Supernova Surveys From Space?!?!

Alex Kim
Lawrence Berkeley Laboratory

Outline

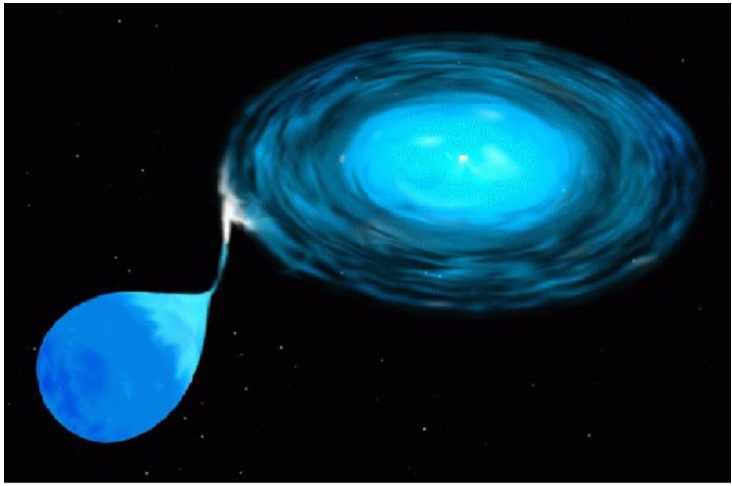
- Type Ia Supernovae as a Cosmological Probe
  - Standard candle distance indicator seen to high redshift
- Current cosmology constraints with SNe
  - Critical piece in measurements of Dark Energy
  - Still room for improvement for both statistical and systematic uncertainties
- Why space?
  - Problems in ground observing irrelevant in space observing

Outline

- Need for a spectrum
  - Traces SN Ia heterogeneity that could bias cosmological measurements
- Existing/planned space telescopes
  - Community (HST/JWST)
    - Not well suited
  - “Dark Energy” Missions (Euclid/WFIRST)
    - No SN component as is
- A perturbative solution exists requiring:
  - Change in SN survey strategy
  - A minor hardware addition

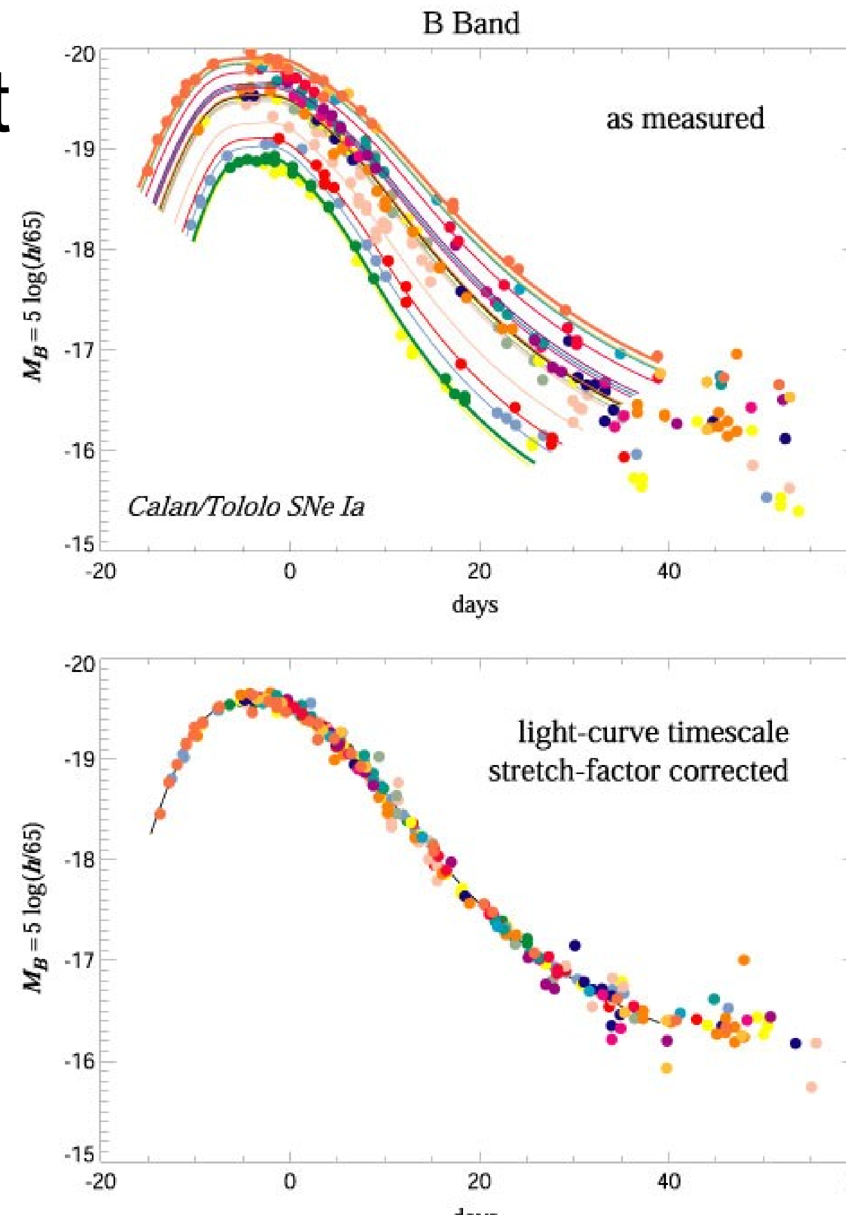
Type Ia Supernovae Defined

- Defined empirically as a point flash without detectable Hydrogen (I) but with Silicon (a)
- Theoretically
  - C/O White Dwarf accreting material from a binary companion
  - As the White Dwarf reaches the Chandrasekhar mass a thermonuclear runaway is triggered
  - A natural standard triggered bomb



Type Ia Supernovae As Standard Candles

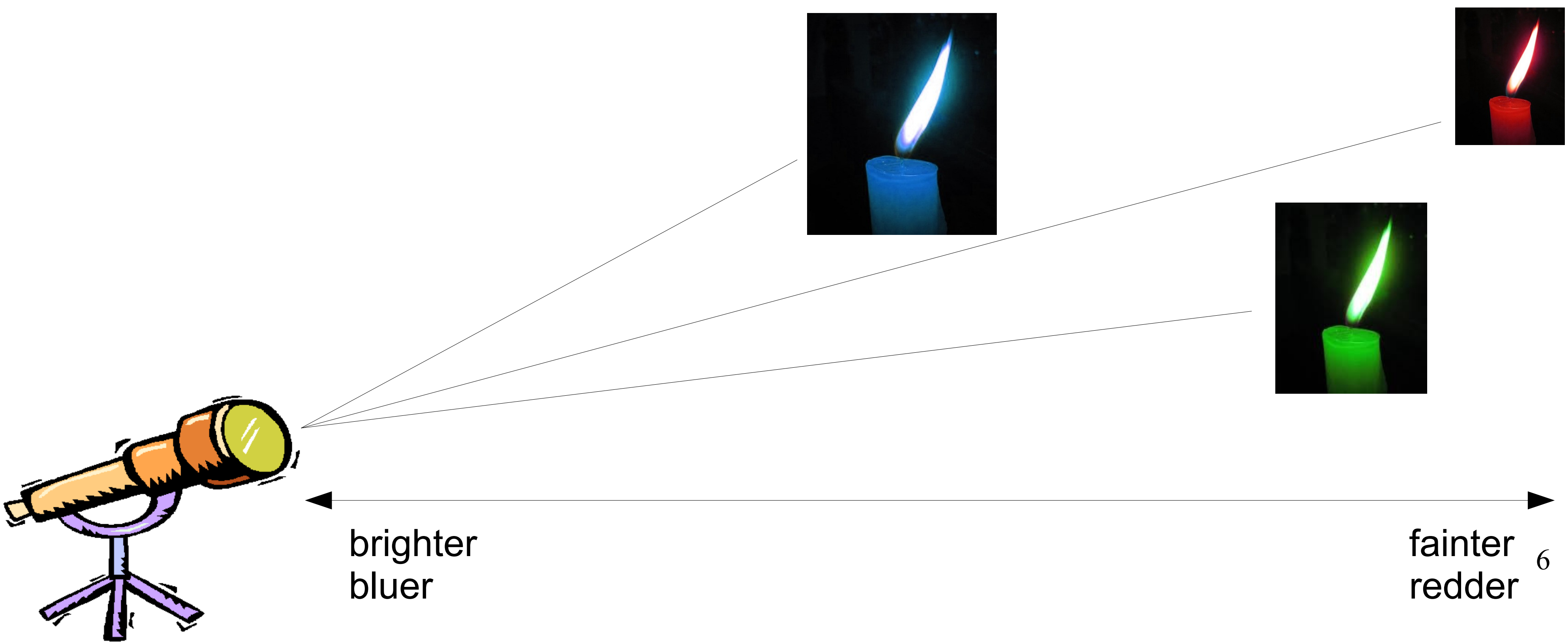
- M~-19.3 at peak (as bright as a galaxy!)
- After correction for dust absorption (color) and light-curve shape SNe are “calibrated” candles with ~0.15 mag dispersion
- In standard analysis distance inferred from multi-band temporal flux evolution



Kim, *et al.* (1997)

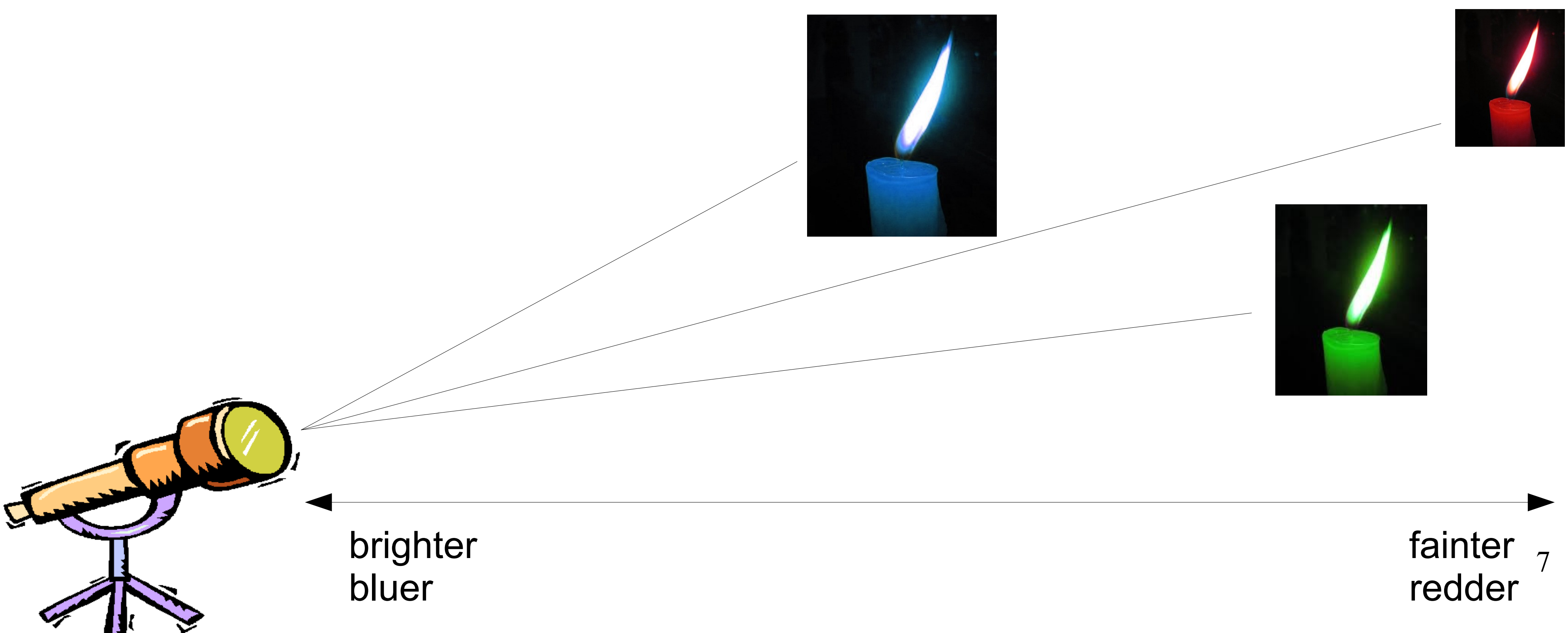
Standard Candles to Cosmology: Observed Flux

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



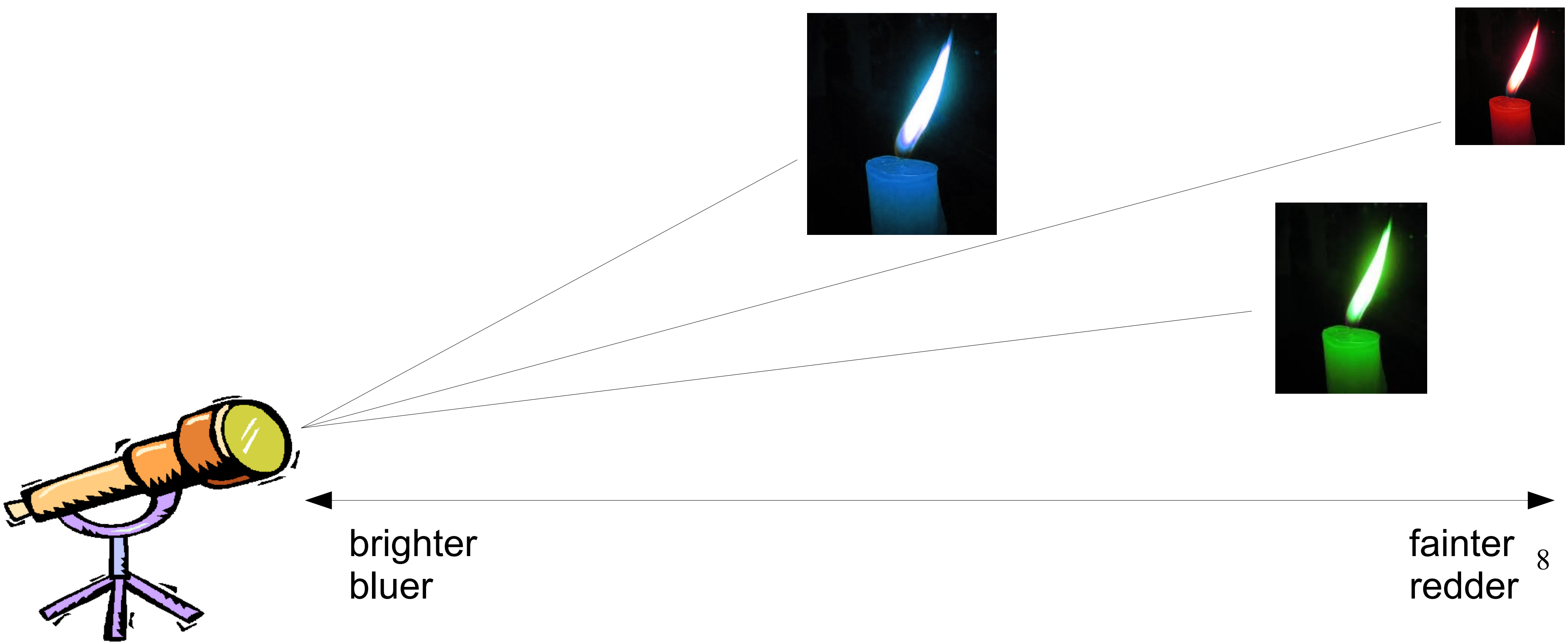
Standard Candles Used to Measure Expansion History

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



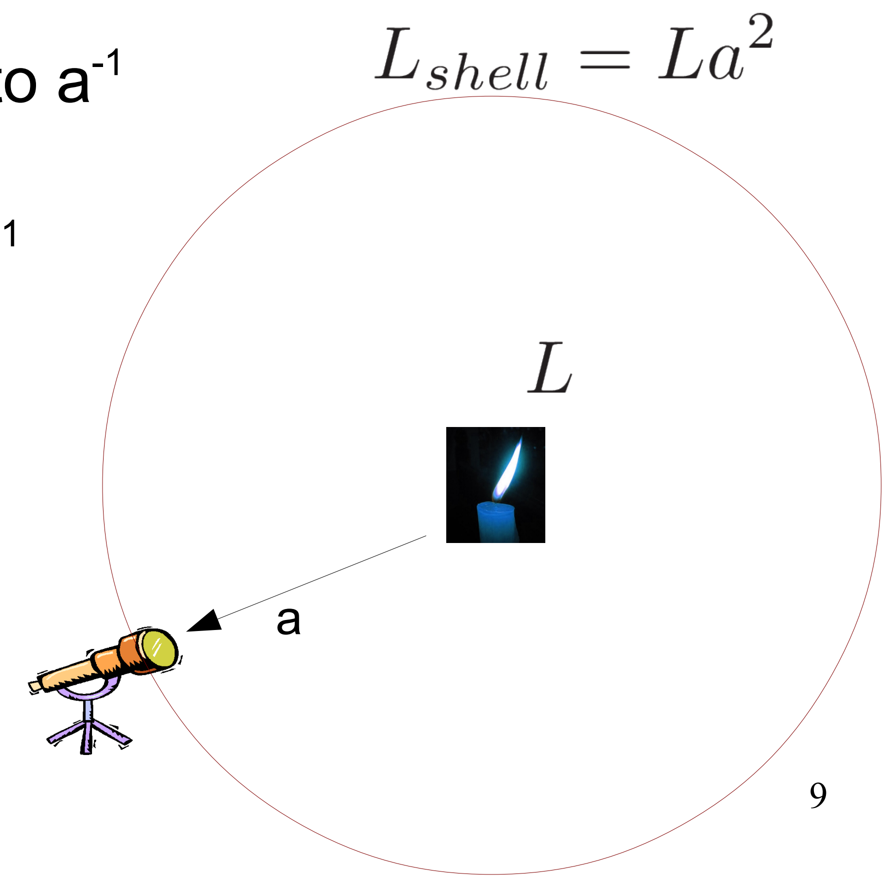
Standard Candles to Cosmology: Observed Flux

