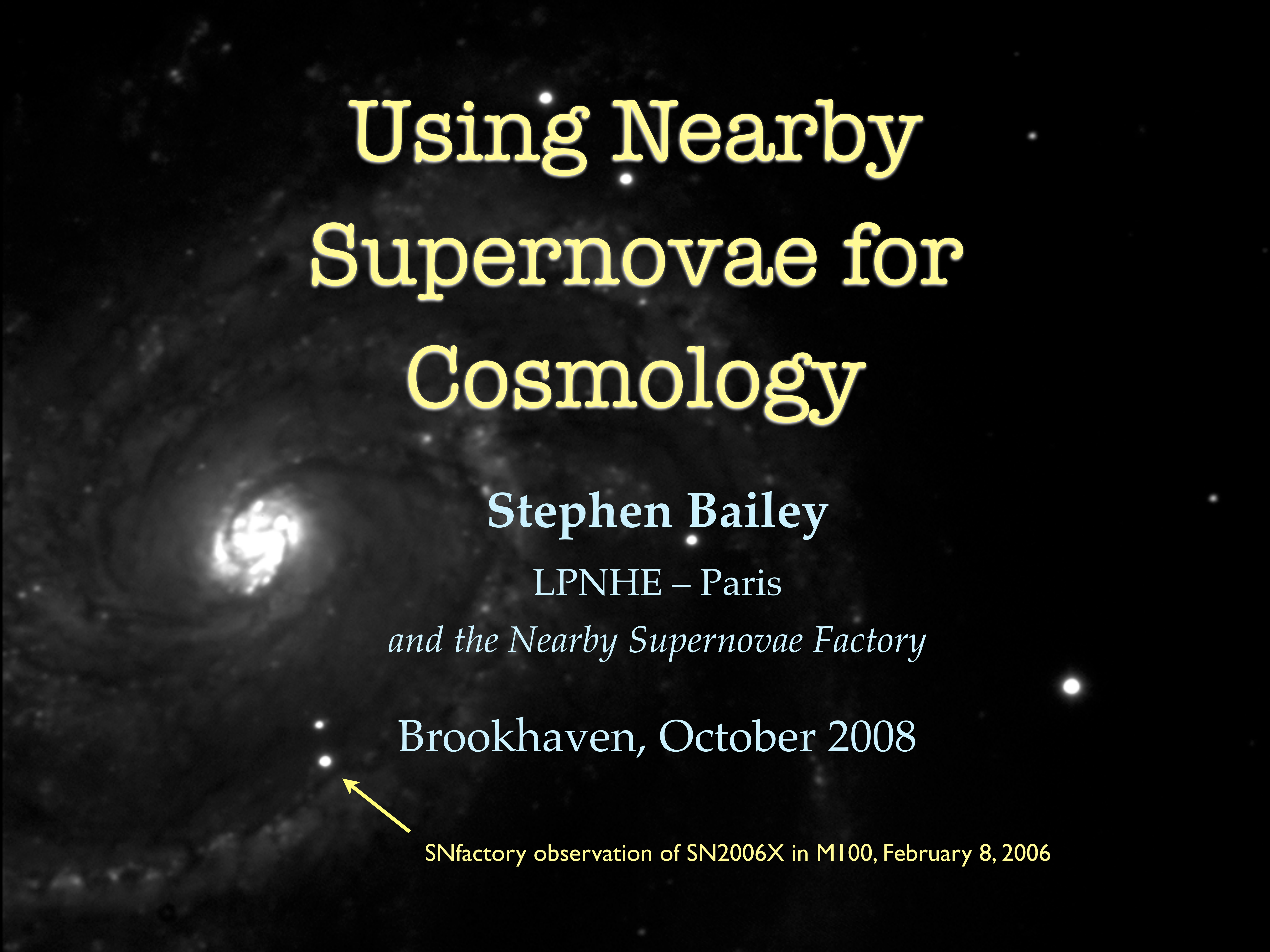
Using Nearby Supernovae for Cosmology

Stephen Bailey

LPNHE – Paris

and the Nearby Supernovae Factory

Brookhaven, October 2008



SNfactory observation of SN2006X in M100, February 8, 2006

Cosmic Connections

- Particle Physics and Cosmology
  - *CP* violation, neutrino masses, Dark Matter = SUSY ?, ...
- Same Basic Questions:
  - What is the universe made of?
  - What physics describes that?
- Different Strengths:
  - Particle physics: detail
  - Cosmology: breadth
- Data processing requirements are becoming similar

Outline

- Basics of Supernova Cosmology
- The Current Systematics Limit
- The Nearby Supernova Factory
  - Addressing the limiting systematics
  - Beyond systematics: improving the method
- Future

Cosmological Distances


photo: yinghao flickr

Luminosity Distance d_L:

Flux ~ $1/d_L^2$

These are not the same on cosmological scales

Angular Diameter Distance d_A:

$d_A \sim 1/\theta$

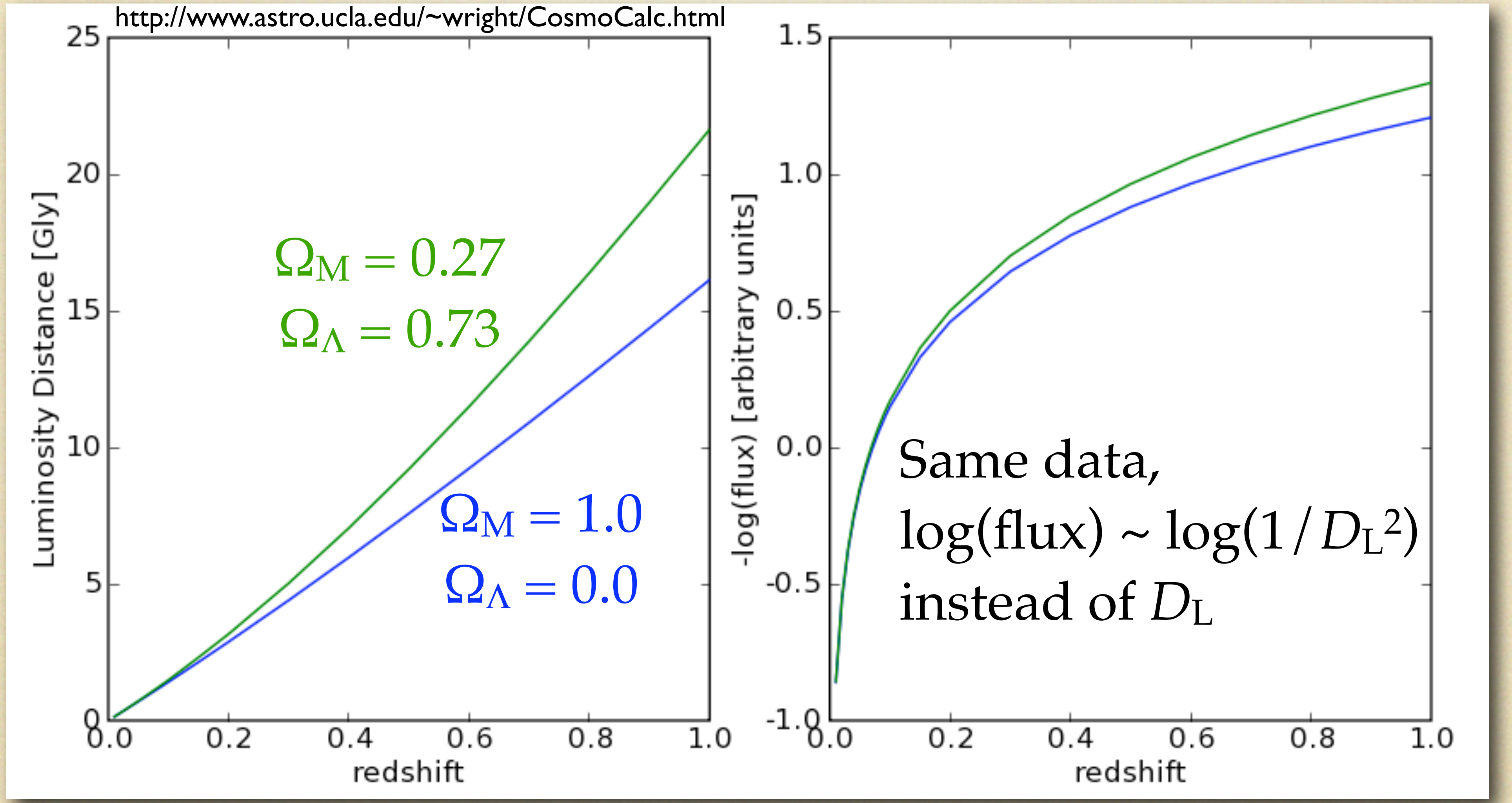
Redshift $z = \Delta\lambda/\lambda$

traces expansion of universe

These are related by cosmology:

$$d_L(z) = (1+z)\frac{c}{H_0}\int dz'\left(\Omega_M(1+z')^3 + \Omega_k(1+z)^2 + \Omega_X \exp\left(\int_0^z 3\frac{1+w(z')}{1+z'}dz'\right)\right)^{-1/2}$$

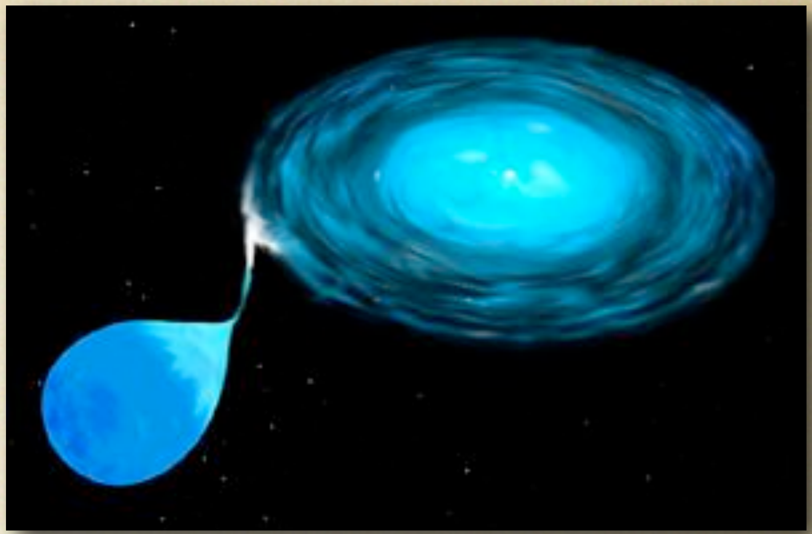
Cosmological Distances



Basic idea:

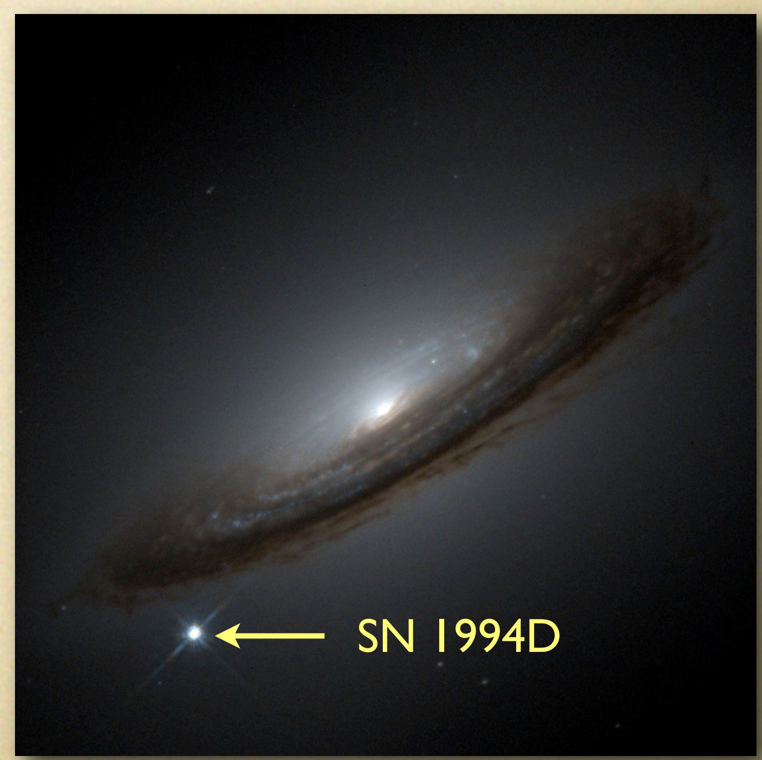
1. Use a large sample of uniformly bright objects to measure d_L across a range of redshifts.
2. Fit for cosmological parameters.

Type Ia Supernovae



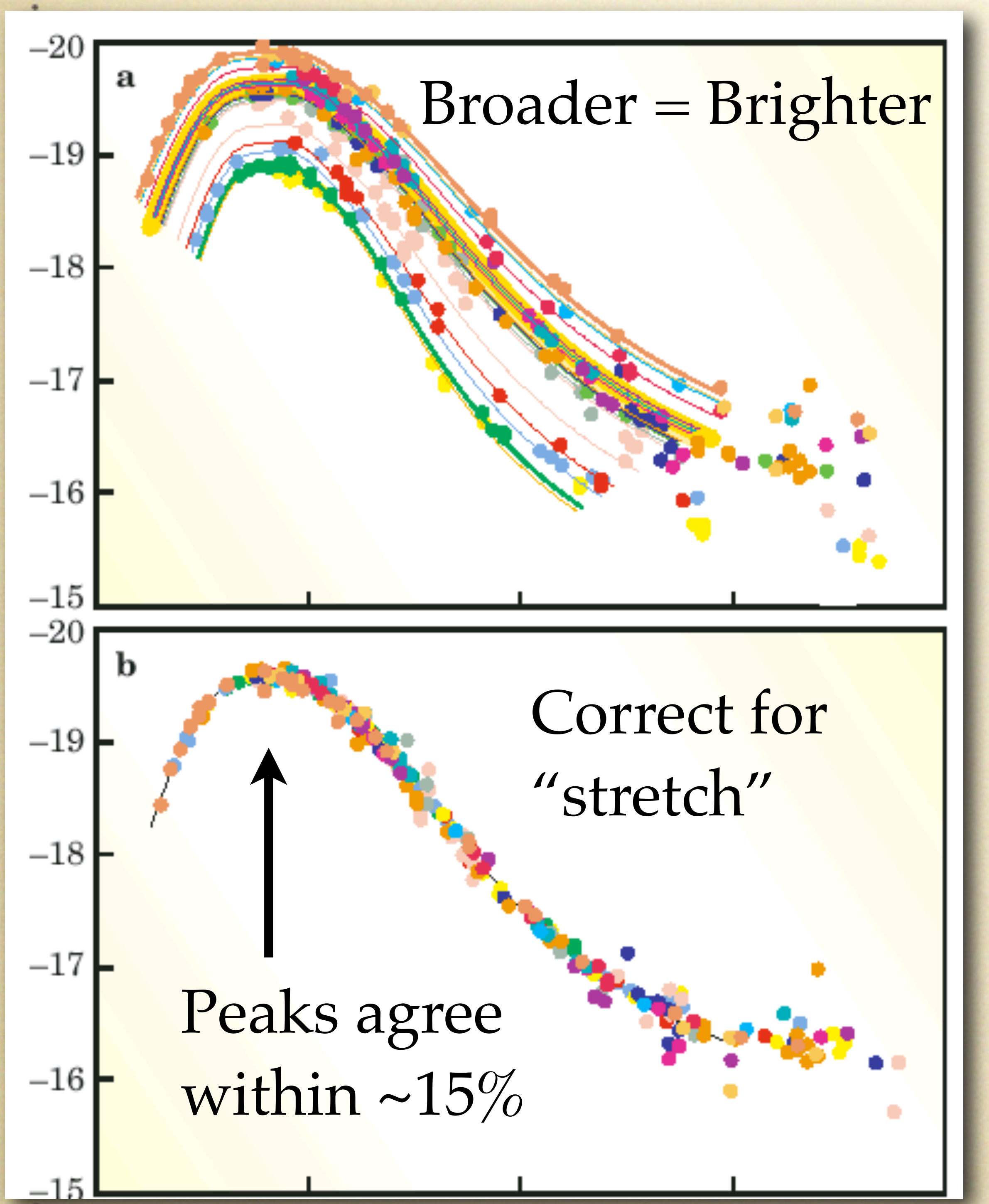
NASA graphic

- C-O white dwarf explosion when accretion reaches Chandrasekhar mass
  - Similar initial state = similar brightness of explosion
- Quite bright: ~billion times brighter than the sun
- Quite rare: ~1 per 100 years per galaxy
- Two weeks from explosion to maximum brightness; then another 6 weeks to fade away
- Peak brightness is used as standard candle to measure luminosity distance



Calibration 1: Color

Calibration 2: LC Width

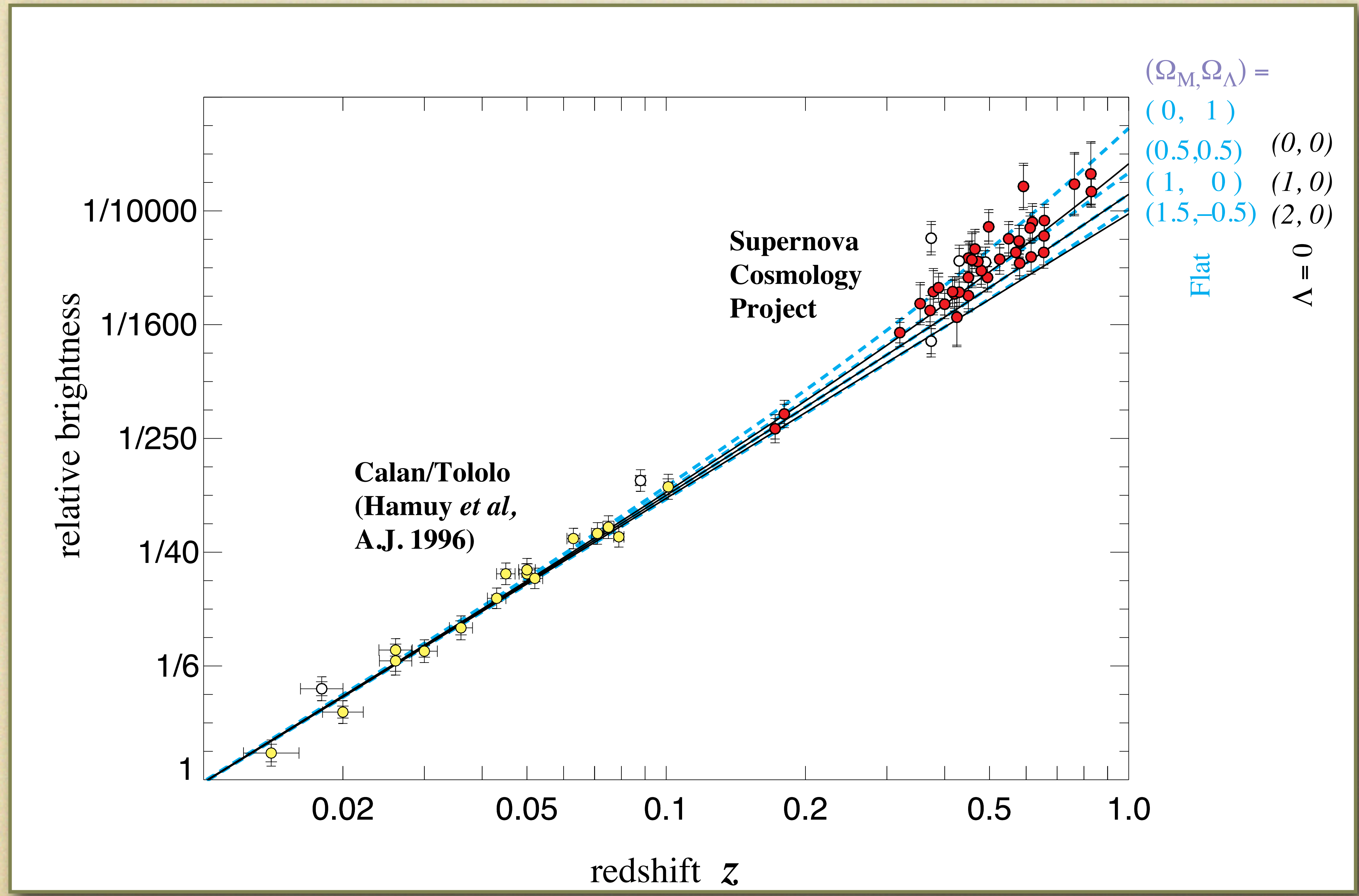


S. Perlmutter, Physics Today, April 2003, p. 54

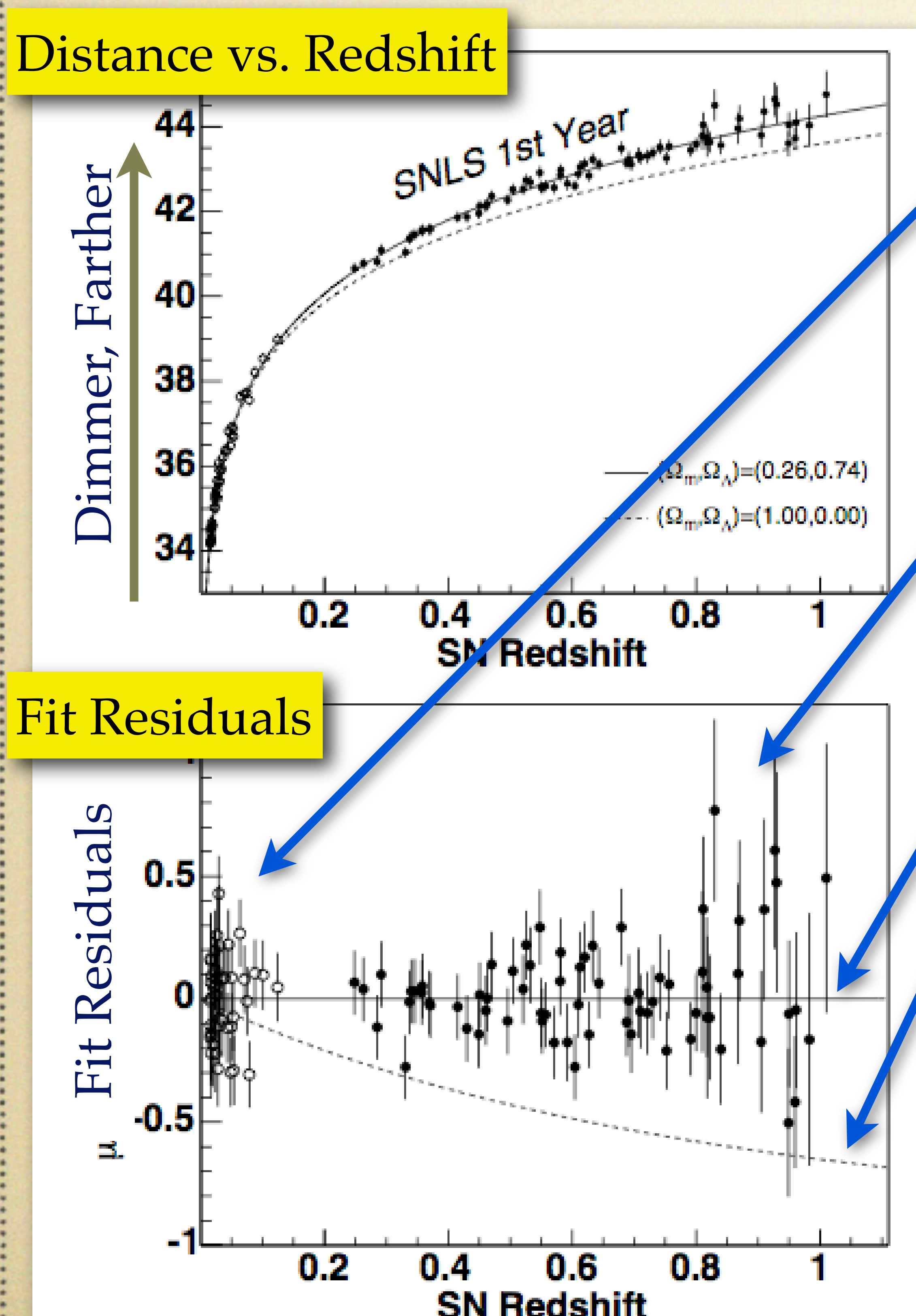
- Empirical relationship between lightcurve width (stretch) and peak brightness allows calibration to ~15%
- Color and Stretch relationships are calibrated on "smooth Hubble flow" SNe ($0.03 < z < 0.08$):
  - Near enough that $d_L(z)$ is independent of cosmology
  - Far enough that z is dominated by expansion, not gravitational peculiar velocities

