

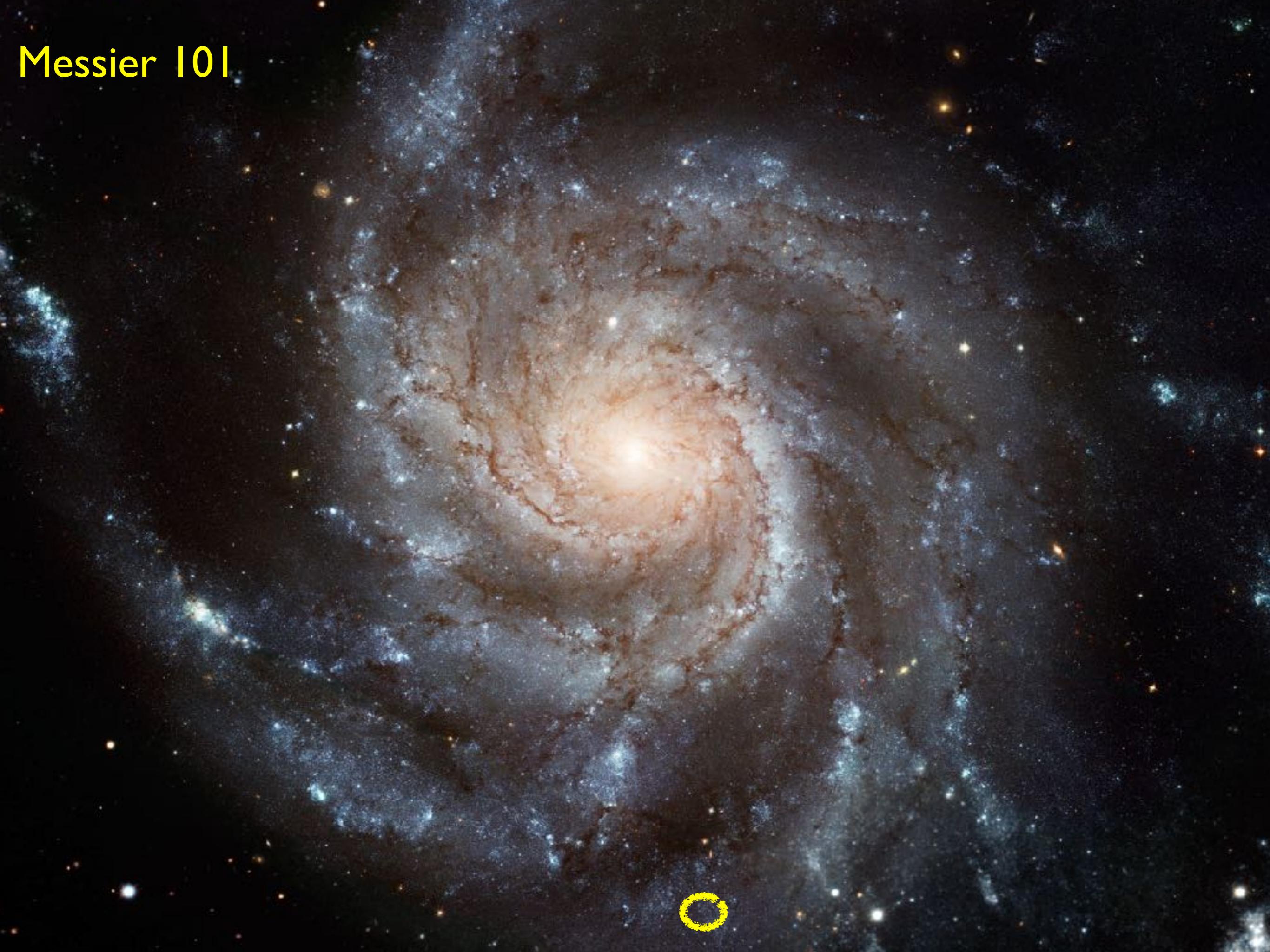
Improved description of SNIa variability for a better understanding of dark energy properties

Pierre-François Léget
Postdoc @ LPNHE

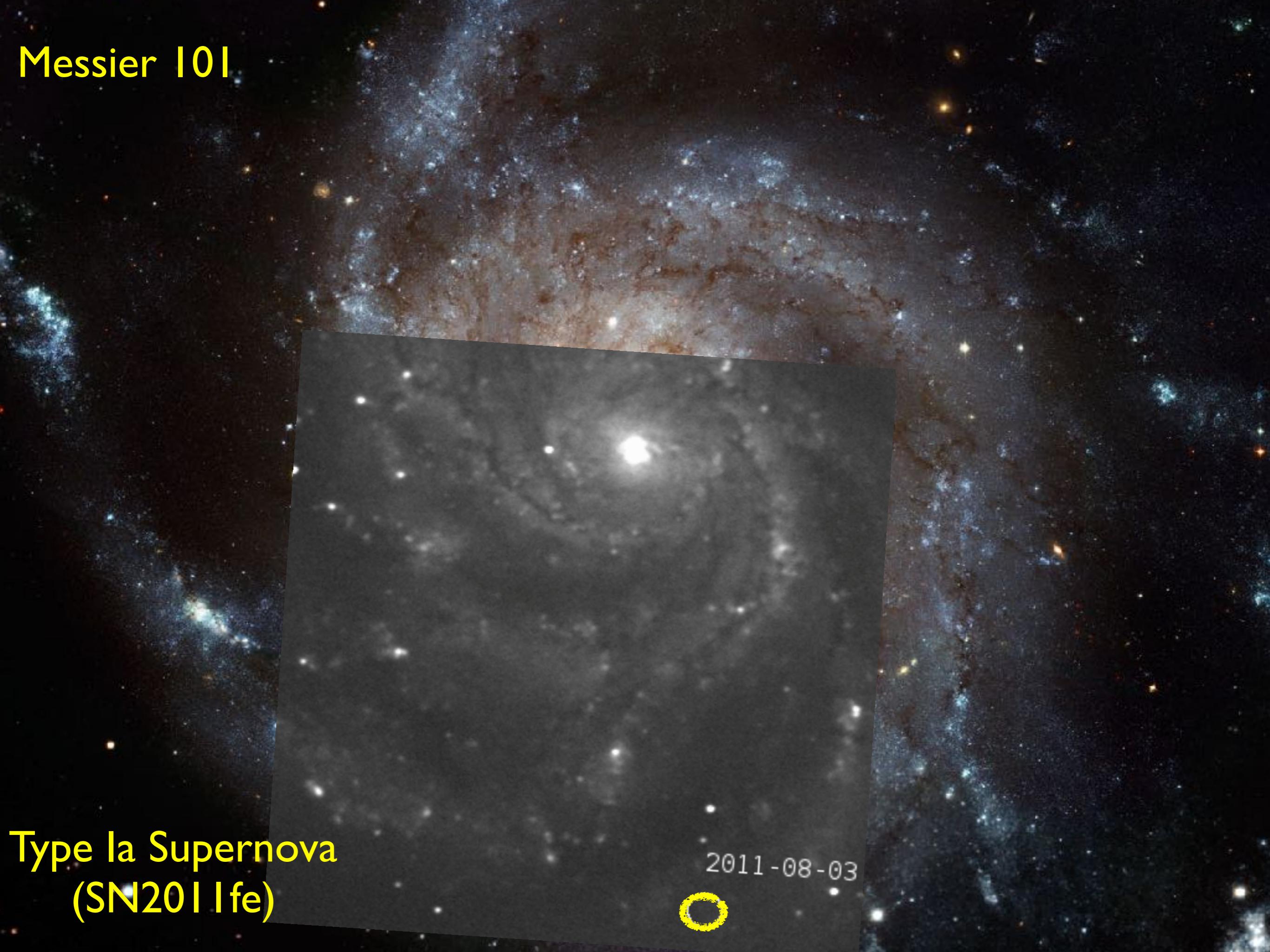
Messier 101



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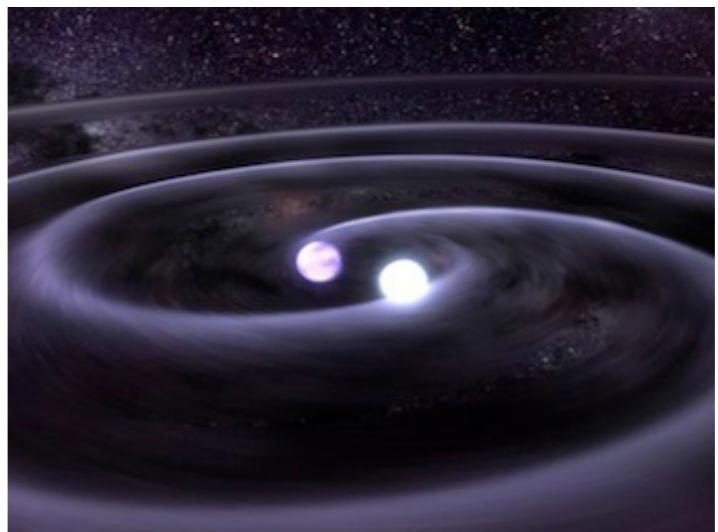
Type Ia Supernova
(SN2011fe)

2011-08-03

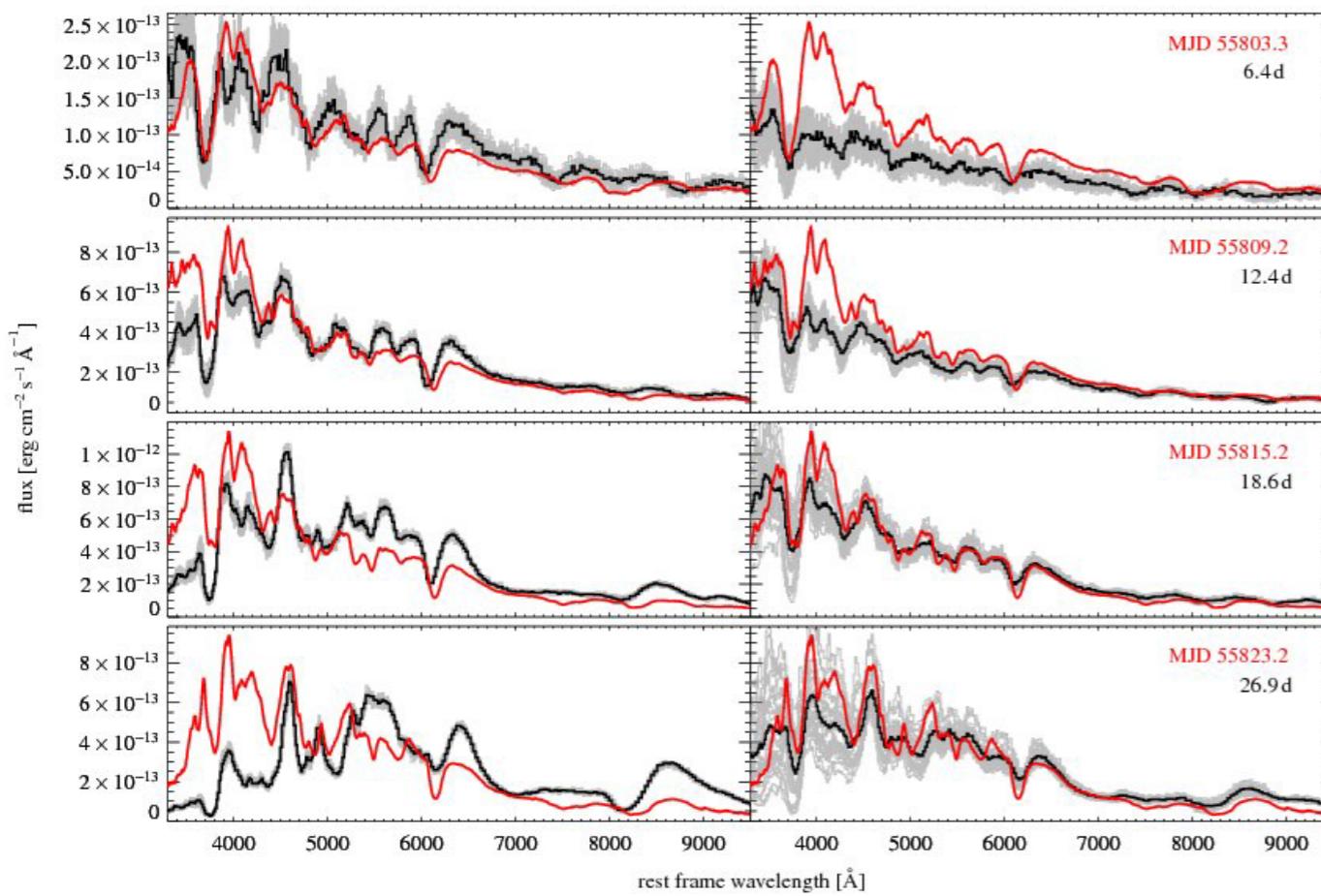
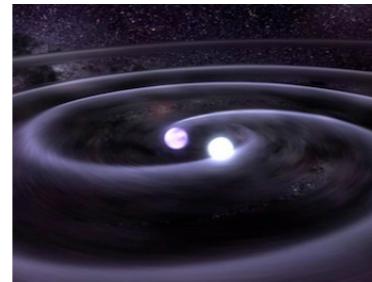


What is a Type Ia Supernova (SNIa) ?

- Carbon-Oxygen White Dwarf
- Needs a « friend » to explode
- Two main scenarios :
 - Single degenerate
 - Double degenerate



What is a Type Ia Supernova (SNIa) ?

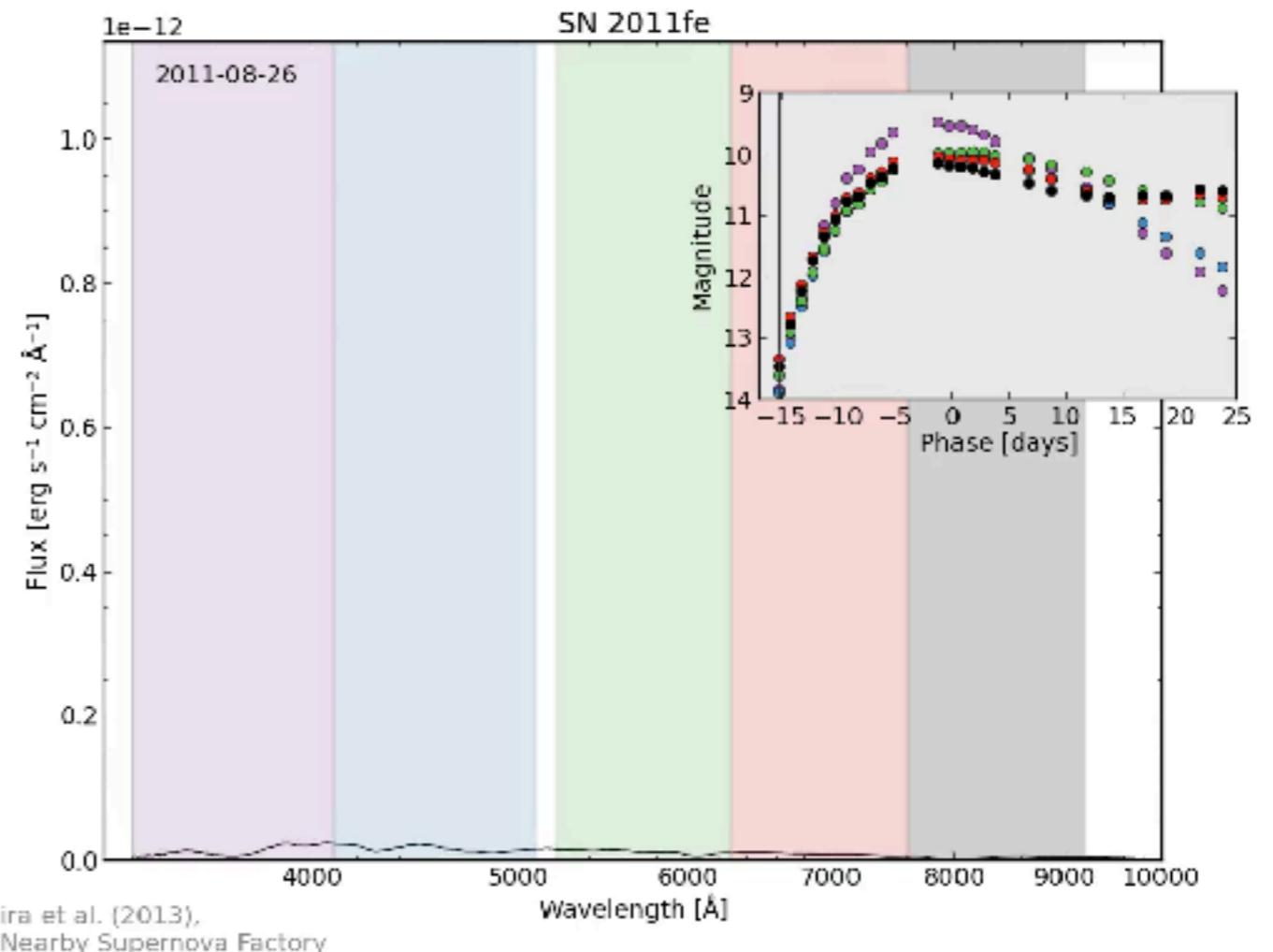


Both scenarios cannot reproduce
the observed SED...

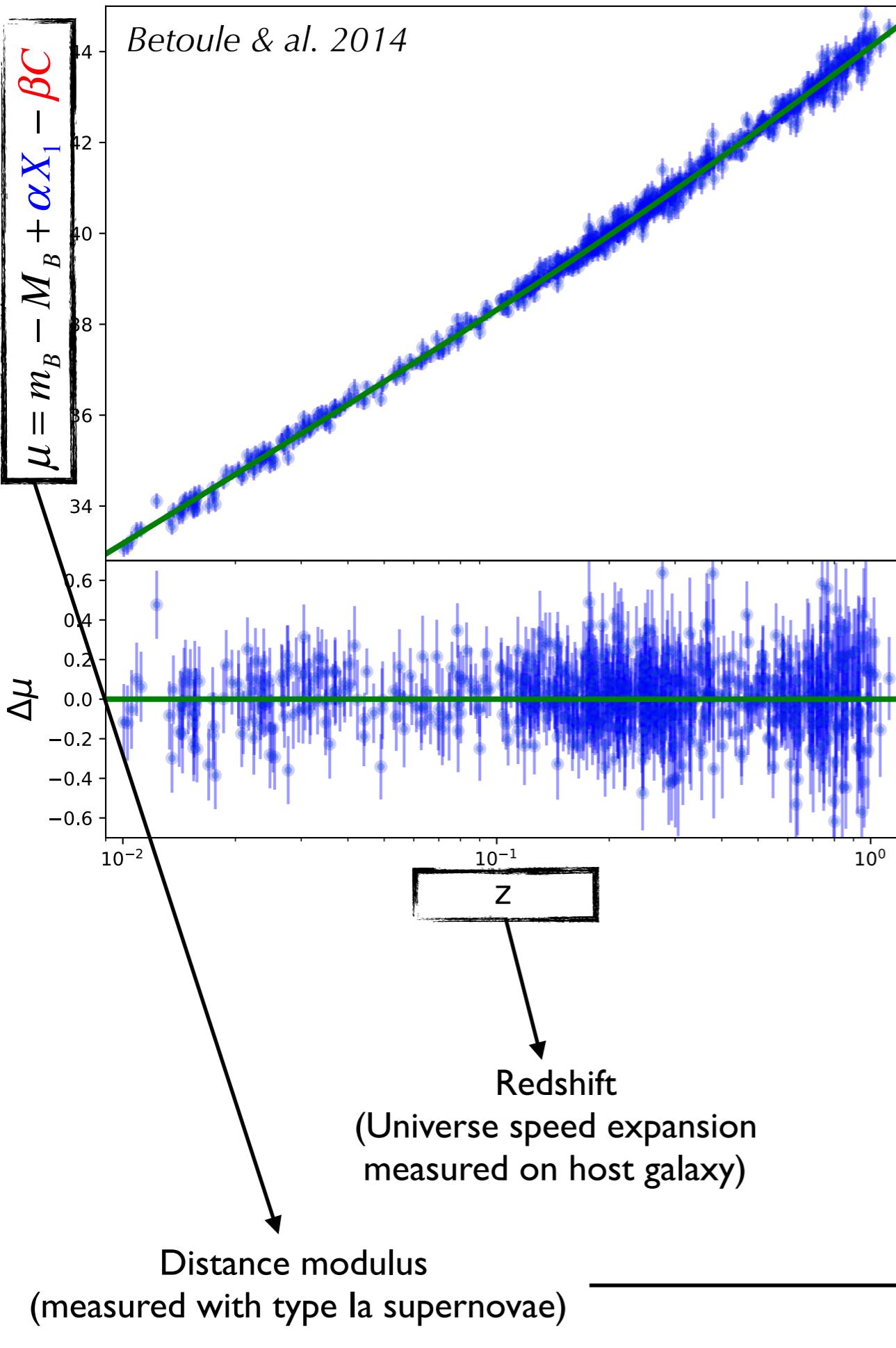
Röpke & al. 2012

What is a Type Ia Supernova (SNIa) ?

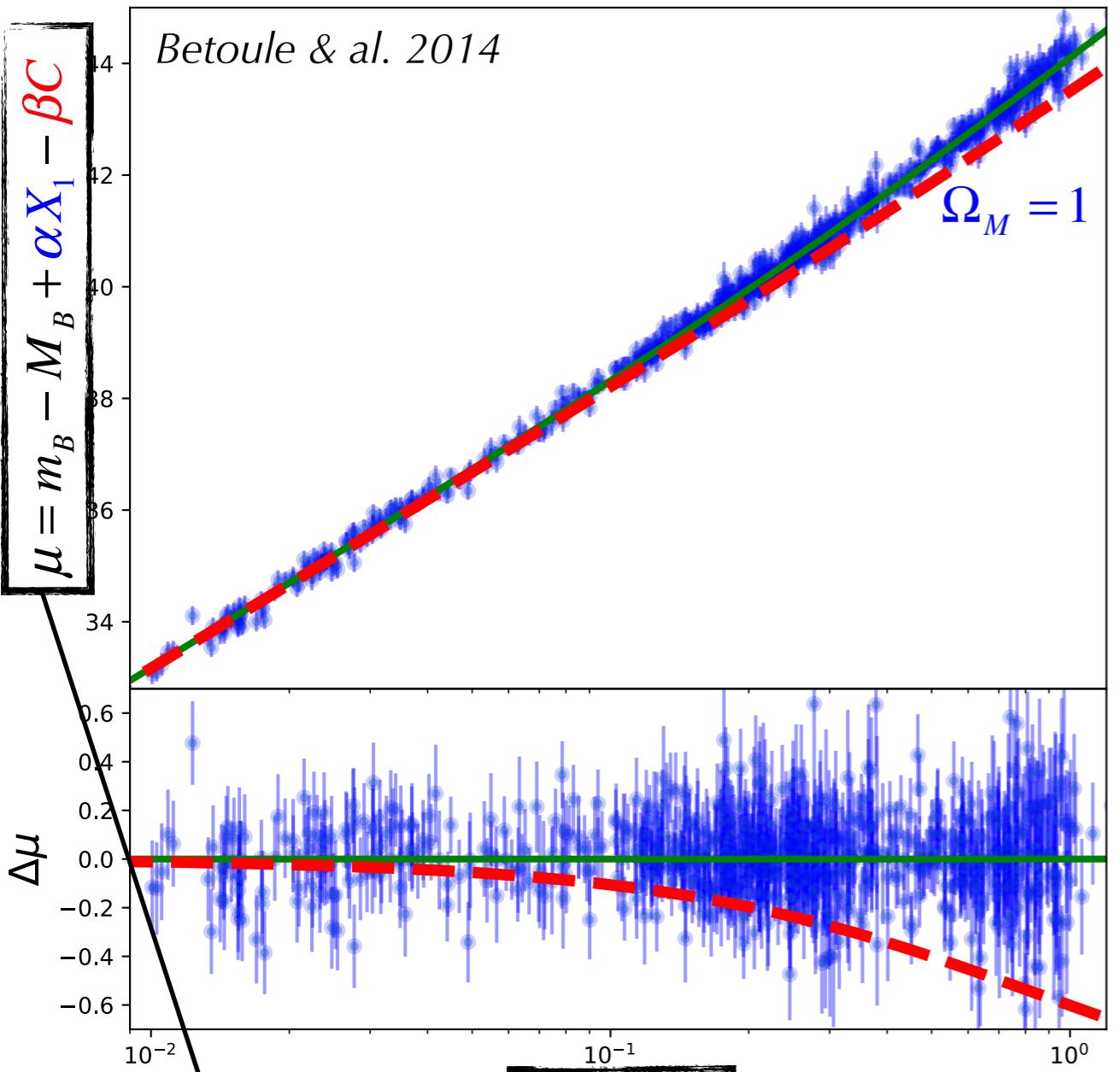
- Transient object
- As bright as the host galaxy
- No hydrogen line
- Deep silicon lines
- All SNIa more or less the same
- SNIa are standard candles!



Betoule & al. 2014



Betoule & al. 2014

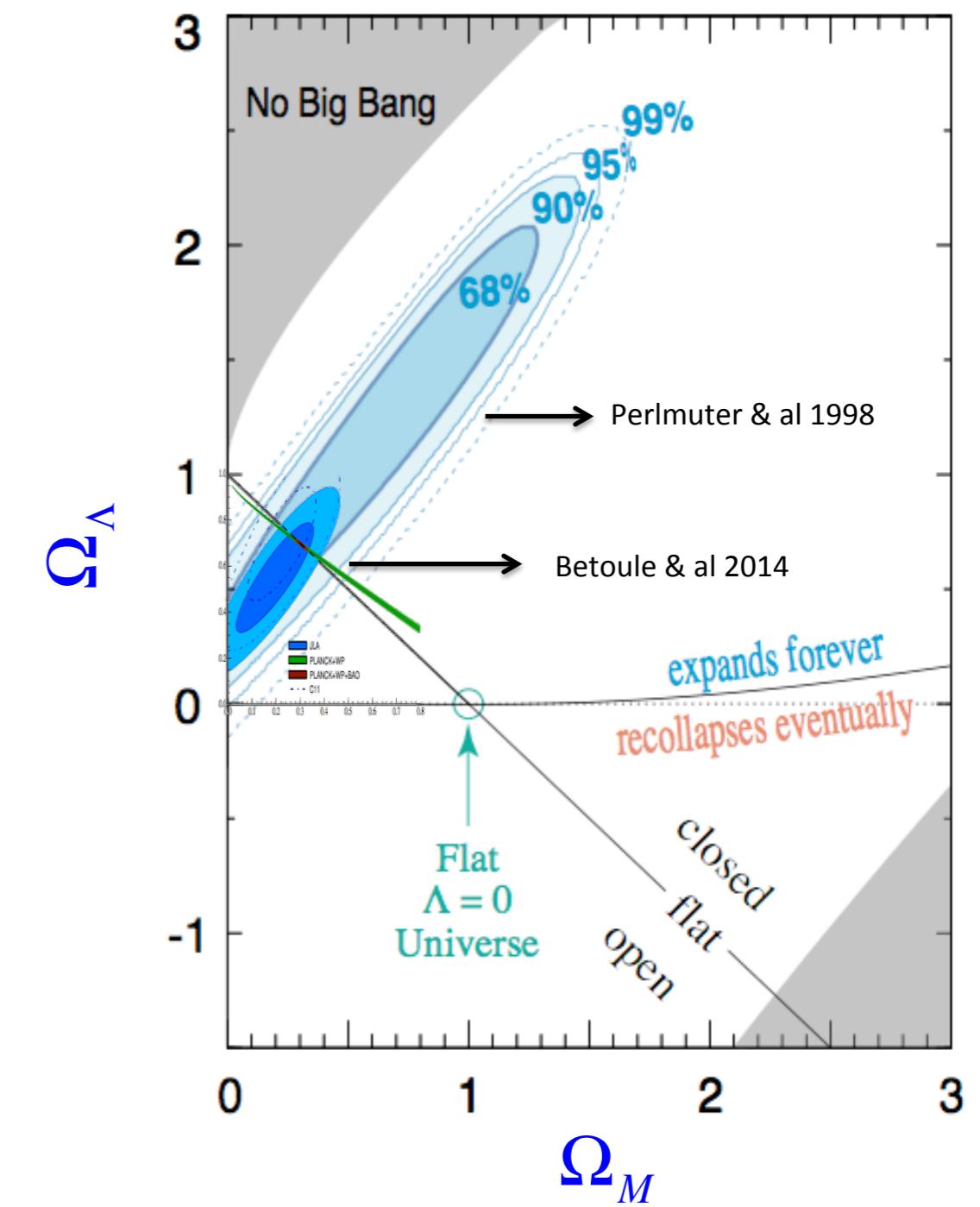
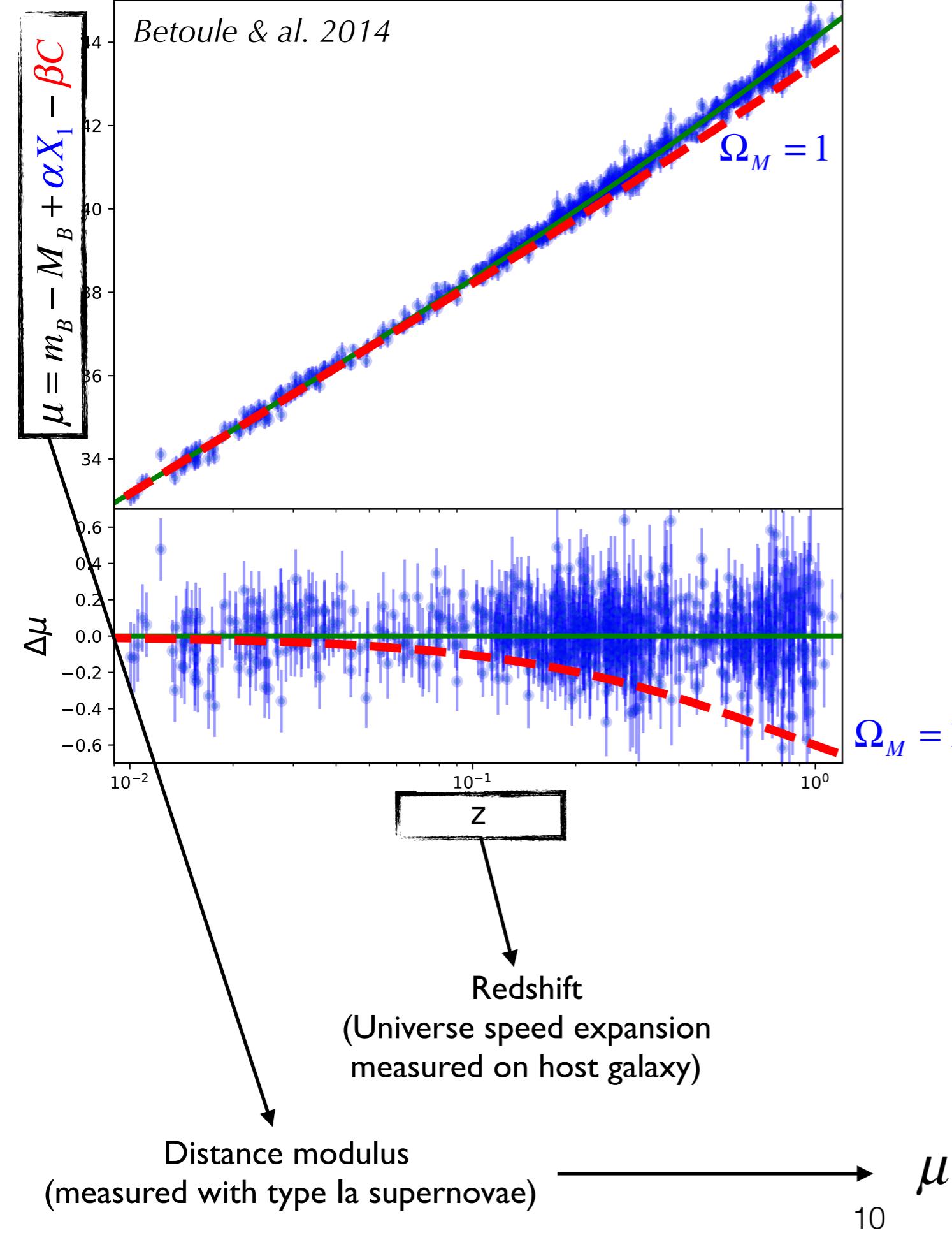


