Integral Field Spectroscopy for a Dark Energy Space Mission

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LBNL

August 15, 2012 PHYSAG Meeting

My IFS Background

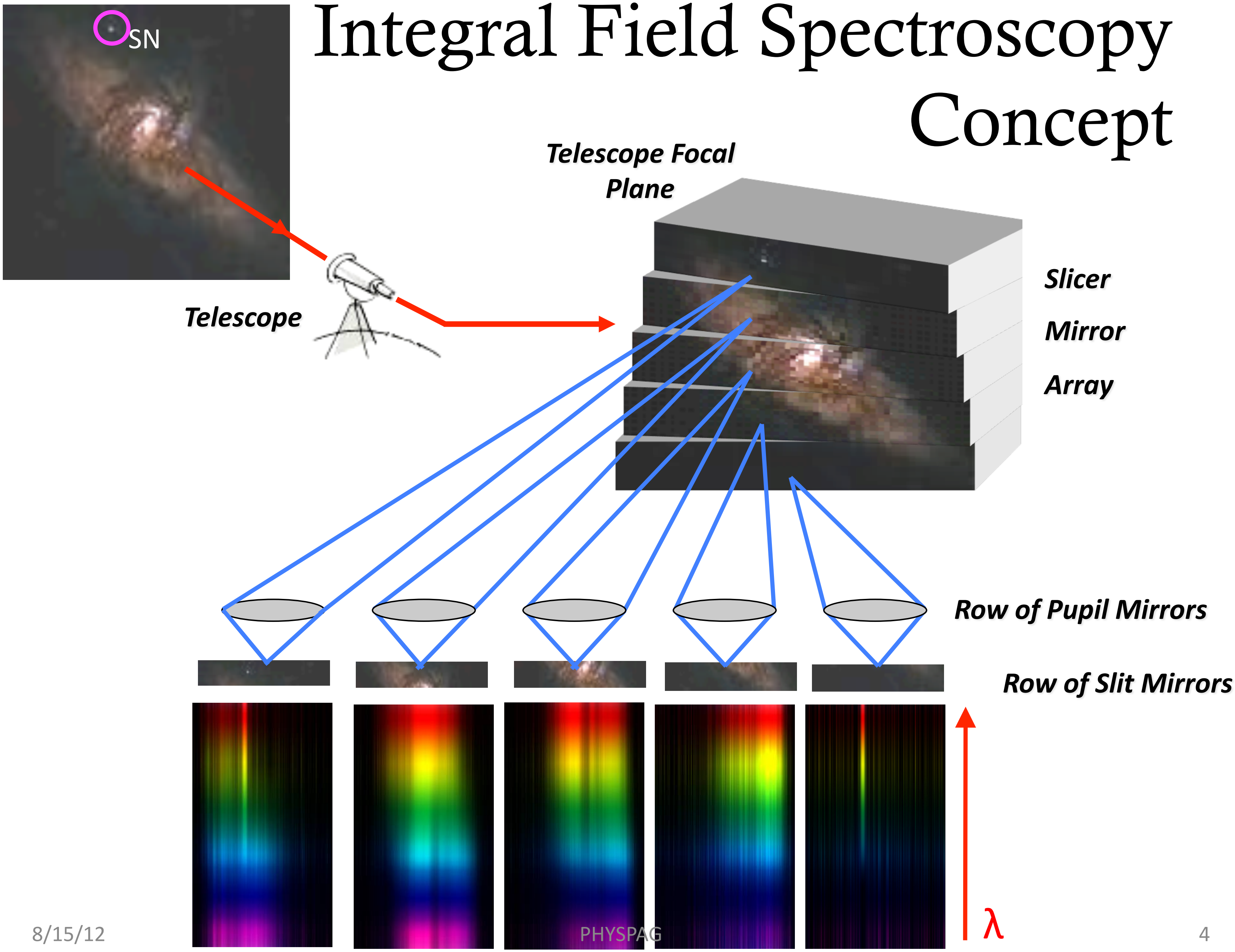
- The concept of using Integral Field Spectroscopy (IFS) for supernova cosmology originated with the first SuperNova Acceleration Probe (SNAP) proposed to DOE in 1999.
- The Nearby SuperNova Factory (SNfactory) built the SuperNova Integral Field Spectrograph, which has been in use on Mauna Kea since 2004.

Thus, my primary focus here will be on the use of Integral Field Spectroscopy for SN cosmology

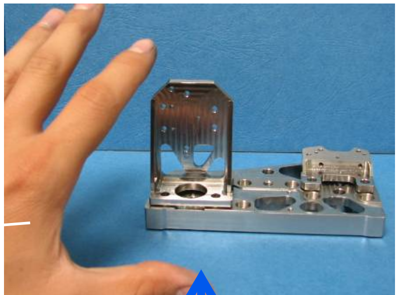
IFS for Space - Background

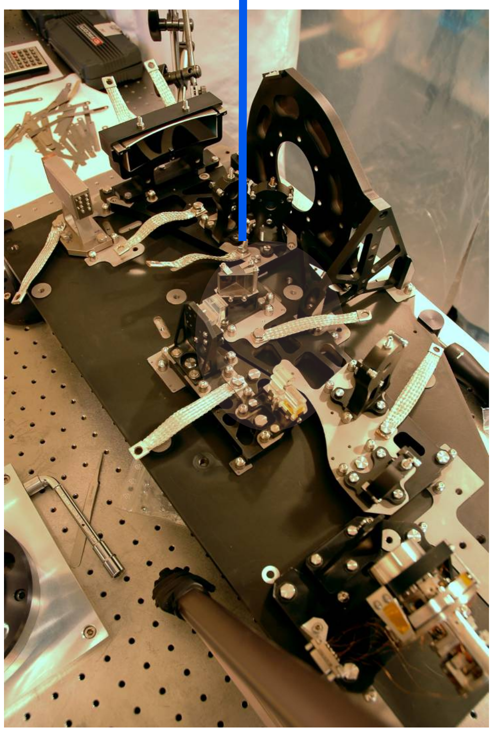
- Under the SNAP/JDEM aegis a R ~ 100 space-qualified prototype optical/NIR IFS was built.
- The JDEM ISWG considered a space SN cosmology program featuring an IFS triggered by detections from coarse-resolution wide-field cameras.
- The WFIRST SDT report also considers an IFS for the SN cosmology program.

Integral Field Spectroscopy Concept



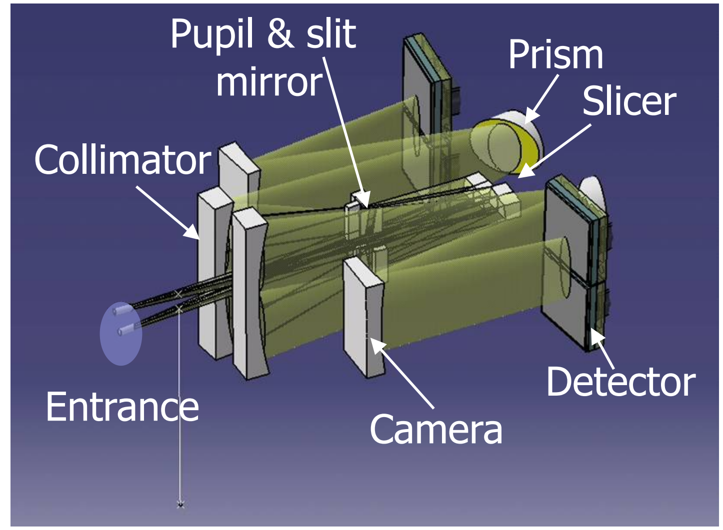
Prototype Space-qualified (TRL5) IFS





IFS performance:

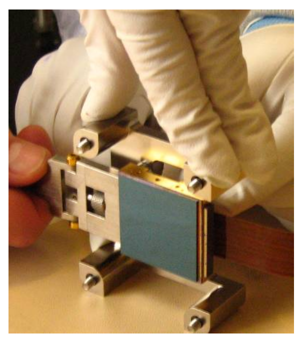
- ❑ 0.35-1.7 micron
- ❑ < 12 kg
- ❑ R of 70 – 200
- ❑ Total thoughput w/ OTA
  - ❑ > 55% in optical
  - ❑ > 40% in NIR

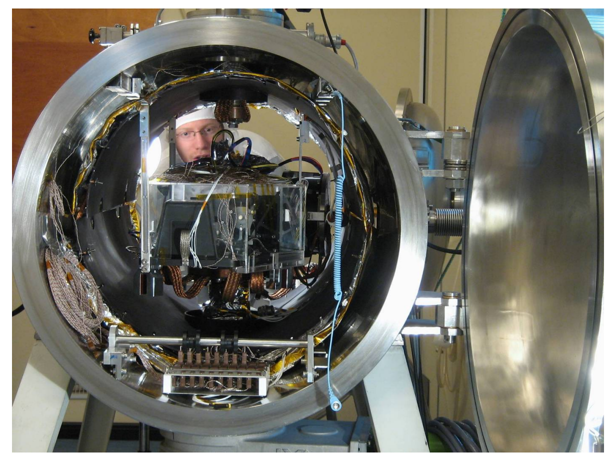


Calibration tests:

- ❑ Straylight measured to be < 10^{-3}
- ❑ Wavelength calibration at the nm level
- ❑ relative flux calibration better than 1 %