The Accelerating Universe

1998: Two groups find that high redshift SNe are dimmer than expected



Important Technical Detail



SNLS A&A 2006, astro-ph/0510447

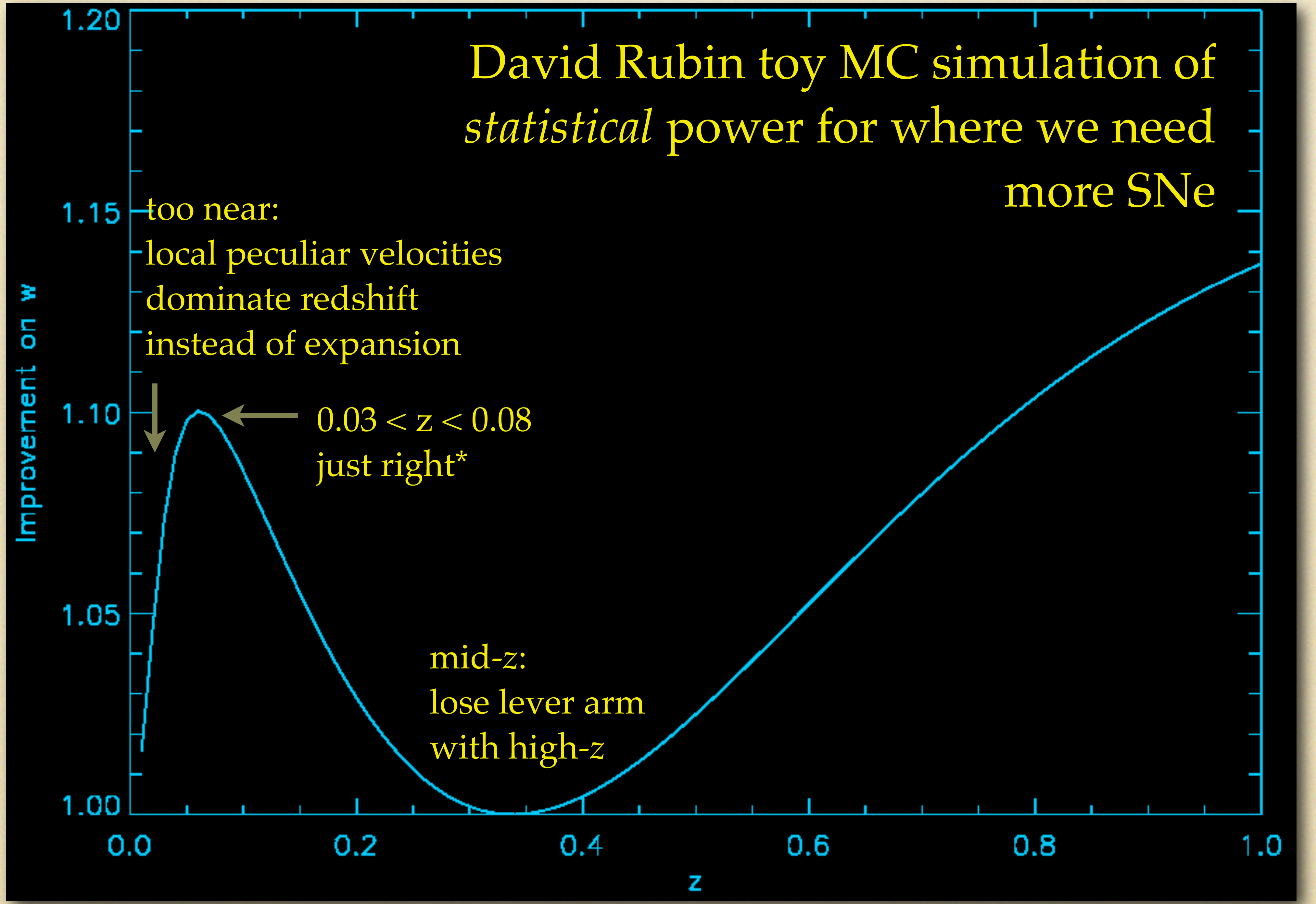
Nearby SNe alone don't constrain cosmology.

But distant SNe alone have degeneracy between cosmology and the absolute magnitude of type Ia SNe.

The nearby sample breaks that degeneracy.

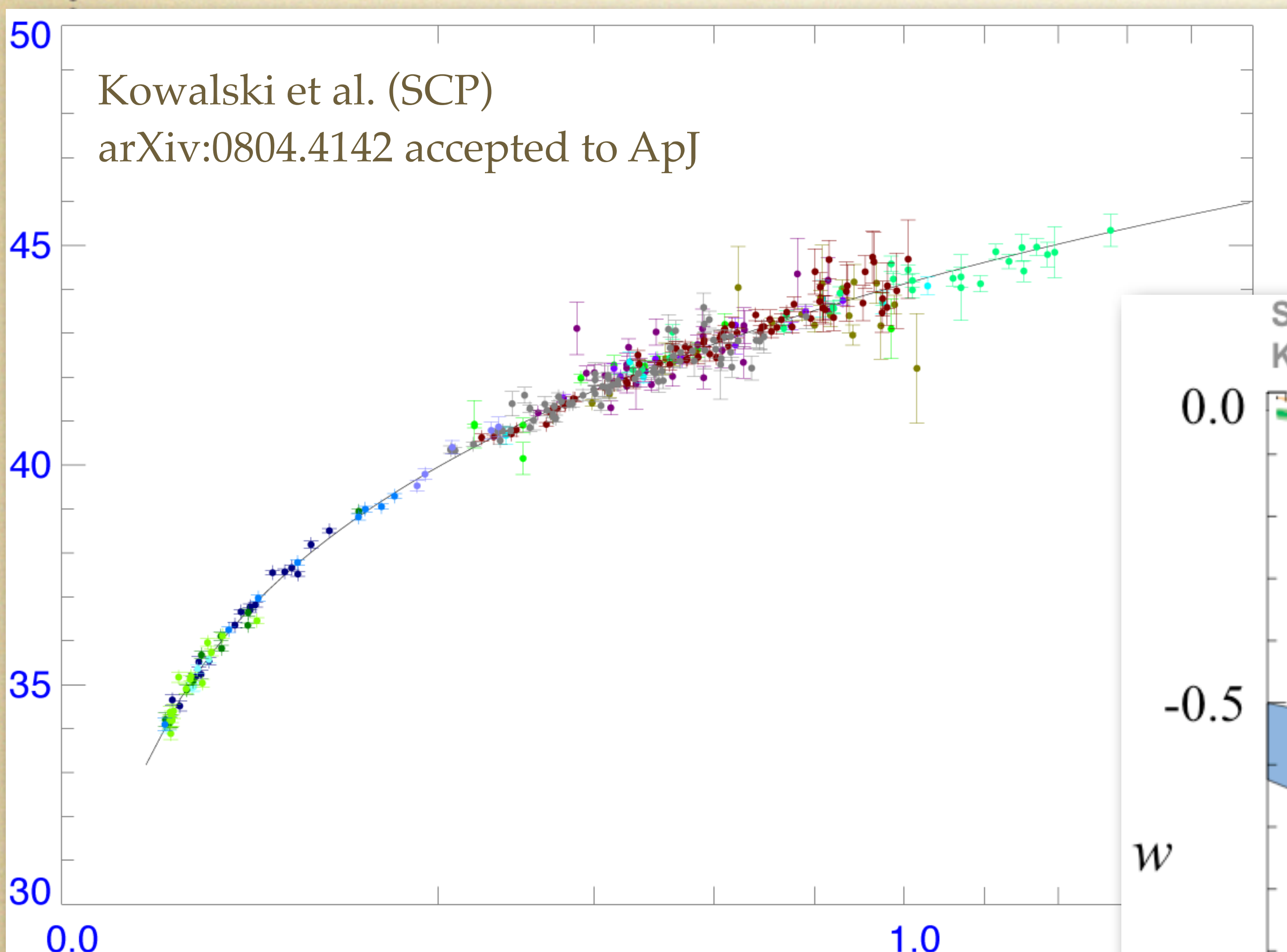
i.e., ratios of fluxes cancels the uncertainty in the absolute brightness – *both nearby and distant SNe are needed*.

How Nearby is "Nearby"?

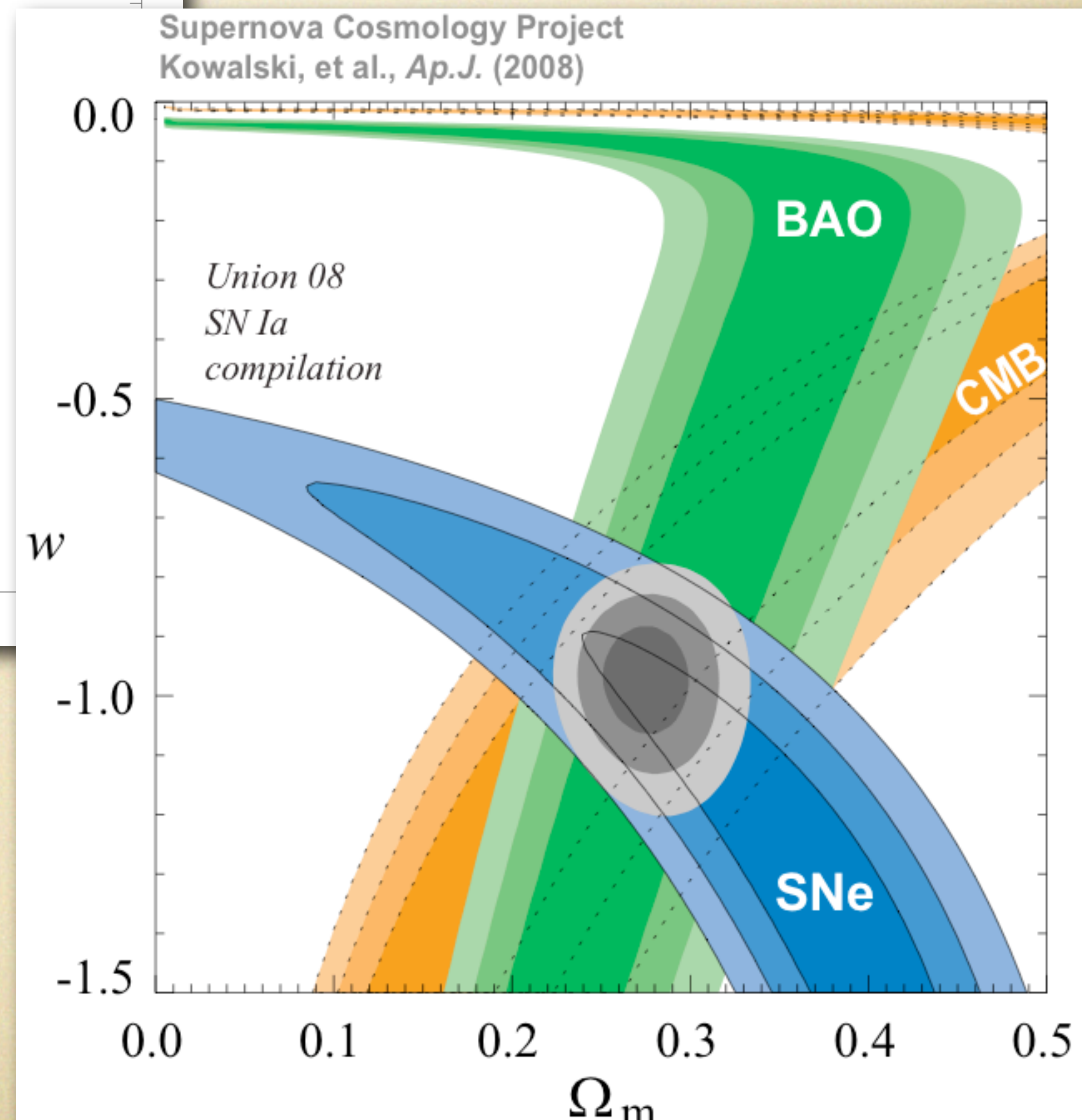


* Statistically, $0.08 < z < 0.15$ SNe are good, but they aren't worth the telescope time if you could observe more $0.03 < z < 0.08$ SNe instead

SCP Union Compilation



Consistent analysis of 414 public SNe (307 in final fit)



Coming soon
(i.e., wrestling with systematics):

* SNLS 3rd year (~240 high-*z* SNe)
* SDSS (~450 mid-*z* SNe)
* ESSENCE (~200? high-*z* SNe)
* SCP HST (a few $z > 1$)

Systematics Limit

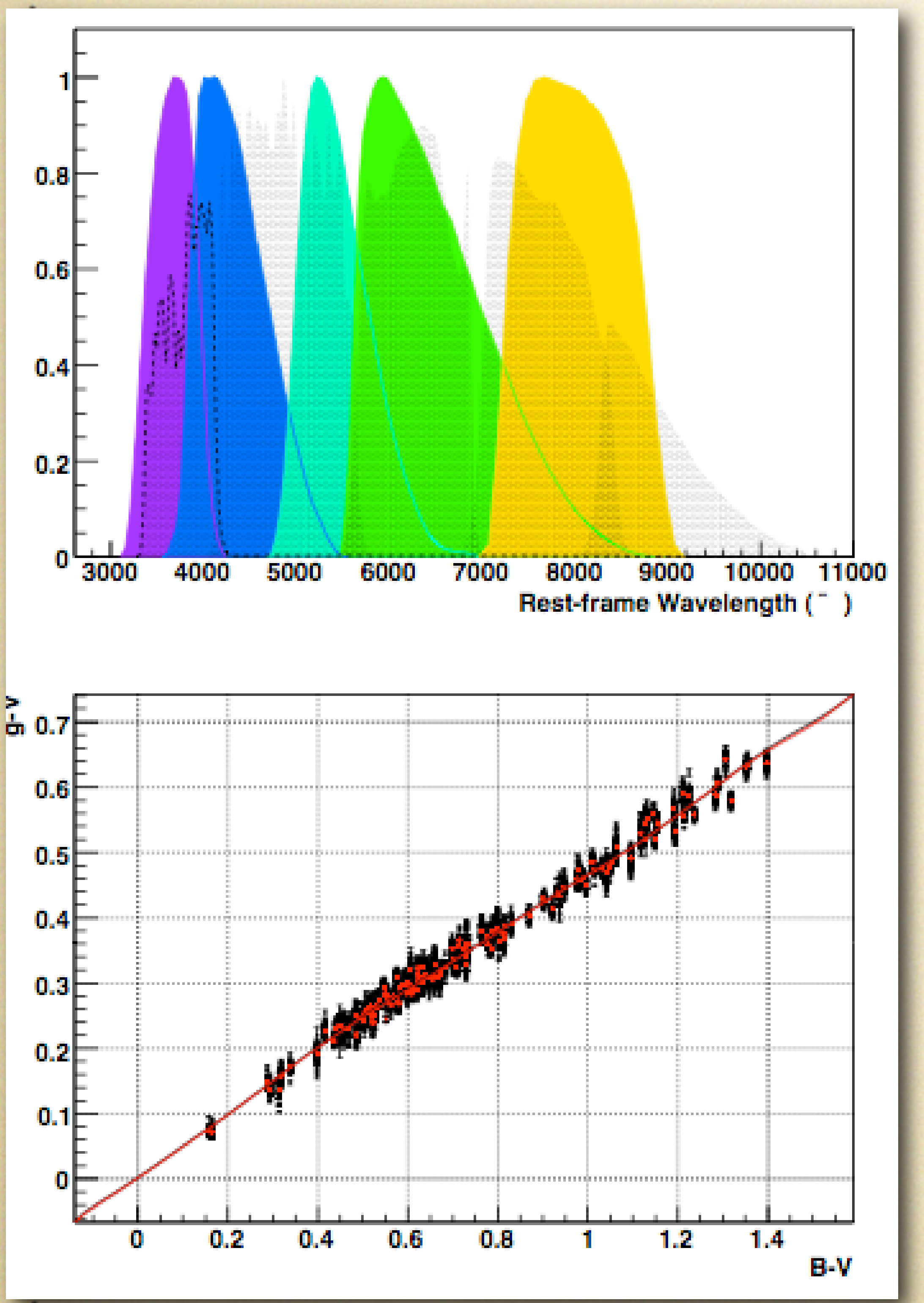
Alex Conley/SNLS, AAS January 2007

Systematic	w Error
Colour of Vega on Landolt system	0.0391
SNLS zeropoints	0.0311
SNLS bandpasses	0.0286
SN model	0.0278
Evolution in colour-luminosity (β)	0.0242
Landolt bandpasses	0.0146
Local flows	0.0137
SED of Vega	0.0131

SN cosmology has hit its systematics limit (temporarily)

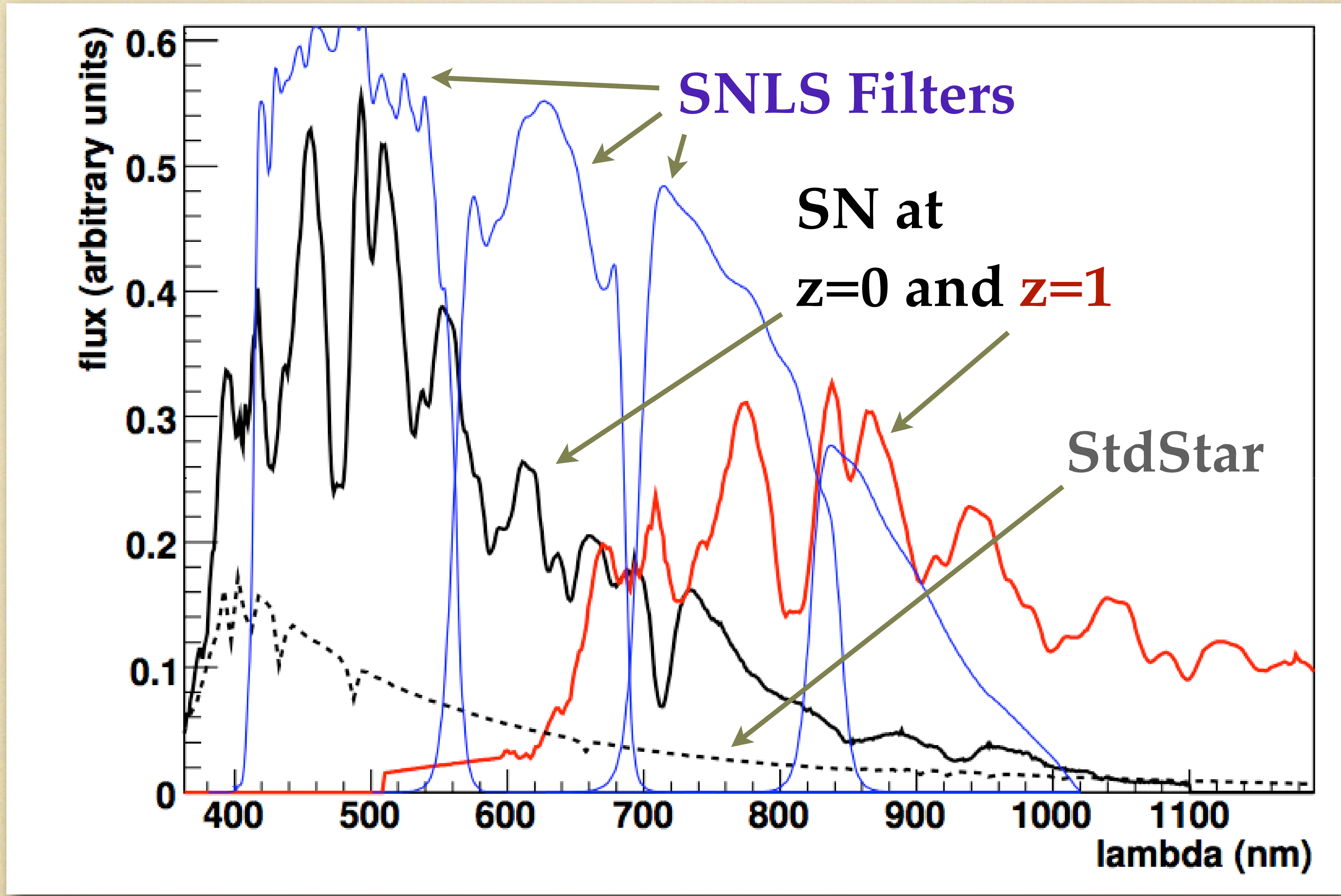
But the systematics are dominated by terms which can be addressed with an improved nearby SN sample

