SNe Ia spectral analysis with the SNfactory spectrophotometric data sample

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Summary

Context

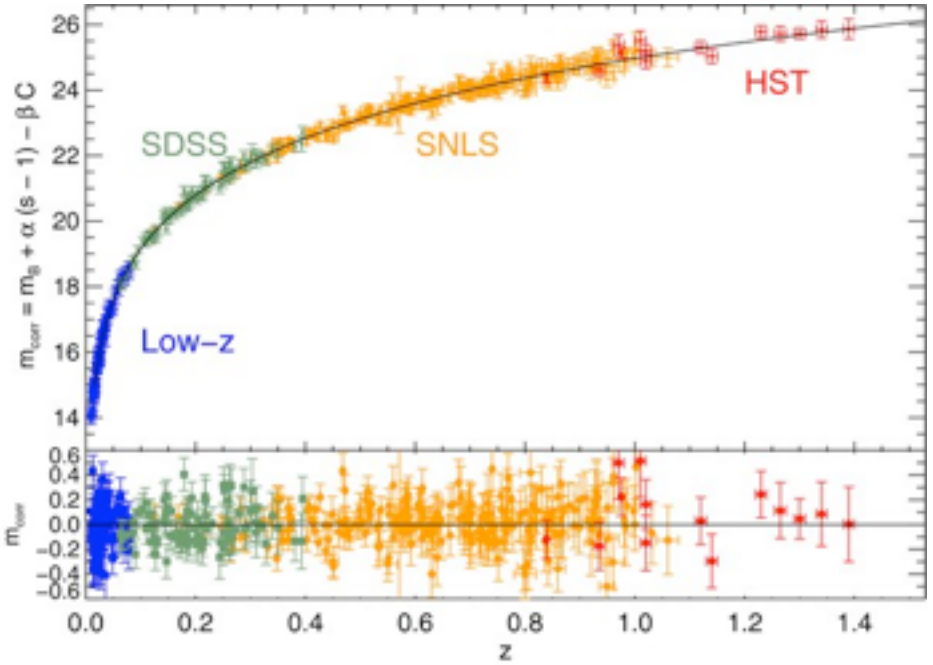
- ✦Observational cosmology with SNe Ia
- ✦The Nearby Supernova Factory project

SNe Ia spectral analysis

- ✦ SNe Ia variability
- ✦ Standardization _Bailey, et al., A&A. (2009)_
- ✦ Extinction law _Chotard, et al., A&A. (2011)_

SNfactory status

Conley et al 2011



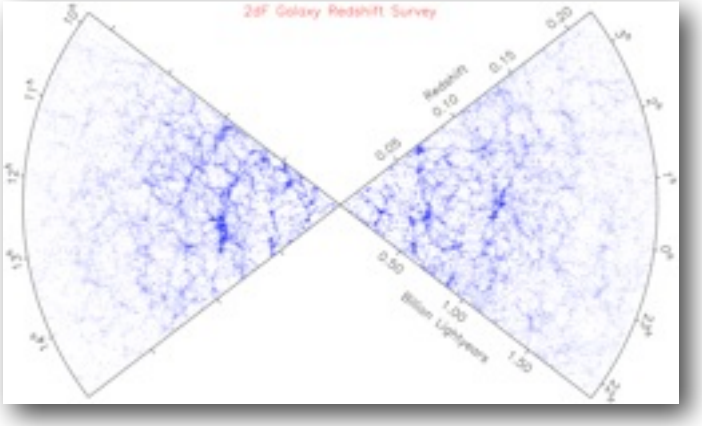
SN 1994D

Framework: concordance cosmology

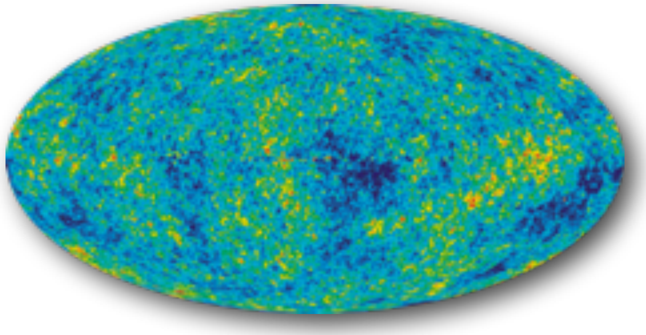
Three principal probes

Standard candles (SNe Ia)
(Nearby and distant surveys)

Large scale structures
(BAO, Weak lensing, Clusters)



CMB
(COBE, WMAP, PLANCK)

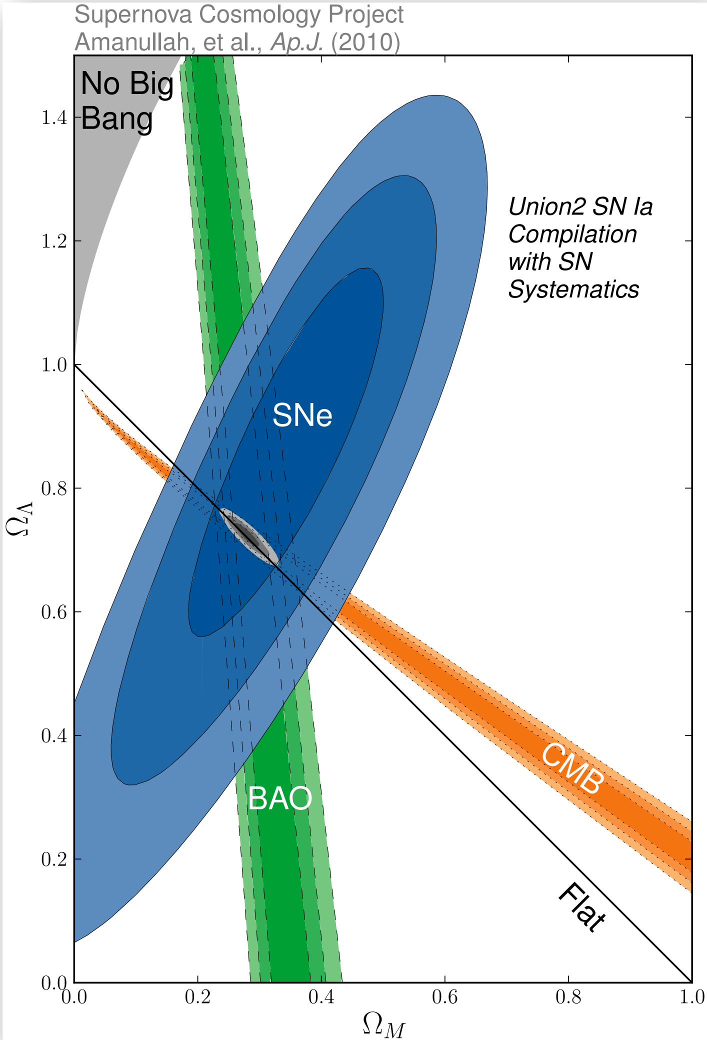


Three independent measurements

Cosmological parameters

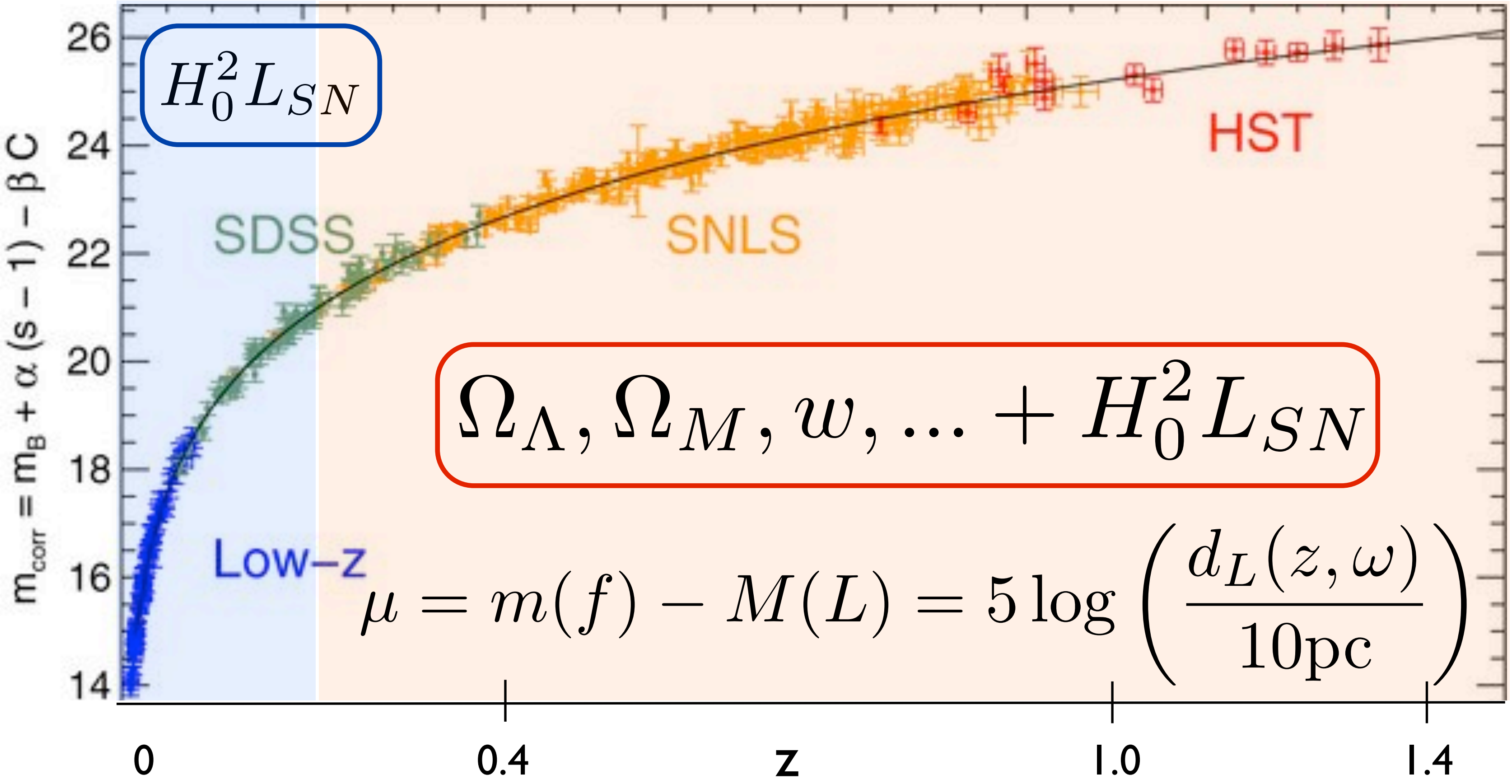
- ✦ Ω_M matter density
- ✦ Ω_Λ dark energy density
- ✦ $w = p/\rho \simeq -1$

$$\Omega_M \simeq 0.27$$
$$\Omega_\Lambda \simeq 0.73$$


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

Hubble diagram

Conley et al 2011



$$H_0^2 L_{SN}$$

$$\Omega_\Lambda, \Omega_M, w, ... + H_0^2 L_{SN}$$

$$\mu = m(f) - M(L) = 5 \log \left(\frac{d_L(z, \omega)}{10\text{pc}} \right)$$

- **Hubble diagram:** distance modulus vs. redshift
- **High-z SNe:** cosmological parameters + $H_0^2 L$
- **Nearby SNe:** constrain the degeneracy between cosmology and SNe Ia luminosity

- **High quality data** of **low redshift SNe Ia** needed to reduce systematics

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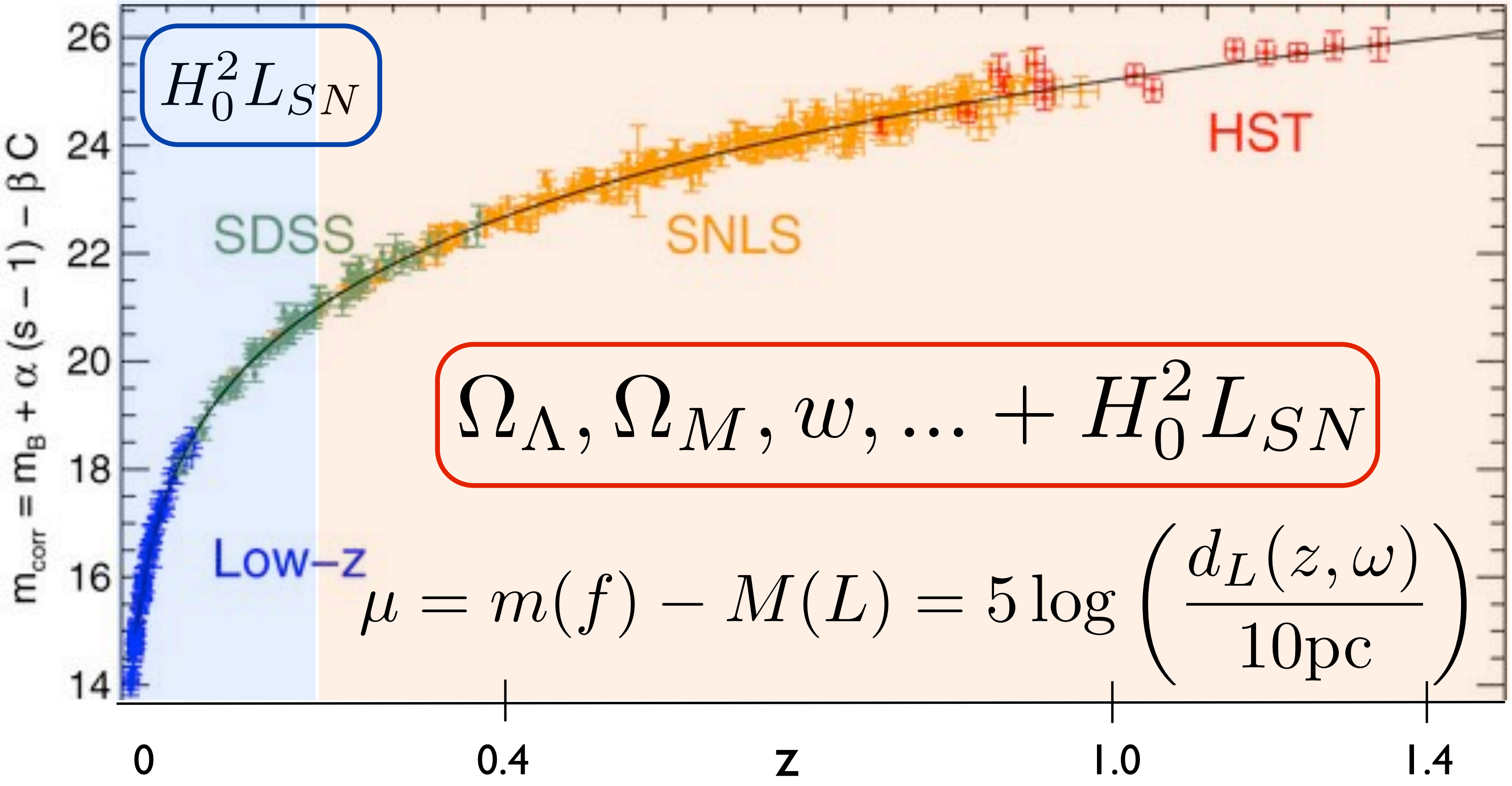
Conley et al 2011



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SNfactory

The Nearby Supernovae Factory

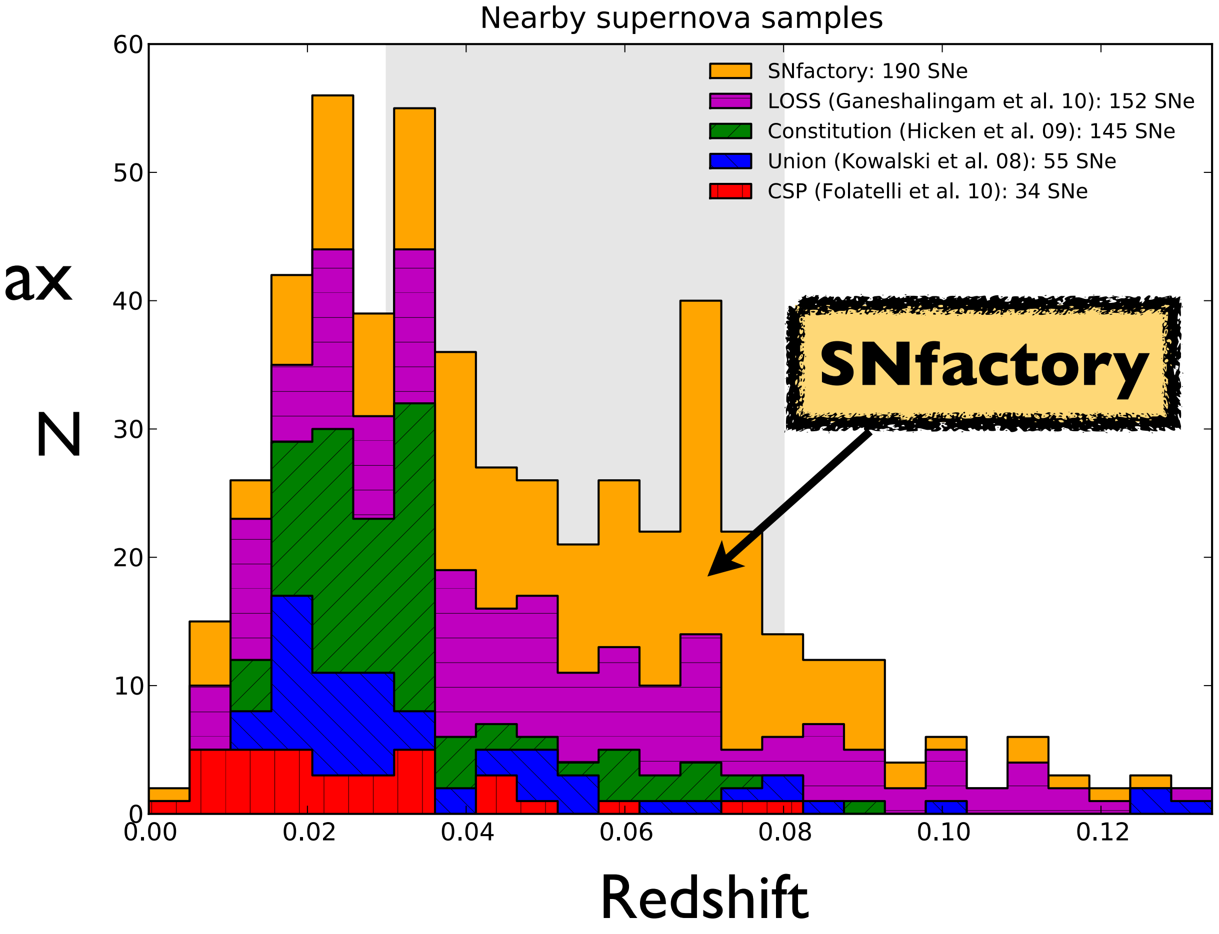
A unique data set of spectrophotometric type Ia supernovae spectra

Main Goals

- ✦ Anchor the Hubble diagram: control of systematics
- ✦ Spectrophotometric time series of nearby SNe Ia
- ✦ **Standardization**
- ✦ **SN Ia physics:** spectral properties, **extinction studies**...

Data sample

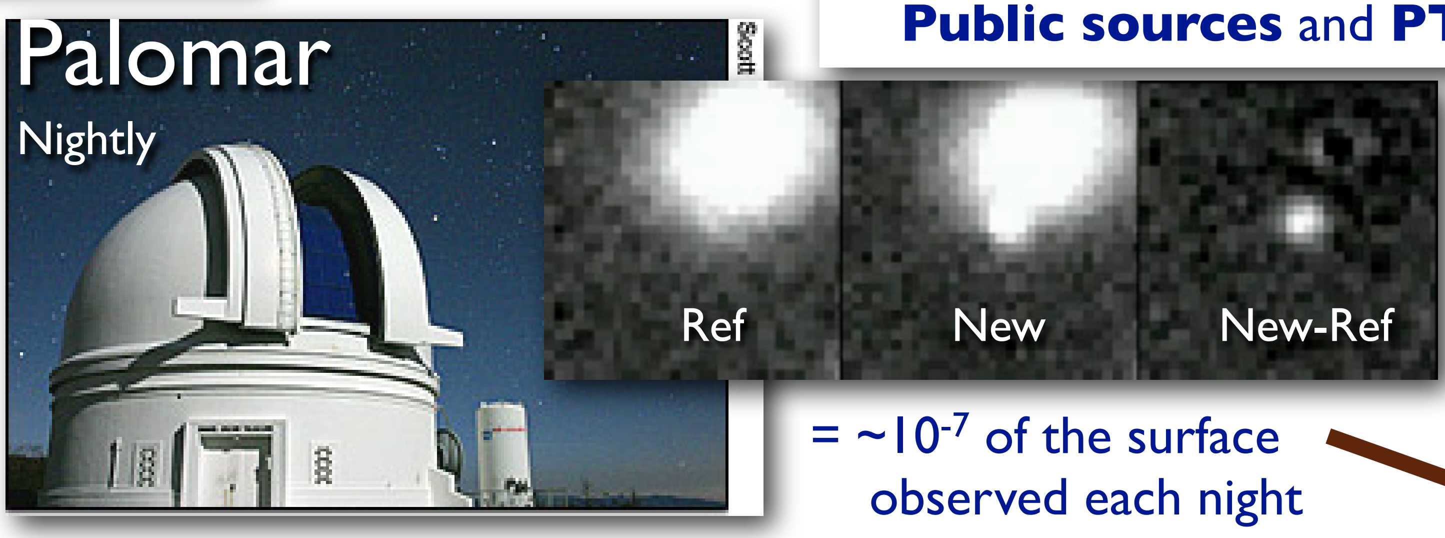
- ✦ **~200 SNe** with more than 5 spectra
- ✦ **~3000 spectra** from -15 to +40 days / max
- ✦ 0.01 < redshift < 0.1
- ✦ median phase of 1st spec: -4 days
- ✦ mean cadence of observation: ~3 days
- ✦ spectral coverage 3200 - 9000 Å



SNfactory: Observations

1. Search

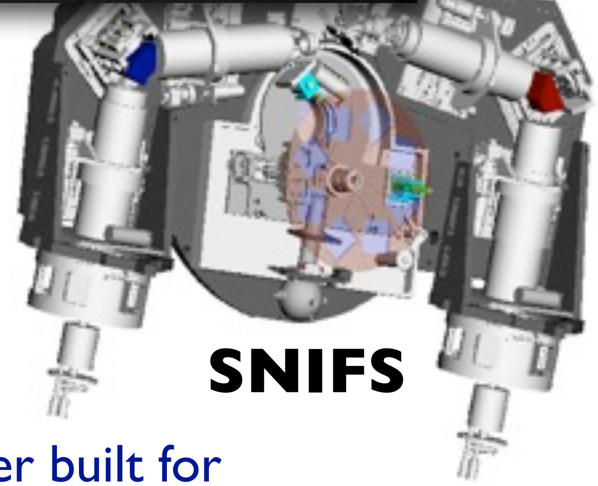
Dedicated search until 2008.
Public sources and **PTF** after.



= ~10^{-7} of the surface observed each night

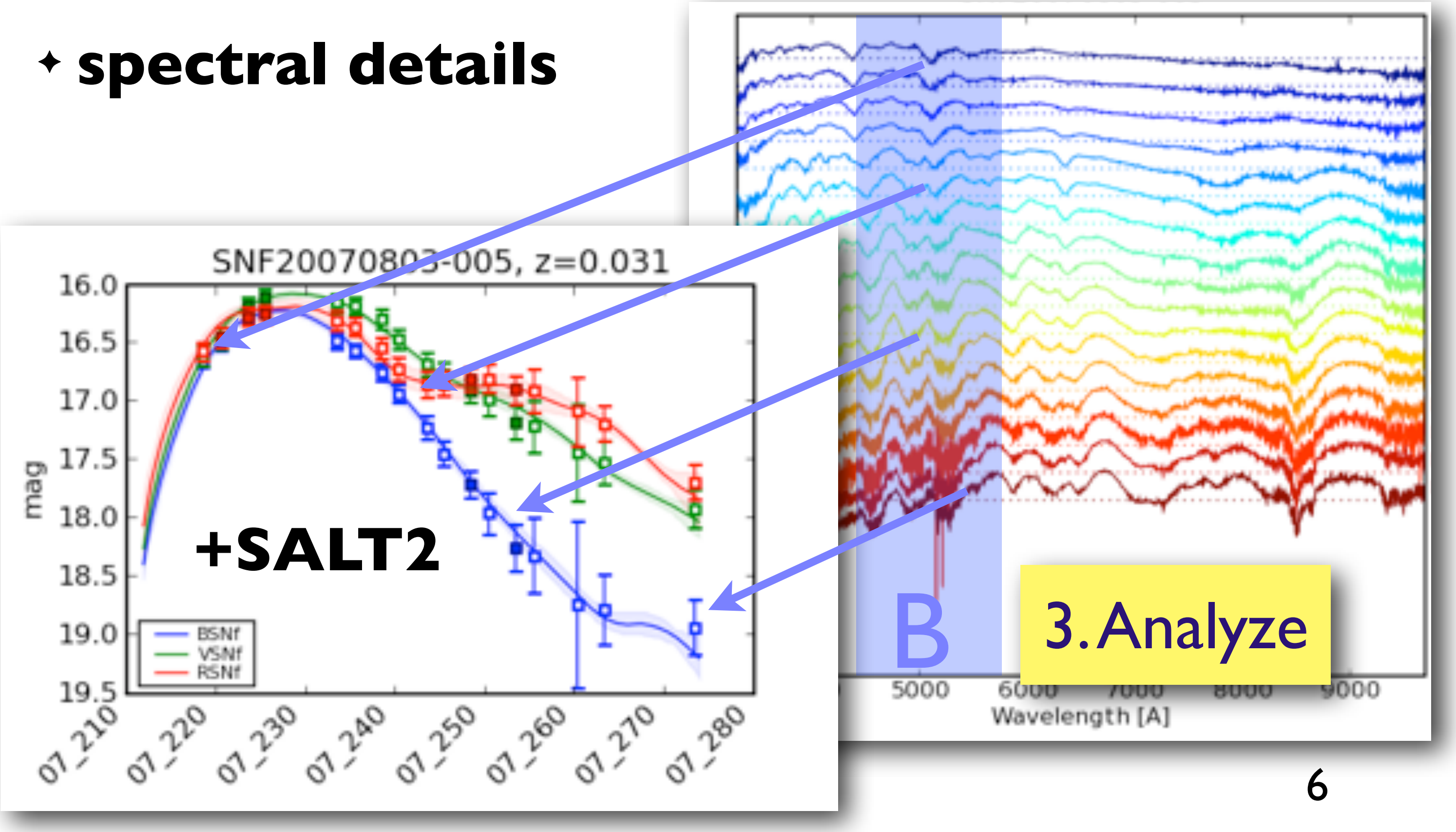
2. Observation

Follow up



Spectrometer built for nearby SNe Ia observations

- synthetic light curve in **any filter**
- **spectral details**



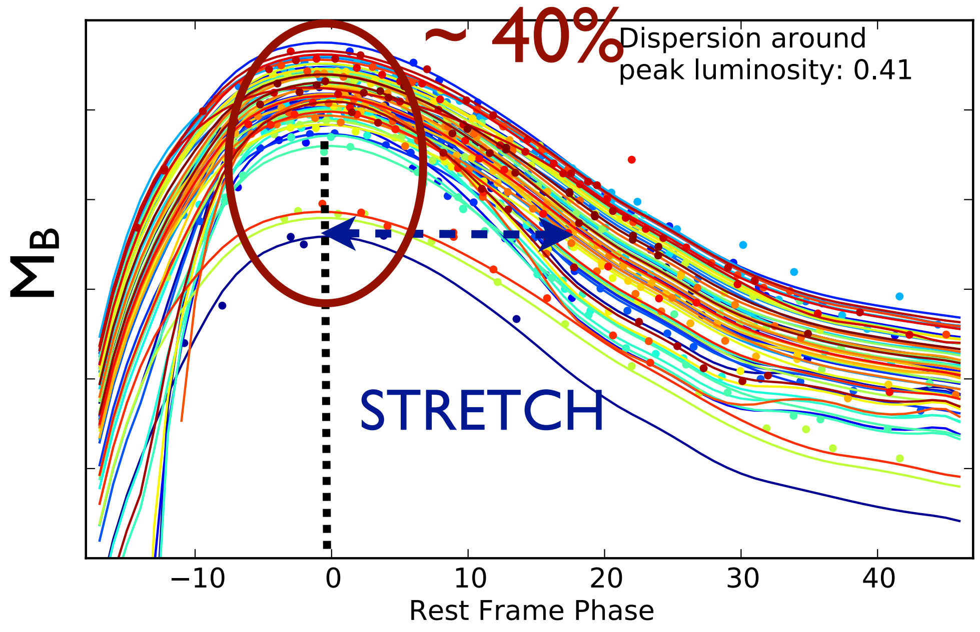
3. Analyze

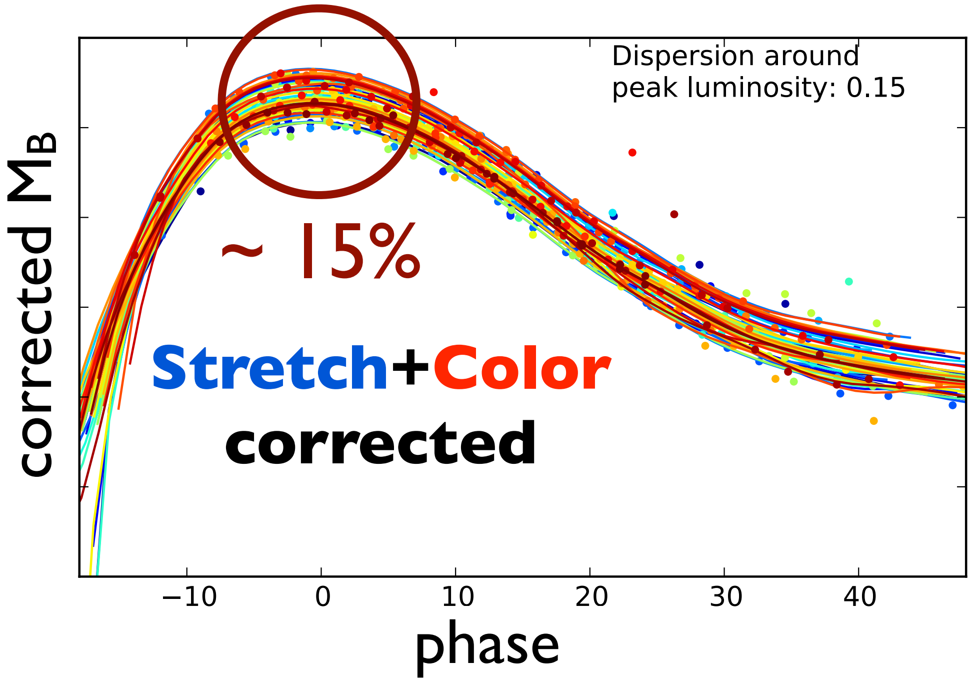
SNe Ia : quasi-standard candles

Homogeneity up to ~0.4 mag

Expected sources of Variability

- intrinsic:
  - *progenitor composition (metallicity)*
  - *progenitor explosion (^{56}Ni mass)*
- extrinsic:
  - *host interstellar medium extinction*





