Near-infrared SN Ia as standard candles

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Pittsburgh, April 2018

The problem

Optical samples of SN Ia for cosmology have reached their limit to constrain the dark energy (DE) because of the systematic uncertainties.

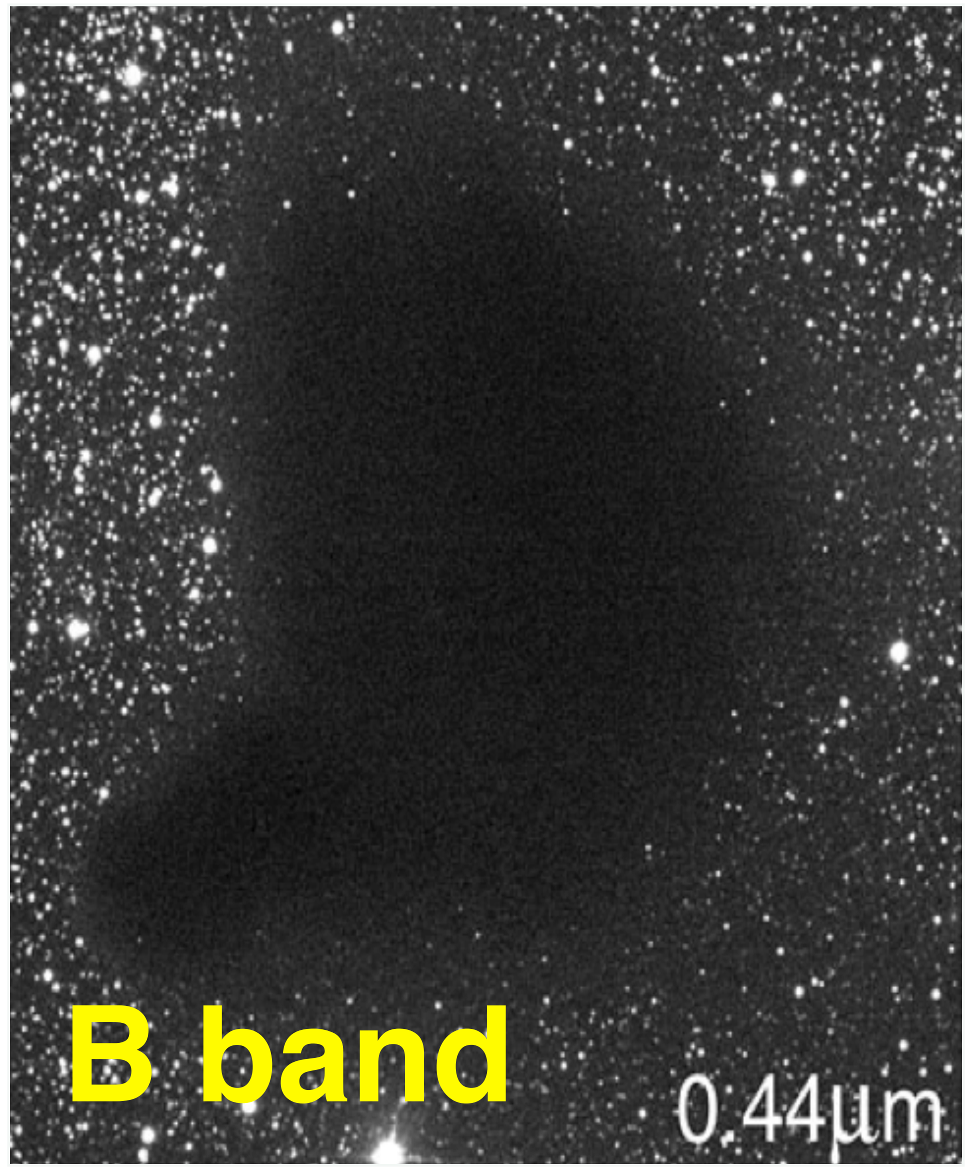
- More optical data *doesn't* mean better DE constraints.

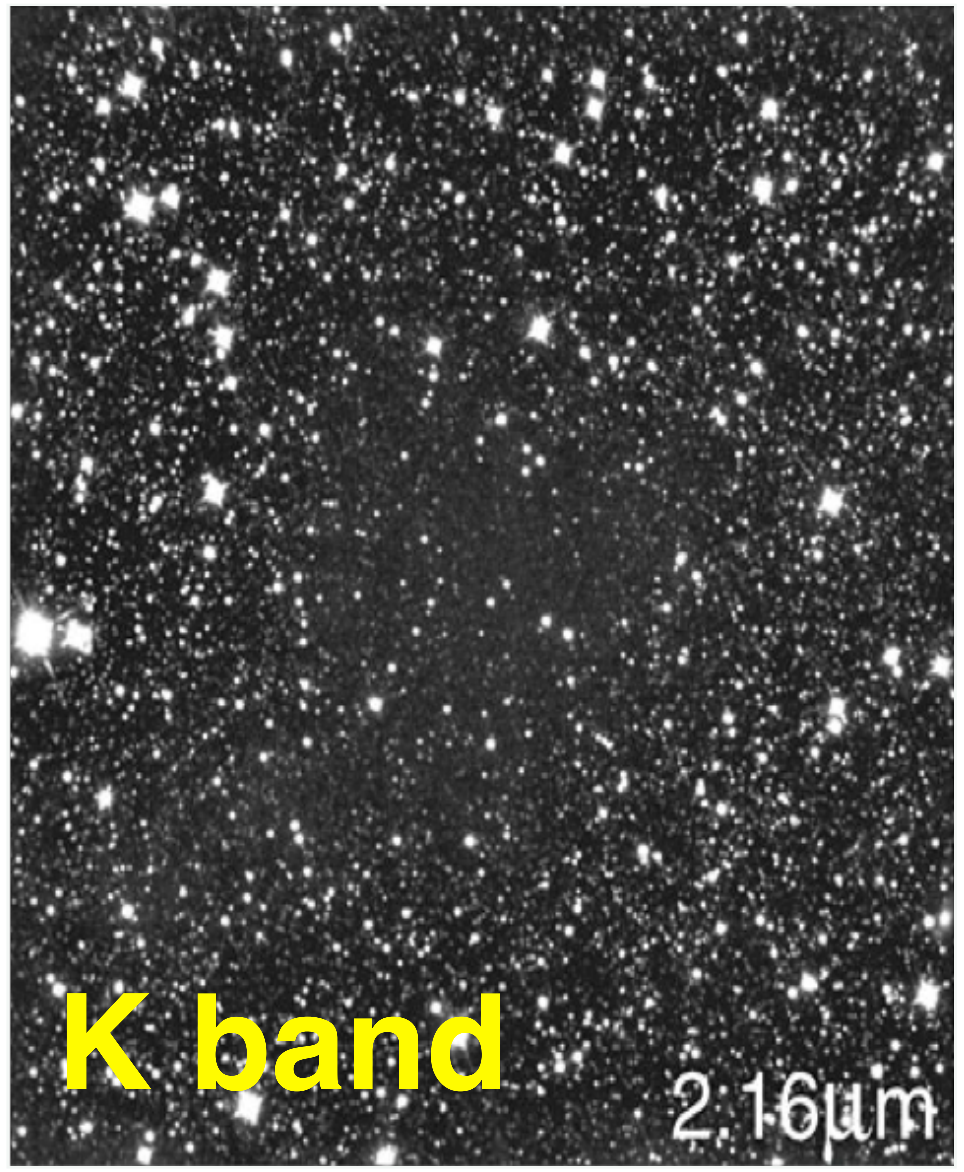
- Optical light is dimmed and reddened by dust

A solution: NIR observations!

- Near infrared (**NIR**) light is much **less sensitive to dust** than the optical wavelengths.

