SNEMO: Type Ia Supernova Modeling with Data from the Nearby Supernova Factory

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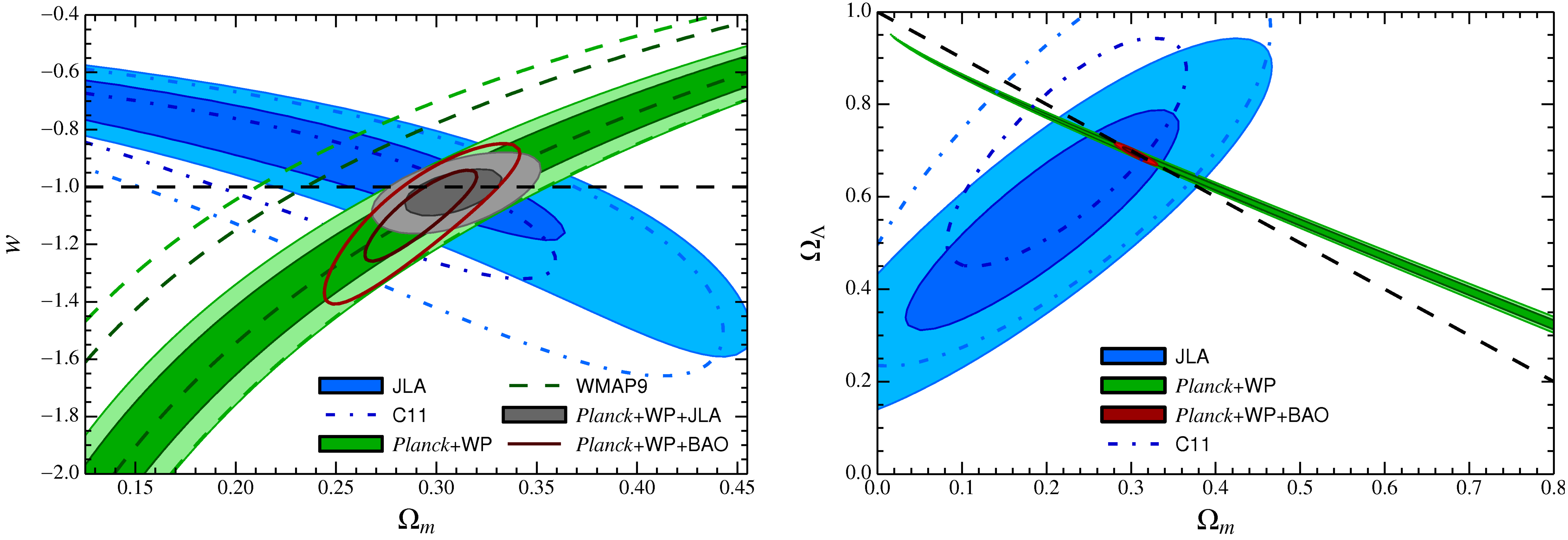
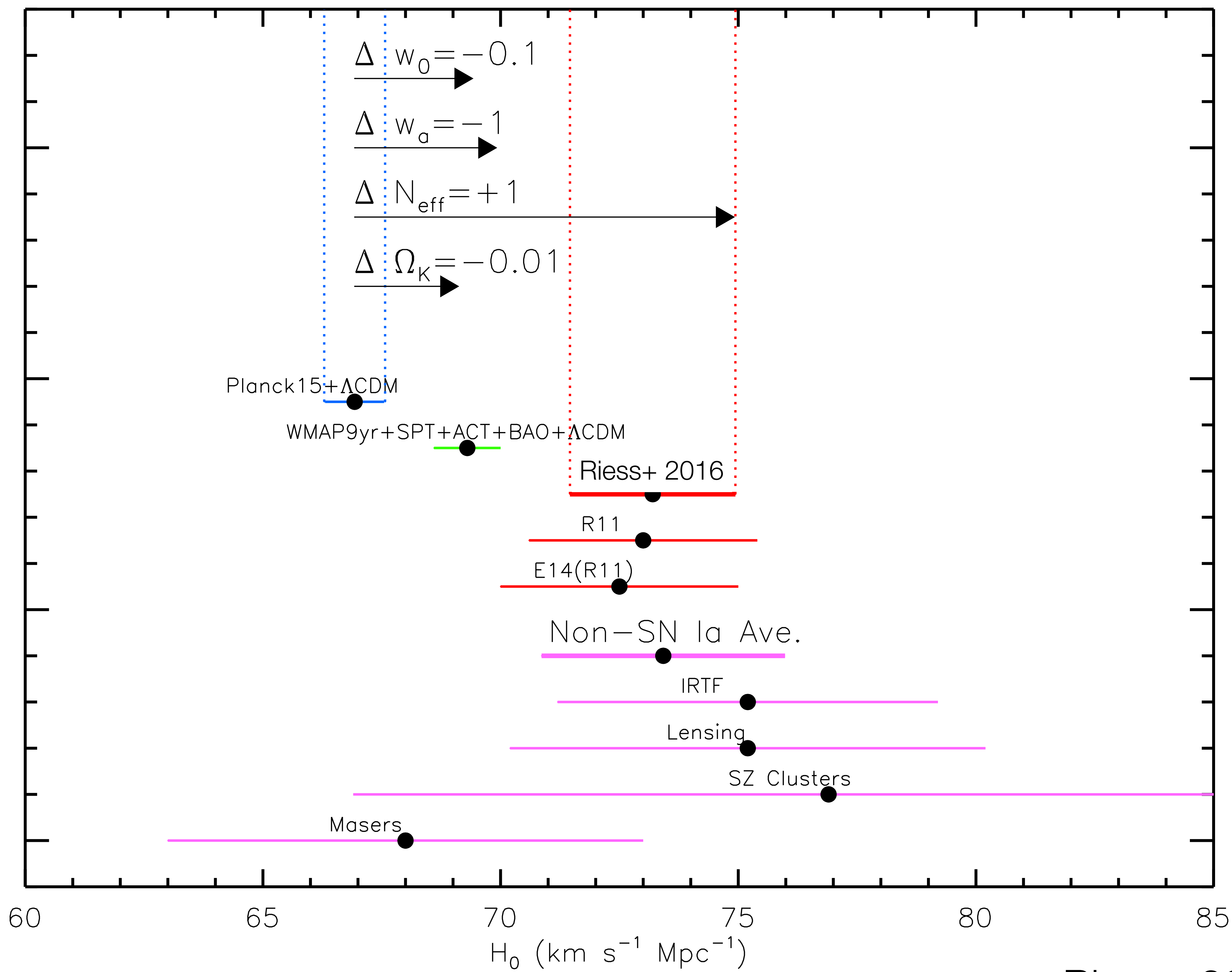
Constraining cosmological parameters



