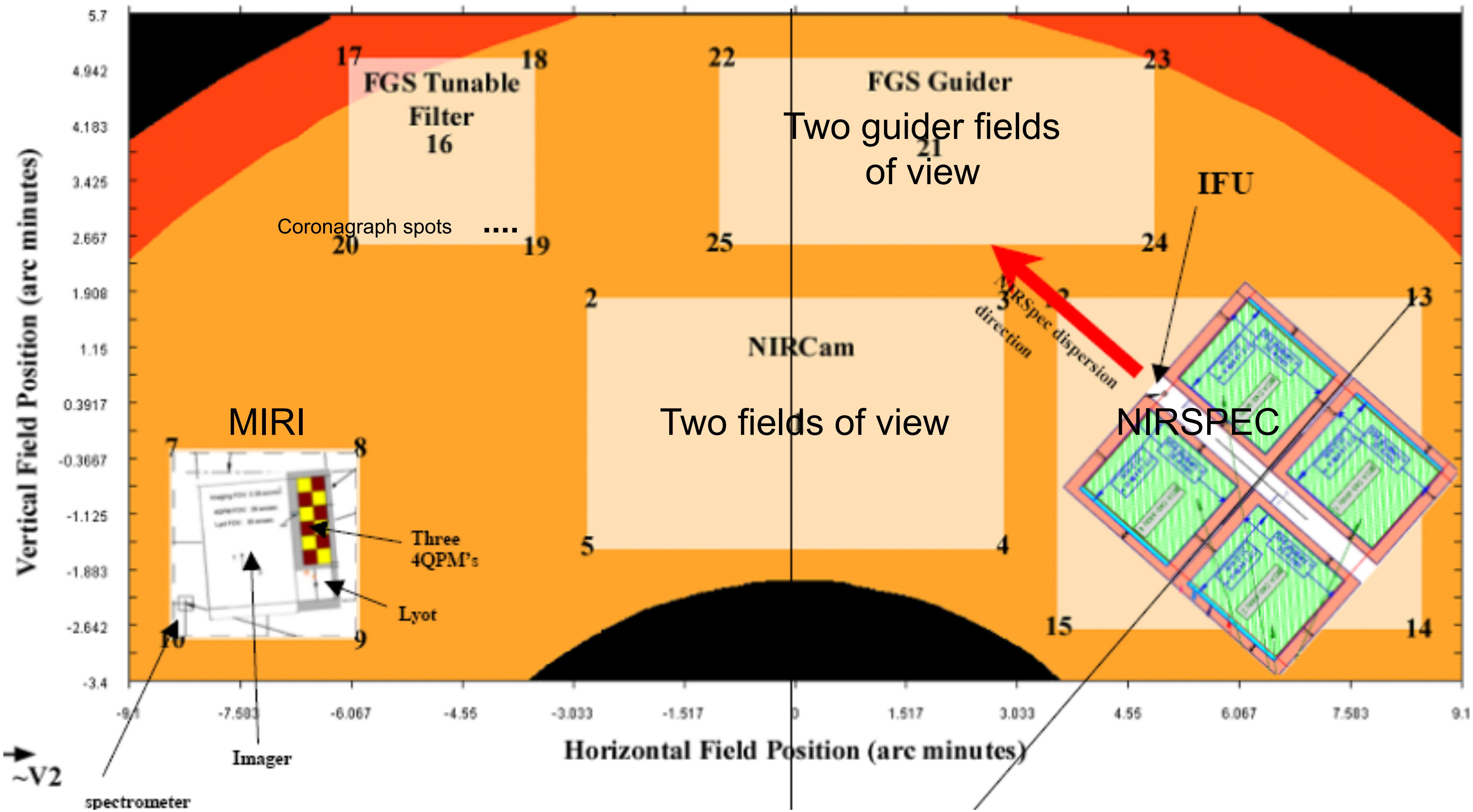
FGS/TFI instruments

- Two redundant guider fields
- Tunable Filter Imager (TFI) instrument
- Mounted on opposite sides of single optical bench
- Separate operations and pickoff mirrors
- Provided by CSA as JWST partner hardware contribution
- Principal contractor ComDev Ltd, Ottawa
- John Hutchings (NRC Canada) Guider PI
- Rene Doyon (U de Montreal) TFI PI

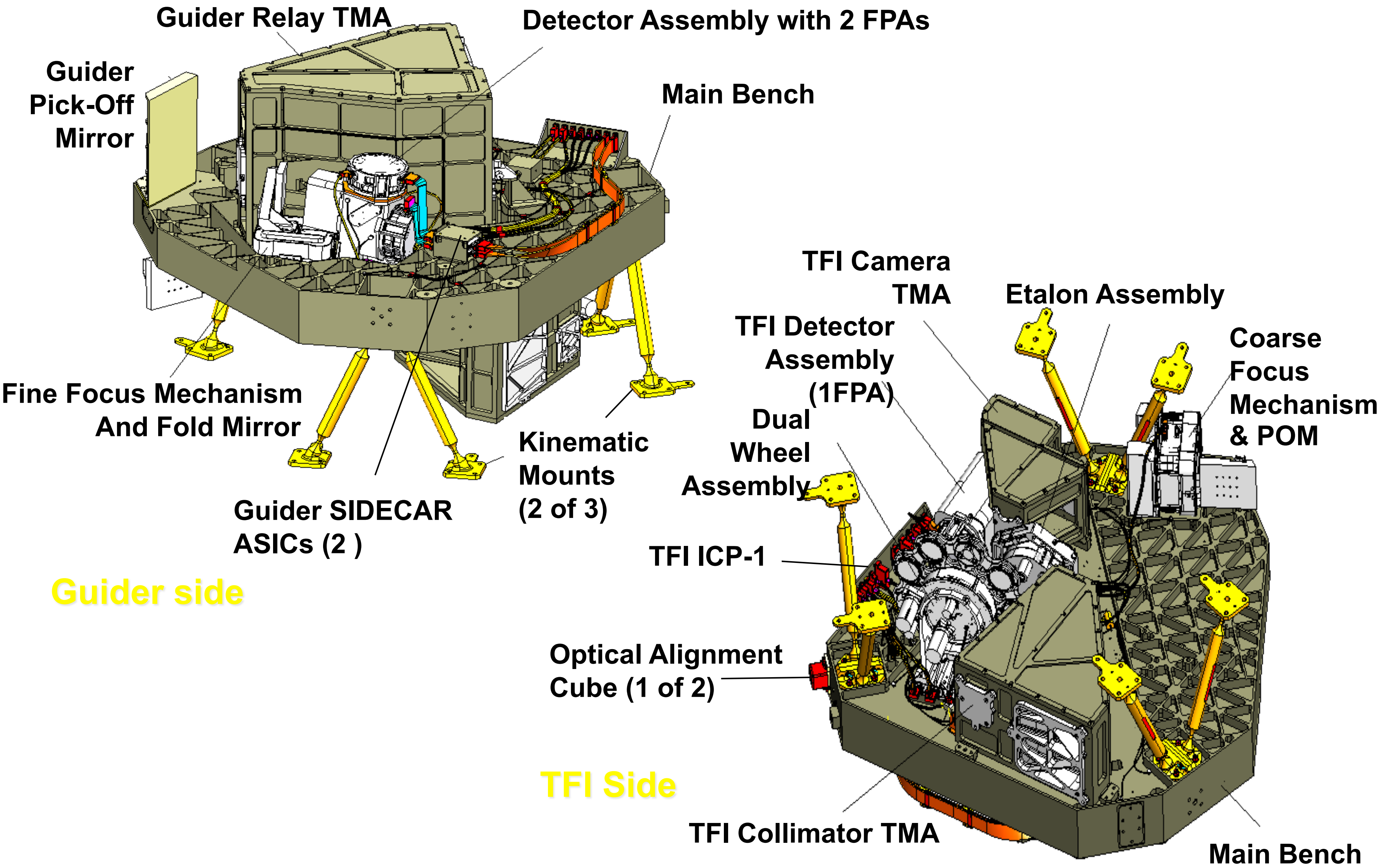
JWST instrument layout on the sky



The FGS Science team

- R. Doyon (U. Montréal)
- J.Hutchings (HIA)
- R. Abraham (U of Toronto)
- L. Ferrarese (HIA)
- R. Jayawardhana (U of Toronto)
- D. Johnstone (HIA)
- D. Lafrenière (U. Montréal)
- M. Meyer (ETH, Zurich)
- J. Pipher (U.Rochester)
- M. Sawicki (St-Mary's University)
- A. Sivaramakrishnan (AMNH ⟶ STScI)

Mechanical Design



Guider

Top level requirements

- 2 Fully redundant fields of view
- Guide star position updated at 16 Hz
- Guide star centroid (NEA) 3.5mas or better
- 95% probability of GS, any place in the sky

Guider performance drivers

NEA depends on

- Guide star brightness and SED
- Optical throughput and pixel scale
- Image quality/focus
- Detector QE and read noise

Dark current not an issue – rapid reads

All these combine to require ~5 arcmin field of view to have 95% chance of useable GS present

No filter – all photons from 0.8 to 5 microns used

Other guider tasks

- Guiding with detector latency, dead pixels
- Target identification by pattern/brightness matching

  Crowded and sparse fields, extra stars, double stars, compact galaxies
- Tracking on moving targets

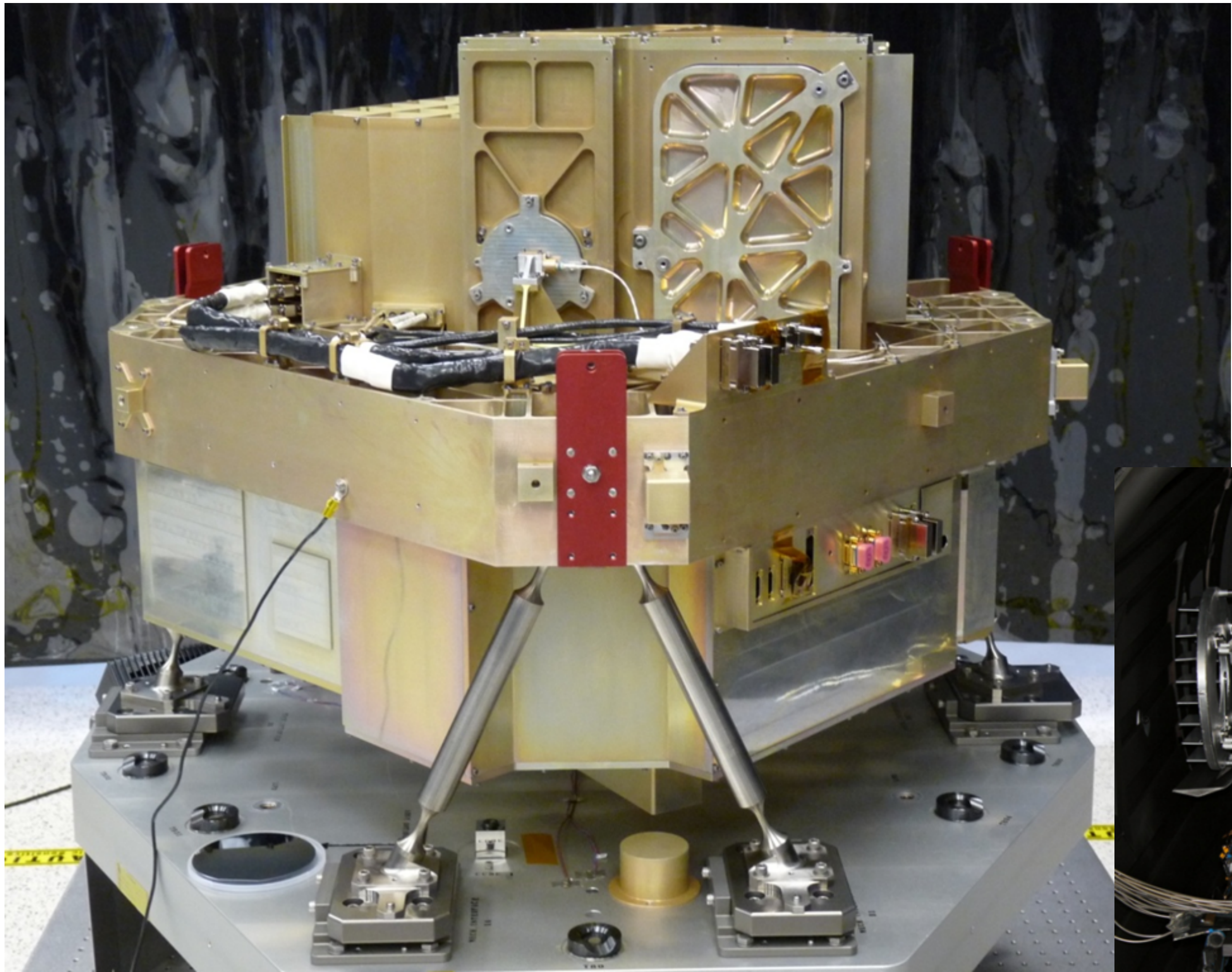
  9mas NEA moving up to 30mas/sec
- Guide on images during primary mirror focus, alignment, phasing

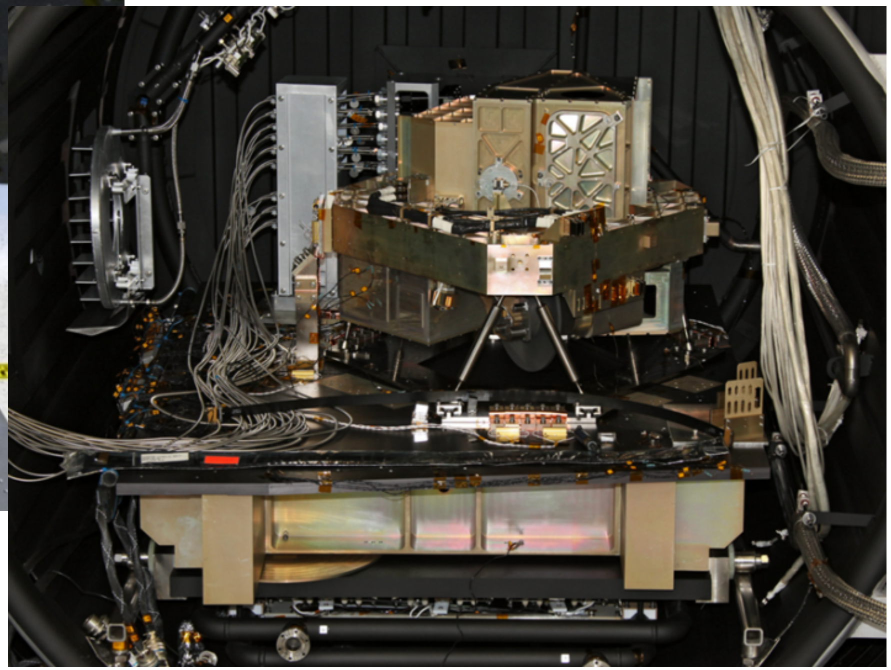
  Range of image quality, flux, and focus
- Focus sweep images for wavefront sensing

  Modelling images, tracking to interpret the results
- Full field imaging (science!) in non-guiding FOV

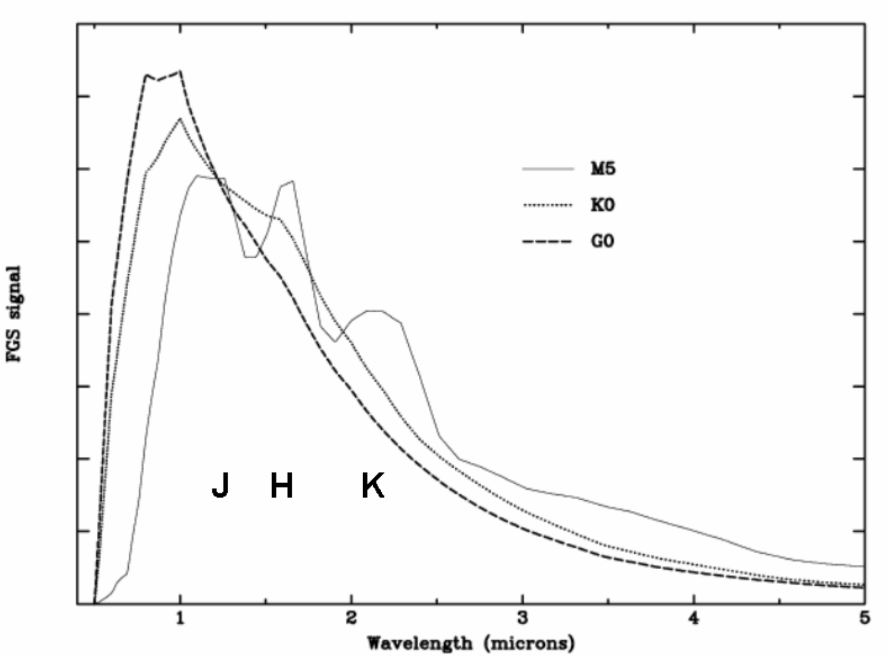
  JWST's deepest images
- Calibrated boresight movement with guider/OTE focus
- Stable, known position wrt other instruments to 5mas