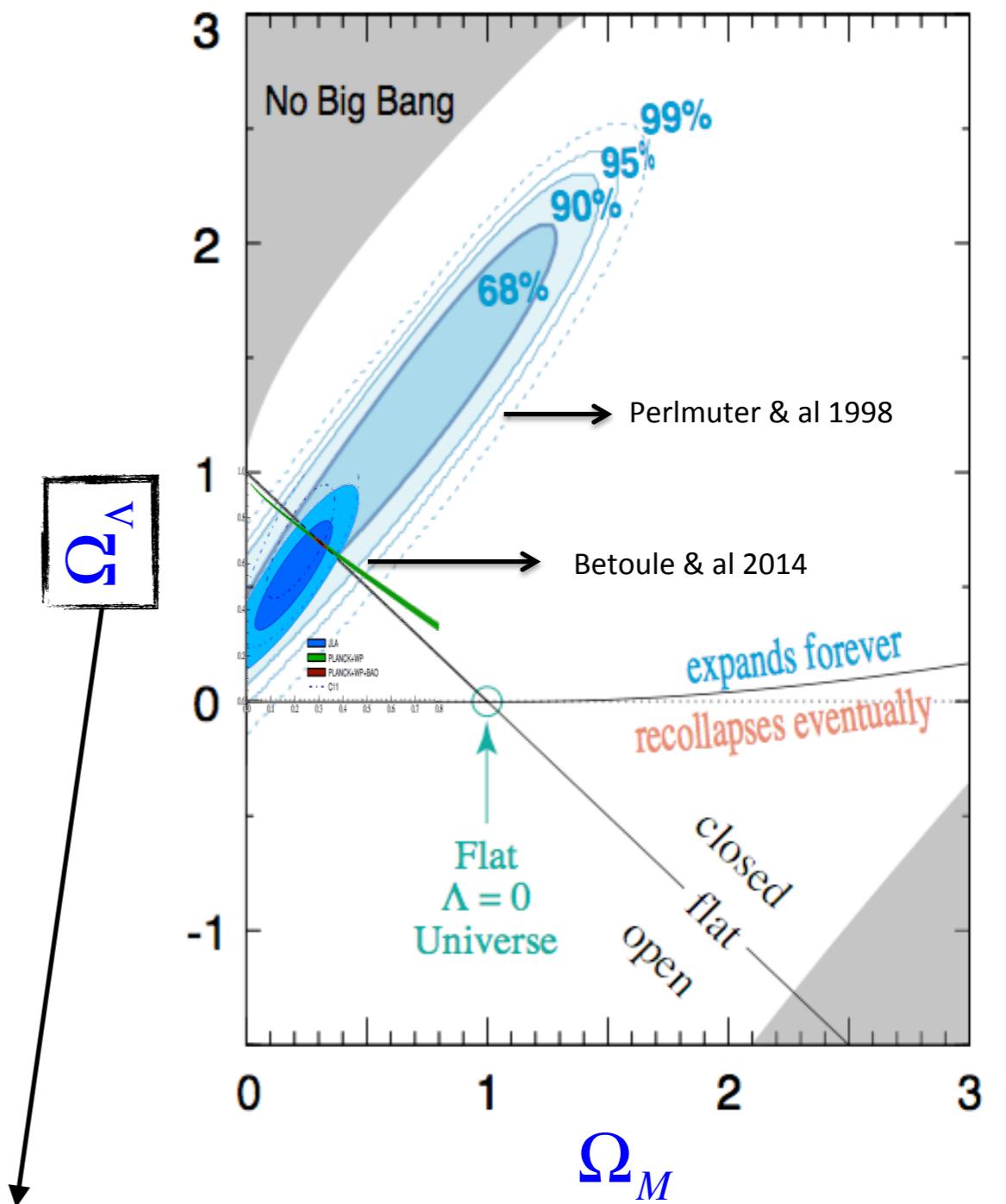
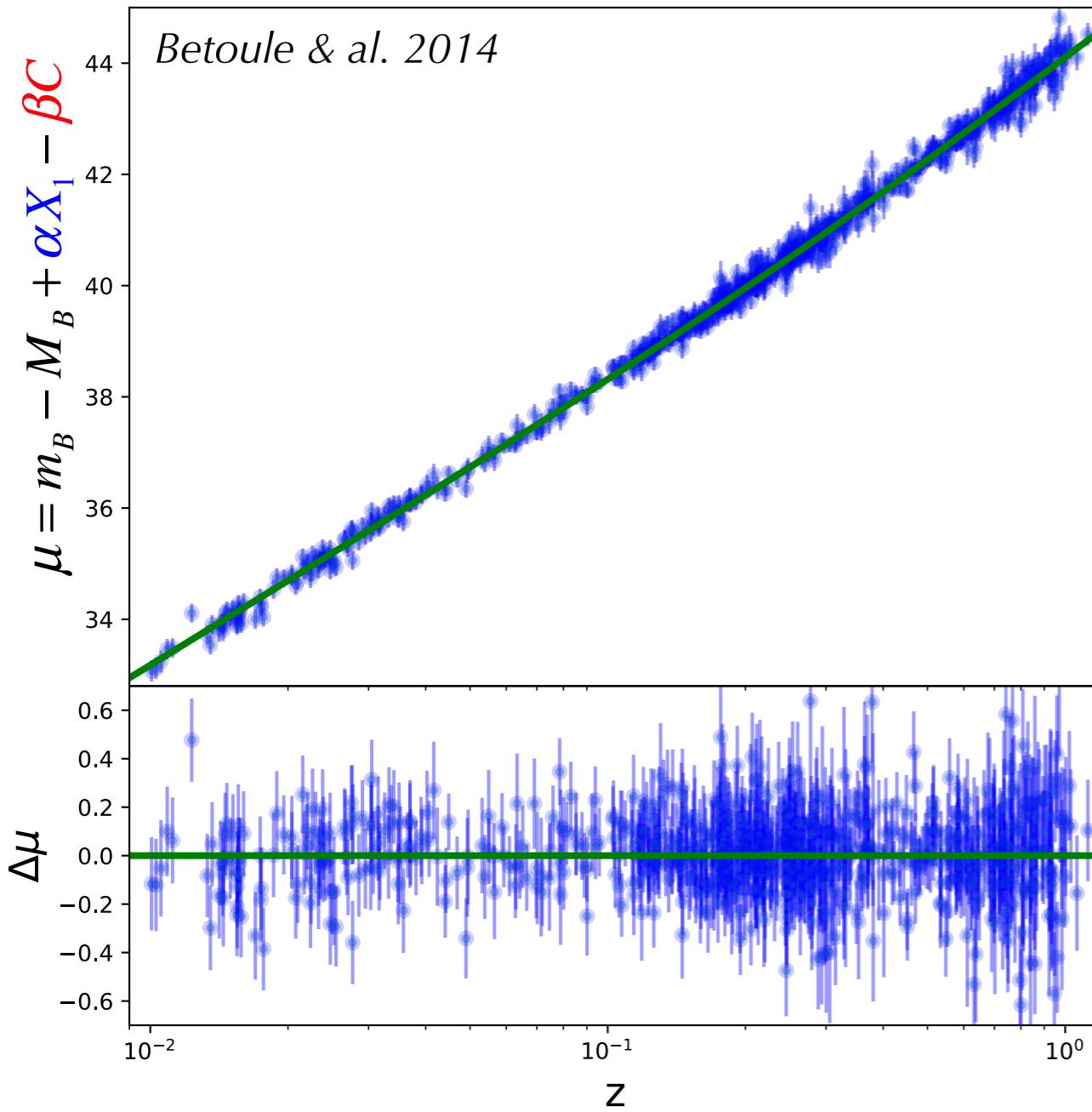
Z

Redshift
(Universe speed expansion measured on host galaxy)

Distance modulus
(measured with type Ia supernovae)

$\mu = 5 \log_{10}(d_l(z, H_0, \Omega_M, \Omega_\Lambda)) - 5$

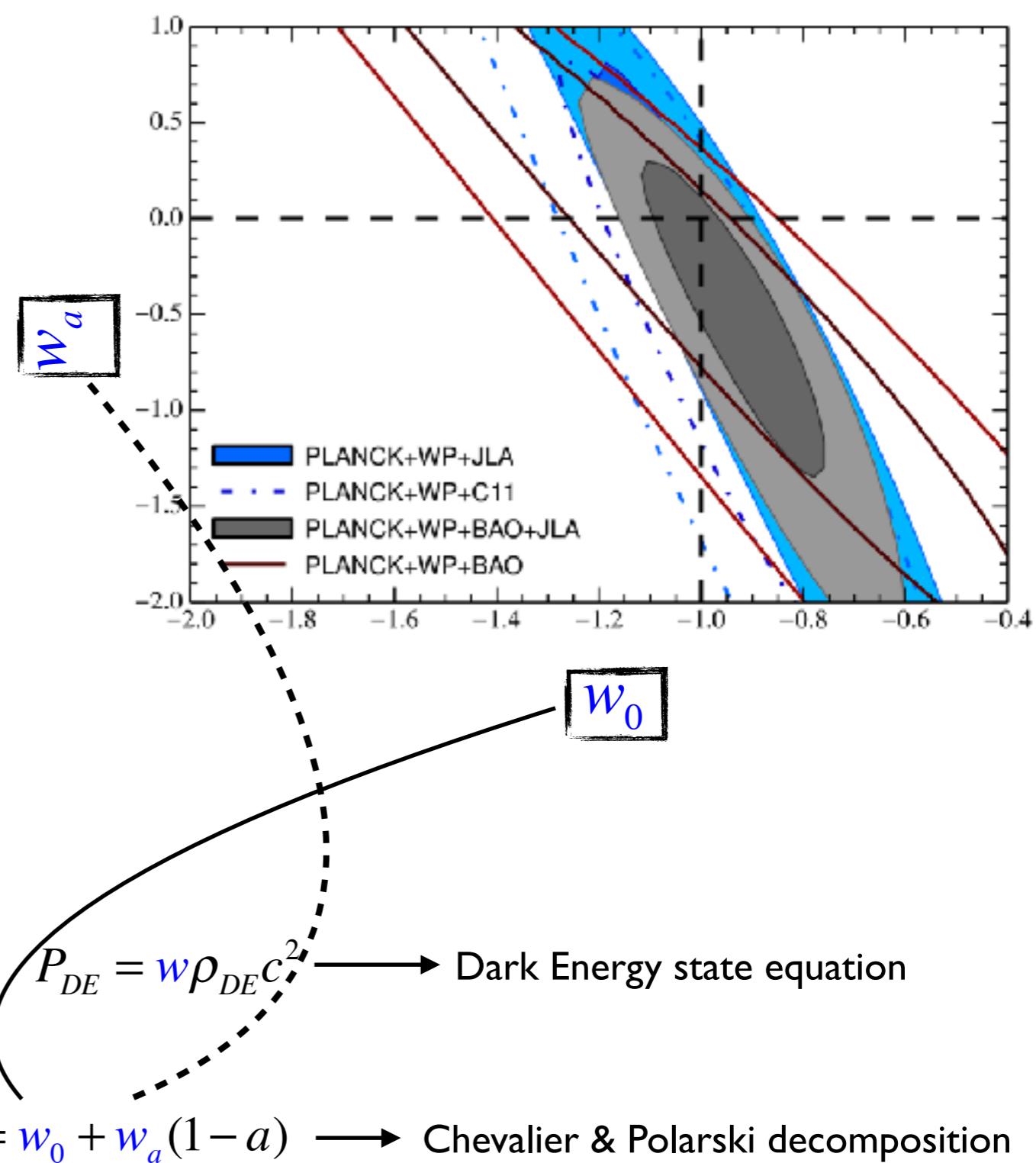
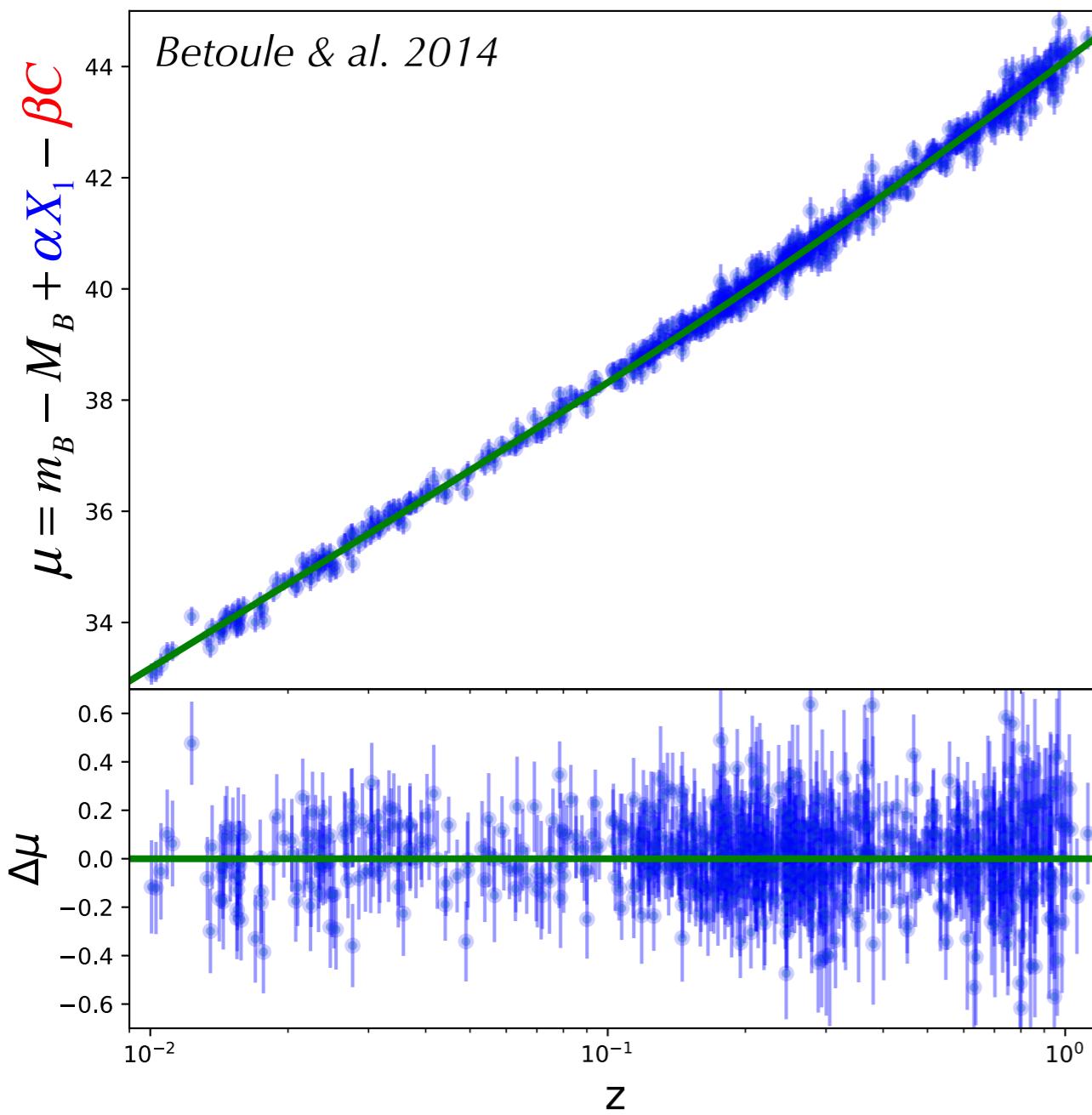




$$P_{DE} = w \rho_{DE} c^2 \longrightarrow \text{Dark Energy state equation}$$

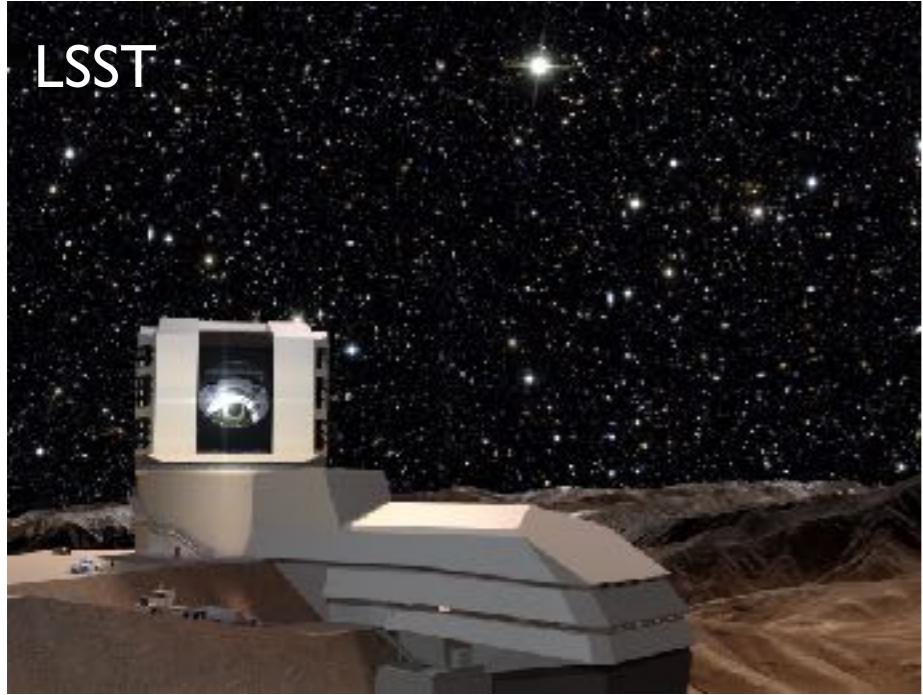
$$w = w_0 + w_a(1-a) \longrightarrow \text{Chevalier & Polarski decomposition}$$

$$w_0 = -1 \quad w_a = 0 \longrightarrow \text{Cosmological constant}$$

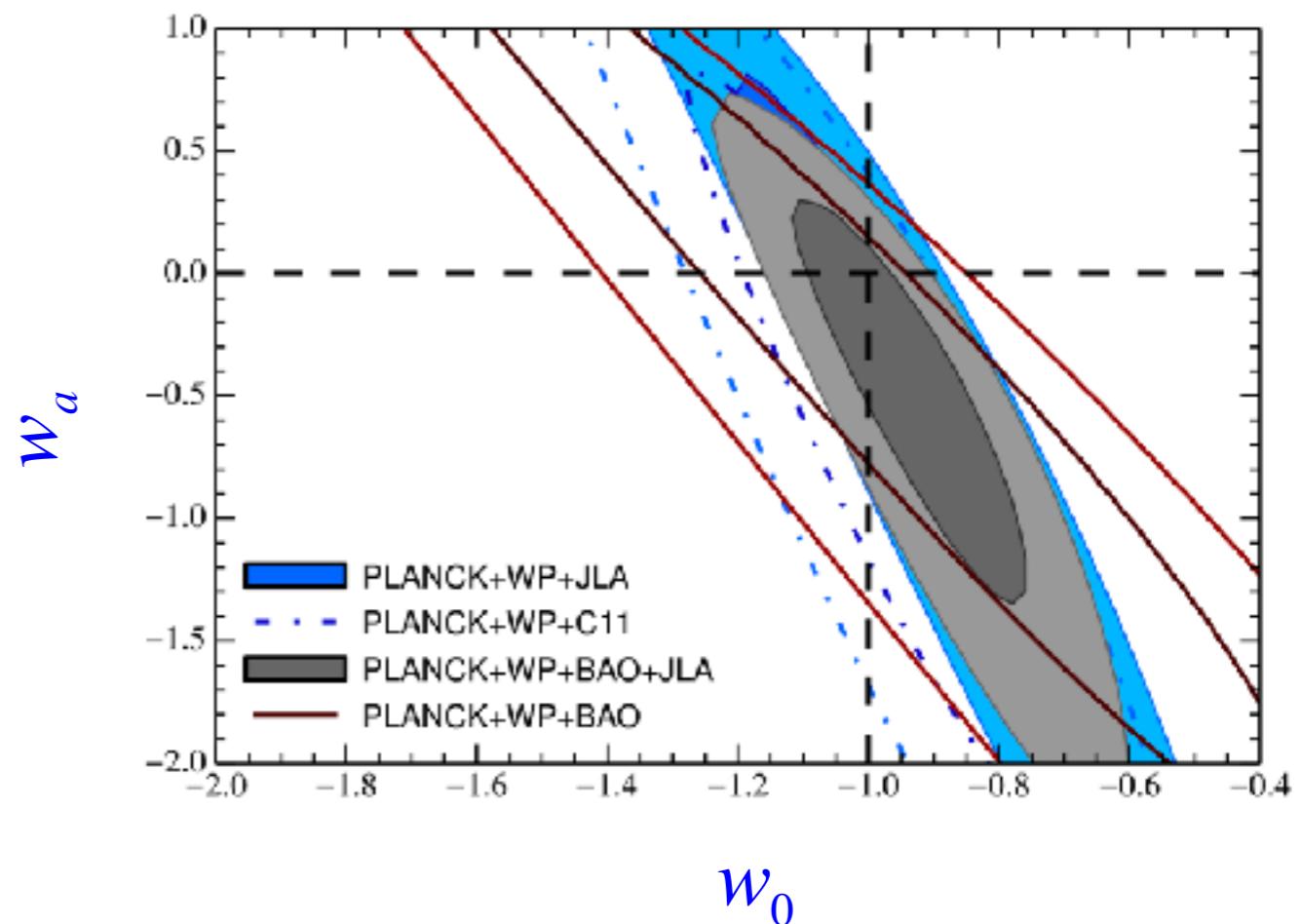


SNIa currently best probes in the redshift range [0;1.5] !

LSST



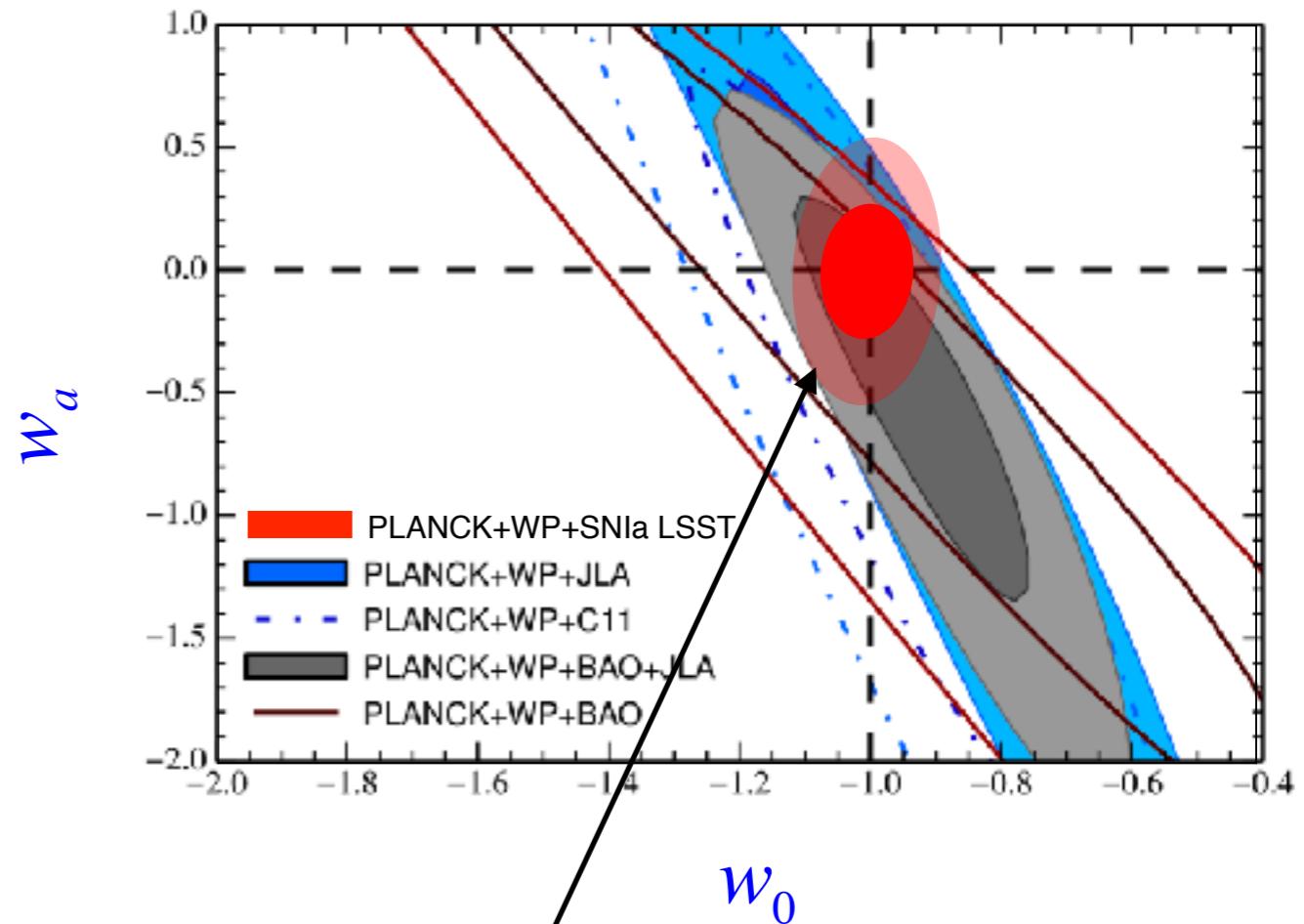
Betoule & al. 2014



- LSST: 8 meters telescope with a huge fields of view
- LSST will observe $\sim 300\,000$ SNIa (compared to the ~ 1000 now)