Optical





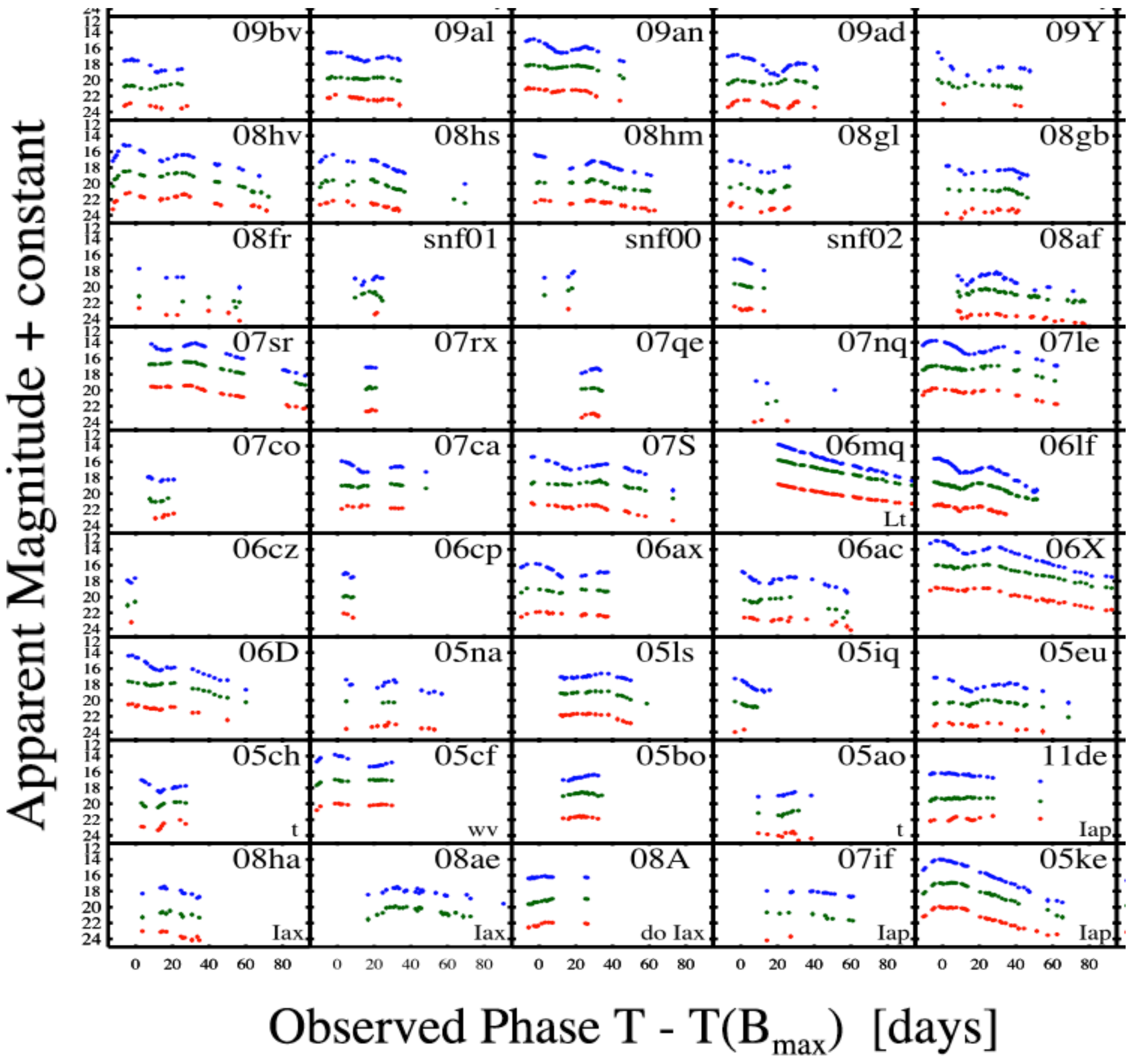
Near infrared

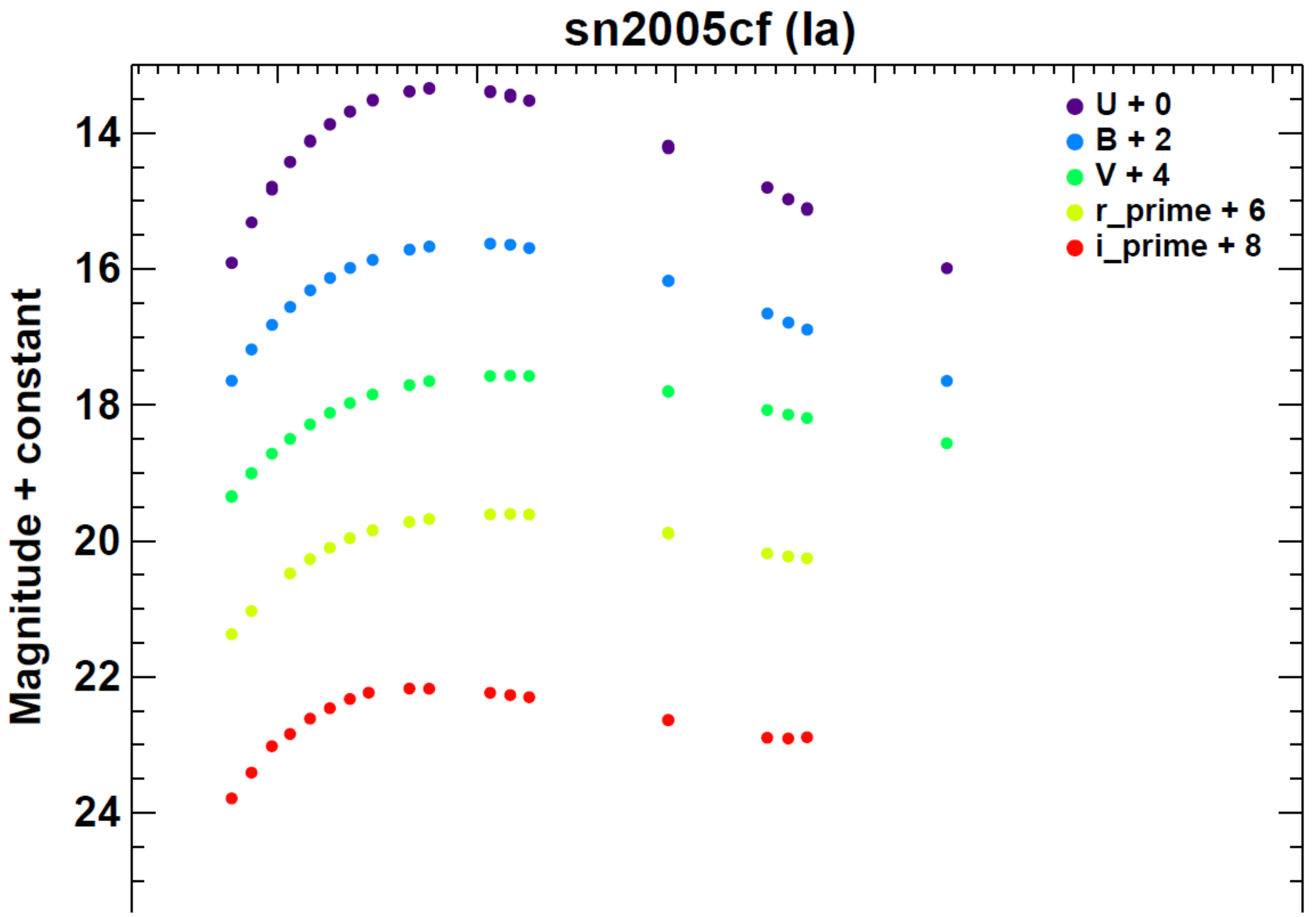
Low-z NIR sample

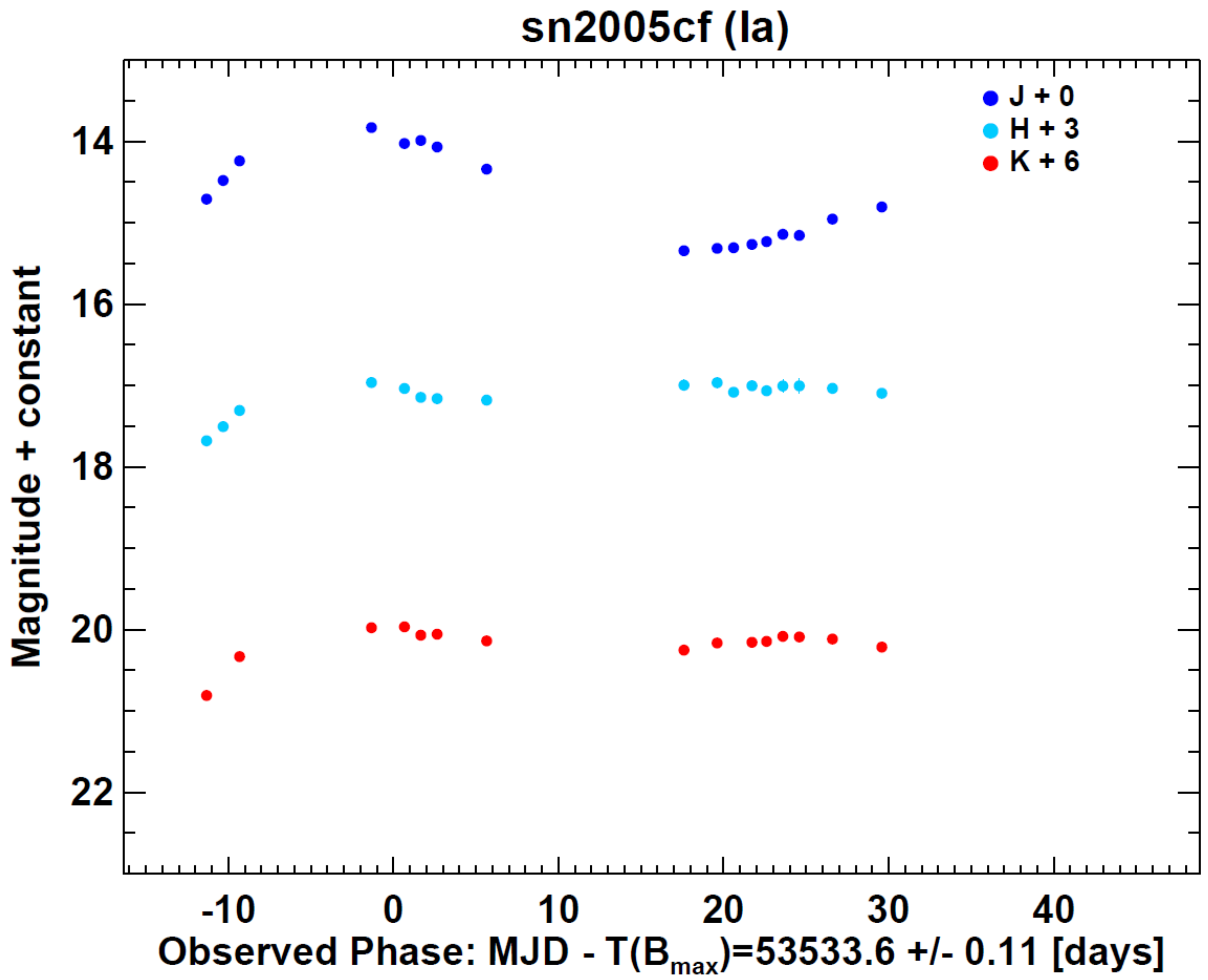
Friedman+2015

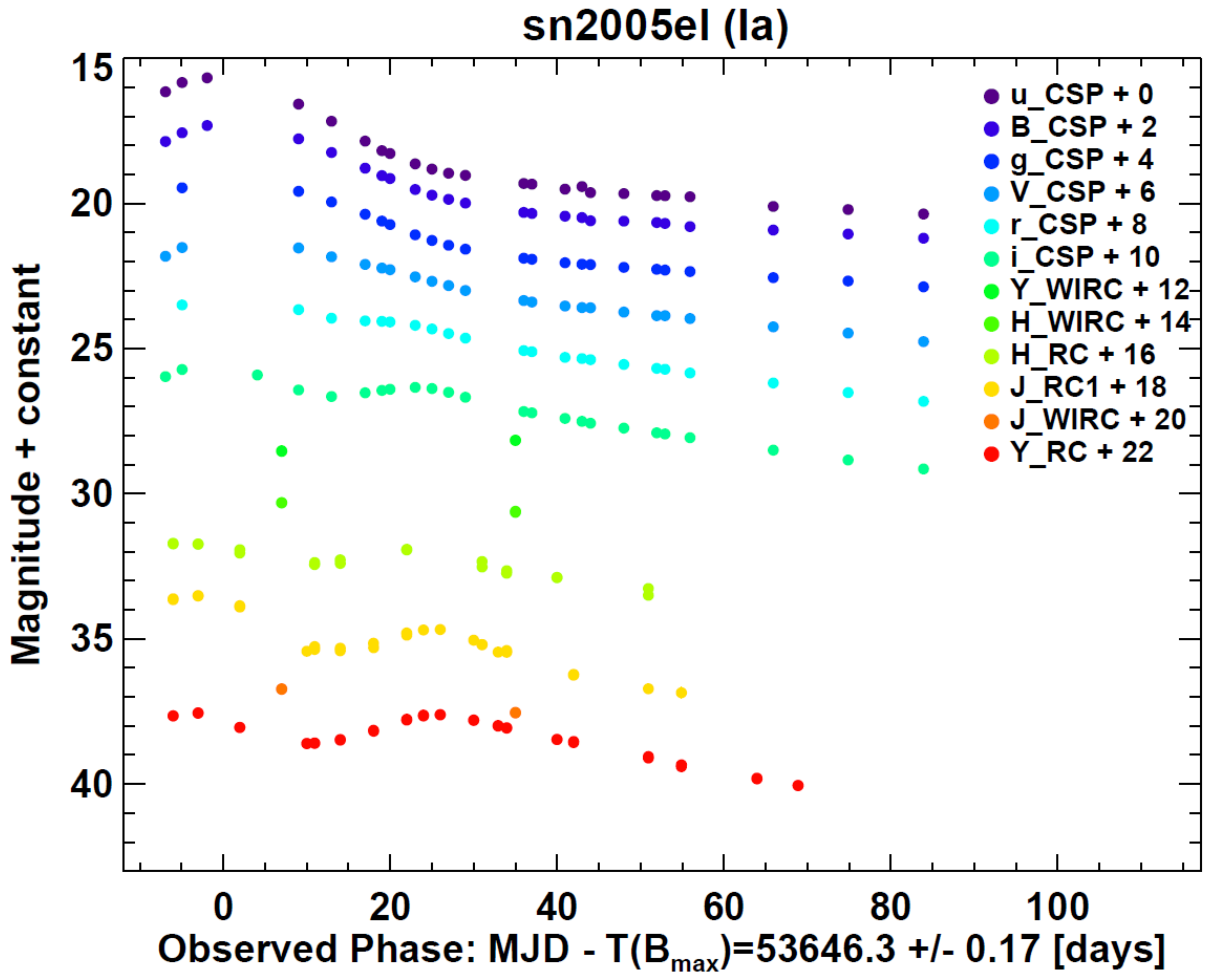
Compiled by **Andrew Friedman** (UCSD):

- **CfA, CSP**, Literature
- 190 SN Ia with optical + NIR (YJHK) light curves




sn2005cf (Ia)
U + 0
B + 2
V + 4
r_prime + 6
i_prime + 8
Magnitude + constant
14
16
18
20
22
24


sn2005cf (Ia)
J + 0
H + 3
K + 6
Magnitude + constant
14
16
18
20
22
-10
0
10
20
30
40
Observed Phase: MJD - T(B_max)=53533.6 +/- 0.11 [days]

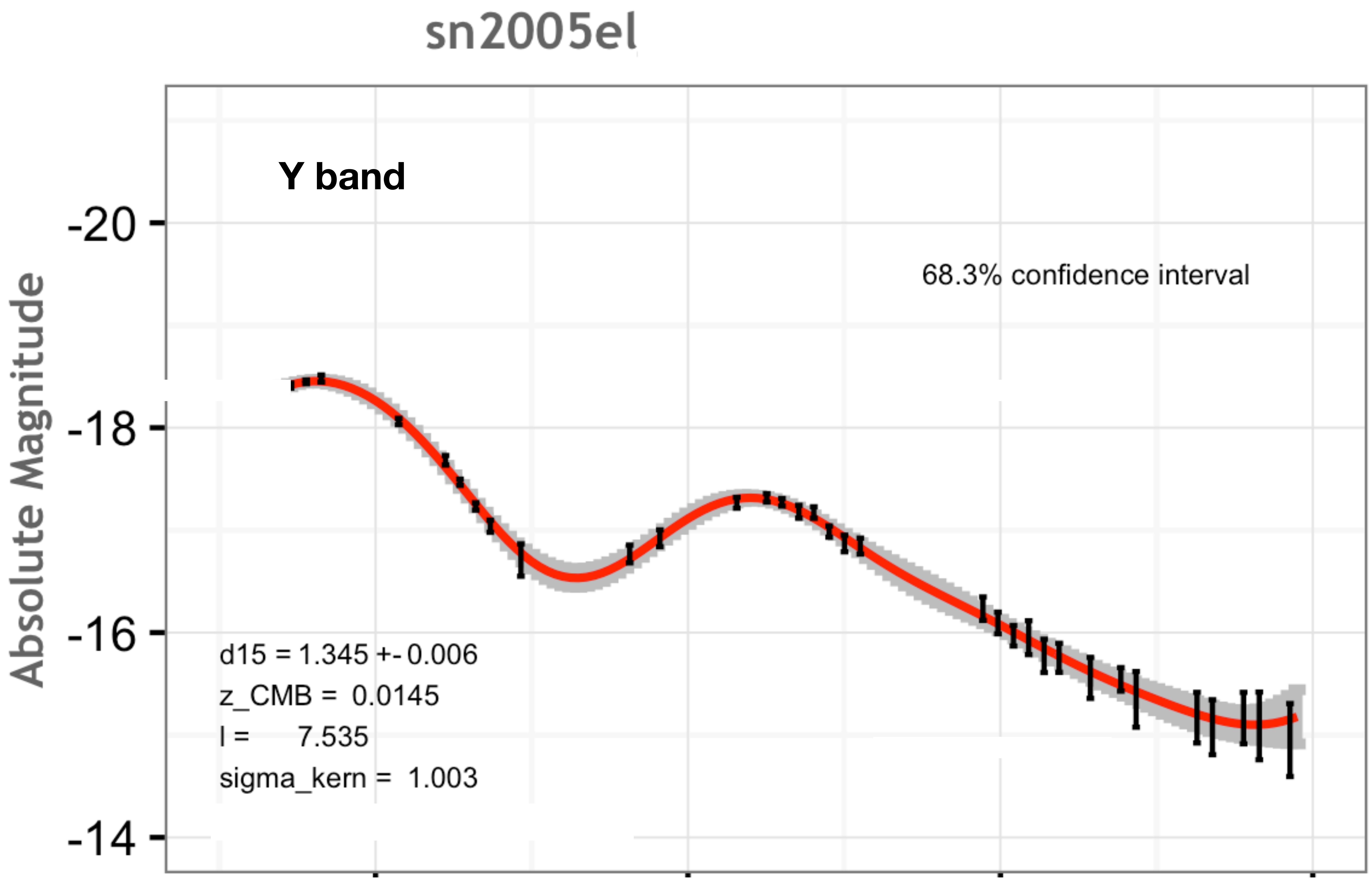

sn2005el (Ia)
u_CSP + 0
B_CSP + 2
g_CSP + 4
V_CSP + 6
r_CSP + 8
i_CSP + 10
Y_WIRC + 12
H_WIRC + 14
H_RC + 16
J_RC1 + 18
J_WIRC + 20
Y_RC + 22
Magnitude + constant
15
20
25
30
35
40
0
20
40
60
80
100
Observed Phase: MJD - T(B_max)=53646.3 +/- 0.17 [days]

