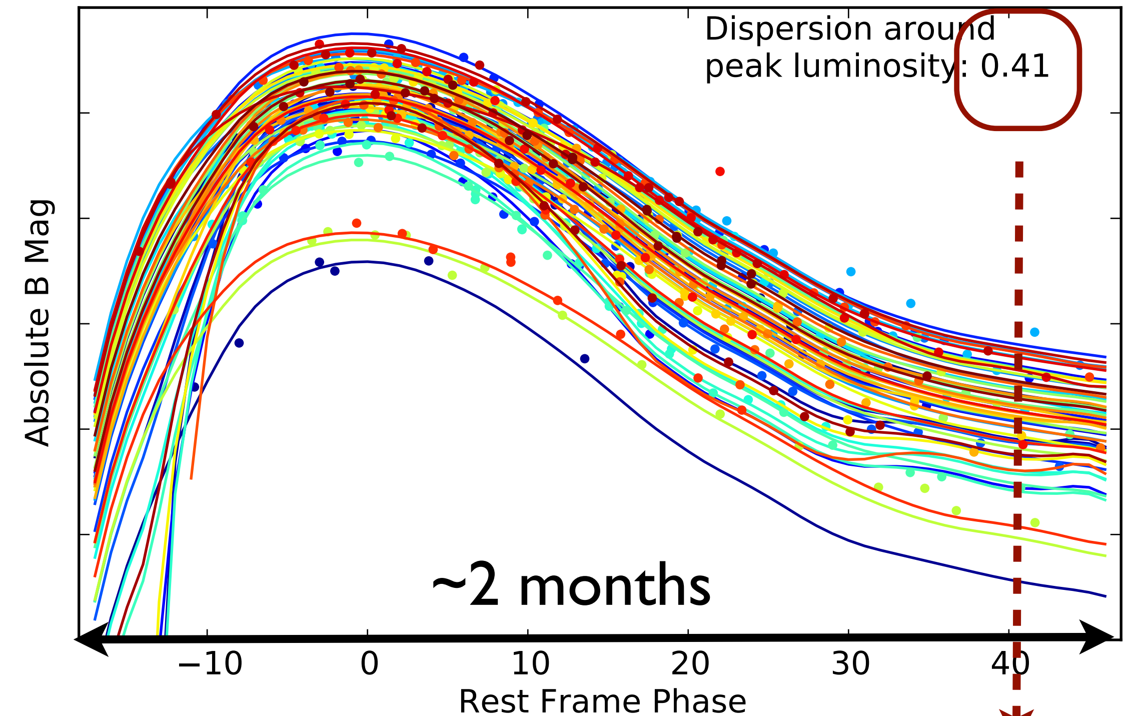




SNe Ia : quasi-standard candles

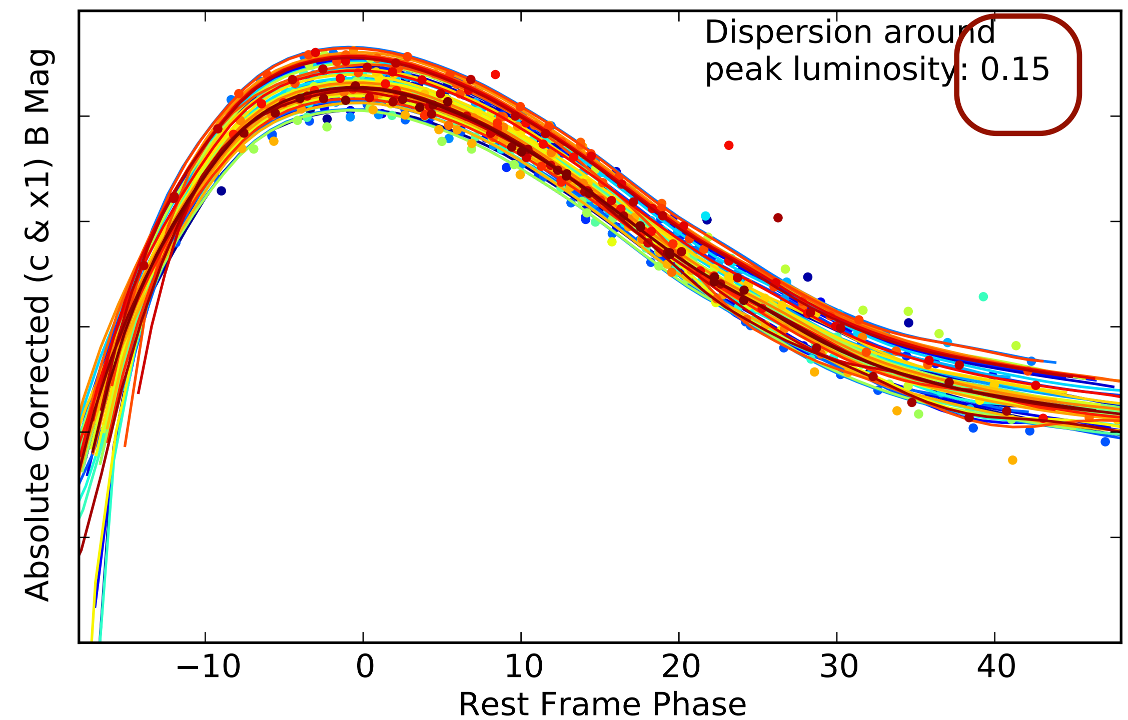
Homogeneity

* similar progenitor (white dwarf)
* similar mass - similar luminosity (Chandrasekhar mass)
* but dispersion around **40% without any correction**



Variability

* Sources of variabilities:
  * **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: $\mu_B = m_B - M_B + \alpha x_1 - \beta c$

➡ 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)**
- **Cardelli extinction law:**

described by:

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

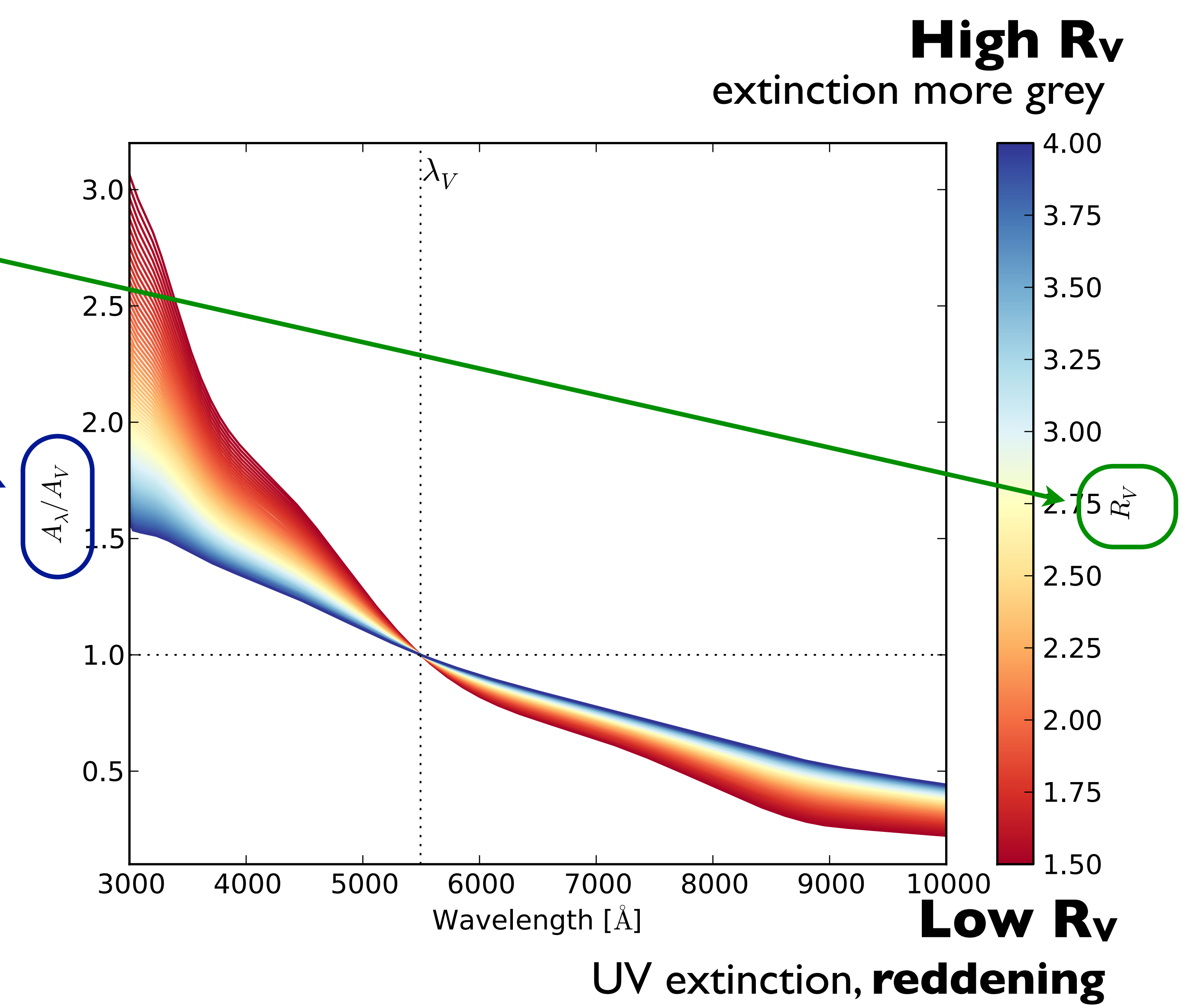
with:

a_λ et b_λ, given parameters

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

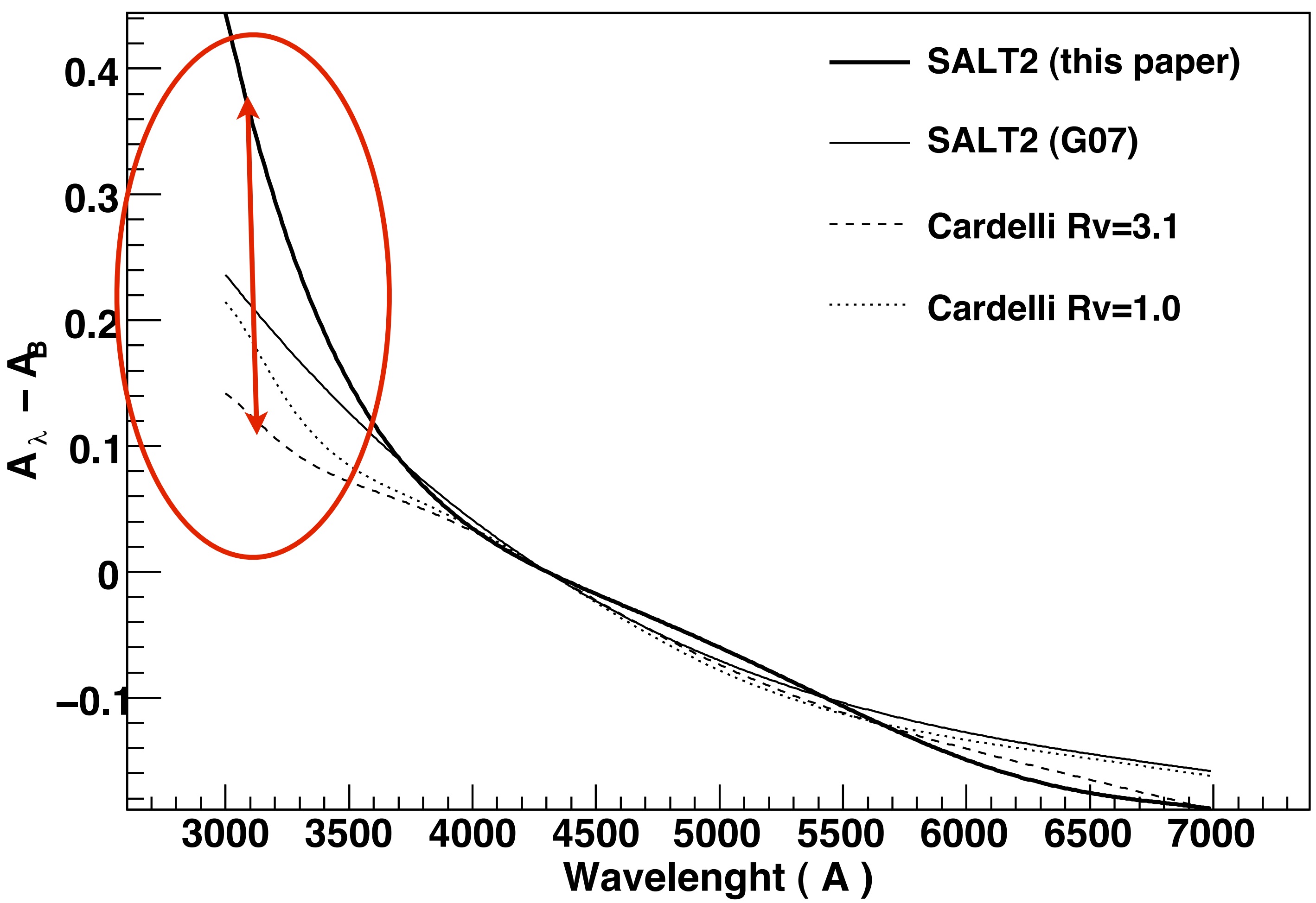
- Absorption for a given wavelength:

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



Which extinction law for SNe Ia?

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



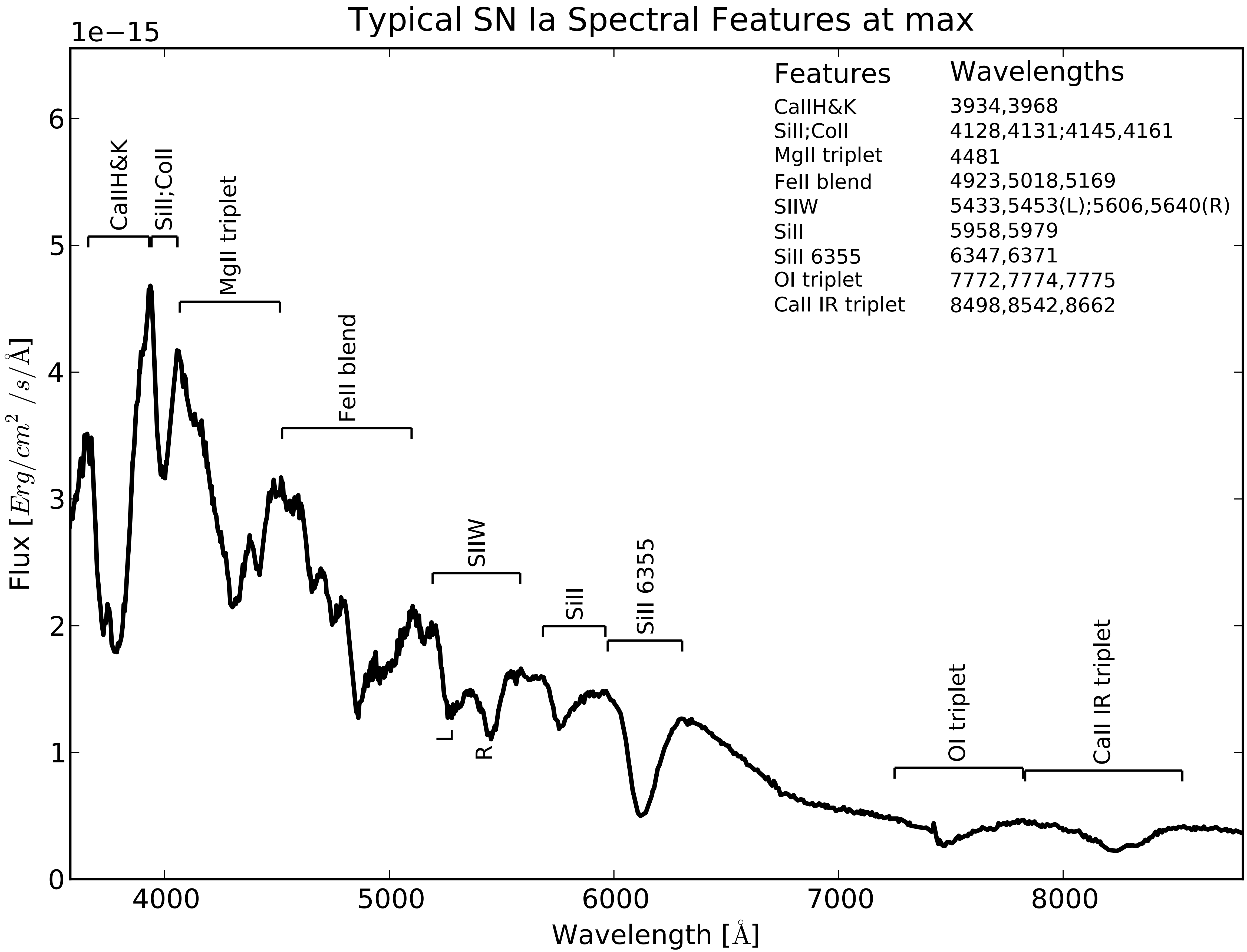
Guy, et al., A&A. (2010)