Fully integrated ETU

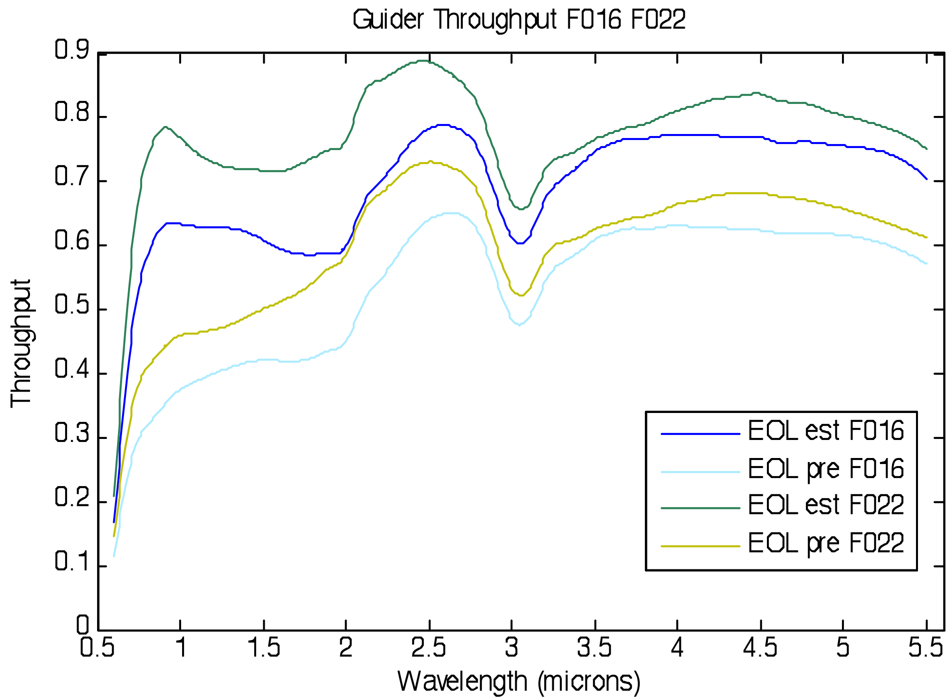




Guider signal depends on the detector selected

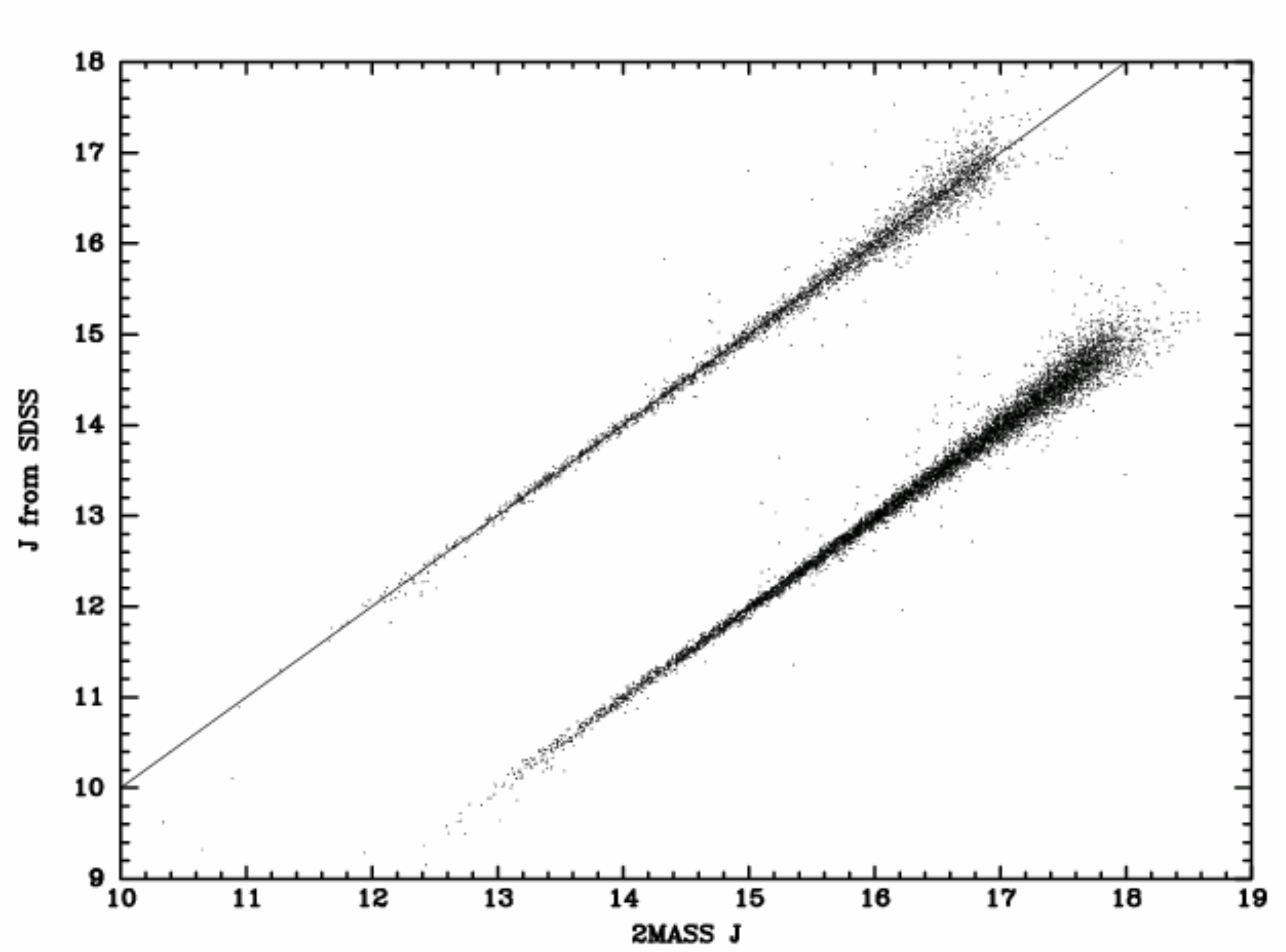


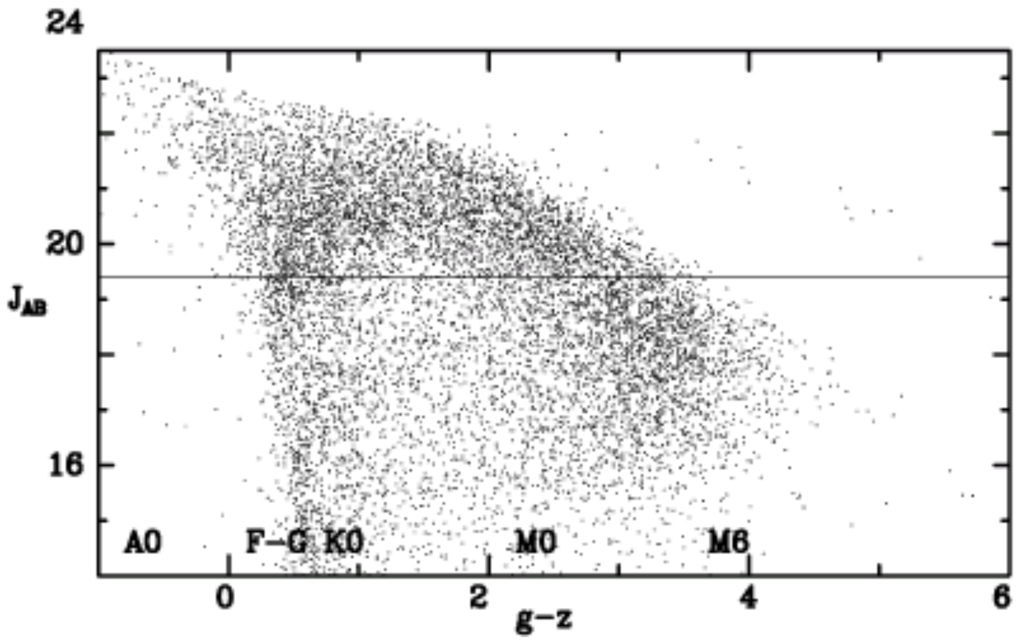
Guide star signal mostly at short wavelengths



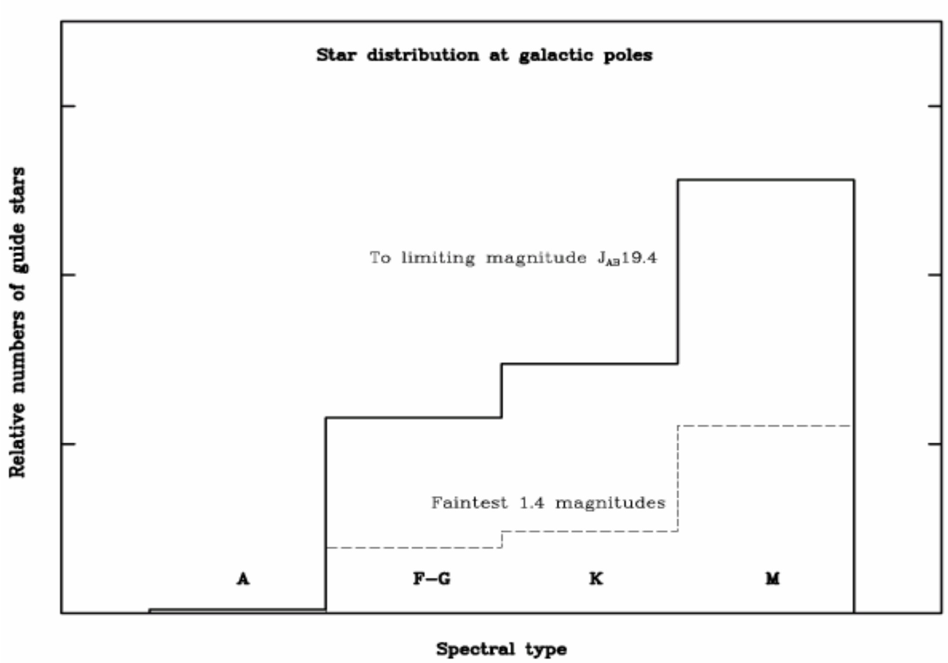
Estimates for the presently-considered PFM and flight detectors
F022 good choice for guider

Conversion from visible to J band magnitudes





Colour distribution and number counts of guide stars at the Galactic pole



Distribution of available guide stars at Galactic pole

Available guide stars and catalogues

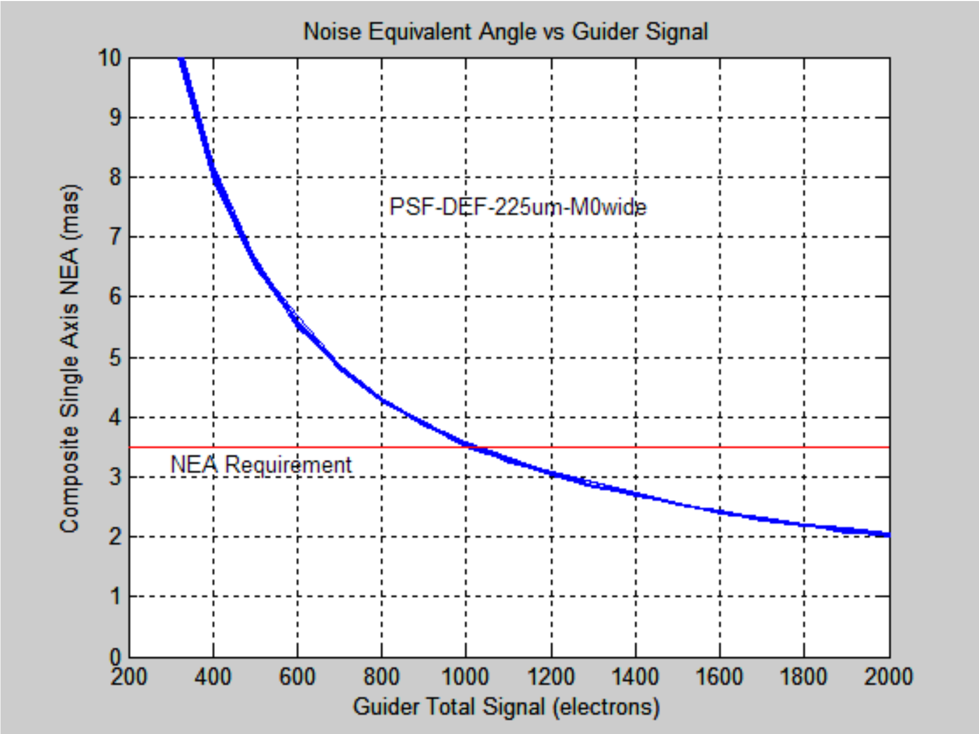
SDSS stars to FGS limit per single FGS field at galactic pole:	6.3
to J_{AB} =18.0	3.9
10 degrees off this direction, to FGS limit	7.1

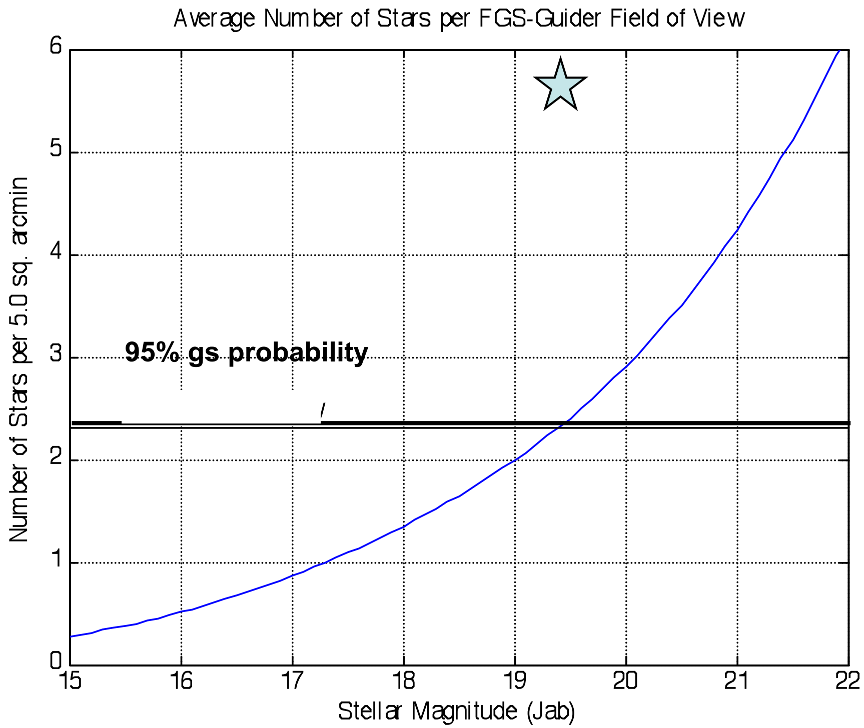
GSC2 useable stars are estimated to be 2.6 per single FGS field.
Total stars to GSC2 limit are about 10 per single FGS field at pole

FGS can guide on double stars and compact extended objects
Above SDSS numbers will likely include some of those

Need for J-band catalogue of stars near galactic poles
But need good spatial resolution: HST or ground-AO

Guide star limiting counts and magnitudes





NEA with GS signal

1000 counts is J_{AB}~19.4

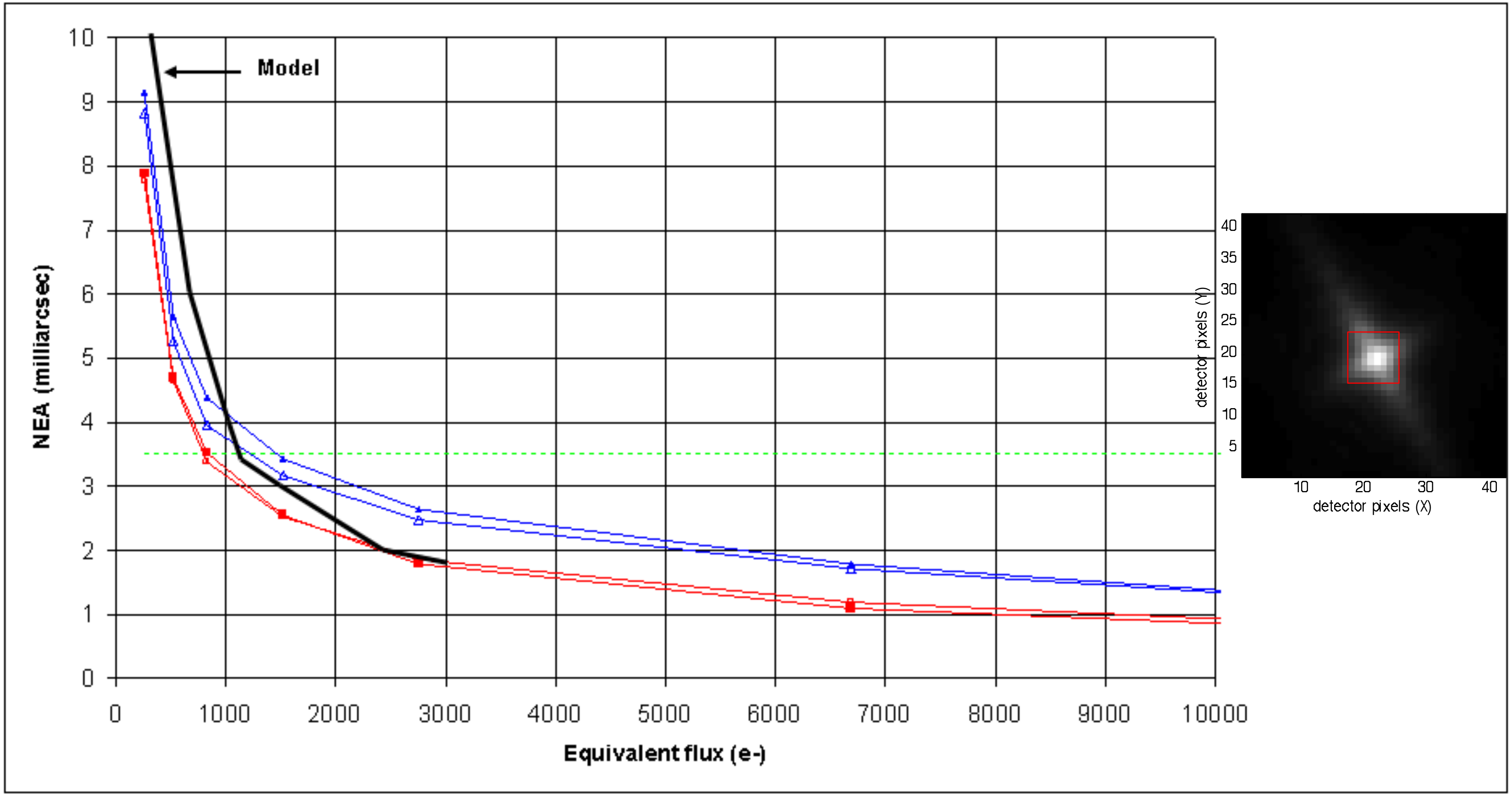
Read noise estimates crucial

Number of GSC2 stars per FOV

Nominal FOV is 10% larger
3 stars per field is ~95% prob

☆ *SDSS point sources J mag*

Guider: NEA vs signal from lab data

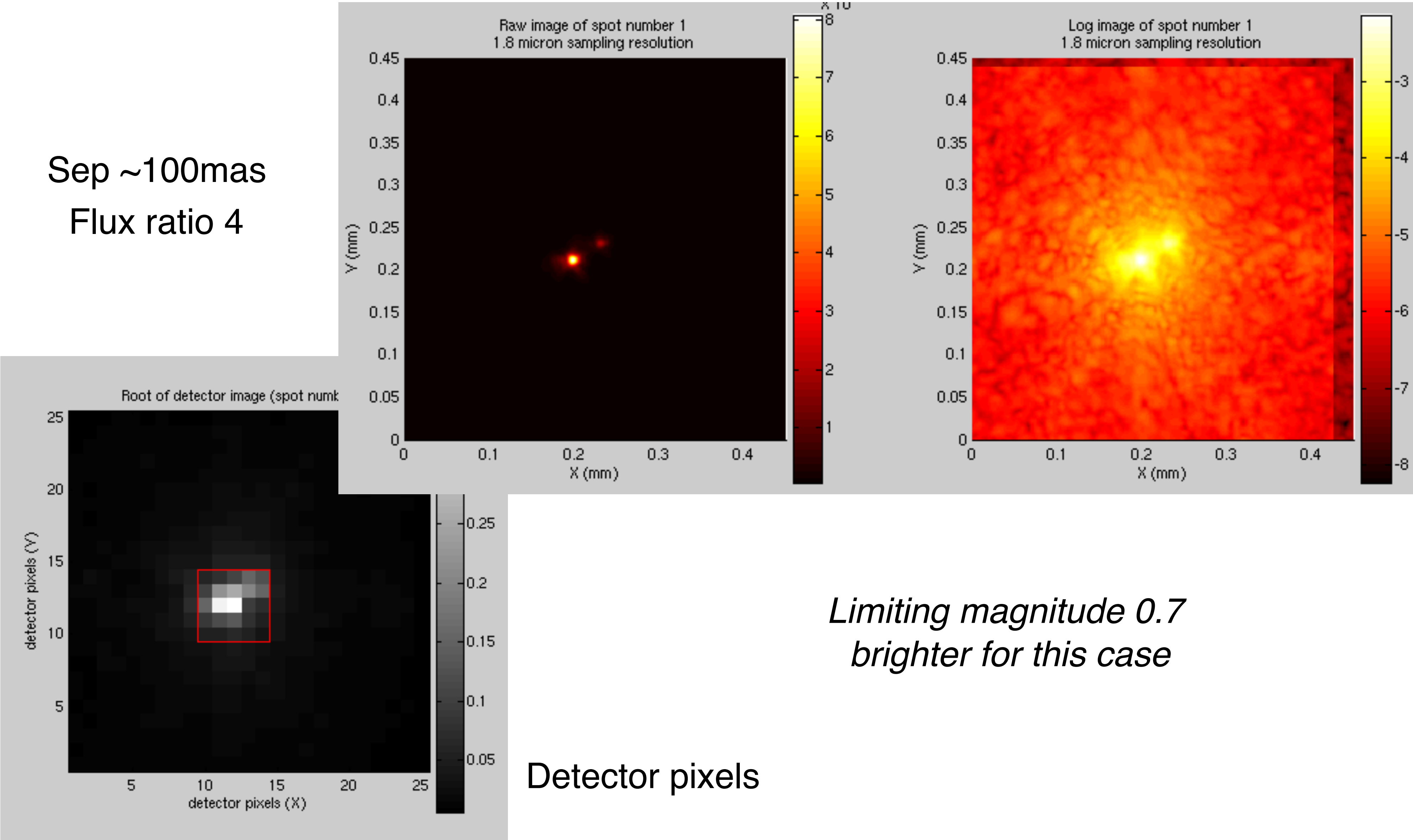


Heavy line is model for similar centroid window and noise, flight centroid algorithm