Photometric Calibration



- Historically, Low-*z* and high-*z* projects used different filters tied to different standard star systems
- Even the low-*z* filter bandpasses for public data aren't very well calibrated
- Large systematics arise from the large photometric corrections
- We need a low-*z* sample more directly tied to the calibration of the high-*z* sample

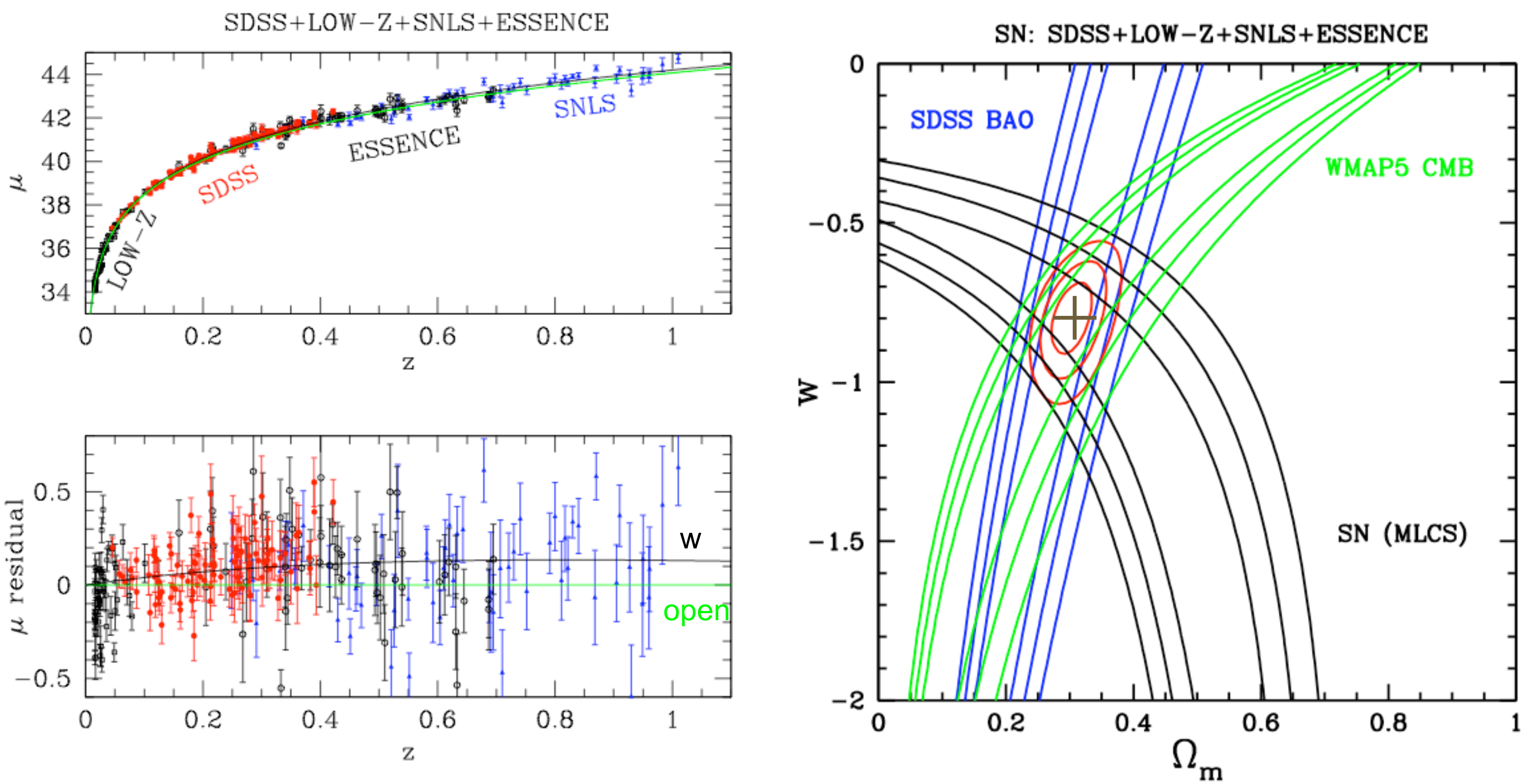
SN Modeling



Accurate modeling of SN and filters is needed

SN Modeling: Example

Preliminary Cosmology Results

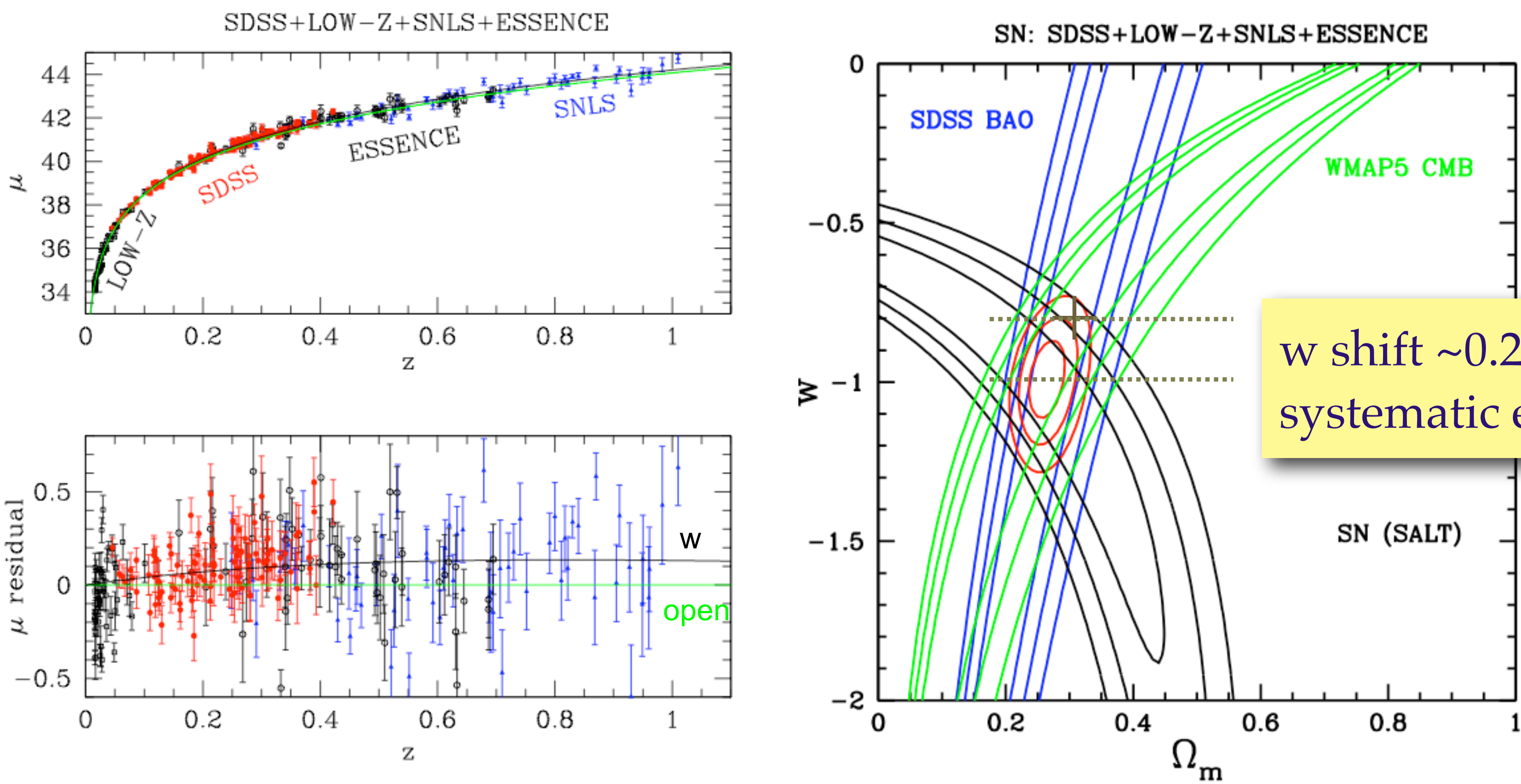


Kessler, et al. 2008

Slide from J. Frieman, SDSS-SN, ICHEP08

SN Modeling: Example

Preliminary Cosmology Results



w shift ~0.2 << 0.028 systematic estimate (!)

Kessler, et al. 2008

Slide from J. Frieman, SDSS-SN, ICHEP08

Different SN lightcurve fitters give different cosmology
= large systematic still under investigation

Problems with the Low-z Sample

- Not enough of them
  - Statistically the high-z sample outweighs the low-z sample
- Tied to a different calibration system
  - Nearby: Classic Landolt filters with calibration tied to Vega
  - Distant: SDSS style filters with calibration to physical flux units
- Nearby sample not as rigorously calibrated
  - 1% photometry wasn't the goal back then
- Inhomogeneous sample
  - Different telescopes, filters, calibration software and methods
- Discovery biases
  - Focused on bright nearby galaxies = not representative
  - Color distribution is bluer (brighter) than high-z sample

Why So Few Low-z SNe?

- Volume, Volume, Volume
  - Must search a larger area to find as many low-z SNe
- Telescope design
  - Most designed to look at small/distant objects, not large areas
- Time dilation
  - You have twice as much time to catch a rising SN at z=1
- Psychology
  - The original cosmology (and glory) came with the high-z results
  - But to advance the science, we now need better nearby SNe

Nearby Supernova Factory

A US/French collaboration and an Astro/HEP collaboration

LBL

G. Aldering, C. Aragon, M. Childress, S. Loken, P. Nugent,
K. Runge, S. Perlmutter, H. Swift, R. C. Thomas

LPNHE (Paris)

P. Antilogus, S. Bailey, S. Bongard, R. Pain, R. Pereira, P. Ripoche, C. Wu

IPNL (Lyon)

C. Buton, Y. Copin, N. Chotard,
E. Gangler, G. Smadja, C. Tao

CRAL (Lyon)

E. Pecontal, G. Rigaudier

Yale

C. Baltay, D. Rabinowitz, R. Scalzo

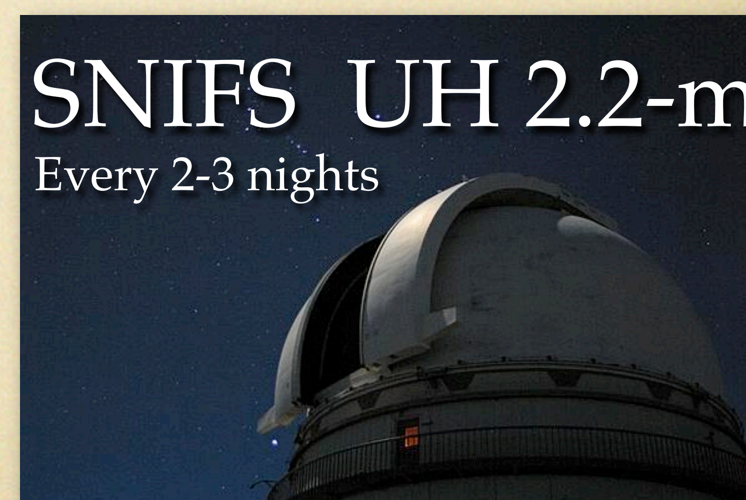
(artist's concept)

Nearby Supernova Factory

1. Discover

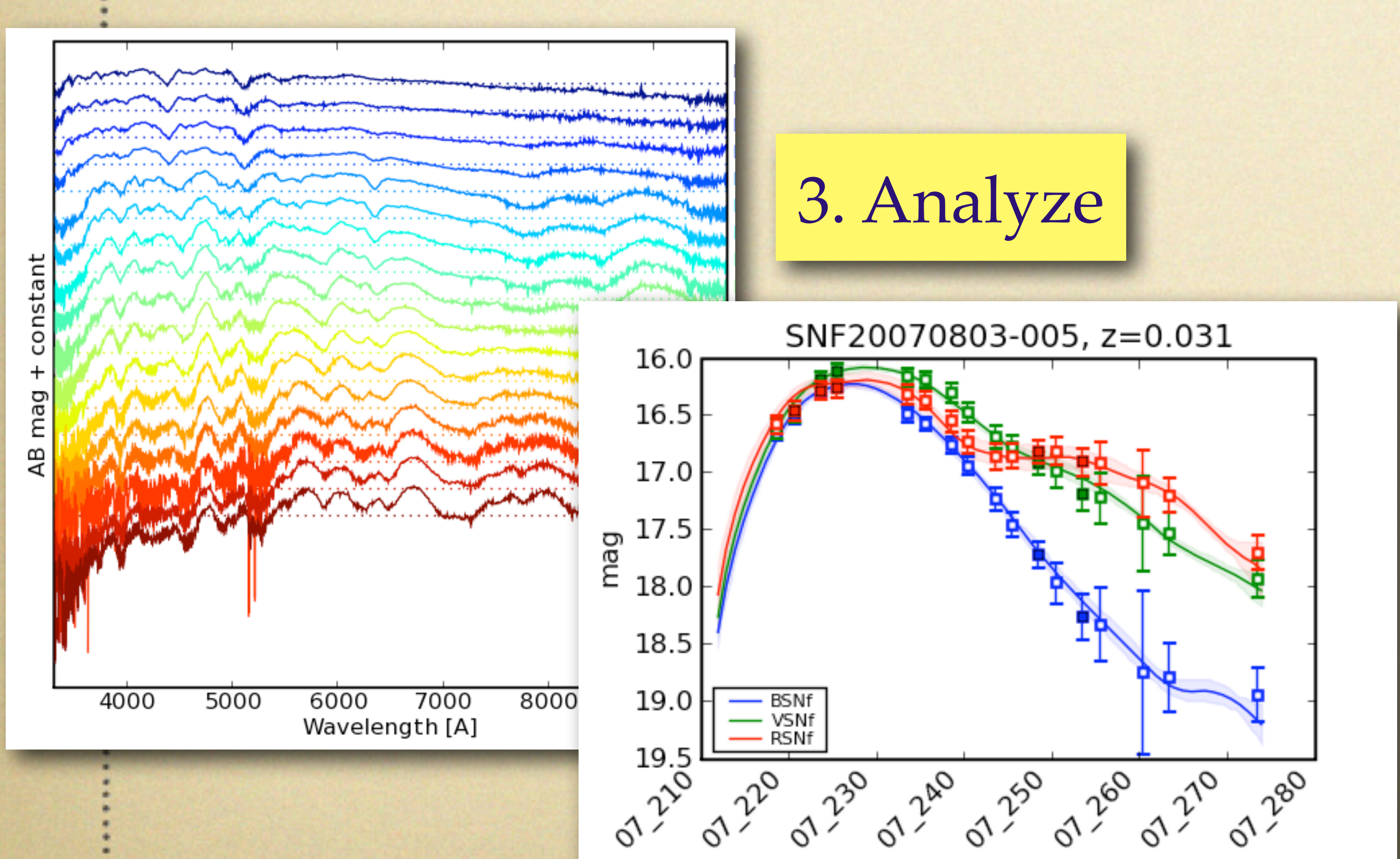
= ~10^{-7} of the area observed per night

2. Observe



Custom, unique spectrometer designed for nearby SN obs

3. Analyze



The Search

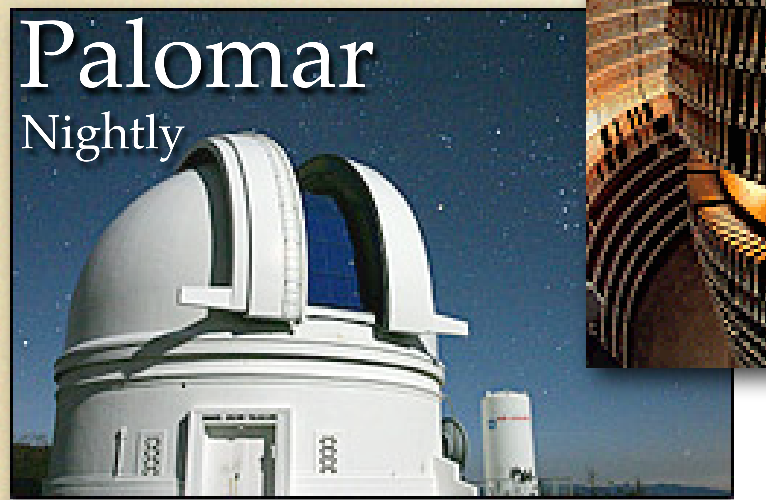
~10^{-7} of the area observed per night

- 350-850 square degrees per night (30k images; 50GB compressed)
  - SDSS: 150 square degrees per night (300 sq. deg. total)
  - SNLS: 1 square degree every few nights (4 sq. deg. total)
- Compare new observations with historic ones, looking for new objects
- Revisit fields, cadence optimized for followup resources
  - Need SNe? Cover more area less frequently to get the most SNe
  - Queue mostly full? Repeat same field frequently to find early SNe
- Monitor ~3500 square degrees at a time, covering ~20,000 square degrees over the year

Search Trigger System

- Level 1:
  - Process images, subtract reference images, identify leftovers
  - 200k - 800k objects/night
- Level 2:
  - Boosted Decision Tree to select most likely candidates
  - 50-100 objects per night (original code >1000 objects left)
- Level 3:
  - Humans select objects for further study
  - ~10 objects per night
- Development for the future:
  - SNfactory is largest area and data volume SN search ever done
  - Our candidate selection algorithms and experience are important for future transient searches [Bailey et al. 2007ApJ 665.1246B]

Followup



1. Discover

= ~10^{-7} of the area observed per night

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Custom, unique spectrometer designed for nearby SN obs

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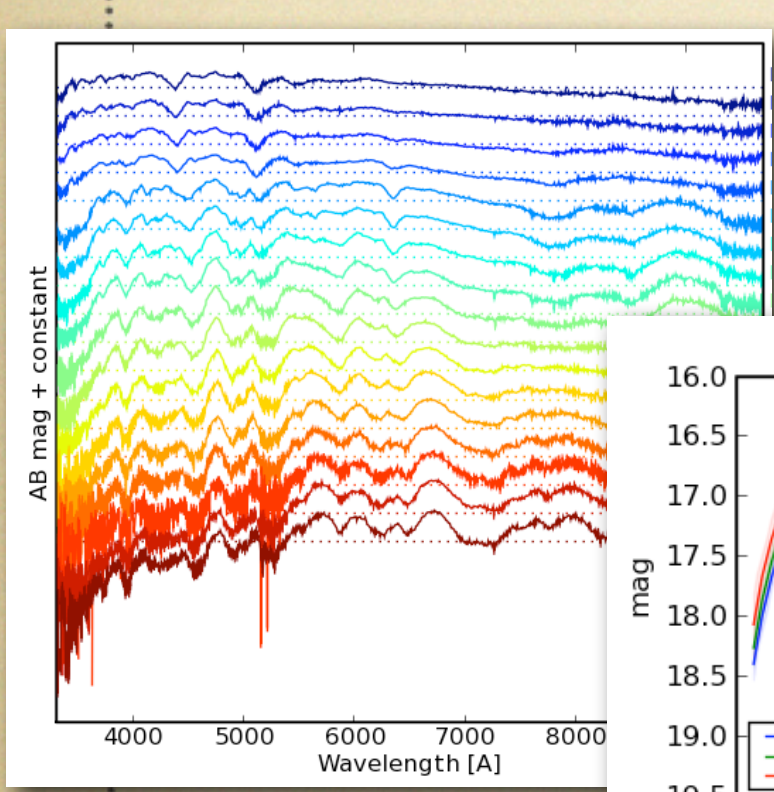
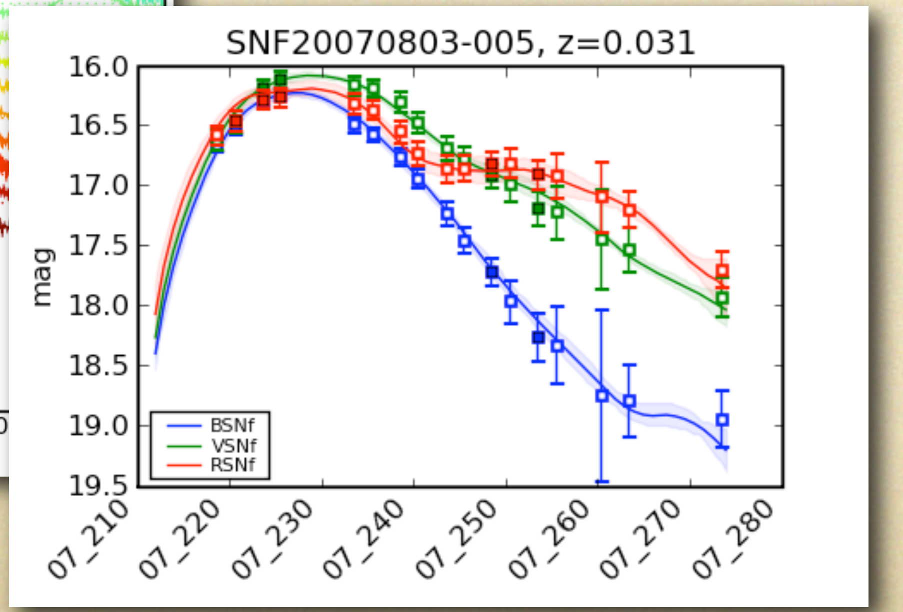
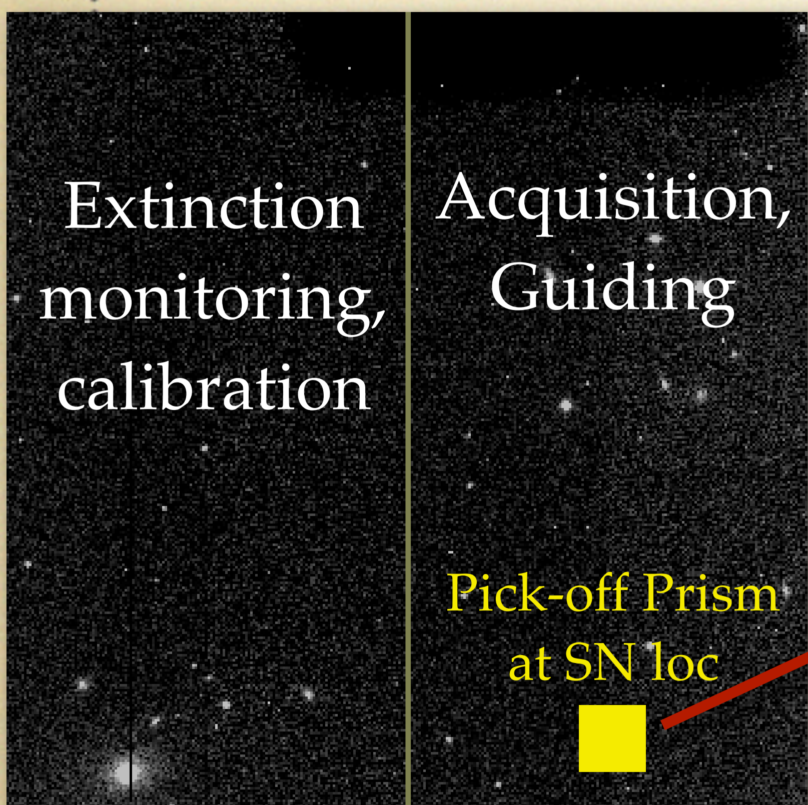




