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PhD defense
04 Oct. 2013

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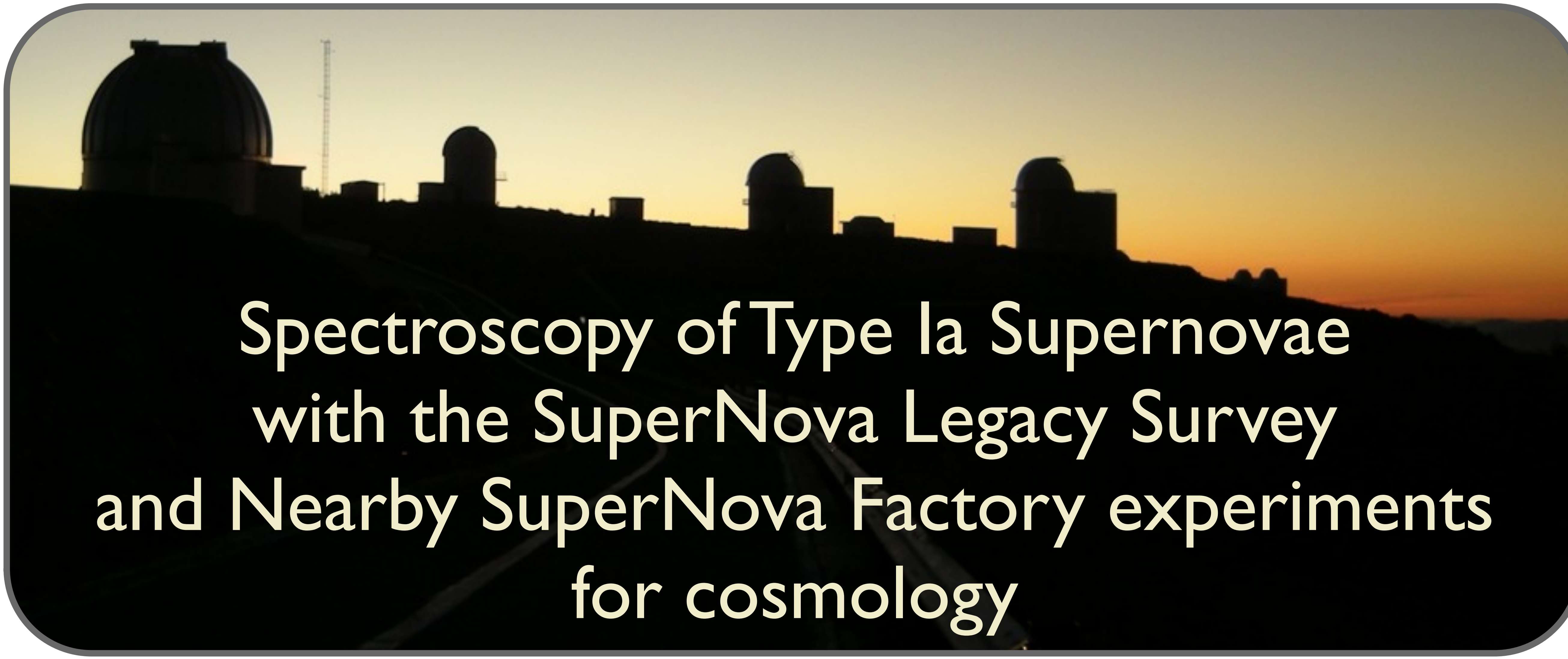

Spectroscopy of Type Ia Supernovae with the SuperNova Legacy Survey and Nearby SuperNova Factory experiments for cosmology

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supervisors : Christophe BALLAND and Pierre ANTILOGUS

Outline

- Type Ia supernovae and cosmology
- SNLS and SNF experiments
- SNLS 5yrs : the final VLT spectroscopic sample
- Fundamental study for cosmology with SNe Ia : is there evolution of SNe Ia ?
- Understanding SNe Ia physical properties : comparison of model predictions with observed spectra
- Conclusions

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Accelerated expansion of the universe

- **History of the expansion :** expansion rate as a function of the age of the Universe

(Nobel Prize 2011)

↳ accelerated expansion *Perlmutter et al. (1997;1999) Riess et al. (1998) Schmidt et al. (1998)*

↳ experimental evidence of a dark energy component $p = w \times \rho$

- **Probing dark energy :**

↳ redshift linked to the scale factor : $1+z = \frac{\lambda_{obs}}{\lambda_{em}} = \frac{a(t_0)}{a(t)}$

↳ luminosity distance depends on cosmological parameters $\Omega_m = \frac{8\pi G\rho_{m0}}{3H_0^2}$ and $\Omega_\Lambda = \frac{\Lambda}{3H_0^2}$

$$d_L = (1+z)a(t_0)\chi = \frac{(1+z)c}{H_0}\int_{(1+z)}^{1} \frac{d\hat{a}}{\hat{a}^2\sqrt{\Omega_\Lambda + \Omega_m \hat{a}^{-3}}} \quad \text{with} \quad \hat{a} = \frac{a(t)}{a(t_0)}$$

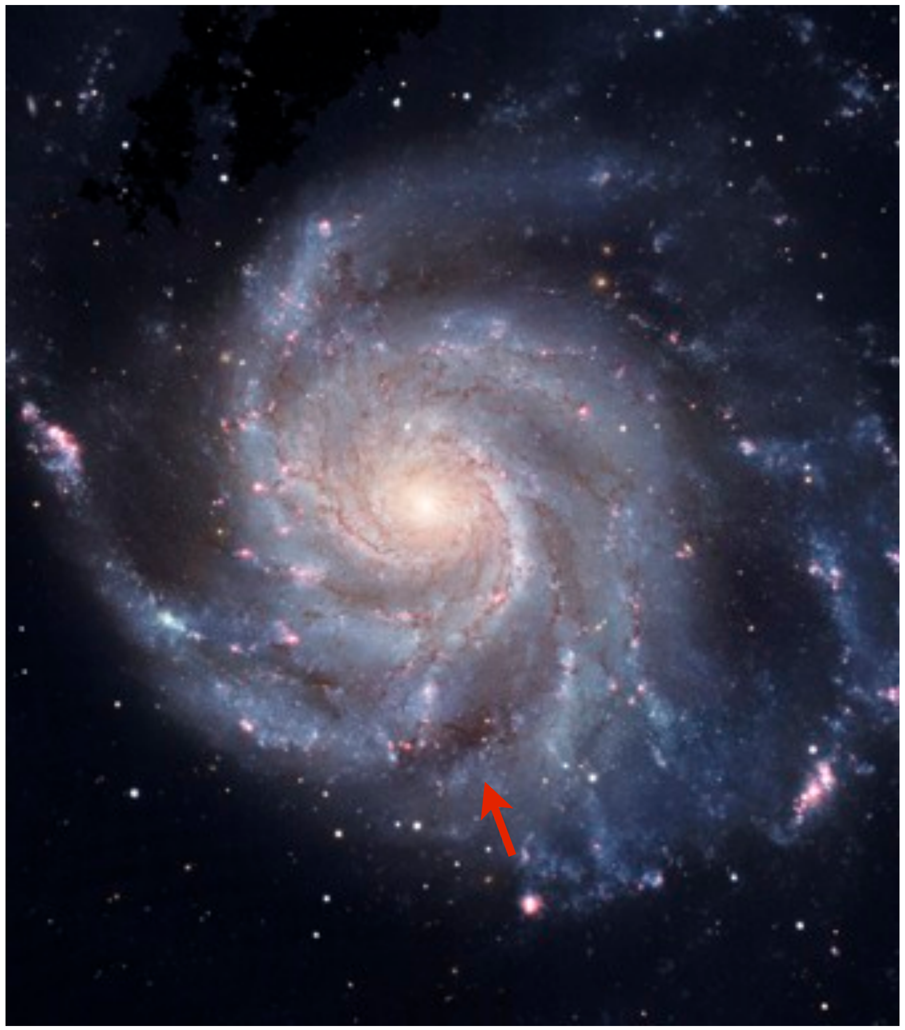
- **How to measure d_L ?** not directly accessible : depends on the intrinsic luminosity L : $d_L = \sqrt{\frac{L}{4\pi f}}$

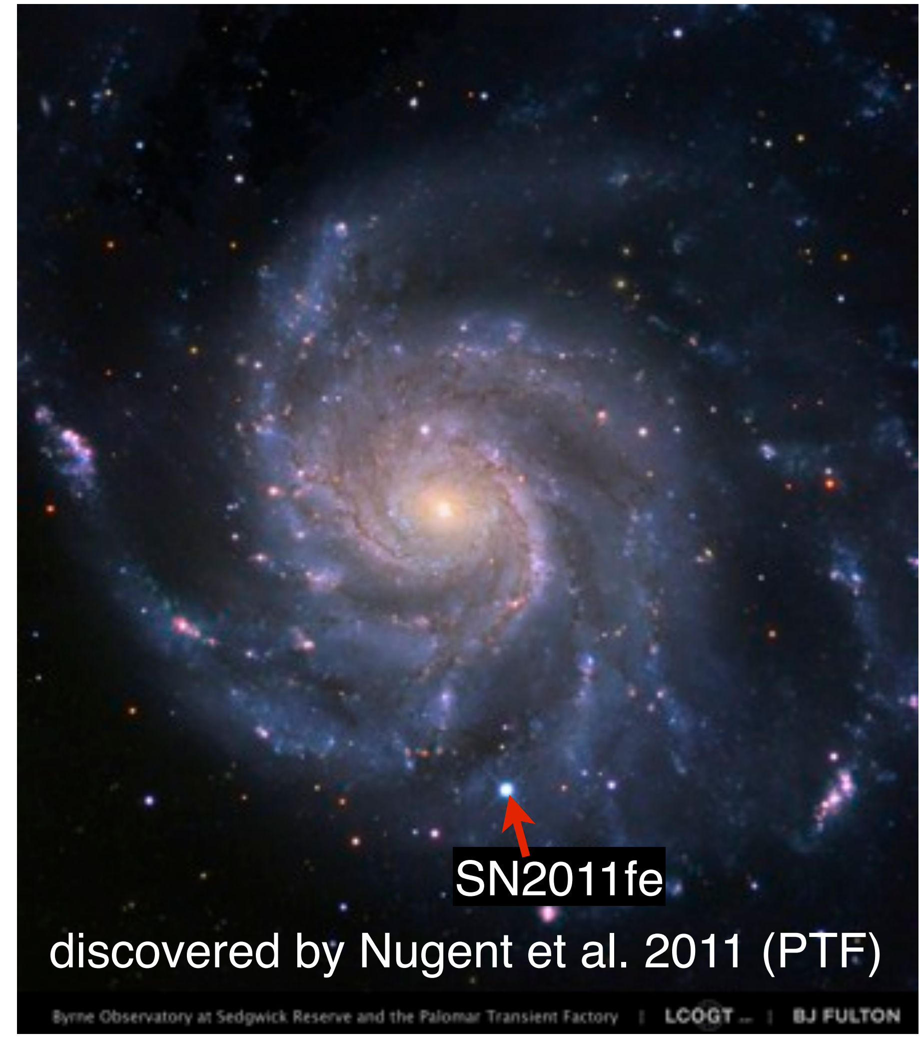
↳ distance modulus $\mu = m - M = 5\log_{10}(d_L) - 5$

- **Standard candles :** ➔ same intrinsic luminosity ➔ very bright object $\Big\}$ **Type Ia Supernovae (SNe Ia)**

Type Ia supernova ?

- **What is a SN Ia ?** thermonuclear explosion of a C+O white dwarf at the Chandrasekhar mass ($1.4M_{\odot}$) *Chandrasekhar (1931)*





- **Progenitor scenario :** 2 competitive models

→ single degenerate : white dwarf accretes matter (He) from a companion (red giant)

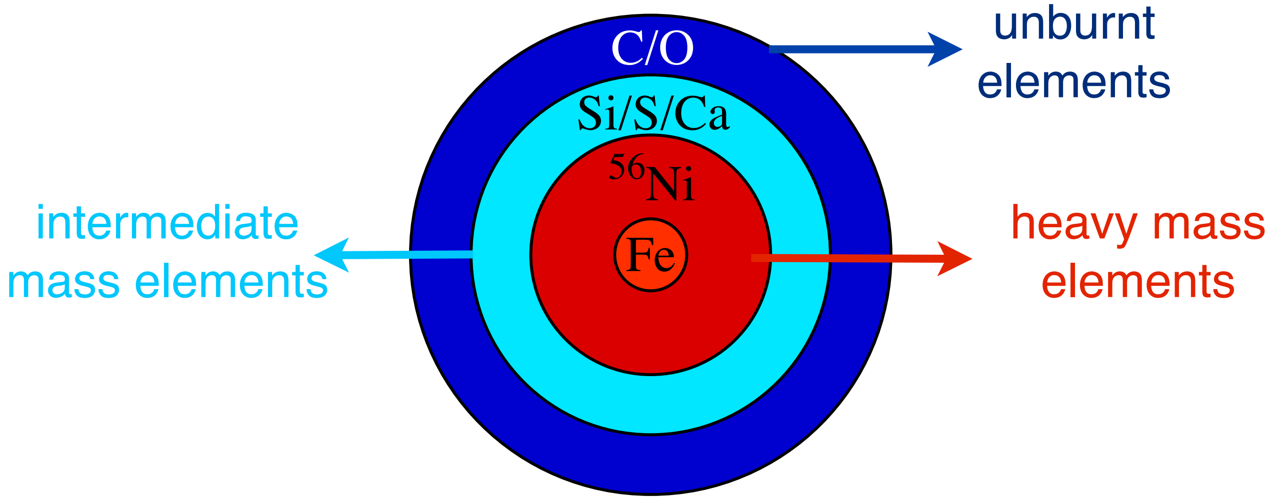
Whelan & Iben (1973)

→ double degenerate : merging of 2 white dwarfs in a binary system

Iben & Tutukov (1984) ;Webbink (1984)

Life of a SN Ia after explosion

- **Structure after explosion :**



- **Light propagation :**

radioactive desintegration of $^{56}Ni \longrightarrow {}^{56}Co \longrightarrow {}^{56}Fe$

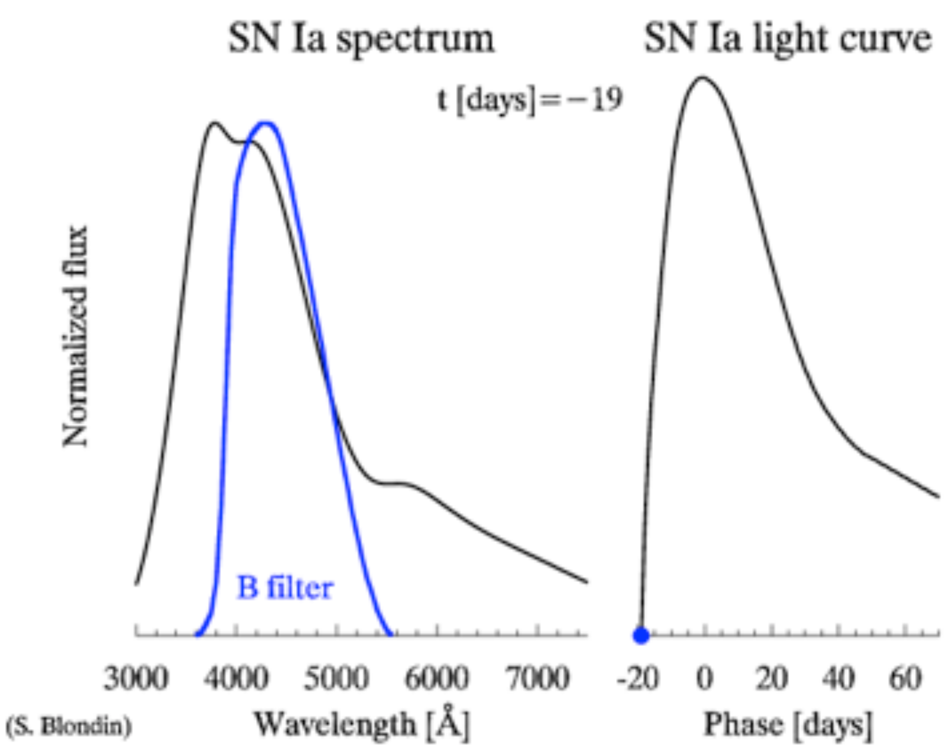
↳ SN Ia luminosity + star expansion

↳ decrease of density and opacity

↳ light propagation + absorption by external layers

➔ Spectrum + light curve

- **Light curve and spectrum evolution :**



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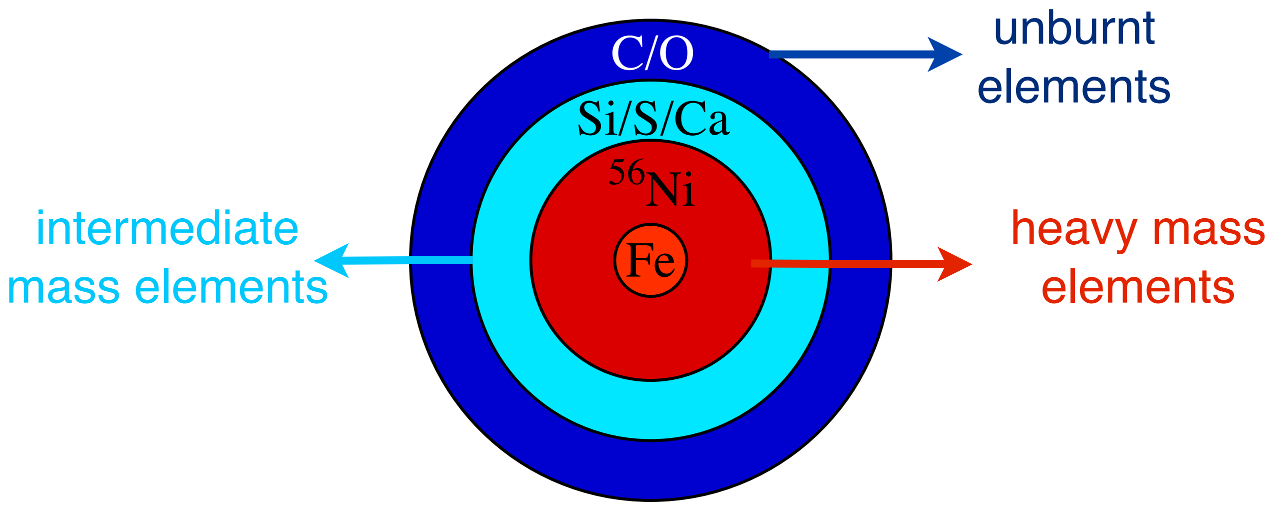

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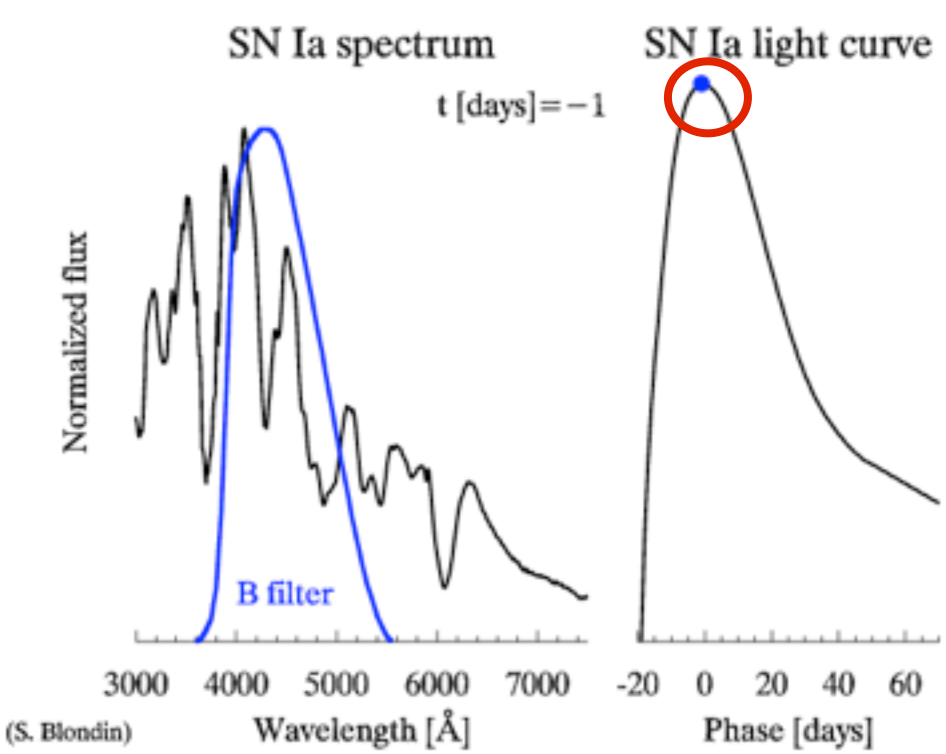
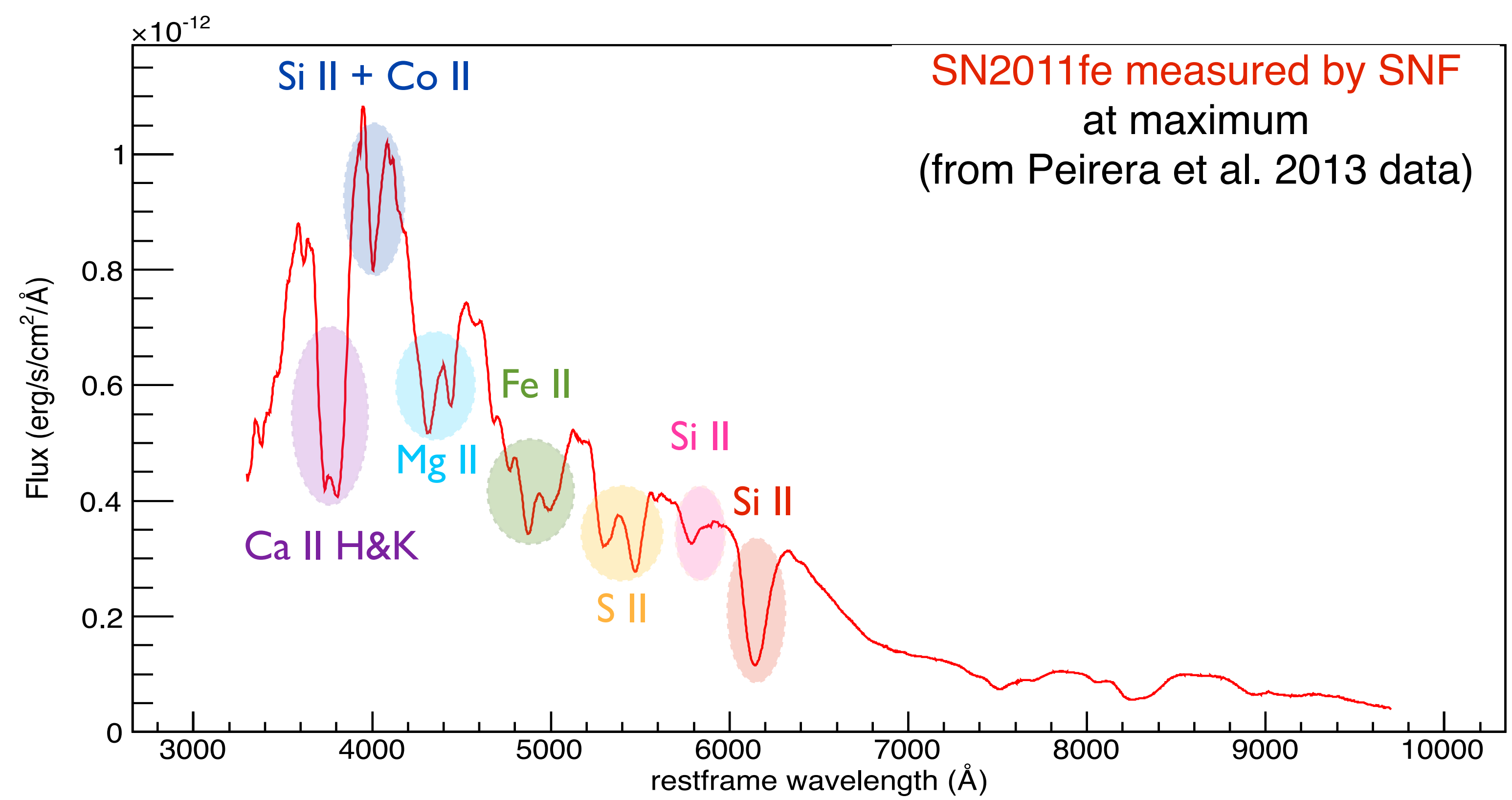
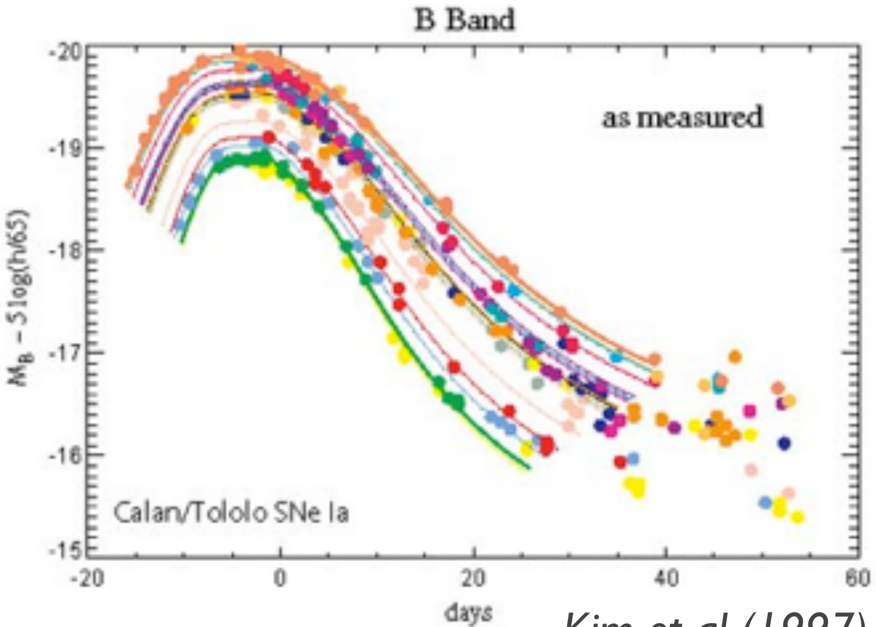




Variability of SNe Ia

- **Standard(izable) candles :**
  - ➔ ~ 40% magnitude dispersion at maximum
  - ➔ standardization reduces dispersion



Kim et al (1997)

