The Tunable Filter Imager – TFI

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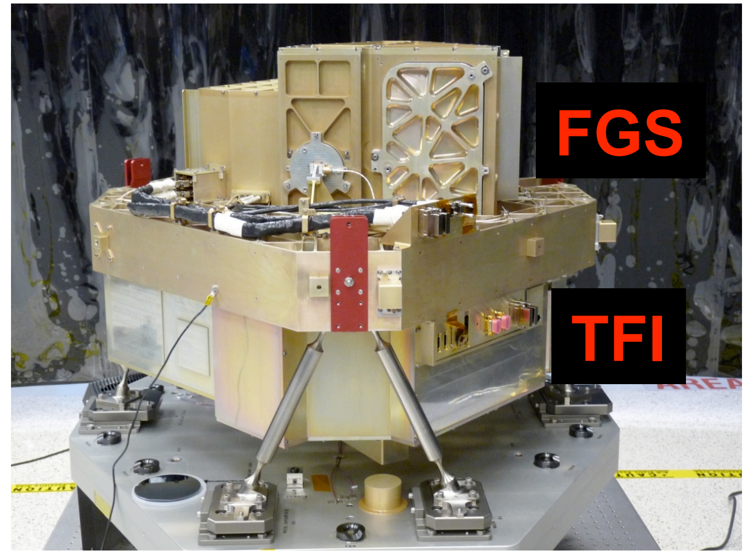
& the TFI science team

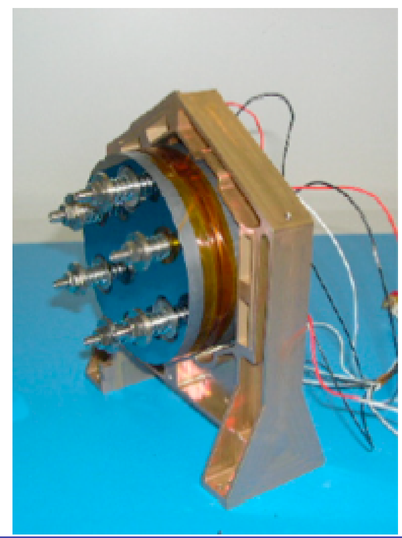
JWST and the ELTs: An Ideal Combination
ESO Garching, April 13, 2010

The Fine Guidance Sensor (FGS) – Tunable Filter Imager (TFI) module

- TFI is a science instrument packaged within the FGS module
  - Canadian Space Agency (CSA) contribution to JWST
    - Prime contractor is COM DEV Canada
  - PI of TFI: René Doyon (U Montreal)
  - PI of FGS: John Hutchings (HIA)



- TFI provides narrow band imaging between 1.5 μm and 5.0 μm
  - Based on a Fabry-Perot etalon



CSA ASC · Université de Montréal · NRC·CNRC · COM DEV

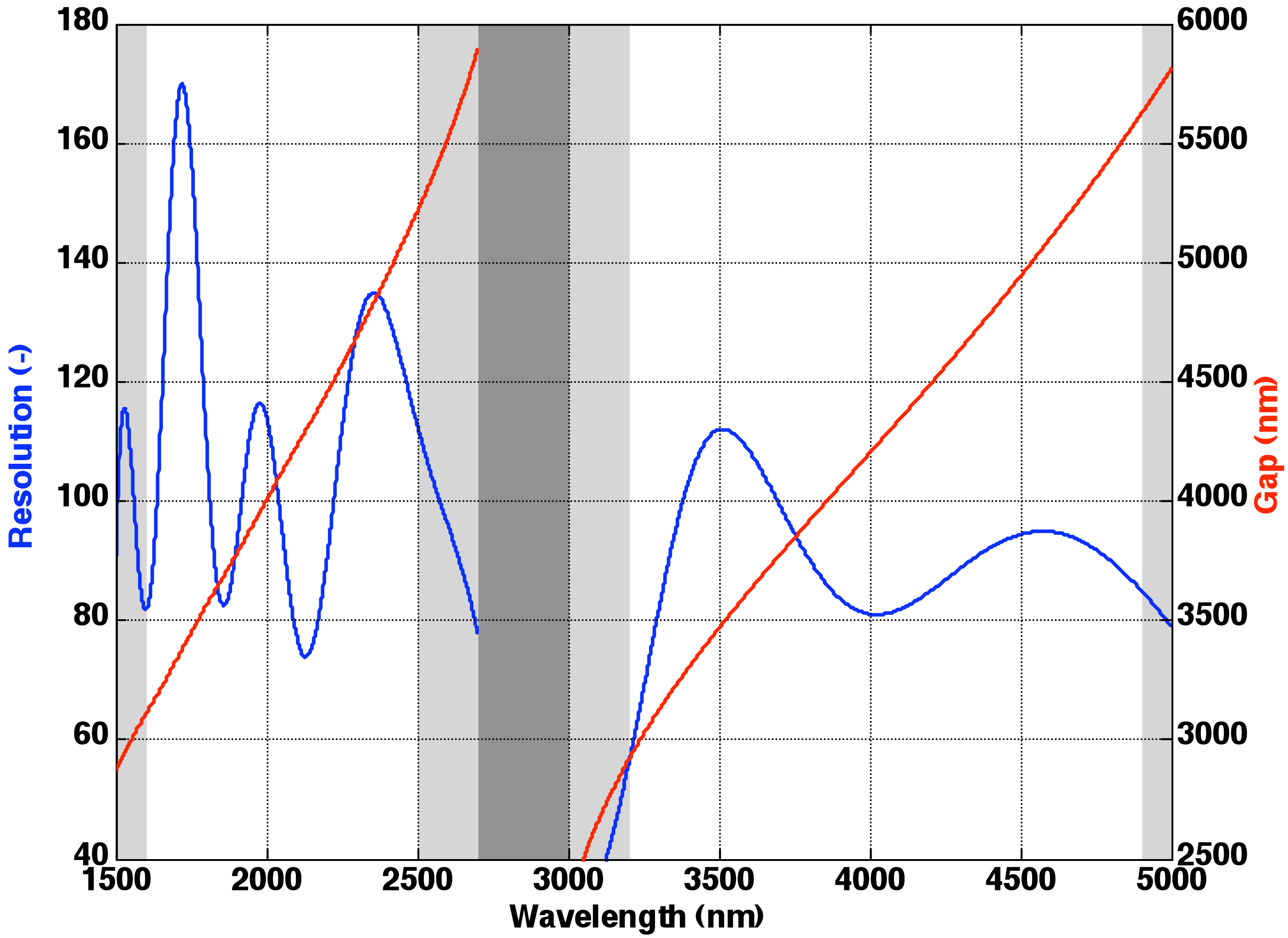
TFI at a glance

- FOV: 2.2'x2.2'
  - 65 mas pixel sampling (Nyquist at 4.0 μm)
  - 2048x2048 pixels (Hawaii 2RG)
- Wavelength range: 1.6-2.6 μm 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 →

