Type Ia SN Light Curve Inference: Hierarchical Models for Nearby SN in the Rest-Frame Near Infrared and Optical

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Astrostatistics Seminar
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Related Papers

Mandel, K., G. Narayan, R.P. Kirshner.
Type Ia Supernova Light Curve Inference:
Hierarchical Models in the Optical and Near Infrared.
2011 submitted to ApJ, arXiv:1011.5910

Mandel, K., W.M. Wood-Vasey, A.S. Friedman, R.P. Kirshner.
Type Ia Supernova Light Curve Inference:
Hierarchical Bayesian Analysis in the Near Infrared.
2009, ApJ, 704, 629-651

Blondin, S., K. Mandel, R.P. Kirshner.
Do Spectra improve distance measurements of SN Ia?
2011, A&A 526, A81

Wood-Vasey, et al. Type Ia Supernovae are Good Standard Candles in the Near Infrared: Evidence from PAIRITEL.
2008, ApJ, 689, 377-390

Outline

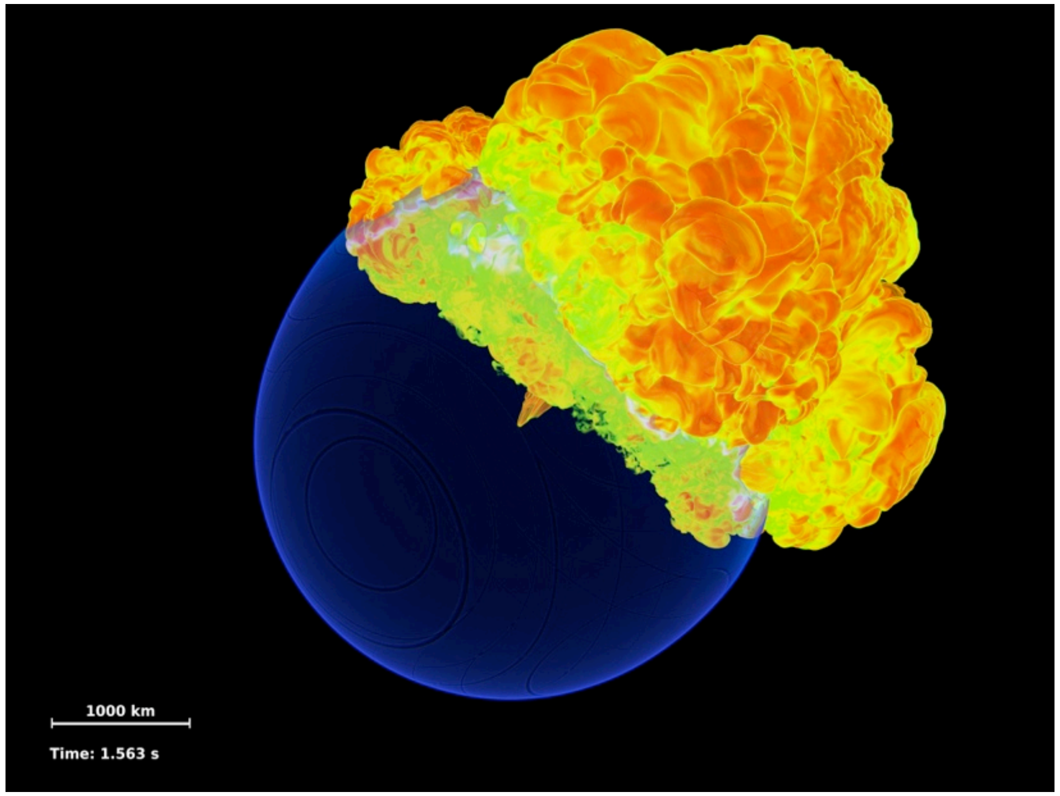
- Type Ia SN and Cosmology
- Statistical Inference with SN Ia Light curves
    - Hierarchical Framework for Structured Probability Models for Observed Data
    - Describing Populations & Individuals, Multiple Random Effects, Covariance Structure
- Statistical Computation with Hierarchical Models
    - BayeSN (MCMC)
- Application & Results: Hierarchical Model for Nearby CfA NIR (PAIRITEL) and Optical (CfA3) SN Ia light curves

Standard Candle Principle

1. Know or Estimate Luminosity L of a Class of Astronomical Objects
2. Measure the apparent brightness or flux F
3. Derive the distance D to Object using Inverse Square Law: $F = L / (4\pi D^2)$
4. Optical Astronomer's units: $m = M + \mu$

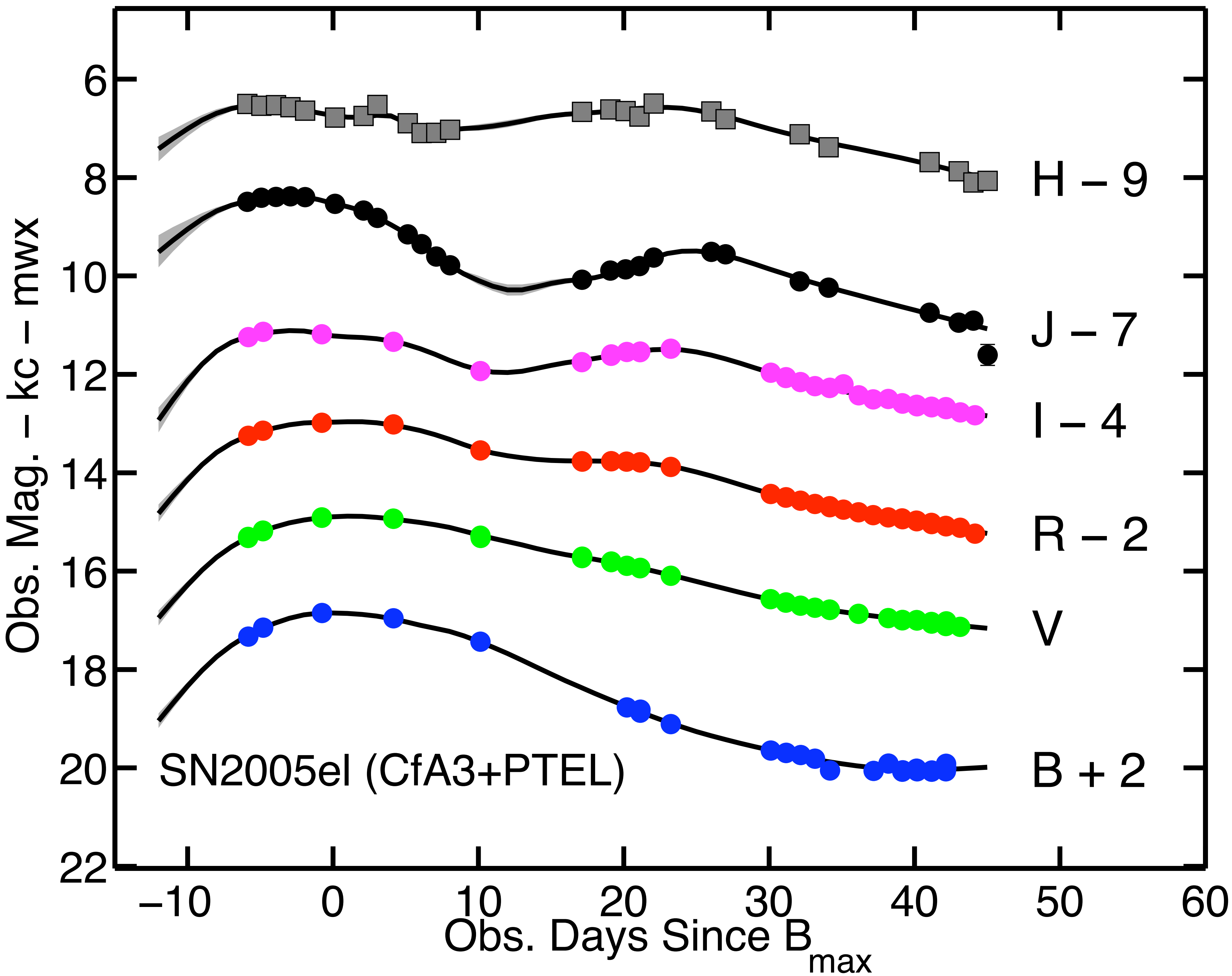
Type Ia Supernovae are Almost Standard Candles

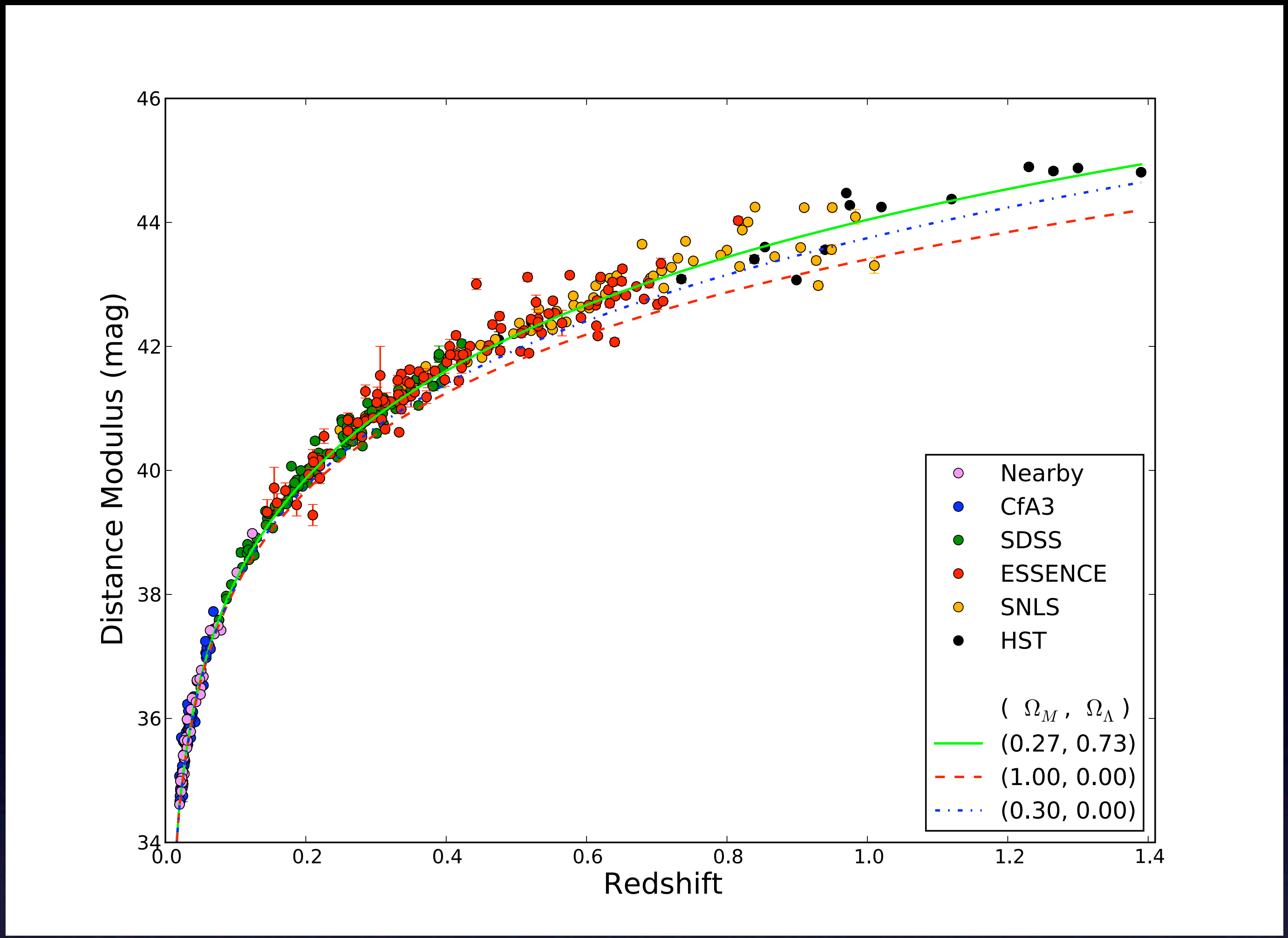
- Progenitor: C/O White Dwarf Star accreting mass leads to instability
- Thermonuclear Explosion: Deflagration/Detonation
- Nickel to Cobalt to Iron Decay + radiative transfer powers the light curve
- SNe Ia progenitors have nearly same mass, therefore energy



Credit: FLASH Center

Type Ia Supernova Apparent Light Curve

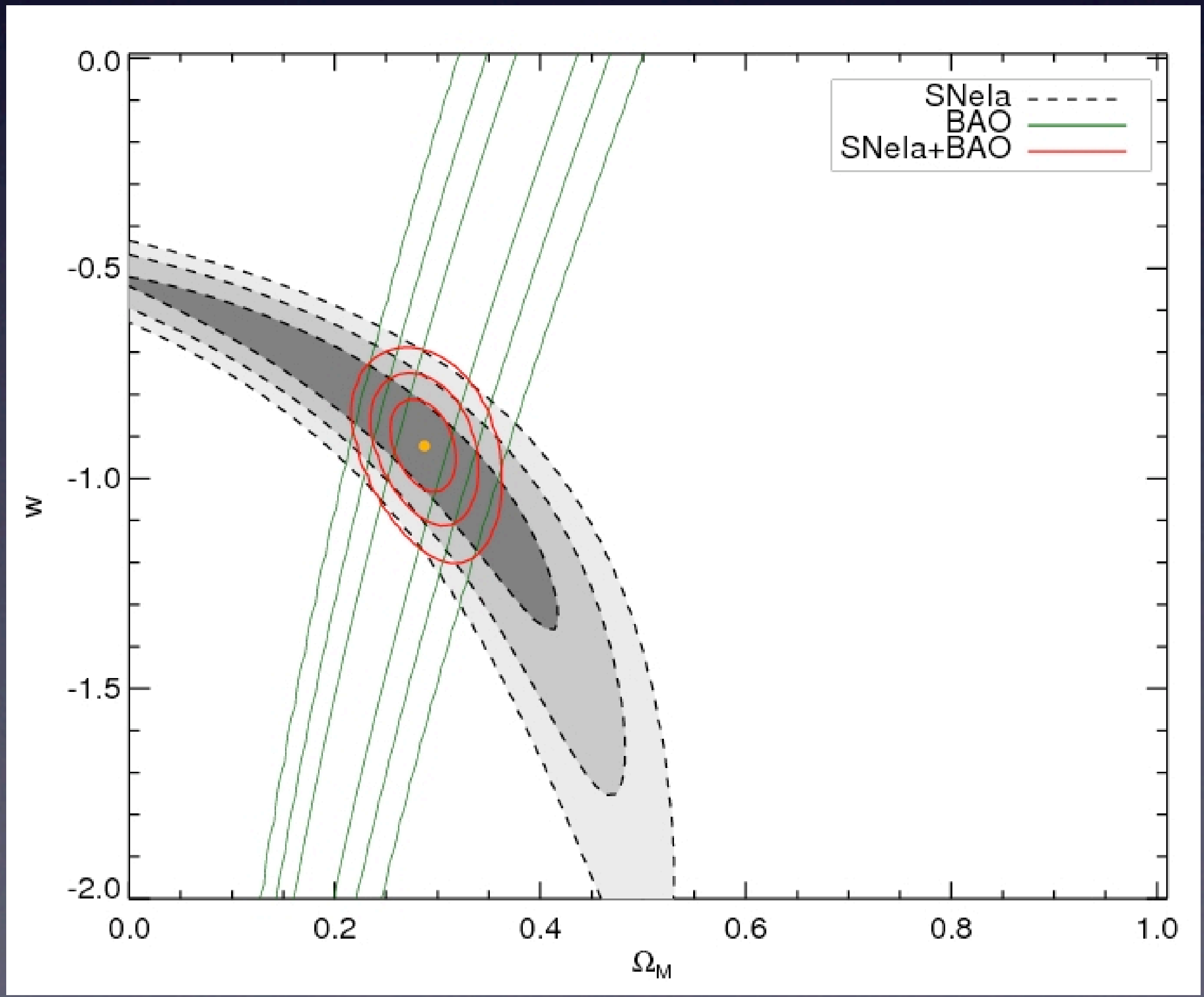




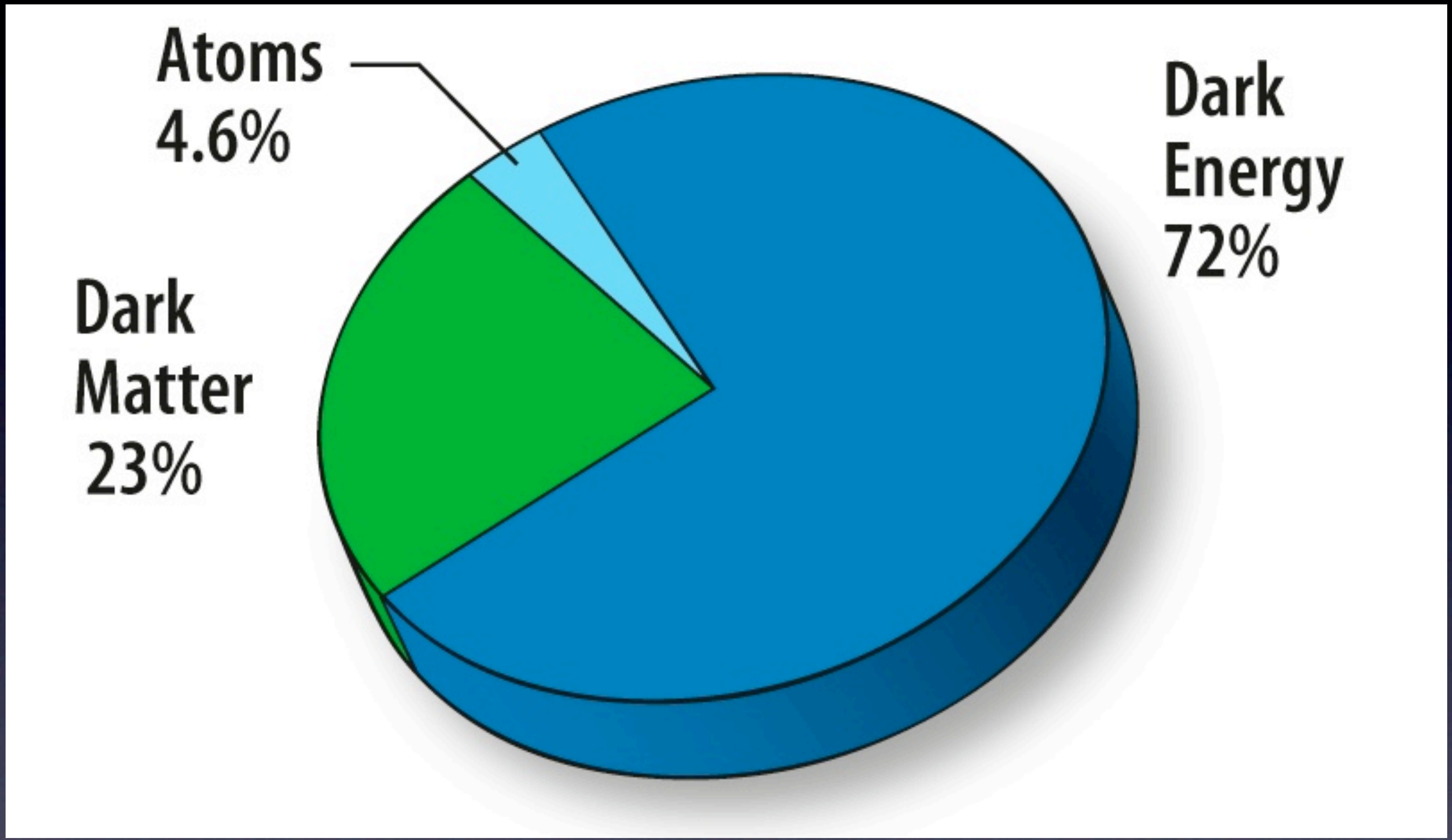
Supernova Cosmology: Constraining Cosmological Parameters using Luminosity Distance vs. Redshift

Credit: Gautham Narayan

- Nearby Hubble law is linear
- High-z depends on cosmology
- Host Galaxy Dust is a Major Confounding Factor



