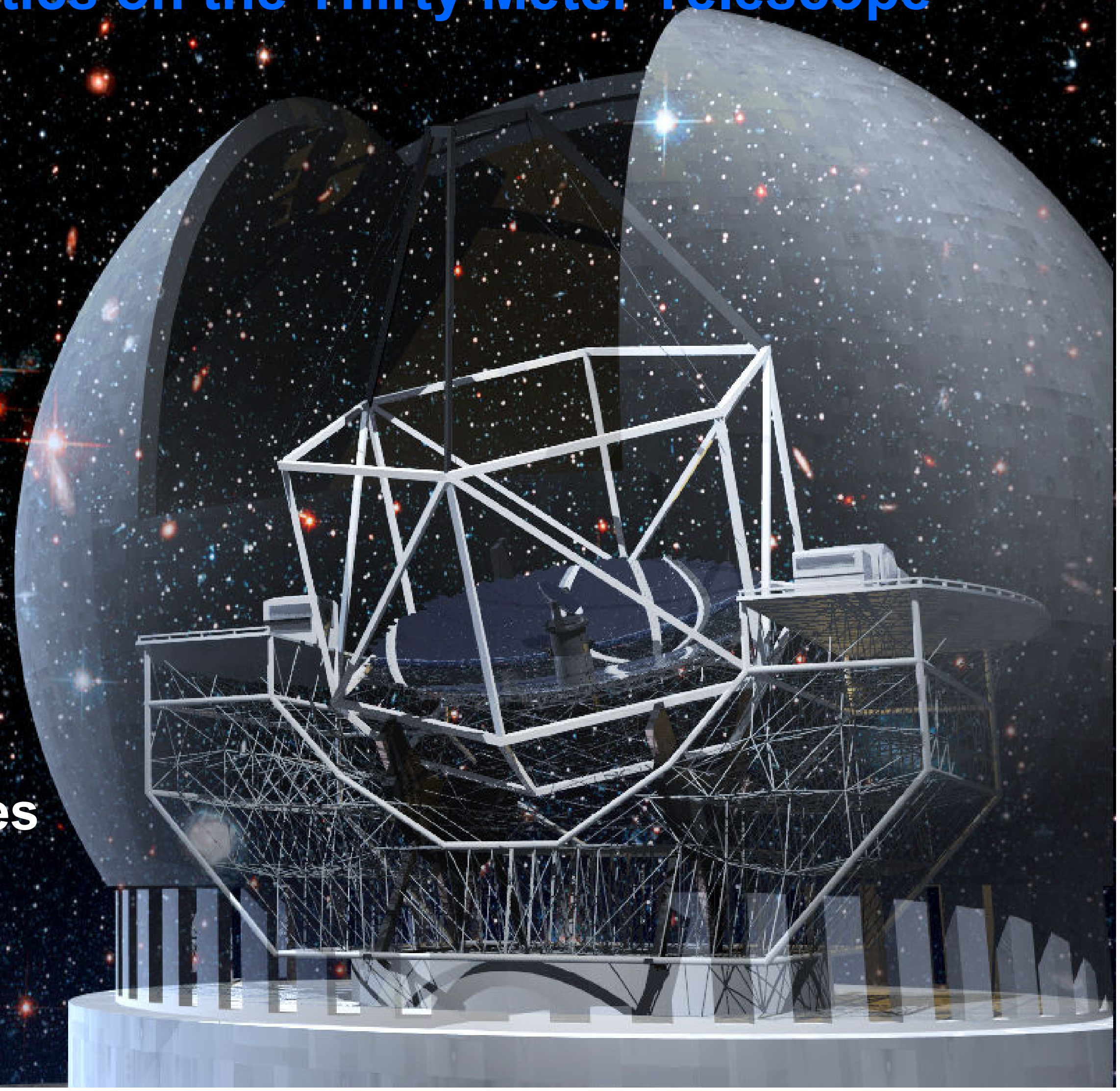
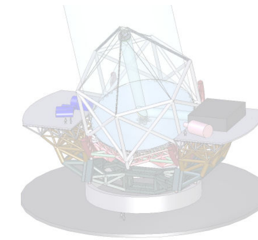
The Planet Formation Instrument:

Extreme Adaptive Optics on the Thirty Meter Telescope

Ian J. Crossfield
Jet Propulsion Laboratory, Pasadena

UC Berkeley
Star Formation Seminar Series
January 23, 2007





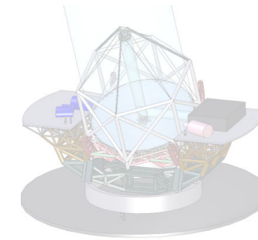
Overview

- Introducing the Thirty Meter Telescope (TMT)
- Science with the TMT
- Planet Formation Instrument (PFI)
- PFI Science case
- Using PFI to design the TMT

