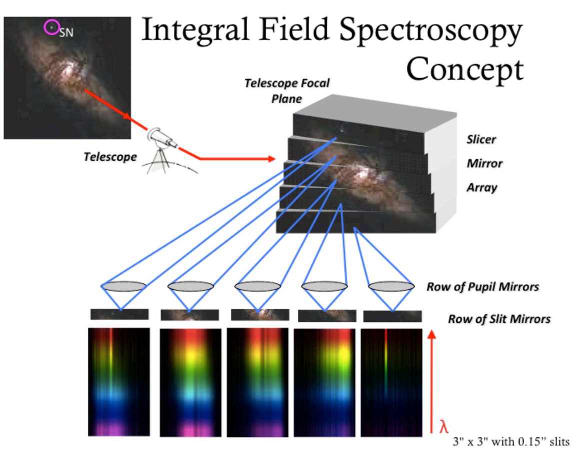
Supernova Spectroscopy with an Integral Field Unit Spectrograph (IFU)

WFIRST is a powerful survey telescope, and will collect such large and deep surveys that we expect the final SN measurements of dark energy to be systematics limited. The systematic errors can be created by the instrument, and these are addressed by design and calibration. However, many of the most important systematics that can only be addressed in space are astrophysical in nature. For example, it is known that not all Type Ia SN are identical, and that sub-classes exist with different light curves. Ignoring this subtlety will limit the strength of the scientific conclusions that can be drawn from a large data set that cannot remove this systematic uncertainty.

The large 2.4-m aperture of the AFTA mission offers the capability of addressing this issue, through the use of an Integral Field Unit Spectrograph (hereafter, IFU) to sub-classify the observed SNe and reduce the systematic errors in the analysis.

An IFU uses a compact splayed arrangement of mirrors to slice a small image (including, e.g., a supernova, its host galaxy, and some background galaxies) into separate elements that each get dispersed (see Figure WWW).



The resulting data cube of flux at each position and wavelength has many times higher signal-to-noise than a slitless spectrum with the same exposure time – or, equivalently, significantly reduced exposure times for the same signal-to-noise. In contrast, a slitless spectrum includes contributions from the full sky in each spectral bin -- each pixel sees the whole wavelength range of 0.6 to 2.0 microns -- making it more difficult to isolate the faint SNe signal. (Thus where the IFU spectra see 0.017 counts/sec/pixel of zodiacal light, slitless spectra see 2.32 counts/sec/pixel.)

D.E. Science Improvement with a 2.4-m and an IFU

From a science perspective, the signal-to-noise gain using a 2.4-m telescope with an IFU is quite important. The supernova program that could be accomplished with a smaller telescope or lower-signal-to-noise slitless spectroscopy is only sufficient to recognize the supernovae as "Type Ia" and provide its redshift. With the dramatically higher signal-to-noise of an IFU together with a 2.4-m aperture telescope the spectral features of the supernova can be used to:

1. Distinguish intrinsic color variations from the effects of dust (Chotard et al, 2011). Currently, these two sources of reddening and dimming are not distinguished at high redshift, so the mix of these two effects is assumed to stay constant over the redshifts studied. For the precision measurements of $w(z)$ it would be important to separate them, since both are important corrections in the distance modulus calculation. This systematics control remains important even in the redder NIR observer wavelengths that WFIRST can reach.

2. Improve the "standard candle" calibration of the Type Ia supernova. Bailey et al (2009) showed that with spectral feature ratios of sufficient signal-to-noise the magnitude dispersion of SN Ia distance modulus in the restframe optical can be reduced from 0.16 mag to 0.12 mag dispersion, while more recent full spectral time series studies show dispersion in the 0.07 to 0.09 mag range. These results are as good as the improvement in dispersion using restframe H band observations. With IFU spectroscopy, however, this distance modulus improvement can be obtained over a large redshift range (beyond $z = 1.7$), while the restframe H band photometry is only available to redshift $z = 0.1$ (and J band only to $z = 0.4$) even with an instrument observing out to 2 microns.

3. Compare the detailed composition and physical state of high-redshift supernovae to that of low-redshift supernovae. Type Ia supernovae are not all identical, but we can find spectroscopic matches

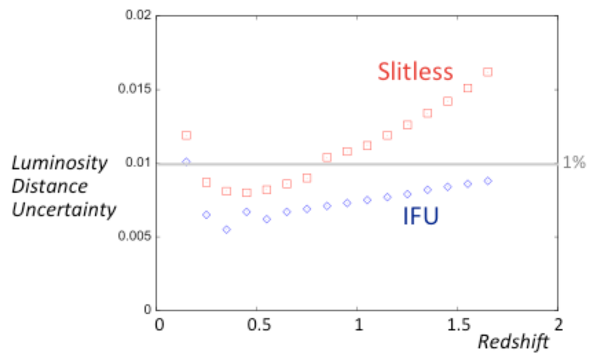
of subsets of SNe Ia. If surprising cosmologies are inferred from supernova distance measurements over a range of redshifts it will be important to show that the effect is not simply an artifact due to a population of SNe Ia that is demographically drifting from one distribution of these spectroscopic subsets to another. With IFU spectroscopy it is possible to obtain the signal-to-noise sufficient to distinguish the different matching spectroscopic subsets.

4. Remove the K-correction systematics from the measurement. Filter-based photometry programs use only three filters over the whole redshift range studied, introducing the need for K corrections. The low signal-to-noise slitless grism spectra must then be combined to statistically remove any systematic biases in these K corrections (although this approach has not yet been studied to see what systematics will remain). With IFU spectrophotometry providing the lightcurves there is no need for K corrections at all.

