Supernova Cosmology in the Near-Infrared with Hierarchical Bayesian Light Curve Models

Kaisey Mandel
CfA Supernova Group
& iCHASC

Harvard-Smithsonian
Center for Astrophysics

Astrostatistics Seminar
25 Jan 2016

Collaborators

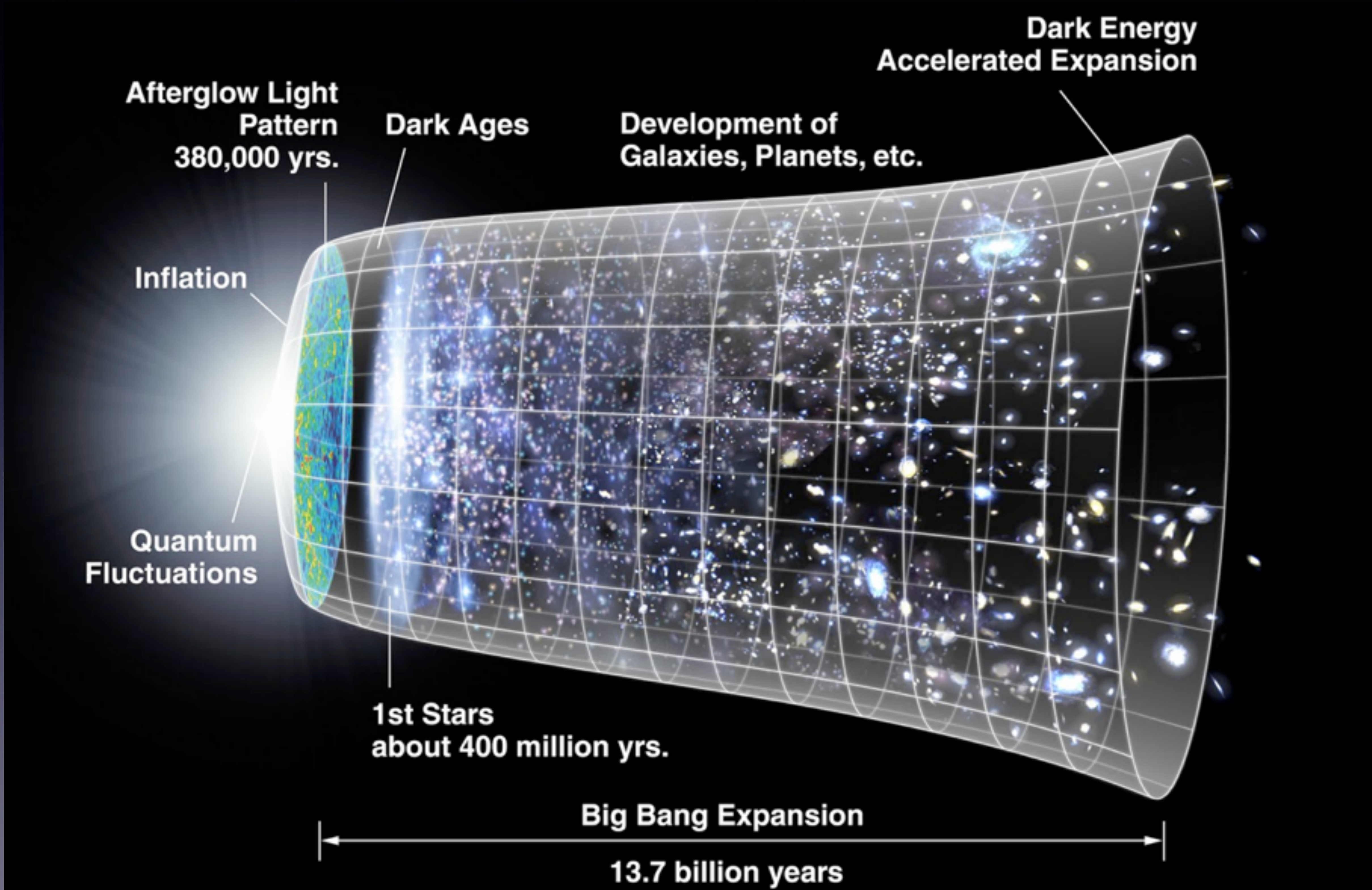
(they get the data)

- CfA Supernova Group (R. Kirshner, P. Challis, A. Avelino, A. Friedman)
- Ryan Foley (U. Illinois), Dan Scolnic (KICP/Chicago), Armin Rest (STSci), Gautham Narayan (Arizona, NOAO)…
- Pan-STARRS & RAISIN1 team
- Dark Energy Survey & RAISIN2 team

Outline

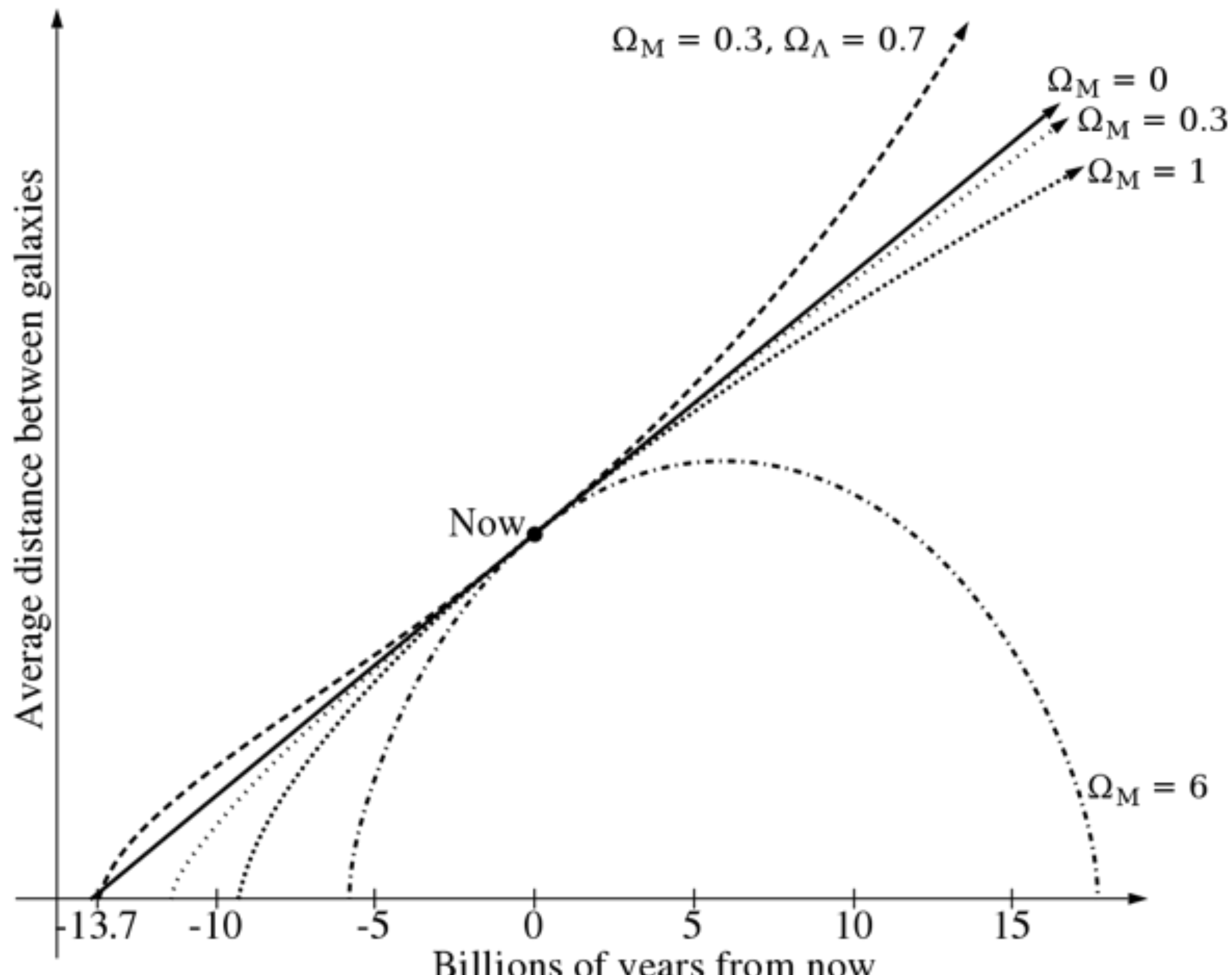
- Introductory Background and Scientific Motivation: Supernova Cosmology in the NIR
- Hierarchical Bayesian Statistical Modeling of Supernova Light Curves
- New Application: Tracing the History of Cosmic Expansion with NIR observations of Distant Supernovae using the Hubble Space Telescope

The History of Cosmic Expansion

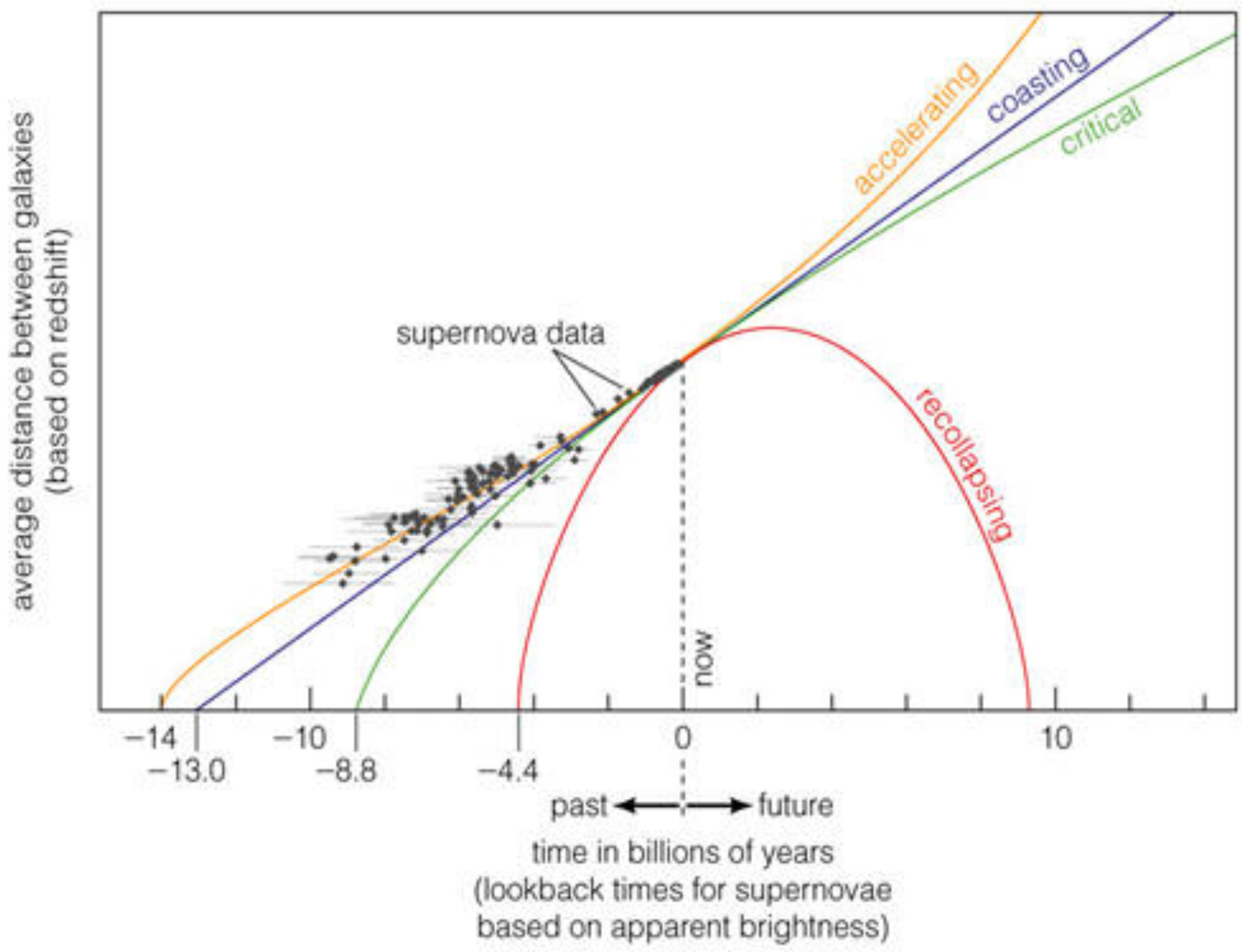


Expansion History (and Future) of the Universe: Determined by its Physical Energy Content

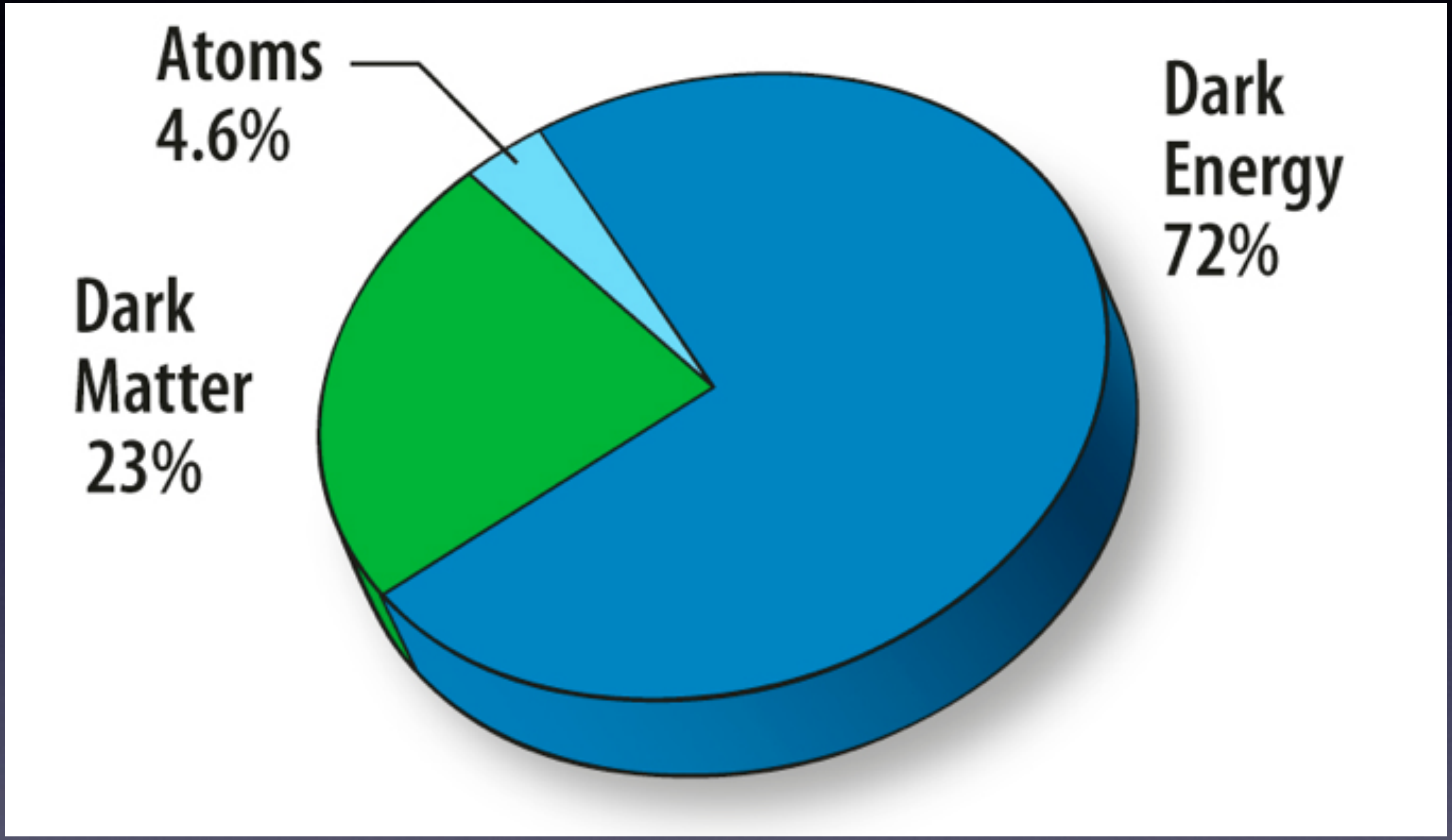
Ω_M = Matter Density; Ω_Λ = Dark Energy Density



Supernovae Trace the History of Cosmic Expansion



Cosmological Energy Content

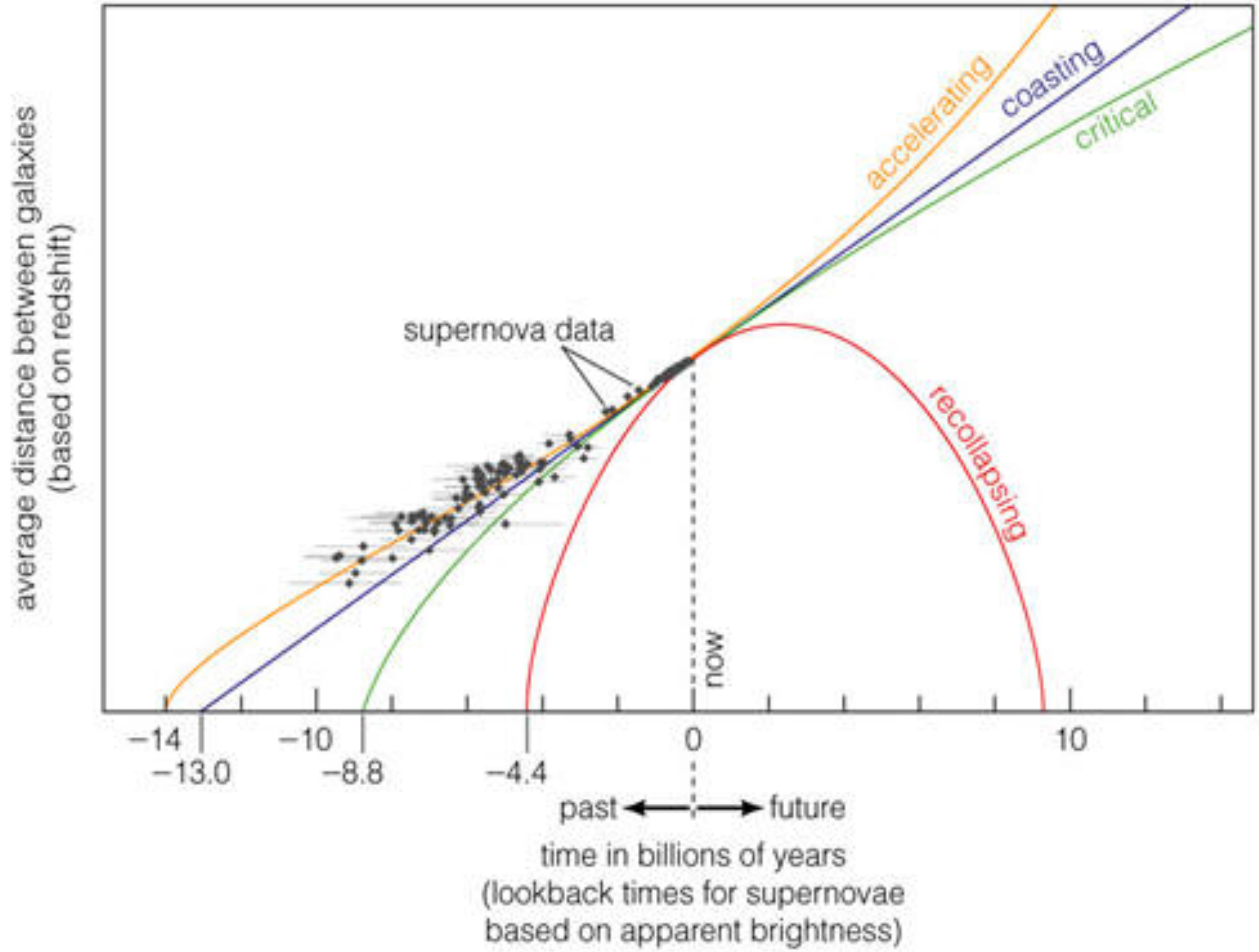


What is Dark Energy?