Determine distances from the NIR data

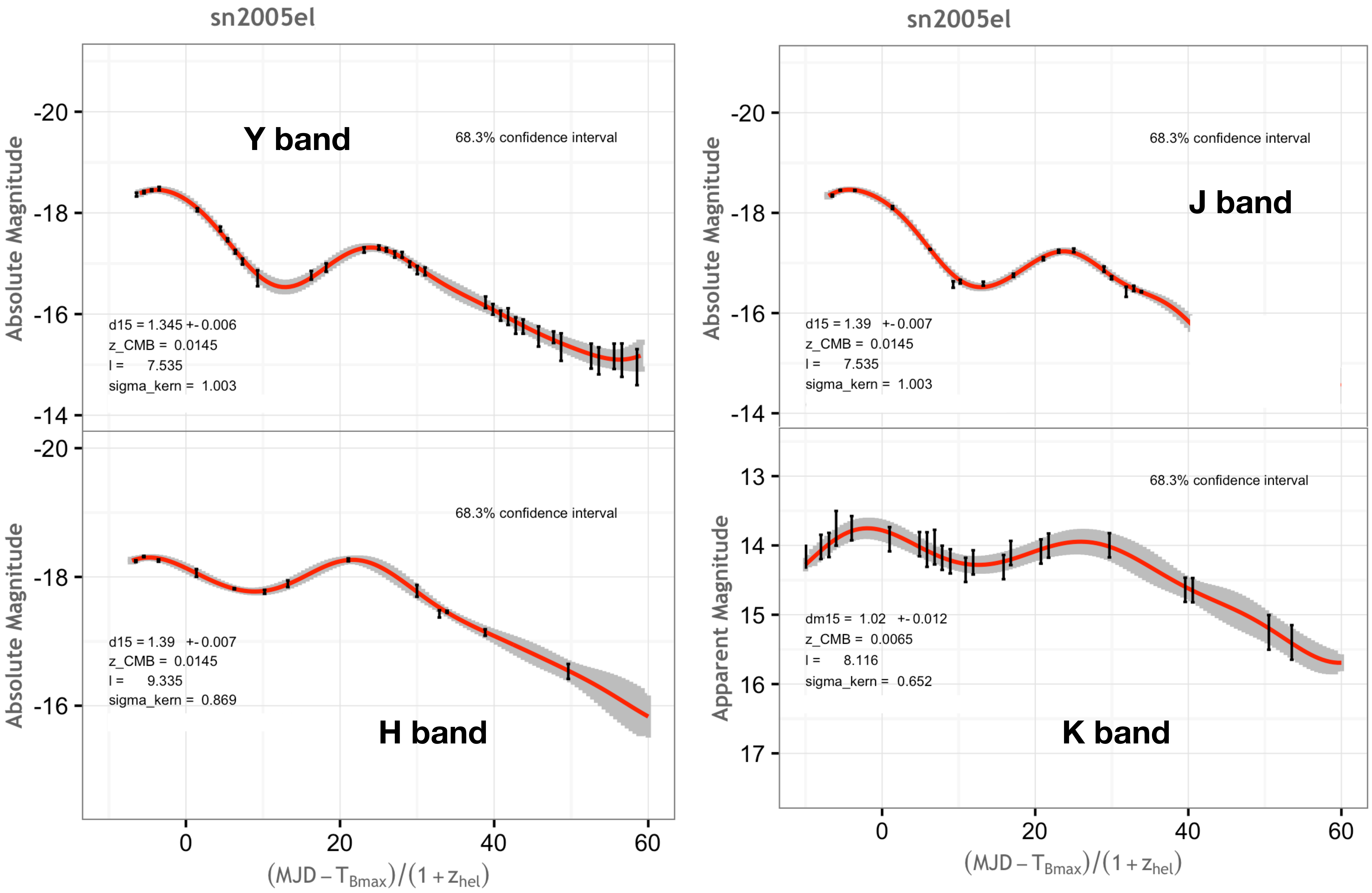
Template method

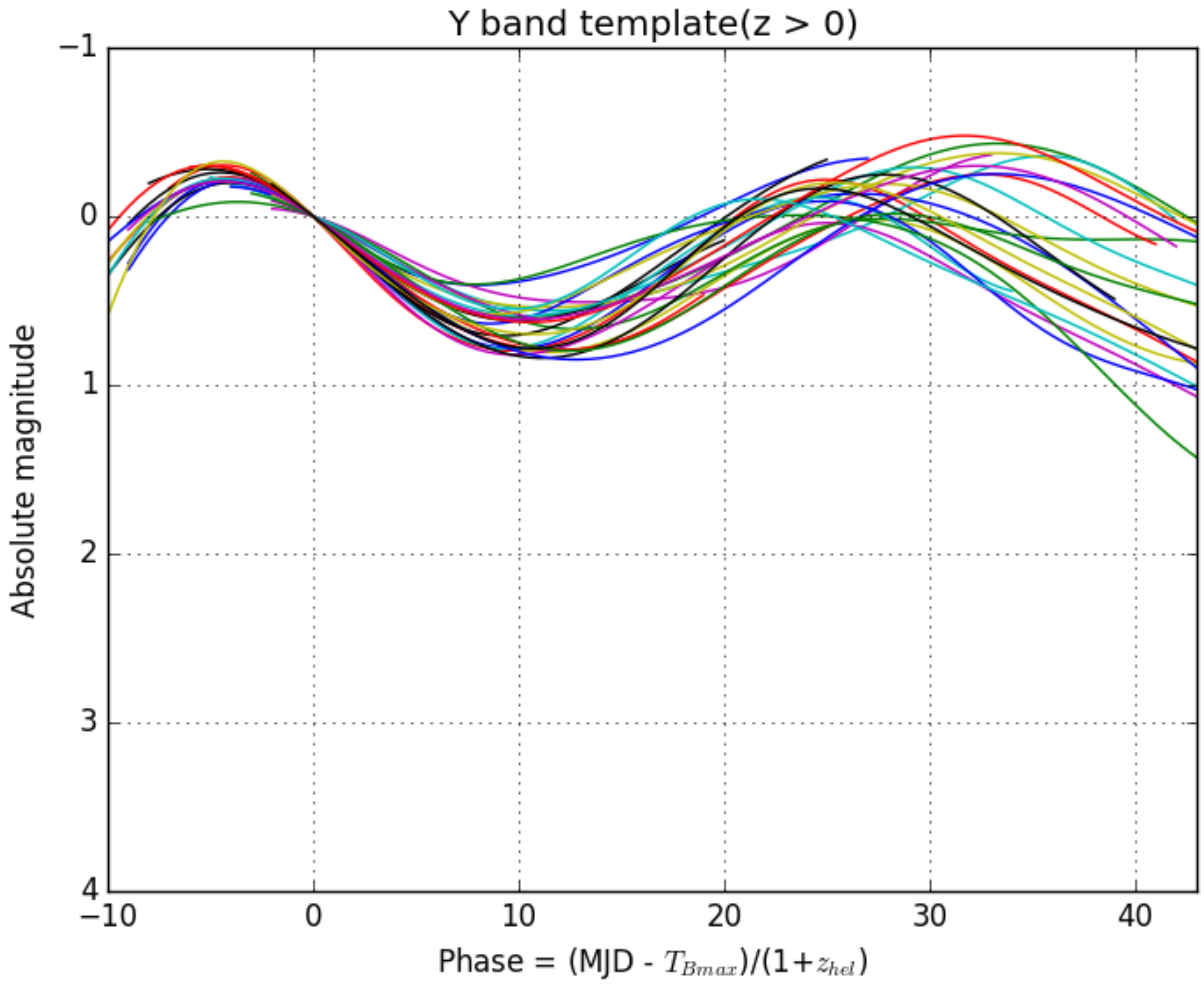
Gaussian-Process method

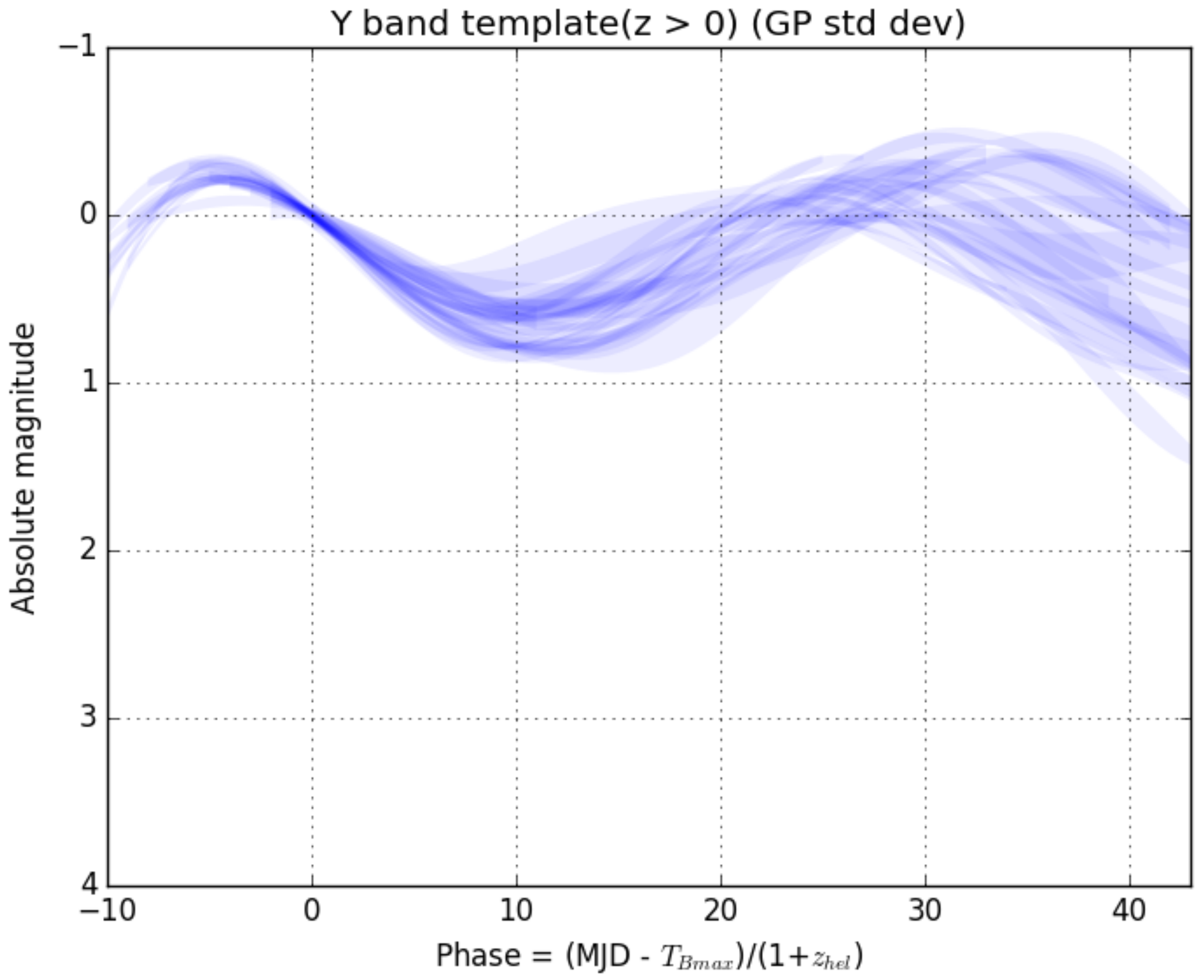
Gaussian-Process fit



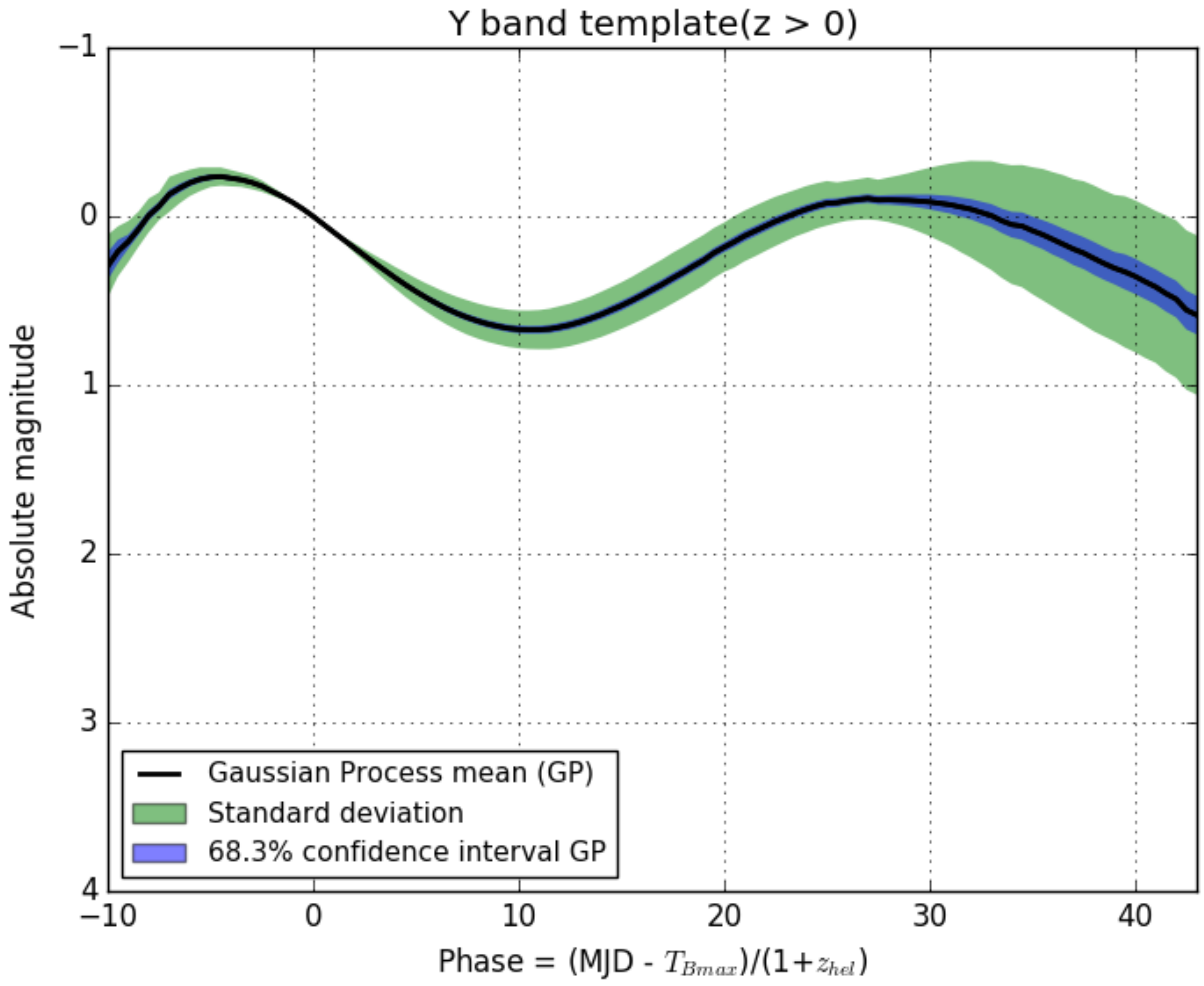
Gaussian-Process fit



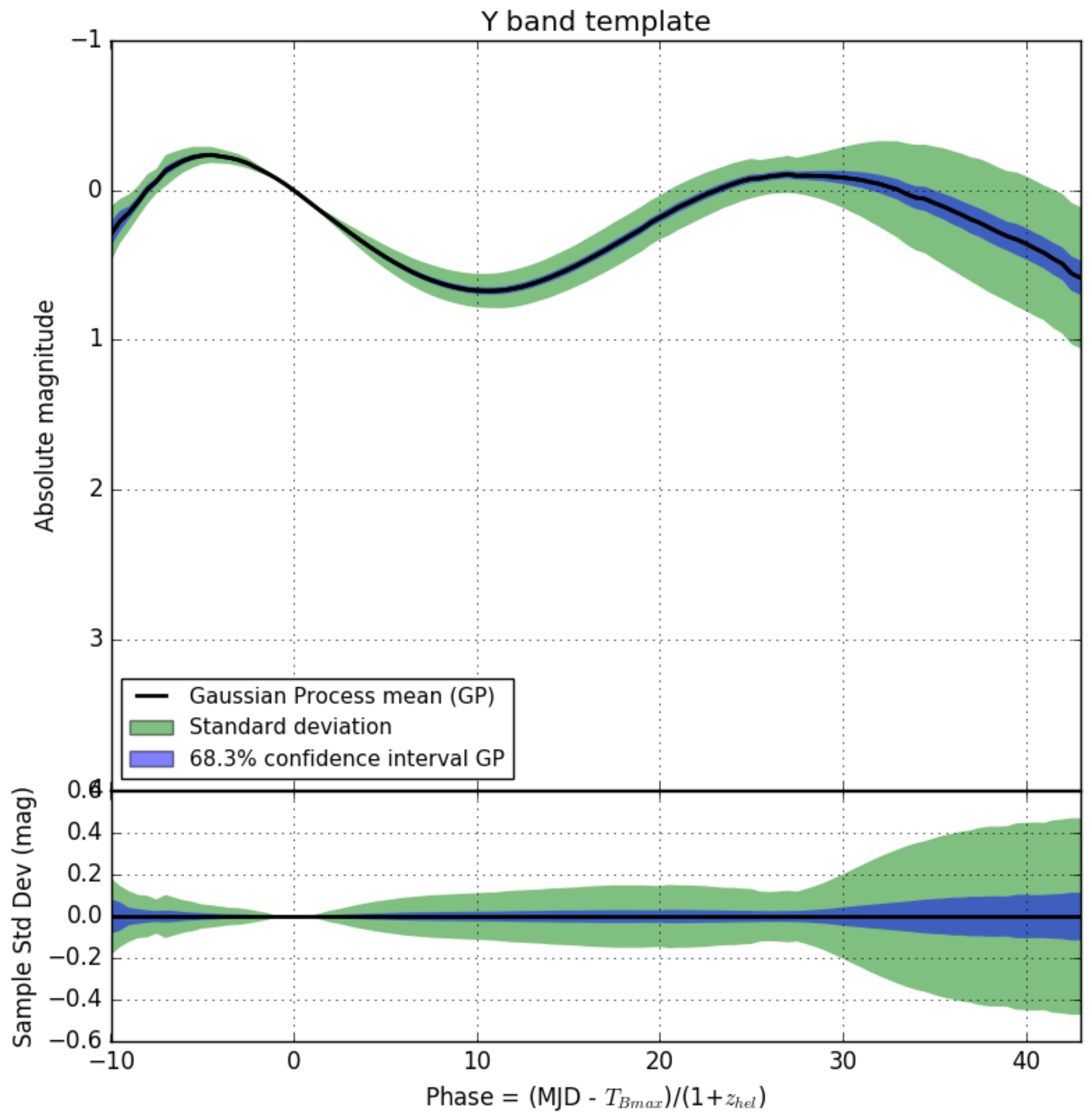

Y band template(z > 0)
−1
0
1
2
3
4
Absolute magnitude
−10
0
10
20
30
40
Phase = (MJD - T_{Bmax})/(1+z_{hel})