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

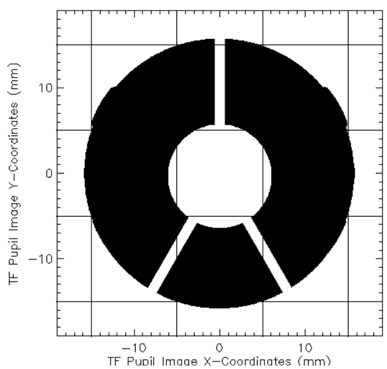
- Operating modes
  - Normal imaging
  - Lyot coronagraphy
    - 4 occulting spots, 3 lyot masks
  - Non-Redundant Masking interferometry (NRM)

Spectral Resolution



Coronagraphy

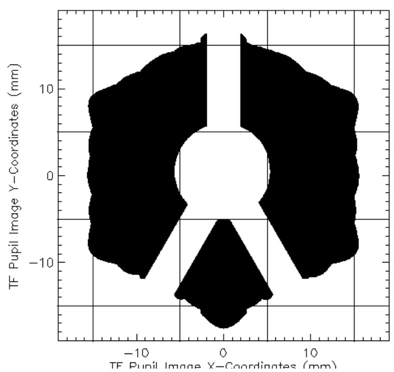
- 4 occulting spots engraved on pick-off mirror
  - Diameters of 0.58”, 0.75”, 1.5” and 2.0”
- 3 lyot masks
  - Transmissions of 71%, 66% and 21%
  - Robust against pupil shear of up to 4%



C71

0.58” and 0.75”

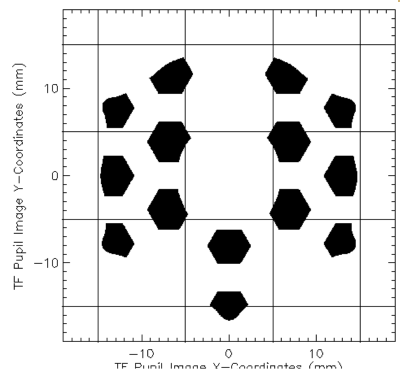
<1”



C66

1.5”

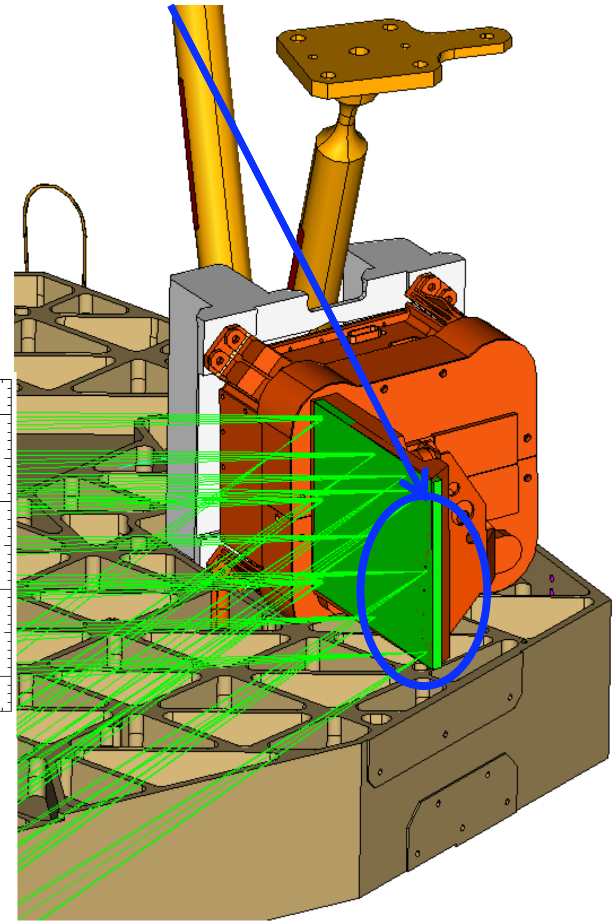
1”-2”



