Cosmology with Type Ia Supernovae

Pierre-François Léget

Kavli Institute for Particle Astrophysics and Cosmology
Stanford University

1. Cosmology & Type Ia Supernovae

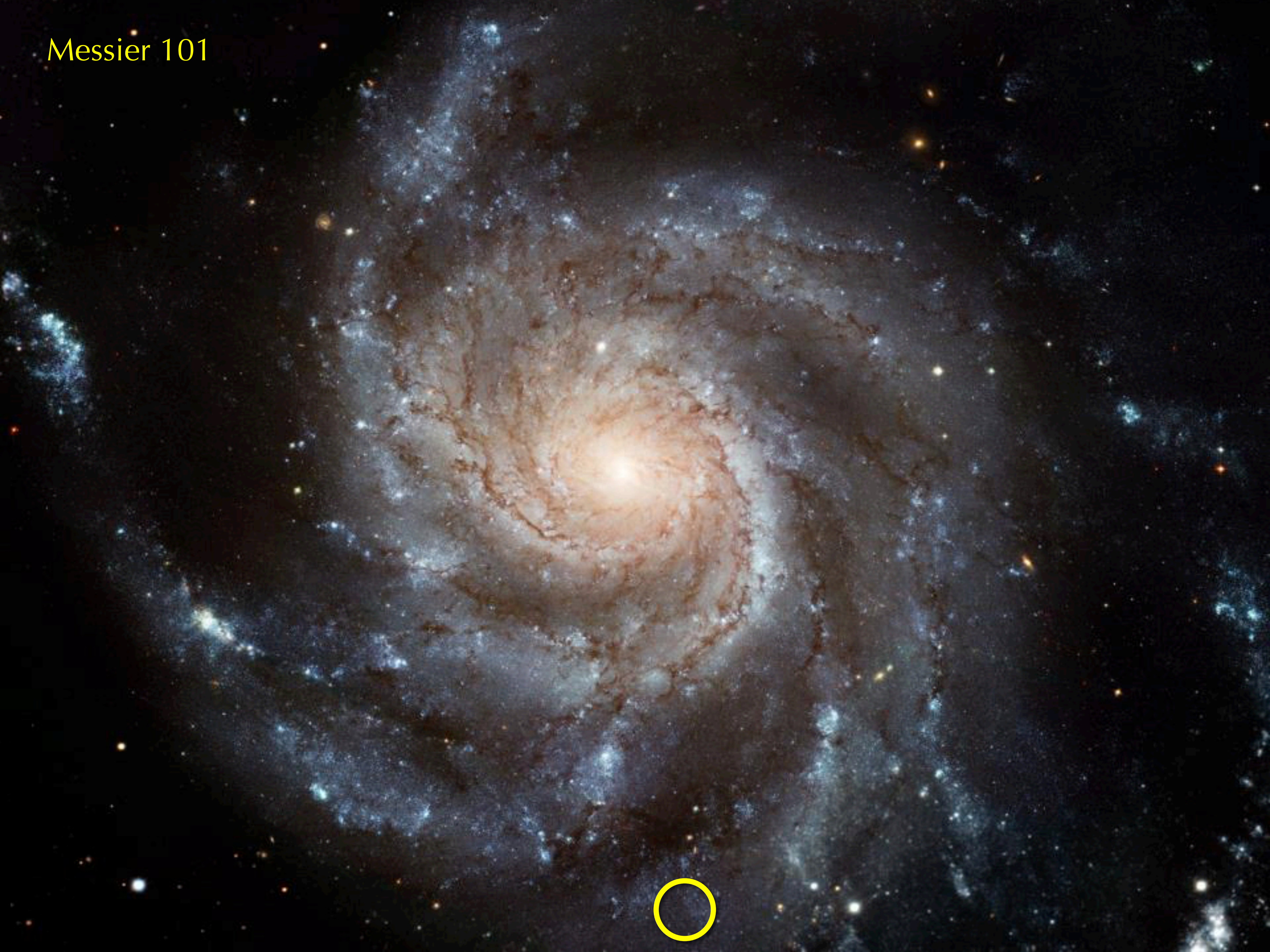
2. Towards a new SNIa model

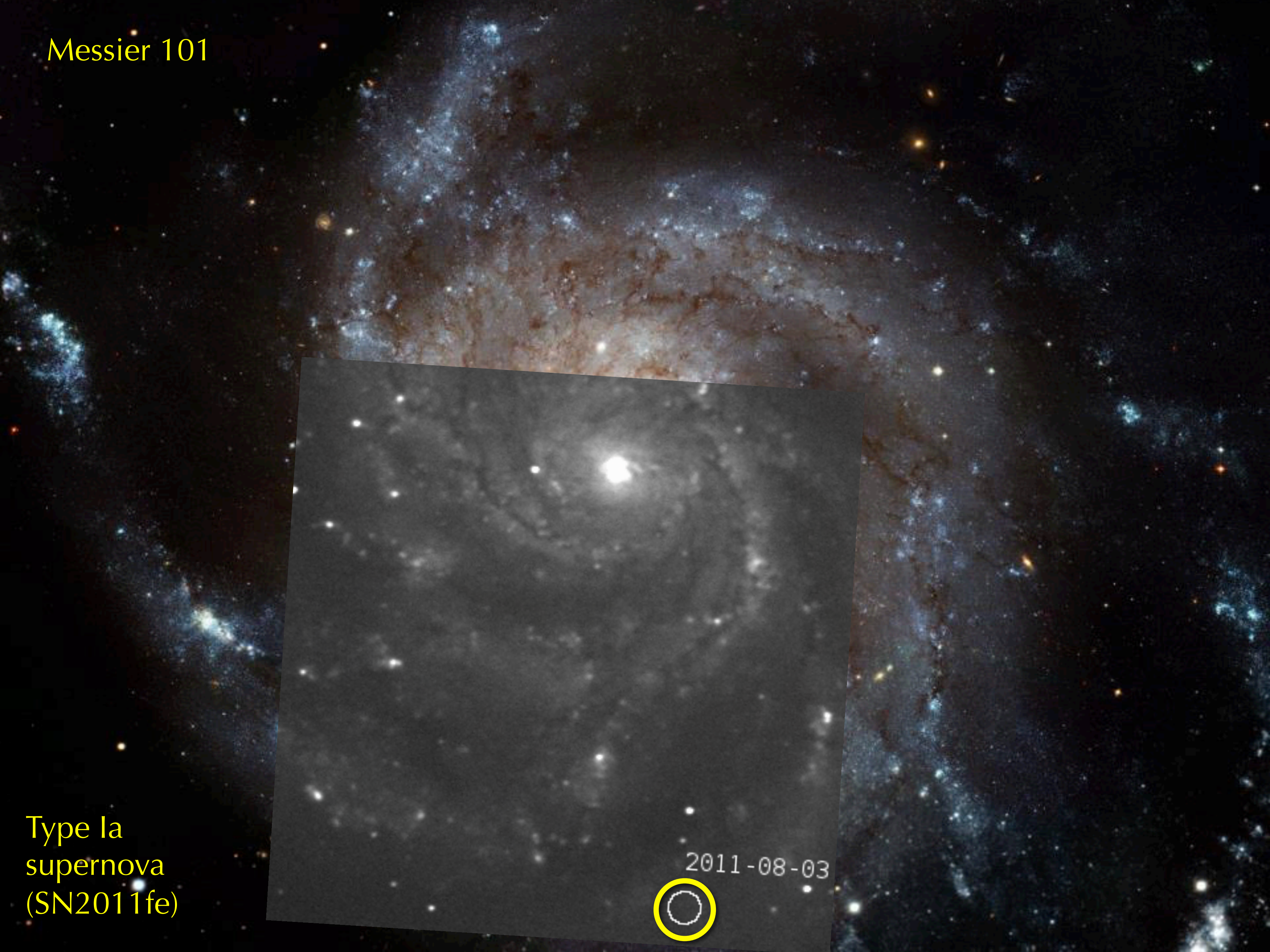
3. Building the Supernova Useful Generator And Reconstructor model

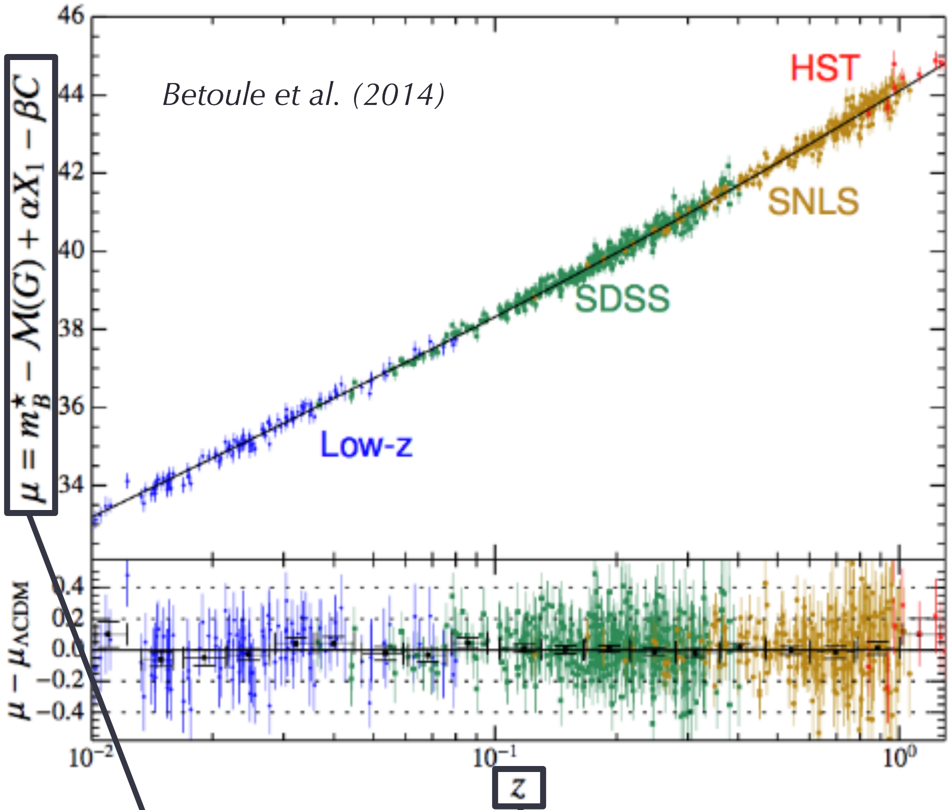
4. SUGAR model results

5. Conclusions & perspectives


Messier 101

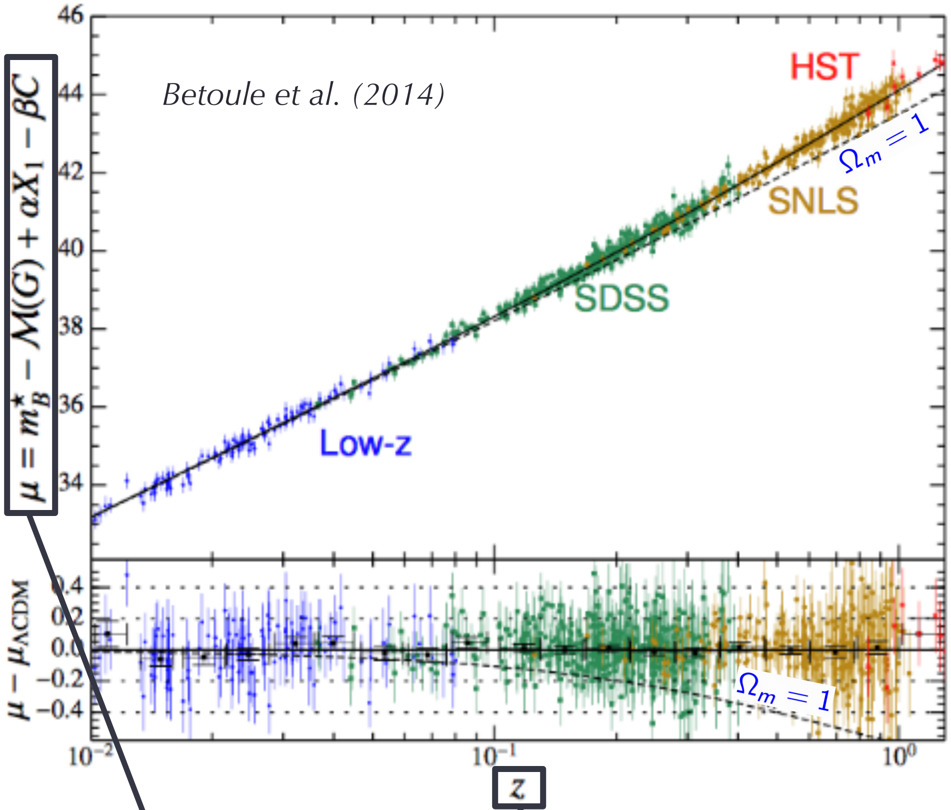

Messier 101


Messier 101
2011-08-03
Type Ia
supernova
(SN2011fe)



Redshift
(Universe speed expansion
measured on host galaxy)

Distance modulus
(measured with type Ia supernovae) → $\mu = 5\log_{10}\left[d_L\left(z, H_0, \Omega_m, \Omega_\Lambda, \ldots\right)\right] - 5$



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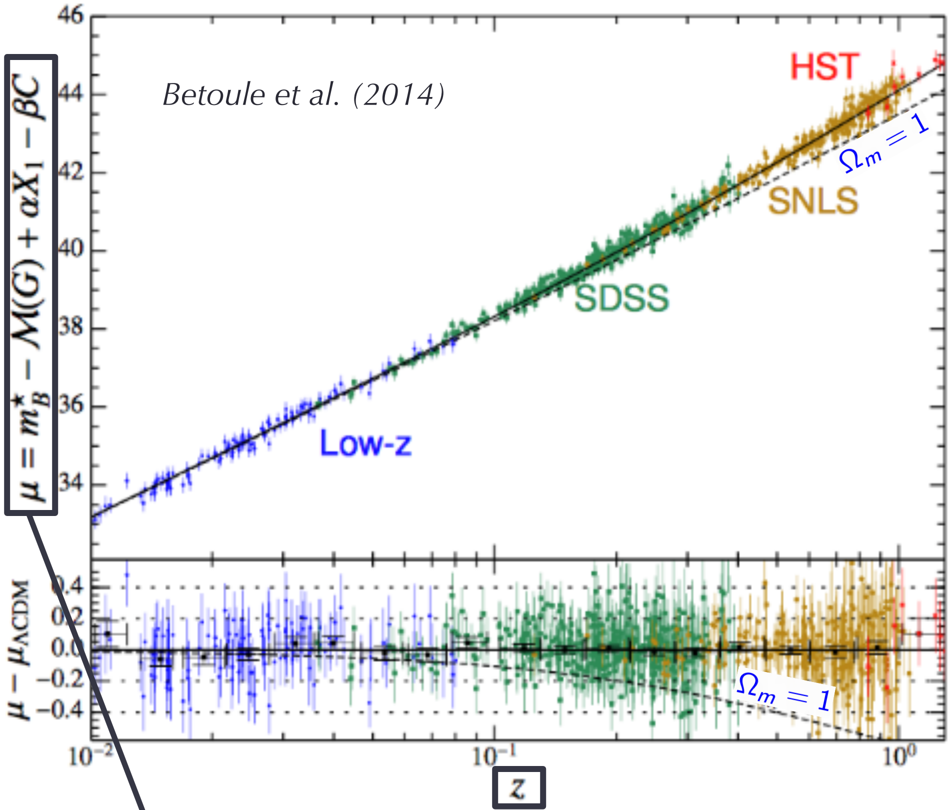