Cosmological Energy Content

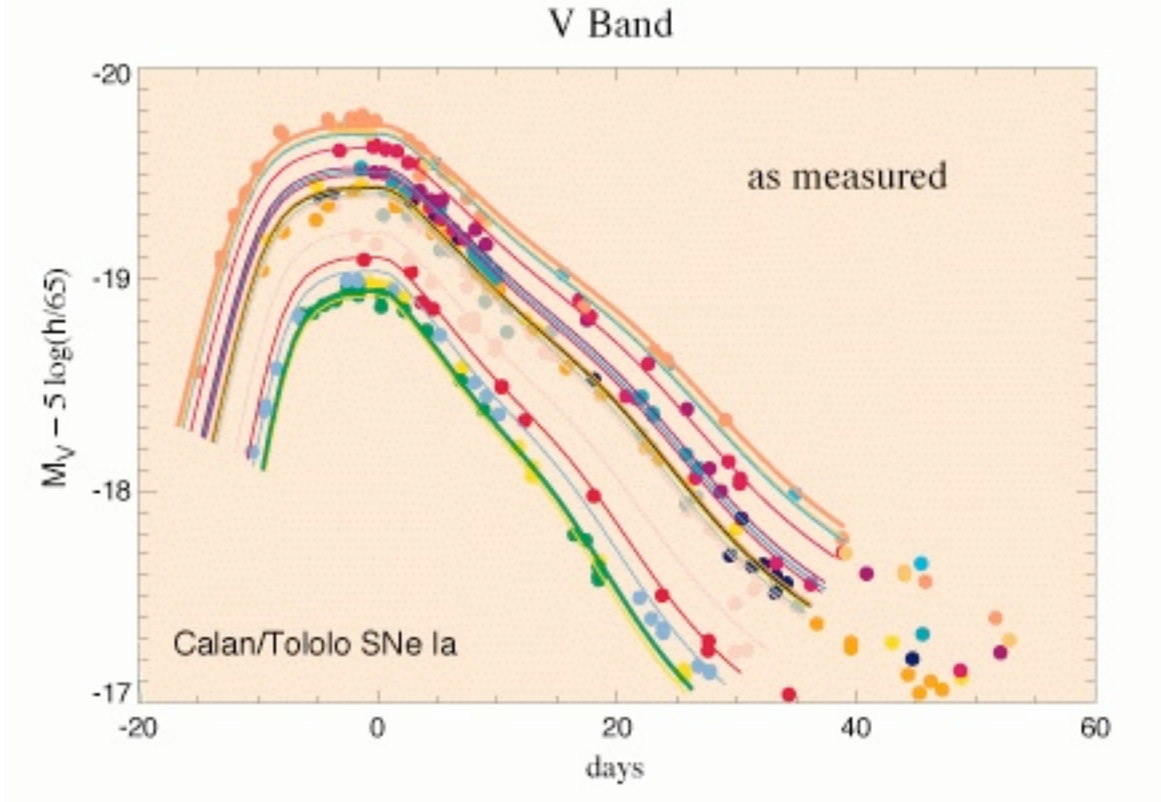


Dark Energy Equation of state $P = w\rho$

Is $w + 1 = 0$? Cosmological Constant

Reading the Wattage of a SN Ia: Empirical Correlations

- Width-Luminosity Relation: an observed correlation (Phillips)
- Observe optical SN Ia Light Curve Shape to estimate the peak luminosity of SN Ia: ~0.2 mag
- Color-Luminosity Relation
- Methods:
  - $\Delta m_{15}(B)$
  - MLCS, Abs LC vs Dust
  - SALT, App. Color single factor



Intrinsically Brighter SN Ia have broader light curves and are slow decliners

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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 errors
2. "Intrinsic Variation" = Population Distribution of SN Ia
3. Random Peculiar Velocities in Hubble Flow
4. Host Galaxy Dust: extinction and reddening.

- Apparent Distributions are convolutions of these effects
- How to incorporate this all into a coherent statistical model? (How to de-convolve?)

Advantages of Hierarchical Models

- Incorporate multiple sources of randomness & uncertainty
- Express structured probability models adapted to data
- Hierarchically Model (Physical) Populations and Individuals simultaneously: e.g. SN Ia and Dust
  - Intrinsic Covariance: Color/Luminosity/Light Curve Shape
  - Dust Reddening/Extinction
- Full (non-gaussian) probability distribution = Global, coherent quantification of uncertainties
- Completely Explore & Marginalize Posterior trade-offs/degeneracies/ joint distributions
- Deals with incomplete/missing data problems
  - Make best inference/estimate for the observed data
- Modularity

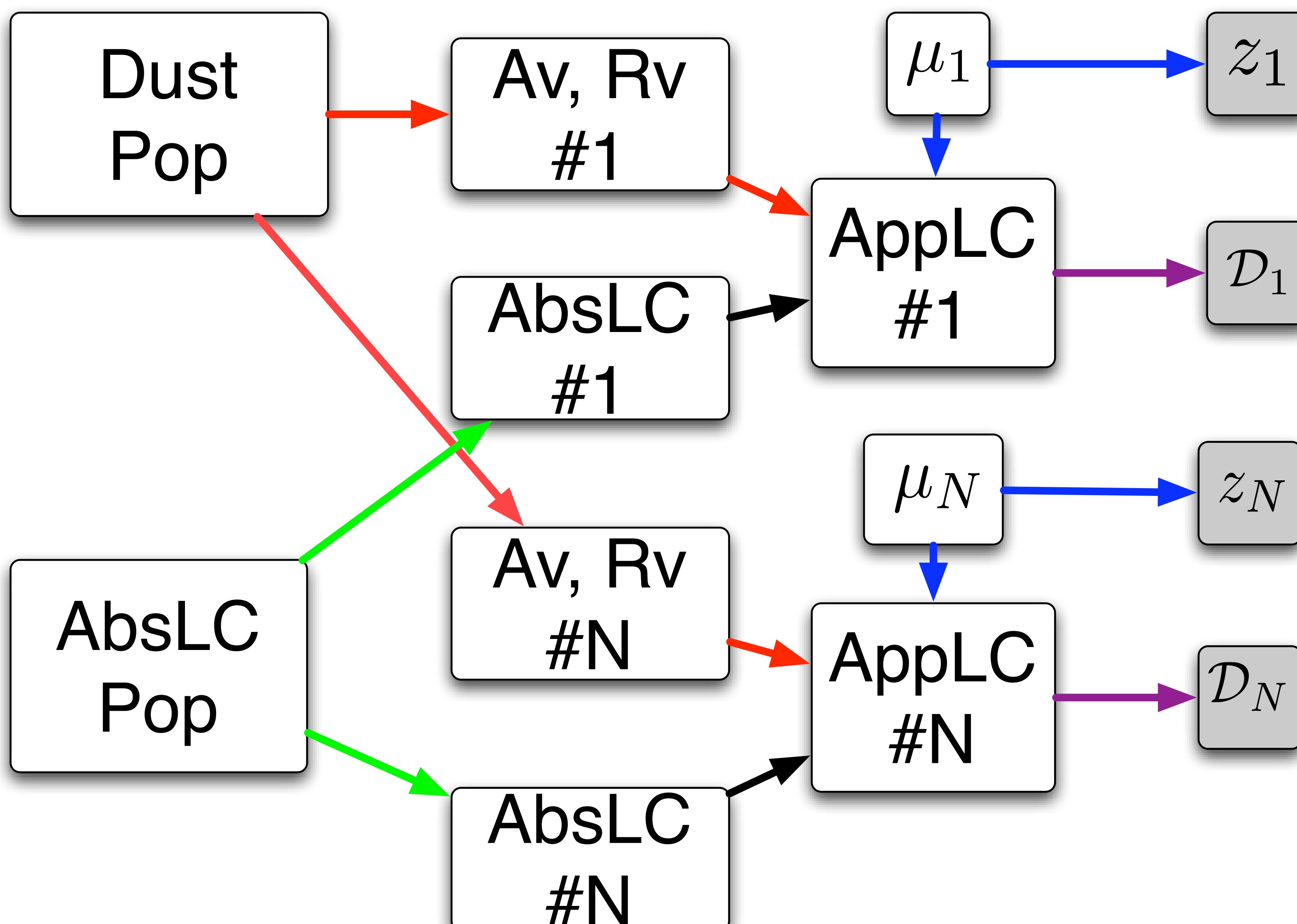
Directed Acyclic Graph for SN Ia Inference with Hierarchical Modeling

- Intrinsic Randomness
- Dust Extinction & Reddening
- Peculiar Velocities
- Measurement Error

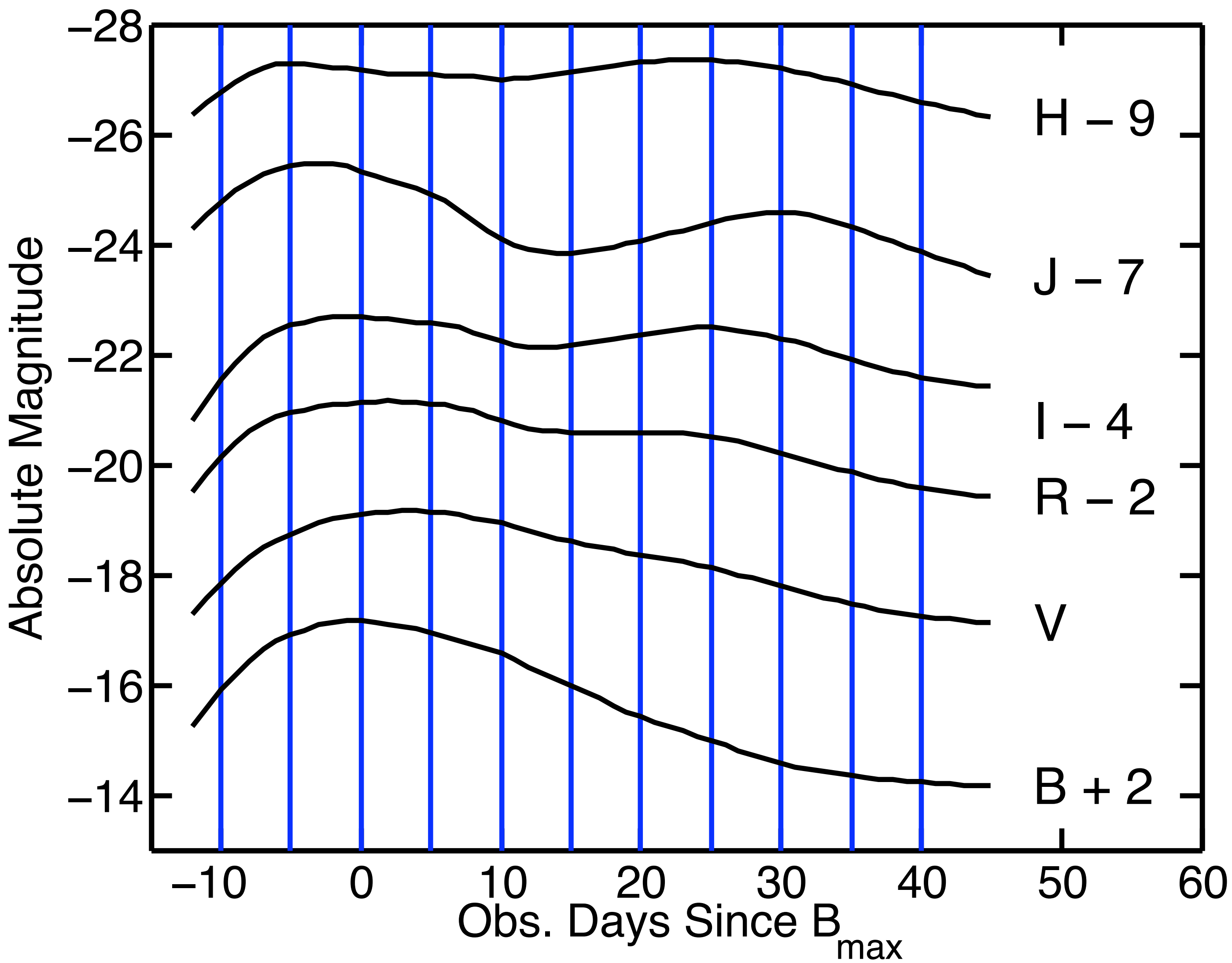
"Training" - Learn about Populations

Generative Model

Global Joint Posterior Probability Density Conditional on all SN Data

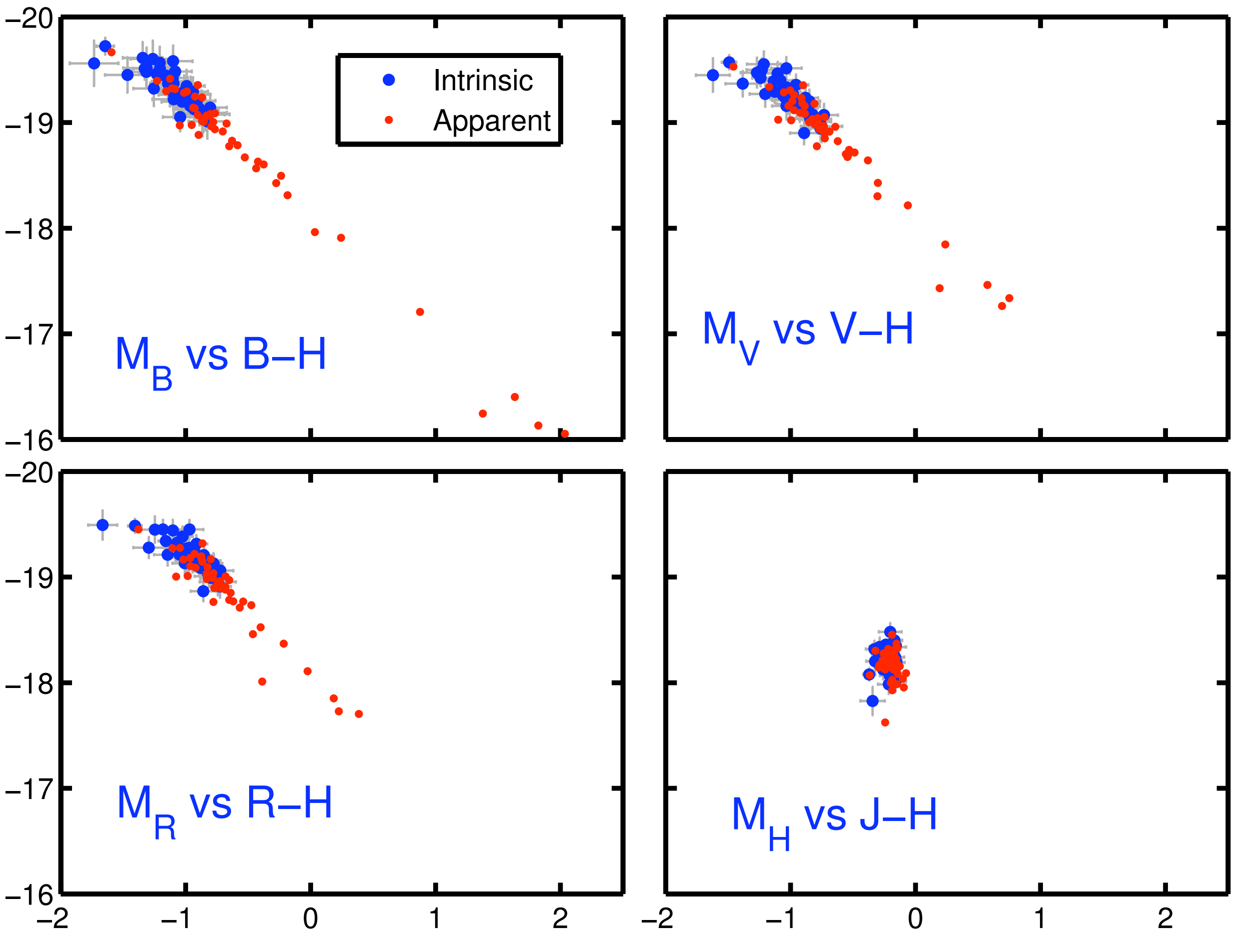


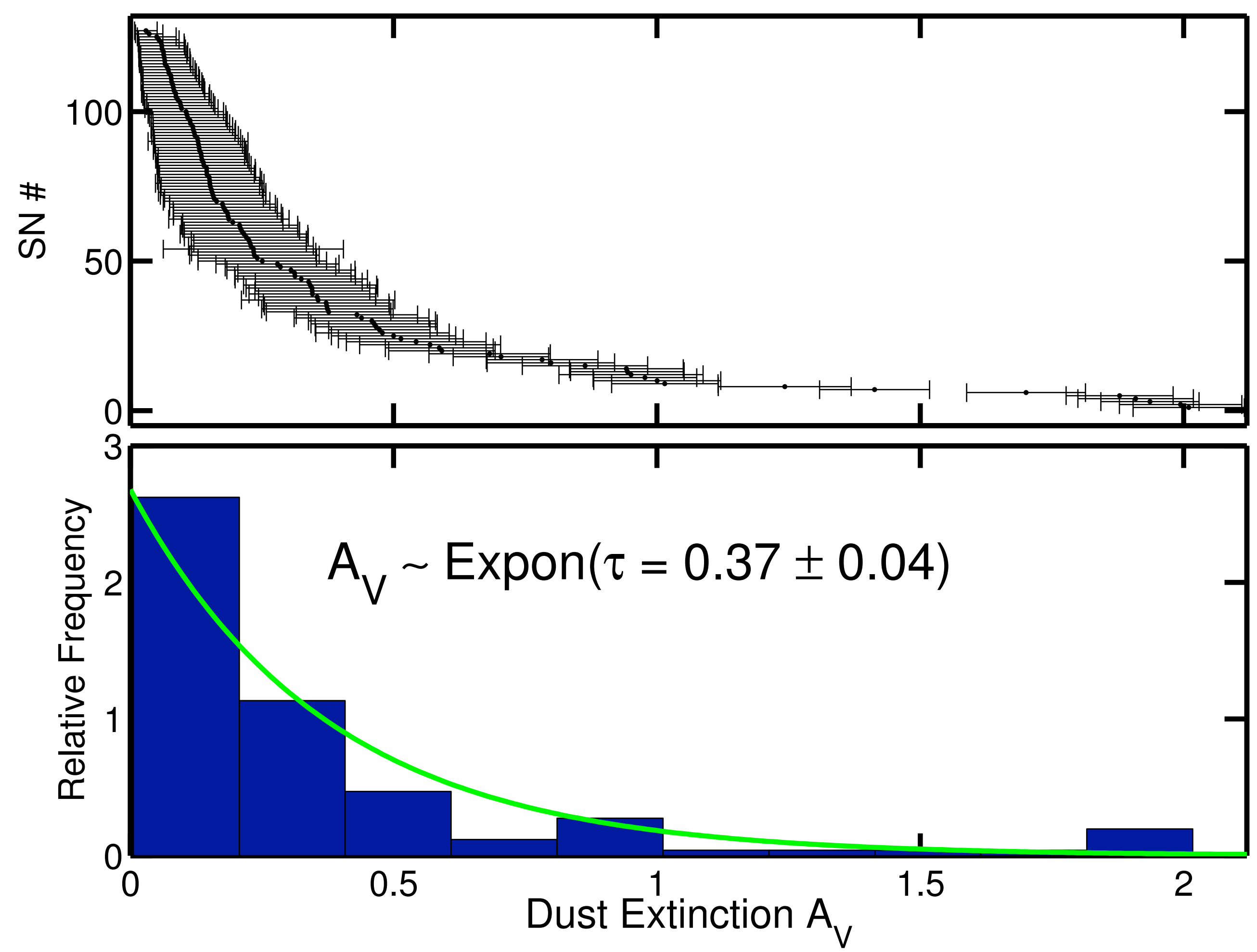
Representing SN Ia Light curves: Differential Decline rates