Guiding on double stars

Sep ~100mas

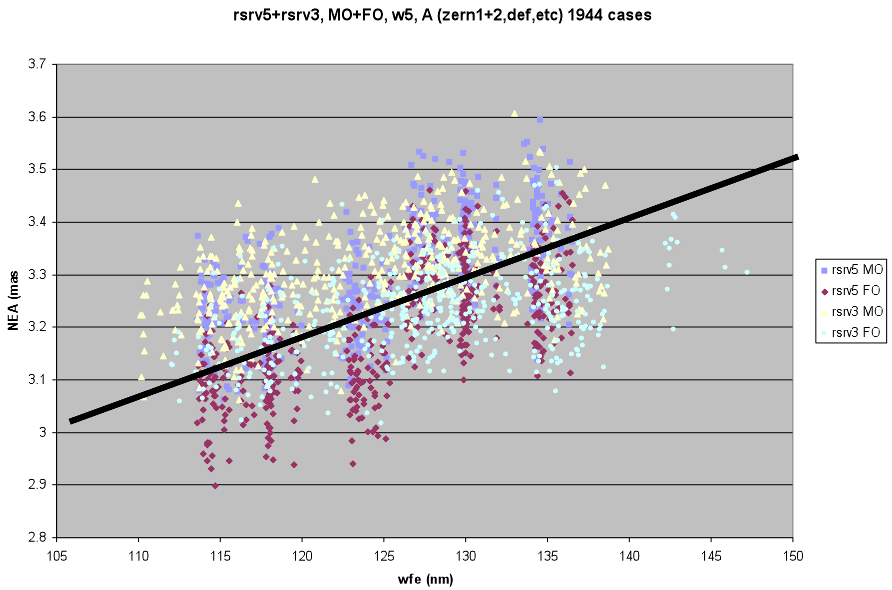
Flux ratio 4

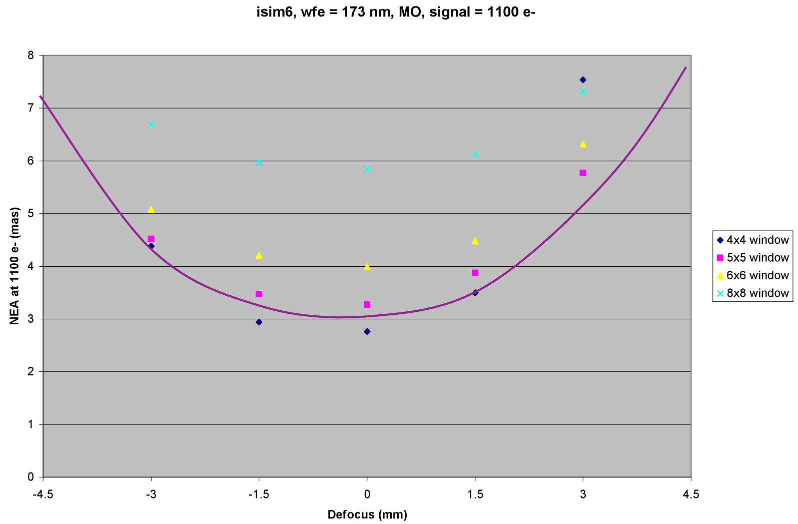


Limiting magnitude 0.7 brighter for this case

Detector pixels

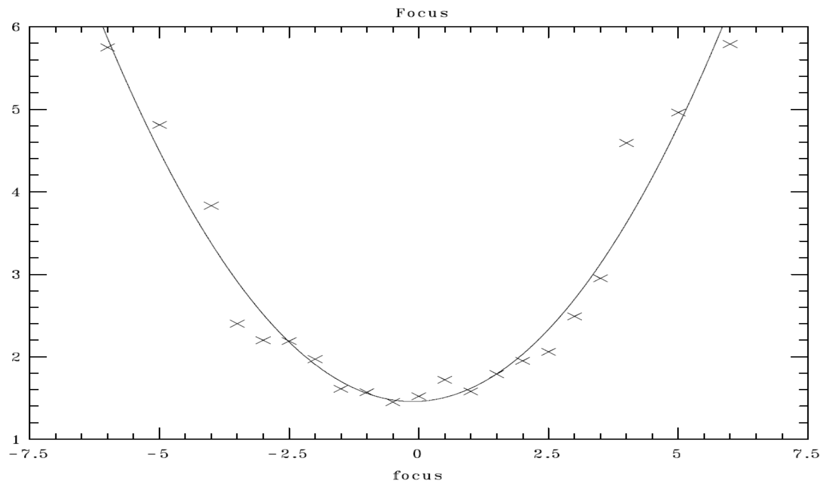
NEA variation with OTE focus and WFE



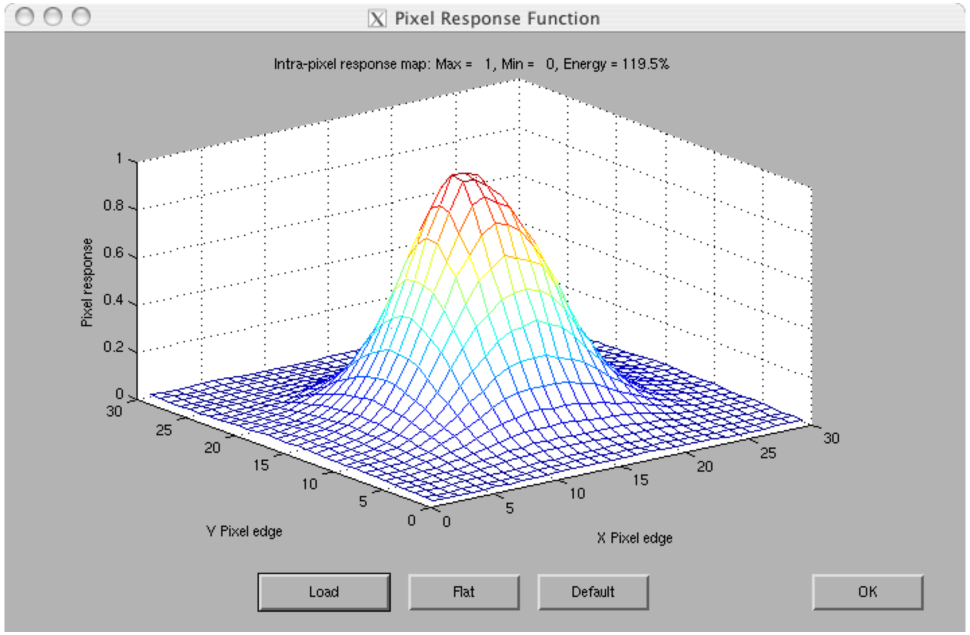


Top – models

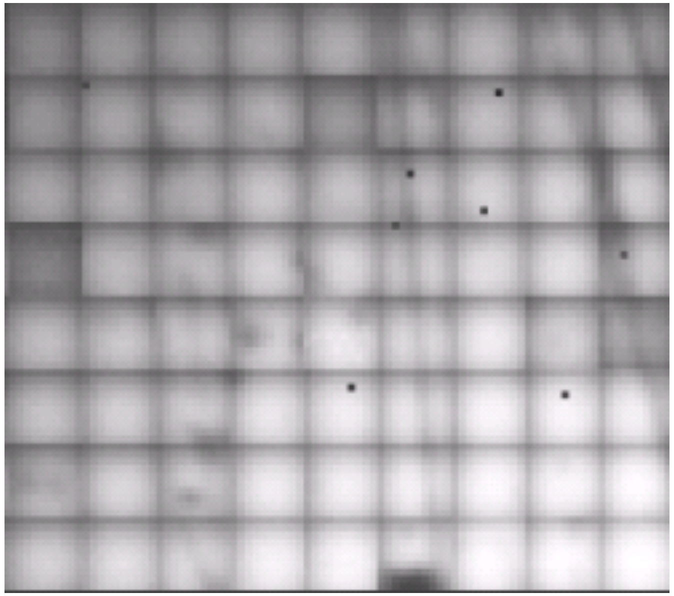
Lower – measures from ETU



Intra-pixel sensitivity systematically offsets centroids



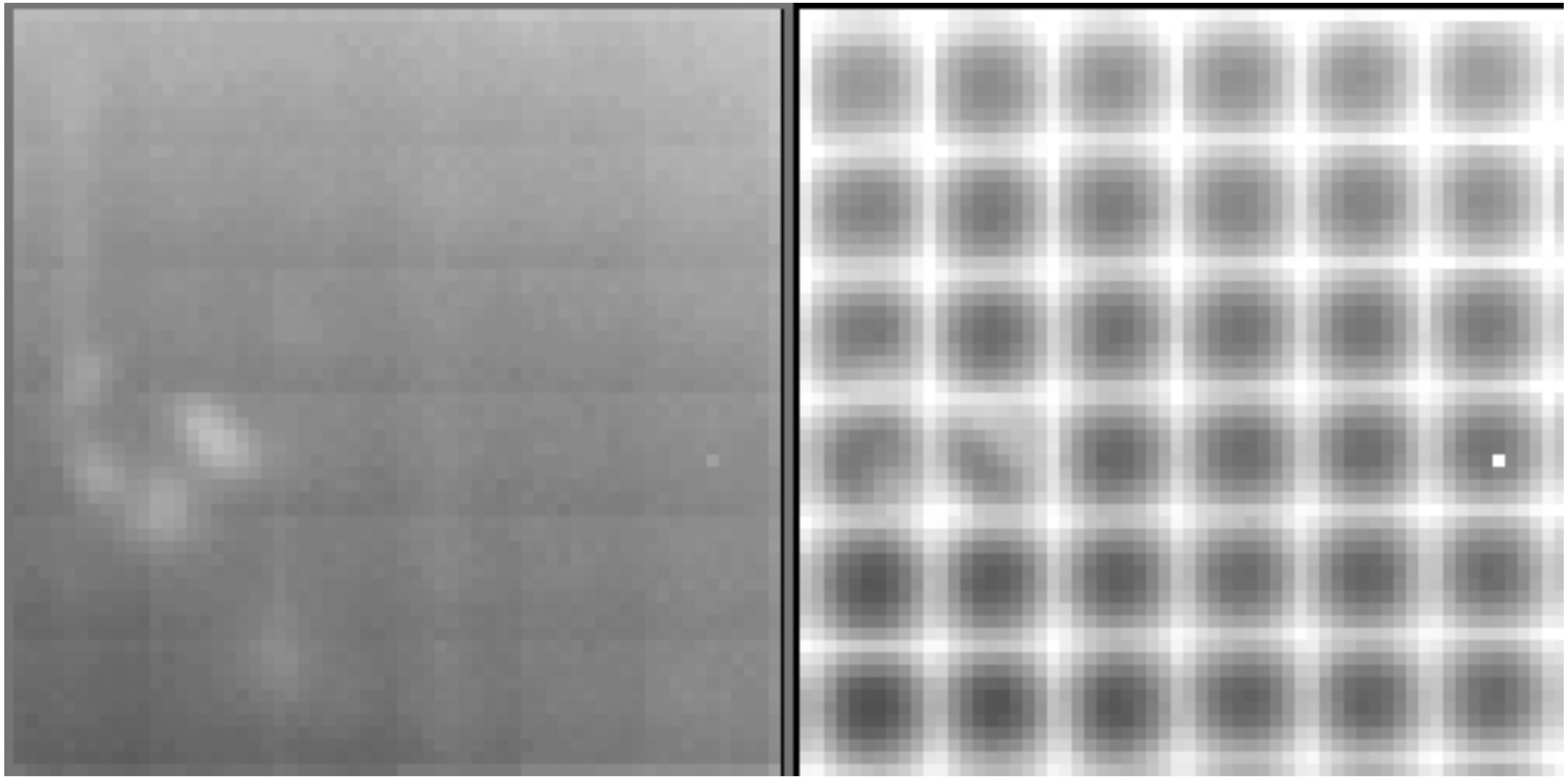
Model of pixel sensitivity for NEA calculation



Map of intra-pixel variations

JWST detector intra-pixel sensitivity

HIA lab results at 2.2microns



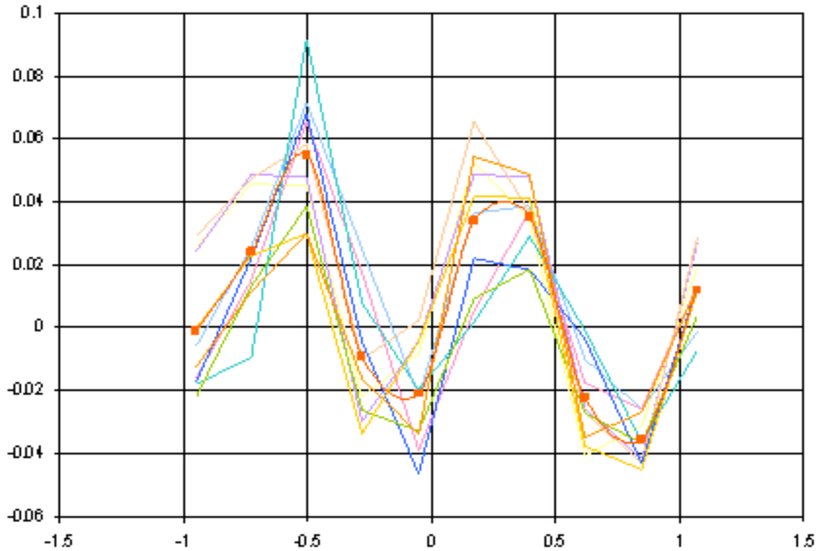
Response corrected for charge spread   Raw response within pixels

Guider: CNL measured from lab data

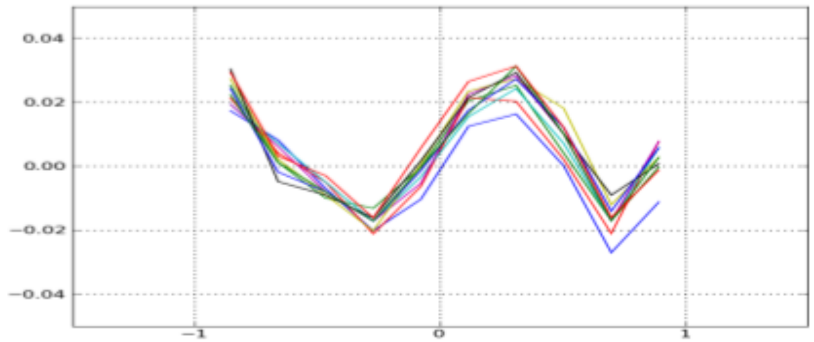
Systematic centroid offsets from pixel-sampled data

X-direction cuts through different places within detector pixel

This will be corrected for in reporting guider centroids



2 mas

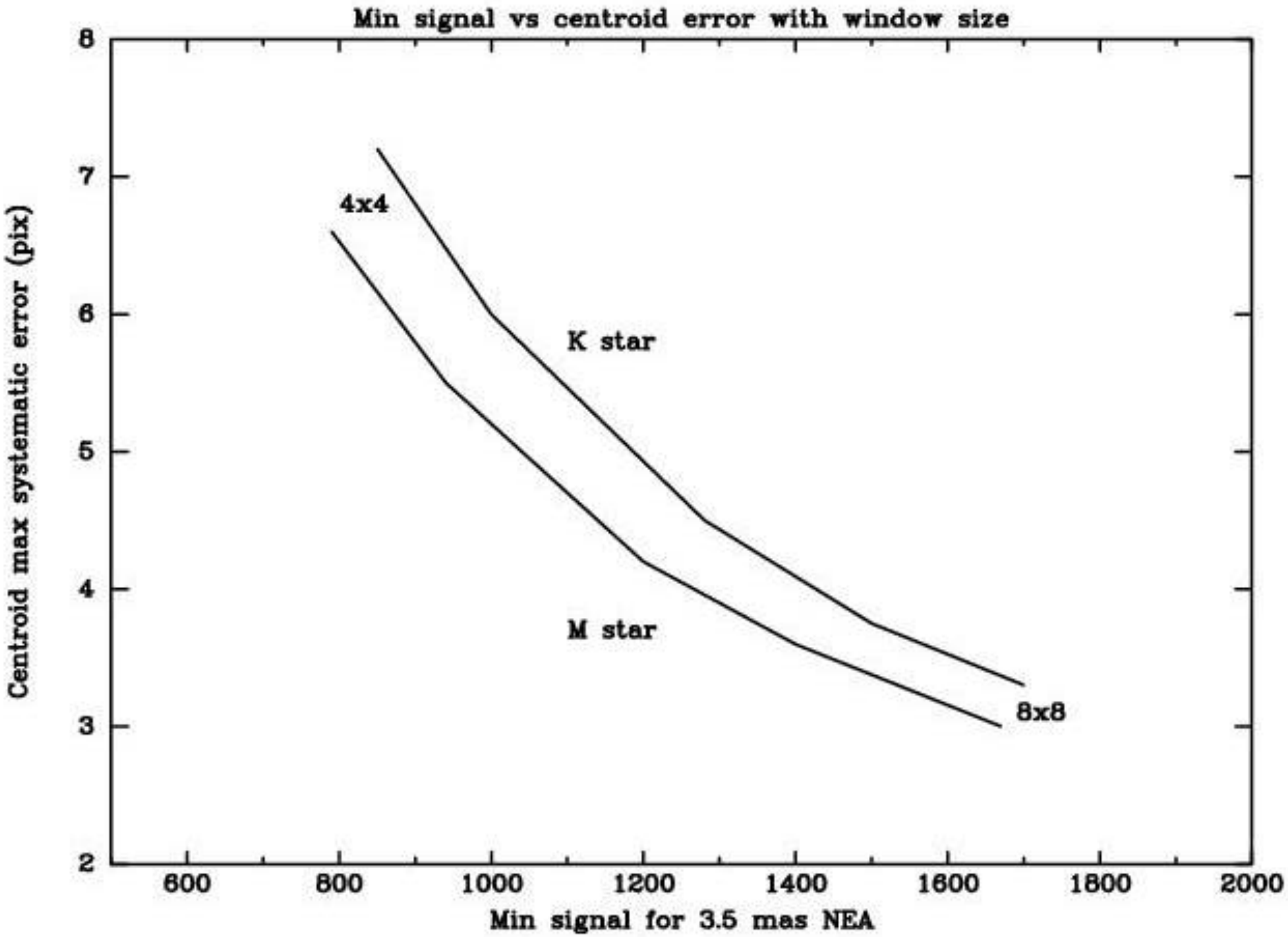


Signal 900e, 1.5 microns

Signal 5000e, 3.2 microns

Verification of modelled performance, plus pixel-to-pixel non-uniformities, ongoing

Centroid offsets moving across pixels



Angular rates of Solar System objects seen by JWST

Object	Min. Rate (mas/sec)	Max Rate (mas/sec)	Distance Traveled in 10 hrs at Min Rate (asec)	Time to Travel 1Õ at Max Rate (hrs)
Mars	2.5	28.6	90.0	0.6
Jupiter	0.070	4.5	2.5	3.7
Jupiter,Io	0.004	10.2	0.14	1.6
Saturn	0.040	2.9	1.4	5.7
Uranus	0.020	1.4	0.7	17
Neptune	0.004	1.0	0.14	24
Pluto *	0.160	1.0	5.7	24
KBO	0.002	0.5	0.07	48

