On the location of dust in Type Ia supernovae

Mattia Bulla

Ariel Goobar, Suhail Dhawan,
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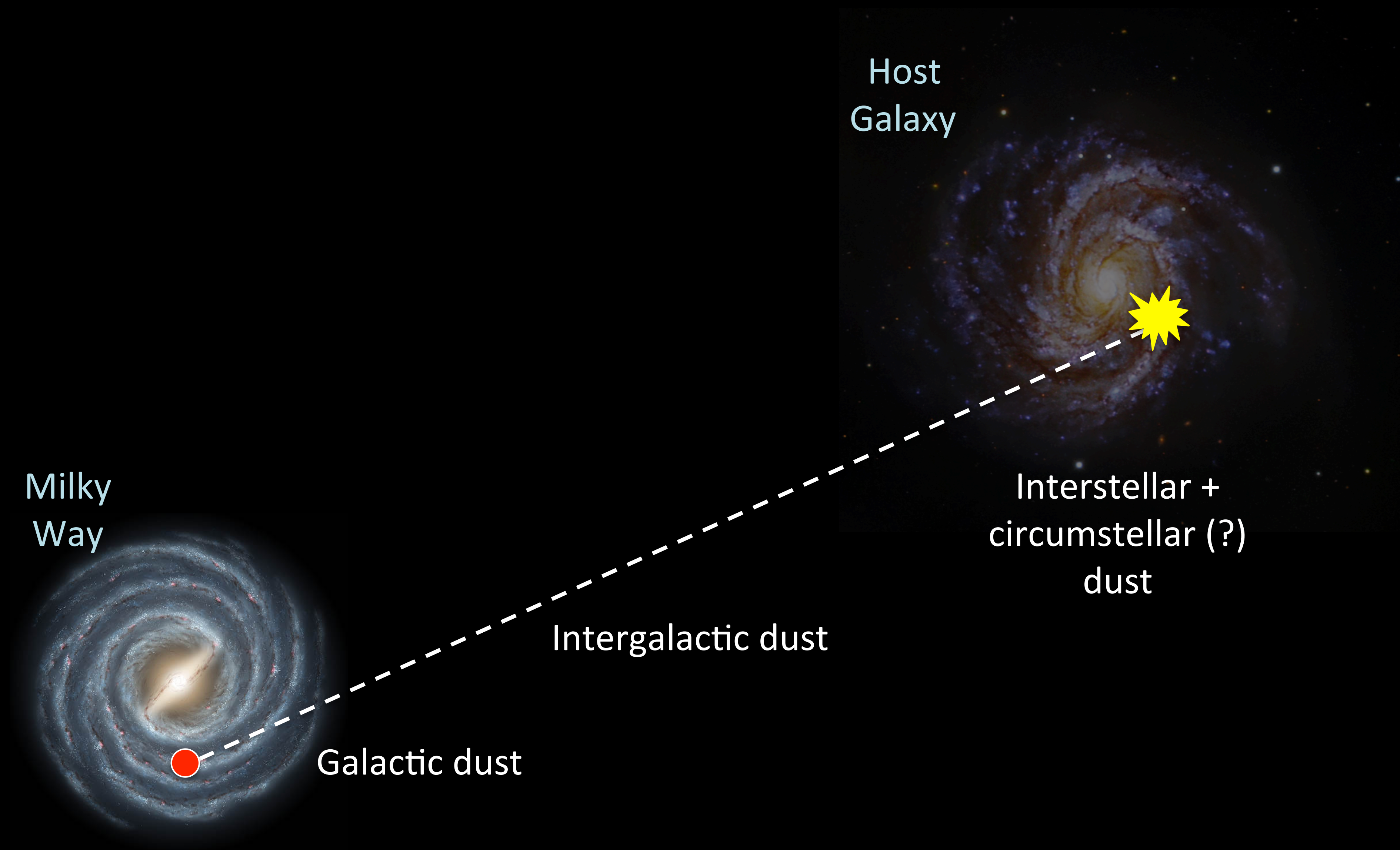
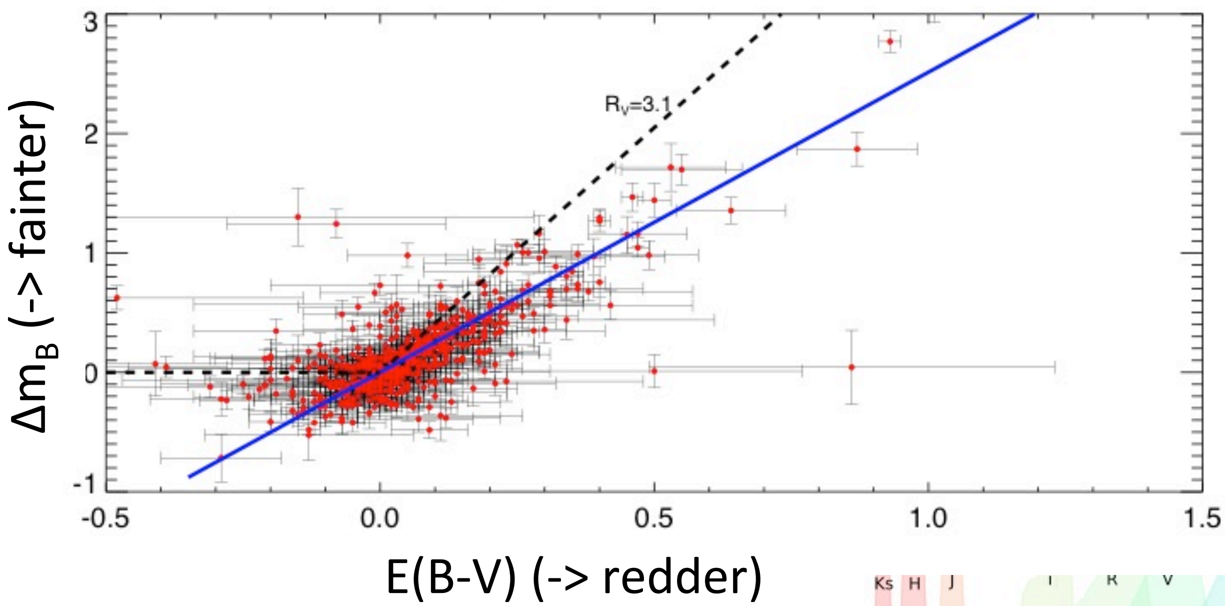
Bulla, Goobar, Amanullah, Feindt & Ferretti, 2018, MNRAS, 473, 1918
Bulla, Goobar and Dhawan, 2018, submitted to MNRAS

New advances in NIR type Ia supernova science
Pittsburgh, 2018 April 11-13


Host
Galaxy
Milky
Way
Interstellar +
circumstellar (?)
dust
Intergalactic dust
Galactic dust

Properties of reddened Type Ia supernovae



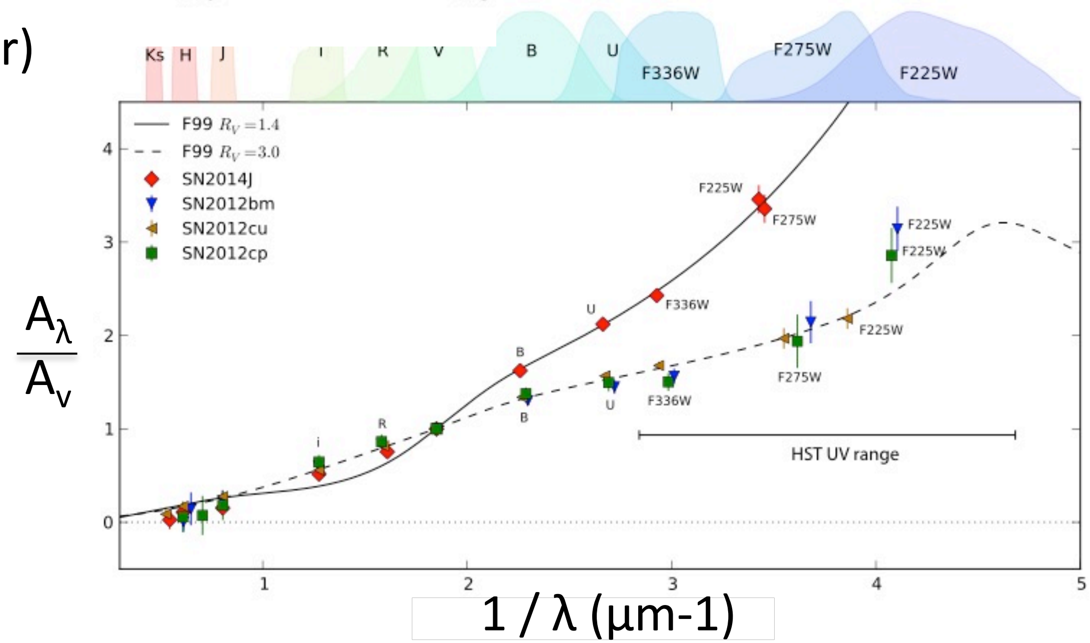
Sample study

Adapted from Amanullah+2010

Individual SNe

Amanullah+2015

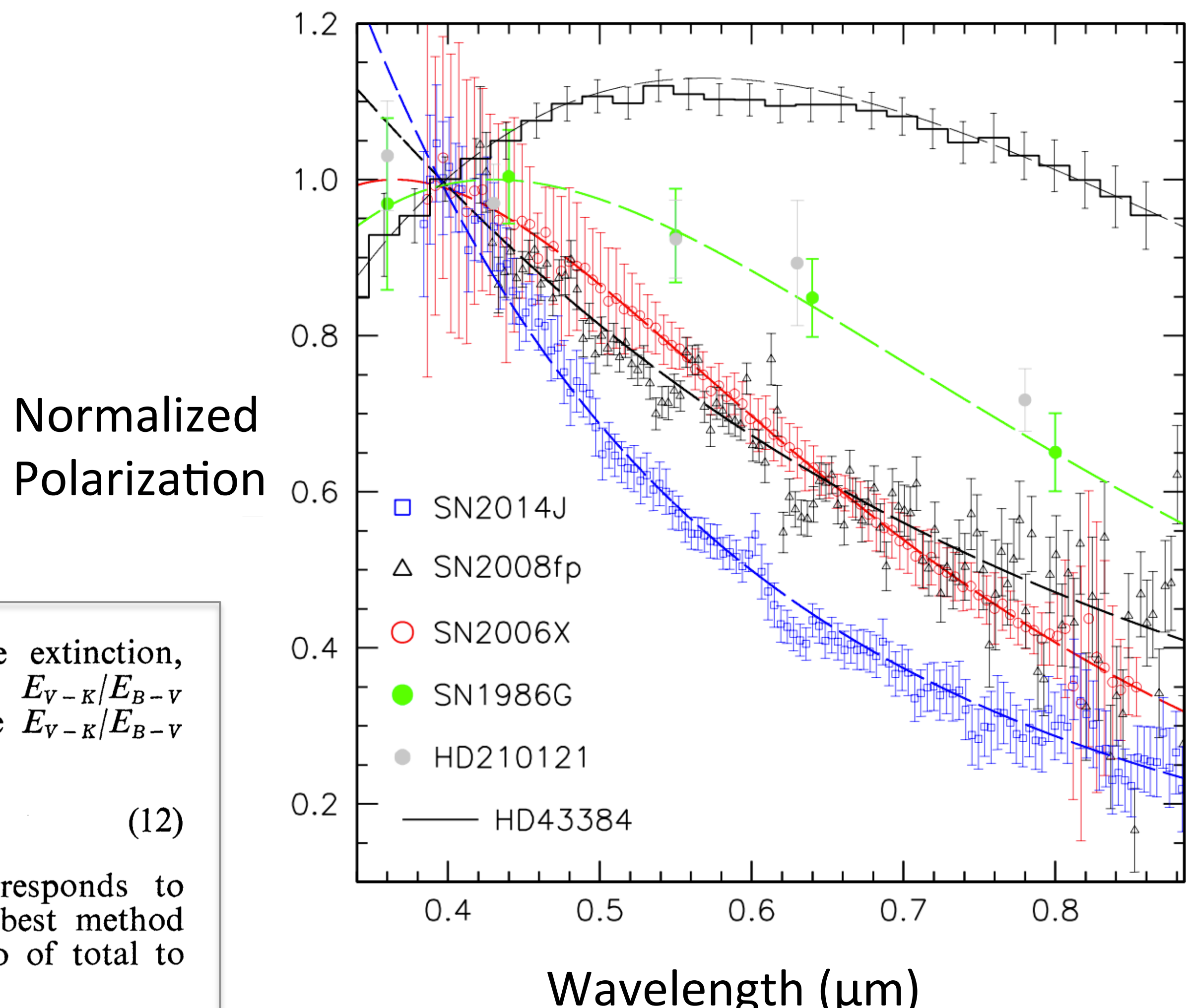
Low R_V



Properties of reddened Type Ia supernovae

Patat+2015, see also Zelaya+2017

Peculiar Polarization



Serkowski+1975

Since the ratio of total to selective extinction, $R = A_V/E_{B-V}$, equals approximately 1.1 E_{V-K}/E_{B-V} (Carrasco *et al.* 1973), the straight line $E_{V-K}/E_{B-V} = 5.0\ \lambda_{max}$ in figure 8*a* indicates that

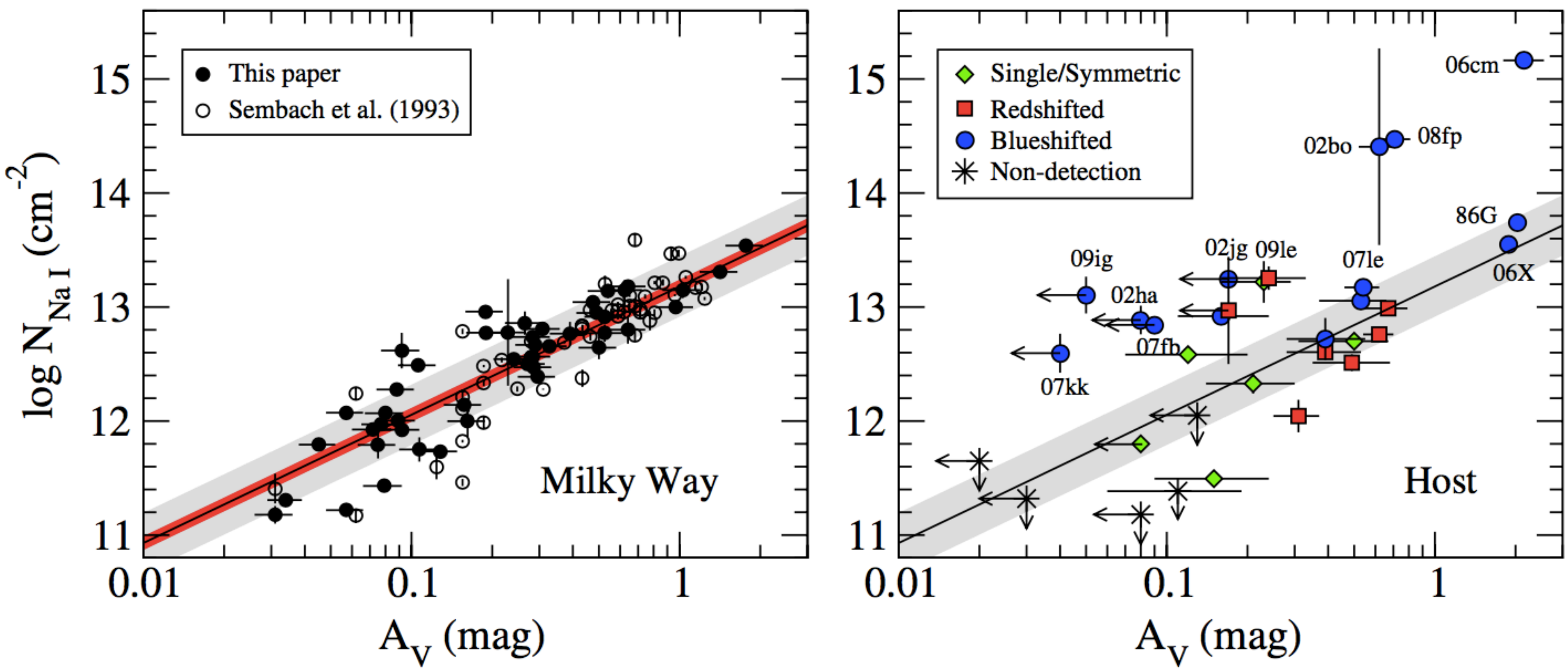
$$\boxed{R = 5.5\ \lambda_{max}\ ;} \qquad (12)$$

the median value $\lambda_{max} = 0.545\ \mu$ corresponds to $R = 3.0$. Measuring λ_{max} may be the best method for finding the local values of the ratio of total to selective extinction.