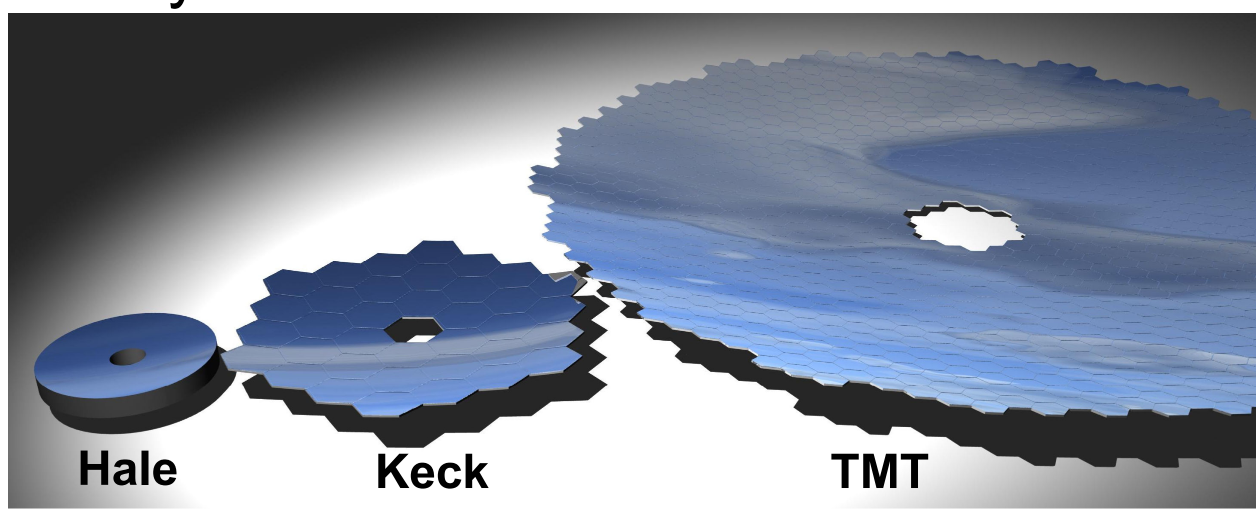
Jet Propulsion Laboratory
California Institute of Technology

THIRTY METER TELESCOPE

Introduction to the TMT



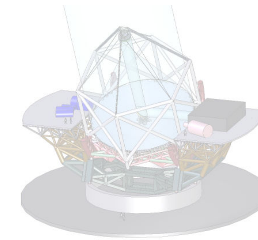
- A 30-m telescope is a powerful step in astronomy that recognizes the technology advances achievable in one generation
- NAS Decadal Survey (2001) recommended a 30-m telescope as its highest priority
- A partnership to build a 30-m telescope
  - University of California, Caltech, Canada (ACURA)
- Construction start: early 2009
- First Light: 2015



Jet Propulsion Laboratory
California Institute of Technology

THIRTY METER TELESCOPE

Science with the TMT



- Many of today's science projects tend to be photon starved and/or limited by angular resolution
- Sensitivity and resolution both increase with aperture size
  - As D^2 when seeing limited
  - As D^4 when diffraction limited
- Projected to perform 50% science with Adaptive Optics
- Tomorrow's projects will be enabled by a 30-m
  - Planet studies
  - Tomography of distant universe
  - 1st generation of stars
  - Stars in nearby galaxies
- For astronomy, bigger is better, so 30-m is a judgment about the proper balance between **science benefit**, cost, technological readiness, and schedule

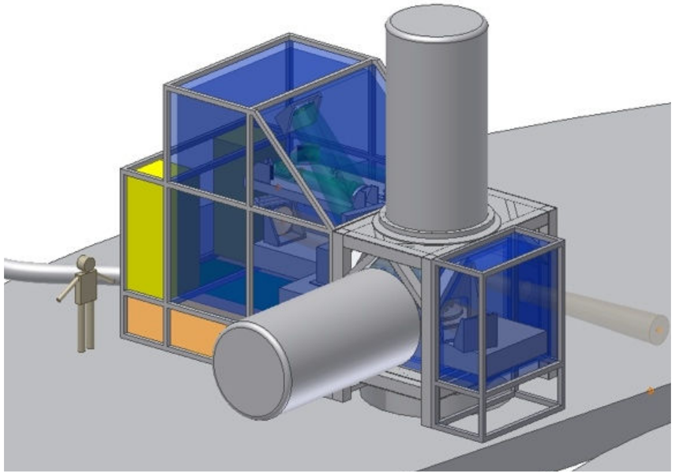
Jet Propulsion Laboratory
California Institute of Technology

