SUGAR : when spectra help standardizing type Ia supernovae

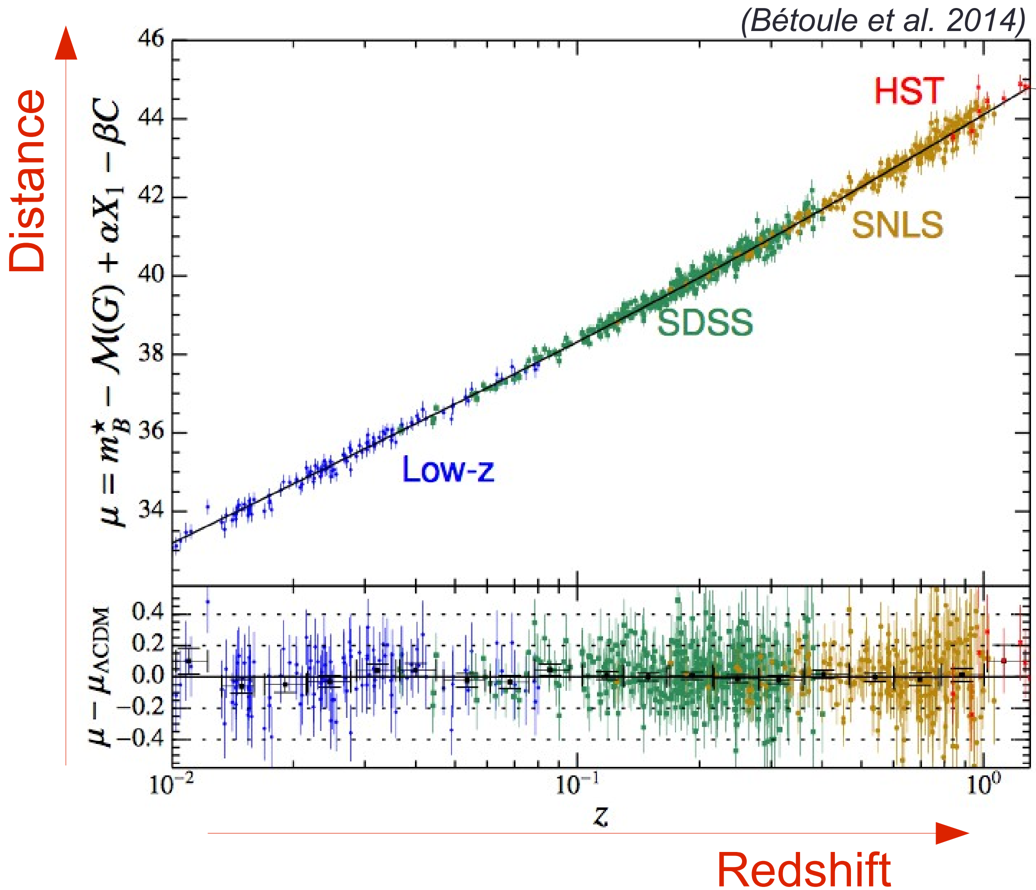
(artist's concept)

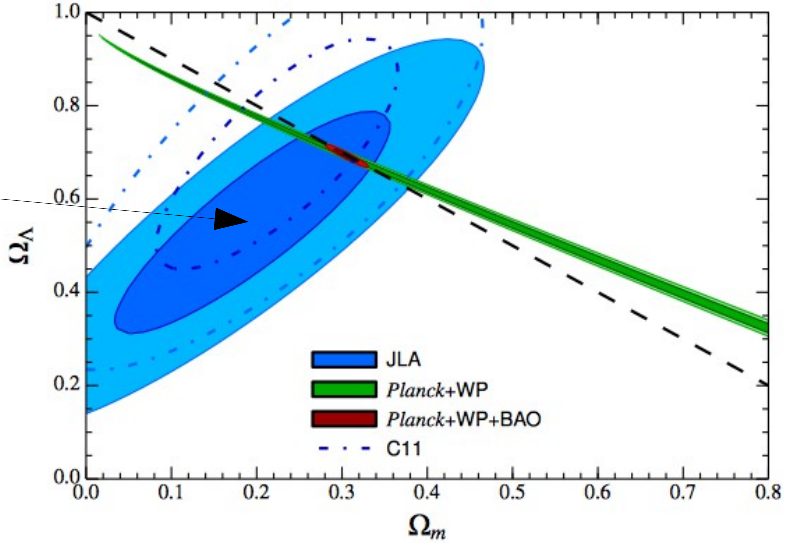
E. Gangler and P.-F. Leget
For the SNFactory

G. Aldering, P. Antilogus, C. Aragon, S. Bailey, C. Baltay, S. Bongard, K. Boone, C. Buton, M. Childress, N. Chotard, Y. Copin, P. Fagrelius, H. K. Fakhouri, U. Feindt, M. Fleury, D. Fouchez, B. Hayden, A. Kim, M. Kowalski, S. Lombardo, J. Nordin, R. Pain, E. Pécontal, R. Pereira, S. Perlmutter, D. Rabinowitz, M. Rigault, K. Runge, D. Rubin, C. Saunders, R. A. Scalzo, G. Smadja, C. Sofiatti, N. Suzuki, C. Tao, R. C. Thomas, B.A. Weaver

SN as standard candles

Fit to Hubble diagram
→ cosmological parameters

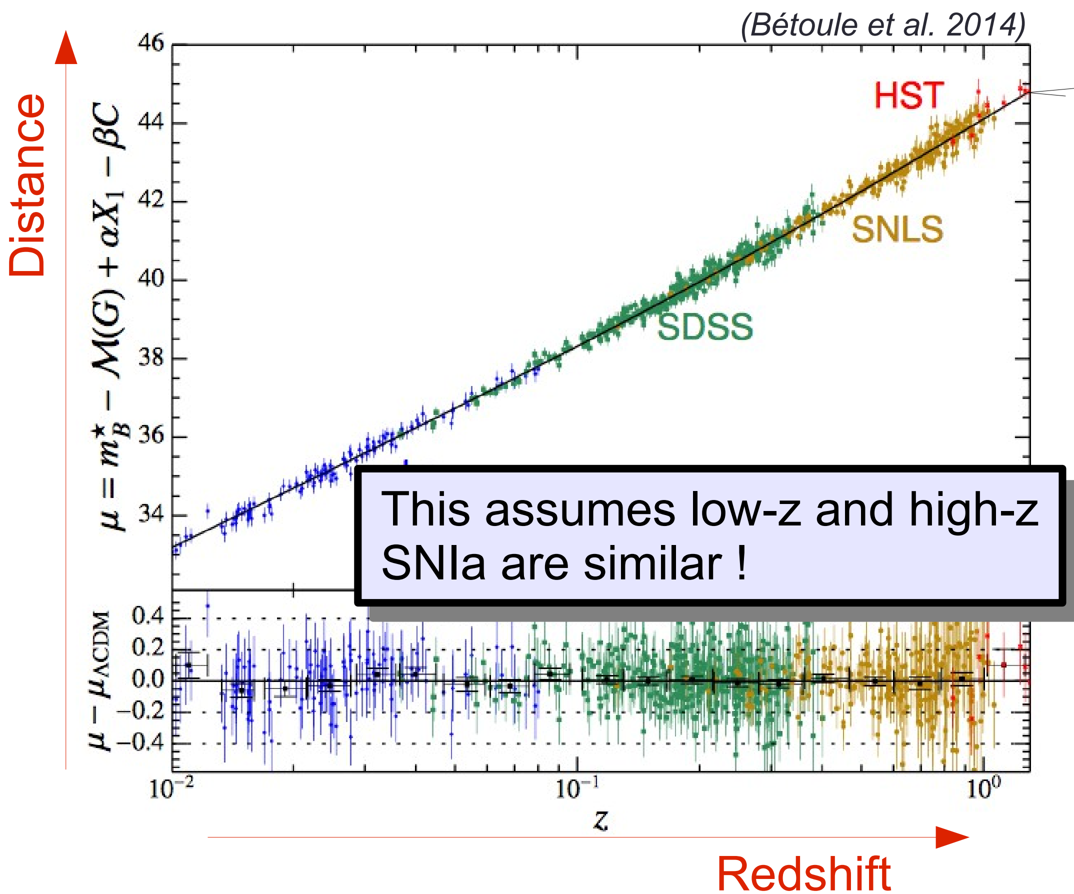




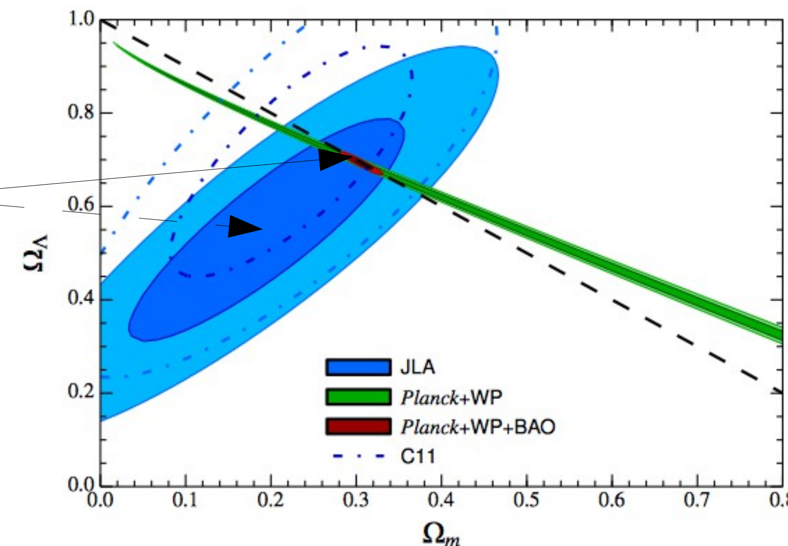
Concordance model :
SN/CMB/BAO → LCDM
Probe combination for w

SN as standard candles

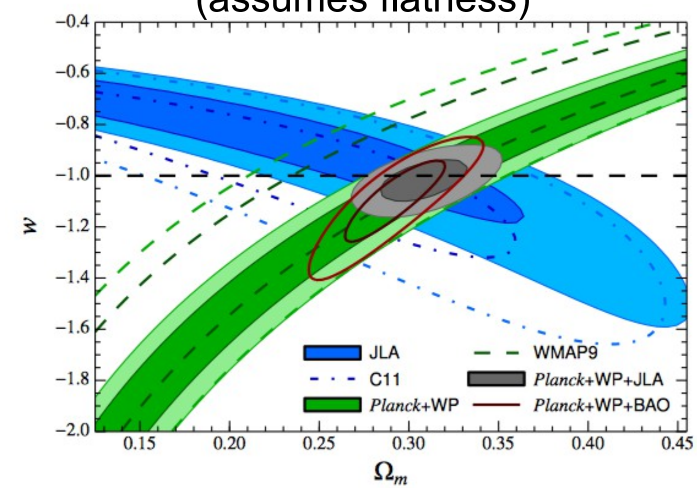
Fit to Hubble diagram
→ cosmological parameters



This assumes low-z and high-z SNIa are similar !