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

Is $w + 1 = 0$? (Cosmological Constant: $w = -1$)

Supernovae Trace the History of Cosmic Expansion

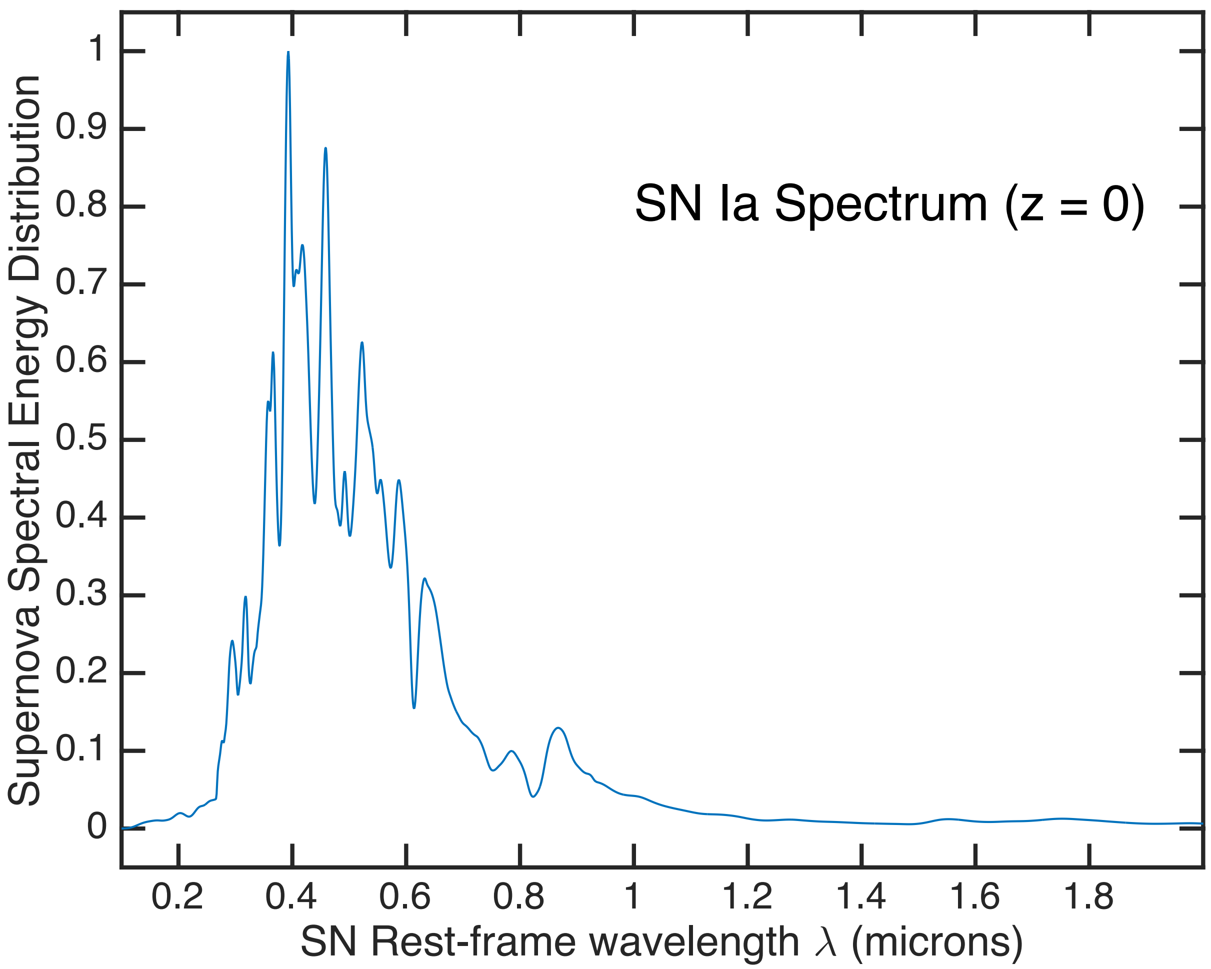


But we don’t actually measure these things!

Time → Distance (μ)

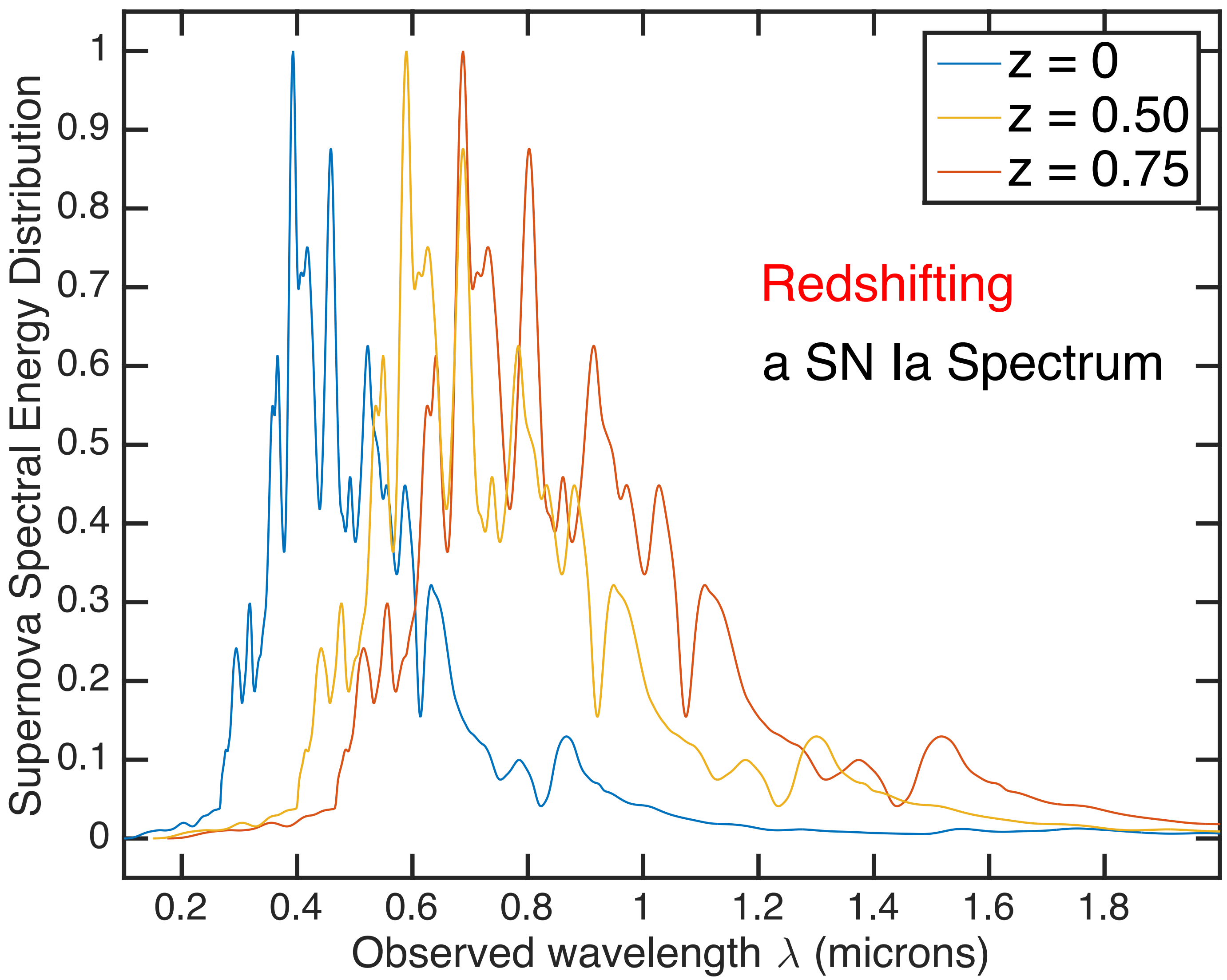
Relative Size of Universe → Redshift (z)

Expansion of the Universe: Redshifts



Expansion of Space "stretches" out wavelengths of light

Spectral Lines are observed at longer wavelengths than originally emitted by the supernova: redshift



Determining Astronomical Distances using Standard Candles

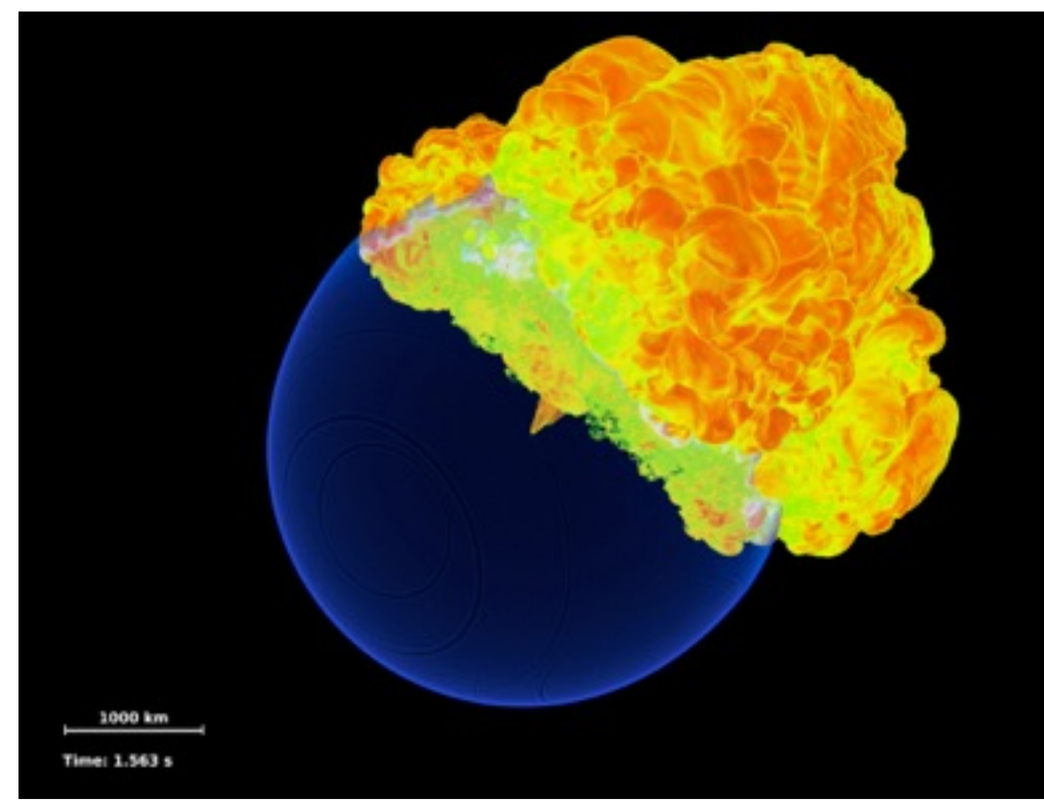
1. Estimate or model Luminosity L of a Class of Astronomical Objects
2. Measure the apparent brightness or flux F
3. Derive the distance D to Object using Inverse Square Law: $F = L / (4\pi D^2)$
4. Optical Astronomer's units: $\mu = m - M$

(m = apparent magnitude, M = absolute magnitude,

μ = distance modulus [log distance])

Type Ia Supernovae (SN Ia) are Almost Standard Candles

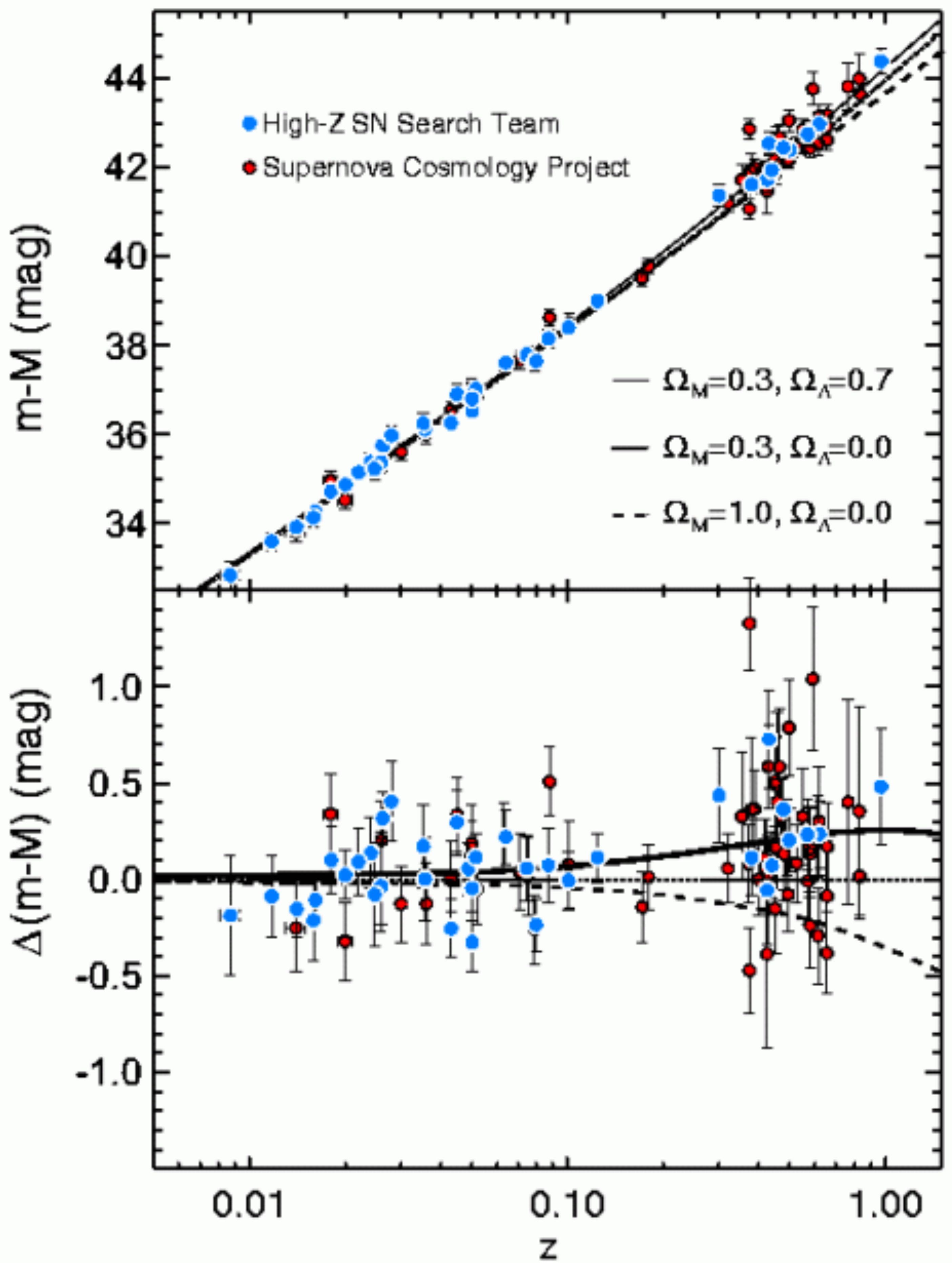
- Progenitor: C/O White Dwarf Star accreting mass leads to instability (single / double degenerate)
- Thermonuclear Explosion: Deflagration/Detonation
- Nickel to Cobalt to Iron Decay + radiative transfer powers the light curve



Credit: FLASH Center

SN Ia Hubble Diagram (Distance Moduli vs. redshift):

The Universe is accelerating ($\Omega_\Lambda > 0$)!



