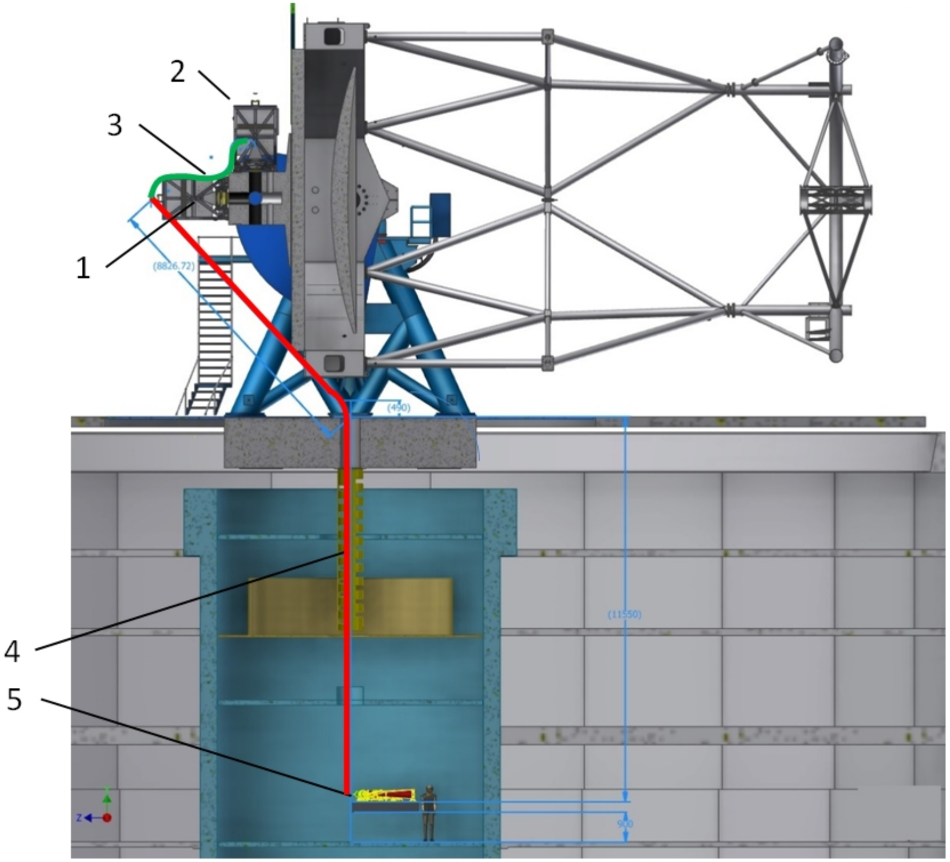
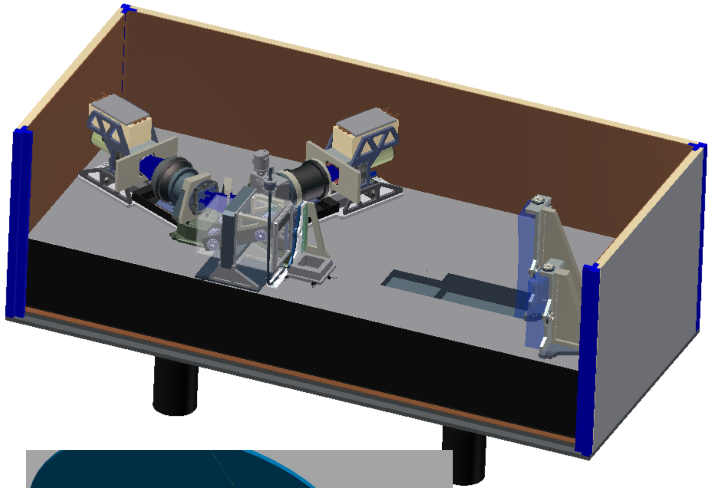
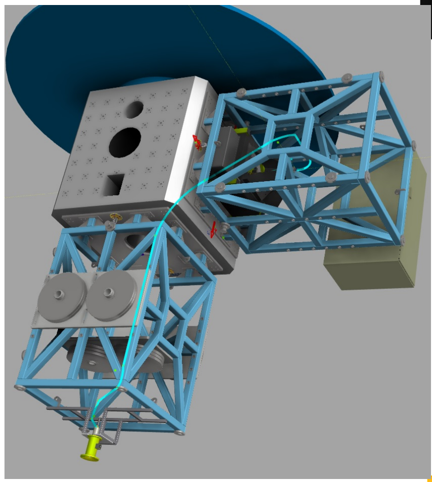
GEMINI HIGH-RESOLUTION OPTICAL SPECTROGRAPH (GHOST)
INSTRUMENT OVERVIEW

ANDY SHEINIS: HEAD OF INSTRUMENTATION, AAO





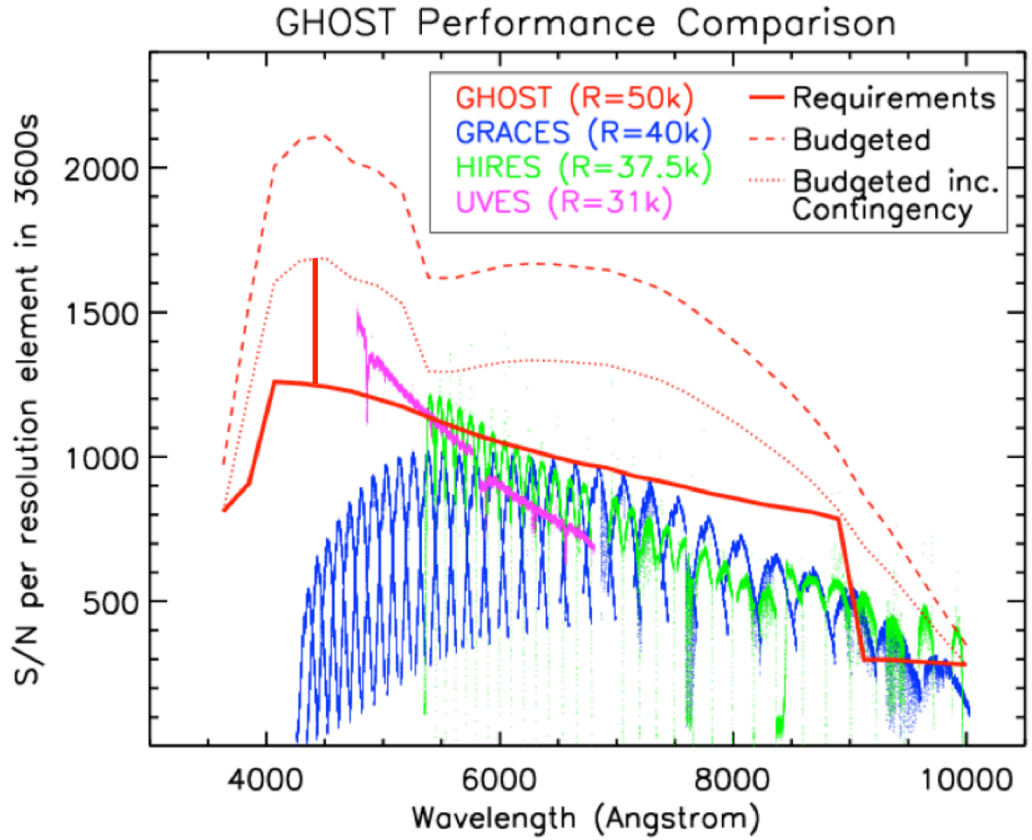


Australian National University

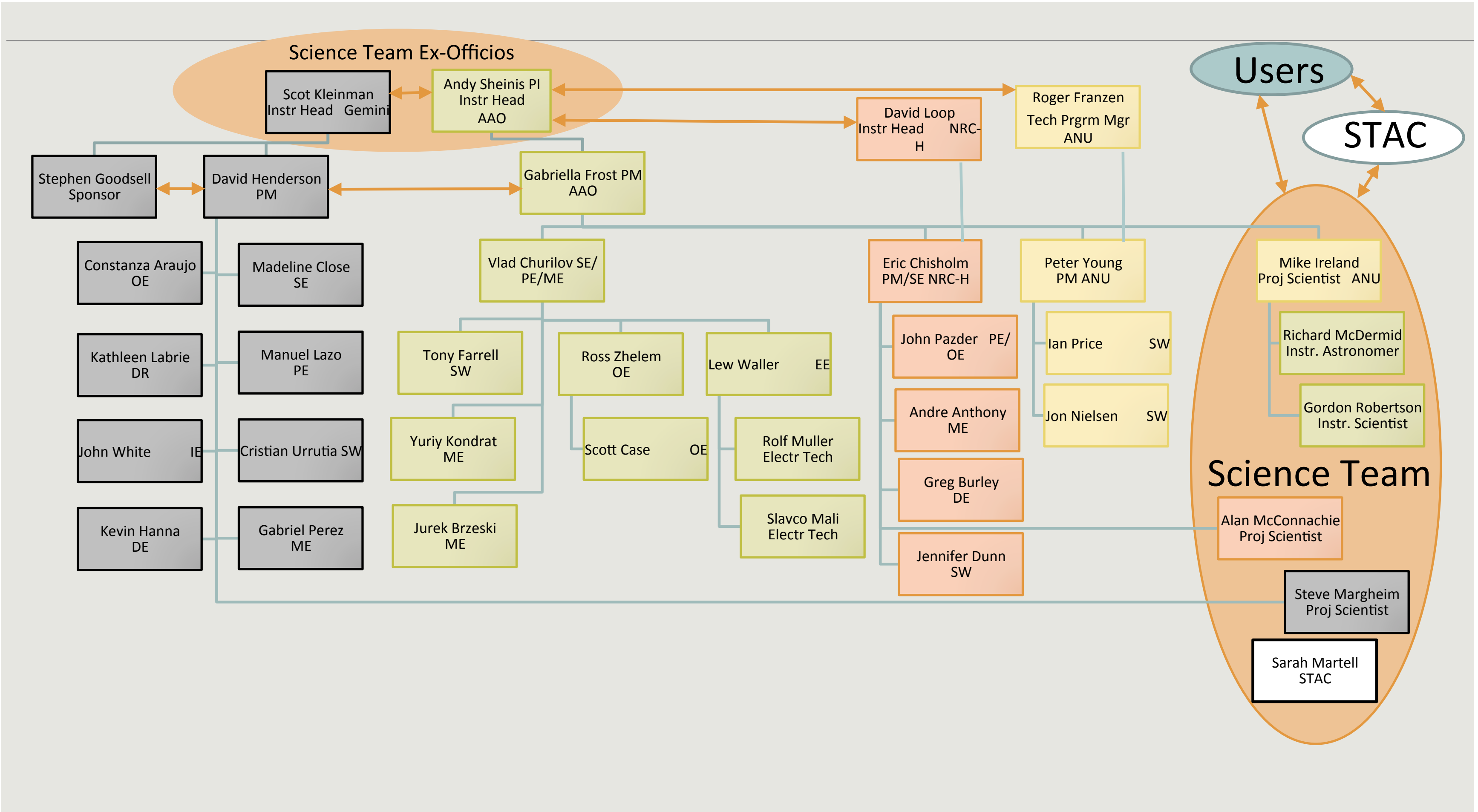
- 2011: CoDR proposals
- mid-2012: A CoDR in Hilo, including both AAO and NRC-Herzberg. AAO's bid included Kiwistar Optics as the primary subcontractor.
- mid-2013: After many miscellaneous delays, Kiwistar optics decided to change their business model and not participate in GHOST. A new team was formed with NRC-Herzberg (ex-HIA, Victoria, Canada). YAY NRC!
- April 2014. Preliminary design begins.
- Dec 2014 AAO/ANU/NRC pass the PDR (first successful PDR at Gemini in 10 years) Long lead item order start.
- CDR/FDR - Dec 2015
- Dec 2016 Build & Integration completed
- May 2017 Pre-shipping acceptance test completed –
- July 2017 Shipping to Gemini
- Sep 2017-Commissioning starts
- Semester 2, 2018- Full science