- 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



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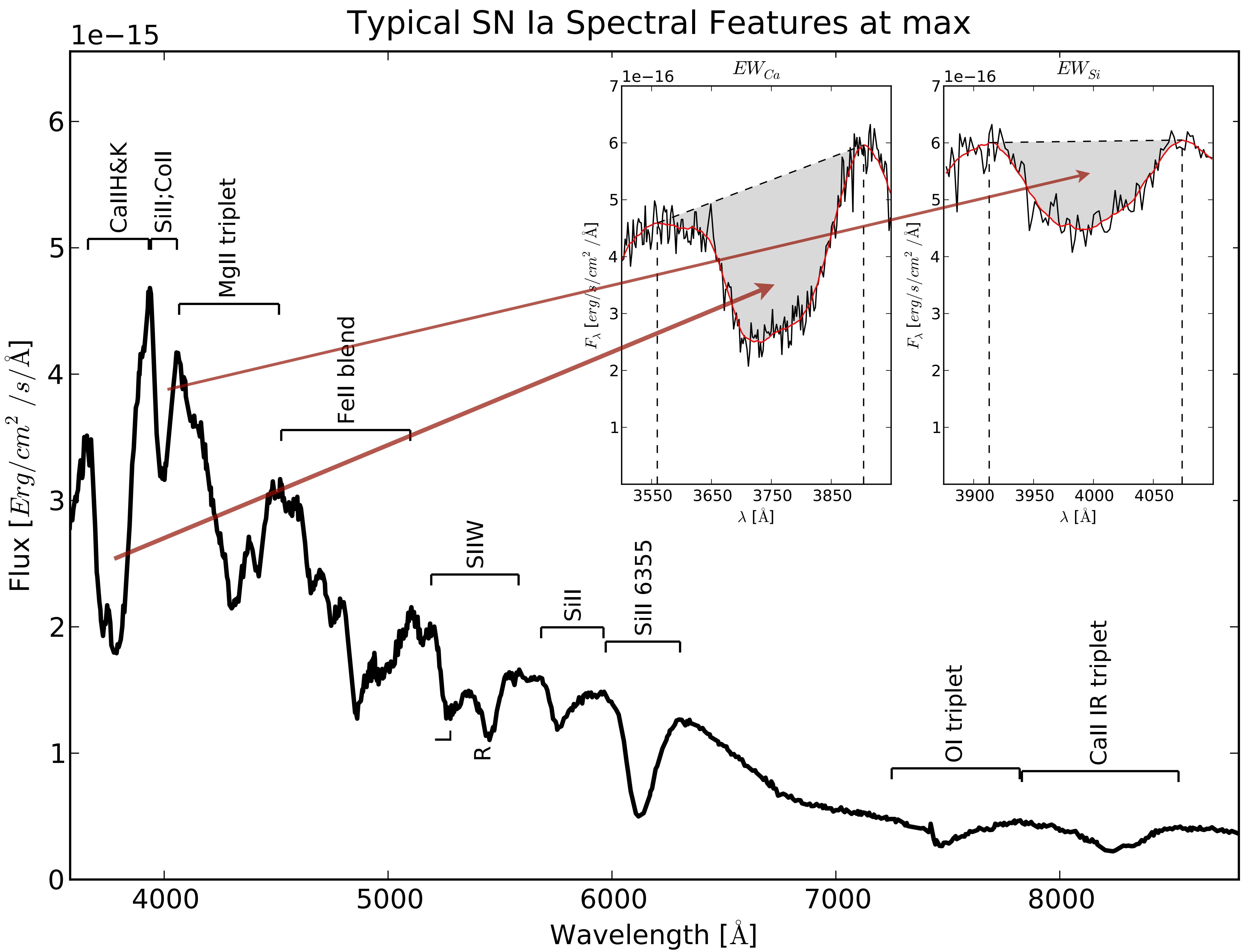
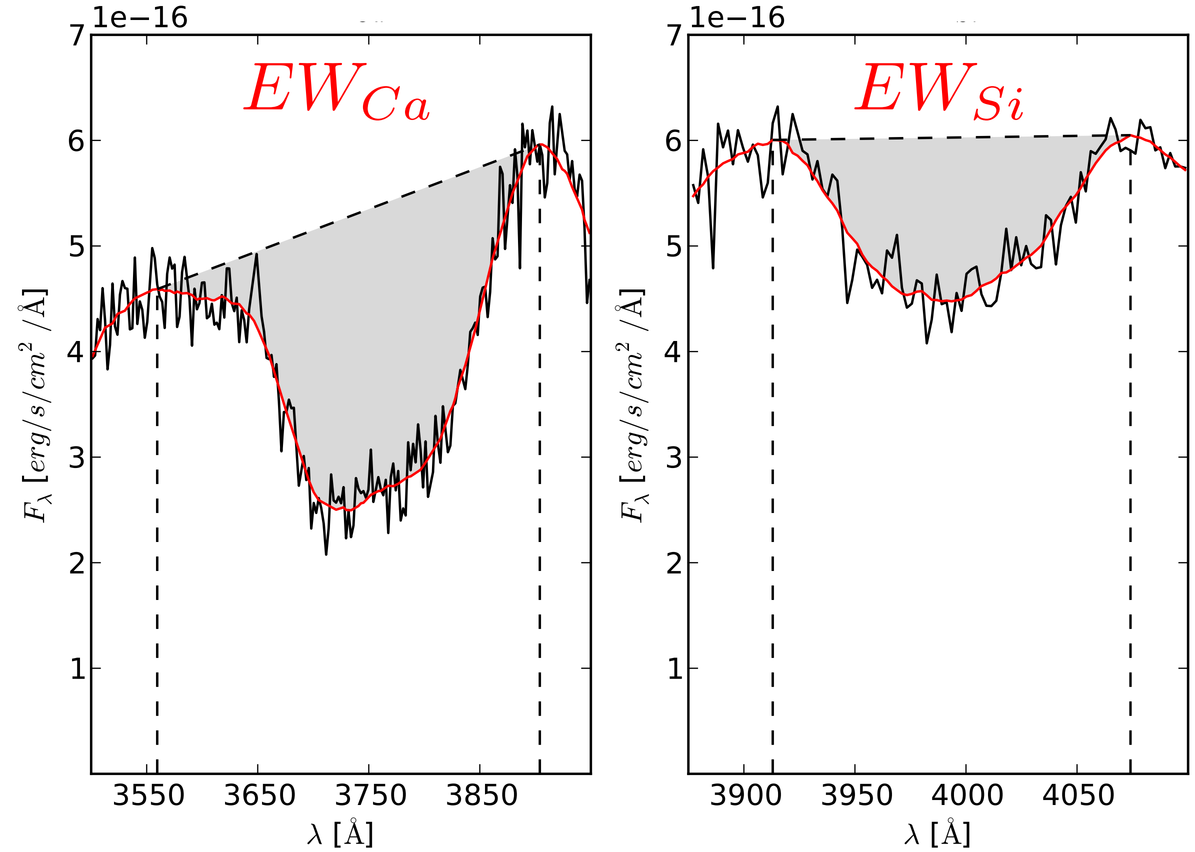