The Accelerating Universe
2011 Nobel Prize in Physics

Photo: U. Montan

Saul Perlmutter

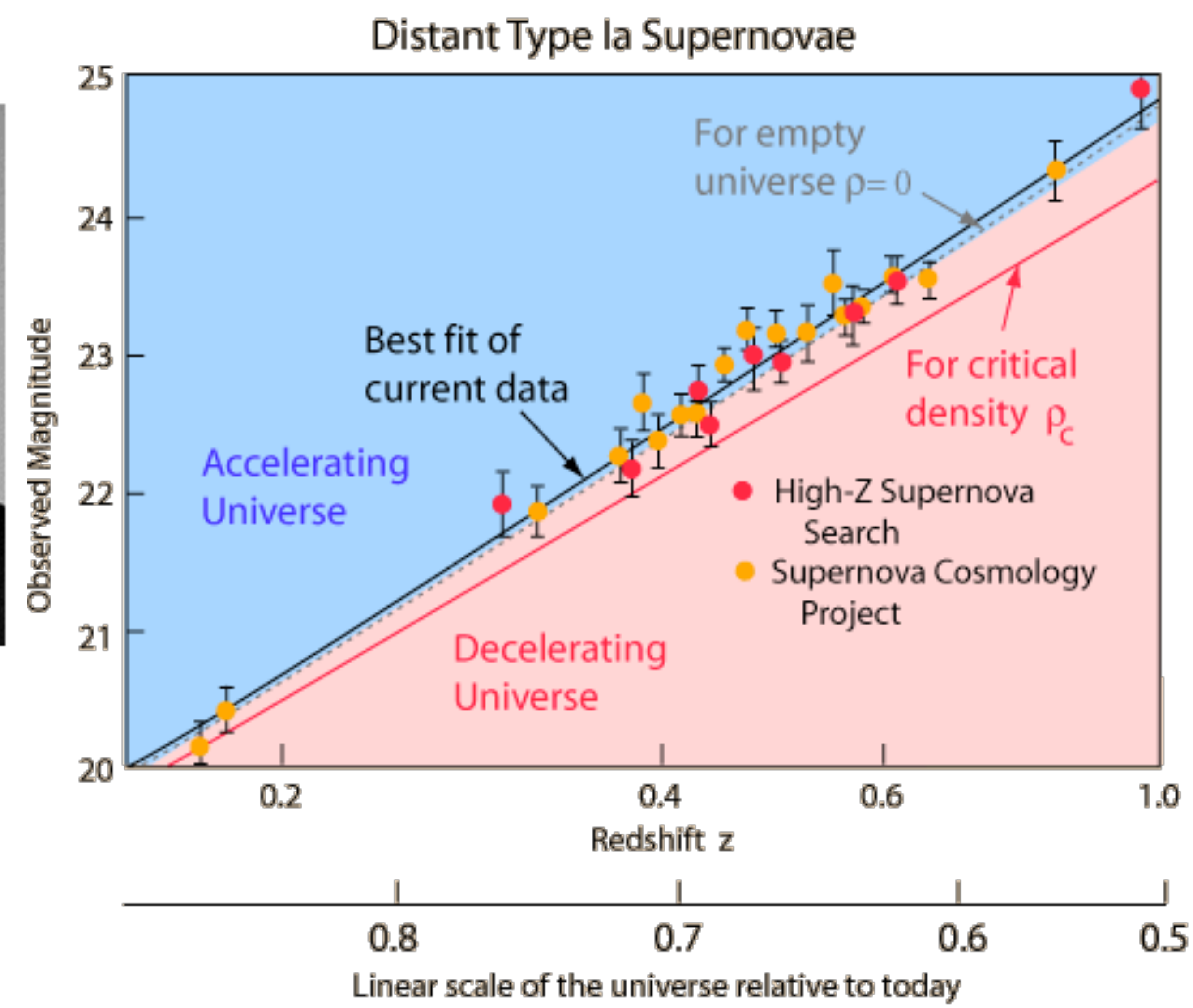
Photo: U. Montan

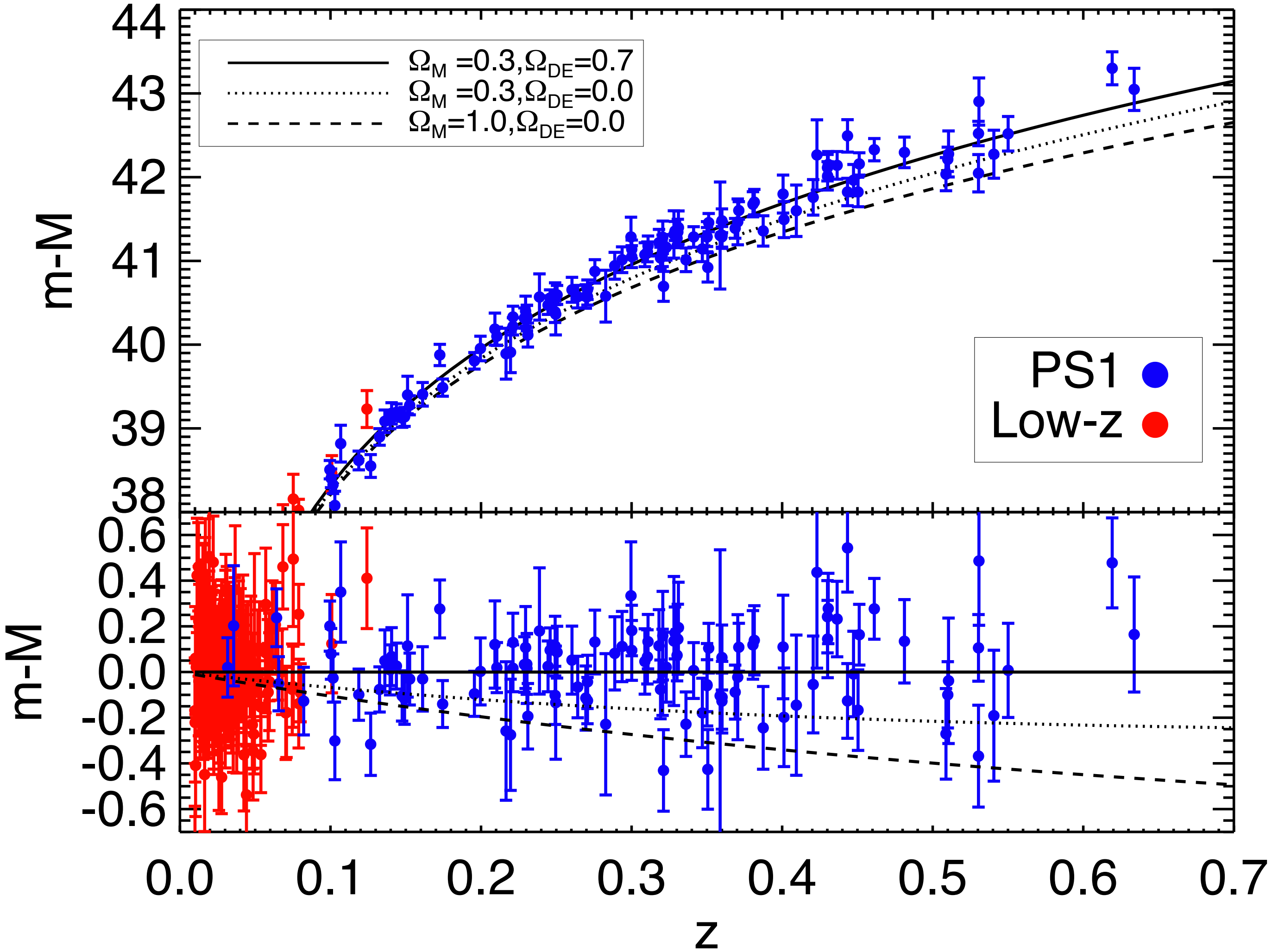
Brian P. Schmidt

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"*.



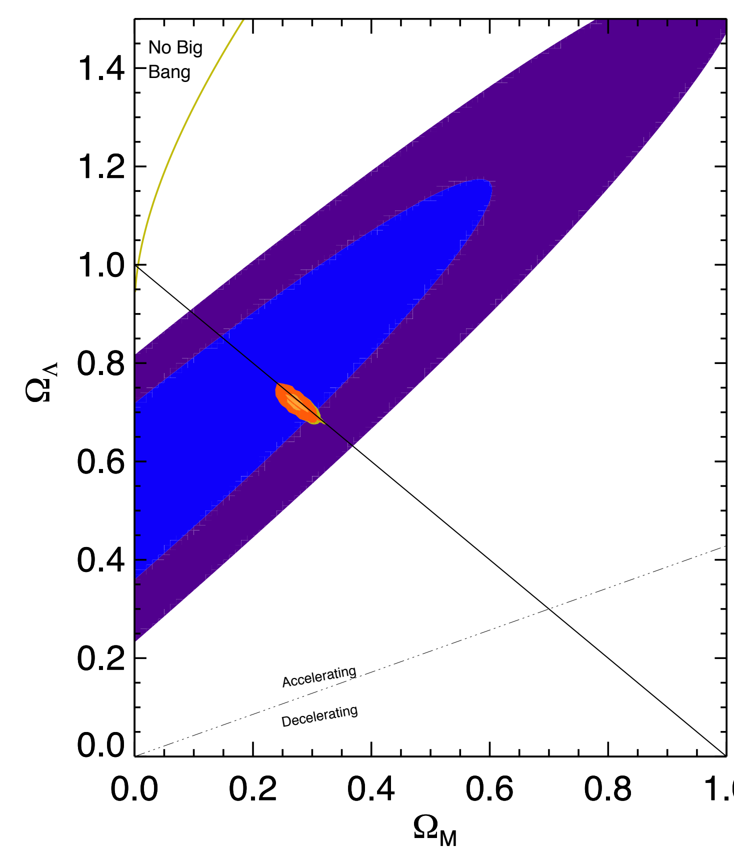


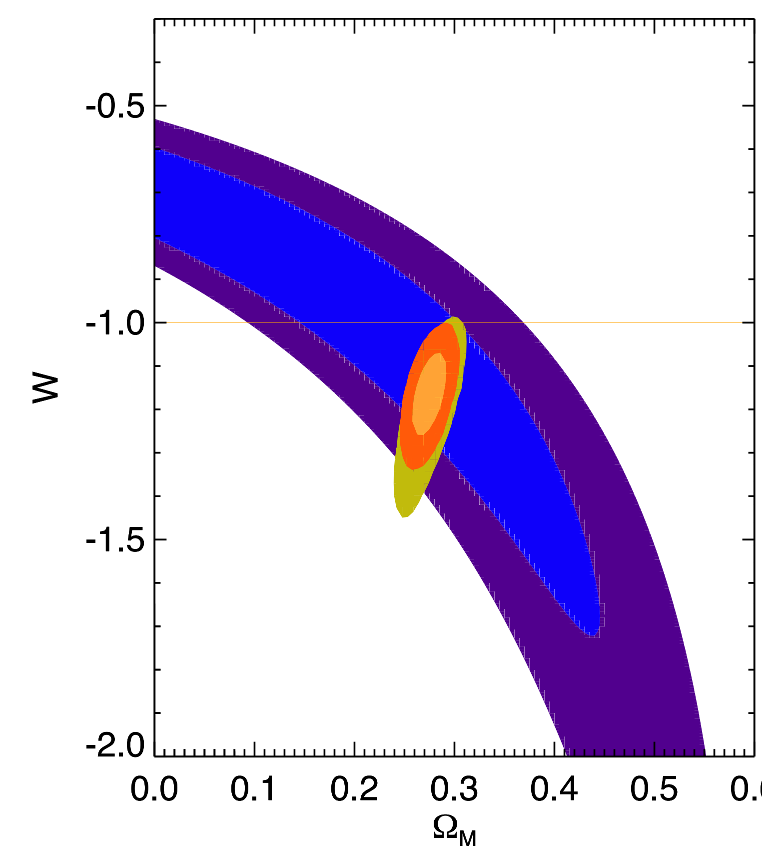
First Pan-STARRS PS1results (Rest et al., 2014, Scolnic et al., 2014)

Combined PS1+Lz + Planck+BAO+H$_o$:

Ω_M = 0.280 (0.013)

w = −1.166 (0.07)





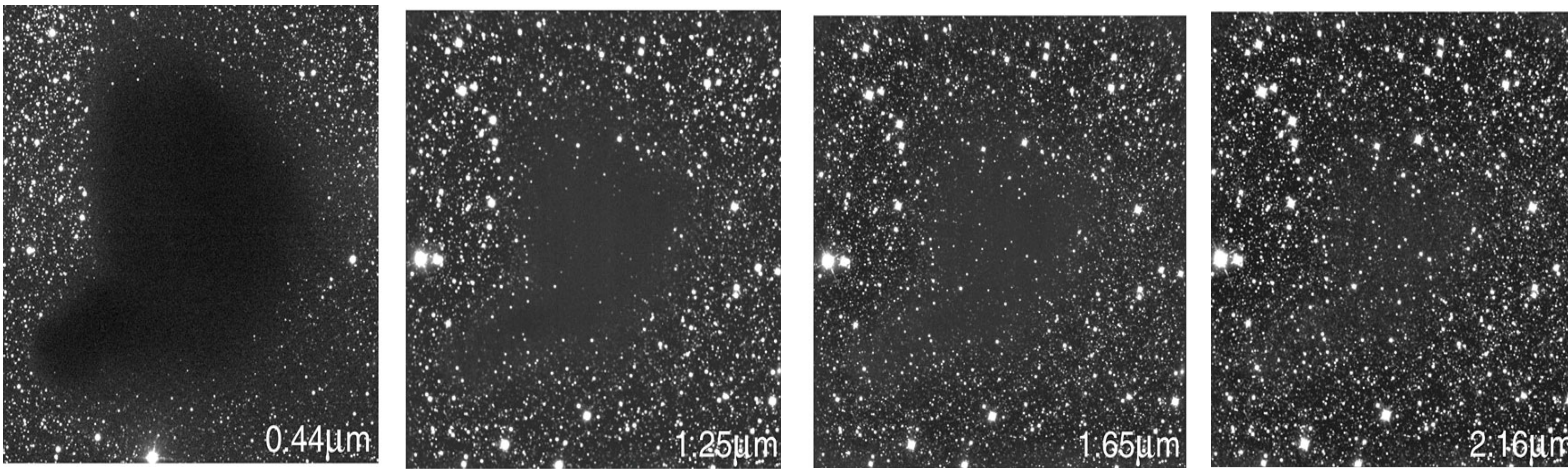
Current State of Play

- Current optical surveys are now limited by systematic uncertainties, e.g. photometric calibration error and modeling error, rather than "statistical" (number of supernovae).
- Standard analysis method does not distinguish between intrinsic SN variations and extrinsic effects of host galaxy dust and reddening
- Scolnic et al. 2014 : a different modeling interpretation of the data results in a 4% systematic shift in w
- Modeling and/or mitigating host galaxy dust effects is important for accurate cosmological constraints

Interstellar Dust is a real physical effect

Optical light

Near Infrared Wavelengths



B-band J-band H-band K-band

Seeing through interstellar dust

What about the host galaxy dust?

Dust Absorption vs. Wavelength of Light

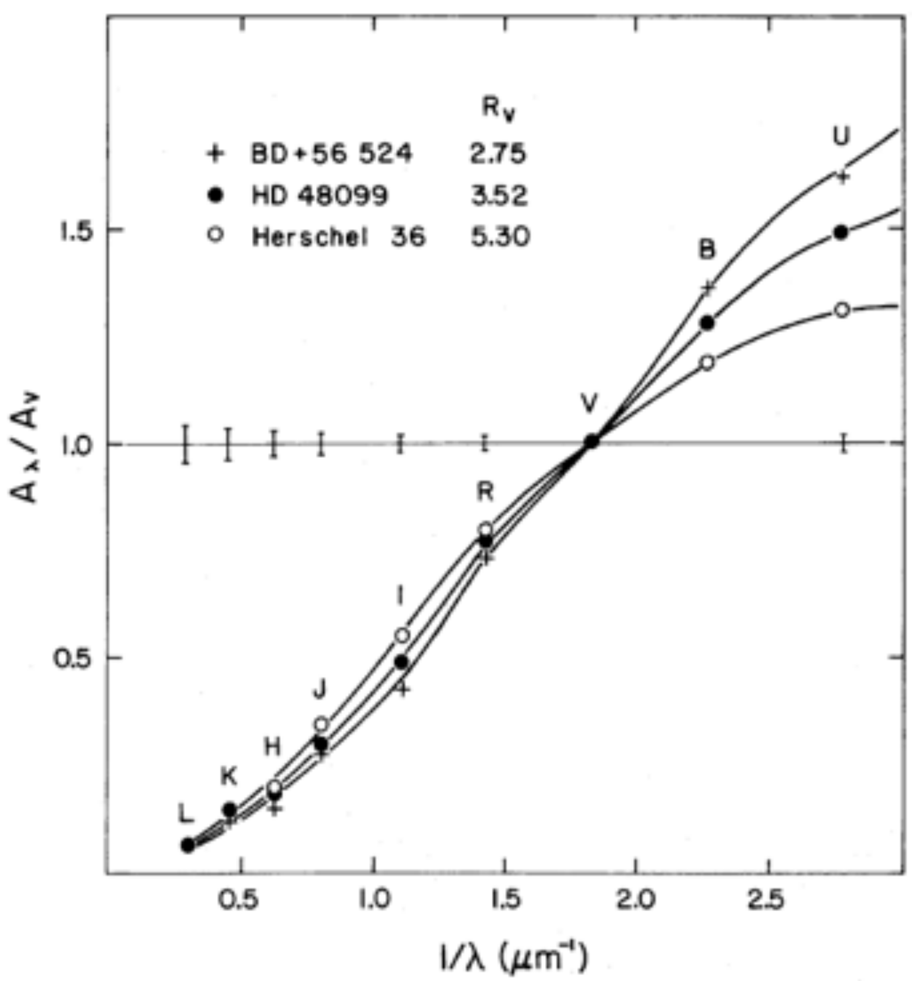


FIG. 3.—Comparison between the mean optical/NIR R_V-dependent extinction law from eqs. (2) and (3) and three lines of sight with largely separated R_V values. The wavelength position of the various broad-band filters from which the data were obtained are labeled (see Table 3). The "error" bars represent 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.

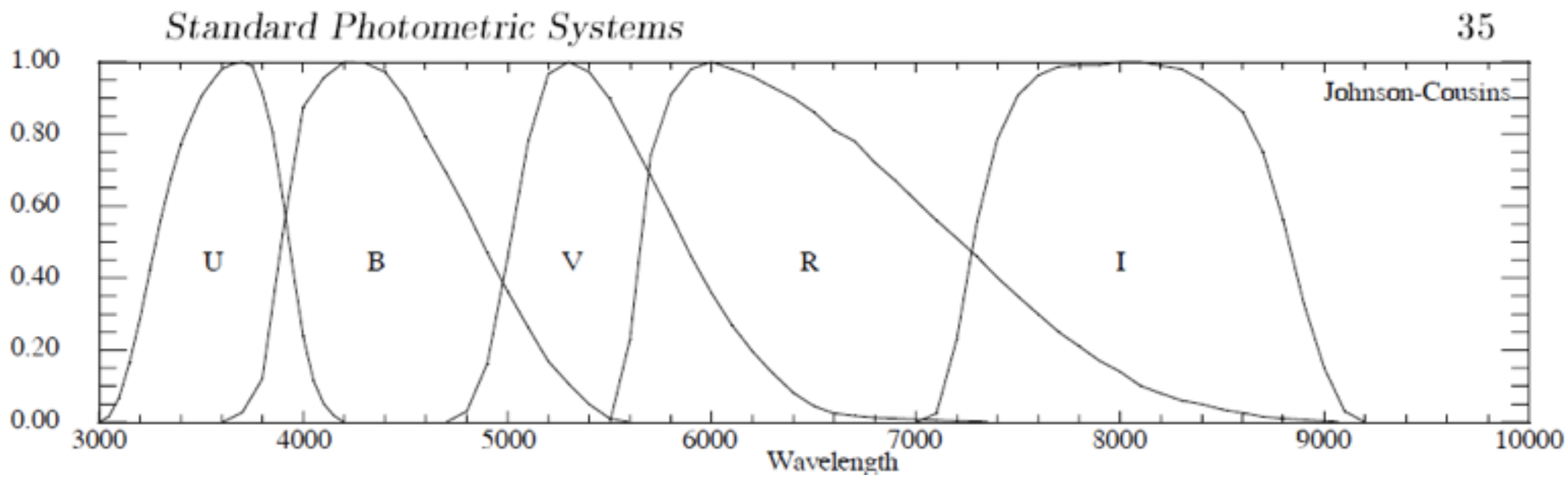
- Absorption of light (dimming) depends on λ, causing reddening
- Interstellar lines of sight to SN in different galaxies can pass through different random amounts of dust
- Key Parameters of Interstellar Dust (different for each SN)
  - A_V ~ Amount of Dust Absorption (dimming)
  - R_V ~ Wavelength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

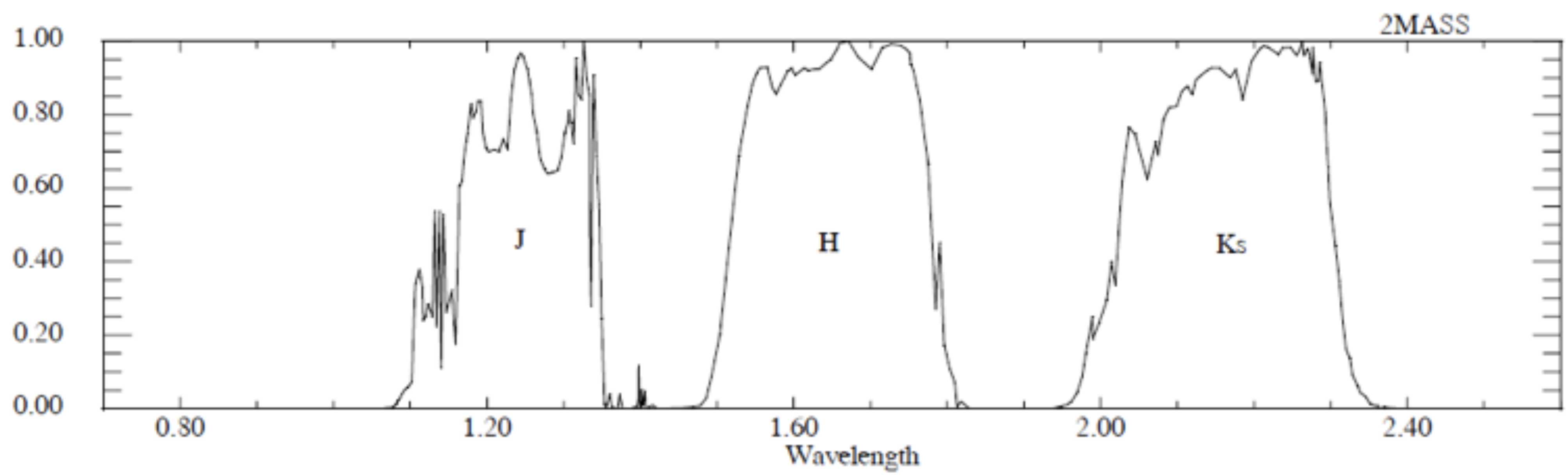
Strategy: Go to the infrared!