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



Standard Candles to Cosmology: Predicted Flux

- Piece 1 – Luminosity through the shell centered on the candle and intersecting the observer
  - In the FRW metric
    - Photon energy proportional to a^{-1}
      - Redshift
    - Clocks appear to move as a^{-1}
      - Time dilation
  - $L_{shell}=La^2$



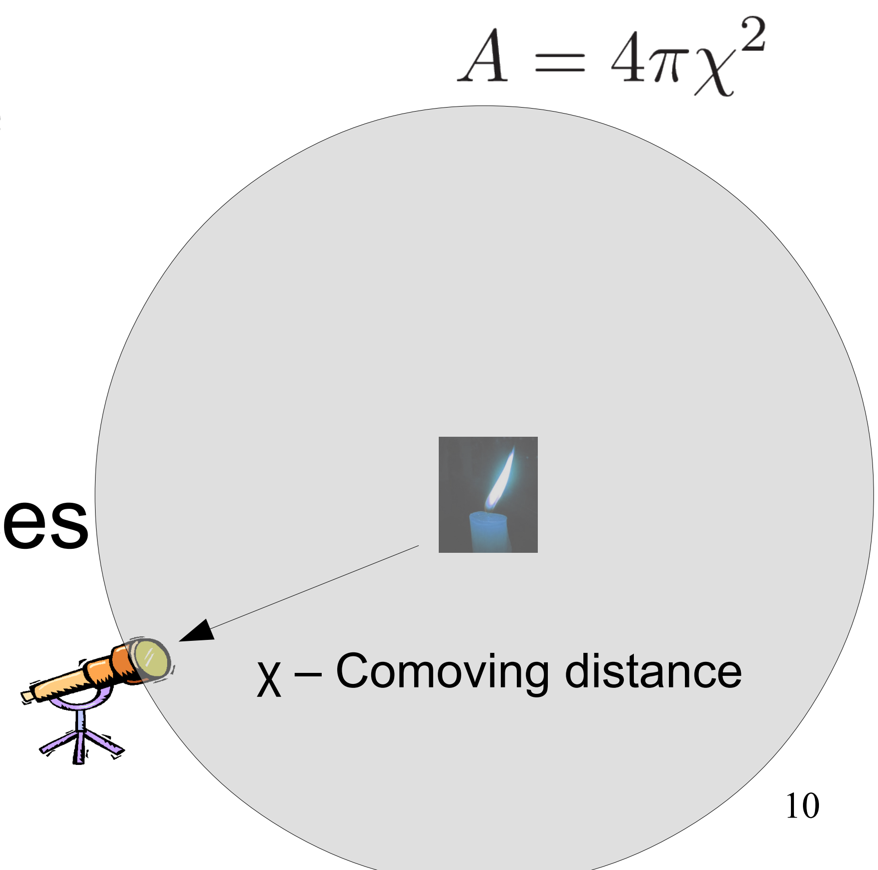
Standard Candles to Cosmology: Predicted Flux

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

- FRW metric 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 2 pieces

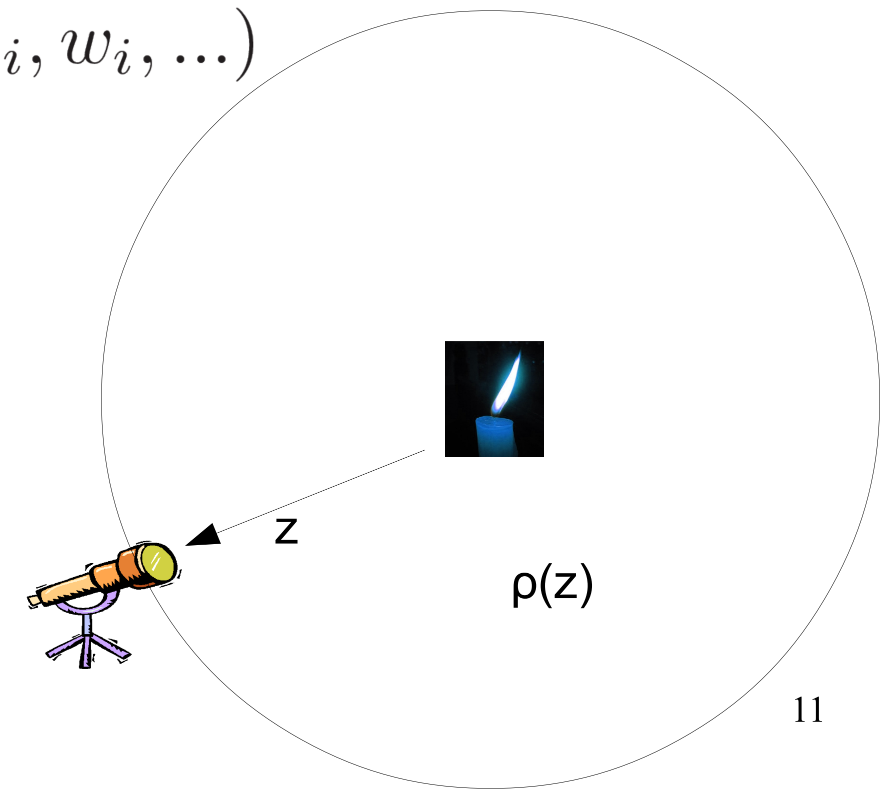
$$f = \frac{La^2}{4\pi\chi^2}$$

Standard Candles to Cosmology: Theoretical Flux

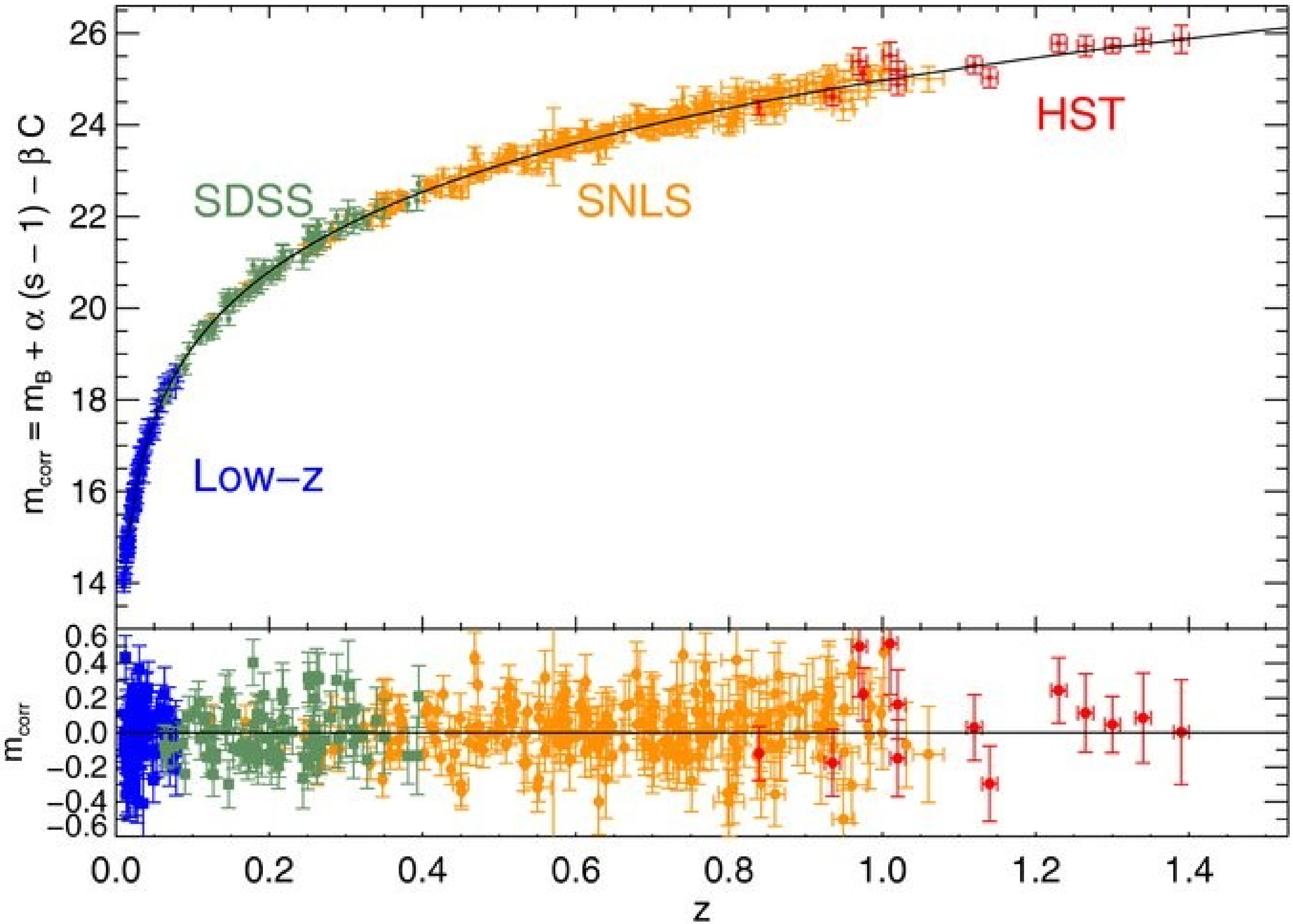
- Physics (General Relativity) provides expected evolution of a(t) based on the energy content of the Universe

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

$$\int_{t_e}^{t_o} \frac{dt}{a(t)} = \int_0^z \frac{dz}{H^{1/2}(z)}$$



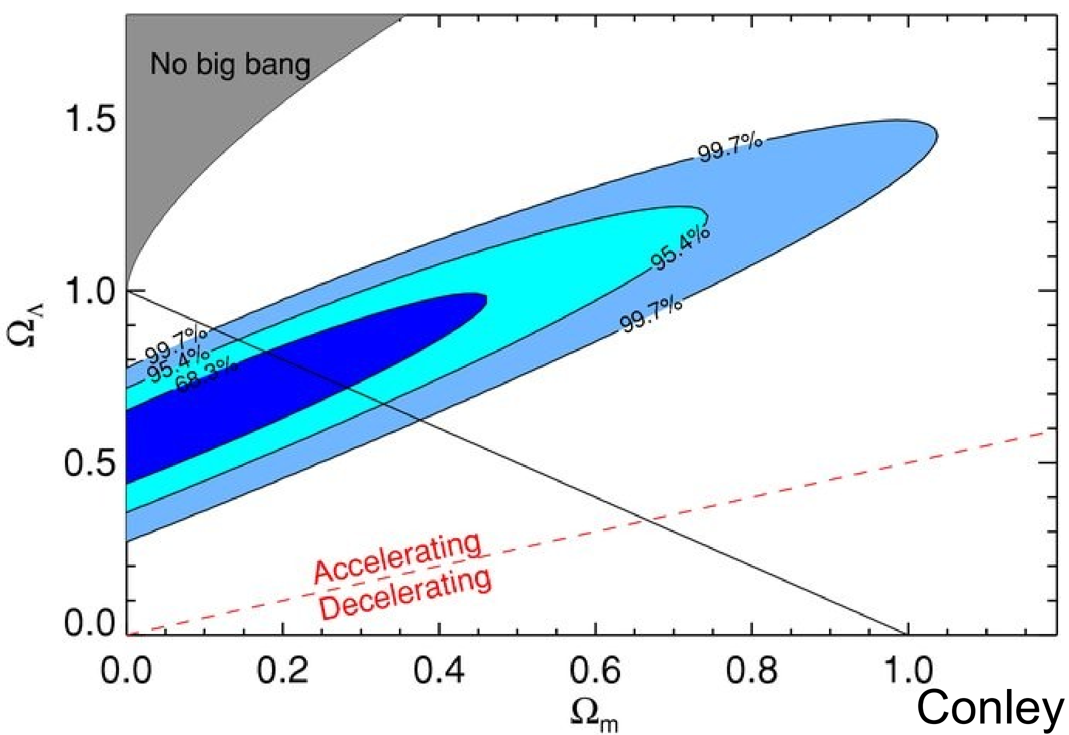
SN Ia Hubble Diagram

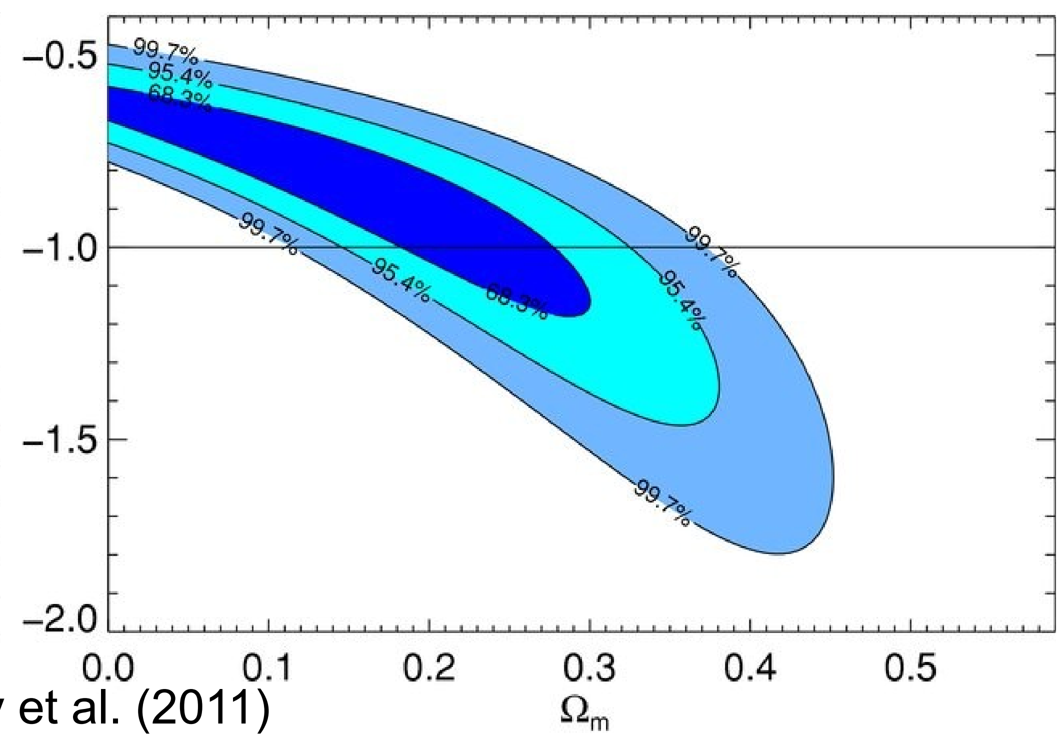


Conley et al. (2011)