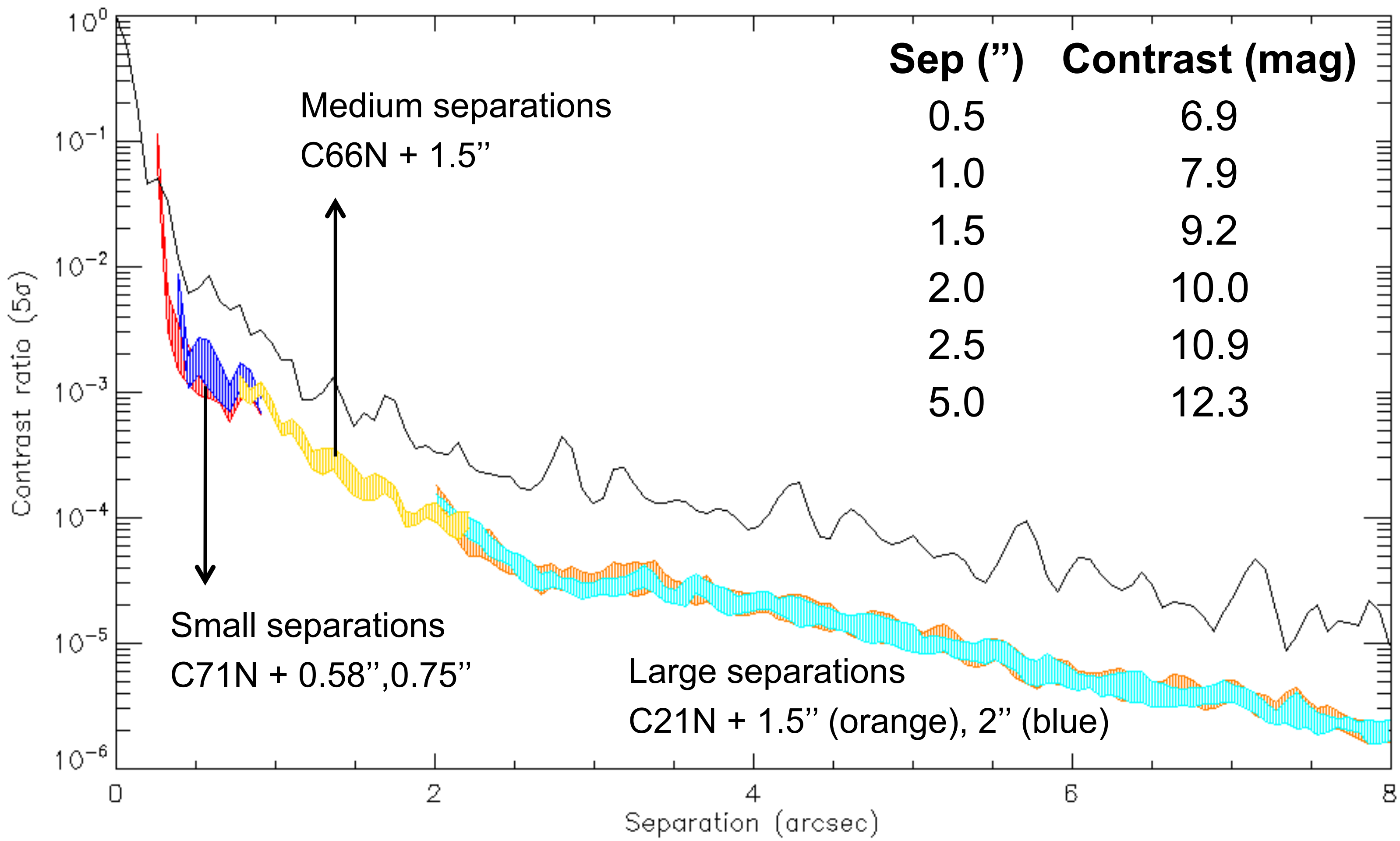
C21

1.5” and 2.0”

>2”



Coronagraphy constrast limits (3% pupil shear)

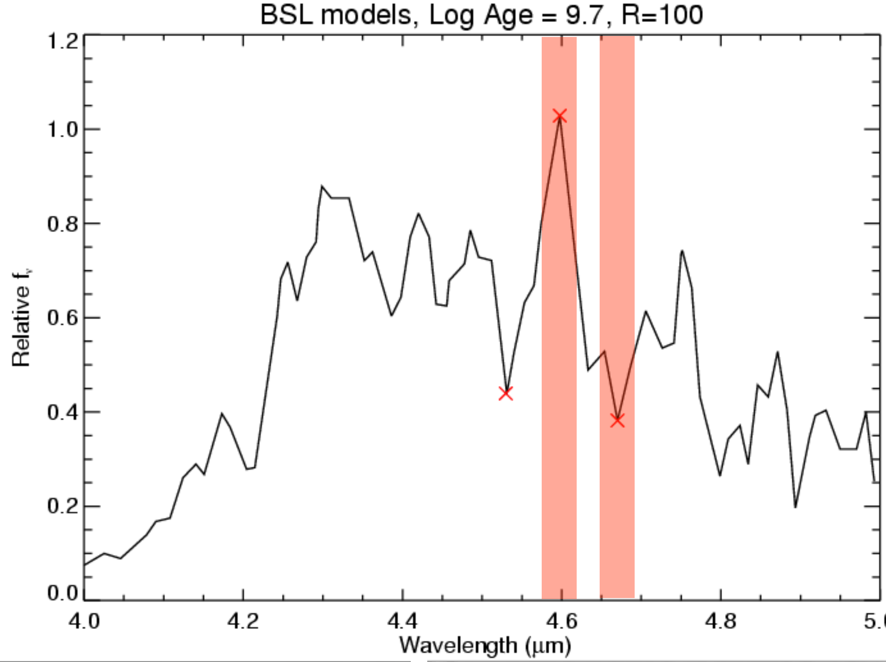


Sep ('')	Contrast (mag)
0.5	6.9
1.0	7.9
1.5	9.2
2.0	10.0
2.5	10.9
5.0	12.3

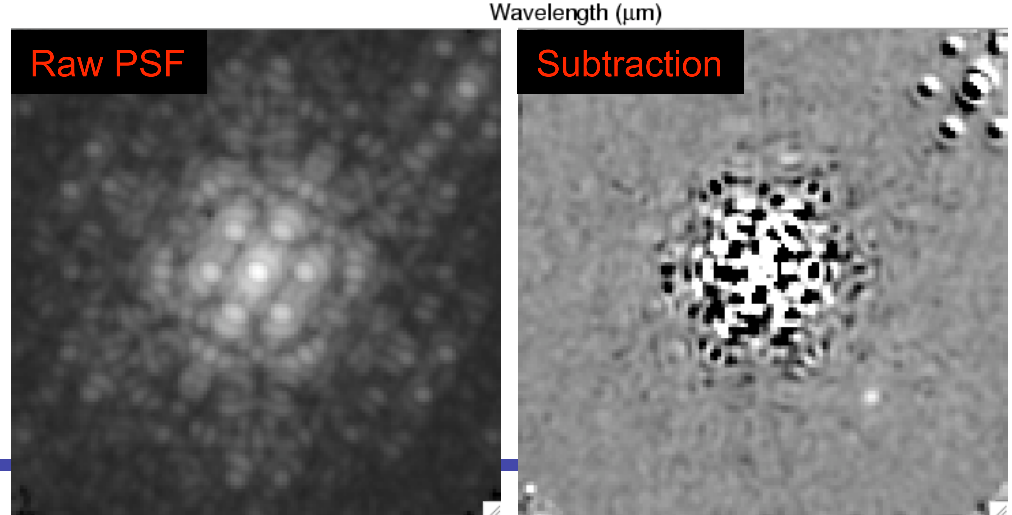
These contrasts can be improved further with PSF subtraction

