SNe Ia in the Hubble flow and H_0

Bruno Leibundgut @ 65

Pilar Ruiz-Lapuente

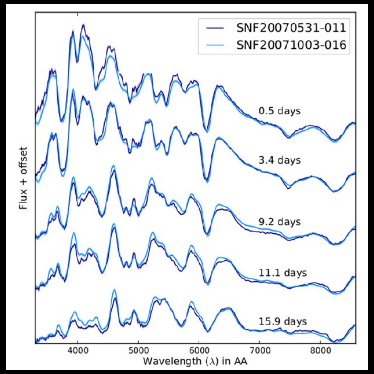
IFF (CSIC), Madrid, Spain
ICC-UB, Barcelona, Spain

- SNe Ia in the Hubble flow: distances in a single step using twin SNe Ia
- First results: individual distances in the SH0ES,Pantheon+ and CSP
- Isotropy in CSP and Pantheon+ samples
- Prospects ZTF, more

The twin SNeIa method

In this approach:

Two steps of the cosmological distance ladder

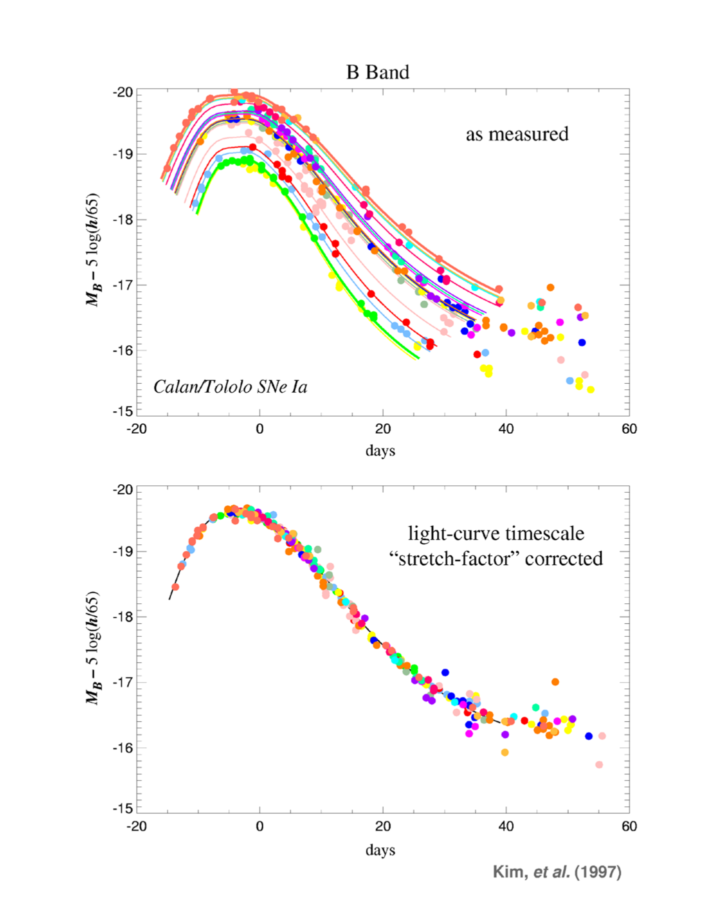


SNeIa twins of the "anchors" in the Hubble flow ($z \approx 0.015$-0.03)

Distances to nearby SNeIa ("anchors")

RL & González Hernández (2024)

SNeIa light curves



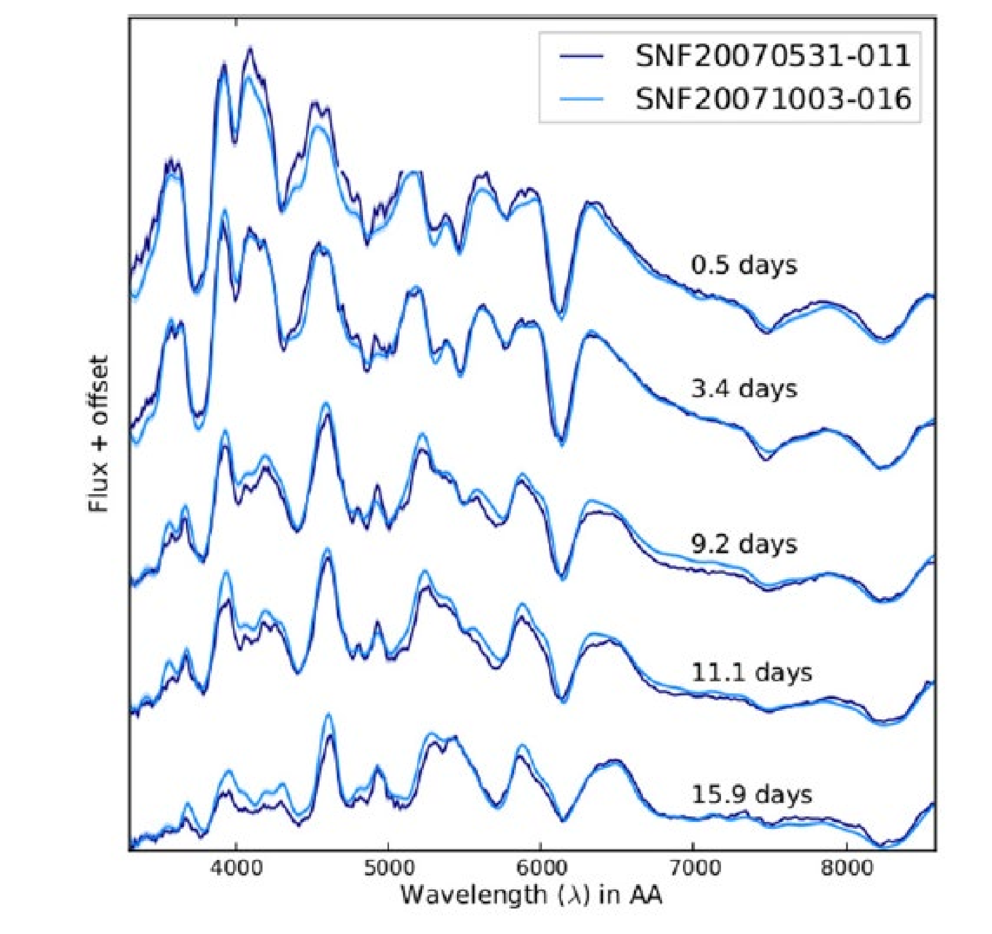
With **light-curve fitting, distance moduli are obtained with an error of σ_μ** = 0.11 mag

By **fitting spectra of twin SNeIa, distance moduli are obtained with an error of σ_μ** = 0.04 mag only

Ruiz-Lapuente & González Hernández 2024, ApJ 977, 180

Twin SNeIa

Using twin SNeIa, Fakhouri et al. (2015) were able to standardize SNeIa in the redshift range $0.03 \leq z \leq 0.08$ within 0.06-0.07 mag



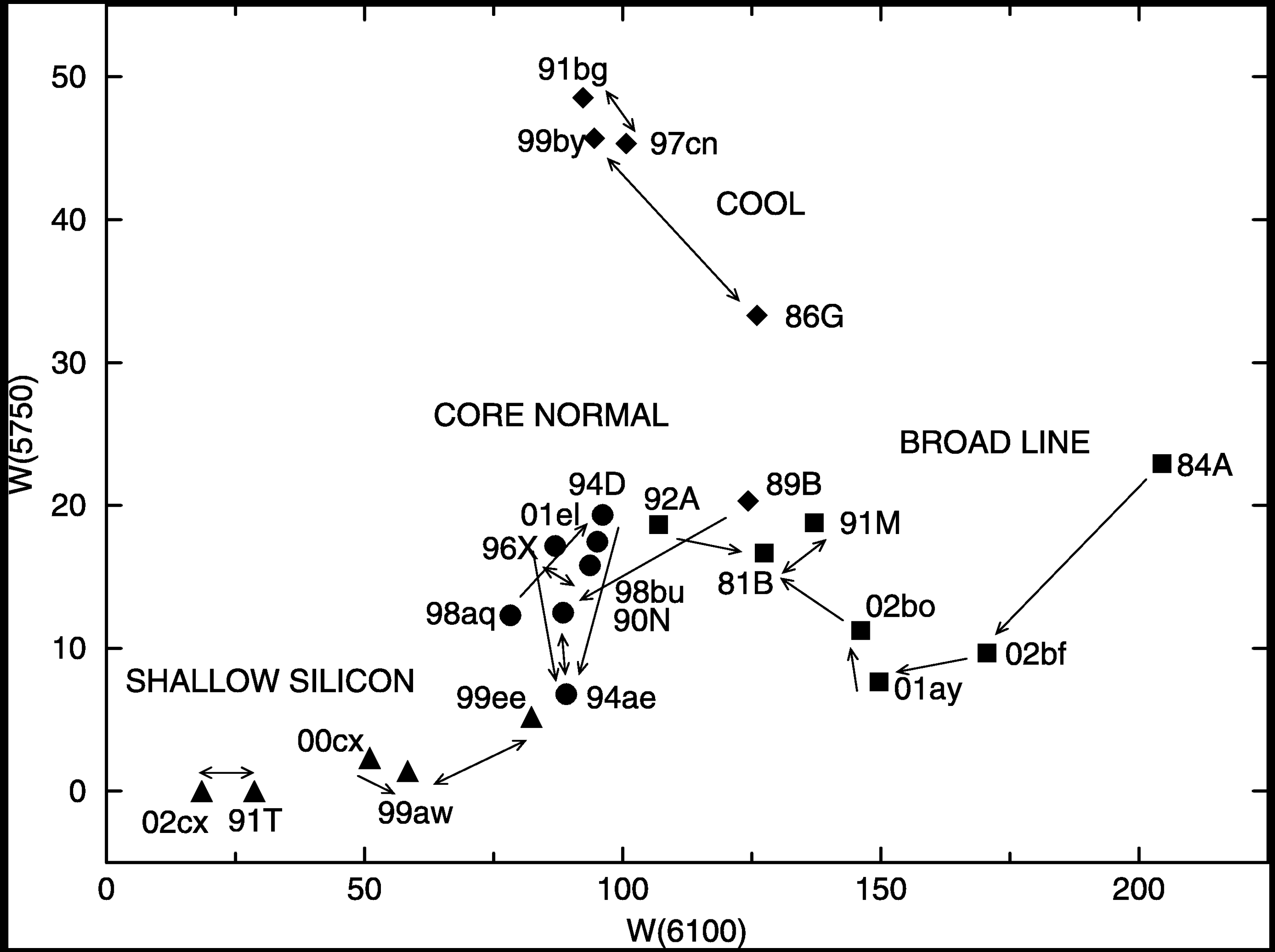
Twins are used there to connect the absolute magnitude estimate at maximum brightness with parameters corresponding to the spectral diversity of the SNeIa

Here, instead, we use twin SNeIa in all phases, from the early to the late, nebular phases, what we call “twins for life”

(from Fakhouri et al. 2015)

Searching for twins: SNe Ia subtypes

W(5750) plotted against *W*(6100). Core_normal SNeIa are shown as circles, broad-lined SNeIa as squares, cool SNeIa as diamonds and shallow-silicon SNeIa as triangles

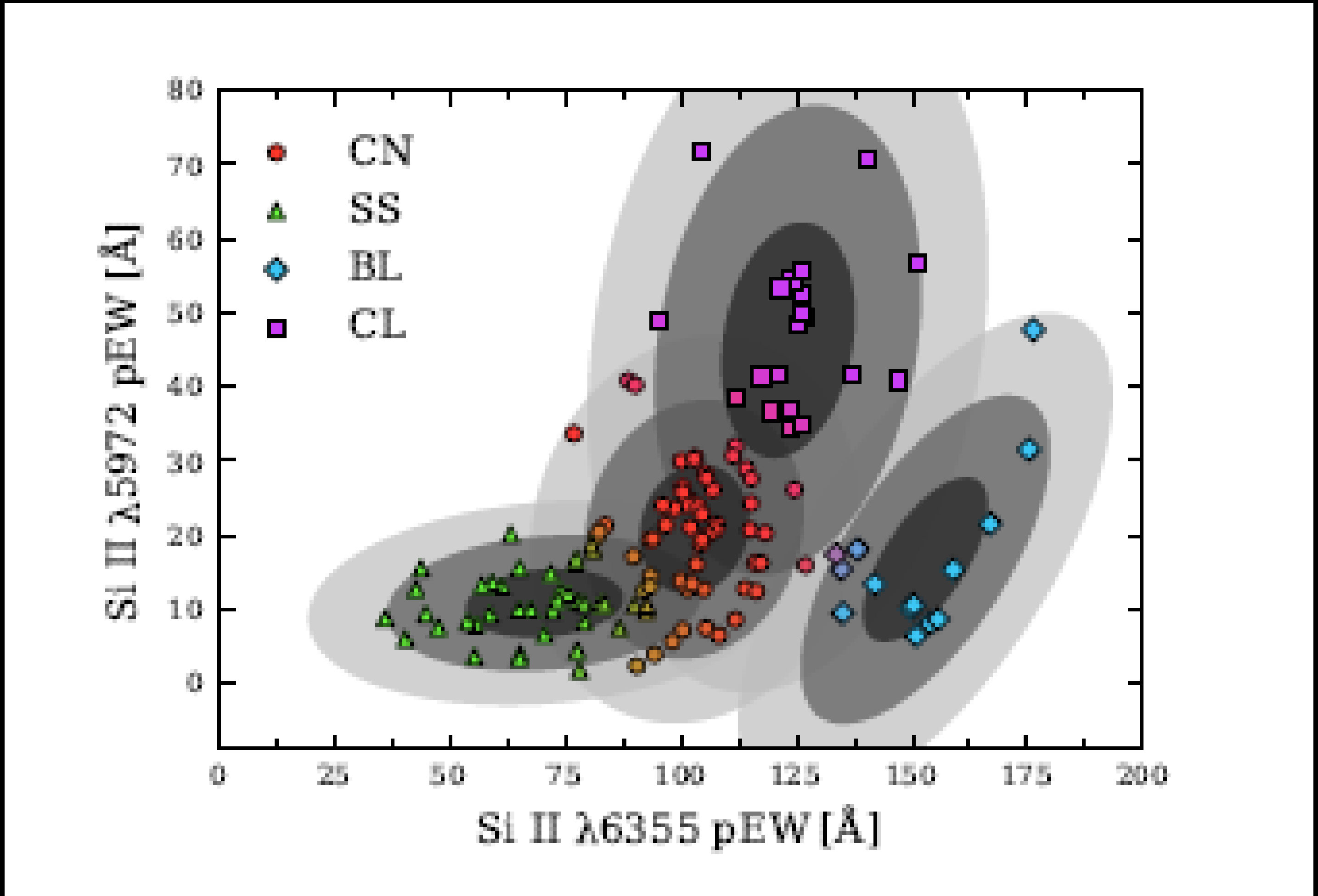


(from Branch et al. 2006)

The Branch diagram with the contours of 1σ, 2σ and 3σ from the mean of each group.