SNe Ia By Itself Is A Powerful Cosmological Probe

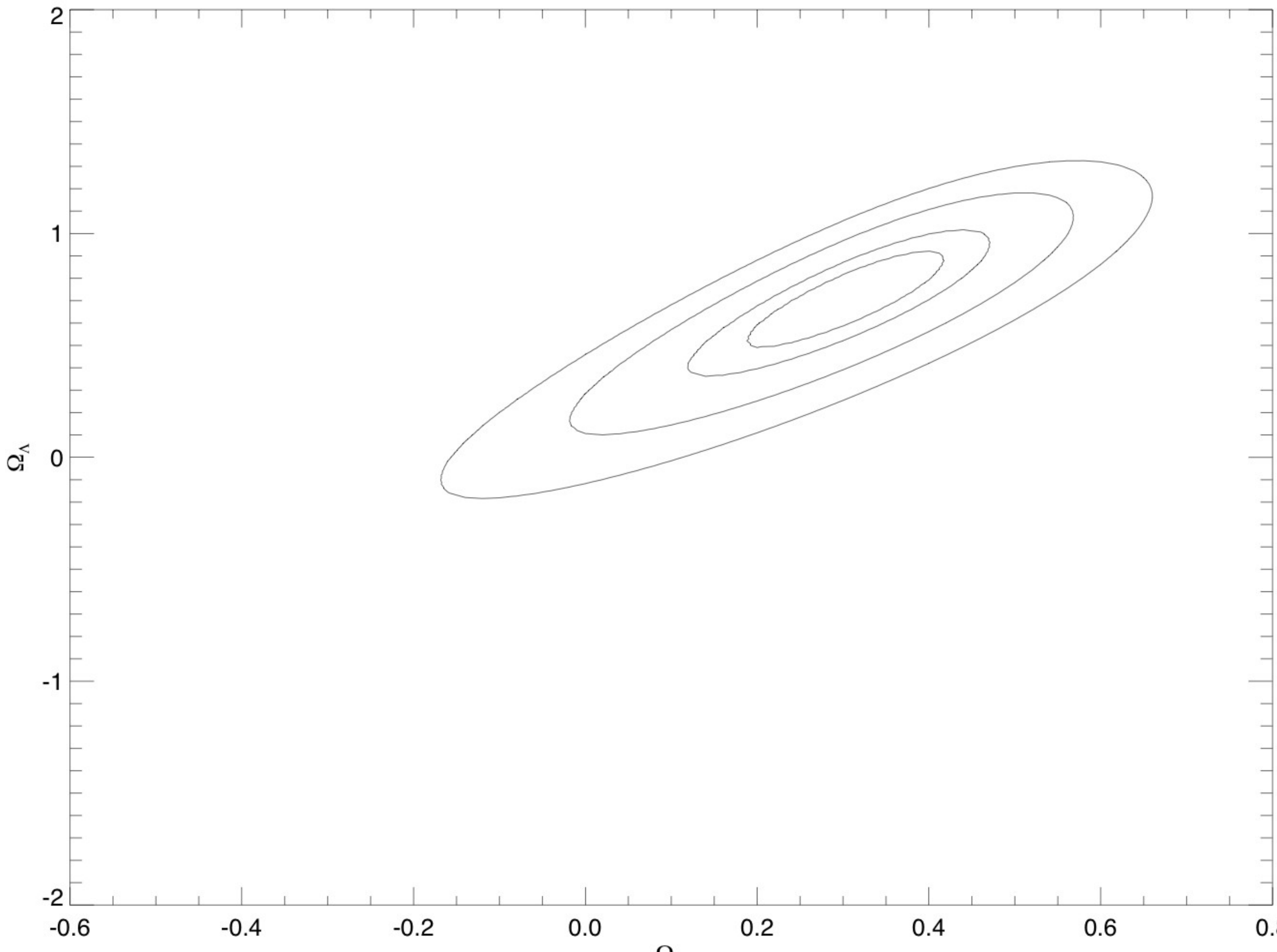
- Sensitive to the acceleration of the universe
- Constrains the mass density, dark energy density, and a constant dark energy equation of state w





Conley et al. (2011)

Likelihood



Current Error Budget

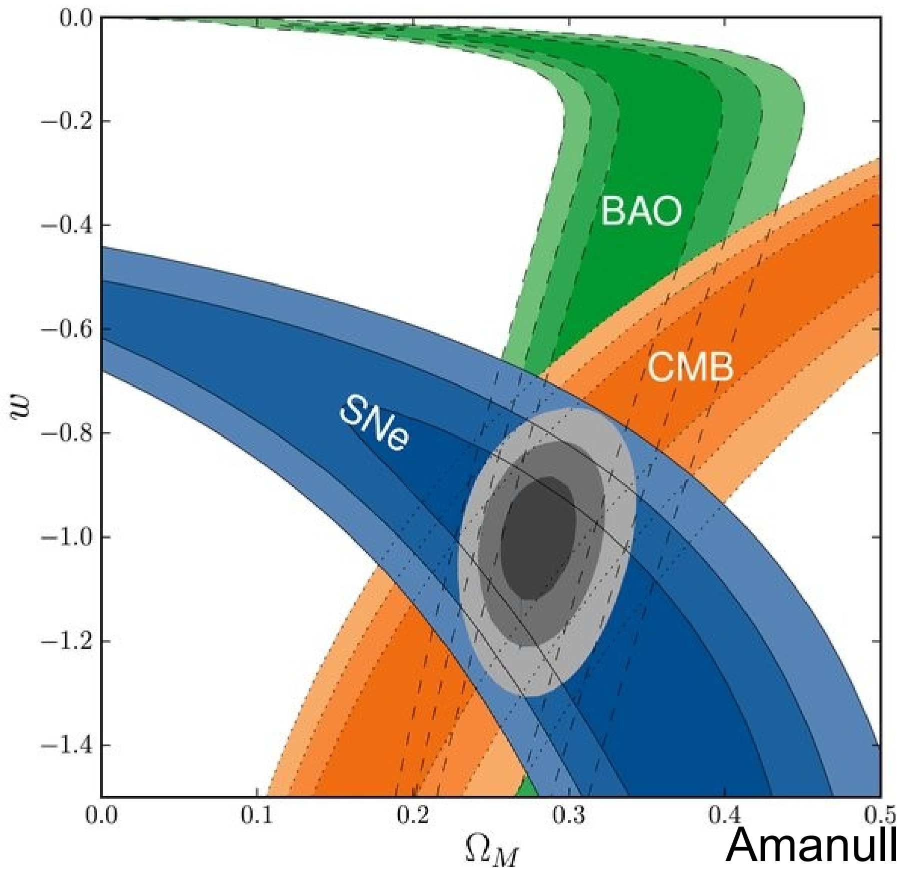
Description	Ω_m	w	Rel. Area [a]	w for $\Omega_m = 0.27$
Stat only	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058
All systematics	0.18 ± 0.10	$-0.91^{+0.17}_{-0.24}$	1.85	$-1.08^{+0.10}_{-0.11}$
Calibration	$0.191^{+0.095}_{-0.104}$	$-0.92^{+0.17}_{-0.23}$	1.79	-1.06 ± 0.10
SN model	$0.195^{+0.086}_{-0.101}$	$-0.90^{+0.16}_{-0.20}$	1.02	-1.027 ± 0.059
Peculiar velocities	$0.197^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.03	-1.034 ± 0.059
Malmquist bias	$0.198^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.07	-1.037 ± 0.060
Non-Ia contamination	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058
MW extinction correction	$0.196^{+0.084}_{-0.100}$	$-0.90^{+0.16}_{-0.20}$	1.05	-1.032 ± 0.060
SN evolution	$0.185^{+0.088}_{-0.099}$	$-0.88^{+0.15}_{-0.20}$	1.02	-1.028 ± 0.059
Host relation	$0.198^{+0.085}_{-0.102}$	$-0.91^{+0.16}_{-0.21}$	1.08	-1.034 ± 0.061

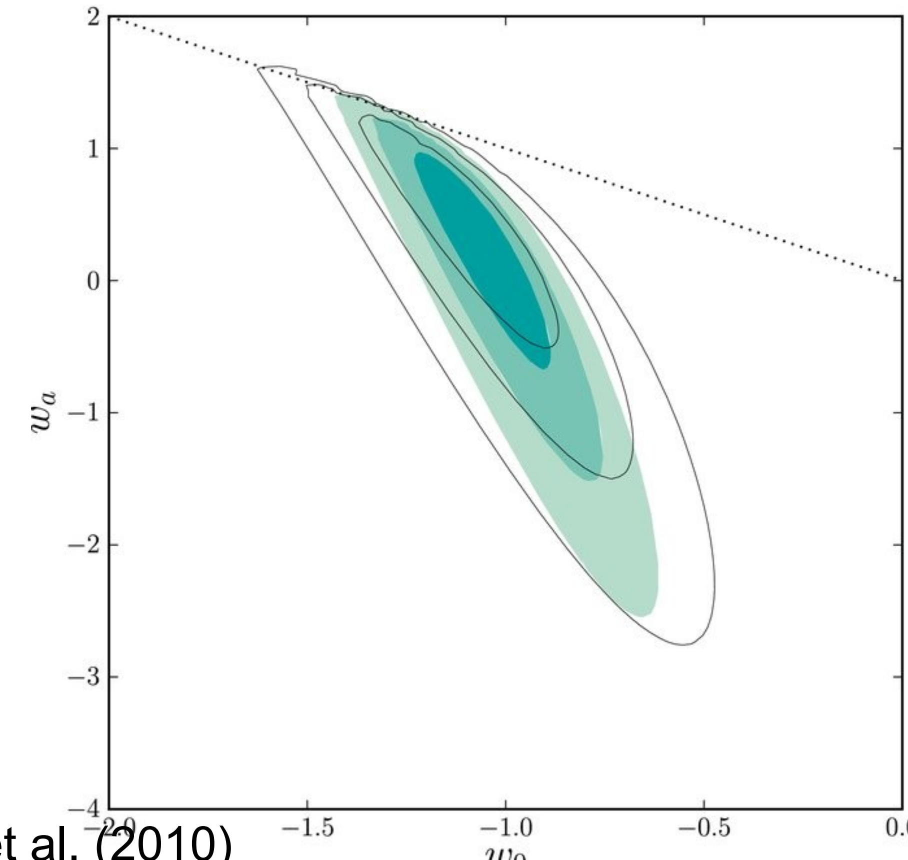
Conley et al. (2011)

- Statistics dominated per parameter (?)
- Systematics dominated per error ellipse
- Calibration the dominant systematic

SNe Ia Works 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

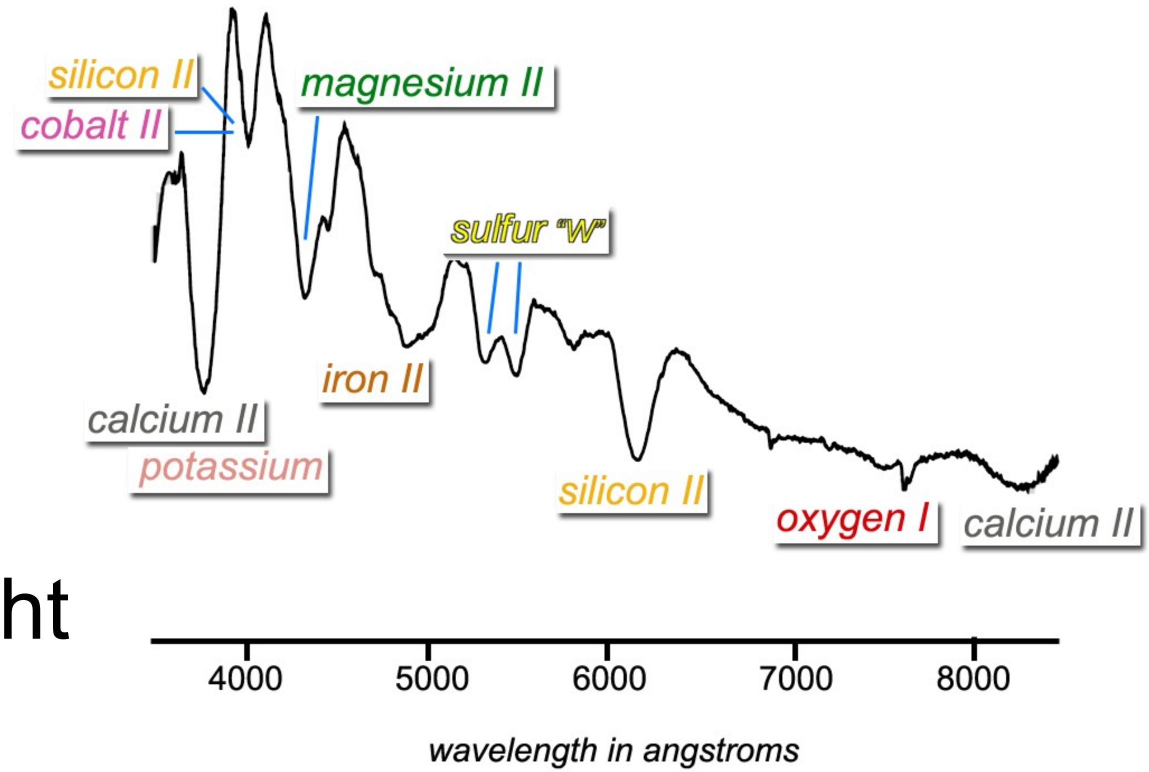




Amanullah et al. (2010)

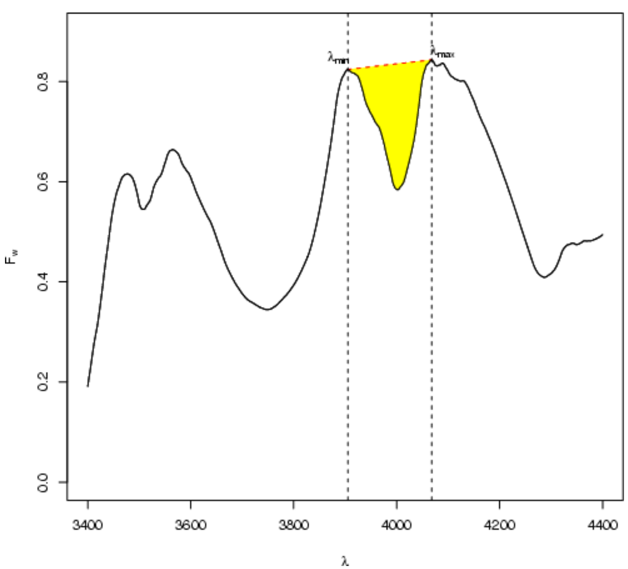
Supernova Heterogeneity Through Spectrum

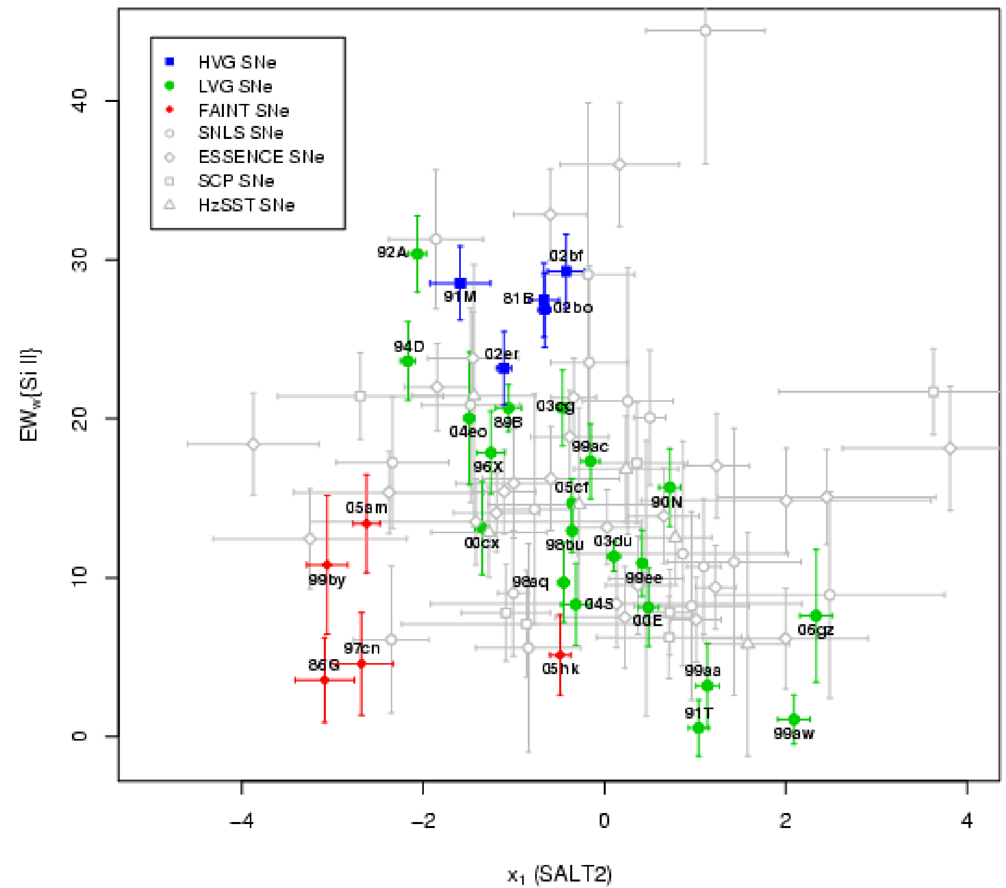
- SNIa subclasses (heterogeneity) observed at low-z
- Heterogeneity may affect determination of distances
- Tracers seen in spectrum but not light curves



Single Epoch Spectrum Contains Light Curve Shape Info?