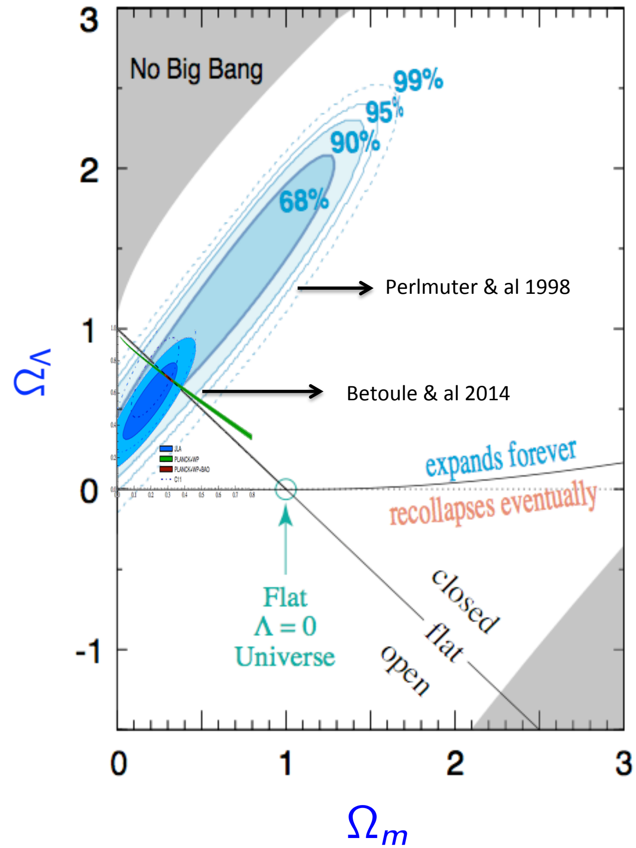

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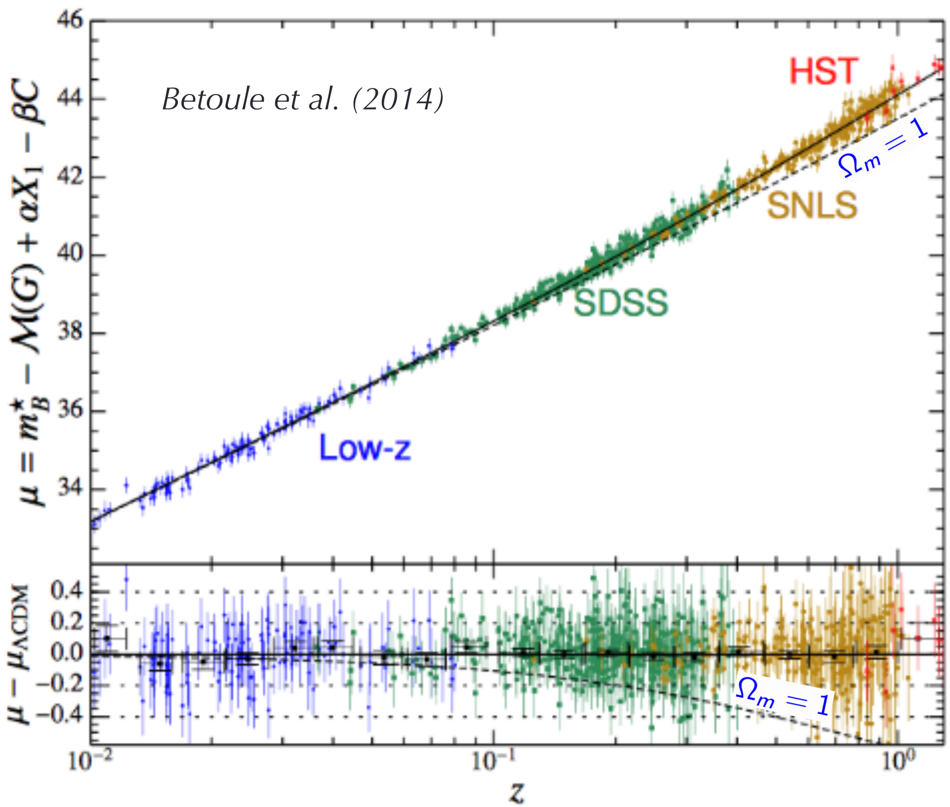
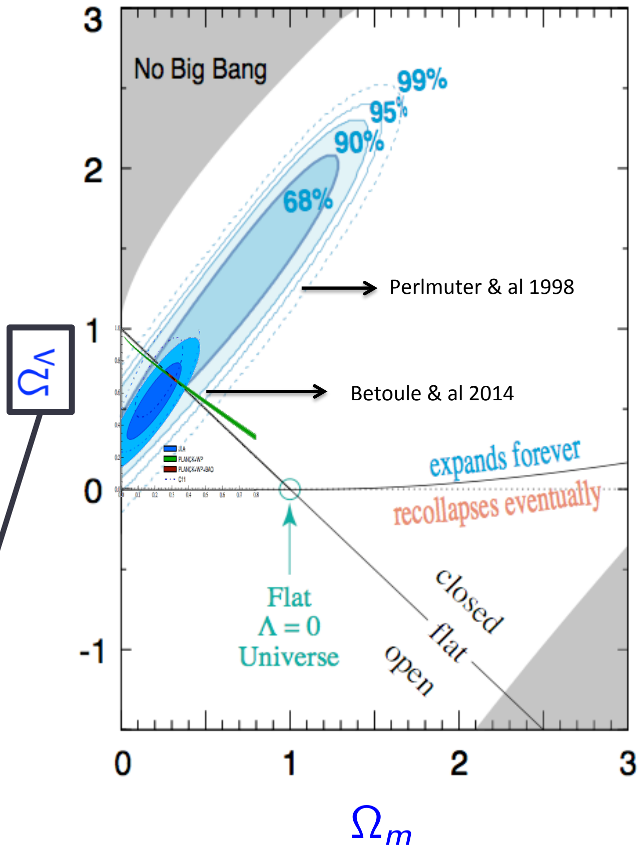
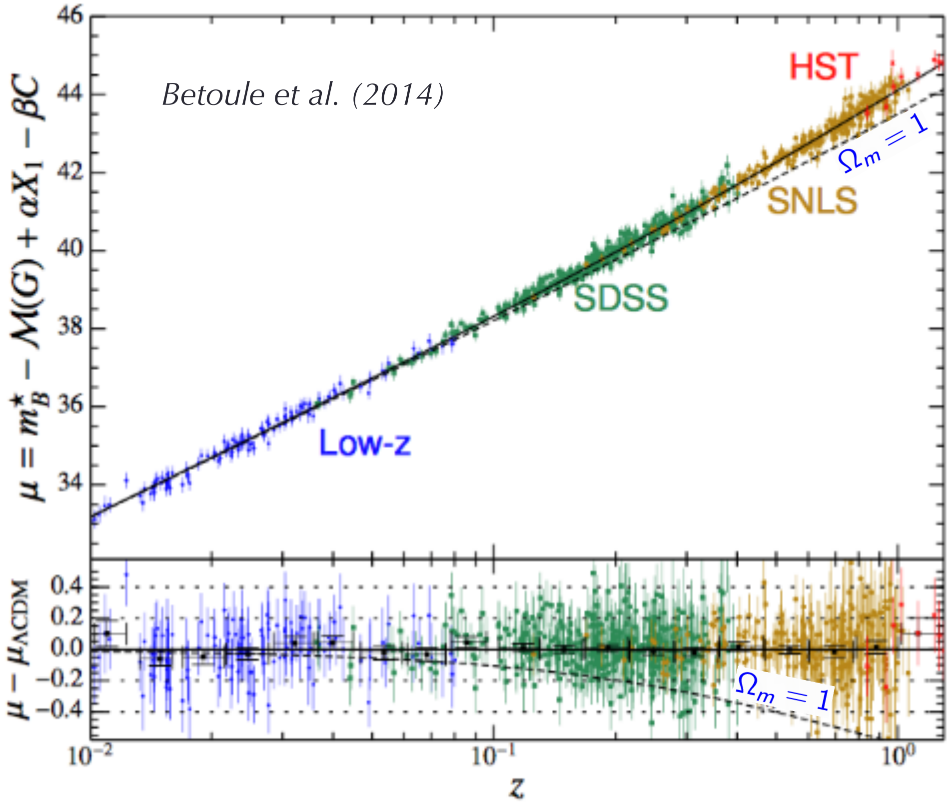
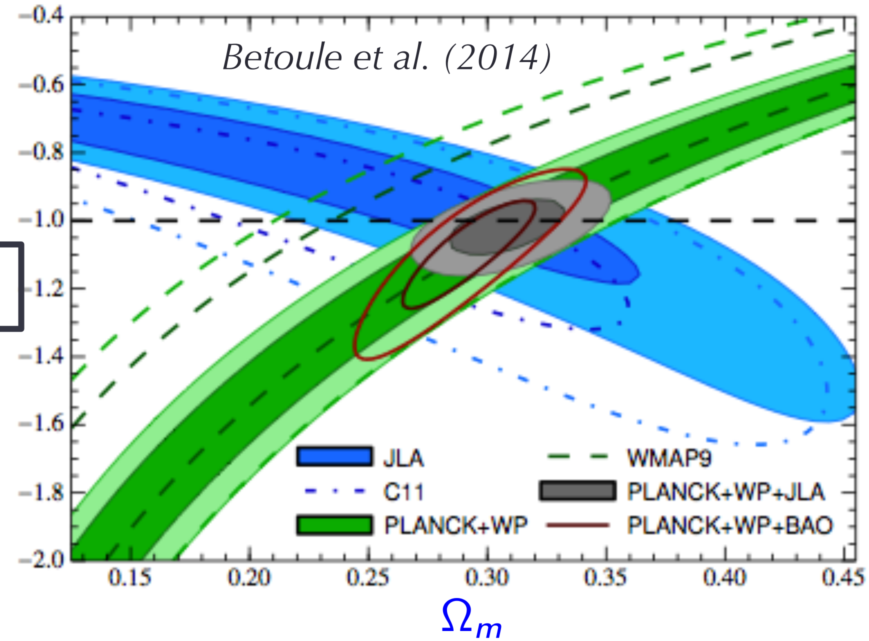




$P_{DE} = w \ \rho_{DE} \ c^2$ Dark Energy state equation

$w = -1$ → Cosmological constant



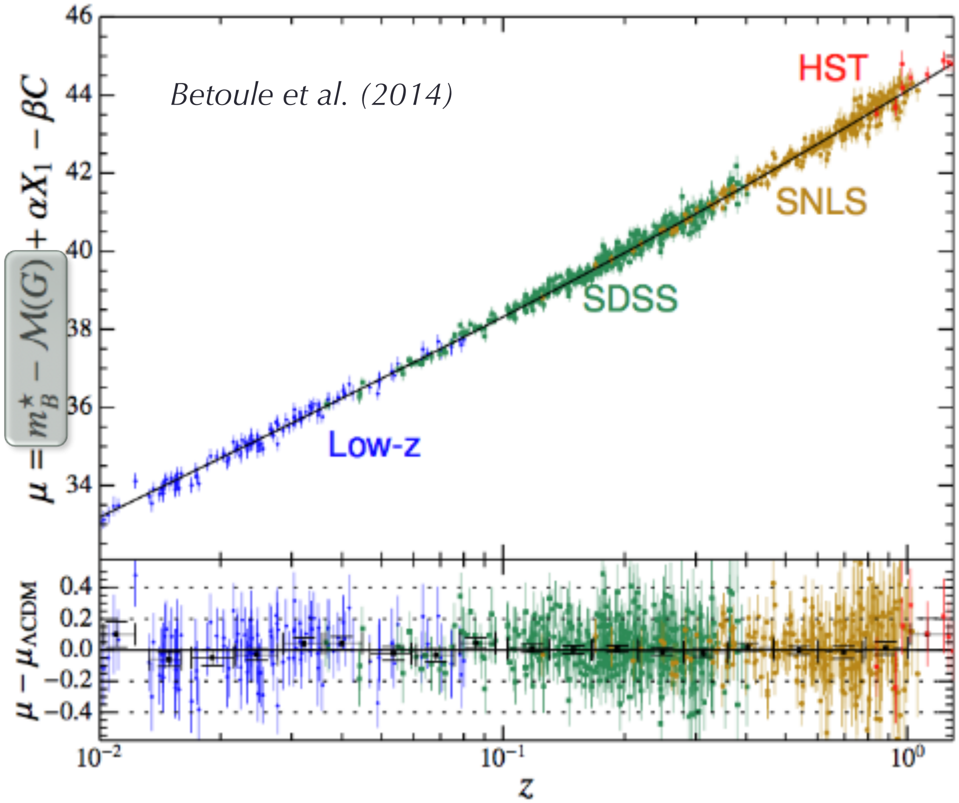


$P_{DE} = w \, \rho_{DE} \, c^2$ Dark Energy state equation

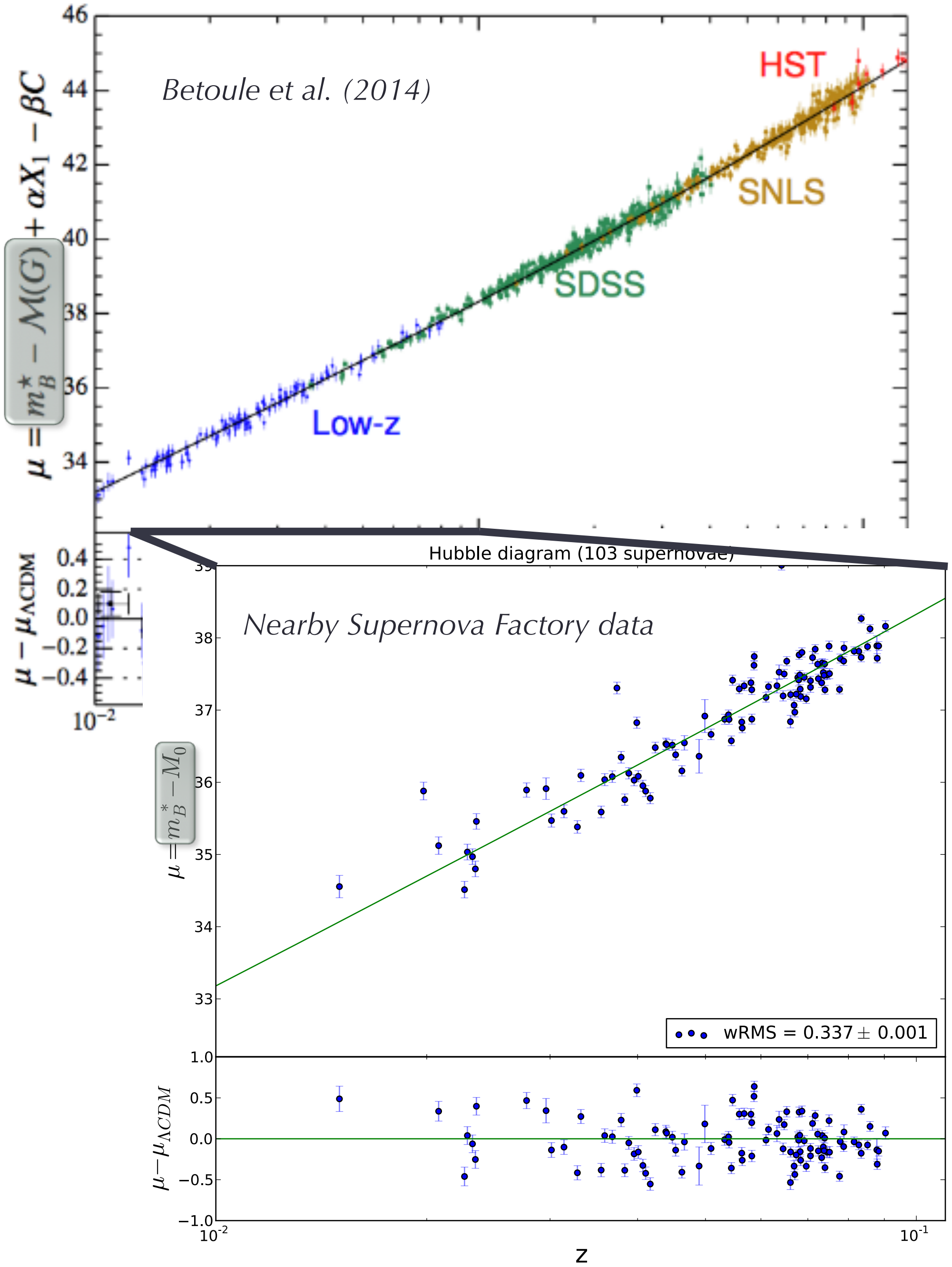
$w = -1$ → Cosmological constant

- Constraints on dark energy parameters come from cosmological **probes combination**
- We need to improve measurements for each cosmological probe

Focus here on SNIa → Currently best probes in the redshift range [0;1.5]



Supernovae are quasi-standard candles:



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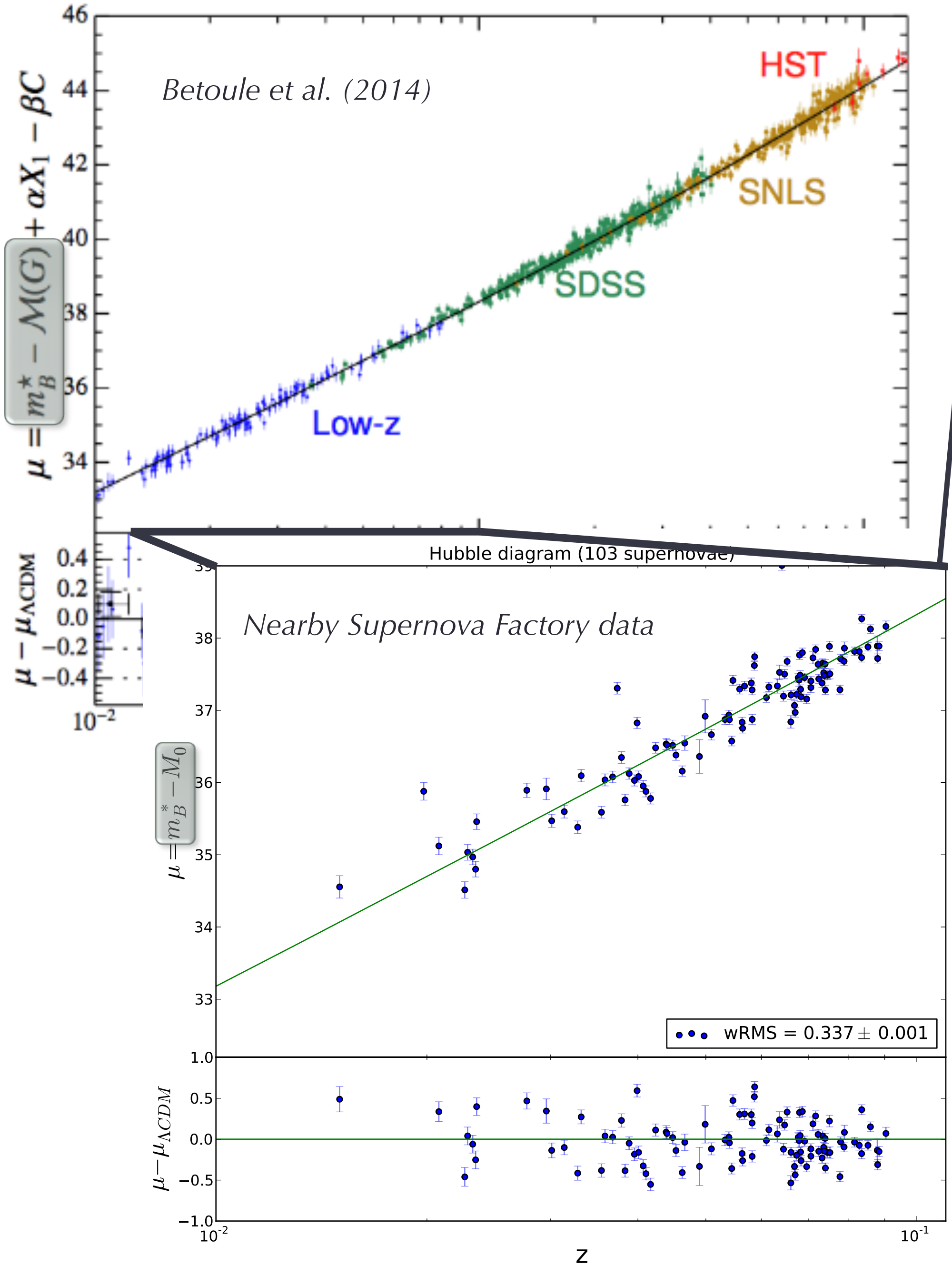
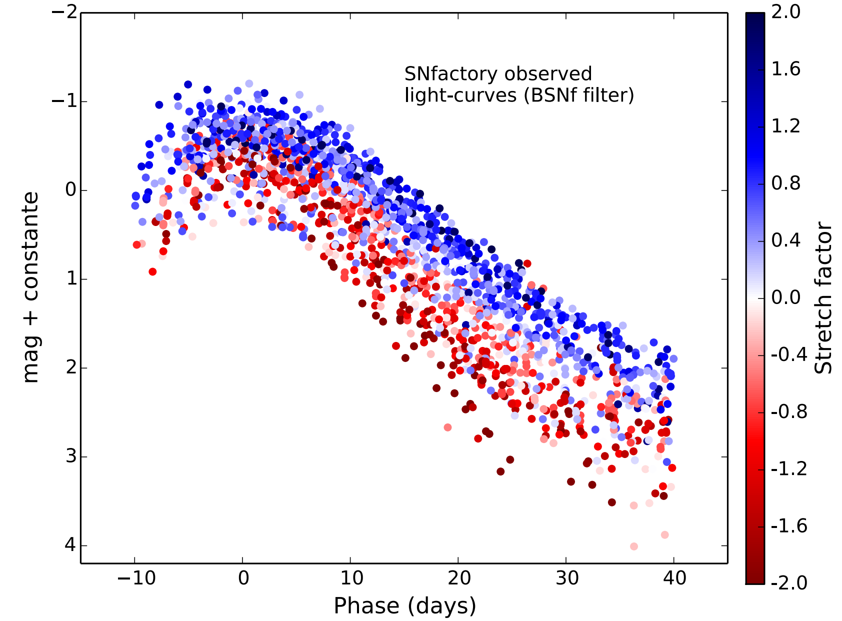


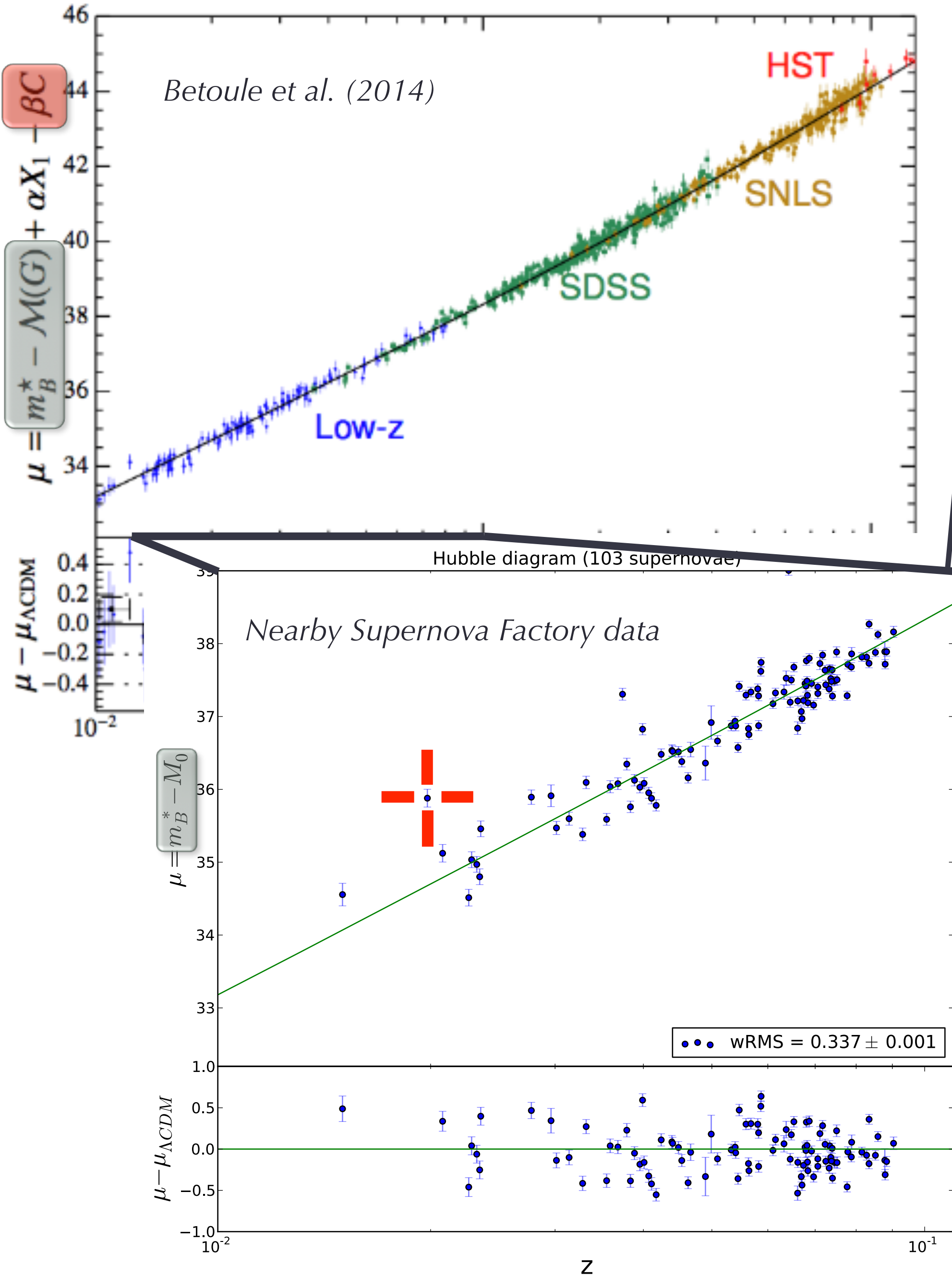
Supernovae are quasi-standard candles:

Two main sources of variability

1) Stretch: intrinsic variability



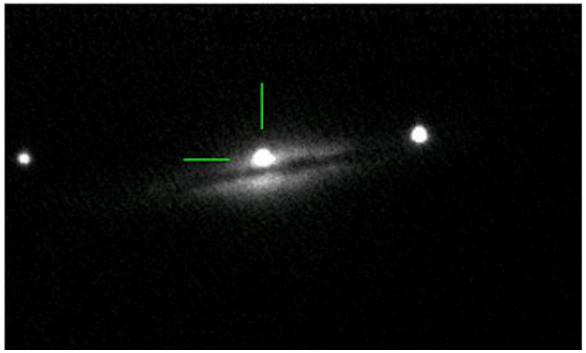
Link to physical properties



Supernovae are quasi-standard candles:

Two main sources of variability

1) Stretch: intrinsic variability
2) Color: dust extinction + intrinsic color ?