NIR 2k x 2k Teledyne device integrated with optics and readout system





Orientation: Type Ia Supernova Spectrum

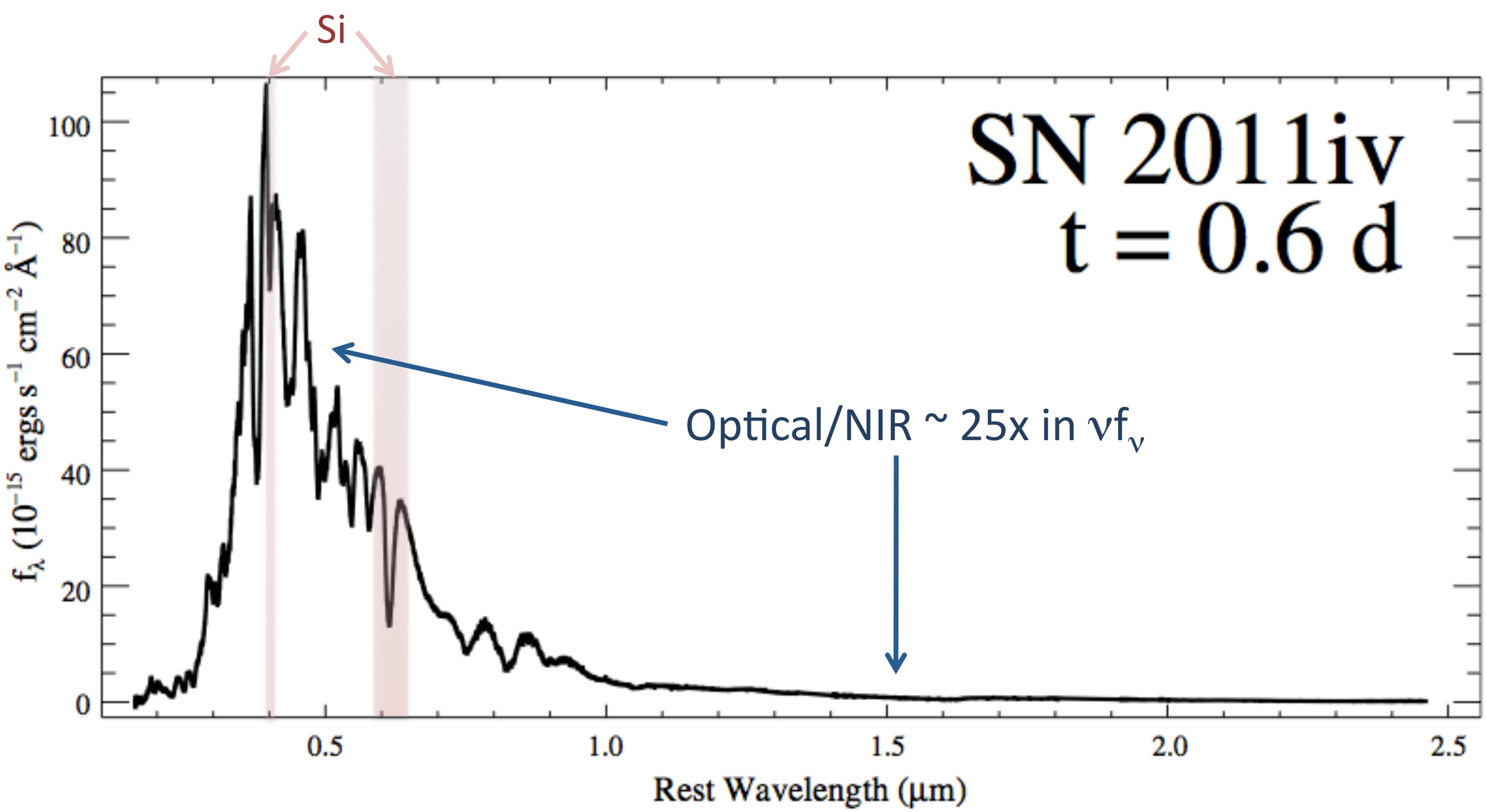
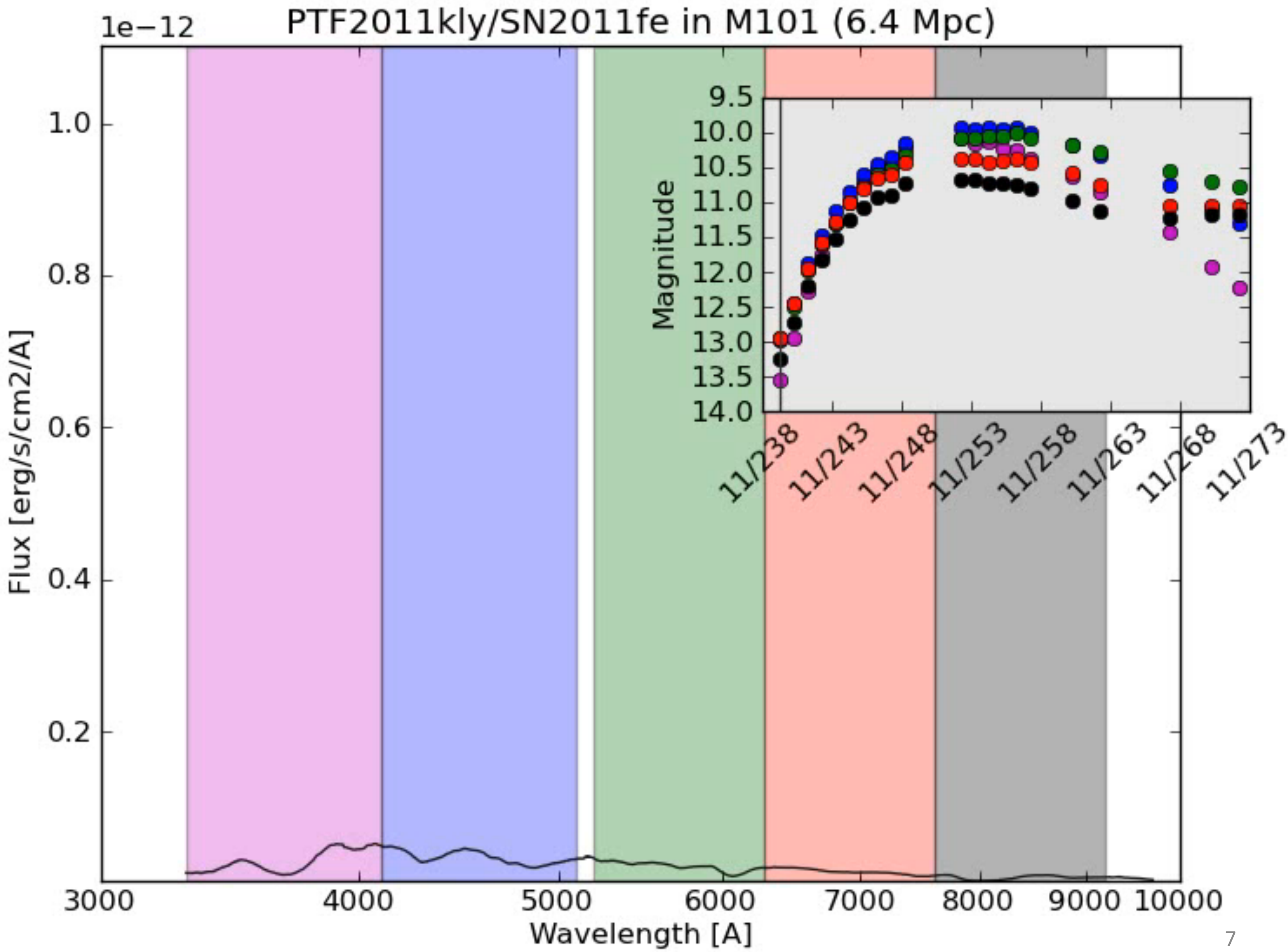
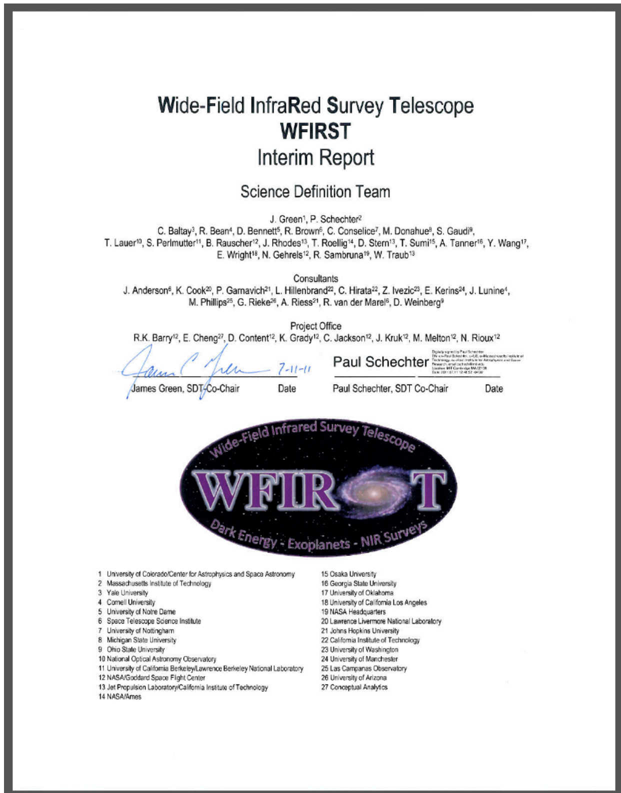


Figure 2. UVOIR *HST*/STIS and Magellan/FIRE maximum-light spectrum of SN 2011iv.

Foley et al 2012, ApJ


PTF2011kly/SN2011fe in M101 (6.4 Mpc)
1e−12
Flux [erg/s/cm2/A]
1.0
0.8
0.6
0.4
0.2
3000
4000
5000
6000
7000
8000
9000
10000
Wavelength [A]
Magnitude
9.5
10.0
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0
11/238
11/243
11/248
11/253
11/258
11/263
11/268
11/273

Projections for Dark Energy Constraints: The Science Case for a Integral Field Spectrograph



Wide-Field InfraRed Survey Telescope
WFIRST
Interim Report

Science Definition Team

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7-11-11
James Green, SDT-Co-Chair Date

Paul Schechter
Paul Schechter, SDT Co-Chair Date

Wide-Field Infrared Survey Telescope
WFIRST
Dark Energy - Exoplanets - NIR Surveys

1 University of Colorado/Center for Astrophysics and Space Astronomy
2 Massachusetts Institute of Technology
3 Yale University
4 Cornell University
5 University of Notre Dame
6 Space Telescope Science Institute
7 University of Nottingham
8 Michigan State University
9 Ohio State University
10 National Optical Astronomy Observatory
11 University of California Berkeley/Lawrence Berkeley National Laboratory
12 NASA/Goddard Space Flight Center
13 Jet Propulsion Laboratory/California Institute of Technology
14 NASA/Ames
15 Osaka University
16 Georgia State University
17 University of Oklahoma
18 University of California Los Angeles
19 NASA Headquarters
20 Lawrence Livermore National Laboratory
21 Johns Hopkins University
22 California Institute of Technology
23 University of Washington
24 University of Manchester
25 Las Campanas Observatory
26 University of Arizona
27 Conceptual Analytics

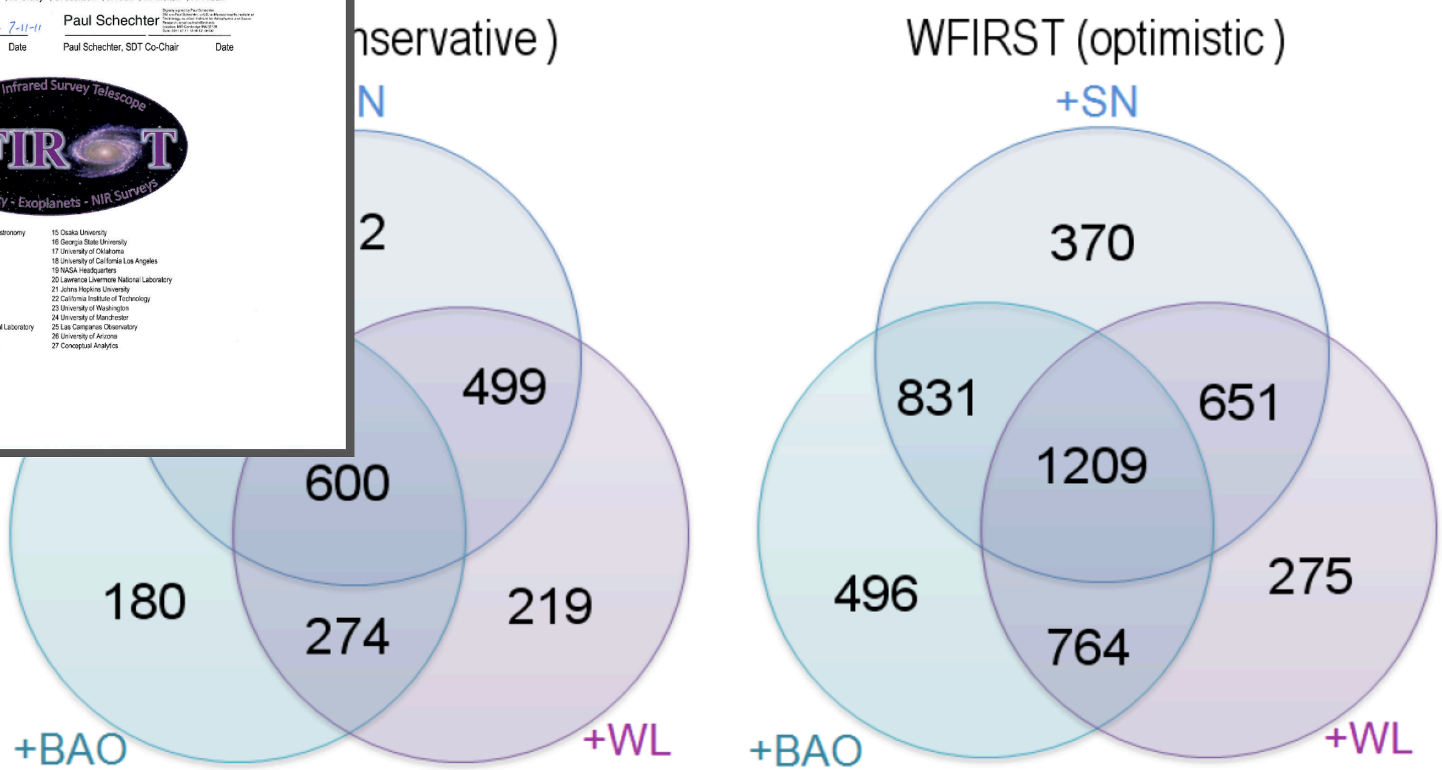
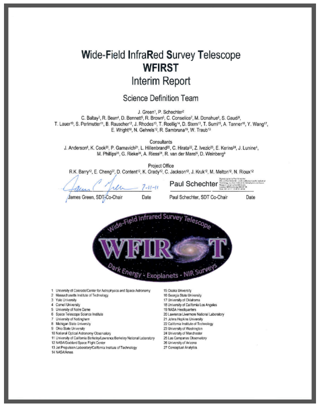


Figure 7: DETF FoM calculations for conservative and optimistic WFIRST assumptions. The stage II baseline (knowledge upon completion of ongoing projects) is a DETF FoM ~50.



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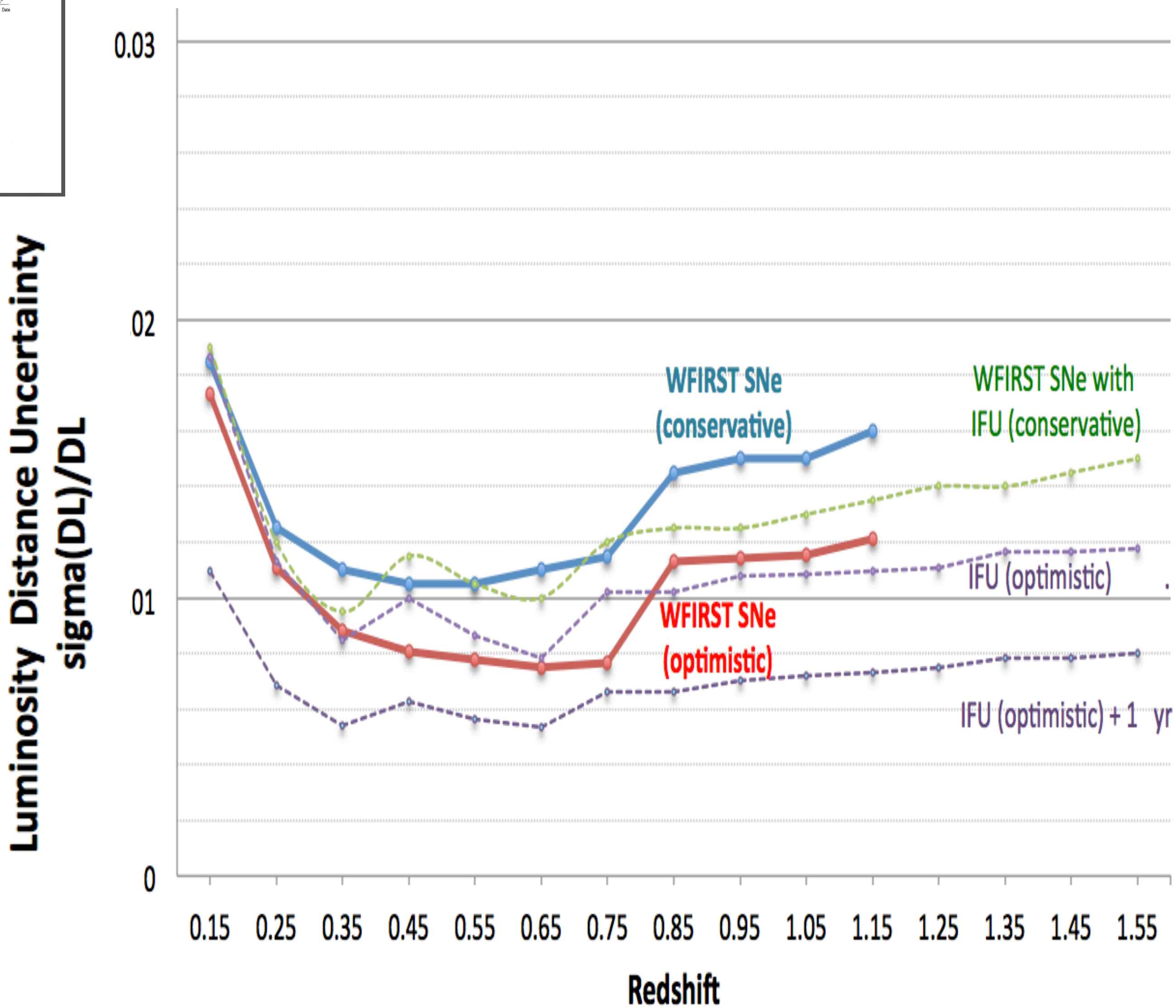
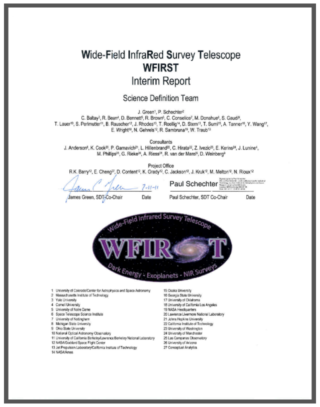