The temperatura effect can be seen, shallow-silicon SNeIa being hottest, that corresponding to their low Si II λ5972 Å vs Si II λ6355 Å *pEW* ratios .

The opposite can be seen for the cool SNeIa.



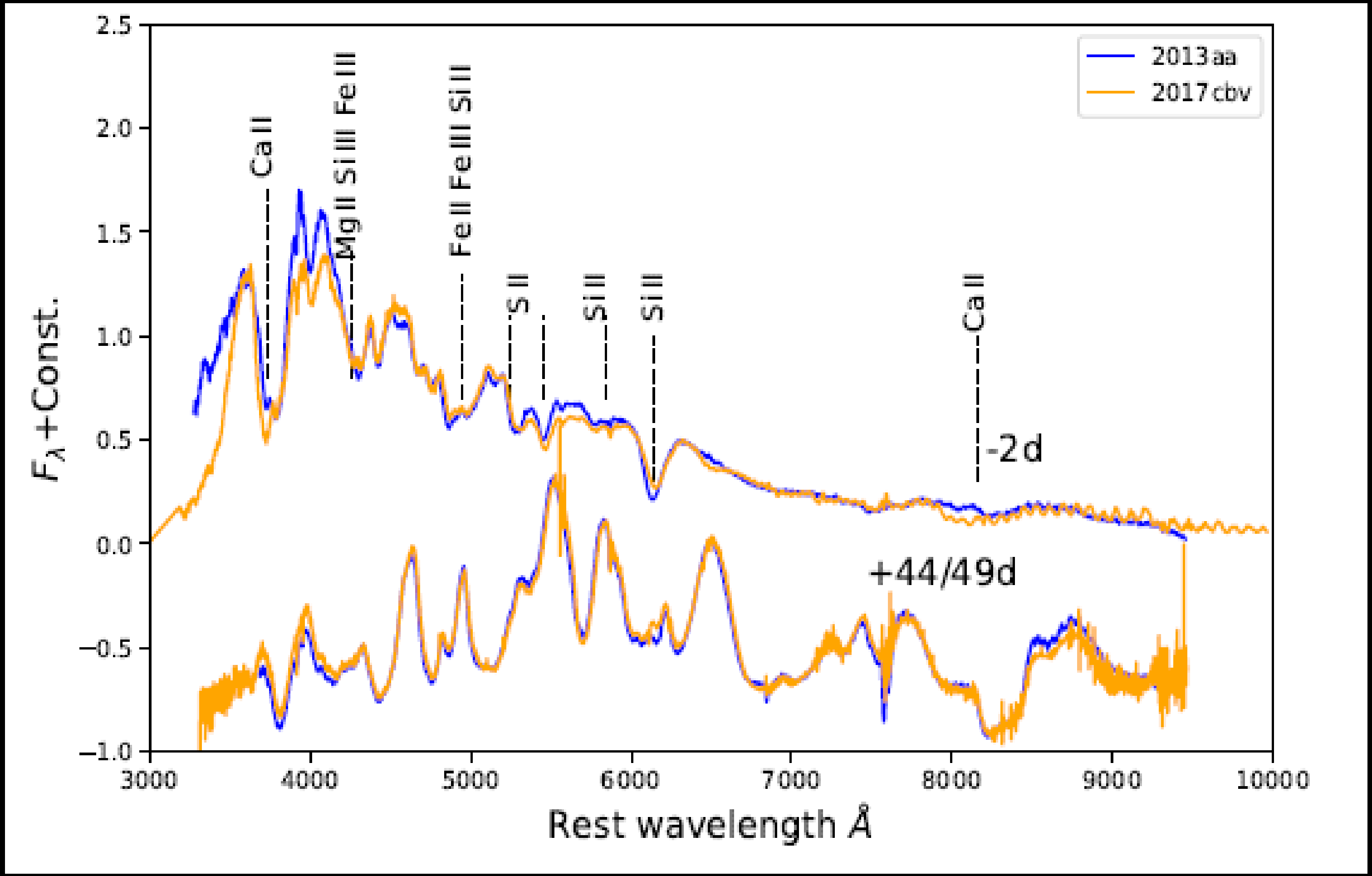
(from Burrow et al. 2020)

The twin SNeIa method

The gain in using the “twins for life” approach is that it provides a direct measurement of distance, intrinsic color and reddening by Galactic and extragalactic dust by the use of the whole spectra of the SNeIa.

It allows the consistent pairing of SNeIa through all phases. The selection of twins is made of SNeIa with a similar stretch, being then of similar luminosities, but n addition the “twinness factor” can make more precise the distance estimate, with a modulus error of 0.04 mag in all filters, as we will show. So, all this makes it a very useful tool to establish the right distance ladder

Spectral characterization of twins



Spectral characterization of twins

pWs at Maximum Light (Angstrom)

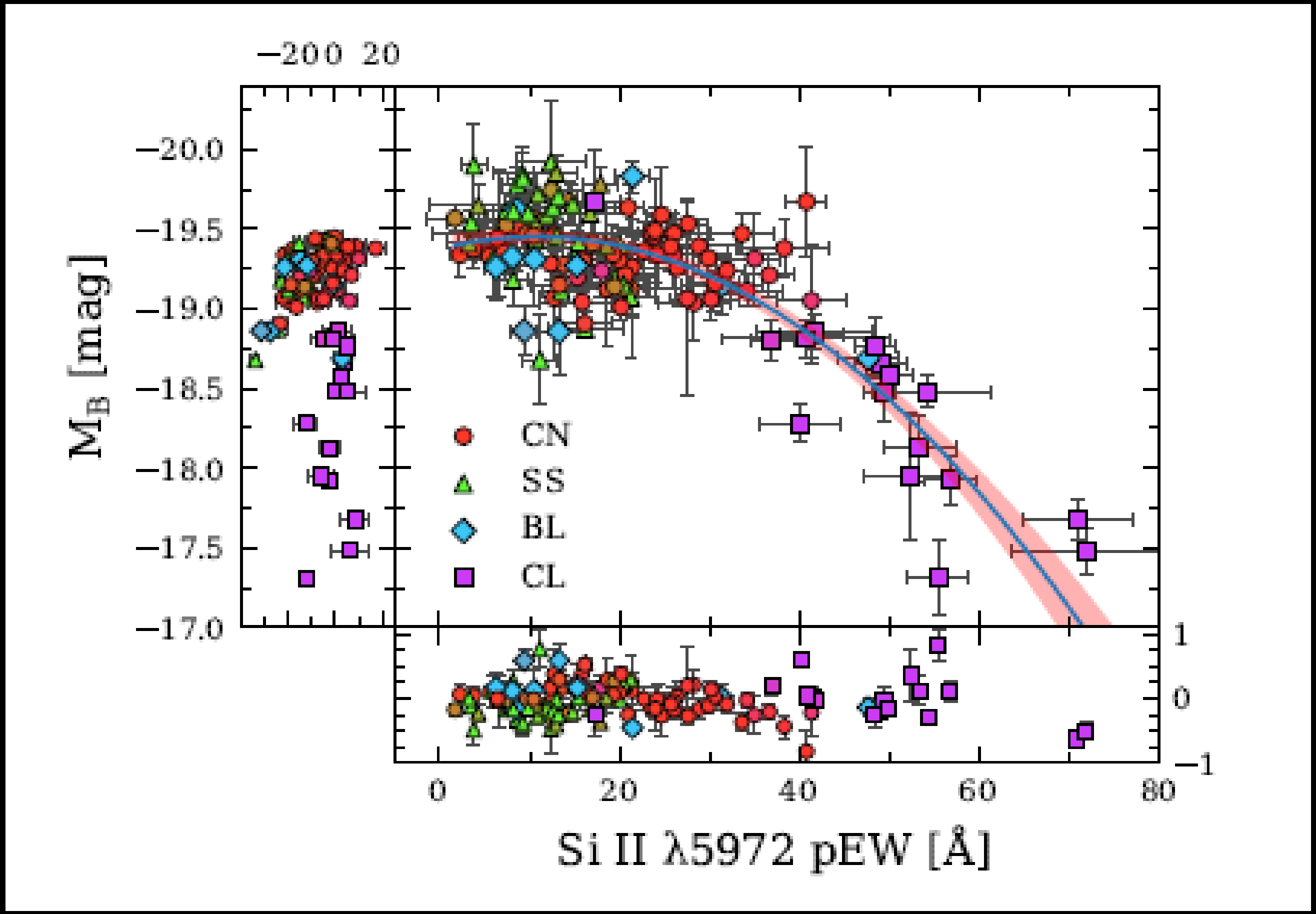
SN	pW1 Ca II H&K	pW2 Si II 4130	pW3 Mg II	pW4 Fe II	pW5 S II W	pW6 Si II 5972	pW7 Si II 6355	pW8 Ca II IR	Project
CN									
2007ol	106(1)	22(1)	80(1)	82(1)	56(1)	16(1)	78(1)	...	CSP-I
2008bz	86(2)	22(2)	70(1)	106(2)	88(1)	17(1)	99(1)	105(3)	CSP-I
2008fr	107(2)	11(1)	71(2)	109(1)	80(1)	17(1)	82(2)	72(5)	CSP-I
2009I	140(3)	9(1)	82(3)	111(2)	72(1)	10(1)	70(1)	89(3)	CSP-I
2009cz	120(1)	9(1)	92(1)	131(1)	67(1)	12(1)	81(1)	104(4)	CSP-I
2009le	60(2)	11(1)	104(2)	124(1)	62(1)	9(1)	86(1)	114(2)	CSP-I
ASASSN-14hr	135(2)	32(1)	101(2)	138(1)	67(2)	30(1)	104(2)	107(4)	CSP-II
ASASSN-14hu	150(2)	11(1)	97(2)	115(1)	76(1)	7(1)	83(1)	...	CSP-II
ASASSN-14kq	139(1)	11(1)	100(1)	115(1)	73(1)	11(1)	77(1)	127(3)	CSP-II
ASASSN-14lp	116(3)	10(1)	93(4)	140(3)	69(1)	13(1)	70(1)	117(4)	CSP-II

We have measured lines relevant for describing the similarity of the spectra. Those of the twins have very similar pseudo-equivalent widths (*pWs*) in the list of lines (Morrell et al. 2024), *pW1* (Ca H & K), *pW2* (Si II λ 4130 Å), *pW3* (Mg II λ 4481 Å blended with Fe II), *pW4* (Fe II at ≈ λ 4600 Å blended with S II), *pW5* (S II "W" ≈ λ 5400 Å), *pW6* (Si II λ 5972 Å), *pW7* (Si II λ 6355 Å) and *pW8* (Ca II IR).

