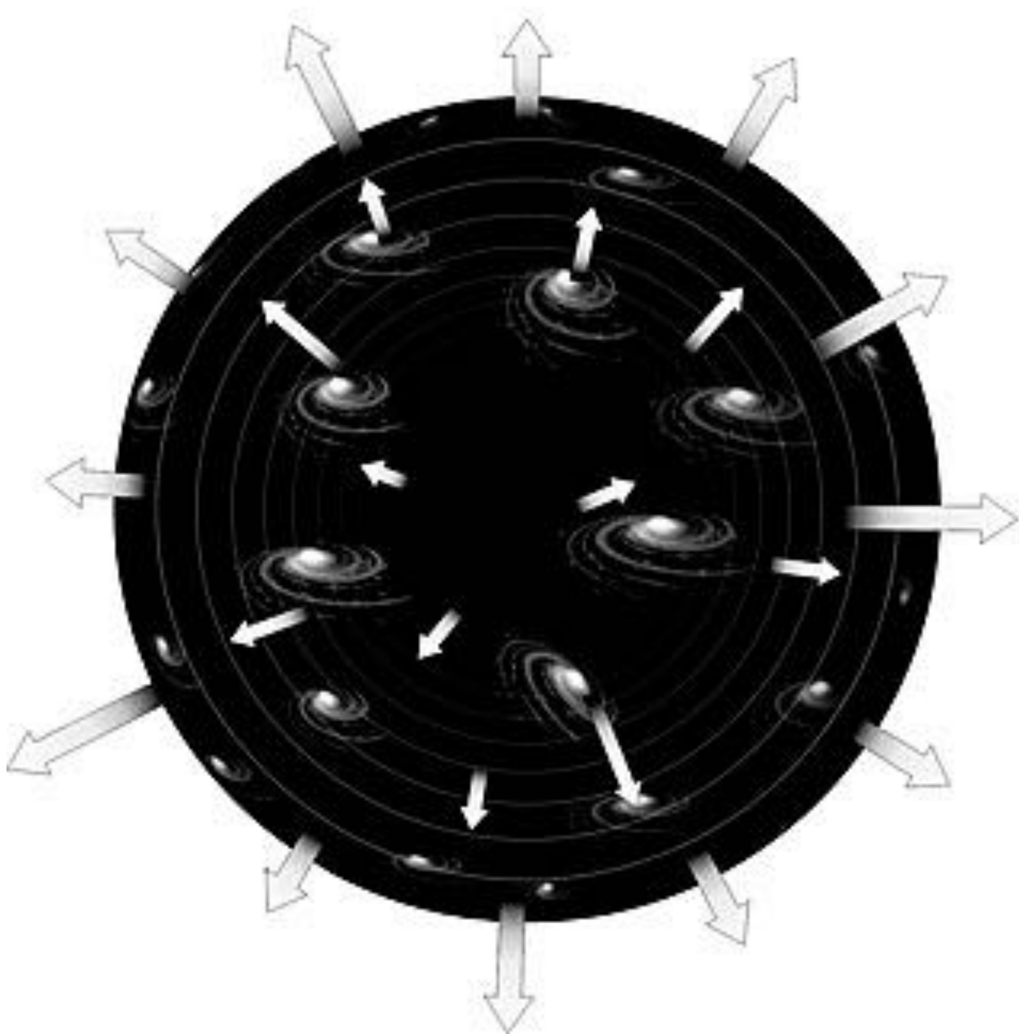
Near-infrared SN Ia as standard candles

Arturo Avelino

CfA, Harvard

CfA, April 24, 2018

Accelerated expansion of the Universe



Type Ia Supernova (SN Ia)

The problem

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

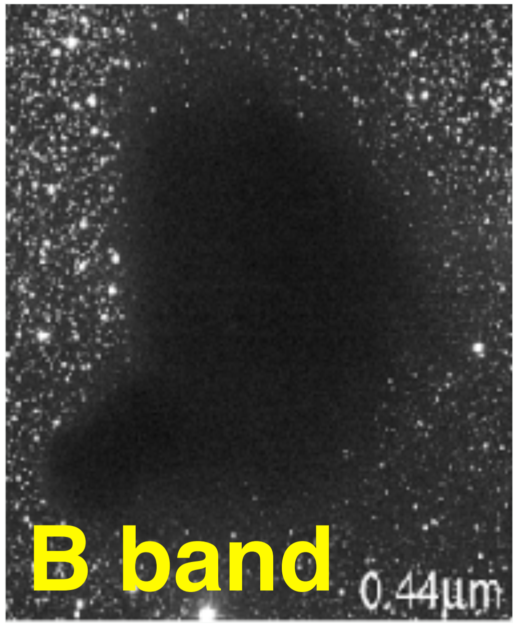
- More optical data *doesn't* mean better DE constraints.

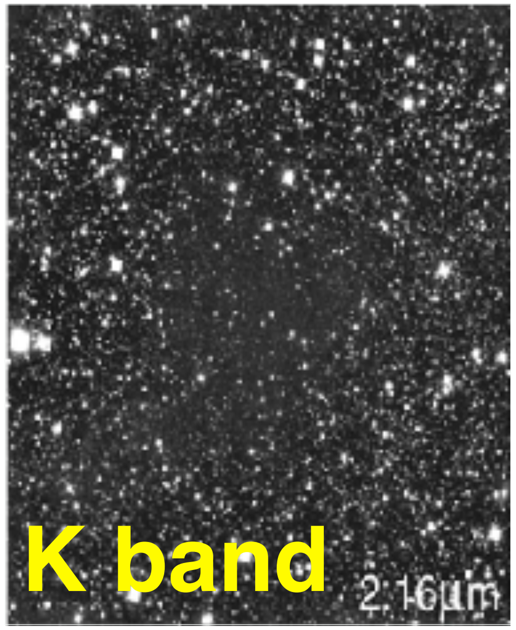
- **Optical** light is **dimmed** and **reddened** by **dust** in the host galaxy, the Milky Way, and the extragalactic medium.

A solution: NIR observations!

