Bayesian Modeling for Type Ia Supernova Data, Dust, and Distances

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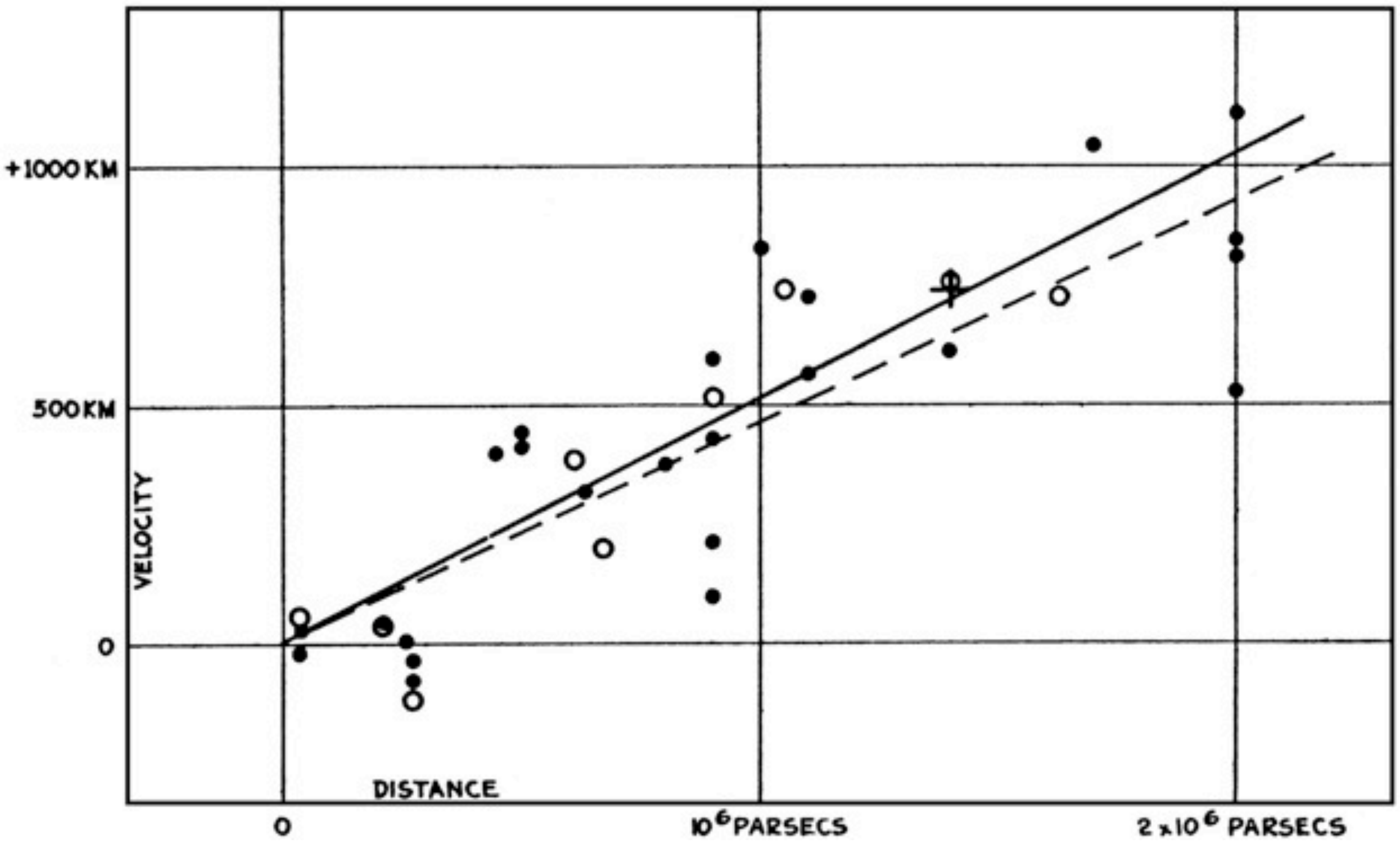
Outline

- Brief Introduction to Type Ia Supernovae & Cosmology
- Part I: Supernova Classification with Host Galaxy Data
- Part II: Hierarchical Bayesian Regression Model for SN Ia colors and spectroscopic velocities

SN Ia Basics: Estimating Astronomical Distances with 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: $m = M + \mu$

The Expanding Universe: Galaxies are moving apart! Hubble's Law (1929)



Hubble: @Einstein, you're wrong

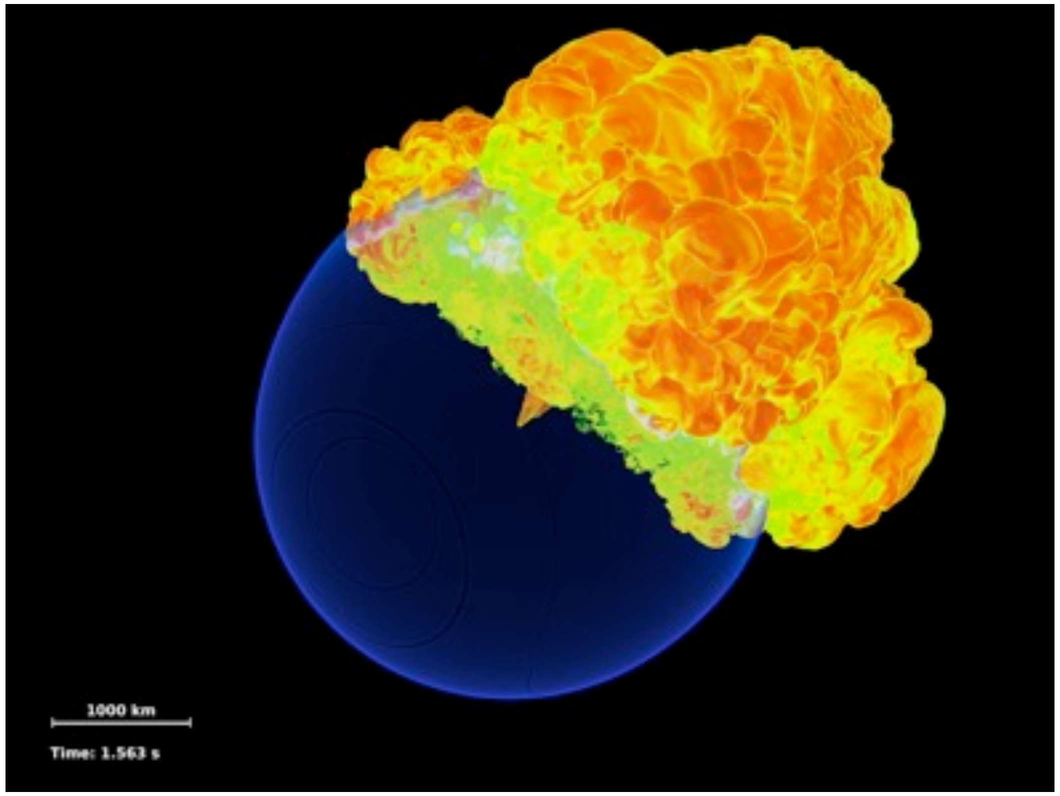
Distance ∝ Velocity (Redshift)

But what is the rate of change of the expansion?

(the deceleration parameter)

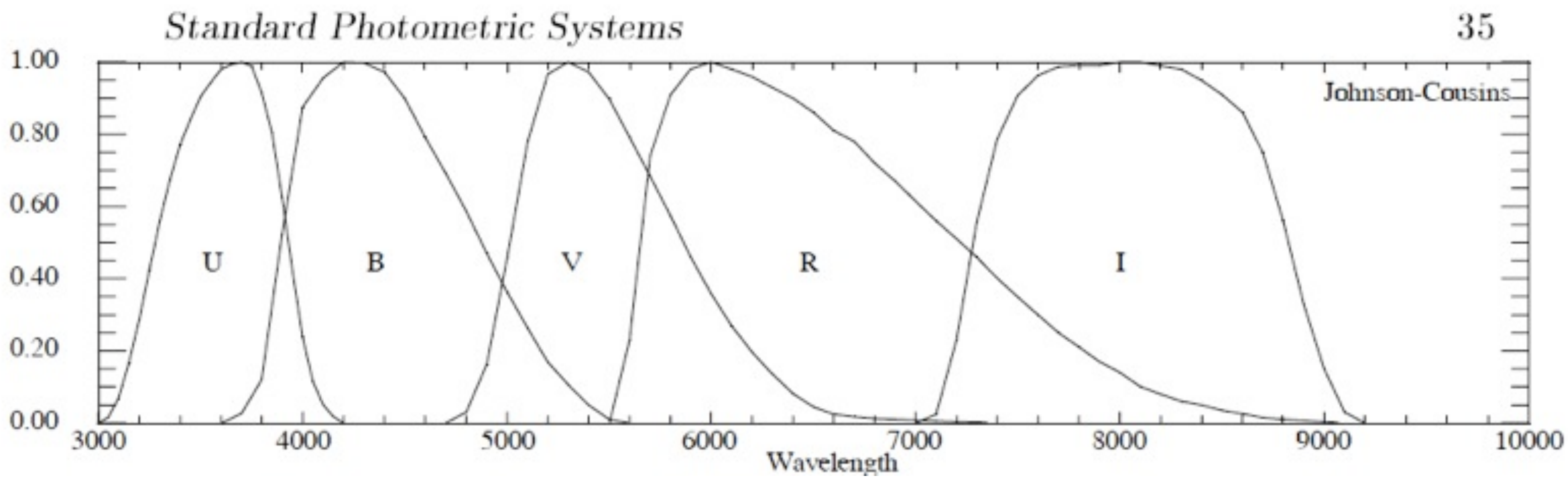
Type Ia Supernovae are Almost Standard Candles

- Progenitor: C/O White Dwarf Star accreting mass leads to instability (single / double degenerate)
- Thermonuclear Explosion: Deflagration/Detonation
- Nickel to Cobalt to Iron Decay + radiative transfer powers the light curve