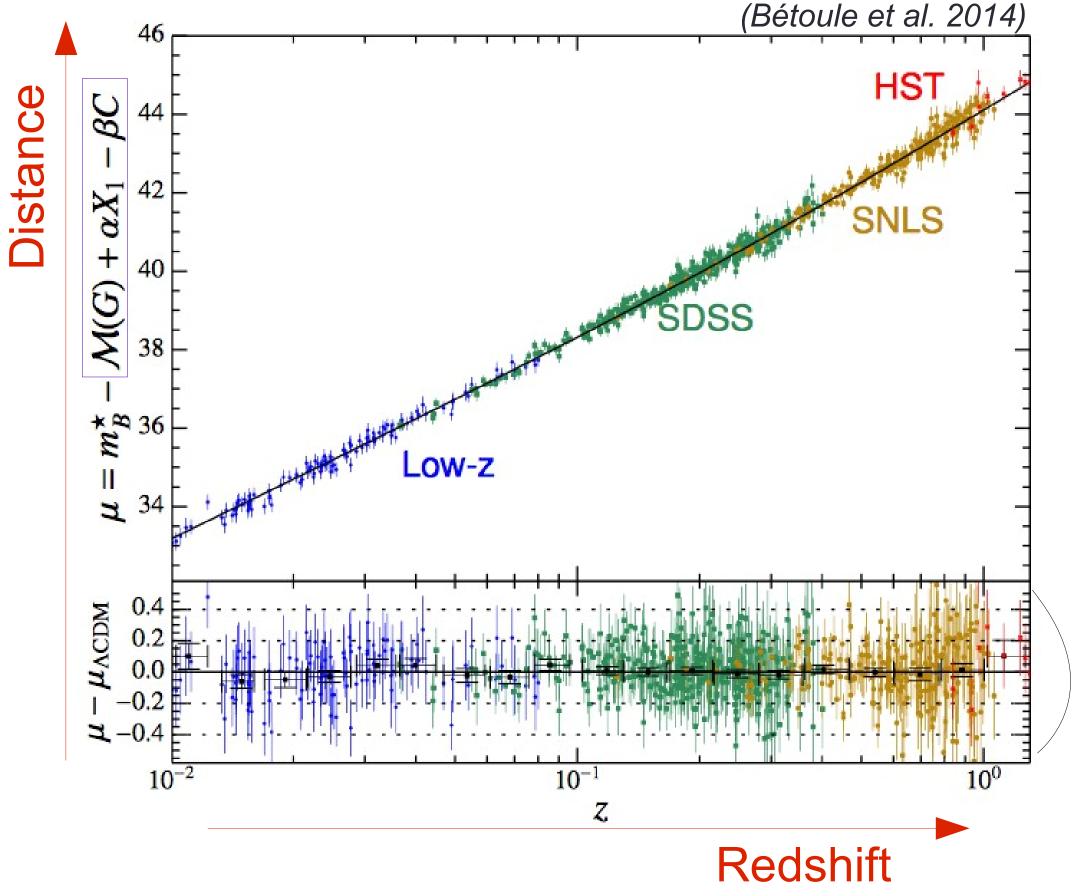
Concordance model :
SN/CMB/BAO → LCDM
Probe combination for w
(assumes flatness)



SN as standardizable candles

Fit to Hubble diagram
→ cosmological parameters
→ Supernova parameters

(Bétoule et al. 2014)



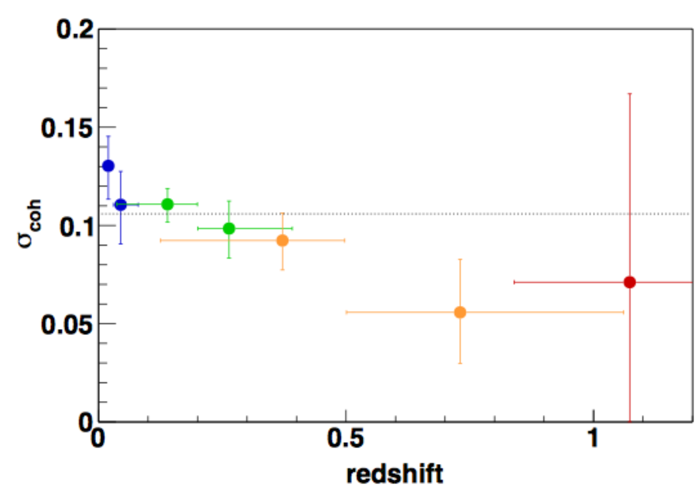
$$\mu = m_B^\star - \mathcal{M}(\mathcal{G}) + \alpha X_1 - \beta C$$

Supernova properties impact magnitude

C : Color
X_1 : Stretch
Host galaxy

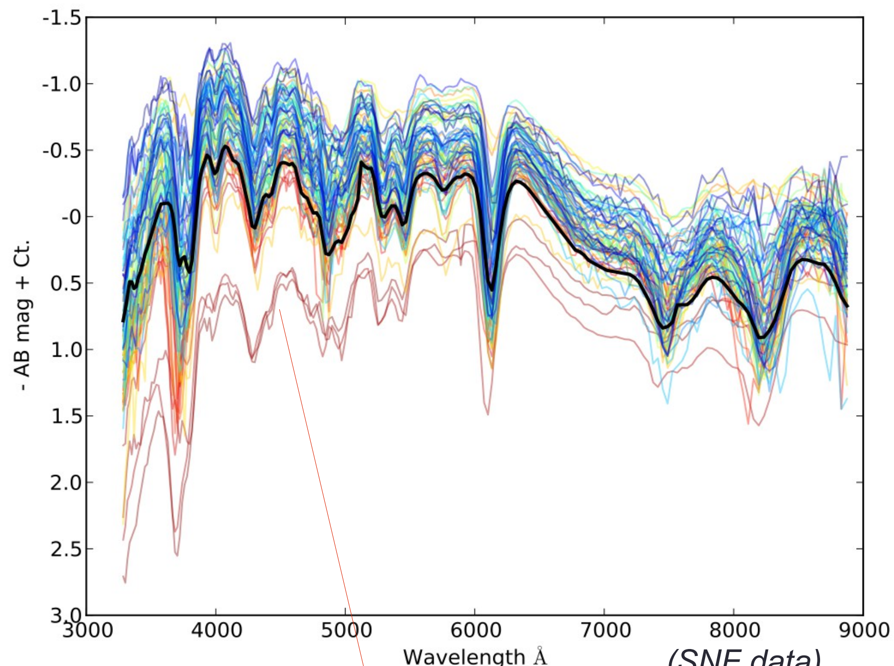
→ SALT2

Additional dispersion :
What we don't control !

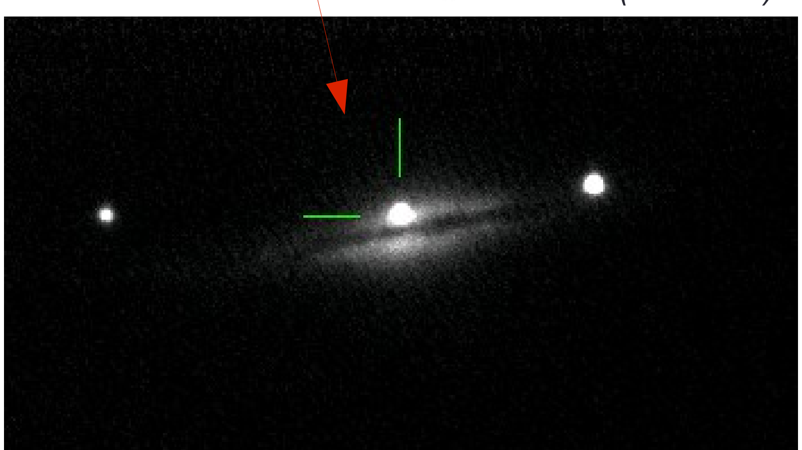


SN as standardizable candles

Maximum light spectrum



(SNF data)



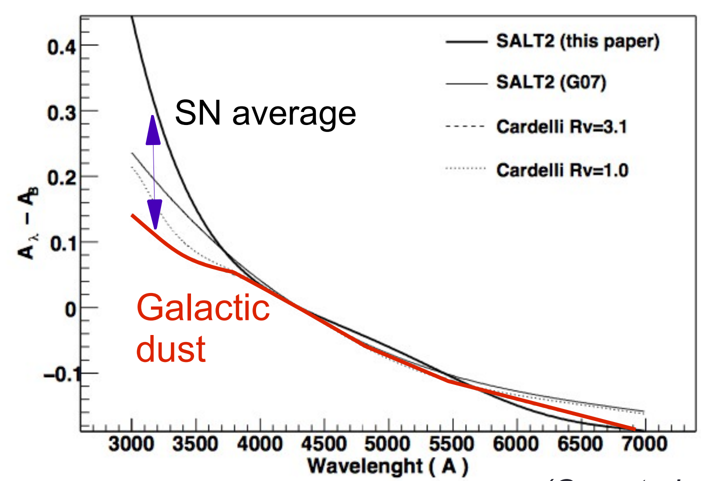
$$\mu = m_B^\star - \mathcal{M}(\mathcal{G}) + \alpha X_1 - \beta C$$

Supernova properties impact magnitude

C : Color

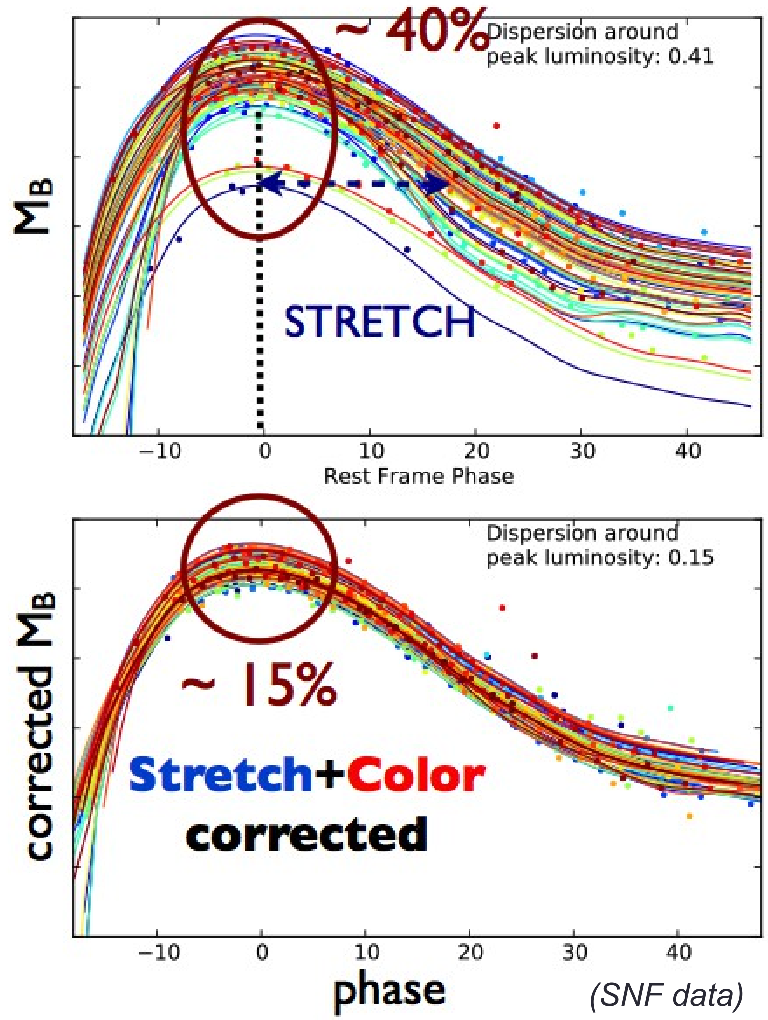
Redder - Fainter relation

Association with dust
. . . But average color law departs from reddening by dust (Fitzpatrick or CCM)



(Guy et al. 2010)

SN as standardizable candles



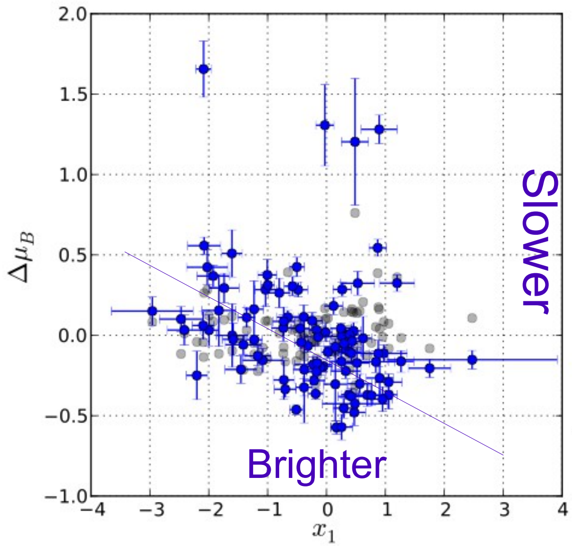
$$\mu = m_B^\star - \mathcal{M}(\mathcal{G}) + \alpha X_1 - \beta C$$

Supernova properties impact magnitude

C : Color

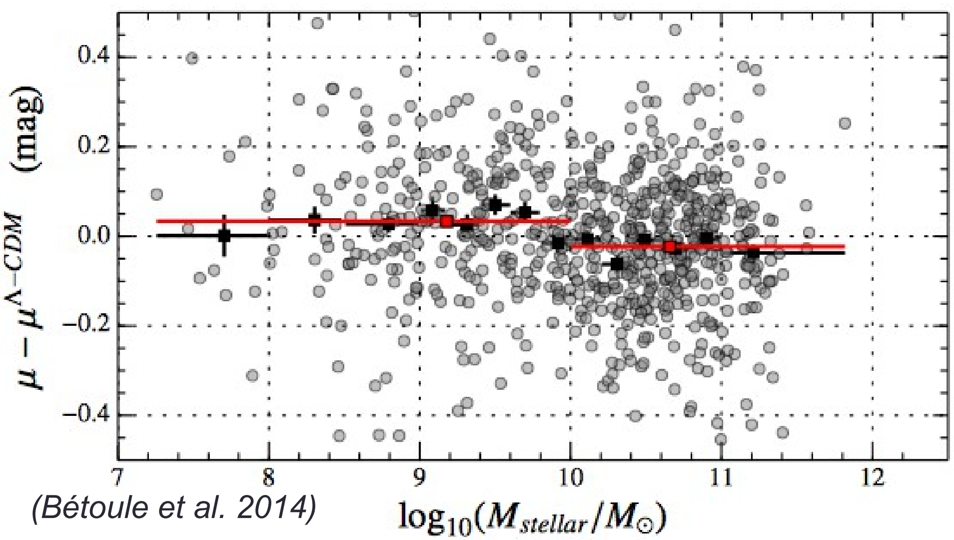
X_1 : Stretch (Brighter-Slower relation)