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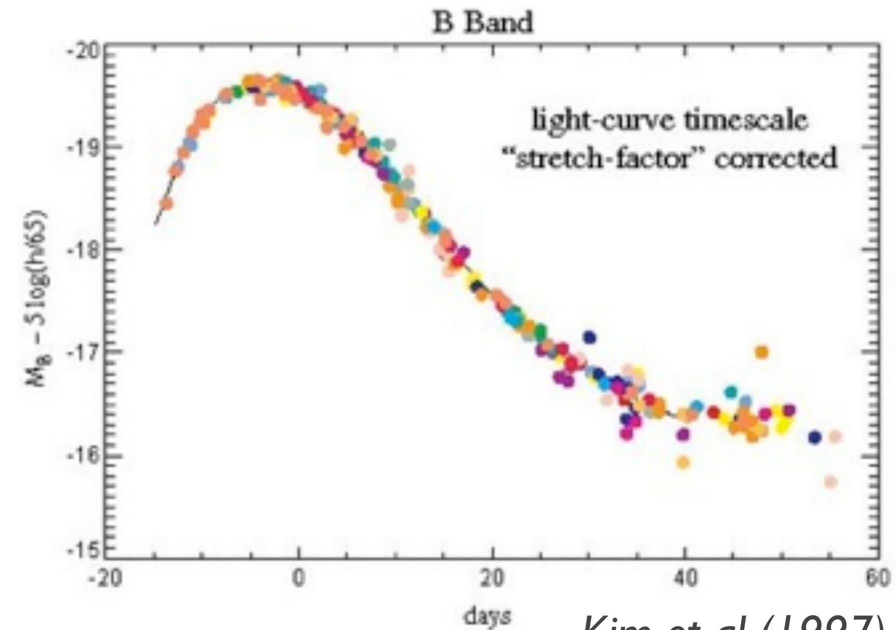


Kim et al (1997)

- **Corrections to standardize SNe Ia :**

  - **stretch factor** (light-curve shape) : Brighter-Slower correlation *(Phillips 1993)*

  - **color** $(B-V)_{Bmax}$: Brighter-Bluer correlation *(Tripp 1998)*

  - **host properties** :
    ➔ brighter SNe Ia with high stretch preferentially found in early type galaxy *(Hamuy et al 1996 ; Howell et al 2007)*

    ➔ SNe Ia in early type, massive galaxies of high metallicity are ~10% brighter *(Sullivan et al 2010 ; Lampeitl et al 2010 ; Kelly et al 2010)*

  - **spectral indicators** :
    ➔ equivalent width : SNe Ia with deeper Si II absorption (4000Å) have lower stretch *(Arsenijevic et al 2008 ; Walker et al 2010)*

    ➔ absorption ratio : SNe Ia with higher $\mathcal{R}_{5800\,\text{Å}/6150\,\text{Å}}$ (for Si II) are brighter *(Nugent et al 1995)*

Cosmology with SNe Ia

- **Standardizable candles :** good distance indicator

  ↳ Compute the distance modulus
  ↳ $m_B{}^*$, *s* and *c* = intrinsic parameters
  ↳ M, α and β = fitting parameters

Absolute magnitude at max

Color correction : Brighter-Bluer correlation

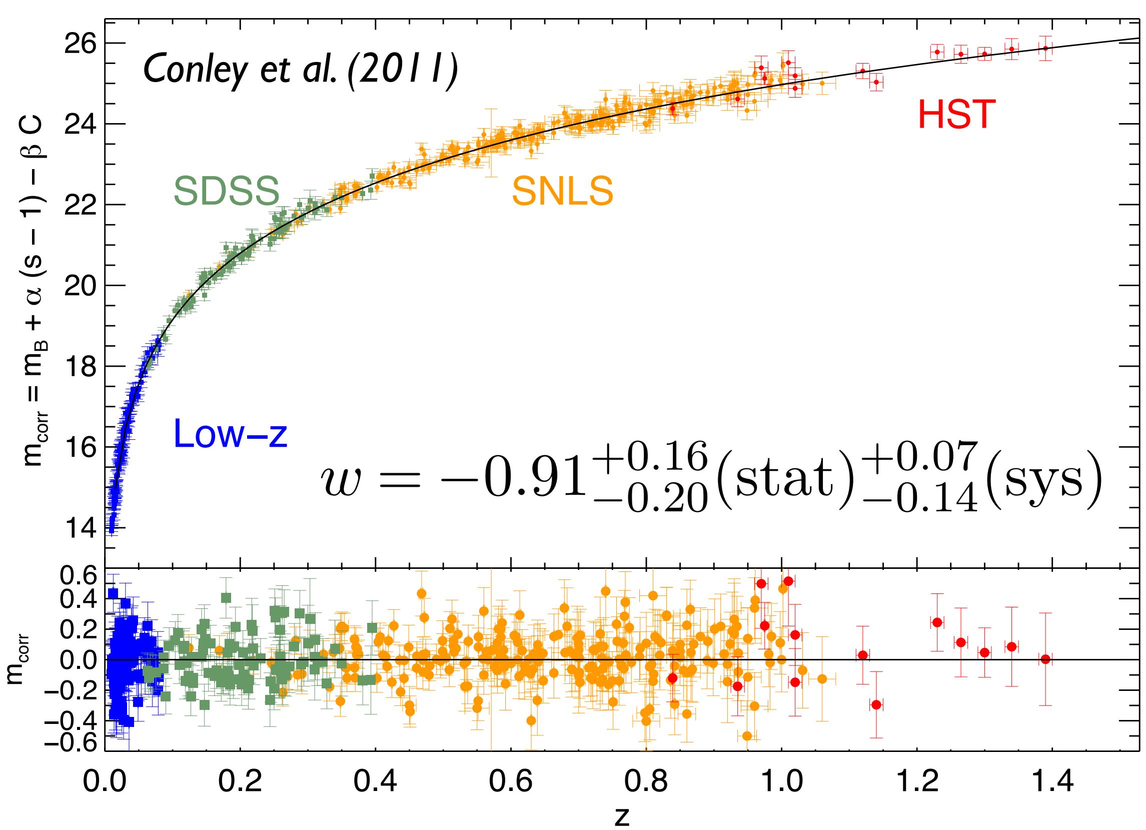
$$\mu_B = m_B^* - M + \alpha(s-1) - \beta C$$

Restframe apparent magnitude at max

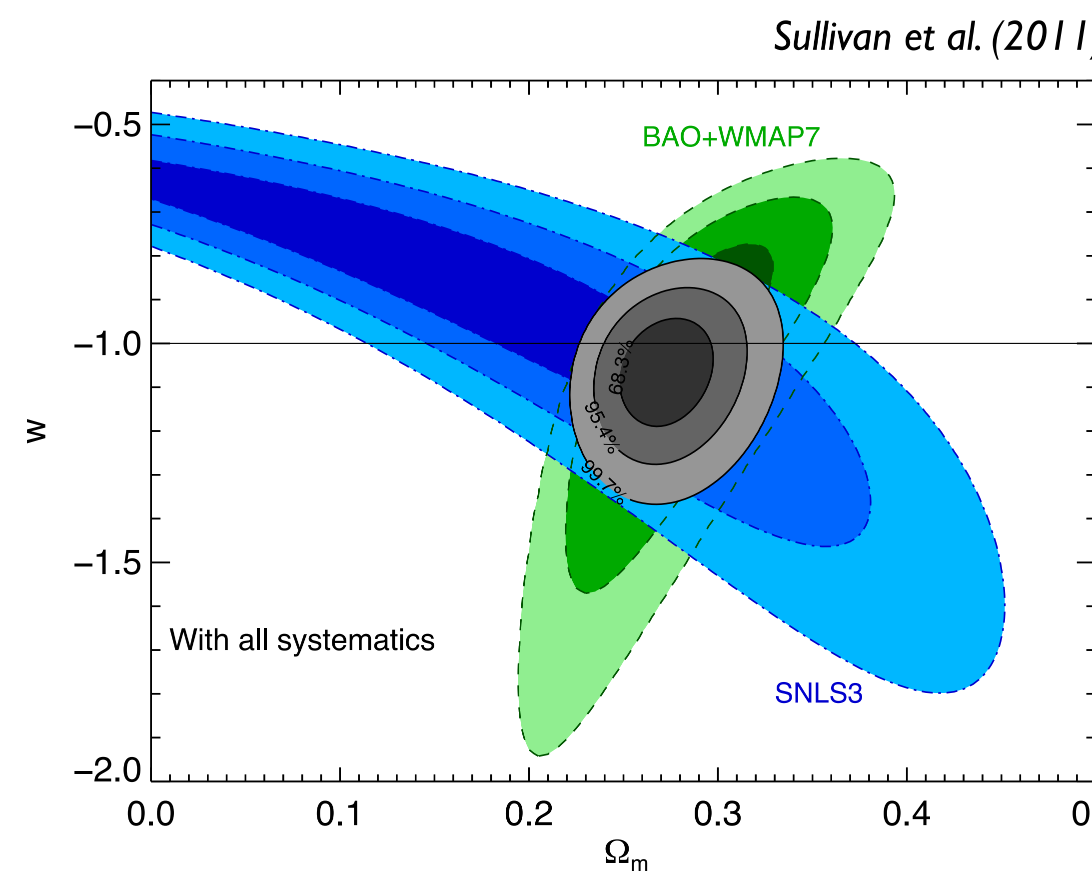
Stretch correction : Brighter-Slower correlation

- **Hubble diagram :**

$$\chi^2 = \sum_{SNe\ Ia} \frac{[\mu_B - 5\log_{10}(d_L(z,\Omega_m,\Omega_\Lambda,w)/10\mathrm{pc})]^2}{\sigma^2_{\mu_B} + \sigma^2_{int}}$$



- **Combination with other probes :**



↳ **matter : 26.9 % + dark energy : 73.1 %**

Cosmology with SNe Ia

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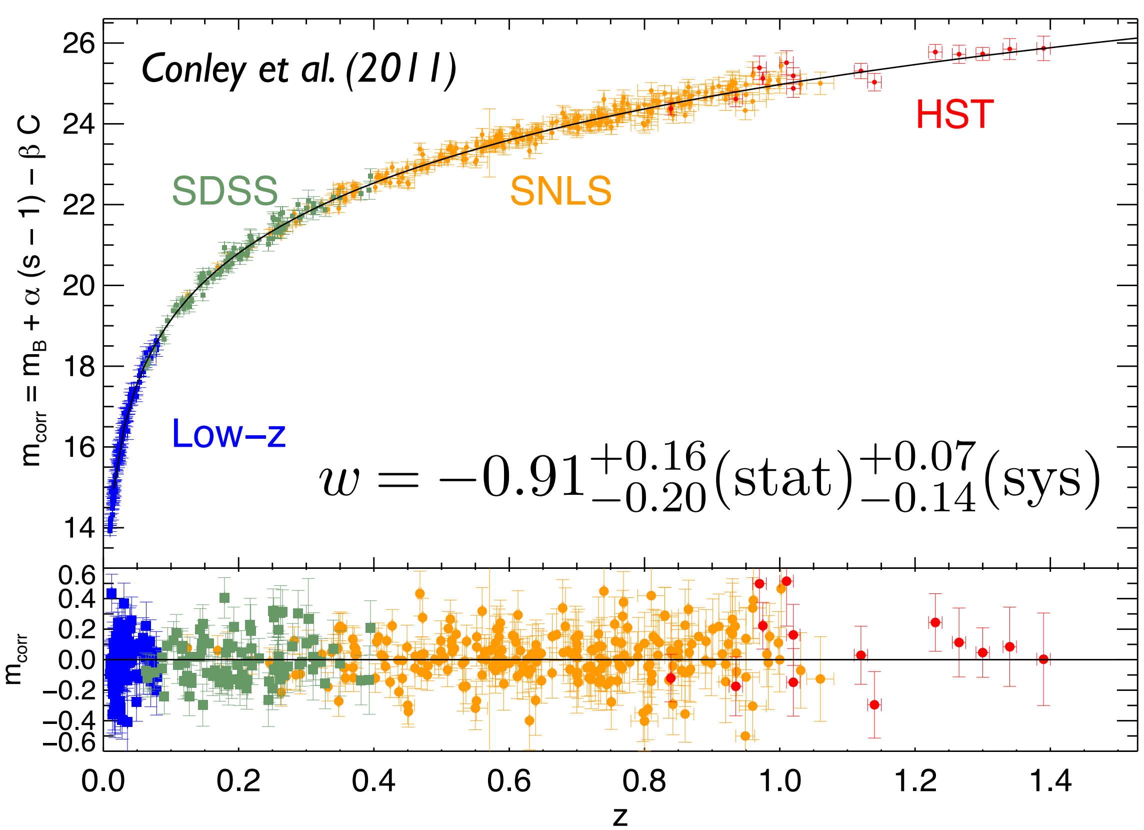

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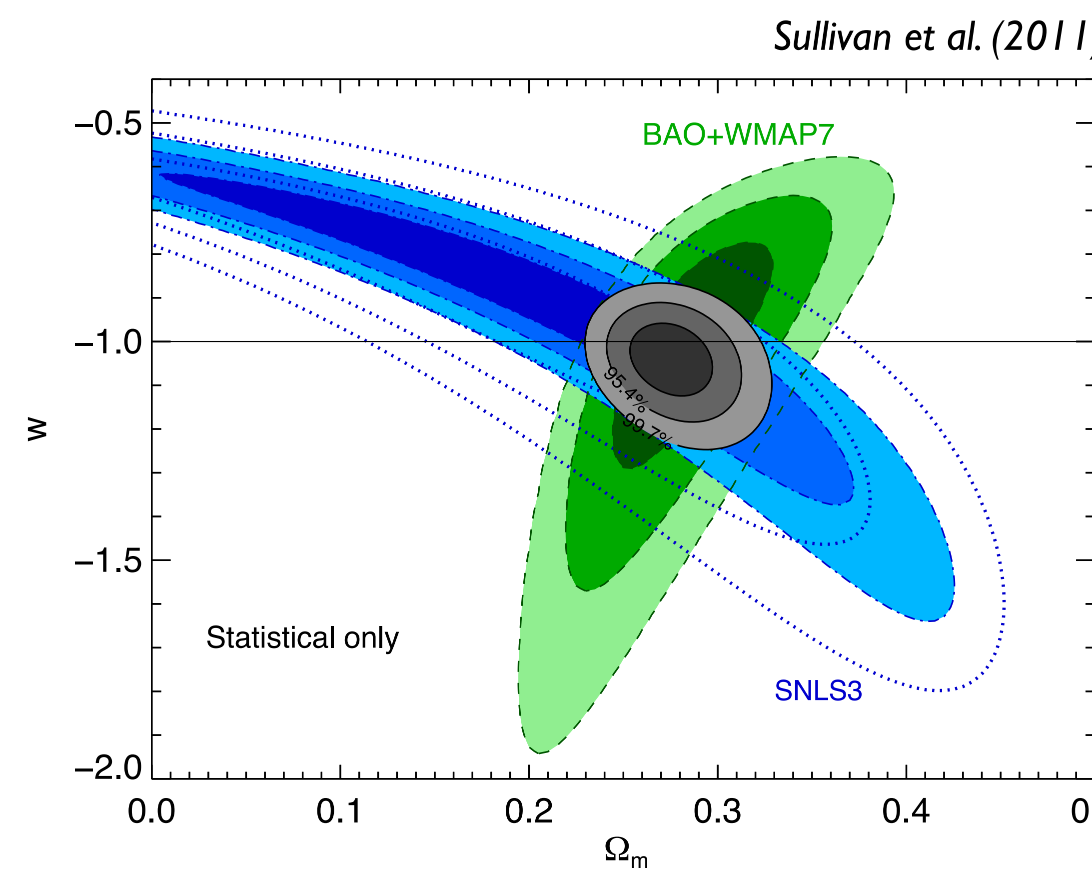

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SuperNova Legacy Survey

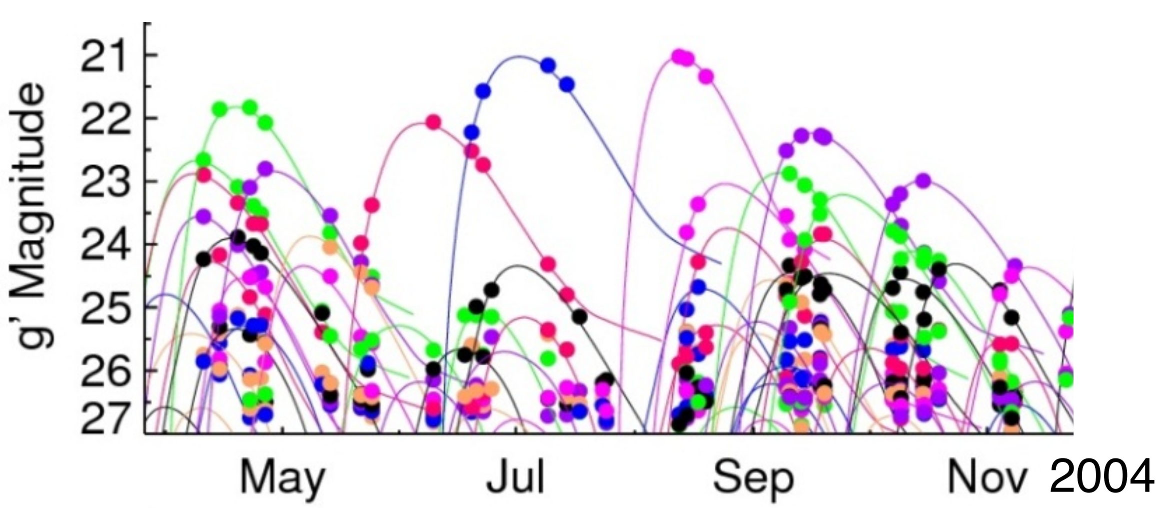
- **Aim** : measuring luminosity distances to a large number of intermediate and high redshift SNe Ia ($0.15 < z < 1.1$) in order to build a Hubble diagram to constrain cosmological parameters
- **When ?** 2003-2008
- **How many ?** 242 SNe Ia (SNLS 3yr)
- **Method :**

imaging survey

at the Canada-France Hawaii Telescope (CFHT) in Hawaii

➔ a rolling-search to detect new SN Ia candidates and to monitor their light-curves in several photometric bands

➔ more than 1000 light curves have been gathered



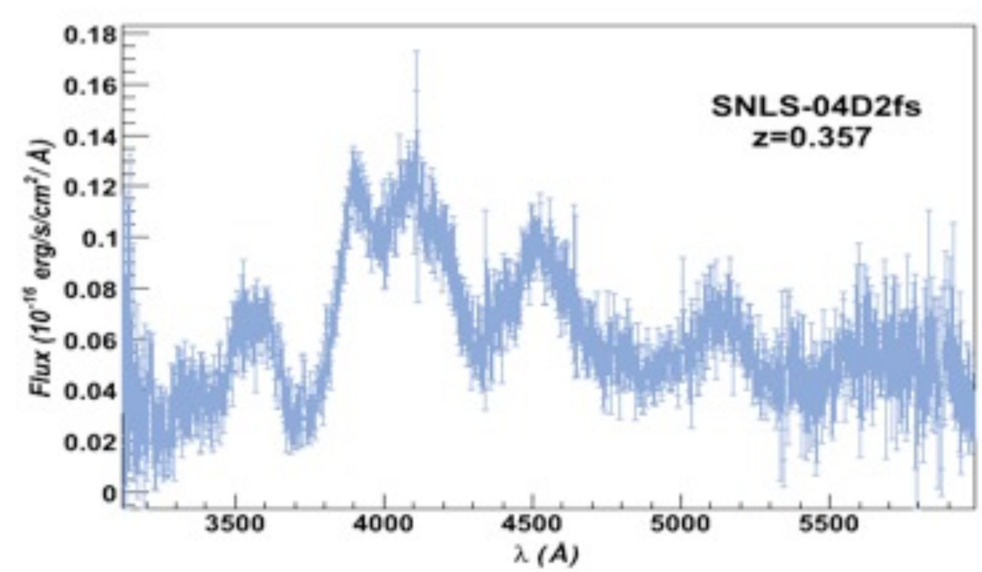
spectroscopic programs

at the Very Large Telescope (VLT), Gemini, Keck telescopes

➔ ~1500h of observing time on 8-10m telescopes over the course of the survey

➔ to confirm the nature of the SN Ia candidates

➔ to measure their redshift



Nearby SuperNova Factory

- **Aim** : measuring spectral time series of a large number of nearby SNeIa (0.03 < z < 0.08) in order to complete the Hubble diagram and for a better knowledge of SNe Ia properties

- **When ?** 2004-today

- **How Many ?** 232 SNe Ia (2004-2009)

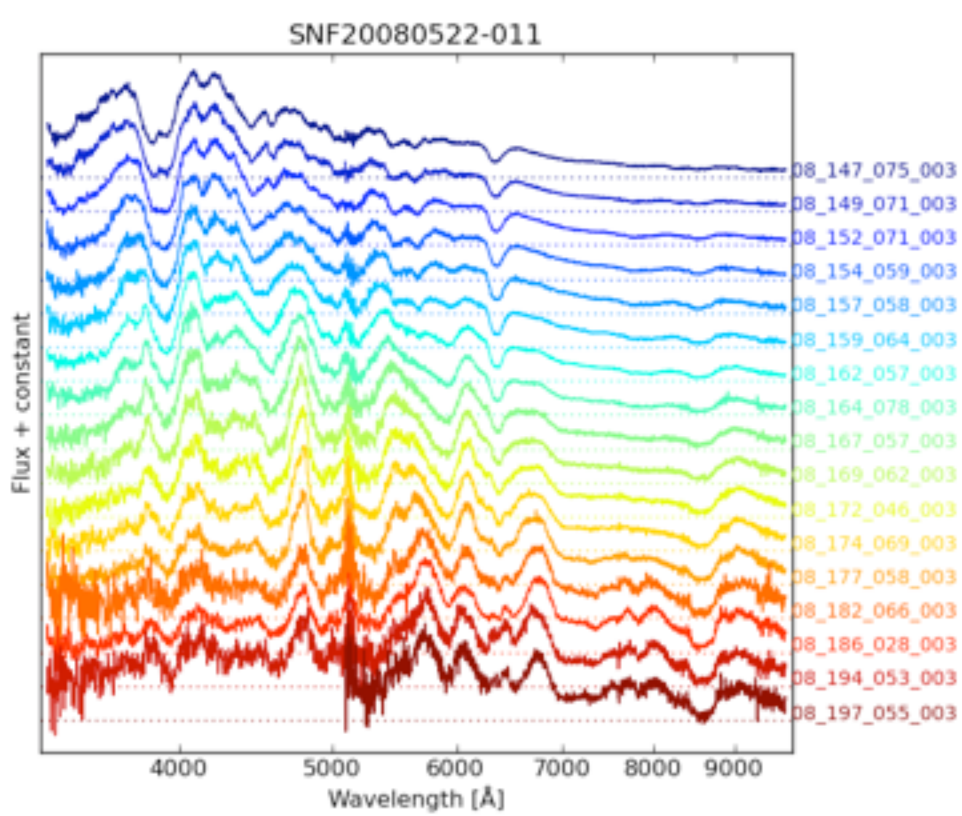
➔ 120 for cosmology (with more than 5 spectra (1 before max) per SN Ia)

↳ 2 independent samples : «training» and «validation»

- **Method :**

➔ detection of candidates with the PTF telescope (Palomar Transient Factory)

➔ spectro-photometric follow-up with SNIFS (SuperNova Integral Field Spectrograph) at the UH88 telescope



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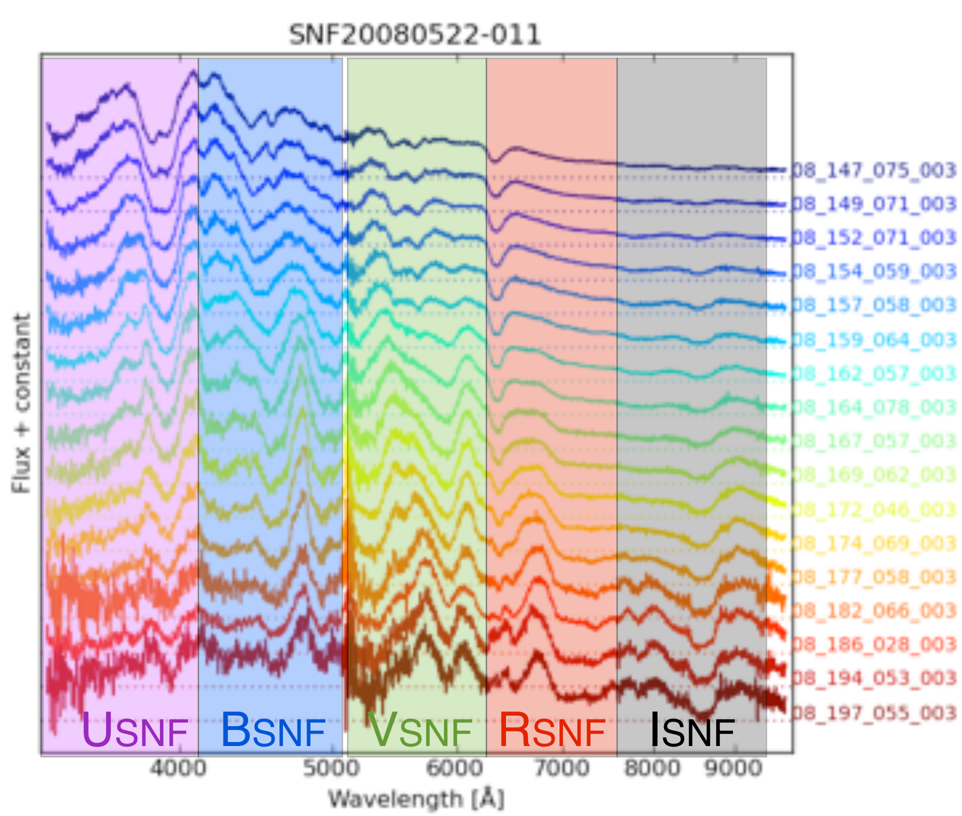