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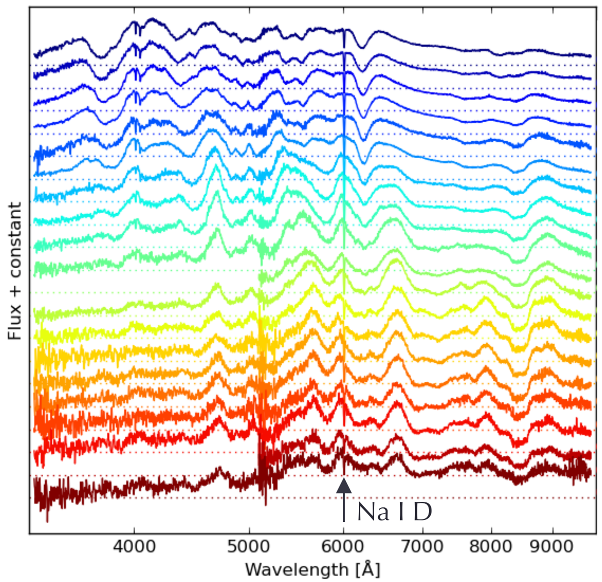

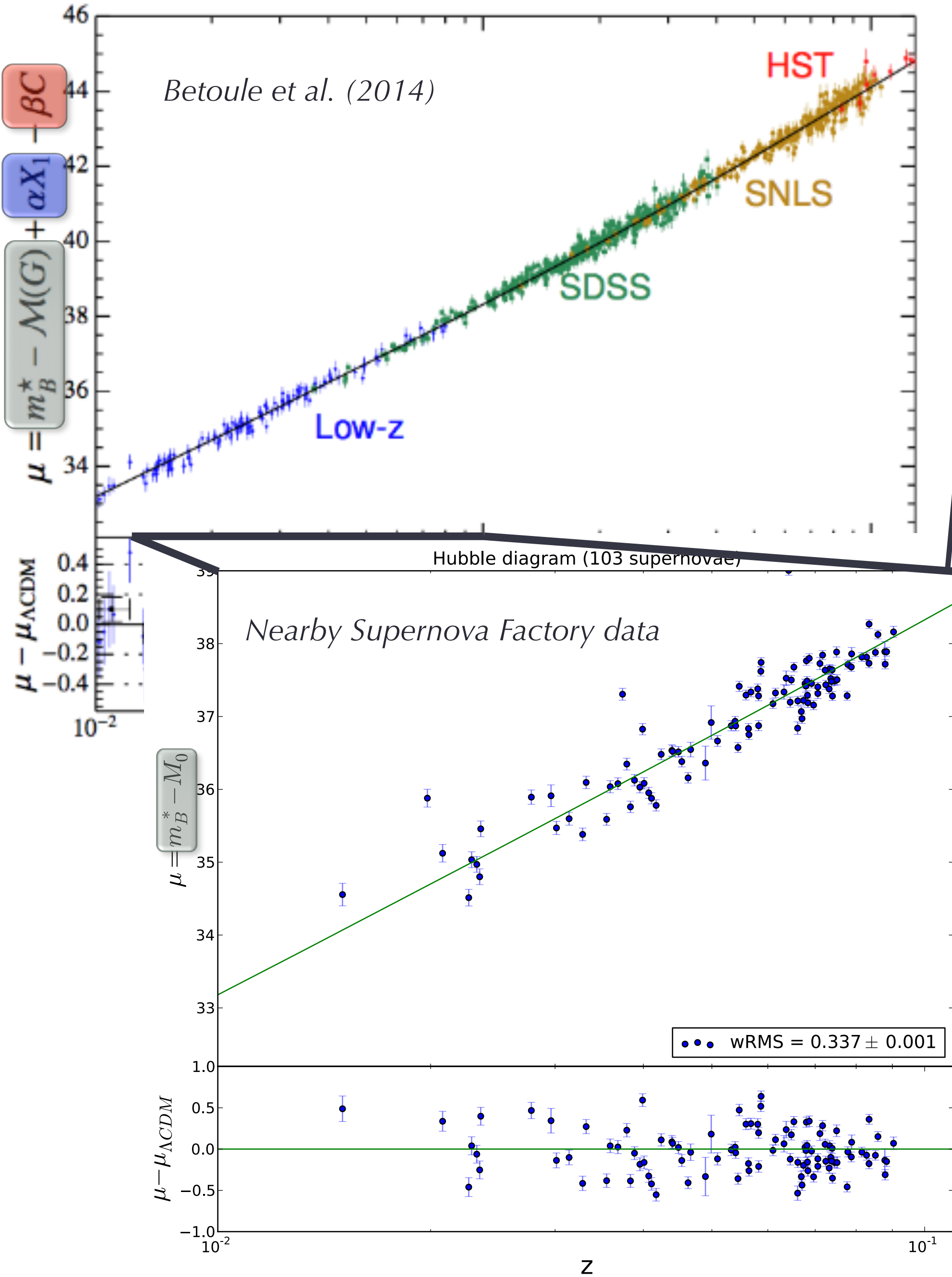

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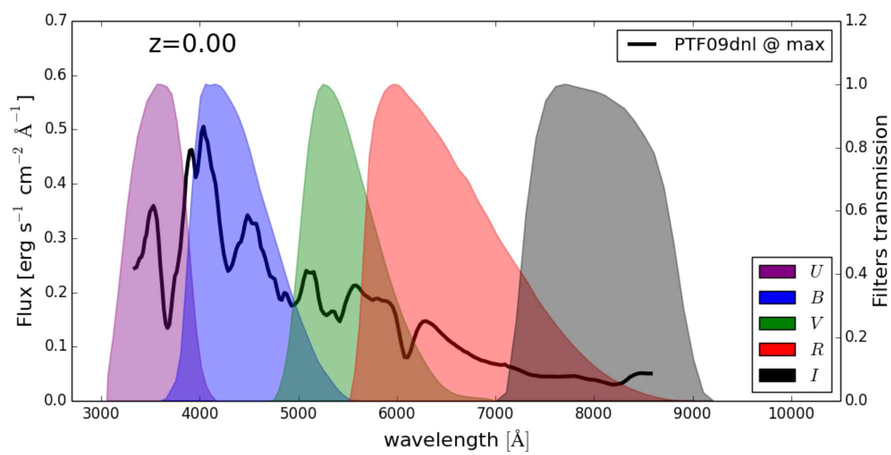
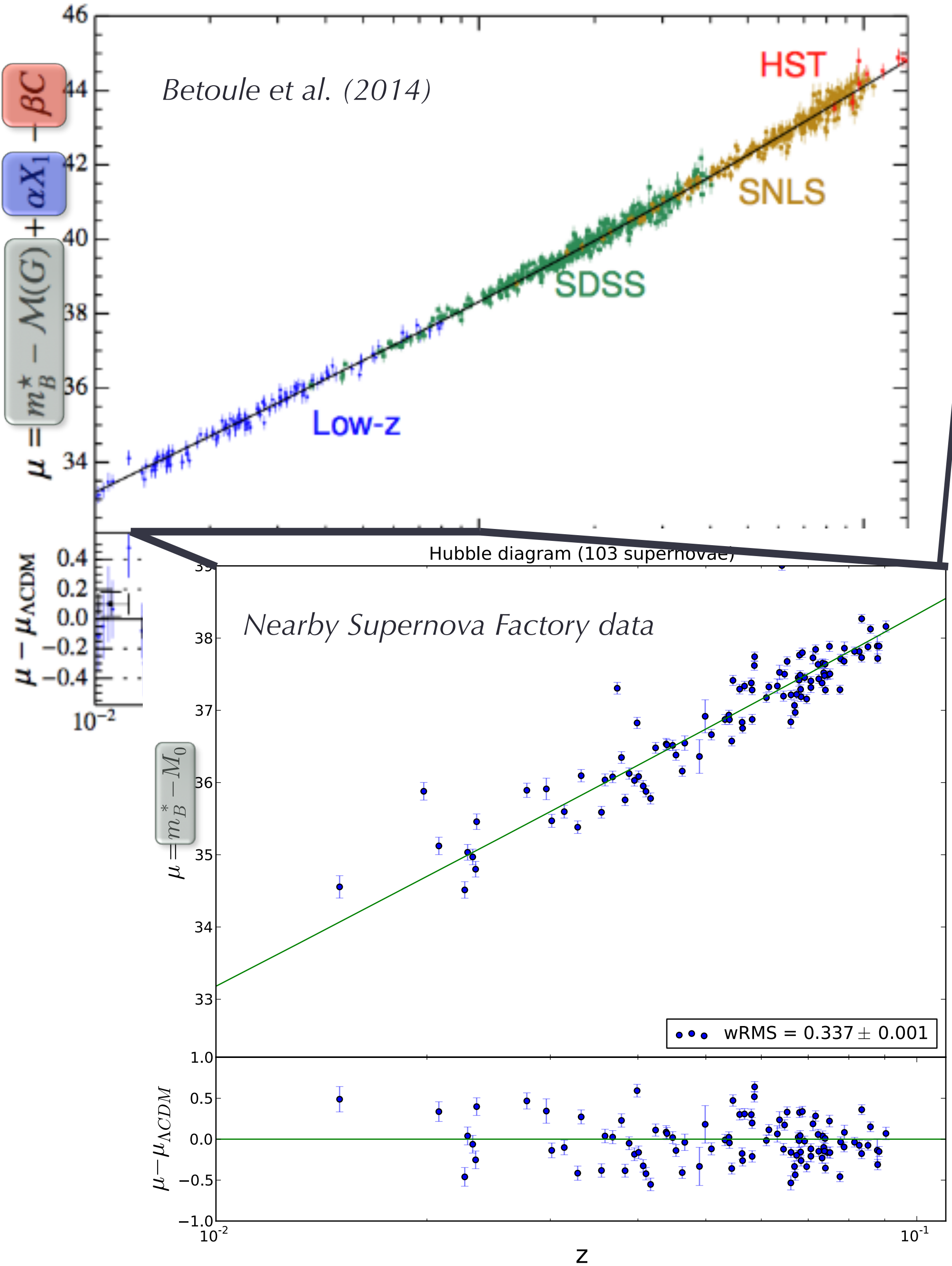


- Measured on light curves with photometric survey
- Need of SNIa model to take into account redshift effect



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Two main sources of variability

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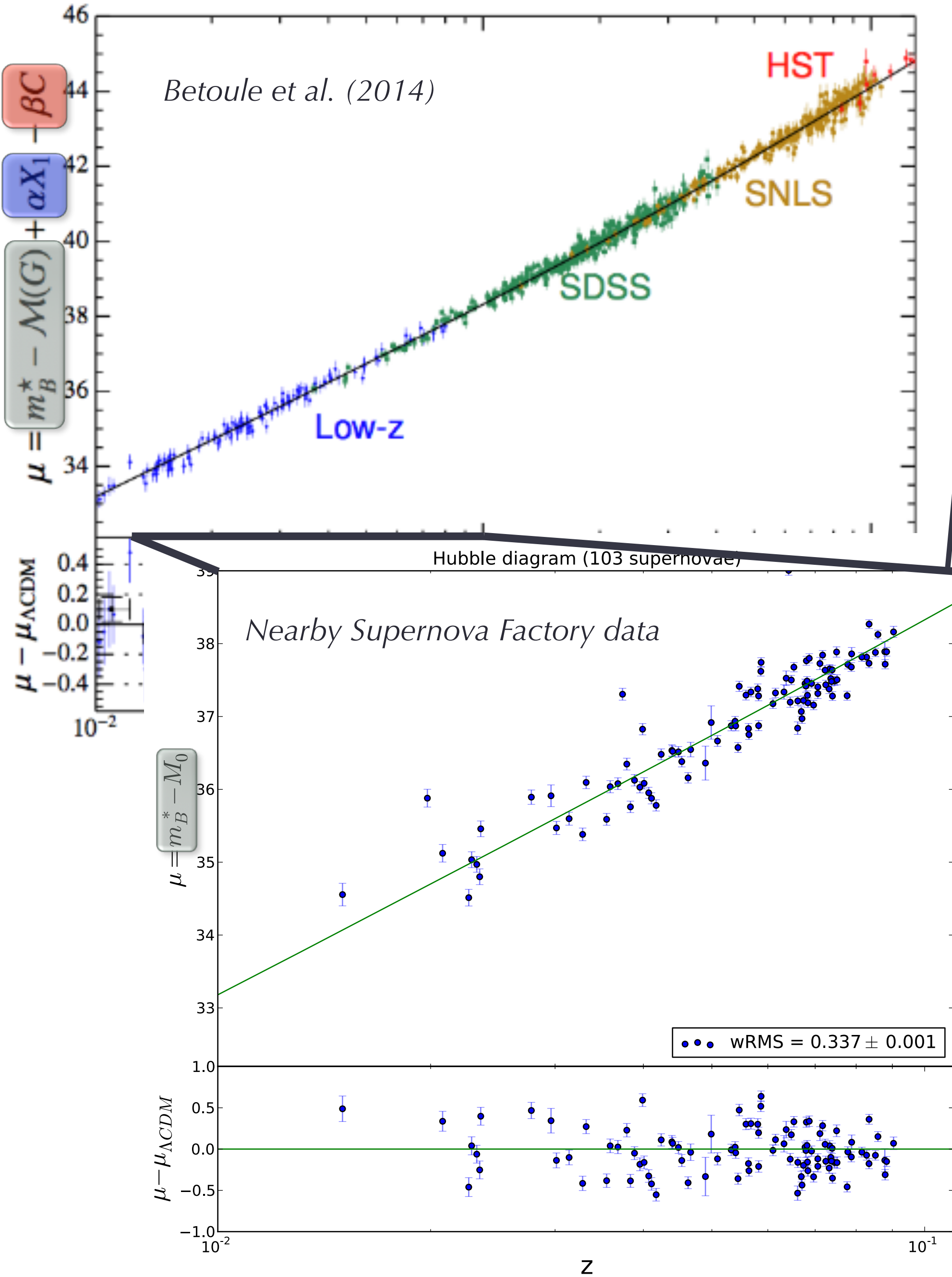
SALT2 (*Guy & al (2007)*) :

$$F(p;\lambda) = x_0 \times [S_0(p;\lambda) + x_1 S_1(p;\lambda)] \times \exp[cCL(\lambda)]$$

- X0 → correlated to redshift
- X1 → Stretch effect, associated to intrinsic variability
- C → Color effect, fit a global SNIa color (intrinsic and extrinsic color)



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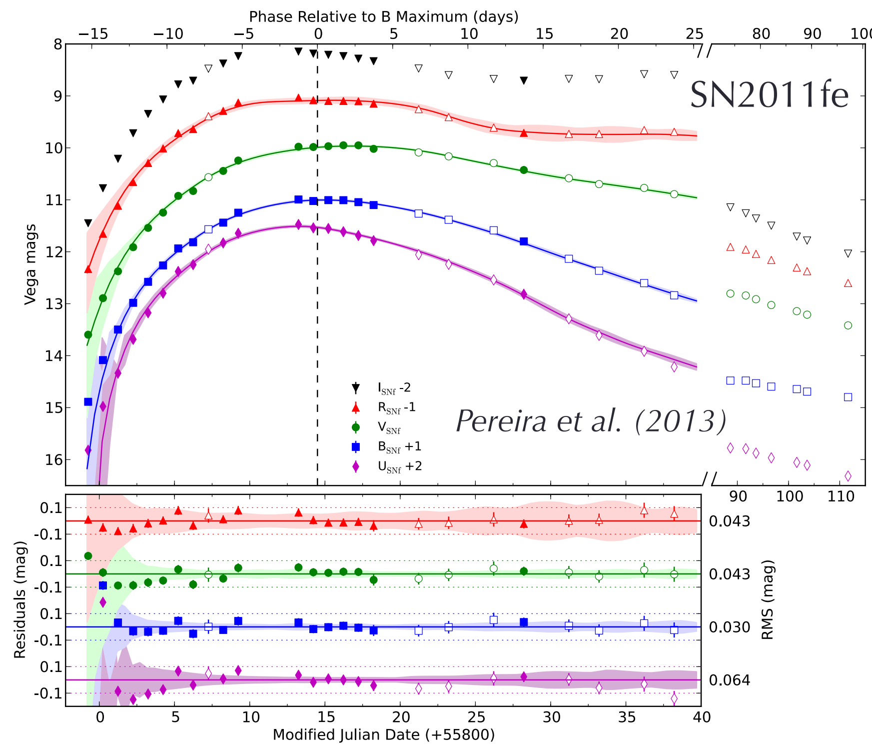