Betoule & al. 2014



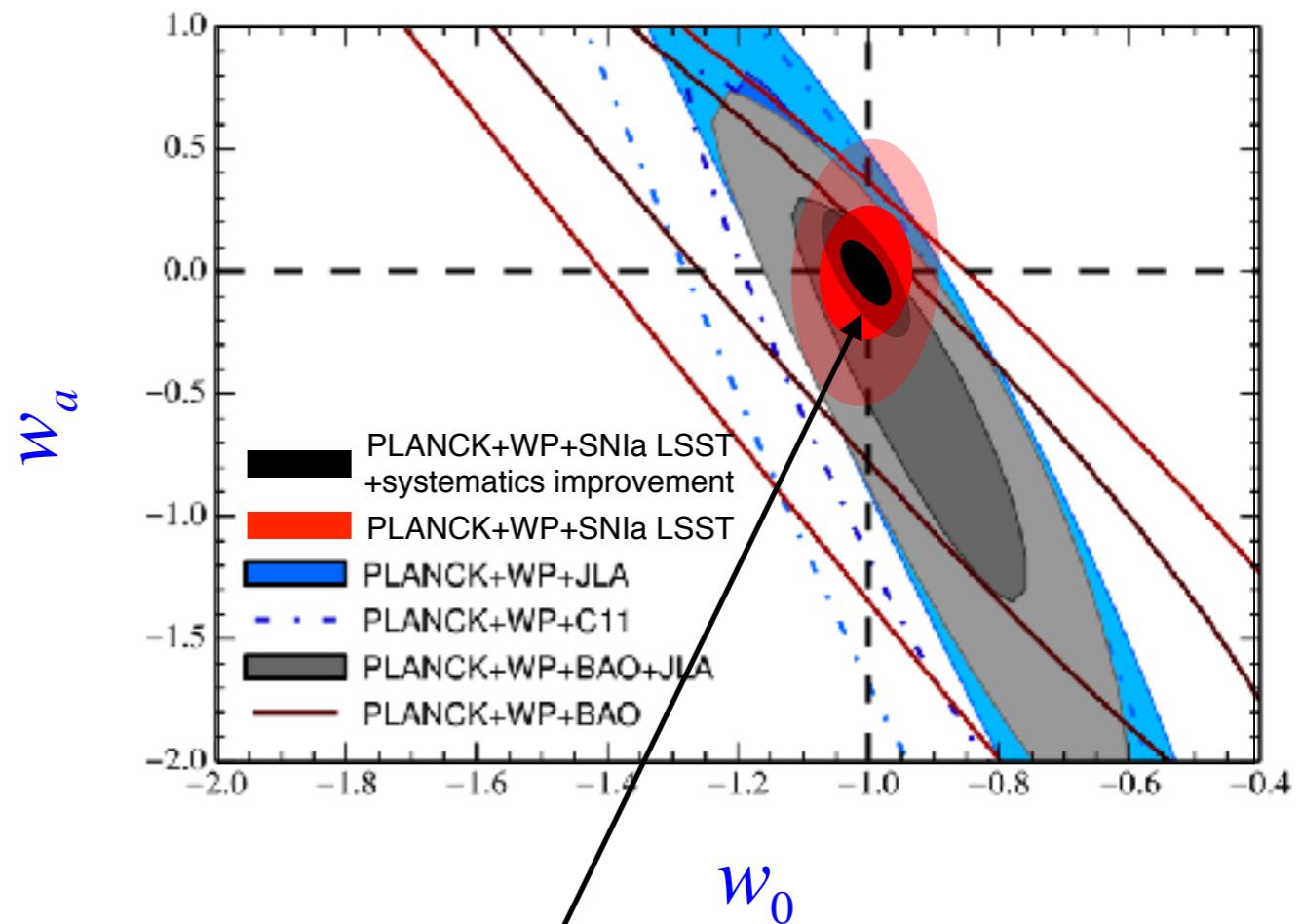
Just by increasing
the statistics

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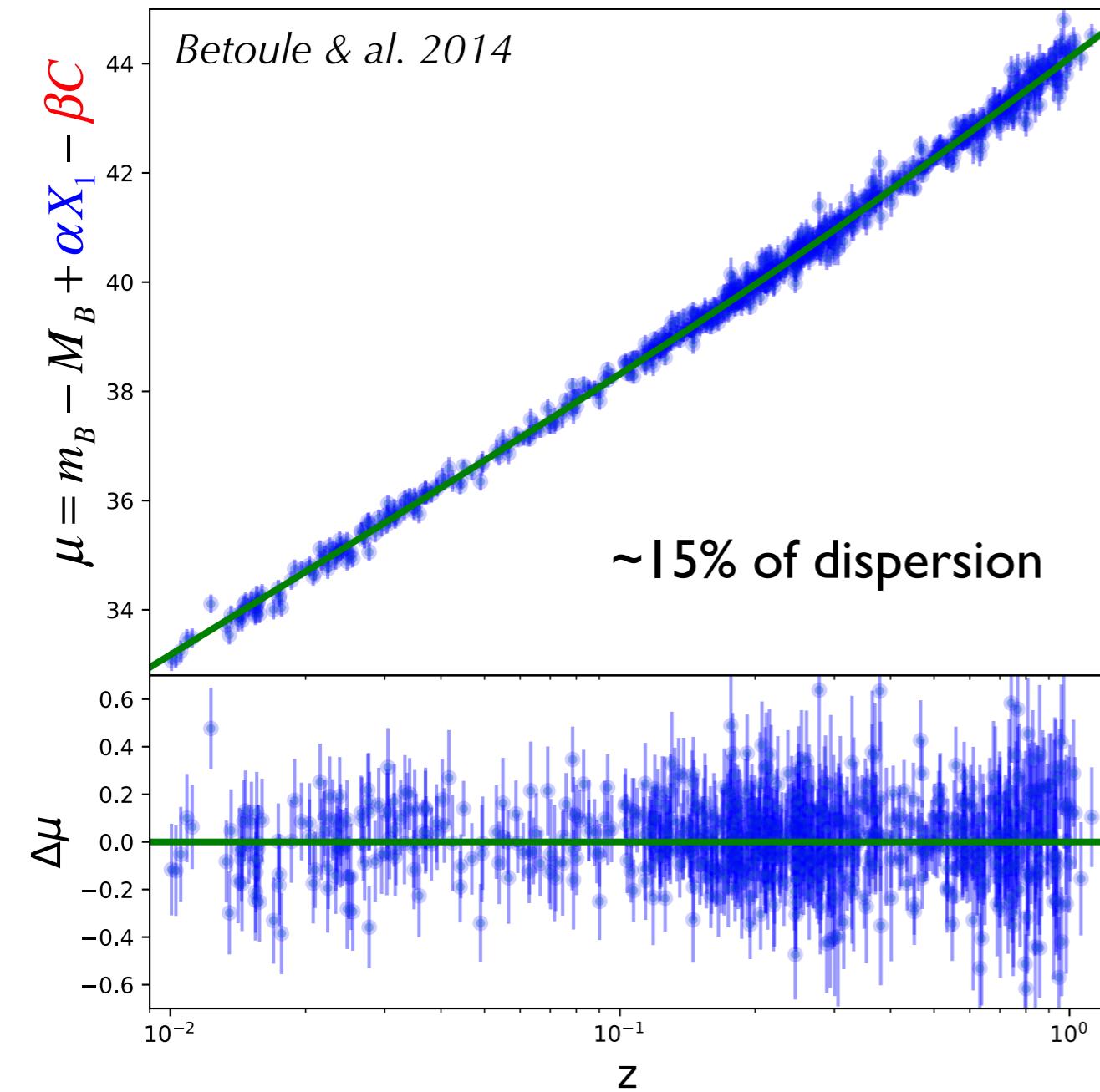


w_0

Just by increasing
the statistics
+
Improving distance
measurements

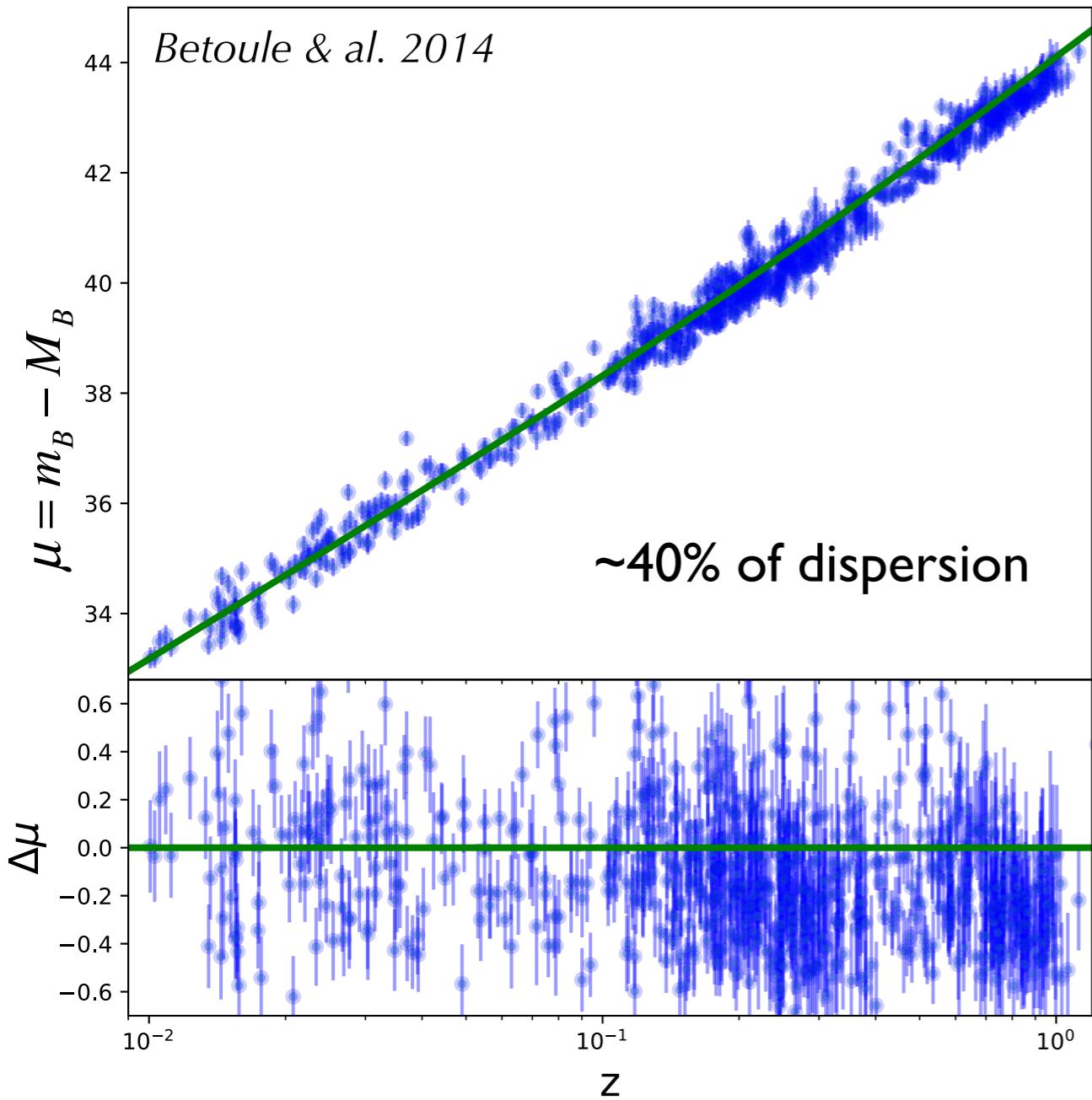
Betoule & al. 2014

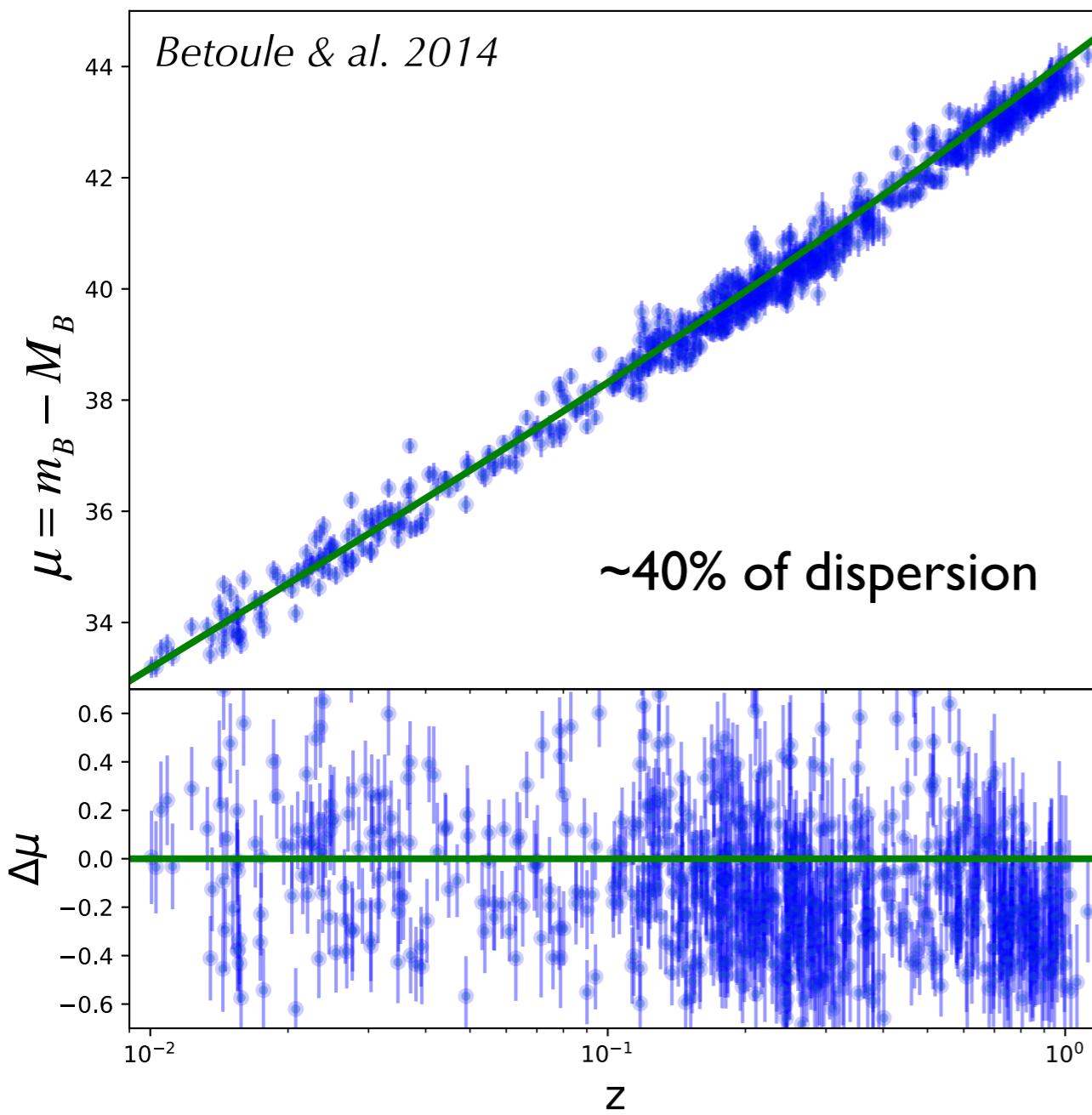
Supernovae are quasi-standard candles:



Betoule & al. 2014

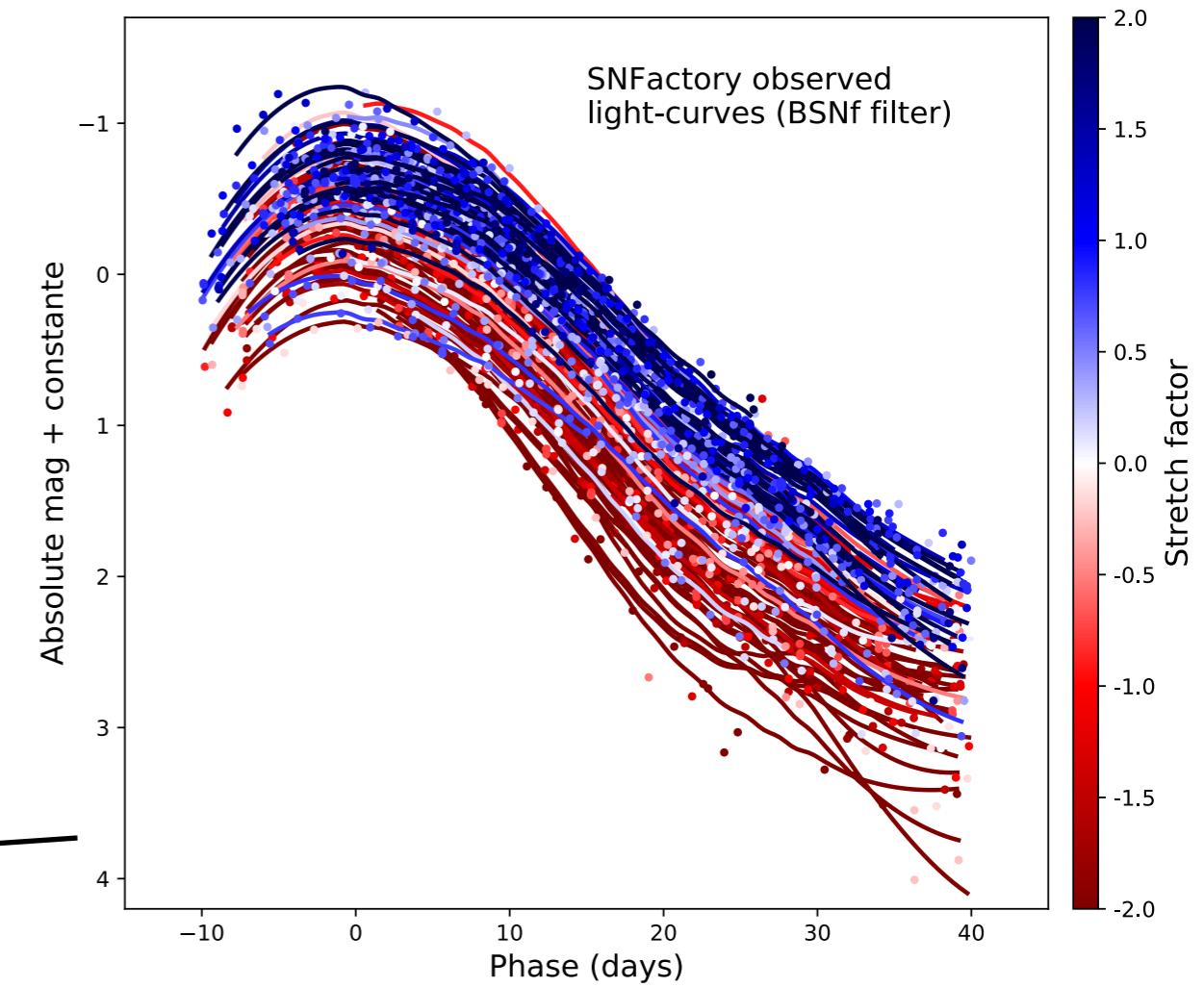
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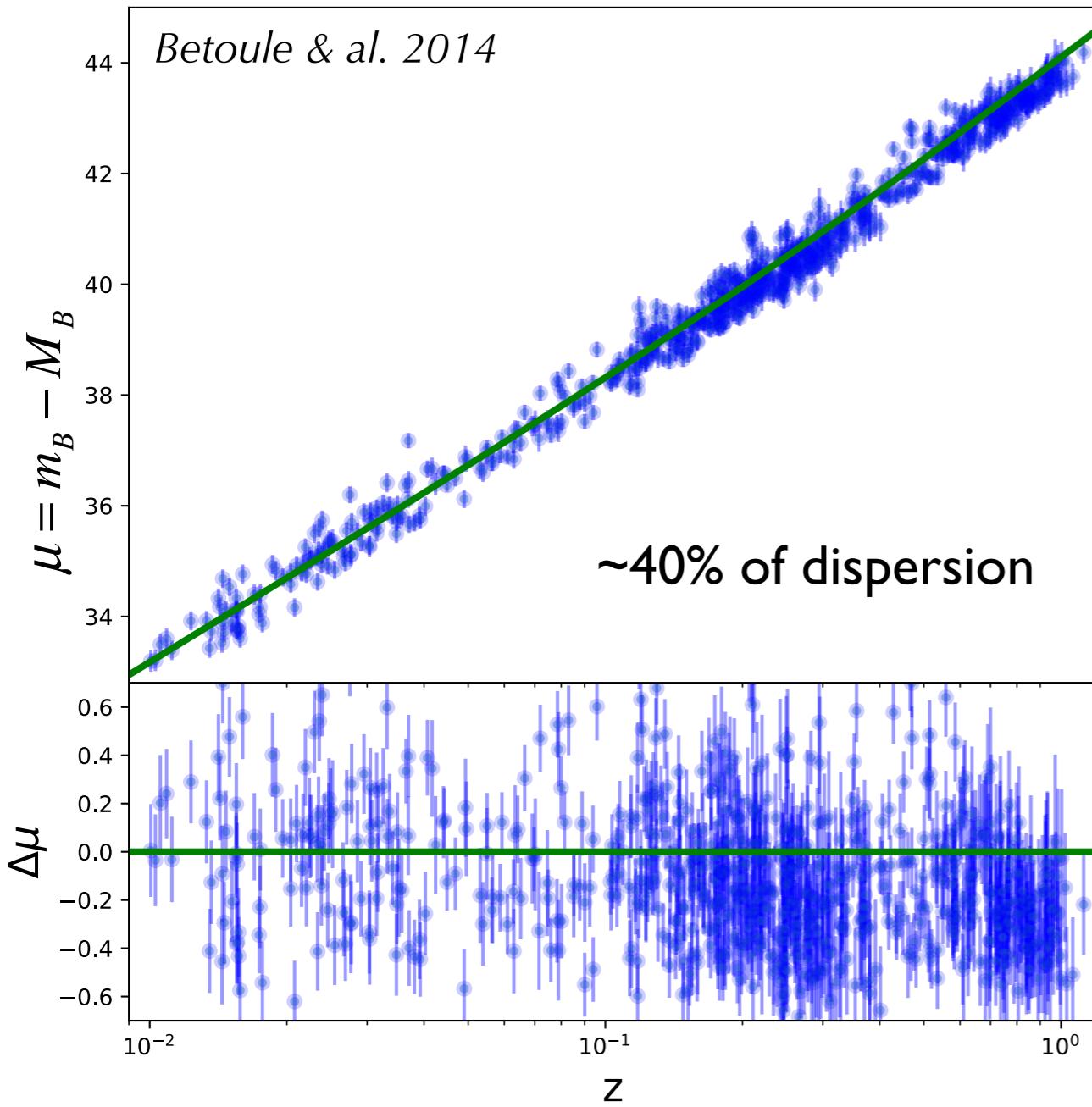


Link to physical properties

Supernovae are quasi-standard candles:
Two main sources of variability:
I. Stretch: intrinsic variability



Betoule & al. 2014

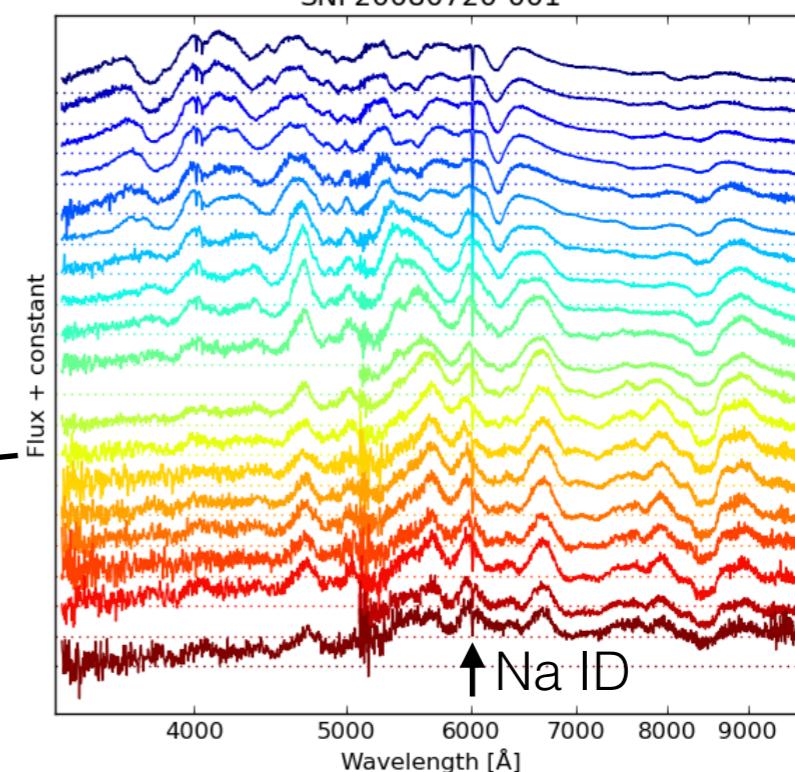
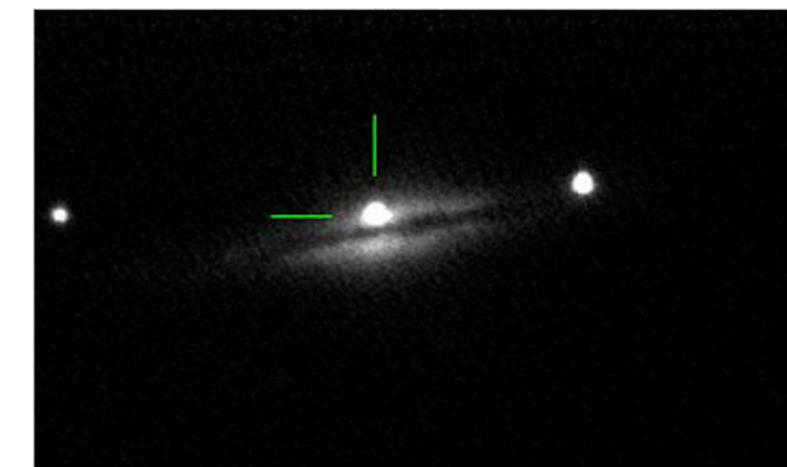


Extinction by host dust

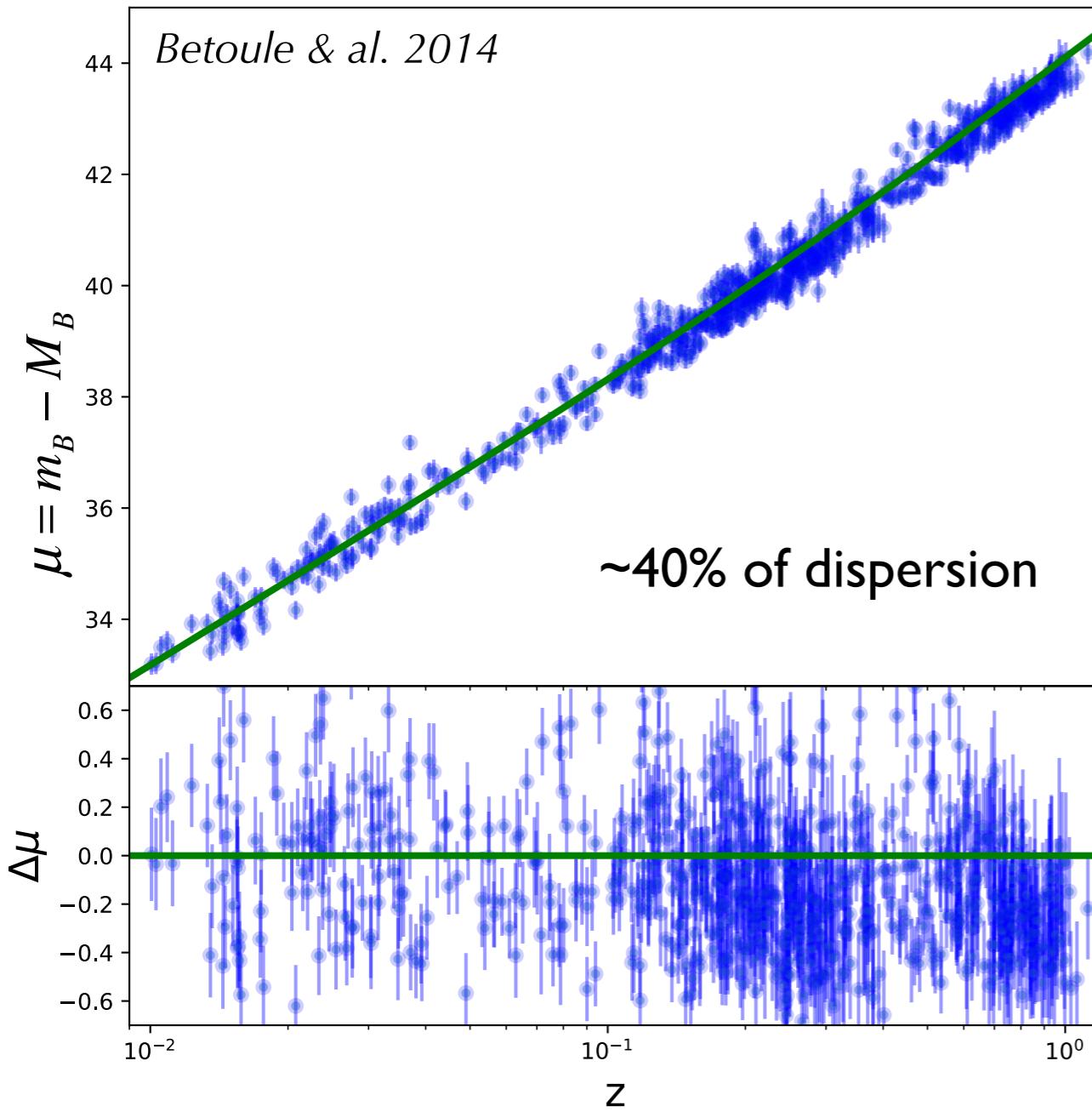
Supernovae are quasi-standard candles:

Two main sources of variability:

1. **Stretch**: intrinsic variability
2. **Color**: extrinsic variability



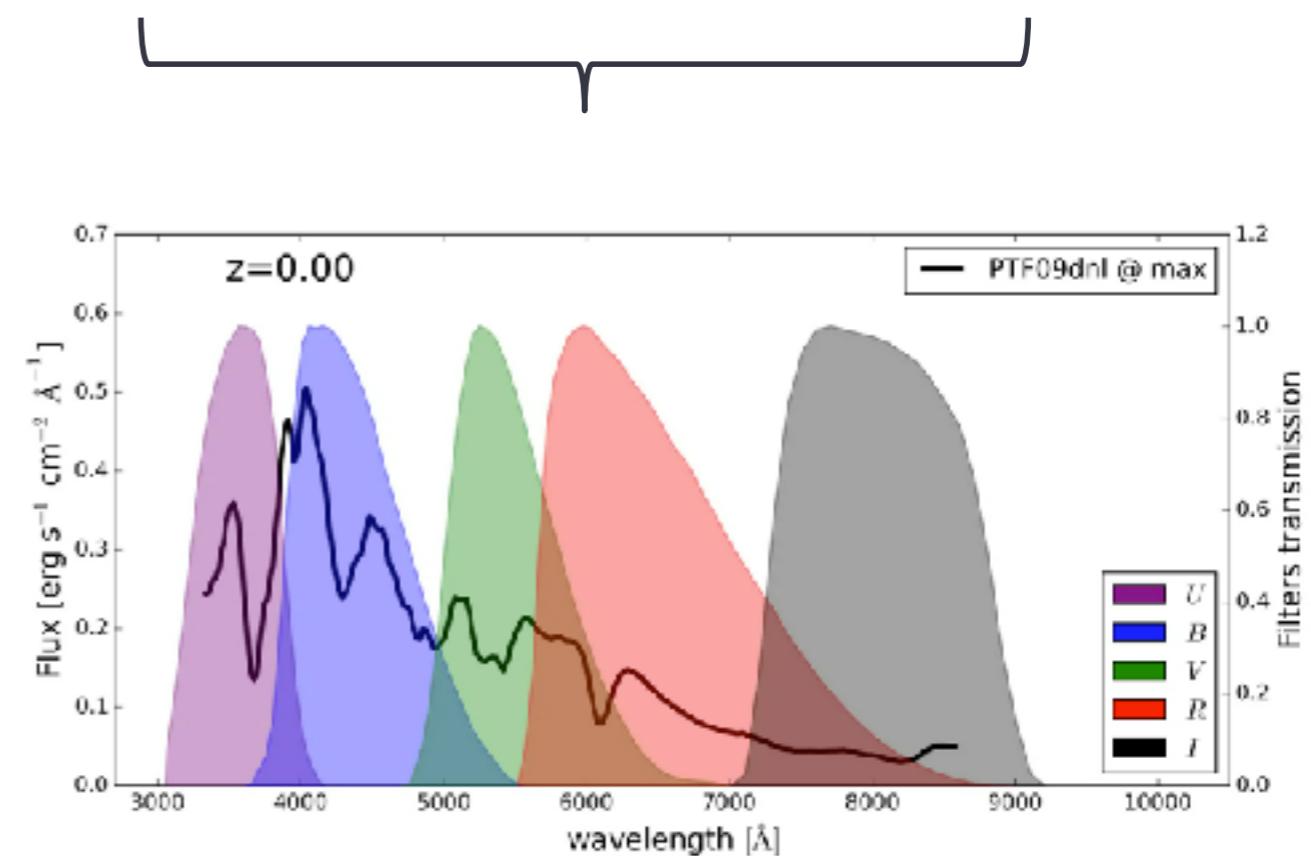
Betoule & al. 2014



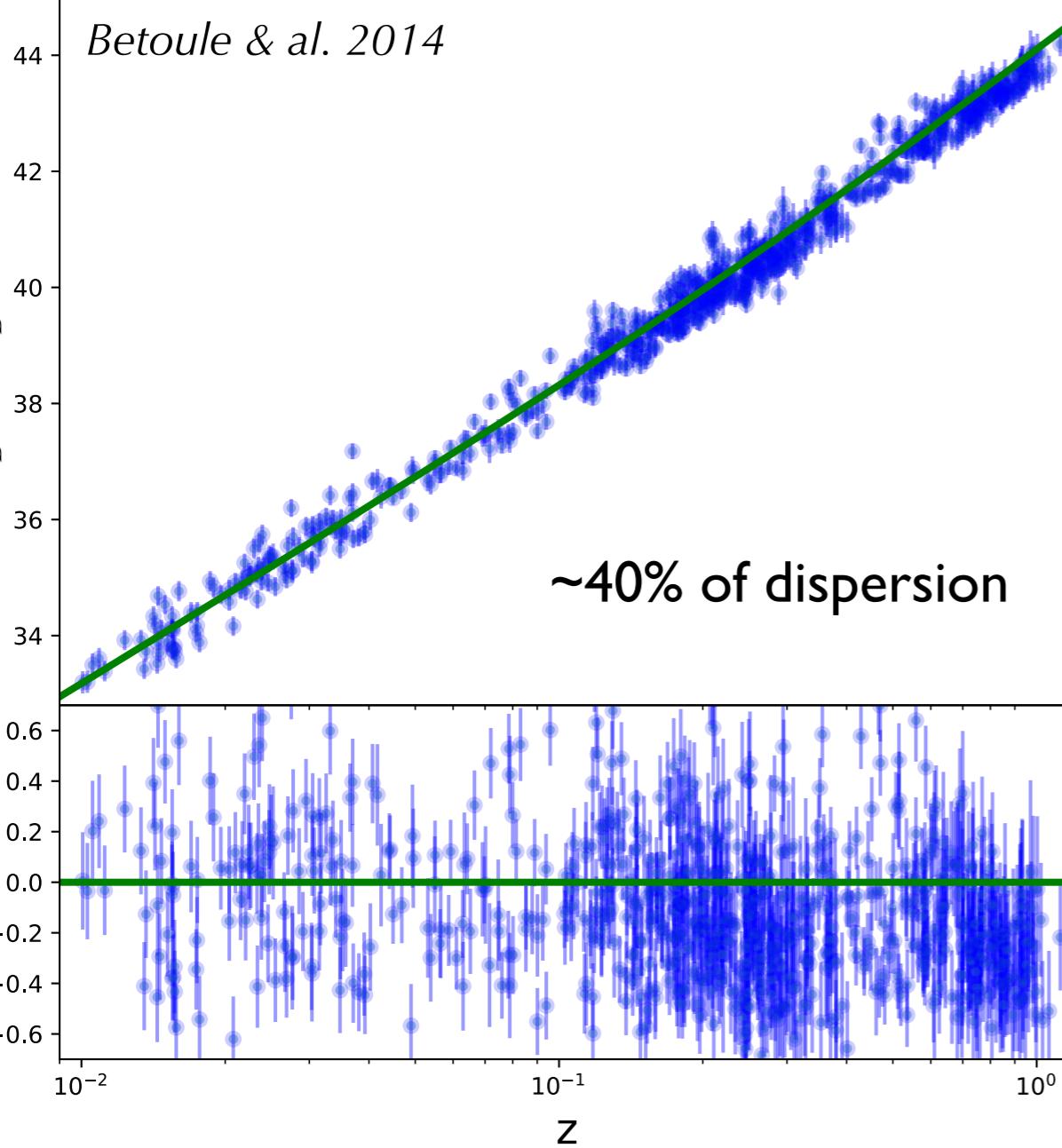
Supernovae are quasi-standard candles:

Two main sources of variability:

1. Stretch: intrinsic variability
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- Measured on light curves with photometric survey
- Need of SNIa model to take into account redshift effect



Supernovae are quasi-standard candles:

Two main sources of variability:

1. **Stretch**: intrinsic variability
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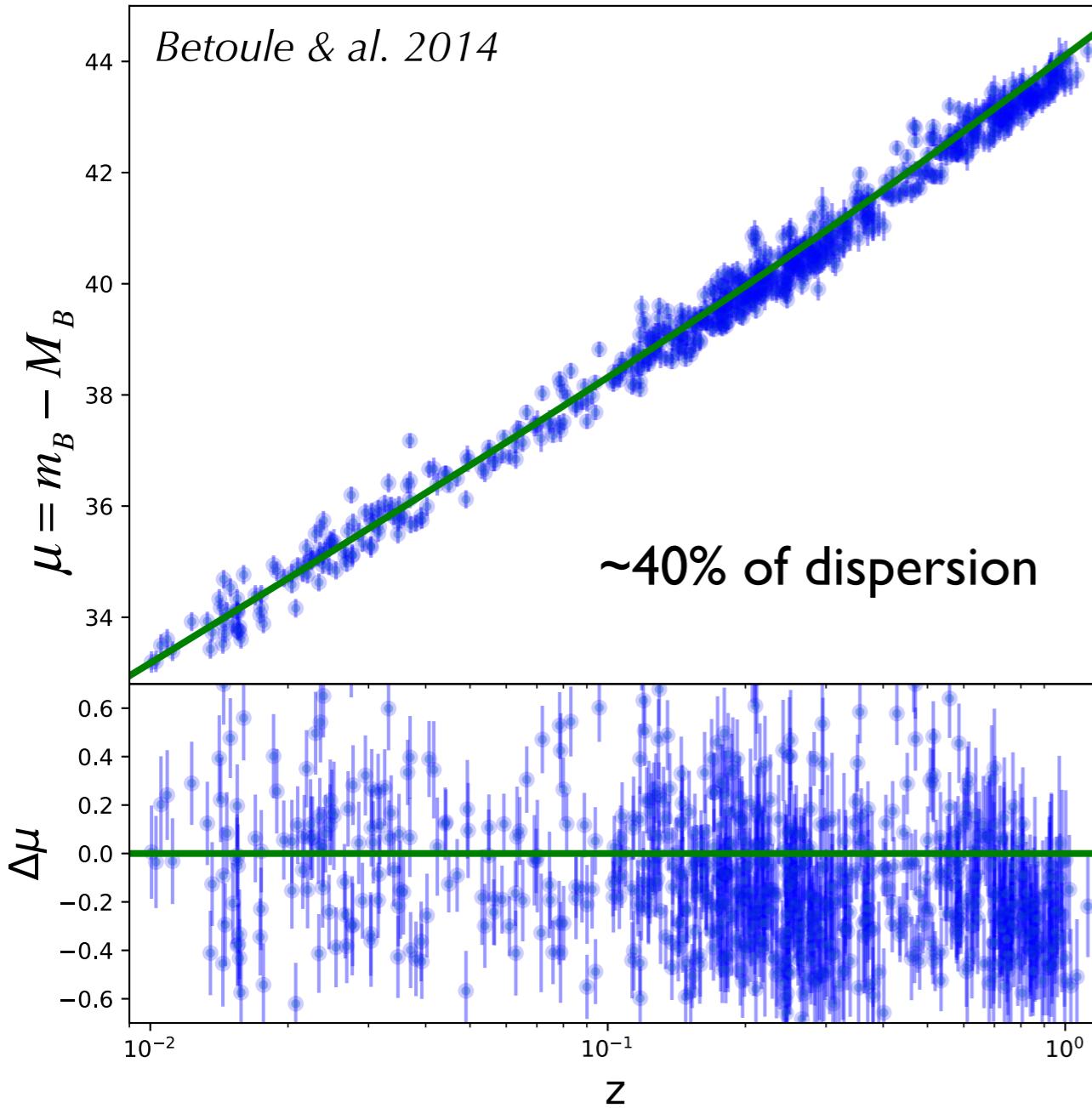
SALT2 model (Guy & al. 2007)

$$F(p, \lambda) = X_0 \times (S_0(p, \lambda) + X_1 S_1(p, \lambda)) \times \exp(C \times CL(\lambda))$$

Measured on each SNIa

- X_0 → Correlated to redshift
- X_1 → Stretch effect, associated to intrinsic variability
- C → Color effect, fit a global SNIa color

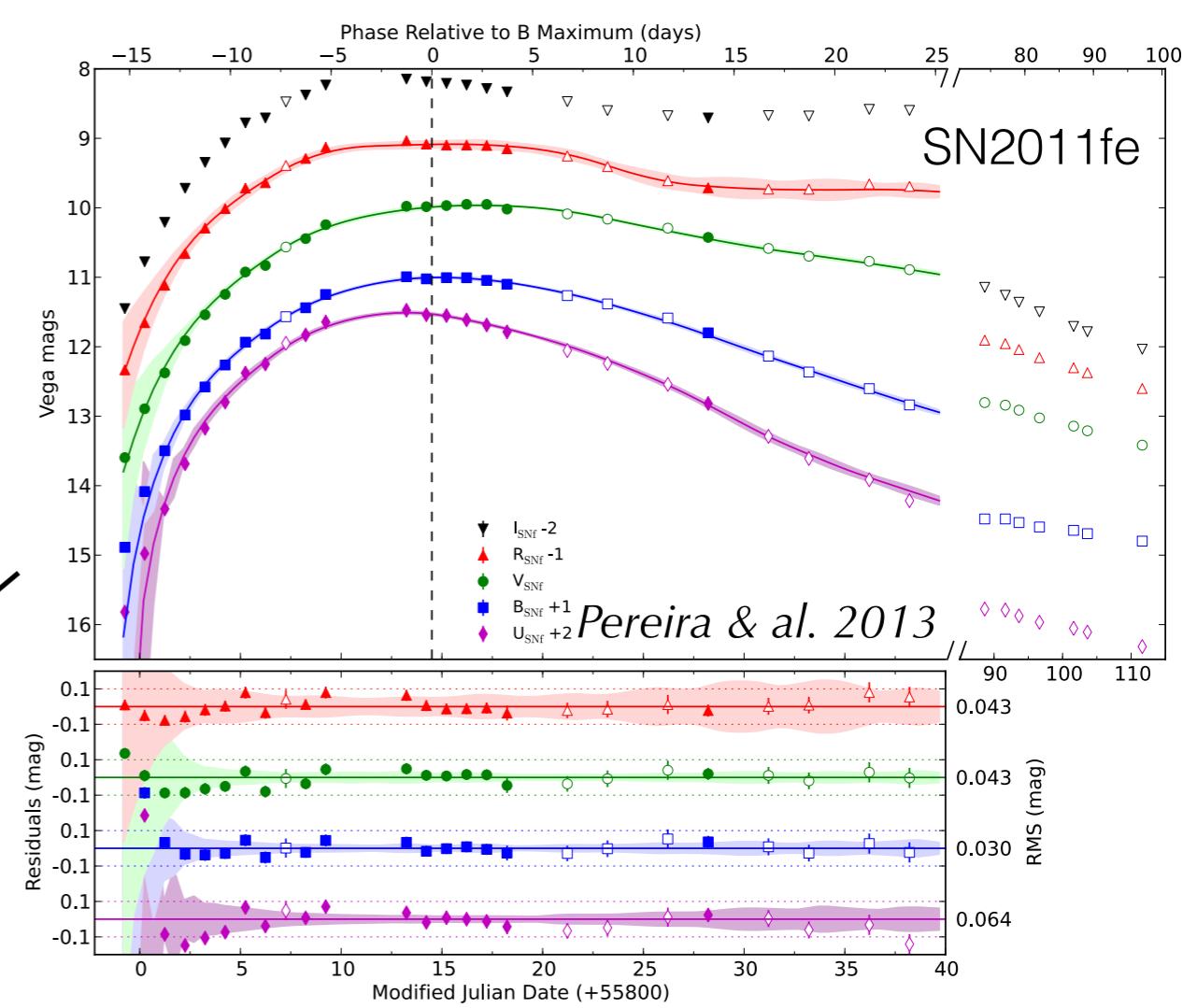
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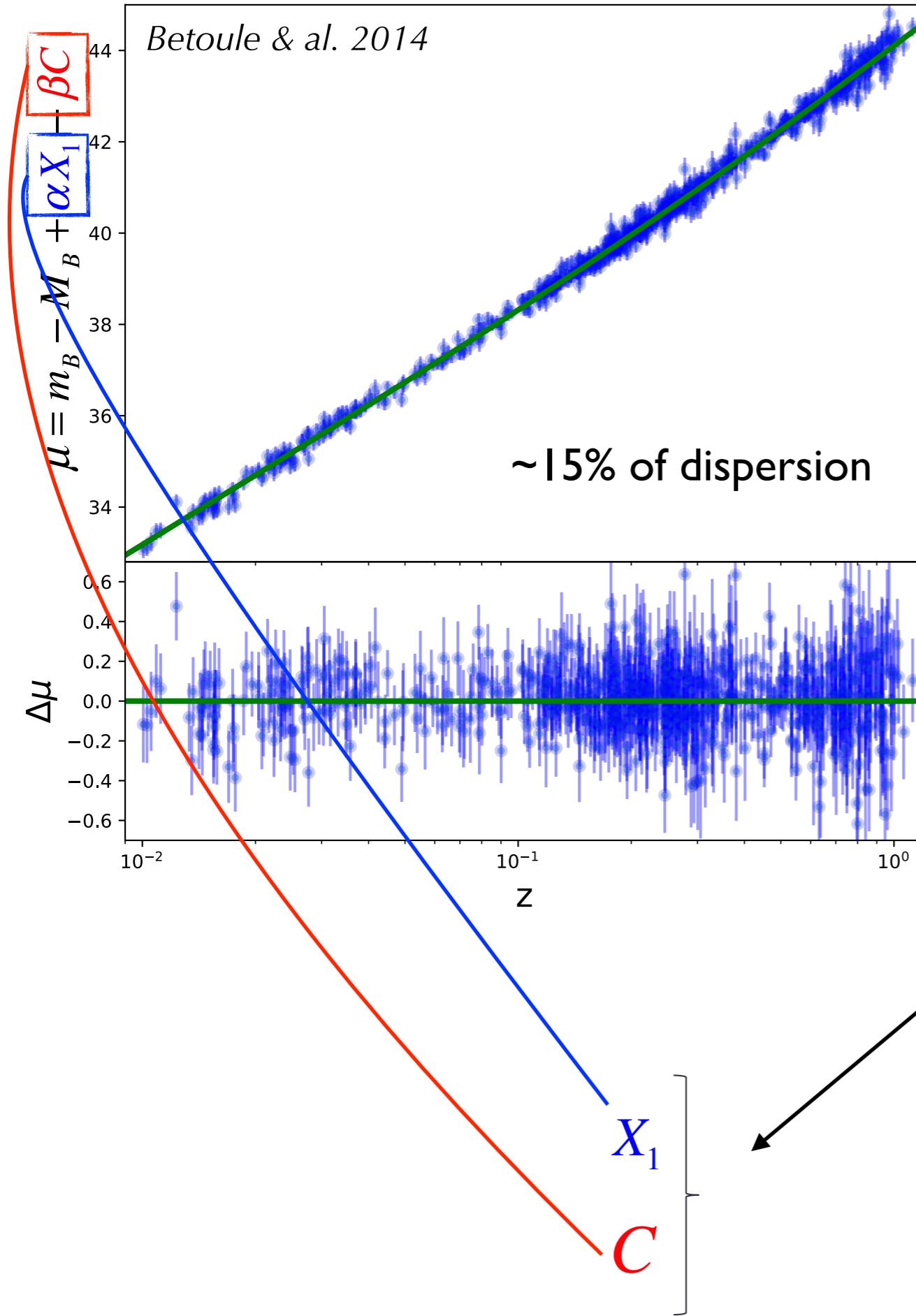
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$$C = \{X_0, X_1\}$$

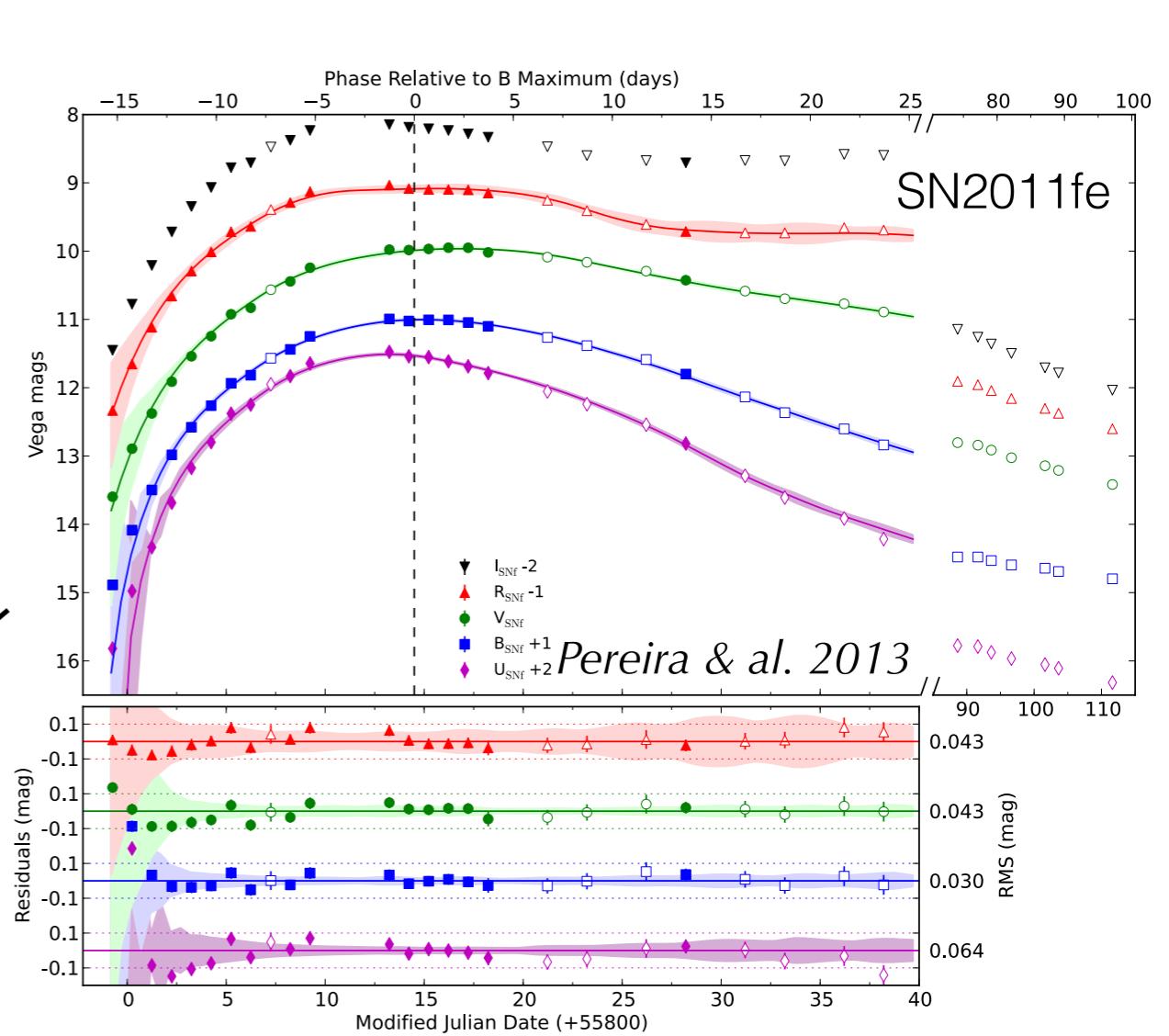
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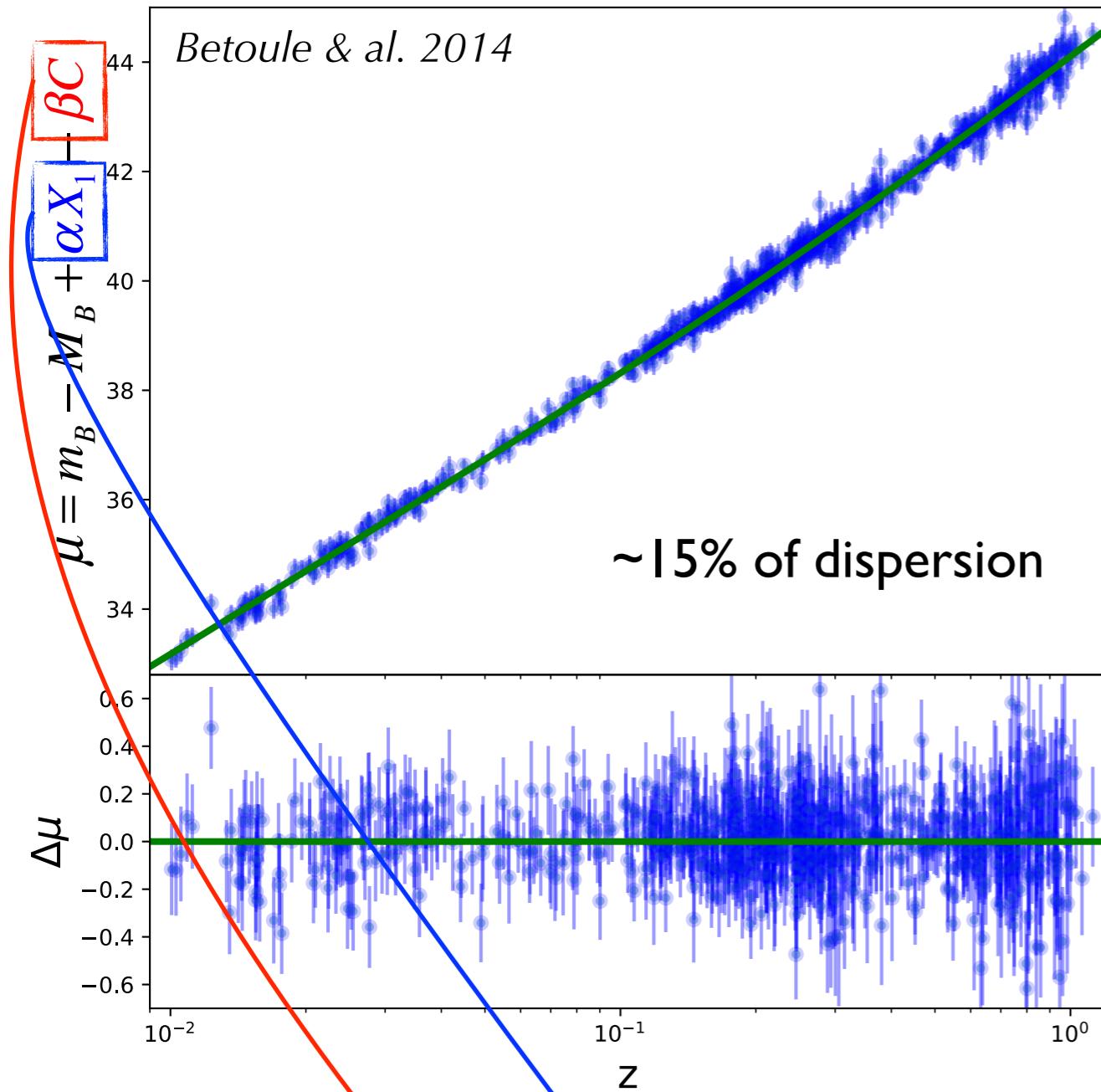
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Betoule & al. 2014



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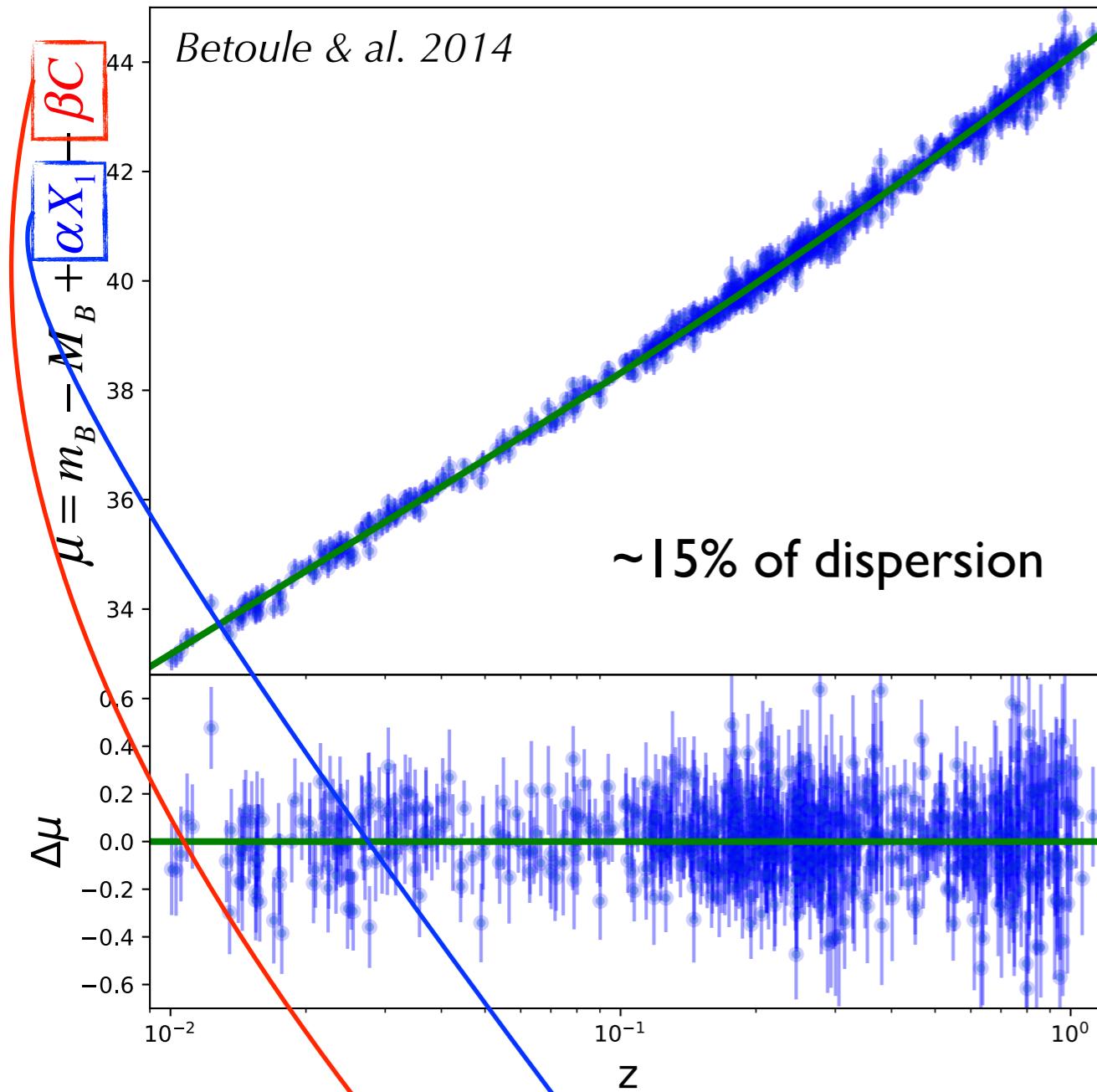
1. Stretch: intrinsic variability
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Do those corrections are optimal ?