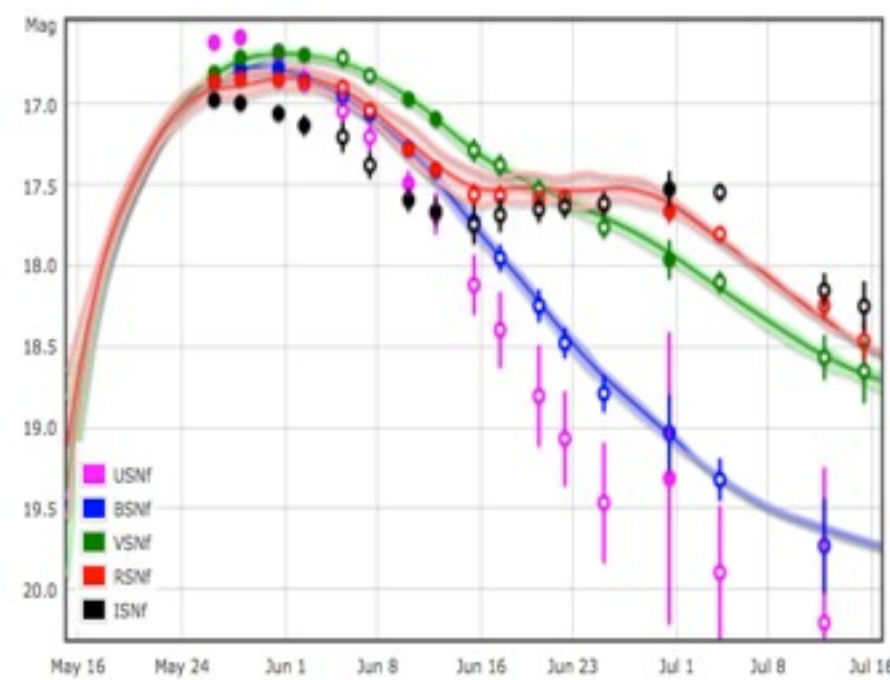

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Context of the VLT 5 year analysis

SNLS progress

- **SNLS 3yrs cosmological analysis :** ✓ Guy et al. (2010) ; Sullivan et al. (2011) ; Conley et al. (2011)
- **SNLS 3yrs recalibrated :**
  - photometric calibration : ✓ Betoule et al. (2013)
  - distance measurement of SNe Ia and cosmological constraints : ✓ paper in prep
- **SNLS 5yrs :**
  - SNLS 5yrs photometry : on going
  - SNLS 5 yrs spectroscopy : identification and redshift estimates ✓ VLT : Cellier-Holzem et al. (2013)

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VLT spectroscopy

- **VLT 3yr spectroscopic sample :** 120 SNe Ia ✓ Balland et al. (2009)

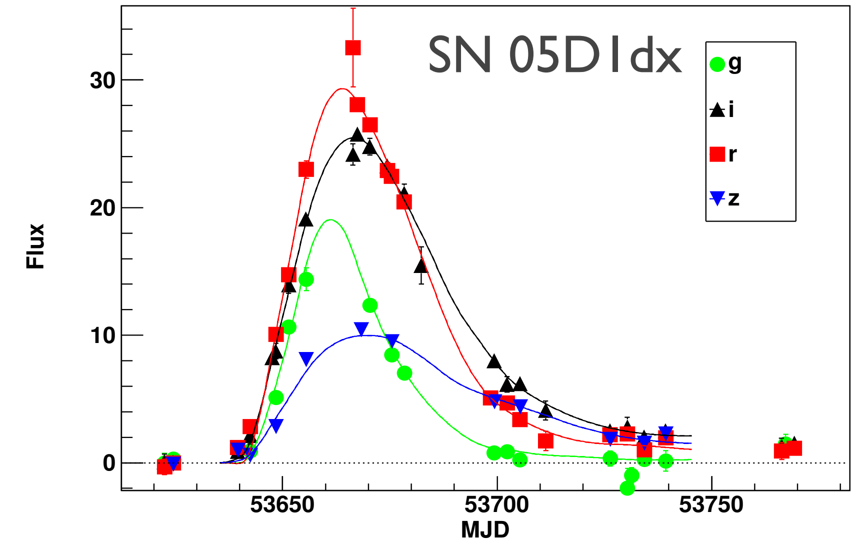
  → **VLT1 sample**

- **Last two year of VLT data :** 85 new candidates (2006-2007)
  + 17 candidates measured in Multi-Object Mode (2003-2006)
  + 06D2bo re-extracted by Bazin et al. 2011

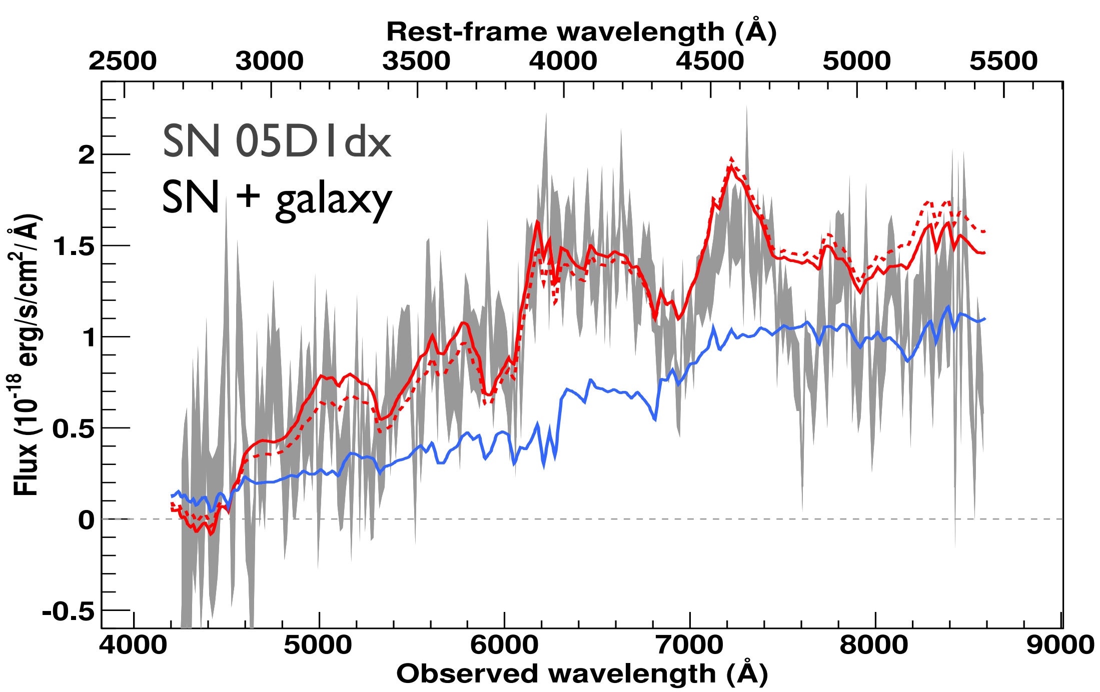
  → **VLT2 sample** *(spectra extraction by C. Lidman)*

SALT2 : spectro-photometric model of SN Ia
(Guy et al. 2007)

- **Fit lightcurves** with a χ^2 minimisation procedure
  - B band magnitude at maximum
  - date of B band maximum
  - x1 parameter (linked to s)
  - color c

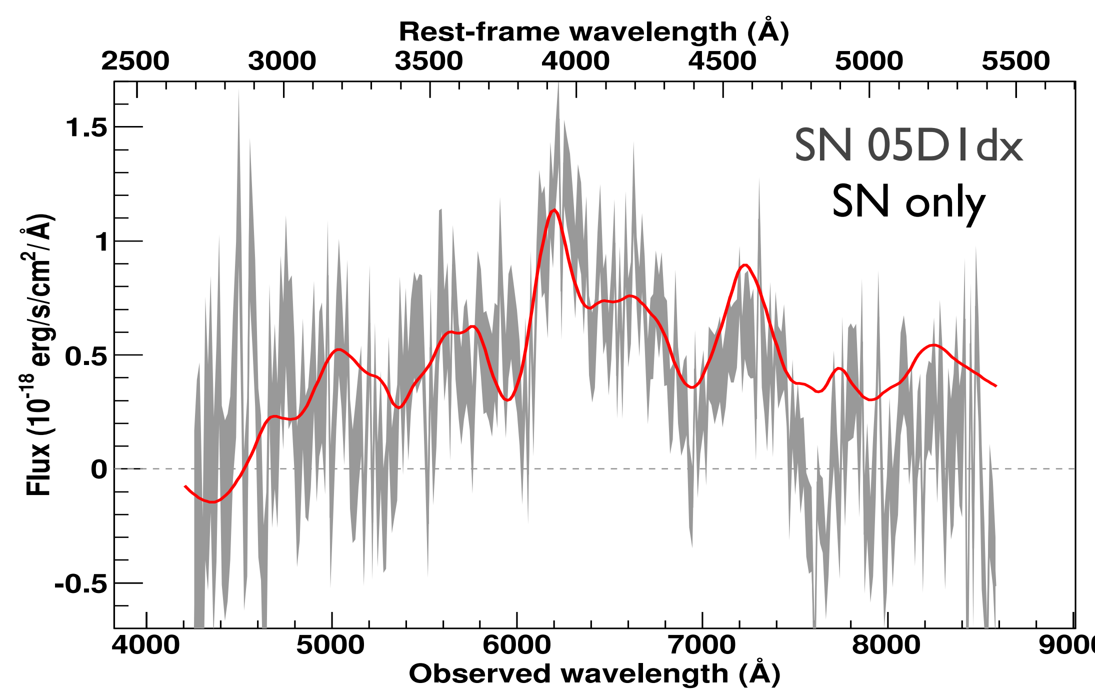


- **Fit the spectral sequence** with fixed photometric parameters
  - phase = restframe date from B band maximum
  - host type + fraction from templates *(Kinney 1996 ; PEGASE2 by Fioc & Rocca-Volmerange 1997 ; 1999)*
  - recalibration of the spectro-photometric model

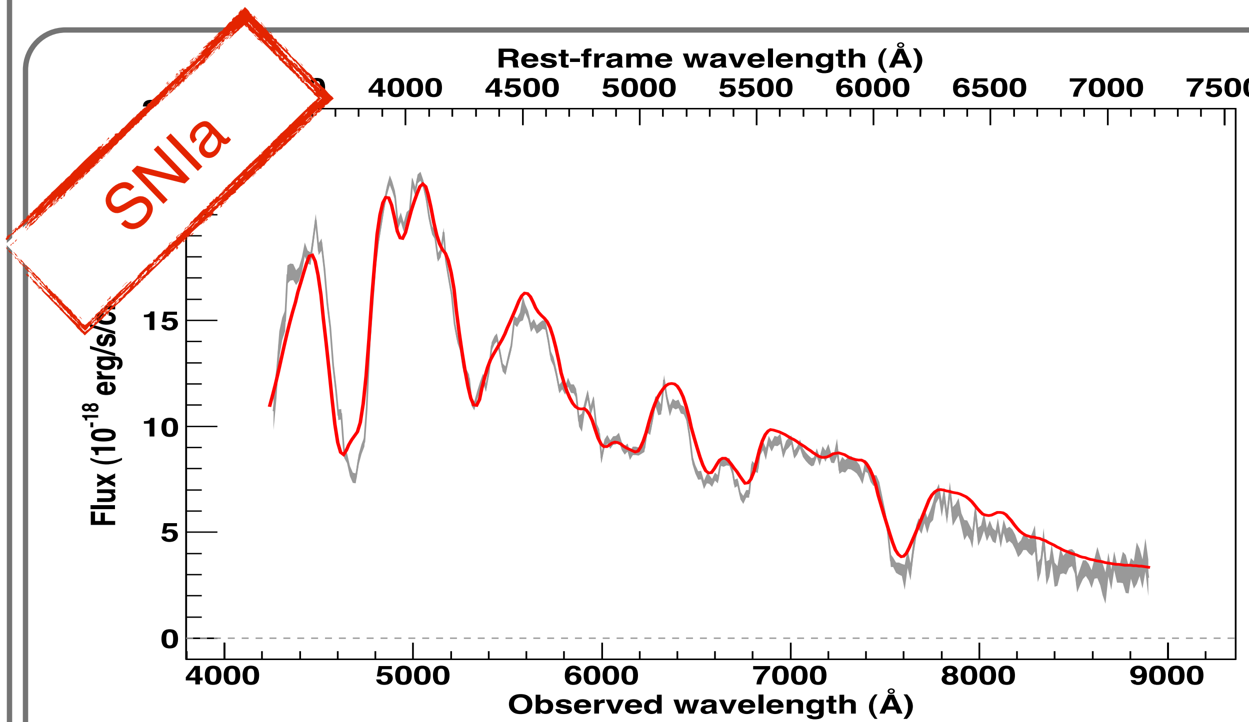


host subtraction

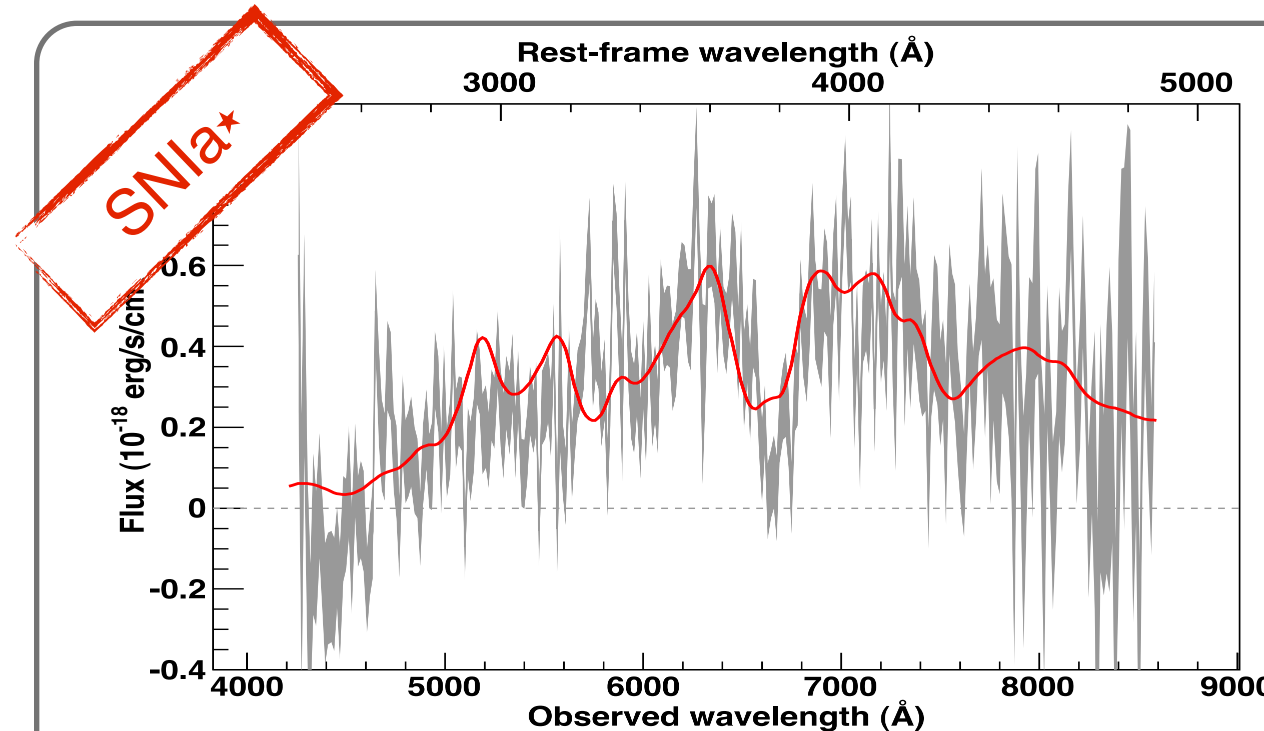
recalibration



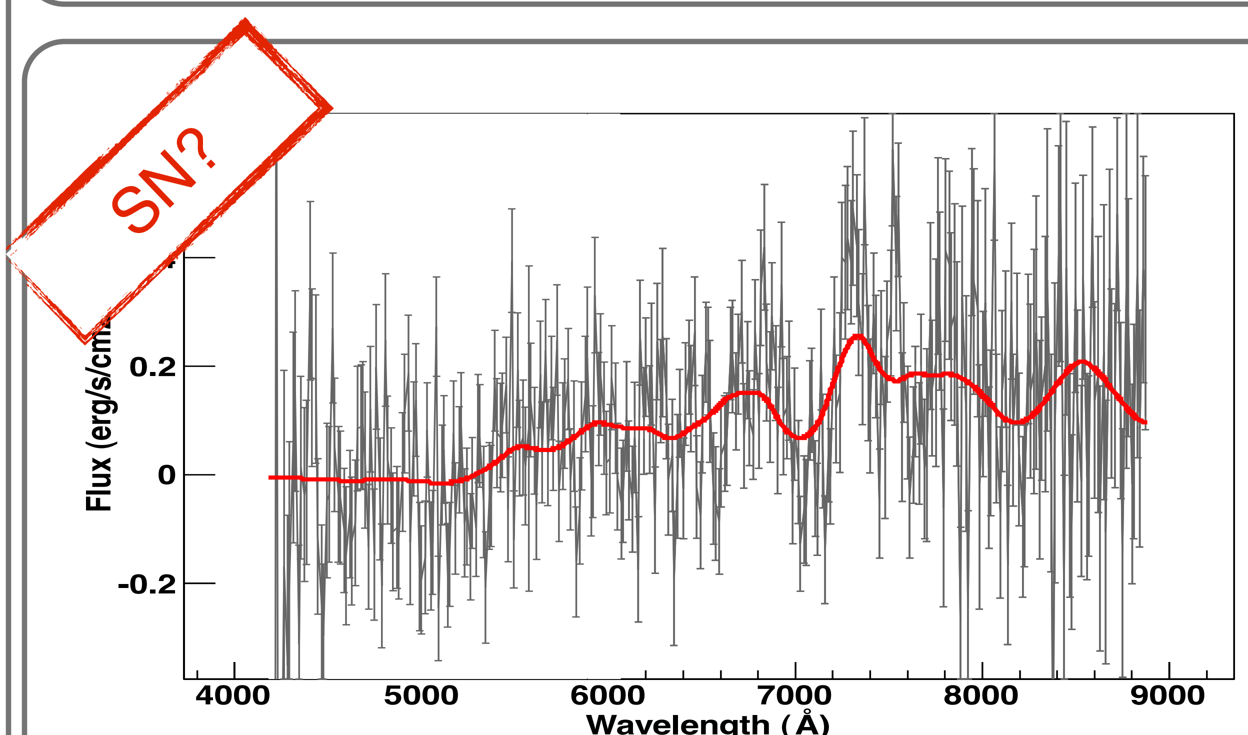
SN Ia identification



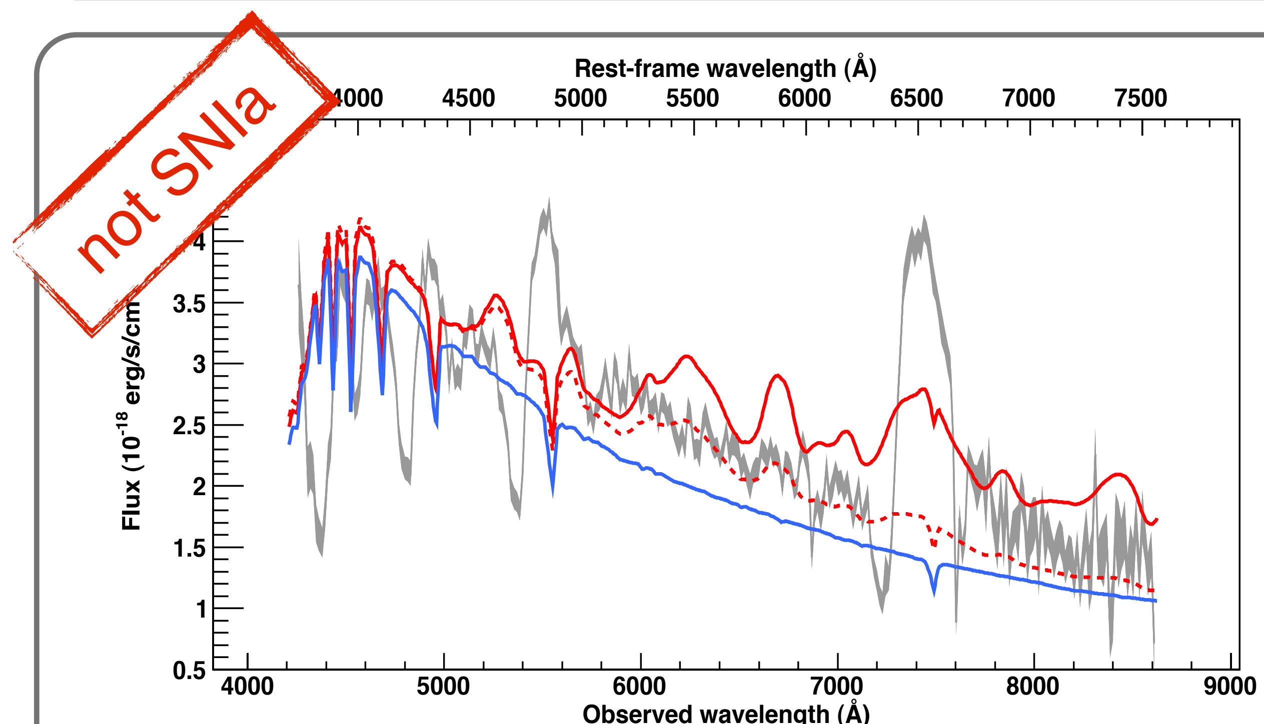
↳ SN 06D1du at maximum with z = 0.24 ± 0.01



↳ SN 06D4jt 3 days after maximum with z = 0.76 ± 0.01

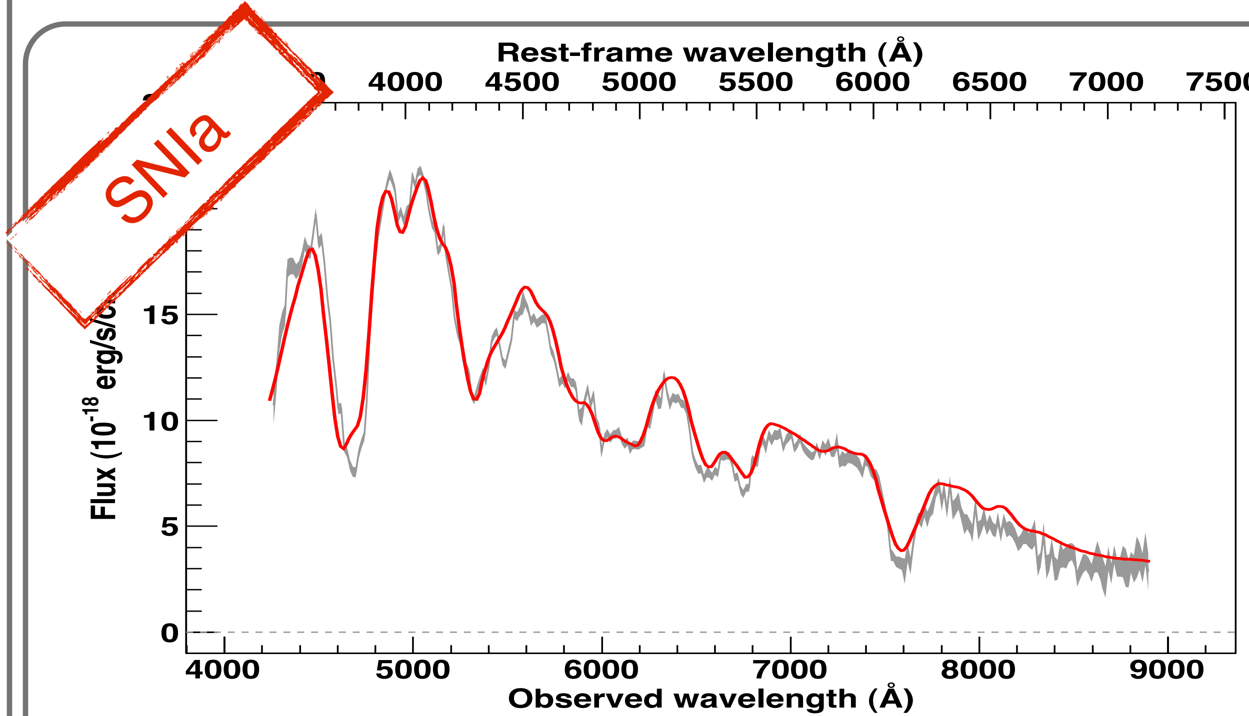


↳ SN 05D4he 11days after maximum with z = 0.87 ± 0.01



↳ SN IIp 06D1jx with z ~ 0.14 ± 0.01

SN Ia identification



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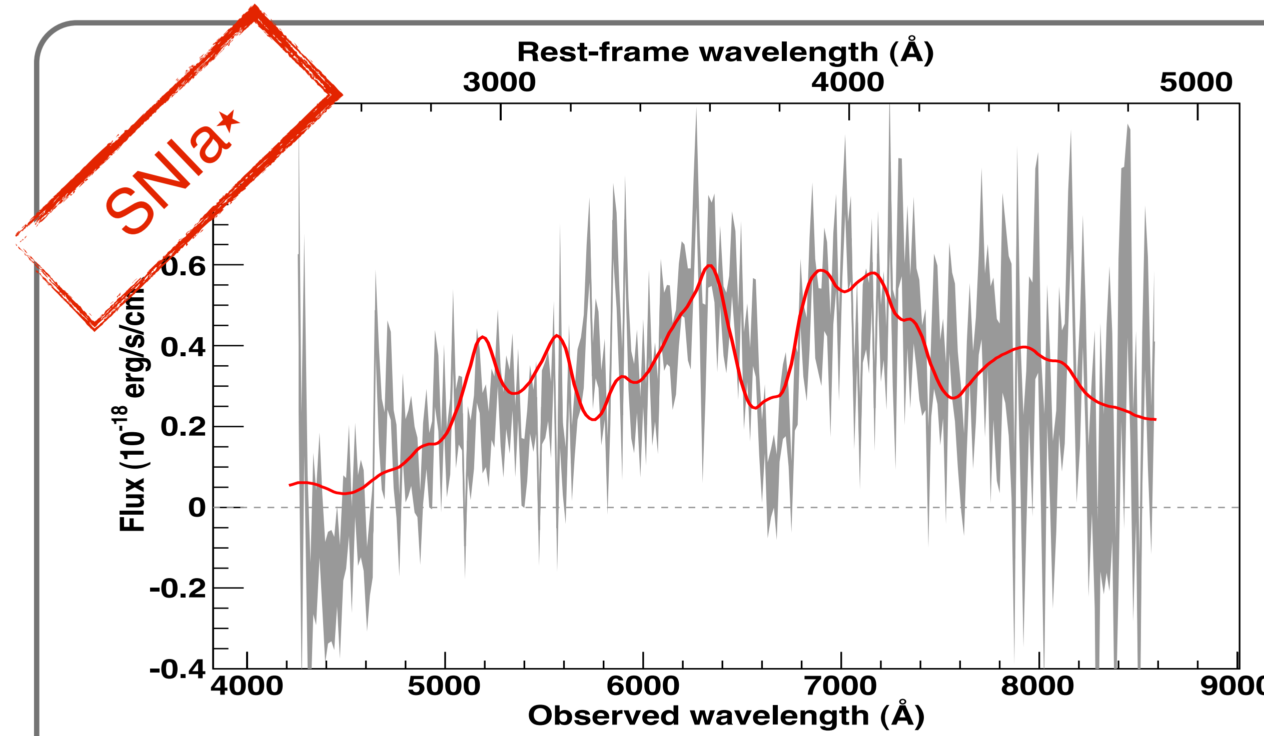