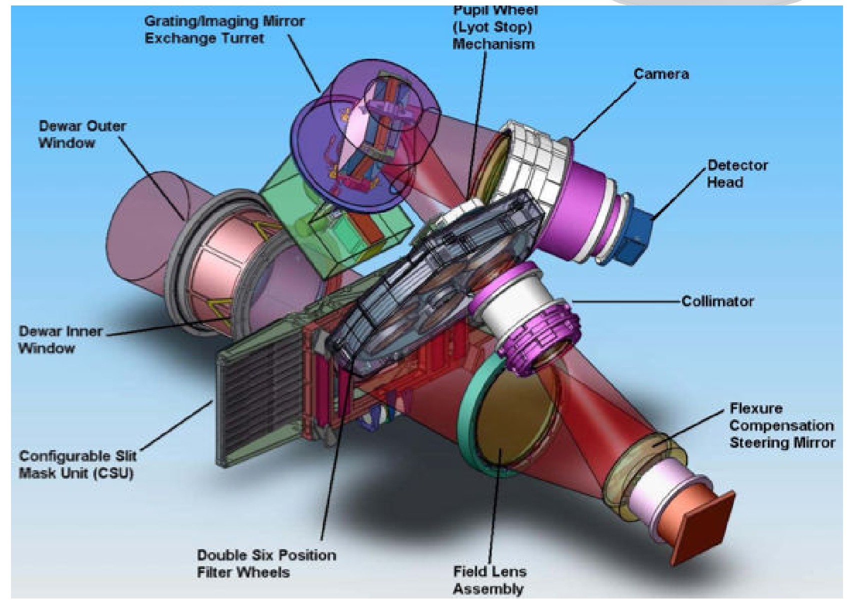
TMT science instrument summary

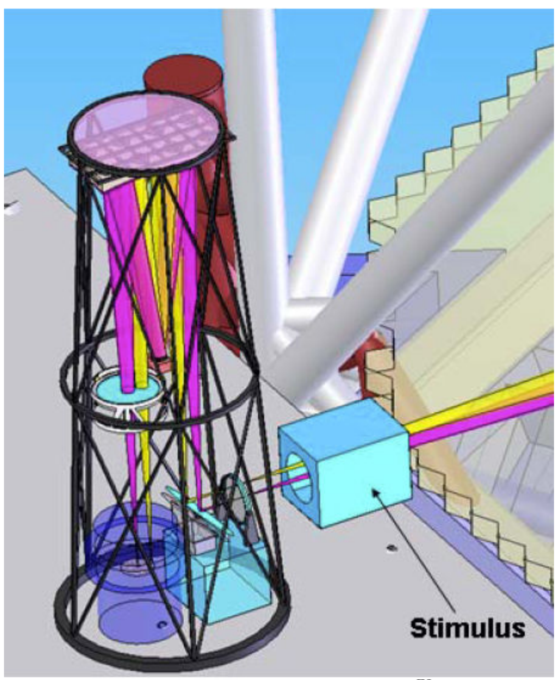
Instrument	Spectral Resolution	Science Case
Near-IR DL Spectrometer & Imager (IRIS)	≤4000	• Assembly of galaxies at large redshift • Black holes/AGN/Galactic Center • Resolved stellar populations in crowded fields
Wide-field Optical Spectrometer (WFOS)	500 - 7500	• IGM structure and composition $2<z<6$ • High-quality spectra of $z>1.5$ galaxies suitable for measuring stellar pops, chemistry, energetics
Multi-IFU, near-DL, near-IR Spectrometer (IRMOS)	2000 - 10000	• Near-IR spectroscopic diagnostics of the faintest objects • JWST followup
Mid-IR Echelle Spectrometer & Imager (MIRES)	5000 - 100000	• Physical structure and kinematics of protostellar envelopes • Physical diagnostics of circumstellar/protoplanetary disks: where and when planets form during the accretion phase
Optical Echelle (HROS)	30000 - 50000	• Stellar abundance studies throughout the Local Group • ISM abundances/kinematics, IGM characterization to $z\sim6$ • Extra-solar planets!
ExAO I (PFI)	50 - 300	• Direct detection and spectroscopic characterization of extra-solar planets
MCAO imager (WIRC)	5 - 100	• Galactic center astrometry • Stellar populations to 10Mpc
Near-IR, DL Echelle (NIRES)	5000 - 30000	• Precision radial velocities of M-stars and detection of low-mass planets • IGM characterizations for $z>5.5$

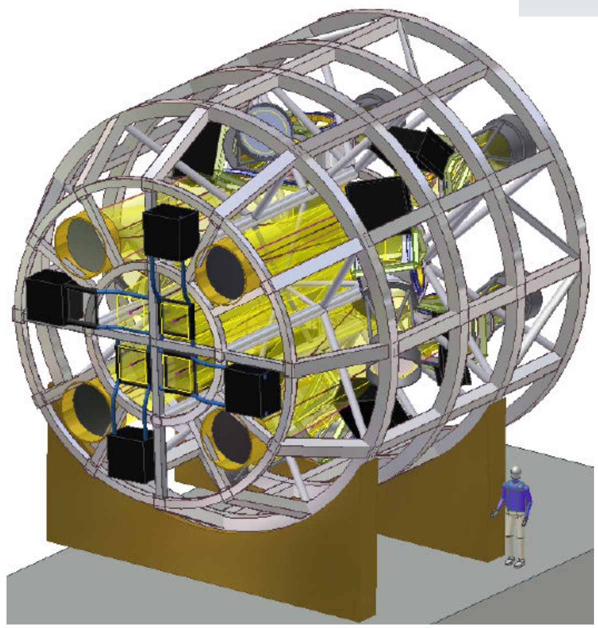
THIRTY METER TELESCOPE

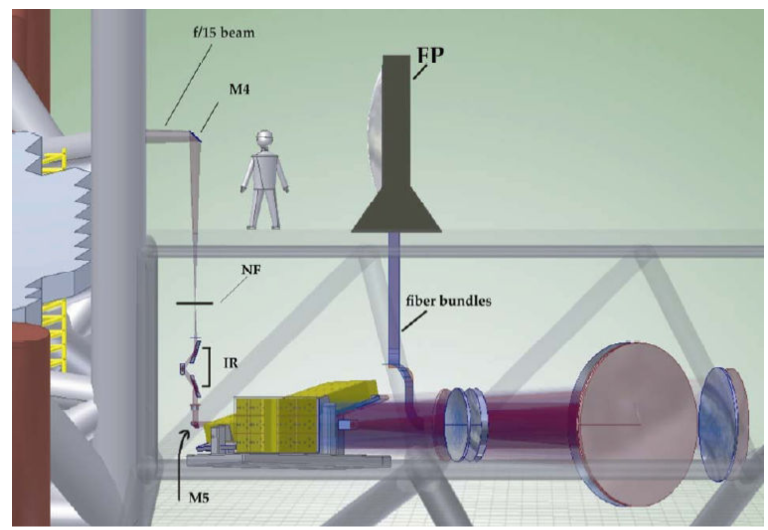
TMT instrument concepts





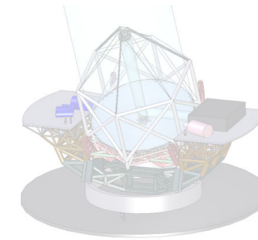






THIRTY METER TELESCOPE

Planet Formation Instrument



- High-contrast / “extreme AO” instrument
- Large collaboration: LLNL, JPL, UC Berkeley, Universite de Montreal, COM DEV, Immervision Inc.
- J, H, K imaging, spectroscopy, and polarimetry
- PFI Requirements and goals:

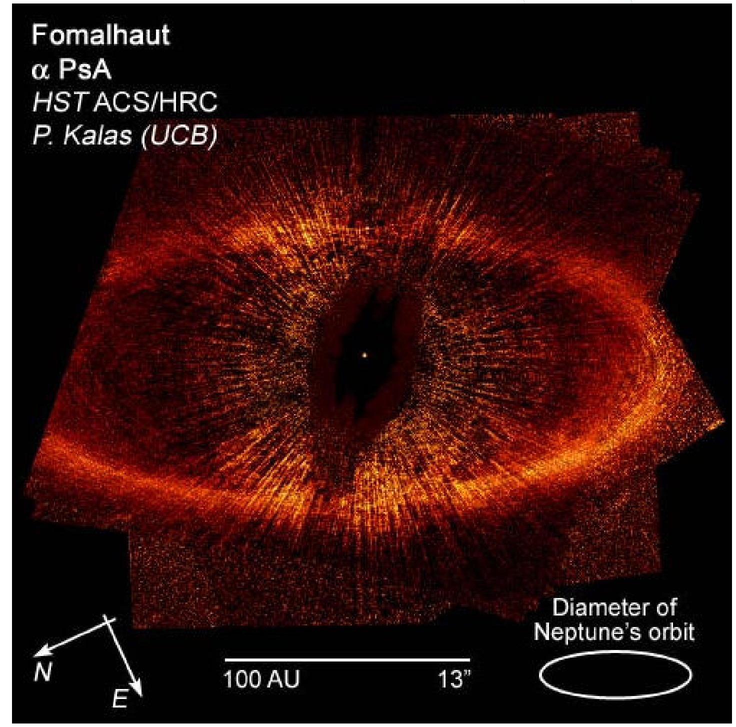
	Requirement	**Goal**
Contrast & IWA (I<8)	10^{-8} @ 50 mas	10^{-9} @ 100 mas
Contrast & IWA (H<10)	10^{-6} @ 30 mas	2×10^{-7} @ 30 mas

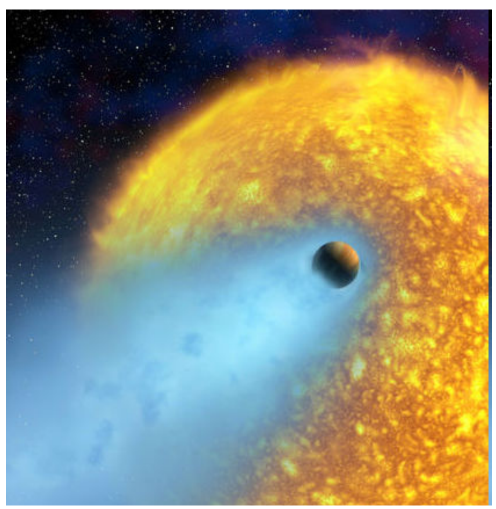
Jet Propulsion Laboratory
California Institute of Technology