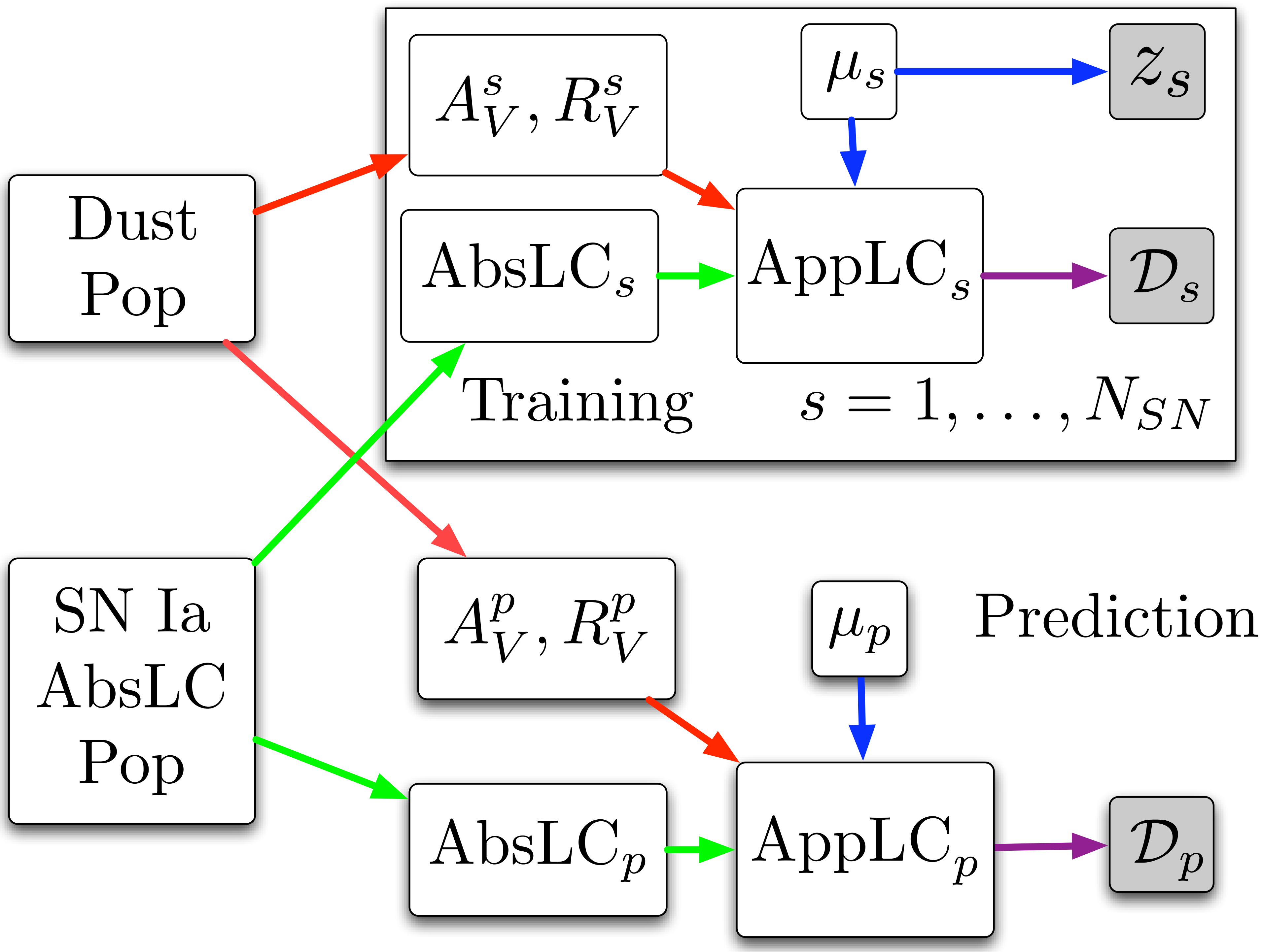
- Gaussian Process over Decline Rates at different Wavelengths / Phases and Peak Luminosities
- Goal: Infer the Intrinsic Covariance Structure of SN Ia light curves over multiple wavelengths and phases
- Use to make "best" distance predictions

Positive Dust only Dims and Reddens





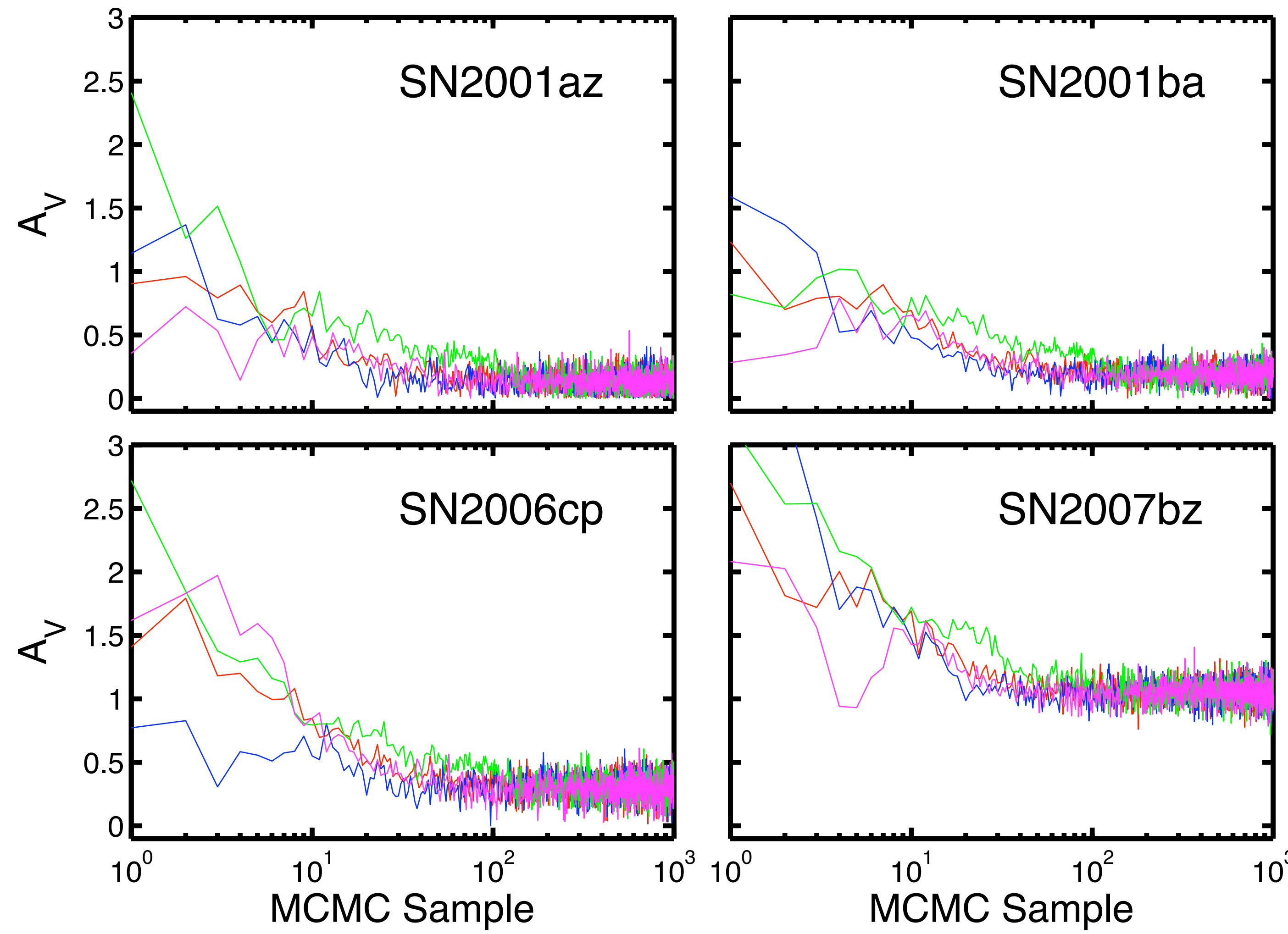
Directed Acyclic Graph for SN Ia Inference: Distance Prediction



Statistical Computation with Hierarchical SN Ia Models: The BayeSN Algorithm

- Strategy: Generate a Markov Chain to sample global parameter space (populations & all individuals) => seek a global solution

- Chain explores/samples trade-offs/degeneracies in global parameter space

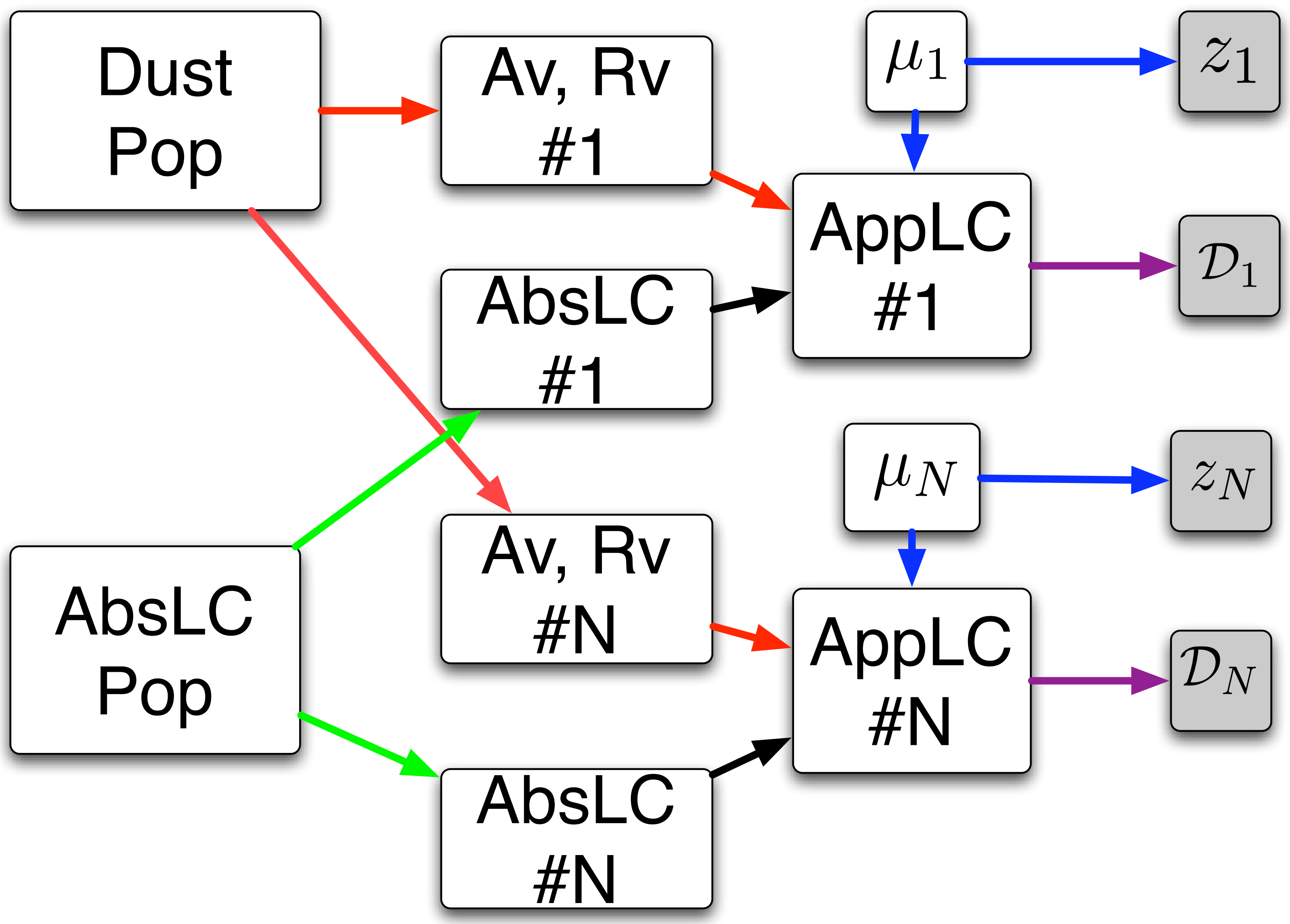


Multiple chains globally converge from random initial values

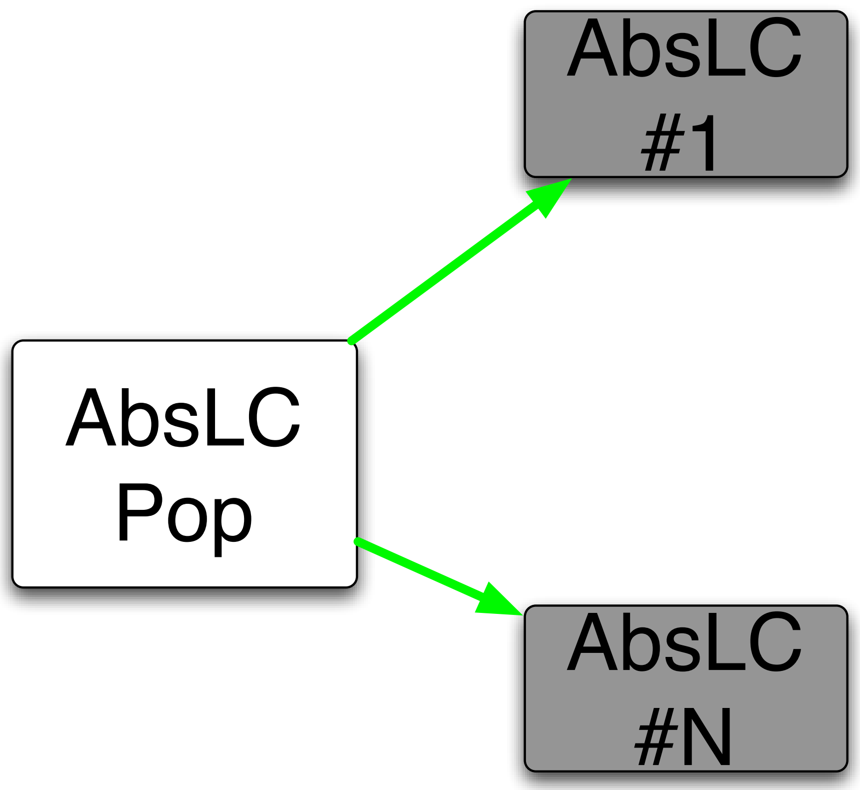
BayeSN

- Metropolis-Hastings within Gibbs Sampling Structure to exploit conditional structure
- Requires (almost) no tuning of jump sizes
- Generalized Conditional Sampling to speed up exploring trade-off between dust and distance: $(A_V, \mu) \rightarrow (A_V, \mu) + \gamma(1, -x)$
- Run several (4-8) parallel chains and compute Gelman-Rubin ratio to diagnose convergence

BayeSN in Graphs



BayeSN in Graphs



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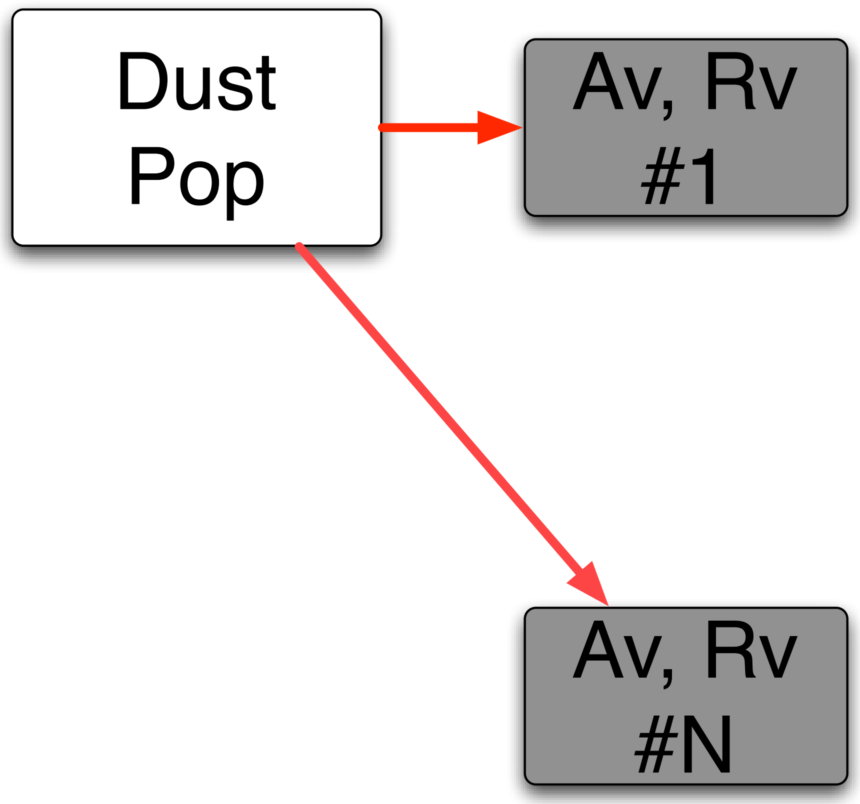
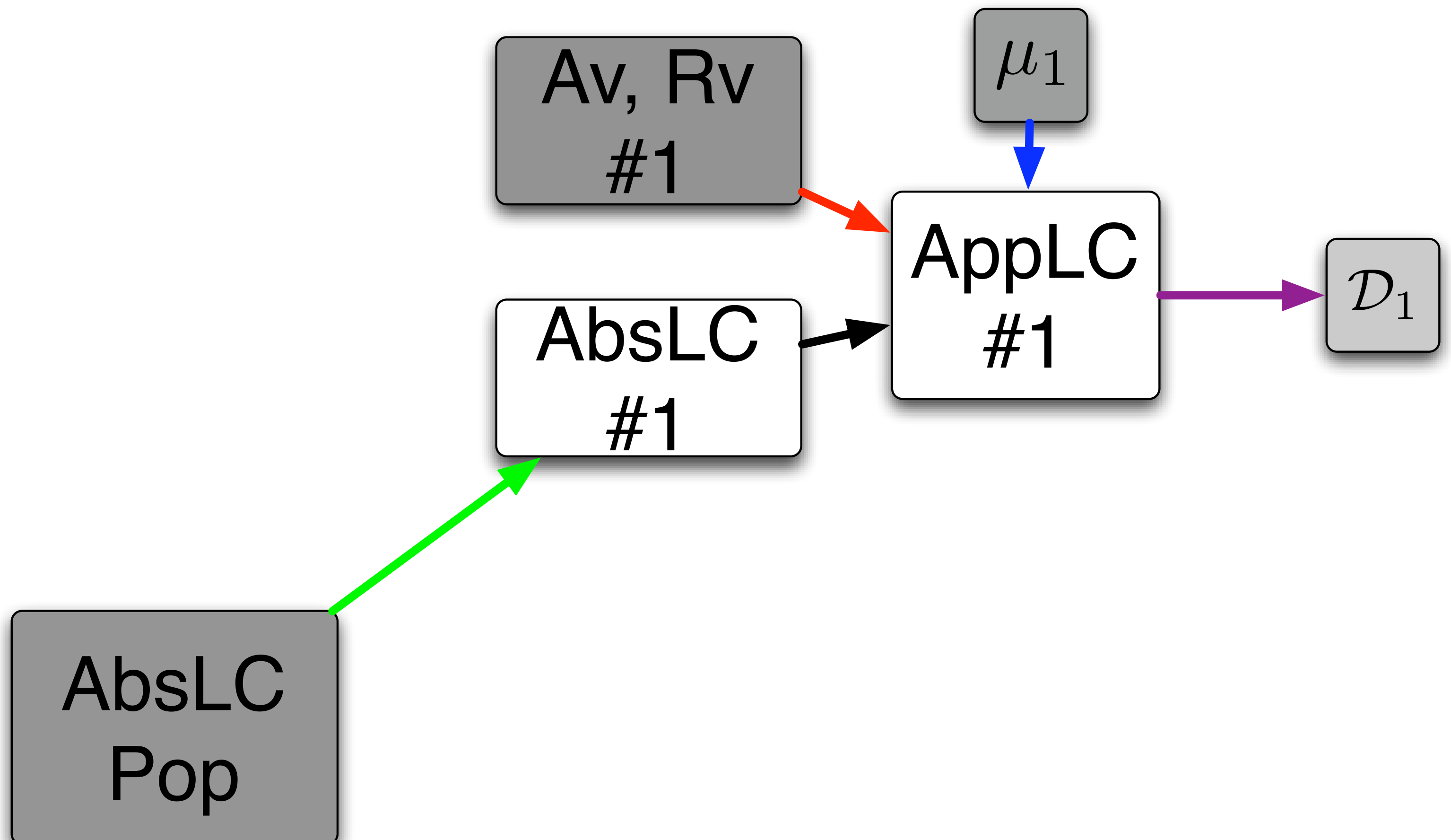
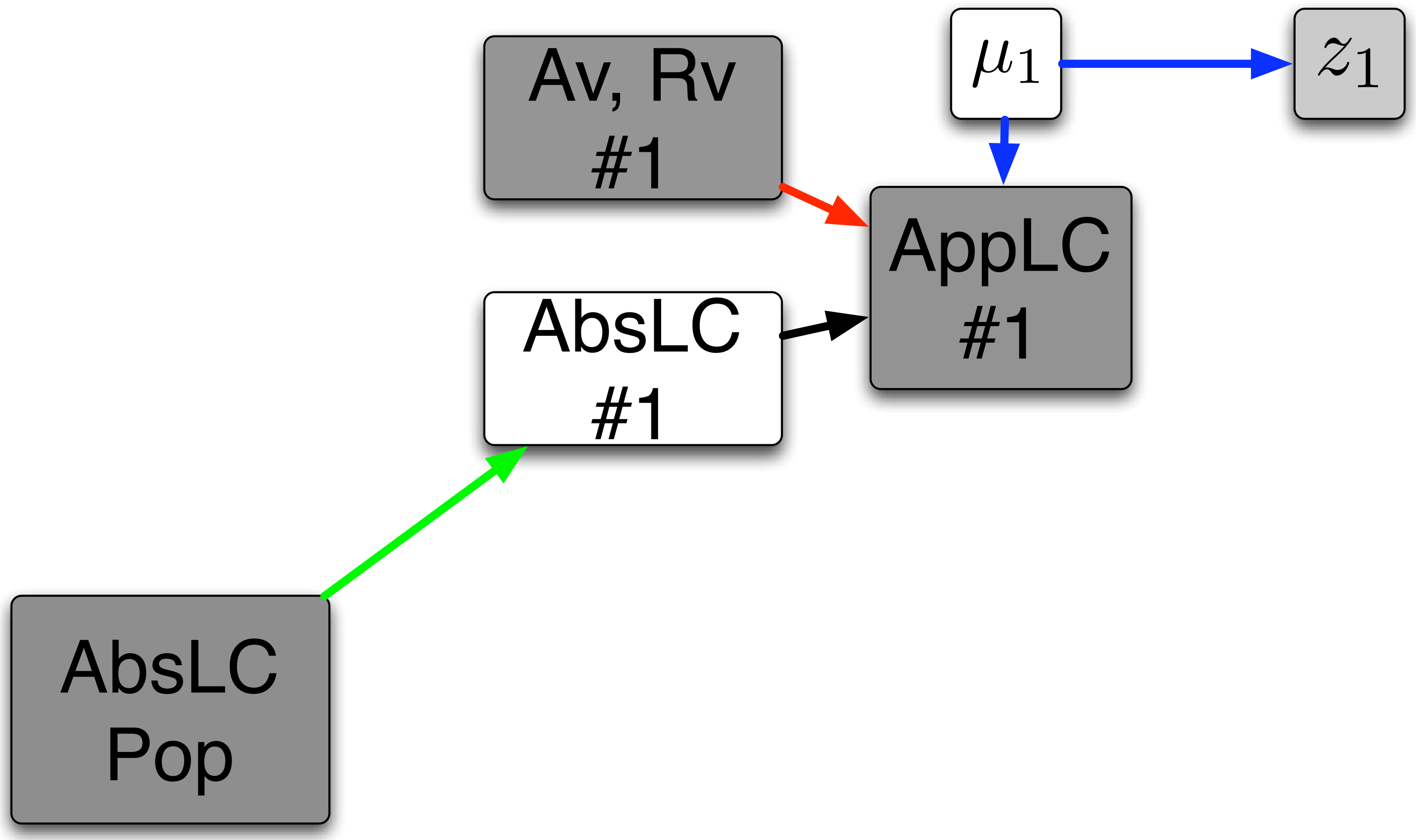