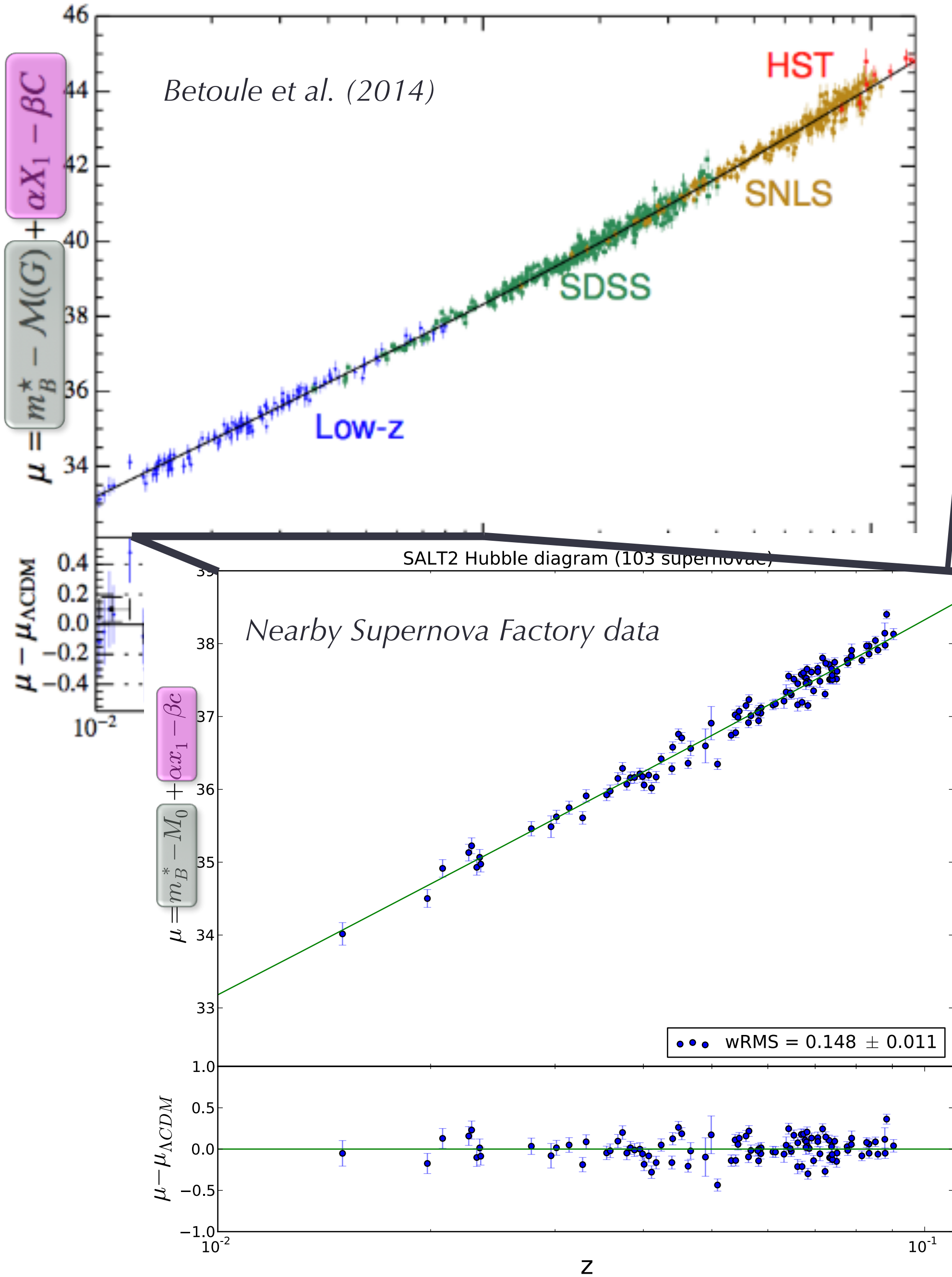

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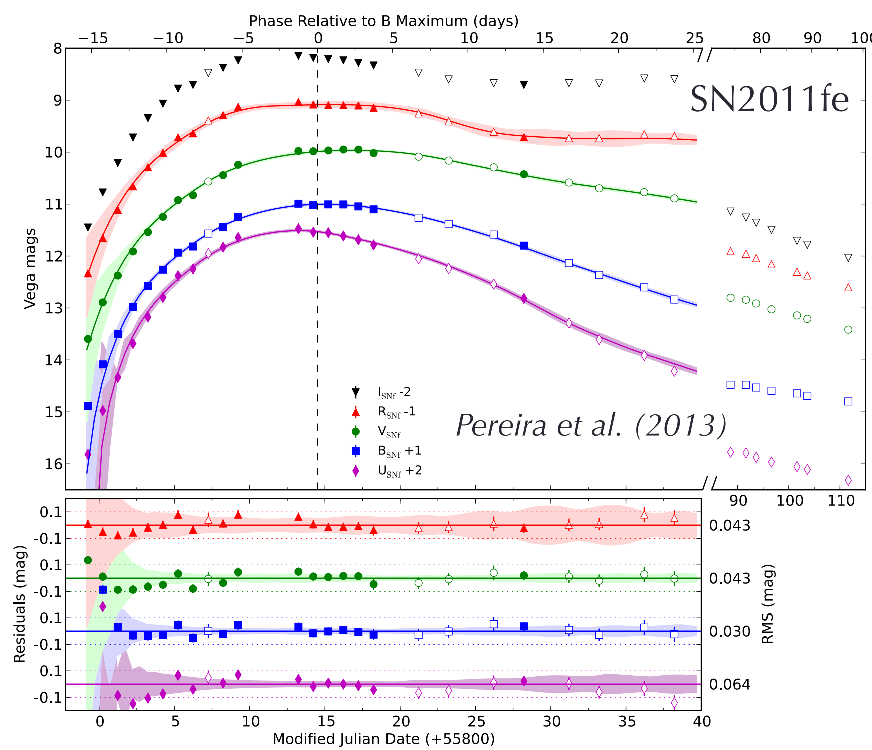
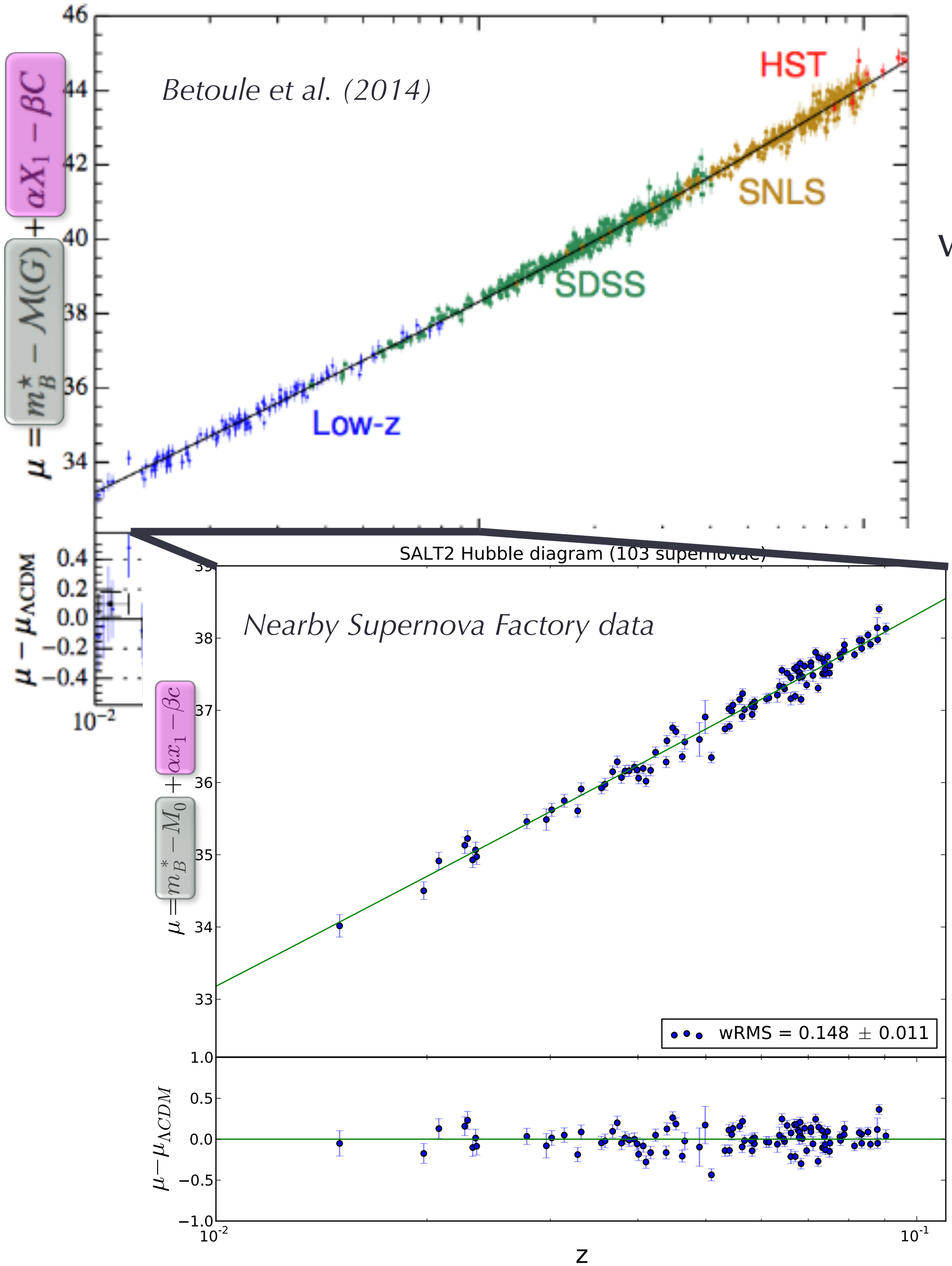
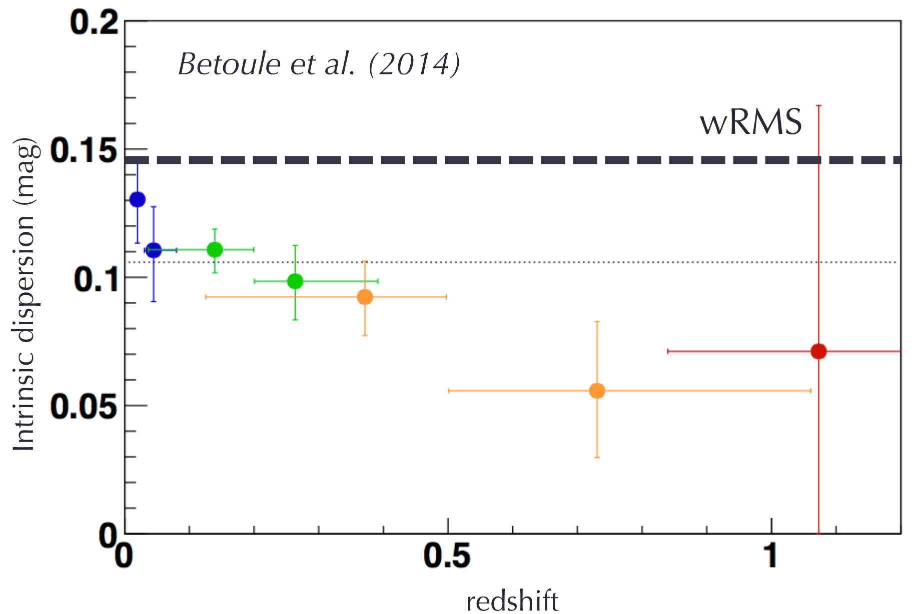




State of the art with SNIa

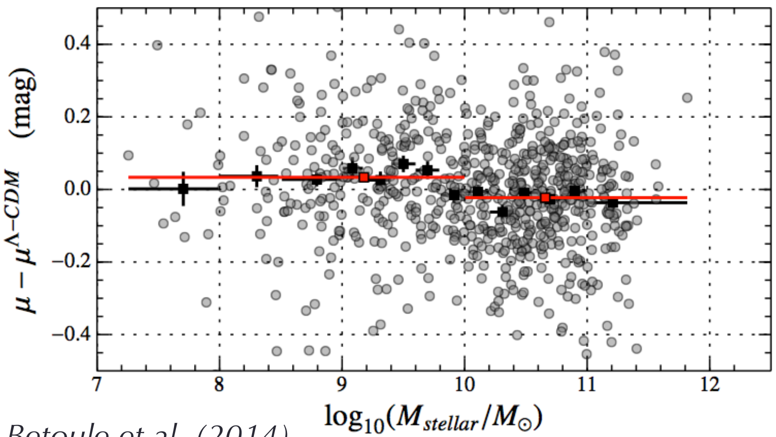
wRMS ~ intrinsic dispersion + measurement noise



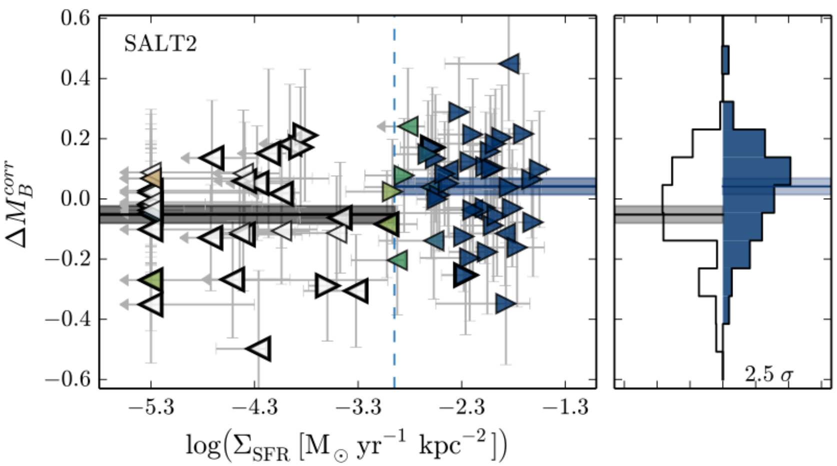
Evolution with redshift of intrinsic properties

Limits of current SED model:

Host Dependancies:



Betoule et al. (2014)

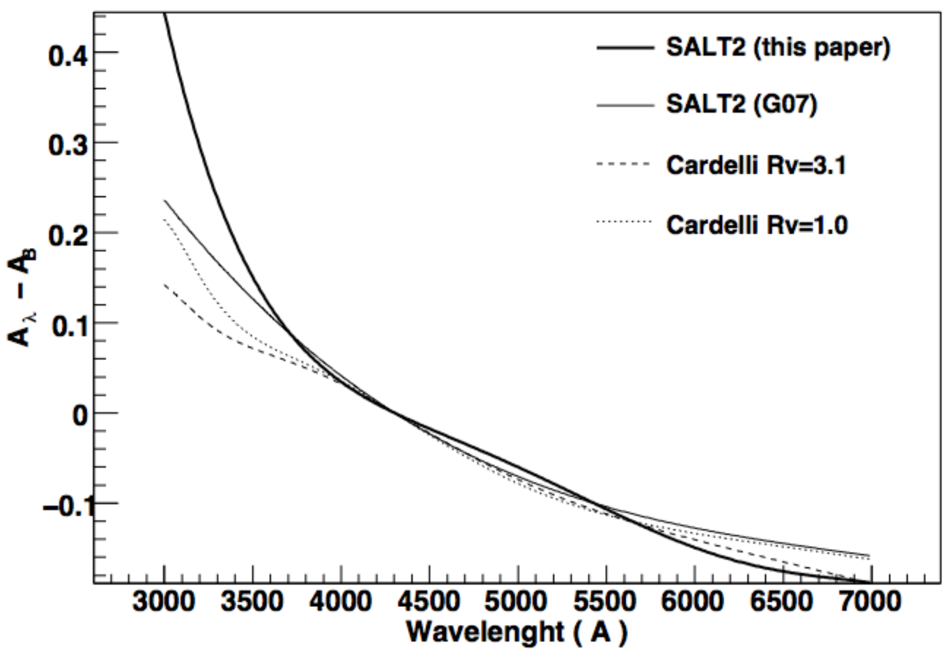


Rigault et al. (2015)

- Dependency of Hubble residuals after standardisation with Host mass
- Correlated to local Host properties :
  - The local H alpha emission (*Rigault et al. (2013)*)
  - The local Star Formation Rate (*Rigault et al. (2015)*)
- Bias in the cosmology analysis : → Host mass added to standardise SNIa

Limits of current SED model:

Intrinsic color vs extrinsic color:

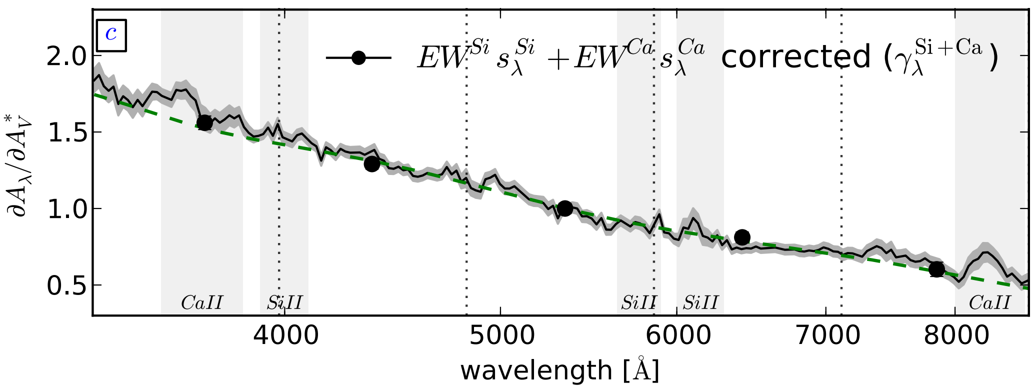


Guy et al. (2010)

- Really low value of the extinction ratio Rv compared to Milky Way Rv
- Global properties of Host?
- Mixing between intrinsic color and extrinsic color? Do we need to add other parameters?
- Systematic errors that are not taken into account?

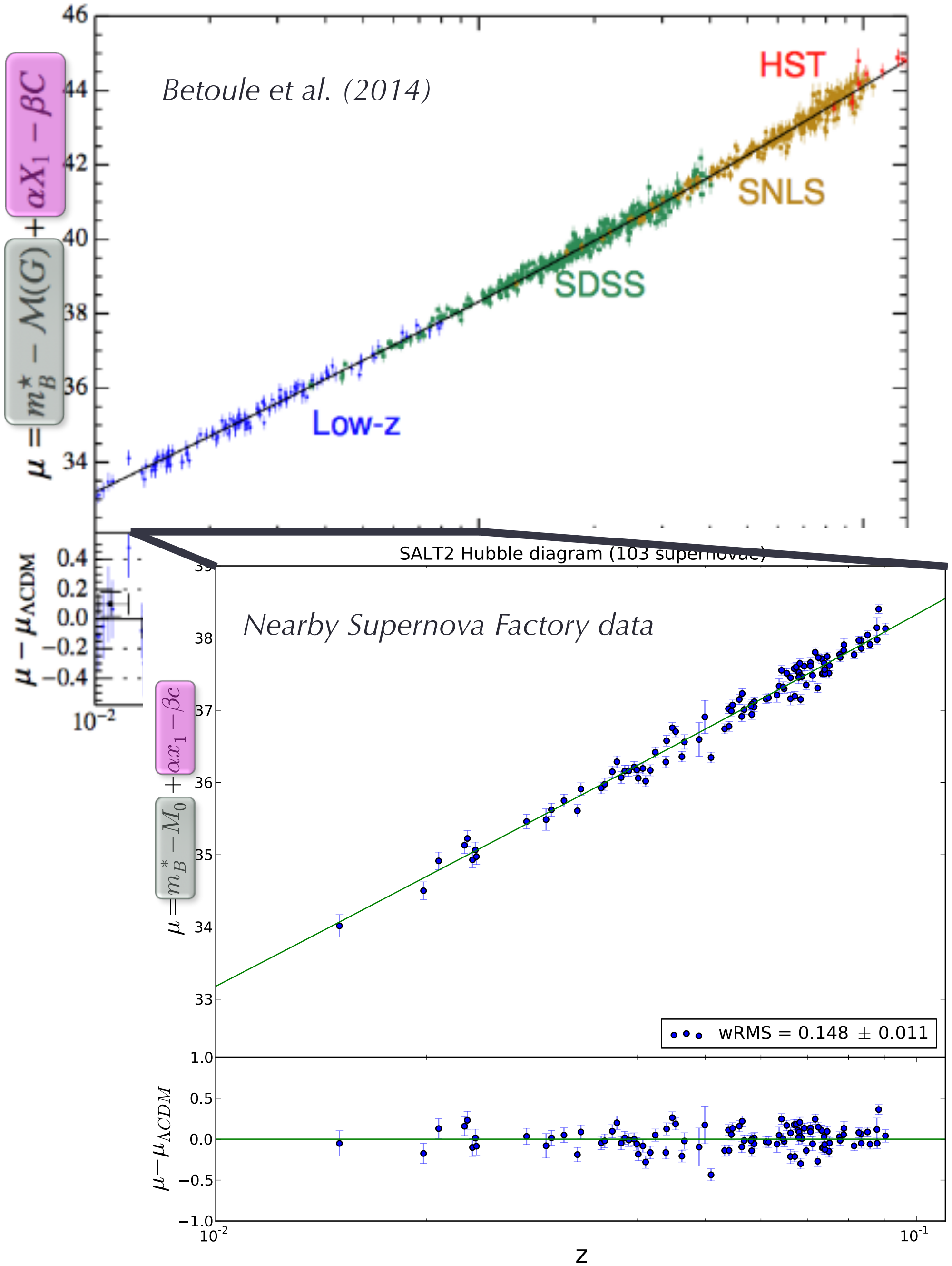
Limits of current SED model:

Chotard et al. 2011 analysis (C11) :



Chotard et al. (2011)

- Two parameters rather than one. Come from spectral features.
- Better understanding of systematic error
- Rv=2.8±0.3 (compatible with Milky way)
- Confirmed in recent analysis (*Scolnic et al. 2014*)



Residual dispersion source of systematics

↓

Different ways to improve distance measurement :

Calibration improvement

New supernova model

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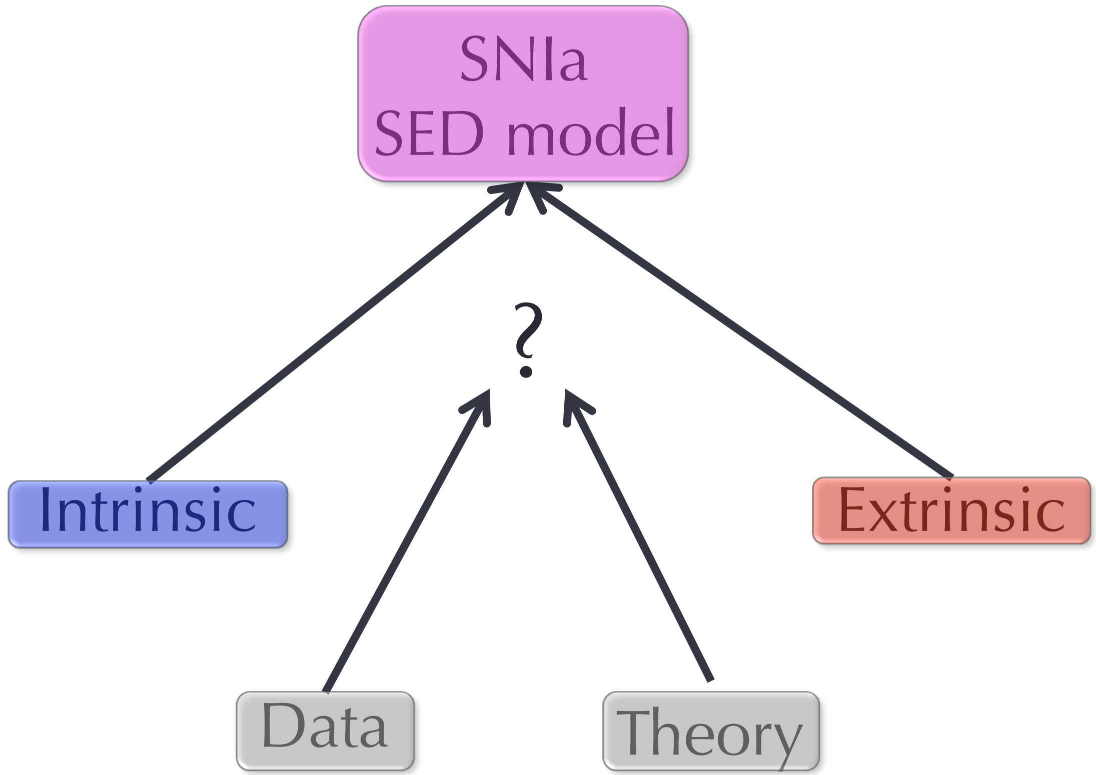
Go beyond : Describing the Spectral Energy Distribution