X_1
C

Do those corrections involve bias ?

Betoule & al. 2014



Supernovae are quasi-standard candles:

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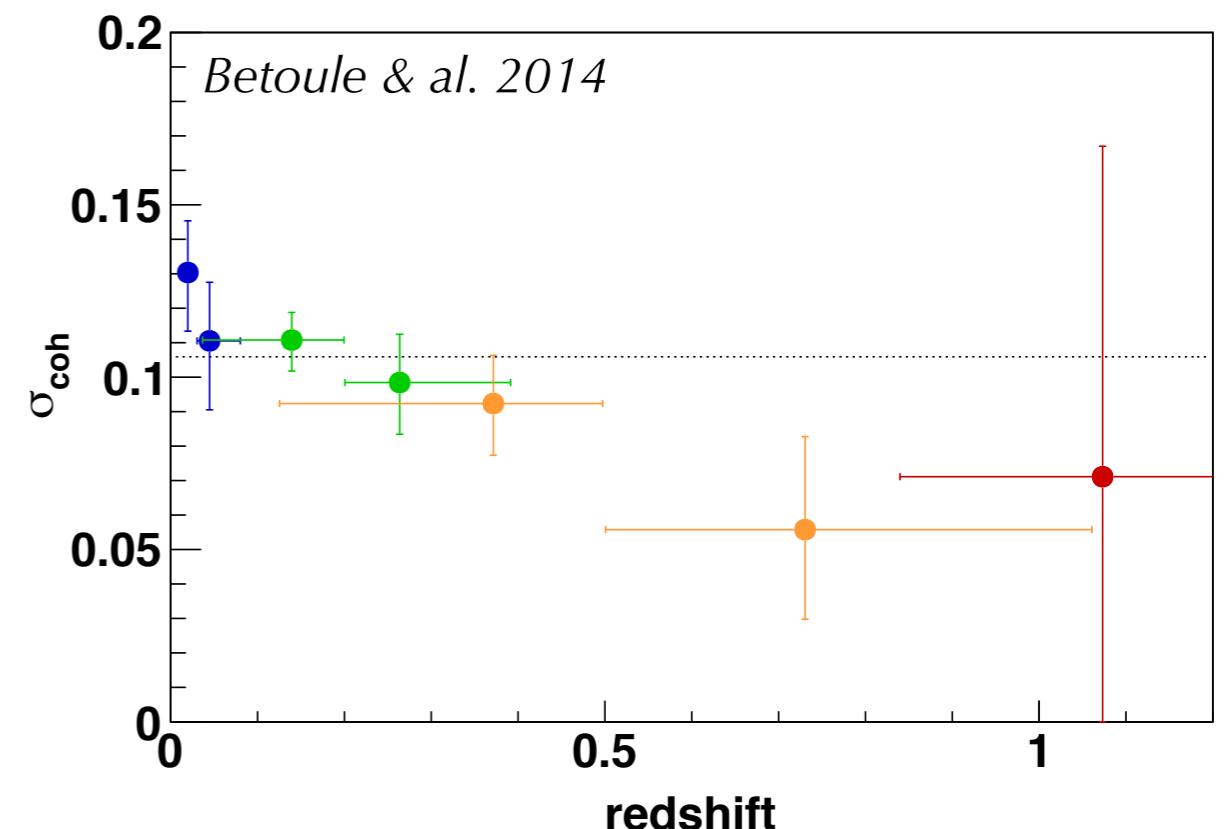
Do those corrections are optimal ? No ...

X_1
C

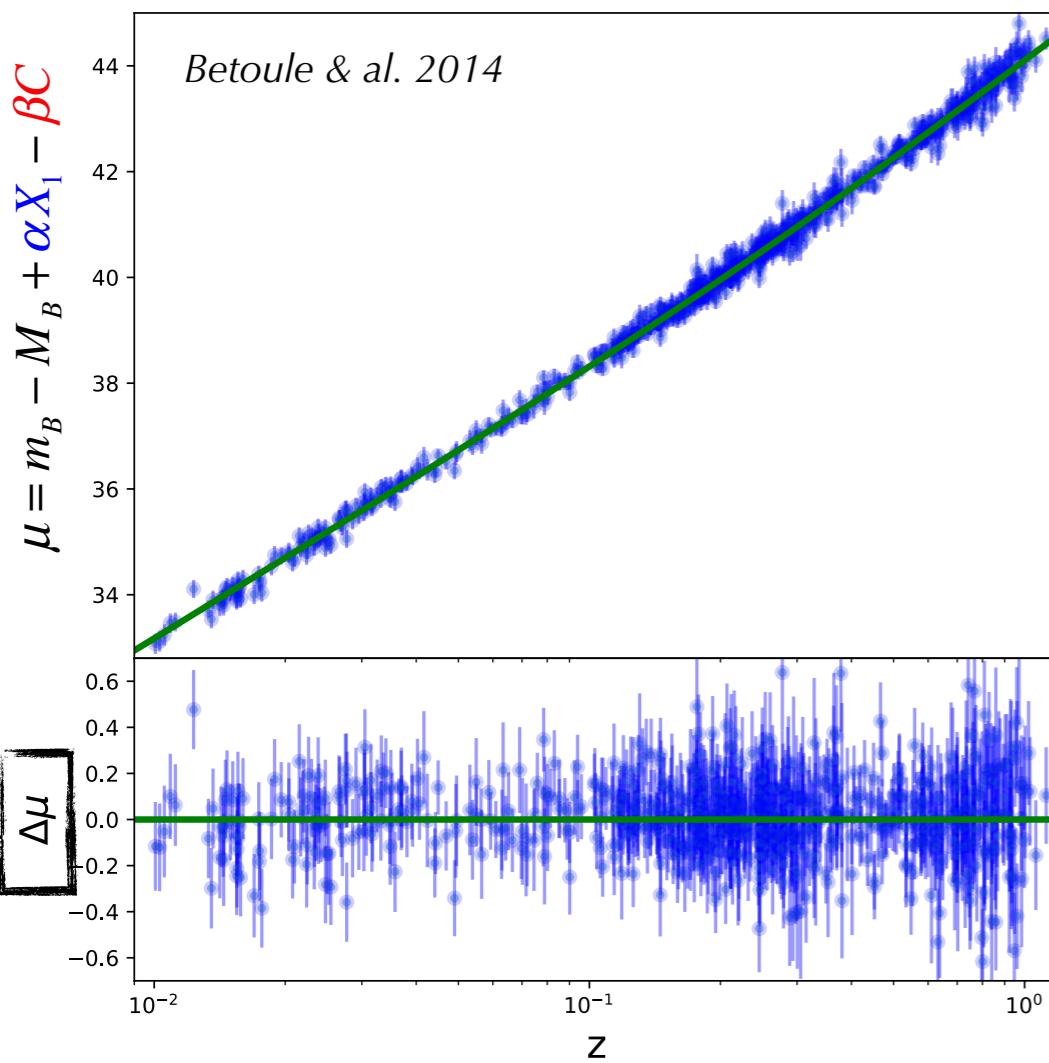
Do those corrections involve bias ? Yes ...

Do Stretch & Color corrections are optimal ?

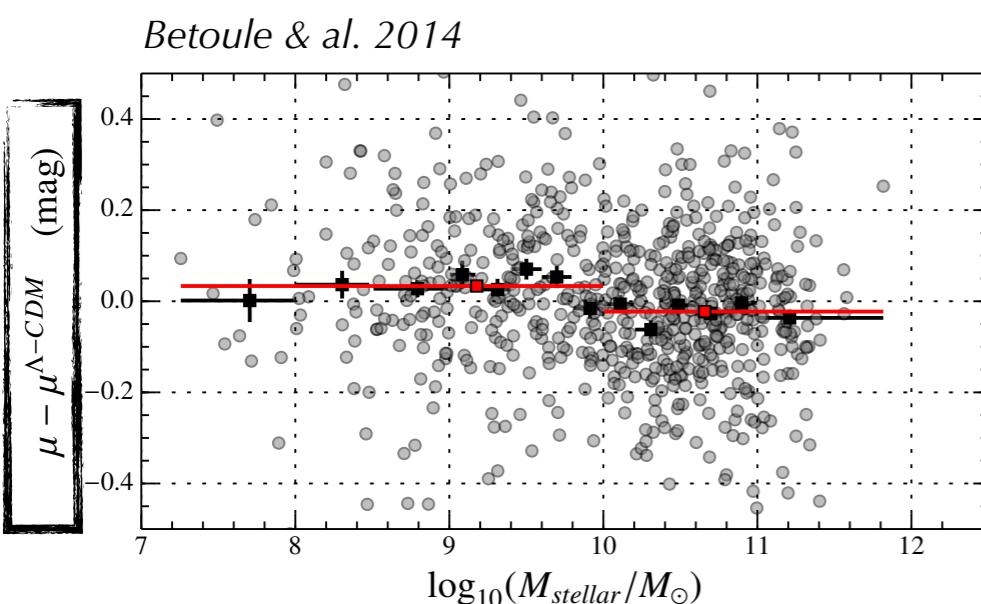
- Remaining scatter on Hubble Diagram:
 - Noise
 - Intrinsic scatter
- Intrinsic scatter: remaining variability of SNIa
- Non-zeros and evolves in terms of redshift
- Limits precision and could potentially bias cosmological analysis with SNIa



Do Stretch & Color corrections involve bias ?

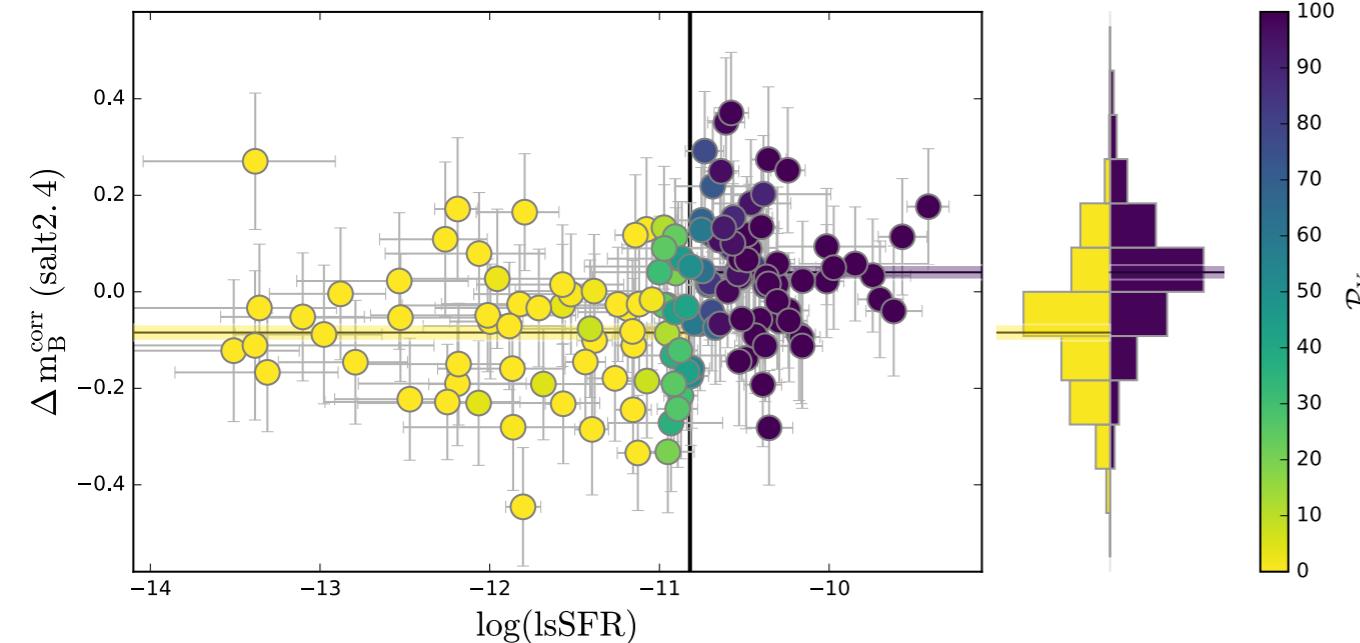


- Dependency of Hubble residuals after stretch & color with Host mass
- Called the « Mass-step »
- $\Delta M = -0.06 \pm 0.012 \text{ mag} (5\sigma)$

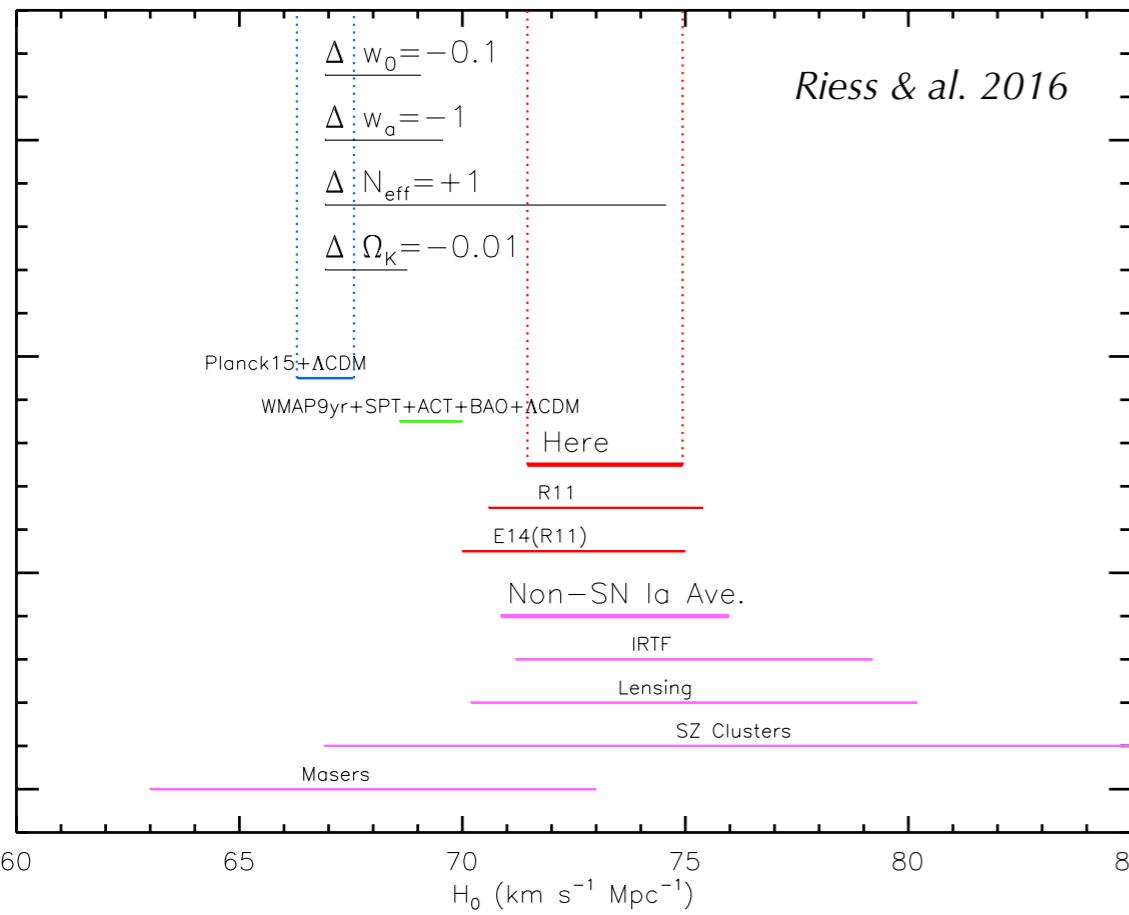


Do Stretch & Color corrections involve bias ?

Rigault & al. 2018



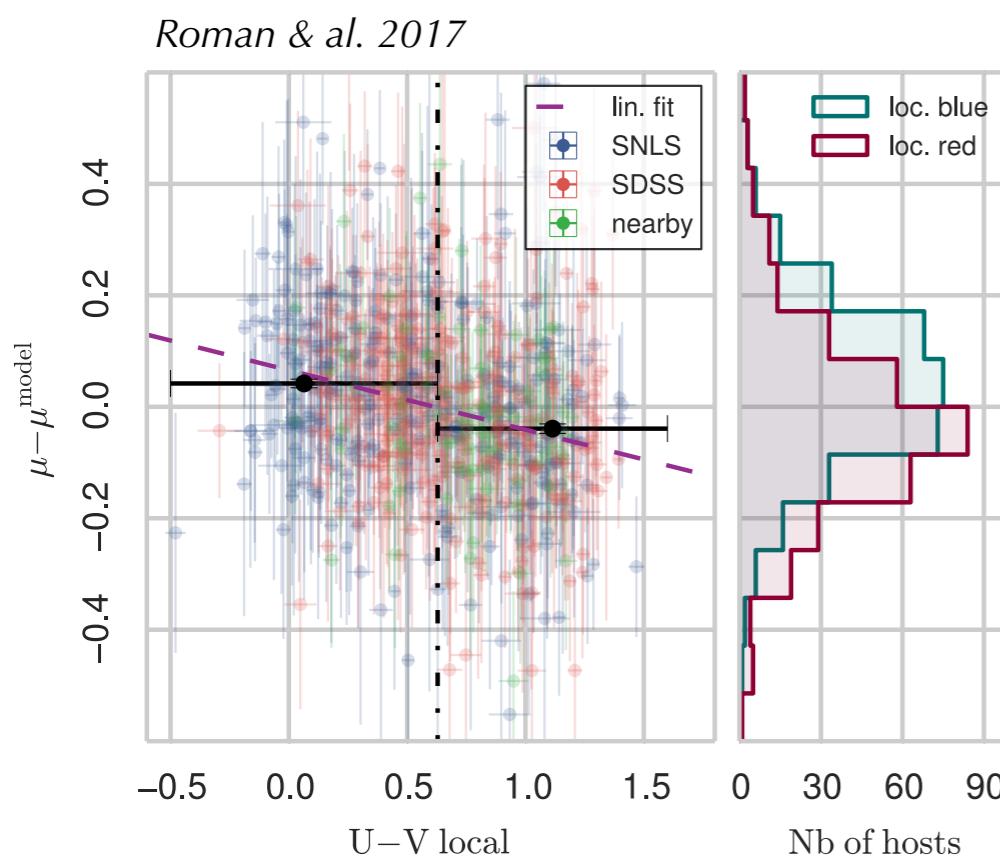
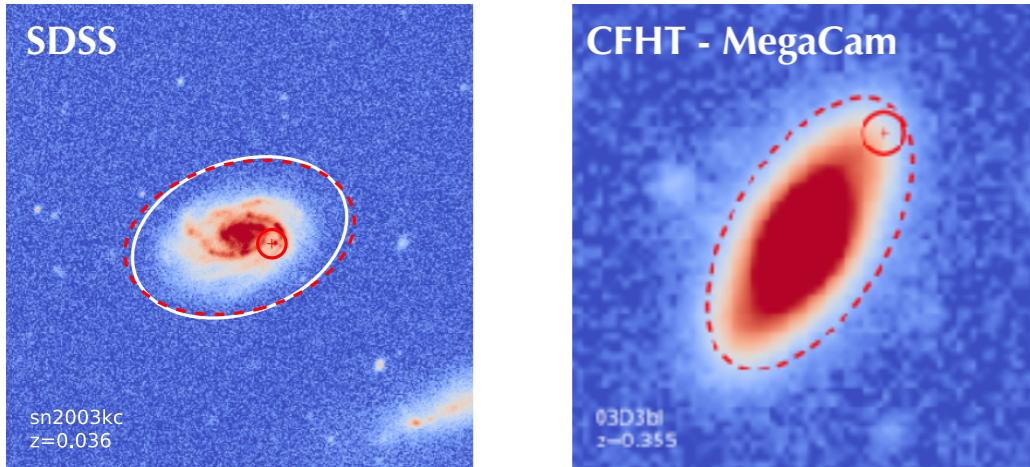
- SNIa & Host from SNFactory
- Compute local sSFR (1 kpc radius)
- 141 SNe Ia
- Low z ($z < 0.1$)
- $\Delta M = 0.12 \pm 0.03$ mag (5.5σ)



- Distance estimation are biased after stretch and color correction
- It demonstrates that something is missing in the description of SNIa
- May explain the tension of Hubble constant between local measurement and the CMB

Do Stretch & Color corrections involve bias ?

Roman & al. 2017

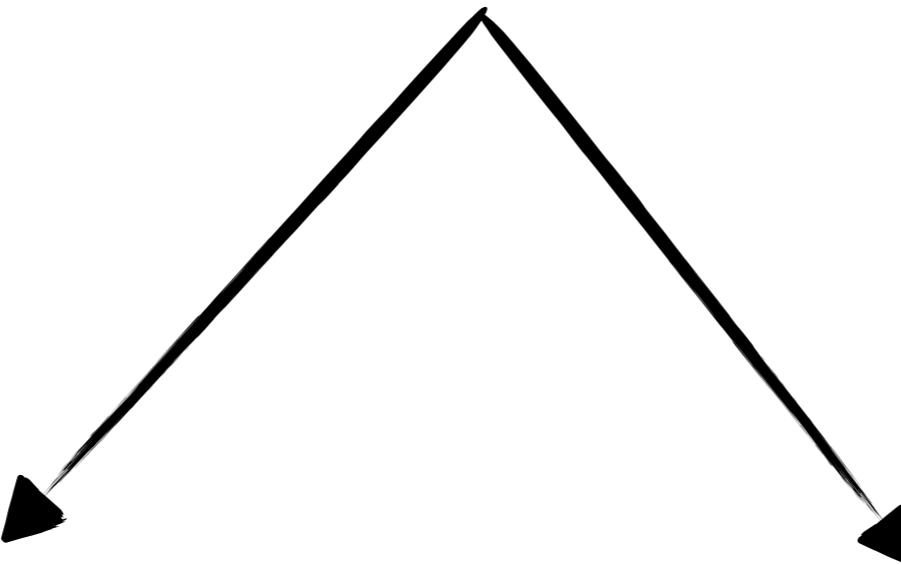


- SNIa & Host from SDSS & SNLS
- Compute local U-V (3 kpc radius)
- 882 SNe Ia
- all range of redshift
- $\Delta M = -0.091 \pm 0.013 \text{ mag} (7\sigma)$

Residual dispersion
source of systematics



Different ways to improve
distance measurement



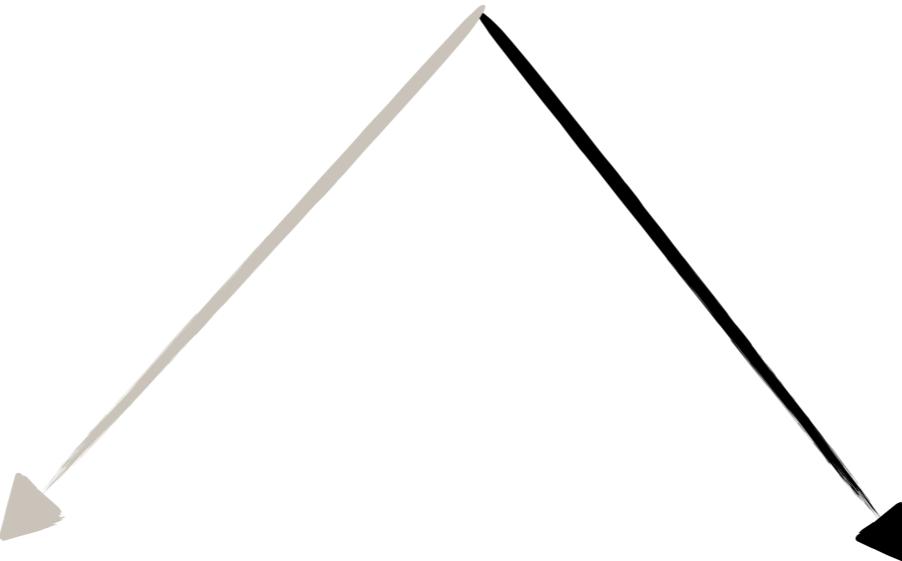
Studies host properties

New SNIa model

Residual dispersion
source of systematics



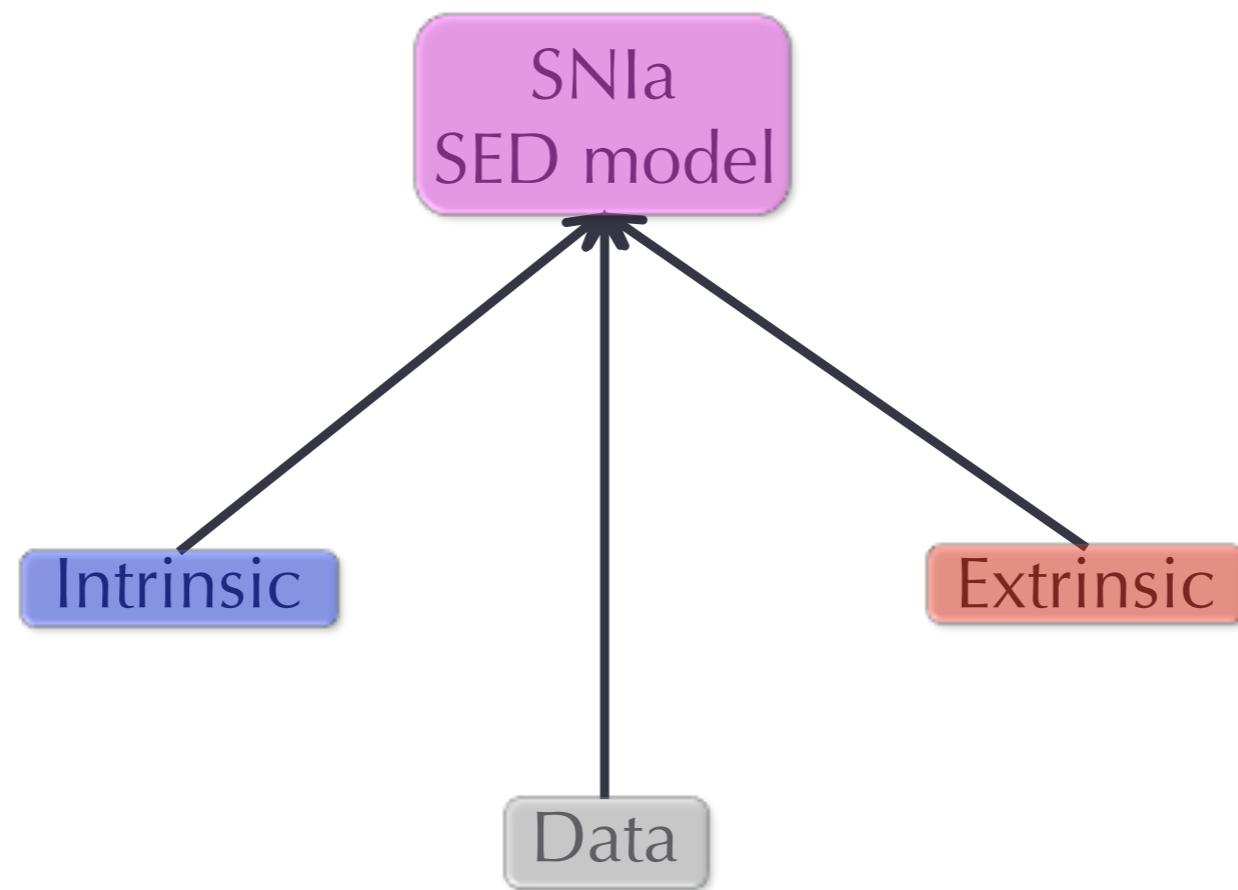
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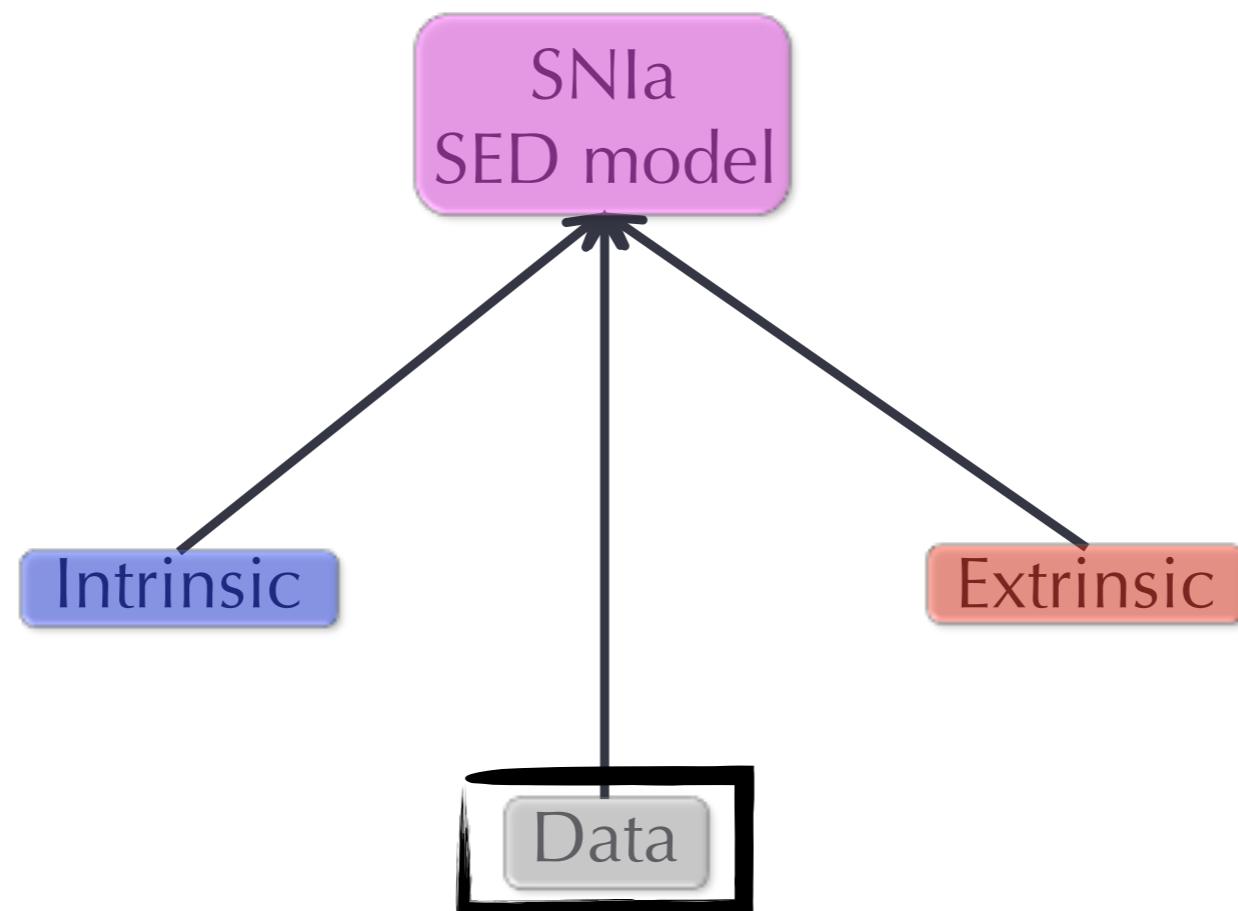
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New SNIa model