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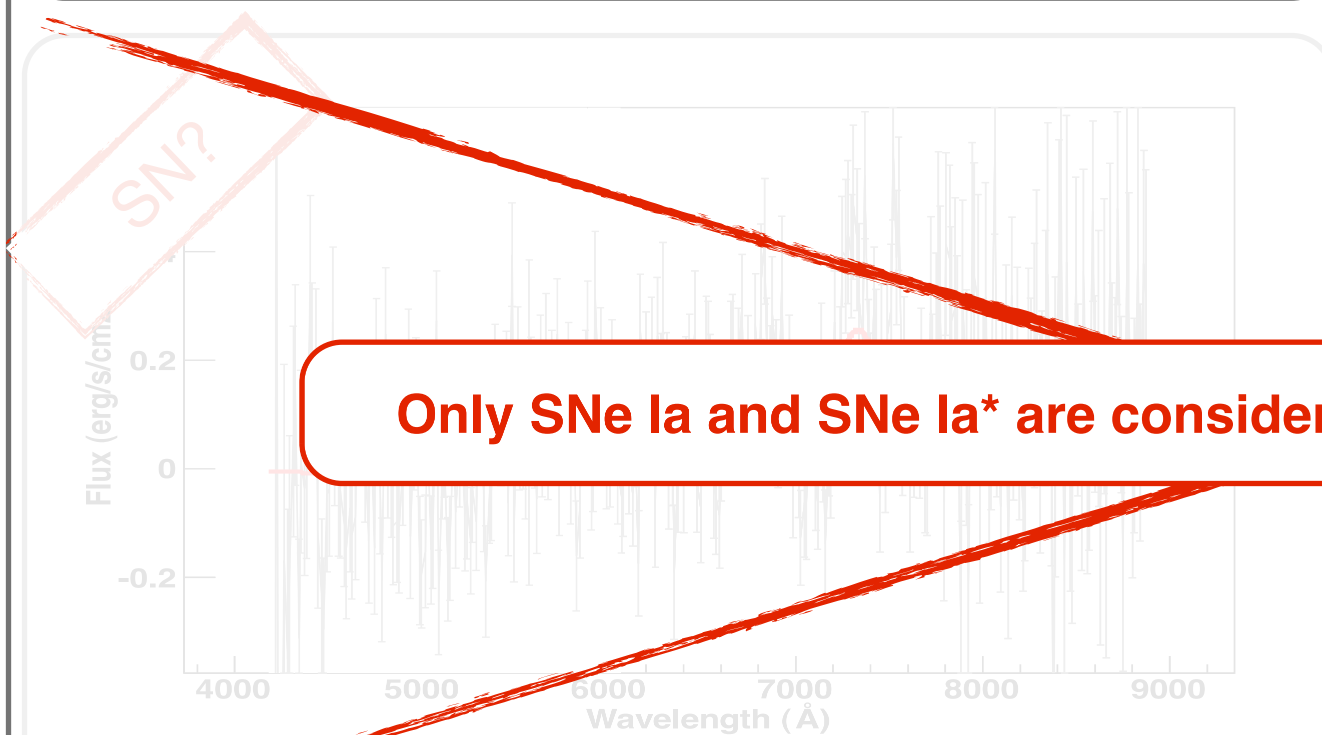

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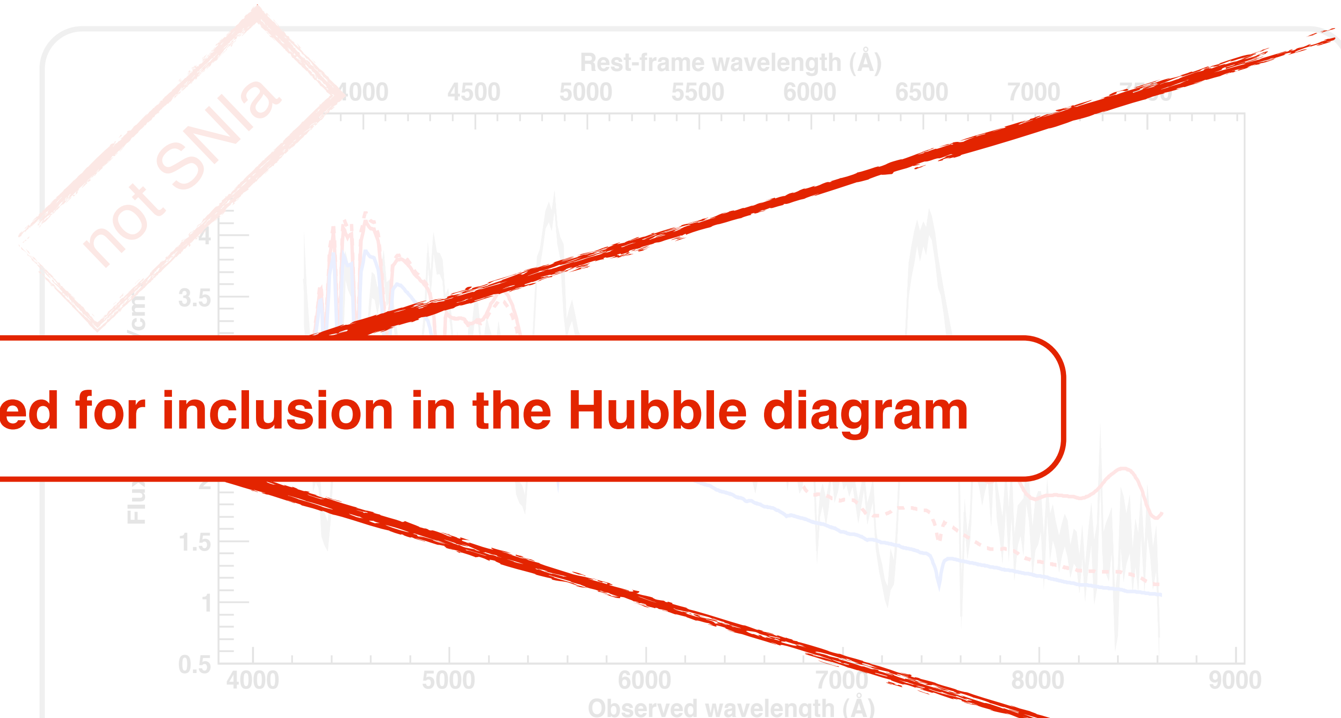
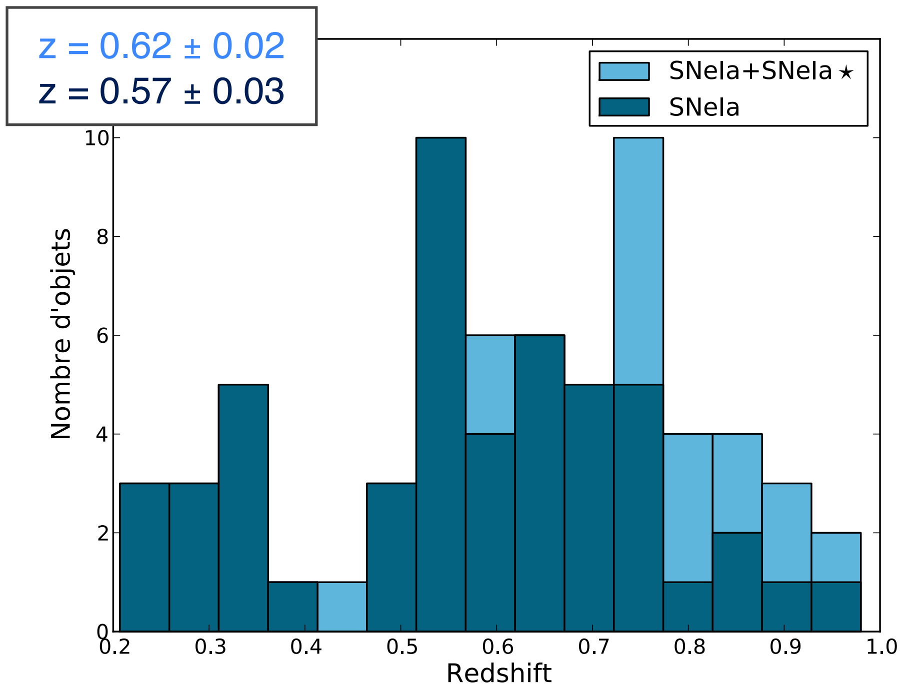


↳ SN IIp 06D1jx with z ~ 0.14 ± 0.01

Only SNe Ia and SNe Ia* are considered for inclusion in the Hubble diagram

Results : VLT2 spectroscopic sample

- **VLT2 sample :**
  - ➔ 66 type Ia supernovae (68 spectra)
    - ↳ 50 SNe Ia and 16 SNe Ia*
    - ↳ to be published in Cellier-Holzem et al (2013)
  - ➔ Large sample at intermediate and high z with relatively good S/N spectra



- **Properties of the SNe Ia and SNe Ia* samples :**

➔ SNe Ia and SNe Ia* represent the same population on average

➔ Limited contamination on average

	50 SNe Ia	16 SNe Ia*
$\langle z\rangle\ (\sigma_z)$	$0.57\pm0.03\ (0.18)$	$0.77\pm0.03\ (0.12)$
$\langle\Phi\rangle\ (\sigma_\Phi)$	$1.0\pm0.7\ (5.1)$	$2.8\pm0.9\ (3.7)$
$\langle f_{gal}\rangle\ (\sigma_{f_{gal}})$	$0.39\pm0.03\ (0.25)$	$0.61\pm0.04\ (0.17)$
$\langle S/N\rangle\ (\sigma_{S/N})$	$5.5\pm0.9\ (6.5)$	$1.6\pm0.2\ (0.9)$
$\langle m_B^*\rangle\ (\sigma_{m_B^*})$	$23.285\pm0.127\ (0.895)$	$24.217\pm0.086\ (0.342)$
$\langle m_B^{*c}\rangle\ (\sigma_{m_B^{*c}})$	$23.965\pm0.045\ (0.319)$	$23.981\pm0.089\ (0.357)$
$\langle c\rangle\ (\sigma_c)$	$-0.016\pm0.014\ (0.101)$	$-0.045\pm0.033\ (0.131)$
$\langle s\rangle\ (\sigma_s)$	$1.001\pm0.010\ (0.070)$	$0.988\pm0.020\ (0.081)$

expected differences between SNe Ia* and SNe Ia (classification criteria)

similar photometric parameters on average

VLT2 sample : galaxy subtraction

- **Spectra sample :**
  - Only SNe Ia
  - Phase cut : -4 < phase < 4 days
  - Color cut : -0.2 < c < 0.2
  - 2 bins : $f_{gal} < 50\%$ and $f_{gal} > 50\%$

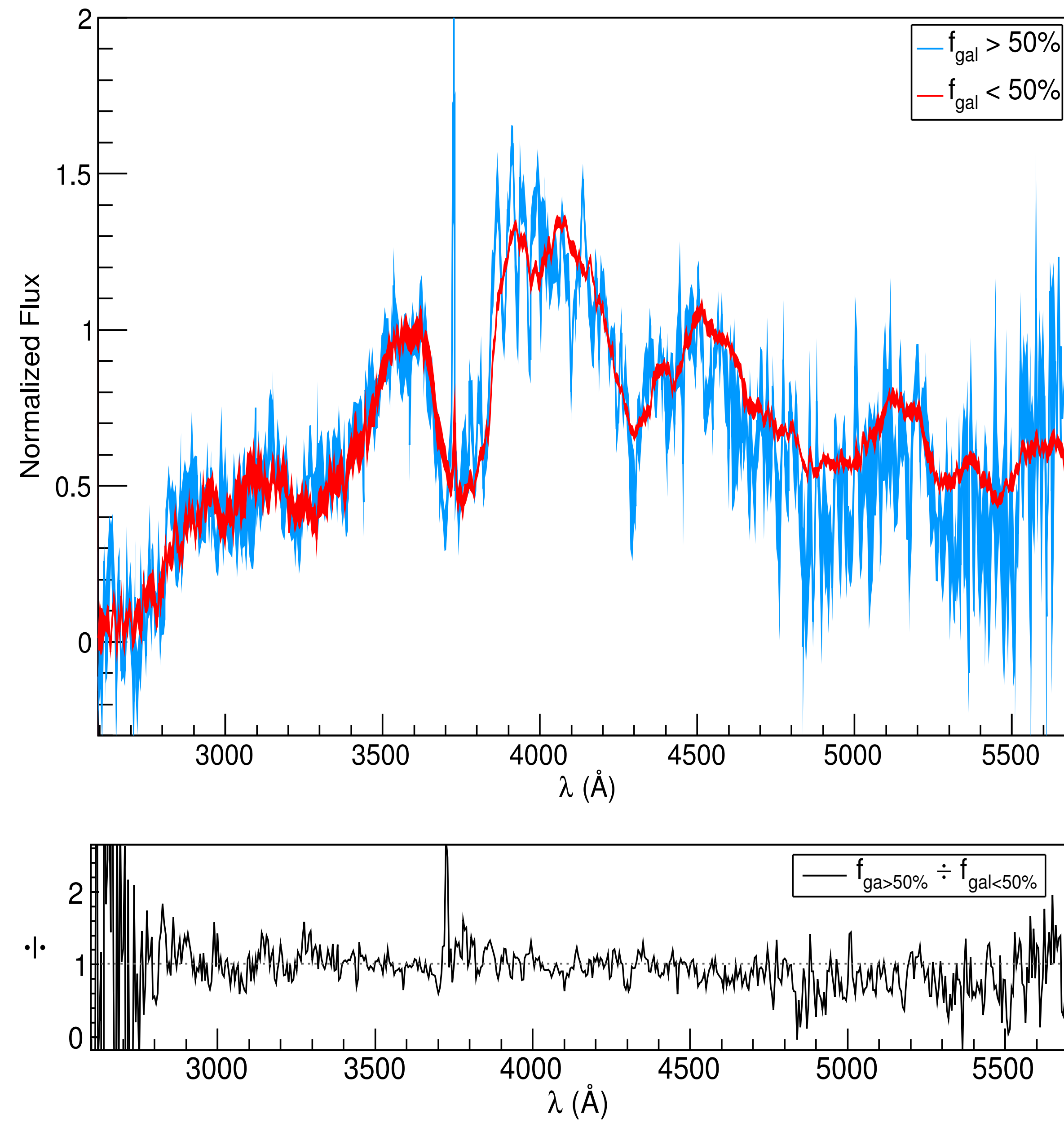
high f_{gal} : 7 spectra
low f_{gal} : 17 spectra

- **Building mean spectra :**
  - Spectra are de-redshifted + rebinned to 5Å
  - Normalisation : same flux integral over 4000-4500Å
  - Average weighted flux + dispersion in each bin
  - Error : 1σ confidence level

↳ mean spectra with low and high host contamination are similar on average

↳ local spectral differences due to :
- lower S/N
- stronger host line residuals
- over subtracting host signal (λ > 4700Å)

→ host subtraction under control



Comparison with the VLT1 sample

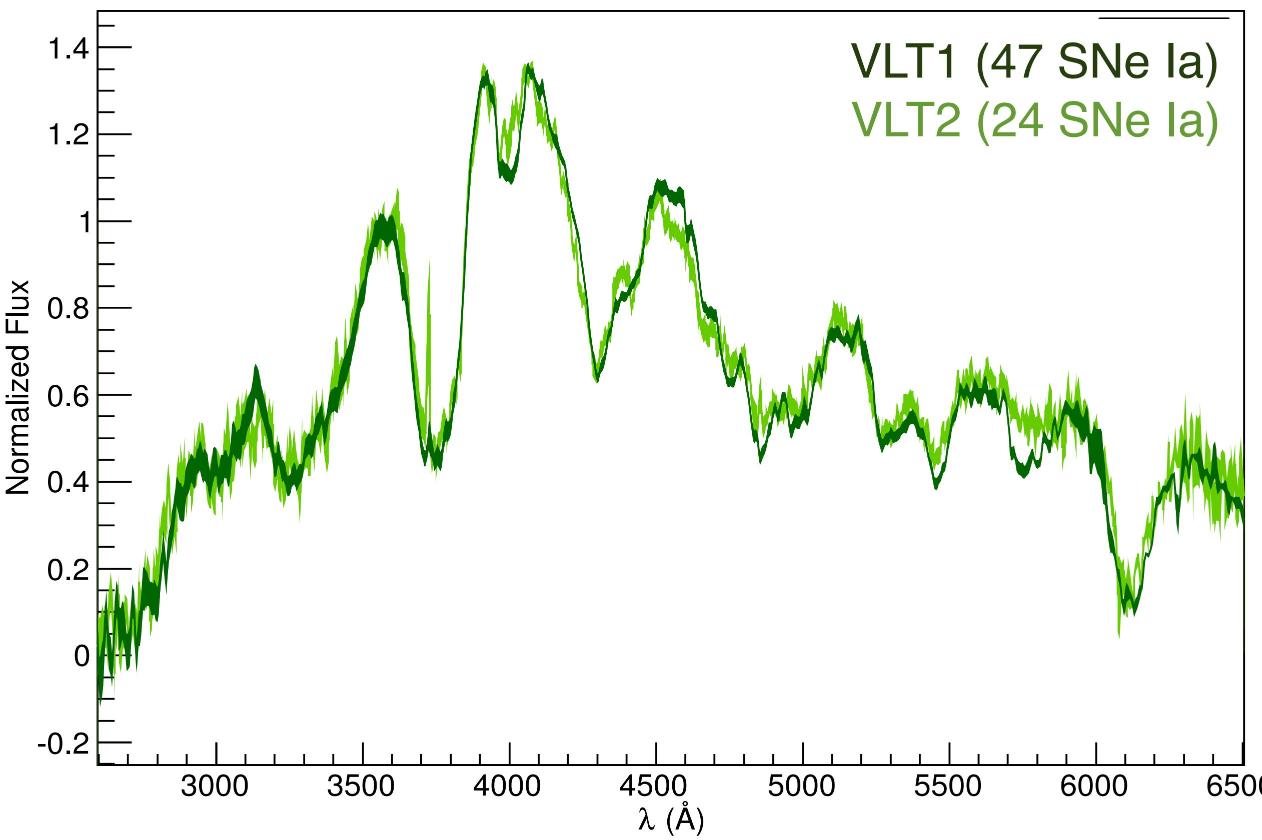
- **VLT samples :** 2 independent sub-samples with 2 different extraction methods and with not SNe Ia in common
  - ➔ VLT1 (Balland et al. 2009)
  - ➔ VLT2 (Cellier-Holzem et al. 2013)

- **Comparing average properties :**

	VLT1 120 SNe Ia + Ia*	VLT2 66 SNe Ia + Ia*
$\langle m_B^{*c}\rangle$ $(\sigma_{m_B^{*c}})$	24.005 ± 0.037 (0.407)	23.969 ± 0.040 (0.326)
$\langle c\rangle$ (σ_c)	-0.016 ± 0.011 (0.121)	-0.023 ± 0.013 (0.109)
$\langle s\rangle$ (σ_s)	1.018 ± 0.008 (0.087)	0.998 ± 0.009 (0.072)

➔ average photometric properties are similar

- **Comparing raw spectra :** mean spectrum for the 2 sub-samples (only SNe Ia)

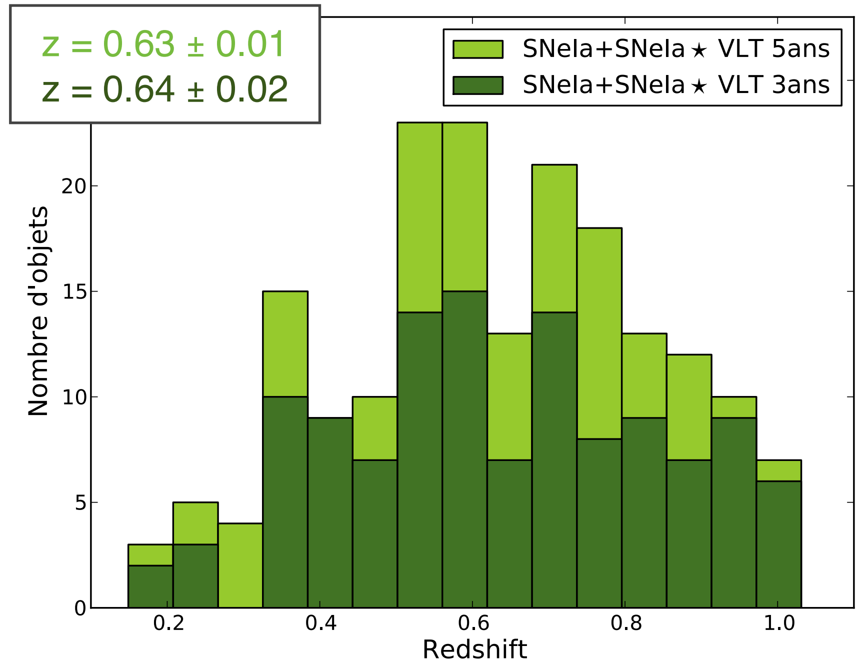


➔ mean spectra are remarkably similar

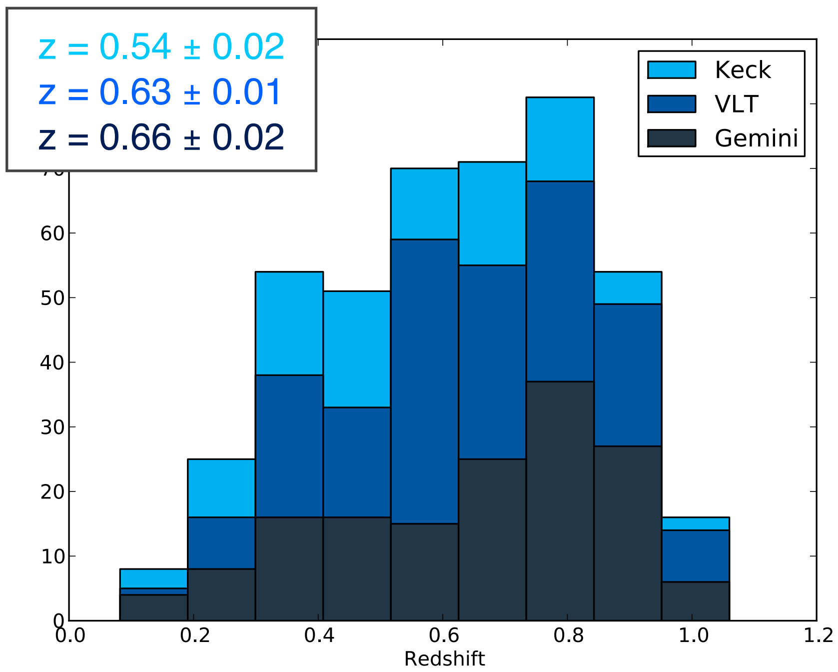
➔ SNe Ia of the 2 independent samples are consistent on average

Final spectroscopic sample of SNLS

- **VLT 5 yrs sample =** VLT1 (120 SNe Ia) + VLT2 (66 SNe Ia)
  - ➔ **186 type Ia supernovae (203 spectra)**
  - ➔ Homogenous sample without apparent calibration bias
    - ↳ Ready to be used in spectral analysis of SNe Ia
    - ↳ characteristics in Cellier-Holzem et al (2013)



- **SNLS 5 yrs spectroscopic sample =** VLT 5yrs (45%) + Gemini (35%) + Keck (20%)
  - ➔ **427 type Ia supernovae** (76% SNe Ia + 24% SNe Ia*)
  - ➔ **Unique spectroscopic survey with ~1500h of observation on 8-10m telescopes**
  - ➔ Presented in the 25th Rencontre de Blois
    - ↳ Ready for cosmological analysis (SNLS 5yrs)



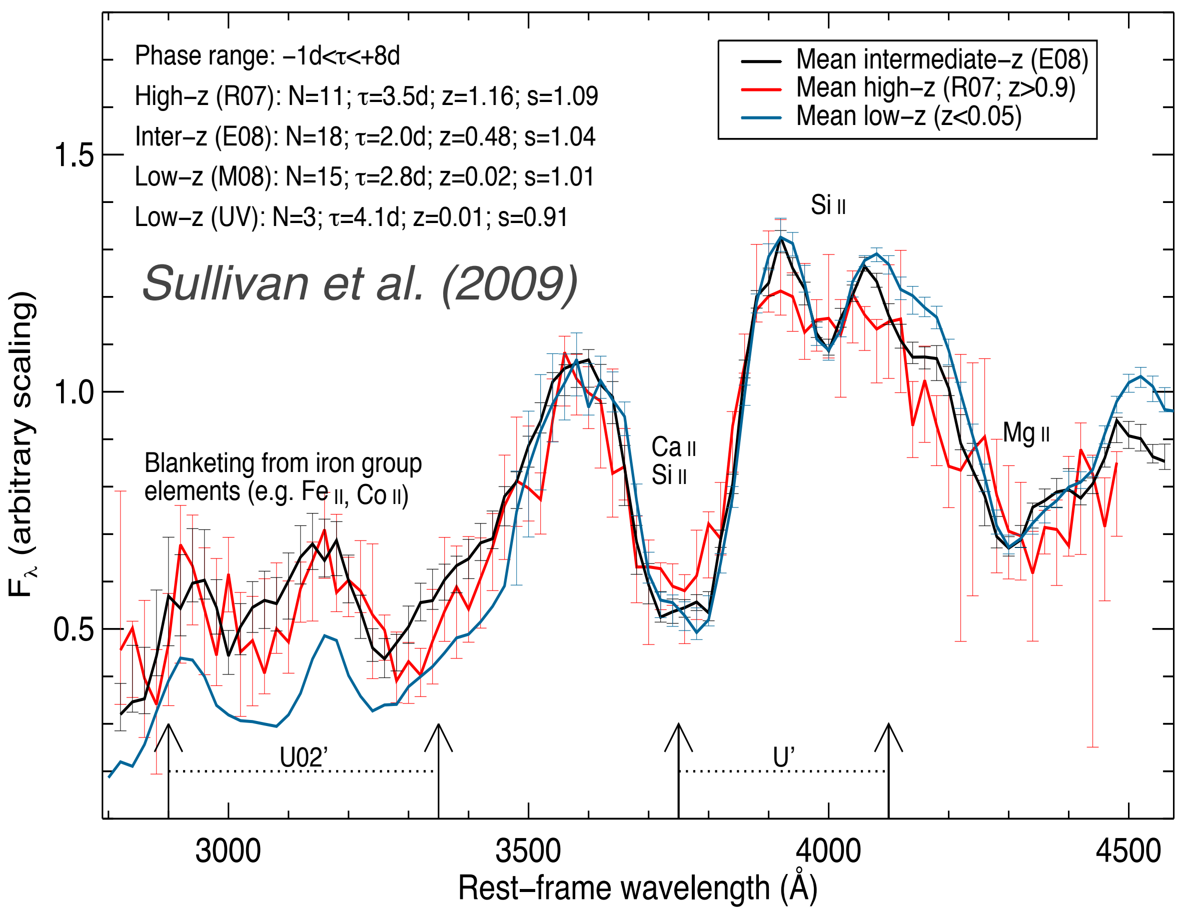
Outline

- Type Ia supernovae and cosmology
- SNLS and SNF experiments
- SNLS 5yrs : the final VLT spectroscopic sample
- Fundamental study for cosmology with SNe Ia : is there evolution of SNe Ia ?
- Understanding SNe Ia physical properties : comparison of model predictions with observed spectra
- Conclusions

Is there evolution ?