Properties of reddened Type Ia supernovae

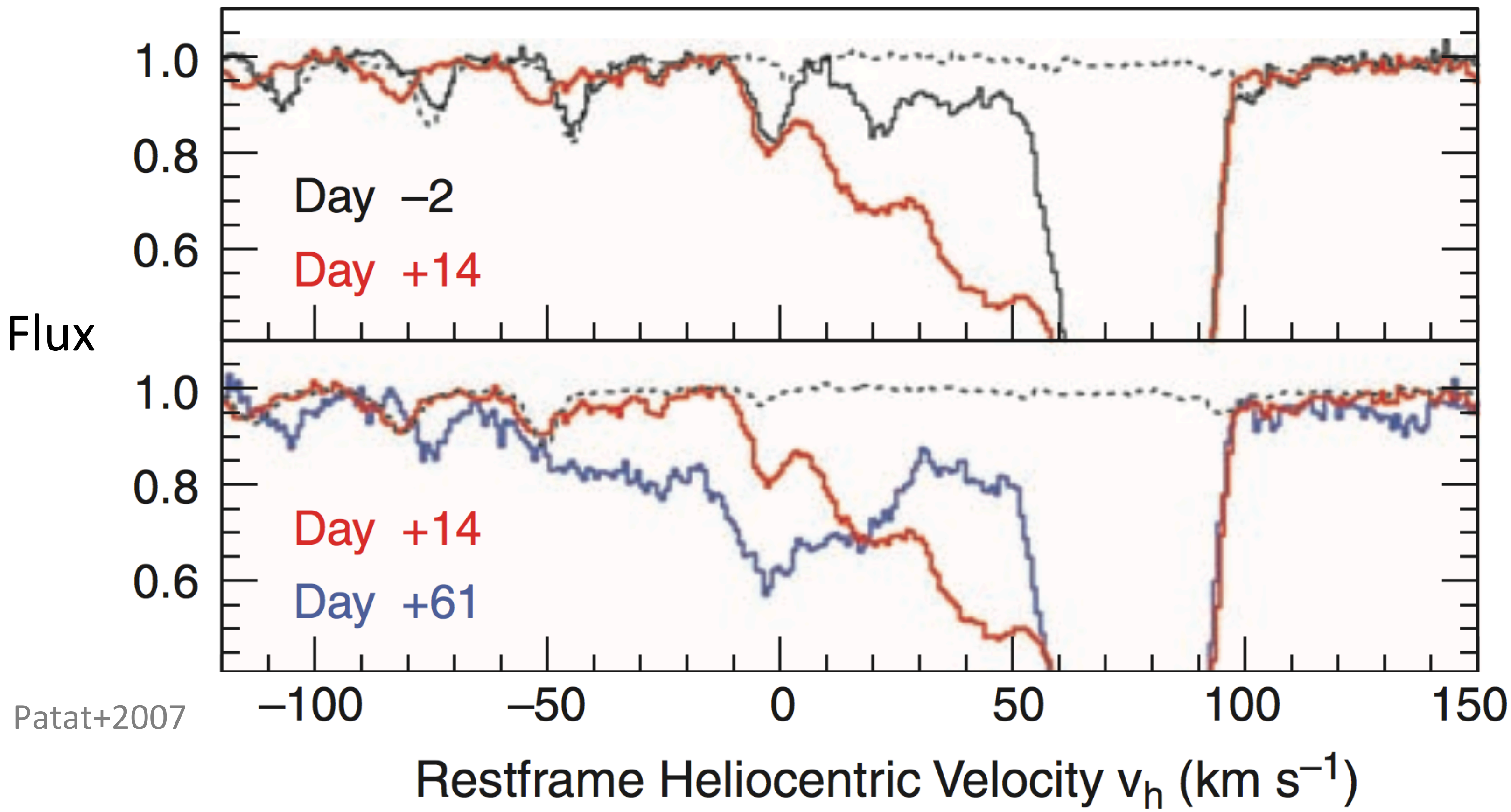
Unusually strong Na

Phillips+2013



Properties of reddened Type Ia supernovae

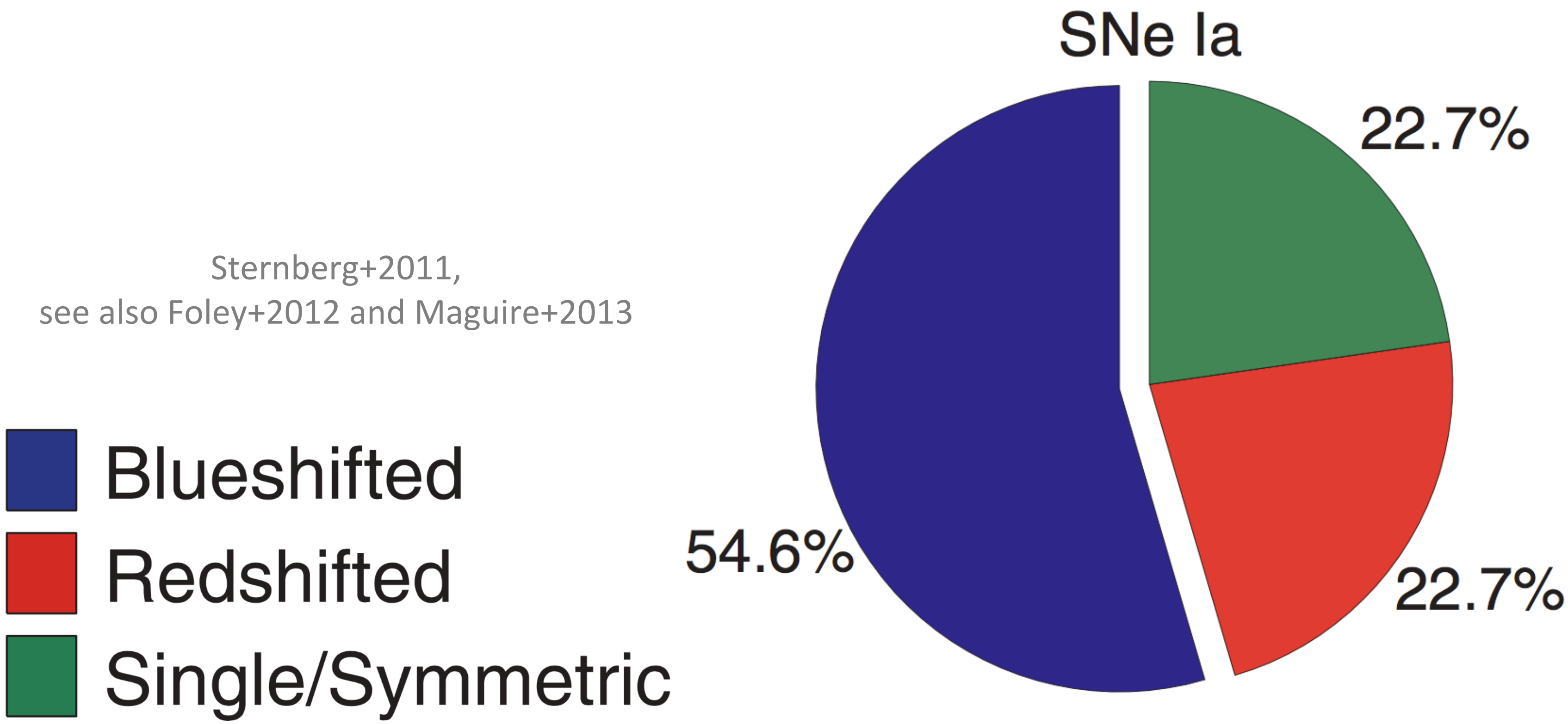
Time-variable Na and K



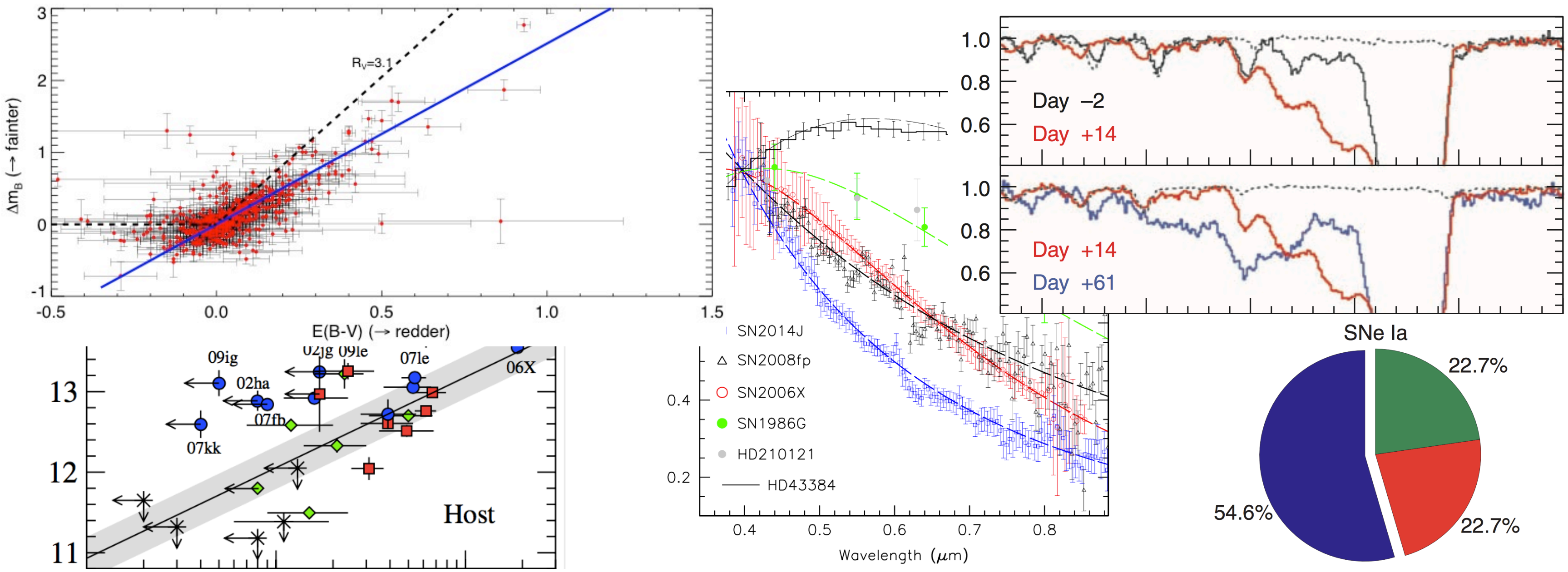
Patat+2007

Preference for blue-shifted Na

Sternberg+2011,
see also Foley+2012 and Maguire+2013

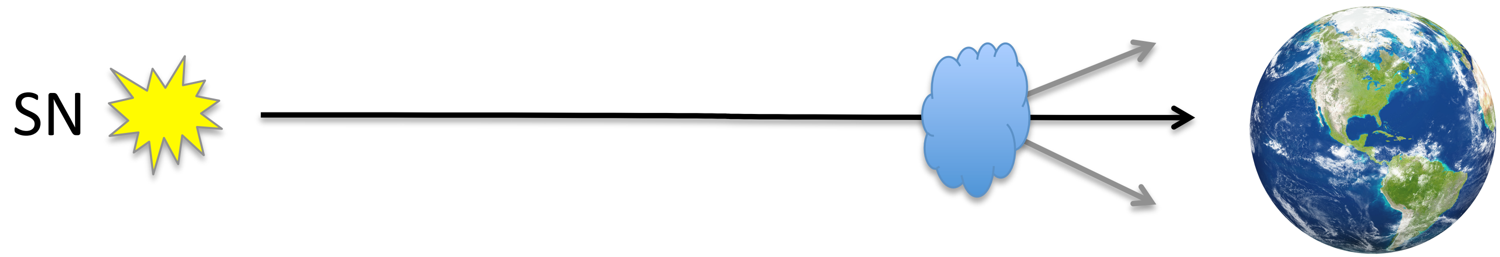


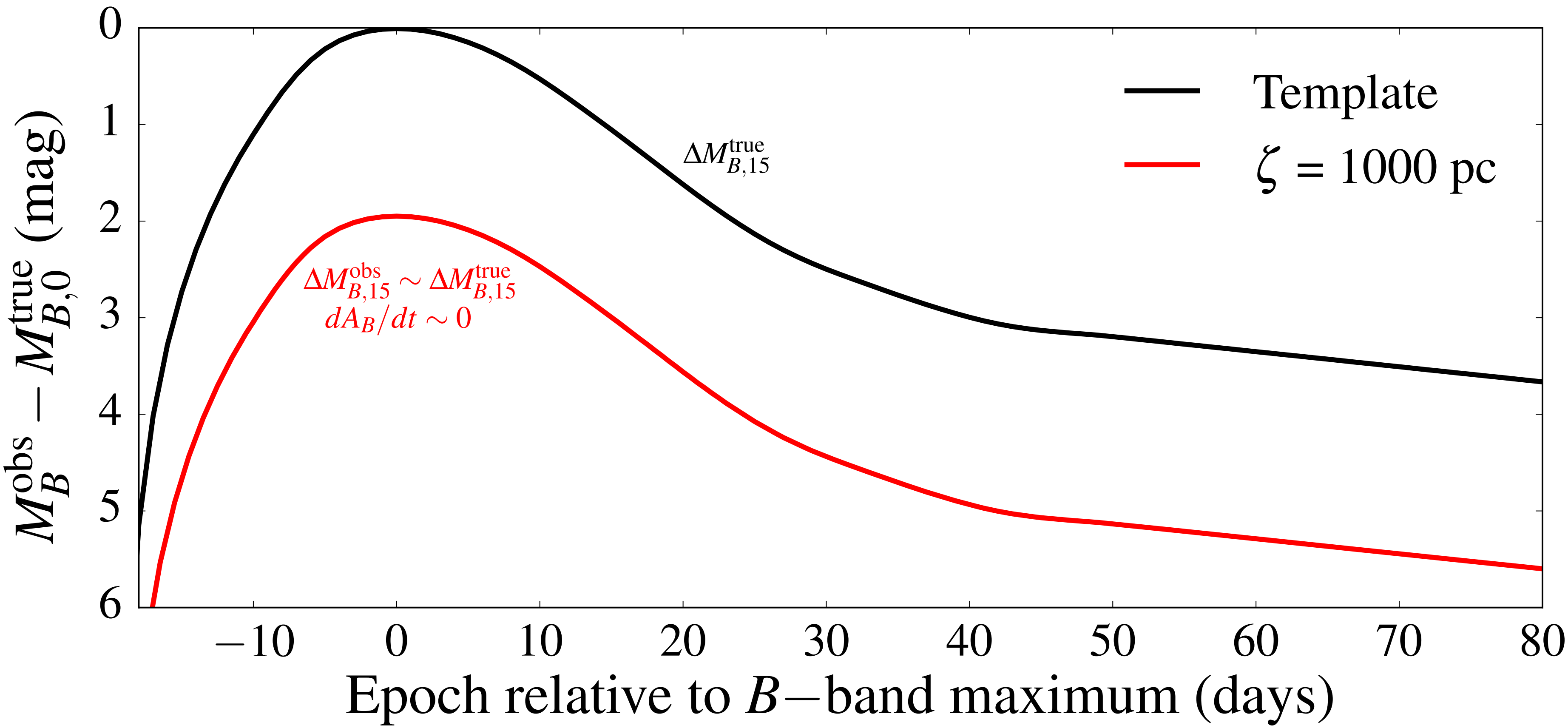
Circumstellar vs Interstellar material



OBSERVATION	INTERSTELLAR	CIRCUMSTELLAR
Low R_V (extinction + polarization)	Grains smaller than MW	Multiple scattering (Wang 2005, Goobar 2008)
Unusually strong Na I D	?	? Phillips+2013 for possible interpretations
Blue-shifted absorption features	?	Outflowing material
Variable absorption features	Geometric effects	Ionization/recombination effects (Patat+2007)

Estimating dust location from photometry





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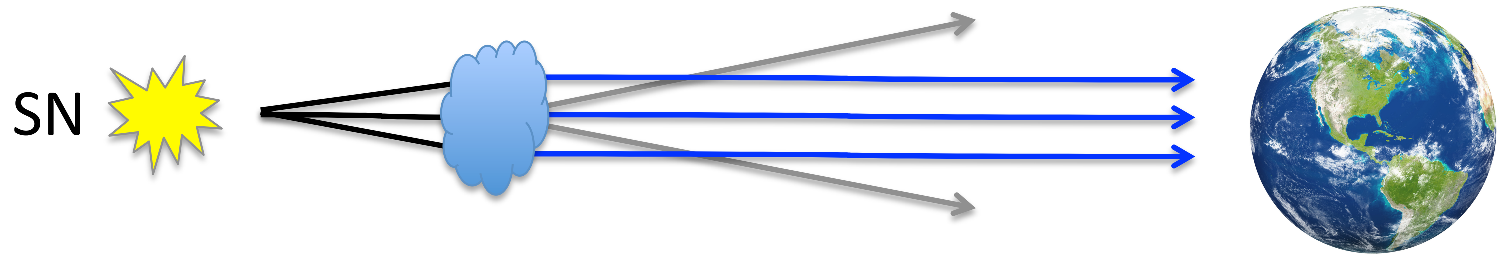
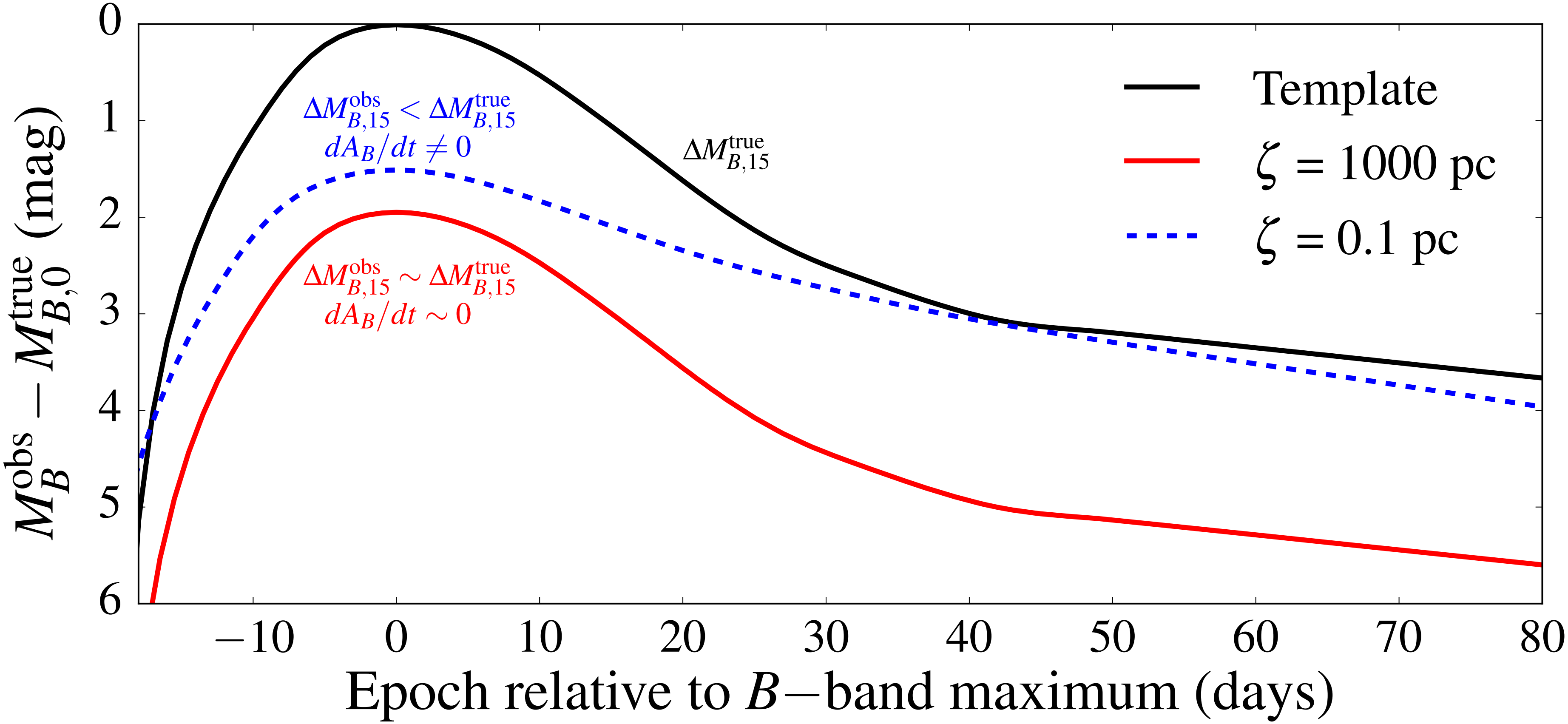
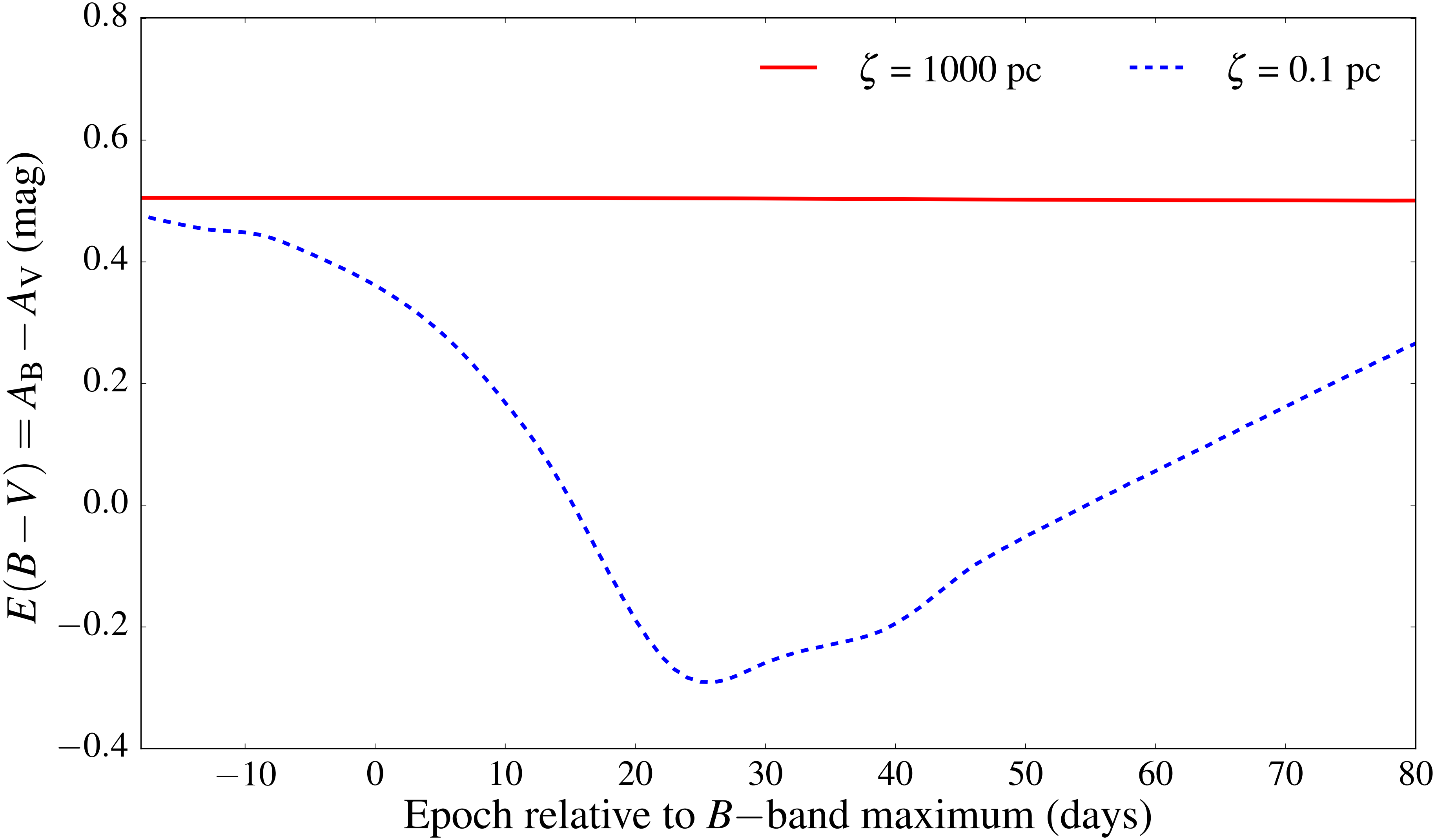