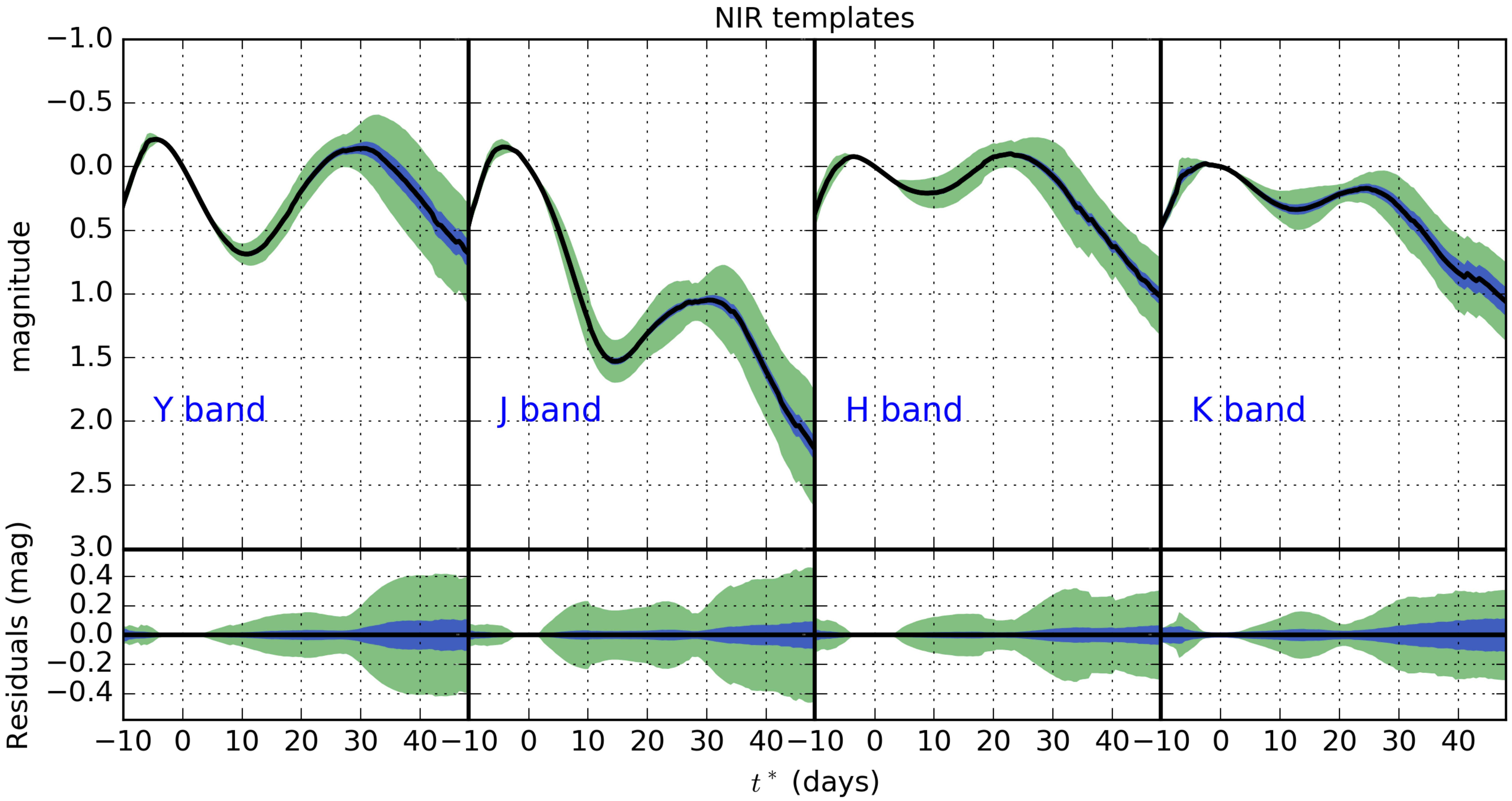
Y band template(z > 0) (GP std dev)
Absolute magnitude
−1
0
1
2
3
4
−10
0
10
20
30
40
Phase = (MJD - T_{Bmax})/(1+z_{hel})



Y band template(z > 0)
Absolute magnitude
Phase = (MJD - T_{Bmax})/(1+z_{hel})
−1
0
1
2
3
4
−10
0
10
20
30
40
Gaussian Process mean (GP)
Standard deviation
68.3% confidence interval GP



Arturo Avelino, "Near-infrared SN Ia as standard candles"



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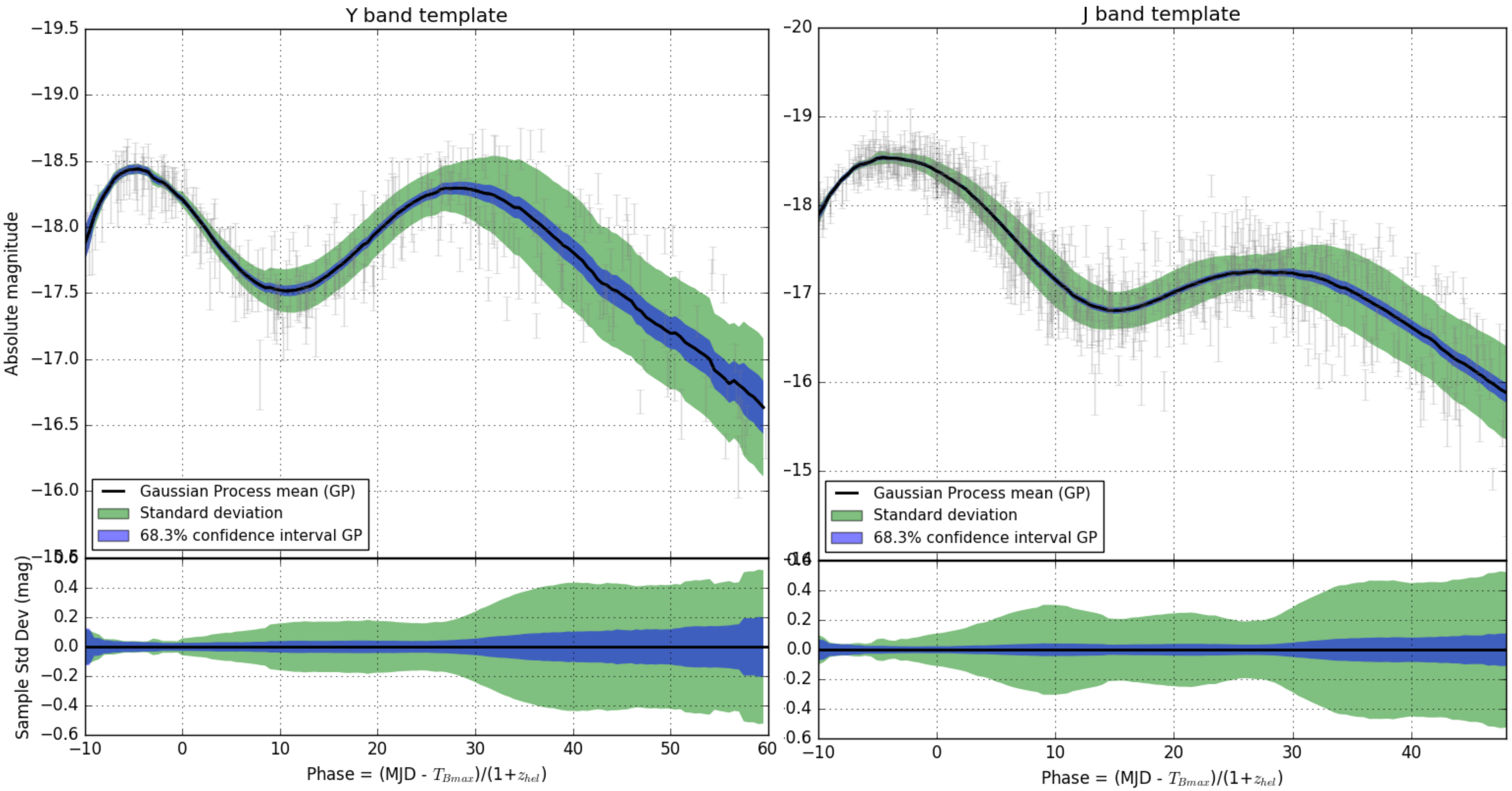
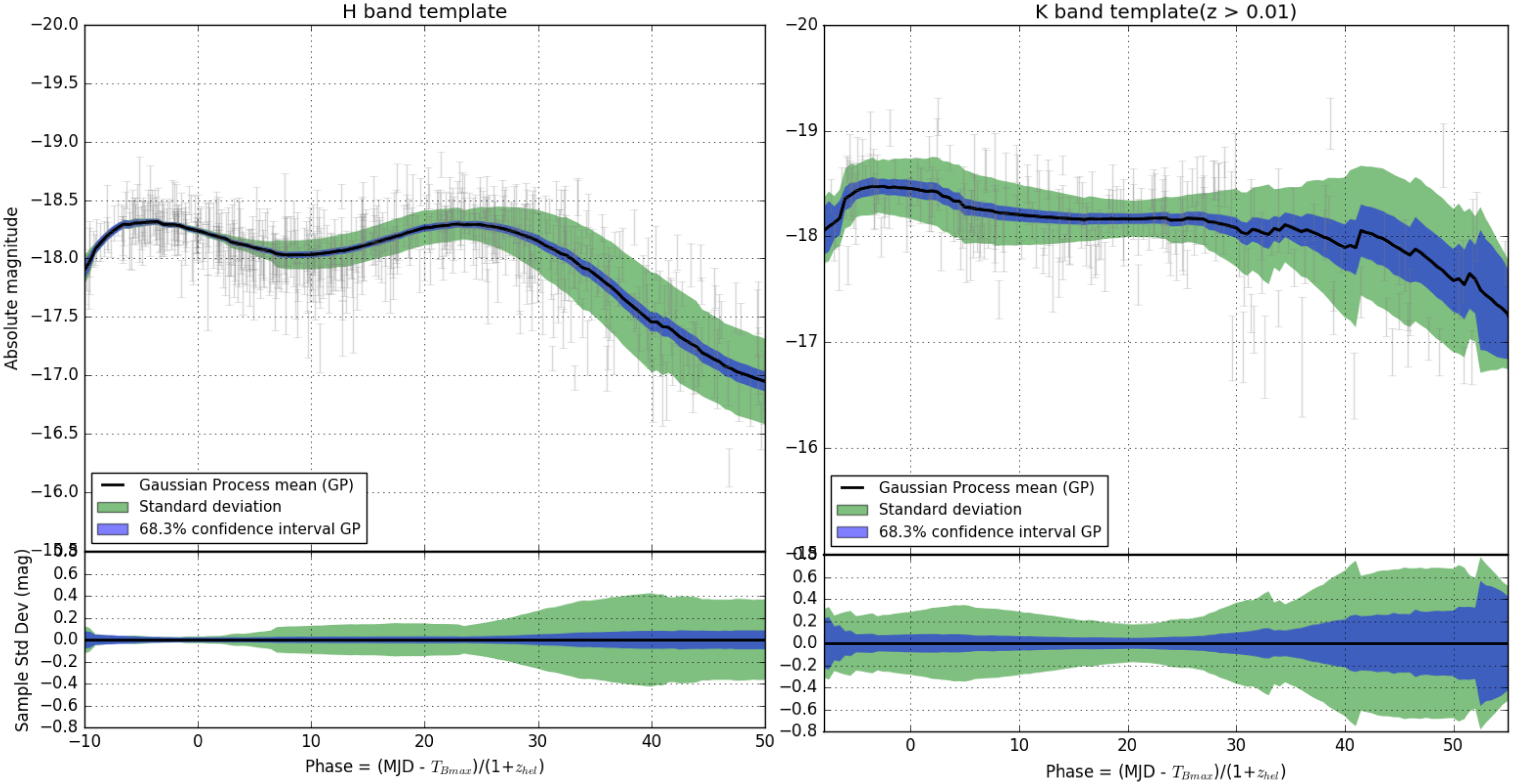
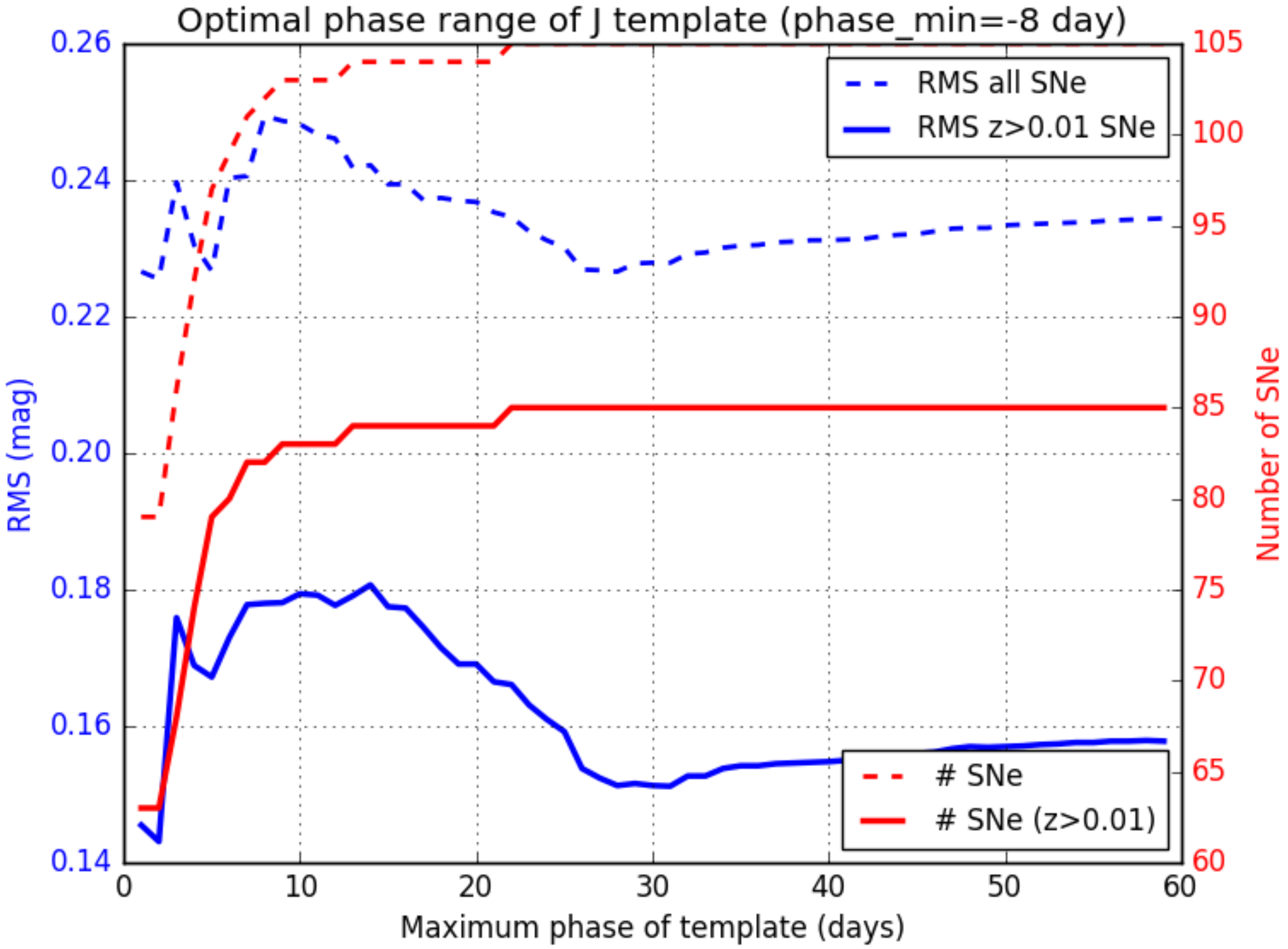
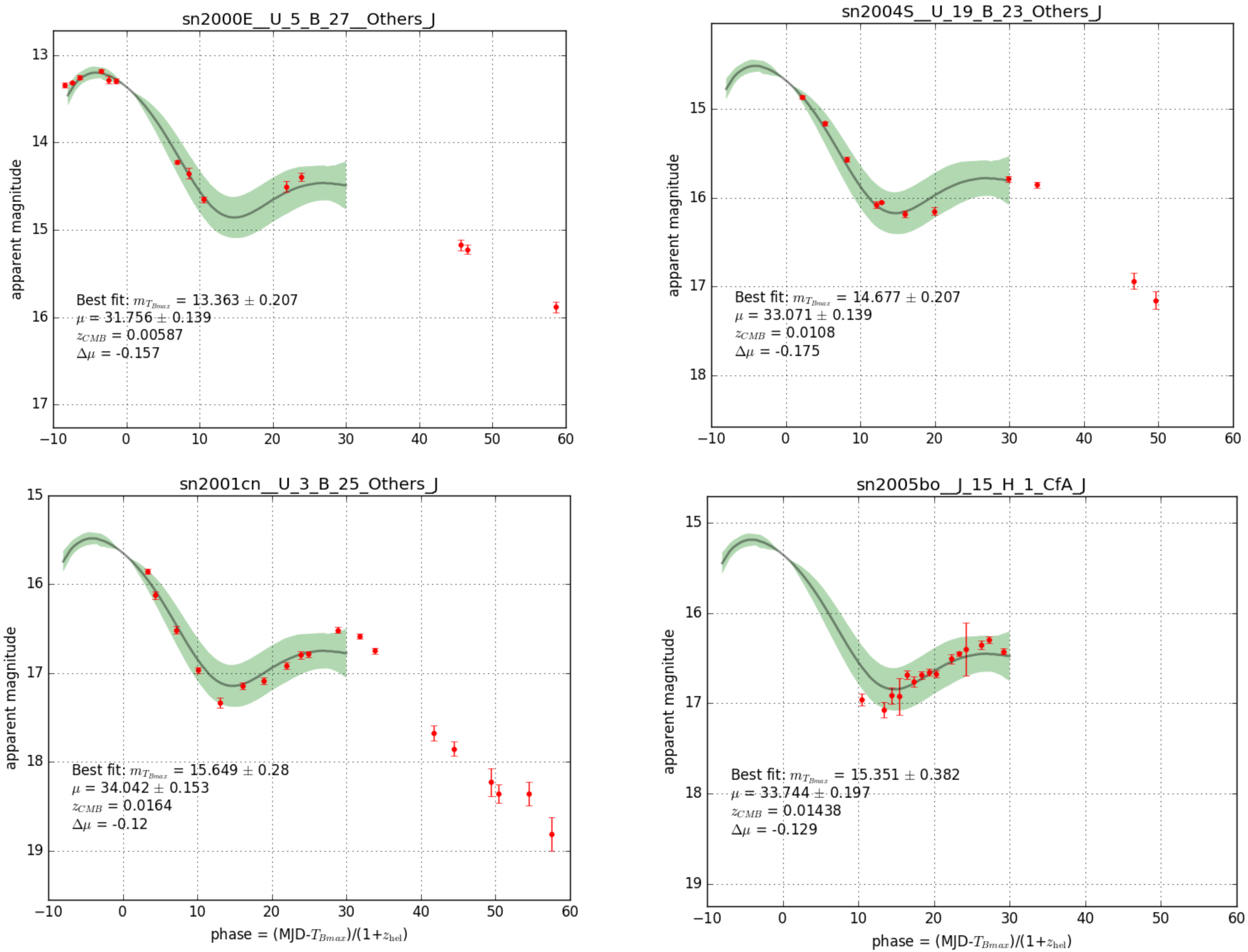


