The Adaptive Optics and Extremely Large Telescope Perspective

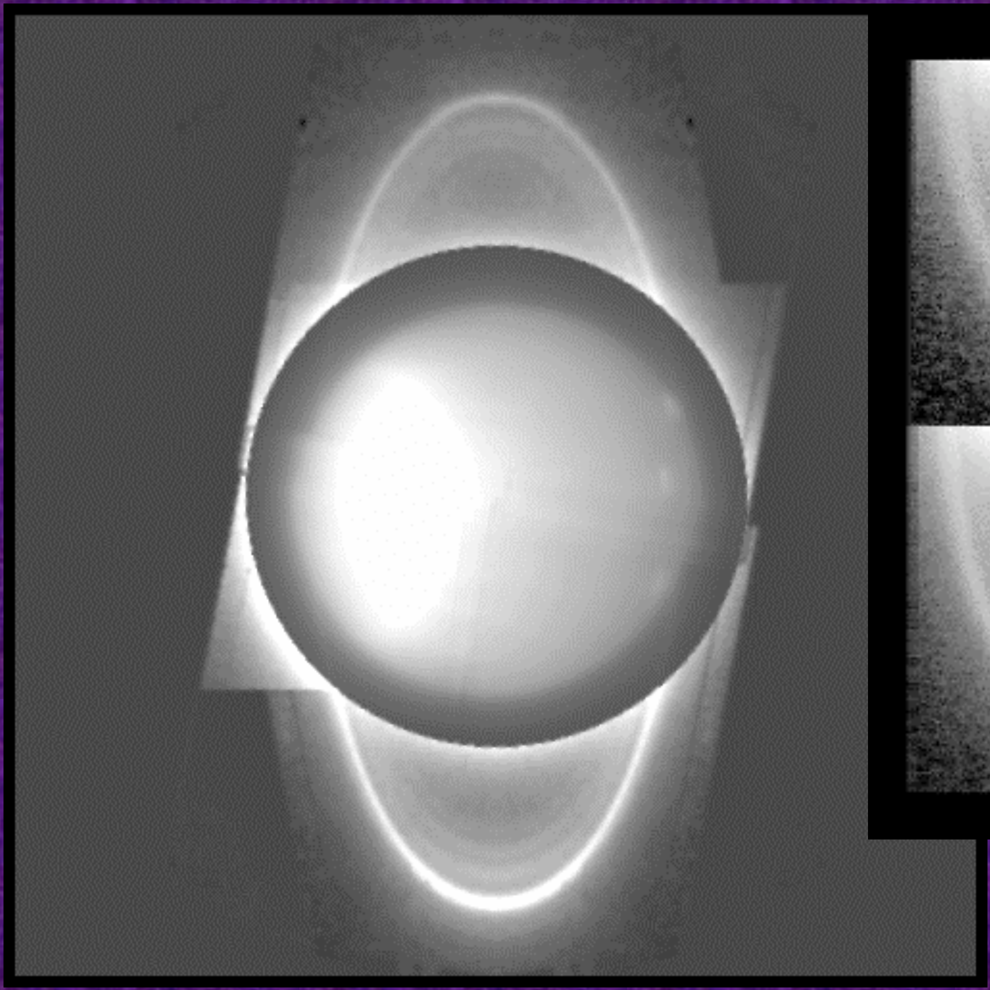
Bruce Macintosh
(TMT: James Graham, Paul Hickson, James Larkin, Tim Davidge)

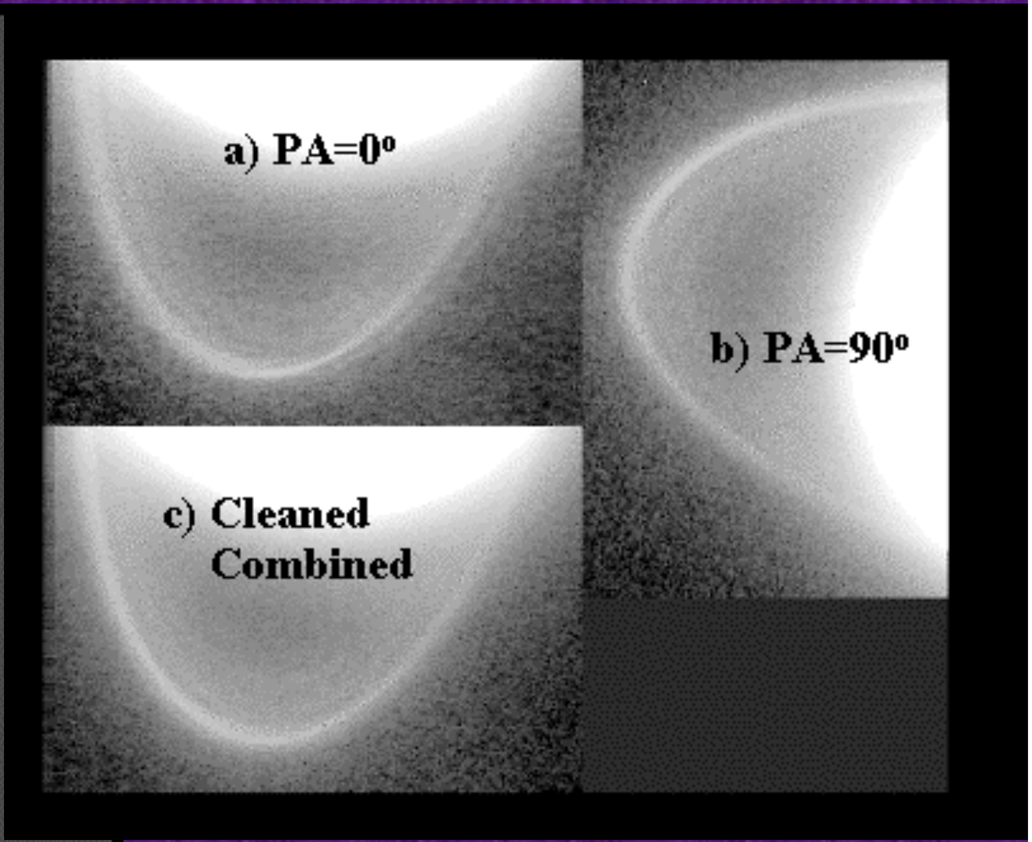
Non-redundant people: Peter Tuthill, John Monnier, Jamie Lloyd

Outline

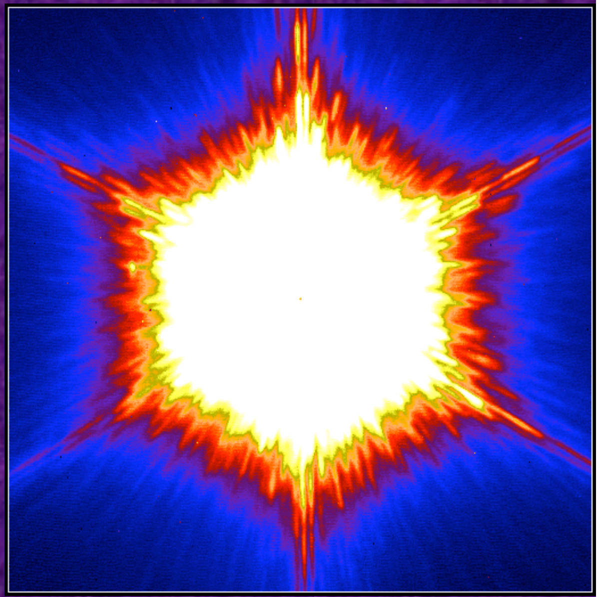
- **AO problems and promise in a single slide**
- **Quick ELT introduction**
  - Major science roles
- **Adaptive optics on ELTs**
- **Extrasolar planet detection with ELT AO:**
  - TMT Planet Formation Imager
- **Aperture masking interferometery on large telescopes**

Early Keck AO images of Uranus (de Pater et al 2002)





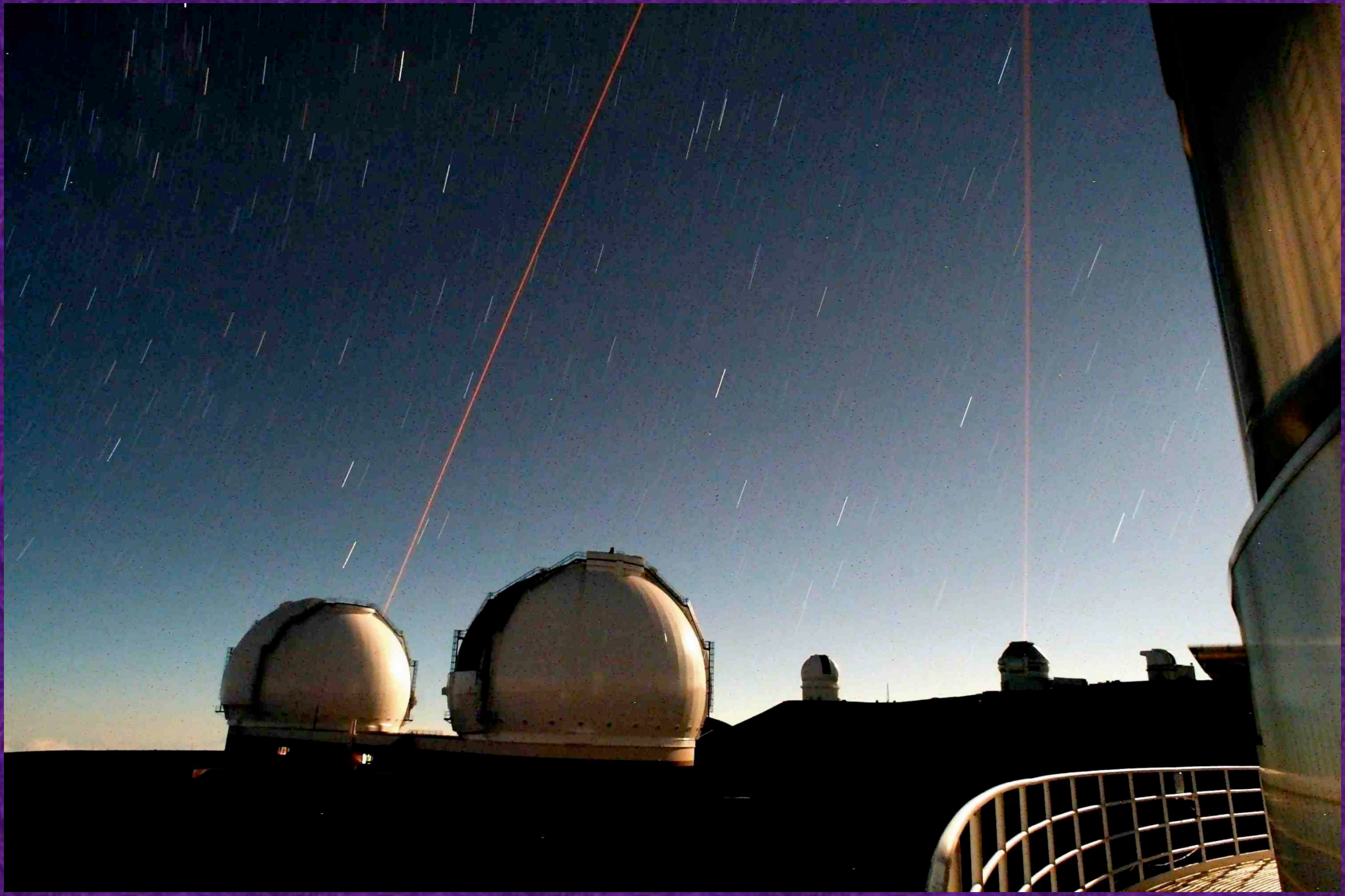
AO PSFs have strong quasi-static structures (but this may improve in the future)



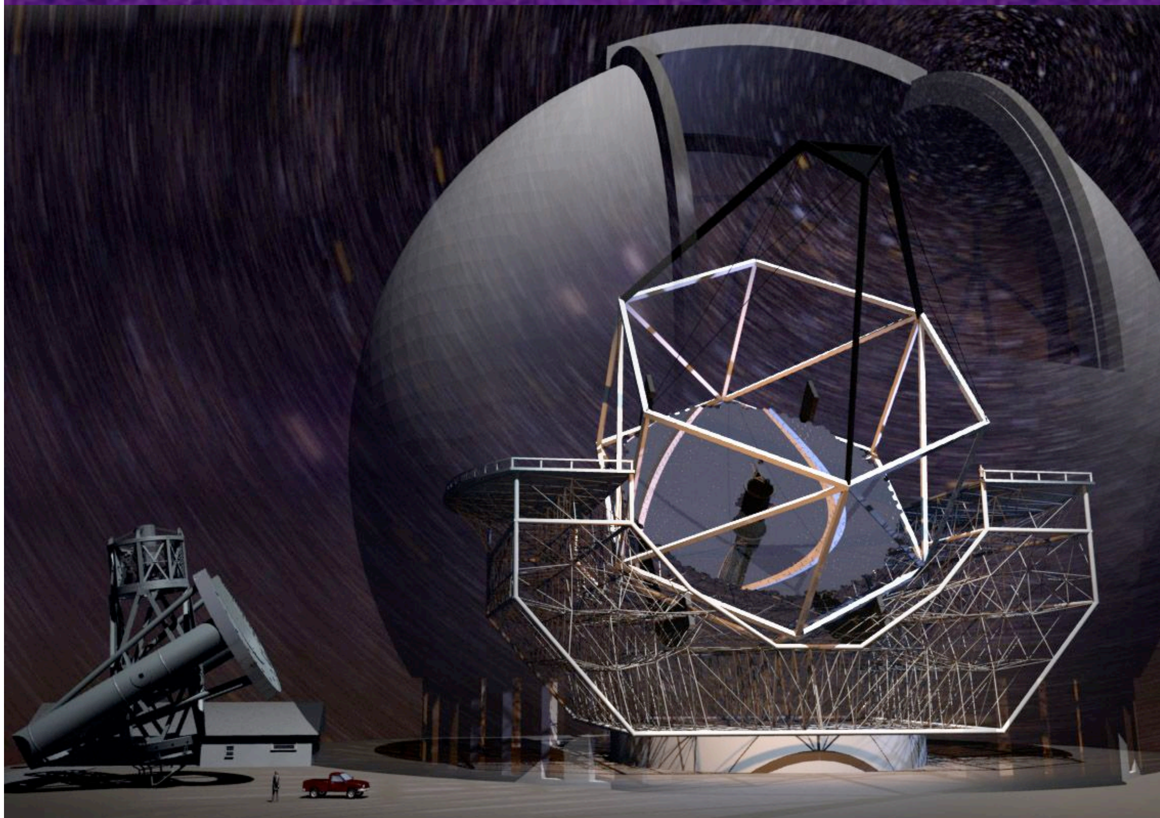
Keck AO PSFs
(0.01 arcsec/pixel)