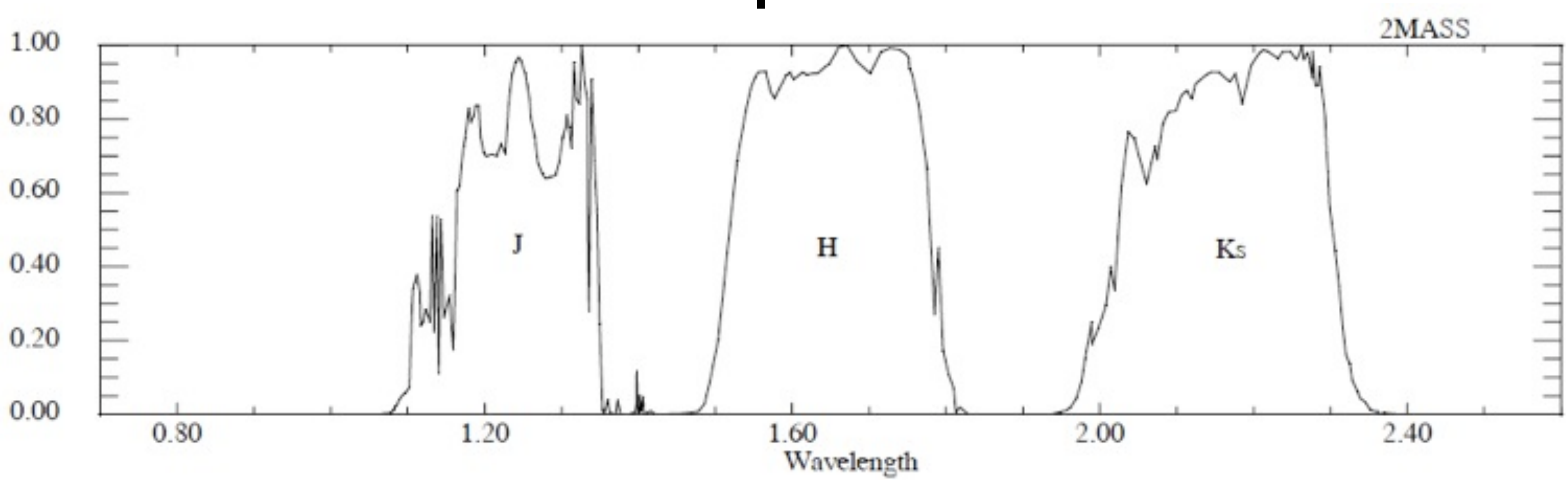


Credit: FLASH Center

Telescopes collect light of different wavelengths

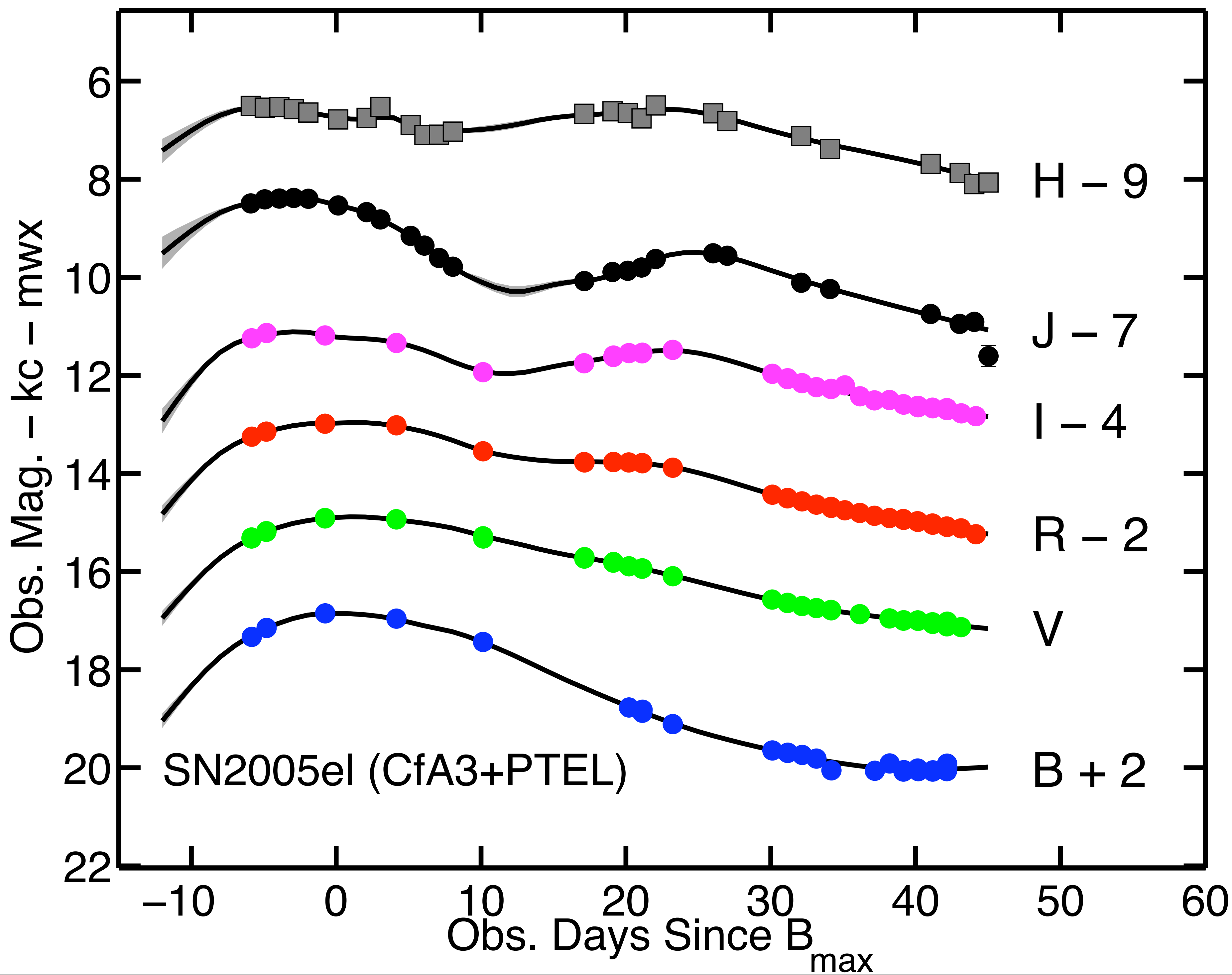


Optical

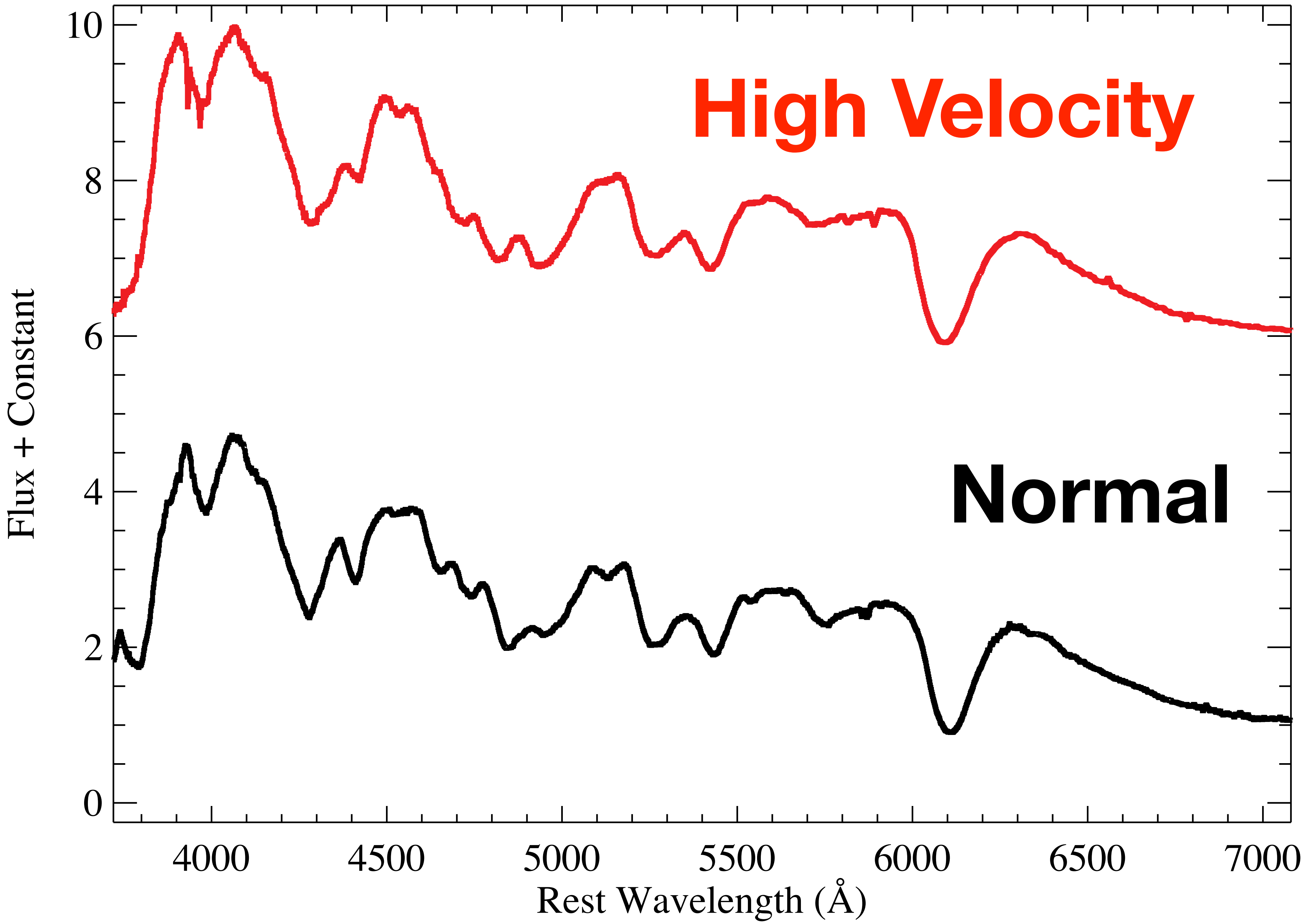


Near Infrared

Observable:
Type Ia Supernova Apparent Light Curve (time series)