INTERNATIONAL CONTEXT

GHOST is (mostly) not unique. There are other high-resolution spectrographs in the world, all of which are in high demand none of which (except GRACES?) are accessible to the Gemini community. GHOST must have high efficiency (throughput and observational efficiency) and cover a broad range of science.



GHOST is a Partnership!



gineers: OE=Optics, SE=Systems, PE=Project, DR=Data Reduction, DE=Detector, SW=Software, ME=Mechanical, IE=Instrumentation, EE=Electrical

“Science Cases”

- 17 Science cases in the “Concept of Operations”, derived from white papers.
- Mostly abundances (e.g. metal-poor stars, GAIA follow-up, cool dwarfs, clusters). Mostly <900nm.
- Two polarimetric science cases (magnetic fields etc)
- Exoplanets added by AAO (2m/s, primarily transit follow-up).
- The only extragalactic cases are varying constants in the Universe and GRB follow-up (ToO, also added by AAO).
- About half the science cases had more than 1 object per 7 arcminute field of view.

Ghost is driven By the science needs of the Community

Science Req. / Science Case	1001: Wavelen. range (nm)	1002: Res.	1003: Mag. Limit	1004: Obj./ field	1005. RV prec.	1006: Obj. type	1007: Polarimetry
Stellar chemistry in stars with planets	380-1000	30k +45k	16	1	200	Point source	n/a
Galactic structure	350-930 310-930	35k	17	1	200	Point source	n/a
Extremely metal-poor stars	390-1000	15-40k	18	>1	200	Point source	n/a
Extreme metal-poor stars in dwarfs	360-960	20-60k	19	>1	200	Point source	n/a
Abundance studies of extra-galactic GCs	390-860	20-30k	19	>1	200	Point source	n/a
Globular cluster studies	350-800	30-60k	19	>1	200	Point source	n/a
Cool dwarfs	500-1000	30-60k	18	1	200	Point source	n/a
Astrophysics with open clusters	390-777 +300-1000	45-100k	14	>1	200	Point source	n/a
Dwarf galaxy shapes	520	20k	n/a	1	200	Extended object	n/a
Nucleo-chronometry of the oldest stars	330-870	60k	12	1	200	Point source	n/a
MW assembly history via dwarf galaxies	330-870 +420-700	20-40k	19	>1	200	Point source	n/a
GAIA Follow-up	450-700	40k	17	>1	200	Point source	n/a
Magnetic Fields in Star Formation/ exoplanets	380-1000	50-100k	11	>1	200	Point source	yes
Precision spectropolarimetry	390-1000	50-100k	11	1	200	Point source	yes
Exoplanets	400-900	75k	19	>1	2-50	Point source	n/a
Varying constants	400-900	75k	17	1	10	Point source	n/a
GRB spectroscopy	400-900	40k	14	1	200	Point source	n/a

Science flows down to instrument requirements!

Science	REQ-1000		Science	
Science	REQ-1001.01	Wavelength range	GHOST shall provide simultaneous wavelength coverage from 363 nm to 1000 nm.	Science white papers
Science	REQ-1002.01	Spectral resolution	GHOST shall have two selectable spectral resolution modes: standard resolution mode with R>50,000 and high resolution mode with R>75,000.	Science white papers
Science	REQ-1003.02	Sensitivity	GHOST shall obtain a sensitivity of Vega mag=18.0 in a 1 hour observation for 30 sigma per resolution element in standard resolution mode in dark time (50th sky brightness percentile) at the order centre closest to a wavelength of 450 nm.	Science white papers
Science	REQ-1004.02	Targets and field size	GHOST shall have the capability to observe 2 targets simultaneously over a 7.5 arcmin diameter field of view (in low resolution mode).	Science white papers
Science	REQ-1005.02	Radial velocity precision	GHOST shall provide a radial velocity precision of 200 m/s over the full wavelength range in standard resolution mode and shall have the capability to provide a radial velocity precision of 10 m/s (goal 1m/s) over the wavelength range from 430nm to 750nm in the high spectral resolution mode.	Science white papers
Science	REQ-1006.01	Spatial sampling	GHOST shall spatially sample each target object over a field size of 1.2 arcsec.	Science white papers
Science	REQ-1007.02	Spectro-polarimetry	GHOST shall have provision for future implementation of a spectropolarimetric capability that can measure the Stokes V parameter.	Science white papers

363nm – 1000nm

R=50,000 and R=75,000

Limiting magnitude = 18 at 450nm

30 sigma per resolution element

2 objects over 7.5 arcmin field

PRV = 10 m/s (2m/s goal)

Spatial sampling = 1.2 arcsecs

Spectropolarimetry options future

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Science	REQ-1005.02	Radial velocity precision	GHOST shall provide a radial velocity precision of 100 m/s over the full wavelength range in standard resolution mode and shall have the capability to provide a radial velocity precision of 10 m/s (goal 1m/s) over the wavelength range from 430nm to 750nm in the high spectral resolution mode.	Science white papers
Science	REQ-1006.01	Spatial sampling	GHOST shall spatially sample each target object over a field size of 1.2 arcsec.	Science white papers
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Throughput

Resolution

Image stability

363nm – 1000nm

R=50,000 and R=75,000

Limiting magnitude = 18 at 450nm

30 sigma per resolution element

2 objects over 7.5 arcmin field

PRV = 10 m/s (2m/s goal)

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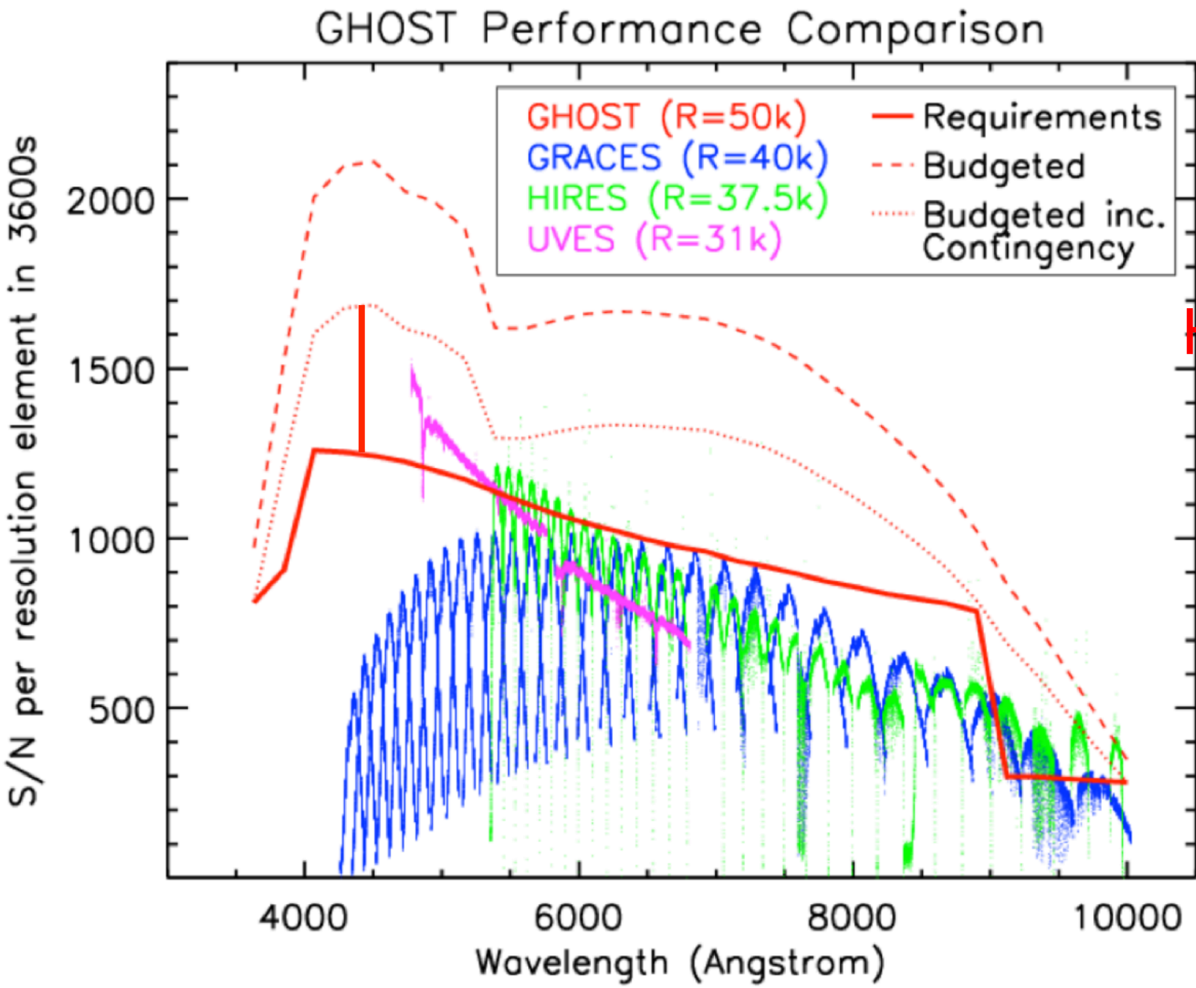
Spectropolarimetry options future

