Correcting for peculiar velocities of Type Ia Supernovae in galaxy clusters

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Introduction

Data

- Nearby Supernova Factory data
- Host clusters data
- Redshift measurement

Results

- Impact on the Hubble diagram
- Physical properties of SNe Ia and their hosts in galaxy clusters

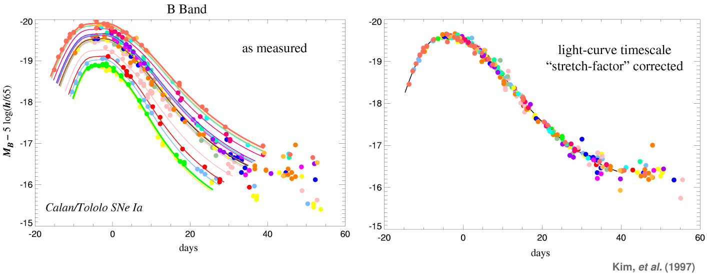
Conclusions

Cosmology with SN Ia
SN Ia are standardizable candles

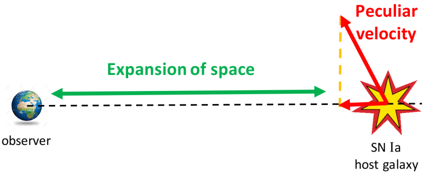
- $\Omega_\Lambda = 0.705 \pm 0.034$ (Betoule et al. 2014)
- "luminosity distance-redshift" relation

- standardization of SN Ia (Rust 1974, 1975; Pskovskii 1977, 1984; Phillips 1993; Phillips et al. 1999; Riess et al. 1996; Perlmutter et al. 1997, 1999; Wang et al. 2003; Guy et al. 2005, 2007; Jha et al. 2007)

$$M = M_B - \alpha X1 + \beta C$$



Cosmology with SN Ia
Peculiar velocities



(from A. Ciulli)

- Is the uncertainty in the redshift negligible?
  $(1+z_{obs}) = (1+z_c)(1+z_d)$
- For low and intermediate redshifts ($z < 0.2$):
  - to remove all SNe with $z < 0.015$ from the Hubble diagram & to add a 300–400 km/s peculiar velocity dispersion as z uncertainty (Astier et al. 2006; Wood-Vasey et al. 2007; Amanullah et al. 2010; Union 2.1)
  - velocity maps of the nearby Universe (150 km/s, Hudson et al. 2004; Conley et al. 2011; Betoule et al. 2014; JLA)

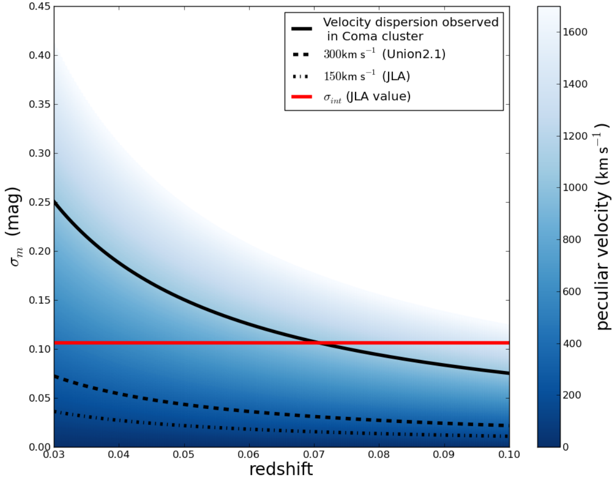
Coma cluster

$\sigma_V = 1038$ km/s

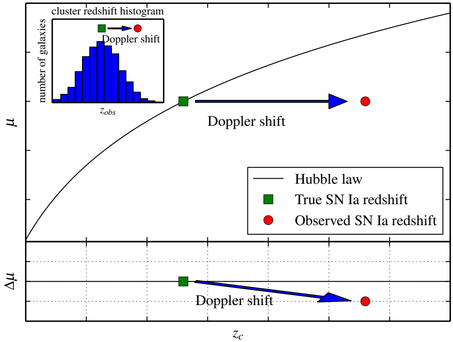
(Colless & Dunn 1996)

$$\sigma_m = \frac{5\,\sigma_V}{cz \ln 10}$$

Standard methods to take into account peculiar velocities can not be applied for galaxy clusters!