Observable: Type Ia SN Spectrum



The Accelerating Universe
2011 Nobel Prize in Physics

Photo: U. Montan

Saul Perlmutter

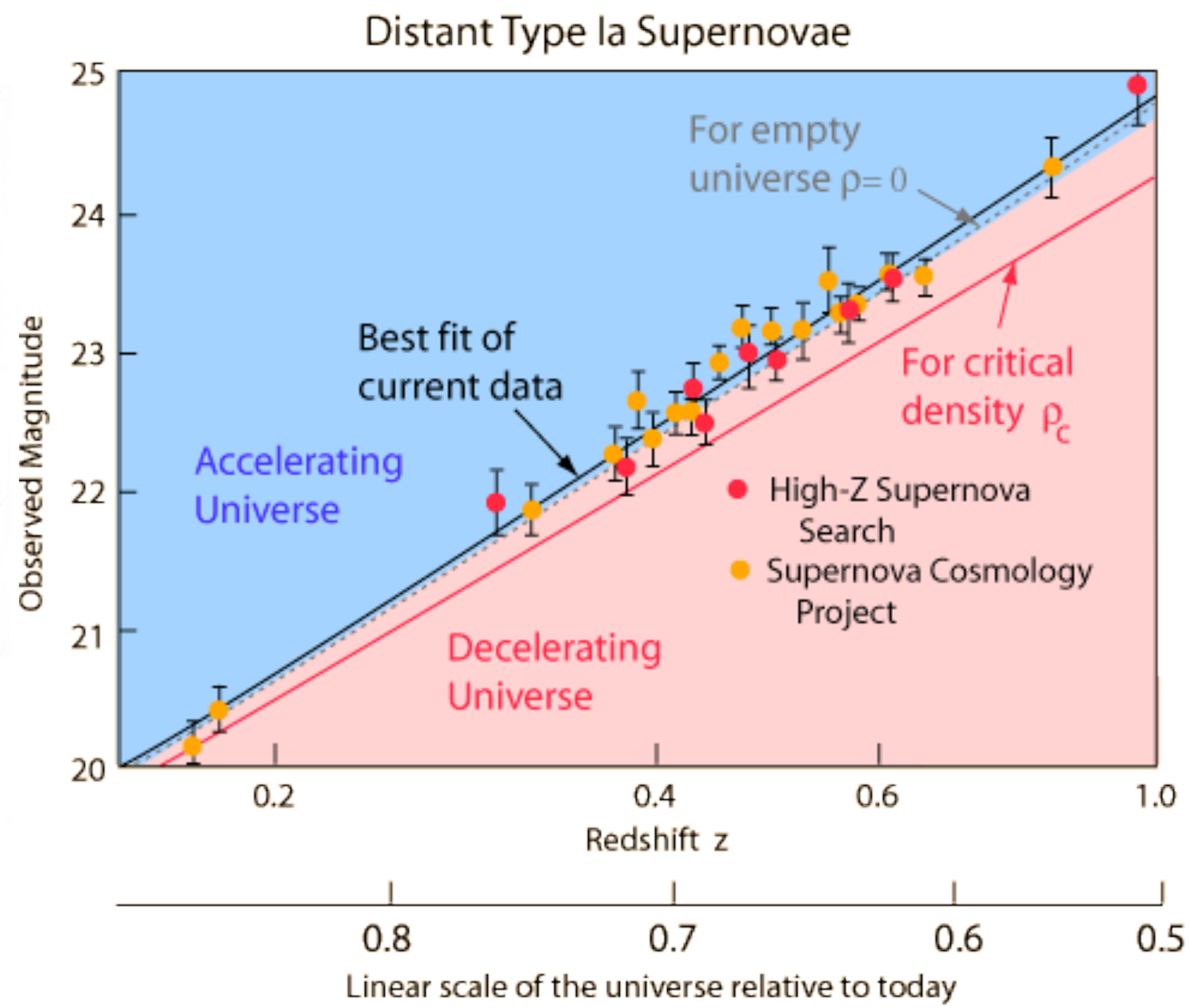
Photo: U. Montan

Brian P. Schmidt

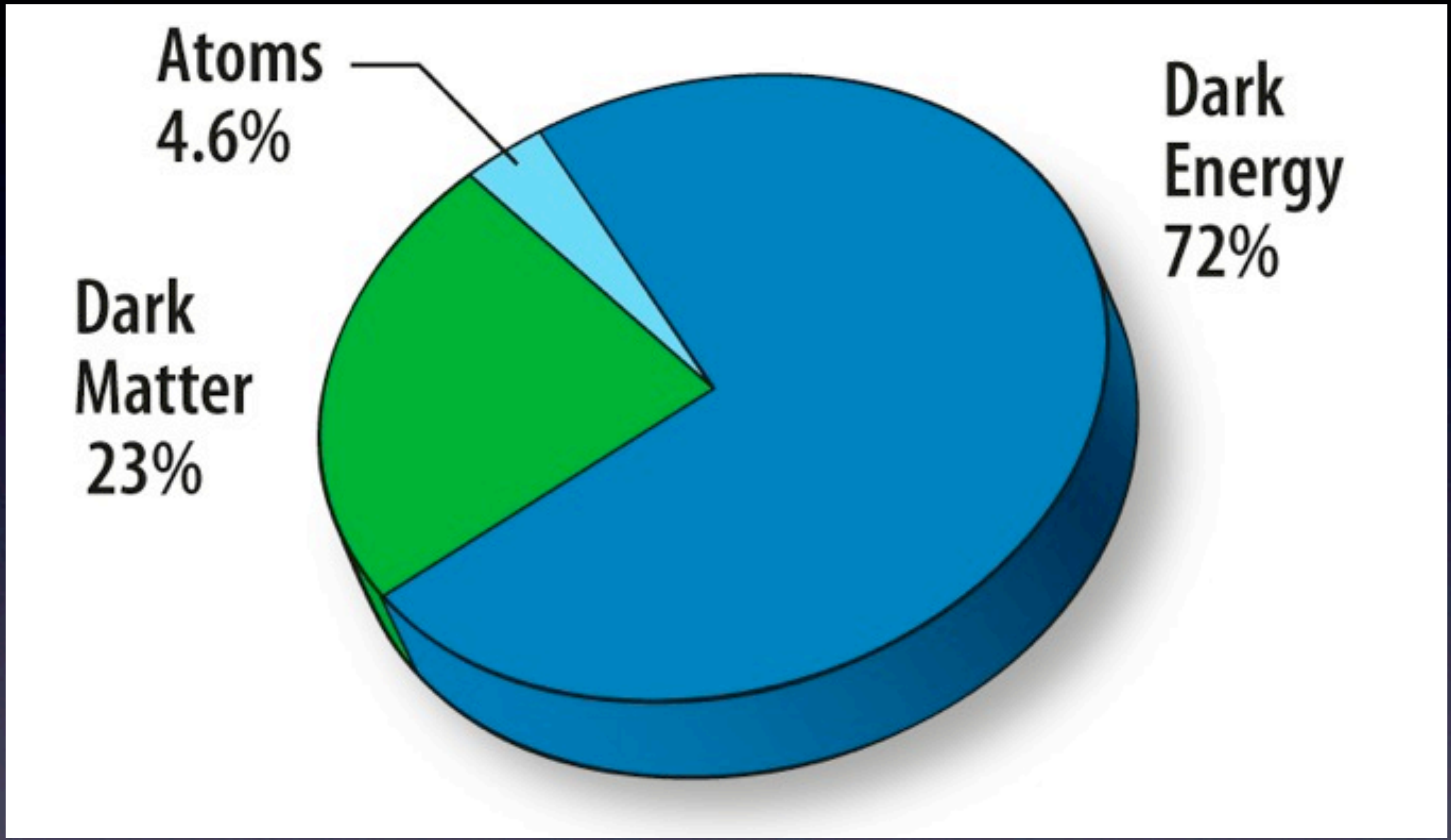
Photo: U. Montan

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

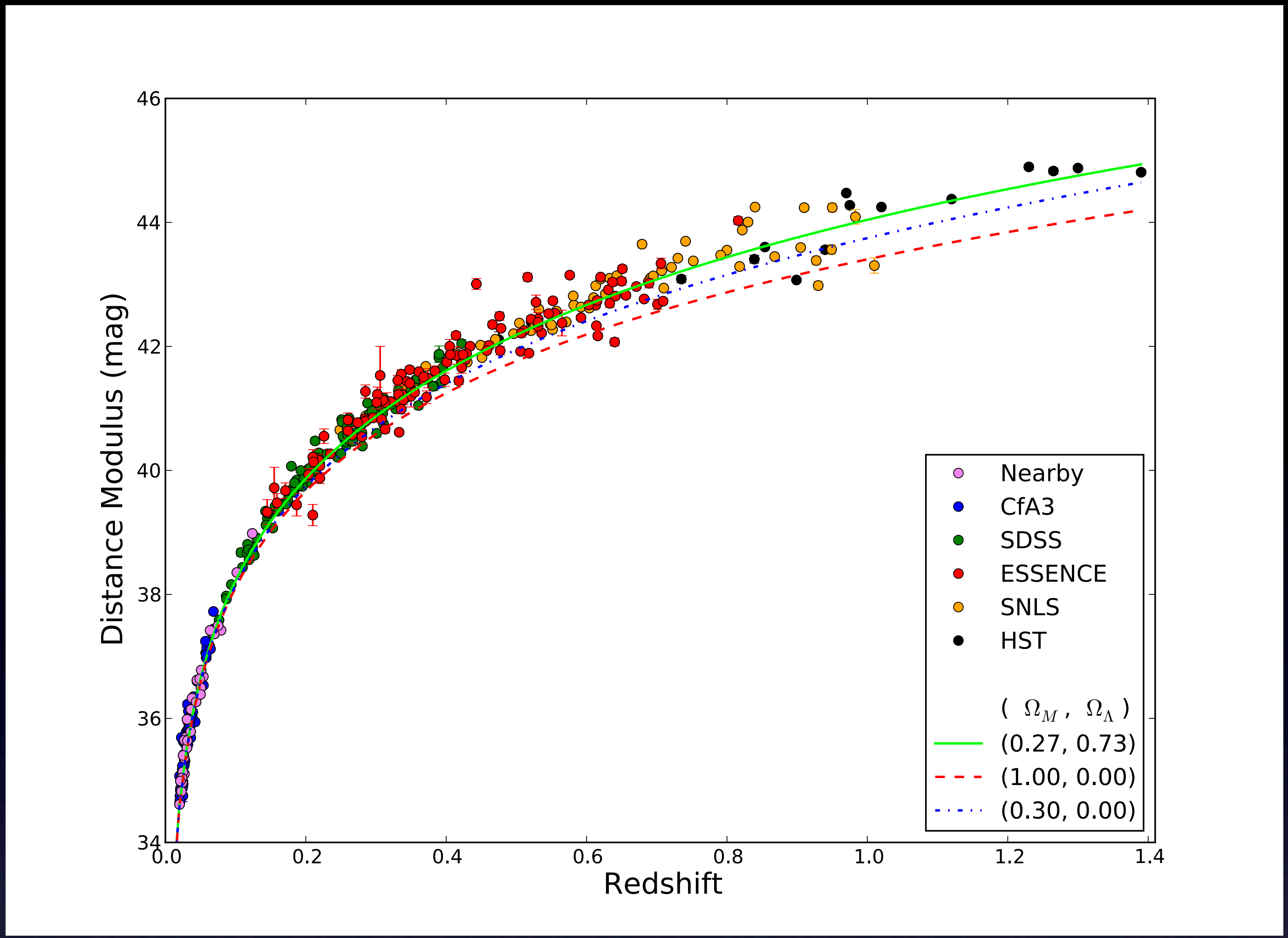


Cosmological Energy Content



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

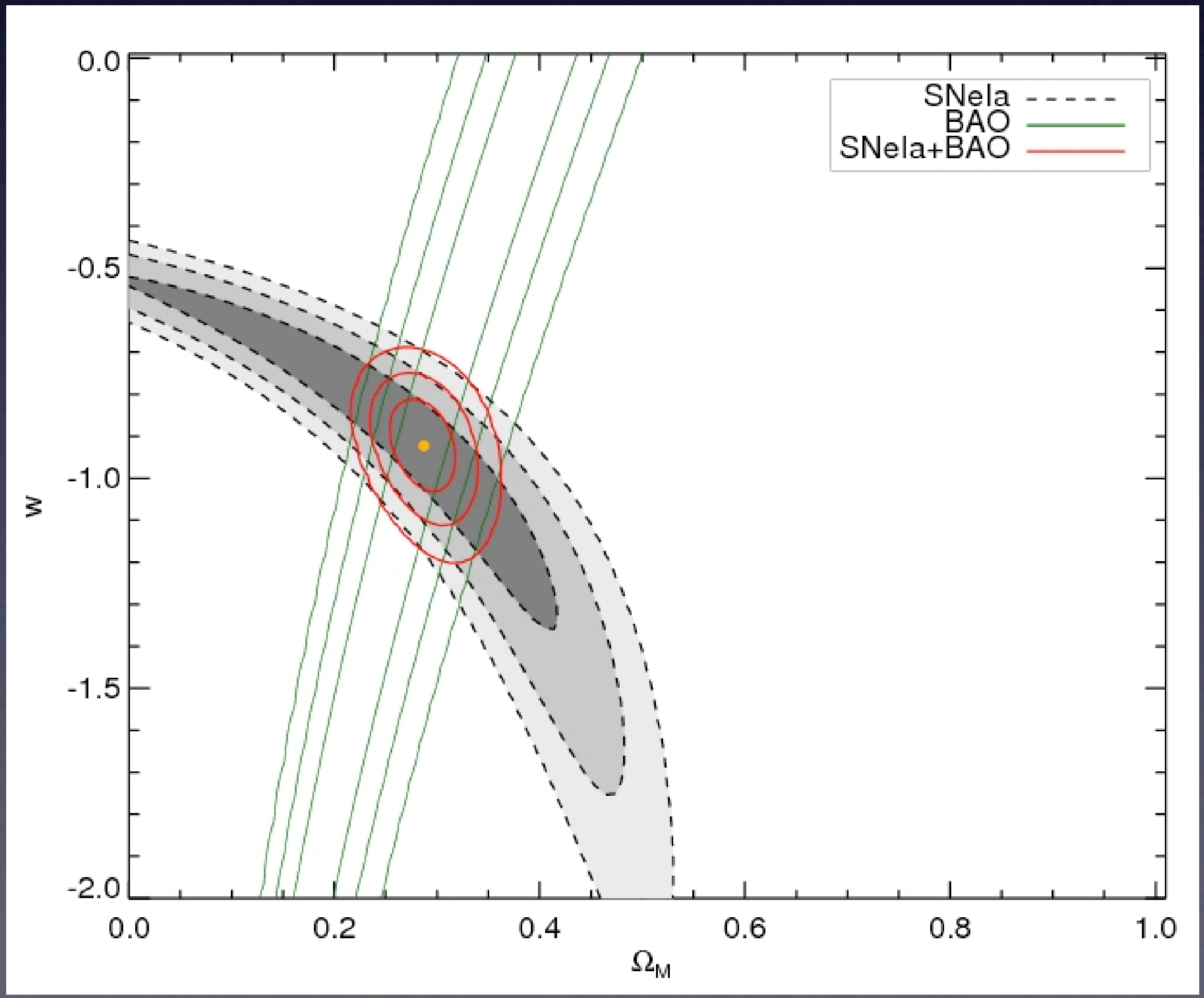
Is $w + 1 = 0$? Cosmological Constant



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

Credit: Gautham Narayan (ESSENCE)

Need accurate distances! Host Galaxy Dust is a Major Confounding Factor



Part I: Supernova Classification

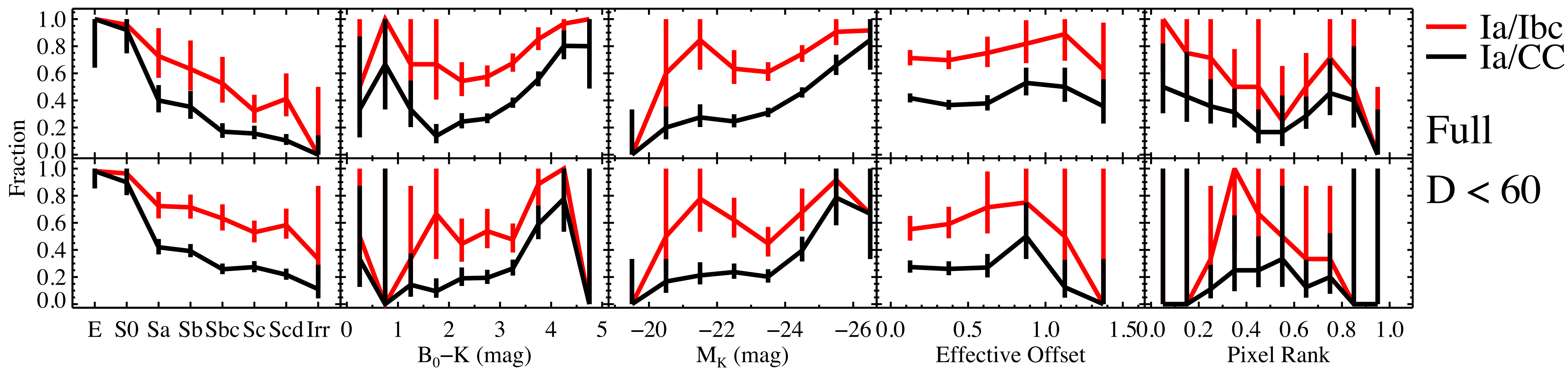
- Core Collapse (CC: II/Ibc) vs. Type Ia(SN Ia)
- Spectroscopic: Obtain spectrum, compare against library of spectrum with known types (SNID)
- For current and future large automated transient surveys (e.g. DES, LSST), too many SN targets, too little telescope time to obtain spectrum for each one
- Photometric: Properties of Broadband light curves

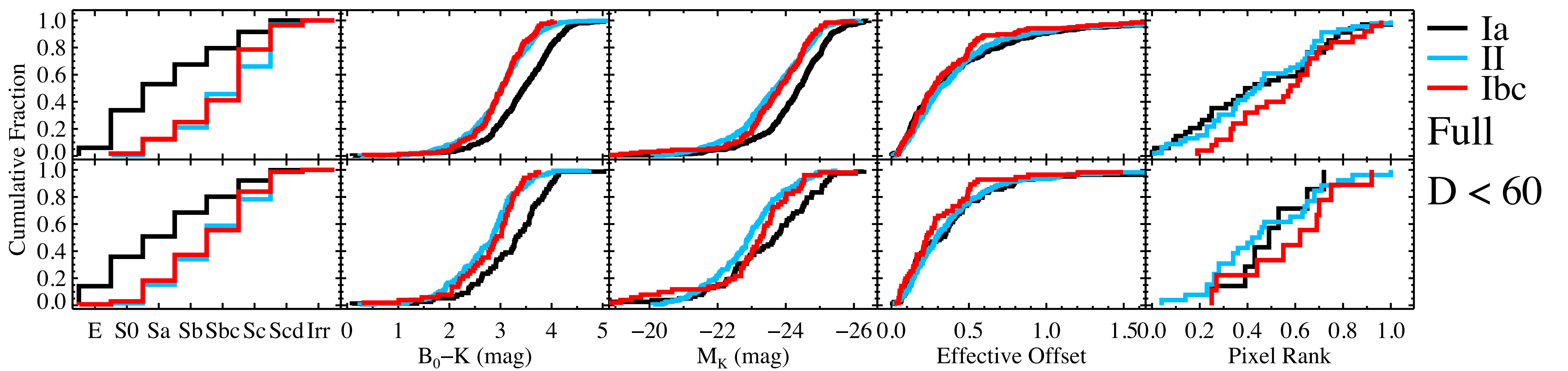
New Alternate Strategy: Use Host Galaxy Properties

(Foley & Mandel 2013, last week! arxiv.org/abs/1309.2630)

- Use correlations between SN Type and properties of the Host Galaxy (Morph, Color, Luminosity, Position/offset, Pixel brightness rank)
- CC SN rarely occur in red, luminous, early-type galaxies
- CC SN explode in late-type galaxies in spiral arms, SN Ia explode in all types of galaxies
- Uses different data source than traditional typing methods

Distribution of the SN Ia fraction vs. host galaxy property (using LOSS sample)





galsnid: a Naive Bayes Classifier

- Want P(Ia | **D**) ∝ P(**D** | Ia) P(Ia)
- Modeling P(**D** | Ia) is hard for multidimensional **D**
- Simplify by assuming D_i are conditionally independent given the class
- $P(\mathbf{D}|Ia) = \prod_{i=1}^{n} P(D_i|Ia)$
- galsnid probability $P(Ia|\mathbf{D}) \propto P(Ia) \prod_{i=1}^{n} P(D_i|Ia)$

Application to LOSS training set

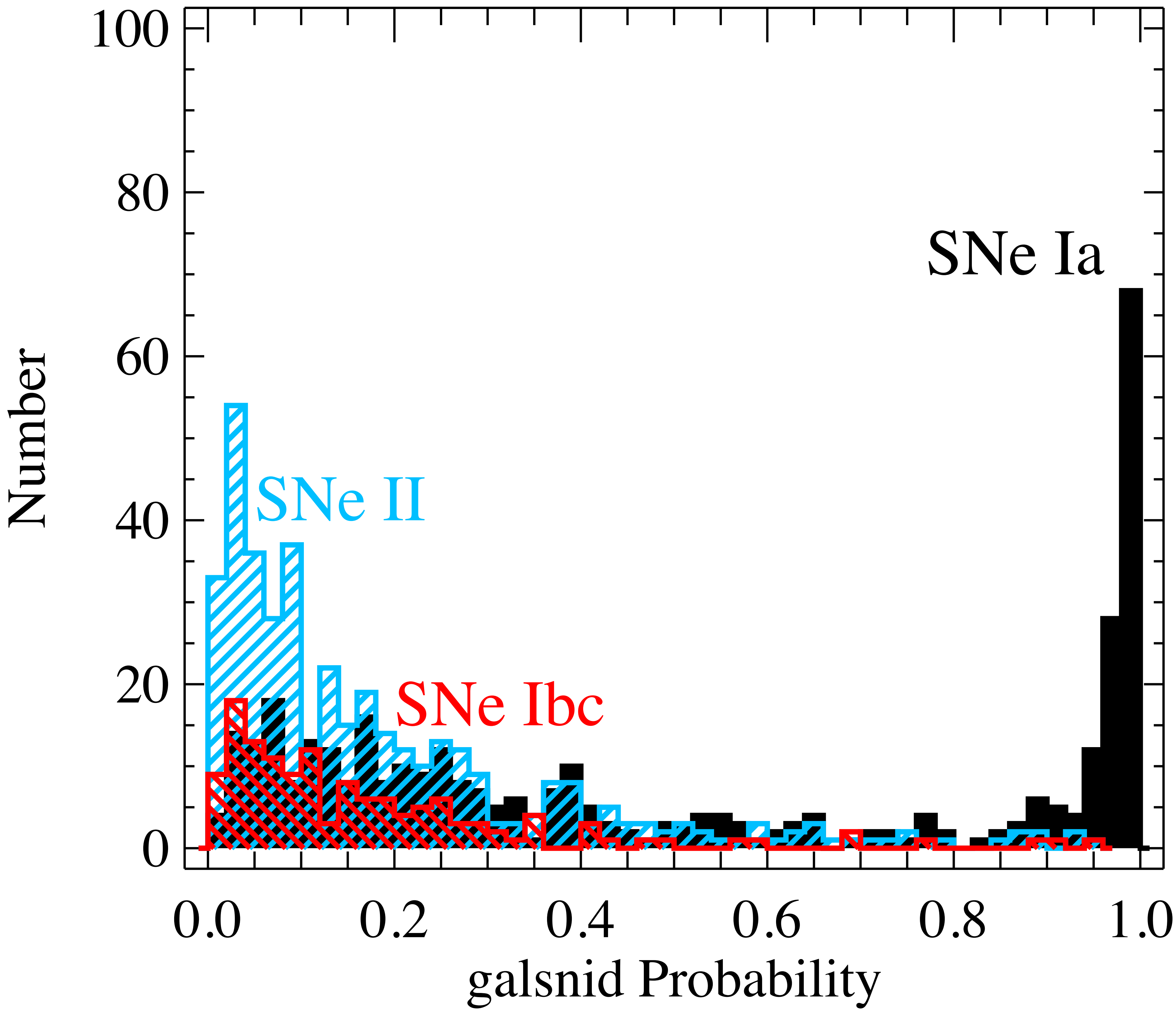


Figure of Merit

- Choose a subset with galsnid p > threshold p*
- FoM = Efficiency x Pseudopurity
- Efficiency $\epsilon_{\mathrm{Ia}} = N_{\mathrm{Ia}}^{\mathrm{Sub}} / N_{\mathrm{Ia}}^{\mathrm{Tot}}$
- Pseudopurity $PP_{\mathrm{Ia}} = \dfrac{N_{\mathrm{Ia}}^{\mathrm{Sub}}}{N_{\mathrm{Ia}}^{\mathrm{Sub}} + W_{\mathrm{Ia}}^{\mathrm{False}} N_{\mathrm{Non\text{-}Ia}}^{\mathrm{Sub}}}$
- W = 5, penalizes misclassified SN Ia