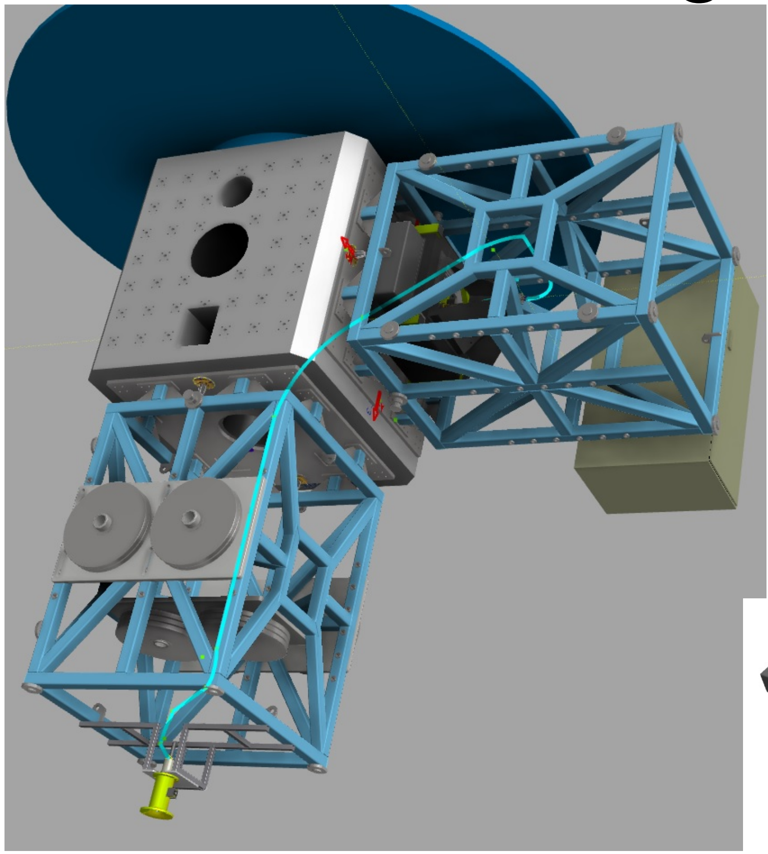
GHOST Throughput

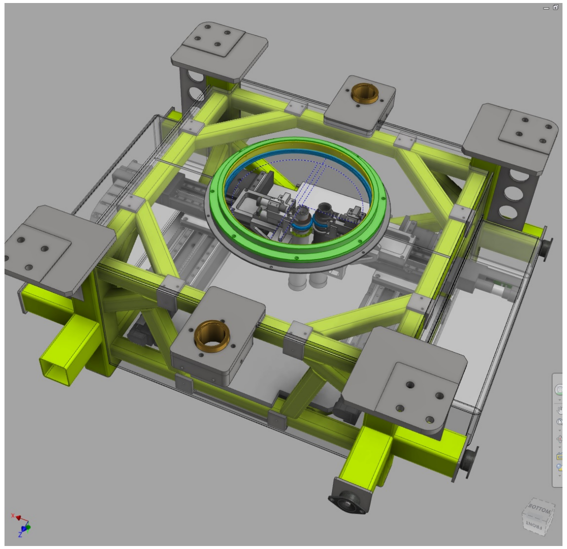


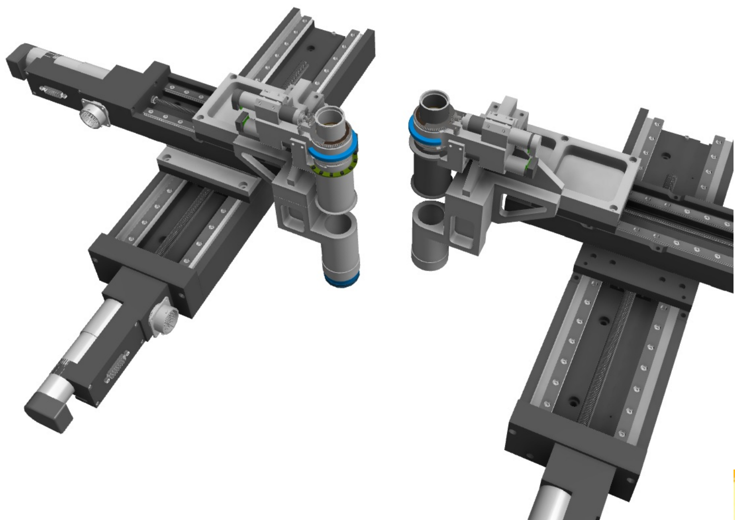
High Sensitivity Detectors
"Hot" Grating
Image Slicing
VPH Cross dispersion
New enhanced coatings
High efficiency ADC

Adapted from Chené et al. 2014

Cassegrain Component

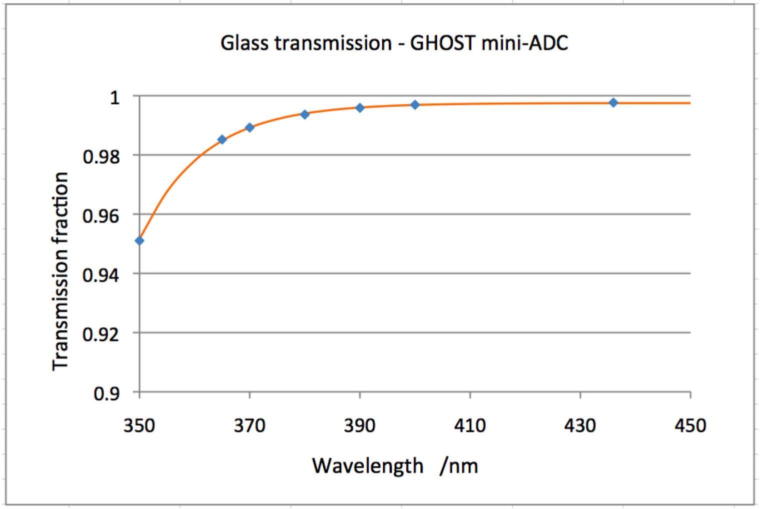






Less glass =high throughput

Individual ADCs per IFU



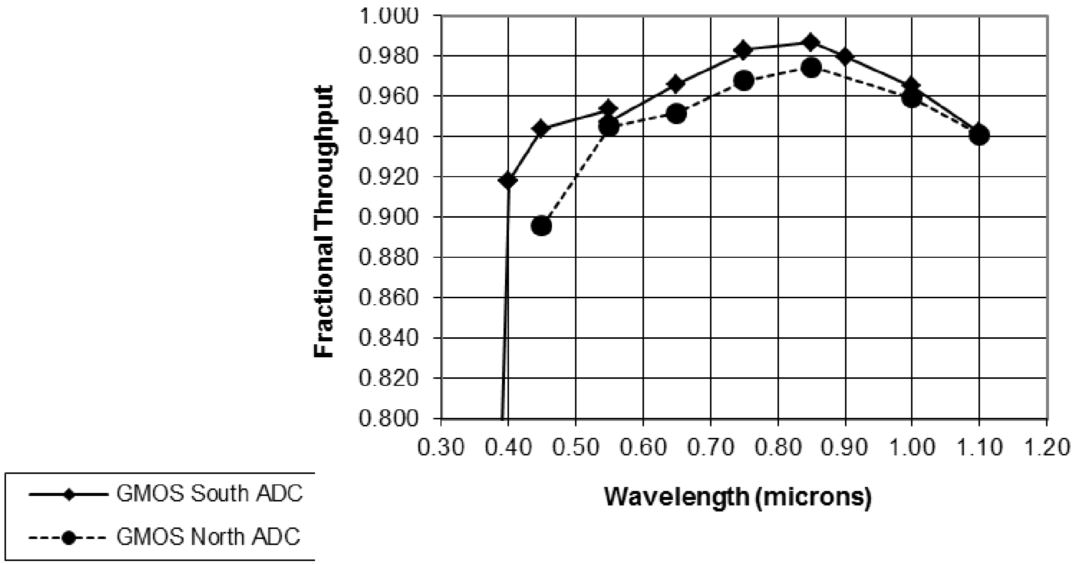
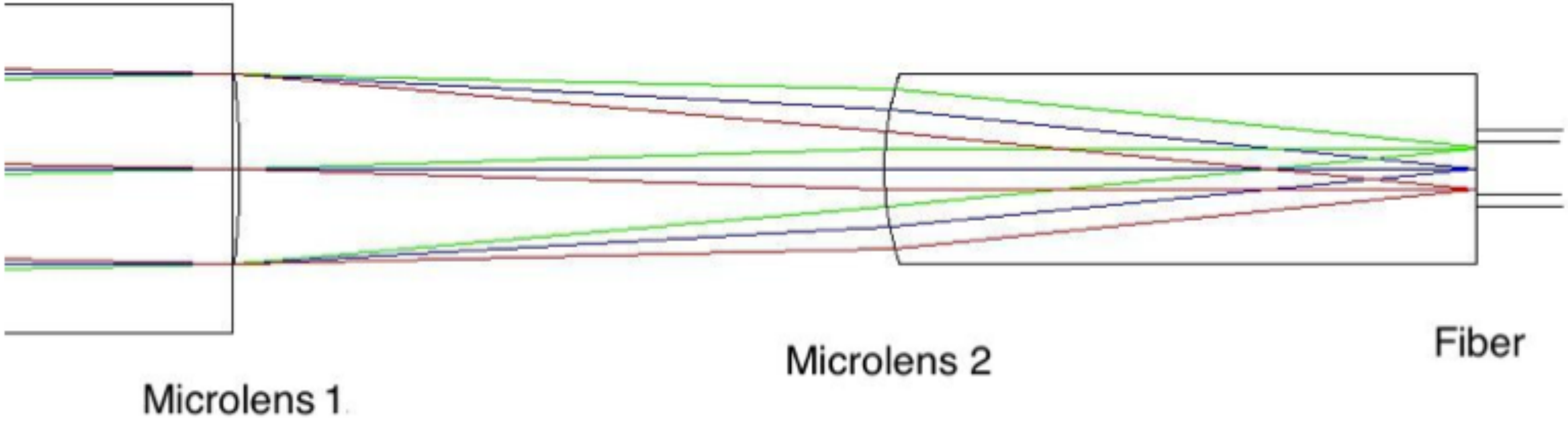
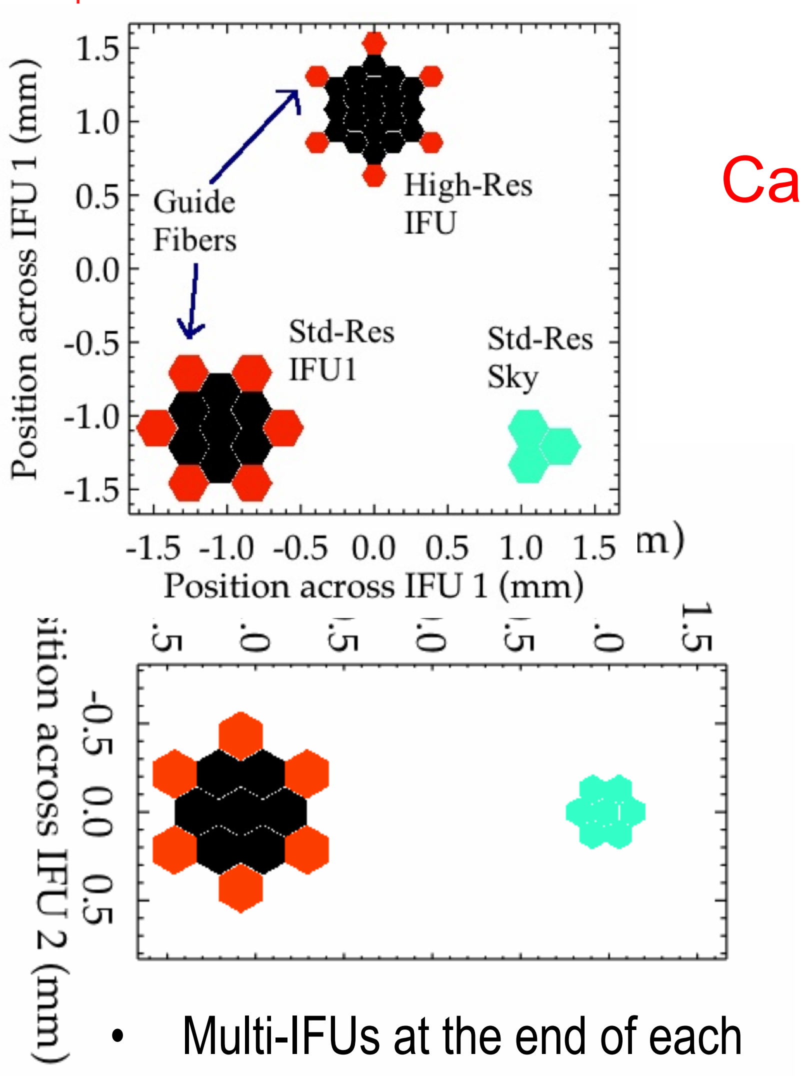