Luminosity Distance Uncertainty sigma(DL)/DL
0.03
02
01
0
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
1.05
1.15
1.25
1.35
1.45
1.55
Redshift
WFIRST SNe (conservative)
WFIRST SNe with IFU (conservative)
IFU (optimistic)
WFIRST SNe (optimistic)
IFU (optimistic) + 1 yr



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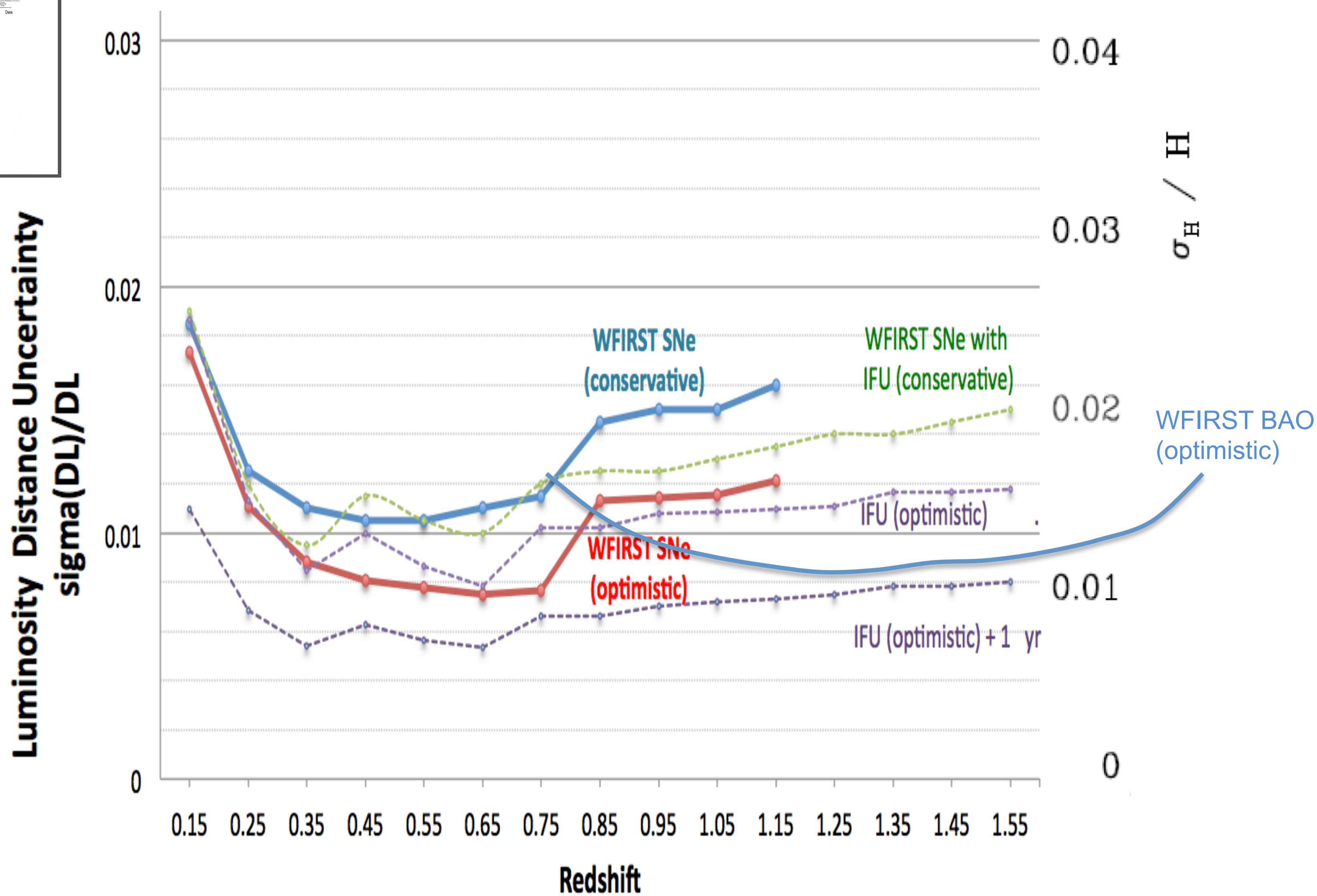
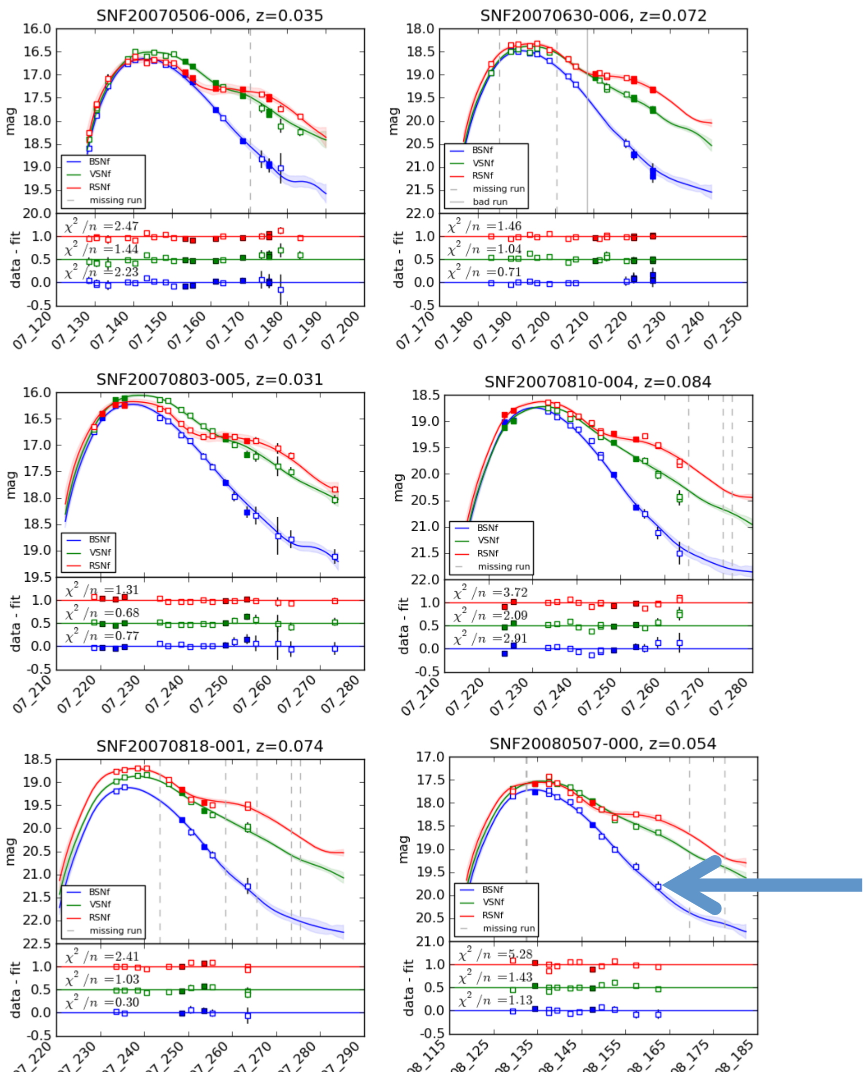
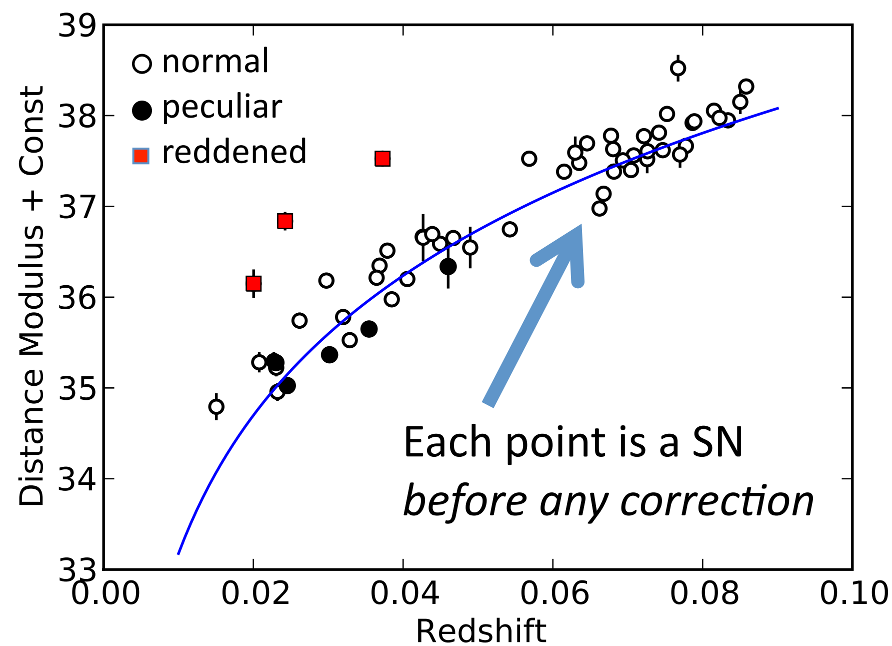


Luminosity Distance Uncertainty
sigma(DL)/DL
0.03
0.02
0.01
0
0.04
0.03
0.02
0.01
0
σ_H / H
WFIRST SNe
(conservative)
WFIRST SNe with
IFU (conservative)
WFIRST BAO
(optimistic)
IFU (optimistic)
WFIRST SNe
(optimistic)
IFU (optimistic) + 1 yr
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
1.05
1.15
1.25
1.35
1.45
1.55
Redshift

How are Type Ia Standardized with a Integral Field Spectrograph?