- Dust extinction is significantly diminished (by ~5) in the rest-frame NIR (i.e. YJHK) compared to optical
- SN Ia are excellent candles in the NIR (small variance in absolute magnitude)
- Wavelength Range of Optical+NIR data helps constrain dust absorption & reddening better
- CfA, CSP groups are building up large samples of nearby SN Ia light curves in the NIR
- Latest data release: CfAIR2 (94 SN Ia LCs in JHK, Friedman et al., 2015, ApJ) - ground-based data
- RAISIN1+2: 200 HST orbits to observe ~50 SN Ia in the NIR at z = 0.2-0.6 discovered with Pan-STARRS and Dark Energy Survey

Telescopes collect light of different wavelengths

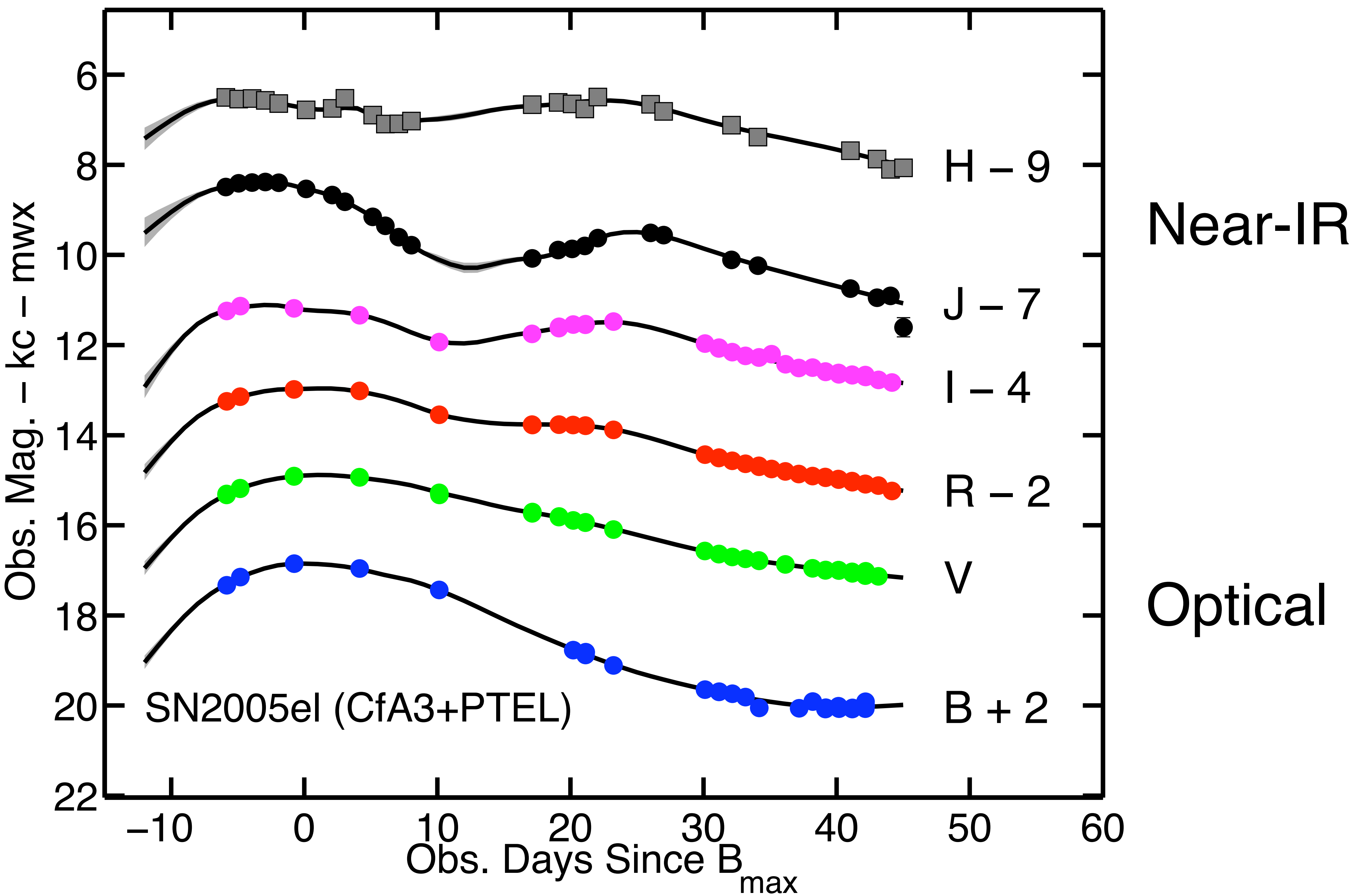
Optical



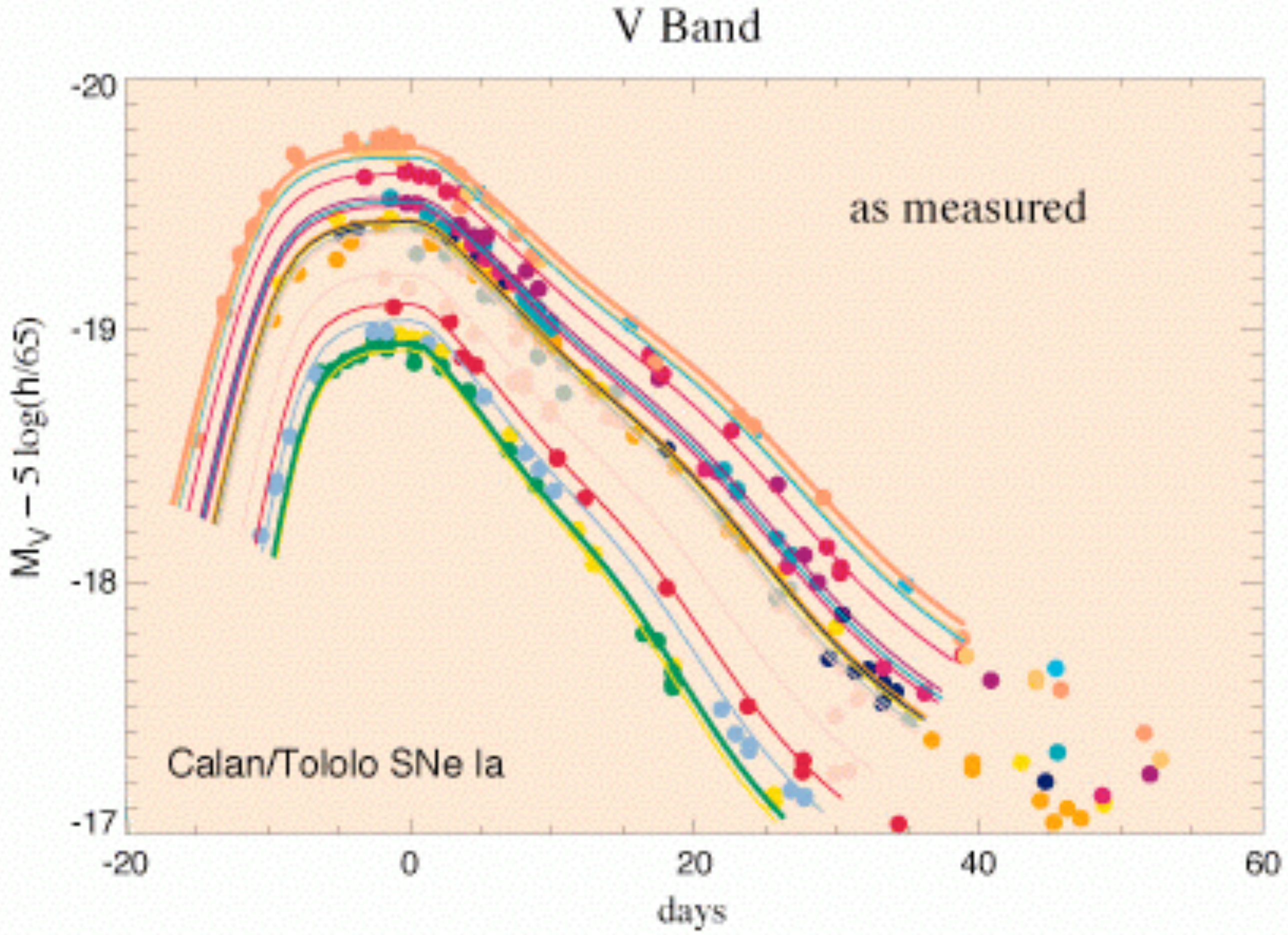


Near Infrared

The Data:
Type Ia Supernova Apparent Light Curve (time series)

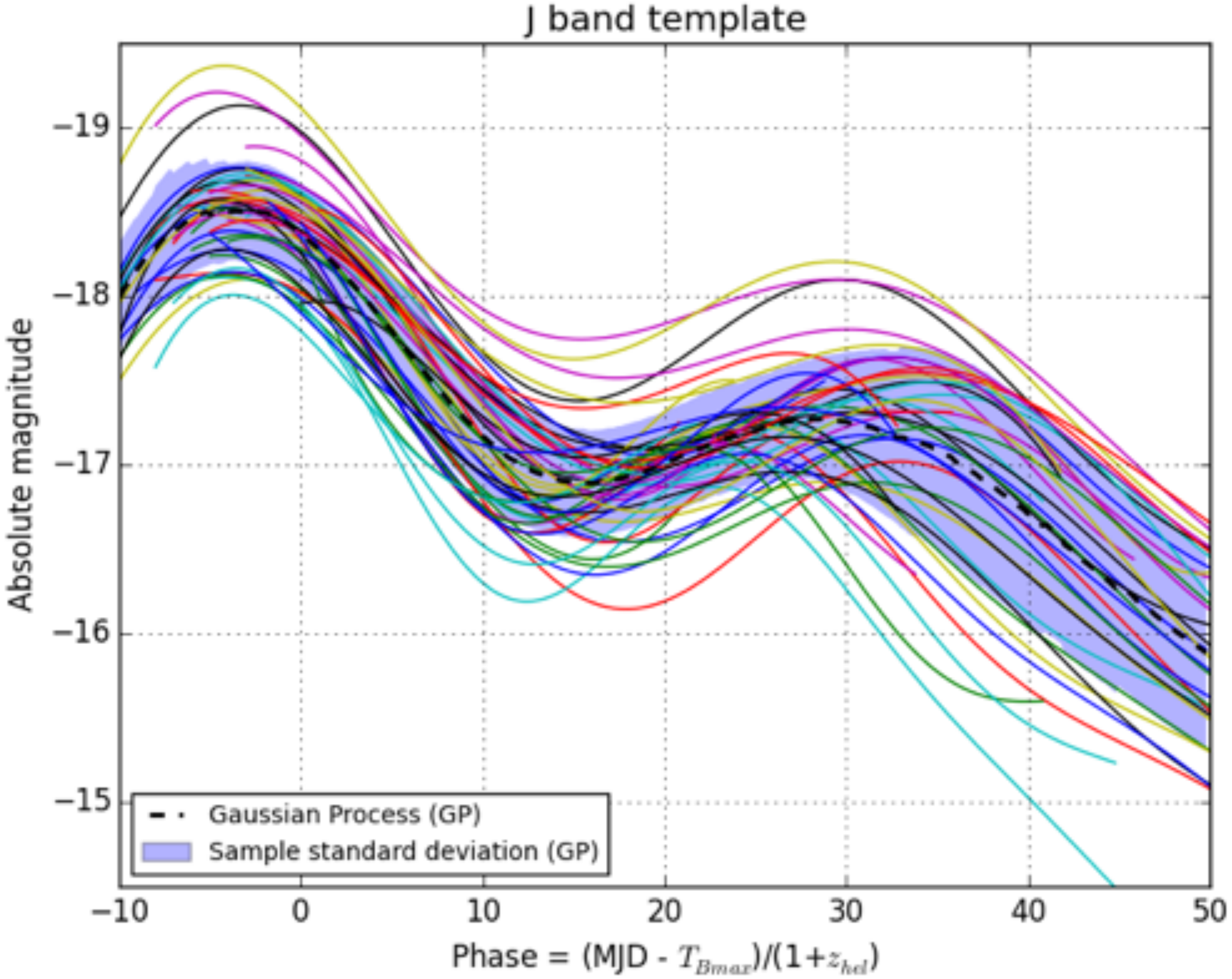


Light Curve & Luminosity Variations and Correlations



Optical:
Intrinsically Brighter SN Ia have broader light curves and are slow decliners (Phillips Relation)

Near-Infrared:
Doubled Peaked Light Curve Variations



(credit: Arturo Avelino)

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 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?)

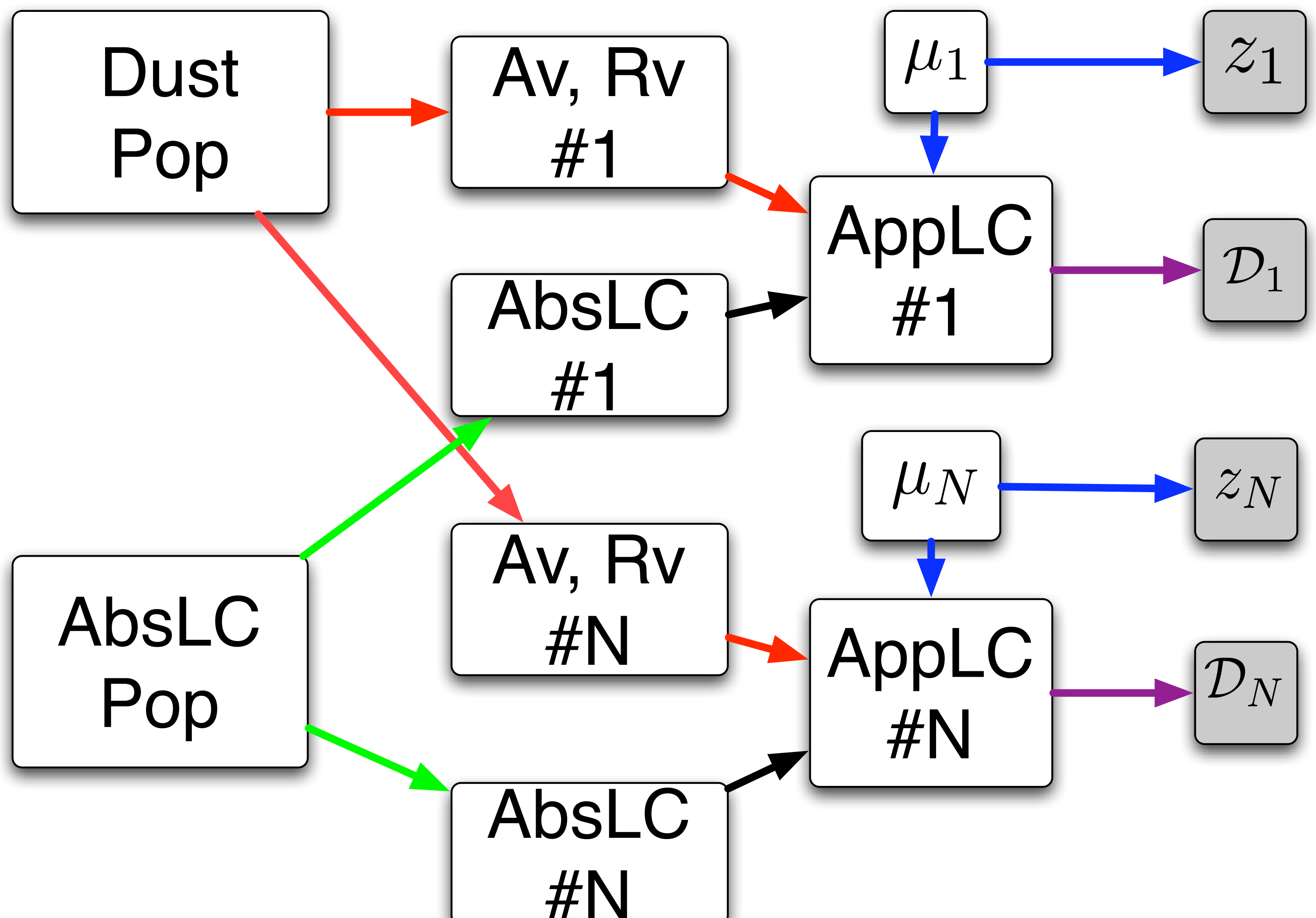
My Thesis Work (ISBA Savage Award Winner):
Hierarchical Bayesian Models for SN Ia Light Curve Inference

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

Generative Model

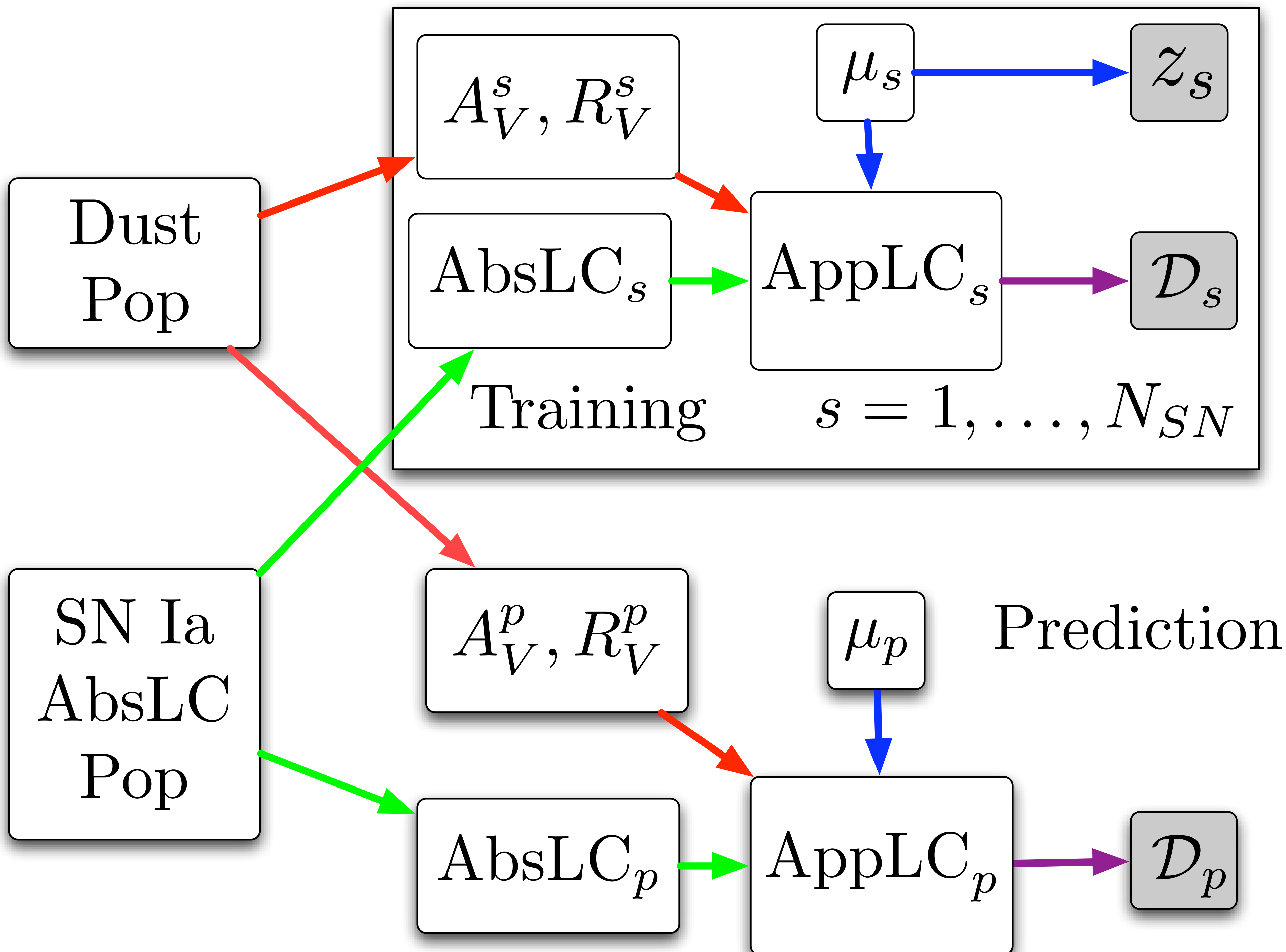
Global Joint Posterior Probability Density Conditional on all SN Data

