Introduction to Type Ia Supernova Cosmology

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Outline

- Why SN cosmology is relevant
- Standard candles as a cosmological probe
- What observational resources are used to discover and measure SNe Ia
- SNIa: What we see and what we infer they are
- Type Ia homogeneity with slight heterogeneity
- Inferring SN Ia distances from measurements
- Systematic uncertainties
- Existing SN Ia sample used for cosmology
- Ongoing and future SN Ia surveys

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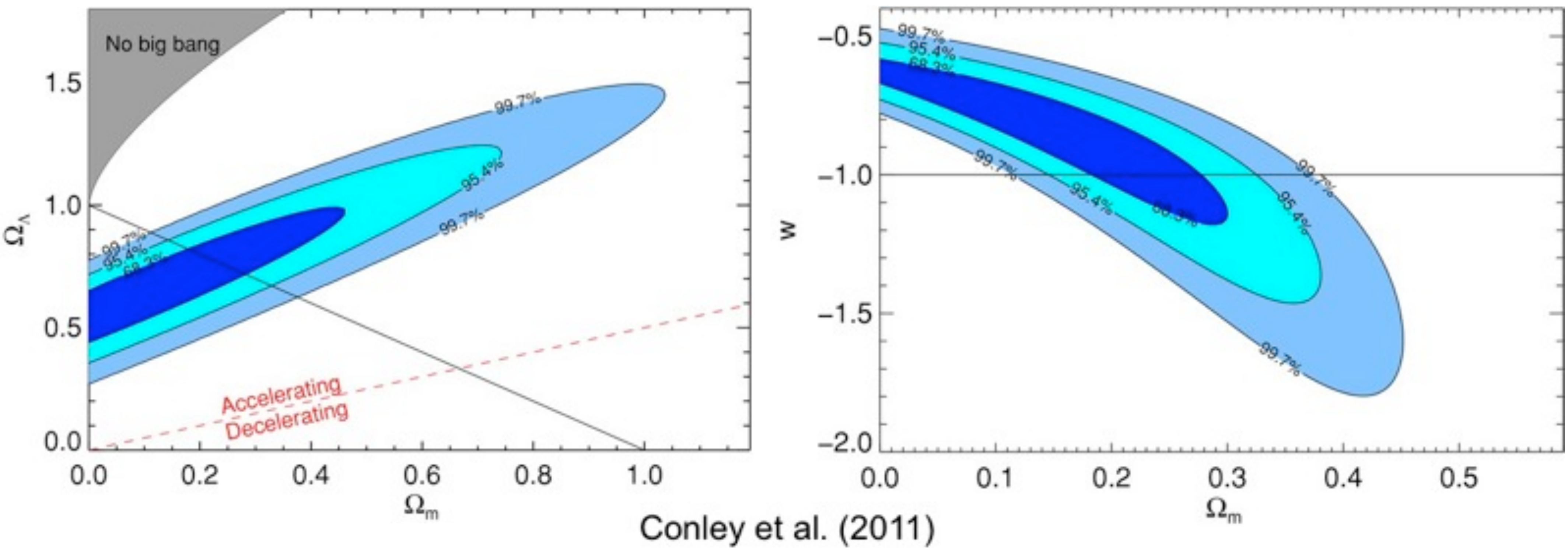
Why Learn About SN Cosmology

- Original discovery of the accelerating universe made with Type Ia SNe
- Measure of the expansion history of the Universe with SNe Ia continue to be an important probe of dark energy
- Among viable cosmological probes uniquely measures distances in the local to z~1.5 Universe spanning accelerating and decelerating regimes
- Major surveys in the future will provide improved measurements
  - Important contribution when combined with other probes
- Critical to have a basic understanding of how data are transformed into cosmological constraints

SNe Ia By Themselves a Powerful Probe of the Universe

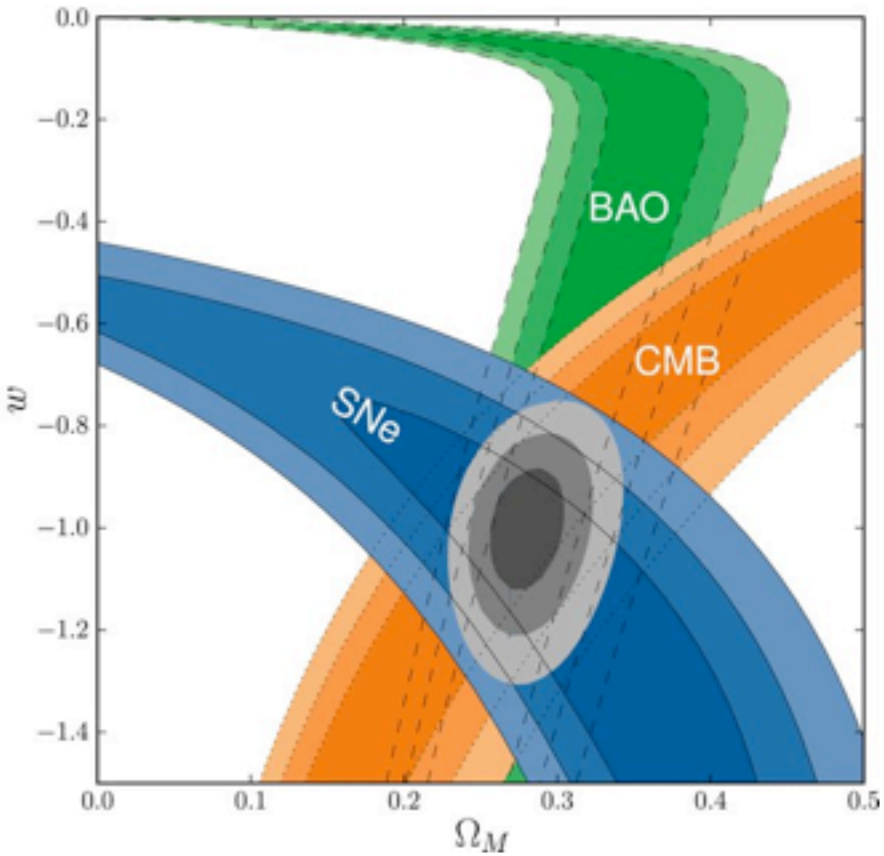
- Sensitive to the acceleration of the universe
- Constrains cosmological parameters: mass density, dark energy density, and a constant dark energy equation of state w
  - (Described later in a few slides!)

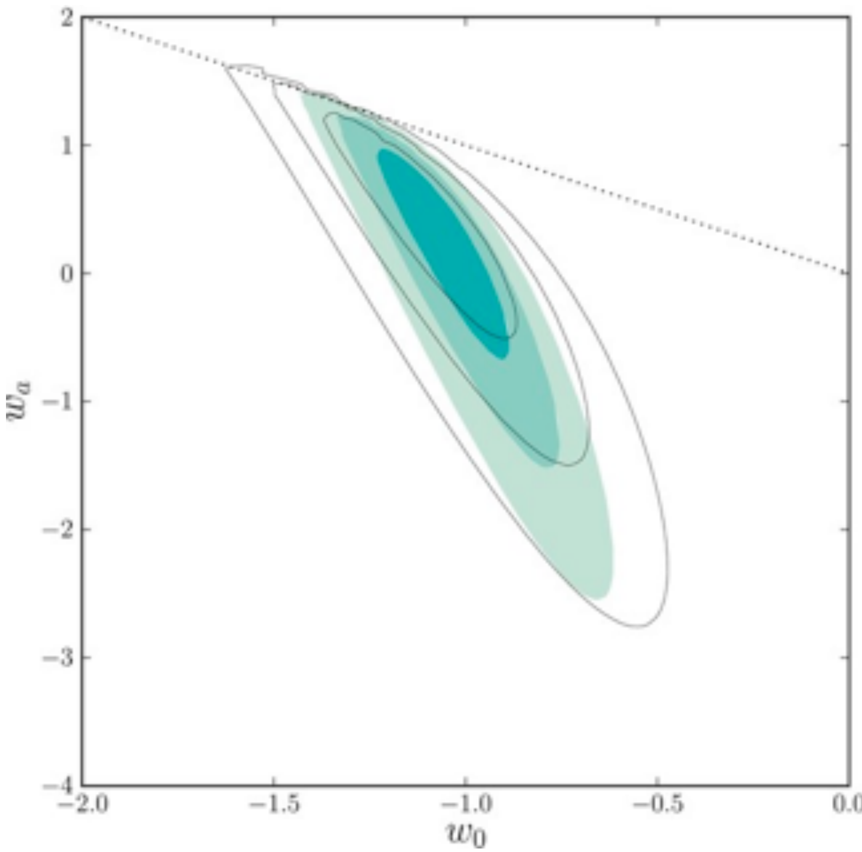


SNe Ia Work Well With Other Cosmological Probes

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

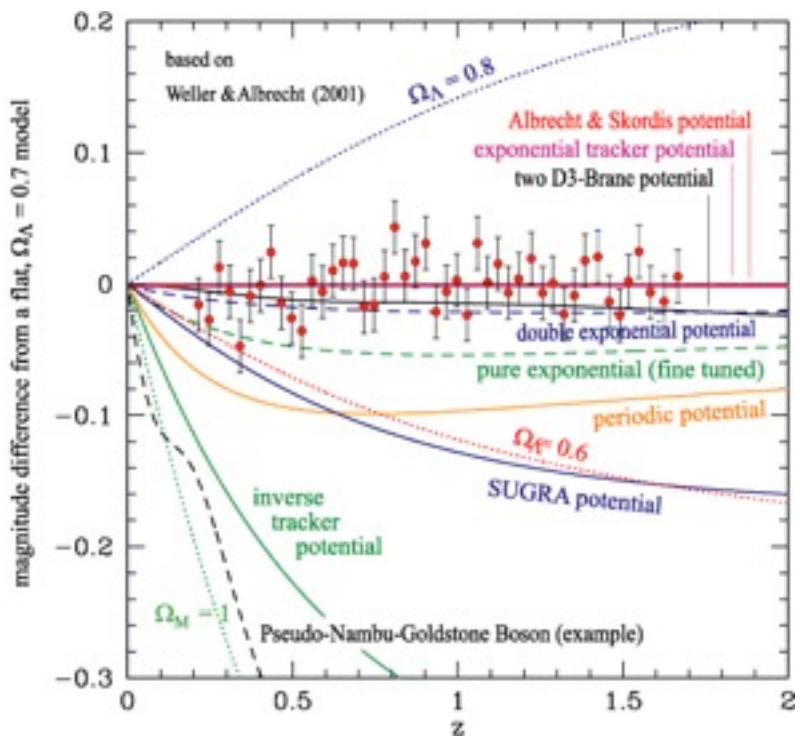
Amanullah et al. (2010)





Room For Improvement

- Decrease systematic uncertainty: within the current redshift range the uncertainty contours are systematics dominated
- Expand the redshift range to provide leverage for testing dark energy models
- Improvement requires high-quality photometry and spectroscopy with broad wavelength coverage

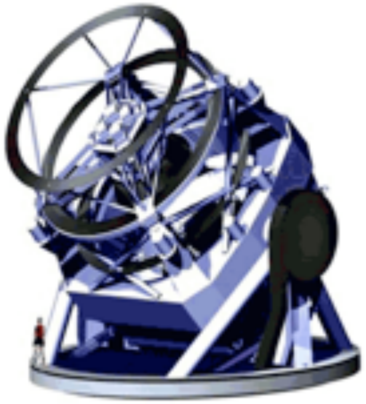


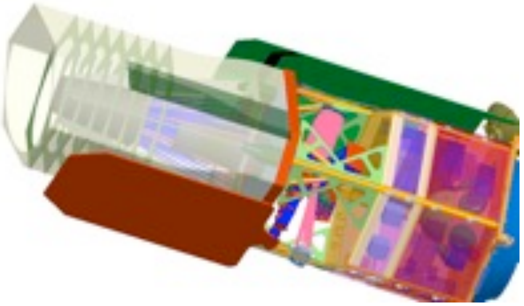
Description	Ω_m	w	Rel. Area [a]
Stat only	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1
All systematics	0.18 ± 0.10	$-0.91^{+0.17}_{-0.24}$	1.85

Conley et al. (2011)

Ongoing/Upcoming SN Surveys

- Local SNe
  - SkyMapper, LaSilla-Quest, PTF, SNFactory
- High-redshift
  - Dark Energy Survey, Large Synoptic Survey Telescope, KDUST, HST, WFIRST, Euclid
- Need people to analyze the data: You!





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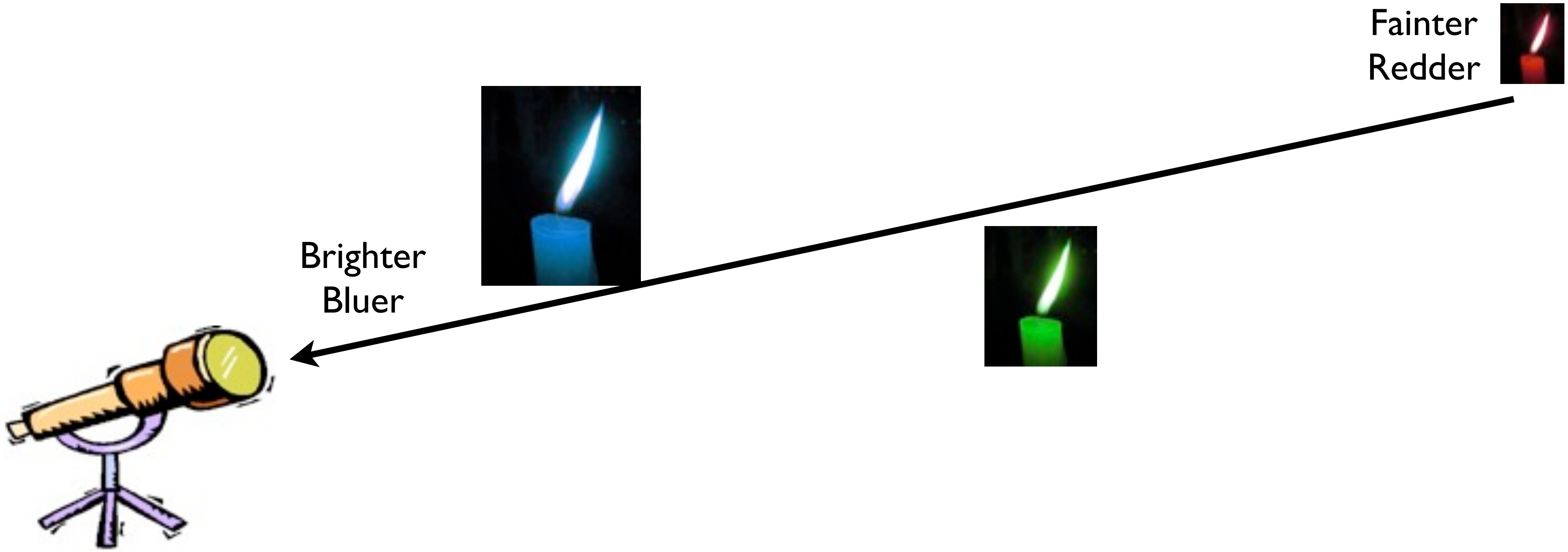
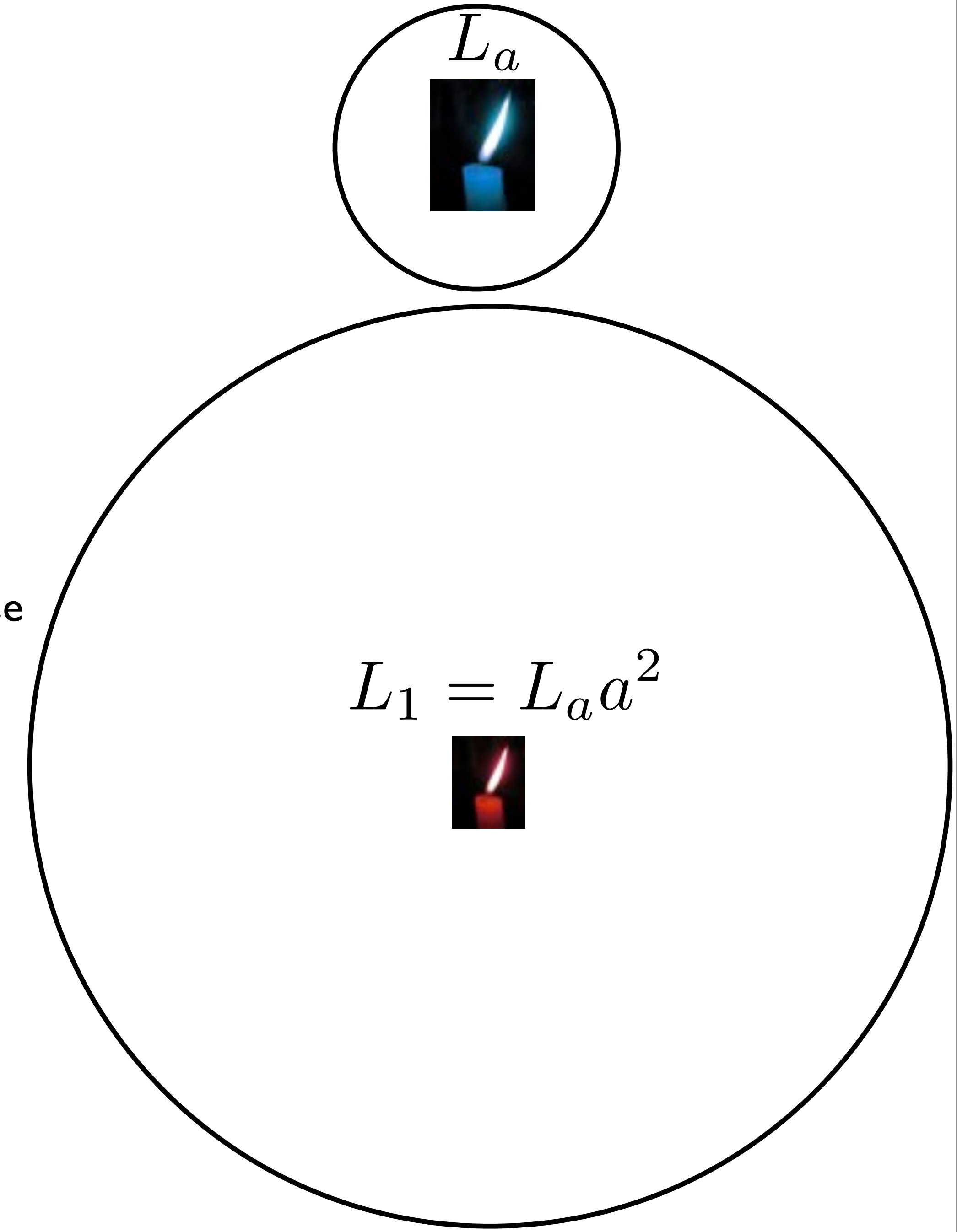
Standard Candles To Cosmology: Measurement



- For a set of standard candles of luminosity *L*
  - Measure flux *f*
  - Measure redshift *z*

Standard Candle To Cosmology: Predicted Flux

- Piece 1 - Luminosity emitted (L_a) versus what that same energy looks like today (L_1)
  - In the FRW metric
    - a(t) is the scale factor that describes the size of the Universe
    - Photon energy proportional to a^{-1}
      - Redshift
    - Clocks appear to move as a^{-1}
      - Time Dilation
  - $L_1 = L_a a^2$



Standard Candle To Cosmology: Predicted Flux

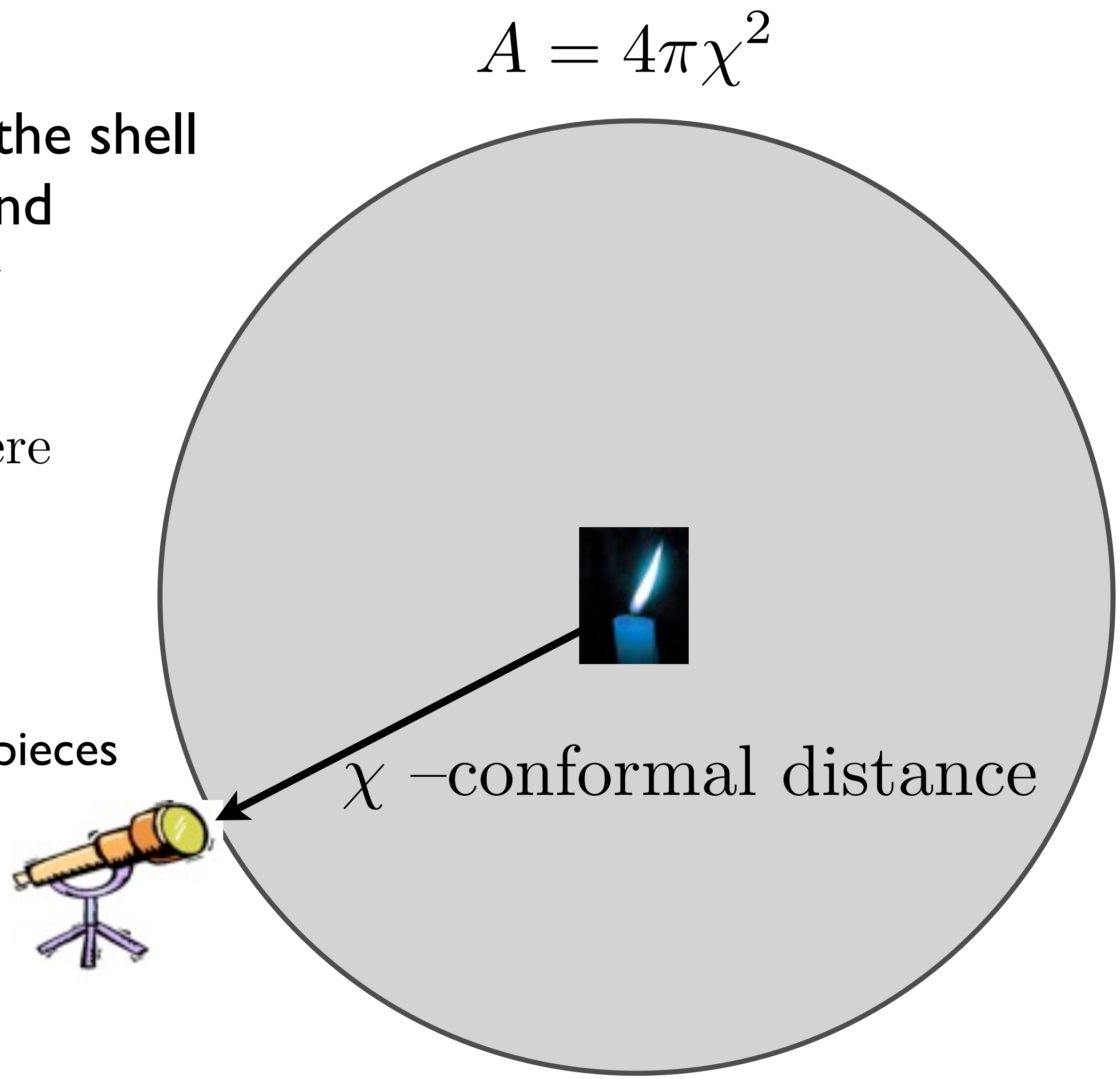
- Piece 2 - Surface area of the shell centered on the candle and intersecting the observer
  - FRW says

$$A = 4\pi\chi^2, \text{ where}$$

$$\int_0^{\chi} \frac{dr}{\sqrt{1-kr^2}} = \int_{t_e}^{t_o} \frac{dt}{a(t)}$$

  - Putting together the two pieces

$$f = \frac{L_a a^2}{4\pi\chi^2}$$



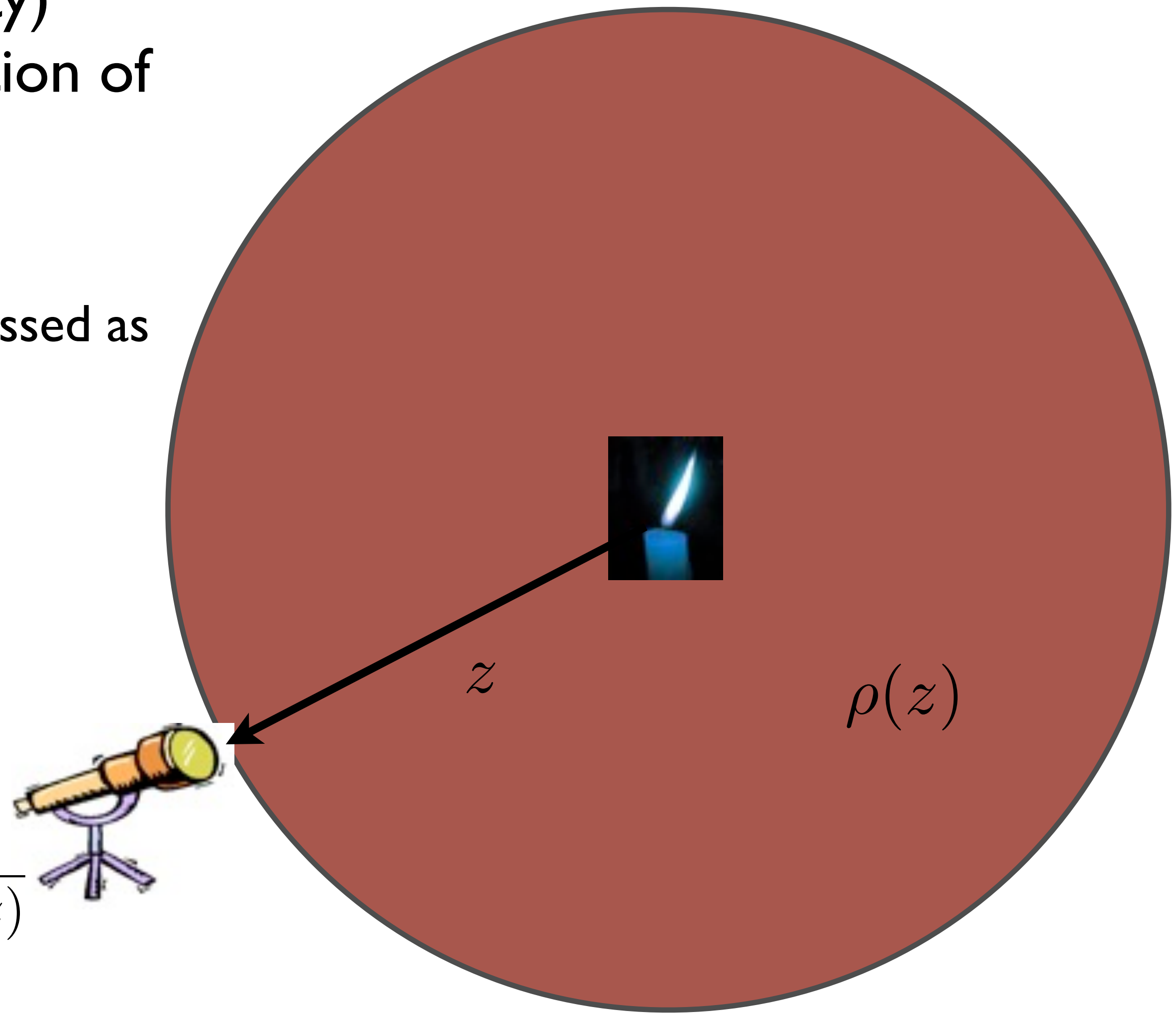
Standard Candle To Cosmology: Theoretical Flux

- Physics (General Relativity) provides expected evolution of a(t) based on the energy contents of the Universe
  - For convenience re-expressed as H(z)

$$z = \frac{1}{a} - 1$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(a; \Omega_i, w_i, \ldots)$$

$$\int_0^{\chi} \frac{dr}{\sqrt{1-kr^2}} = \int_{t_e}^{t_o} \frac{dt}{a(t)} = \int_0^z \frac{dz}{H(z)}$$



Standard Candle Flux and the Matter Content

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

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

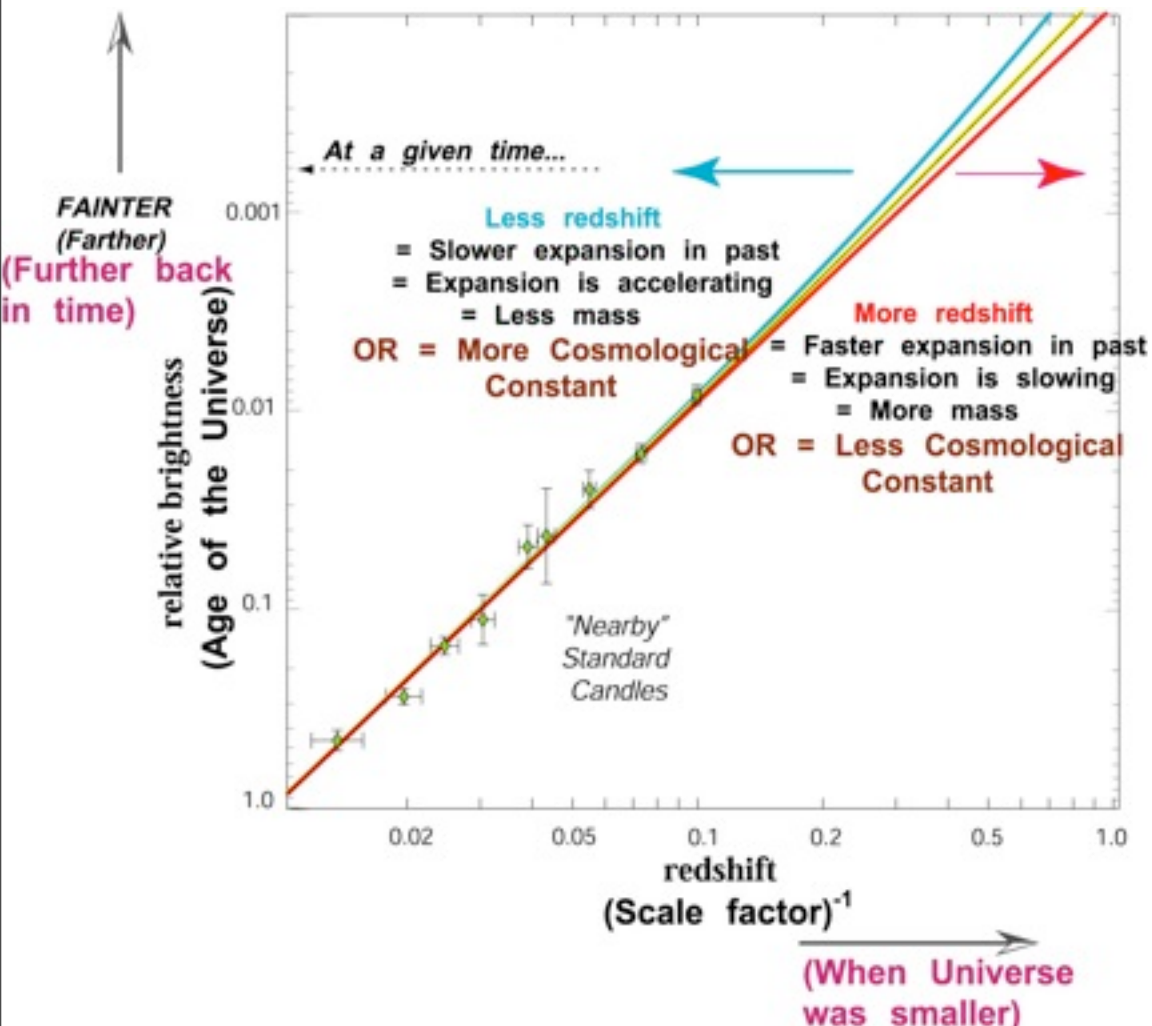
$$H^2 = H_0^2\left(\sum_{i\in\text{energy states}} \Omega_i(1+z)^{3(1+w_i)}\right)$$

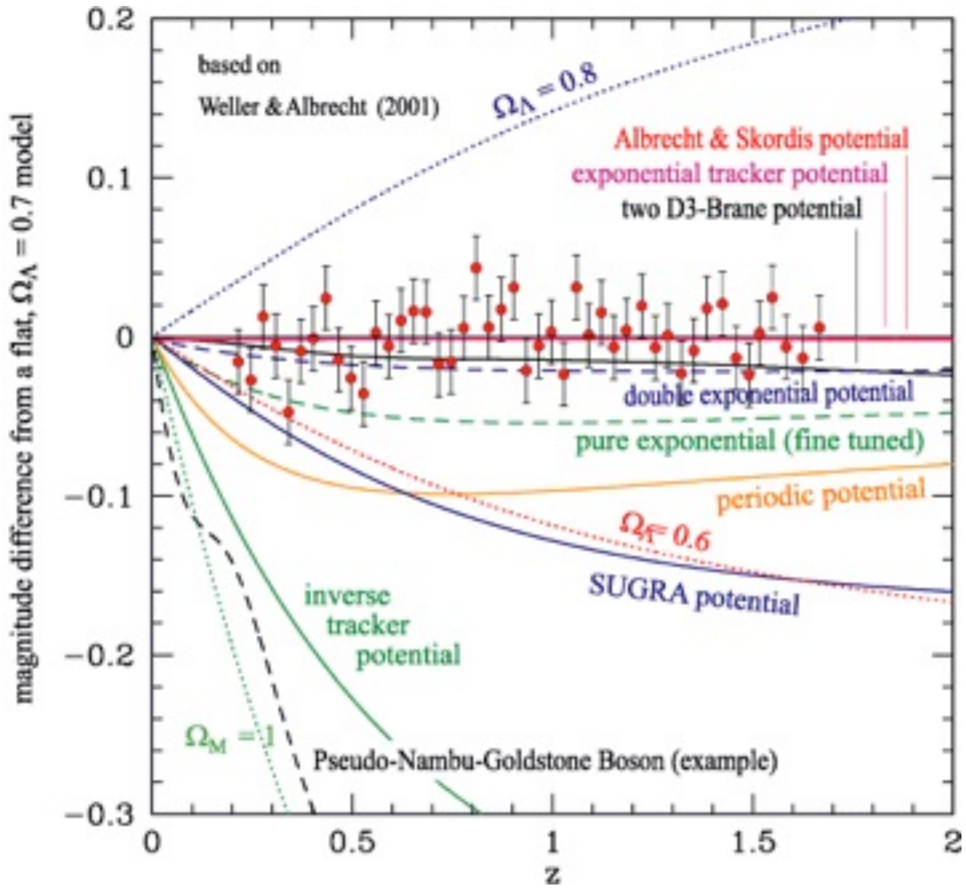
$$d_L = (1+z)\chi \text{ –Luminosity Distance}$$

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

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

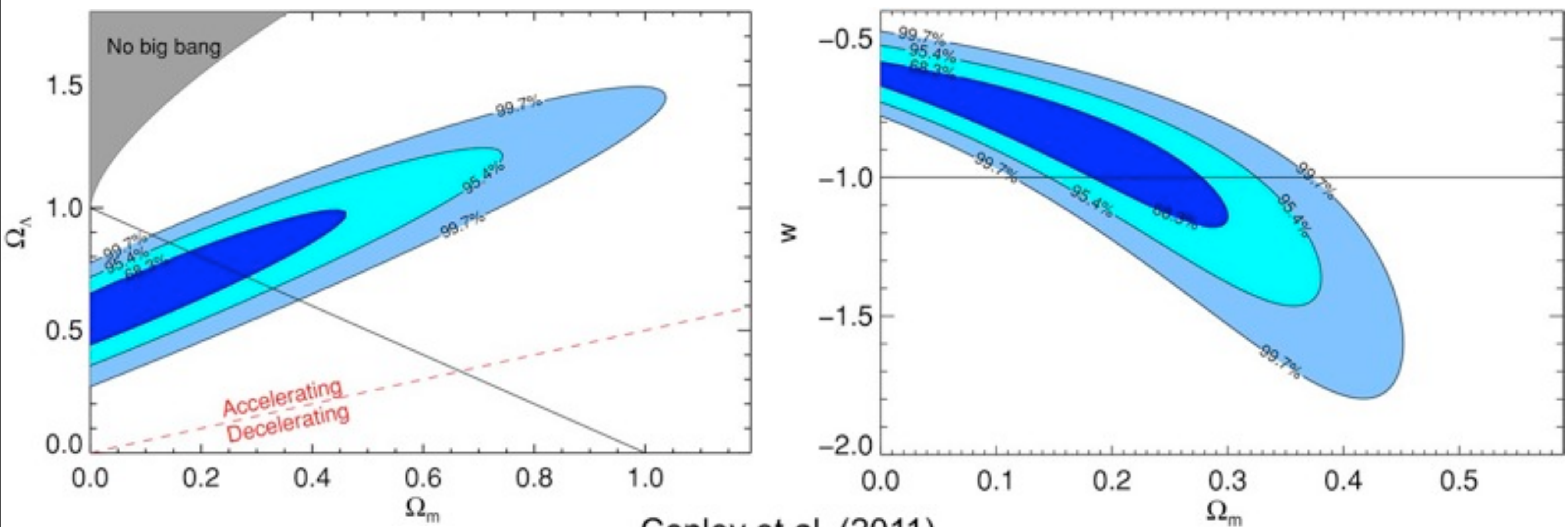
Hubble Diagram for Different Dark Energy Models





