Hierarchical Bayesian Models for SN Ia in the Optical and NIR

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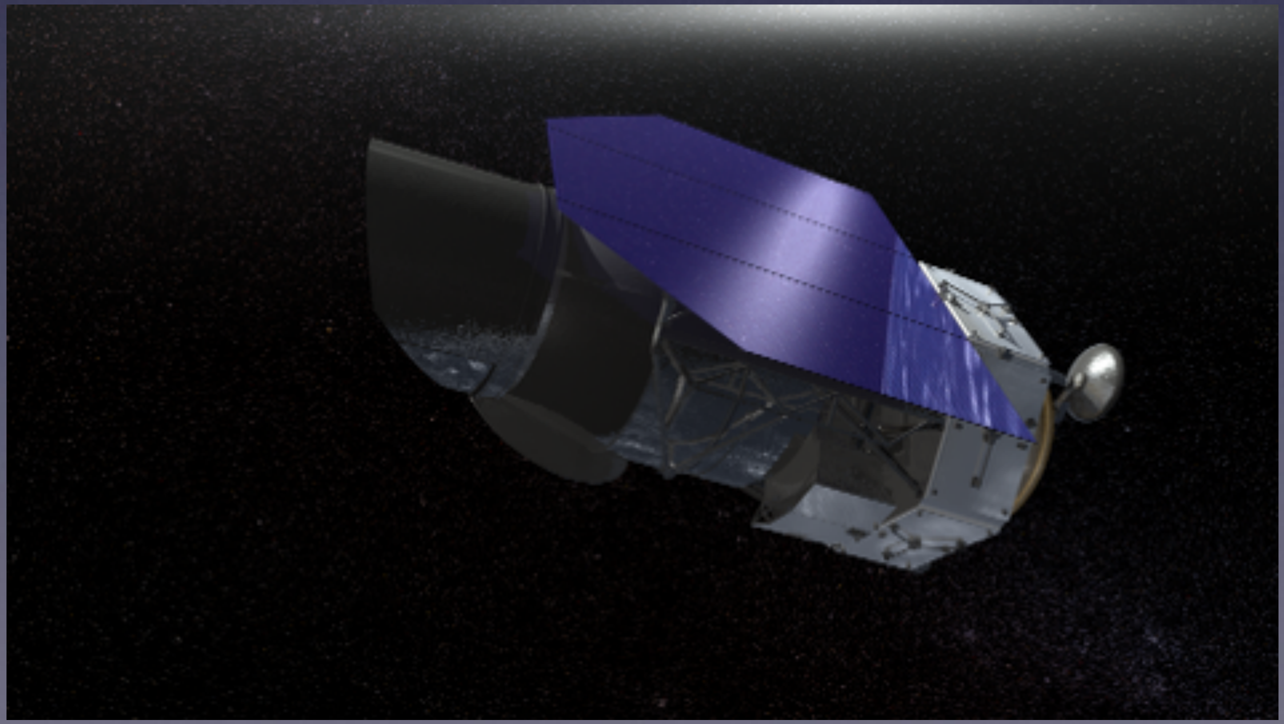


SN Ia NIR Meeting
U. Pittsburgh
12 April 2018

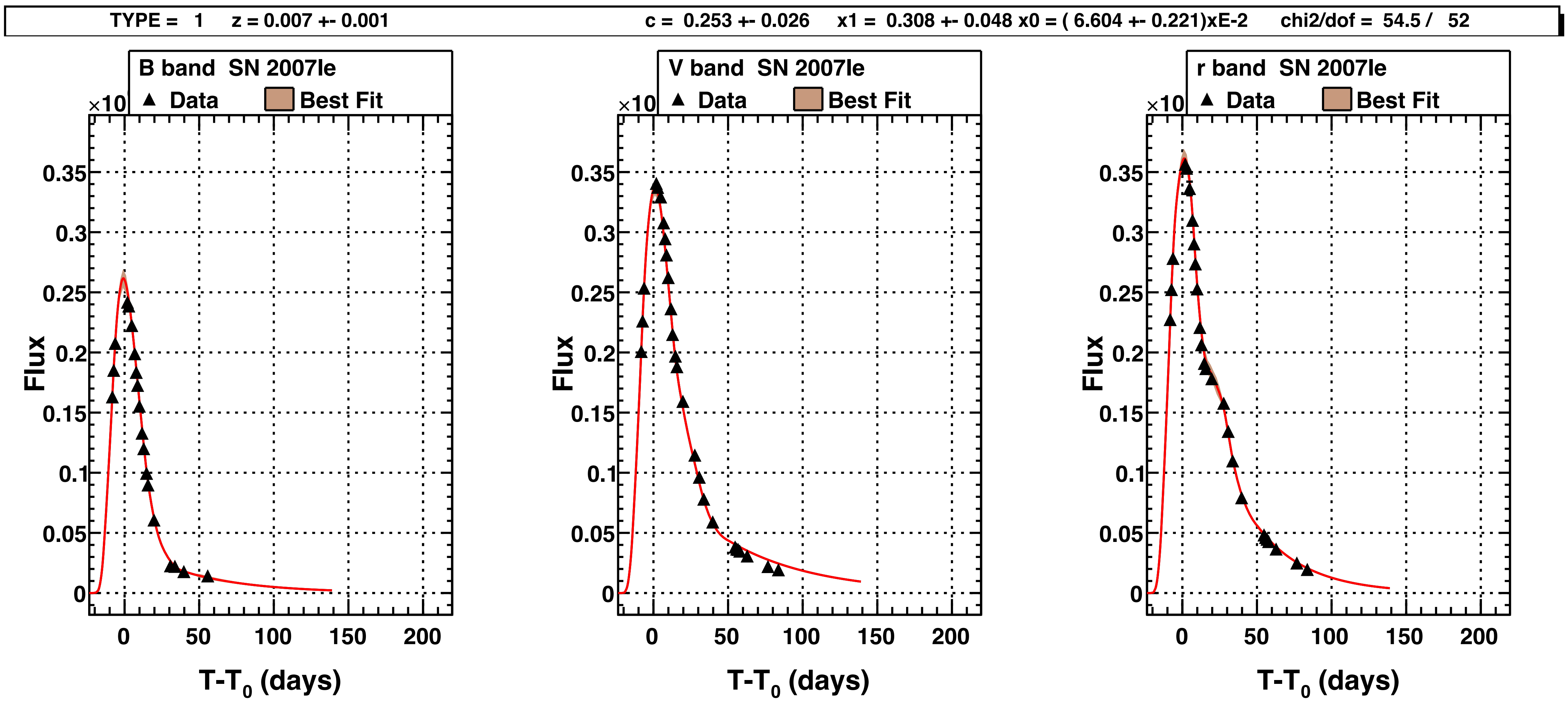
Outline

- Simple-BayeSN:
  (Mandel, Scolnic, Shariff, Foley & Kirshner 2017)
  - A statistical model for the SN Ia colour-magnitude relation (with intrinsic variation and dust effects)
  - Implications for Optical and NIR
- BayeSN Optical+NIR LC model (Mandel et al. 2011)

Current State of Play

- Current optical surveys are now limited by systematic uncertainties, e.g. photometric calibration error and modeling error, rather than “statistical” (number of supernovae).
- Conventional analysis method (SALT2) does not distinguish between different physical effects of intrinsic SN variations and extrinsic host galaxy dust extinction/reddening
- Scolnic et al. 2014 : a different colour/mag modeling interpretation of the Hubble Diagram scatter results in a 4% systematic shift in w
- Confounding of host galaxy dust extinction/reddening with intrinsic SN Ia optical color variations systematically limits the accuracy and precision of SN Ia distances & cosmological constraints

Conventional Approach



- SALT2 continuous light curve model fit to irregularly samples, noisy optical data (SN2007le, BVR, CfA4)
- Estimates peak apparent magnitude m_B, peak apparent color c = (B-V), and light curve shape x

Conventional Tripp Formula

$$\text{Abs Mag} = m_B - \mu = M_0 + \alpha \cdot x + \beta \cdot c$$

- A Simplistic Linear Model for Absolute Magnitude with width-luminosity (α) and color-luminosity trends (β)
- Typically find β ≈ [ΔMag in B / ΔColor B-V] ≈ 3
  Unusually low β compared to normal MW interstellar dust c.f. $R_B \approx 4.1$ ($R_V = R_B - 1 \approx 3.1$).
- Problem: Regresses dust-extinguished magnitude M_s^{ext} vs dust-reddened apparent color c_s^{app}

  $$m_B^s - \mu_s = M_s^{\text{ext}} = M_0^{\text{ext}} + \alpha \cdot x_s + \beta \cdot c_s^{\text{app}}$$

- Does not distinguish between intrinsic SN Ia variations and host galaxy dust (only one β for all color-mag effects)
- Realistically, SN Ia magnitudes and colors contain both intrinsic SN Ia variations and host galaxy dust effects

  $$M_s^{\text{ext}} = M_s^{\text{int}} + A_B^s \qquad c_s^{\text{app}} = c_s^{\text{int}} + E(B-V)_s$$

Problem with Conventional Tripp Formula

$$m_B^s - \mu_s = M_s^{\text{ext}} = M_0^{\text{ext}} + \alpha \cdot x_s + \beta \cdot c_s^{\text{app}}$$

Intrinsic $\quad M_s^{\text{int}} \leftarrow \beta_{\text{int}} \rightarrow c_s^{\text{int}}$

Dust $\quad A_B^s \rightarrow R_B \leftarrow E(B-V)_s$

Two Color-Mag effects (intrinsic β_{int}, dust R_B), one β Slope parameter!

Words (and Notation) Matter!

"Intrinsic" : Latent parameters of SN in absence of host galaxy dust

- Intrinsic Abs. Mag: M_s^{int}
- Intrinsic Color: c_s^{int}

Effects of Host Galaxy Dust for each SN (only positive!)

- Reddening $E_s \equiv E(B-V)_s$
- Extinction (dimming) $A_B^s = R_B \times E(B-V)_s$

"Dusty" : Latent parameters of SN including effects of host galaxy dust

- Extinguished Abs. Mag $M_s^{\text{ext}} = M_s^{\text{int}} + A_B^s$
- Apparent Color $c_s^{\text{app}} = c_s^{\text{int}} + E(B-V)_s$

Two Physically distinct correlations cannot be captured with one β color-mag relation!

$$M_s^{\text{int}} \sim c_s^{\text{int}}$$
$$A_B^s \sim E(B-V)_s$$

What about the host galaxy dust?

Dust Absorption vs. Wavelength of Light

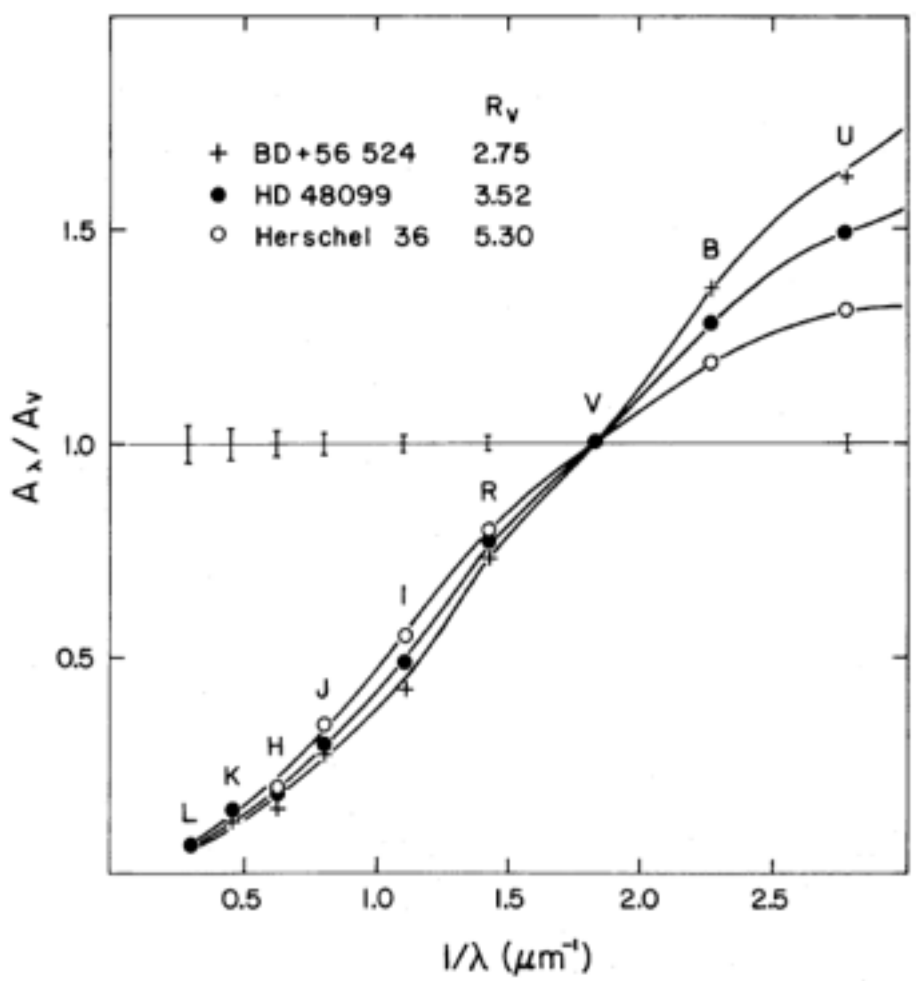
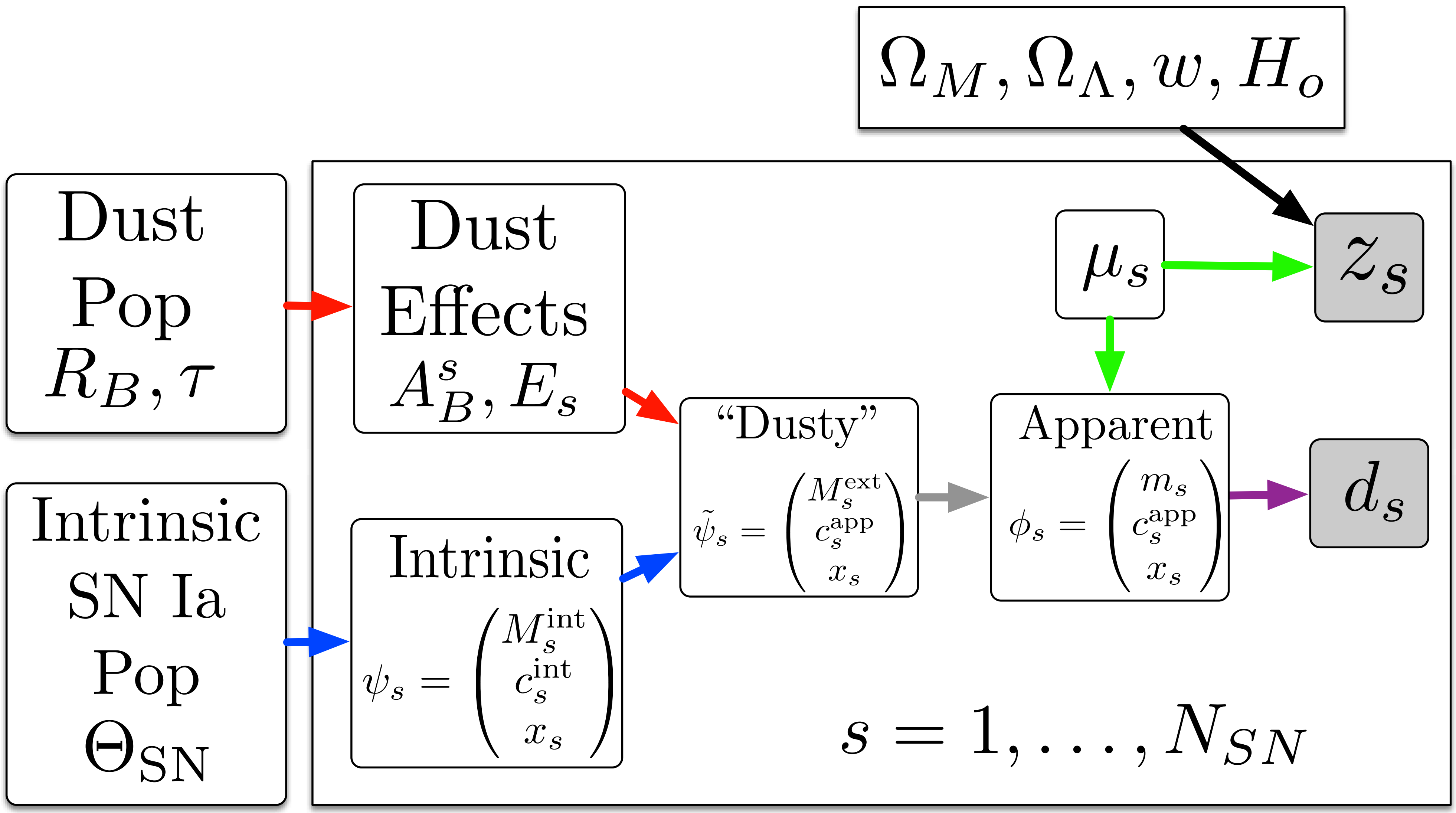