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

Optical





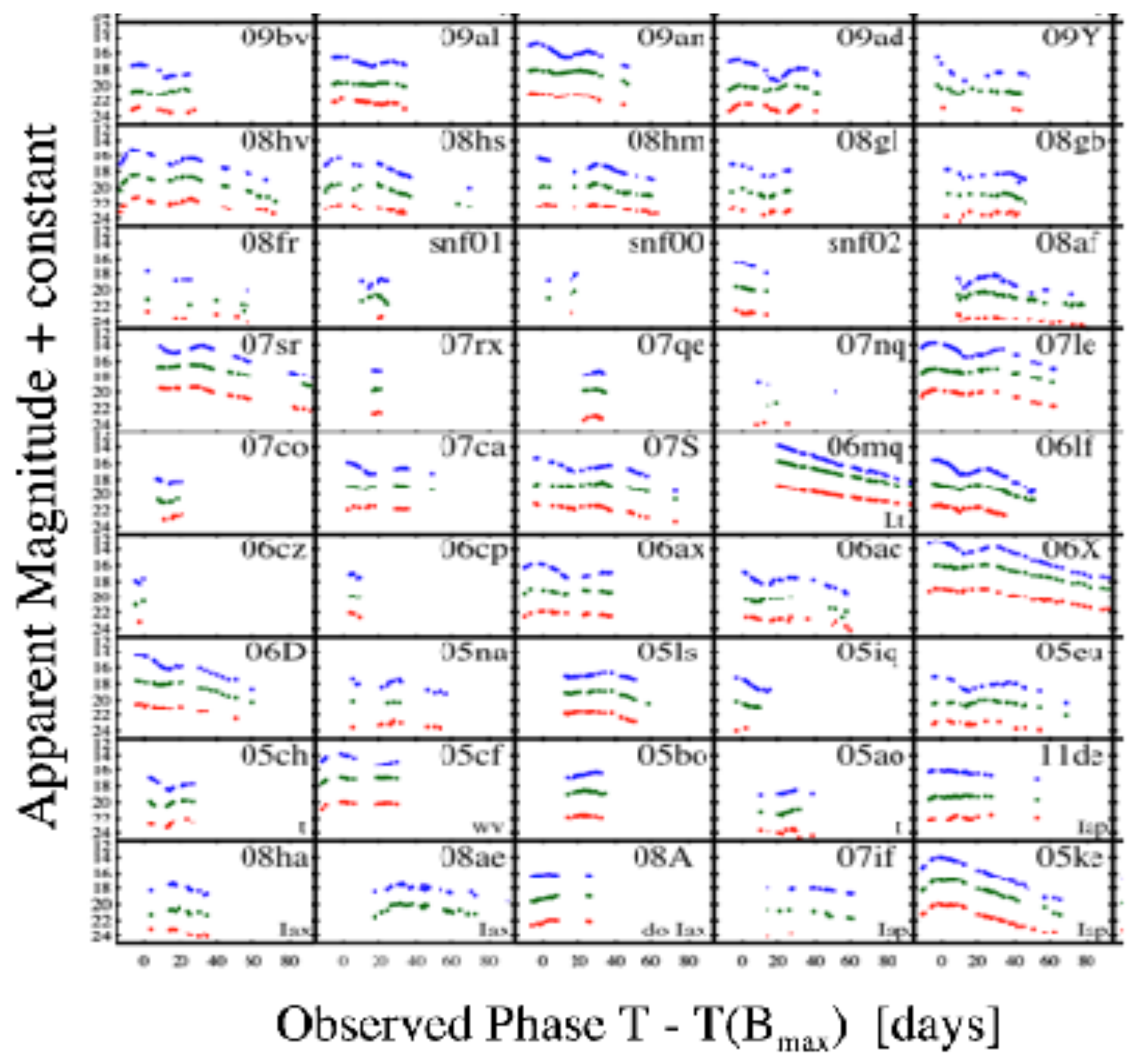
Near infrared

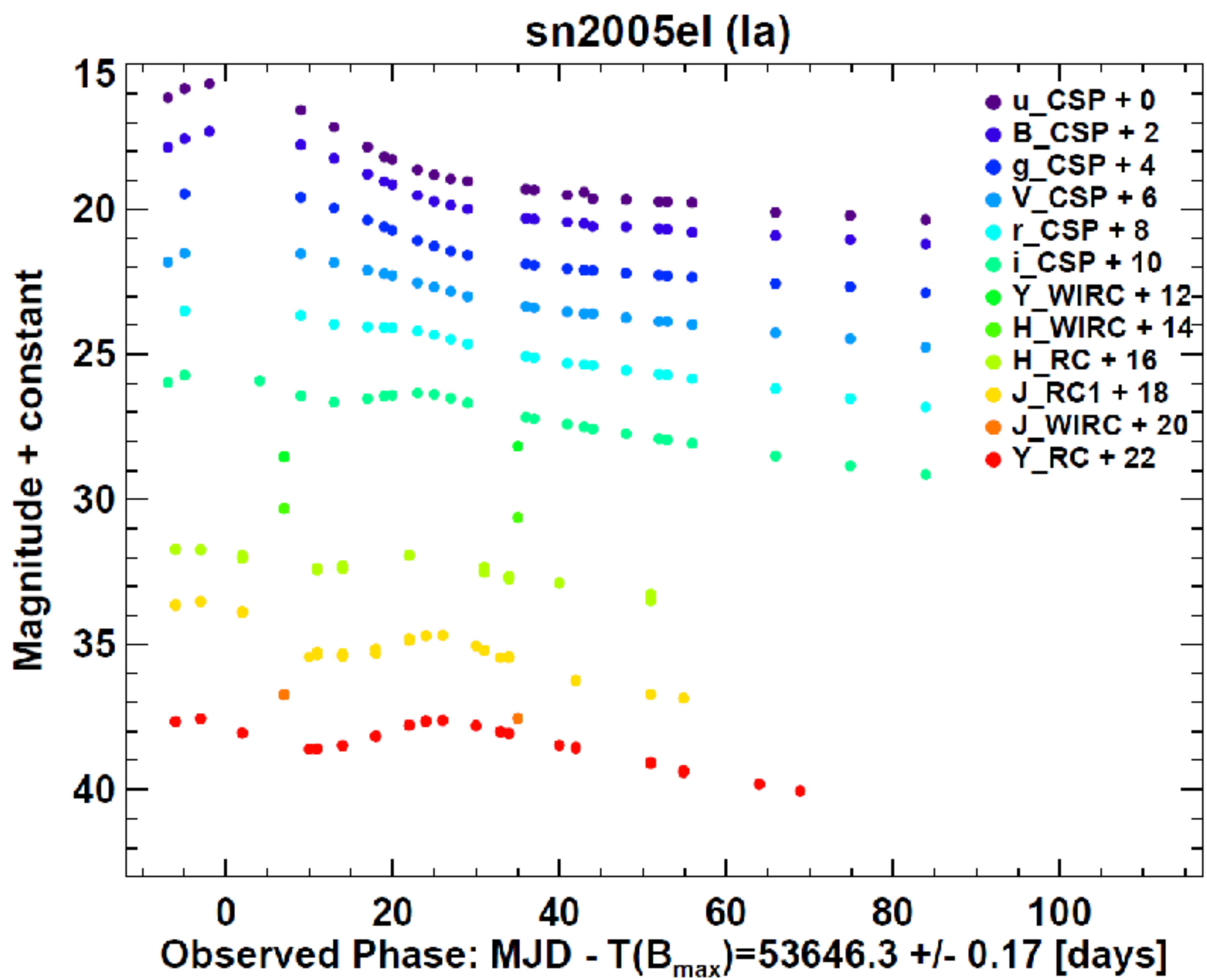
Low-z NIR sample

Friedman+2015

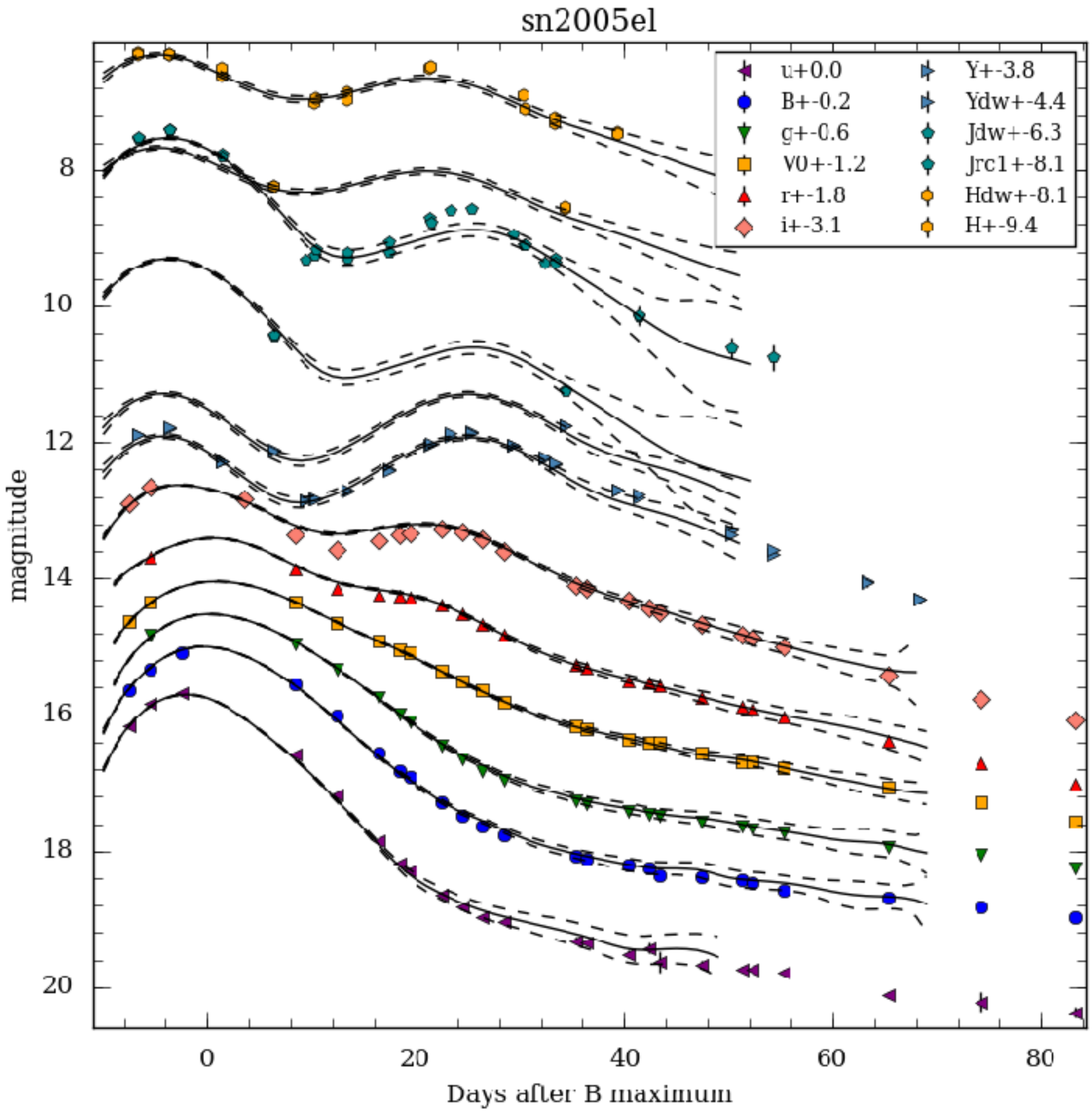
Compiled by **Andrew Friedman** (UCSD):

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





sn2005el (Ia)
Magnitude + constant
Observed Phase: MJD - T(B$_{max}$)=53646.3 +/- 0.17 [days]
15
20
25
30
35
40
0
20
40
60
80
100
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



sn2005el
u+0.0
B+-0.2
g+-0.6
V0+-1.2
r+-1.8
i+-3.1
Y+-3.8
Ydw+-4.4
Jdw+-6.3
Jrc1+-8.1
Hdw+-8.1
H+-9.4
magnitude
Days after B maximum

Goal

Infer the distance modulus (luminosity distance) of each SNIa from their near-infrared time-series data (aka, light curves)

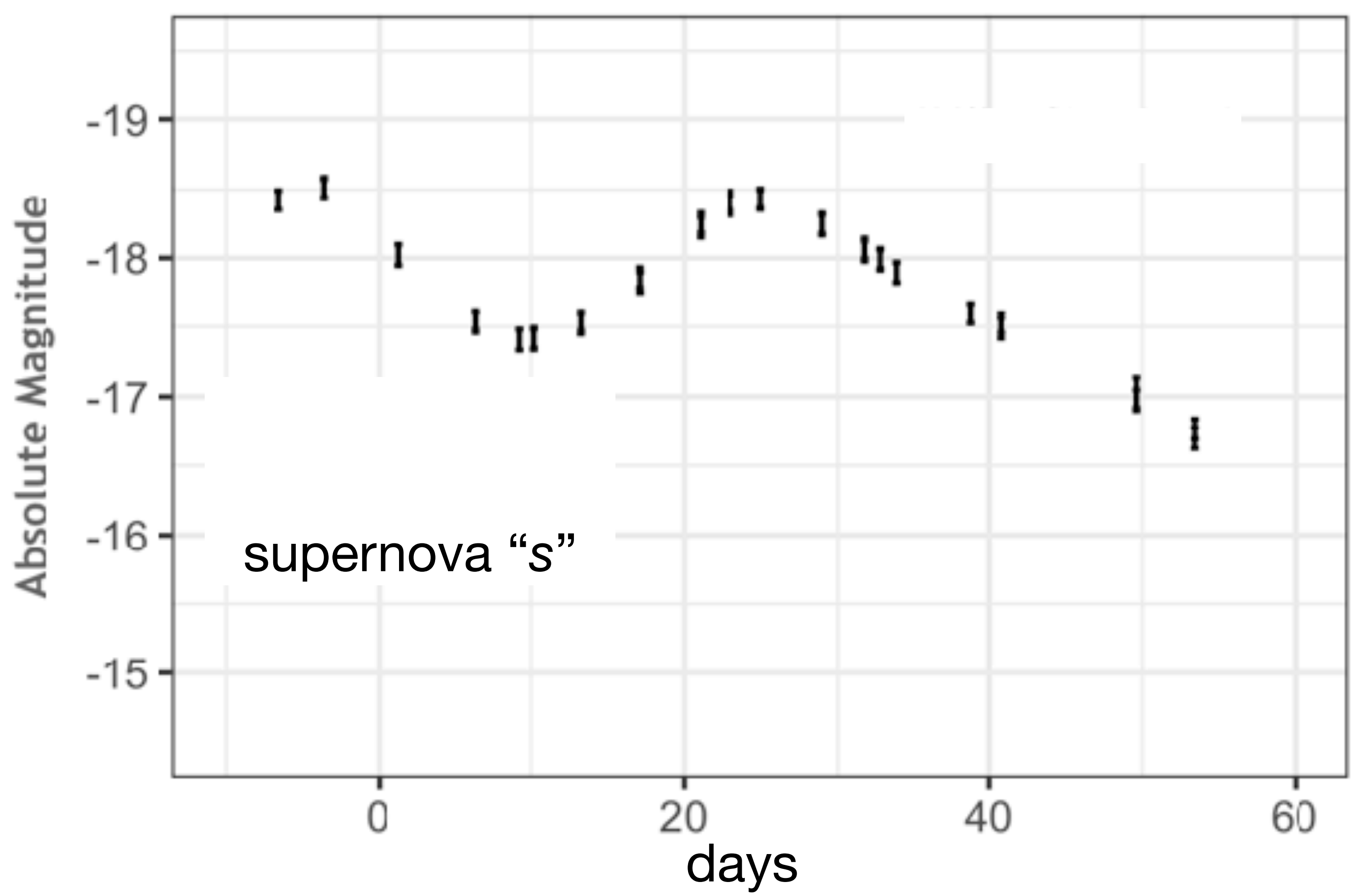
Method

- ⋆ Construct NIR light-curve templates
  - Gaussian-Processes regression
  - Hierarchical Bayesian model
- ⋆ Fit the NIR light-curve template to the time series data

Gaussian Processes

Interpolating the time series using Gaussian Processes regression

$M_{\mathrm{r},s}(\hat{t}_s)$ = datum at a given time, for a given supernova “s" and band.



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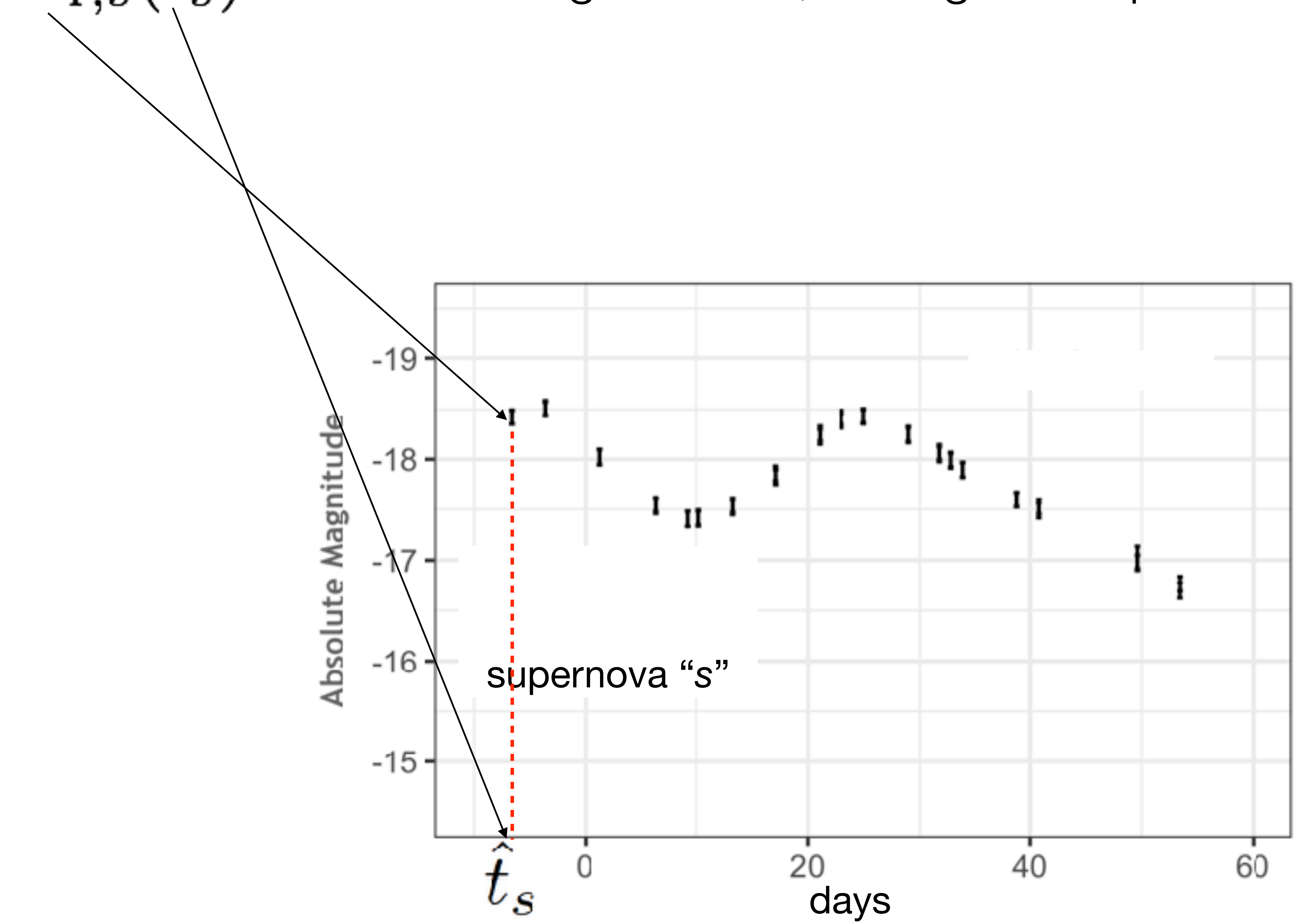
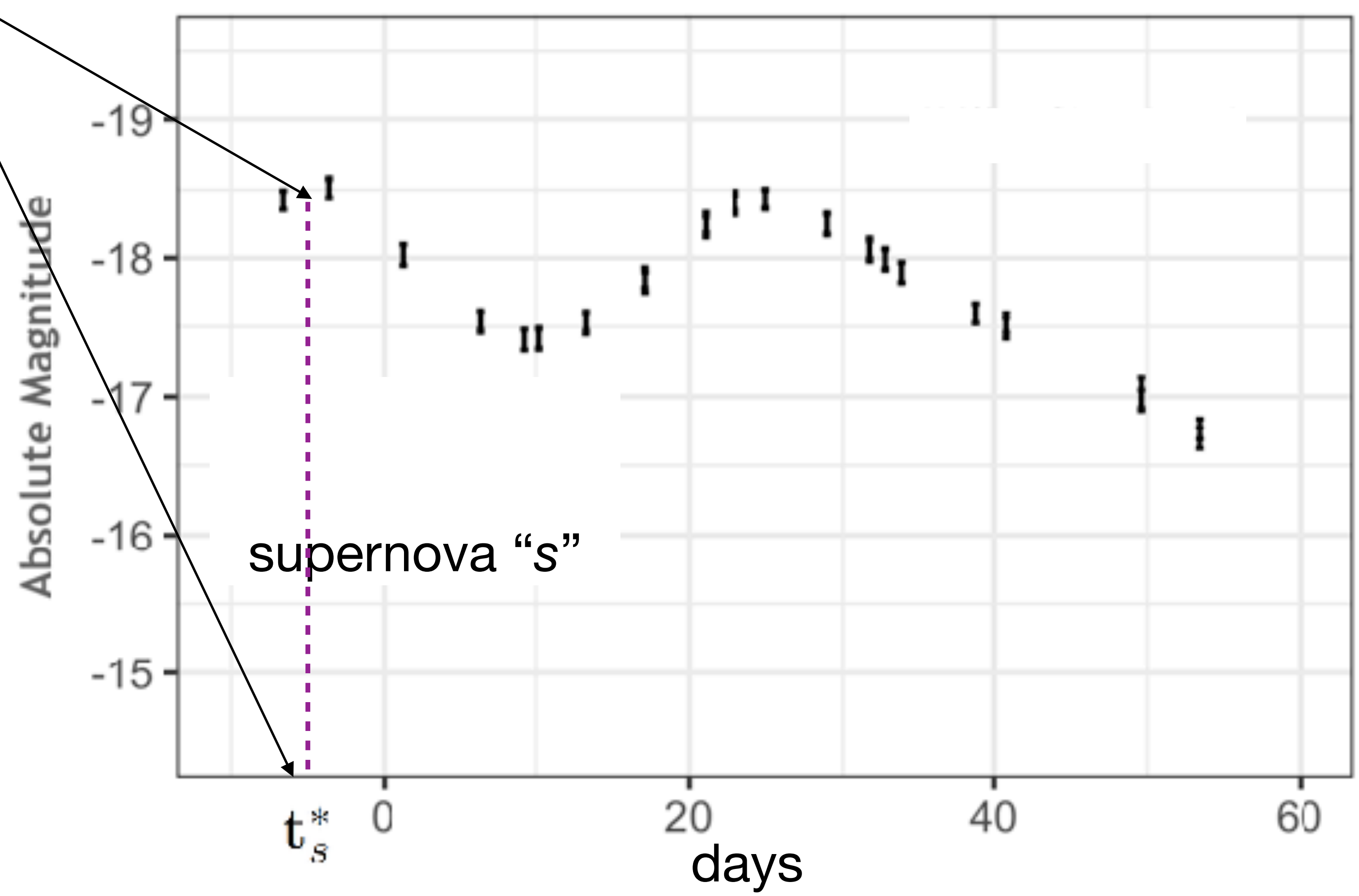