Arturo Avelino, "Near-infrared SN Ia as standard candles"



Arturo Avelino, "Near-infrared SN Ia as standard candles"


Optimal phase range of J template (phase_min=-8 day)
RMS (mag)
Number of SNe
Maximum phase of template (days)
RMS all SNe
RMS z>0.01 SNe
SNe
SNe (z>0.01)
0.26
0.24
0.22
0.20
0.18
0.16
0.14
105
100
95
90
85
80
75
70
65
60
0
10
20
30
40
50
60


sn2000E__U_5_B_27__Others_J
apparent magnitude
Best fit: $m_{T_{Bmax}}$ = 13.363 ± 0.207
μ = 31.756 ± 0.139
z_{CMB} = 0.00587
$\Delta\mu$ = -0.157
sn2004S__U_19_B_23_Others_J
apparent magnitude
Best fit: $m_{T_{Bmax}}$ = 14.677 ± 0.207
μ = 33.071 ± 0.139
z_{CMB} = 0.0108
$\Delta\mu$ = -0.175
sn2001cn__U_3_B_25_Others_J
apparent magnitude
Best fit: $m_{T_{Bmax}}$ = 15.649 ± 0.28
μ = 34.042 ± 0.153
z_{CMB} = 0.0164
$\Delta\mu$ = -0.12
phase = (MJD-T_{Bmax})/(1+$z_{\rm hel}$)
sn2005bo__J_15_H_1_CfA_J
apparent magnitude
Best fit: $m_{T_{Bmax}}$ = 15.351 ± 0.382
μ = 33.744 ± 0.197
z_{CMB} = 0.01438
$\Delta\mu$ = -0.129
phase = (MJD-T_{Bmax})/(1+$z_{\rm hel}$)

Distance modulus

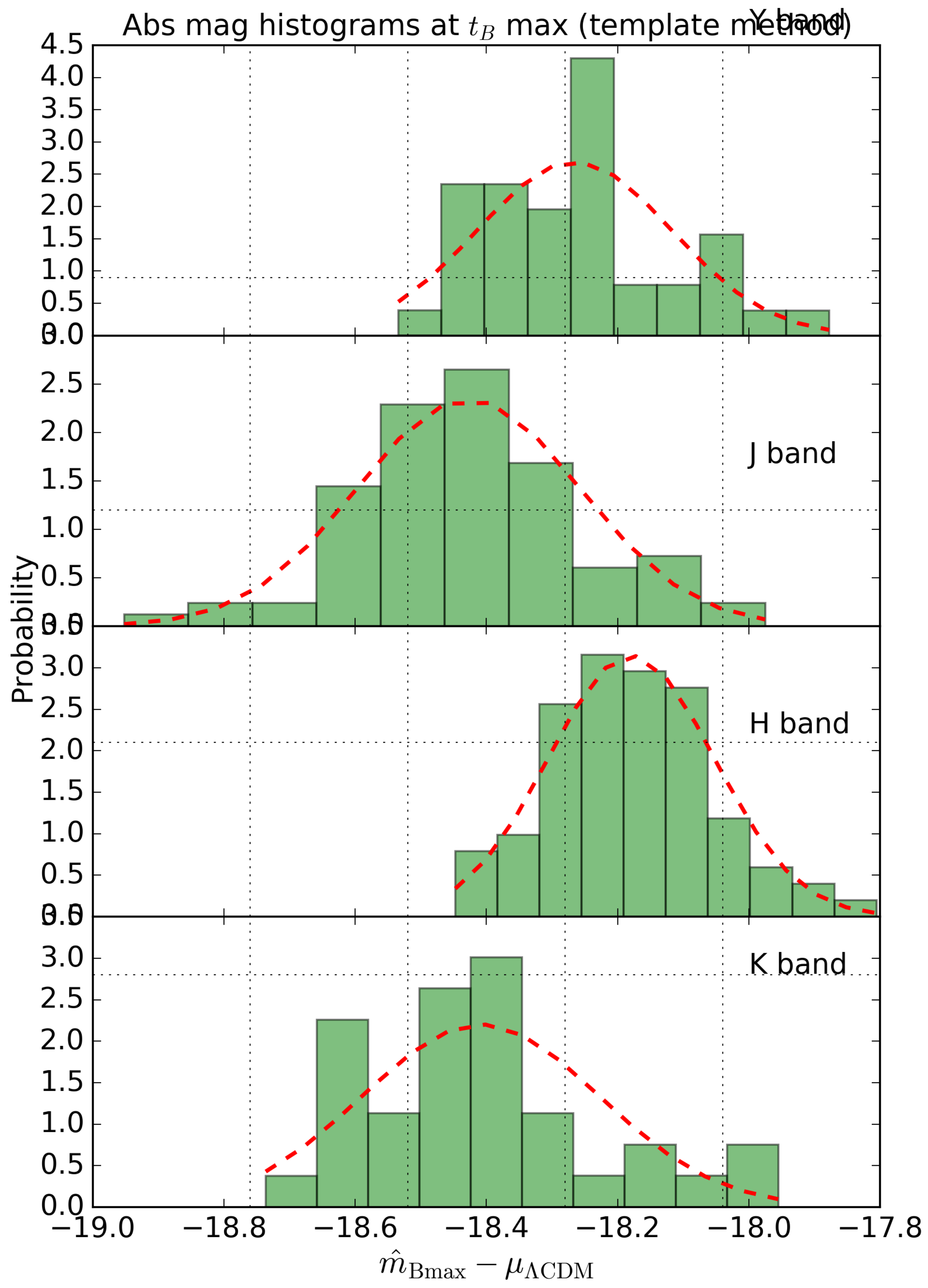
$$\Delta m_s(\hat{t}) \equiv m_s(\hat{t}) - \mathcal{M}(\hat{t}) - m_{0,s} \tag{11}$$

where $m_s(\hat{t})$ and $\mathcal{M}(\hat{t})$ are the apparent magnitude and the magnitude of the normalized template at phase $\hat{t}$, respectively. We can express this difference for all the $N_{\mathrm{LC},s}$ phases in a given LC as the vector,

$$\boldsymbol{\Delta m}_s \equiv \begin{pmatrix} \Delta m_s(\hat{t}_1) \\ \Delta m_s(\hat{t}_2) \\ \vdots \\ \Delta m_s(\hat{t}_{N_{\mathrm{LC},s}}) \end{pmatrix} . \tag{12}$$

Then, to determine $m_{0,s}$ we minimize the negative of the log likelihood function $L(m_{0,s})$ defined as

$$-2 \ln L(m_{0,s}) = \boldsymbol{\Delta m}_s^{\top} \cdot C^{-1} \cdot \boldsymbol{\Delta m}_s \tag{13}$$



Arturo Avelino, "Near-infrared SN Ia as standard candles"

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where C is the $N_{\mathrm{LC},s}$-dimensional covariance matrix where the $(\hat{t}_i, \hat{t}_j)$ component is given by:

$$C_{ij} \equiv \mathrm{Cov}\left(\Delta m_s(\hat{t}_i), \Delta m_s(\hat{t}_j)\right) \qquad (14)$$

$$= \sigma_{\mathcal{M}}(\hat{t}_i)\sigma_{\mathcal{M}}(\hat{t}_j)\exp\left[-\frac{(\hat{t}_i - \hat{t}_j)^2}{2l^2}\right] + \hat{\sigma}^2_{m,s}(\hat{t}_i)\delta_{ij} \qquad (15)$$

where $\sigma_{\mathcal{M}}(\hat{t})$ is the population standard deviation of the sample distribution of magnitudes at time $\hat{t}$, determined from Eq. (B2) during the training process used to construct the mean LC template, with the hyperparameter l computed via Eq. (A6), while $\hat{\sigma}^2_{m,s}(\hat{t}_i)$ is the photometric error of the datum $m_s(\hat{t}_i)$.