FIG. 3.—Comparison between the mean optical/NIR R_V-dependent extinction law from eqs. (2) and (3) and three lines of sight with largely separated R_V values. The wavelength position of the various broad-band filters from which the data were obtained are labeled (see Table 3). The "error" bars represent the computed standard deviation of the data about the best fit of $A(\lambda)/A(V)$ vs. R_V^{-1} with $a(x) + b(x)/R_V$ where $x \equiv \lambda^{-1}$. The effect of varying R_V on the shape of the extinction curves is quite apparent, particularly at the shorter wavelengths.

- Absorption of light (dimming) depends on λ, causing reddening
- Interstellar lines of sight to SN in different galaxies can pass through different random amounts of dust
- Key Parameters of Interstellar Dust (different for each SN)
  - A_B ~ Amount of Dust Absorption (dimming)
  - $R_B = A_B/E(B-V)$ ~ Wavelength Dependence of Dust Absorption
- Don't really know a priori which SN are unaffected by dust; must model probabilistically

My Approach (Mandel+09,11,14,17):

Hierarchical Bayesian / Probabilistic Generative Model



Observed SN Ia Data = Sum of latent random effects:

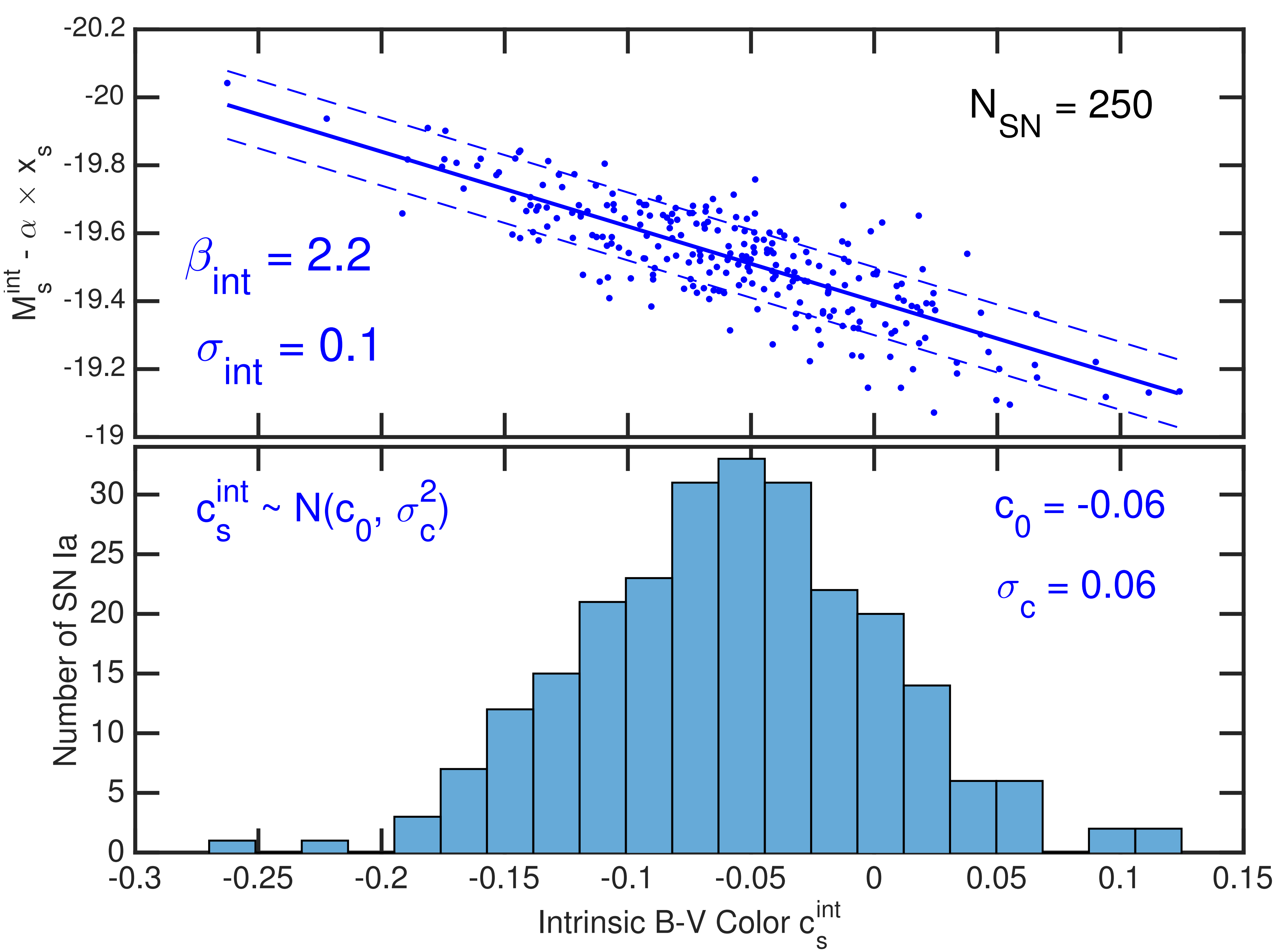
intrinsic variation, dust, measurement error

(Simple-BayeSN)

Understanding the Probabilistic Generative Model via Forward Simulation

Intrinsic Color-Luminosity Variations

Intrinsic Absolute Mag



Intrinsic Color

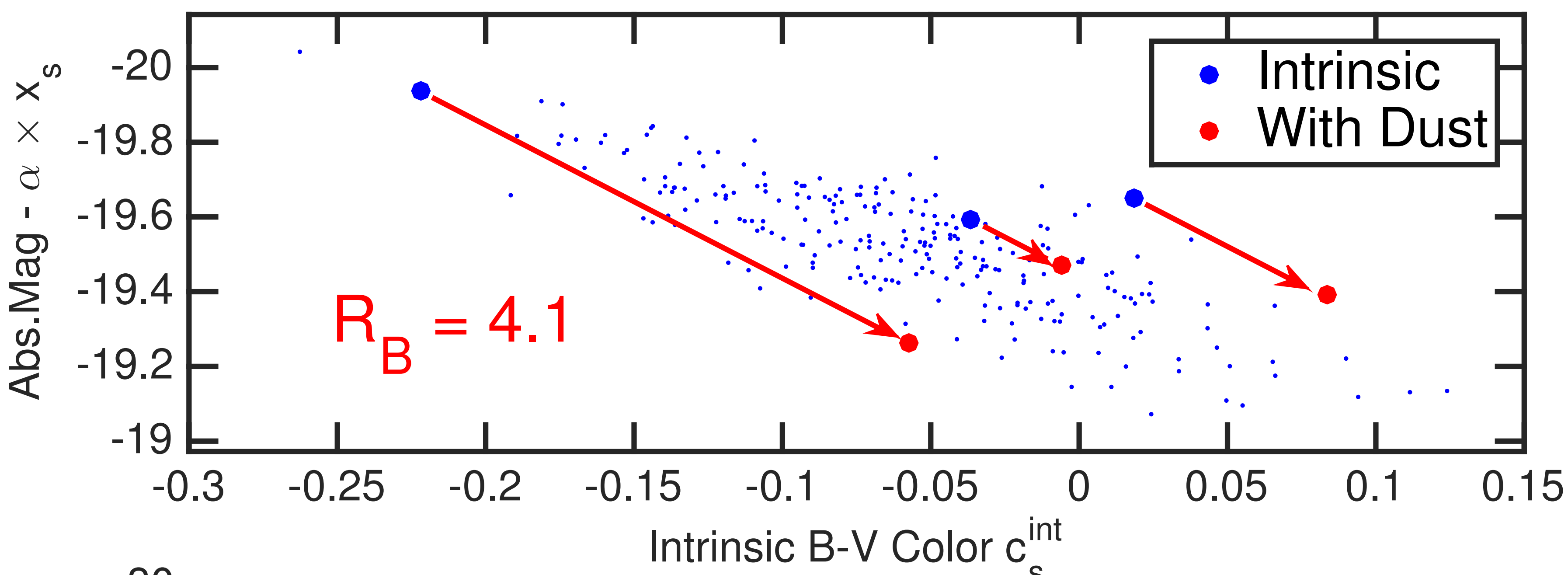
Host Galaxy Dust Effects:

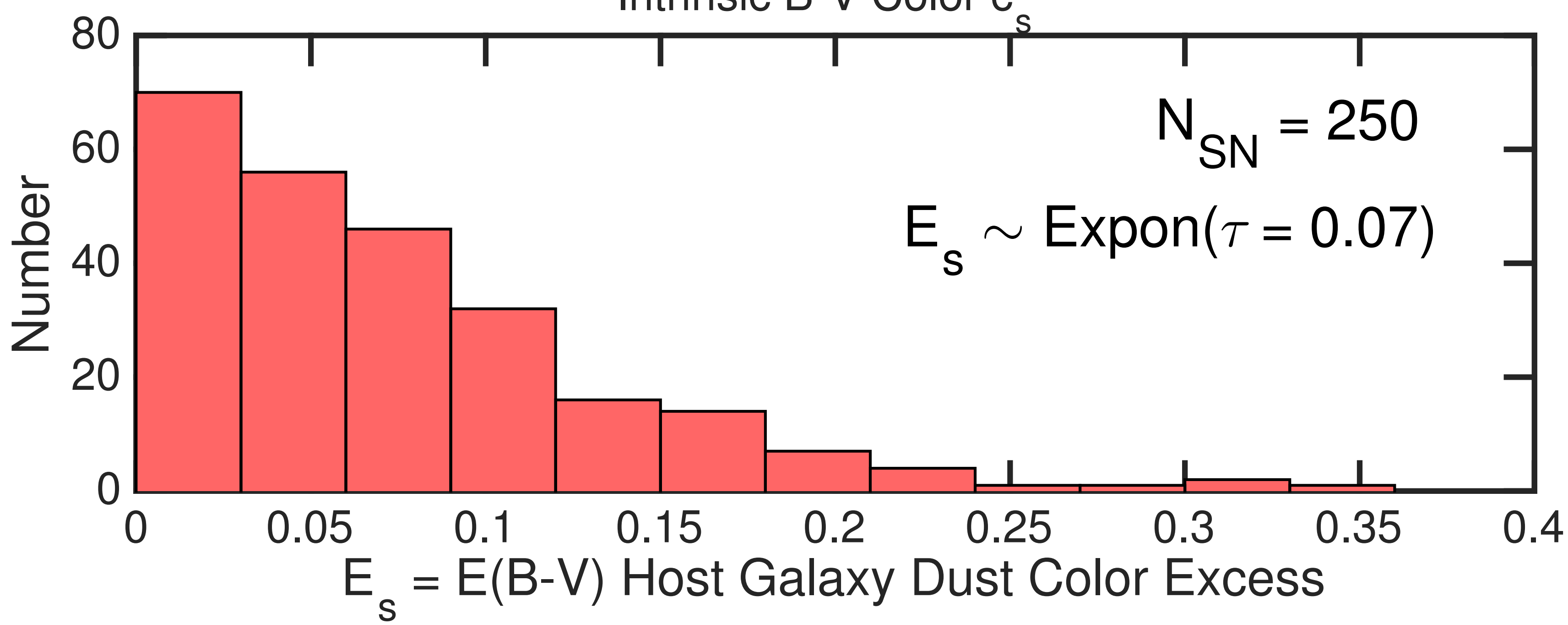
Reddening: $c_s^{\text{app}} = c_s^{\text{int}} + E(B-V)_s$

Extinction: $M_s^{\text{ext}} = M_s^{\text{int}} + A_B^s$

Dust Law: $R_B = R_V + 1 = A_B / E(B-V)$

(Simulation)