In particular, the *pW6* should be very similar between twin SNeIa, the dicrepancy being by less than 5%. This line correlates with stretch (Δm_{B15}, s_{BV}), being similar in SNeIa with similar stretches and nearly identical in twins. In the *pW6 vs pW7* diagram, twins should fall into almost the same place

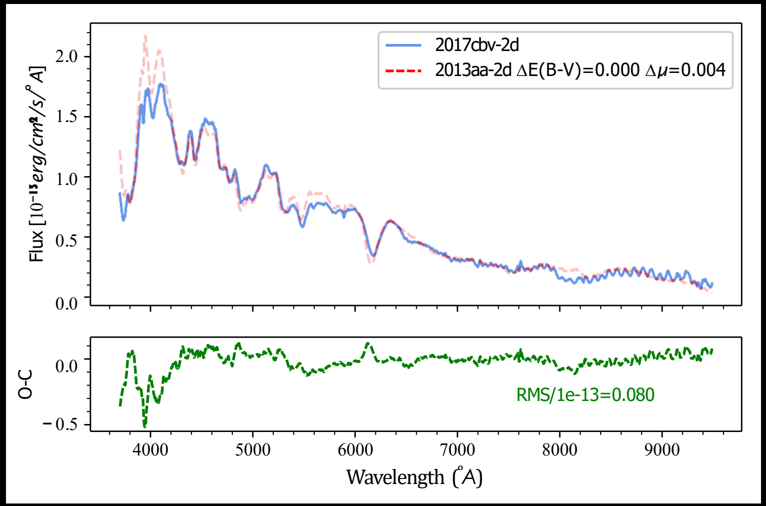
Morrell al. 2024

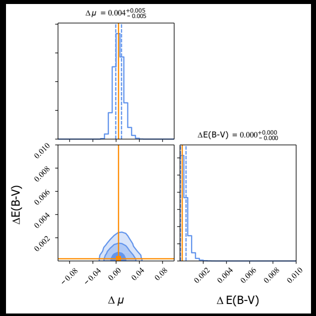
M_B vs the pEW of the Si II λ5972 Å line



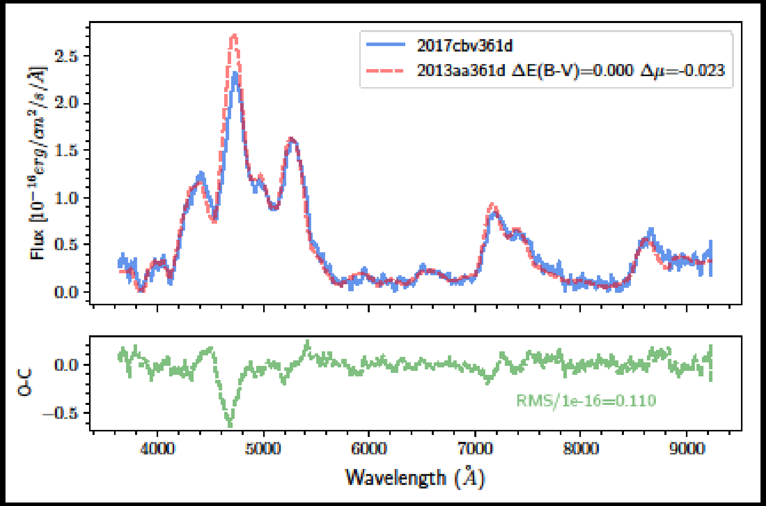
(from Burrow et al. 2020)
Carnegie Supernova Project

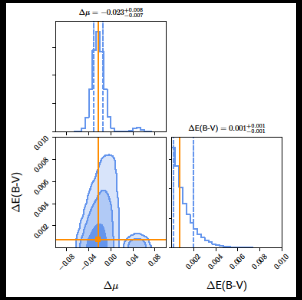
SN 2013aa/SN 2017cbv in NGC 5643

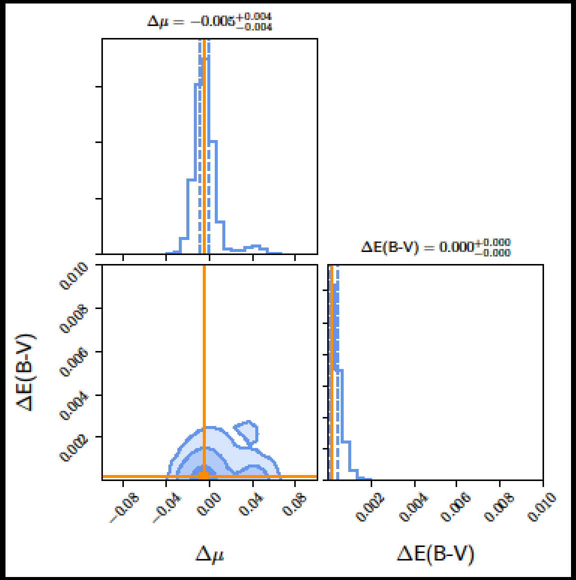


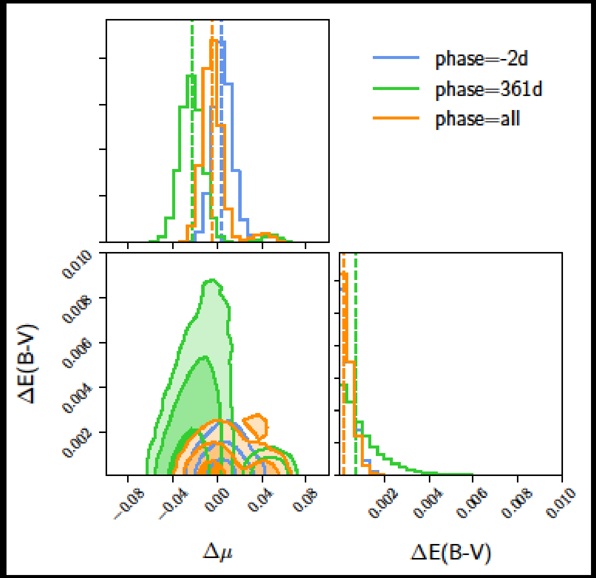


Comparison of early (-2d) and late time (+361d) spectra of the twin SNe Ia SN 2013aa and SN 2017cbv, both in the galaxy NGC 5643, with the 1σ, 2σ and 3σ contours of the probability distribution for Δμ (difference in distance moduli) and ΔE(B-V) (difference in reddening), in each case. We use Markov Chain Monte Carlo techniques and the EMCEE Python package to obtain the best values and their uncertainties for the two variables. We obtain the final joint result for the two phases









Carnegie Supernova Project

Optical Spectroscopy of Type Ia Supernovae by the Carnegie Supernova Projects I and II

N. Morrell[1], M. M. Phillips[1], G. Folatelli[2,3], M. D. Stritzinger[4], M. Hamuy[5], N. B. Suntzeff[6], E. Y. Hsiao[7], F. Taddia[4], C. R. Burns[8], P. Hoeflich[7], C. Ashall[9], C. Contreras[1], L. Galbany[10,11], J. Lu[7], A. L. Piro[8], J. Anais[1], E. Baron[12,13,14], A. Burrow[14], L. Busta[1], A. Campillay[1,15], S. Castellón[1], C. Corco[1,16], T. Diamond[7,17], W. L. Freedman[18], C. Gonzalez[1], K. Krisciunas[6], S. Kumar[7], S. E. Persson[8], J. Serón[19], M. Shahbandeh[7], S. Torres[16], S. A. Uddin[20], J. P. Anderson[21,22], C. Baltay[23], C. Gall[4,24], A. Goobar[25], E. Hadjiyska[23], S. Holmbo[4], M. Kasliwal[26], C. Lidman[27], G. H. Marion[28], P. A. Mazzali[29,30], P. Nugent[31,32], S. Perlmutter[31,32], G. Pignata[33], D. Rabinowitz[23], M. Roth[1,34], S. D. Ryder[35,36], B. J. Shappee[37], J. Vinkó[28,38,39,40], J. C. Wheeler[28], T. de Jaeger[41], P. Lira[42], M. T. Ruiz[42], J. A. Rich[8], J. L. Prieto[43], F. Di Mille[1], D. Osip[1], G. Blanc[1], and P. Palunas[1]

Archive for spectra and light curves in

the Hubble Flow.

Standard method

In all the preceding methods:

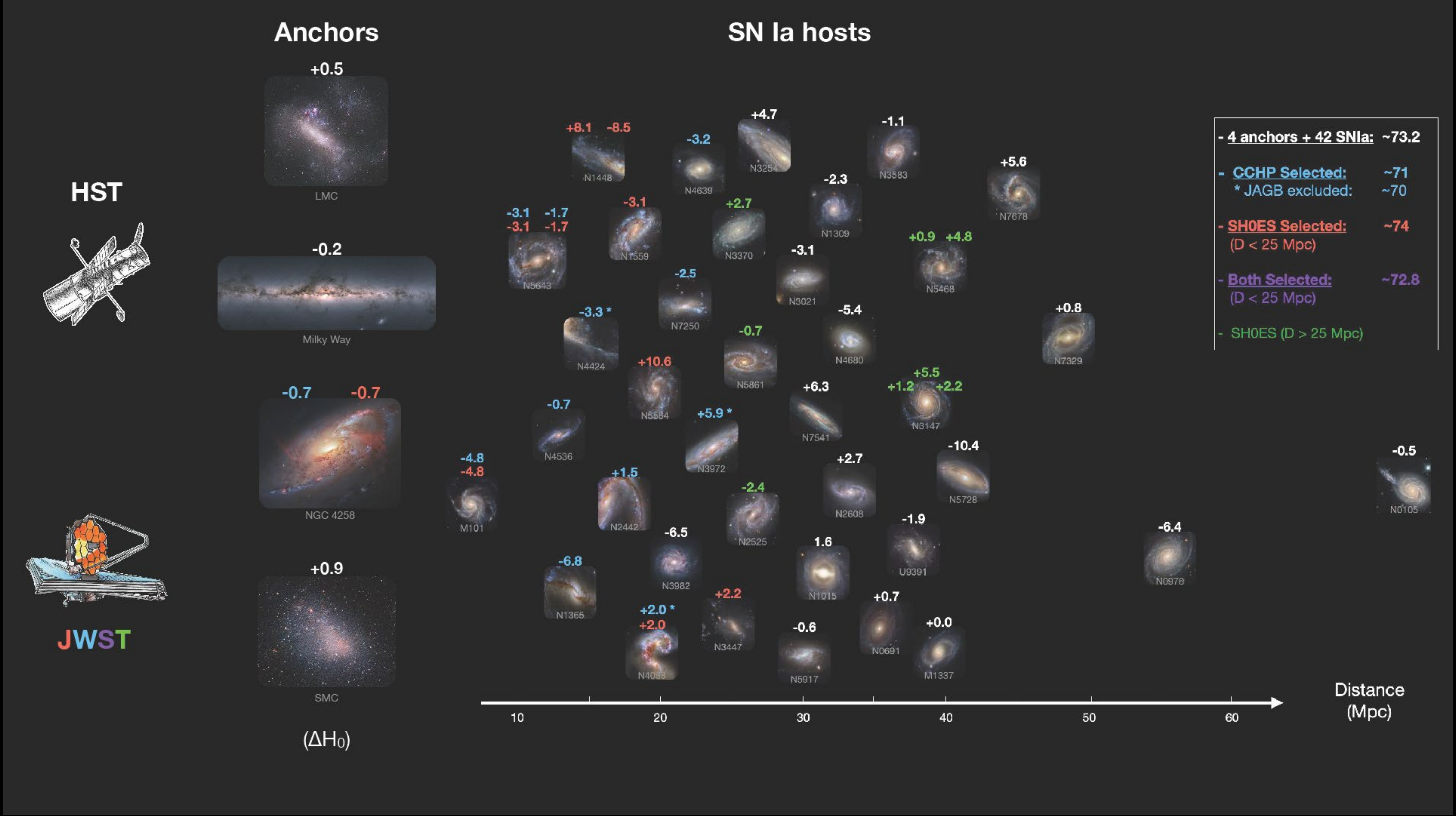
Three steps of the cosmological distance ladder

Calibration of the primary distance indicators (*Cepheids, TRGB, JAGB …*) in nearby galaxies

Standardization of SNeIa sample by determining an average M_B^{max} (z still too low to measure H_0)

SNeIa sample in the Hubble flow ($z \approx 0.01$-0.03)

$M_b^{max} - H_0$

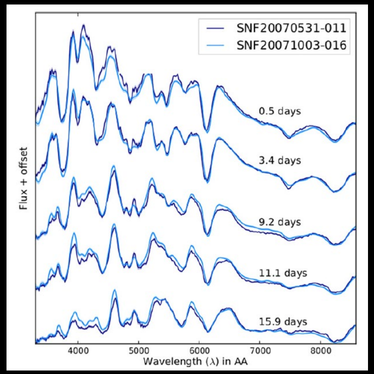


(from Riess et al. 2024)

The twin SNeIa method

In this approach:

Two steps of the cosmological distance ladder



SNeIa twins of the “anchors” in the Hubble flow ($z \approx 0.015$-0.03)

Distances to nearby SNeIa (“anchors”)

RL & González Hernández (2024)

The H_0 tension

To test these parameterizations

$$m_X = m_B + \alpha x_1 + \beta c + \delta_{B,a} + \delta_{Host}$$

Modified Tripp formula, SH0ES+Pantheon+

$$\mu(z, H_0, q_0) = 5\,\log_{10}\{\frac{(1-z_{hel})cz}{(1+z)H_0}(1+\frac{(1-q_0)}{2}z)\} + 25$$

CCHP

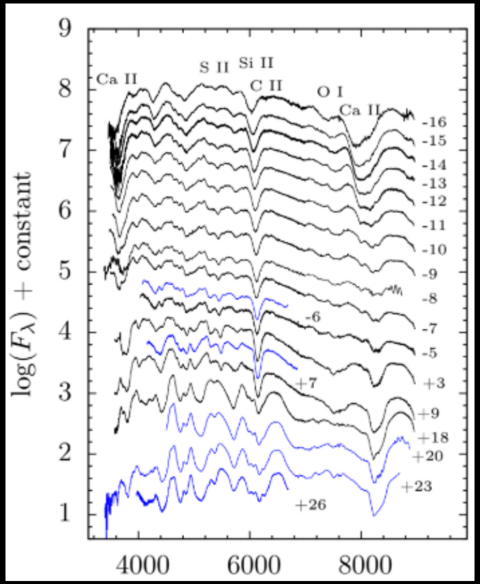
$$\mu_{\rm obs} = m_x - P^0 + P^1(s_{BV}-1) + P^2(s_{BV}-1)^2 + \beta(B-V) + \alpha_M(\log_{10}M_*/M_\odot - M_0)$$

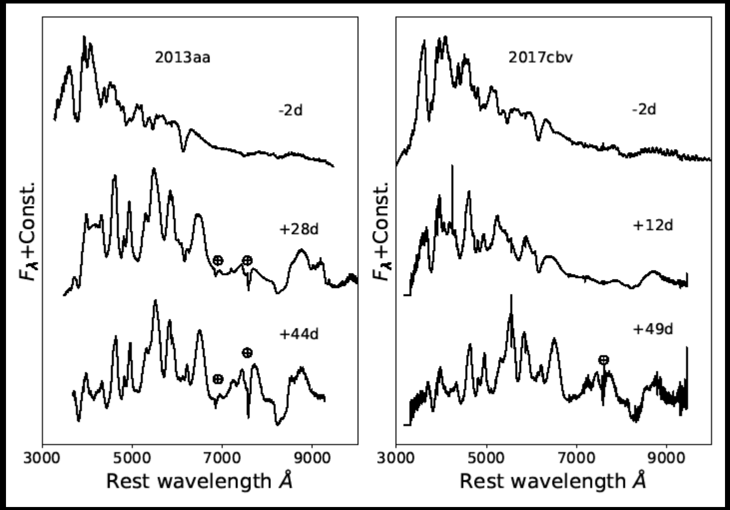
where μ_{obs} is the observed distance modulus, m_x the peak magnitude in the x band and P^0 the absolute magnitude M_x of a SNIa with zero (B-V) color, color stretch $s_{BV} = 1$ and in a host galaxy with stellar mass $M = M_0$