SN Ia in clusters



Virgo, Fornax:

Blakeslee et al. 1999; Radburn-Smith et al. 2004

For SNe:

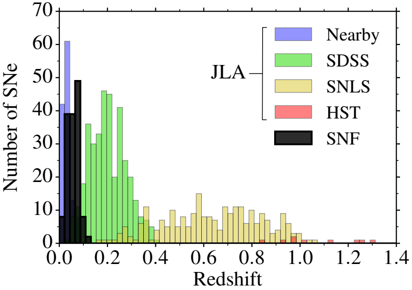
Feindt et al. 2013; Dhawan et al. 2017

How to estimate better the impact of peculiar velocities on the redshift measurements?

- to match the host galaxies of SNe Ia with known clusters of galaxies
- to use the host cluster redshift instead of the host galaxy redshift

Nearby Supernova Factory data

- 145 SN Ia (CABALLOv2, 2004 – 2009; Aldering et al. 2002)
- The sample contains the objects with good final references and properly measured light-curve parameters, including quality cuts suggested by Guy et al. (2010).
- m_B^*, X_1, and C are estimated with the SALT2.4 lightcurve fitter (Guy et al. 2007, Betoule et al. 2014).



Galaxy clusters

Methods for identifying the clusters:

- over-density regions on the images
- red sequence method
- diffuse X-ray emission
- Sunyaev-Zel'dovich effect

SIMBAD database

- only clusters of galaxies (exclude groups of galaxies)
- $d < 2.5$ Mpc
- $\Delta z < 0.015$

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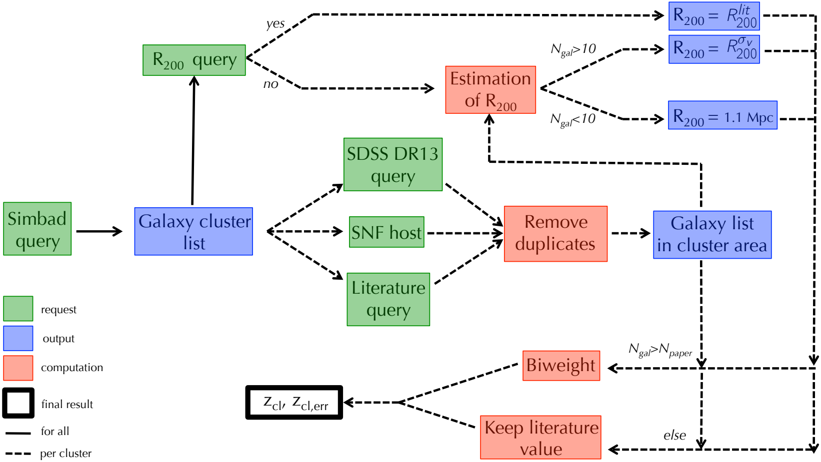
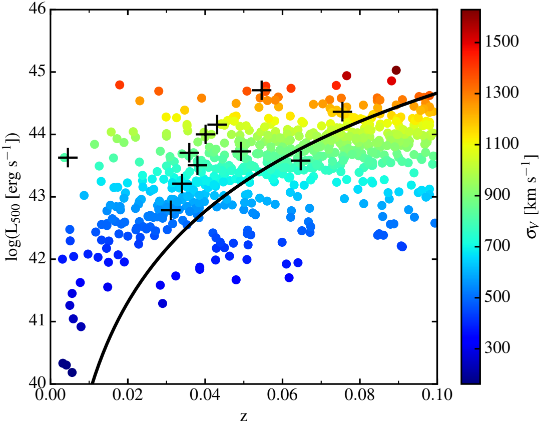
Redshift calculation

$$\sigma_V \simeq 10R_{200}H(z) \rightarrow z_{er}^{cl} = \frac{\sigma_V}{\sqrt{N_{gal}}}$$