Distance modulus

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From Eq. (13), we can calculate an analytic expression for the maximum likelihood estimator (MLE) of the apparent magnitude at B-band maximum light, $\hat{m}_{0,s}$, given by:

$$\hat{m}_{0,s} = \left[\sum_{i,j}^{N_{\mathrm{LC},s}} (C^{-1})_{ij}\right]^{-1} \times \sum_{i}^{N_{\mathrm{LC},s}} \left[\left(m_s(\hat{t}_i) - \mathcal{M}(\hat{t}_i)\right) \sum_{j}^{N_{\mathrm{LC},s}} (C^{-1})_{ij}\right], \tag{16}$$

with the MLE of the uncertainty of $\hat{m}_{0,s}$ given as

$$\sigma_{0,s} = \left[\sum_{i,j}^{N_{\mathrm{LC},s}} (C^{-1})_{ij}\right]^{-1/2}. \tag{17}$$

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$$\mu_s = \hat{m}_{0,s} - \langle M_0 \rangle \quad (19)$$

with uncertainty given as

$$\sigma_{\mu,s} = \sqrt{\sigma^2_{0,s} + \sigma^2_{\mathrm{int}}} \quad (20)$$

where C is the $N_{\mathrm{LC},s}$-dimensional covariance matrix where the $(\hat{t}_i, \hat{t}_j)$ component is given by:

$$C_{ij} \equiv \mathrm{Cov}\left(\Delta m_s(\hat{t}_i), \Delta m_s(\hat{t}_j)\right) \quad (14)$$

$$= \sigma_{\mathcal{M}}(\hat{t}_i)\sigma_{\mathcal{M}}(\hat{t}_j) \exp\left[-\frac{(\hat{t}_i - \hat{t}_j)^2}{2l^2}\right] +$$

From Eq. (13), we can calculate an analytic expression for the maximum likelihood estimator (MLE) of the apparent magnitude at B-band maximum light, $\hat{m}_{0,s}$, given by:

$$\hat{m}_{0,s} = \left[\sum_{i,j}^{N_{\mathrm{LC},s}} (C^{-1})_{ij}\right]^{-1} \times \sum_i^{N_{\mathrm{LC},s}} \left[\left(m_s(\hat{t}_i) - \mathcal{M}(\hat{t}_i)\right) \sum_j^{N_{\mathrm{LC},s}} (C^{-1})_{ij}\right], \quad (16)$$

with the MLE of the uncertainty of $\hat{m}_{0,s}$ given as

$$\sigma_{0,s} = \left[\sum_{i,j}^{N_{\mathrm{LC},s}} (C^{-1})_{ij}\right]^{-1/2}. \quad (17)$$

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Then, to determine $m_{0,s}$ we minimize the negative of the log likelihood function $L(m_{0,s})$ defined as

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$$\mu_s = \hat{m}_{0,s} - \langle M_0 \rangle \tag{19}$$

with uncertainty given as

$$\sigma_{\mu,s} = \sqrt{\sigma_{0,s}^2 + \sigma_{\mathrm{int}}^2} \tag{20}$$

where C is the $N_{\mathrm{LC},s}$-dimensional covariance matrix where the $(\hat{t}_i, \hat{t}_j)$ component is given by:

$$\begin{aligned} C_{ij} \equiv & \mathrm{Cov}\left(\Delta m_s(\hat{t}_i), \Delta m_s(\hat{t}_j)\right) \\ = & \sigma_{\mathcal{M}}(\hat{t}_i)\sigma_{\mathcal{M}}(\hat{t}_j) \exp\left[-\frac{(\hat{t}_i - \hat{t}_j)^2}{2l^2}\right] + \end{aligned} \tag{14}$$

From Eq. (13), we can calculate an analytic expression for the maximum likelihood estimator (MLE) of the apparent magnitude at B-band maximum light, $\hat{m}_{0,s}$, given by:

$$\begin{aligned} \hat{m}_{0,s} = & \left[\sum_{i,j}^{N_{\mathrm{LC},s}} (C^{-1})_{ij}\right]^{-1} \times \\ & \sum_{i}^{N_{\mathrm{LC},s}} \left[\left(m_s(\hat{t}_i) - \mathcal{M}(\hat{t}_i)\right) \sum_{j}^{N_{\mathrm{LC},s}} (C^{-1})_{ij}\right] , \end{aligned} \tag{16}$$

with the MLE of the uncertainty of $\hat{m}_{0,s}$ given as

$$\sigma_{0,s} = \left[\sum_{i,j}^{N_{\mathrm{LC},s}} (C^{-1})_{ij}\right]^{-1/2} . \tag{17}$$

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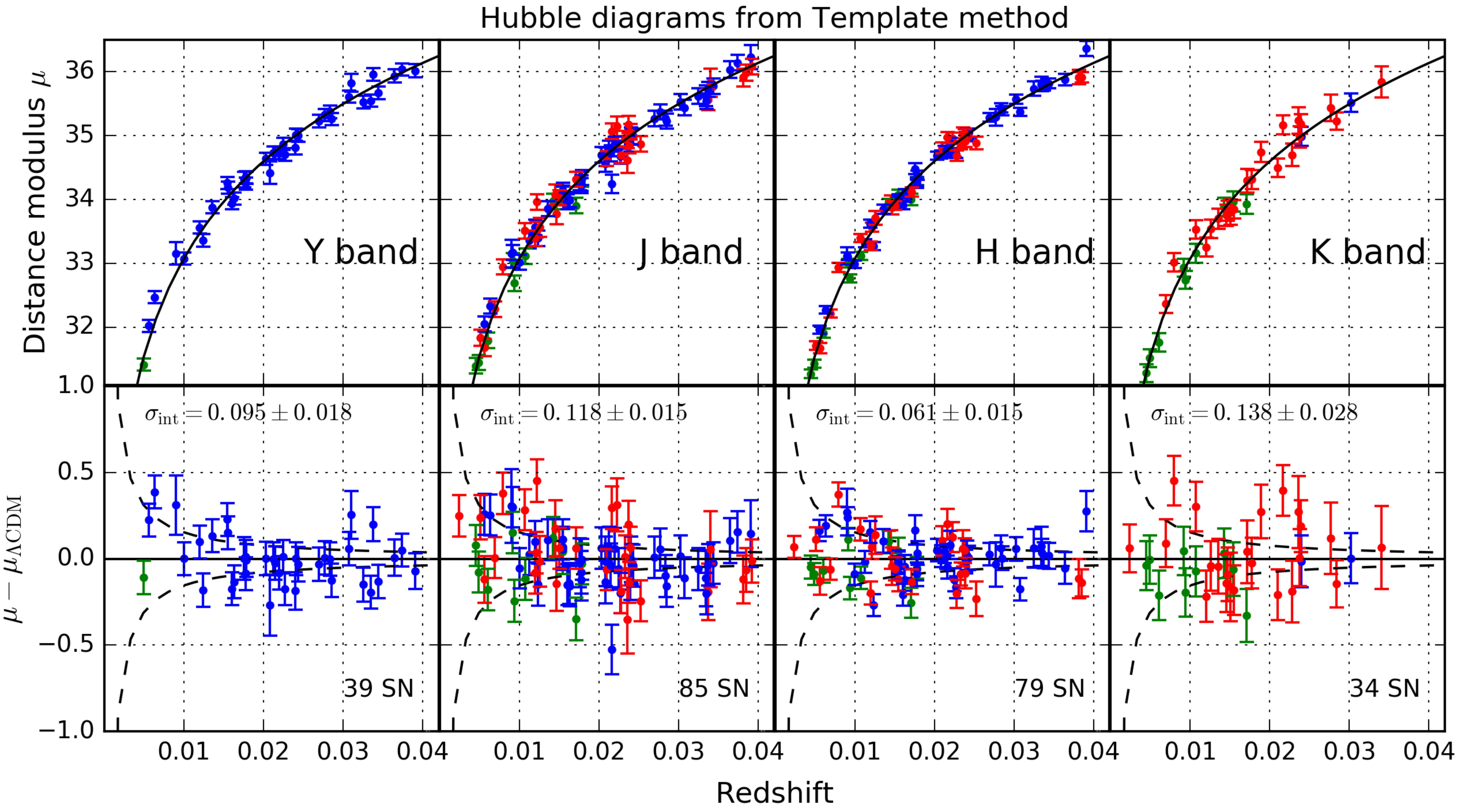
Intrinsic dispersion

Scatter in the Hubble residuals after accounting for peculiar-velocity and photometric uncertainties.

Intrinsic dispersion $\sigma_{\rm int}$:

$$-2\ln\mathcal{L}(\sigma^2_{\rm int}) = \sum_{s}^{N_{\rm SN}} \left[\ln\left(\sigma^2_{0,s} + \sigma^2_{\rm int} + \sigma^2_{\mu_{\rm pec},s}\right) + \frac{\delta\mu_s^2}{\sigma^2_{0,s} + \sigma^2_{\rm int} + \sigma^2_{\mu_{\rm pec},s}} \right]$$

Blondin, Mandel, Kirshner, 2011



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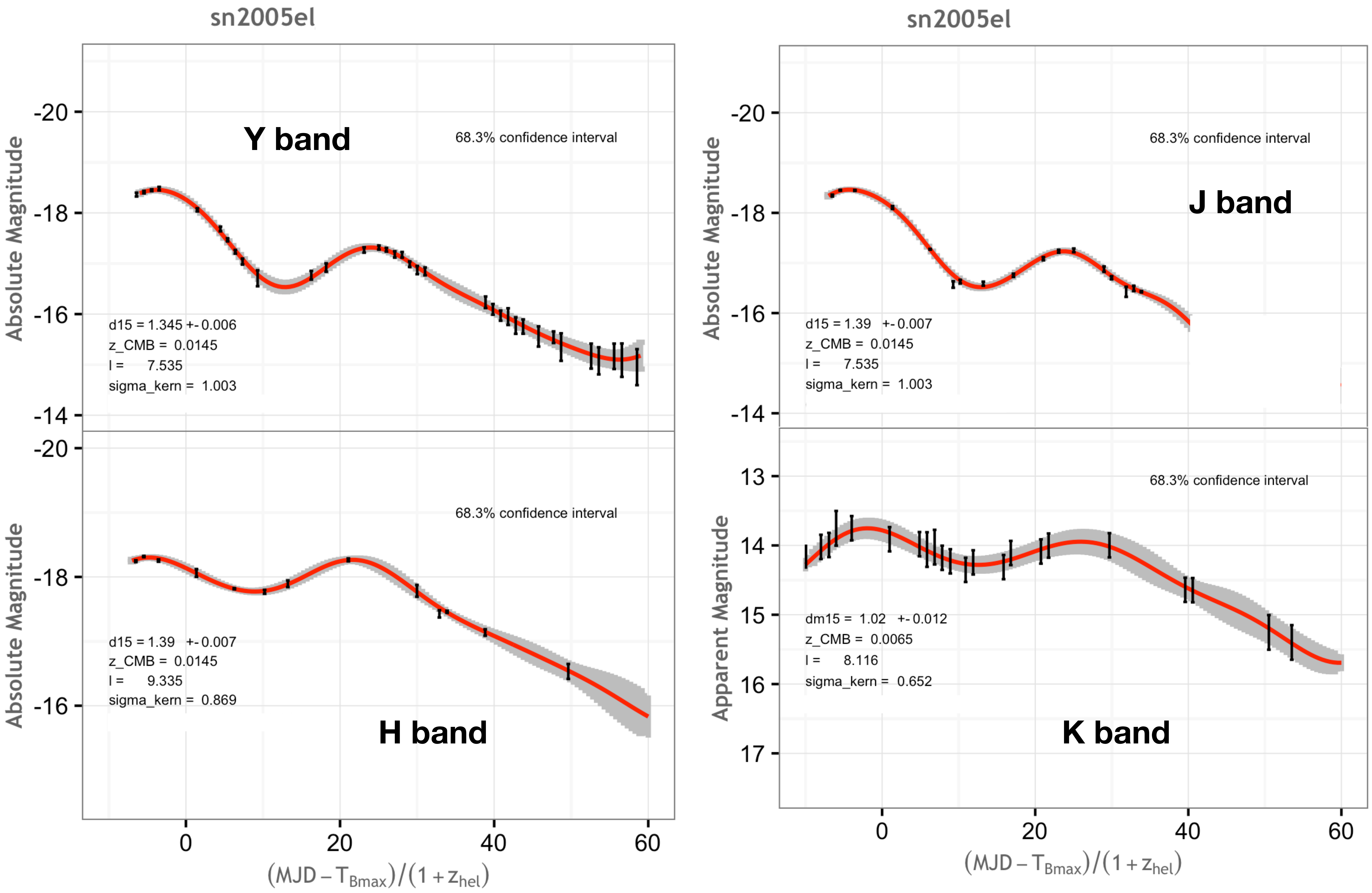
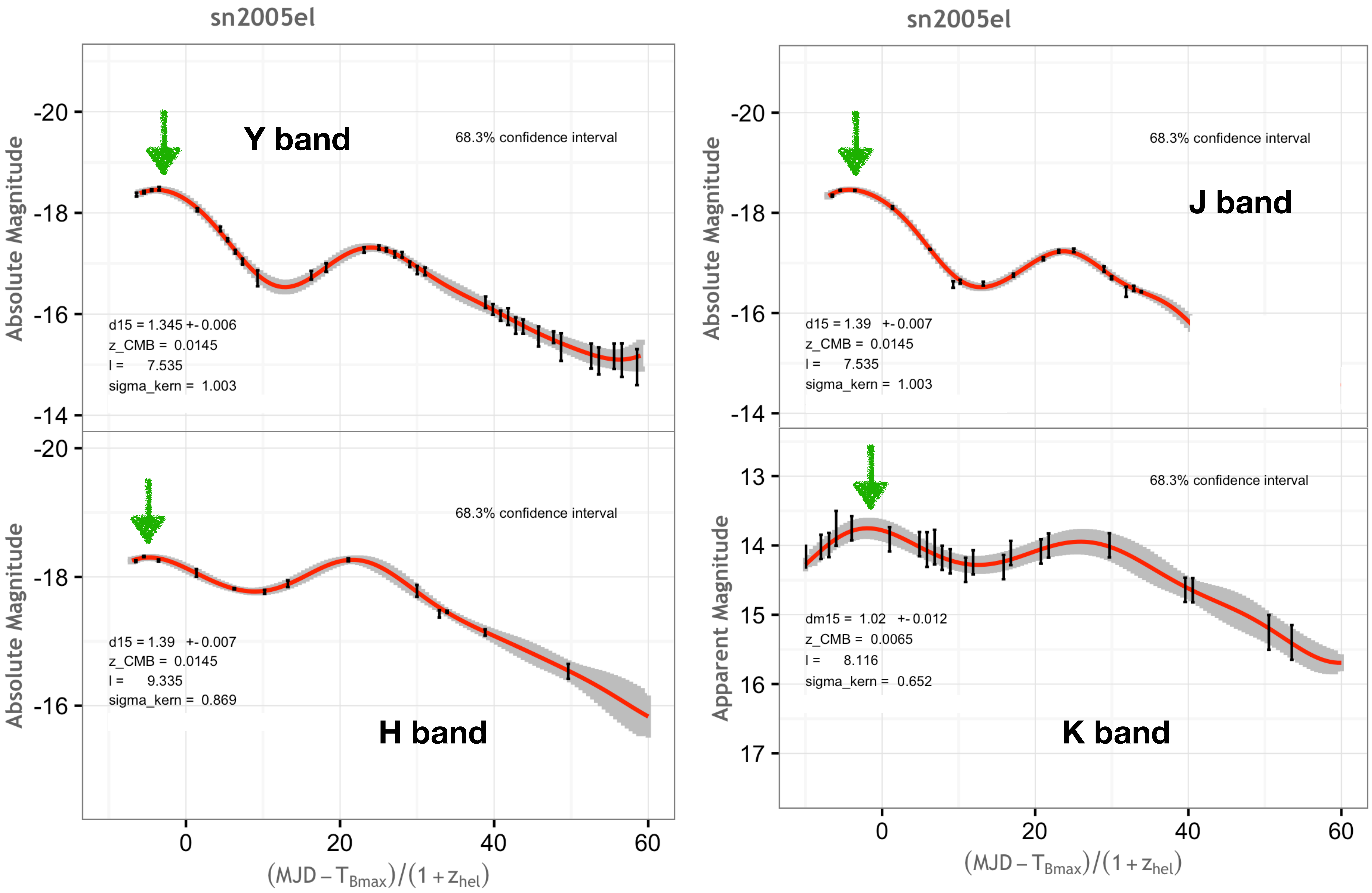
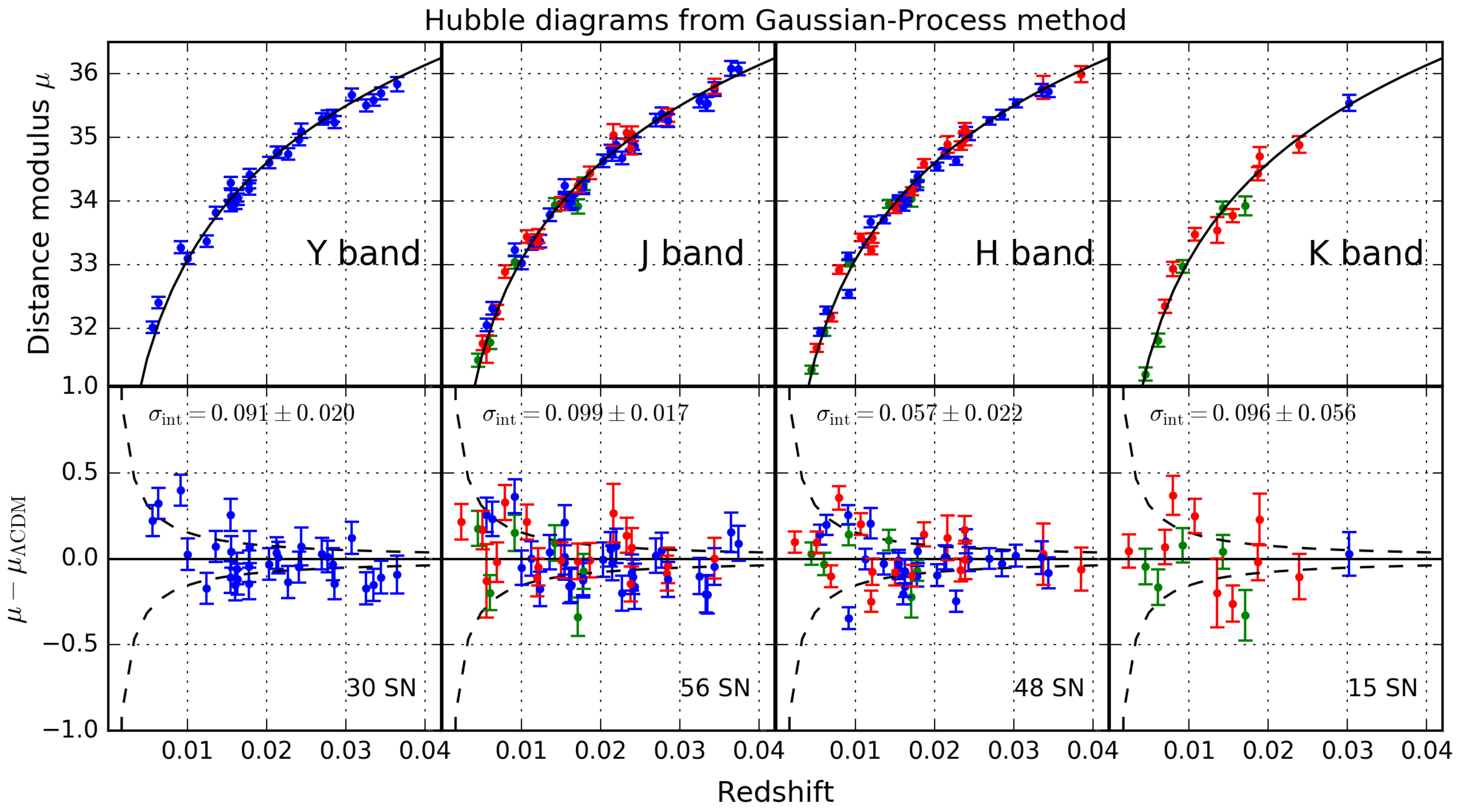
Gaussian-Process method