Image stability: Pupil imaged onto Fiber face
Fiber face imaged onto grating

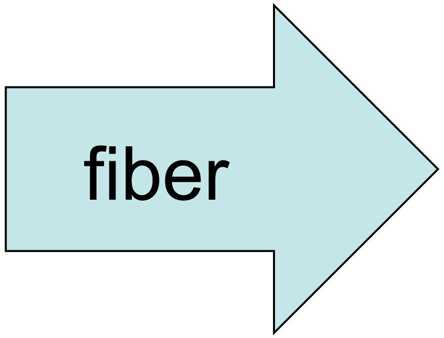


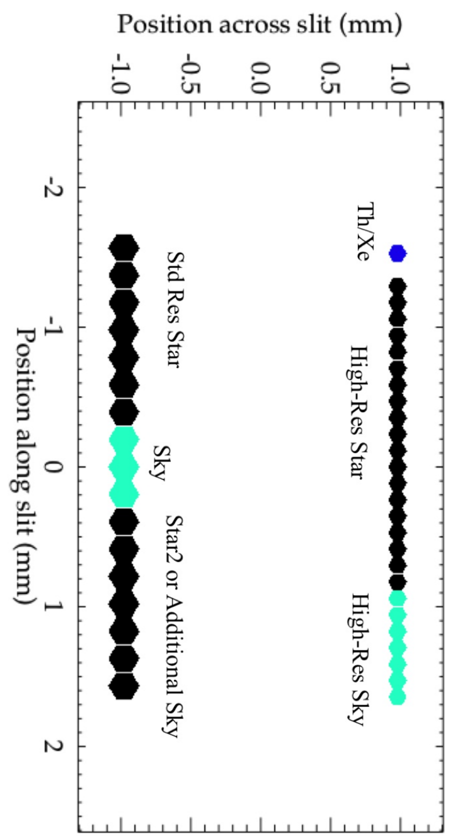
- Telecentric Fiber Injection. f/16 input, nominal 250 micron lenslet pitch (0.41” flat to flat for a hexagonal array)
- *Microlens 1*: Hexagonal. *Microlens 2*: Circular in Hex grid.
- Fiber has ~56 micron core.
- Input optics image telescope pupil on to the fiber face.
- Output is the same: *imaging the fiber face onto the grating* – essential for PSF stability.

Reformatting/Image slicing



High efficiency
Captures all the light





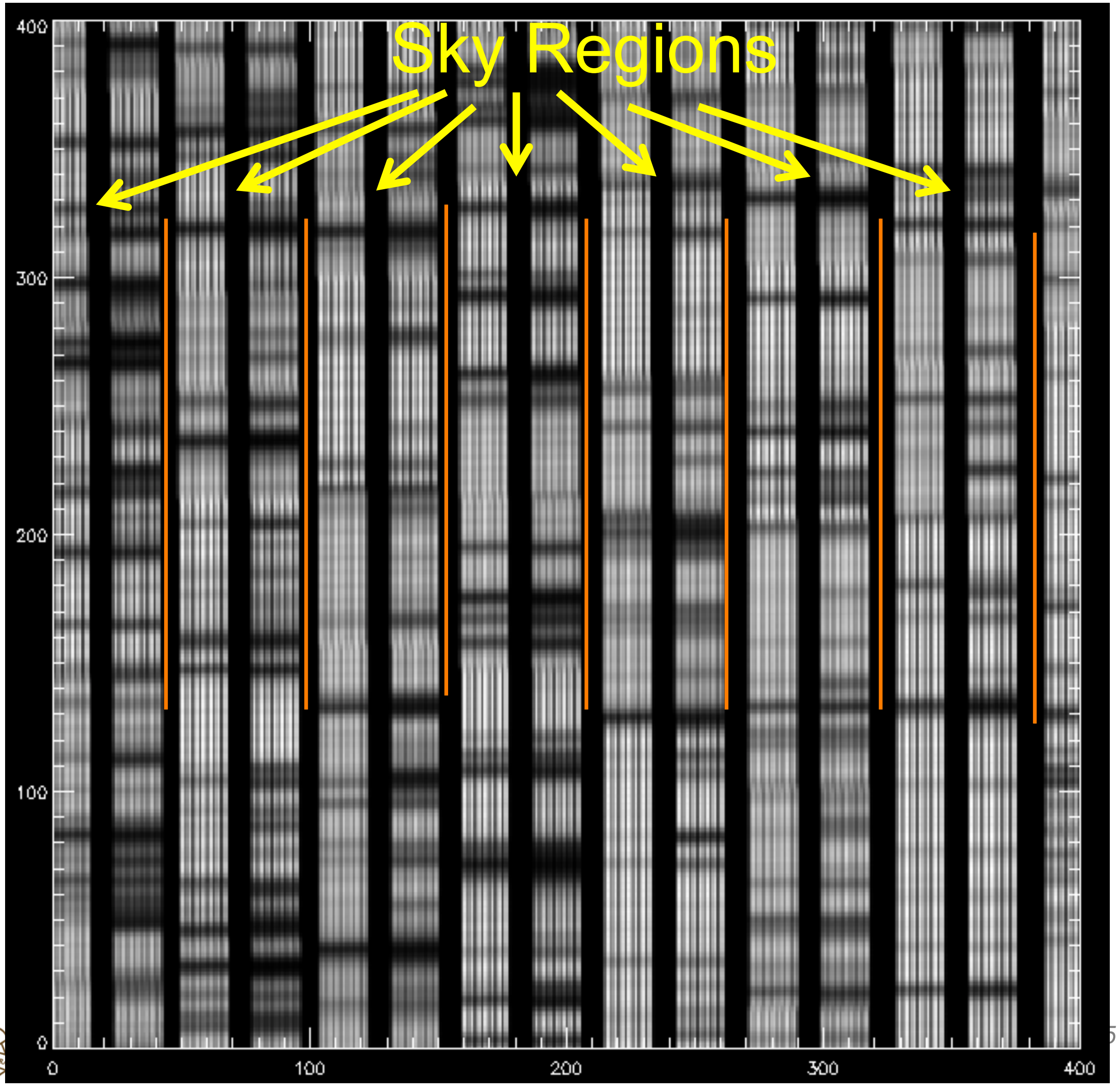
- Multi-IFUs at the end of each positioner arm for object (black) and sky (green) fibers.

- Two fixed slits (one illuminated at a time) at the spectrograph entrance, at R~51,500 and R~80,000.
- R~80,000 has simultaneous Th/Ar.

Australian National University

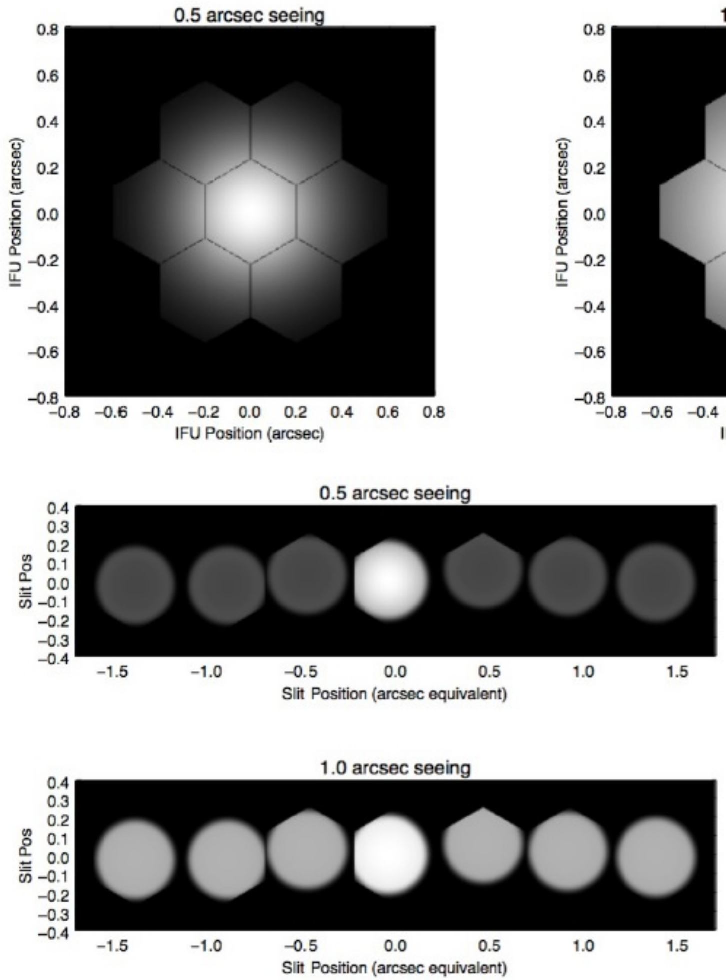
Science Data Overview

Sky availability and ThAr injection = image stability



- Some sky is always available, even in 2-object mode.
- Separation between orders is tight (<3 pix) only for the bluest few orders of each detector