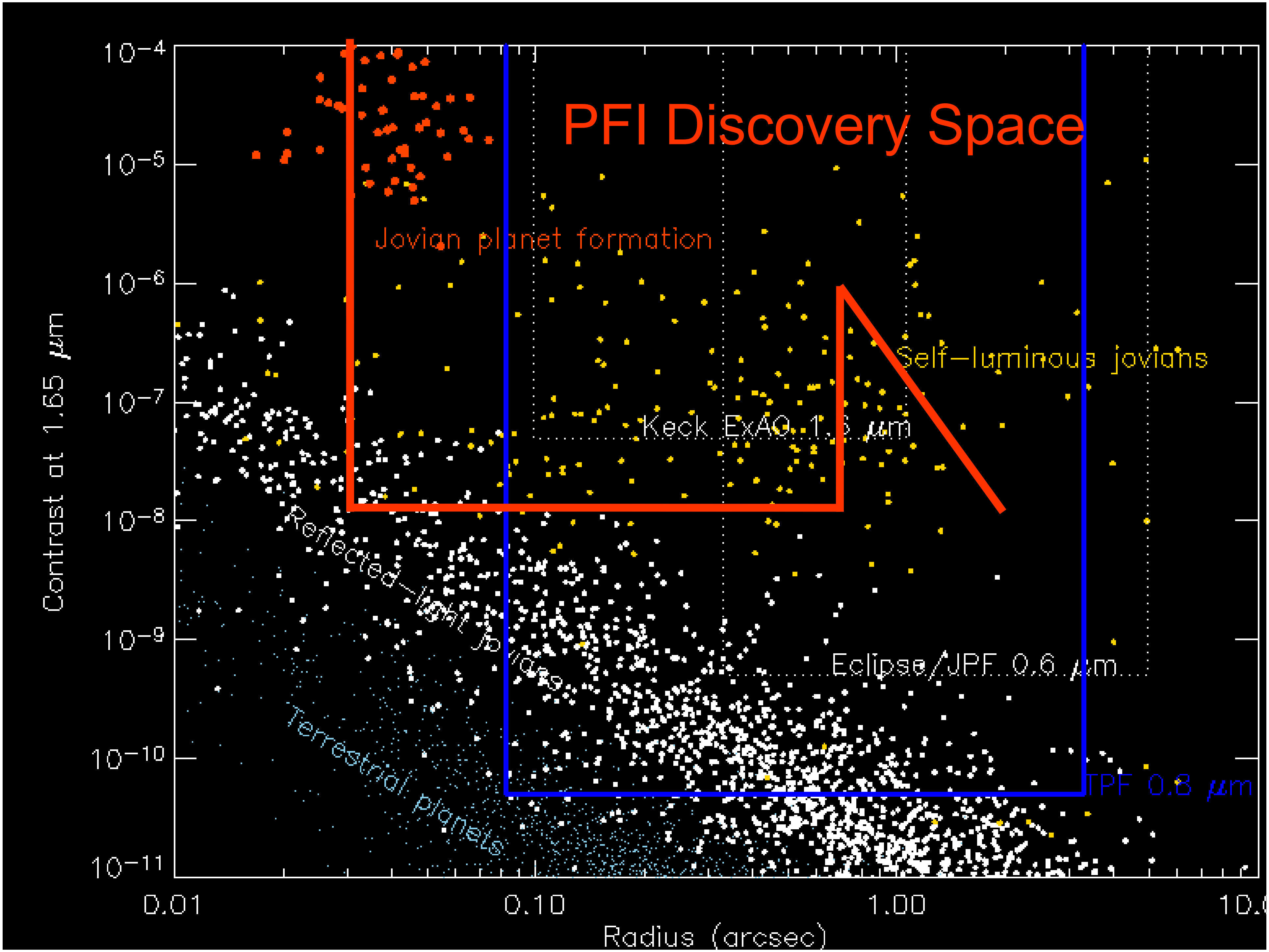
TMT
THIRTY METER TELESCOPE

PFI science case

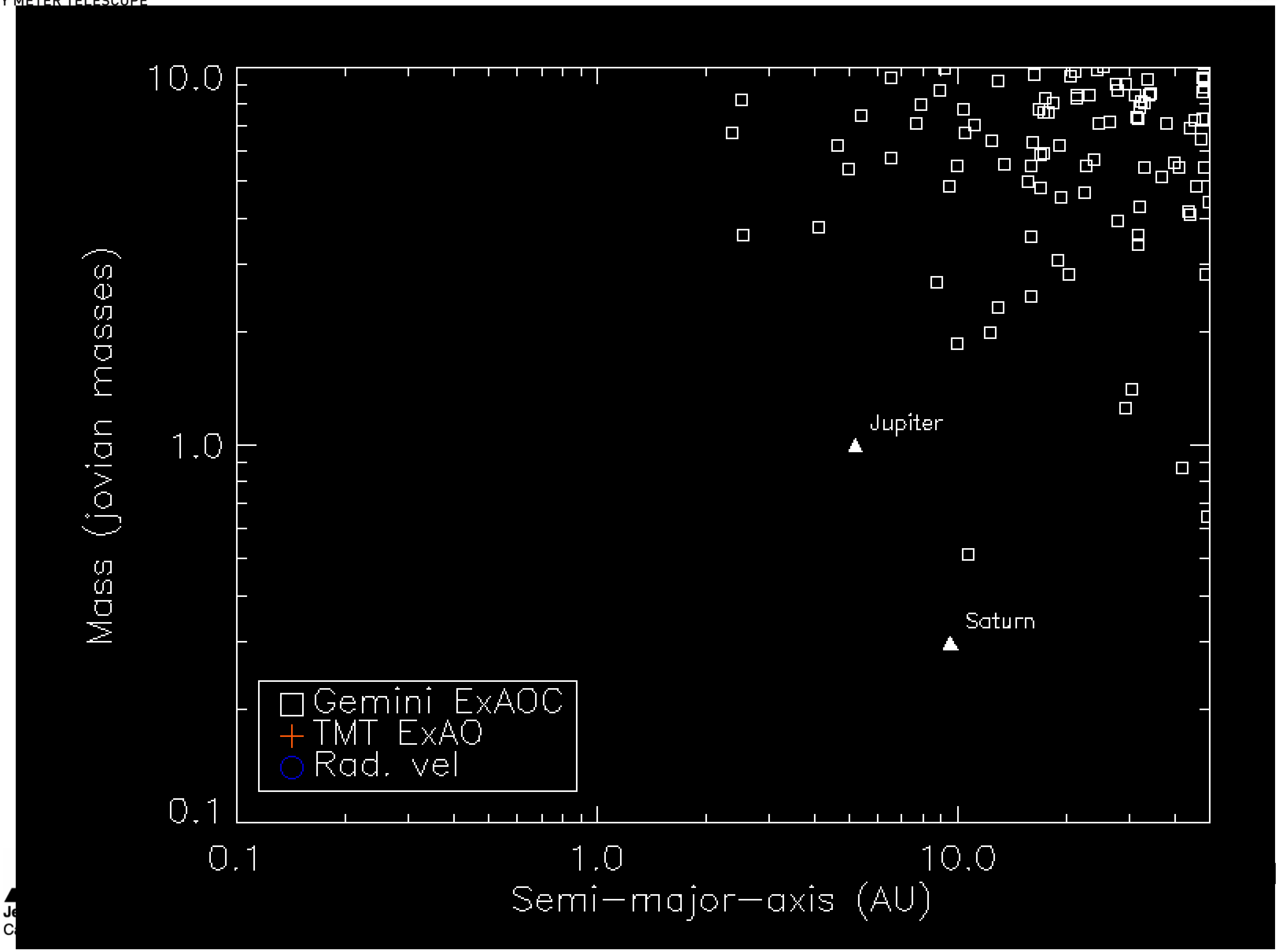
- Planetary disks
- In-situ planet formation
- Self-luminous “hot Jupiters”
- Mature, reflected-light planets
- Exoplanetary spectroscopy