The twin SNeIa method

Extending the method to reach SNeIa that are on the Hubble flow should allow to avoid using a fiducial absolute magnitude M_B-H_0 relation and to get a direct comparison of distances, that leading straightforwardly to the value of H_0

Anchors: D < 15 Mpc





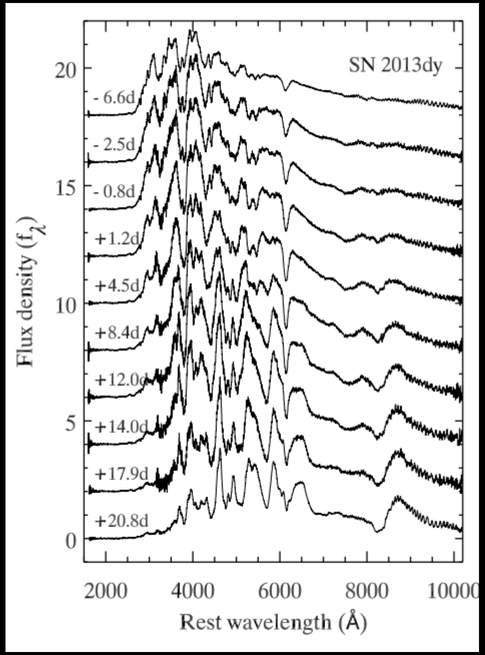
SN 2011fe
M101

R22 (SH0ES): μ = 29.188 ± 0.055 mag
F24 (CCHP): μ = 29.18 ± 0.04 mag (TRGB)
F25 (CCHP): μ = 29.151 ± 0.04 mag (TRGB)

SN 2013aa/SN 20 17cbv
NGC 5643

R22 (SH0ES): μ = 30.55 ± 0.063 mag
F24 (CCHP): μ = 30.61 ± 0.07 mag (TRGB)

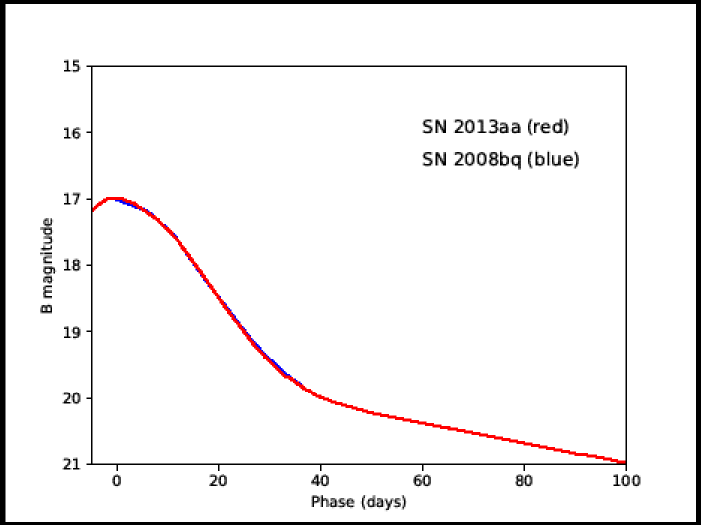
ANCHOR

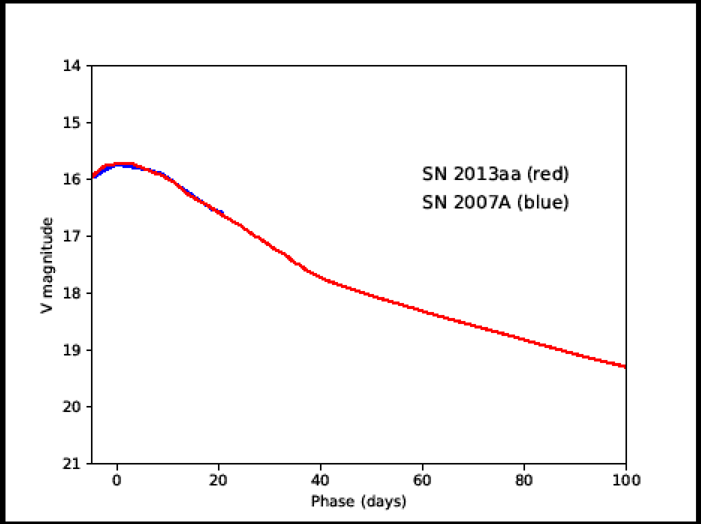


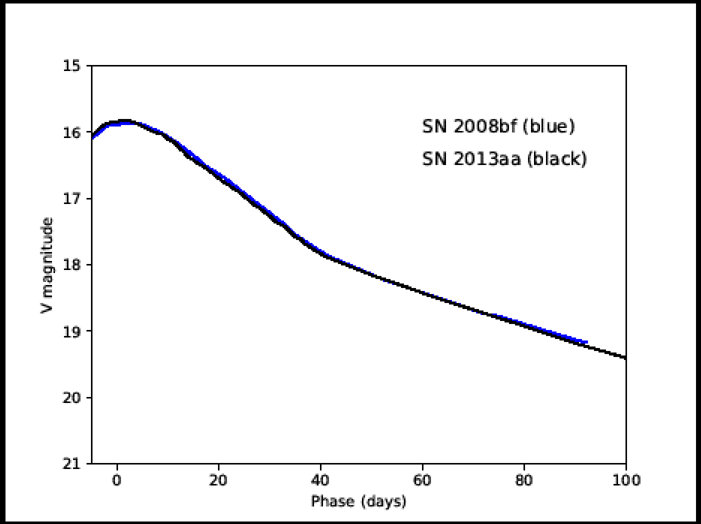
SN 2013dy
NGC 7250

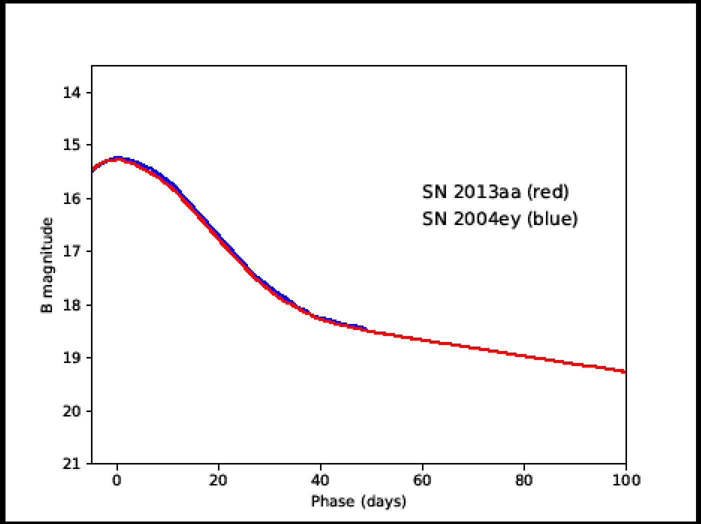
R24 (SH0ES): μ = 31.58 ± 0.065 mag (Ceph)
F24 (CCHP=: μ = 31.62 ± 0.04 mag (TRGB)

Light-curve comparisons

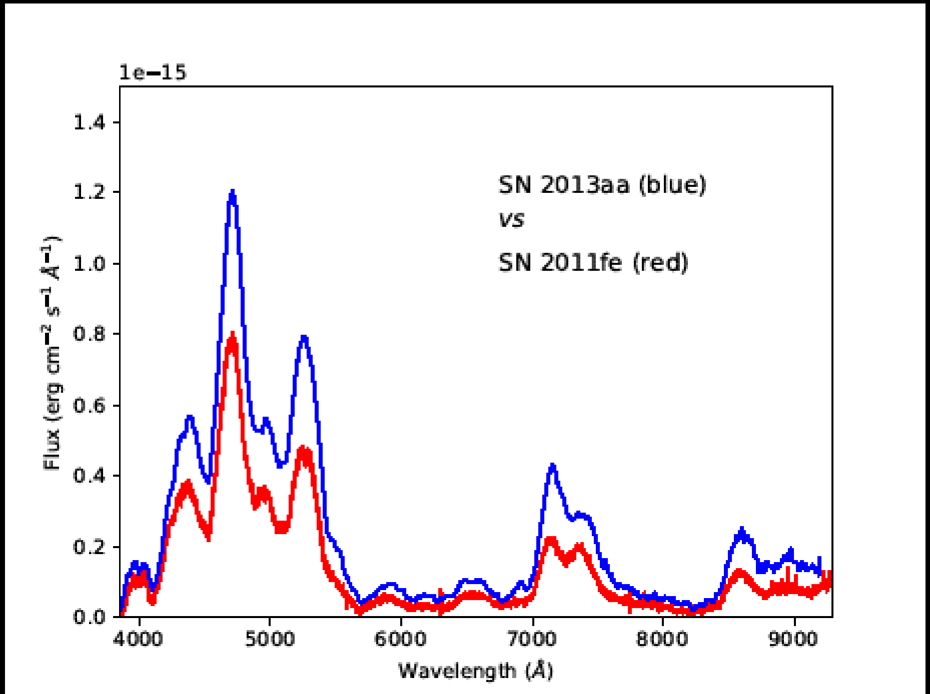








Twin and not twin SNeIa

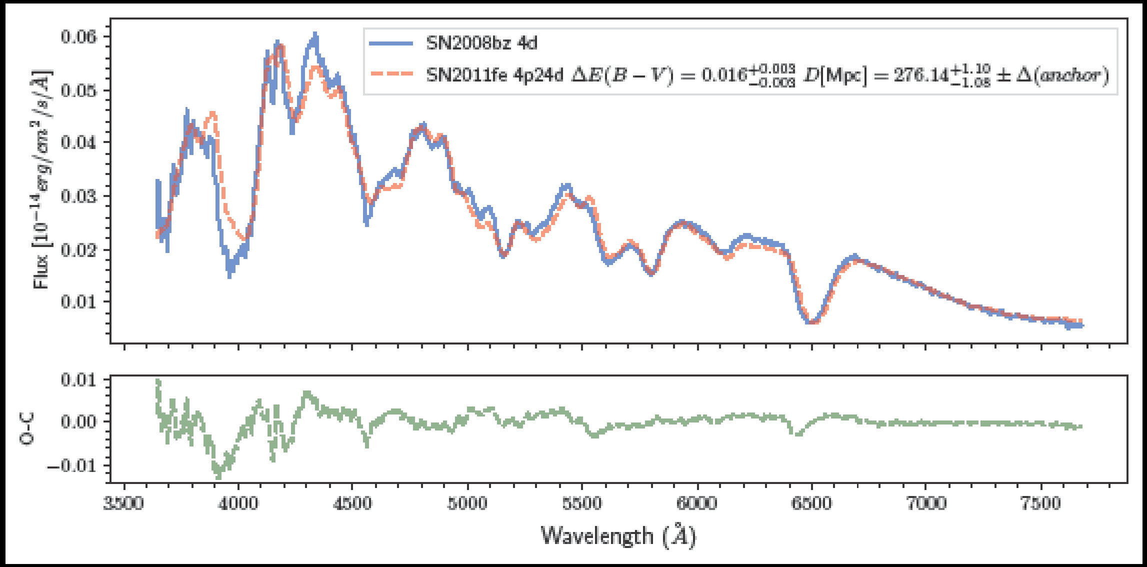


Comparison of the spectra of SN 2013aa and SN 2011fe at he same phase. A reddening of E(B-V) = 0.15 mag has been applied to SN 2011fe for that. Factor in distance similar to the one assumed for the anchor.

Table 1: The SN Ia sample

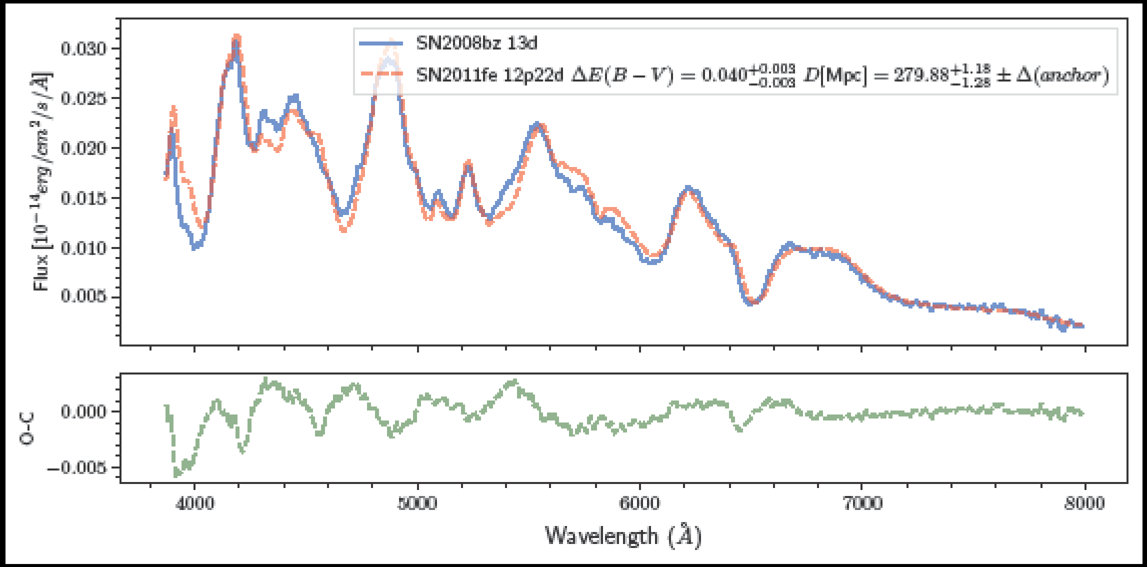
SN	RA	DEC	z_{He}	z_{CMB}
2012bo	12:50:45.23	-14:16:08.5	0.0254	0.0265
2008bq	06:41:02.51	-38:02:19.0	0.0340	0.0344
2008bz	12:58:57.74	11.07:46.2	0.0603	0.0614
LSQ12fxd	05:22:16.99	-25:35:47.0	0.0312	0.0310
2008bf	12:04:02.90	20:14:42.6	0.0235	0.0251
2007A	00:25:16.66	12:53:12.5	0.0176	0.0164
LSQ14gov	04:06:01.33	-16:01:41.4	0.0896	0.0900
2004ey	21:49:07.81	00:26:39.2	0.0158	0.0146