"Training":
Learn about Populations from nearby SN Ia set

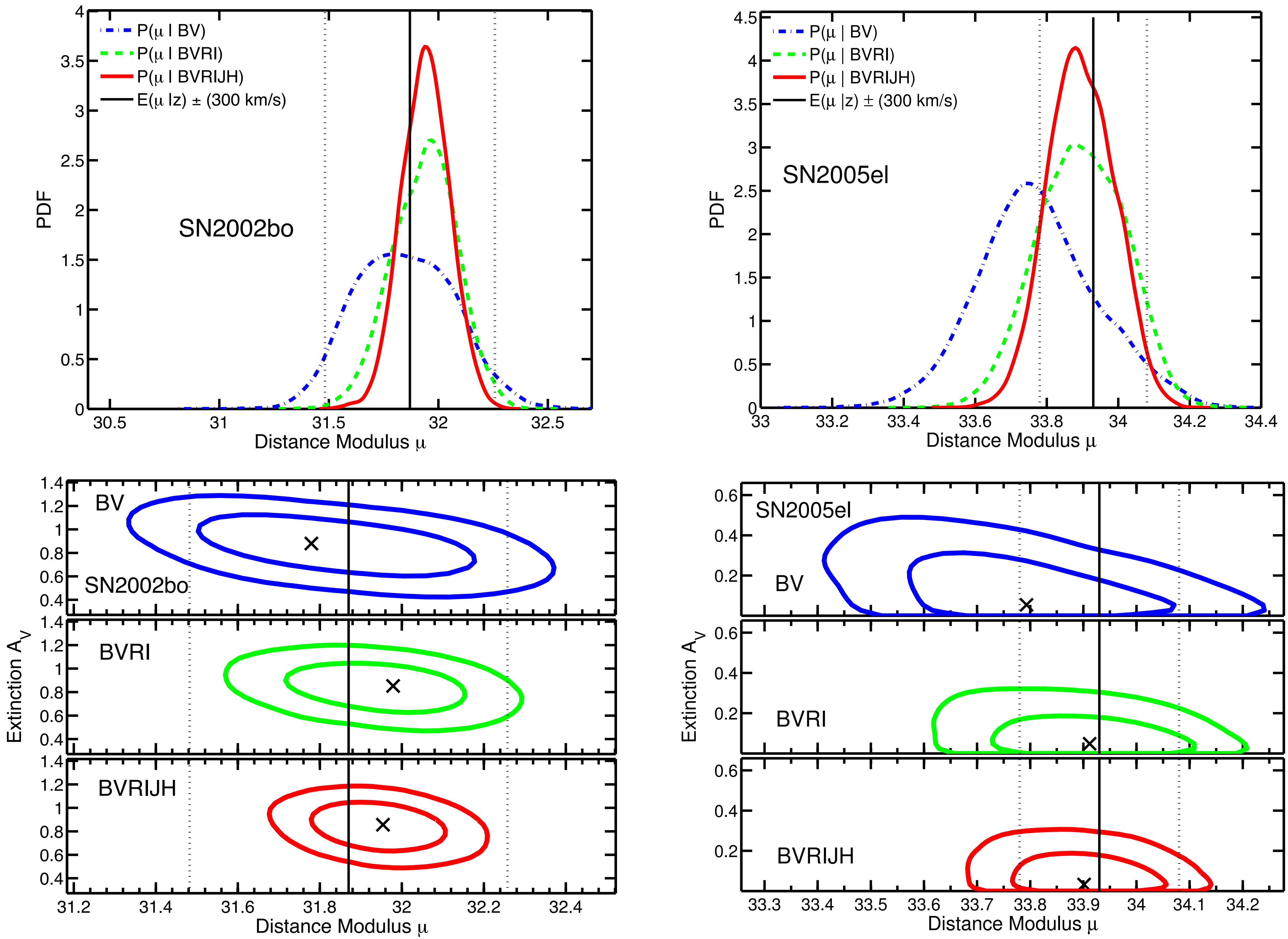


Directed Acyclic Graph

Directed Acyclic Graph for SN Ia Inference: Distance Prediction

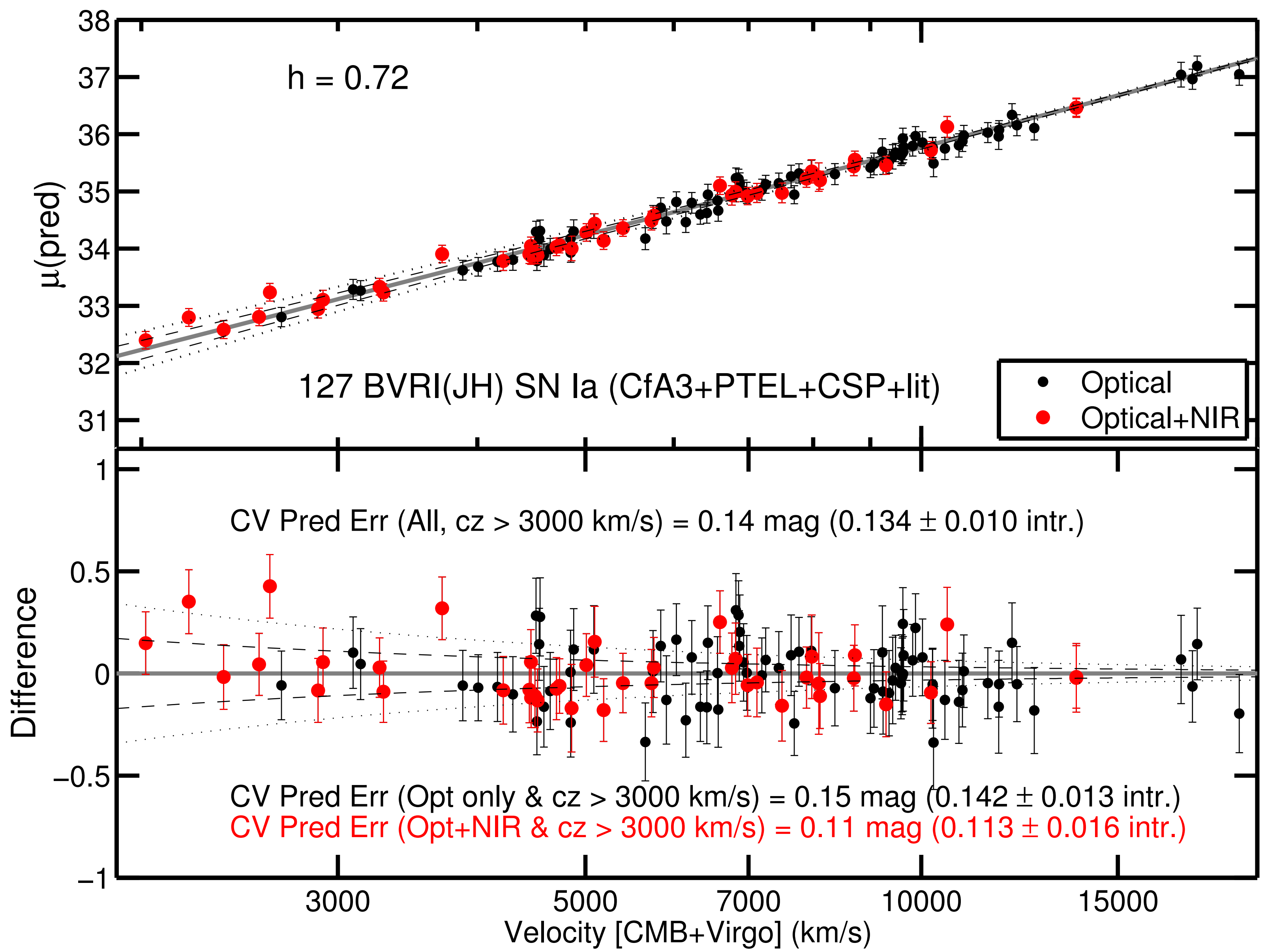


Distance Estimates: Optical vs Optical+Infrared



Nearby Optical+NIR Hubble Diagram

Cross-Validated Distance



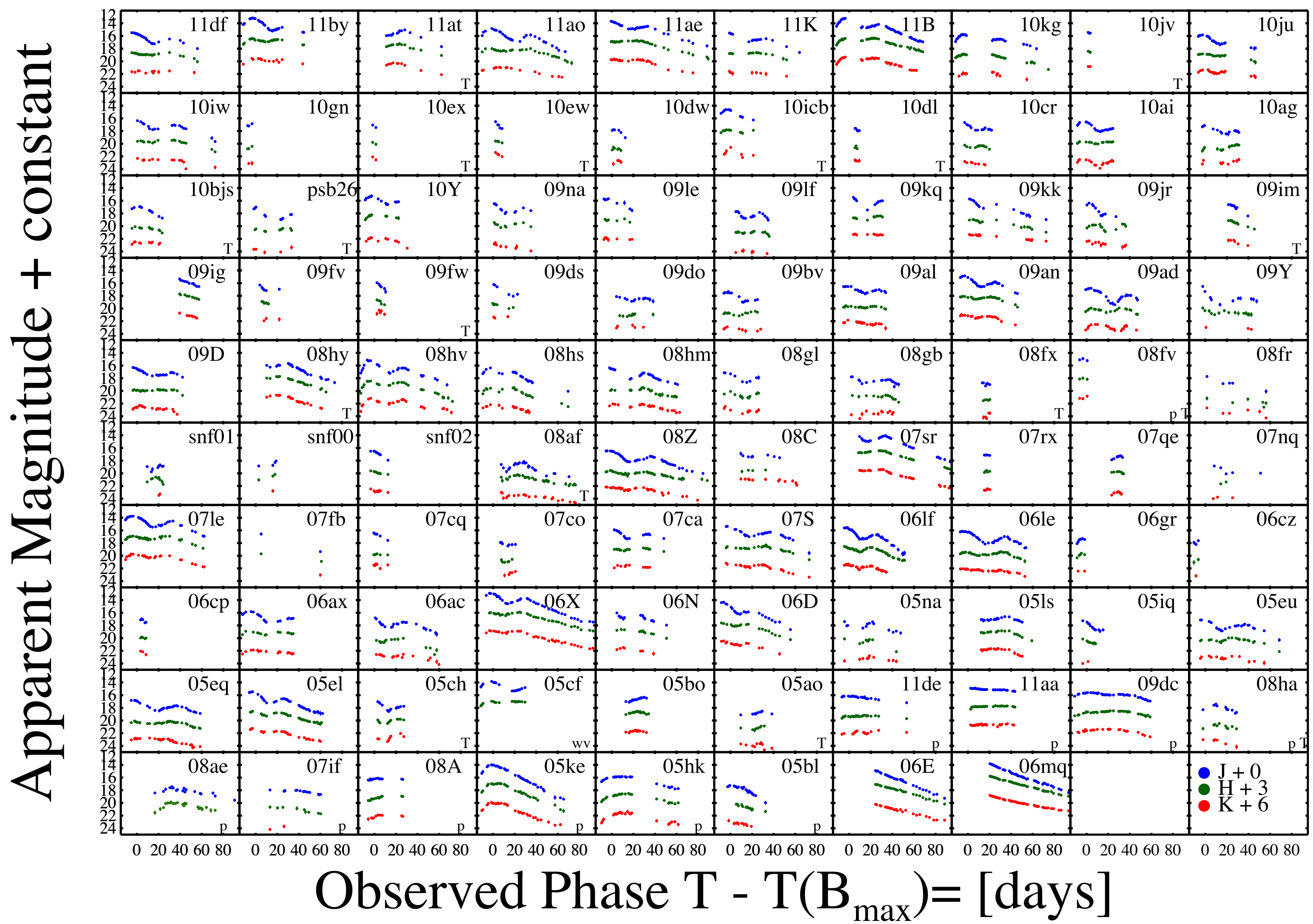
(Opt Only) rms Distance Prediction Error = 7.5% (0.15 mag)

(Opt+NIR) rms Distance Prediction Error = 5% (0.11 mag)

Overall Improved Precision ~ $(7.5/5)^2 \approx 2$!

(Relative Weight in Hubble Diagram)

New Much Larger Dataset to retrain model: ~100 Nearby SN Ia in the NIR with PAIRITEL



CfAIR2: Andrew Friedman, et al. 2015, ApJS, 220, 9

How can we leverage the good NIR properties at high-z?

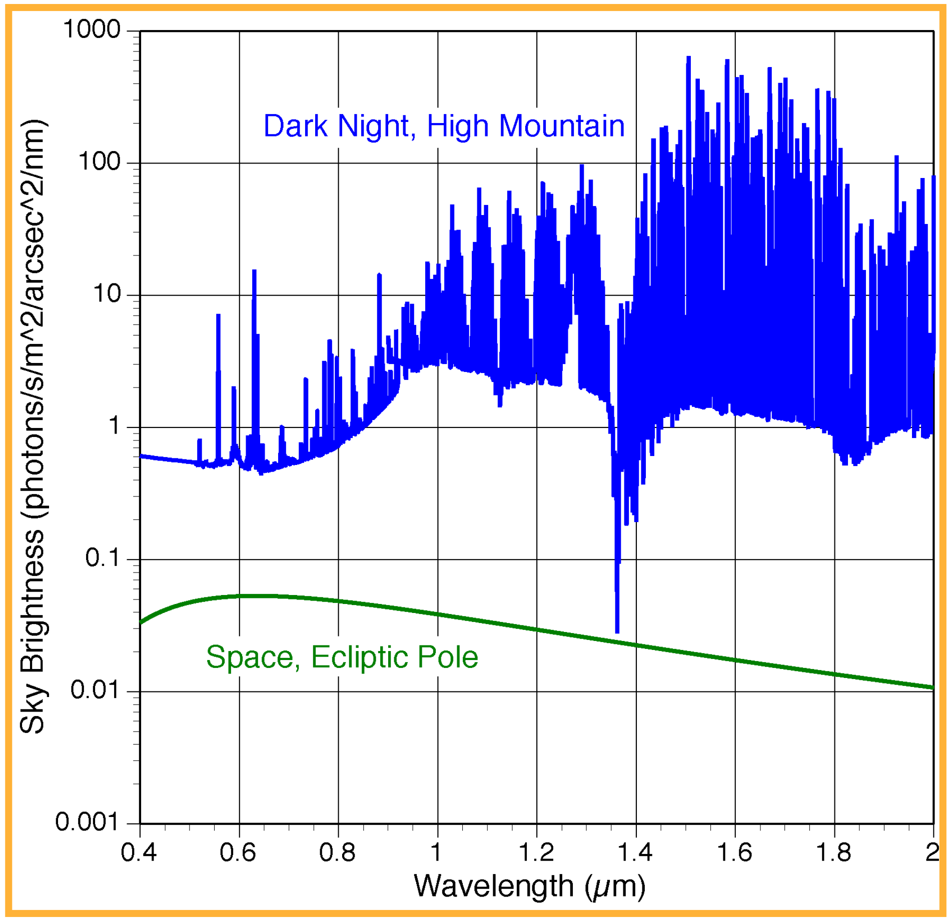
Only in space!

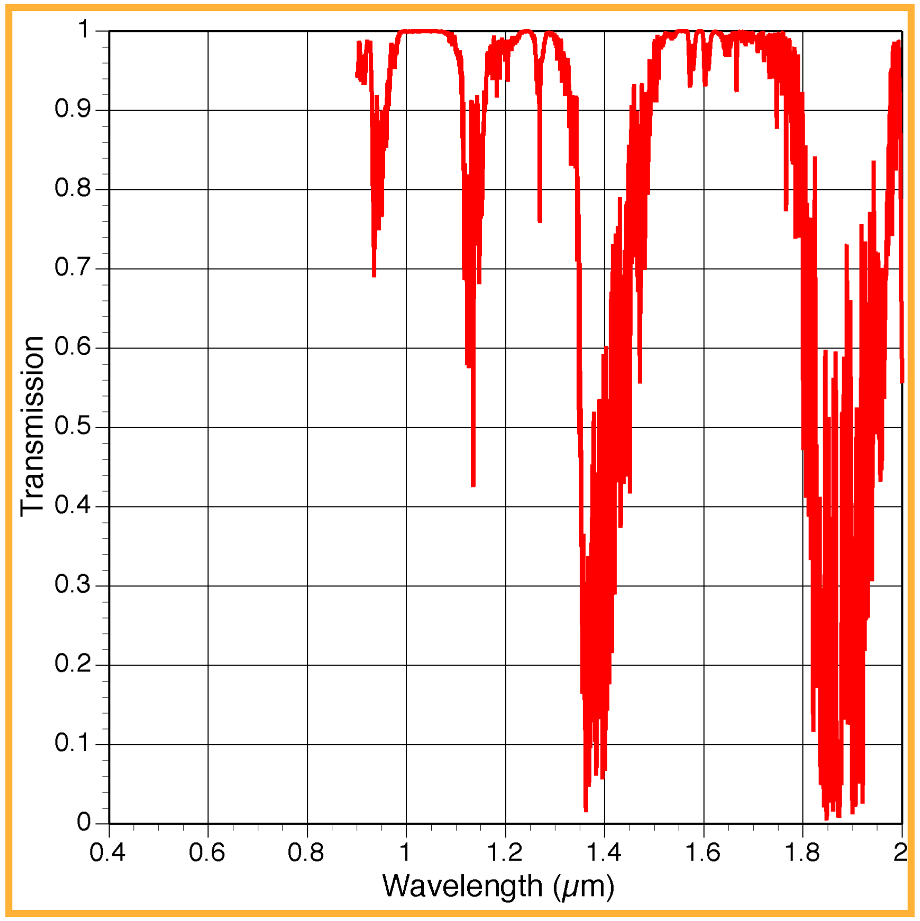
Rest frame IR measurements of z~1 supernovae are not possible from the ground

Go as far into the IR as technically feasible!

Sky is very bright in NIR: >100x brighter than in space

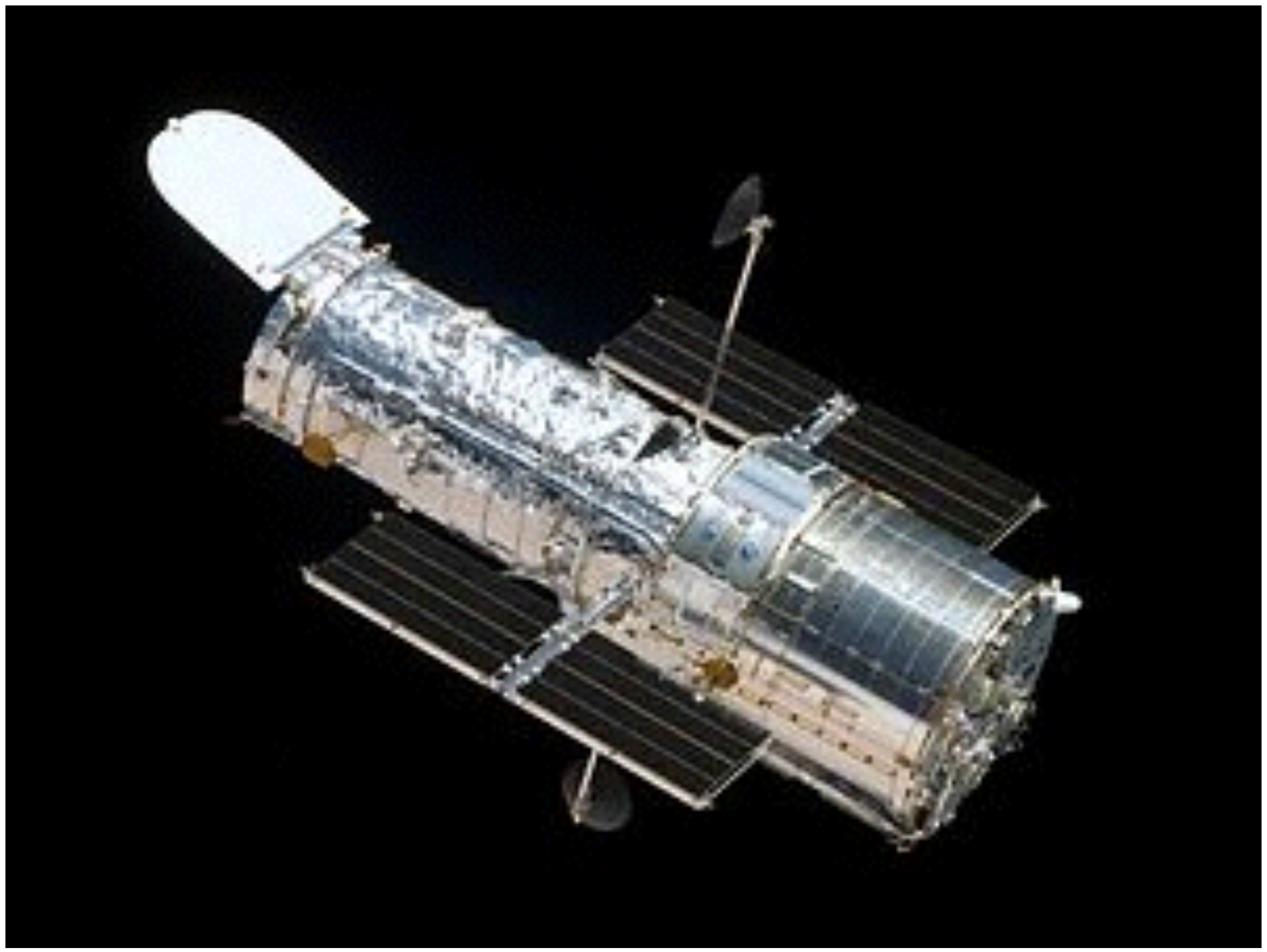
Sky is not transparent in NIR: absorption due to water is very strong and extremely variable





RAISIN (R. Kirshner, R. Foley, P. Challis, K. Mandel, + PS1 SN Ia group, et al.)