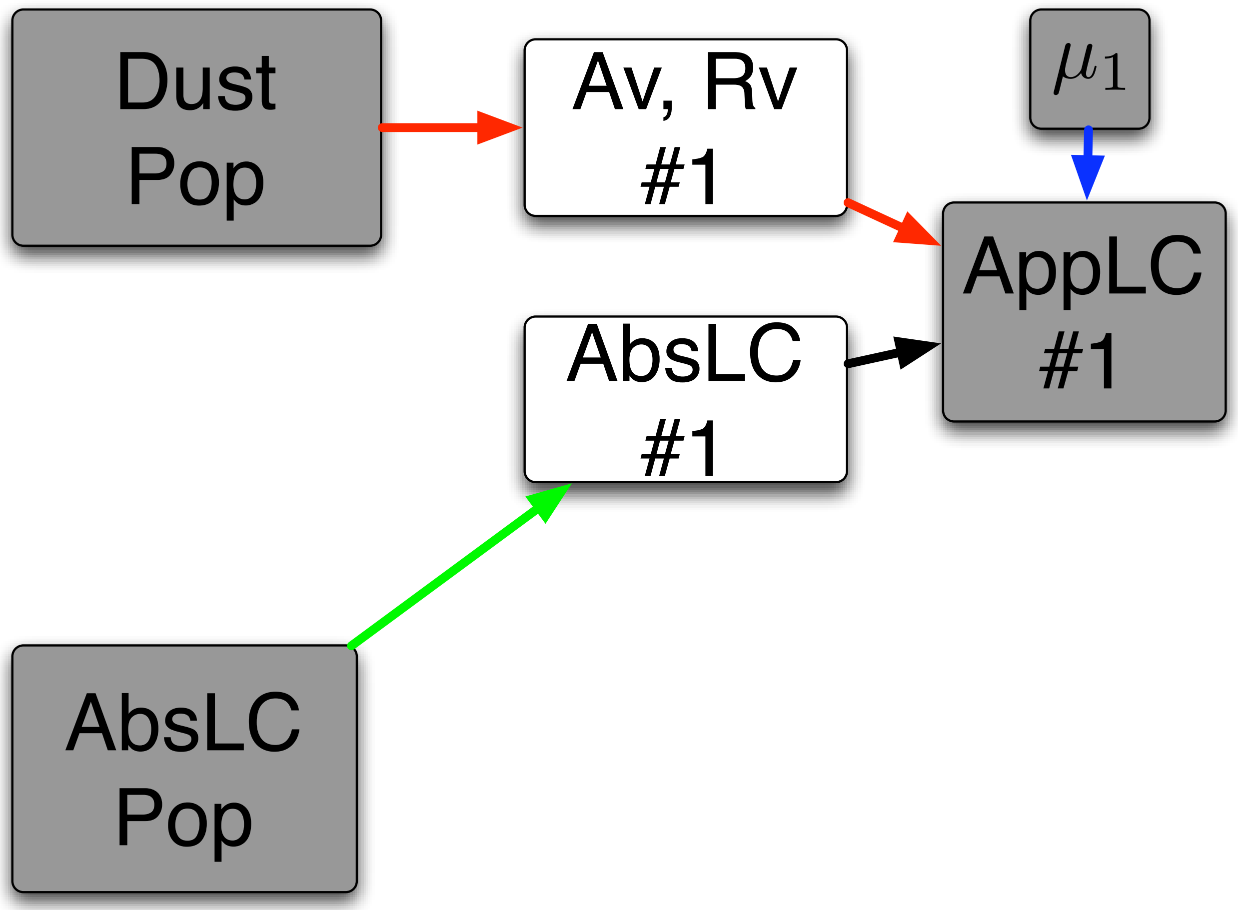
BayeSN in Graphs



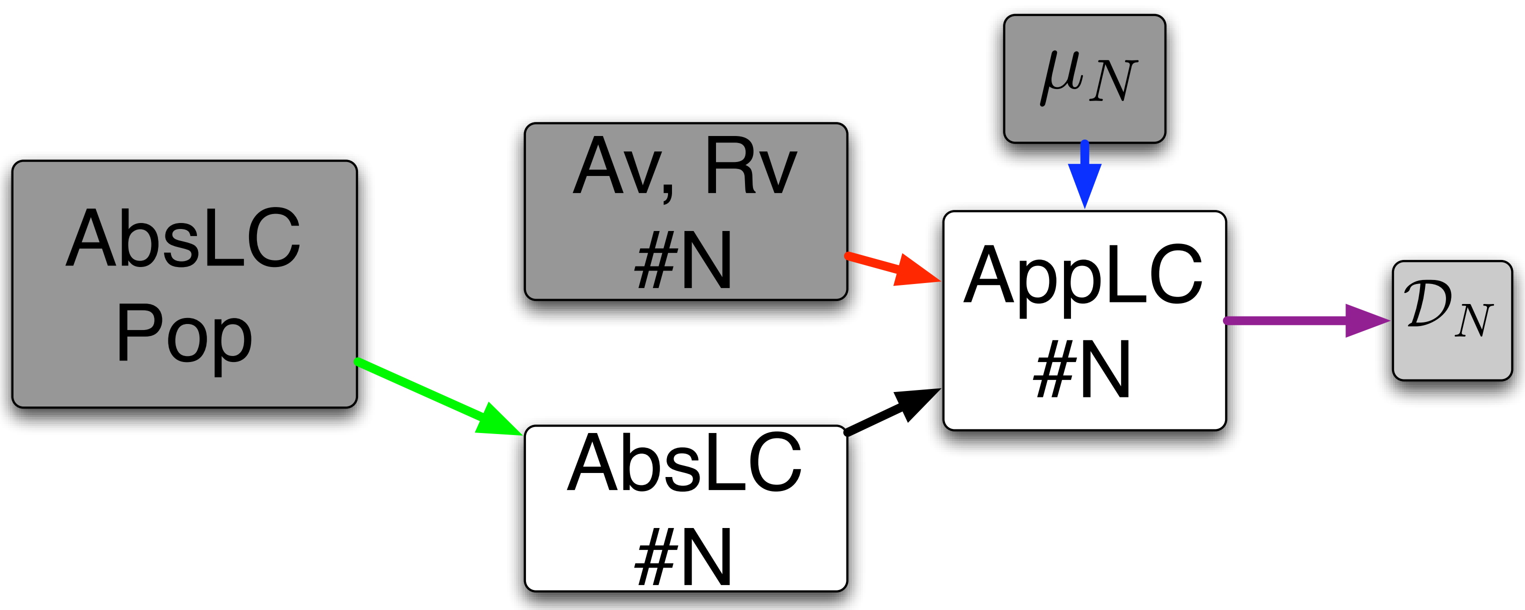
BayeSN in Graphs



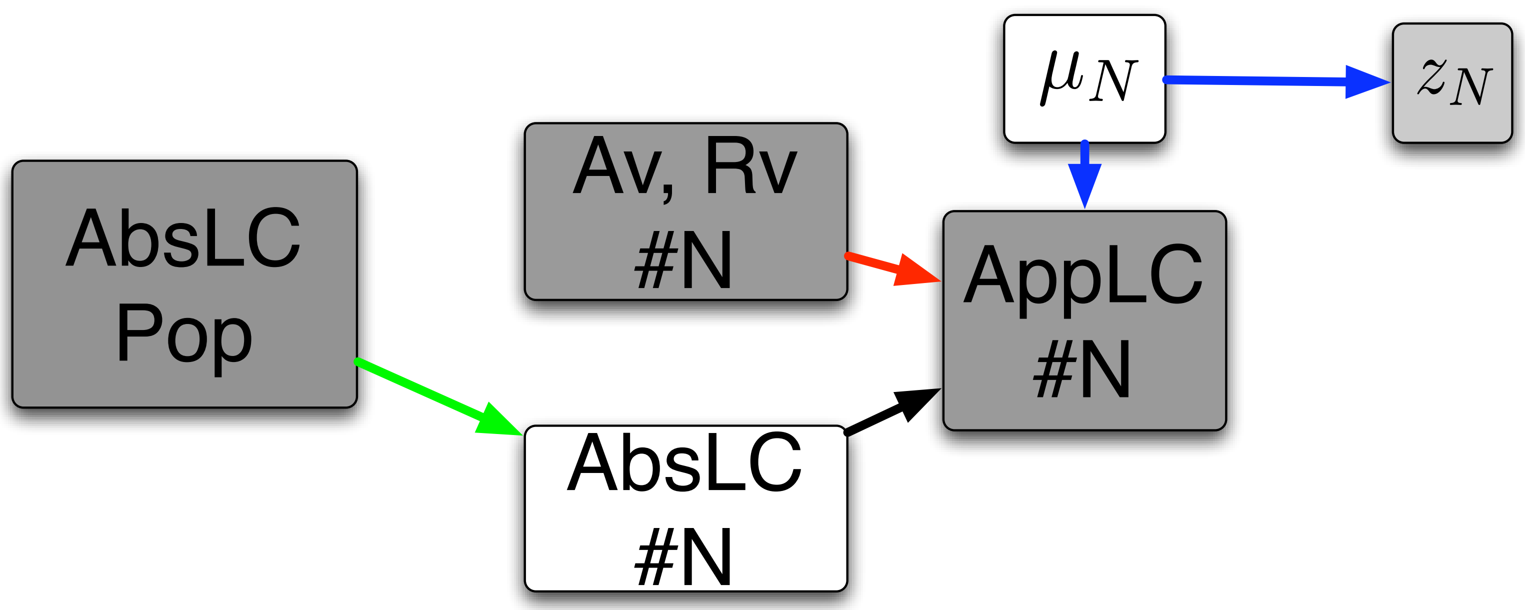
BayeSN in Graphs



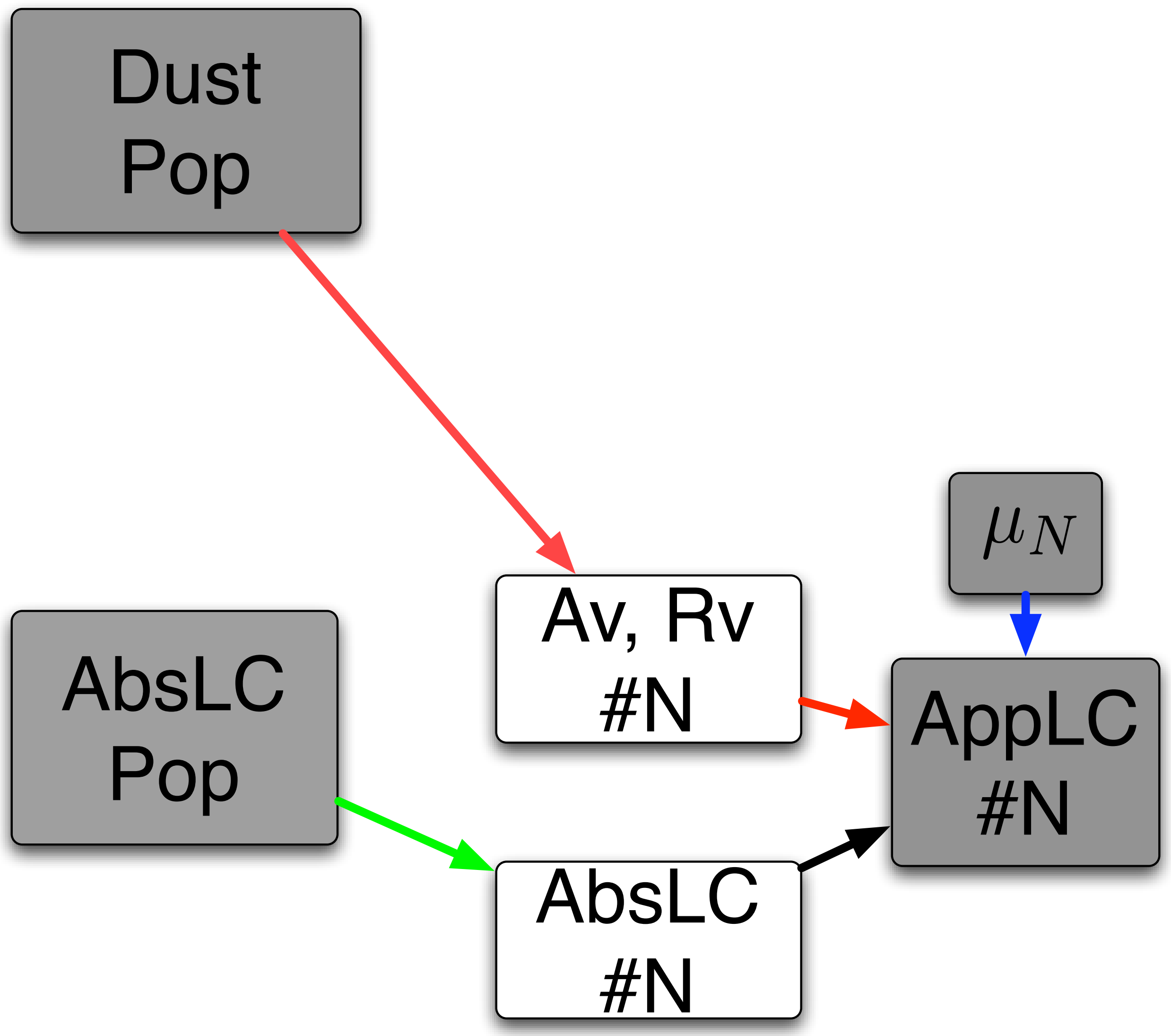
BayeSN in Graphs



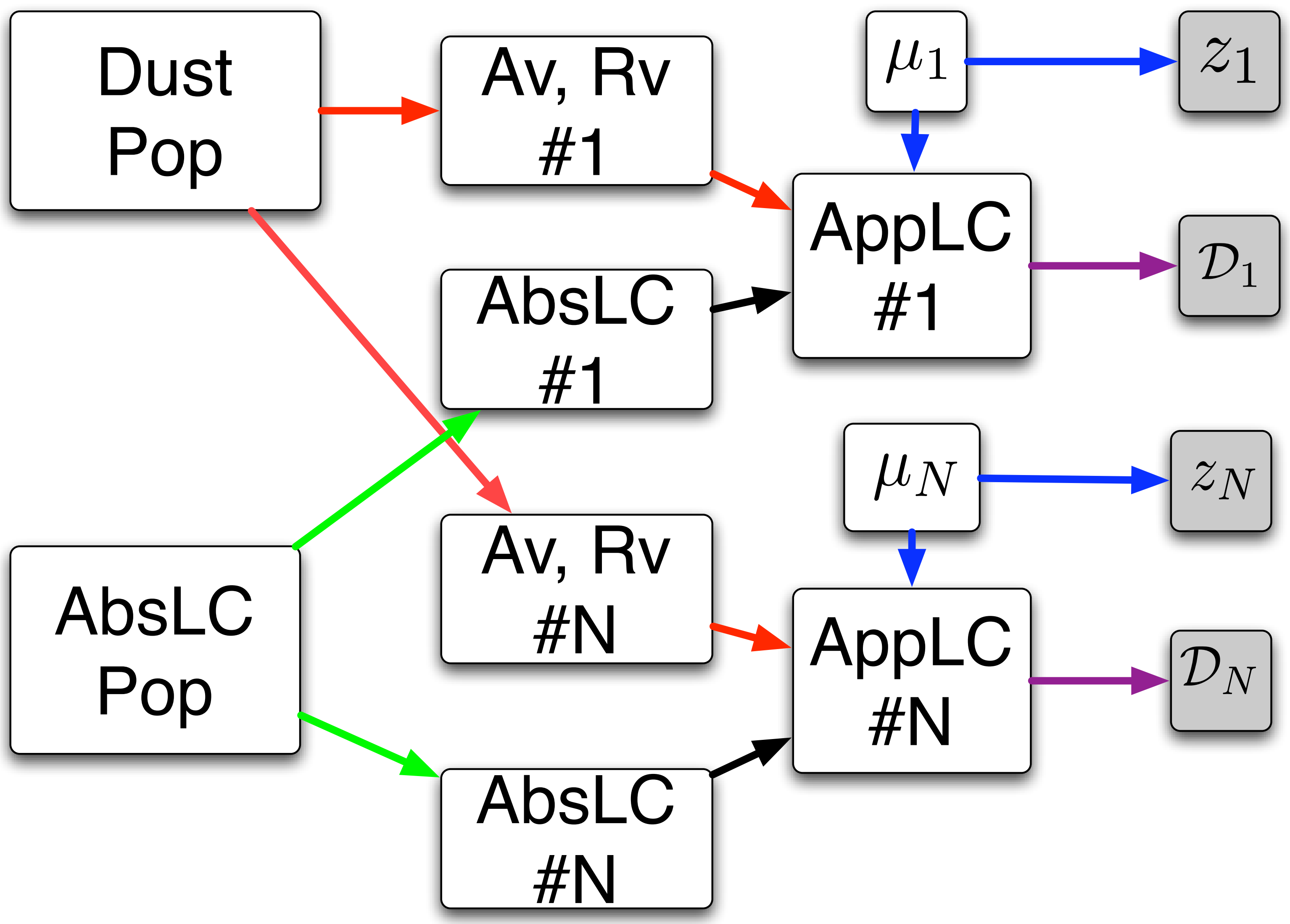
BayeSN in Graphs



BayeSN in Graphs



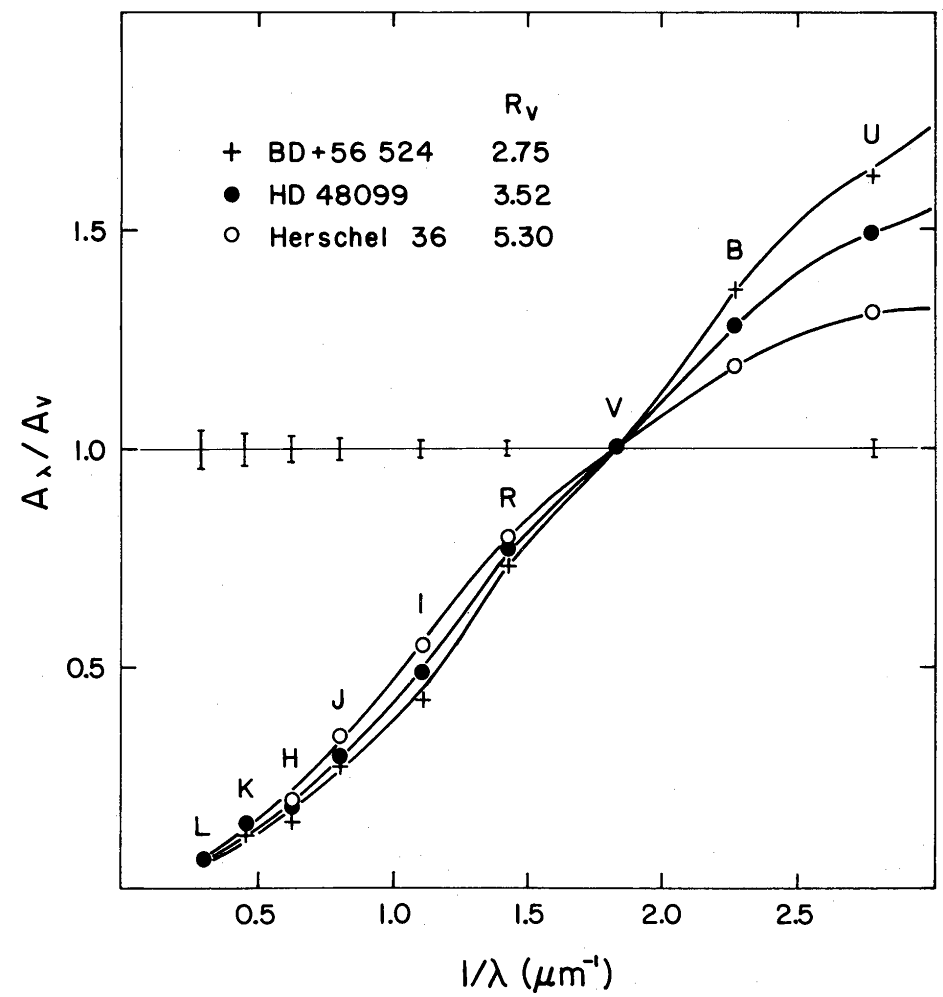
BayeSN in Graphs



Practical Application of Hierarchical Model: NIR SN Ia

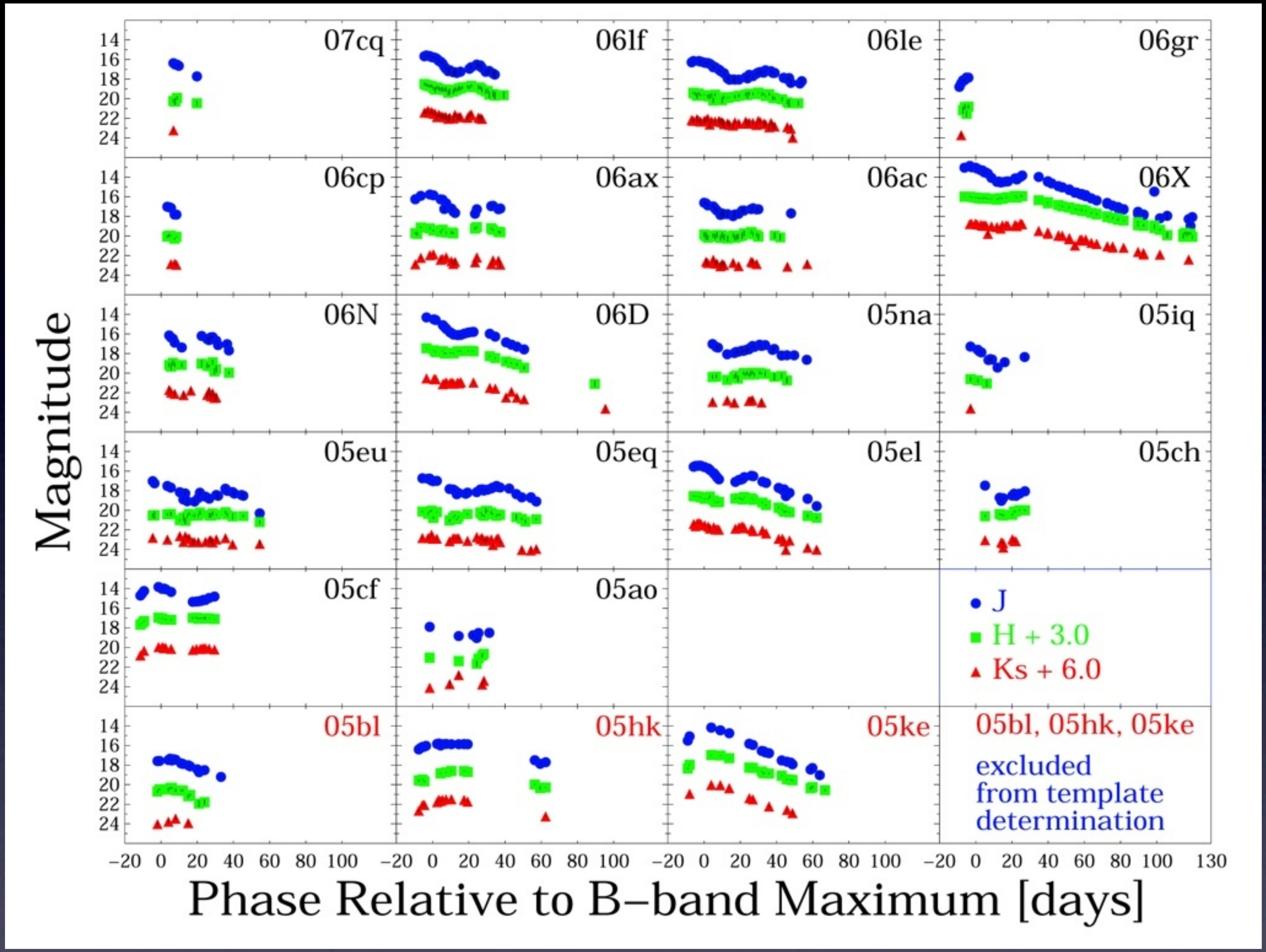
Why are SN Ia in NIR interesting?

- Host Galaxy Dust presents a major systematic uncertainty in supernova cosmology inference