Gaussian Processes

Interpolating the time series using Gaussian Processes regression

$M_{\mathrm{r},s}(\hat{t}_s)$ = datum at a given time, for a given supernova “s" and band.

$$M_{\mathrm{r},s}(\mathbf{t}_s^*) | M_{\mathrm{r},s}(\hat{\mathbf{t}}_s), \hat{\mathbf{t}}_s, \mathbf{t}_s^* \sim N[\bar{M}_{\mathrm{r},s}(\mathbf{t}_s^*), \mathrm{cov}(M_{\mathrm{r},s}(\mathbf{t}_s^*))]$$



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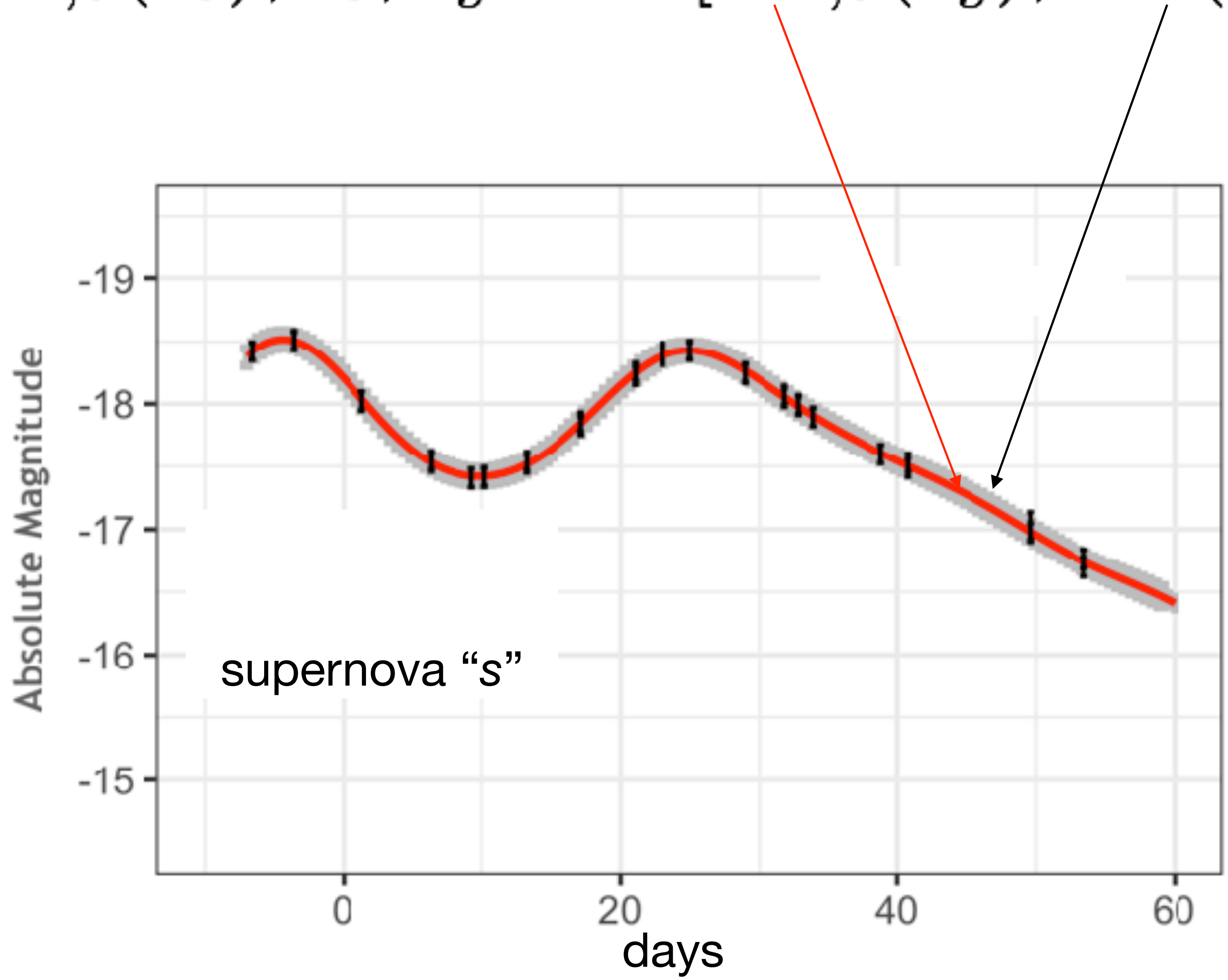

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$$M_{\mathrm{r},s}(\mathbf{t}_s^*)|M_{\mathrm{r},s}(\hat{\mathbf{t}}_s), \hat{\mathbf{t}}_s, \mathbf{t}_s^* \sim N[\bar{M}_{\mathrm{r},s}(\mathbf{t}_s^*), \mathrm{cov}(M_{\mathrm{r},s}(\mathbf{t}_s^*))]$$

Mean function is computed as:

$$\bar{\mathbf{M}}_{\mathrm{r},s}(\mathbf{t}_s^*) = K(\mathbf{t}_s^*, \hat{\mathbf{t}}_s) \cdot \left[K(\hat{\mathbf{t}}_s, \hat{\mathbf{t}}_s) + W(\hat{\mathbf{t}}_s, \hat{\mathbf{t}}_s)\right]^{-1} \cdot \mathbf{M}_{\mathrm{r},s}(\hat{\mathbf{t}}_s)$$

Covariance matrix is computed as:

$$\mathrm{cov}(\mathbf{M}_{\mathrm{r},s}(\mathbf{t}_s^*)) = K(\mathbf{t}_s^*, \mathbf{t}_s^*) - K(\mathbf{t}_s^*, \hat{\mathbf{t}}_s) \cdot \left[K(\hat{\mathbf{t}}_s, \hat{\mathbf{t}}_s) + W(\hat{\mathbf{t}}_s, \hat{\mathbf{t}}_s) + \sigma^2_{\mu\mathrm{pec},s} I_s \cdot I_s^\top\right]^{-1} \cdot K(\hat{\mathbf{t}}_s, \mathbf{t}_s^*)$$

Gaussian Processes

Kernel: $K(t,t') = \sigma_K^2 \exp\left[-\frac{(t-t')^2}{2l^2}\right]$

Notation: $W(\hat{t},\hat{t}') = \sigma_M^2 \delta_{tt'}$

$$\bar{\mathbf{M}}_{\mathrm{r},s}(\mathbf{t}_s^*) = \{\bar{M}_{\mathrm{r},s}(t_s^*)\}$$

$$\mathbf{M}_{\mathrm{r},s}(\hat{\mathbf{t}}_s) = \{M_{\mathrm{r},s}(\hat{t}_s)\}$$

Mean function is computed as:

$$\bar{\mathbf{M}}_{\mathrm{r},s}(\mathbf{t}_s^*) = K(\mathbf{t}_s^*, \hat{\mathbf{t}}_s) \cdot \left[K(\hat{\mathbf{t}}_s, \hat{\mathbf{t}}_s) + W(\hat{\mathbf{t}}_s, \hat{\mathbf{t}}_s)\right]^{-1} \cdot \mathbf{M}_{\mathrm{r},s}(\hat{\mathbf{t}}_s)$$

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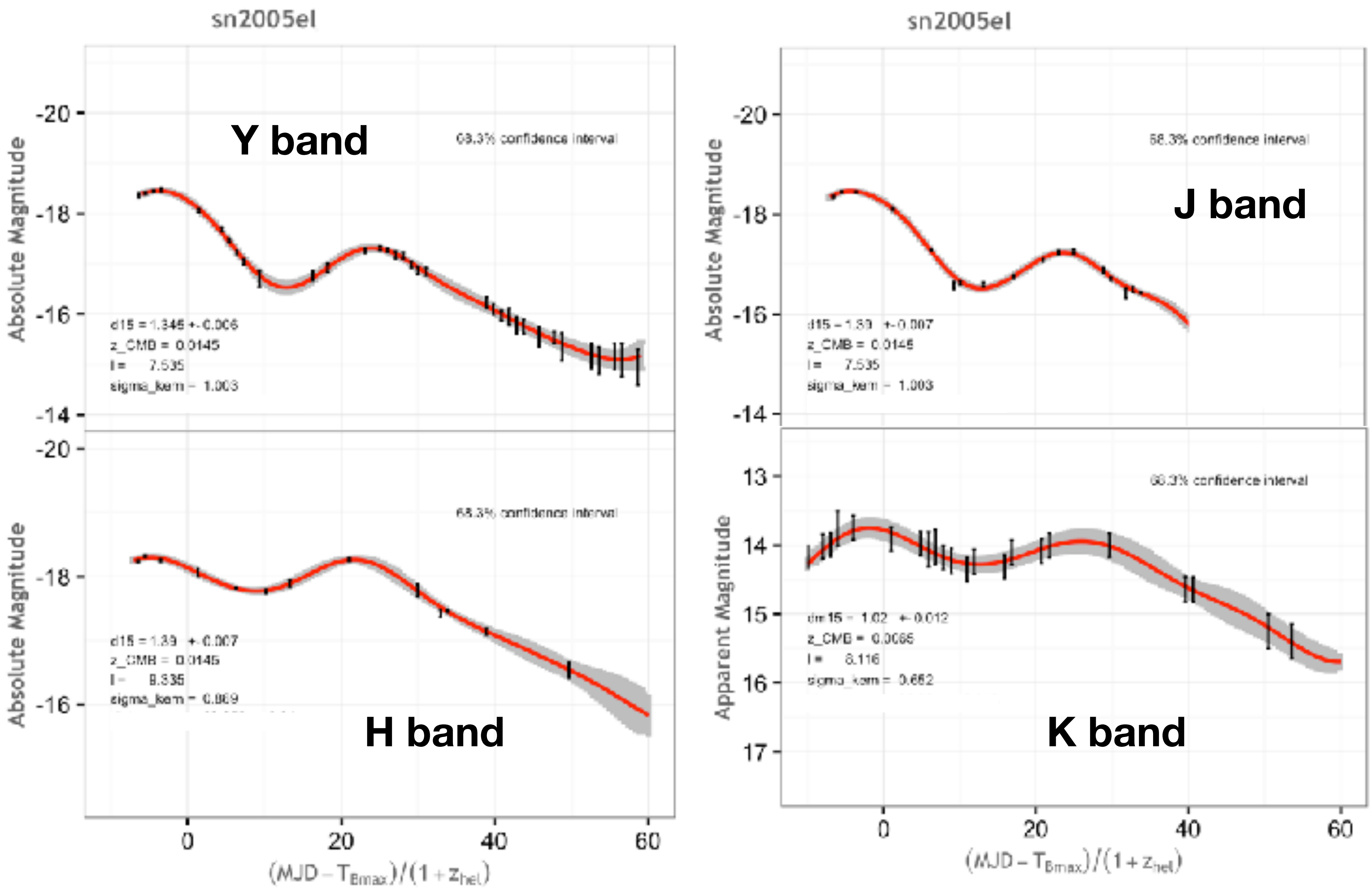
Gaussian Processes

Kernel: $$K(t,t') = \sigma_K^2 \exp\left[-\frac{(t-t')^2}{2l^2}\right]$$

Hyperparameters computed as:

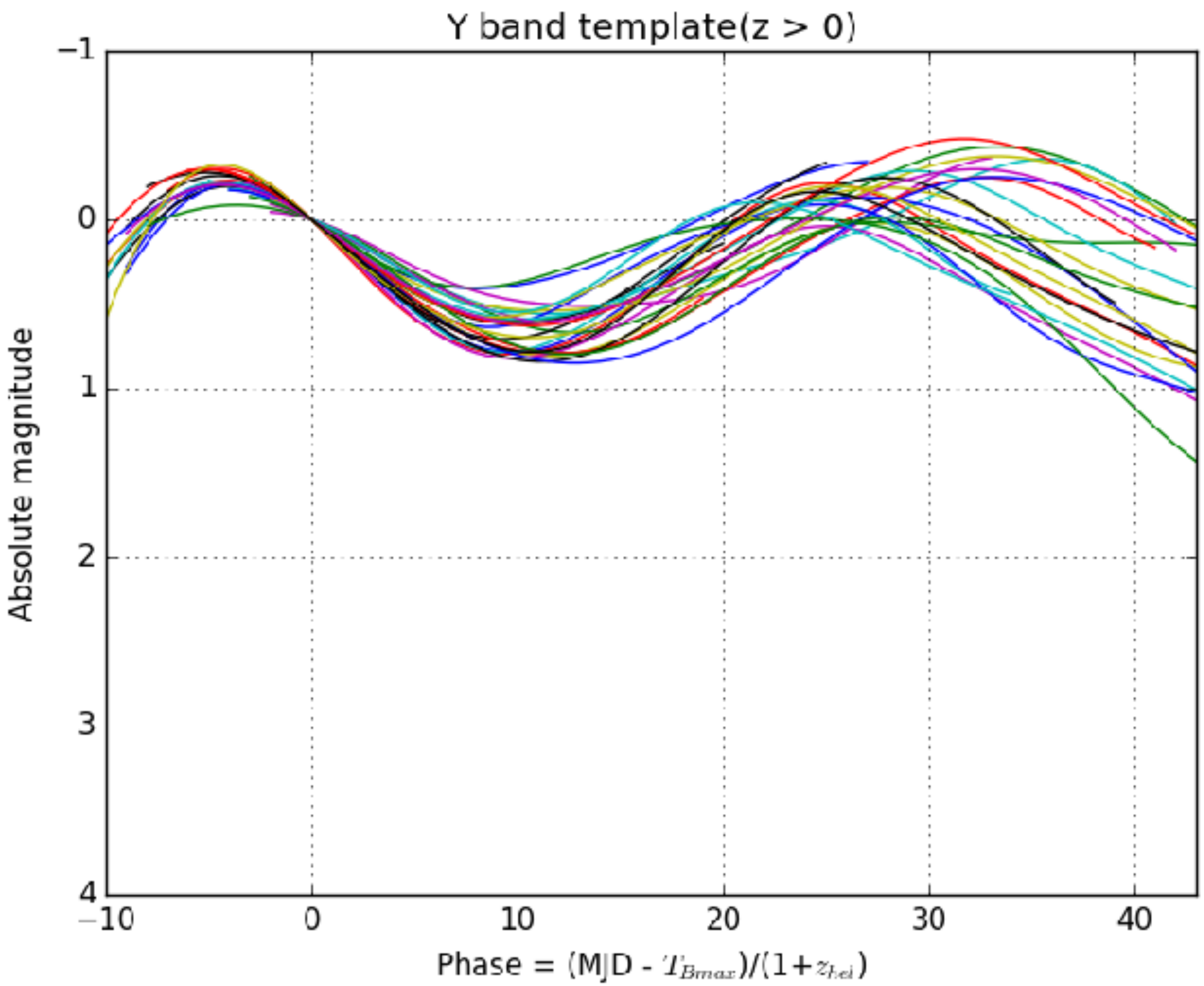
$$\ln p(\{\mathbf{M}_{\mathrm{r},s}\}|\{\hat{\mathbf{t}}_s\},\sigma_K,l) =$$
$$-\frac{1}{2}\sum_{s=1}^{N_{\mathrm{SN}}}\{\mathbf{M}^{\top}_{\mathrm{r},s}(\hat{\mathbf{t}}_s)\cdot[K_s(\hat{\mathbf{t}}_s,\hat{\mathbf{t}}_s)+W_s(\hat{\mathbf{t}}_s,\hat{\mathbf{t}}_s)+$$
$$\sigma^2_{\mathrm{pec},s}I_s\cdot I_s^{\top}]^{-1}\cdot\mathbf{M}_{\mathrm{r},s}(\hat{\mathbf{t}}_s)+$$
$$\ln\left(\det\left[K_s(\hat{\mathbf{t}}_s,\hat{\mathbf{t}}_s)+W_s(\hat{\mathbf{t}}_s,\hat{\mathbf{t}}_s)+\sigma^2_{\mu_{\mathrm{pec}},s}I_s\cdot I_s^{\top}\right]\right)+$$
$$N_{\mathrm{LC},s}\ln 2\pi\}\,, \quad \text{(A6)}$$