Go beyond : Describing the Spectral Energy Distribution



Go beyond : Describing the Spectral Energy Distribution



The Nearby Supernova Factory



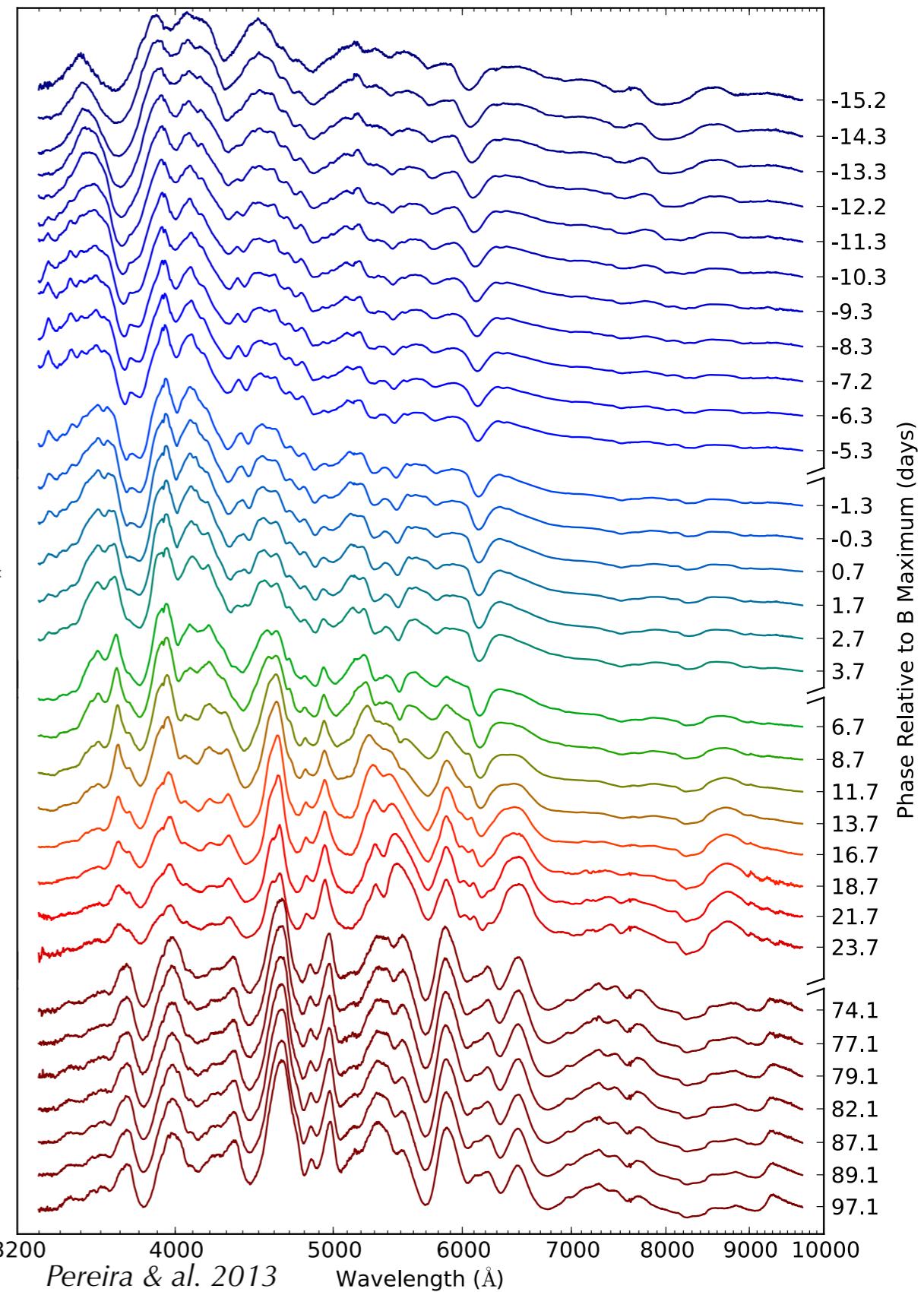
- UH88 + Supernova Integral Field Spectrograph (SNIFS)
- SNIFS Gives high quality spectro-photometry time series (Great example: SN2011fe, Pereira et al. (2013))
- ~300 supernovae at low redshift ($z < 0.1$)
- Best data that provide tools to standardize SNIa or build empirical SED model



The Nearby Supernova Factory



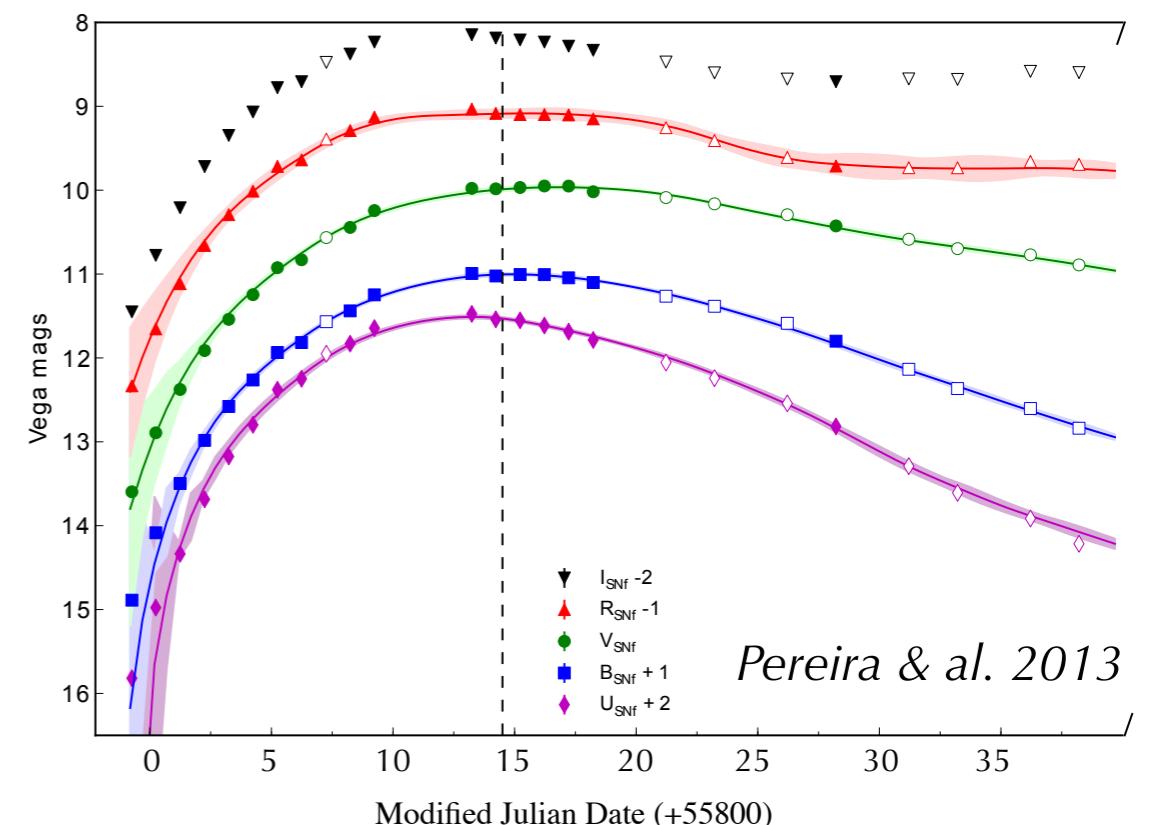
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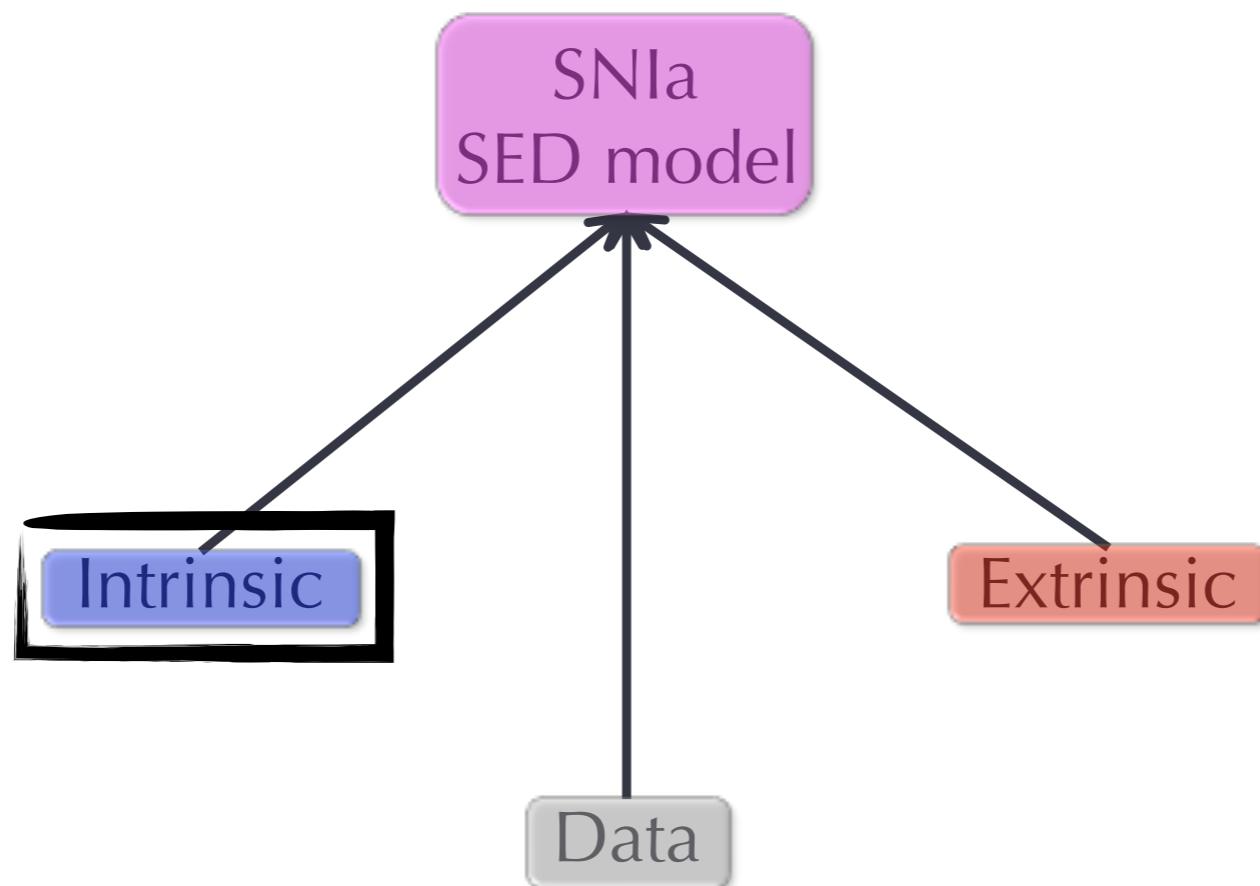
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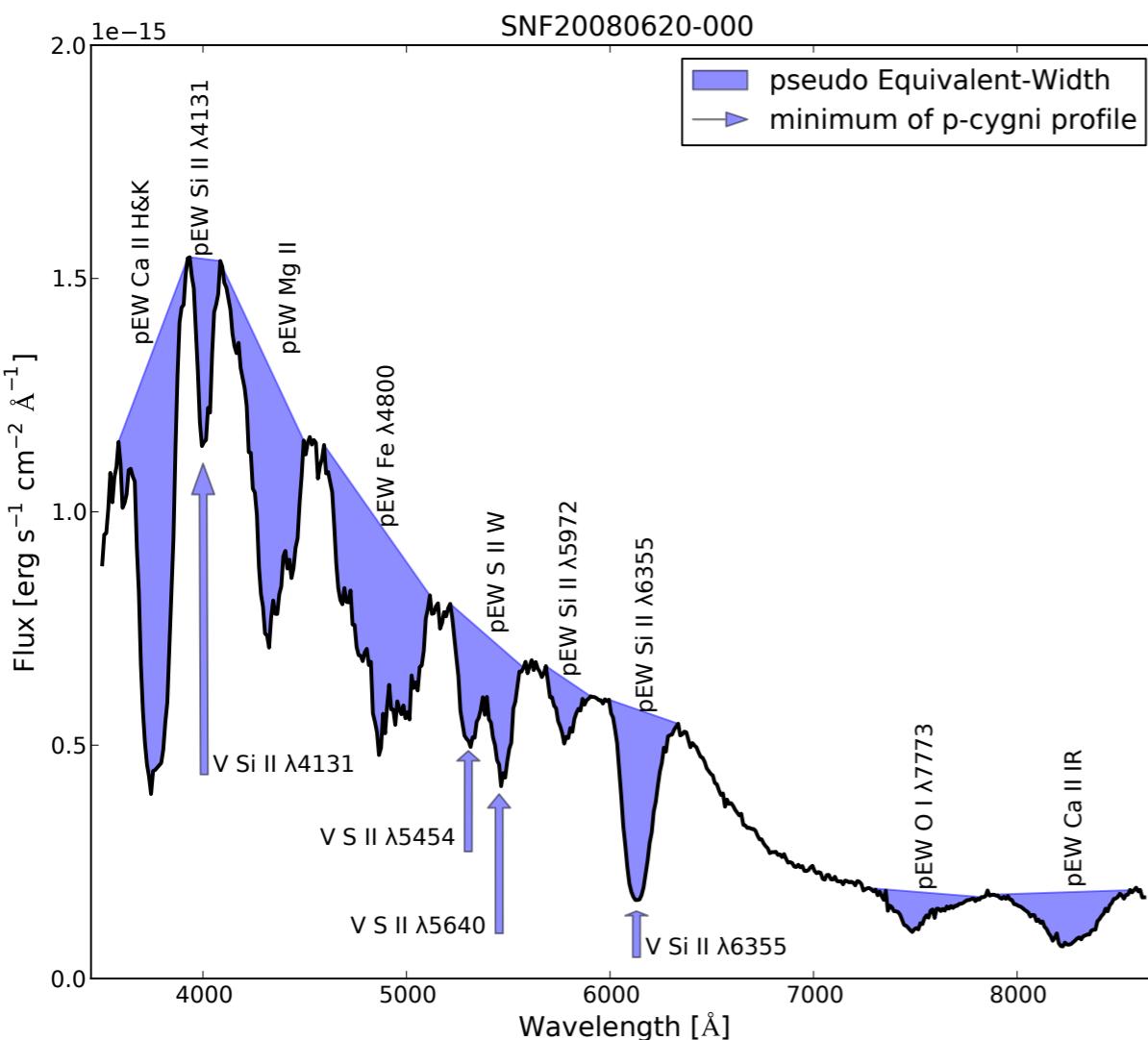
Go beyond : Describing the Spectral Energy Distribution



SUpernova Generator And Reconstructor (SUGAR)

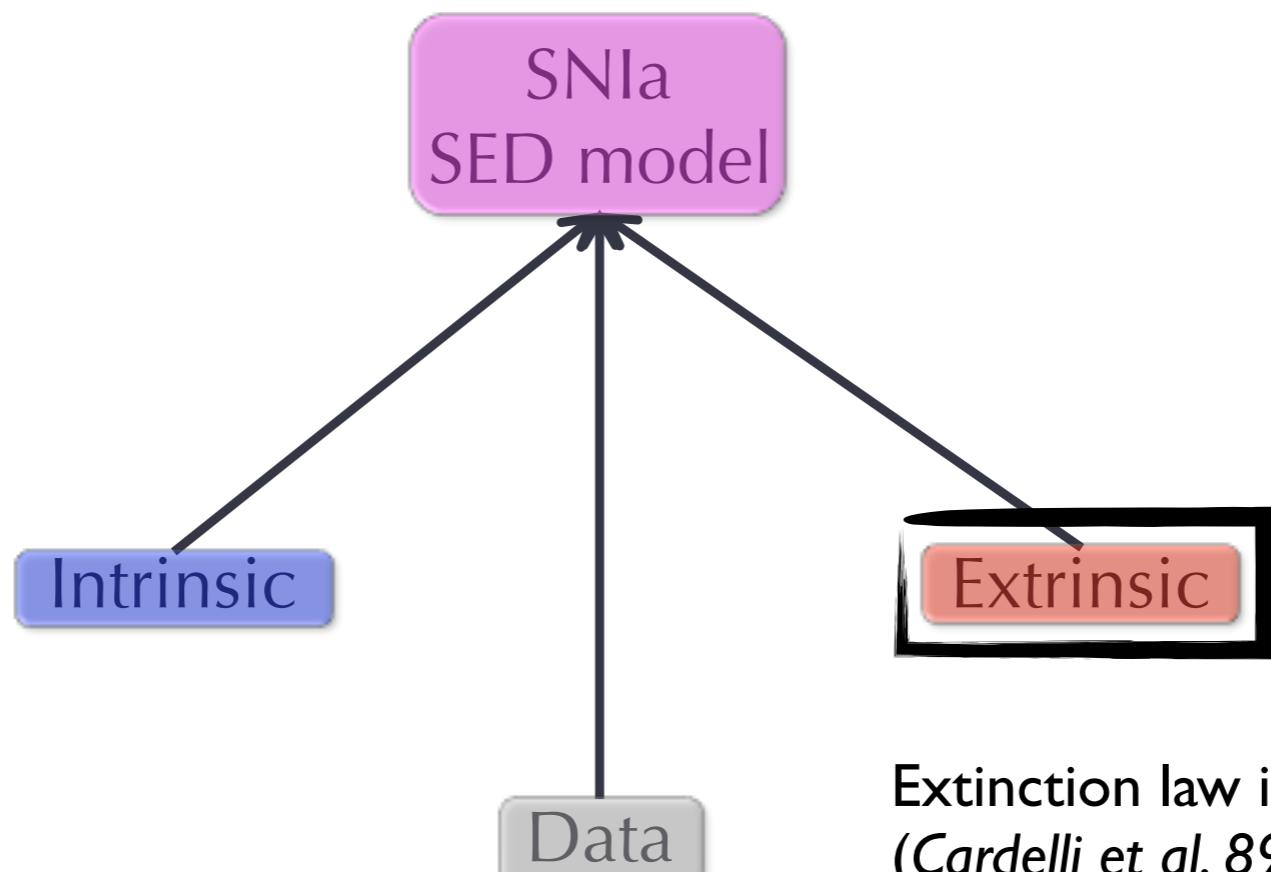
Léget & al. submitted

Basic idea of SUGAR modeling —> Used spectral features measured at maximum light in B-band to describe intrinsic variability of SNe Ia:



- Spectral features are related only to the physics of the explosion
 - * Pseudo-equivalent width
 - * Minimum position of p-cygni profile
- Do not depend on host dust
- Do not depend on distance
- 13 computed at maximum light and used to train the SUGAR model

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)

SUpernova Generator And Reconstructor (SUGAR)

Léget & al. submitted

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

SUpernova Generator And Reconstructor (SUGAR)

Léget & al. submitted

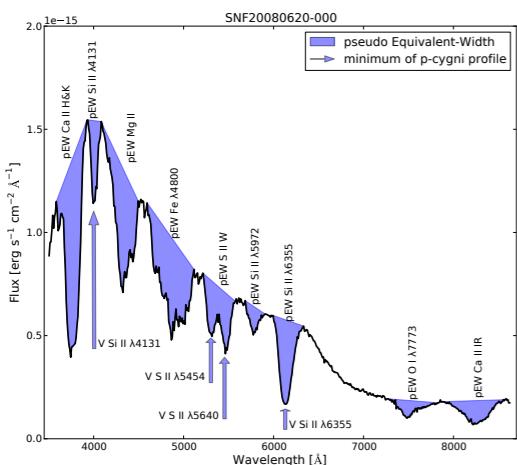
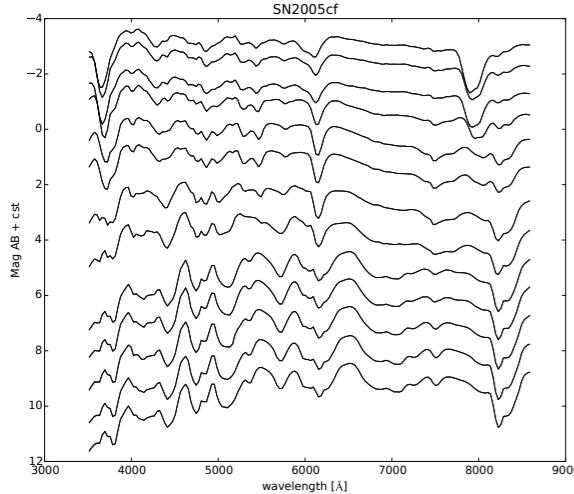
$$M(t; \lambda) = M_0(t; \lambda) + \boxed{\sum_{i=1}^{1=3} \alpha(t; \lambda) q_i} + A_V f(\lambda; R_V) + \Delta M_{grey}$$

↓

3 components
instead of I for SALT2

SUpernova Generator And Reconstructor (SUGAR)

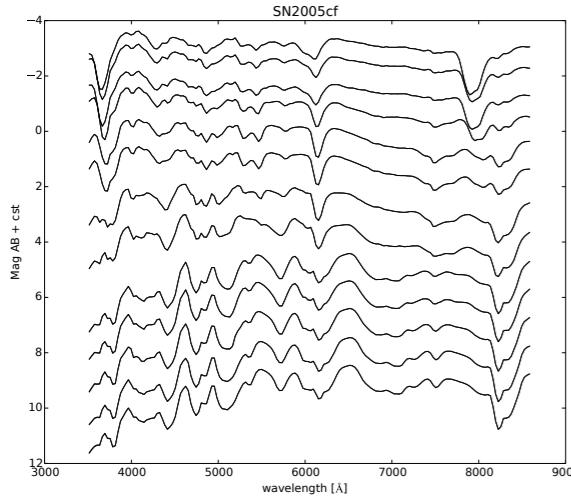
Léget & al. submitted



→ SUGAR model

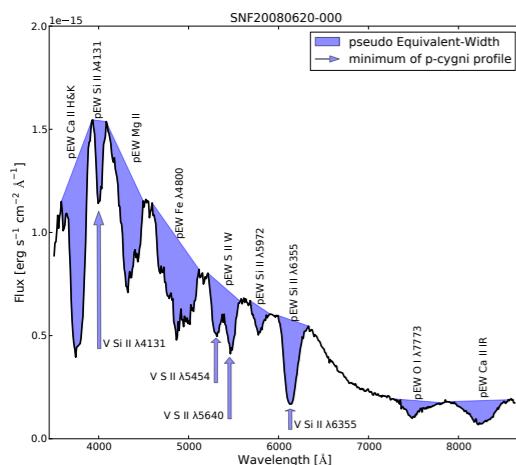
SUpernova Generator And Reconstructor (SUGAR)

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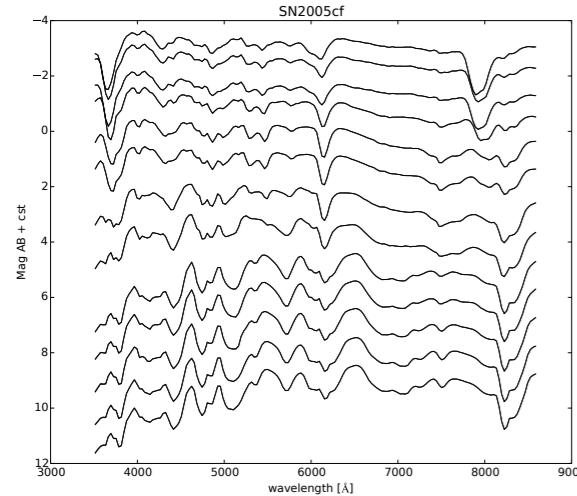
- Dimensionality reduction
- Estimation of the extinction law
- Time interpolation of spectra
- Global SED fitting

→ SUGAR model



SUpernova Generator And Reconstructor (SUGAR)

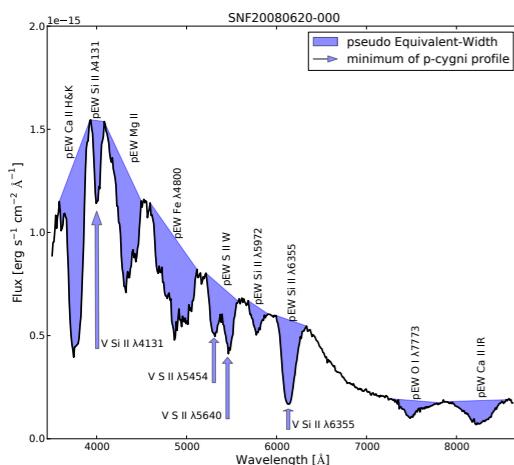
Léget & al. submitted



Only linear algebra

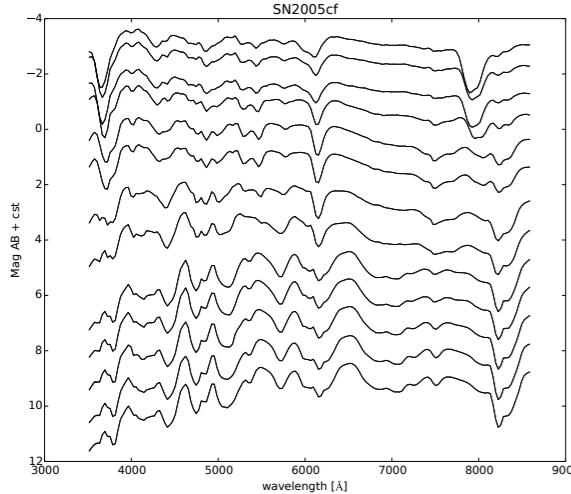
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SUGAR model



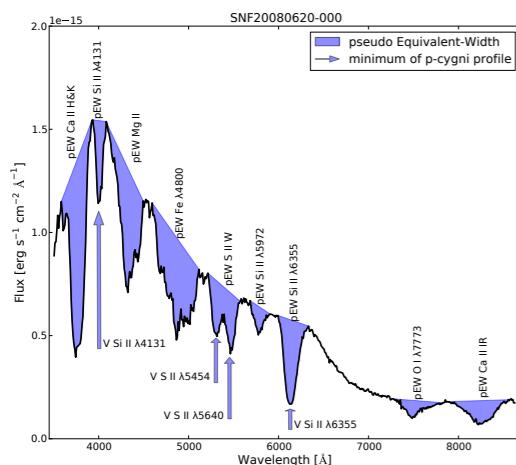
SUpernova Generator And Reconstructor (SUGAR)