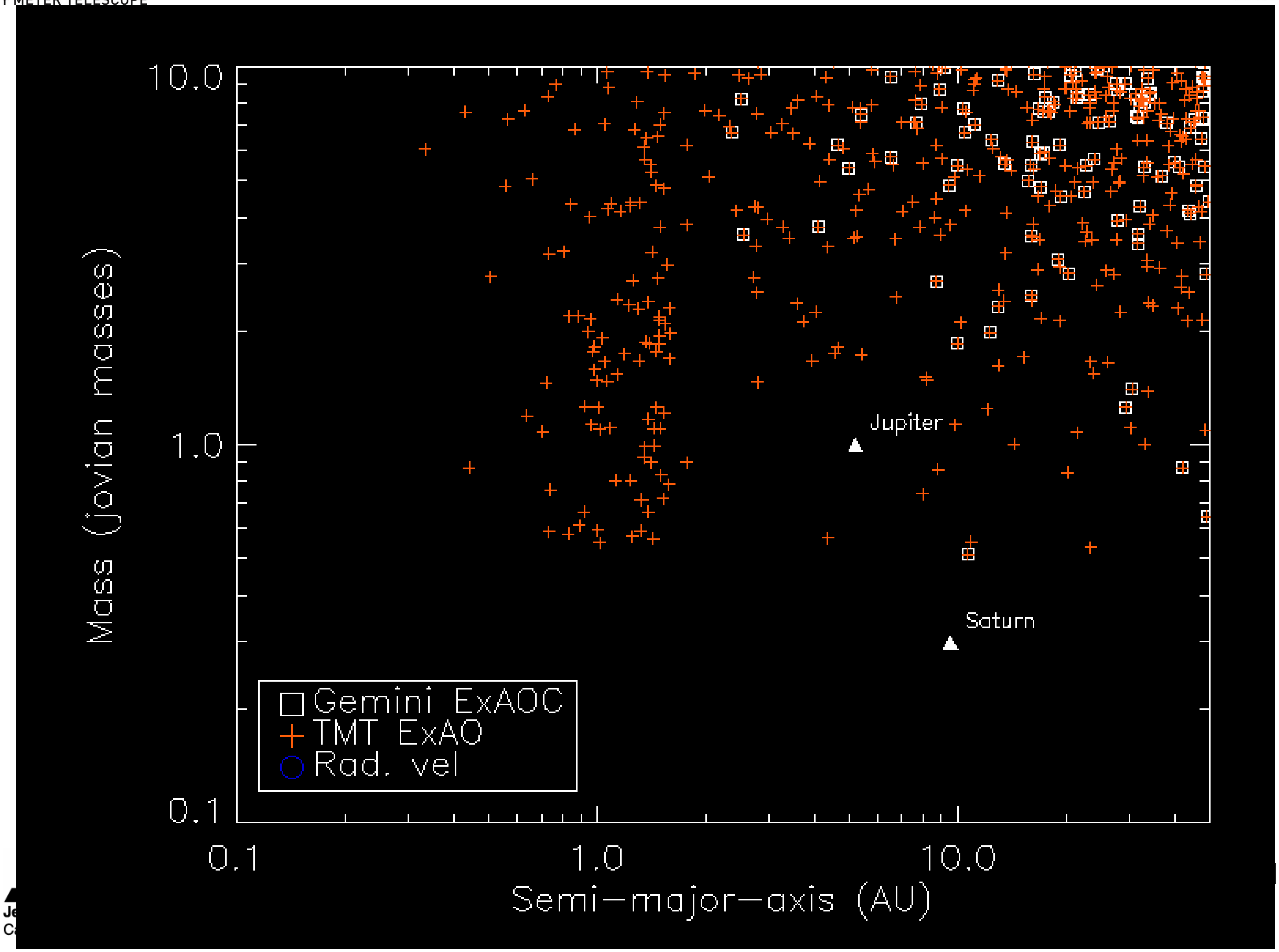



PFI Discovery Space
Jovian planet formation
Self-luminous jovians
Keck ExAO 1.6 μm
Eclipse/JPF 0.6 μm
TPF 0.8 μm
Reflected-light jovians
Terrestrial planets
Contrast at 1.65 μm
Radius (arcsec)