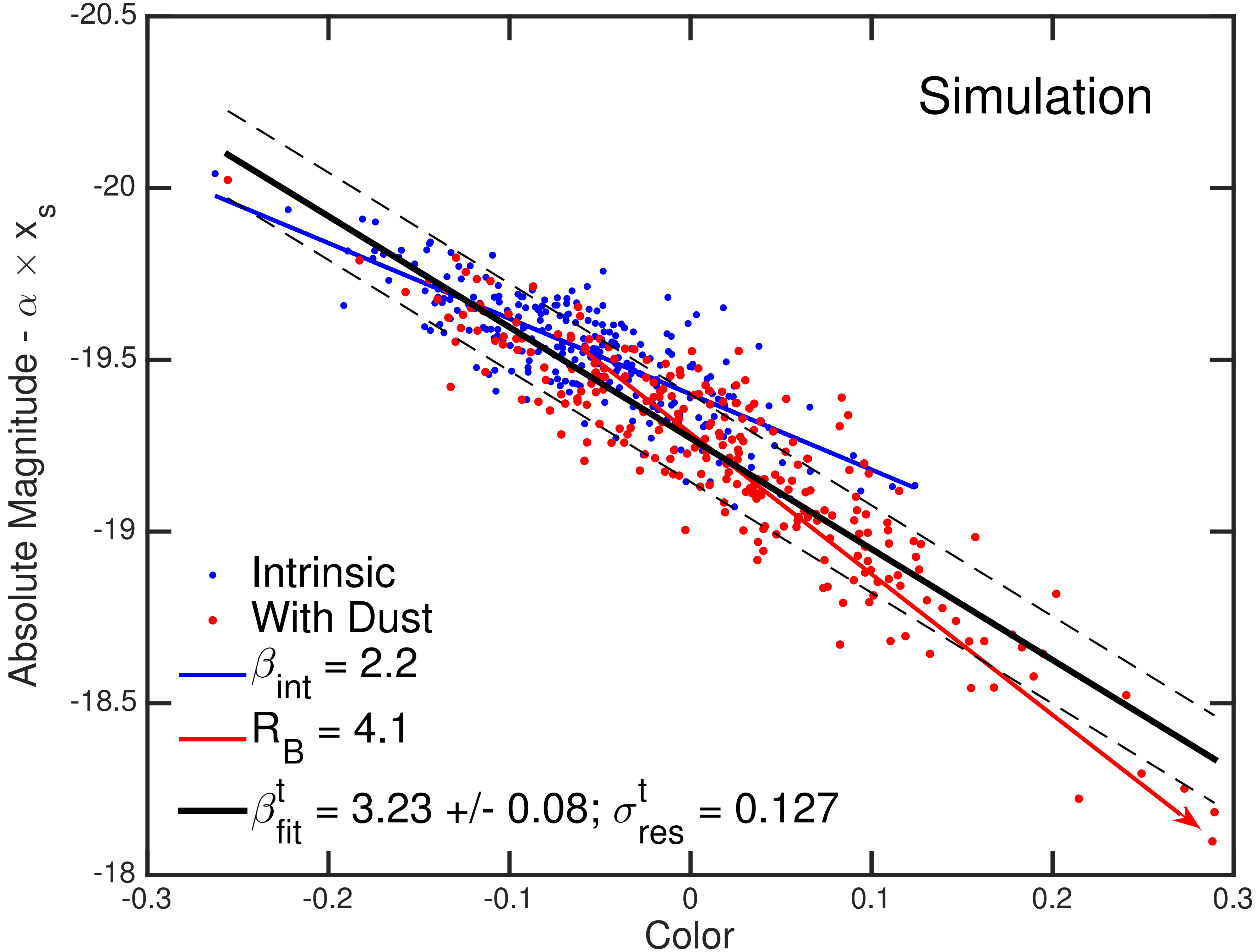




Dust Extinction & Reddening are Only Positive! (E_s > 0)

SN Ia Color-Mag Distribution (intrinsic vs dusty)

(Simulation)

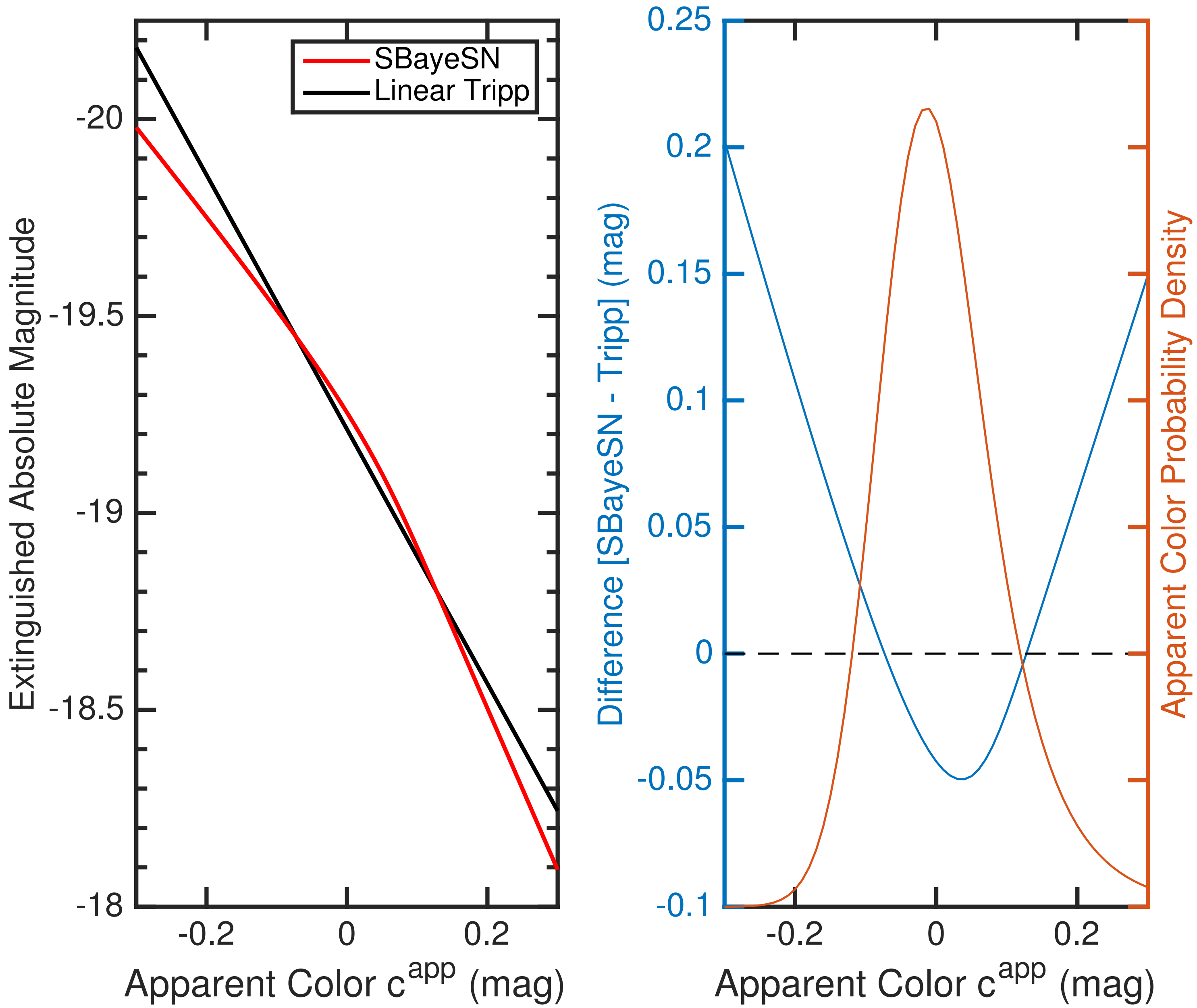


(Black: Conventional Tripp Fit)

$$m_B^s - \mu_s = M_B^{\rm ext} = M_0^{\rm ext} + \alpha \cdot x_s + \beta \cdot c_s^{\rm app}$$

Effective “Dusty” Color-Magnitude Distribution is a Convolution of the Intrinsic & Dust Distributions: Effective Color-Mag Trend is a Curve!

(Simulation)



Model Predicts Positive Distance Bias for Linear Tripp Fit in the tails of apparent color distribution

Tripp Fit is a linear approx. to curve near mean apparent color

Inverse Problem: Statistical inference with SN Ia

- SN Ia cosmology inference based on empirical relations
- Statistical models for SN Ia are learned from the data
- Several Sources of Randomness & Uncertainty

  1. Photometric (Measurement) & LC Fitting errors
  2. "Intrinsic Variation" = Population Distribution of SN Ia
  3. Random Peculiar Velocities in Hubble Flow
  4. Host Galaxy Dust: extinction and reddening.

- Observed Distributions are convolutions of these effects
- How to incorporate this all into a coherent statistical model? (How to "de-convolve"?) - Hierarchical Bayes!

Advantages of Hierarchical Models

- Incorporate multiple sources of randomness & uncertainty underlying the observed data
- Express structured probability models adapted to conceptual / physical data-generating forward process
- Hierarchically Model (Physical) Populations and Individuals simultaneously: e.g. intrinsic SN Ia properties and Dust Reddening/Absorption
- Inference = probabilistically de-convolves multiple latent effects underlying data
- Full Posterior probability distribution = Global, coherent quantification of uncertainties at individual and population levels

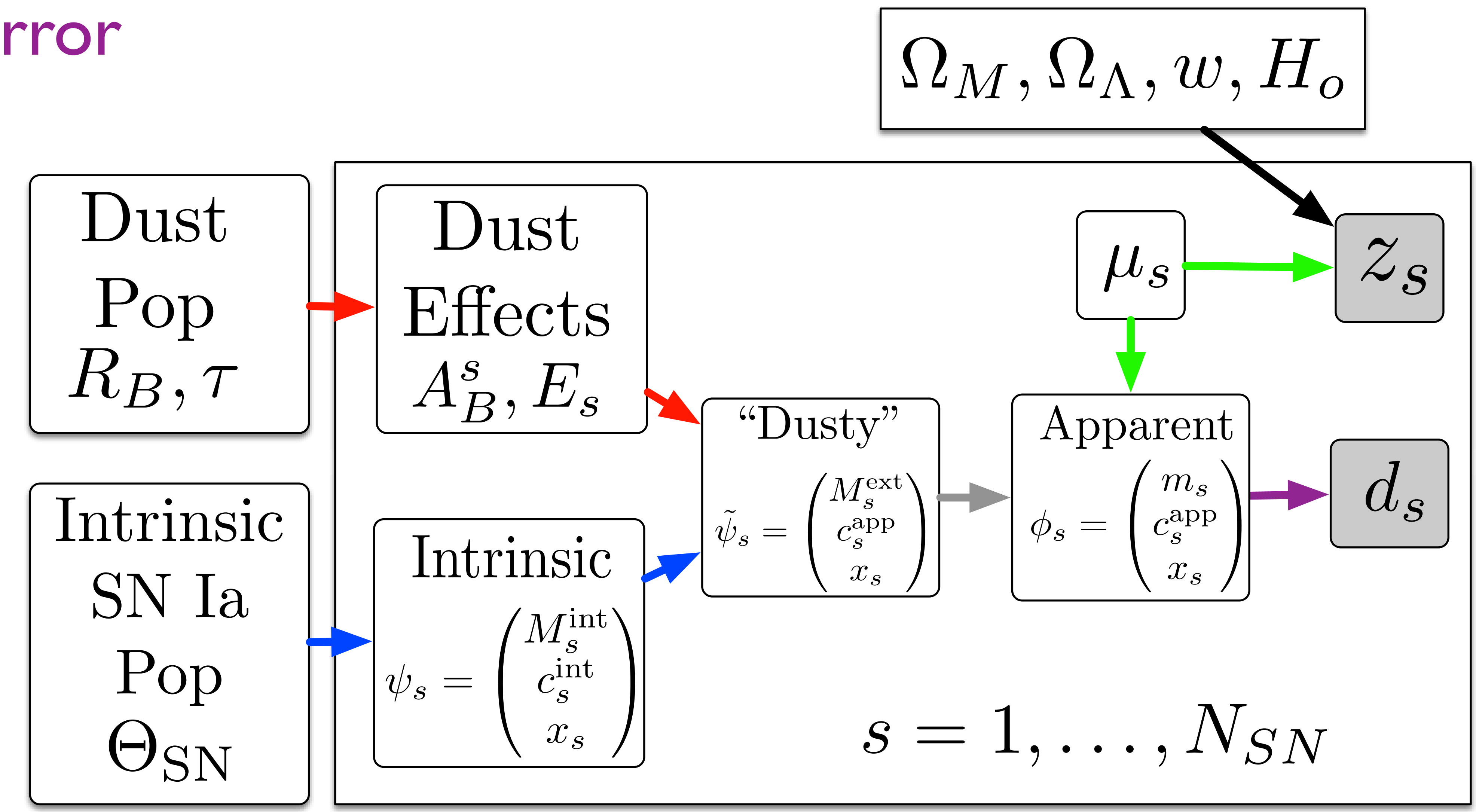
Directed Acyclic Graph for SN Ia Inference with Hierarchical Bayesian Model (Simple-BayeSN)

(Mandel et al. 2016)

- Intrinsic Variation of SN Ia
- Dust Extinction & Reddening
- Peculiar Velocities
- Measurement Error