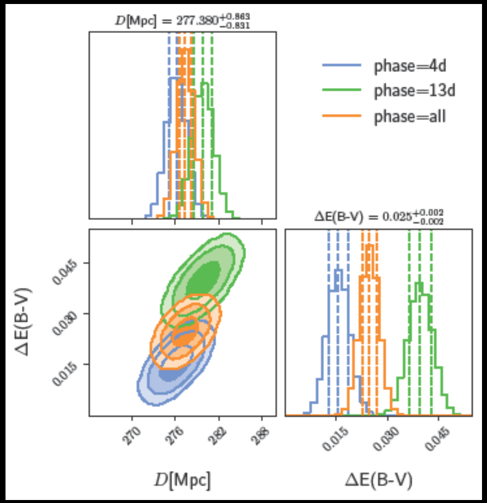
SN 2008bz at z = 0.060

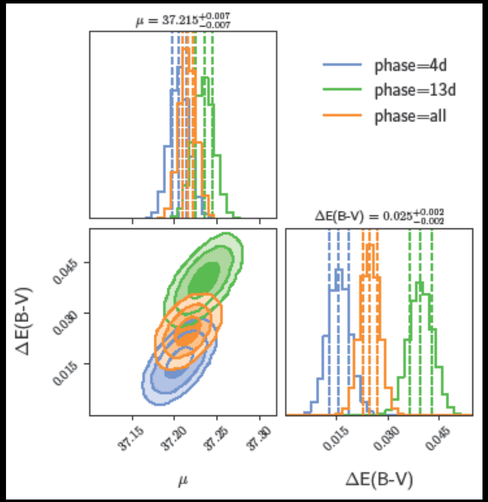


Comparison of the spectra of SN 2008bz at +4d and +13d with those of SN 2011fe at the same phases (left panels) and the 1σ, 2σ and 3σ contours of the probability ofdistribution ofμ (distance moduli) and ΔE(B-V) (difference in reddening) for the joint result of the two phases (lower panels)

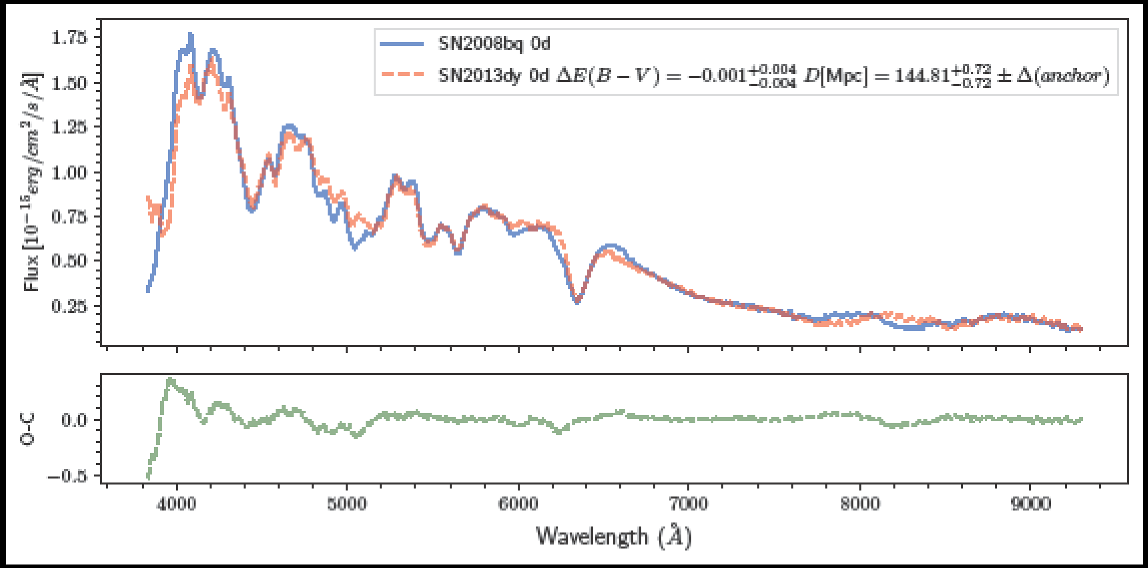
We obtain a distance modulus of μ = 37.215 ± 3.03 mag for comparison, SH0ES values are μ = 37.163 ± 0.124 mag





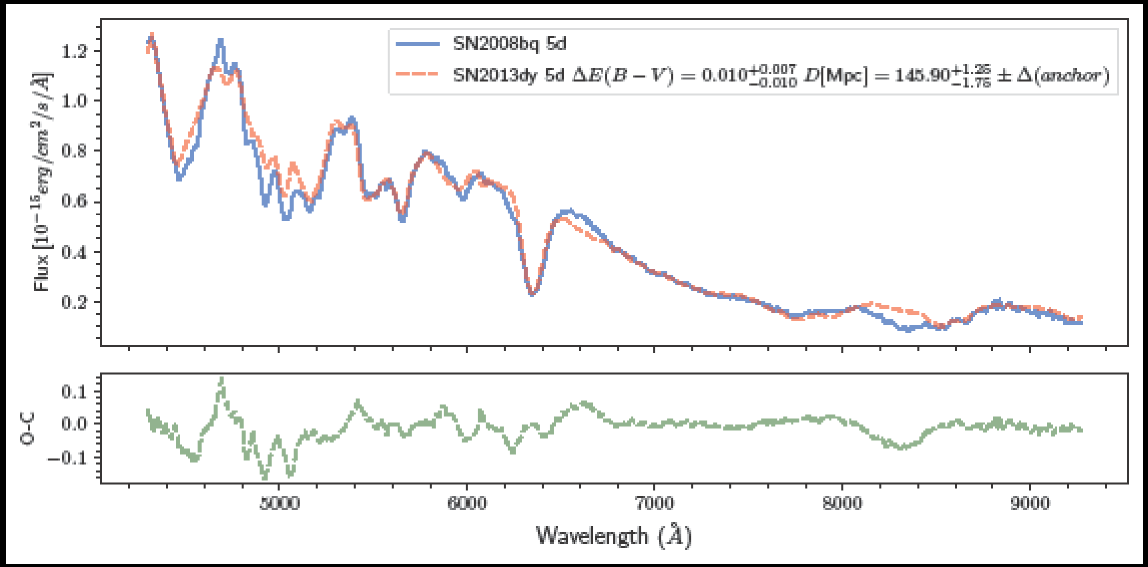


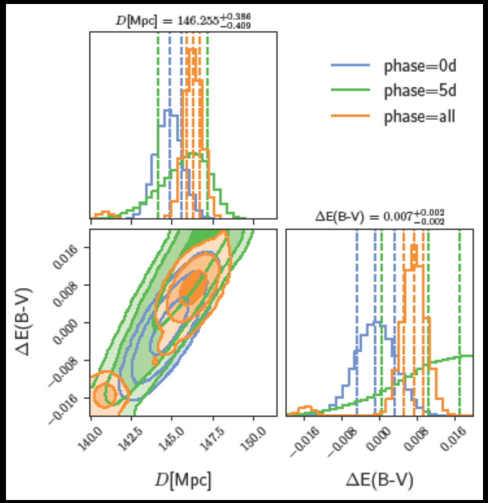
SN 2008bq at z = 0.034

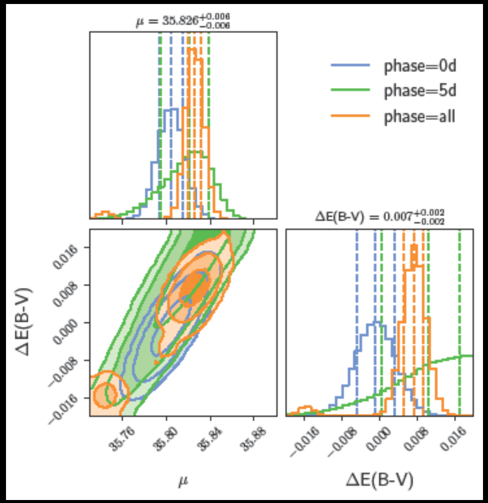


Comparison of the spectra of SN 2012bq at 0d and +5d with those of SN 2013dy at the same phases (left panels) and the 1σ, 2σ and 3σ contours of the probability distribution of μ (distance moduli) and ΔE(B-V) (difference in reddening) for the joint result of the two phases (lower panels)

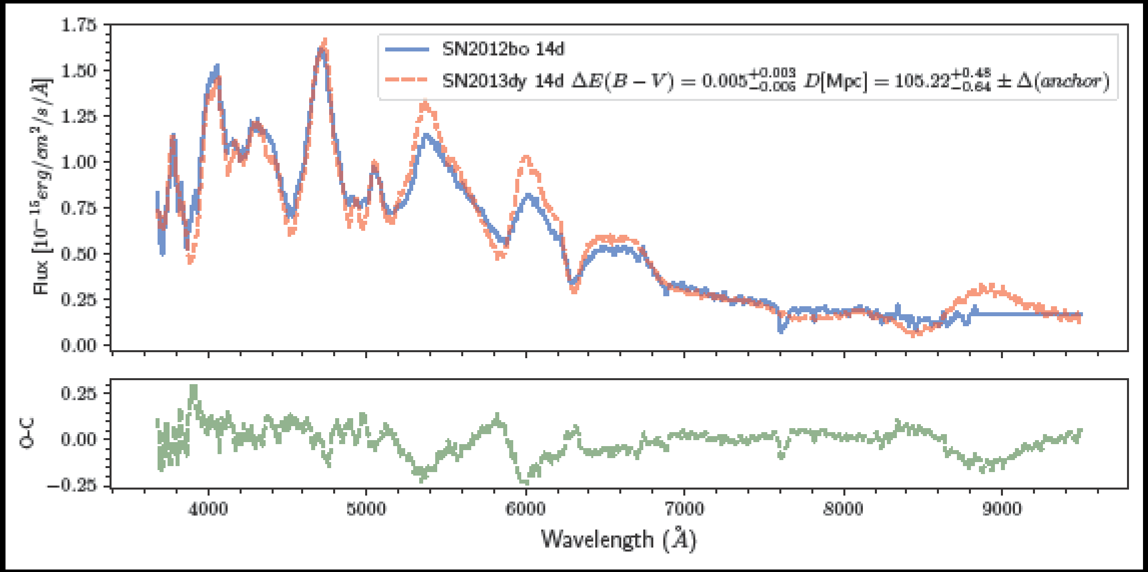
We obtain a distance modulus of μ = 35.826 ± 3.01 mag (for comparison, the PANTHEON+SH0ES value is μ = 35.728 ± 0.178 mag)