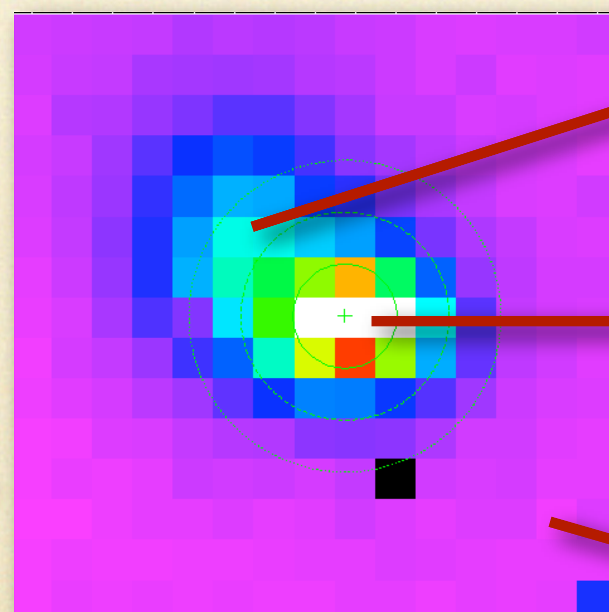
SuperNova Integral Field Spectrometer (SNIFS)

Photometric Channel



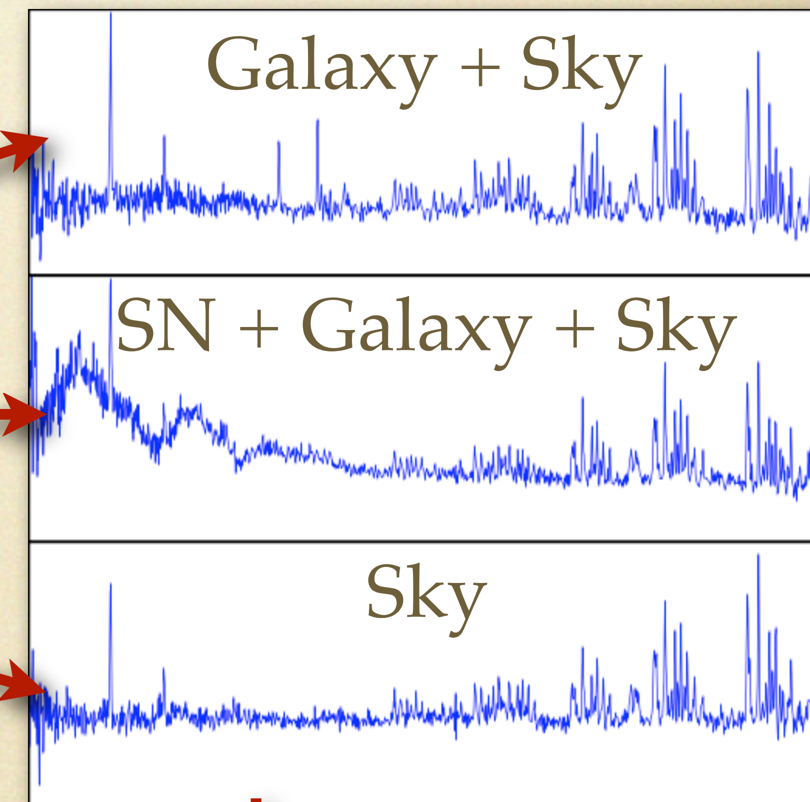
9.4′ x 9.4′ FOV; 0.14″/pix

Microlens array to two channel spectrograph 15x15 = 225 spectra

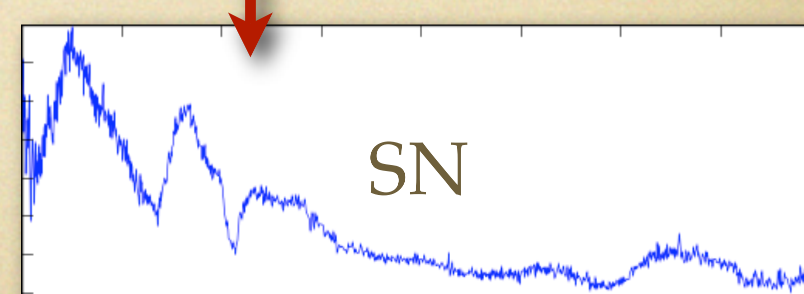


6″ x 6″ FOV; 0.4″/spaxel

R channel:

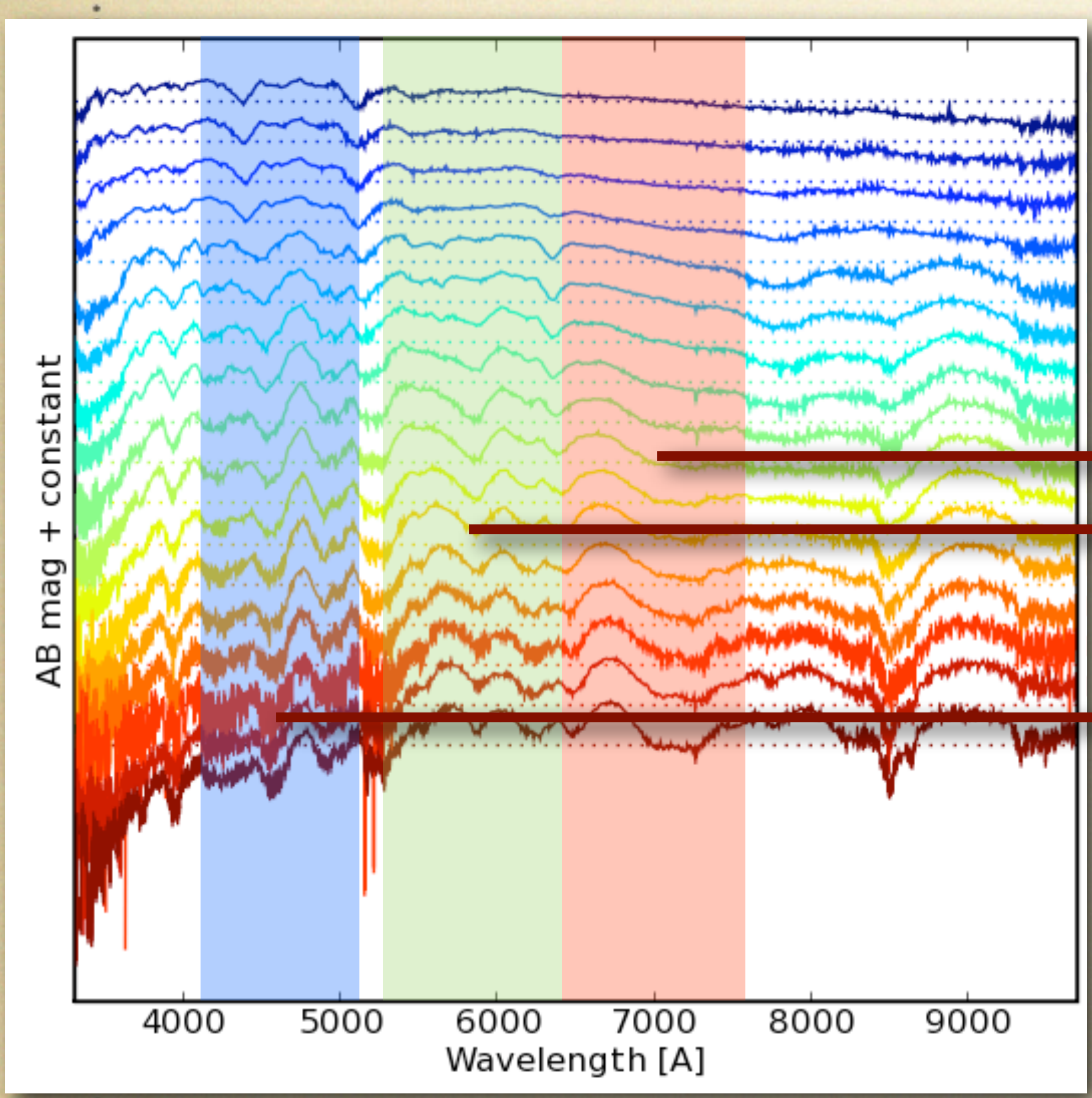


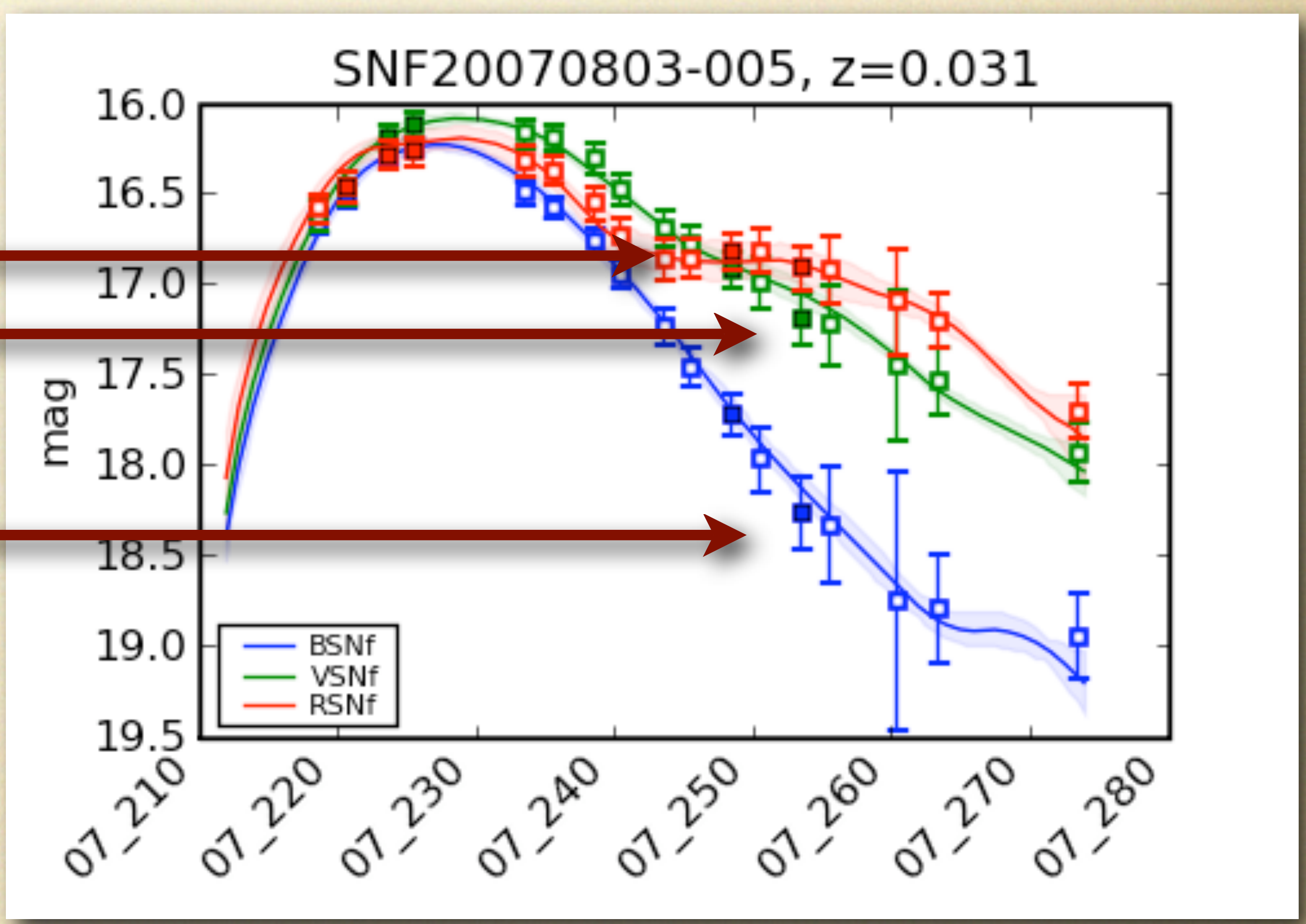
Hard work...



Every obs: flux calibrated spectra, 320 – 520, 510 – 1000 nm coverage

From Spectra to Lightcurves

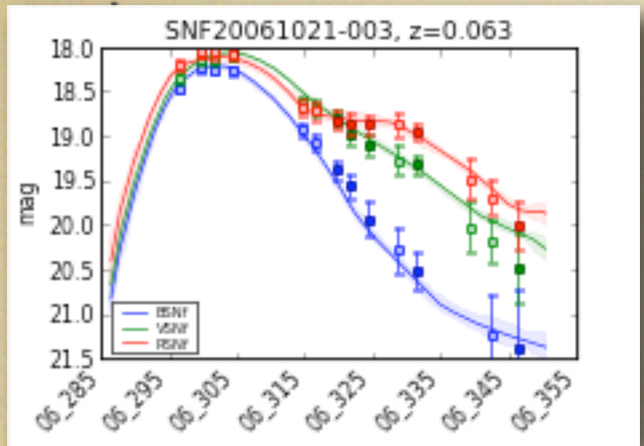


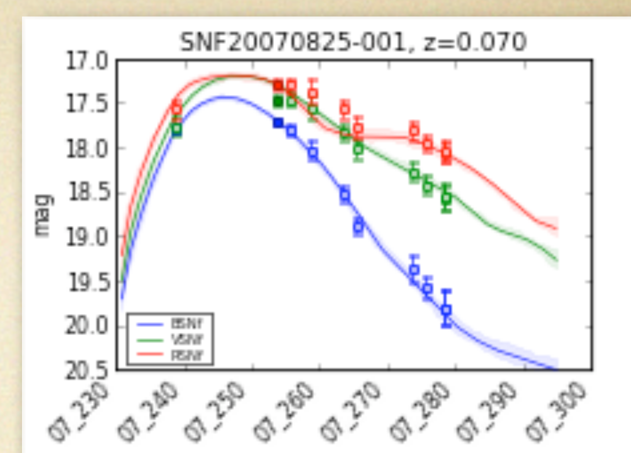


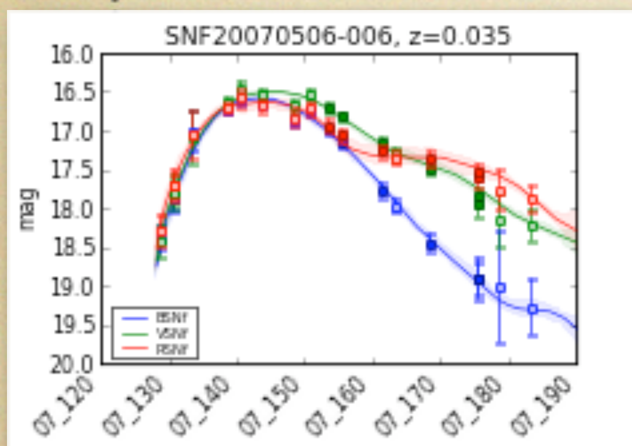
Integrate flux calibrated spectra to synthesize classic filter photometry

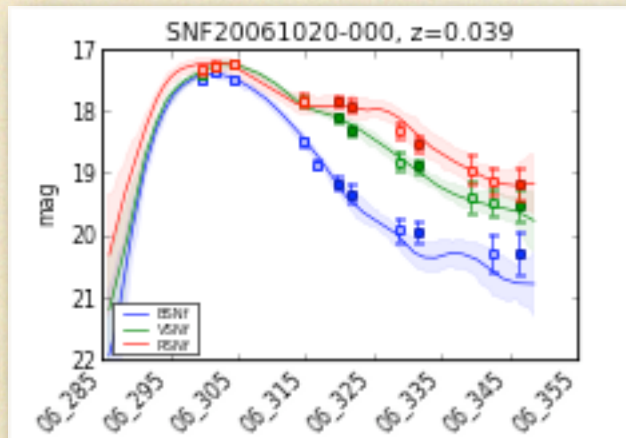
Some Lightcurves

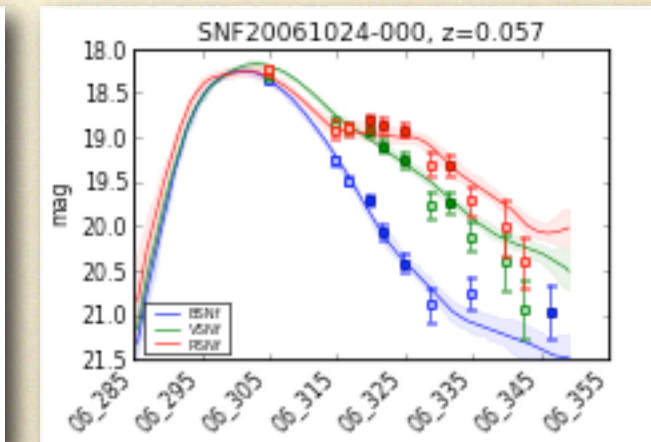
Every observation is a
flux calibrated spectrum