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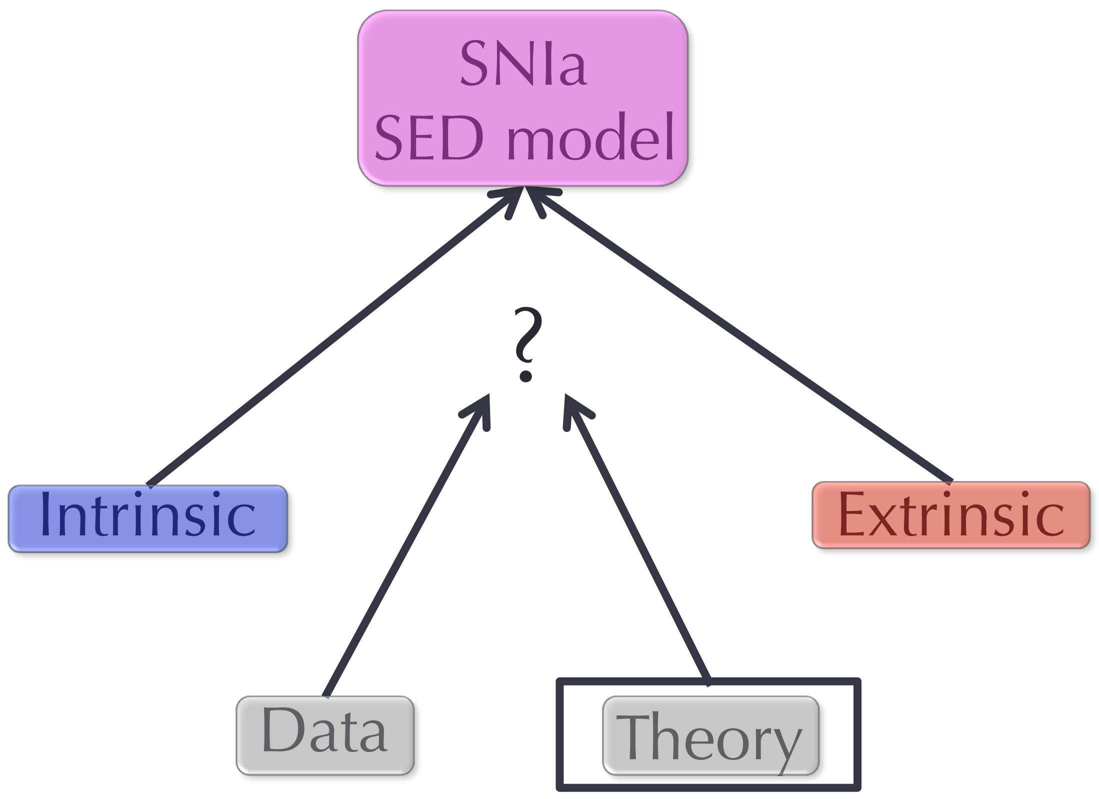
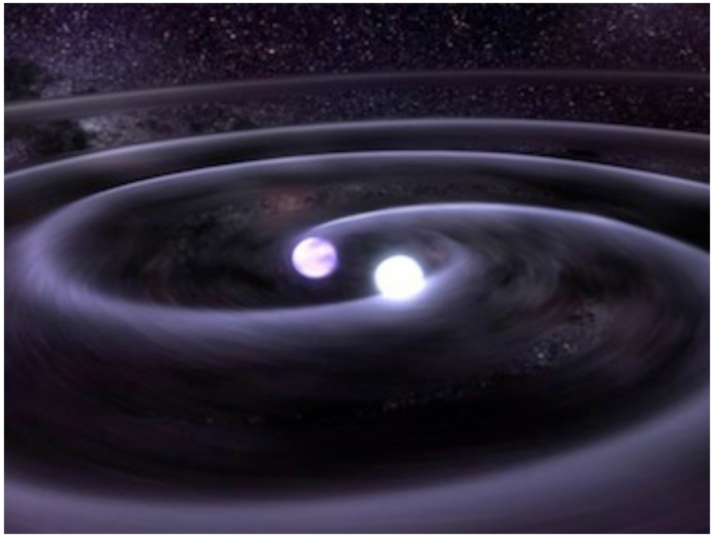


Type Ia supernovae ?

- Carbon-Oxygen White Dwarf

- Need to have a 'friend' to explode.

- Two main scenarios :
  - Single degenerate
  - Double degenerate



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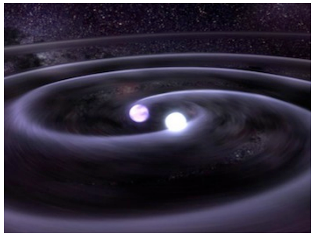
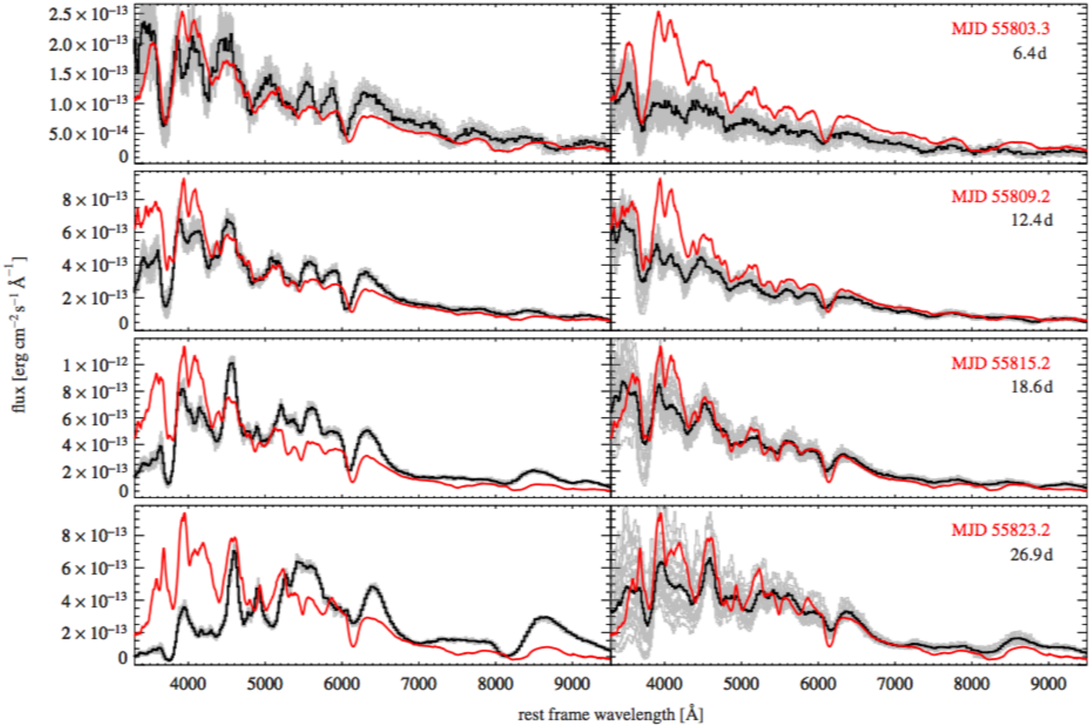




Röpke et al. (2012)

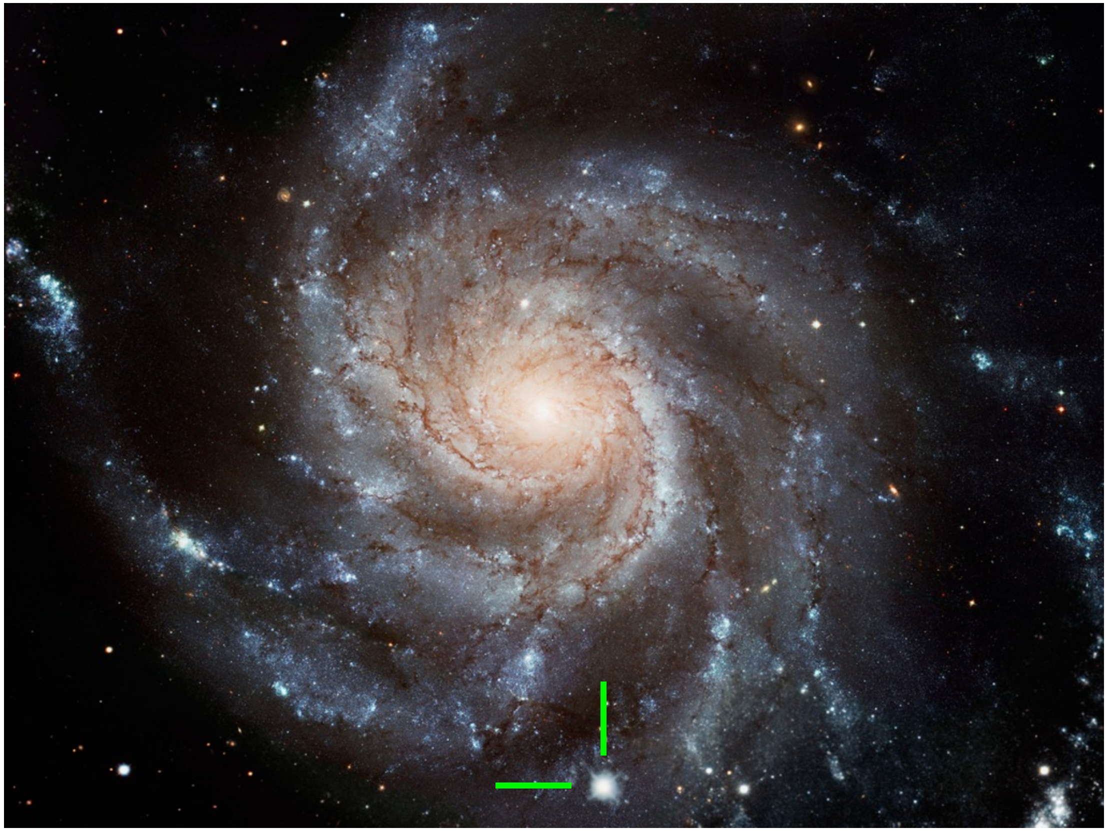
- Both scenarios can not reproduce the observed SED.

Type Ia supernovae ?

- Transient Object
- No hydrogen line and strong silicon lines

Messier 101

Type Ia supernovae ?



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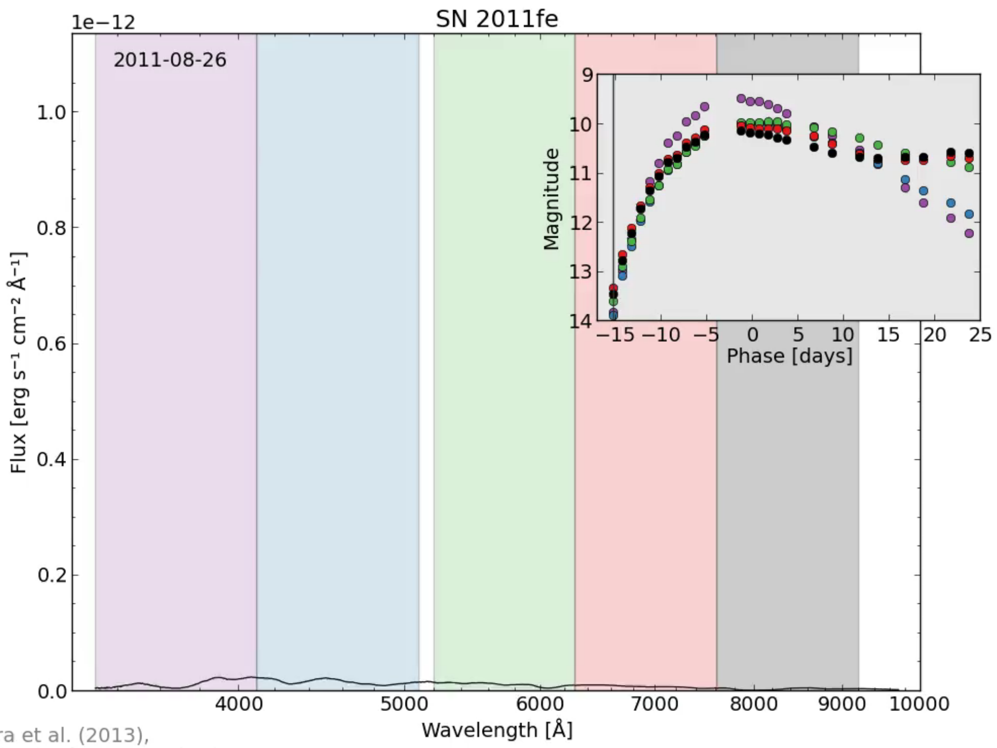
Messier 101 & SN2011fe

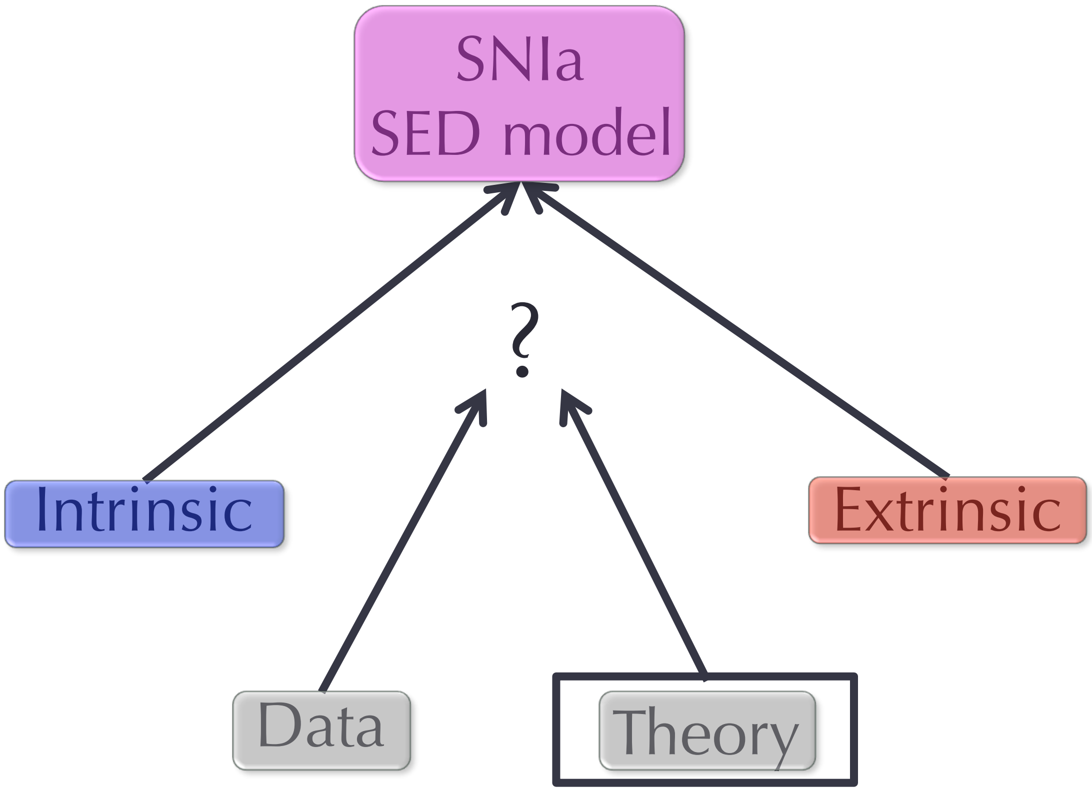
Type Ia supernovae ?



Pereira et al. (2013), The Nearby Supernova Factory

- Quasi-standard objects → Usable to measure distance
- Need of a SED model to describe the 'Quasi'

Go beyond : Describing the Spectral Energy Distribution



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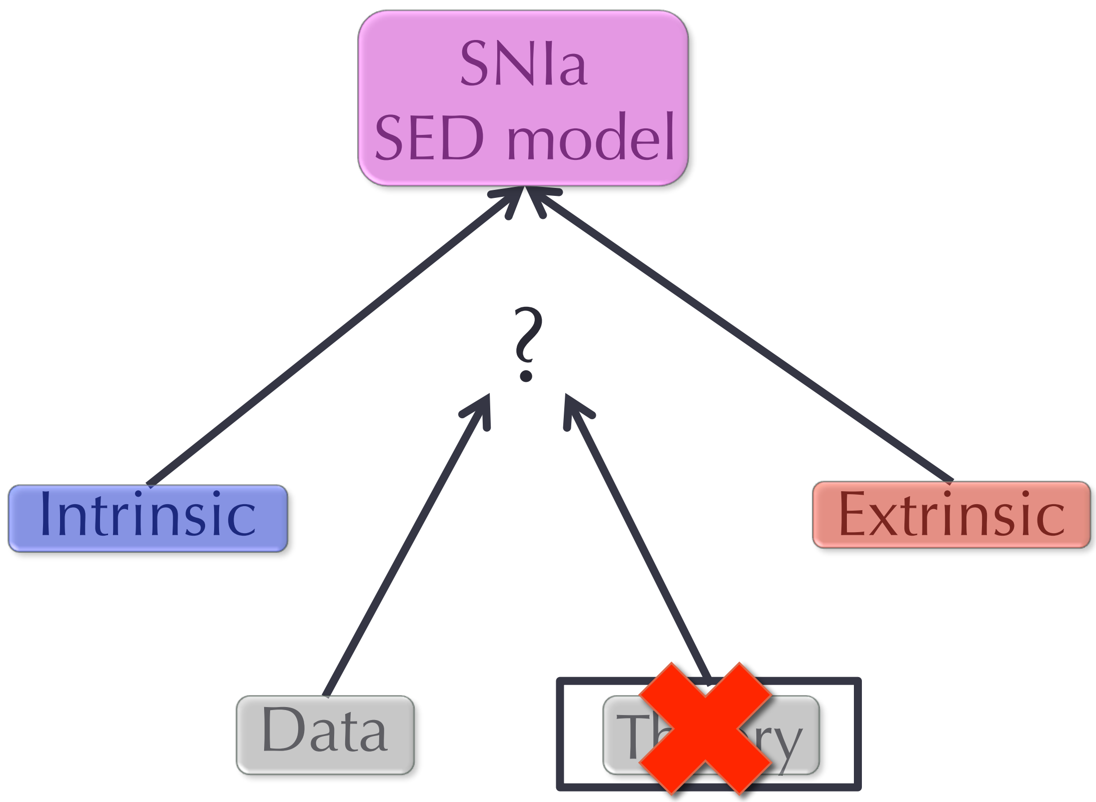

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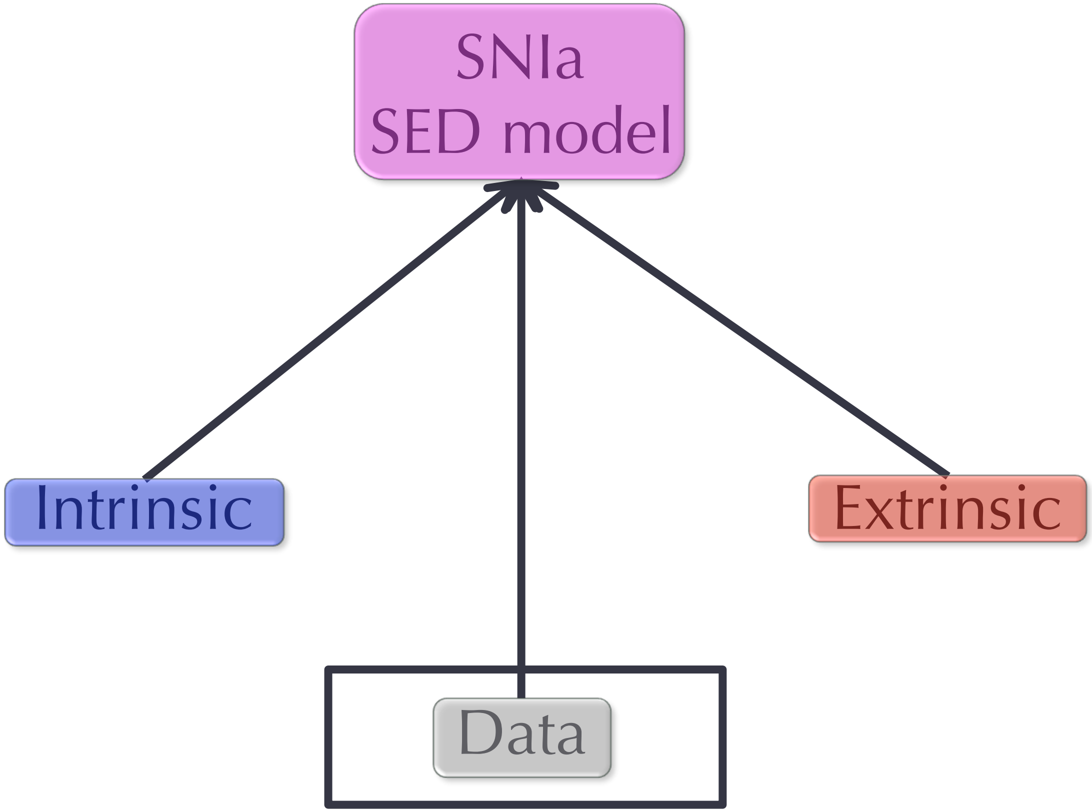
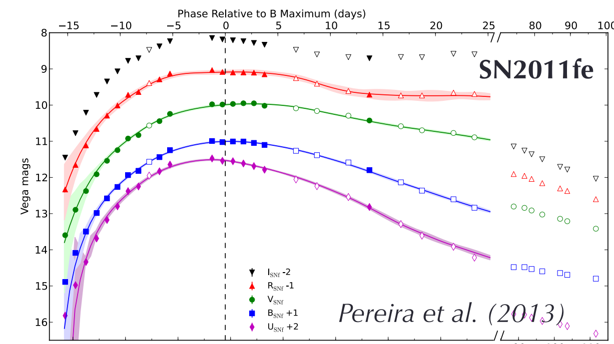