Dark Energy Parameter Estimates With Standard Candles

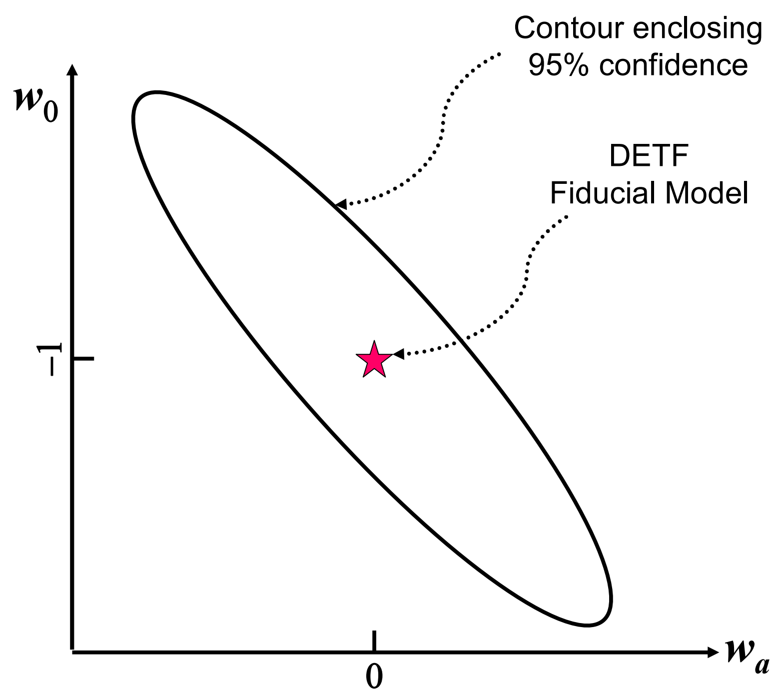
- Sensitive to the acceleration of the universe
- Constrains the mass density, dark energy density, and a constant dark energy equation of state w



Conley et al. (2011)

Figure of Merit

- A single number to compare performance of dark energy experiments
- Dark Energy Task Force Figure of Merit
  - Reciprocal of the area of the error ellipse in the w0-wa plane that encloses the 95% contour
- SNe Goals
  - ~15 Today
  - ~100 Upcoming ground-based
  - ~400 Space-based
- Common, useful, but doesn't capture all the science



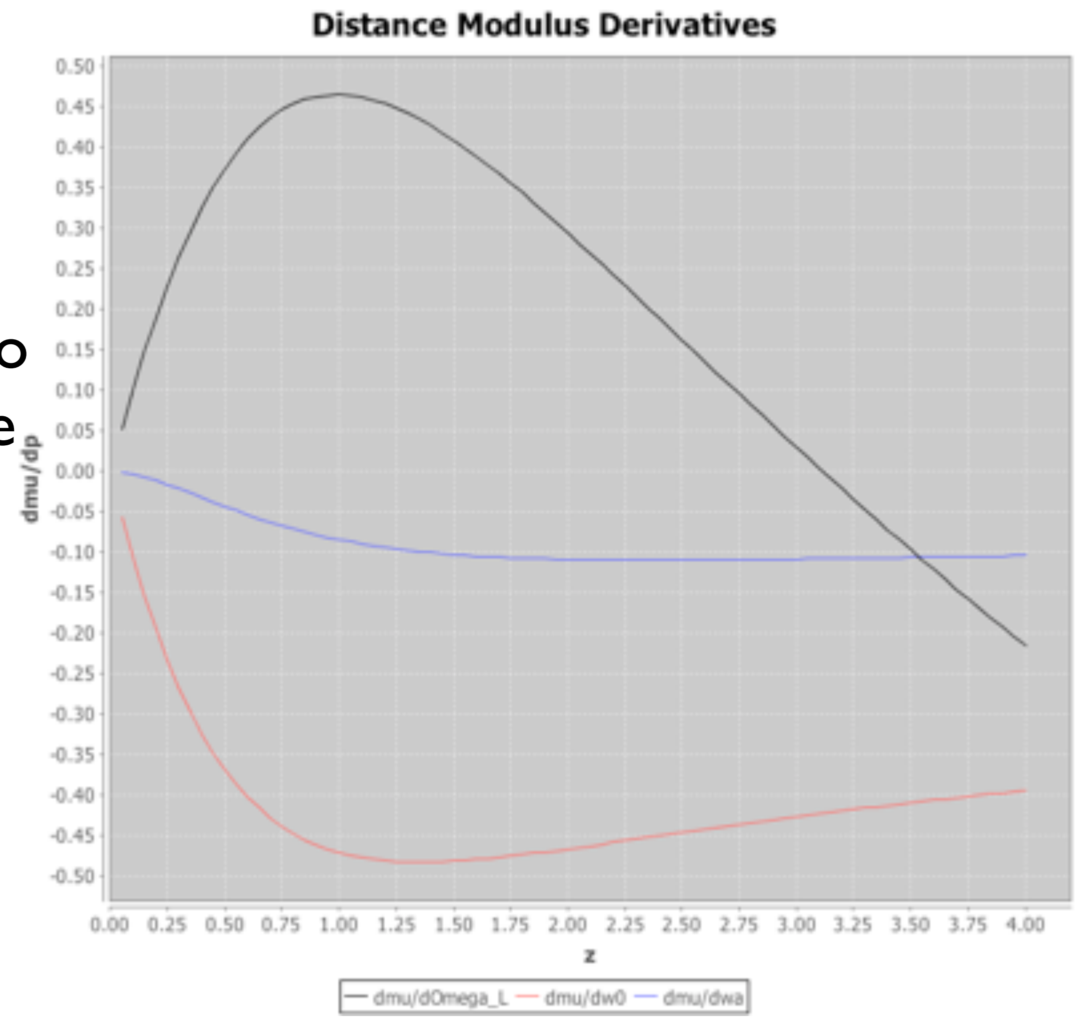
Constraining Dark Energy Model Parameters

- Fisher Information Matrix a useful bound of parameter uncertainties from an experiment

$$F_{ij} = \frac{\partial \mu(z_\alpha)}{\partial p_i} V^{-1}_{\alpha\beta} \frac{\partial \mu(z_\beta)}{\partial p_j}$$

  - μ - Model distance modulus
  - p_i - Model parameter i
  - V - Measurement covariance matrix
- Parameter uncertainties bounded by F^{-1}: depends on
  - Size of $\partial\mu/\partial p$, measurement uncertainty
  - Similarity of shapes of $\partial\mu(z)/\partial p$
  - Small measurement errors V

Parameter Sensitivity at Different Redshifts: $\partial\mu/\partial p$



- Distance modulus sensitive to Ω_Λ, w_0, and not very sensitive to w_a
- Shapes are more distinctive within broad redshift windows
  - Large redshift coverage provides leverage

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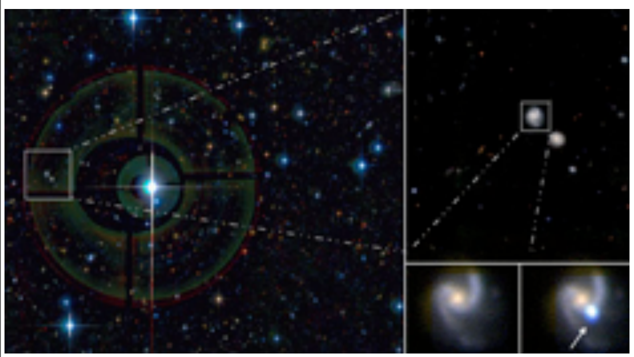
Introduction To What We Measure From Supernovae

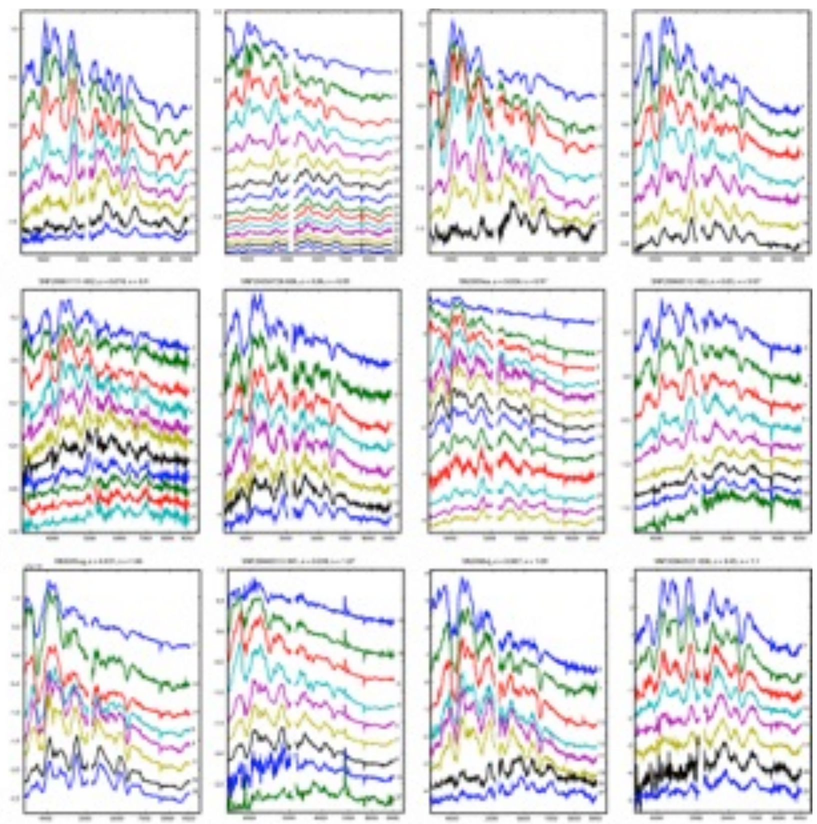
- Most SN data obtained from optical wavelengths (0.35-0.8 μm) some in near-infrared wavelengths (0.8 - 2.5μm)
- Photometry and spectroscopy (polarization)

Classic Survey

- Periodic (low-quality) wide-field imaging contains new point sources
- Triggers independent observations tailored to meet photometric/ spectroscopic accuracy requirements for individual candidates

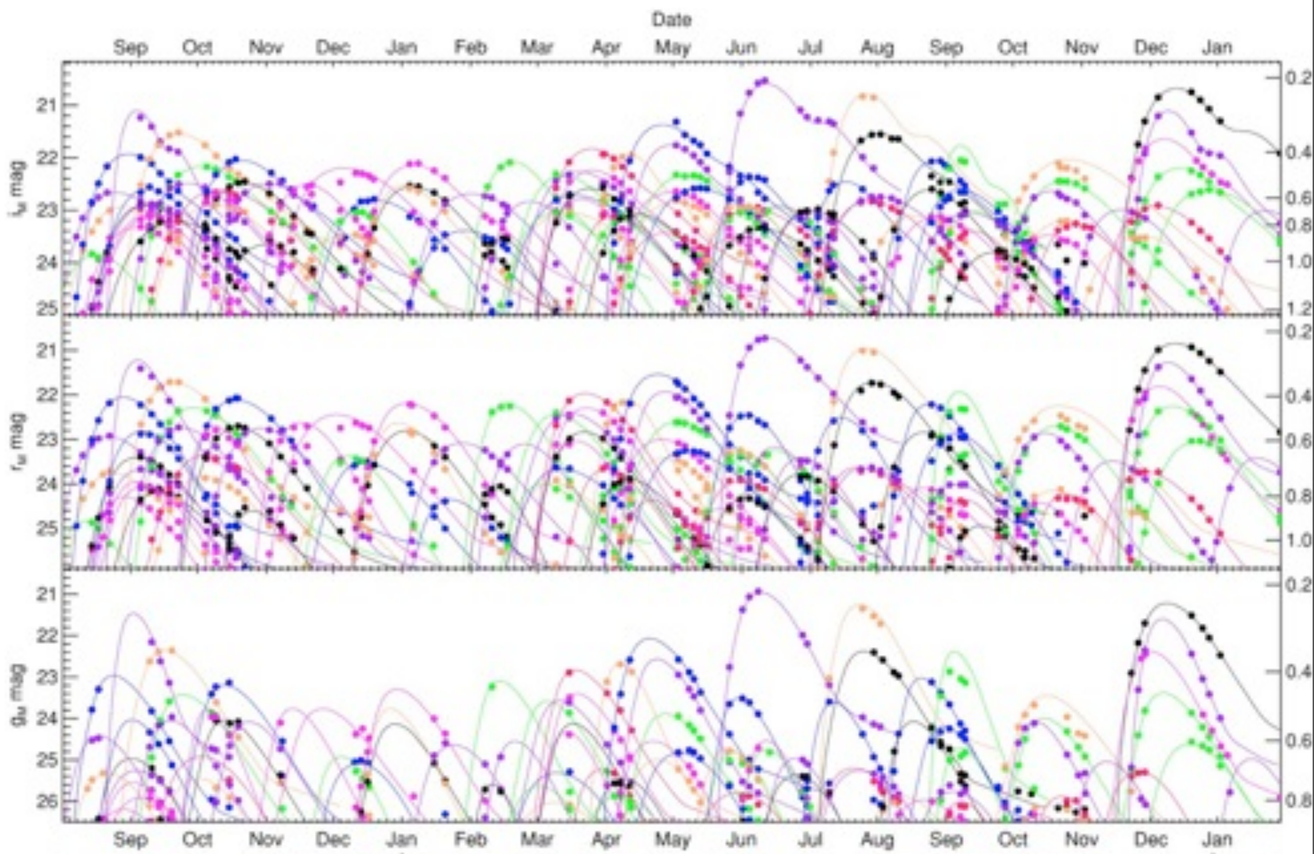


SNFactory



Rolling Survey Supernova Legacy Survey

- Cadenced wide-field imaging automatically produces photometry of all sources in the field
- Triggers independent spectroscopic observation for individual candidates



Perrett et al. (2010)

Photometry Measurement

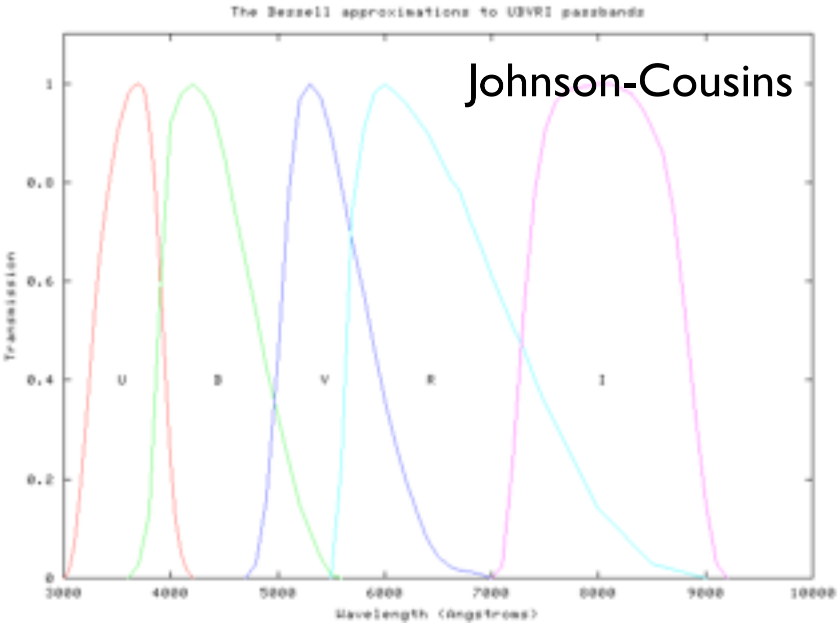
- Imagers
  - Wide-field to measure many SNe at once
  - Detectors
    - Optical - CCD, NIR - HgCdTe

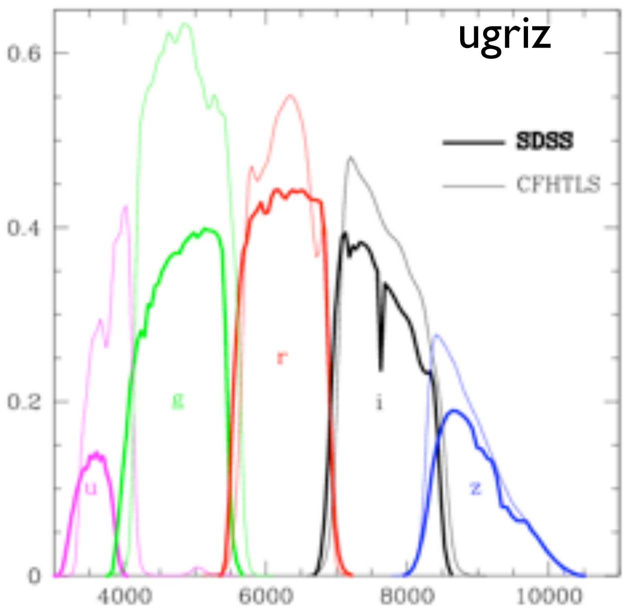
Megacam

Redshift	Telescope Aperture
z<0.1	<1m (ground)
z~0.3	~2m (ground)
z~0.5	~4m (ground)
z~1.5	~1.5m (space)

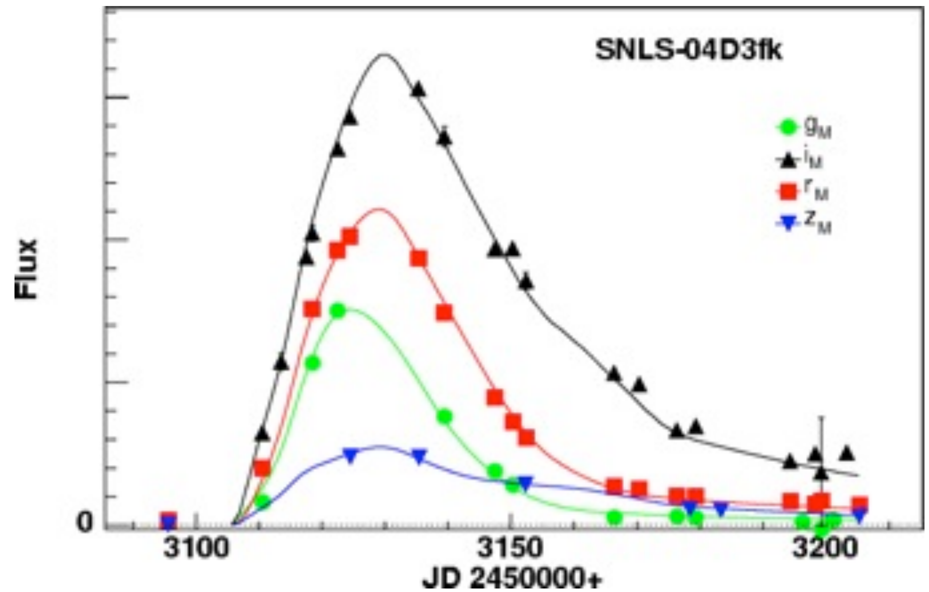
Photometric Data

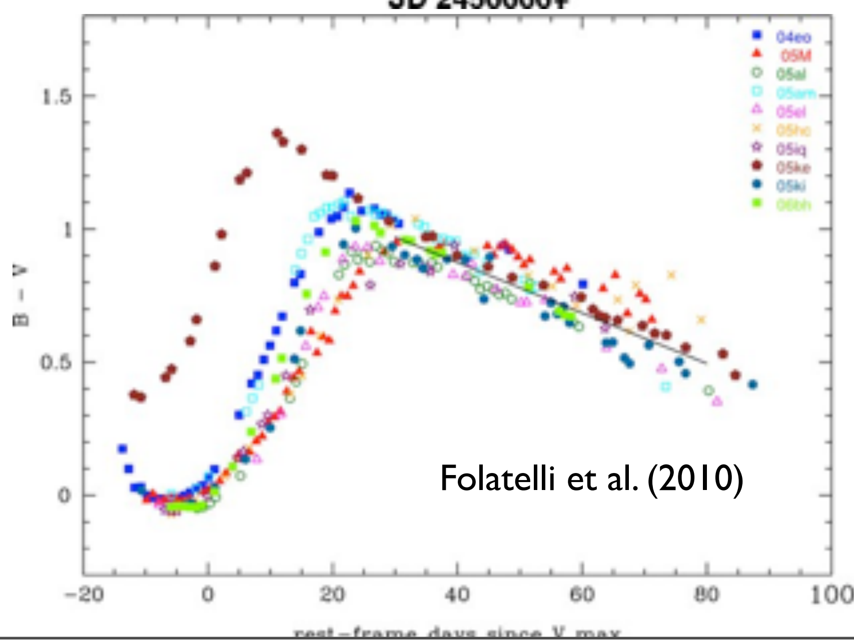
Passbands



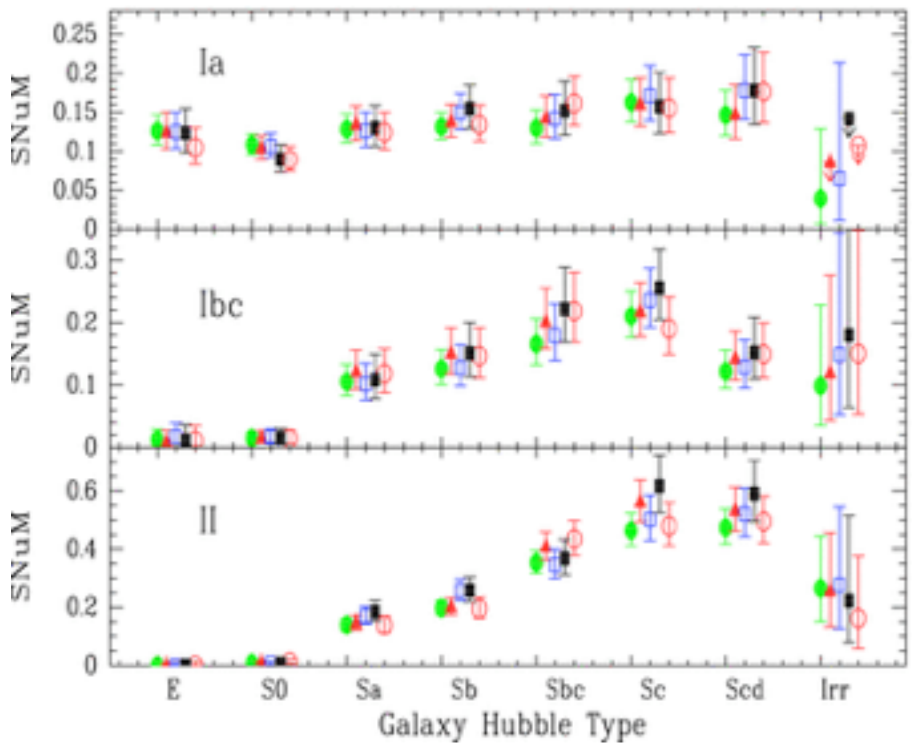


Light Curve and Color Curves





Supernova Rates

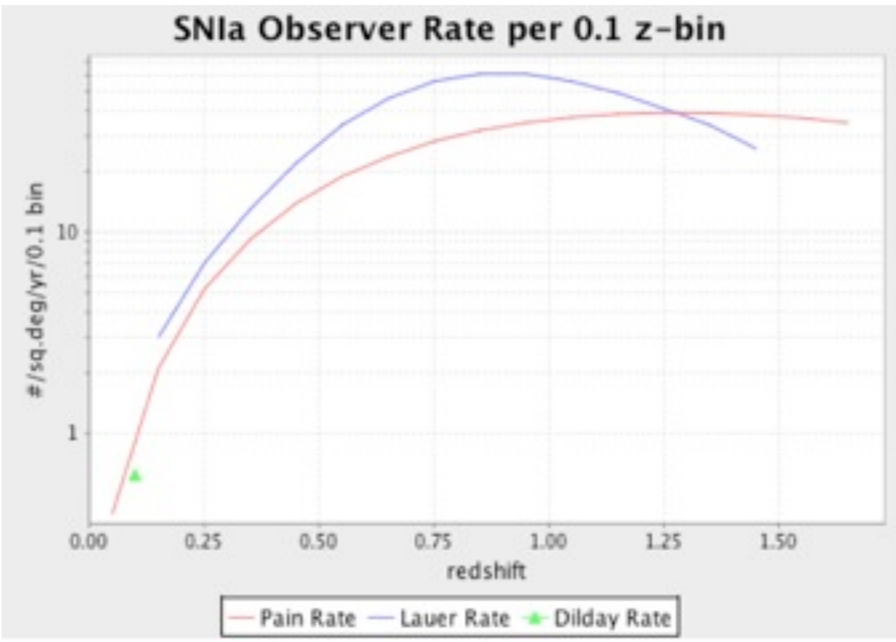


Li et al. (2011)

- SNuM - 1 SN per 100 years per 10^{10} solar mass
- SNe Ia have lower rates per volume but higher rates per magnitude-limited sample

Observer SN Rate

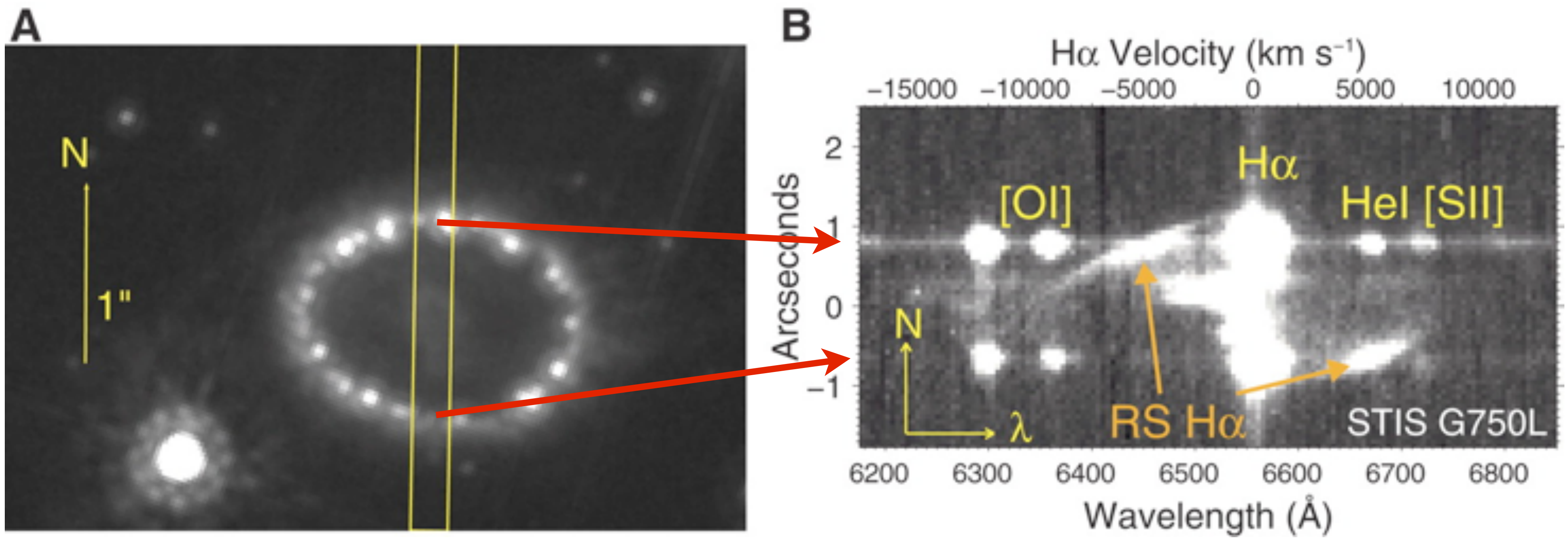
- Includes time dilation
- Shows how big a survey has to be
- Shows how big an imager has to be



Spectroscopy Measurement

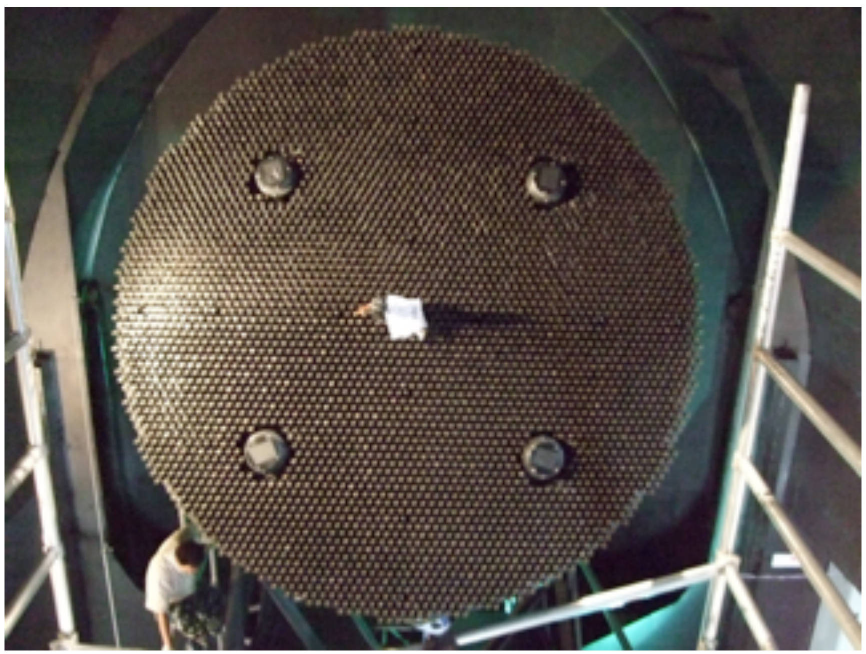
Spectroscopy Measurement

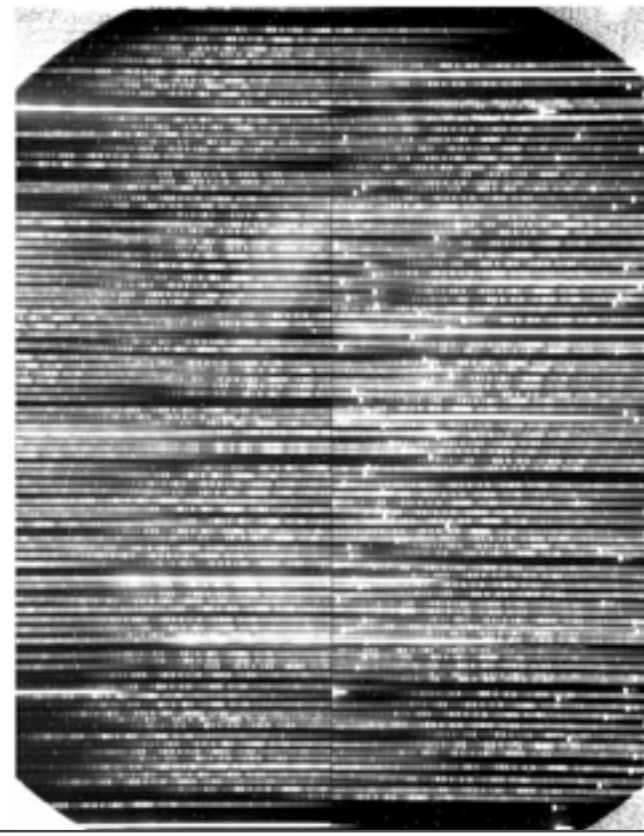
- Different ways to select the piece of sky to be dispersed
  - Slit



Spectroscopy Measurement

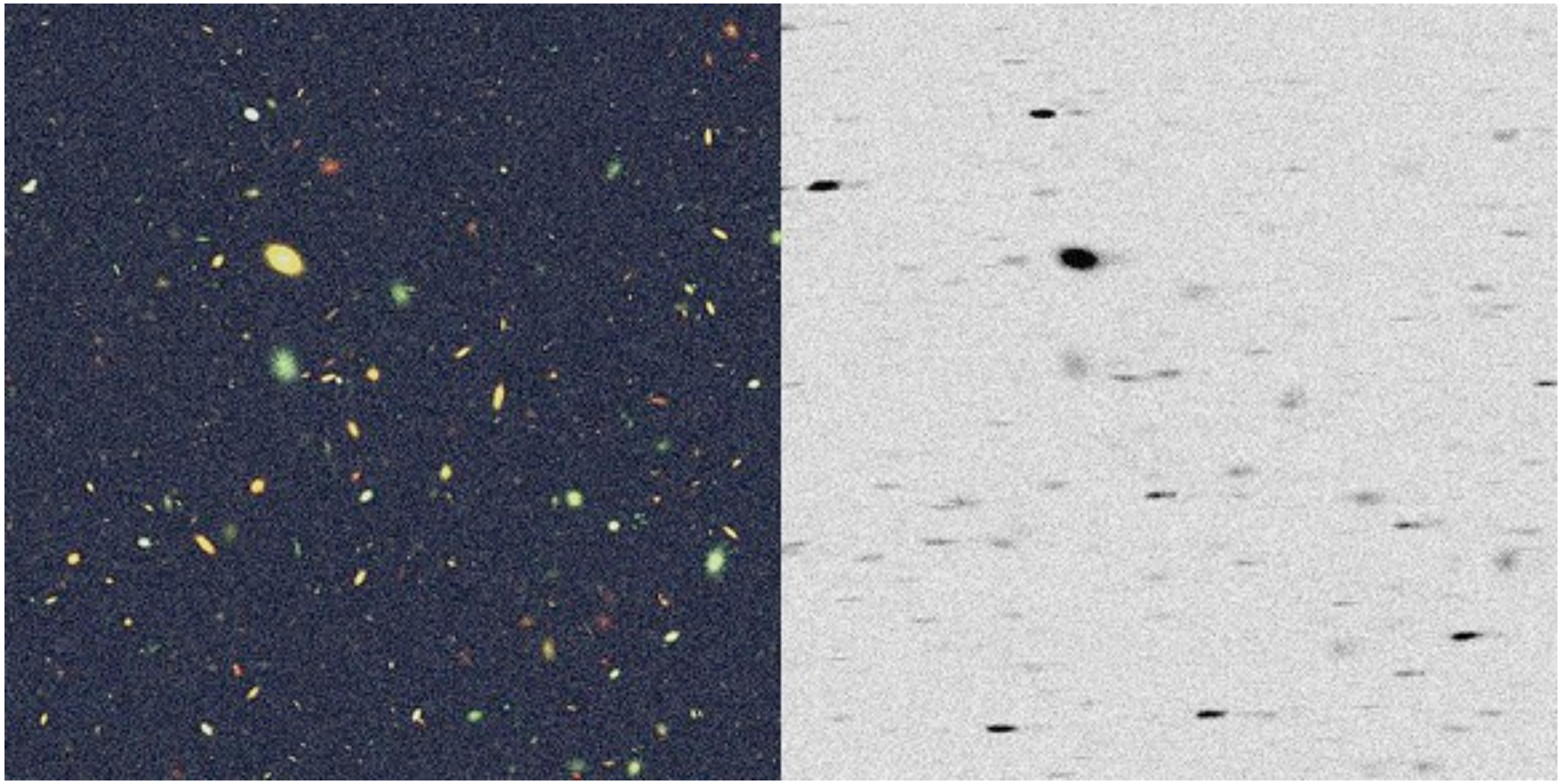
- Different ways to select the piece of sky to be dispersed
  - Slit
  - Fiber