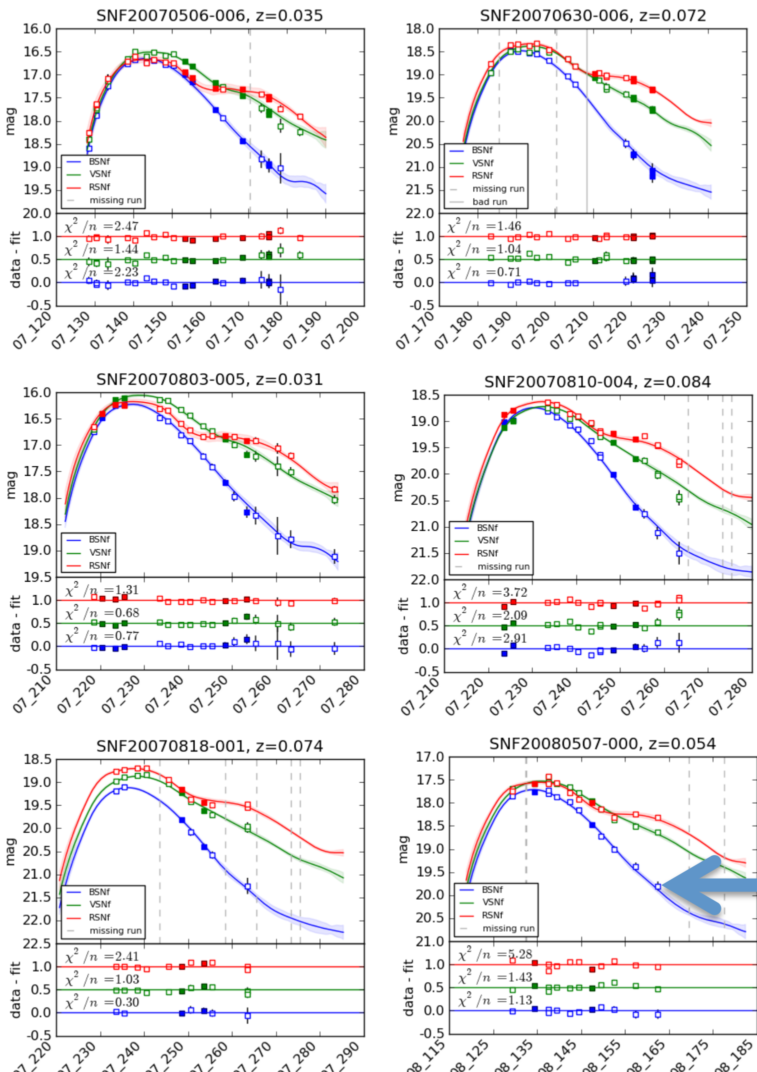
Standardization

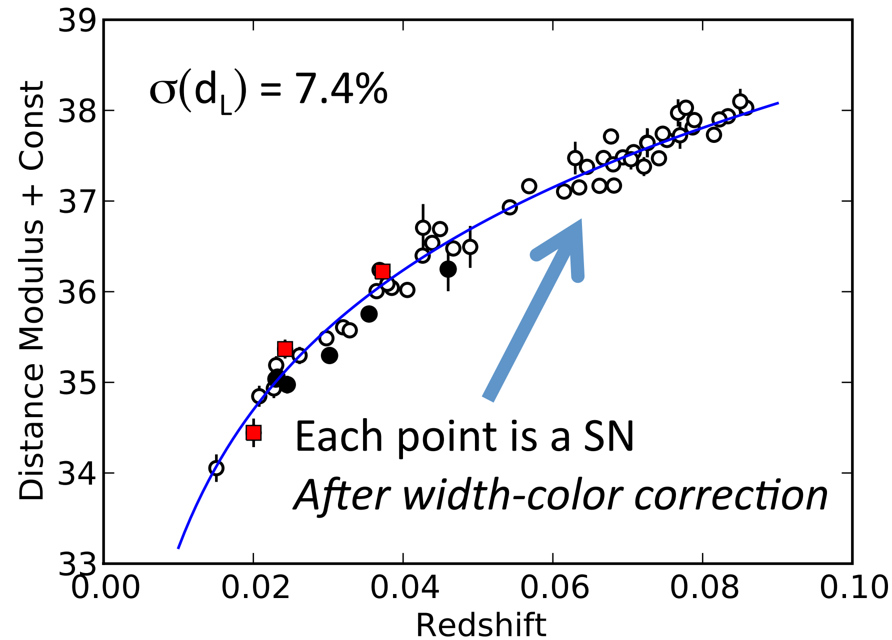




Each point is synthesized photometry from a flux-calibrated spectrum

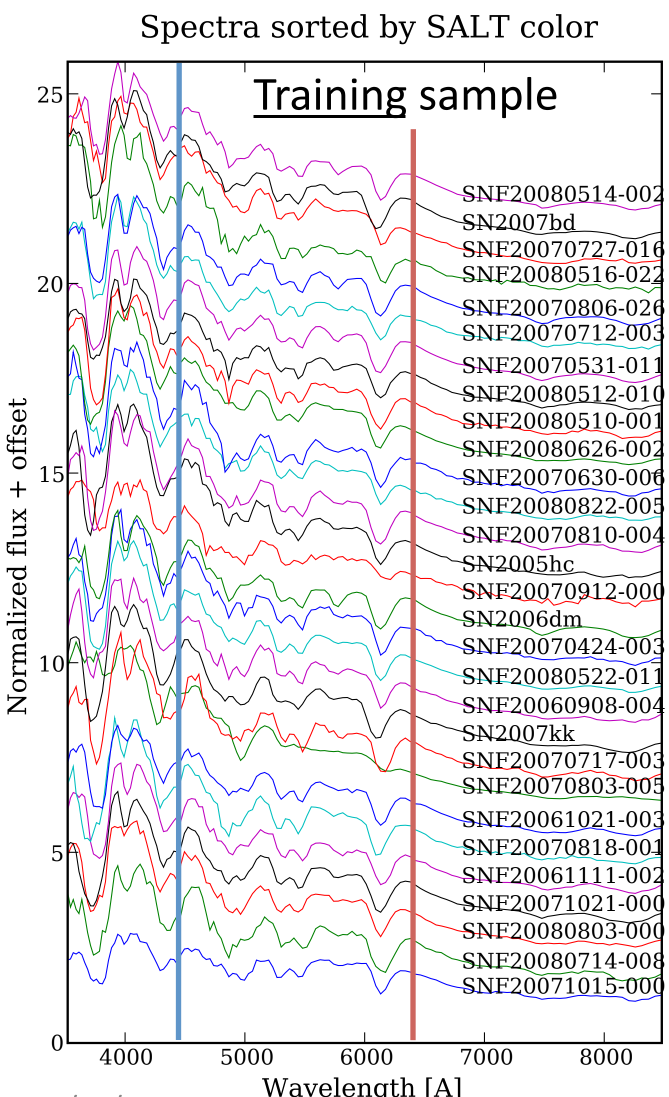
Lightcurve Standardization

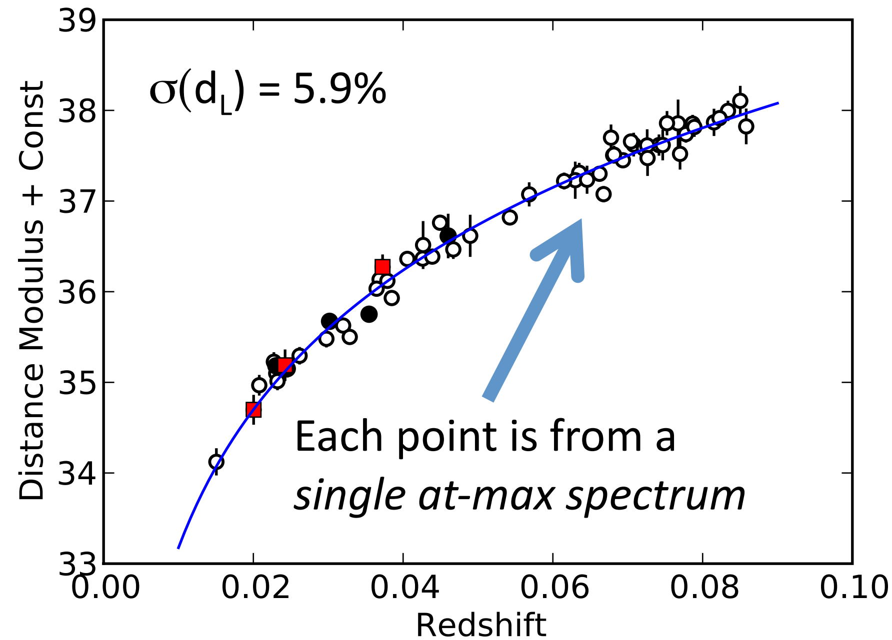




Each point is synthesized photometry from a flux-calibrated spectrum

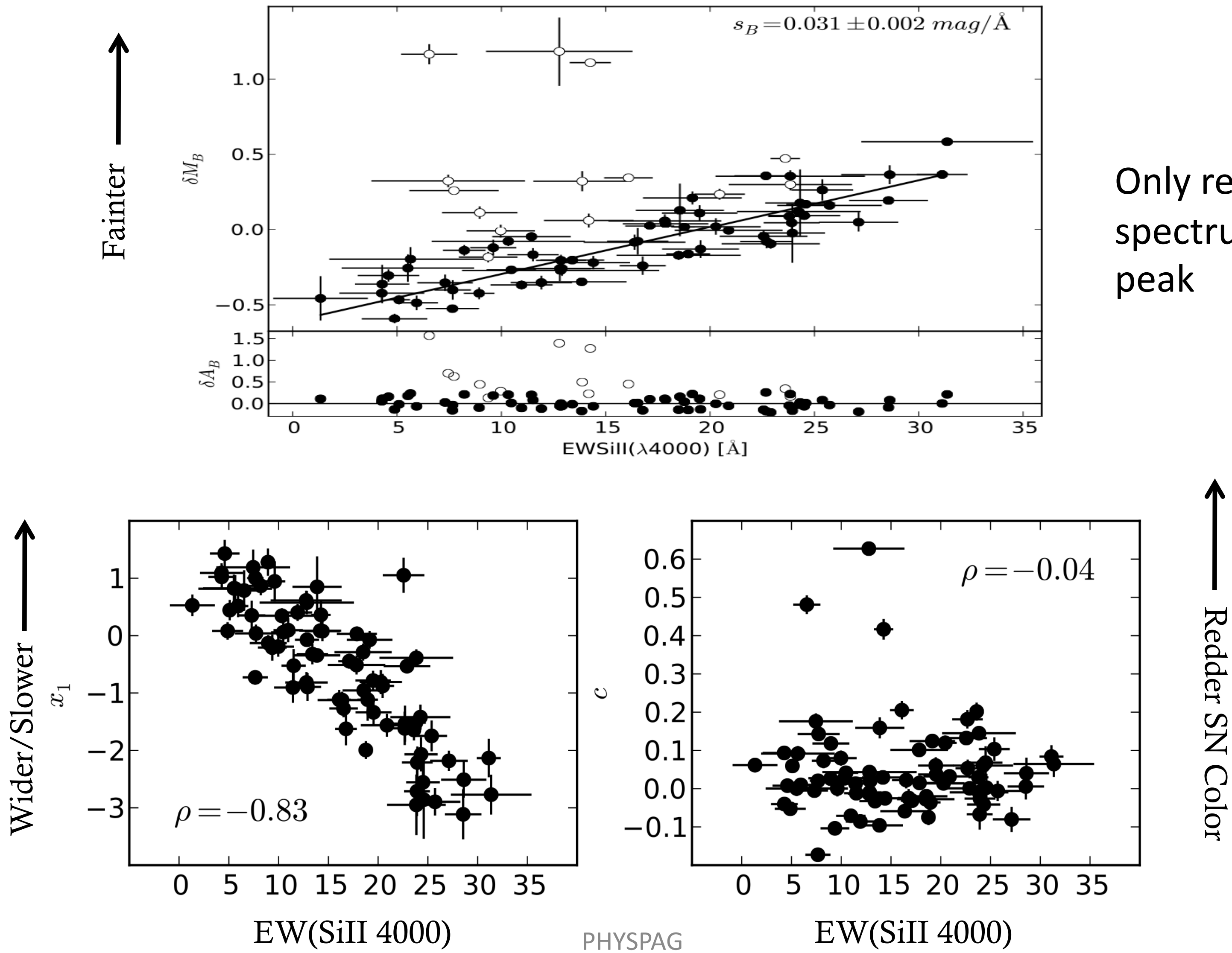
Spectral Flux Ratio Standardization





- Bailey, et al., A&A (2009; SNfactory)
- Requires S/N ~ 15 @ R ~ 100
- Now tested on 2x larger sample!

EW(SiII 4000) Standardization



Only requires spectrum at peak

How does an Integral Field Spectrograph Help in Controlling Systematics?

SN Uncertainty & Bias - Both Natural and Man-Made

Amanullah *et al.* 2010 (SCP)

Source	Error on w
Zero point	0.037
Vega	0.042
Galactic Extinction Normalization	0.012
Rest-Frame U-Band	0.010
Contamination	0.021
Malmquist Bias	0.026
Intergalactic Extinction	0.012
Light curve Shape	0.009
Color Correction	0.026
Quadrature Sum (not used)	*0.073*
Summed in Covariance Matrix	0.063

Type Ia ASTRO2010 *arXiv:0903.1086*

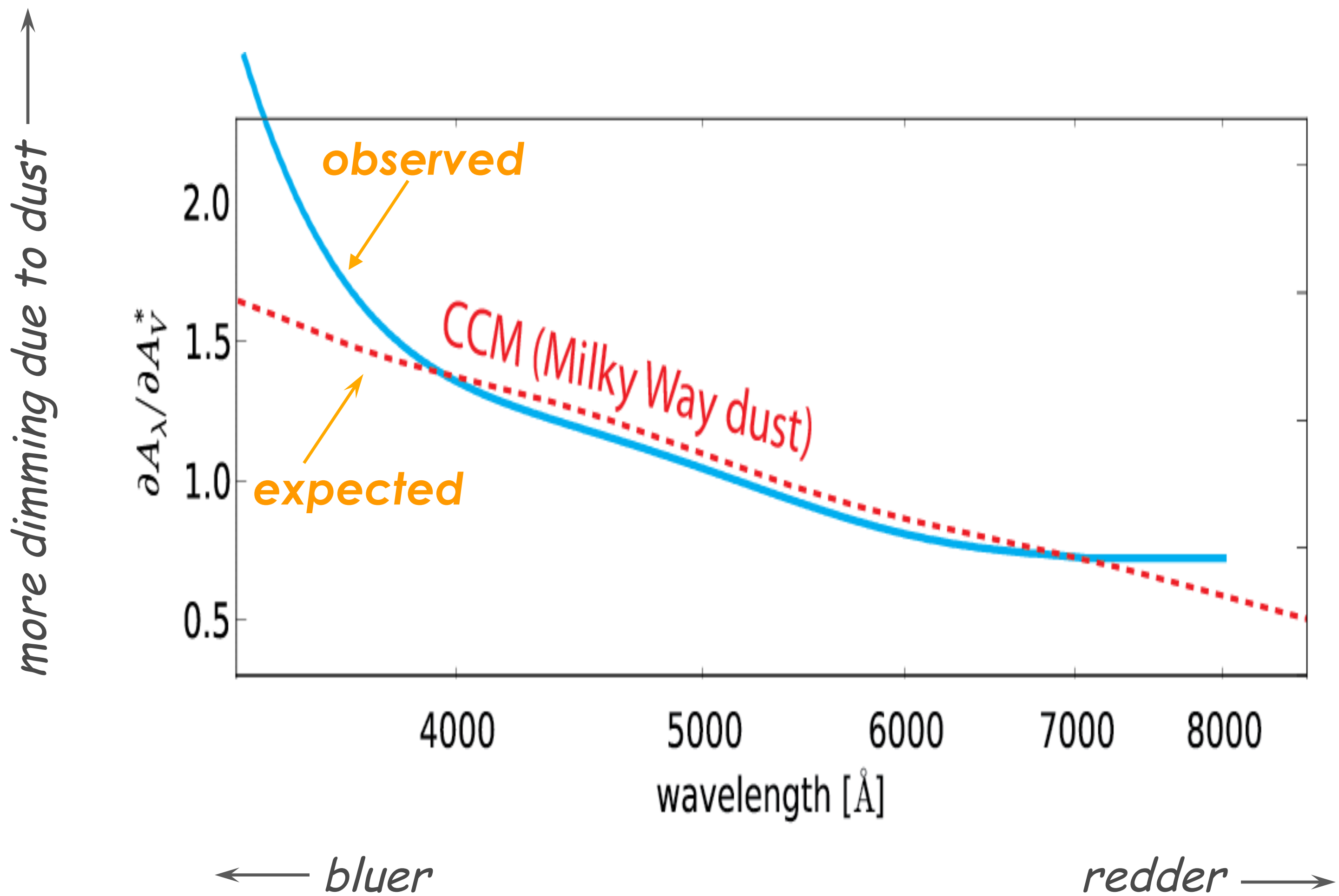
CURRENT ESTIMATES OF SYSTEMATIC ERRORS ON W