- **Key question for cosmology :** do SNe Ia population properties evolve with z ?
  - evolution ? (intrinsic or demographic)
  - selection biais ?

- **Investigation of the SN Ia evolution :** comparing low and high z SNe Ia
  - Howell et al. (2007) : two populations as a function of the progenitor age
  - Foley et al. (2008) : galaxy fraction increases with z
  - Ellis et al. (2008) : no evolution but dispersion increases in UV
  - Sullivan et al. (2009) : demographic evolution of the SN Ia population
  - Balland et al. (2009) : selection biais
  - Cooke et al. (2011) : sample variation
  - Maguire et al. (2012) : decrease in metallicity with increasing z in agreement with galaxy evolution
  - Foley et al (2012) : host differences
  - Cellier-Holzem et al (2013)



Building mean spectra with VLT 5yrs sample

- **Method using VLT spectra from SNLS 5yrs spectroscopic sample :**

→ **SN Ia samples :**
- Only SNe Ia
- Phase cut : -4 < phase < 4 days
- Color cut : -0.2 < c < 0.2

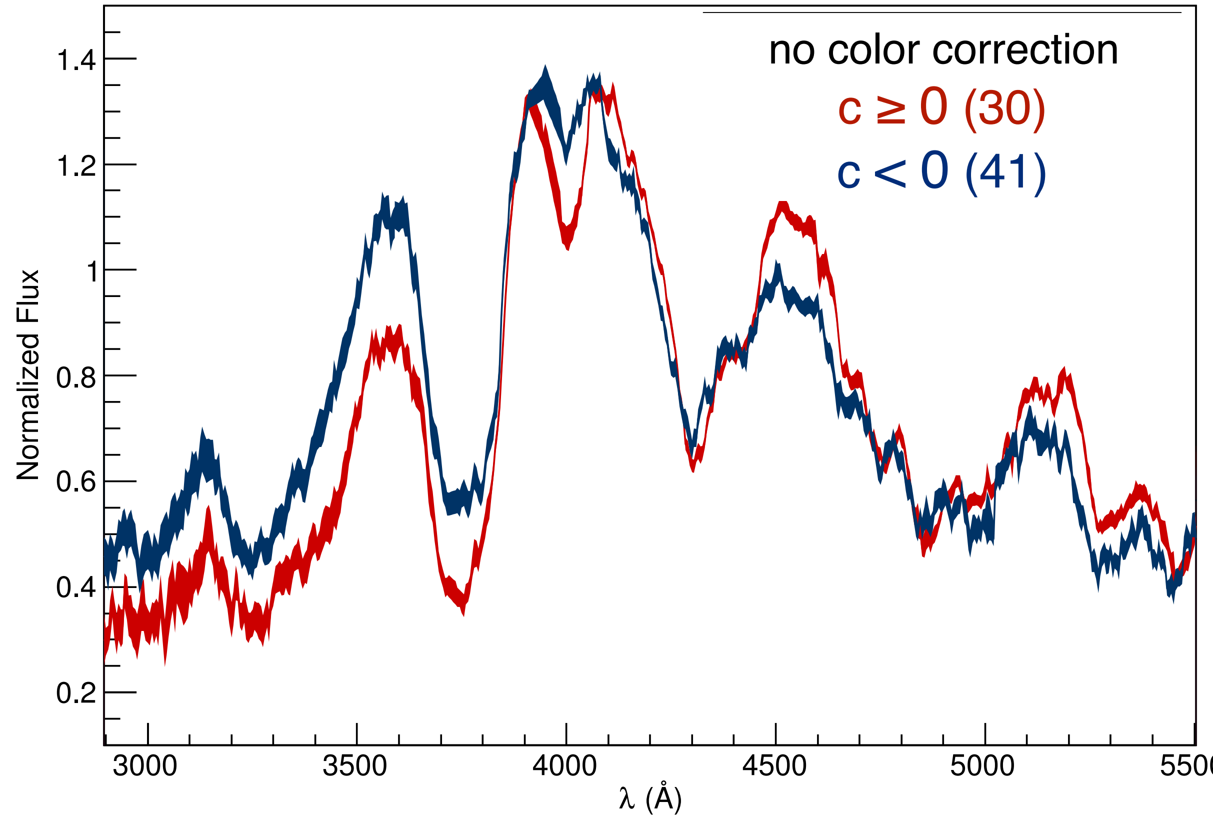
→ **Building SN Ia mean spectra :**
- Recalibration
- Color correction using the SALT2 color law (Guy et al. 2010)

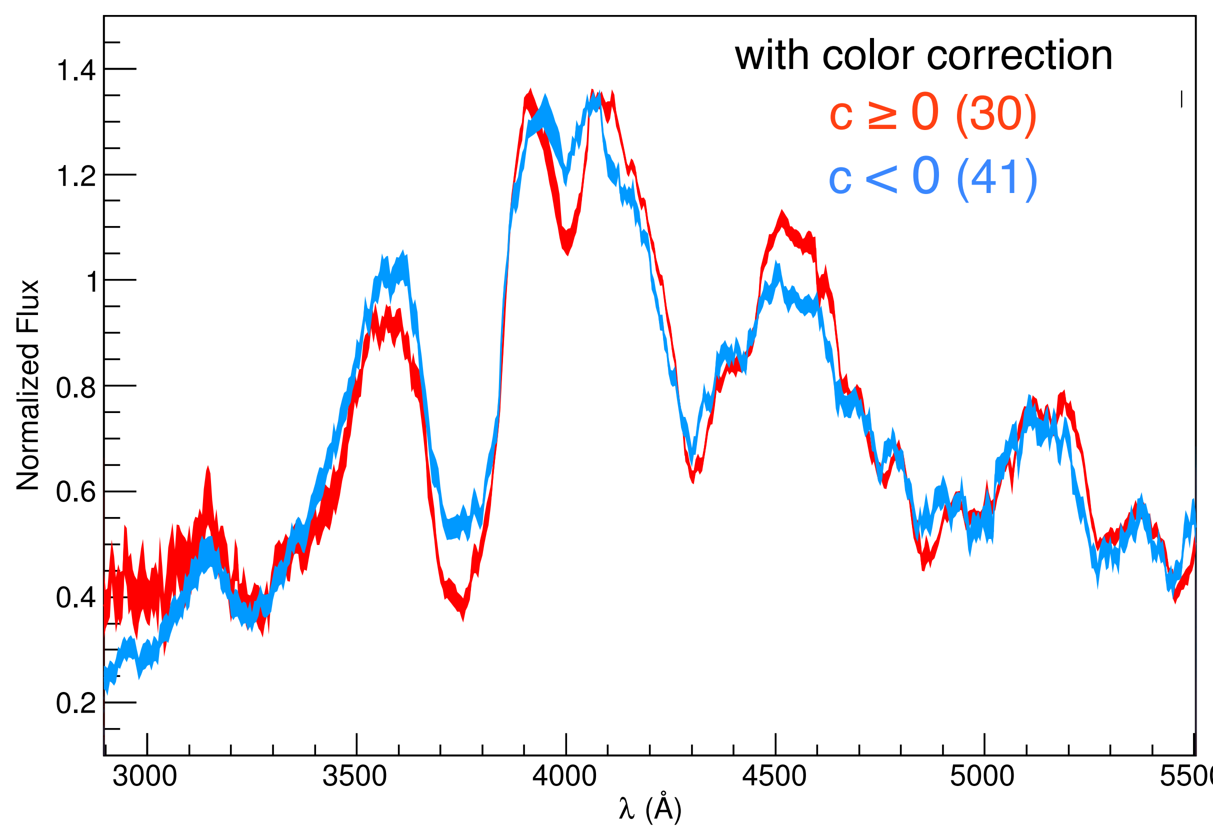
↳ **Test the color correction effect**

Color effect on VLT mean spectra

- **Cut in color :**

	$c<0$	$c\geq 0$
Nb spec	41	30
$\langle z \rangle$	0.65 ± 0.02	0.59 ± 0.03
$\langle \Phi \rangle$	0.3 ± 0.4	0.3 ± 0.4
$\langle c \rangle$	-0.097 ± 0.008	0.058 ± 0.007
$\langle s \rangle$	1.014 ± 0.010	1.012 ± 0.012
$\langle m_B^{*c} \rangle$	23.791 ± 0.025	24.108 ± 0.044





➔ Color correction : $F_c(\lambda) = F(\lambda) \times \exp[c\, CL(\lambda)]$

(Guy et al. 2010)

↳ smooth correction of reddening by dust : no influence on absorption depths

➔ Bluer and brighter SNe Ia have lower IME absorptions (Ca II and Si II)

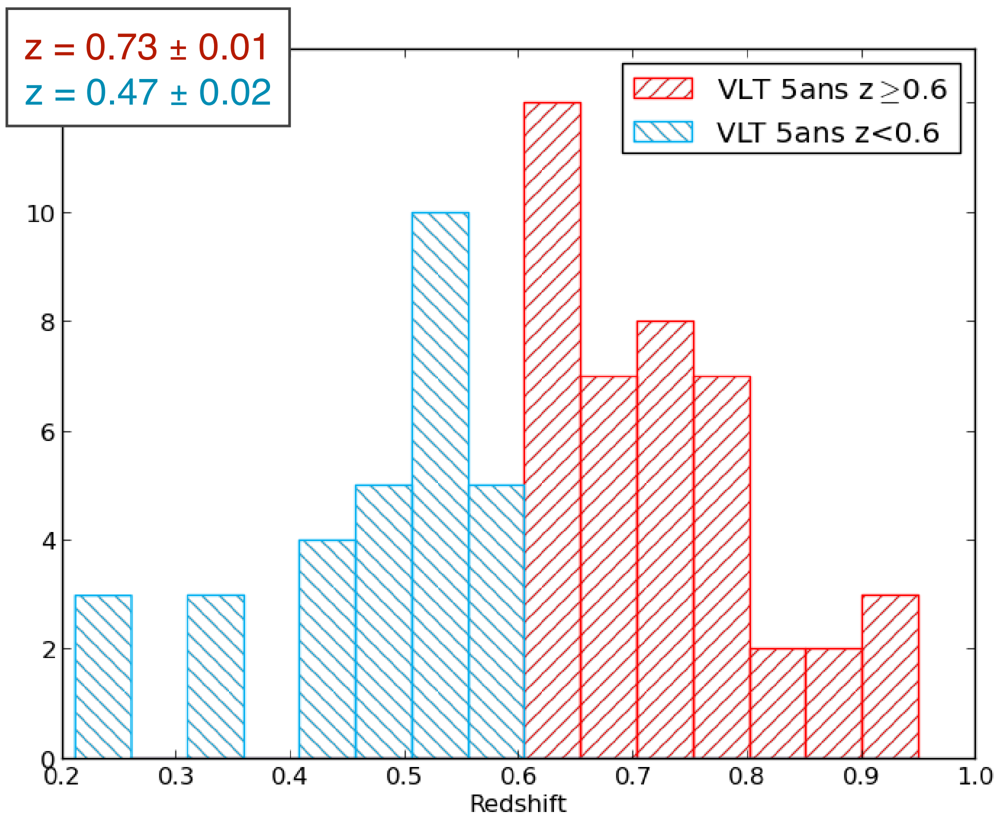
↳ bluer and brigther SNe Ia ionise more IMEs

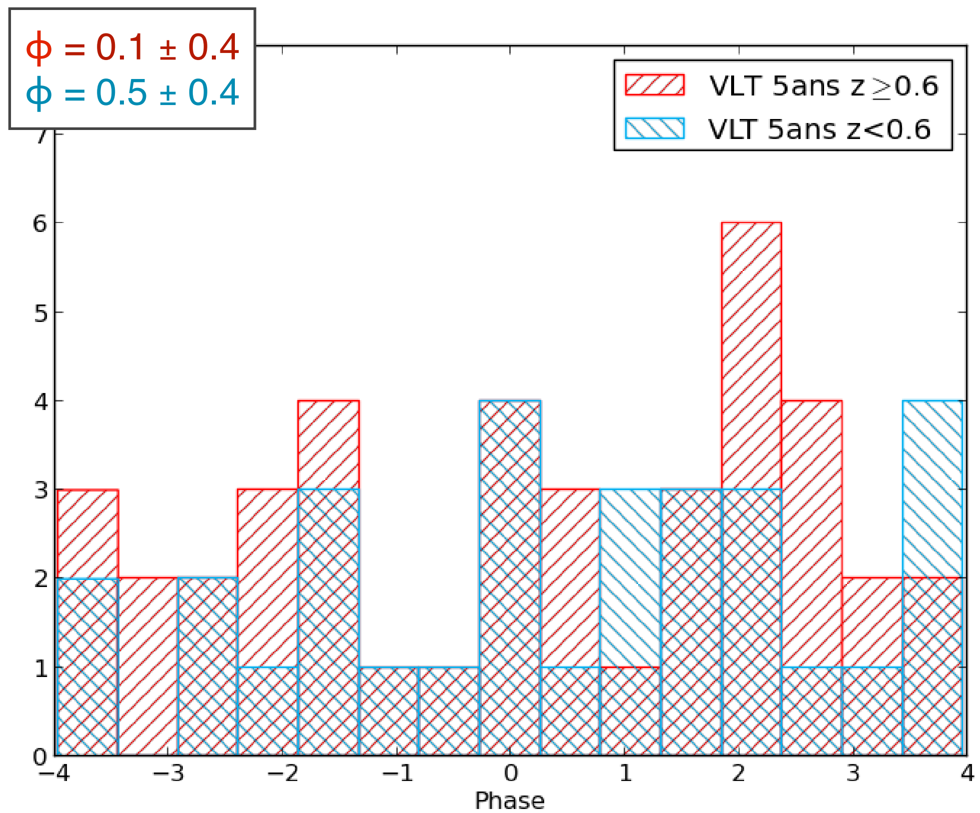
Dividing the VLT 5yrs sample in 2 z bins

- **New analysis using VLT spectra from SNLS 5yrs spectroscopic sample :**

➔ **SN Ia samples :**
- Phase cut : -4 < phase < 4 days
- Color cut : -0.2 < c < 0.2
- 2 redshift bins : z < 0.6 and z ≥ 0.6

intermediate z : 30 spectra
high z : 41 spectra





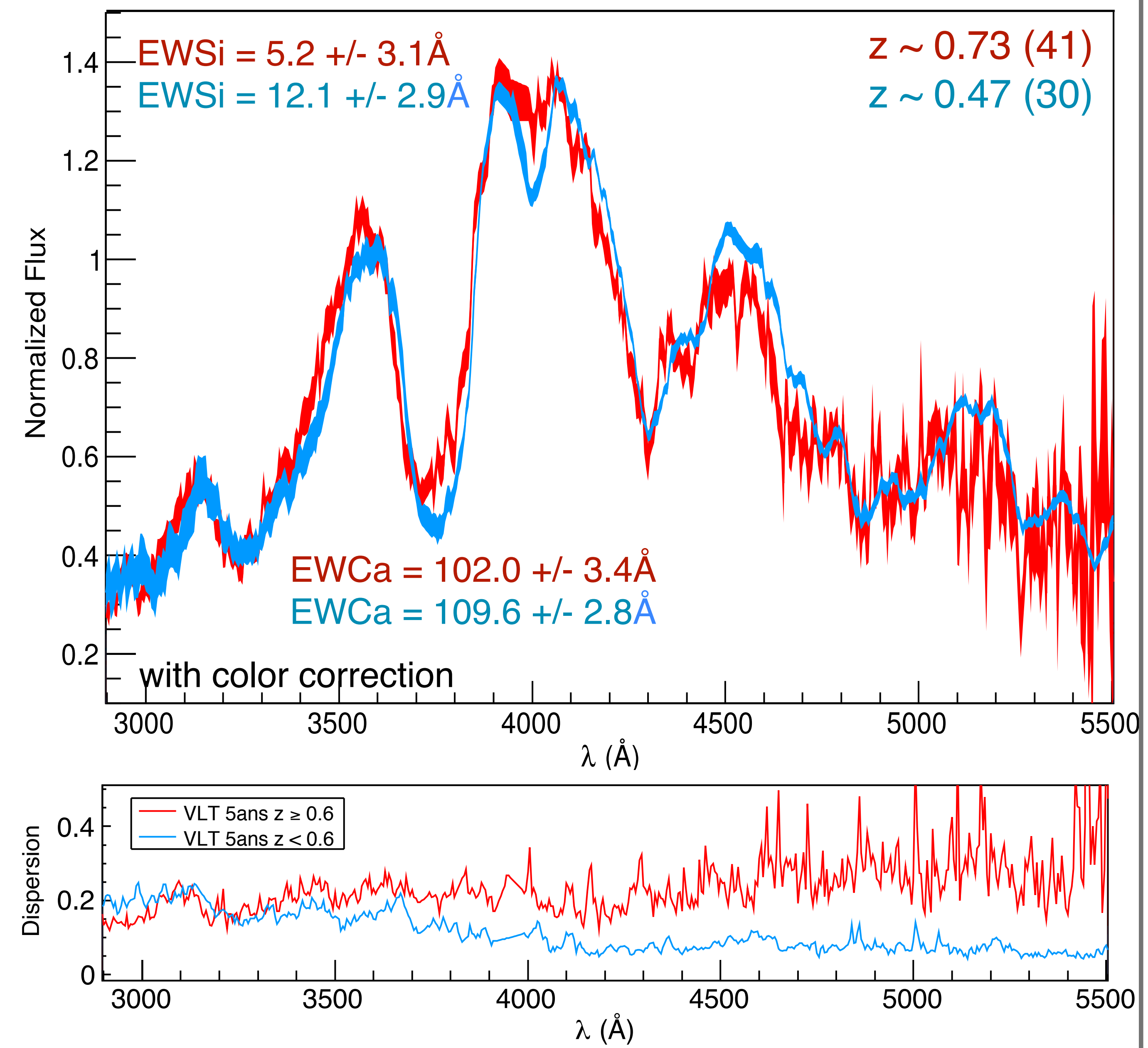
High vs intermediate z mean VLT spectra

- **Spectral differences :**

→ Intermediate z spectra : deeper absorptions of intermediate mass elements (Ca II, Si II)

↳ Consistent with previous studies

	VLT 5yrs	
	$z < 0.6$	$z \geq 0.6$
Nb spec	30	41
$\langle z \rangle$	0.47 ± 0.02	0.73 ± 0.01
$\langle \Phi \rangle$	0.5 ± 0.4	0.1 ± 0.4
$\langle c \rangle$	0.001 ± 0.015	-0.055 ± 0.014
$\langle s \rangle$	1.018 ± 0.010	1.010 ± 0.011
$\langle m_B^{*\,c} \rangle$	24.022 ± 0.048	23.853 ± 0.035



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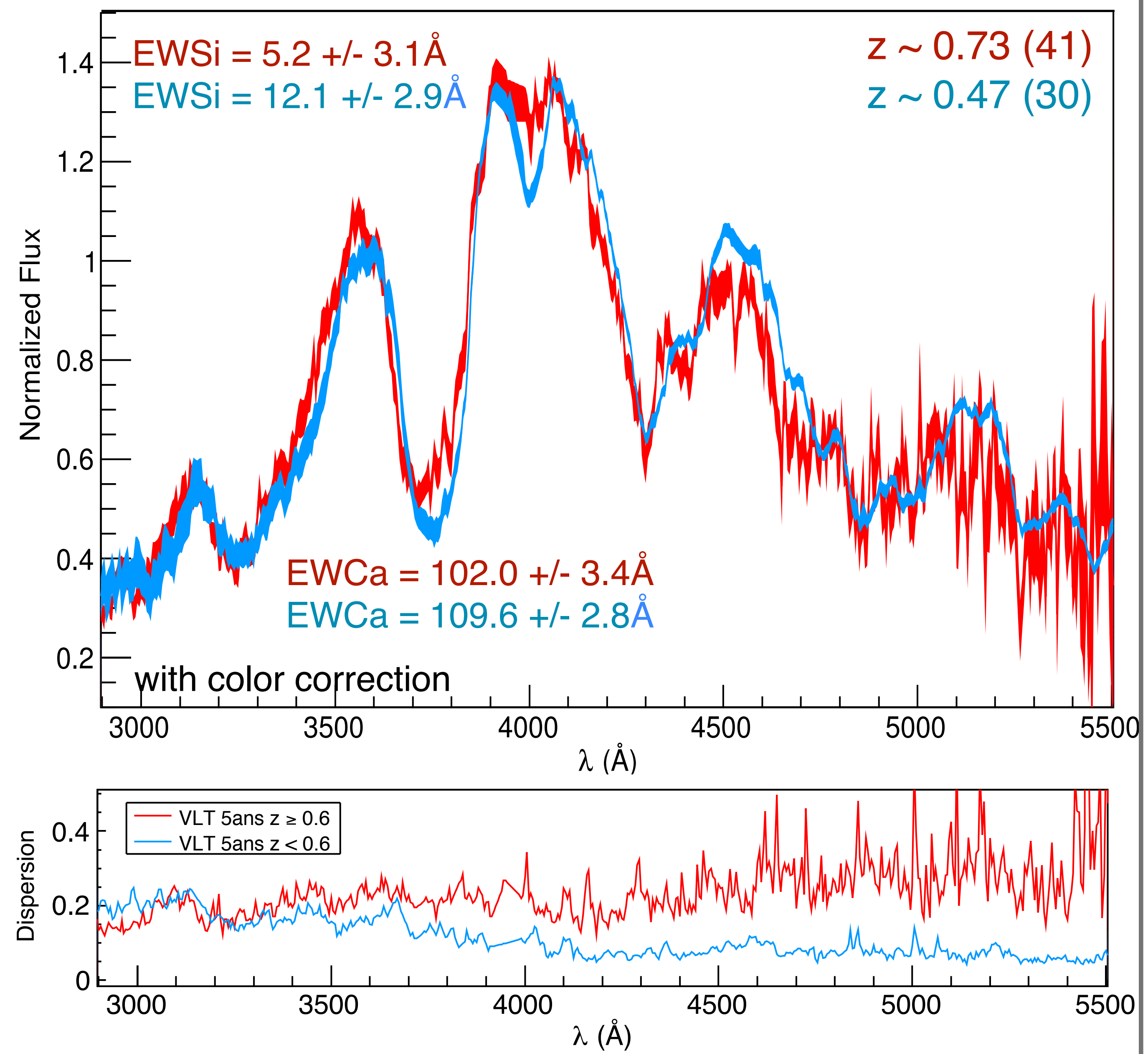
➔ high z SNe Ia : bluer and brighter