Physics : opacity / luminosity competition



SN as standardizable candles

Global : Mass step

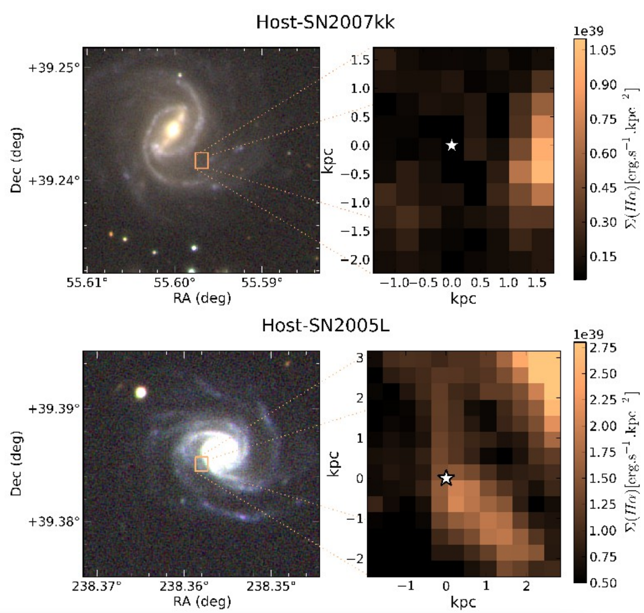


(Bétoule et al. 2014)

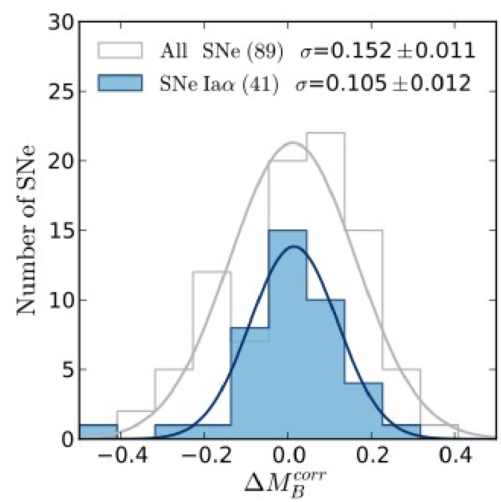
$$\mu = m_B^\star - \mathcal{M}(\mathcal{G}) + \alpha X_1 - \beta C$$

Supernova properties impact magnitude

C : Color
X_1 : Stretch
Host galaxy



(Rigault et al. 2013,2015)



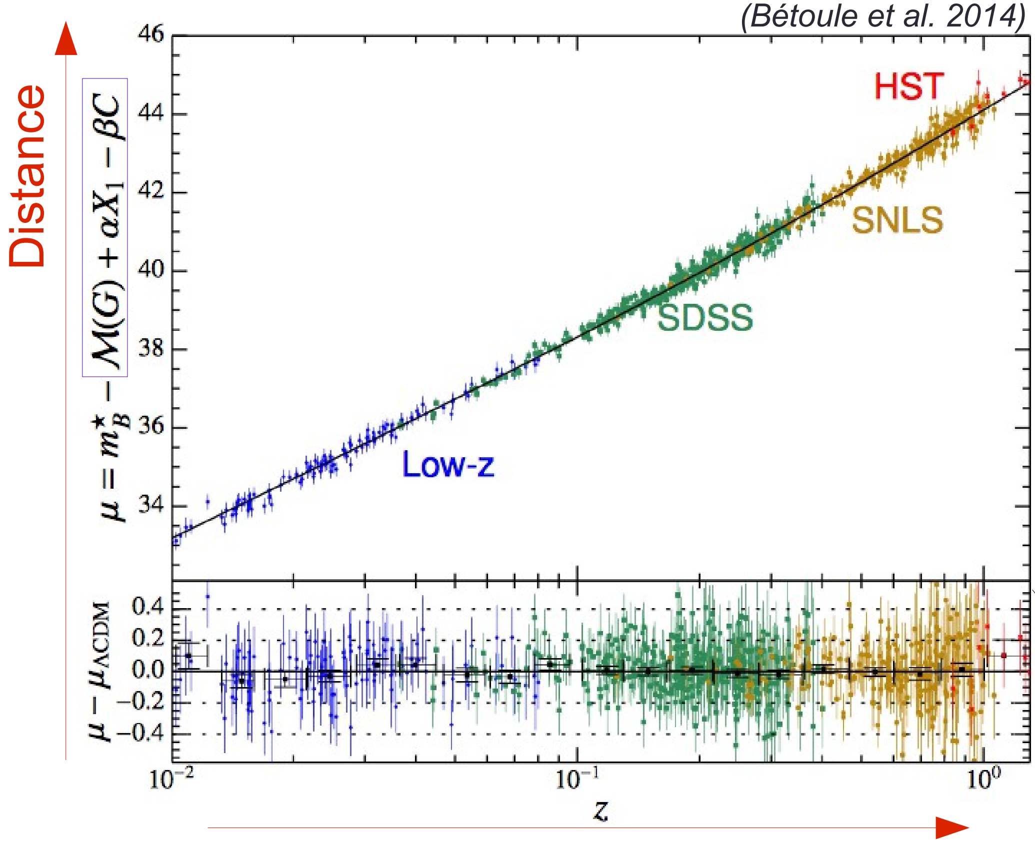
Local : SFR step
Active → less dispersion

Is host galaxy a proxy for
some hidden parameters ?

SN as standardizable candles

Fit to Hubble diagram
→ cosmological parameters
→ Supernova parameters

(Bétoule et al. 2014)

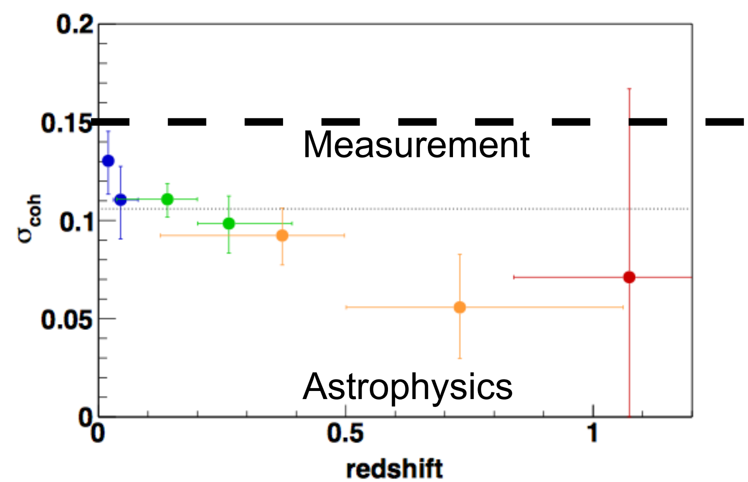


$$\mu = m_B^\star - \mathcal{M}(\mathcal{G}) + \alpha X_1 - \beta C$$

Supernova properties impact on magnitude

C : Color
X_1 : Stretch
Host galaxy
→ SALT2

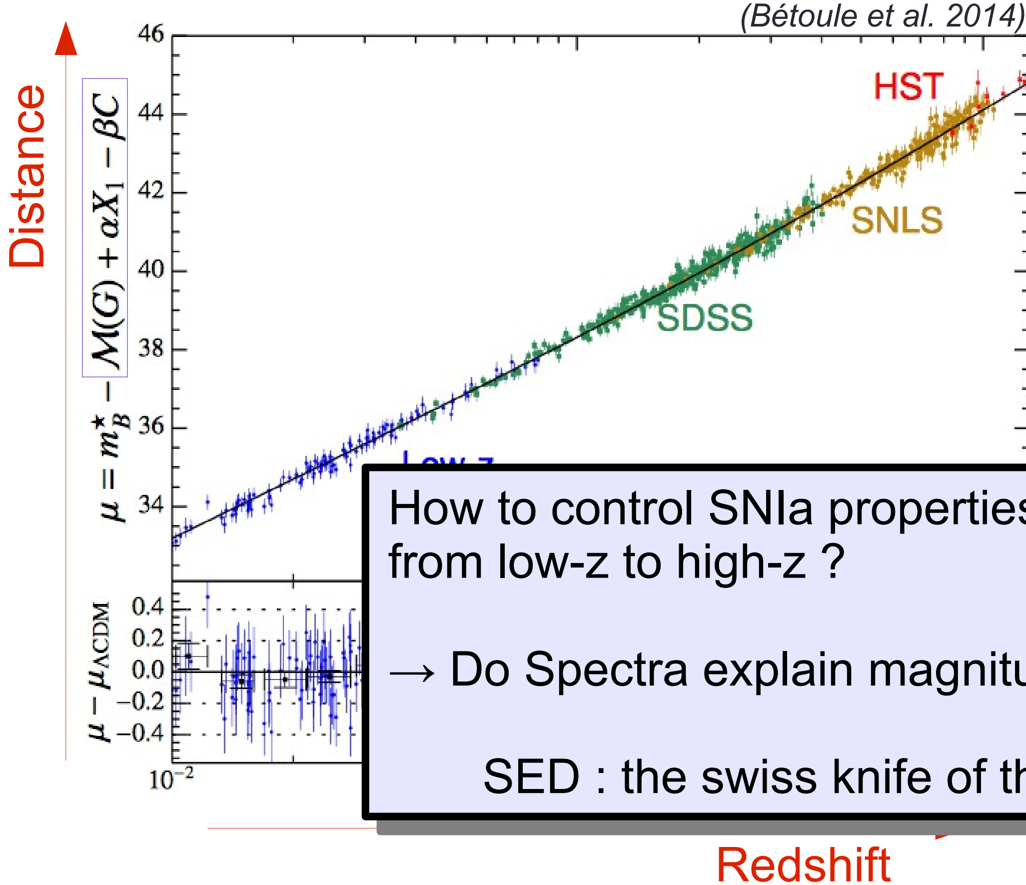
Additional dispersion :
What we don't control !



SN as standardizable candles

Fit to Hubble diagram
→ cosmological parameters
→ Supernova parameters

(Bétoule et al. 2014)



$$\mu = m_B^\star - \mathcal{M}(\mathcal{G}) + \alpha X_1 - \beta C$$

Supernova properties impact on magnitude

C : Color
X_1 : Stretch
Host galaxy

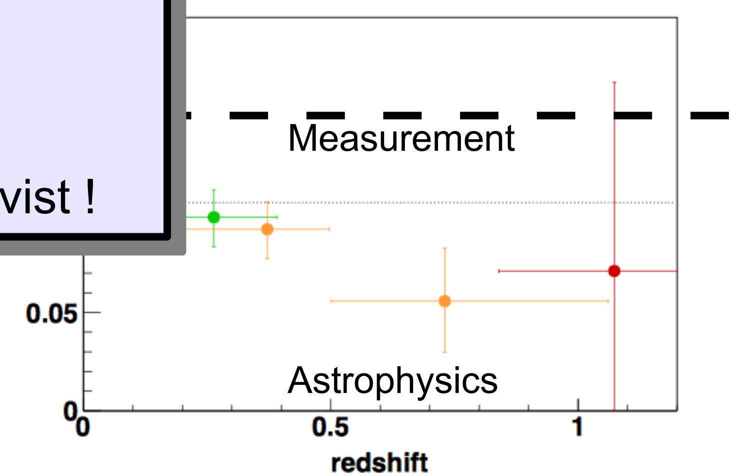
→ SALT2

How to control SNIa properties behave similarly from low-z to high-z ?

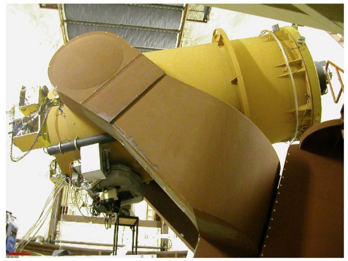
→ Do Spectra explain magnitude ?

SED : the swiss knife of the supernovist !

ersion :
on't control !