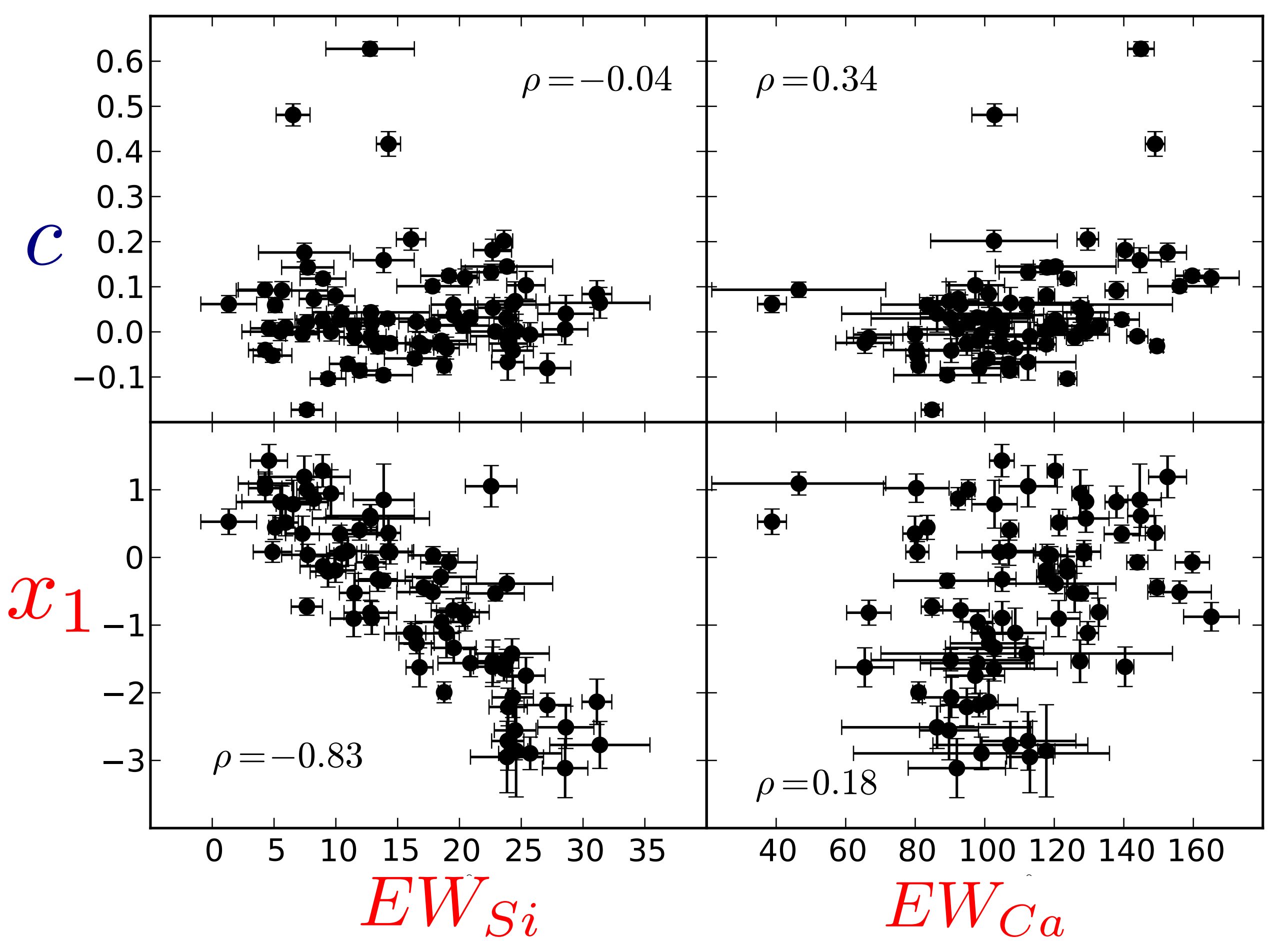
Spectral analysis at max

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%)
* 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)*

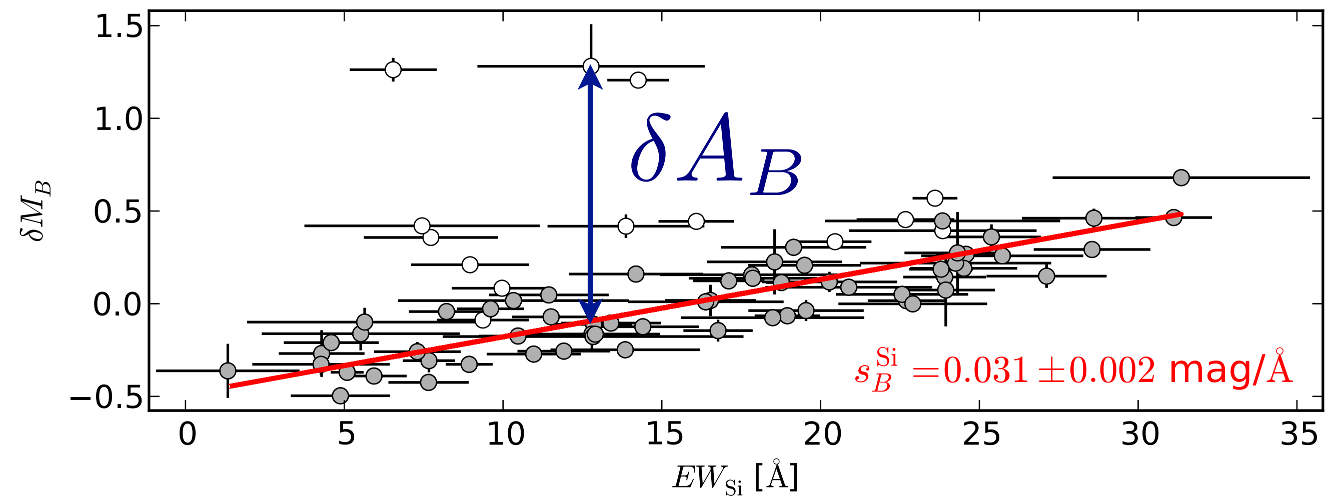
2 set of filters:

* 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 : Correct the Hubble residuals from intrinsic variabilities to get the relative absorptions δA_λ (up to a constant term)



Three cases :

(a) SNe Ia are **perfect candles** : only 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}

$$\delta M_\lambda = \begin{cases} \delta A_\lambda^0 & (a) \quad \textbf{\textit{No correction}} \\ s_\lambda^{\mathrm{Si}} \mathrm{EW}^{\mathrm{Si}} + \delta A_\lambda^{\mathrm{Si}} & (b) \quad \textbf{\textit{One intrinsic correction}} \\ s_\lambda^{\mathrm{Si}} \mathrm{EW}^{\mathrm{Si}} + s_\lambda^{\mathrm{Ca}} \mathrm{EW}^{\mathrm{Ca}} + \delta A_\lambda^{\mathrm{Si+Ca}} & (c) \quad \textbf{\textit{Two intrinsic corrections}} \end{cases}$$