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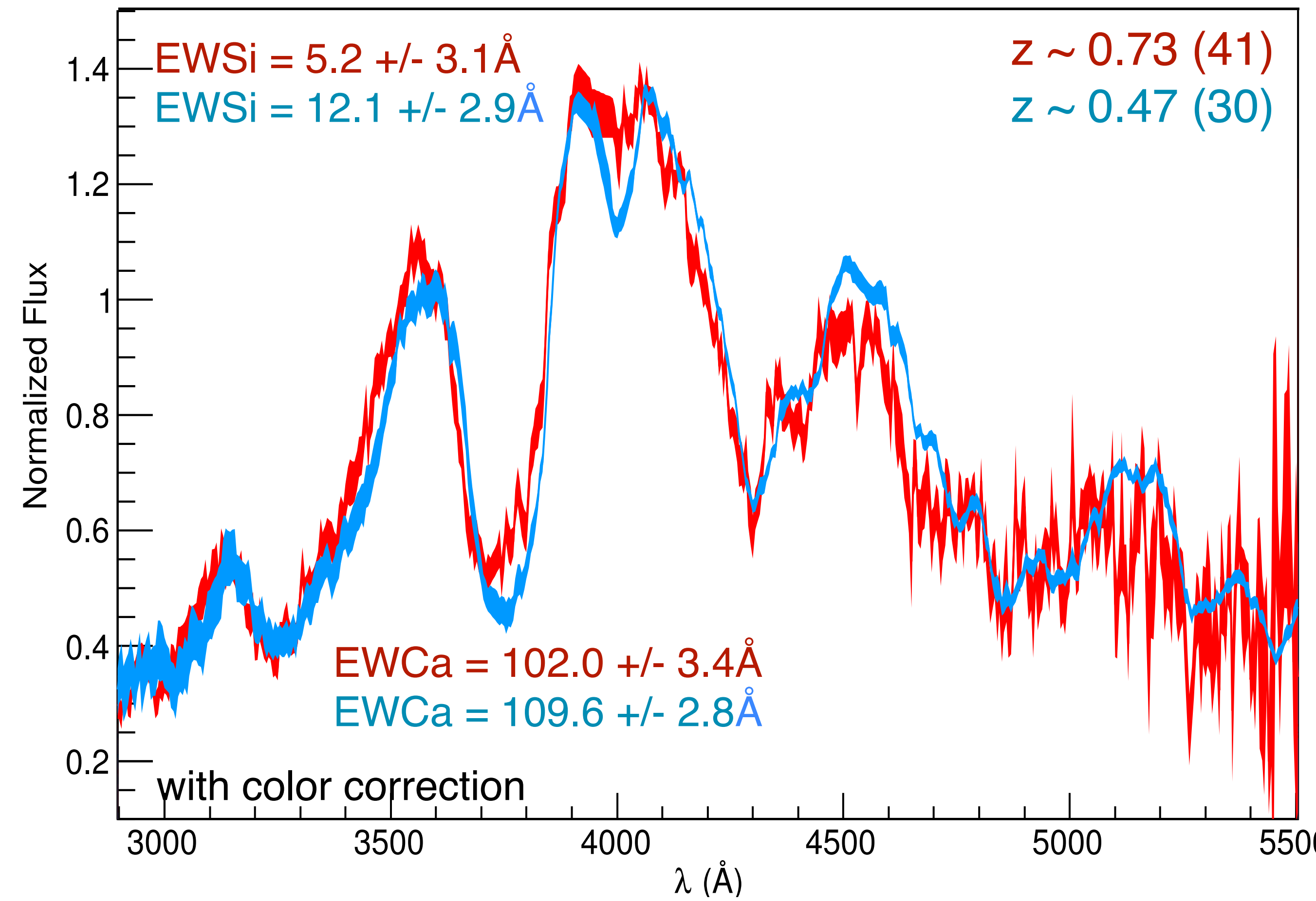
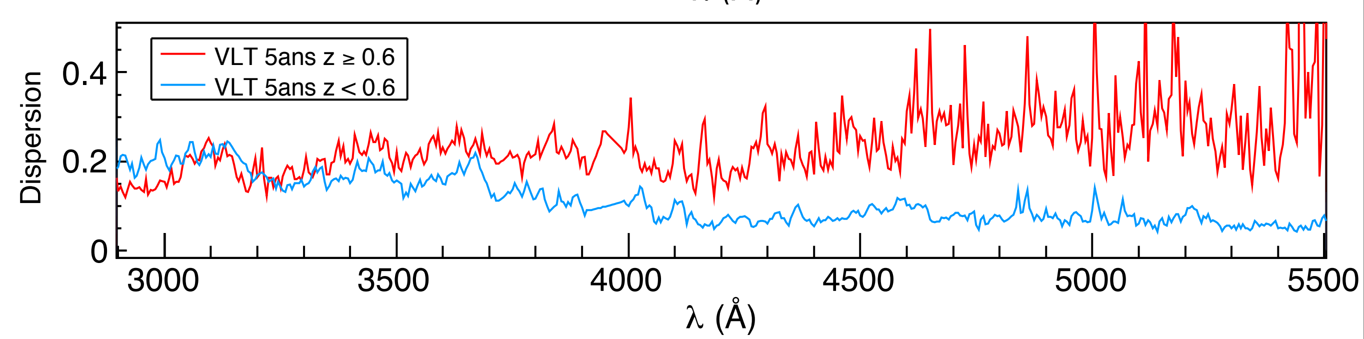




$$\Delta(m_B^{*c}) = 0.169 \pm 0.059 \simeq |\alpha\Delta(s) - \beta\Delta(c)| = 0.168 \pm 0.070$$

with $\{\alpha;\beta\} = \{1.295 \pm 0.112; 3.181 \pm 0.131\}$ (Guy et al. 2011)

➔ Photometric differences consistent with a brigther-bluer and brighter-slower correlation

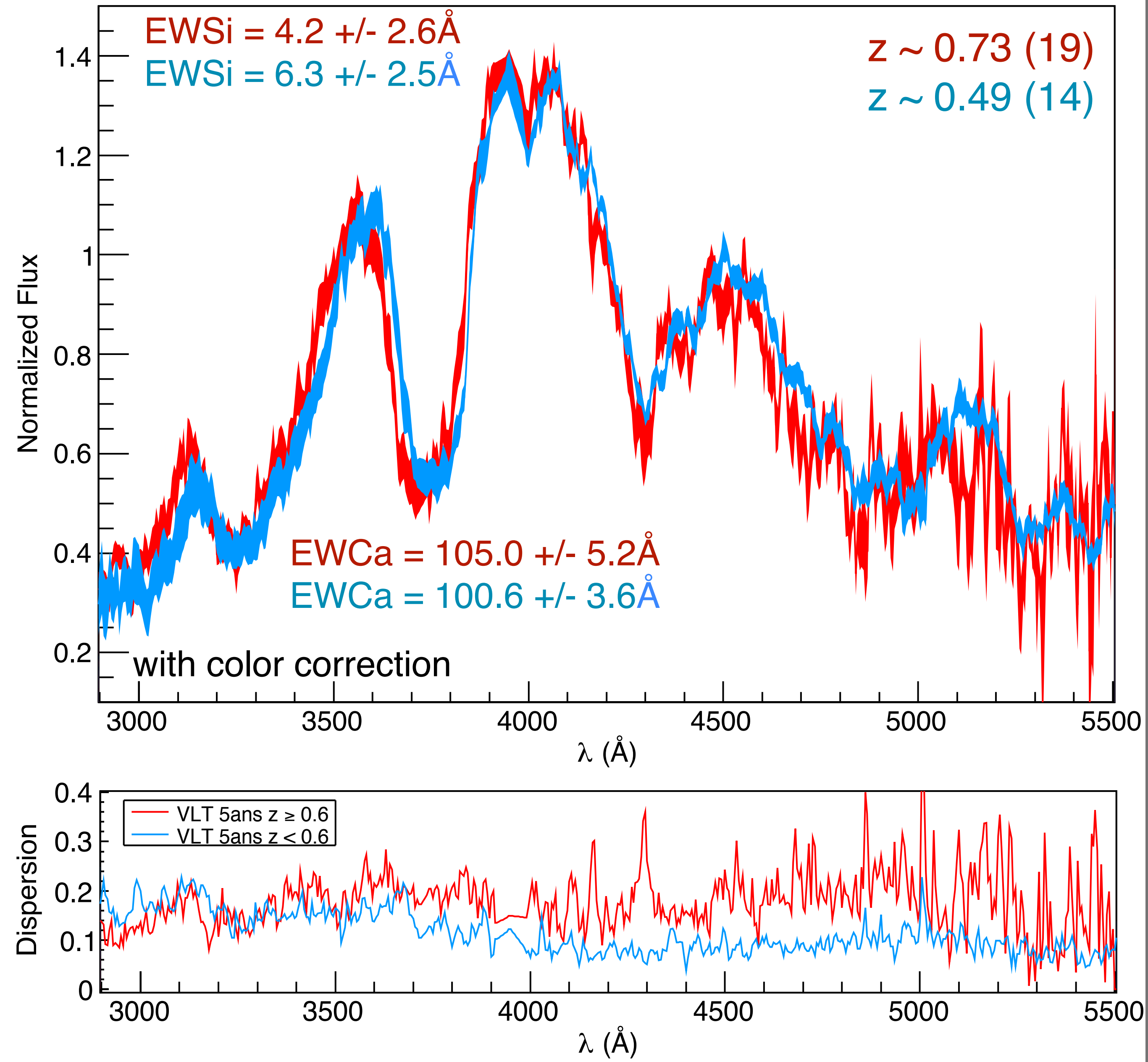
➔ **consistent with a selection effect**

SNe Ia with similar photometric properties

- **Comparing comparable SNe Ia :** select 2 sub-samples with same distributions of photometric properties

	$z < 0.6$	$z \geq 0.6$
Nb spec	14	19
$\langle z \rangle$	0.49 ± 0.03	0.73 ± 0.02
$\langle \Phi \rangle$	0.2 ± 0.7	0.1 ± 0.5
$\langle c \rangle$	-0.073 ± 0.011	-0.087 ± 0.010
$\langle s \rangle$	1.017 ± 0.013	1.015 ± 0.018
$\langle m_B^{*c} \rangle$	23.824 ± 0.042	23.792 ± 0.030

↳ Spectral differences are significantly reduced



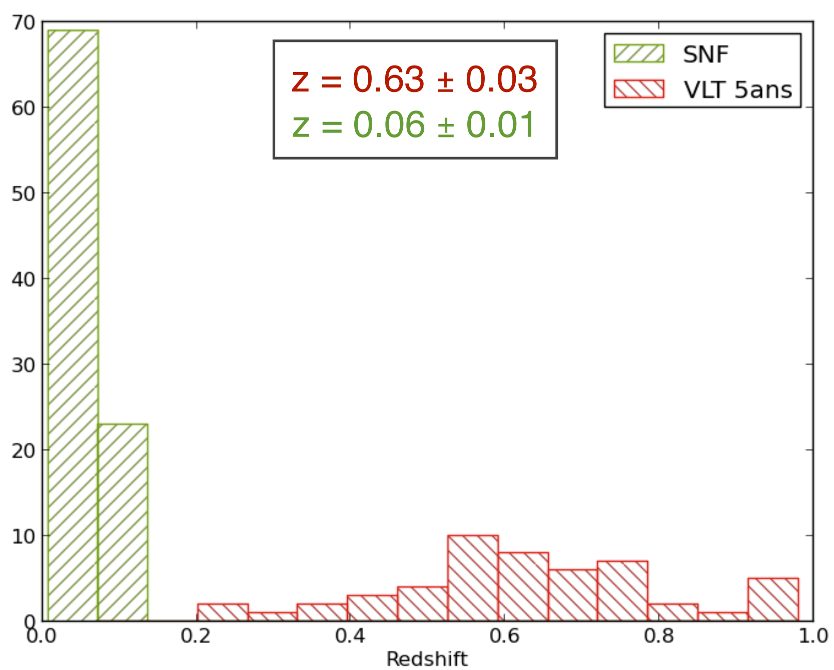
spectral differences in redshift are consistent with a selection effect
no evidence of evolution

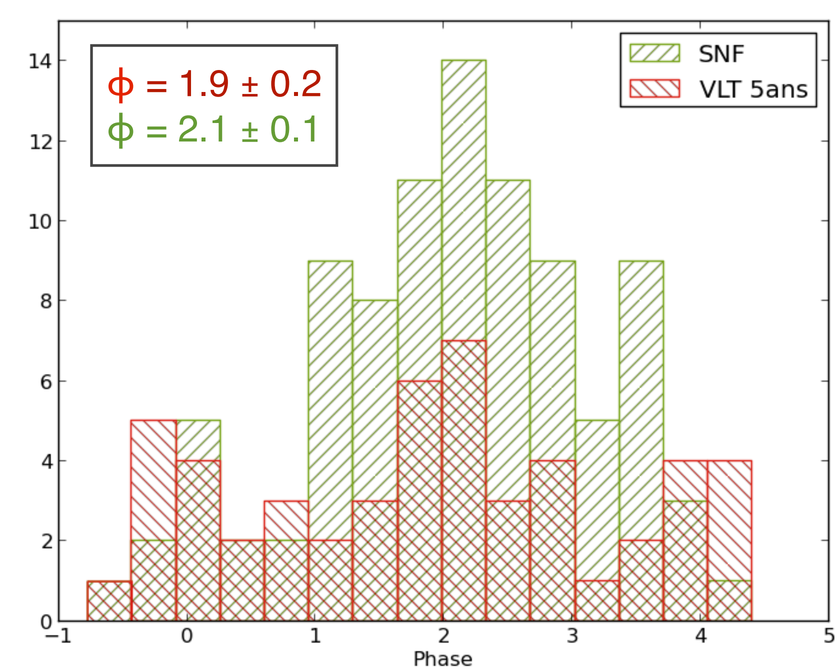
Comparison with low z SNF spectra

- **New analysis using VLT spectra as high z sample and SNF spectra as low z sample :**

→ **SN Ia samples :**
- Phase cut : -4.5 < phase < 1 days
- Color cut : -0.2 < c < 0.2
- 2 redshift bins : z_{SNF} and z_{SNLS}

low z : 92 spectra
high z : 51 spectra





→ **SN Ia mean spectra** are color corrected using the SALT2 color law (Guy et al. 2010)

SNF vs VLT mean spectra

- **Spectral differences :**

  → Similar spectra in the red part

  → Low z spectra : flux excess in UV

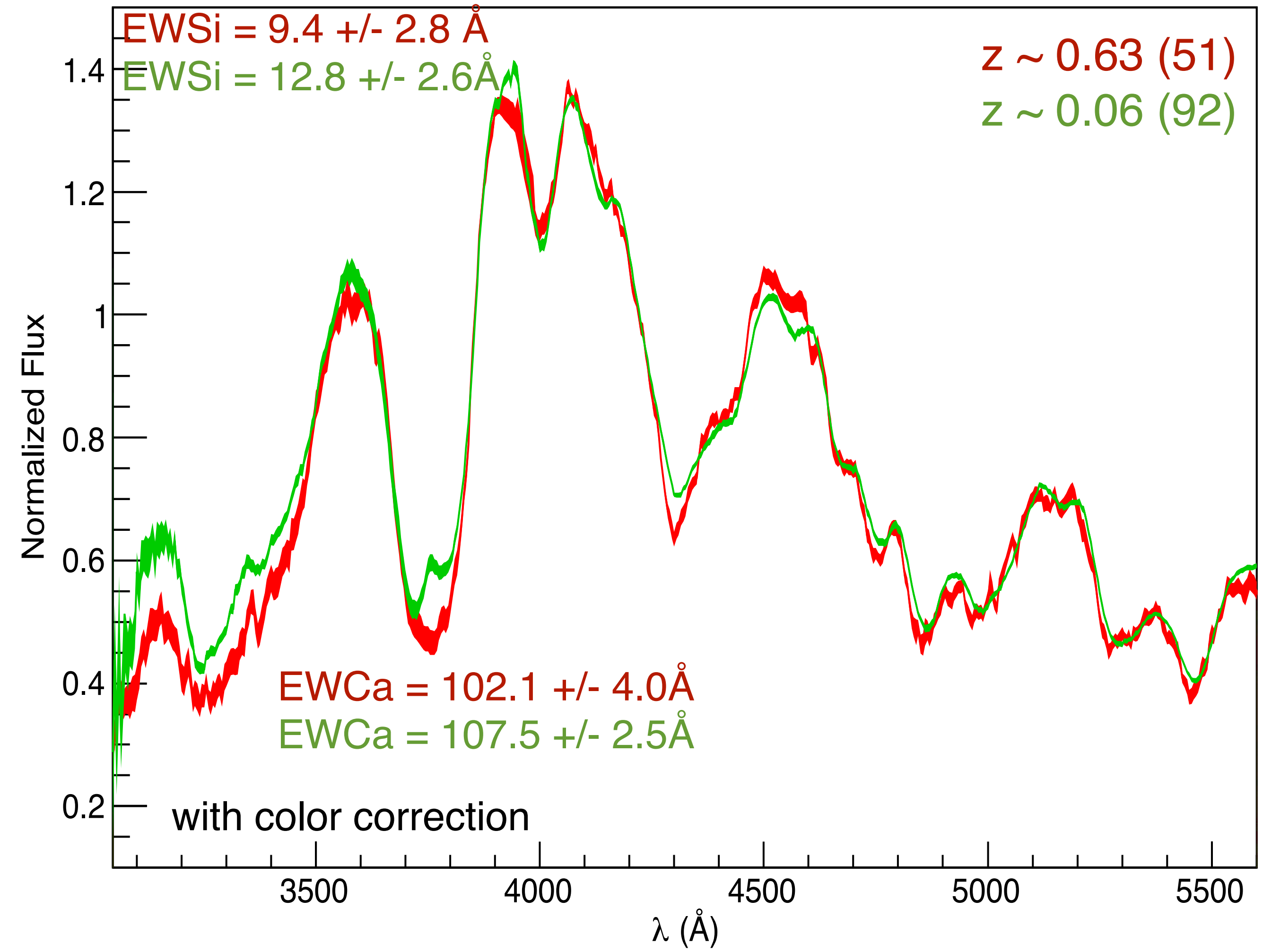
  ↳ Contradiction with previous studies

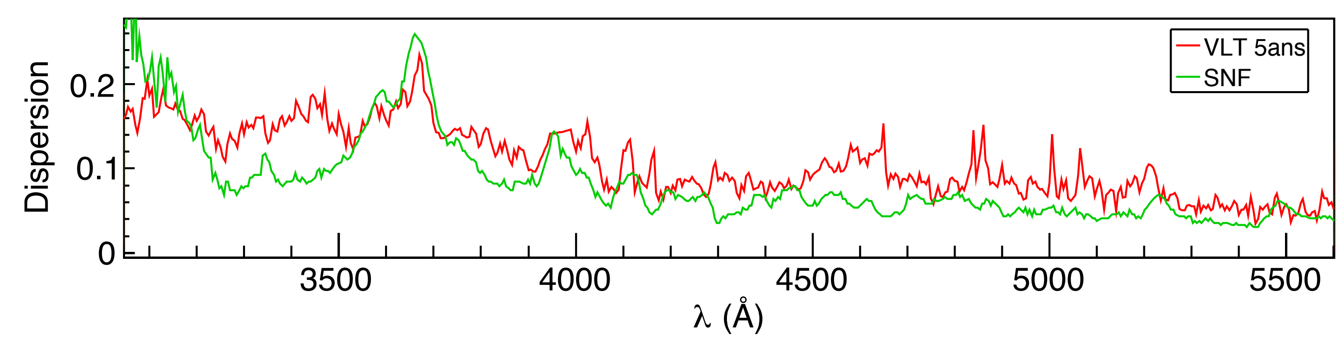
  → Low z spectra : higher absorptions for Ca II (3700Å) and Si II (4000Å) features

	SNF	VLT
Nb spec	92	51
$\langle z \rangle$	0.06 ± 0.01	0.63 ± 0.03
$\langle \Phi \rangle$	2.1 ± 0.1	1.9 ± 0.2
$\langle c \rangle$	0.040 ± 0.006	-0.040 ± 0.013
$\langle s \rangle$	0.964 ± 0.009	1.020 ± 0.010
$\langle m_B^{*c} \rangle$	23.914 ± 0.023	23.887 ± 0.031

  → High z SNe Ia : bluer, brighter with higher stretch

  ↳ Consistent with VLT study

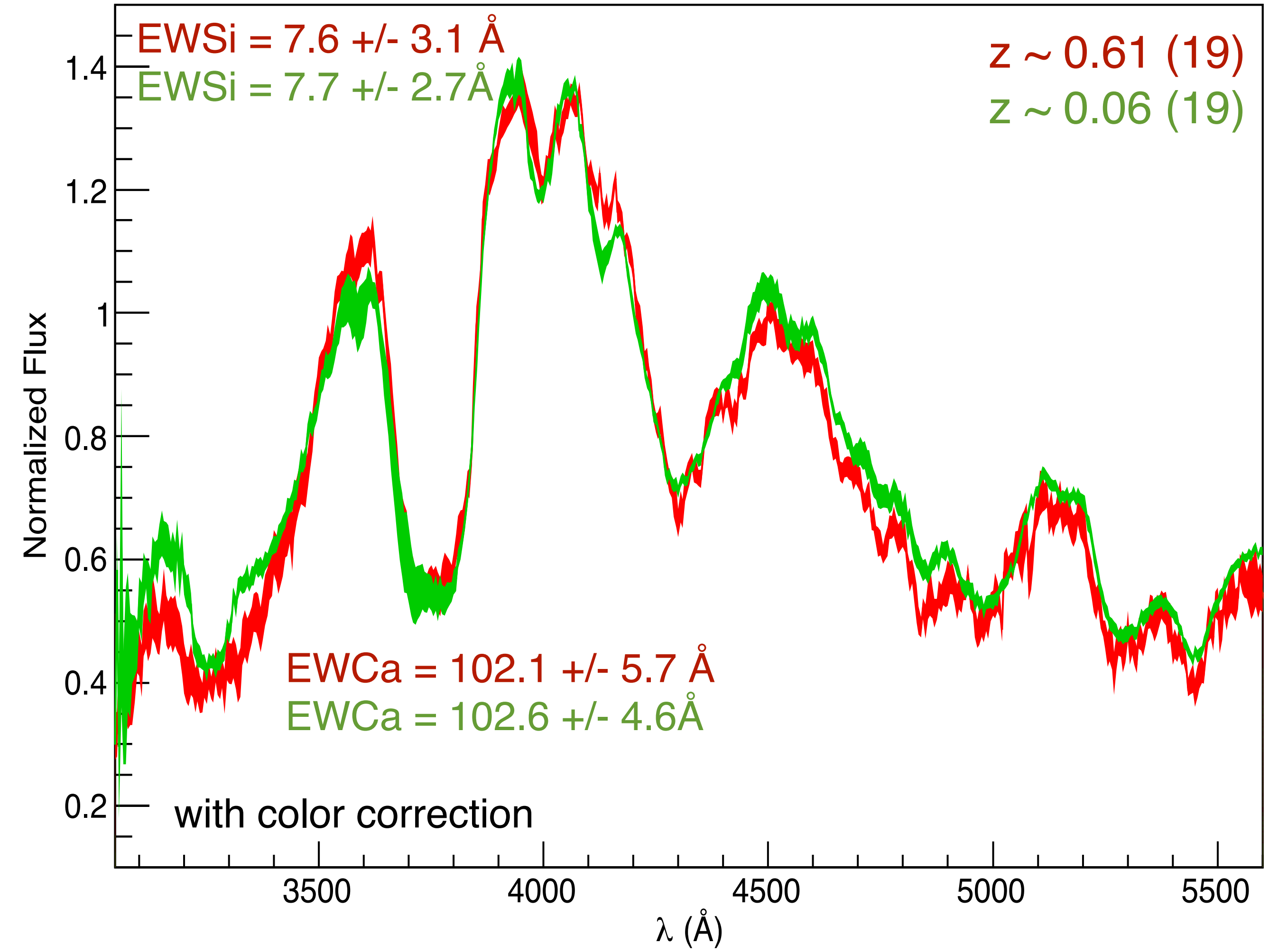


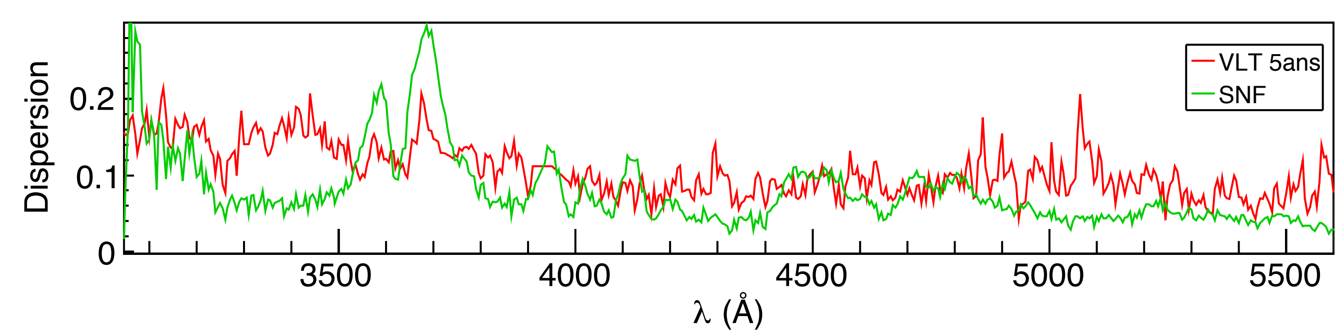


SNe Ia with similar photometric properties

- **Comparing comparable SNe Ia :** select 2 sub-samples with ~ same distributions of photometric properties

	SNF	VLT 5 ans
Nb spec	19	19
$\langle z \rangle$	0.06 ± 0.01	0.61 ± 0.04
$\langle \Phi \rangle$	2.4 ± 0.3	2.3 ± 0.3
$\langle c \rangle$	-0.008 ± 0.007	-0.014 ± 0.011
$\langle s \rangle$	1.010 ± 0.013	1.007 ± 0.012
$\langle m_B^{*c} \rangle$	23.781 ± 0.027	23.834 ± 0.038





↳ Differences are significantly reduced

↳ No contradiction with a selection effect

↳ Spectral differences remain in UV
- → calibration problem ? (difficult calibration for λ < 3500Å)
- → photometric bias ?
- → intrinsic differences ?

Conclusion on SNe Ia evolution

- **VLT spectra : intermediate vs high redshifts**

spectral differences with redshift consistent with a selection effect

- **SNF and VLT spectra : low vs high redshifts**

same conclusion to explain spectral differences with redshift

are consistent with a selection effect

no need to invoke SN Ia evolution

Outline

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Better knowledge of SN Ia properties

- **Aim :** better knowledge of SNe Ia physical properties

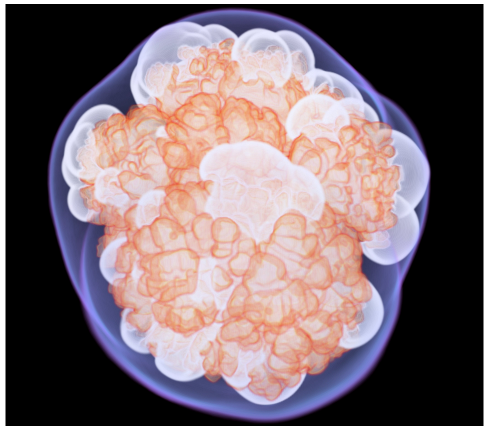
  ↳ What physical ingredients can explain the observed SN Ia spectra and light curves ?

  ↳ What is the origin of the SNe Ia variability ?