Empirical corrections to reduce the dispersion at maximum light:

- *Light curve width: Δm15, stretch, x1*

  brither - slower *(intrinsic)*
- *Color: B-V at max, SALT2 color*

  brighter - bluer *(extrinsic)*

From an empirical LC fitter (SALT2, Guy et al. 07) ⟶

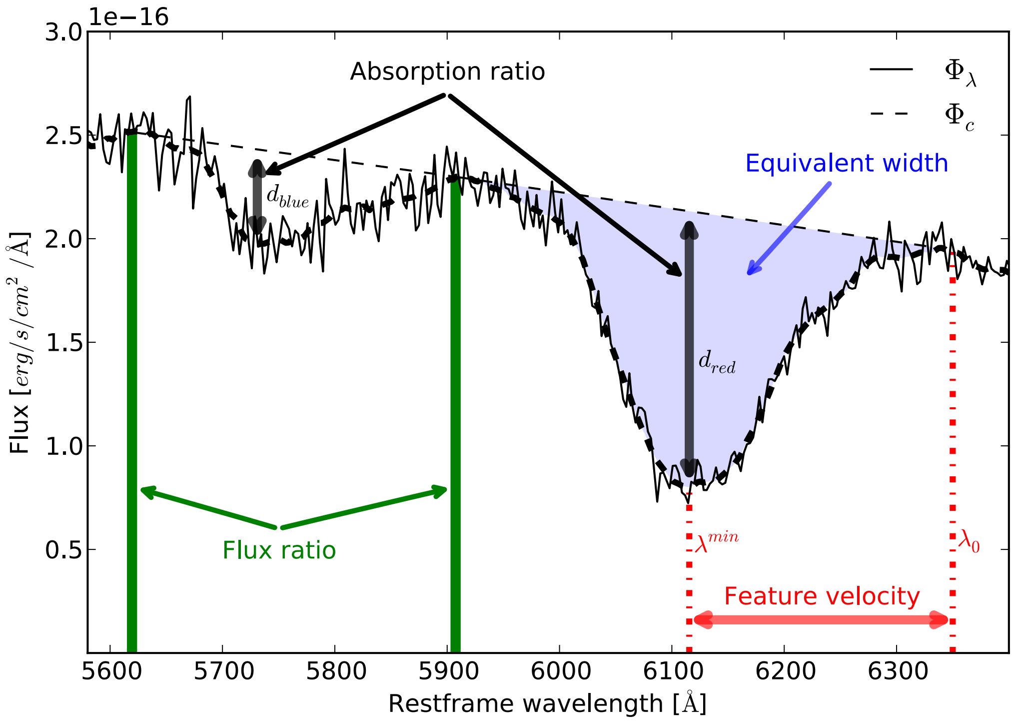
Empirically corrected Hubble diagram

$$\mu_B^i = \boxed{m_B^i} - M_B + \alpha \times \boxed{x_1^i} - \beta \times \boxed{c^i}$$

Spectral indicators

At a given phase **(at max), spectral differences** between SNe are linked to the **different types** of **variabilities**

- **Spectral indicators:** tracer of these variabilities
- **4 type of spectral indicators:**
  - flux ratio
  - depth ratio
  - equivalent width
  - feature velocity



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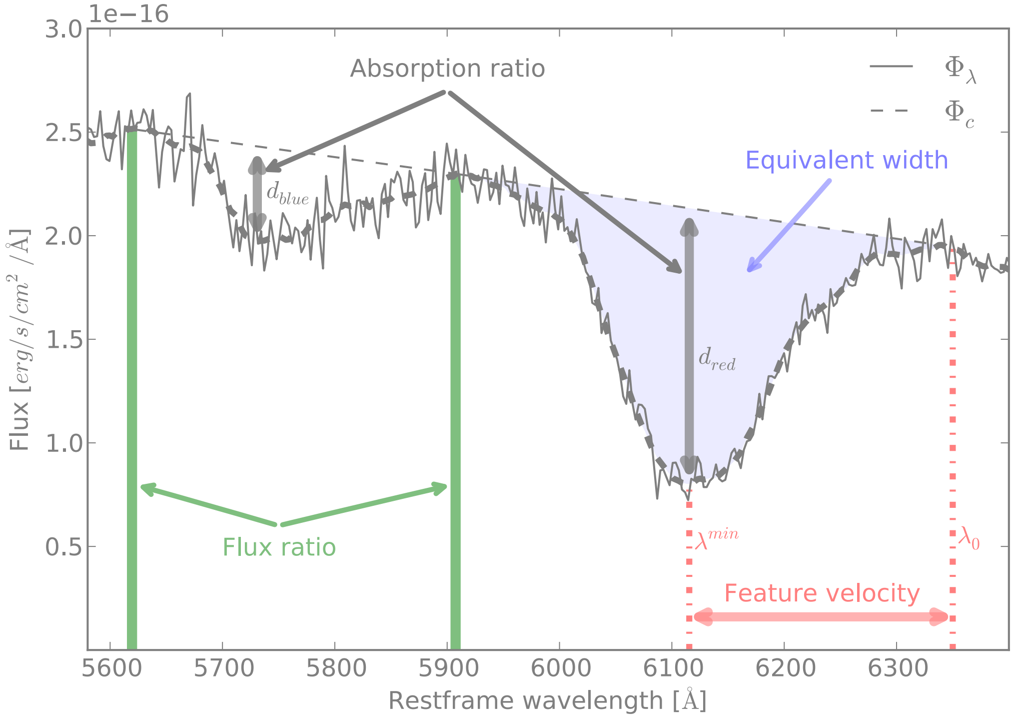
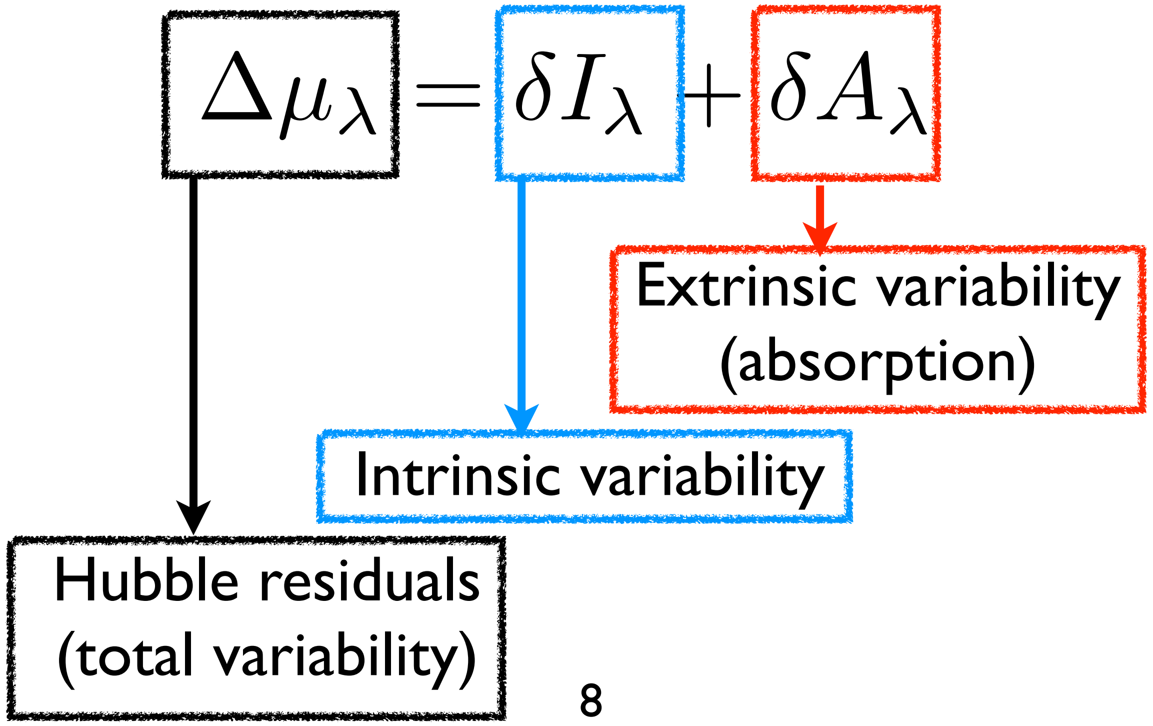


2 examples of SNfactory spectral analysis at maximum light.



$$\boxed{\Delta\mu_\lambda} = \boxed{\delta I_\lambda} + \boxed{\delta A_\lambda}$$

Extrinsic variability (absorption)

Intrinsic variability

Hubble residuals (total variability)

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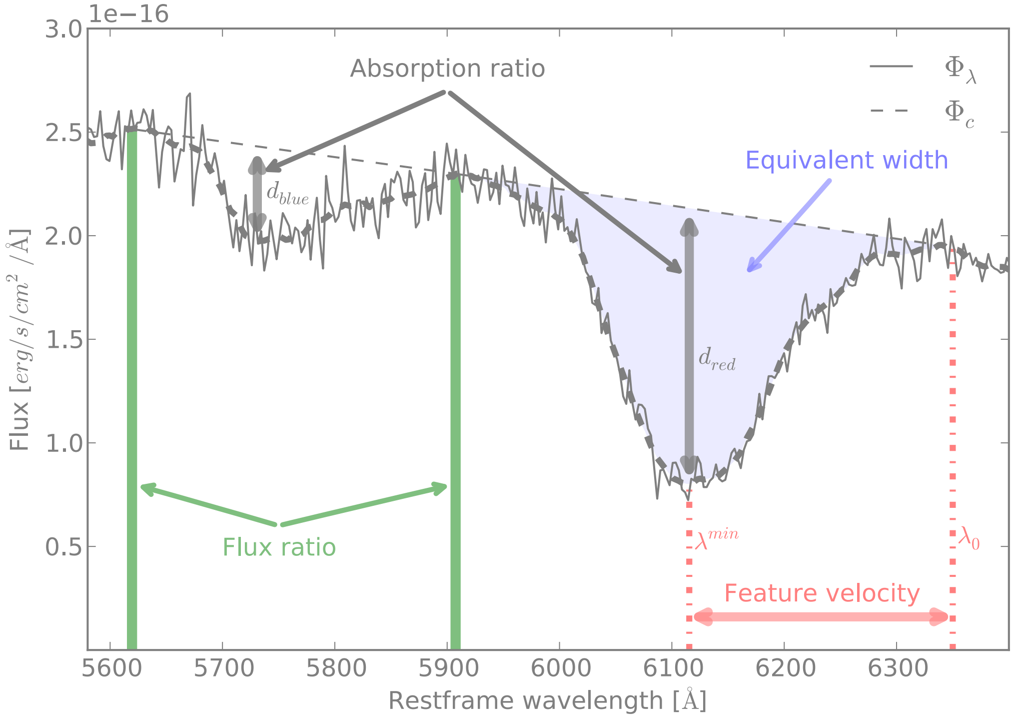
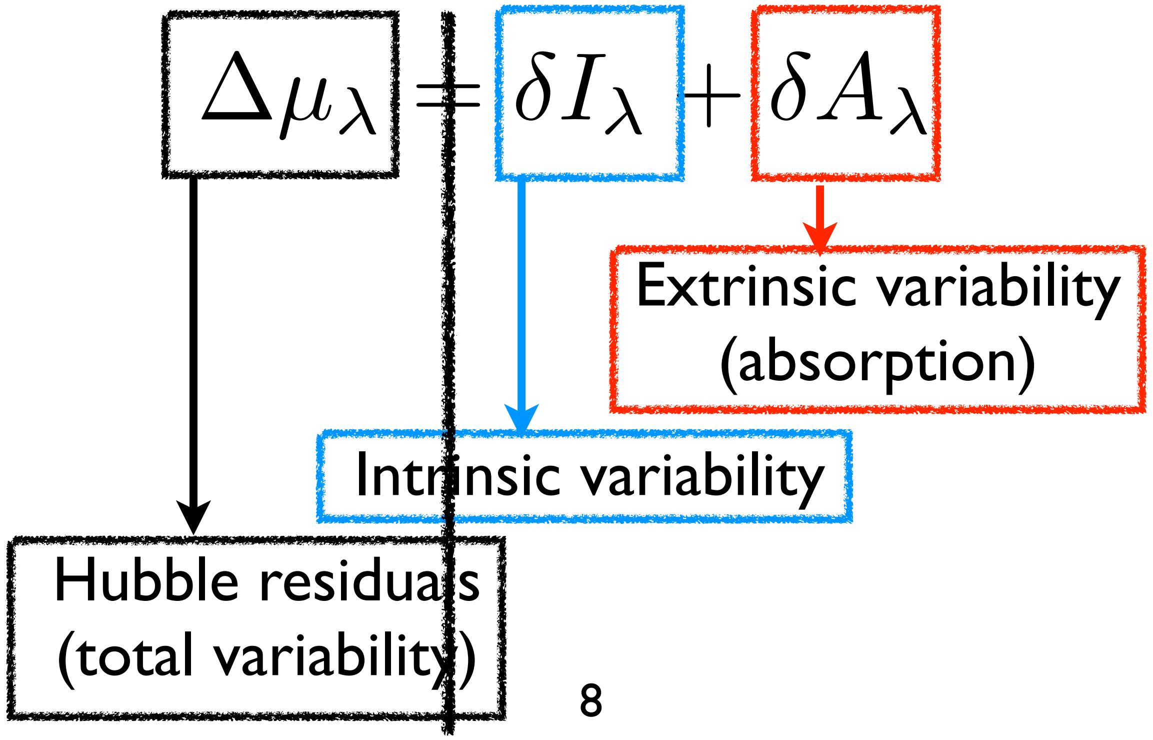


2 examples of SNfactory spectral analysis at maximum light.

1

Is there one spectral indicator able to **standardize SNe Ia**?



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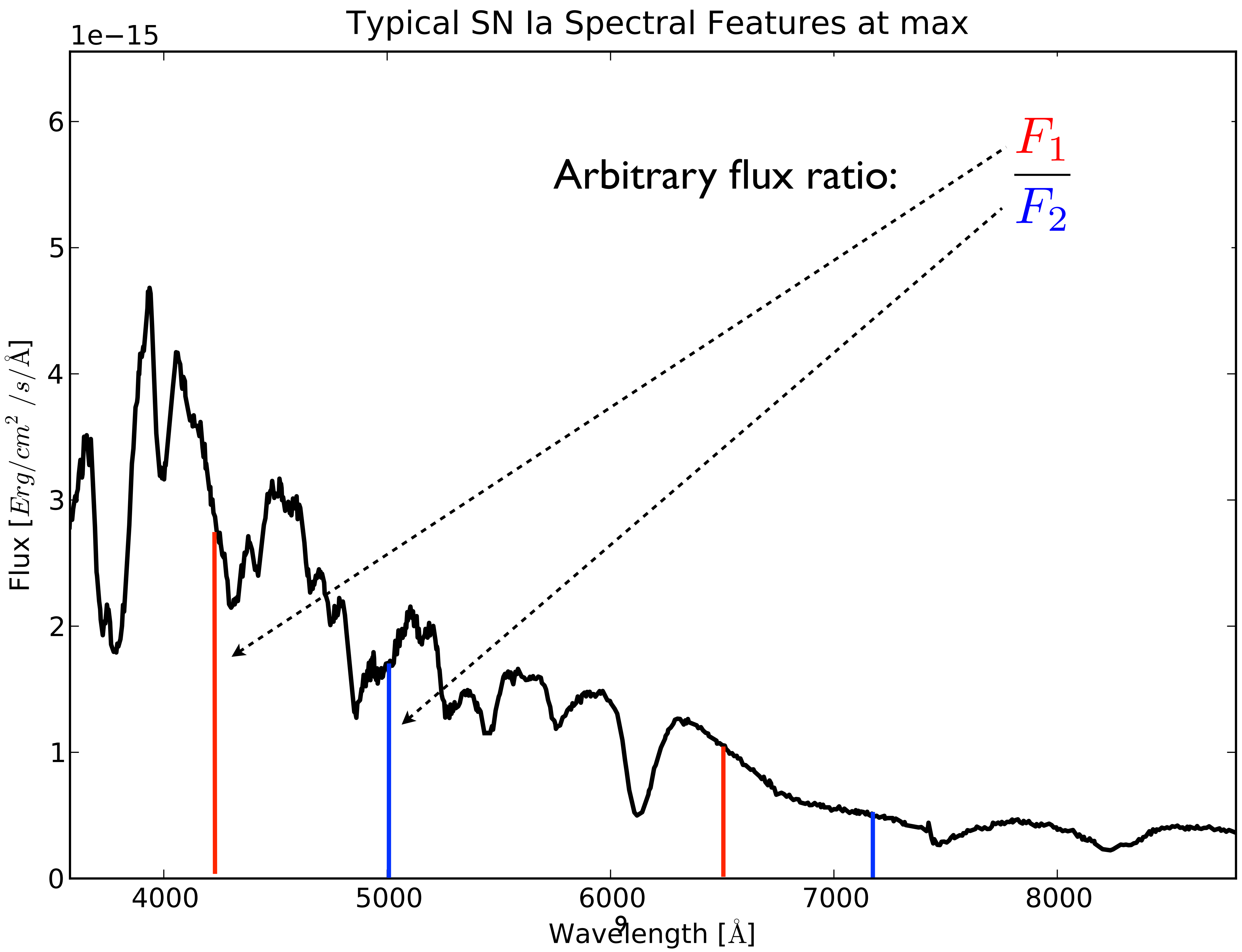
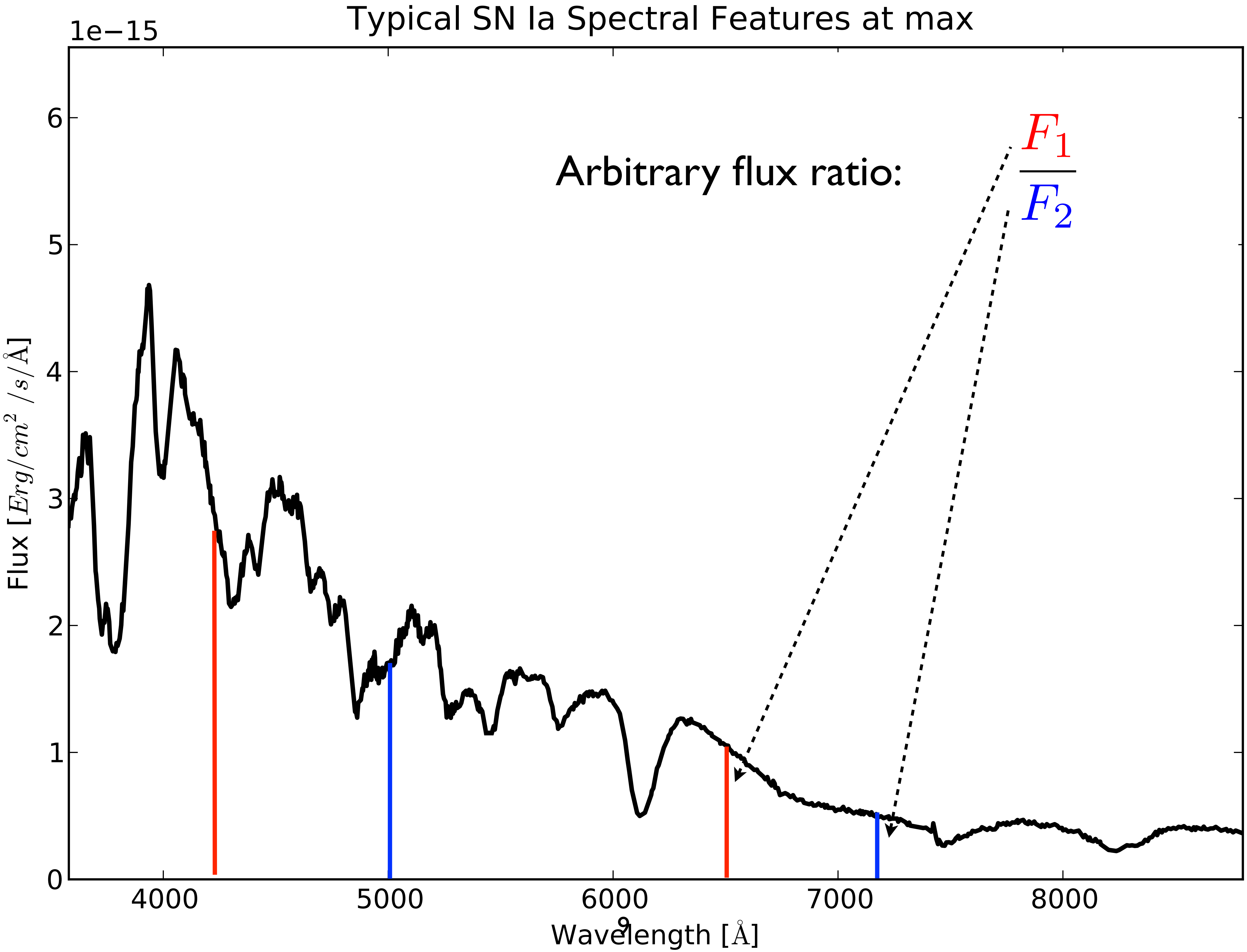
Spectral analysis at max



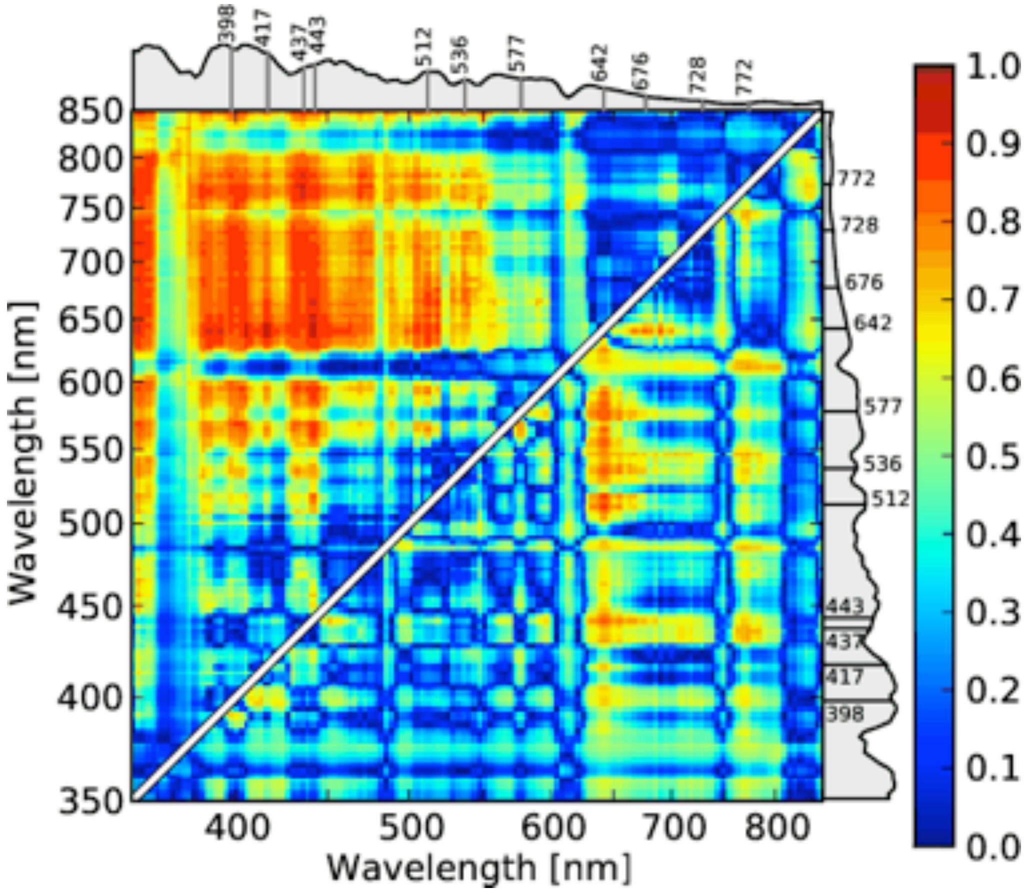
$$\frac{F_1}{F_2}$$

Spectral analysis at max



Spectral flux ratios to standardize SN Ia

Bailey et al. 2009



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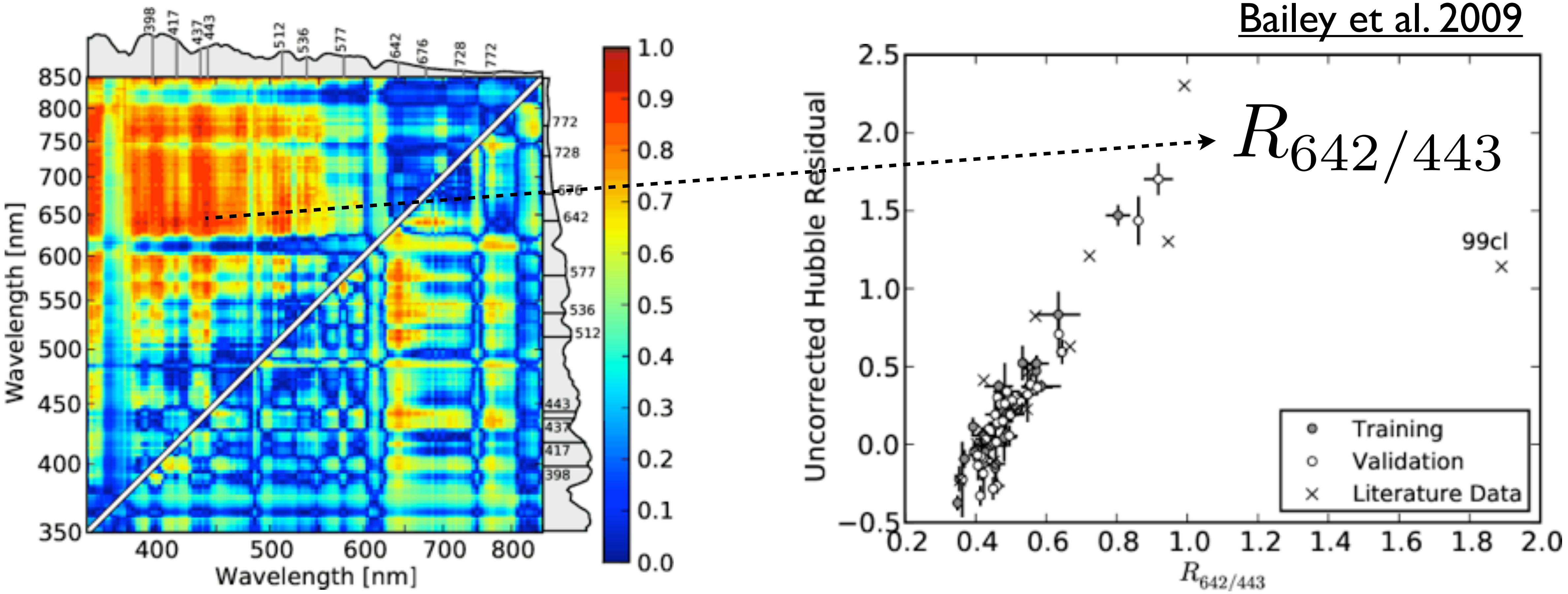

