Near-infrared distances to type Ia supernovae

Saurabh W. Jha

NOAO 4m image of SN 2011fe in M101 (T.A. Rector, H. Schweiker & S. Pakzad)

SN 2014J in M82 (Marco Burali, Osservatorio MTM Pistoia)

Supernova Cosmology Analysis Meeting KICP, University of Chicago October 2, 2019

RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

REVIEW ARTICLE
https://doi.org/10.1038/s41550-019-0858-0

nature astronomy

NATURE ASTRONOMY | VOL 3 | AUGUST 2019 | 706–716 | www.nature.com/natureastronomy

Observational properties of thermonuclear supernovae

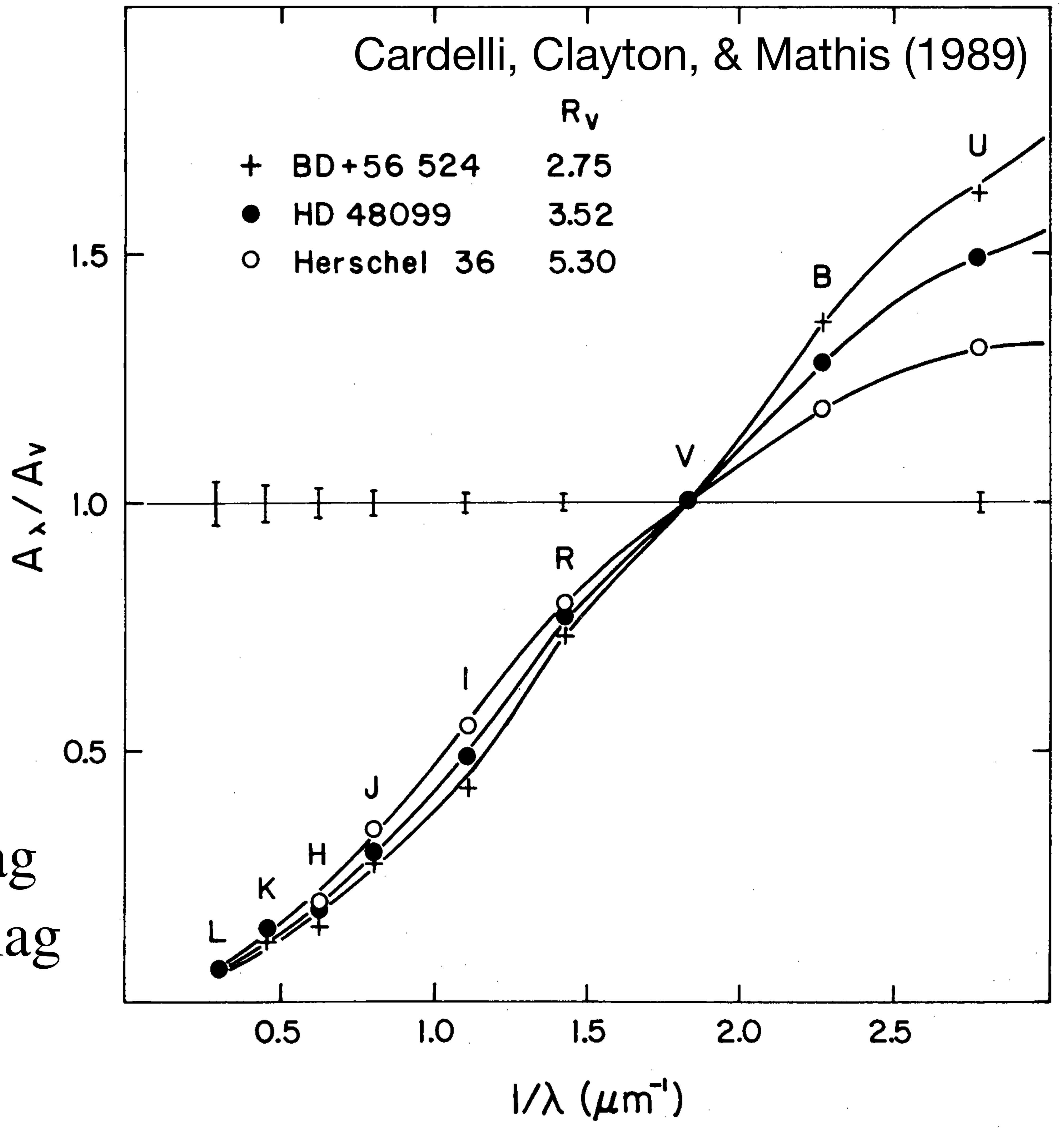
Saurabh W. Jha[1,2*], Kate Maguire[3,4] and Mark Sullivan[5]

The explosive death of a star as a supernova is one of the most dramatic events in the Universe. Supernovae have an outsized impact on many areas of astrophysics: they are major contributors to the chemical enrichment of the cosmos and significantly influence the formation of subsequent generations of stars and the evolution of galaxies. Here we review the observational properties of thermonuclear supernovae—exploding white dwarf stars resulting from the stellar evolution of low-mass stars in close binary systems. The best known objects in this class are type-Ia supernovae (SNe Ia), astrophysically important in their application as standardizable candles to measure cosmological distances and the primary source of iron group elements in the Universe. Surprisingly, given their prominent role, SN Ia progenitor systems and explosion mechanisms are not fully understood; the observations we describe here provide constraints on models, not always in consistent ways. Recent advances in supernova discovery and follow-up have shown that the class of thermonuclear supernovae includes more than just SNe Ia, and we characterize that diversity in this review.

https://arxiv.org/abs/1908.02303

Why NIR?

- mitigate dust extinction



Tripp (1998) standardization, e.g., SALT2

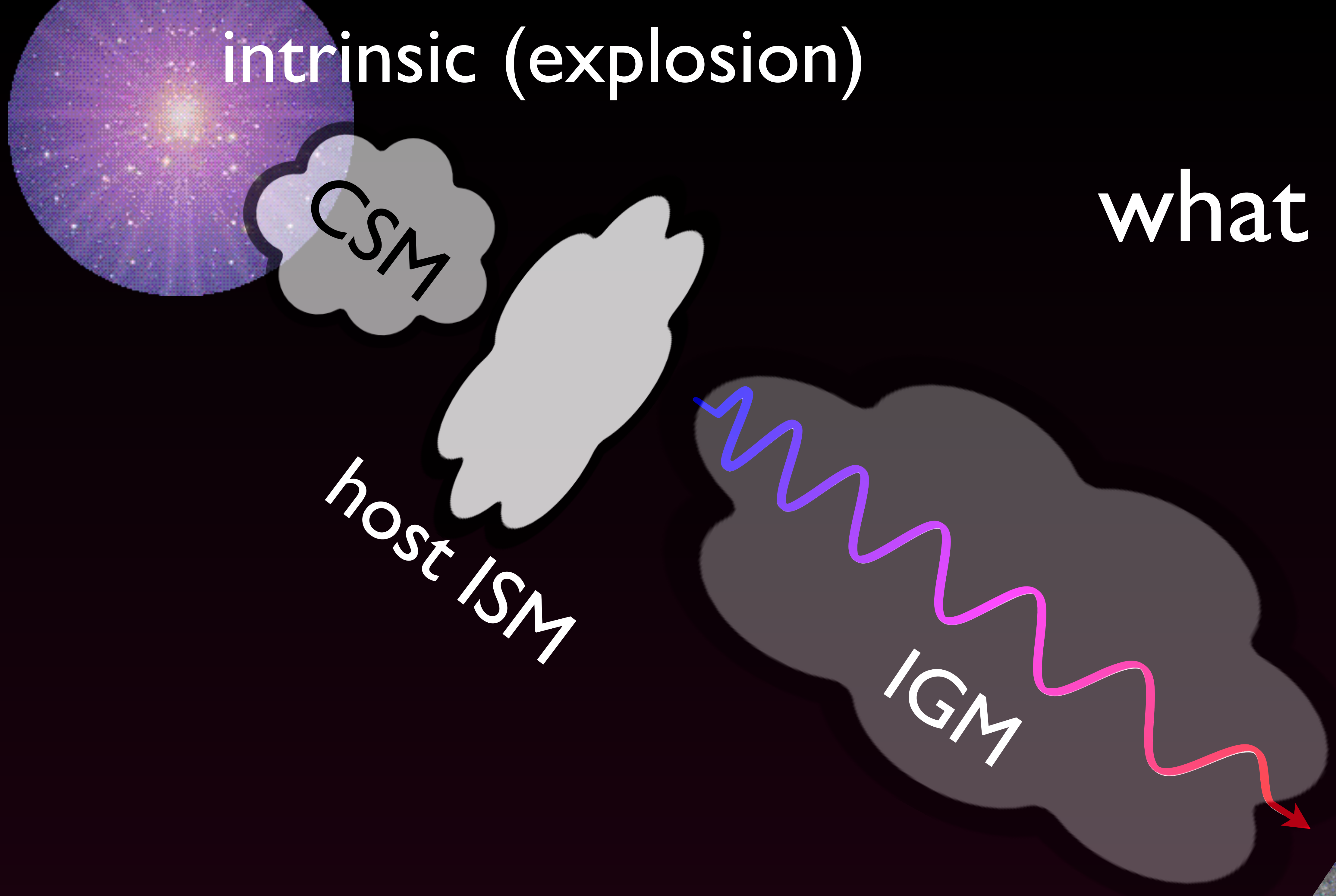
$$m_B - \alpha x_1 + \beta c$$

$$\alpha \approx 0.14 \quad x_1 \in [-2,2] \;\Rightarrow -0.28 \le \alpha x_1 \le +0.28\,\mathrm{mag}$$

$$\beta \approx 3.1 \quad c \in [-0.1,0.3] \;\Rightarrow -0.31 \le \beta c \le +0.93\,\mathrm{mag}$$

color gives the largest correction for supernova cosmology analysis

what affects SN Ia colors?



intergalactic extinction could
be significant for highest-z SN Ia

Menard et al. (2010)

evidence for CSM: variable Na I D lines

Patat et al. (2007), Blondin et al. (2009), Simon et al. (2009),
Sternberg et al. (2011), Phillips et al. (2013), Maguire et al. (2013)

intrinsic colors depend on host galaxy, viewing angle,
velocity? (ask Rutgers grad student Kyle Dettman here!)

Why NIR?

- mitigate dust extinction

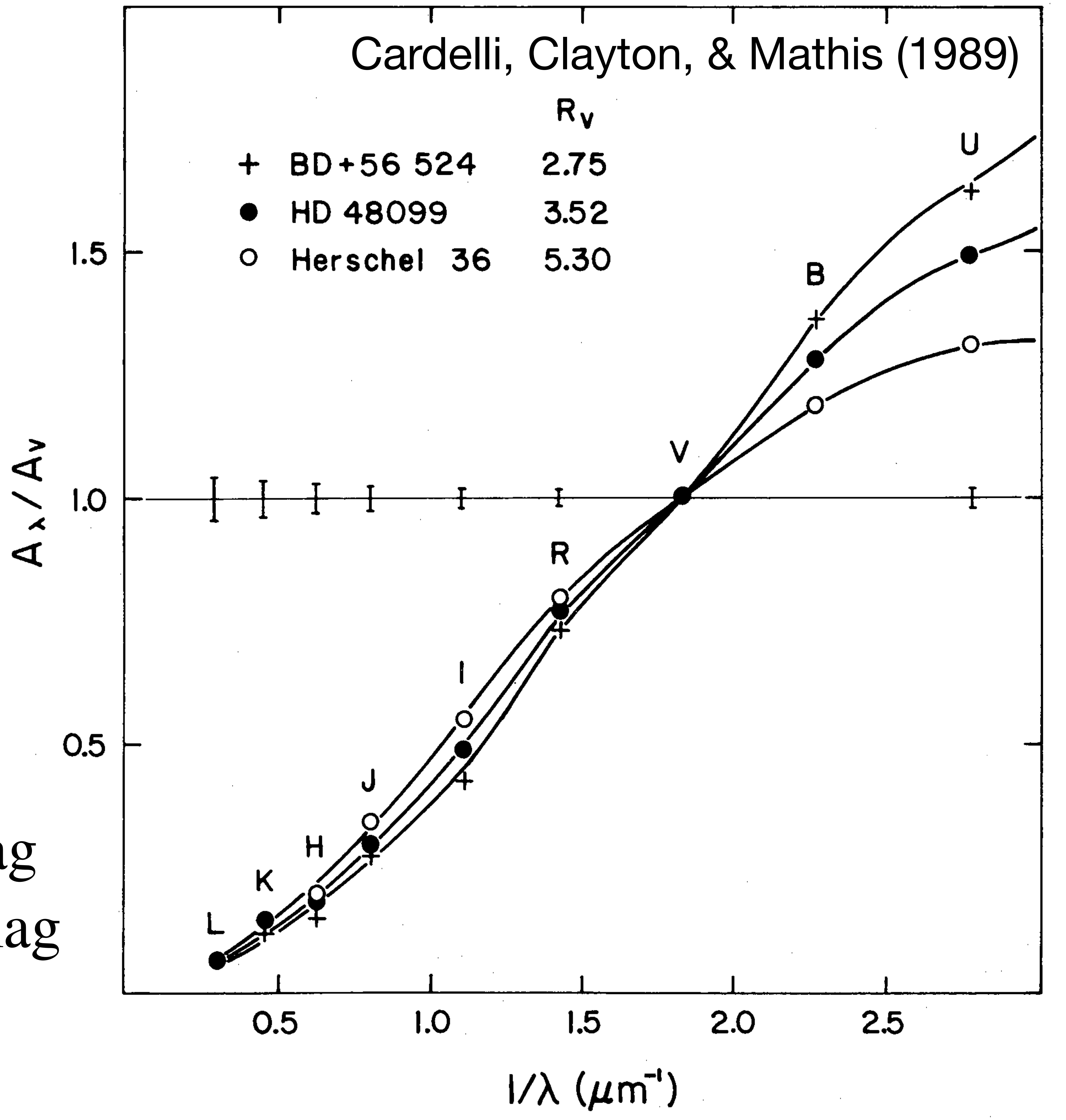
Tripp (1998) standardization, e.g., SALT2

$$m_B - \alpha x_1 + \beta c$$

$$\alpha \approx 0.14 \quad x_1 \in [-2,2] \;\Rightarrow -0.28 \le \alpha x_1 \le +0.28\,\mathrm{mag}$$