Gaussian-Process Method



Gaussian-Process Method





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Combining multiple NIR bands

Distance modulus

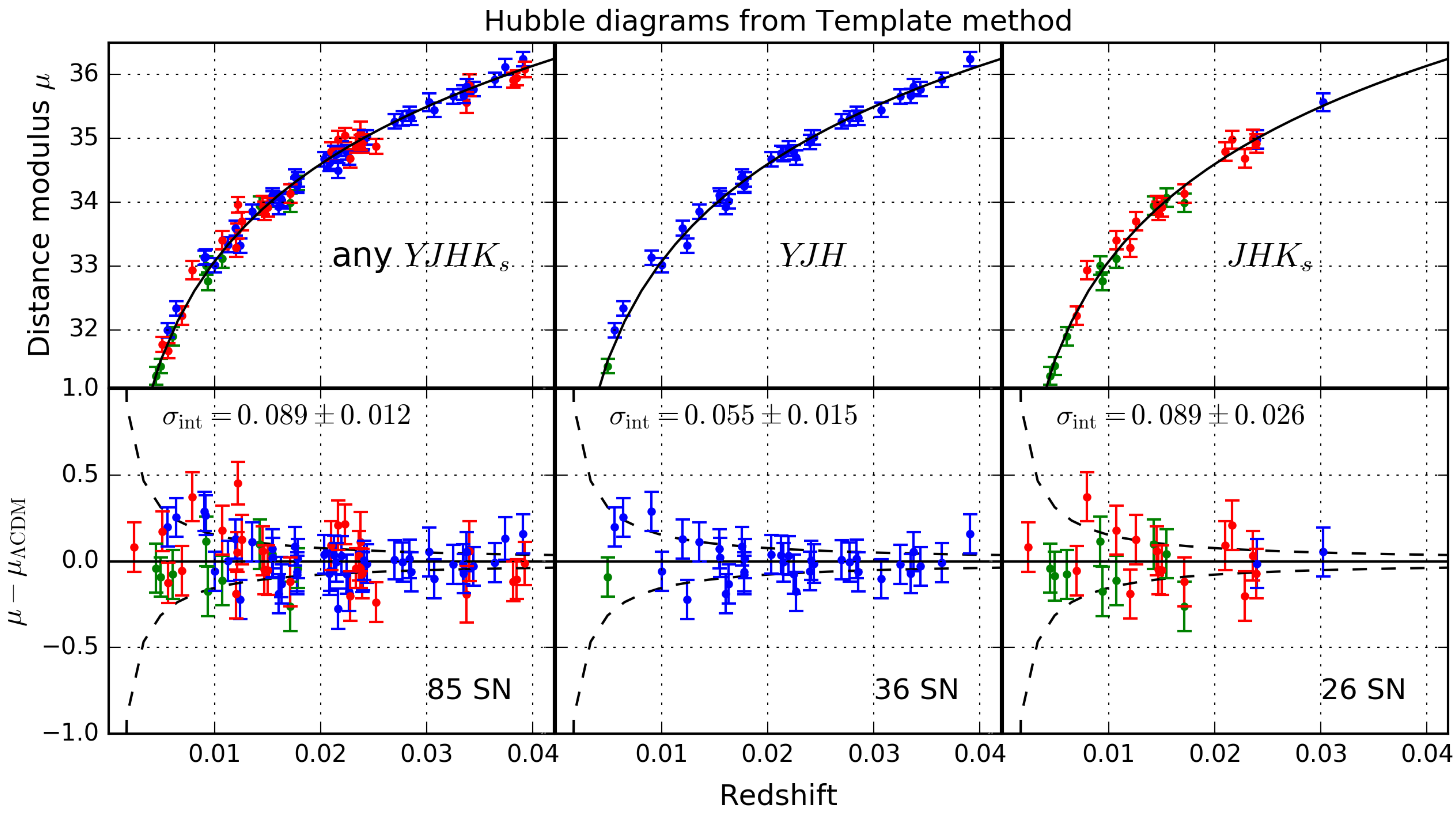
4.3. *Distance modulus from the combined NIR bands*

From the distance moduli $(\mu_s^Y, \mu_s^J, \mu_s^H, \mu_s^K)$ for a given supernova s determined from each NIR band following either of the two methods described above, we determine the "total" distance modulus $\hat{\mu}_s$ in each method. First we define the vector of residuals

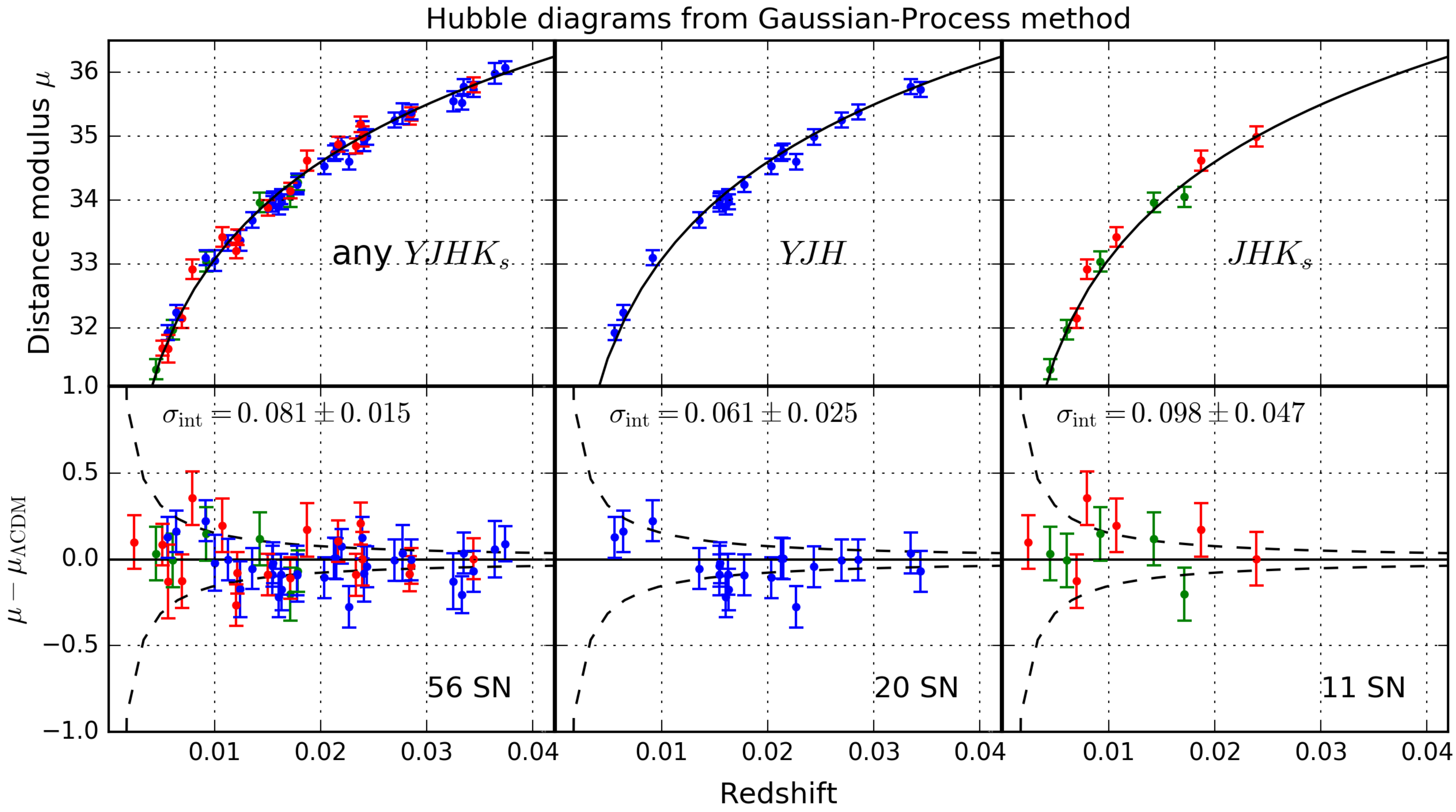
$$\delta\boldsymbol{\mu}_s \equiv \begin{pmatrix} \mu_s^Y - \hat{\mu}_s \\ \mu_s^J - \hat{\mu}_s \\ \mu_s^H - \hat{\mu}_s \\ \mu_s^K - \hat{\mu}_s \end{pmatrix} . \qquad (25)$$

where μ_s^Z is given by either Eq. (19) or (23). Then, to determine $\hat{\mu}_s$ we minimize the negative of the likelihood function $L(\hat{\mu}_s)$ defined as

$$-2 \ln L(\hat{\mu}_s) = \delta\boldsymbol{\mu}_s^\top \cdot C_\mu^{-1} \cdot \delta\boldsymbol{\mu}_s \qquad (26)$$



Arturo Avelino, "Near-infrared SN Ia as standard candles"



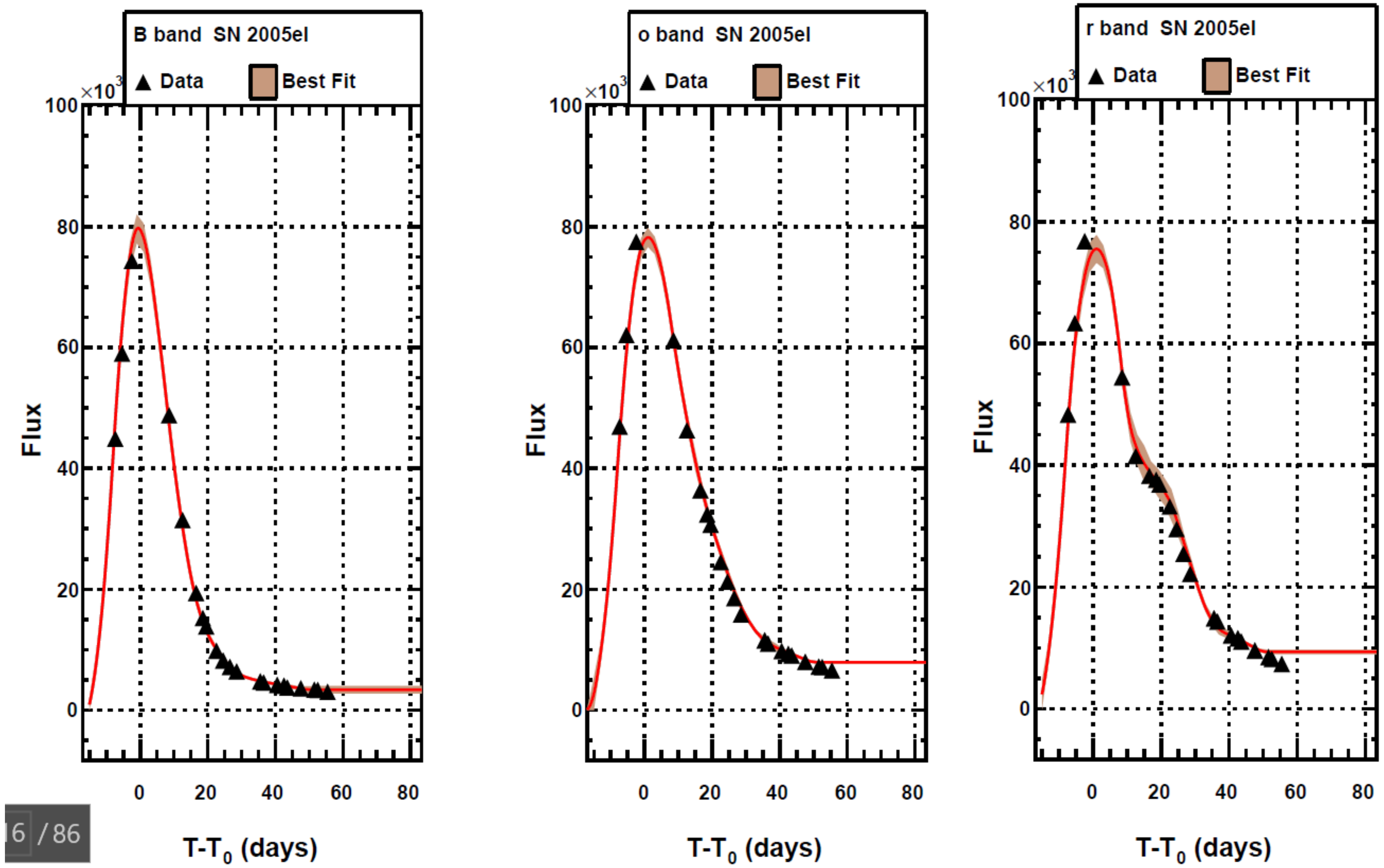
Arturo Avelino, "Near-infrared SN Ia as standard candles"

How good or bad are these results?