Building an SED model



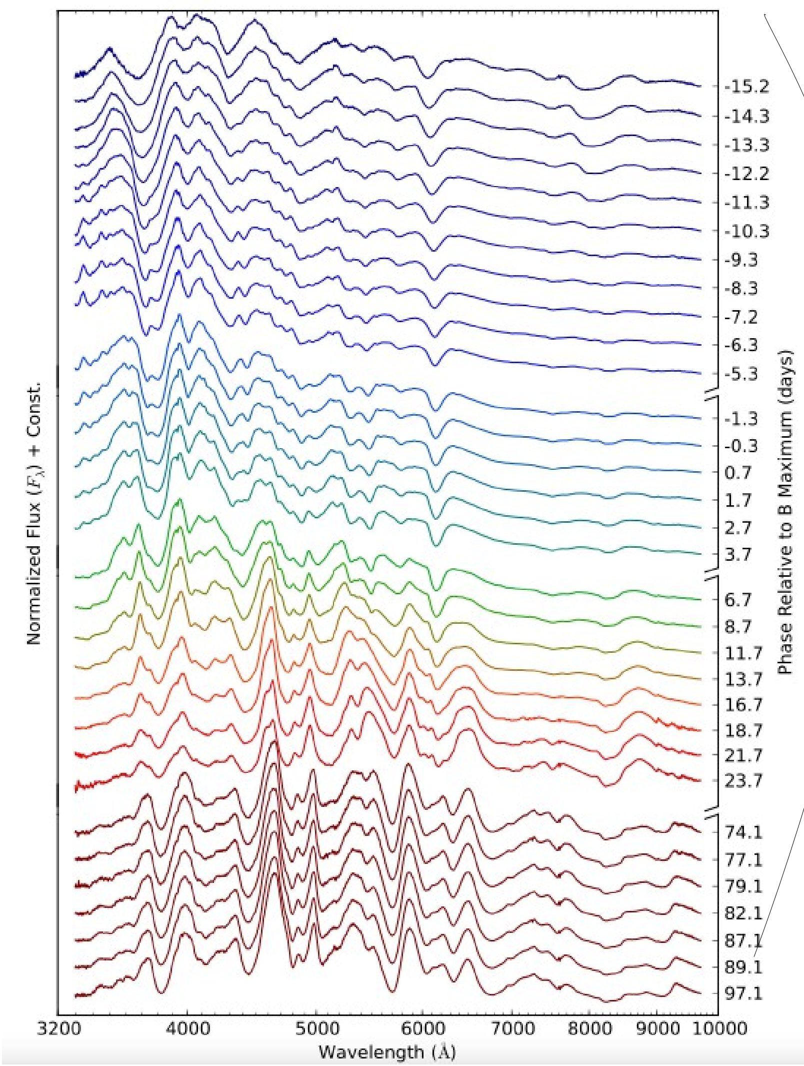
beyond **stretch/color**

Input data : **spectrophotometric time series**

From SNFactory collaboration
UH 88 + SNIFS instrument (2004-2013)

232 « Good » Supernovae
3462 Spectra → ~15 spectra/SN

Photometric calibration 0.03-4 mag



SN2011fe *(Pereira et al. 2013)*

SED

$$M(\lambda,t)^{SN} = f(\, M_i(\lambda,t), q_i^{SN}\,)$$

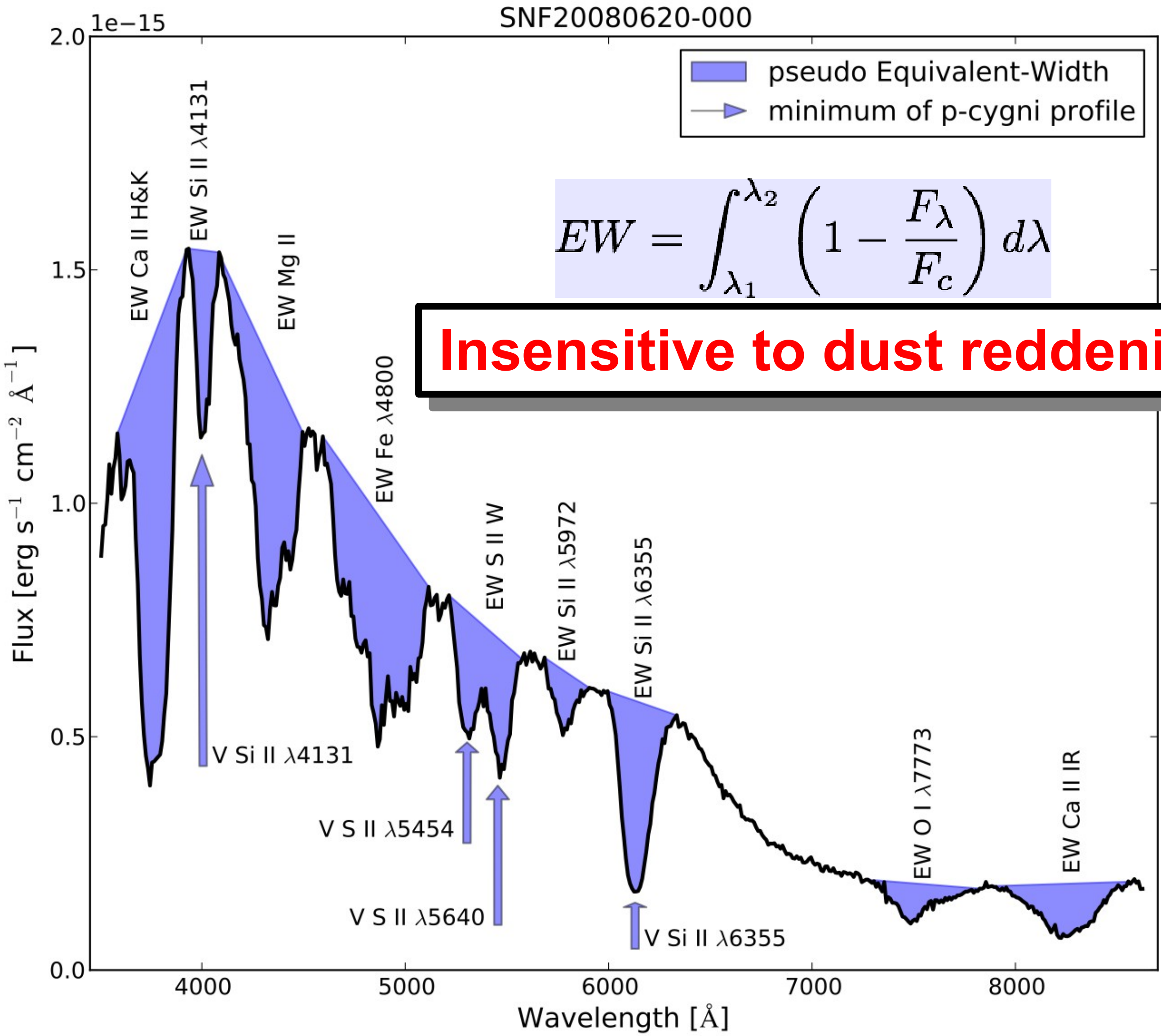
- q_i^{SN} → **SN parameters**
- $M_i(\lambda,t)$ → Model response
- $M(\lambda,t)^{SN}$ → Observed spectral serie (restframe)

How to choose parameters ?
→ physically inspired inputs

Average of ~35 100 measurements/SN
→ dimensional reduction !

Dimensional reduction

1) Define set of Spectral indicators
2) Further reduction to meaningful set



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

Insensitive to dust reddening

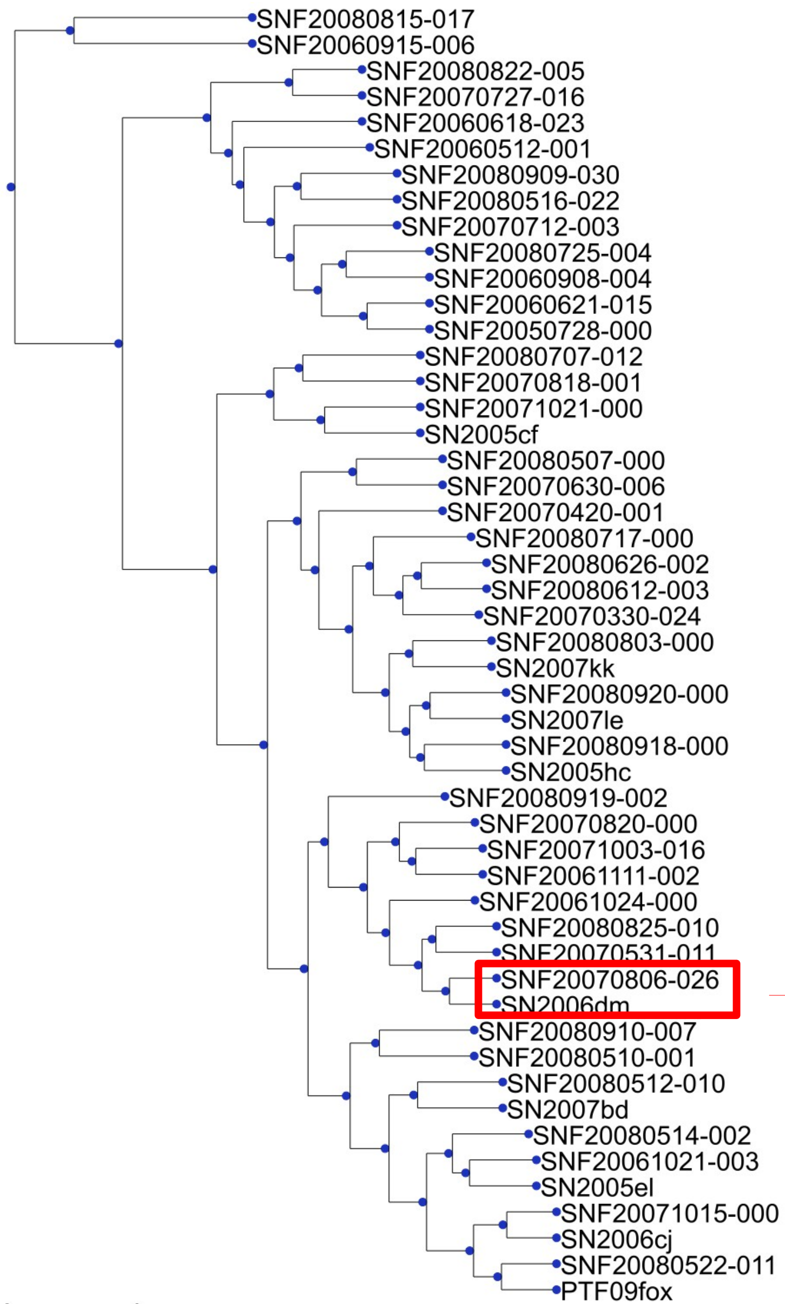
Spectral indicators at Maximum :

- 9 Pseudo Equivalent Widths
  Linked to composition
  & temperature
- 4 Velocities
  Linked to kinetic nergy

→ 13 dimensional space

Extracted by :
Optimal smoothing
Automatic edge detection
MC error estimation

Spectral Indicator space as a similarity space



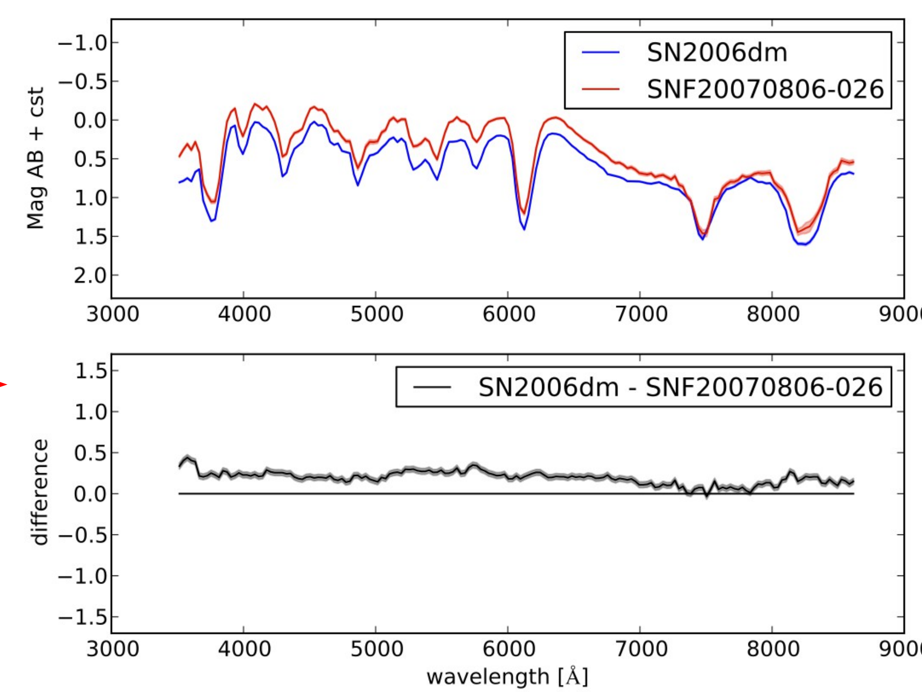
Phylogenetic tree of Supernovae :

Distance in the SI space (instead of DNA)

