The Bright Future for Supernova Cosmology

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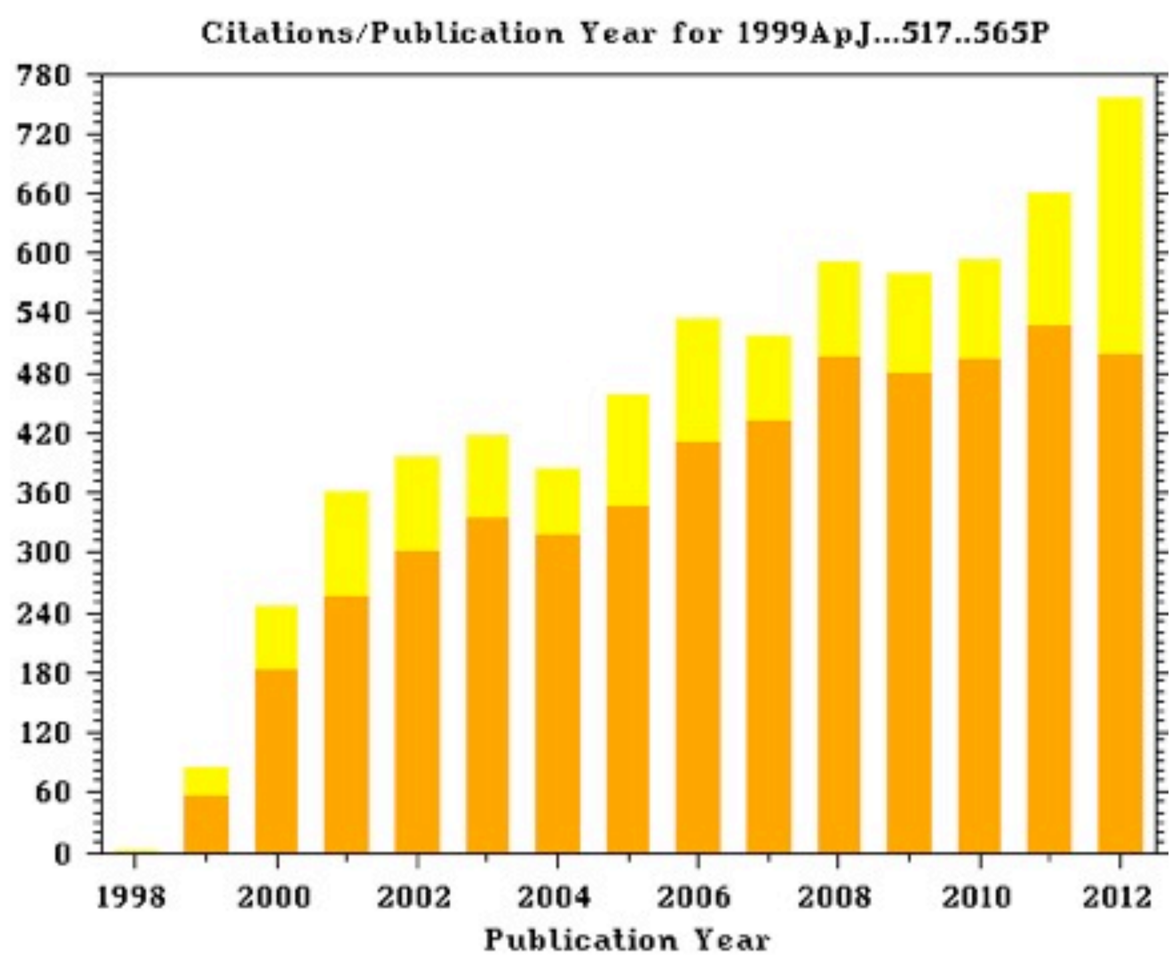
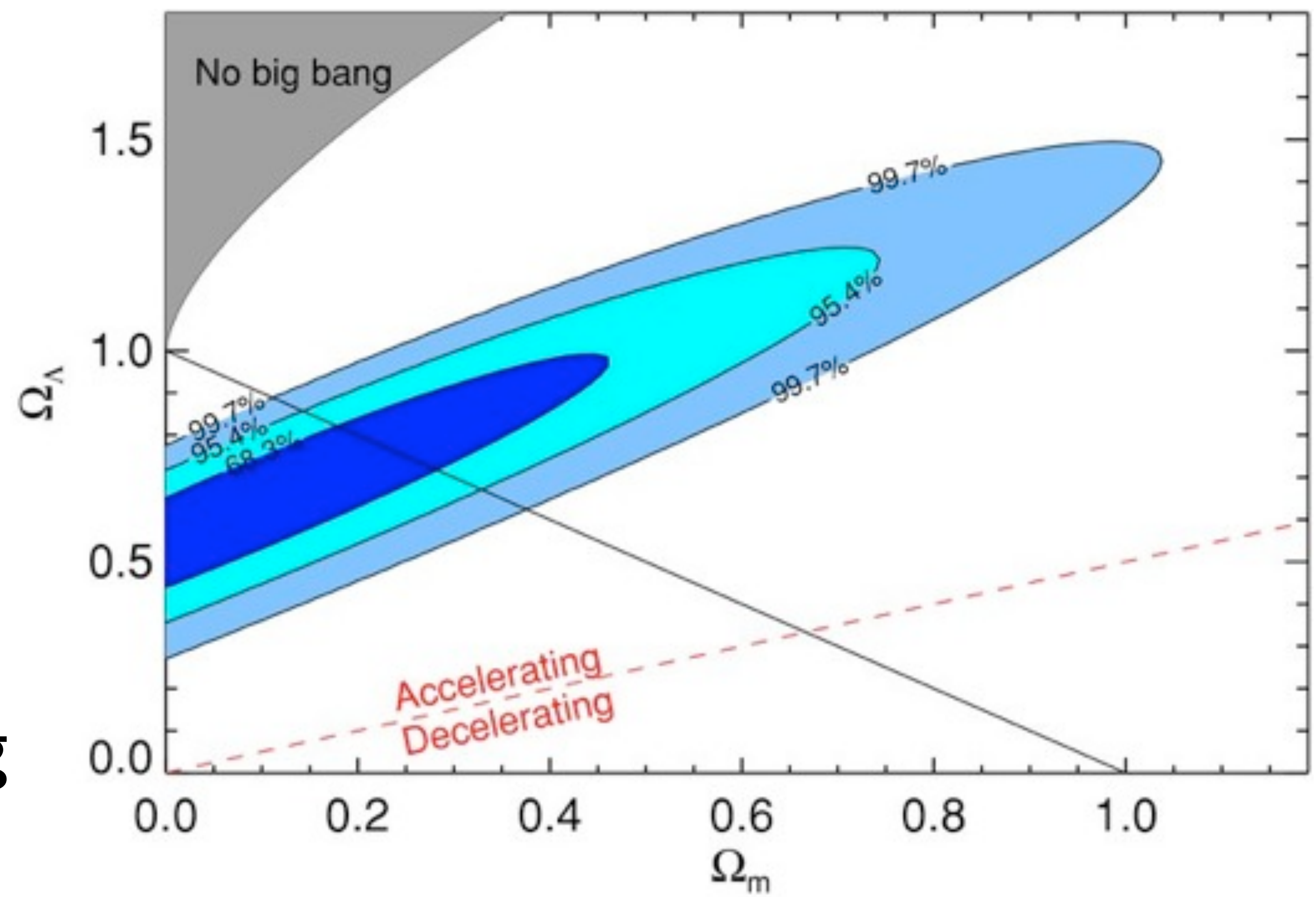
Why Care About SN Cosmology

- Addresses the major puzzle confronting physics today
  - Accelerated expansion of the universe
  - Mysterious "Dark energy" constitutes 73% of the energy of the Universe
- Original discovery of the accelerating universe made with Type Ia SNe



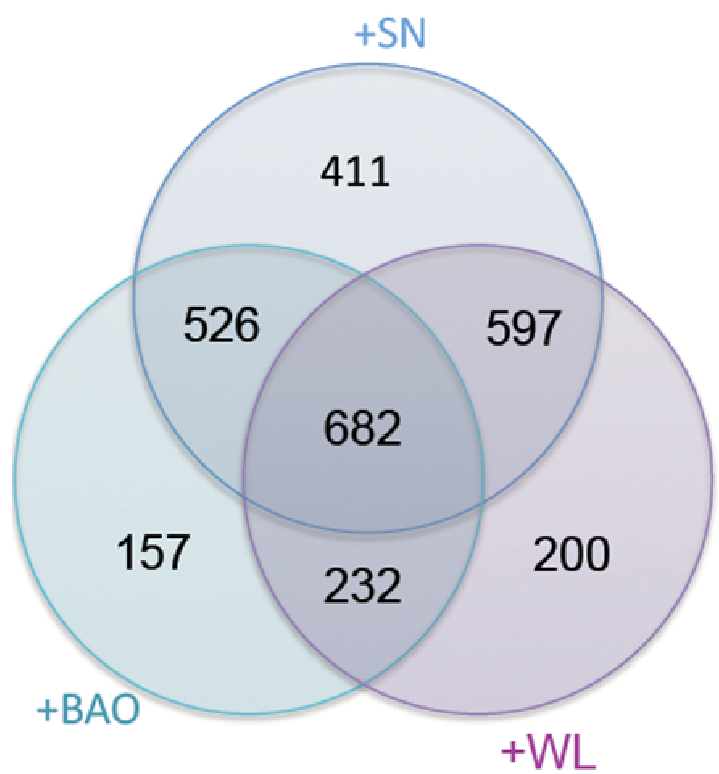
Why Care About SN Cosmology

- Measure of the expansion history of the Universe with SNe Ia continue to be an important probe of dark energy
- Uniquely measures distances from 0<z<1.5 spanning accelerating and decelerating regimes



Why Care About SN Cosmology

- Major future surveys will provide improved measurements
  - Important contribution when combined with other probes
  - Measured in terms of "Figure of Merit"



From WFIRST Final Report

Standard Candle Flux and the Matter Content

$$f = \frac{L}{4\pi(1+z)^2\chi^2}$$

$$\int_0^\chi \frac{dr}{\sqrt{1-kr^2}} = \int_0^z \frac{dz}{H(z)}$$

$$H^2 = H_0^2 \left(\sum_{i \in \text{energy states}} \Omega_i (1+z)^{3(1+w_i)} \right)$$

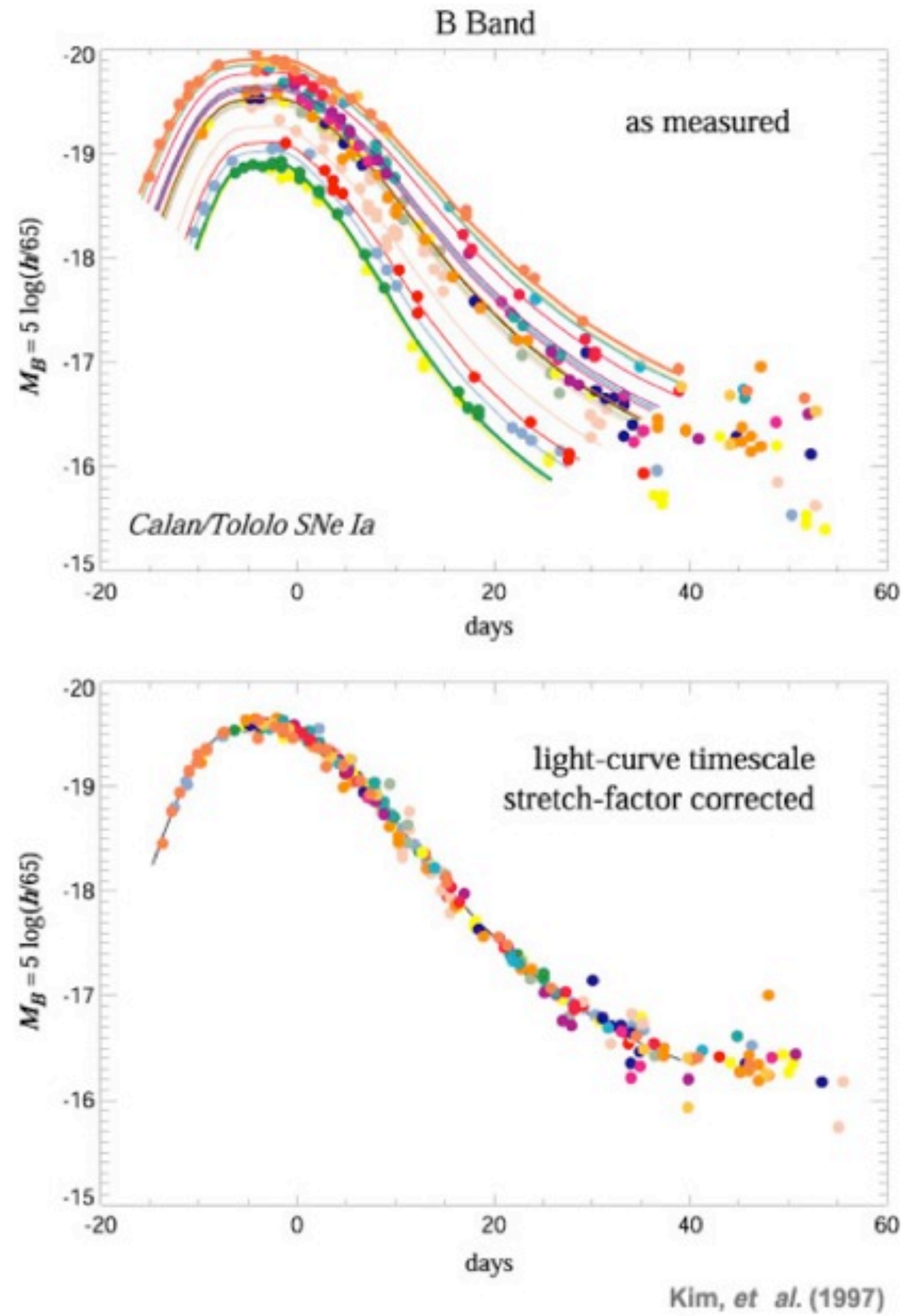
$$d_L = (1+z)\chi \text{ –Luminosity Distance}$$

$$\mu = 5\log\left(d_L/10\text{pc}\right) \text{ –Distance Modulus}$$

Energy State	Matter (CDM, Baryons)	Radiation (γ, ν)	Cosmological Constant Λ	"Dark Energy"	Curvature
w=p/ρ	0	1/3	-1	w(a) modeled as: constant w<-1/3 $w=w_0+w_a(1-a)$	-1/3