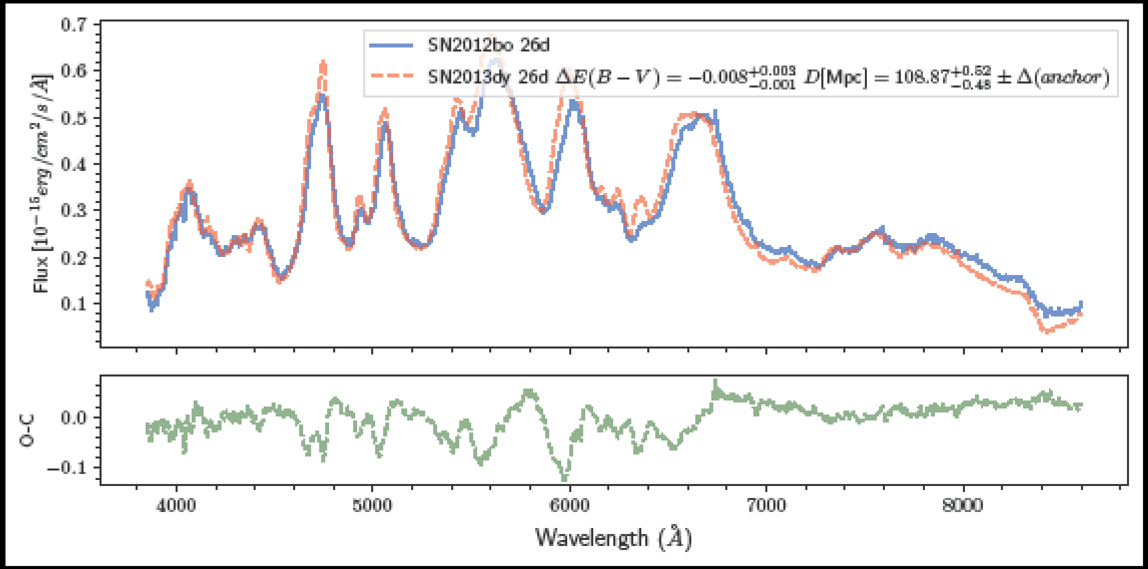






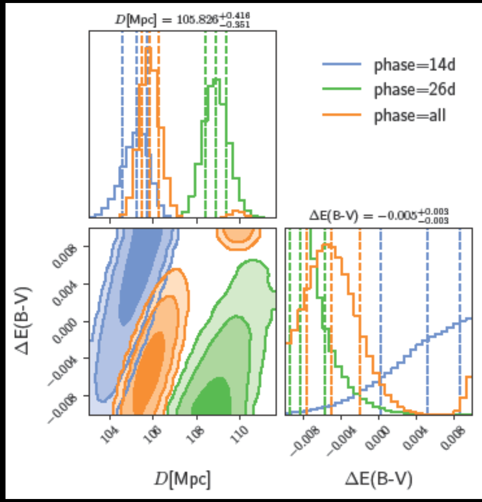
SN 2012bo at z = 0.026

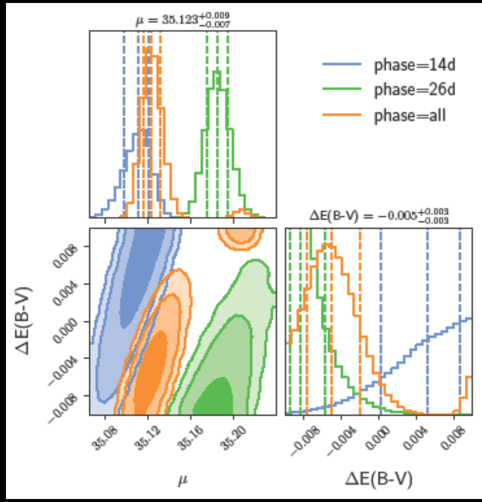




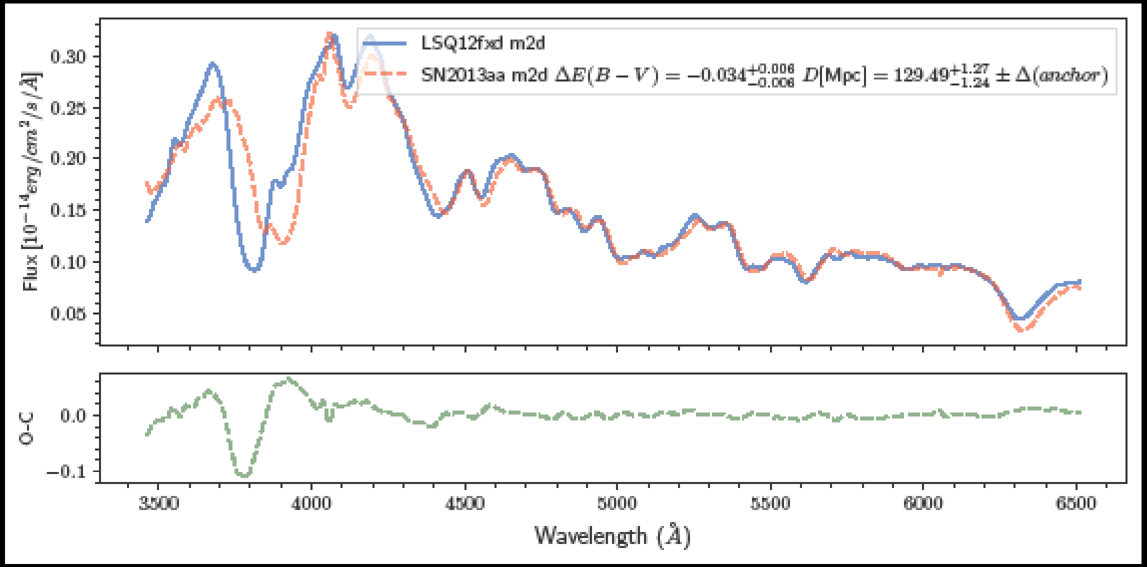
Comparison of the spectra of SN 2012bo at +14d and +26d with those of SN 2013dy at the same phases (left panels) and the 1σ, 2σ and 3σ contours of the probability distribution of μ (distance moduli) and ΔE(B-V) (difference in reddening) for the joint result of the two phases (lower panels)

We obtain a distance modulus of μ = 35.123 ± 0.223 mag



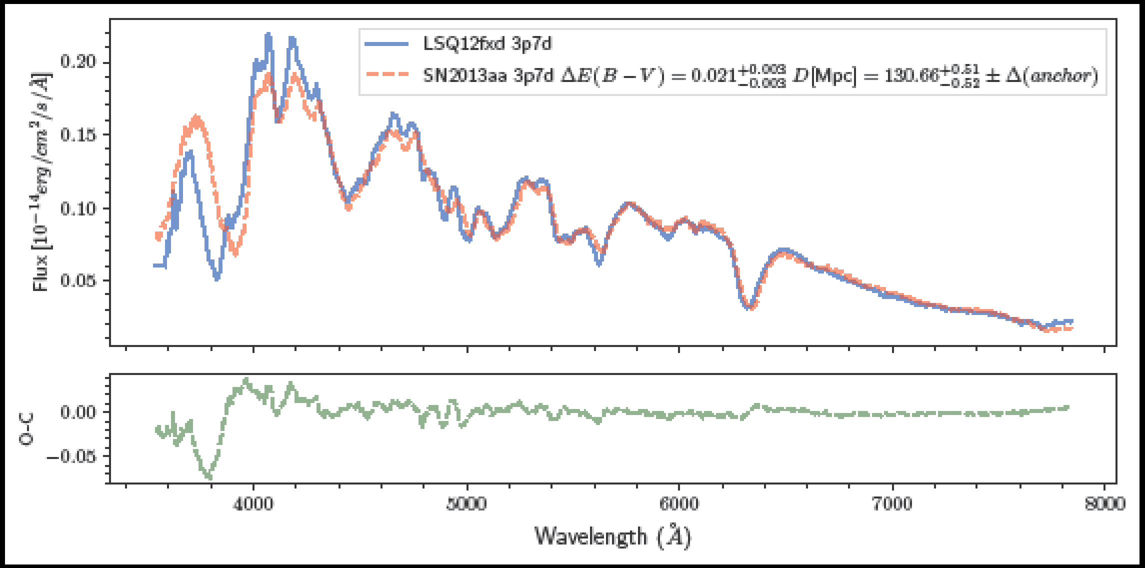


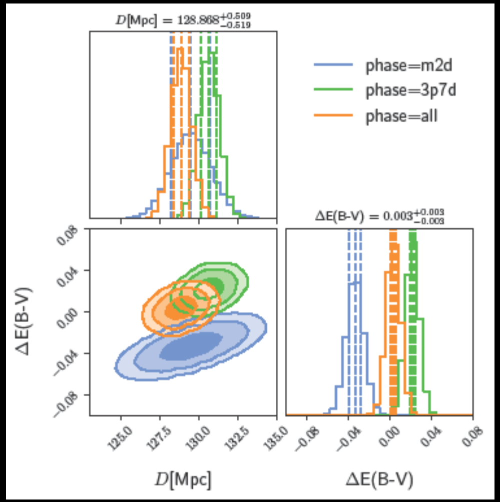
LSQ12fxd at z = 0.031

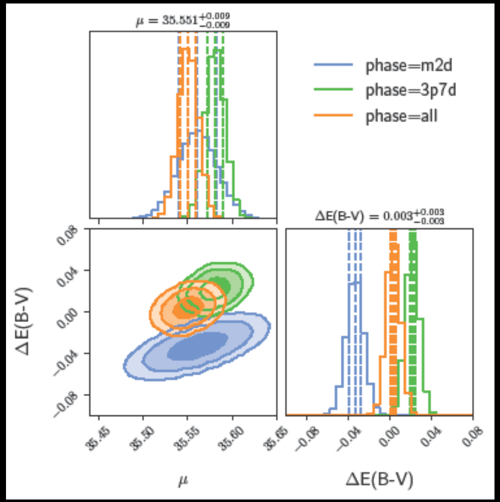


Comparison of the spectra of LSQ12fxd at -2d and +3.7d with those of SN 2013aa at the same phases (left panels) and the 1σ, 2σ and 3σ contours of the probability distribution of μ (distance moduli) and ΔE(B-V) (difference in reddening) for the joint result of the two phases (lower panels)

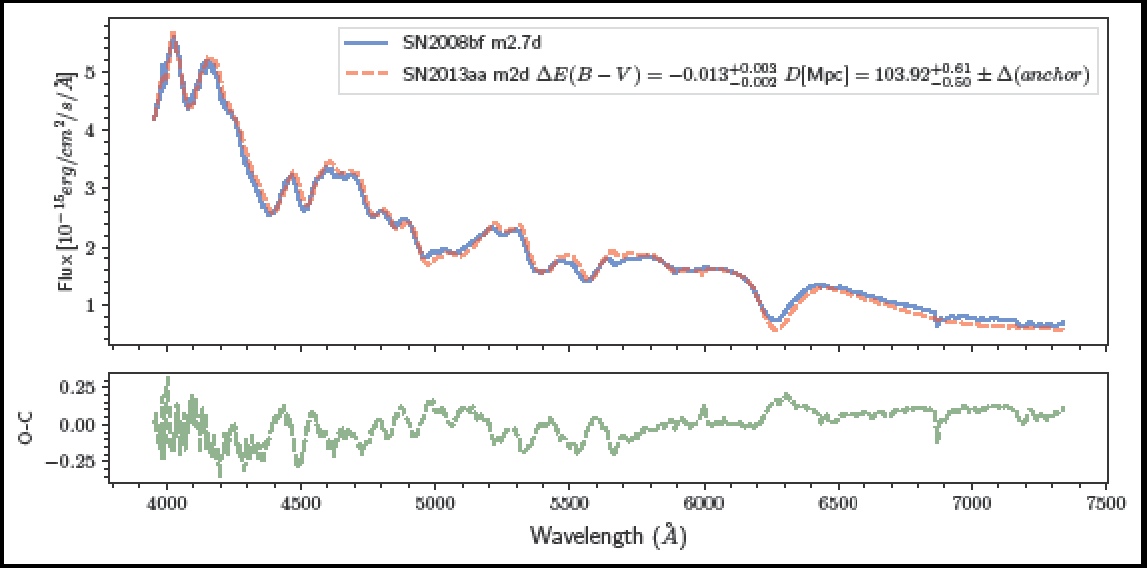
We obtain a distance modulus of μ = 35.551 ± 2.68 mag