Multi-Wavelength PSF subtraction

- Image of the target itself at a different wavelength is used as a reference PSF image
- Uses sharp spectral feature in companion spectrum
  - Image 1: companion bright
  - Image 2: companion faint



- Demonstrated in the lab using the TFI etalon prototype P0

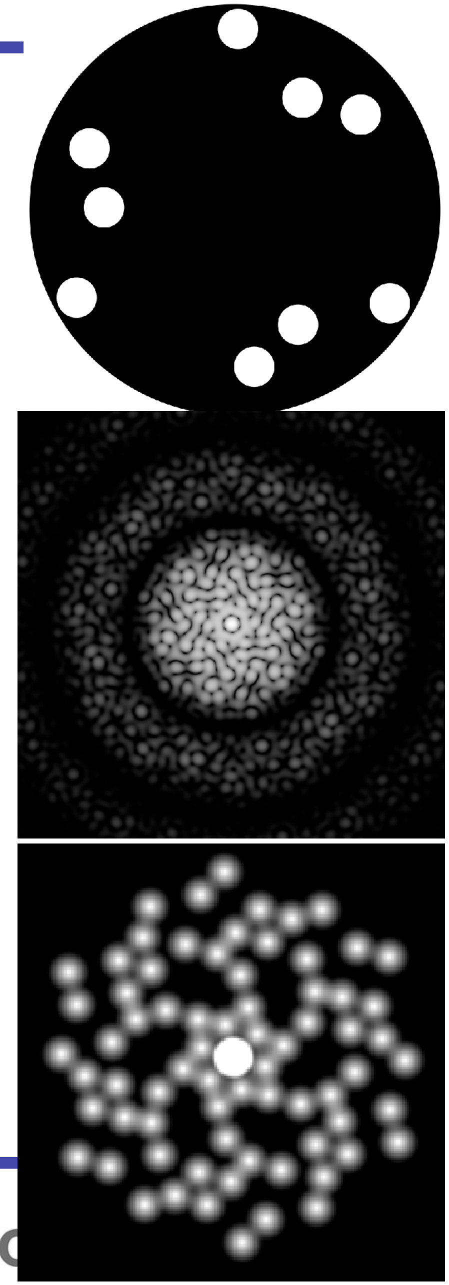


Achieved speckle noise attenuation of 10

Non-Redundant Masking interferometry

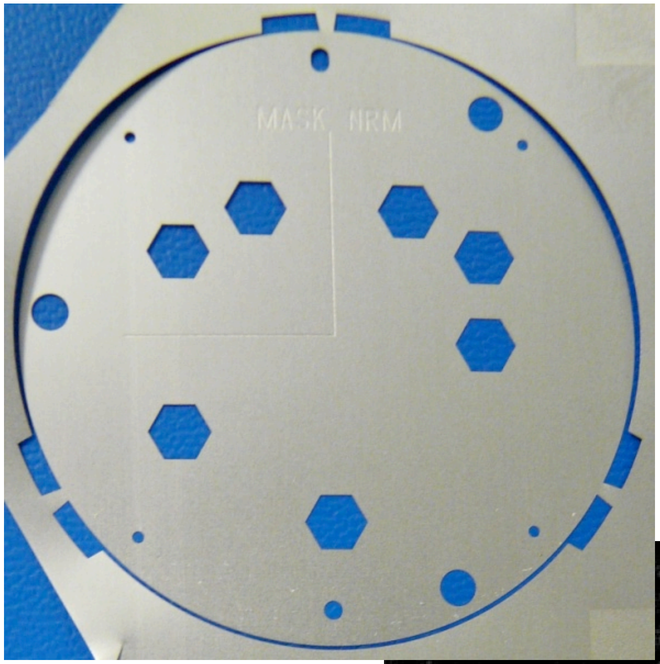
- Insert a mask containing multiple small apertures at a pupil plane
  - No line joining any two sub-aperture has the same length and PA as another one
- From FT of interferogram, amplitude & phase of interference fringe coming from each pair can be measured “easily”
- Fit a model to measured phases and amplitudes

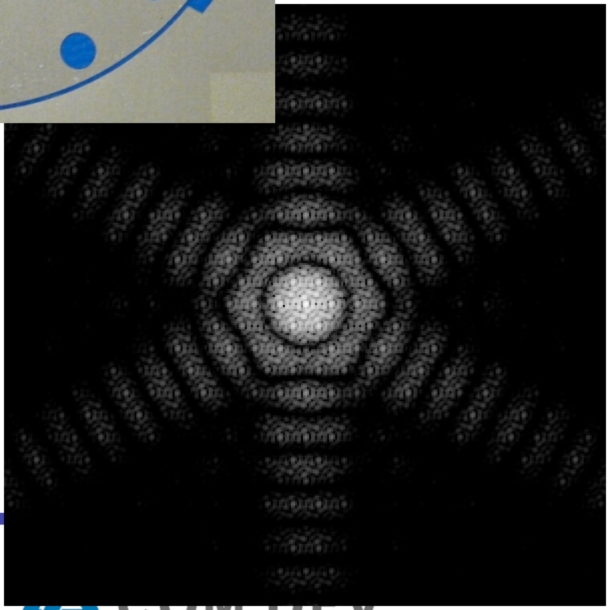
- Two advantages:
  - **Better resolution** - two sources can be resolved for a separation of **0.5 λ/D**
  - **Better contrast at small separations** - Wave front phase errors have little effect on closure phase