Adopted: linear tracking over FGS FOV at max 30mas/sec

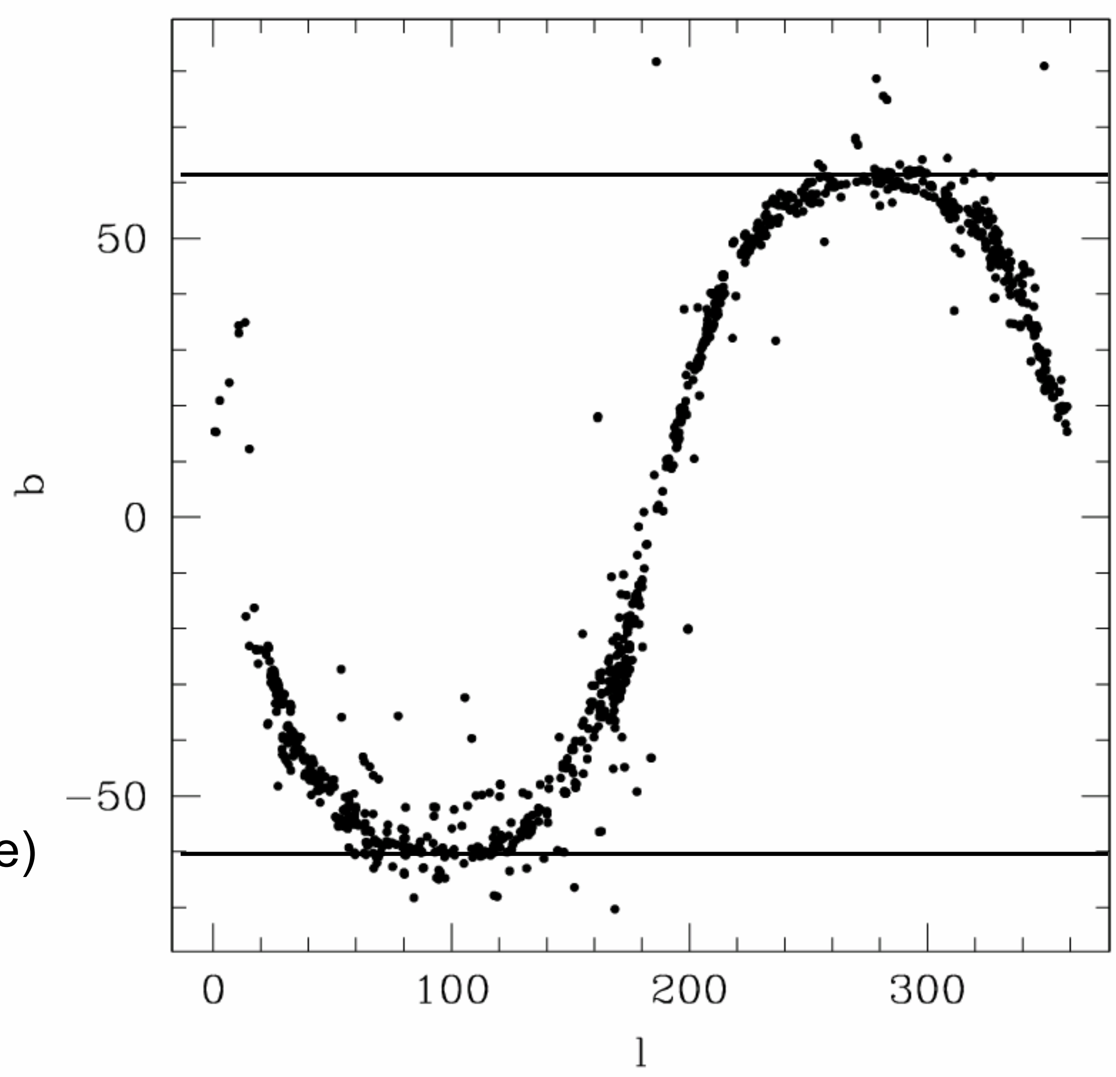
Galactic coordinates of all known KBOs

Compared with galactic poles:
At b=60 star counts up by x1.6
At b=50 star counts up by x2.1

From J=19.4 to 18.0 star counts down by x1.6

For almost all KBOs we have >95% probability of GS giving 6mas in 32x32 guide box.

Extending the observing window by ~hours (FGS field crossing time) will double the GS numbers again



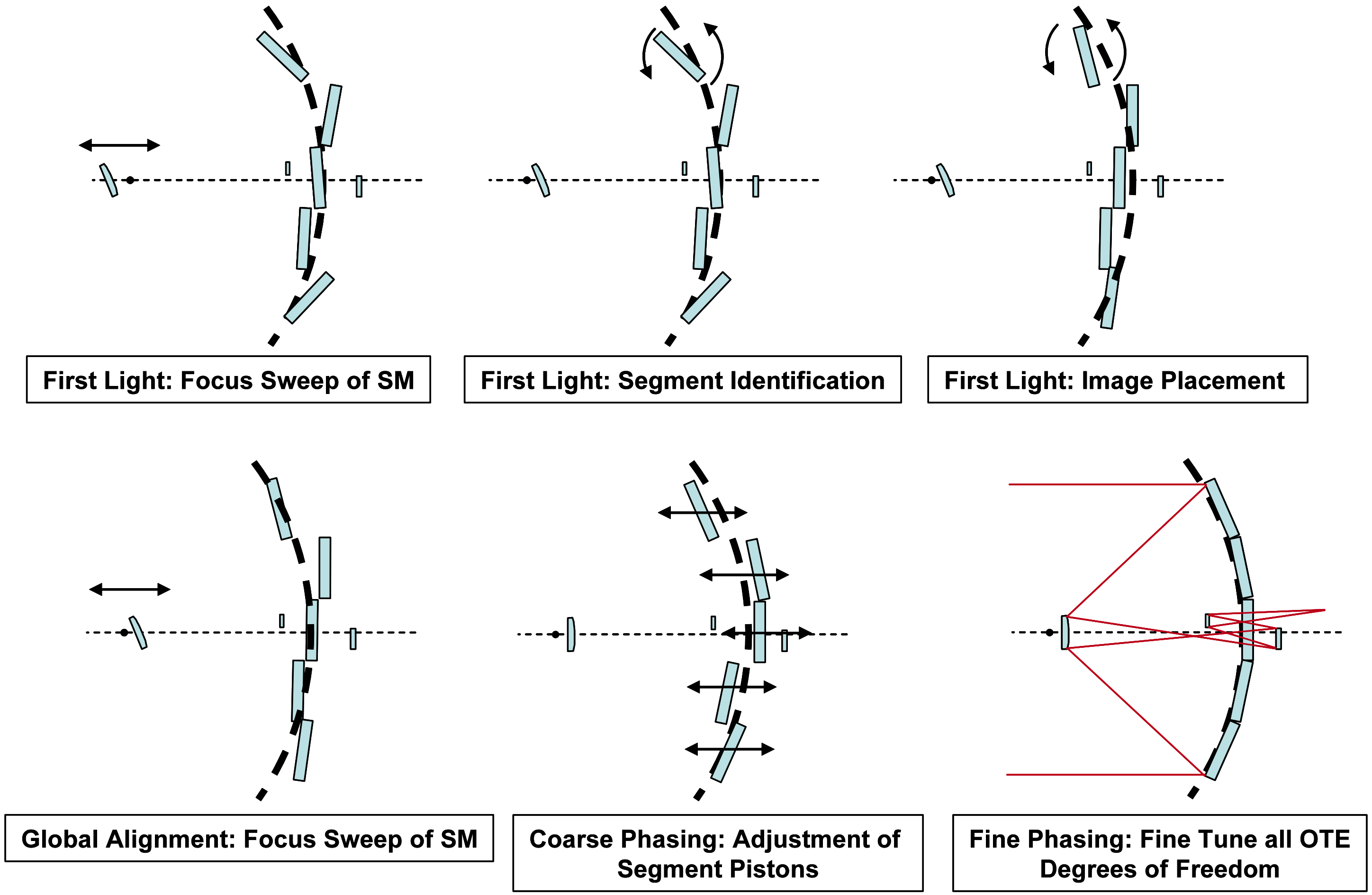
ETU on DFL Vib table Oct 21

ID and acq issues

- Full field is read in strips to create ID map
- Spacecraft is drifting, so strips should overlap to avoid losing stars
- CRs are several times the GS faint limit signal
- Double-reads needed to eliminate CRs
- Pixel-to-pixel variations larger than star signals
- Require CDS reads, and avoidance of first-frame settling
- All this easily breaks original timing budget of 45 secs – up to 83 secs
- Can reduce number of strips (i.e. FOV) and overlap to save time
- Tradeoff between time and success rate

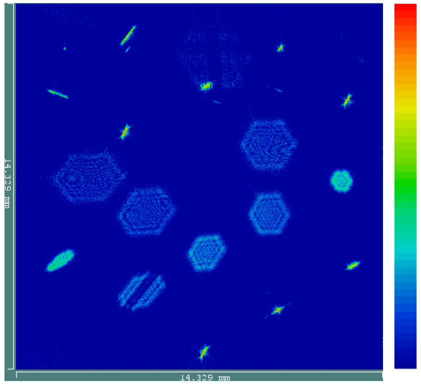
- There are several non-GSC stars and compact galaxies per FOV
- Can guide on close doubles and compact galaxies, unlike HST
- All above affect the ID success rate and/or observing efficiency
- Plan Monte-Carlo runs for ID success stats by FGS team at STScI

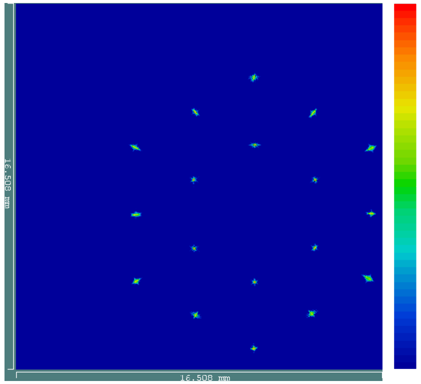
Wavefront Sensing and Control (WFSC)

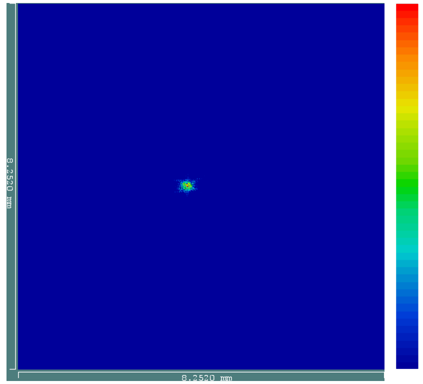


- WFSC must capture and correct the initial post launch state of the OTE,
- It must sense the WFE of the Secondary and PMSA to 10 nm of WFE each
- It must unambiguously correct the Low Spatial Frequency WFEs of the OTE to within 19 nm over the FOV of the OTE

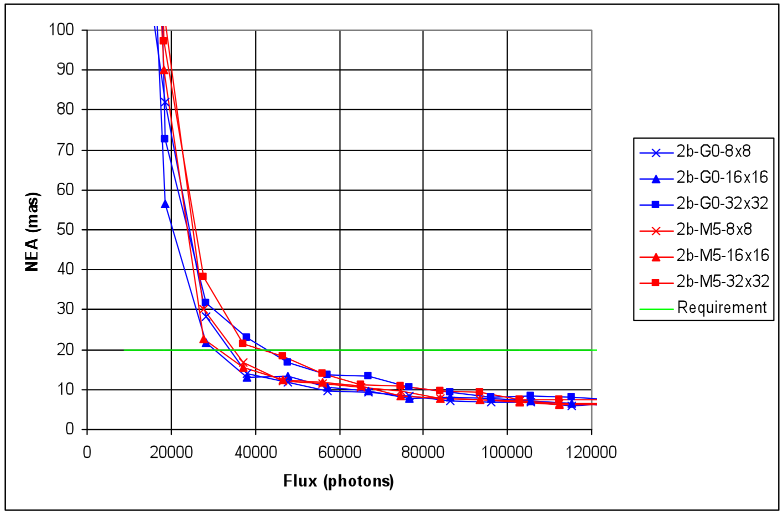
Steps in primary phasing







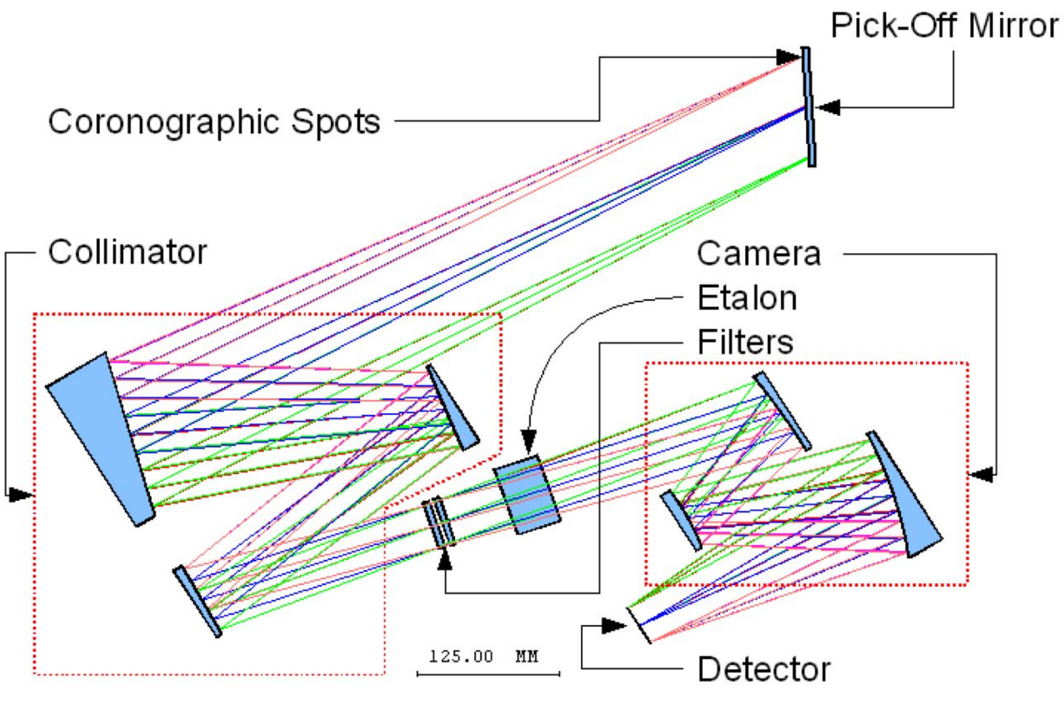
Guiding performance modelled for all cases.



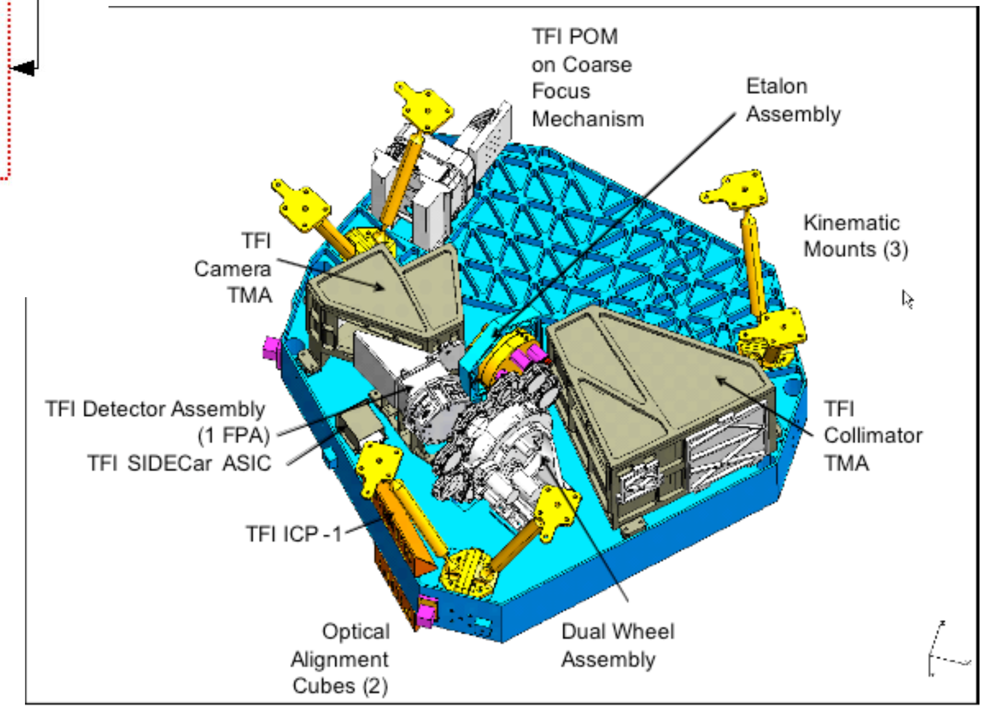
Little difference between G0 and M5 guide star types.

Require isolated star of mag ~14.5

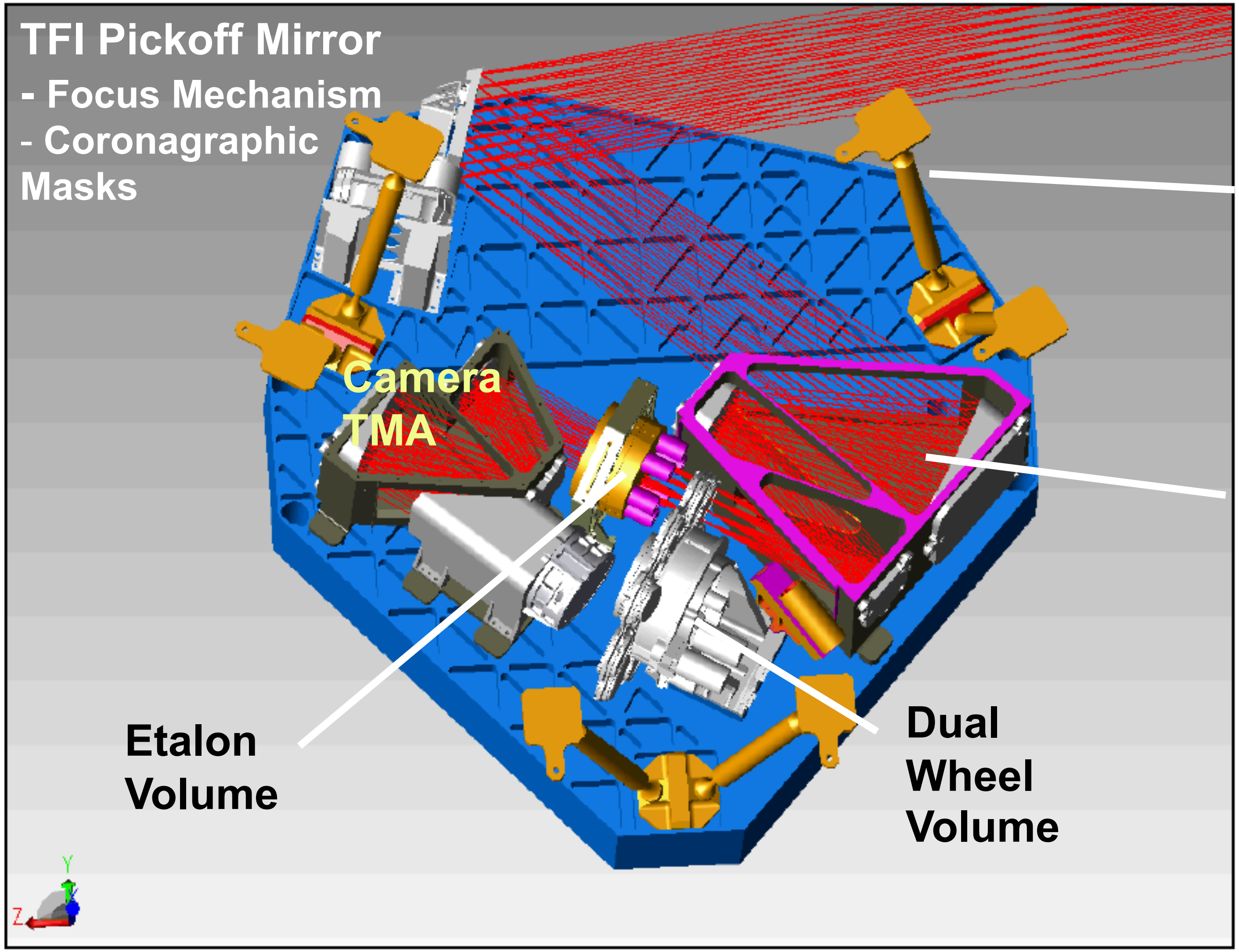
TFI design



- All reflective optics, except etalon & blocking filters
  - 79 nm rms wave front error
- Dual wheel for blocking filters and masks