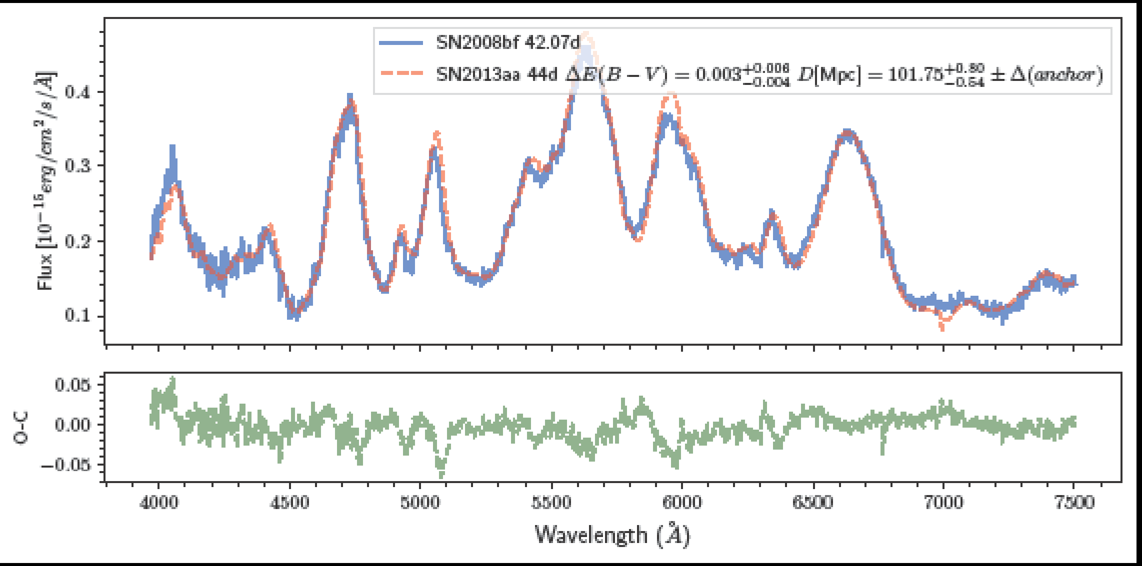






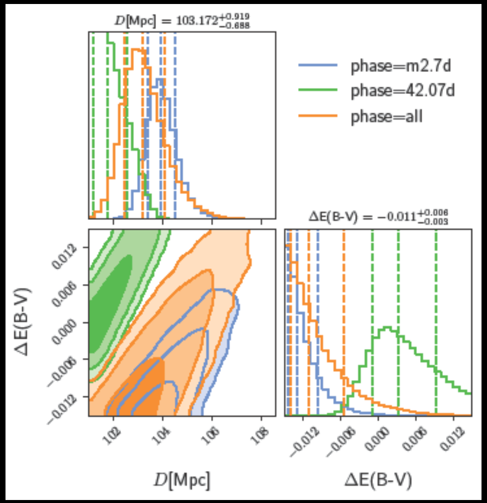
SN 2008bf at z = 0.025

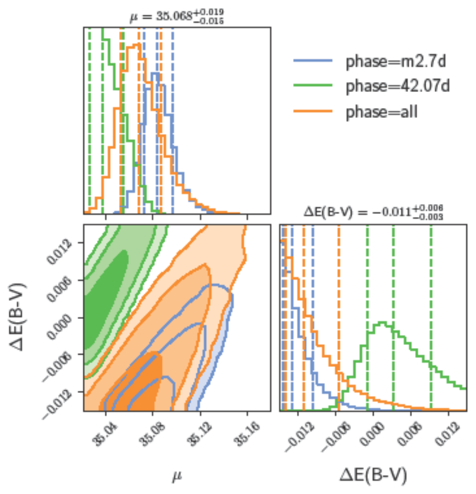




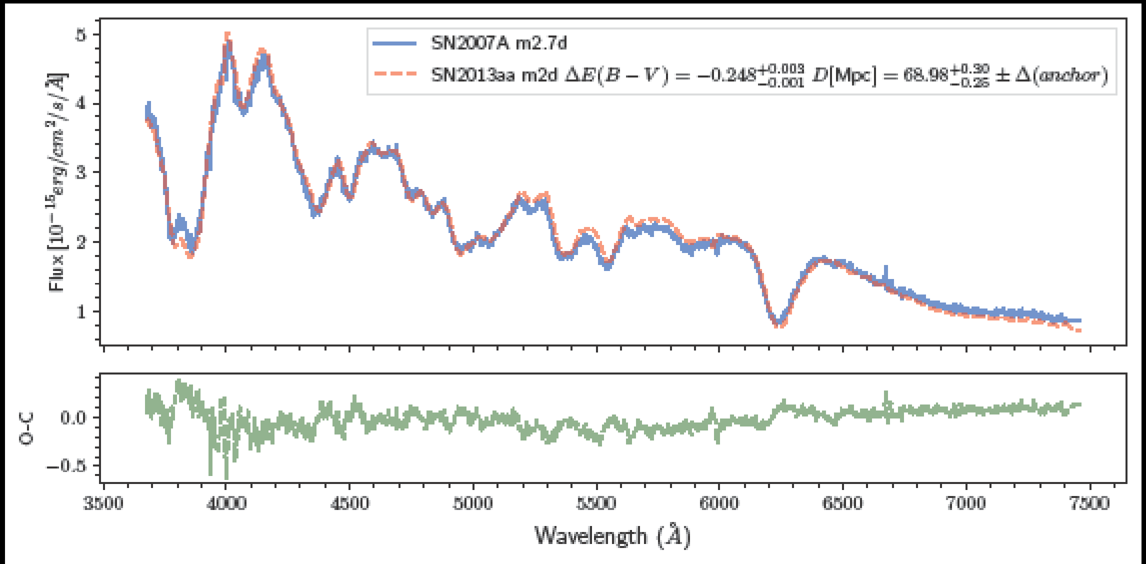
Comparison of the spectra of SN 2008bf at -2.7d and +42.07d with those of SN 2013aa at the same phases (left panels) and the 1σ, 2σ and 3σ contours of the probability distribution of μ (distance moduli) and ΔE(B-V) (difference in reddening) for the joint result of the two phases (lower panels)

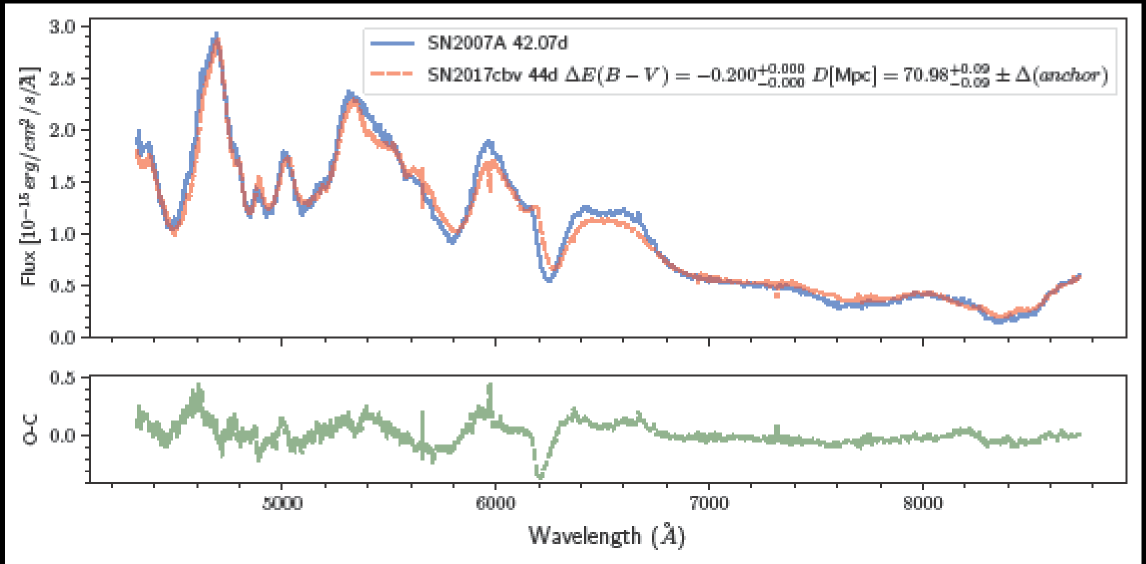
We obtain a distance modulus of μ = 35.068 ± 0.106 mag (for comparison, PANTHEON+SH0ES values are μ = 35.106 ± 0.235 mag,
μ = 35.052 ± 0.231 mag or μ = 34.889 ± 0.233 mag, depending on the sample used)





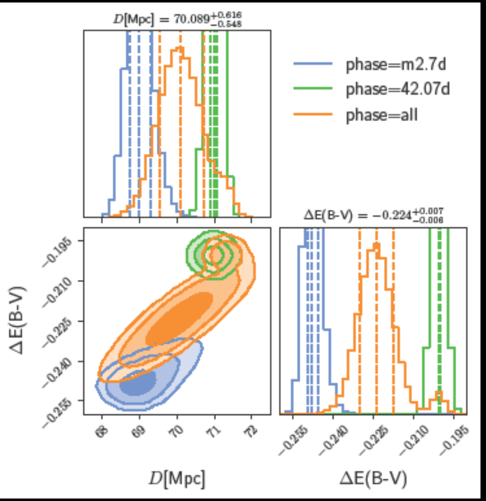
SN 2007A at z = 0.016

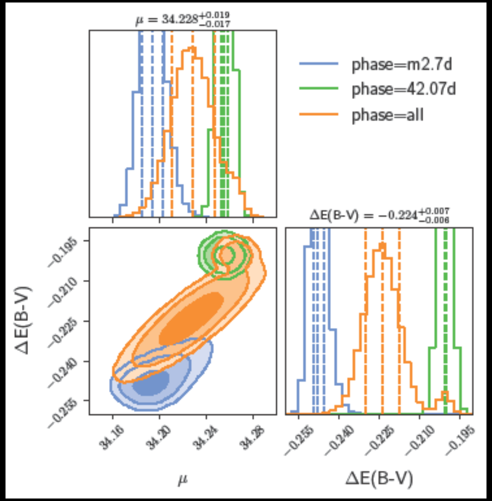




Comparison of the spectrum of SN 2007A at -2.7d with that of SN 2013aa (upper left panel) and at +42.07d with that of SN 2017cbv (lower left panels), and the 1σ, 2σ and 3σ contours of the probability distribution of μ (distance moduli) and ΔE(B-V) (difference in reddening) for the joint result of the two phases (lower panels)

We obtain a distance modulus of $\mu = 34.228 \pm 0.084$ mag (for comparison, SH0ES values are $\mu = 34.465 \pm 0.358$ mag or $\mu = 34.534 \pm 0.341$ mag, depending on the sample used)





Standard method: M_B^{max} and H_0

$$\mu_{obs} = m_x - P^0 + P^1(s_{BV} - 1) + P^2(s_{BV} - 1)^2 + \beta(B - V) + \alpha_M(\log_{10} M_*/M_\odot - M_0)$$

where μ_{obs} is the observed distance modulus, m_x is the peak magnitude in the *x* band and P^0 the absolute magnitude M_x of a SNIa with zero $(B - V)$ color, color stretch $s_{BV} = 1$ and in a host Galaxy with stellar mass $M = M_0$

P^1 is the linear coefficient and P^2 a quadratic coefficient in $(s_{BV} - 1)$; β is the slope of the color correction, *V* is the apparent peak magnitude at *V*, *K*-corrected, and α_M is the slope of the correlation between peak luminosity and host stellar mass M_*

The apparent magnitudes at maximum are computed by fitting the light curves with *SNooPy*, providing the time of maximum, the light-curve shape s_{BV}, and the magnitude at maximum for each filter.

These quantities are then provided as inputs to a *Markov Chain Monte Carlo* sampler that simultaneously provides the corrected magnitudes for all the correction factors P^1, P^2, α_M and β.

The *MCMC* sampler then provides the corrected magnitudes, as well as the full covariance matrix, which is used when determining H_0 and its errors

p p1 p2 rv alpha sig vel h0
-19.12251628497113 -0.9814276880269512 -0.6360363744996469 2.970925930928784 -
0.005399687786785605 0.17452111083486196 448.2695867666578 72.11500326091713

B_ceph_update3.csv

Using Cepheids as in the CCHP H0= 72.11

The H_0 tension

To test these parameterizations

$$m_X = m_B + \alpha x_1 + \beta c + \delta_{B,a} + \delta_{Host}$$

Modified Tripp formula, SH0ES Pantheon+

$$\mu(z, H_0, q_0) = 5\,\log_{10}\{\frac{(1-z_{hel})cz}{(1+z)H_0}(1+\frac{(1-q_0)}{2}z)\} + 25$$

CCHP

$$\mu_{\rm obs} = m_x - P^0 + P^1(s_{BV}-1) + P^2(s_{BV}-1)^2 + \beta(B-V) + \alpha_M(\log_{10}M_*/M_\odot - M_0)$$

where μ_{obs} is the observed distance modulus, m_x the peak magnitude in the x band and P^0 the absolute magnitude M_x of a SNIa with zero (B-V) color, color stretch $s_{BV} = 1$ and in a host galaxy with stellar mass $M = M_0$

Table 1: Comparison of distance moduli and H_0

This work			SH0ES		CCHP	
SN	μ	H_0	μ	H_0	μ	H_0
2012 bo	35.123±0.223	76.657±3.311	–	–	35.429	66.579
2008bq	35.826±0.301	72.467±3.506	35.728±0.178	74.797±3.004	35.861	71.291
2008bz	37.215±0.303	69.378±4.453	37.163±0.124	71.072±0.429	37.151	71.466
LSQ12fxd	35.551±0.268	73.845±3.402	–	–	35.610	72.546
2008bf	35.068±0.106	74.224±2.235	35.052±0.231	74.767±3.794	34.995	76.755
2007A	34.228±0.084	71.424±1.790	34.534±0.342	64.061±5.761	34.292	69.357

The H_0 tension

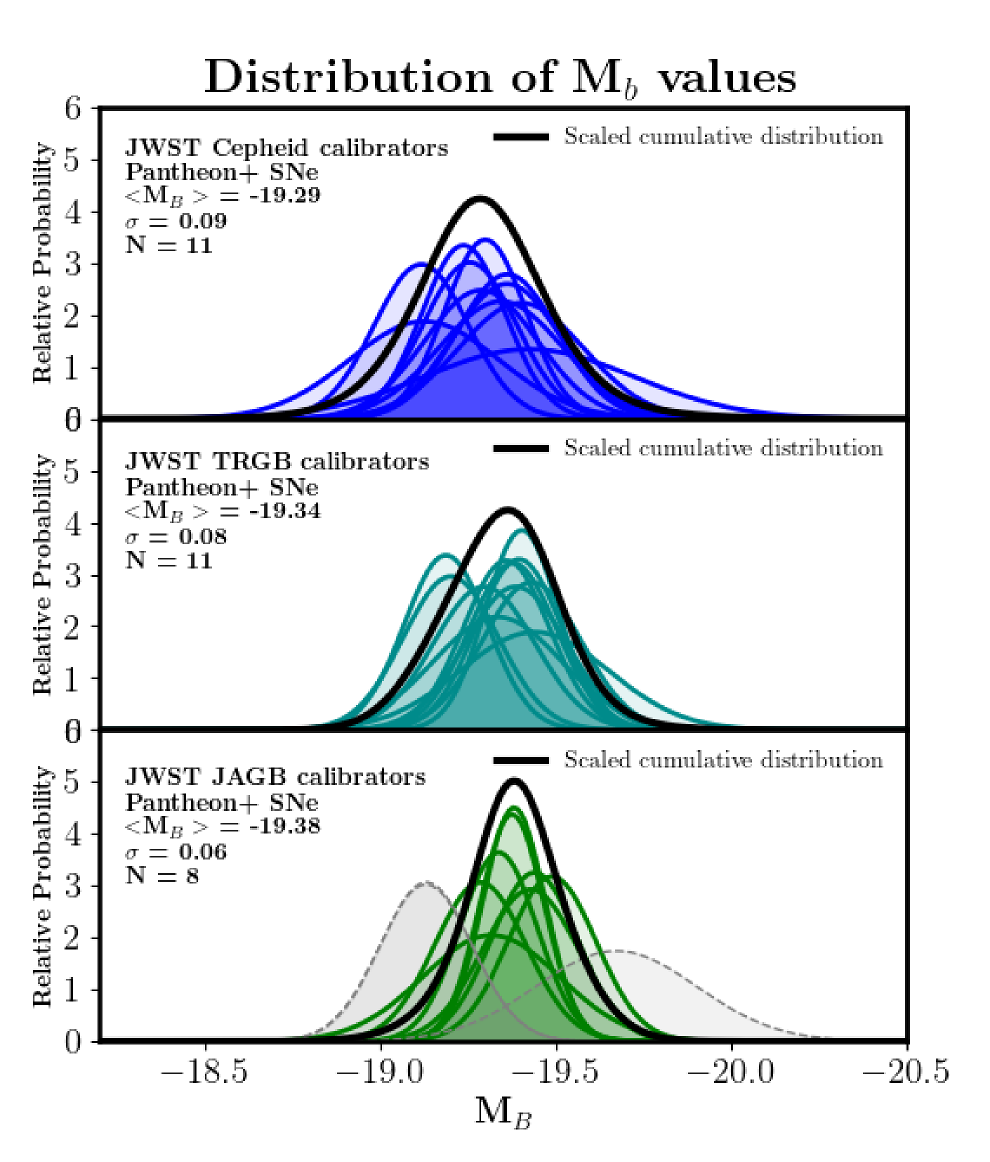
Results recently obtained with the JWST

We see the distribution of M_B values from different distance calibrators

$<M_B>$ = -19.29 mag (JWST Cepheids)