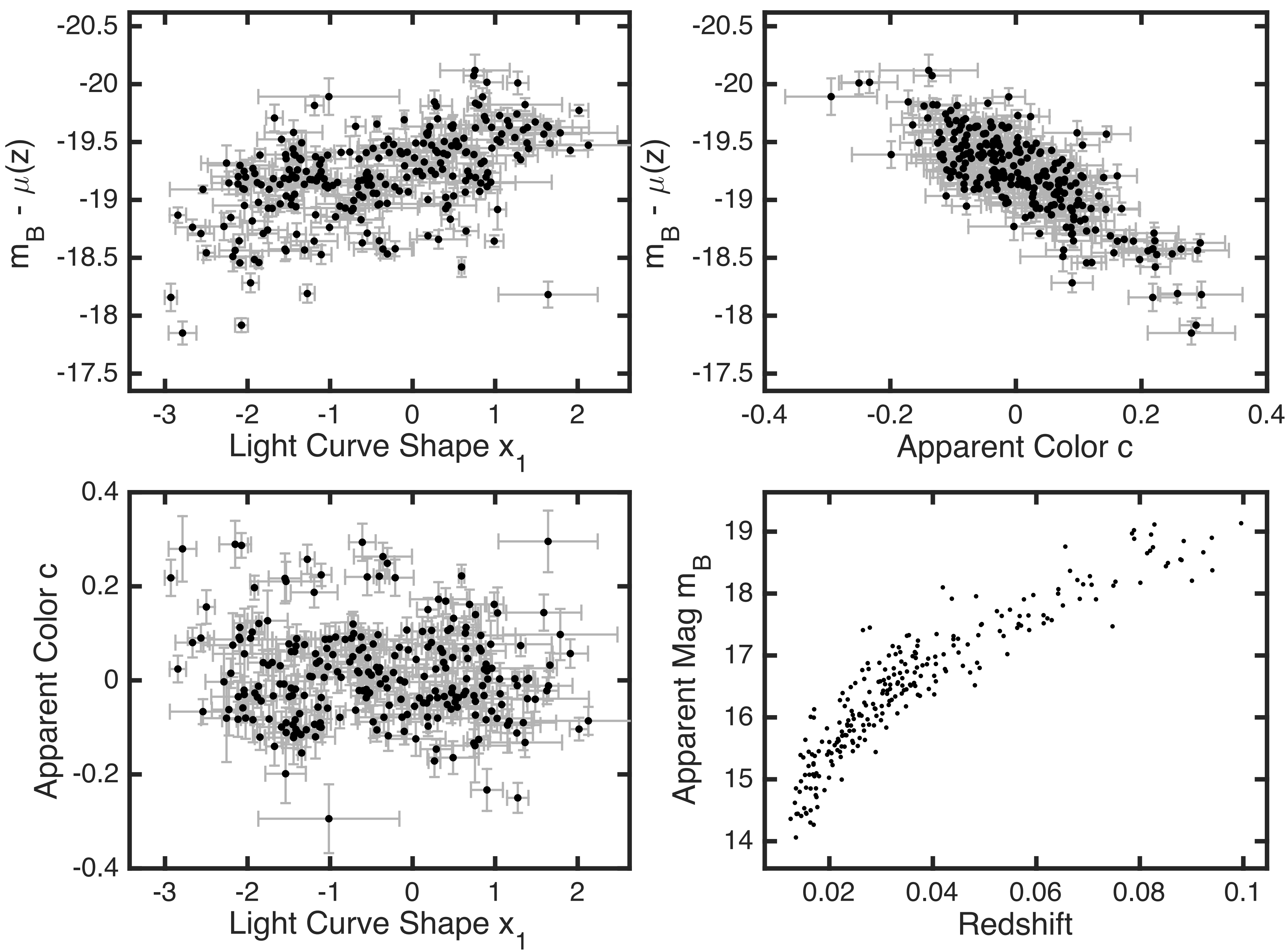
Probabilistic Graphical Model

Global Joint Posterior Probability Density Conditional on all SN Data



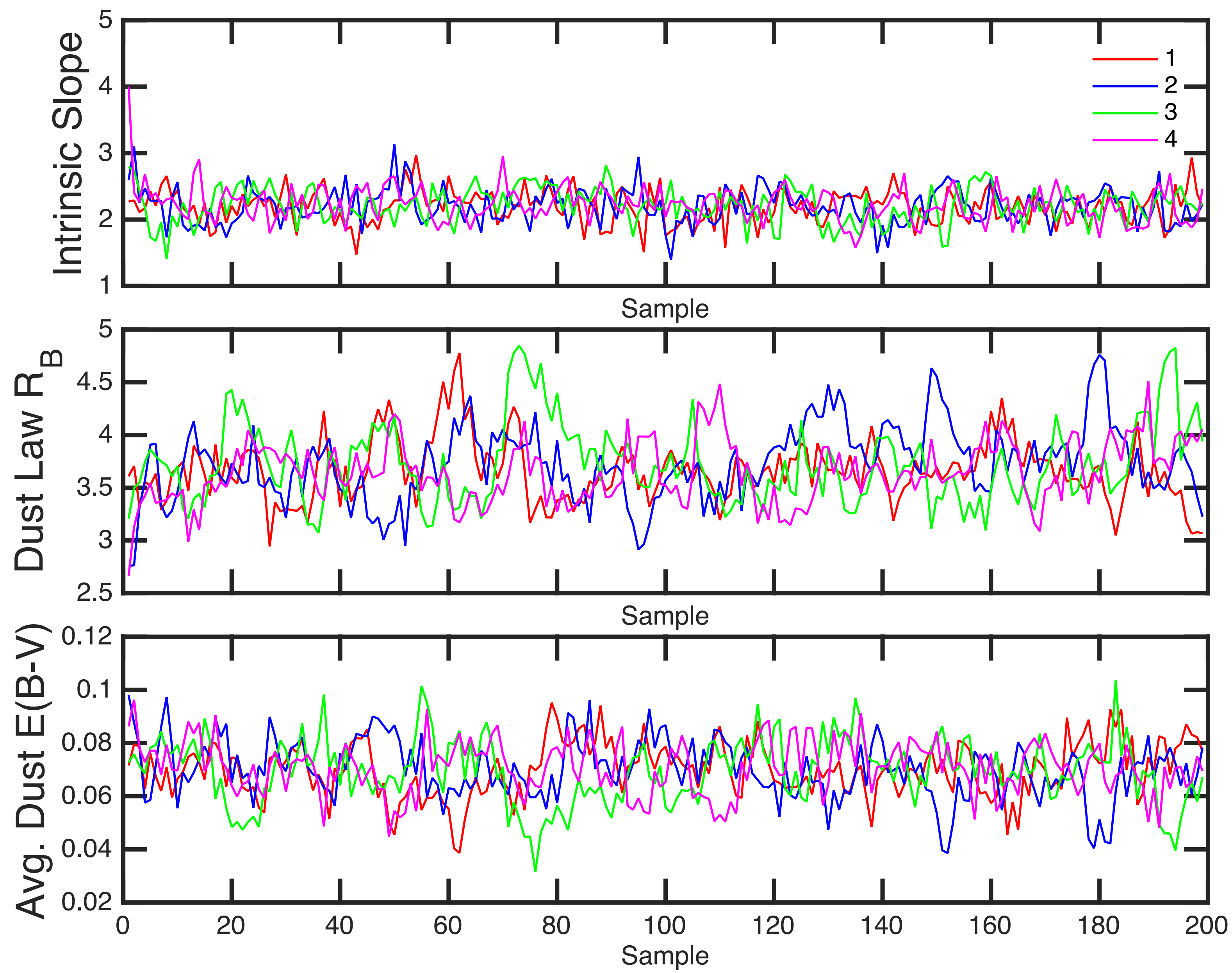
The Data:

Optical LC fits for 248 nearby (low-z < 0.1) SN Ia (CfA, CSP) cross-calibrated with Pan-STARRS [Scolnic+15]



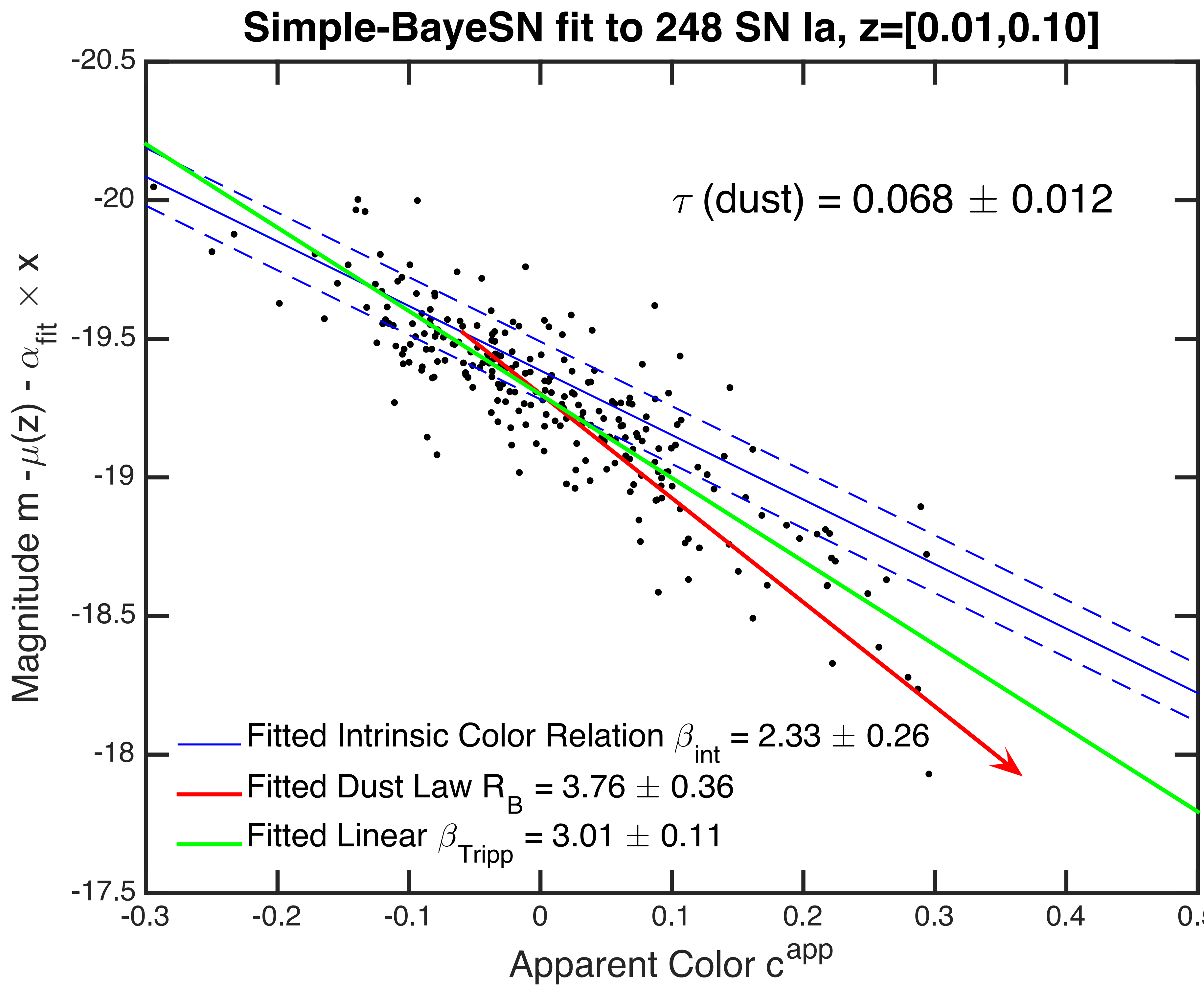
Bayesian Posterior Inference & Statistical Computation

- Estimate Intrinsic Relation, Dust Law, Dust Population, etc.
- Gibbs Sampling utilizes conditionals of full posterior to update MCMC steps
- Explore joint posterior probability of all parameters



Four Parallel MCMC Chains

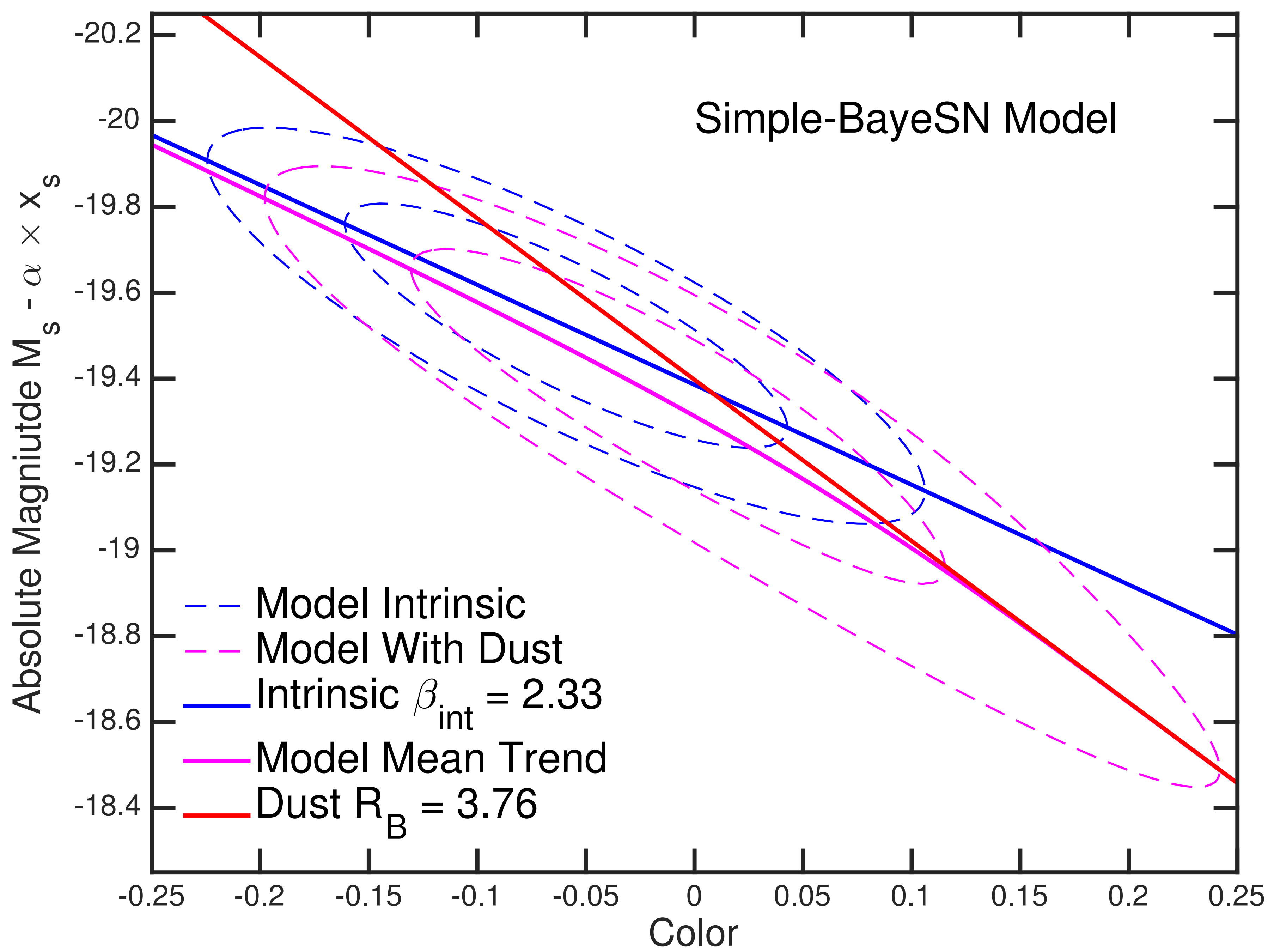
Results: Discerning Dust vs. Intrinsic Variations



Intrinsic Color-Magnitude Slope ≠ Dust Reddening Vector!