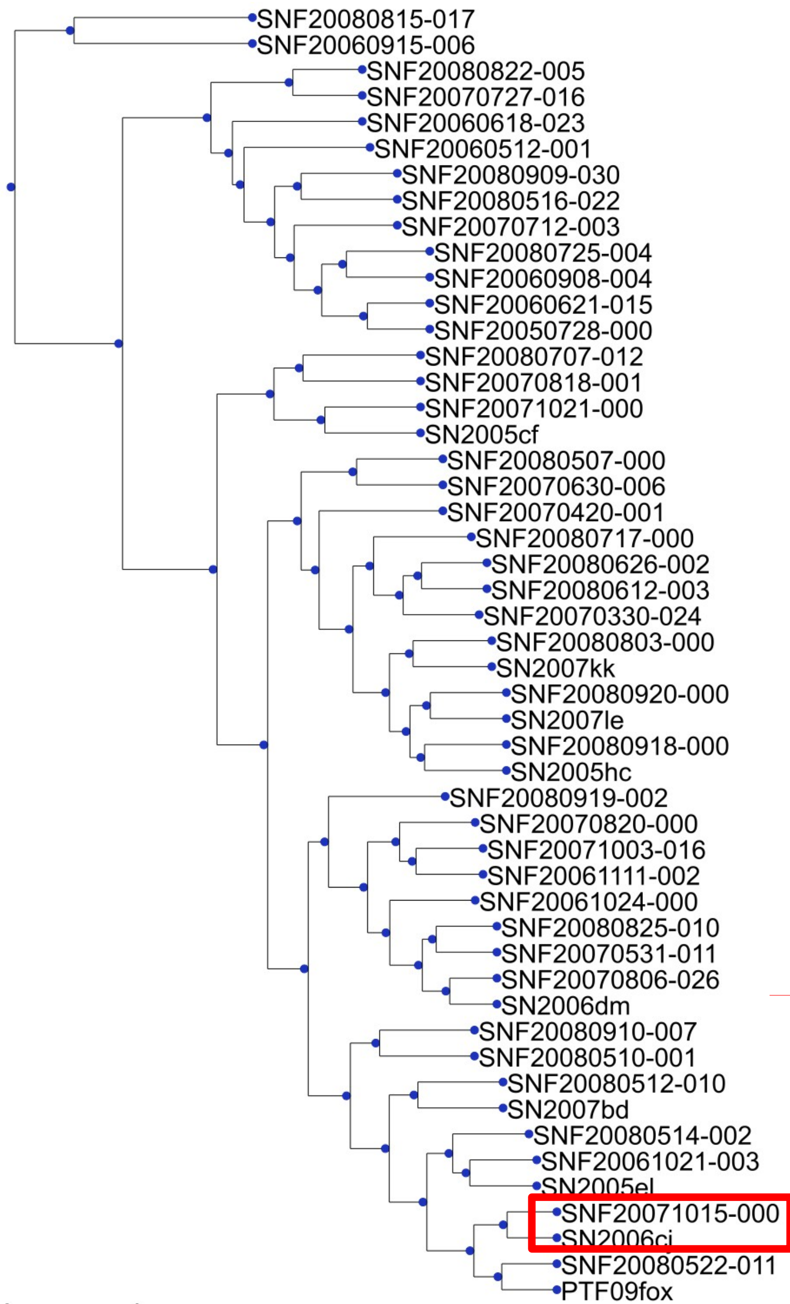
Twins supernovae are grouped together

→ Are SI Twins spectrally similar ?

Yes !



Spectral Indicator space as a similarity space



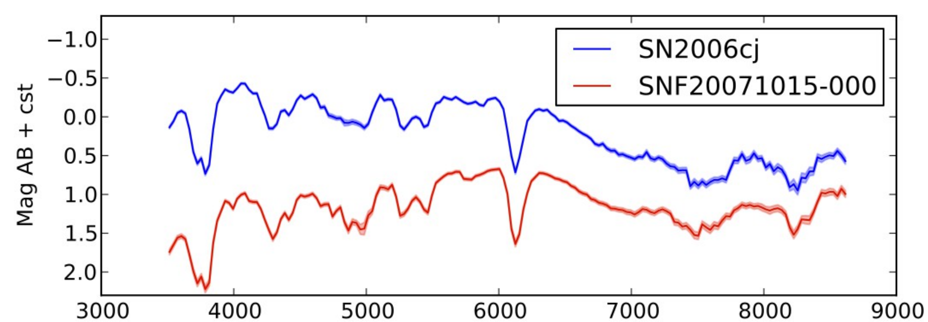
Phylogenetic tree of Supernovae :

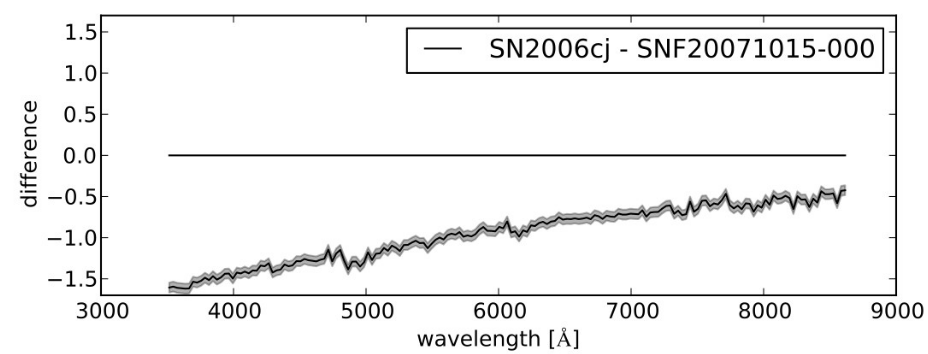
Distance in the SI space (instead of DNA)

Twins supernovae are grouped together

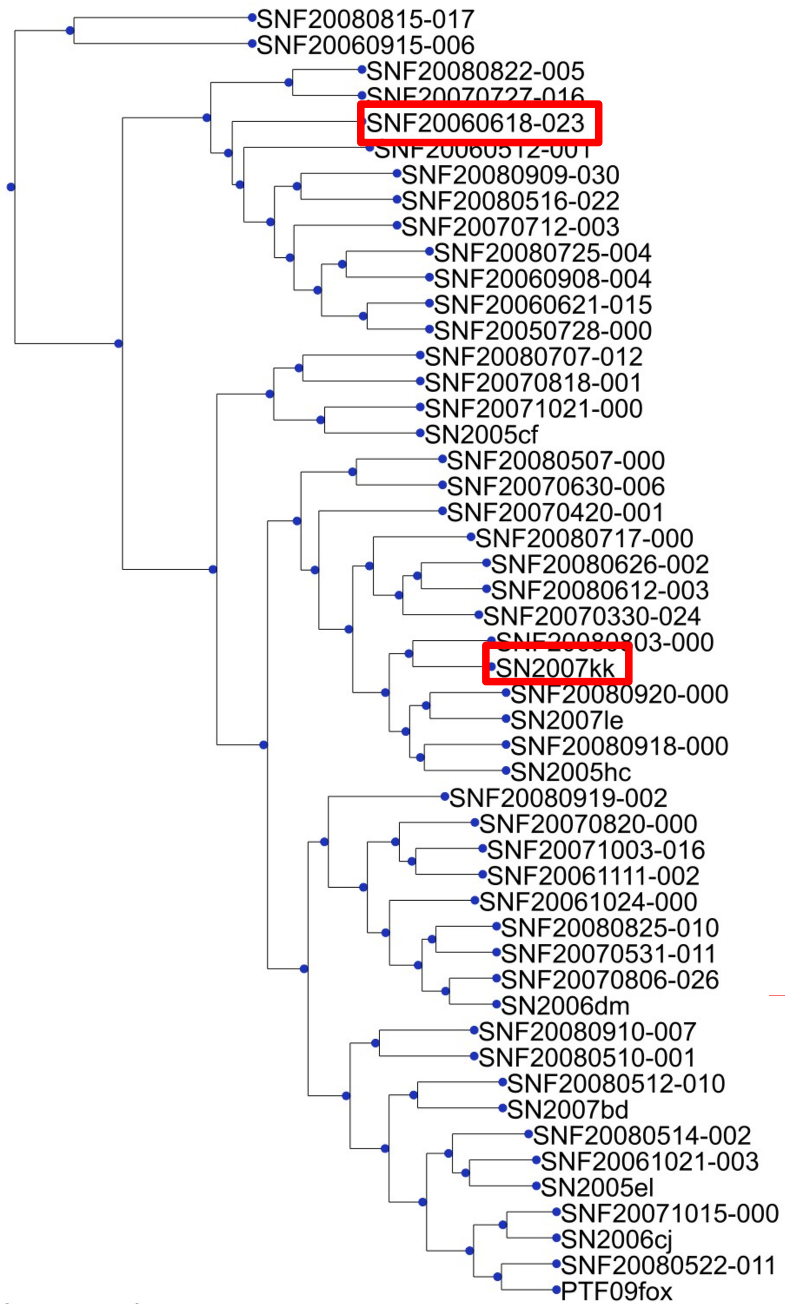
→ Are SI Twins spectrally similar ?

Still Yes !





Spectral Indicator space as a similarity space



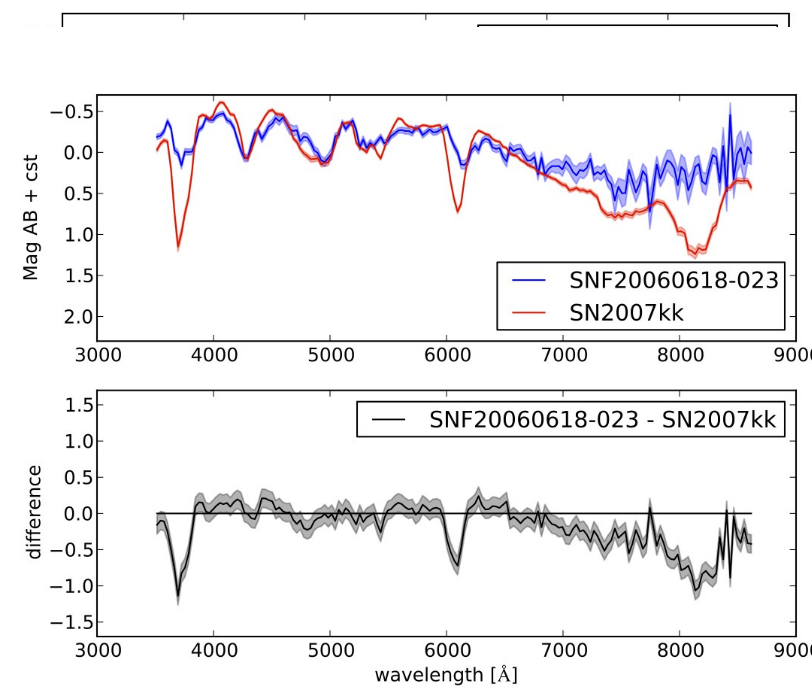
Phylogenetic tree of Supernovae :

Distance in the SI space (instead of DNA)

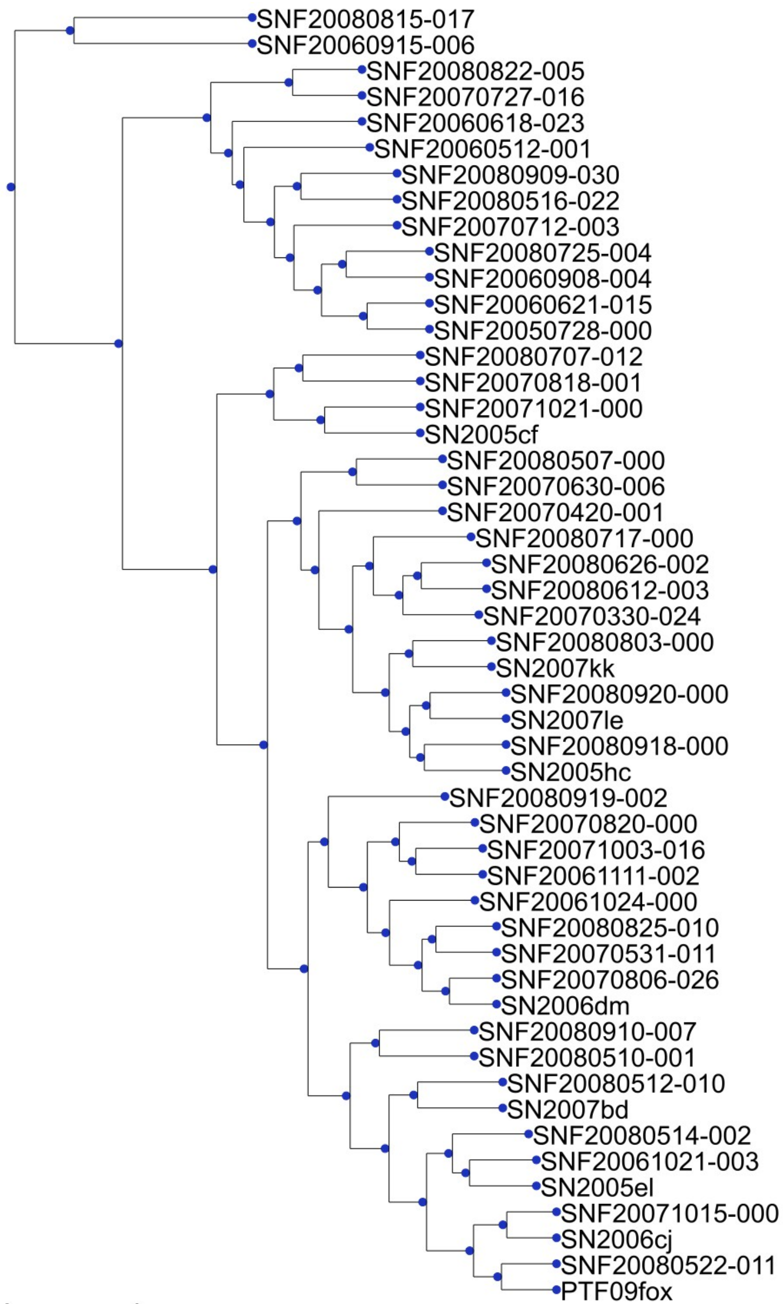
Twins supernovae are grouped together

→ Are SI-different SN spectrally different ?