Optical Subsystem – TFI Layout



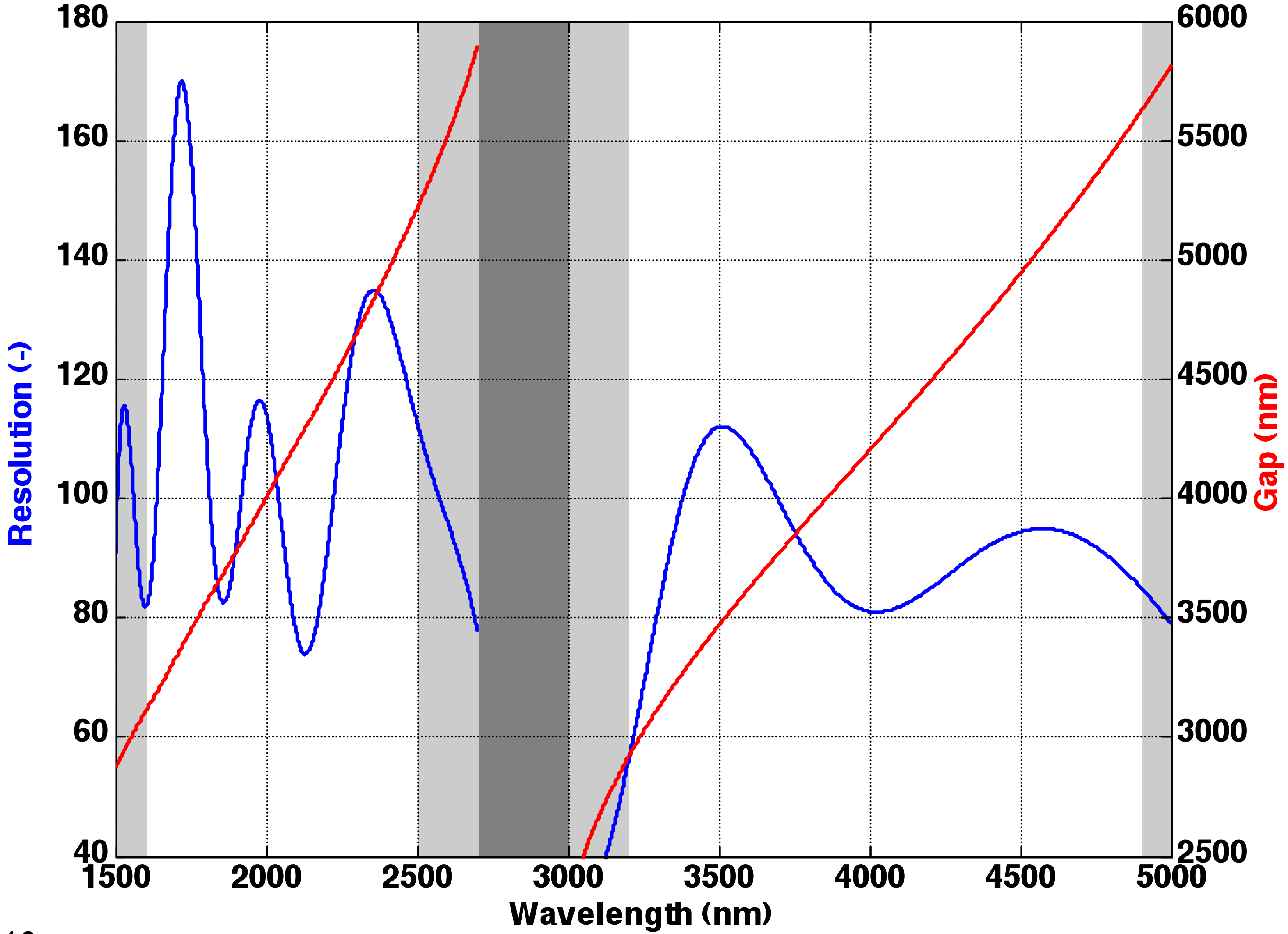
TFI Optical Assembly

TFI at a glance

- FOV: 2.2'x2.2'
  - 65 mas pixel sampling (Nyquist at 4.0 μm)
  - 2048x2048 pixels (Hawaii 2RG)
- Wavelength range: 1.6-2.6 and 3.2-4.9 μm
  - (actually 1.5-2.7 μm and 3.1-5.0 μm)
- Resolving power of ~100 (80-120)
- Sensitivity, 10σ 10x1000 s
- Operating modes
  - Normal imaging
  - Lyot coronagraphy
    - 4 occulting spots, 3 lyot masks
  - Non-Redundant Masking interferometry (NRM)

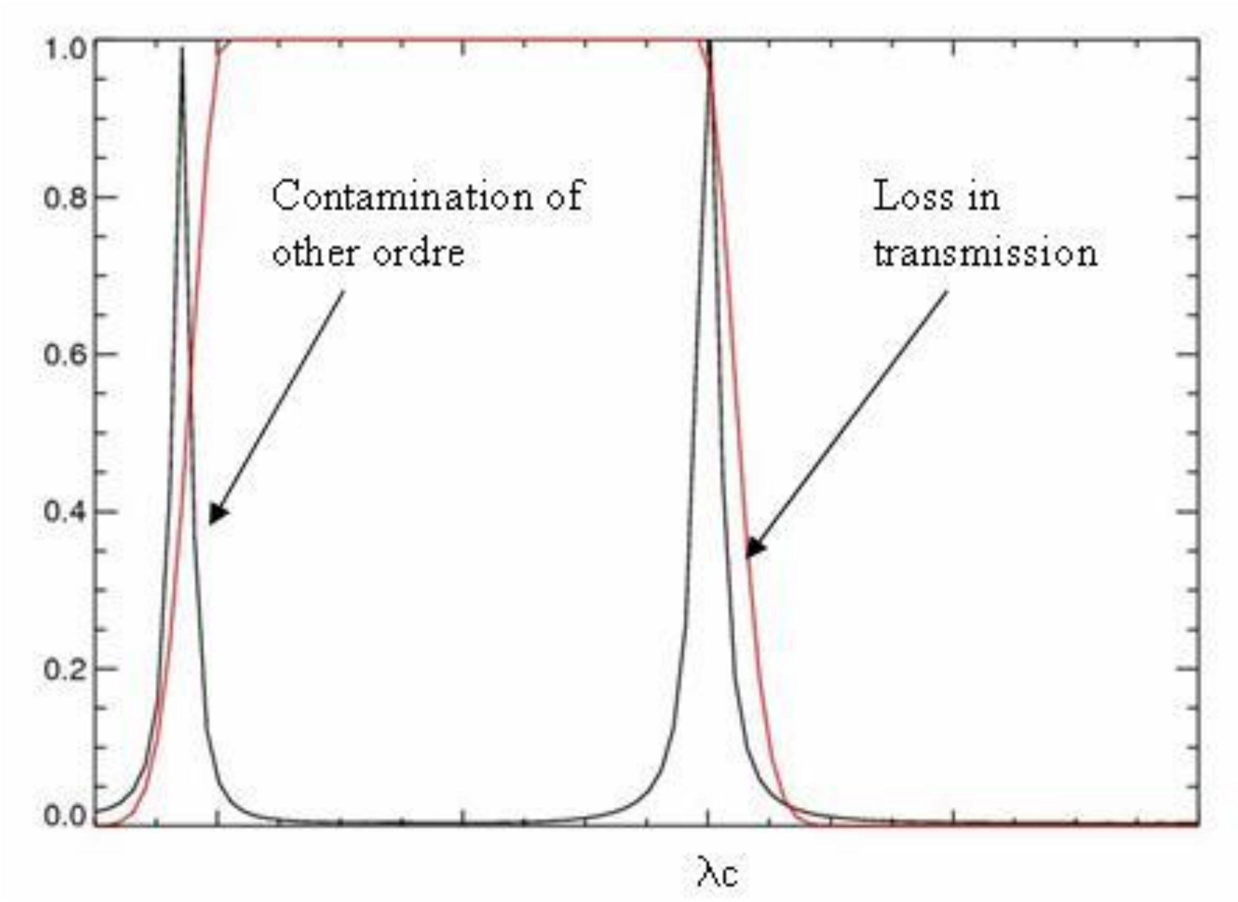
Wavelength μm	**Sensitivity nJy**	**Sensitivity mag**
1.5	149	24.8
2.0	139	24.3
2.5	119	24.1
3.5	110	23.5
4.0	136	23.1
4.5	142	22.8

Spectral Resolution



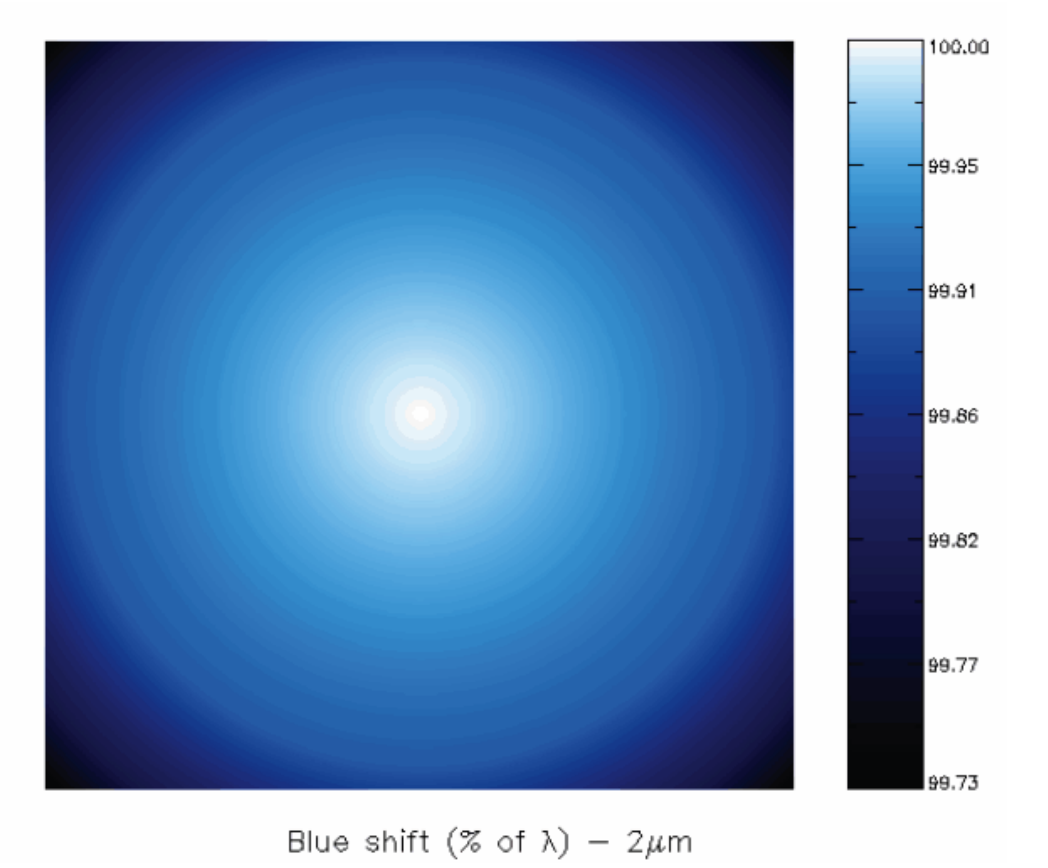
Filter is defined (λ_c, $\Delta\lambda$) so that …

- Transmission is maximized over the working interval
- Contamination from other orders is minimized

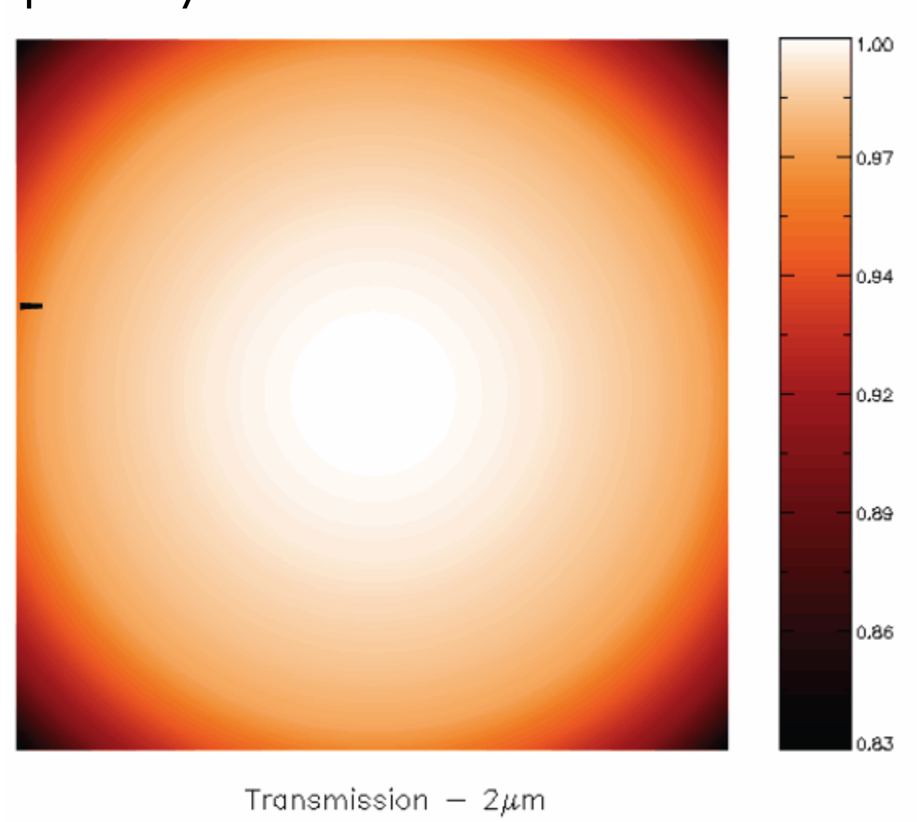


Spectral/spatial uniformity

~0.1% wavelength shift at edge of field

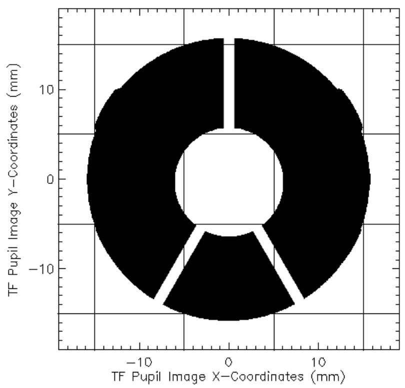


~4% drop in flux at edge of field for perfectly monochromatic source



Coronagraphy (Lyot coronagraph)

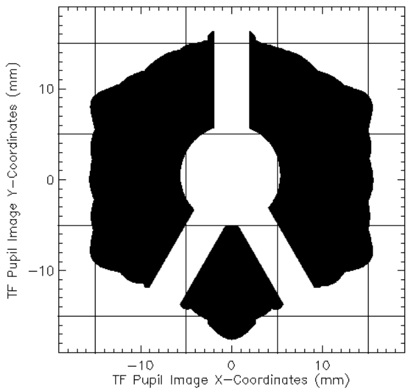
- 4 occulting spots engraved on pick-off mirror
  - Diameters of 0.58”, 0.75”, 1.5” and 2.0”
- 3 lyot masks
  - Transmissions of 71%, 66% and 21%
  - Robust against pupil shear of up to 4%



C71

0.58” and 0.75”

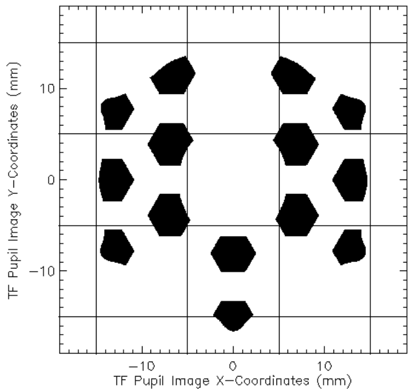
<1”



C66

1.5”

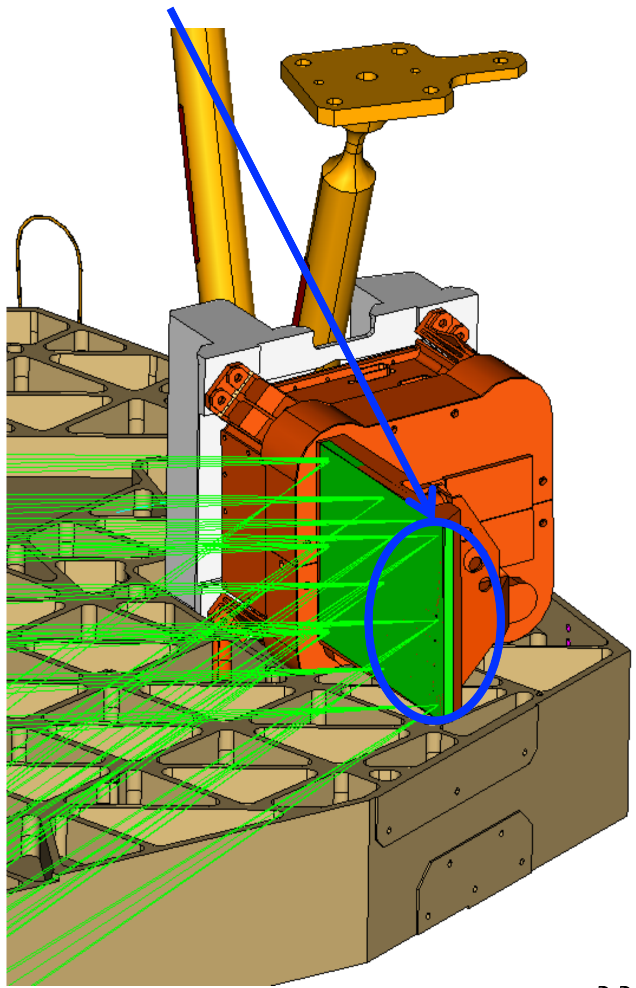
1”-2”



C21

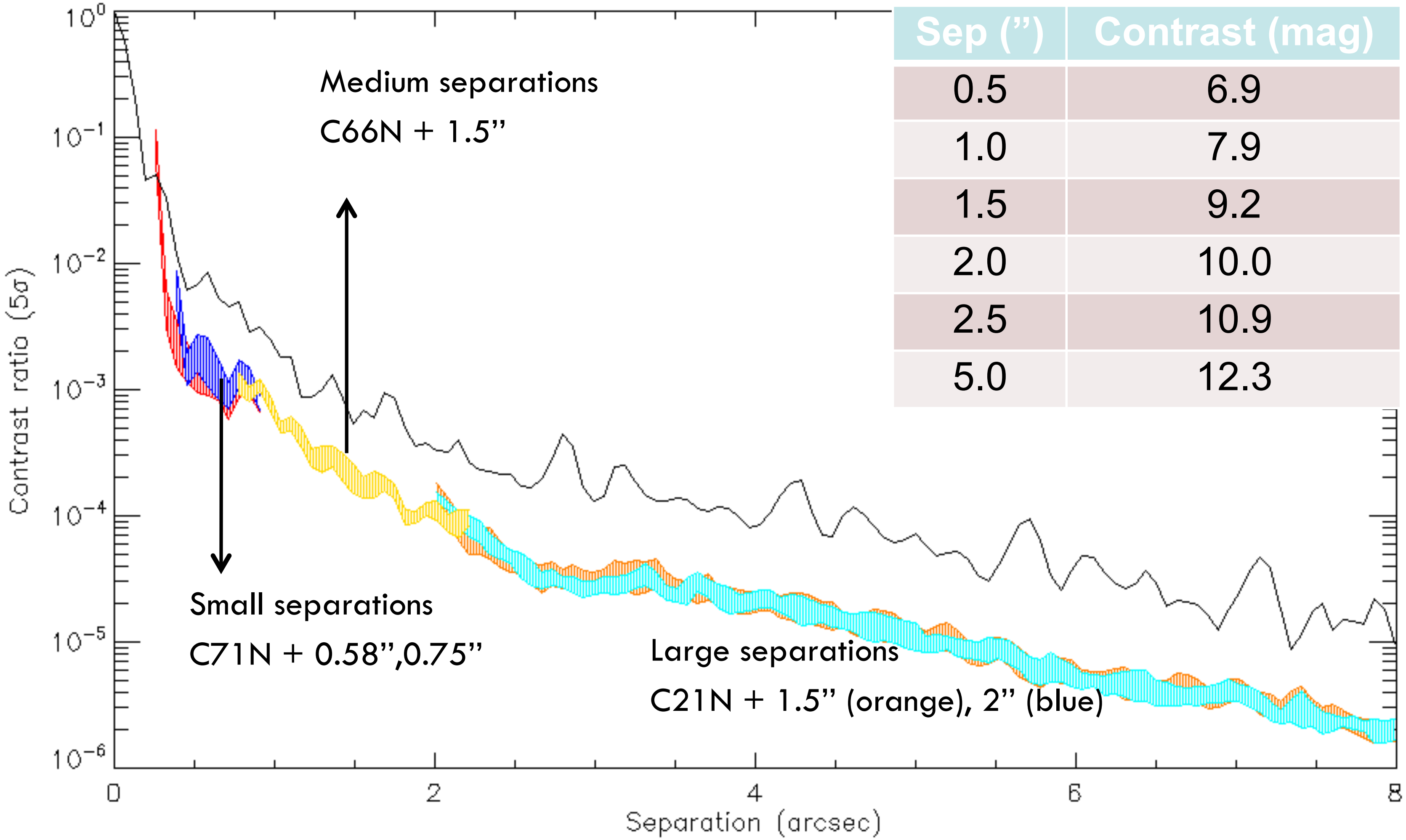
1.5” and 2.0”