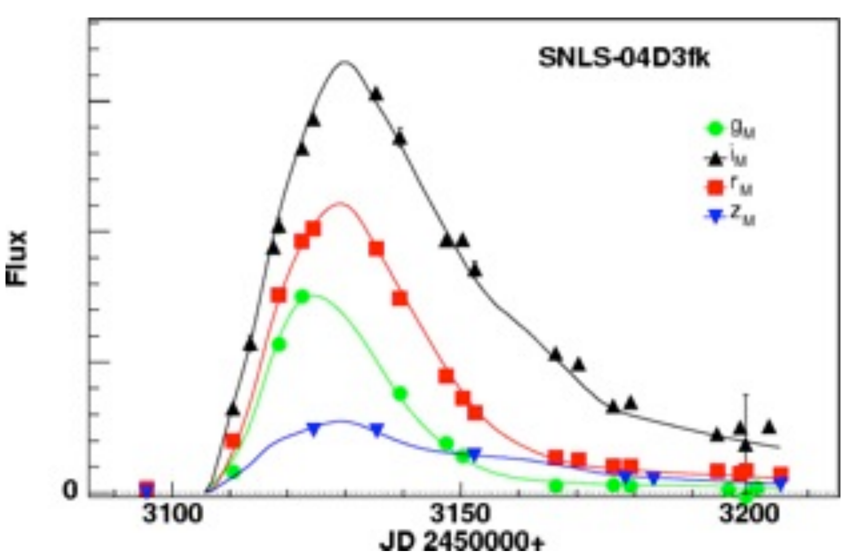
Supernovae Almost But Not Perfect Standard Candles

- Heterogeneity in supernova brightnesses and light curve shapes
- After correction for foreground dust supernovae have peak-magnitude dispersion of ~0.3 mag
- We can determine luminosity per object
- After correction for light-curve shape supernovae become "calibrated" candles with ~0.15 mag dispersion



Estimating the Luminosity of the Standard Candle

- Supernova luminosities determined from fits of multi-band light curves
  - Depends on magnitude at peak brightness, light-curve decline rate , and color



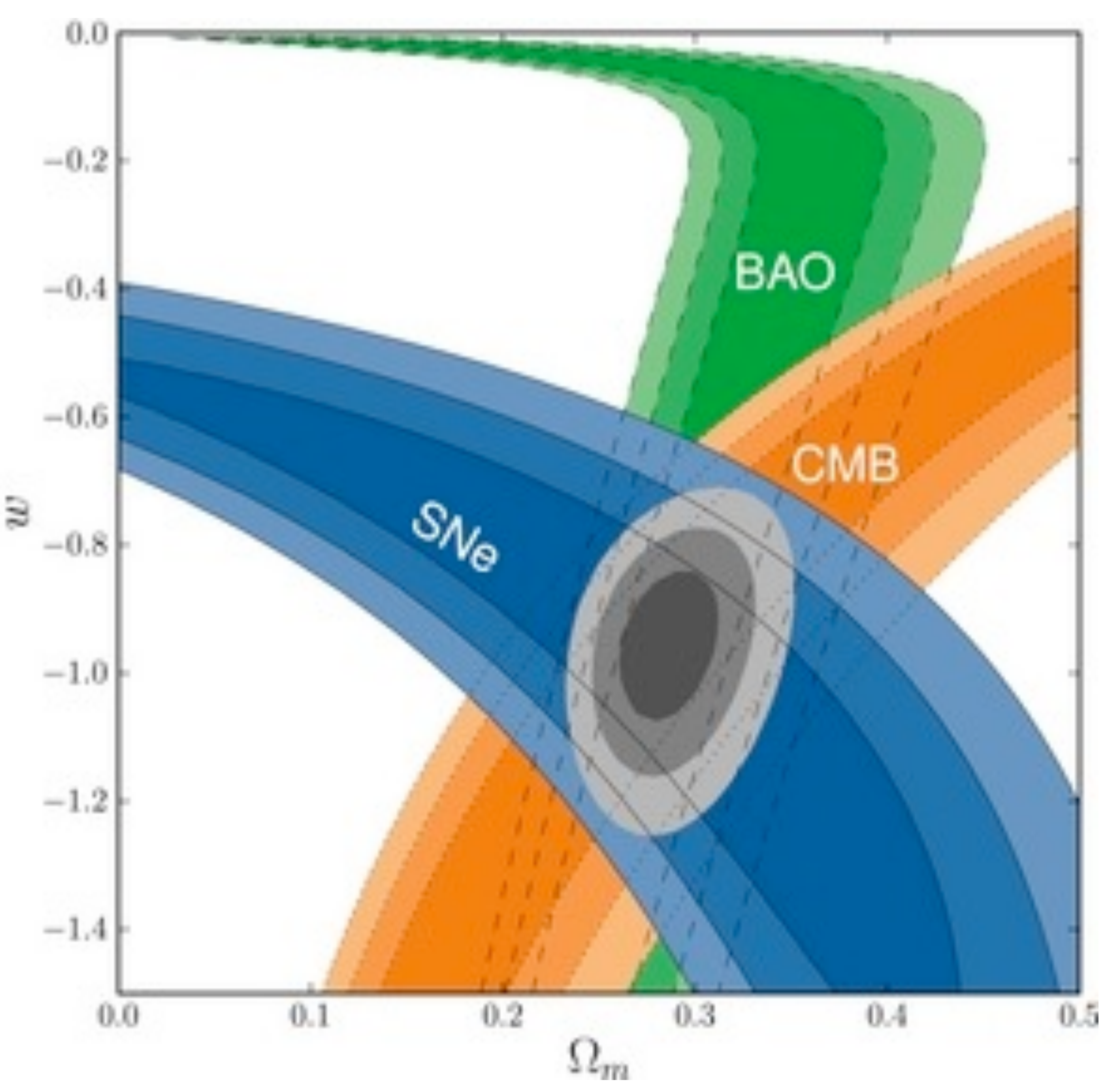
→

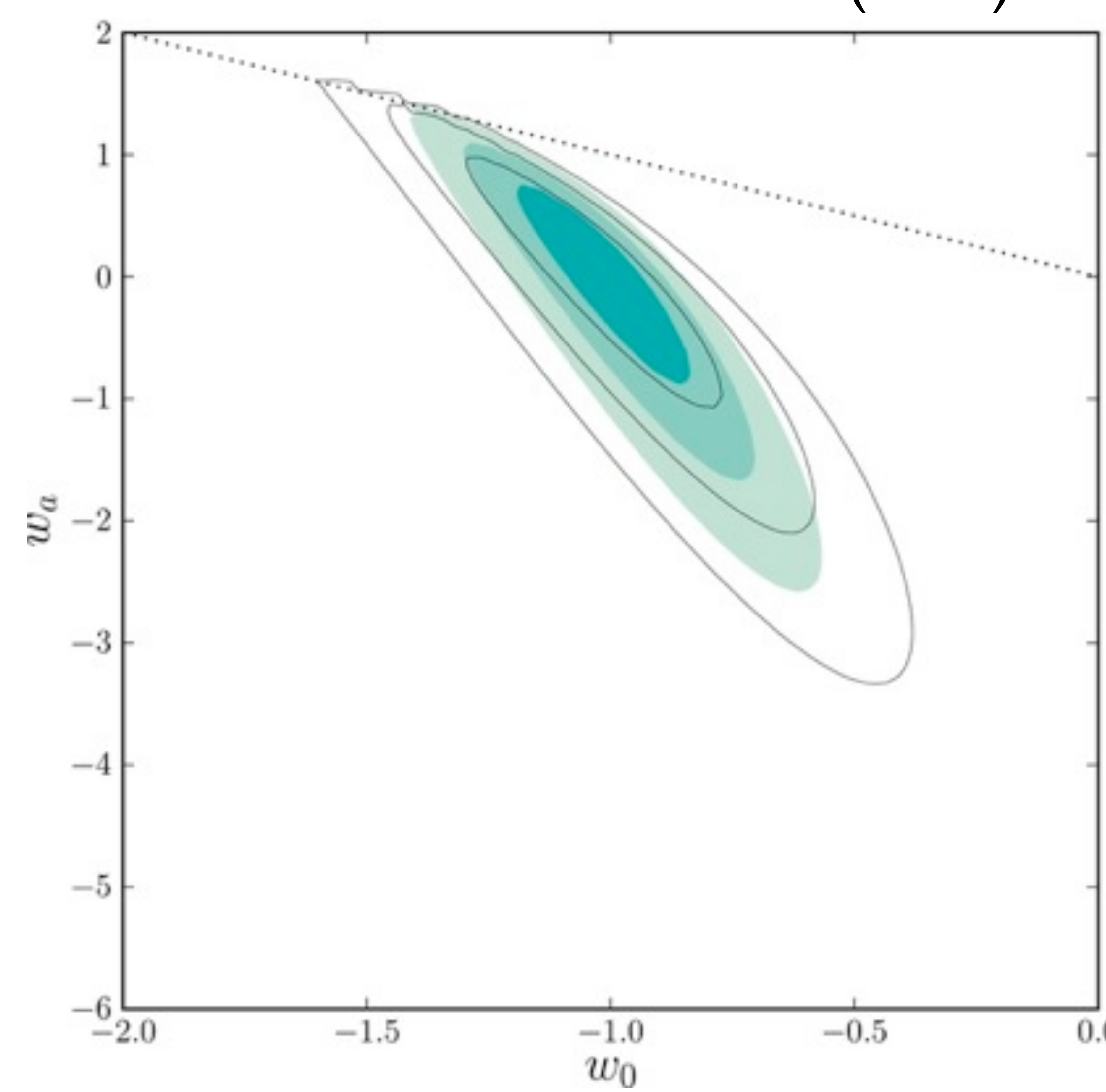
→ Luminosity

SNe Ia Work Well With Other Cosmological Probes

- SNe Ia with BAO and CMB
  - Tighten dark energy equation of state measurement
  - Probe time evolution of the equation of state

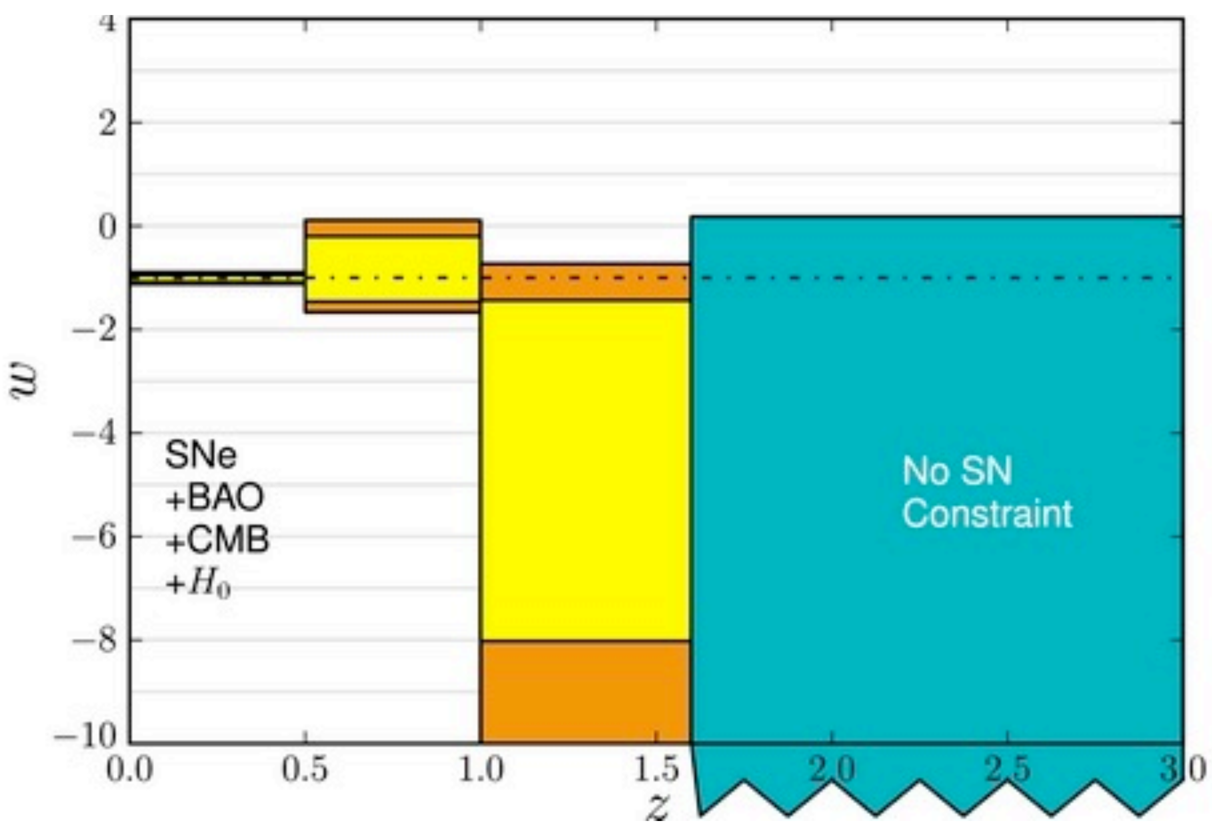
Suzuki et al. (2012)