Tracers of cosmic expansion with SN Ia in the IR with the Hubble Space Telescope (HST)



Large HST program executed 2012-14 with 100 orbits to observe ~23 SN Ia at z ~ 0.35 discovered by Pan-STARRS

Combining NIR HST observations with (ground-based) Optical improves statistical uncertainty by ~2x
Reduces systematic sensitivity to dust error

PanSTARRS: A Supernova Discovery Machine

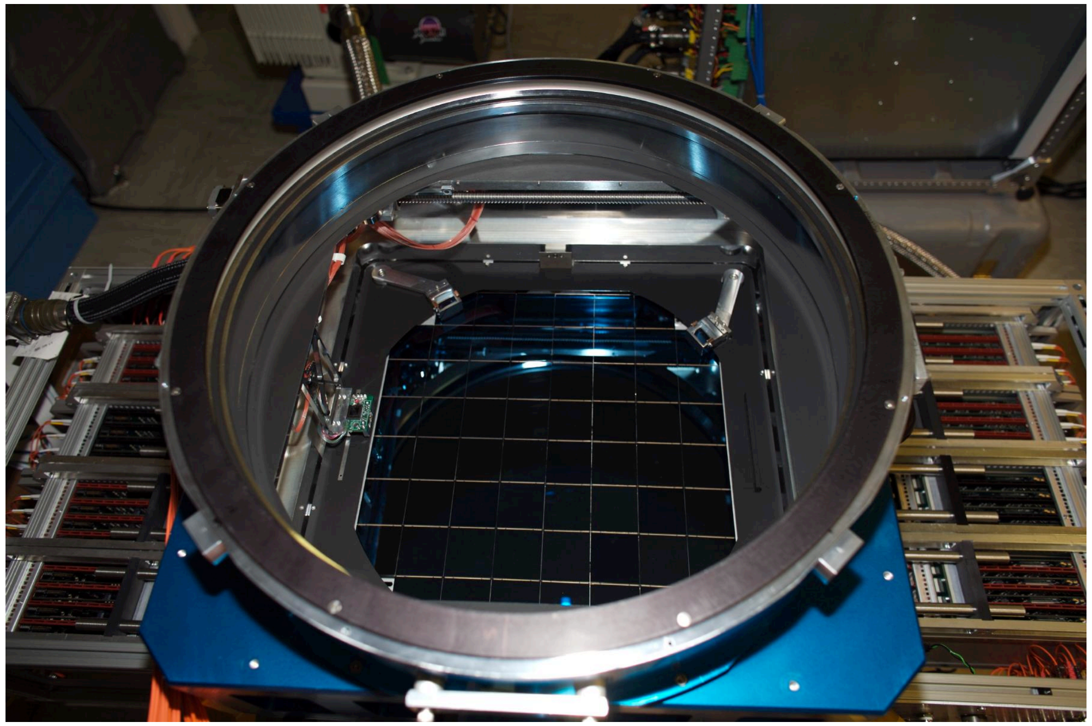
Medium-Deep Fields

Good light curves at z~0.4

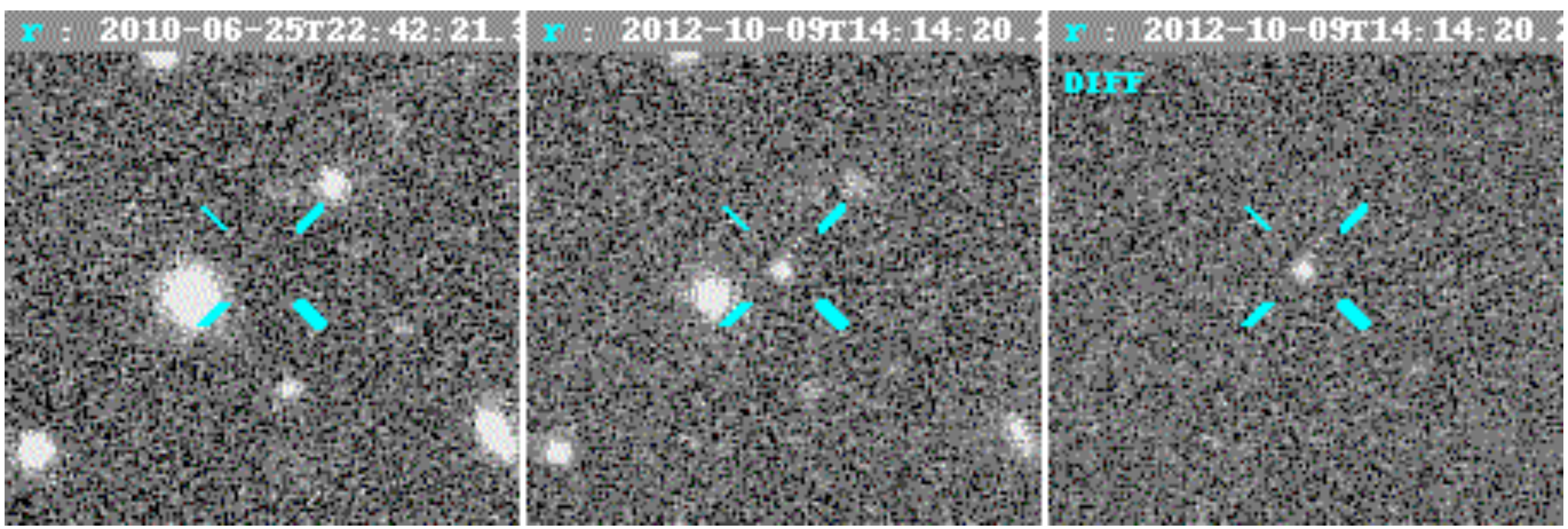
Every 4 days griz

7 square degrees 0.26”/pixel

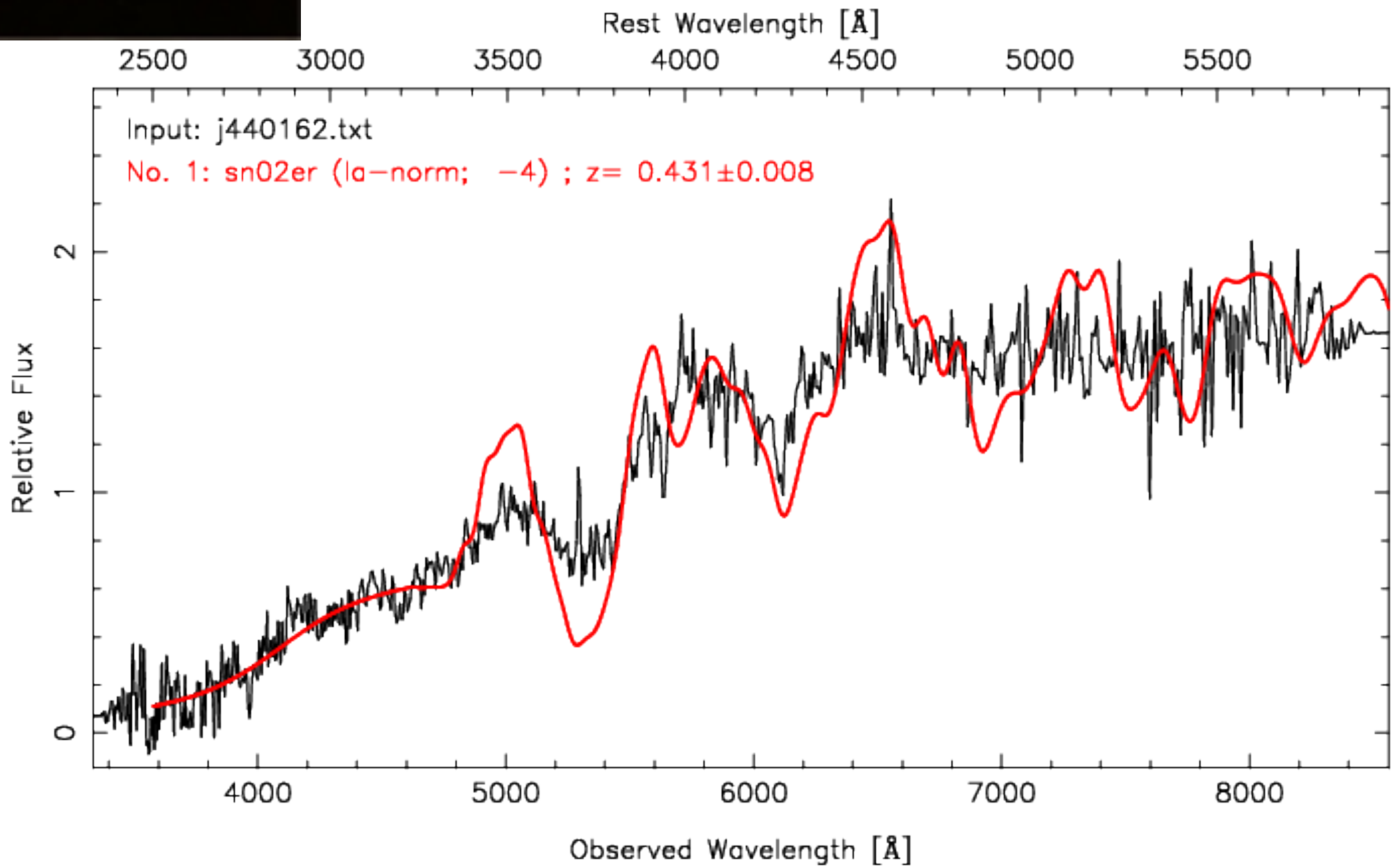
Dozens of supernova candidates every month!



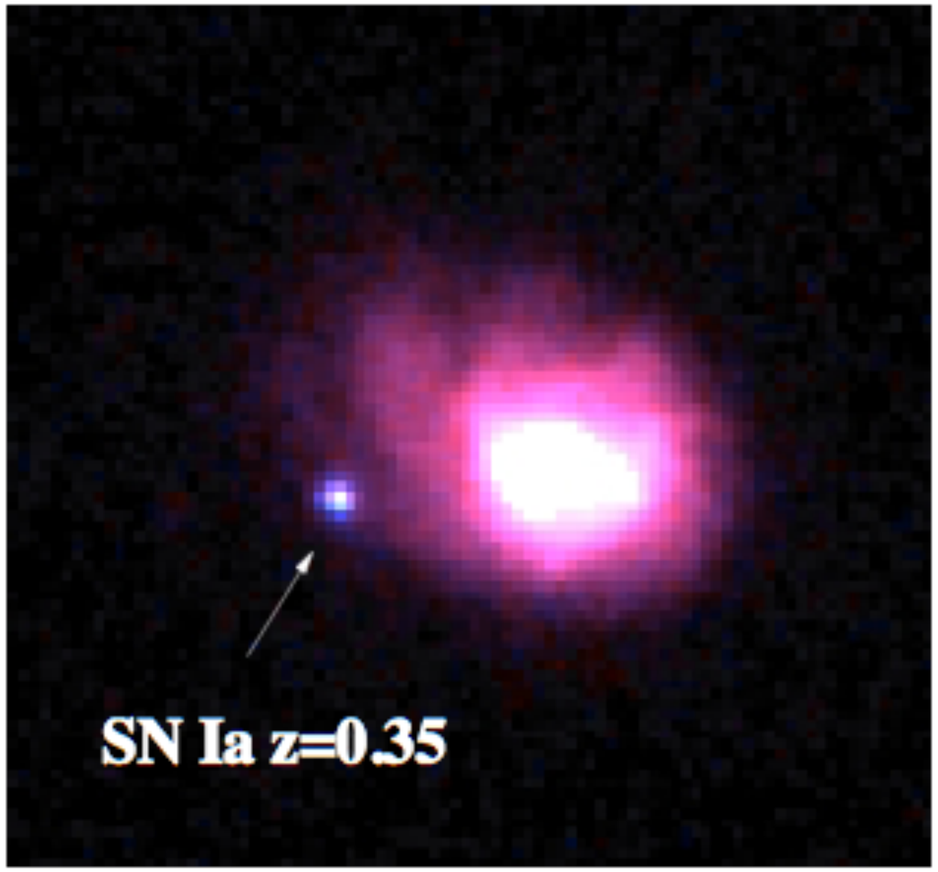
Discover Supernovae with Pan-STARRS and Difference Imaging

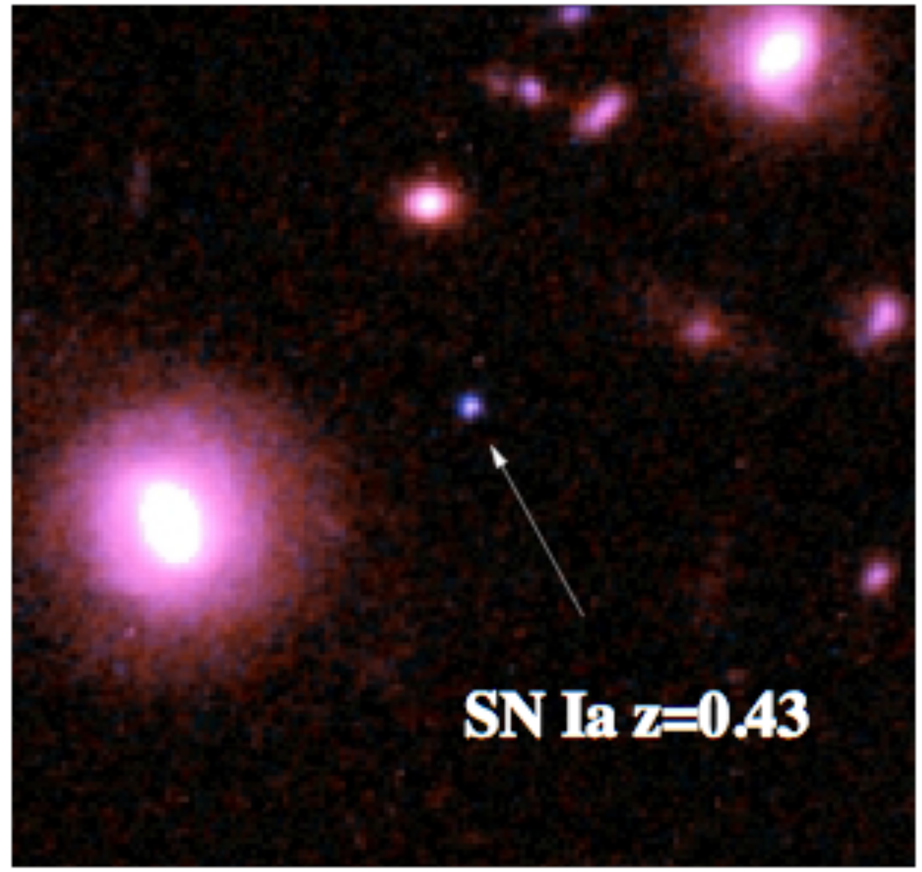


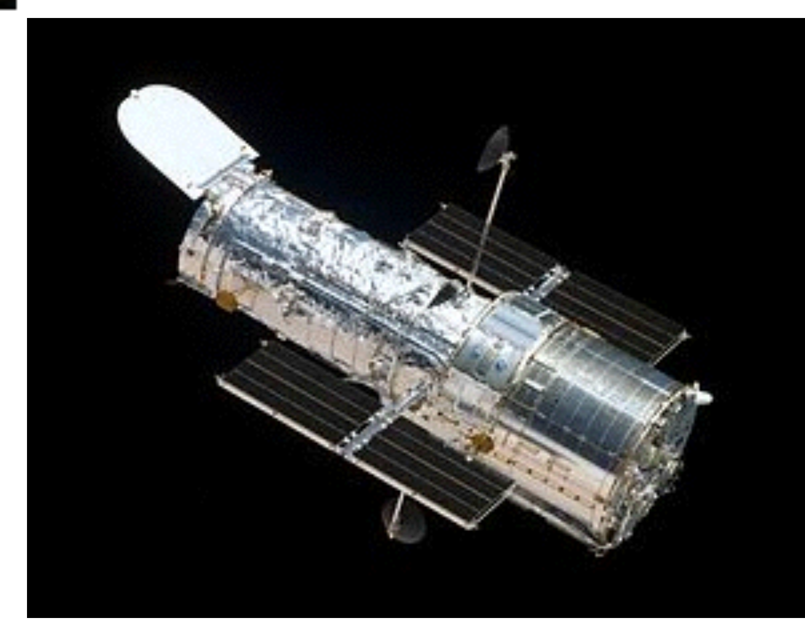
Get spectrum with MMT
(or Magellan, Gemini or Keck)
358 Spectroscopic SN Ia