Betoule+ 2014

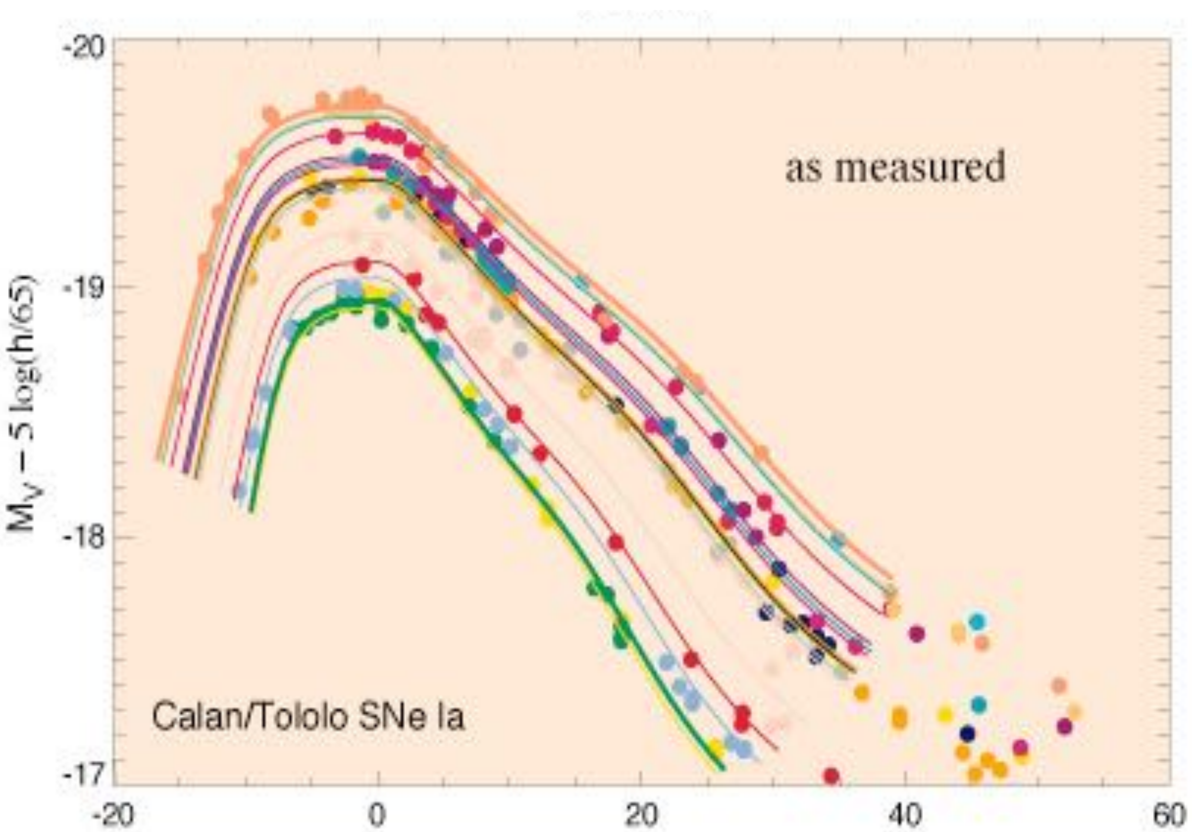
Hubble constant discrepancies

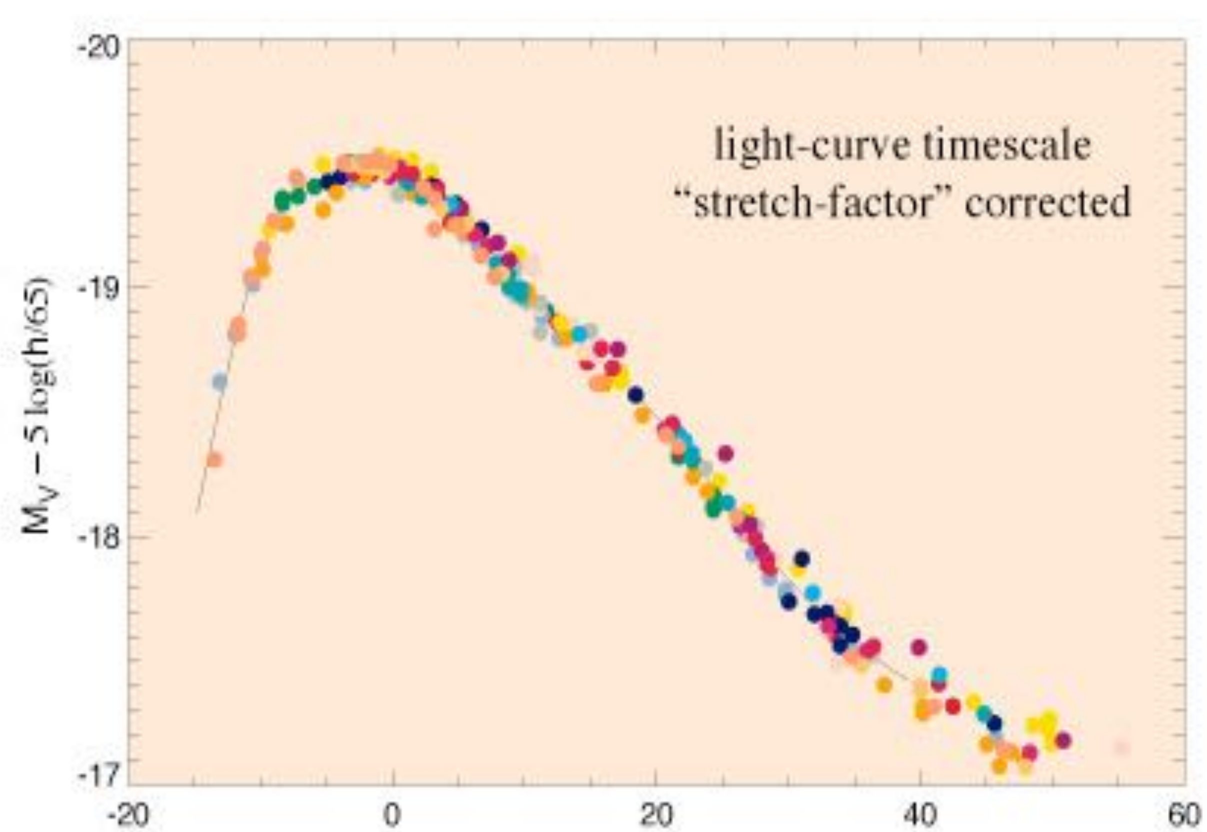


Riess+ 2016

How are Type Ia Supernovae used for cosmology?

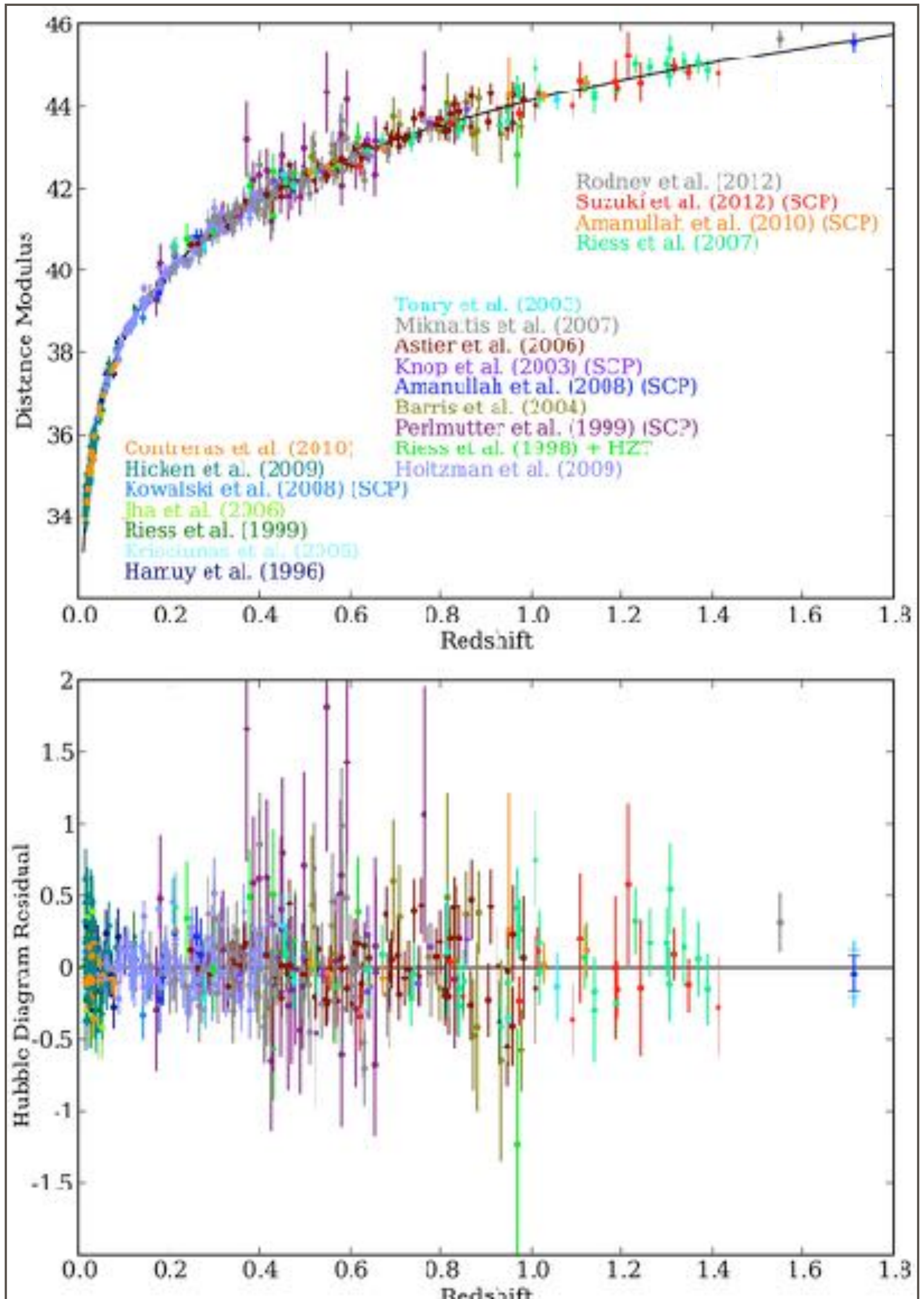
- Type Ia supernovae are standardizable candles
- By taking several observations of a supernova over the course of its lightcurve in multiple bands, measured supernova properties can be used to ‘correct’ the supernova’s magnitude.





Perlmutter+ 1998

What determines precision?



Rubin+ 2013

Hubble diagram will be filled in by DES, PanSTARRS, LSST, SeeChange, etc.

➡Statistical errors will be greatly reduced.

Scatter is combination of calibration uncertainty, ‘intrinsic dispersion’ in supernova magnitudes, and other causes

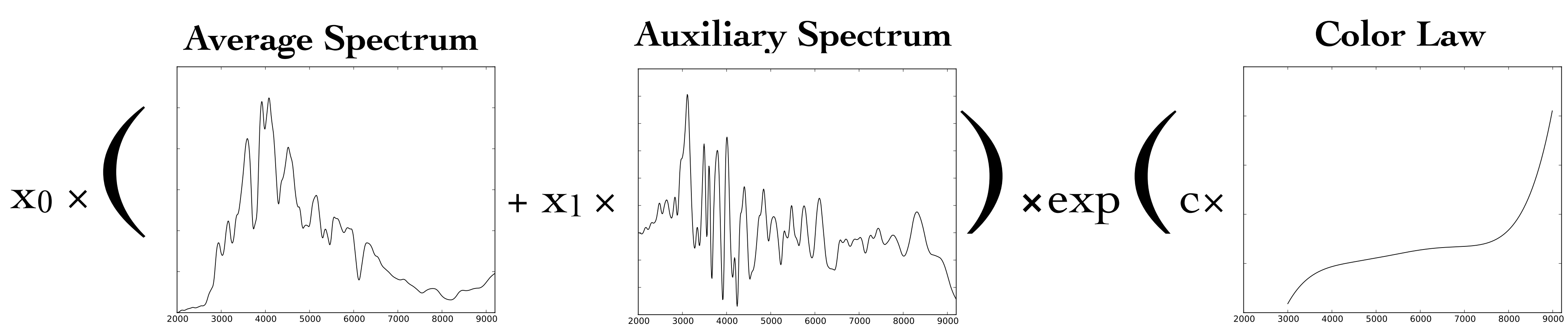
➡Current surveys working to reduce calibration uncertainty.

➡Better models needed to reduce the ‘intrinsic dispersion’.

Current Standards

- SALT2, MLCS2k2 (not based on spectral time series templates)
- Simple, only a few degrees of freedom, trained mostly on photometry.