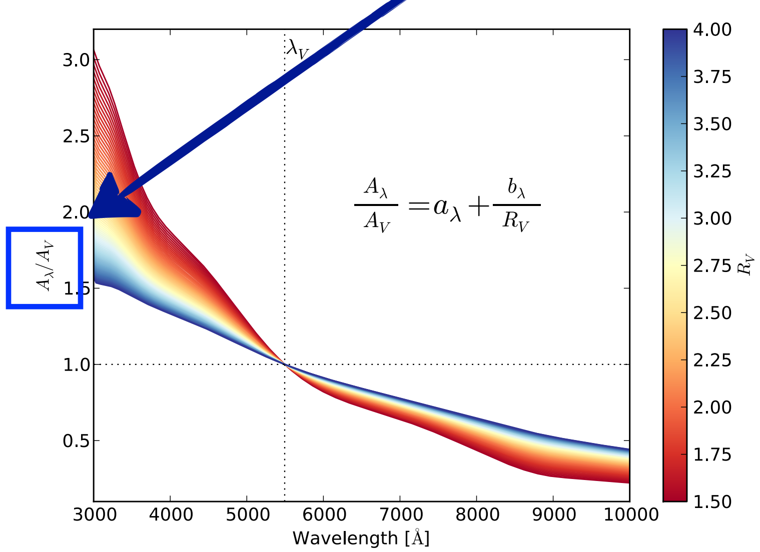
Construct the extinction law

GOAL : Construct a mean extinction law for SNe Ia

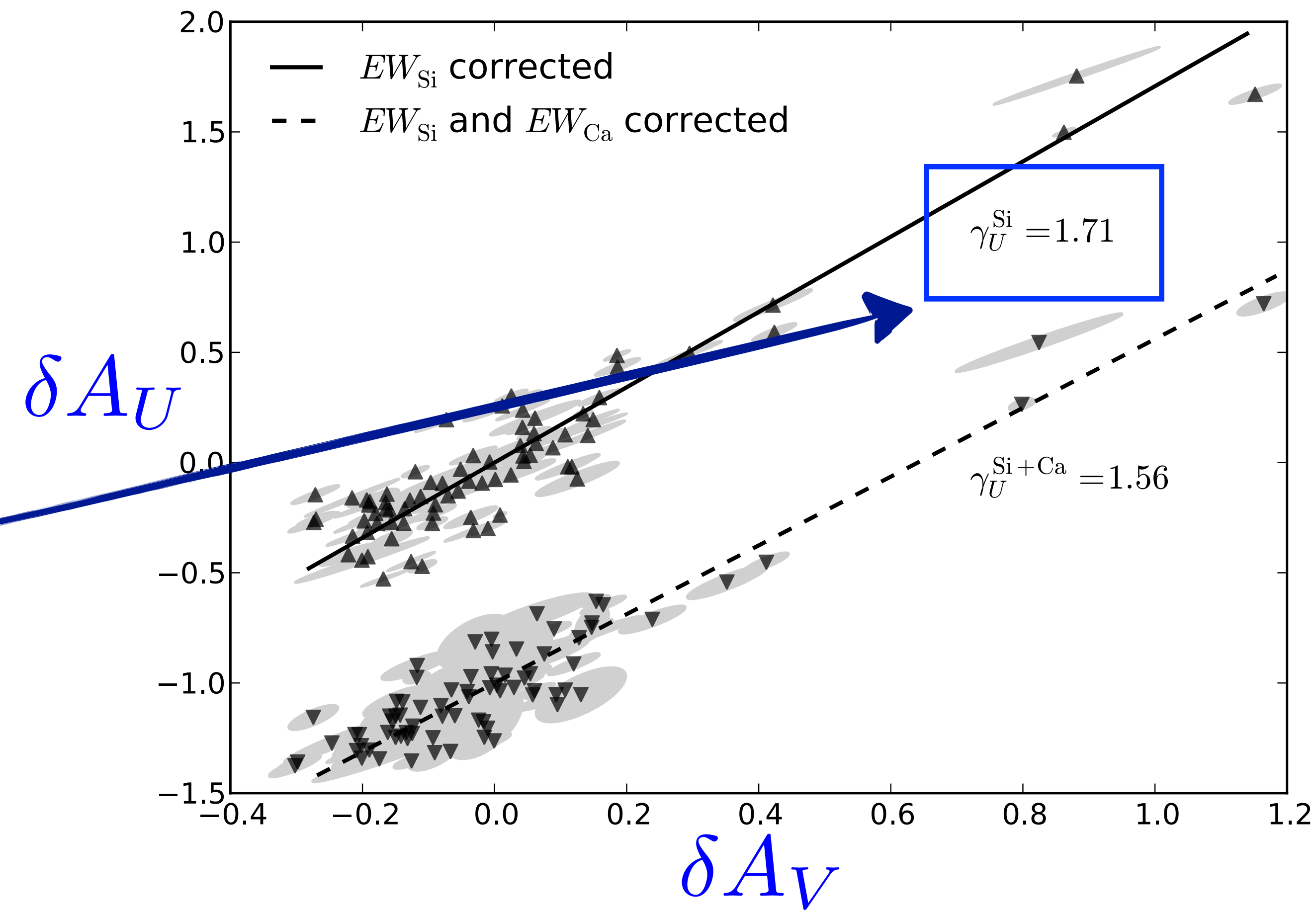
1st step : Correct the Hubble residuals from intrinsic variabilities to get the relative absorptions δA_λ (up to a constant term)
2nd step : Use the relation between the δA_λ to construct the law

Linear model :

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



Slopes

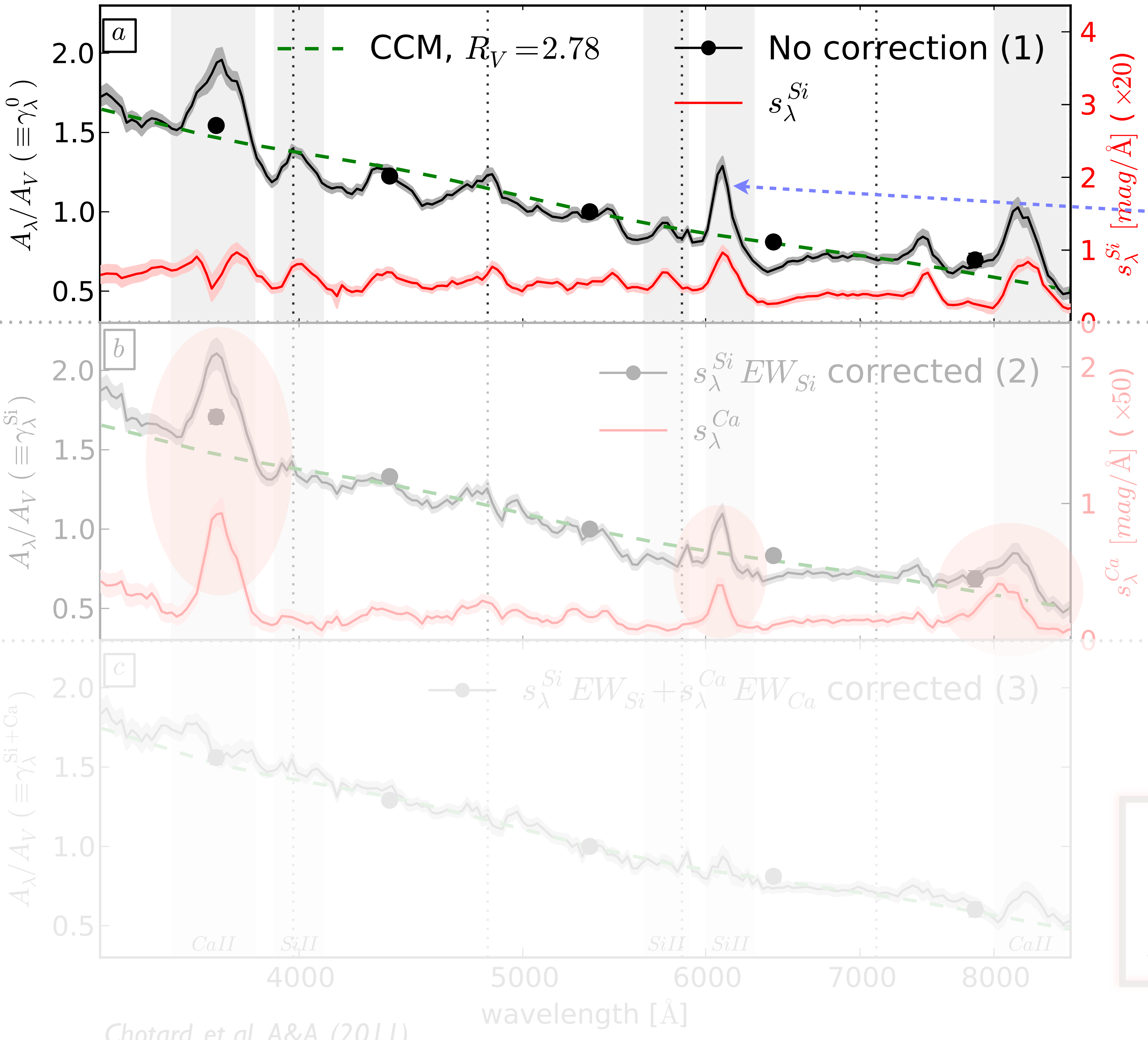


Estimation of R_V when forcing :