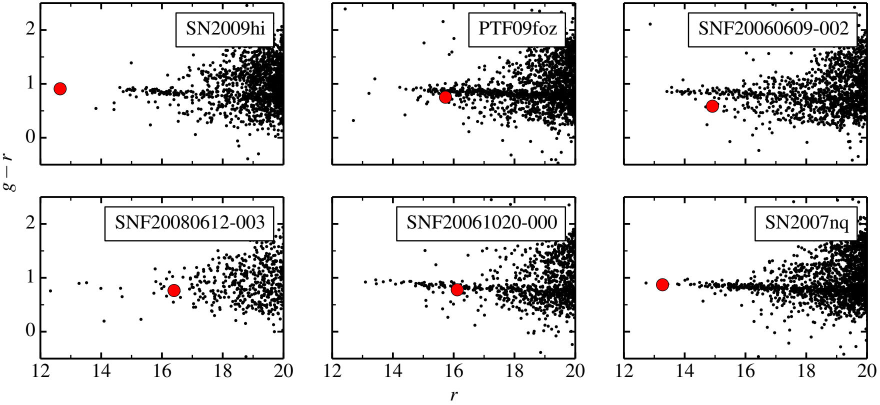
Final matching



- $d < R_{200}$
- $|z_{host} - z_{cl}| < 3\frac{\sigma_V}{c}$
- + X-ray → 11 SNe

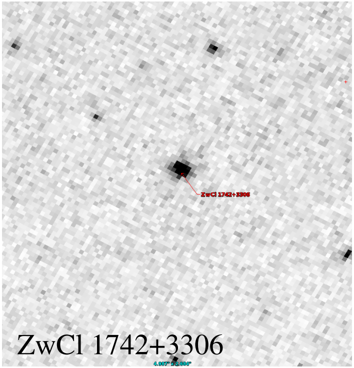
Xavier et al. 2013 (1.5 Mpc, $\sigma_V = 500$ km s^{-1});
Dilday et al. 2010 (1.0 Mpc h^{-1}, $\Delta z = 0.015$)

Red sequence

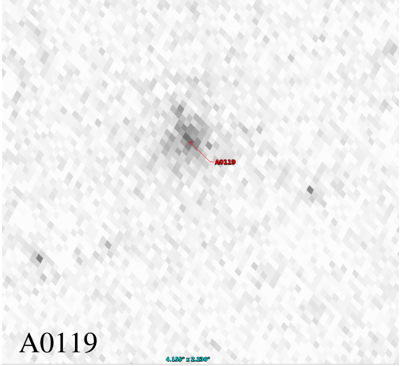


X-ray emission (ROSAT)

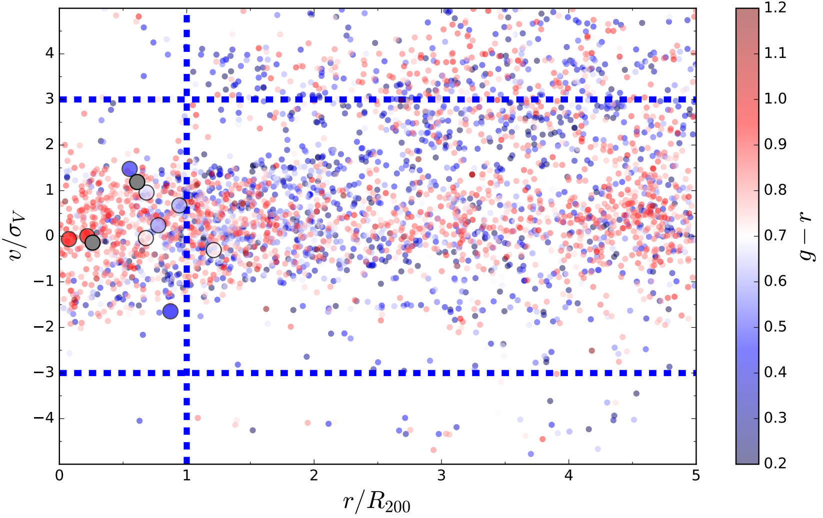
SNF20080731-000



SN2007nq



Host clusters data. Ensemble cluster



Hubble diagram

$$\chi^2 = \sum \left(\frac{\mu_i(M_B, \alpha, \beta) - \mu_i^{th}}{\sigma_i^{tot}} \right)^2 \qquad (1)$$

$$\mu = m_b^* - M_B + \alpha X_1 - \beta C \qquad (2)$$

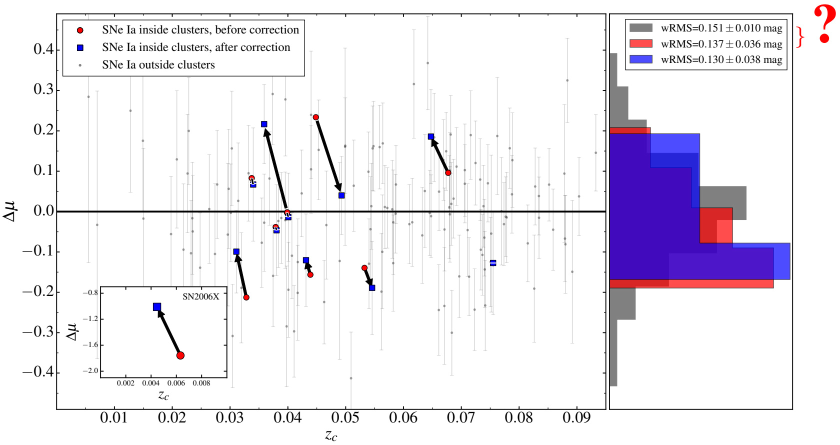
$$\mu^{th} = 5\log_{10} d_{\mathrm{L}} - 5, d_{\mathrm{L}} = \frac{c}{H_0}(1+z_{\mathrm{h}}) \int_0^{z_c} \frac{dz_c'}{\sqrt{\Omega_\Lambda + \Omega_m(1+z_c')^3}} \qquad (3)$$