$<M_B>$ = -19.34 mag (JWST TRGB)

$<M_B>$ = -19.38 mag (JWST JAGB)

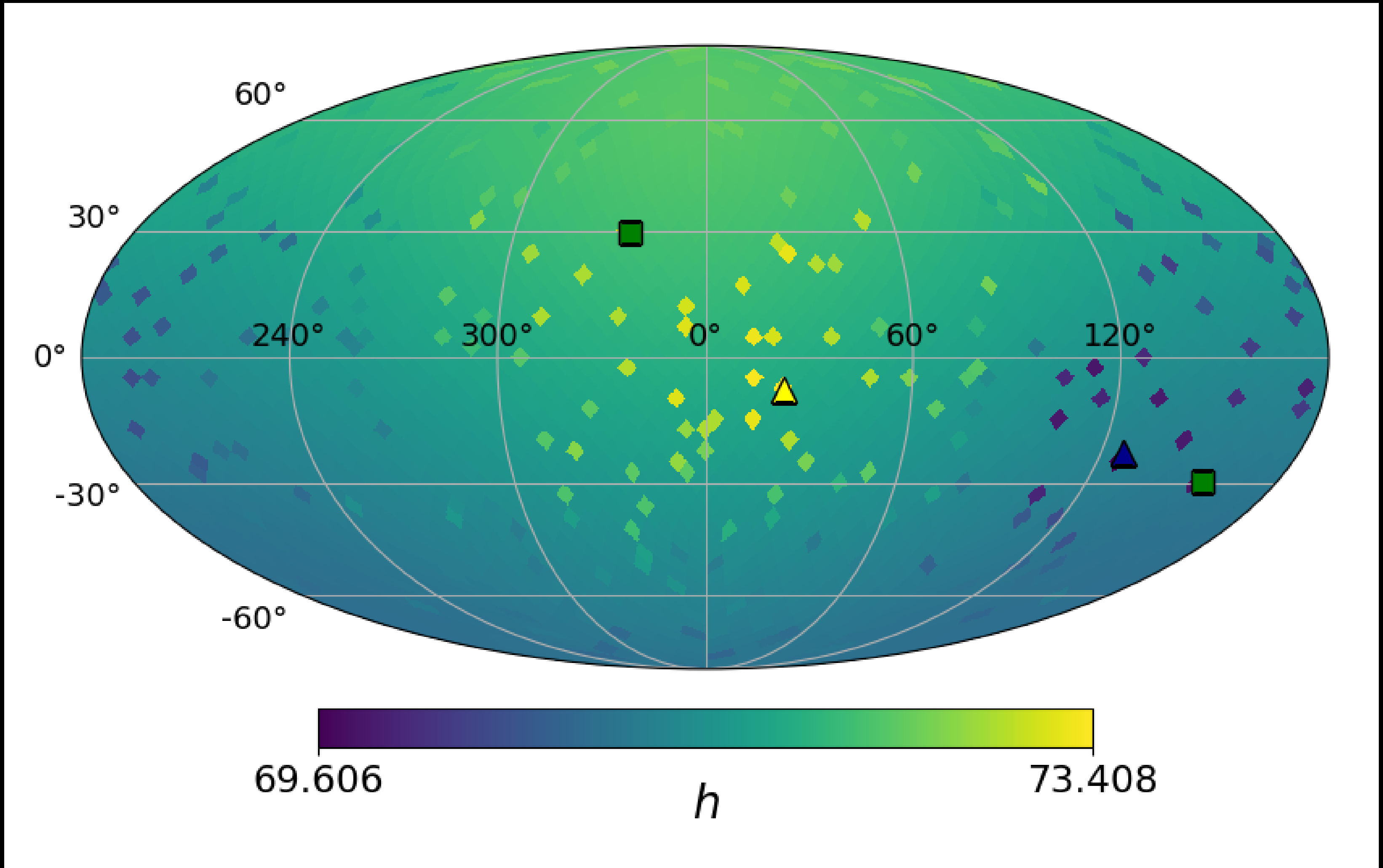


(from Freedman et al. 2024)

Is there any anisotropy causing the scatter?

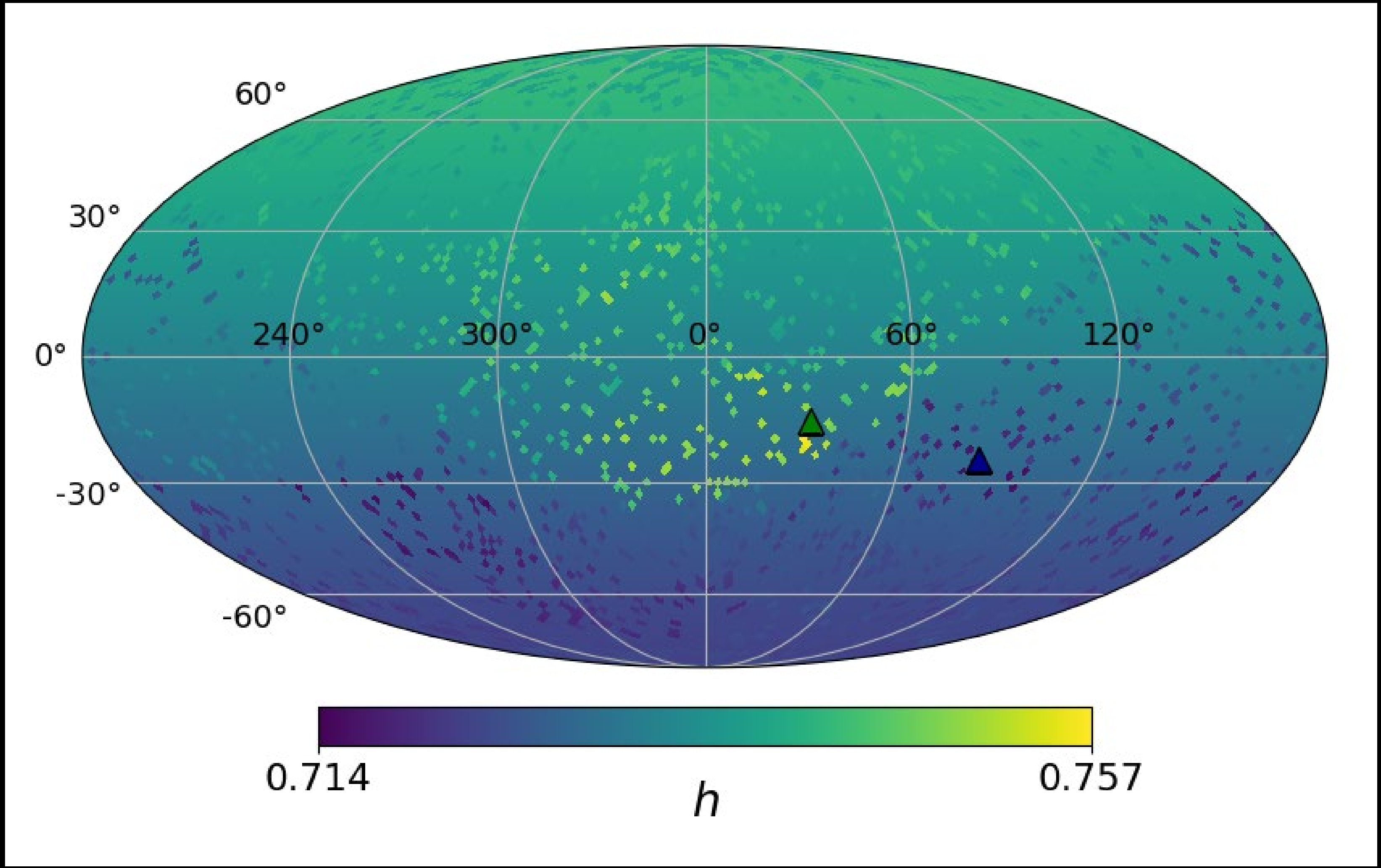
We generate 1000 randomly distributed directions (l,b) to identify a prefered direction

Hemisphere comparison method to test anisotropy in the CSP I sample

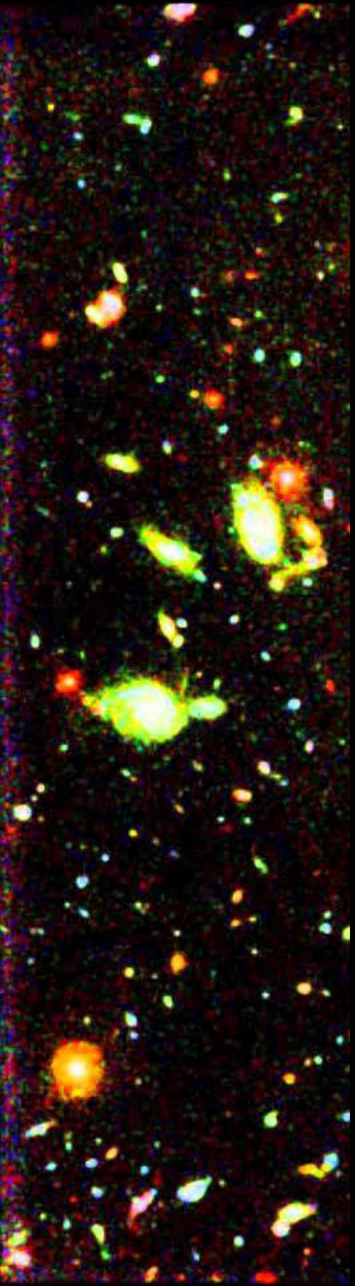


A. Quintana-Estellés & RL 2025

Region fitting method applied to Pantheon+ to test anisotropy



Quintana-Estellés & RL , 2025



Conclusions

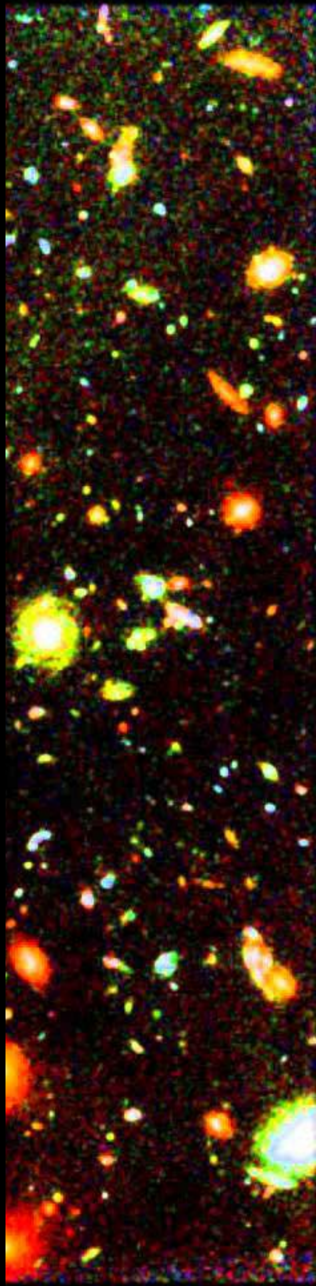
- Similar distances to individual SNe Ia at z ~ 0.02 as Pantheon+ SH0ES , in 1 step , from SNe Ia at d < 15 Mpc

- Some individual distances are wrong both in the Pantheon+ sample and in the CCHP . This method detects them.

- Anchors SN 2011fe in M101 and SN 2013aa/SN2017cbv in NGC 5643 Agreement on SN 2011fe from Cepheids and TRGB (great anchor)

- We take large error bars for the other anchors and carry their error up to z > 0.02 (H0 ~73± 3.23 km/s/Mpc)

- Possibility to access the ZTF data for more accurate distances with this method.



SN 2013aa/SN 2017cbv in NGC 5643

$\mu = 30.48 \pm 0.065$ mag (D = 12.47 ± 0.37 Mpc)

(Ruiz-Lapuente & González Hernández 2024)

Other distance determinations are:

From Cepheids:

$\mu = 30.570 \pm 0.050$ mag (D = 13.00 ± 0.30 Mpc) (Riess et al. 2022)

$\mu = 30.518 \pm 0.033$ mag (D = 12.69 ± 0.20 Mpc) (Riess et al. 2024a)

$\mu = 30.52 \pm 0.02$ mag (D = 12.70 ± 0.12 Mpc) (*JWST +HST* Riess et al. 2024b)

$\mu = 30.51 \pm 0.02$ mag (D = 12.64 ± 0.12 Mpc) (Freedman et al. 2024)

Consistent distance scale!!

From TRGB:

$\mu = 30.48 \pm 0.1$ mag (D = 12.47 ± 0.59 Mpc) (Hoyt et al. 2021)

$\mu = 30.42 \pm 0.07$ mag (D = 12.13 ± 0.40 Mpc (Anand et al. 2024)

$\mu = 30.61 \pm 0.07$ mag (D = 13.24 ± 0.42 Mpc) (Freedman et al. 2024) ?

$\mu = 30.59 \pm 0.04$ mag (D = 13.12 ± 0.24 Mpc) (Freedman et al. 2024)

Light curve rate of decline and supernova of the CN subtype

Supernova	Δm_{15} (B) [mag]	s_{BV}^{D}	$pW1$ (Ca II H&K) [Å]	$pW5$ (S II W) [Å]	$pW6$ (Si II 5972) [Å]	$pW7$ (Si II 6355) [Å]
SN 2011fe	1.07±0.06	0.919±0.004	111±1	74±1	16.0±0.5	98±1
SN 2013aa	0.96±0.01	1.11±0.02	74±1	67±1	10.0±0.5	84±1
SN 2017cbv	0.96±0.02	1.11±0.03	64±1	69±1	10.0±0.5	76±1

Supernova	$\Re_{Si}$
SN 2011fe	0.23±0.05
SN 2013aa	0.10±0.05
SN 2017cbv	0.13±0.05

(from R-L & G H 2024: ApJ 977, 180)