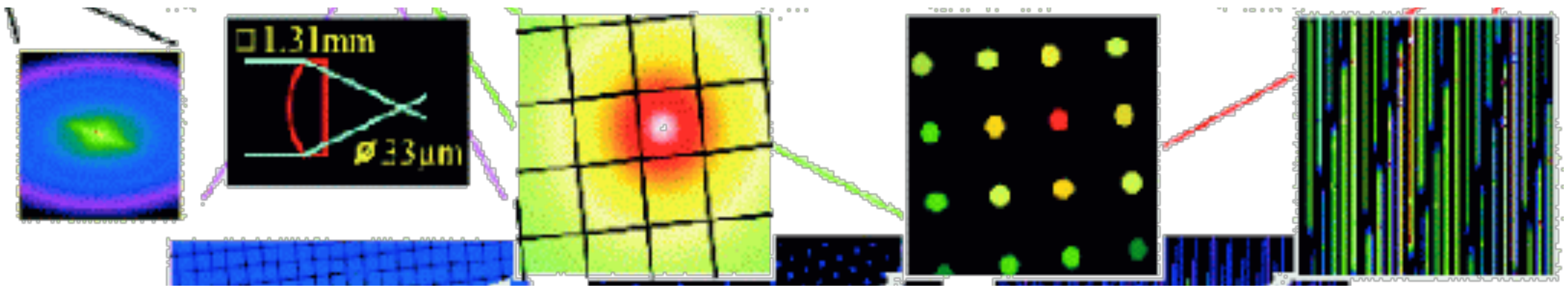
Spectroscopy Measurement

- Different ways to select the piece of sky to be dispersed
  - Slit
  - Fiber
  - Slitless



Spectroscopy Measurement

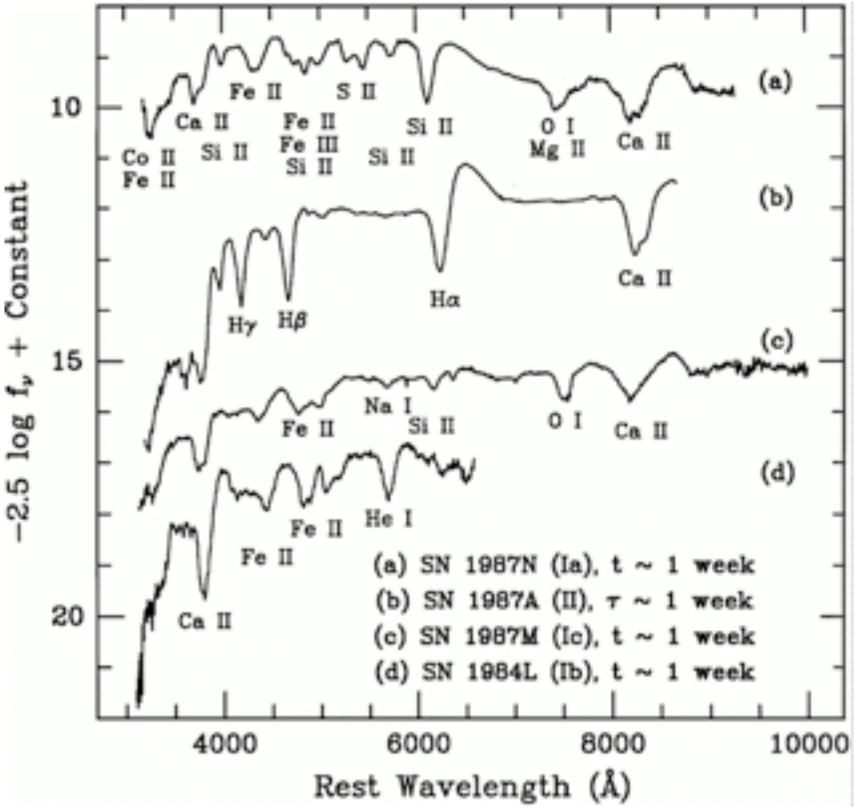
- Different ways to select the piece of sky to be dispersed
  - Slit
  - Fiber
  - Slitless
  - IFU



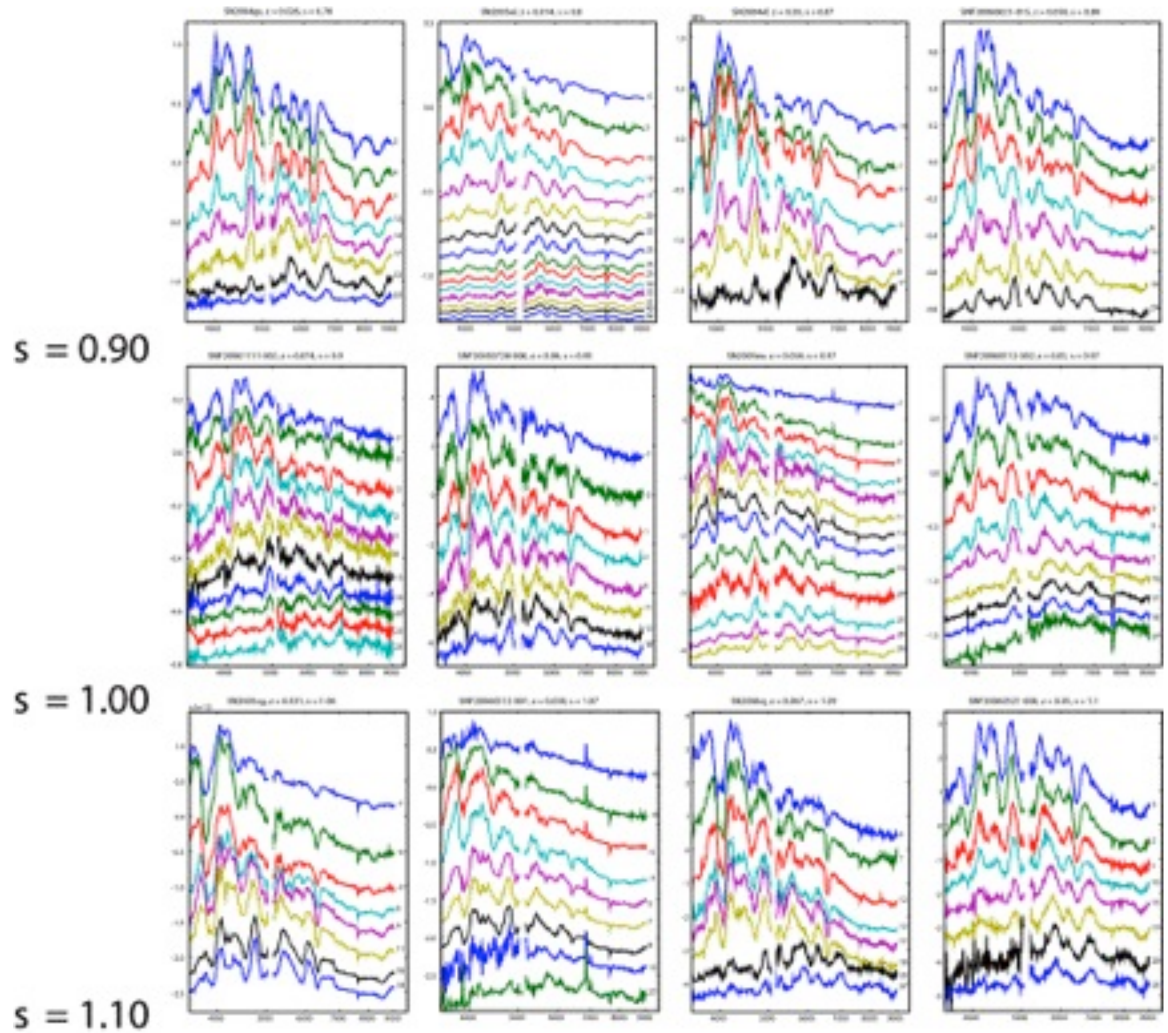
Telescopes Used for Spectroscopy Measurement

Redshift	Telescope Aperture
z<0.1	<2m (ground)
z~0.3	~4m (ground)
z~0.5	~8m (ground)
z~1.5	~1.5m (space)

Spectroscopic Data



Filippenko et al. (1997)



Aldering et al. (2010)

$L_{SNIa} \sim 10^{10} L_{Sun}$

Magnitude/Flux Units

- Photometric fluxes given in terms of magnitudes
- Filter magnitude systems are NOT fundamentally tied to physical units
- Conversion from detector counts to source flux ambiguous
  - Two objects with same magnitude can have different energy flux and vice versa
- Color is magnitude difference in different filters e.g. B-V
- An incorrect but useful approximation

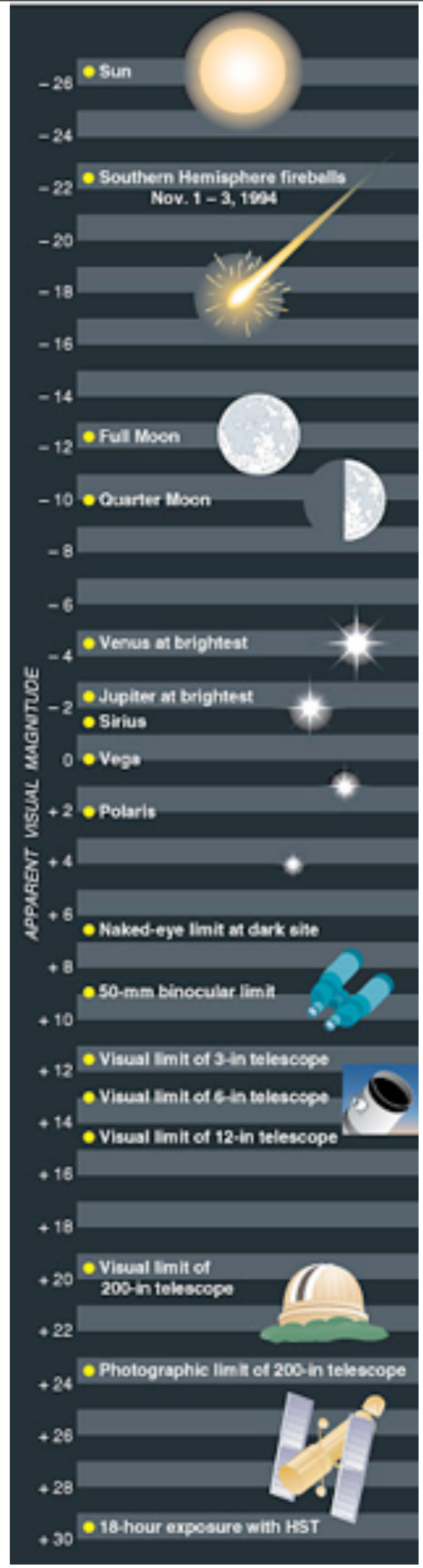
$$m = 2.5 \log f + \text{zeropoint}$$

$$\delta m \sim \frac{2.5}{\log 10} \frac{\delta f}{f} \sim \frac{\delta f}{f}$$

$$m = 0 \rightarrow f \sim 3.7 \times 10^{-9} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$$

z~0.1 SNIa

z~1.5 SNIa



Filter Count Magnitudes

- Filter magnitudes based on relative photon flux between standard star and object
  - Detectors are photon counters not bolometers

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

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

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

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

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

Filter Count Magnitudes

- Filter magnitudes based on relative photon flux between standard star and object
  - Detectors are photon counters not bolometers

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

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

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

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

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

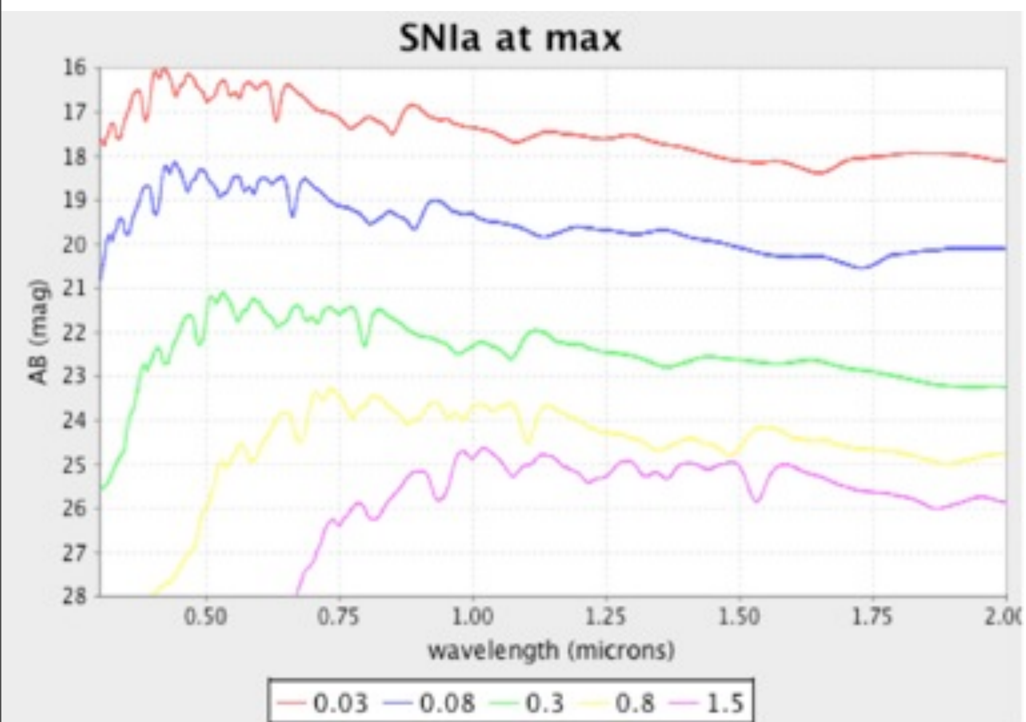
$$\mu = 5\log\left(d_L/10\text{pc}\right) \text{ –Distance Modulus}$$

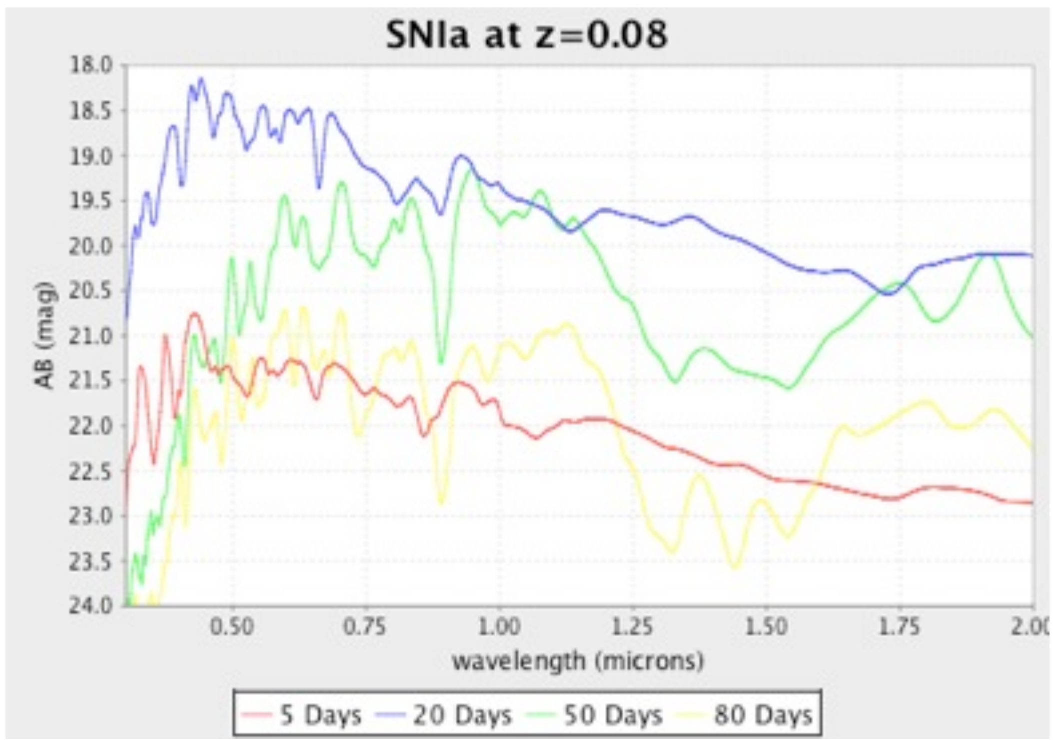
Spectroscopy Units

- Connected to physical units
  - Source flux and system transmission flat in spectral bin

$$AB = -2.5 \log f_\nu - 48.60$$

$$[f_\nu] = \text{erg s}^{-1}\text{cm}^{-1}\text{Hz}^{-1}$$





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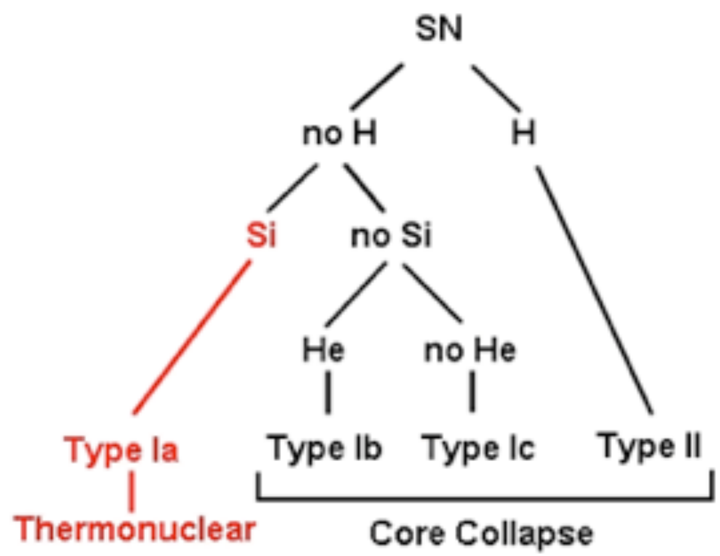
Supernova: An Empirical View

- New point source that doesn't repeat
- Very very bright
  - 10^{53} erg
- Associated with a galaxy
- Deduction: Explosive stellar death

- Empirical classification



Type Ia Supernova

- Movie of the spectral time evolution of a SN Ia
  - (Thickness represents interpolation uncertainties)

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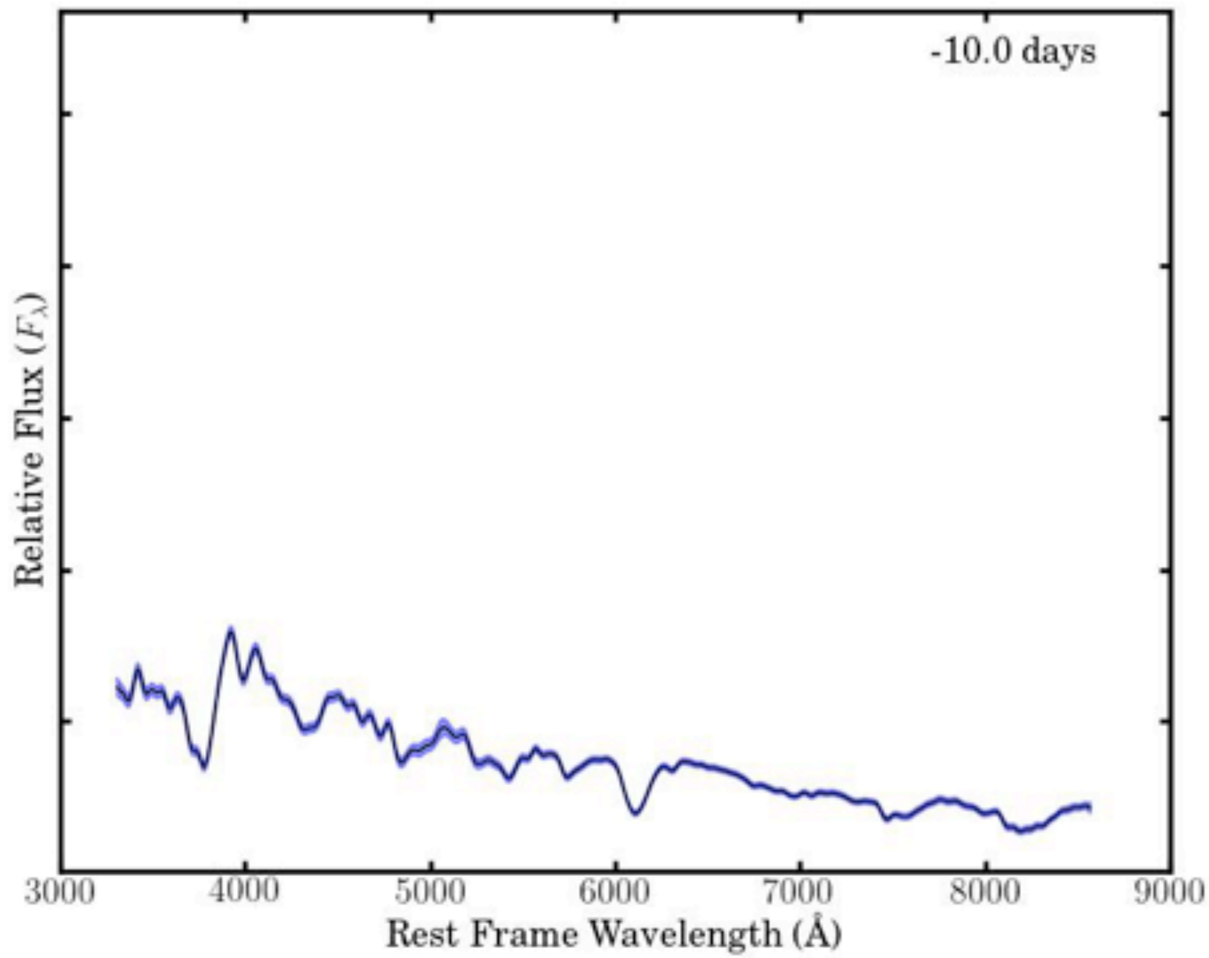
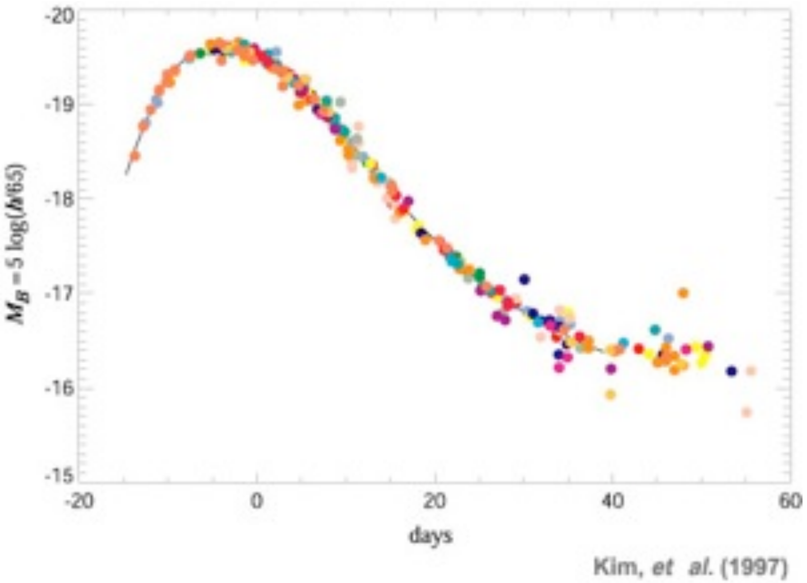
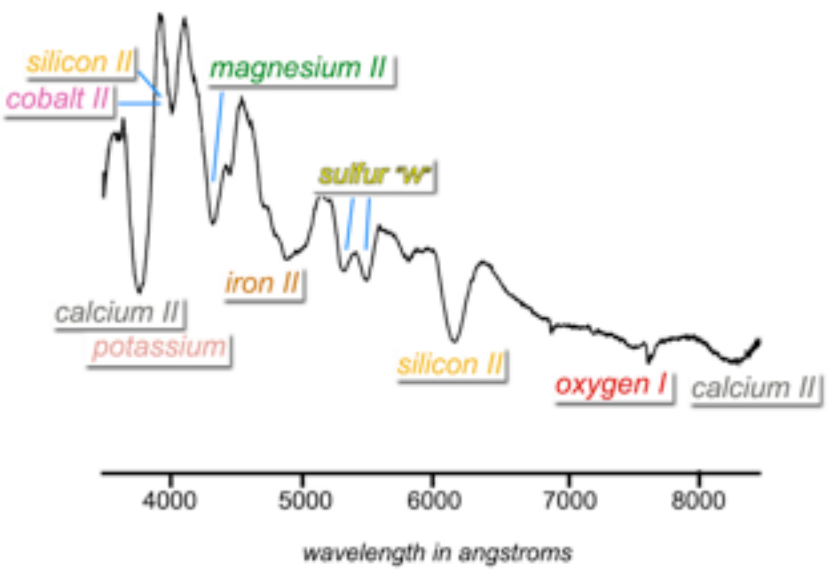


Clues to Supernova Ia Identity

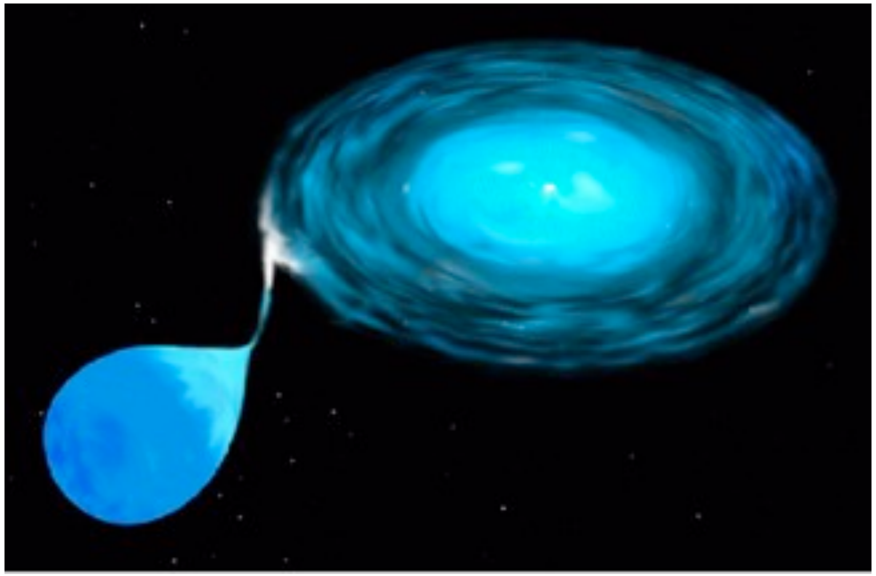




- Found in early and late host galaxies
- Light curves and spectra homogeneous
- Light curve consistent with ^{56}Ni decay
  - Energy from decay of ~1 solar mass ^{56}Ni to ^{56}Fe
  - Rise and fall of light curve consistent with ^{56}Ni and ^{56}Co half-lives
- Spectra
  - No Hydrogen
  - Intermediate mass elements produced (not only iron)
  - Wide P-Cygni features from expanding photosphere

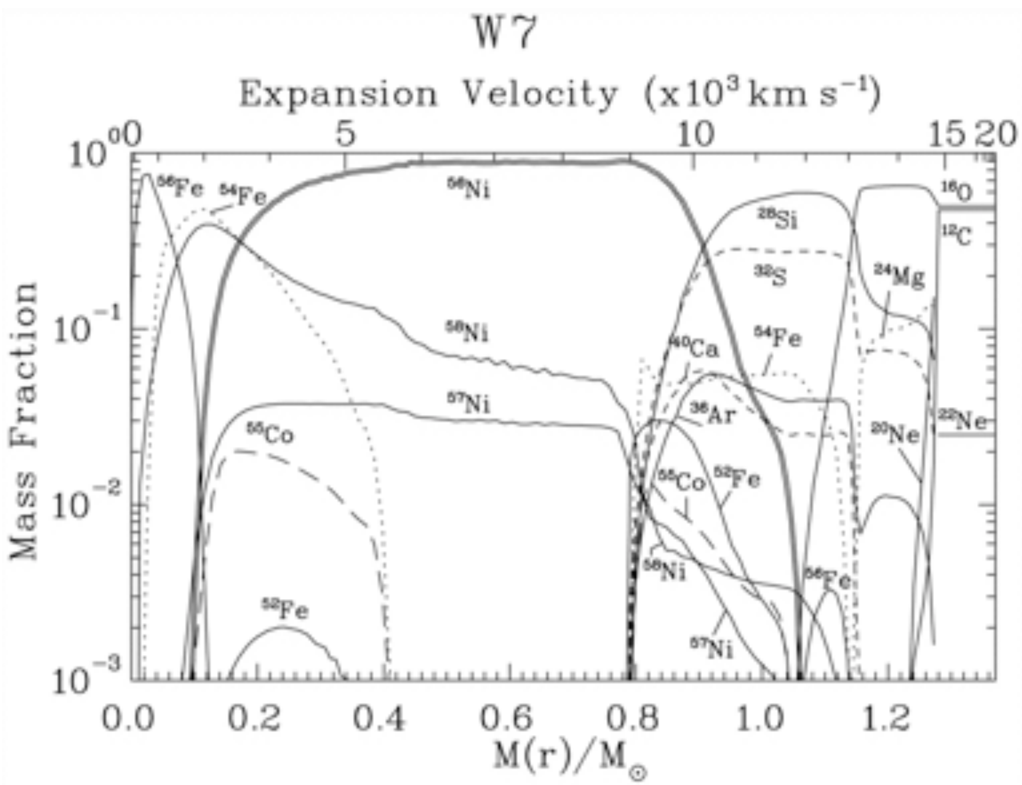
Type Ia Supernova Explained

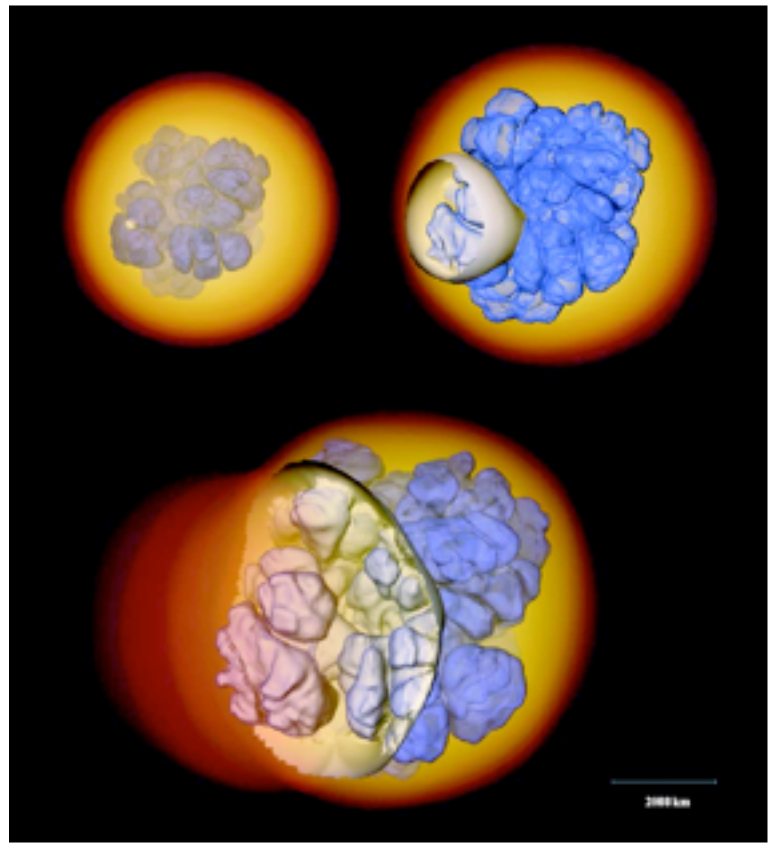
- C/O white dwarf gaining material from a binary companion
- As the white dwarf reaches the Chandrasekhar mass (1.4 solar mass) a thermonuclear runaway is triggered
  - Two burning phases: subsonic produce intermediate mass elements and supersonic produces ^{56}Ni
  - $>10^{51}$ ergs explosion energy disrupts star
  - Debris in homologous expansion
- Observed light from radioactive decay of ^{56}Ni to ^{56}Fe
- A homogeneous triggered bomb



Computational Supernova Ia Explosion

- 1-d parameterized delayed detonation model
- 3-d models show interesting structure but insufficient computer time to calculate from turbulence to white-dwarf scales over interesting time scales





SNe Ia Progenitors Not Completely Understood

- Understanding SN Ia progenitor system is an active subject of research
- Nature of the binary companion. Red giant or another white dwarf?
- Not many white-dwarf binary systems seen
- Other explosion channels
- Range of central ignition density
- How to explain subsonic and supersonic burning fronts
- 3-d modeling a big computational problem
- SOURCE OF SYSTEMATIC UNCERTAINTY IN COSMOLOGICAL MEASUREMENTS

Outline

- Why SN cosmology is relevant
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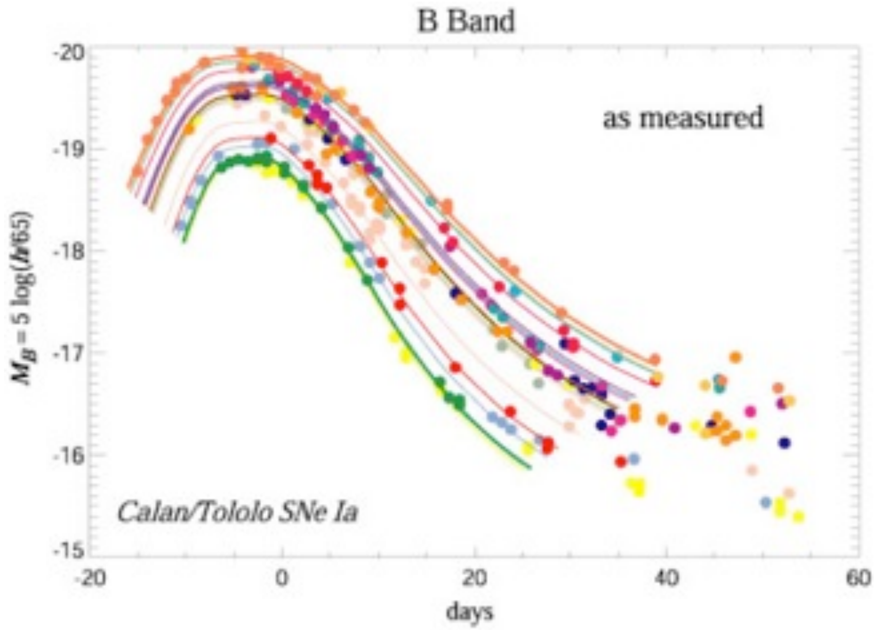
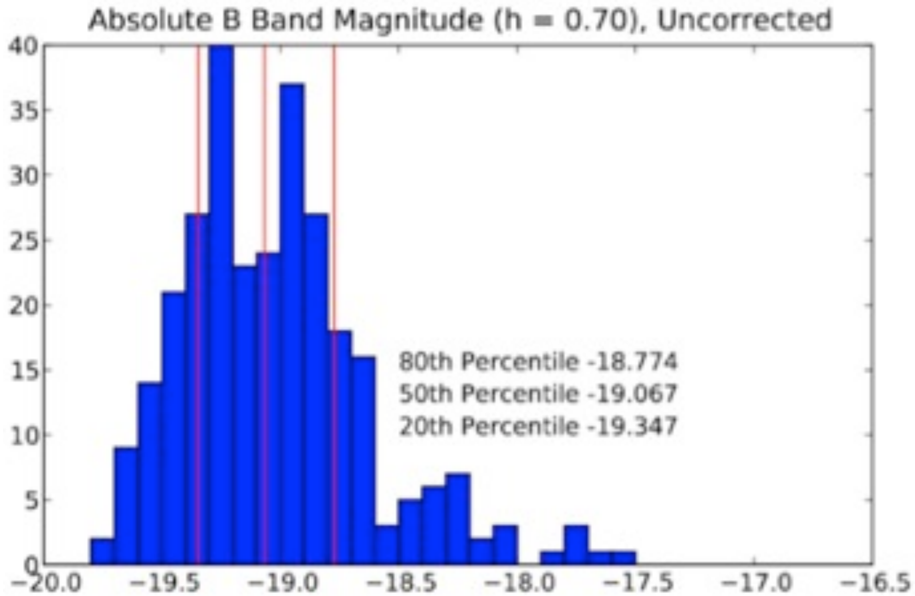
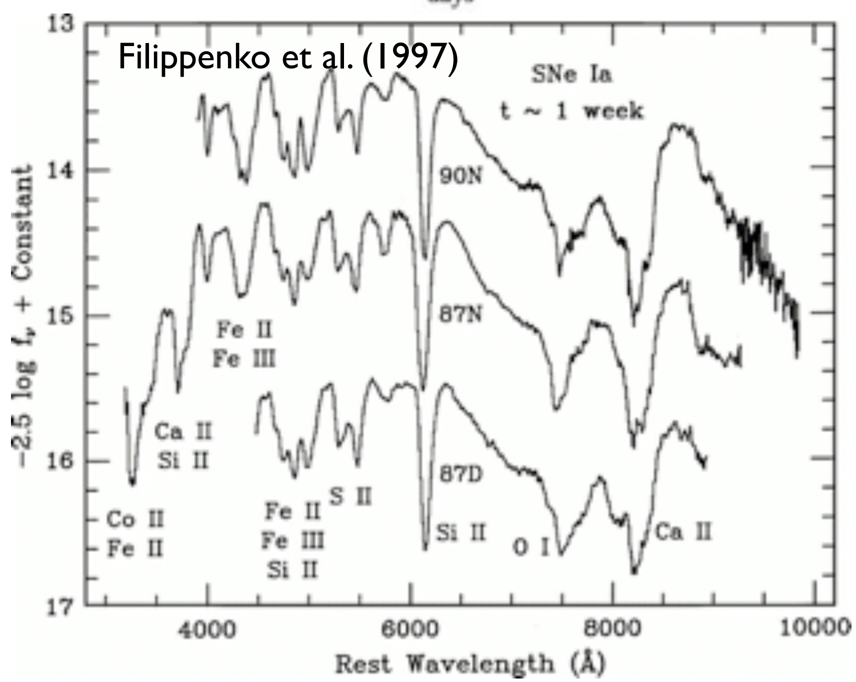
Type Ia Supernovae Homogeneity