- Dust extinction has significantly reduced effect in NIR bands
- NIR SN Ia are good standard candles (Elias et al. 1985, Meikle 2000, Krisciunas et al. 2004+, Wood-Vasey et al. 2008, Mandel et al. 2009).
- Observe in NIR!: PAIRITEL /CfA



Nearby SN Ia in the NIR: PAIRITEL

Observed in NIR
J (λ=1.2 μm)
H (λ=1.6 μm)
Ks (λ=2.2 μm)



Credit: Michael Wood-Vasey, Andrew Friedman

CfA3:
183 Optical SN Ia Light Curves
(Hicken et al. 2009)

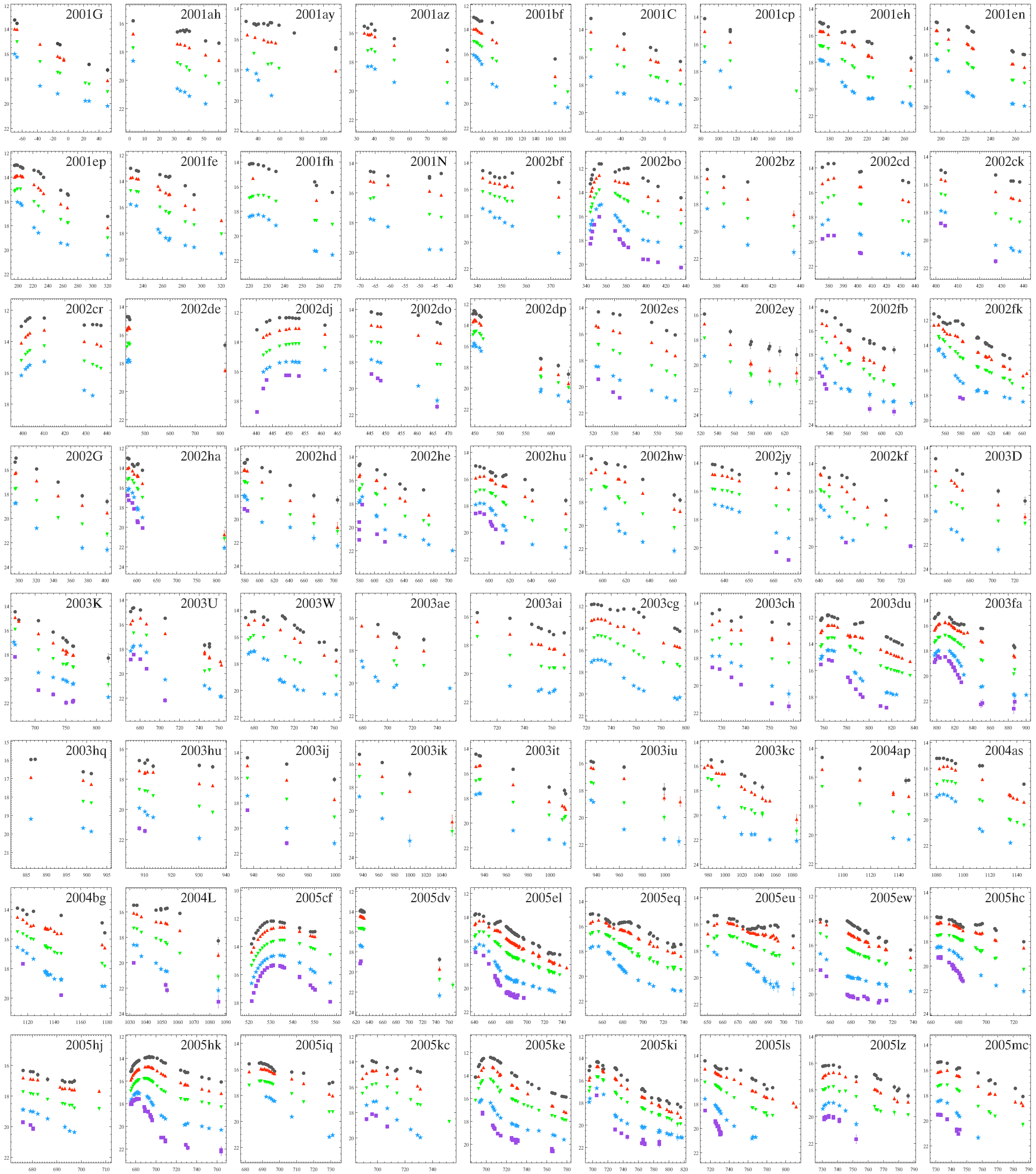
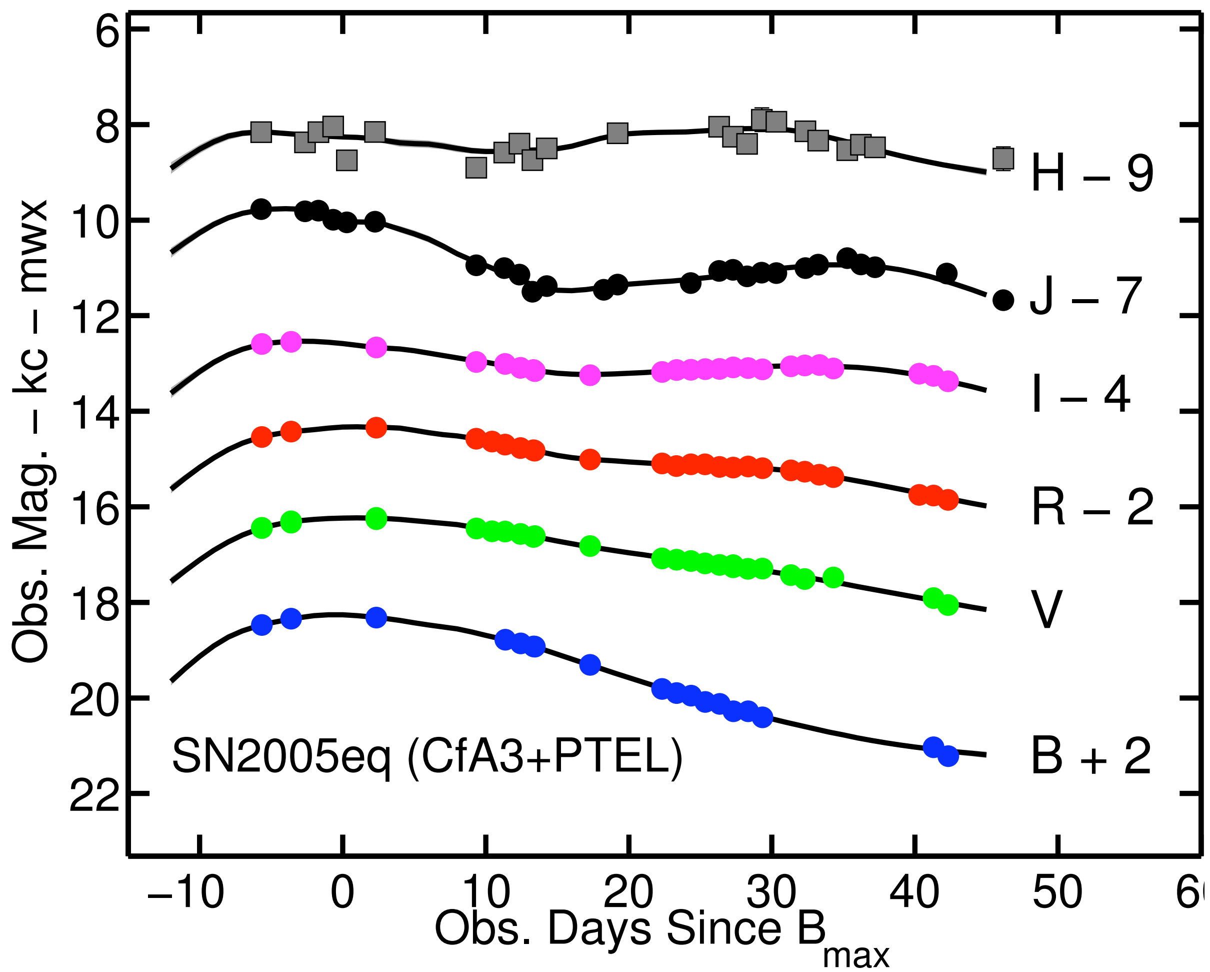


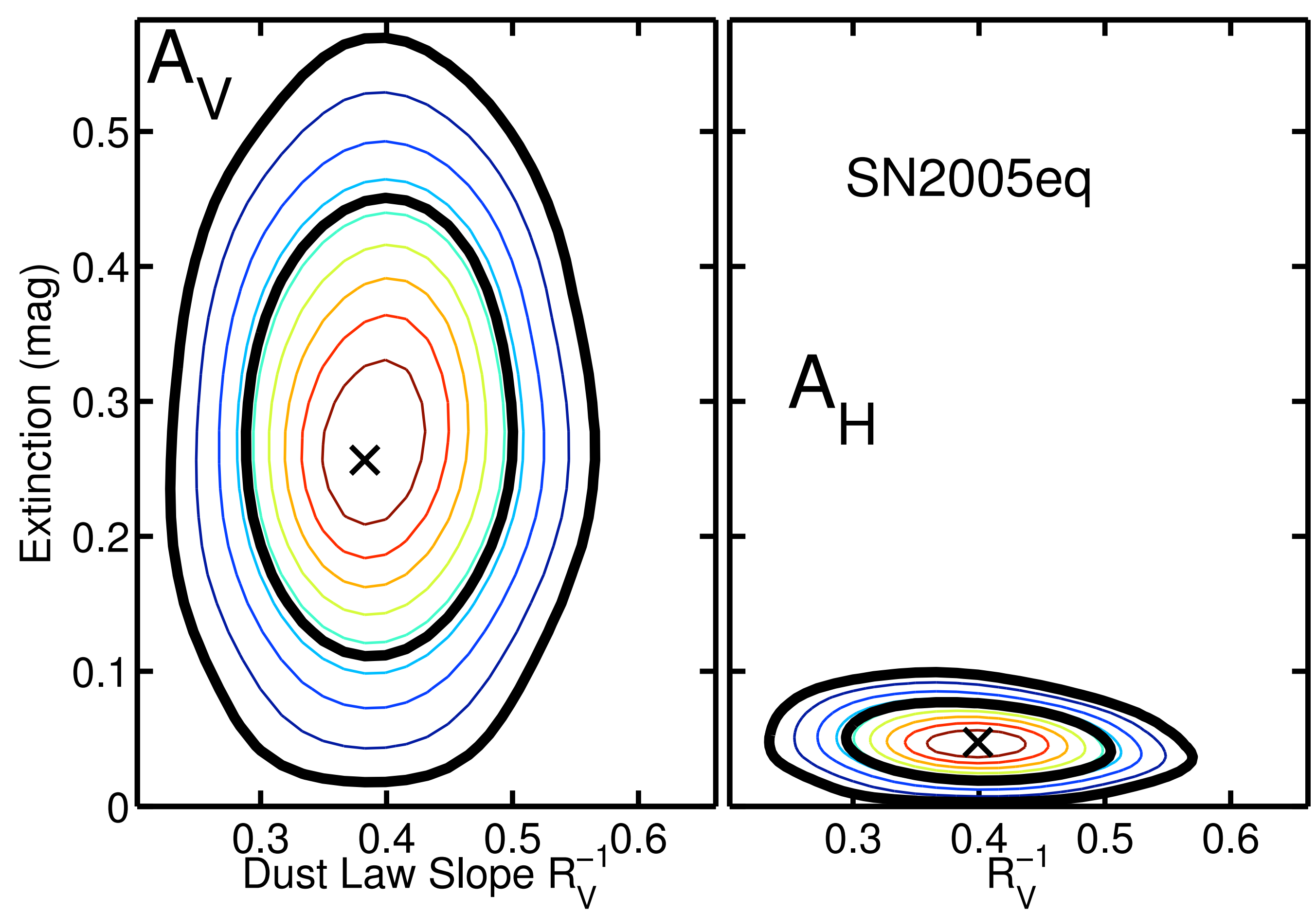
Figure 1: 142 CfA Light curves from 2000-2004 ($UBVRI$) and 2004-2007 ($UBVri$)