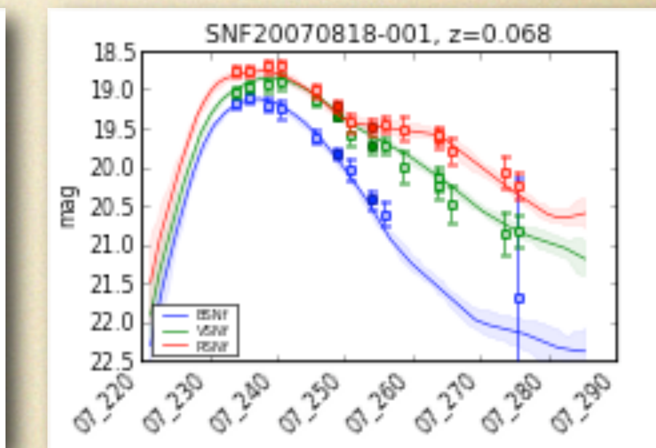


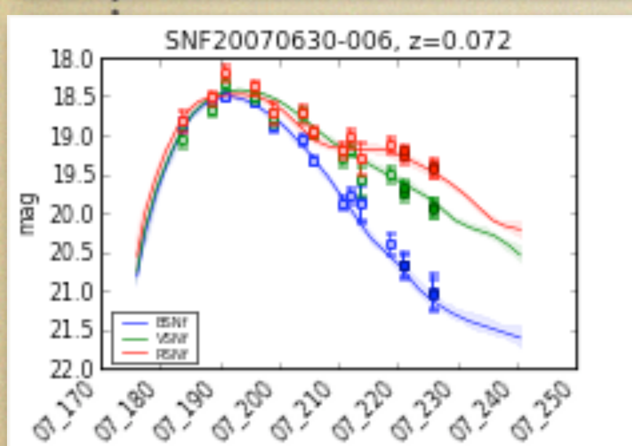


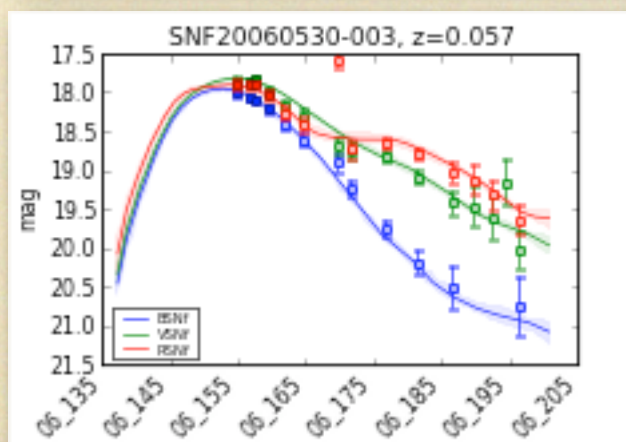


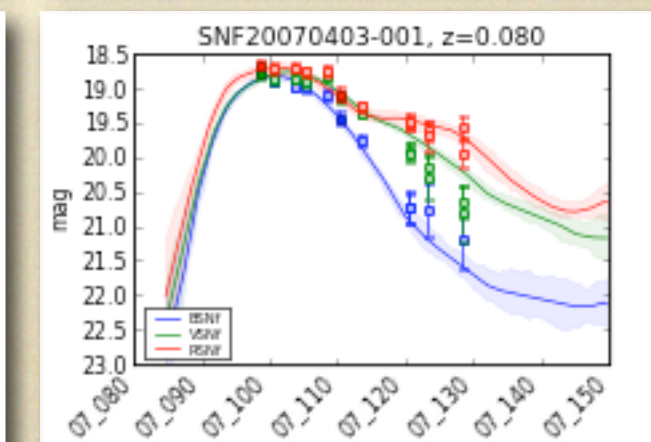


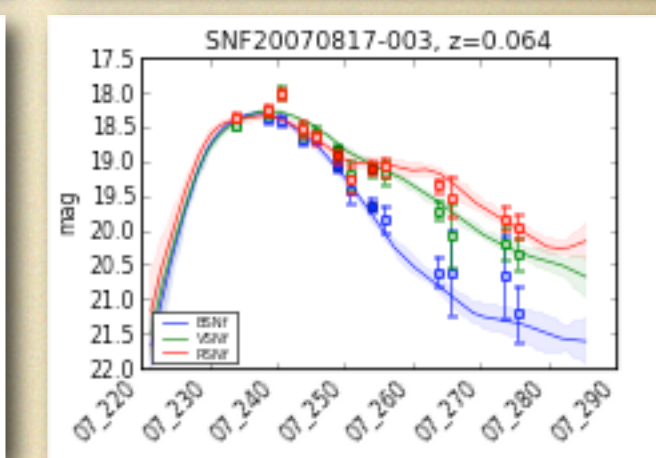


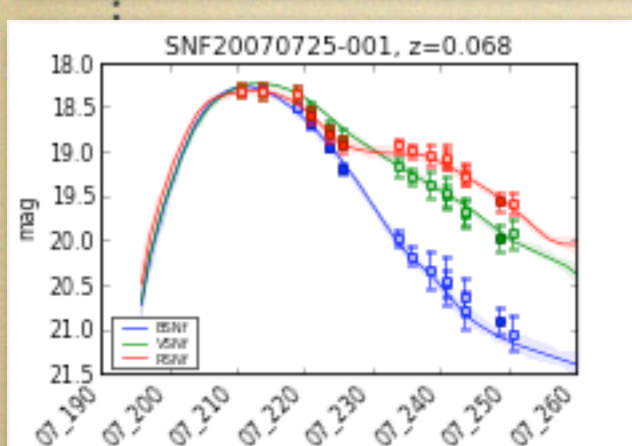


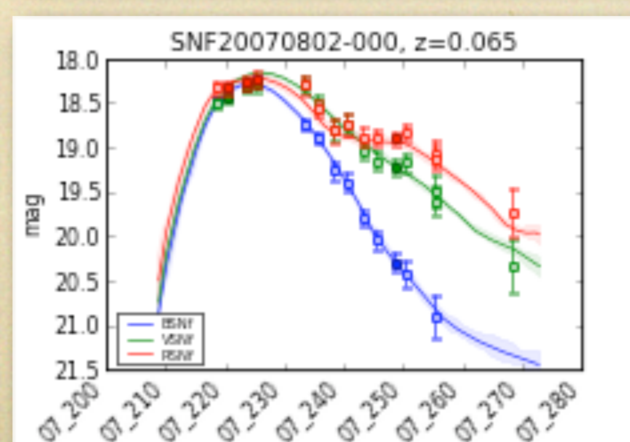


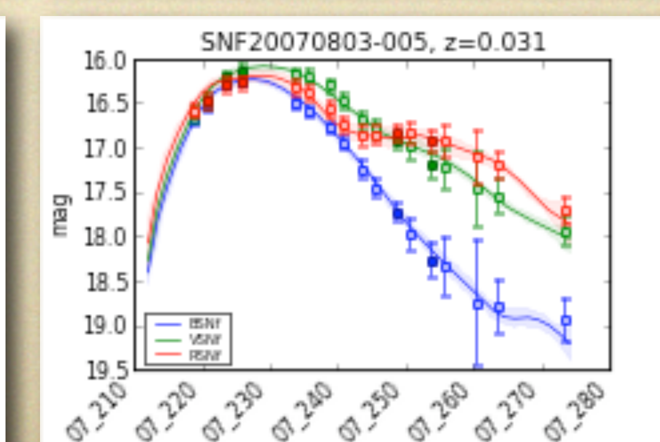


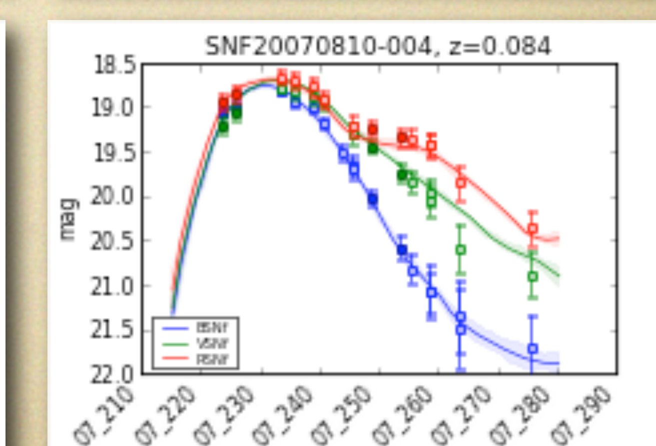




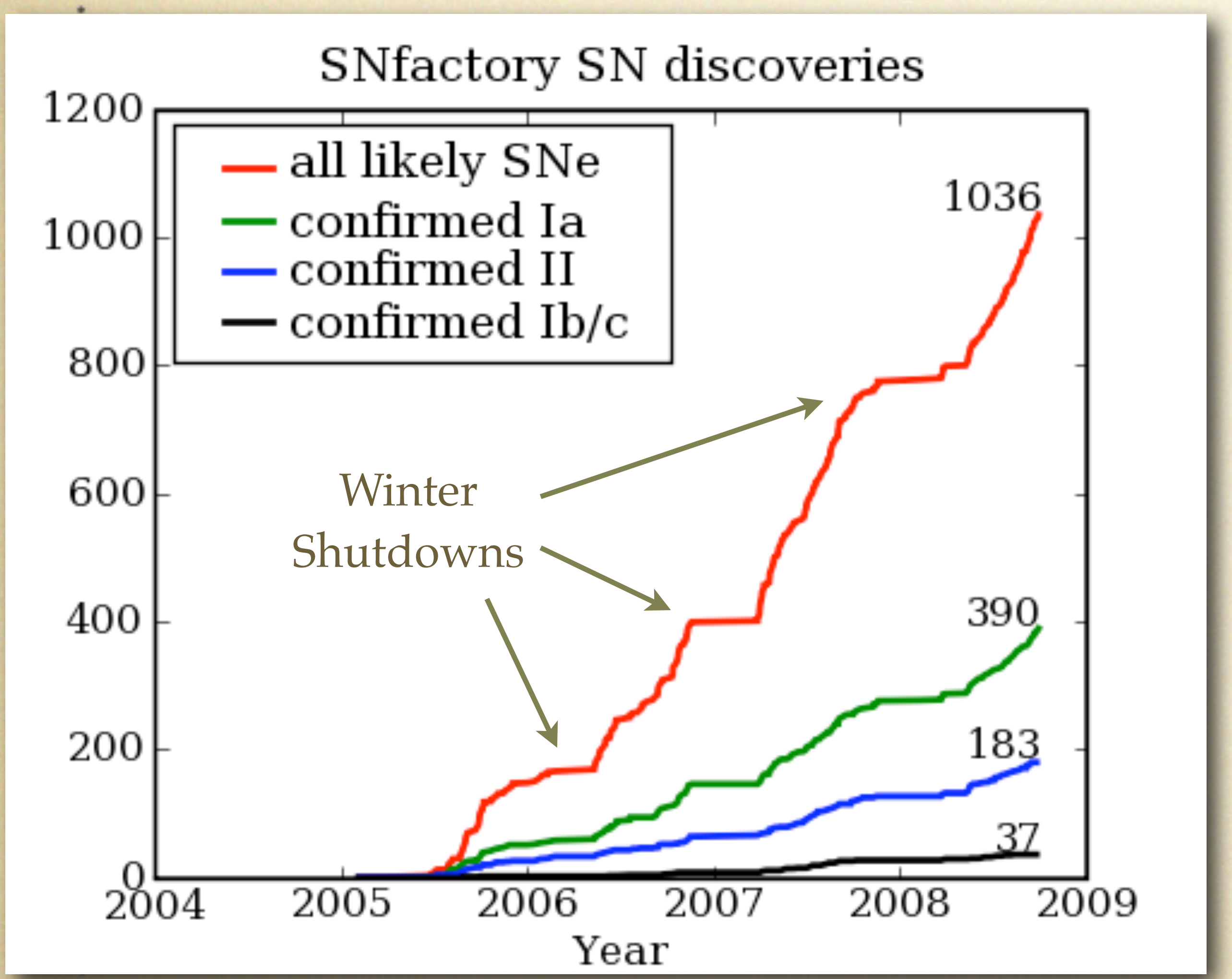


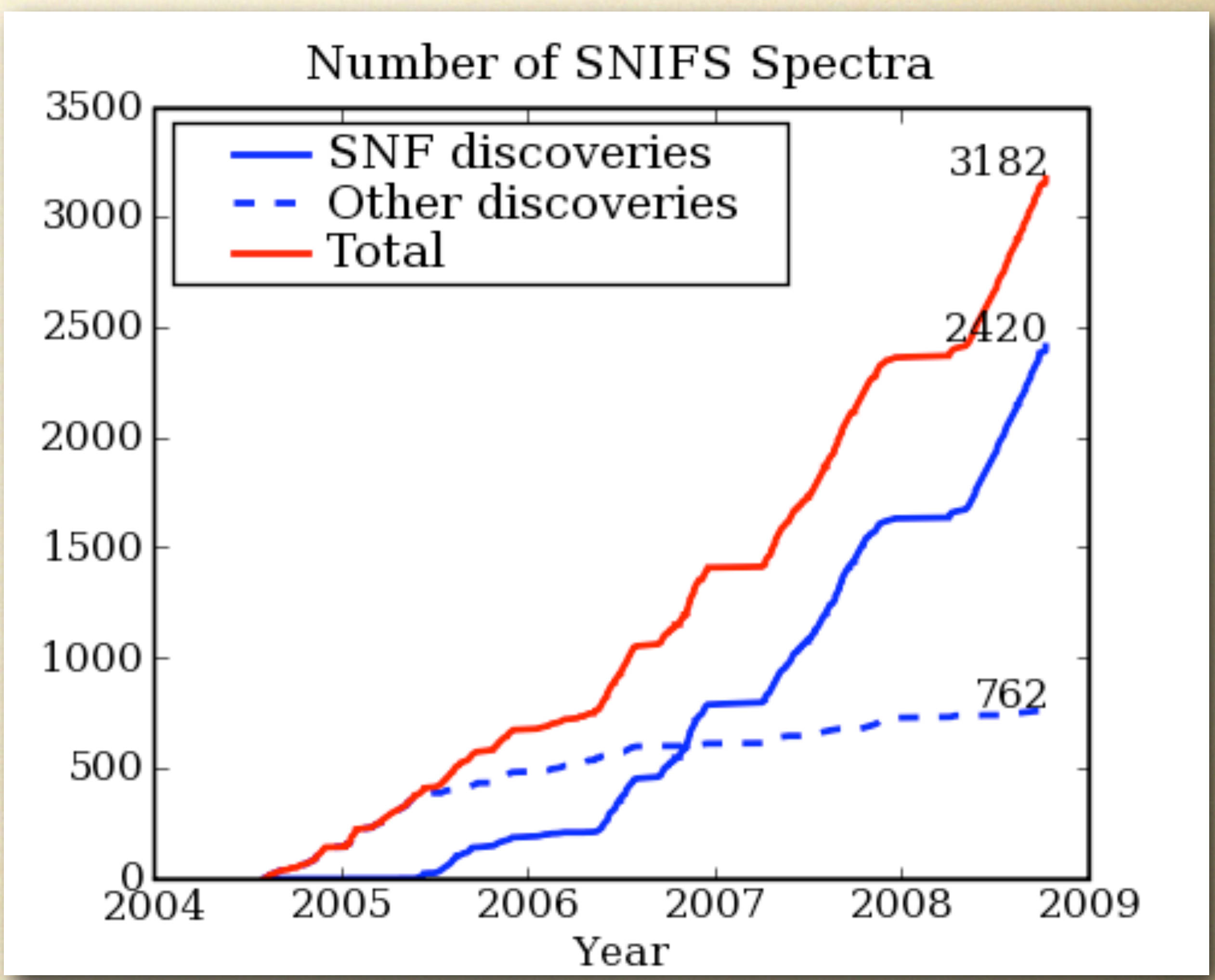






“Integrated Luminosity”





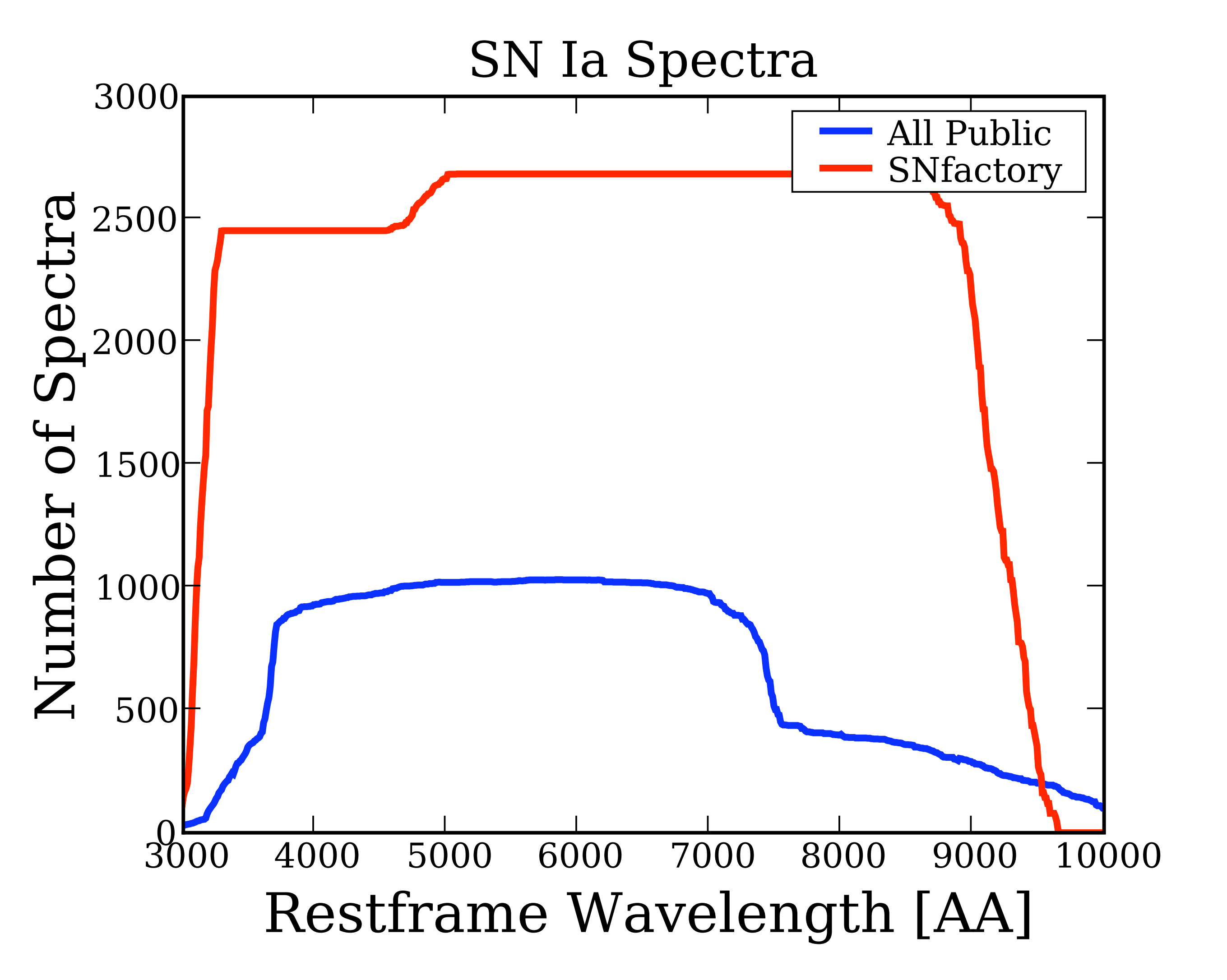
SNe with multi-epoch spectral time-series:

2473 spectra of 184 SNe (*7 Oct 2008*)

http://snfactory.lbl.gov/snf/open_access/

A Unique Legacy Dataset

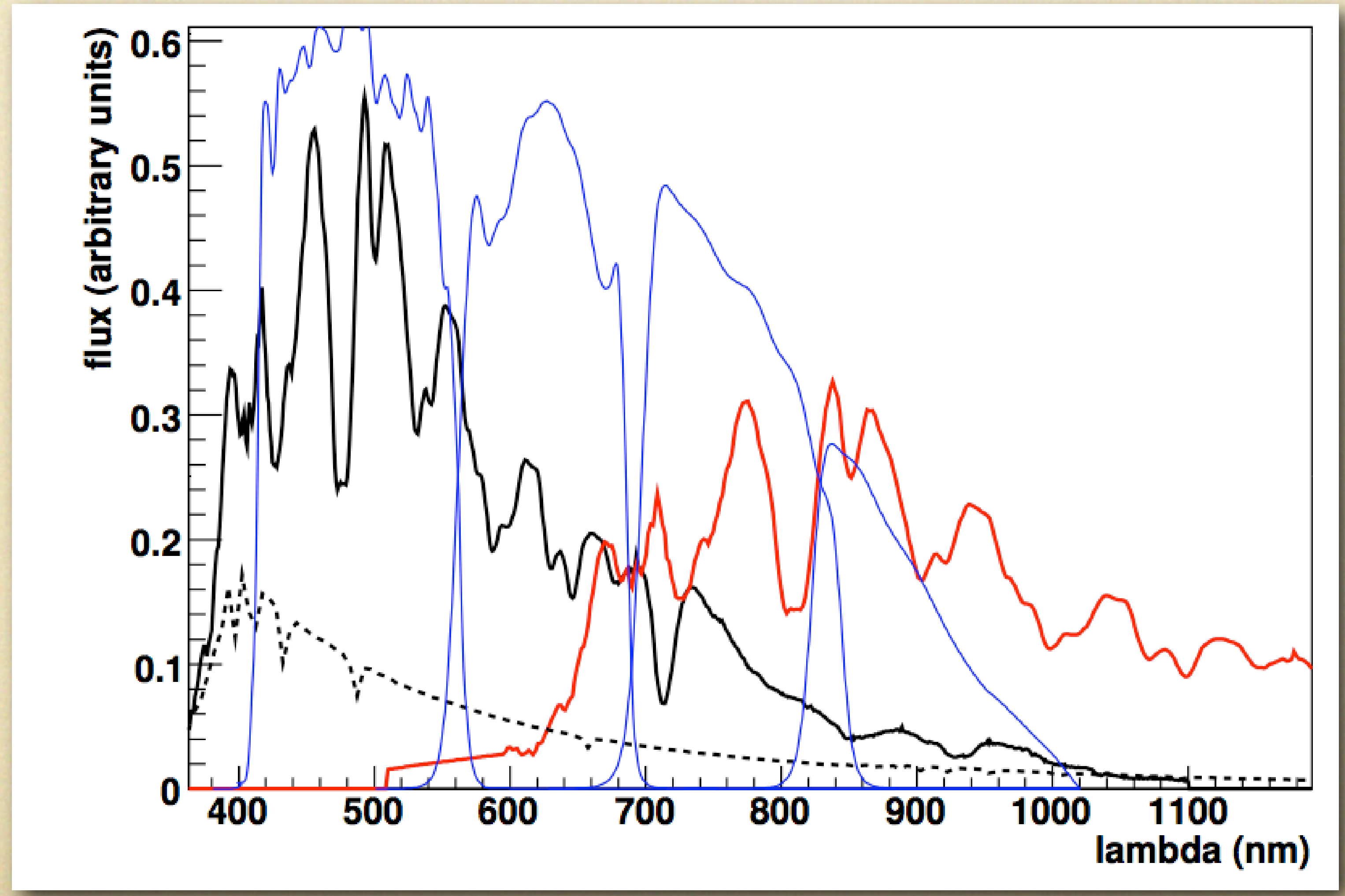
- Other SN projects are primarily photometric
  - A few spectra, primarily for confirming type (Ia, not II or Ib/c)
- SNfactory is only large sample of flux calibrated spectro-photometric SN Ia timeseries
  - ~3/4 of SNF spectra are from spectral timeseries – much more information than from isolated spectra
  - Data will become public after were finish our primary scientific analyses



SNfactory processed data – more are in the queue

Systematics Reminder

- Photometric calibration of nearby sample
- Cross calibration of the nearby and distant samples
  - Filters, standard stars, calibration system
- SN lightcurve modeling