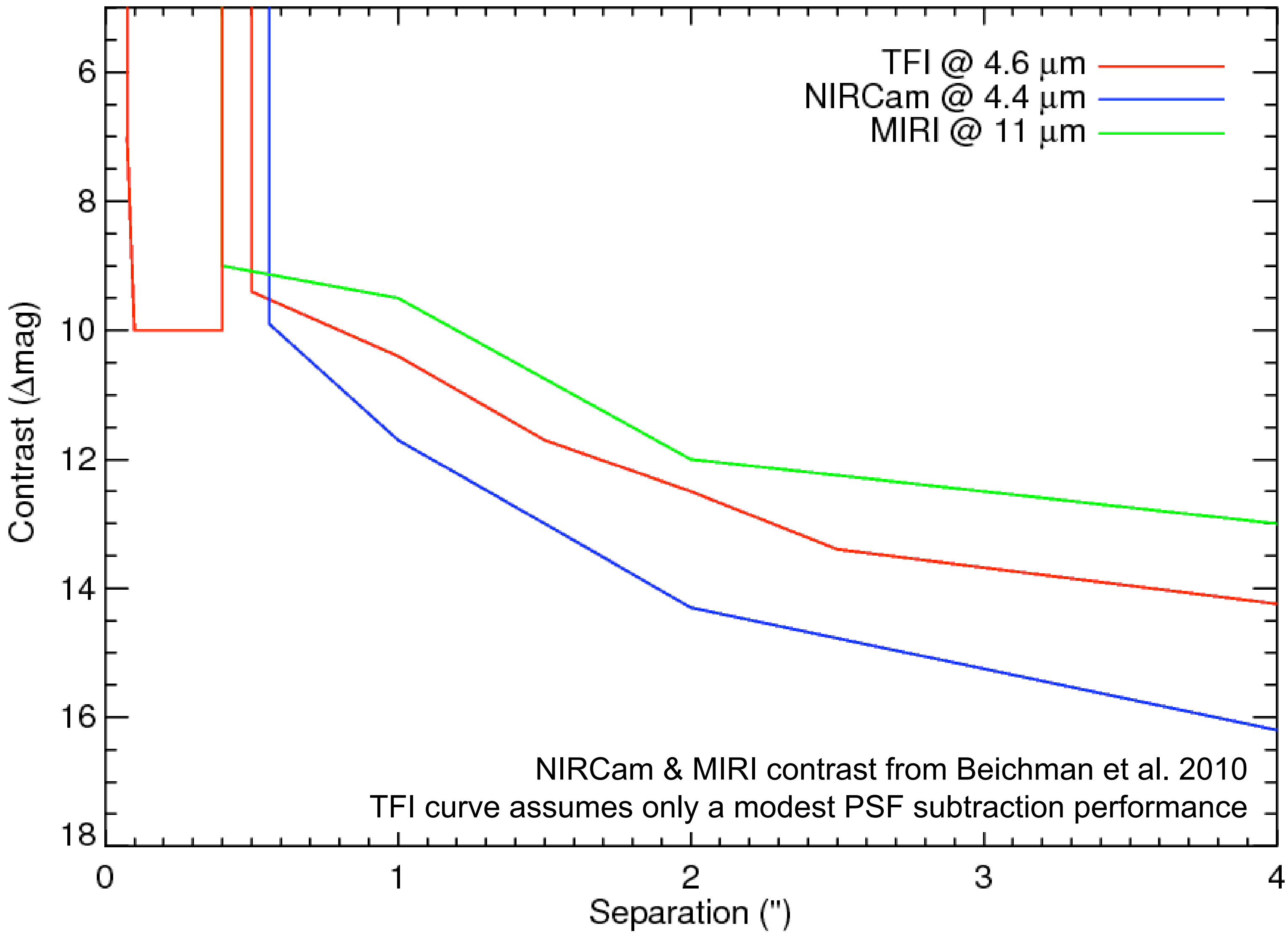
TFI Non-Redundant Mask

- 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**





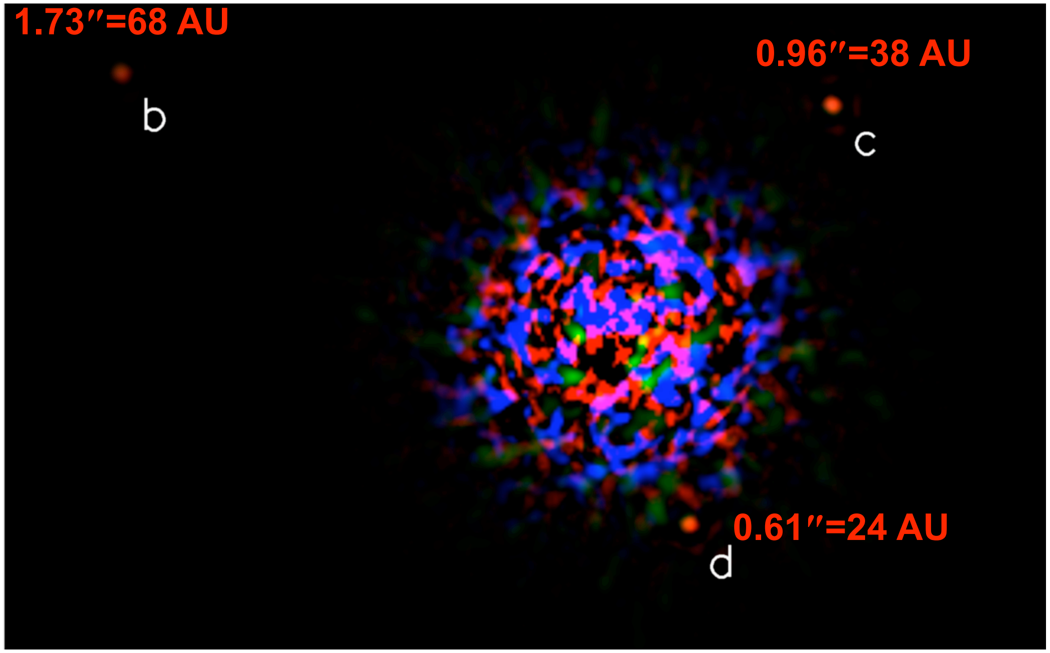
TFI/NRM occupies a unique niche



The HR 8799 planetary system

- Three 7-10 M_{Jup} planets imaged
- A dusty disk with three components
  - Warm (150 K) dust belt at 6-15 AU – inside planet d
  - Cold (45 K) planetesimal belt just outside planet b
  - A surrounding halo of dust out to ~1000 AU