Go beyond : The Nearby Supernova Factory

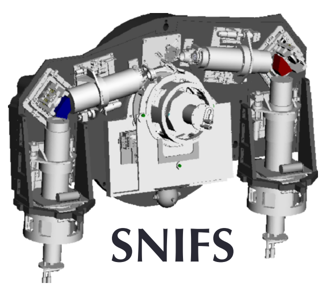
A unique data set of spectrophotometric SNIa spectral time series



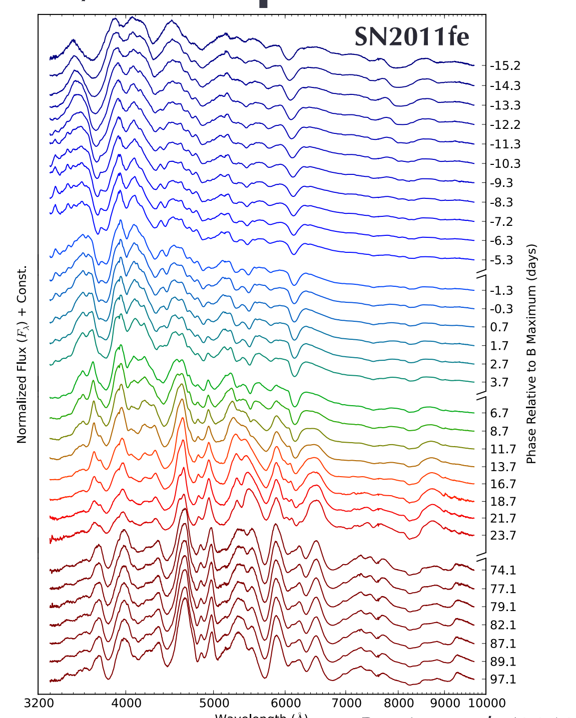
Spectra integration provides photometry

Spectro-photometry of nearby SNIa

IFS spectroscopy + photometry



Reduction Calibration → Spectral Time series →



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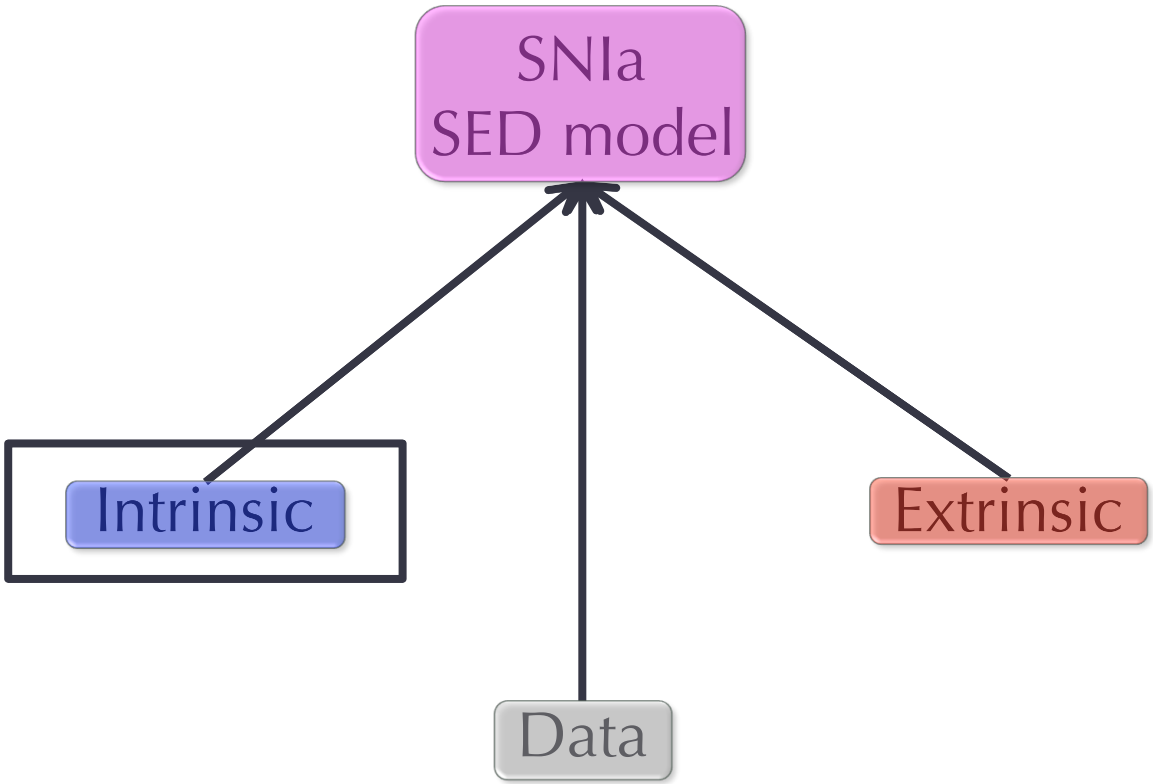
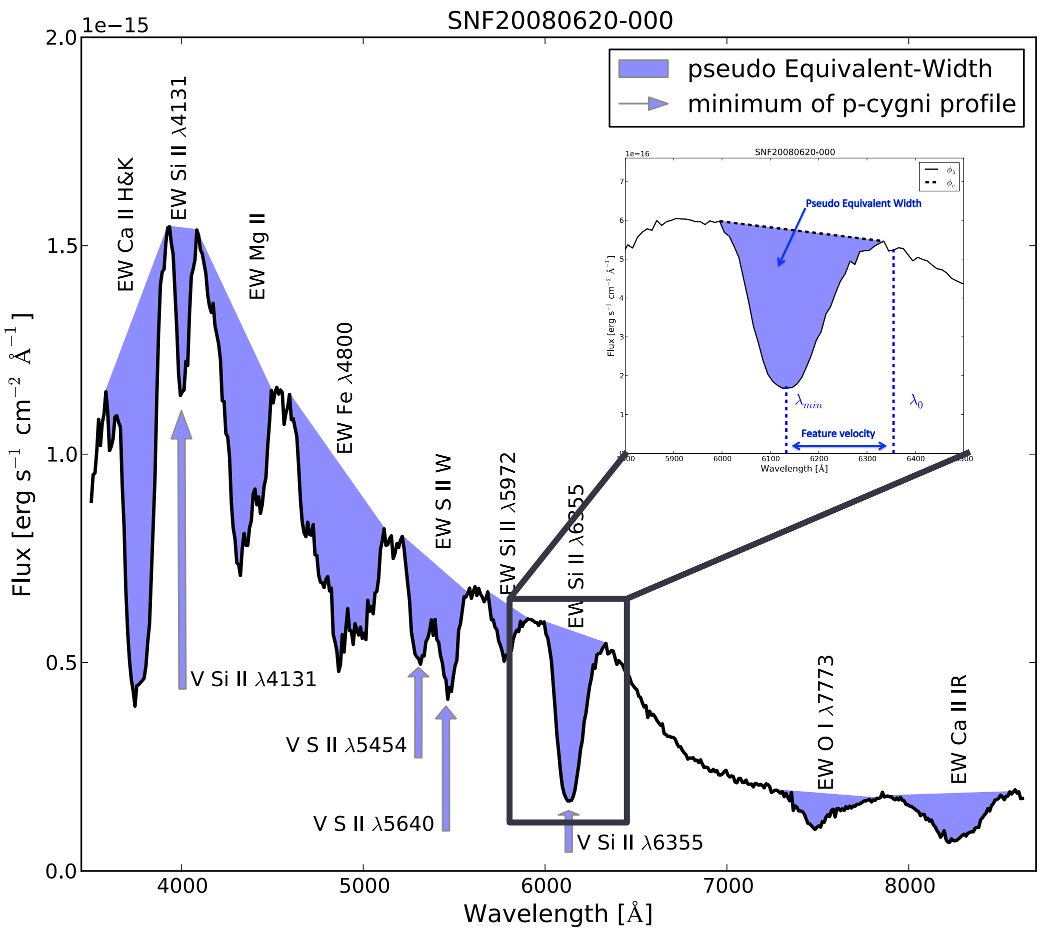


Go beyond : Describing the intrinsic part

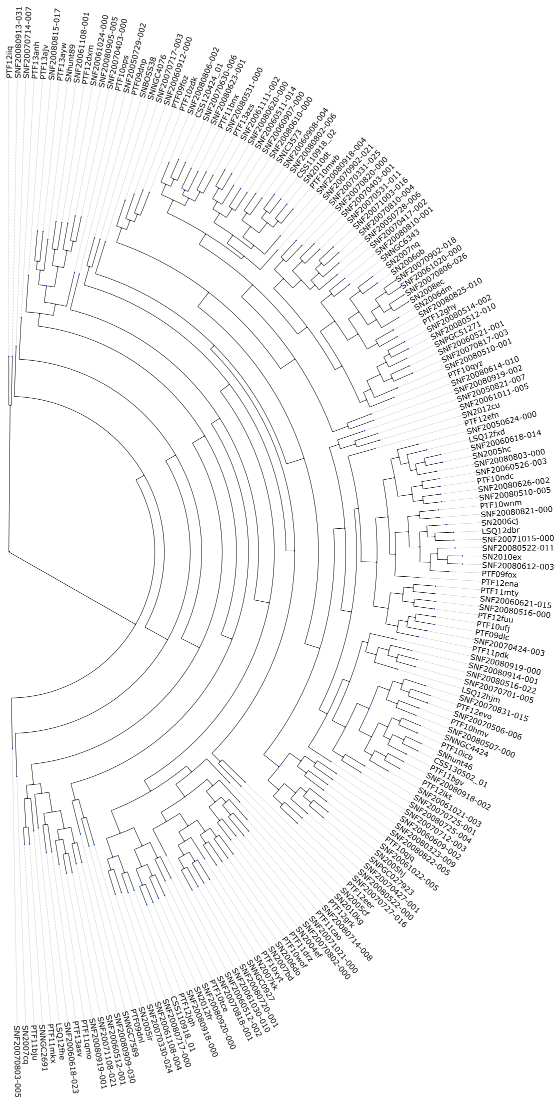
Spectral Indicators of Type Ia Supernovae



- 13 spectral indicators at maximum light:
- 9 equivalent widths (all)
- 4 velocities
- Distance independent
- Reddening independent
- Phase = max ± 2.5 days
- Spectra closest to max

Go beyond : Describing the intrinsic part

Visualization of spectral indicator space: phylogenetic tree

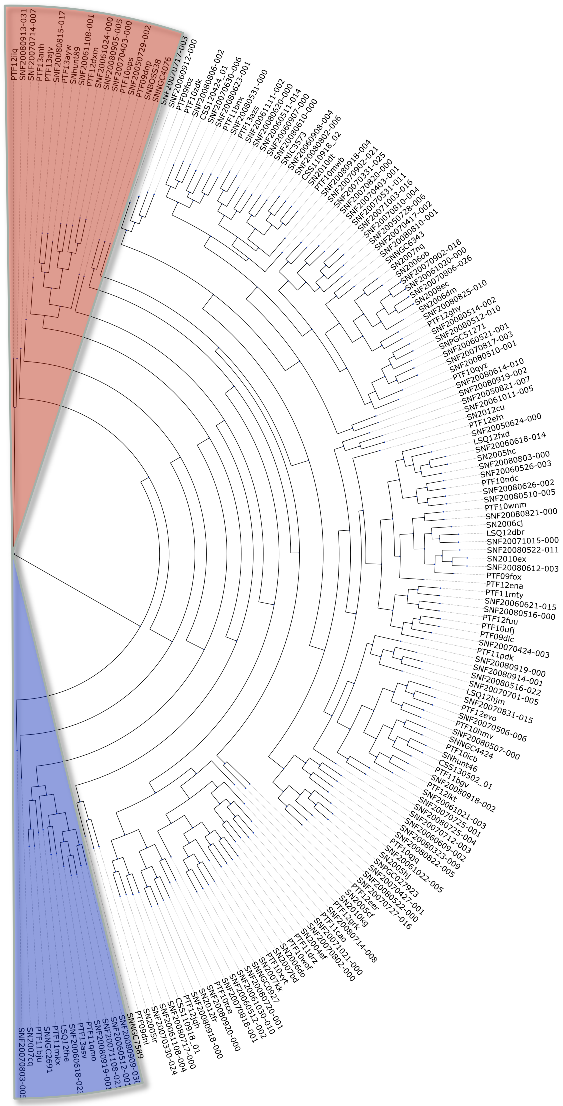


- Built from distance in spectral indicator space (instead of DNA)

Go beyond : Describing the intrinsic part

Visualization of spectral indicator space: phylogenetic tree

Sub-luminous ~SN1991bg



Sur-luminous ~SN1991T

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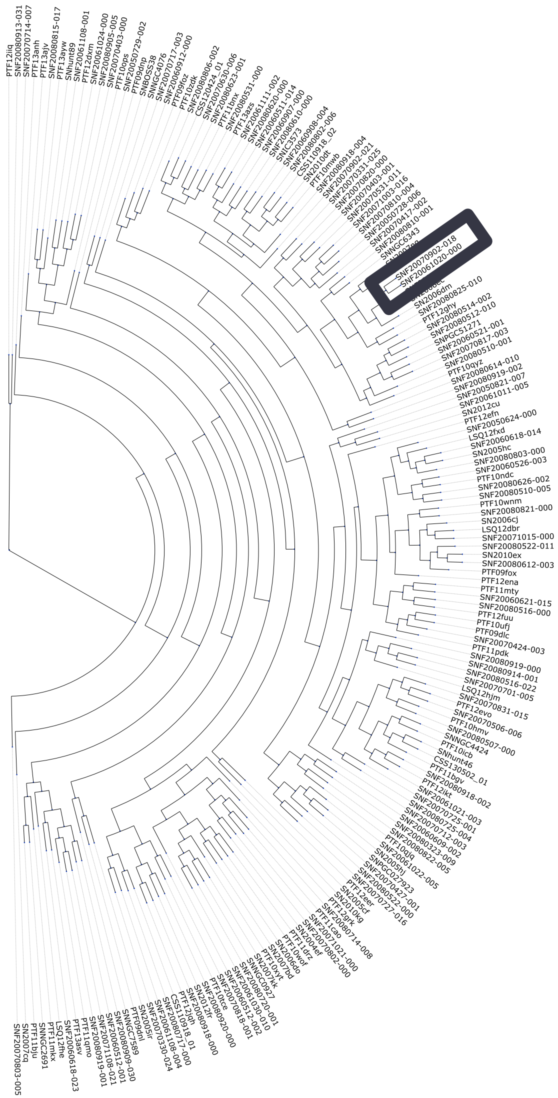
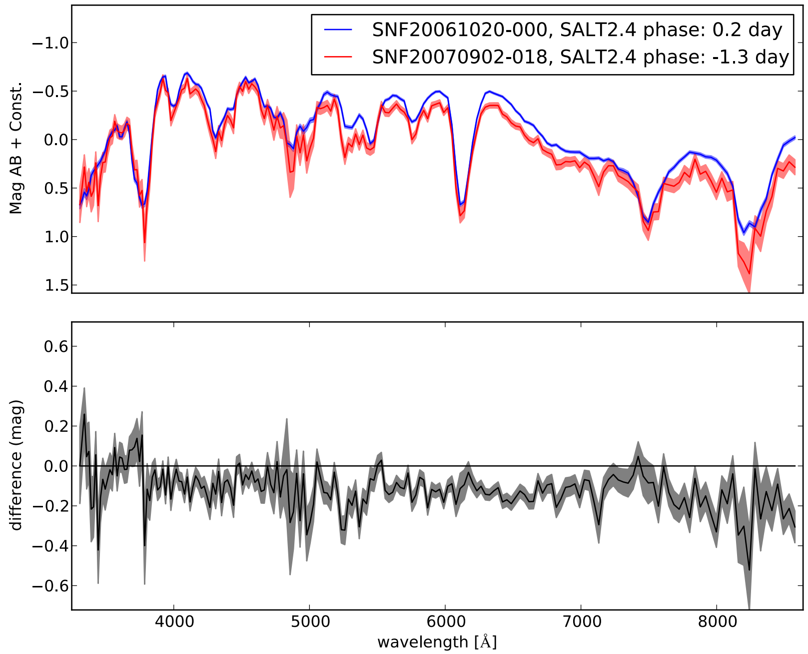
- Purpose: classification

Go beyond : Describing the intrinsic part

Visualization of spectral indicator space: phylogenetic tree



- Built from distance in spectral indicator space (instead of DNA)
- Purpose: classification
- If spectral indicator are sufficient to describe intrinsic part:
  - SNIa should have similar features
  - Could be different in color due to dust



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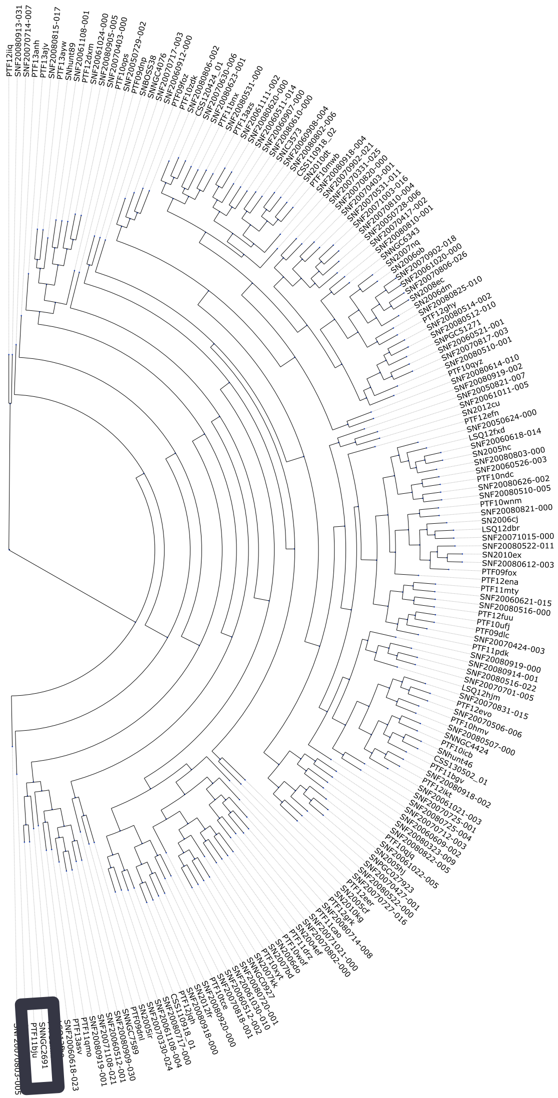

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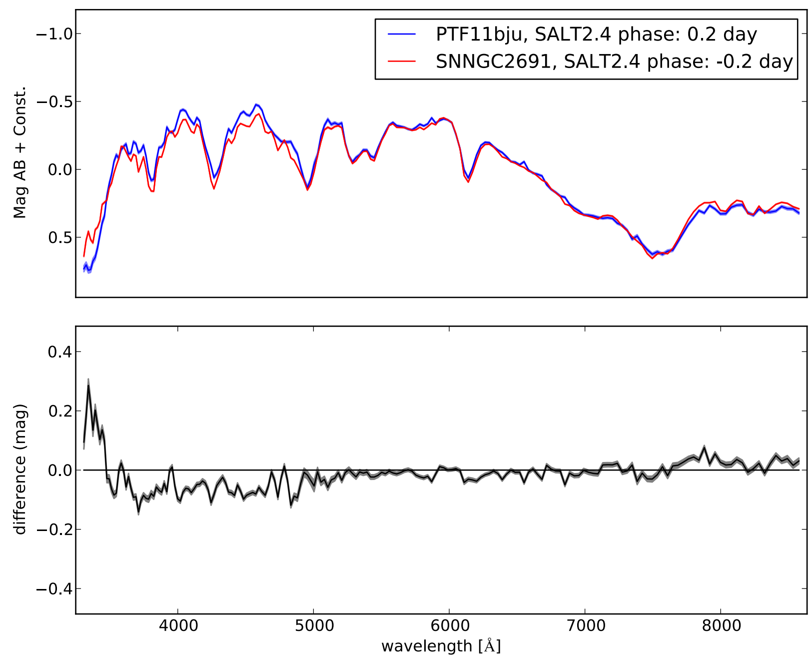