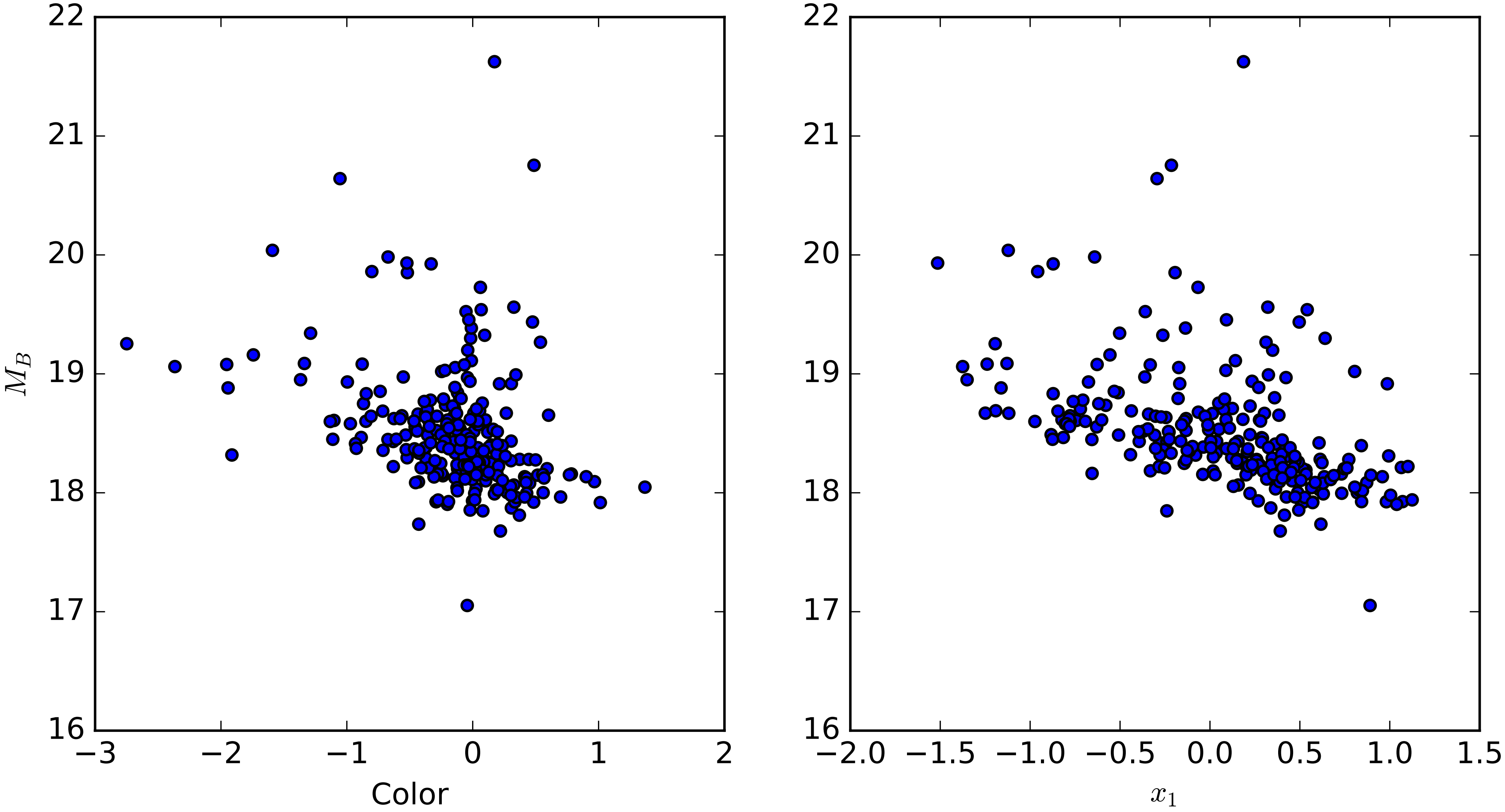
SALT2 model = flux(phase, λ) =



Current Supernova Standardization

- Fit parameters to minimize the quantity

$$\Delta\mu = m_B - M + \alpha\, x_1 - \beta\, c$$

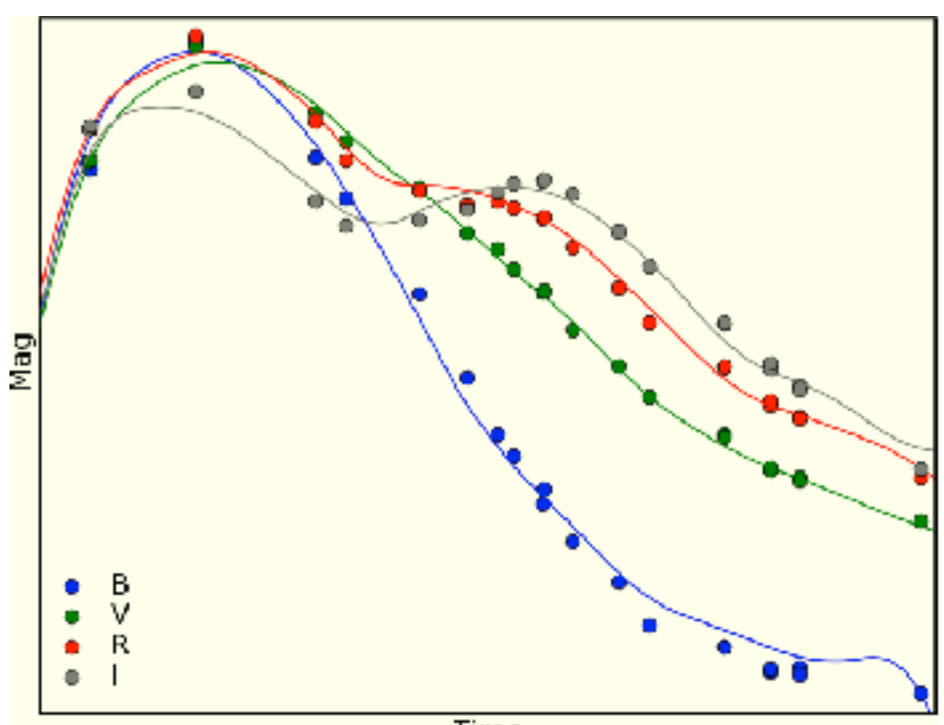


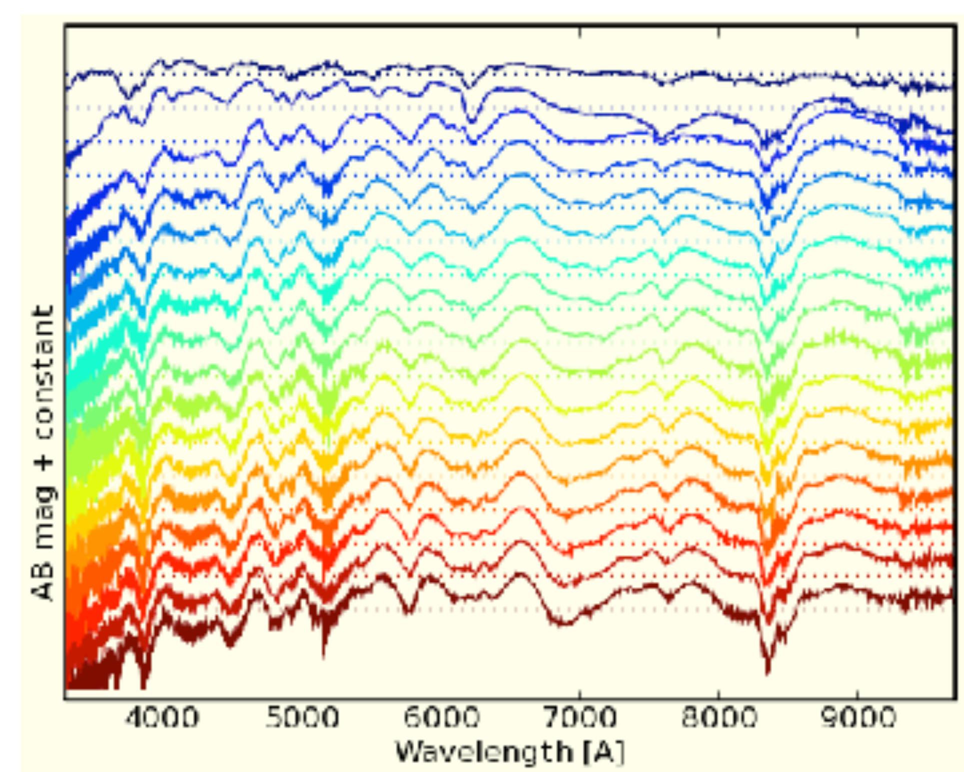
A new model for Type Ia supernovae

- Why is this necessary?
  - Decrease uncertainty in the Hubble diagram.
  - Dispersion is a sign of unmodeled processes
      - leads to bias if population changes as a function of redshift
- With the Nearby Supernova Factory, we have the data to make a better model.

The Nearby Supernova Factory

- Spectrophotometric data
- Observations of > 1100 supernovae
- Full light curves for almost 400 SNIa
- Redshifts < 0.1





Plan for Making a New Supernova Model

- Use data from SNfactory
- Do something like SALT2 -- linear spectral time series templates
- Add complexity to capture more of SNIa diversity
- Result: SNEMO = SuperNova Empirical MOdel

Making the Model

- Use Gaussian Processes to model each individual SN
- (Optional) Deredden with a color relation
- Use EMFA (PCA-like process) to calculate model components
- Use K-fold cross-validation to determine model parameters:
    - What color relation to use
    - Model training set selection
    - Number of components in the final model