Estimating dust location from color evolution



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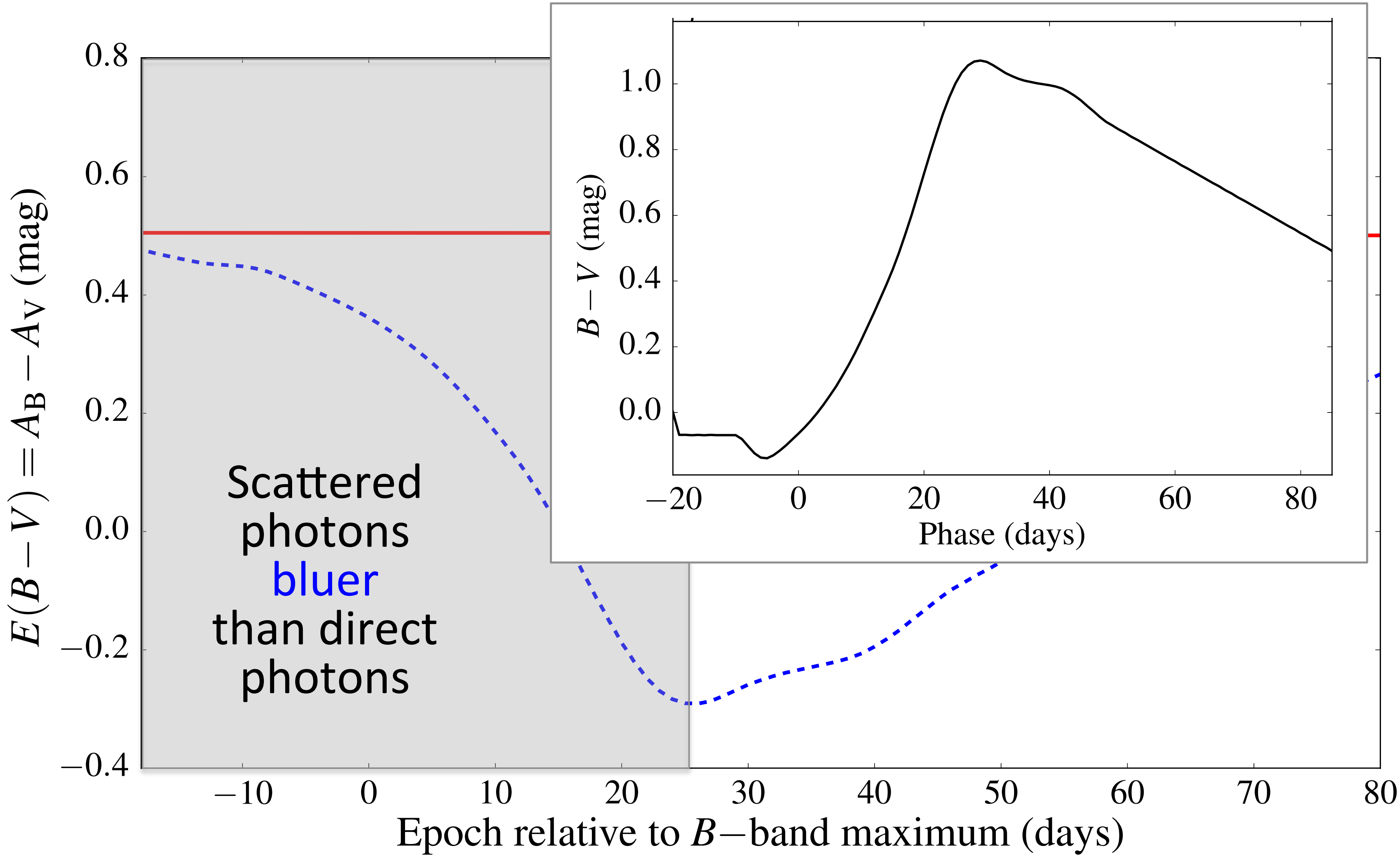
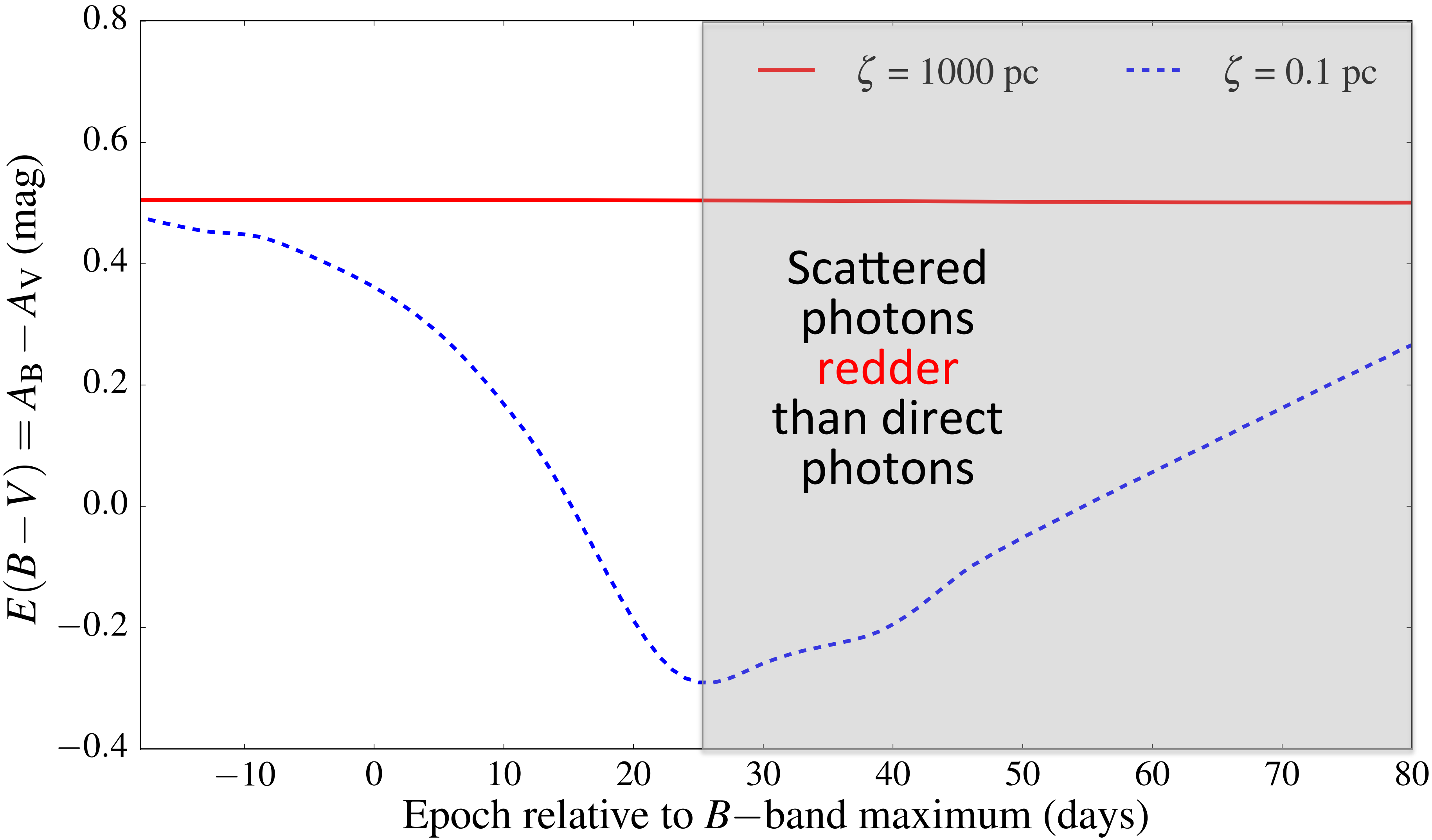


Estimating dust location from color evolution



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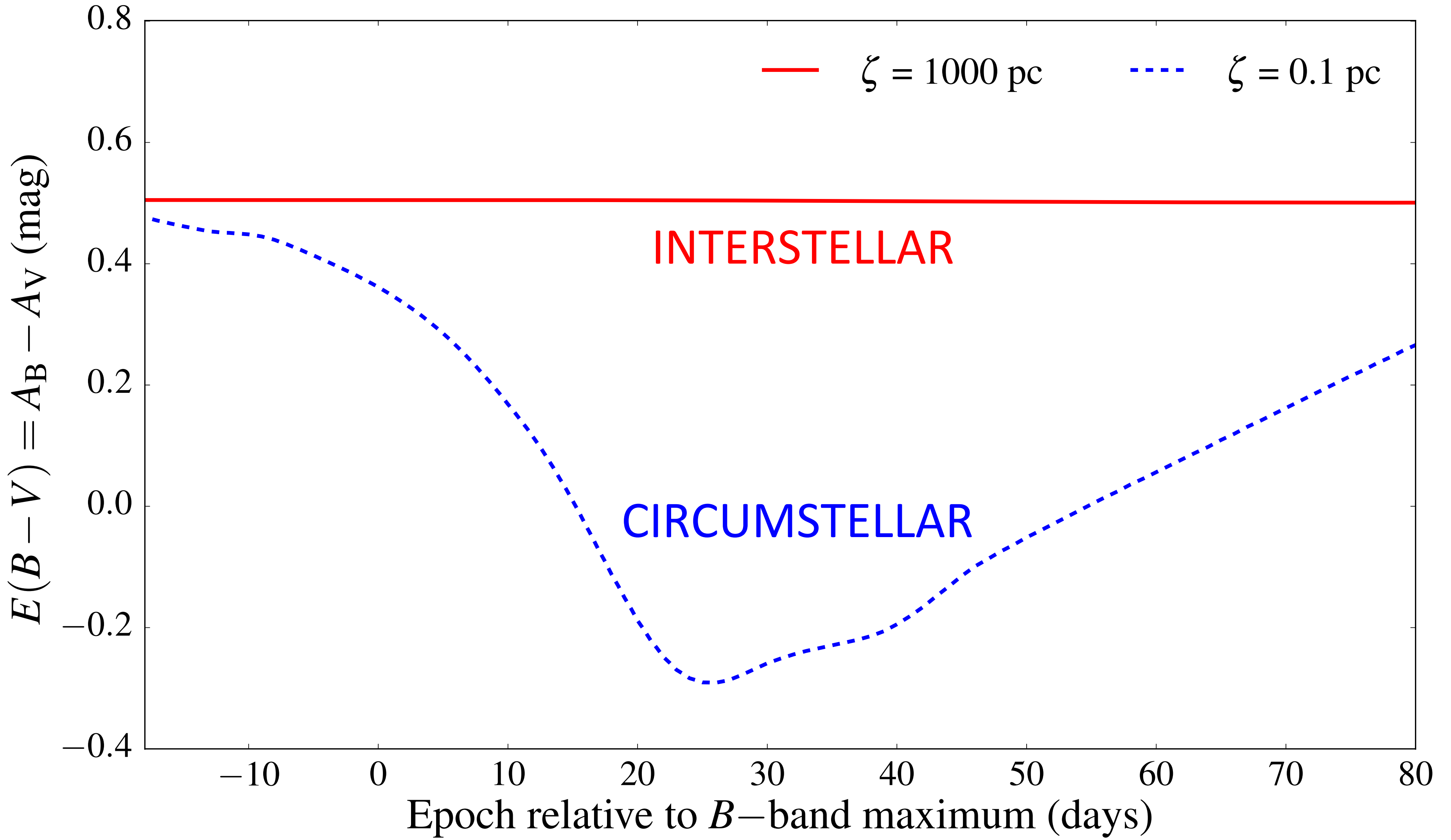
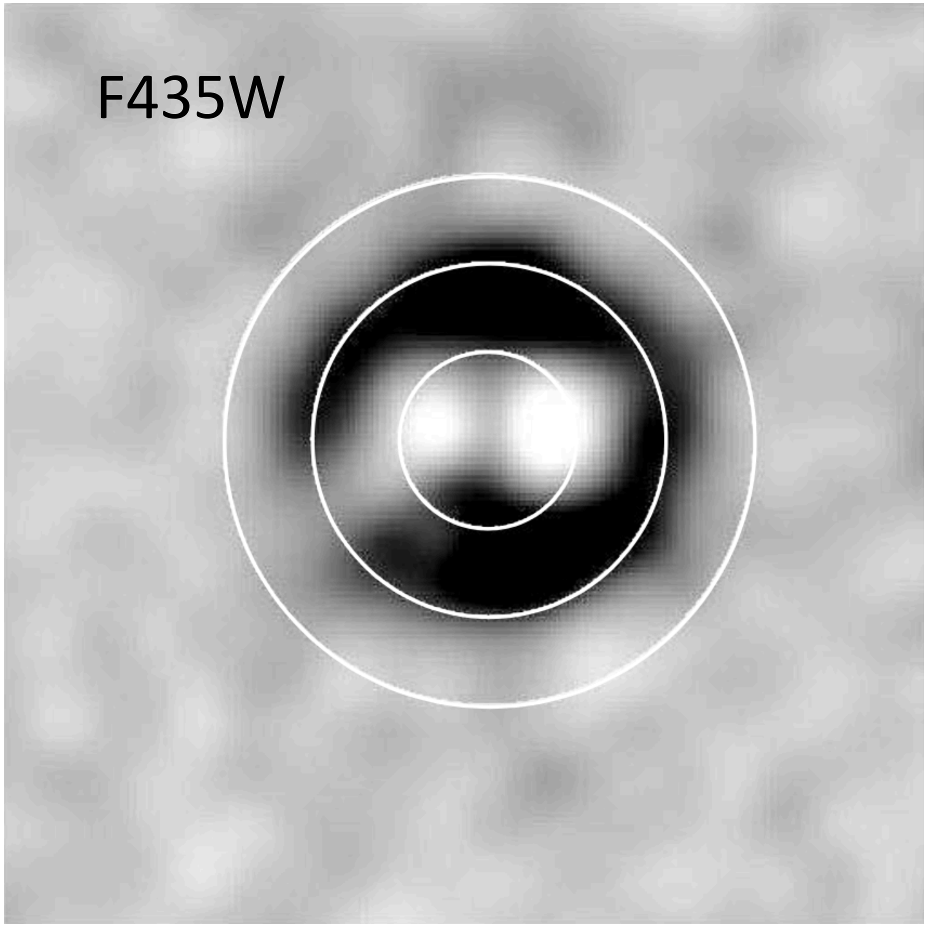


SN 2006X



Wang+2008, Crotts & Yourdon 2015

the source. Assuming that the SN light is an instantaneous pulse, then the geometry of a LE is straightforward: the distance of the illuminated dust material lying on the paraboloid can be approximated as

$$\boxed{R \approx \frac{D^2\theta^2 \mp (ct)^2}{2ct},} \tag{1}$$

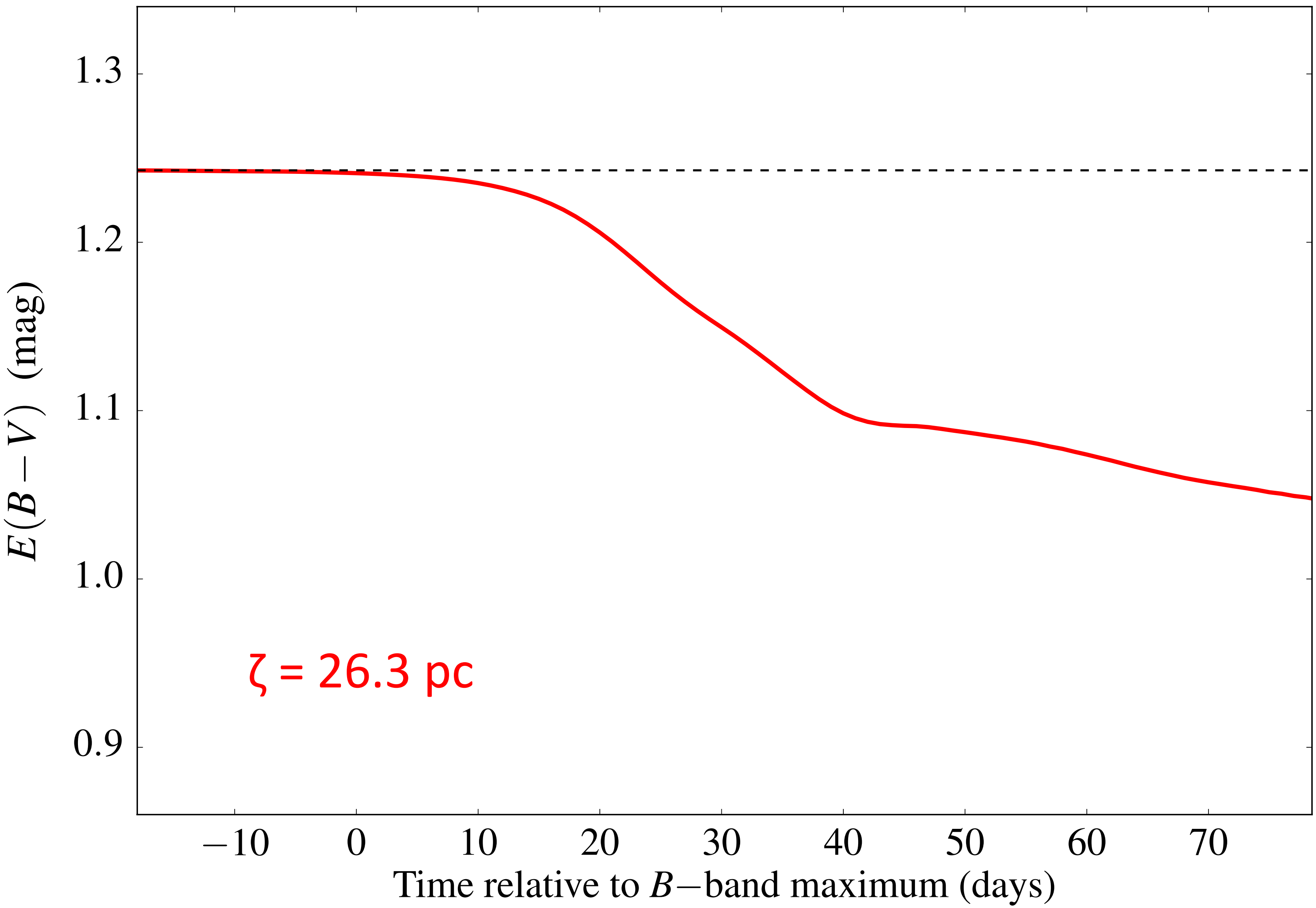
where D is the distance from the SN to the observer, θ is the angular radius of the echo, c is the speed of light, and t is the time since the outburst. The equation with a minus sign corresponds to the single dust slab, while the plus sign represents the case for a dust shell.

Light echo measurement:

$\zeta = 26.3 \pm 3.2$ pc

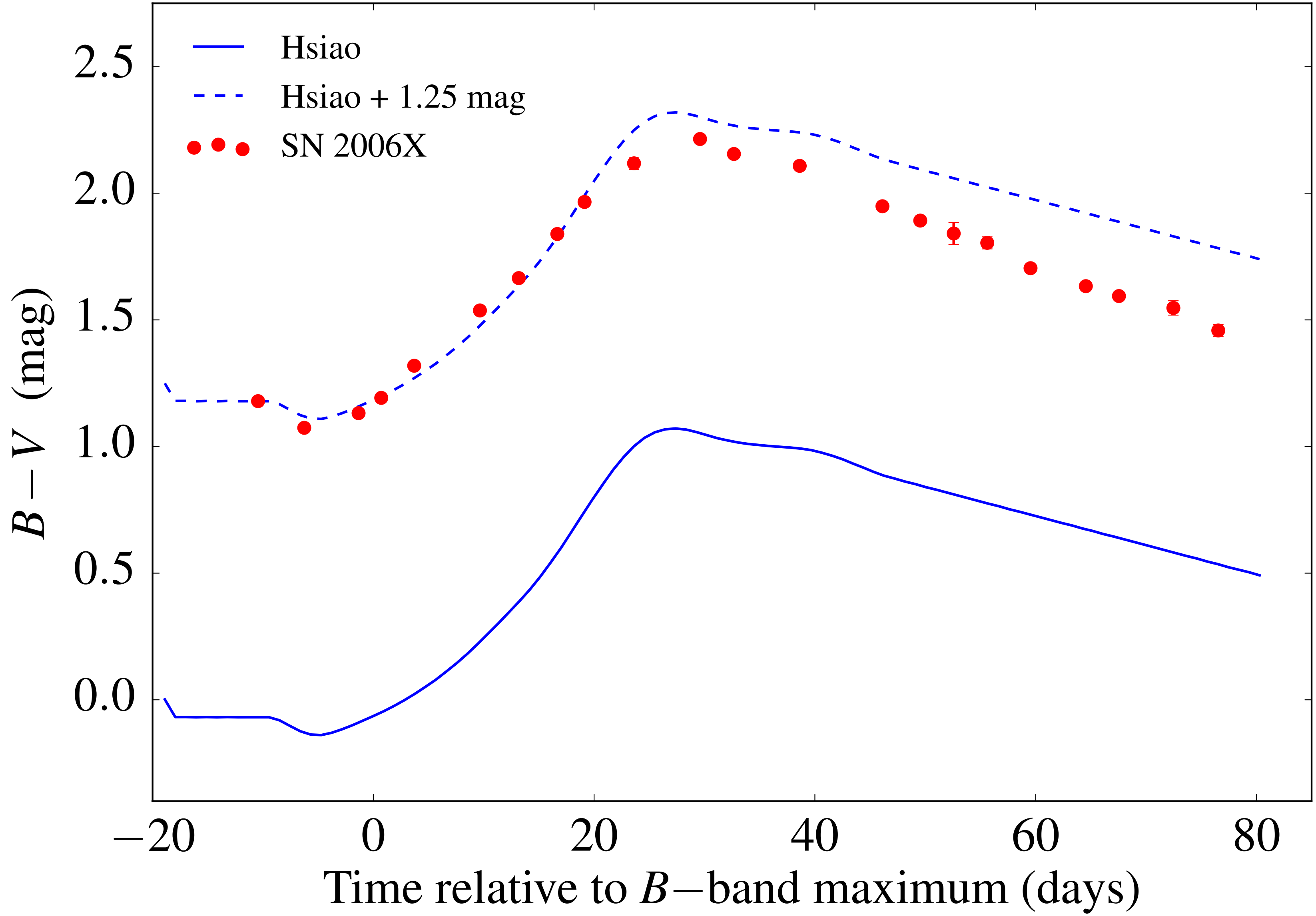
Interstellar

SN 2006X



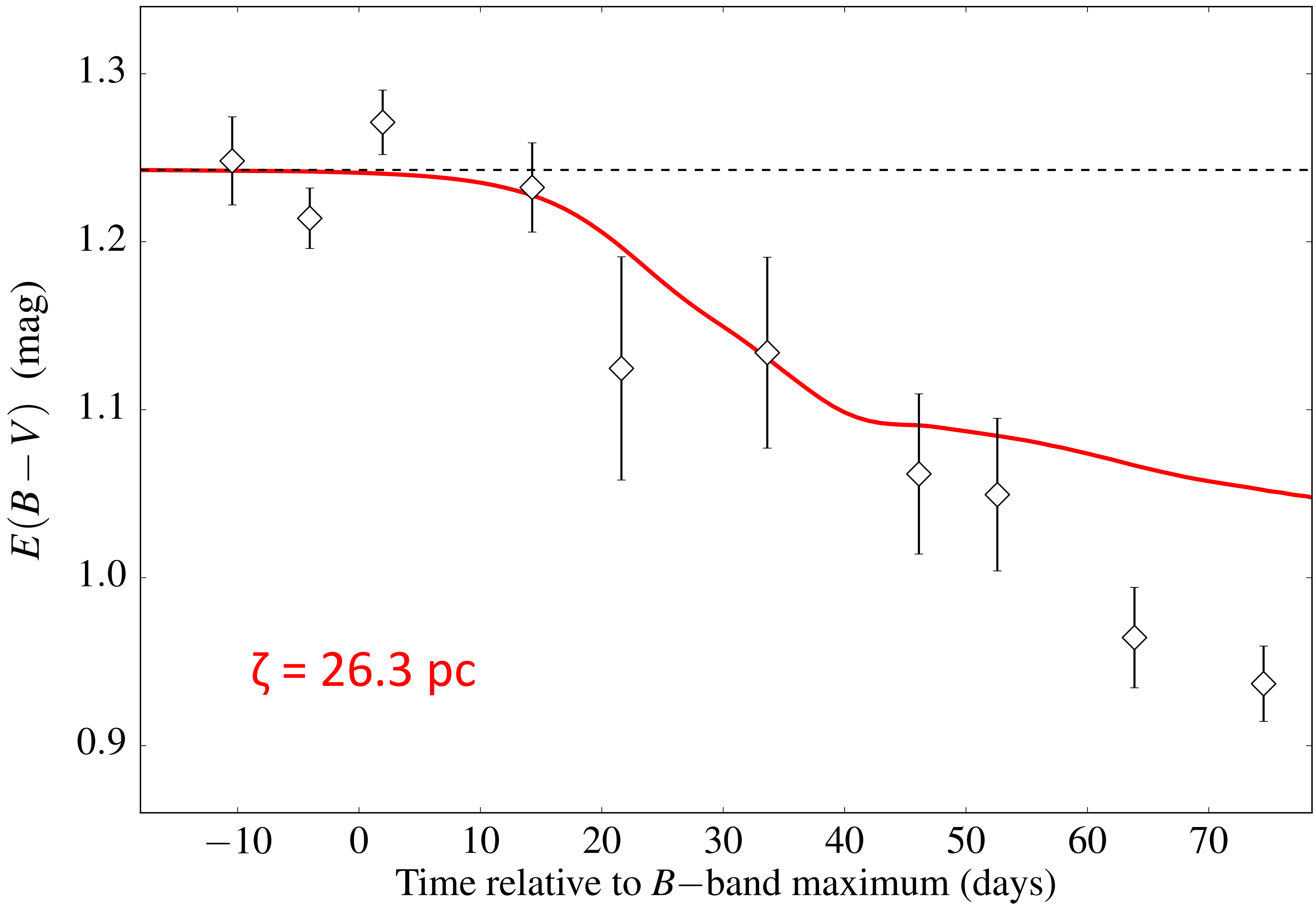
1.3
1.2
1.1
1.0
0.9
$E(B-V)$ (mag)
ζ = 26.3 pc
−10
0
10
20
30
40
50
60
70
Time relative to B−band maximum (days)

SN 2006X



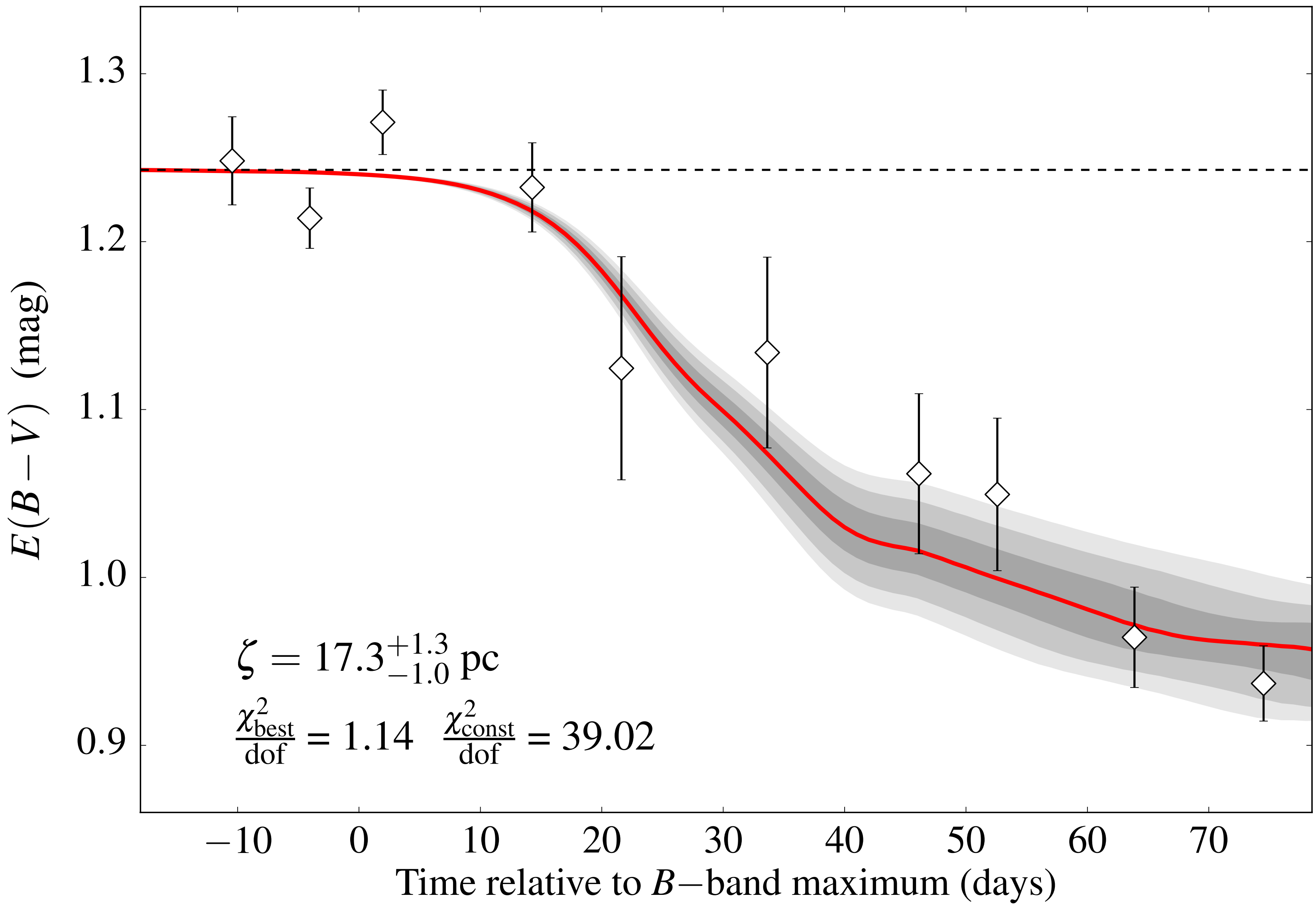
Hsiao
Hsiao + 1.25 mag
SN 2006X
2.5
2.0
1.5
1.0
0.5
0.0
$B - V$ (mag)
−20
0
20
40
60
80
Time relative to B−band maximum (days)

SN 2006X



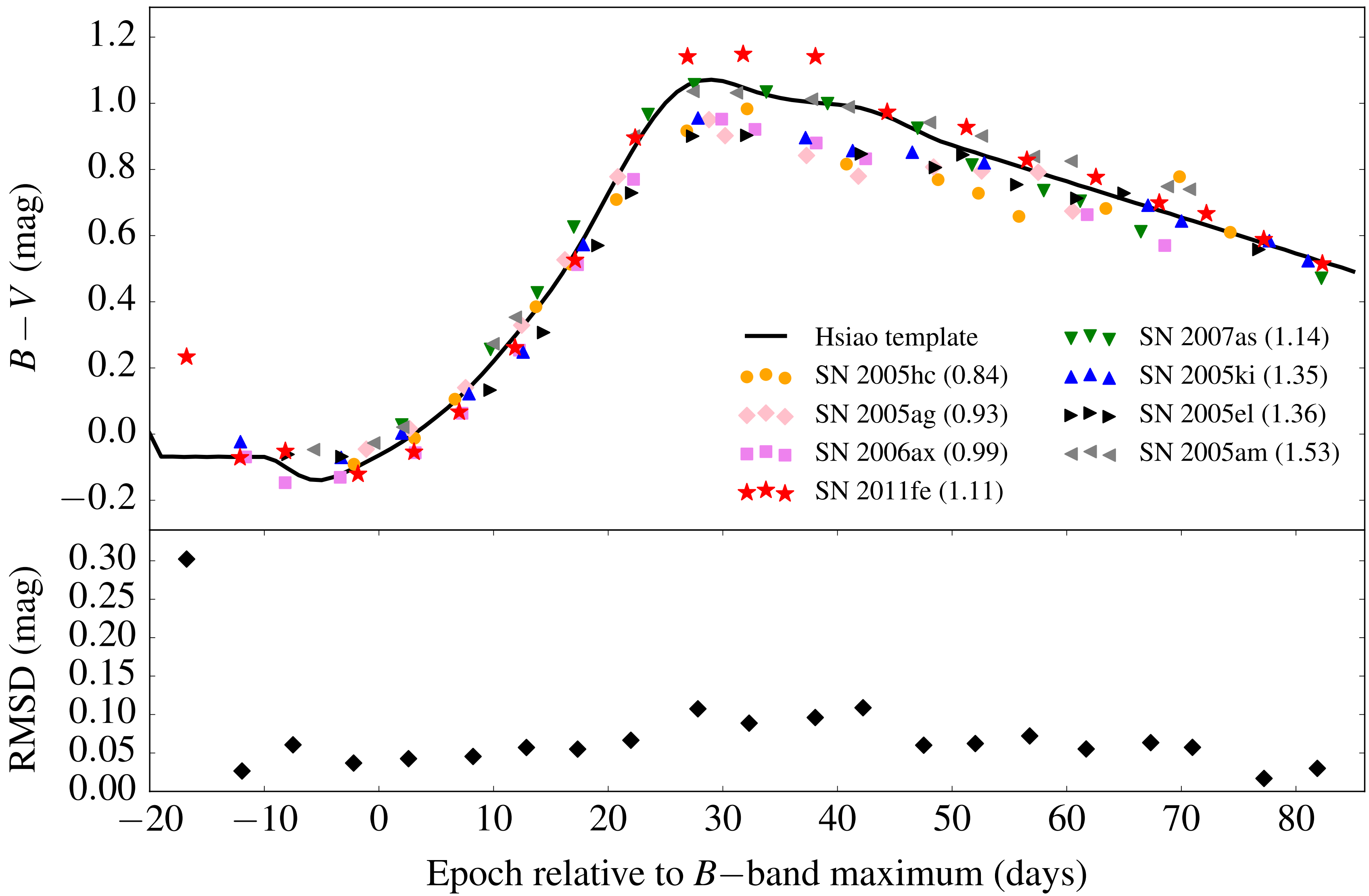
1.3
1.2
1.1
1.0
0.9
$E(B-V)$ (mag)
ζ = 26.3 pc
−10
0
10
20
30
40
50
60
70
Time relative to $B-$band maximum (days)

SN 2006X



$\zeta = 17.3^{+1.3}_{-1.0}$ pc
$\frac{\chi^2_{\rm best}}{\rm dof} = 1.14$ $\frac{\chi^2_{\rm const}}{\rm dof} = 39.02$
$E(B-V)$ (mag)
1.3
1.2
1.1
1.0
0.9
−10
0
10
20
30
40
50
60
70
Time relative to B−band maximum (days)

Intrinsic color variations



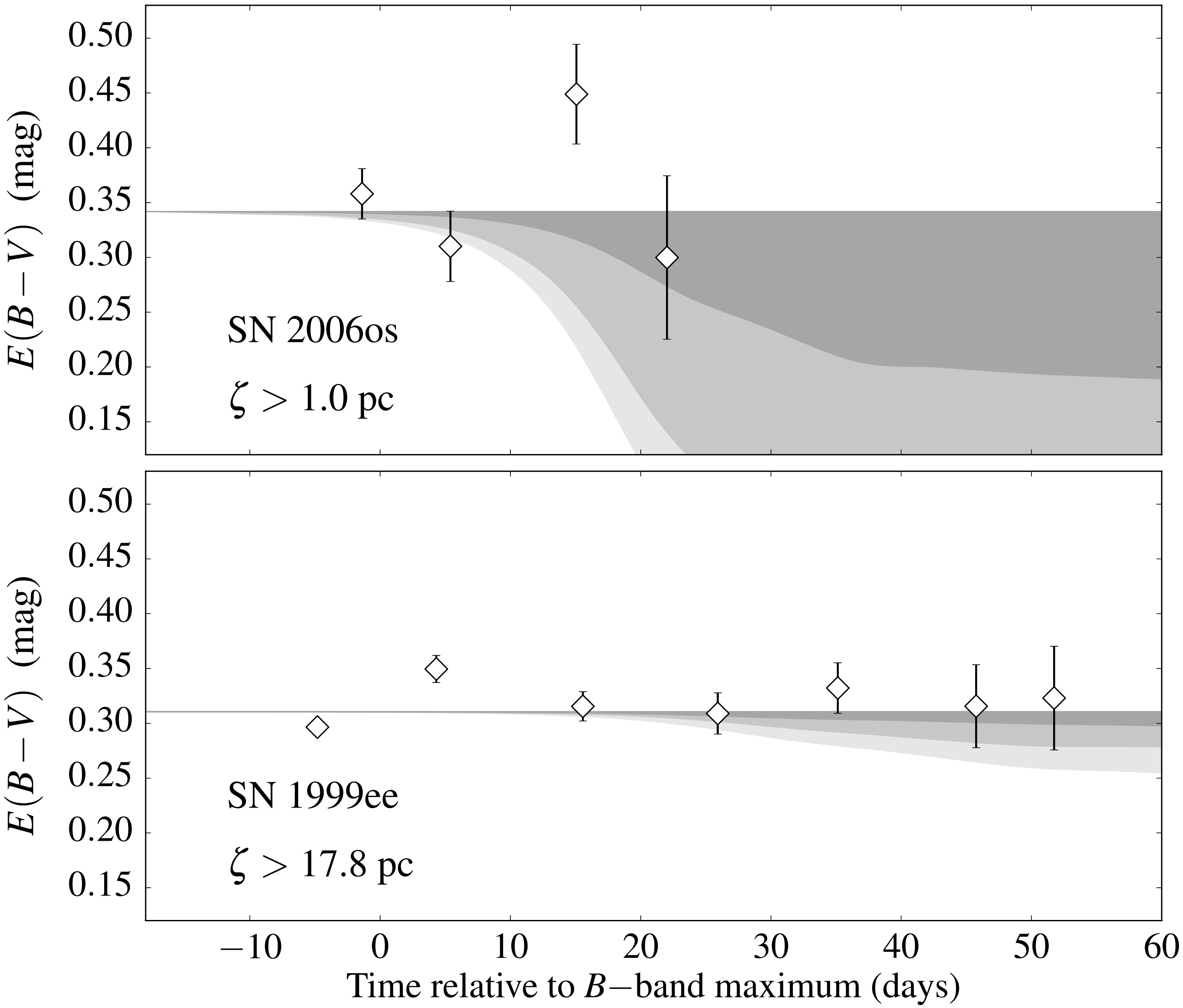
Dust location for 48 Type Ia supernovae

48 SNe Ia from the literature with E(B-V) > 0.3 mag

- 16 from CfA
- 11 from CSP
- 11 from LOSS

SN	$t_{\max}(B)$ (MJD)	$\Delta M^{\rm obs}_{B,15}$ (mag)
SN 1986G	46560.79	1.66
SN 1989B	47563.84	1.09
SN 1995E	49774.00	0.98
SN 1996ai	50255.30	0.99
SN 1996bo	50386.24	1.21
SN 1997dt	50785.83	1.15
SN 1998bu	50952.30	1.02
SN 1998dm	51060.14	0.86
SN 1999cl	51341.80	1.09
SN 1999ee	51468.32	0.82
SN 1999gd	51519.61	1.27
SN 2000ce	51665.24	0.93
SN 2000cp	51722.21	1.26
SN 2001E	51925.88	0.97
SN 2001dl	52130.90	0.91
SN 2002G	52299.02	1.38
SN 2002bo	52356.79	1.14
SN 2002cd	52383.32	0.91
SN 2002hw	52595.81	1.39
SN 2002jg	52609.82	1.39
SN 2003cg	52729.62	1.09
SN 2003hx	52892.50	1.44
SN 2004ab	53056.32	1.17
SN 2005A	53379.58	1.14
SN 2005bc	53470.33	1.37
SN 2005kc	53698.04	1.25
SN 2006X	53785.62	1.11
SN 2006br	53853.89	1.53
SN 2006cc	53873.83	0.91
SN 2006cm	53885.48	0.91
SN 2006gj	53999.94	1.55
SN 2006os	54067.08	1.27
SN 2007S	54143.29	0.80
SN 2007bm	54224.58	1.17
SN 2007ca	54226.68	0.77
SN 2007cg	54230.62	1.06
SN 2007cs	54275.66	0.80
SN 2007le	54398.74	0.95
SN 2007ss	54452.55	1.12
SN 2008dt	54646.04	0.93
SN 2008fp	54730.52	0.92
SN 2009I	54851.94	0.87
SN 2009fv	55000.44	1.76
SN 2010ev	55384.51	1.14
SN 2012bm	56018.00	0.72
SN 2012cp	56081.10	0.86
SN 2012cu	56105.16	0.90
SN 2014J	56689.64	0.96

Dust location for 48 Type Ia supernovae



Constant E(B-V)

Lower limits on the dust distance for 33 SNe

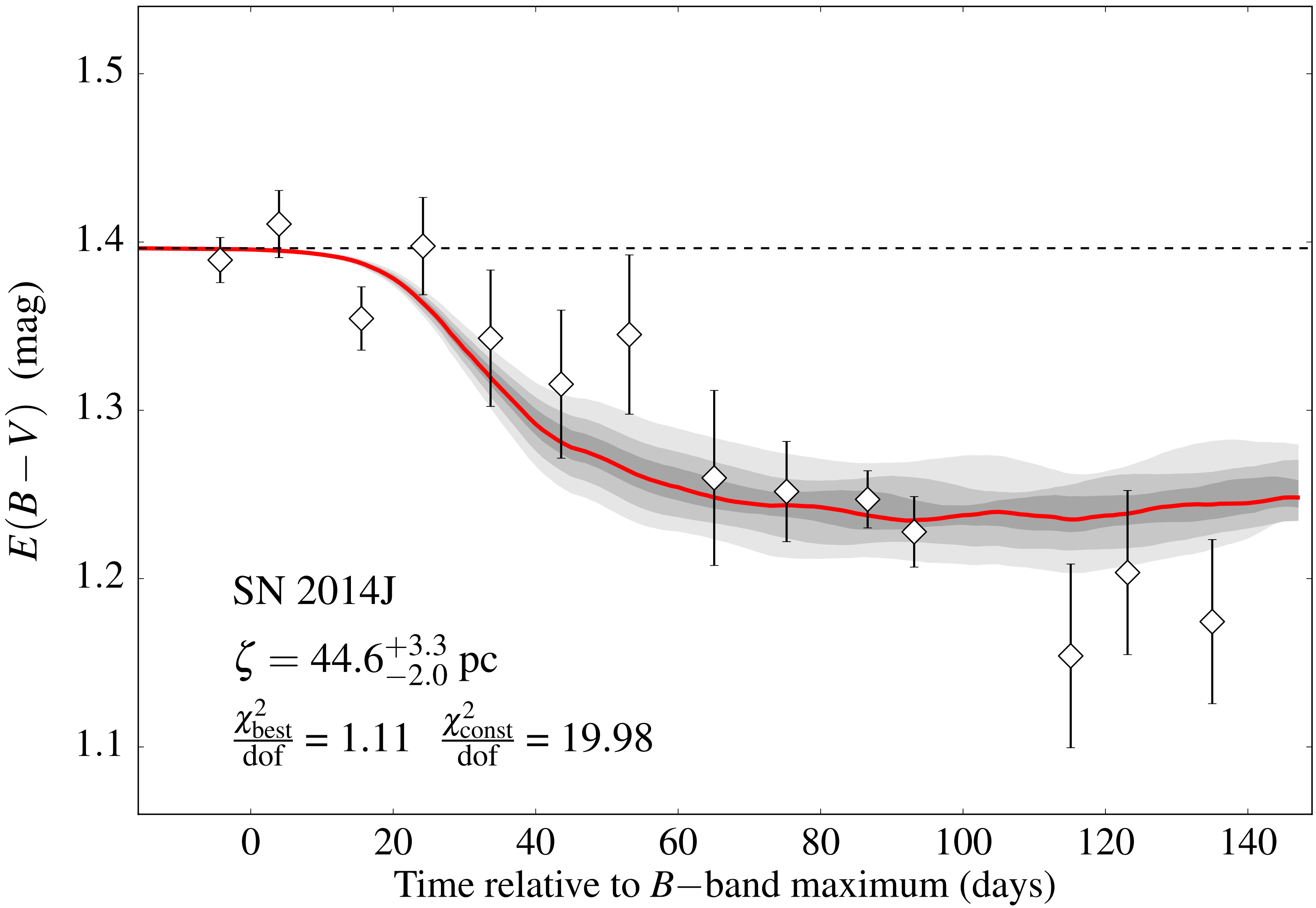
All consistent with dust at $\zeta \gtrsim 1$ pc