>2”



Coronagraphy constrast limits (3% pupil shear)

These contrasts can be improved further with PSF subtraction

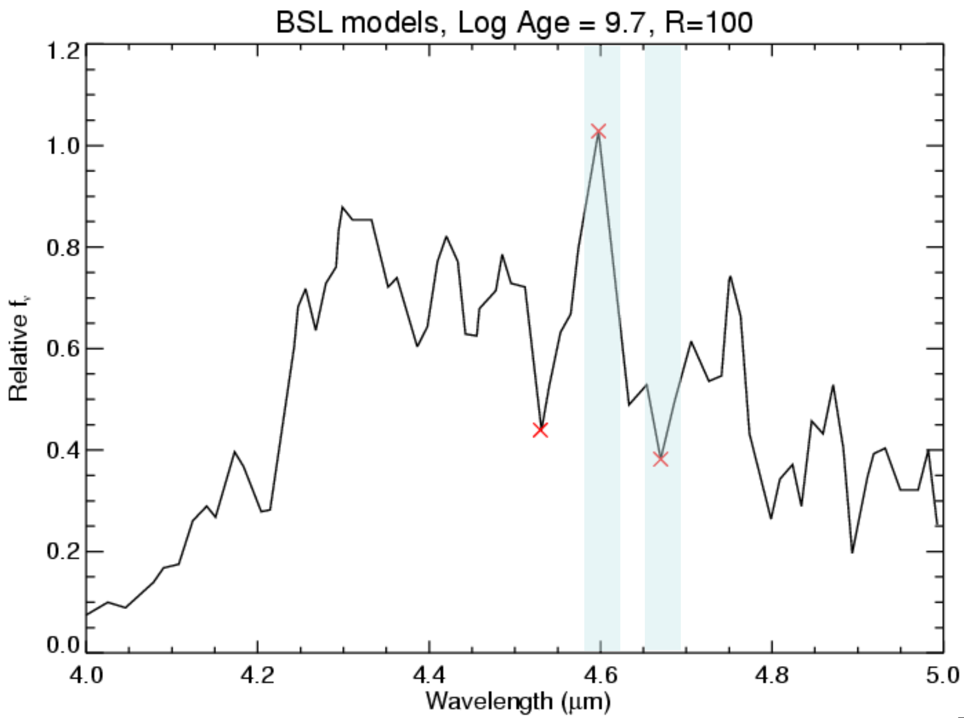


Sep (”)	Contrast (mag)
0.5	6.9
1.0	7.9
1.5	9.2
2.0	10.0
2.5	10.9
5.0	12.3

Differential imaging with TFI

- Reference star PSF subtraction
  - Narrow-band relieves requirement of similar spectral shape within band (speckles are chromatic)
  - May perform better than for other instruments

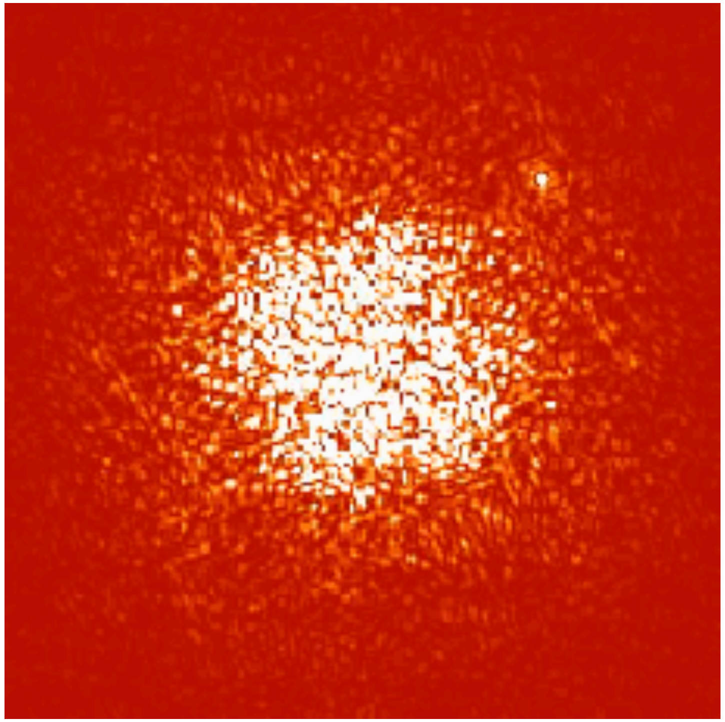
- SDI (Spectral Differential Imaging)
  - Unique to TFI
  - Can be used in addition to reference star PSF subtraction
  - Simpler than roll subtraction (which other instruments may require)
  - There are several spectral features suitable for SDI in exoplanet spectra



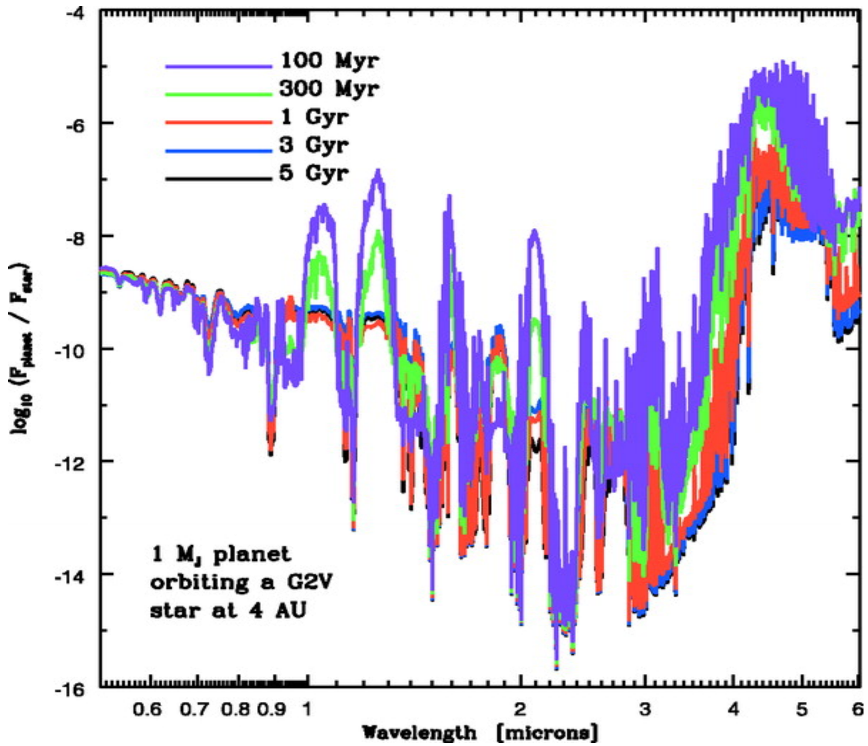
Case for 4-5 µm λ coverage: Exoplanet SEDs

- Identification and statistics of extrasolar planets: direct observation
- Scan through wavelengths of maximum planet/star contrast
- **The combination of coronagraphy and TFI wavelength scanning is ten times more sensitive than other JWST fixed filter observations.**

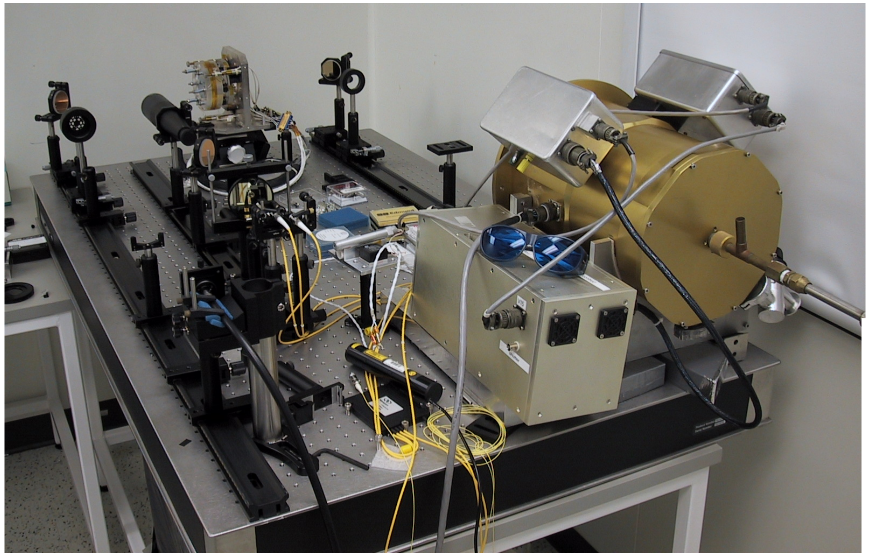
TFI planet detection simulation: Monochromatic PSF movie: 4 to 5 µm



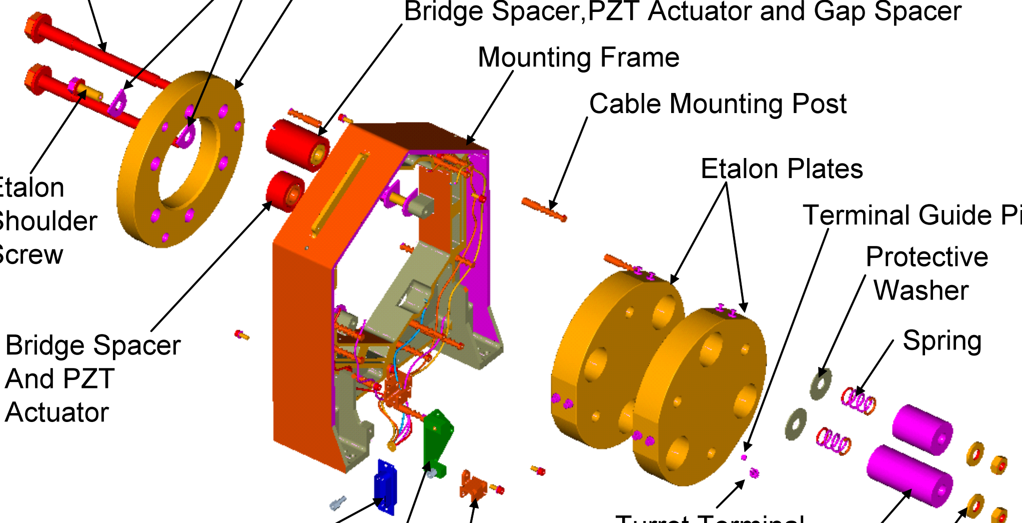
Planets are bright at 4-5 µm

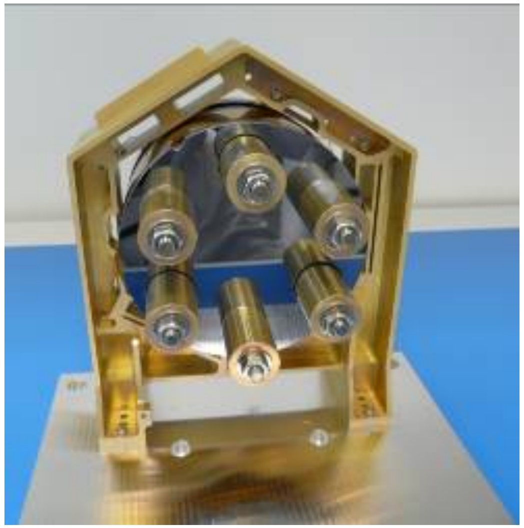


Etalon: design, lab and flight models



U de Montreal lab model

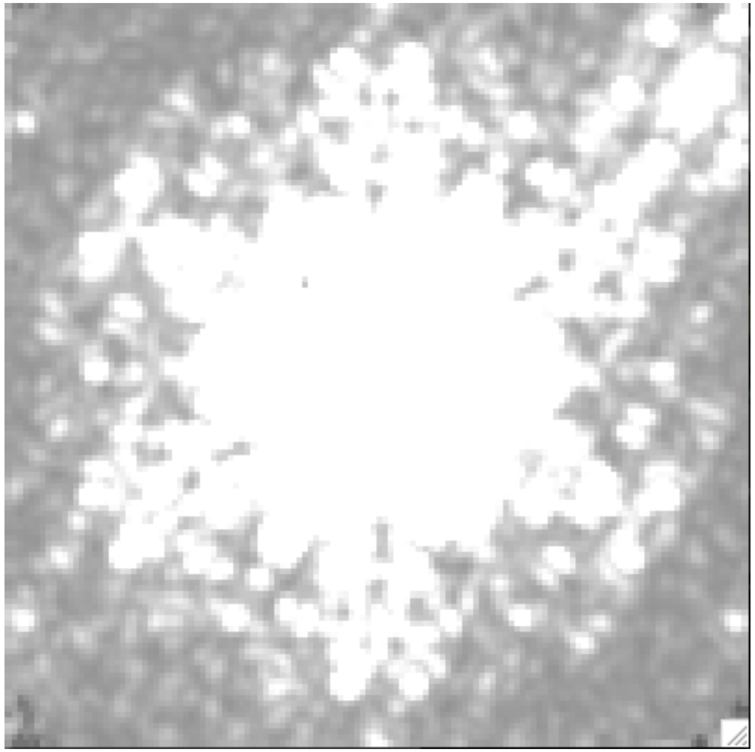


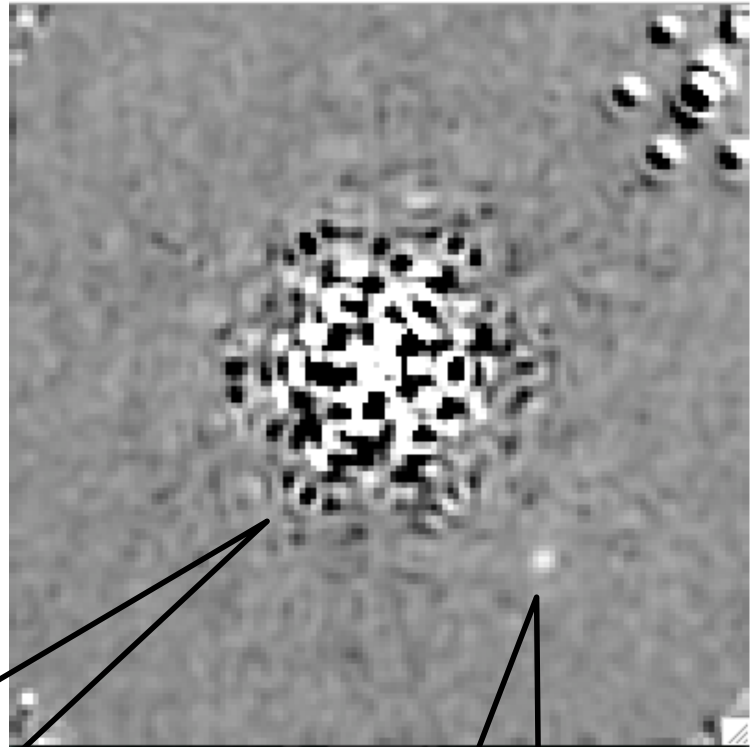


Flight design test

Find Charlie! (fake companion added)

U de Montreal lab results

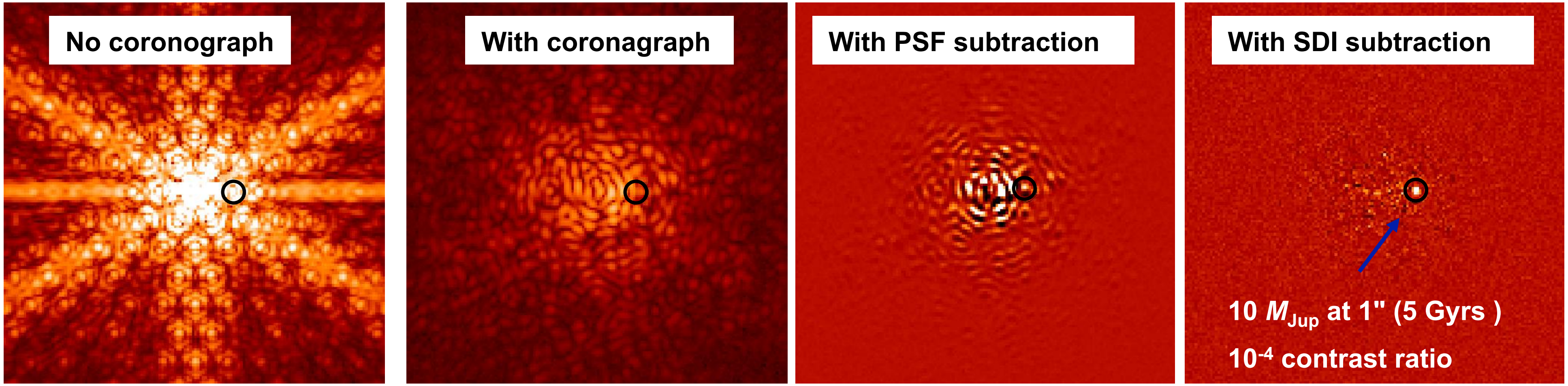




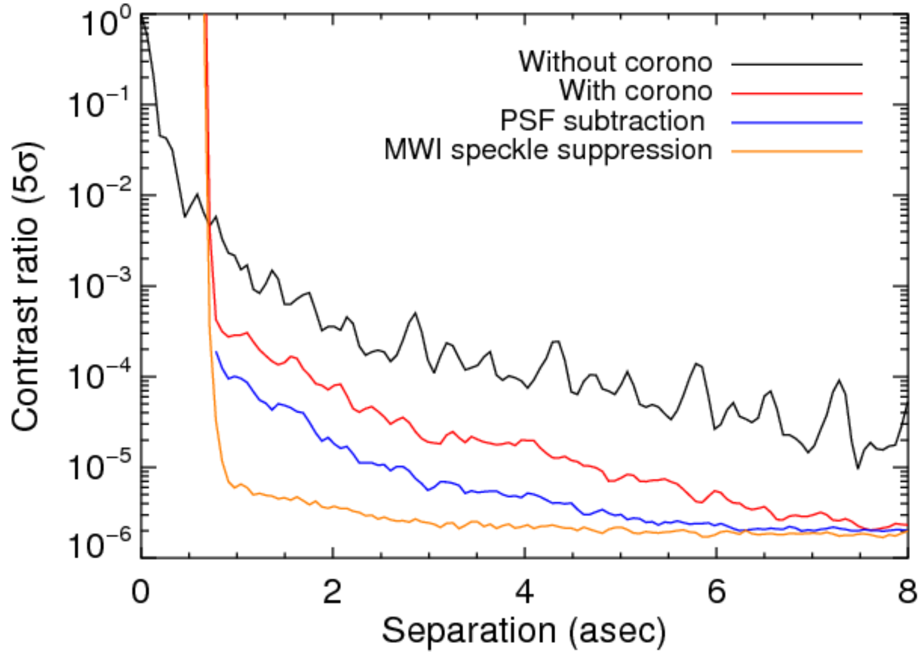
Subtraction from two adjacent wavelengths