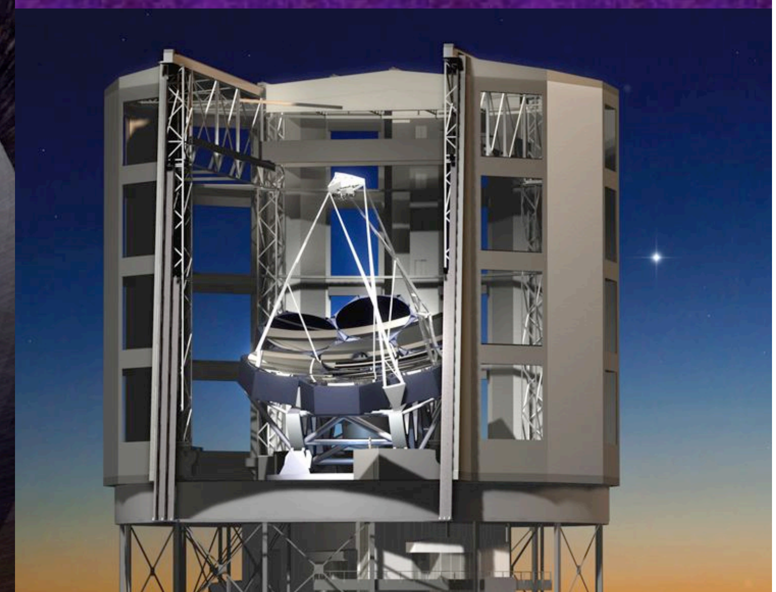
Deep Keck AO PSF
4 arcsec FOV

Sky coverage => Science



Extremely Large Telescopes





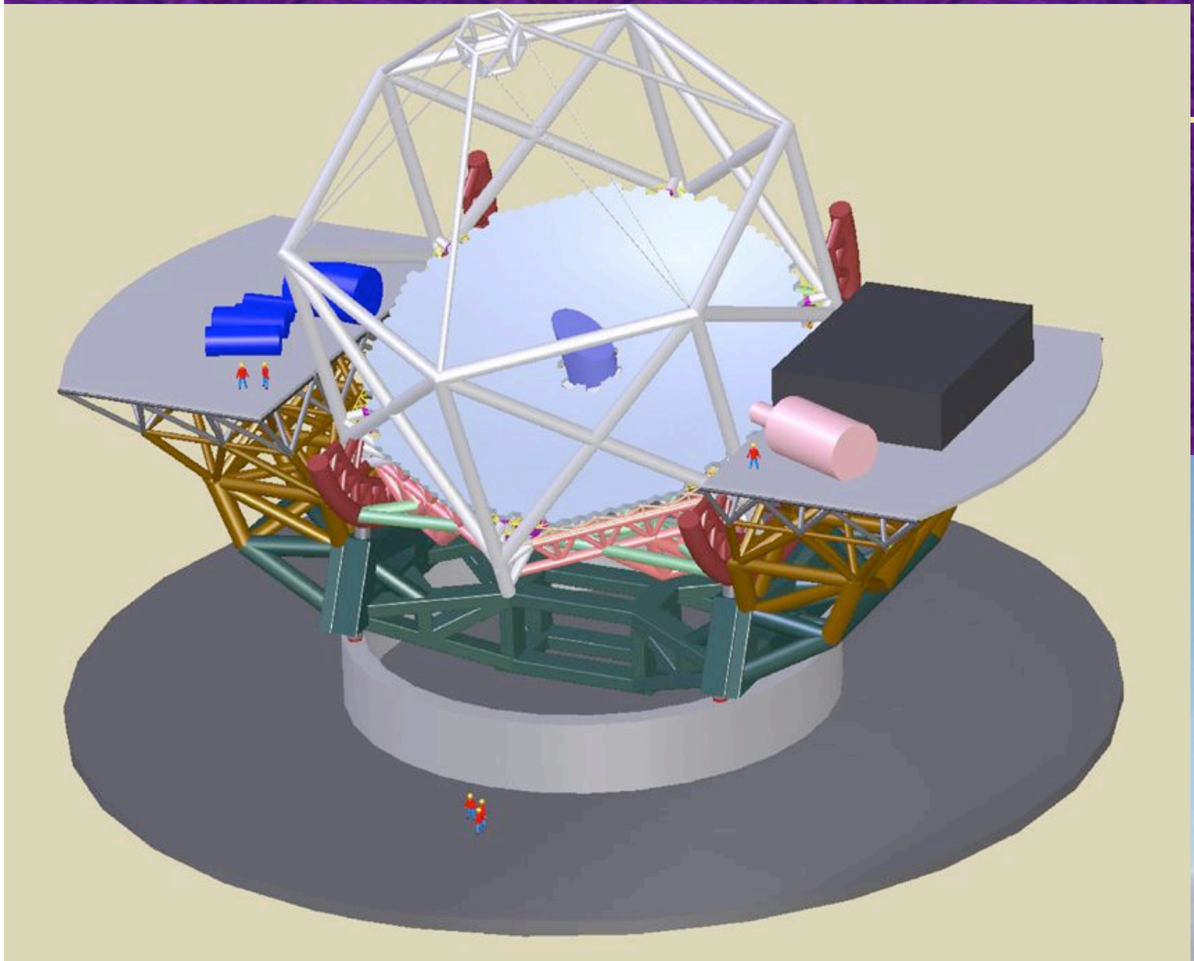
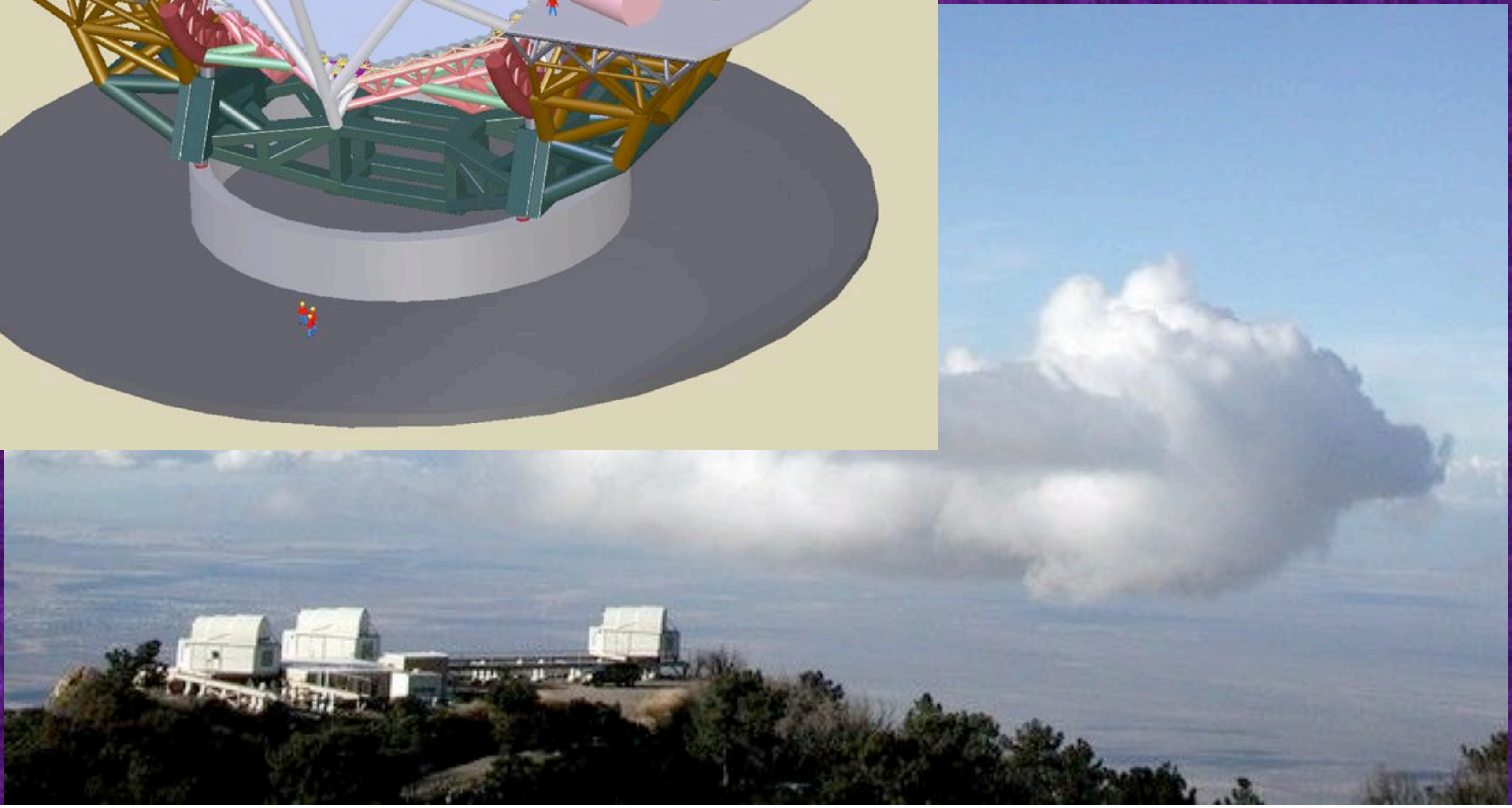
Thirty Meter Telescope

- 30-m resolution + collecting area
- 1.2 – 1.5 m hexagonal segments

Giant Magellan Telescope

- 7 x 8-m segments
- 25-m resolution + 21 m area
- Adaptive secondary

Both architectures (and European 30 - 42 m ELT) have very similar capabilities

THIRTY METER TELESCOPE

TMT Key Science Areas (Paul Hickson from TMT CoDR)

- Cosmology and fundamental physics
- The early universe and first light
- Intergalactic medium beyond z = 7

- Galaxy formation and evolution
- Black holes and active galactic nuclei

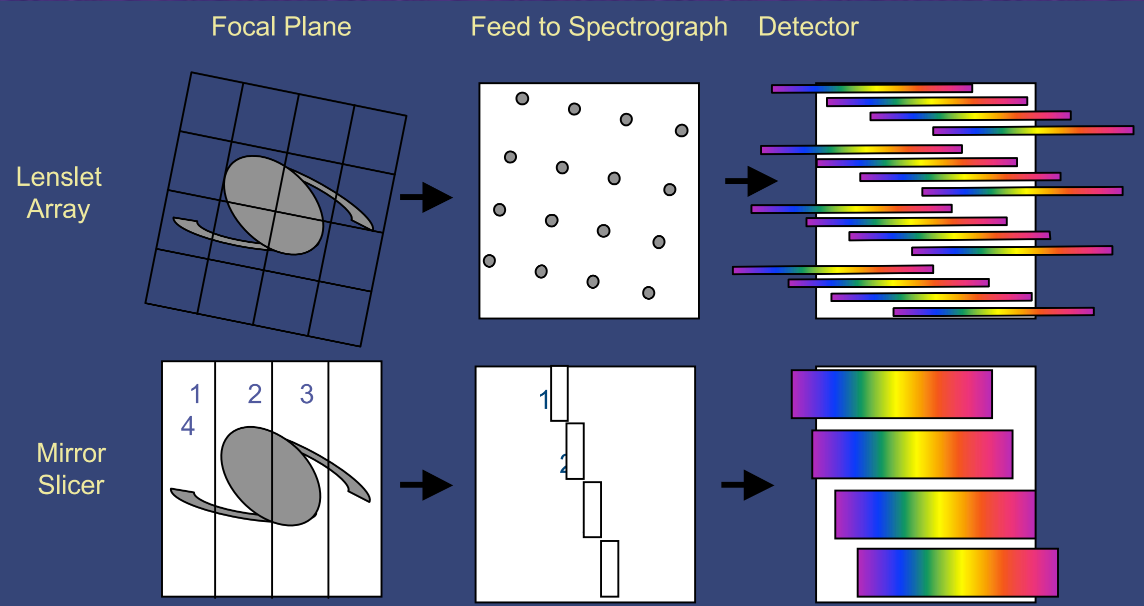
- Stellar populations and star-formation histories in the local Universe
- Evolution of star clusters and the IMF

- Physics of star and planet formation
- Characterization of extrasolar planets
- Solar System studies

First-light instruments: wide-field optical spectrograph; high-strehl narrow-field AO; mid-IR spectroscopy + AO; high-resolution optical spectrograph

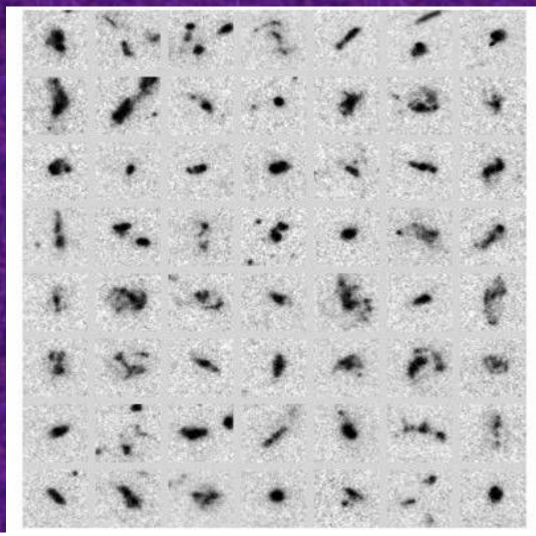
IFS example: Not enough pixels or photons

- **Key first-light AO instruments are integral field spectrographs**
- **Pixel and detector limitations will lead to operation below diffraction limit**
- **Extragalactic / high Z targets are ~1", very faint**
  - Structure / velocities require 0.10~0.05" resolution
- **Multiplexing (multiple IFS deployed across wide field of view) is high priority**
- **Other science missions do require full diffraction limit**