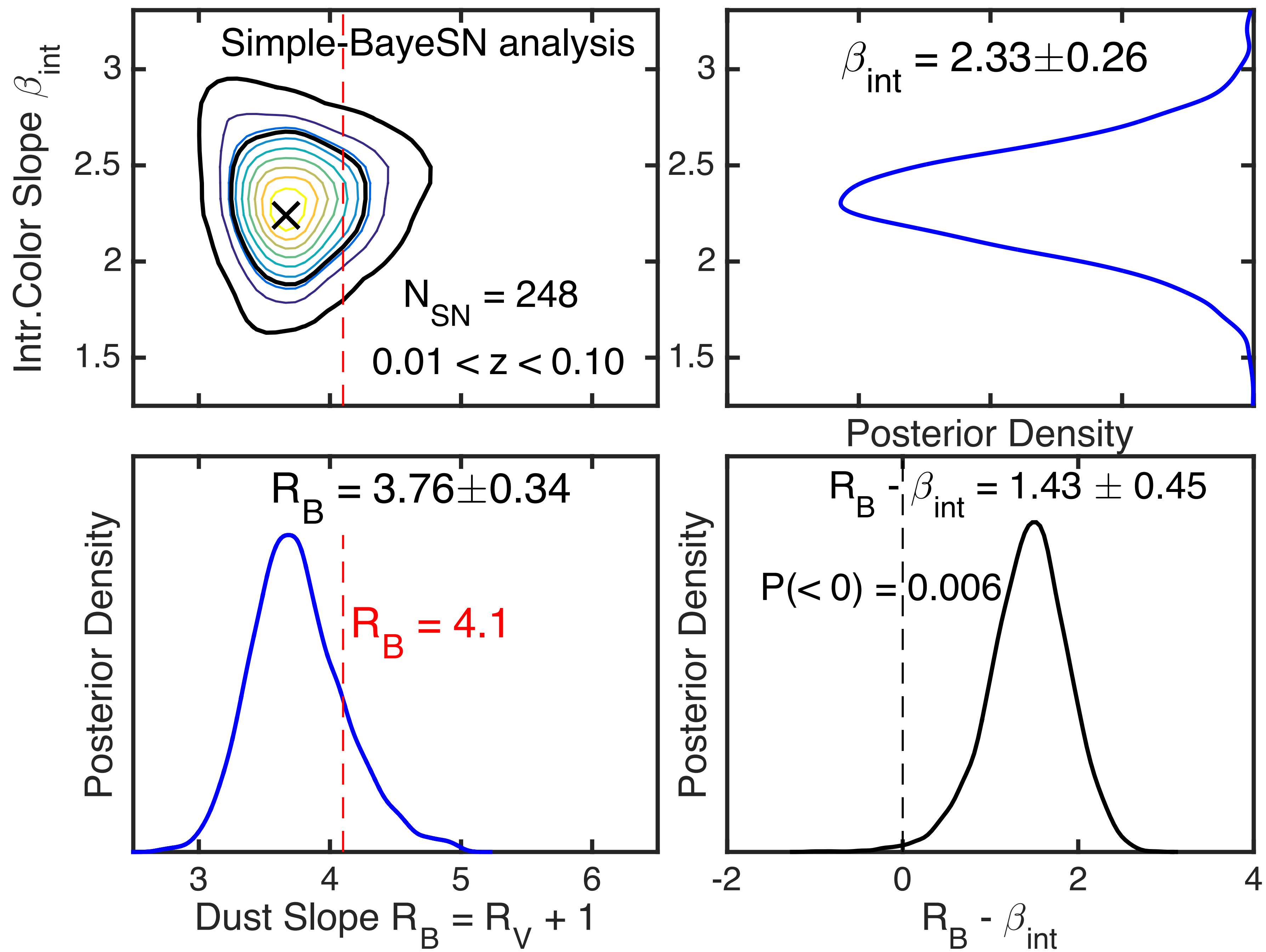
(Color-Magnitude Effects NOT described by a single slope β!)

Effective Colour-Mag Distribution



Nonlinear Mean Apparent Colour-Magnitude Relation

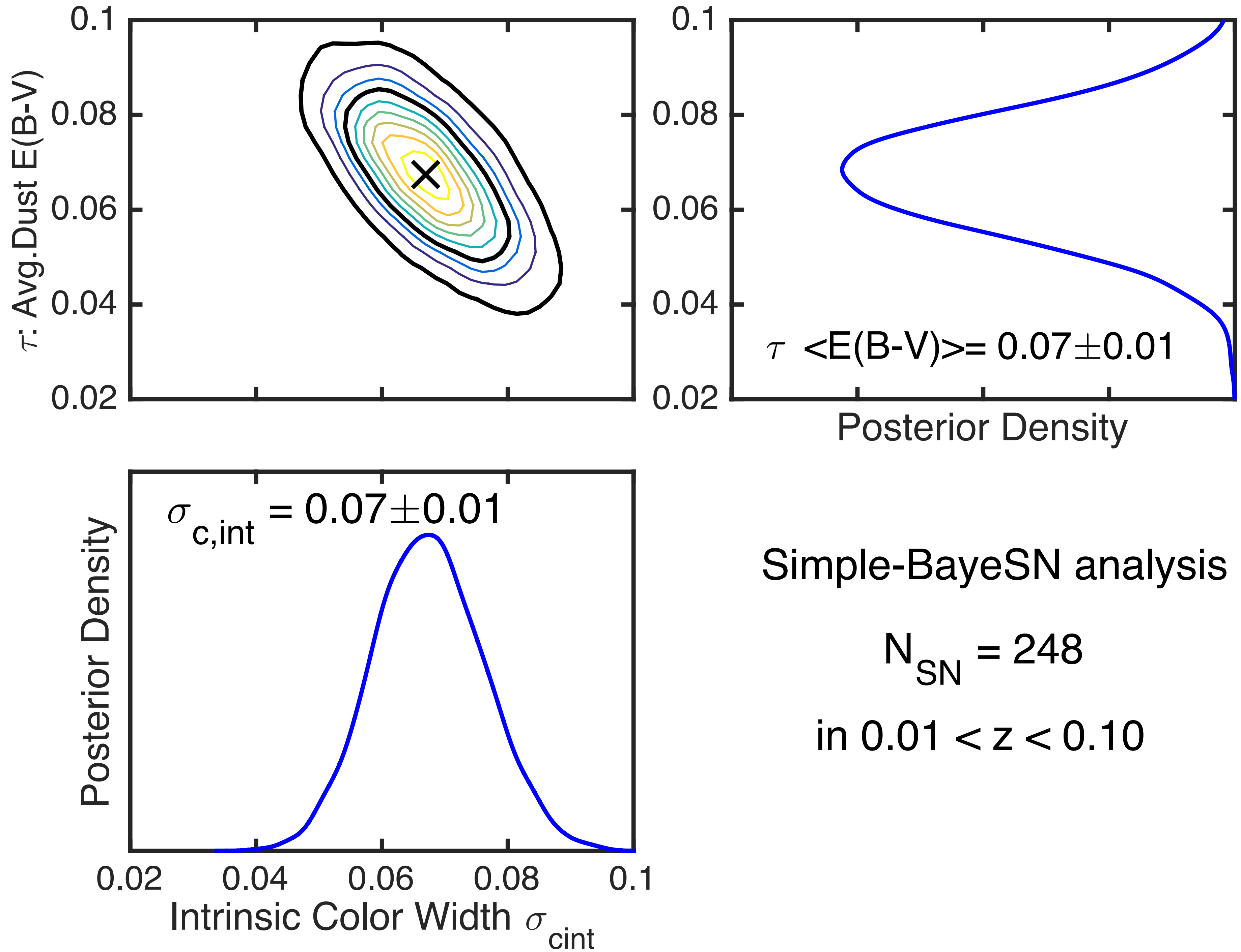
Results: Inferring Dust Extinction/Reddening (R_B) vs. Intrinsic Color-Luminosity Trend (β_{int})



Dust Reddening Vector consistent with Milky Way dust (R_V = 3.1)!

Intrinsic Color-Magnitude Slope ≠ Dust Reddening Vector!

Results: Inferring Population Distributions of SN Ia Intrinsic Color vs Host Galaxy Dust