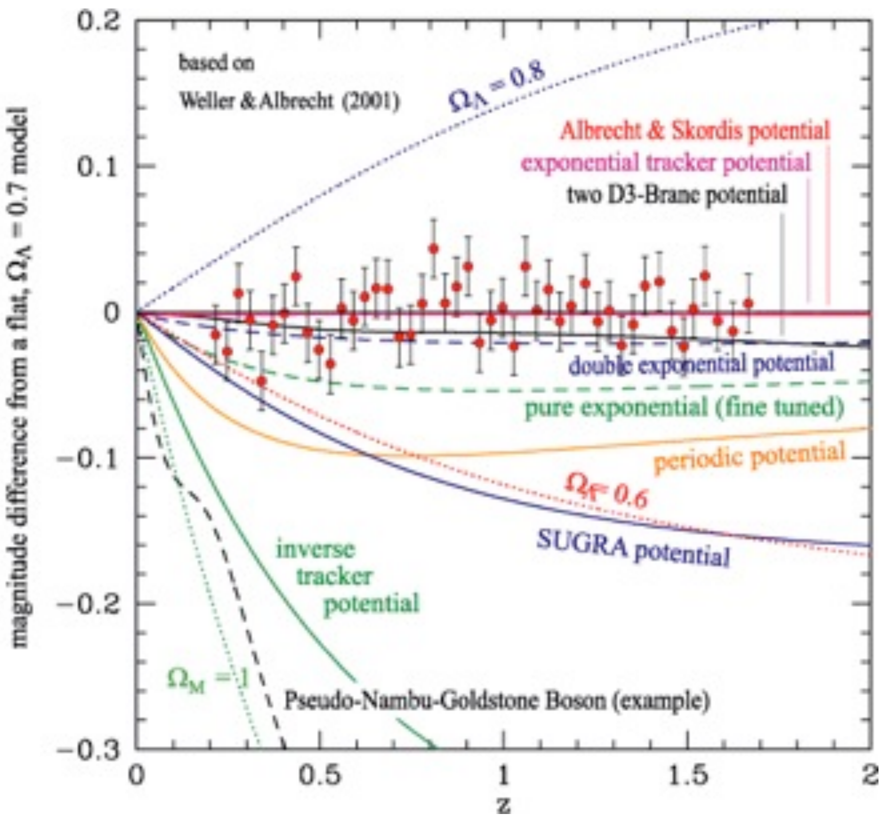




Room For Improvement

- Expand the redshift range to provide leverage for testing dark energy models





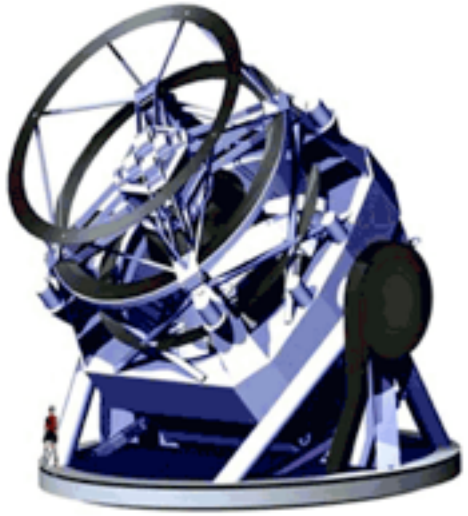
- Decrease systematic uncertainty: within the current redshift range the uncertainty contours are systematics dominated

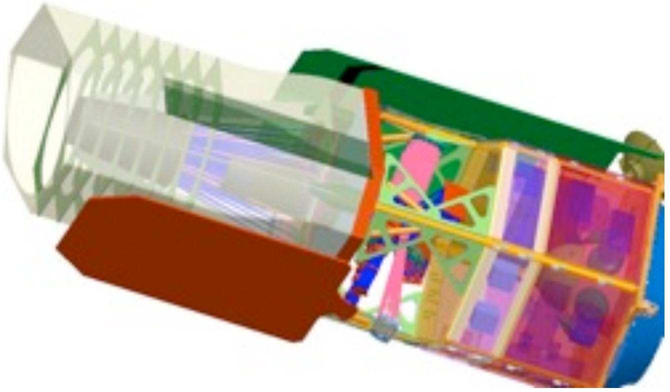
Description	Ω_m	w	Rel. Area [a]
Stat only	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1
All systematics	0.18 ± 0.10	$-0.91^{+0.17}_{-0.24}$	1.85

Conley et al. (2011)

Ongoing/Upcoming SN Surveys

- Better experiments
  - High-quality photometry and spectroscopy with broad wavelength coverage
- Local SNe
  - SkyMapper, LaSilla-Quest, PTF, SNFactory
- High-redshift
  - Dark Energy Survey, Large Synoptic Survey Telescope, KDUST, HST, WFIRST, Euclid



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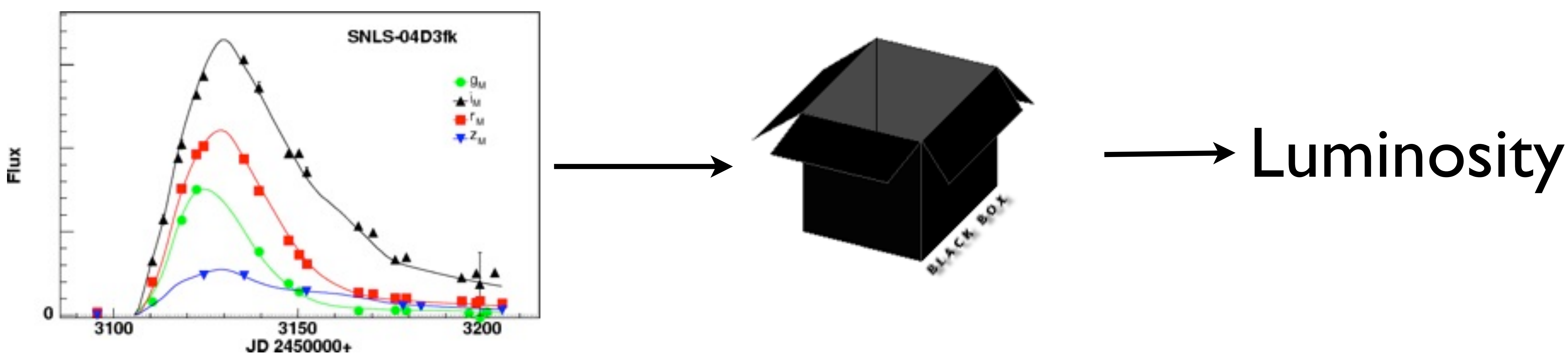

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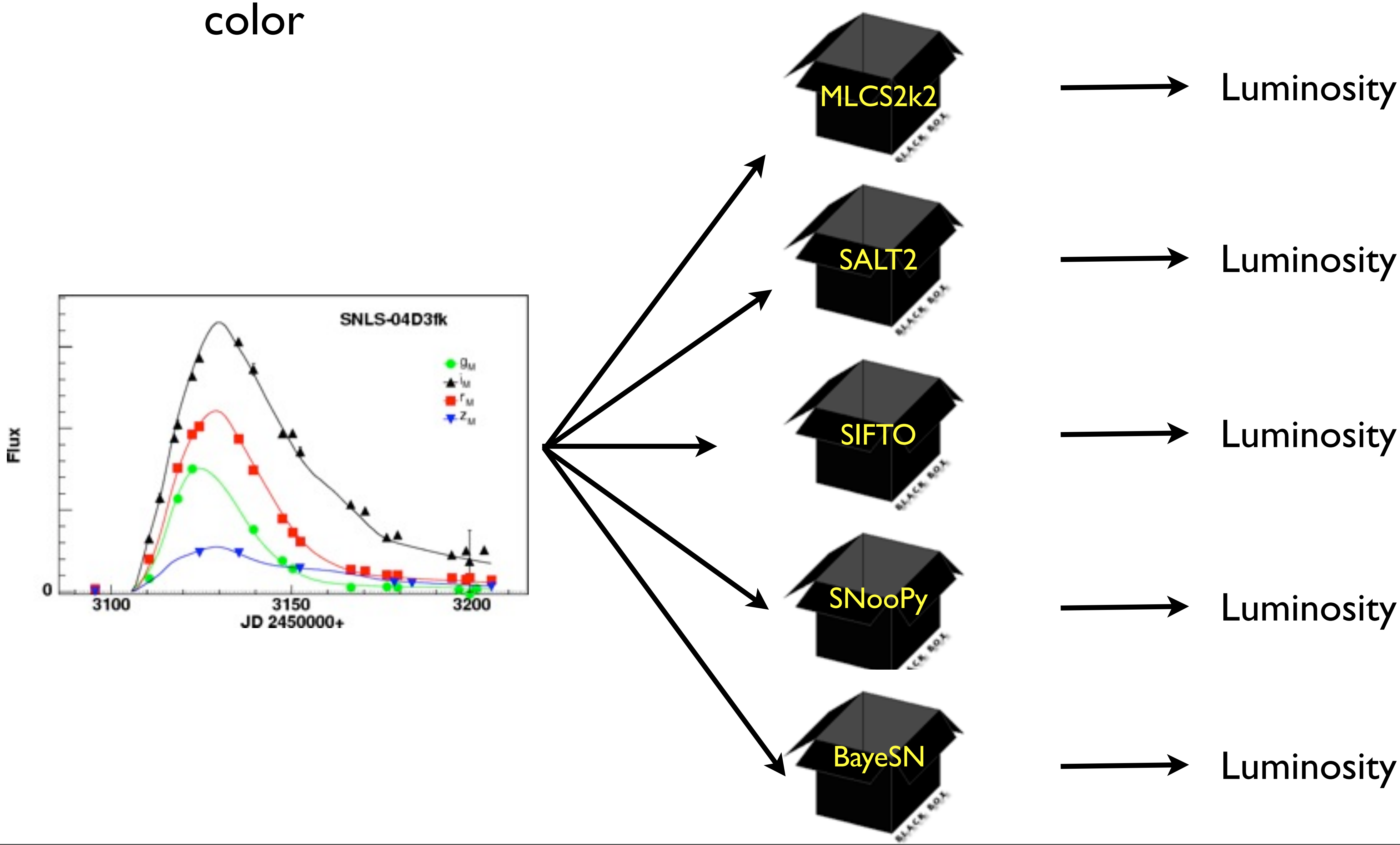
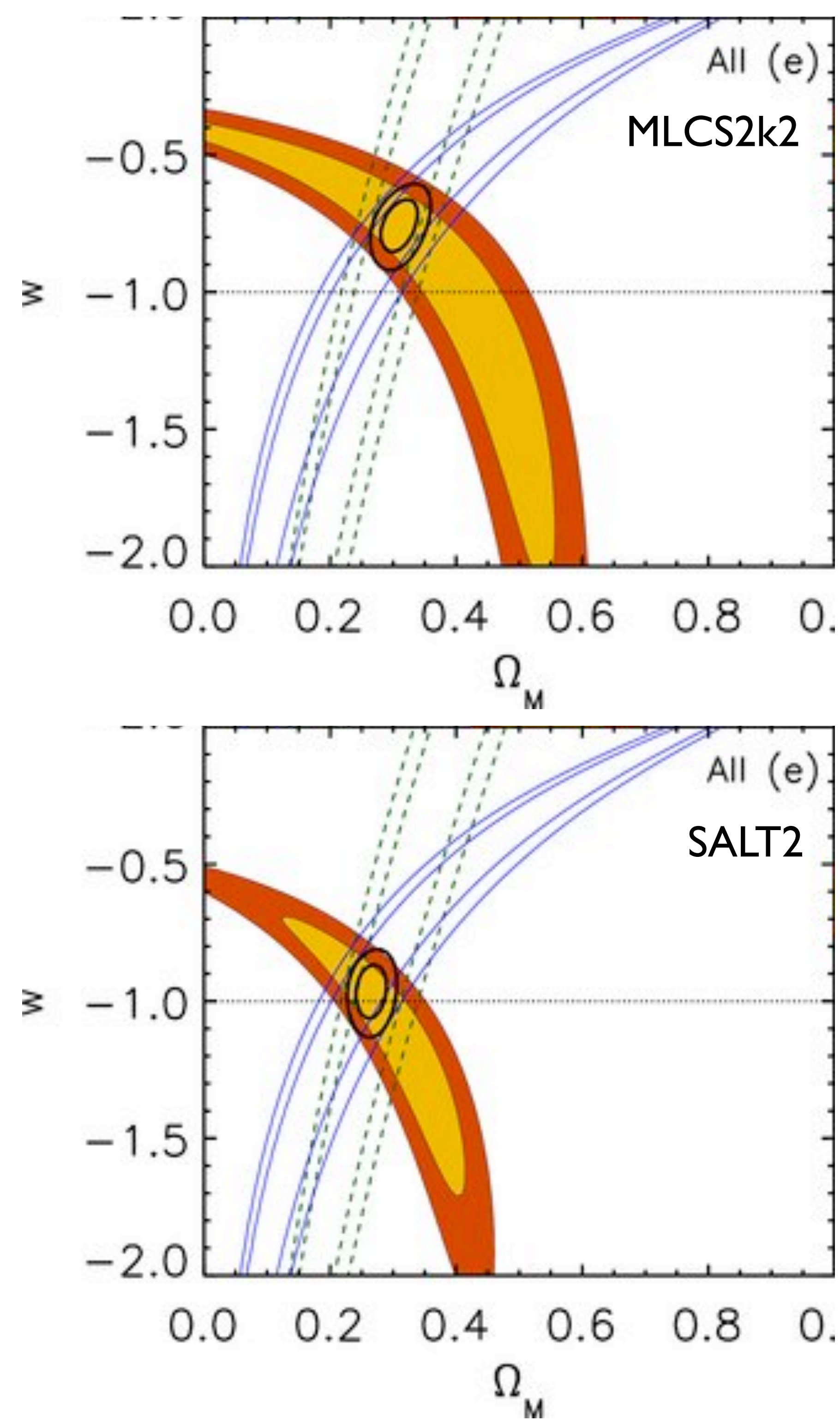