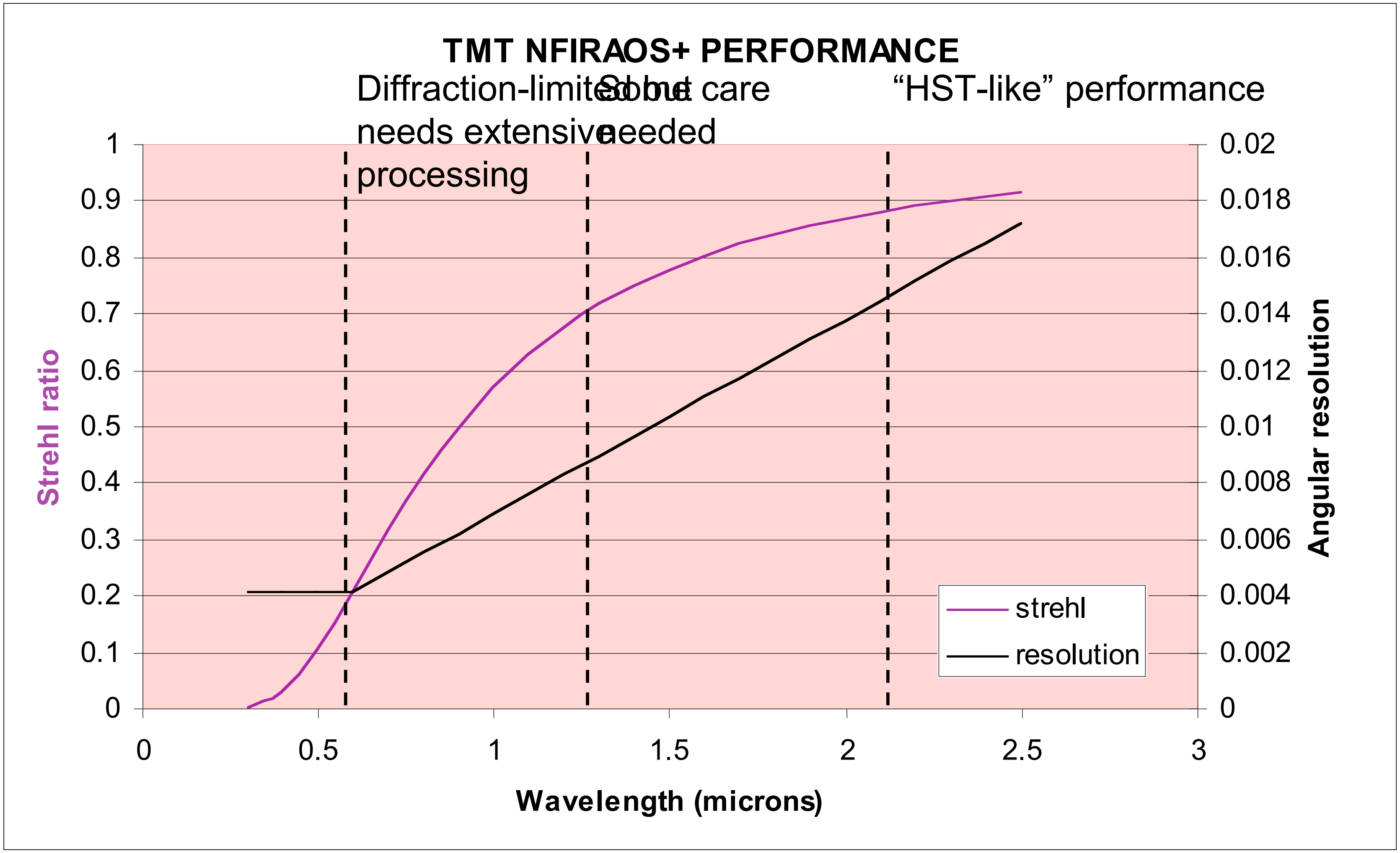
2"x2" at 0.008"/pix => 40-160 million pixels

GOODS-N galaxies 1.5<z<2. Each image is 3"x3"

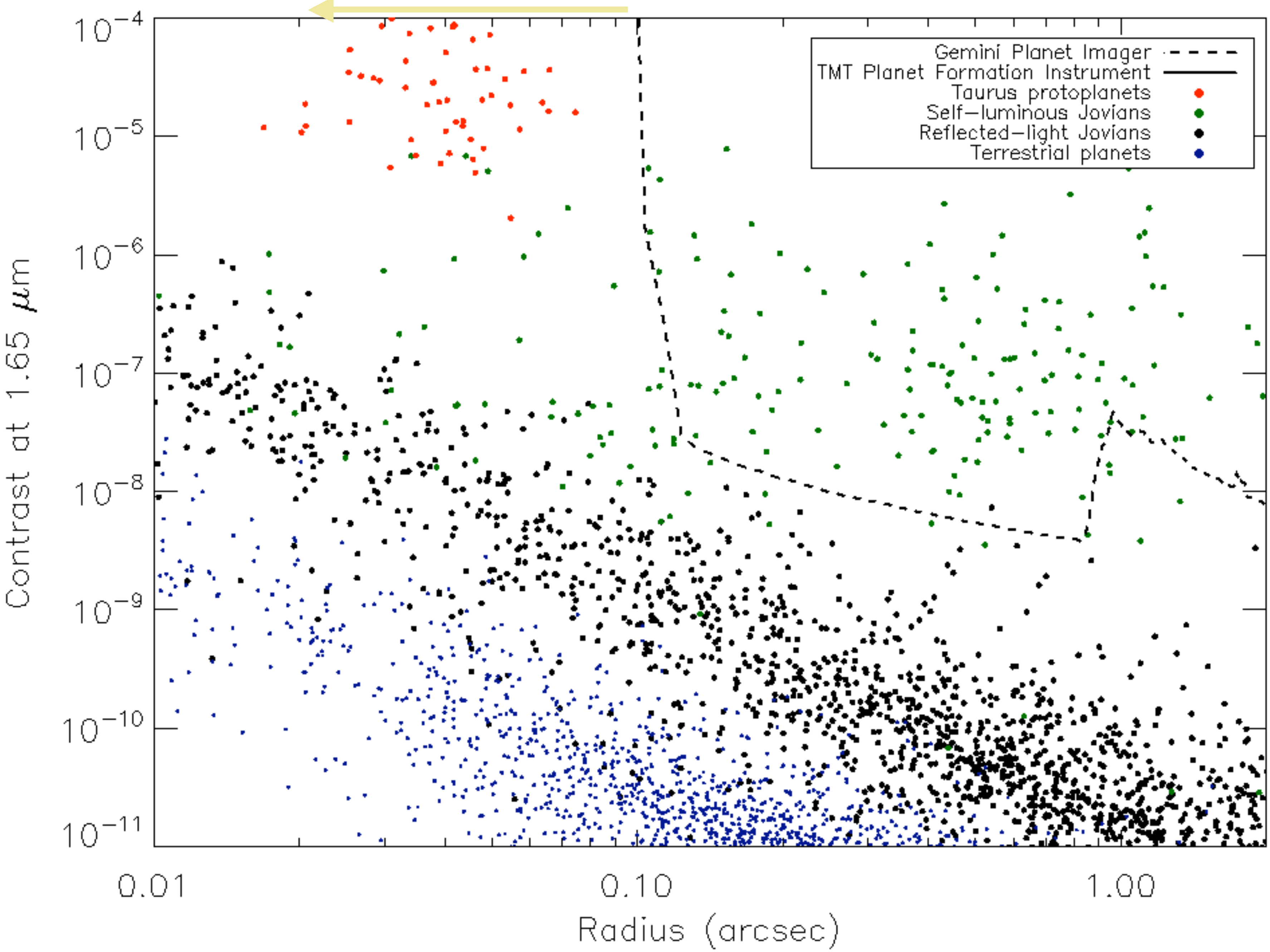


Figures from James Larkin + Tim Davidge

Next-generation AO can provide very good visible-light Strehl and high resolution



Inner working distance (IWD) ~2-4 λ/D



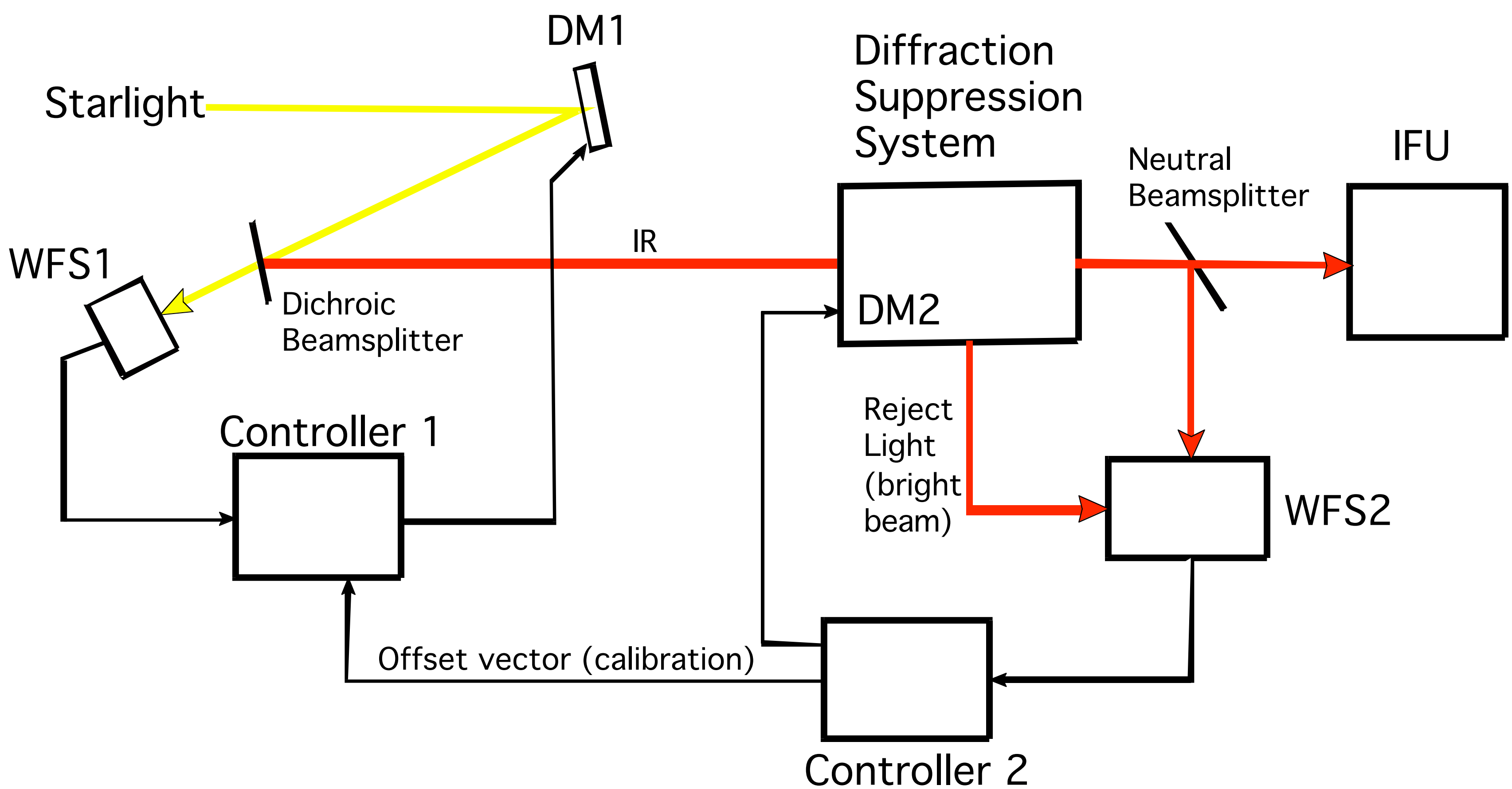
TMT Planet Formation Imager
Science missions and requirements

THIRTY METER TELESCOPE

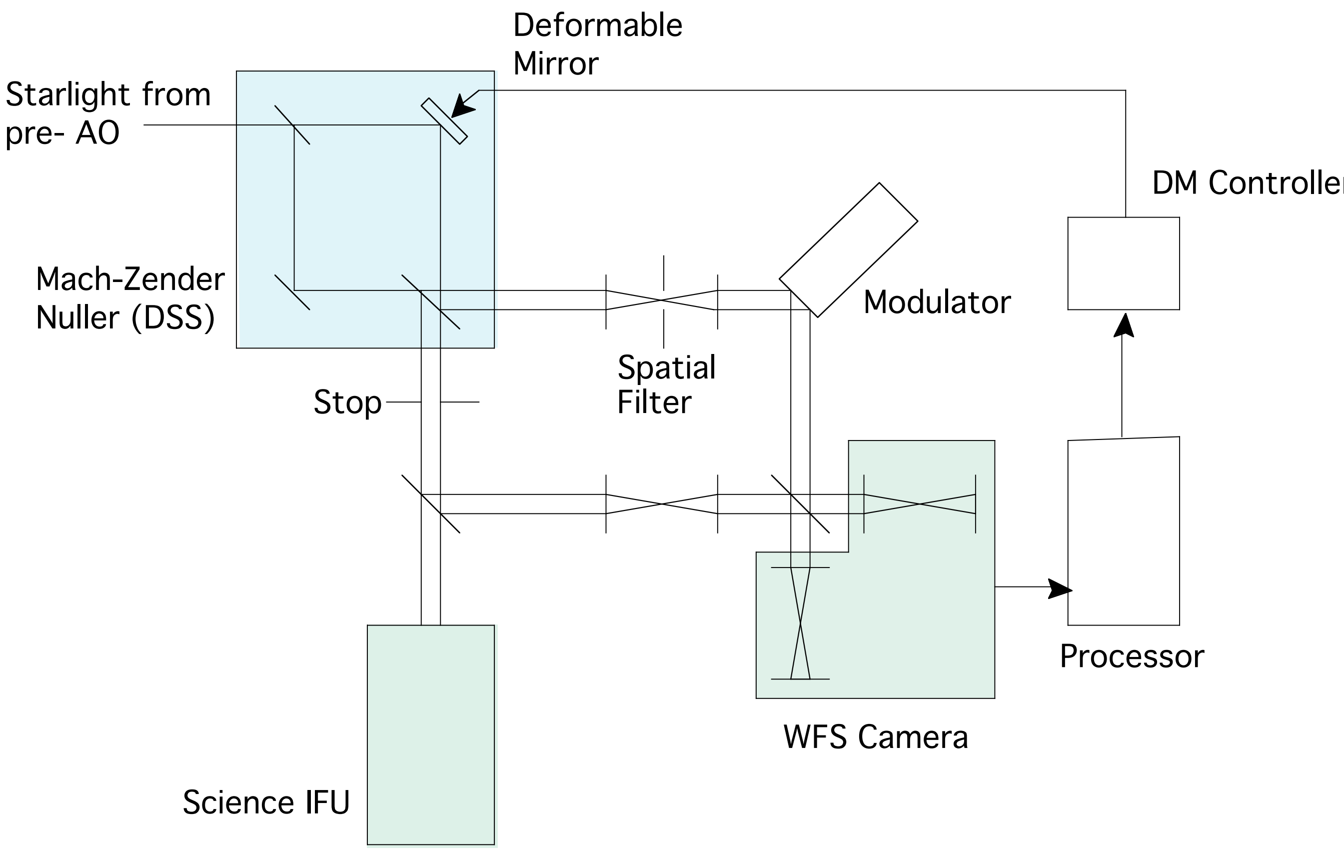
1. Detect and characterize a large sample of extrasolar planets (T_{eff}, R, g)
   - ➡ 10^{-8} @ 50 mas, I<8
   - Sub-nm static errors, 2000+ Hz
   - R~100 spectroscopy
2. High-SNR spectroscopy of planets (abundances)
   - ➡ R~1000 spectroscopy
3. Detection of planets in the process of formation
   - ➡ 10^{-6} @ 30 mas, H<10
   - IR WFS
   - Polarimetry
4. Studies of circumstellar dust on AU scales
   - ➡ Polarimetry
   - 2"+ FOV