FoM as function of threshold galsnid p

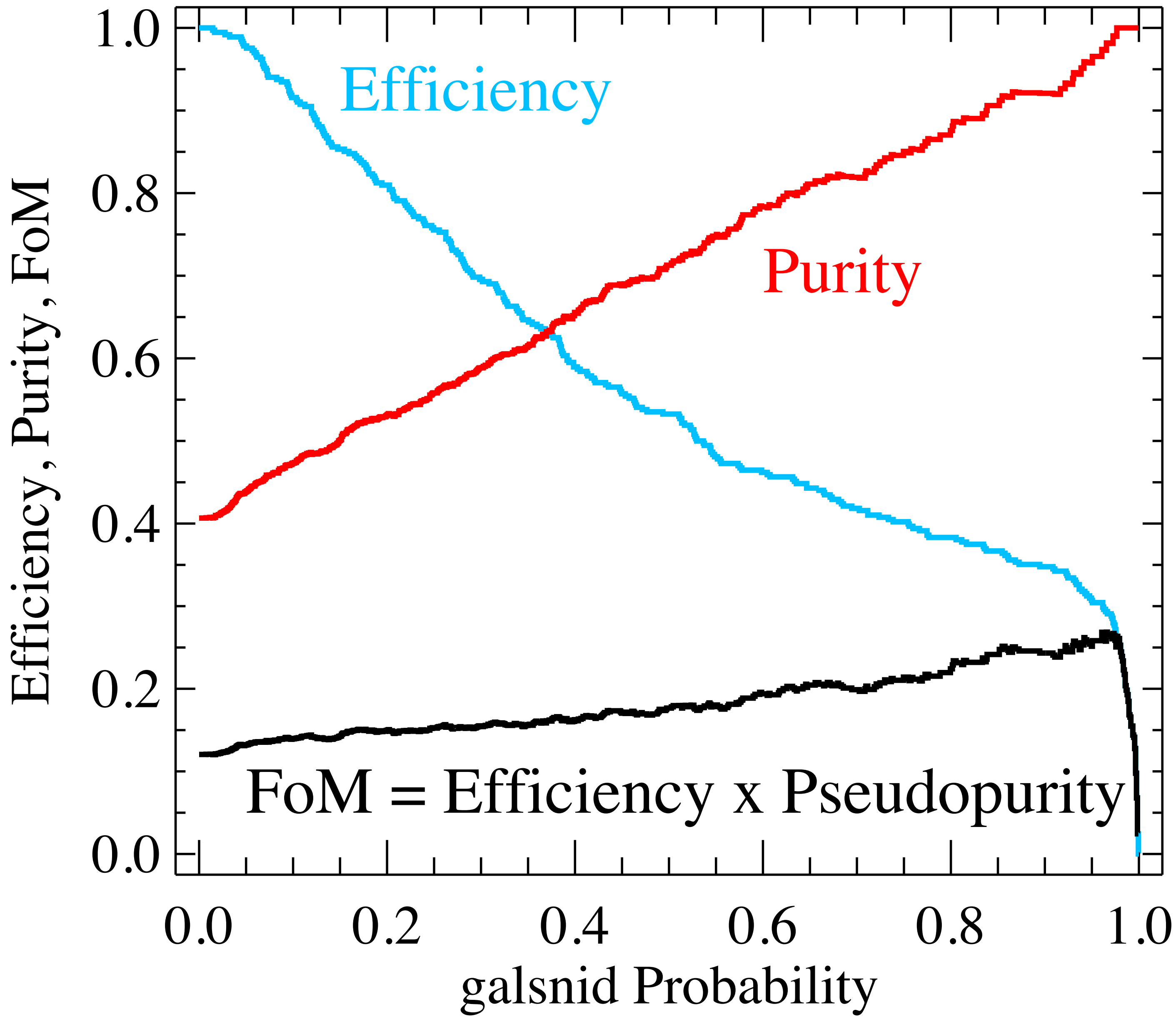
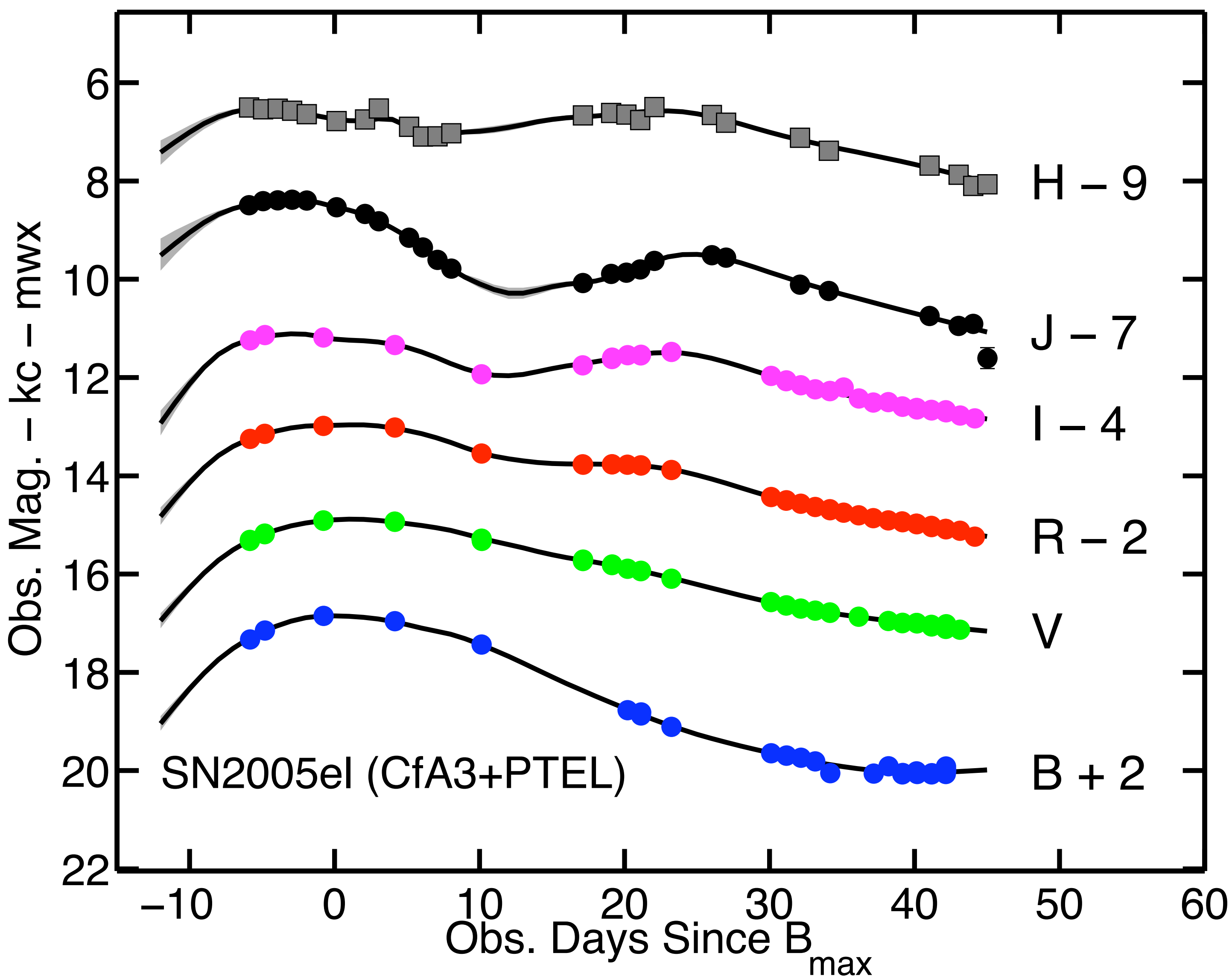


FIG. 3.— Efficiency, purity, and FoM (blue, red, and black curves, respectively) for subsamples of the LOSS sample defined by a particular *galsnid* probability or larger. The FoM peaks at $p = 0.97$ at a value that is 2.23 times larger than the FoM for the entire sample.

galsnid evaluation

- Max FoM is 2.23x improvement over baseline
- Comparable to photometric light curve method (2.6x)
- 2-fold Cross-Validation (split into two samples, alternate training and test sets)
- CV FoM = 1.4 (even training), 2.4 (odd training)
- Also test on independent SN samples (SDSS, PTF)
- galsnid: an effective and independent SN classifier

Part II: Hierarchical Bayesian Regression Model for SN Ia Colors and Spectroscopic Velocities



Astronomer's Definition: Color = Numerical difference in brightness magnitude in two passbands

e.g. B - V Color

More Positive = "Redder"

More Negative = "Bluer"

Observed Color = Intrinsic Color + Dust Reddening + Measurement Error

I will show you fear in a handful of dust

Dust Absorption vs. Wavelength of Light

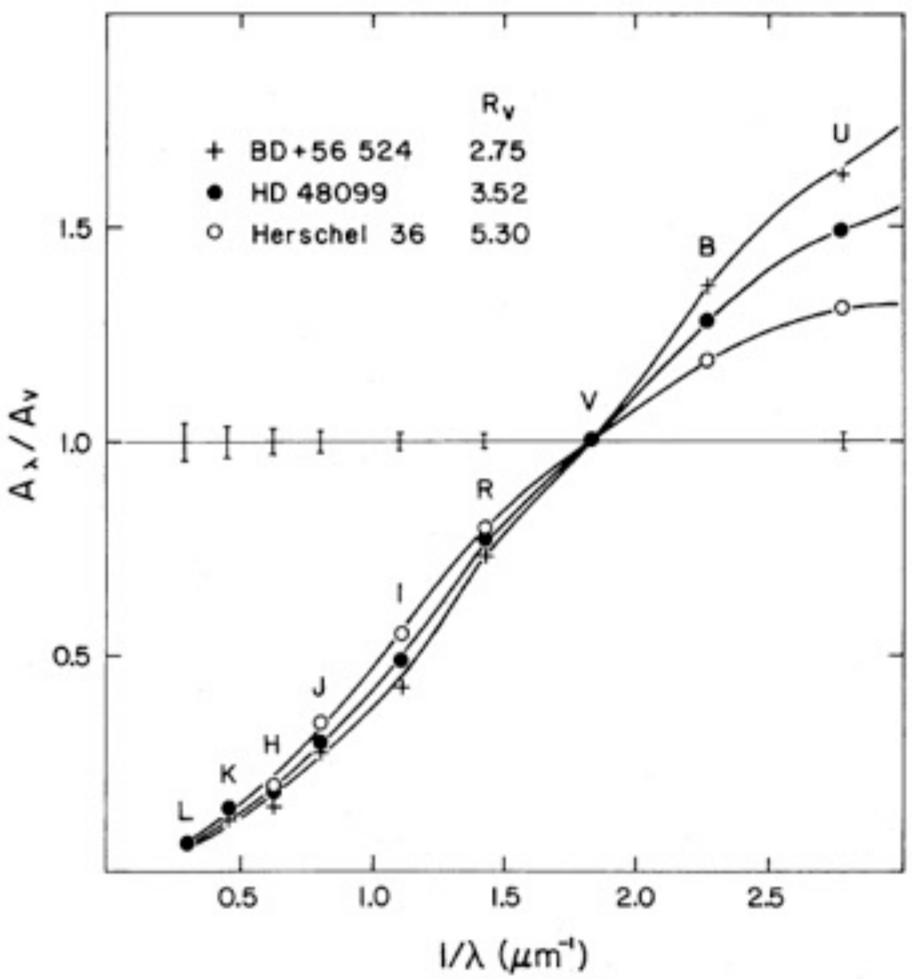
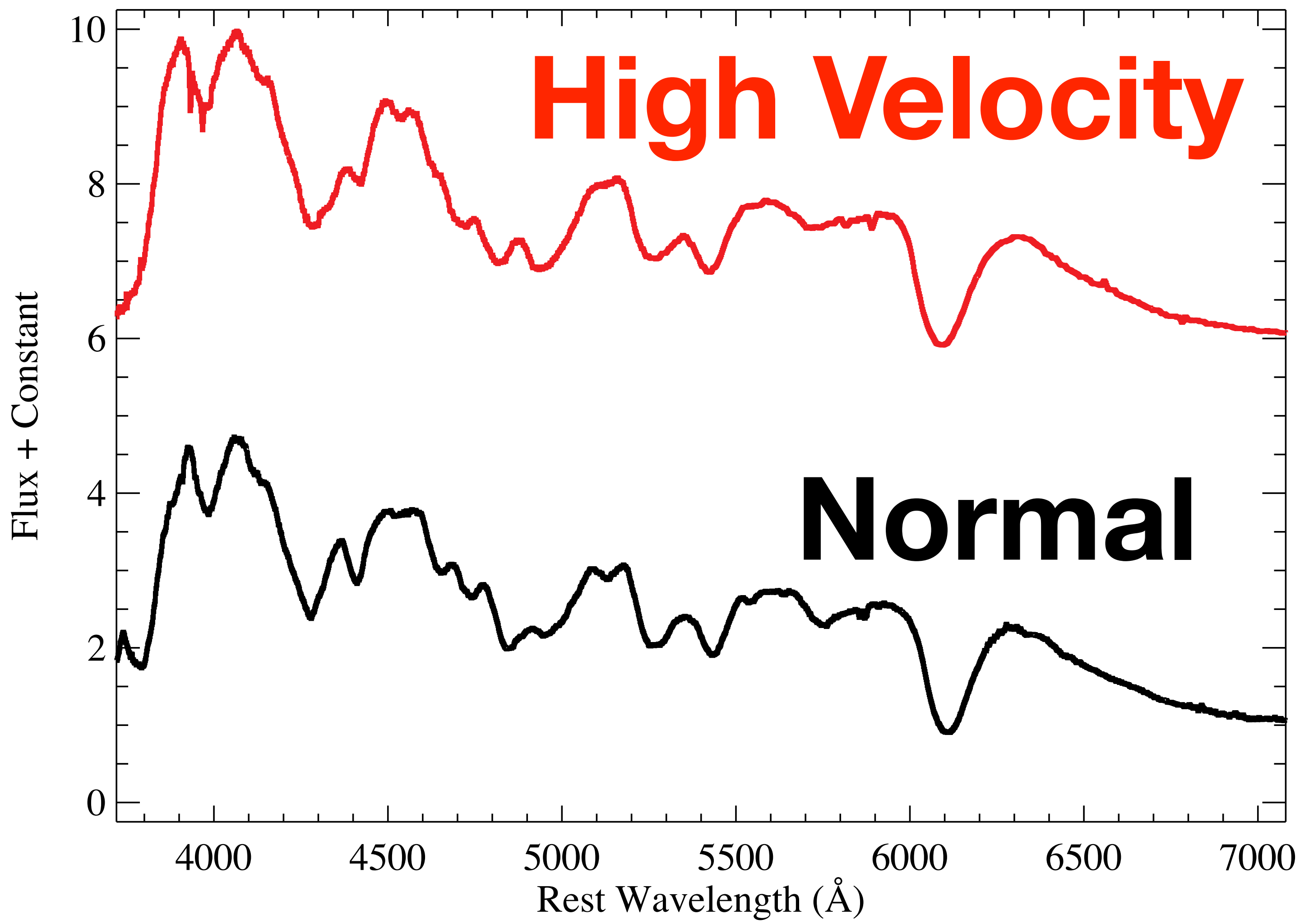


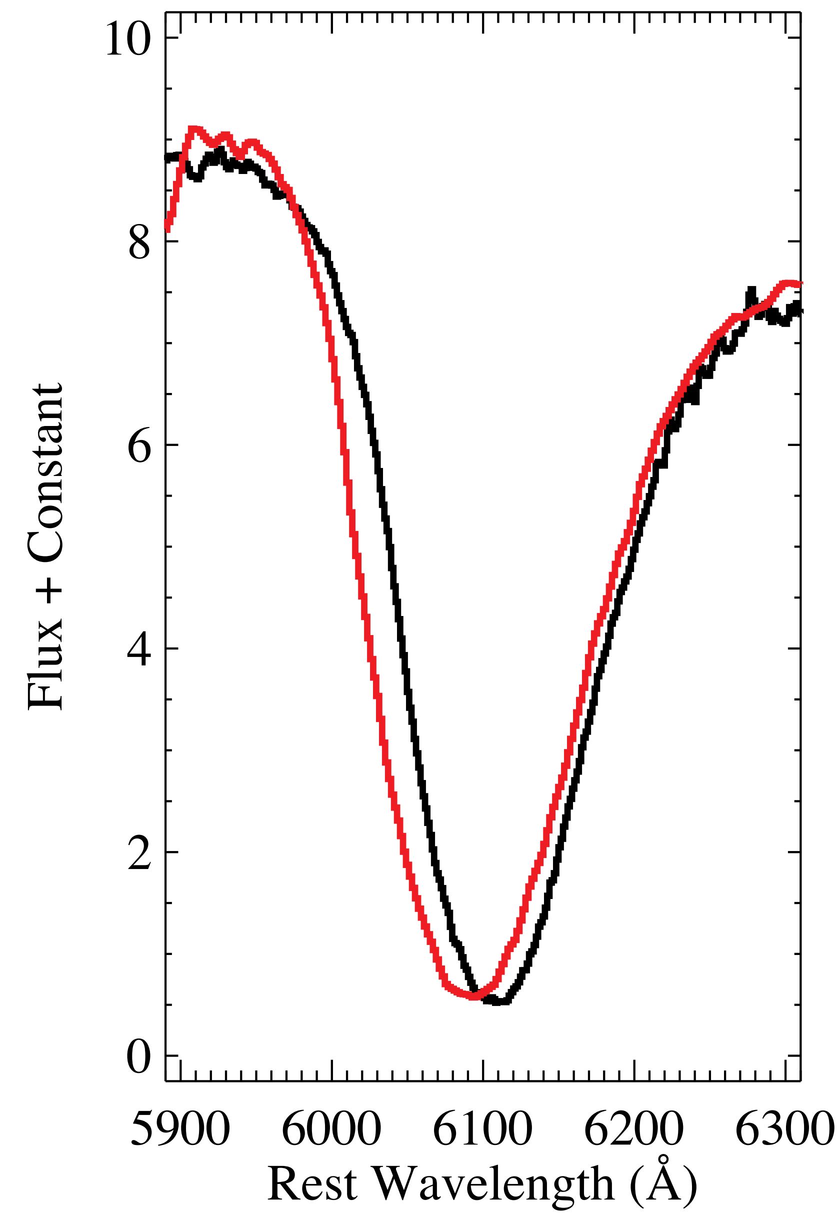
FIG. 3.—Comparison between the mean optical/NIR R_V-dependent extinction law from eqs. (2) and (3) and three lines of sight with largely separated R_V values. The wavelength position of the various broad-band filters from which the data were obtained are labeled (see Table 3). The "error" bars represent 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 depends on λ (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_V ~ Amount of Dust Absorption (only positive!)
  - R_V ~ Wavelength Dependence of Dust Absorption
- Don't really know a priori which SN are unaffected by dust; must model probabilistically