Optical+NIR Hierarchical Model Inference

PTEL+CfA3 Light-curves

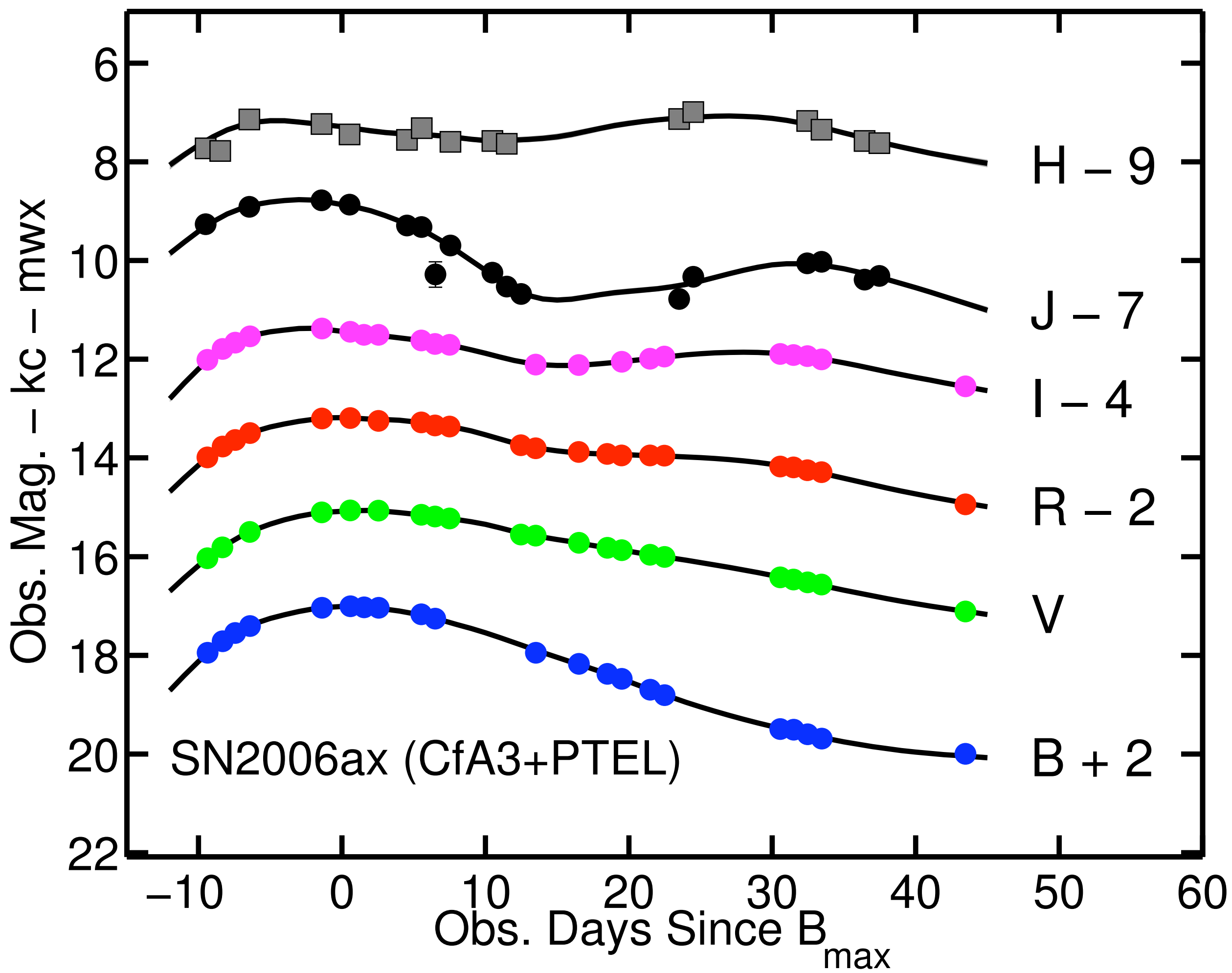


Marginal Posterior of Dust

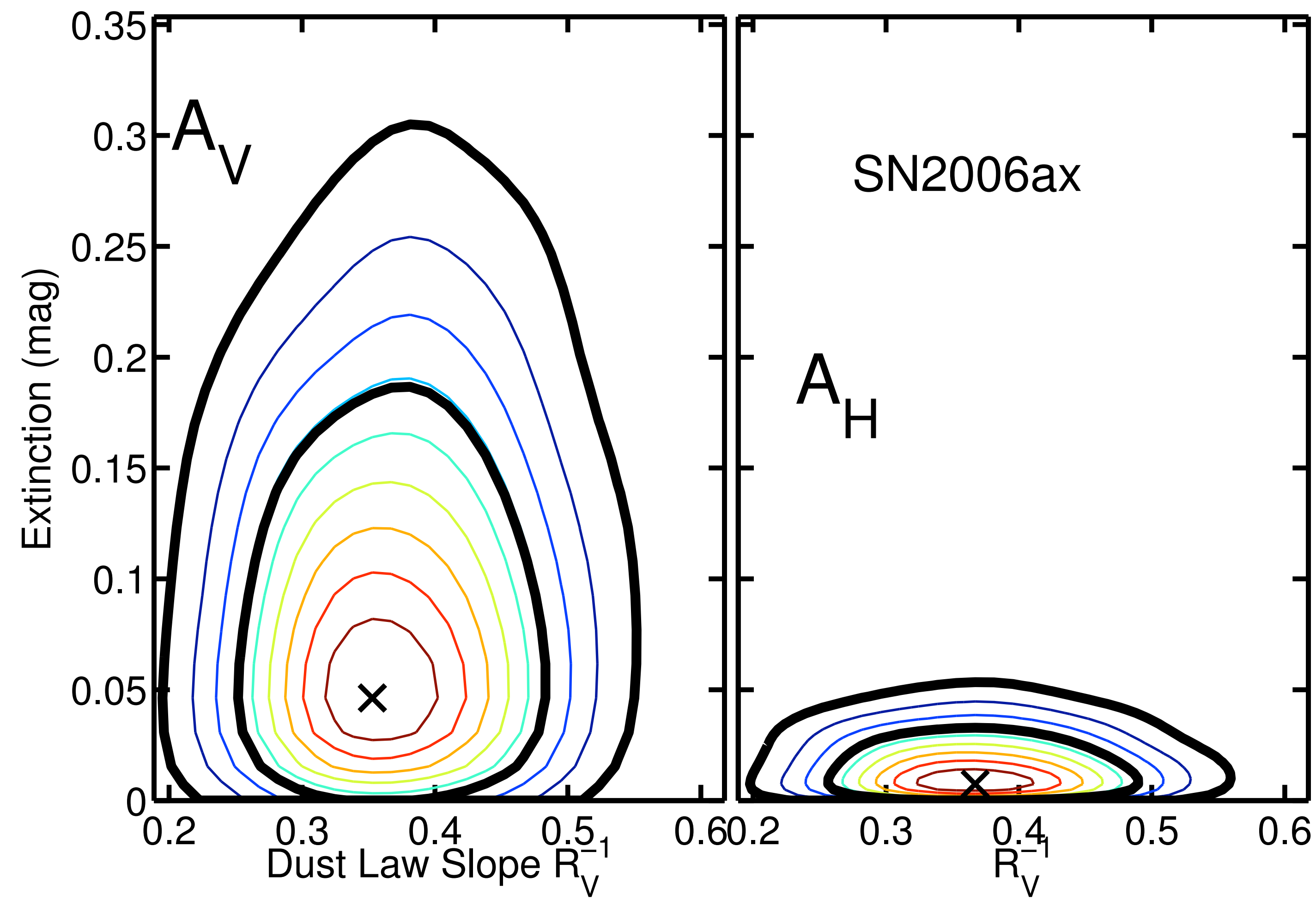


Optical+NIR Hierarchical Model Inference

PTEL+CfA3 Light-curves

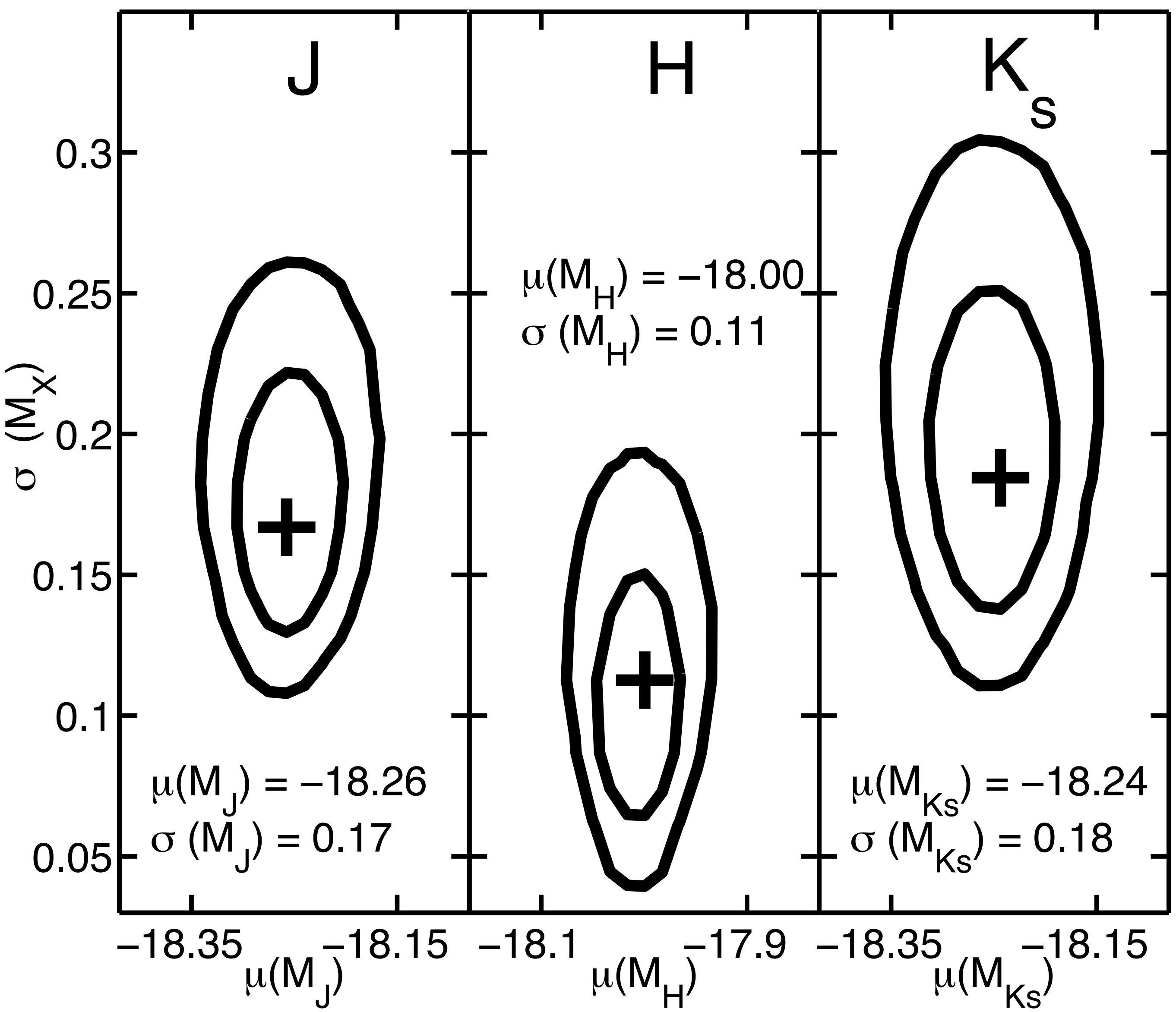


Marginal Posterior of Dust



SN NIR Population Inference: Peak Absolute Magnitudes

Marginal Distributions of SN Ia NIR Absolute Magnitude Variances



Mandel et al. 2009

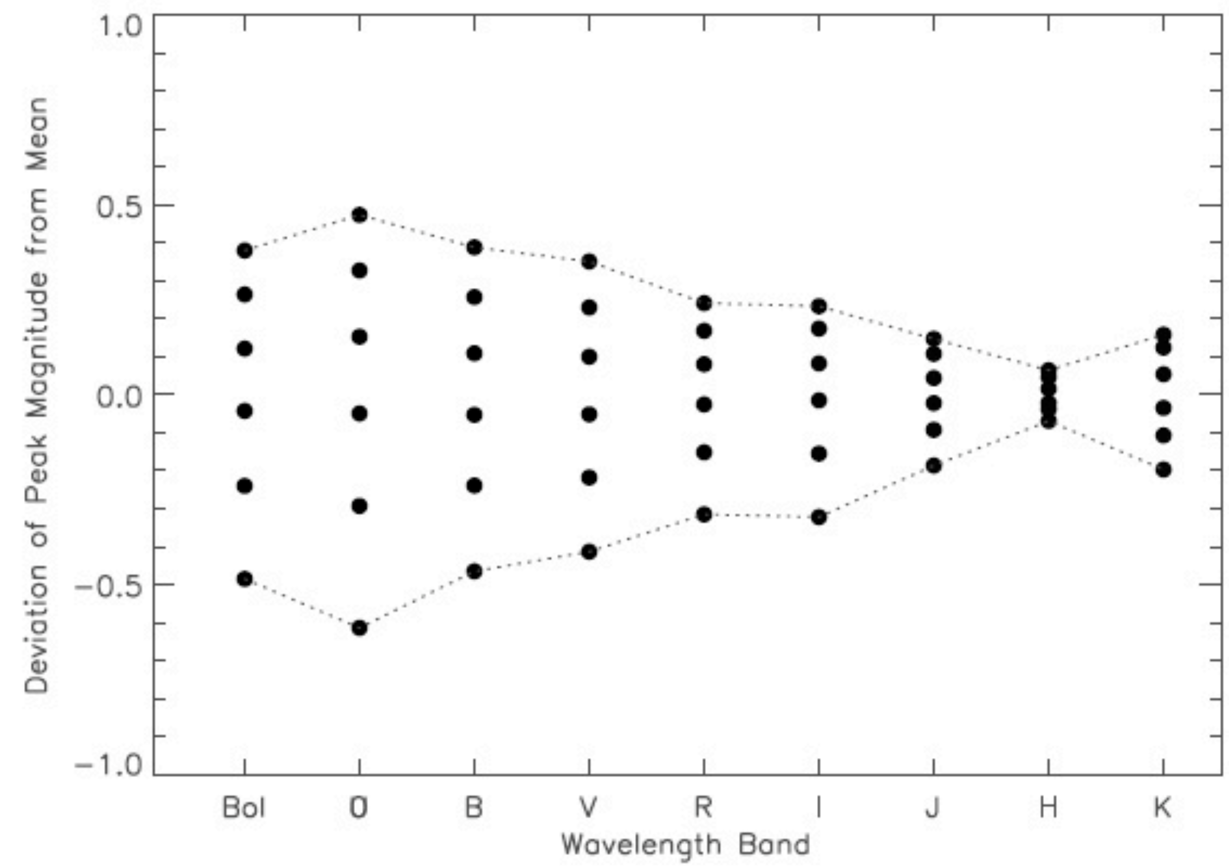
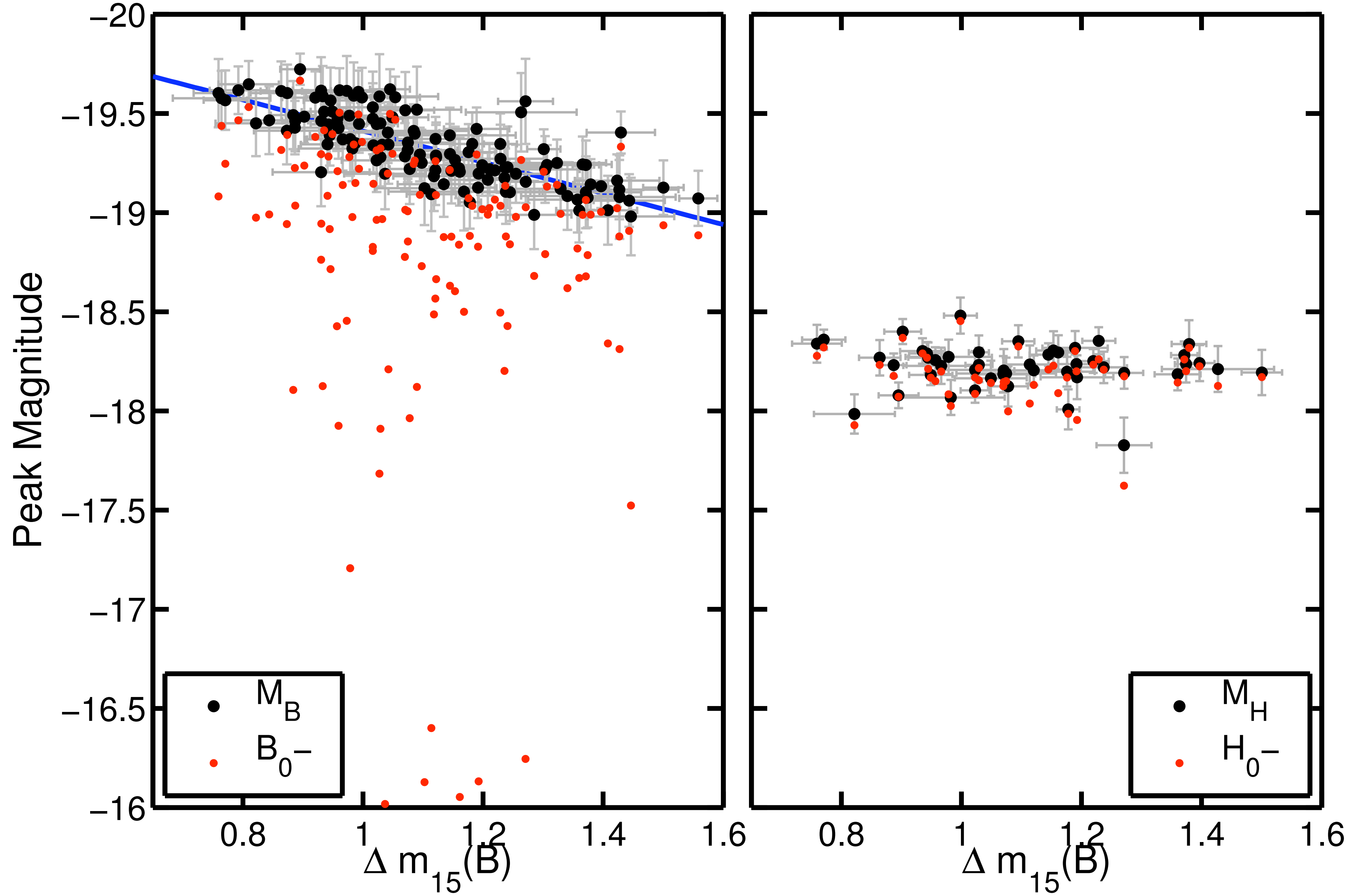