- SiII feature at ~4000A at peak brightness
  - Can be used to identify subclasses
  - Strongly correlated with light-curve shape

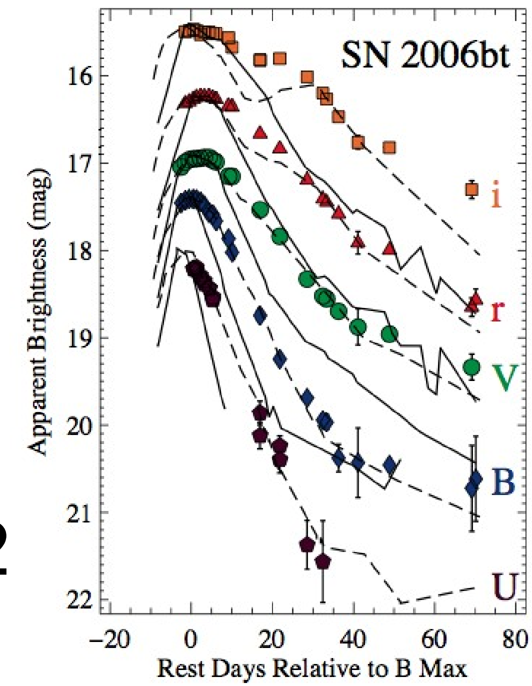


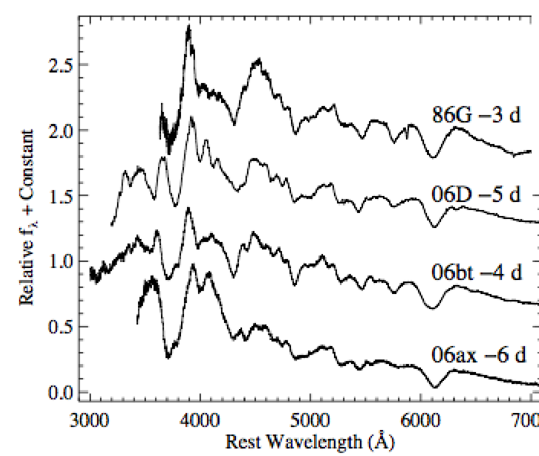


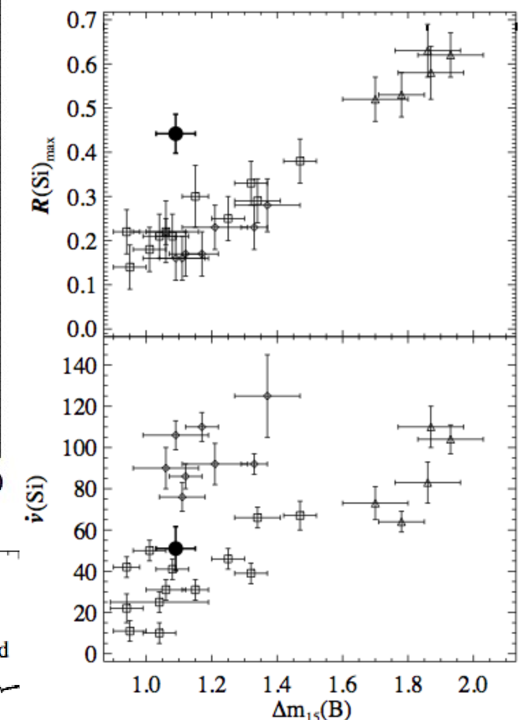
Arsenijevic et al. (2008)
see also Nordin et al. (2011)

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





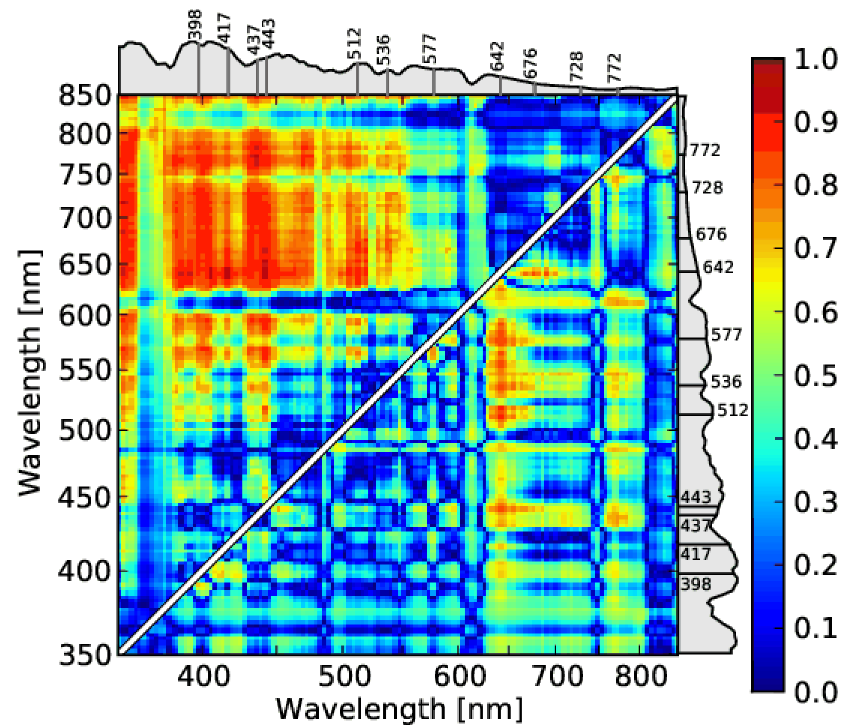


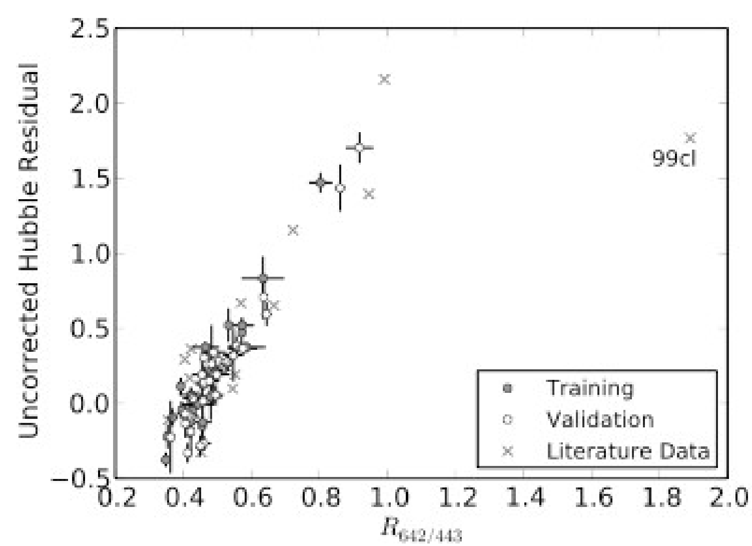
Foley et al. (2009)

Spectra Contain Intrinsic Magnitude Info

Bailey et al. (2009)

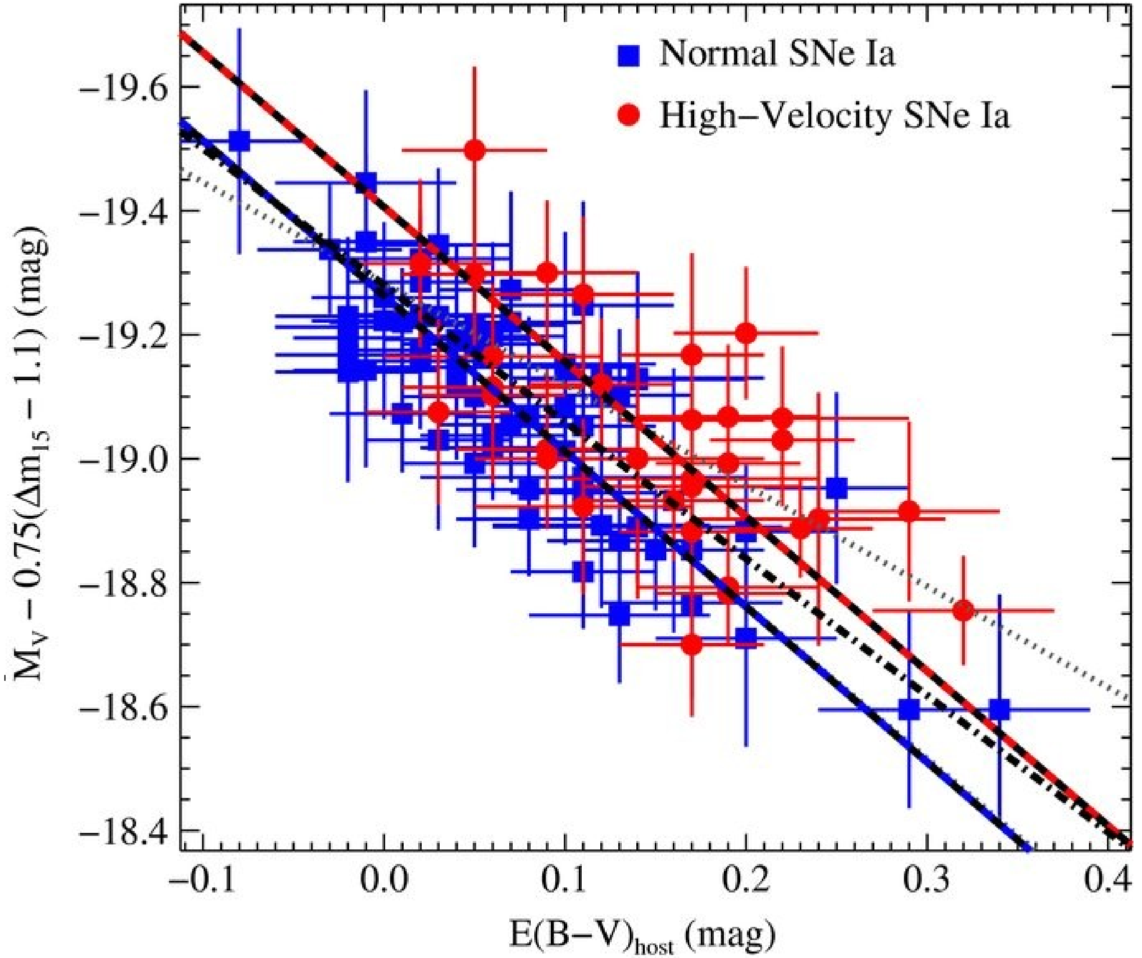
- Figure shows correlation between spectral flux ratios and absolute magnitude
- Flux ratio almost linearly related to absolute magnitude
- More information than is in shape





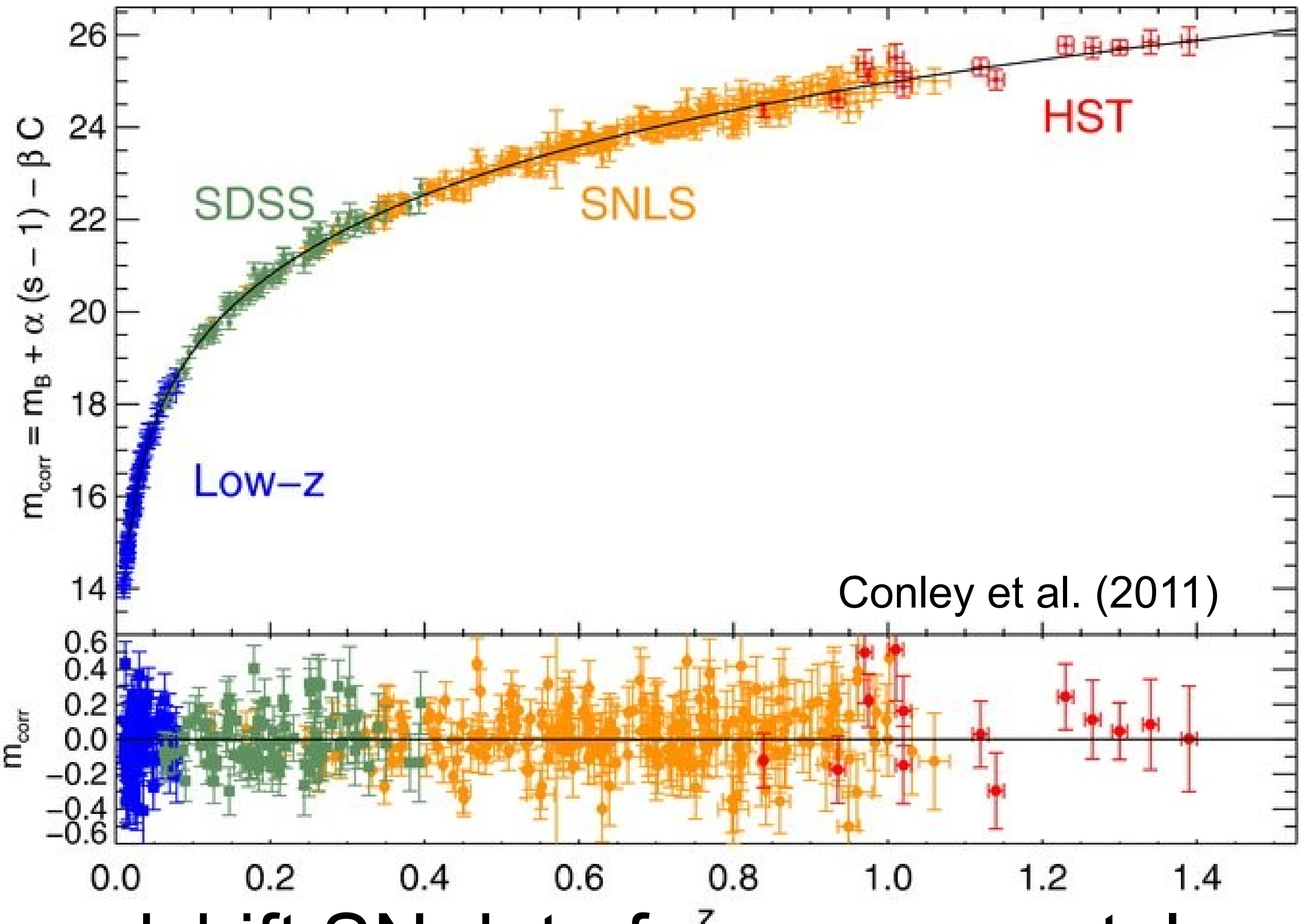
Spectra Contain Intrinsic Magnitude/Color Info

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



Foley et al. (2011)

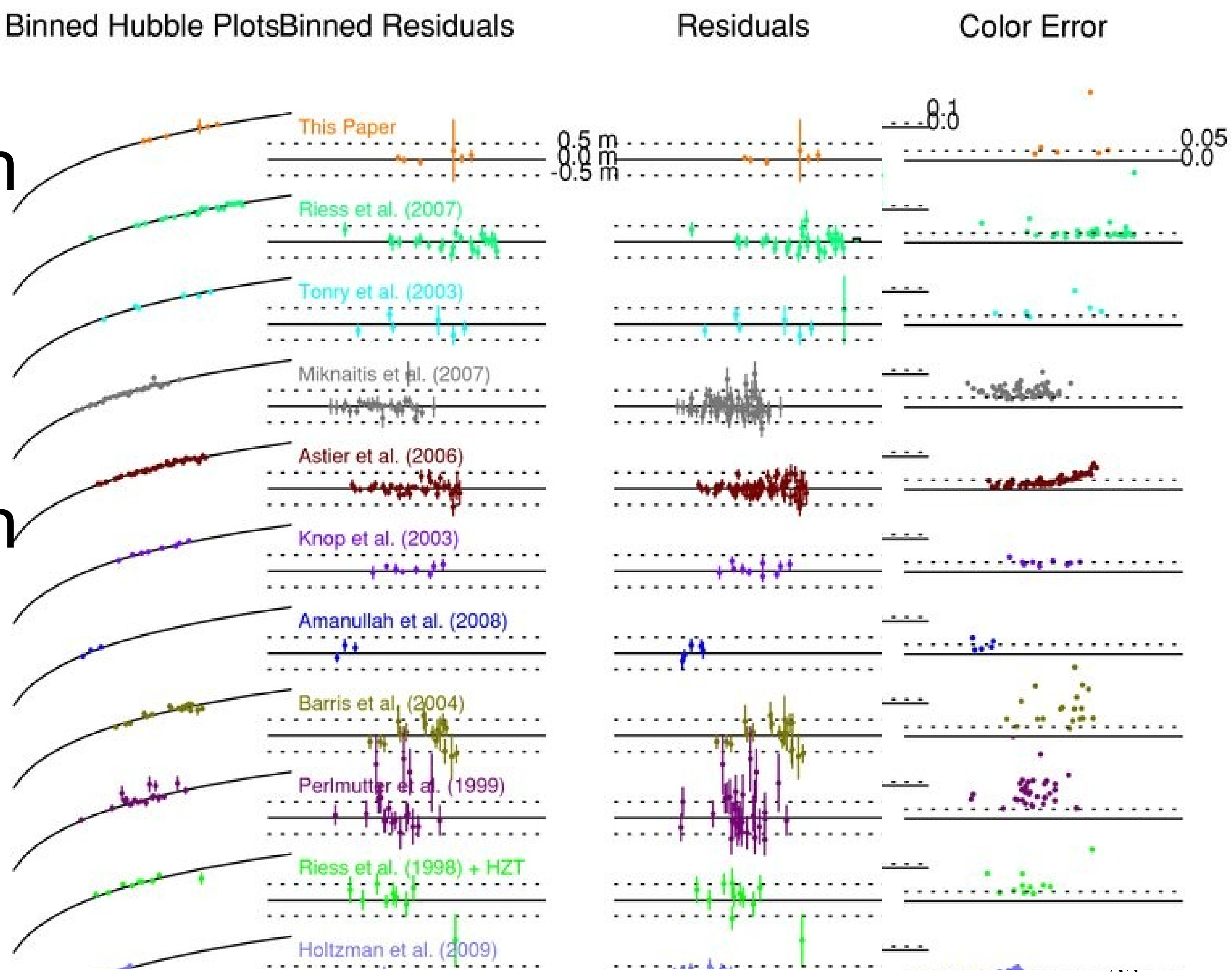
A Feature of the Current Data Set



- High-redshift SN data from a space telescope because light is redshifted to near-infrared