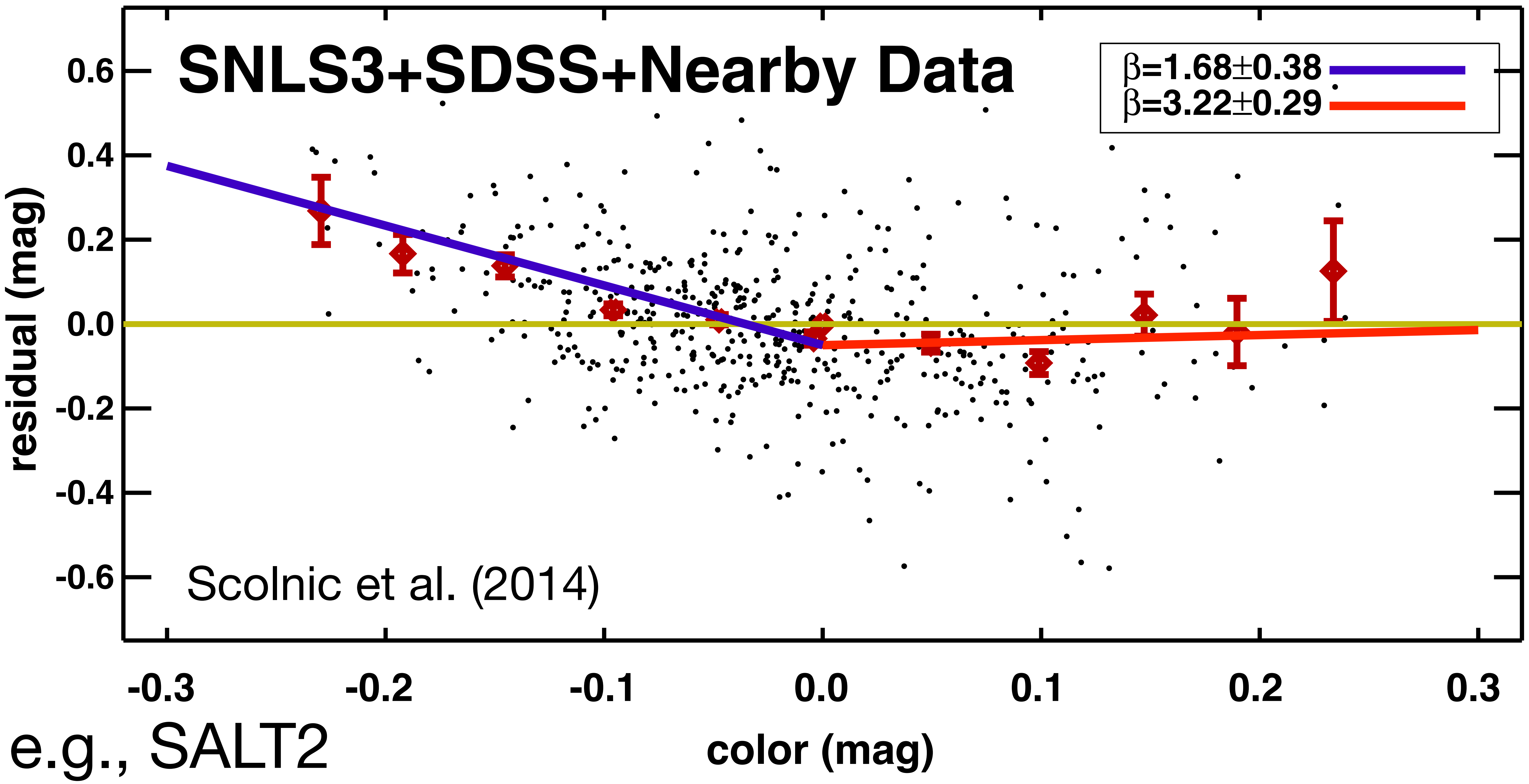
$$\beta \approx 3.1 \quad c \in [-0.1,0.3] \;\Rightarrow -0.31 \le \beta c \le +0.93\,\mathrm{mag}$$

color gives the largest correction for supernova cosmology analysis



Why NIR?

- mitigate dust extinction



Tripp (1998) standardization, e.g., SALT2

$$m_B - \alpha x_1 + \beta c$$

$$\alpha \approx 0.14 \quad x_1 \in [-2,2] \;\Rightarrow -0.28 \leq \alpha x_1 \leq +0.28\,\mathrm{mag}$$

$$\beta \approx 3.1 \quad c \in [-0.1,0.3] \;\Rightarrow -0.31 \leq \beta c \leq +0.93\,\mathrm{mag}$$

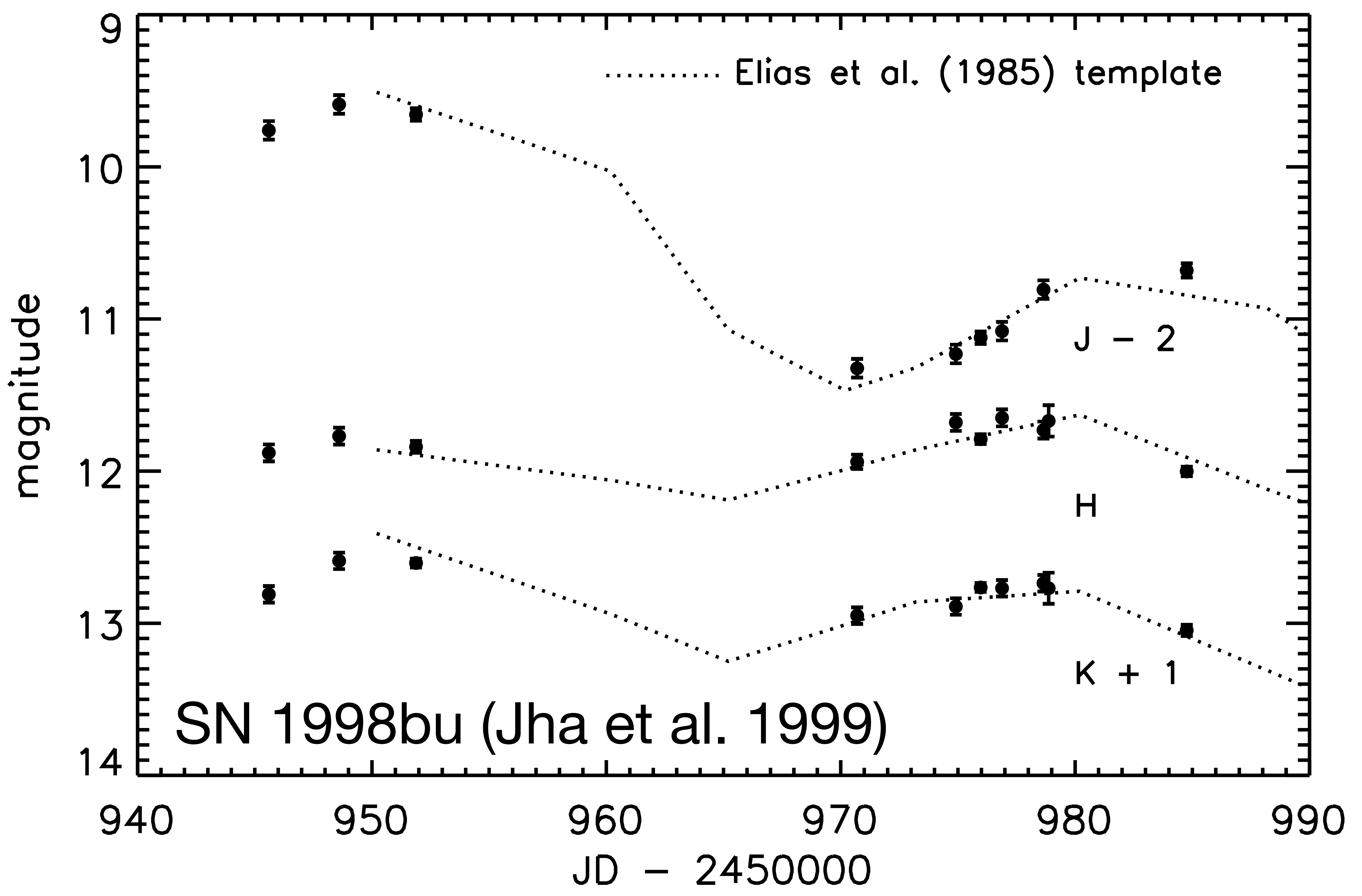
color gives the largest correction for supernova cosmology analysis

Why NIR?

- mitigate dust extinction
- observations (and theory) show SN Ia are better standard candles in NIR

Second, an examination of the use of infrared photometry of Type Ia supernovae for distance determinations suggests that distance moduli to individual galaxies may be accurate to ± 0.2 mag, and possibly ± 0.1 mag, but the data set is still too small for this conclusion to be independent of our initial assumptions.

Elias et al. (1981, 1985)



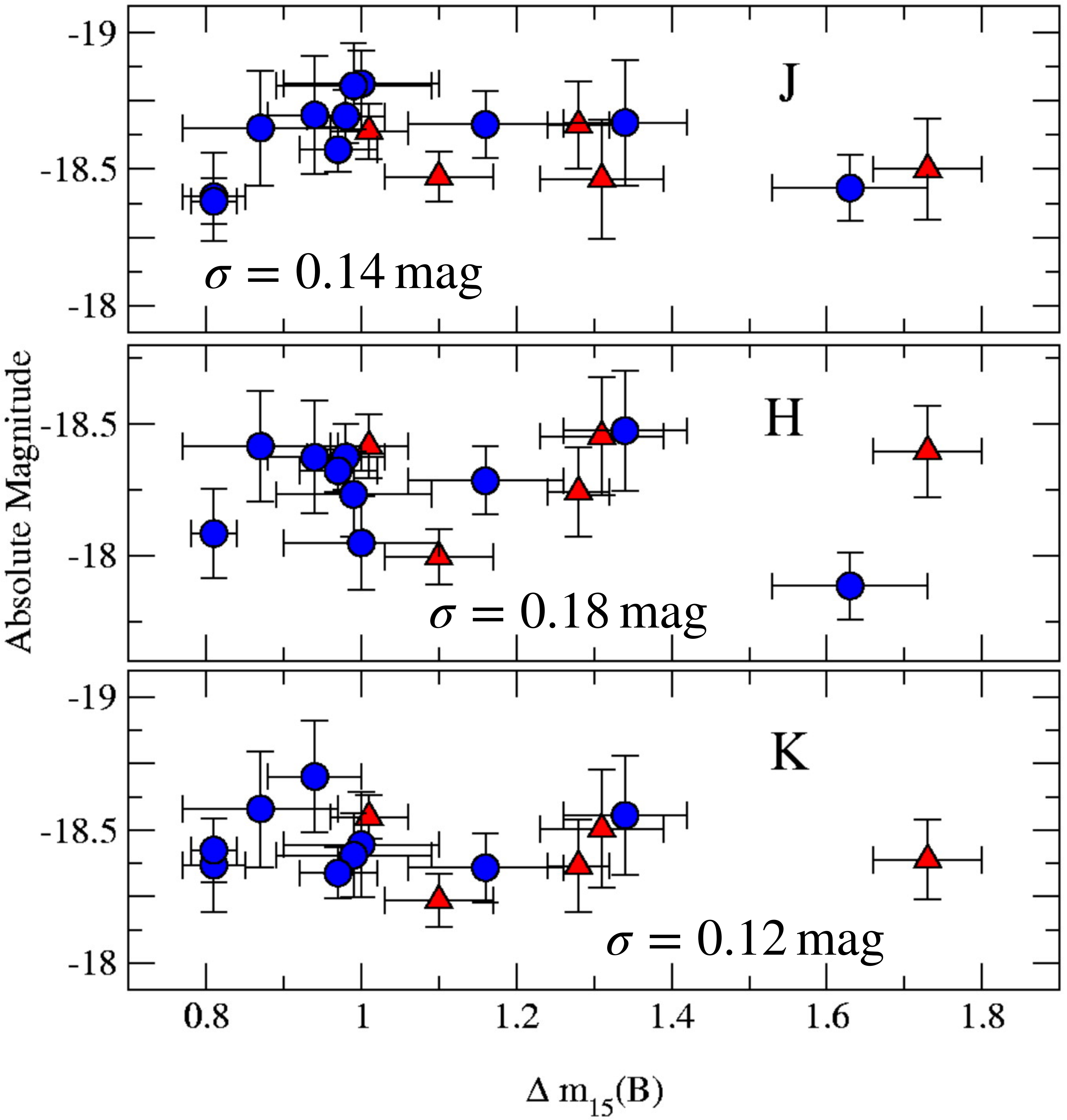
The light curves of the six similar supernovae can be represented fairly consistently with a single light curve in each of the three bands. In all three IR bands the dispersion in absolute magnitude is about 0.15 mag, and this can be accounted for within the uncertainties of the individual light curves. No significant variation of absolute IR magnitude with *B*-band light curve decline rate, $\Delta m_{15}(B)$, is seen over the range $0.87 < \Delta m_{15}(B) < 1.31$. However, the data are insufficient to allow us to decide whether or not the decline rate relation is weaker in the IR than in the optical region. IR light curves of type Ia supernovae should eventually provide cosmological distance estimates that are of equal, or even superior, quality to those obtained in optical studies.