Yes (again) !



Spectral Indicator space as a similarity space



Phylogenetic tree of Supernovae :

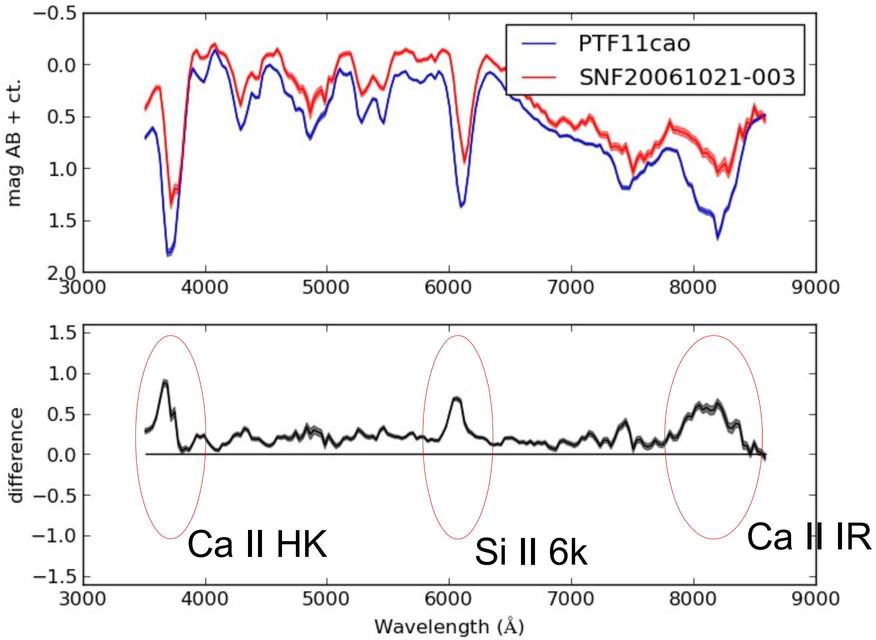
Distance in the SI space (instead of DNA)

Twins supernovae are grouped together

→ And SALT-2 Twins ?

(Same color, same stretch ± 0.01)

Not quite ...



Further Dimensionality reduction : From 13 to 3 dimensions

Eigenvectors	Eigenvalues	Variability
1	4.41	33.92%
2	3.46	26.61%
3	1.37	10.53%
4	0.60	4.62%
5	0.59	4.54%
6	0.34	2.62%
7	0.18	1.38%
8	0.14	1.07%
9	0.09	0.69%
10	0.02	0.15%
11	0	0%
12	0	0%
13	0	0%
Noise	/	13.87%

3 Eigenvectors + noise explains 85% of data variance

Expectation-Minimization Factor Analysis :

- PCA-like
- Correct treatment of measurement uncertainties
  (Likelihood optimization)

$$X^{SN} = \mathcal{N}(X_0, \Lambda\Lambda^T + \psi^{SN})$$

→ Dispersion in SI space

+ Orthogonalization

$$X^{SN} = \Lambda Q^{SN} + \epsilon^{SN}$$

→ Unknown Factors = SN Parameters

- Orthogonal solution w/o loss of generality

Further Dimensionality reduction : From 13 to 3 dimensions

Eigenvectors	Eigenvalues	Variability
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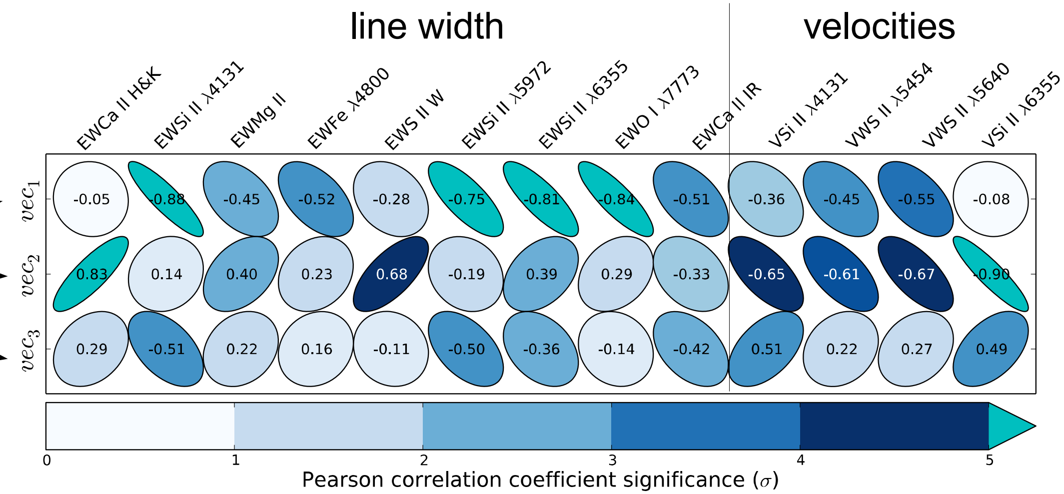
Noise	/	13.87%



3 Eigenvectors + noise explains 85% of data variance

Vector 1 : Line depth correlation
→ expected for stretch

Vector 2 : Ca II HK Width / Si II 6k velocity
→ not seen by Salt2 (?)

Vector 3 : Possibly Si II lines internal variation
→ interpretation unclear

Vectors 4 & more : Unstable vs. sample

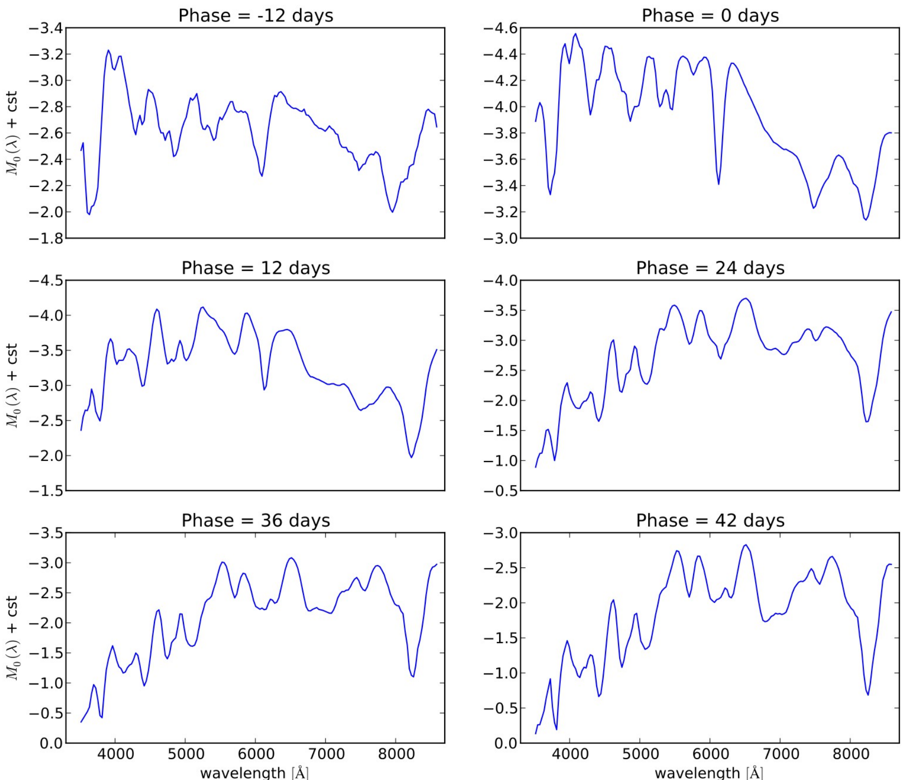
SUGAR Spectral Energy Density model :

$$M(t;\lambda) = M_0(t;\lambda) + \sum_{i=1}^{i=3} \alpha_i(t;\lambda) q_i + A_V f(R_V;\lambda) + \Delta M_{grey}$$

Supernova parameters :

Model response :

Average spectrum



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Model response :

Average spectrum

3 intrinsic parameters

→ non-linear transform of spectra

3 Spectral intrinsic response

(time-dependant)

SUGAR Spectral Energy Density model :

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Supernova parameters :

Model response :

Average spectrum

3 intrinsic parameters

→ non-linear transform of spectra

3 Spectral intrinsic response

(time-dependant)

1 extinction

1 color law

(time-independant)

SUGAR Spectral Energy Density model :

$$M(t;\lambda) = M_0(t;\lambda) + \sum_{i=1}^{i=3} \alpha_i(t;\lambda) q_i + A_V f(R_V;\lambda) + \Delta M_{grey}$$

Supernova parameters :

Model response :

Average spectrum

3 intrinsic parameters

→ non-linear transform of spectra

3 Spectral intrinsic response

(time-dependant)

1 extinction

1 color law

(time-independant)

1 global luminosity offset (distance)

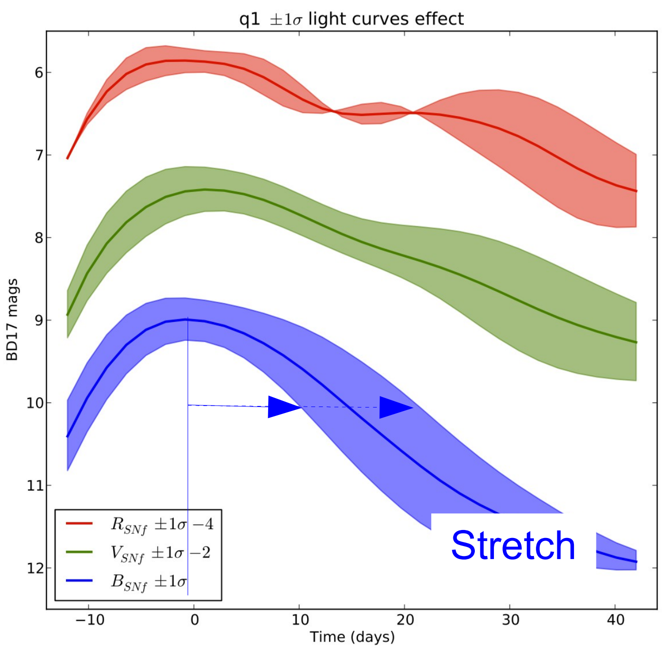
Global fit on a training data set

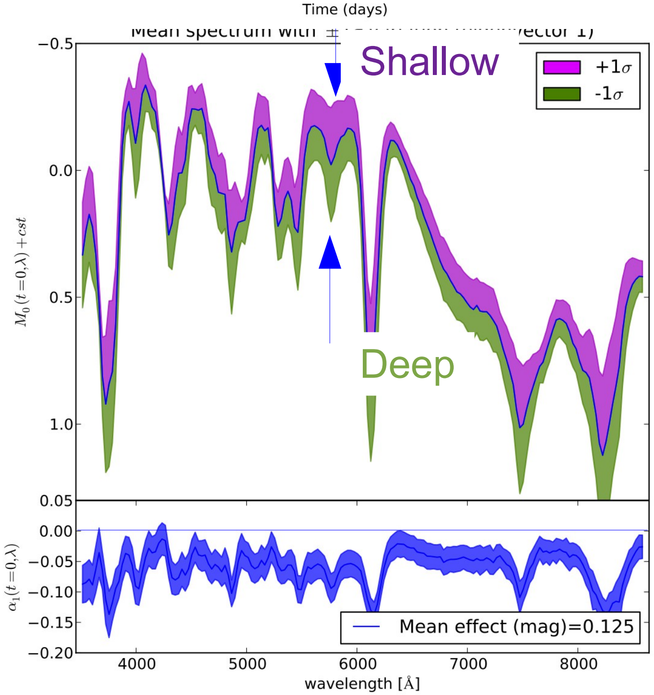
q_i fitted both on SI vectors and on spectral data

→ possible to fit SN w/o SI data.