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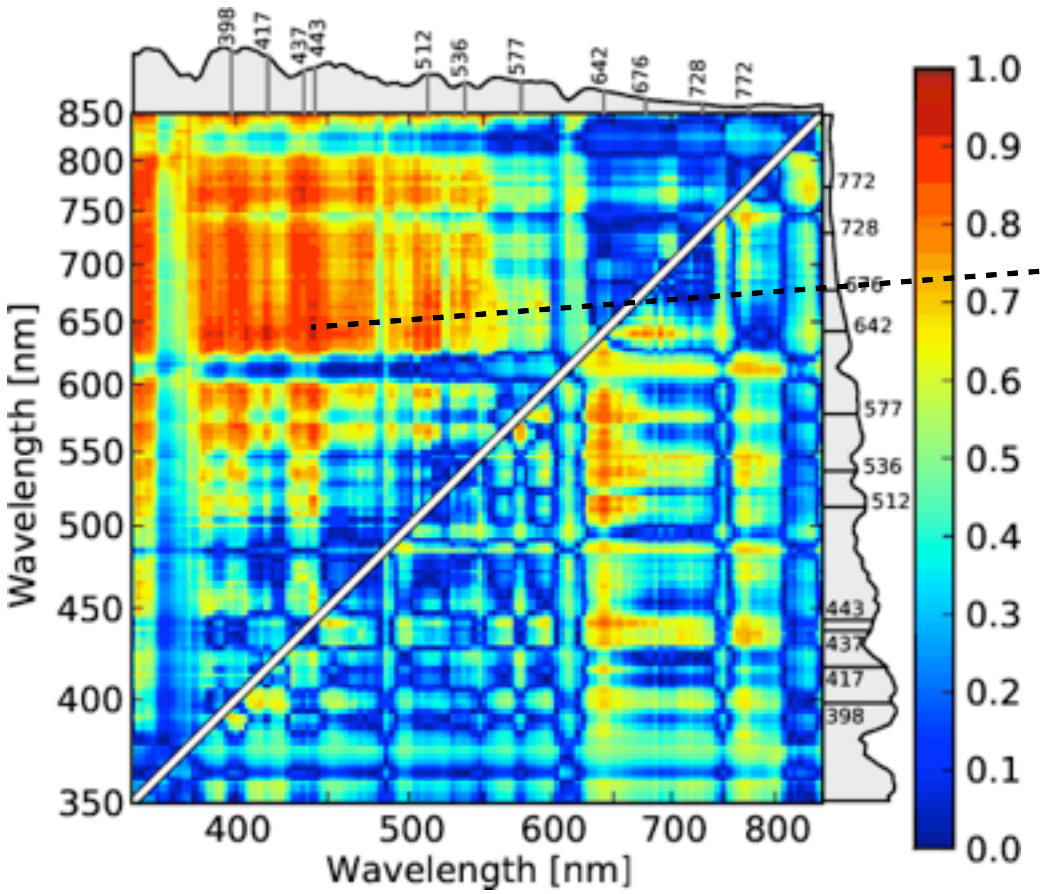
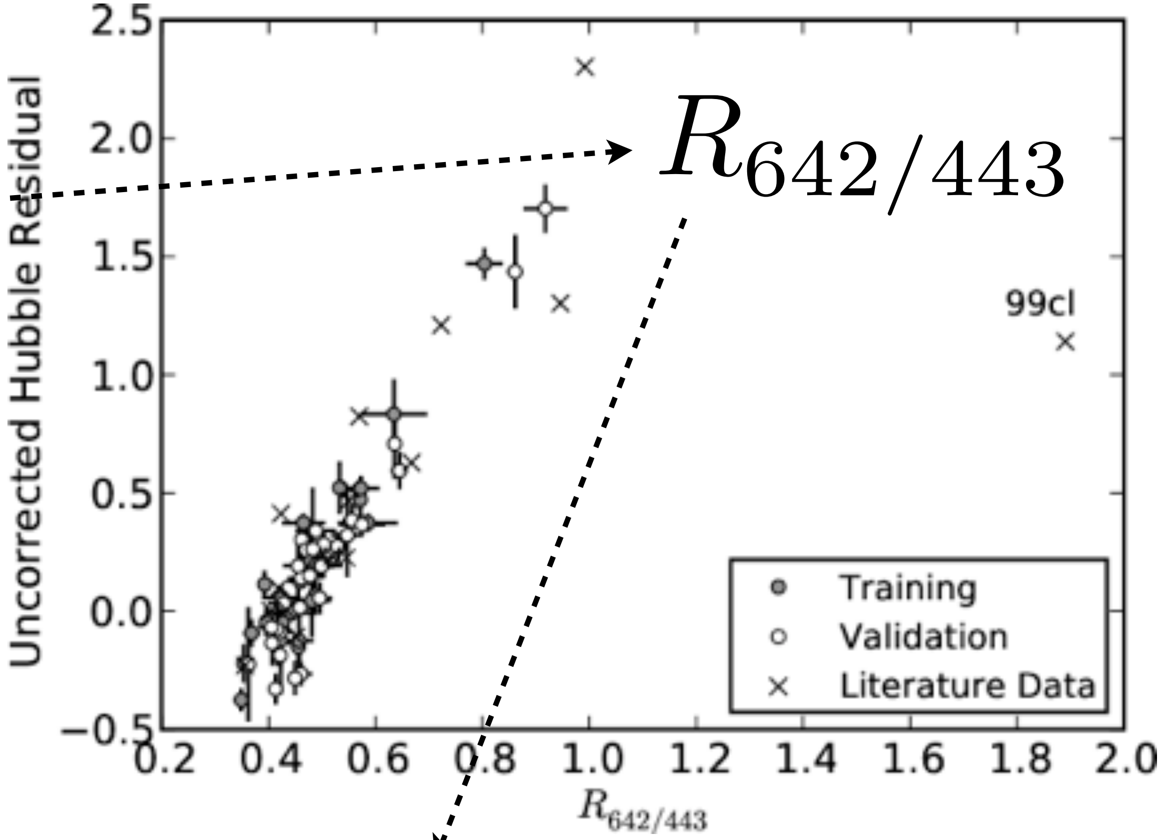
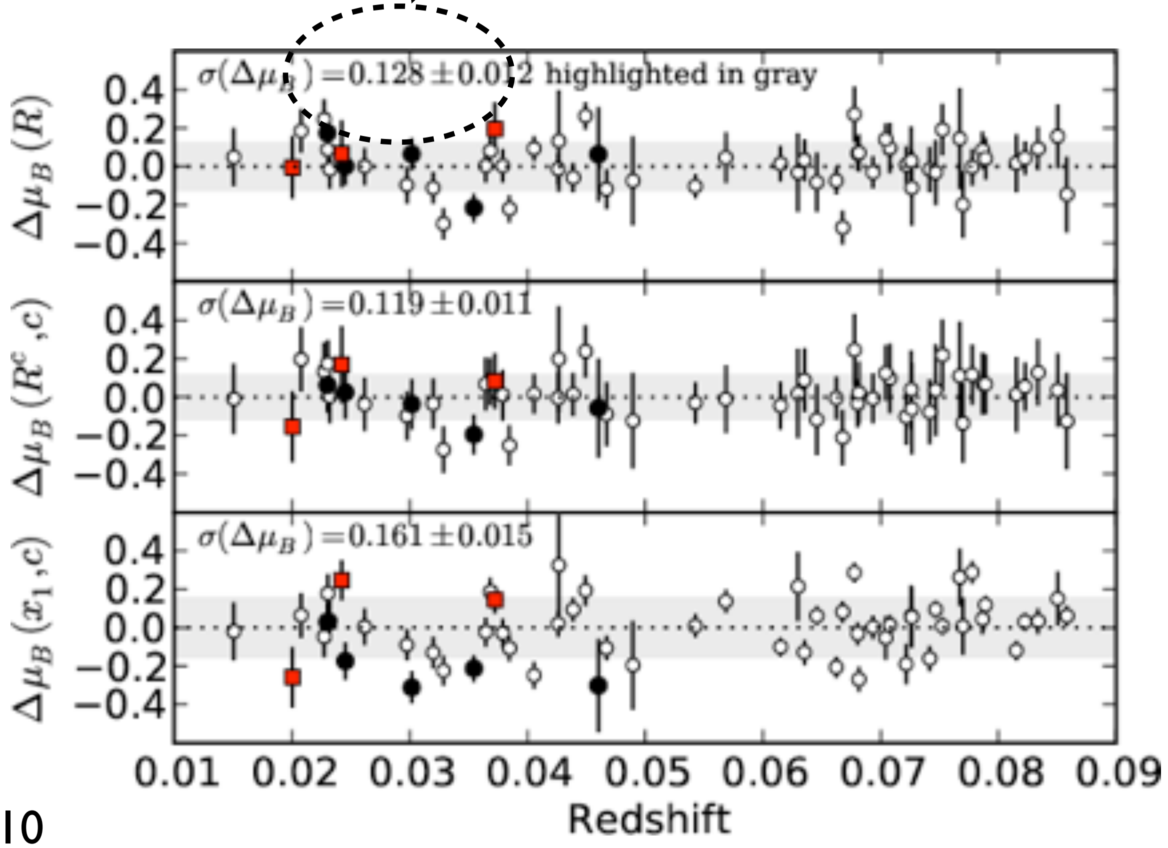


$R_{642/443}$





- ✦ Spectral flux ratios measured at max
- ✦ All correlation with Hubble residuals
- ✦ Only 1 ratio do better than (x_1,c)
- ✦ SNfactory publication: Bailey et al. 2009

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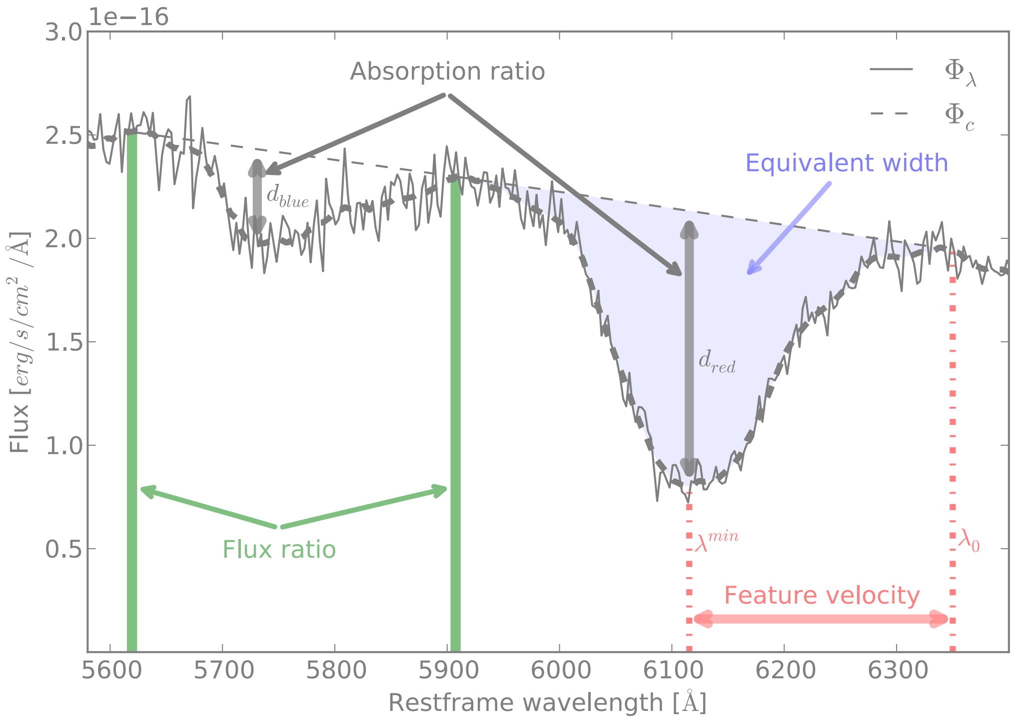

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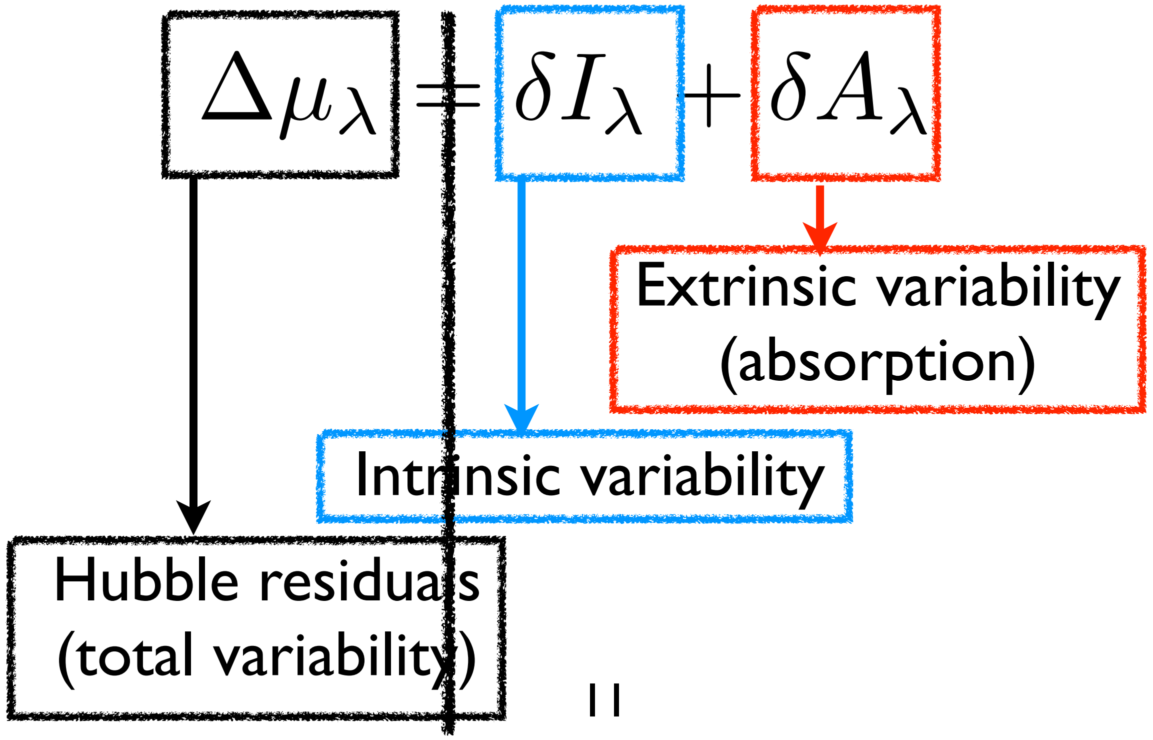

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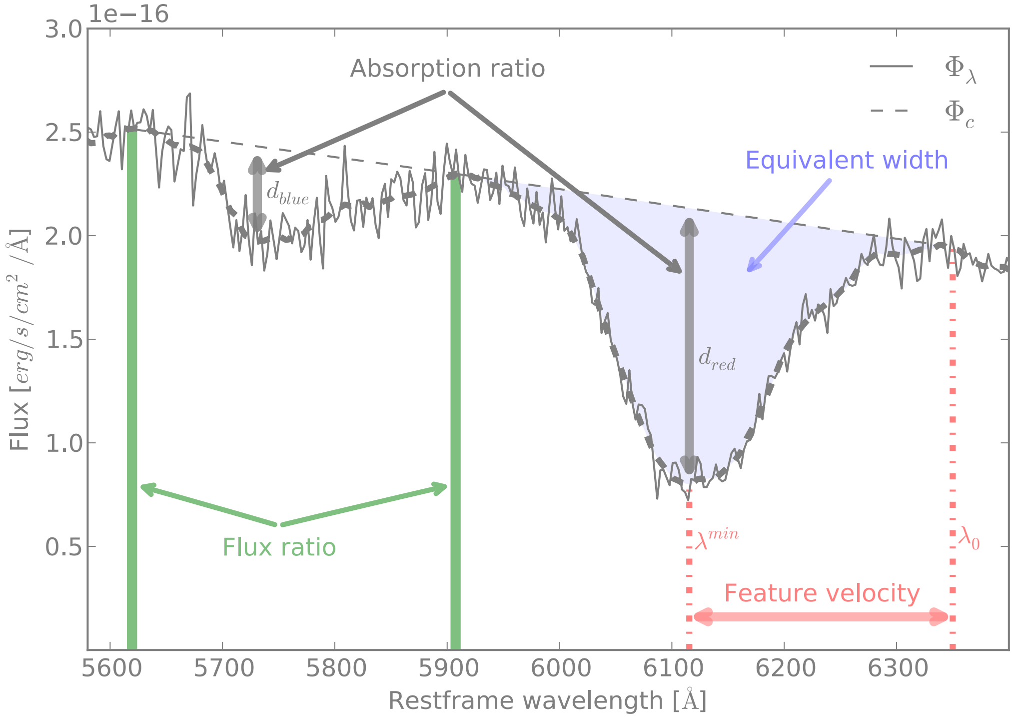

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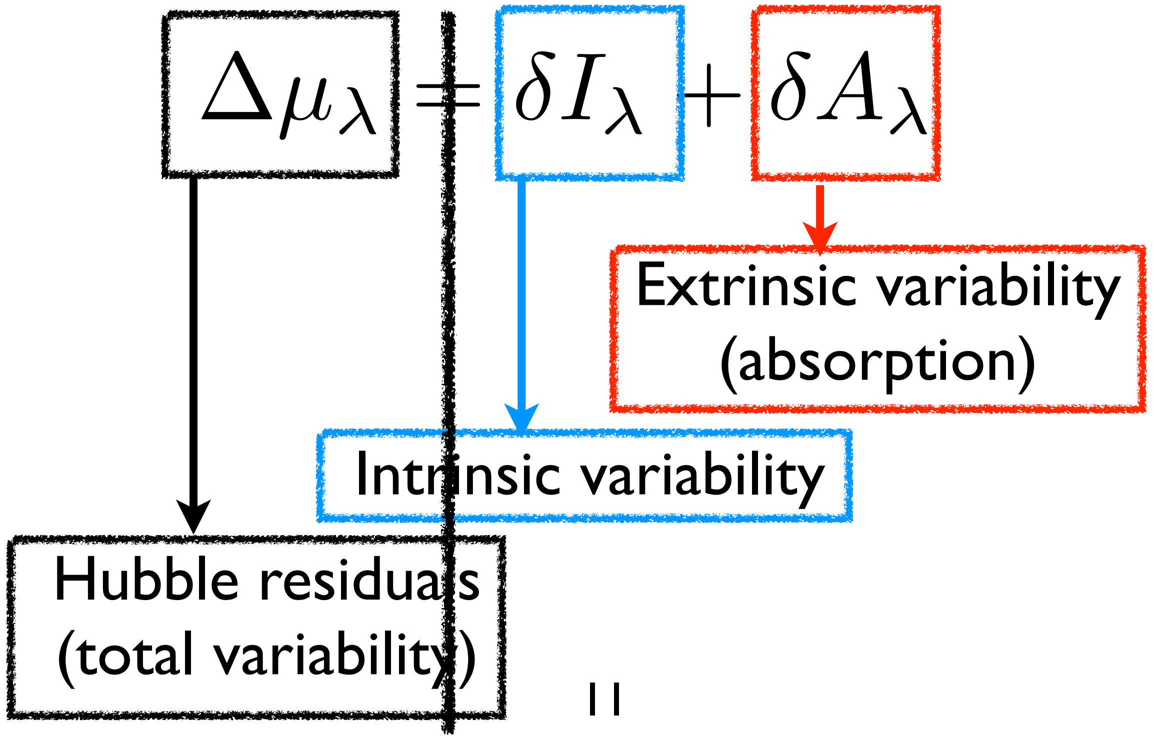

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2

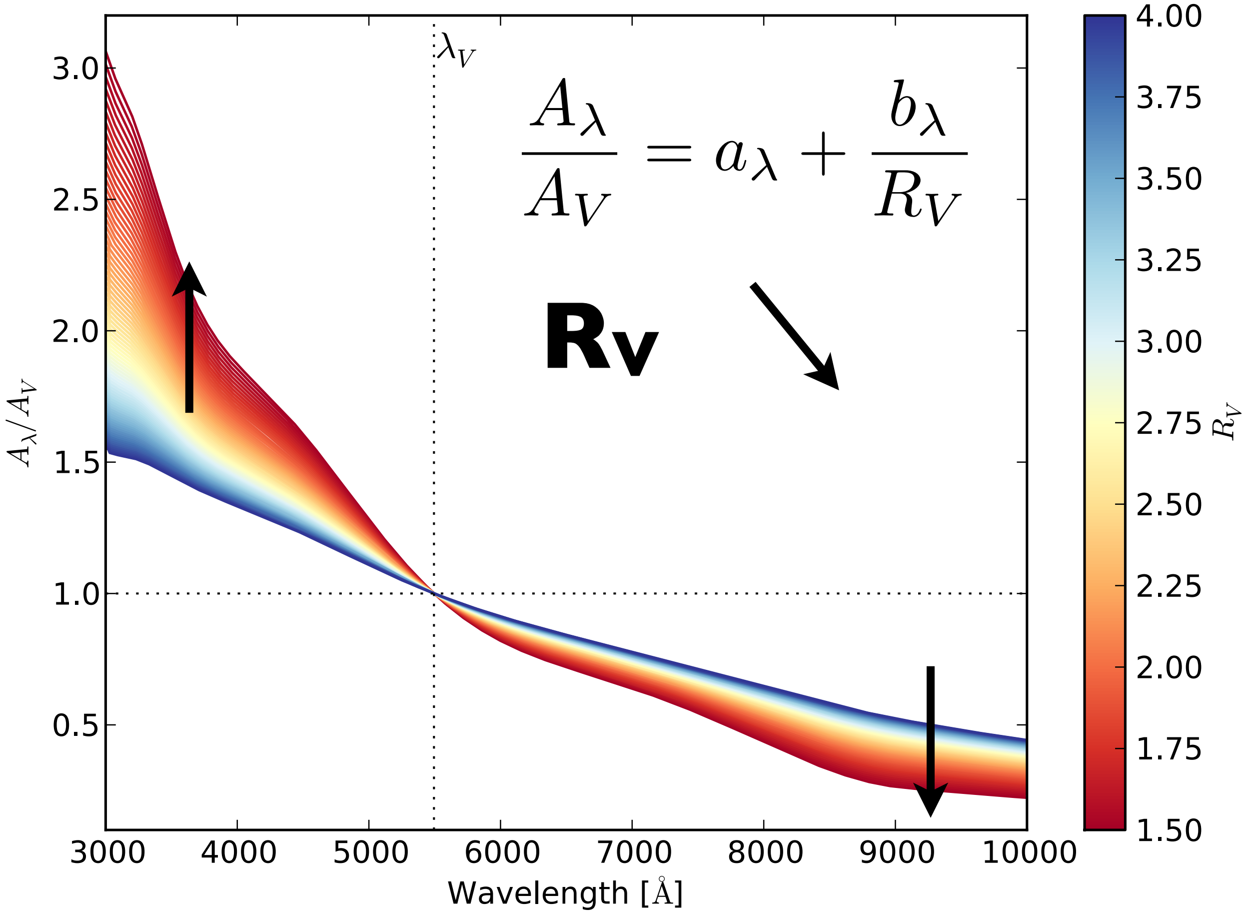
Can we use spectral indicators to **separate the SNe Ia variabilities**?

Which extinction law for SNe Ia?

- ✦ **SNe Ia dispersion dominated by extinction variability**
- ✦ **Recurrent issue** in SNe Ia analysis: **extinction law or 'Rv'?**

extinction more grey

High R_V



UV extinction, **reddening**

Low R_V

Cardelli extinction law: *Cardelli 89*

- ✴ dust properties: **R_V**
- ✴ amount of dust: **E(B-V)**

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

Our Solution: Measure the **intrinsic variability** with **equivalent widths**

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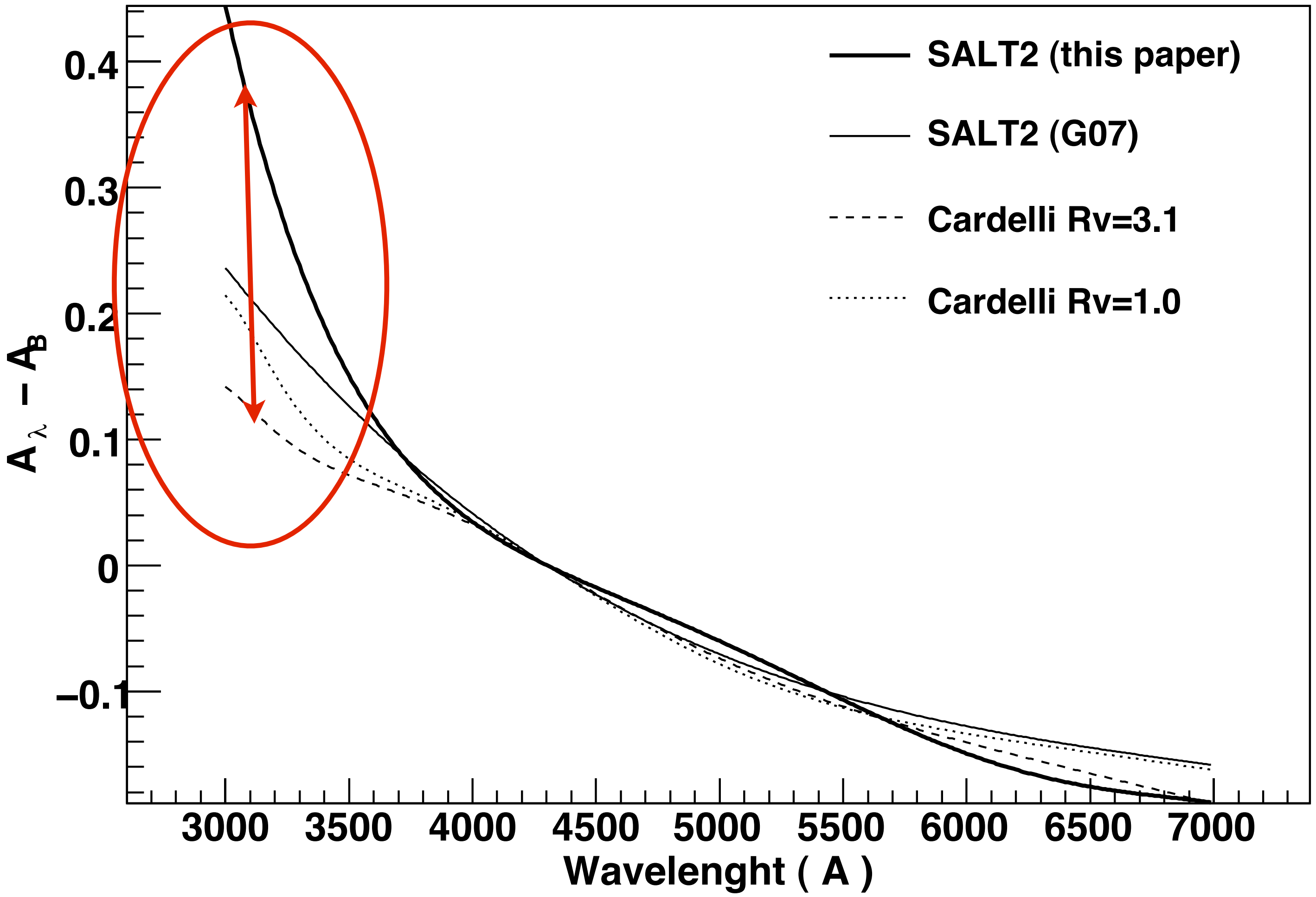

Guy, et al., A&A. (2010)

Cardelli extinction law: *Cardelli 89*

- ✴ dust properties: $\mathbf{R_v}$
- ✴ amount of dust: **E(B-V)**

SNe Ia: 1.5 < Rv < 2.2 (or β)
Our galaxy: <Rv> = 3.1

Lower values than the Milky Way one usually found
+
Large dispersion in these values

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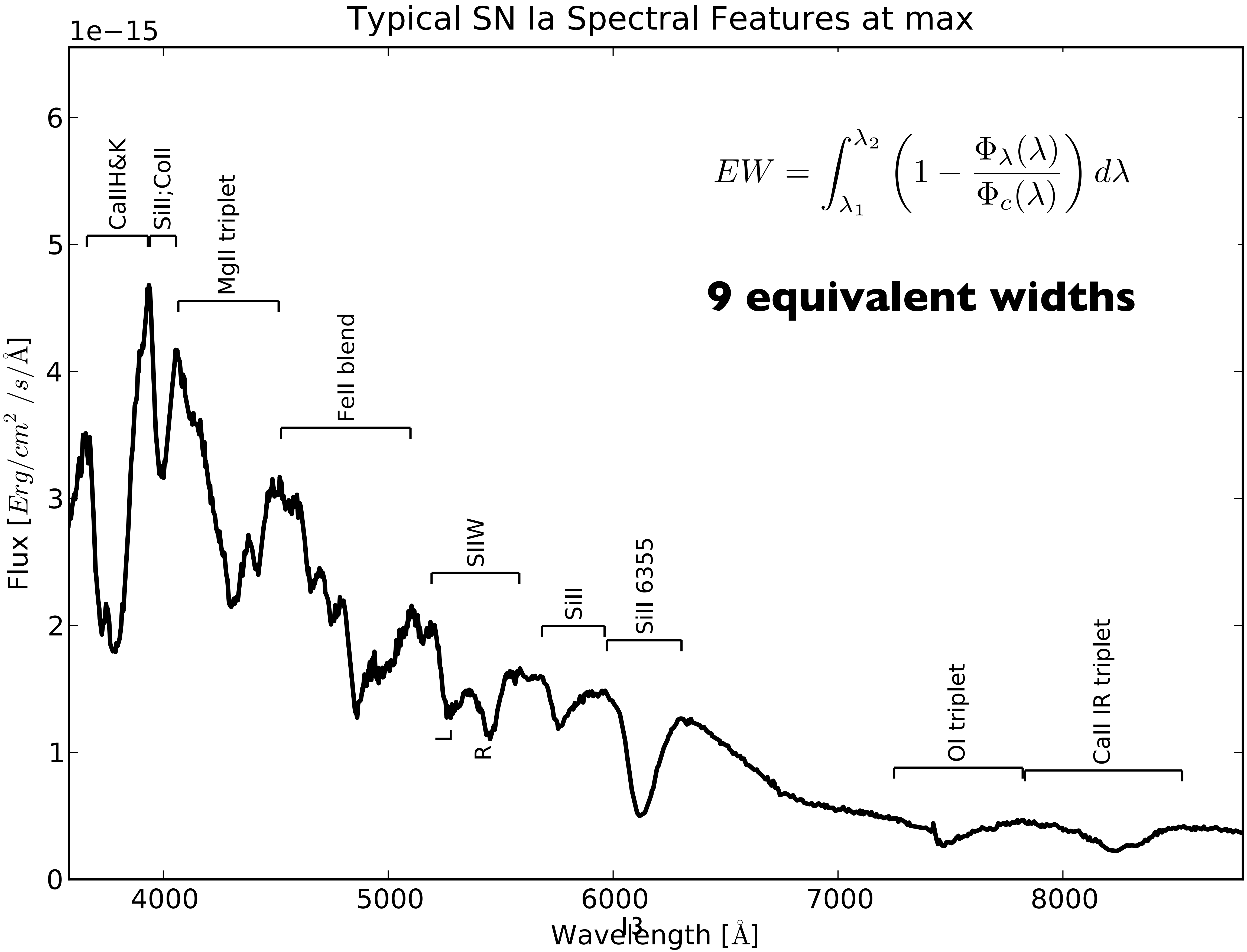
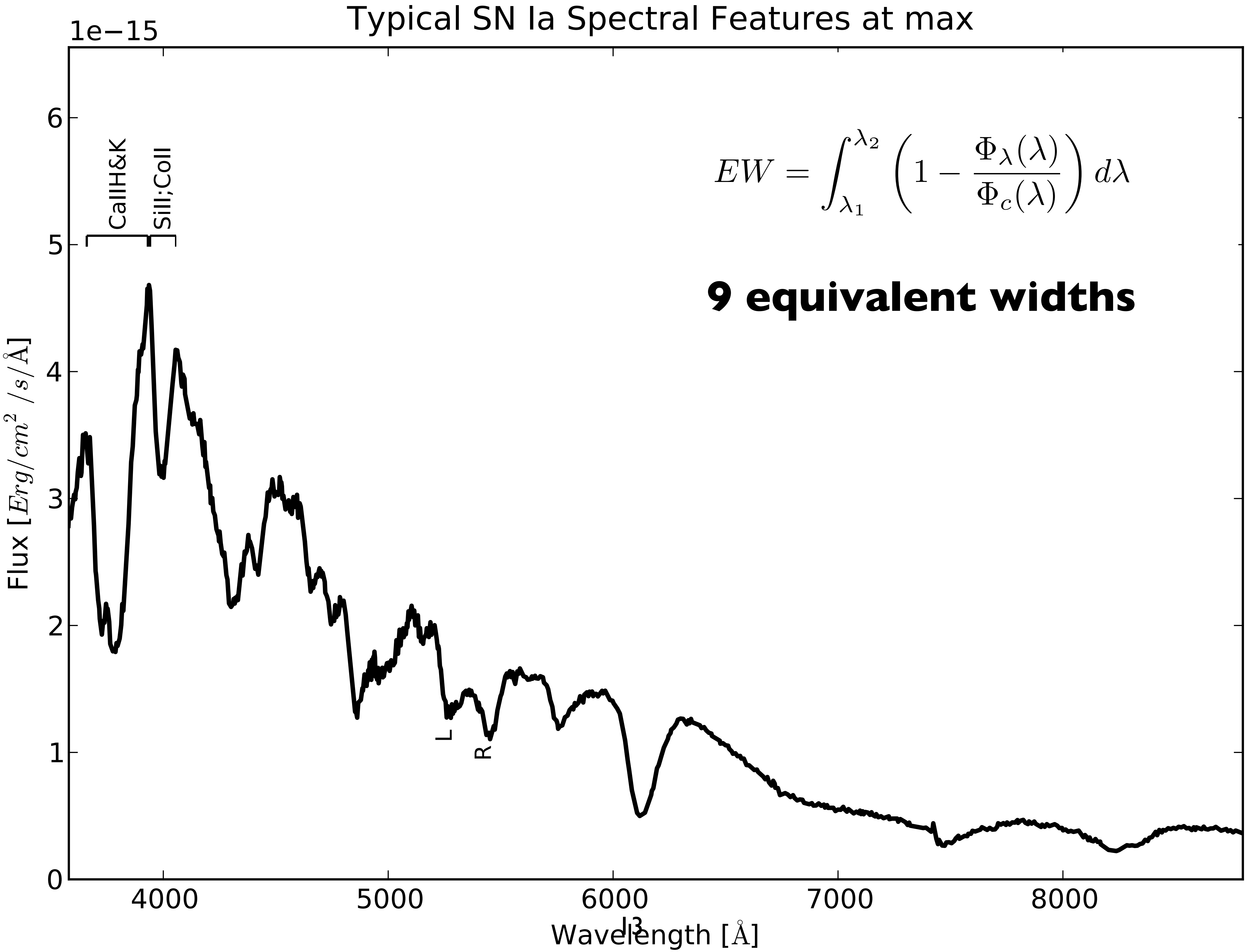
Spectral analysis at max



$$EW = \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{\Phi_\lambda(\lambda)}{\Phi_c(\lambda)}\right) d\lambda$$