Companion 10000 fainter

Summary: TFI can achieve excellent contrast



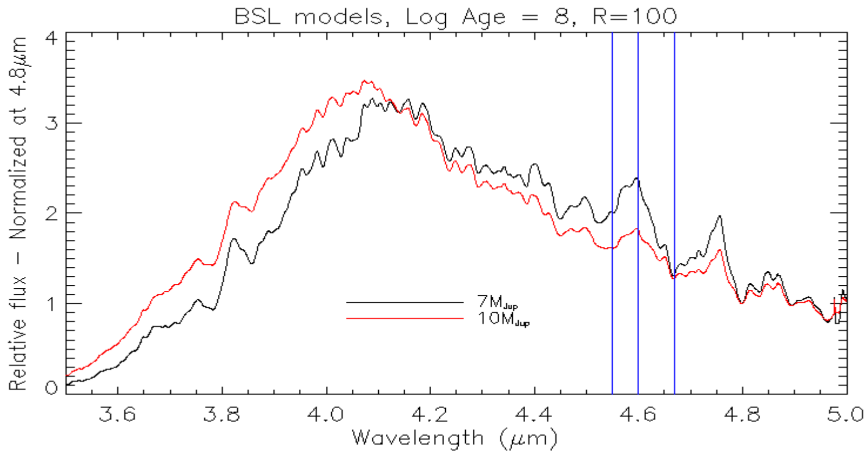
- Contrast of ~10^{-5} possible at >1"

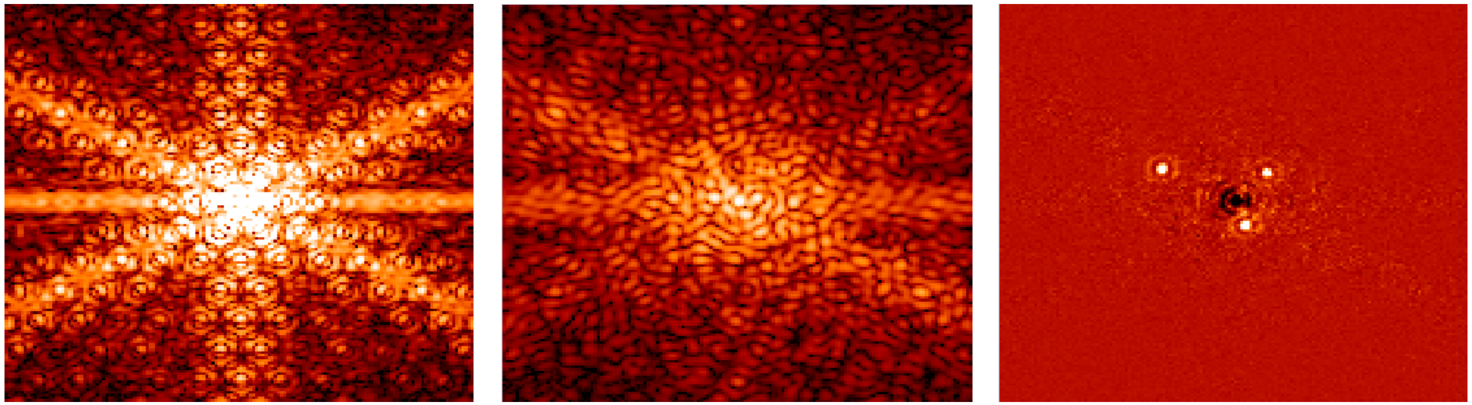


Simulation: M. Beaulieu

HR 8799 seen with TFI

- Example shown with SDI
  - 3 λ
- Could use reference star PSF subtraction instead





Without coronagraph

With coronagraph

With SDI

Simulation:
M. Beaulieu

Non-Redundant Masking interferometry

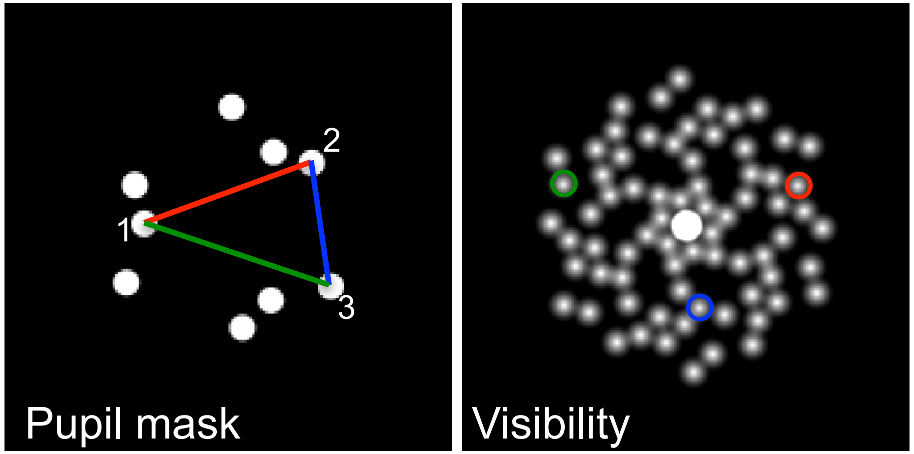
Mask containing multiple small apertures at a pupil plane

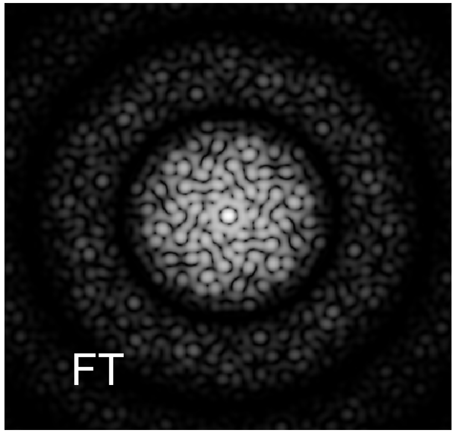
No line joining any two sub-aperture has the same length and PA as another one

From FT of interferogram, amplitude & phase of interference fringe coming from each pair can be measured

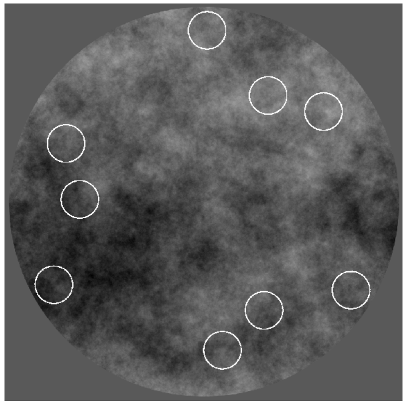
Fit a model to measured phases and amplitudes

- **Better resolution** Two sources can be resolved for a separation of 0.5 λ/D
- **Better contrast at small separations** Wave front phase errors have little effect on closure phase





Phase error



Measured = true + phase error+ meas. error

$$\phi(2-1) = \phi_0(2-1) + \psi_2 - \psi_1 + \varepsilon_{12}$$

$$\phi(1-3) = \phi_0(1-3) + \psi_1 - \psi_3 + \varepsilon_{13}$$

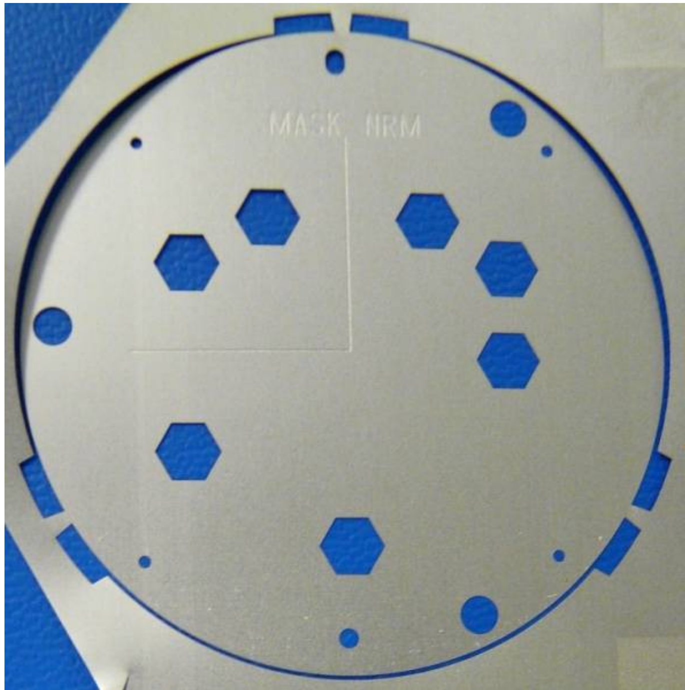
$$\phi(3-2) = \phi_0(3-2) + \psi_3 - \psi_2 + \varepsilon_{32}$$

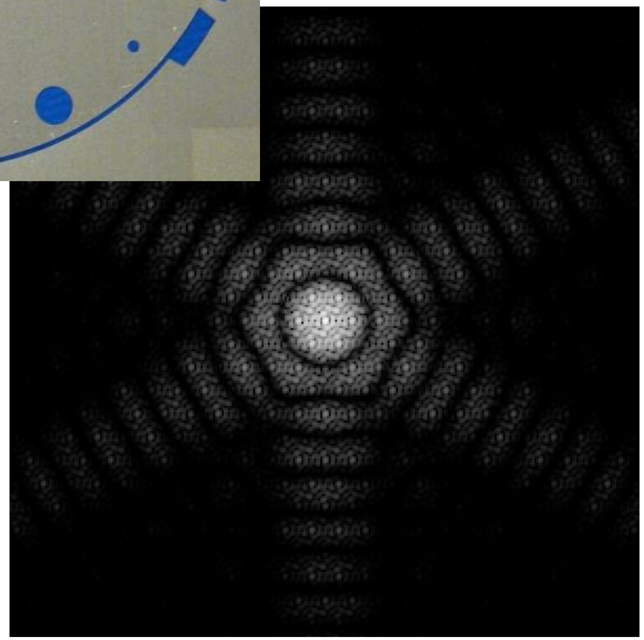
Sum these (closure phase) and phase errors cancel out

TFI Non-Redundant Mask

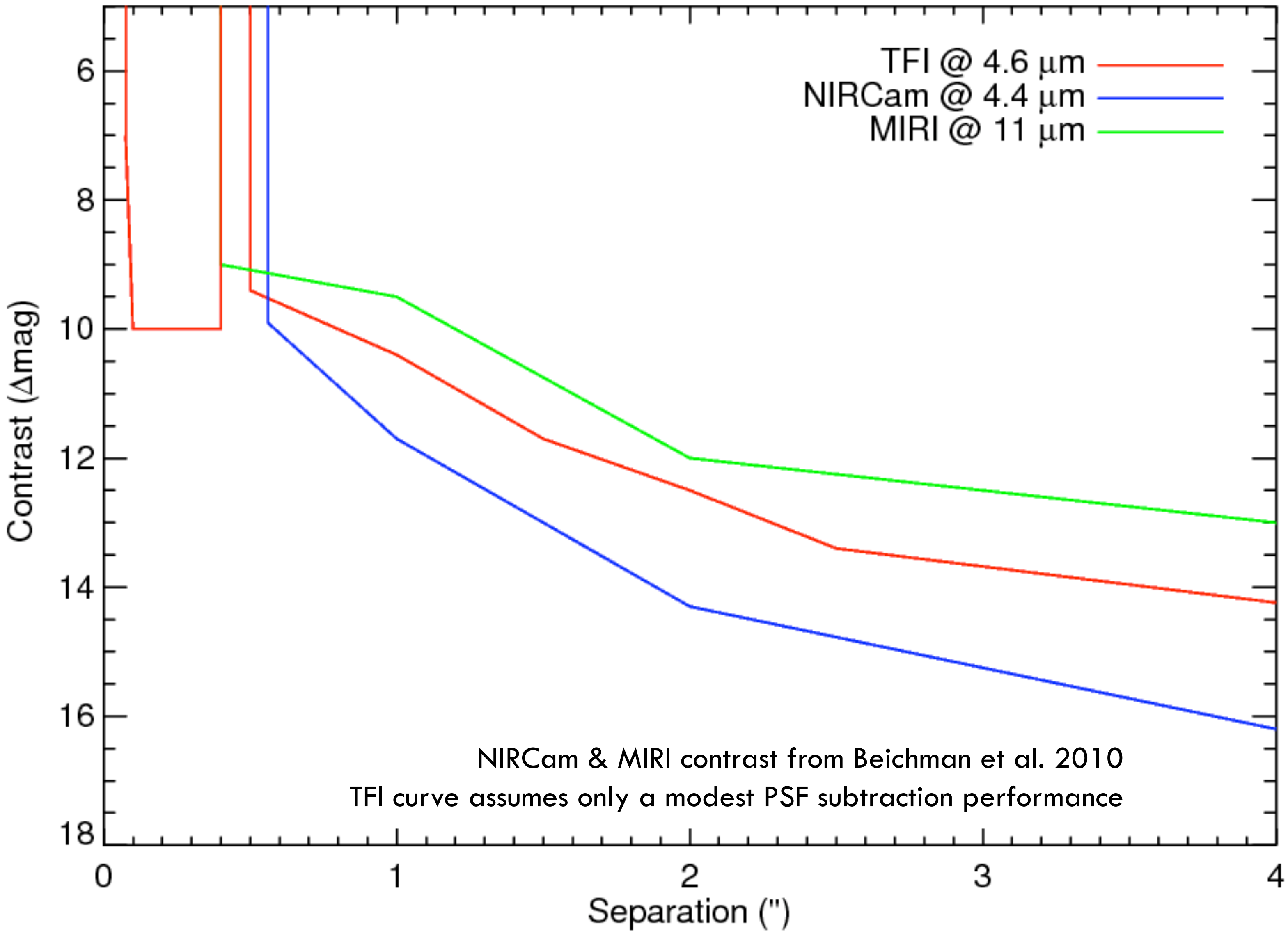
- 7 apertures
  - 5.28 m longest baseline
  - 1.32 m shortest baseline
- Throughput
  - 15%

- Resolution ($\lambda/2B_L$)
  - **≈75 mas at 4.6 μm**
- Nominal FOV ($\lambda/2B_S$)
  - **≈0.4” at 4.6 μm**
- Contrast sensitivity
  - **≈10 mag**



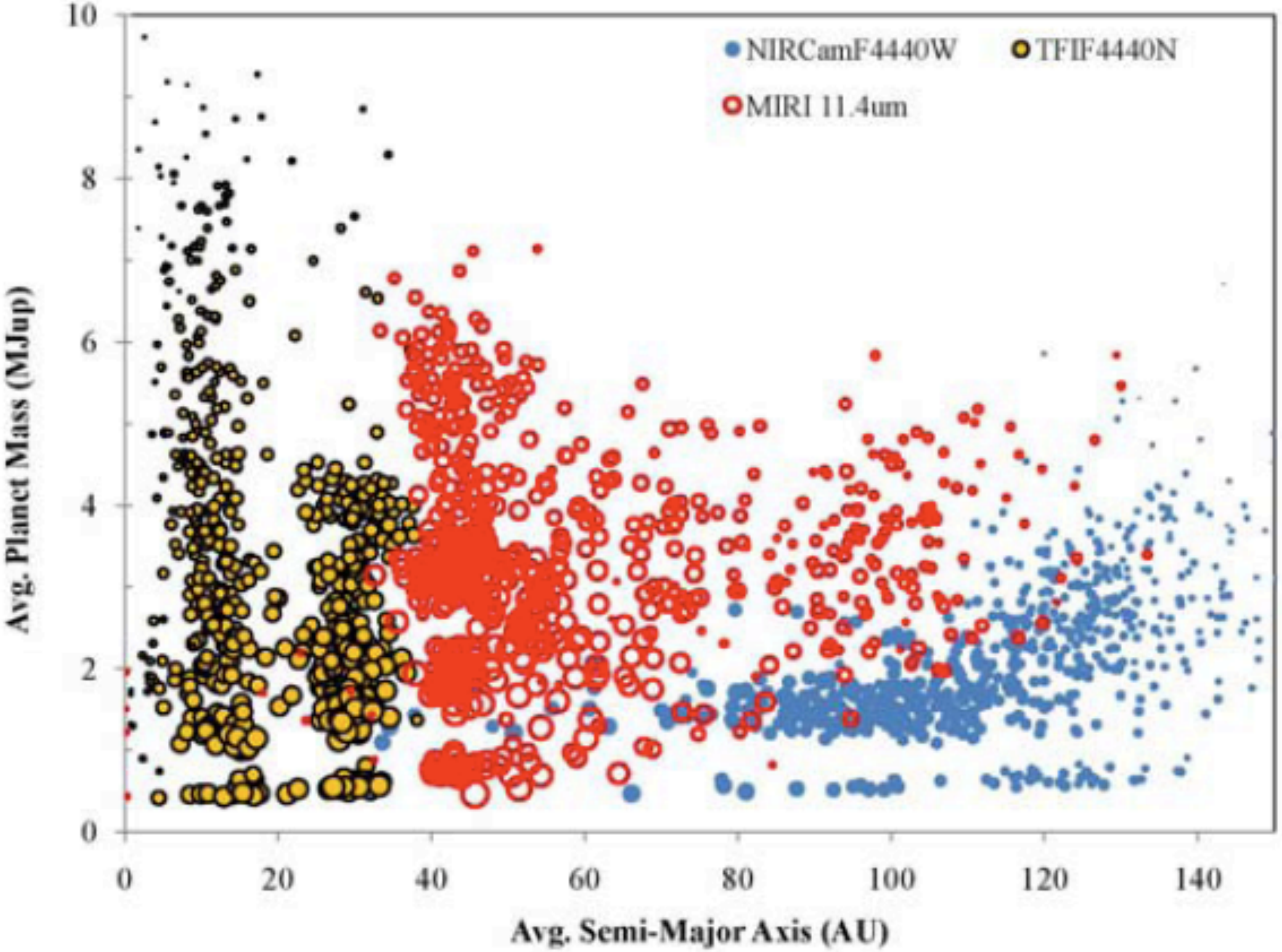


TFI/NRM defines unique capability



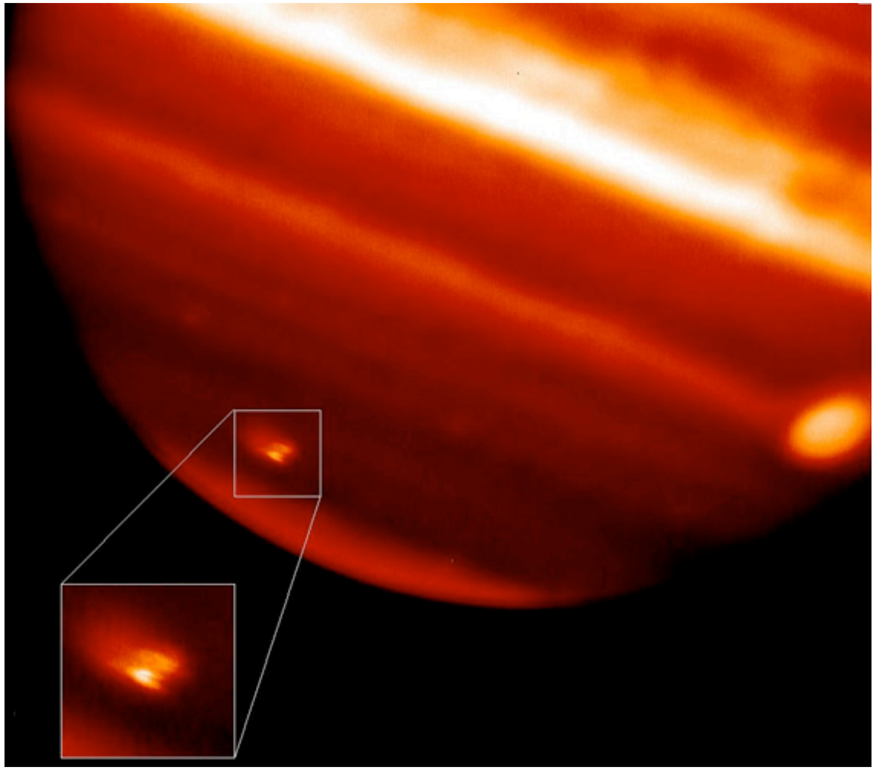
TFI/NRM will be a powerful tool for finding young planets within 30 AU