Gaussian Processes

- Idea--supernova data is some true function plus a gaussian error

$$y = f(x) + \mathcal{N}(0, \sigma_n^2)$$

- Data points have some correlation

$$\mathbf{f}_\star \sim \mathcal{N}(m(X_\star), K(X_\star, X_\star))$$

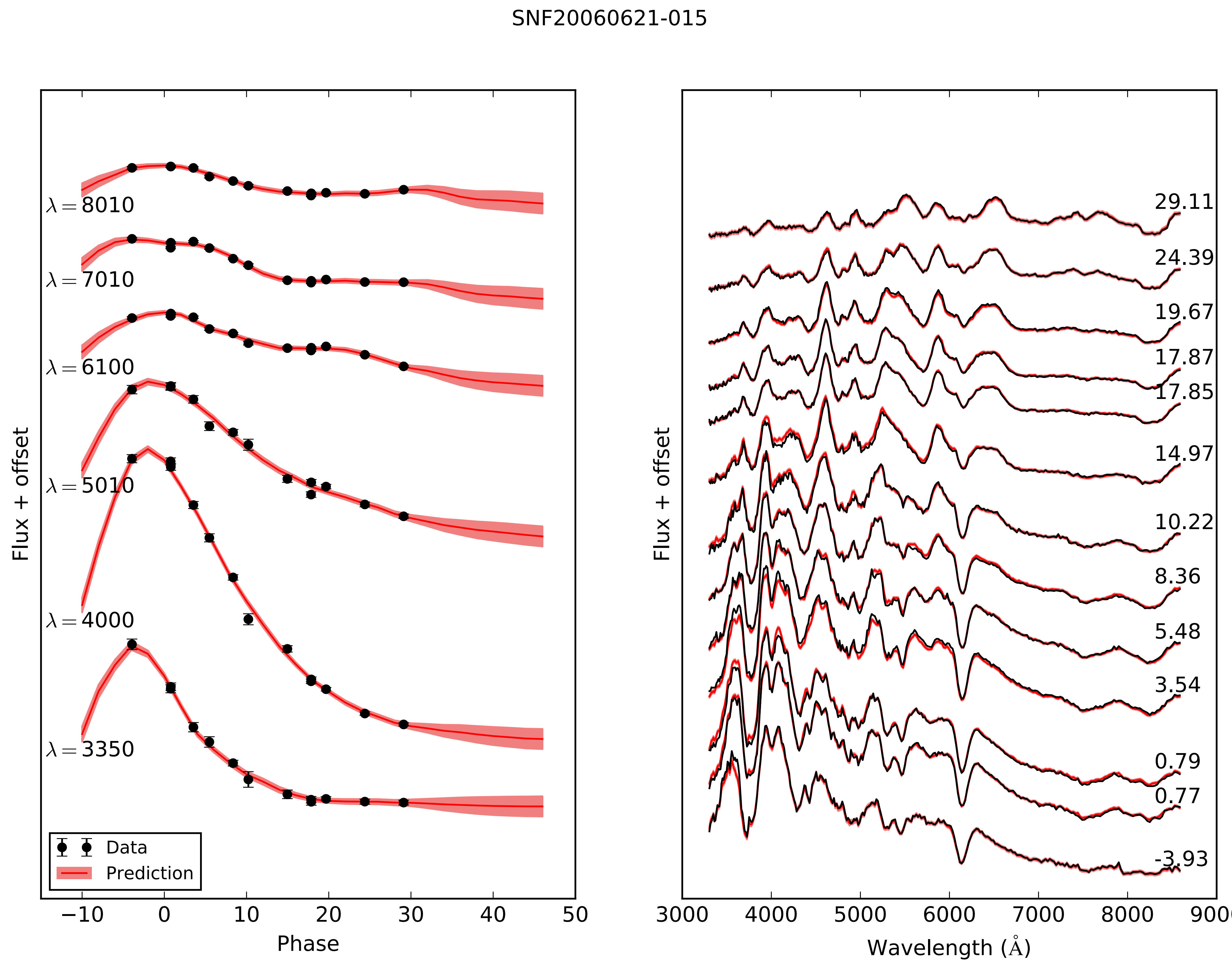
- Given these assumptions, one can predict the true supernova flux

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{f}_\star \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} m(X) \\ m(X_\star) \end{bmatrix}, \begin{bmatrix} K(X,X)+V & K(X,X_\star) \\ K(X_\star,X) & K(X_\star,X_\star) \end{bmatrix}\right)$$

- The matrix K is made up of Matérn kernel elements:

$$k(x,x') = \sigma_f^2 \left[1 + \frac{\sqrt{5}(x-x')}{l} + \frac{5(x-x')^2}{3l^2}\right] \exp\left(-\frac{\sqrt{5}(x-x')}{l}\right)$$

Gaussian Processes

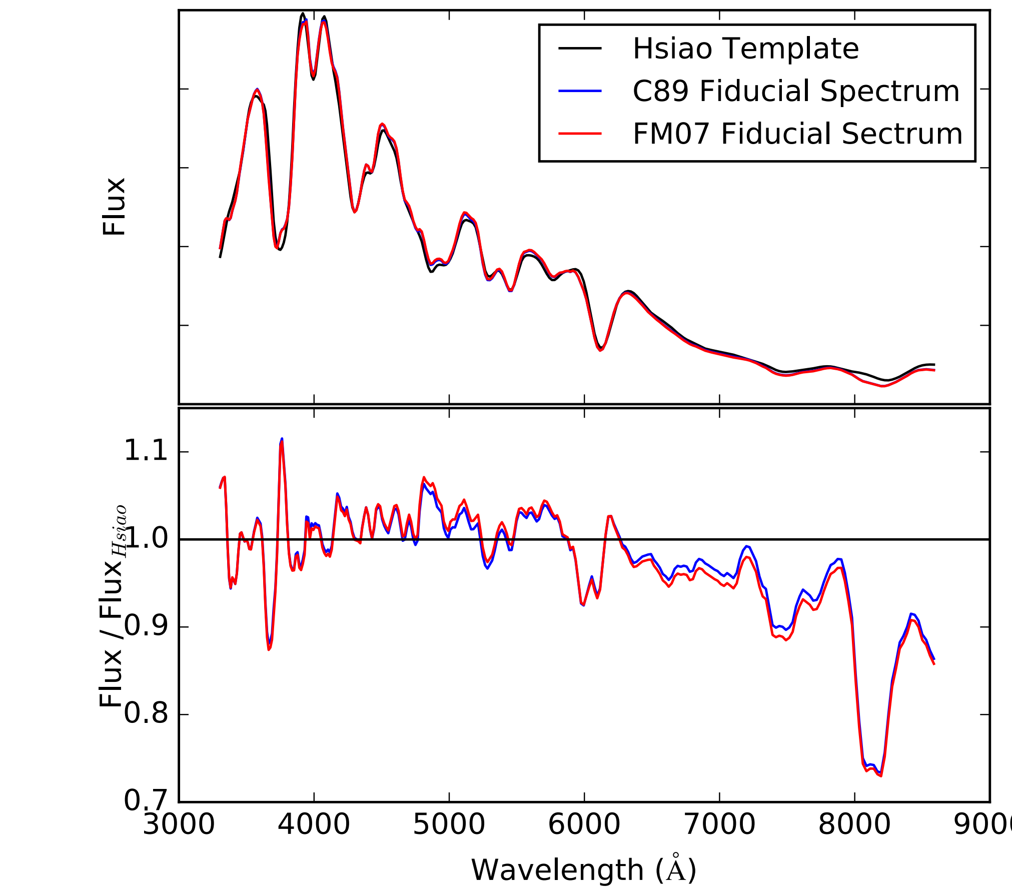


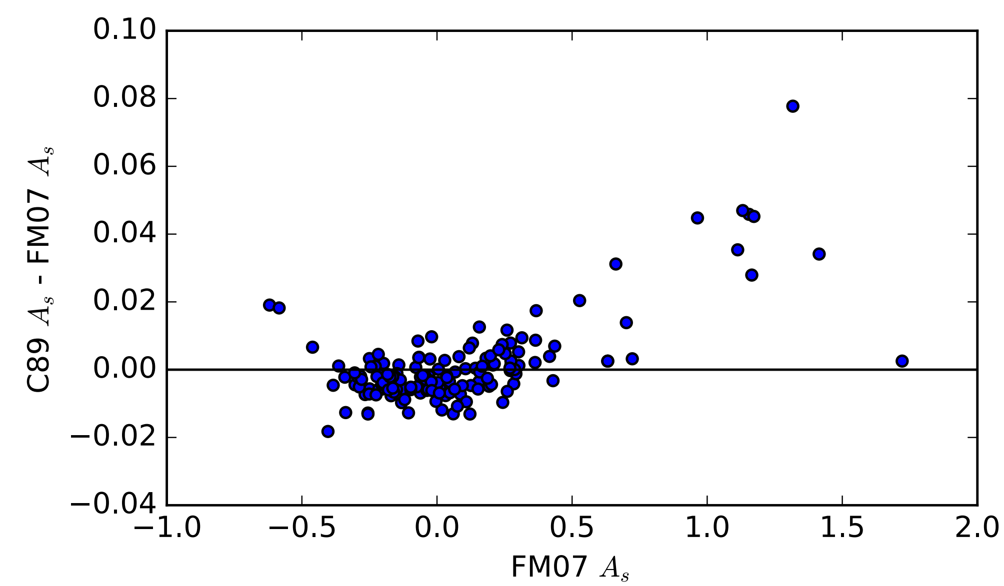
Dereddening

- Minimize the quantity

$$\sum_{SNe}\sum_{p,\lambda} \frac{\left(f_{SN_i}(p,\lambda) - a\;10^{-0.4\;E(B-V)\;c(\lambda)}\;f_{fid}(p,\lambda)\right)^2}{\sigma^2_{SN_i}}$$