Systematic errors must be controlled at the nanometer level

Instrument overview

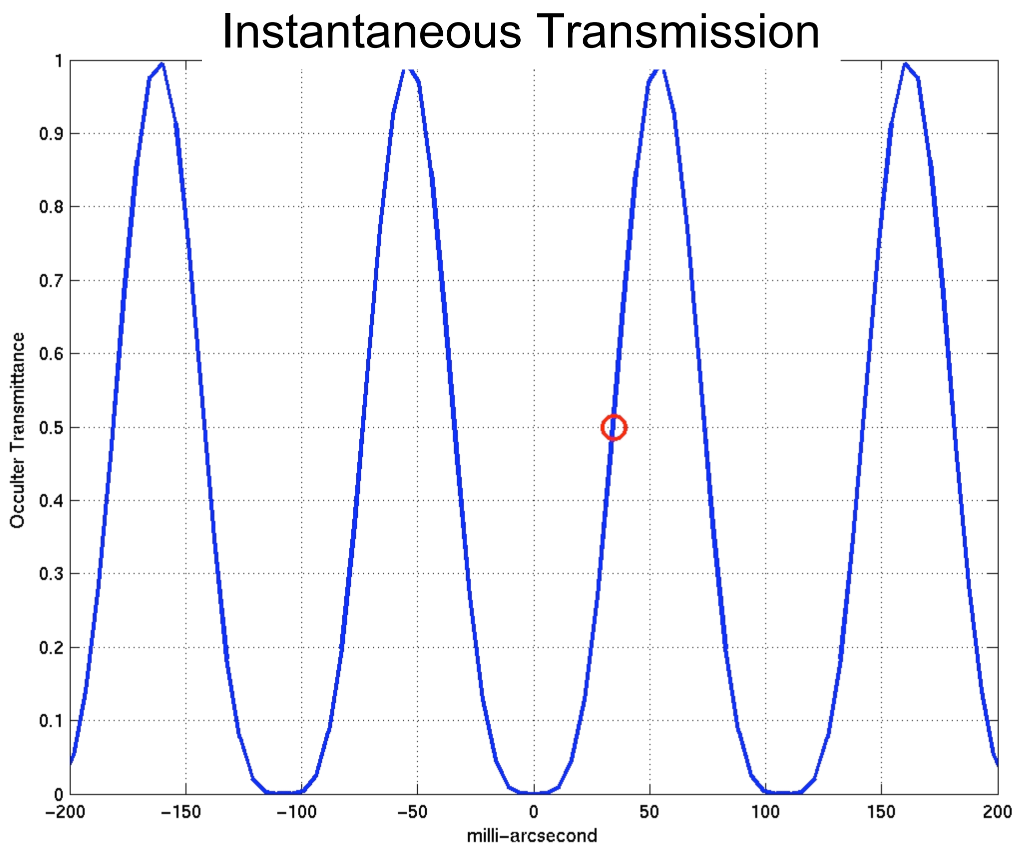


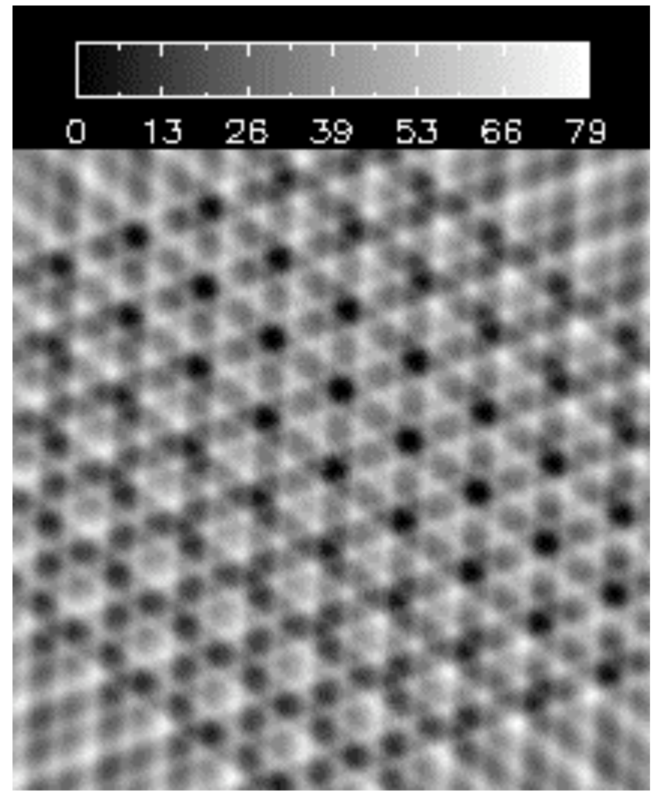
Nulling interferometer + WFS



Nuller transmittance/sky response

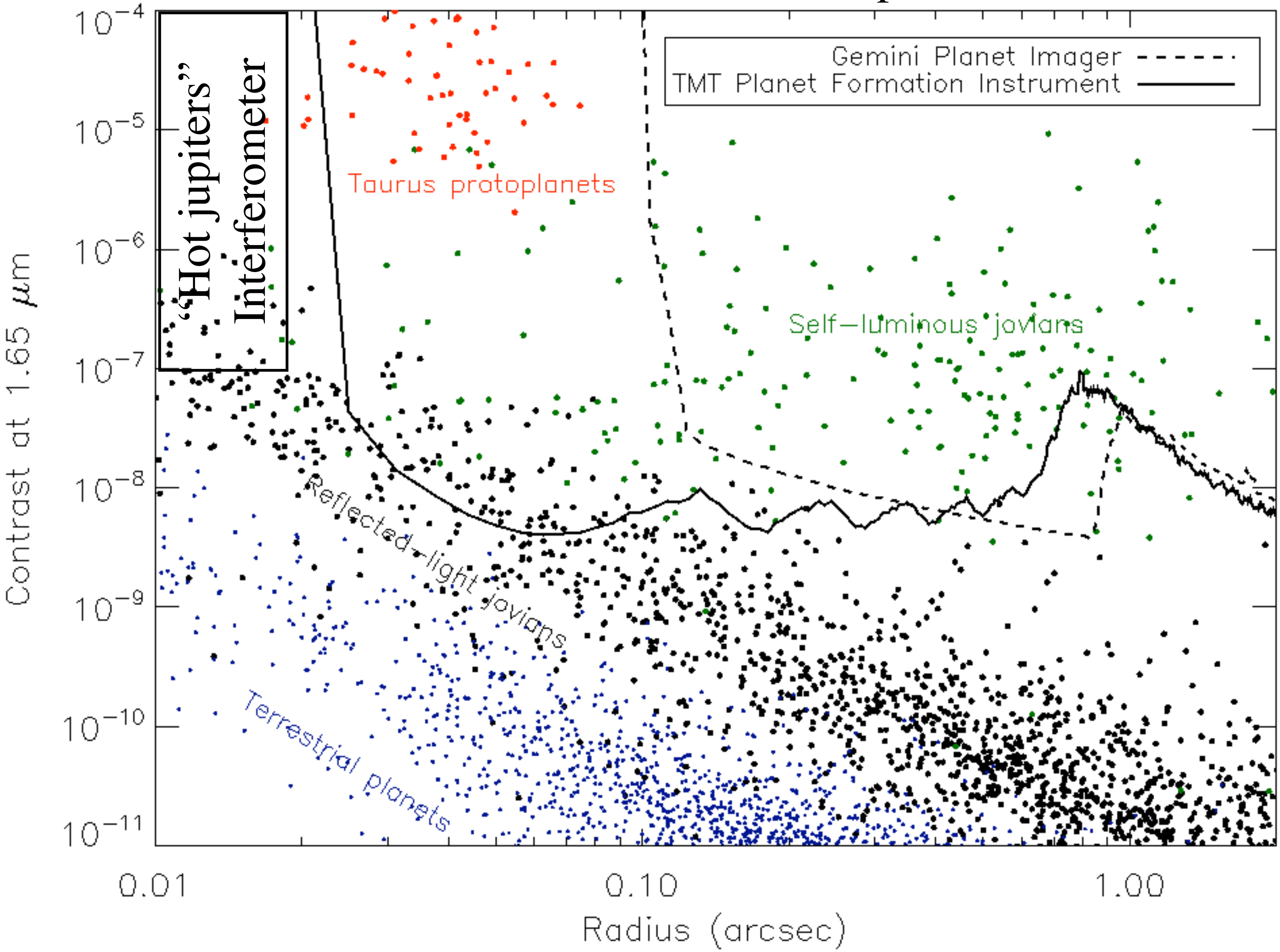
Transmittance





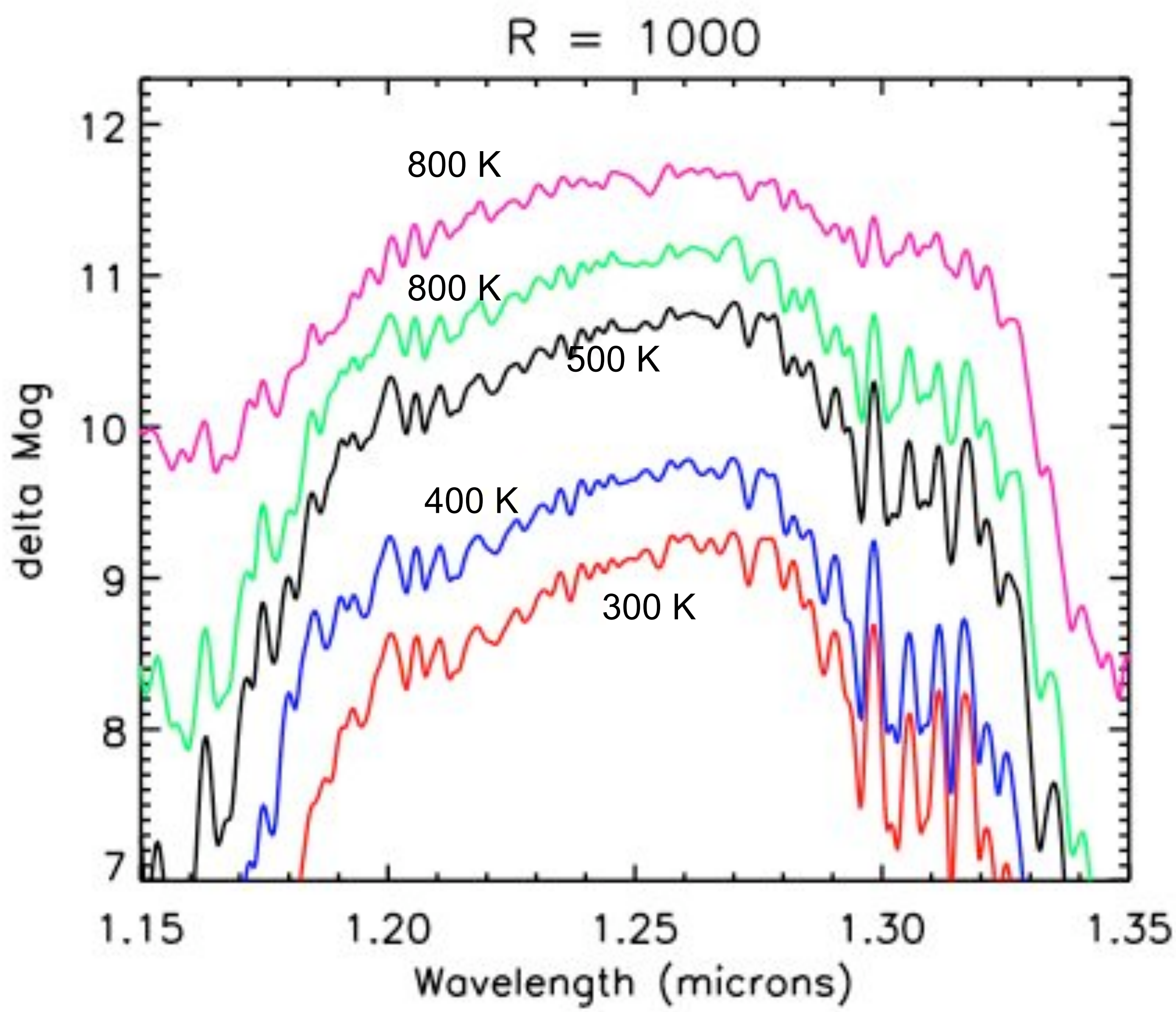
2-hour exposure 1.2x1.2 arcsec

Monte Carlo Extrasolar Planet Populations



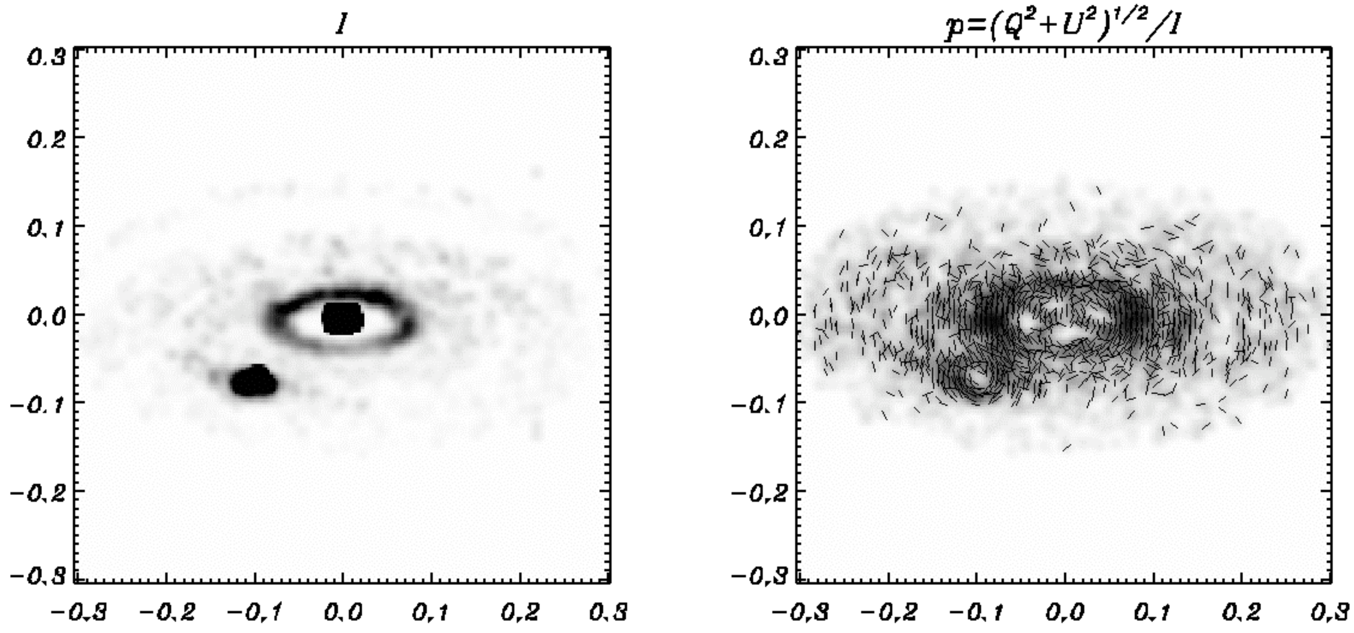
Spectral characterization: R=1000 for composition