Léget & al. submitted



- Dimensionality reduction
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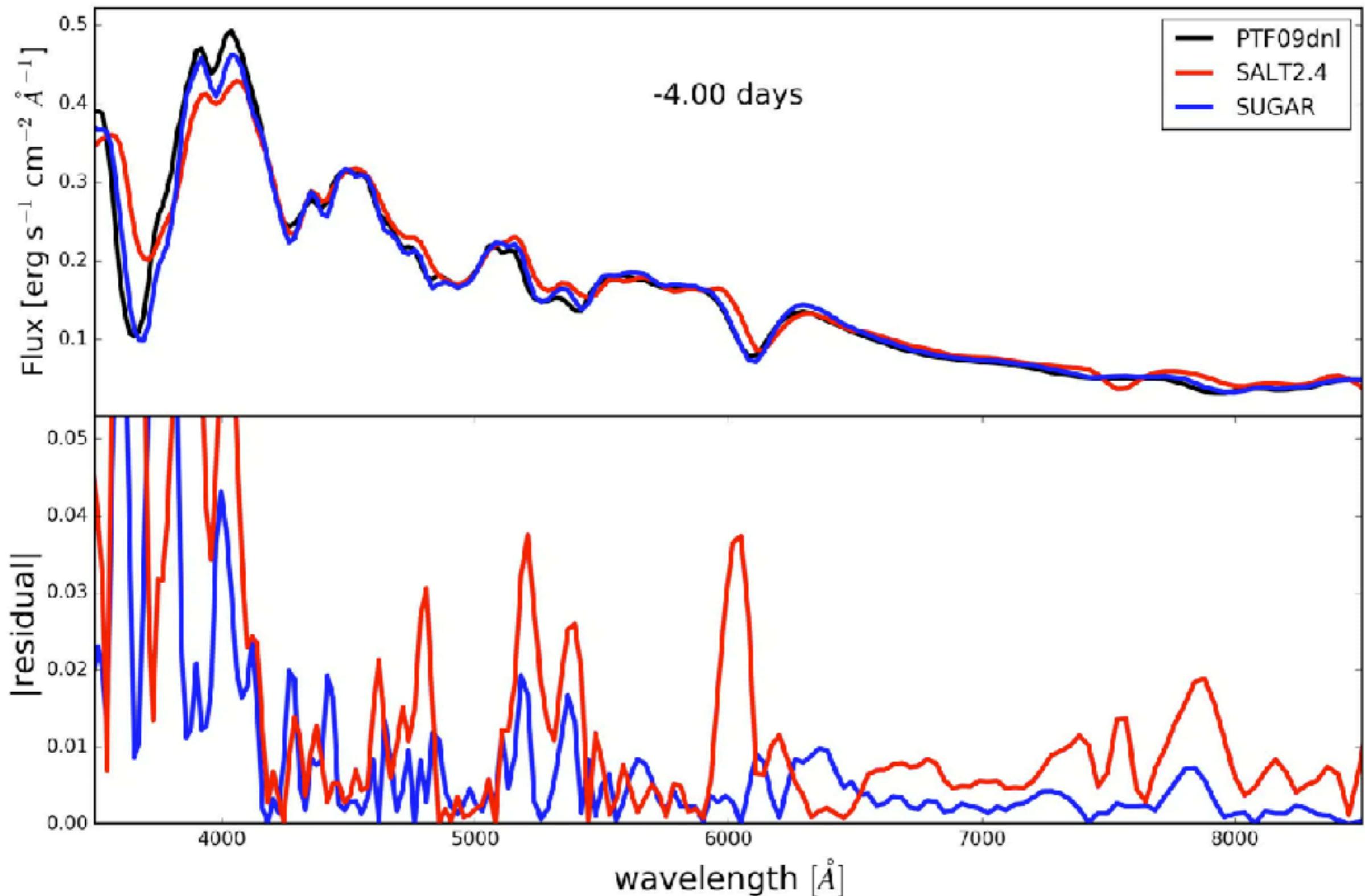
→ SUGAR model



~ 16 000 parameters to estimate
~ 1 hours on a laptop with good choice of matrix inversion

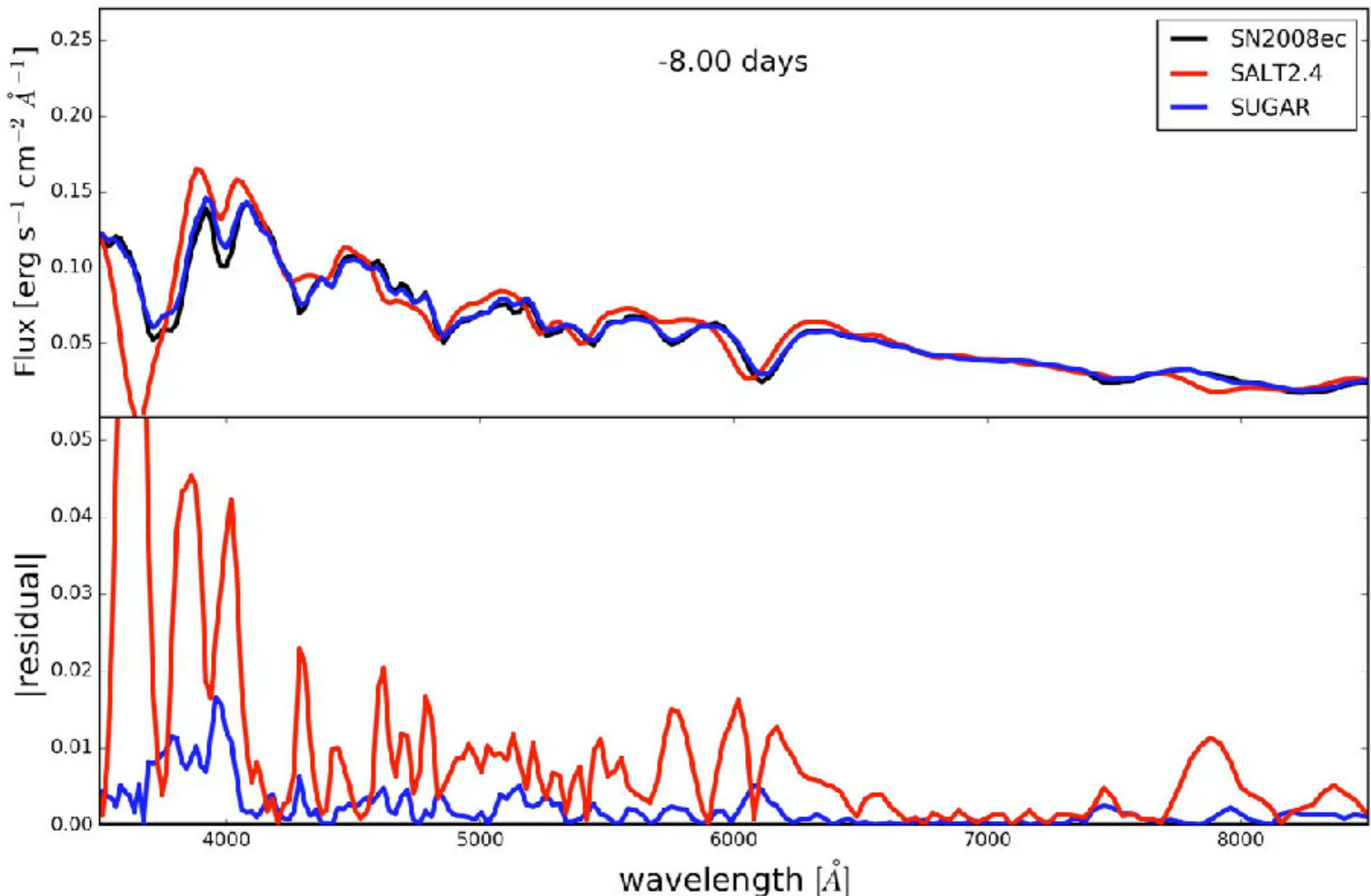
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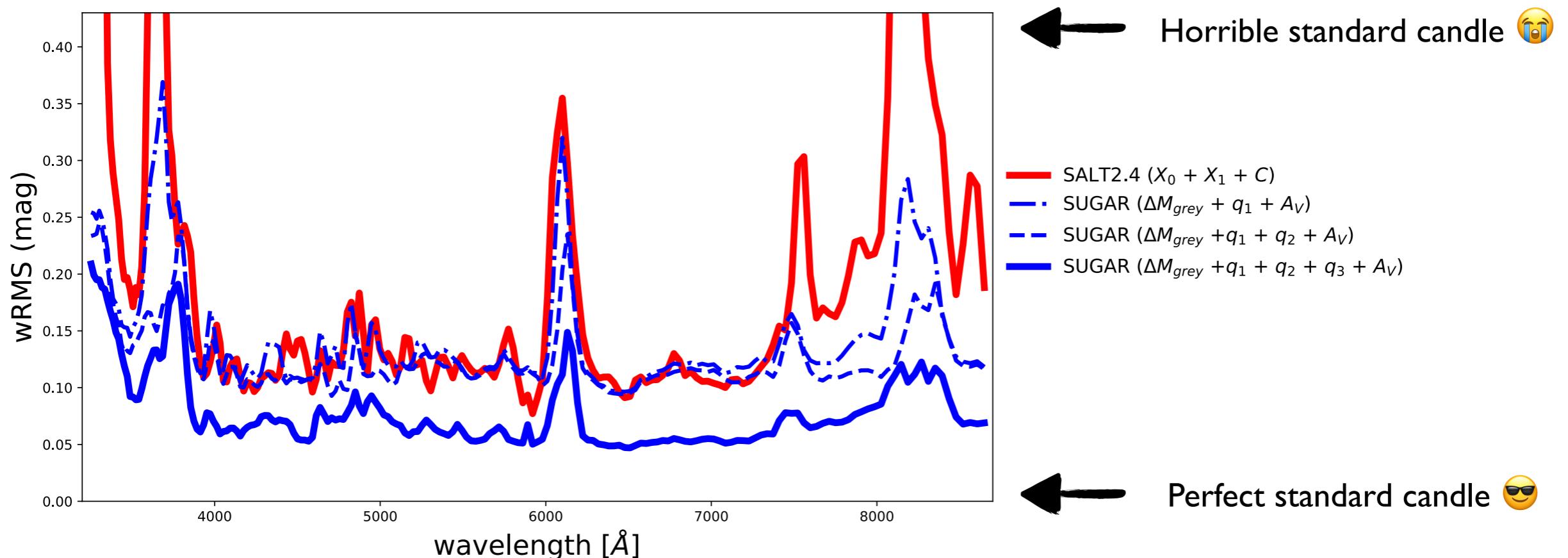
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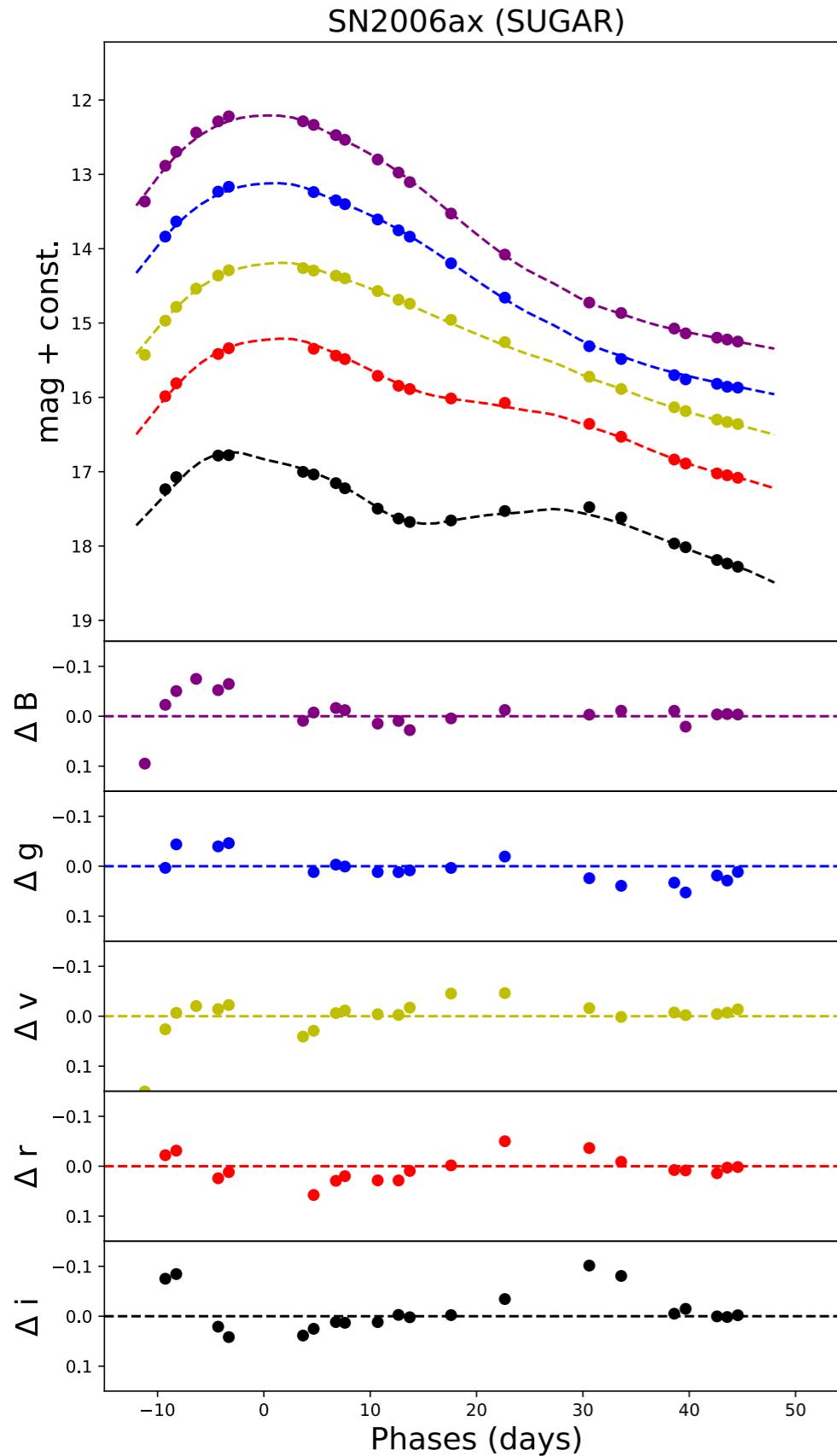
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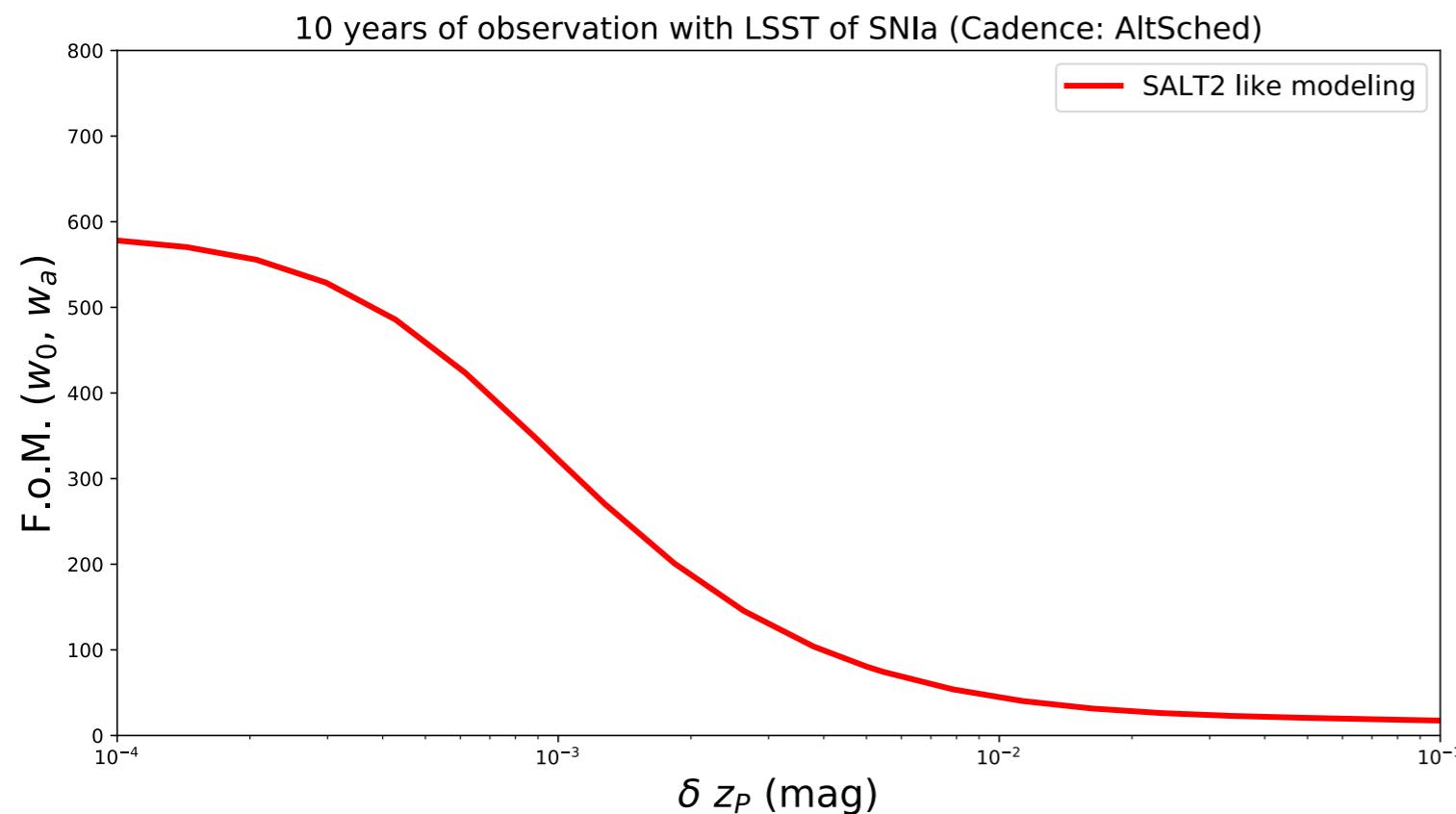
SUGAR improves SNIa spectral variability description in all spectral range!

Application on an external data set:



- SUGAR validated on external data set
- CSP III —> Purely photometric survey
- No spectroscopic information
- Intrinsic dispersion reduce by 20 % in comparaison of a Stretch & Color correction

Impact of SUGAR on LSST science:



- LSST like survey for ten years
- Calibration of SNIa are one of the other main challenges
- Drive precision on Dark Energy state equation parameters

Impact of SUGAR on LSST science:

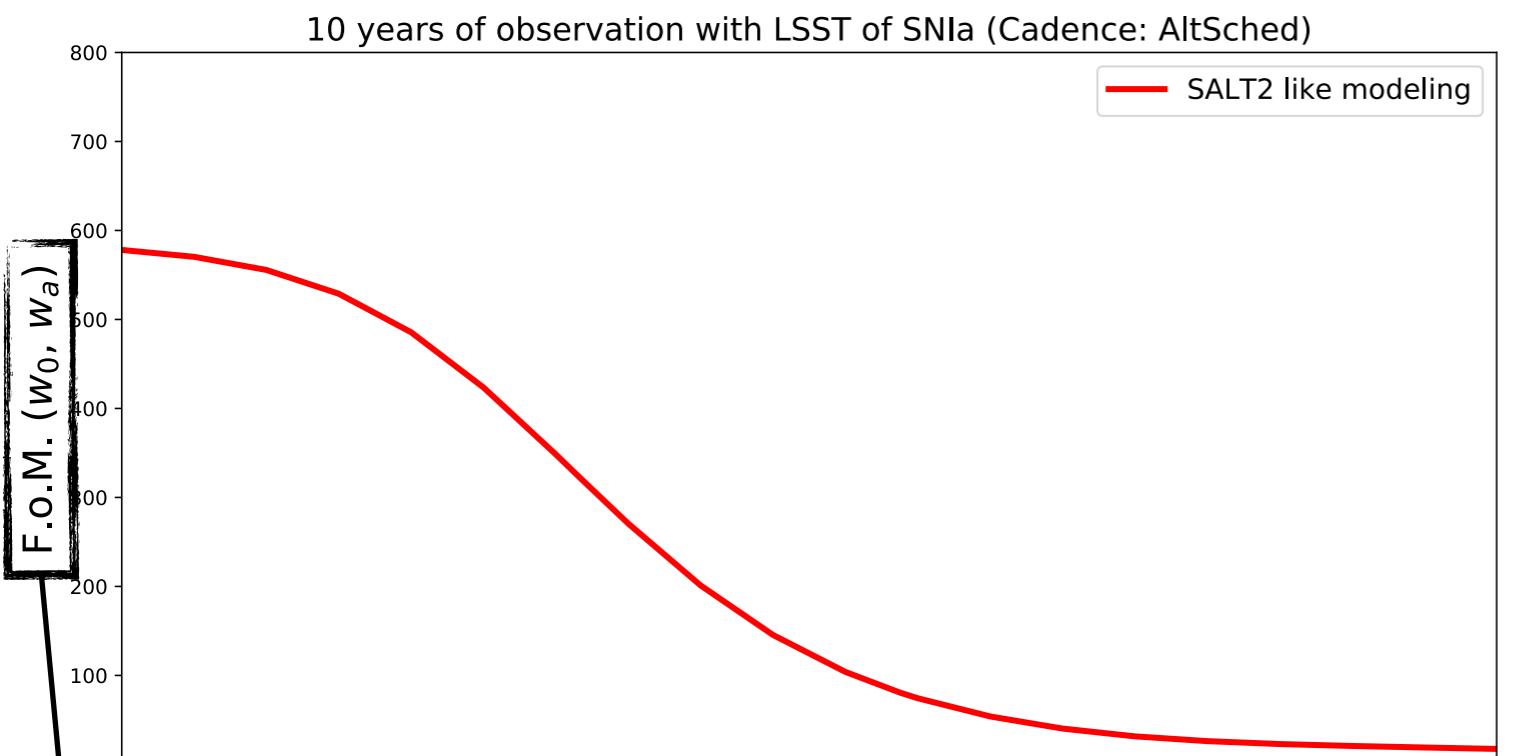


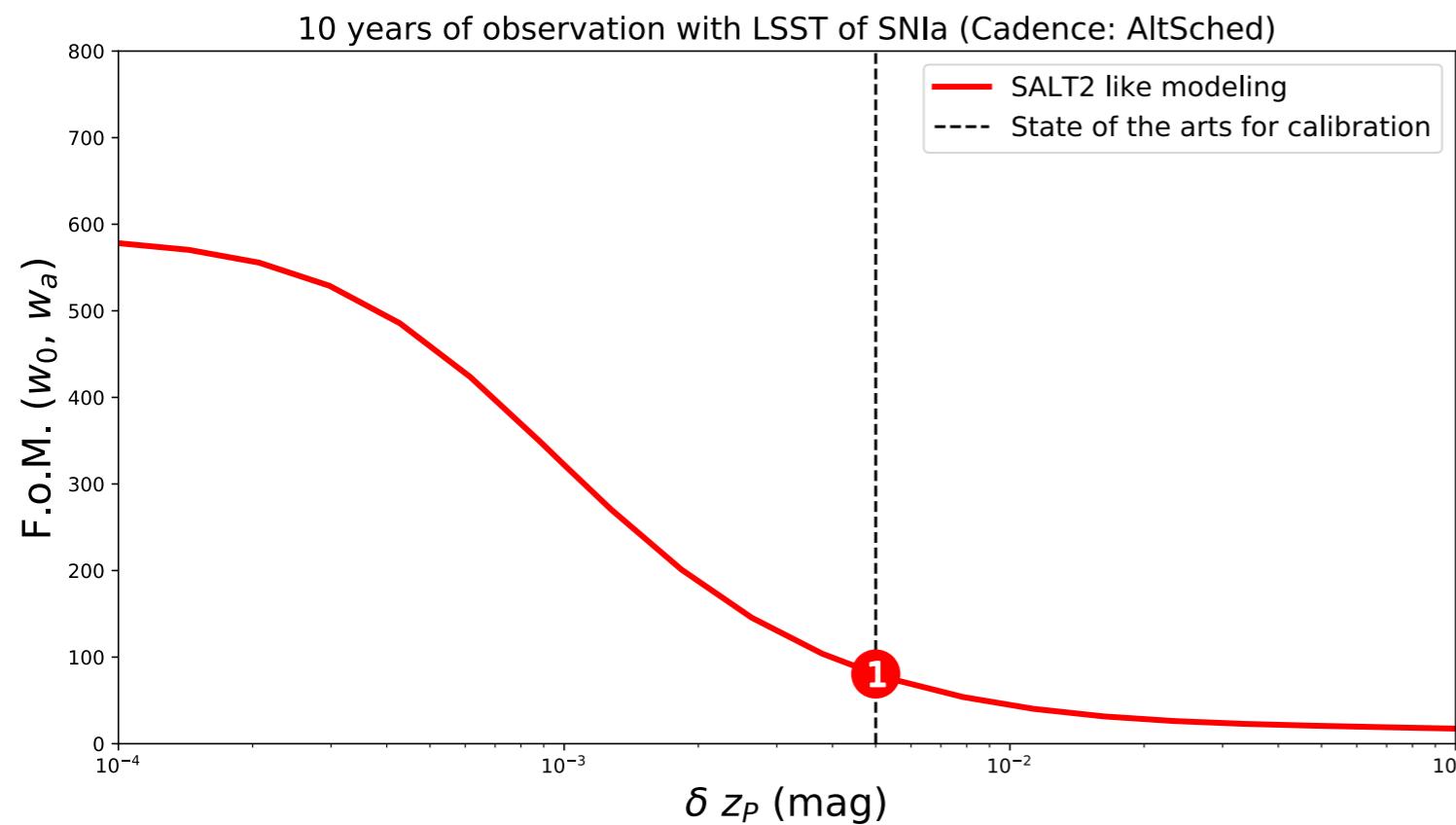
Figure of merit
on Dark Energy
state equation
parameters

δz_p (mag)

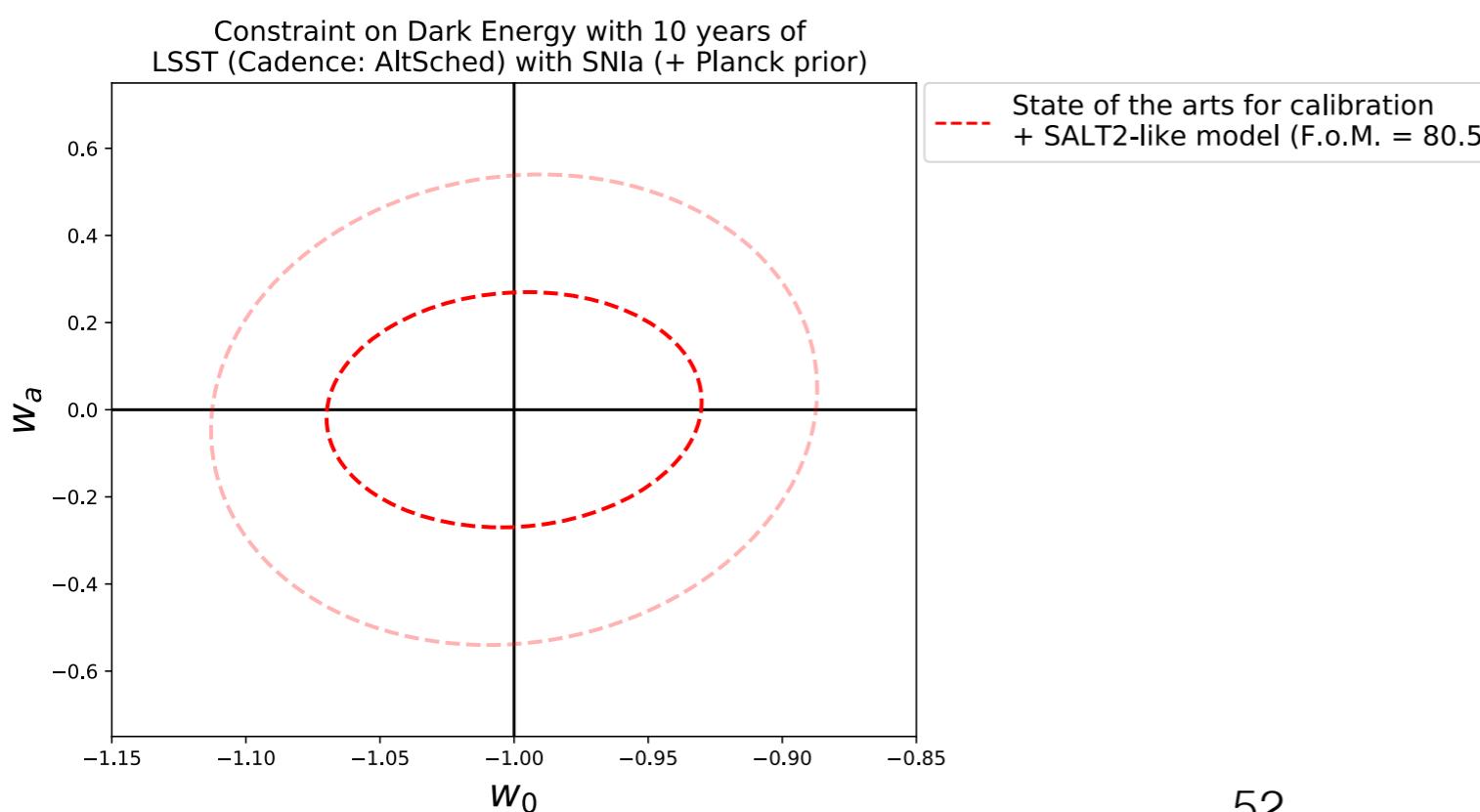
Uncertainties on
Zero points
~
Uncertainties on
Calibration

- LSST like survey for ten years
- Calibration of SNIa are one of the other main challenges
- Drive precision on Dark Energy state equation parameters