  Su et al. 2009, Reidemeister et al 2009

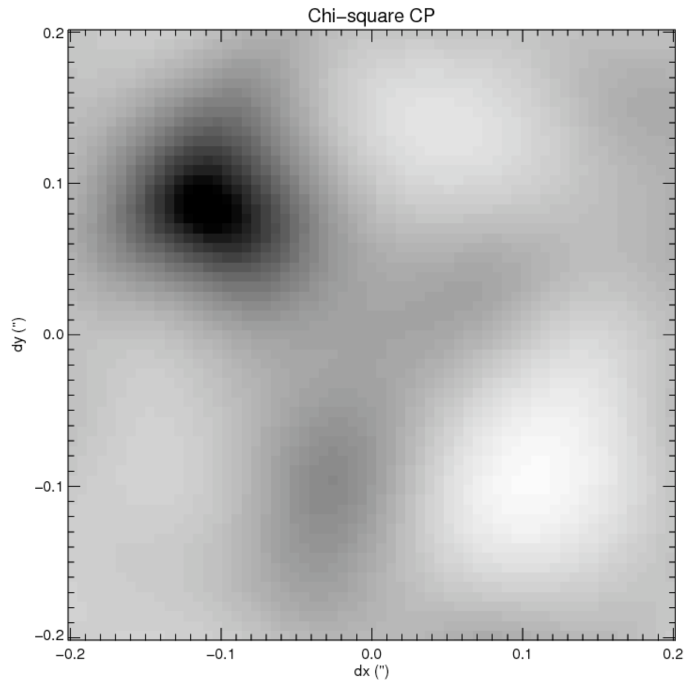


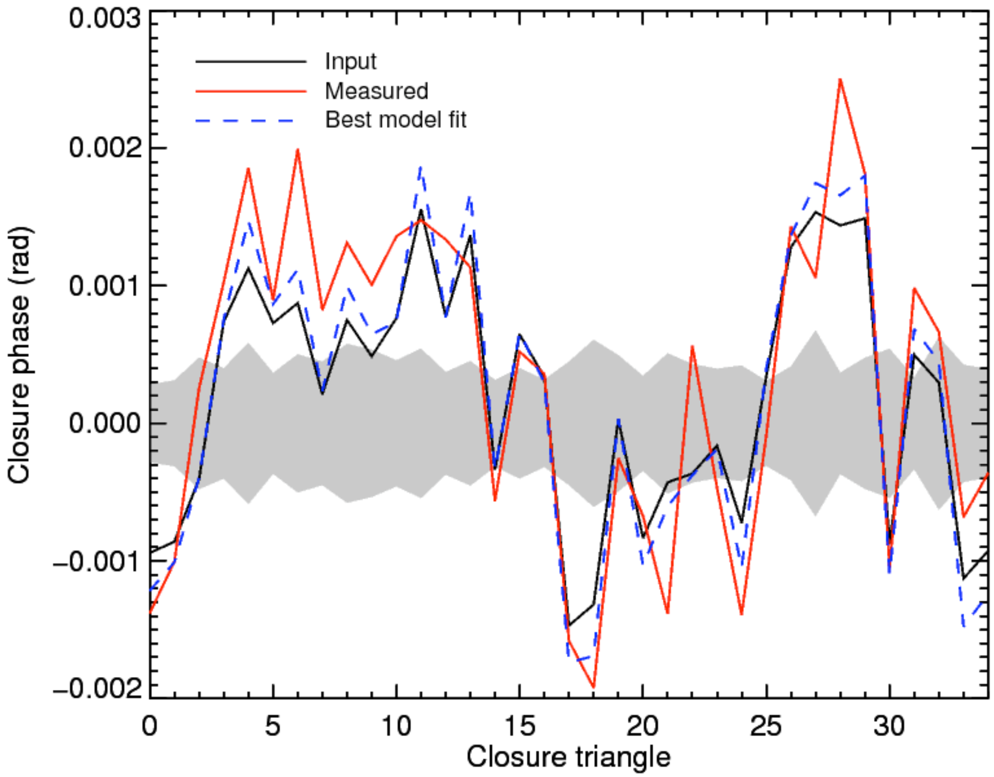
Marois et al. 2008

- Is there a planet inside the inner belt?
  - ~5 AU, separation of 0.13” ➔ NRM

TFI/NRM simulation of “HR 8799 e”

- Simulation
  - 10 M_{Jup} planet at 5 AU
  - age of 50 Myr assumed
  - 20 min total integration over 9 dithers
  - Includes realistic noise sources





	Input	Measured
Sep (mas)	132	138 ± 15
PA (deg)	50.7	52.7 ± 2.6
Contrast (mag)	8.0	7.87 ± 0.11

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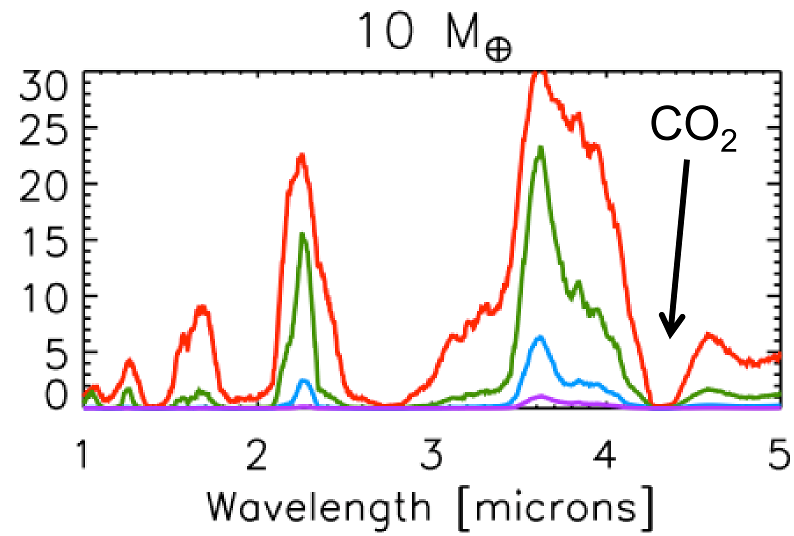
TFI/NRM exoplanet science