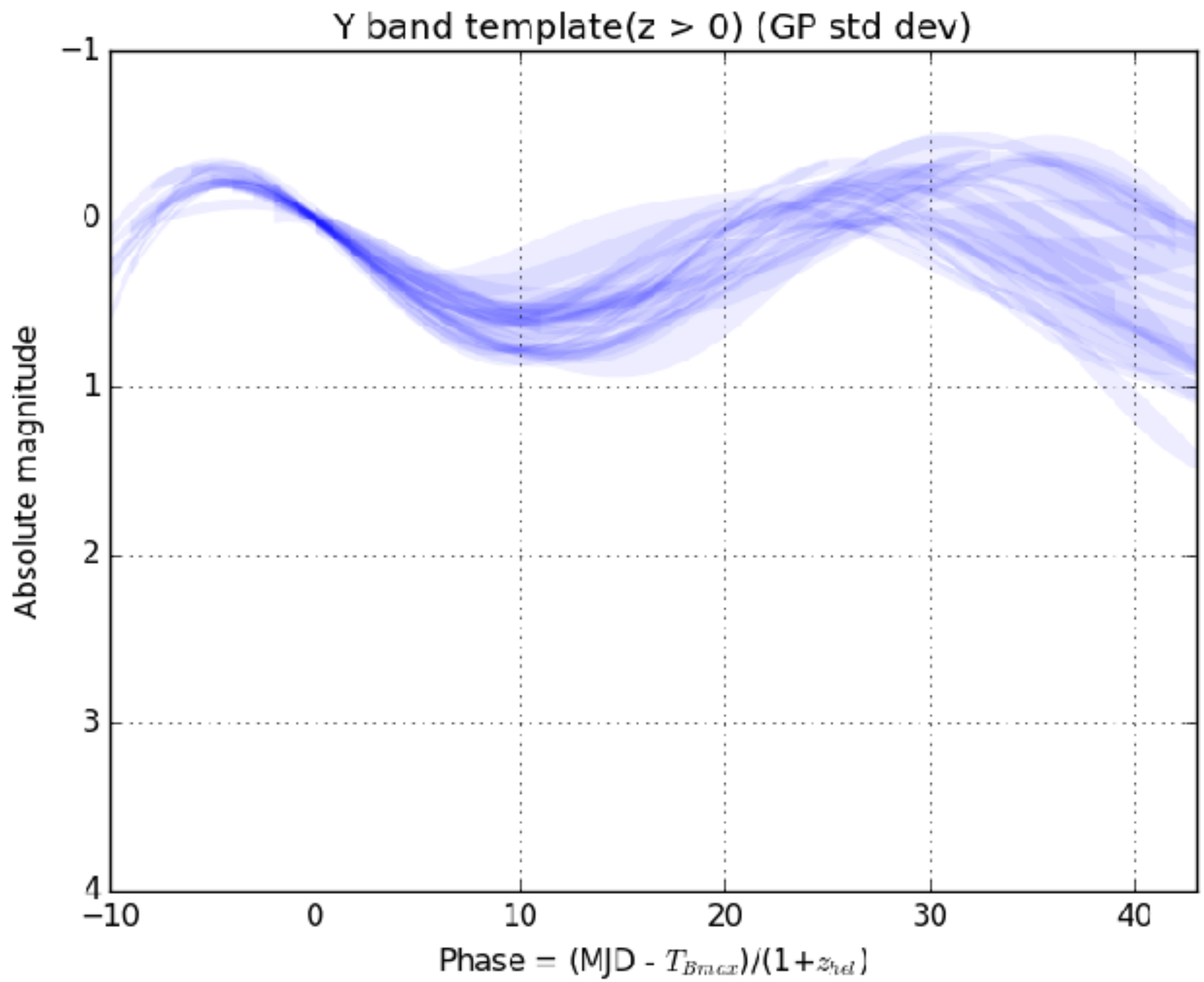
Gaussian-Process fit



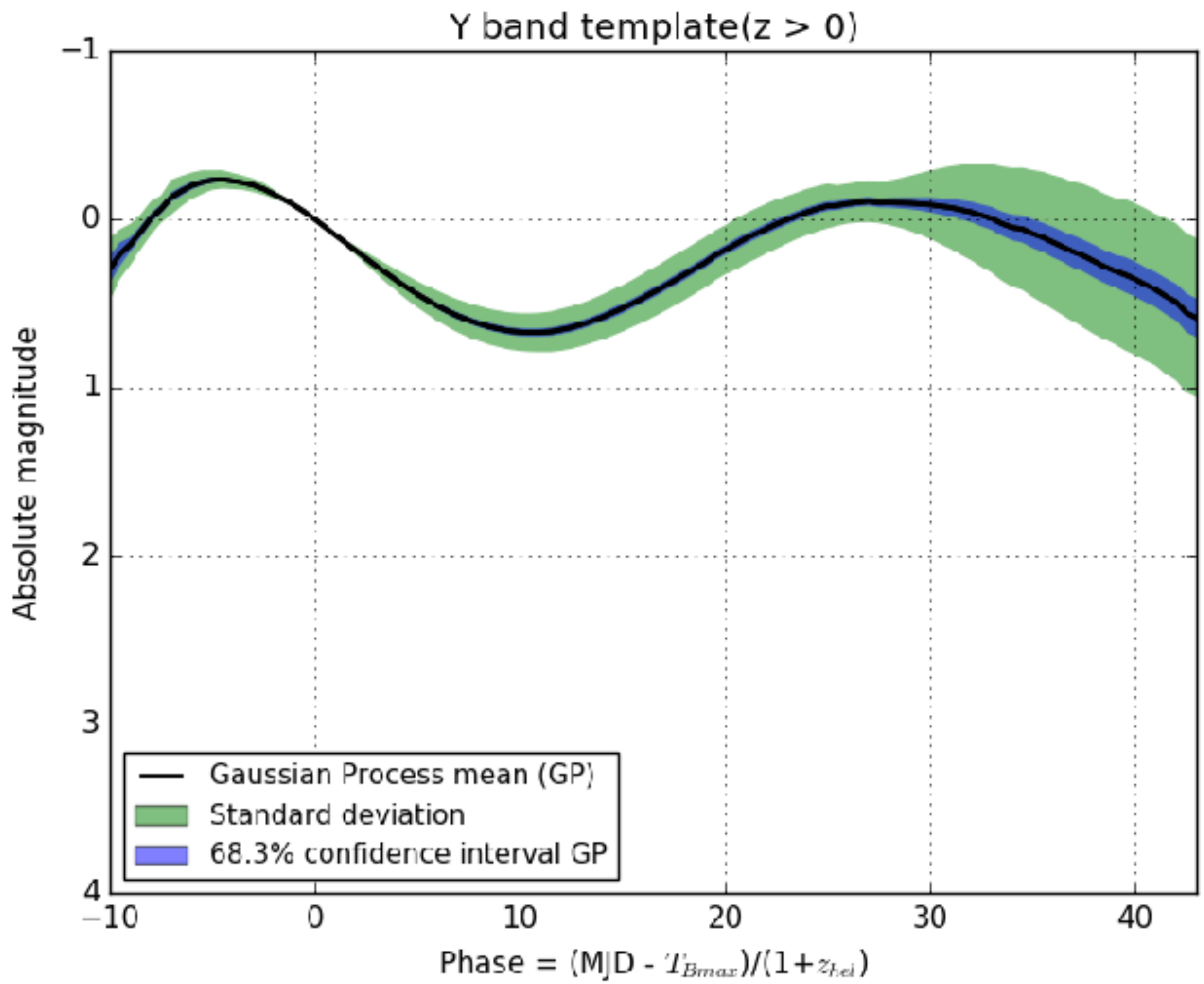
Templates

Hierarchical Bayesian model


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
Phase = (MJD - T_{Bmax})/(1+z_{hel})
−1
0
1
2
3
4
−10
0
10
20
30
40


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

Bayesian Hierarchical model

Constructing the NIR light-curve templates

1st level of the hierarchy:

$$\bar{M}_s \sim N(\tilde{M}_s, \sigma^2_{\bar{M},s})$$

Bayesian Hierarchical model

Constructing the NIR light-curve templates

1st level of the hierarchy:

$$\bar{M}_s \sim N(\tilde{M}_s, \sigma^2_{\bar{M},s})$$

2nd level of the hierarchy:

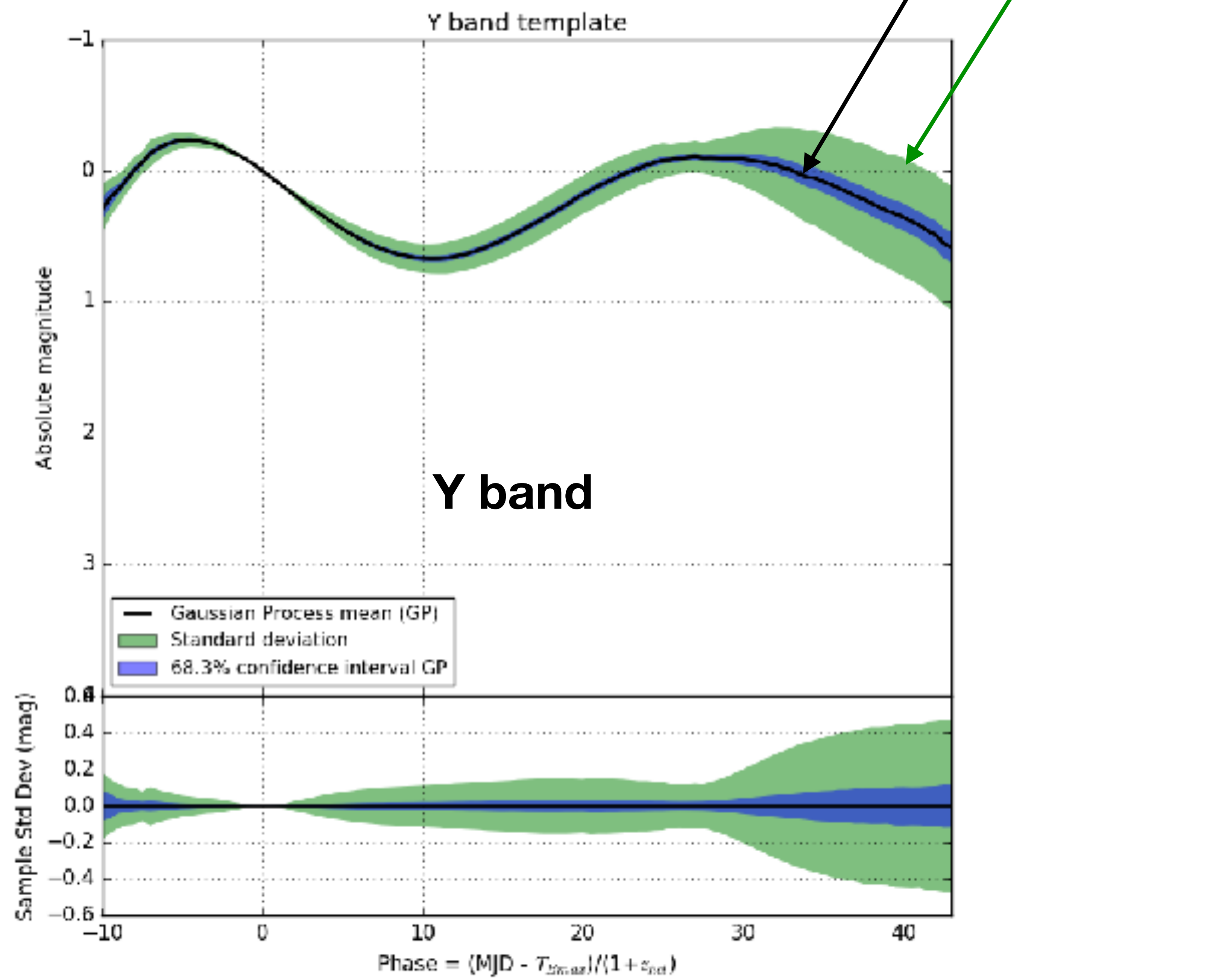
We assume that the $\tilde{M}_s(t_*)$ are drawn from a Gaussian distribution with mean $\mathcal{M}(t_*)$ and variance $\sigma^2_{\mathcal{M}}$:

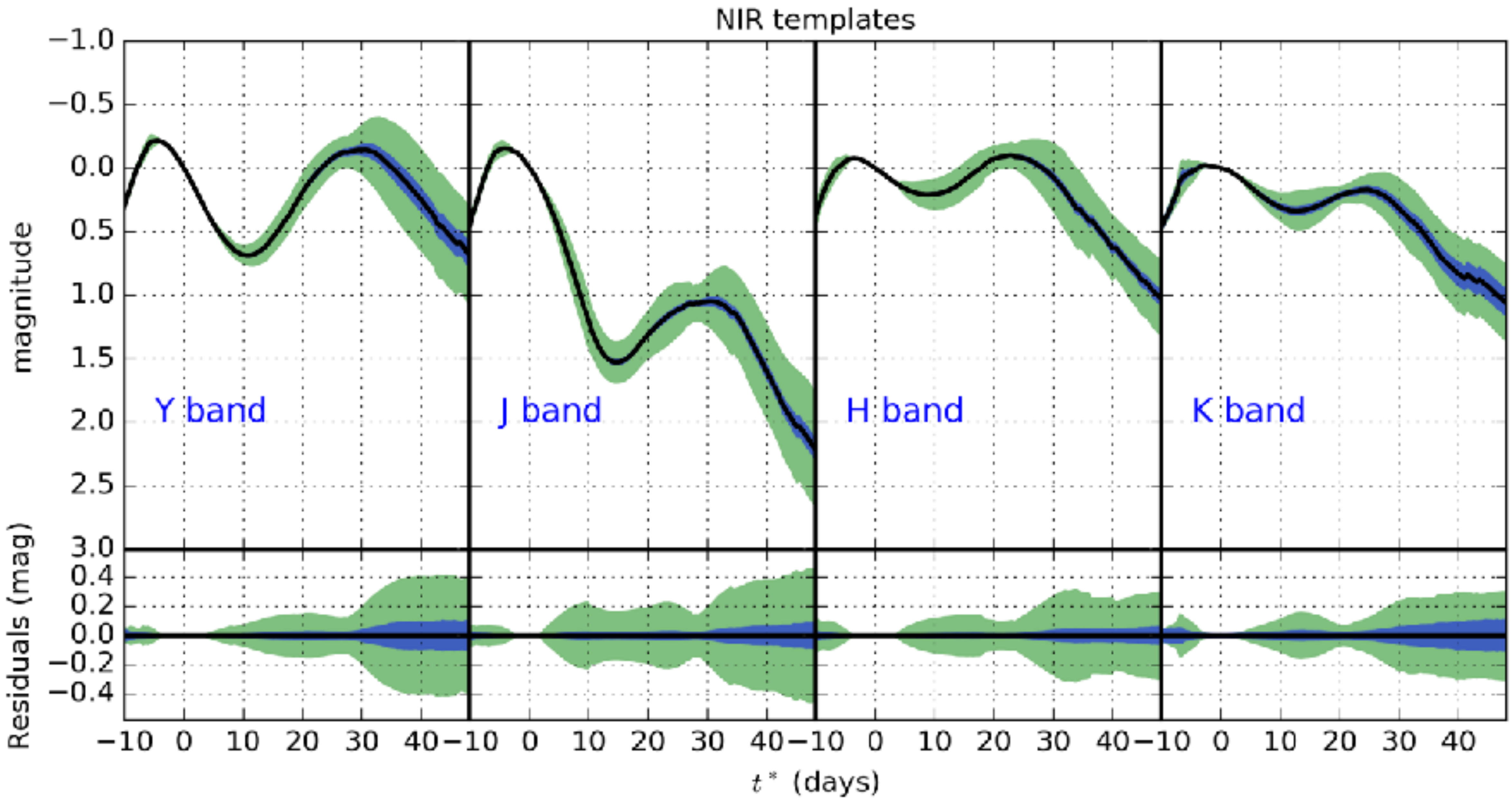
$$p\left(\{\tilde{M}_s\}|\mathcal{M}, \sigma_{\mathcal{M}}\right) = \prod_{s=1}^{N_{\mathrm{SN}}} N\left(\tilde{M}_s|\mathcal{M}, \sigma^2_{\mathcal{M}}\right)$$

Template

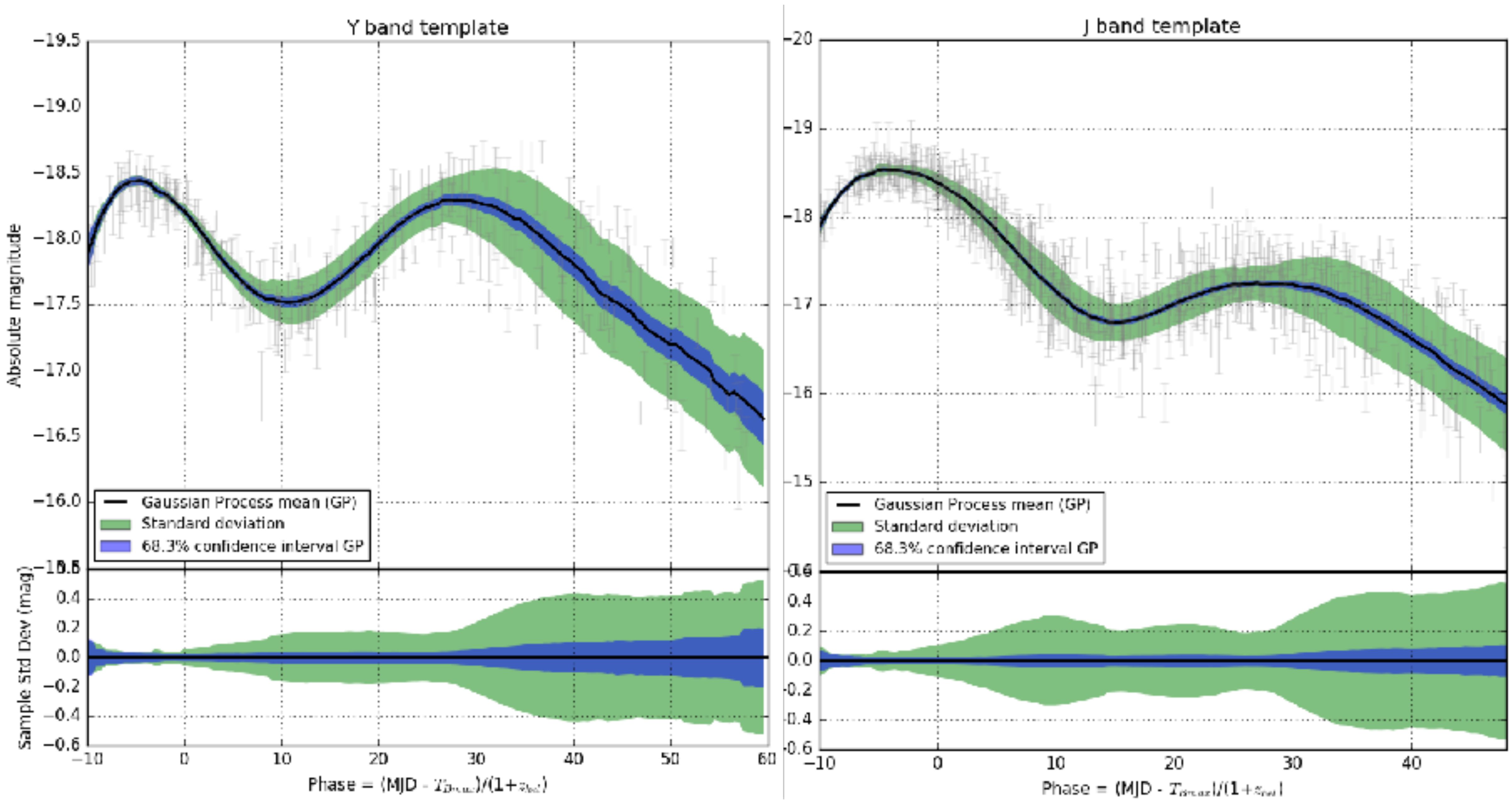
Hierarchical Bayesian model

$$p\left(\{\tilde{M}_s\}|\mathcal{M},\sigma_{\mathcal{M}}\right) = \prod_{s=1}^{N_{\rm SN}} N\left(\tilde{M}_s|\mathcal{M},\sigma^2_{\mathcal{M}}\right)$$





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



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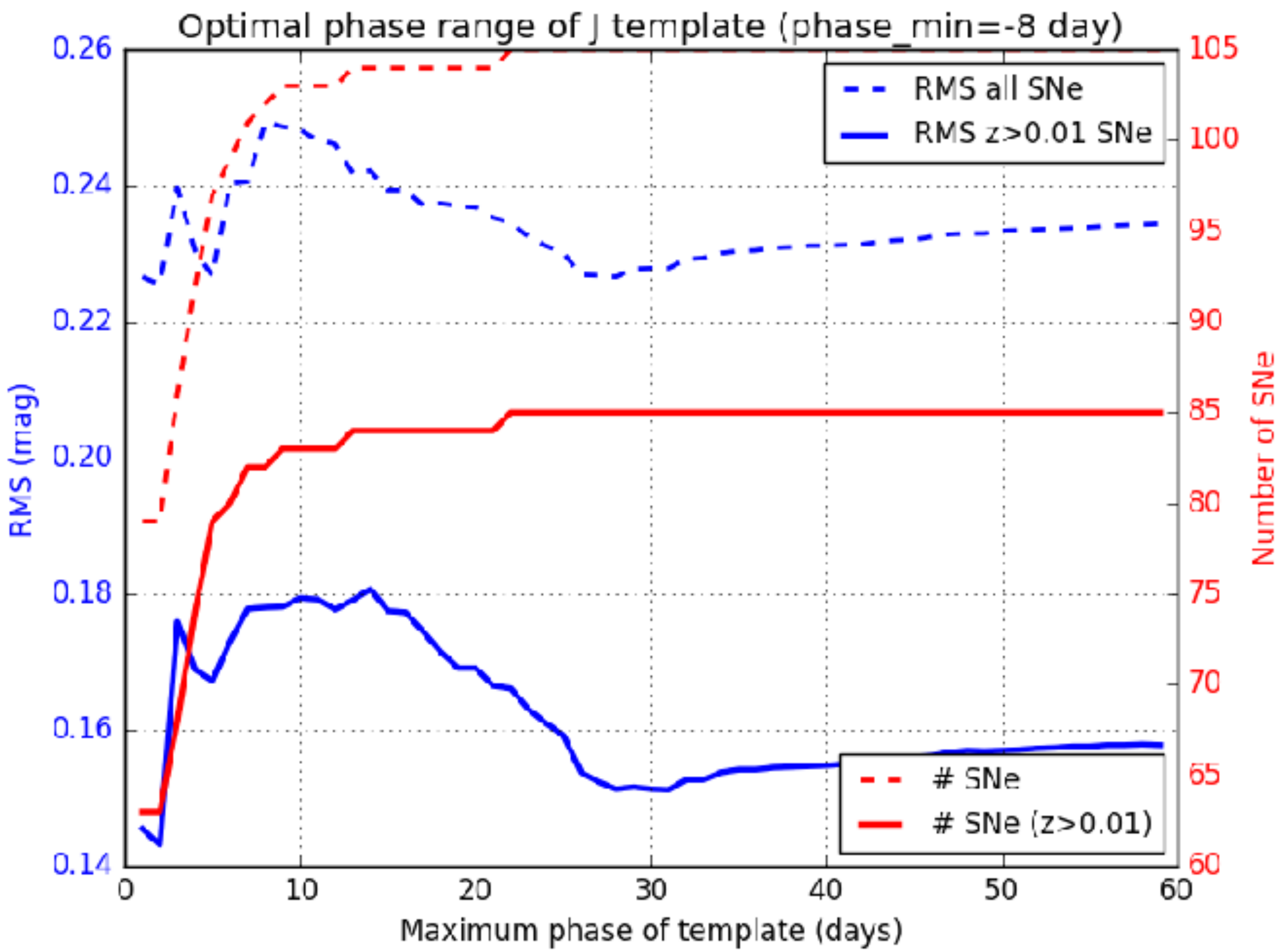
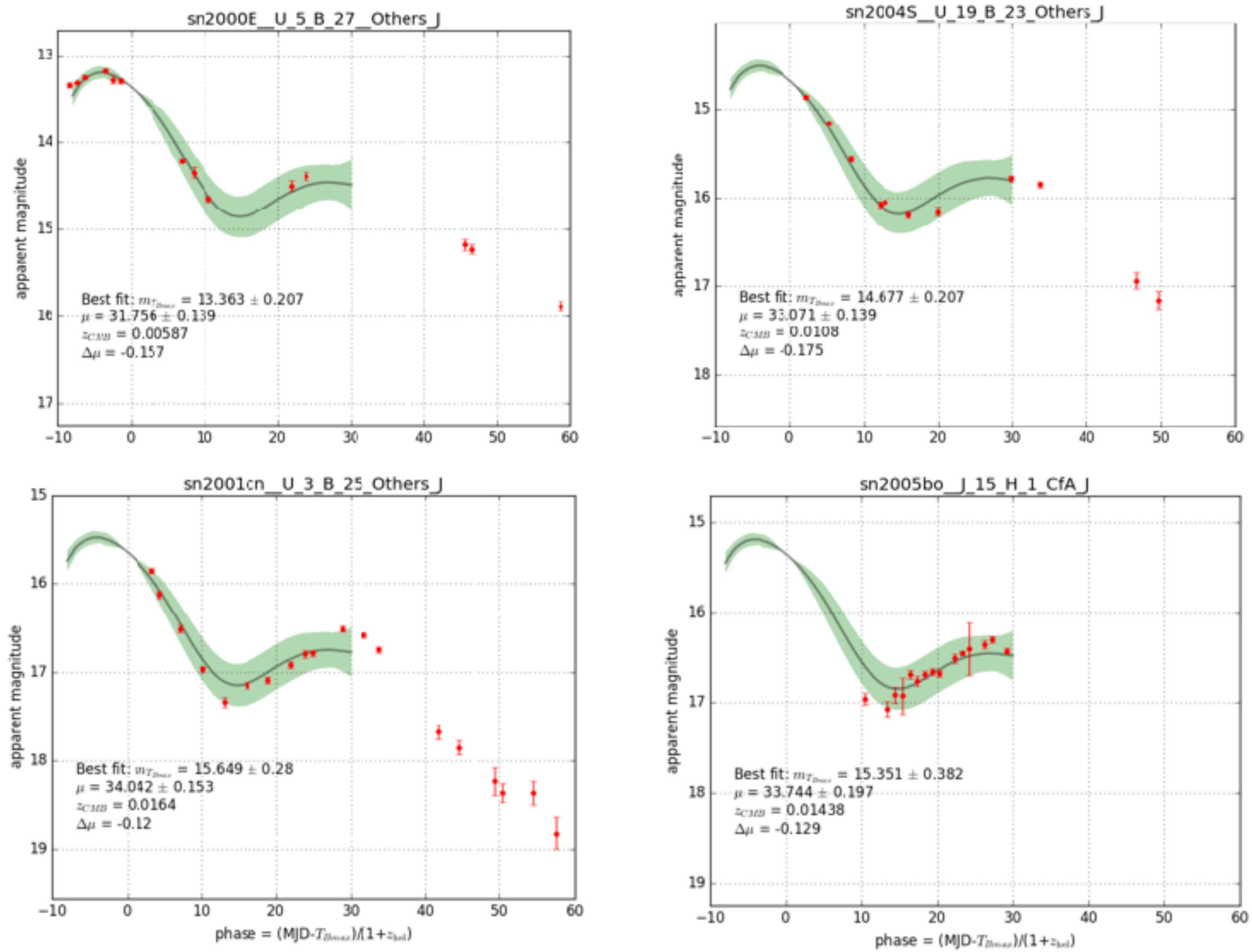