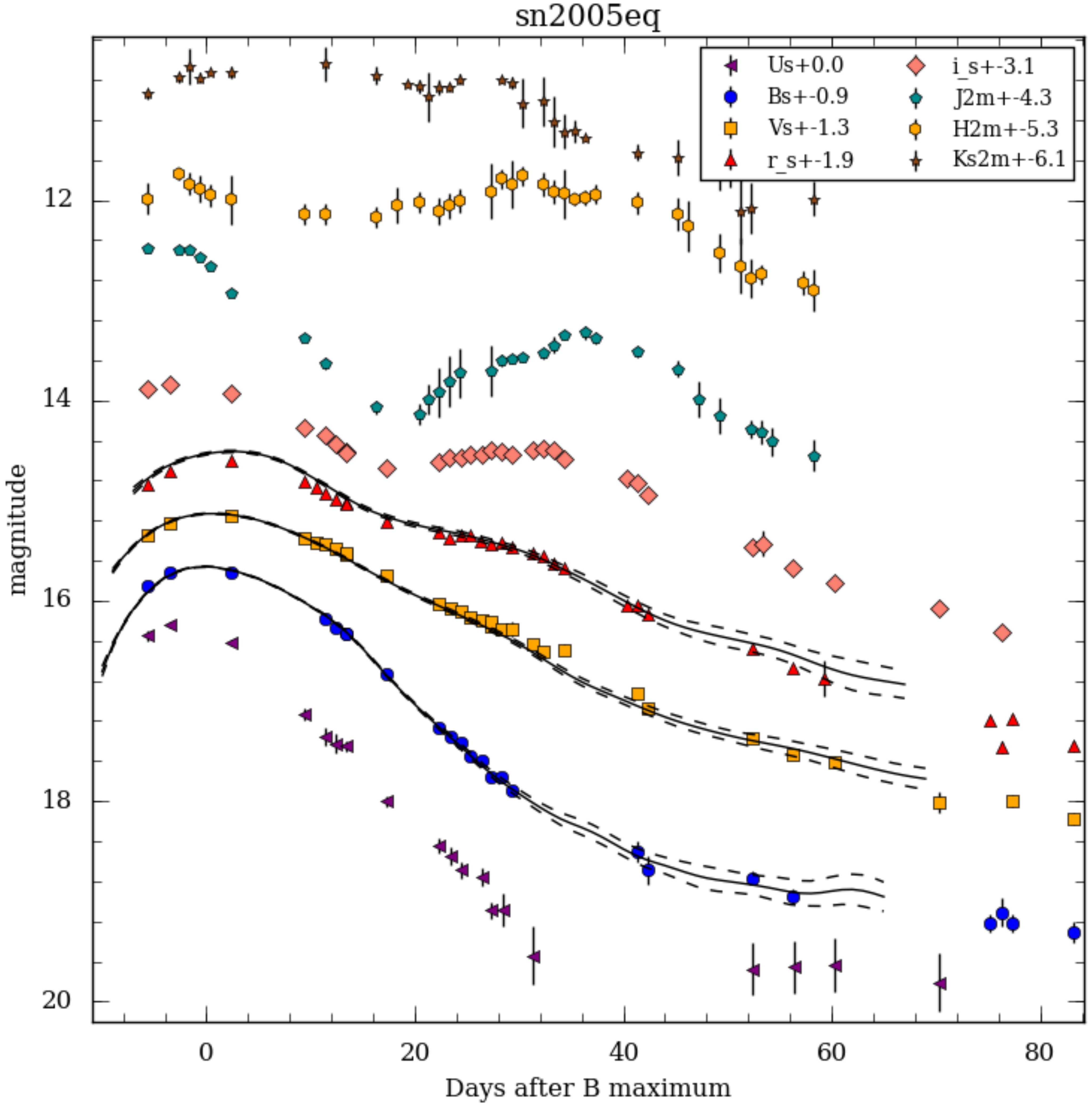
Optical Hubble diagram

Fitting the *optical* light curves only

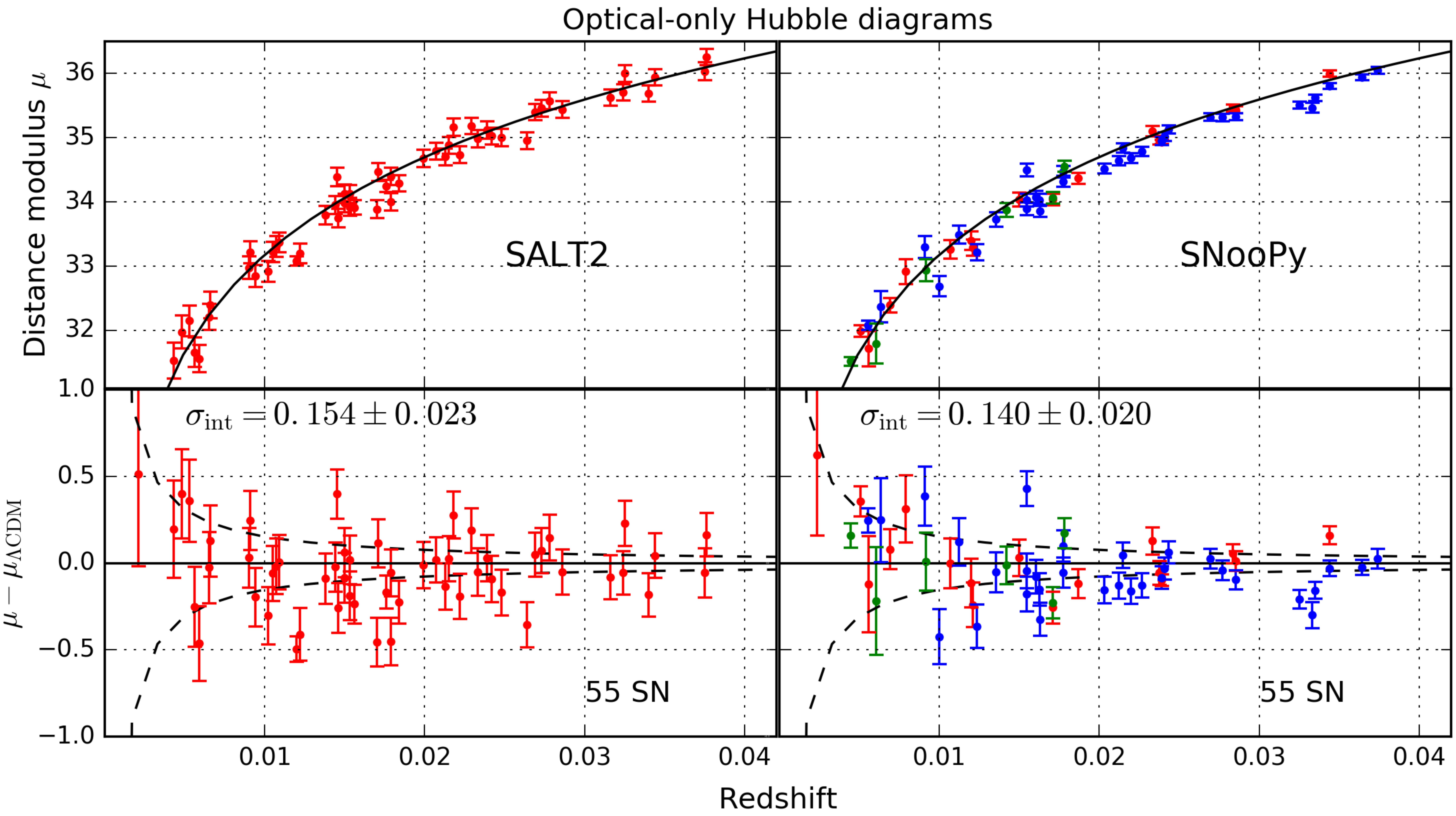
SALT2



SNooPy



Arturo Avelino, "Near-infrared SN Ia as standard candles"



Arturo Avelino, "Near-infrared SN Ia as standard candles"

Intrinsic dispersion and wRMS summary

Band	Method	σ_{int}	wRMS (mag)
Y	Template	0.095 ± 0.018	0.129
Y	GP	0.091 ± 0.020	0.125
J	Template	0.118 ± 0.015	0.156
J	GP	0.099 ± 0.017	0.137
H	Template	0.061 ± 0.015	0.113
H	GP	0.057 ± 0.022	0.117
K_s	Template	0.138 ± 0.028	0.180
K_s	GP	0.096 ± 0.056	0.170
any $YJHK_s$	Template	0.089 ± 0.012	0.123
any $YJHK_s$	GP	0.081 ± 0.015	0.118
YJH	Template	0.055 ± 0.015	0.097
YJH	GP	0.061 ± 0.025	0.105
JHK_s	Template	0.089 ± 0.026	0.134
JHK_s	GP	0.098 ± 0.047	0.149
Optical	SALT2	0.154 ± 0.023	0.216
Optical	SNooPy	0.140 ± 0.020	0.146

RAISIN = SN IA in the IR

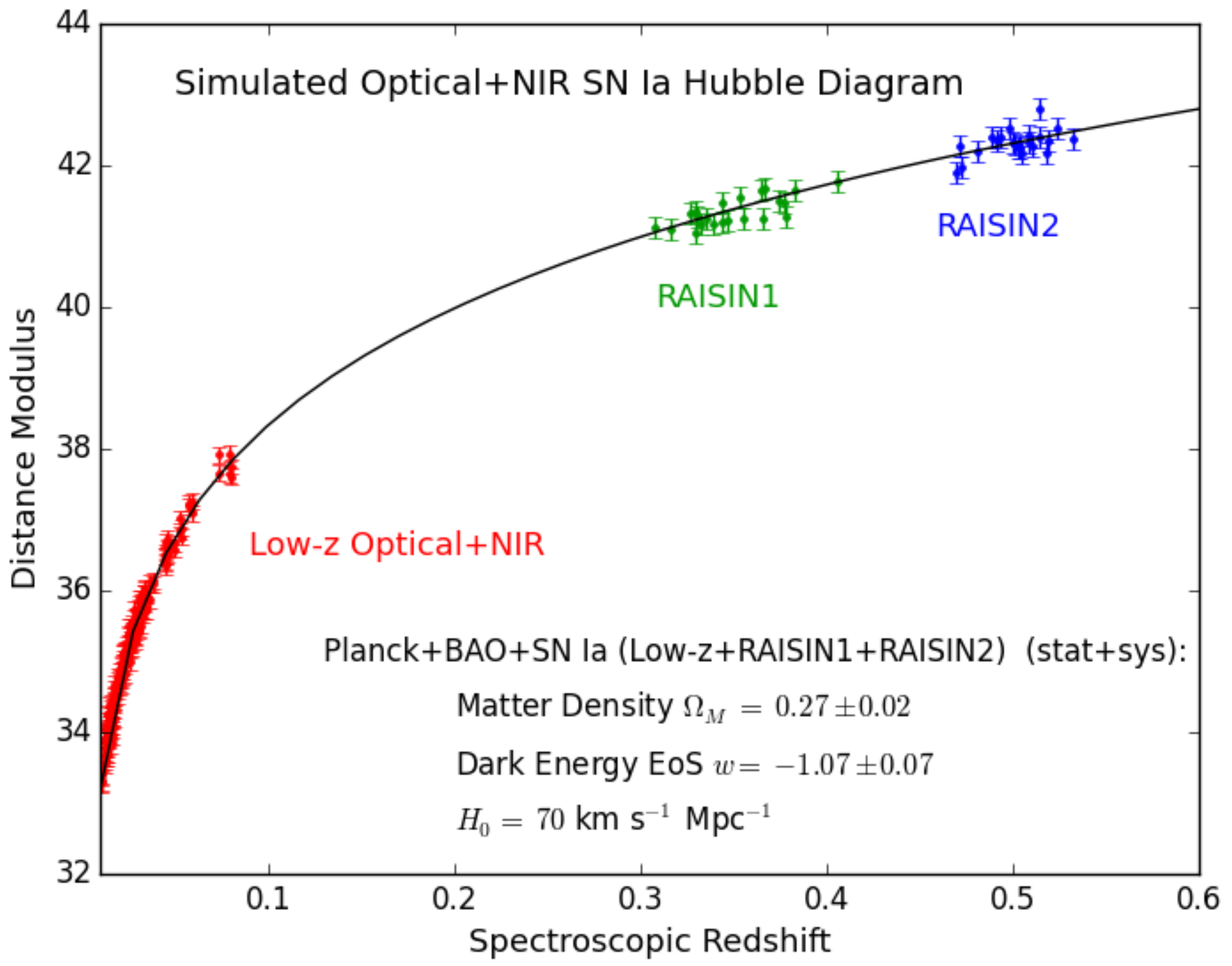
Tracing cosmic expansion with SN Ia in the Near Infrared

RAISIN-1

- 23 SN Ia, redshift ~ 0.3

RAISIN-2

- 24 SN Ia, redshift ~ 0.5



Take away

- NIR SN Ia are very good standard candles compared with optical observations.

Optical

- Very promising for cosmology when combining optical+NIR observations: **RAISIN** program, WFIRST.