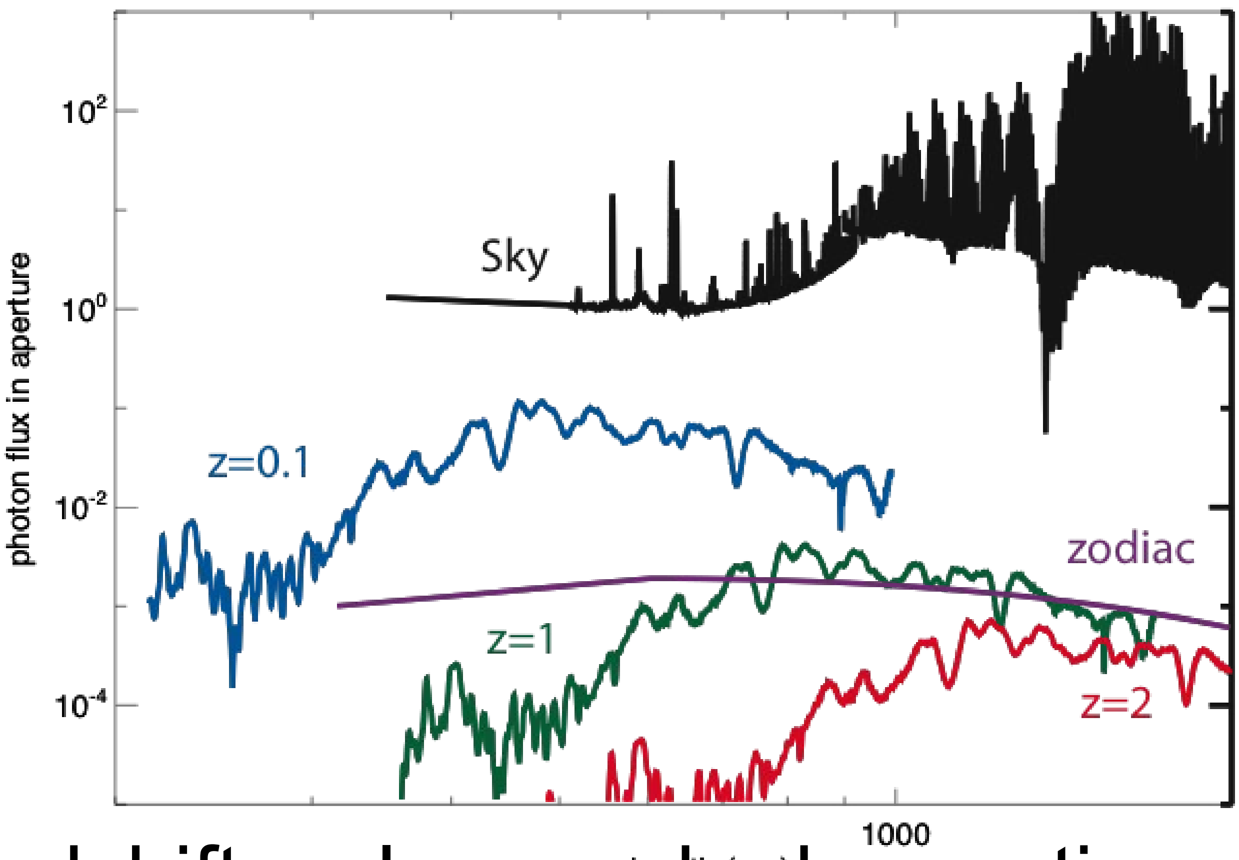
A Feature of the Current Data Set

- Color errors increase with redshift
- Distance errors increase with color errors
- Exacerbated with 2 color parameters (3 filtets)



Amanullah et al. (2010)

A Wall: Going Red

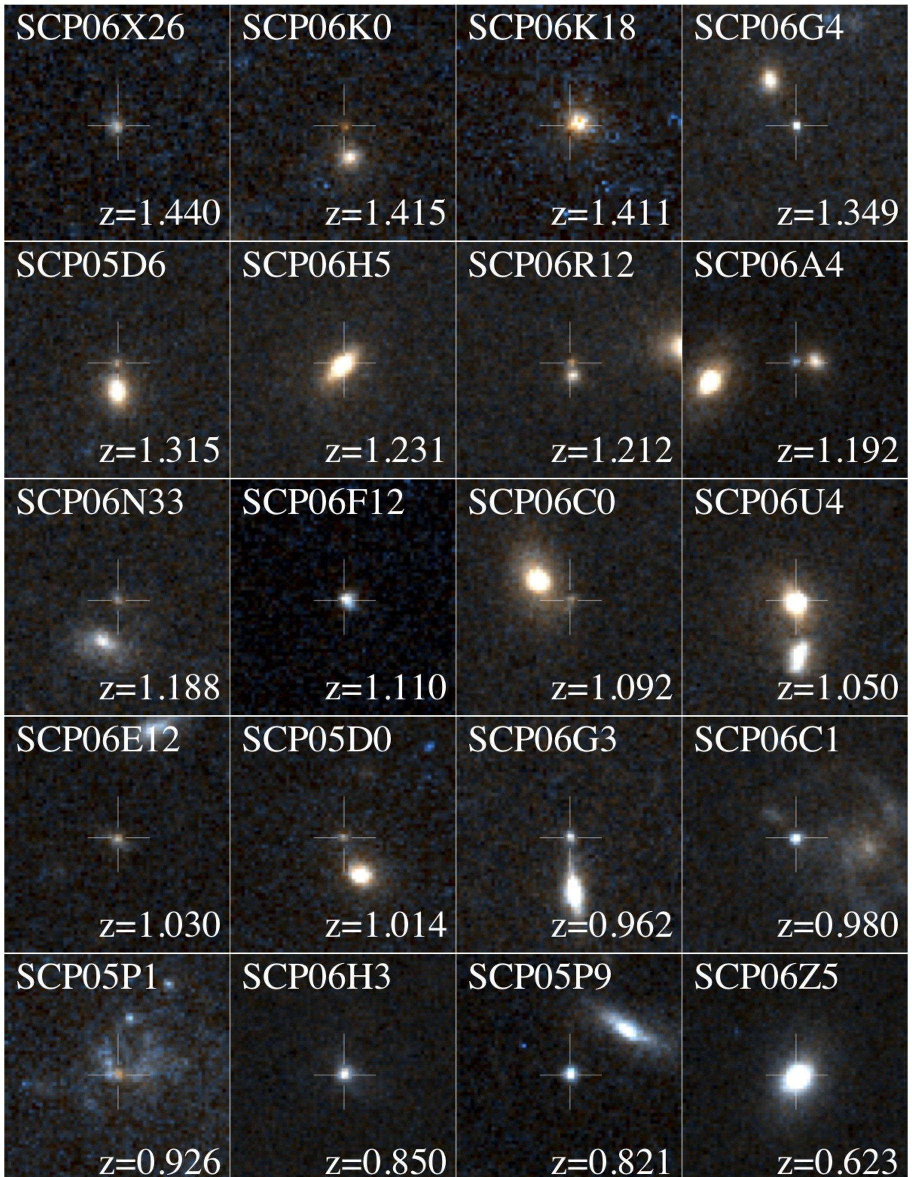


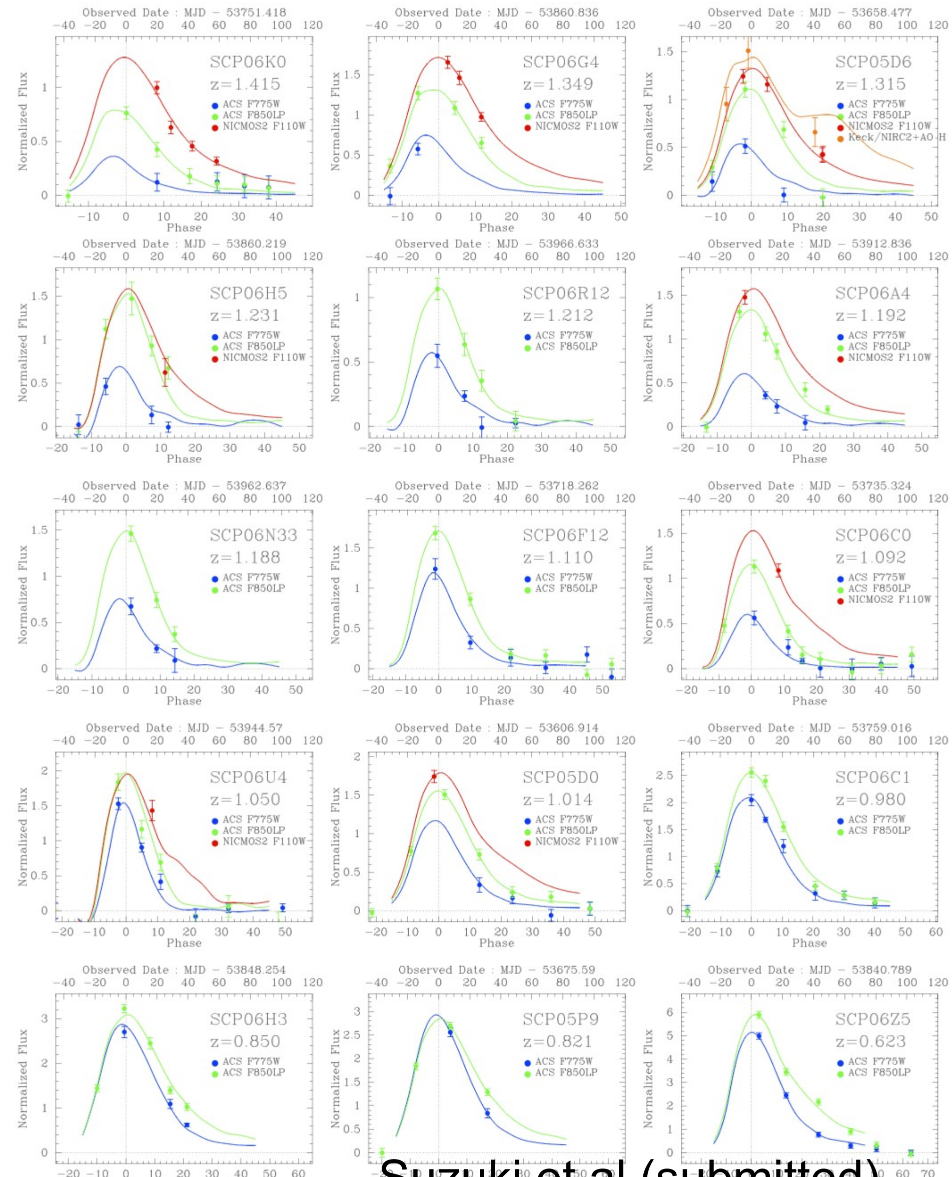
- High-redshift, colors push observations to NIR
  - Ground sky background bright
  - Space zodiacal background faint
- Makes photometry and spectroscopy difficult

Realm of Precision Cosmology

- If today's high-z SN data suggested a ~1.5σ-inconsistency from a cosmological constan we could could come up with a plausible explanation based o population evolution of the spectral diversity just shown
  - No high-quality high-z spectra
- We shouldn't feel too comfortable that we are consistent with cosmological constant
- Next generation surveys need to be robust for systematic uncertainties we know may affect the measurements

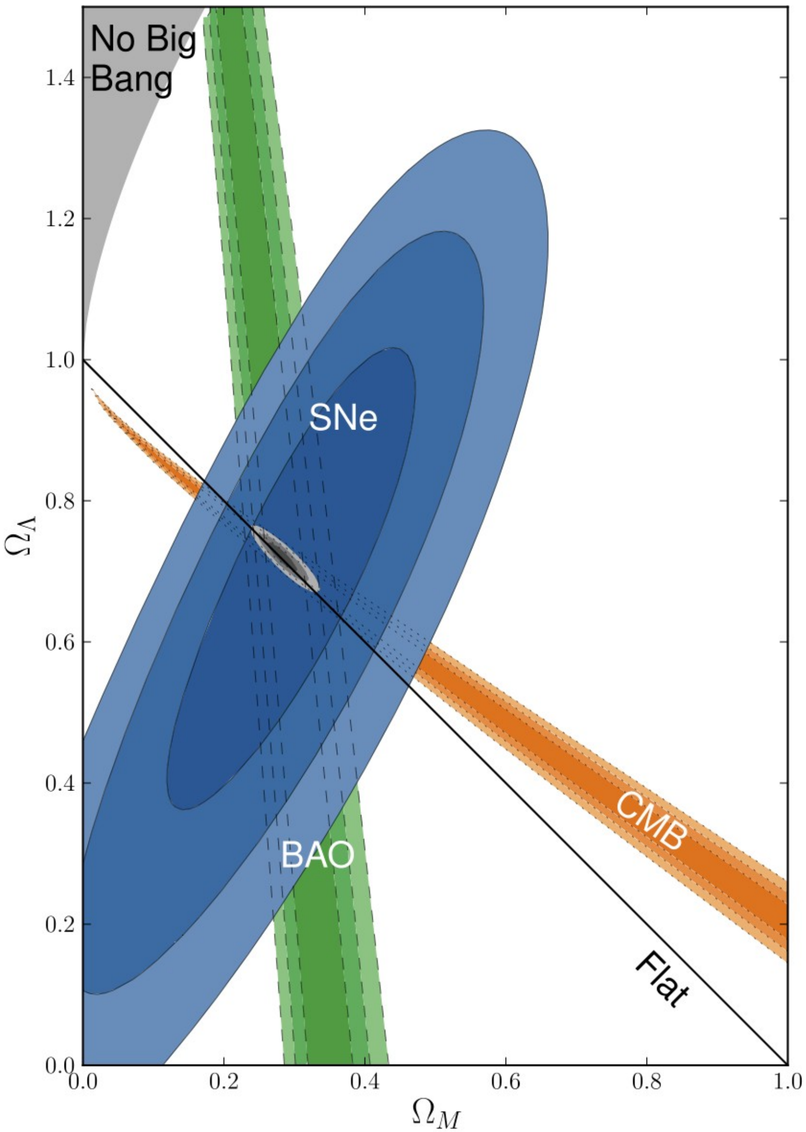
HST Cluster SN Survey

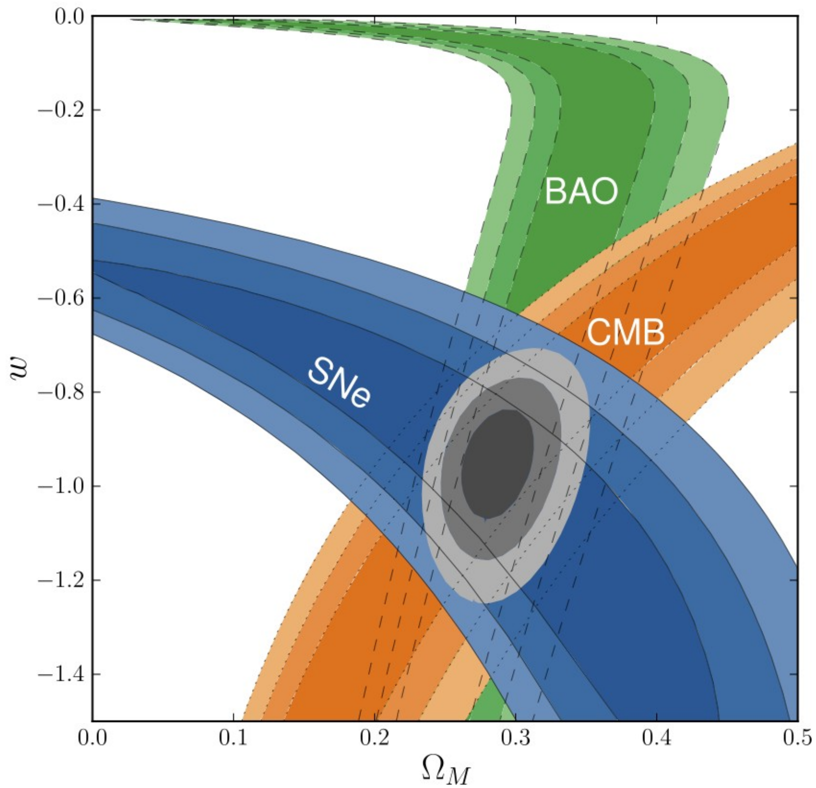




Suzuki et al (submitted)