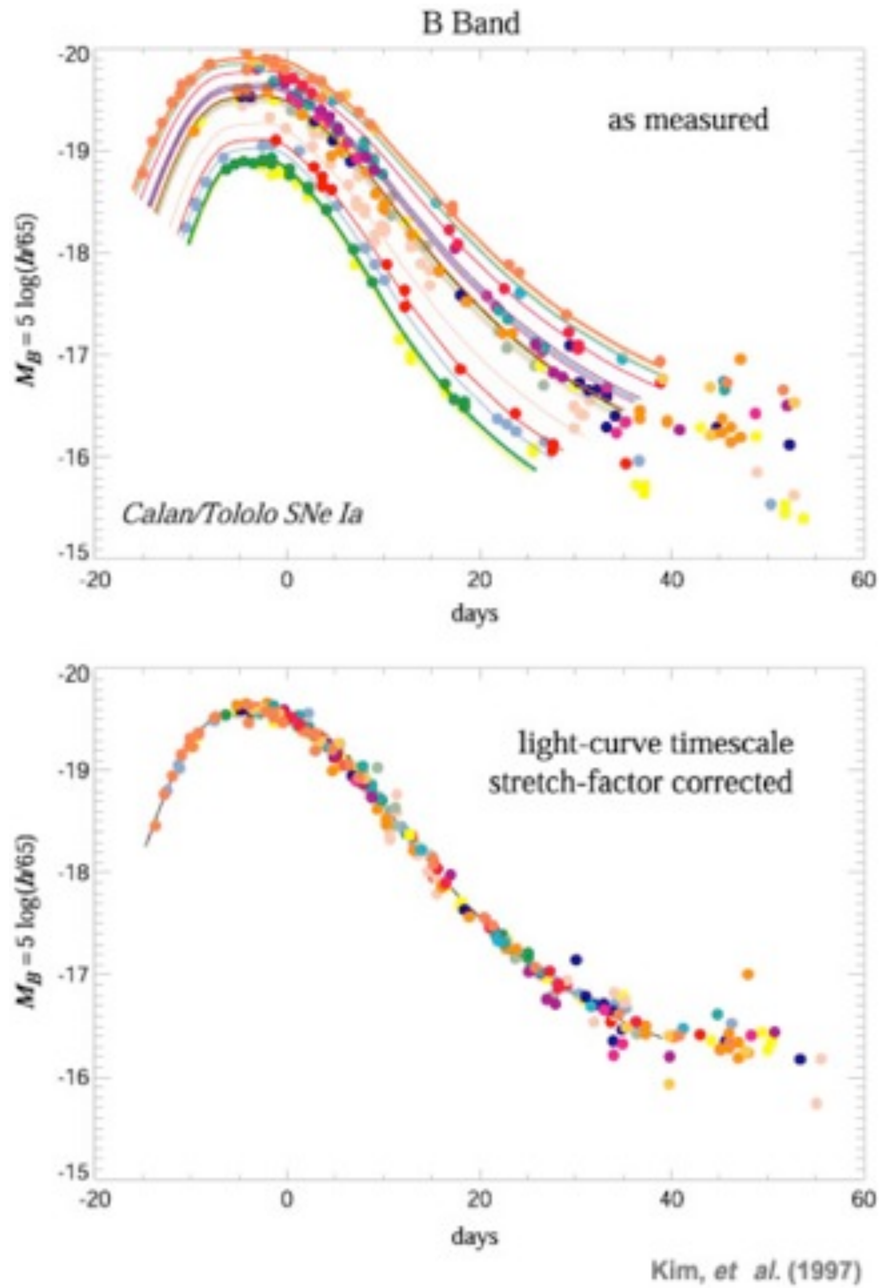






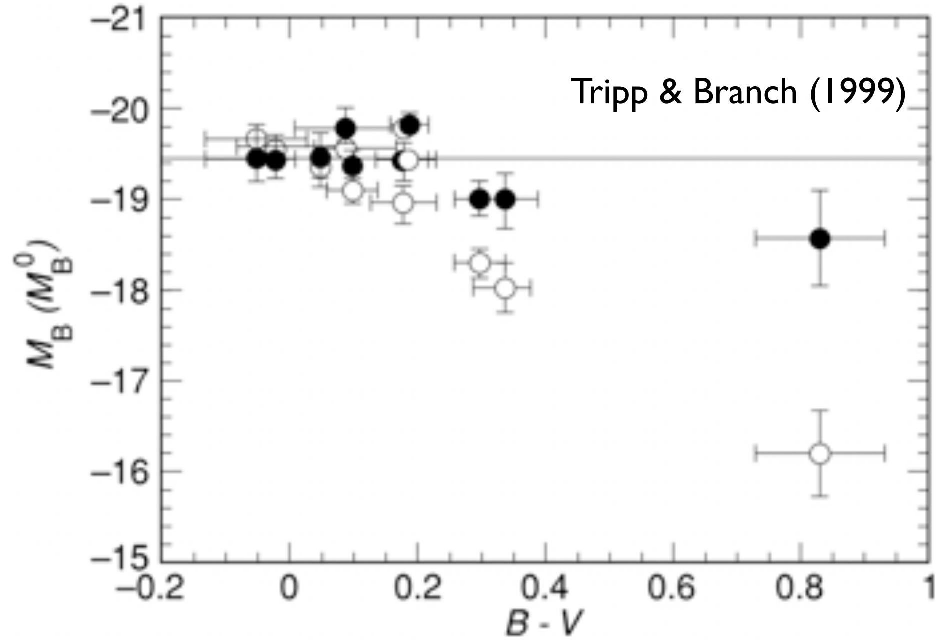
Actually A Little Heterogeneous But Correctable

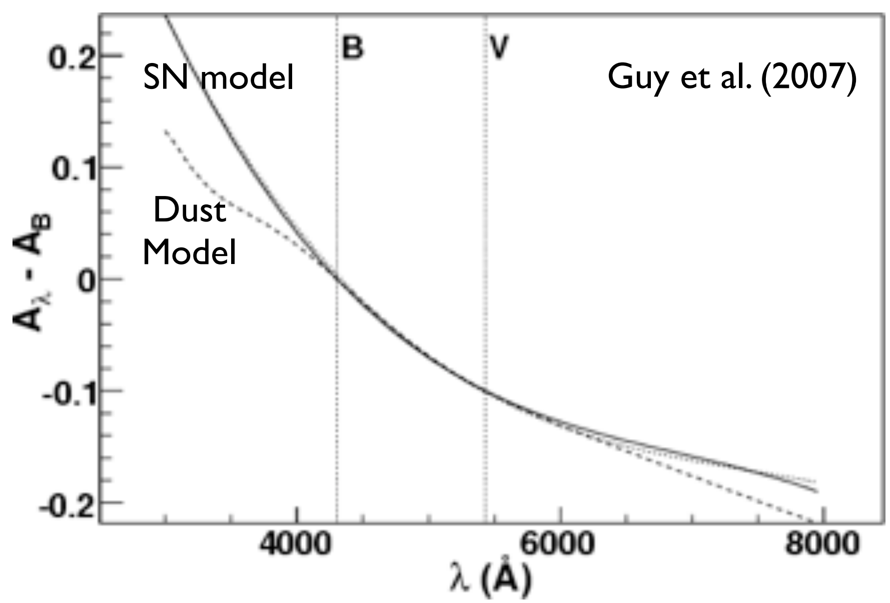
- Heterogeneity in supernova brightnesses and light curve shapes
- Due to different opacities
- After correction for foreground dust supernovae have peak-magnitude dispersion of ~0.3 mag
- After correction for light-curve shape supernovae become "calibrated" candles with ~0.15 mag dispersion



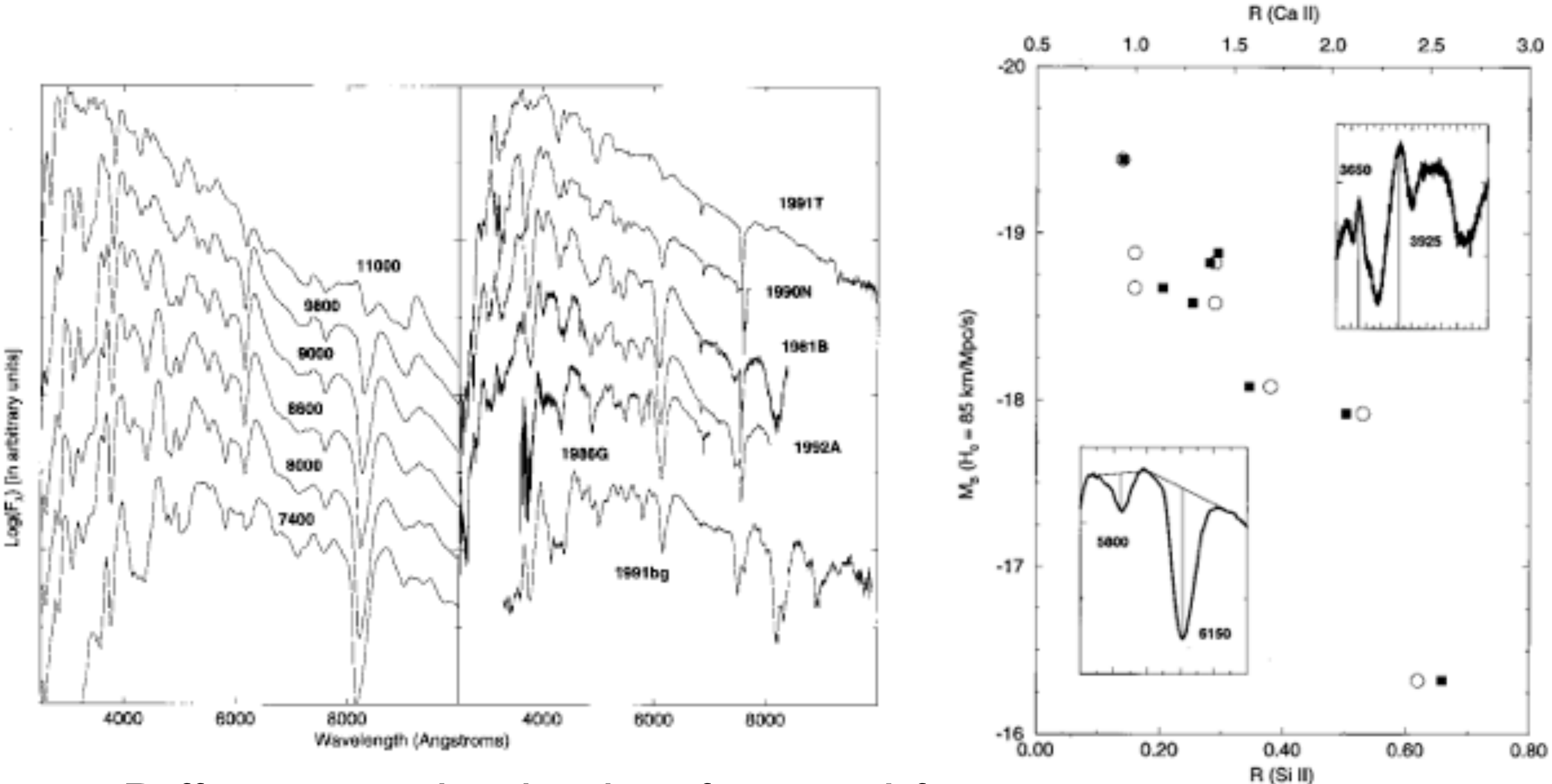
Correction for Dust (Color)

- Peak luminosity correlated with color
- Could be due to
  - Absorption from dust in the host-galaxy
  - Intrinsic to supernova or its local environment
- Peak luminosity corrected given brightness-offset as a function of wavelength





Actually A Little Heterogeneous But Correctable



- Difference in the depths of spectral features
- Correlated with peak brightness
- Related to the temperature of the supernova

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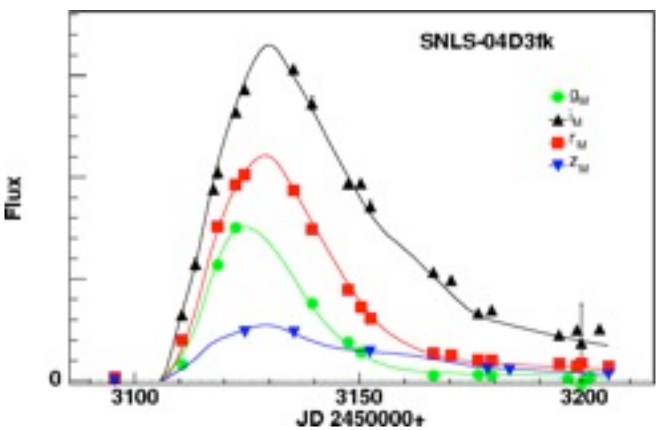
Observed Light Curves to Distances

- For the most part supernova distances determined from their multi-band light curves
  - Quality of spectra poor



μ

Observed Light Curves to Distances

- For the most part supernova distances determined from their multi-band light curves
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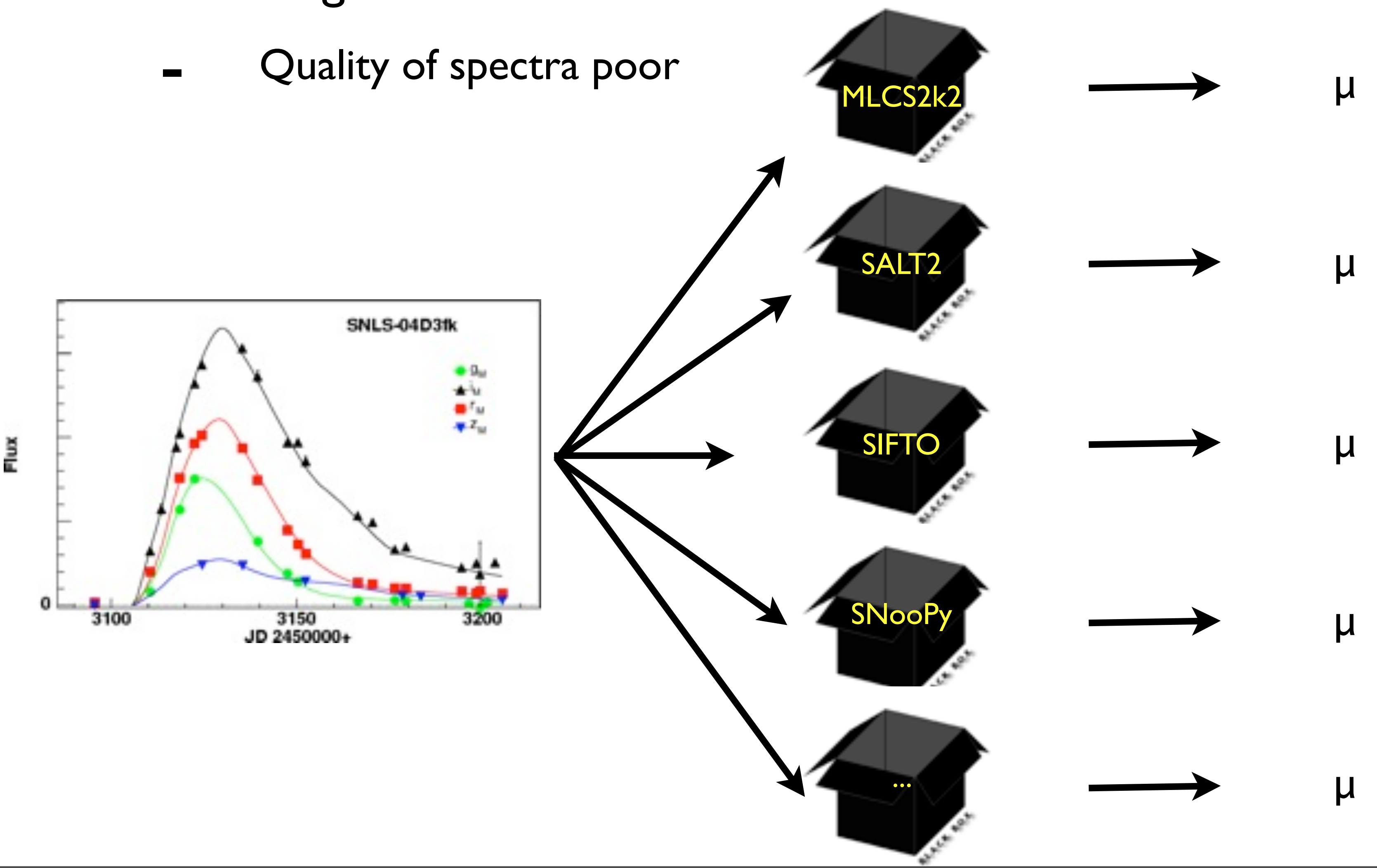
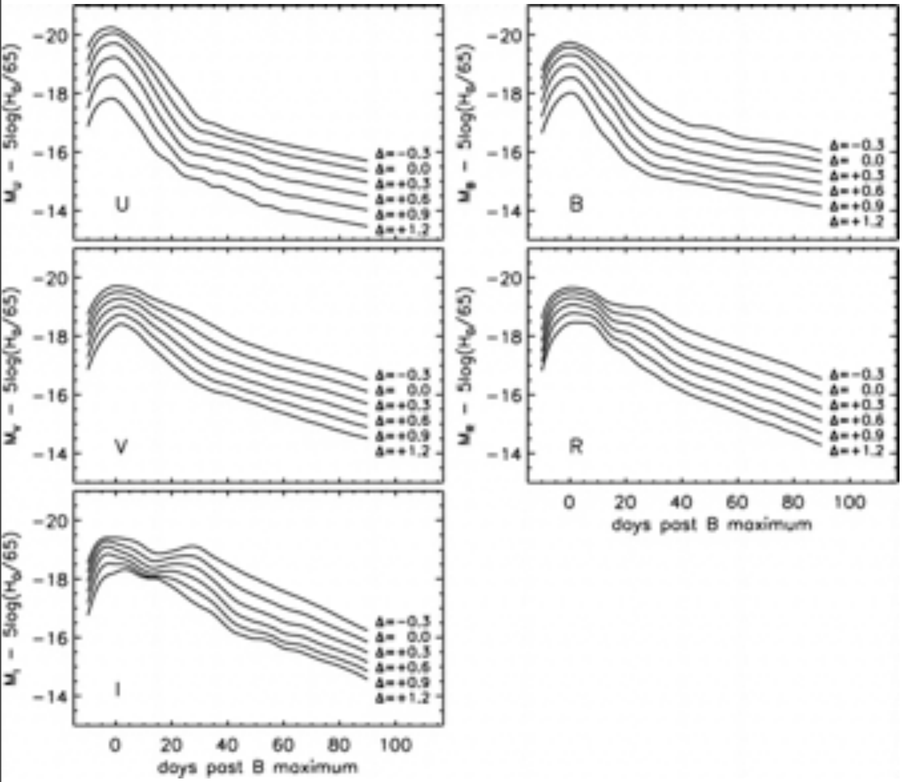


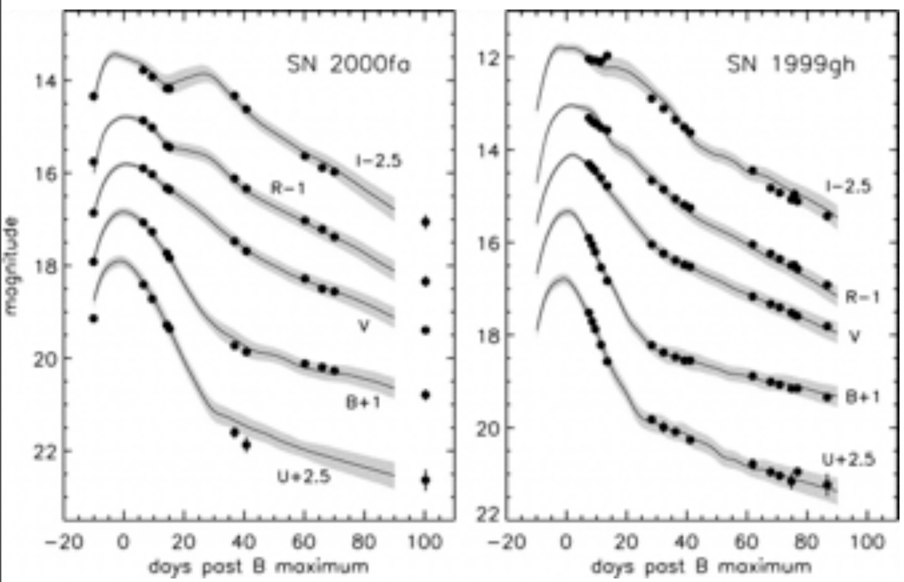
MLCS2k2/SALT2 Comparison

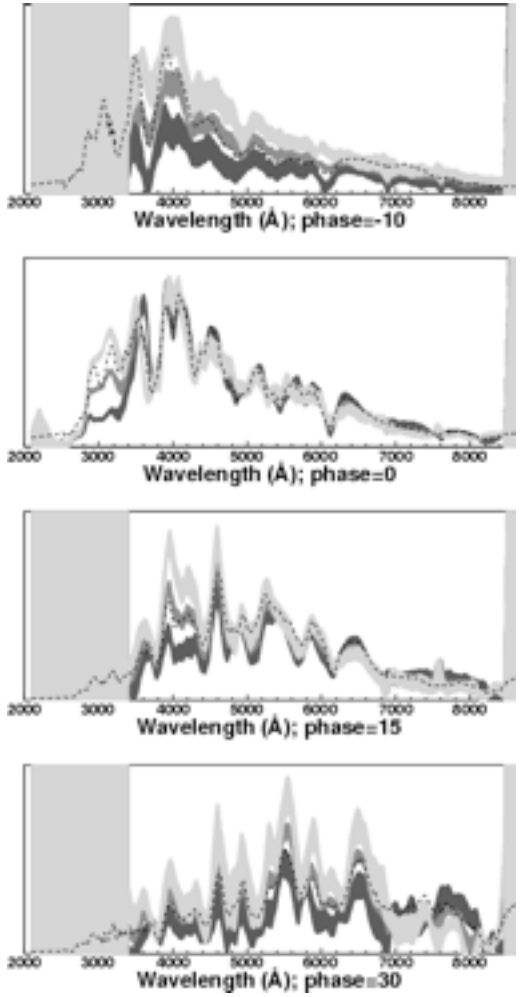
	MLCS2k2	SALT2
Data Model	$\mathbf{m}_X = \mathbf{M}^0_X + \mu_0 + \eta_X \left(\alpha_X + \frac{\beta_X}{R_V}\right) A^0_V$ $+\mathbf{P}_X \Delta + \mathbf{Q}_X \Delta^2$	$F(p,\lambda) = x_0 \left[M_0(p,\lambda) + x_1 M_1(p,\lambda)\right]$ $\times e^{cCL(\lambda)}$
Data Parameters	$\mu_0,\ A^0_V,\ \Delta$	$x_0,\ x_1,\ c$
Data Templates	$\mathbf{M}^0(\lambda),\ \mathbf{P}(\lambda),\ \mathbf{Q}(\lambda)$, covariance	$M_0,\ M_1,\ CL$, covariance
Distance	μ_0	$-2.5\log x_0 + m_0 - M + \alpha_x x_1 - \beta c$
Distance Parameters		$\alpha_x,\ \beta$

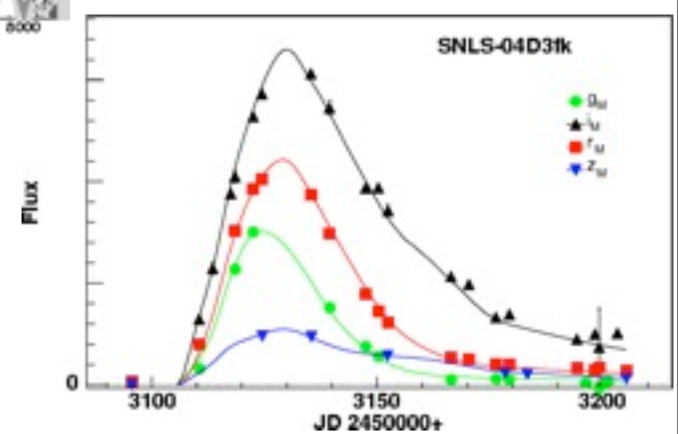
- 3 Data Model Parameters
  - Normalization (μ_0, x_0)
  - Light-curve Shape (Δ,x_1)
  - Color (A_V^0, c)
- Color
  - MLCS2k2
    - Dust attenuation law η
    - Incorporates a prior on A_V^0
  - SALT2: Trained template CL
- Data templates and covariance built using training set
- SALT2 determines distances in two-steps
  - α_x, β, M fit with cosmology
  - Inherently Bayesian
- Magnitude vs flux space

MLCS and SALT2









Statistics: Frequentist vs. Bayesian

- Frequentist
  - Likelihood a compact way of summarizing experimental measurements given a model for expected observations
  - Confidence limits represent experimental fluctuations
  - Important for sharing experimental results
- Bayesian
  - Posterior give the probabilities of model parameters given observations
  - Important for sharing conclusions on based on experimental results
- All supernova cosmology results in the literature are from Bayesian analysis
  - Keep this in mind when interpreting and manipulating SN results
  - There is an impetus to also provide frequentist results

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Source of the Accelerating Universe: Your Opinion

- 4-d General Relativity doesn't describe the Universe
- Previously unknown form of matter with negative equation of state (dark energy)
- Cosmological constant

Hans von Osten

Hans von Osten

- Famous early 20th century mathematician
- Performed addition, subtraction, fractions, square roots
- Spelled German

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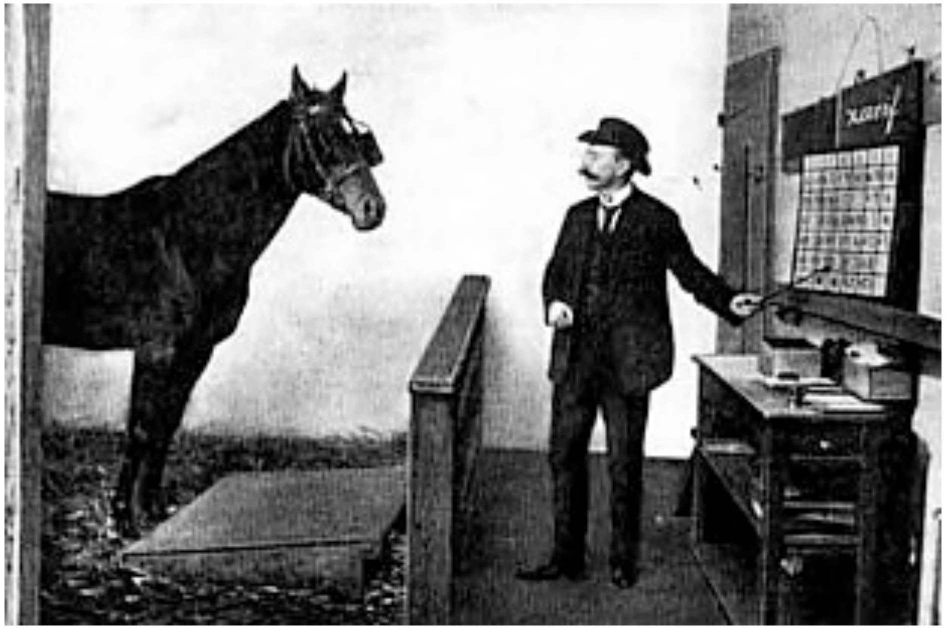
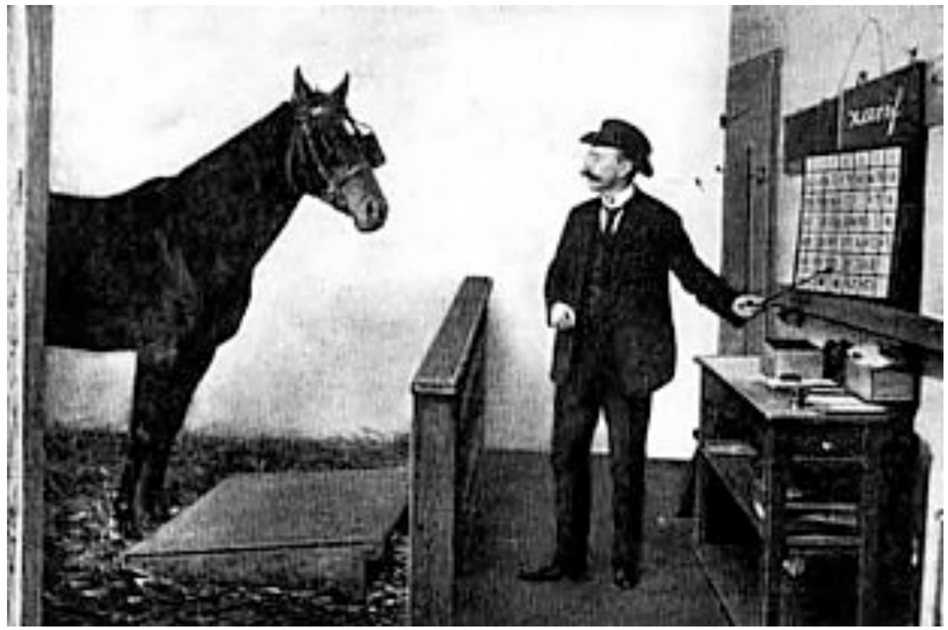


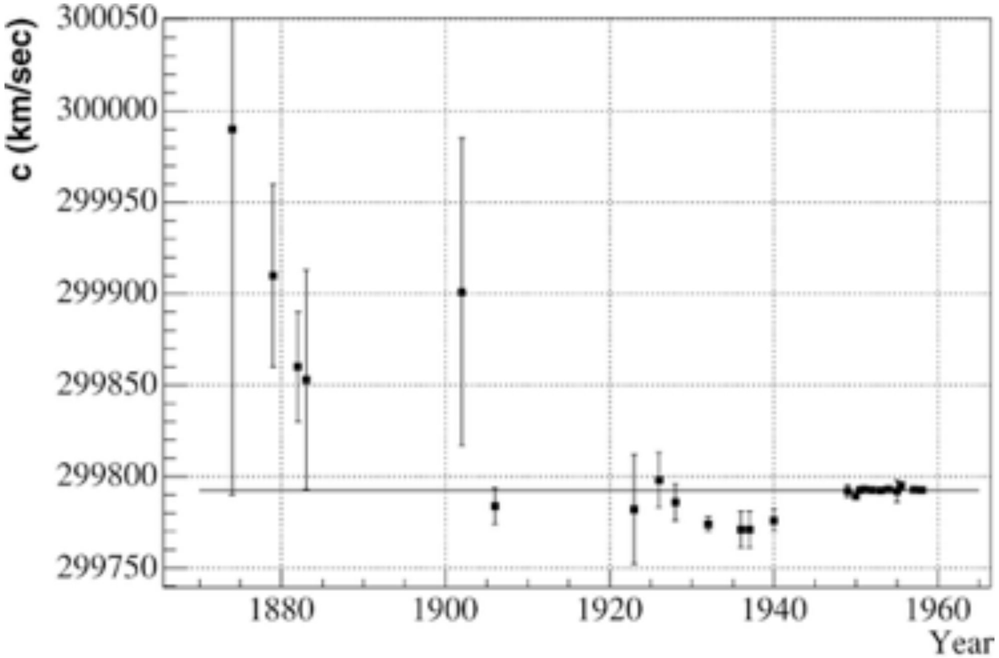
Hans von Osten

- Famous early 20th century mathematician
- Performed addition, subtraction, fractions, square roots
- Spelled German
- Investigation by the Prussian Minister of Education and the director of the Natural History Museum found no evidence of fraud



Clever Hans Explained

- Subsequent tests by Oskar Pfungst showed Hans performed poorly when the questioner didn't know the answer or if Hans couldn't see the questioner
- Hans was answering based on the involuntary reaction of human observers
- Experimenter bias can affect results

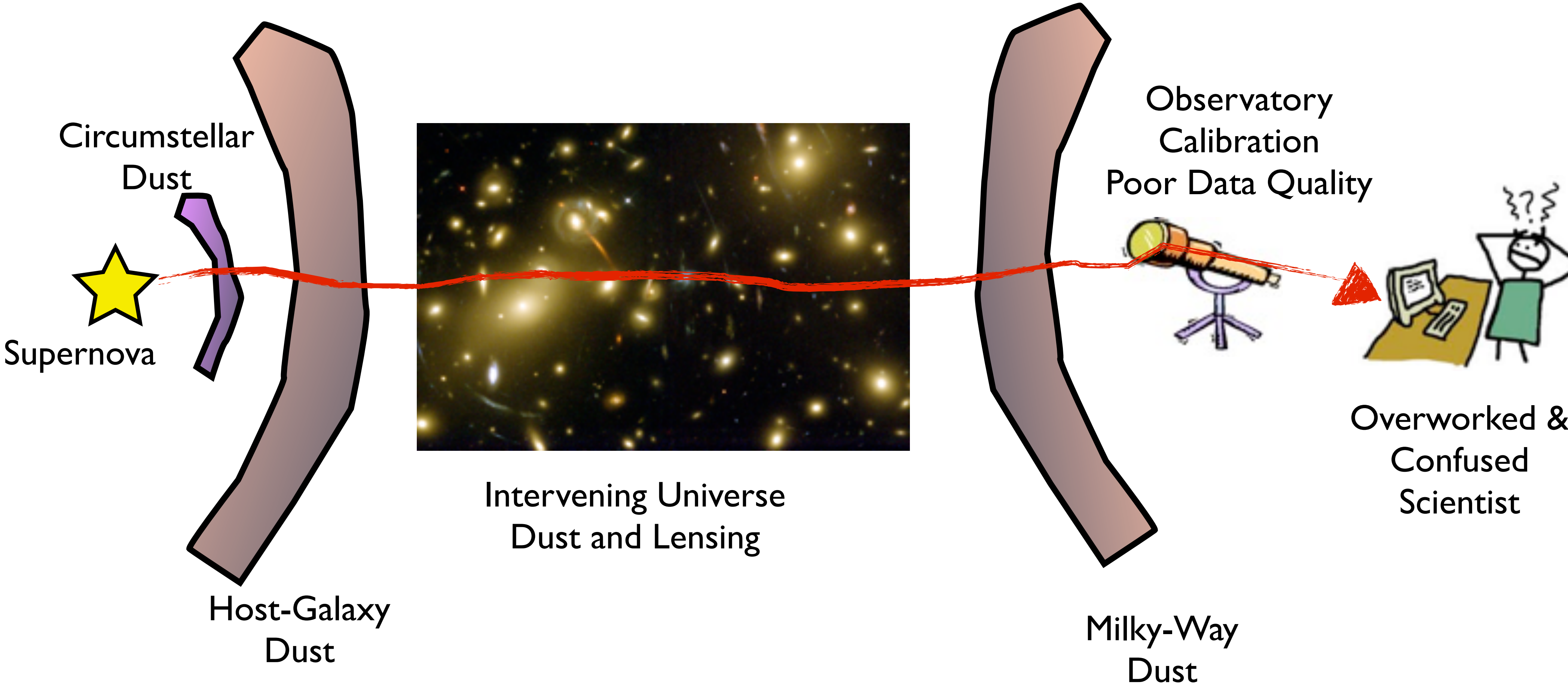


Klein JR, Roodman A. 2005.
Annu. Rev. Nucl. Part. Sci. 55:141–63

Blind Analysis

- Blind analysis is any method to hide some aspect of the data or result to prevent experimenter's bias
  - Dark energy parameters honing in on a Cosmological Constant - a special value preconceived to be good
- Blind analysis techniques for SN cosmology
  - Fit dark-energy values hidden during analysis
  - Hidden offset to magnitudes
  - Independent group decides when to unblind
  - Analysis procedure and selection criteria defined before data arrives
  - Unblinded analysis of a fraction of the data set
- Personally I find it hard to trust non-blind cosmology analysis

Sources of Systematic Uncertainty



Systematic Uncertainties in Error Budget

Table 5
Effect on constant w error bars and area of the 95% $w_0 - w_a$ confidence contour (inverse DETF FoM) for each type of systematic error, when SN Ia constraints are combined with constraints from CMB, H_0, and BAO.