Meikle (2000)

Why NIR?

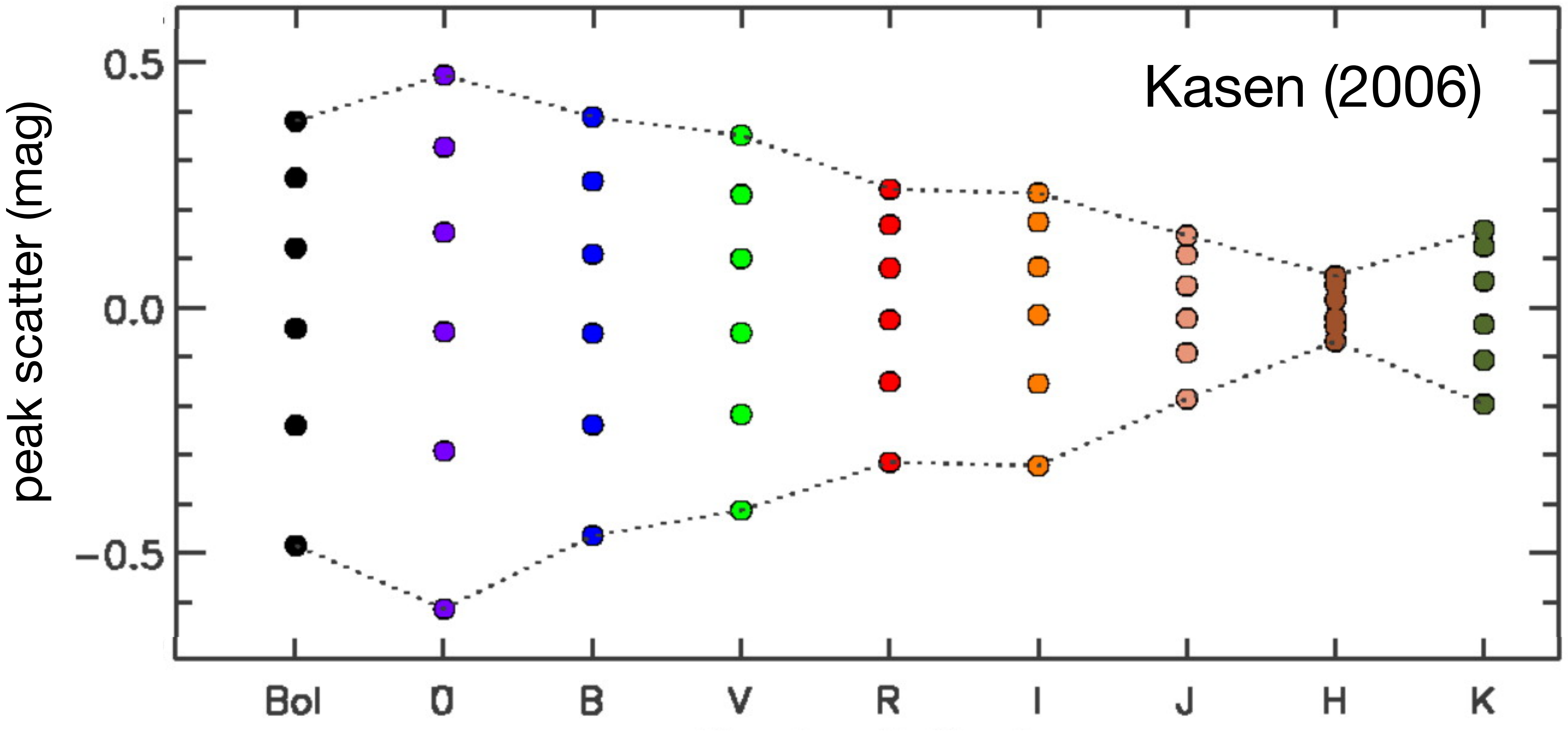
- mitigate dust extinction
- observations (and theory) show SN Ia are better standard candles in NIR

Krisciunas, Phillips, & Suntzeff (2004)

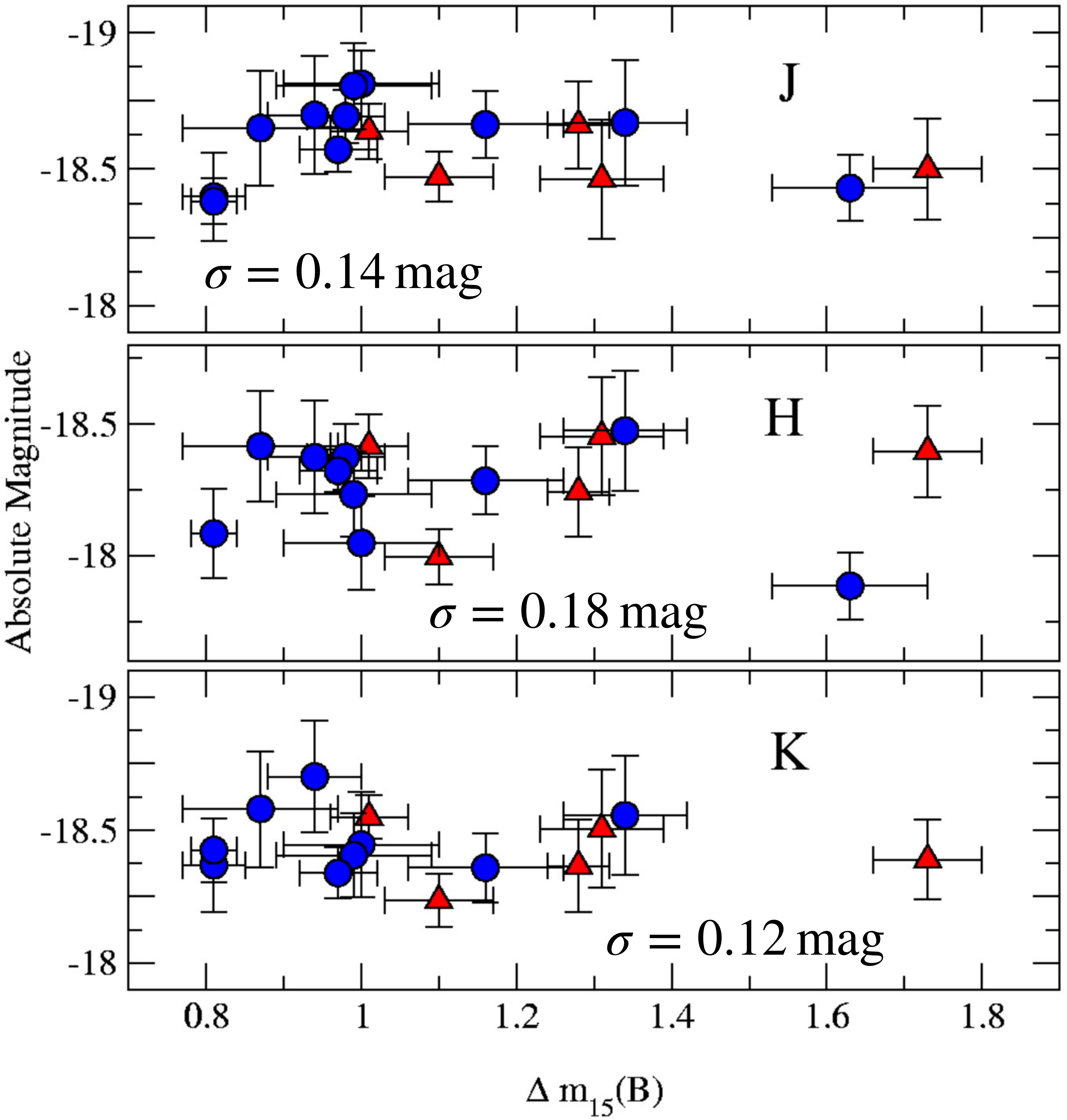


Why NIR?

- mitigate dust extinction
- observations (and theory) show SN Ia are better standard candles in NIR



Krisciunas, Phillips, & Suntzeff (2004)

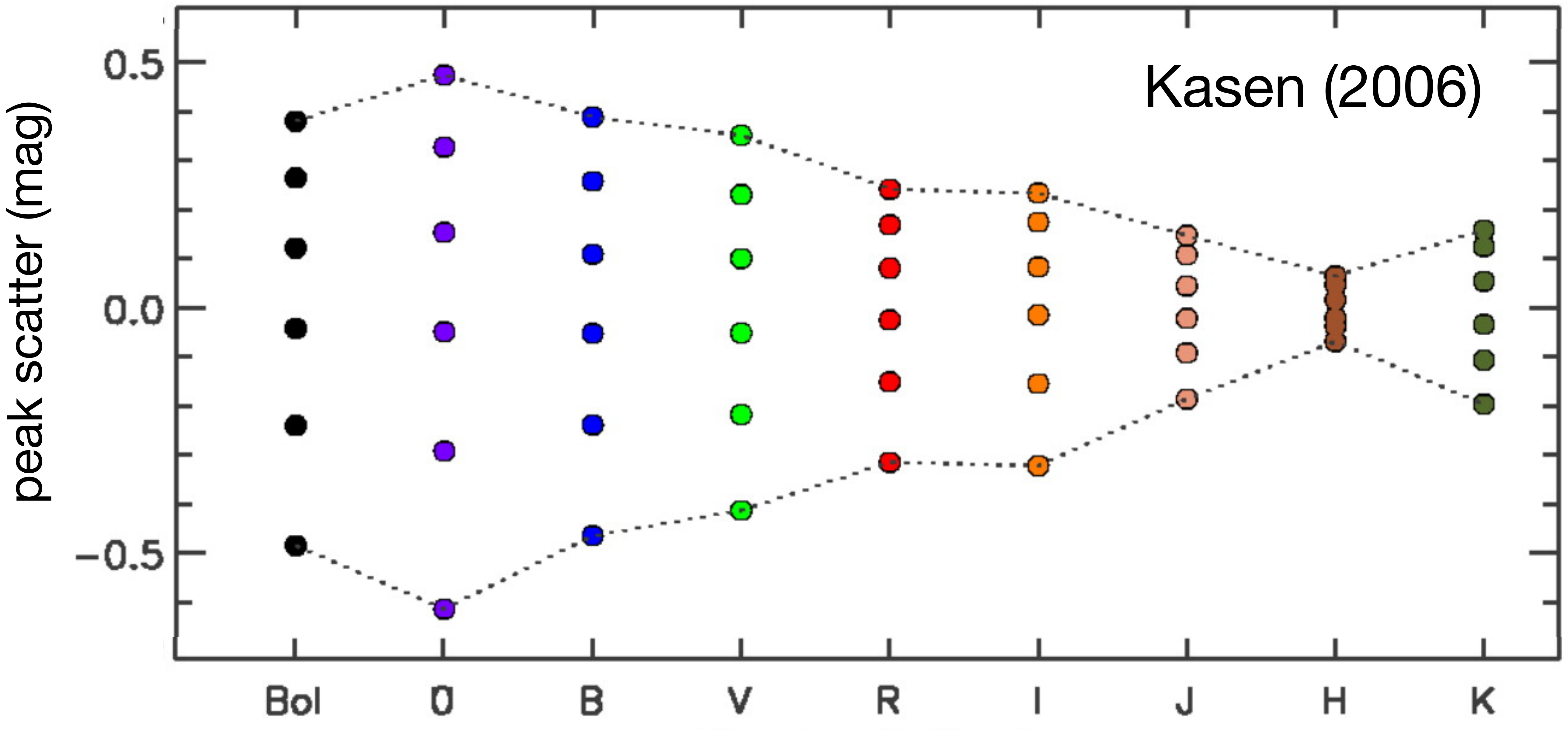


Why NIR?