While the control of systematic uncertainties is the primary motivation for the use of an IFU, its shorter exposure times can also be used to improve the depth of the survey and therefore the Figure of Merit. Exposure times and results from an example six-month-observing-time program are shown in Table XXX, Figure YYY, and Table ZZZ.

Calculation of the slitless and IFU exposure times to get S/N=15 in Filter Bands1,2,3

Z	IFU			Z	Slitless		
0.15	10.29	13.55	22.34	0.15	40.06	57.16	114.84
0.25	21.92	31.66	42.44	0.25	111.67	195.13	312.49
0.35	40.65	54.44	67.70	0.35	291.20	472.70	683.69
0.45	68.27	77.25	100.40	0.45	693.48	856.06	1338.58
0.55	85.86	104.25	153.20	0.55	1025.13	1427.05	2727.36
0.65	101.67	141.56	208.48	0.65	1367.65	2391.02	4515.19
0.75	112.71	200.30	260.66	0.75	1629.11	4232.95	6439.53
0.85	131.31	274.42	289.95	0.85	2108.14	6978.31	7600.60
0.95	166.36	292.01	361.93	0.95	3125.60	7684.18	10652.03
1.05	201.96	304.11	439.34	1.05	4289.56	8179.68	14183.98
1.15	257.59	330.37	568.98	1.15	6320.96	9282.46	20522.72
1.25	299.00	345.52	728.24	1.25	7969.42	9934.07	28817.69
1.35	342.98	378.83	859.24	1.35	9824.05	11403.05	35934.87
1.45	391.01	450.60	826.68	1.45	11951.81	14715.55	34145.42
1.55	406.35	520.53	824.91	1.55	12651.35	18101.53	34048.58
1.65	437.27	603.27	878.60	1.65	14086.77	22268.28	37004.04



Survey Strategy	FoM without Stage III priors
1.3 m DRM1 slitless, imaging lightcurves	153
1.1 m DRM2 slitless, imaging lightcurves	141
2.4 m DRM A slitless, imaging lightcurves	180
2.4 m DRM A slitless, spectro lightcurves	197
2.4 m DRM A IFU Deep spectro lightcurves	303

Note: with the lower systematic errors with the IFU we could approach a FoM of 400 with extended time for the supernova survey.

Non-Supernova Science with an Integral Field Unit Spectrograph (IFU)

An IFU spectrograph together with a 2.4-m telescope also offers a wide range of science potential, some of which is best obtained by parallel observations during large surveys (e.g., the high latitude survey and the supernova survey) and some by pointed observations. In Table ZZZ, we list likely GO programs that the IFU would make possible. Two of these are of particular note because they reinforce other key WFIRST programs:

- *Spectroscopic Sample For Photo-z Calibration.*

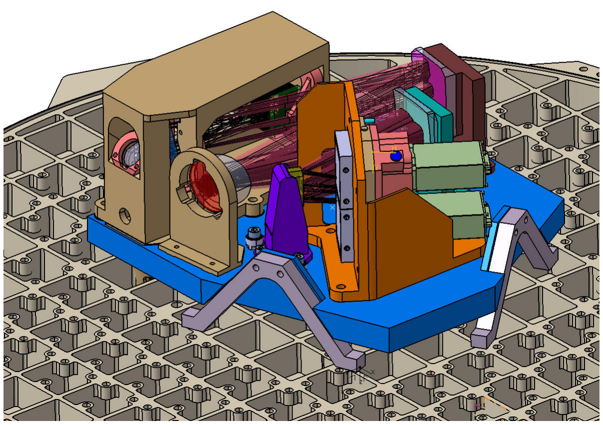
The Weak Lensing measurements depend on the accuracy and outlier rejection of their photometric redshift calibration. Parallel observations with the IFU during the high latitude survey and the spectroscopic survey can provide >10,000 spectroscopic redshifts, with ~50% confident redshift identifications out to redshifts of $z \sim 4$. Such a calibration set can improve Weak Lensing D.E. measurement Figures of Merit by factors of….

- *Exoplanet Transit Spectroscopy*

…

Mission Design Considerations for IFU

The draft mission design puts the Integral Field Unit (IFU) spectrograph next to the guider detectors on the…. Two previous IFU designs are currently both possible to use for this purpose. One is … and was used in the … mission, and the other has been prototyped and space-qualified for JDEM by the LAM/Marseille group. The latter IFU spectrograph was the subject of a NASA/Goddard Mission Design Lab (MDL) study and has had substantial oversight from GSFC. Such a spectrograph provides R=75--100 visible-to-infrared spectrophotometry with 100% fill factor for every pixel in a 3 arcseconds by 3 arcseconds FOV at a pixel scale of 0.15 arcseconds per pixel. A complete IFU has been designed to fit within a small 20x27x27 cm volume, with a weight of <12 kg (see Figure VVV).



There are practical advantages to using an IFU instead of a slitless prism approach. The IFU is much less demanding in its pointing and stability requirements compared to slitless approaches, and provides a calibration capability without the need for additional calibration hardware. In particular, an IFU spectrograph acts as the calibration system for JDEM broadband photometry, providing the transfer mechanism from the bright fundamental standard stars to primary and/or secondary standard stars.

We note that trade studies have been performed that show a rather simple operations plan can schedule the IFU observations to be slotted into regular observing slots throughout the year, with several weeks of time available to comfortably prepare the entries for a given observing slot. A small percentage (typically <15%) of the supernovae that are near a high-brightness-gradient on the galaxy image are scheduled for a repeat visit after the supernova has faded.