Si II λ6355 line

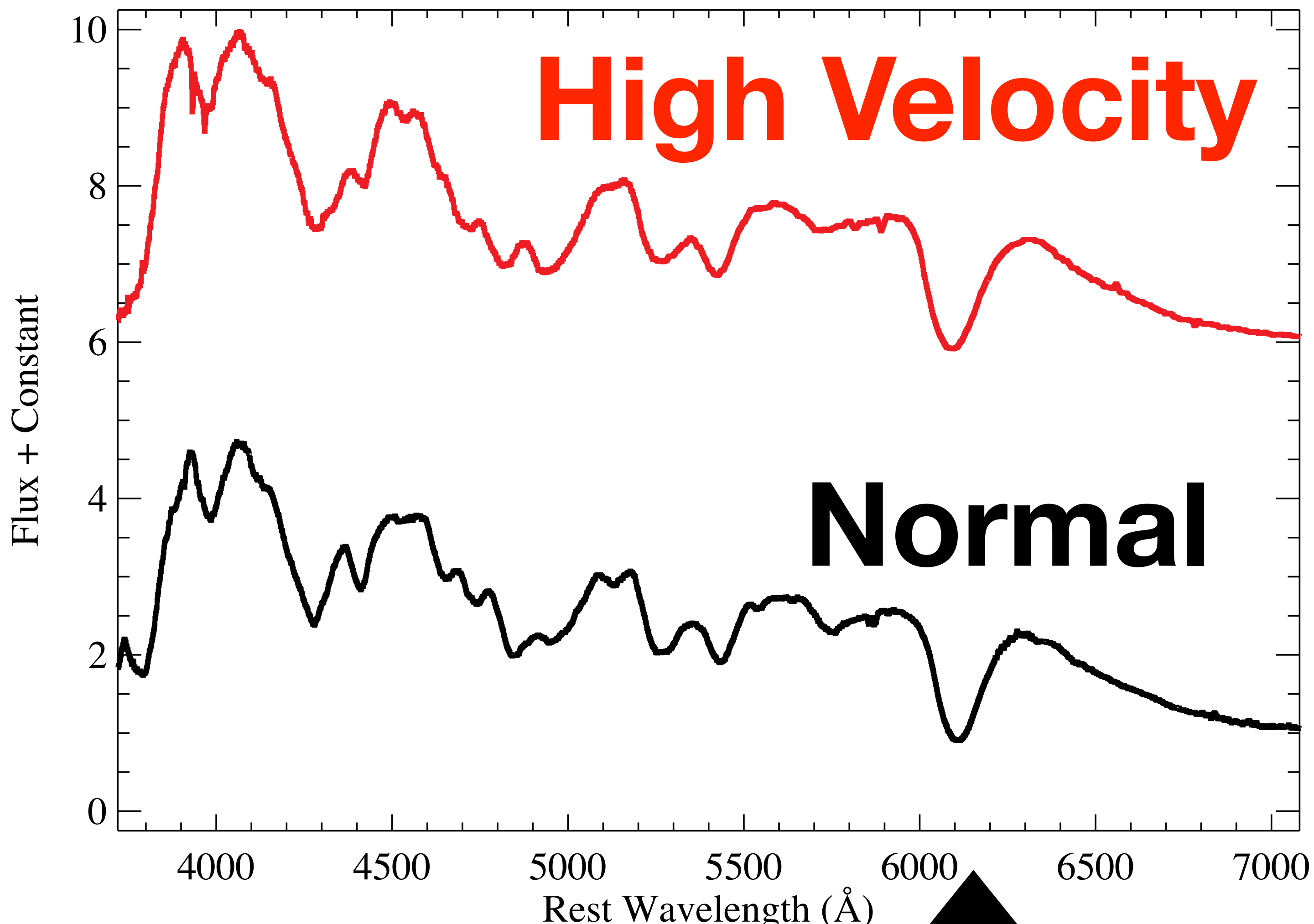


Ryan Foley,
Stephane Blondin



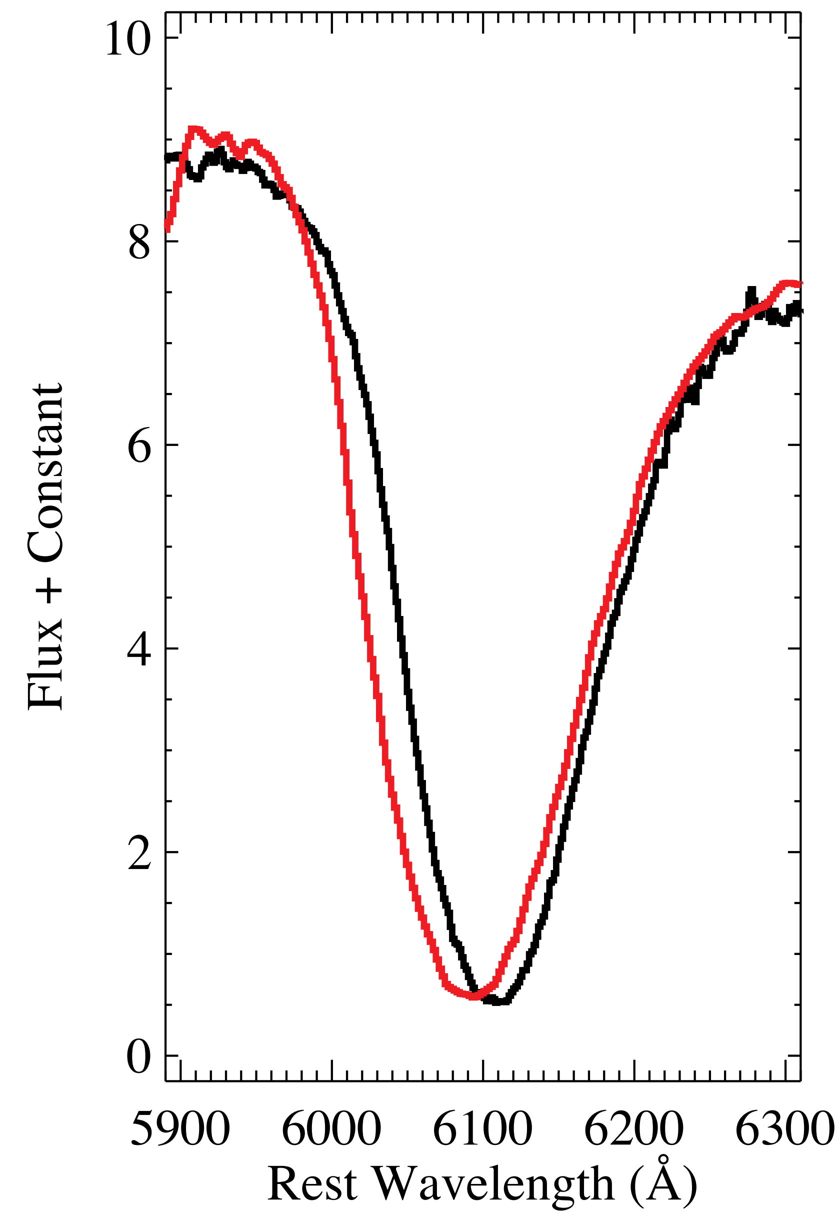
Foley & Kasen 2011 : Velocity Related to Line opacity in B

Si II λ6355 line



Ryan Foley,
Stephane Blondin

Silicon

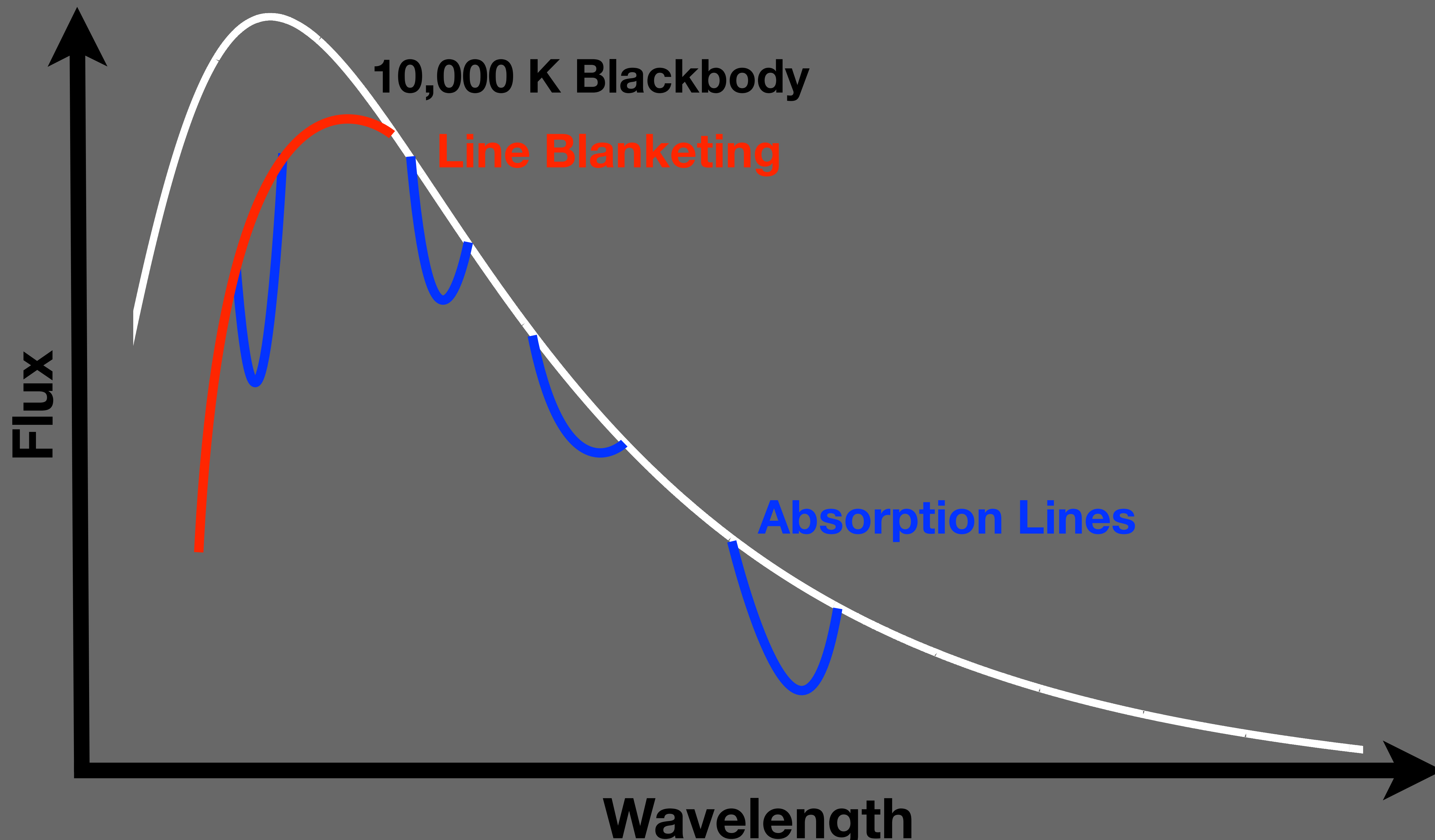


Foley & Kasen 2011 :
Velocity Related to
Line opacity in B

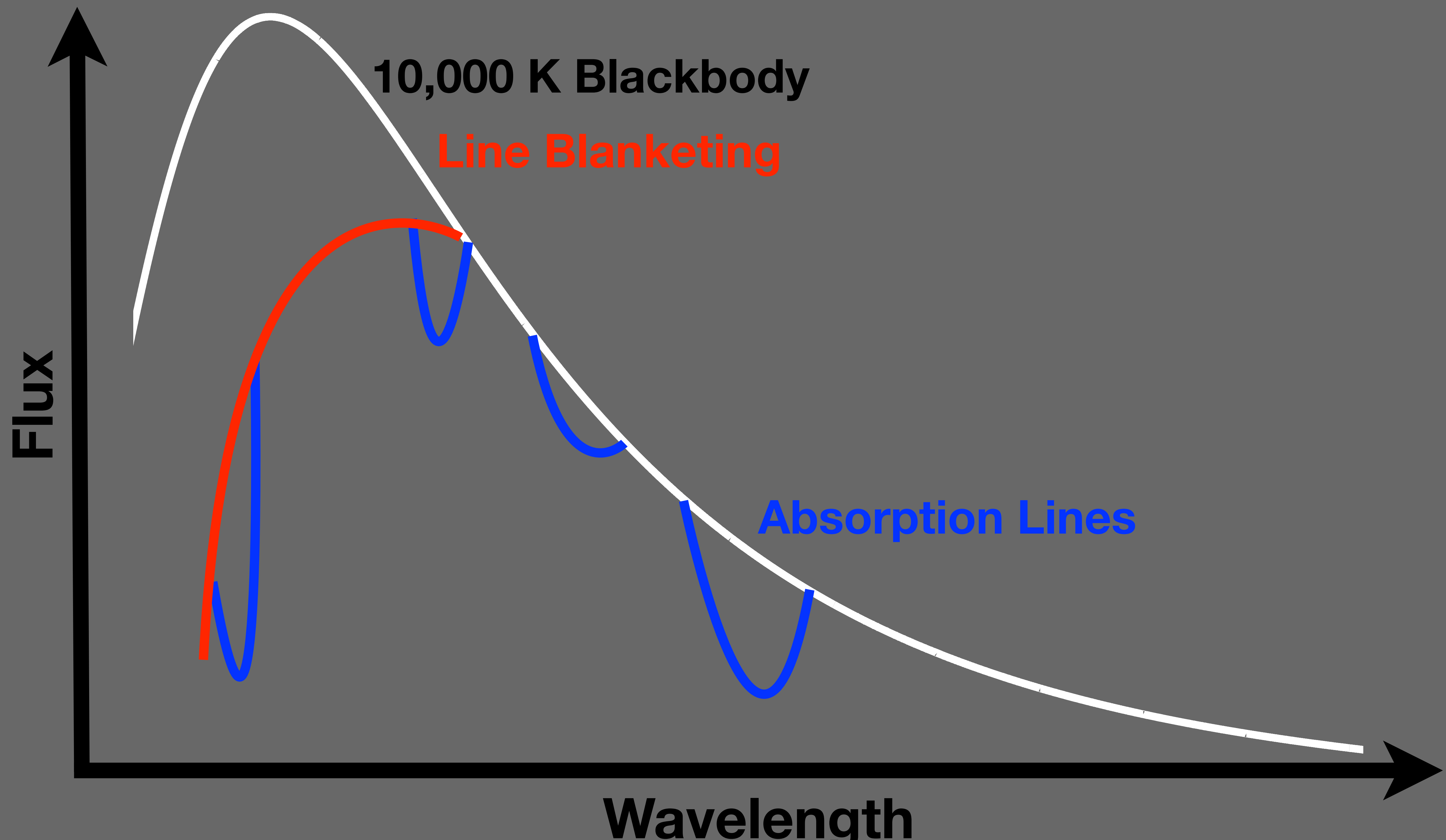
SN Ia Ejecta Velocities and Optical Colors

- Foley & Kasen (2011): Si II velocity is correlated with Peak Intrinsic B-V color
- High Ejecta Velocity : Broader Absorption Lines in B-band : Redder SN color
- Velocity can help determine intrinsic color, improve SN Ia dust and distance estimates