HST Cluster SN Survey

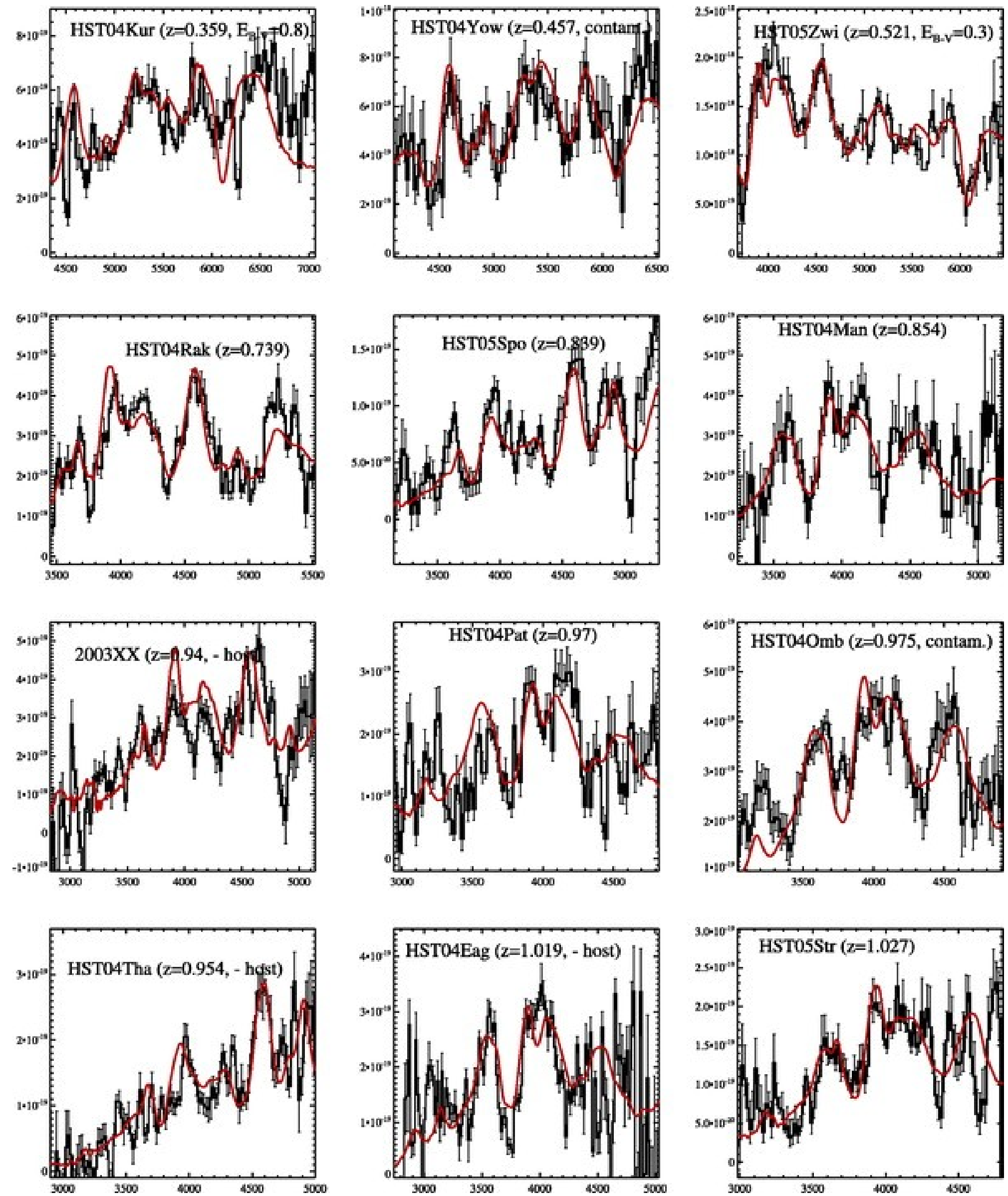




Suzuki et al (submitted)

HST SN Spectroscopy

- Limited wavelength range
- Slitless spectrograph has low signal-to-noise



Riess et al. (2007)

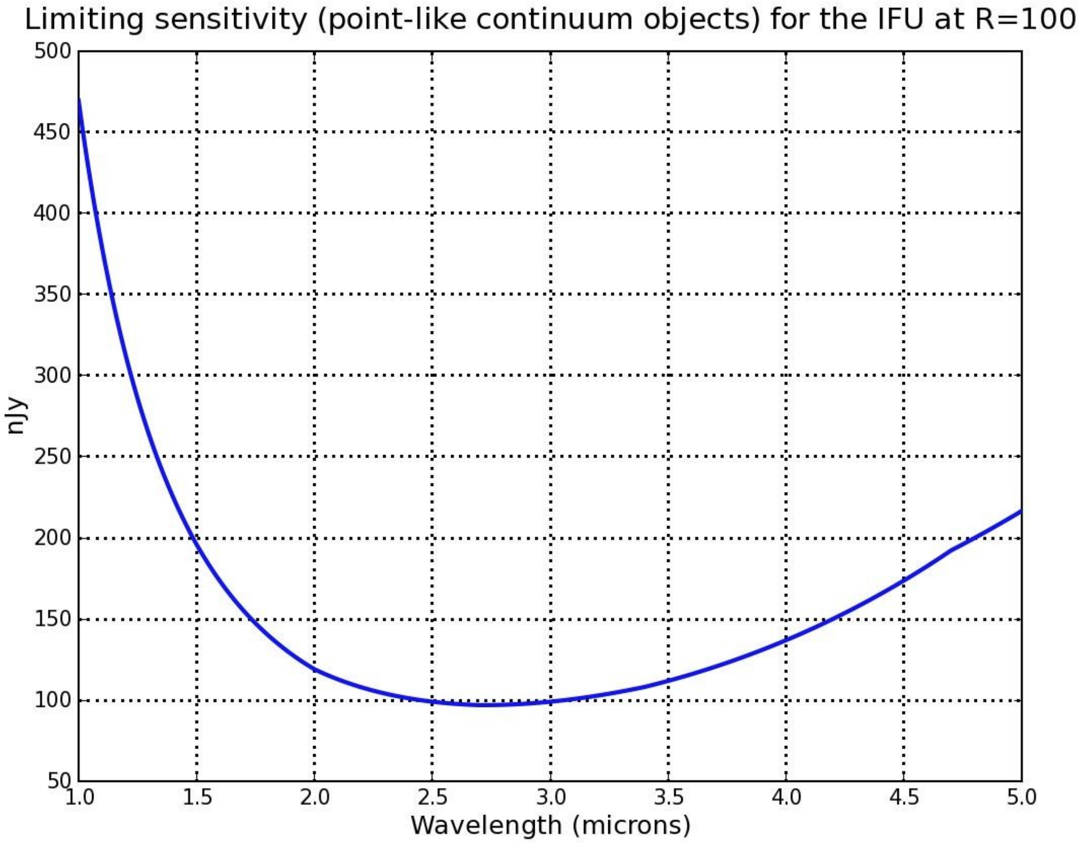
HST Not The Solution

- Adam expects to get only ~8 more high-z SNe
  - Field of view is too small
- Slitless spectroscopy OK for typing but not for distinguishing subtypes

JWST Not An Optimal Solution

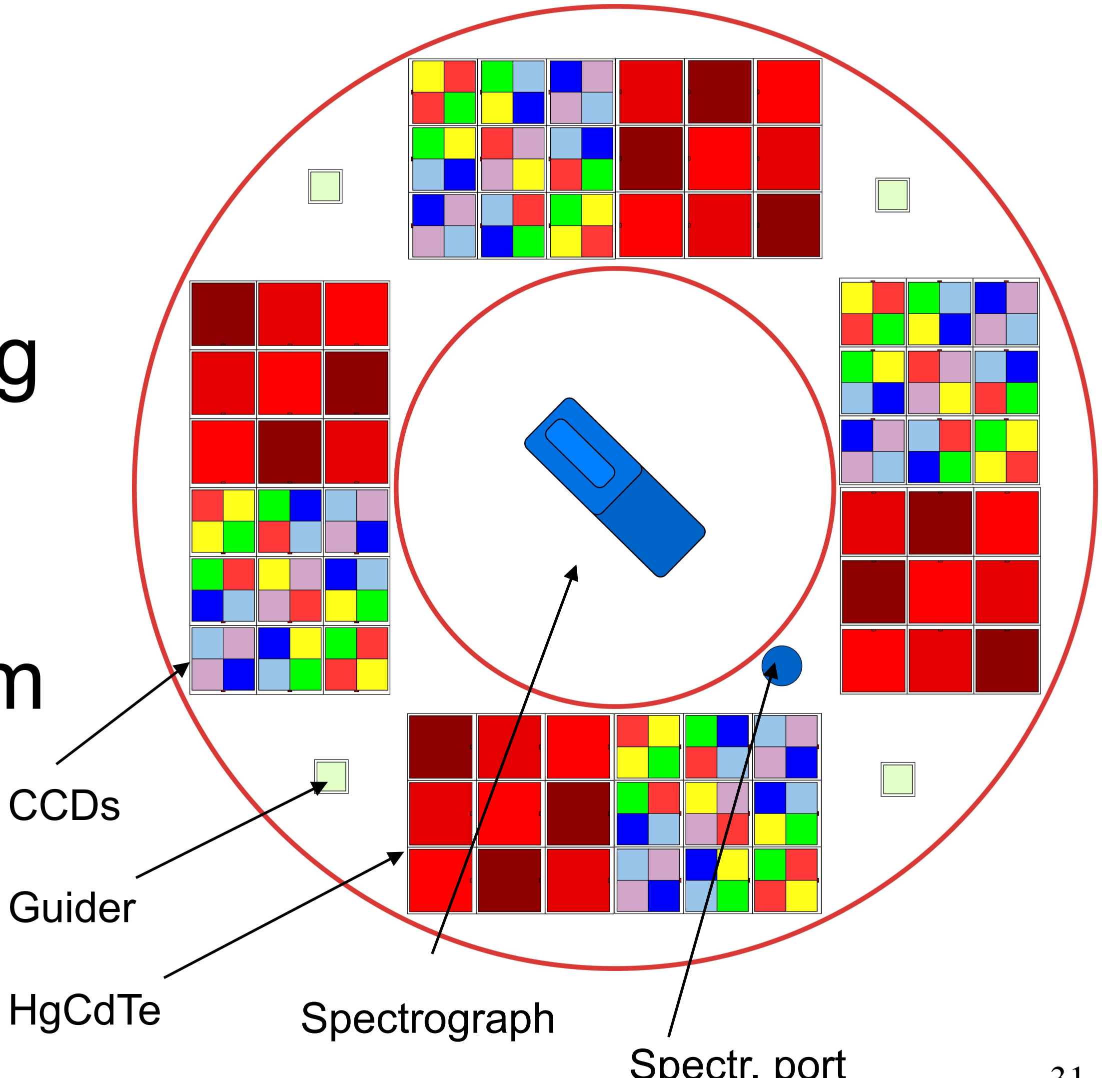
- Near Infrared Camera (NIRCam)
  - FOV: 2.2' x 2.2'
- Near Infrared Spectrograph
  - 0.1" slice (undersampled at 1 um)
  - Total throughput 20% on average
  - Inefficient at <2 μm

S/N=10
After 10^4 sec



Logical Next Step: A Supernova Cosmology Satellite

- 2-m aperture telescope
- Multiplexed light curves from a rolling search with a large field imager
- Deep spectrum from targeted spectroscopy

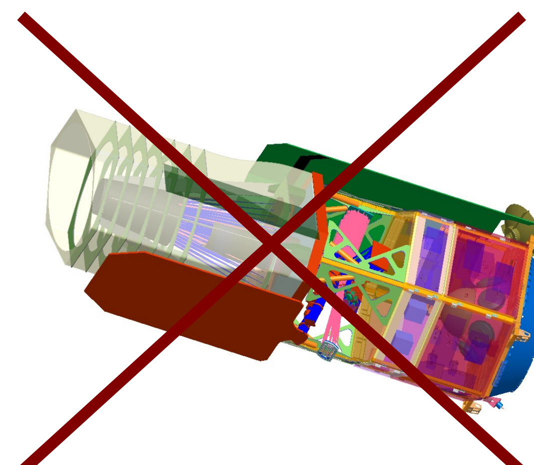


SNAP focal plane

Logical Next Step: A Supernova Cosmology Satellite

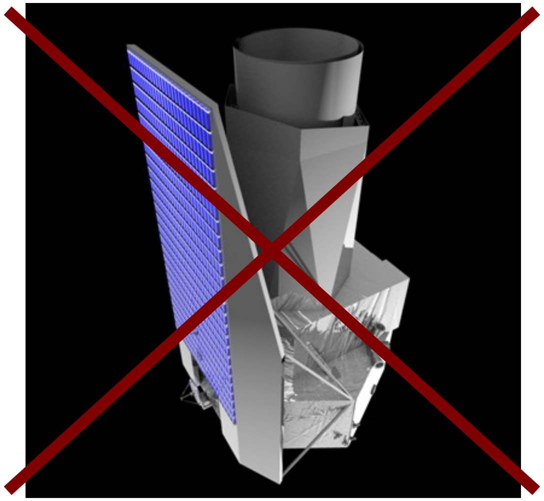
- SNAP was a satellite optimized for SNIa and Weak Lensing with an added BAO survey
- JDEM was a satellite optimized for SNIa, Weak Lensing, and BAO survey
- WFIRST is a satellite optimized for exoplanets, dark energy, and NIR imaging surveys
  - Baseline has no IFU spectrometer





Logical Next Step: A Supernova Cosmology Satellite

- Euclid the ESO Dark Energy satellite
- No SN survey



JDEM-ISWG

- Lesson from the JDEM-Interim Science Working Group
- Charged with designing a SN/BAO/WL DE mission with a $600M cost cap
- Imager was the high risk item in the cost model
- All three probes need a wide-field imager but different requirements drove different costs

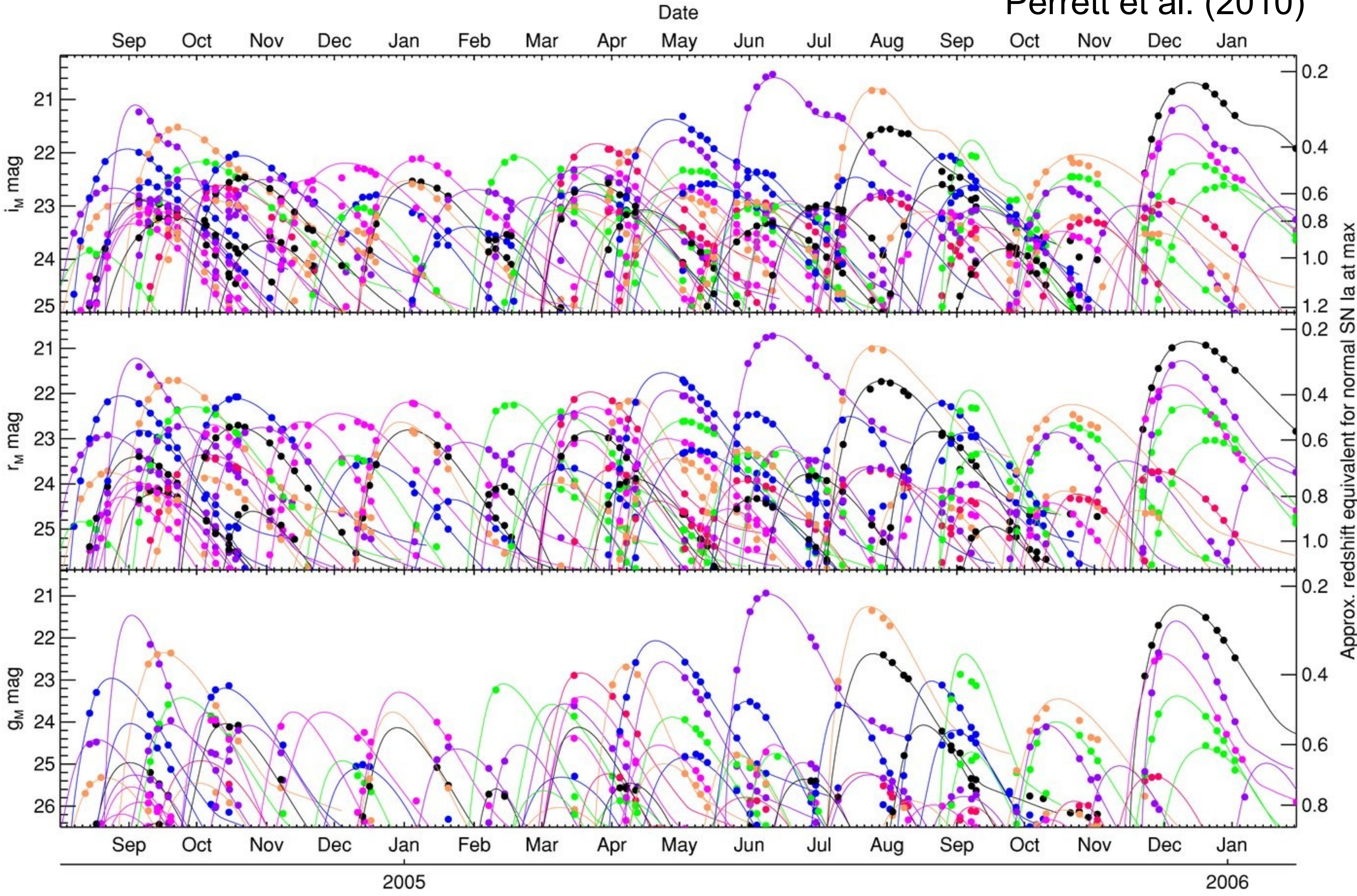
	Nyquist Sampling	Wavelength	~10 Filters	
				$
BAO	No	NIR	No	
WL	Yes	Red-NIR	No	
SNe Ia	Yes	Blue-NIR	Yes	$$$