Need to monitor slit images for stability



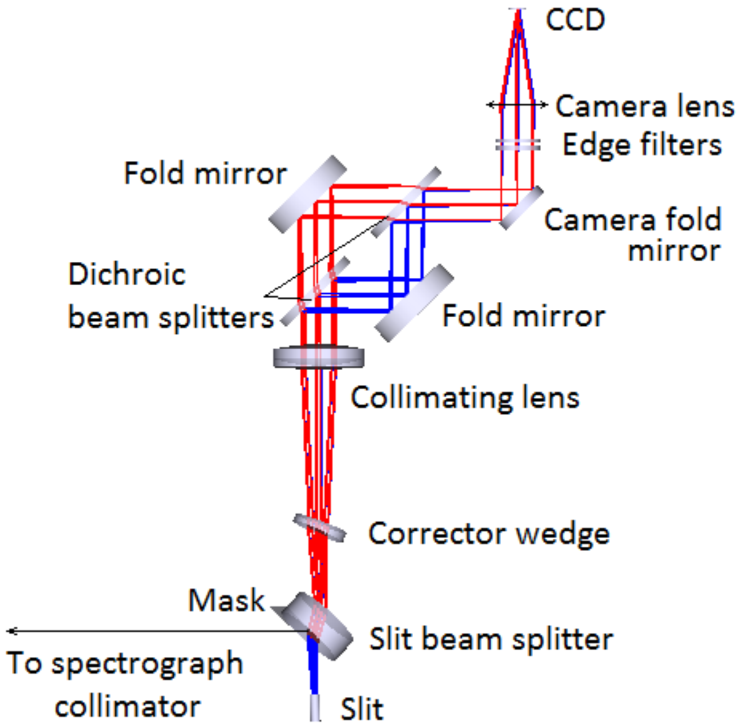
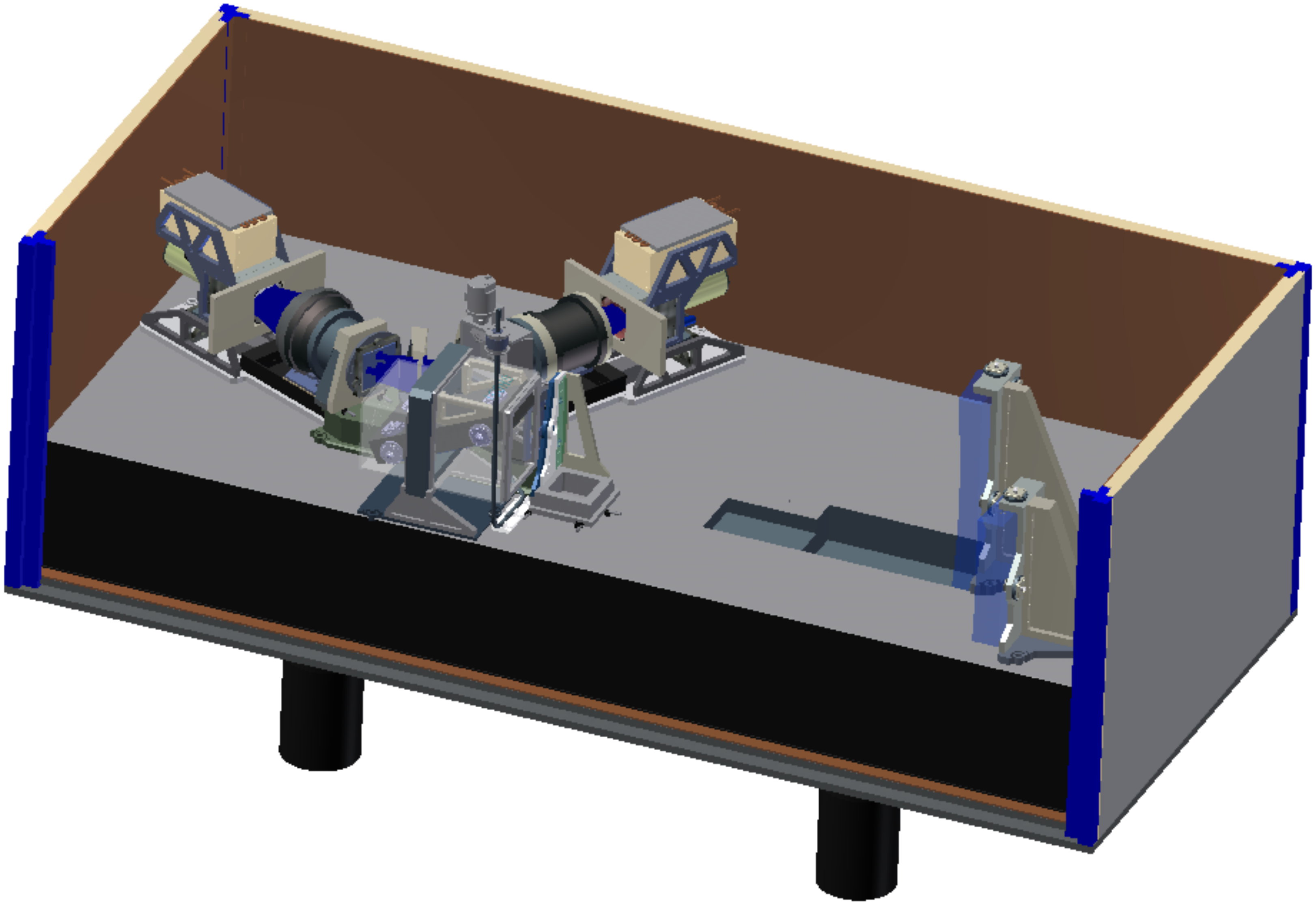


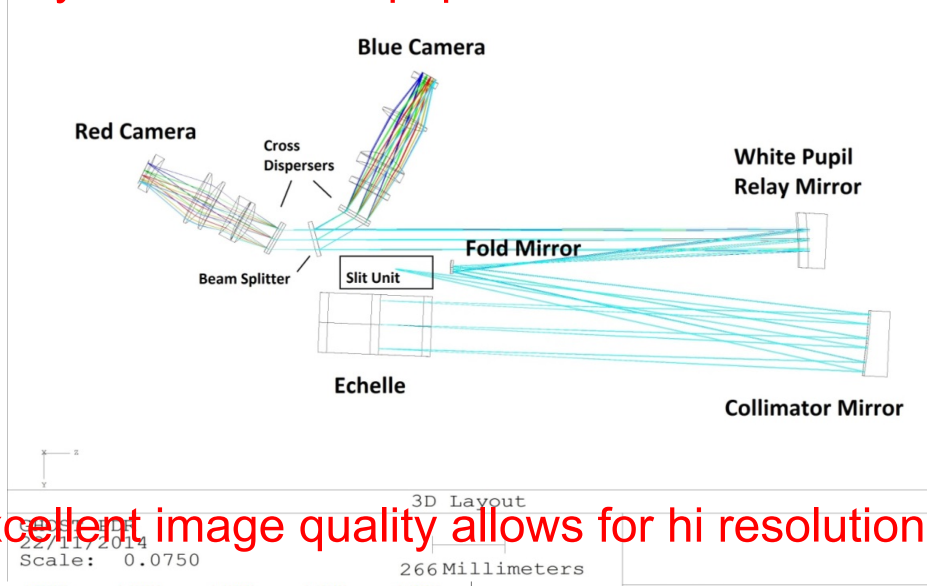
Figure 36 - Layout of slit viewing optics

GHOST will be isolated in the pier lab for image and wavelength stability

Instrument Overview



Asymmetric white pupil is efficient



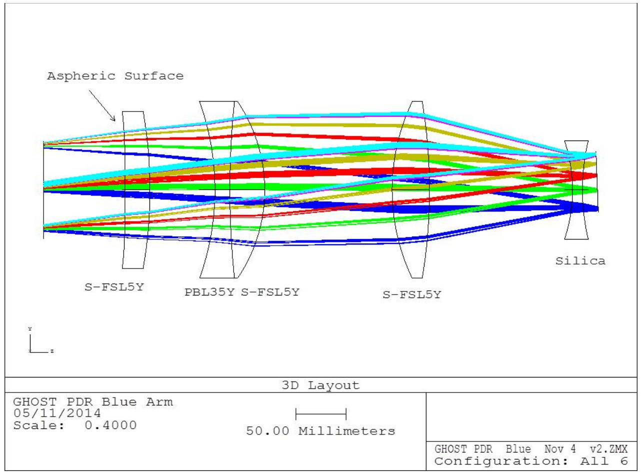


Figure 59 - GHOST blue camera layout

Excellent image quality allows for hi resolution

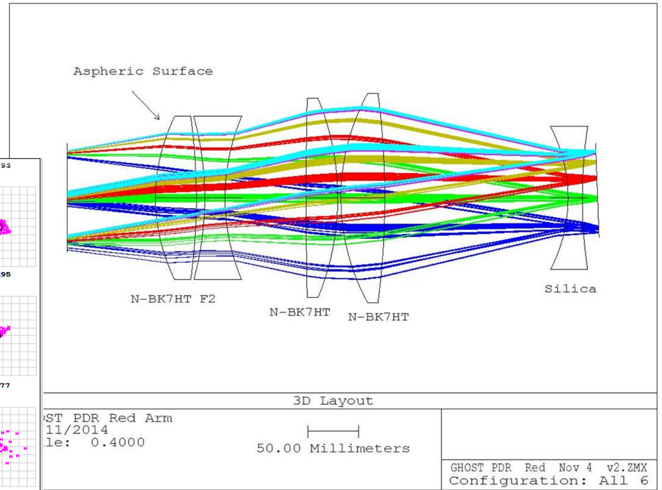


Figure 60 - GHOST red camera layout

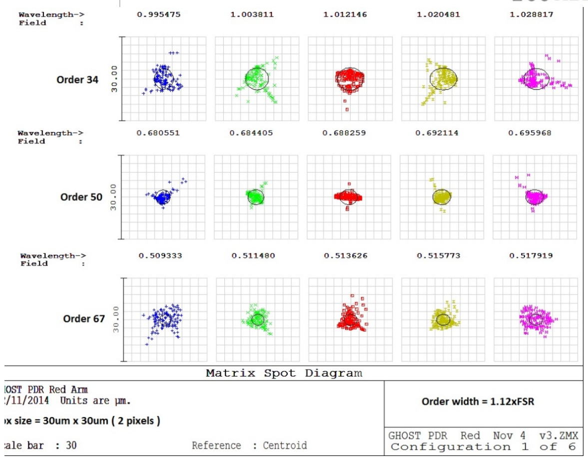


Figure 62 - Red camera spot diagram (boxes are 2 pixels, order width is 1.12xFSR)