as a function of *a*, *E(B-V)* and f_{fid}

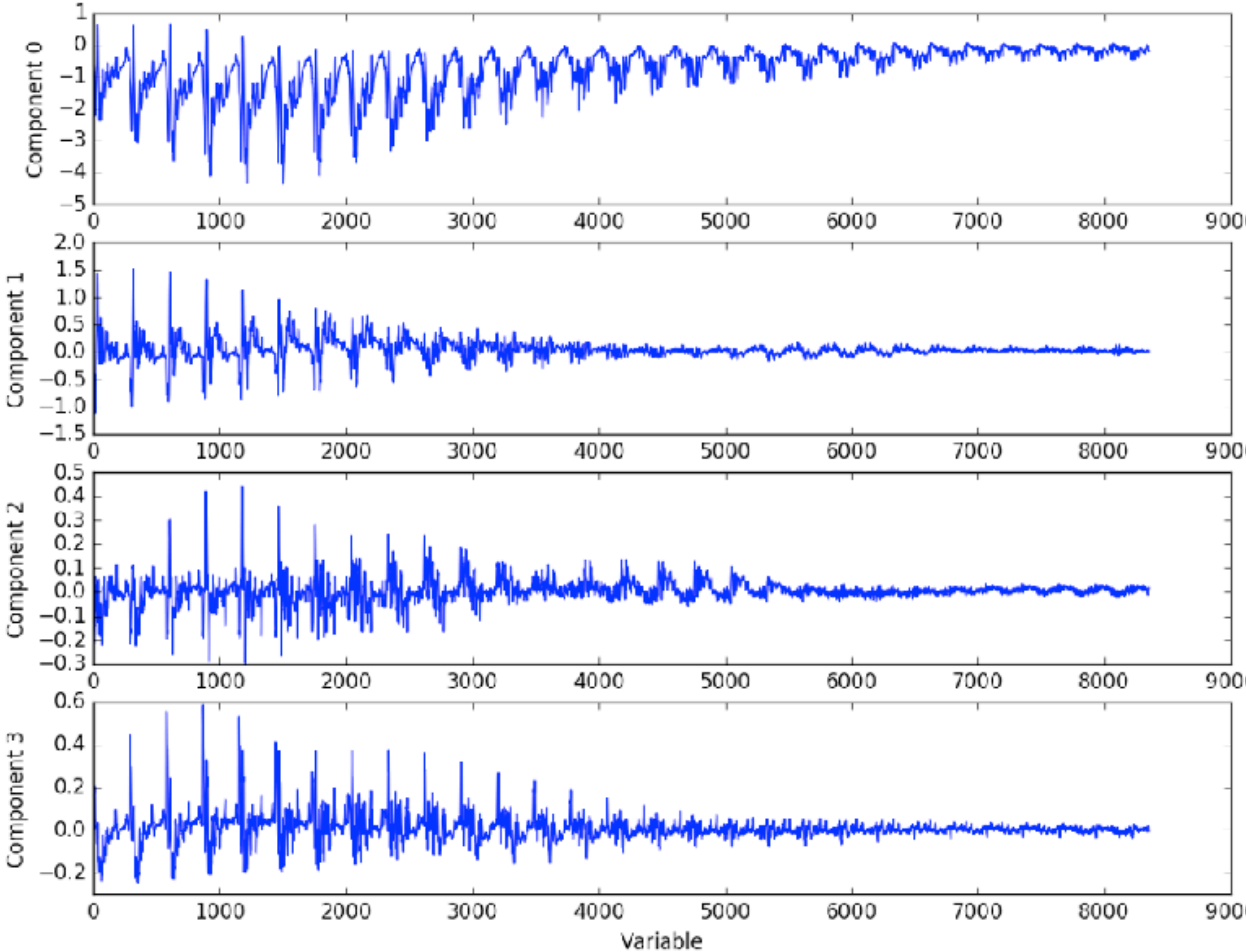




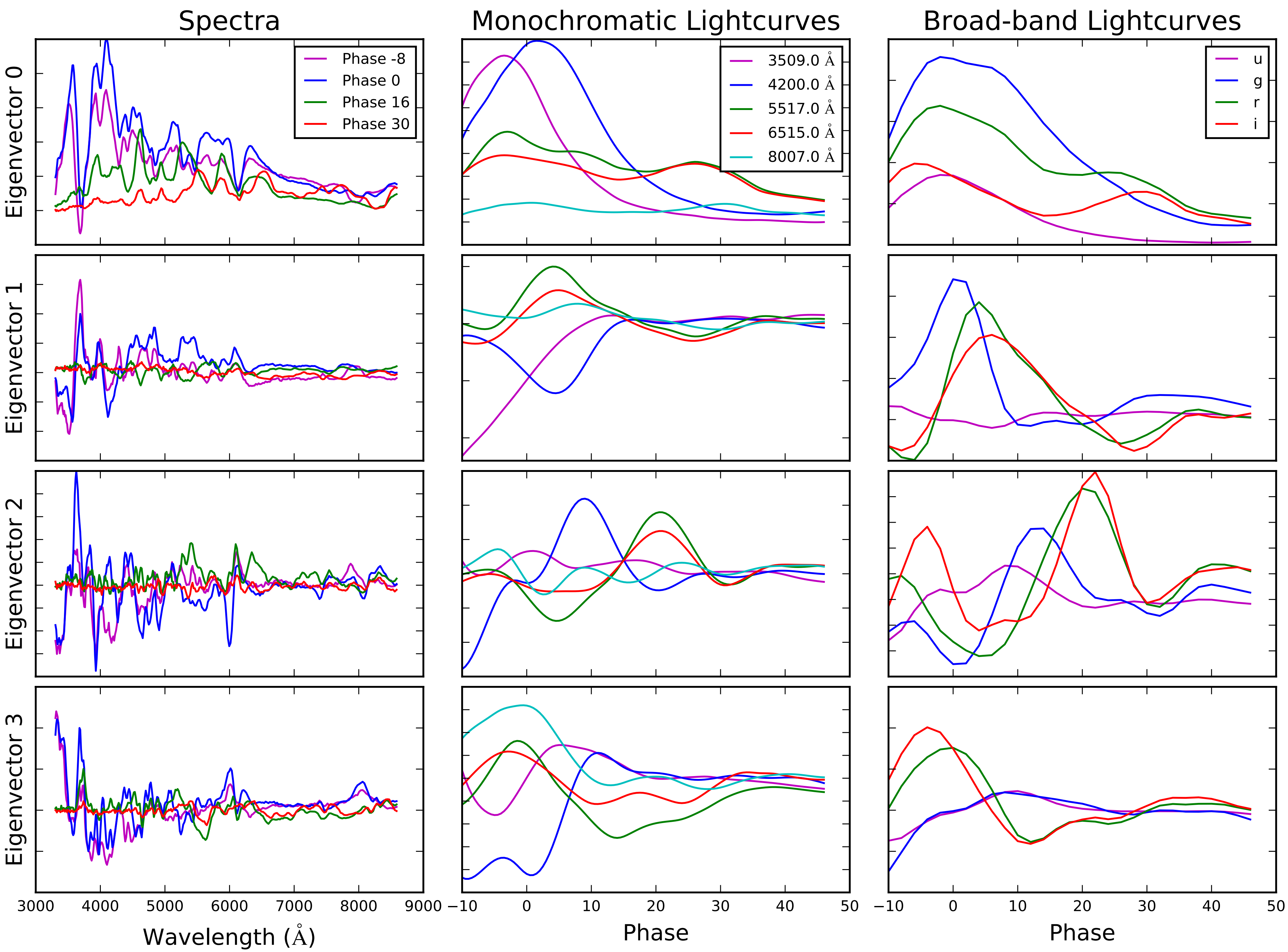
Expectation Maximization Factor Analysis (EMFA)

- A way to calculate orthogonal eigenvectors (Ghahramani and Hinton, 1996)
- Uses the noise in the data
- More robust than similar methods, such as EMPCA
- Only calculates first N components

Eigenvectors output by EMFA



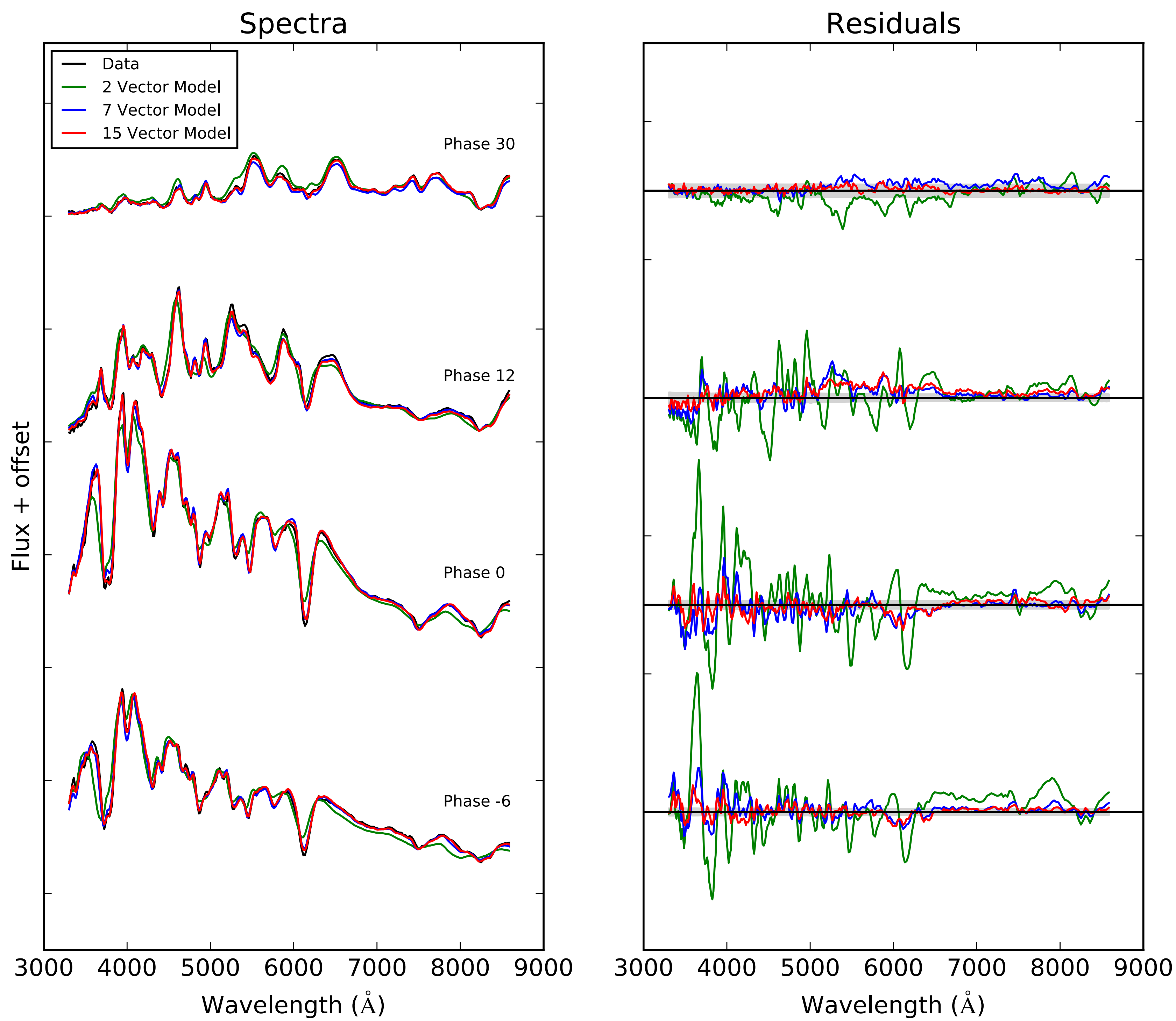
Eigenvectors Reconstructed into Spectral Time Series