Dust location for 48 Type Ia supernovae

Time-variable E(B-V) and dust distance estimates for 15 SNe

SN	$E(B-V)_{\mathrm{DLOS}}$ (mag)	ζ (pc)	χ^2_ν	$\chi^2_{\nu,\mathrm{const}}$	$\Delta M^{\mathrm{obs}}_{B,15}$ (mag)	$\Delta M^{\mathrm{true}}_{B,15}$ (mag)
SN 2003hx	0.50	$0.013^{+0.001}_{-0.001}$	4.14	22.68	1.36	$1.69^{+0.06}_{-0.04}$
SN 1996bo	0.39	$0.70^{+0.22}_{-0.04}$	4.12	21.70	1.21	$1.46^{+0.01}_{-0.06}$
SN 2007cs	1.38	$1.0^{+0.3}_{-0.3}$	0.54	19.66	0.80	$1.66^{+0.48}_{-0.25}$
SN 2008dt	0.62	$1.0^{+0.6}_{-0.2}$	0.26	5.11	0.93	$1.17^{+0.05}_{-0.09}$
SN 2006br	1.00	$1.7^{+0.4}_{-0.2}$	1.85	14.81	1.53	$1.85^{+0.04}_{-0.06}$
SN 2005A	1.04	$4.7^{+1.3}_{-0.8}$	2.31	8.34	1.14	$1.27^{+0.03}_{-0.03}$
SN 2007S	0.42	$5.7^{+1.5}_{-1.0}$	0.22	4.94	0.80	$0.82^{+0.01}_{-0.01}$
SN 2007le	0.34	$5.9^{+1.2}_{-1.0}$	0.29	6.51	0.95	$0.97^{+0.01}_{-0.01}$
SN 2008fp	0.53	$9.4^{+1.1}_{-0.7}$	2.18	22.25	0.92	$0.94^{+0.01}_{-0.01}$
SN 2002cd	0.70	$9.6^{+1.2}_{-1.7}$	1.36	6.18	0.91	$0.94^{+0.01}_{-0.01}$
SN 1999cl	1.08	$12.8^{+4.9}_{-2.9}$	0.49	3.74	1.09	$1.13^{+0.01}_{-0.01}$
SN 1986G	1.00	$14.5^{+3.3}_{-1.4}$	1.27	10.36	1.66	$1.70^{+0.01}_{-0.01}$
SN 2002bo	0.46	$15.9^{+3.5}_{-2.8}$	1.16	4.26	1.14	$1.15^{+0.01}_{-0.01}$
SN 2006X	1.24	$17.3^{+1.3}_{-1.0}$	1.14	39.02	1.11	$1.15^{+0.01}_{-0.01}$
SN 2014J	1.40	$44.6^{+3.3}_{-2.0}$	1.11	19.98	0.96	$0.97^{+0.01}_{-0.01}$

Dust location for 48 Type Ia supernovae



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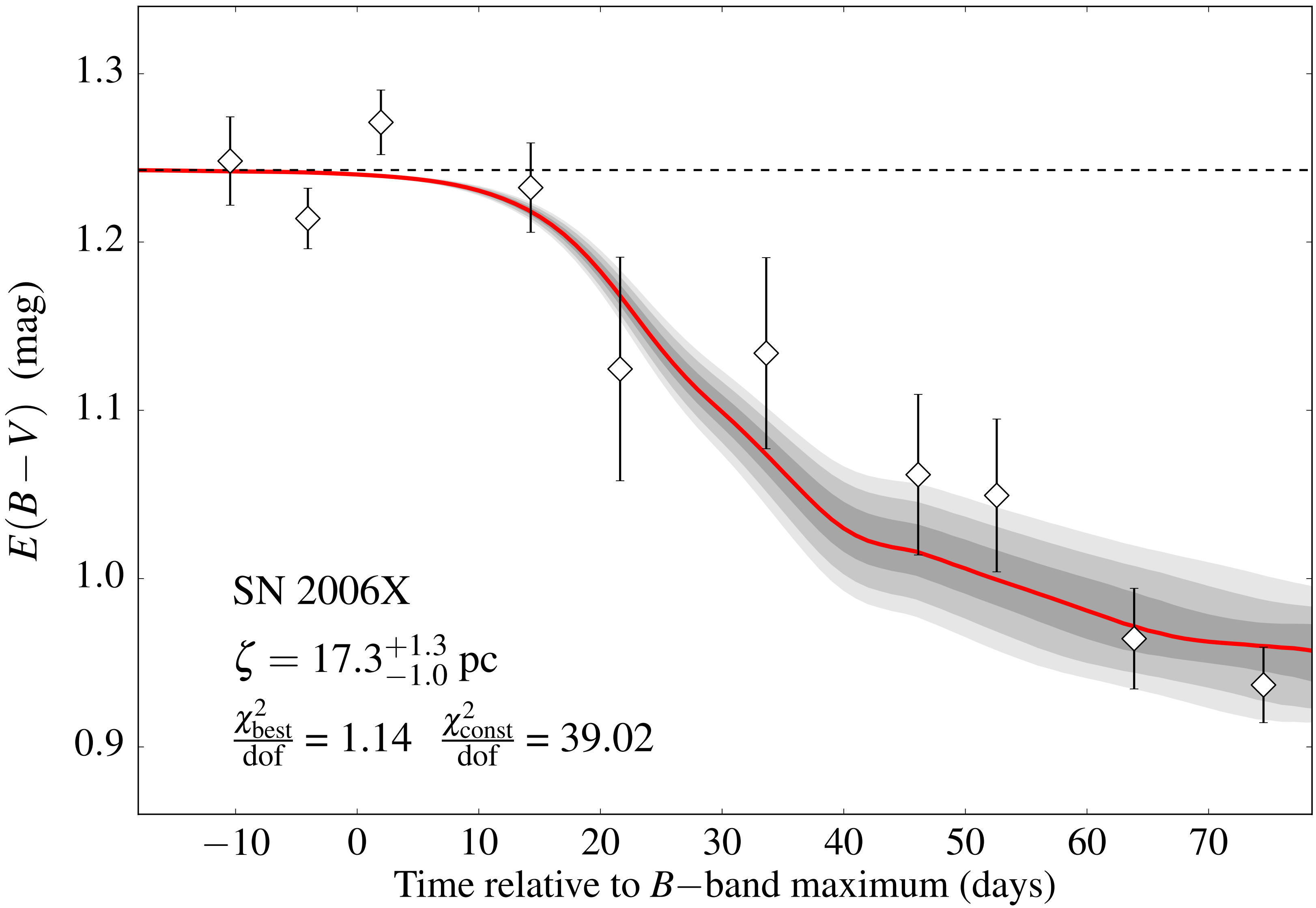

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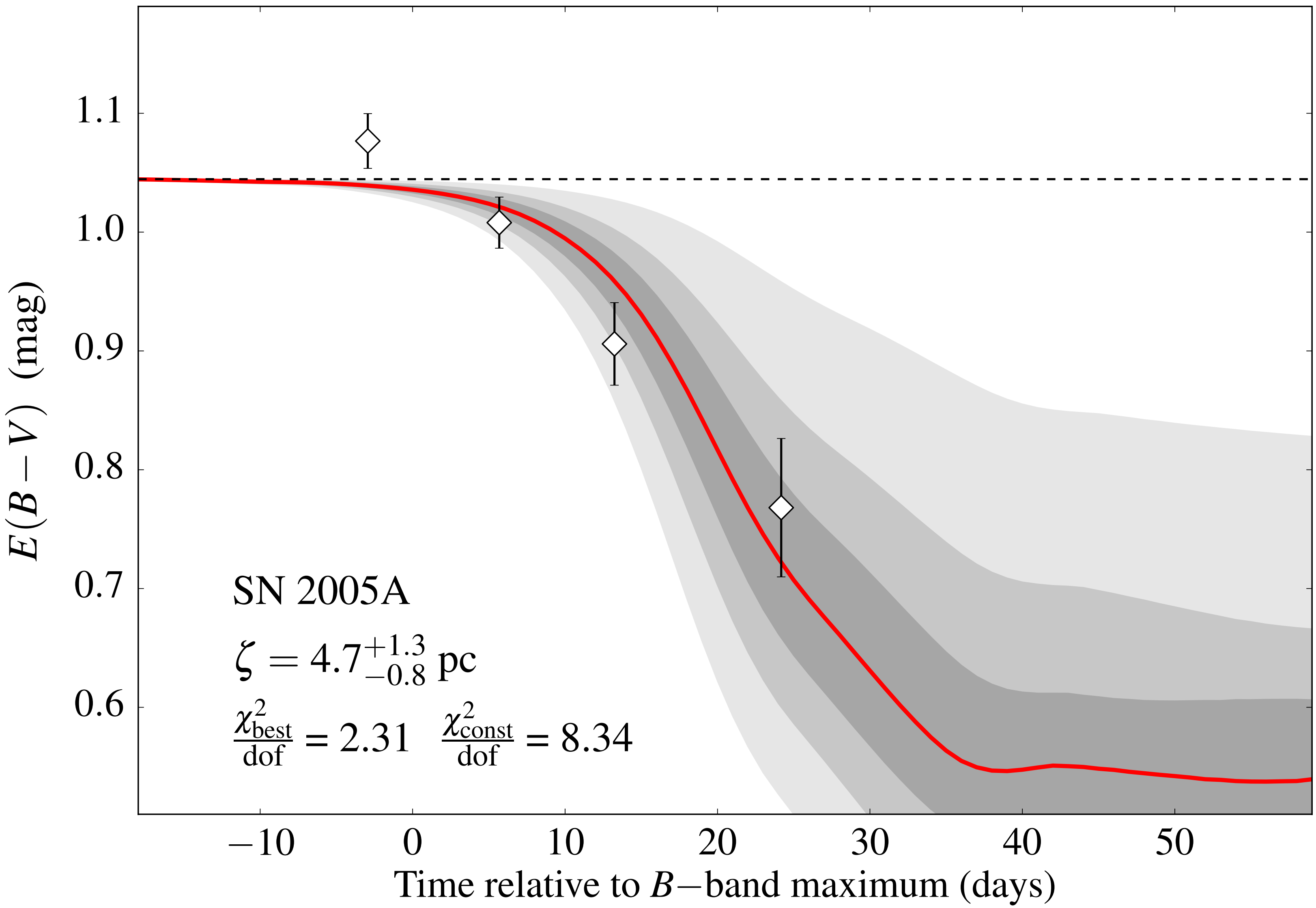

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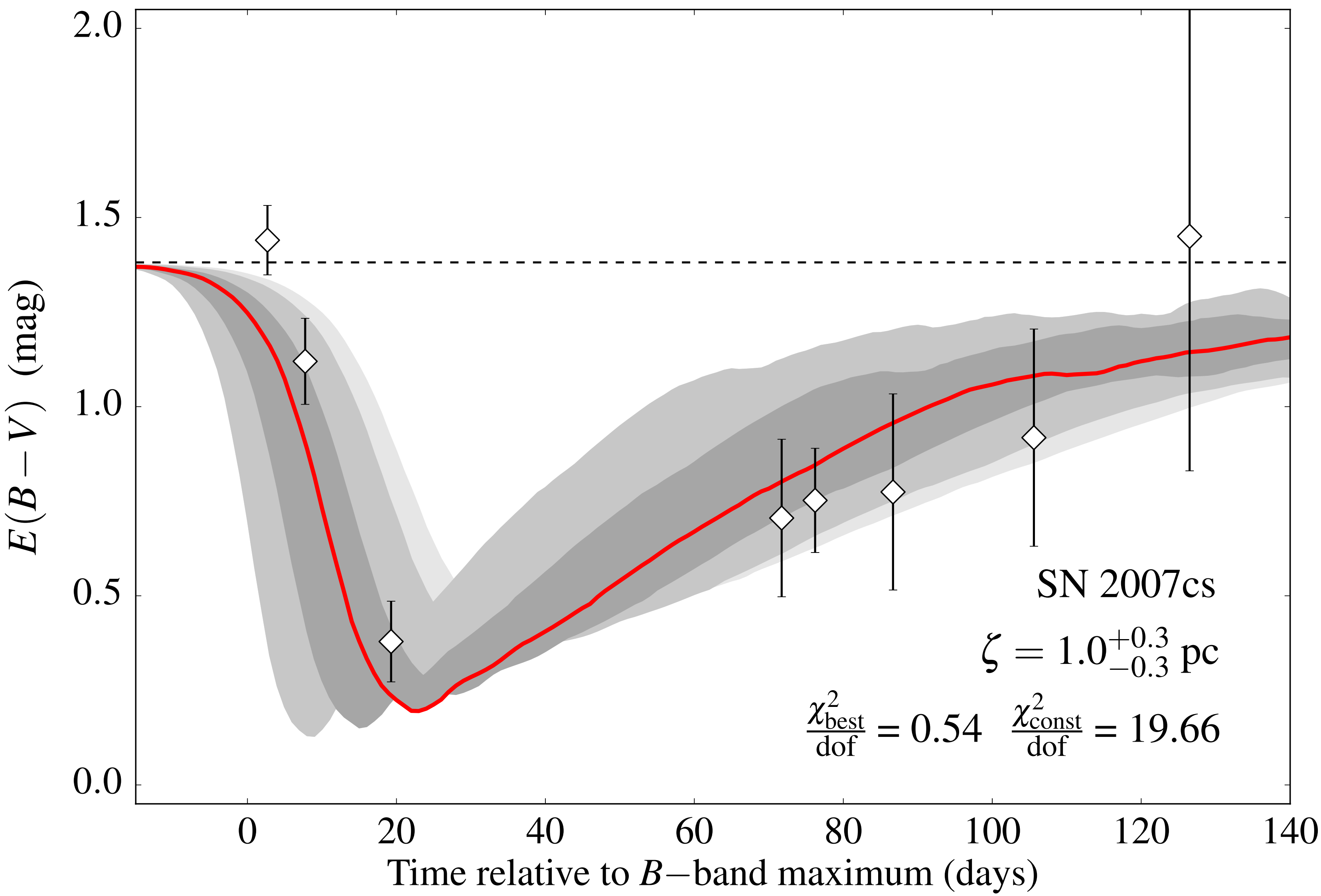

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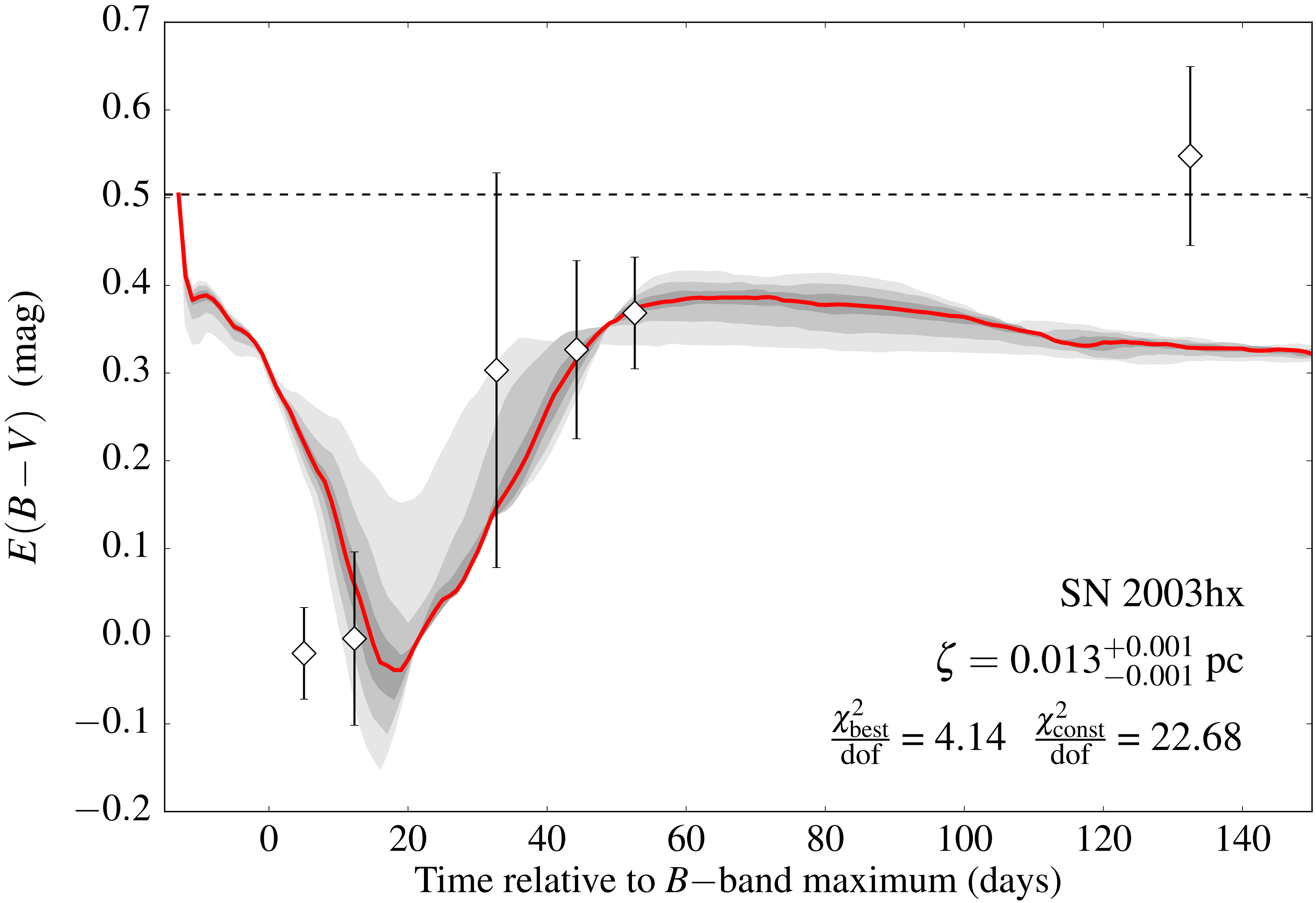

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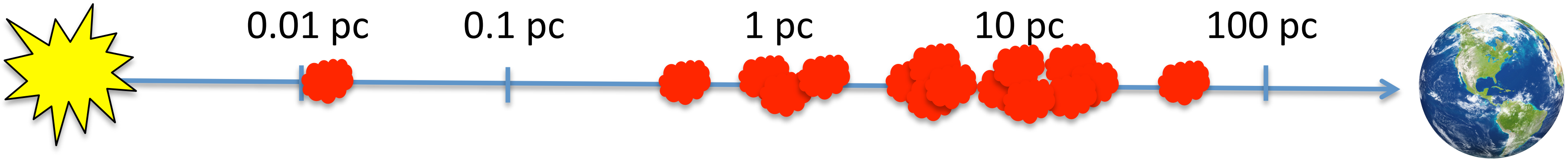