- **R=100 spectroscopy needed for G / Teff**
- **R=1000 spectroscopy could measure compositions**
- **Planet *H*>24 mag**
- **Require multi-hour exposures on 20-30m filled apertures**

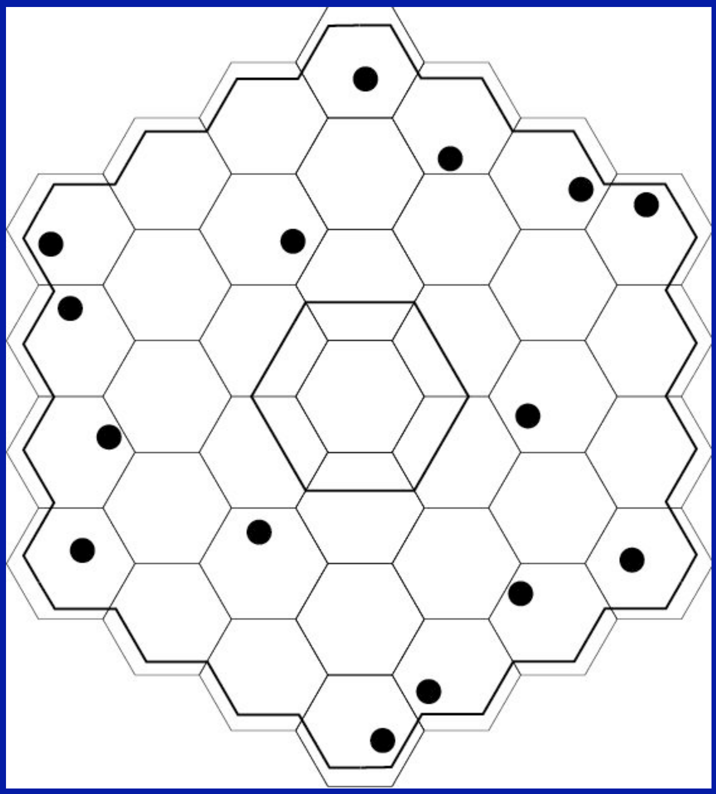


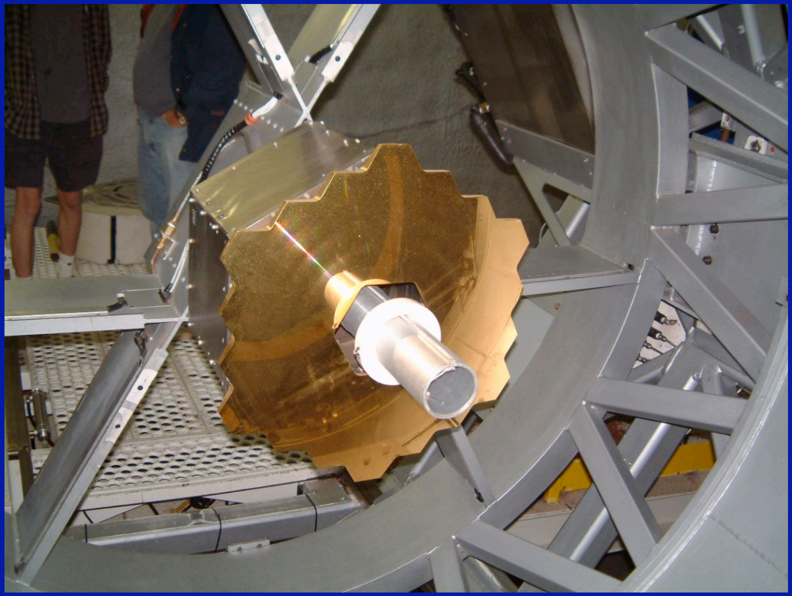
Polarization for studying young dusty systems

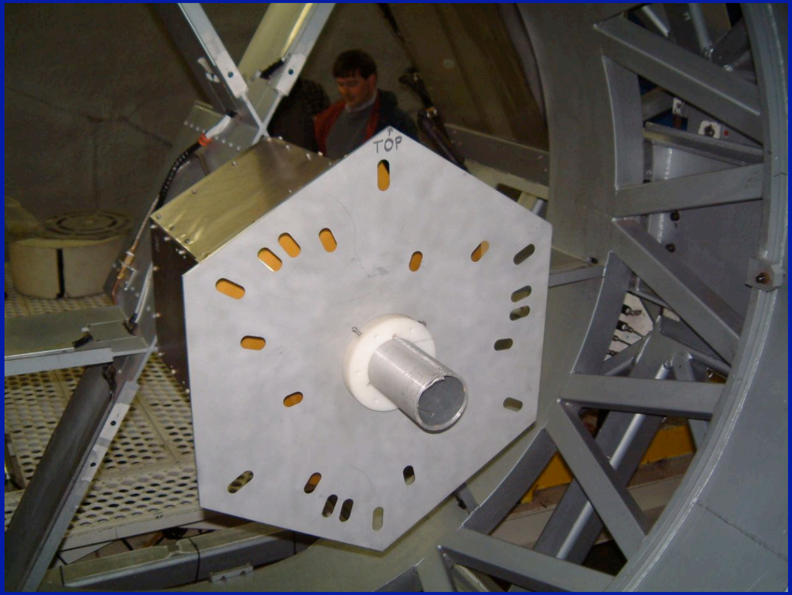
- T Tauri star (150 pc) with a ΔH = 10 mag. companion in an optically thick disk (i = 66°)
  - M = 3 M_J, t = 10 Myr



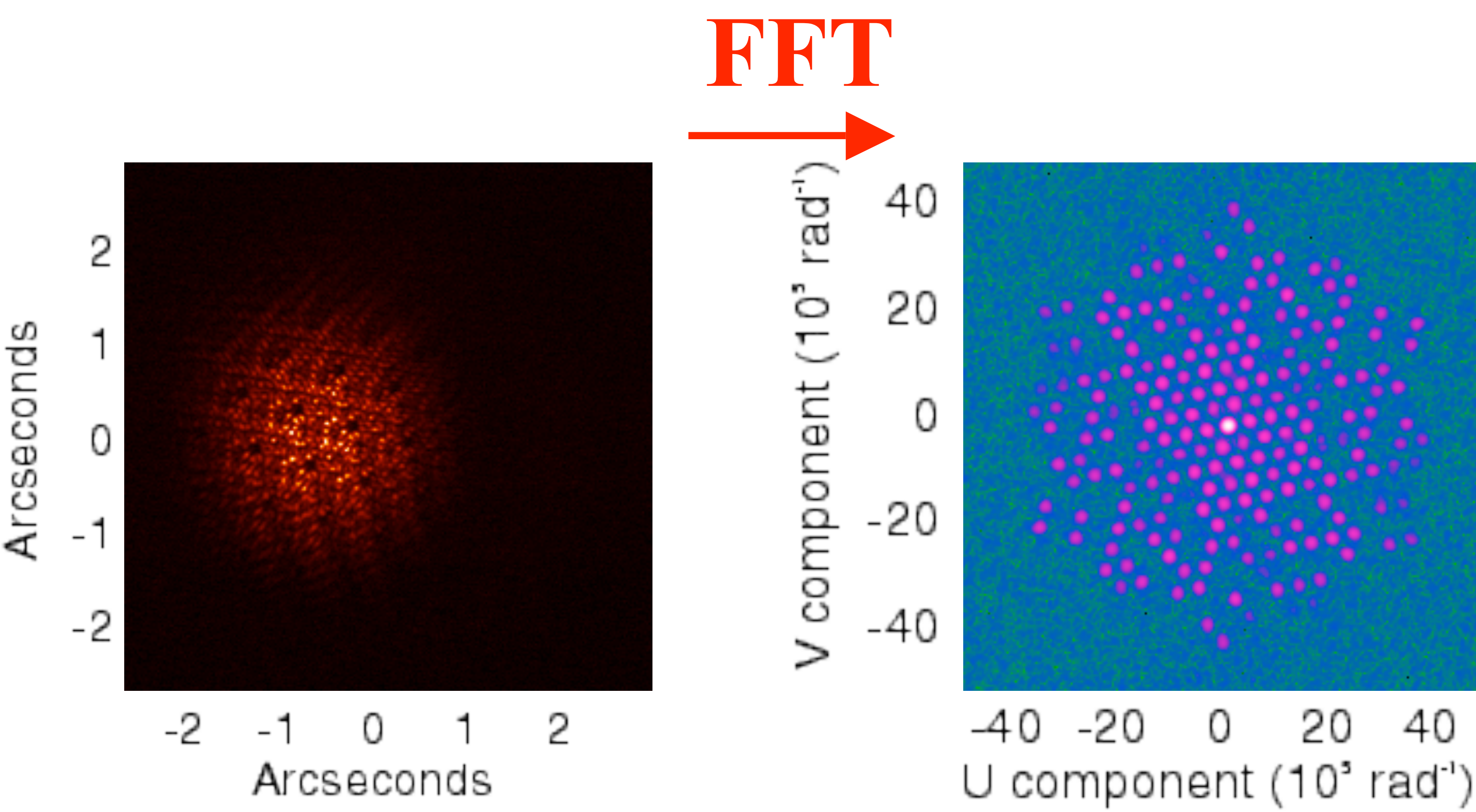
Non-redundant masking (Keck)