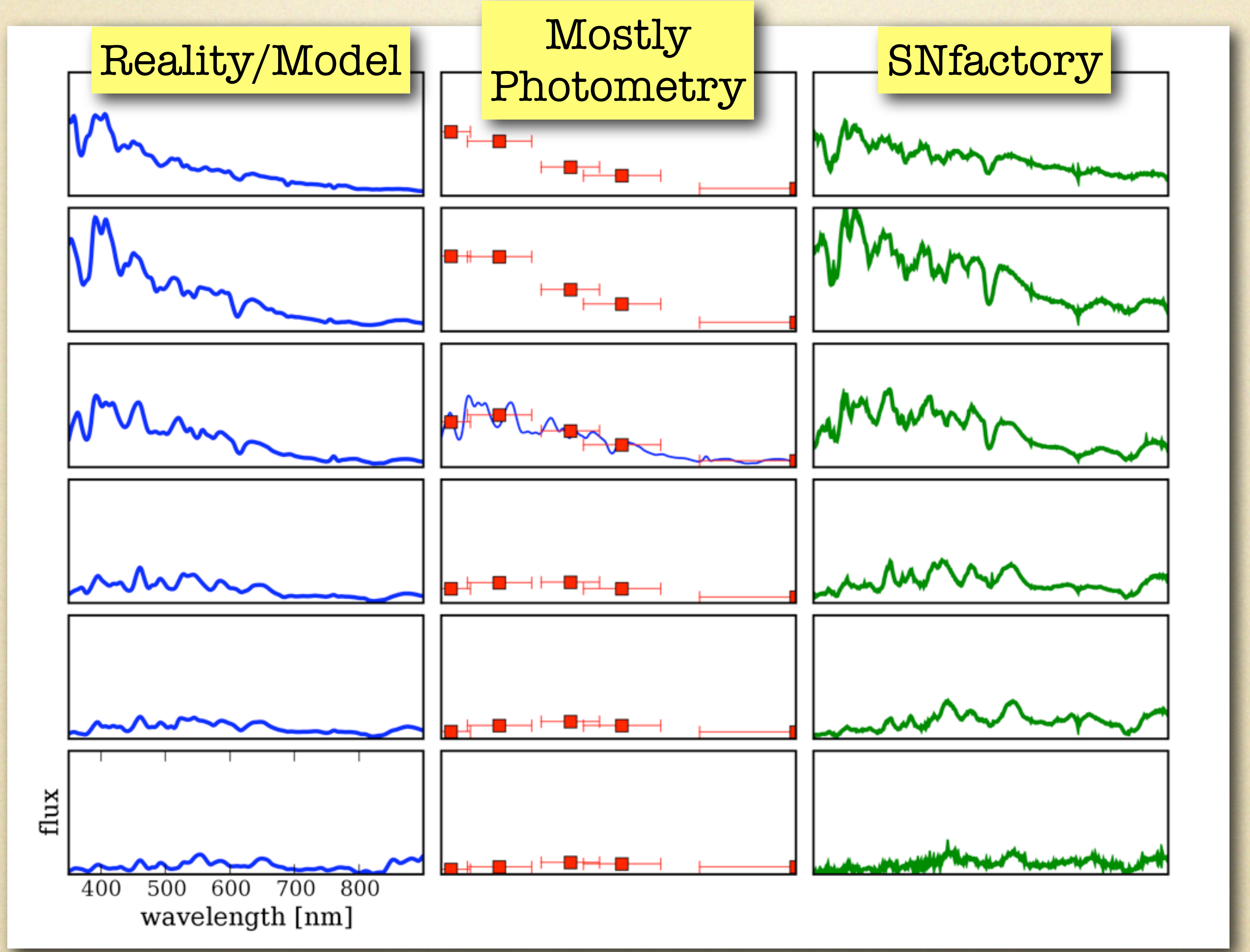


SN Calibration

- The Nearby Supernova Factory observations have a traceable calibration to the same standard stars used by SDSS, SNLS, and the Hubble Space Telescope
- It was designed specifically for the purpose of complimenting the systematic calibration needs of high-*z* supernova programs
- Still a work in progress – primary challenges:
  - extraction of SN with large galaxy background
  - calibration of non-photometric nights

Building a SN model

Time

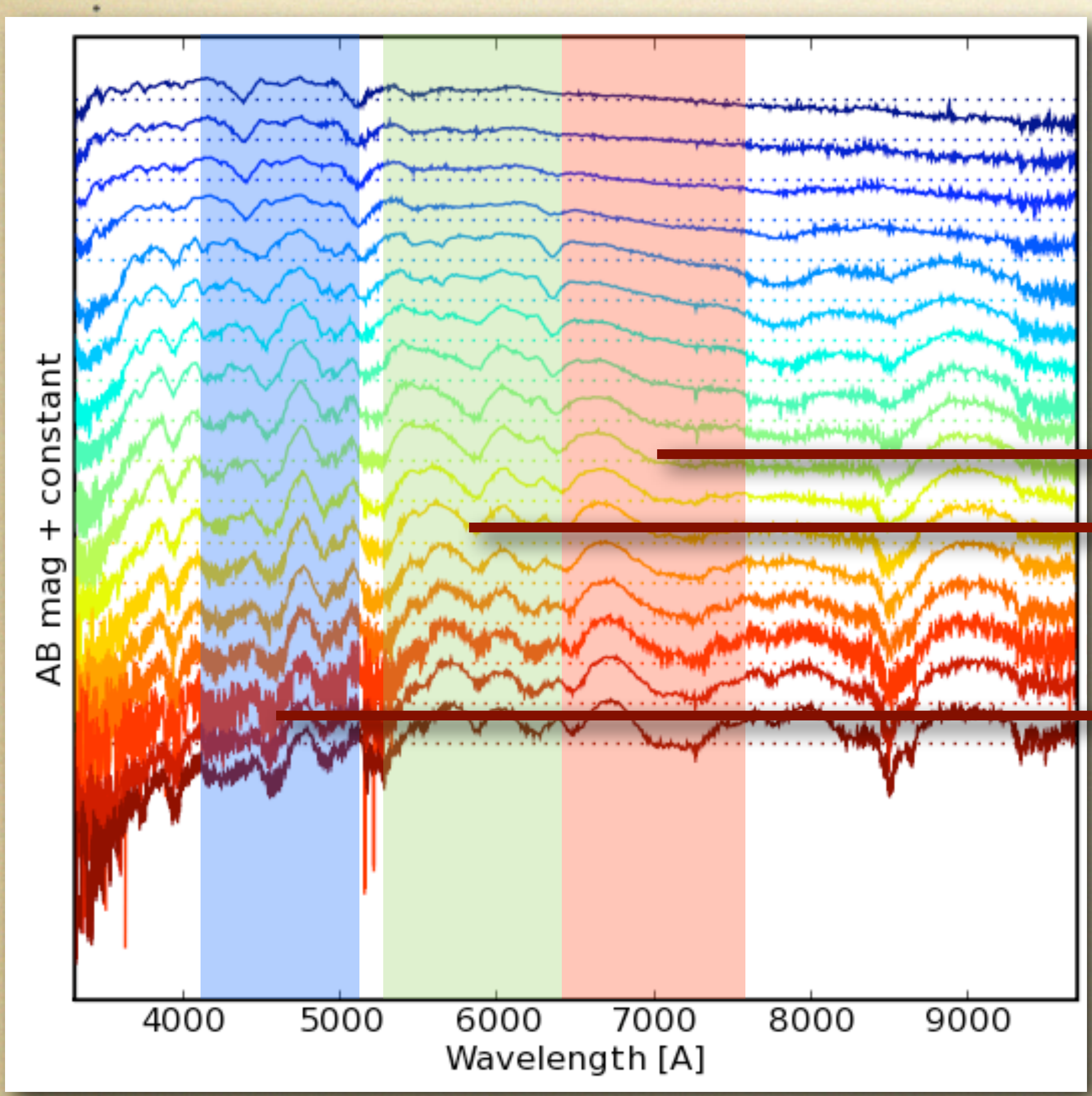


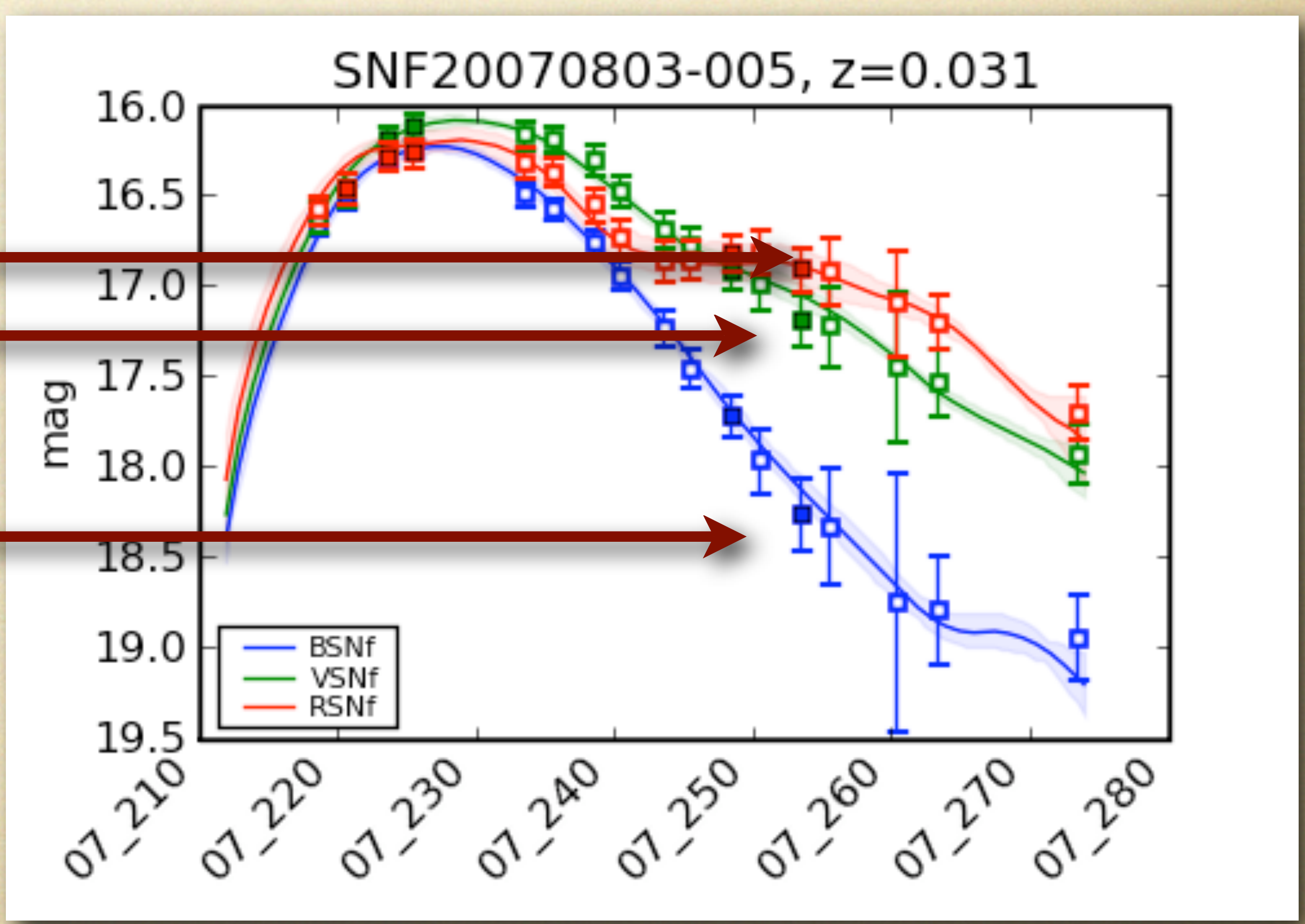
For many SNe, we have 15-20 spectra

Spectro-photometric timeseries enables better SN models, addressing another significant systematic

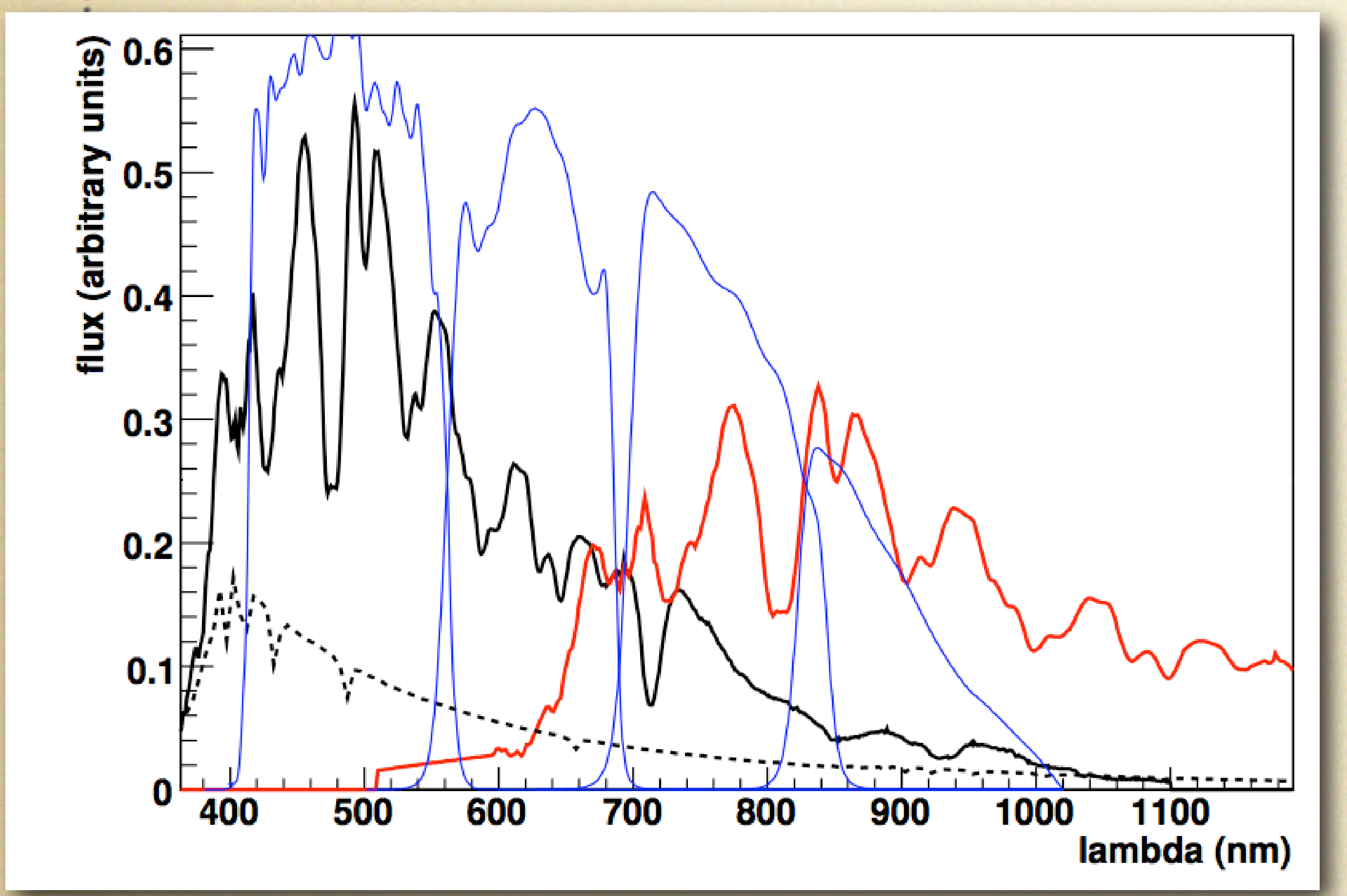
Custom Filter Bandpasses

We can synthesize any filter at any redshift (almost) to address the dominant low/high-z systematics



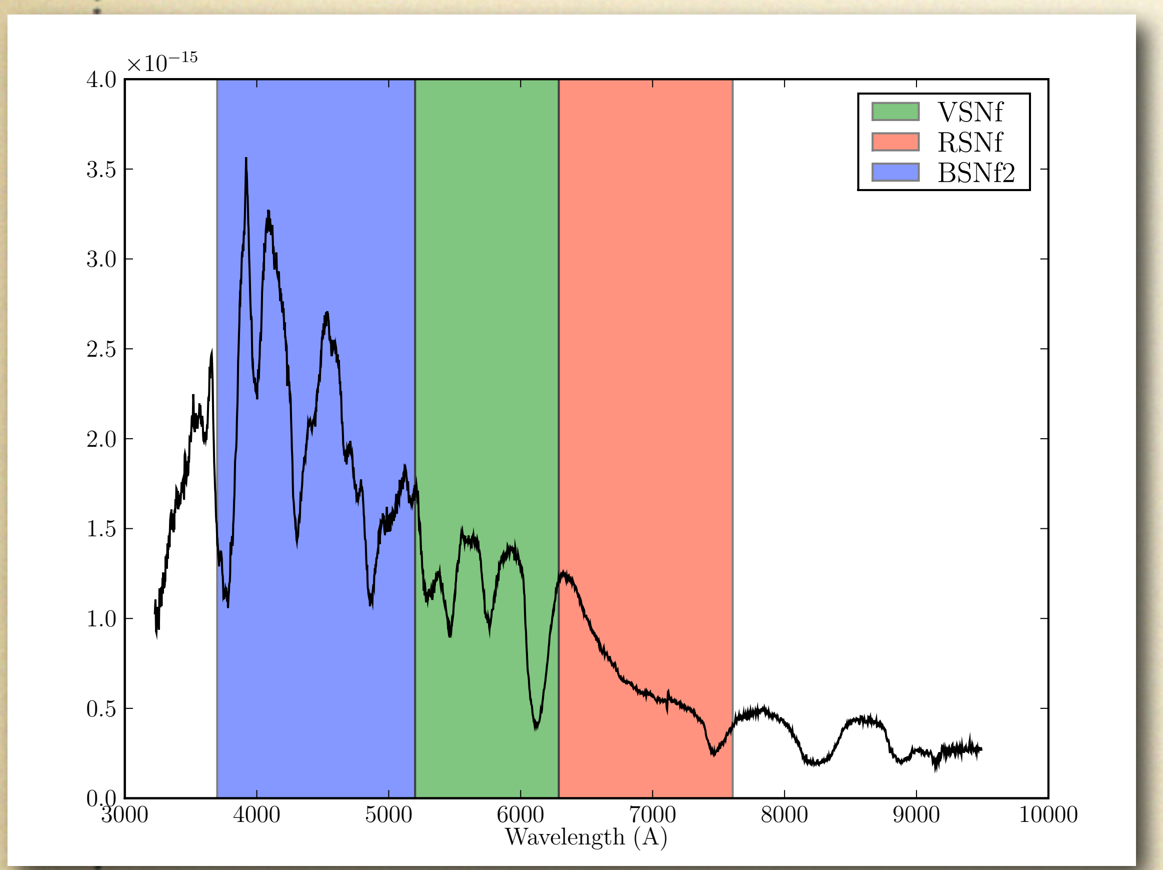


A Related Systematic: K-corrections



- Related to both filter calibrations and SN lightcurve modeling
- SNe at different redshifts probe different parts of spectra
- Getting back to same filter (*B*-band restframe) requires "K-corrections" either explicitly or built into model

K-correctionless fits



R. Pereira Thesis

	all	gold
BSNf	0.147 0.052	0.138 0.076
VSNf	0.047 0.059	0.060 0.062
RSNf	0.058 0.081	0.064 0.079

LC fit core RMS
(normal LC vs restframe)

Synthesize lightcurves in SN restframe instead of redshifted observer frame –

Significant improvement in B (somewhat worse in R)

SNfactory is first dataset with which this can be directly tested

K-correctionless Hubble Diagram

RMS scatter of fit to Hubble Diagram

	normal	restframe	# objects
all	0.188 ± 0.024	0.161 ± 0.021	33
good	0.141 ± 0.020	0.127 ± 0.018	28
gold	0.139 ± 0.037	0.104 ± 0.028	10

R. Pereira Thesis

Clear improvement in Hubble diagram scatter, larger than what is generally recognized as the systematic error from K-corrections

The SNfactory dataset can directly measure this systematic and build better models to reduce it in the future

Addressing Systematics

Alex Conley/SNLS, AAS January 2007

Systematic	w Error
Colour of Vega on Landolt system	0.0391
SNLS zeropoints	0.0311
SNLS bandpasses	0.0286
SN model	0.0278
Evolution in colour-luminosity (β)	0.0242
Landolt bandpasses	0.0146
Local flows	0.0137
SED of Vega	0.0131

Gone: bypass Landolt/Vega and directly calibrate with SNLS filters and standards

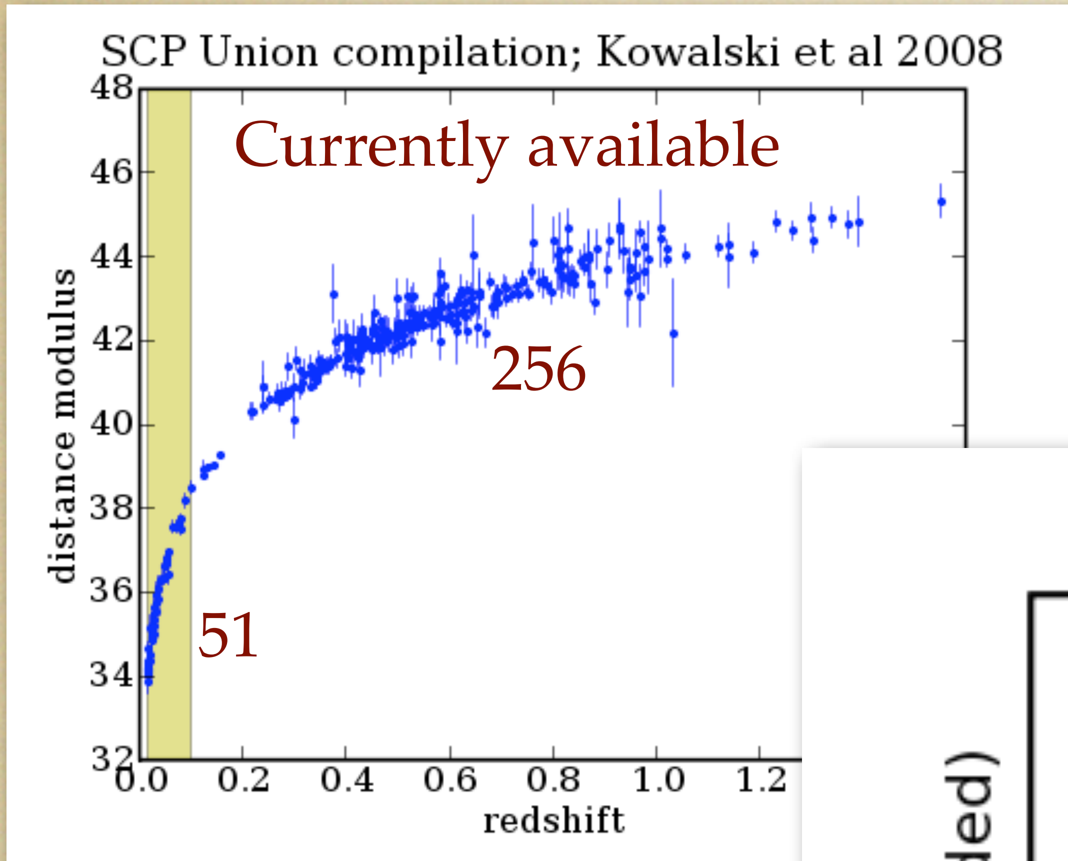
Smaller (½?) traceable inter-calibration