SN	$E(B-V)_{\mathrm{DLOS}}$ (mag)	ζ (pc)	χ^2_ν	$\chi^2_{\nu,\mathrm{const}}$	$\Delta M^{\mathrm{obs}}_{B,15}$ (mag)	$\Delta M^{\mathrm{true}}_{B,15}$ (mag)
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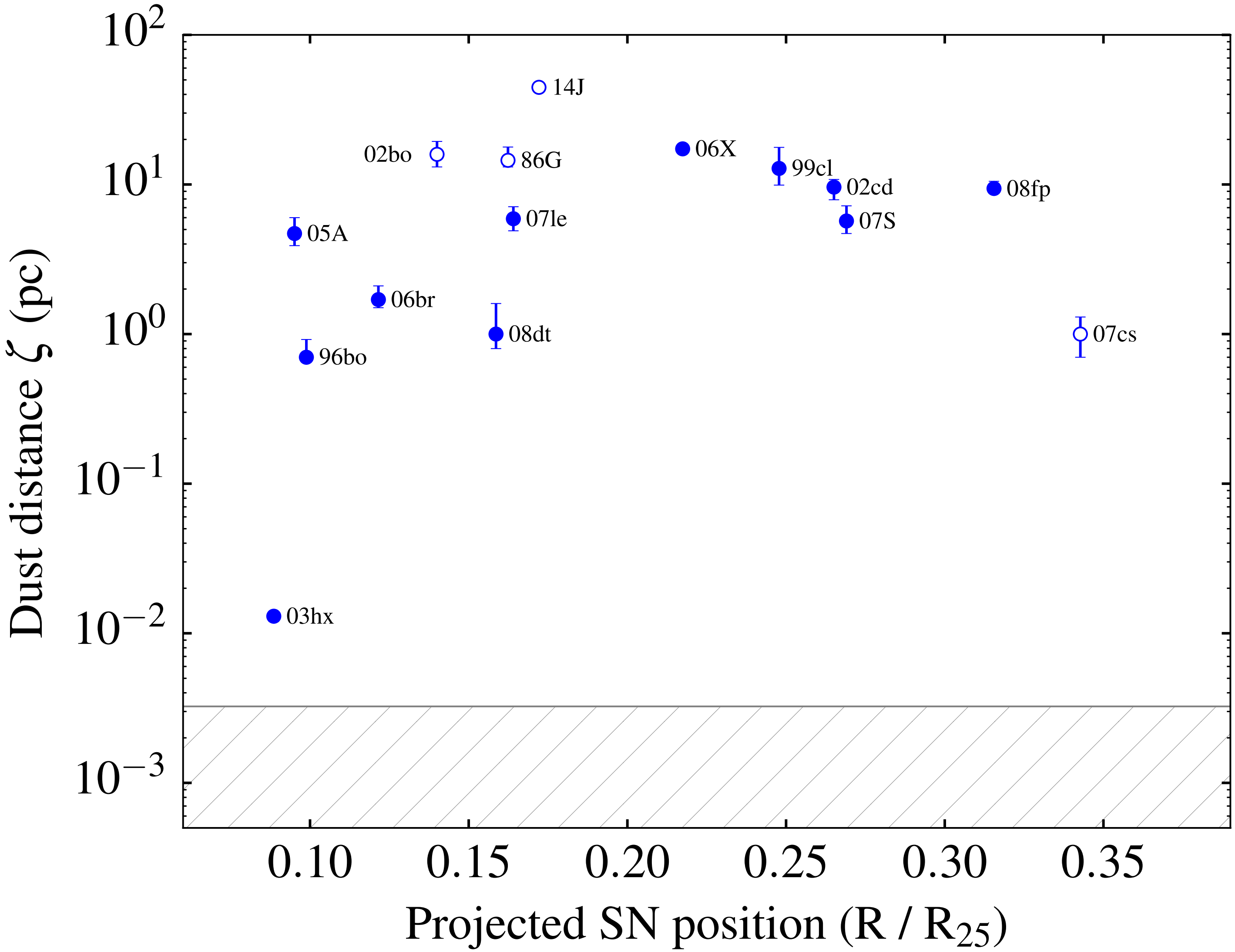
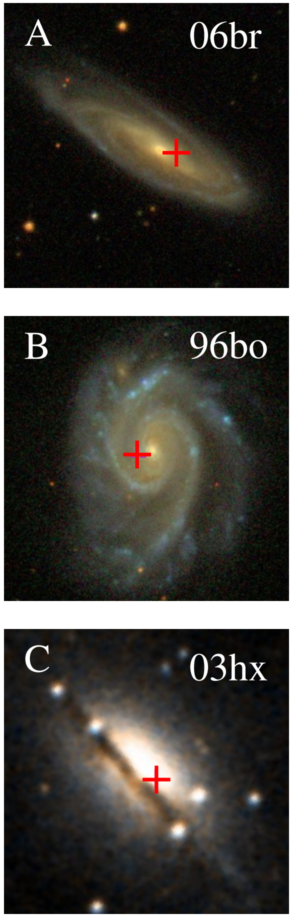
Position in the host galaxy





A scenario for interstellar dust

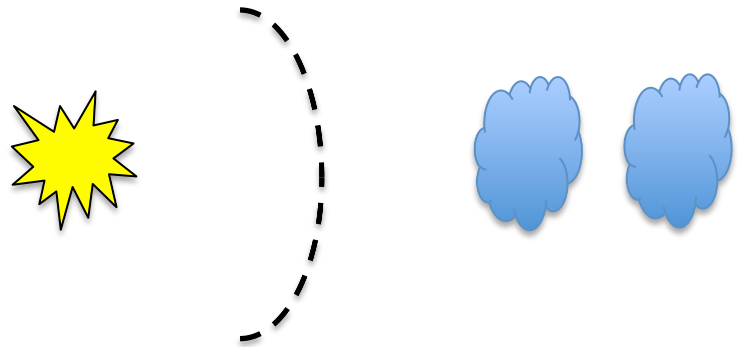
Extinction in SNe Ia stems from the interstellar medium.

OBSERVATION	INTERSTELLAR SCENARIO
Low R_V (extinction + polarization)	Grains smaller than MW: is MW peculiar?
Unusually strong Na I D	?
Blue-shifted absorption features	?
Variable absorption features	Expanding SN photosphere / geometric effects

A scenario for interstellar dust

Extinction in SNe Ia stems from the interstellar medium

Hoang 2017: cloud-cloud collisions induced by SN radiation pressure



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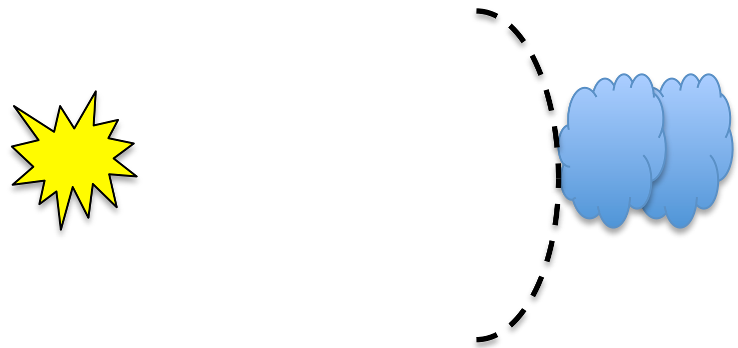

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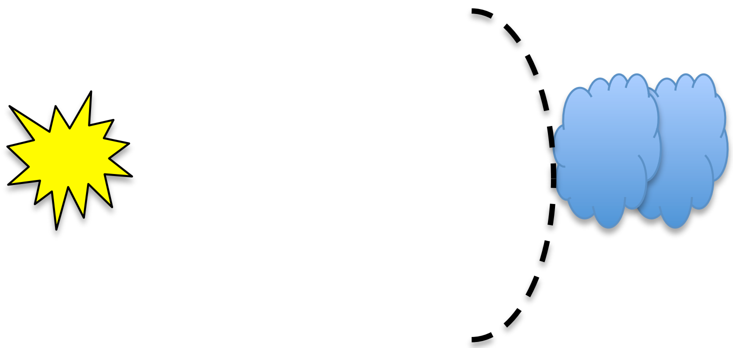
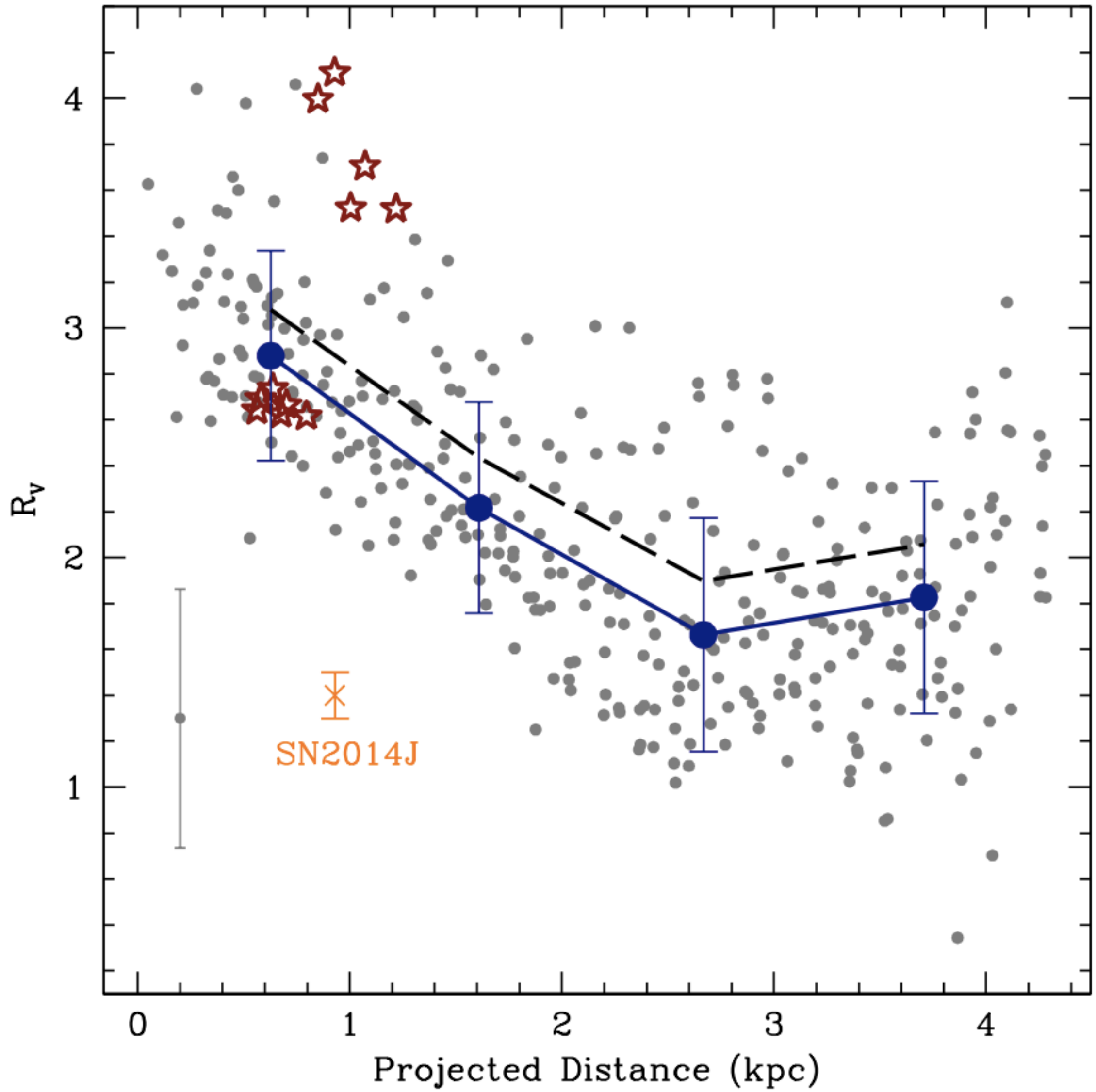


OBSERVATION	INTERSTELLAR SCENARIO
Low R_V (extinction + polarization)	Collisions -> from big to small grains
Unusually strong Na I D	?
Blue-shifted absorption features	?
Variable absorption features	Expanding SN photosphere / geometric effects

A scenario for interstellar dust

Hutton+2015



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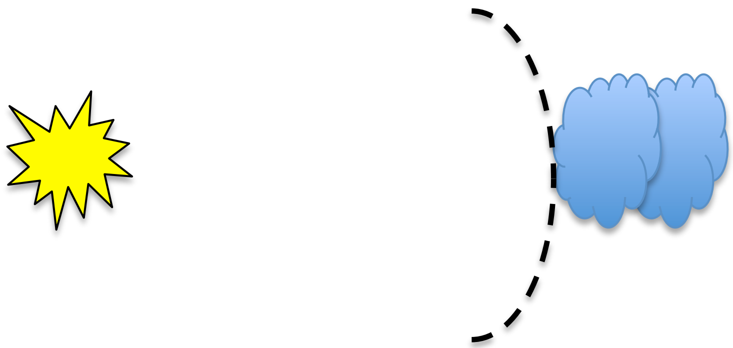

OBSERVATION	INTERSTELLAR SCENARIO
Low R_V (extinction + polarization)	Collisions -> from big to small grains
Unusually strong Na I D	Collisions -> enhancement of Na in gaseous phase
Blue-shifted absorption features	?
Variable absorption features	Expanding SN photosphere / geometric effects

A scenario for interstellar dust

Extinction in SNe Ia stems from the interstellar medium

Hoang 2017: cloud-cloud collisions induced by SN radiation pressure

vicinity. Specifically, grains of size a at distance ζ from the SN will be accelerated to velocities

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where $L_{\rm bol}$ is the bolometric luminosity of the SN (see also Hoang et al. 2015). Hence, even relatively distant dust clouds

OBSERVATION	INTERSTELLAR SCENARIO
Low R_V (extinction + polarization)	Collisions -> from big to small grains
Unusually strong Na I D	Collisions -> enhancement of Na in gaseous phase
Blue-shifted absorption features	Collisions -> clouds accelerated towards the observer
Variable absorption features	Expanding SN photosphere / geometric effects

A scenario for interstellar dust

Extinction in SNe Ia stems from the interstellar medium

Hoang 2017: cloud-cloud collisions induced by SN radiation pressure

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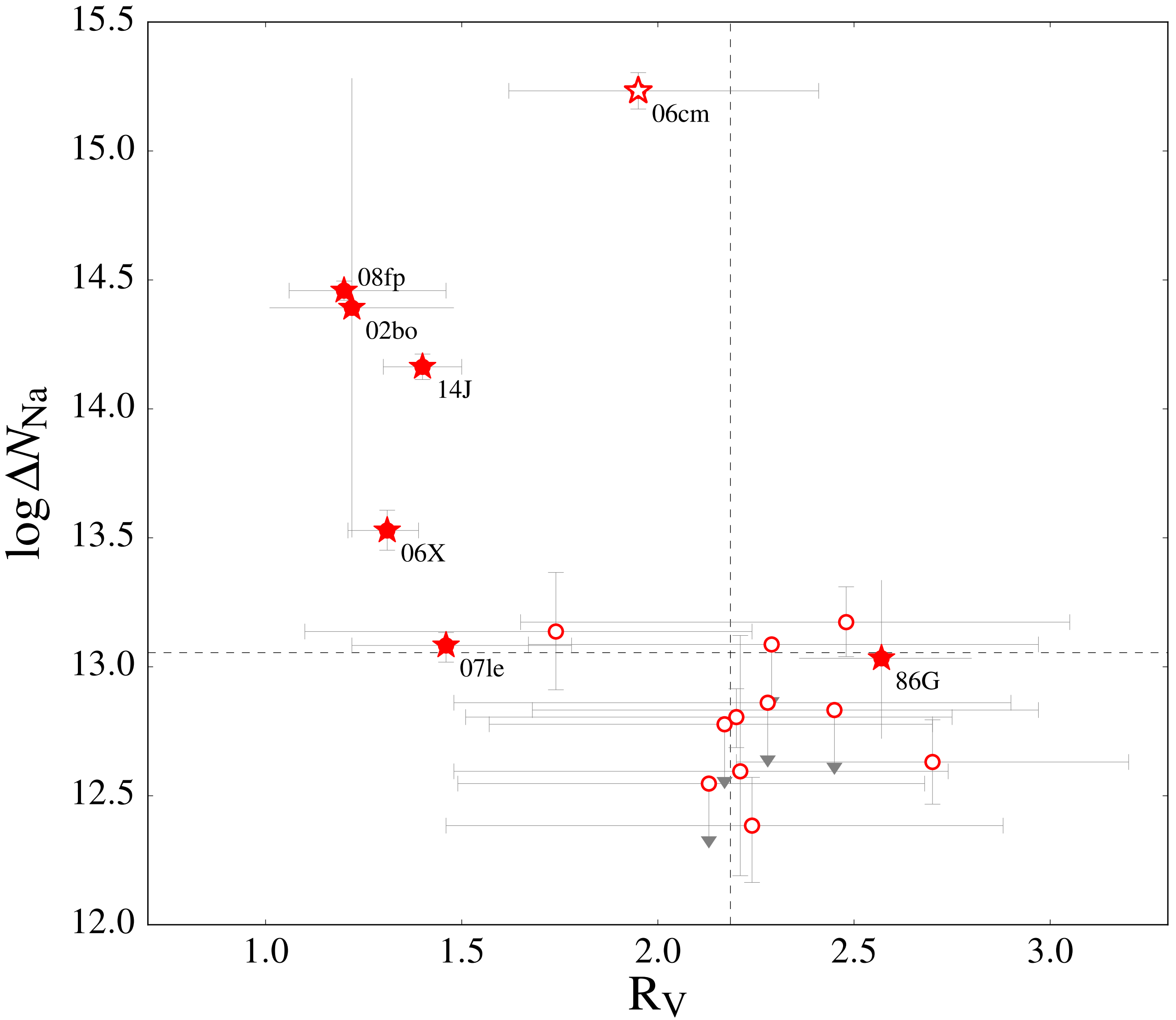
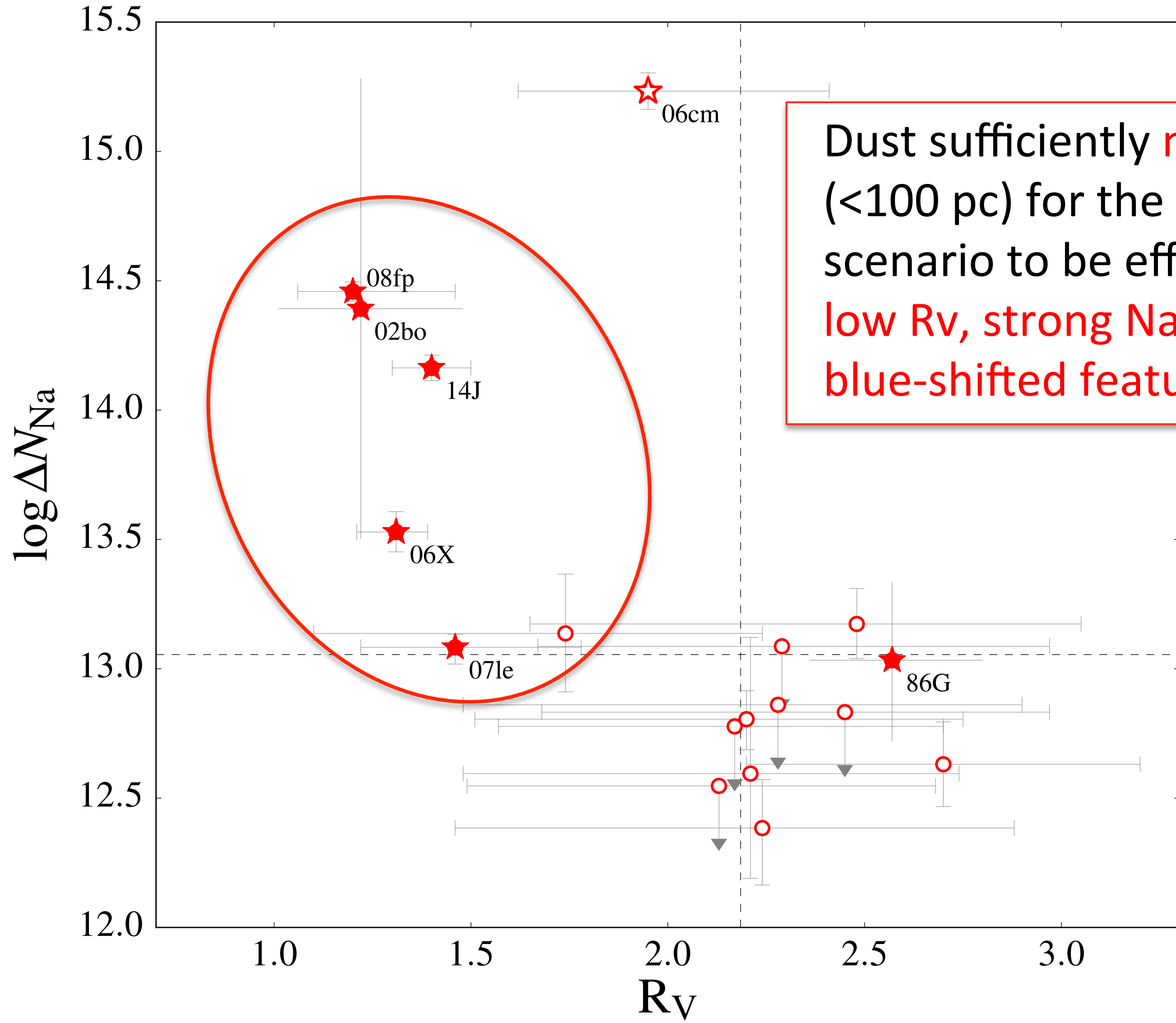
A scenario for interstellar dust