Performances on pre-validation set

SUGAR Spectral Energy Density model :





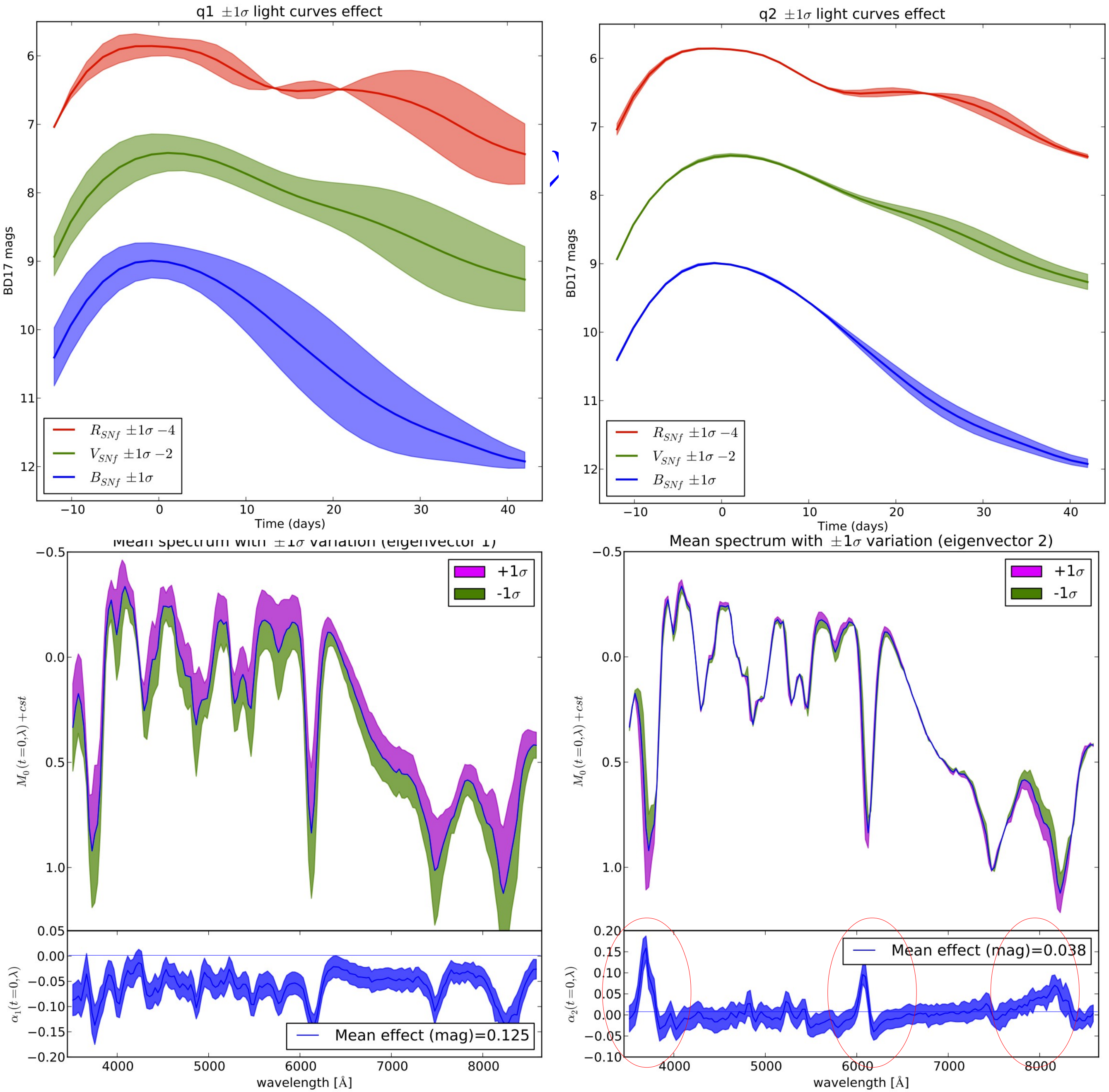
$$\lambda) + \sum_{i=1}^{i=3} \alpha_i(t;\lambda) q_i + A_V f(R_V;\lambda) + \Delta M_{grey}$$

Model response :

Average spectrum

Spectral vector 1 : (0.13 mag)
→ Brighter / Shallower
= stretch

SUGAR Spectral Energy Density model :



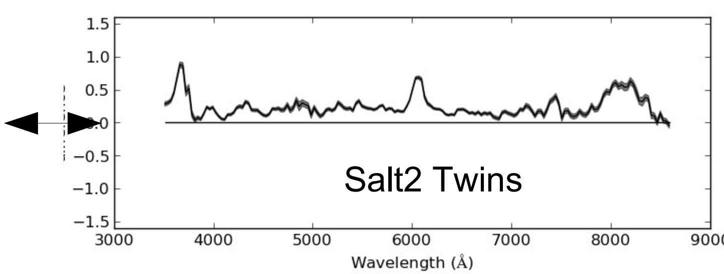
$(R_V;\lambda) + \Delta M_{grey}$

Model response :

Average spectrum

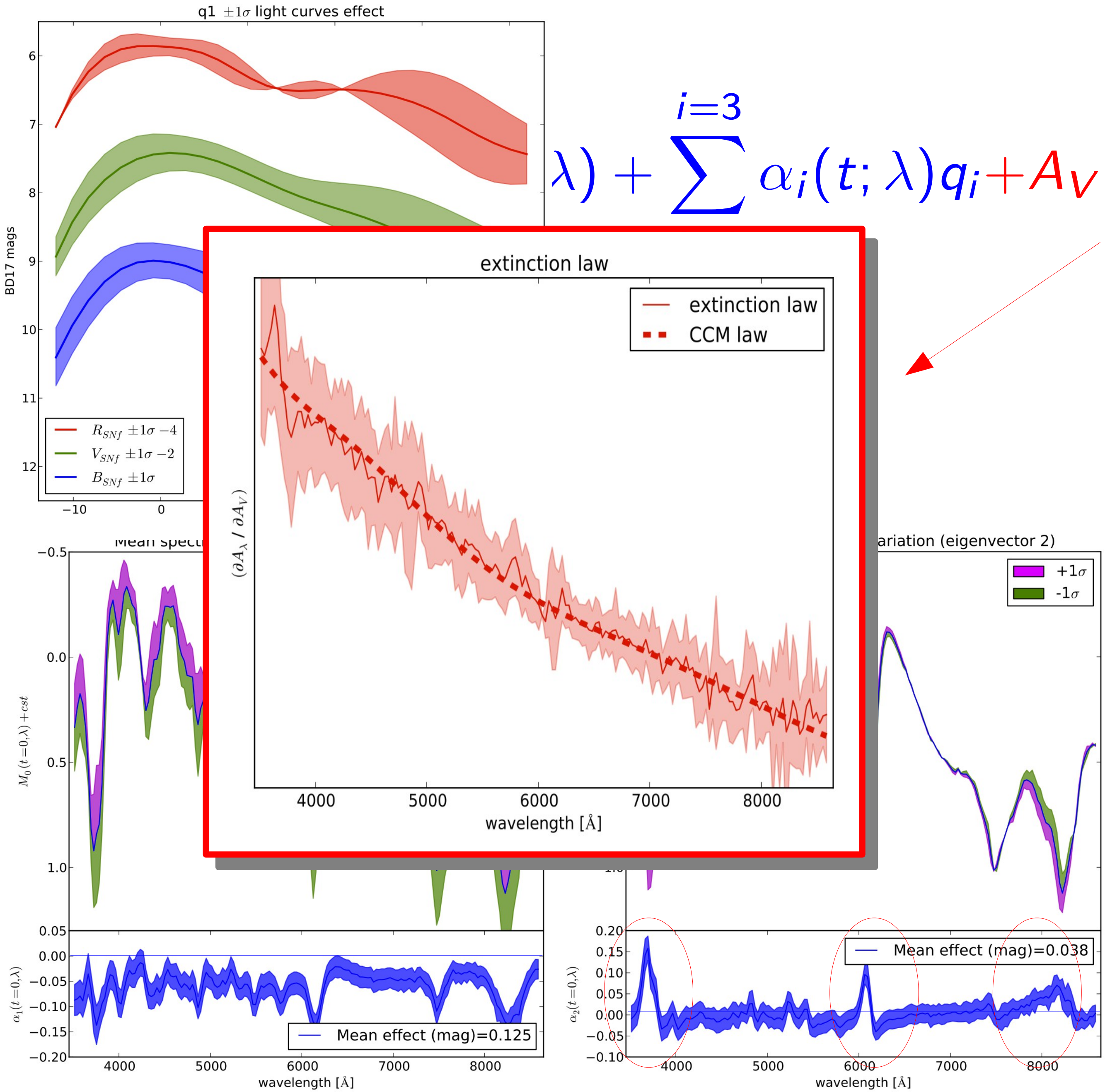
Spectral vector 1 :(0.13 mag)
→ Brighter / Shallower
= stretch

Spectral vector 2 :(0.04 mag)
→ Ca / Si correlation
= marginal on LC



SUGAR Spectral Energy Density model :

$$\ldots\lambda) + \sum^{i=3} \alpha_i(t;\lambda) q_i + A_V f(R_V;\lambda) + \Delta M_{grey}$$

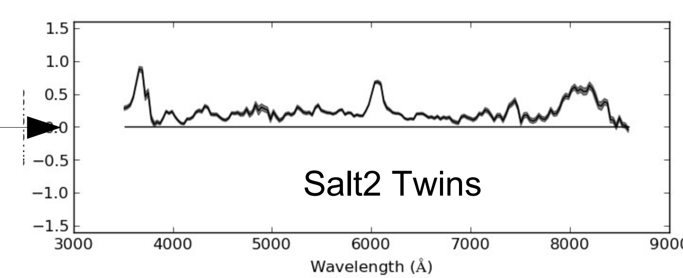


Model response :

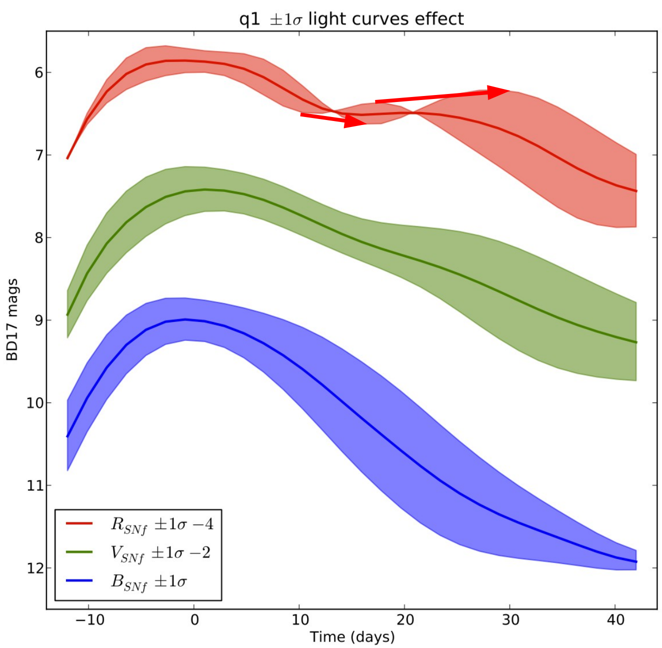
Average spectrum

Spectral vector 1 :(0.13 mag)
→ Brighter / Shallower
= stretch

Spectral vector 2 :(0.04 mag)
→ Ca / Si correlation
= *not seen by SALT2*
Impact on color law



SUGAR Spectral Energy Density model :



Model response :

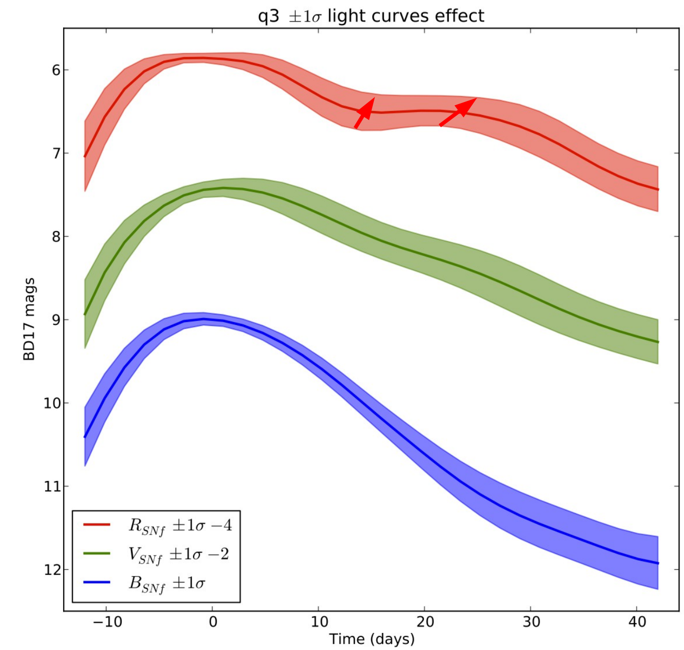
Average spectrum

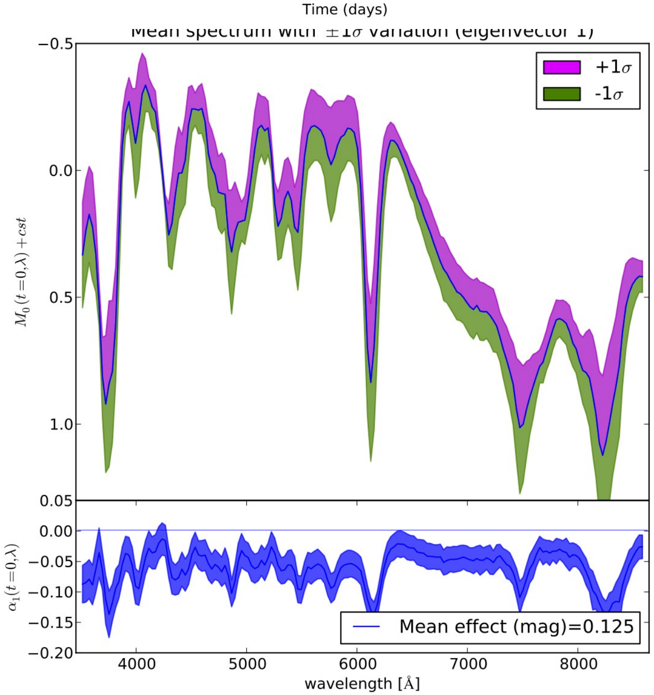
Spectral vector 1 :(0.13 mag)
→ Brighter / Shallower
= stretch