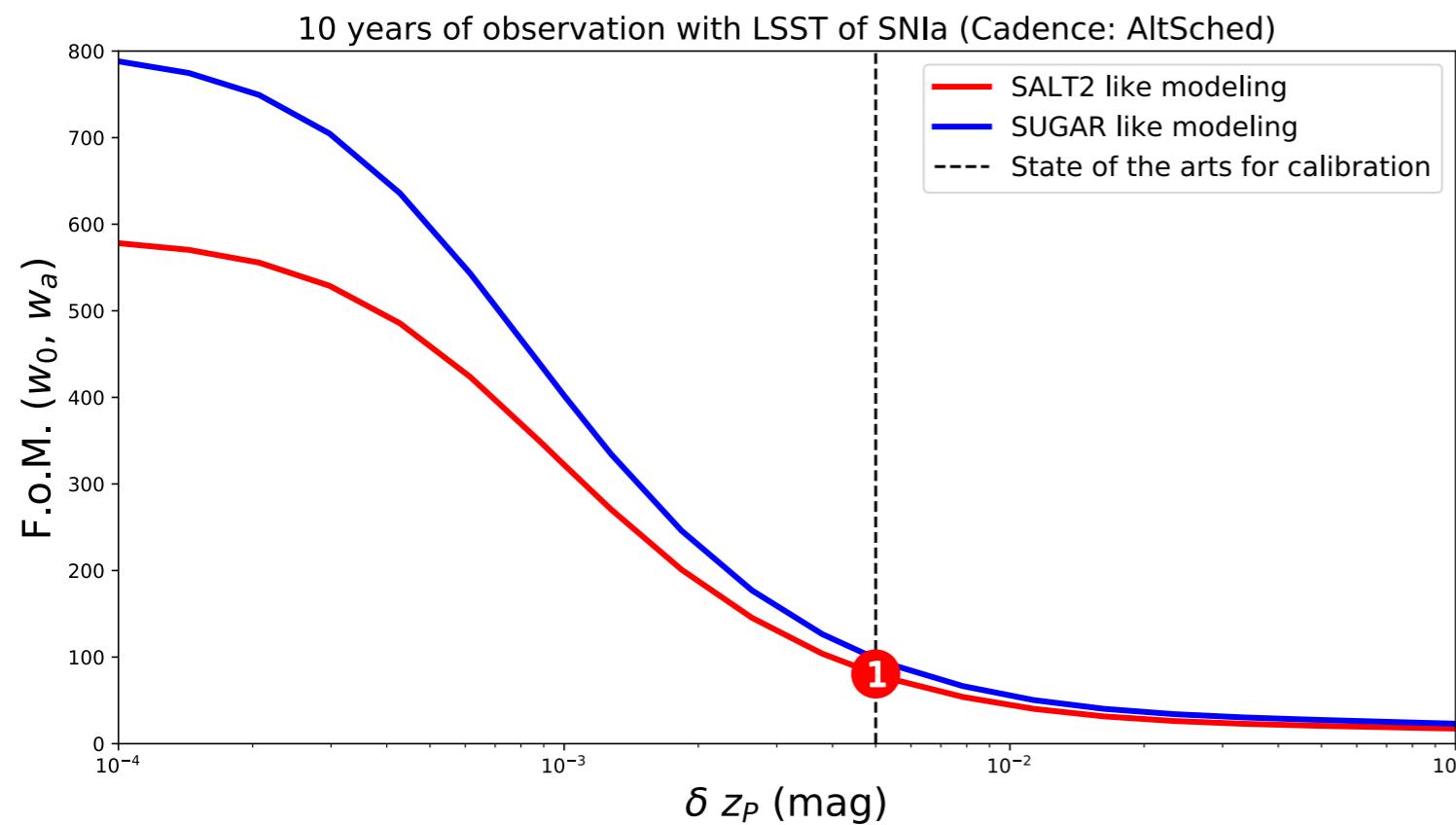
Impact of SUGAR on LSST science:



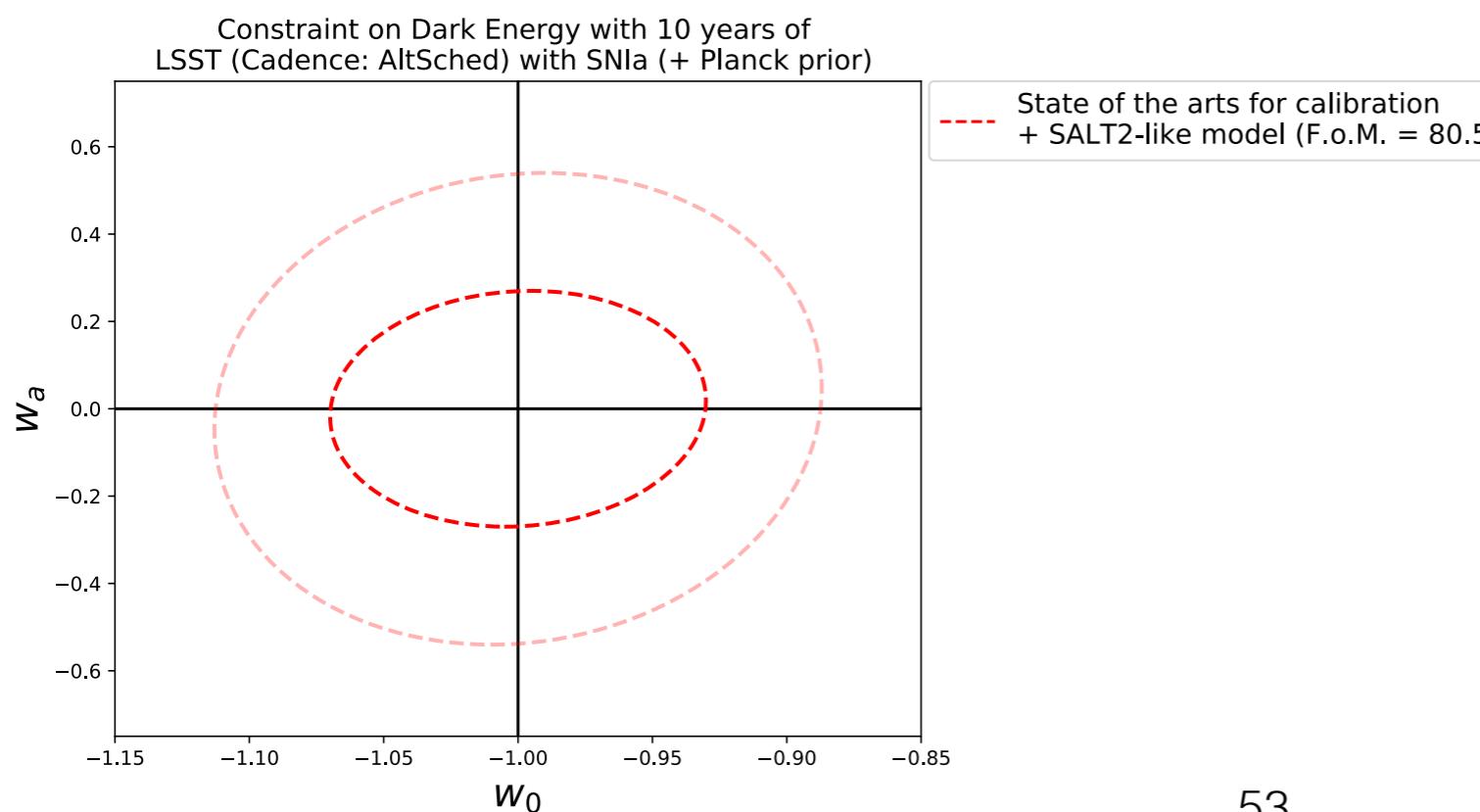
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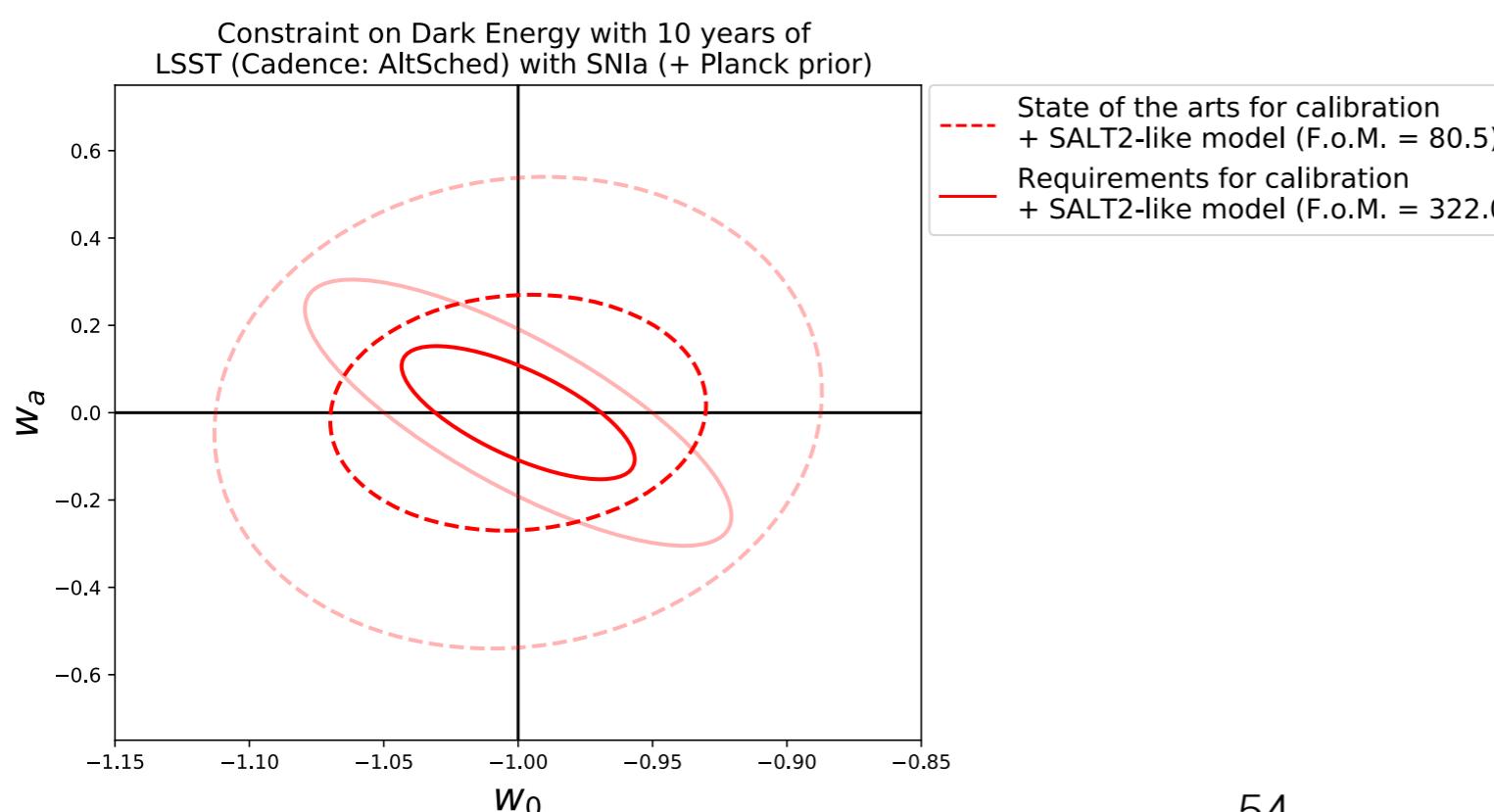
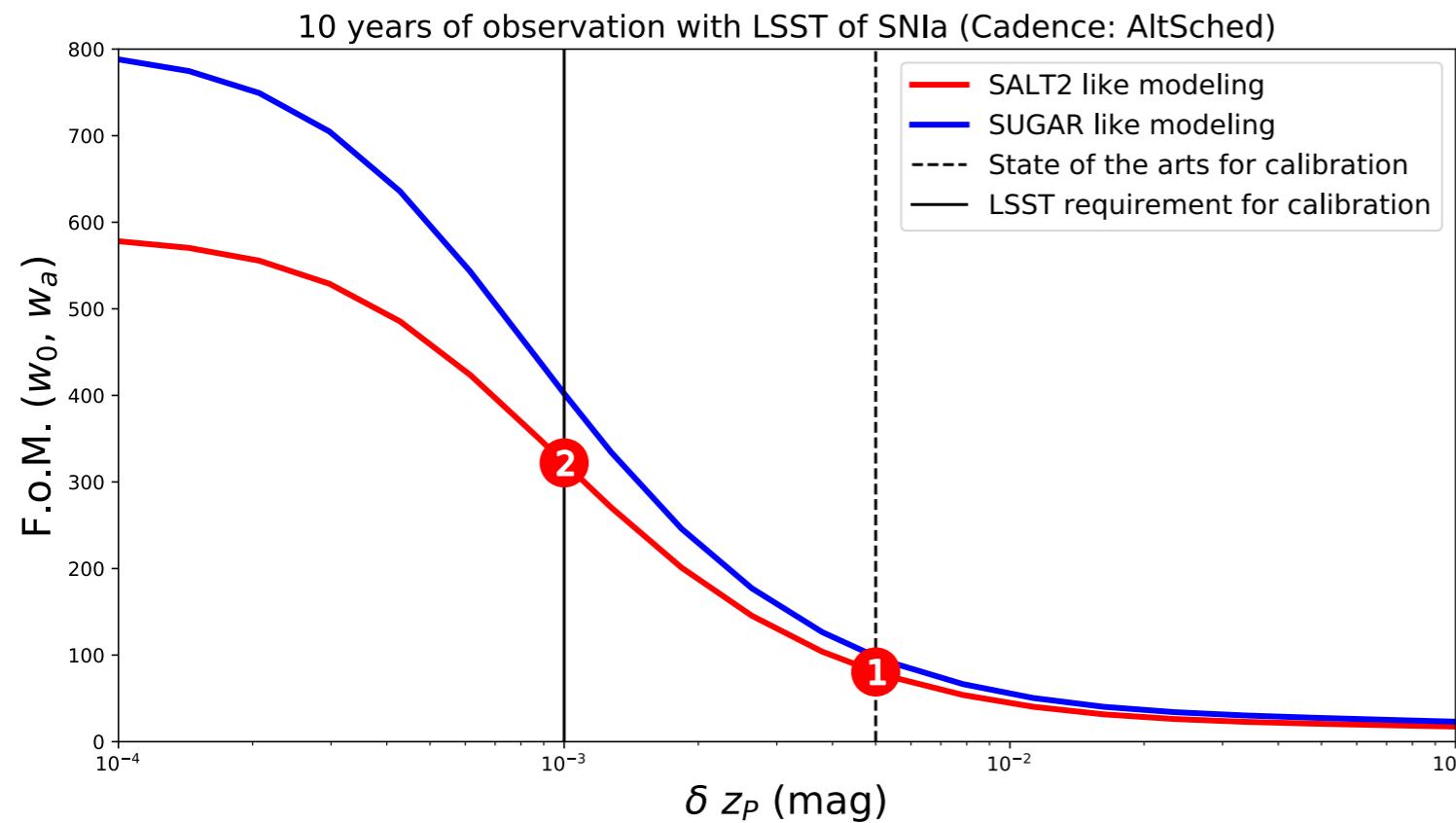
Impact of SUGAR on LSST science:



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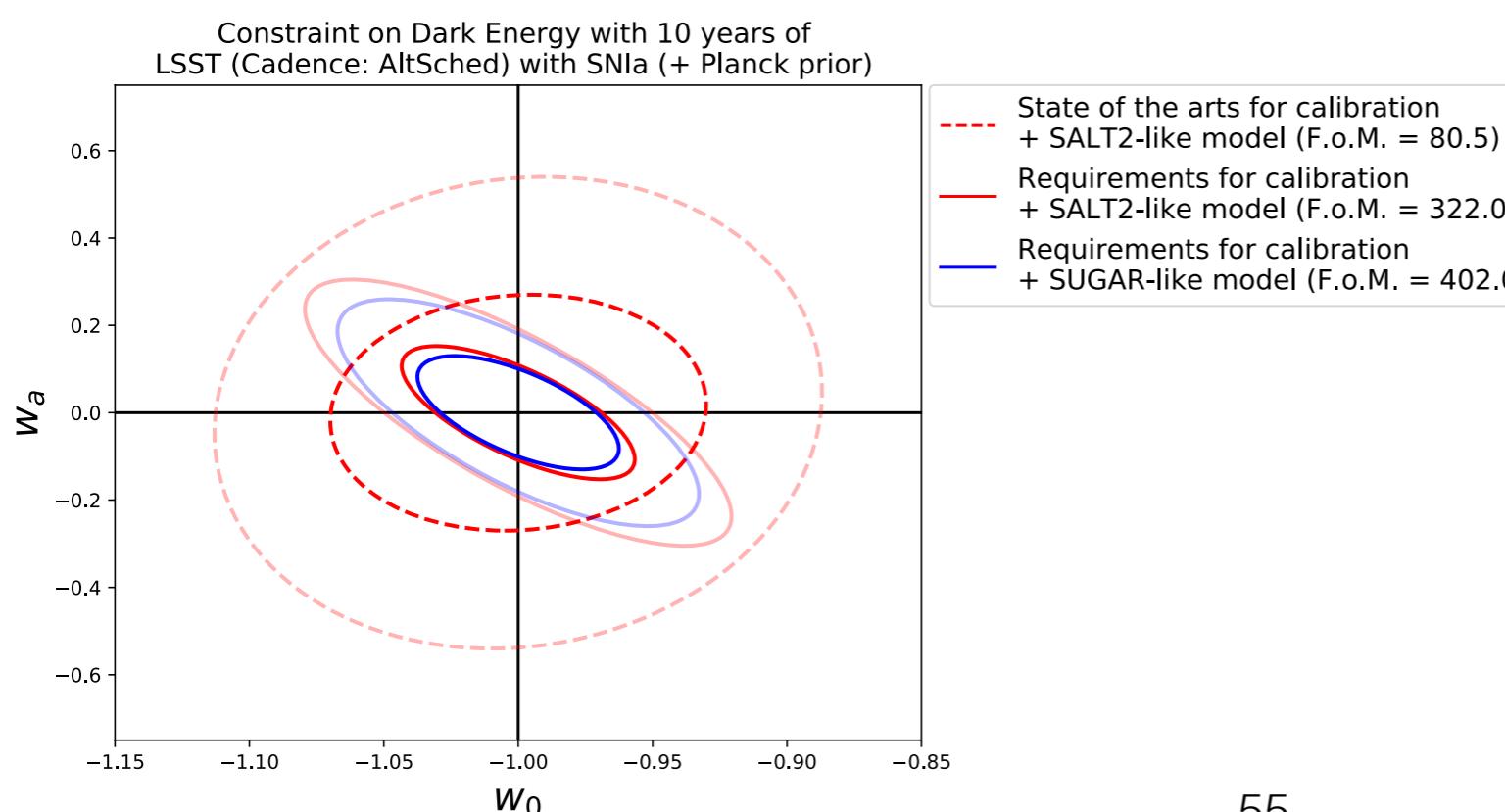
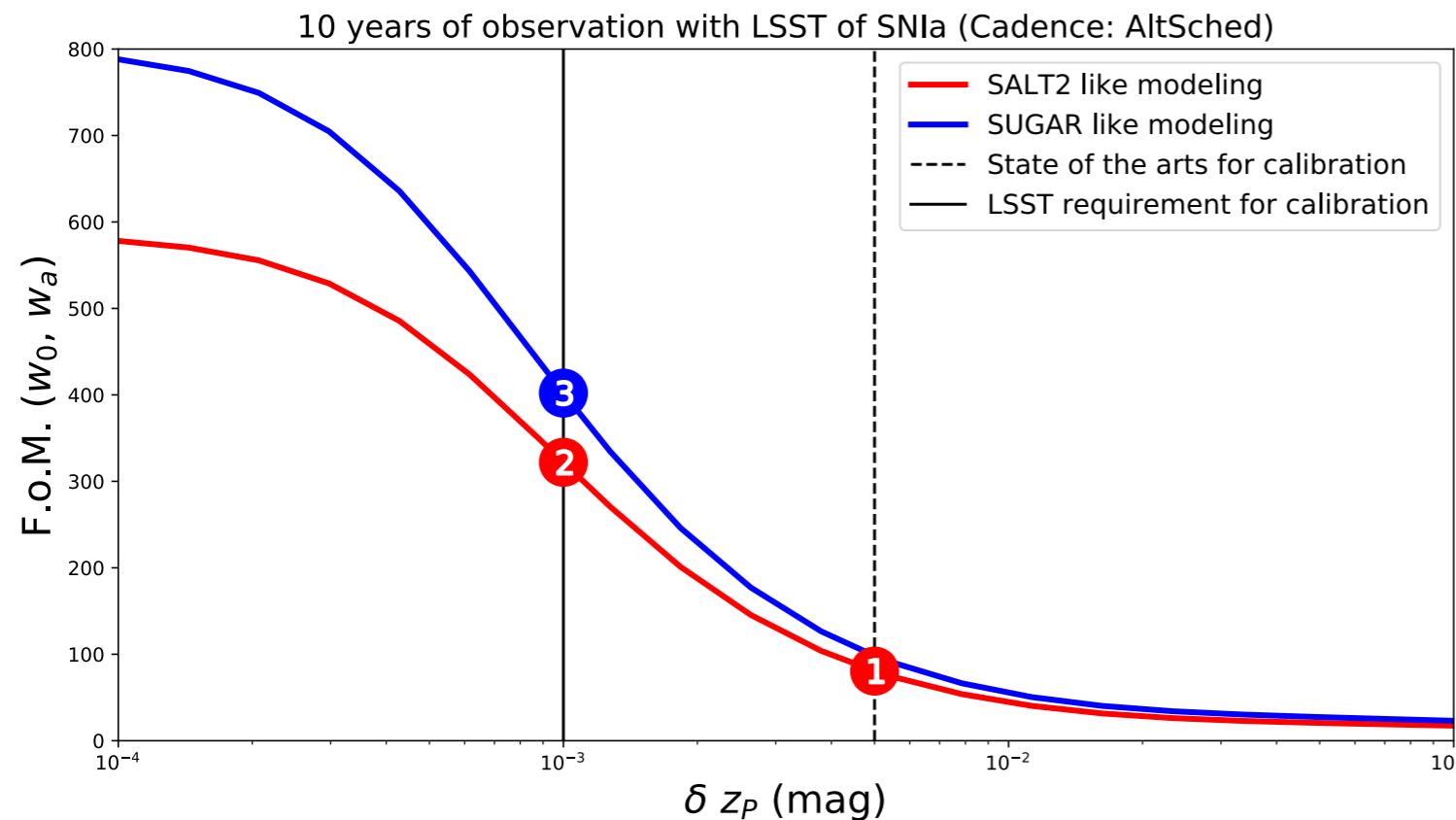


Impact of SUGAR on LSST science:



- LSST like survey for ten years
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- Drive precision on Dark Energy state equation parameters
- Adding SUGAR does not matter for the current state of the arts for calibration
- Expected Calibration for LSST + SALT2 give an improvement of 20% on w_0 and 45% on w_a

Impact of SUGAR on LSST science:



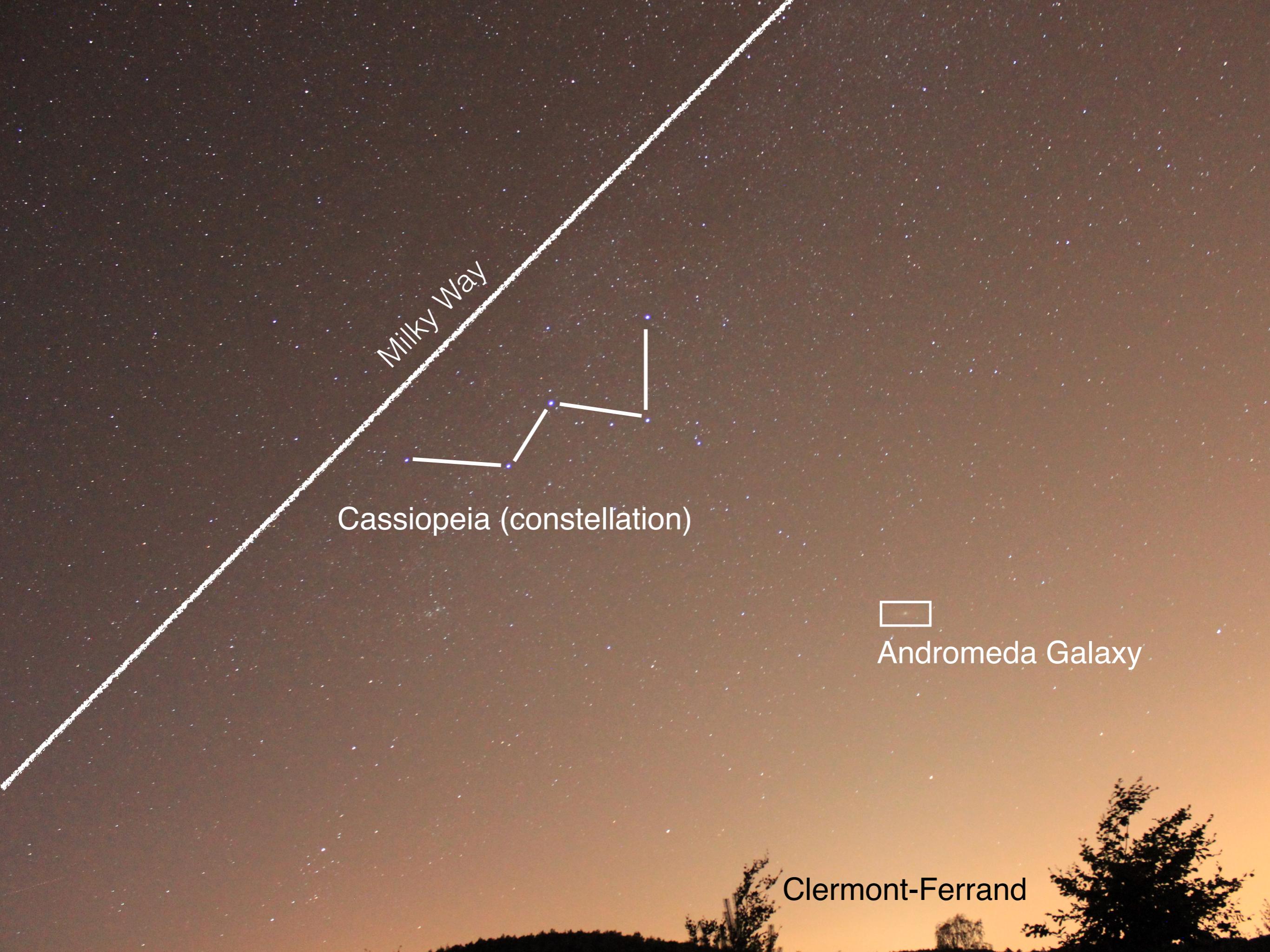
- LSST like survey for ten years
- Calibration of SNIa are one of the other main challenges
- Drive precision on Dark Energy state equation parameters
- Adding SUGAR does not matter for the current state of the arts for calibration
- Expected Calibration for LSST + SALT2 give an improvement of 20% on w_0 and 45% on w_a
- Expected Calibration for LSST + SUGAR give a total improvement of 45% on w_0 and 50% on w_a

Conclusions:

- **New SED model: SUGAR**
 - 3 intrinsic components instead of the classical stretch effect
- **Model performances:**
 - Better spectral description
 - Intrinsic scatter reduced by ~20% on external data
 - Could improve by ~20% constraint on Dark Energy (compared to SALT2)
 - Reduce the problem of the correlation of Hubble residual & Host properties
- **New tools for cosmology analysis**
 - Need to be implemented for following experiment to get the best constraint on Dark Energy using SNIa!

Merci !





Milky Way

Cassiopeia (constellation)

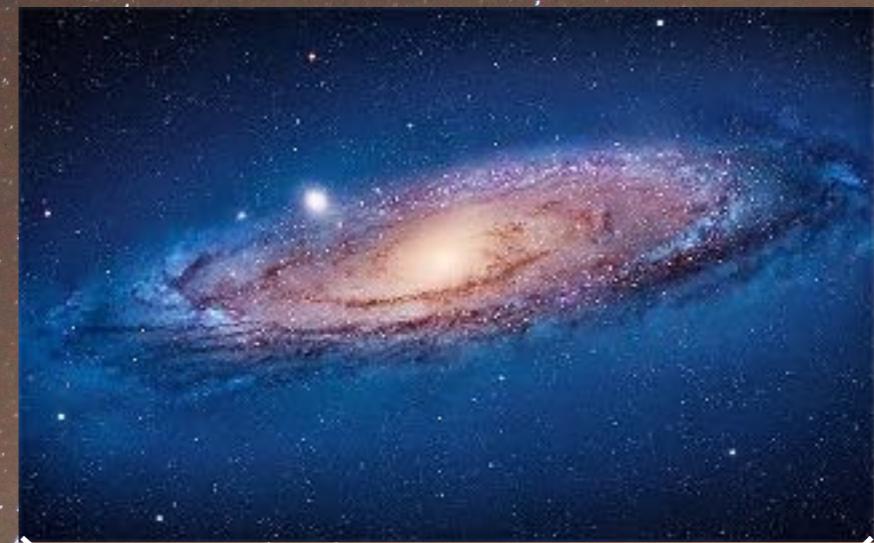


Andromeda Galaxy

Clermont-Ferrand

Milky Way

Cassiopeia (constellation)



Andromeda Galaxy

Clermont-Ferrand

Merci !