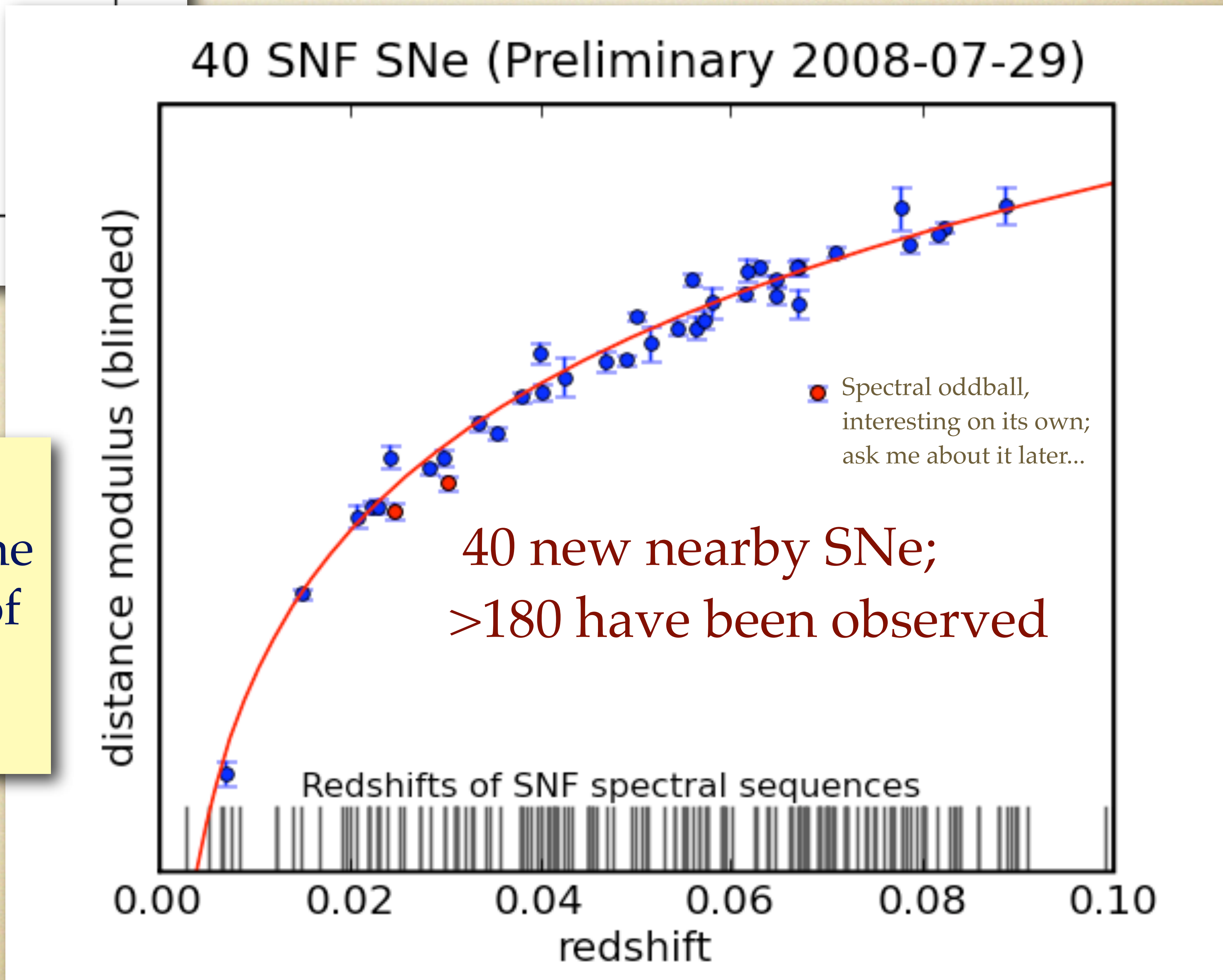
Spectrophotometric timeseries enables much more detailed models (exact improvement not yet quantified)

Gone (mostly): pick the filters you need in software; residual miscalibrations are small

This work is still in progress, but the SNfactory dataset allows dramatic improvements on the limiting systematics

SNfactory Hubble Diagram

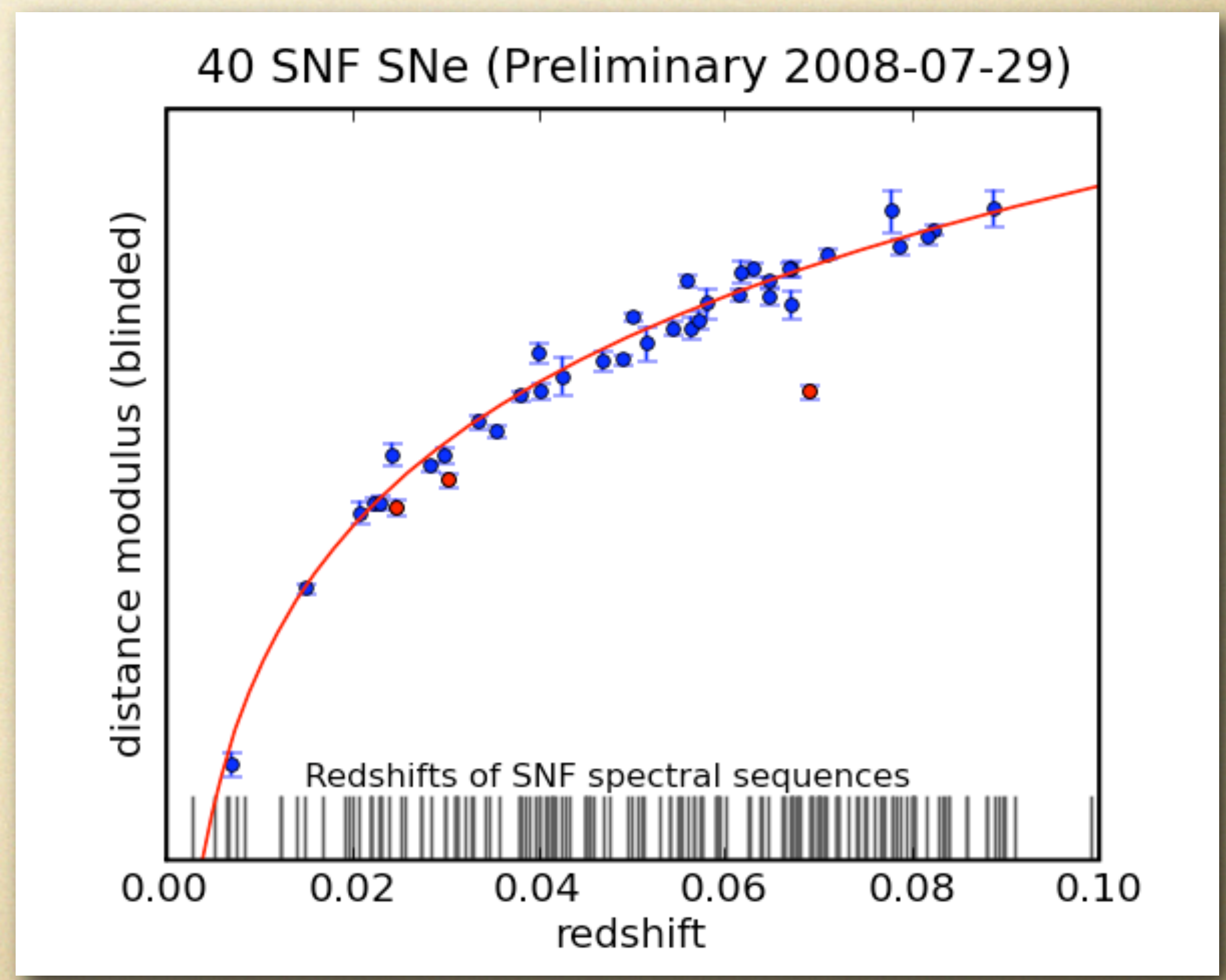




~¼ of our data nearly doubles the world's sample of nearby SNe for cosmology

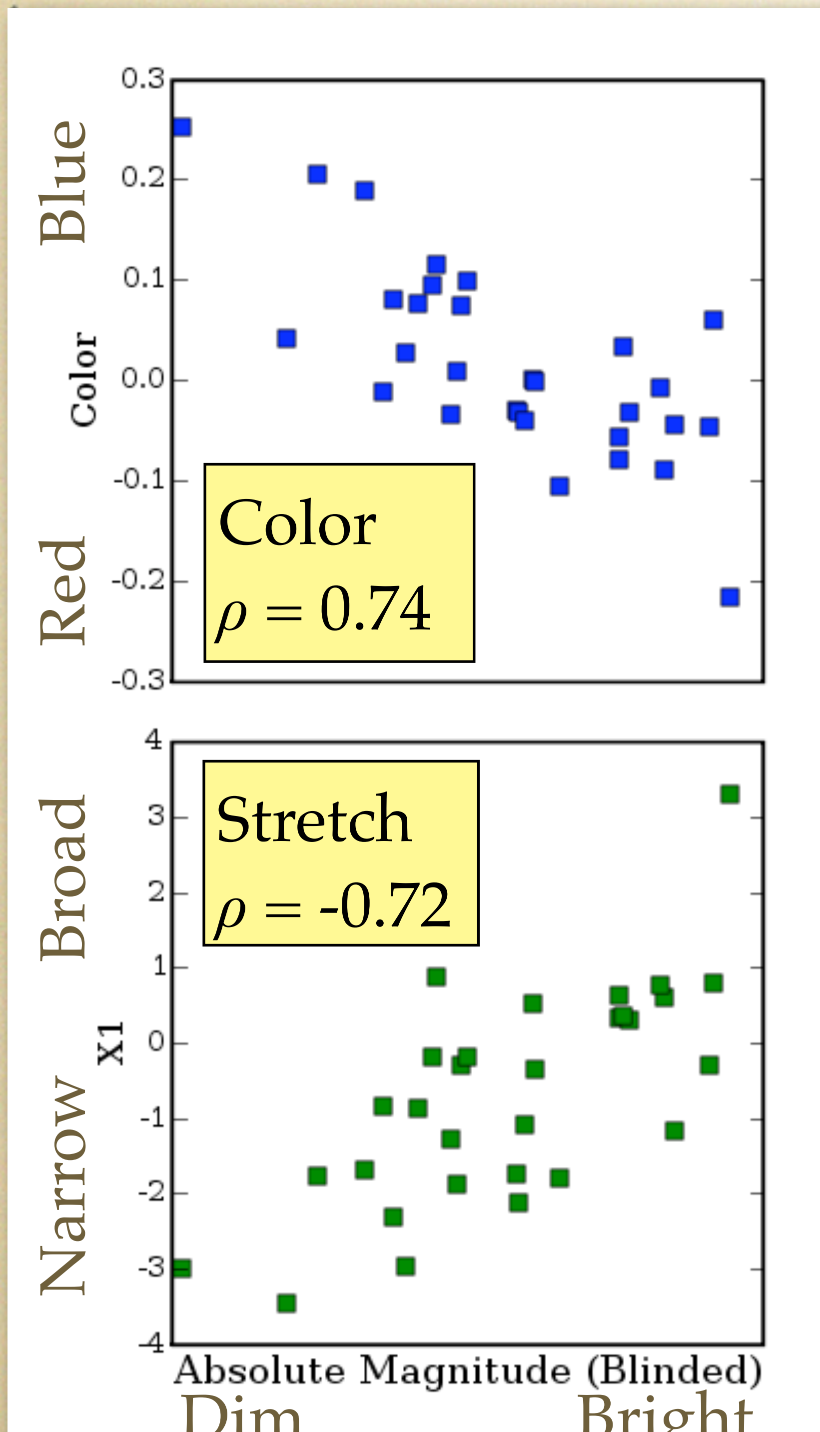
Before Unblinding Cosmology

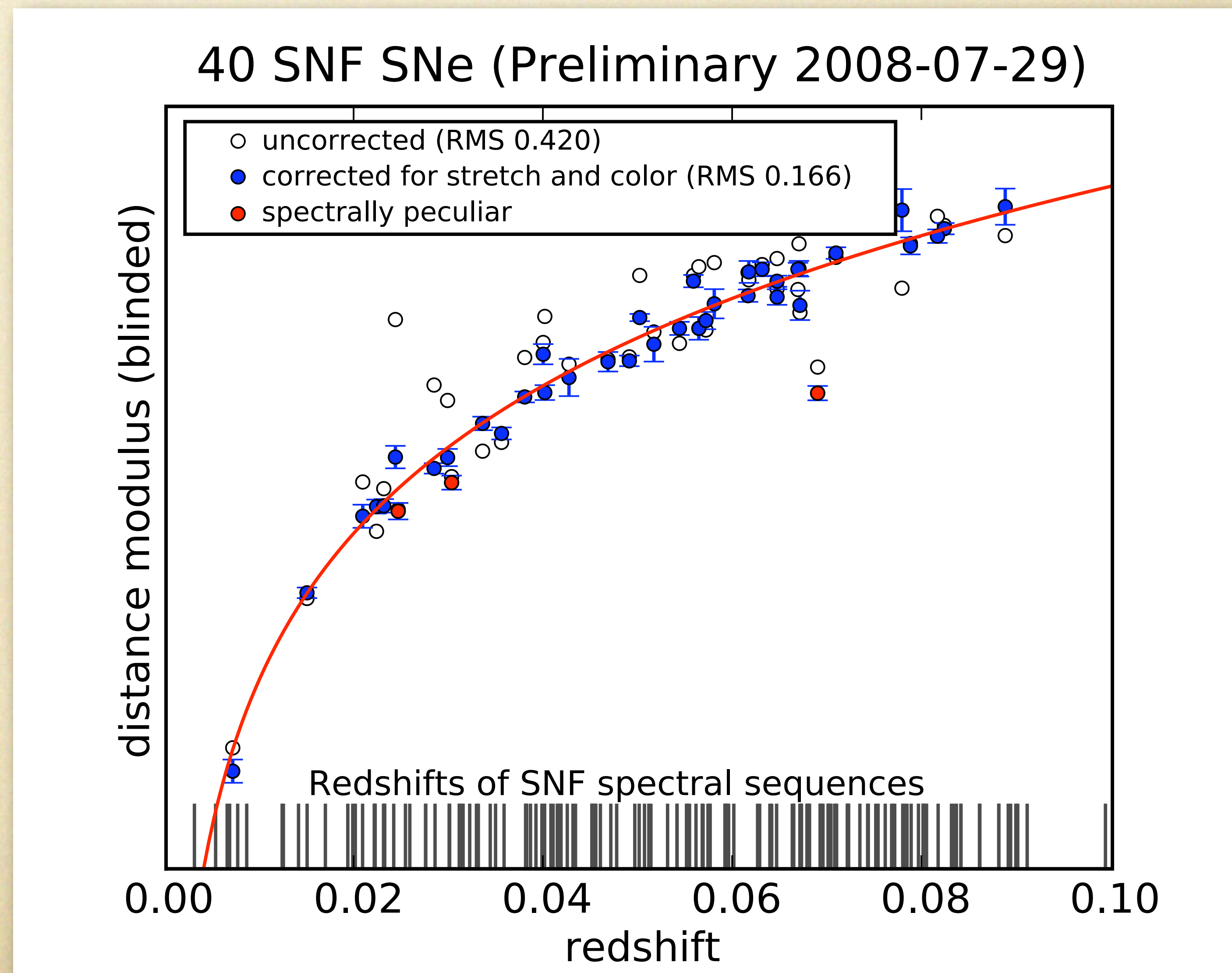
- Perform crosschecks for biases on absolute calibration
- Quantify systematic errors
- Understand full error chain
- In parallel:
    - Improve calibration algorithms
    - Get more data
    - Develop novel techniques for systematics
    - Perform analyses which only require relative calibration



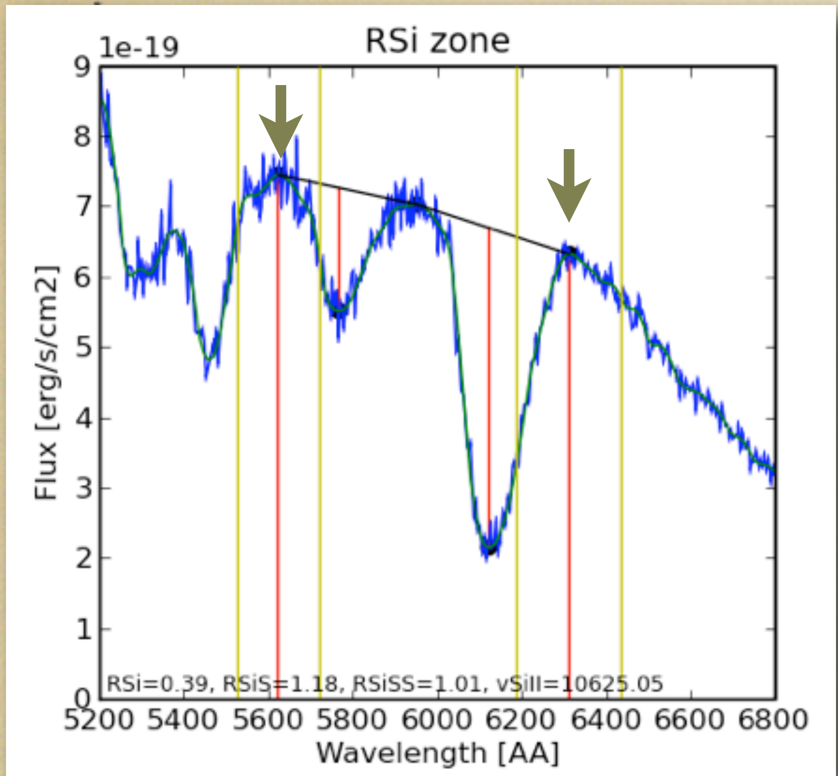
Beyond Systematics: Improving SNe as Distance Estimators

- Color and Stretch can normalize SN peak brightness to ~15%
- We would like to find additional parameters to improve this calibration

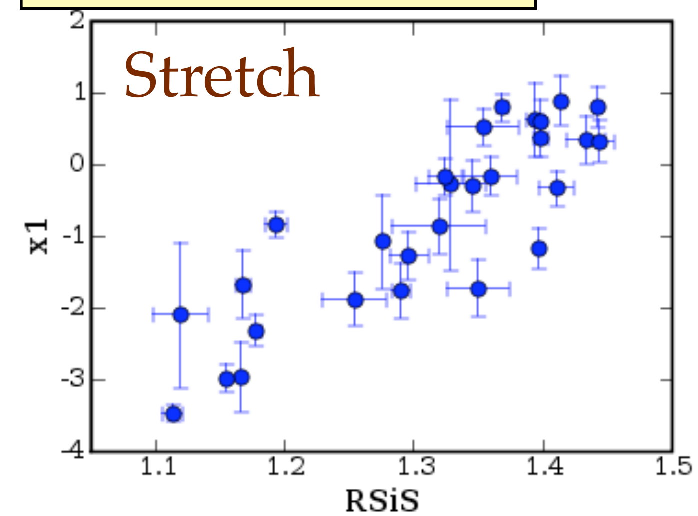


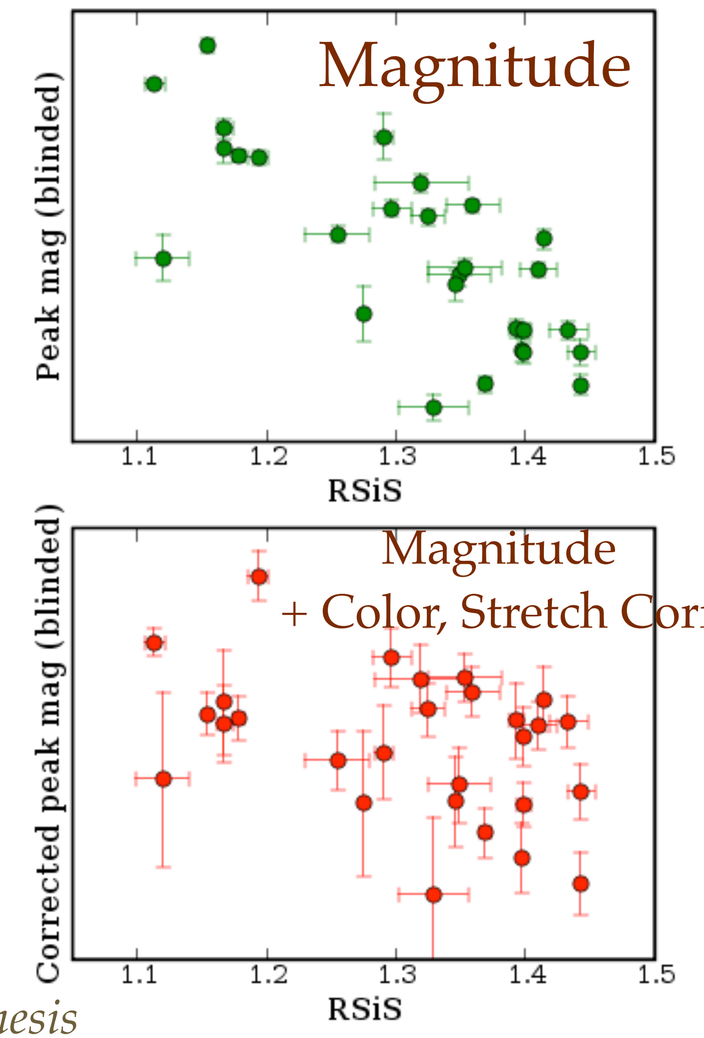


Classic Feature Ratios



Correlation with:





RSiS = ratio of Si to S peaks

Classic metrics study: N. Chotard Thesis

- Ratios of spectral features are correlated with stretch and absolute magnitude
- But this is redundant information
- We want a metric:
  - with information beyond stretch and color
  - which statistically combines combines multiple correlations

NB: Even the correlation with absolute magnitude is a new result enabled by the SNfactory data; previously only correlation with stretch was confirmed

Generalized Correlations

With apologies, the next few slides of the talk are restricted from digital release until submission of the paper (Dec08/Jan09)

The AAS abstract summarizing this work:

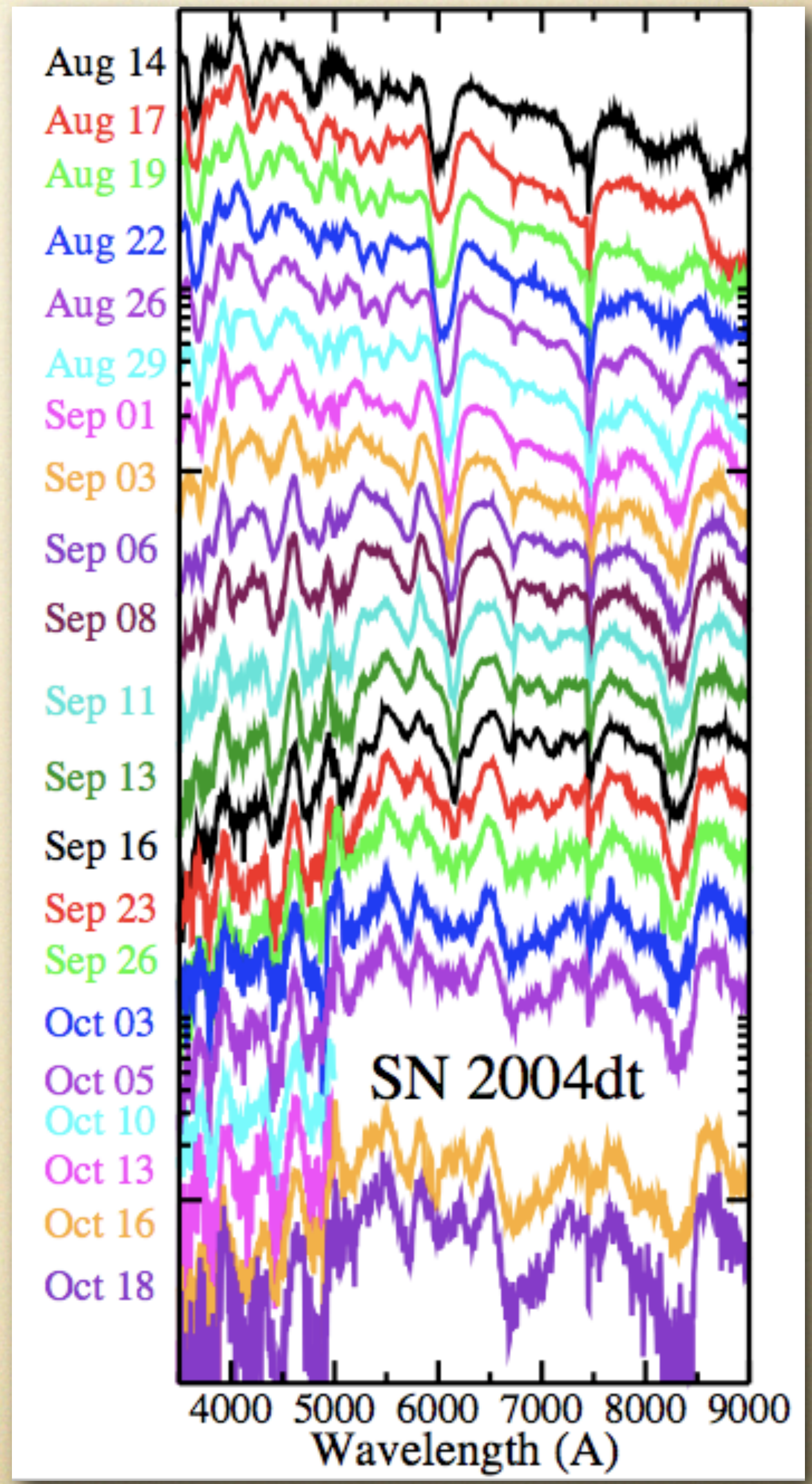
We present a generalized correlation analysis of type Ia supernova spectra with a focus on spectral features that correlate with absolute magnitude in ways that are not already accounted for by color and lightcurve stretch.
The results reveal new spectral correlations beyond those of the classic metrics of feature ratios (RSi, RSiS, RCa, EDCa).
These new correlations could be used to improve the calibration of type Ia supernovae for cosmology measurements beyond what is possible with stretch and color alone.

SNfactory Schedule

- 2008 SN Search: Finished (>1000 SNe in 4 years)
  - Discovery camera is moving from Palomar to La Silla
  - Improved camera commissioned for next generation search (Palomar Transient Factory)
- 2008 Followup:
  - Finish observations of 19 current SNe
  - Take final reference calibration spectra of 2007 targets
- 2009: Finish final reference observations
- The science analysis has just begun
- SNIFS will remain available for SN observations, but our core focus will be analyzing our current data

Rich Dataset for the Future

- Addresses dominant systematics for SN cosmology
    - Photometric cross-calibration
    - SN modeling
- Large area search developed algorithms for future transient discovery pipelines
- Detailed spectro-photometric timeseries provides unrivaled detail for understanding supernovae as cosmological probes



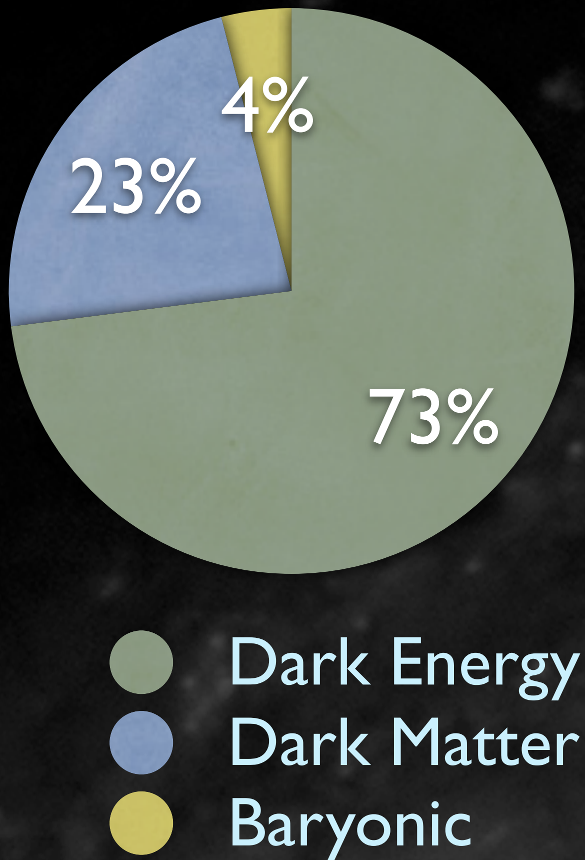
Upcoming SN Programs

- Awaiting publications from SNLS, Essence, SDSS, SCP
- KAIT/LOSS (disc) and CSP (follow): ongoing very nearby
- Palomar Transient Factory
  - New improved nearby transient search, including SNe
- SkyMapper
  - Southern version of SDSS with interleaved SN program
- Dark Energy Survey, PanSTARRS
  - Medium/high-z SN observations
- Joint Dark Energy Mission (JDEM)
  - Space based mission with high-z SN program
- LSST...

We don't need another SNLS (medium/high-z). We need more SNe with $0.02<z<0.1$ and $1.0<z$ and/or better control of systematics.

The Future with LSST

- >100,000 SNe per year
- Drowning in statistics in an era limited by systematics?
- What can LSST do which is new?
  - Nearby and distant SNe from same program
    - controls filter zeropoint, bias, LC sampling systematics
  - Measure expansion vs. location on sky
    - tests homogeneity/isotropy, improves bulk flow systematics
  - Lightcurve "likes to likes"
    - reminder: cosmology comes from ratio of fluxes
    - take ratios between most similar distant and nearby SNe
    - controls modeling systematics
  - Many "systematics" can be improved with more statistics from well calibrated observations = LSST



Conclusion

~3/4 of the Universe is Dark Energy, yet we know almost nothing about it

➔ ***Huge potential for discovery***

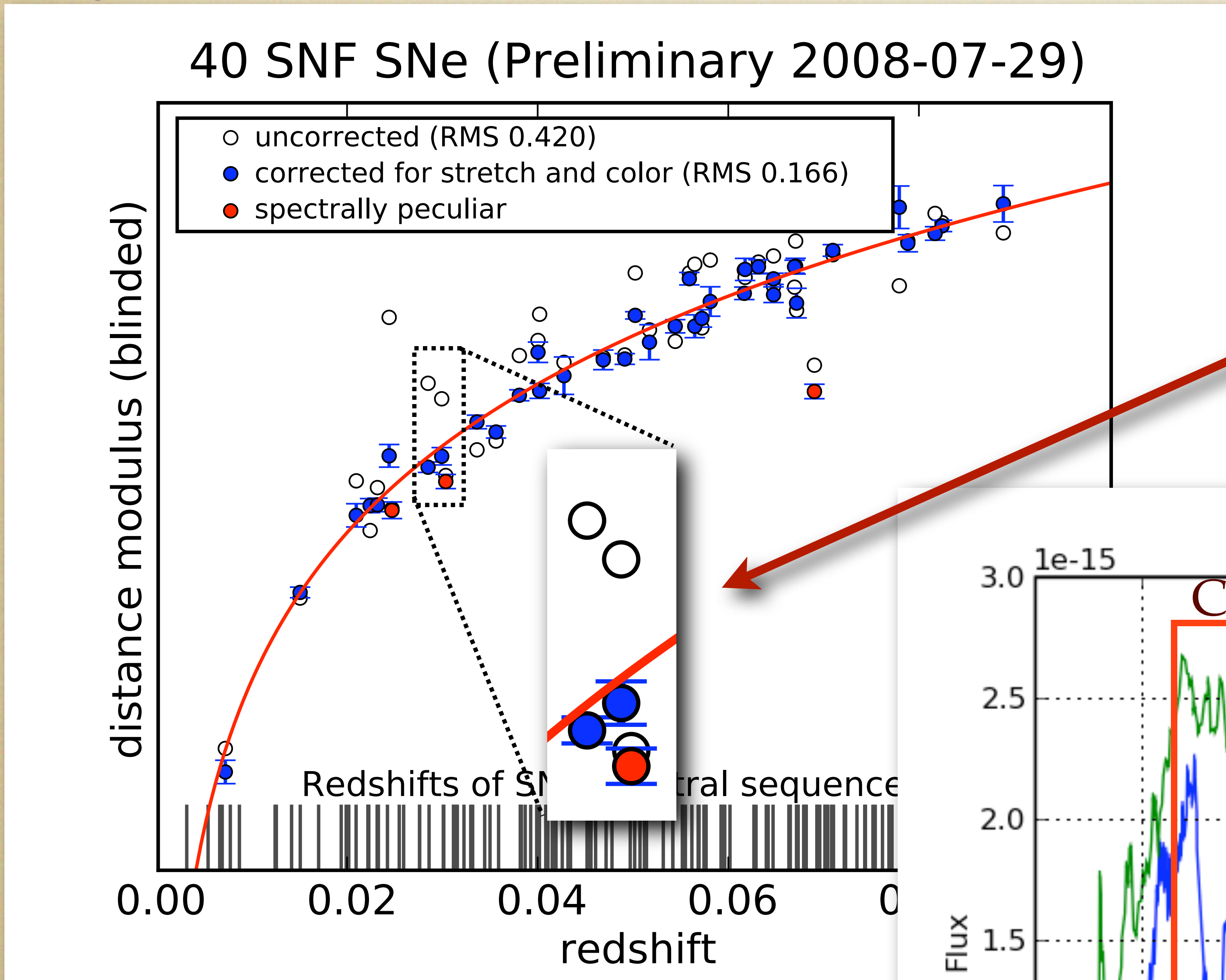
We've known about it for less time than it took to build the LHC

➔ ***Huge opportunity for innovation***

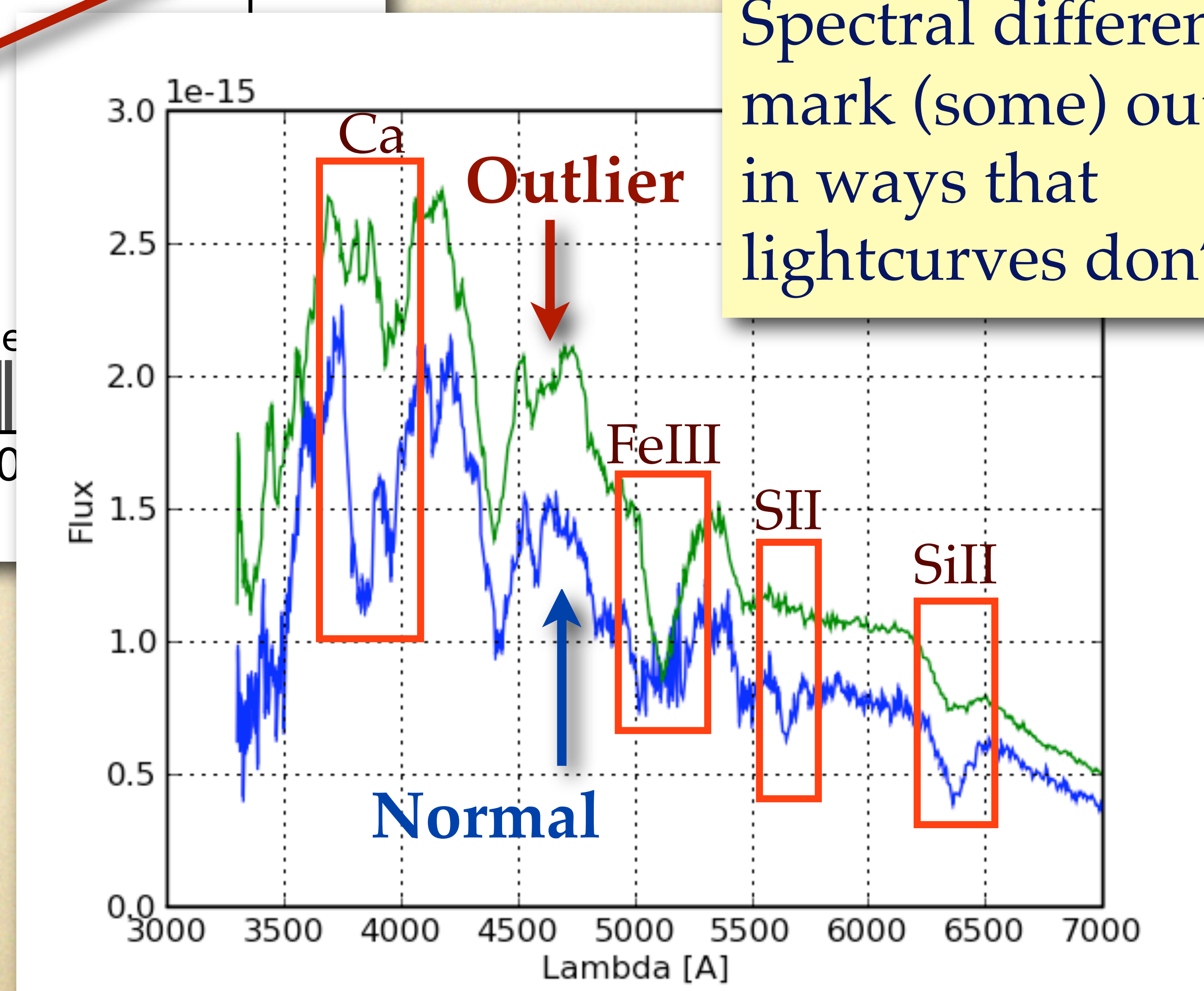
The SNfactory is strengthening the foundations of SN cosmology by ***addressing the current limiting systematics*** and ***preparing us for future observations***.

Backup Slides

Spectra and Outliers

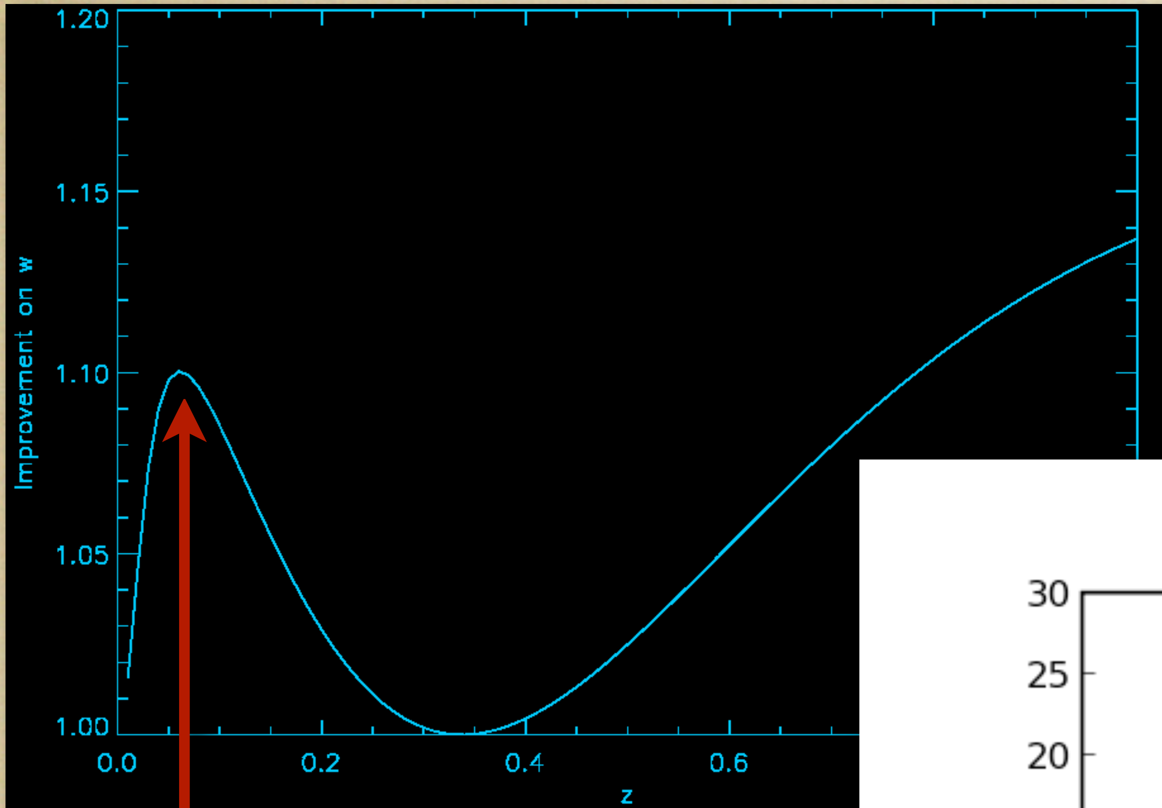


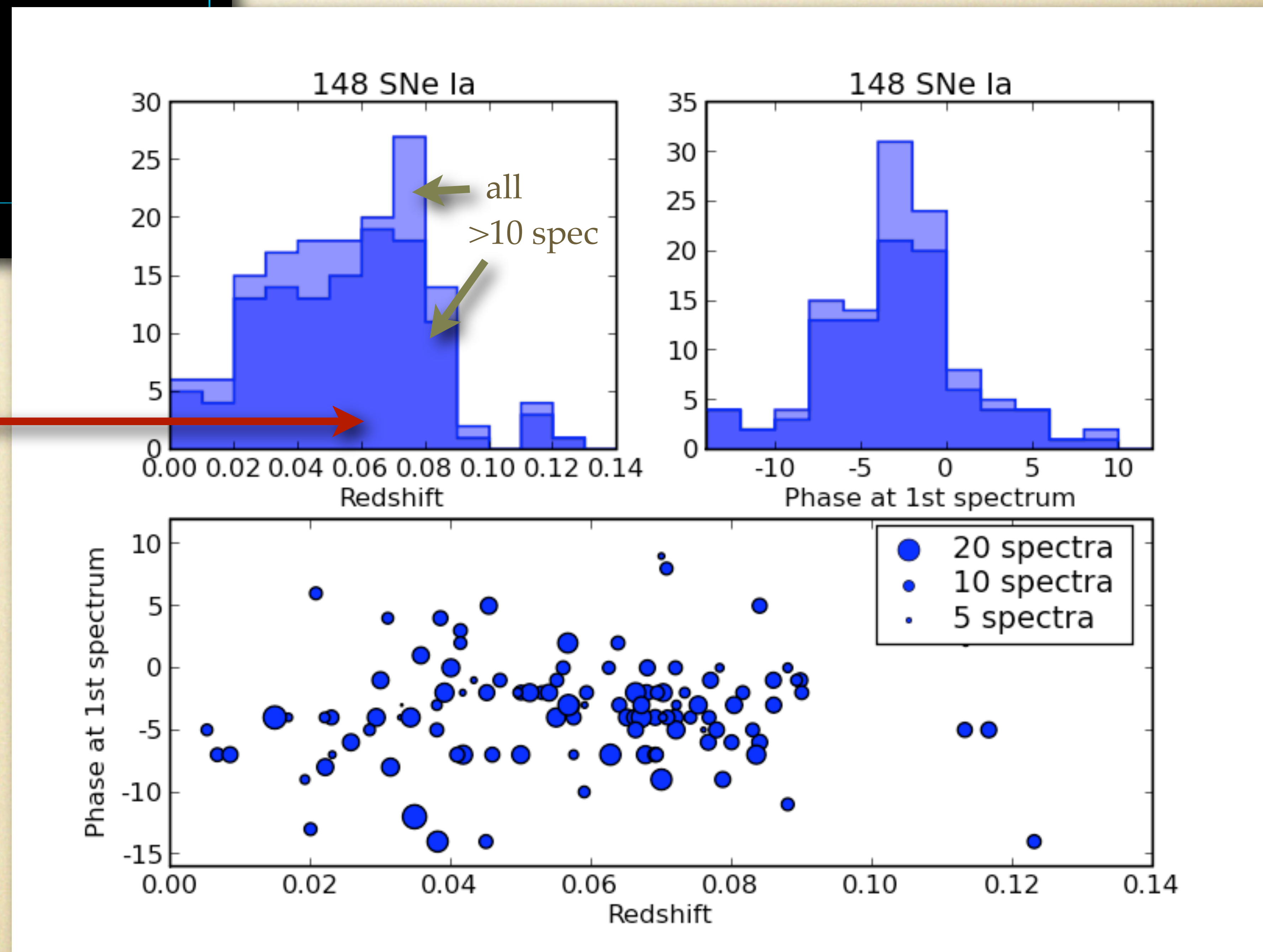
- Peak mag corrections for
  - Color (bluer = brighter)
  - Stretch (broader = brighter)
- Some correct better than others...



Spectral differences mark (some) outliers in ways that lightcurves don't

Dataset Stats





Optimal redshift **~0.06** for nearby SNe

Strange SNe

- SN2005gj – Ia with hydrogen lines (!) – SN in a gas cloud
- SN2006X – Ia with unusual carbon signature
- Time-series of several 91T-like SNe
- SNF20070825-001 – spectral time-series of super-chandra candidate
- SNF20080720-001 – highly extincted, direct measure of dust?