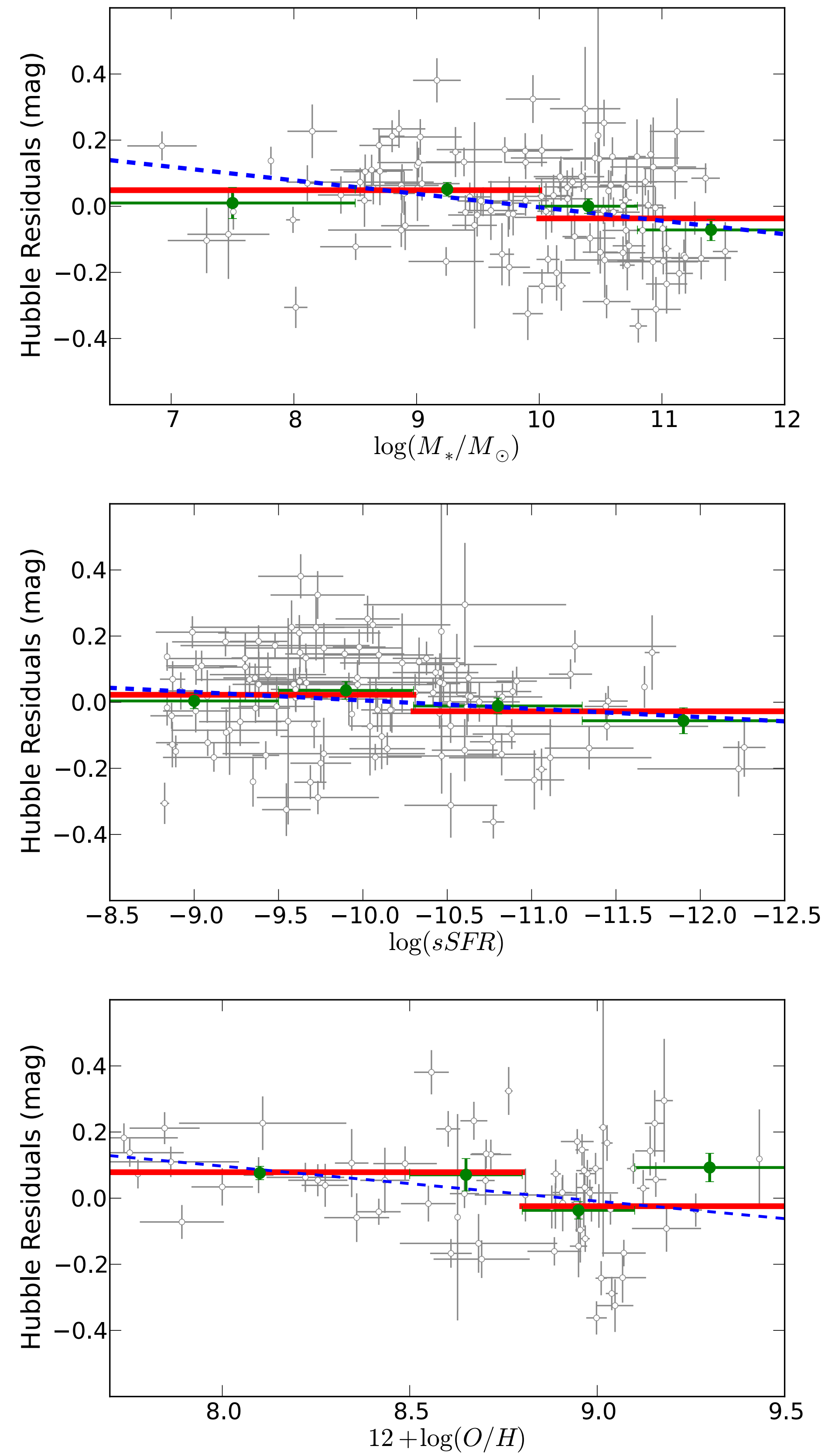
Our Ignorance of Supernovae: Systematic

- Bulk of high-quality SN measurements in optical wavelengths and near peak
  - SNe less well understood in UV and NIR, well before and well after peak brightness
- Issue manifest in discrepancy of distances from different light-curve fitters
  - Inconsistent U-band templates
  - Different interpretation of color
  - Different priors

Kessler et al. (2009)

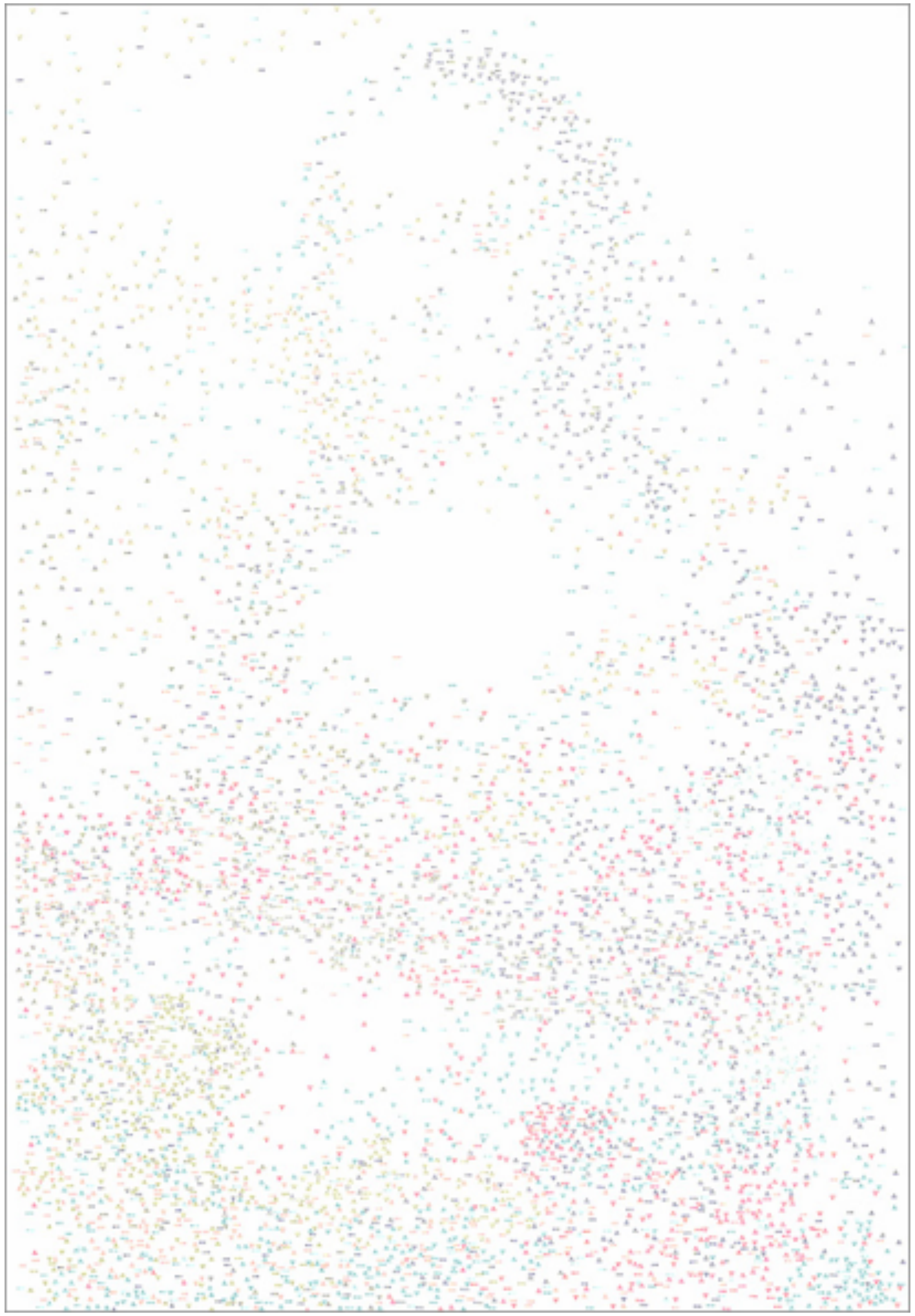


Host Galaxy Systematics



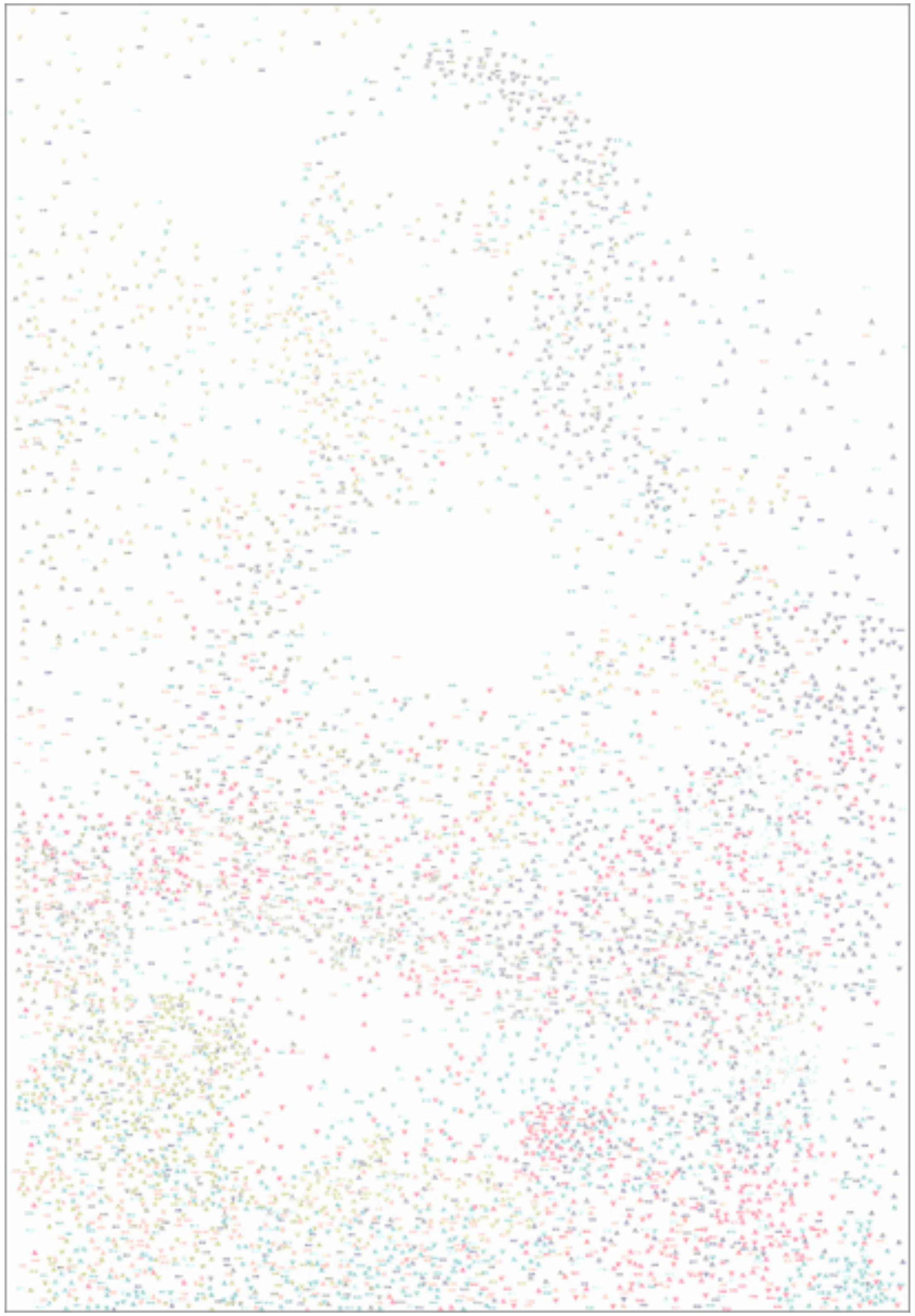
- Residuals in the supernova Hubble Diagram correlated with host-galaxy properties
- Supernova light-curve fitters do not fully capture supernova heterogeneity