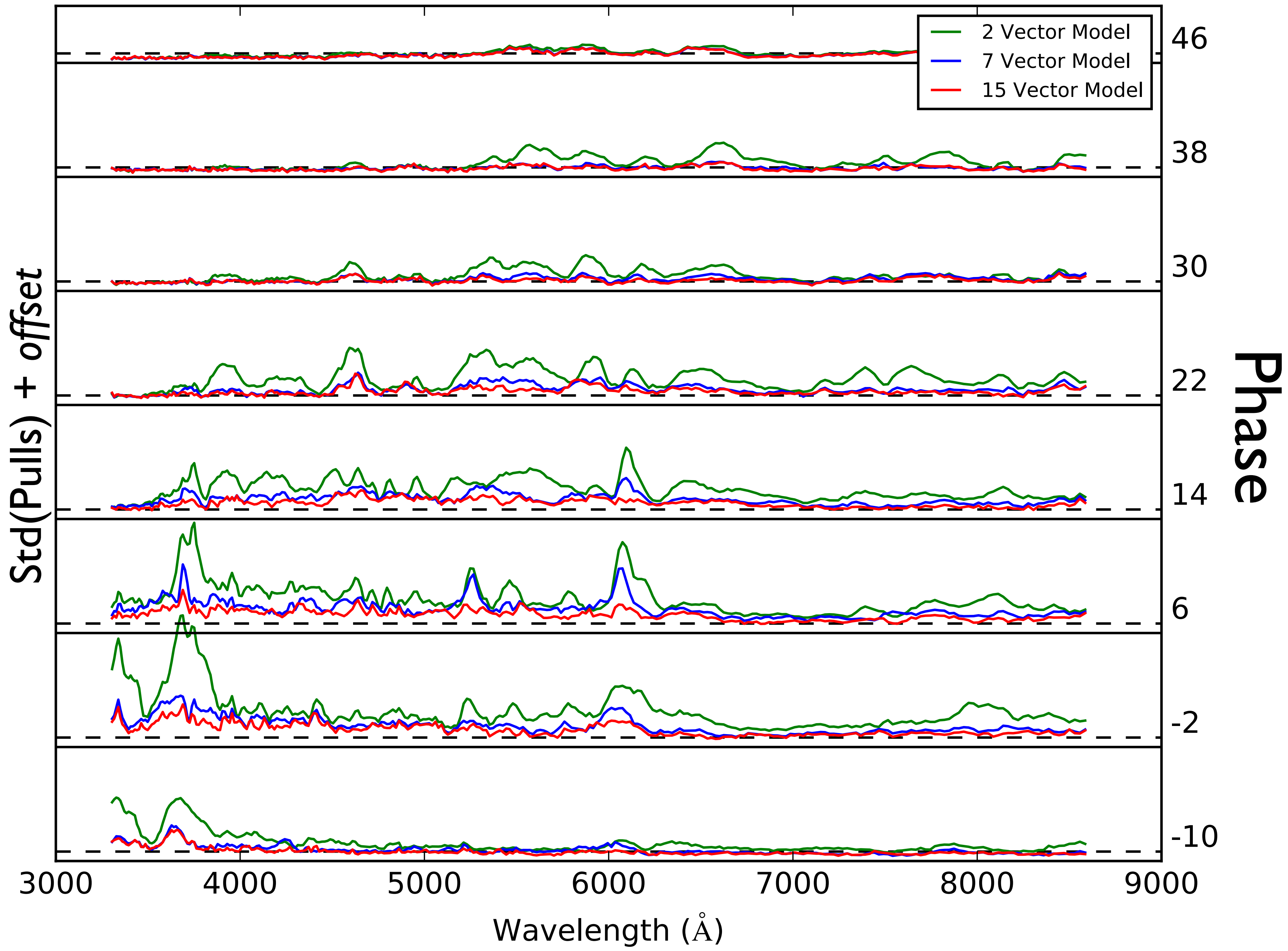
Choosing the number of model components

- Multiple Goals:
  - SNEMO2: Comparing the model to SALT2
  - SNEMO7: Finding the number of components with which we can minimized dispersion in the standardized magnitudes, following the SALT2 method
  - SNEMO15: Finding the model that best captures Type Ia supernovae diversity.

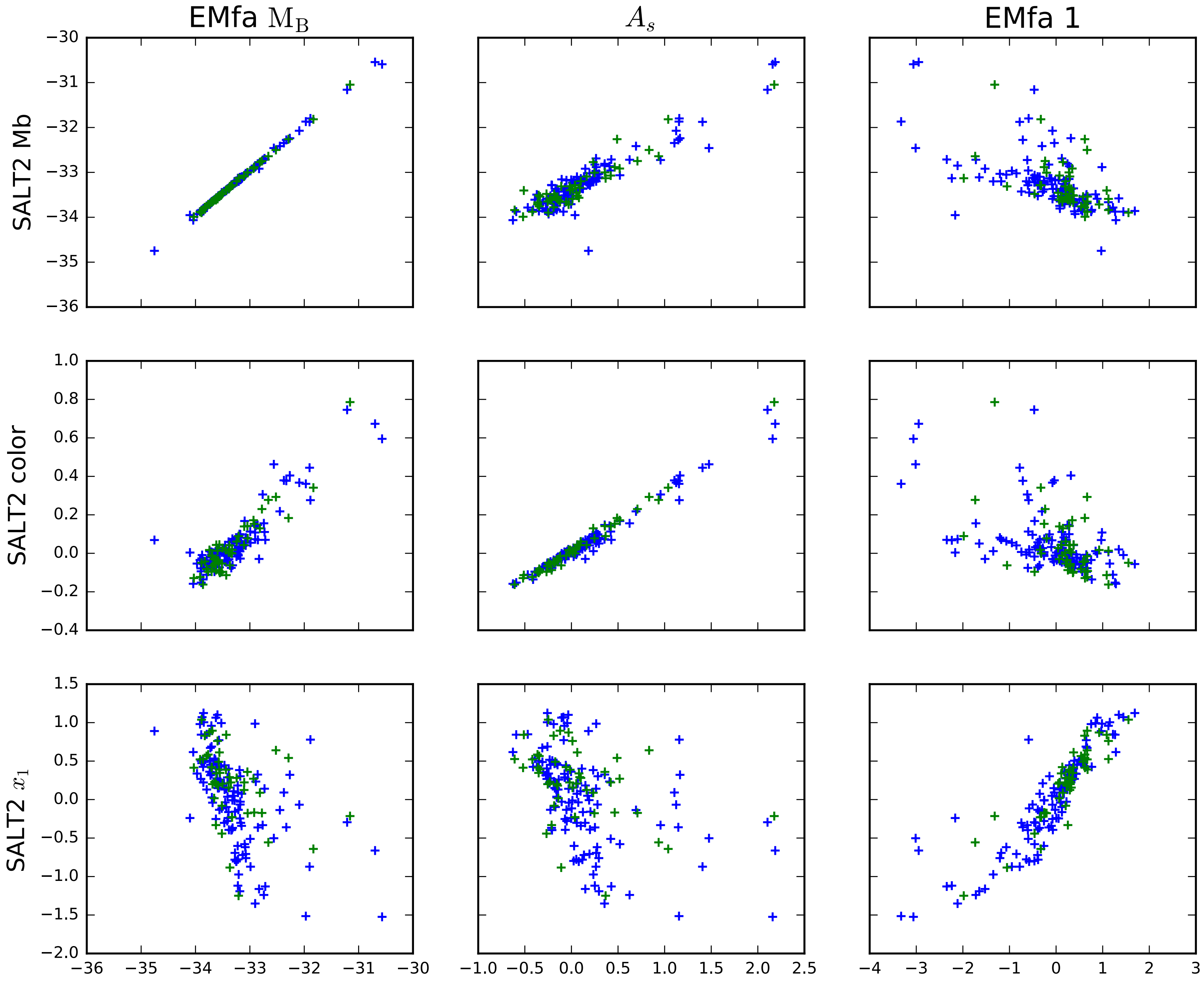
Out of sample SN reconstruction



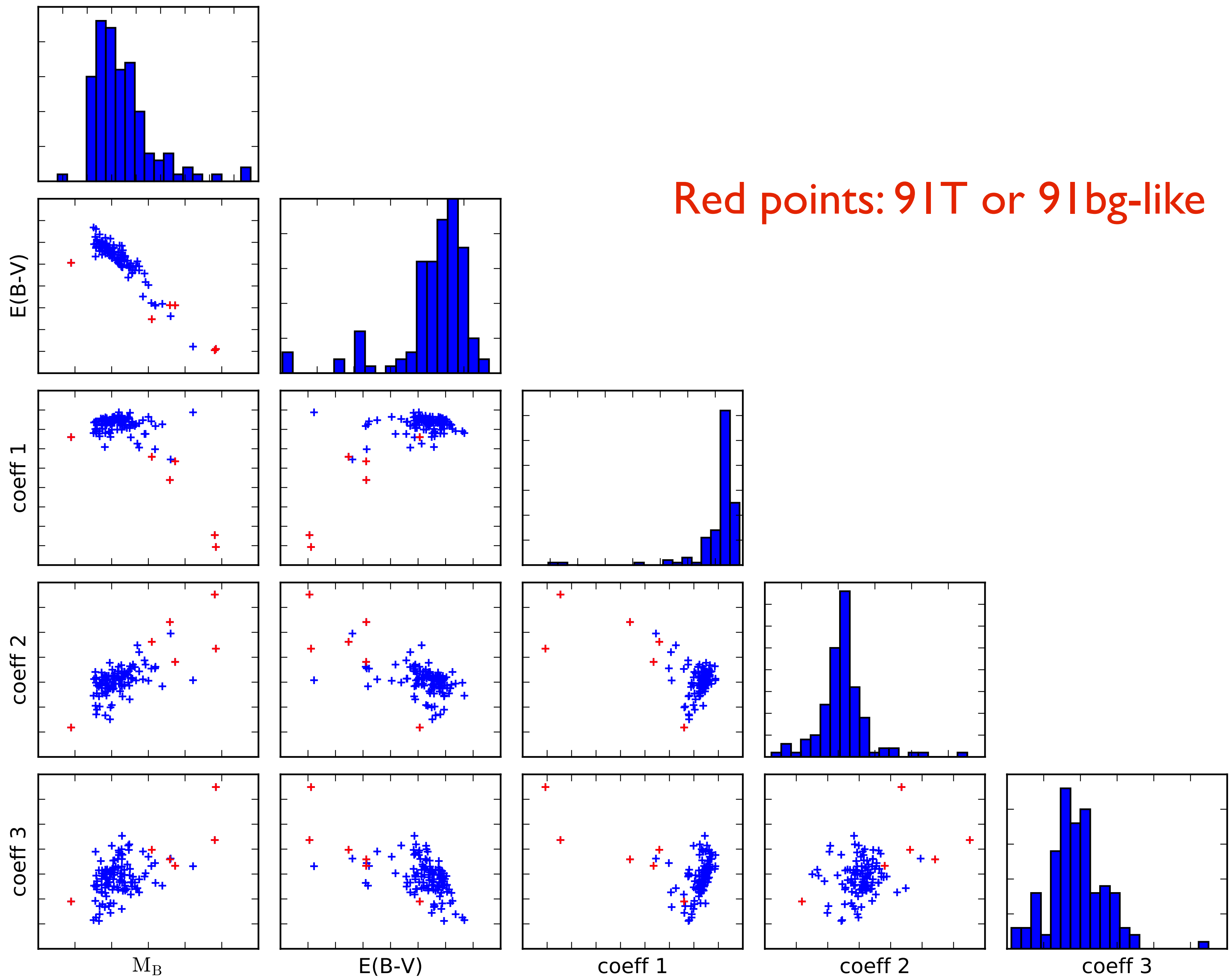
Standard deviation of out-of-sample SNe pulls