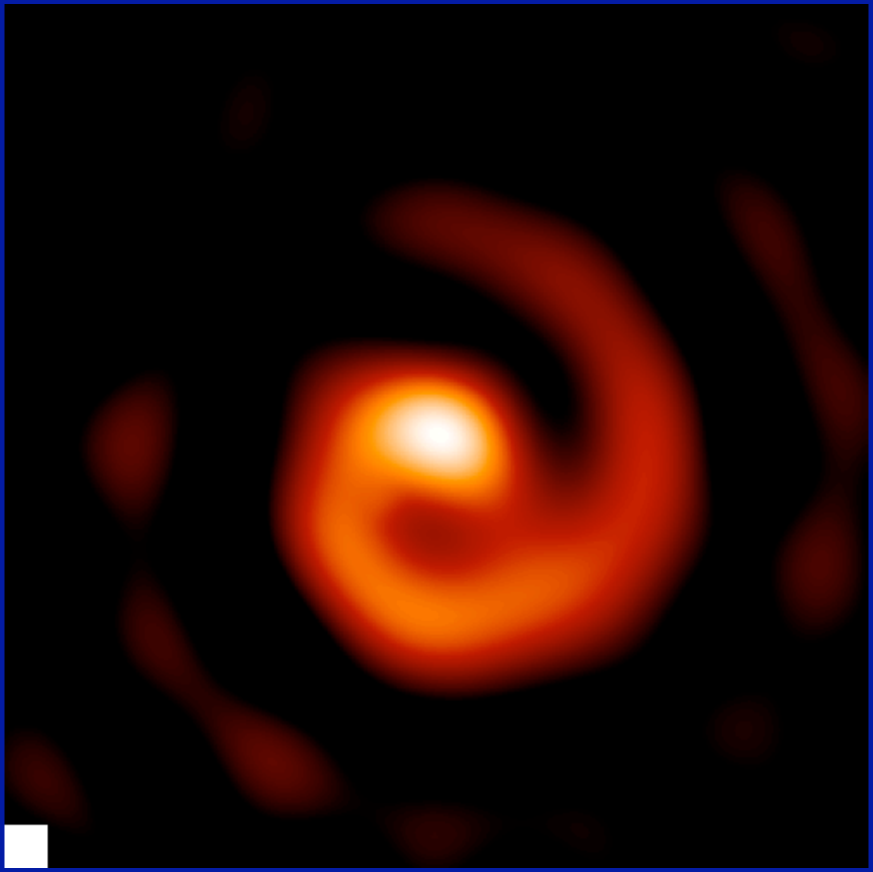


Speckles and Power Spectra

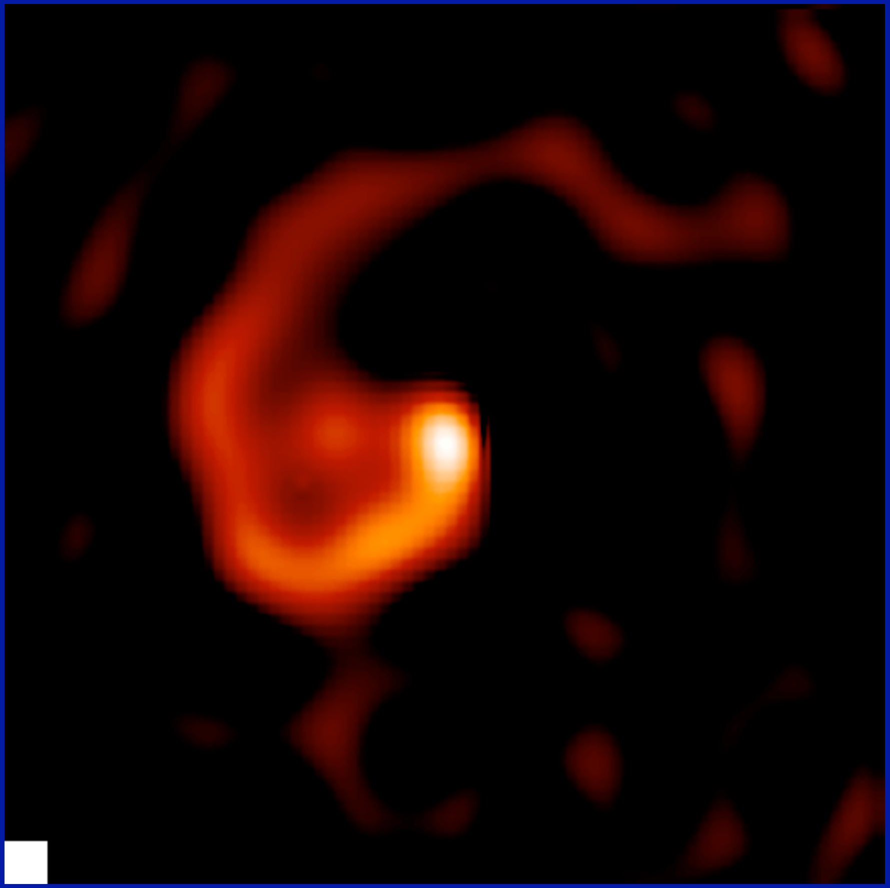


Pinwheels: Colliding-Wind Wolf-Rayet Binaries

WR 104 **50 mas (75 AU)**

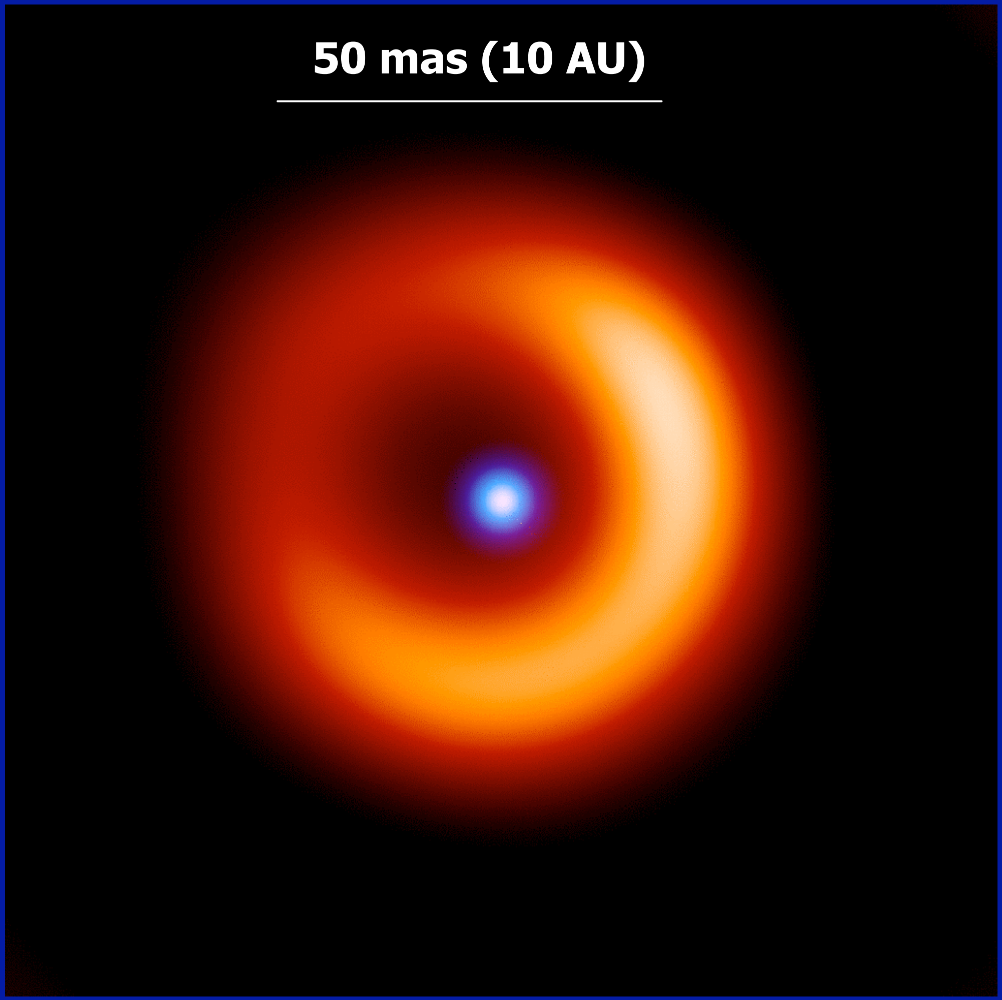


WR 98a **100 mas**



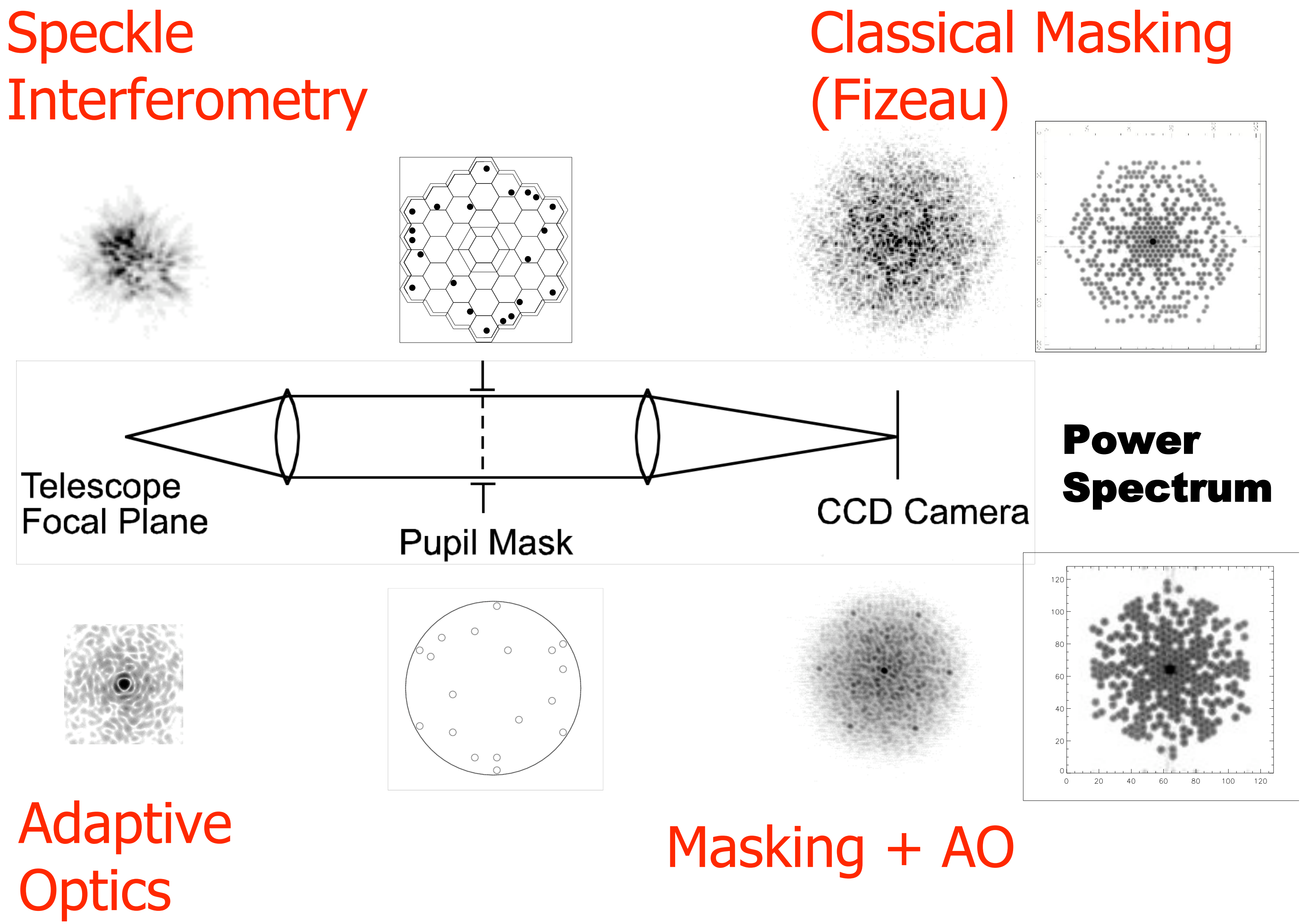
Tuthill, Monnier & Danchi 1999

LkHα 101: Our closest image of a starbirth



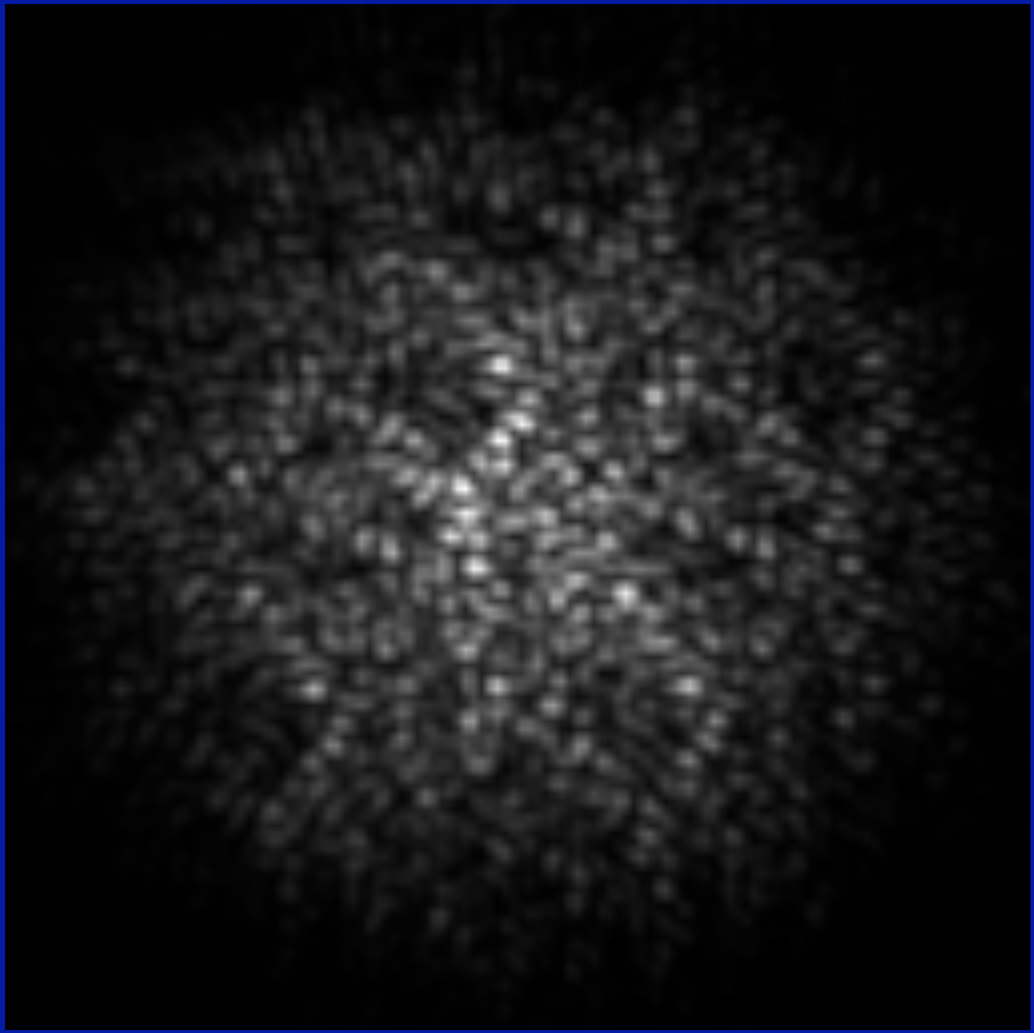
Tuthill et al 2000, 2002

- Herbig Ae/Be star
- Settle debate: Disk vs Envelope
- SED fitting ambiguous: central cavities now proven
- Overturn power-law thermal

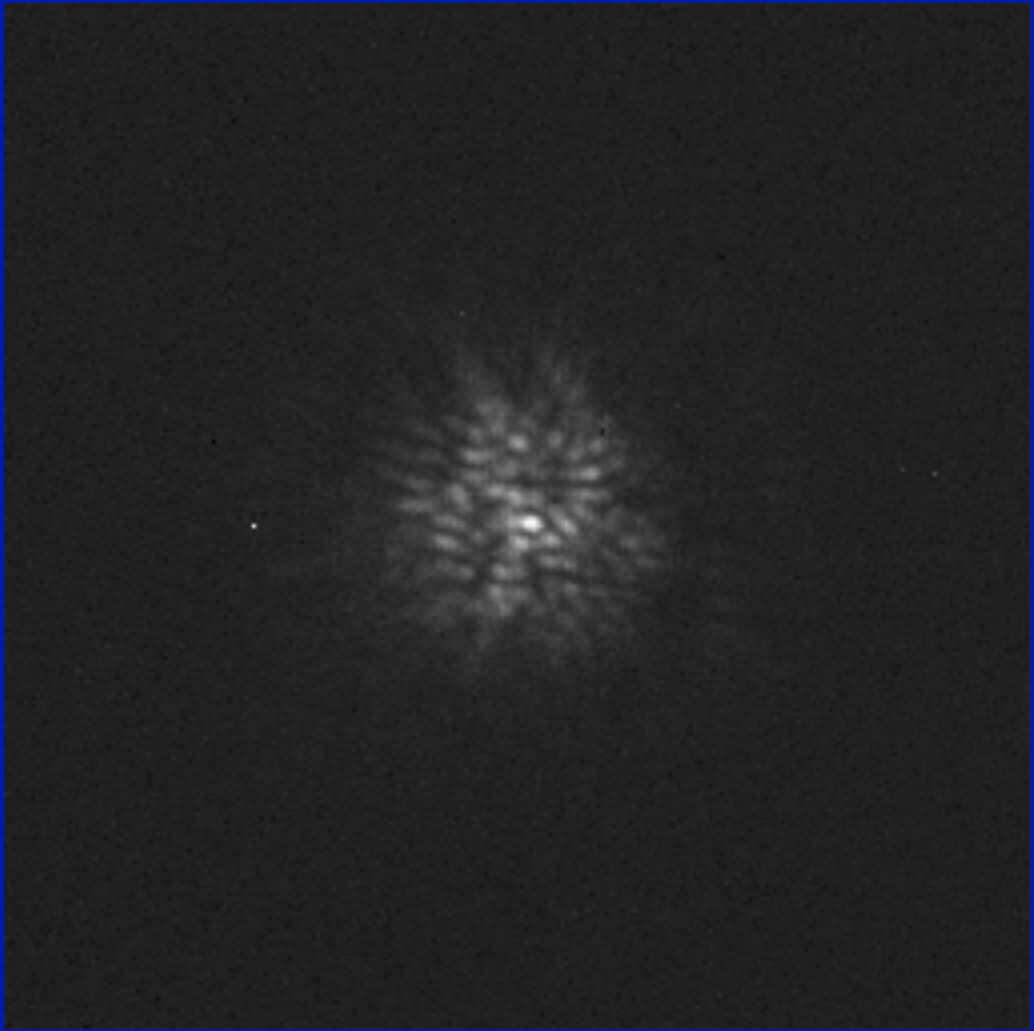


Speckle Interferometry
Classical Masking (Fizeau)
Telescope Focal Plane
Pupil Mask
CCD Camera
Power Spectrum
Adaptive Optics
Masking + AO
120
100
80
60
40
20
0
0
20
40
60
80
100
120