Regression



Regression

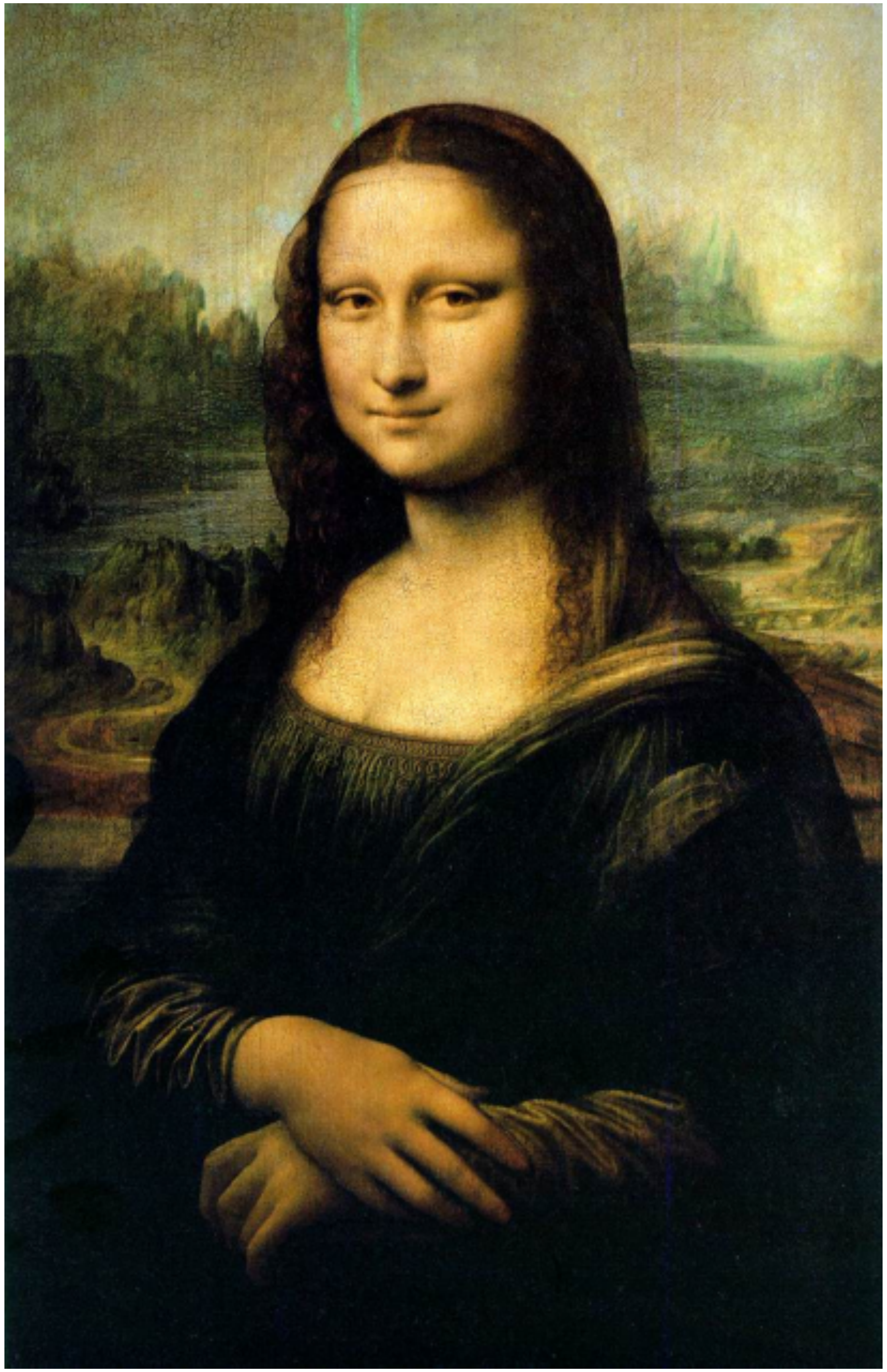
- Dots



Regression

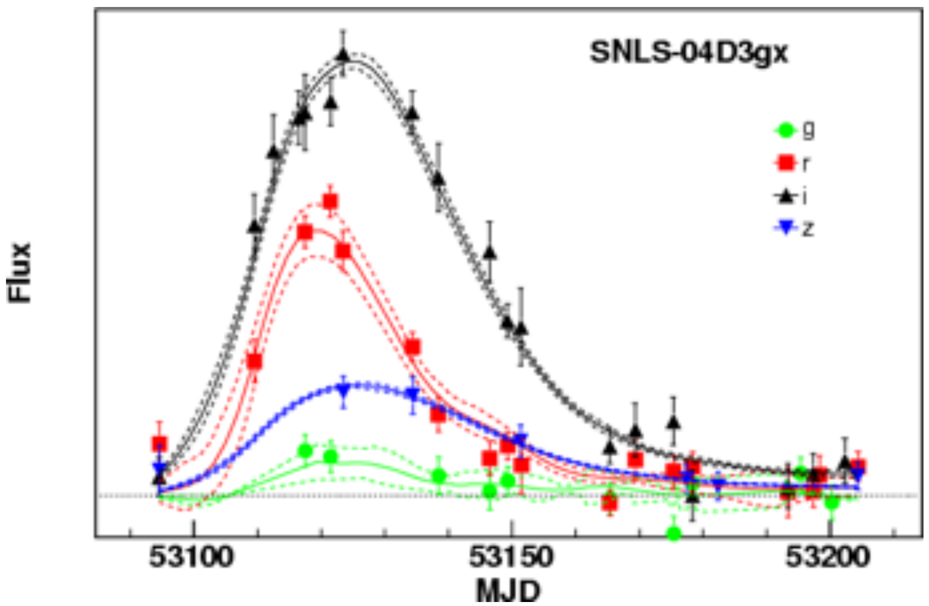
- Dots
- Connect the dots

Regression



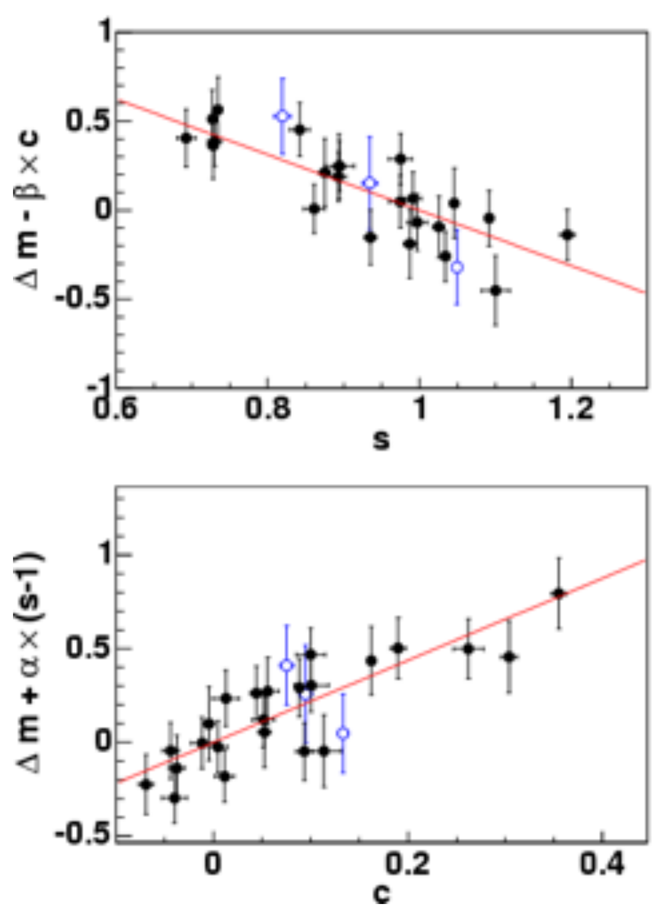
- Dots
- Connect the dots
- Fuzzy non-linear regression

Dots in SN Cosmology

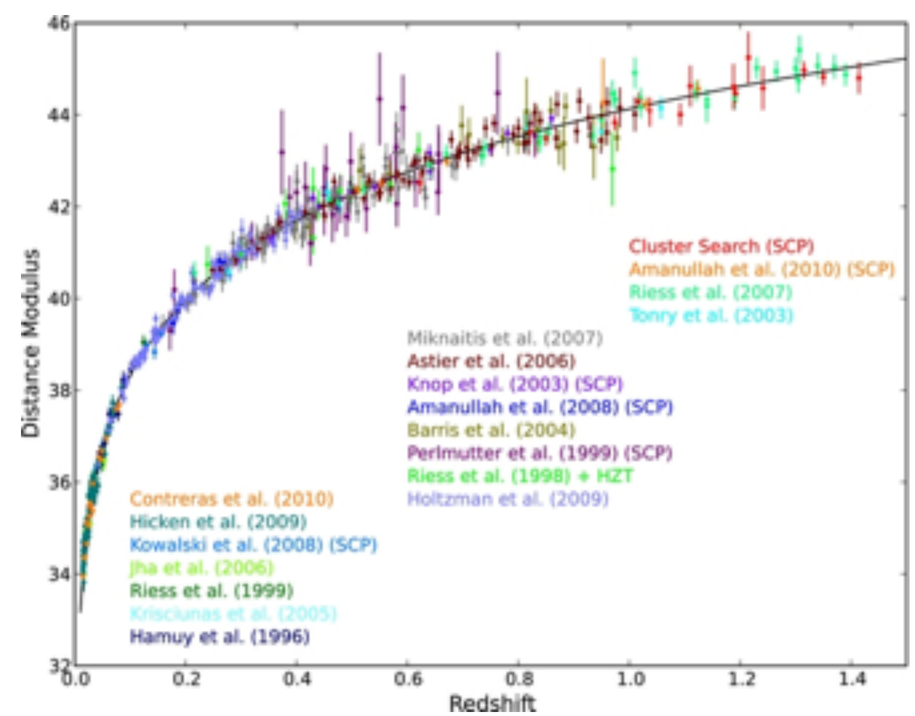


Photometry to light-curve parameters

- Fit data to models with a few parameters
  - Photometry to light-curve model (e.g. SALT2, MLCS)
  - Light-curve parameters to linear or quadratic absolute magnitude model
  - Hubble diagram to dark energy model

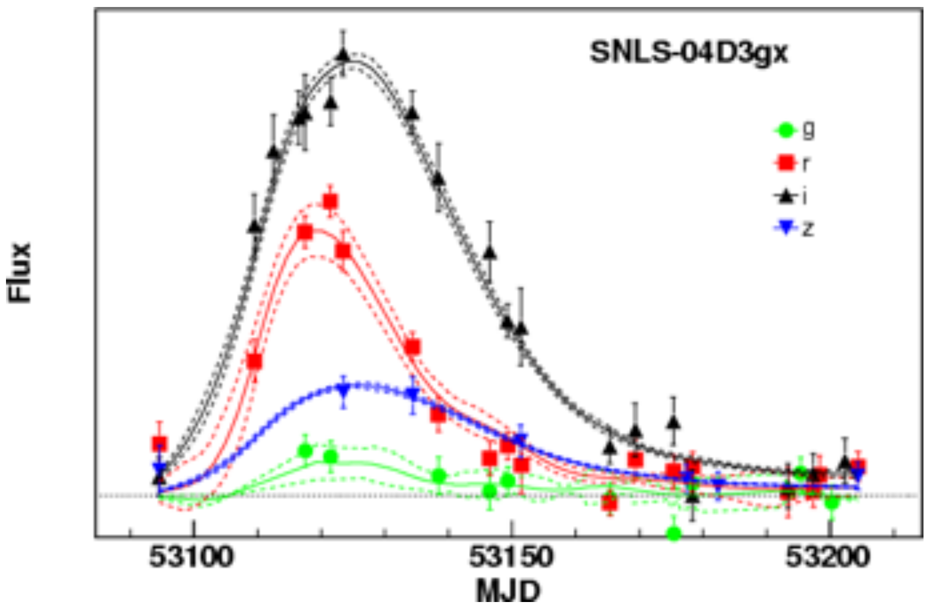


Light-curve parameters to absolute magnitude



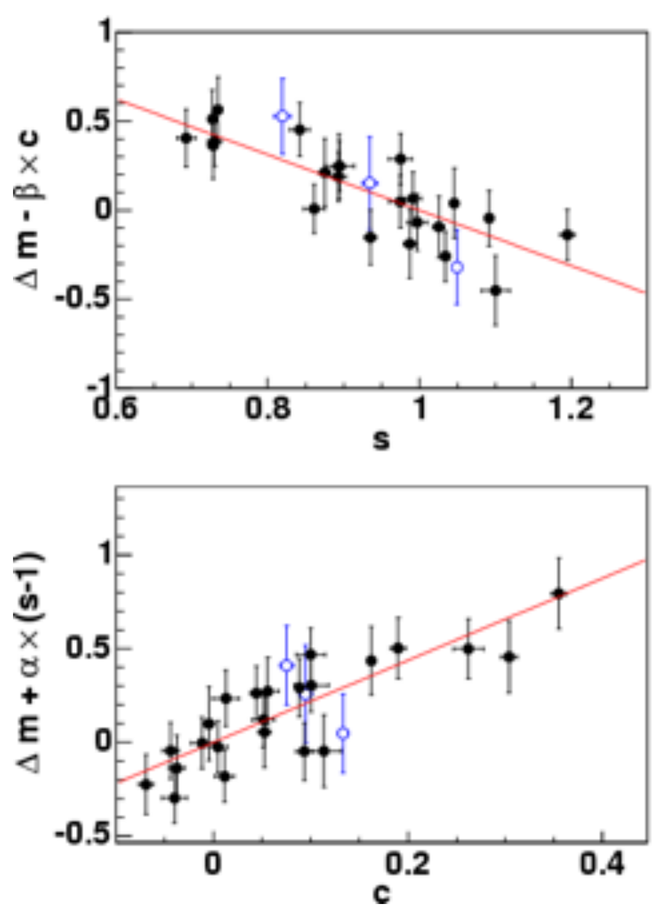
Hubble diagram to cosmological parameters

Dots in SN Cosmology

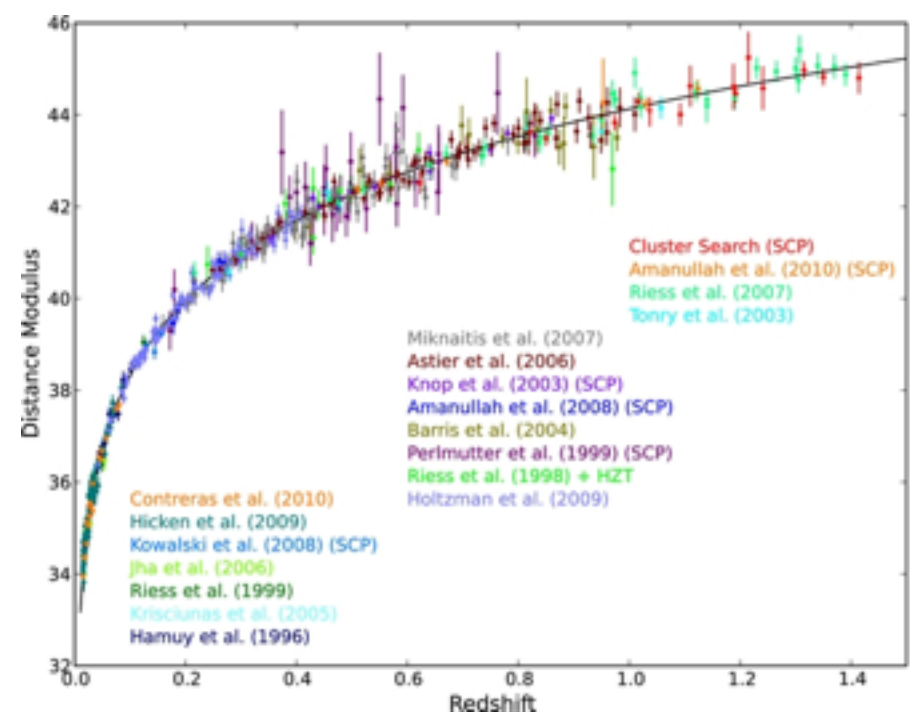


Photometry to light-curve parameters

- Regression gives model independent way to give more numbers to characterize data
  - More light-curve parameters to correlate with absolute magnitude
  - Non-linear relation between light-curve parameters and absolute magnitude
  - Kinematic measurement of H (Shafieloo, Kim, Linder 2012)