9 equivalent widths

Spectral analysis at max


Typical SN Ia Spectral Features at max

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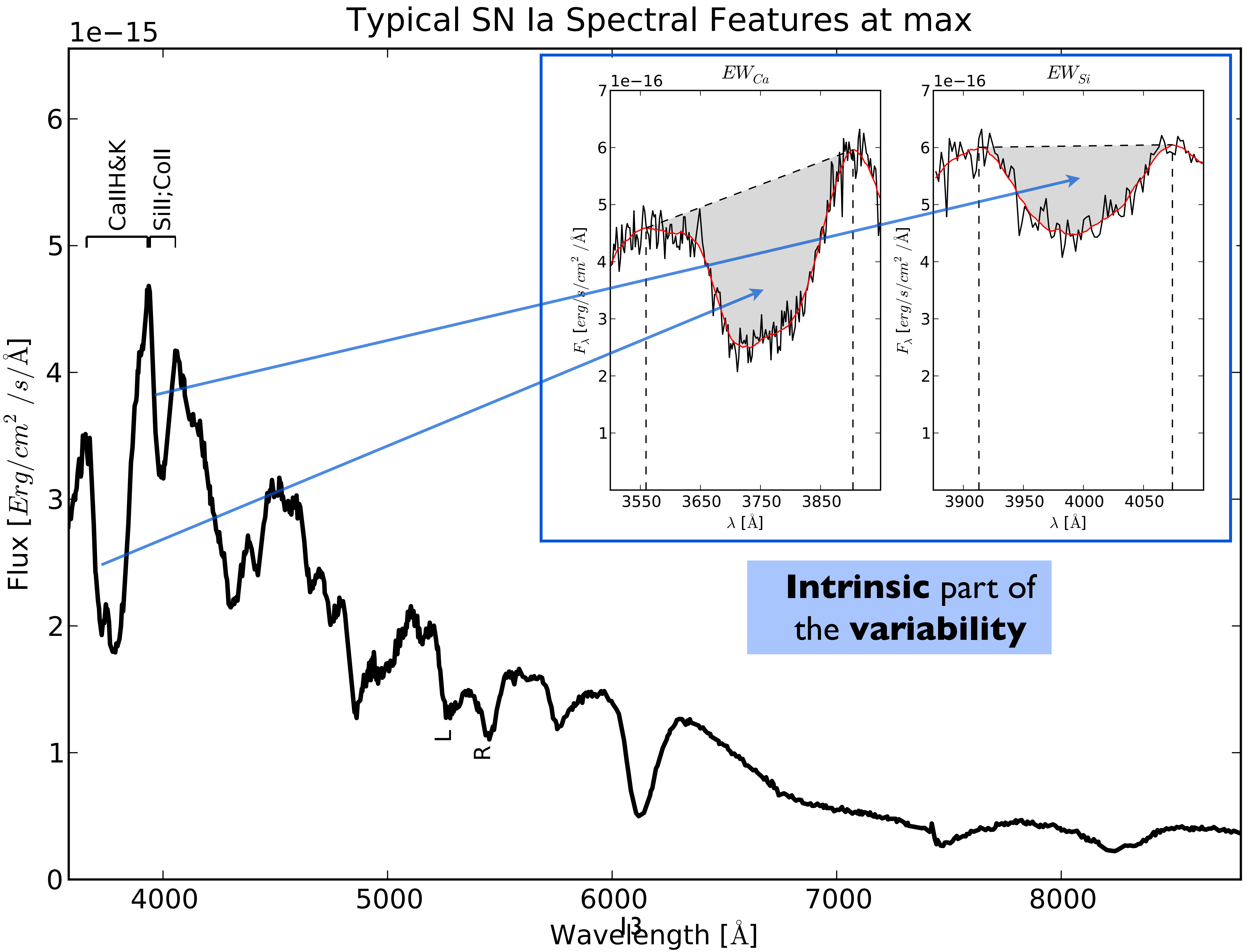
Spectral analysis at max



Intrinsic part of the **variability**

Extinction law construction

1st step: Decompose the Hubble residuals into intrinsic variabilities and relative absorptions δA_λ

$$\boxed{\delta A_\lambda = \Delta\mu_\lambda - \delta I}$$

Two intrinsic corrections

$$\delta I_\lambda = s_\lambda^{\mathrm{Si}} \mathrm{EW}^{\mathrm{Si}} + s_\lambda^{\mathrm{Ca}} \mathrm{EW}^{\mathrm{Ca}}$$

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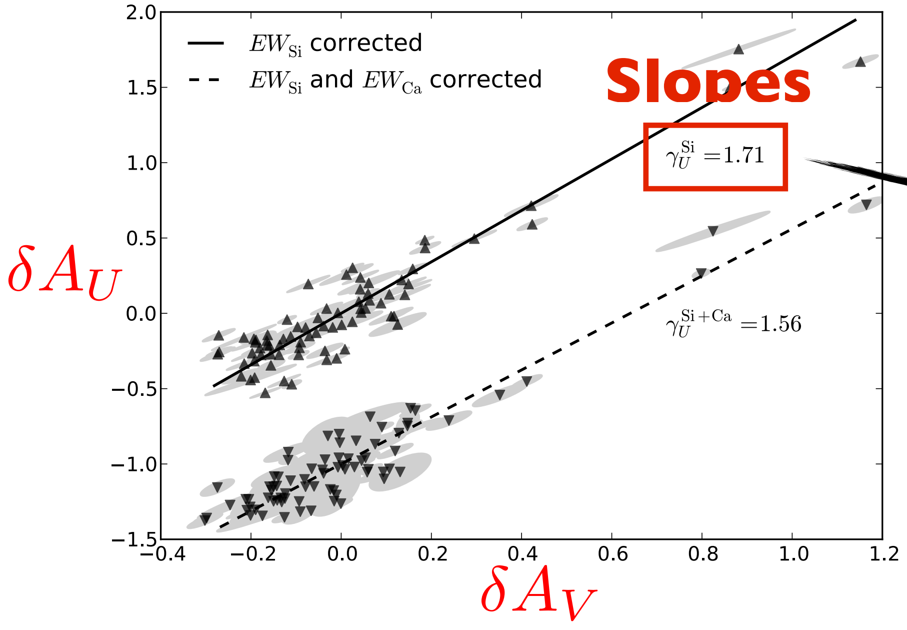
2nd step: Use the relation between the δAλ to construct the law



Linear model

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

Measured

Extinction law

Extinction

Extinction law construction

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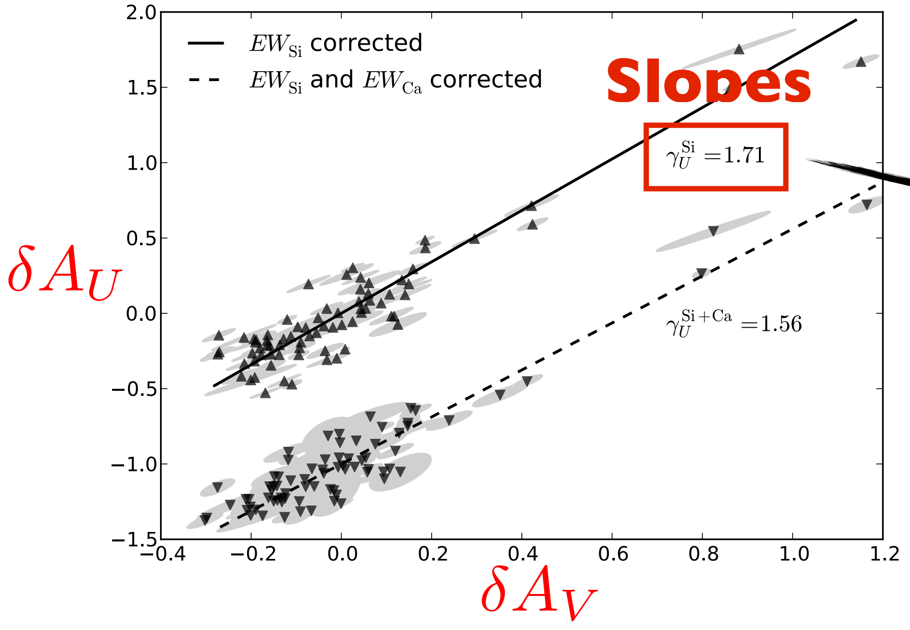

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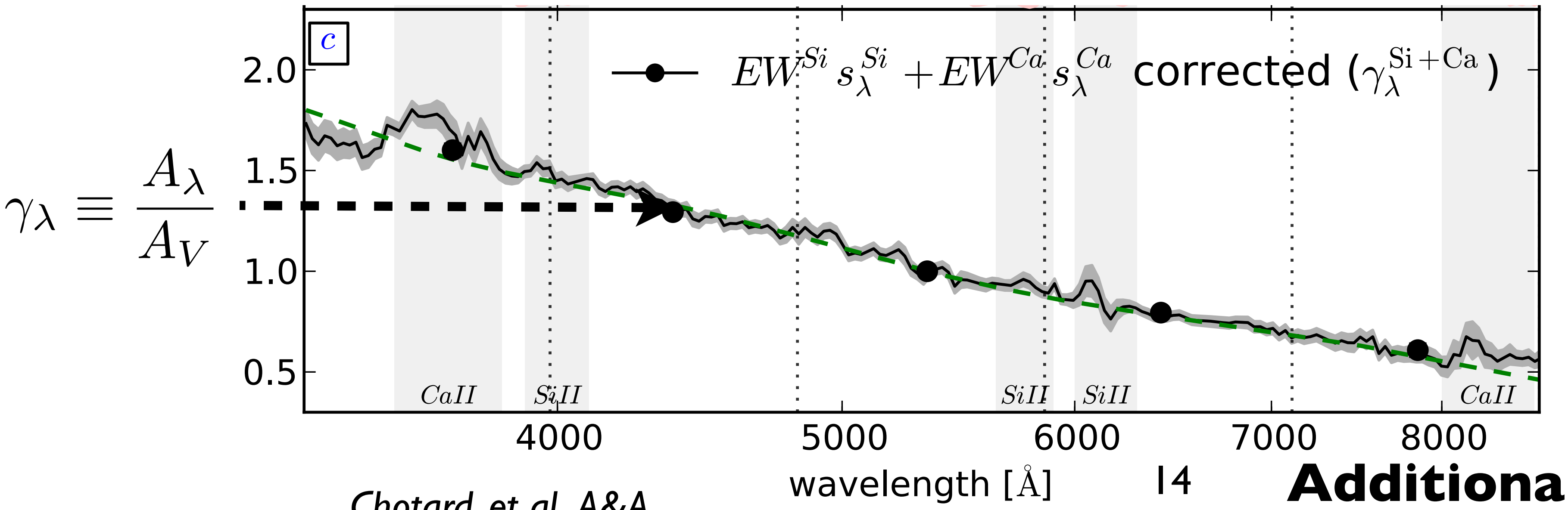


Classic extinction law

+

$$R_V = 2.6 \pm 0.4$$

Additional color dispersion needed...

Chotard, et al., A&A.

SNfactory status

- All published analysis: Peculiar SNe (Aldering 06, Thomas 07), Standardization (Bailey 09), Super-C (Scalzo 10), Host (Childress 11), Extinction (Chotard 11), Carbon-footprint (Thomas 11)
- Ongoing analysis: *Standardization*, *Classification*, *Reddening analysis*, Host galaxies analysis, NaID absorption line analysis, Twin supernovae analysis, Spectral data / Explosion model comparison, SN2011fe, etc. **Some of them already under publication process.**
- More data taken in a regular basis to feed these analysis.

- **Chinese collaboration** to SNfactory phase II since 2011 (obs/reduc/analysis)
- French (CPPM/IPNL) / Chinese (THCA) collaboration on several sides:
  - Data transfert / Calibration process runing
  - Spectral analysis / Classification / SNe Ia velocity studies (see Wang Xiaofeng from THCA)
- Autumn SNf II collaboration meeting probably in Tsinghua

BACKUP

Cosmology and standard candles

- Need an object for which the **luminosity L is known**

$$f = \frac{L}{4\pi d_L(z,\omega)^2}$$

flux

Standard candles

- Luminosity distance depends on redshift and cosmological parameters

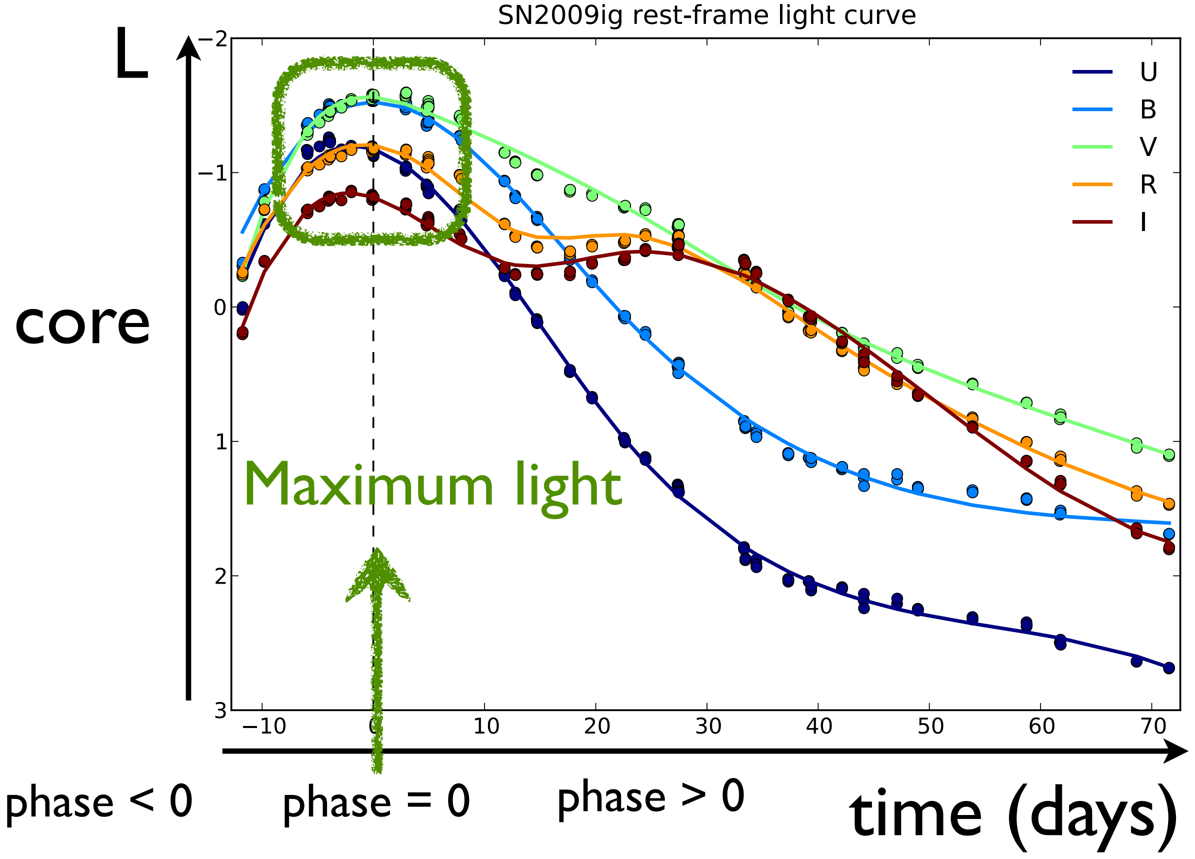
$$\omega = \{\Omega_\Lambda, \Omega_M, w, H_0\}$$

- **Measurements**:
  - redshift
  - distance modulus: μ

$$\mu = \overset{\text{apparent}}{m(f)} - \overset{\text{absolute}}{M(L)} = 5\log\left(\frac{d_L(z,\omega)}{10\mathrm{pc}}\right)$$

SN Ia: properties

- **Progenitor**: White dwarf (C+O) in a binary system
- **Explosion**:
  - Accretion of the companion (?) mass up to the Chandrasekhar mass limit (~1,4 $M_\odot$)
  - Thermonuclear fusion in the SN core gives Ni, Si, S, Ca



- **Competition between:**
  - Opacity: decrease with the expansion
  - Radioactive decay rate: decrease in the SN core

$$^{56}Ni \xrightarrow{\tau_{Si} \approx 6j} {}^{56}Co \xrightarrow{\tau_{Co} \approx 77j} {}^{56}Fe$$

⟶ **light curve**

- **Properties**:
  - ~same luminosity $L > 10^9 L_\odot$
  - ~spectroscopic homogeneity

Visible up to cosmological distances

&

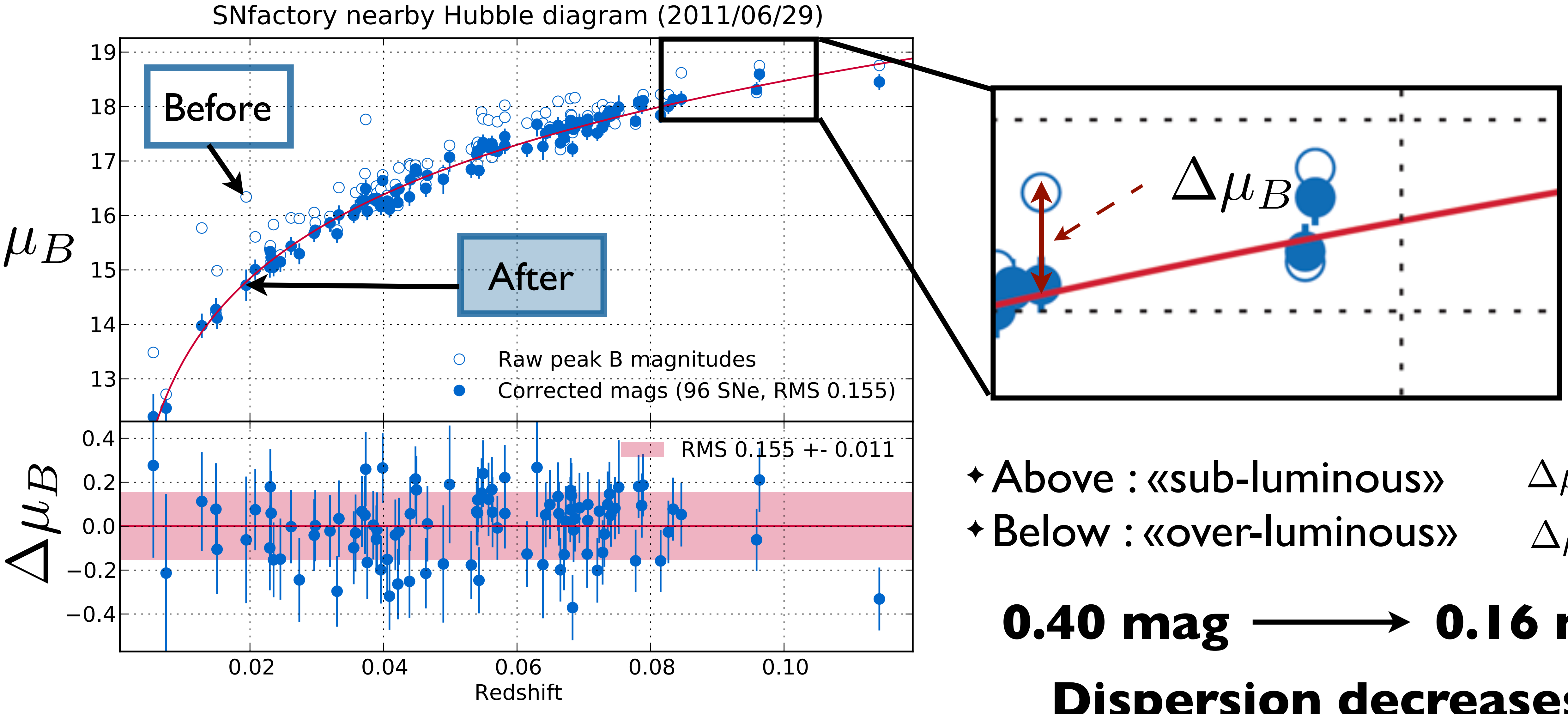
Identification by spectral features

Nearby Hubble diagramm

Empirically corrected Hubble diagram

$$\mu_B^i = \boxed{m_B^i} - M_B + \alpha \times \boxed{x_1^i} - \beta \times \boxed{c^i}$$

α, β and M_B optimized
&
dispersion in magnitude added to reach $\chi^2=1$



- Above : «sub-luminous» $\Delta\mu_B > 0$
- Below : «over-luminous» $\Delta\mu_B < 0$

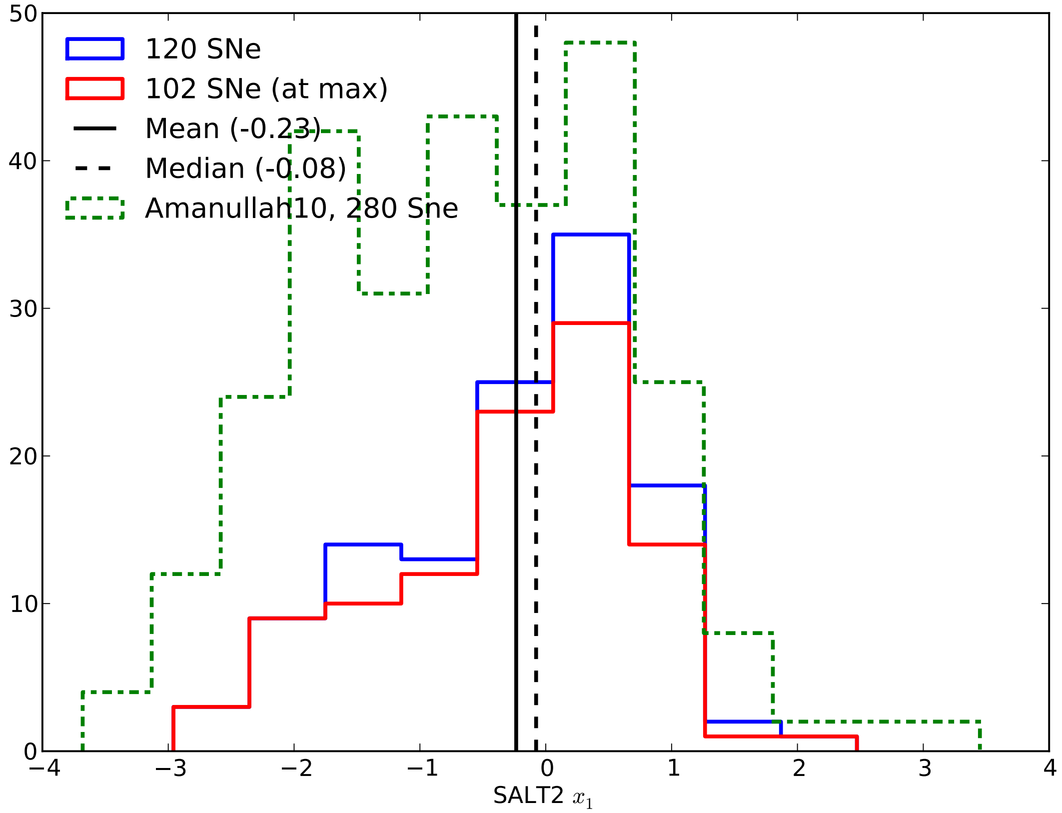
0.40 mag ⟶ 0.16 mag

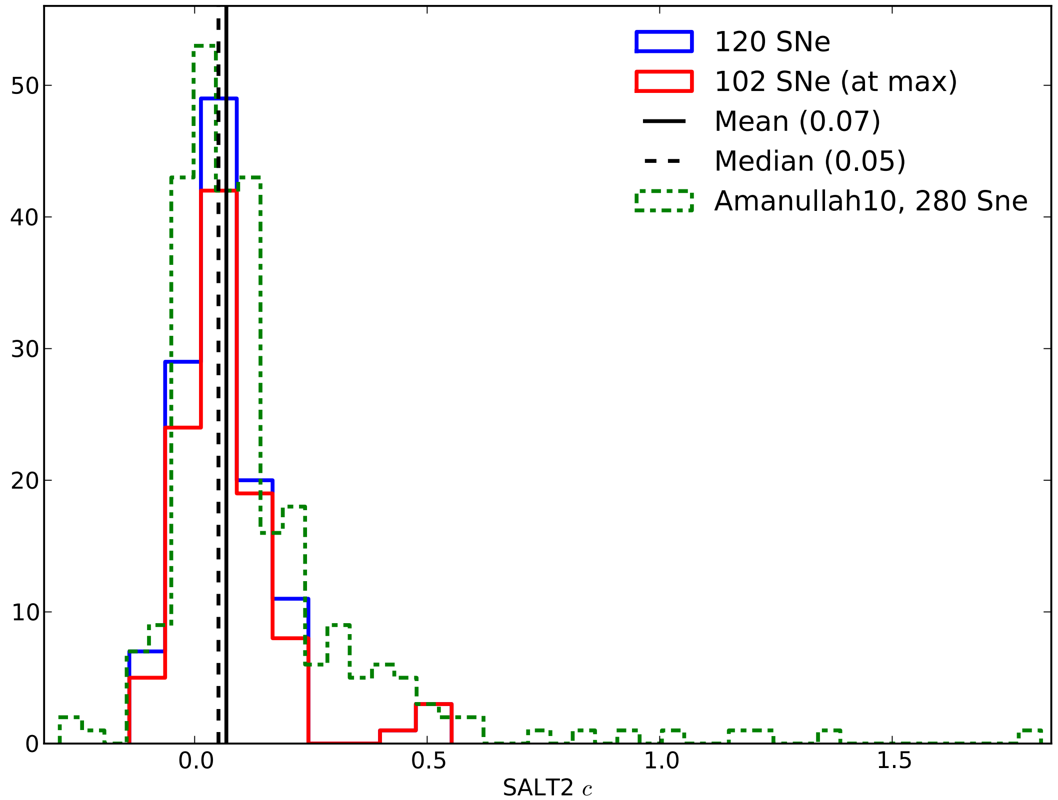
Dispersion decreases

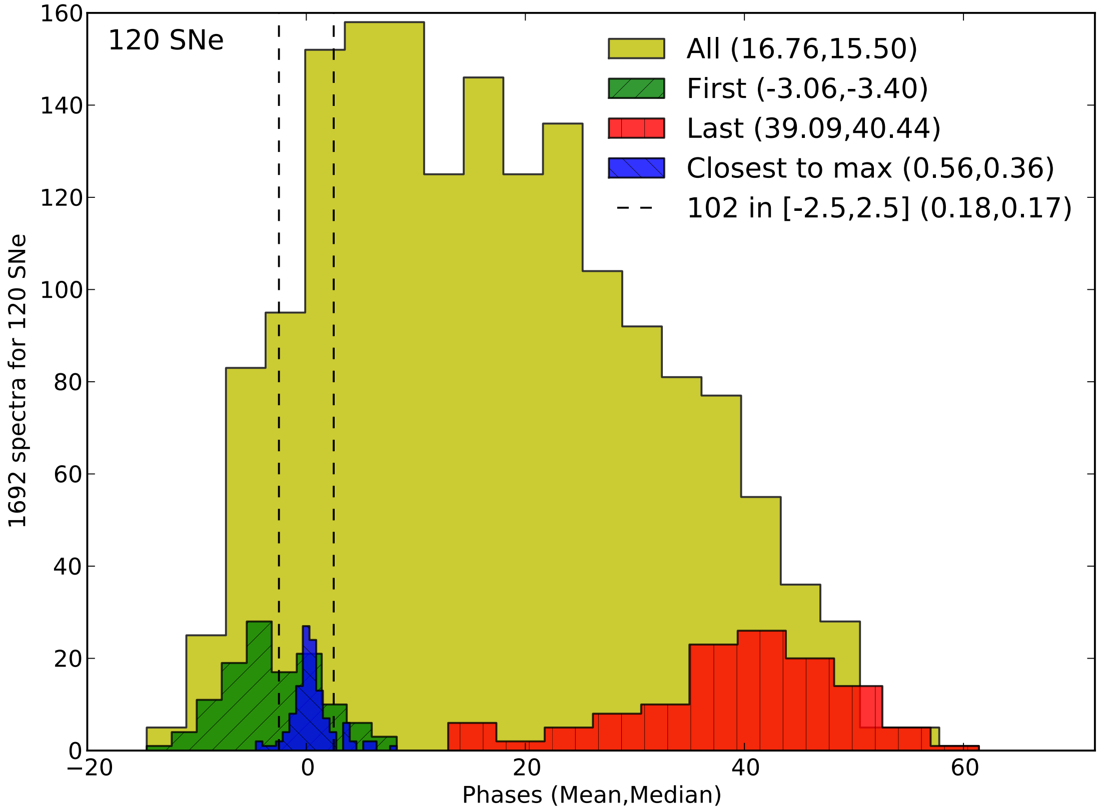
Analysis sample

Quality cut on the SALT2 light curve fit:

- at least 5 points/night on the light curvea
- a «good» fit to the light curve (RMS)