Simple-BayeSN analysis

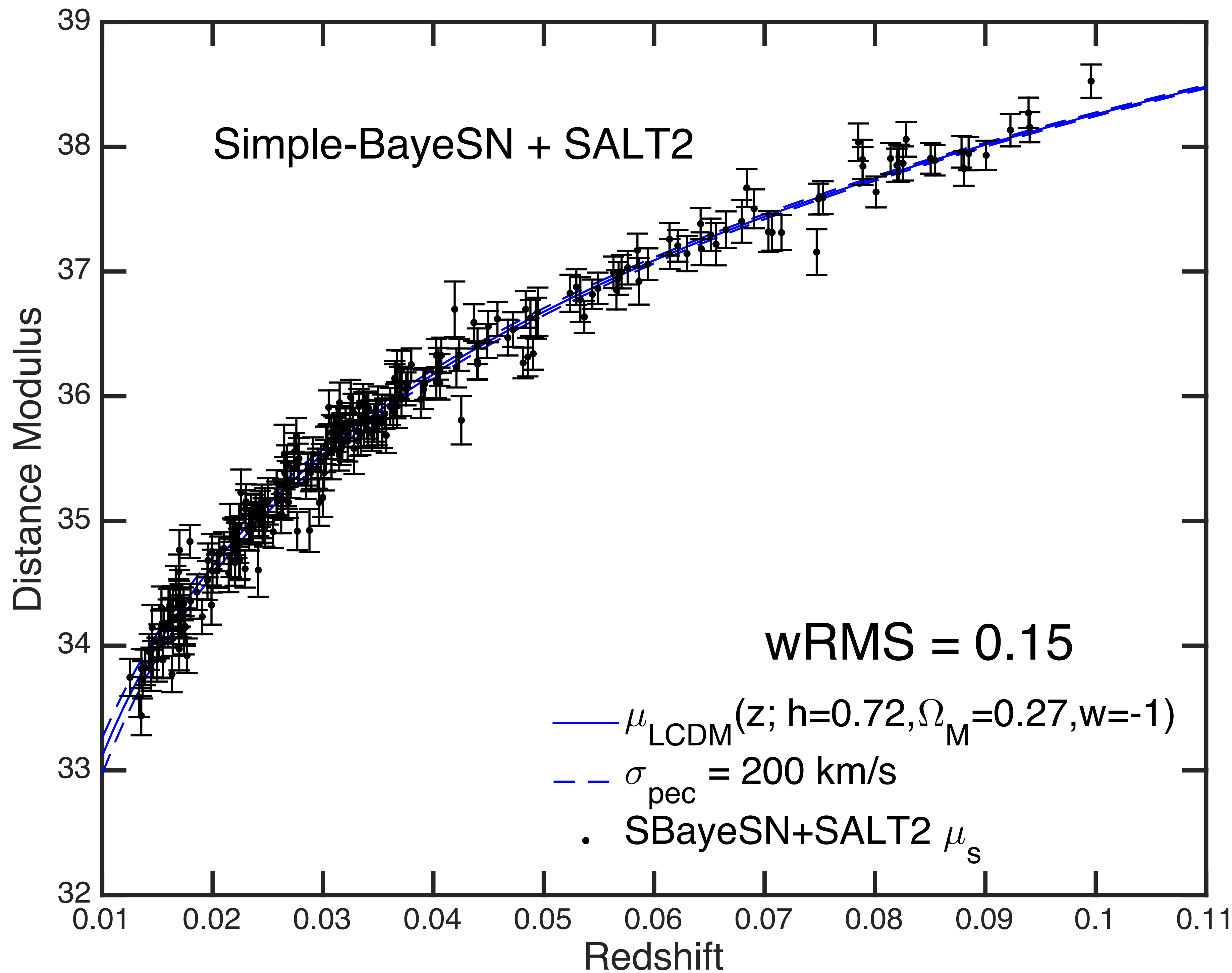
$N_{SN} = 248$

in $0.01 < z < 0.10$

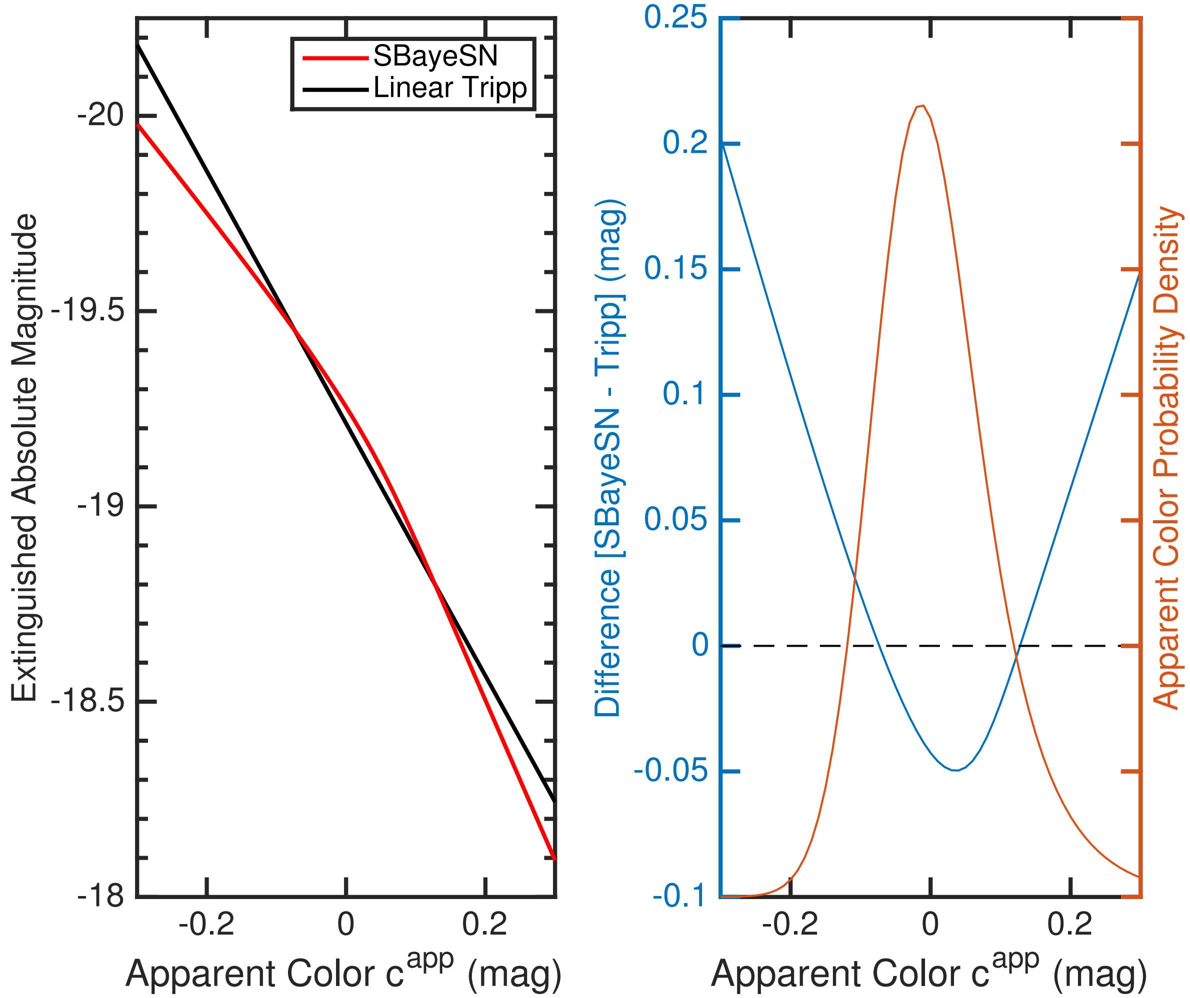
Roughly Equal Contributions to Total Apparent Color Variance

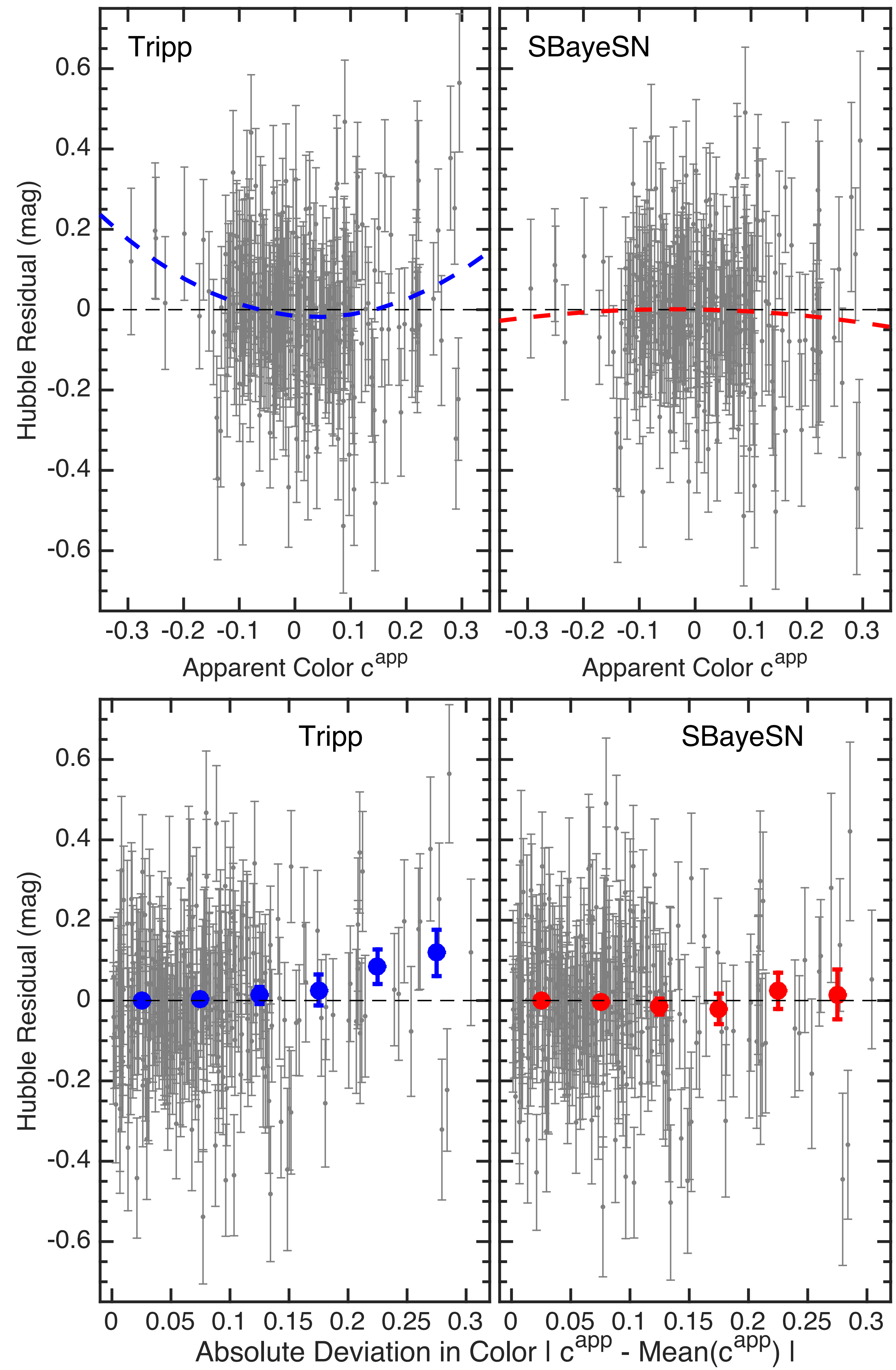
Hubble Diagram: Use Trained Model Hyperparameters to Predict Photometric Distances based on SN Ia Light Curve Data:

$$P(\mu_s | \, d_s, \hat{\Theta}_{\rm SN}, \hat{\tau}, \hat{R}_B)$$



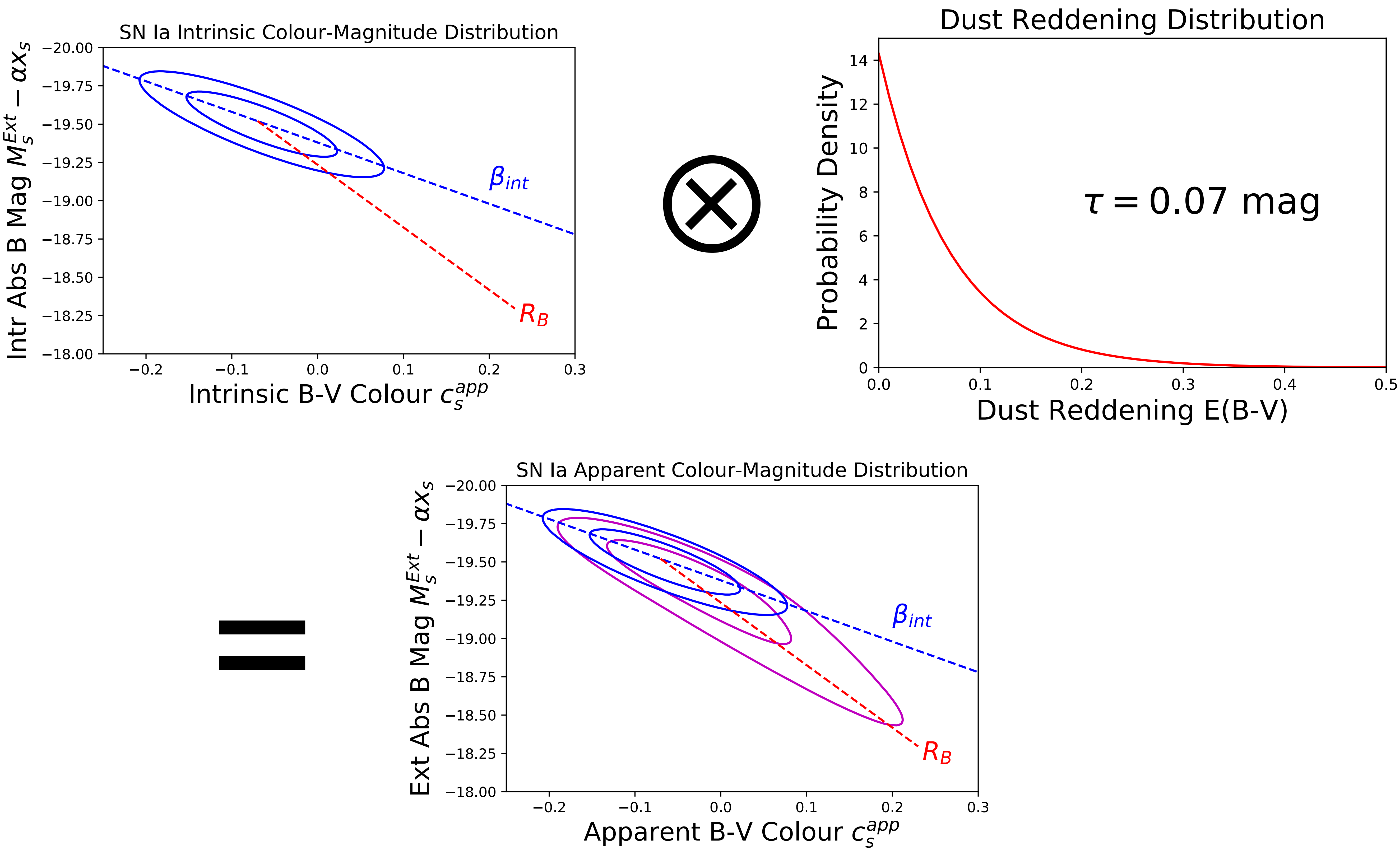
Hubble Residuals



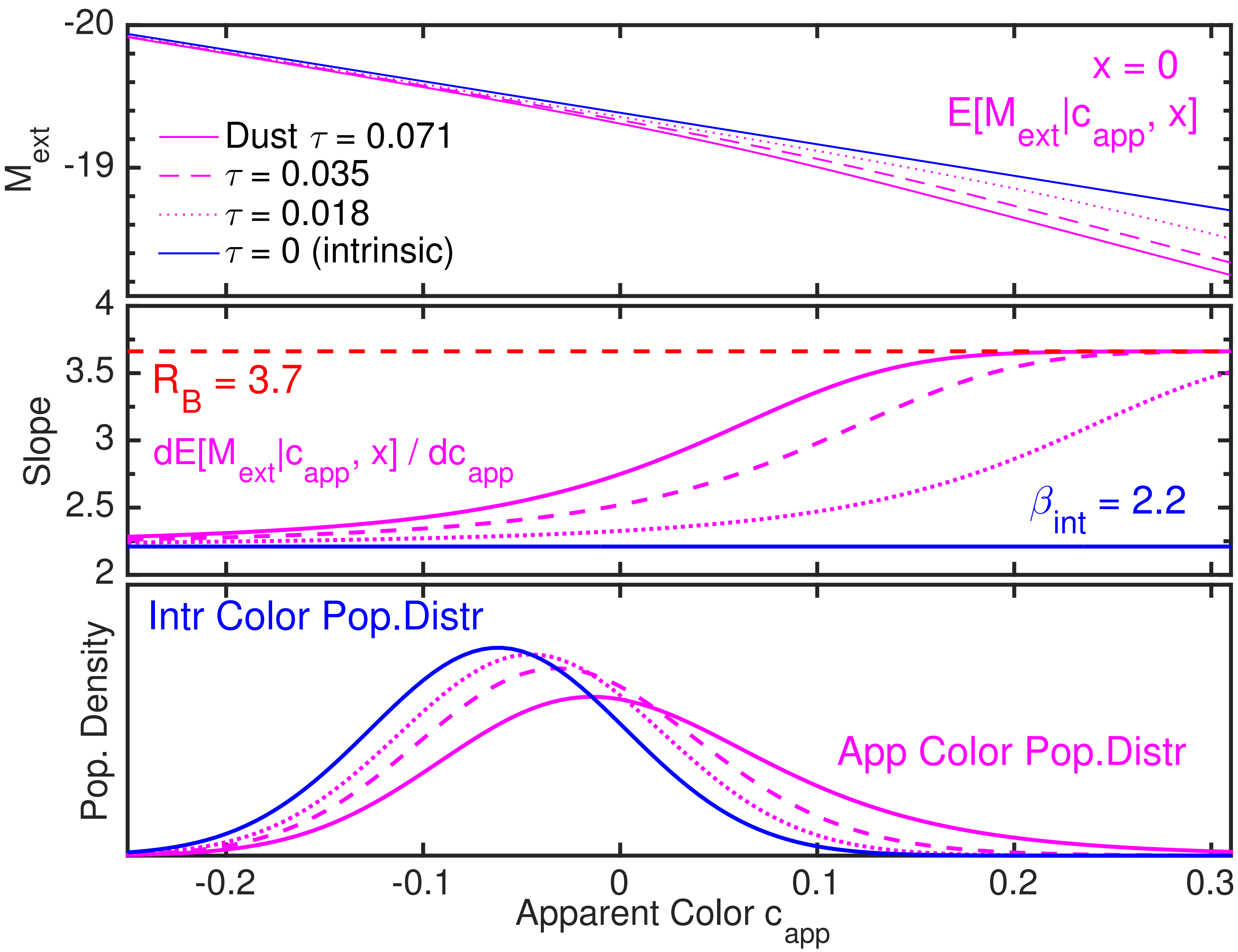


Simple-BayeSN
Corrects ~ 0.1 mag bias
in tails of SN Ia
color distribution
relative to Linear Tripp fit