Light-curve parameters to absolute magnitude

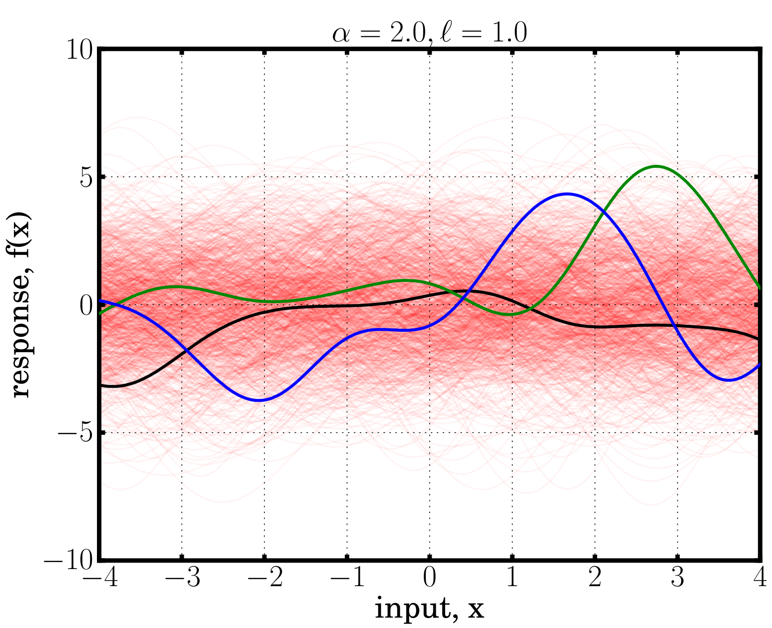
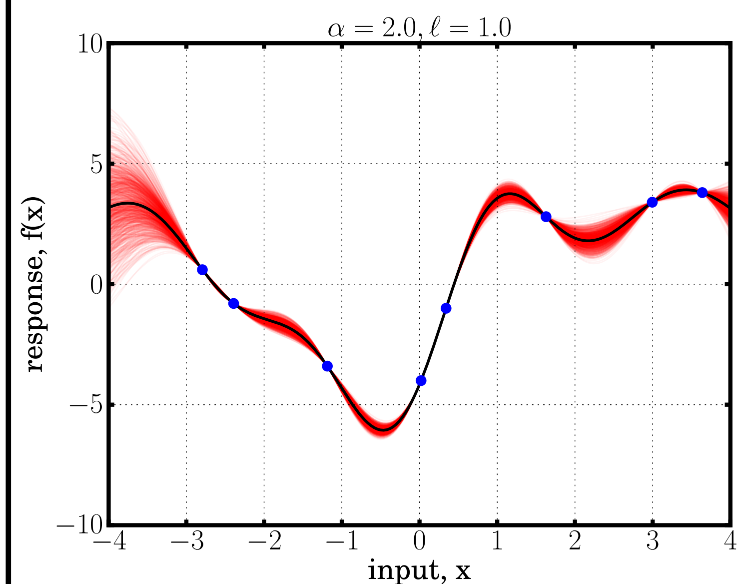
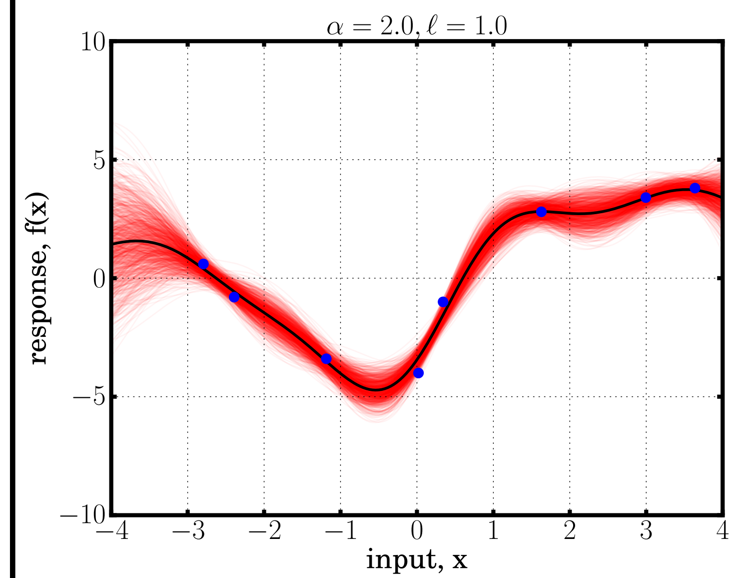


Hubble diagram to cosmological parameters

Gaussian Process

	No Observations	Noiseless Observations	Noisy Observations

Gaussian Process

	No Observations	Noiseless Observations	Noisy Observations
Model 1			

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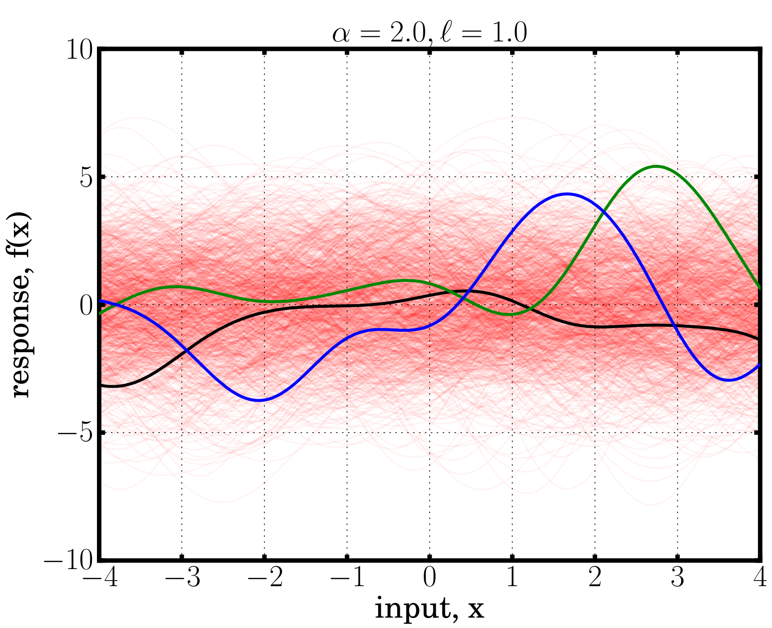
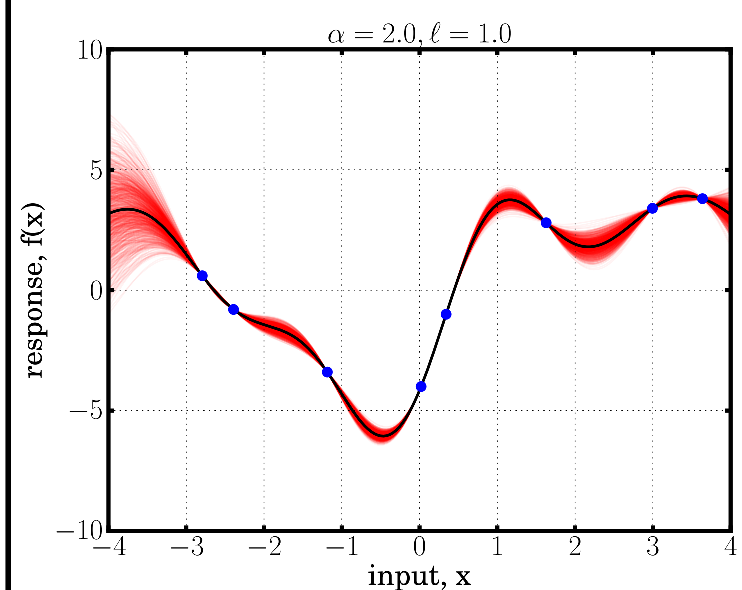
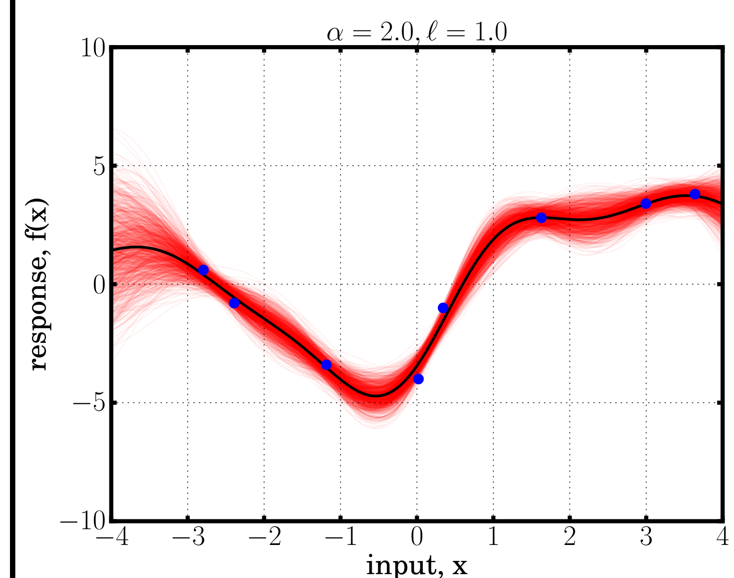
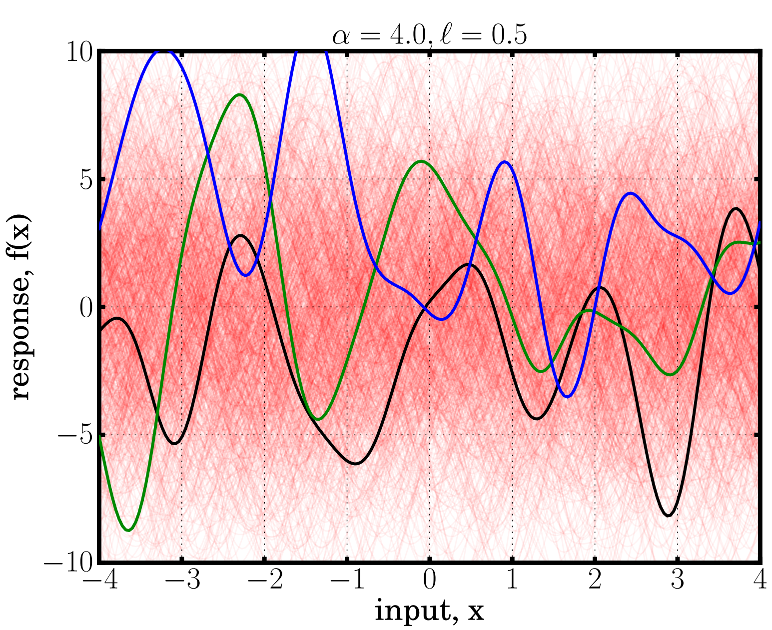
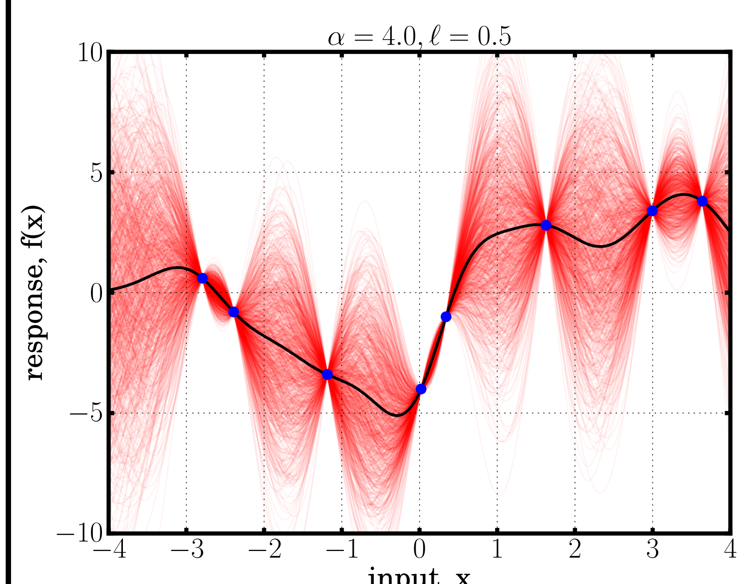
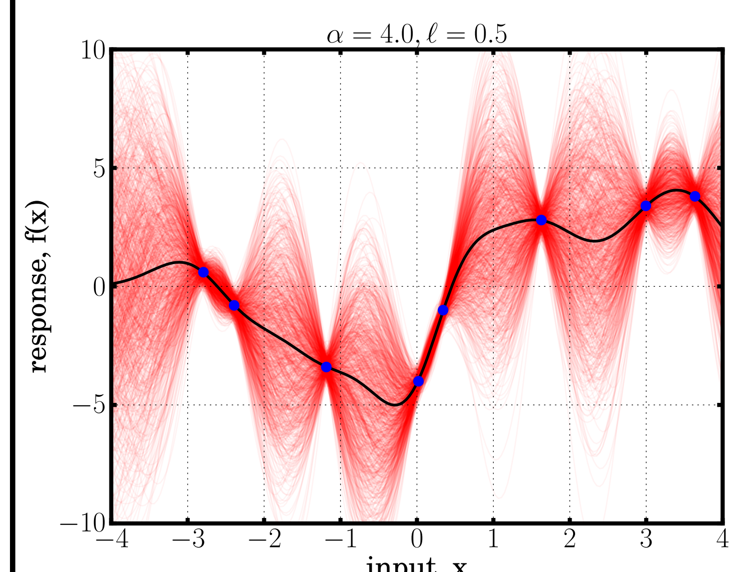
Model 1			
Model 2			

Gaussian Process Regression

A Gaussian process is notated as

Modeled through parameterized mean and kernel

$$f(\mathbf{x}) \sim GP(m(\mathbf{x}), k(\mathbf{x}, \mathbf{x}')). \quad (1)$$

For a set of input points $X_\star$, the values of the function are drawn from a Normal distribution

Values from a normal distribution

$$\mathbf{f}_\star \sim \mathcal{N}\left(m(X_\star), K(X_\star, X_\star)\right), \quad (2)$$

where the covariance matrix K has elements filled with all input pairs of $k(\mathbf{x}_{\star,i}, \mathbf{x}_{\star,j})$.