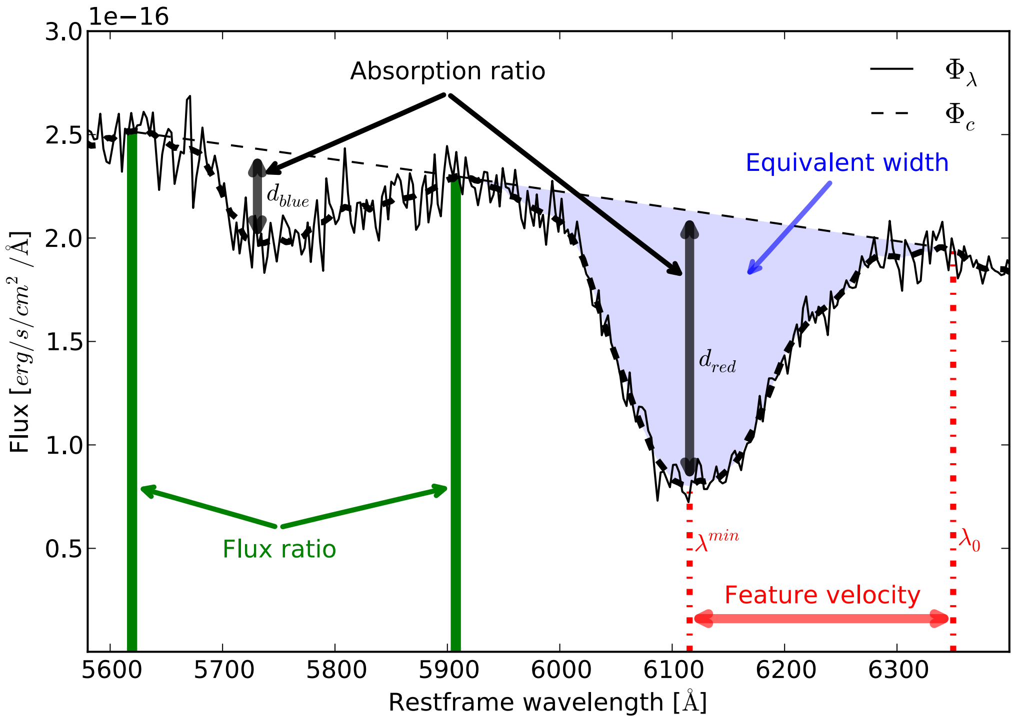






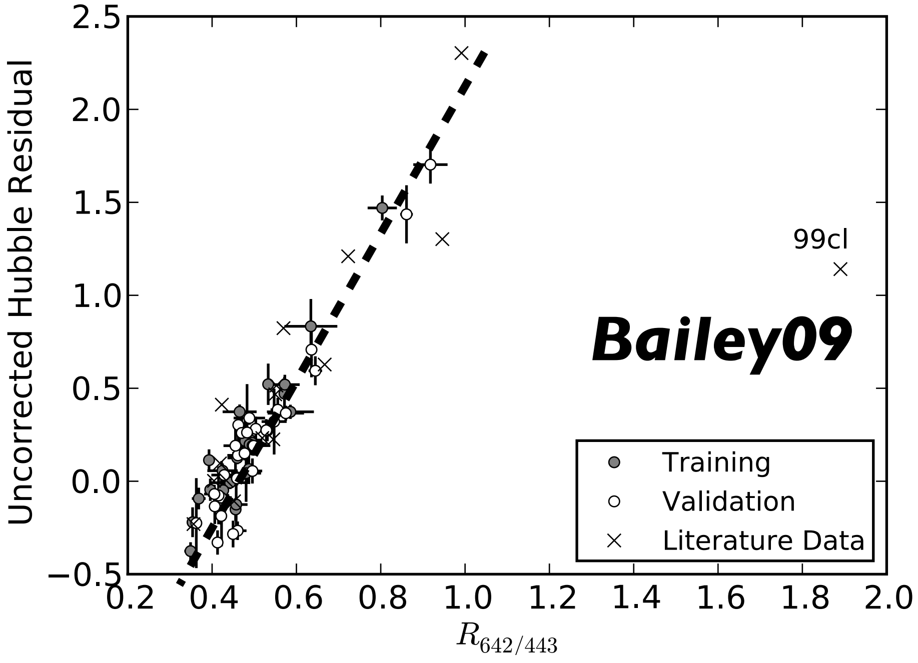
Spectral analysis

At a given phase **(at max), spectral differences** between SNe are linked to the **different types** of **variabilities**



- **Spectral indicators:** tracer of these variabilities
- **4 type of spectral indicators:**
  - ✳ flux ratio
  - ✳ depth ratio
  - ✳ equivalent width
  - ✳ feature velocity

- **Different goals**
  - ✳ Standardization
  - ✳ Sub-classification
  - ✳ Extinction parameters



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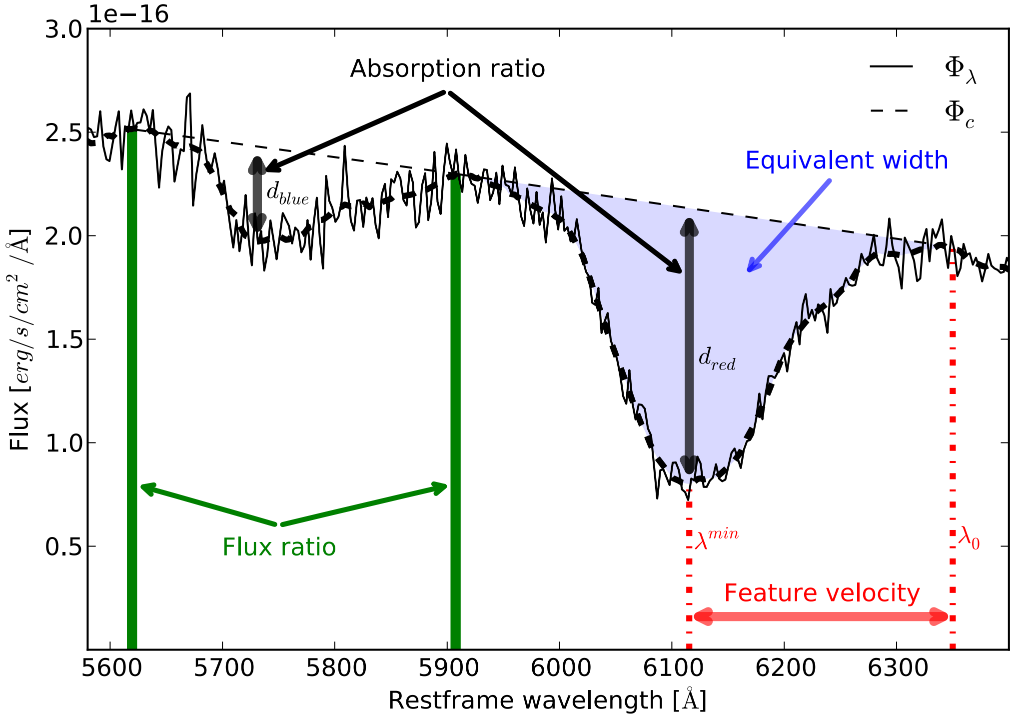

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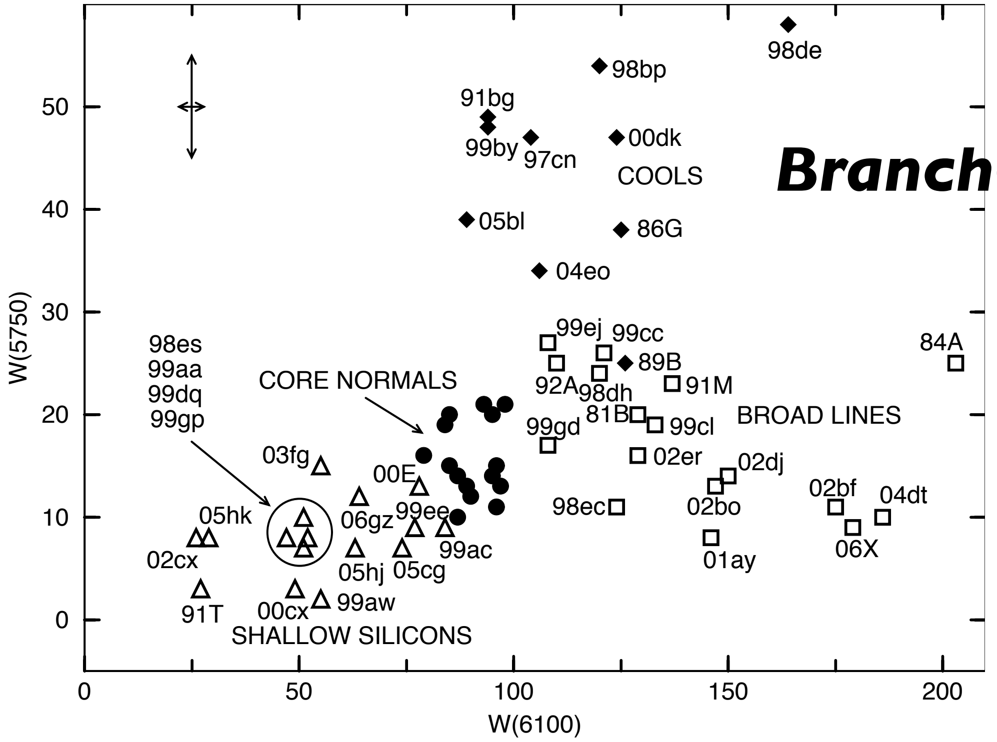

Branch09

Spectral analysis

At a given phase **(at max), spectral differences** between SNe are linked to the **different types** of **variabilities**

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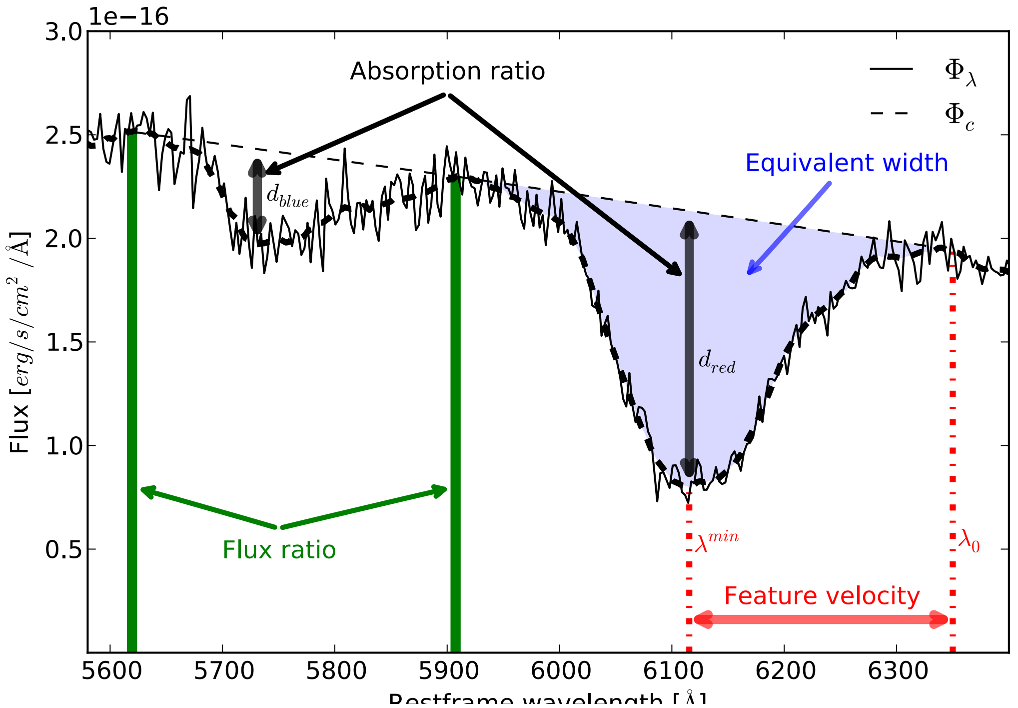
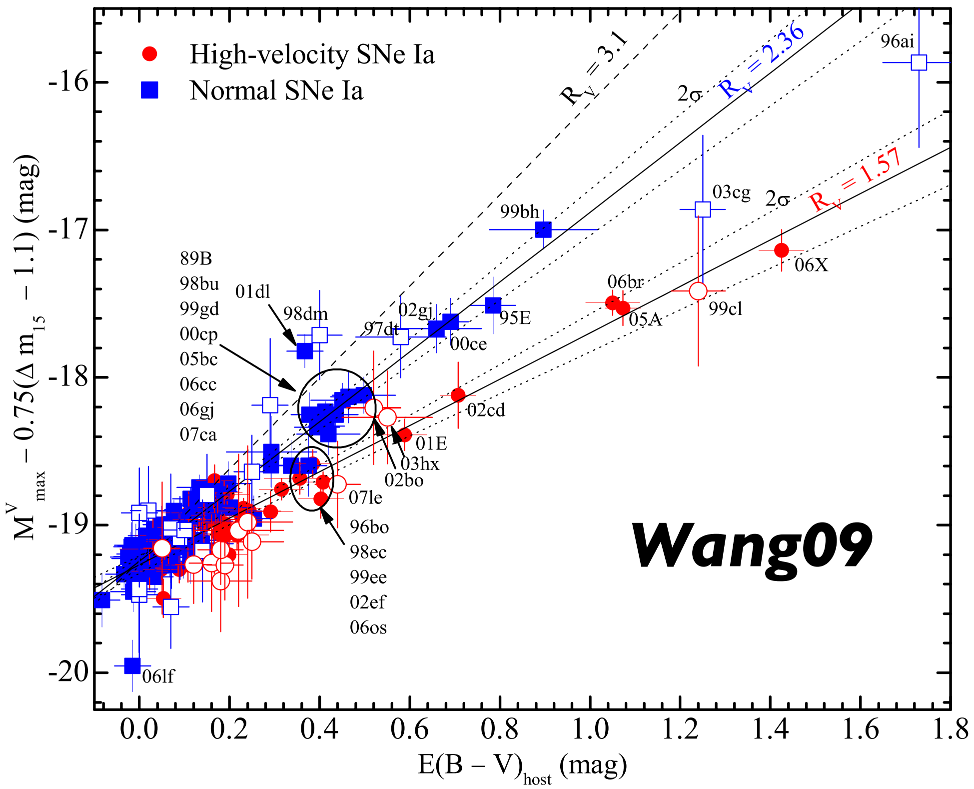


- **Different goals**
  - Standardization
  - Sub-classification
  - Extinction parameters



Spectral analysis

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- ✦ **Spectral indicators:** tracer of these variabilities
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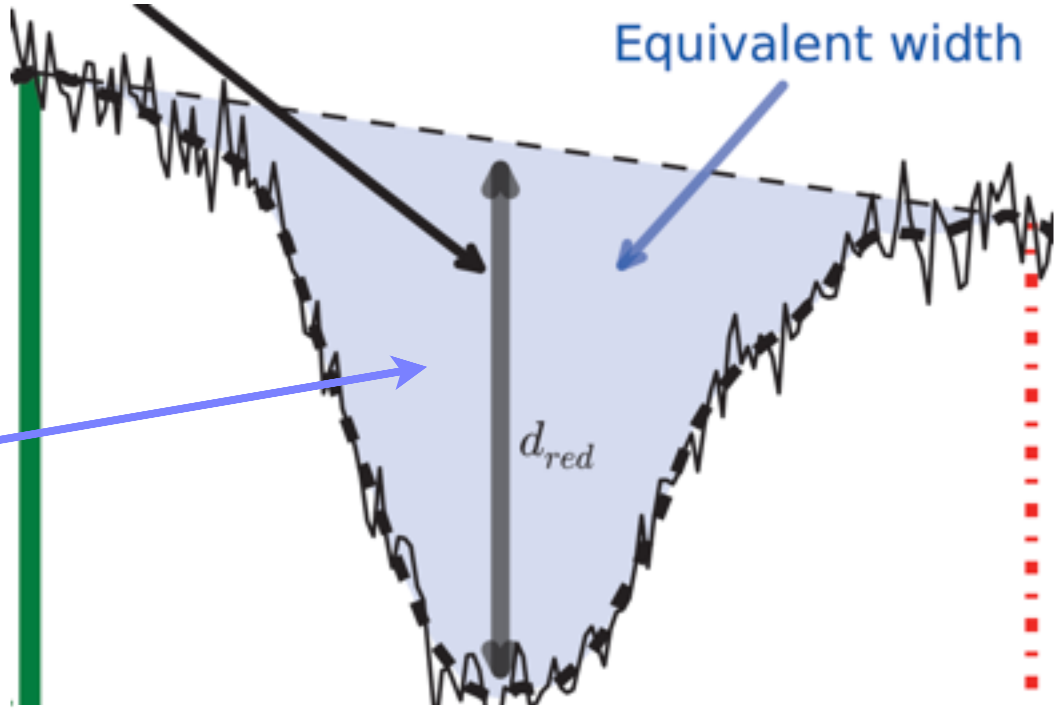
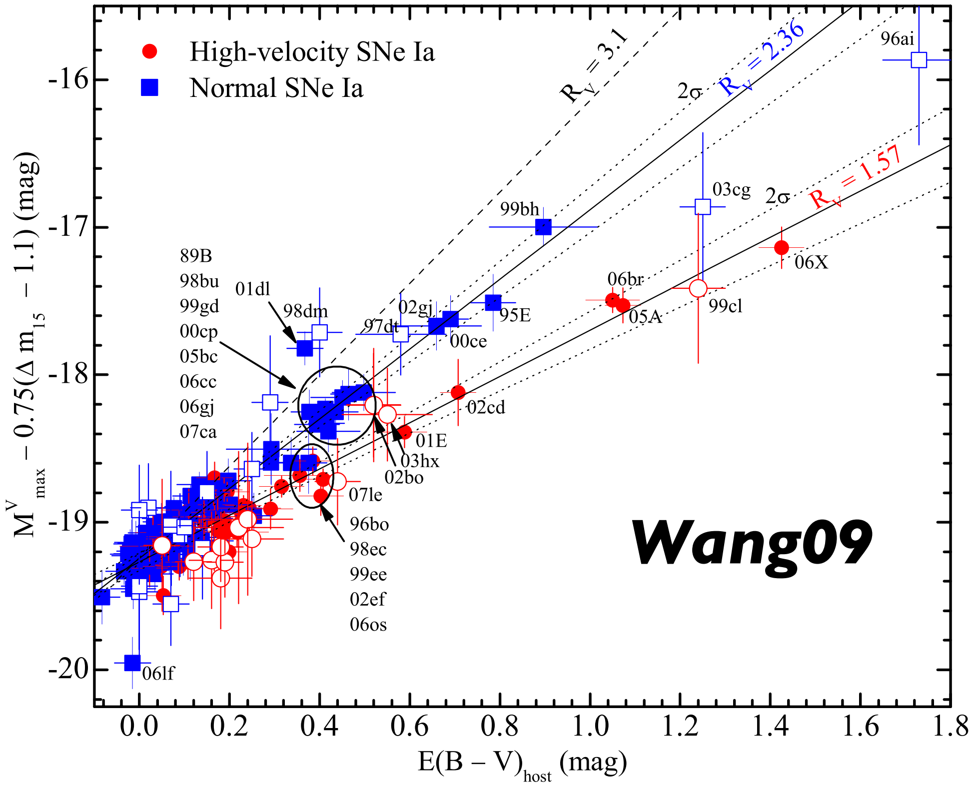


- ✦ Insensitive to dust extinction <3%
- ✦ Correlated to intrinsic variabilities



Wang09

Dust extinction

- **Dust** in the ISM/CSM responsable for an **extinction, function of the wavelength**
- A **2 parameters law**:
  - dust properties: **R_V**
  - amount of dust: **E(B-V)**

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

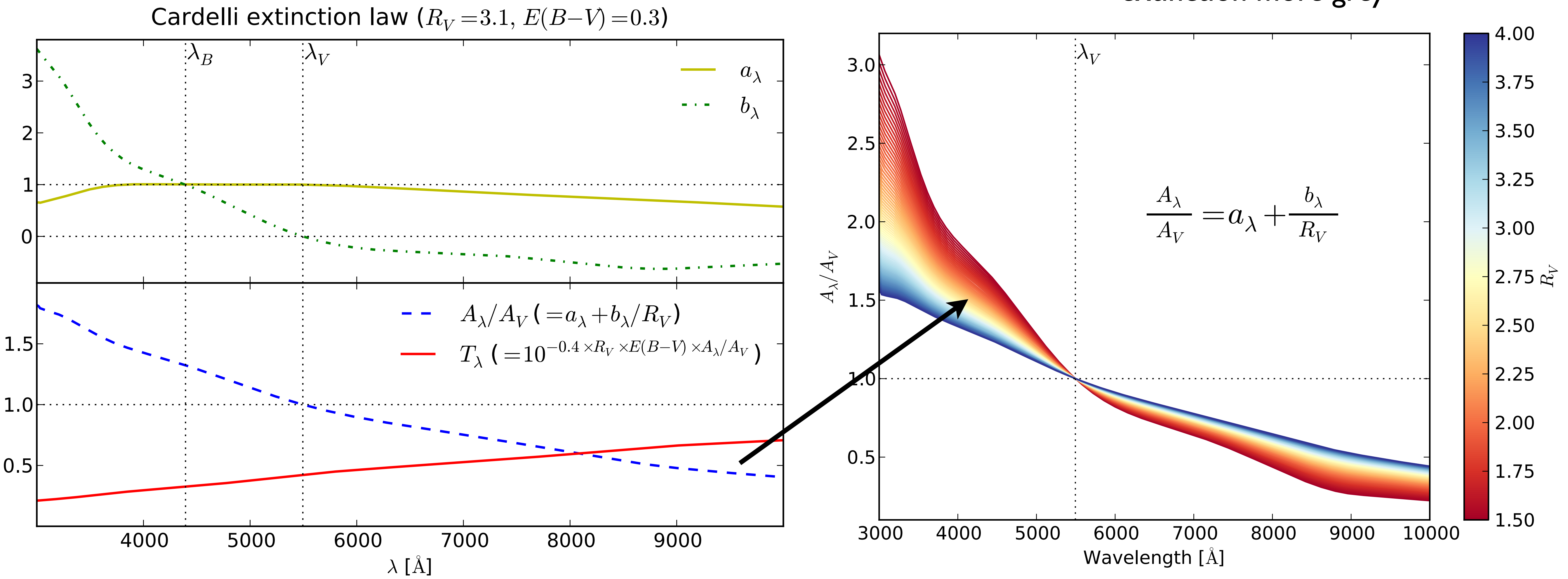
$$\frac{A_\lambda}{A_V} = a_\lambda + \frac{b_\lambda}{R_V}$$

- **Cardelli extinction law:**

  Cardelli, Clayton, Mathis, ApJ. (1989)

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

High R_V
extinction more grey



UV extinction, **reddening** **Low R_V**

Sensitivity to dust extinction

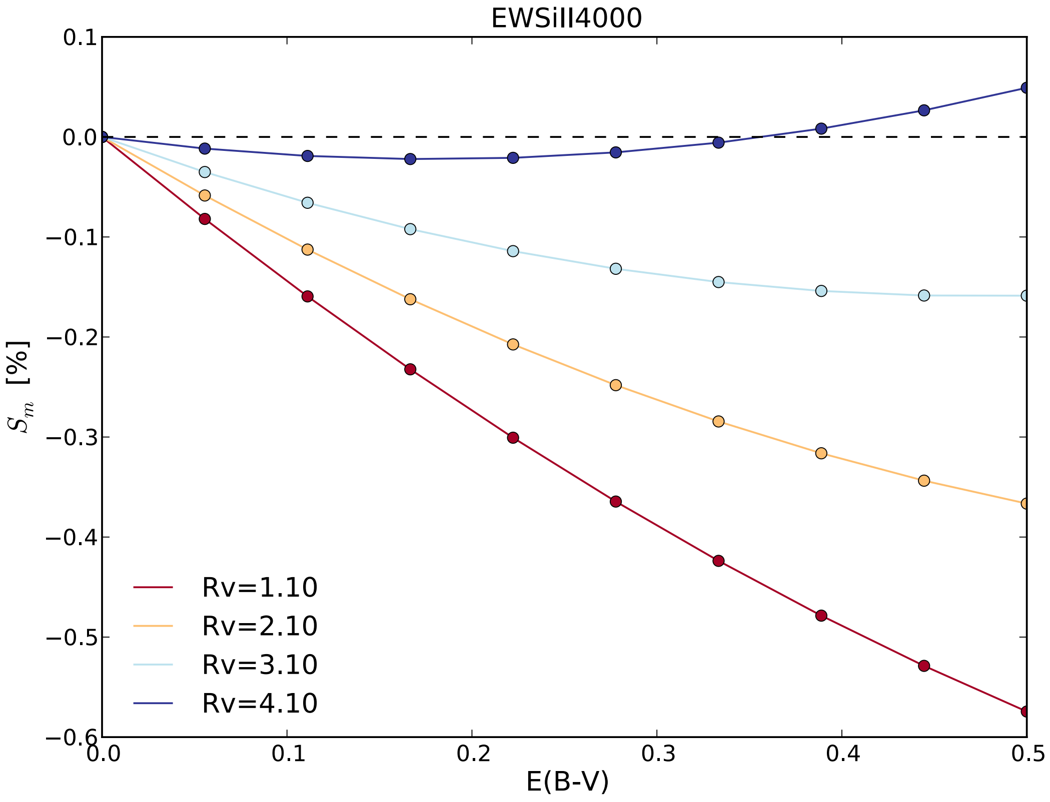
Considering ***S*** as the **sensitivity** of spectral indicators **to dust** (in %)

Spectral indicators could trace a:

- purely **intrinsic effect** of the SNe Ia variability **S=0**
- **mixt** of **intrinsic** and **extrinsic** variability **0<S<100**
- purely **extrinsic effect** of the variability **S=100**

S depends on the :

- type of spectral indicators
- reddening : E(B-V) and R_V
- position in the spectrum (width, central wavelength, depth...)



For a mean extinction

Indicator	<***S***> (%)
Flux ratio	> 10
Depth ratio	> 10
EW	< 3
Velocity	a few %

Mixt

Intrinsic

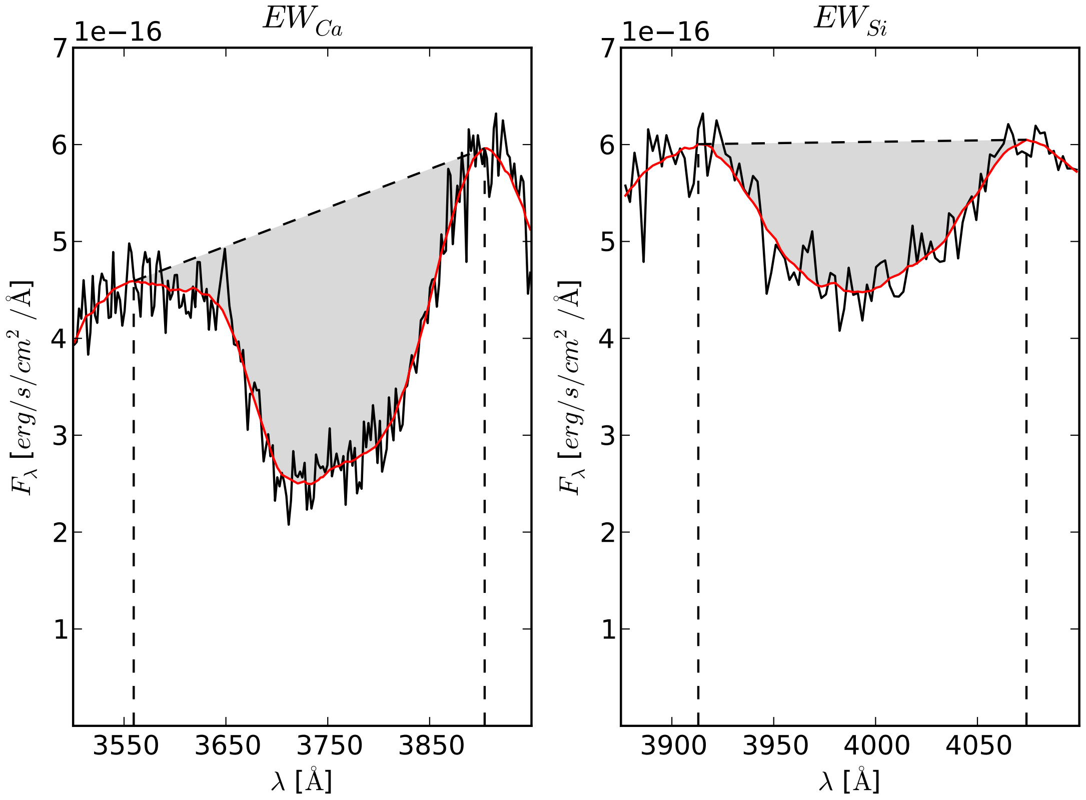
Spectral indicator measurements

- Automated measurement of these spectral indicators on spectra at max
  1. Milky Way **dereddening**
  2. **Deredshifting** (from observer frame to restframe)
  3. **Peak finding** after **optimal smoothing**
  4. **EWs measurements**

  \+ Monte-Carlo estimate for **statistical** and **systematic uncertanties**

- **96 SNe selected for their:**
  - good phase sampling
  - good SALT2 fit
  - spectrum between ± 2.5 days around max

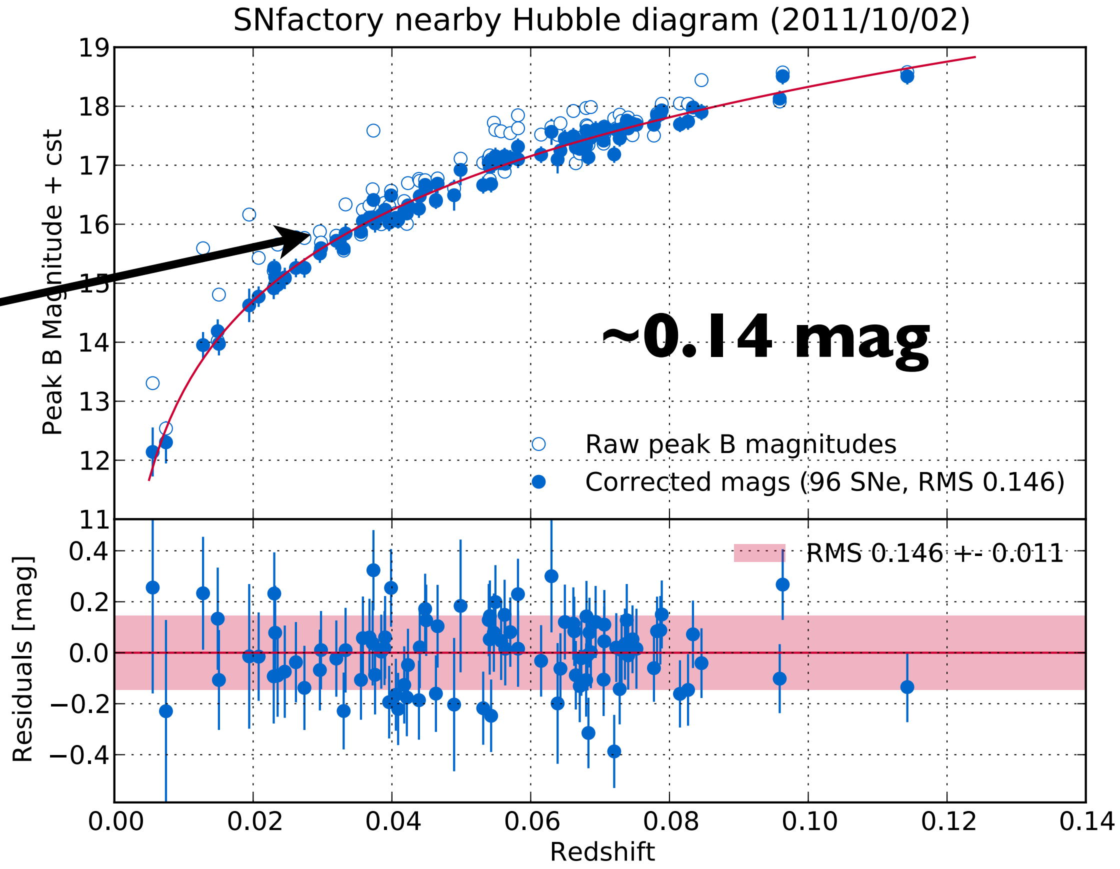
How can we use their properties and which one of them?