Trigger ToO HST observations



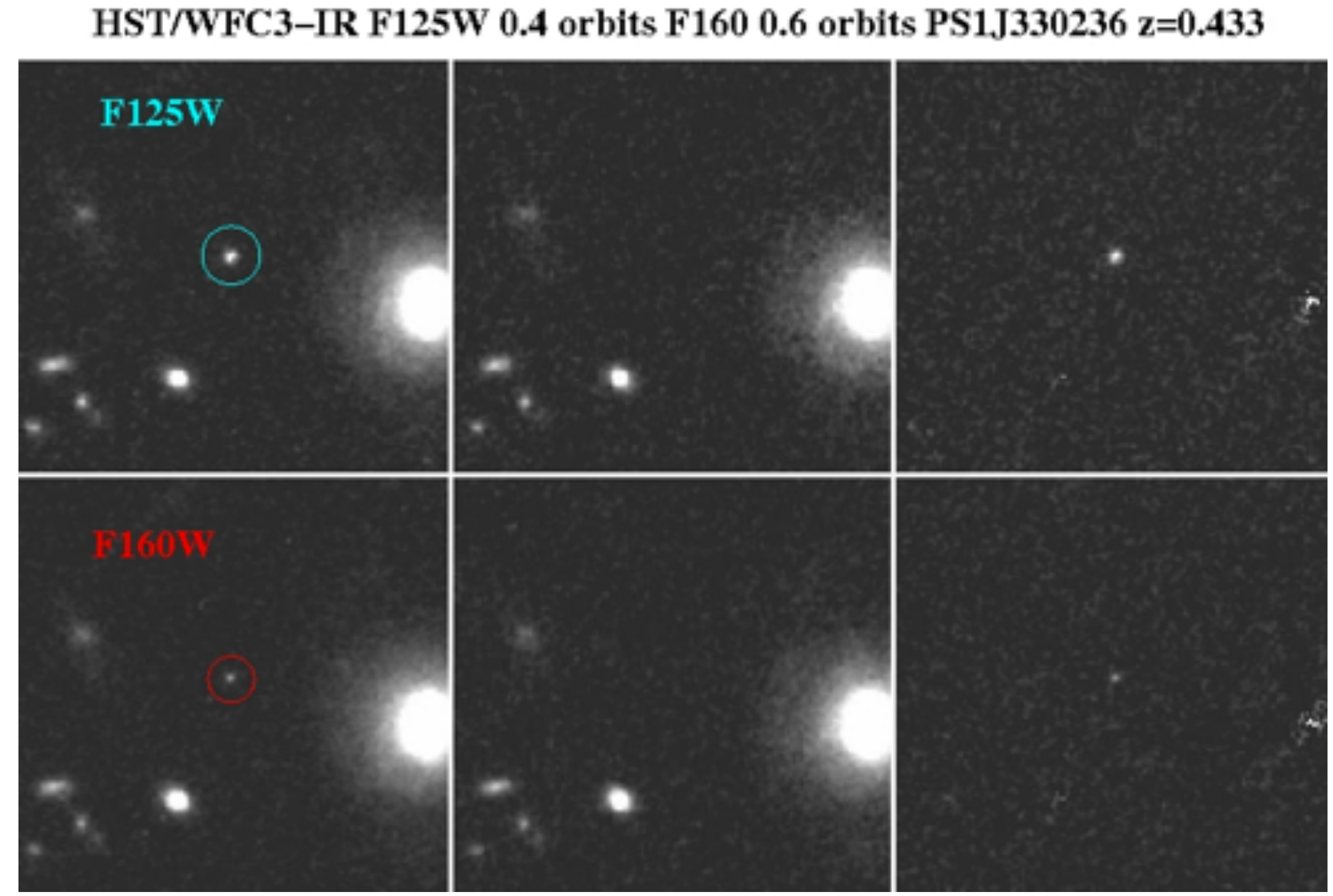


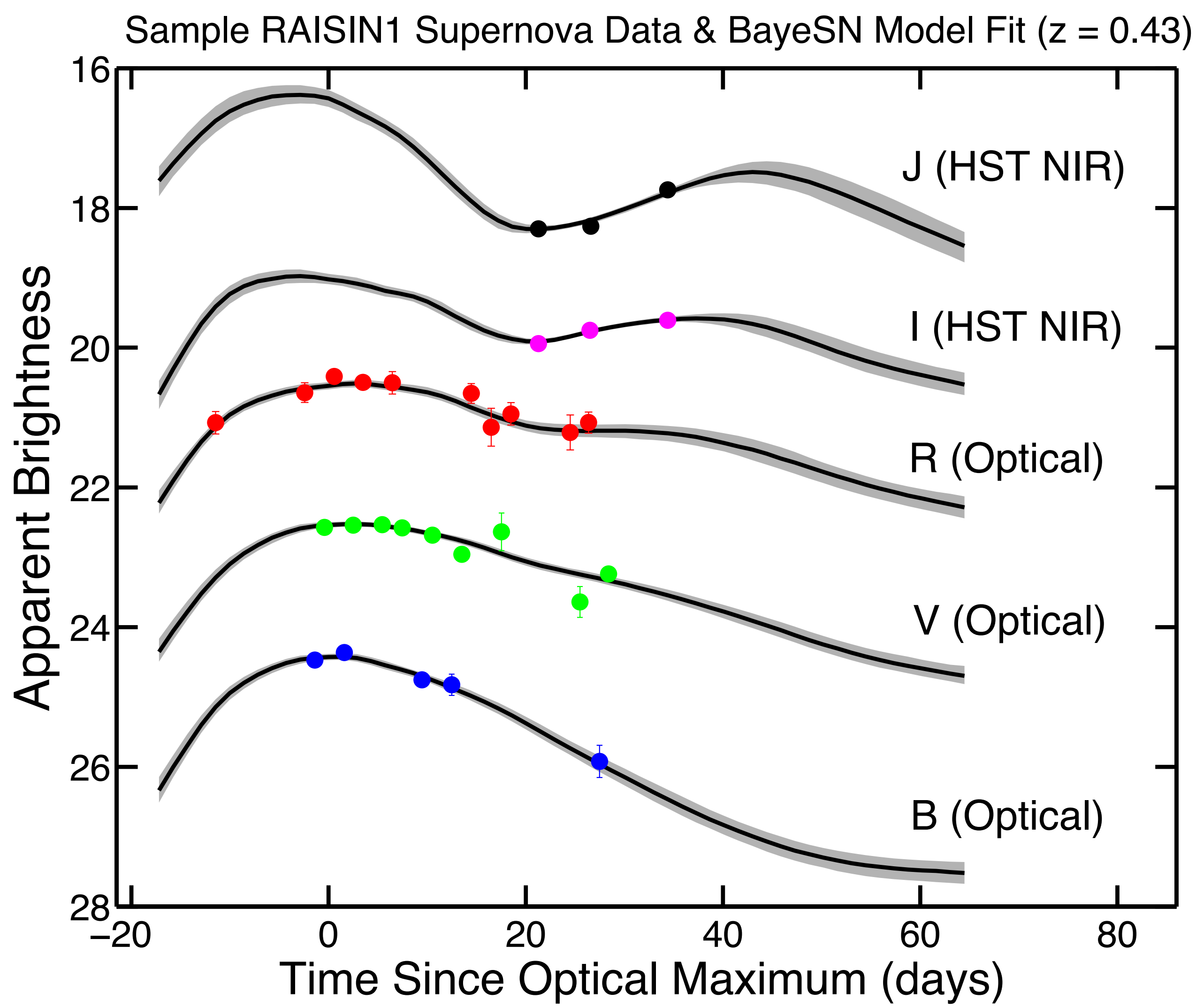


Observed through F125W (1.25 μm) and F160W (1.60 μm) on WFC3/IR

Usually need to return much later to get image for galaxy subtraction

Pan-STARRS + RAISIN1 data with BayeSN Analysis

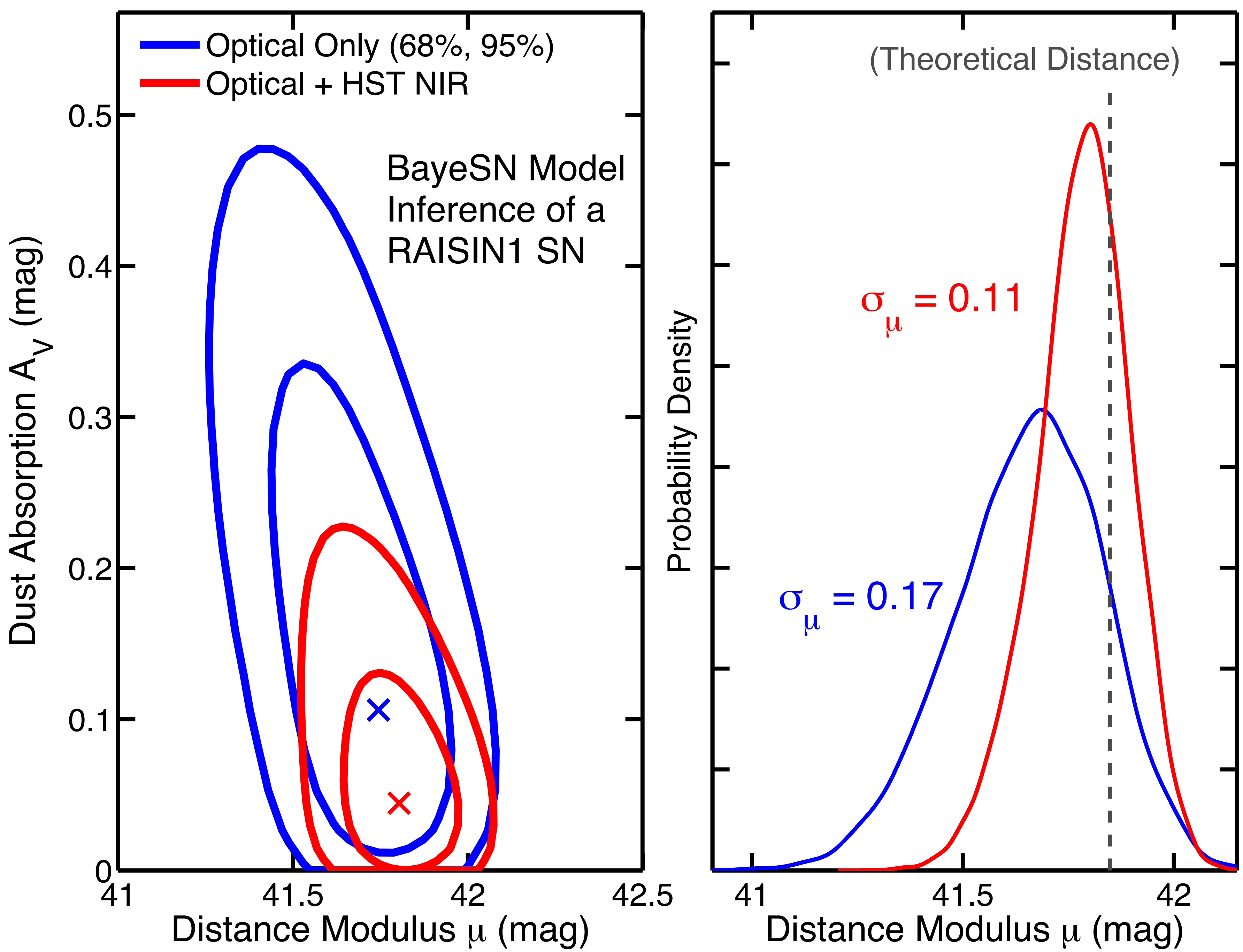




HST/WFC3 NIR
J & H bands

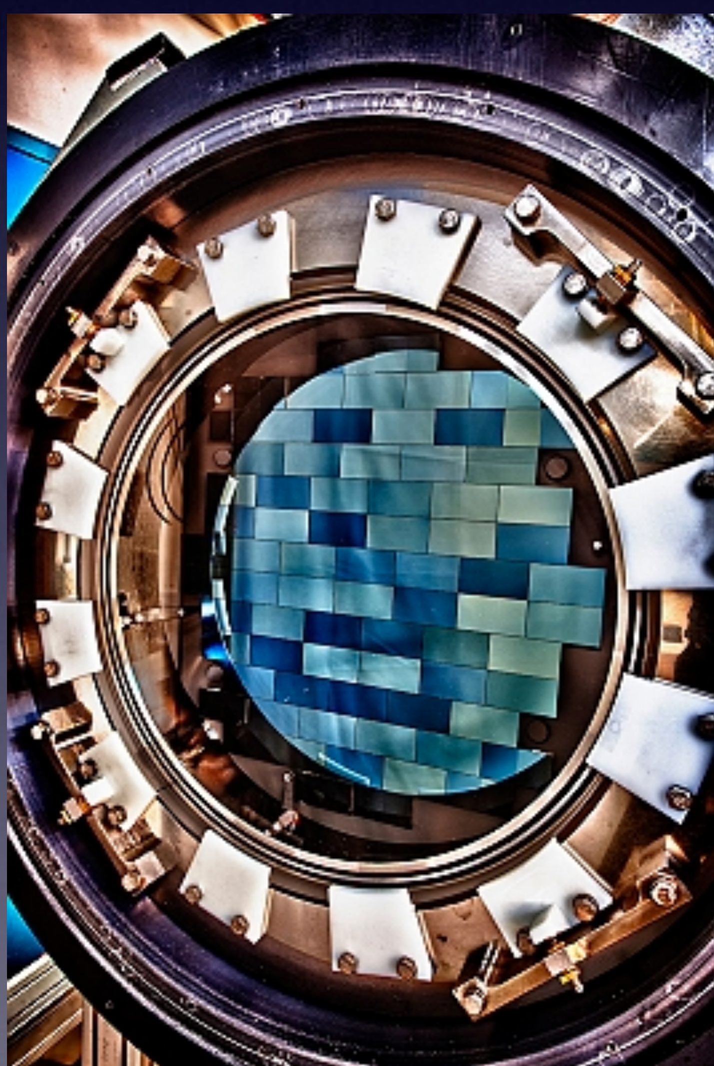
Pan-STARRS
Optical bands

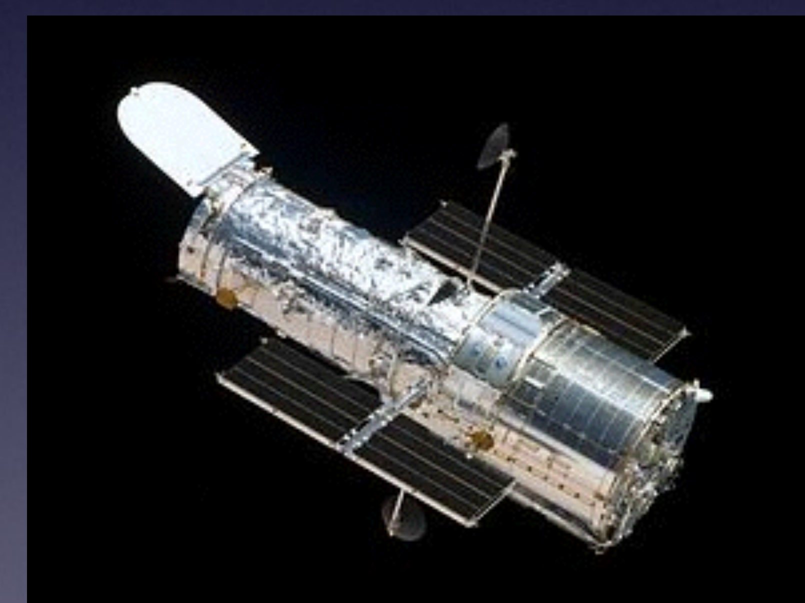
Improving dust and distance estimates with HST/WFC3/IR and BayeSN



Distance Precision improved by ~ $(0.183/0.116)^2$ = 2.5x using NIR

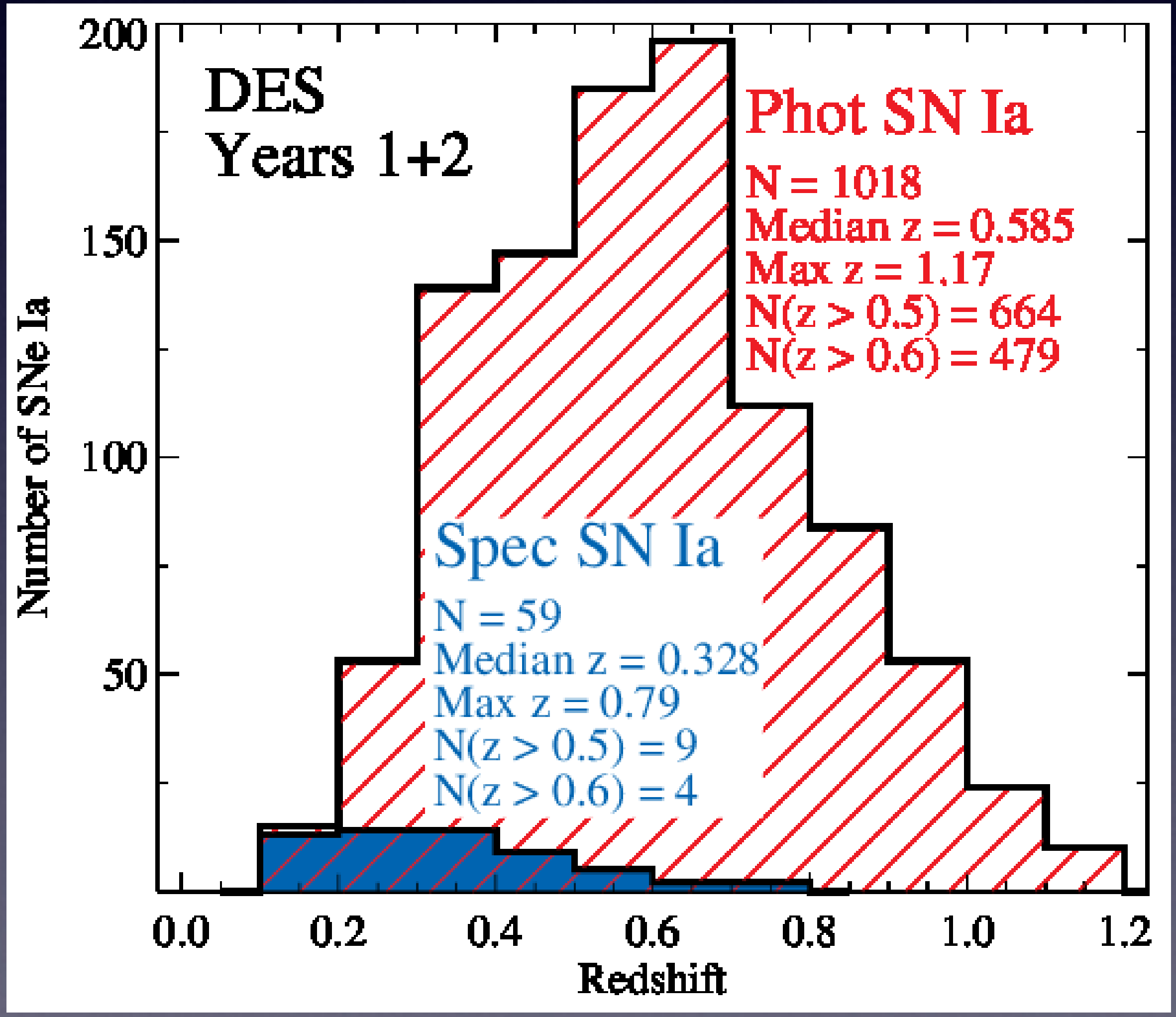
RAISIN2 (ongoing 2015-2017): 100 HST orbits for NIR observations of z ~ 0.5 SN Ia discovered by Dark Energy Survey (DES)