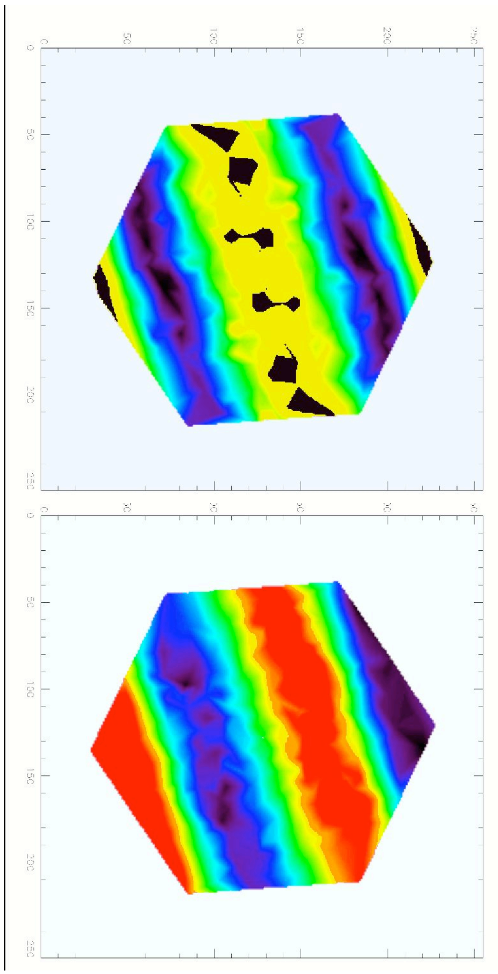
Masking: No AO (Keck)

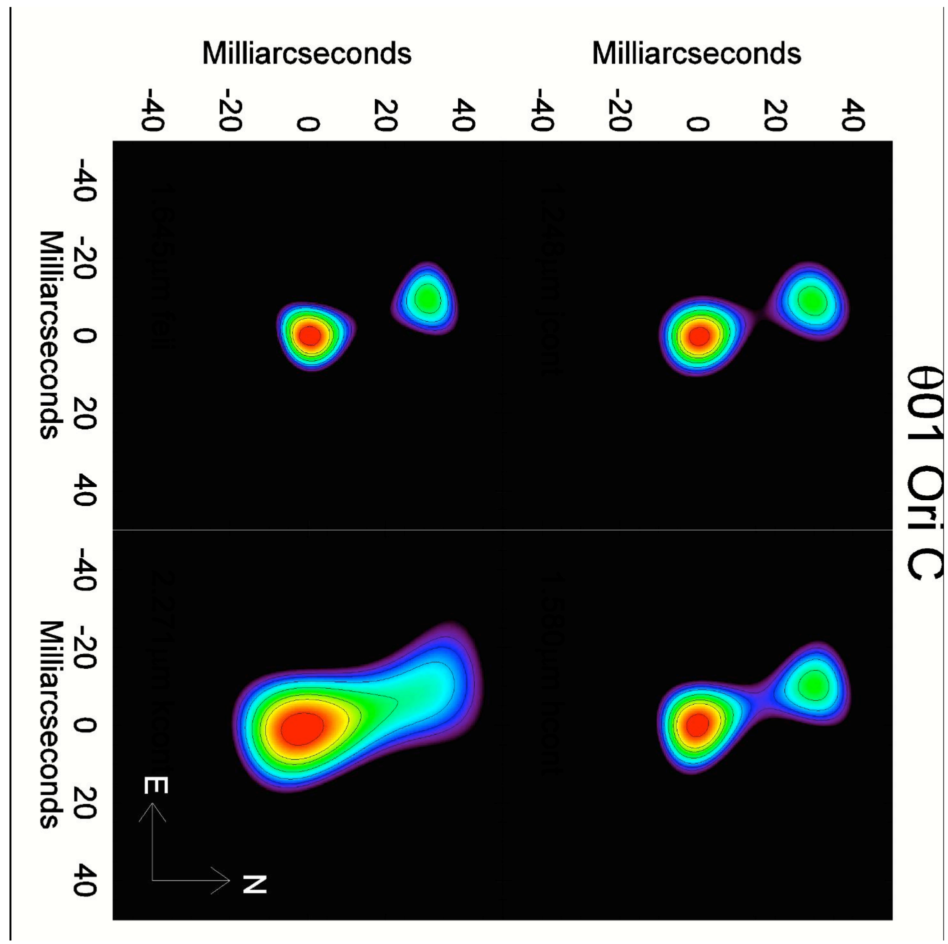


Masking + AO (PALAO+PHARO)

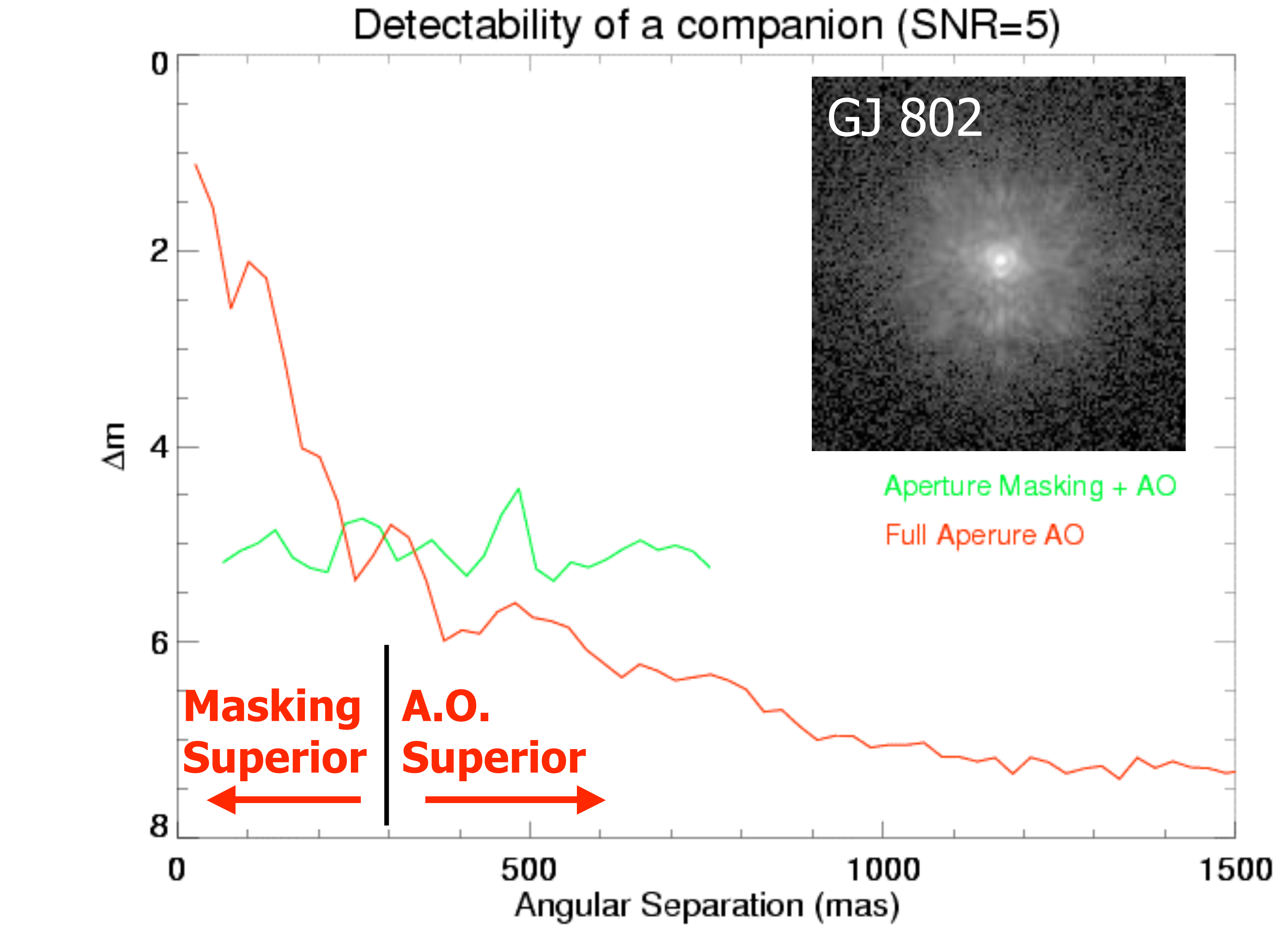


Sparse-Aperture AO results



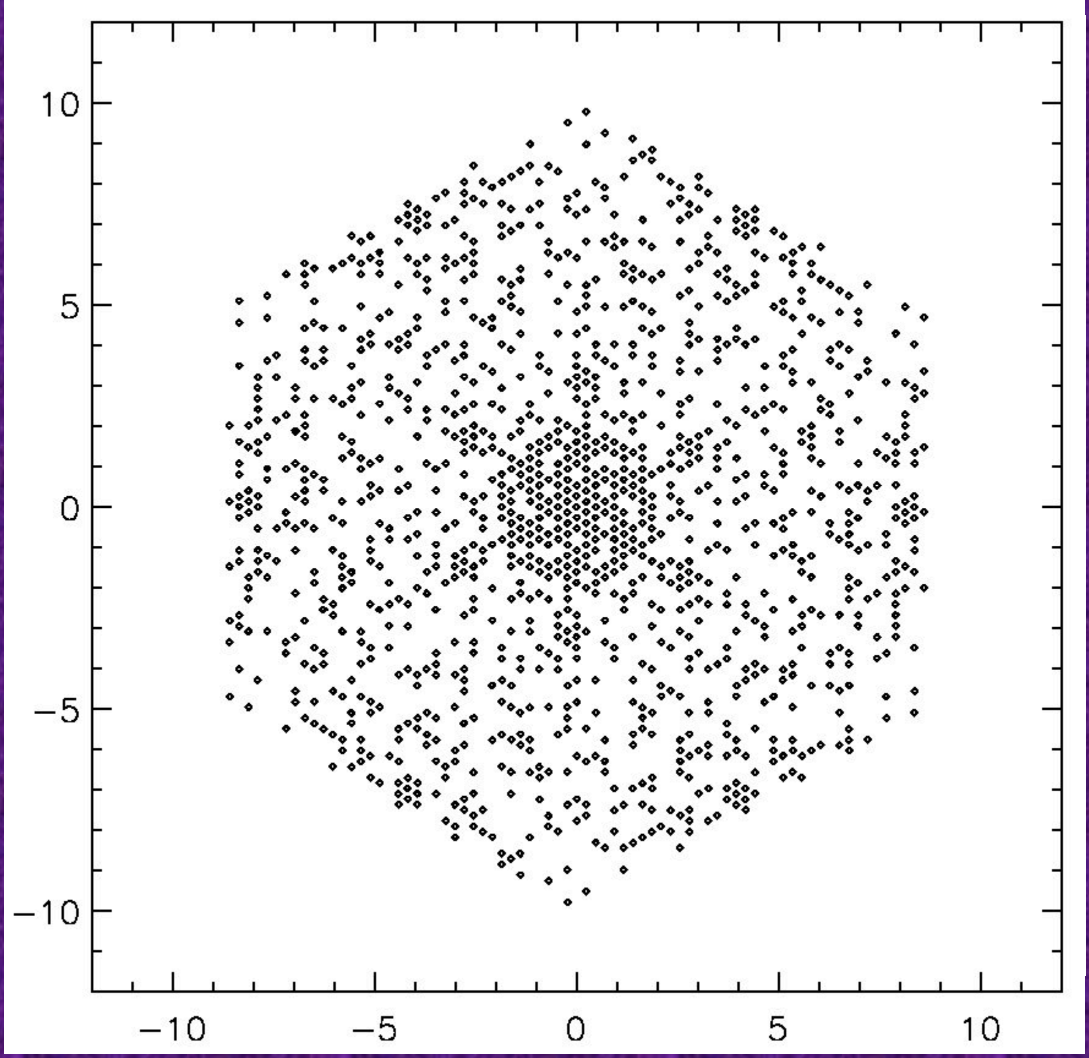


Palomar Faint Companion Program



36-aperture geometry

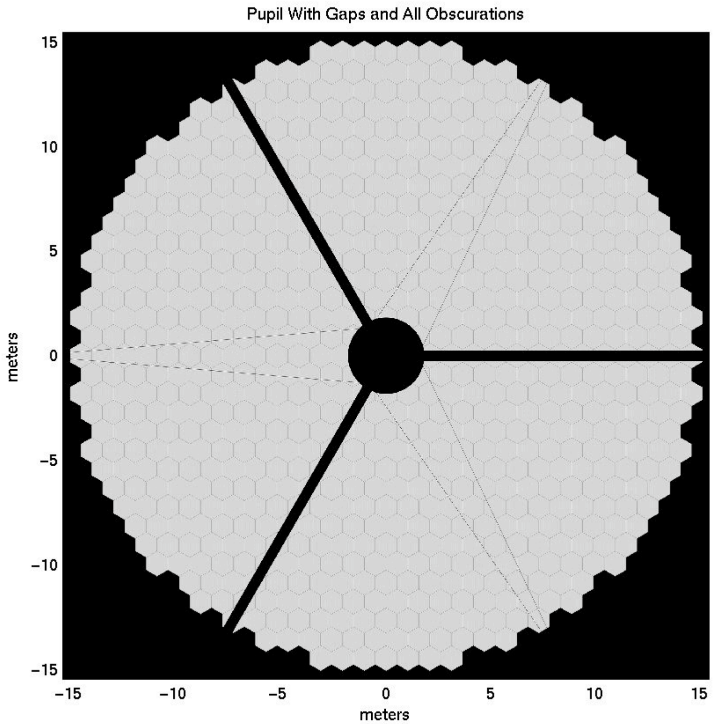
- Non-redundant masking provides many more baselines than conventional interferometers, but lower resolution and sensitivity
- Complex targets with strong signals at 30-m spatial frequencies
- e.g. searching 2MASS for 30-m resolvable hot dust leads to 150 targets (up from 12 on 10-m)