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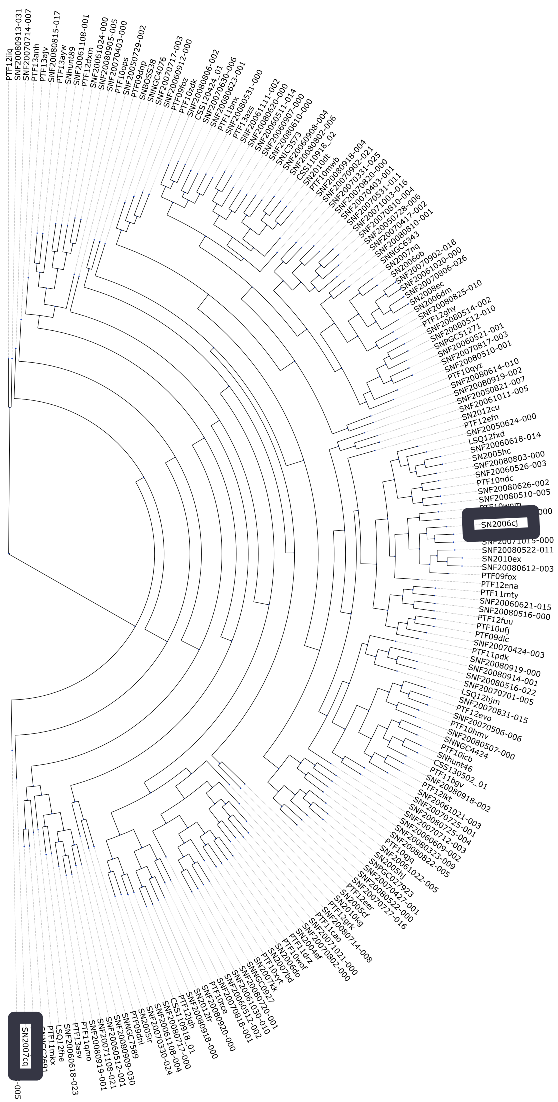

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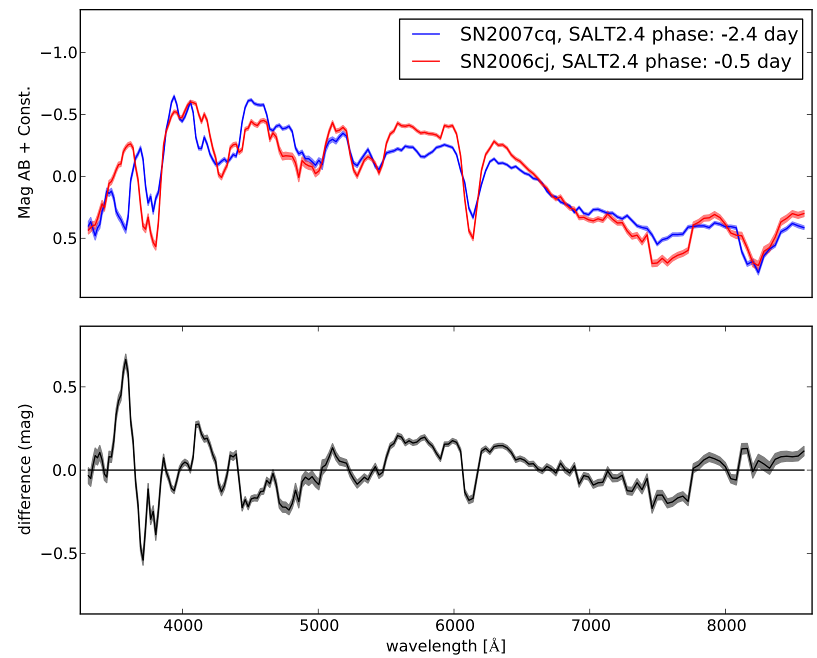
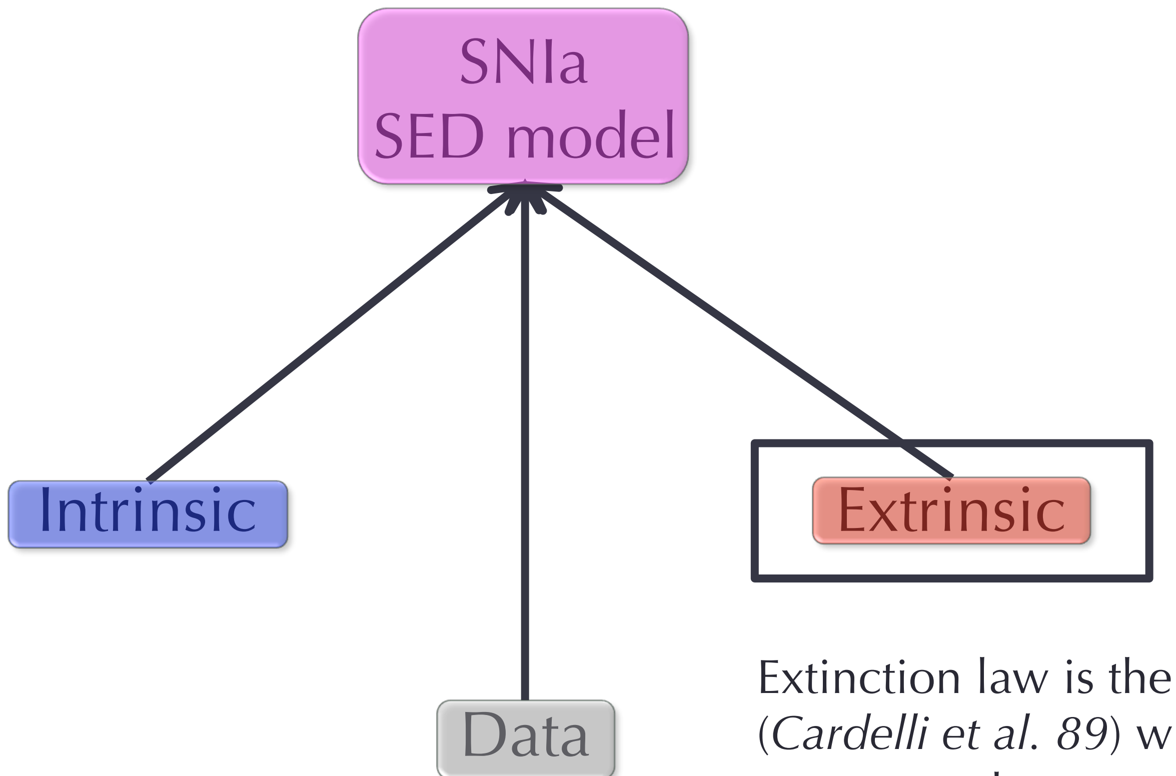


Go beyond : Describing the Spectral Energy Distribution



Extinction law is the Cardelli law (*Cardelli et al. 89*) with one free parameter that represents dust properties (R_V)

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SUGAR model:

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

SUGAR model:

Observation (AB Mag)

↑

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

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For all SNIa

SUGAR model:

Observation (AB Mag)

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

Average sequence

For all SNIa

SUGAR model:

Observation (AB Mag)

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

Average sequence

Intrinsic law (many compnents instead of 1 in SALT2)

For all SNIa

SUGAR model:

Observation (AB Mag)

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

Average sequence

Intrinsic law (many compnents instead of 1 in SALT2)

Extinction law (Cardelli law instead of global color law in SALT2)

For all SNIa

SUGAR model:

For one SNIa

Observation (AB Mag)

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

For all SNIa

Average sequence

Intrinsic law (many compnents instead of 1 in SALT2)

Extinction law (Cardelli law instead of global color law in SALT2)

SUGAR model:

For one SNIa

Observation (AB Mag)

Linear combinaison of spectral indicators

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

Average sequence

Intrinsic law (many compnents instead of 1 in SALT2)

Extinction law (Cardelli law instead of global color law in SALT2)

For all SNIa

SUGAR model:

For one SNIa

Absorption in V band

Linear combinaison of spectral indicators

Observation (AB Mag)

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

Average sequence

Intrinsic law (many compnents instead of 1 in SALT2)

Extinction law (Cardelli law instead of global color law in SALT2)

For all SNIa

SUGAR model:

For one SNIa

Observation (AB Mag)

Linear combinaison of spectral indicators

Absorption in V band

Grey offset (adjust distance)

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

Average sequence

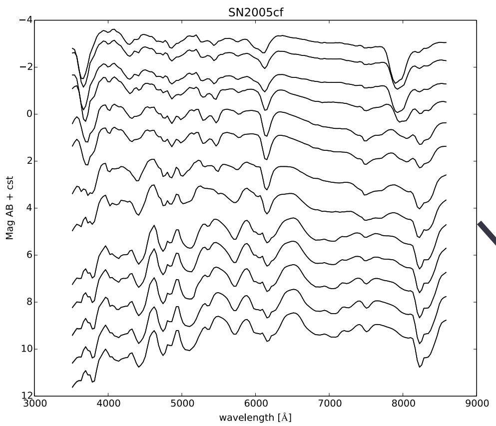
Intrinsic law (many compnents instead of 1 in SALT2)

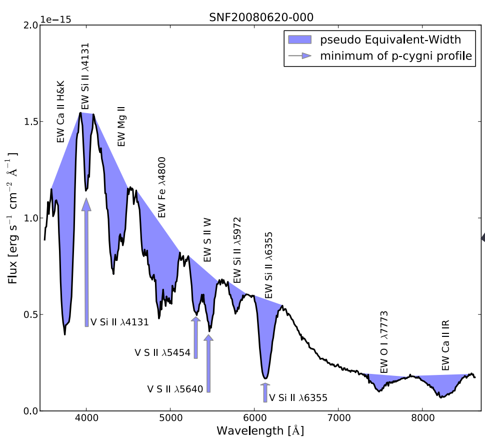
Extinction law (Cardelli law instead of global color law in SALT2)

For all SNIa

SUGAR model building:

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





- Dimensionality reduction
- Estimation of the extinction law
- Time interpolation of spectra
- Global SED fitting in wavelength and time

→ SUGAR

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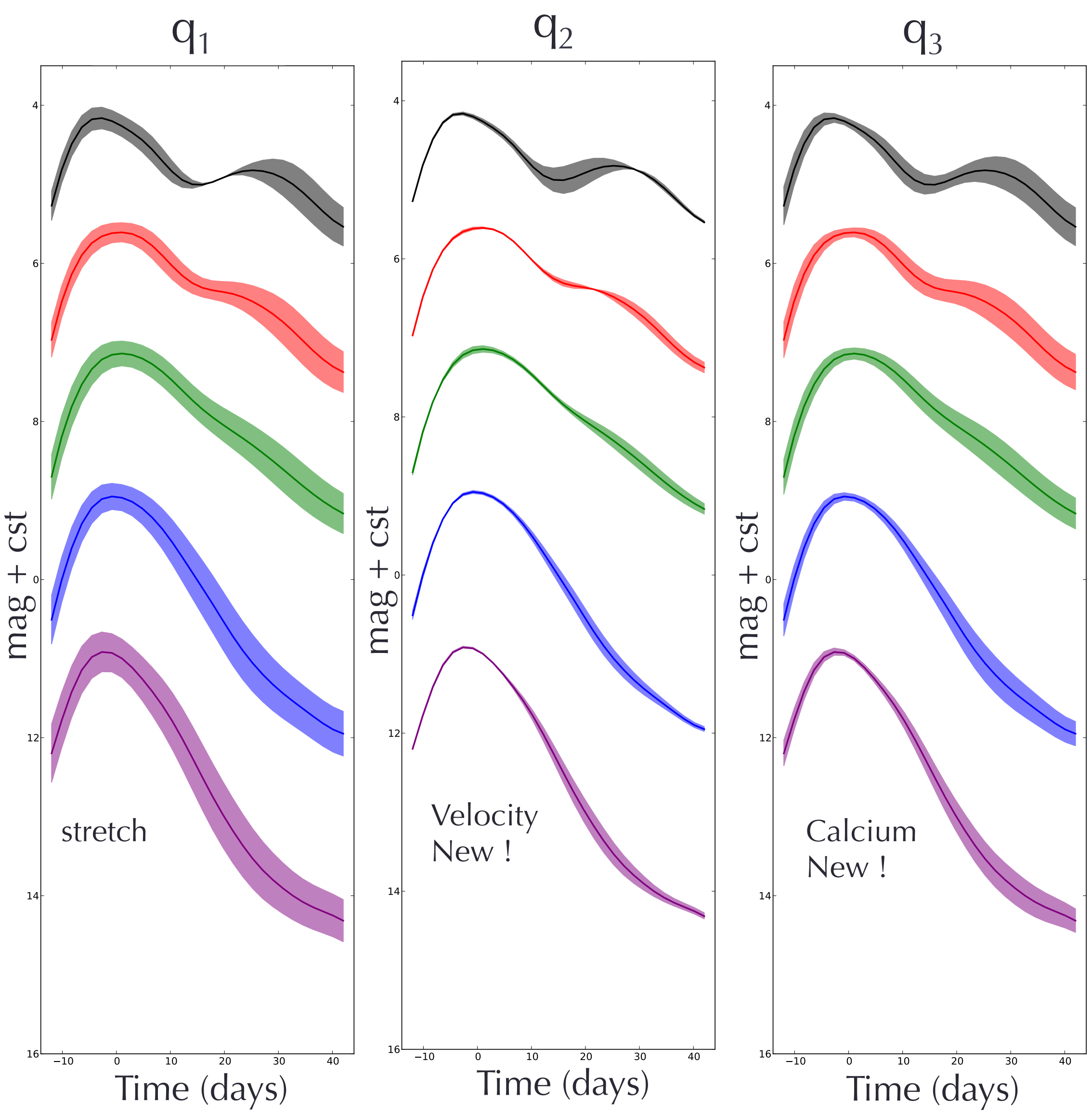
4. **SUGAR model results**

5. Conclusions & perspectives

SUGAR results: third intrinsic component



- Two new components
- Velocity and calcium
- Effect visible in photometry

SUGAR model results:

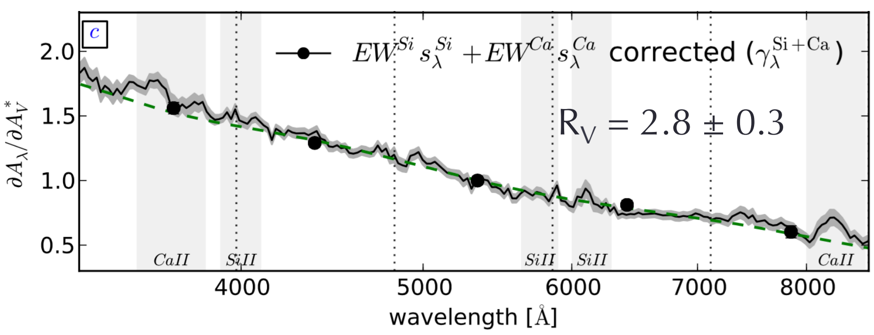
Estimation of extinction law:

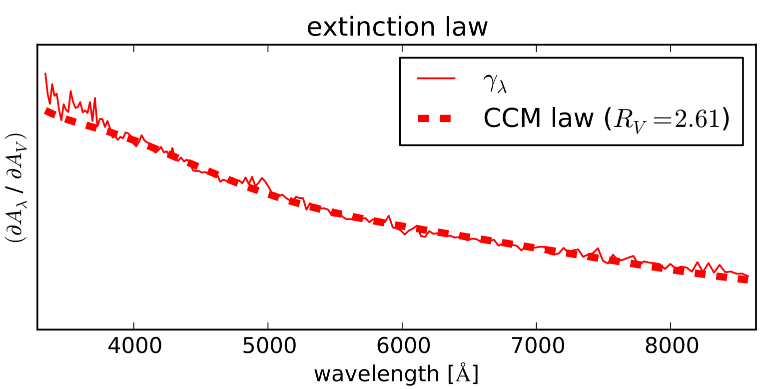
Chotard et al. 2011

- Employs 2 spectral features to separate intrinsic and extrinsic
- Iterative fitting to fit intrinsic part and extrinsic part
- Dispersion matrix
- 78 SNIa

Léget Ph.D. 2016

- Employs 3 factors from EM-FA to separate intrinsic and extrinsic
- Global fit
- Dispersion matrix
- 103 SNIa