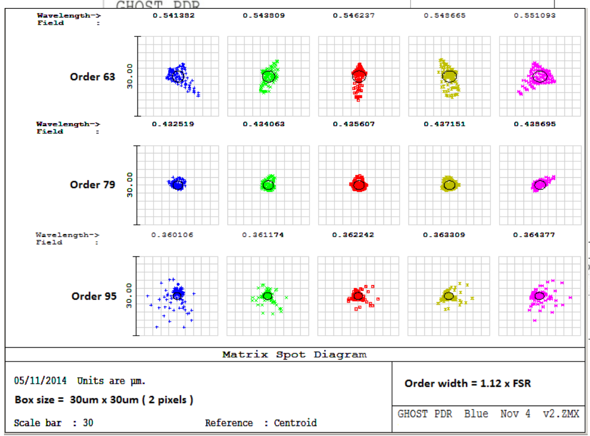
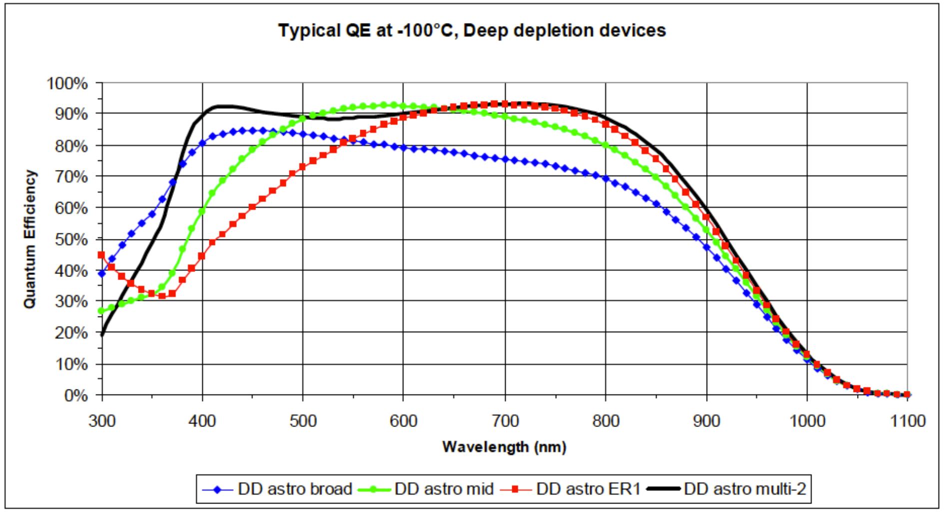


Figure 61 - Blue camera spot diagram (boxes are 2 pixels, order width is 1.12xFSR)

Detectors(NRC-Herzberg)

- The detectors were ordered at the end of April, so the science devices are expected at 12 months (or earlier) for the blue 4kx4k, and 15 months (or earlier) for the red 6kx6k.
- The blue device is standard thickness silicon, with the thin-astro-multi2 multi-layer coating (which gives a boost approx 360-400nm).
- The red device is deep-depletion silicon, with the regular astro-multi2 multi-layer coating.



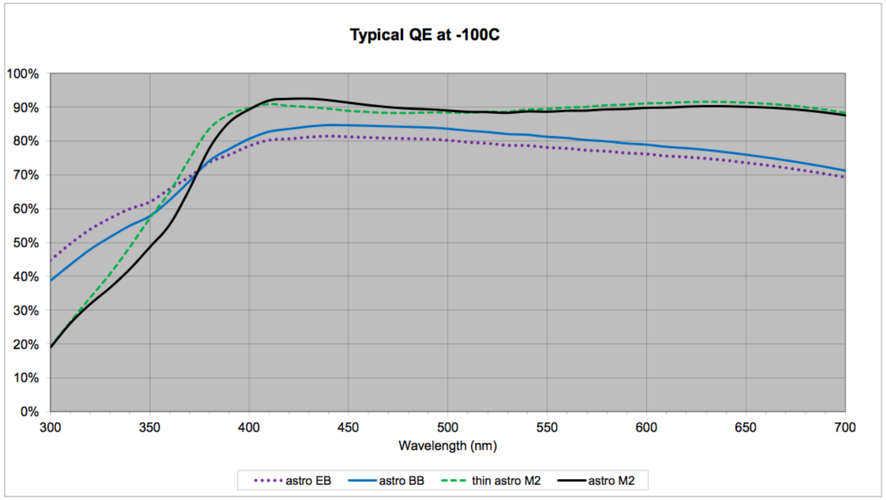


Figure 216 - e2v QE curves for standard silicon at -100 °C

Hot Grating

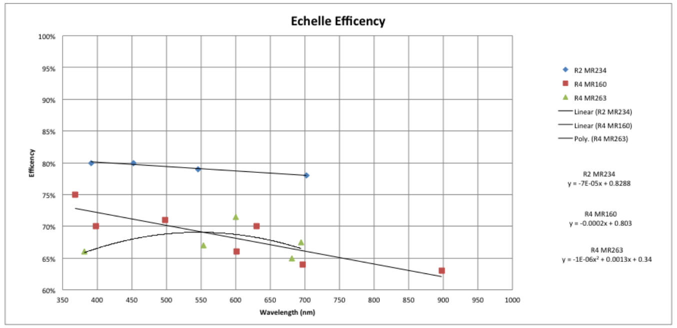
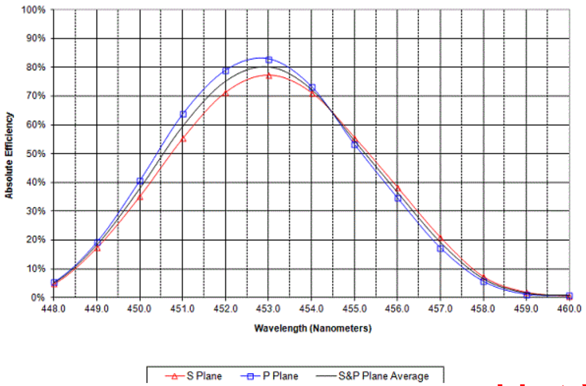


Figure 52 - Measured Efficiencies for the candidate échelles (Richardson Gratings Lab)



Hot VPH

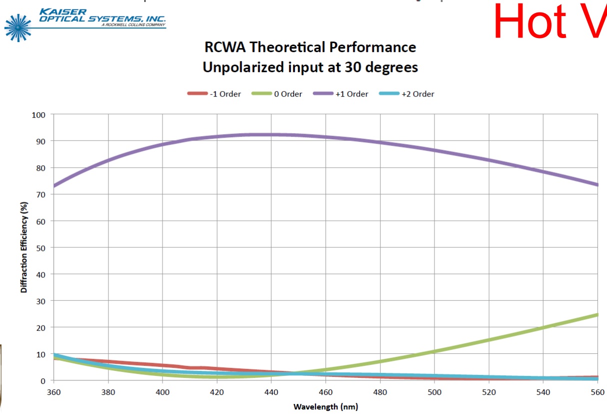
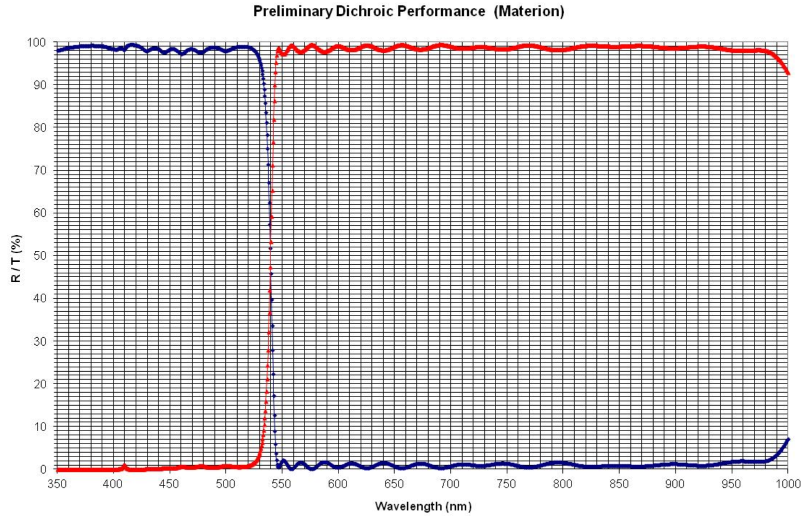


Figure 54 - Preliminary VPHG efficiency for the Blue VPHG

BS coatings



Overall high transmission cameras

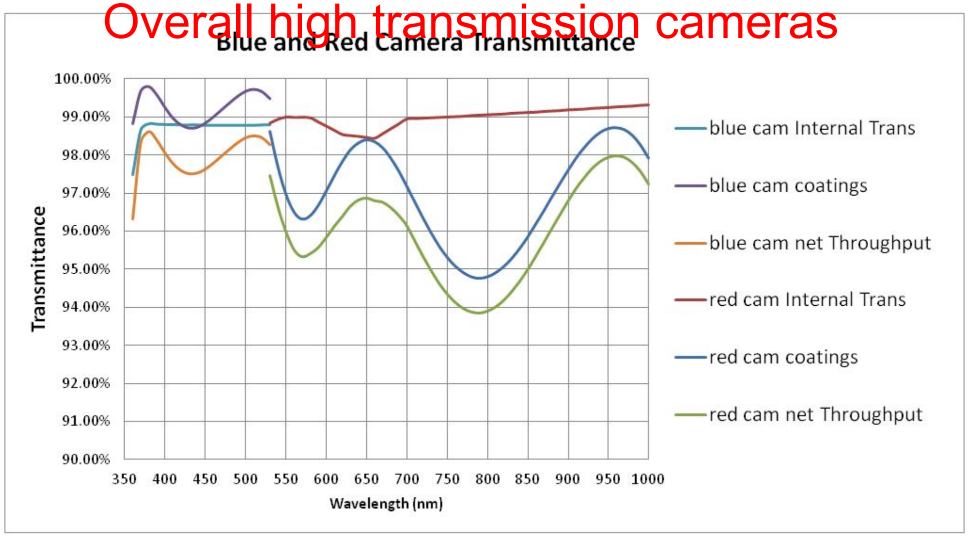


Figure 66 - predicted transmittance for the blue and red cameras

University

GHOST design features → **advantages**

- Focal-plane image-slicing → scale hence cost saving.
- Microlens-based IFUs → compact and high throughput.
- Miniature-ADCs → enhanced blue throughput.
- Dual slits and multiple-IFUs → enabling high resolution mode.
- Multi-object positioning system → double throughput for some science.
- Broadspectrum optical fibers → high throughput all wavelengths.
- Asymmetric white-pupil Echelle spectrograph → compact hence cost saving.
- Two-arm spectrograph design → high throughput over broad bandwidth.
- VPH grism cross-dispersers → high throughput.
- A&G camera → obviates OIWFS cost and complexity.
- Simultaneous wavelength calibration + slit viewing → high radial velocity precision.
- Future Polarisation mode→ allows spectropolarimetry.