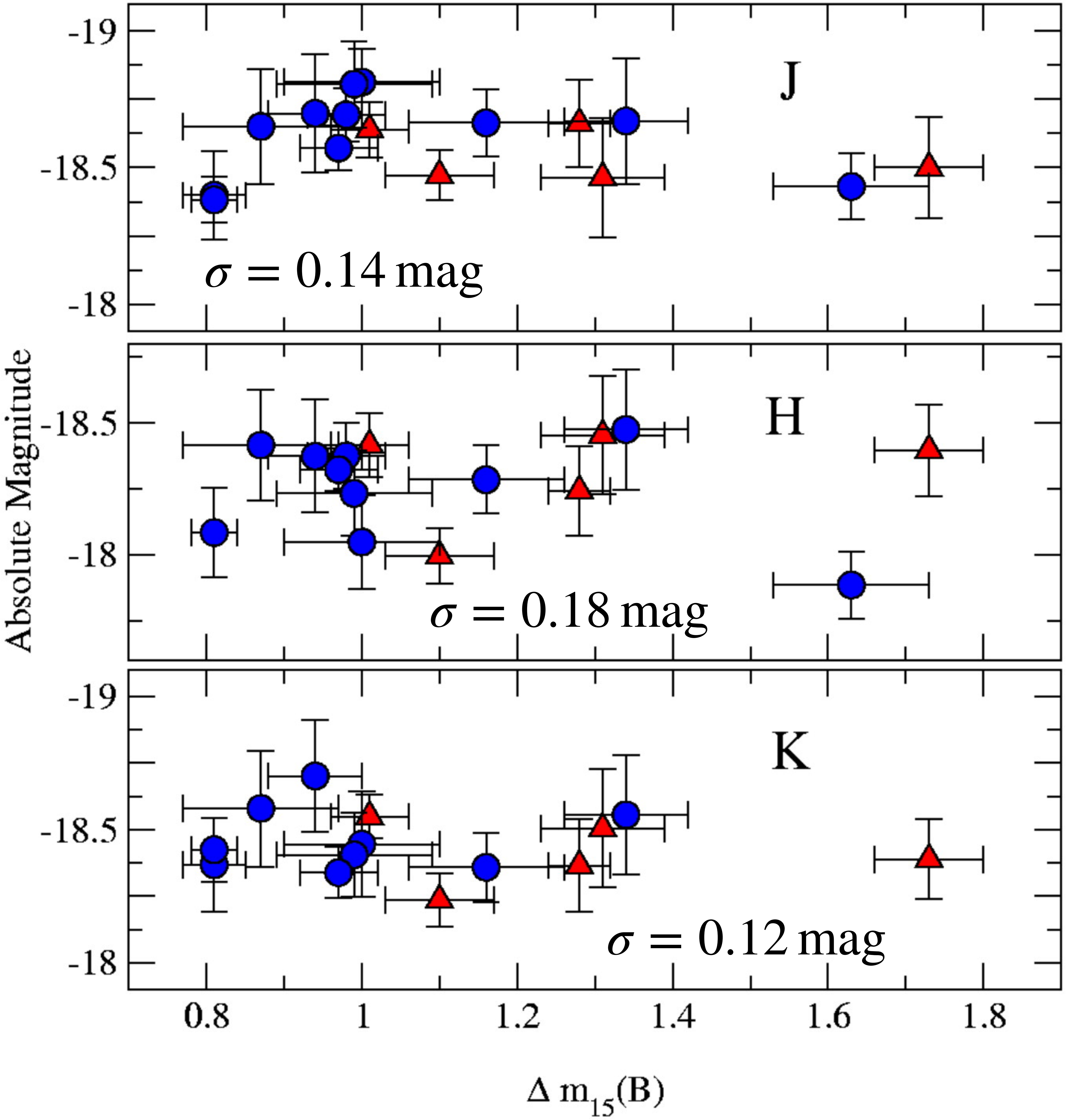
Krisciunas, Phillips, & Suntzeff (2004)

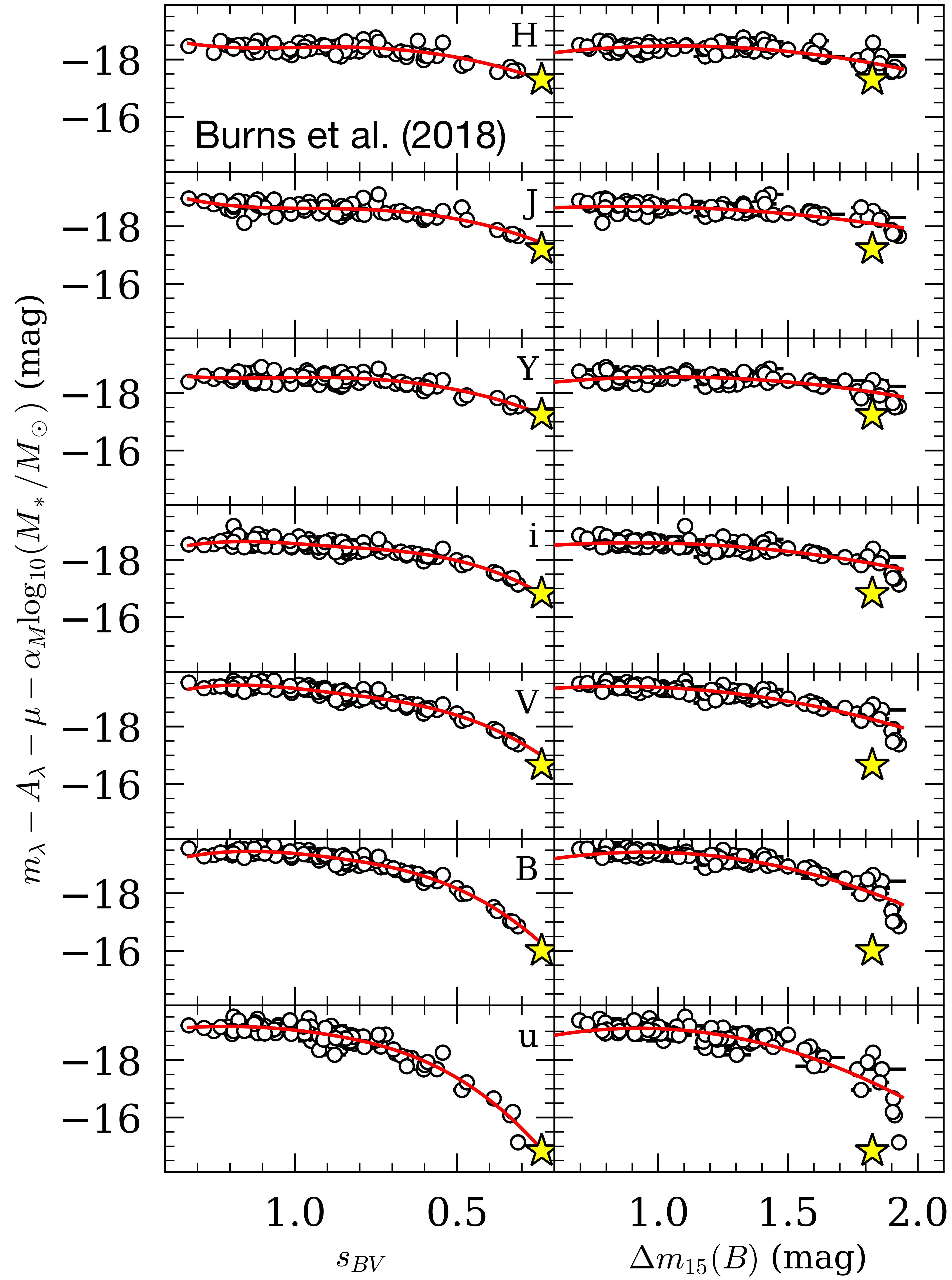
- mitigate dust extinction

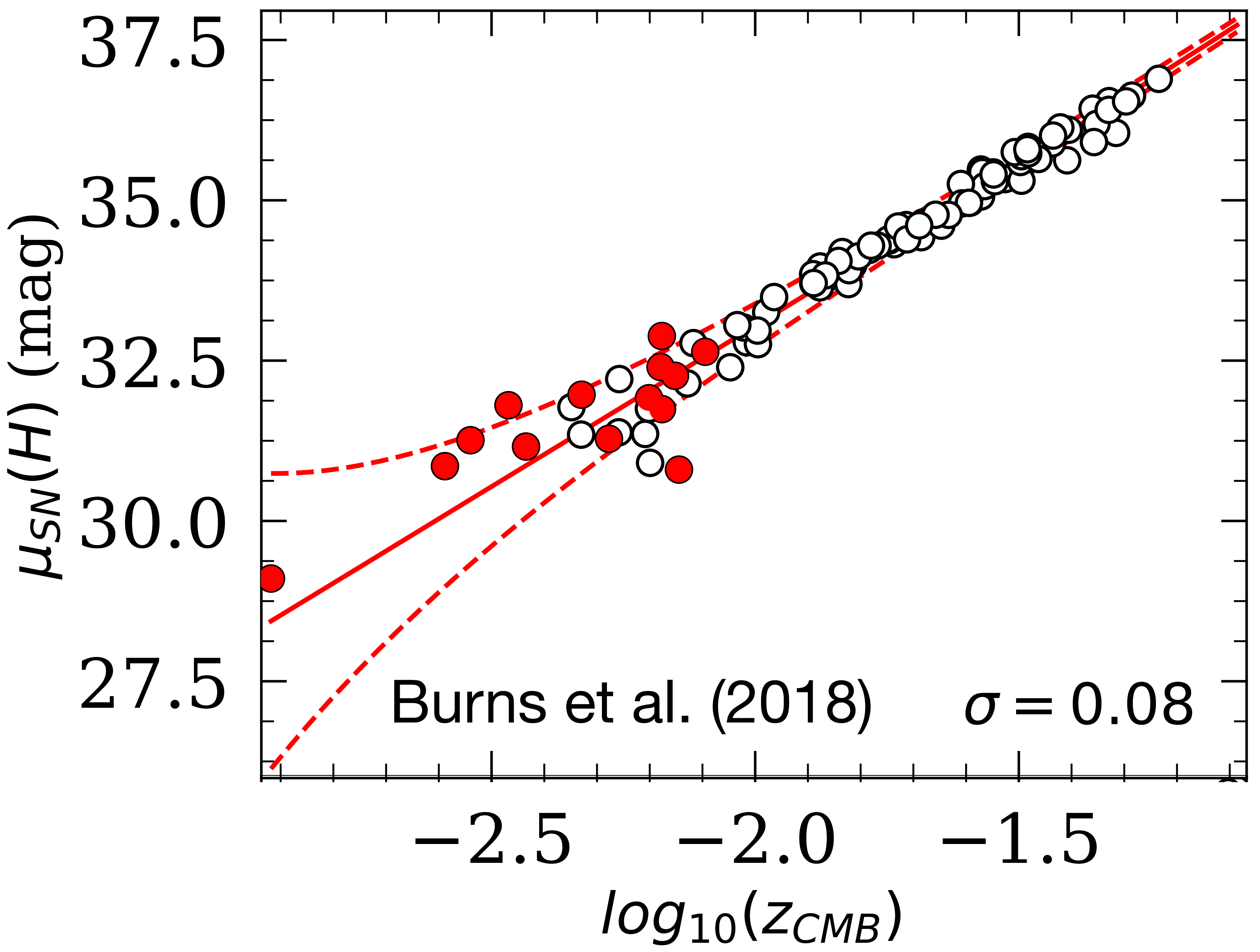
- observations (and theory) show SN Ia are better standard candles in NIR



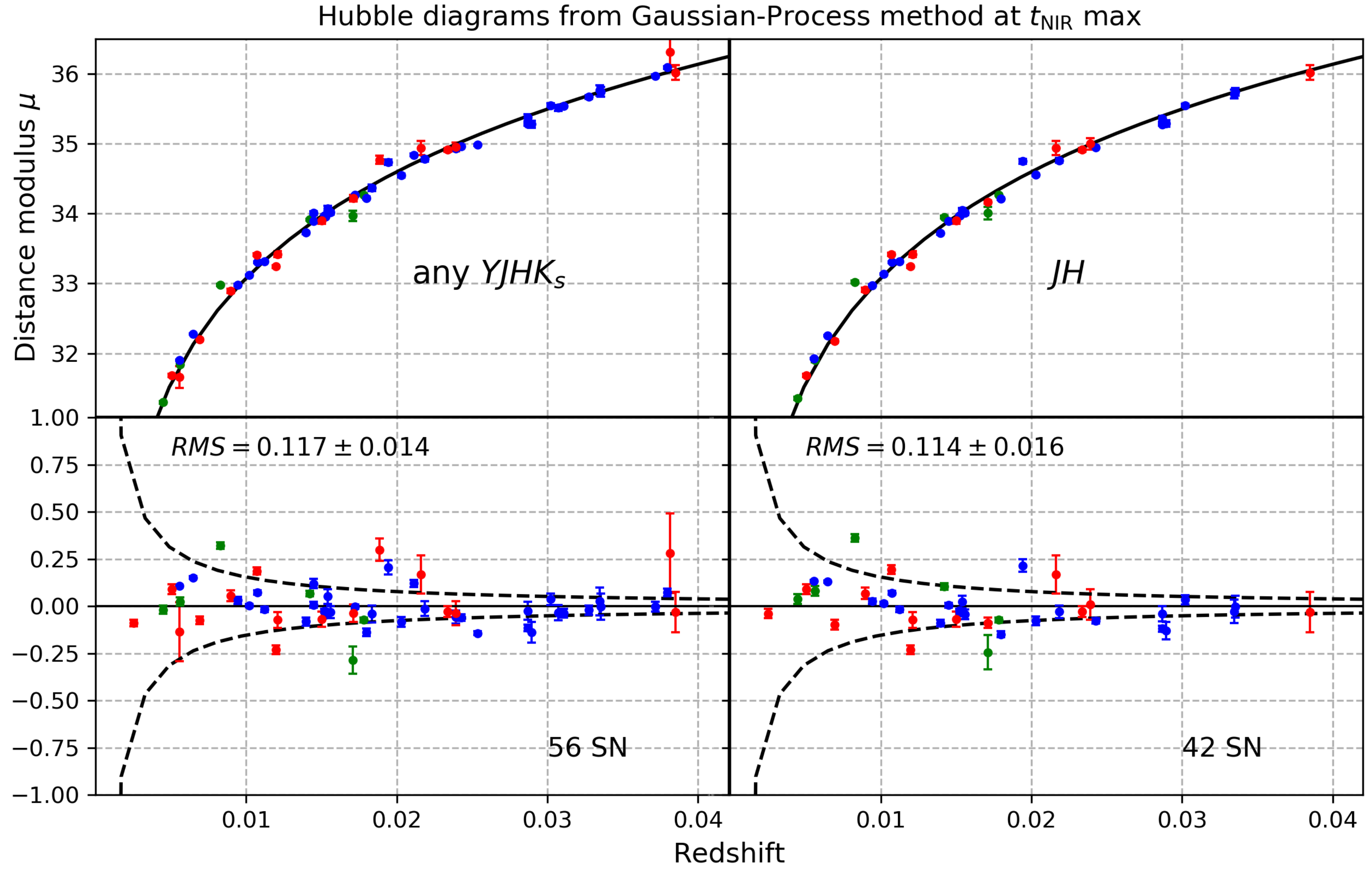
- NIR has only a few percent of SN Ia flux; standardizing the tail rather than the dog?