	Source	Error on Constant w	Inverse DETF FoM
	Vega	0.033	0.19
	All Instrument Calibration	0.030	0.18
Calibration	(ACS Zeropoints)	0.003	0.01
	(ACS Filter Shift)	0.007	0.04
	(NICMOS Zeropoints)	0.007	¡0.01
Data Quality	Malmquist Bias	0.020	0.07
SN Ignorance Circumstallar and Host Dust	Color Correction	0.020	0.07
SN Ignorance	Mass Correction	0.016	0.08
Data Quality	Contamination	0.016	0.05
Intergalactic Astrophysics	Intergalactic Extinction	0.013	0.03
Milky Way	Galactic Extinction Normalization	0.010	0.01
	Rest-Frame U-Band Calibration	0.009	¡0.01
SN Ignorance	Lightcurve Shape	0.006	¡0.01
	Quadrature Sum of Errors/ Sum of Area (not used)	*0.061*	*0.68*
	Summed in Covariance Matrix	0.048	0.42

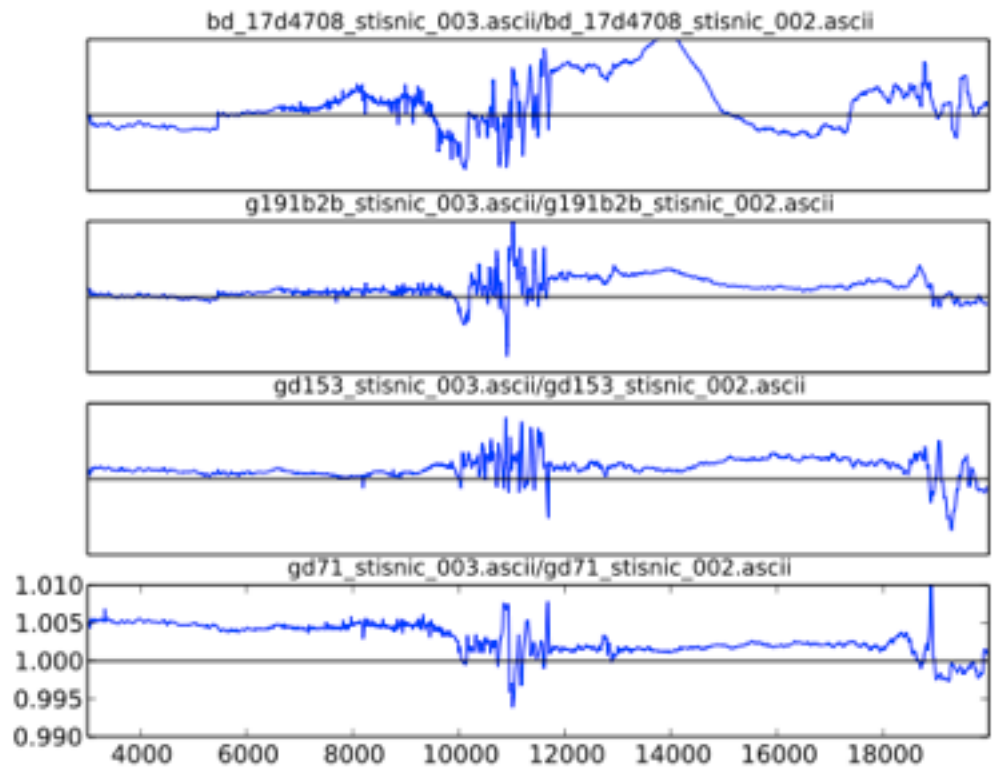
Suzuki et al. (2011)

Sources of Calibration Uncertainty

- Primary calibrator
  - Astronomical source with known flux
  - Best stars have flux in physical units known to 2-3%
  - Secondary calibrators
    - Primary calibrator to bright to observe with big telescopes
    - Uncertainties propagate
- Experimental calibration
  - What happens to a photon from when it enters the atmosphere to readout
  - For every pixel as a function of wavelength

Fundamental Calibrators Measured by HST

- Ratio of calibrated flux of the same star as reported on different dates
- BD+17 the fundamental calibrator of SDSS, SNLS
- G191b, GD154, GD71 are the fundamental calibrators of HST

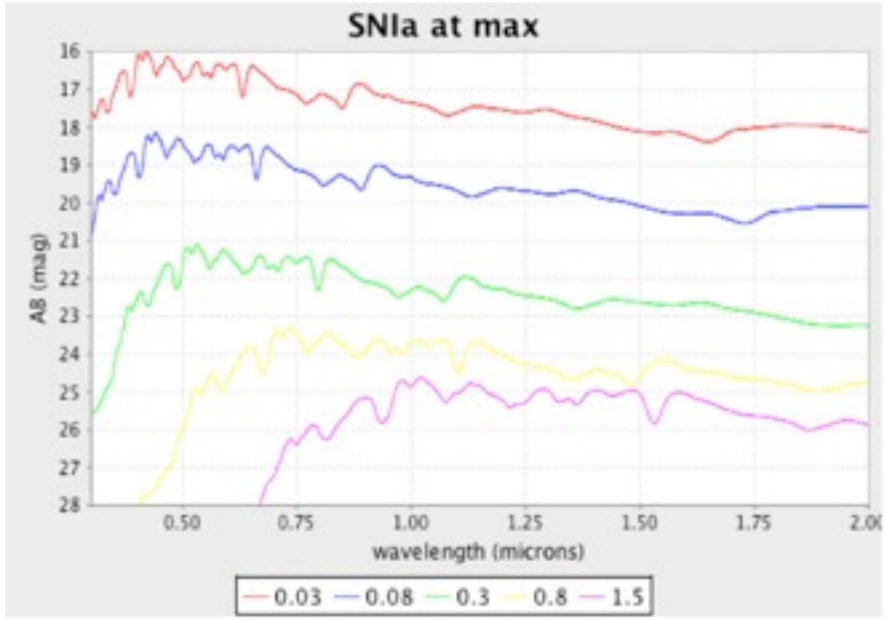


Reducing Calibration Uncertainty

- Absolute calibration
  - ACCESS
    - On a rocket to get above the atmosphere
    - Fly NIST-calibrated photodiode detectors
    - <1% color calibration uncertainty
- Observatory calibration
  - Atmospheric monitoring
  - Tunable laser calibrates the telescope

Why "Color" Calibration Is Important

- Comparing flux at the same restframe wavelength varies with redshift
- Inferred distance of a SN depends on flux at all wavelengths
  - Uncertainties enhanced by 2-4x
  - Coefficient smaller at redder wavelengths



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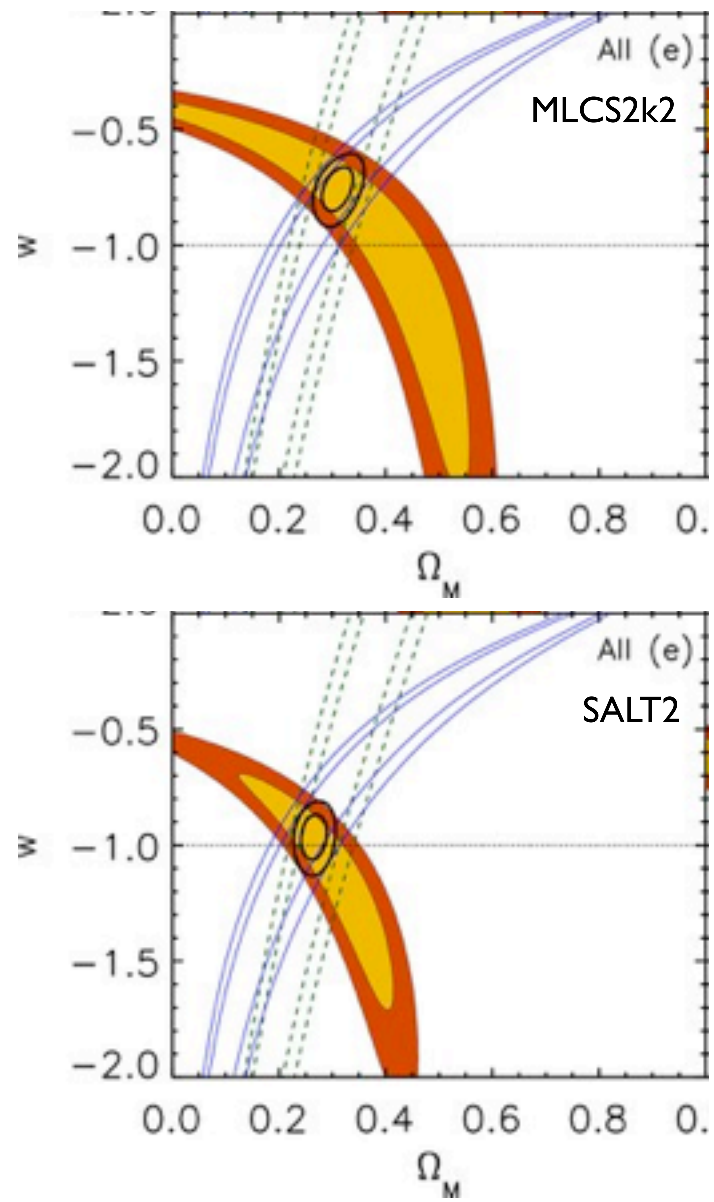
Distance	μ_0	$-2.5 \log x_0 + m_0 - M + \alpha_x x_1 - \beta c$
Distance Parameters		$\alpha_x,\ \beta$

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

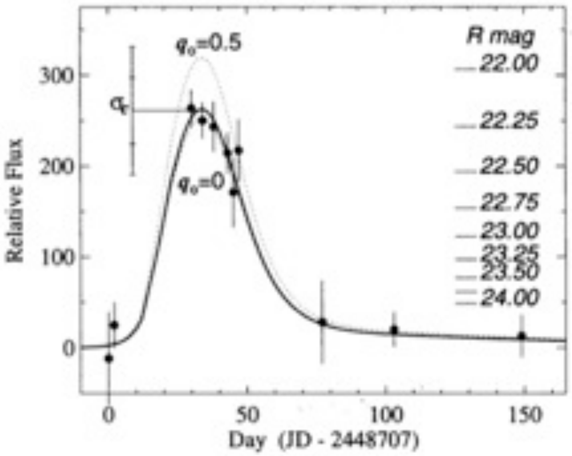
Kessler et al. (2009)



Toward a Better Light Curve Fitter

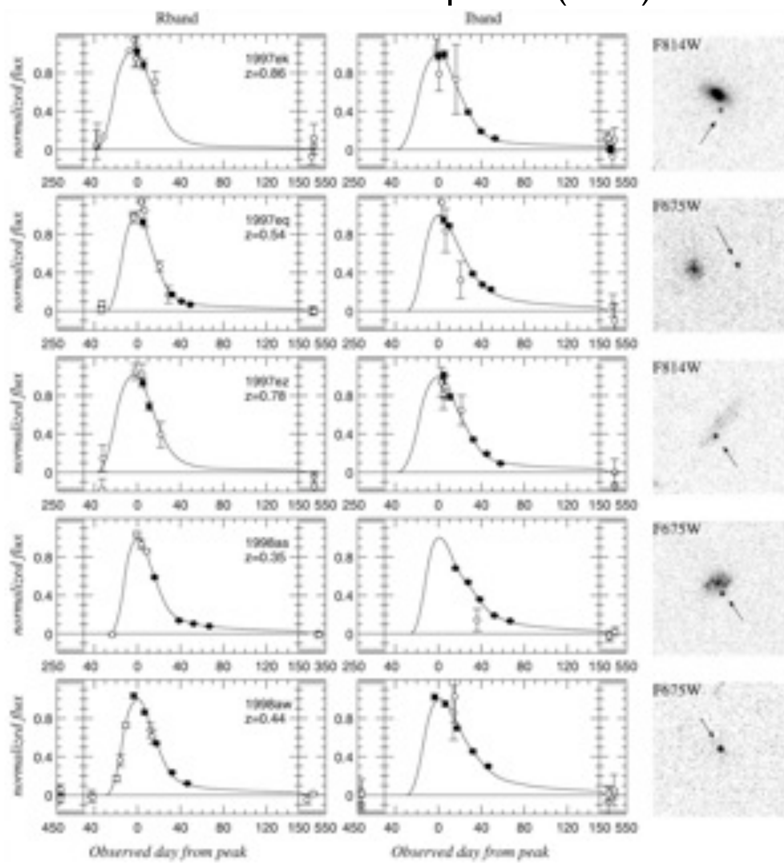
- Inconsistency between light curve fitters (mostly) comes from lack of data not a problem with SNe Ia
- New datasets with excellent time and wavelength coverage are coming available
- Simultaneous training and cosmological parameters
  - Naturally propagate model uncertainties into cosmological error budget
  - Likelihood

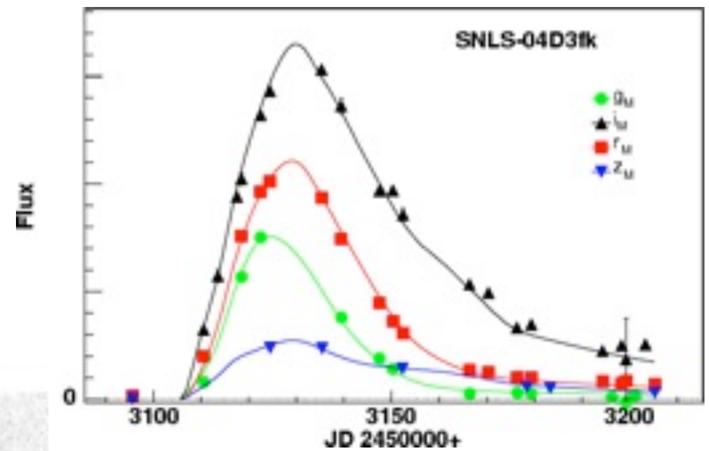
Improvement in Per SN Data



Perlmutter et al. (1995)

Knop et al. (2003)

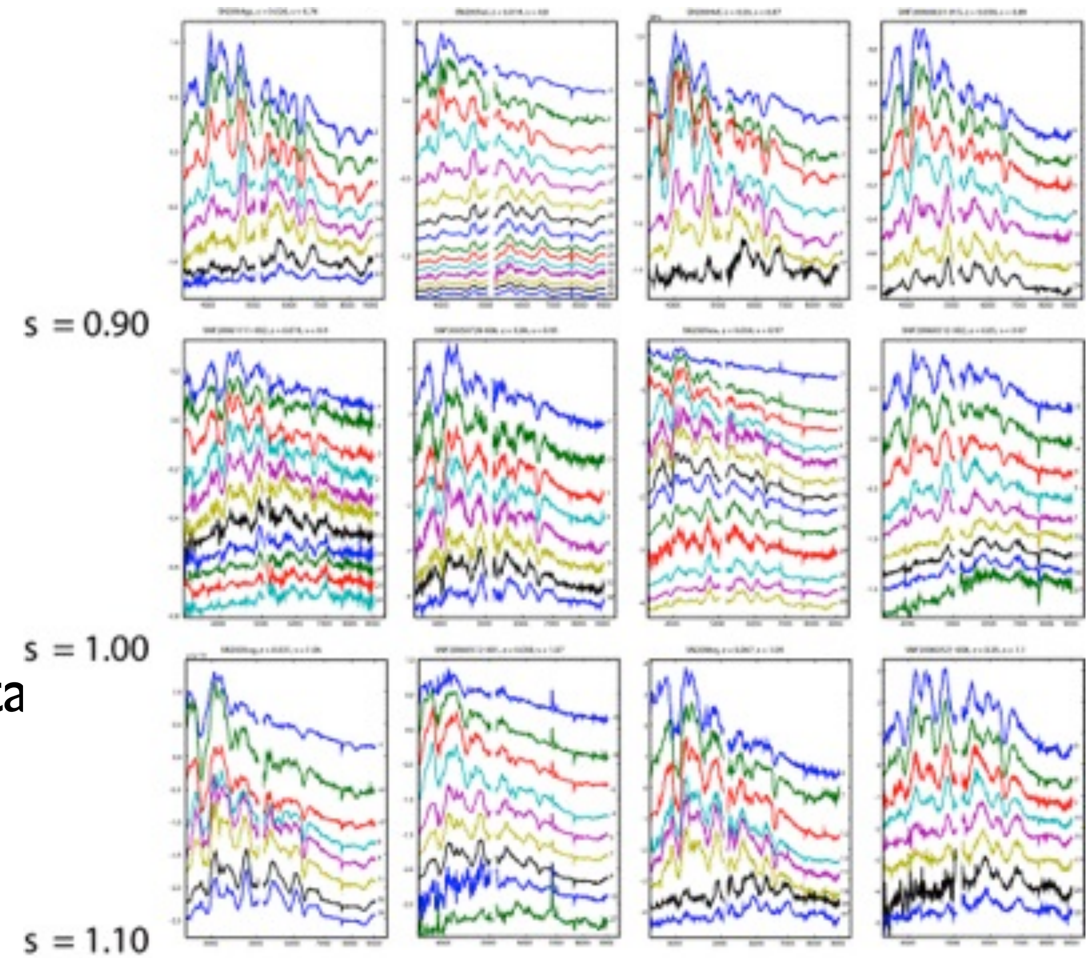




Astier et al. (2006)

Modern SN Data Set

- With better quality data comes better quality distances
- Supersedes previous SN data

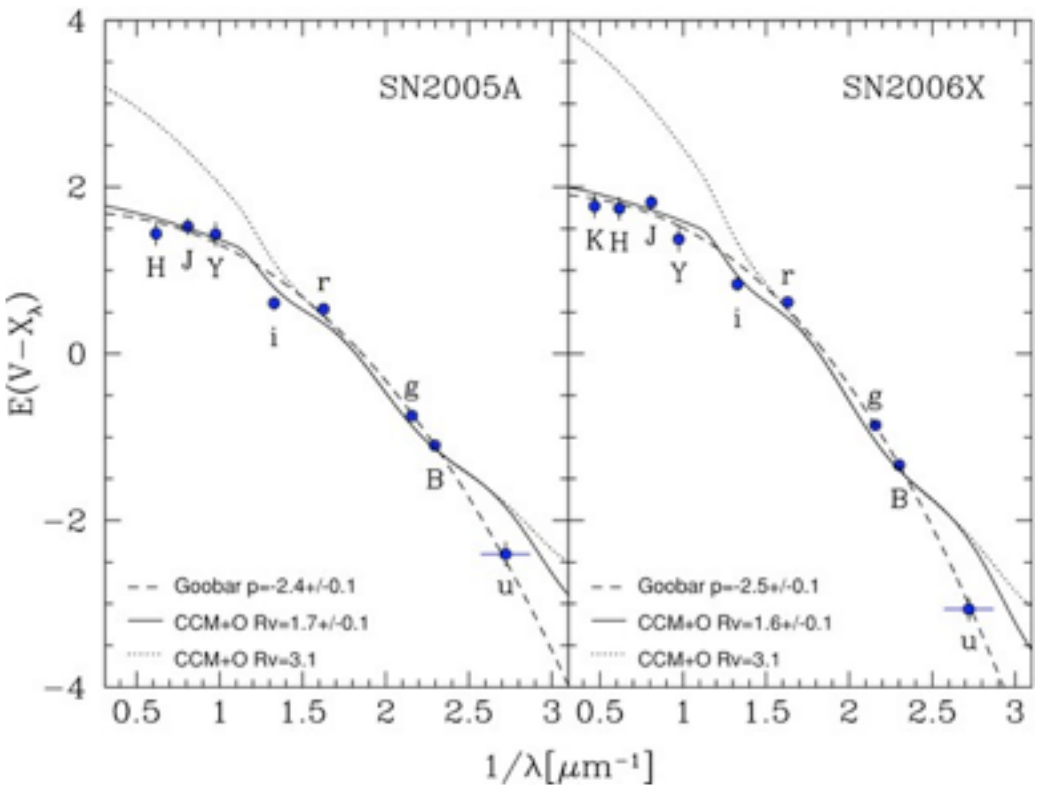


Aldering et al. (2010)

Color Correction Systematics

- Various interpretations of color variations
  - Interstellar dust
    - Milky Way-like
    - non-Milky Way-like
  - Circumstellar dust
  - Intrinsic color variation
    - e.g. from Viewing angle
- Interpretation affects magnitude correction

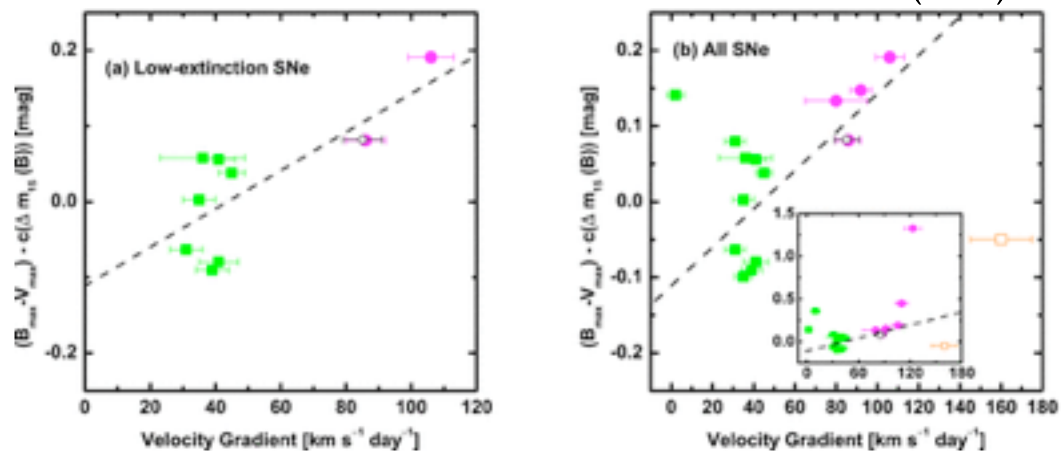
Folatelli et al. (2010)

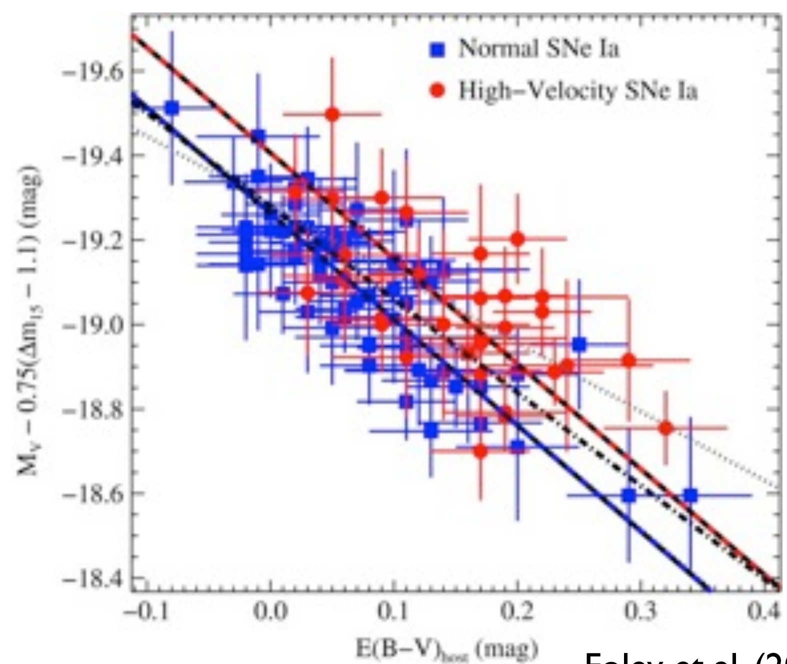


Spectra Contain Intrinsic Magnitude/Color Information

- Split SN set into those with normal versus high-velocity SiII6355 spectral feature
- Color-Luminosity shows similar slope but different intercept
- Different intrinsic color

Maeda et al. (2010)



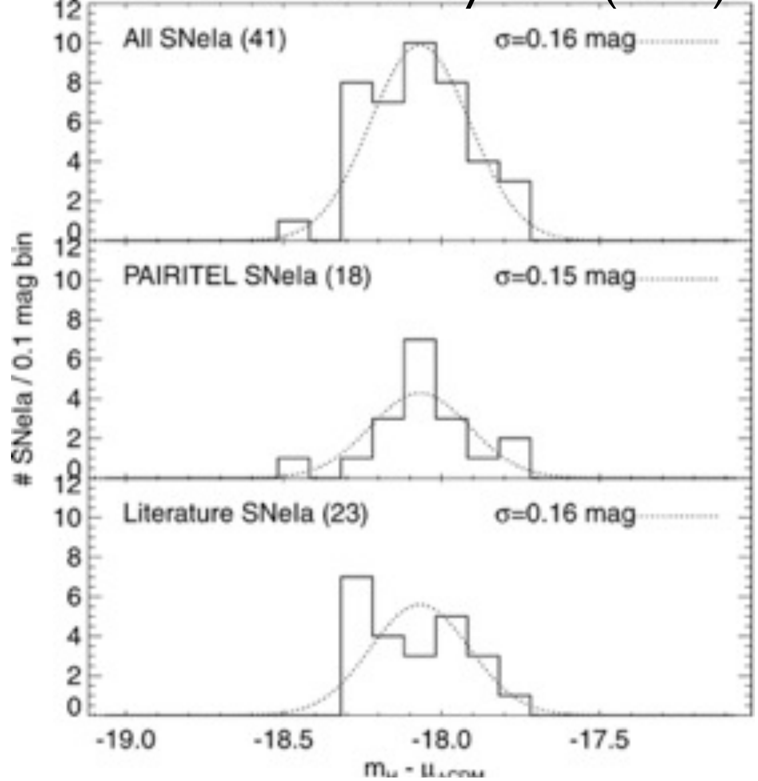


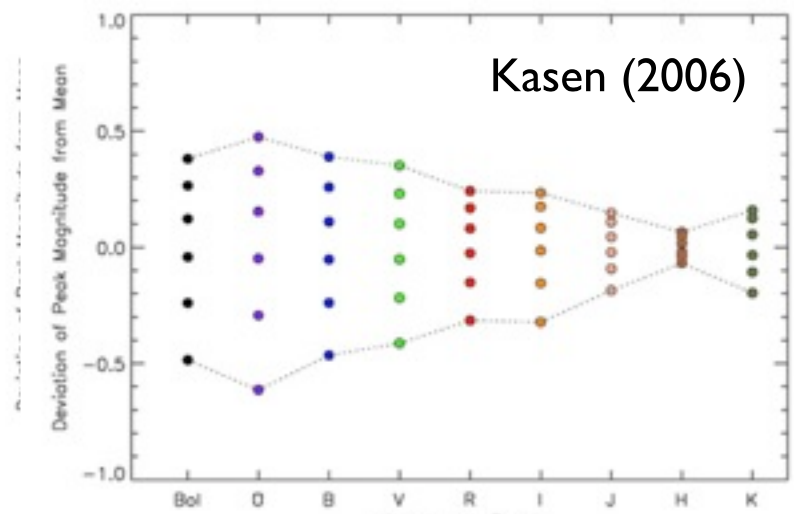
Foley et al. (2011)

Near-Infrared: Another Window

- SNe are observed to have ~0.15 absolute magnitude dispersion in the NIR with no light curve or dust corrections
- Less susceptible to dust extinction
- Small dispersion in the NIR also seen in SN explosion models

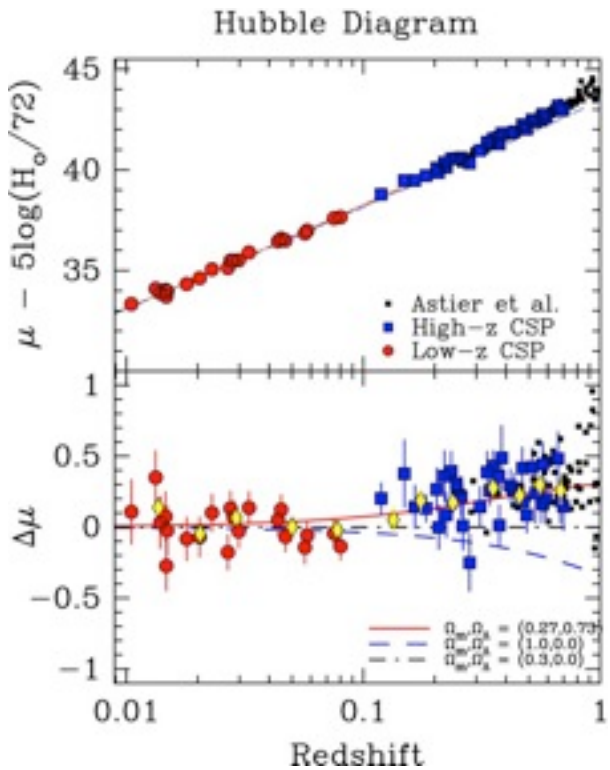
Wood-Vasey et al. (2008)

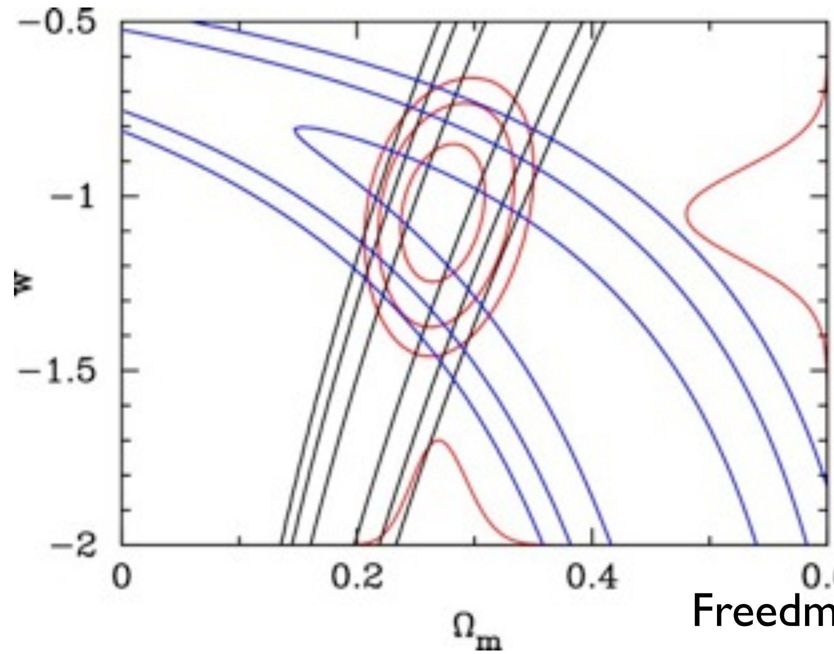




NIR Hubble Diagram

- Carnegie Supernova Project
- I-band Hubble diagram with 21 + 35 SNe Ia
- Magellan (6.5-m) used out to z=0.65

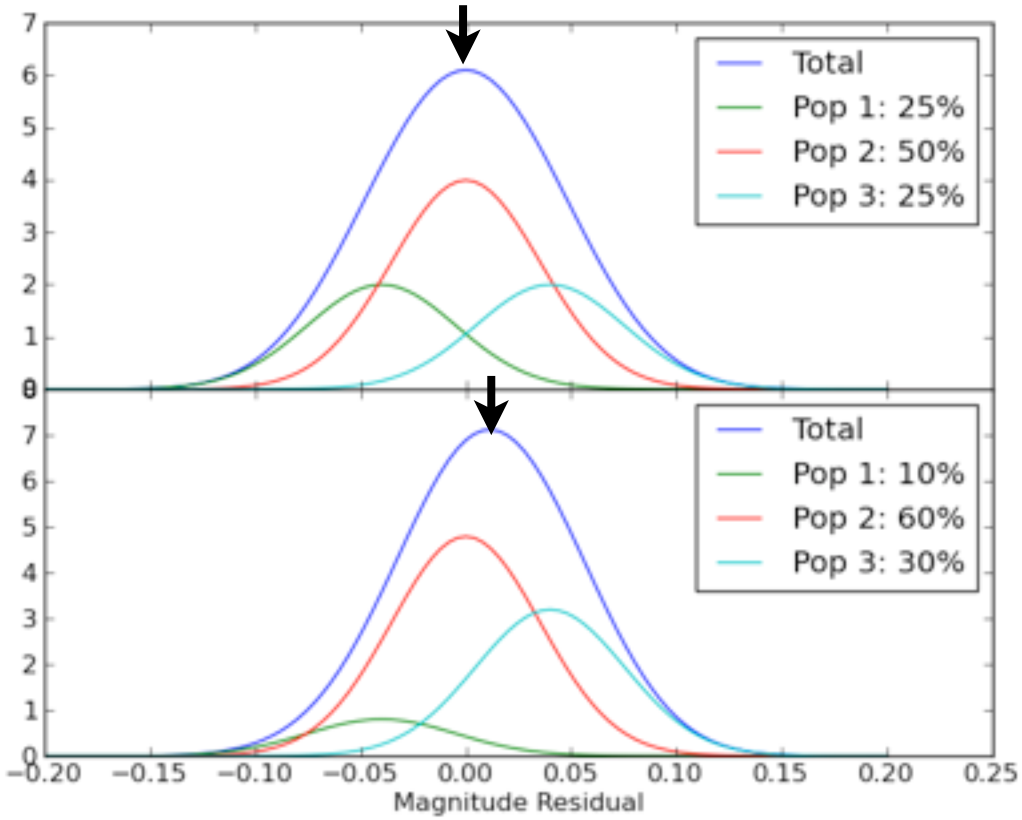




Freedman (2009)