- (molten) proto-Earths around nearby young stars (1-100 Myr)
  - Following collisions, planets could stay at >1000 K for several Myr
  - Region of interest <0.5”
  - Contrast of <10 mag for late-type stars

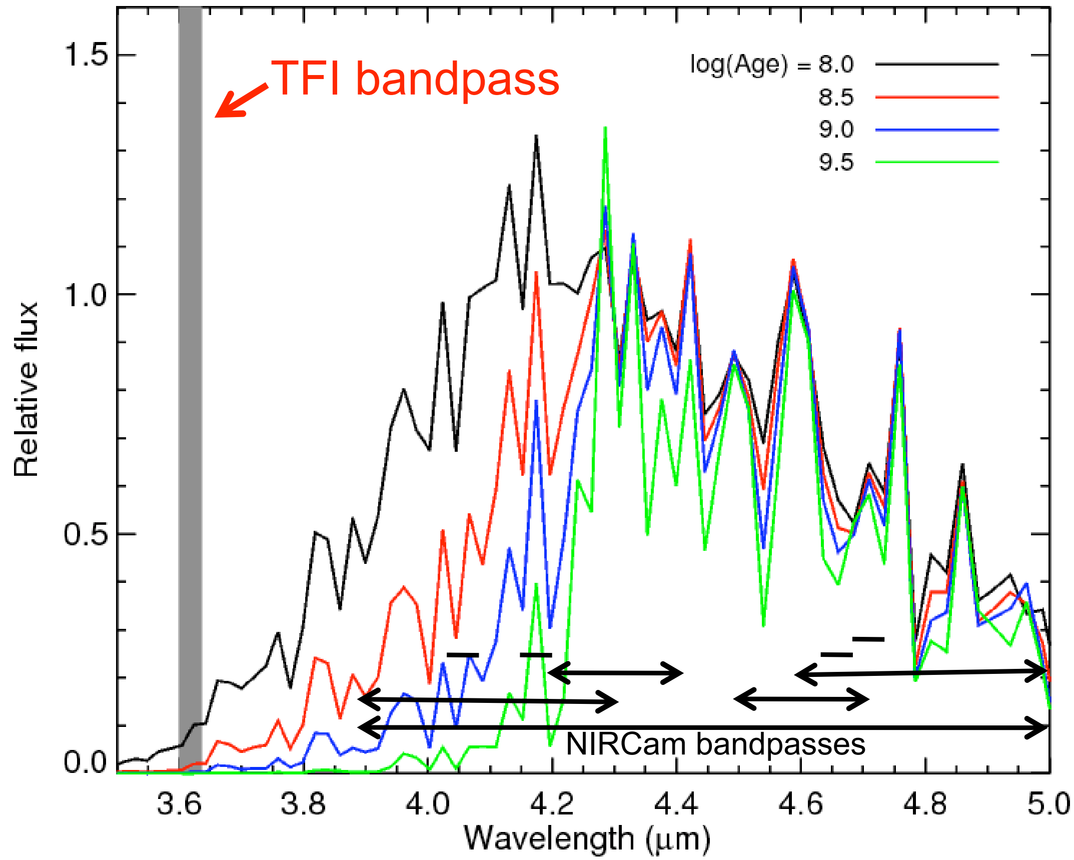


Miller-Ricci et al. 2009

- Long-λ characterization of GPI/SPHERE planets
  - At 4 μm, GPI/SPHERE planets at 0.1”-0.4” and contrasts of 8-10 mag will be accessible only with TFI/NRM
- Planets in star-forming regions (1-5 Myr age)
  - 75-400 mas is 10-60 AU at 150 pc
  - 10 mag contrast sufficient to see gas giants

Exoplanet characterization

- TFI can extract spectral information at R~100, at high contrast, and at any λ
  - For highest contrast planets, TFI could be the only option
- Lots of structure in spectrum at R~100
  - Probe molecular content of atmosphere
  - Constrain Teff & log g
  - Test models
- Follow-up planets found by NIRCam, GPI, SPHERE, etc.