Standardization

$$\mu_B^i = m_B^i - M_B + \boxed{\alpha x_1^i - \beta c^i} + \boxed{\cancel{\gamma X^i + \ldots}}$$

Photometric parameters **Spectral indicators**



~0.14 mag

The two intrinsic indicators:

- EWSi II 4000:
  - + c: ~0.15 mag
  - + x_1 & c: ~0.14 mag
- EWCa II HK:
  - can't replace x_1 or c
  - no improvement when added to them

General results:

- none of the classical spectral indicators itself can standardize better than x_1 & c
- nor a combinaison of them
- only a few of the equivalent widths decrease the RMS when added to x_1 & c

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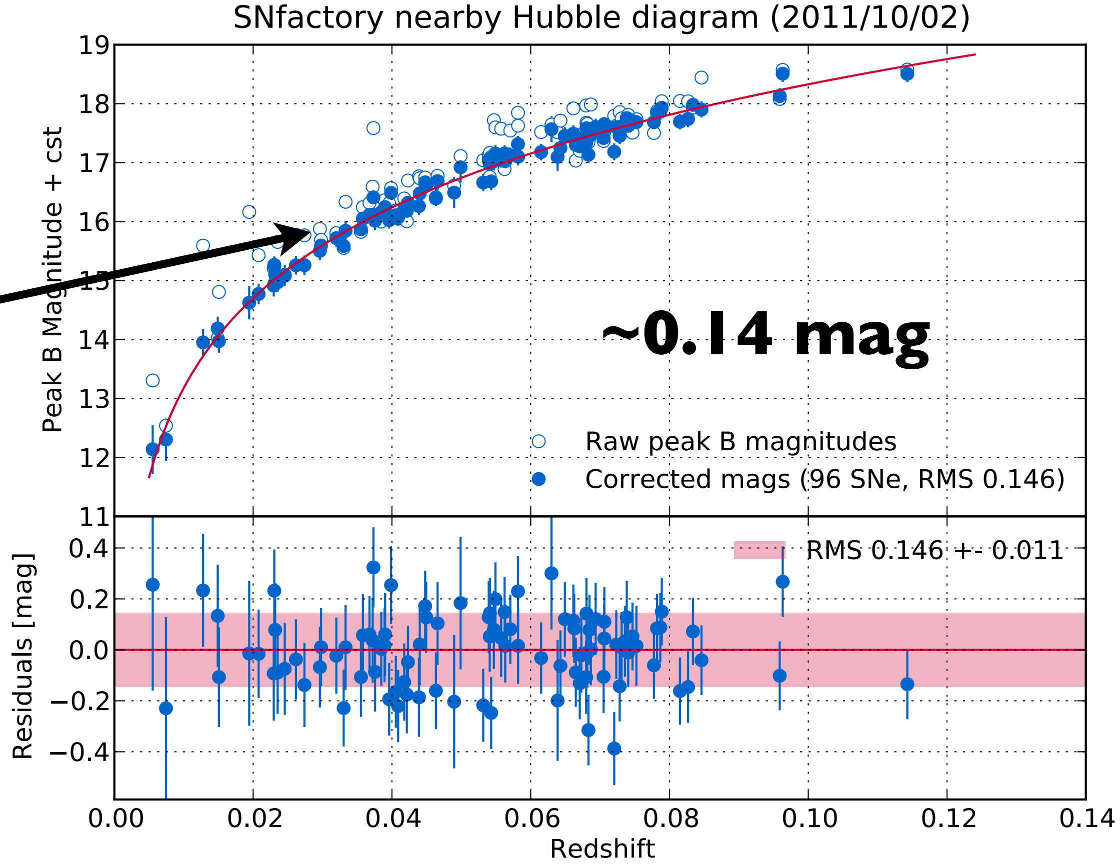

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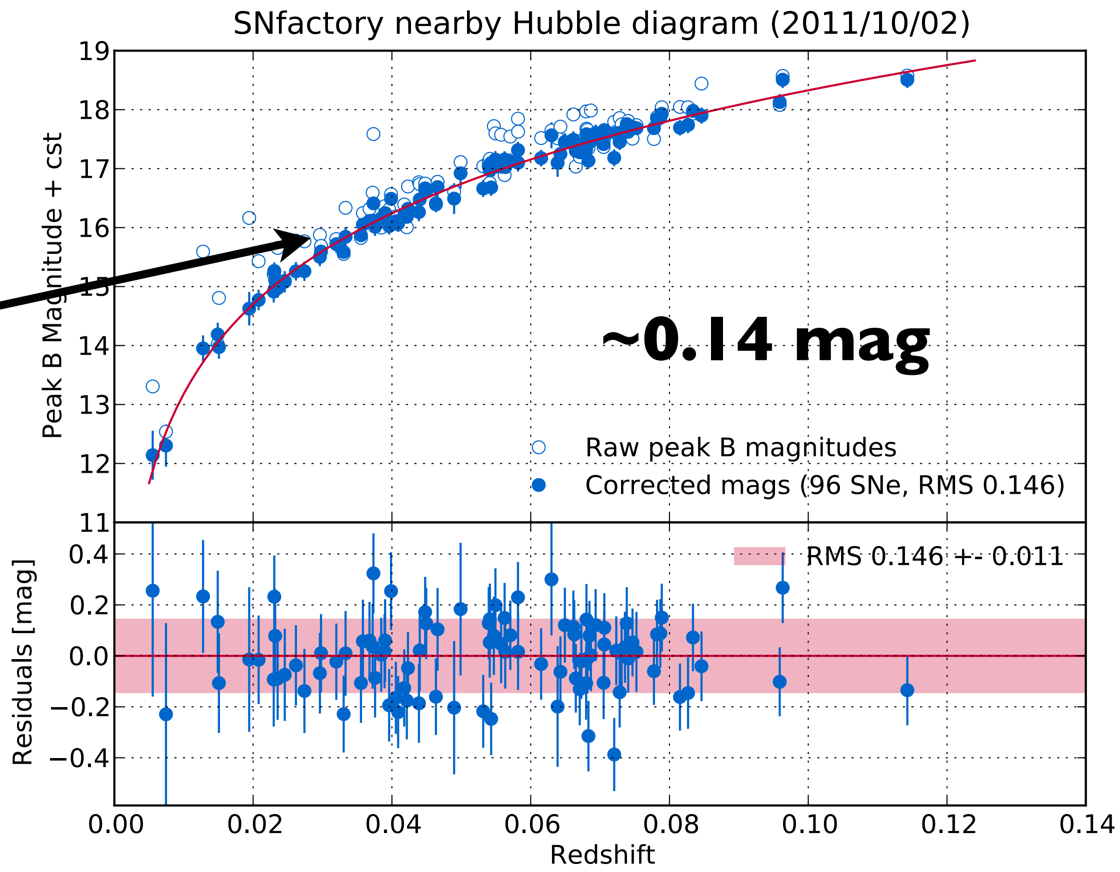

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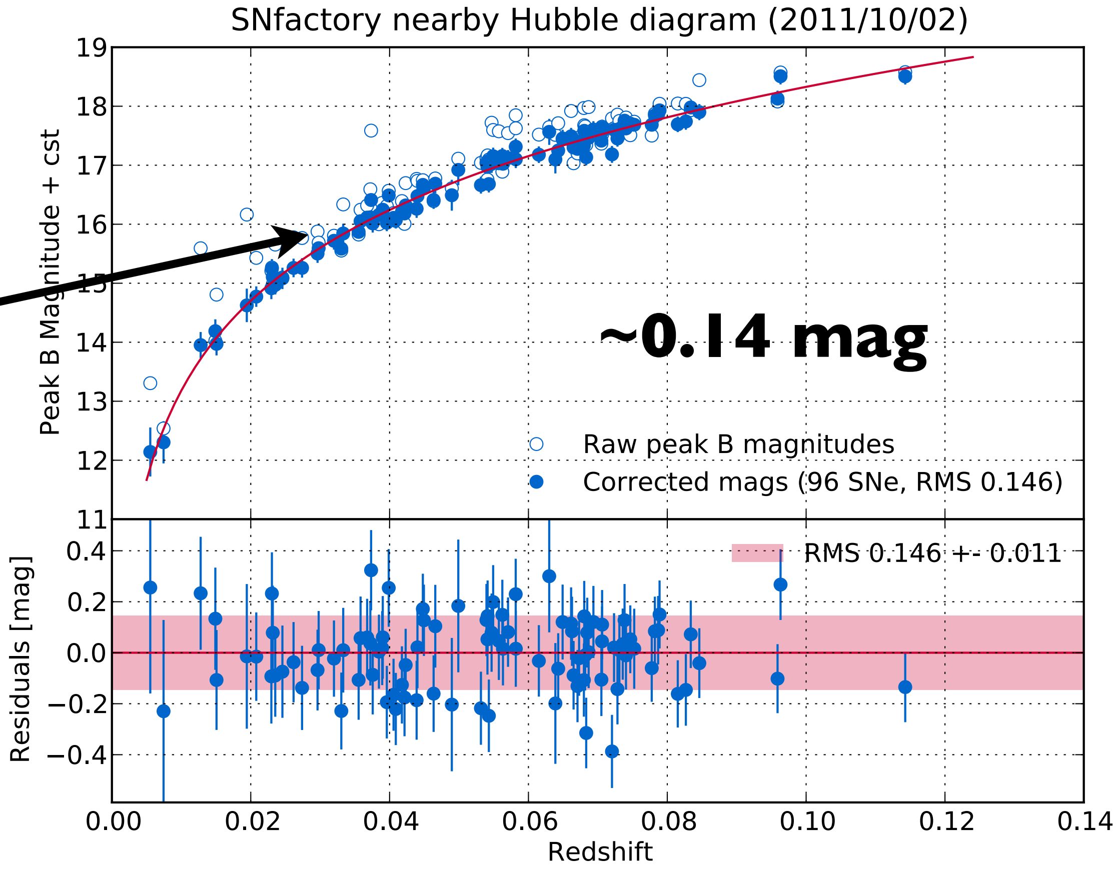

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Photometric parameters

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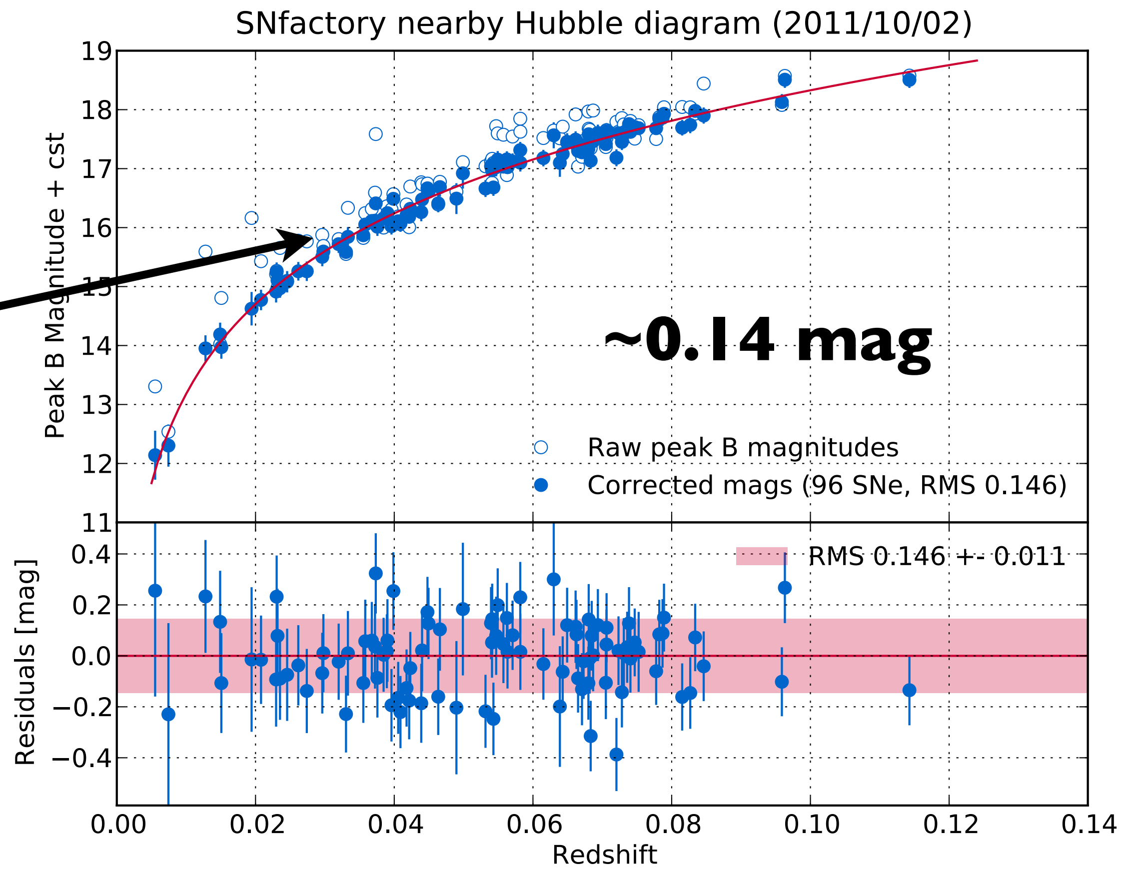

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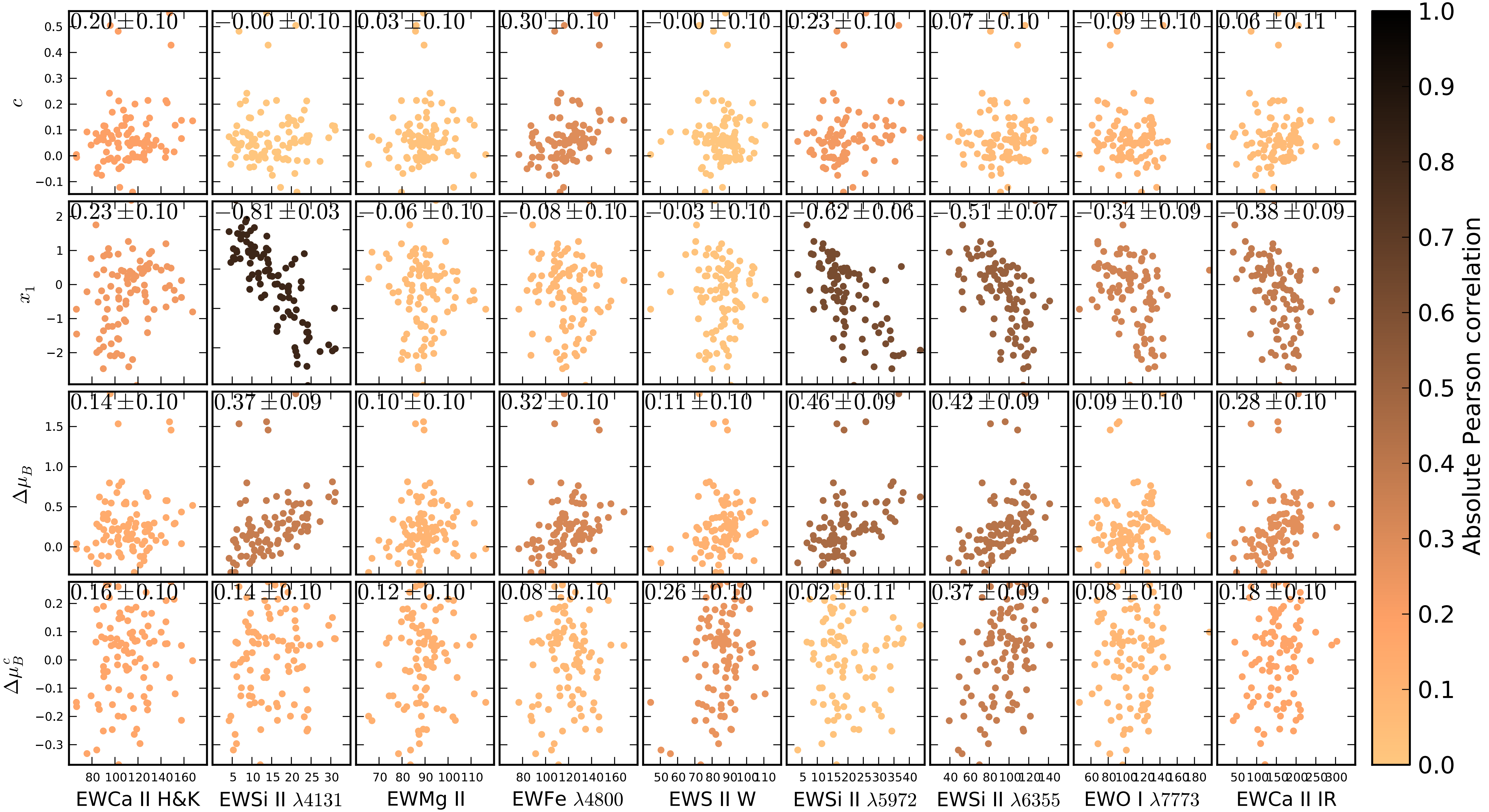
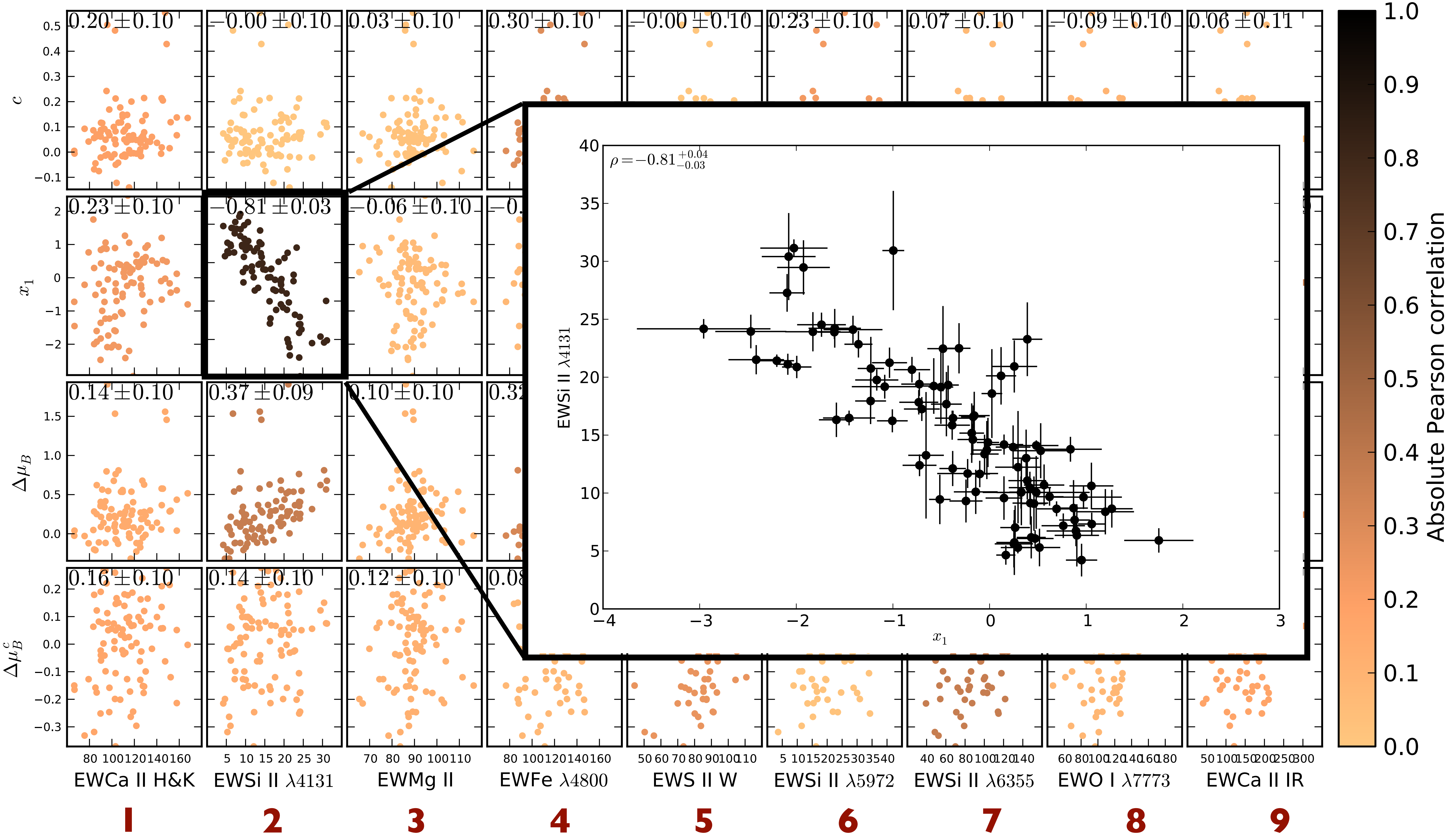
But we can use their intrinsic properties...

Equivalent width properties



1 **2** **3** **4** **5** **6** **7** **8** **9**

Equivalent width properties



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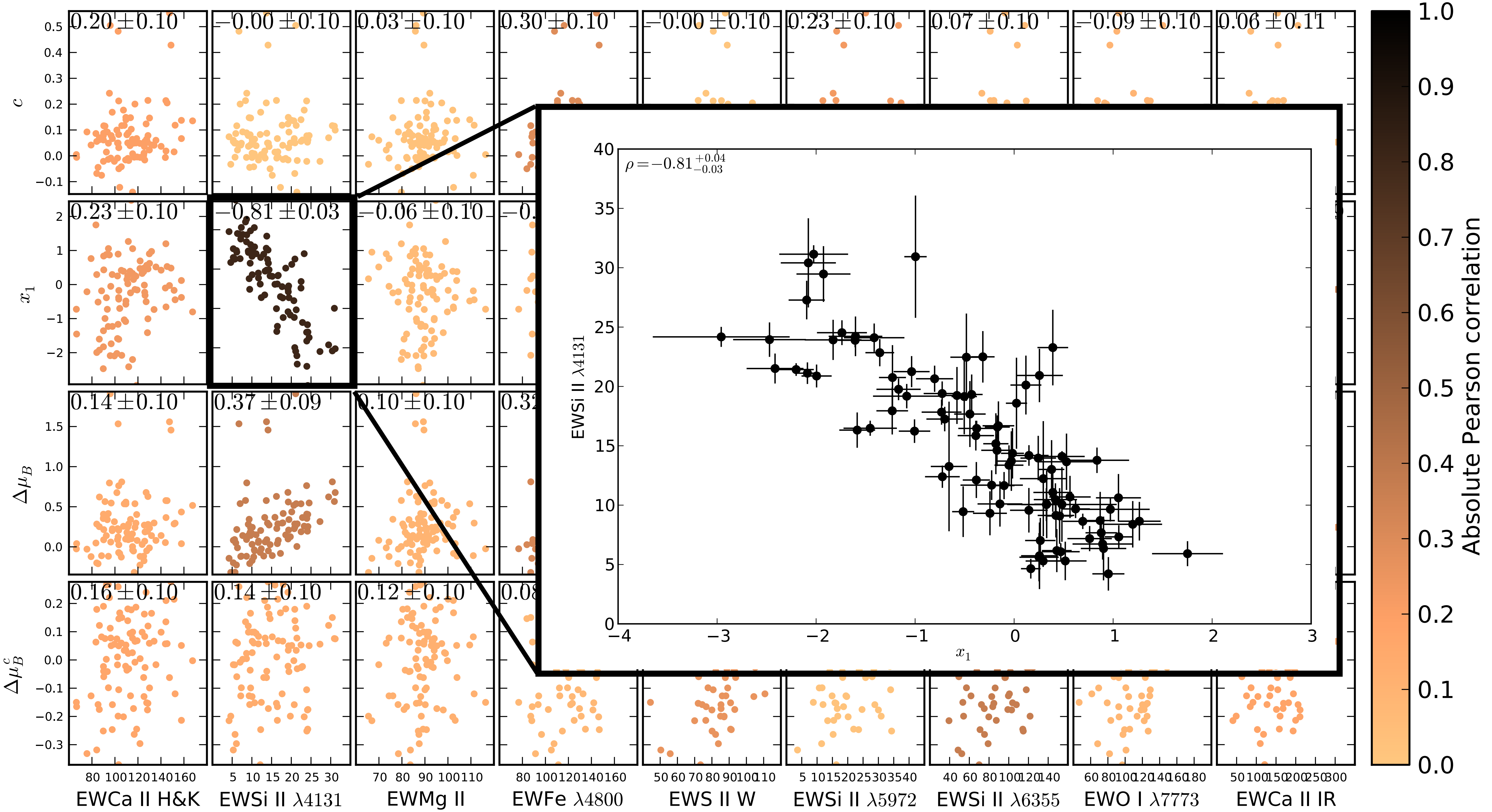
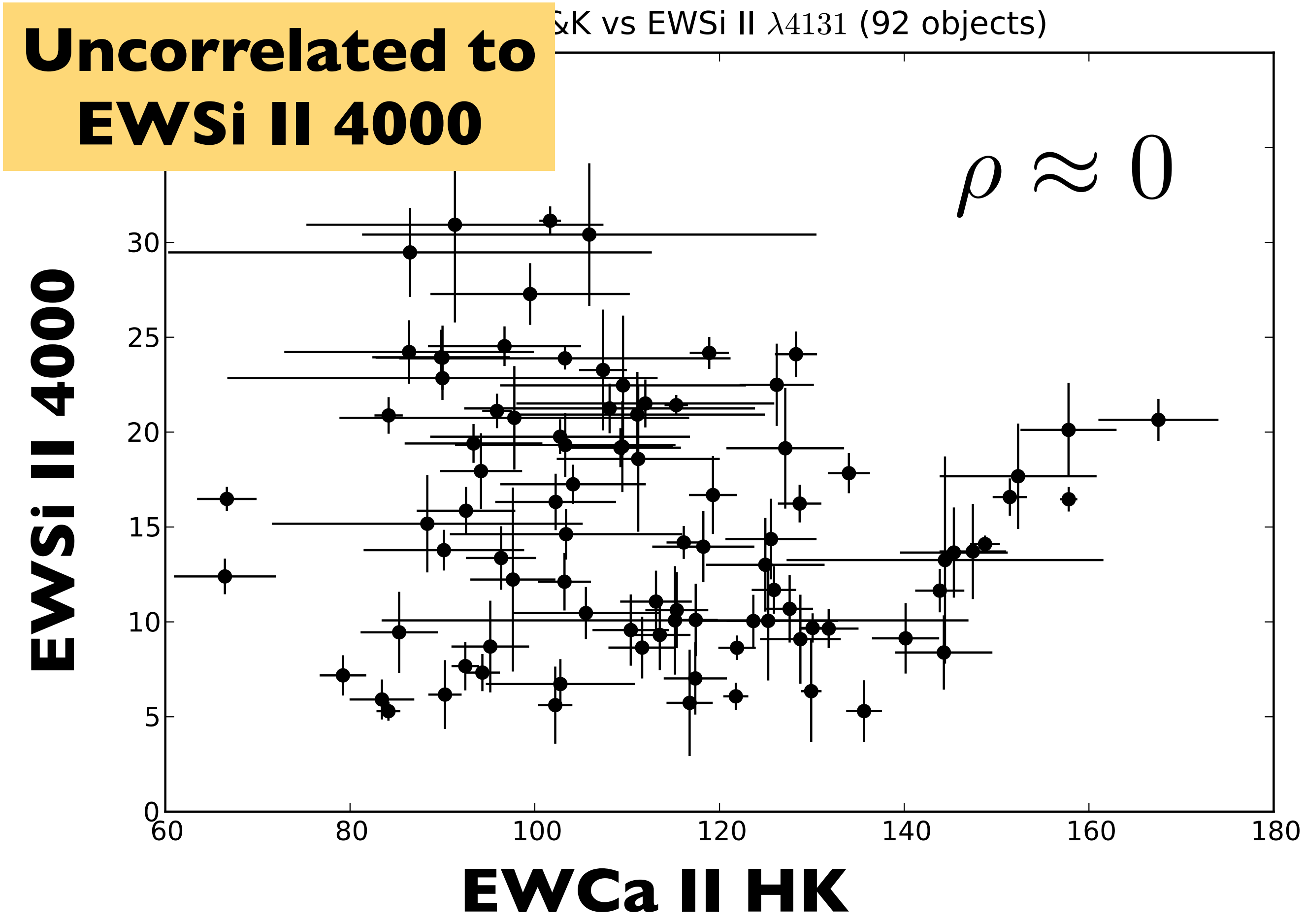