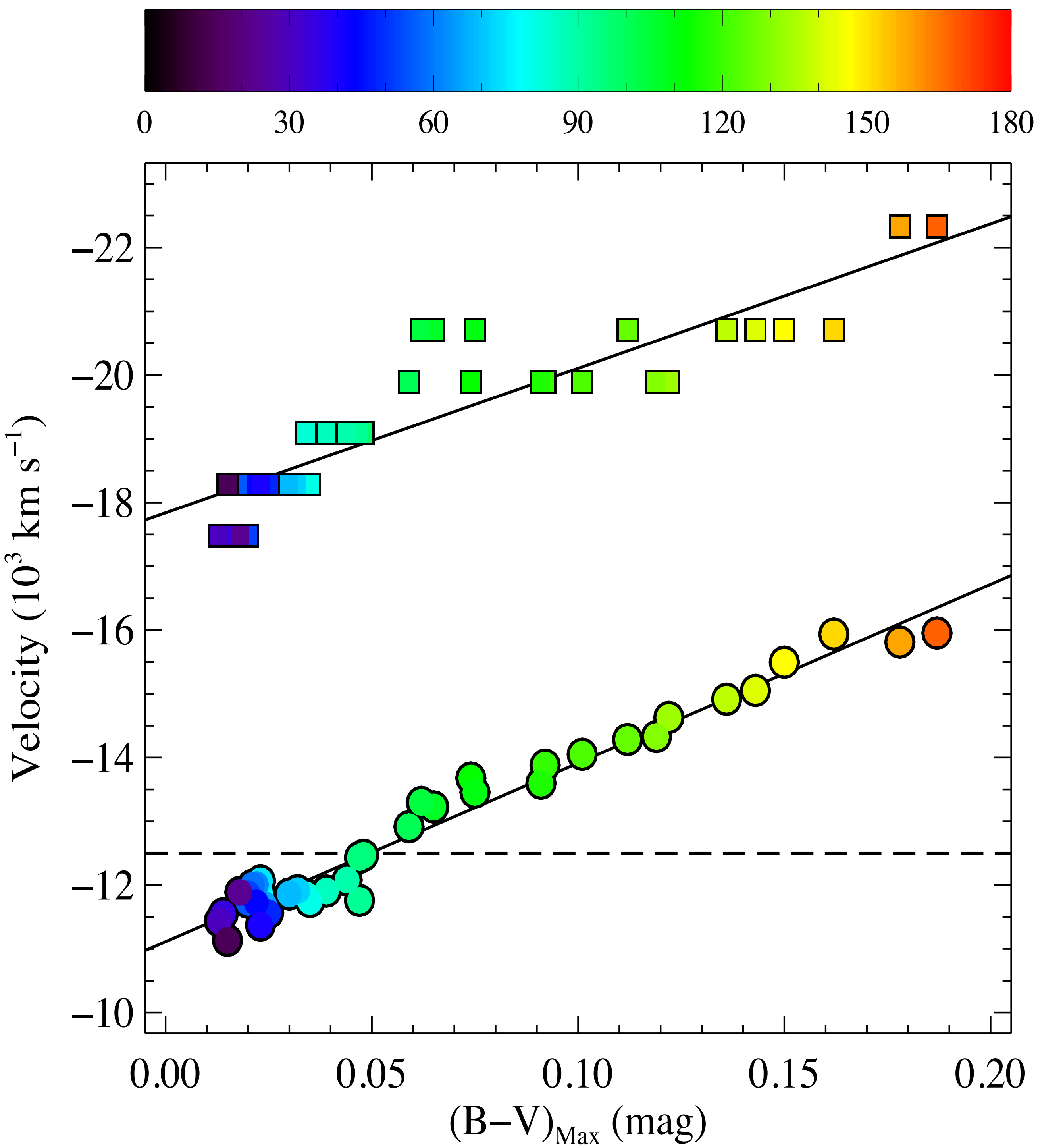
Supernova SED Toy Model



Supernova SED Toy Model



Theoretical Model

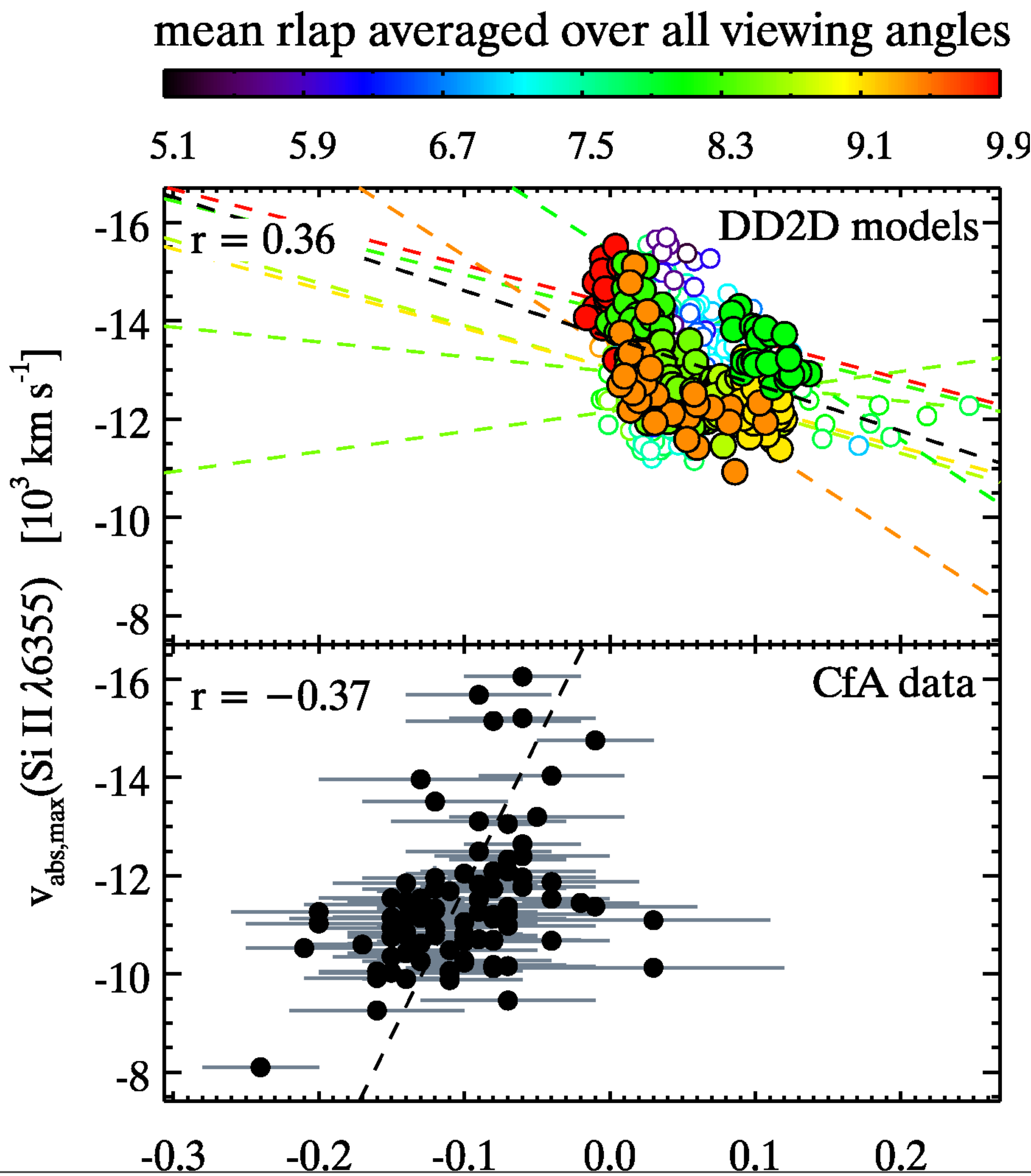


- Asymmetric SN Ia Explosion Model
- Predicts Linear relation between intrinsic color and velocity

Foley & Kasen 2011

Testing Theoretical Explosion Models

Blondin, Kasen, Röpke, Kirshner & Mandel. 2011



Other models do not show a clear relation between Si II velocity vs Intrinsic B-V color

Want to estimate trend from the data

Estimating the Population Intrinsic Color-Velocity Relation

- C = Intrinsic Color, O = Observed Color
- If have measurements (C, v) for each individual SN, then just regress C against v
- But we measure (O, v) where O = C + Dust Reddening + Error
- How do we estimate population relation between C vs v using (O, v) as data?

What is Hierarchical Bayes?

Simple Bayes: $\mathcal{D}|\,\theta \sim \mathrm{Model}(\theta) + \epsilon$

Posterior: $P(\theta|\,\mathcal{D}) \propto P(\mathcal{D}|\,\theta)P(\theta)$

Hierarchical Bayes: $\theta_i = \mathrm{Individual}$

$\alpha, \beta = \mathrm{Group\ or\ Population}$

$$\mathcal{D}_i|\theta_i \sim \mathrm{Model}(\theta_i) + \epsilon$$

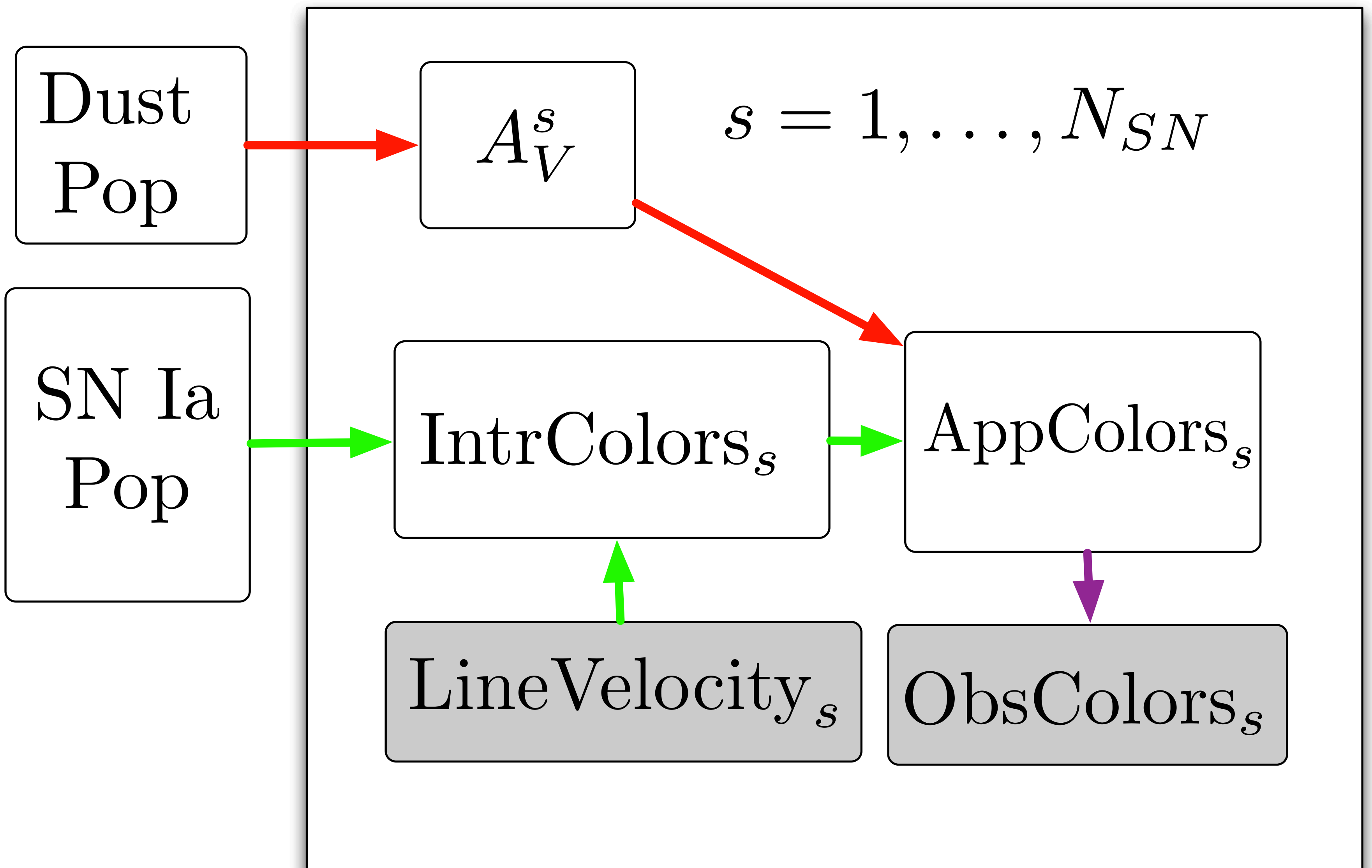
$$\theta_i|\,\alpha, \beta \sim P(\theta|\,\alpha, \beta)$$

Joint Posterior:

$$P(\{\theta_i\}, \alpha, \beta|\{\mathcal{D}_i\}) \propto \left[\prod_{i=1}^{N} P(\mathcal{D}_i|\,\theta_i)P(\theta_i|\alpha, \beta)\right]P(\alpha, \beta)$$

Build up complexity by layering conditional probabilities

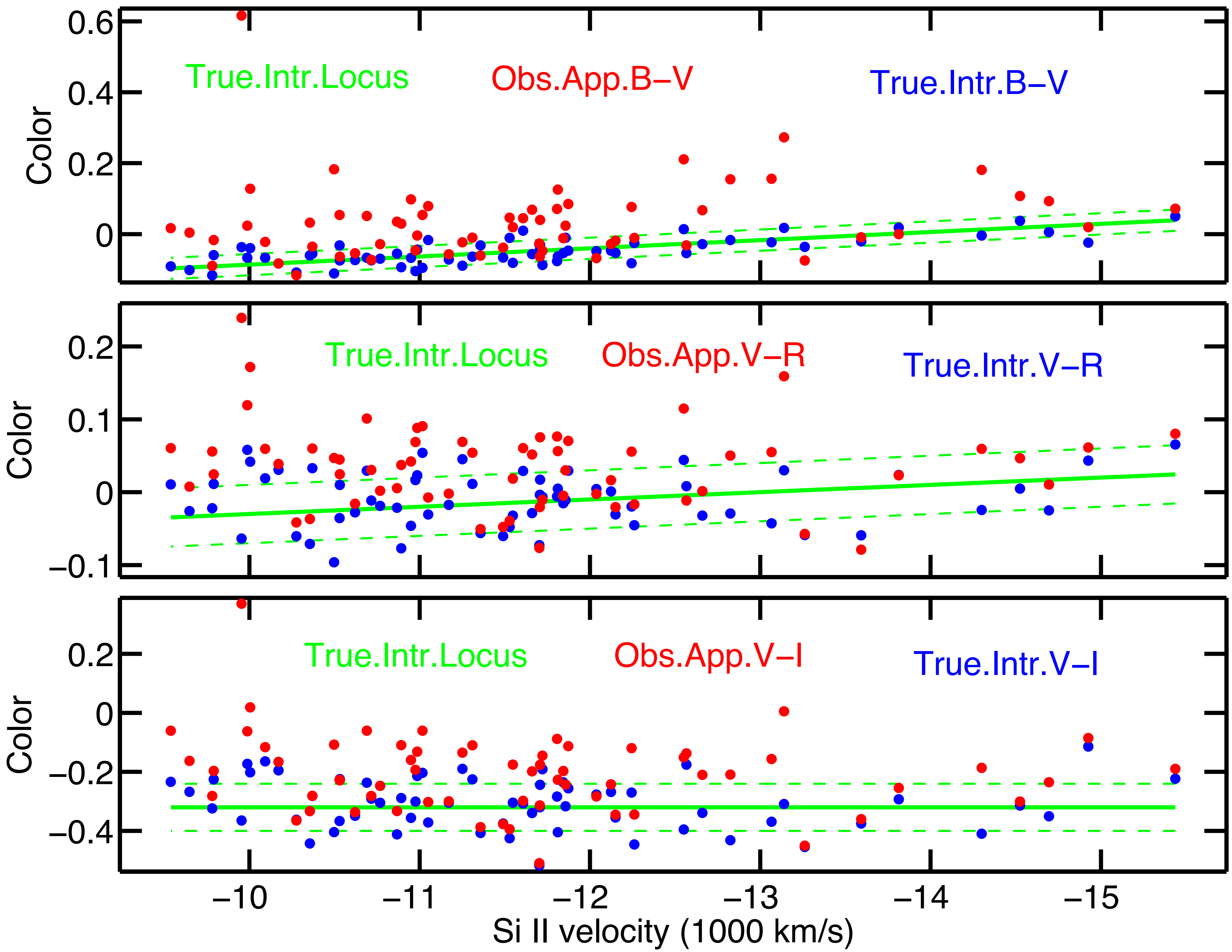
Graphical Model for Color-Velocity Hierarchical Model