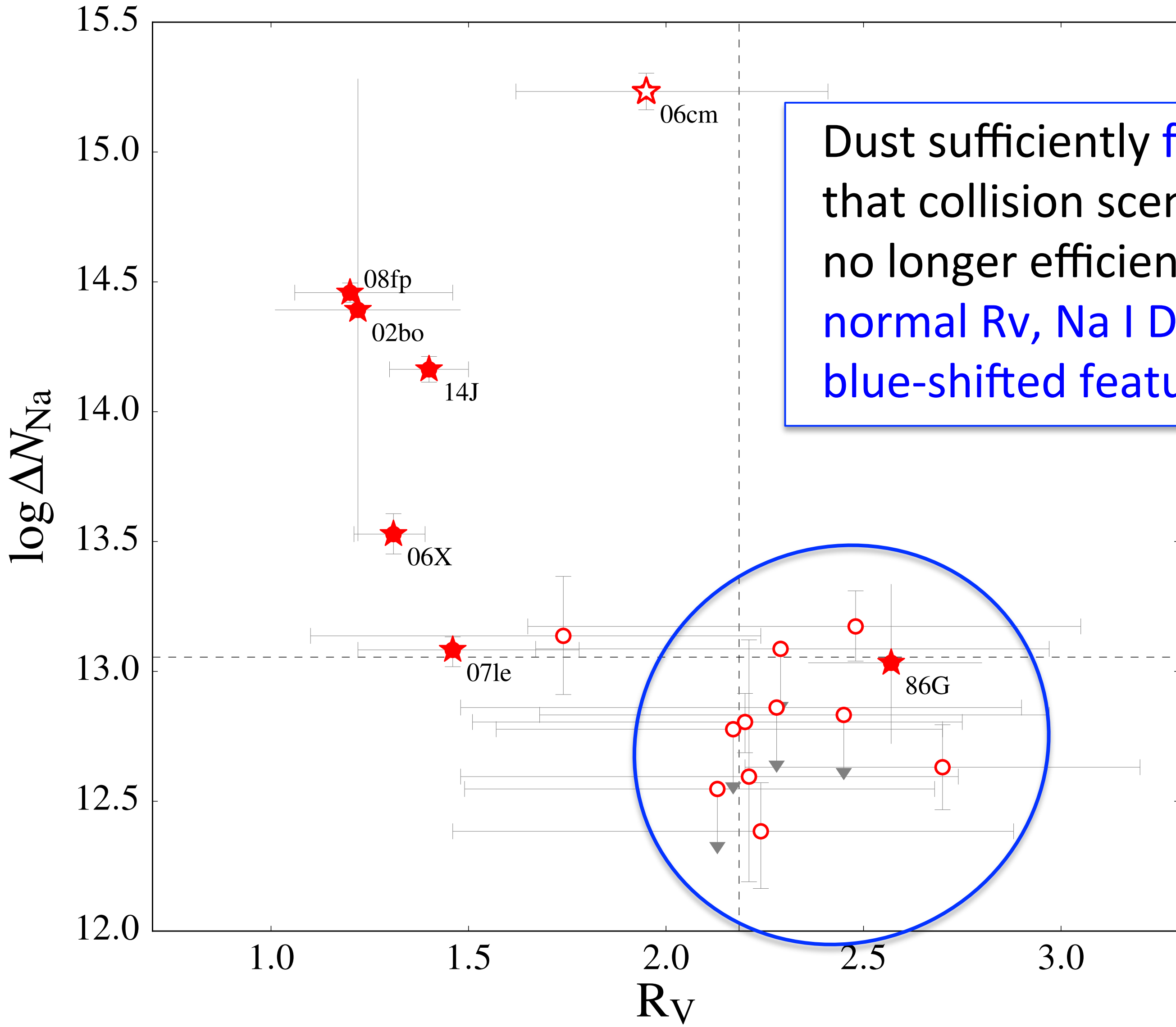


A scenario for interstellar dust



Dust sufficiently nearby (<100 pc) for the collision scenario to be efficient: low Rv, strong Na I D and blue-shifted features

A scenario for interstellar dust



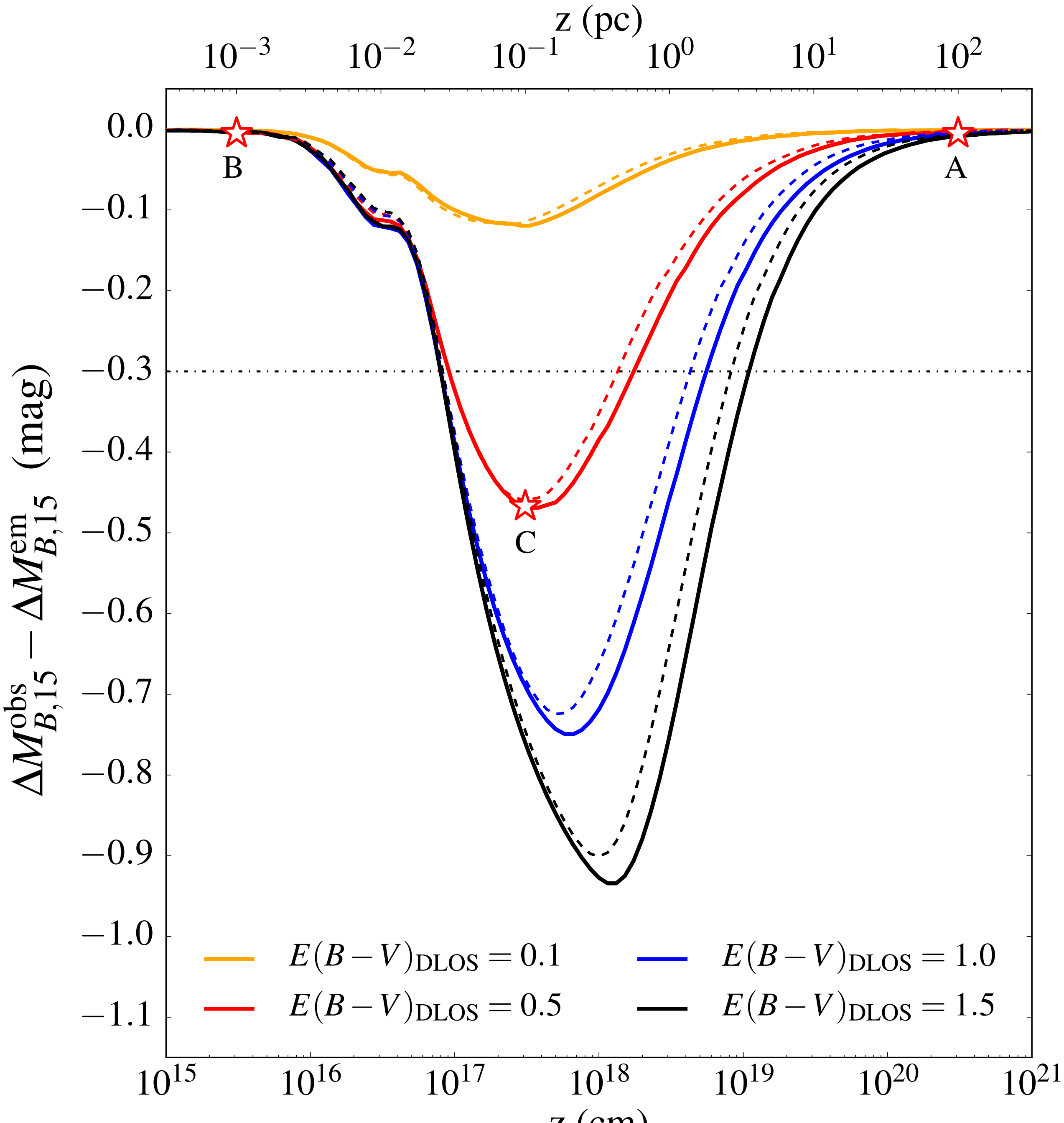
Dust sufficiently far away that collision scenario is no longer efficient: normal Rv, Na I D and no blue-shifted features

Conclusions

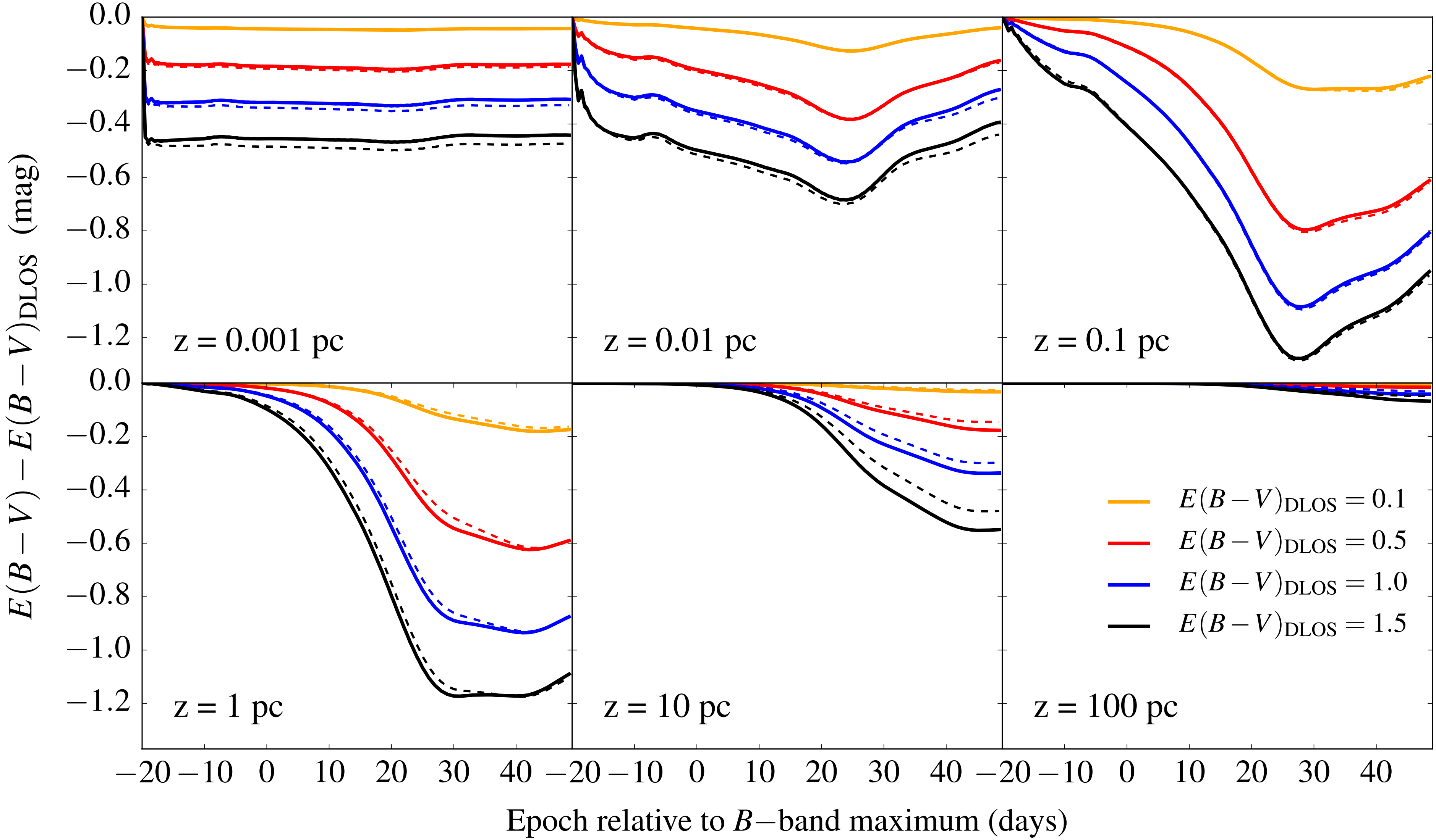
- Color evolution of reddened SNe Ia can place strong constraints on the location of dust

- The analysis of B-V colors for 48 SNe Ia in the literature reveals that the extinction is likely arising within the interstellar medium

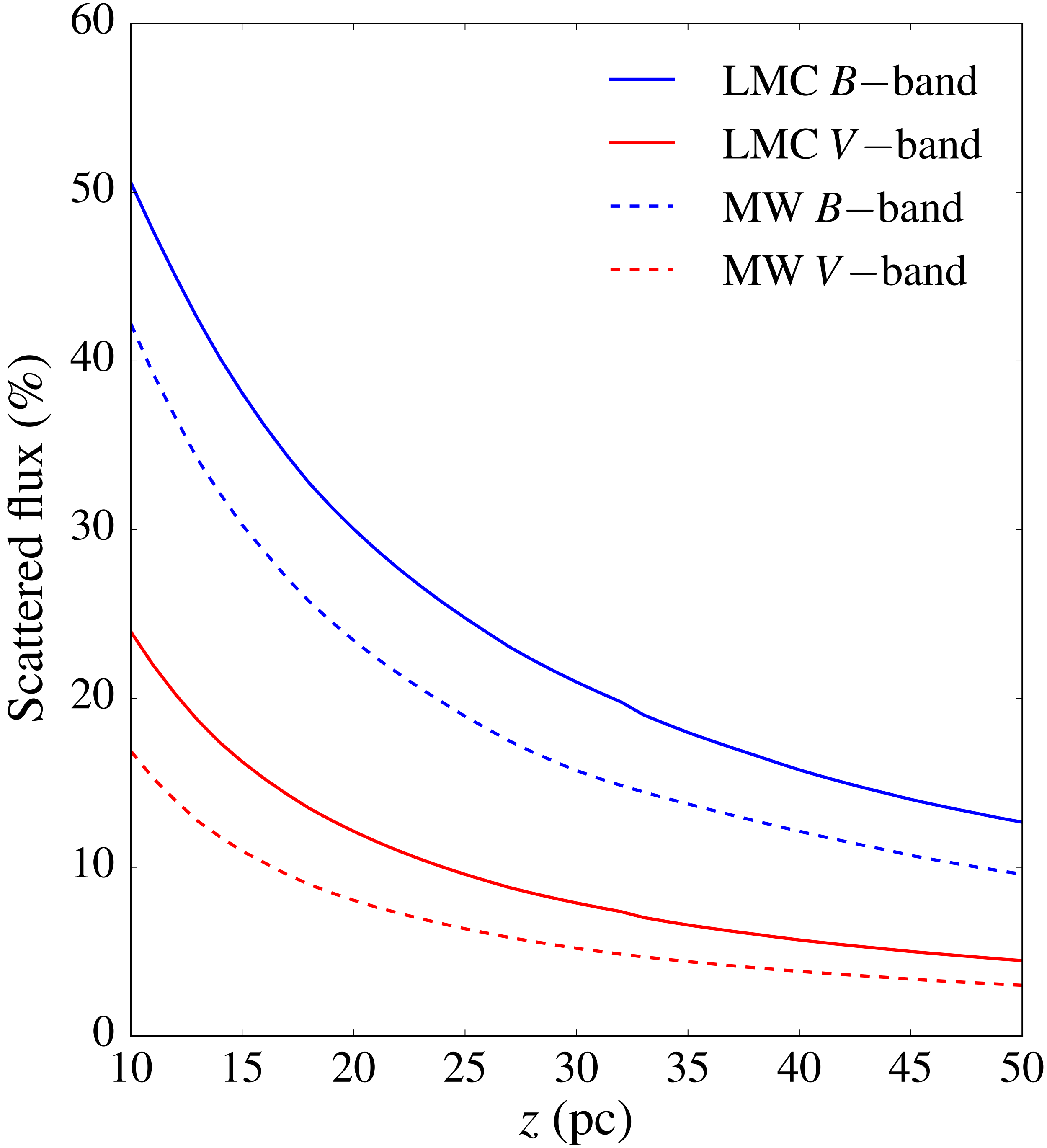
- The cloud-cloud collision scenario proposed by Hoang 2017 holds promises to explain the low R_V values, the unusually strong sodium and the blue-shifted and time-variable absorption features within the interstellar scenario

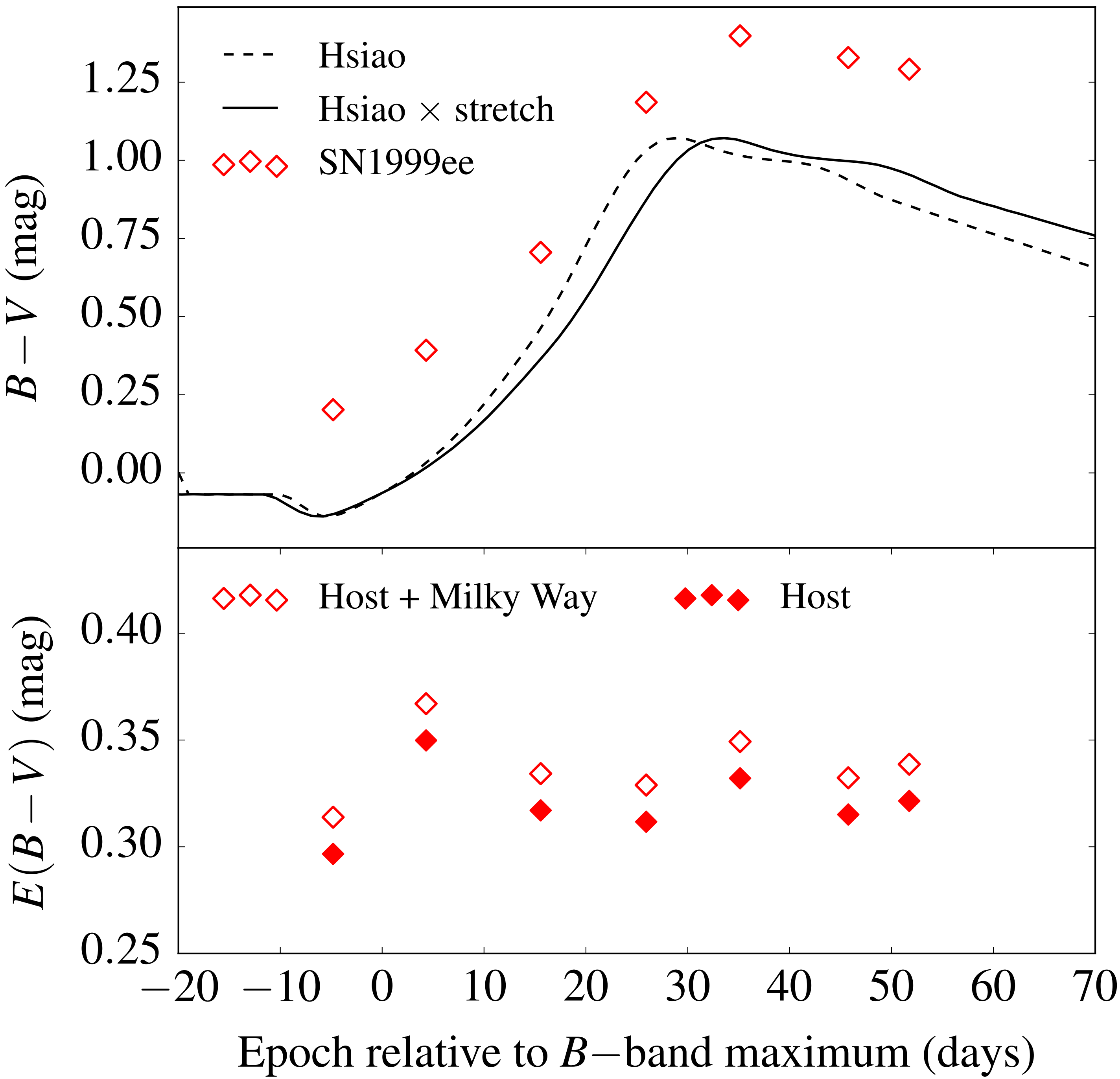


z (pc)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
−1.0
−1.1
$\Delta M_{B,15}^{\rm obs} - \Delta M_{B,15}^{\rm em}$ (mag)
A
B
C
$E(B-V)_{\rm DLOS} = 0.1$
$E(B-V)_{\rm DLOS} = 0.5$
$E(B-V)_{\rm DLOS} = 1.0$
$E(B-V)_{\rm DLOS} = 1.5$
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
z (cm)