$$\sigma_i^{tot\,2} = \sigma_{LC_i}^2 + \ \sigma_z^2 + \ \sigma_{int}^2 \qquad (4)$$

$$z_c = \begin{cases} z_c^{cl} \\ z_c^{host} \end{cases} \qquad \sigma_z = \begin{cases} \frac{5\,\sqrt{z_{err}^{cl\ 2}}}{z^{cl}\ln(10)}, & \text{if inside a galaxy cluster} \\ \frac{5\,\sqrt{z_{err}^{host\ 2} + 0.001^2}}{z^{host}\ln(10)}, & \text{otherwise} \end{cases} \qquad (5)$$

Hubble diagram

$wRMS = 0.137^m$ (without correction); $wRMS = 0.130^m$ (with correction); $p = 5.9 \times 10^{-4}$
$wRMS = 0.130^m$ (inside clusters); $wRMS = 0.151^m$ (outside clusters); $p = 3.8 \times 10^{-1}$



The environment of SN Ia

The influence of the environmental effects on the SN Ia intrinsic luminosity was proved in many works:

- host galaxy morphology and stellar population age (Hamuy et al. 1995,1996,2000; Riess et al. 1999; Sullivan 2003; Hicken et al. 2009; Pruzhinskaya et al. 2011; Hill et al. 2016; Henne et al. 2017)
- galocentric distance (Sullivan et al. 2003; Hill et al. 2016)
- star-formation rate (Sullivan et al. 2006; Neill et al. 2009; Lampeitl et al. 2010; Sullivan et al. 2010; Smith et al. 2012; Johansson 2013)
- local star-formation rate (1-3 kpc; Rigault et al. 2013; Roman et al., arXiv:1706.07697)
- stellar mass of host galaxy (Kelly et al. 2010; Sullivan et al. 2010; Johansson 2013)
- host metallicity (Gallagher et al. 2005,2008; Howell et al. 2009)

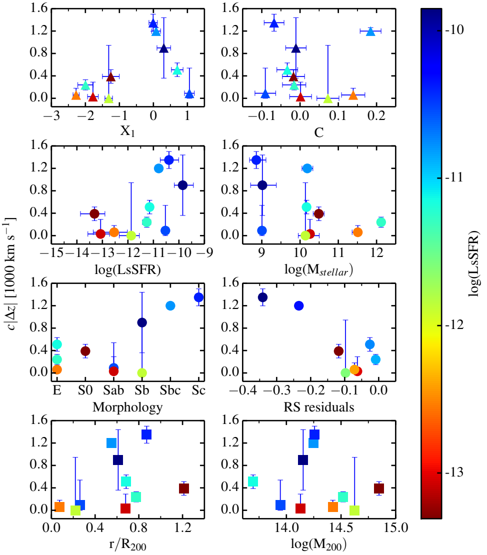
Physical properties of SNe Ia in clusters

Host morphology:

- E/S0 (4), Spirals (7)

Highest correction:

- $X_1 \simeq 0$
- blue galaxies
- high local sSFR
- smaller $M_{stellar}$
- $r/R_{200} \simeq 0.7$



Conclusions

- We studied how the peculiar velocities of SNe Ia in galaxy clusters affect the redshift measurements by matching 145 SNFACTORY supernovae with known clusters of galaxies.
- The applied technique allowed to decrease the spread on the Hubble diagram. For the SNe in clusters *wRMS* is improved from 0.137^m to 0.130^m with p-value $= 5.9 \times 10^{-4}$.
- The described effect influences the distance measurements in the nearby Universe ($z < 0.1$) and has to be taken into account in future cosmological surveys.
- The difference in SN light curve parameters inside and outside the clusters could be fruitful avenue of investigation for future cosmological analysis.

Thanks for the attention!