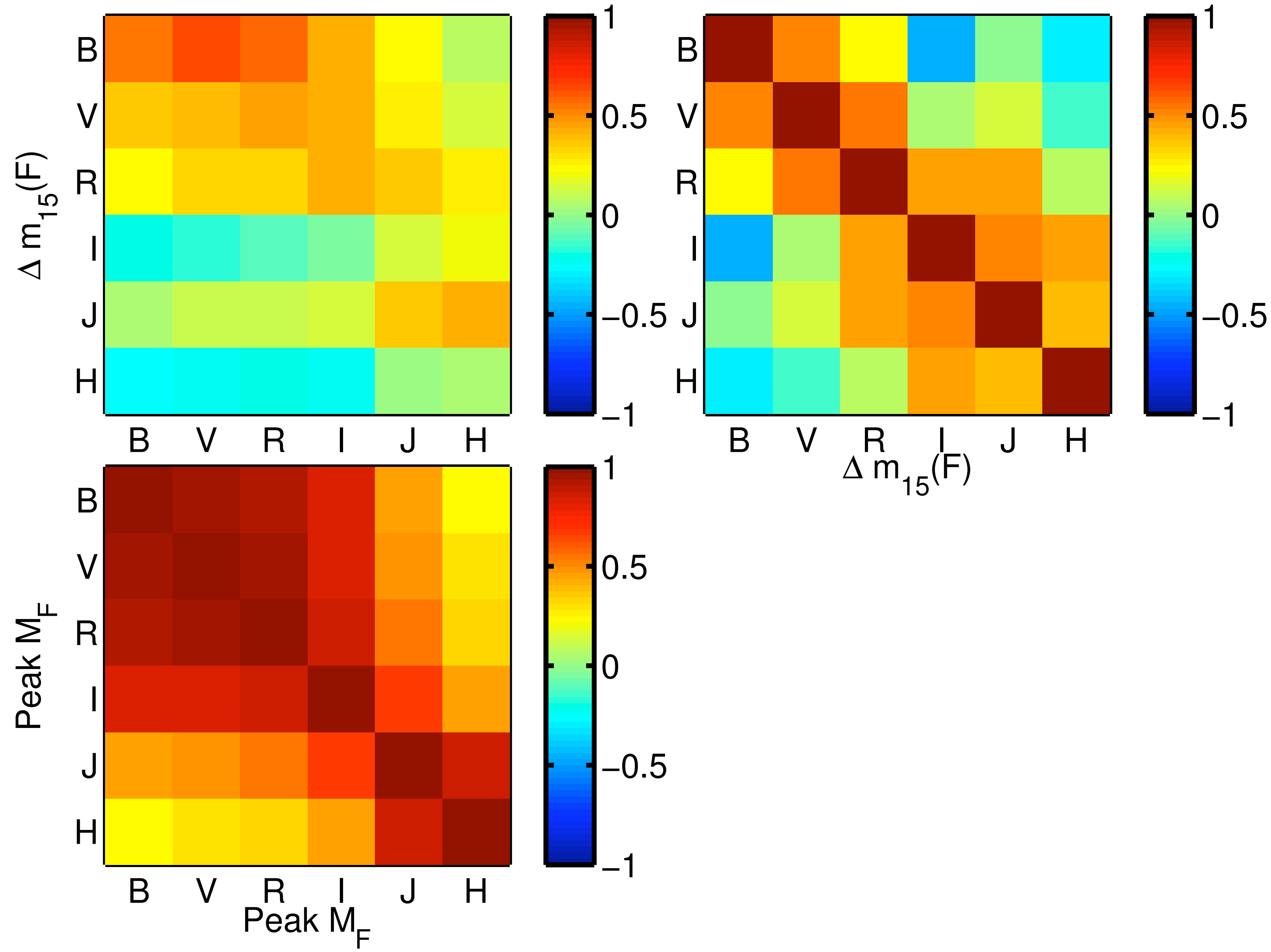
FIG. 15.—Dispersion in peak magnitude (measured at the first light curve maximum) as a function of wavelength band for the models of Fig. 10 with ^{56}Ni masses between 0.4 and 0.9 $M_\odot$. [*See the electronic edition of the Journal for a*

Kasen 2006

Optical and Near Infrared Luminosity vs. Decline Rate



Population Analysis



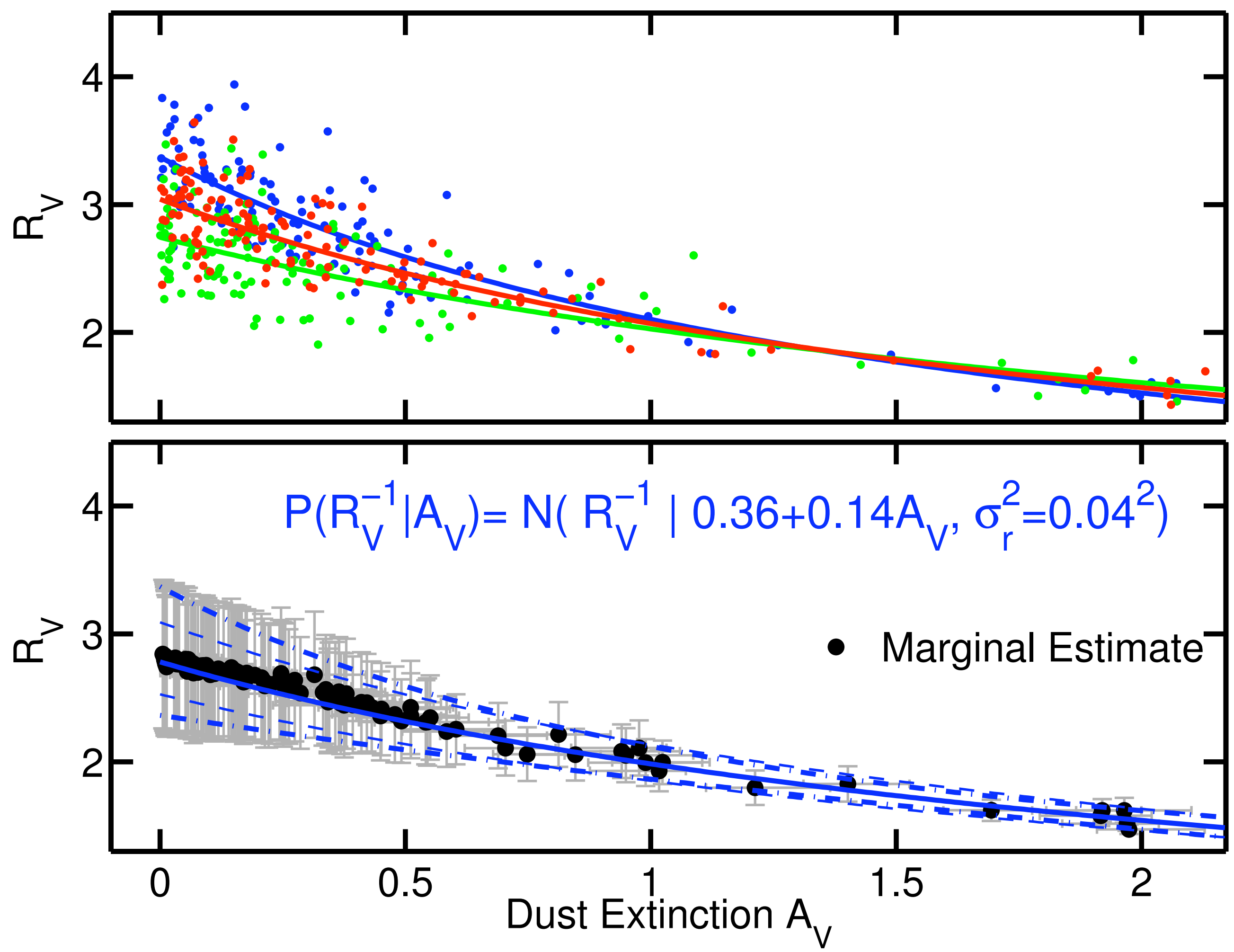
Intrinsic Correlation Map for Abs Magnitudes and Decline Rates

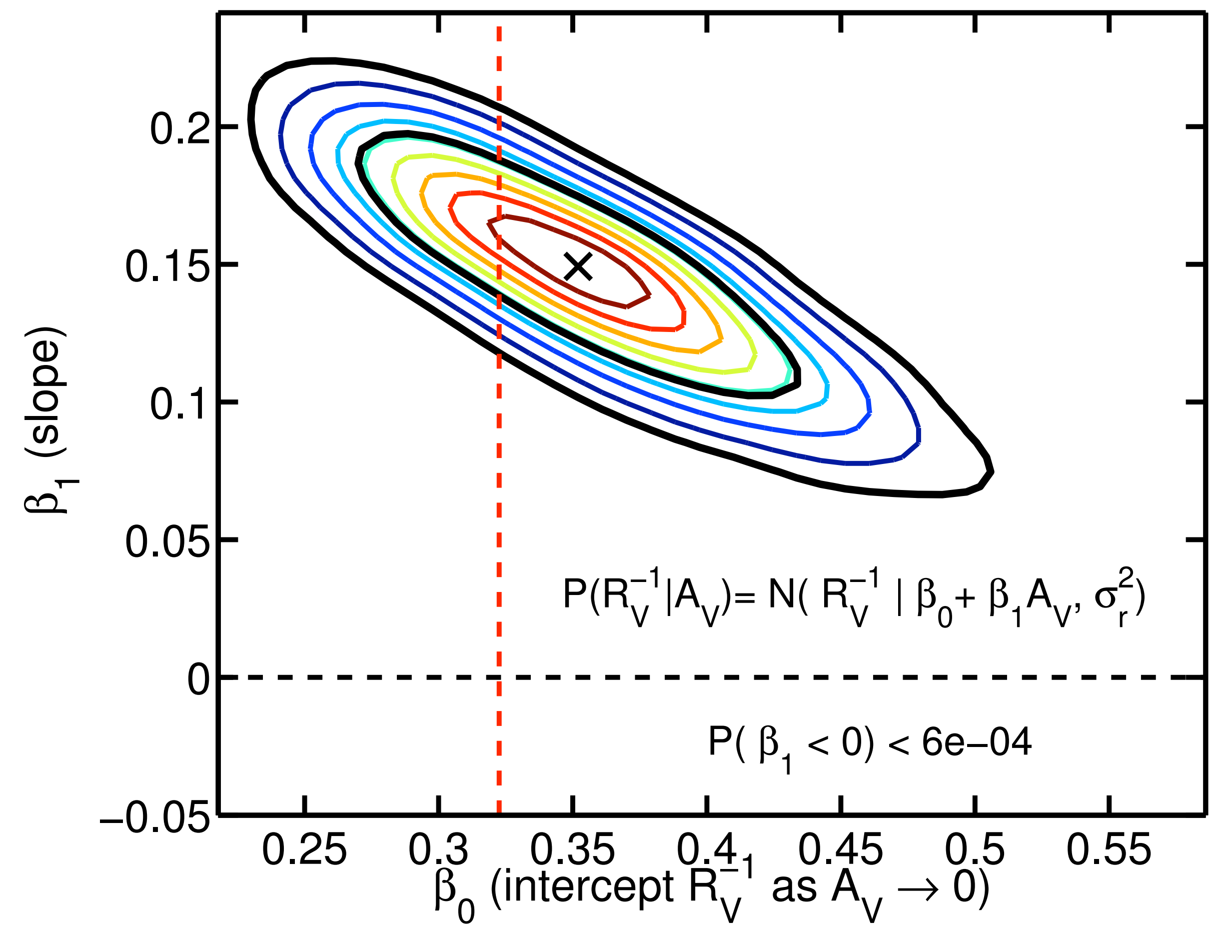
H-band provides nearly uncorrelated information on luminosity distance

Host Galaxy Dust

- Previous Analyses assumed all SN host galaxy dust has same Rv
- Estimated Rv = 1-1.7 (Astier06, Conley07) if attribute all color variation to dust
- But Rayleigh Scattering: Rv = 1.2
- But Hicken09 found Rv = 1.7 with MLCS
- For individual high Av SN, Rv < 2
- But Rv may have a distribution, or depend on Av (e.g. grain growth)

(Av, Rv) for Host Galaxy Dust Assuming Linear Correlation

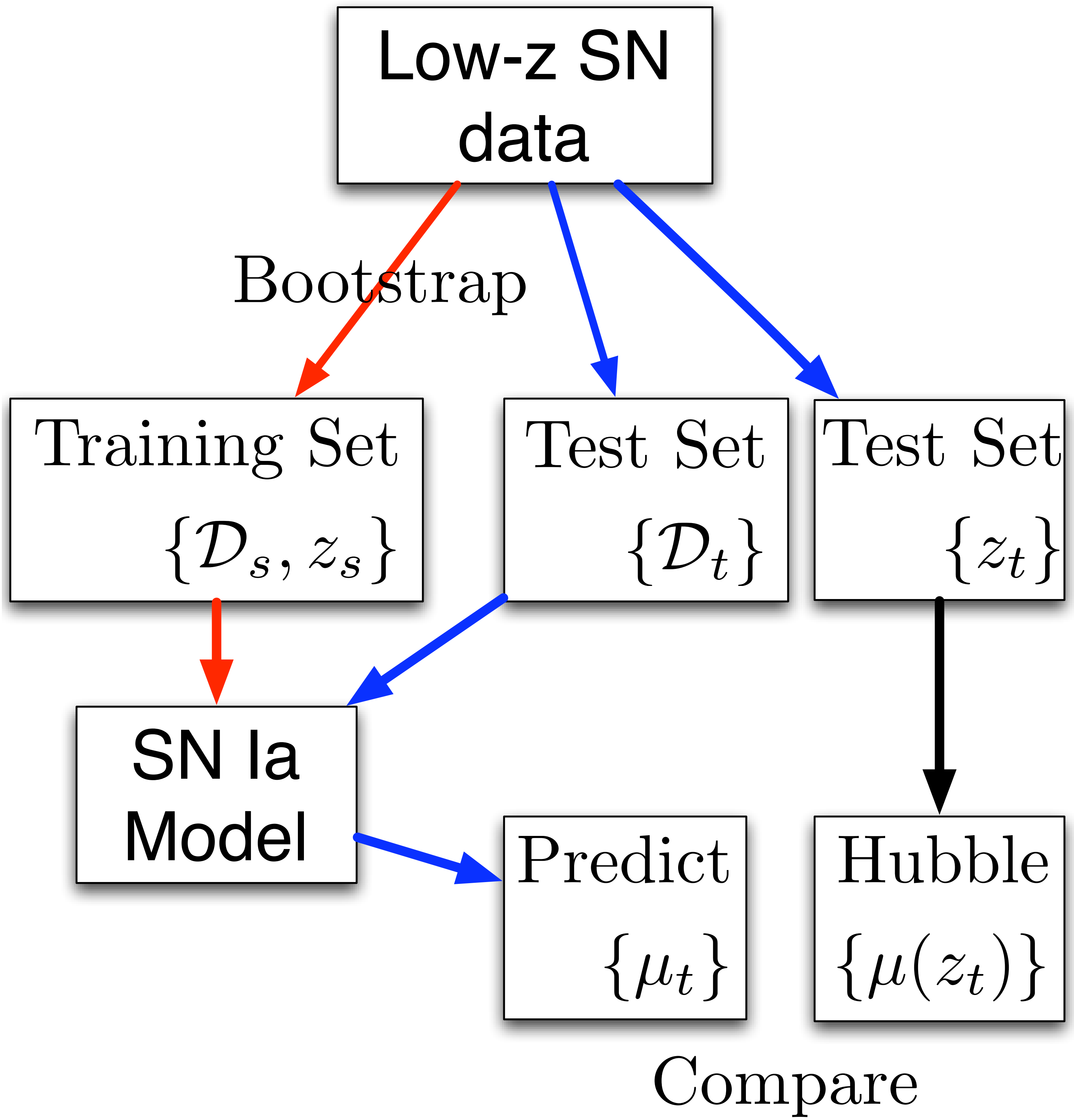




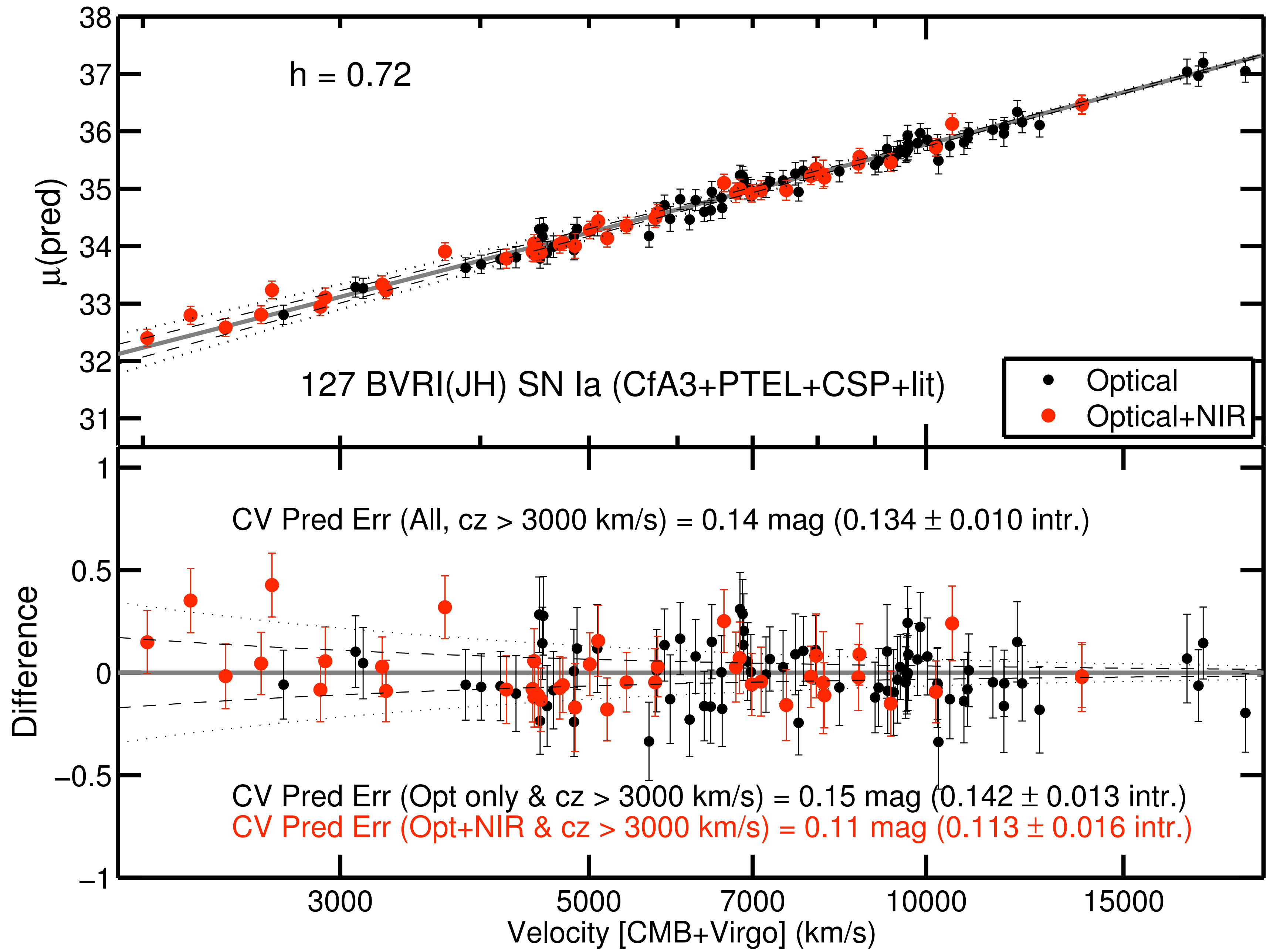
- Apparent Correlation of High Av / Low Rv
- Low Av Rv ≈ 2.5 : High Av has Rv ≈ 1.7
- Circumstellar dust at High Av ?
- Multiple Scattering (Goobar 2008)

Bootstrap Cross-validation

- Test Sensitivity of Statistical Model to Finite Sample
- Avoid using data twice for training and distance prediction
- Prediction/ Generalization Error