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

Cardelli extinction law

Results on the γλ



Perfect candles (a)

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

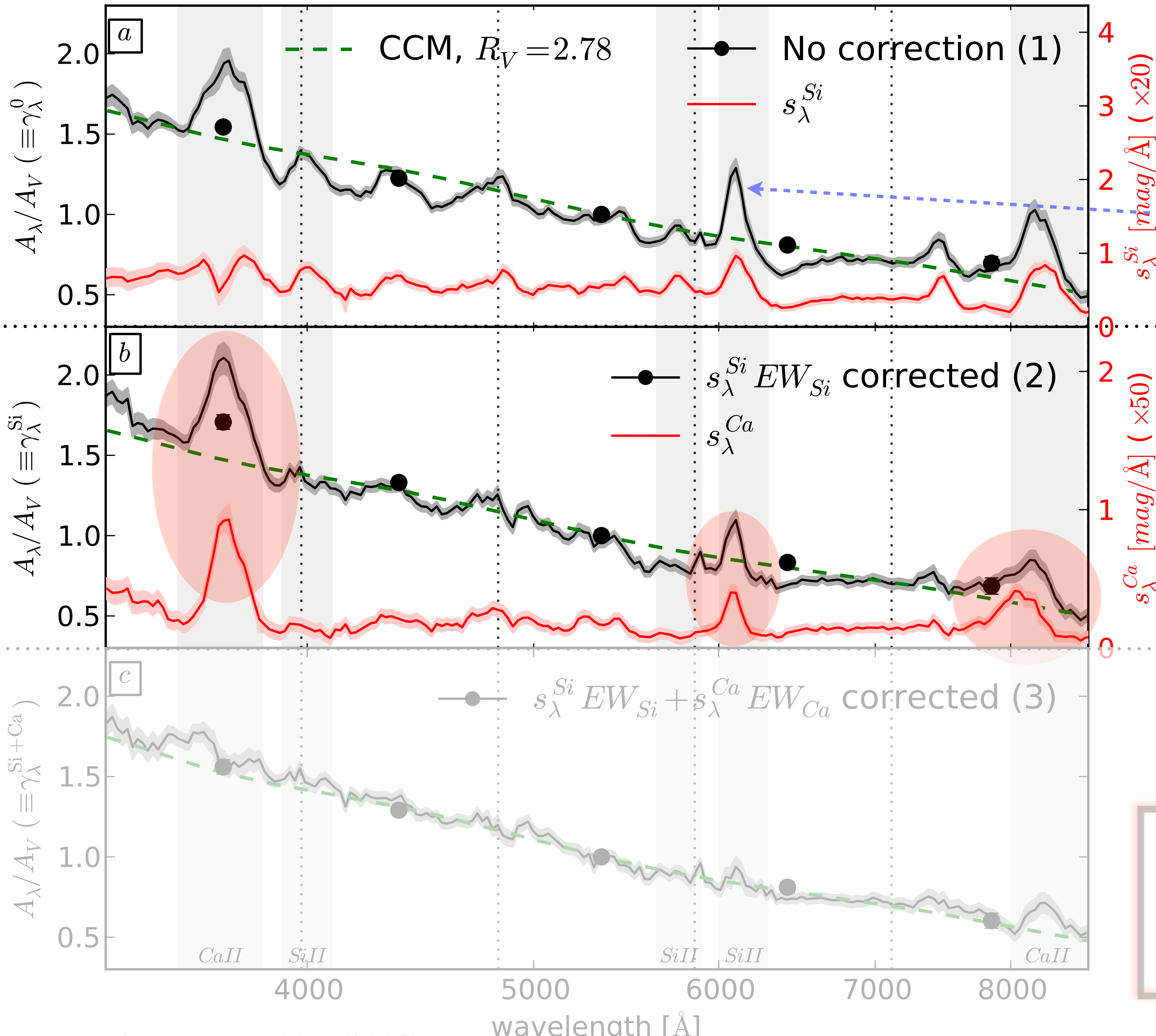
EW^{Si} correction («stretch-like») (b)

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



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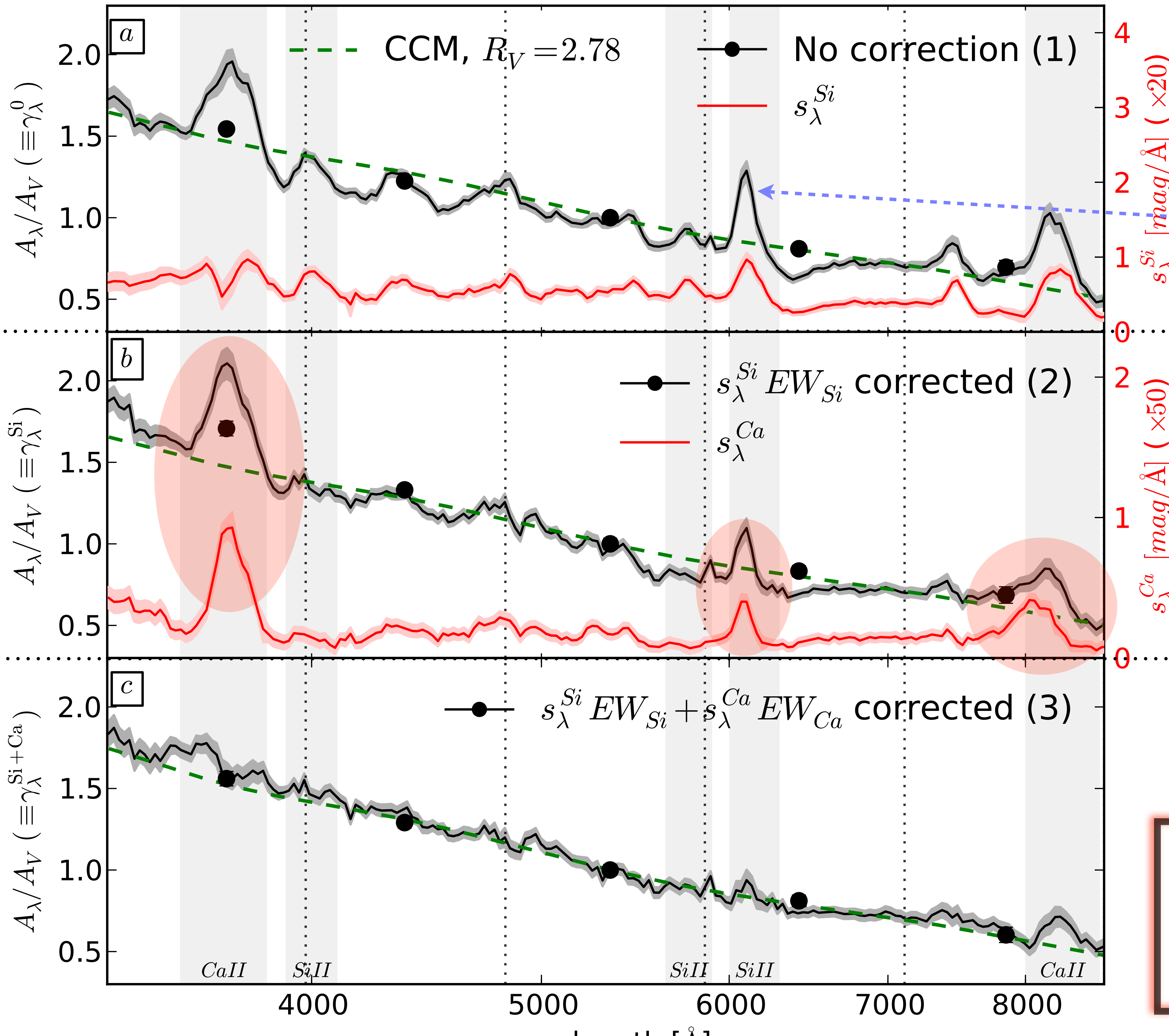