Optimal phase range of J template (phase_min=-8 day)
RMS all SNe
RMS z>0.01 SNe
SNe
SNe (z>0.01)
RMS (mag)
Number of SNe
Maximum phase of template (days)
0.14
0.16
0.18
0.20
0.22
0.24
0.26
60
65
70
75
80
85
90
95
100
105
0
10
20
30
40
50
60


sn2000E__U_5_B_27__Others_J
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
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
Best fit: $m_{T_{Bmax}}$ = 15.649 ± 0.28
μ = 34.042 ± 0.153
z_{CMB} = 0.0164
$\Delta\mu$ = -0.12
sn2005bo__J_15_H_1_CfA_J
Best fit: $m_{T_{Bmax}}$ = 15.351 ± 0.382
μ = 33.744 ± 0.197
z_{CMB} = 0.01438
$\Delta\mu$ = -0.129
apparent magnitude
phase = (MJD-T_{Bmax})/(1+z_{hel})

Distance modulus

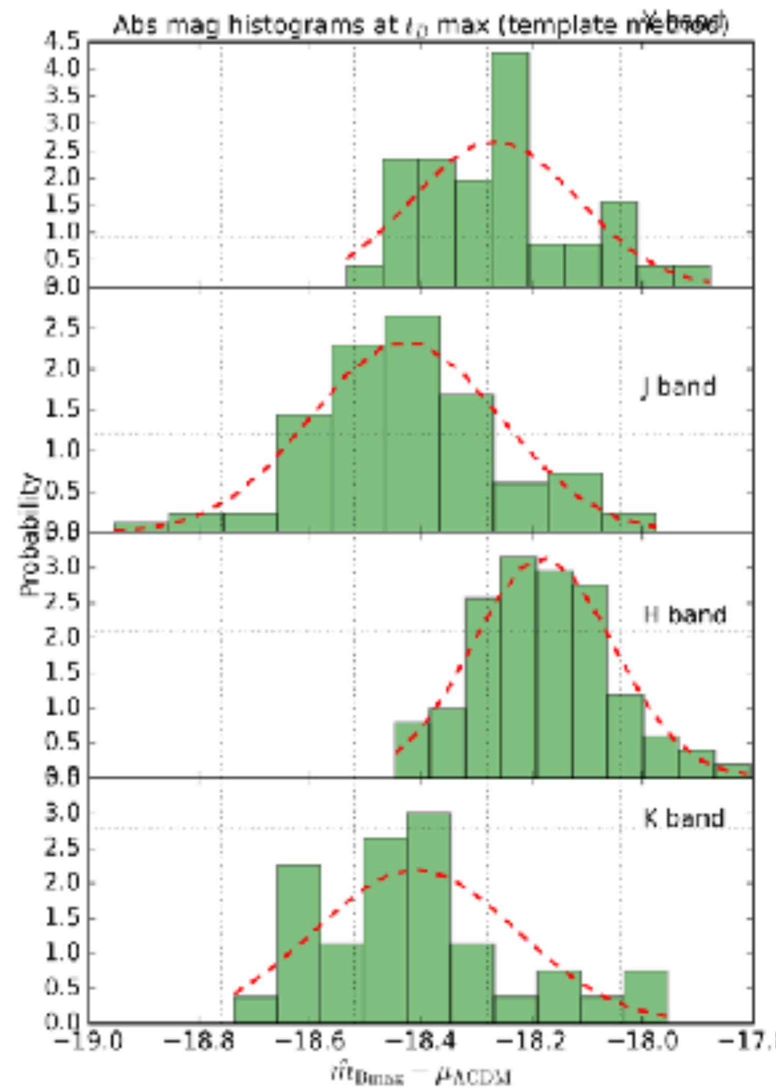
$$\Delta m_s(\hat{t}) \equiv m_s(\hat{t}) - \mathcal{M}(\hat{t}) - m_{0,s} \tag{11}$$

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

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



Distance modulus

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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:

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

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

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

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

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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:

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

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

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

Distance modulus

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

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,

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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