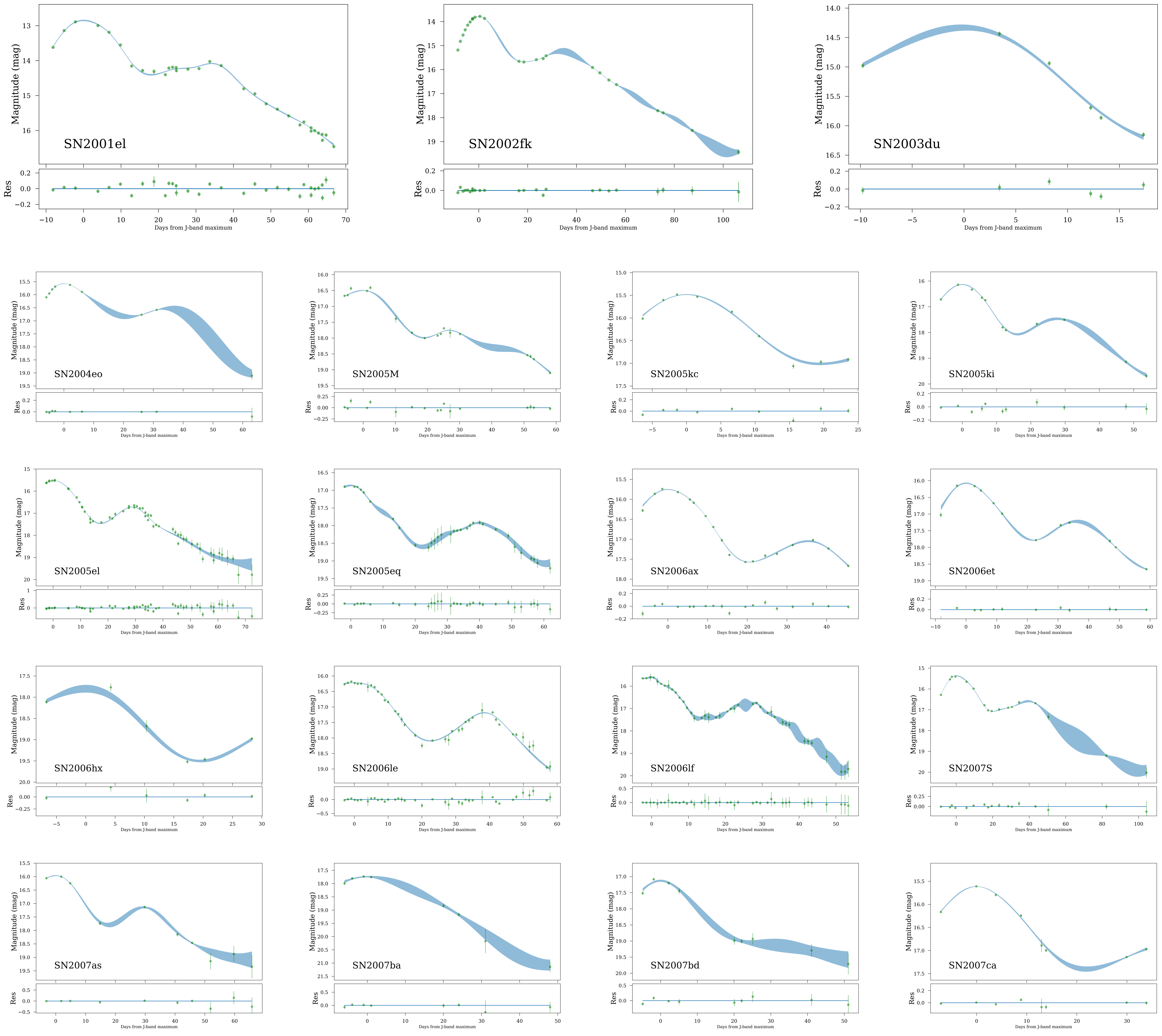


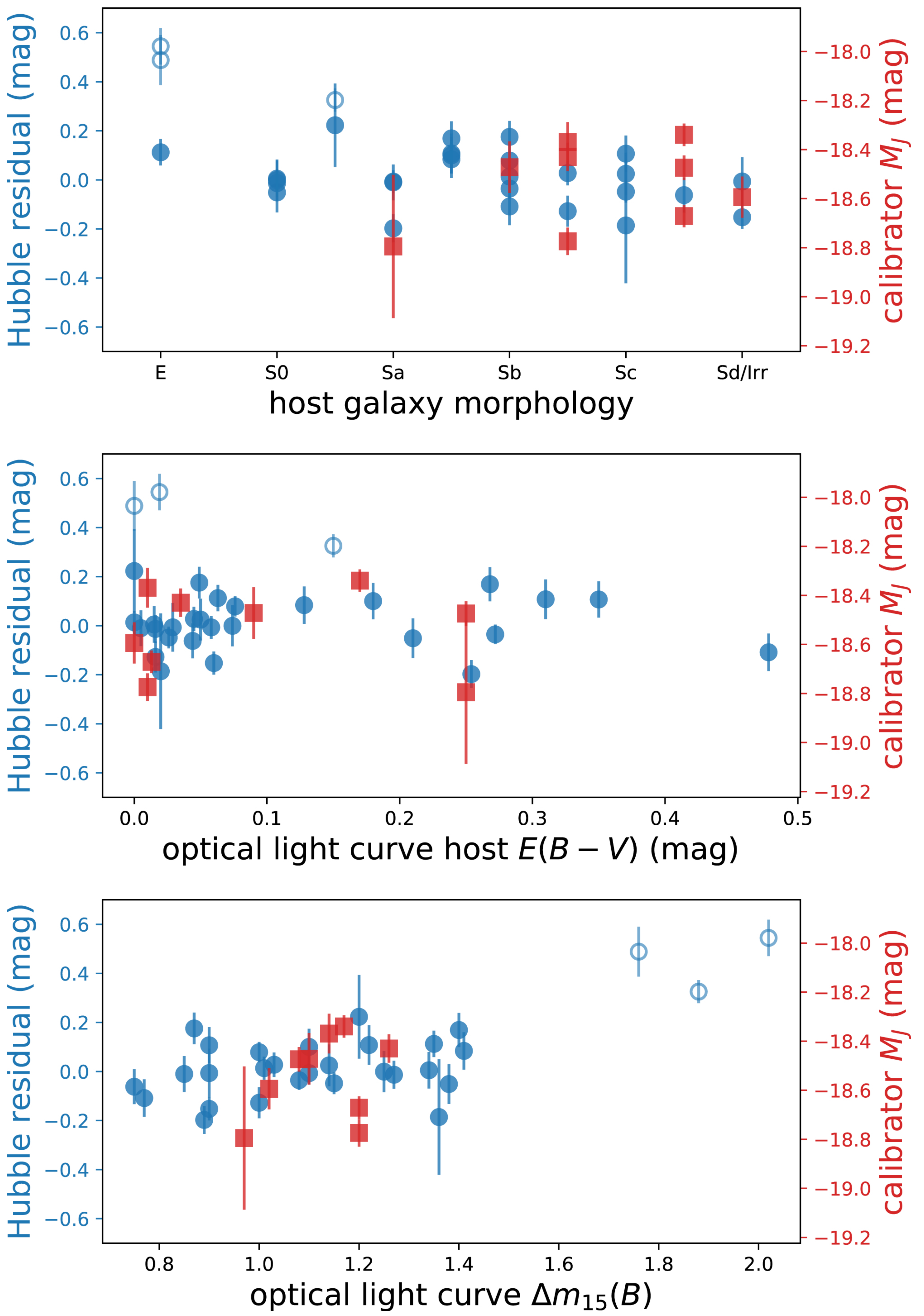


Avelino et al. (2019)

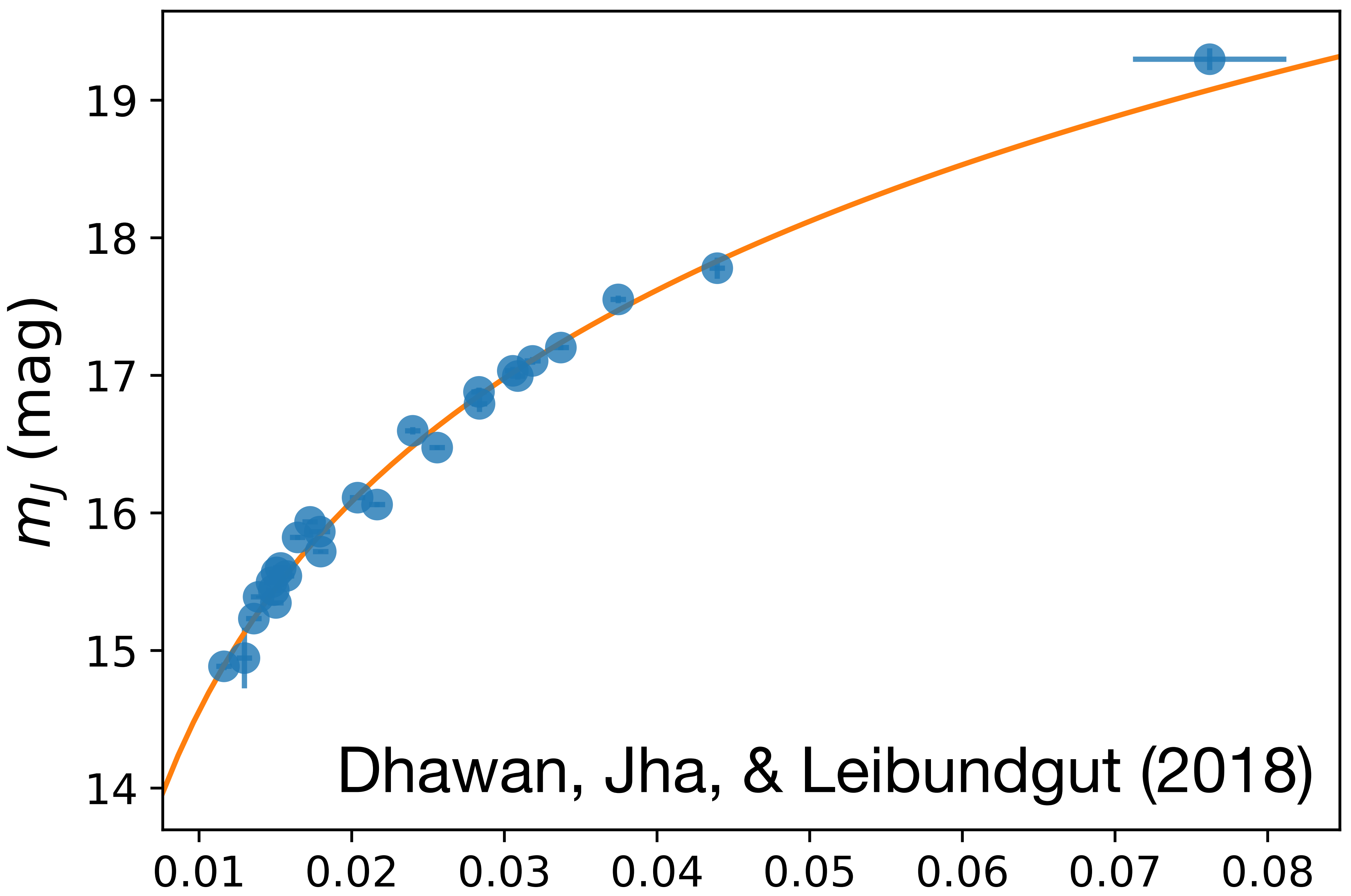


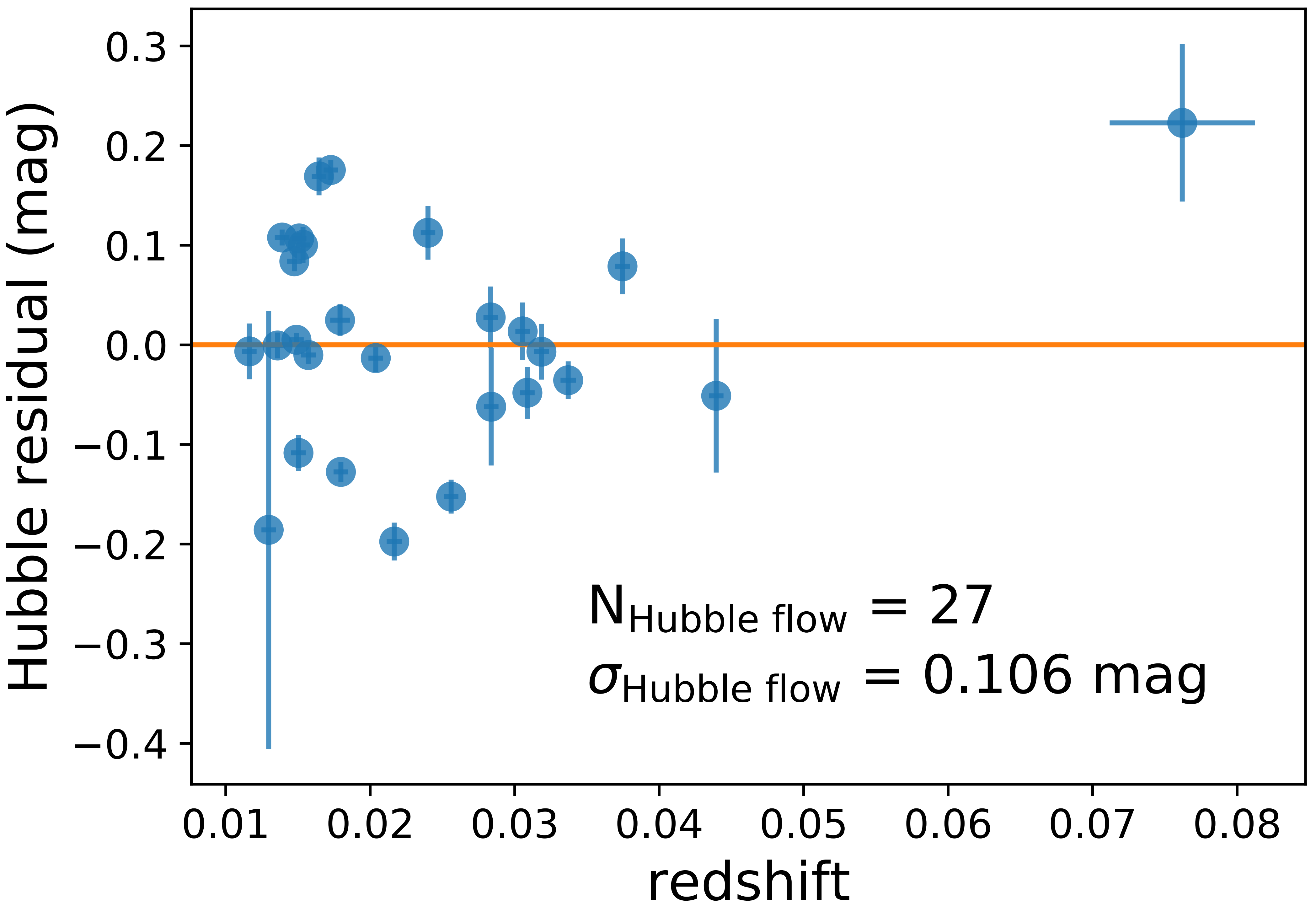
modern samples build upon
Krisciunas et al. (2004)
Hsiao et al. (2007)
Wood-Vasey et al. (2008)
Friedman et al. (2009)
Krisciunas et al. (2009)
Mandel et al. (2009)
Contreras et al. (2010)
Burns et al. (2011)
Mandel et al. (2011)
Stritzinger et al. (2011)
Barone-Nugent et al. (2012)
Kattner et al. (2012)
Matheson et al. (2012)
Phillips et al. (2012)
Stanishev et al. (2012)
Boldt et al. (2014)
Burns et al. (2014)
Weyant et al. (2014)
Amanullah et al. (2015)
Dhawan et al. (2015)
Friedman et al. (2015)
Krisciunas et al. (2017)
Mandel et al. (2017)
Stanishev et al. (2018)
Weyant et al. (2018)
Phillips et al. (2019)...