Main Effect of Model



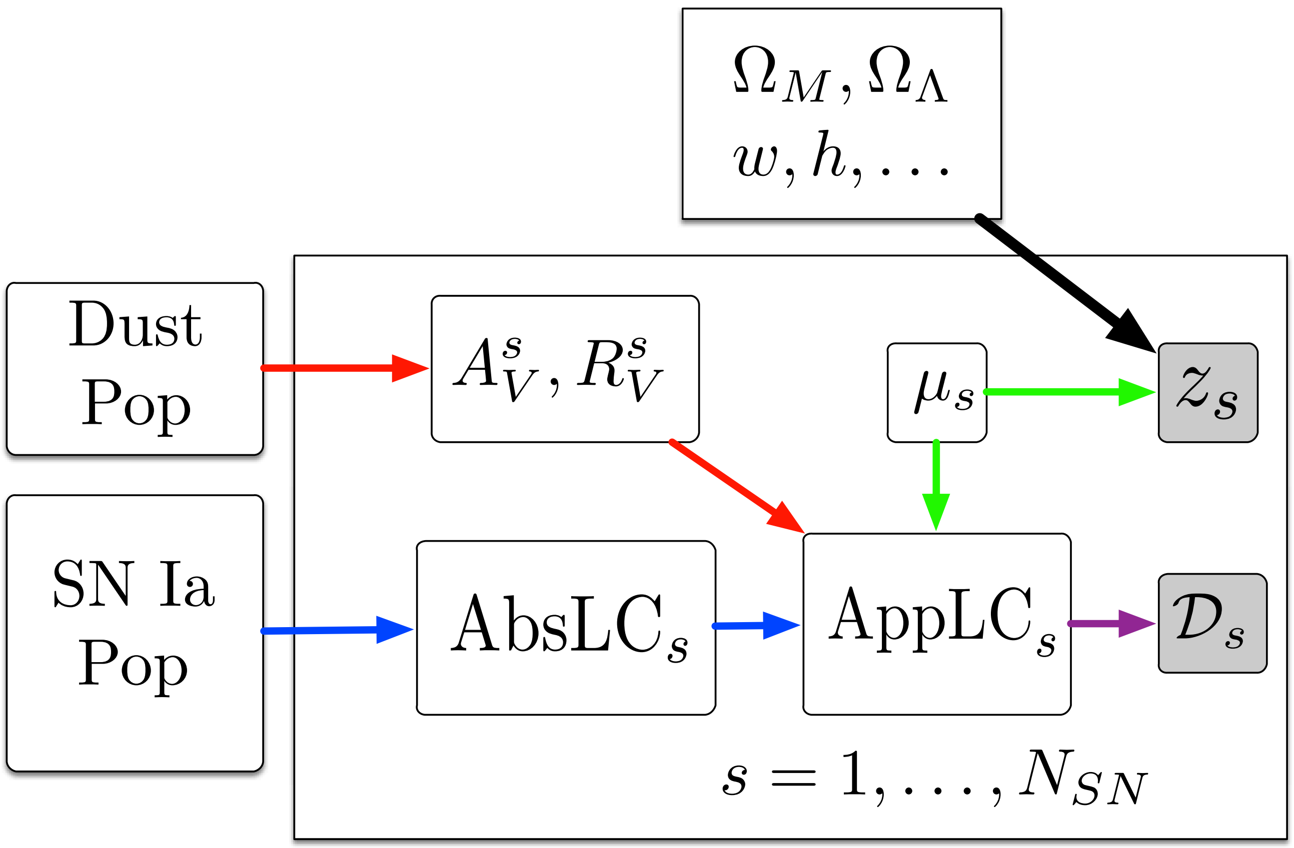
Implications for / Advantages of NIR
change effective τ = Avg. Dust

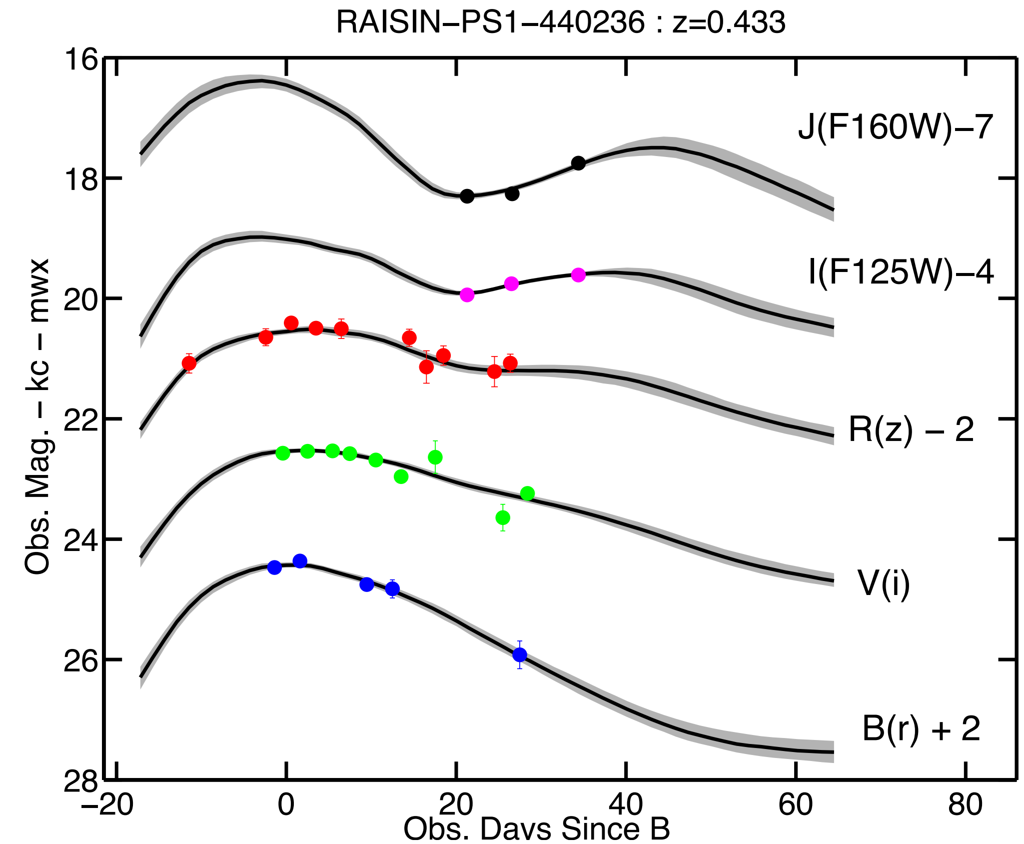


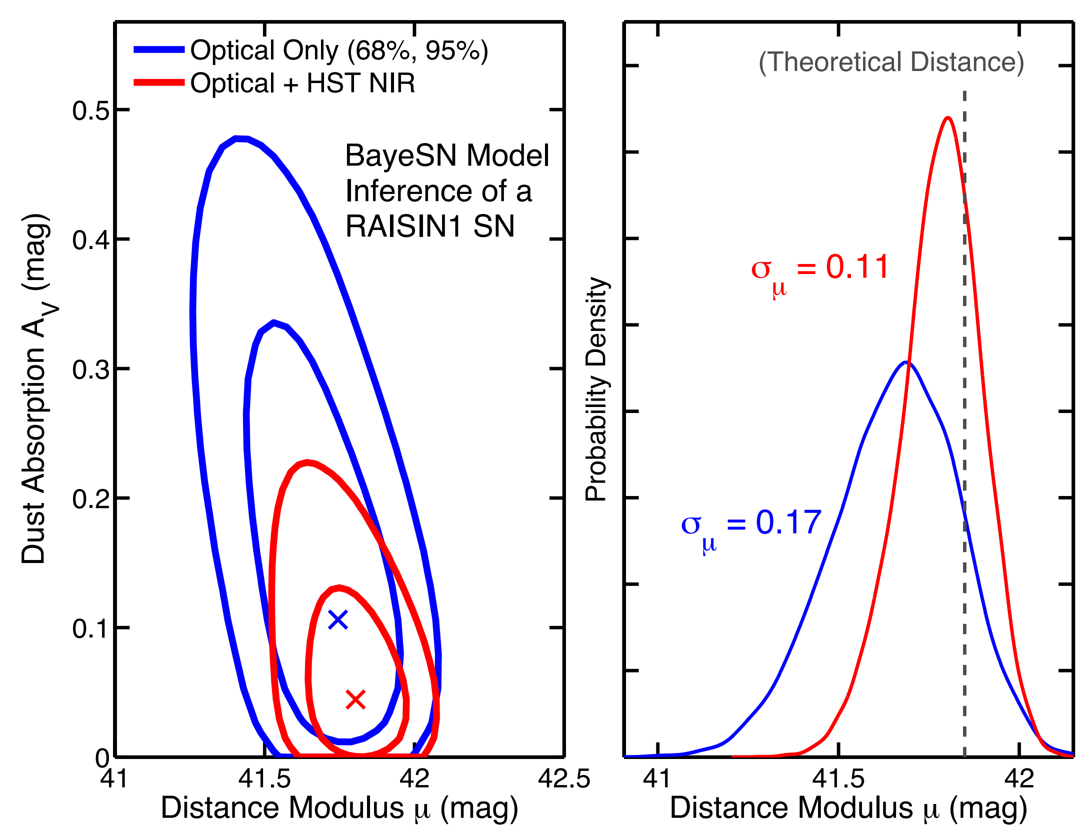
Using M_{NIR} for standard candle, would expect a significant suppression of effect

For any combination of M_F and c_{F-G}, effect depends on relative colour-mag slopes and dispersions of intrinsic vs. dust components

BayeSN:
Optical+NIR LC model

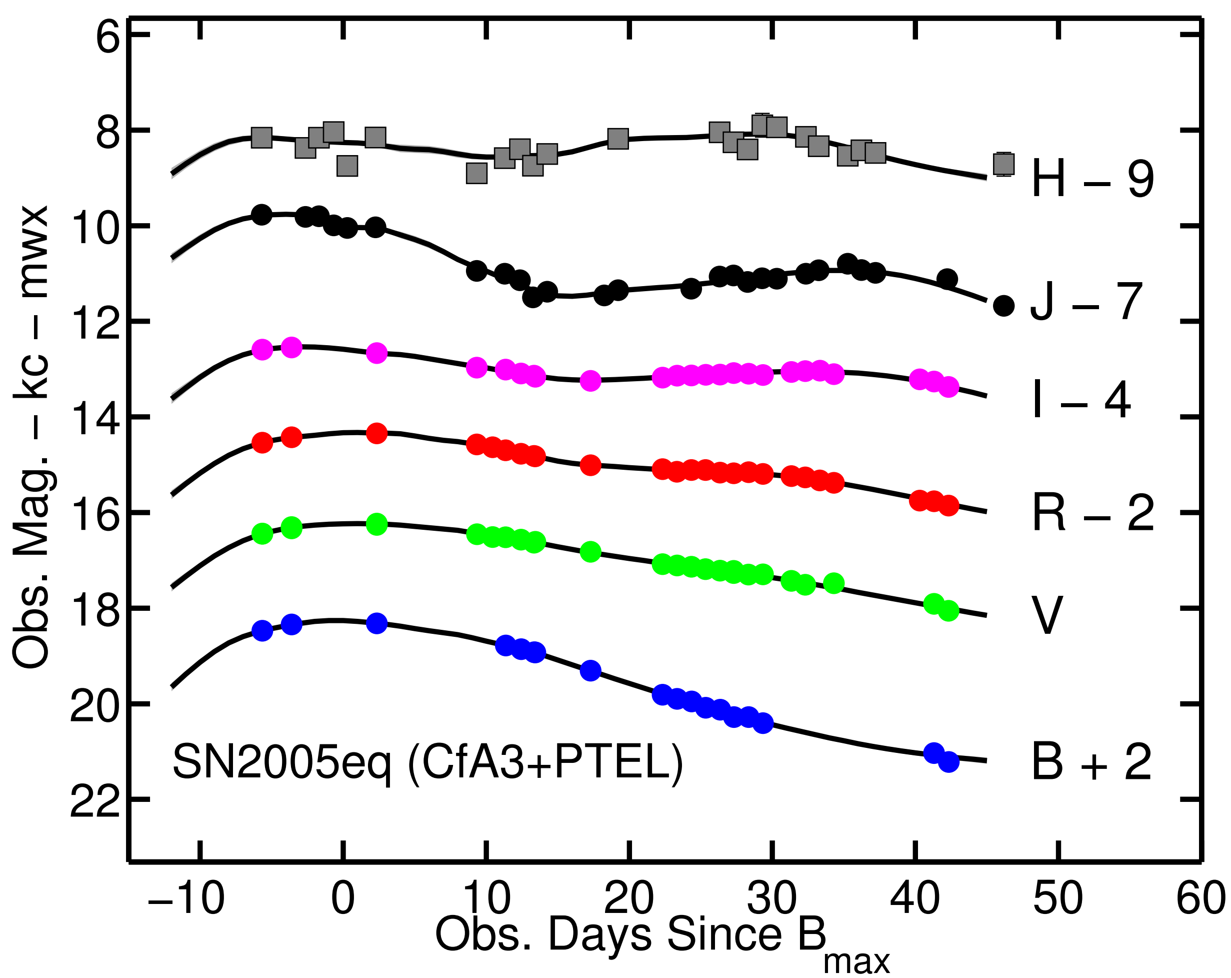






Mandel, Narayan & Kirshner 2011

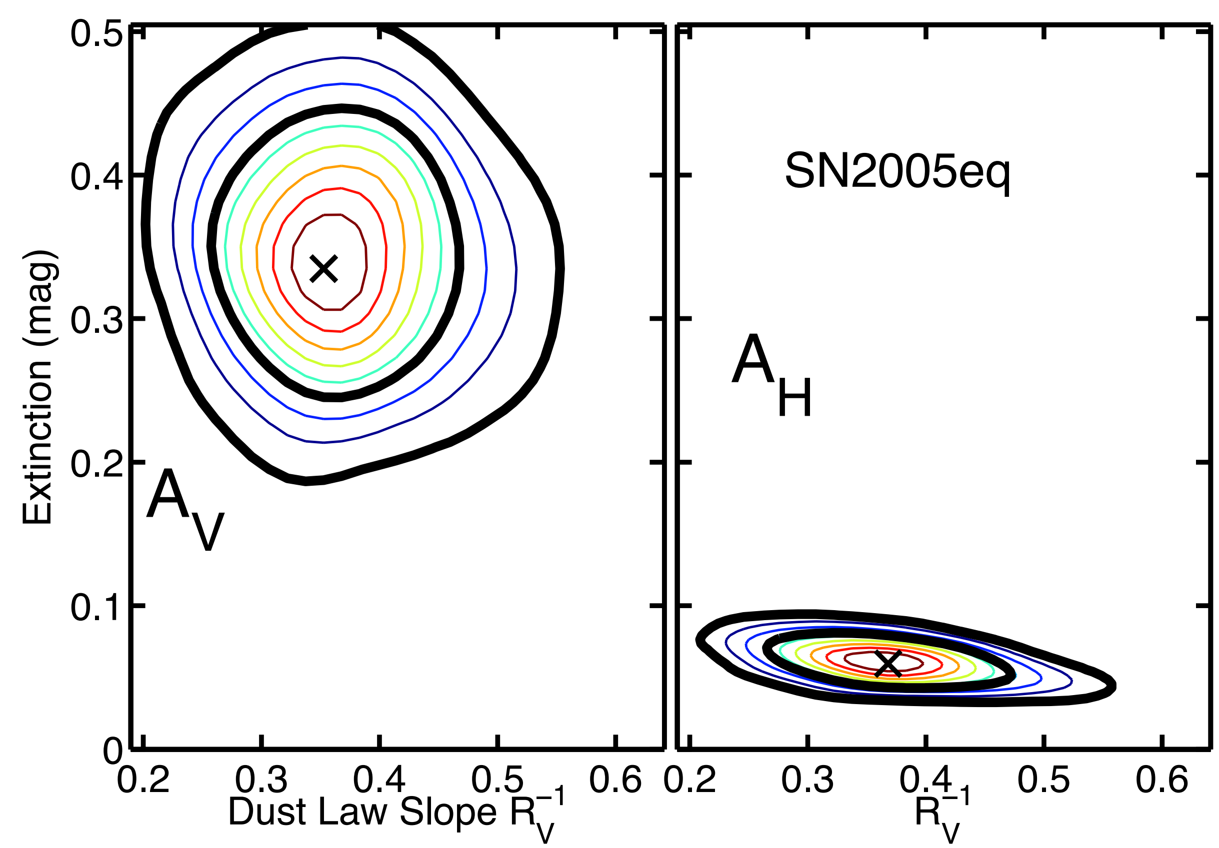
Optical+NIR Hierarchical Model Inference