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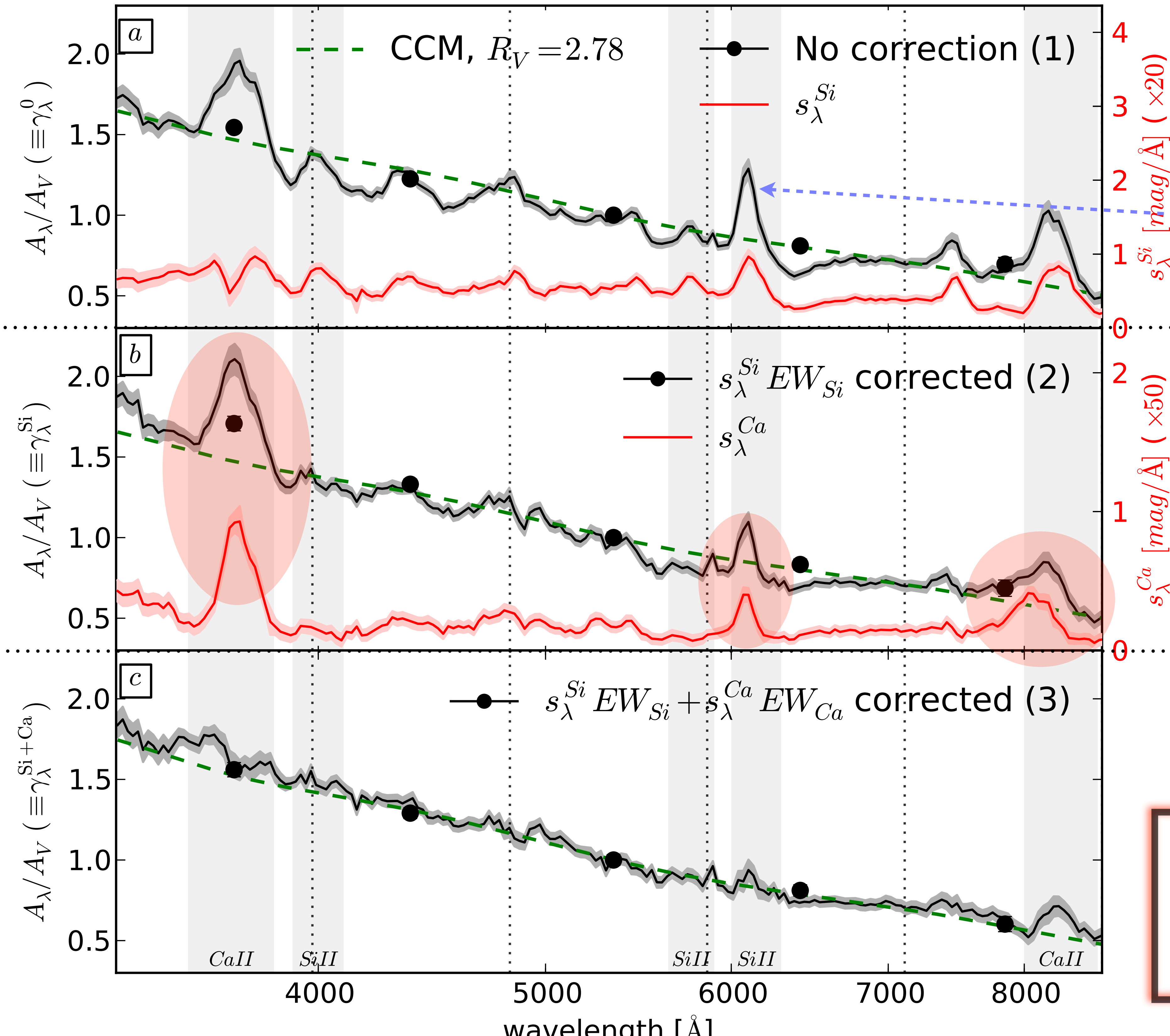

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But need to introduce a dispersion into the fit...

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

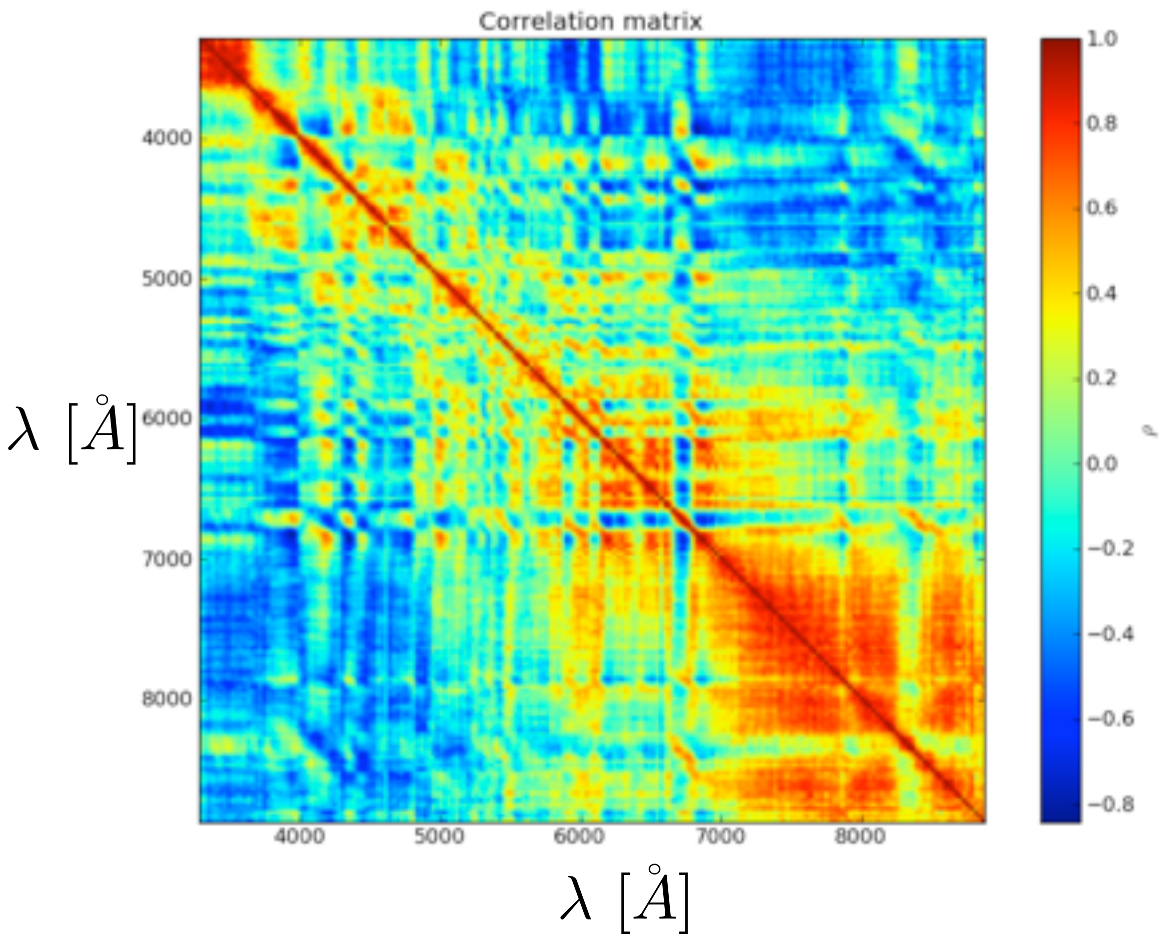
for each of the 3 cases (a,b,c)