SALT2 comparison



Distinguishing Peculiar Type Ia Supernovae

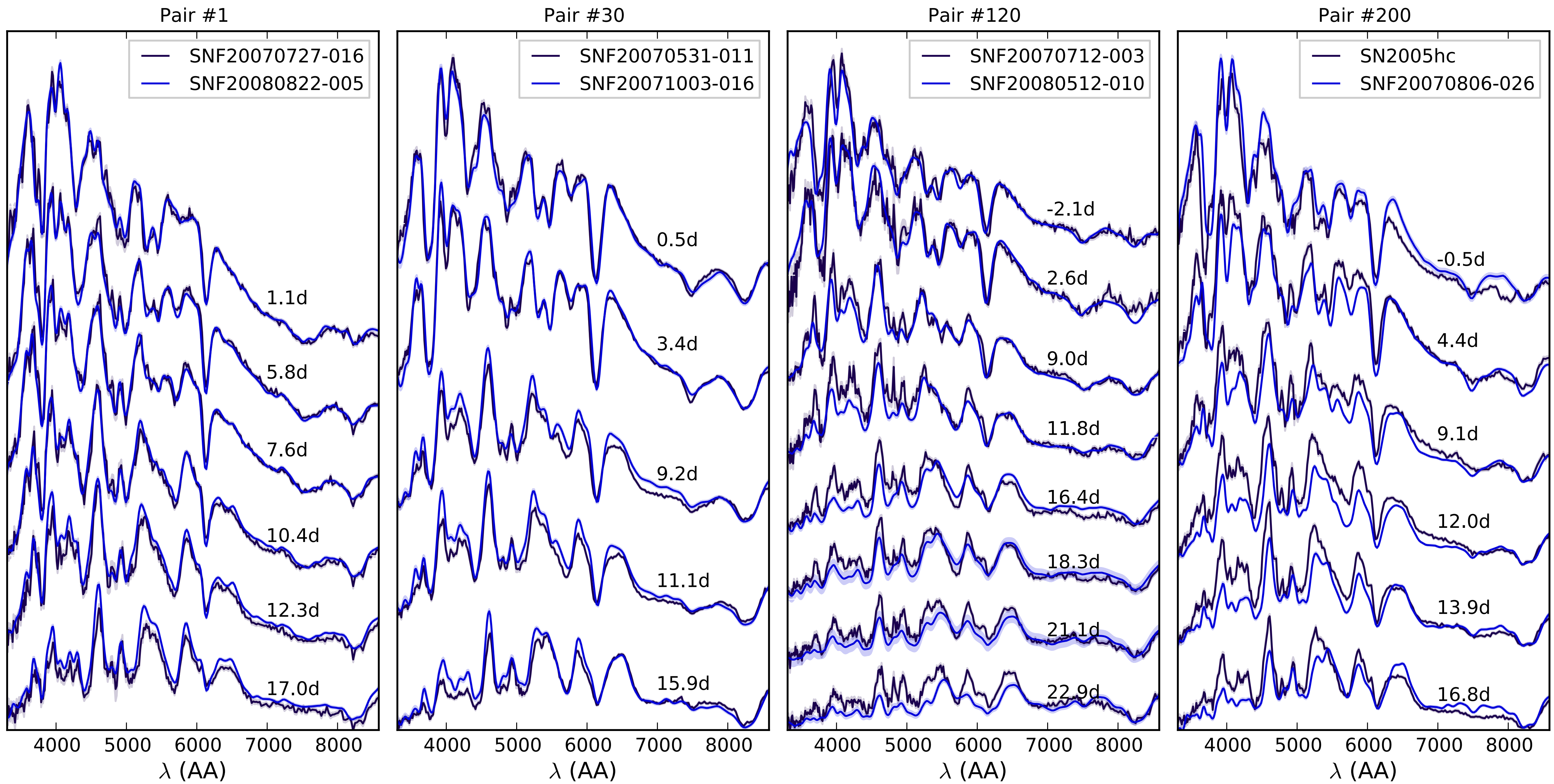


Red points: 91T or 91bg-like

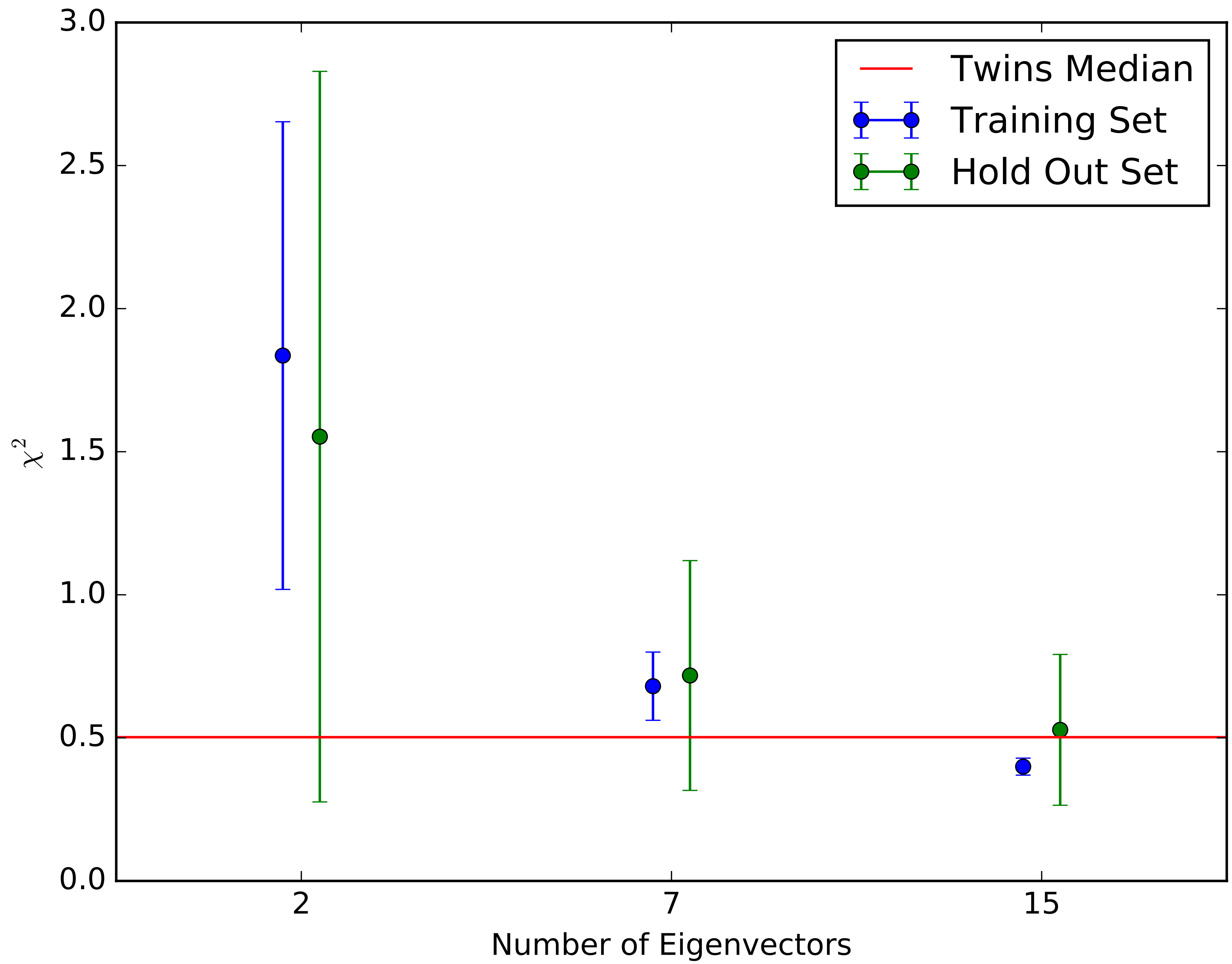
(using SNEMO7)

How good is this model?

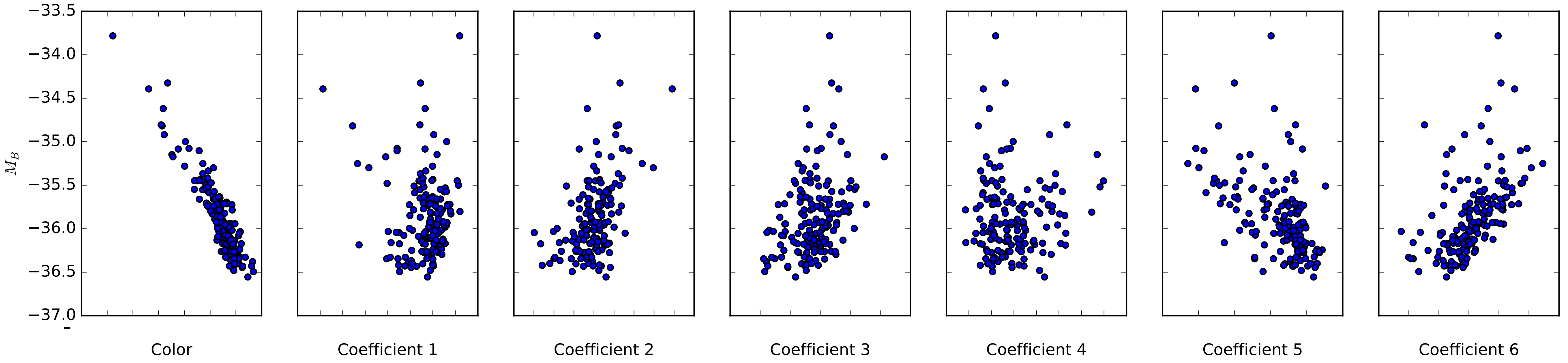
A counter example: twin supernovae
(see Fakhouri et al. 2015)