→ **HIGH THROUGHPUT, ENHANCED FUNCTIONALITY, AND LOW COST**

GHOST design features → **low risk design**

- Focal-plane image-slicing → used in CYCLOPS.
- Microlens-based IFUs → used in MANIFEST and KOALA.
- Miniature-ADCs → modular design using small optics.
- Dual slits and multiple-IFUs → 1 additional mechanism.
- Multi-object positioning system → using COTS stages.
- Broadspectrum optical fibers → used in the SAMI and thoroughly tested.
- Asymmetric white-pupil Echelle spectrograph → many instances, .
- VPH grism cross-dispersers → HERMES experience.
- Slit-viewing camera → COTS detector and small optics, + low cost custom
- Simultaneous wavelength calibration → used in CYLCOPS2.
- Polarisation mode→ COTS components.

→ **LOW RISK**

Gemini High-Resolution Spectrograph

AAO, HIA, ANU Looking forward to building GHOST over the next ~3 years!

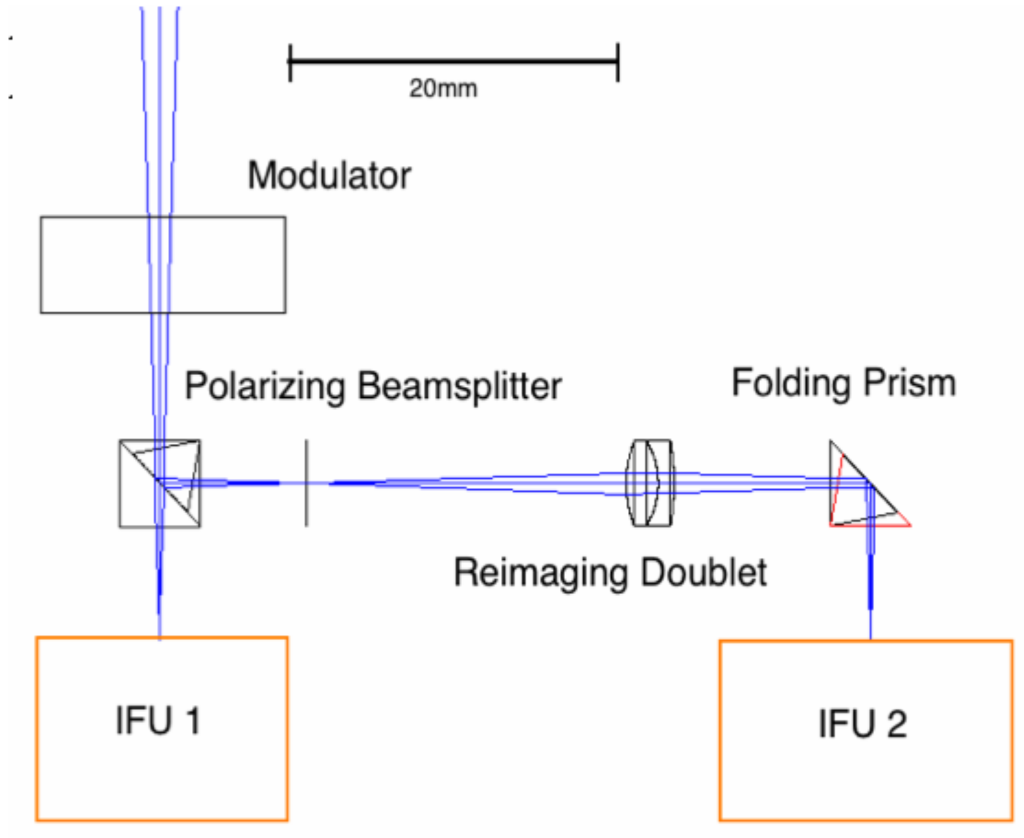
“Science Cases”

- 17 Science cases in the “Concept of Operations”, derived from white papers.
- Mostly abundances (e.g. metal-poor stars, GAIA follow-up, cool dwarfs, clusters). Mostly <900nm.
- Two polarimetric science cases (magnetic fields etc)
- Exoplanets added by AAO (2m/s, primarily transit follow-up).
- The only extragalactic cases are varying constants in the Universe and GRB follow-up (ToO, also added by AAO).
- About half the science cases had more than 1 object per 7 arcminute field of view.

	CCD231-84	CCD231-C6
Number of pixels	4096 (H) × 4112 (V)	6144 (H) × 6160 (V)
Pixel size	15 µm	15 µm
Total image area	61.4 mm × 61.4 mm	92.2 mm × 92.4 mm
Outputs	4	4
Flatness	< 20 µm (peak to valley)	< 40 µm (peak to valley)
Amplifier sensitivity	7 µV/e^-	7 µV/e^-
Read noise	4.0 e^- at 500 kHz 2.0 e^- at 50 kHz	4.0 e^- at 500 kHz 2.0 e^- at 50 kHz
Full well	200,000 e^-	200,000 e^-
Dark current	3 e^-/pixel/hour (at −100 °C)	3 e^-/pixel/hour (at −100 °C)
Charge-transfer efficiency	0.999995 (parallel) 0.999995 (serial)	0.999995 (parallel) 0.999995 (serial)
Readout time	45 seconds (100 kpix/s) 25 seconds (200 kpix/s)	90 seconds (100 kpix/s) 45 seconds (200 kpix/s)
Package	Silicon carbide	Silicon carbide
Price	$140,000 USD	$236,000 USD
Delivery	up to 12 months	up to 15 months

Polarimetry

- Two science cases requested a polarimetric mode (Magnetic fields in star formation/exoplanets, and precision spectropolarimetry) – an *expansion option.*



MULTI-IFU OBSERVING GAIN

AUSTRALIAN ASTRONOMICAL OBSERVATORY

GHOSD-02 CONCEPT OF OPERATIONS DOCUMENT (CONOPS)

3.2.4 Objects and Field Size

Table 4. Objects and field size requirements for multi-object science cases

Number of objects per 7' field	Science case subsections
1-2	EMP stars in dwarf galaxies
1-6	Dwarf galaxies
10	Magnetic fields in star formation
10	Extremely Metal-Poor Stars
3-50	Galactic Globular Clusters
>50	Extragalactic Globular Clusters
1 to >100	Galactic Open Clusters
1 to >100	Exoplanets
100	GAIA follow up

Table 4 provides the typical number of objects per GHOST field of view for the identified science
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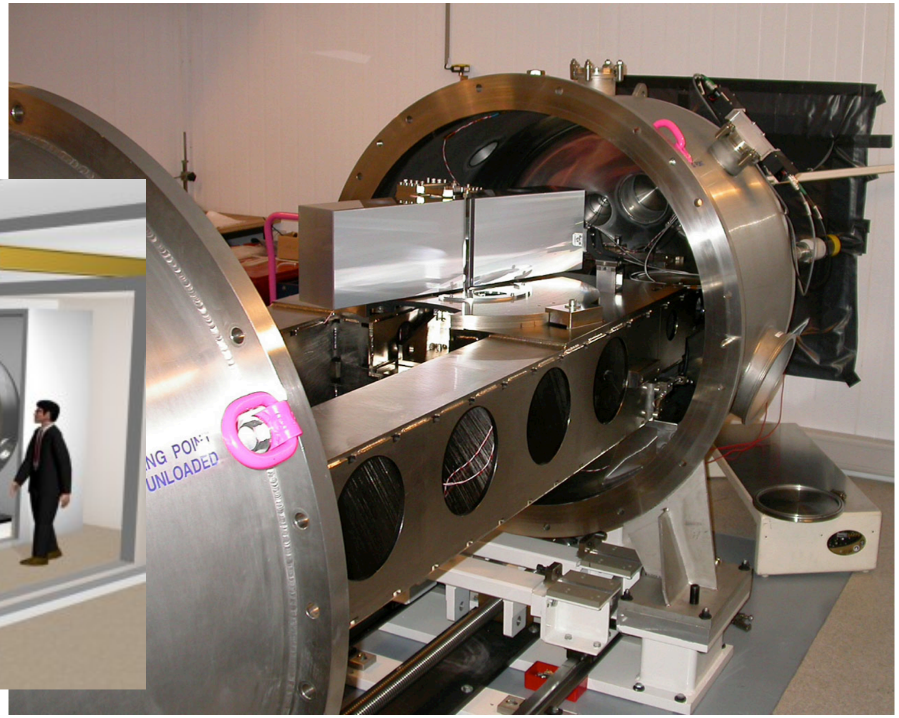
study will also benefit. We have identified >50% of science cases would use such a mode, which provides substantial gains (i.e., it is as favorable as doubling the throughput).