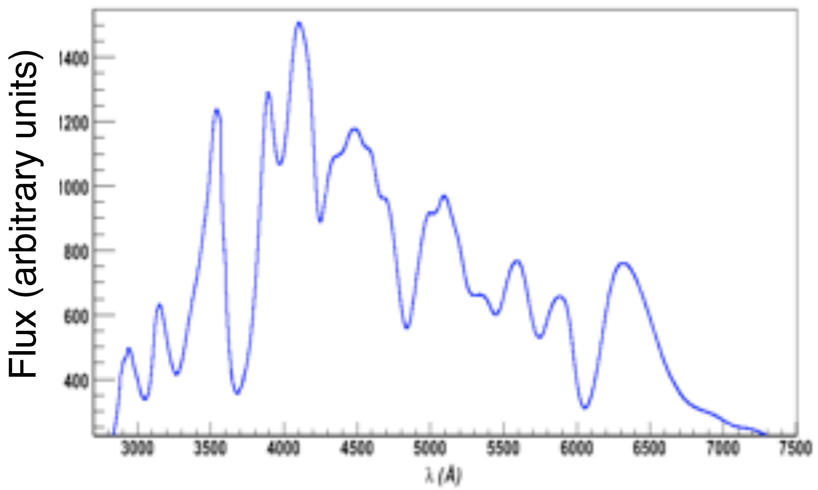
- **How ?** search for spectroscopic indicators that describe SN Ia variability

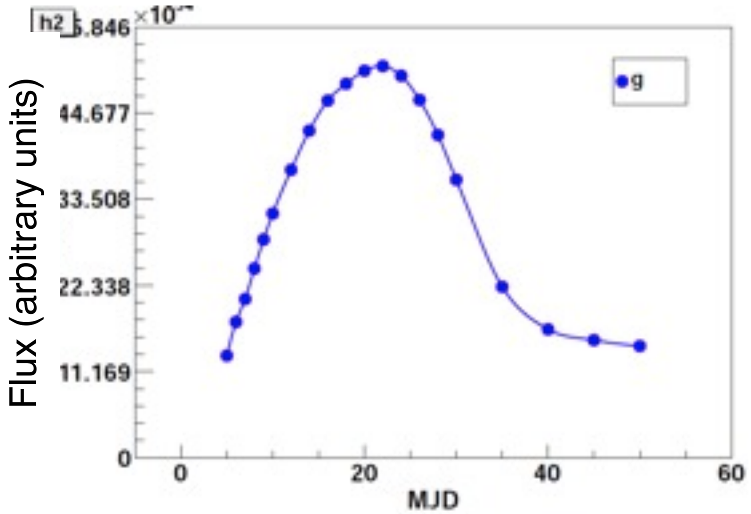
  ↳ comparison between SNF observations and predictions of several models which produce synthetic spectra and light-curves

  - test if data can discriminate different models
  - determine the discriminant spectral zones



→





Two orthogonal SNe Ia formation models

(provided by D. Jack and P. Hauschildt)
(D. Jack thesis 2010)

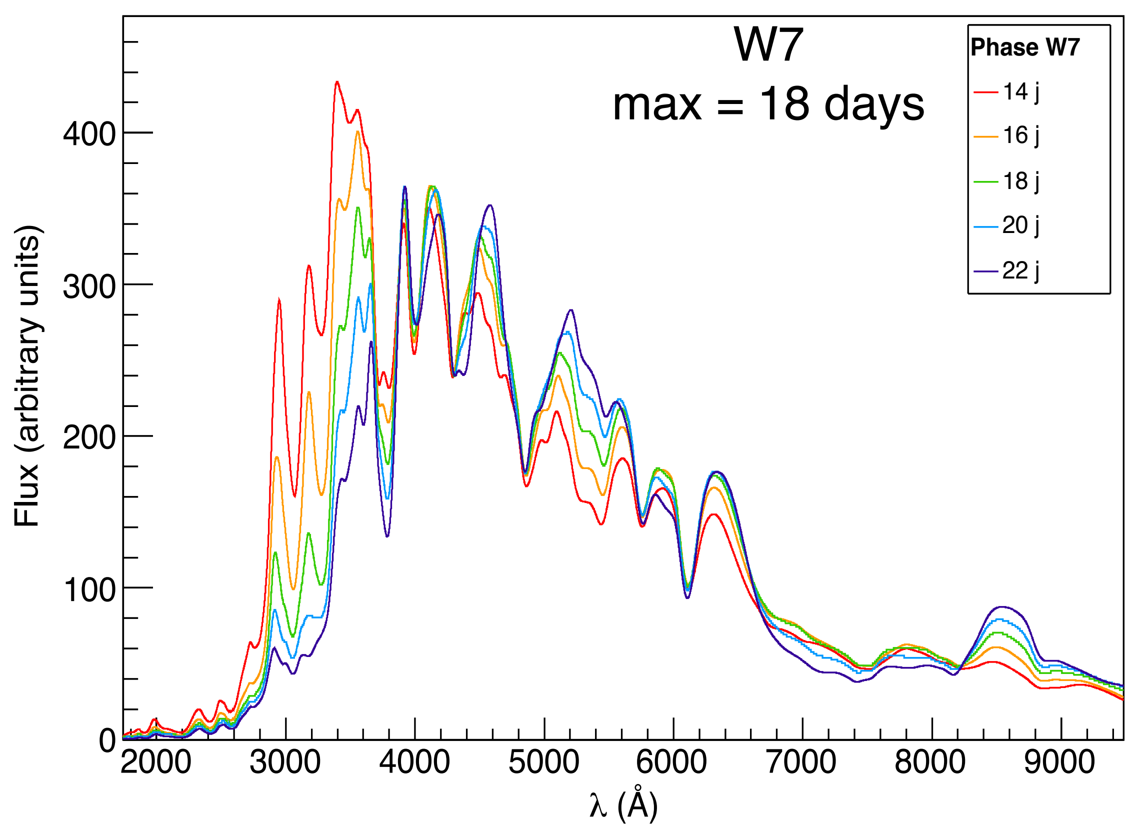
explosion model based on a single degenerate scenario

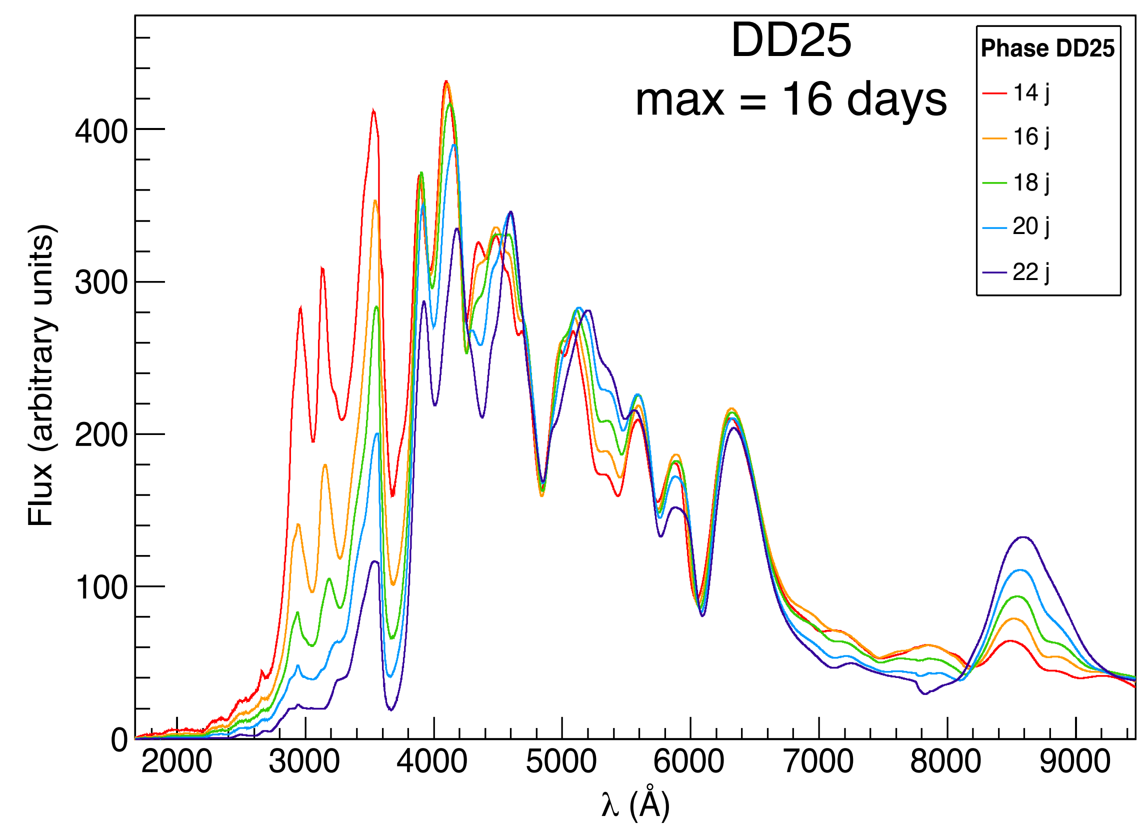
≠ burning front velocity

W7
deflagration model
(Nomoto et al 1984)

DD25
delayed detonation model
(Kokhlov 1991; Hoefflich et al 1984)

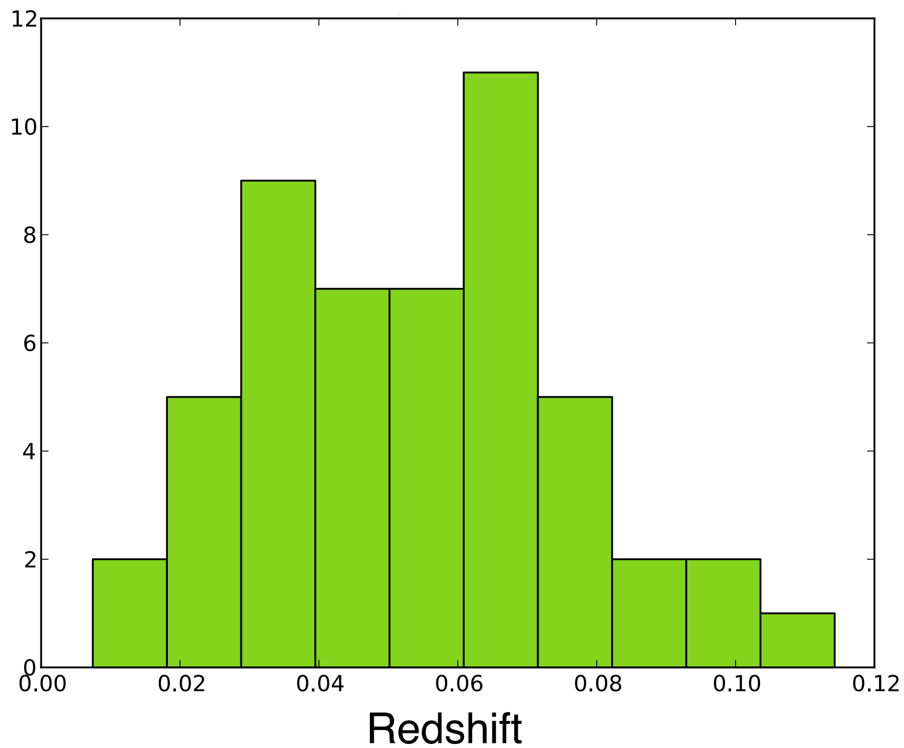
+ radiative transfer code
PHOENIX
(Hauschildt & Baron 1999)

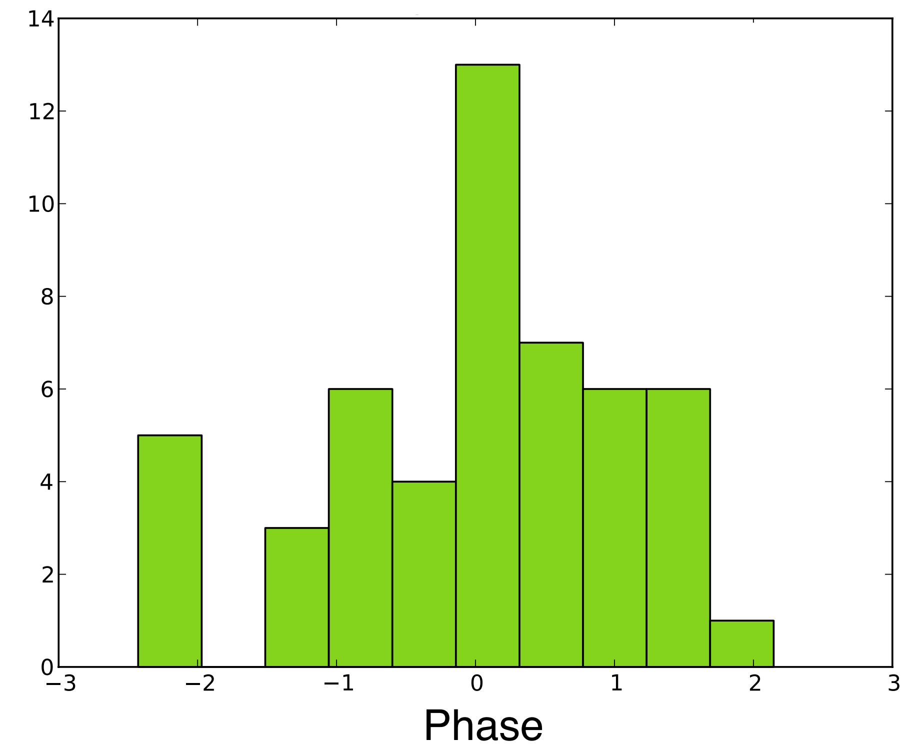




SNF spectra vs models

- **Sample selection :** 62 spectra (1 spectrum per SN Ia) close to the maximum (-2.5 < phase < 2.5 days) from SNF «training» sample





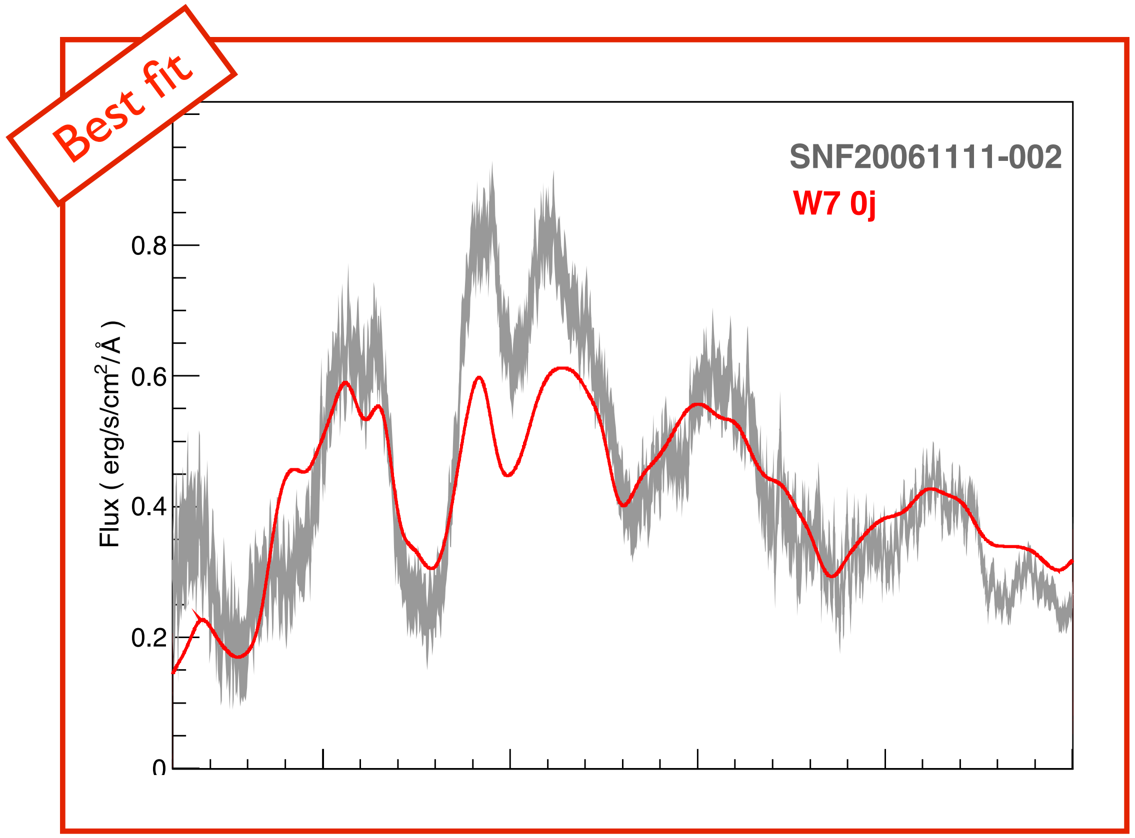
- **Models vs Data :** for each observed spectrum, fit models in amplitude on observed spectra by a χ^2 minimisation procedure (phase = free parameter)

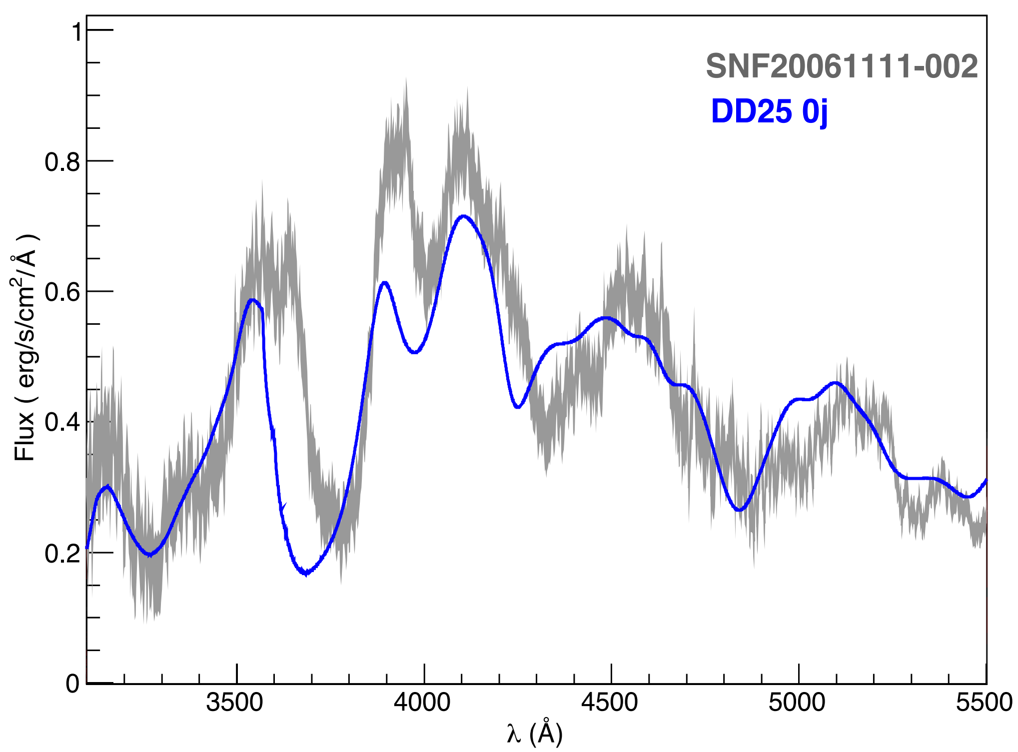
$$\chi^2_\nu = \frac{1}{ndl}\sum_i \left(\frac{F_{obs}(\lambda_i) - A \cdot F_{mod}(\lambda_i)}{\sigma_{obs}(\lambda_i)}\right)^2$$

↳ spectral range : 3100Å < λ < 5500Å

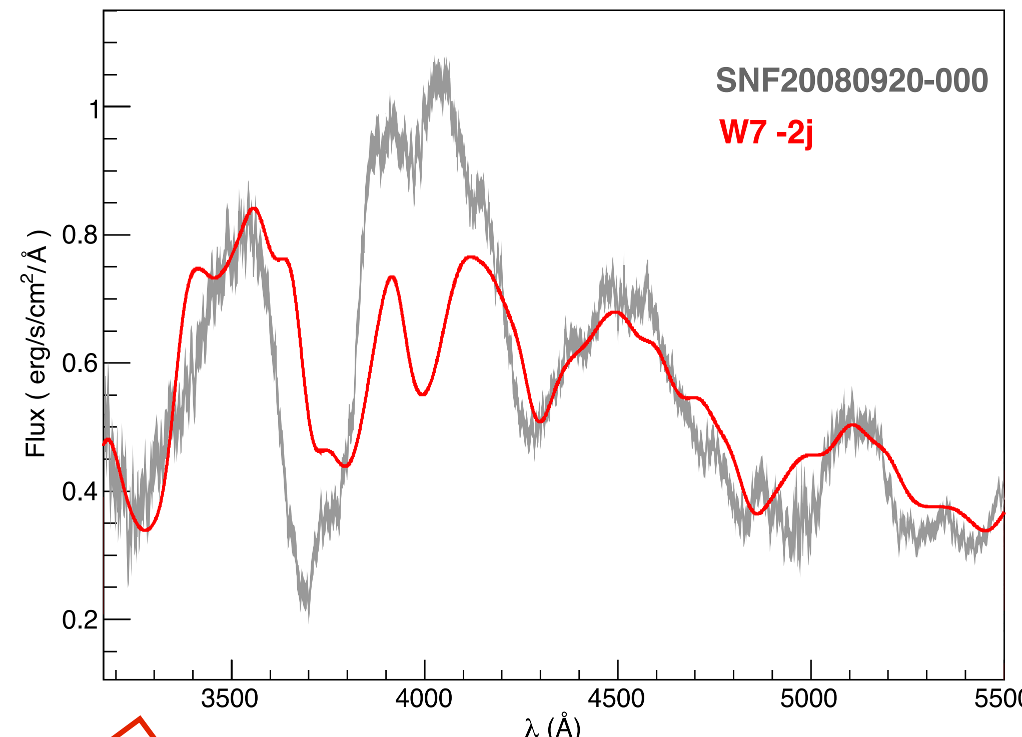
SNF spectra vs models : examples

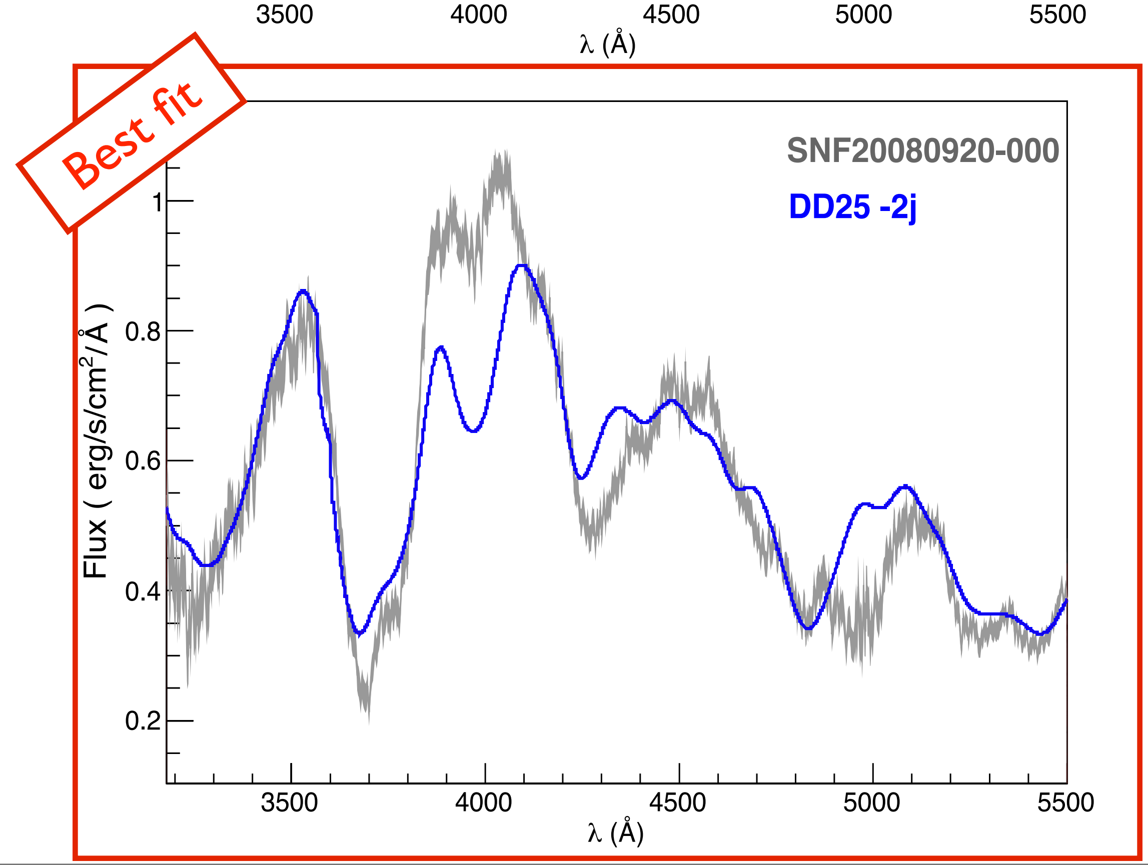
SNF20061111-002 : z = 0.069/ phase = 0.2 jours





SNF20080920-000 : z = 0.040 / phase = -1.2 jours





SNF spectra vs models

- **Model discrimination :**

↳ test the null hypothesis «*models are equivalent to reproduce the data*»

↳ perform a F-test : $F = \frac{\chi^2_{\nu\,max}}{\chi^2_{\nu\,min}}$ follows a *F* probability law *P(F)*

➔ *P(F)* ~ 1 : true hypothesis ➔ models can not be discriminated

➔ *P(F)* << 1 : wrong hypothesis ➔ one model is favoured

↳ for 48 spectra, data can significantly discriminate models

➔ 30 best fitted by W7

➔ 18 best fitted by DD25

Why do the data favor a specific model ?