Comparison with ‘twin’ supernovae

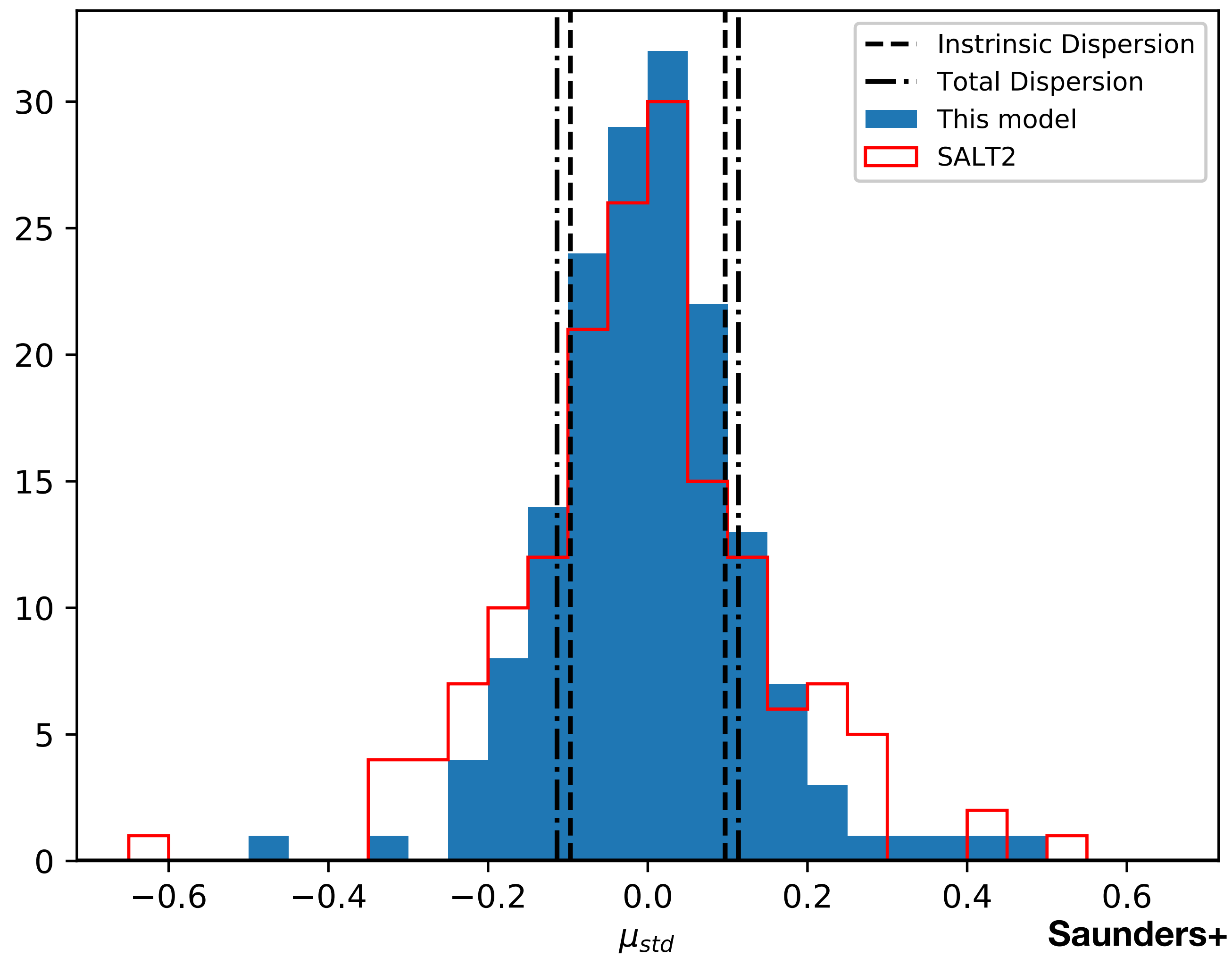


What about the dispersion?



Dispersion in standardized magnitudes

$$\mu_g = m_g^{std} - M_g = m_g + \sum_i \alpha_i\, c_i \; + \; \alpha_c \times A_S - M_g$$



Saunders+ in prep.

Total dispersion = 0.113 mags

Intrinsic Dispersion = 0.097 mags

What about fitting photometry?

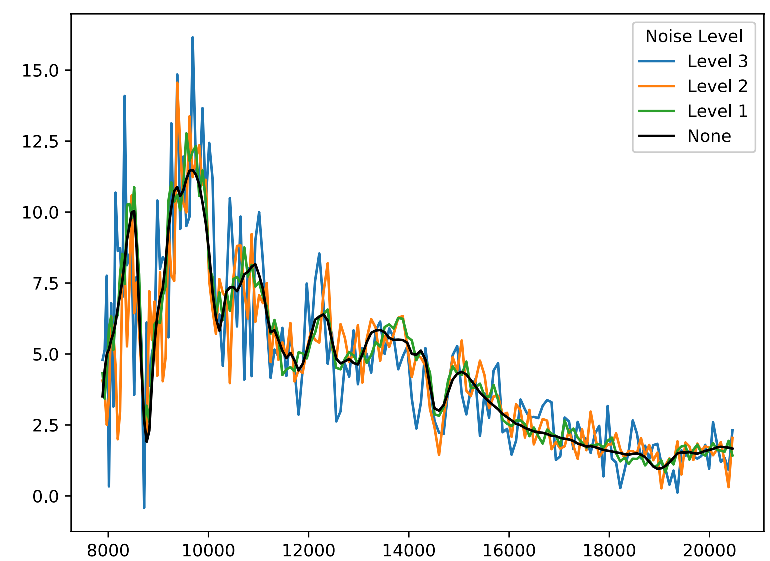
- Can these models be constrained by photometric data?
- This can be tested with a simulation:
  - Use the models to simulate photometric data
  - Fit the models to the simulated data
  - Compare the fit coefficients with the original components

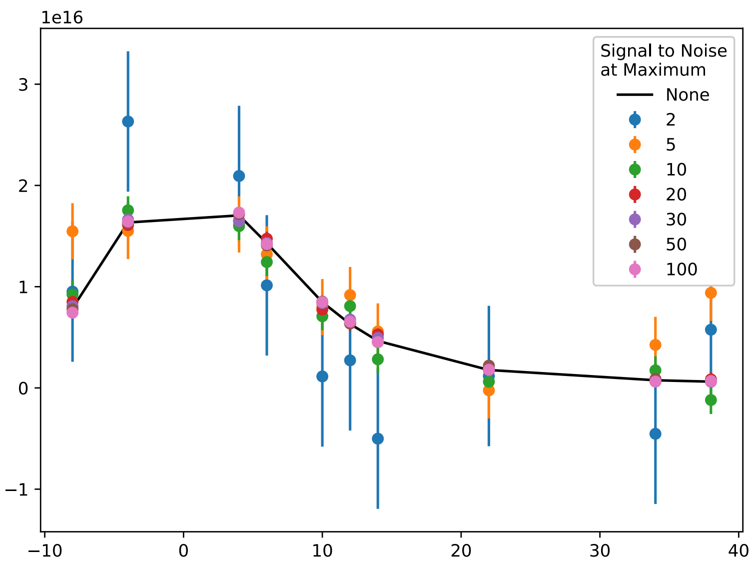
What about fitting photometry?

Scenario 1: Flux-Calibrated Spectra

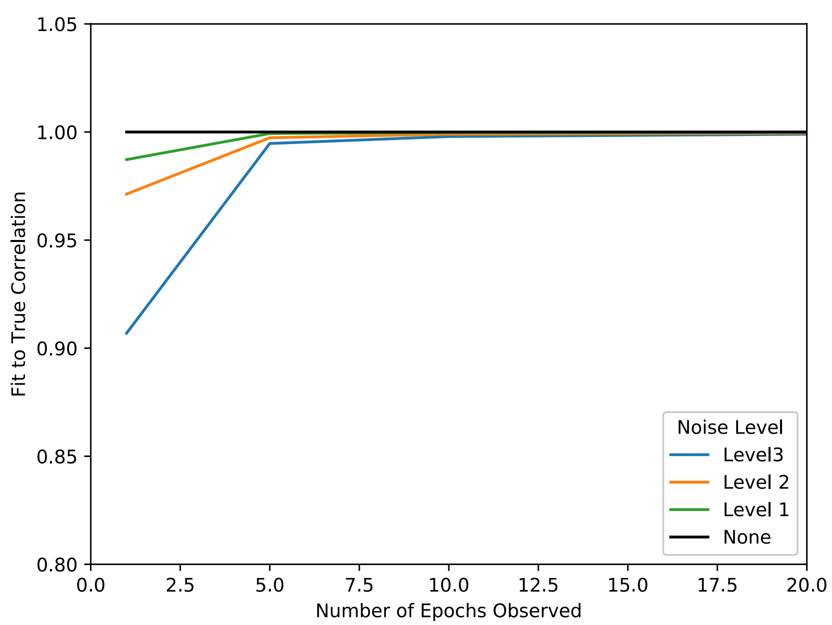
Scenario 2: Photometry

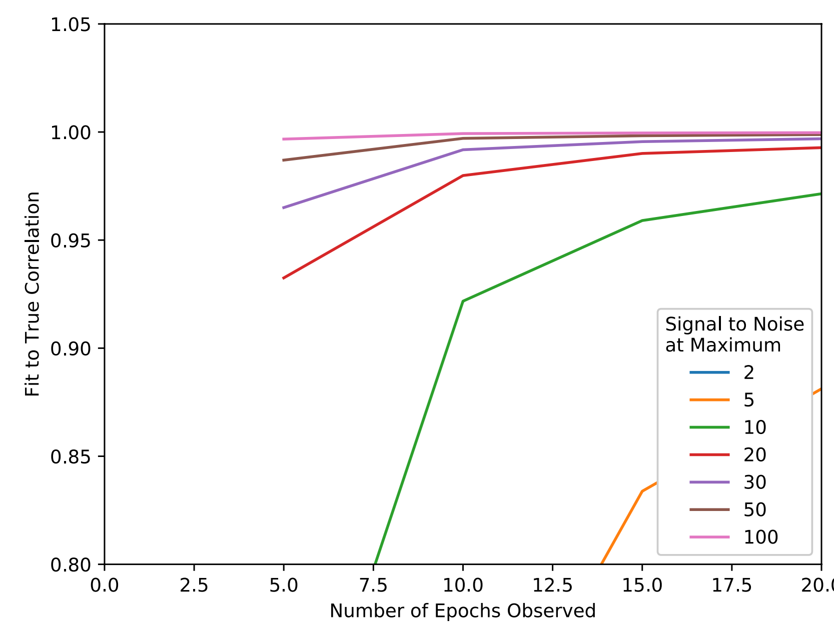
Data:





Model Parameter Recovery:





Summary

- New model developed that captures much more of supernova diversity
    - Two models produced with different levels of complexity, plus simple model for comparison with SALT2/MLCS2k2
    - Usable with photometry
    - SNEMO7 will lead to lower dispersion in corrected magnitudes -- better constraints on cosmology
    - SNEMO15 also usable for more accurate simulations of SNIa populations