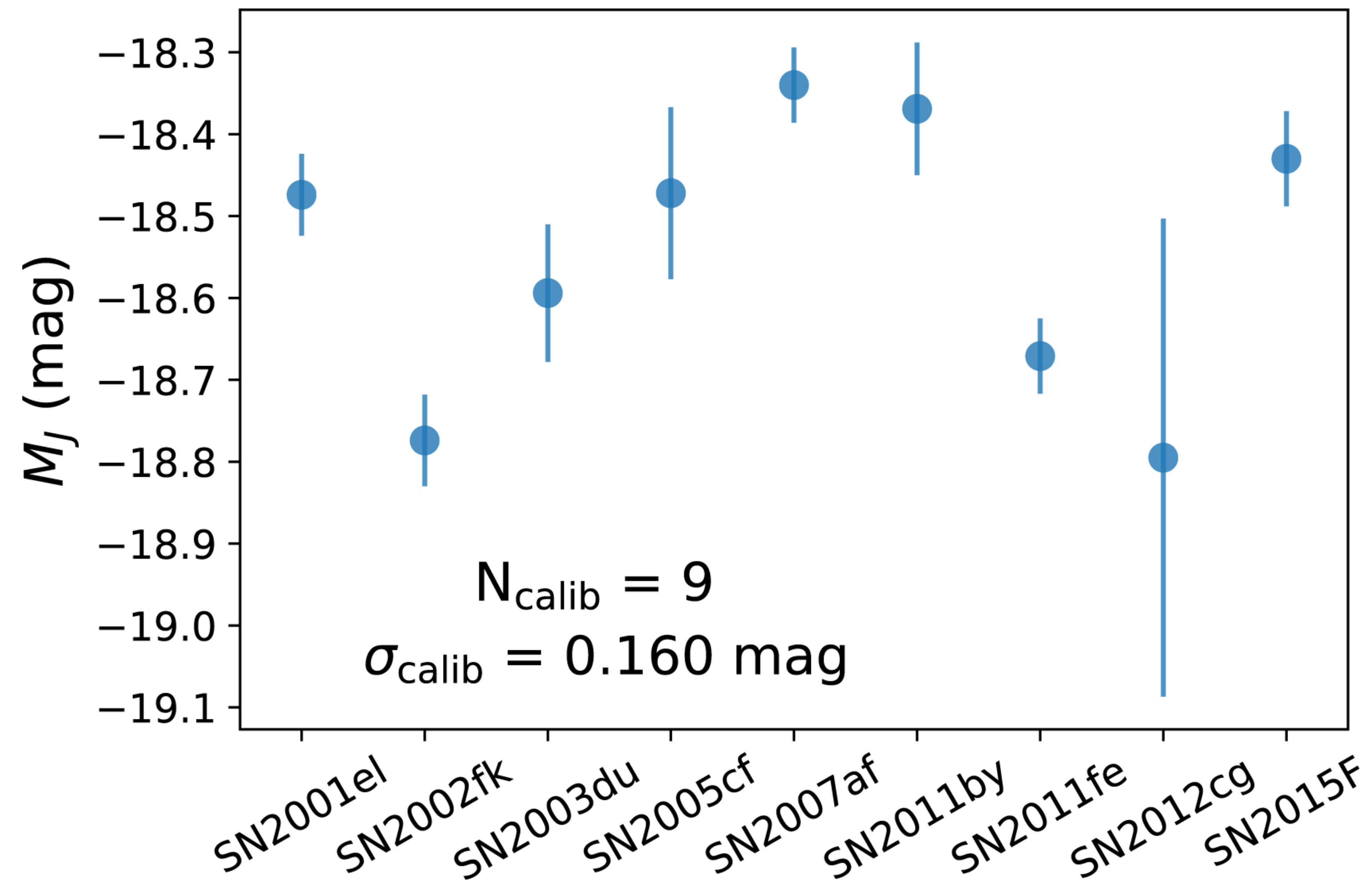




Dhawan, Jha, & Leibundgut (2018) “simple” GP fits to J-band peak







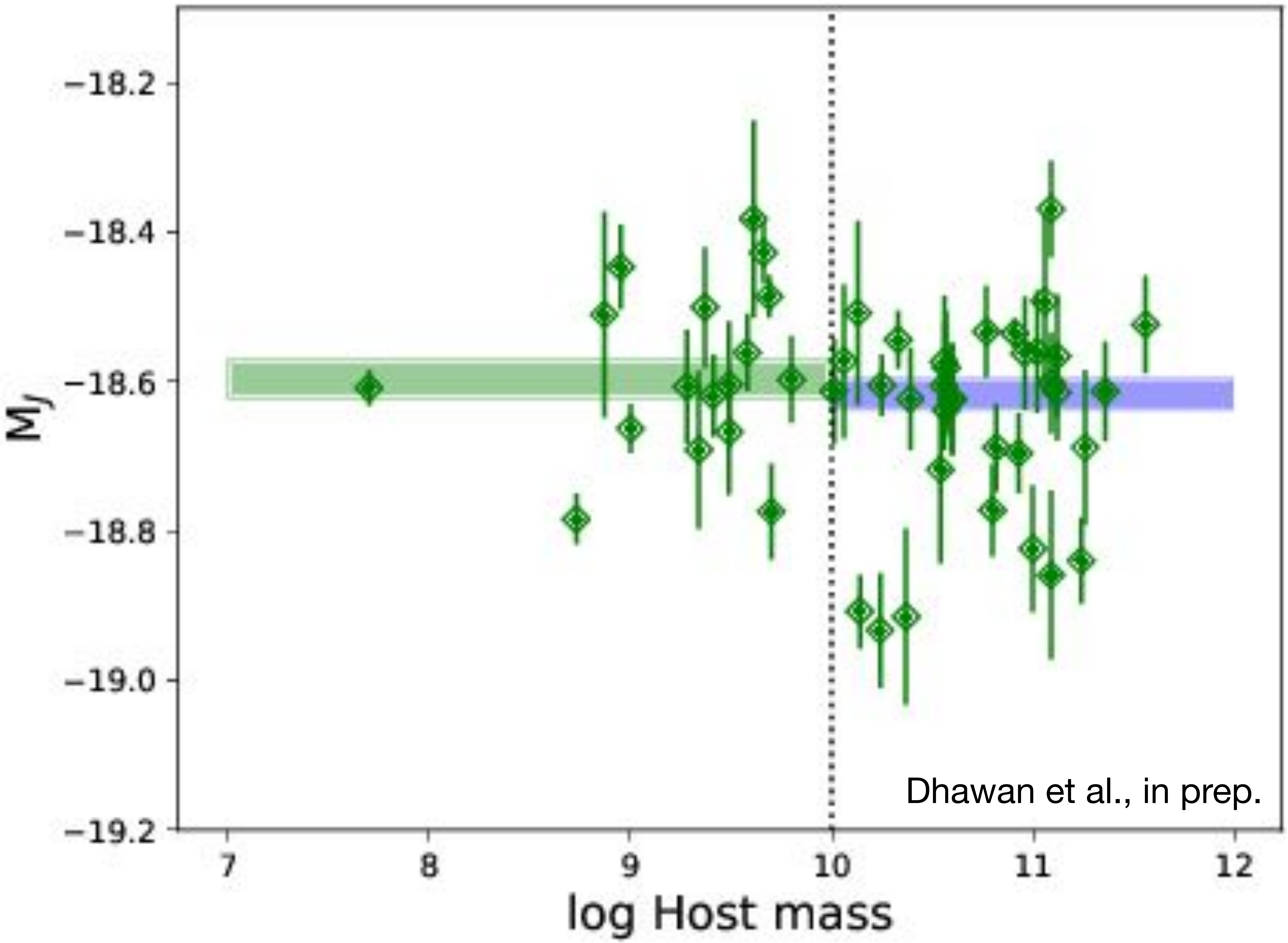
Sample	N_{calib}	σ_{calib} (mag)	N_{Hflow}	σ_{Hflow} (mag)	H_0 (km s^{-1} Mpc^{-1})	M_J (mag)	$-5\,a_J$ (mag)	σ_{int} (mag)
Fiducial	**9**	**0.160**	**27**	**0.106**	$\mathbf{72.78^{+1.60}_{-1.57}}$	$\mathbf{-18.524^{+0.041}_{-0.041}}$	$\mathbf{-2.834^{+0.023}_{-0.023}}$	$\mathbf{0.096^{+0.018}_{-0.016}}$
Flow-corrected redshifts	9	0.160	27	0.115	$73.18^{+1.71}_{-1.68}$	$-18.523^{+0.044}_{-0.044}$	$-2.845^{+0.025}_{-0.025}$	$0.109^{+0.020}_{-0.017}$
Host $E(B-V) \leq 0.3$ mag	9	0.160	24	0.106	$72.90^{+1.61}_{-1.62}$	$-18.523^{+0.041}_{-0.042}$	$-2.837^{+0.025}_{-0.024}$	$0.098^{+0.019}_{-0.016}$
Spirals only (morphology code ≥ 2)	[illegible]	[illegible]	[illegible]	0.107	[illegible]	[illegible]	[illegible]	$0.104^{+0.021}_{-0.018}$
Milky Way $A_J \leq 0.3$ mag	9	0.160	26	0.101	[illegible]	[illegible]	[illegible]	$0.096^{+0.019}_{-0.016}$
Low EBV + Spirals + Low MW A_J	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$-2.857^{+0.031}_{-0.031}$	$0.105^{+0.025}_{-0.019}$
Hubble flow $z \geq 0.02$	9	0.160	13	0.104	$73.66^{+1.86}_{-1.84}$	$-18.524^{+0.043}_{-0.043}$	$-2.860^{+0.034}_{-0.033}$	$0.104^{+0.025}_{-0.020}$
Hubble flow $z \geq 0.03$	9	0.160	7	0.091	$72.79^{+2.25}_{-2.20}$	$-18.524^{+0.045}_{-0.045}$	$-2.835^{+0.049}_{-0.047}$	$0.108^{+0.033}_{-0.024}$
Hubble flow $0.01 < z < 0.05$	9	0.160	26	0.099	[illegible]	[illegible]	[illegible]	[illegible]
Hubble flow $0.02 \leq z \leq 0.05$	9	0.160	12	0.083	[illegible]	[illegible]	[illegible]	$0.104^{+0.026}_{-0.020}$
Strictest overlap[a]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$-2.849^{+0.042}_{-0.042}$	$0.104^{+0.031}_{-0.023}$
Including fast-decliner outliers	9	0.160	30	0.170	$71.30^{+2.11}_{-2.09}$	$-18.524^{+0.057}_{-0.057}$	$-2.789^{+0.030}_{-0.030}$	$0.148^{+0.024}_{-0.020}$
Hubble flow CSP only	9	0.160	14	0.091	$74.09^{+1.91}_{-1.87}$	$-18.523^{+0.043}_{-0.043}$	$-2.872^{+0.034}_{-0.034}$	$0.105^{+0.025}_{-0.020}$
Hubble flow CfA only	9	0.160	13	0.094	$71.47^{+1.80}_{-1.72}$	$-18.523^{+0.041}_{-0.041}$	$-2.794^{+0.034}_{-0.034}$	$0.098^{+0.025}_{-0.020}$
Hubble flow and calibrators CSP only	1	0.000	14	0.091	$80.98^{+2.55}_{-2.57}$	$-18.338^{+0.065}_{-0.066}$	$-2.880^{+0.023}_{-0.022}$	$0.043^{+0.040}_{-0.043}$
Hubble flow and calibrators CfA only	2	0.213	13	0.094	$75.92^{+2.98}_{-2.82}$	$-18.393^{+0.081}_{-0.081}$	$-2.795^{+0.018}_{-0.017}$	$0.000^{+0.028}_{-0.000}$
Cardona et al. (2017) Cepheid distances	9	0.133	27	0.106	$73.83^{+1.61}_{-1.59}$	$-18.492^{+0.042}_{-0.042}$	$-2.833^{+0.022}_{-0.021}$	$0.089^{+0.018}_{-0.016}$