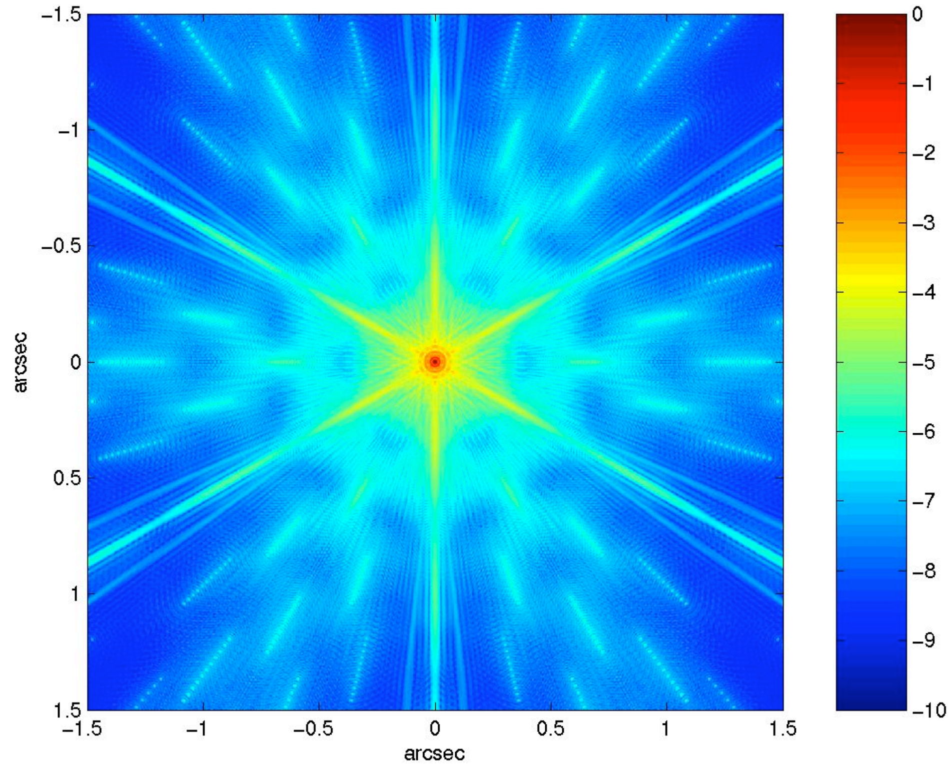


Insufficiently justified conclusions

- **20-40m ELTs with adaptive optics are almost inevitable**
  - AO performance will improve for shorter wavelengths / high Strehl
- **Many ELT science missions require large collecting areas but not necessarily diffraction-limited resolution**
- **Systematic errors complicate interpretation of AO data at the smallest angular scales and moderate contrasts**
  - AO needs new ways of thinking about systematic calibration problem
- **Sample ELT roles: Photon-starved, complex objects**
  - Multiplexed extragalactic science, Crowded and complex fields
  - Planet detection at >0.1", mapping systems, and high-resolution exoplanet spectroscopy
    - Astrometry is highly complementary
- **Interferometer roles: measuring sets of numbers**
  - Objects with complex structure that can be parametrized
  - Planet detection at <0.03" for some systems
  - SKY COVERAGE is a key for the broad community
- **AO aperture masking provides intermediate capabilities**

Diffraction



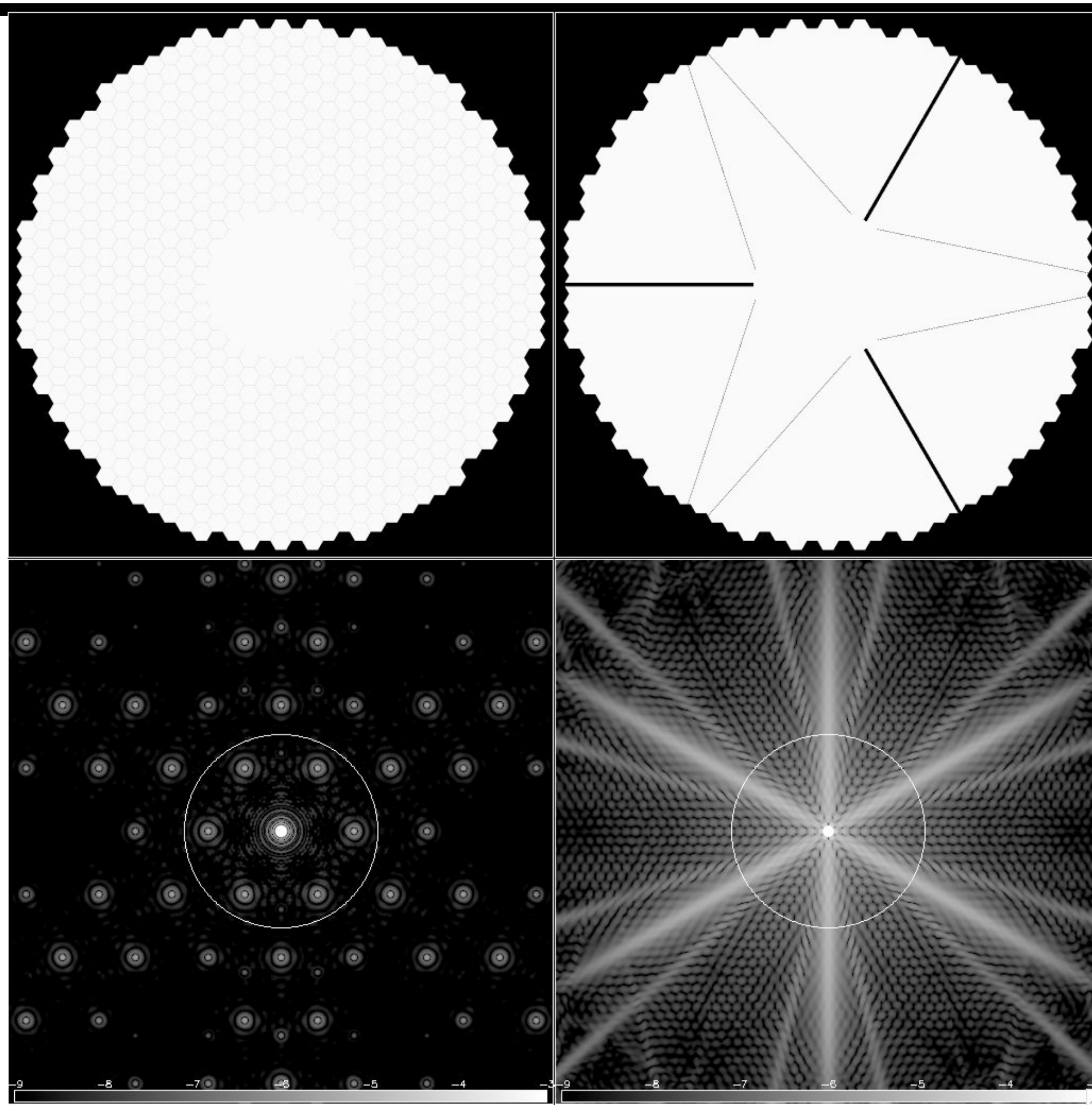


TMT

THIRTY METER TELESCOPE

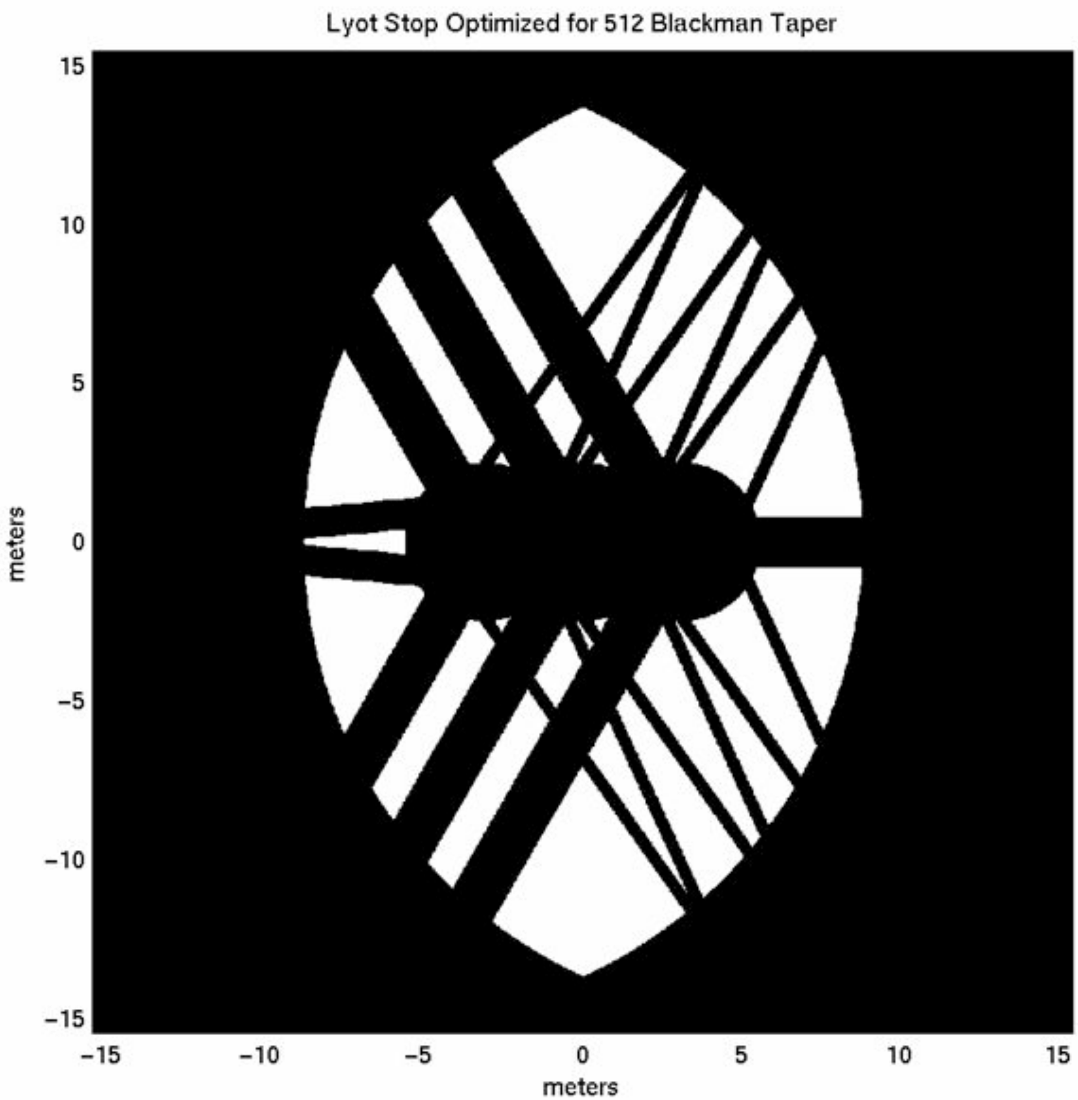
TMT PSFs: Gaps vs M2

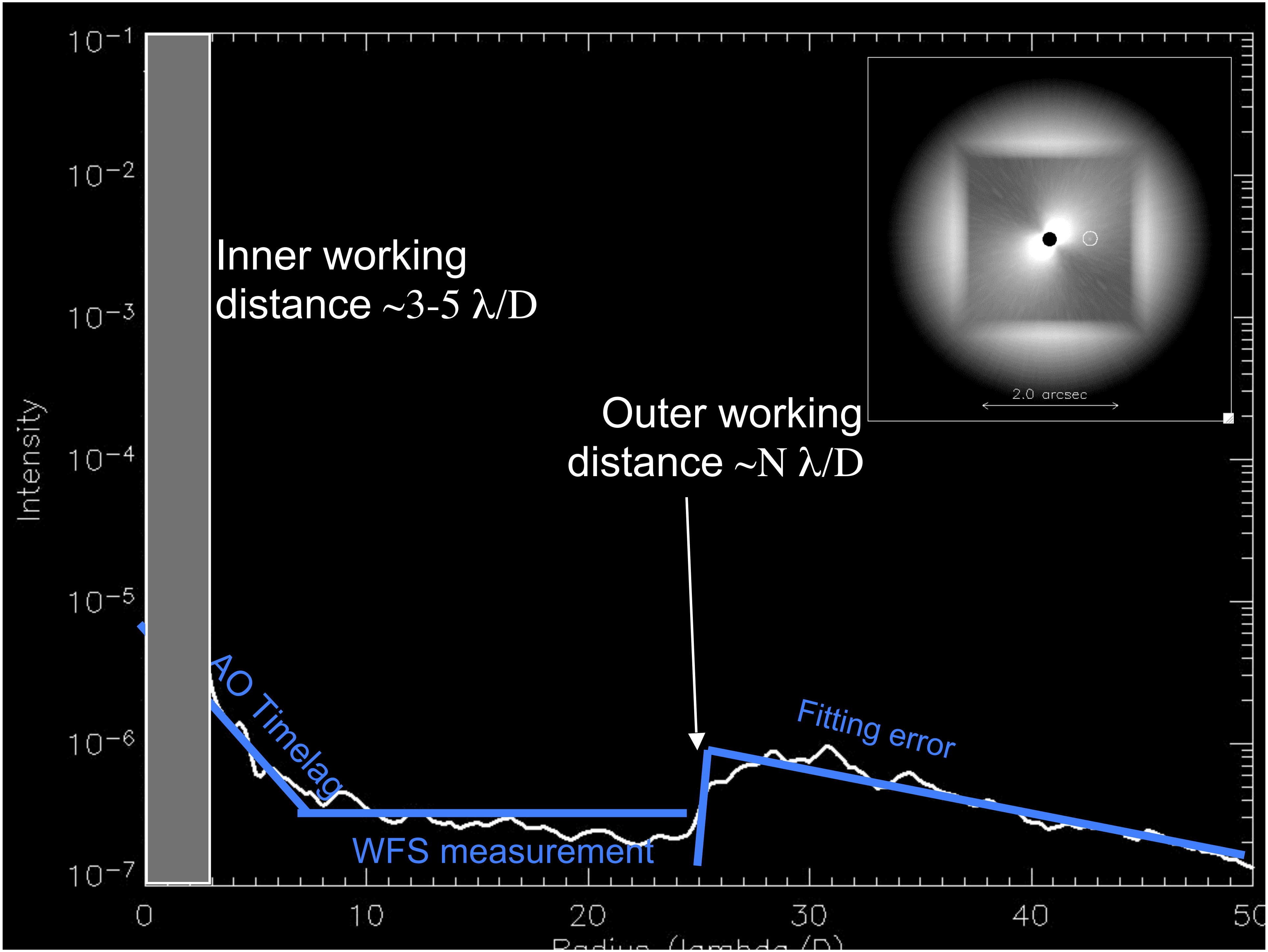
Gaps only



M2 supports only

2-stage nuller output pupil





Intensity
Radius (lambda/D)
Inner working distance ~3-5 λ/D
Outer working distance ~N λ/D
2.0 arcsec
AO Timelag
WFS measurement
Fitting error