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

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

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

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

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

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

with uncertainty given as

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

Distance modulus

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

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,

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

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

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

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

with uncertainty given as

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

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

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

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

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

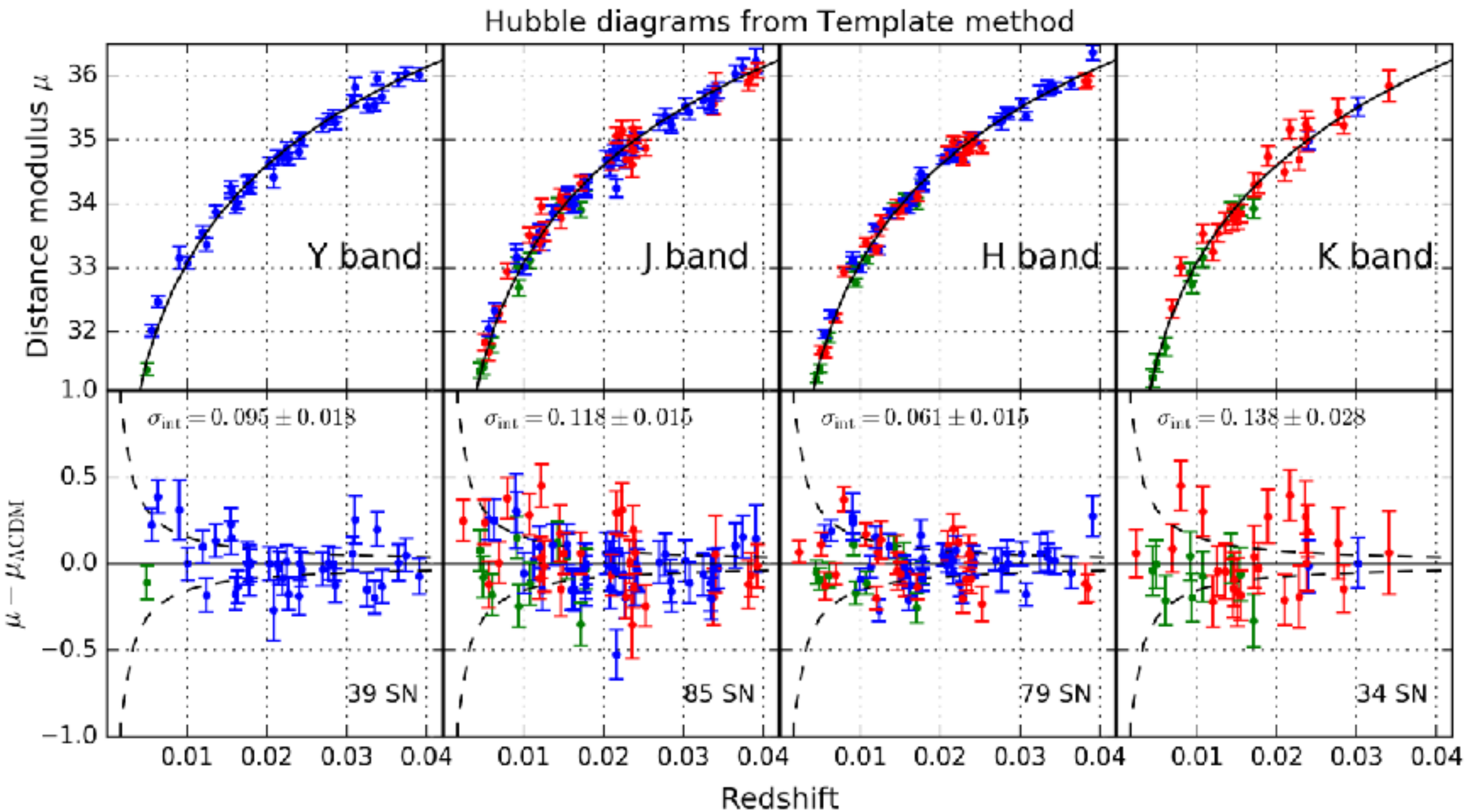
Intrinsic dispersion

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

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

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

Blondin, Mandel, Kirshner, 2011



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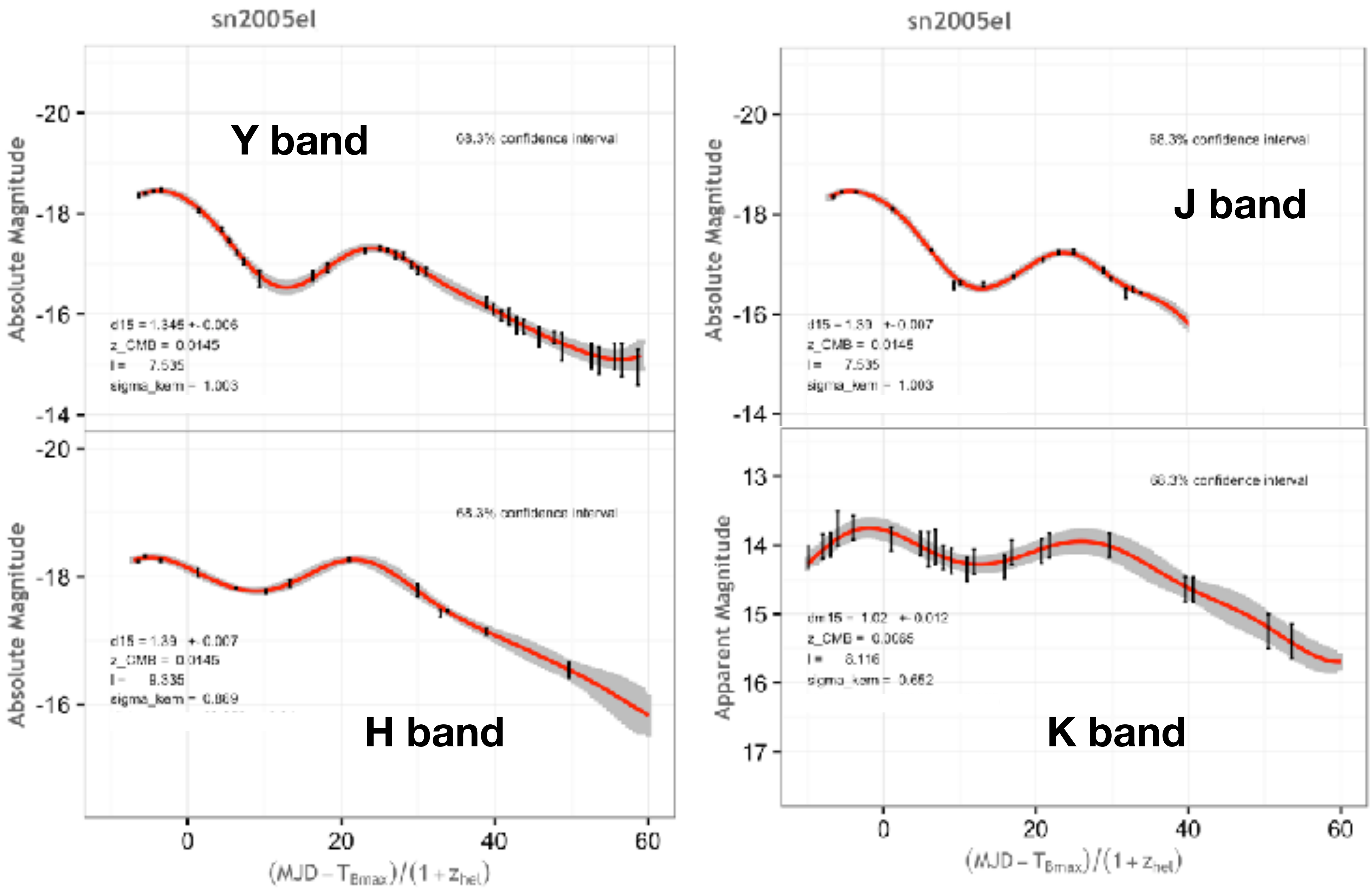
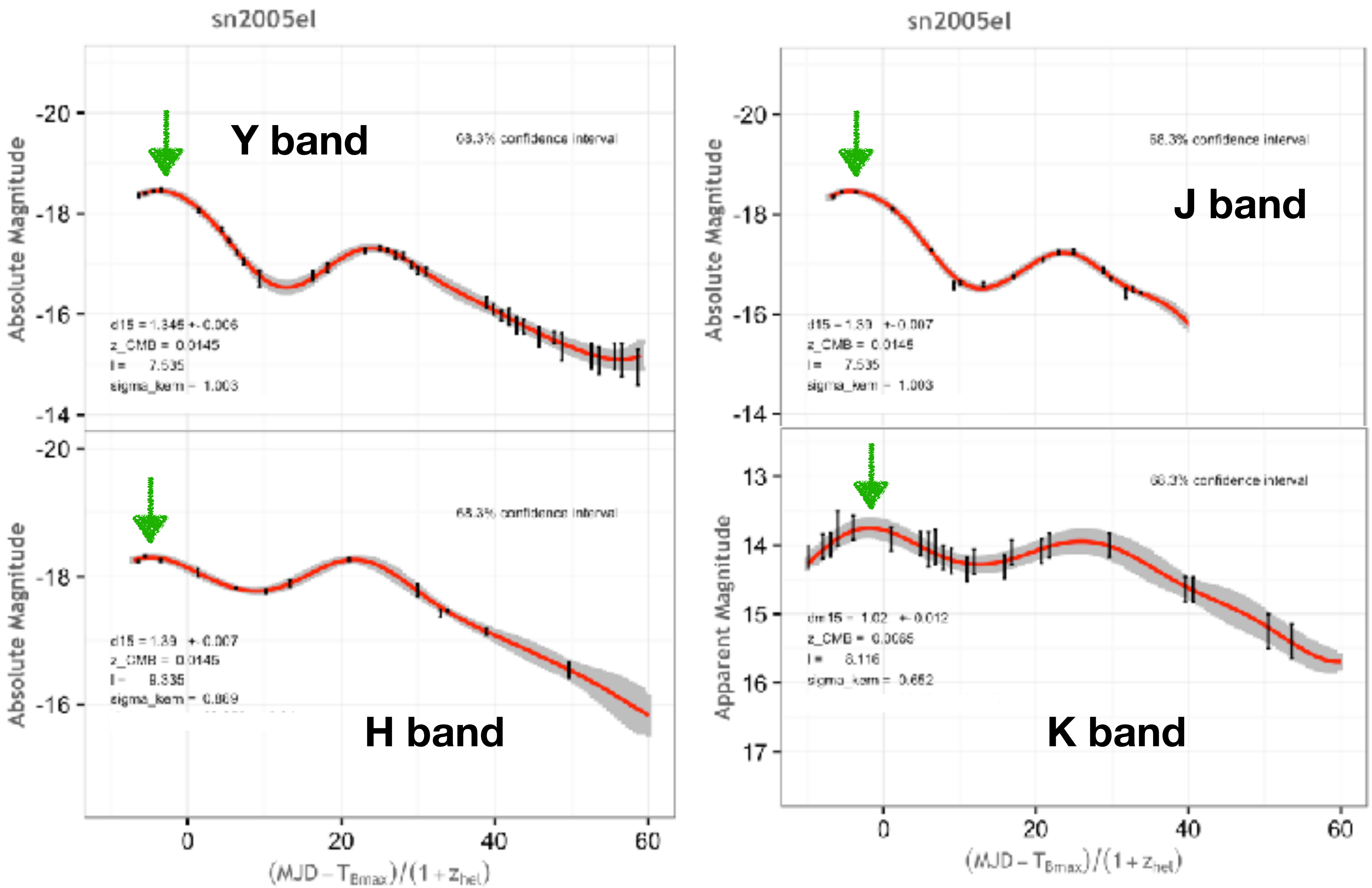
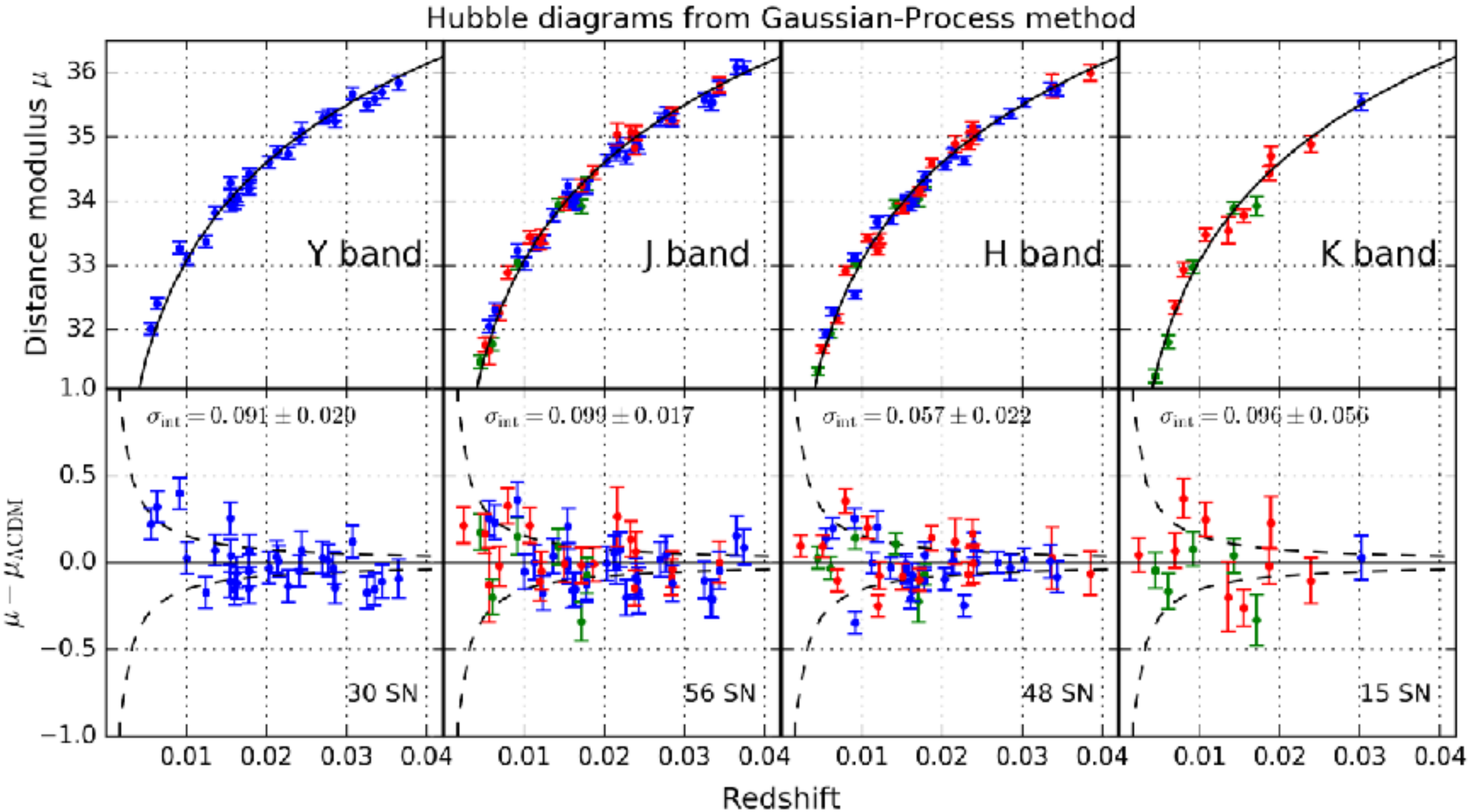
Gaussian-Process method

Gaussian-Process Method



Gaussian-Process Method





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Combining multiple NIR bands

Distance modulus

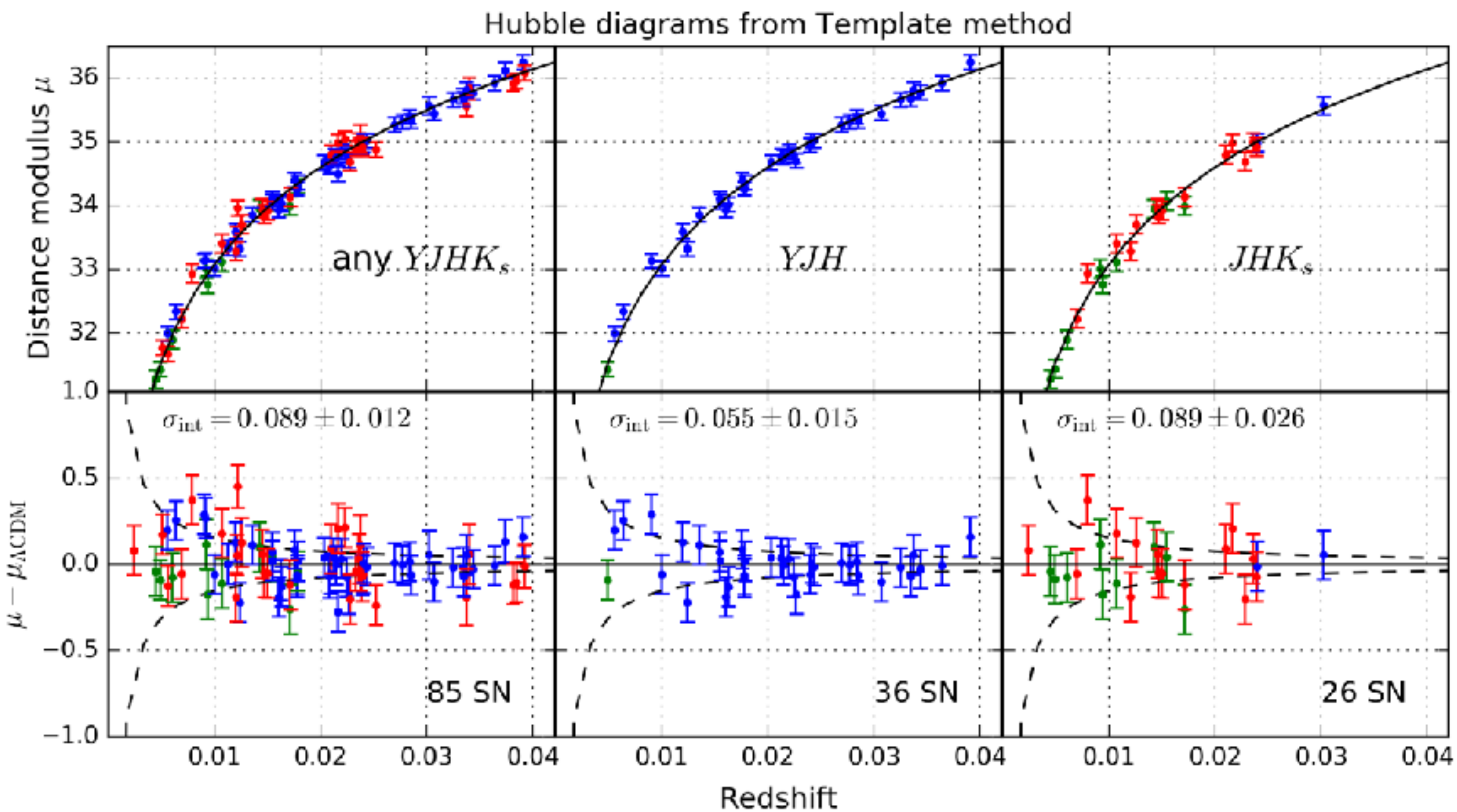
4.3. Distance modulus from the combined NIR bands

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

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

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

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



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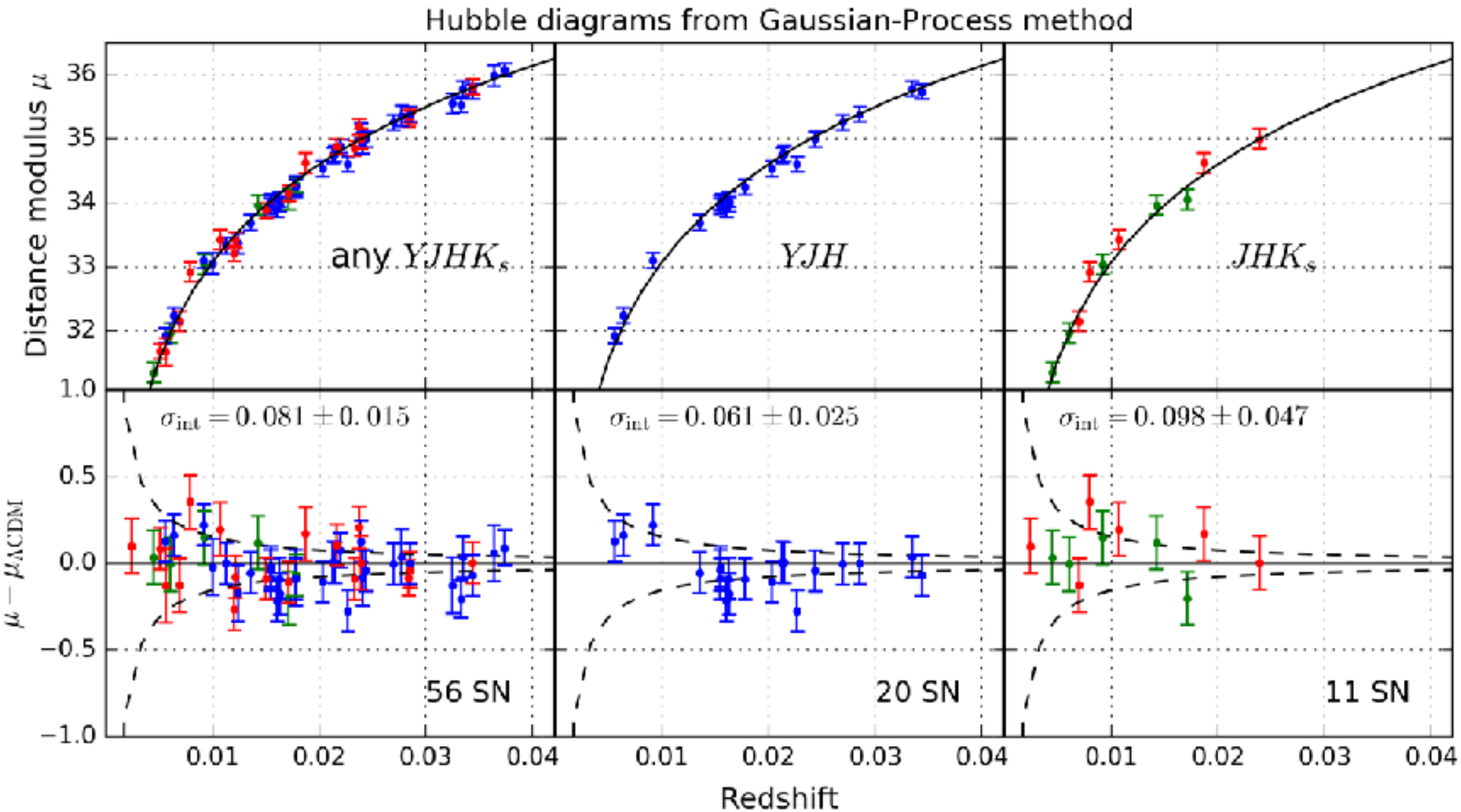