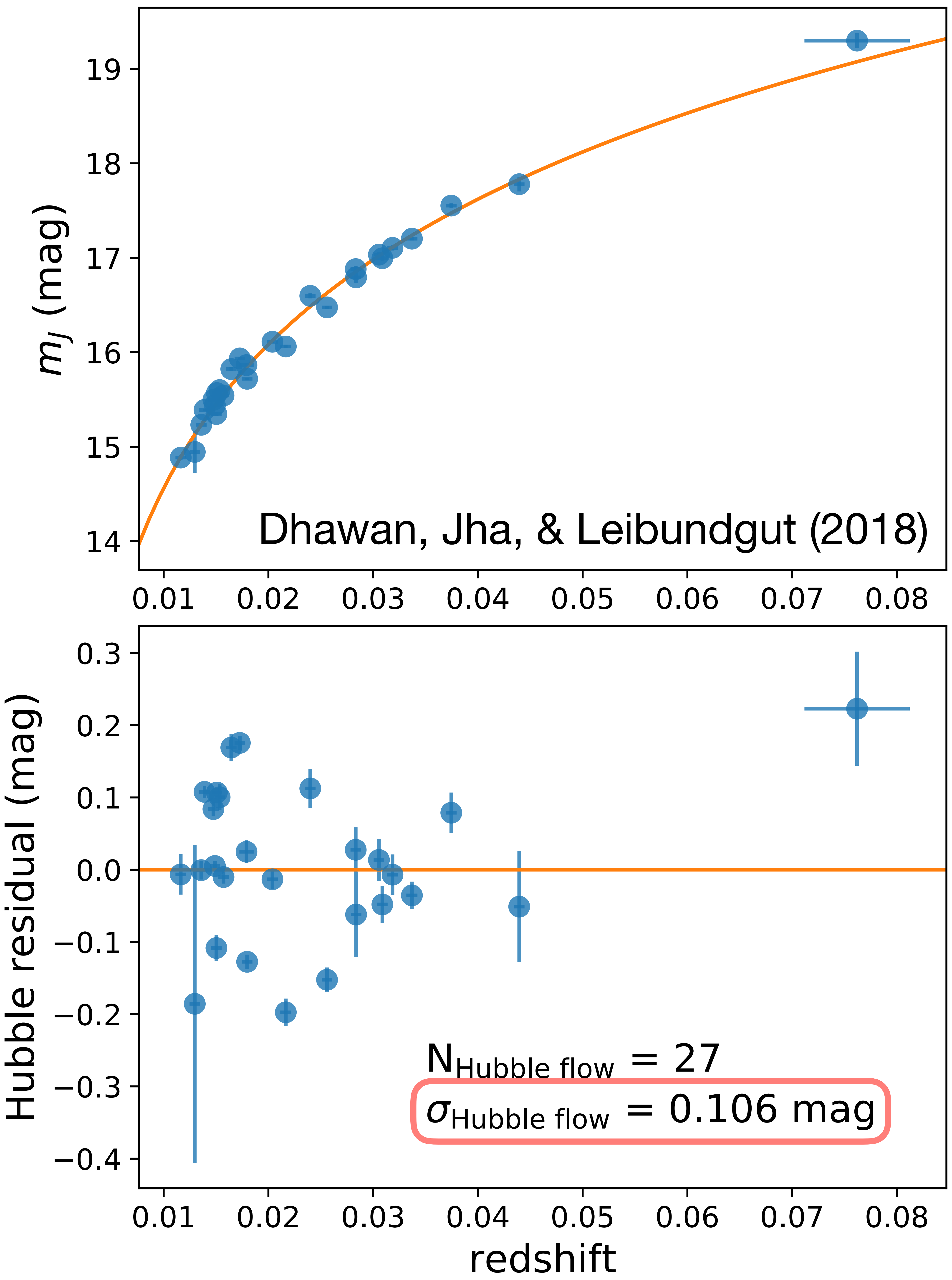
consistent with SH0ES results (Riess et al. 2016)
[using same Cepheid distances]

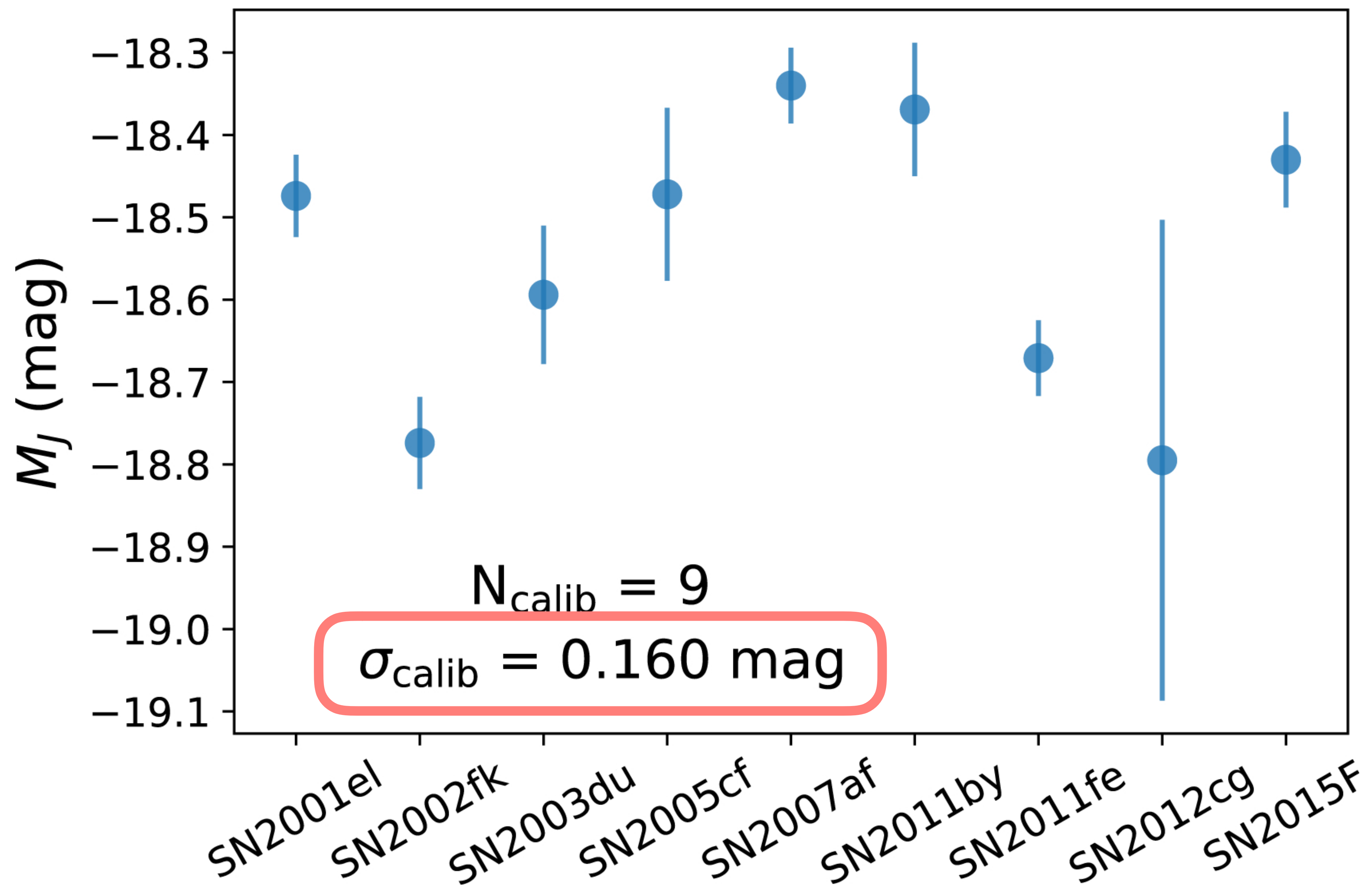
H_0 tension does not result from a wavelength-dependent systematic uncertainty in the SN Ia

Notes. Sample median values of the fit parameters are given, with 16th and 84th percentile differences (statistical uncertainties only). [(a)] This is an extremely restrictive cut to make the calibrators and *Hubble* flow sample as similar as possible: low EBV (host $E(B-V) \leq 0.3$ mag) + spirals only + $1.0 \leq \Delta m_{15}(B) \leq 1.2$ + Milky Way $A_J \leq 0.15$ mag.

less of a host mass effect in NIR?