Systematic	SNLS	ESSENCE	SDSS
Flux reference	0.053	0.02	0.037
Experiment zero points	0.01	0.04	0.014
Low-z photometry	0.02	0.005	⋯
Landolt bandpasses	0.01	⋯	0.019
Local flows	0.014	⋯	0.04
Experiment bandpasses	0.01	⋯	0.014
Malmquist bias model	0.01	0.02	0.017
Dust/Color-luminosity (β)	0.02	0.08	0.017
SN Ia Evolution	⋯	0.02	⋯
Restframe U band	⋯	⋯	0.08

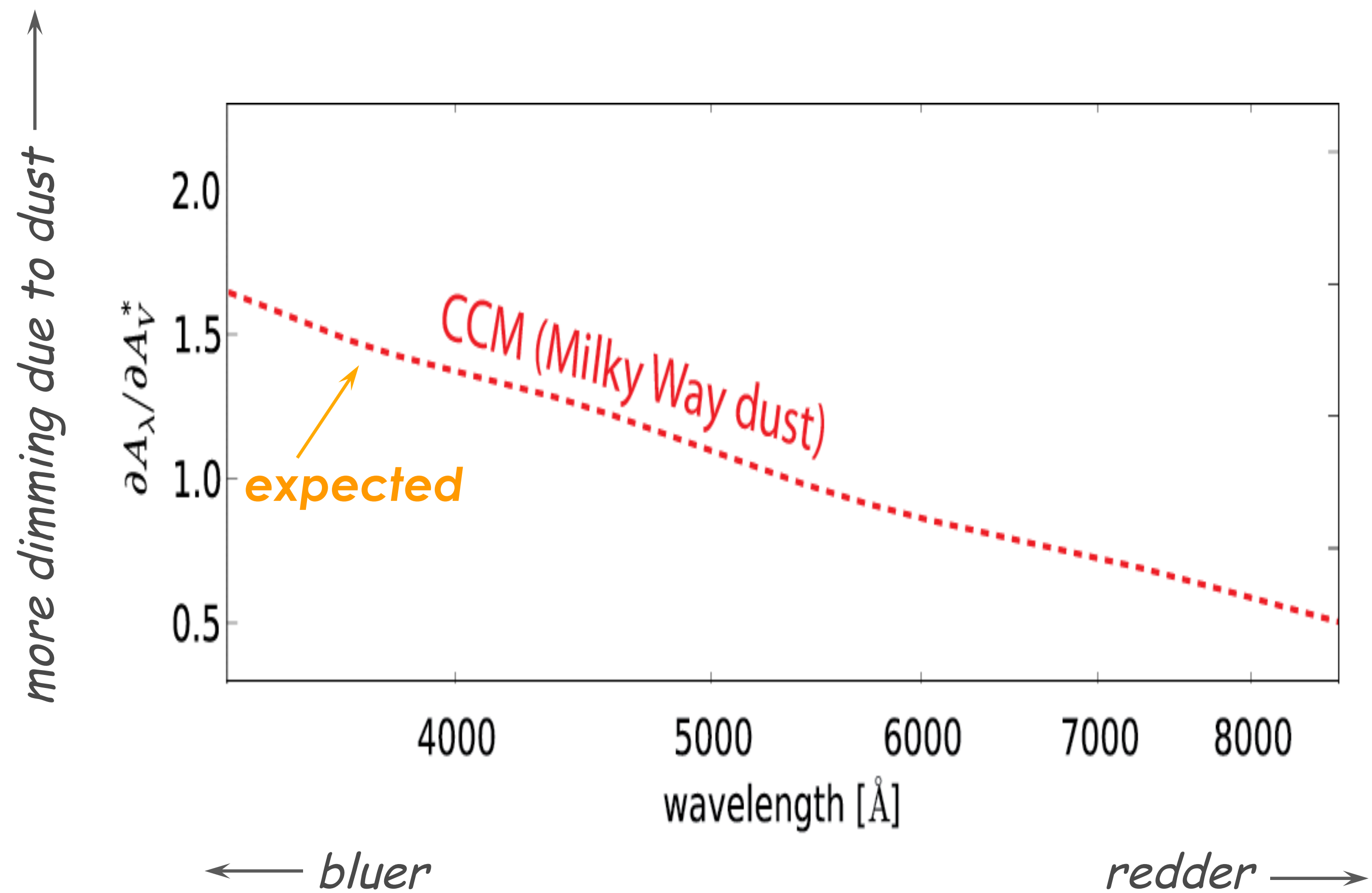
NOTE. — Systematic error estimates on $\langle w \rangle$ from Conley et al. (2009), Wood-Vasey et al. (2007), and Kessler et al. (2009).

IFS SN Cosmology Use Case: the Dust Extinction Law & Intrinsic SN Colors

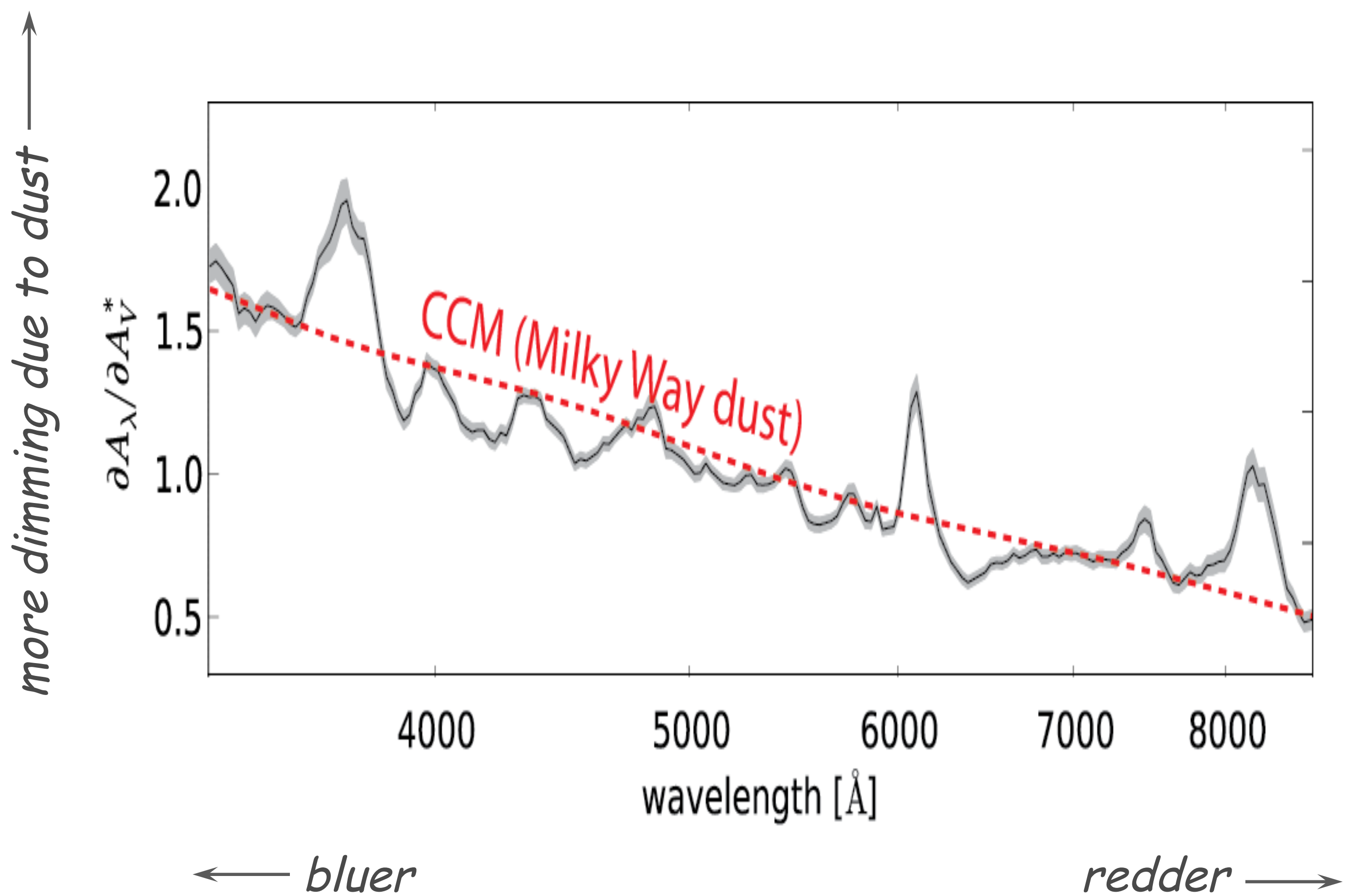
Spectral indicator distinguishes dust reddening from intrinsic SN color

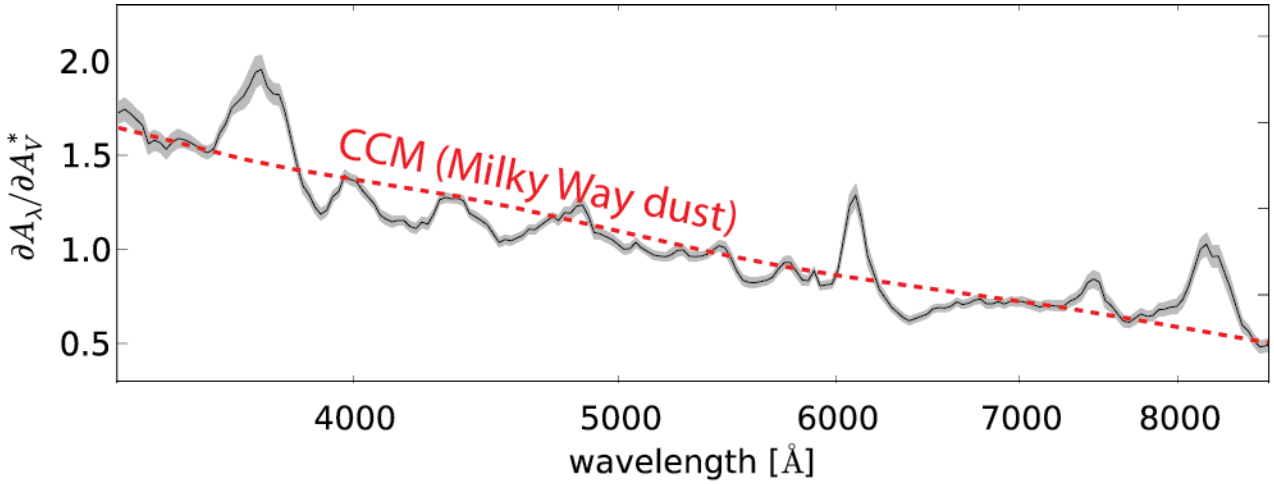


If we assume that all the color variation is due to dust …



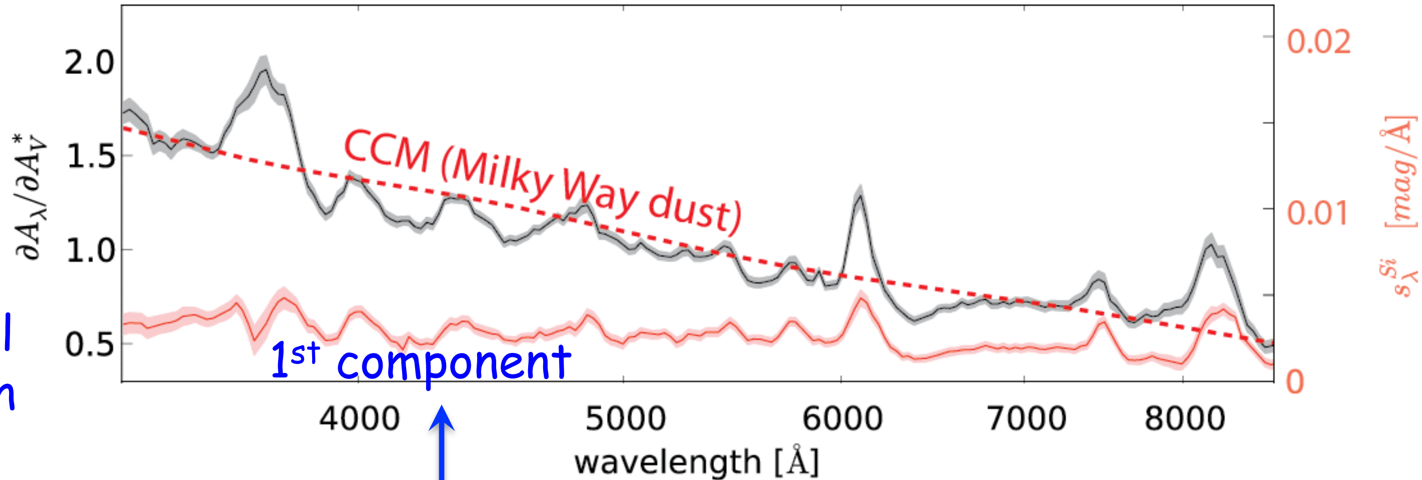
If we assume that all the color variation is due to dust … we *don't* get CCM reddening law:





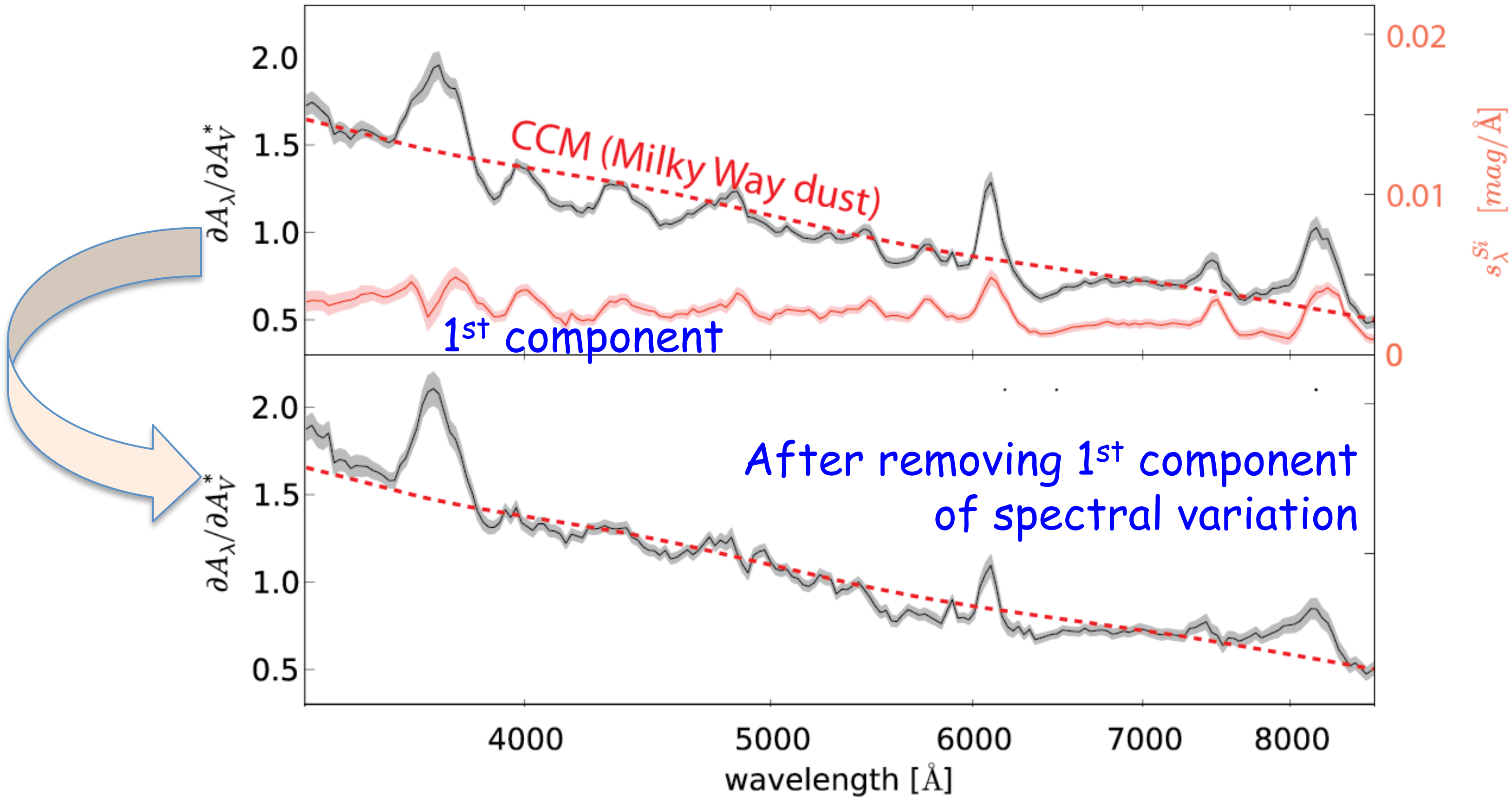
This is not surprising – we already know that there are spectral features associated with the "stretch" of the lightcurve timescale.

Spectral variation



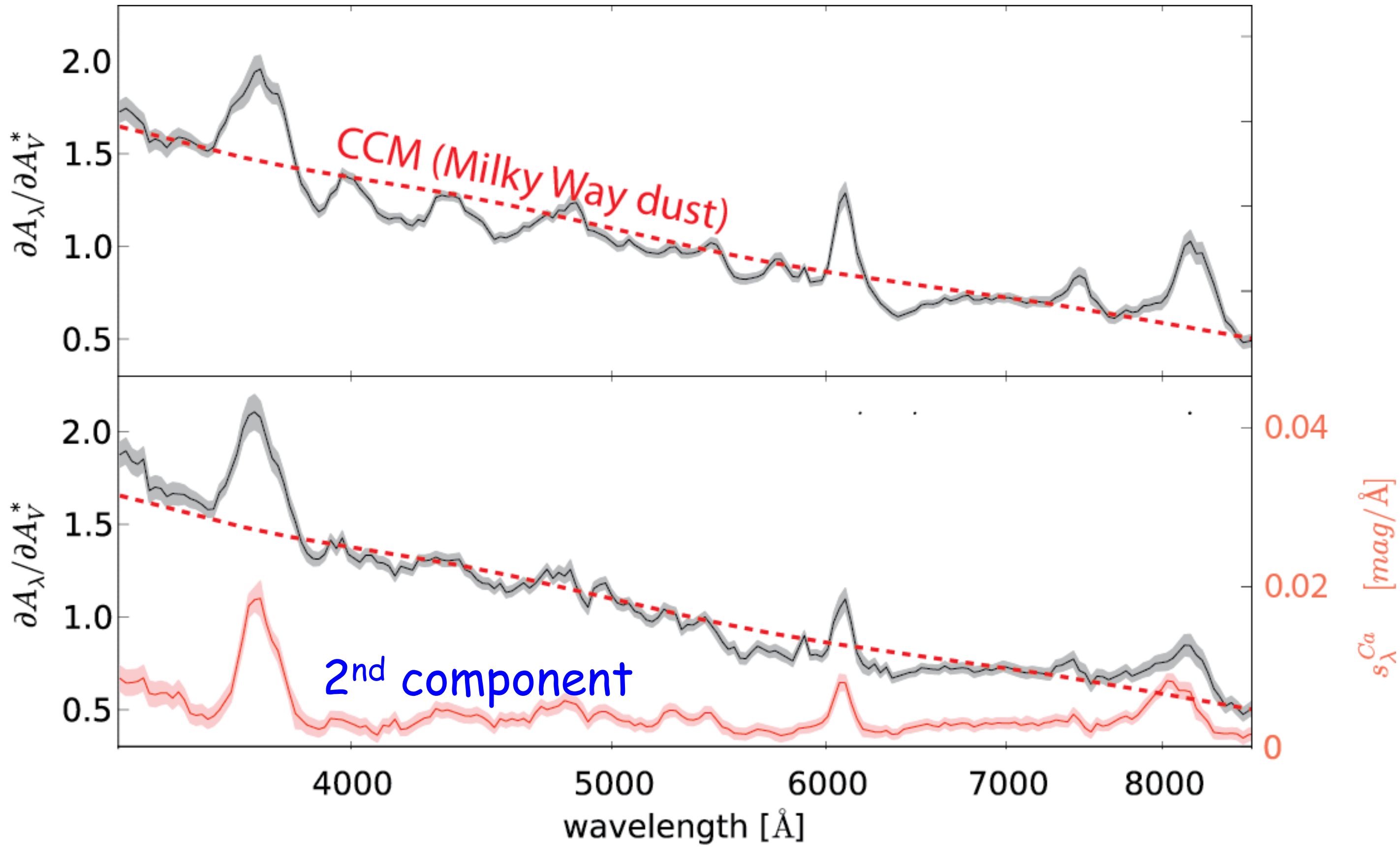
highly correlated with "stretch"

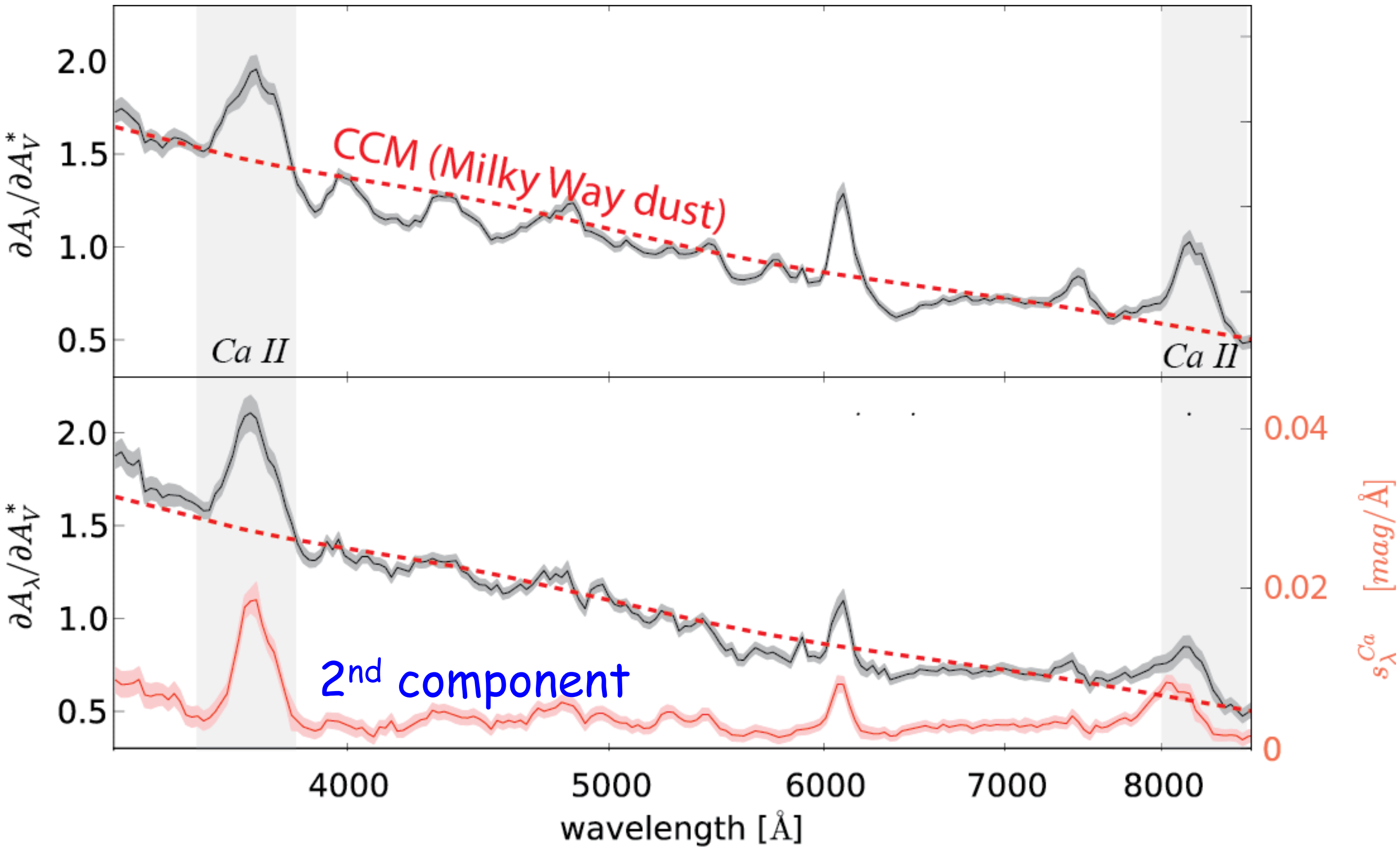
This is not surprising – we already know that there are spectral features associated with the "stretch" of the SN lightcurve timescale.



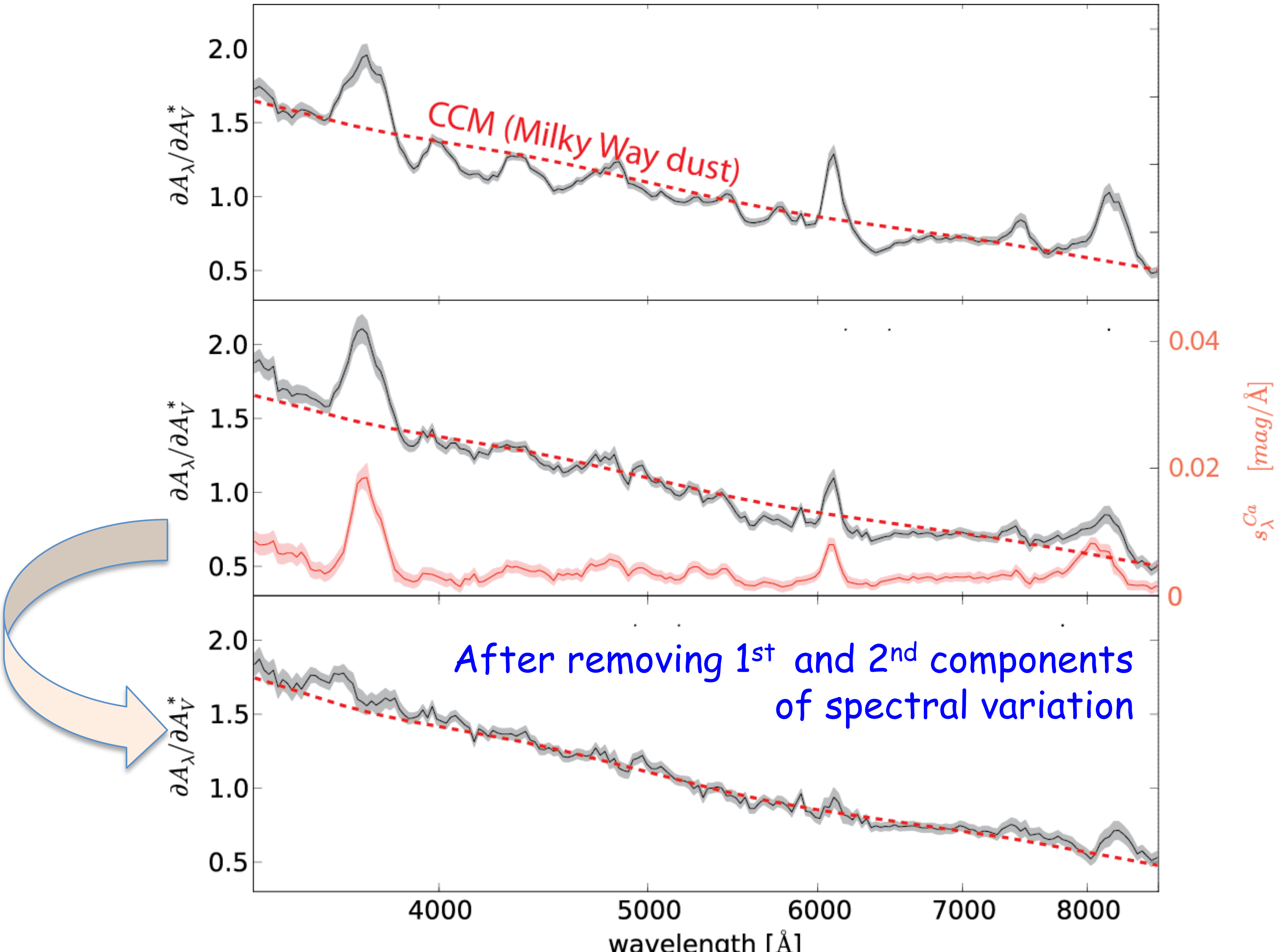
CCM (Milky Way dust)
1st component
After removing 1st component
of spectral variation
2.0
1.5
1.0
0.5
$\partial A_\lambda / \partial A_V^*$
0.02
0.01
0
s_λ^{Si} [mag/Å]
4000
5000
6000
7000
8000
wavelength [Å]