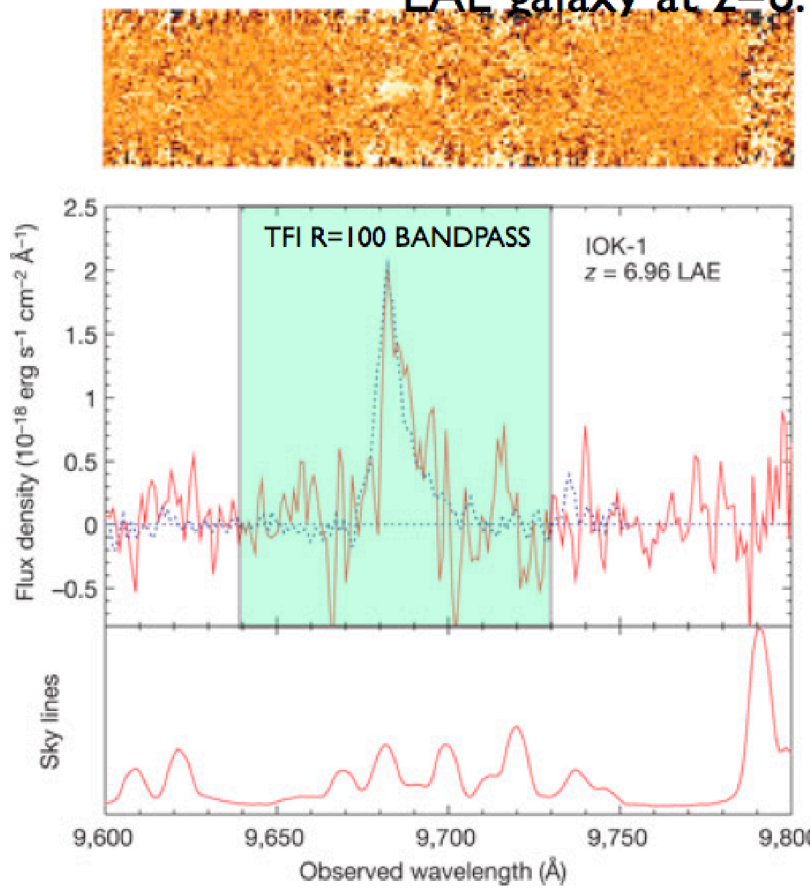


Burrows et al. (2003) models for a 5 M_{Jup} planet binned to R=100

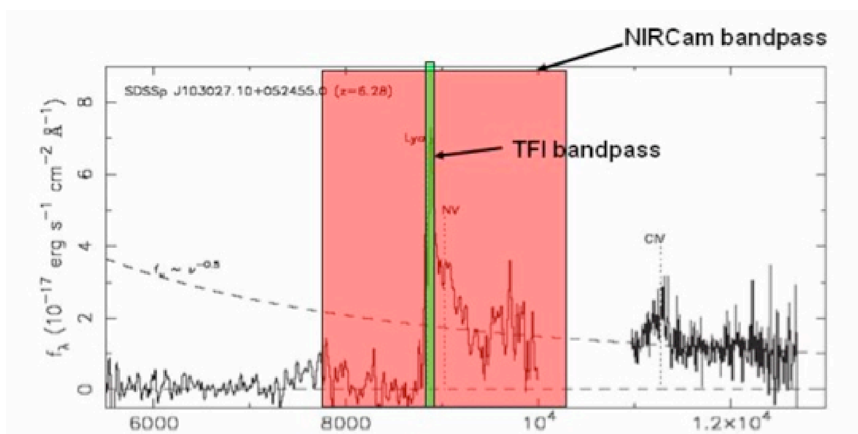
High-Redshift Science with TFI

- 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

LAE galaxy at z=6.96



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

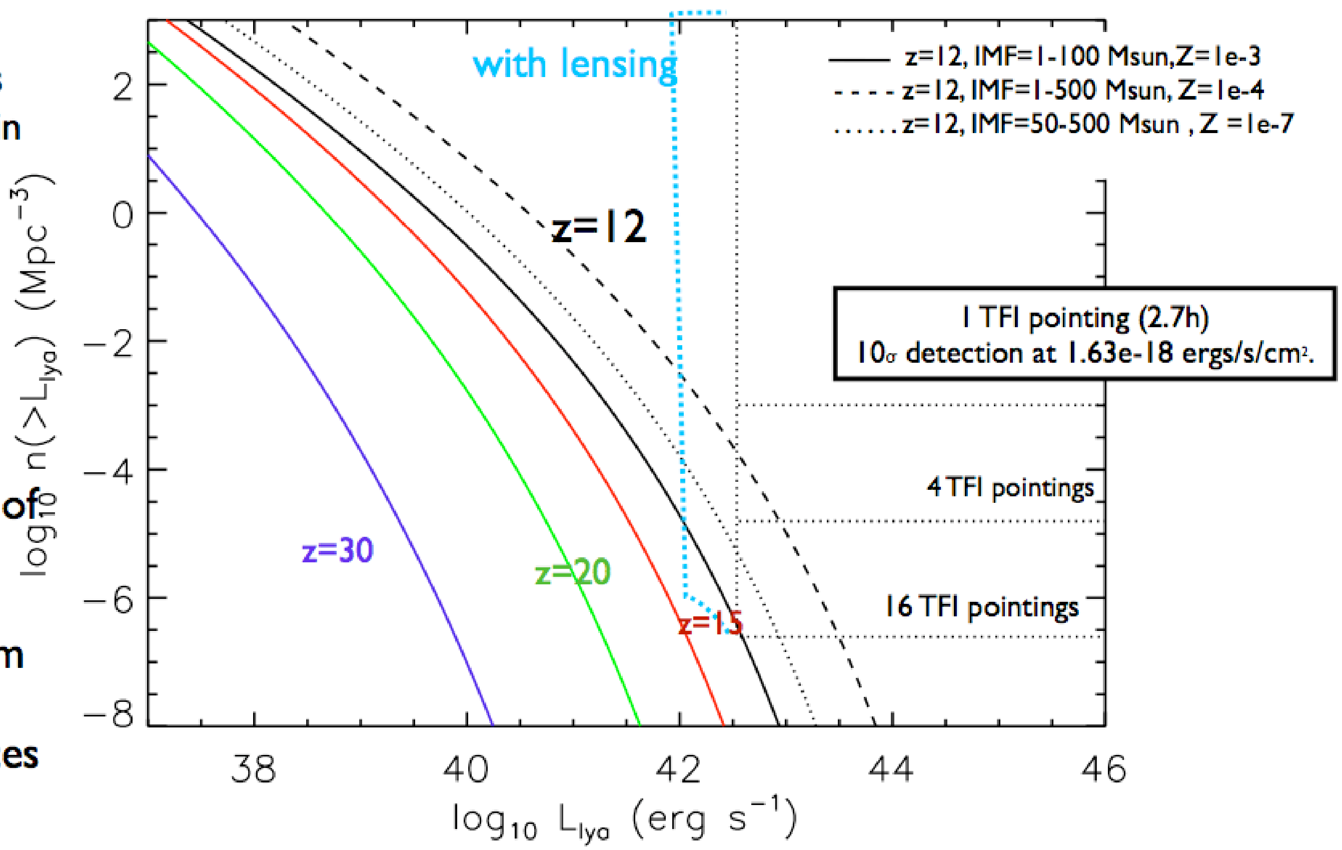
Slides by E. Mentuch, representing the TFI High-z Tiger Team

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.



Slides by E. Mentuch, representing the TFI High-z Tiger Team

The TFI Science team

- R. Doyon (**PI of TFI**, U. Montréal)
- J.Hutchings (**PI of FGS**, HIA) – **Here all week**
- R. Abraham (UofT)
- L. Ferrarese (HIA)
- R. Jayawardhana (U.ofT)
- D. Johnstone (HIA)
- D. Lafrenière (U. Montréal) – **Here all week**
- M. Meyer (ETH, Zurich) – **Here Thu-Fri**
- J. Pipher (U.Rochester)
- M. Sawicki (St-Mary's)
- A. Sivaramakrishnan (AMNH)