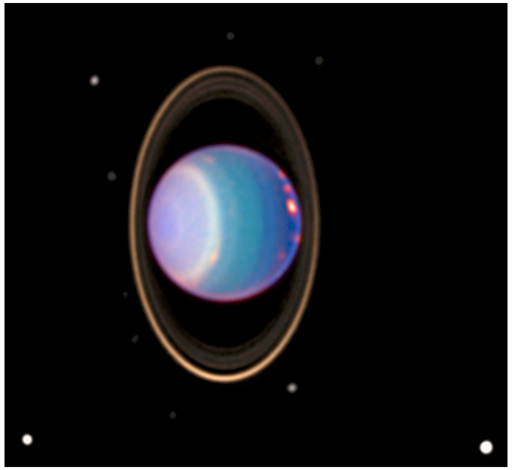
Beichman et al. (submitted)



A note on solar system planets

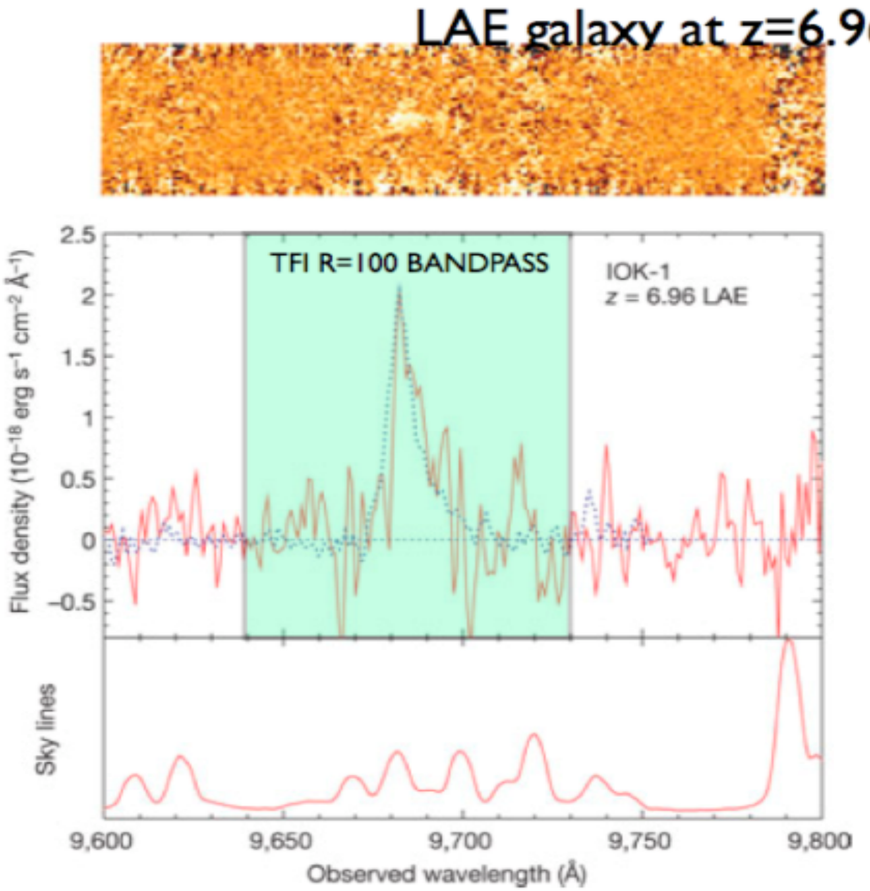
- TFI could be the only instrument on JWST for (spectral) imaging without saturation – rapid subwindow read and narrow bandpass



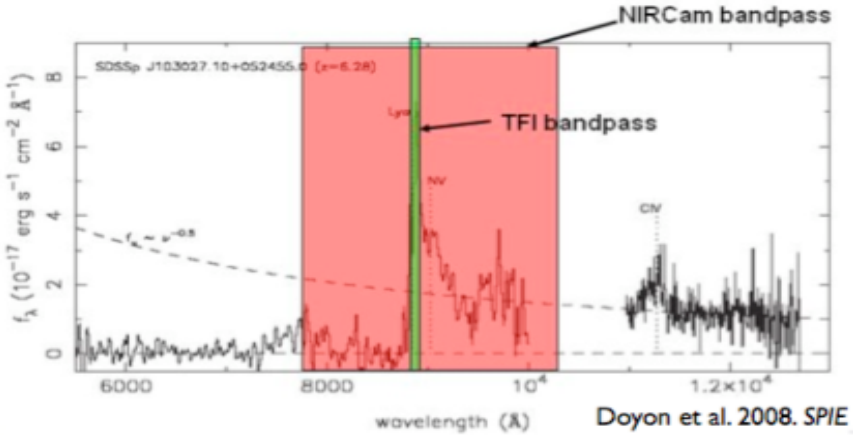


High-Redshift Science with TFI

- TFI wins by detecting line emission in faint objects.
- Lyman Alpha Emisison can be up to 20x as bright than the continuum for a Lyman Alpha Emitting (LAE) galaxy.
- Lα is redshifted into the TFI λ range for z~10-30, covering the era from the dark ages to *first light* where the universe becomes reionized



Iye et al. (2006). *Nature* **443**. 186

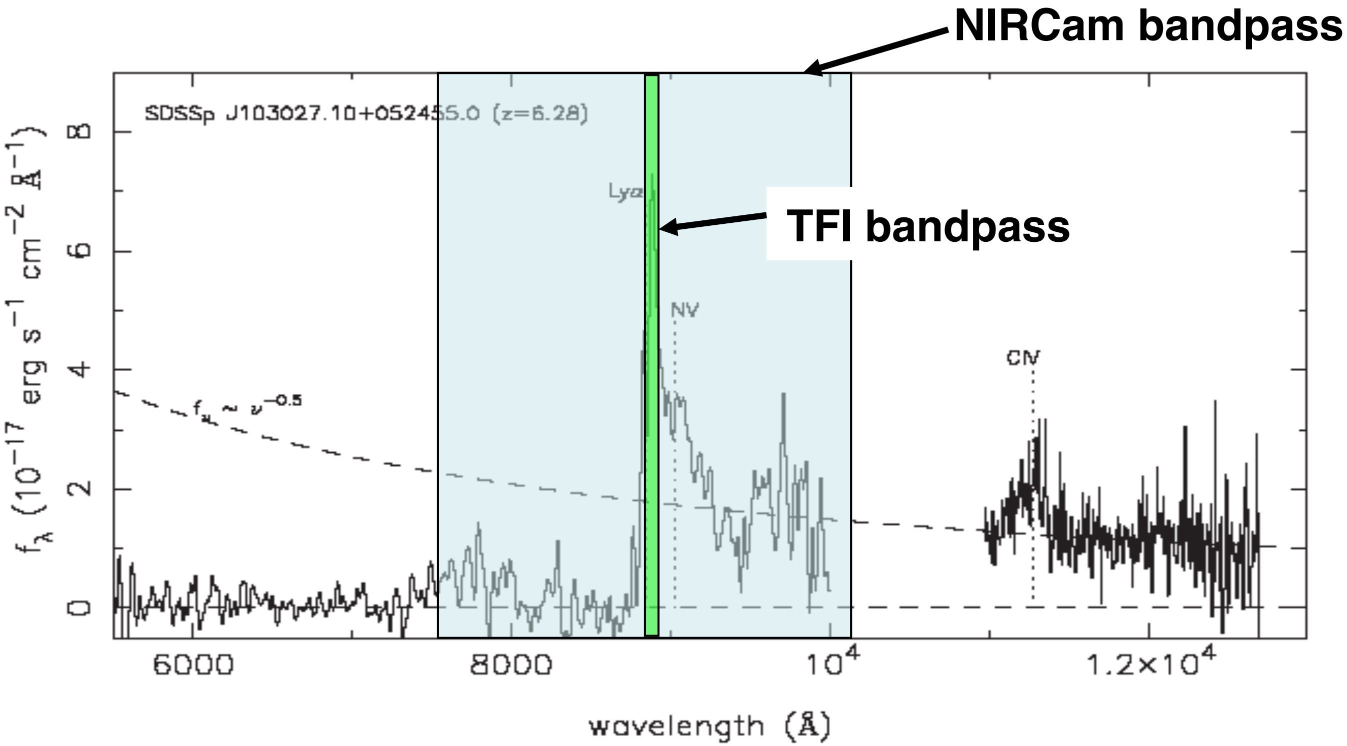


Doyon et al. 2008. *SPIE* **7010**. 70100X

- Its relatively small bandpass yields higher S/N than NIRCam broadband filters, reaching fainter flux sensitivity for line emission

TFI unique science example

Efficient detection of
first-light
Lyman alpha emitters

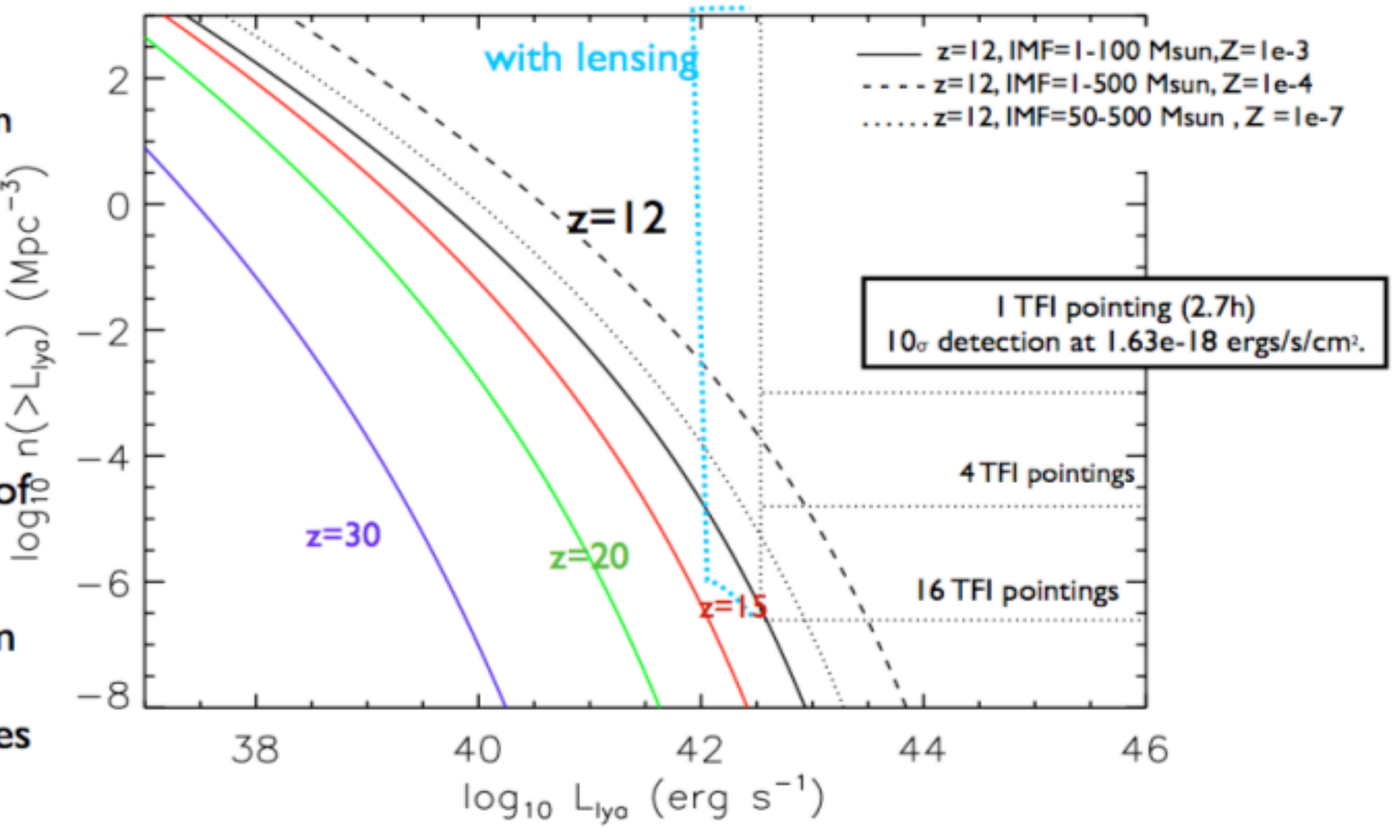


High-Redshift Science with TFI

- Predictions of Lyman Alpha emitting galaxies at z=12,15,30 are highly speculative
- Can make a guess by using the parameters (IMF, metallicity, photon escape fraction) defined by population of LAEs at z=6.5 Kashikawa et al (2006)
- However, **THIS IS EXPLORATORY SCIENCE**, TFI is the *best* and if the sources of *First Light* are very faint, it may be the *only* option

- A single 2.7 hour pointing is sufficient to detect an LAE in the more optimistic, but plausible scenarios. Multiple pointings probe more volume and lead to higher possible detections.

- Can 'tune' TFI to redshifts of suspected galaxy overdensities soon to be predicted from high-z 21cm mapping of neutral hydrogen, increasing chances even more.



TFI can map the ionisation bubble evolution

MAPPING NEUTRAL HYDROGEN DURING REIONIZATION WITH THE Lyα EMISSION FROM QUASAR IONIZATION FRONTS

SEBASTIANO CANTALUPO, CRISTIANO PORCIANI, AND SIMON J. LILLY

Ly alpha emission

from bubble boundaries

Scanning through

wavelengths (redshift)

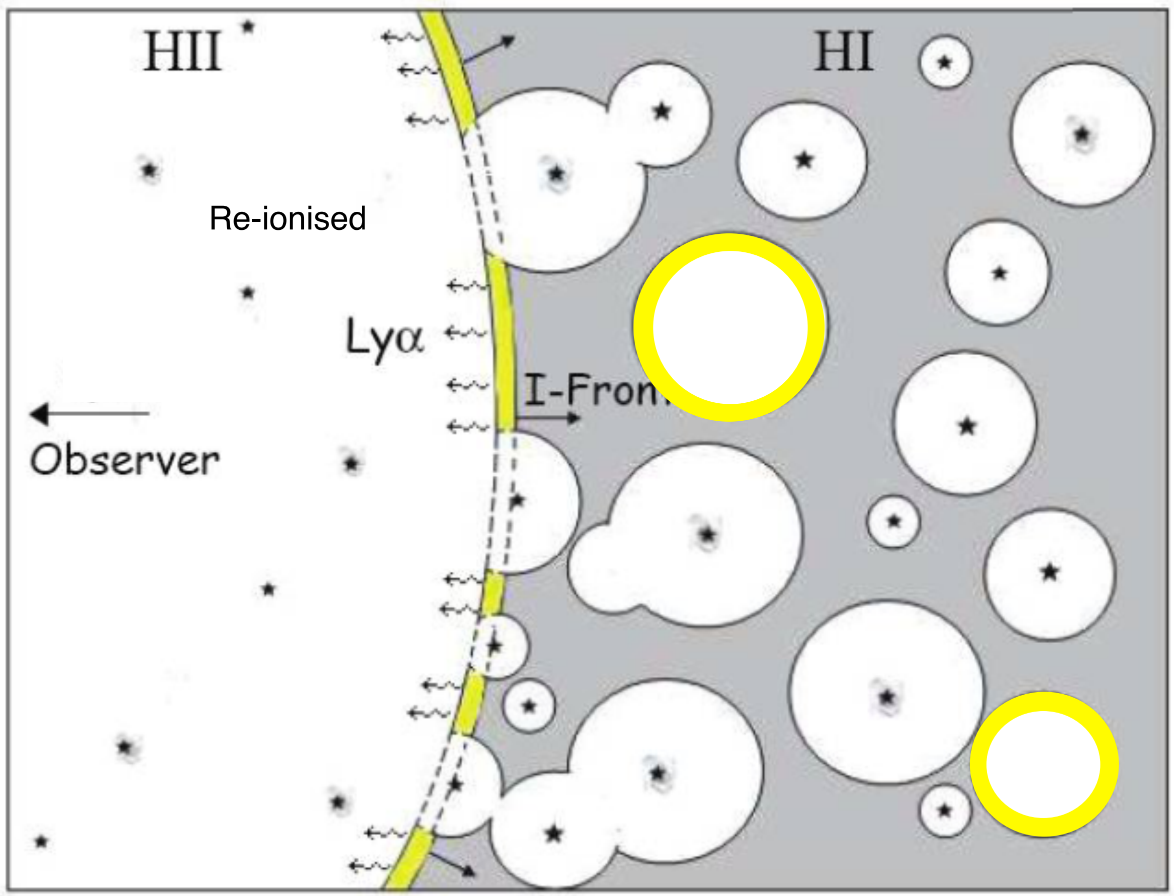
maps bubble

sizes and density

through reionisation

Epoch

Sizes should match TFI field at z>10



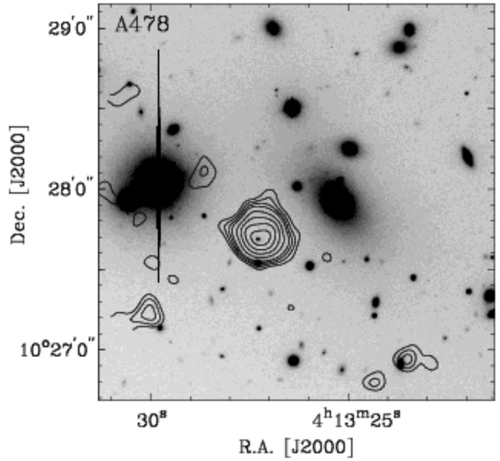
Redshift 7 10 15

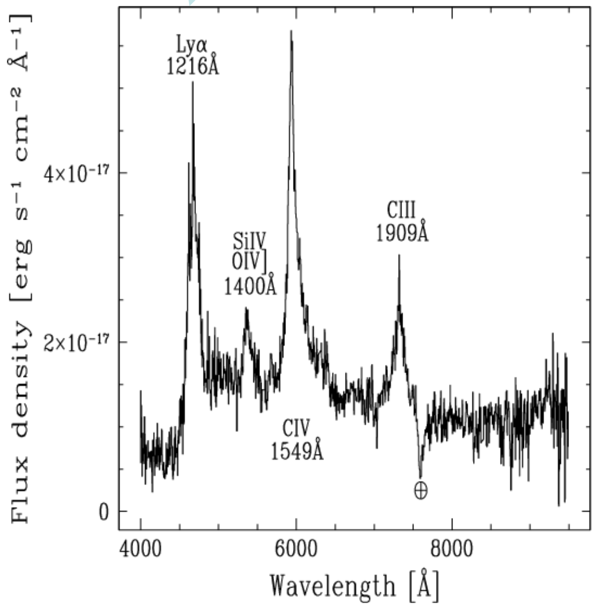
Example Object

- A dusty quasar in the field of cluster Abell 478
- Discovered by its large sub-mm emission
- Redshift ~2.8 from Keck spectroscopy
- Gravitational lens effects are small (~1.3x)
- Scaling this object to other redshifts gives:

Redshift	CIV Emission Line		FGS-TF Sensitivity (10s in 10,000 s)
	wavelength	Flux (W / m^2)	
2.8	0.6 μm	4.6 x 10^{-18}	-
7.0	1.24 μm	2.3 x 10^{-20}	1.0 x 10^{-20}
15.0	2.48 μm	1.5 x 10^{-20}	3.5 x 10^{-21}
20.0	3.26 μm	4.9 x 10^{-21}	2.8 x 10^{-21}

Knudsen etal - Astroph/0308438





Thank you

This lecture was funded in part by the Marie Curie Initial Training Network ELIXIR of the European Commission under contract PITN-GA-2008-214227.