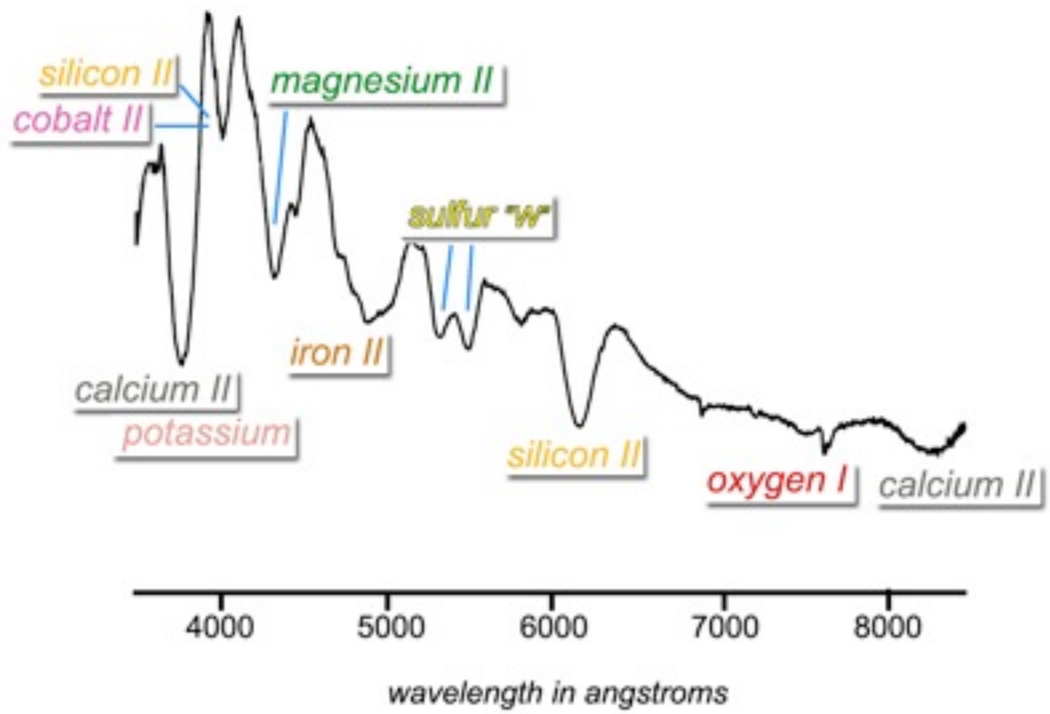
Supernova "Evolution" Systematic

- After corrections there remains a ~0.12 mag residual scatter in brightness
- Could be intrinsic dispersion
    - e.g. random viewing angle
- Could be from unidentified subpopulations
    - If relative distribution of subpopulations vary can cause bias in the Hubble Diagram
- Solved by identifying subpopulations



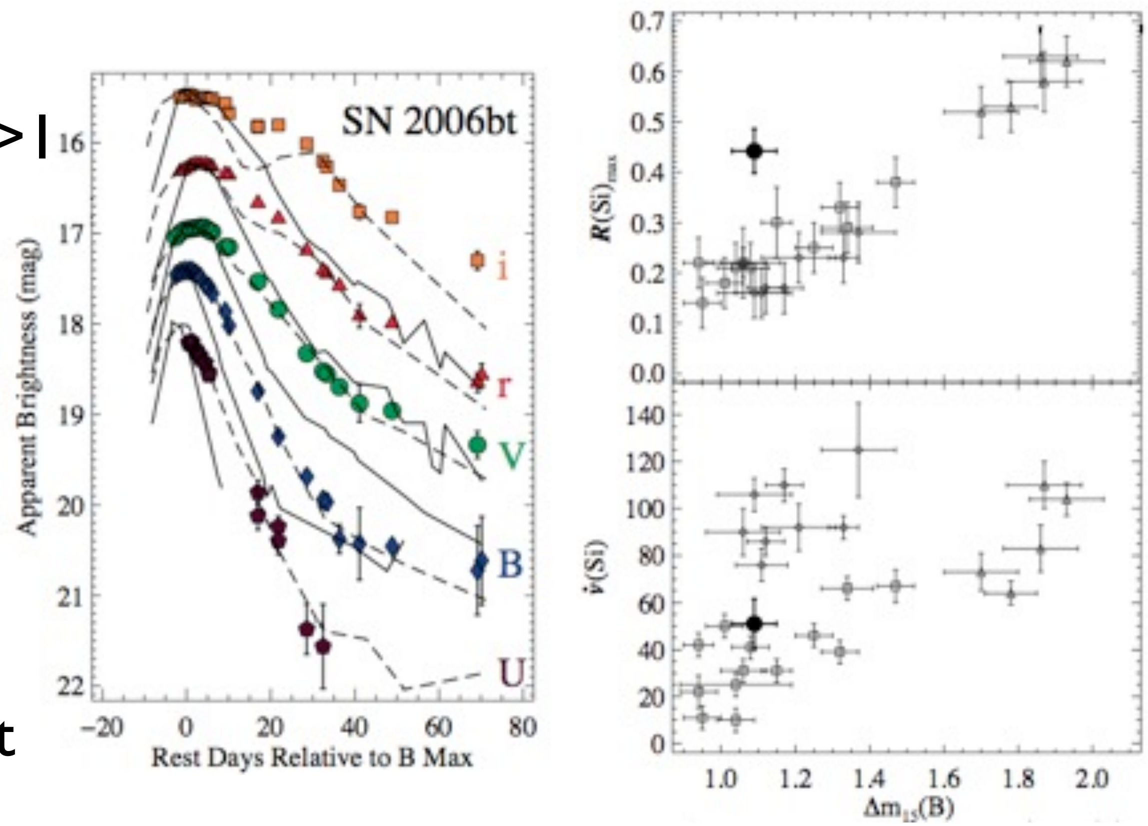
Spectroscopic Subclassifcation

- SNIa subclasses (heterogeneity) observed at low-z
- Heterogeneity may affect determination of distances
- Tracers seen in spectrum but not light curves



Light Curve Shape Doesn't Contain Spectrum Info?

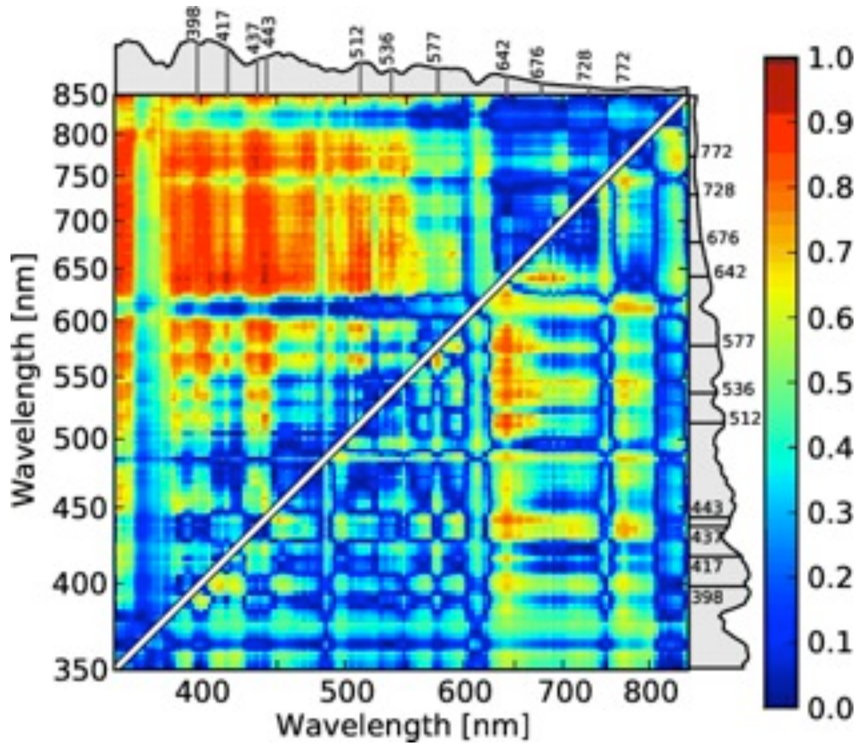
- SN2006bt z=0.032
- Optical light curves consistent with reddened s>1 SN
- Both MLCS and SALT2 give happy fits
- Outskirts of S0 galaxy
- Shouldn't be reddened
- Spectroscopically consistent with s<1 SN

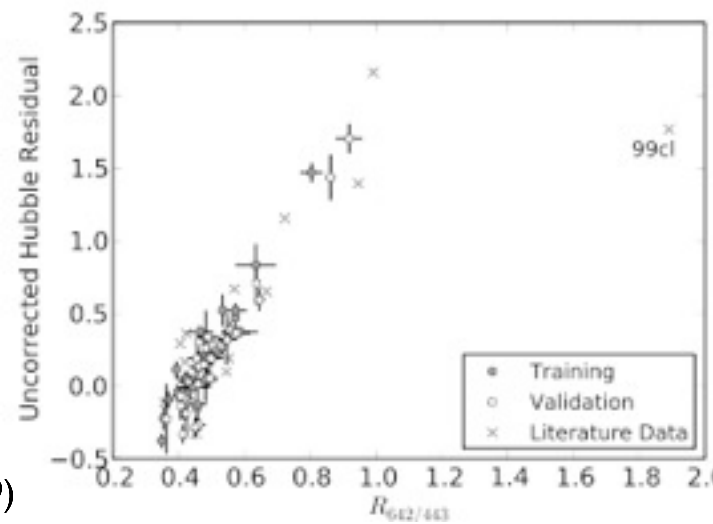


Foley et al. (2009)

Spectra Contain Intrinsic Magnitude Information

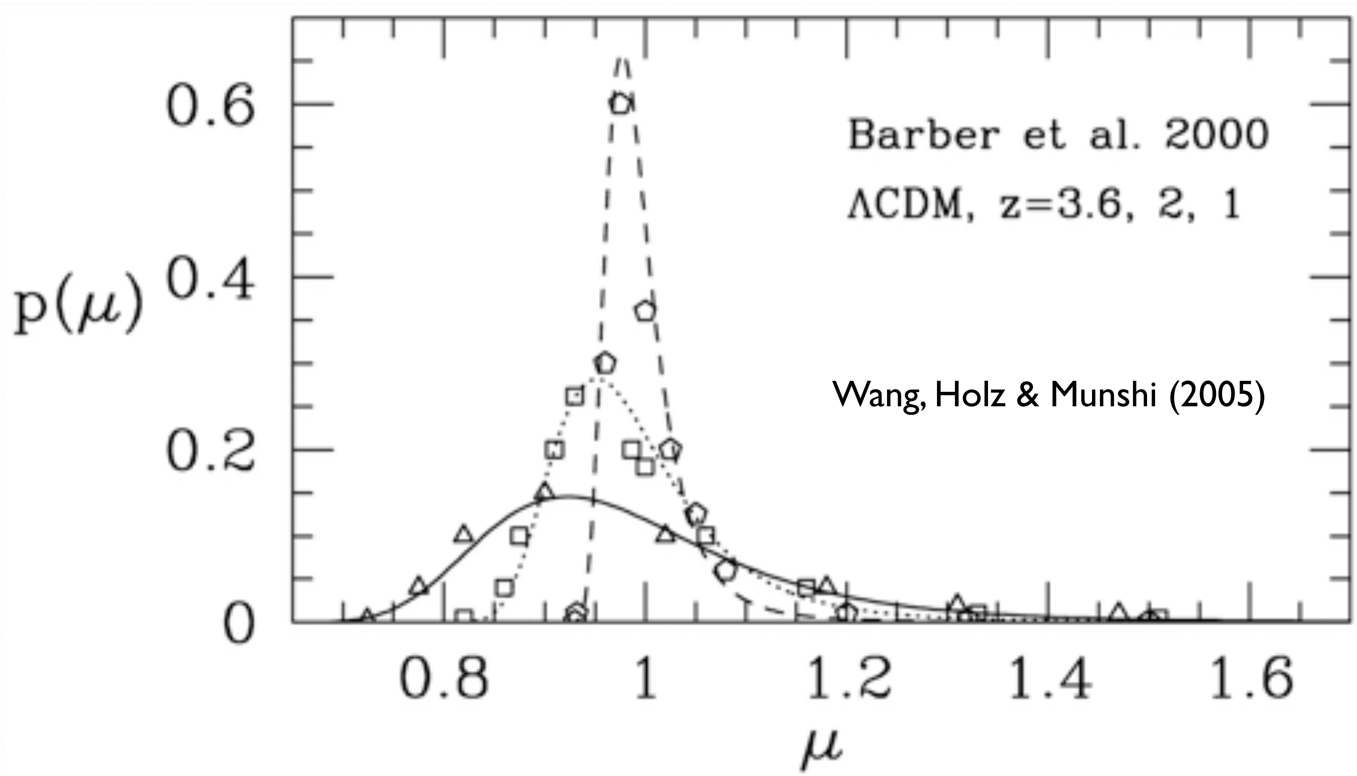
- Figure shows correlation between spectral flux ratios and absolute magnitude
- Flux ratio almost linearly related to absolute magnitude
- More information than is in shape





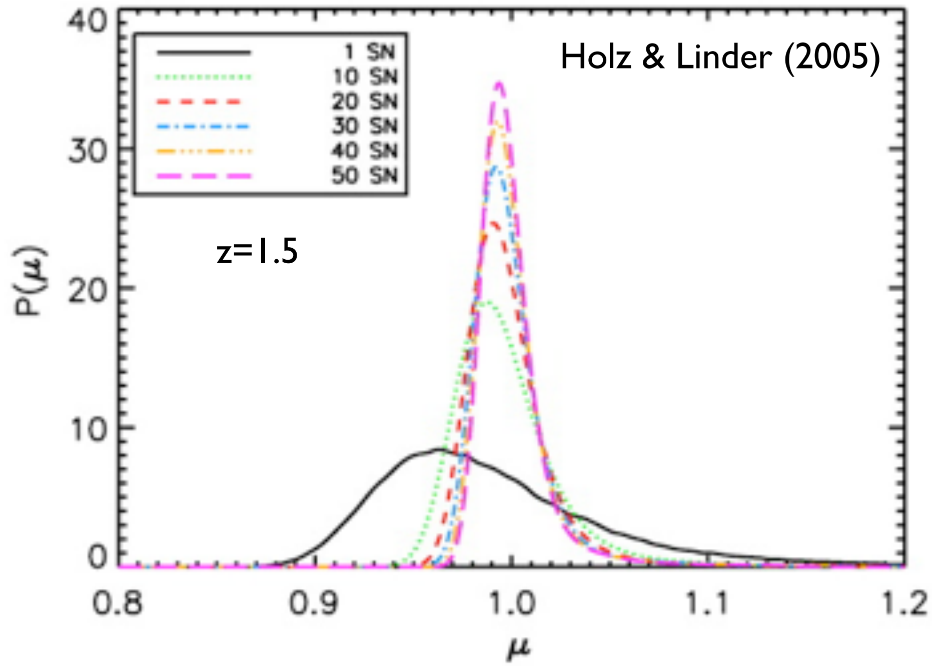
Bailey et al. (2009)

Gravitational Lensing Systematic

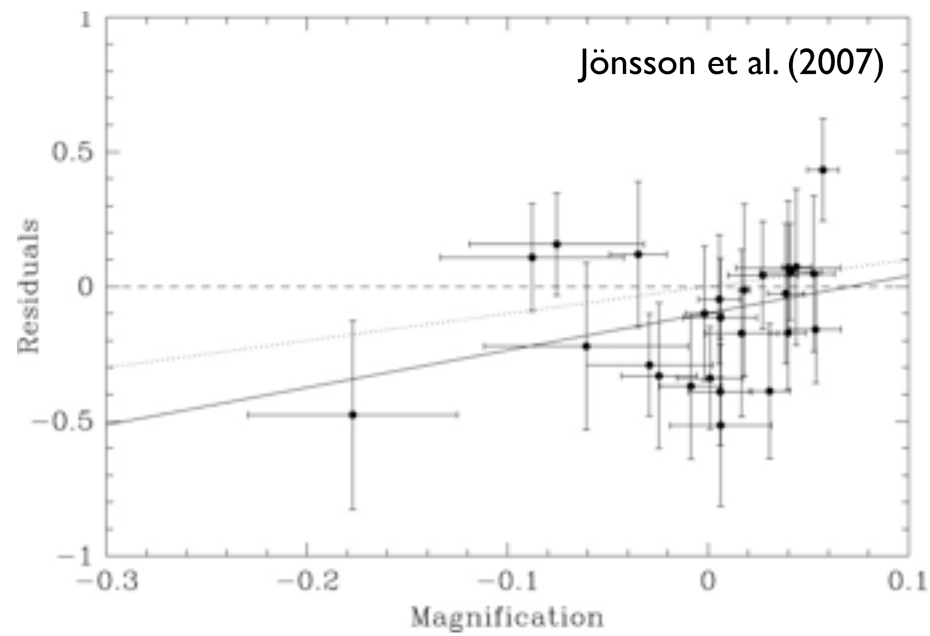


- Inhomogeneous universe (de)magnifies SNe
  - Magnification probability distribution non-Gaussian distribution with demagnified mode
  - No mean magnification on average
  - Distribution depends strongly on redshift

Correcting For Gravitational Lensing



- Supernovae come from independent lines of sight
  - The distribution of the average magnification of many SNe is tightly peaked and close to Gaussian
- Estimate lensing magnification from field galaxies



Measured Signal

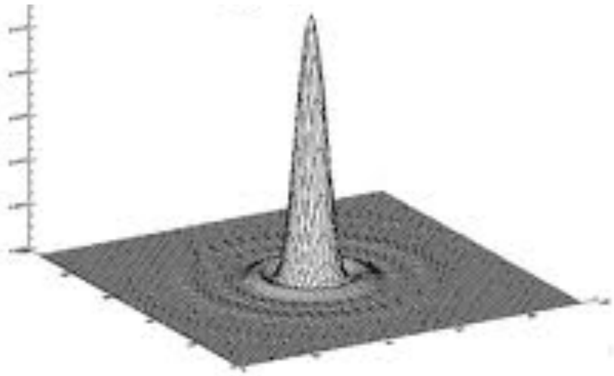
- Sampling a potential systematic particularly relevant to space telescopes
- The expected signal from a detector in a single pointing is

$$I(x,y) = |Object * PSF * Pixel| \text{Ш}\left(\frac{x}{a}, \frac{y}{a}\right)$$

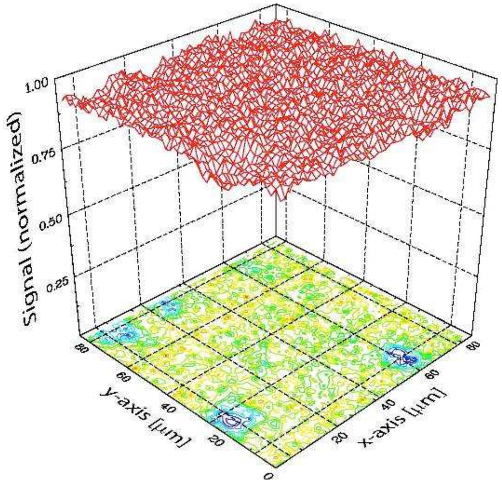
$$\text{Ш}(u,v) = \sum_{i=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \delta(u-i)\delta(v-j)$$

$$a \equiv \text{Pixel size}$$

$*$



$*$

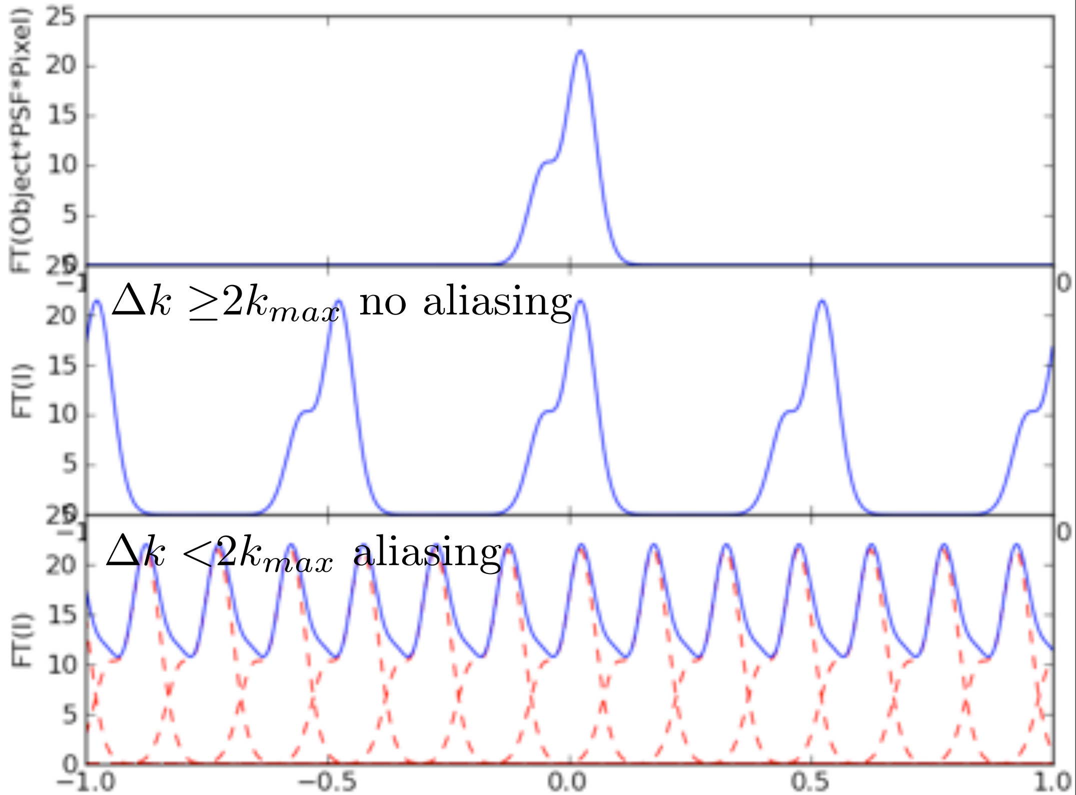


Measured Signal in Fourier Space: Critical Sampling

- Fourier transform of the signal is

$$\tilde{I}(k) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \widetilde{Object}\widetilde{PSF}\widetilde{Pixel}(k_x + m\Delta k, k_y + n\Delta k)$$

$$\Delta k \equiv \frac{2\pi}{a}$$



- When aliased ($\Delta k < 2k_{max}$) the signal:
  - Does not unambiguously give the surface brightness of a galaxy
  - Sometimes determines the flux of a SN if the PSF and Pixel are known
- Dithering a solution: uniform dxd dither pattern is

$$I(x,y) = |Object * PSF * Pixel| Ш\left(\frac{dx}{a}, \frac{dy}{a}\right)$$

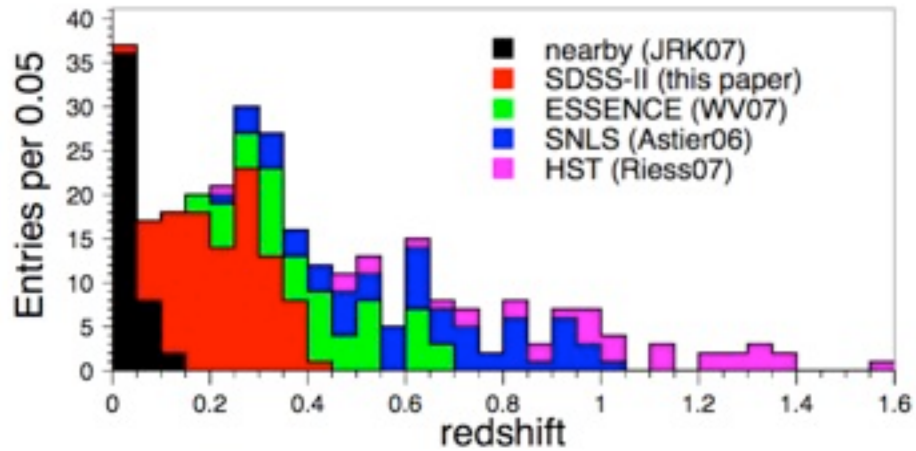
Outline

- Why SN cosmology is relevant
- Standard candles as a cosmological probe
- What observational resources are used to discover and measure SNe Ia
- SNIa: What we see and what we infer they are
- Type Ia homogeneity with slight heterogeneity
- Inferring SN Ia distances from measurements
- Systematic uncertainties
- Existing SN Ia sample used for cosmology
- Ongoing and future SN Ia surveys

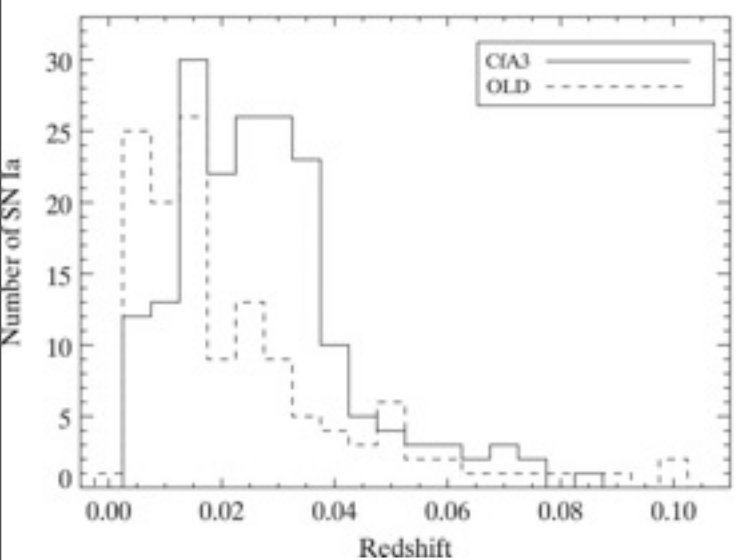
Numbers and Redshift Distribution

- $z<0.08$: ~ 400
- $z\sim0.2$: ~100 (SDSS)
- $z\sim0.5$: ~140 (Essence + SNLS)
- $z>0.8$: ~35 (HST)

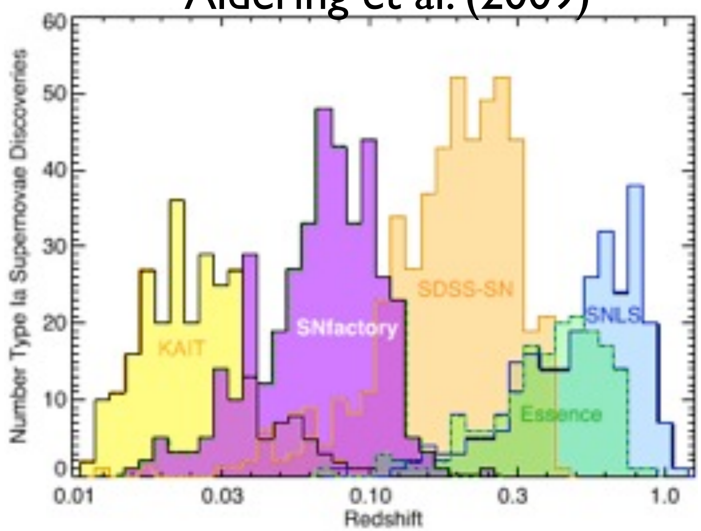
Kessler et al. (2009)



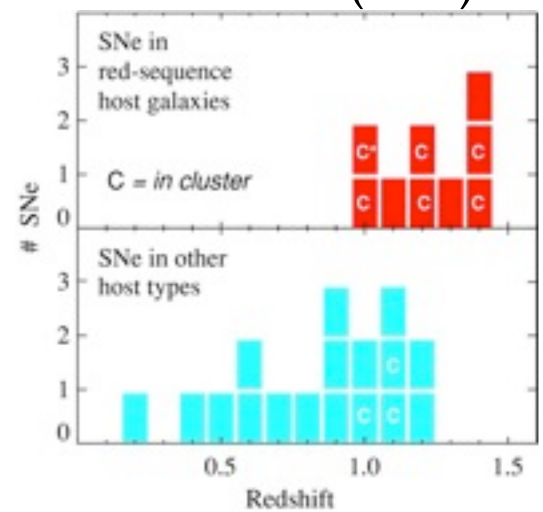
Hicken et al. (2009)



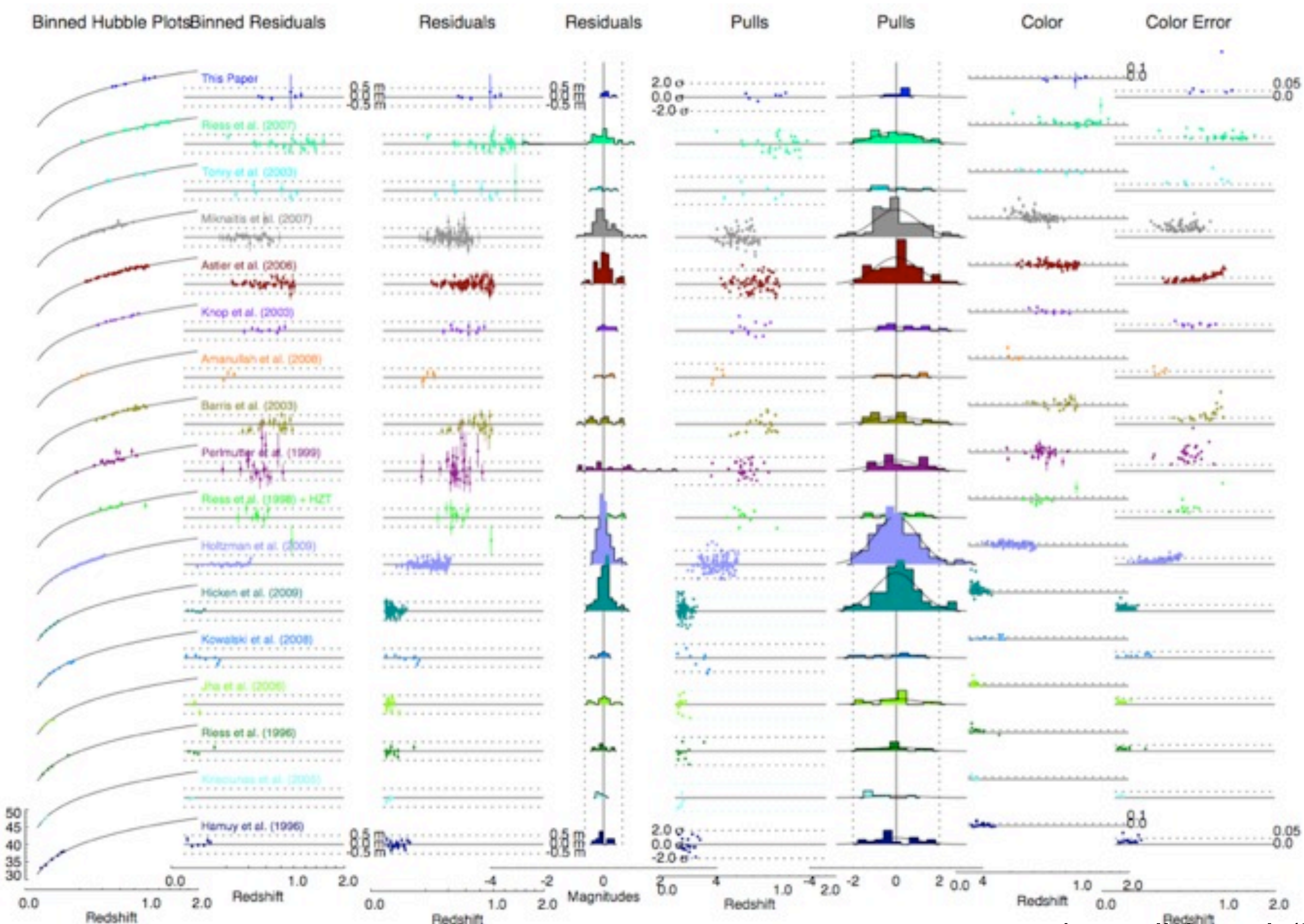
Aldering et al. (2009)



Dawson et al. (2009)



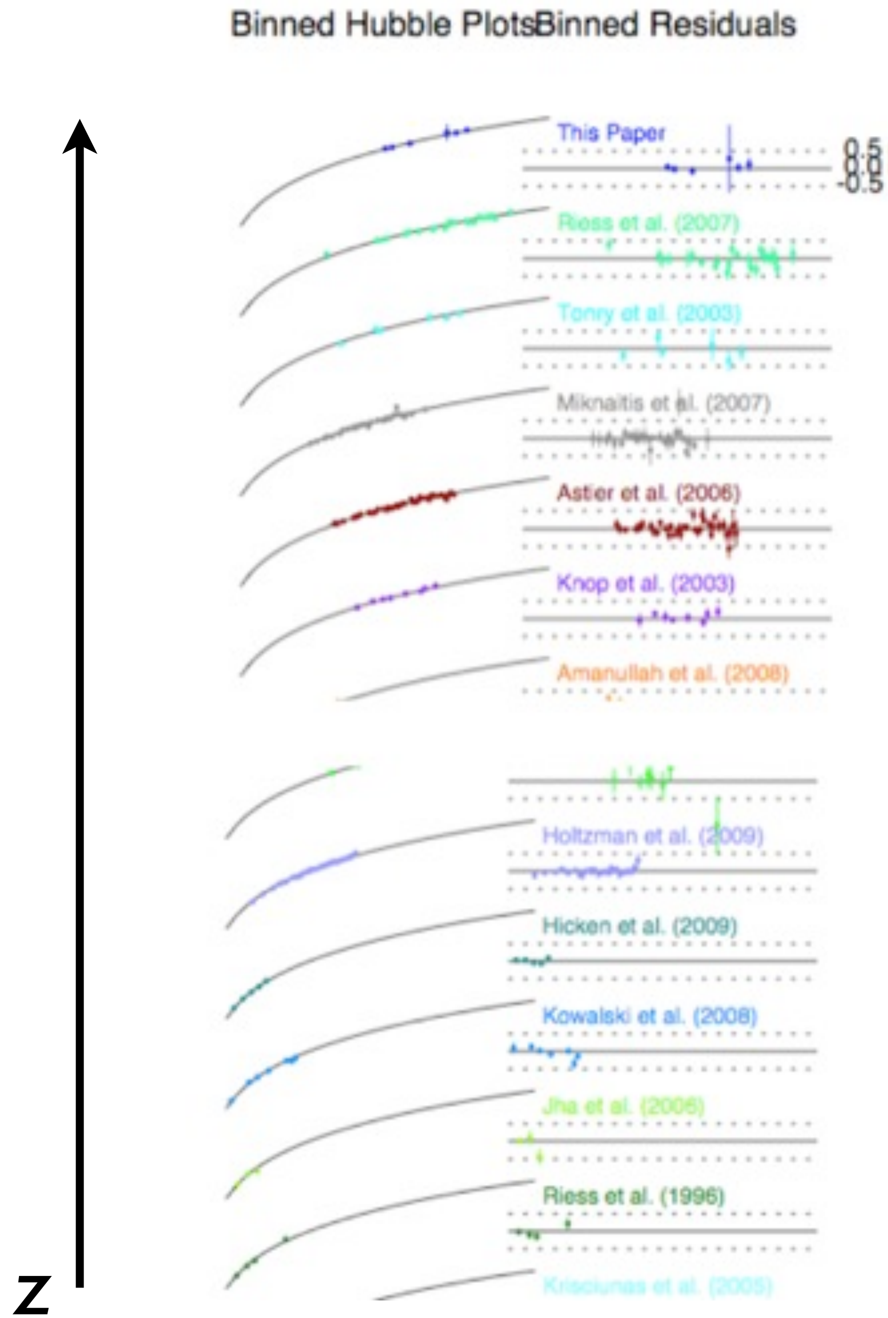
SNIa Cosmology Datasets Today



Amanullah et al. (2010)