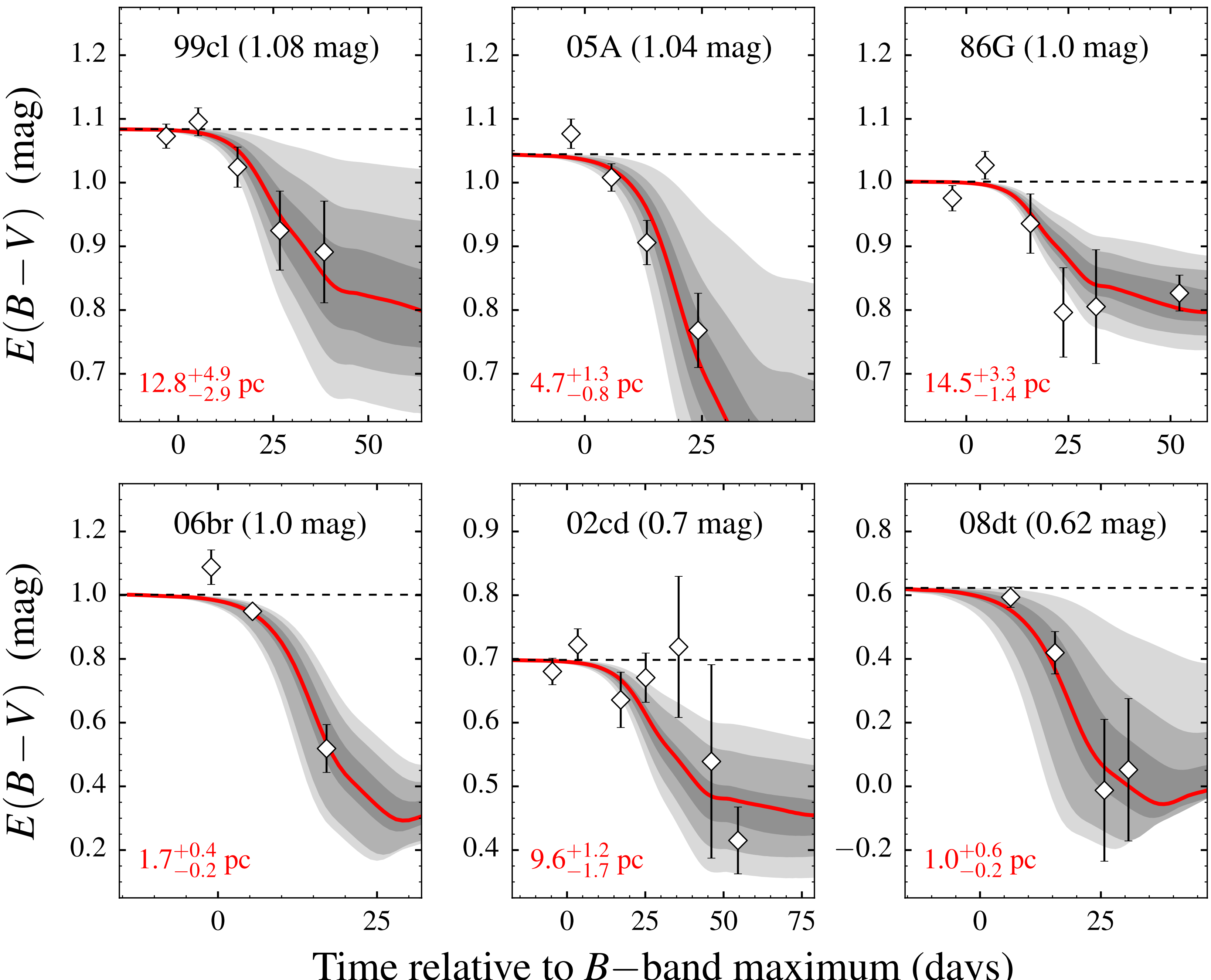


z = 0.001 pc
z = 0.01 pc
z = 0.1 pc
z = 1 pc
z = 10 pc
z = 100 pc
$E(B-V)_{\rm DLOS} = 0.1$
$E(B-V)_{\rm DLOS} = 0.5$
$E(B-V)_{\rm DLOS} = 1.0$
$E(B-V)_{\rm DLOS} = 1.5$
$E(B-V) - E(B-V)_{\rm DLOS}$ (mag)
Epoch relative to $B-$band maximum (days)

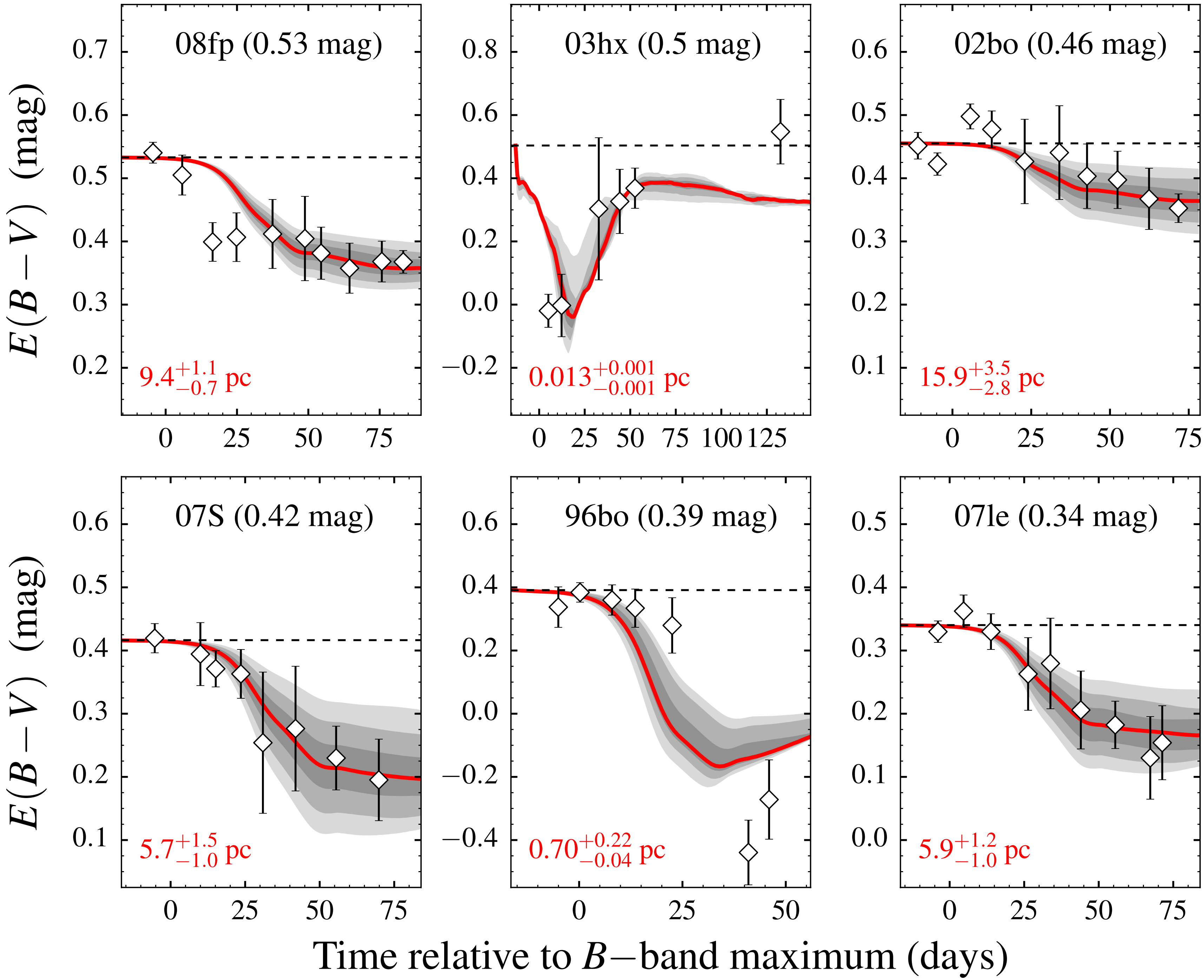

LMC B−band
LMC V−band
MW B−band
MW V−band
Scattered flux (%)
z (pc)
0
10
20
30
40
50
60
10
15
20
25
30
35
40
45
50

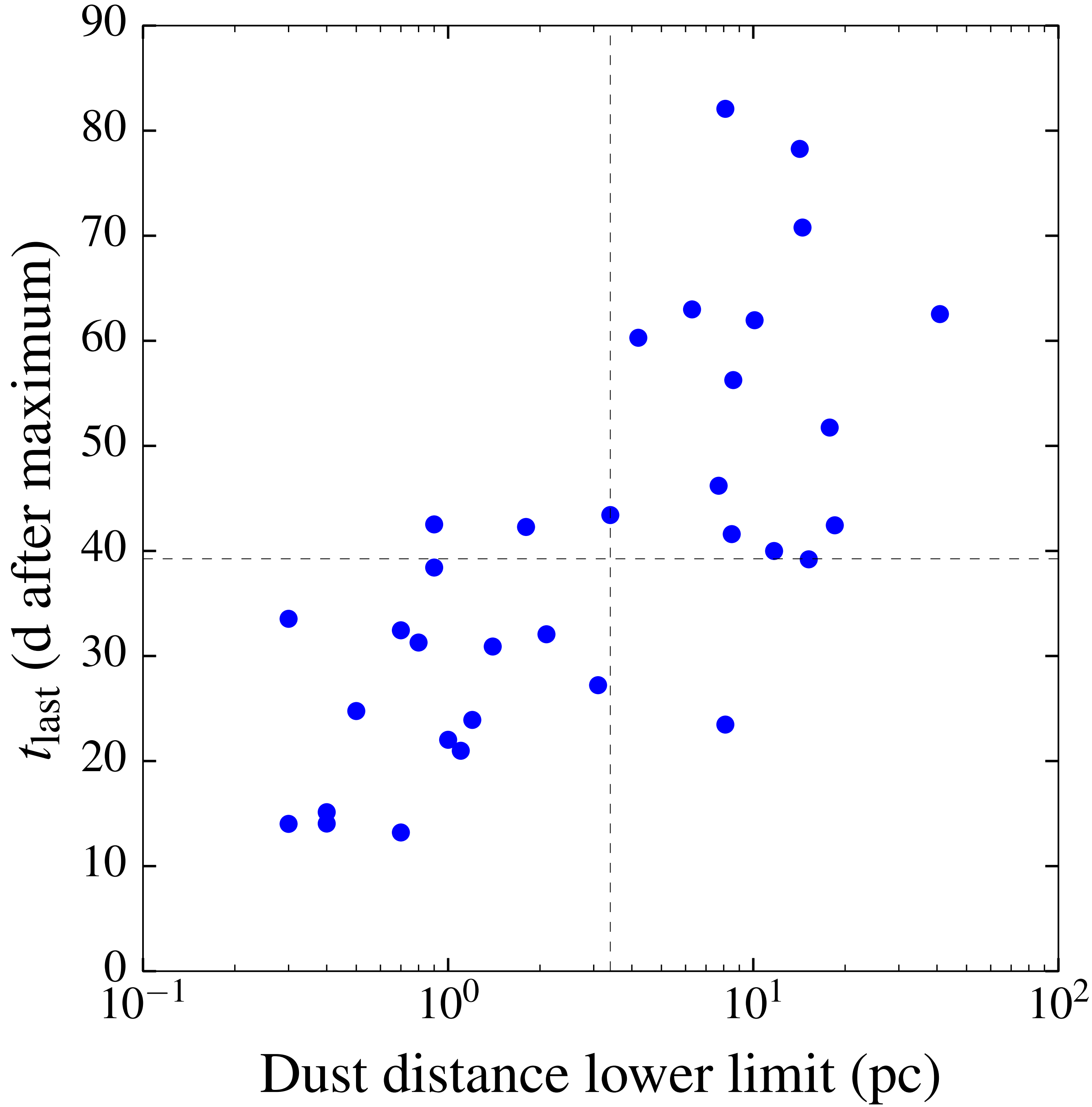


Hsiao
Hsiao × stretch
SN1999ee
Host + Milky Way
Host
1.25
1.00
0.75
0.50
0.25
0.00
B − V (mag)
0.40
0.35
0.30
0.25
E(B − V) (mag)
−20
−10
0
10
20
30
40
50
60
70
Epoch relative to B−band maximum (days)

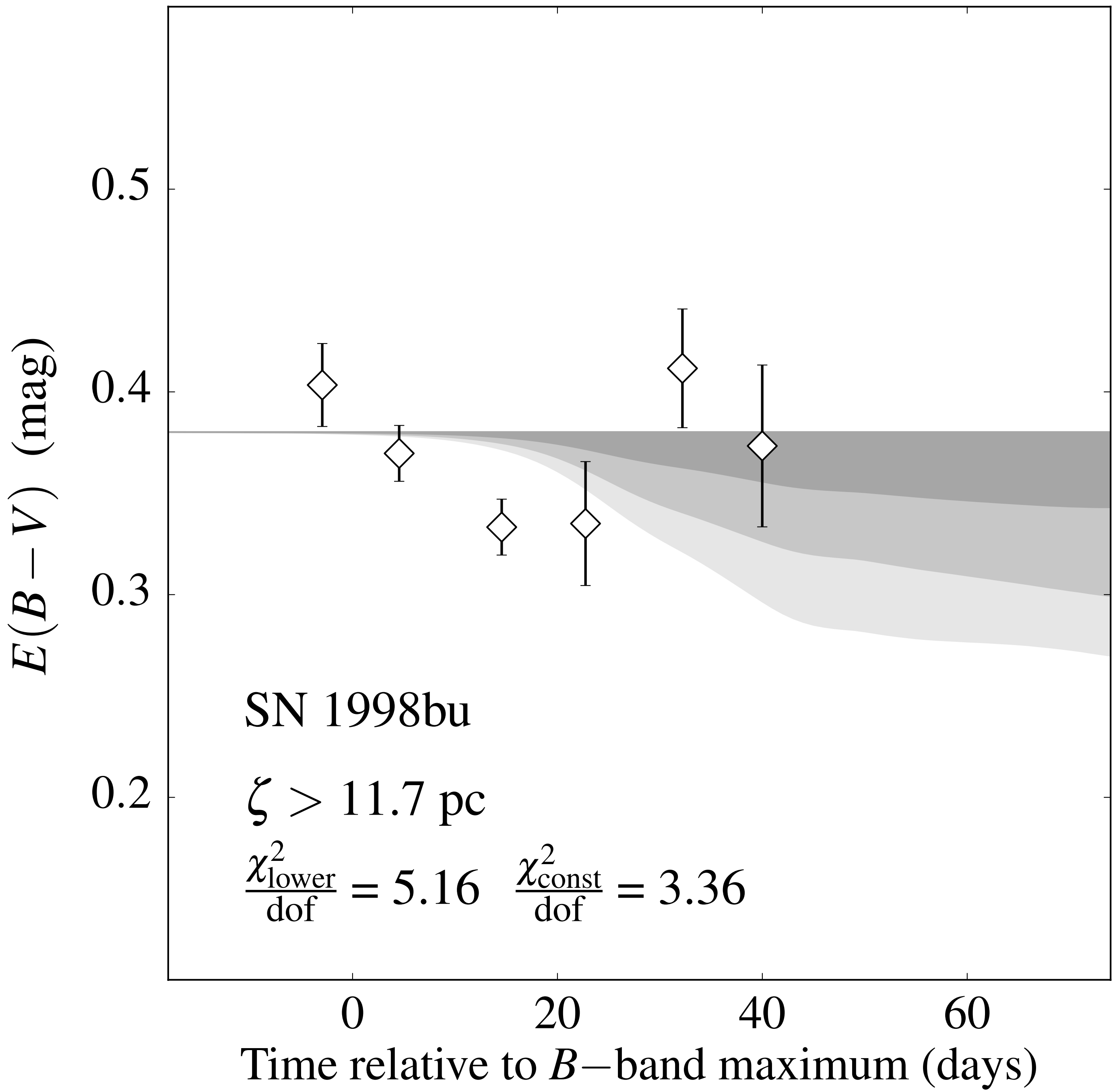


99cl (1.08 mag)
$12.8^{+4.9}_{-2.9}$ pc
05A (1.04 mag)
$4.7^{+1.3}_{-0.8}$ pc
86G (1.0 mag)
$14.5^{+3.3}_{-1.4}$ pc
06br (1.0 mag)
$1.7^{+0.4}_{-0.2}$ pc
02cd (0.7 mag)
$9.6^{+1.2}_{-1.7}$ pc
08dt (0.62 mag)
$1.0^{+0.6}_{-0.2}$ pc
$E(B-V)$ (mag)
Time relative to $B-$band maximum (days)

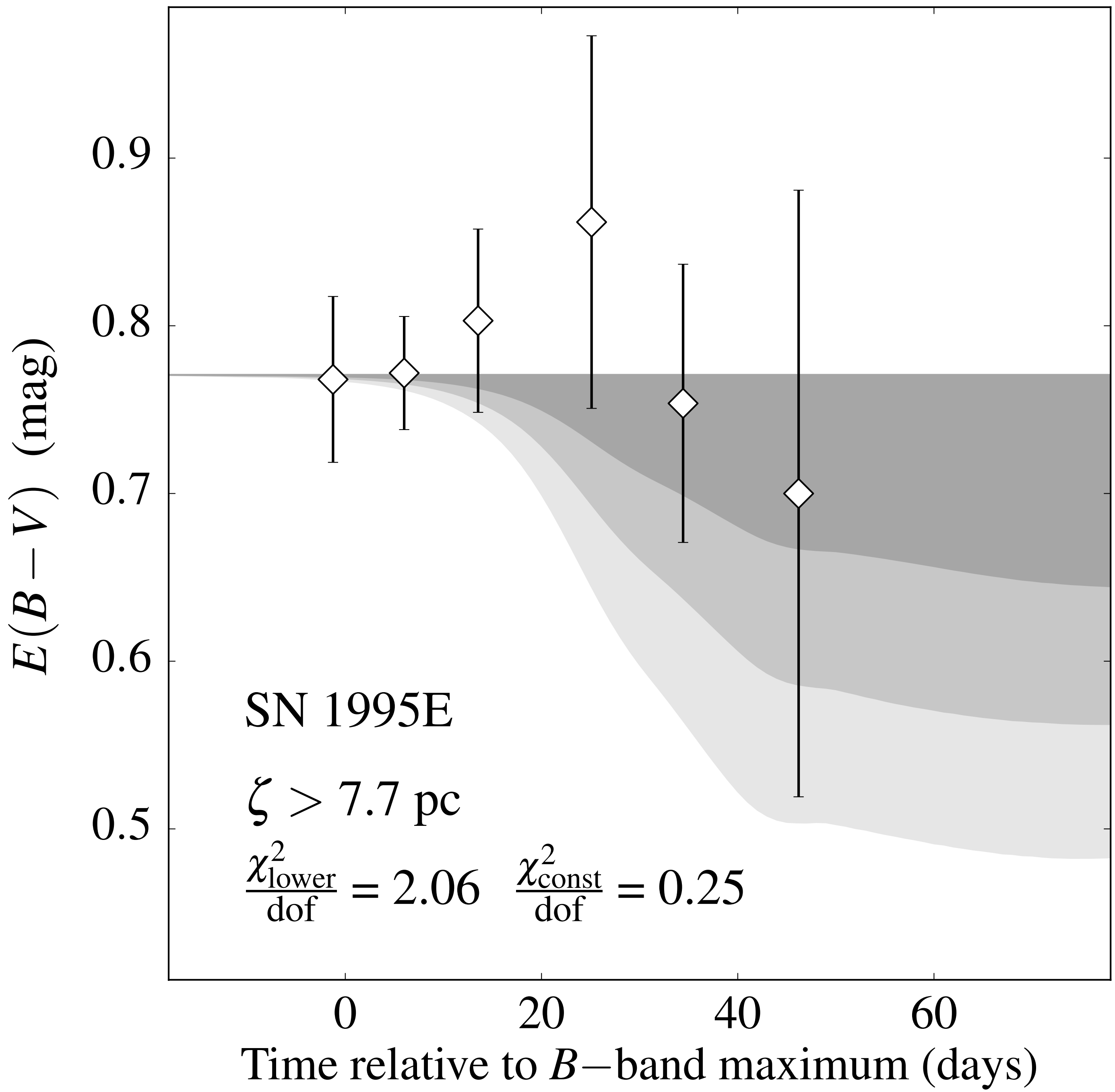

08fp (0.53 mag)
$9.4^{+1.1}_{-0.7}$ pc
03hx (0.5 mag)
$0.013^{+0.001}_{-0.001}$ pc
02bo (0.46 mag)
$15.9^{+3.5}_{-2.8}$ pc
07S (0.42 mag)
$5.7^{+1.5}_{-1.0}$ pc
96bo (0.39 mag)
$0.70^{+0.22}_{-0.04}$ pc
07le (0.34 mag)
$5.9^{+1.2}_{-1.0}$ pc
$E(B-V)$ (mag)
Time relative to $B-$band maximum (days)



90
80
70
60
50
40
30
20
10
0
10^{-1}
10^{0}
10^{1}
10^{2}
t_{last} (d after maximum)
Dust distance lower limit (pc)



0.5
0.4
0.3
0.2
$E(B-V)$ (mag)
SN 1998bu
$\zeta > 11.7$ pc
$\frac{\chi^2_{\rm lower}}{\rm dof} = 5.16$ $\frac{\chi^2_{\rm const}}{\rm dof} = 3.36$
0
20
40
60
Time relative to $B-$band maximum (days)



SN 1995E
$\zeta > 7.7$ pc
$\frac{\chi^2_{\rm lower}}{\rm dof} = 2.06$ $\frac{\chi^2_{\rm const}}{\rm dof} = 0.25$
$E(B-V)$ (mag)
0.5
0.6
0.7
0.8
0.9
0
20
40
60
Time relative to $B-$band maximum (days)