1 **2** **3** **4** **5** **6** **7** **8** **9**

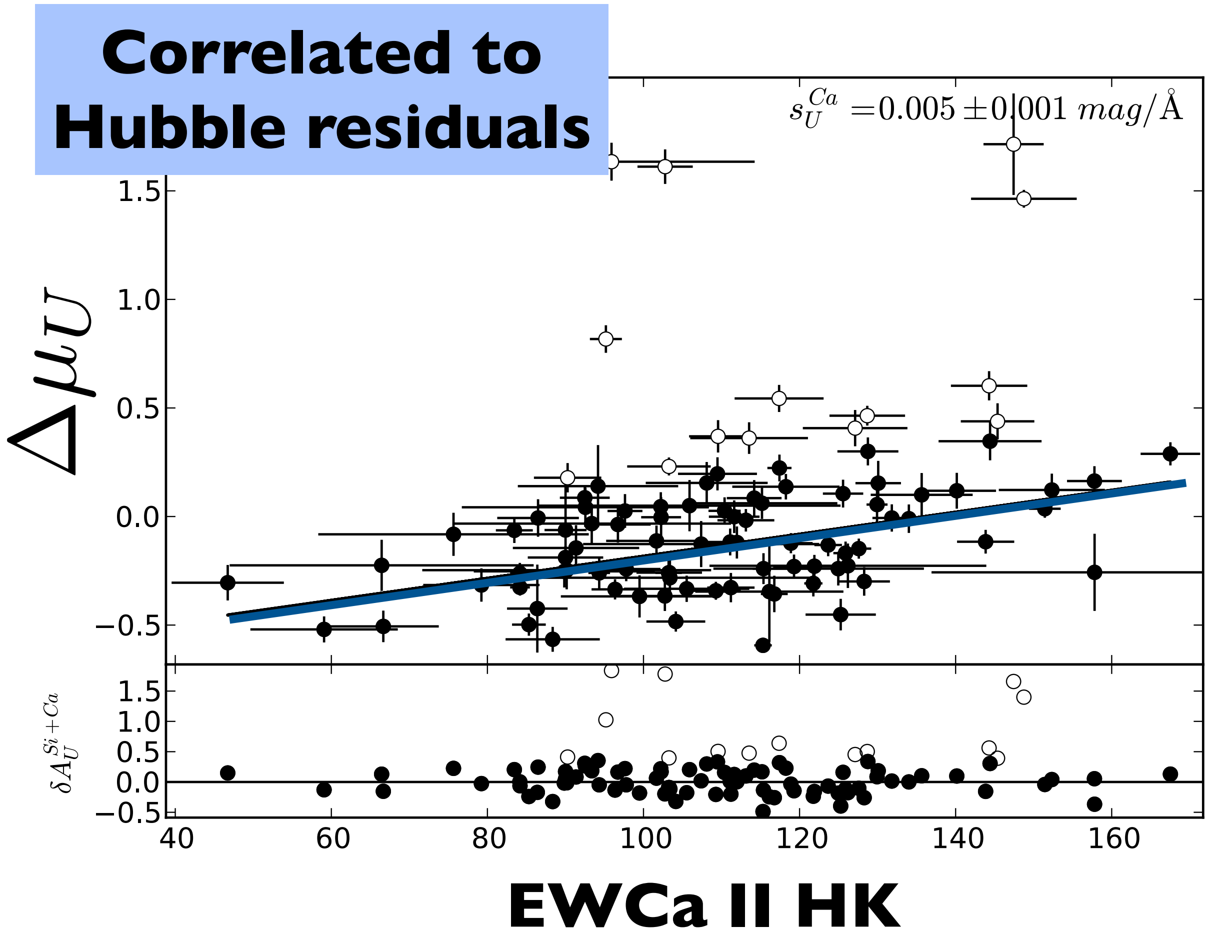
EWSiII4000 : A good proxy for x_1

Calcium equivalent width

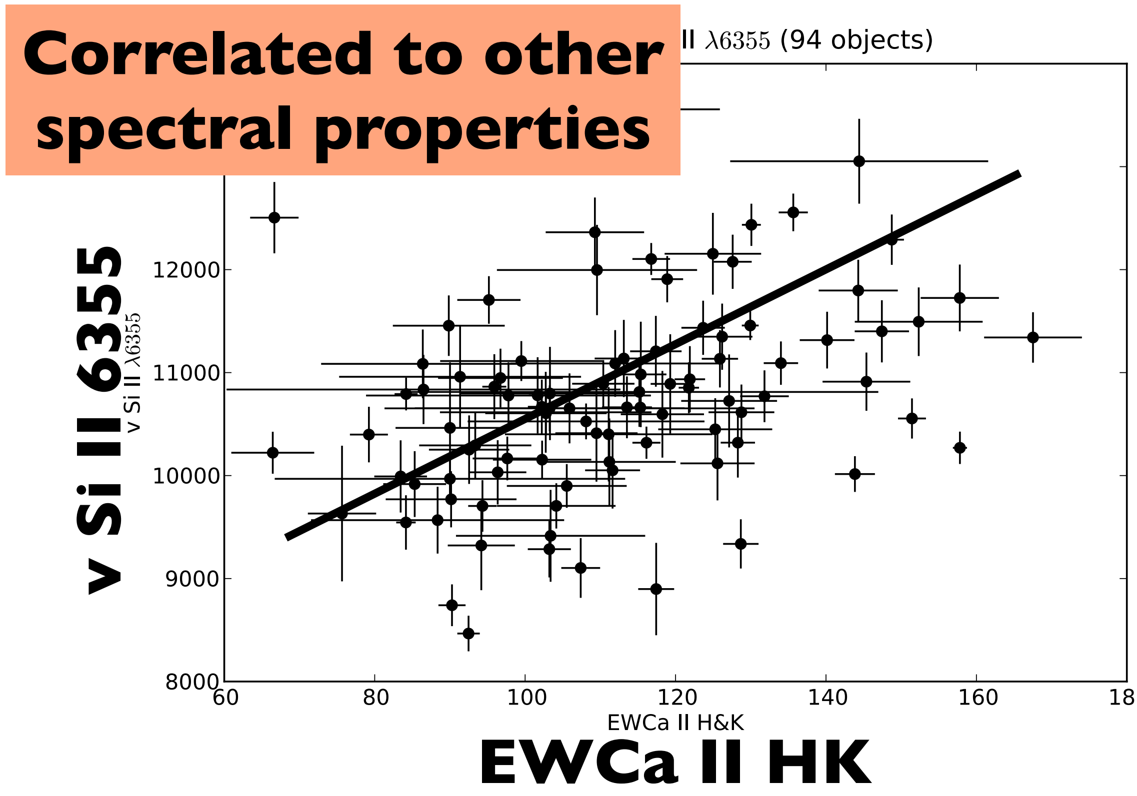
Uncorrelated to EWSi II 4000



Correlated to Hubble residuals



Correlated to other spectral properties



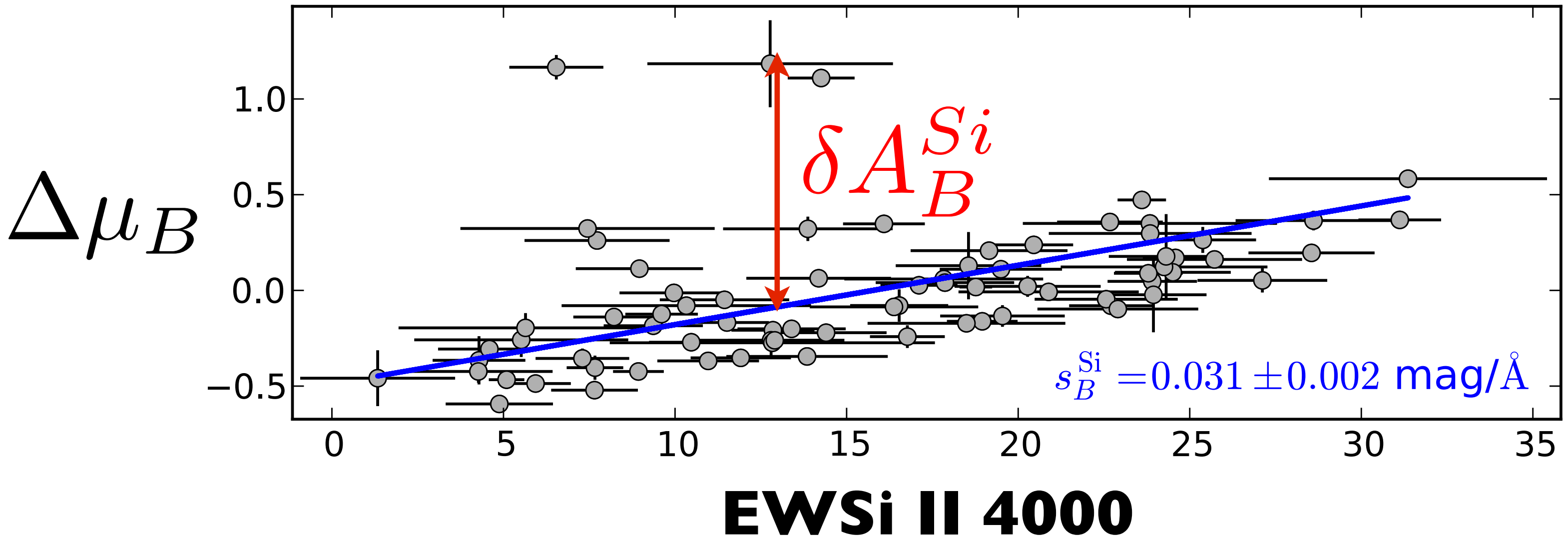
EWCa II HK:

- ✦ Uncorrelated to EWSi II 4000 / x_1
- ✦ Correlated to Hubble residuals
- ✦ Correlated to other spectral properties
- ✦ High signal to noise (<S/N>=40)

Good candidate to be a second intrinsic variable

Separating the variabilities

1st step: Decompose the Hubble residuals into intrinsic variabilities and relative absorptions δA$_\lambda$



$$\delta I = s_B^{Si} \times \mathrm{EWSi\ II\ 4000}$$

Intrinsic variable

$$\Delta\mu_\lambda = \begin{cases} \delta A_\lambda^0 \\ s_\lambda^{\rm Si}\mathrm{EW}^{\rm Si} + \delta A_\lambda^{\rm Si} \\ s_\lambda^{\rm Si}\mathrm{EW}^{\rm Si} + s_\lambda^{\rm Ca}\mathrm{EW}^{\rm Ca} + \delta A_\lambda^{\rm Si+Ca} \end{cases}$$

Hubble residuals

(a) ***No correction***
«perfect candles»

(b) ***One intrinsic correction***
EWSi II 4000 / Strech-like

(c) ***Two intrinsic corrections***
EWSi II 4000 + EWCa II HK

$$\boxed{\Delta\mu_\lambda \quad - \quad \delta I \quad = \quad \delta A}$$

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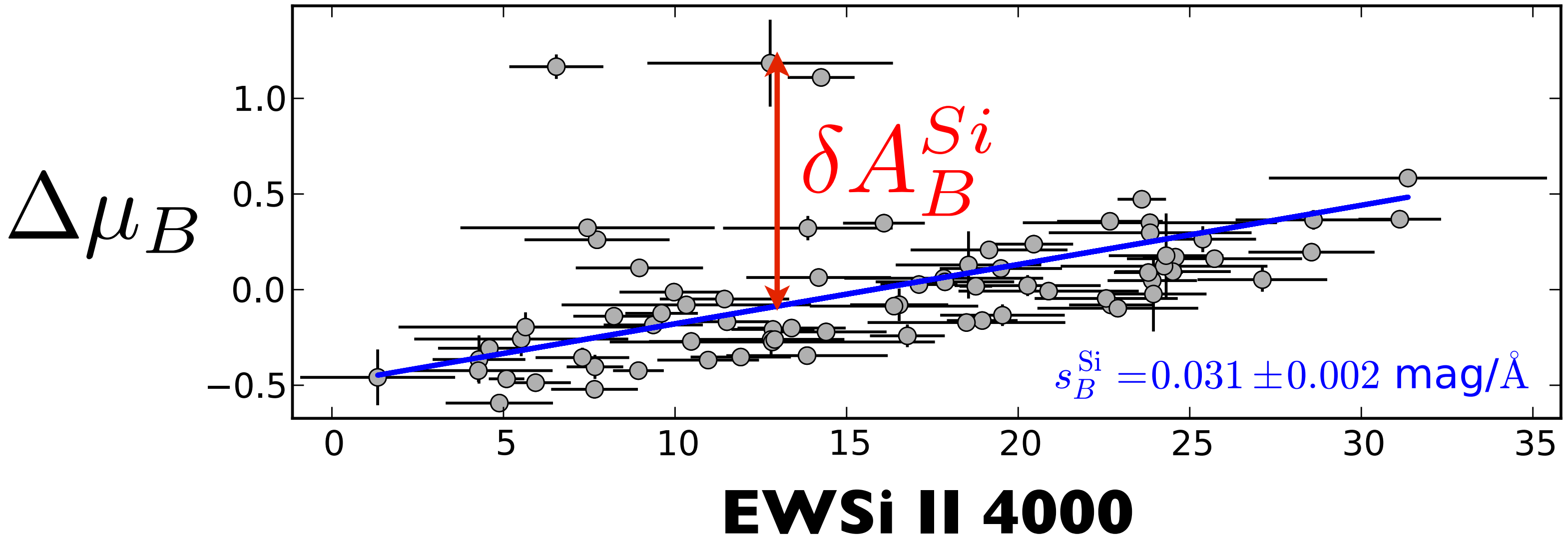

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Intrinsic variable

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

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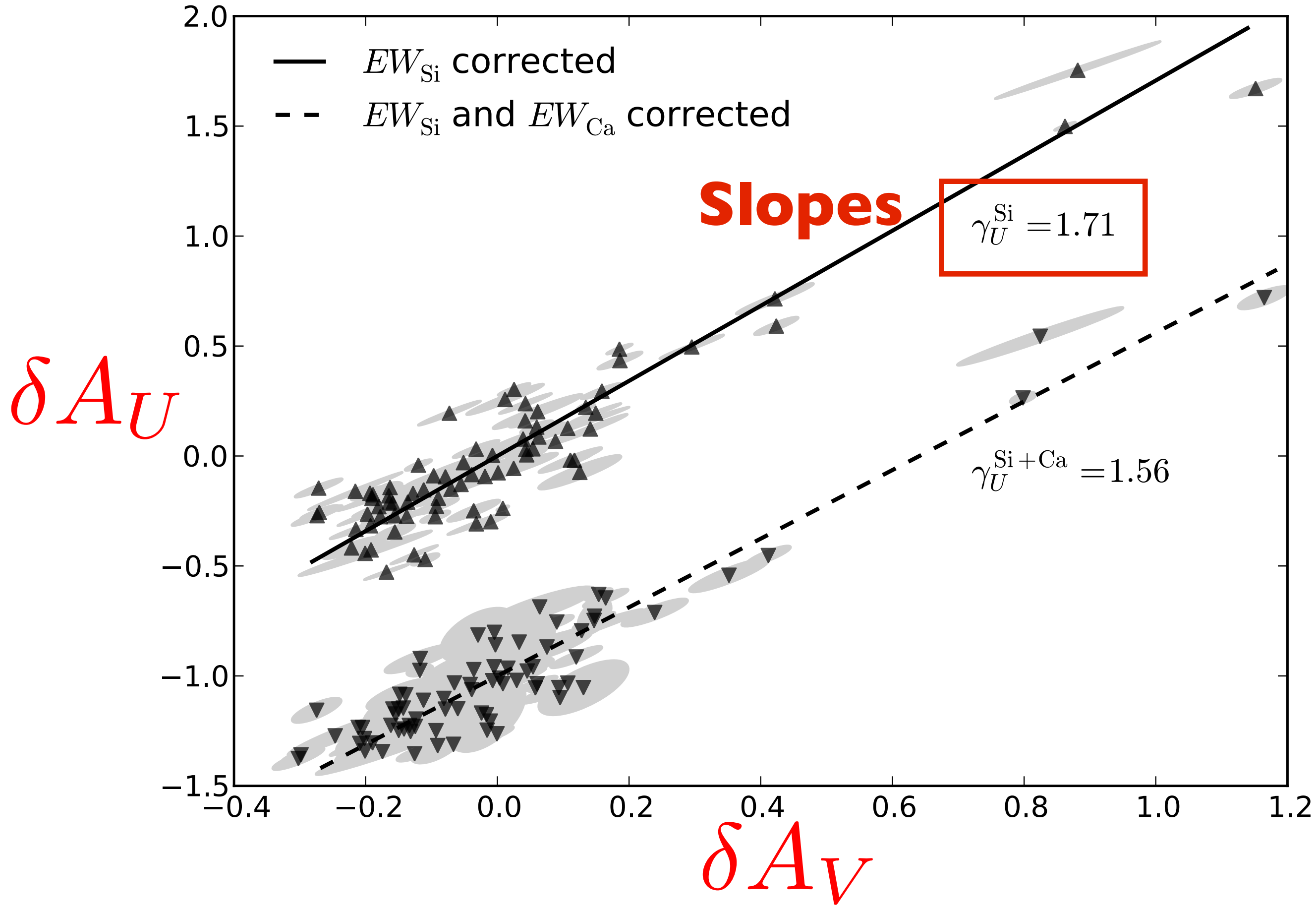
EWSi II 4000 + EWCa II HK

$$\boxed{\Delta\mu_\lambda - \delta I = \delta A}$$

Construct the extinction law

2nd step: Use the relation between the δA_λ to construct the law



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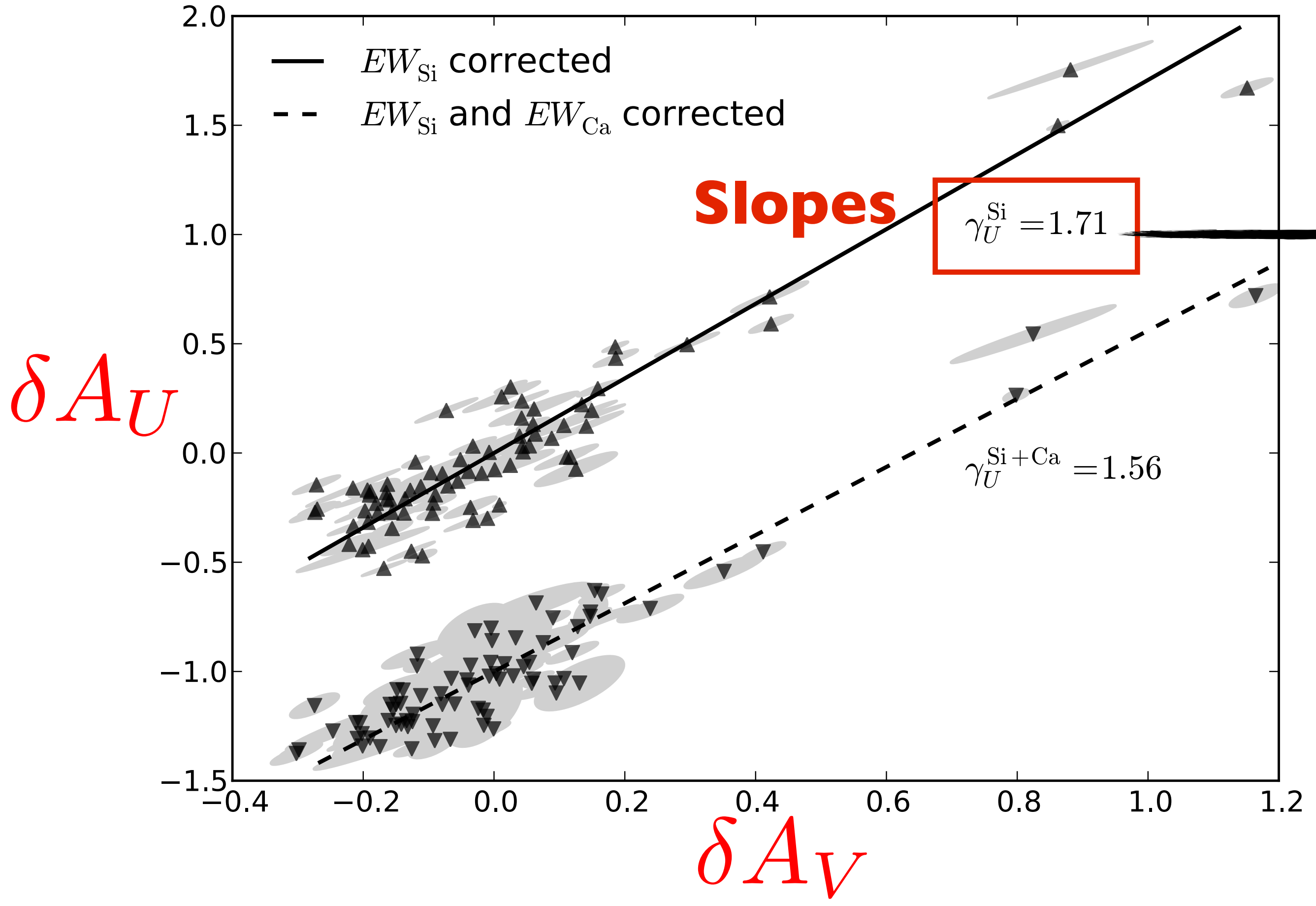
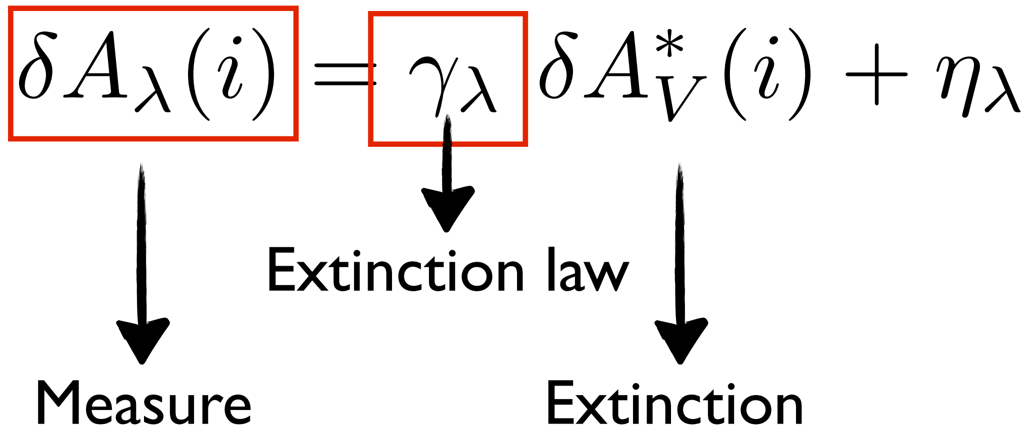


Linear model



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

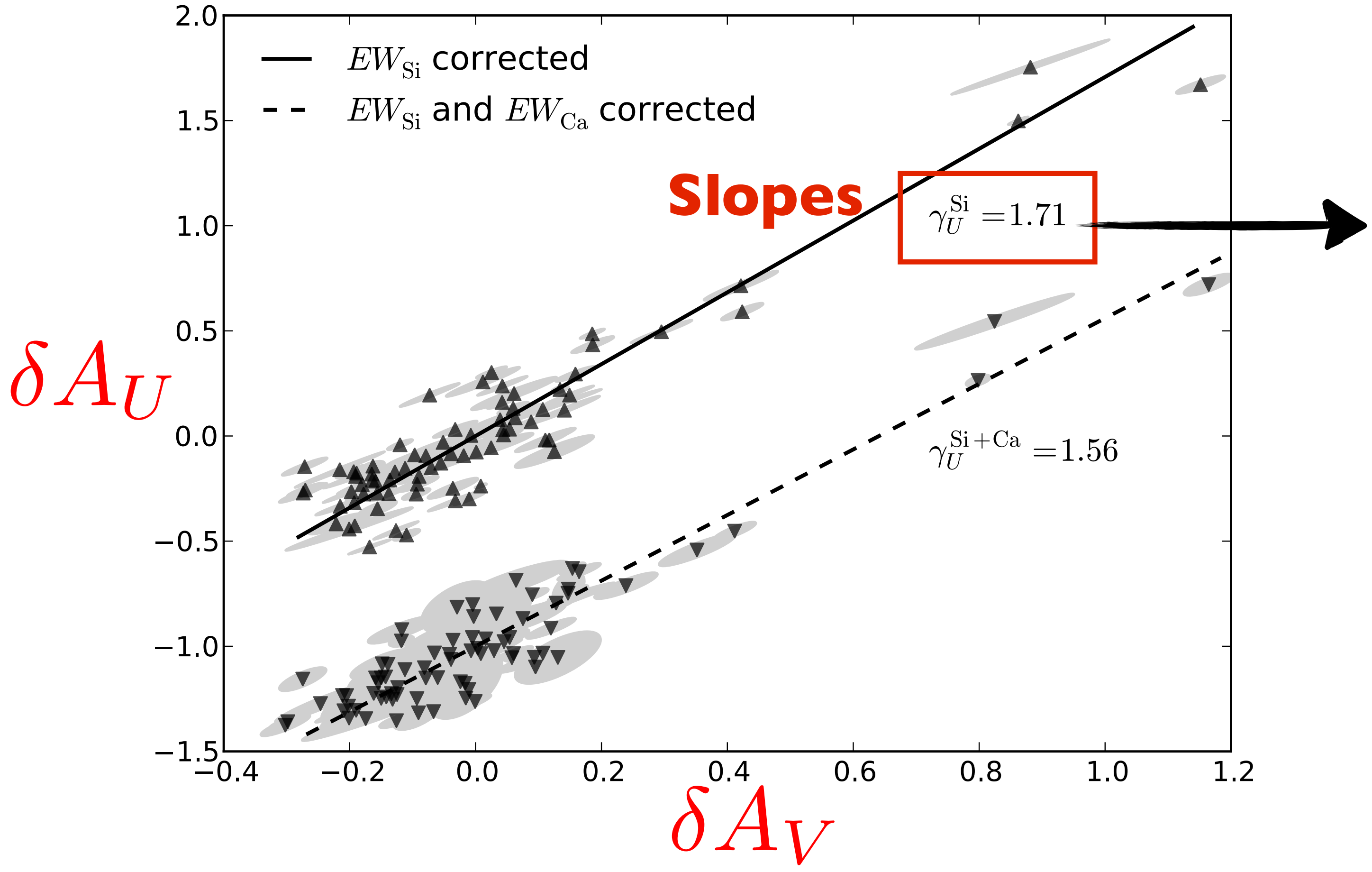
Extinction law

Measure

Extinction

Construct the extinction law

2nd step: Use the relation between the δA_λ to construct the law



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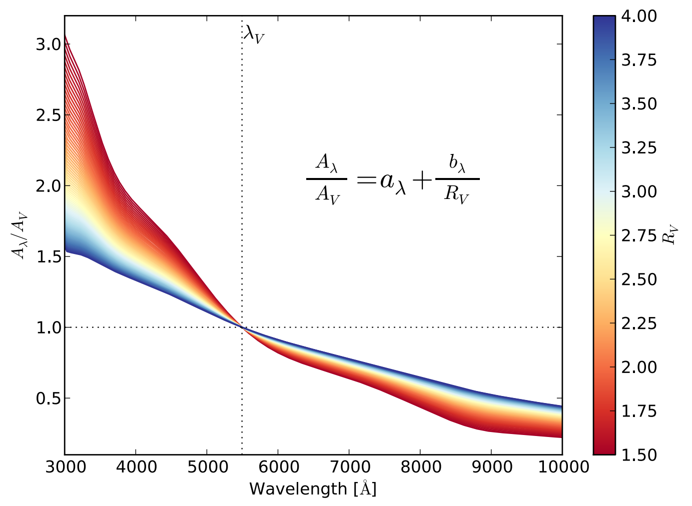
$$\boxed{\delta A_\lambda(i)} = \boxed{\gamma_\lambda} \, \delta A_V^*(i) + \eta_\lambda$$

Measure

Extinction law

Extinction

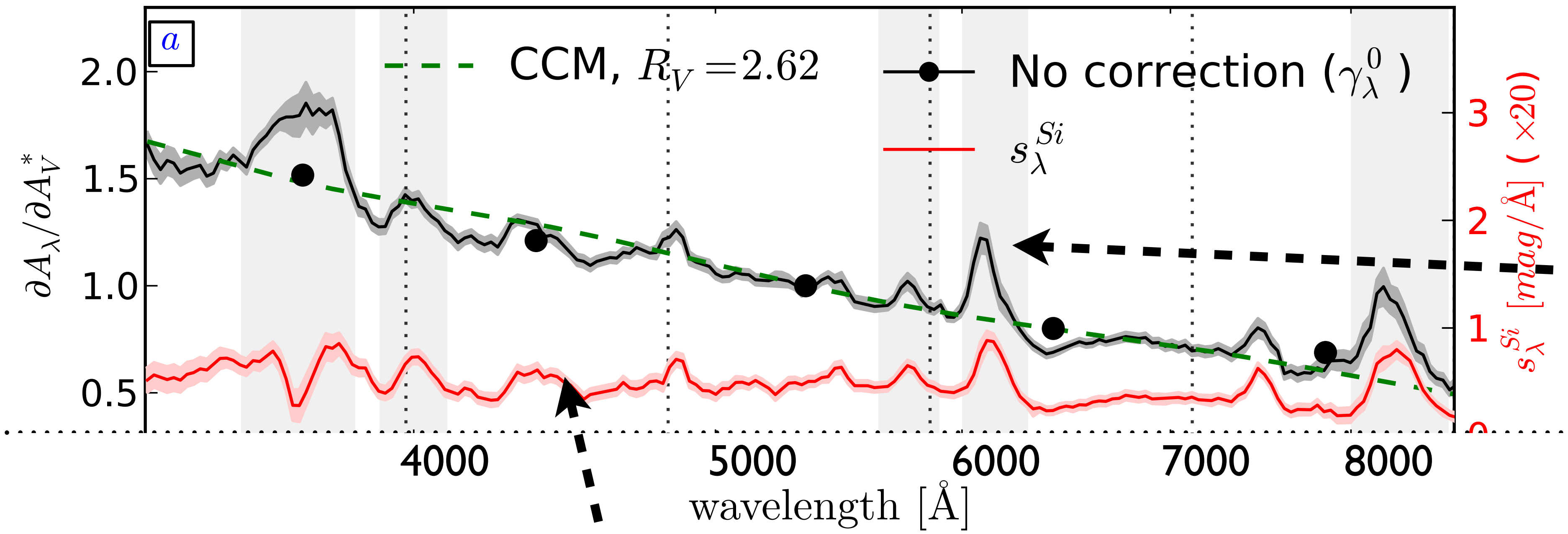


Estimation of R_V when forcing:

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

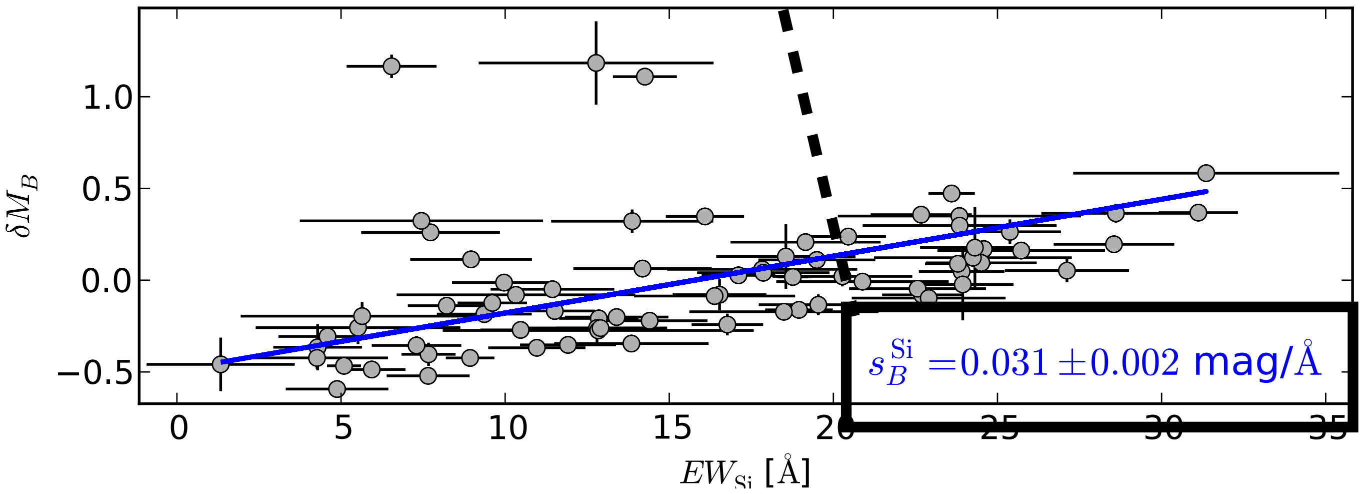
Cardelli extinction law

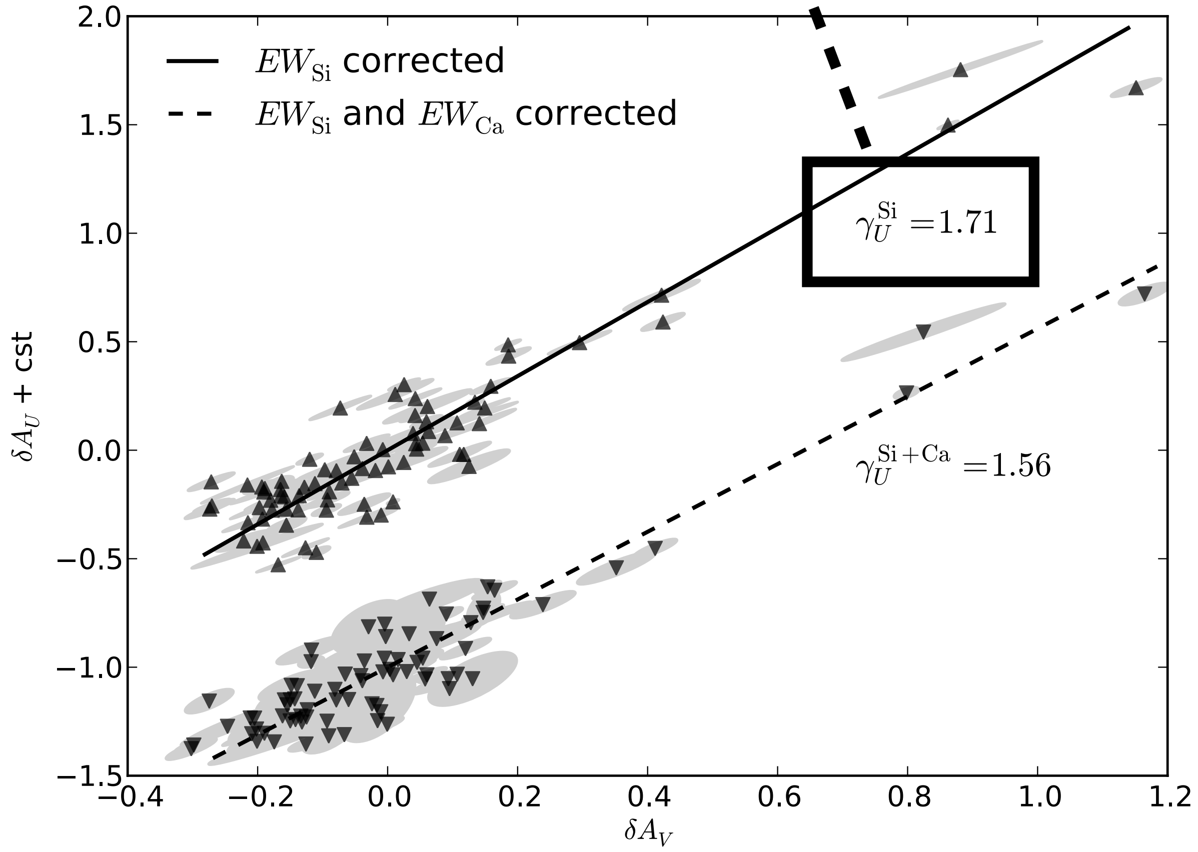
Results on the γ_λ



«Perfect candles» **(a)**

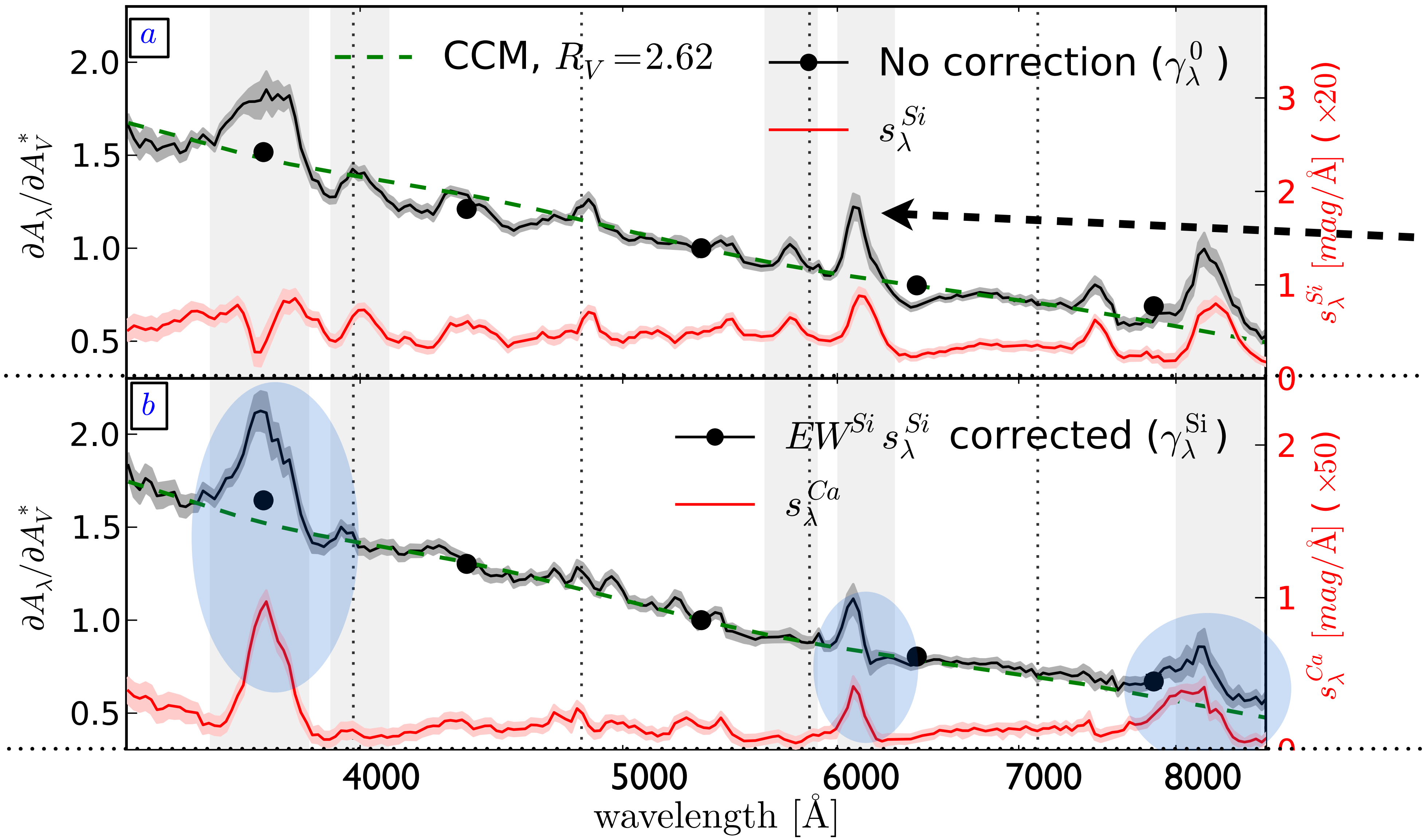
$$\gamma_\lambda \equiv \frac{A_\lambda}{A_V}$$





Reminders

Results on the γ_λ



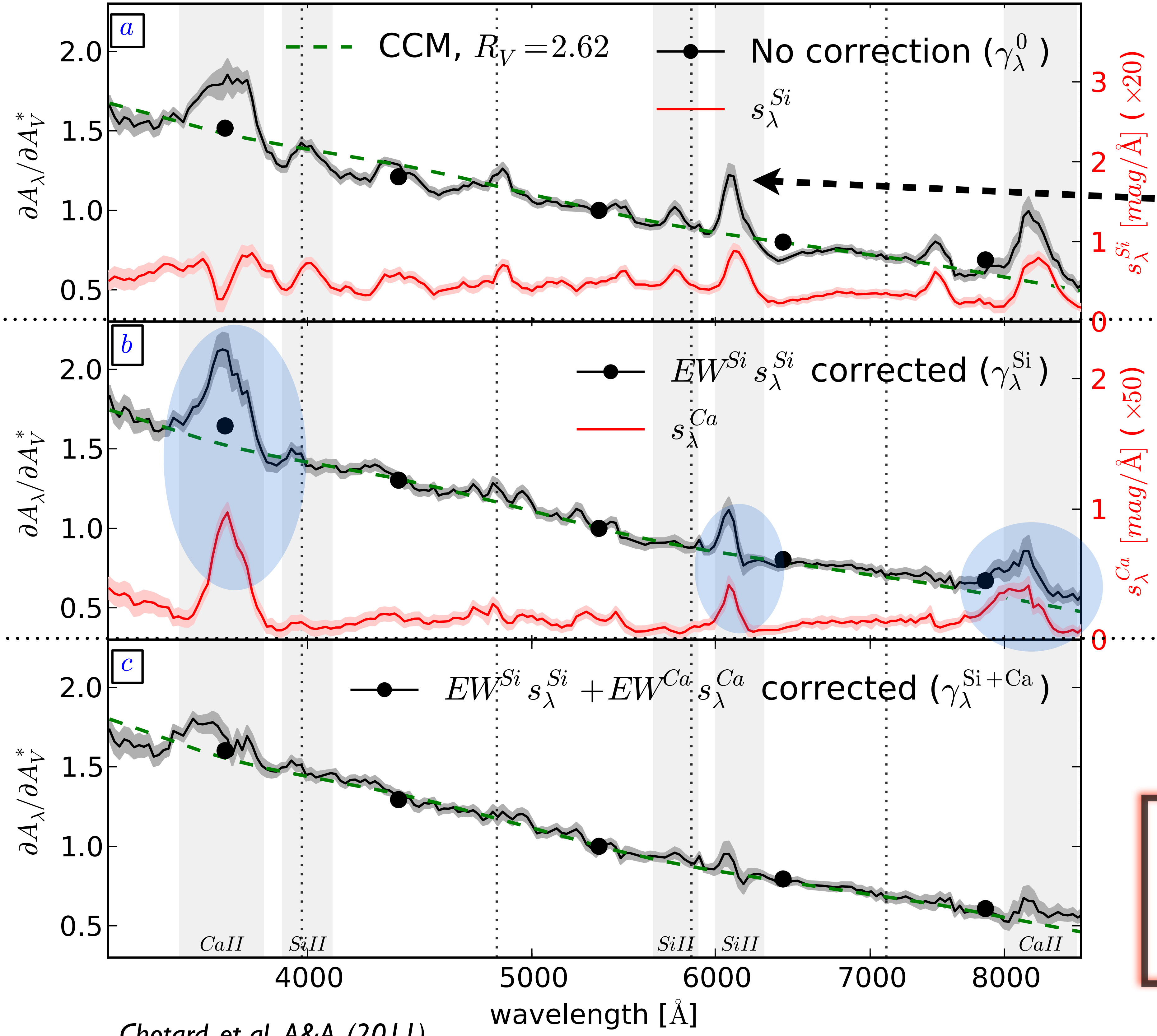
«Perfect candles» **(a)**

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

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

Residual intrinsic variability!

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
+
$R_V = 2.6 \pm 0.4$

Additional color dispersion needed...

Dispersion matrix

Why?

Using the measured covariance matrix only: $X^2 >> 1$ $\delta A_\lambda(i) = \gamma_\lambda \; \delta A_V^*(i) + \eta_\lambda$

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

How?

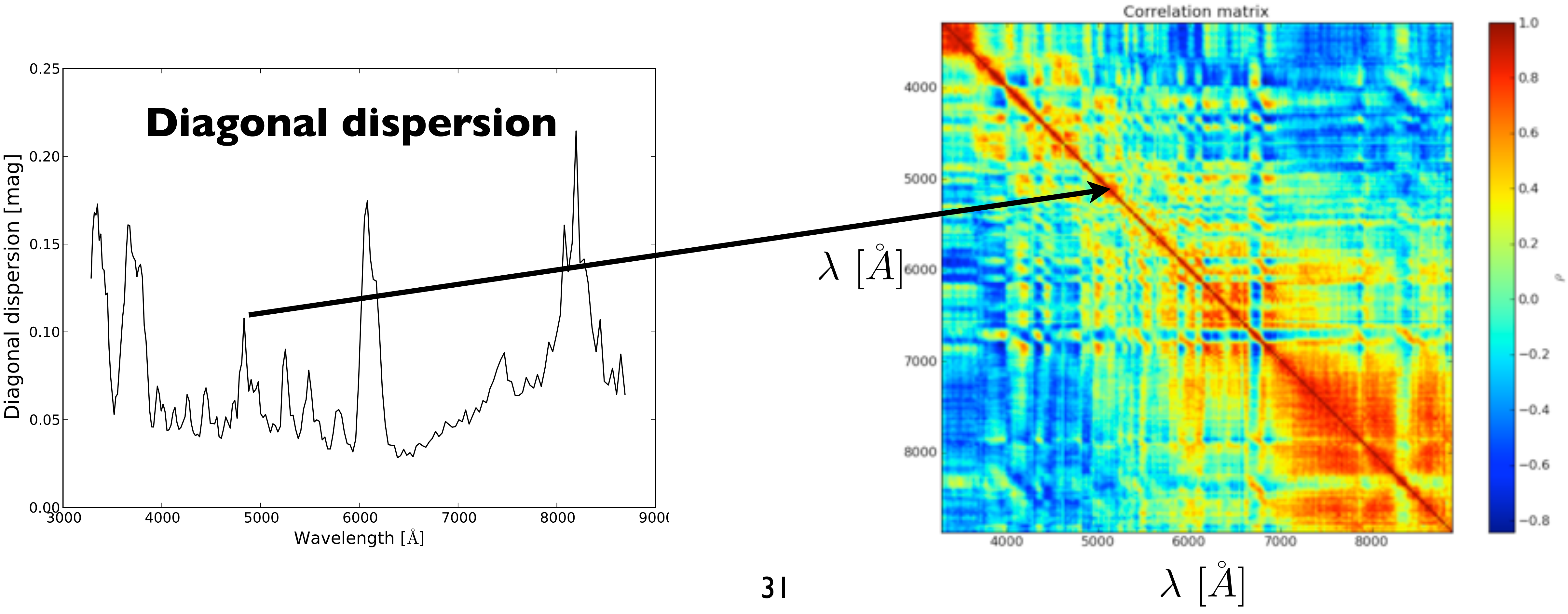
Using the residual $r_\lambda(i)$ to the γ_λ fit to construct the additionnal covariance matrix

Introduction of a **color dispersion**, not used in cosmological fit

Anti-correlation mostly increases with the wavelength differences

Rv = 2.6

For the case (c): 2 intrinsic corrections



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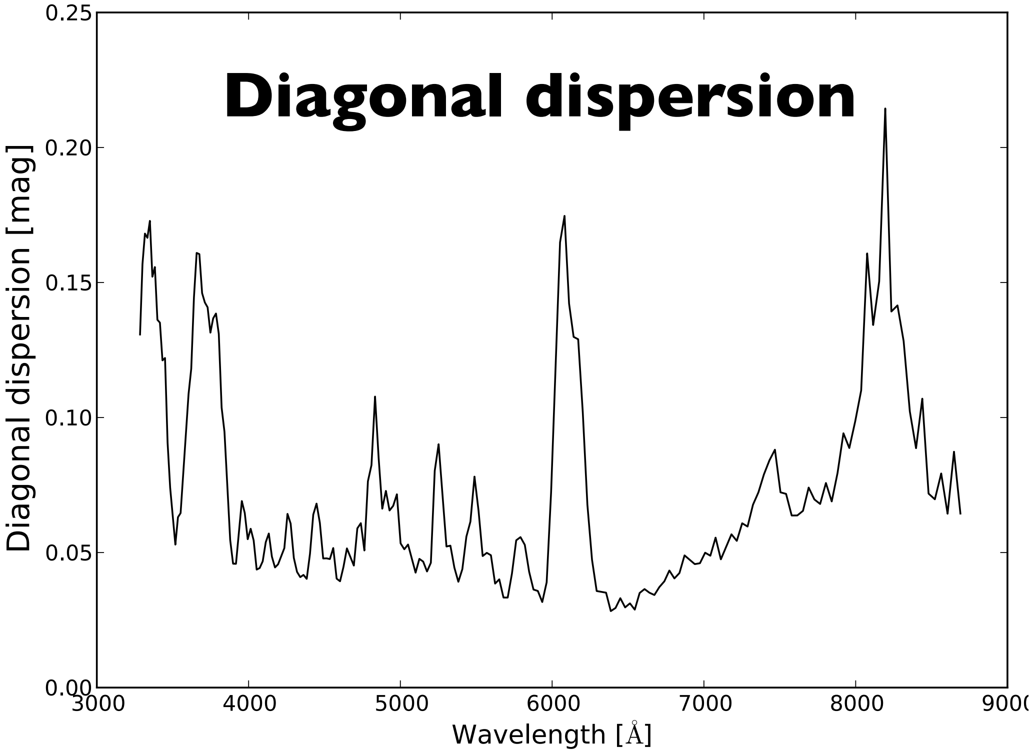

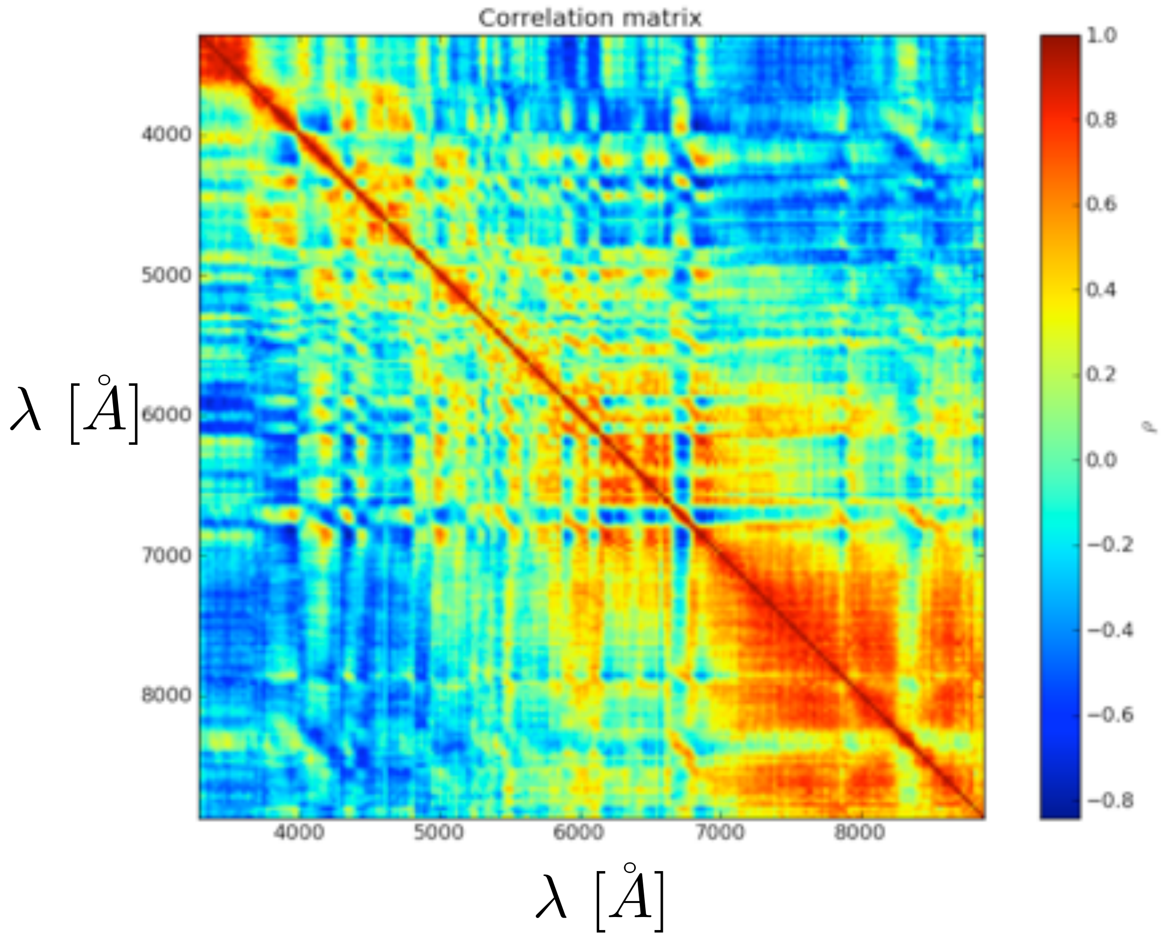

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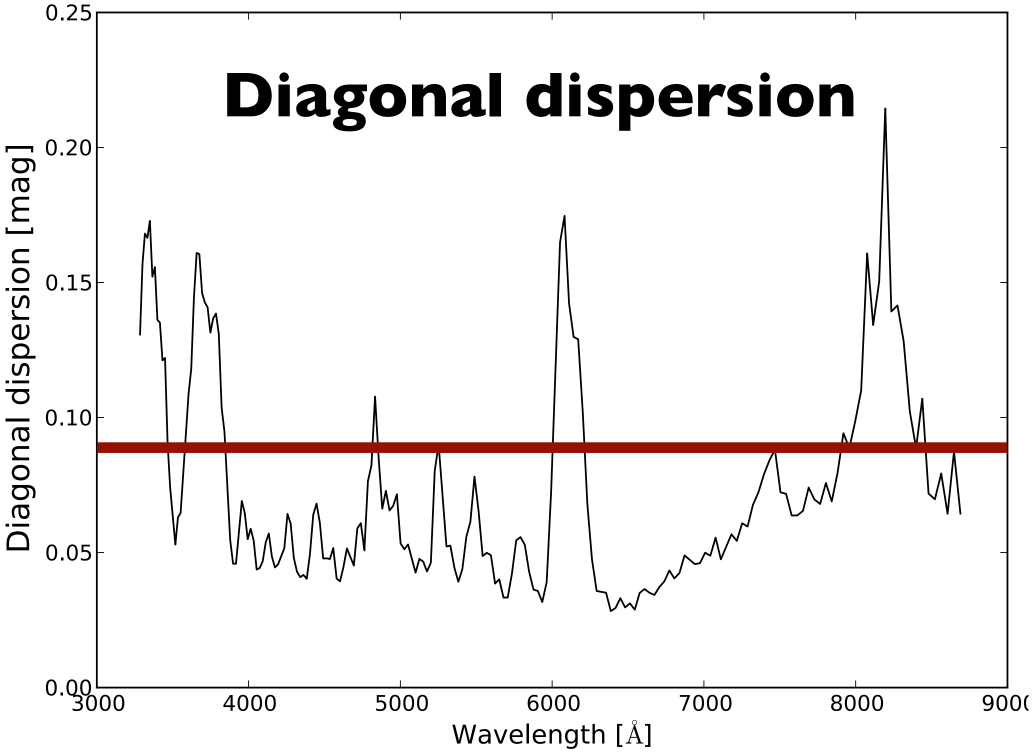
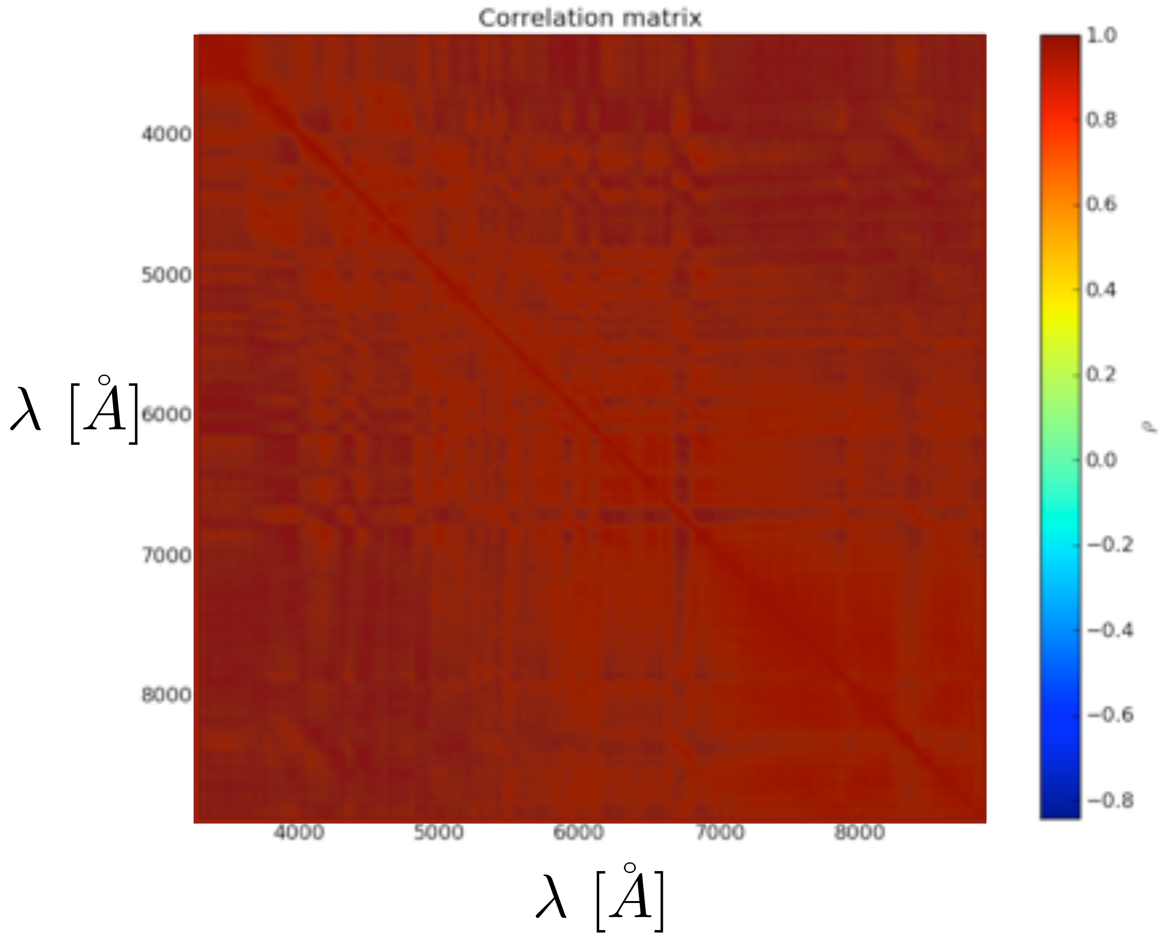
Compatible with literature

Rv < 2





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Why?

Using the measured covariance matrix only: $X^2 >> 1$ $\delta A_\lambda(i) = \gamma_\lambda \ \delta A_V^*(i) + \eta_\lambda$

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

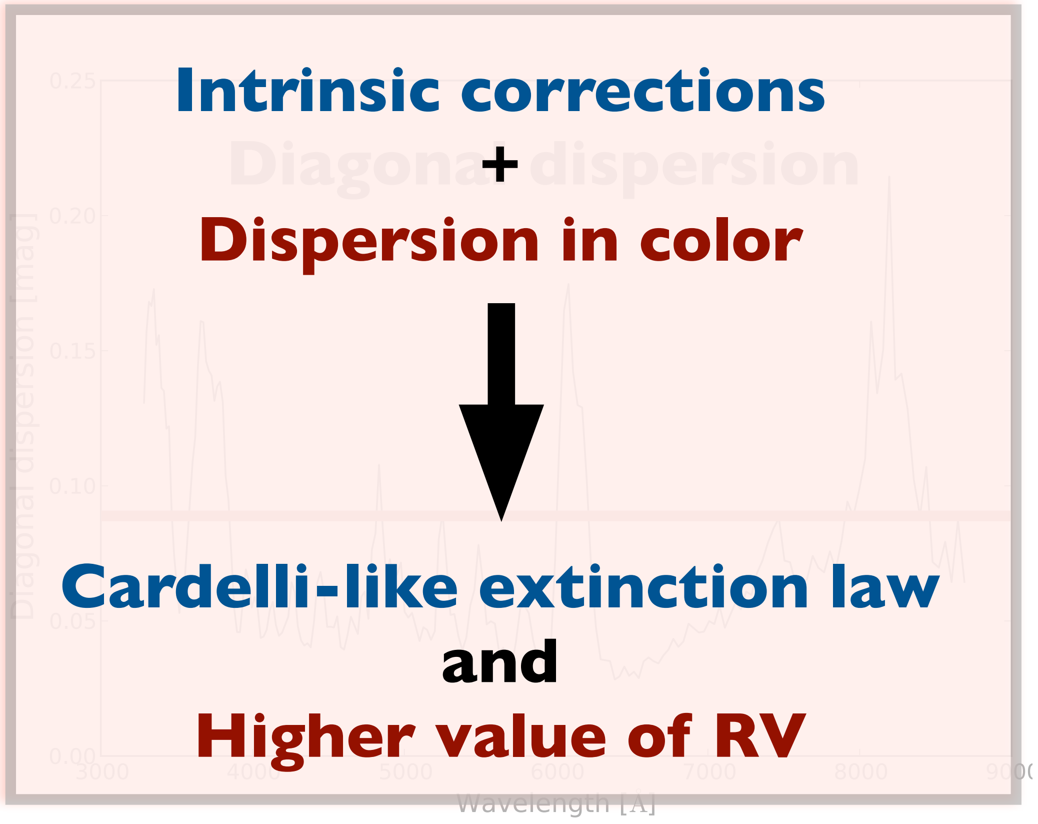
How?

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

Introduction of a **color dispersion**, not used in cosmological fit

Anti-correlation mostly increases with the wavelength differences

For the case (c): 2 intrinsic corrections



Intrinsic corrections

+

Dispersion in color

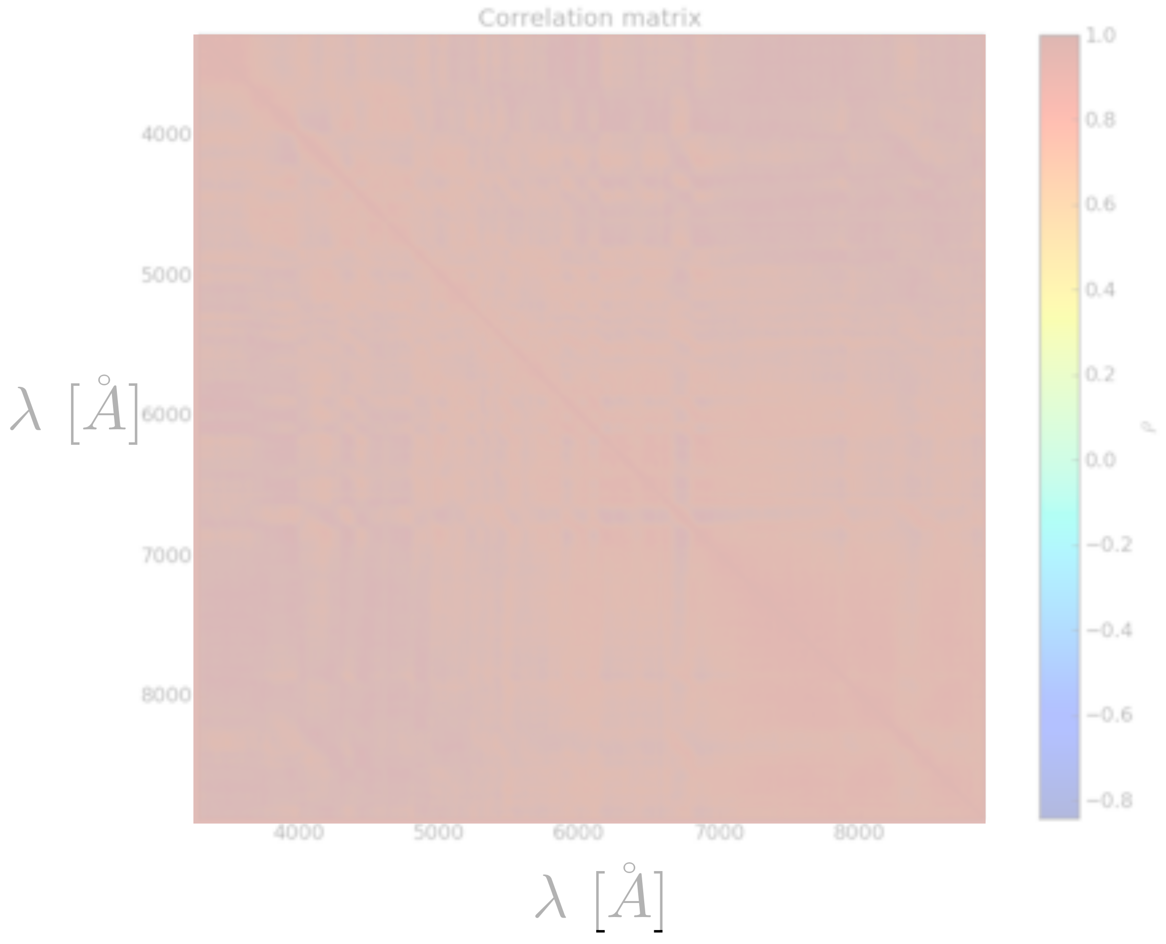
Cardelli-like extinction law

and

Higher value of RV

Compatible with literature

Rv < 2



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