Rolling Survey

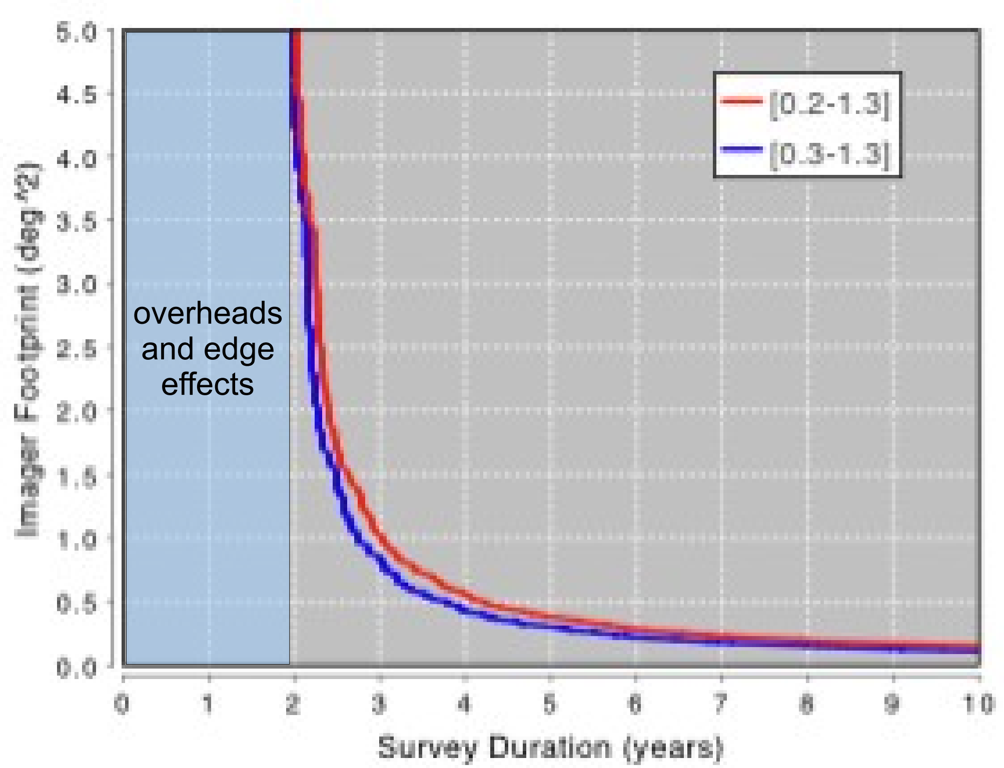
- The observing strategy for all proposed SN dark-energy missions
- Driver for wide-field multi-band Nyquist-sampled SN imager
- Cadenced observing in all channels automatically produces desired light curves for all SNe in the field
  - Multiple SNe in the instrumental footprint give multiplex advantage
  - Exposure times set by faintest targeted supernova

Rolling Survey SNLS

Perrett et al. (2010)



Solid Angle For Multiplex Advantage

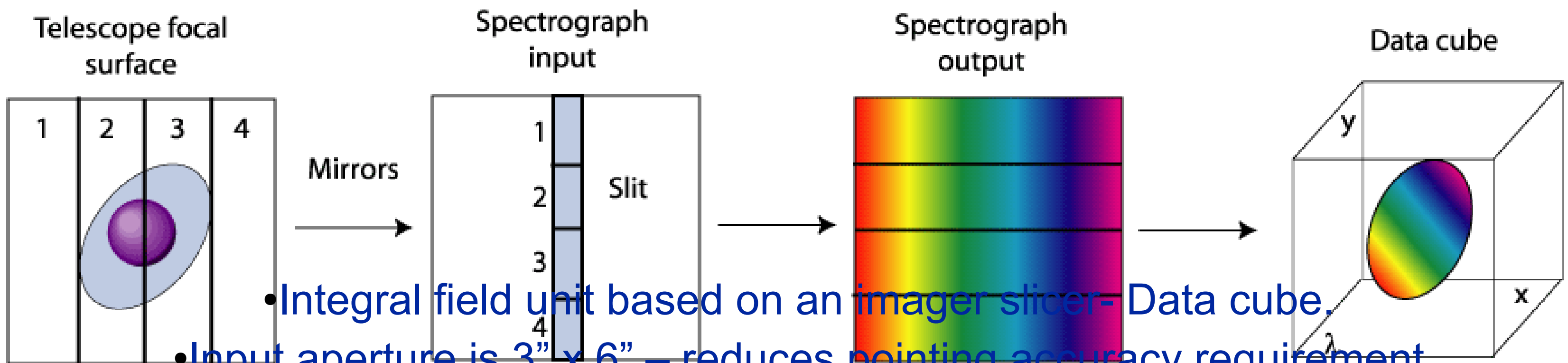


- A rolling survey going out to z=1.3 needs solid angle >~0.9 sq deg to get the powerful advantages of multiplexing

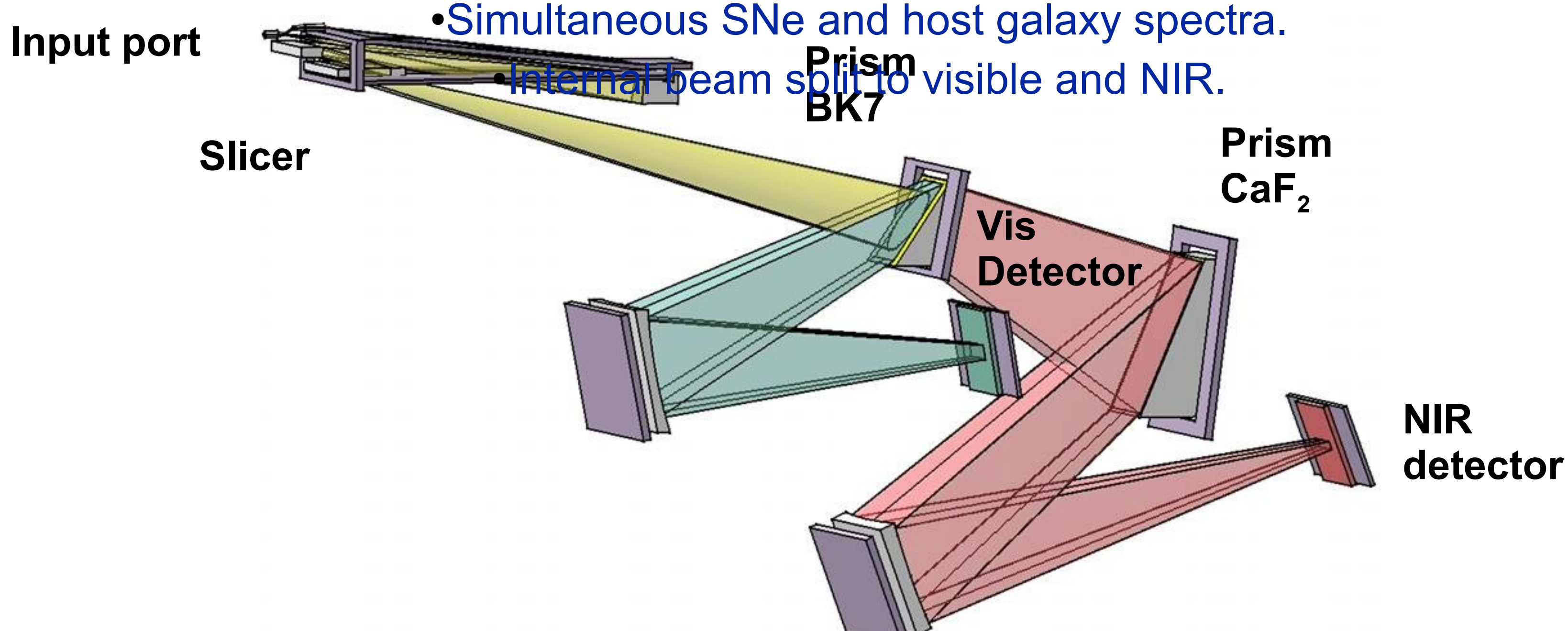
JDEM-ISWG Solution

- SN light curve requirements and cost cap restricted the imager field of view
- Supernova search with imager
  - Image quality not so important
  - 2-3 bands for discovery and typing only rather that 10 for complete color coverage
  - Sculpt redshift distribution
    - $dN/dz/d\Omega$ increases with redshift
    - For a flat redshift distribution taper search from wide/shallow to narrow/deep
- Triggered Spectroscopy

Integral Field Unit Spectrograph

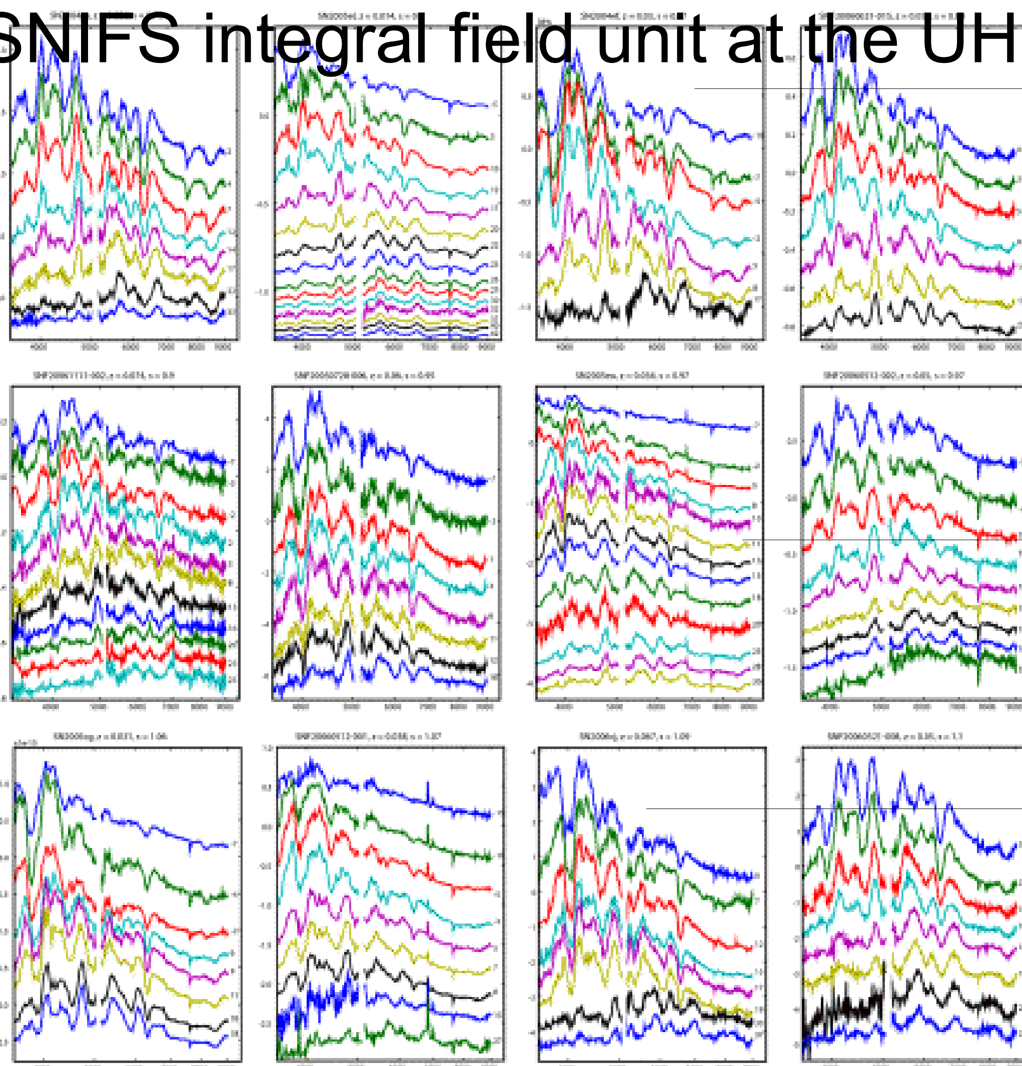


- Integral field unit based on an imager slicer- Data cube.
- Input aperture is 3" x 6" – reduces pointing accuracy requirement
- Simultaneous SNe and host galaxy spectra.
- Internal beam split to visible and NIR.



Not a New Idea

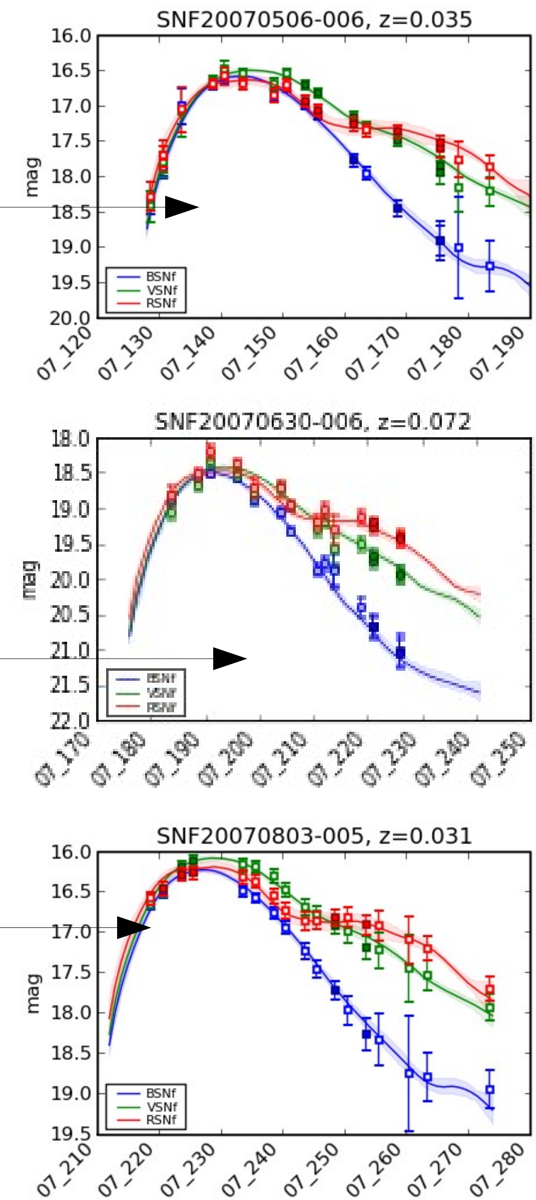
- SNFactory (Aldering et al.)
- SNIFS integral field unit at the UH 88”