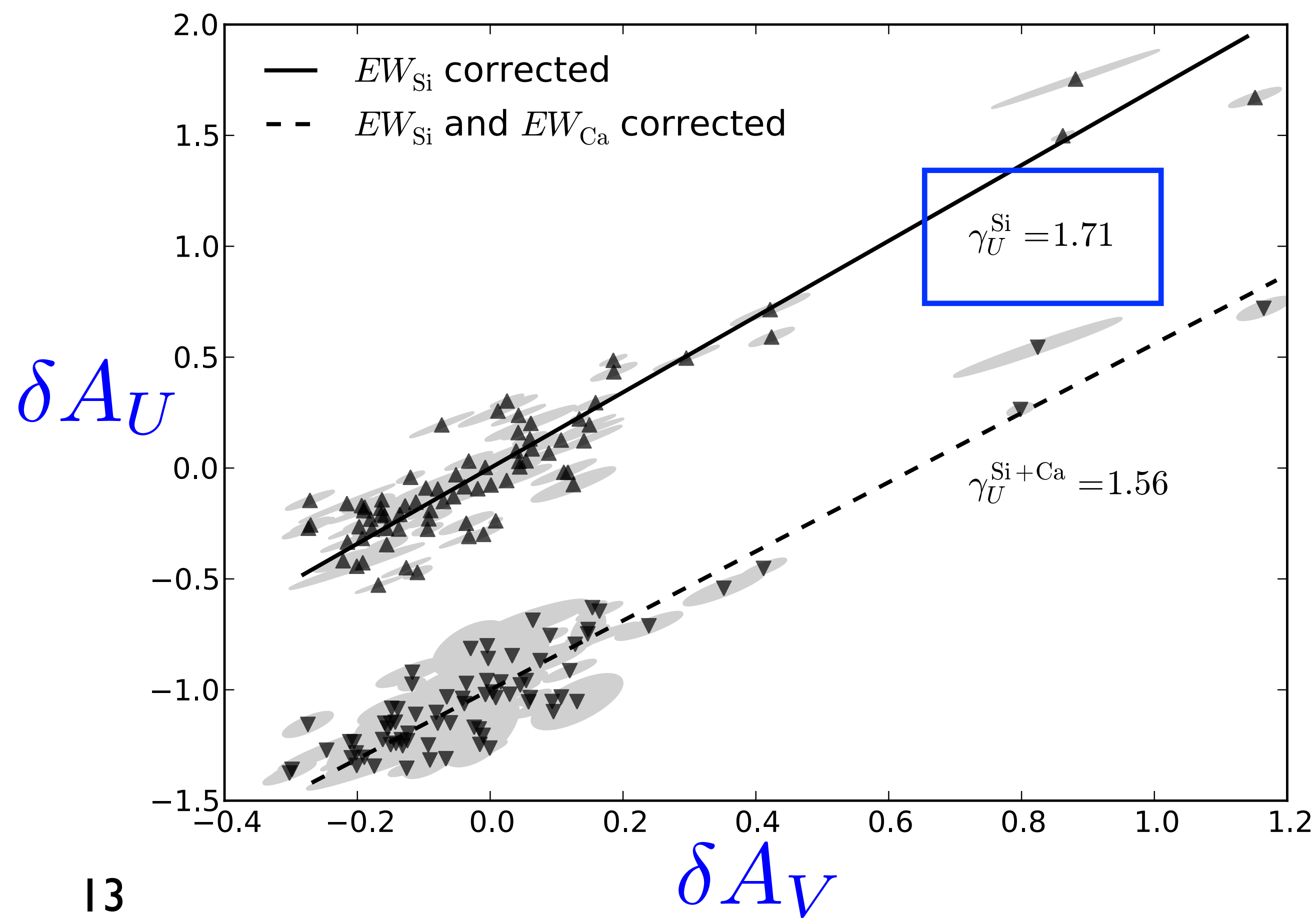
Introduction of a **color dispersion**, not usually used

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





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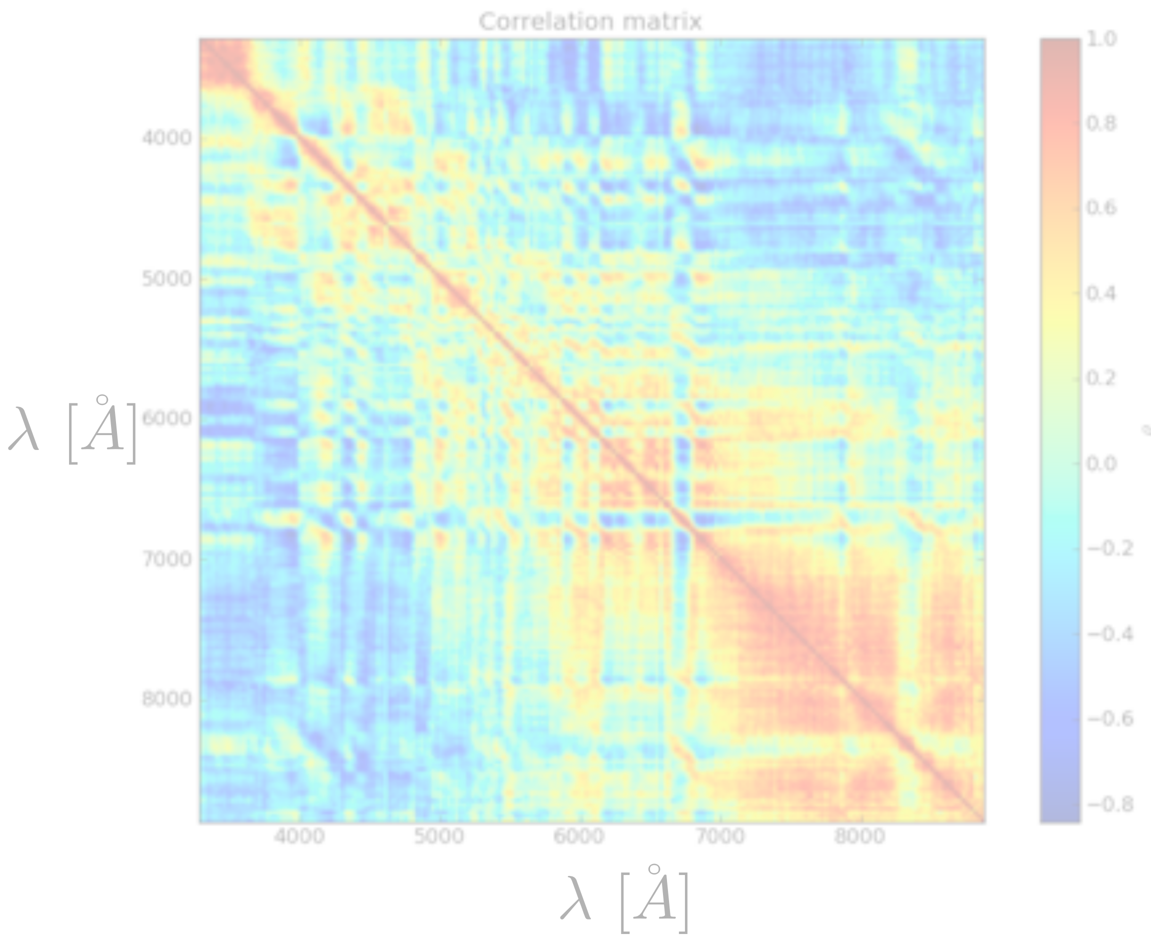

Intrinsic corrections
+
Dispersion in color

↓

Cardelli-like extinction law
and
Higher value of RV

Conclusion / What's next

Result:

- **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 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