The likelihood that $\mathbf{y}$, a set of n measurements of f at inputs X, with measurement covariance V is written as

Likelihood data from this Gaussian process

$$\log p(\mathbf{y}|X) = -\frac{1}{2}(\mathbf{y} - m(X))^T (K+V)^{-1}(\mathbf{y} - m(X)) - \frac{1}{2}\log|K+V| - \frac{n}{2}\log 2\pi. \quad (3)$$

A set of measurements and function values is drawn from a Normal distribution

Data and regressed values from a normal distribution

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{f}_\star \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} m(X) \\ m(X_\star) \end{bmatrix}, \begin{bmatrix} K(X,X)+V & K(X,X_\star) \\ K(X_\star,X) & K(X_\star,X_\star) \end{bmatrix} \right). \quad (4)$$

The conditional distribution of the function values is Gaussian with expected mean

$$\bar{\mathbf{f}}_\star = m(X) + K(X_\star, X)\left[K(X,X)+V\right]^{-1}(\mathbf{y} - m(X)) \quad (5)$$

and covariance

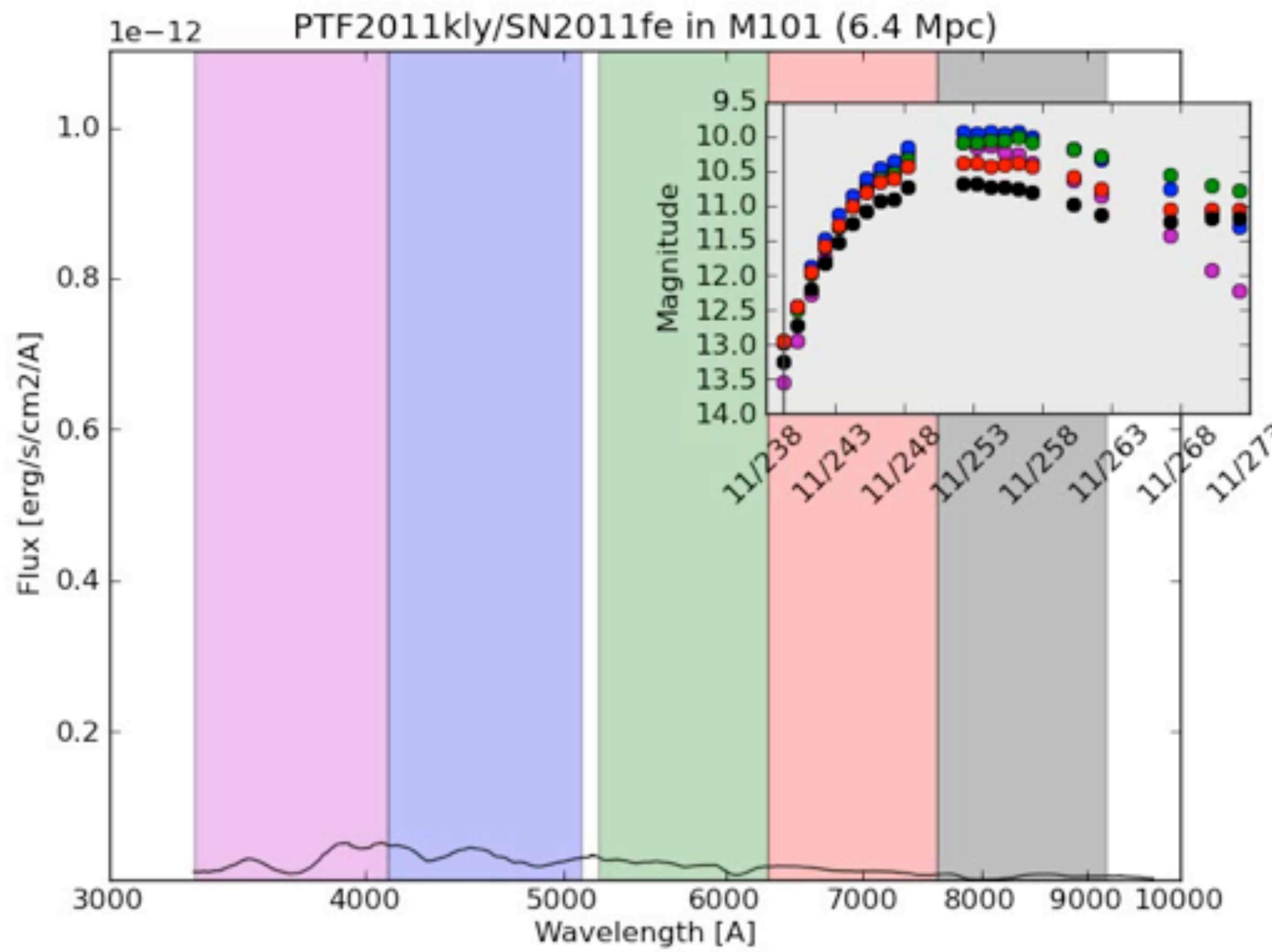
Regressed value PDF mean & covariance after marginalizing over data

$$\mathrm{cov}\left(\bar{\mathbf{f}}_\star\right) = K(X_\star, X_\star) - K(X_\star, X)\left[K(X,X)+V\right]^{-1} K(X, X_\star). \quad (6)$$

The Dots: Nearby Supernova Factory Data

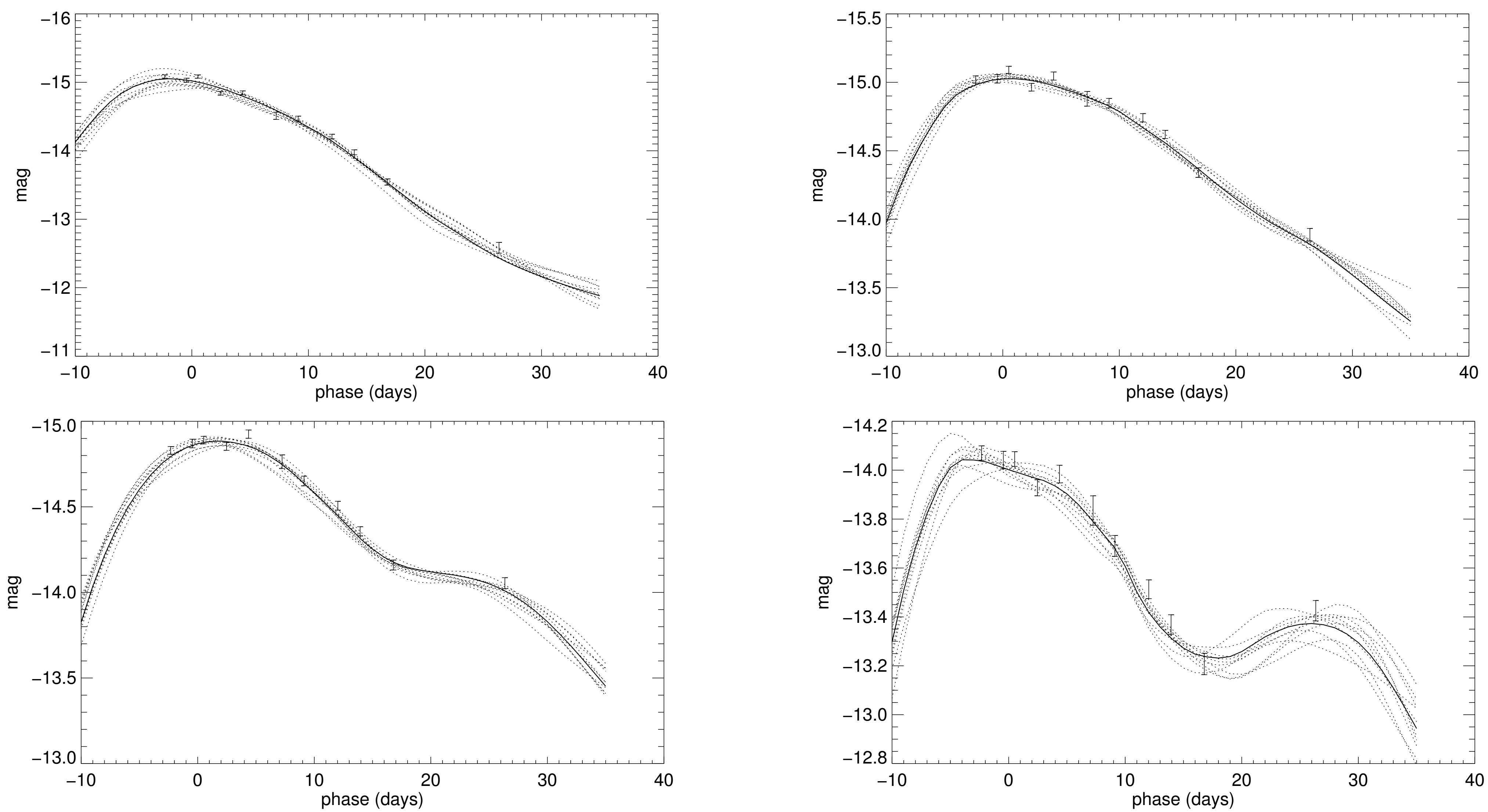
- >200 SNe Ia, 120 used in this analysis
- Spectrophotometric time series blueshifted and flux-normalized to be at a common distance
  - <z>~0.05 in linear Hubble flow
- Synthetic photometry in 4 different blueshifted DES griz filter sets
  - Supernova-frame fluxes of a high-z SN observed with DES griz

- Blueshifted z=0, gri
- Blueshifted z=0.25, griz
- Blueshifted z=0.5, riz
- Blueshifted z=0.75, riz



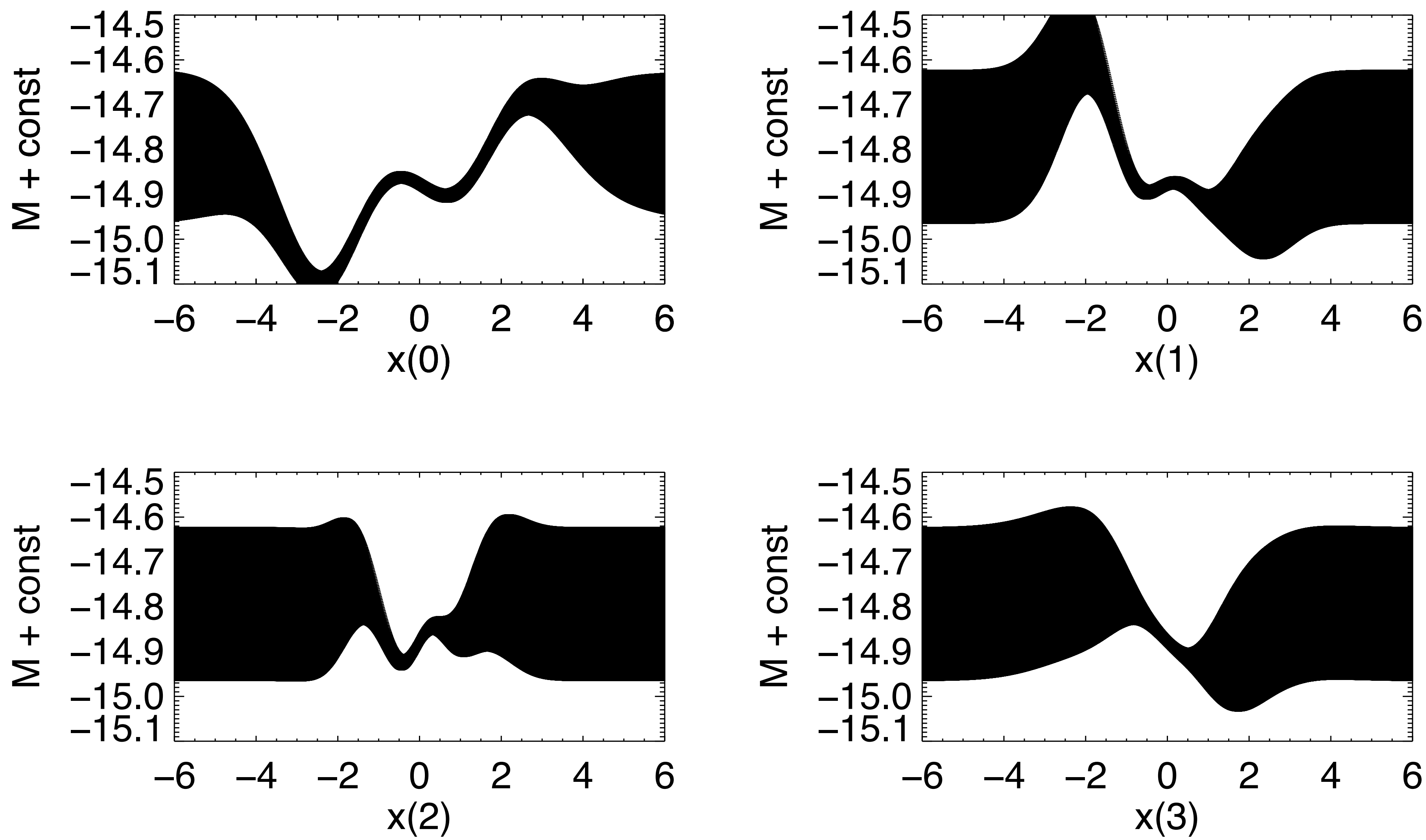
Light Curve Modeled as a GP and Regressed

- Light curves m(band, phase) modeled as a GP
- Best-fit GP model used to regress light curves in each band from -10 to 35 days after peak in 1-day intervals



Absolute Magnitude Modeled as a GP Function of Light Curve Shape and Color

- Absolute magnitude at B-peak as a function of light-curve parameters M({x(i)}) modeled as a different GP
- Best-fit GP model used to regress absolute magnitudes



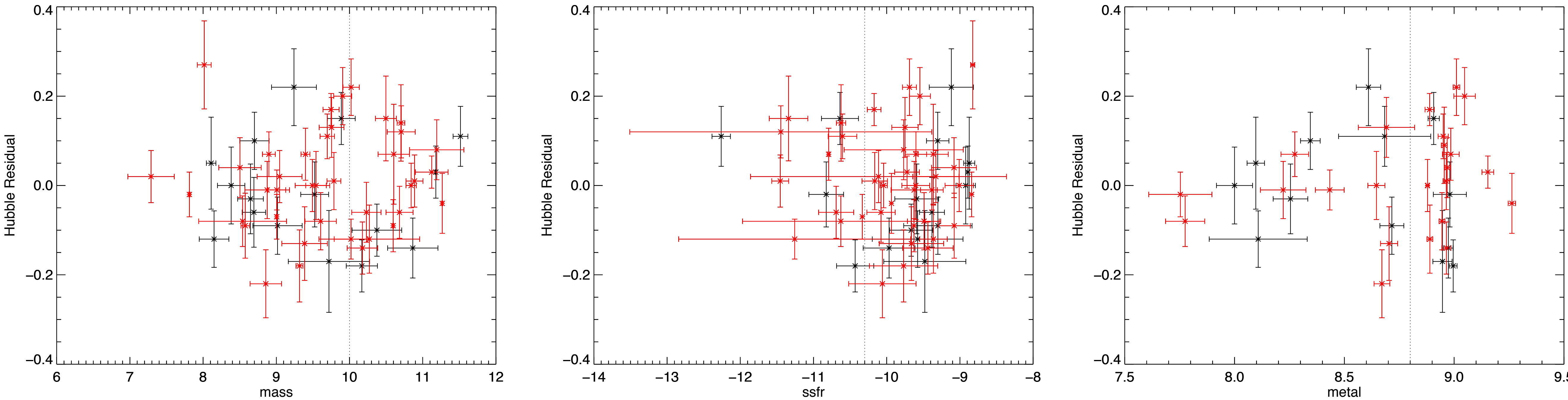
Accuracy of Absolute Magnitude Calibration

Observed Dispersion	0.236 mag
Dispersion Around Predictions	0.100±0.009 mag
Intrinsic Dispersion	0.061±0.014 mag

Comparison with Mandel et al. (2011)

	This Work	Mandel Optical	Mandel Optical + NIR
Apparent Error	0.026	0.14	0.10
Bootstrap	0.135	0.15	0.15
.632 Estimator	0.085	0.16	0.11
Intrinsic Dispersion	0.06	0.13	0.08