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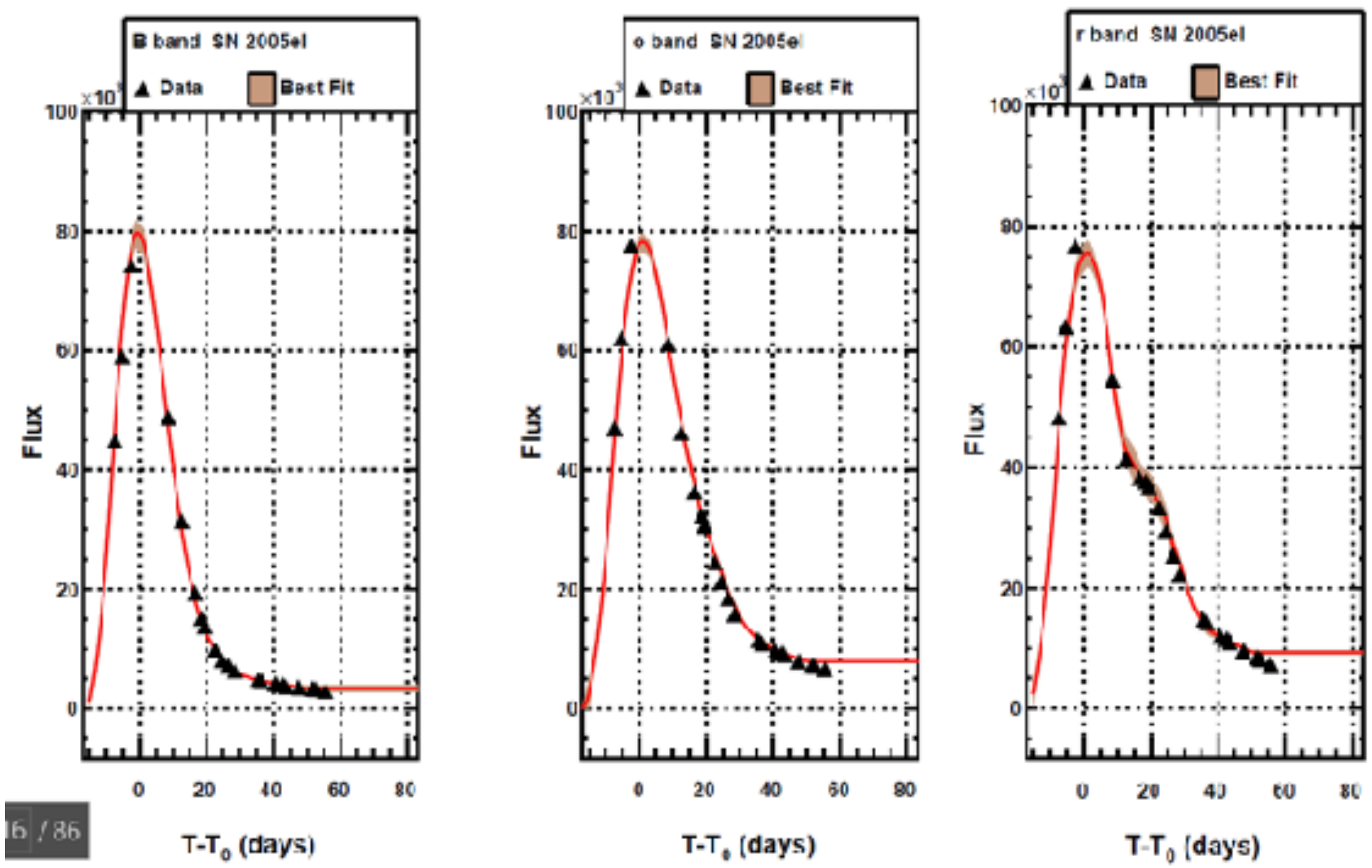
How good or bad are these results?

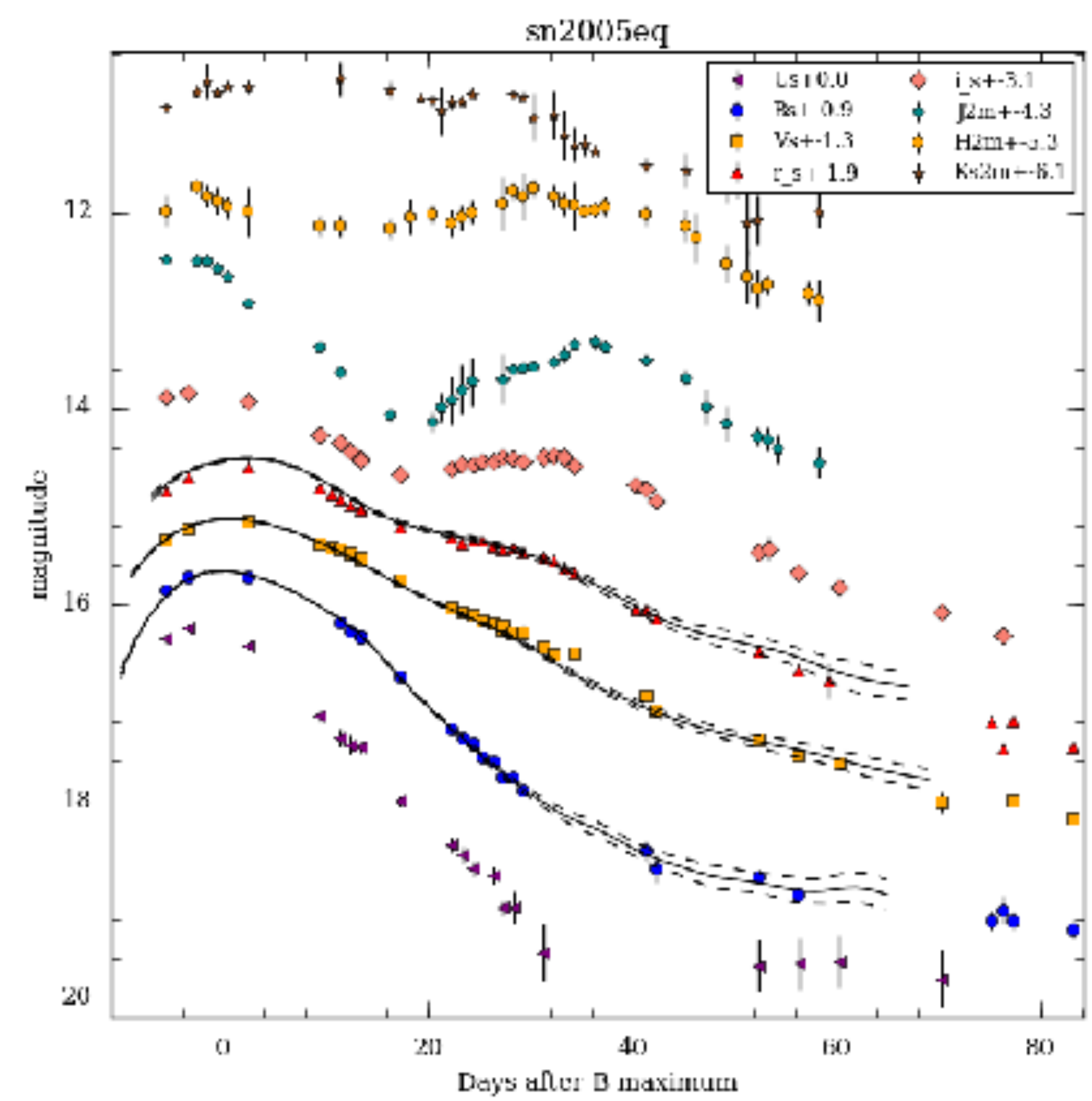
Optical Hubble diagram

Fitting the ***optical*** light curves only

SALT2



SNooPy



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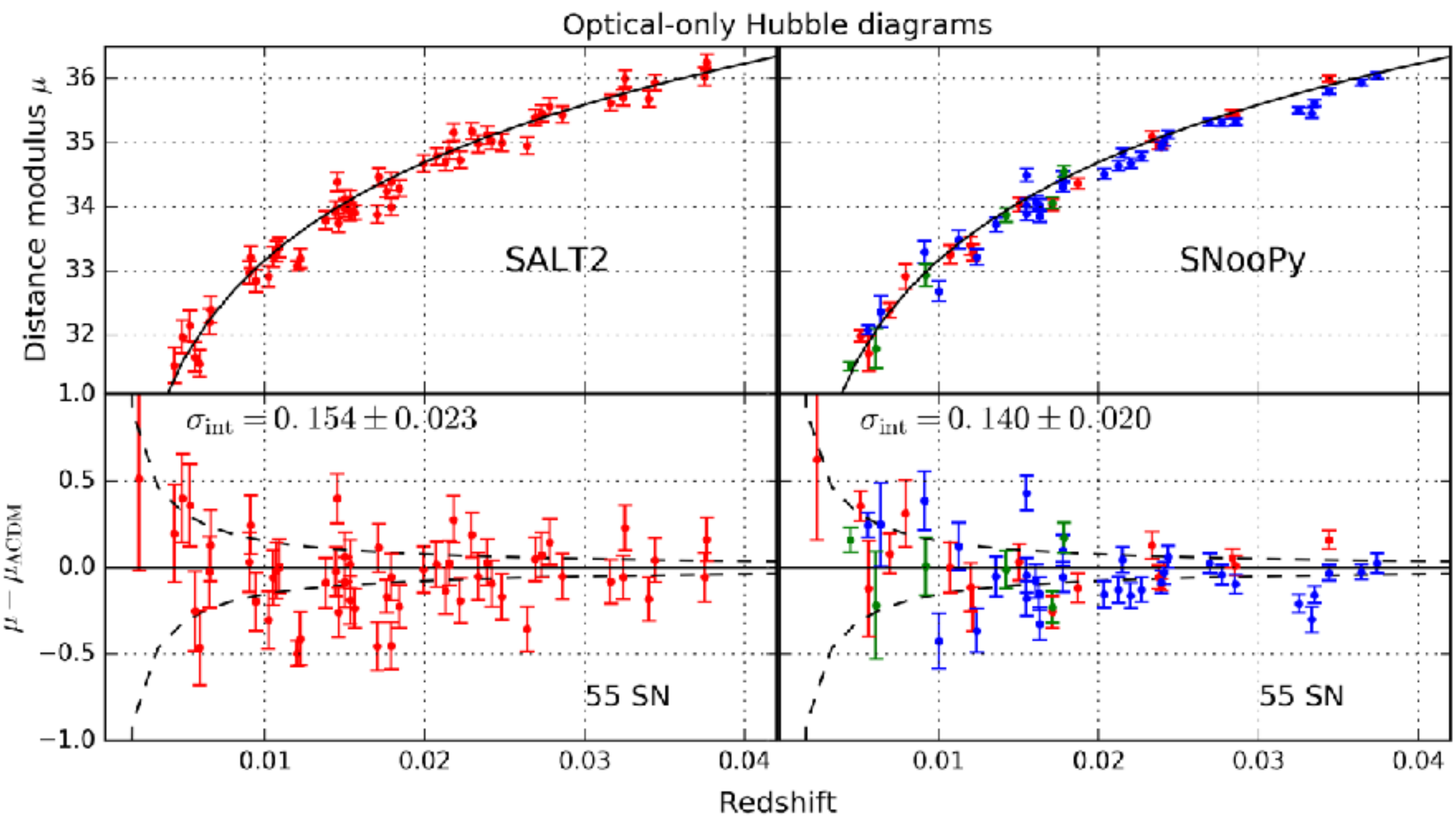

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Intrinsic dispersion and wRMS summary

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

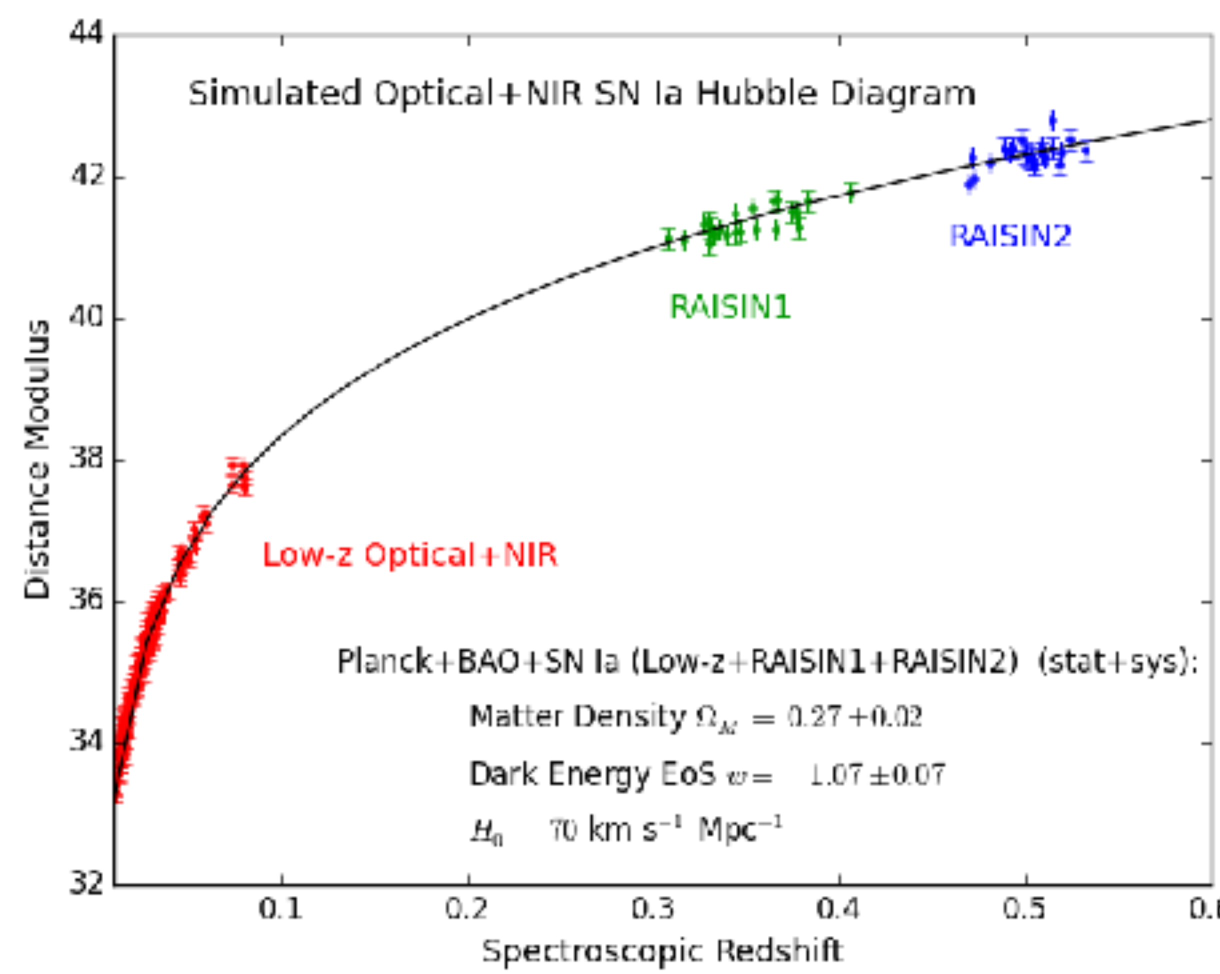
Tracing cosmic expansion with SN Ia in the Near Infrared

RAISIN-1

- 23 SN Ia, redshift ~ 0.3

RAISIN-2

- 24 SN Ia, redshift ~ 0.5



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Take away

Optical

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

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