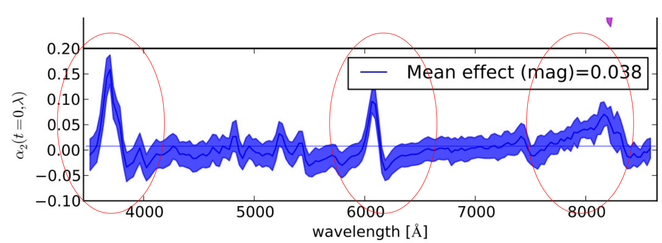
Spectral vector 2 :(0.04 mag)
→ Ca / Si correlation
Impact on color law

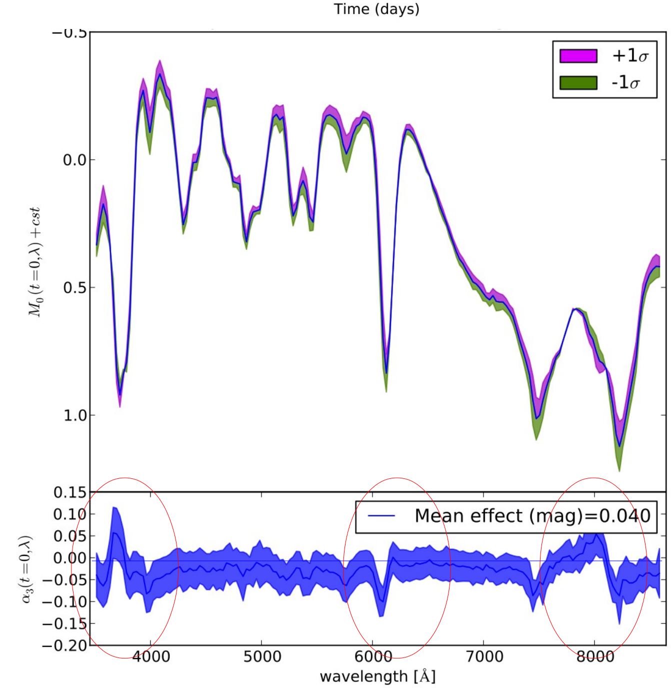
Spectral vector 3 : (0.04 mag)
→ Still Ca / Si influence
→ Global impact on LC

Can be seen in R band !



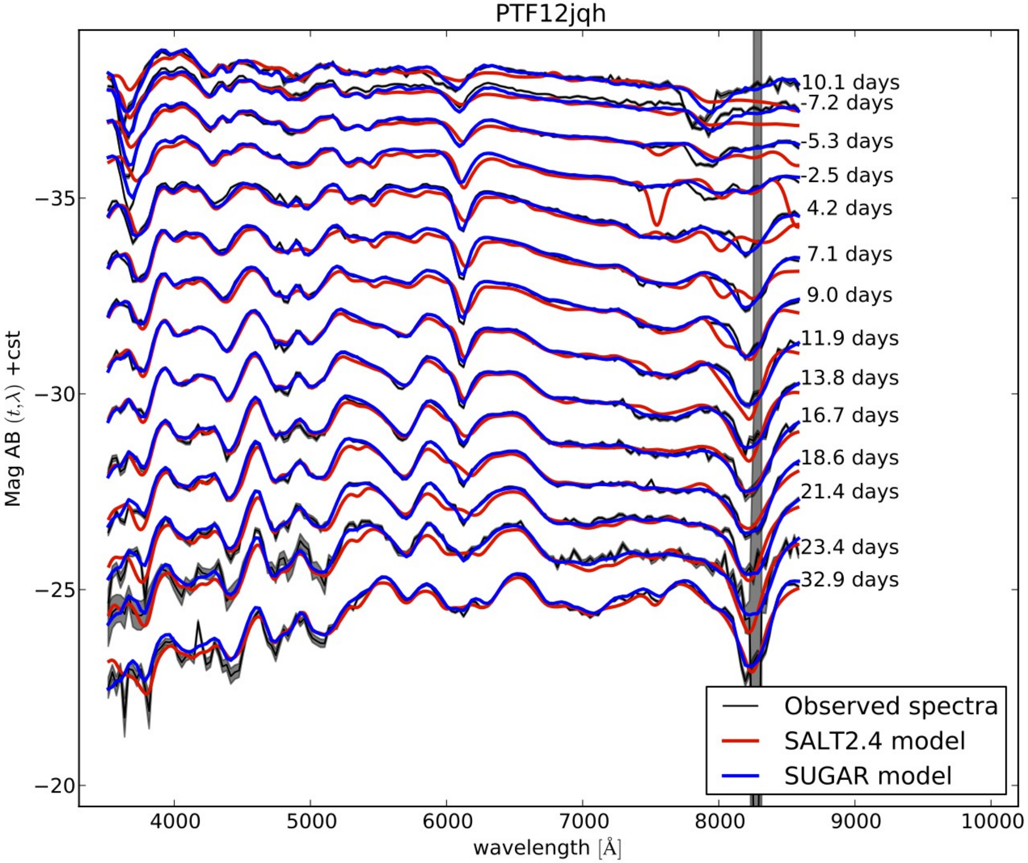




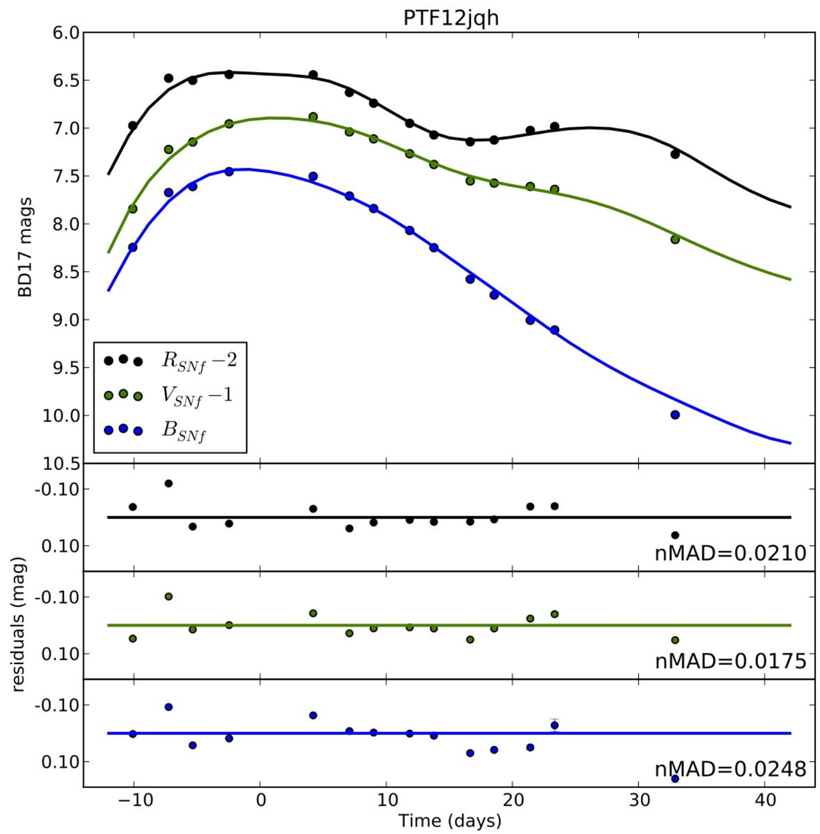


Using SUGAR as a fitter :

Spectral time serie view



Light-curve view

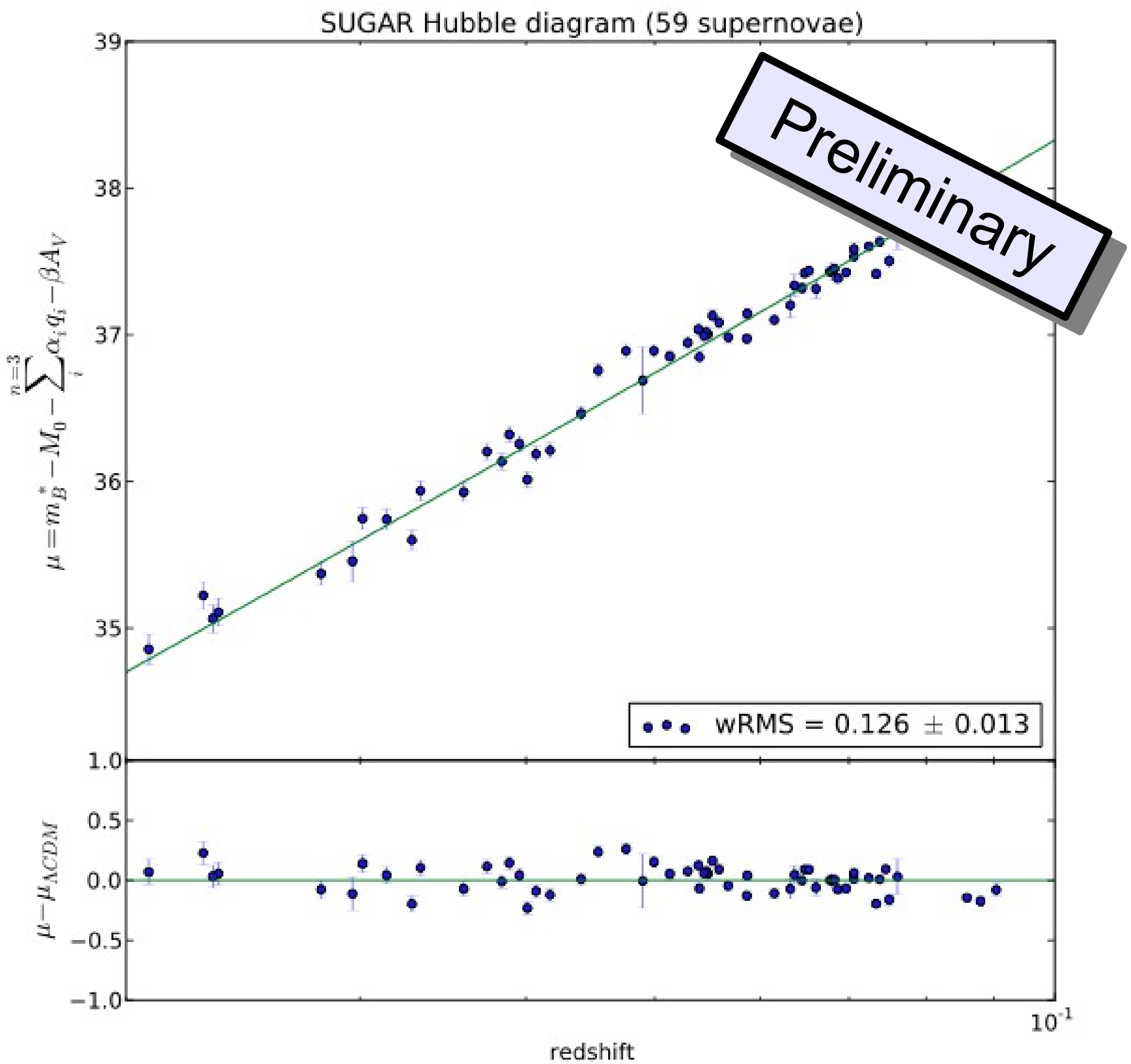


Pre-validation sample

nMAD	Bsnf	Vsnf	Rsnf
SALT2	0.073	0.051	0.056
SUGAR	0.053	0.035	0.037
Calib.	0.030	0.030	0.029

Spectral and Light-curve Description improved

Impact on standardization



Salt2-like standardization :

1) extract supernova parameters

2) fit model parameters

Preliminary results

Salt2 : wRMS = 0.13 – 0.15
SUGAR : wRMS = 0.11 – 0.13

This is SUGAR !

Supernova Useful Generator And Reconstructor

→ Allows **simulation** of more realistic supernovae
2 additional components beyond stretch and color
Confirmation color is dust-like

→ Can be used as a supernova **fitter**
Spectral timeserie fit achieves good results
Some hope for **light-curves** (component 2 may prove difficult to fit w/o spectra)

Some perspectives and open questions :

→ How to link SUGAR with host galaxy properties ?

→ Sensitivity of w to the new parametrization ?

→ Supernova standardization hits a limit near 0.08 – 0.10 mag
What does it mean ?