Spectral variation

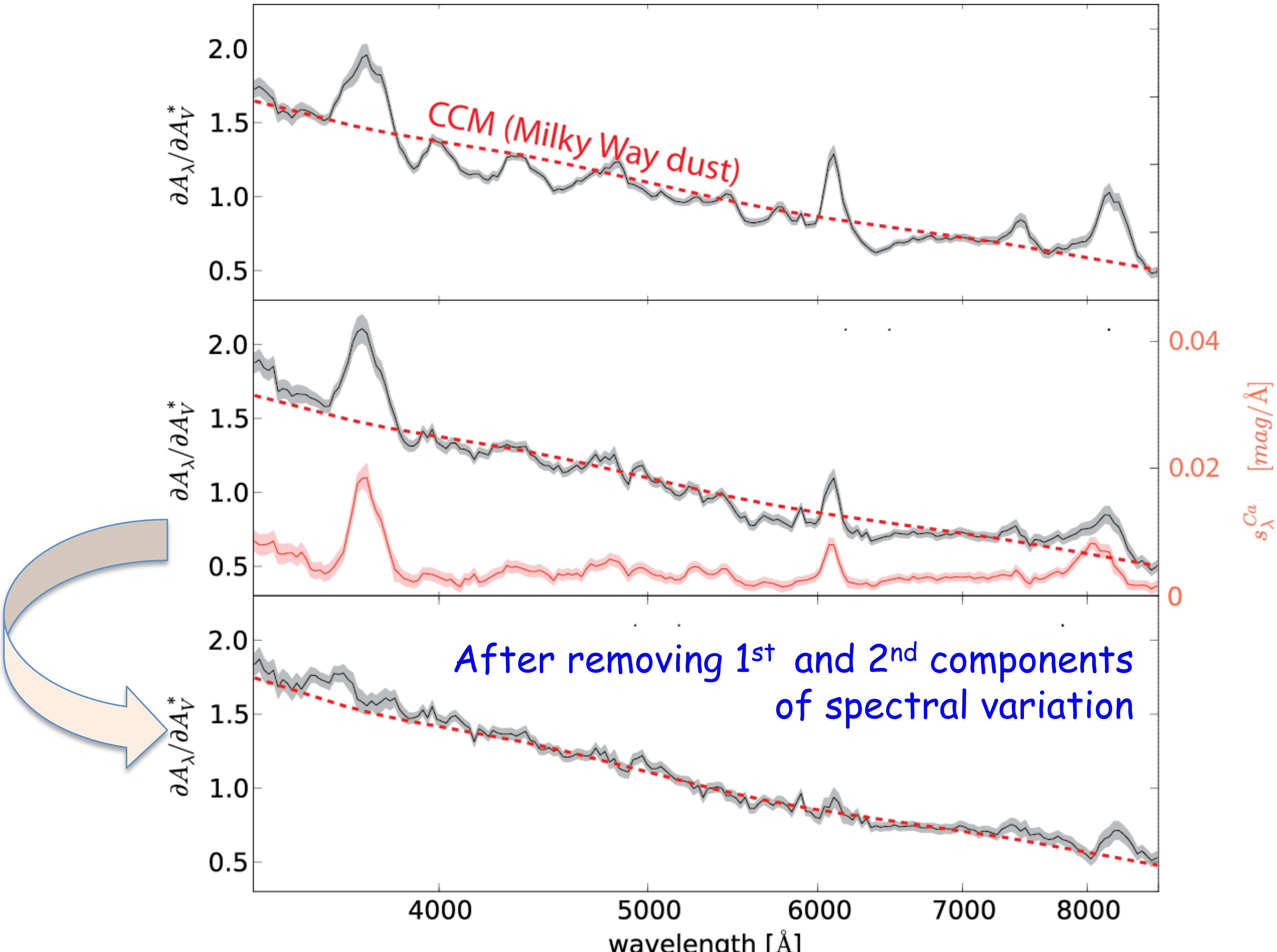




Spectral variation


CCM (Milky Way dust)
After removing 1st and 2nd components of spectral variation
$\partial A_\lambda / \partial A_V^*$
2.0
1.5
1.0
0.5
0.04
0.02
0
s_λ^{Ca} $[mag/Å]$
4000
5000
6000
7000
8000
wavelength [Å]

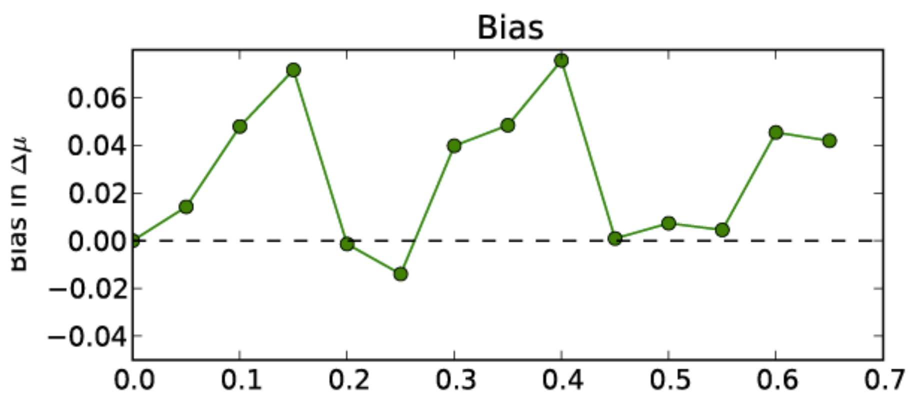
Chotard et al (A&A, 2011) **Nearby Supernova Factory**



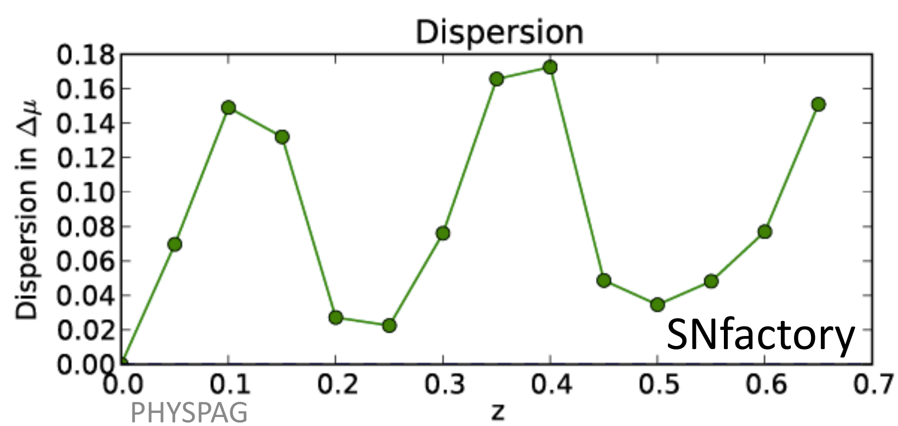
SNe Ia do not all show the exact same spectral time series, so the K corrections are not identical.

Distance measurements should therefore be based on matched low- and high-redshift SNe, with matching spectral time series.

Average error on K-correction using a single-parameter model for spectral time series template

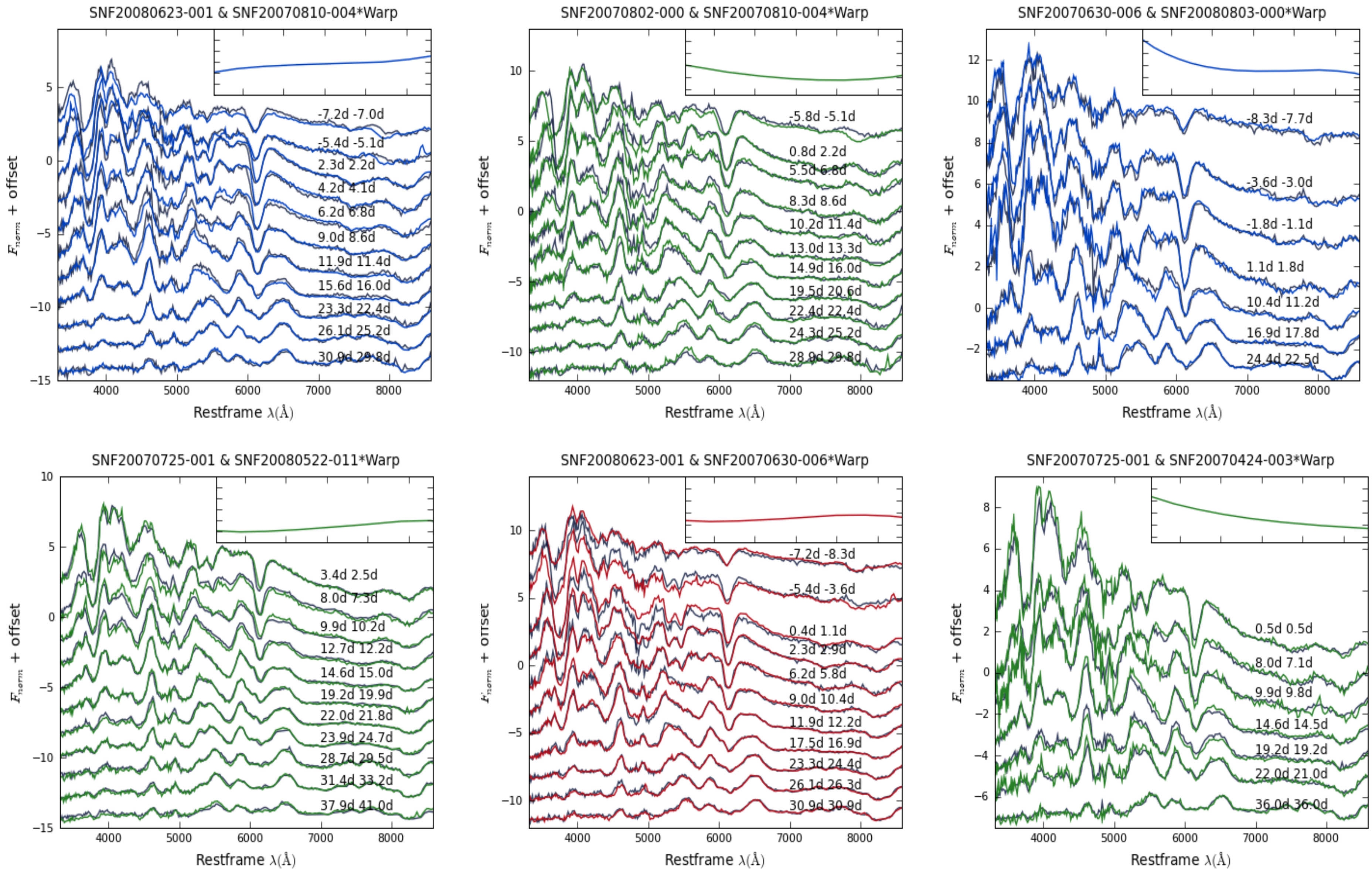


Dispersion of K-correction using a single-parameter model for spectral time series template



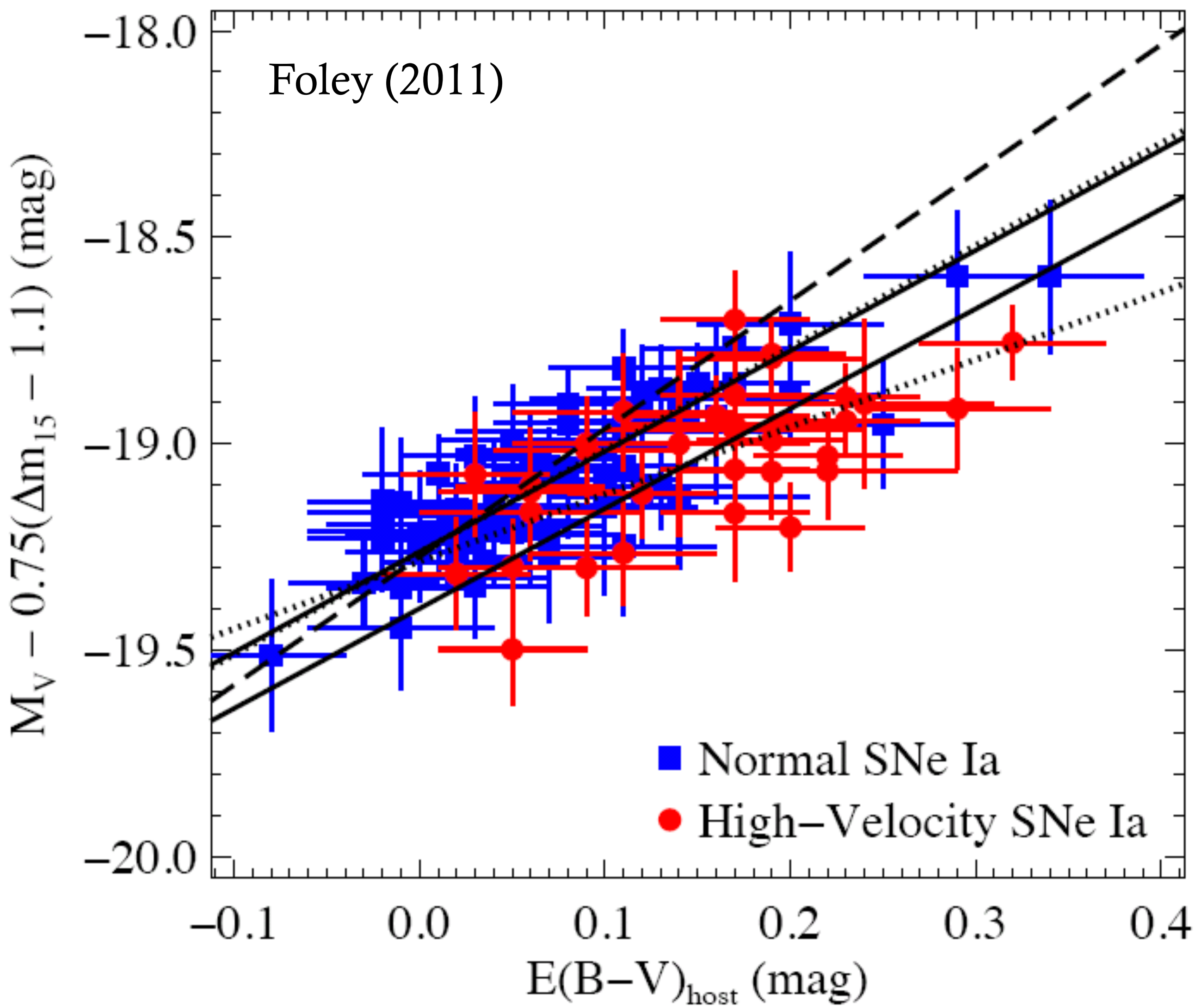
How will an Integral Field Spectrograph Address New Developments?