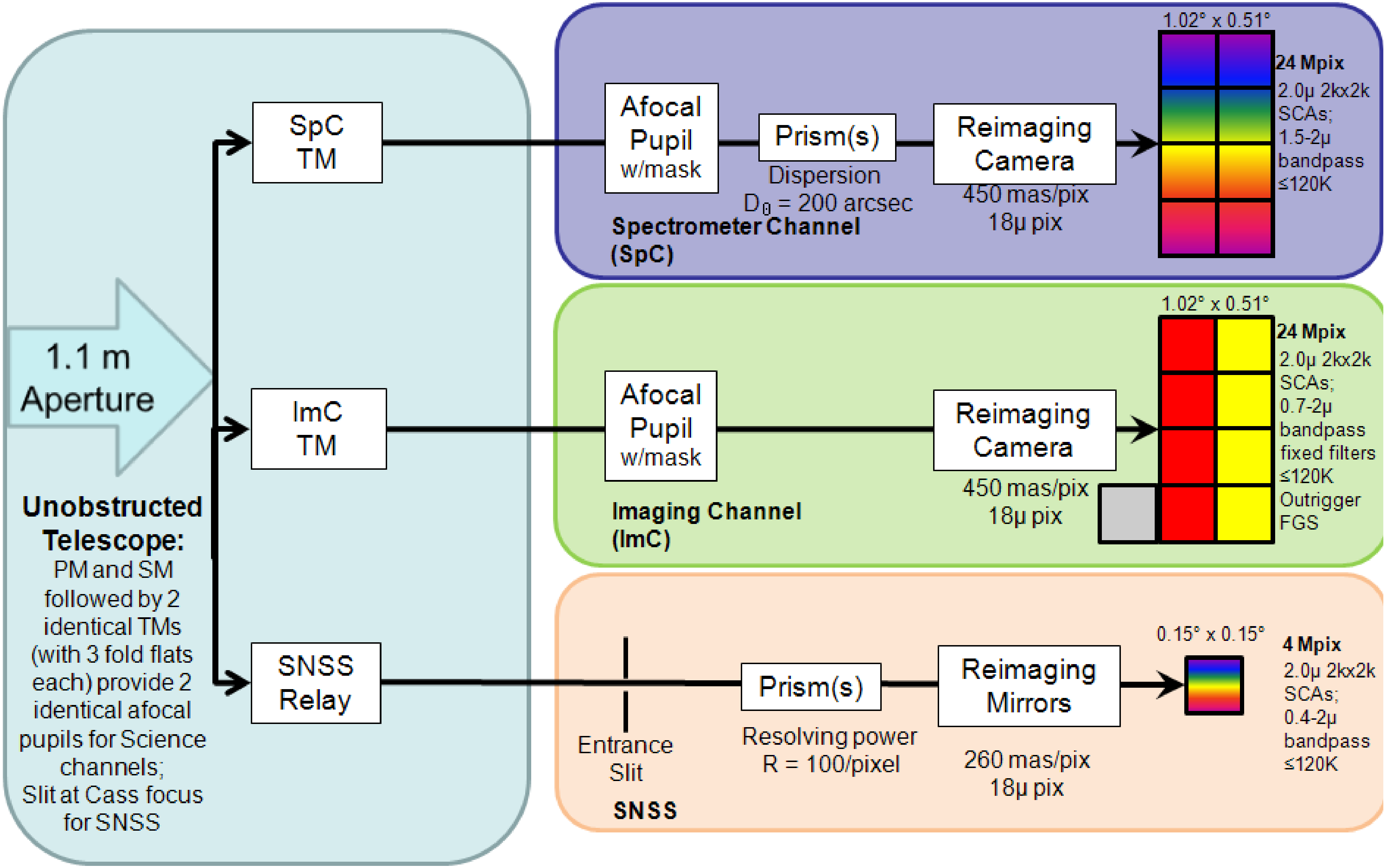
s = 0.90

s = 1.00

s = 1.10

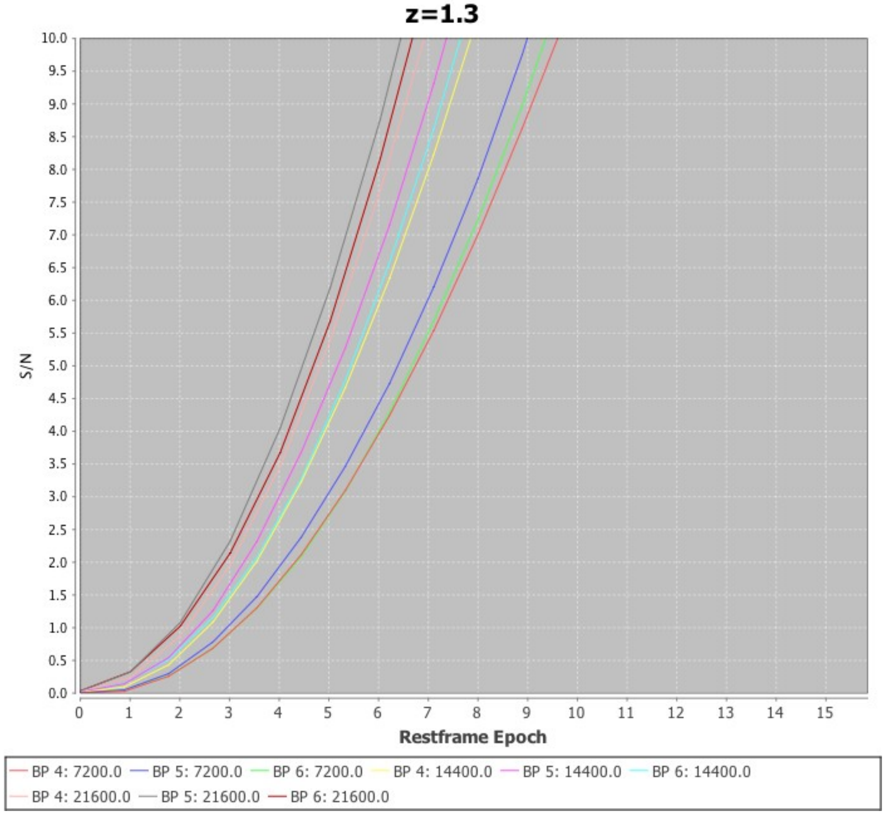


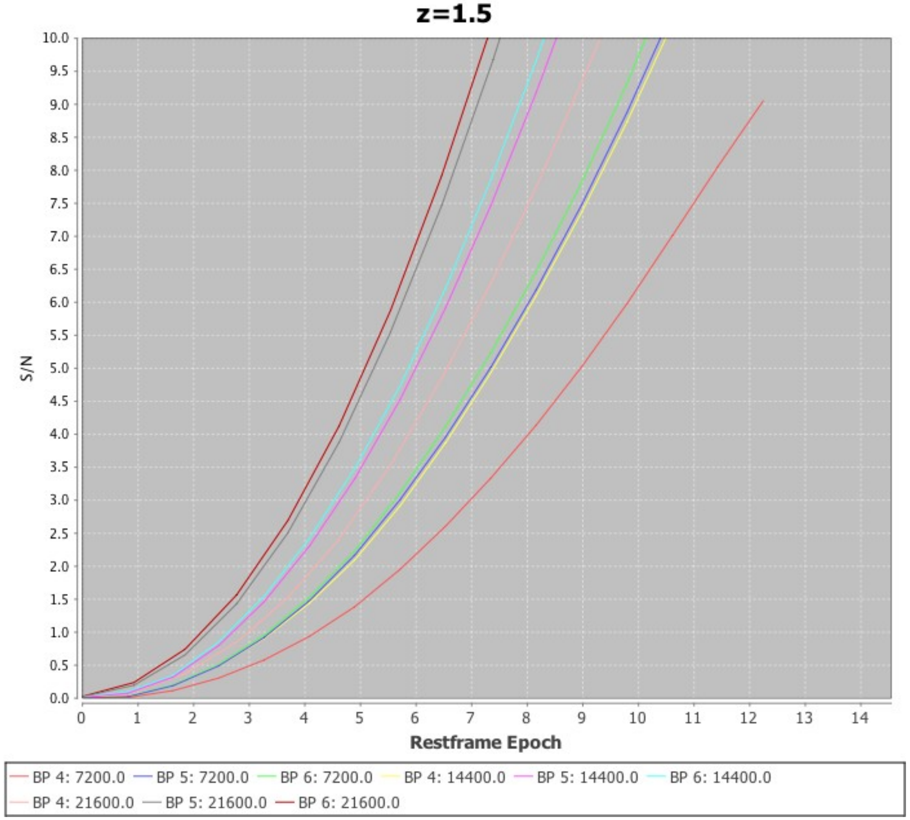
BAO/SNe Probe Concept



FGS = Fine Guidance Sensor

Visualizing Discovery S/N

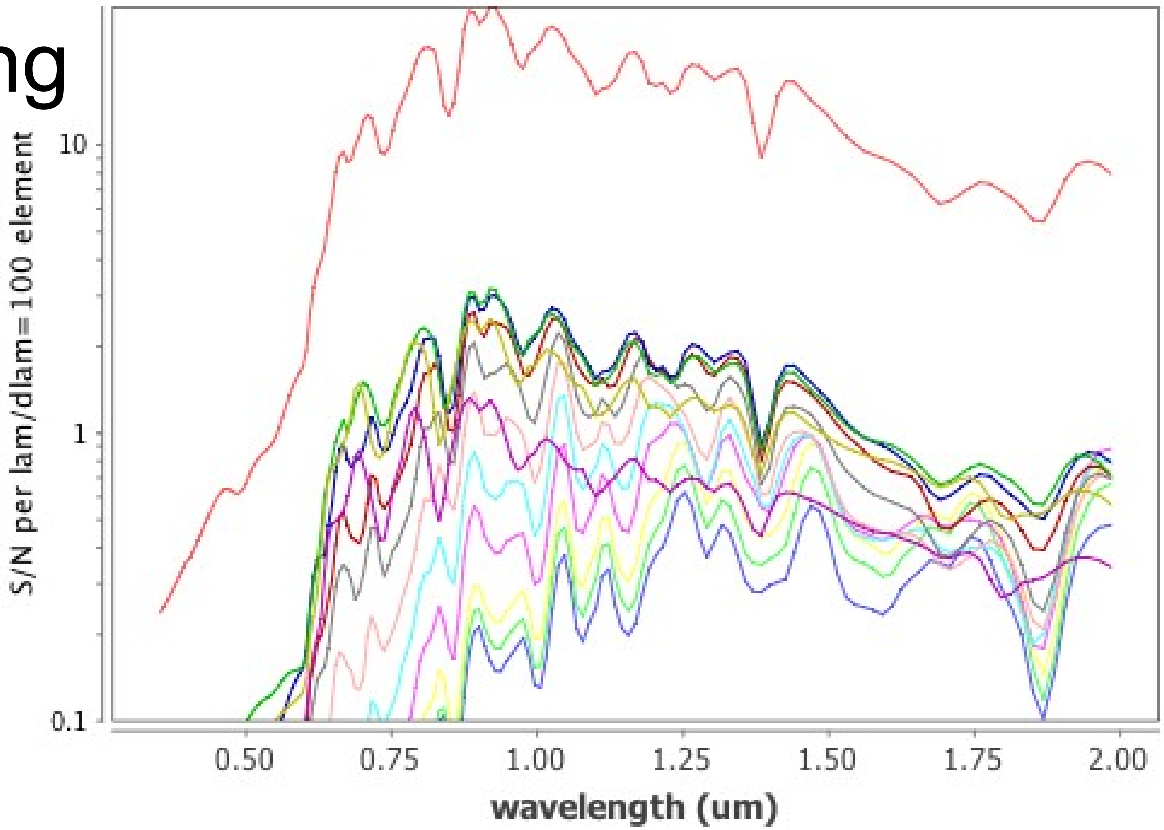




- S/N from BAO imager in different bands and exposure times
- Couple hours in two bands for deepest search

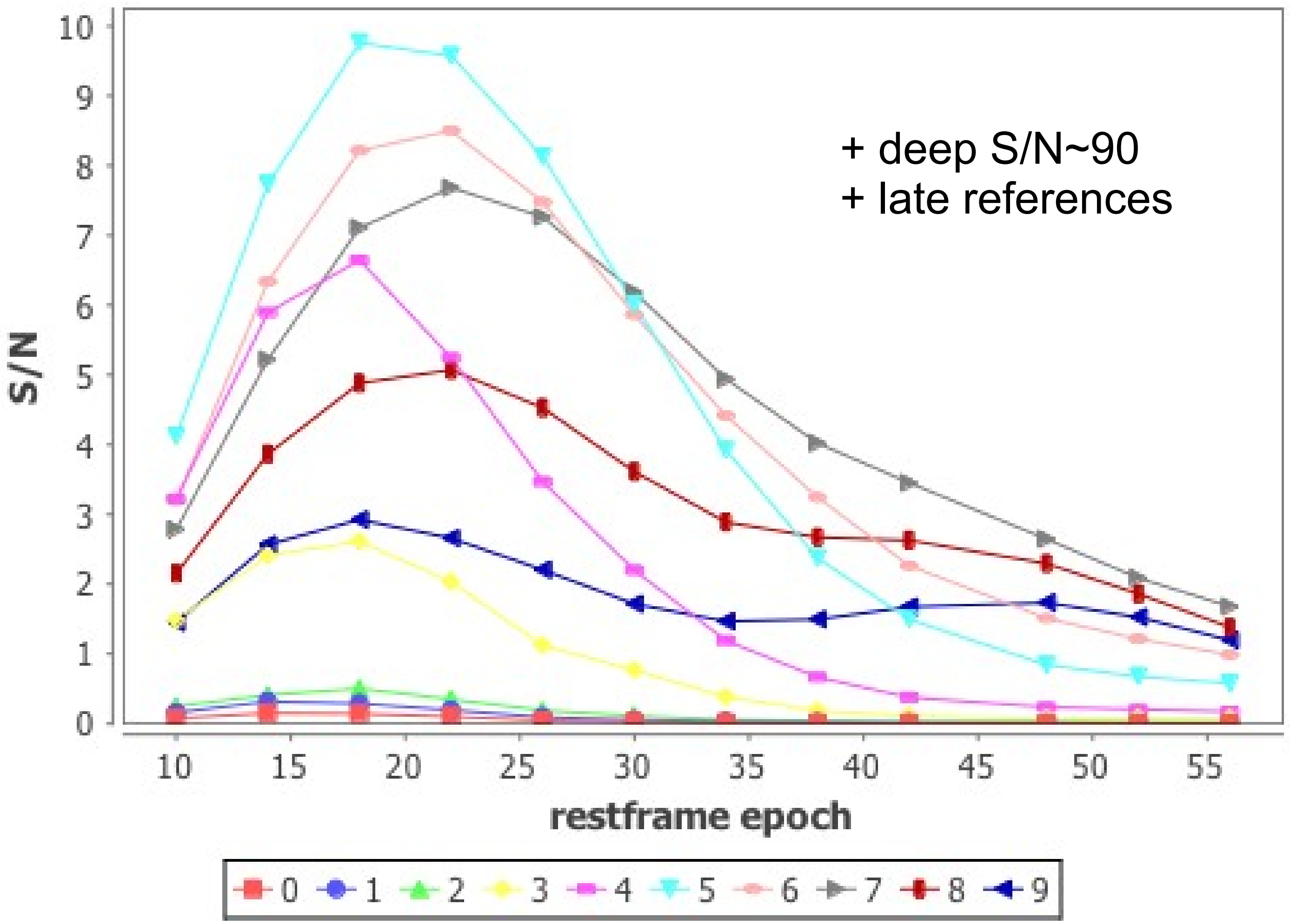
JDEM SN Ia Data Quality: Example

- 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

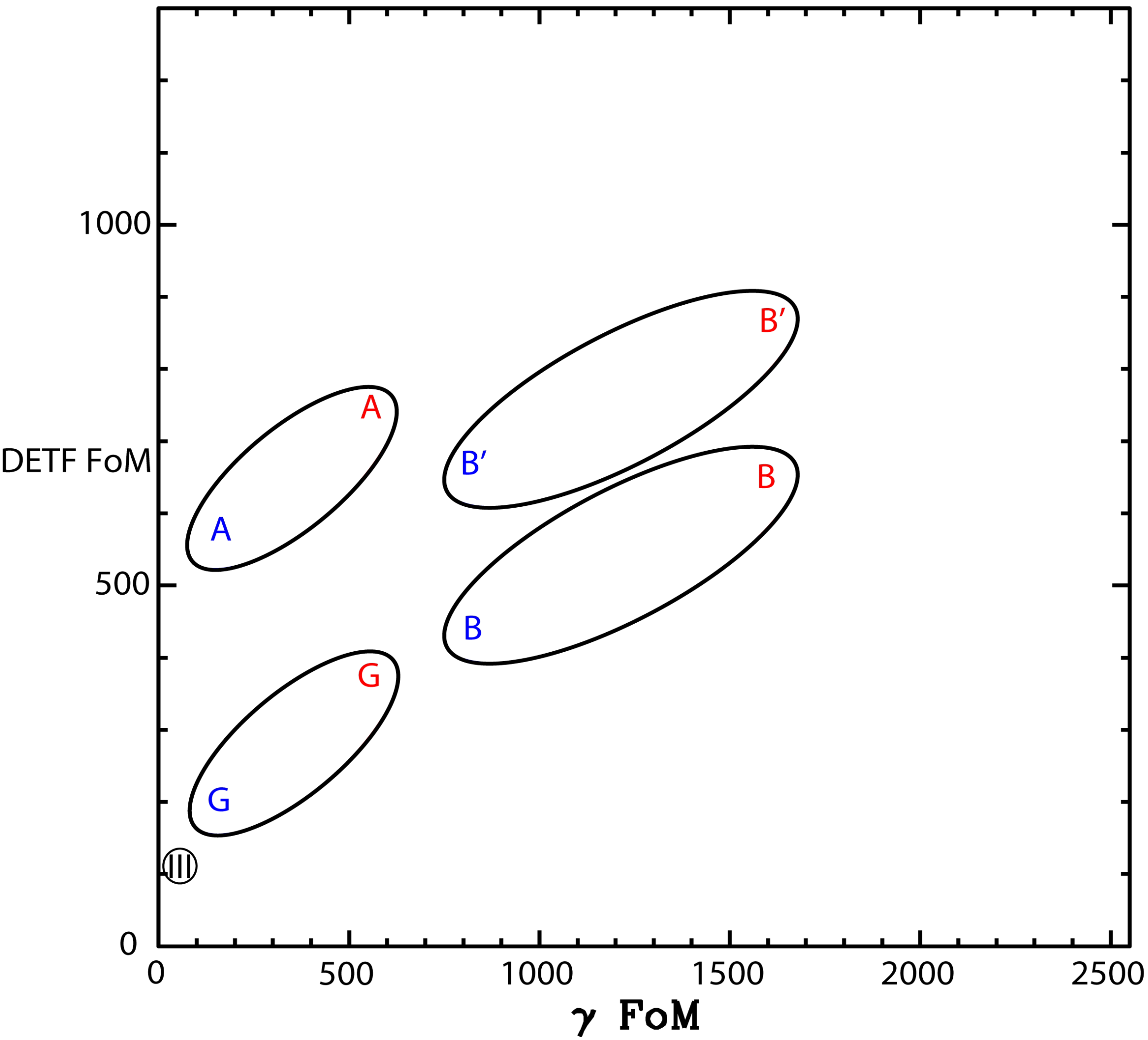
- Light curves in 10 independent synthetic bands



SN Survey Yield: Example

- WL requires a larger and high-resolution imager than BAO
  - Affects the search, SN spectroscopic followup same
- SN+BAO – optimized missions
  - IFU 133 SNe/0.1 bin $0.3<z<1.3$
  - Slit 108 SNe/0.1 bin $0.3<z<1.3$
- SN+BAO+WL – optimized mission
  - IFU 138 SNe/0.1 bin $0.3<z<1.3$
  - Slit 111 SNe/0.1 bin $0.3<z<1.3$
- Can trade numbers for redshift depth

Figure of Merit Summary



III 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

Conclusions=Outline

- Type Ia Supernovae as a Cosmological Probe
  - Standard candle distance indicator seen to high redshift
- Current cosmology constraints with SNe
  - Critical piece in best measurements of Dark Energy
  - Still room for improvement for both statistical and systematic uncertainties
- Why space?
  - Problems in ground observing irrelevant in space observing

Conclusions=Outline

- Need for a spectrum
  - Traces SN Ia heterogeneity that could bias cosmological measurements
- Existing/planned space telescopes
  - Community (HST/JWST)
    - Not well suited
  - “Dark Energy” Missions (Euclid/WFIRST)
    - No SN component as is
- A perturbative solution exists requiring:
  - Change in SN survey strategy
  - A minor hardware addition