Hubble Residuals vs Host-Galaxy Properties

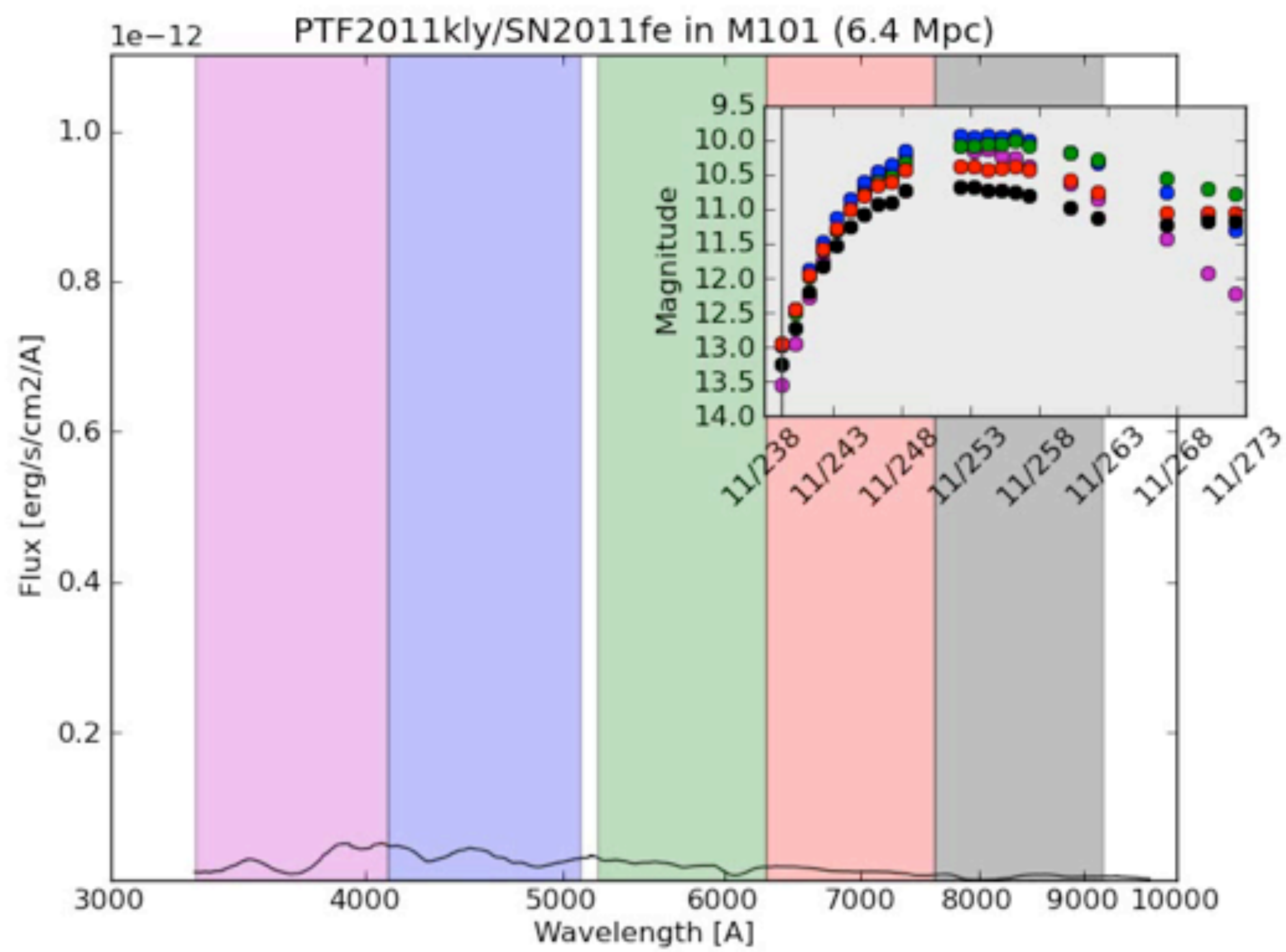


Childress et al. (in prep)
Kim et al. (in prep)

	$\log\left(M/M_{\odot}\right)$		$\log\left(sSFR\right)$		$12+\log\left(O/H\right)$	
Method	offset (mag)	slope (mag dex^{-1})	offset (mag)	slope (mag dex^{-1})	offset (mag)	slope (mag dex^{-1})
GP cut	-0.003 ± 0.031	-0.003 ± 0.016	0.019 ± 0.033	-0.008 ± 0.023	-0.005 ± 0.039	0.017 ± 0.051
SALT2 all	0.086 ± 0.028	-0.043 ± 0.014	-0.050 ± 0.029	0.030 ± 0.017	0.100 ± 0.036	-0.106 ± 0.044

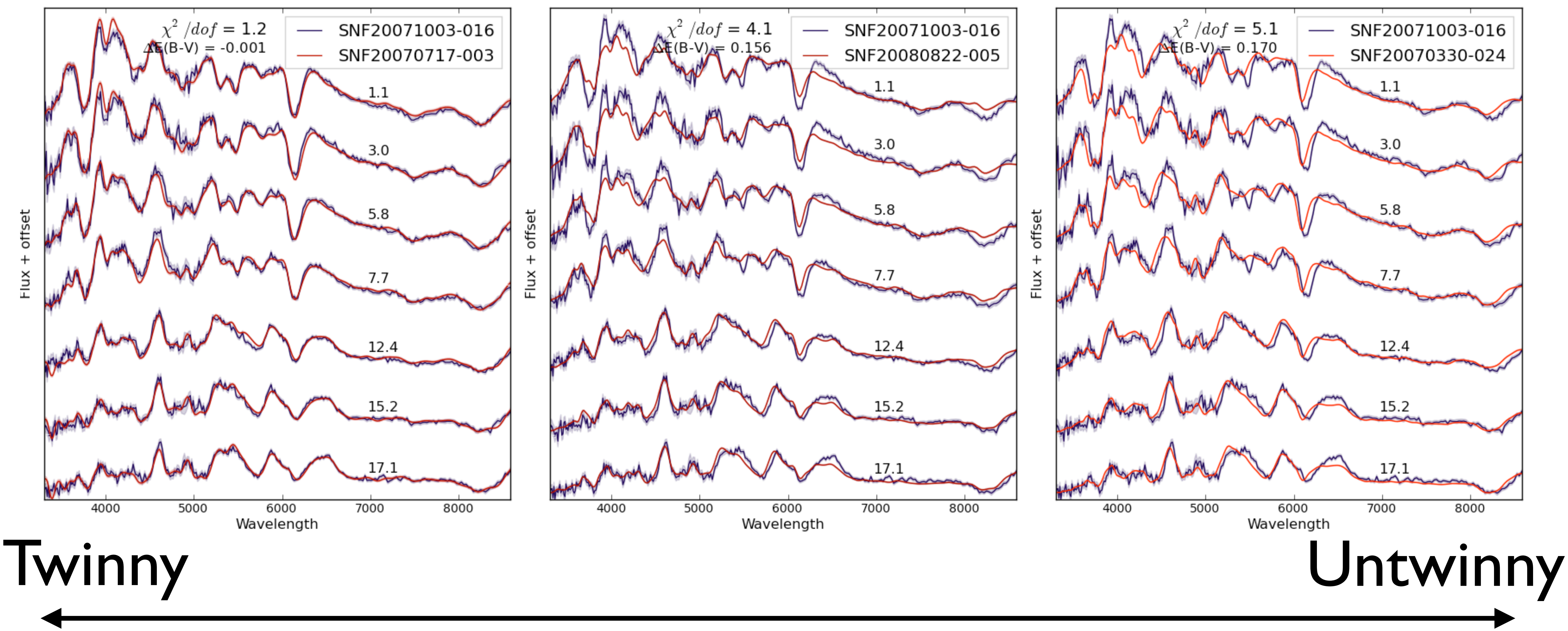
Regressing Spectral Time Series

- SNfactory data does not have uniform data coverage
- Gaussian process used to interpolate spectra in time



Compare Time Series of Different Supernova

- SNe Ia exhibit heterogeneity in their spectra
- Regress to put different SNe on a common time grid
- Compare similarity of spectral time series



- Expect twin supernovae to have the same luminosity

Standard Cosmology and the Accelerating Universe

$$\eta = \int \frac{dt}{a}$$ Conformal time

$$ds^2 = a^2(t)(-d\eta^2 + dr^2 + r^2 d\Omega)$$ Flat universe metric

$$d_L(a) = a^{-1}\eta(a)$$ Luminosity distance

$$H^{-1}(z) \equiv \left(\frac{\dot{a}}{a}\right)^{-1} = \frac{d\eta}{dz}$$ Hubble parameter

$$q(z) \equiv -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{1+z}{H^{-1}}\frac{dH^{-1}}{dz} - 1$$ Deceleration parameter

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Adding General Relativity gives a dynamic inference of an accelerating universe

$$H^2(z) = \Omega_M(1+z)^3 + \Omega_\Lambda$$

$$q_0 \equiv q(0) = \frac{\Omega_M}{2} - \Omega_\Lambda = -0.59$$

Standard Cosmology and the Accelerating Universe

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Can we use supernova data directly to measure deceleration kinematically?

Gaussian Process Regression of Derivatives

- Gaussian process provides a mechanism for regressing derivatives from data

The data can be thought to come from a function that is modeled as Gaussian process, notated as

$$f(\mathbf{x}) \sim GP(m_f(\mathbf{x}), k_f(\mathbf{x}, \mathbf{x}'))). \tag{1}$$

A set of measurements, function values, and function derivative values is drawn from a Normal distribution

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{f}'_\star \\ \mathbf{f}''_\star \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} m_f(X) \\ m'_f(X_\star) \\ m''_f(X_\star) \end{bmatrix}, \begin{bmatrix} \Sigma_{00}(X,X)+V & \Sigma_{01}(X,X_\star) & \Sigma_{02}(X,X_\star) \\ \Sigma_{10}(X_\star,X) & \Sigma_{11}(X_\star,X_\star) & \Sigma_{12}(X_\star,X_\star) \\ \Sigma_{20}(X_\star,X) & \Sigma_{21}(X_\star,X_\star) & \Sigma_{2}(X_\star,X_\star) \end{bmatrix} \right), \tag{2}$$

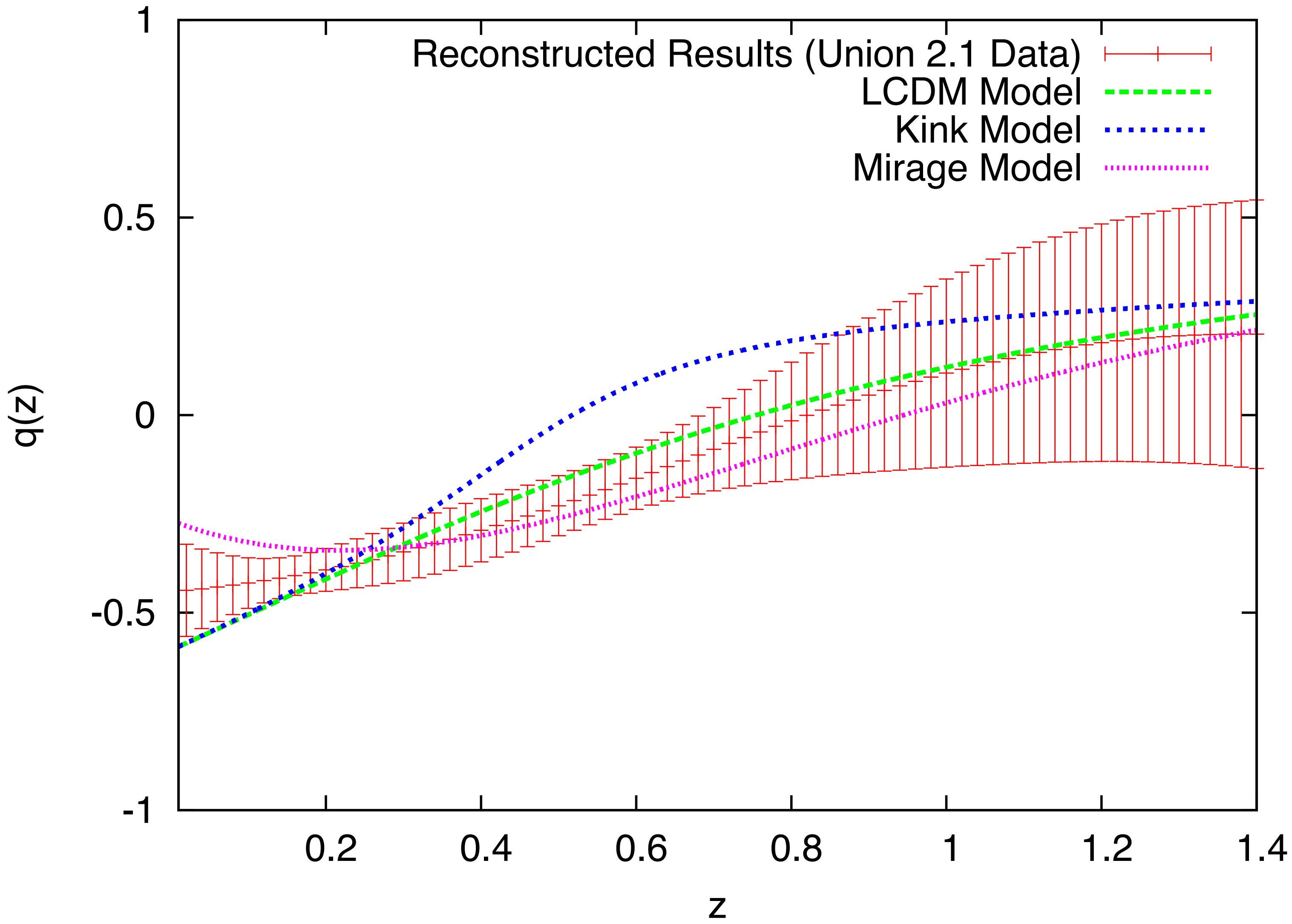
where

$$\Sigma_{\alpha\beta} = \frac{\partial^{(\alpha+\beta)} k_f}{\partial x^\alpha \partial x'^\beta}. \tag{3}$$

Data, regressed derivative values from a normal distribution

Accelerating Universe

- Assume the covariance in Δz is greater than data sampling
- Union2 supernova dataset



Conclusions

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- Many upcoming experiments
- Limiting uncertainties are reduced with better experiments and analysis
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