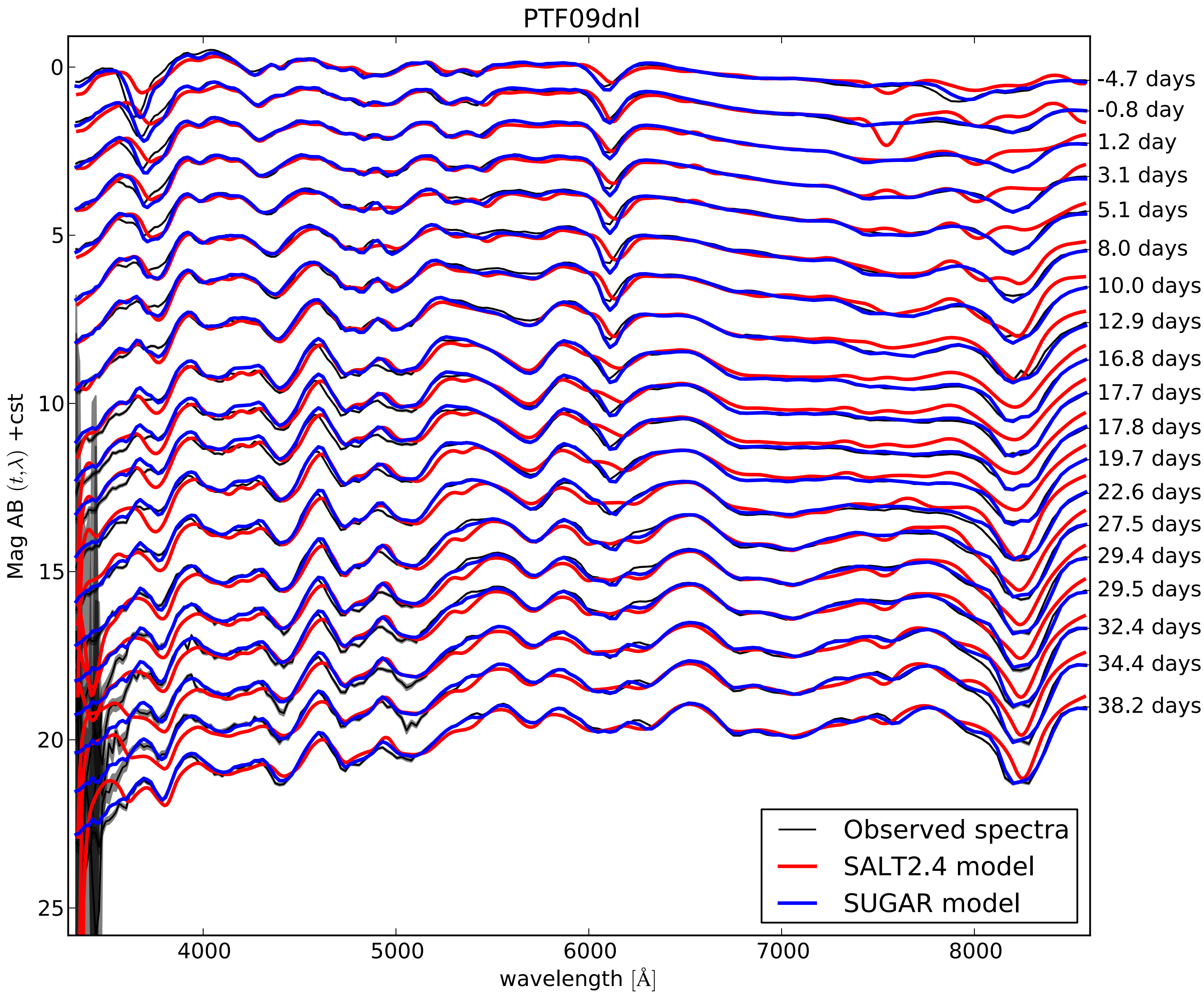




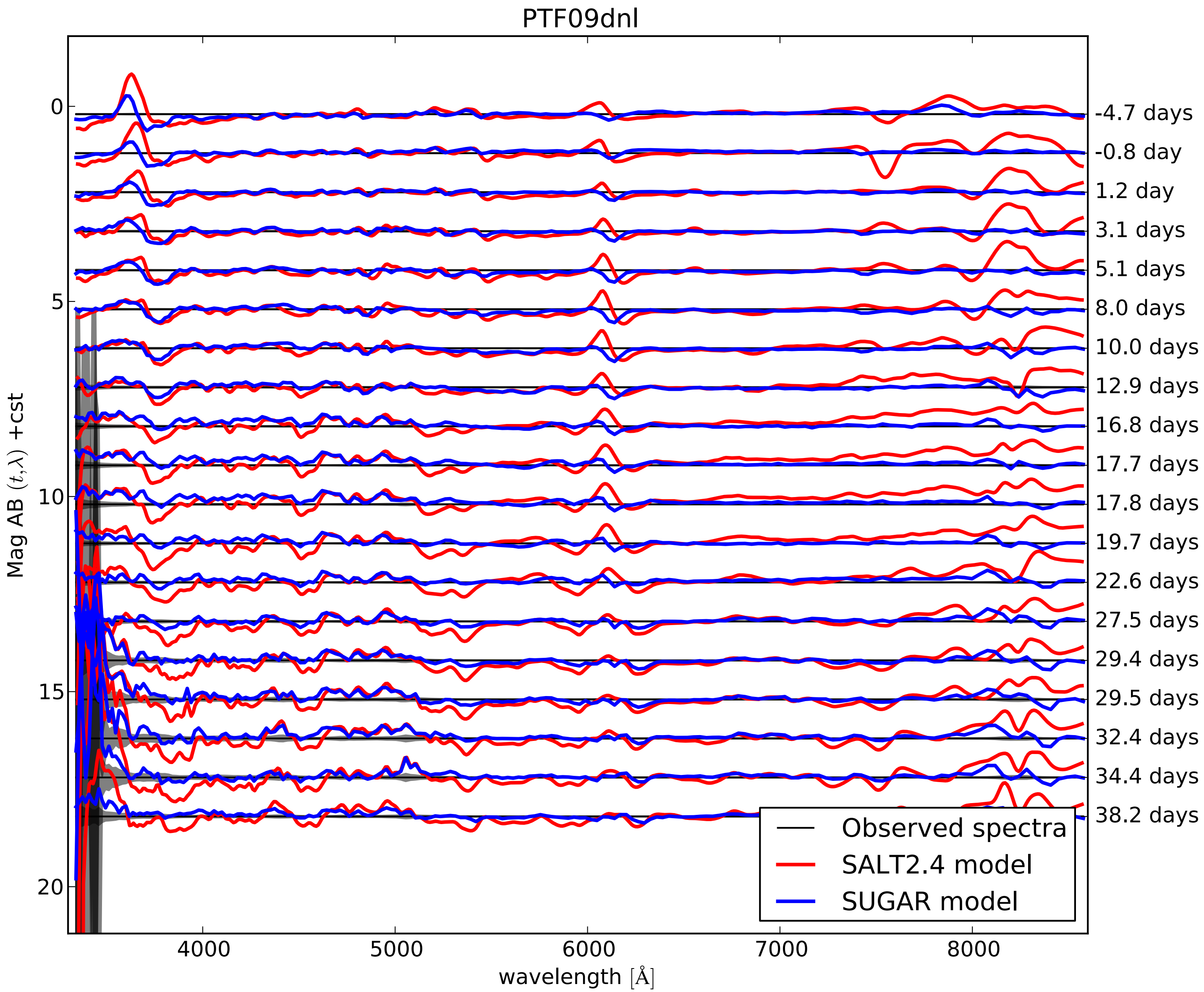
SUGAR results: fit SUGAR parameters

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

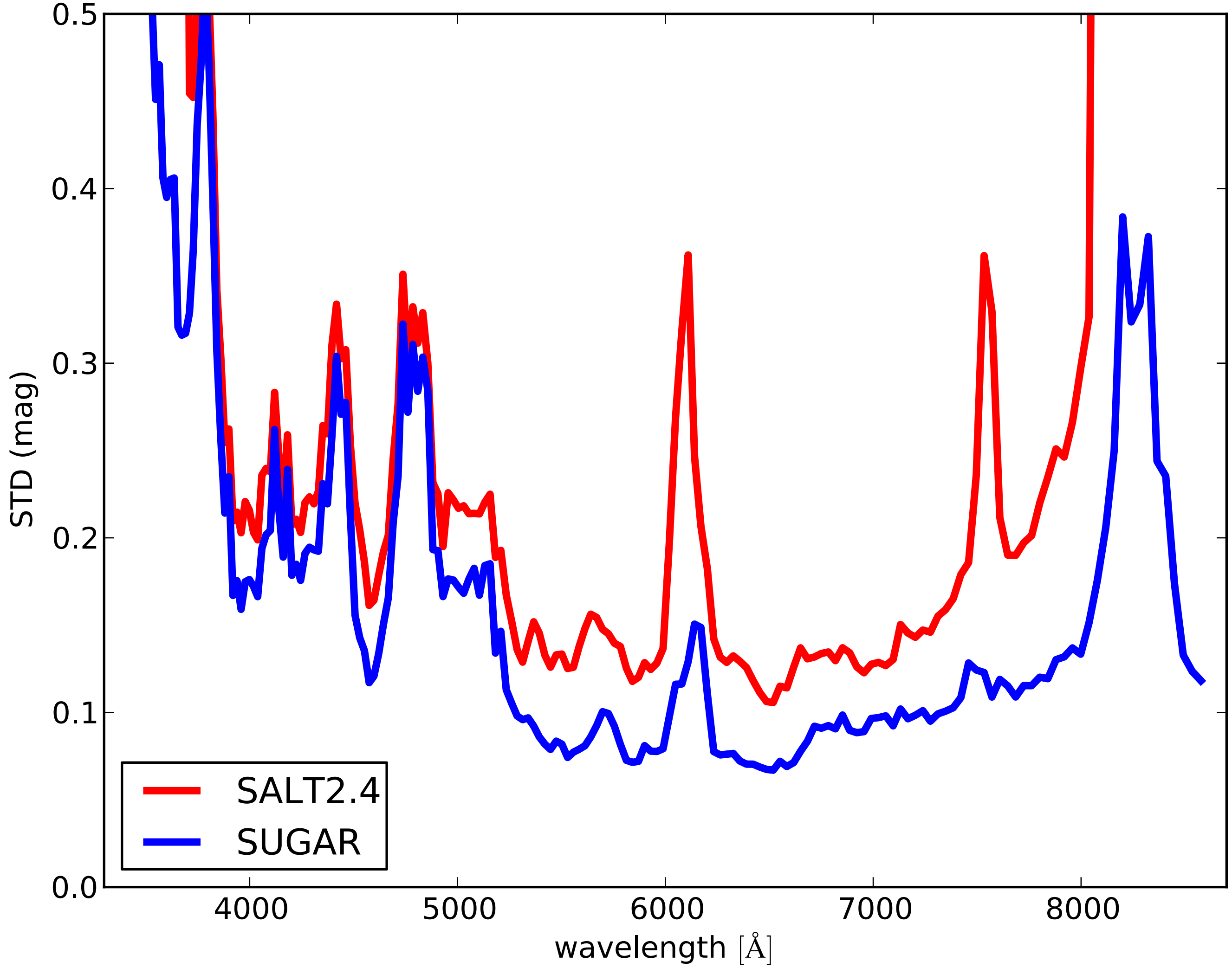
SUGAR results: comparison SUGAR - SALT2



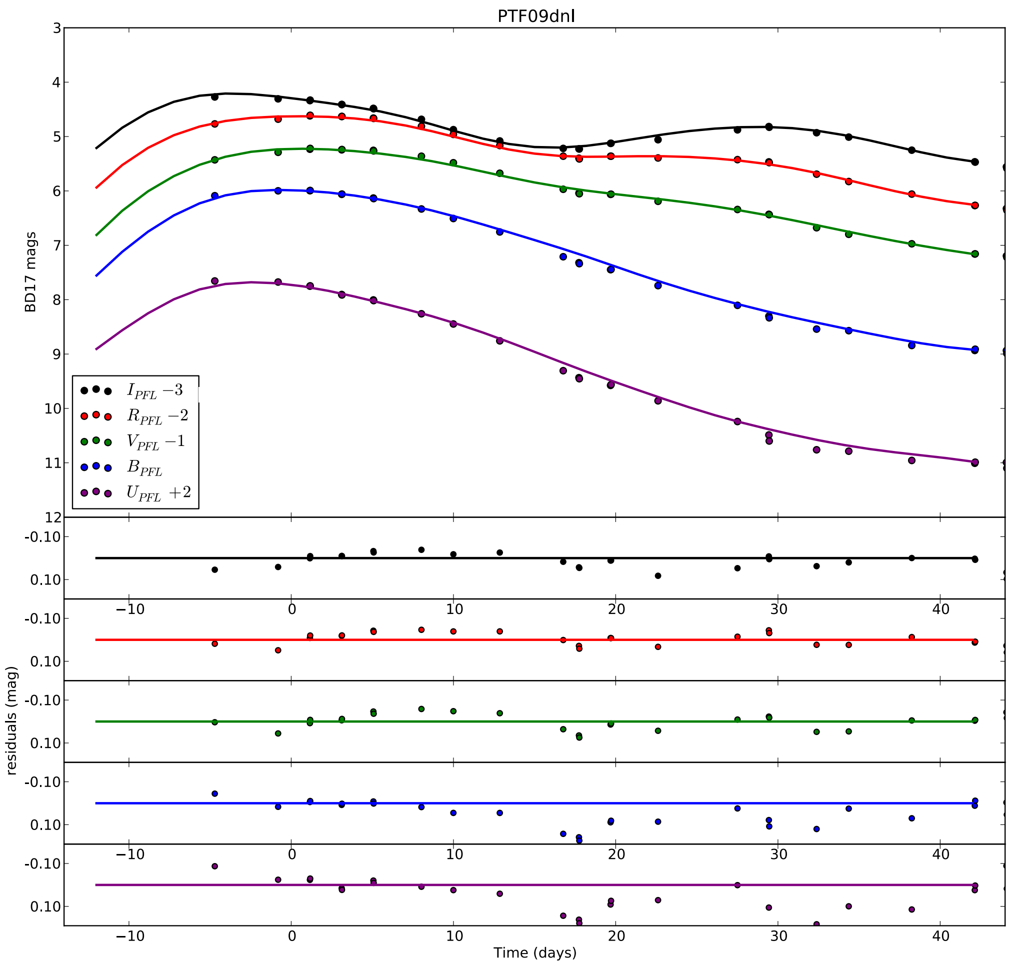
SUGAR results: comparison SUGAR - SALT2



SUGAR results: comparison SUGAR - SALT2



SUGAR results: SUGAR Hubble diagram

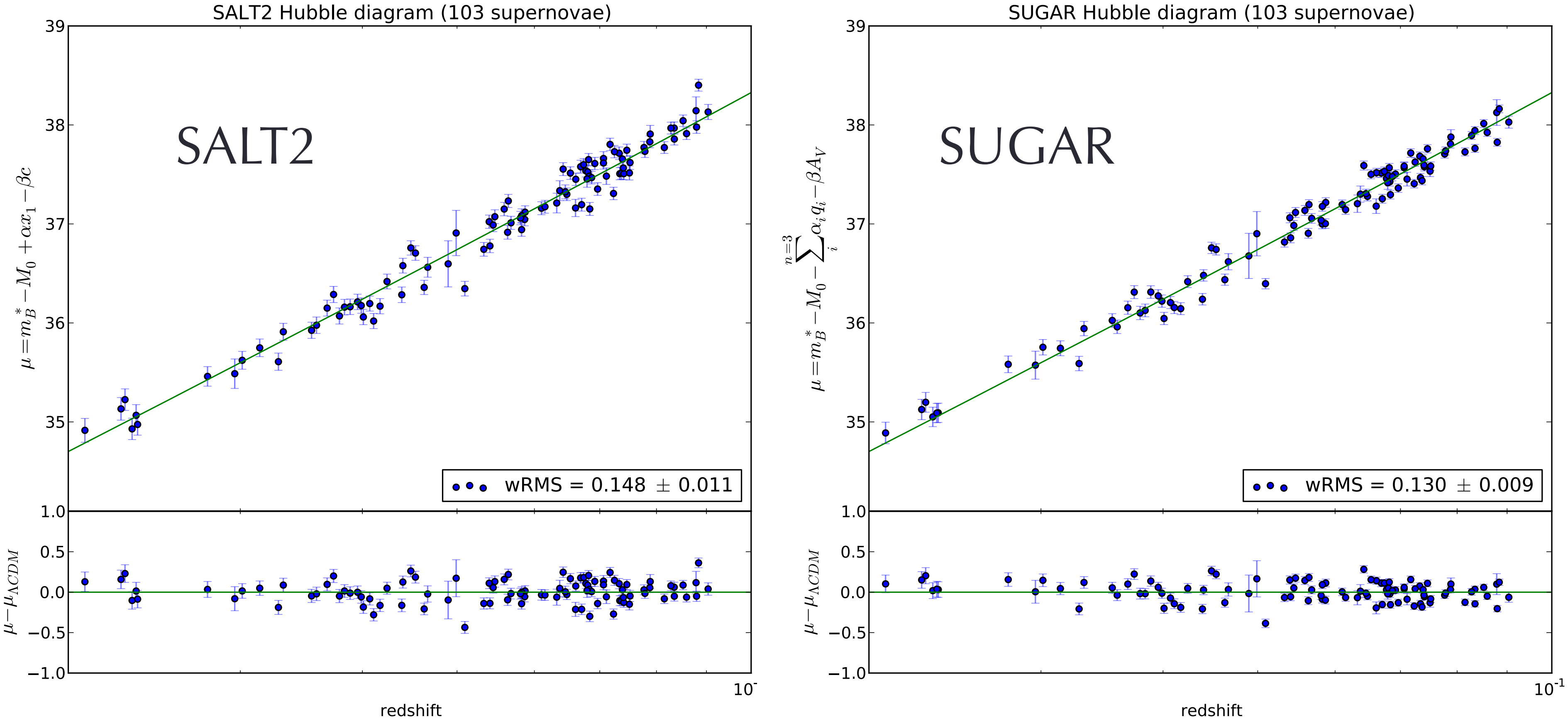


- With SUGAR parameters derived from spectra this is possible to compute photometry
- With the B band we can make Hubble diagram
- SUGAR distance modulus :

$$\mu = m_B - M_B - \sum_{i}^{i=3} a_i q_i - bA_V$$

- 2 intrinsic component added with respect to SALT2
- A_V derived from a Cardelli law instead of a global Color law with SALT2

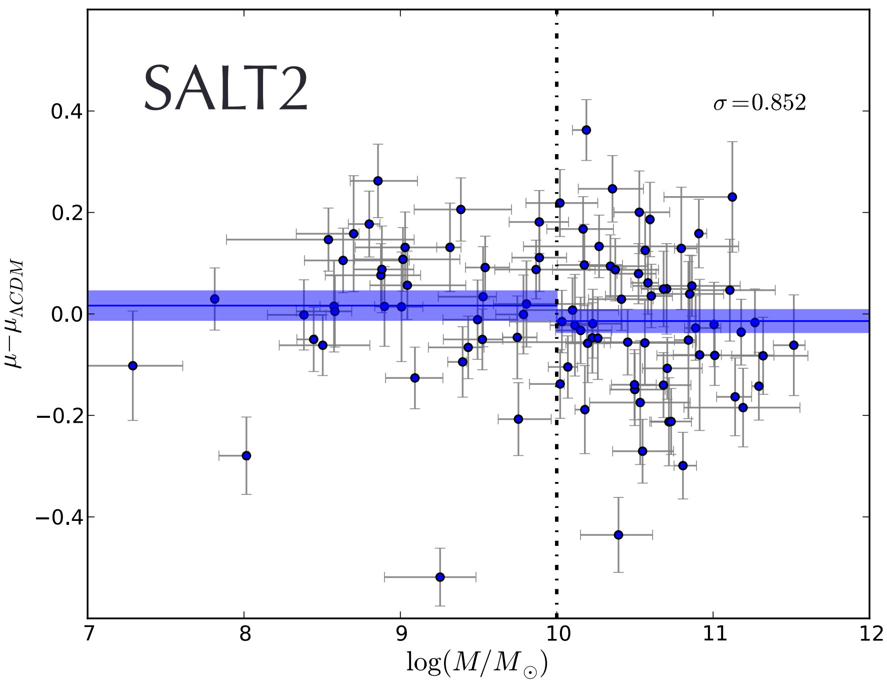
SUGAR results: SUGAR Hubble diagram



Parameters	Values
α_1	-0.107 ± 0.018
α_2	0.017 ± 0.008
α_3	0.019 ± 0.012
b	1.282 ± 0.060

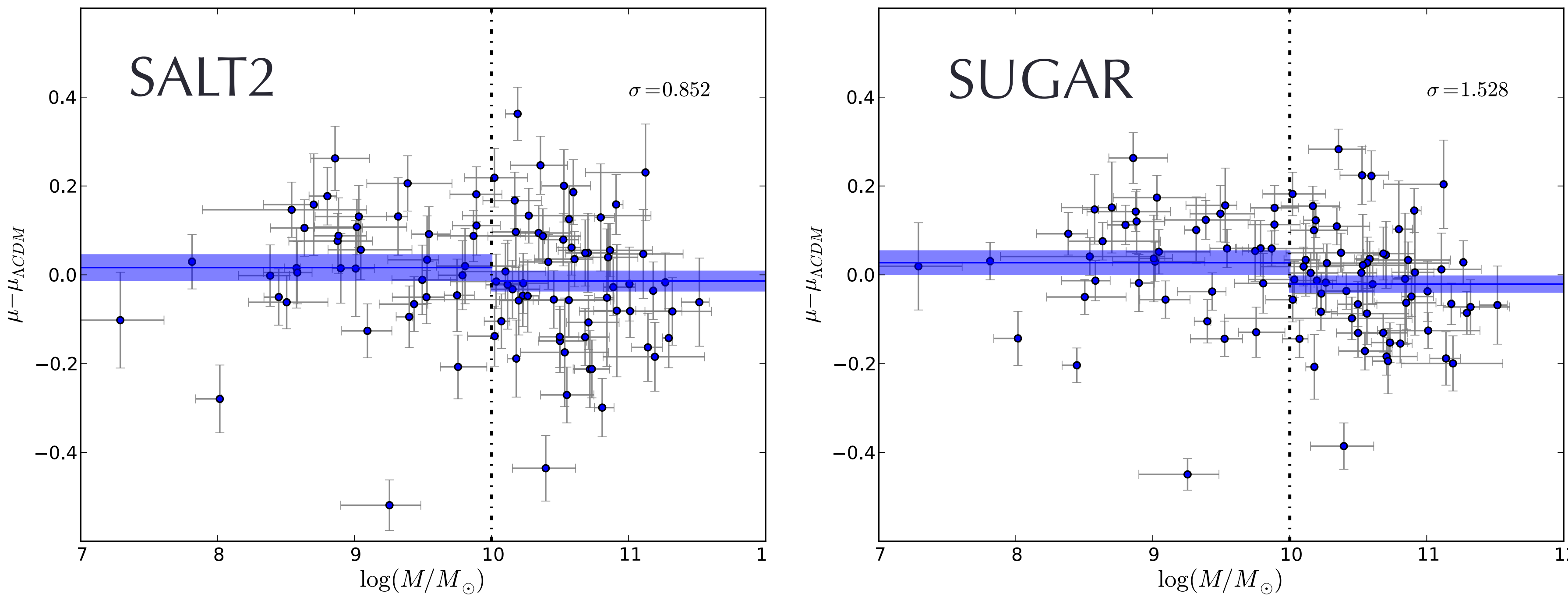
Dispersion in magnitude is 0.02 lower with SUGAR than with SALT2

SUGAR results: SUGAR Hubble diagram & host ?



SALT2 : ΔM = -0.030 ± 0.035 → compatible with previous SNFactory analyis

SUGAR results: SUGAR Hubble diagram & host ?



Mass-step increases with SUGAR:

SALT2 : ΔM = -0.030 ± 0.035 → compatible with previous SNFactory analysis
SUGAR : ΔM = -0.048 ± 0.031

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- Conclusions:

  - **New SED model: SUGAR**
    - 3 intrinsic components: stretch, velocity and detached calcium
    - Cardelli extinction : R_V=2.6
  - **Model performances:**
    - Better spectral description
    - Hubble residual dispersion reduced by 0.02 mag
    - Mass-step still present
  - **New tools for cosmology analysis**

- Perspectives:

  - **Use SUGAR as a supernova Generator:**
    - More realistic simulation:
      - impact for cosmology
      - LSST and WFIRST forecasts
    - Simulation according to host properties

  - **Use SUGAR as a light-curve fitter:**
    - Is it possible to reconstruct two more components with photometric data only
    - Impact for LSST cadence

  - **Extend the model in the UV**

MERCI !