SN Twins



SNF20080623-001 & SNF20070810-004*Warp
-7.2d -7.0d
-5.4d -5.1d
2.3d 2.2d
4.2d 4.1d
6.2d 6.8d
9.0d 8.6d
11.9d 11.4d
15.6d 16.0d
23.3d 22.4d
26.1d 25.2d
30.9d 29.8d
SNF20070802-000 & SNF20070810-004*Warp
-5.8d -5.1d
0.8d 2.2d
5.5d 6.8d
8.3d 8.6d
10.2d 11.4d
13.0d 13.3d
14.9d 16.0d
19.5d 20.6d
22.4d 22.4d
24.3d 25.2d
28.9d 29.8d
SNF20070630-006 & SNF20080803-000*Warp
-8.3d -7.7d
-3.6d -3.0d
-1.8d -1.1d
1.1d 1.8d
10.4d 11.2d
16.9d 17.8d
24.4d 22.5d
SNF20070725-001 & SNF20080522-011*Warp
3.4d 2.5d
8.0d 7.3d
9.9d 10.2d
12.7d 12.2d
14.6d 15.0d
19.2d 19.9d
22.0d 21.8d
23.9d 24.7d
28.7d 29.5d
31.4d 33.2d
37.9d 41.0d
SNF20080623-001 & SNF20070630-006*Warp
-7.2d -8.3d
-5.4d -3.6d
0.4d 1.1d
2.3d 2.9d
6.2d 5.8d
9.0d 10.4d
11.9d 12.2d
17.5d 16.9d
23.3d 24.4d
26.1d 26.3d
30.9d 30.9d
SNF20070725-001 & SNF20070424-003*Warp
0.5d 0.5d
8.0d 7.1d
9.9d 9.8d
14.6d 14.5d
19.2d 19.2d
22.0d 21.0d
36.0d 36.0d
F_{norm} + offset
Restframe λ(Å)

Velocity of Si may pick out subpopulation
with a specific absolute mag offset



Restframe NIR

Another route to better standardization: Add **restframe** *J* and *H* to optical

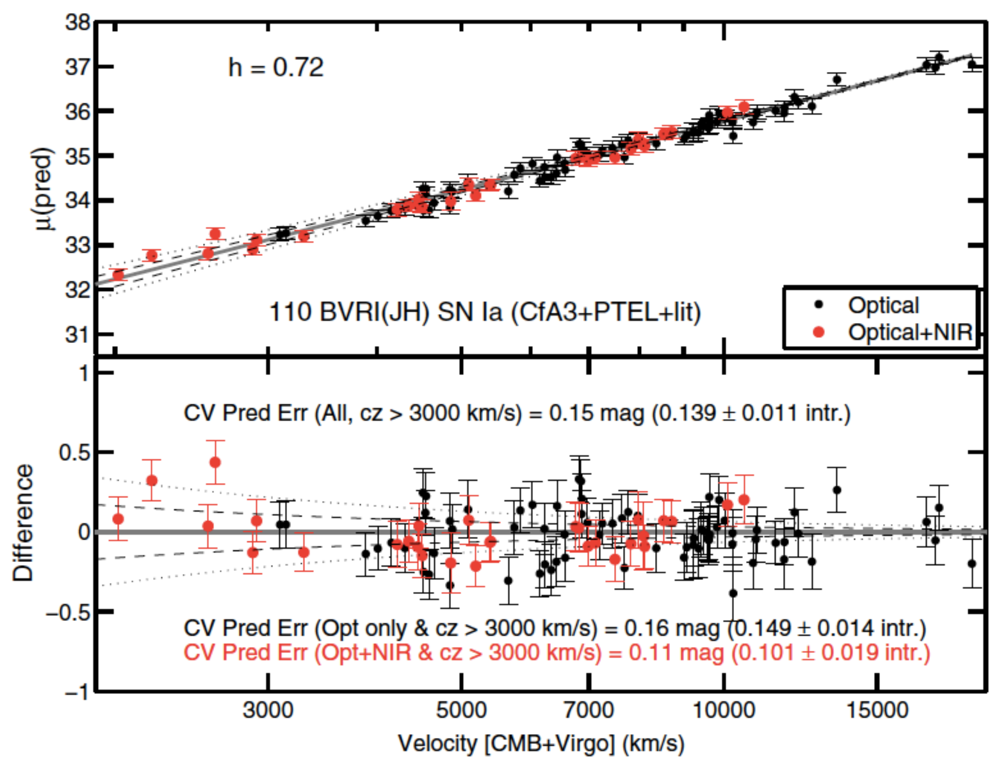
<u>*Problems:*</u>

Restframe *J* is not as big an improvement as *H*.

Restframe *H* not available with *HST* WFC3.

WFIRST can only obtain *H* out to $z = 0.12$ (with 2.0 micron cutoff) or $z = 0.30$ (with 2.4 micron cutoff).

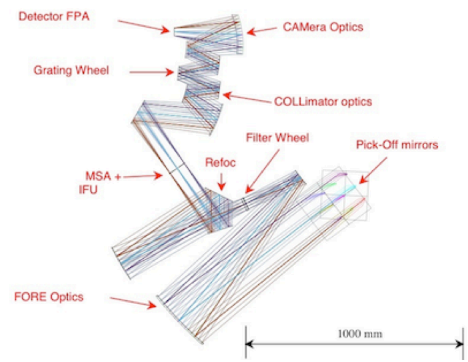
Still need to correct for dust, so a higher scatter (e.g. optical) wavelength is still included.

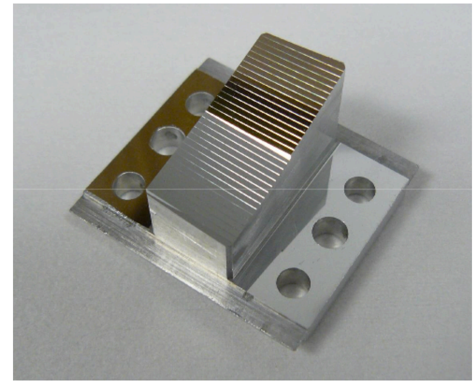


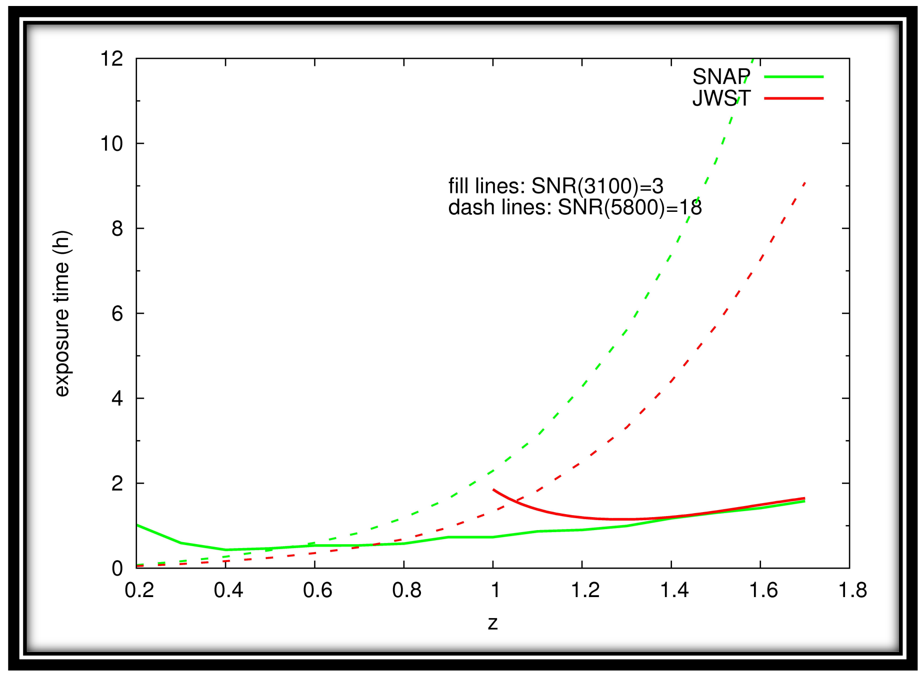
Mandel et al (2011)

The Role of JWST NIRSPEC

- NIRSPEC IFU likely to play a role for special studies:
  - Higher resolution options
  - Redder restframe NIR coverage
- Can observe z >1 SNe at peak in a reasonable amount of time
- Wavelength coverage is not good for $0.2 < z < 0.8$
- Resolution too low over 1-2 microns
- Acquistion/ToO overhead may be important
- Even 300 SNe may require significant time (2 to 4 months)
- Tight coordination necessary with wide-field imaging survey
- Overall cost per SN likely to be high (but pre-paid!)

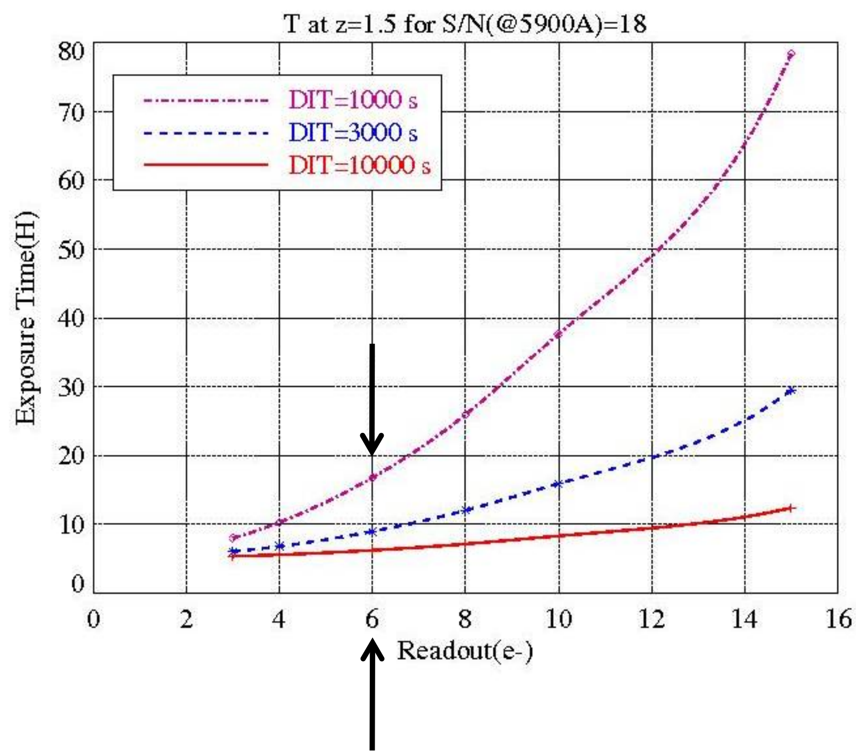






Technology Needs

- Detector critical – especially if aperture or throughput drops
- Simulations assume 6 e-, but can probably do better
- Need to worry about tiny offsets that add across many SNe
  - For grism this could come from contaminating spectra, zodi spectral changes, flatfield or reference
  - For IFS this could come from dark current or electronics
- Stable electronics important
- Stable darks important
- IFS requires just one, but very good, detector



IFS Benefits

- Strong science case
- Photometric (compared to slit spectroscopy)
- High S/N (compared to grism spectroscopy)
- Easier calibration (compared to imager or grism)
- SN systematics control
  - No SN *K*- or *S*-corrections (compared to imager)
  - Less contamination (SN subtype, inc. peculiar Ia)
  - SN evolution (e.g. metallicty affecting SED)
  - Dust correction (decoupling SN features/color from dust)
  - Better host galaxy subtraction (relative to grism or slit)
  - Higher redshift reach (relative to grism)
- Operations ease
  - Relaxed pointing or repointing accuracy requirements
  - No need to stay on a given field to get full lightcurve
- Risk mitigation
  - Triggers could come from any source (inc. ground)
  - Adaptable as more is learned about SN standardization
  - Adaptable as more is learned about Dark Energy!

IFS Discussion Points

- Perceived complexity
  - 1938 technology; 20 IFS in operation world wide; SNAP demonstrator
- Perceived cost
  - now acknowledged to be low wrt WFIRST budget
- Unfamiliar SN standardization
  - Could obtain classical lightcurve from synthesized photometry, inc. multiplex
- No multiplex advantage
  - Regained by higher S/N wrt grism + systematics/calibration advantages
- Less ancillary science
  - Not the same ancillary science, but unique
- JWST IFS could suffice
  - 3x lower throughput plus overheads would make cost per SN higher
  - Uncertain whether the calibration will be adequate
- Triggering would be disruptive
  - Lead time for spectrum at peak should be 5-10 days
  - Could concentrate on one or two regions of sky at a time