Mathematical Details

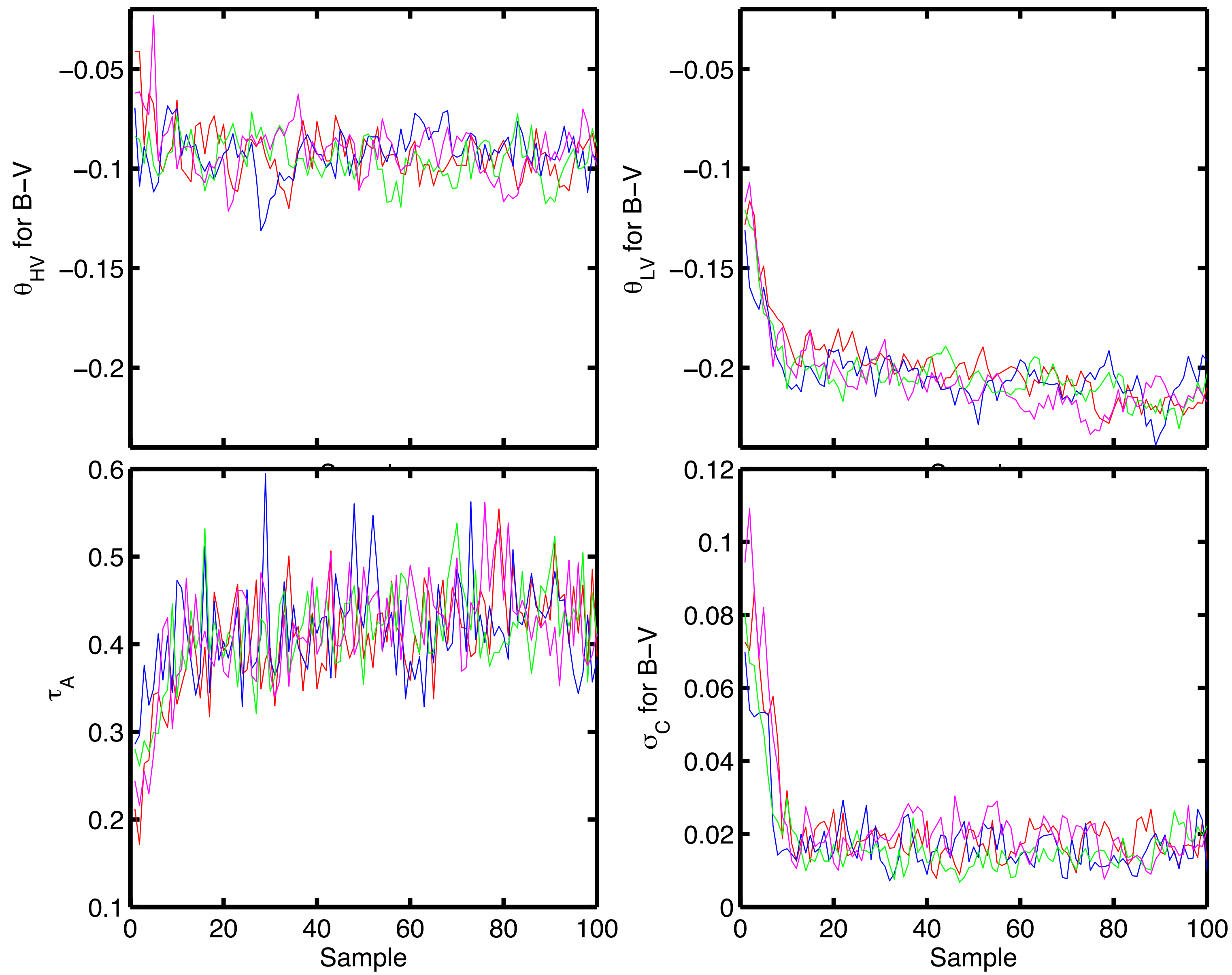
- Pick a form for population mean intrinsic color-velocity function: $\boldsymbol{\mu}_C(v_s;\boldsymbol{\theta})$
- Individual Intrinsic Colors: $\boldsymbol{C}_s = \boldsymbol{\mu}_C(v_s;\boldsymbol{\theta}) + \boldsymbol{\epsilon}_s^C.$
- Observed Colors: $\boldsymbol{O}_s = \boldsymbol{C}_s + A_V^s \boldsymbol{\gamma}(R_V) + \boldsymbol{\epsilon}_s.$
- Dust Distribution: $A_V^s \sim \text{Expon}(\tau_A)$

Simulated Data from Hierarchical Model

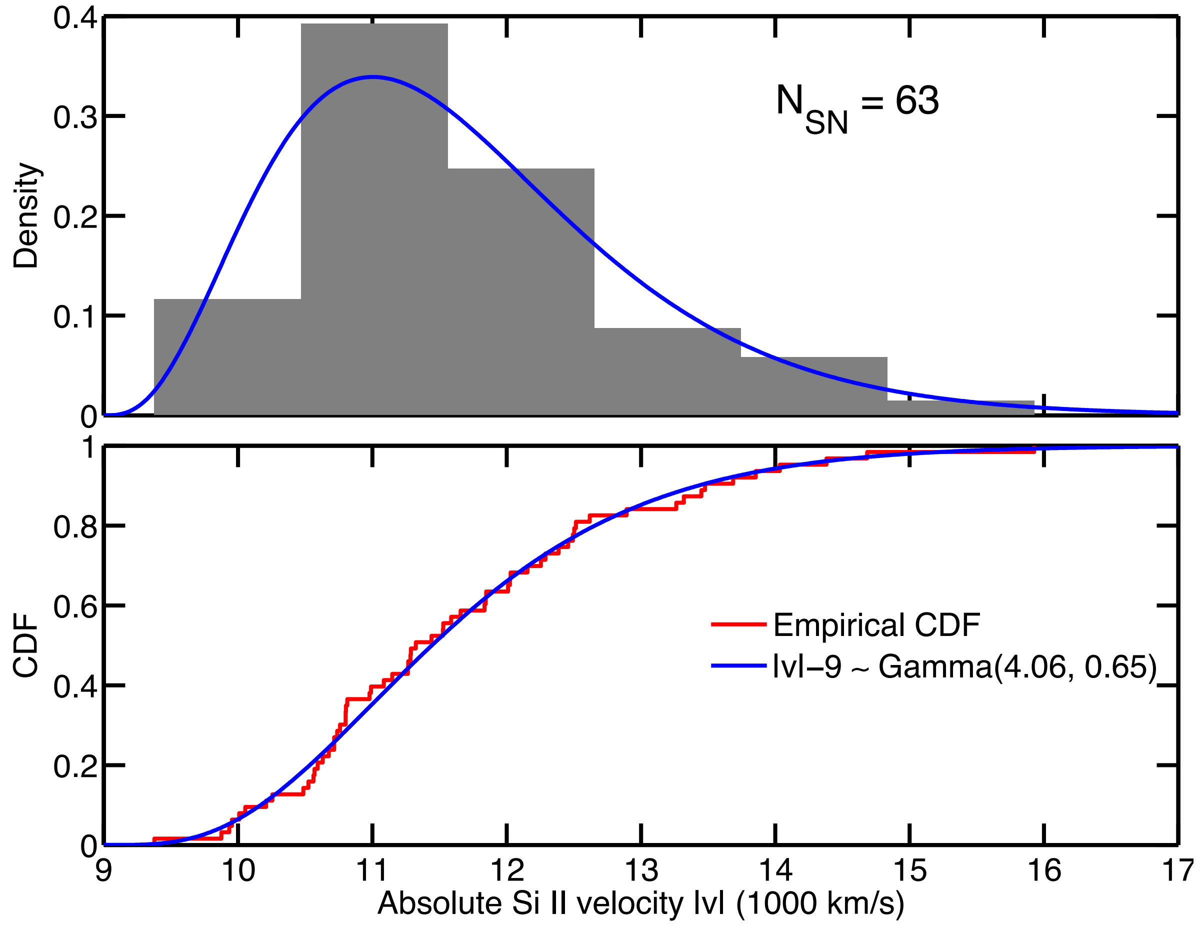


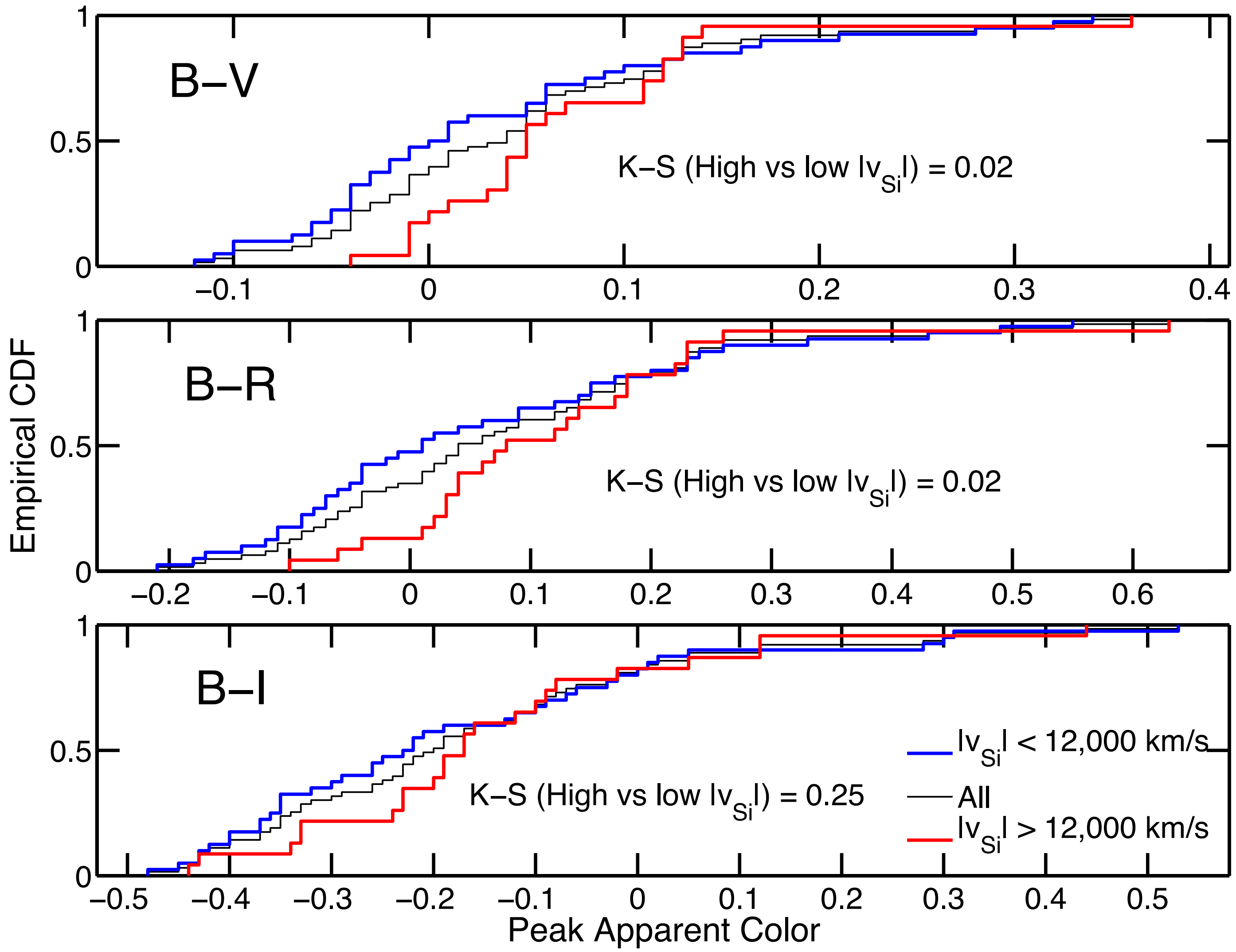
Gibbs Sampling the Posterior Distribution

1. Sample Individual SN parameters given data and population hyperparameters
2. Sample hyperparameters given individual parameters