Mandel, Narayan & Kirshner (2011)

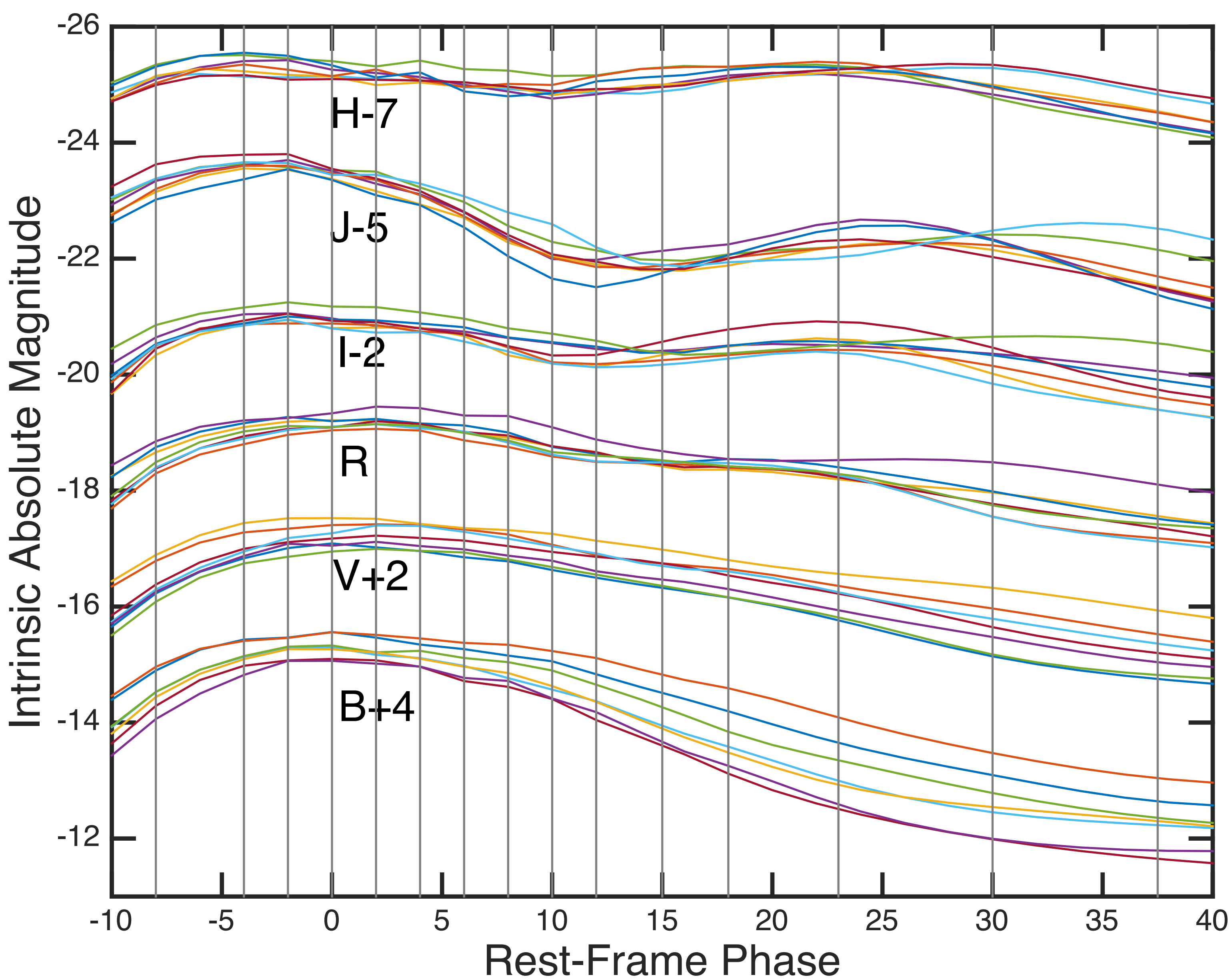
PTEL+CfA3 Light-curves (Moderate Extinction)

Marginal Posterior of Dust



BayeSN: Modeling SN Ia Light curves: Learning the population distribution of LCs

Beyond one parameter: a "non-parametric" approach

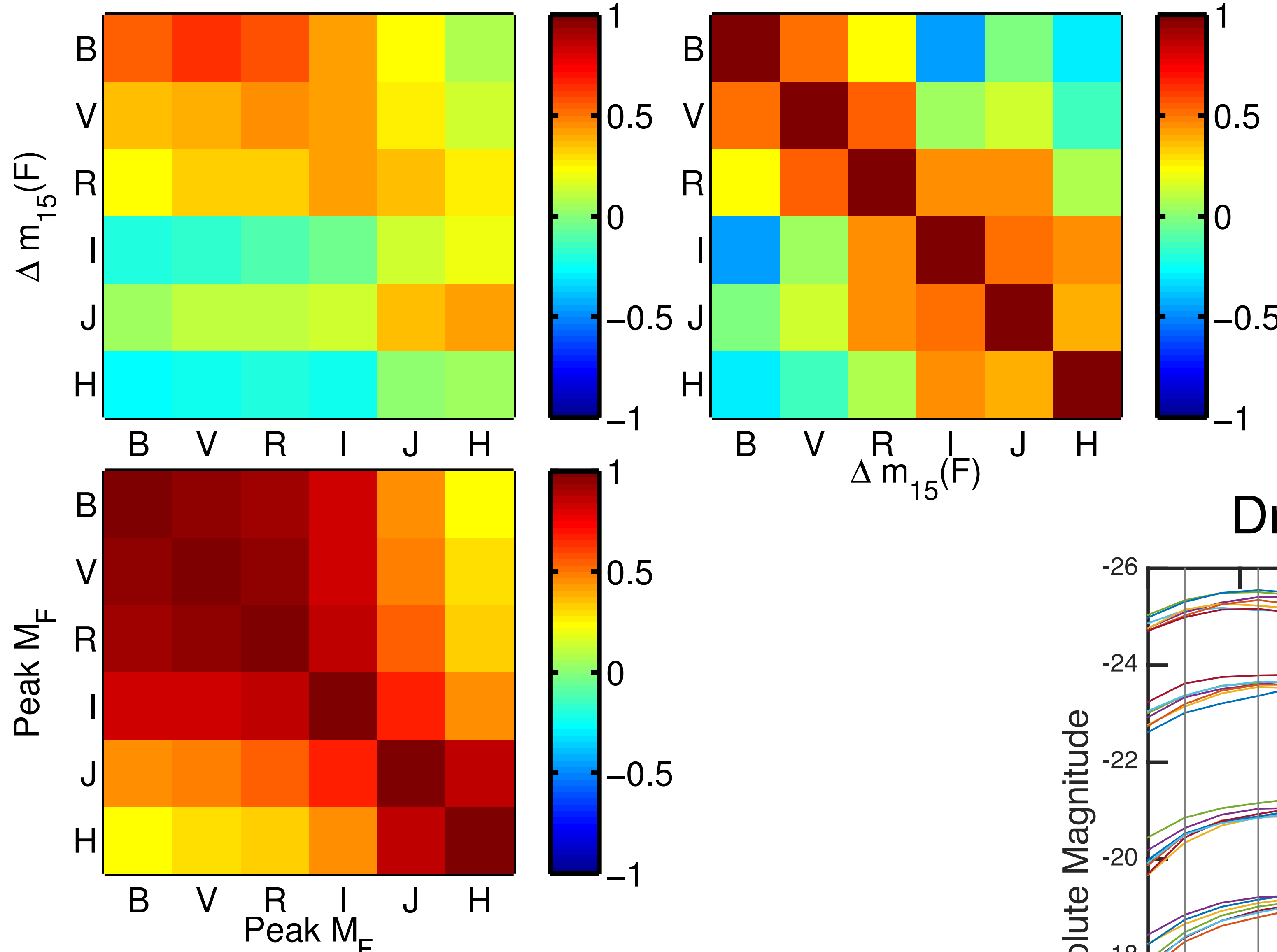


Mandel, Narayan & Kirshner 2011

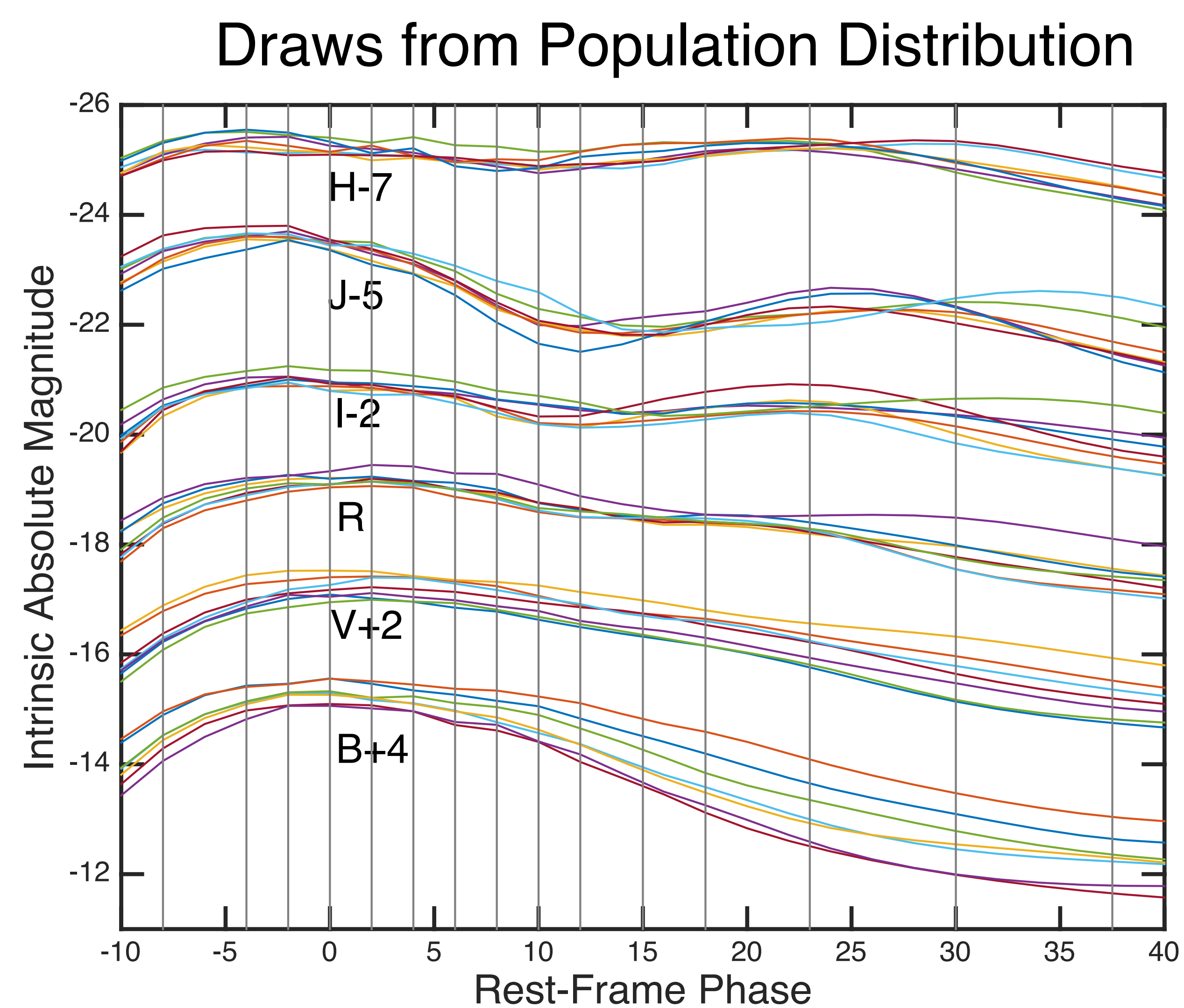
- Many Local Parameters describing intrinsic absolute magnitude and shape of LC over short time segments at each rest-frame λ-filter
- Goal: Learn from the data the (non-stationary) Covariance Structure of SN Ia intrinsic absolute light curves over multiple λ-filters and phases t
- Models Gaussian Process joint intrinsic distribution of LCs (over t and λ-filter)

BayeSN Light Curve Population Analysis

Mandel, Narayan & Kirshner 2011



Learning the Intrinsic Covariance of SN Ia LC Population



Correlation Map for Luminosities and LC Decline Rates