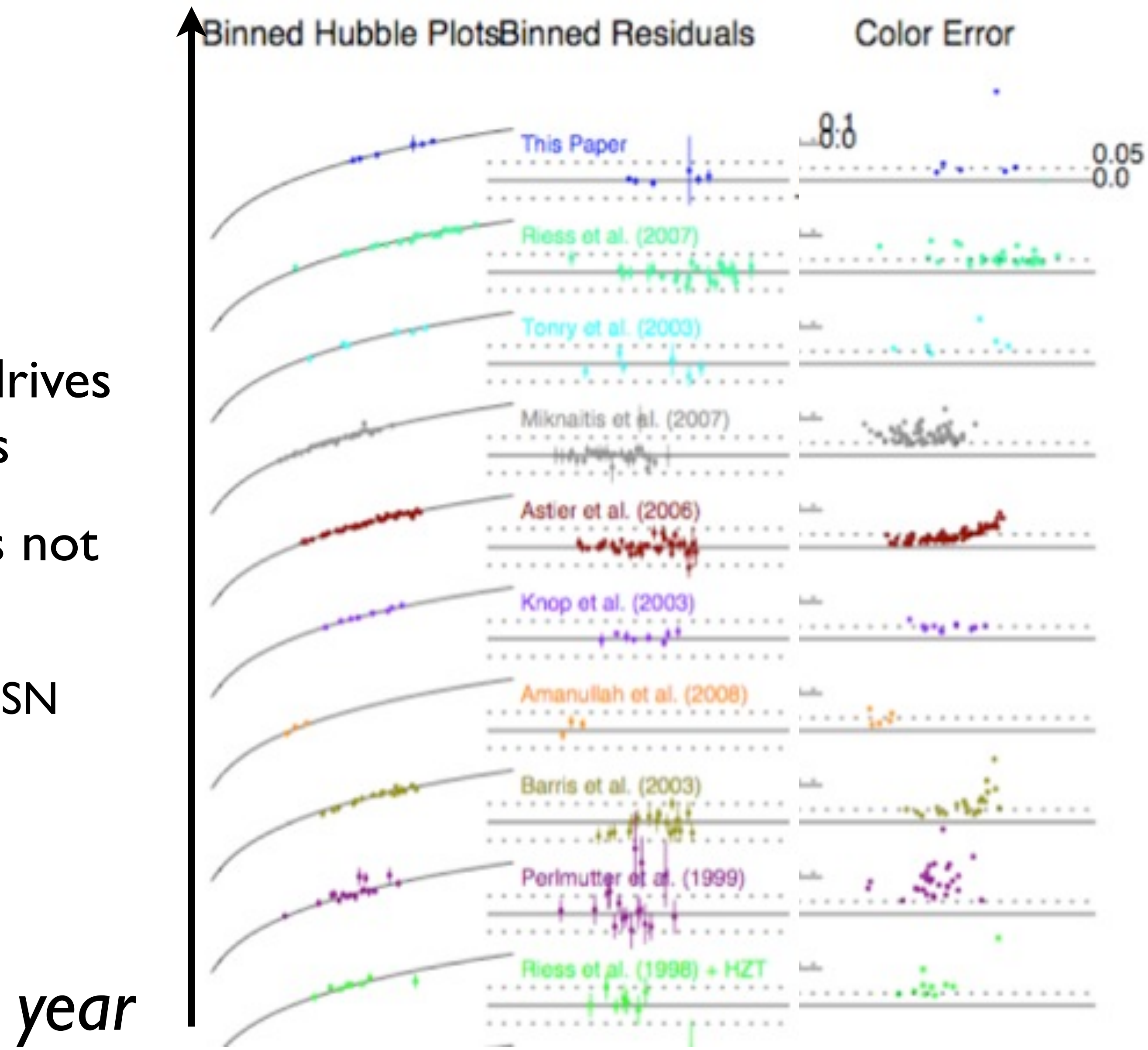
Things Worth Noting

- No survey covers the 0<z<1.7 redshift range
- Low distance uncertainties for z>0.8 SNe from HST
- Non-trivial effort goes into tying different datasets together
  - No guarantee of success
  - Cross-calibration uncertainties



Things Worth Noting

- Color uncertainties drives distance uncertainties
- New data supersedes not supplements old data
  - Still data starved per SN



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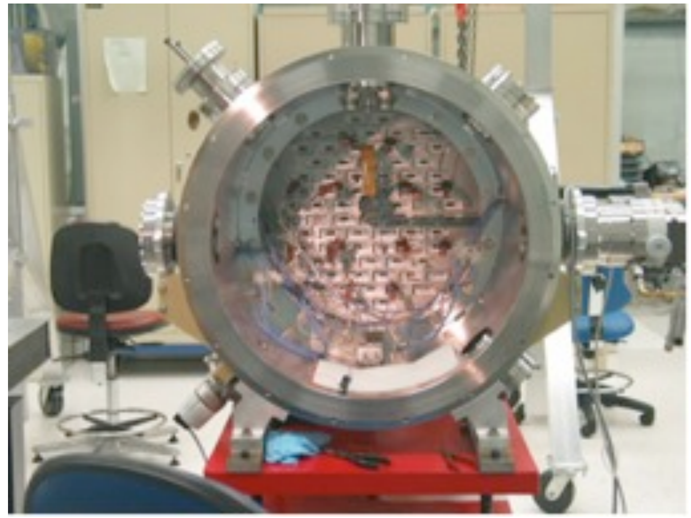
Ongoing and Future Surveys

- Low-redshift
  - Important point in the Hubble Diagram
  - Supernovae bright and easy to observe
  - Supernovae difficult to discover
  - PTF, LaSilla-QUEST, SkyMapper
- High redshift
  - Populate z>0.8 Hubble Diagram
  - Decrease systematic uncertainties compared to existing surveys
  - Dark Energy Survey, Hyper Suprime-Cam, LSST, KDUST, HST, WFIRST

Dark Energy Survey

- 4-m Blanco Telescope at CTIO
- 3 sq deg CCD camera
- Thick fully-depleted CCD's give improved QE in the red
- First light early 2012 (?)
- 525 nights over 5 years
- Survey season
    - Mid-Sep to early-Feb
    - Concentrated Nov-Jan

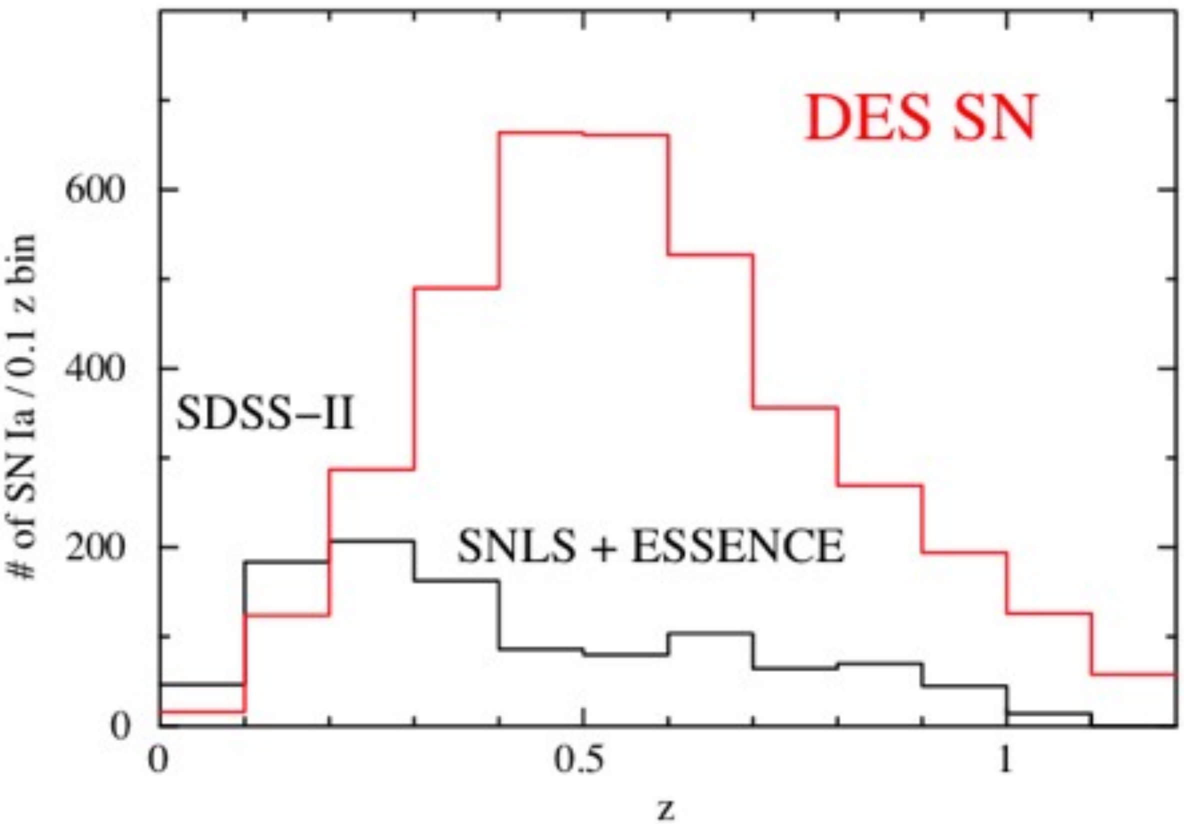


SN Survey Summary

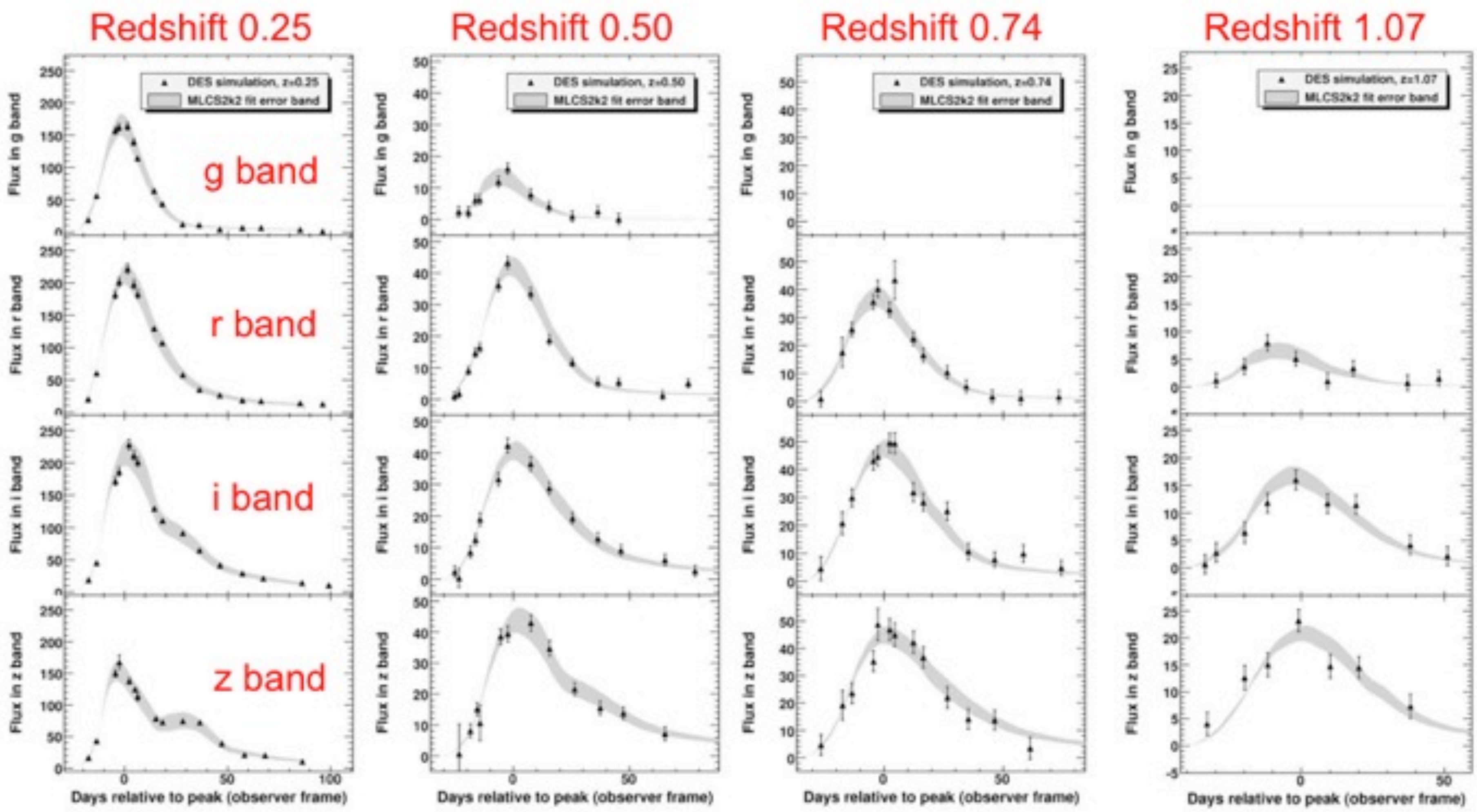
- Rolling survey in griz
- SN observations >1000 hours over 5 years
- ~6000 SN Ia discoveries $0.1<z<1.0$
  - ~3800 with OK light curves (comparable to SNLS)
- DETF FOM~140
  - (Stage II and Planck, systematics)
    - Don’t anticipate getting SN spectrum of all candidates: use photometric typing
- Non-DES observations enhance data quality
- Candidates made public immediately
- Pilot studies beginning 2012, real survey Fall 2012

Redshift Distribution

- More and higher-redshift than existing samples

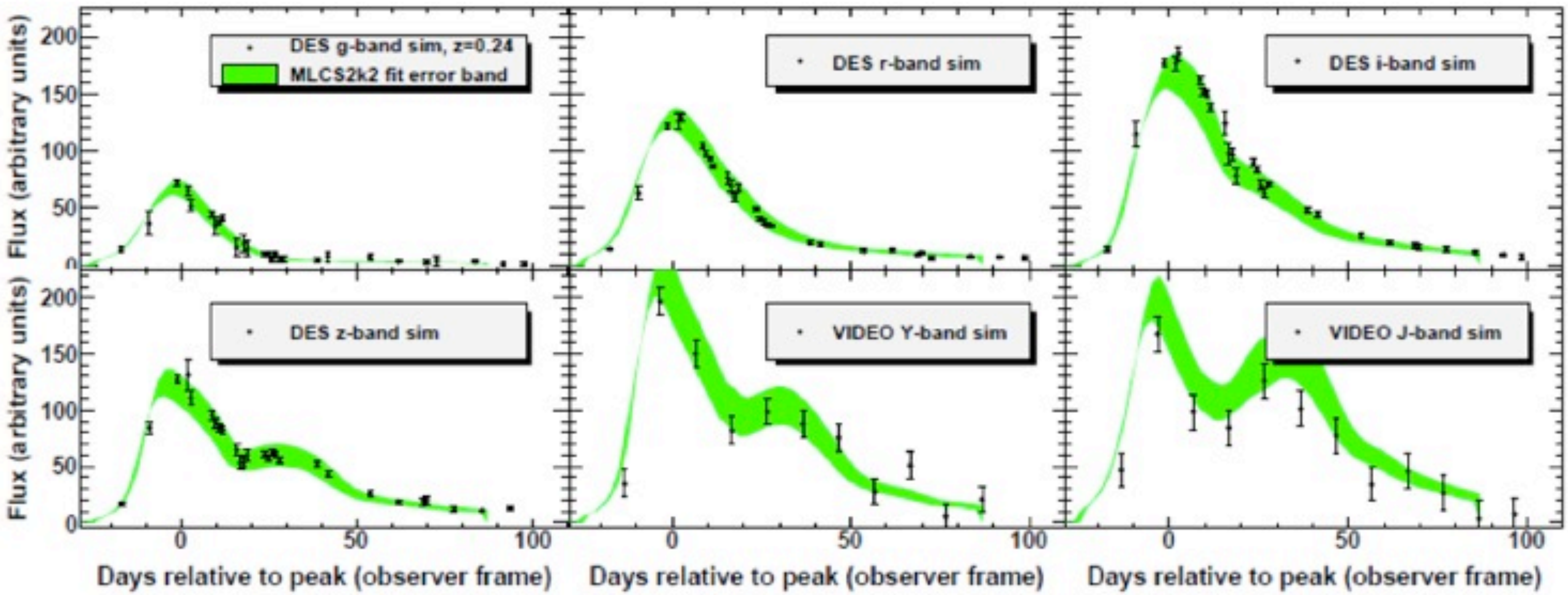


Light Curves

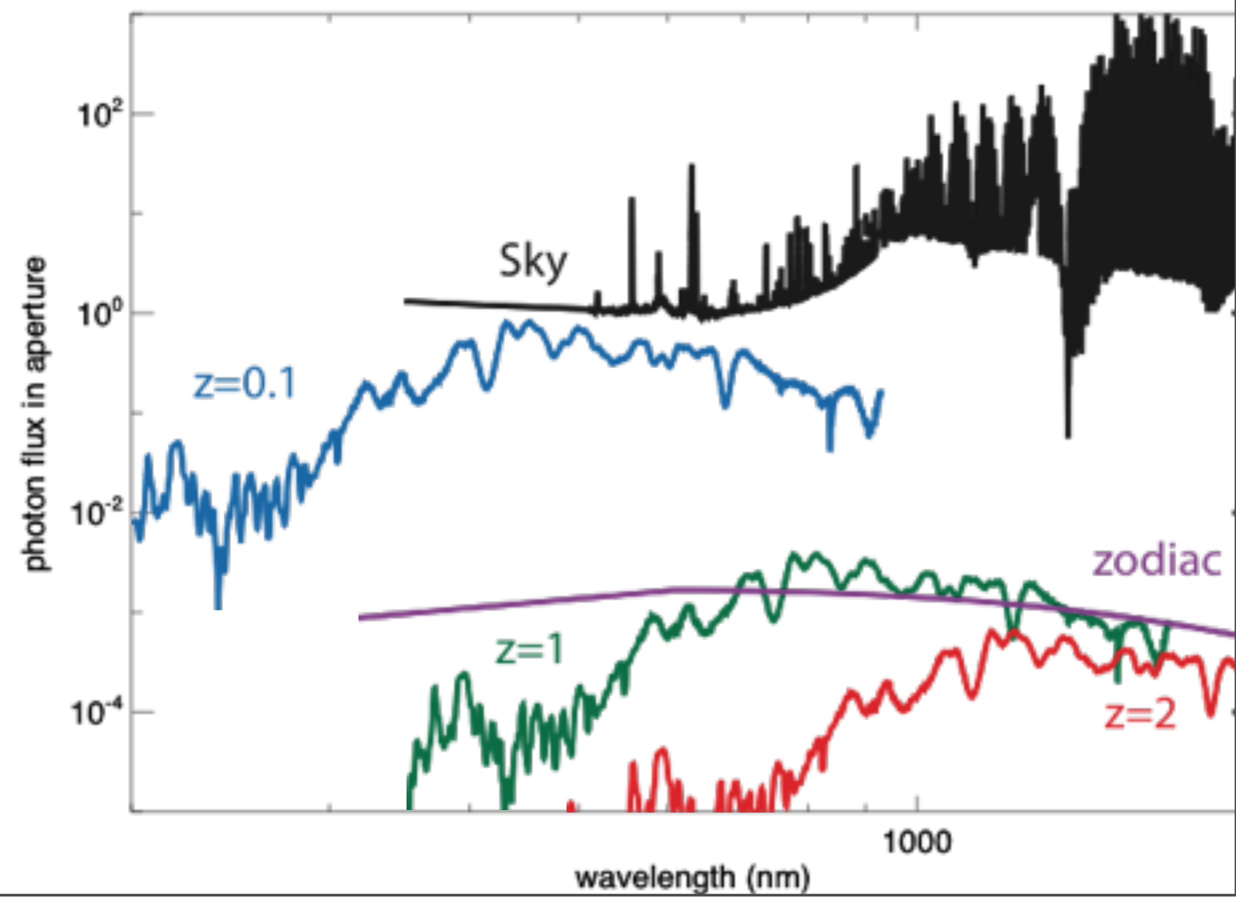


Dark Energy Survey + VIDEO

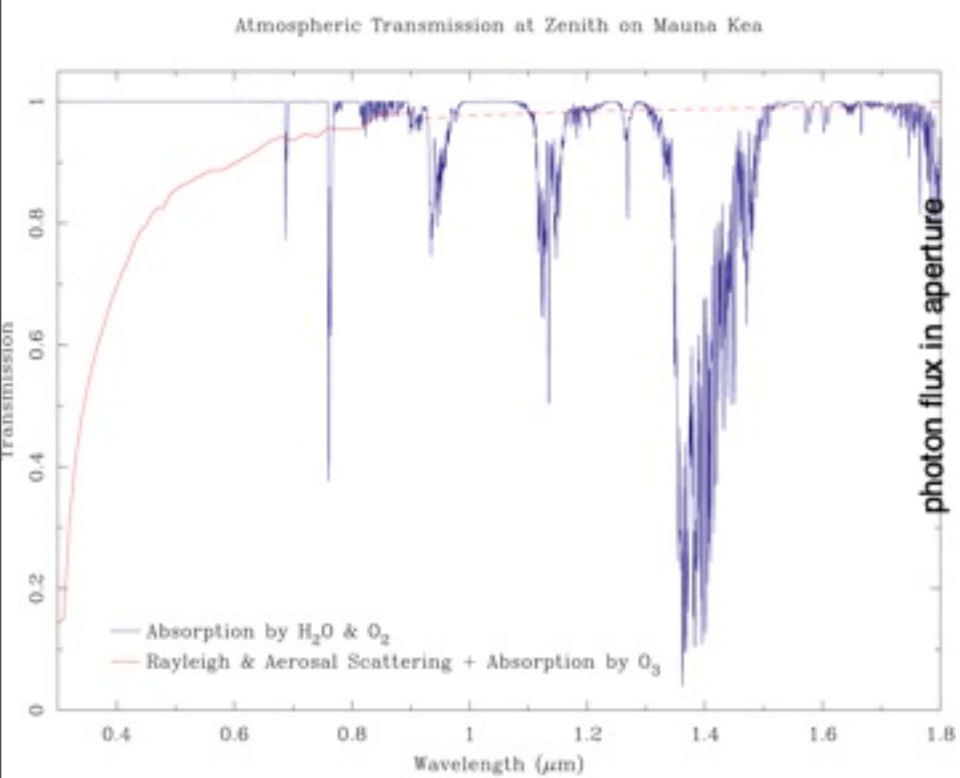
- Common fields with cadenced survey by DES and VIDEO (VISTA telescope)
- Expect 100 SNe with z<0.3

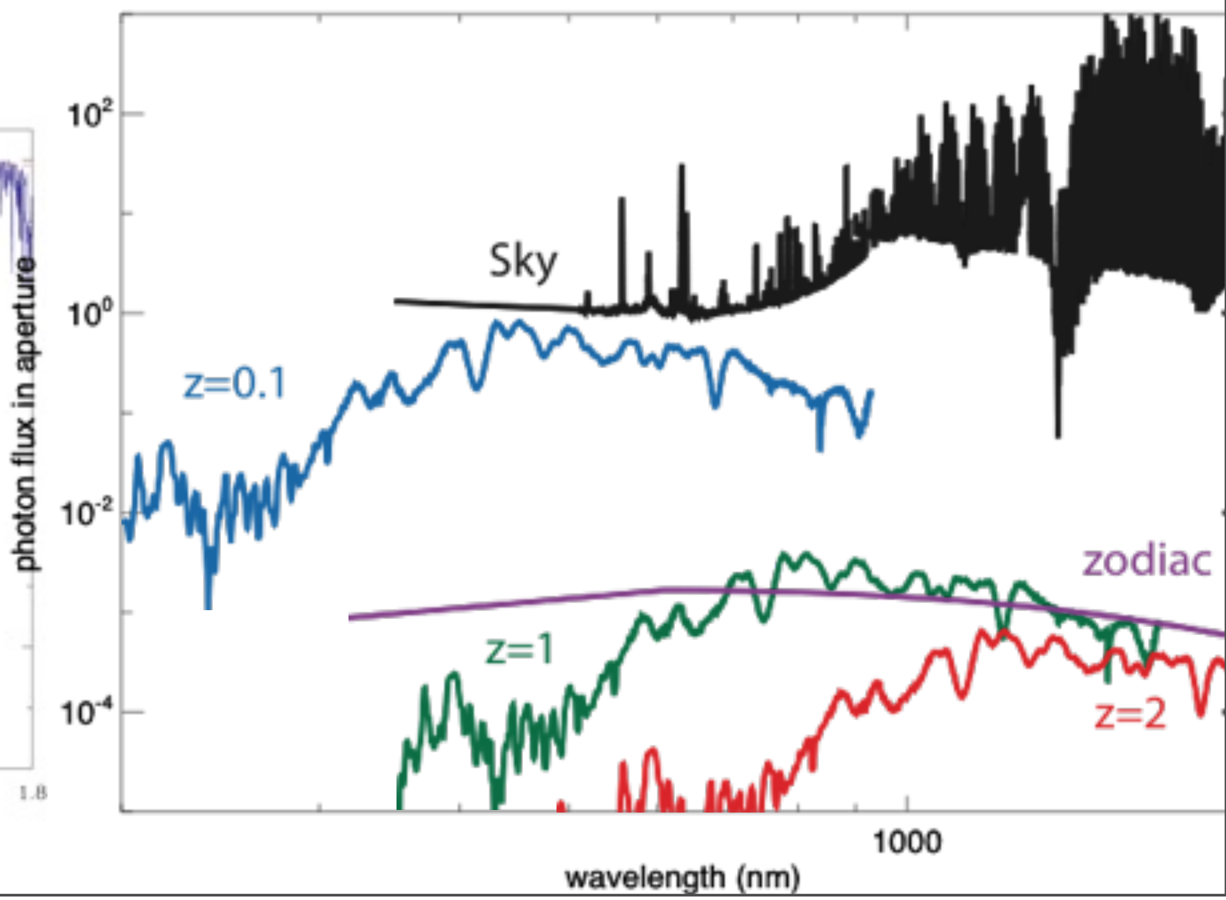


Why Space?

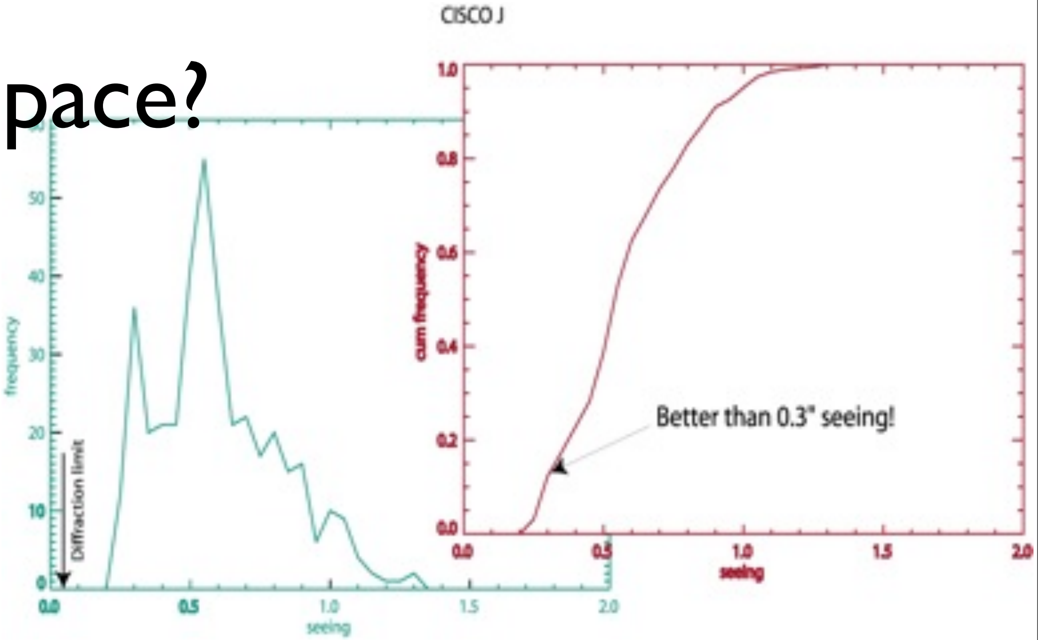

Sky
z=0.1
zodiac
z=1
z=2
photon flux in aperture
10^{2}
10^{0}
10^{-2}
10^{-4}
1000
wavelength (nm)

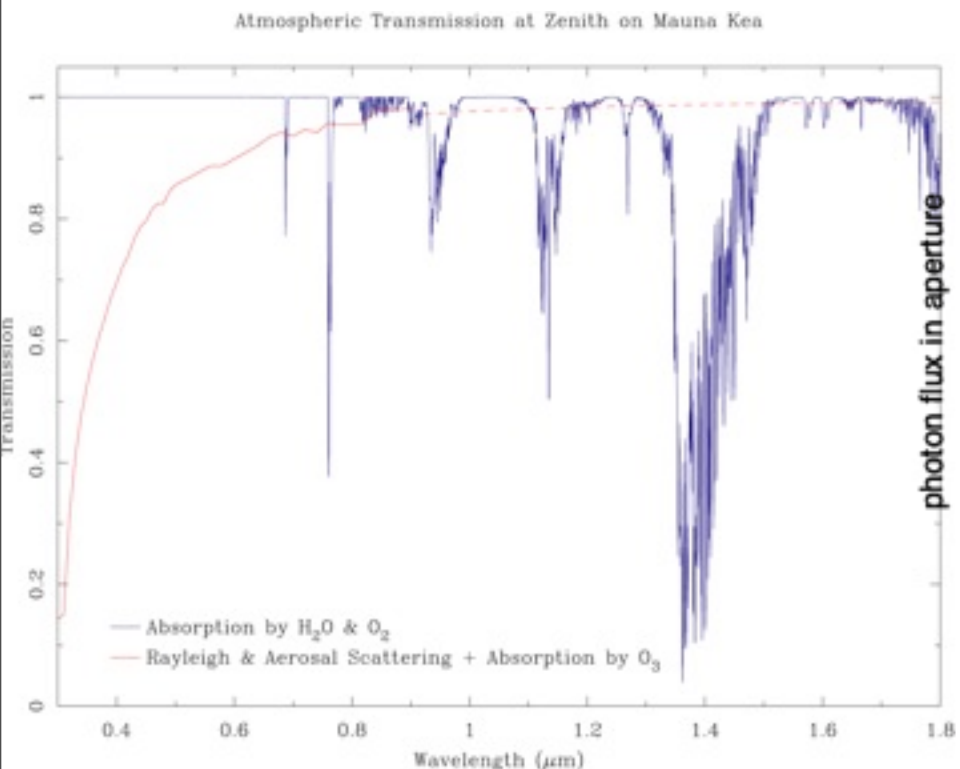
Why Space?


Atmospheric Transmission at Zenith on Mauna Kea
Transmission
Wavelength (μm)
Absorption by H2O & O2
Rayleigh & Aerosal Scattering + Absorption by O3
0
0.2
0.4
0.6
0.8
1
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


photon flux in aperture
wavelength (nm)
Sky
z=0.1
z=1
z=2
zodiac
10^2
10^0
10^-2
10^-4
1000

Why Space?