- **Discriminant spectral zone :**

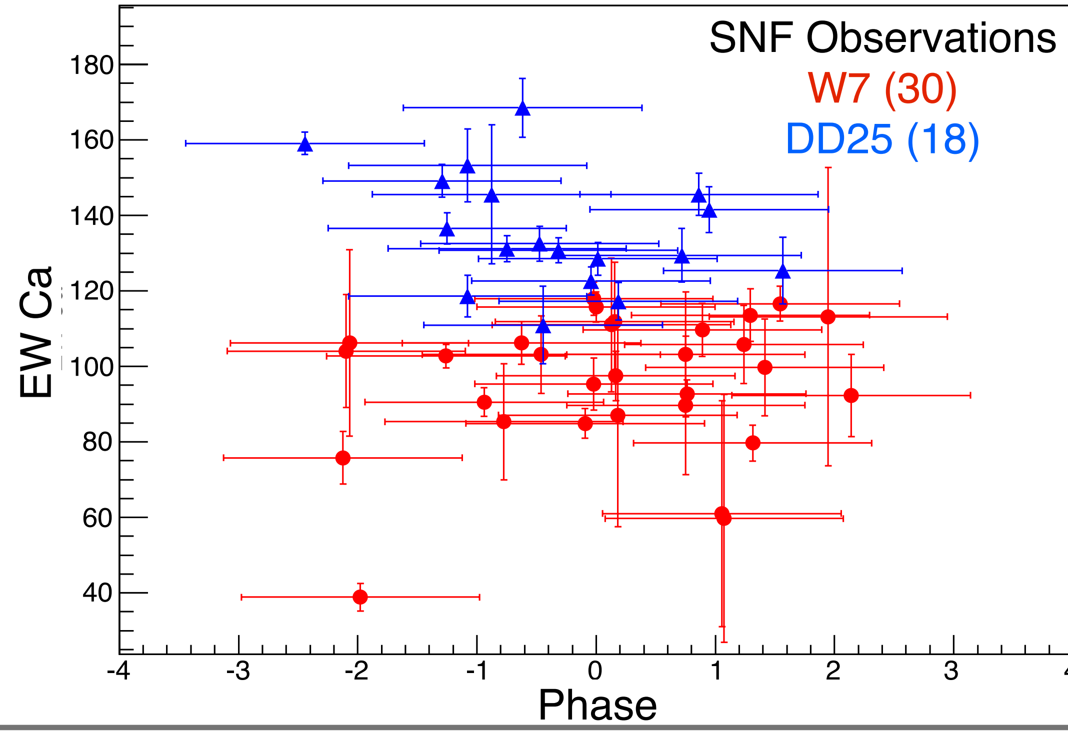
Most of the differences can be attributed to the Ca II (3700Å)

↳ computing the equivalent widths EW Ca for SNF spectra

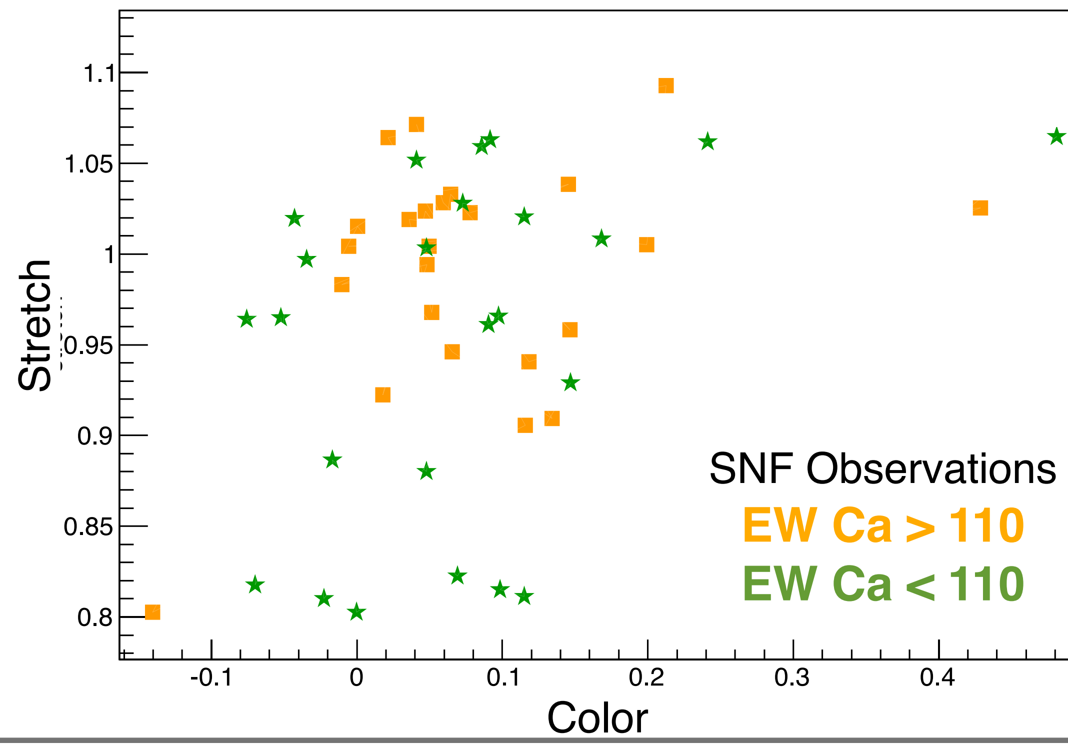
➔ at maximum : DD25 favoured by higher EW Ca

➔ EW Ca sub-division : no evidence for two different populations

- **EW Ca from observed spectra around maximum**

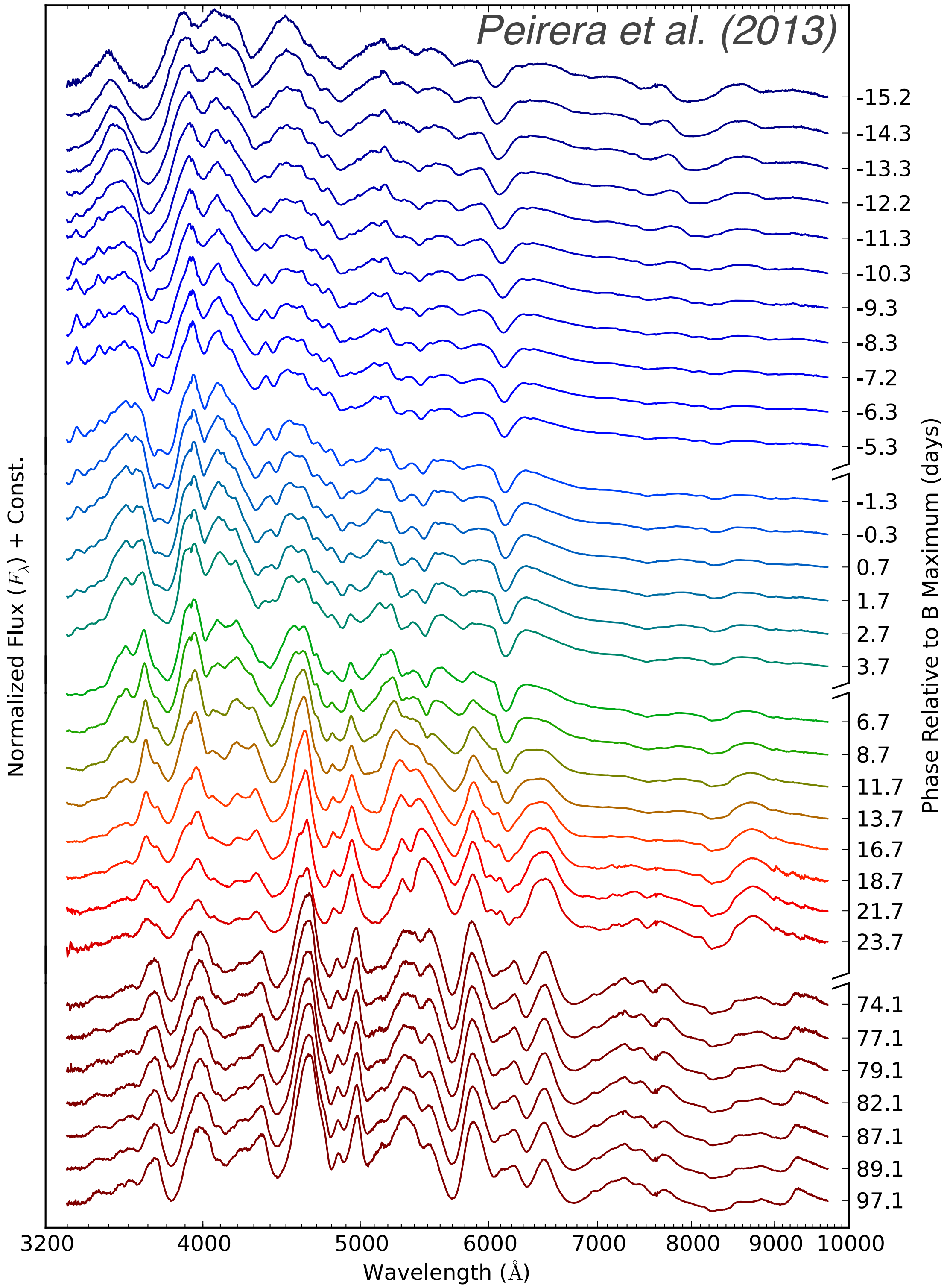


- **EW Ca sub-division**



SN2011fe : a more realistic «model» ?

- **SN2011fe :** nearby SN Ia discovered by Nugent et al. 2011



➔ SN Ia exceptionally standard

➔ observed in detail by SNF (Peirera et al. 2013) with very high quality spectra

↳ Using SN2011fe for a more realistic fit of data

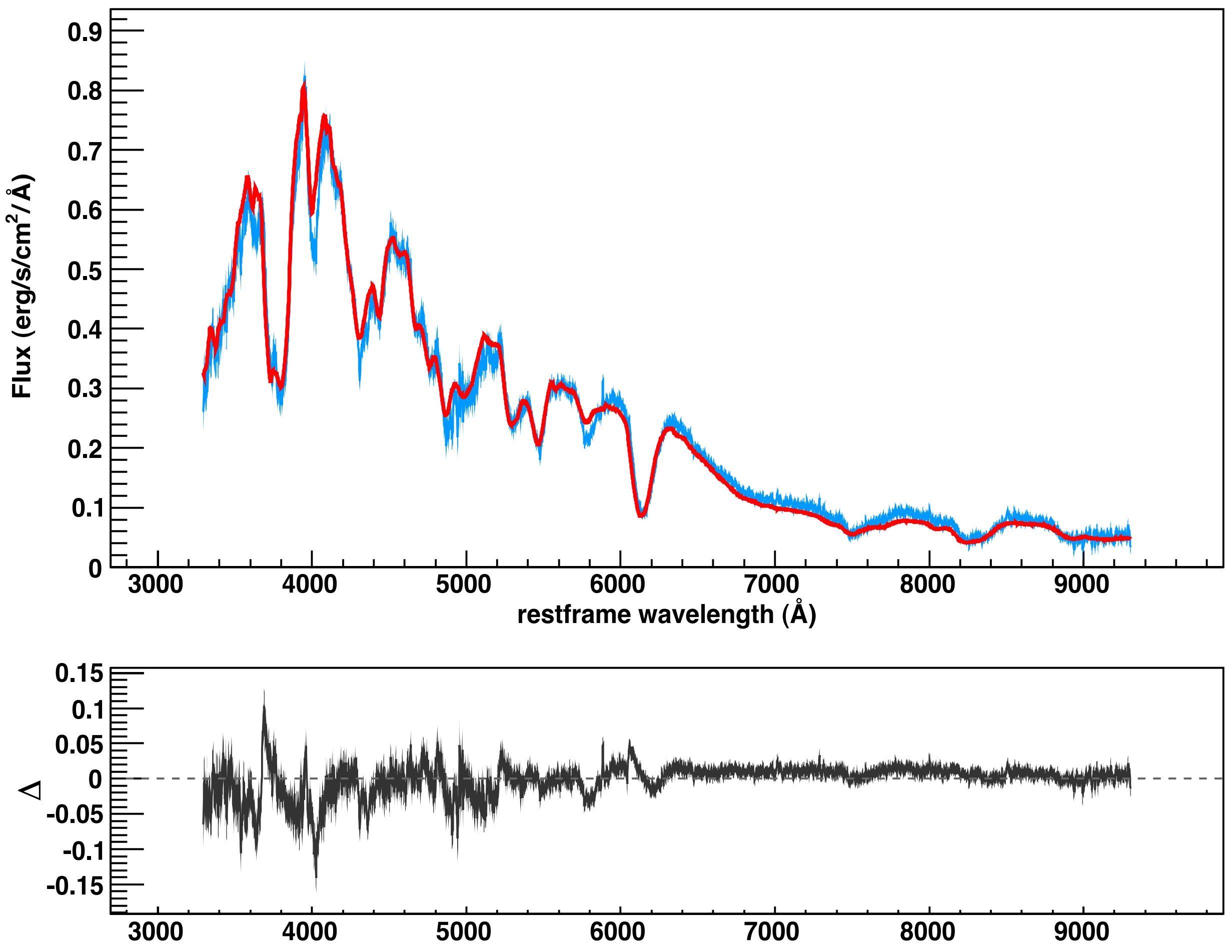
- variability of SN Ia spectra at maximum ?
- search for spectroscopic indicators that describe SN Ia variability

SNF spectra vs SN2011fe

- **Sample selection :** 85 spectra (1 spectrum per SN Ia) close to maximum (-2.5 < phase < 2.5 days) with a color cut (-0.2 < c < 0.2) from SNF «training» + «validation» samples

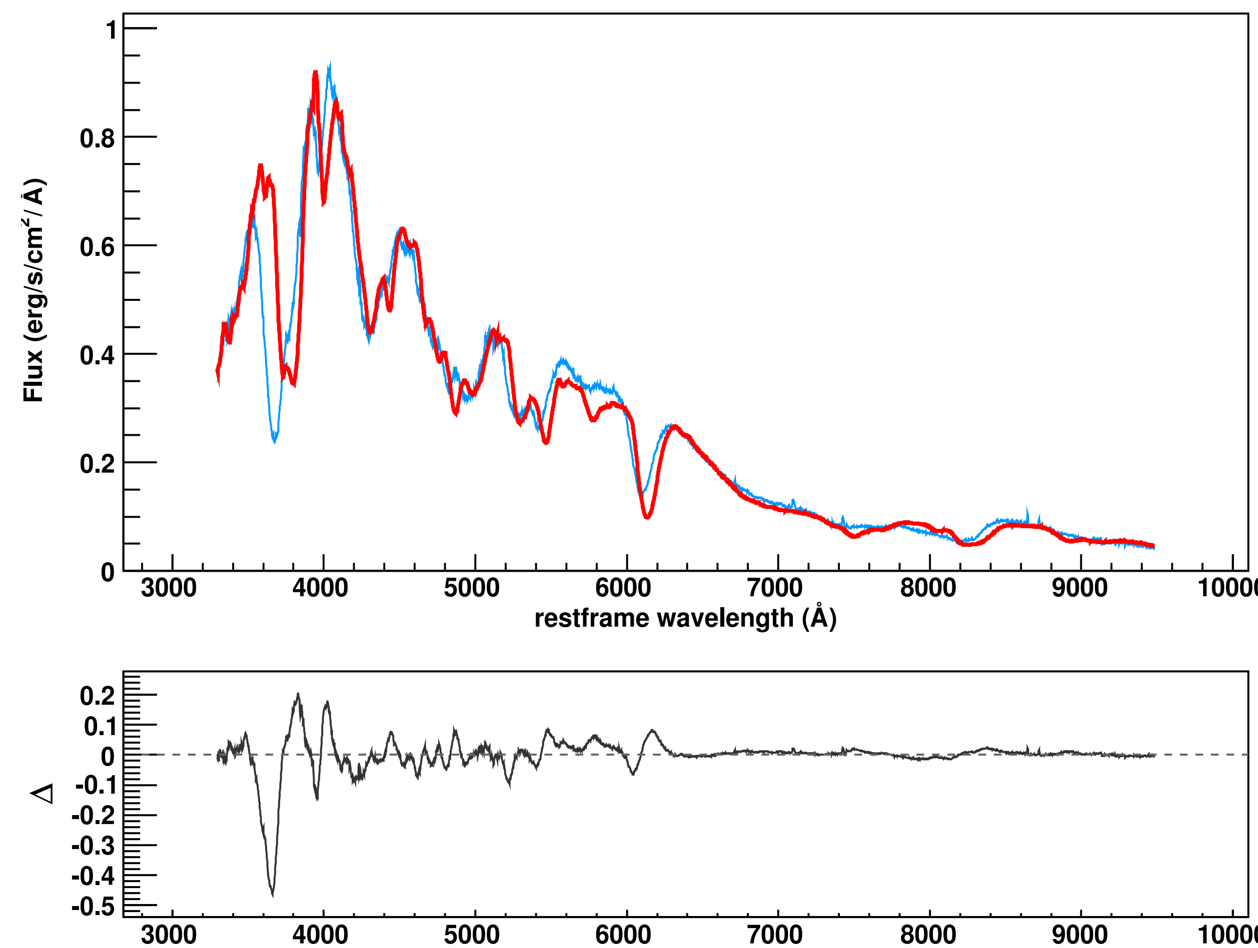
- **SN2011fe vs SNF :** for each observed spectrum, fit models in amplitude on observed spectra by a χ^2 minimisation procedure

SNF20080810-001 : z = 0.042 / phase = 0 jours



→ Spectrum well reproduced by SN2011fe

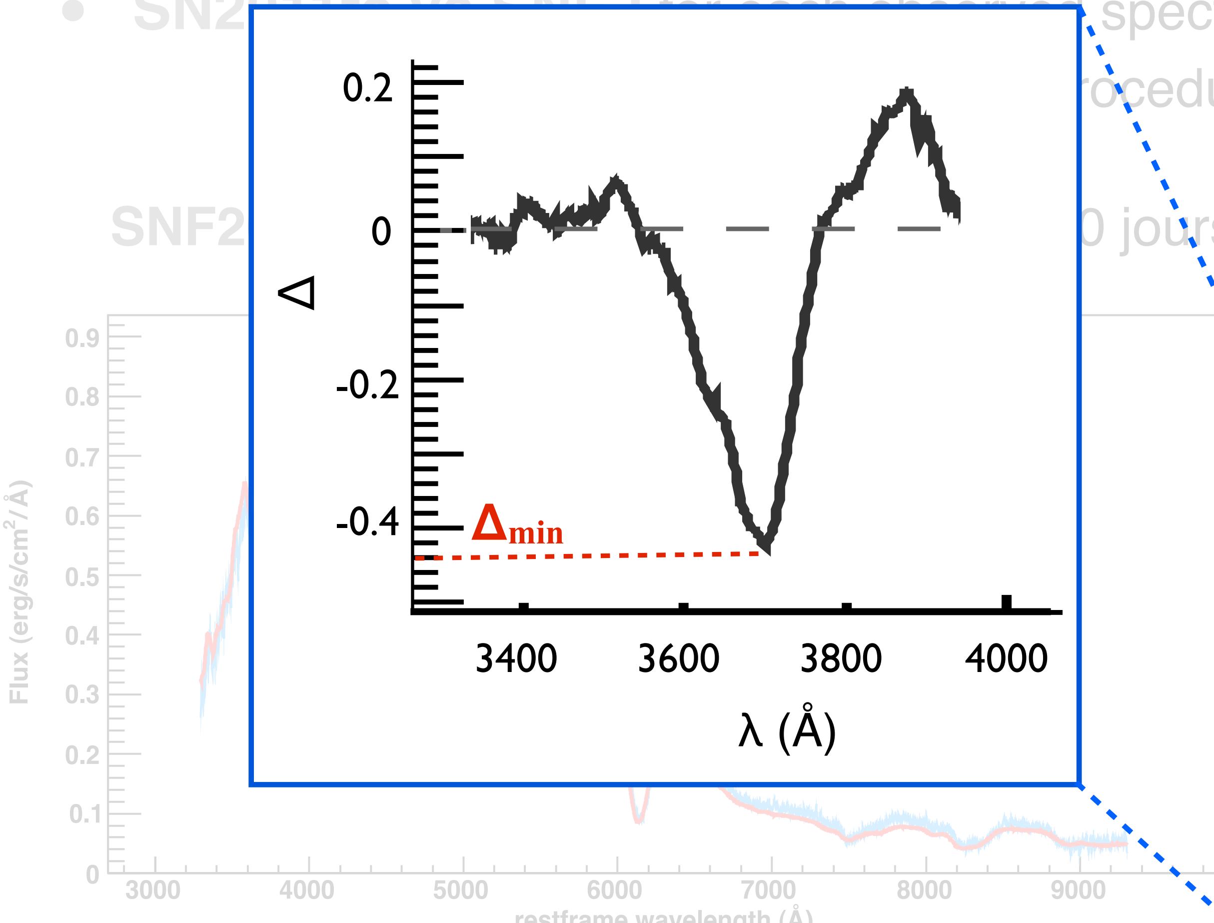
PTF09dnl : z = 0.023 / phase = -0.7 jours



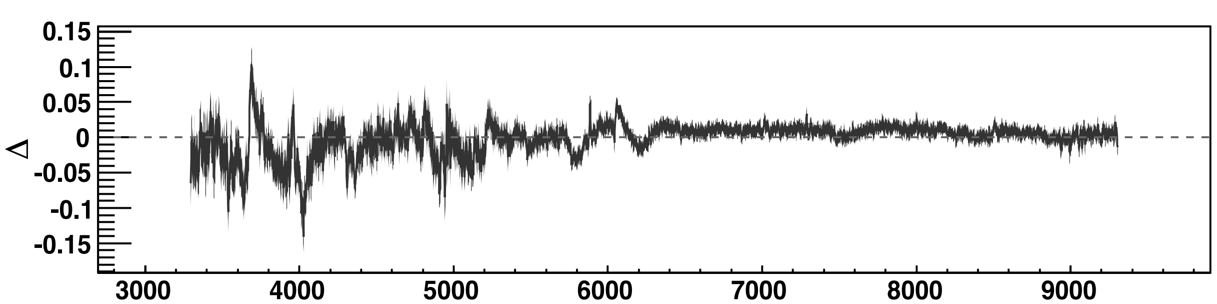
→ Spectral differences with SN2011fe in particular around the Ca II

SNF spectra vs SN2011fe

- **Sample selection :** 85 spectra (1 spectrum per SN Ia) close to the maximum (-2.5 < phase < 2.5 days) with a color cut (-0.2 < c < 0.2) among training + validation SNF samples
- **SN2011fe vs SNF :** for each observed spectrum, fit models in amplitude on observed spectra by a ... procedure



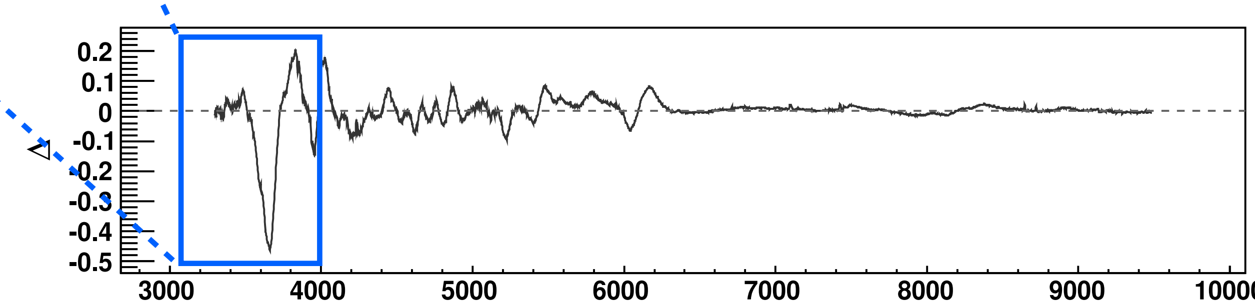
SNF2... 0 jours



→ Spectrum well reproduced by SN2011fe

... / phase = -0.7 jours

→ Δ_{min} (erg/s/cm²/Å) : minimum value of the flux difference around 3700Å



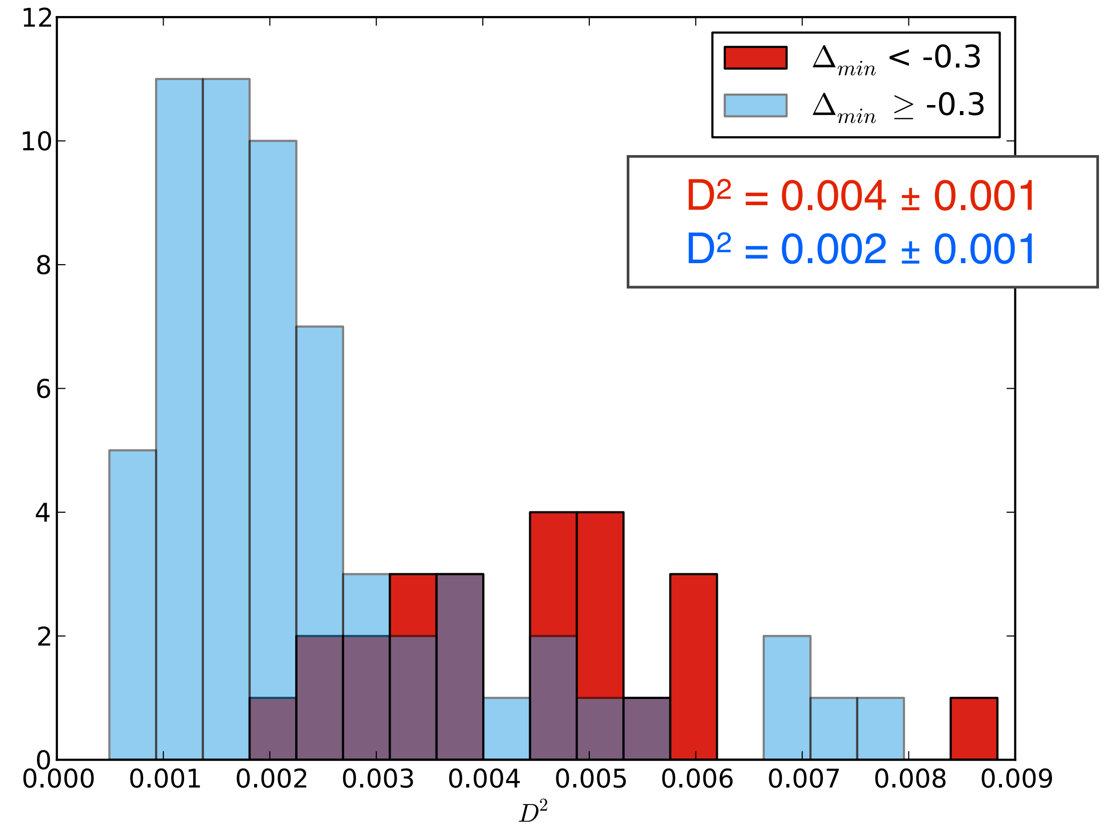
→ Spectral differences with SN2011fe in particular around the Ca II

Δ_{min} discriminates the SNF sample

- **Δ_{min} to discriminate spectra :**
  - ➔ $\Delta_{min} < -0.3\ \mathrm{erg/s/cm^2/\AA}$: 24 spectra poorly reproduced by SN2011fe
  - ➔ $\Delta_{min} \geq -0.3\ \mathrm{erg/s/cm^2/\AA}$: 61 spectra well reproduced by SN2011fe

D^2 $(\mathrm{erg/s/cm^2/\AA})^2$: average quadratic distance between the observed spectrum and SN2011fe over the whole spectral range

$$D^2 = \frac{1}{dof}\sum_i^N (F_{obs}(\lambda_i) - A \cdot F_{fe}(\lambda_i))^2$$



- **Δ_{min} correlates with EW Ca and with velocity shift between the «model» and the observed spectrum**

- **Δ_{min} not simply linked to the photometric parameters**

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Conclusions

- VLT 5yrs spectroscopic sample (Cellier-Holzem et al. 2013)
  - ↳ highly homogenous sample
  - ↳ galactic subtraction and calibration under control
  - ↳ no sign of contamination by other types

- Evolution of SNe Ia with redshift
  - ↳ VLT/SNF spectra : spectral differences with z are consistent with a selection effect
  - ↳ no sign of evolution

- Better knowledge of SN Ia properties
  - ↳ SNF spectra have the power to discriminate models because of Ca II feature variability
  - ↳ tentative new indicator : Δ_{min} encodes the variability around of Ca II absorption
  - ↳ Δ_{min} is not simply linked to photometric parameters

Perspectives

Develop my study of SN Ia spectral variability by :

↳ further characterizing Δ_{min} and searching for possible other indicators

↳ exploring the parameter space of more realistic models to identify the main parameters explaining the observed spectra

Spectroscopy is essential for the redshift and identification for cosmology

AND

to study of the SN Ia properties to investigate fundamental questions and validate their use in cosmology


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