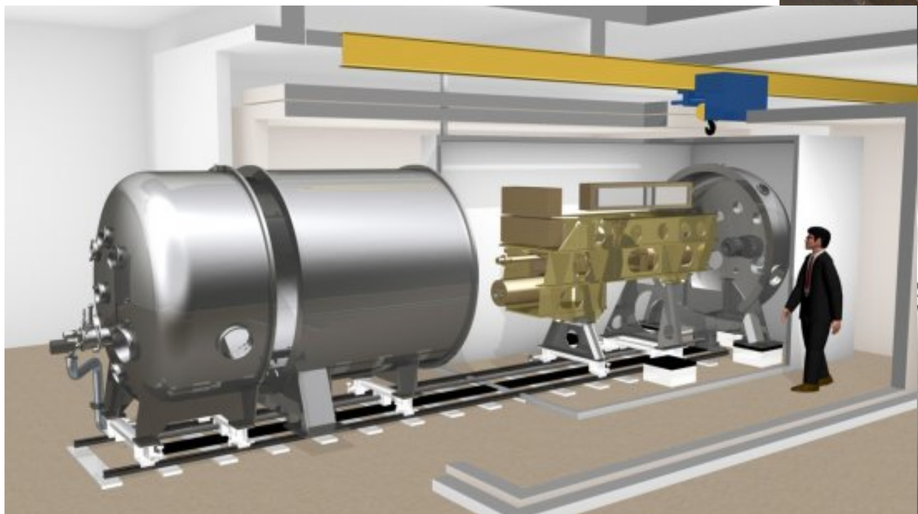
Two-IFU gain factor is typically 1.5 - 2

We thus derive the following science requirement:

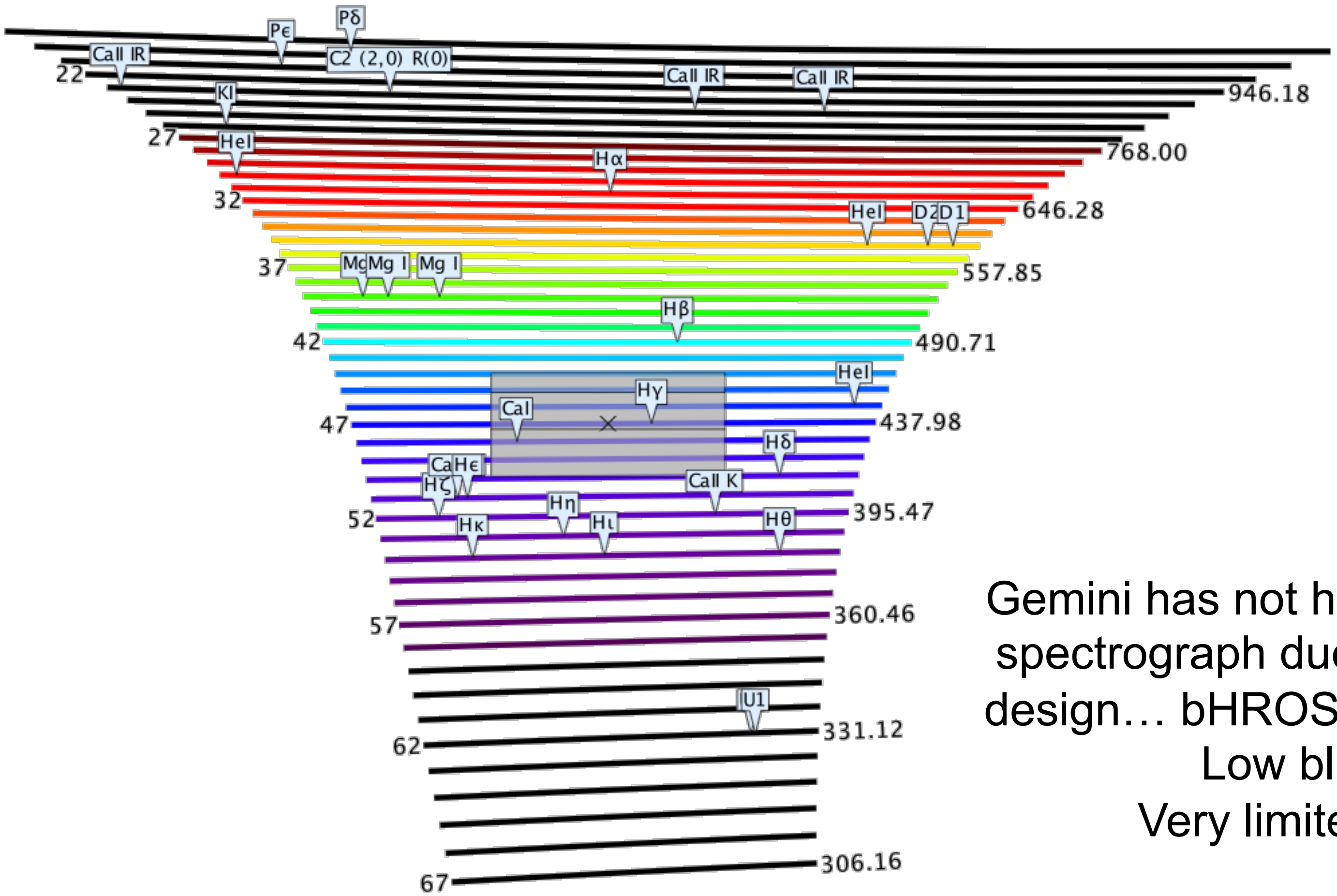
REQ-1004	GHOST shall have the capability to observe 2 targets simultaneously over a 7.5 arcmin diameter field of view.

HARPS is super-expensive and performs very well. The new kids on the block ESPRESSO, PFS, APF… even NRES promise to have their ultra-precise RV niches. Given that PRV almost always compromises efficiency, there is little room for GHOST to directly compete. But there is so much PRV work going on, surely there is room for GHOST PRV…





bHROS format – not useful



Gemini has not had a high-resolution spectrograph due to the Cassegrain design… bHROS had 2 critical flaws:

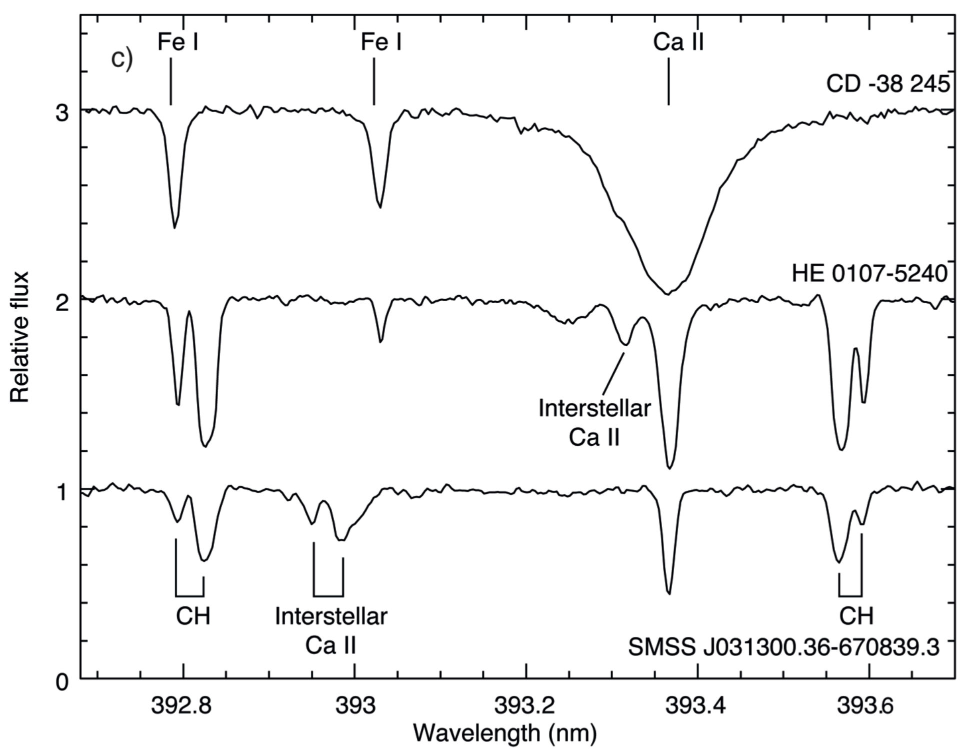
Low blue throughput

Very limited spectral range

Abundances

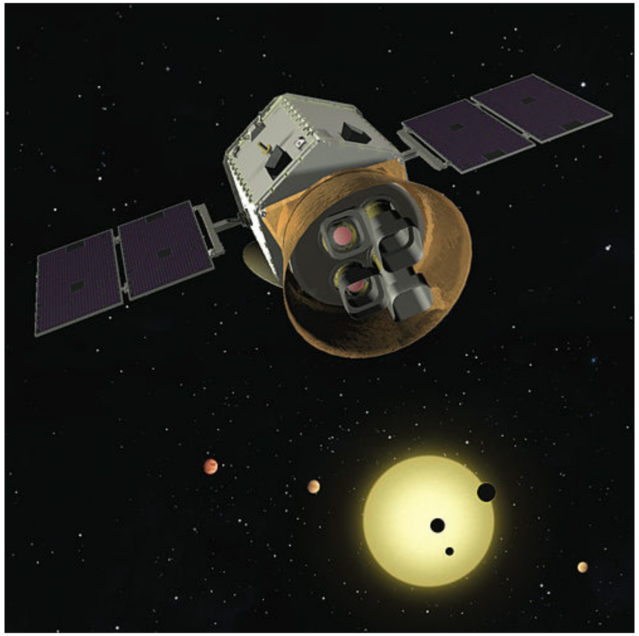
- Metal poor stars (individual, in dwarf Galaxies, in Globular clusters, for Nucleo-Chronometry) made up 5 of the 17 science cases. 5 other abundance cases
- Resolution *requirement* is modest (~30,000), but EW S/N improves as $R^{1/2}$ for photon-limited (i.e. high S/N) observations up to R~50,000.

Right: the "oldest star" discovered by Keller et al, 2014



Exoplanets

- Exoplanet science is a fast-moving target…
- Since 2011, the Transiting Exoplanet Survey Satellited (TESS) mission has been proposed and accepted. This will require *lots* of radial velocity follow-up, with a ~2m/s velocity requirement over ~month or smaller timescales.
- Transit spectroscopy is also frequently used exoplanet techniques.



INSTRUMENT DESCRIPTION
TABLE 20 (GHOSD-06)

GHOST Spectrograph Parameters	
Wavelength range	363 nm – 1000 nm
Échelle Grating	Richardson Grating Labs 424E, master MR234 65 degrees blaze (R2) gamma = 0.56 degrees G= 52.67 grooves/mm Ruled area: 204mm x 410mm
Collimator	1750.6mm f.l. @ f/10 175.7mm beam diameter at échelle
White pupil magnification	0.41
Beam Splitter	Cut on wavelength: 529.4nm (center of order 65) Order Overlap: ±2.5 orders Reflection Band: R > 97% (goal 99%) from 360nm to 514nm Transmission band: R > 96% (goal 98%) from 545nm to 1000nm Substrate: N-BK7HT 160mm x 130mm x15mm
Cross dispersers	Blue: 1137 G/mm VPHG, Alpha = 30 degrees Red: 565 G/mm VPHG, Alpha = 30 degrees Substrate: Fused Silica 127mm x 127mm x 10mm x 2 Beam Diameter at Cross disperser: 72mm
Blue Camera	Orders: 95 to 63 Minimum order width: 1.12 x FSR wavelength range: 360nm to 551nm field of view: 17 degrees focal length: 265mm (CCD: 4kx4k pixel detector area, 15 μm pixels)
Red Camera	Orders: 67 to 34 Minimum order width: 1.12 x FSR wavelength range: 509nm to 1000nm field of view: 29 degrees focal length: 265mm (CCD: 6kx6k pixel detector area on 15 μm pixels)