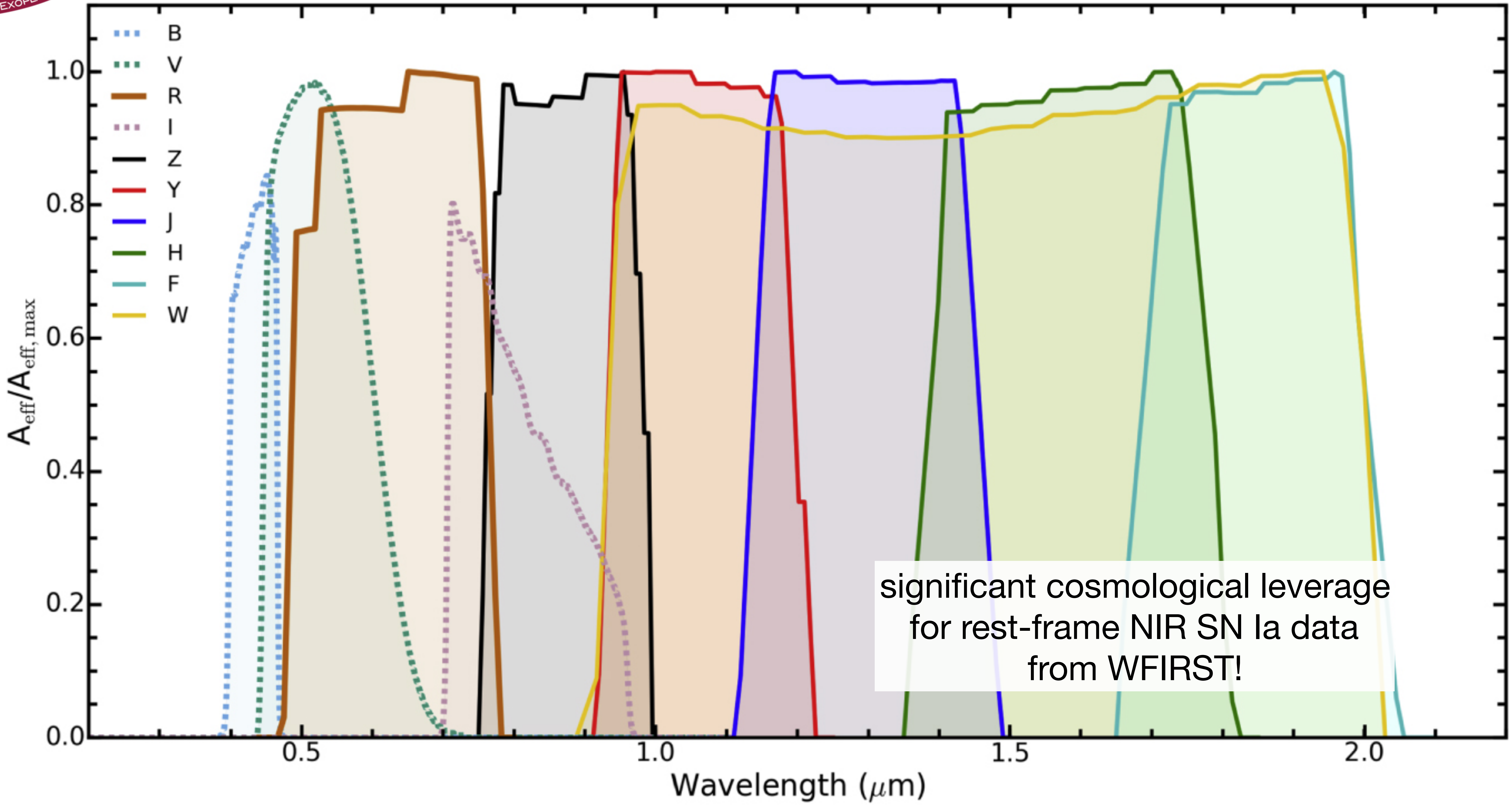


Sample	N_{calib}	σ_{calib} (mag)	N_{Hflow}	σ_{Hflow} (mag)	H_0 (km s^{-1} Mpc^{-1})	M_J (mag)	$-5\,a_J$ (mag)	σ_{int} (mag)
Fiducial	**9**	**0.160**	**27**	**0.106**	$\mathbf{72.78^{+1.60}_{-1.57}}$	$\mathbf{-18.524^{+0.041}_{-0.041}}$	$\mathbf{-2.834^{+0.023}_{-0.023}}$	$\mathbf{0.096^{+0.018}_{-0.016}}$
Flow-corrected redshifts	9	0.160	27	0.115	$73.18^{+1.71}_{-1.68}$	$-18.523^{+0.044}_{-0.044}$	$-2.845^{+0.025}_{-0.025}$	$0.109^{+0.020}_{-0.017}$
Host $E(B-V) \leq 0.3$ mag	9	0.160	24	0.106	$72.90^{+1.61}_{-1.62}$	$-18.523^{+0.041}_{-0.042}$	$-2.837^{+0.025}_{-0.024}$	$0.098^{+0.019}_{-0.016}$
Spirals only (morphology code ≥ 2)	9	0.160	21	0.107	$73.05^{+1.73}_{-1.73}$	$-18.522^{+0.042}_{-0.043}$	$-2.841^{+0.027}_{-0.027}$	$0.104^{+0.021}_{-0.018}$
Milky Way $A_J \leq 0.3$ mag	9	0.160	26	0.101	$72.73^{+1.58}_{-1.56}$	$-18.523^{+0.041}_{-0.041}$	$-2.832^{+0.023}_{-0.023}$	$0.096^{+0.019}_{-0.016}$
Low EBV + Spirals + Low MW A_J	9	0.160	15	0.094	$73.60^{+1.80}_{-1.79}$	$-18.523^{+0.043}_{-0.043}$	$-2.857^{+0.031}_{-0.031}$	$0.105^{+0.025}_{-0.019}$
Hubble flow $z \geq 0.02$	9	0.160	13	0.104	$73.66^{+1.86}_{-1.84}$	$-18.524^{+0.043}_{-0.043}$	$-2.860^{+0.034}_{-0.033}$	$0.104^{+0.025}_{-0.020}$
Hubble flow $z \geq 0.03$	9	0.160	7	0.091	$72.79^{+2.25}_{-2.20}$	$-18.524^{+0.045}_{-0.045}$	$-2.835^{+0.049}_{-0.047}$	$0.108^{+0.033}_{-0.024}$
Hubble flow $0.01 \leq z \leq 0.05$	9	0.160	26	0.099	$72.87^{+1.59}_{-1.55}$	$-18.524^{+0.040}_{-0.041}$	$-2.837^{+0.023}_{-0.023}$	$0.095^{+0.018}_{-0.015}$
Hubble flow $0.02 \leq z \leq 0.05$	9	0.160	12	0.083	$73.93^{+1.88}_{-1.83}$	$-18.523^{+0.043}_{-0.043}$	$-2.868^{+0.034}_{-0.034}$	$0.104^{+0.026}_{-0.020}$
Strictest overlap[a]	7	0.147	8	0.058	$73.04^{+2.21}_{-2.12}$	$-18.532^{+0.049}_{-0.048}$	$-2.849^{+0.042}_{-0.042}$	$0.104^{+0.031}_{-0.023}$
Including fast-decliner outliers	9	0.160	30	0.170	$71.30^{+2.11}$ [illegible]	$-18.524^{+0.057}$ [illegible]	$-2.789^{+0.030}$ [illegible]	$0.148^{+0.024}_{-0.020}$
Hubble flow CSP only	9	0.160	14	0.091	$74.09^{+1.91}_{-1.87}$	$-18.523^{+0.043}_{-0.043}$	$-2.872^{+0.034}_{-0.034}$	$0.105^{+0.025}_{-0.020}$
Hubble flow CfA only	9	0.160	13	0.094	$71.47^{+1.80}_{-1.72}$	$-18.523^{+0.041}_{-0.041}$	$-2.794^{+0.034}_{-0.034}$	$0.098^{+0.025}_{-0.020}$
Hubble flow and calibrators CSP only	1	0.000	14	0.091	$80.98_{-2.57}$ [illegible]	$-18.338_{-0.066}$ [illegible]	$-2.880_{-0.022}$ [illegible]	$0.043^{+0.040}_{-0.043}$
Hubble flow and calibrators CfA only	2	0.213	13	0.094	$75.92^{+2.98}_{-2.82}$	$-18.393^{+0.081}_{-0.081}$	$-2.795^{+0.018}_{-0.017}$	$0.000^{+0.028}_{-0.000}$
Cardona et al. (2017) Cepheid distances	9	0.133	27	0.106	$73.83^{+1.61}_{-1.59}$	$-18.492^{+0.042}_{-0.042}$	$-2.833^{+0.022}_{-0.021}$	$0.089^{+0.018}_{-0.016}$

Notes. Sample median values of the fit parameters are given, with 16th and 84th percentile differences (statistical uncertainties only). [(a)] This is an extremely restrictive cut to make the calibrators and *Hubble* flow sample as similar as possible: low EBV (host $E(B-V) \leq 0.3$ mag) + spirals only + $1.0 \leq \Delta m_{15}(B) \leq 1.2$ + Milky Way $A_J \leq 0.15$ mag.

WFIRST

Hounsell et al. (2018)



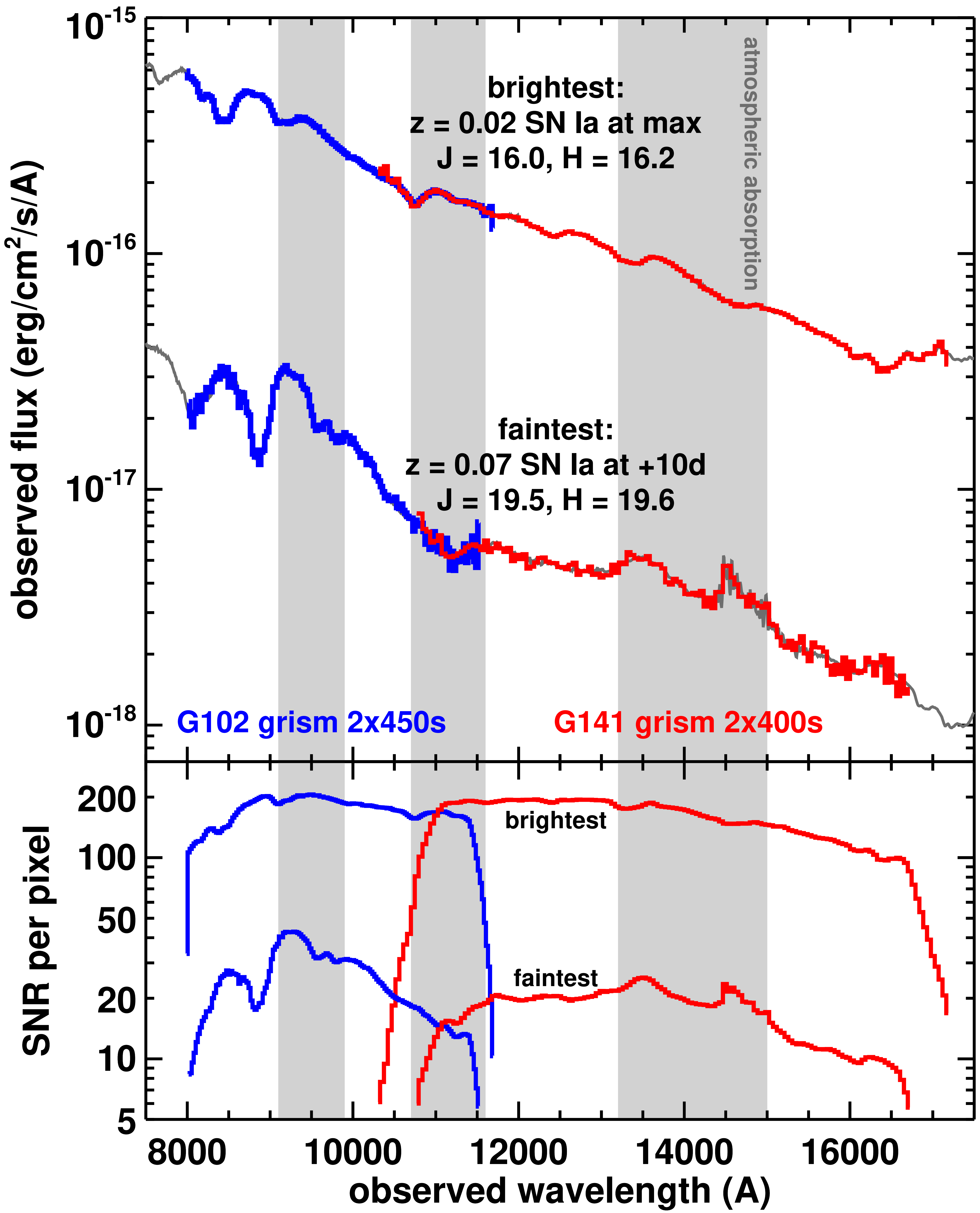
***z* = 1.0:**	**0.25**	**0.5**	**0.75**	**1.0**
***z* = 0.5:**	**0.33**	**0.67**	**1.0**	**1.33**

- 24 Hubble-flow SN Ia (0.02 < z < 0.07) with HST WFC3/IR in Cycles 27 and 28

- F098M, F105W, F125W, F140W, F160W photometry + grism spectroscopy (above the atmosphere!) 1 orbit, 2 epochs

- 3 key science goals:
  ✶ rest-frame NIR SEDs for WFIRST
  ✶ 2.7% NIR SN Ia H_0 measurement
  ✶ w/RAISINs, WFC3/IR-only Hubble diagram to z = 0.6

- need ground-based support, join us!
  ~2 objects/month starting Feb 2020



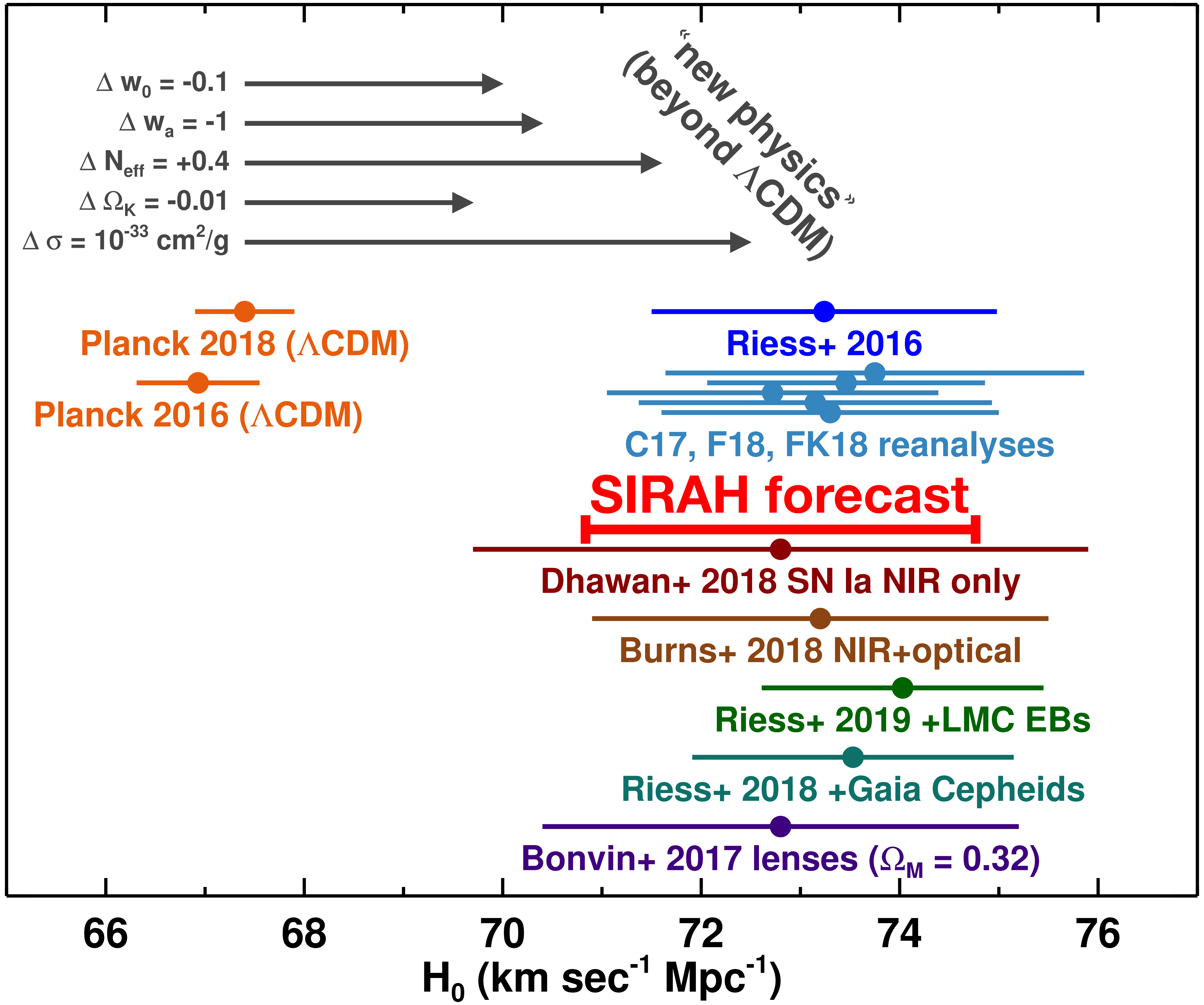
SIRAH

- 24 Hubble-flow SN Ia (0.02 < z < 0.07) with HST WFC3/IR in Cycles 27 and 28

- F098M, F105W, F125W, F140W, F160W photometry + grism spectroscopy (above the atmosphere!) 1 orbit, 2 epochs

- 3 key science goals:
  ✶ rest-frame NIR SEDs for WFIRST
  ✶ 2.7% NIR SN Ia H_0 measurement
  ✶ w/RAISINs, WFC3/IR-only Hubble diagram to z = 0.6

- need ground-based support, join us! ~2 objects/month starting Feb 2020



Avelino, Brown, Burns, Camacho-Neves, Dai, Dettman, Dhawan, Filippenko, Foley, Fox, Friedman, Galbany, Garnavich, Hložek, Holoien, Hounsell, Hsiao, Jha, Jones, Kelly, Kessler, Kirshner, Mandel, Matheson, McCully, Narayan, Pellegrino, Phillips, Ponder, Rest, Riess, Roberts-Pierel, Rodney, Ryan, Sand, Scolnic, Stritzinger, Valenti + you?