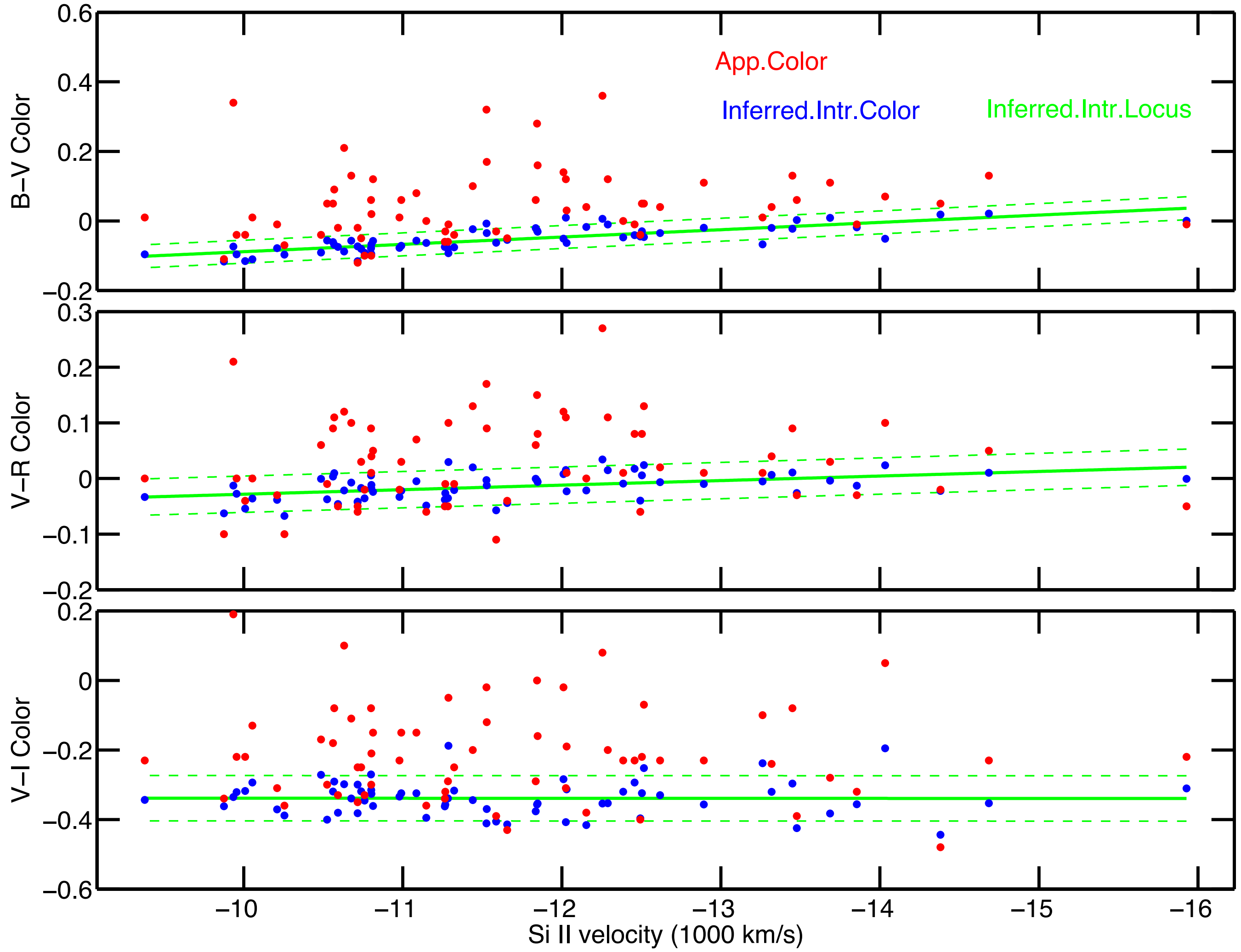


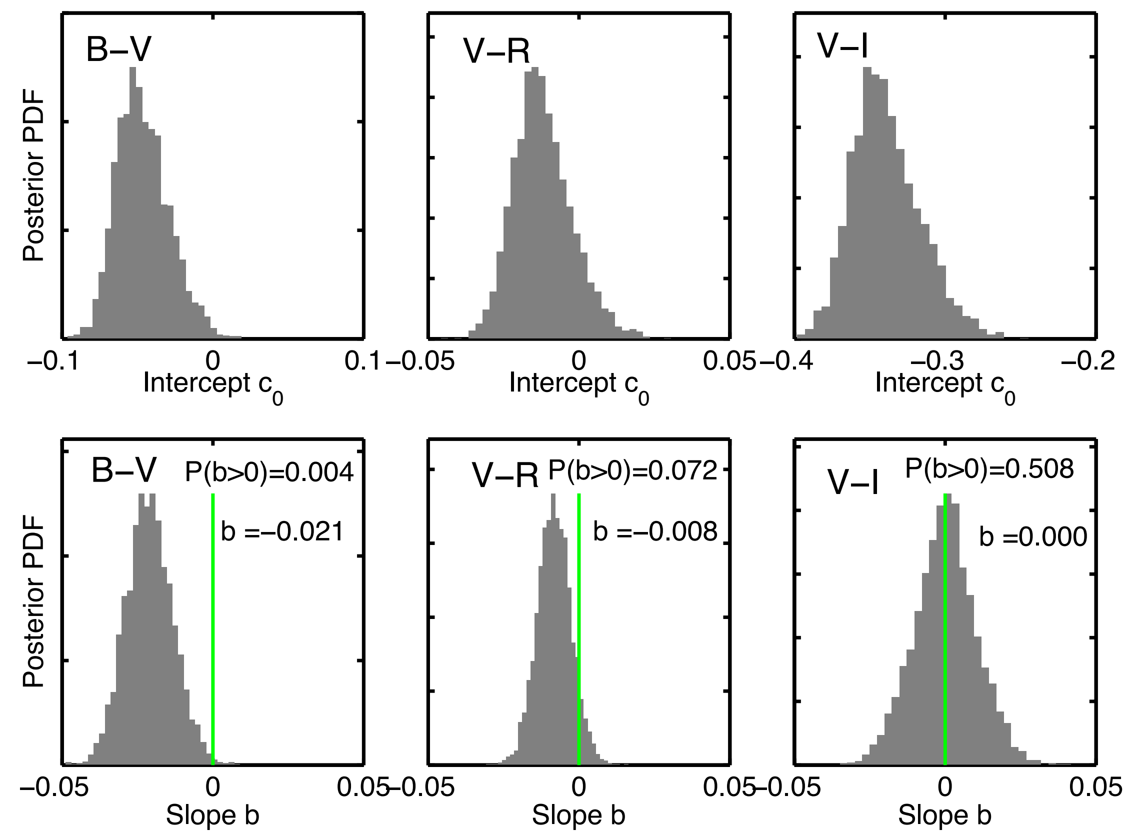
Application to Color-Velocity Data



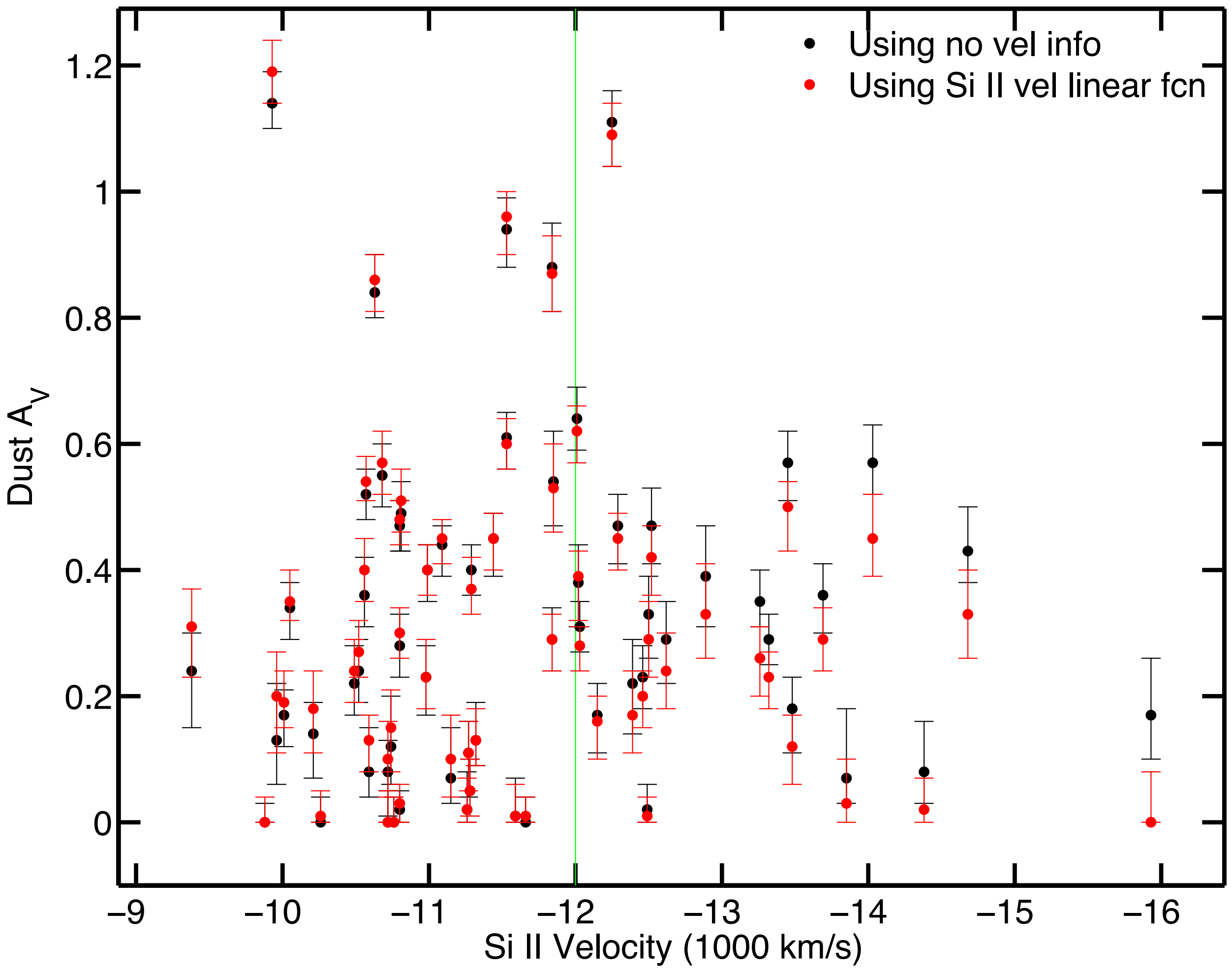


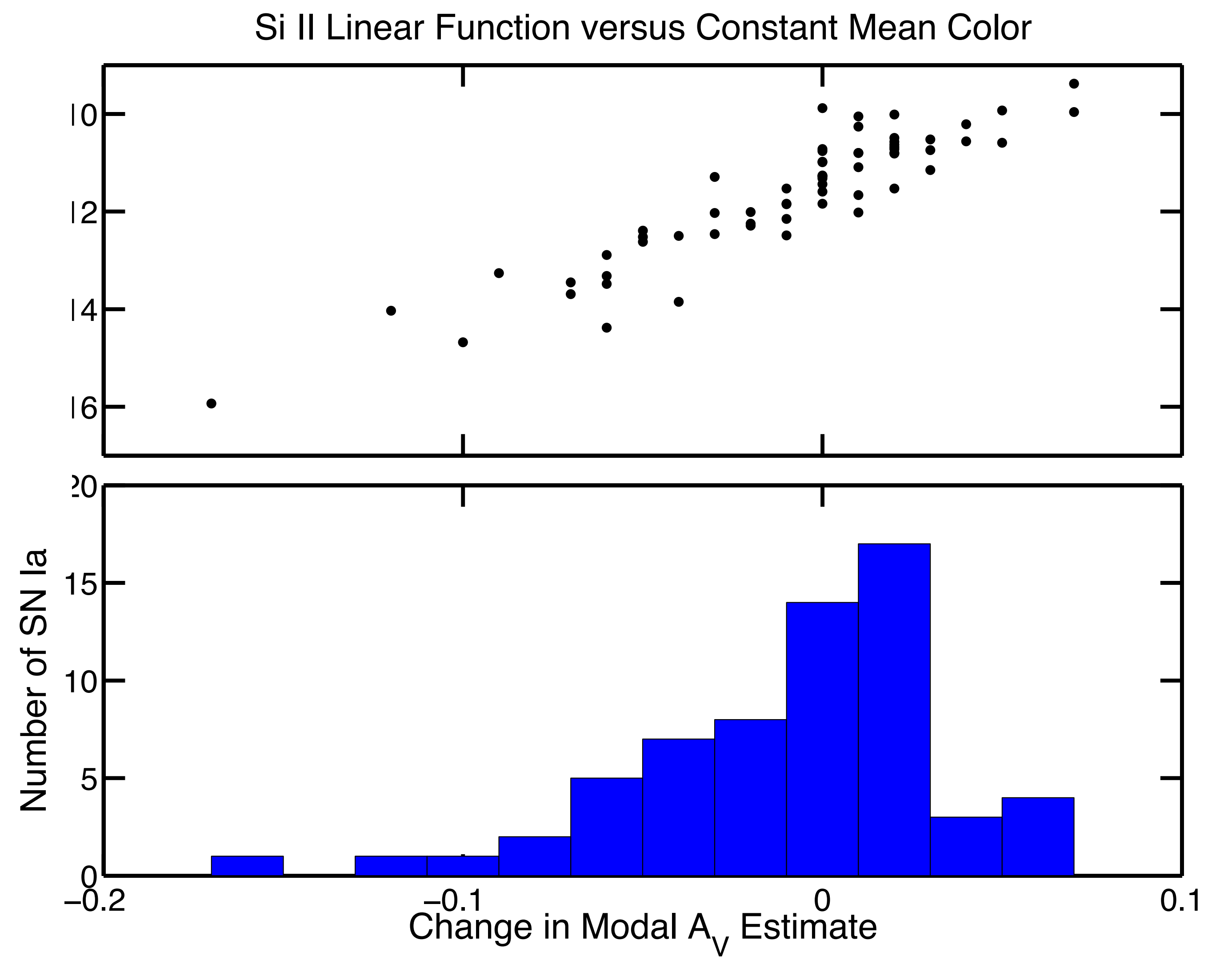
Posterior Inferences:
Linear Intrinsic Color-Velocity Function



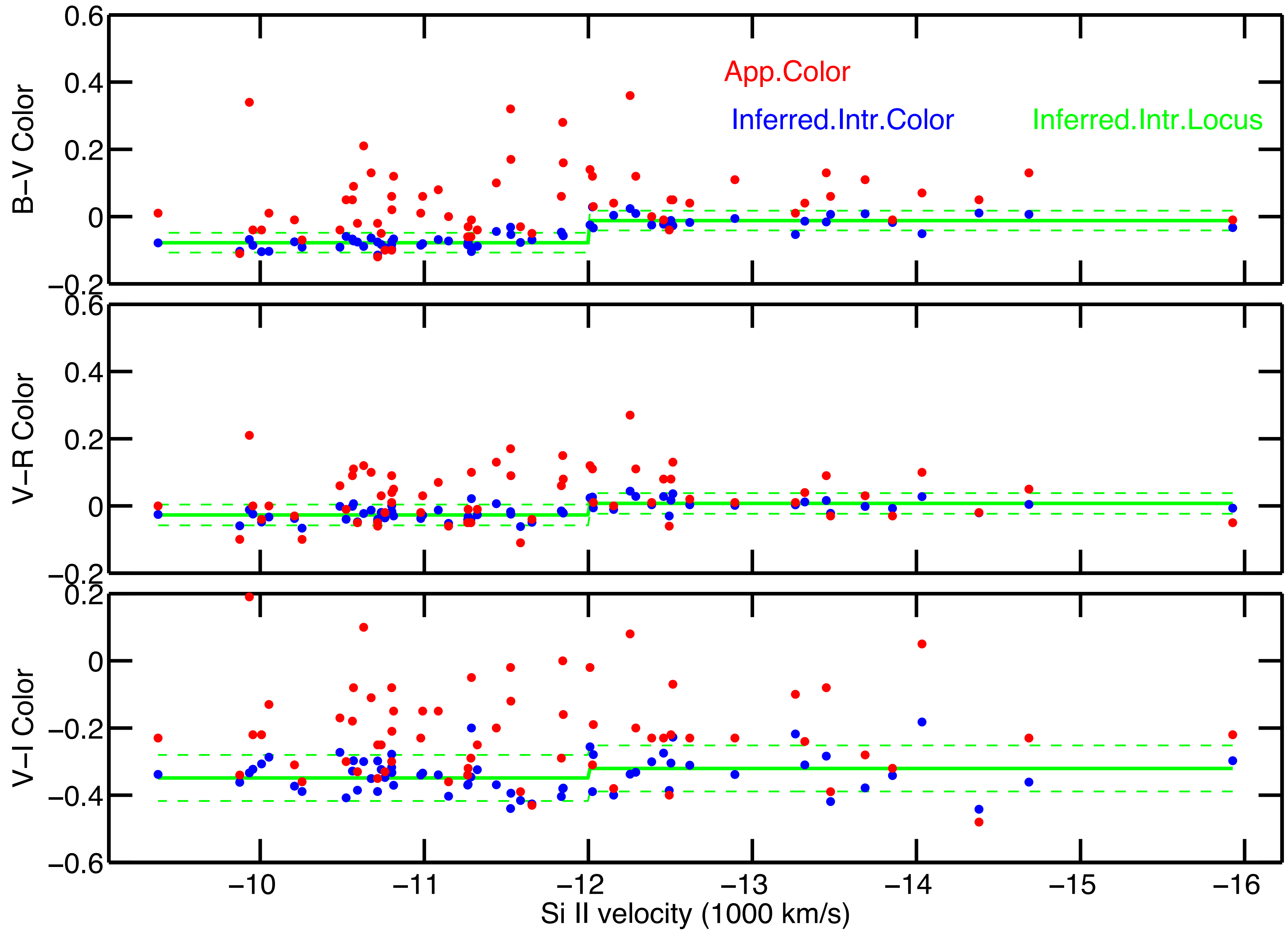


Leveraging Intrinsic Color-Velocity info changes the Dust Estimates





Posterior Inferences: Step Intrinsic Color-Velocity Function



Model Comparison using Deviance Information Criterion

- How complex a model to fit?
- Penalize the posterior average deviance (-2x log likelihood) by the effective number of parameters
- Uses MCMC samples

Table 3. Information Criteria for Color-Velocity Data

Model	$\hat{D}$	$\langle D \rangle$	p_D	DIC	Δ_0[a]
Const/Gaussian	-780.3	-775.0	5.4	-769.6	0.0
Linear	-790.9	-783.1	7.8	-775.3	-5.7
Step	-791.6	-783.7	7.9	-775.8	-6.2
Quadratic	-799.5	-788.8	10.7	-778.1	-8.5
Cubic	-799.1	-785.6	13.5	-772.1	-2.5

[a]Difference in DIC relative to that of the Gaussian (constant mean intrinsic color) model

Conclusion

- Two Applications of Bayesian Modeling applied to Supernova Data
- Naive Bayes Classification of SN using Galaxy Data
- Modeling Intrinsic Color-Velocity trends in presence of dust