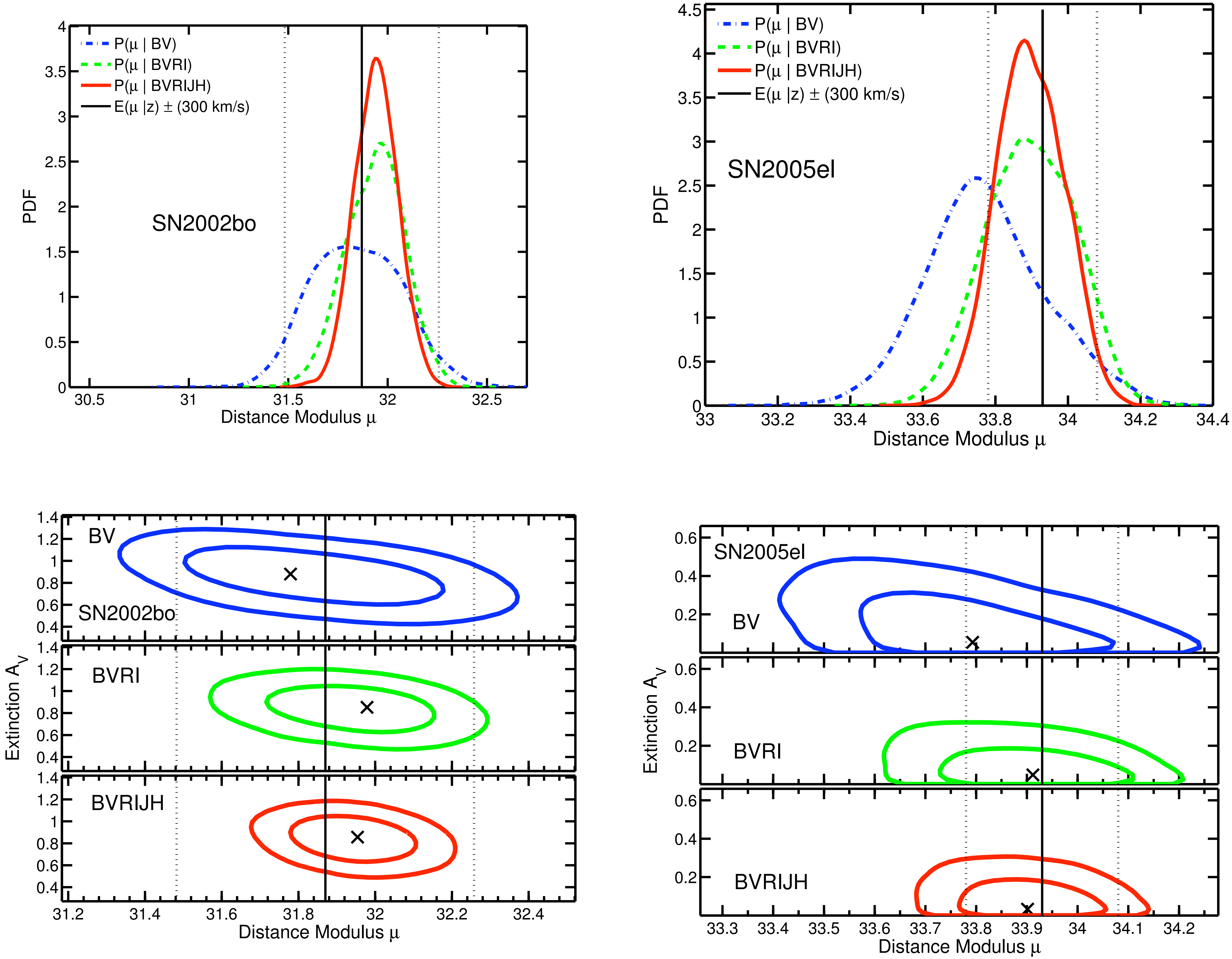
Nearby Optical+NIR Hubble Diagram



(Opt Only) rms Distance Prediction Error = 0.15 mag

(Opt+NIR) rms Distance Prediction Error = 0.11 mag

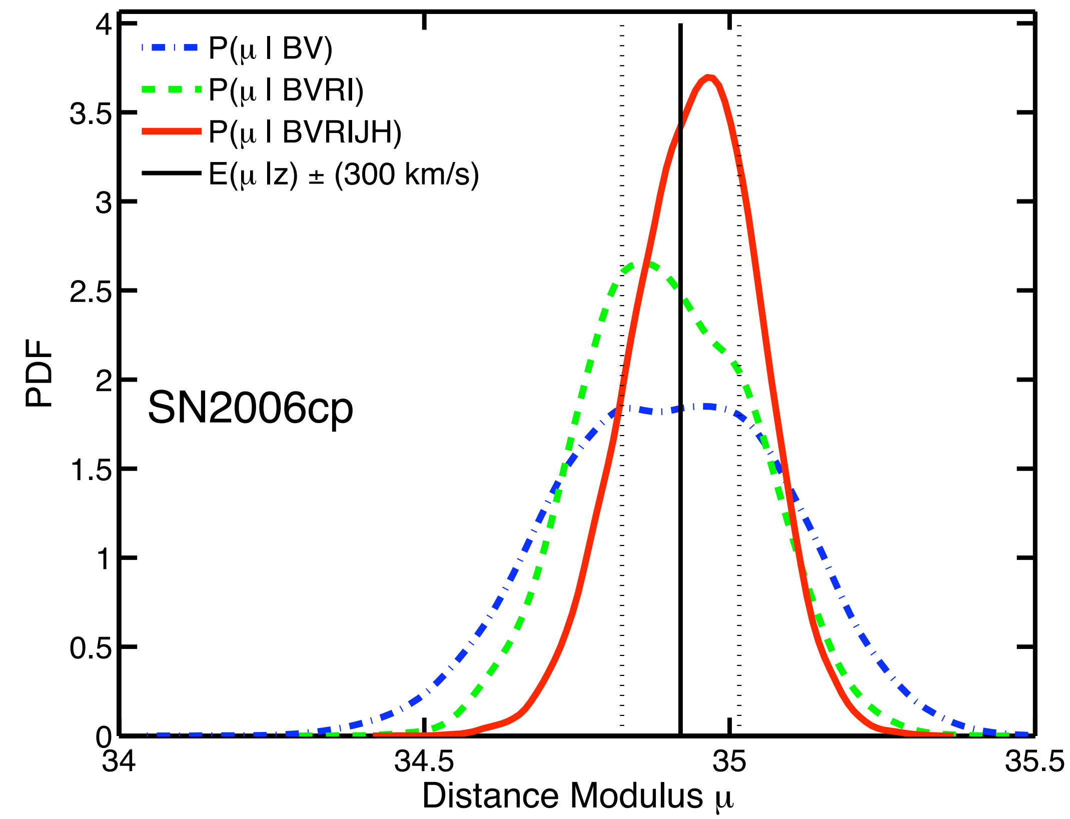
Aggregate Precision ~ $(0.15/0.11)^2 \approx 2$

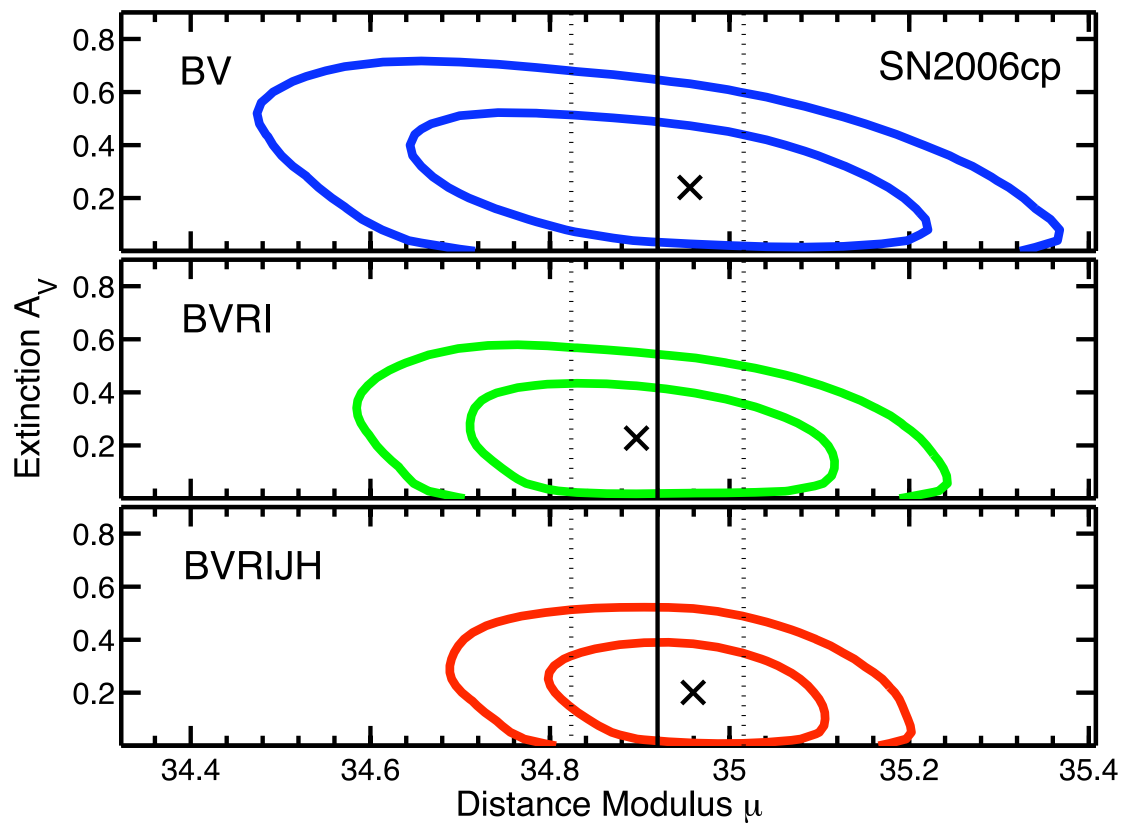


P(μ | BV)
P(μ | BVRI)
P(μ | BVRIJH)
E(μ |z) ± (300 km/s)
SN2002bo
PDF
Distance Modulus μ
SN2005el
BV
BVRI
BVRIJH
Extinction A_V

Improved Distance Precision for Individual Opt+NIR LCs

- Precision = 1/Variance
- On avg, 2.2x better BVRI vs BV
- 3.6x better BVRIJH vs BV
- 60% better BVRIJH vs BVRI





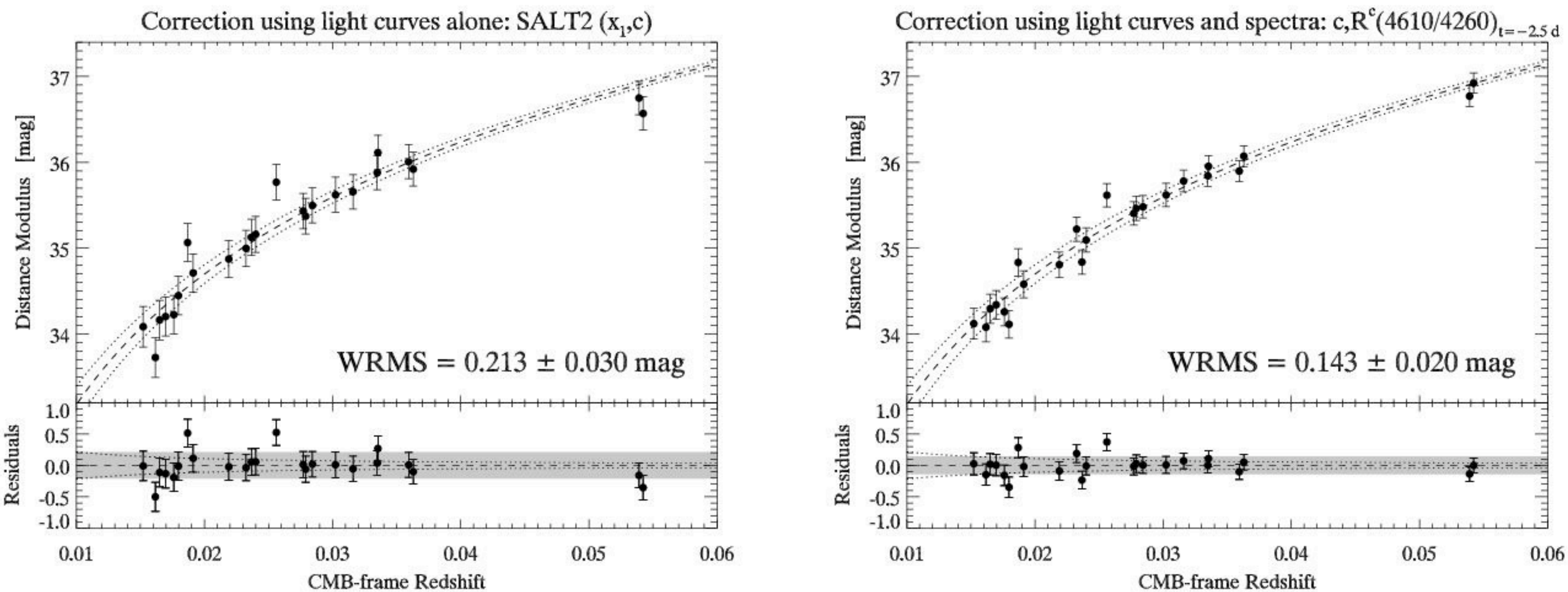
Summary

- Hierarchical models are useful statistical methods for discerning multiple random effects
- BayeSN: an efficient MCMC Sampler for computing inferences with SN hierarchical models
- Apparent differential trend of Rv vs Av (local dust at high Av?)
- NIR Light Curves have low correlation with optical, provide independent information on distance
- SN Ia Optical with NIR: Better dust and distance estimates than with Optical alone

Future Work & Problems

- Application to Larger Sample of Opt+NIR SN Ia
- Application to high-z SN Ia & Cosmological Inference
- Accounting for Selection Effects
- Using Auxiliary Information
  - Host Galaxy Information (e.g. P. Kelly, et al. 2010)
  - Spectral? Blondin, Mandel, & Kirshner 2011
  - Foley & Kasen 2011 (Color / Ejecta Velocity)

Spectral Info correlate with SN Ia luminosity and light curves?

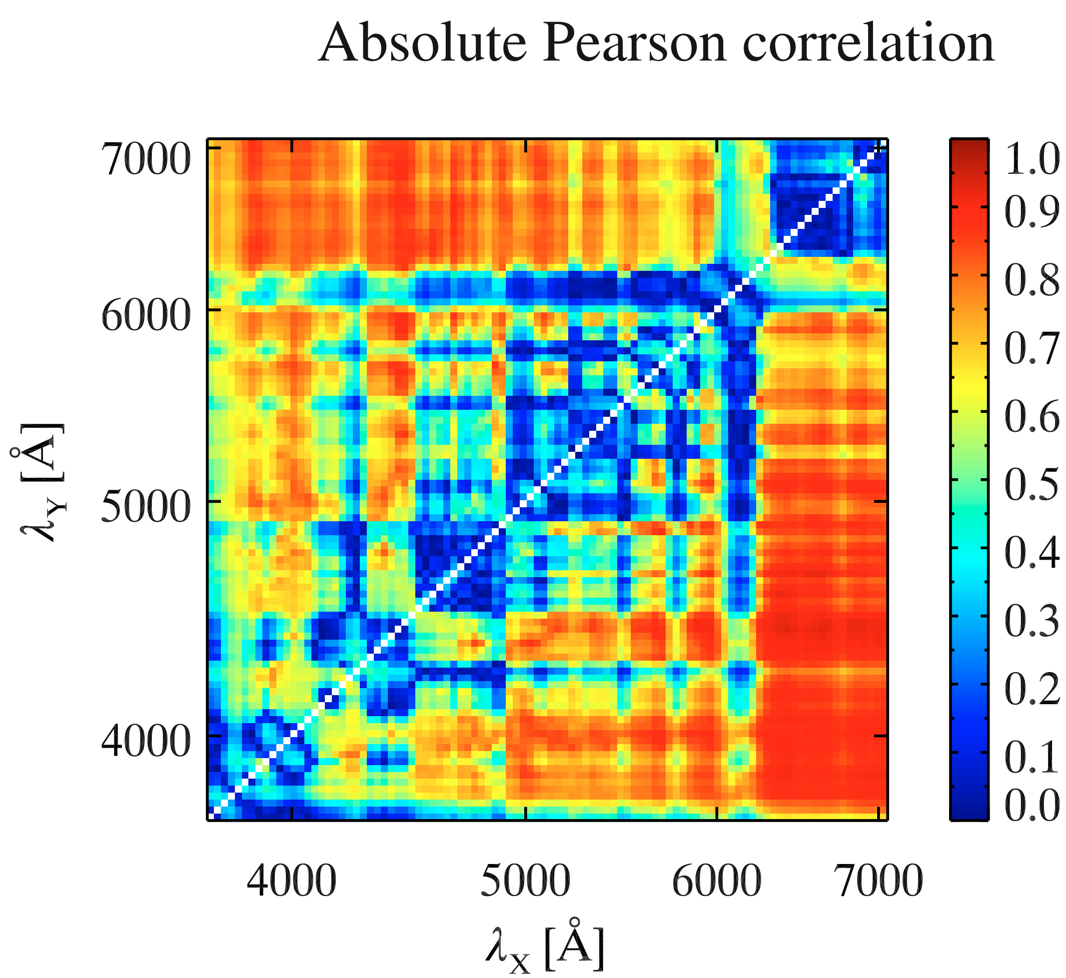


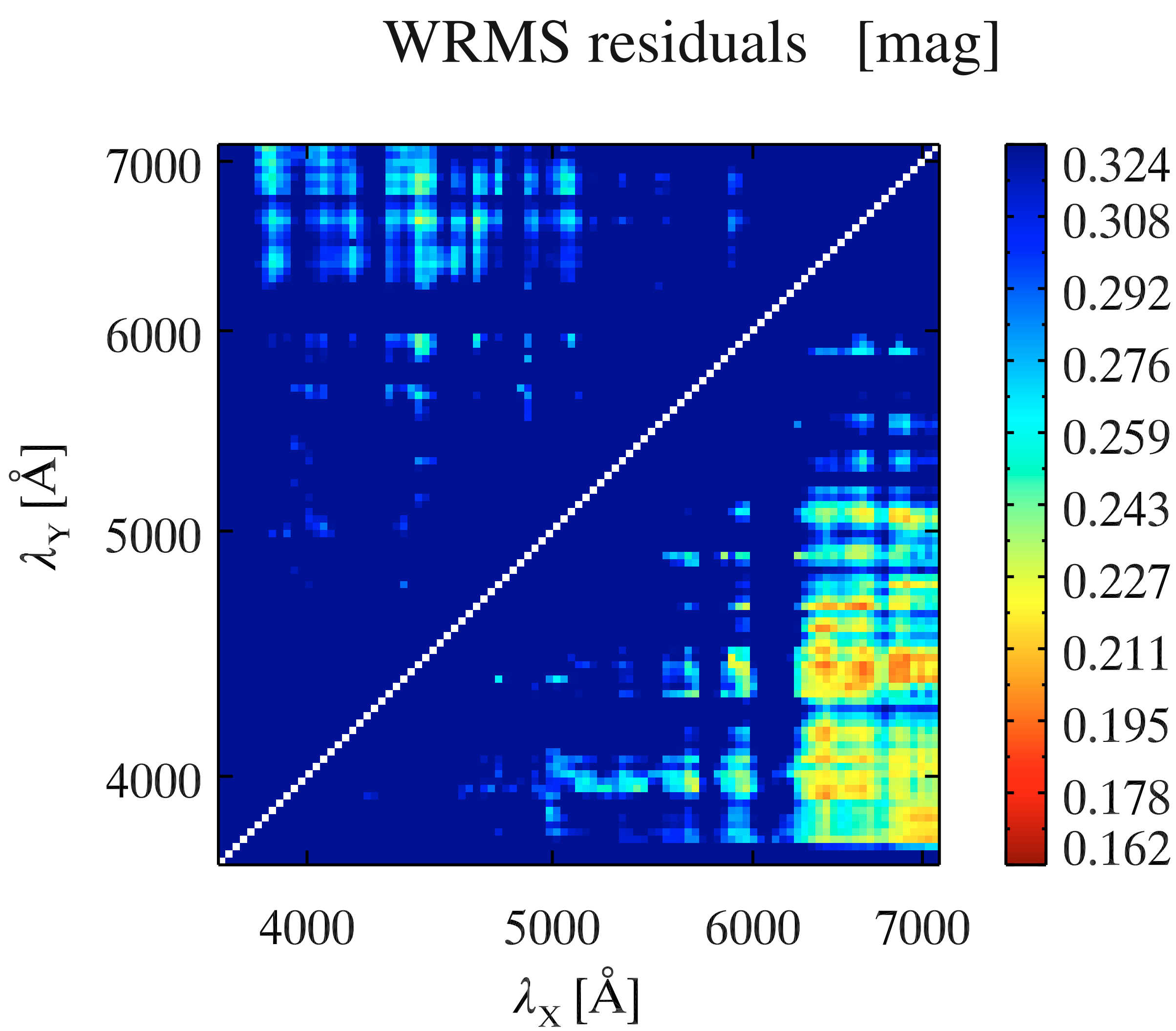
Blondin, Mandel, Kirshner 2011

Multiple Comparisons Problem

Correlating Spectral Ratios with Luminosity

Blondin, Mandel, Kirshner 2011





Multiple Comparisons K-fold Cross-Validation

Open Problems

- Photometric Classification of SN Light Curves
- Classification of SN by Spectra