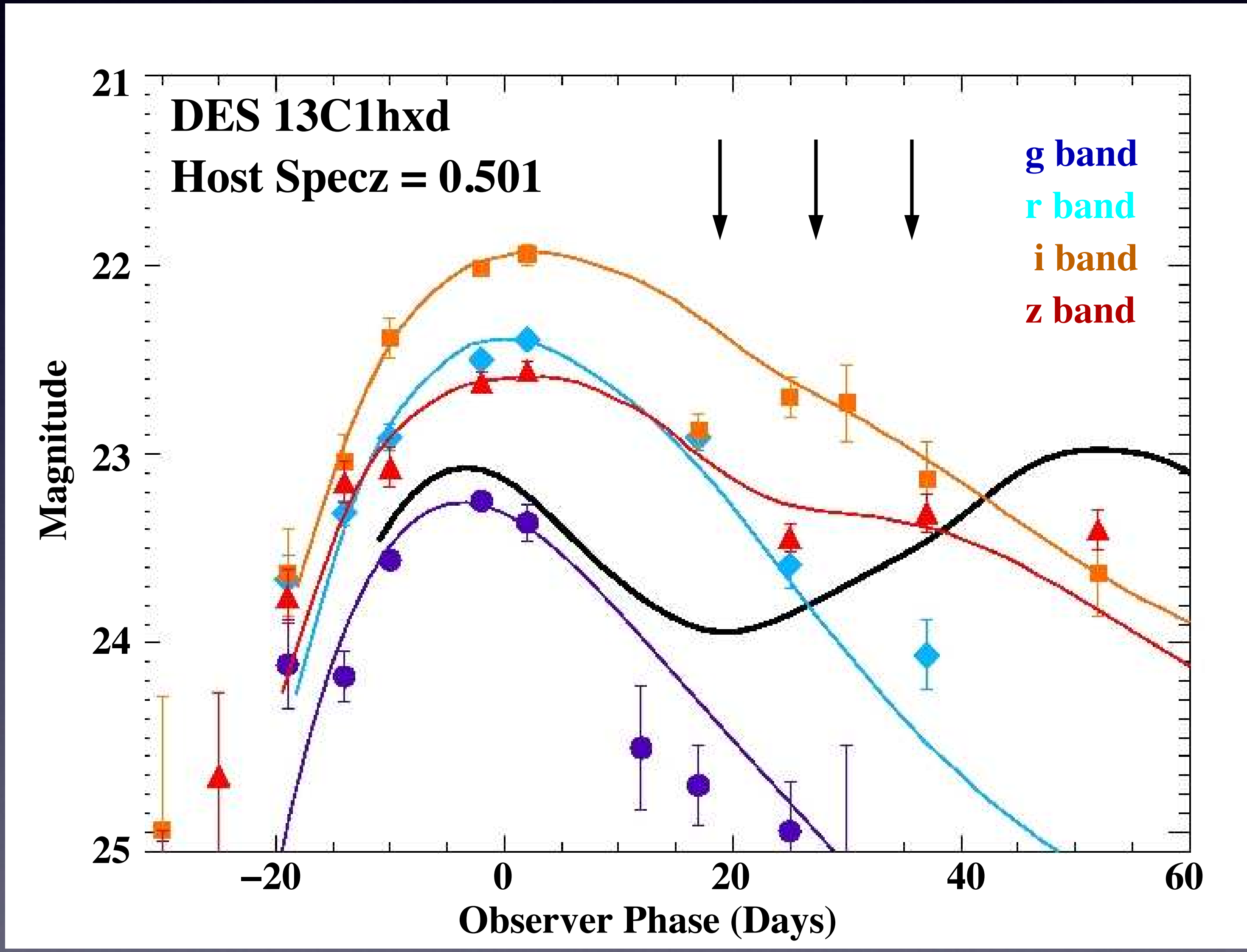




Dark Energy Survey (DES) Supernova Search

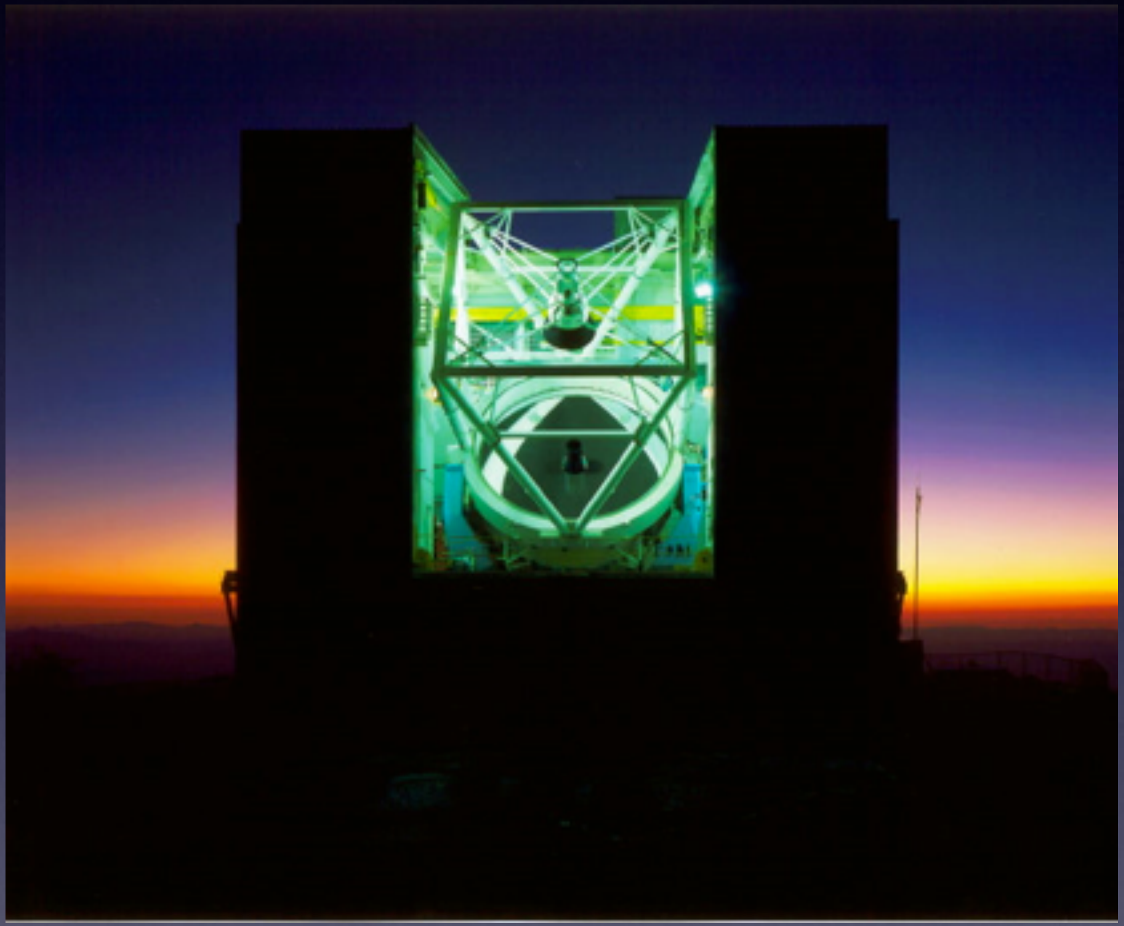
DES SN Ia discoveries

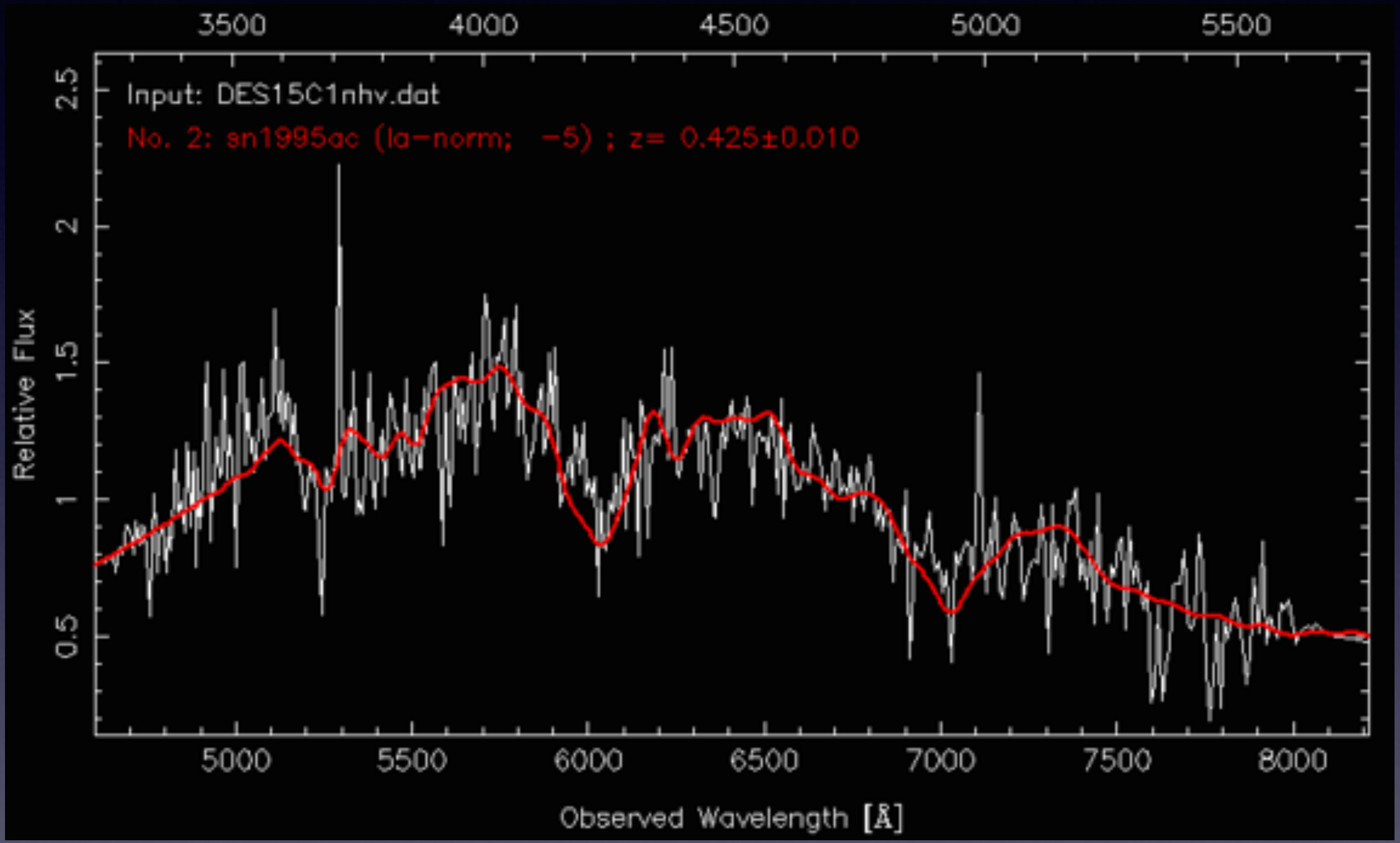




Example DES Optical Light Curve

RAISIN2 Collaboration with DES: Trade Spectra for Targets



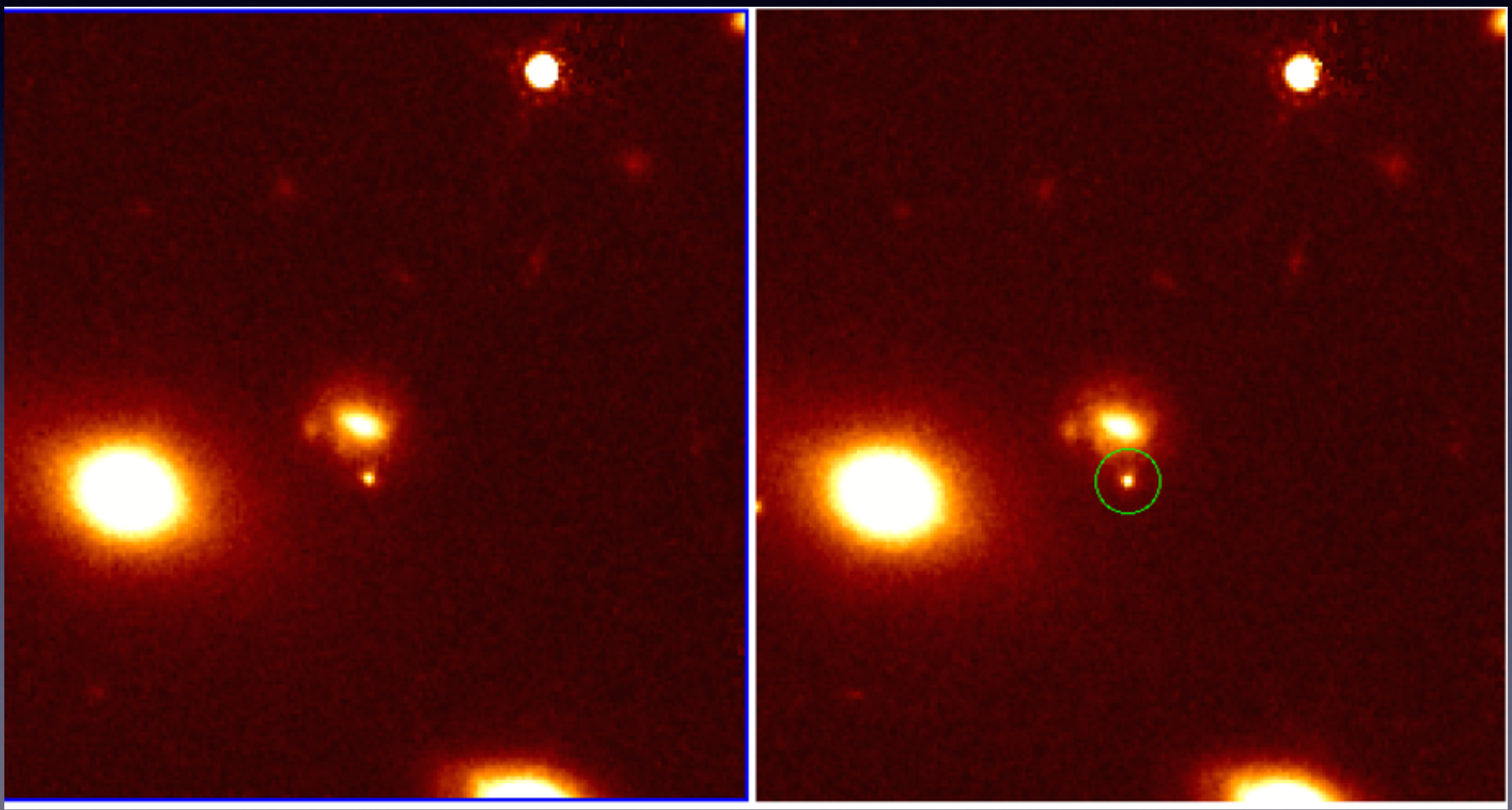


MMT Telescope (Arizona)

(credit: Pete Challis)

Use Spectrum to Confirm Supernova and Measure Redshift

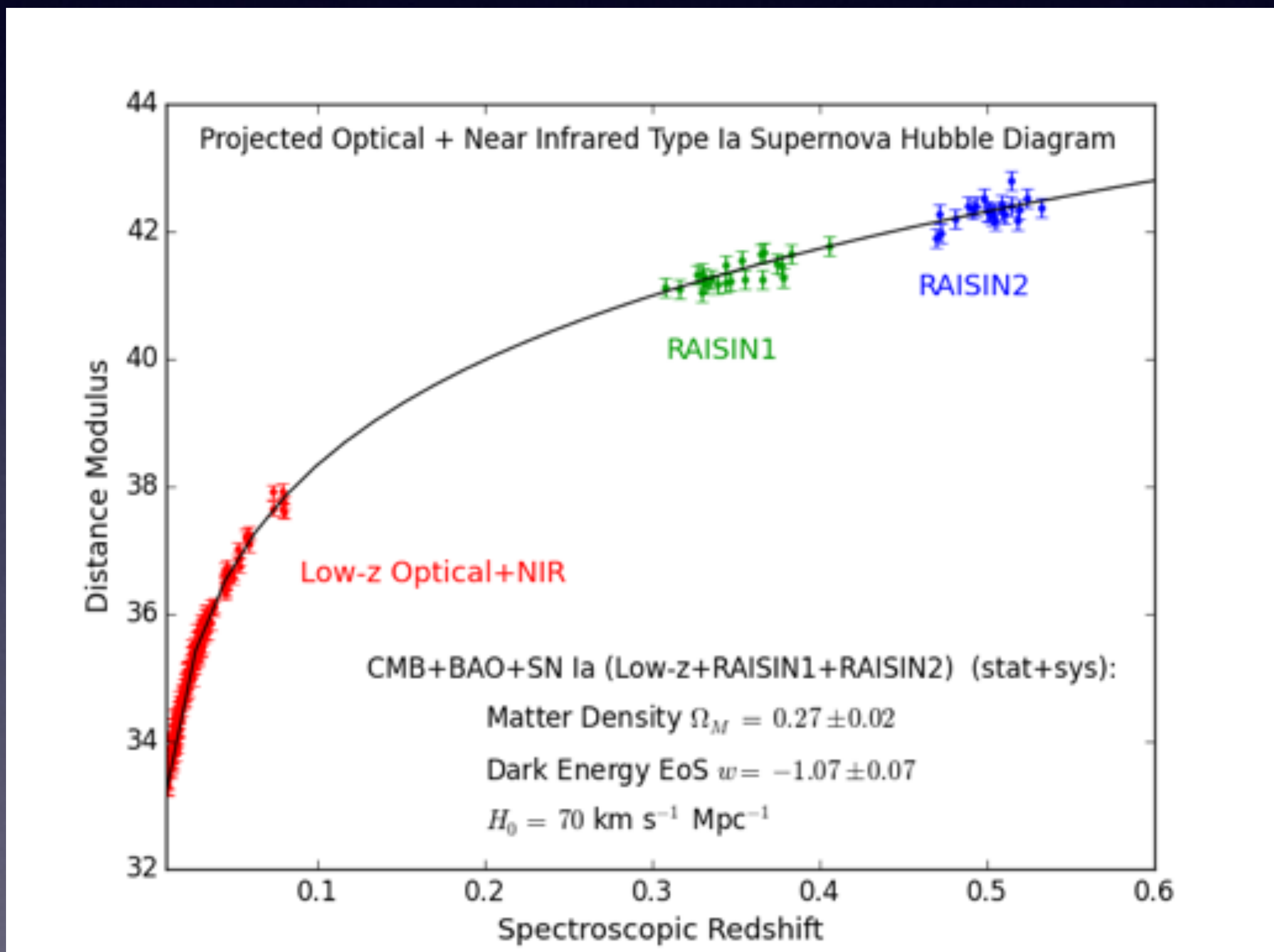
Latest RAISIN2 Hubble Image of DES Supernova at z = 0.43



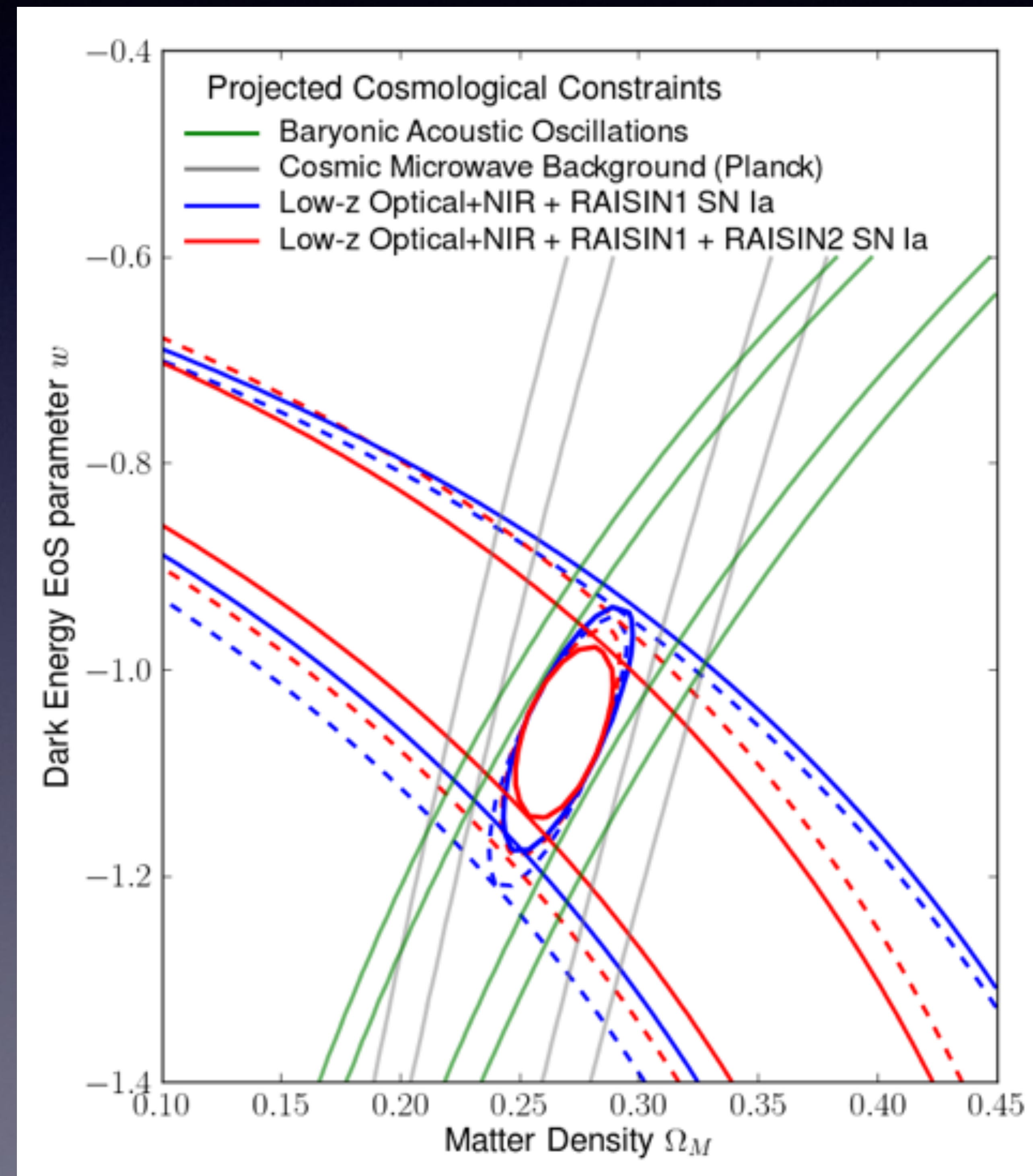
(credit: Pete Challis)

Goal:
Cosmological Hubble Diagram of SN Ia in NIR

Simulation



(credit: Arturo Avelino)



WFIRST ~ 2025
Science Planning for the Wide-Field Infrared Space Telescope