CISCO J
frequency
Diffraction limit
seeing
cum frequency
Better than 0.3" seeing!
seeing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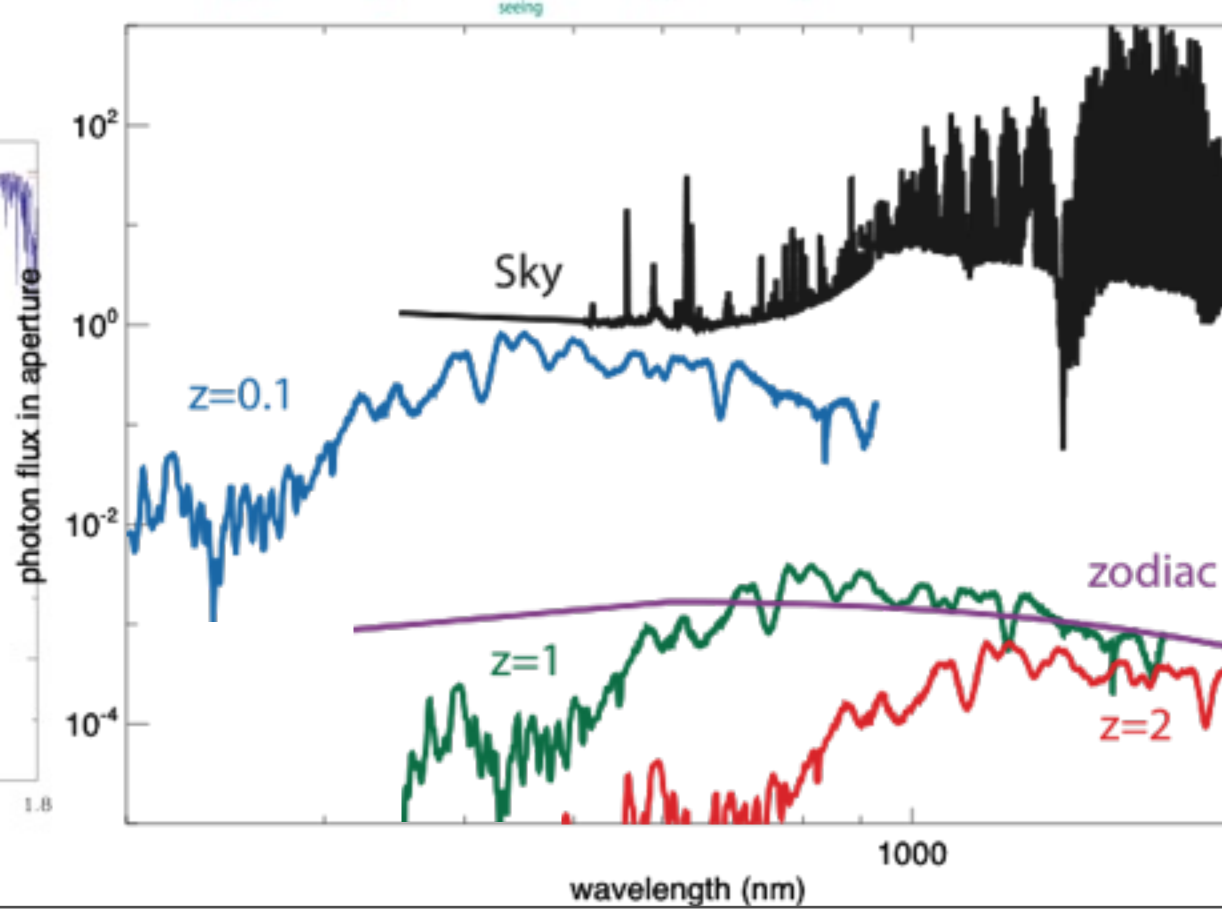
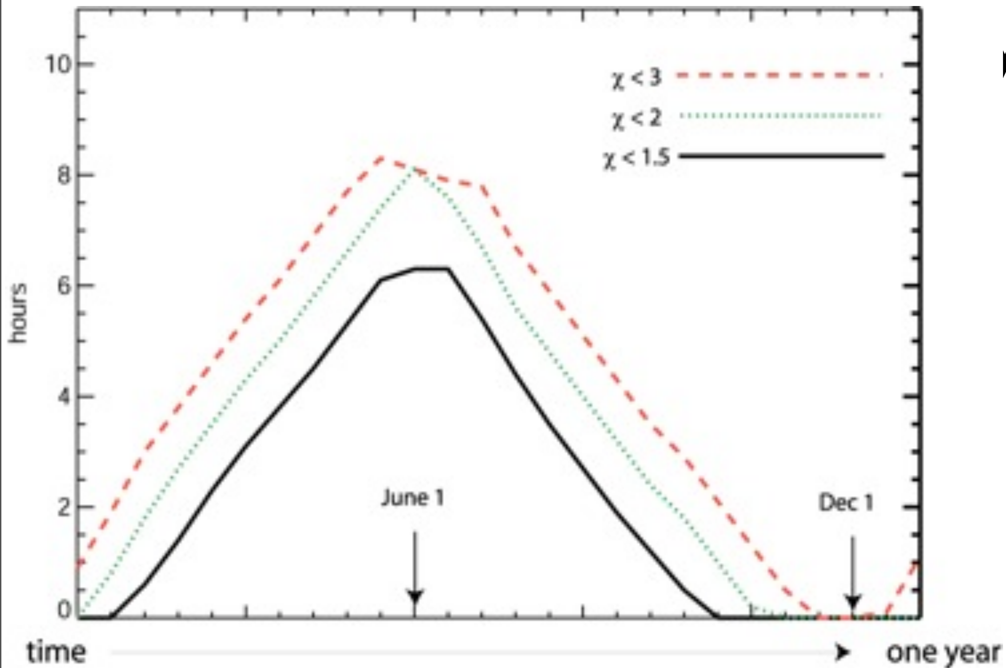
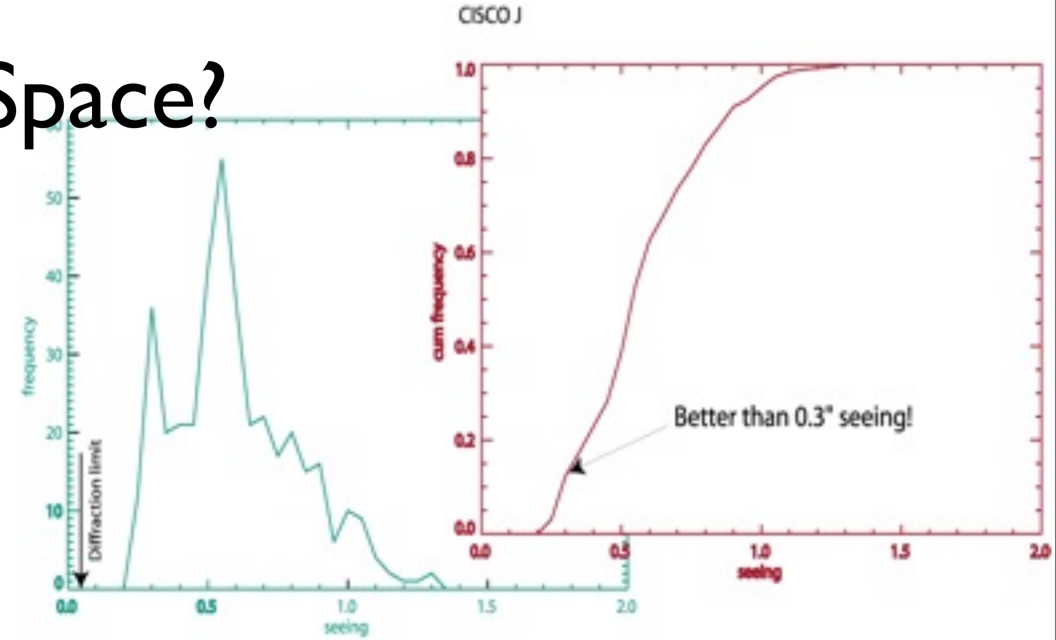
Absorption by H_2O & O_2
Rayleigh & Aerosal Scattering + Absorption by O_3
Wavelength (μm)


Sky
z=0.1
zodiac
z=1
z=2
photon flux in aperture
wavelength (nm)

Space?



hours
10
8
6
4
2
0
χ < 3
χ < 2
χ < 1.5
June 1
Dec 1
time
one year



CISCO J
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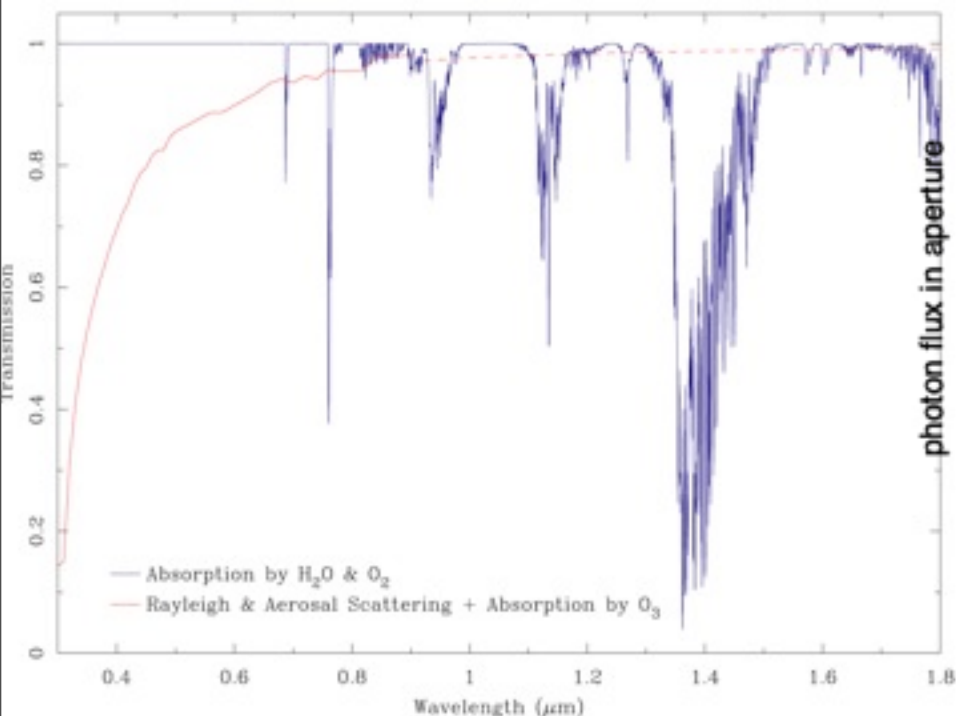

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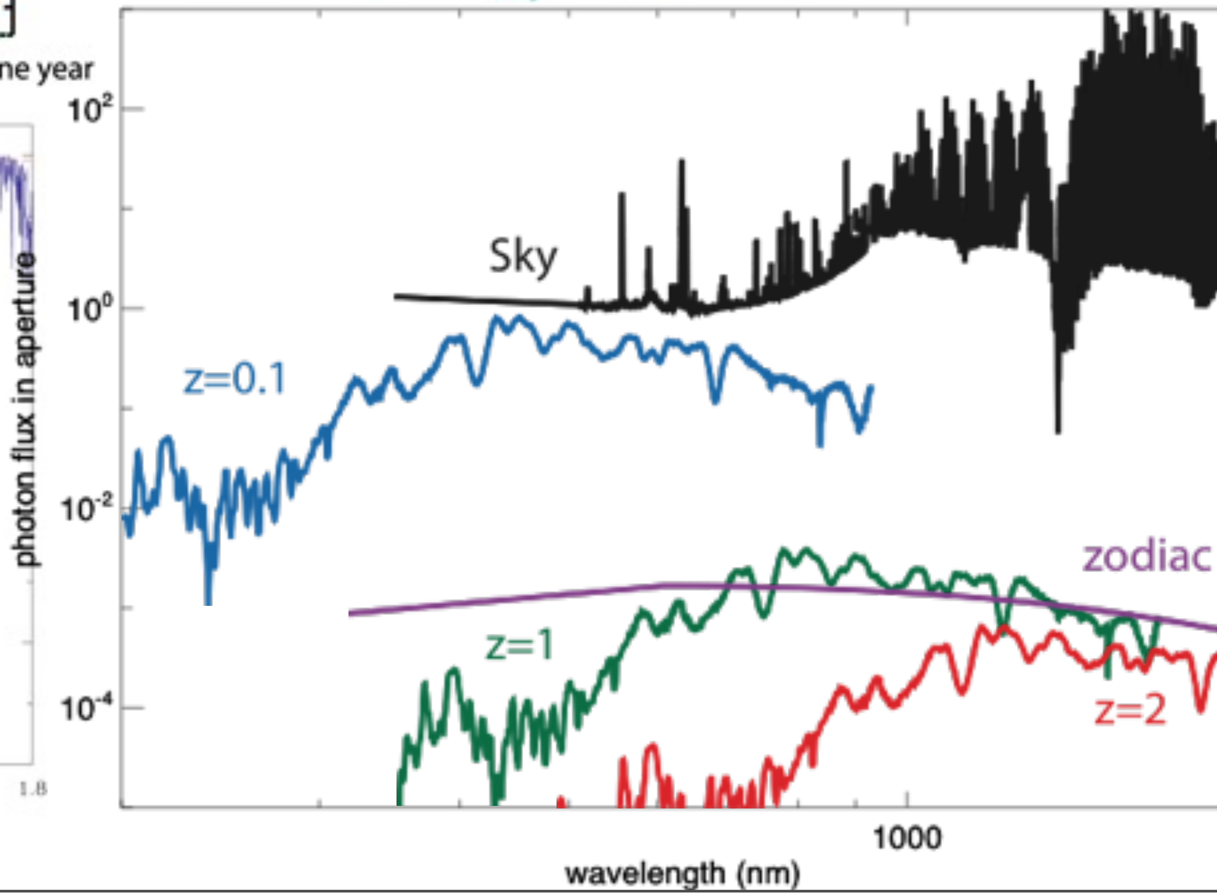
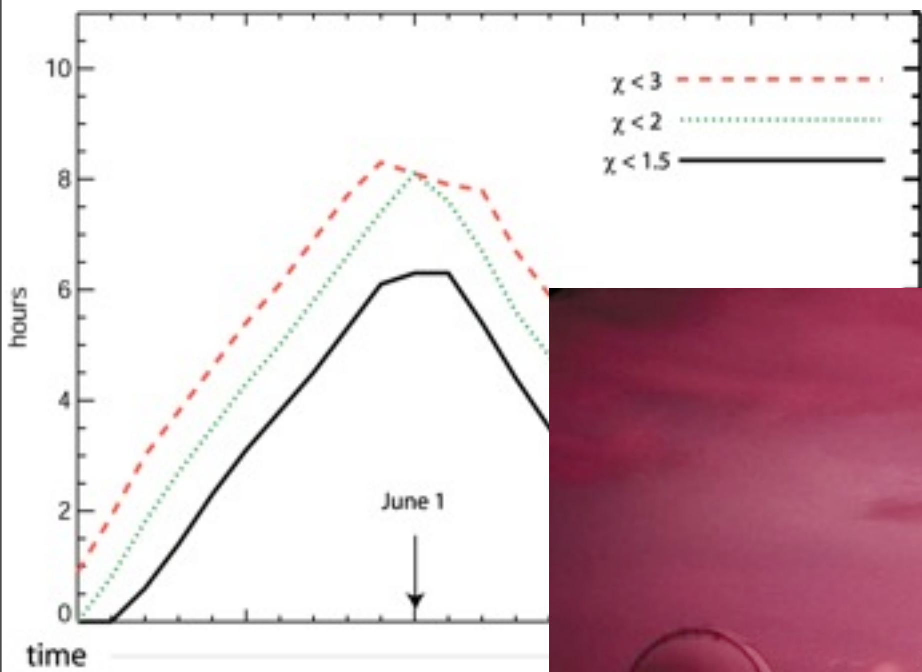
Wavelength (μm)

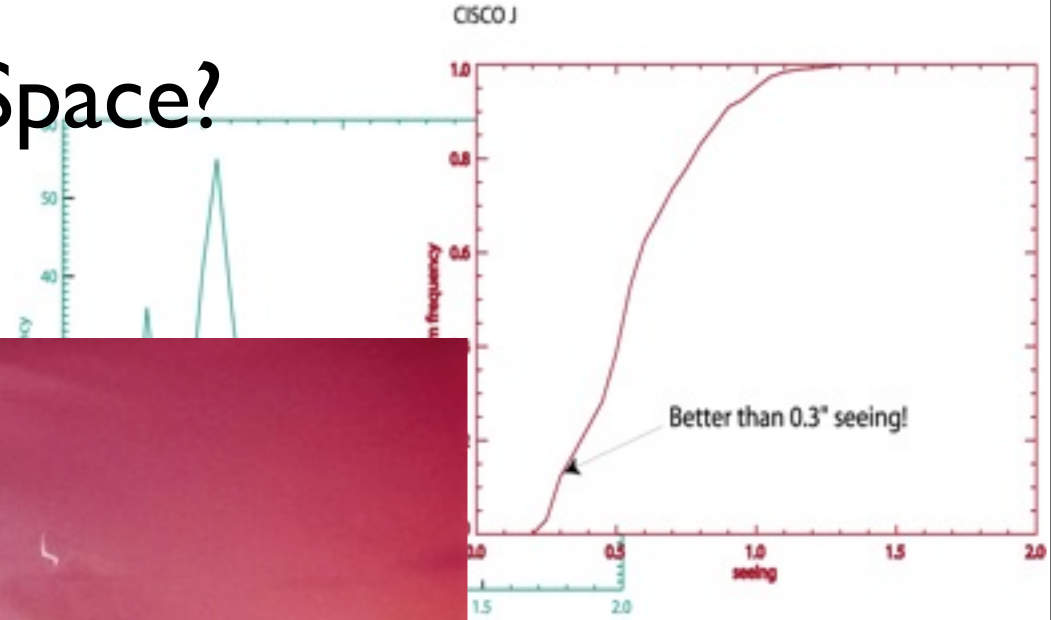


photon flux in aperture
Sky
z=0.1
zodiac
z=1
z=2
1000
wavelength (nm)

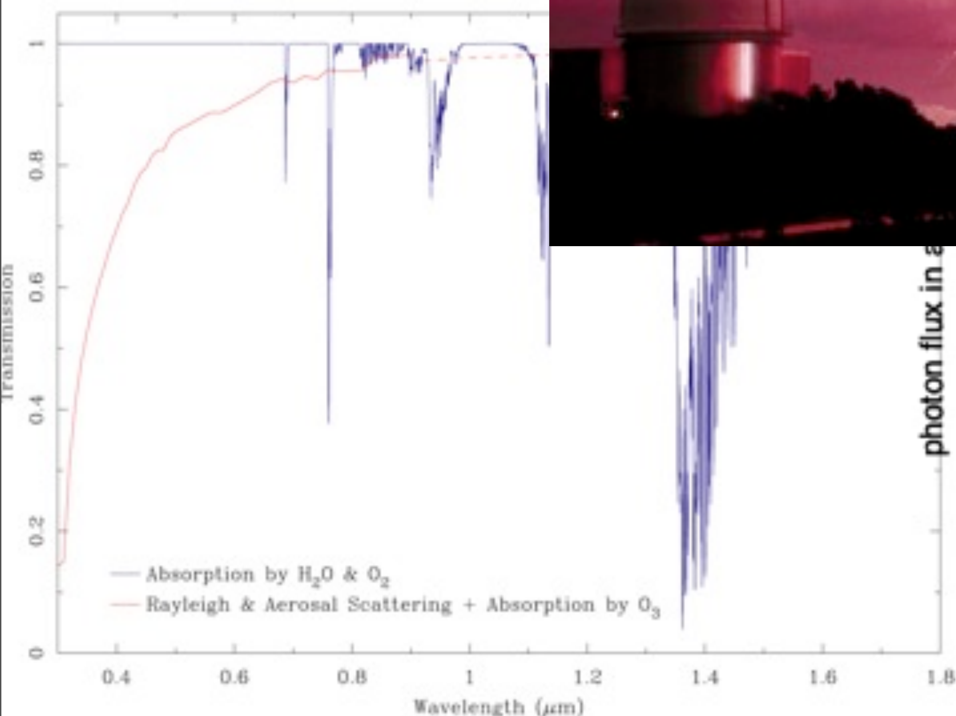
Space?



χ < 3
χ < 2
χ < 1.5
hours
June 1
time



CISCO J
Better than 0.3" seeing!
seeing



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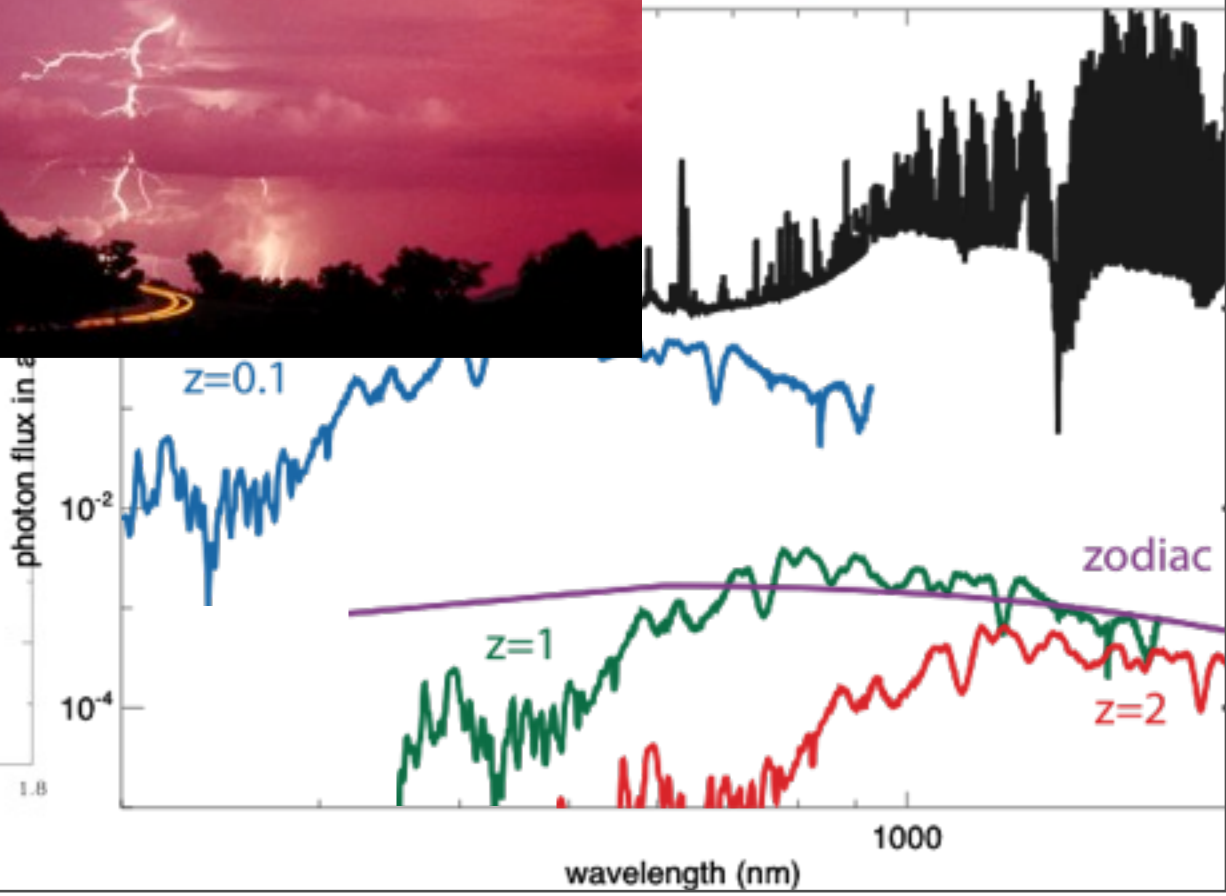
Transmission
Wavelength (μm)



photon flux in a
z=0.1
z=1
z=2
zodiac
wavelength (nm)

Dark Energy Space Missions

- WFIRST - NASA
  - Highest-rated space mission in the US Decadal Survey
  - Supernovae, weak lensing, and galaxy clustering surveys
- Euclid - ESA
  - Weak lensing, galaxy clustering
    - Small tweaks make a SN program possible

Designing a Space Mission

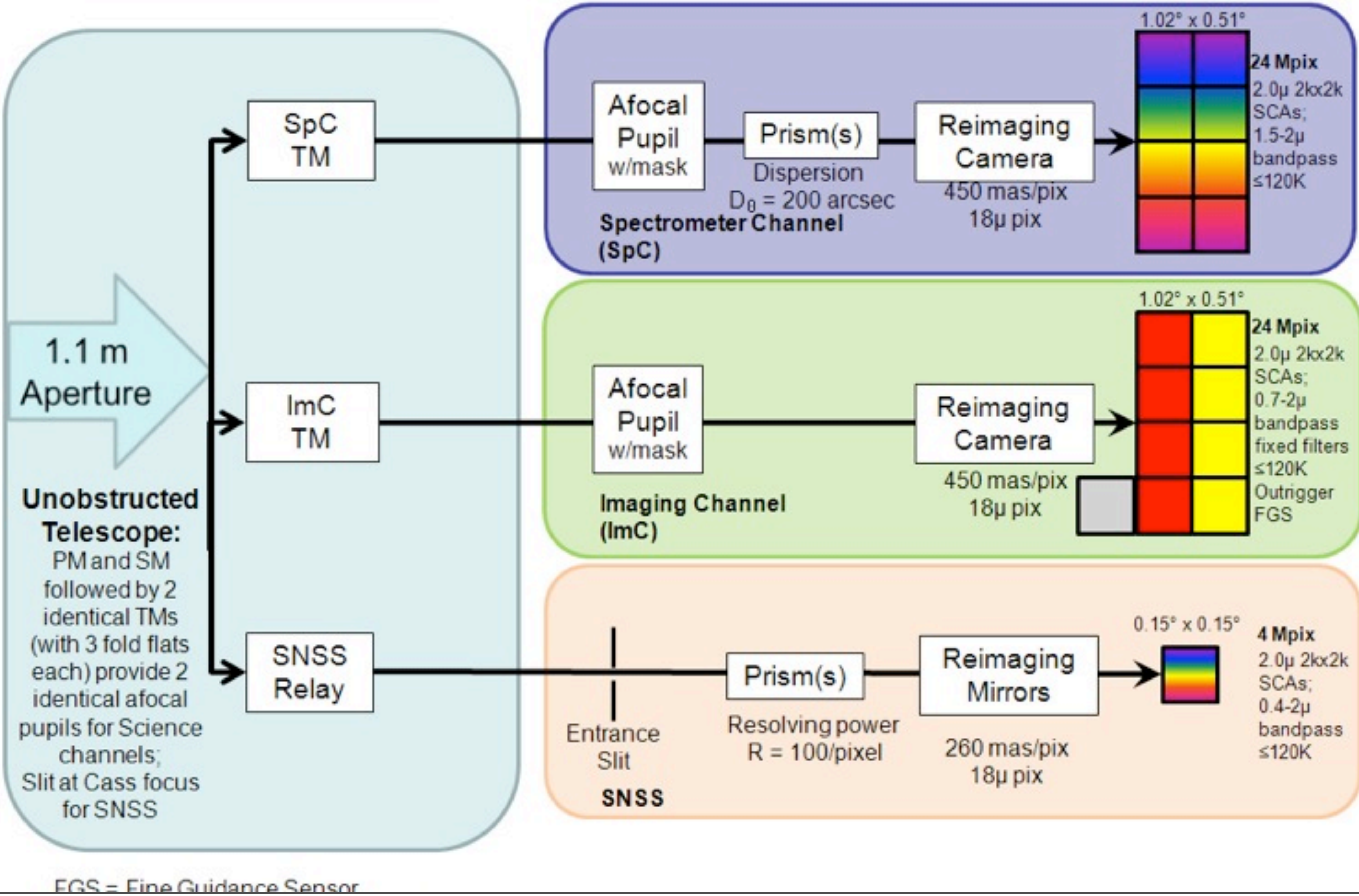
- JDEM-Interim Science Working Group
  - WFIRST evolved from JDEM
- Charged with designing a SN/BAO/WL DE mission with a $600M cost cap
- Imager was the high risk item in the cost model
- Previous proposals called for a SN Rolling Survey: Demanding (expensive) imager requirements

	Nyquist	Wavelength	# Filters
SN	Yes	0.35-1.7 um	10

JDEM-ISWG Solution

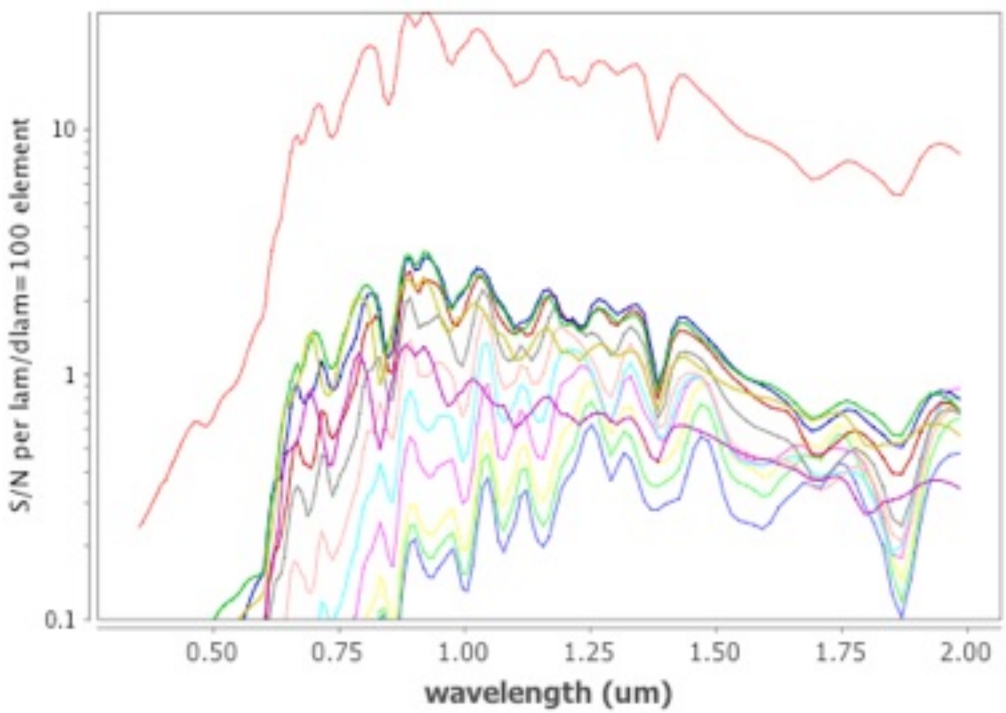
- SN light curve requirements and cost cap restricted the imager field of view
- Classic Survey instead of Rolling Survey
  - Supernova search with imager
    - Image quality not so important
    - 2-3 bands for discovery and typing
  - Triggered Spectroscopy

Dark Energy Satellite Layout



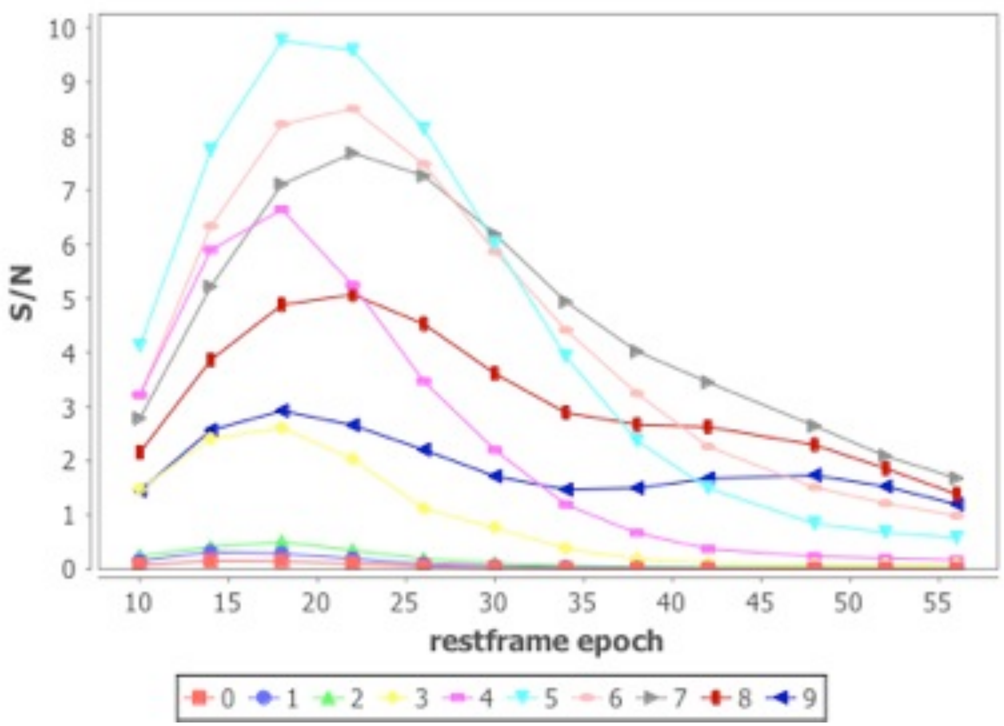
Dark Energy Satellite SN Data Quality

- SN at z=1.3
- One deep spectrum at peak for subtyping
- Shallower spectra for "light curves"
  - 4-day restframe cadence
  - [-10,50] rest-frame epochs
  - 4 deep references

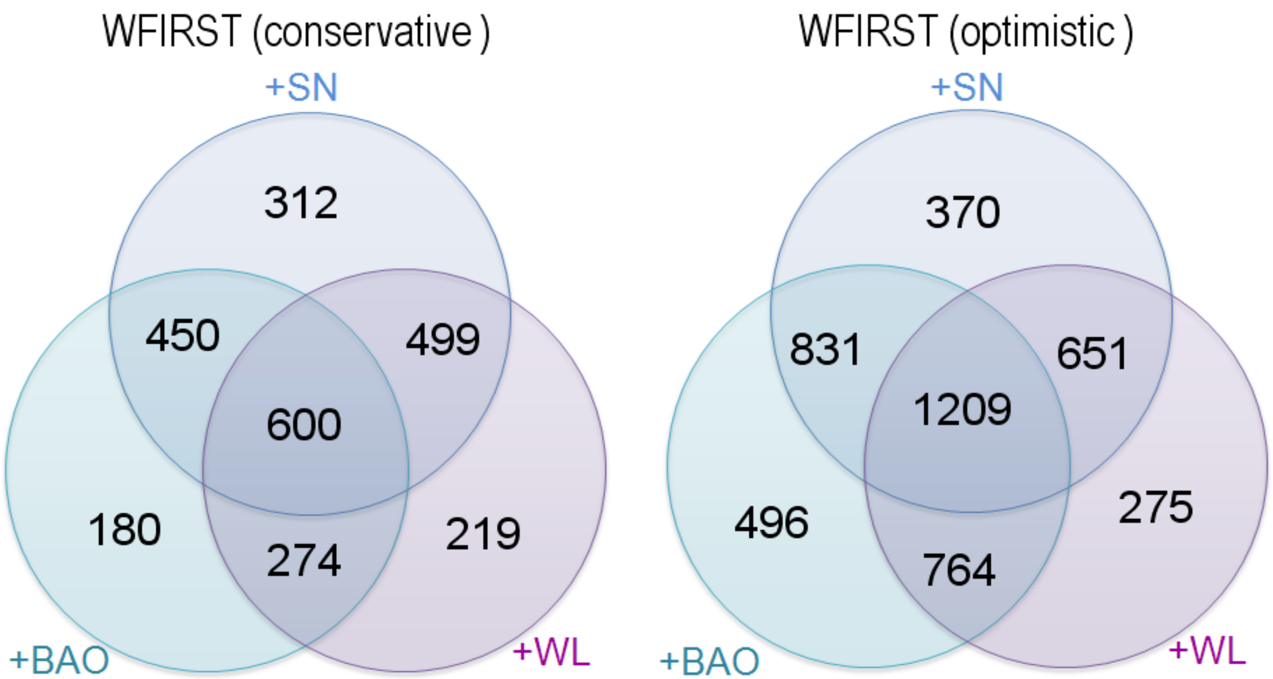


Synthetic Photometry

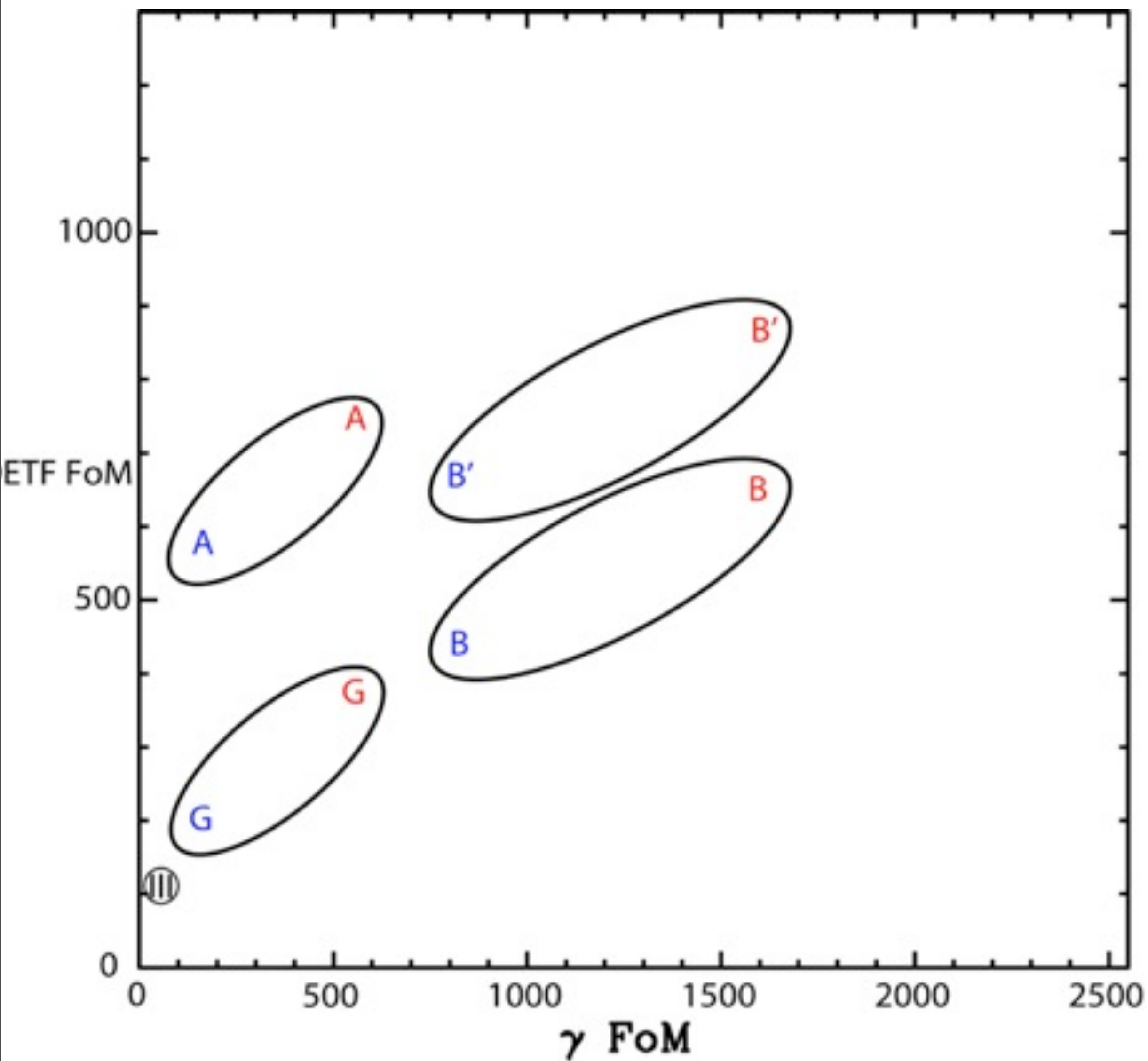
- Light curves in 10 independent synthetic bands



WFIRST Figure Of Merit



Distinguishing Dark Energy and Modified Gravity



I is FoMSWG Stage III FoM

A and B stand for Designs A and B
G is for Ground Based

B is WL and BAO only
B′ includes Supernovae

Blue for minimal ground program Stage III + Double DES + u band

Red is for a maximal Stage IV Ground program including BigBOSS(24,000 sq deg) and LSST

Summary

- Type Ia Supernovae were and are the strongest probe of the expansion history of the Universe
- Supernovae have a bright future
  - Current limitations can be overcome
  - Major projects planned