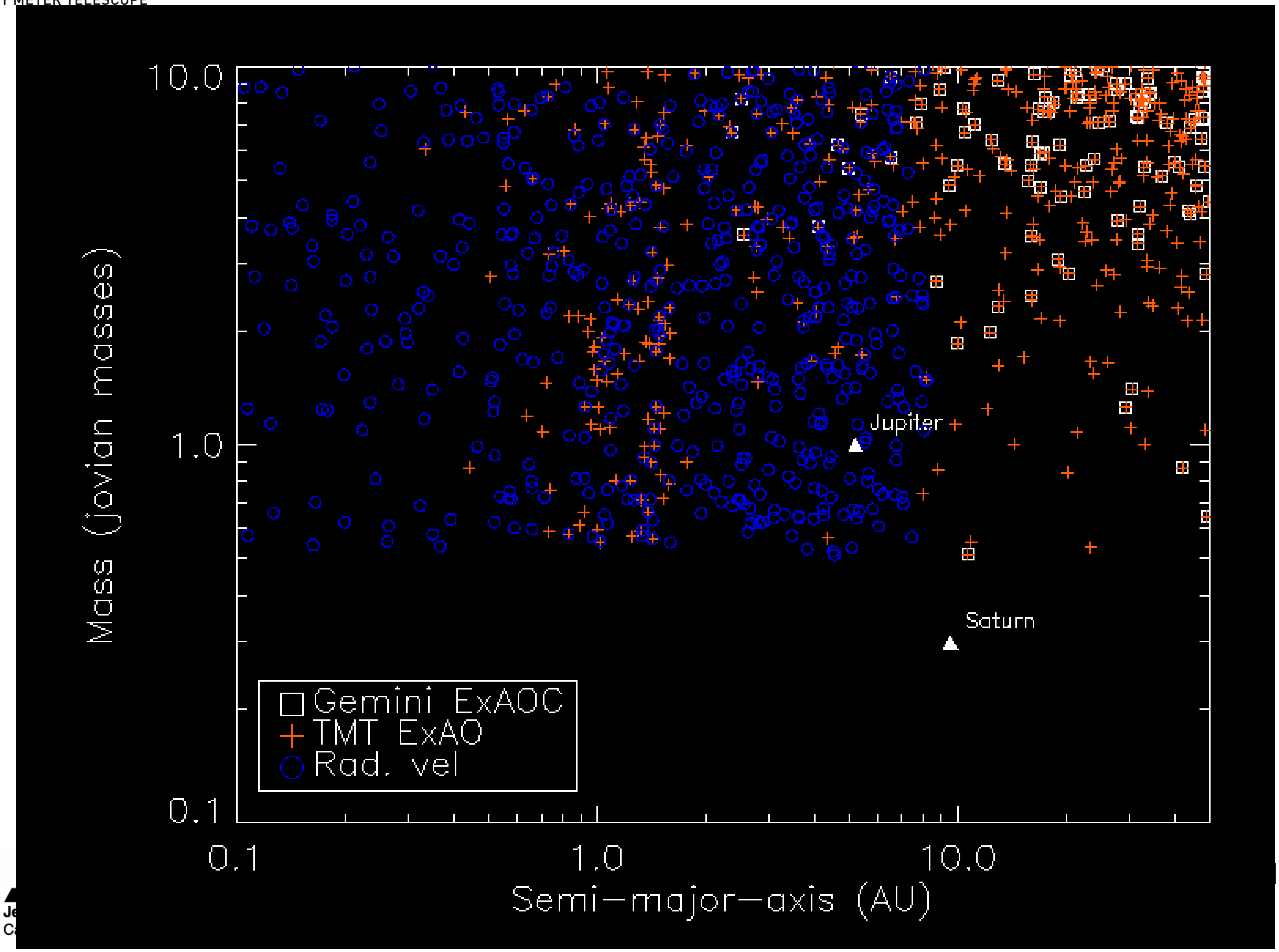
PFI vs. Radial Velocity



PFI vs. Radial Velocity

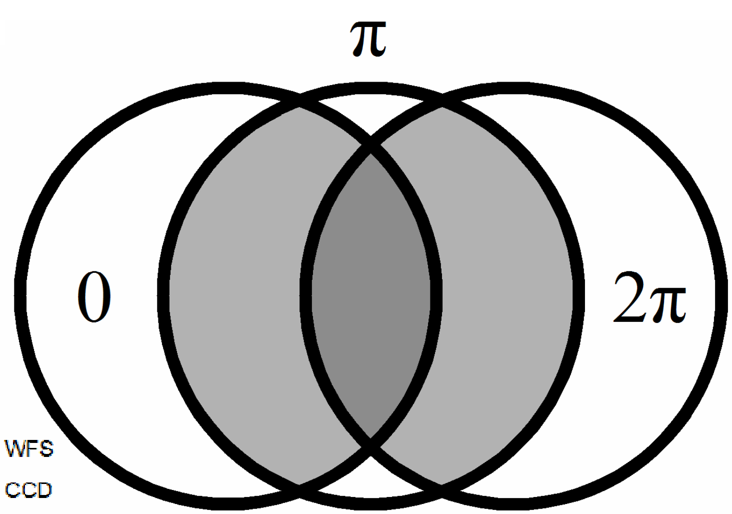


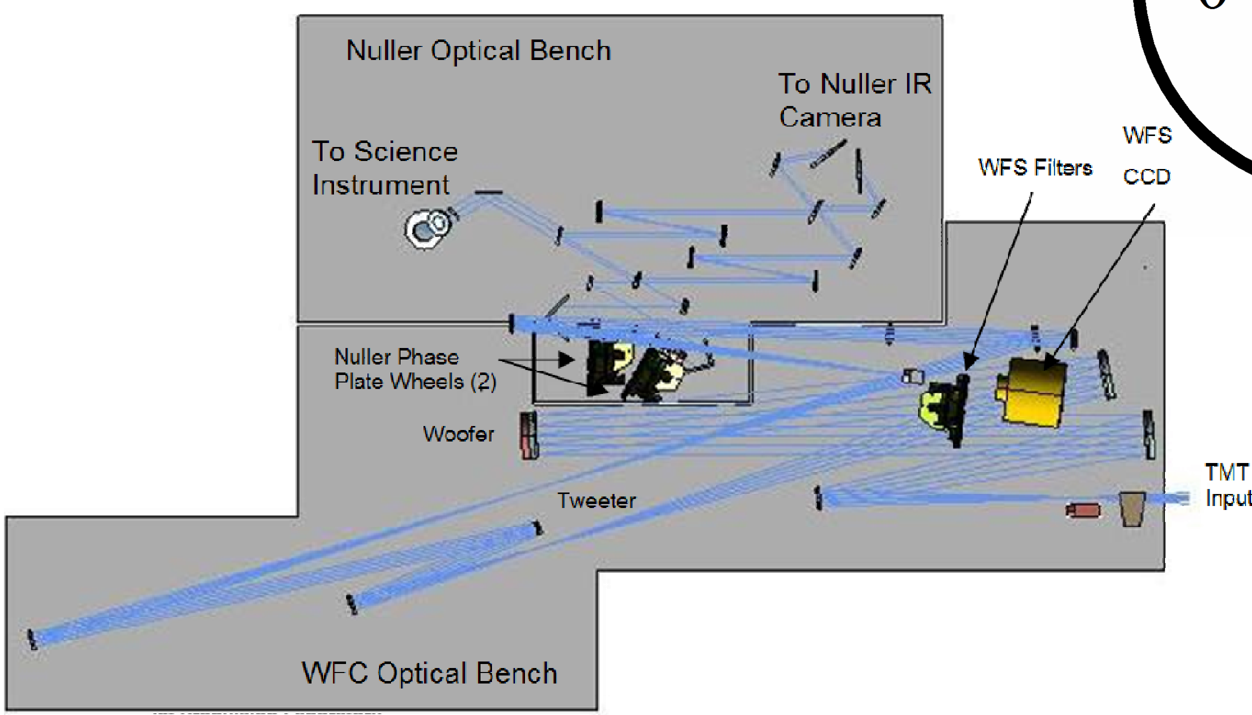
PFI vs. Radial Velocity



PFI Architecture

- Dual-shear nuller
- Integrated, high-order AO system
- Integral Field Spectrograph

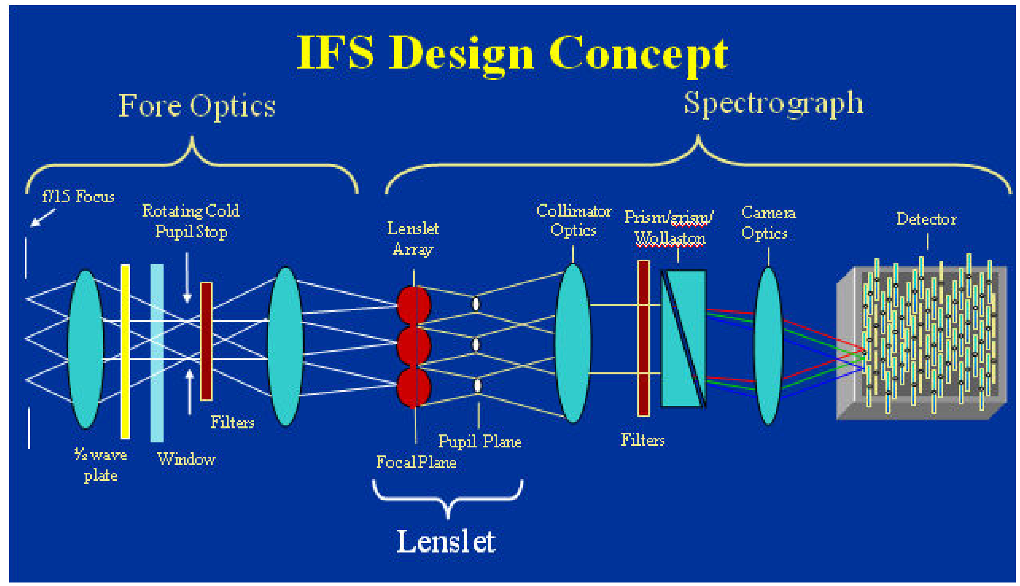




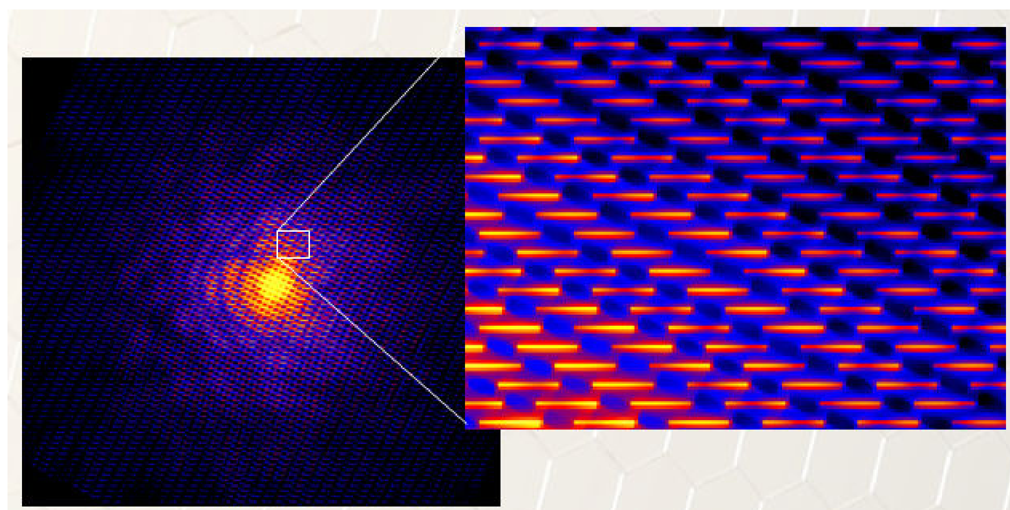
California Institute of Technology

THIRTY METER TELESCOPE

Integral Field Spectrograph



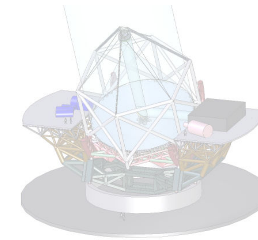
- Observations in J, H, K bands
- Spectroscopy
- Polarimetry
- Speckle noise reduction



Jet Propulsion Laboratory
California Institute of Technology

TMT
THIRTY METER TELESCOPE

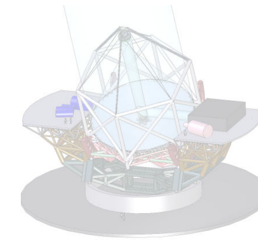
PFI: a TMT design tool



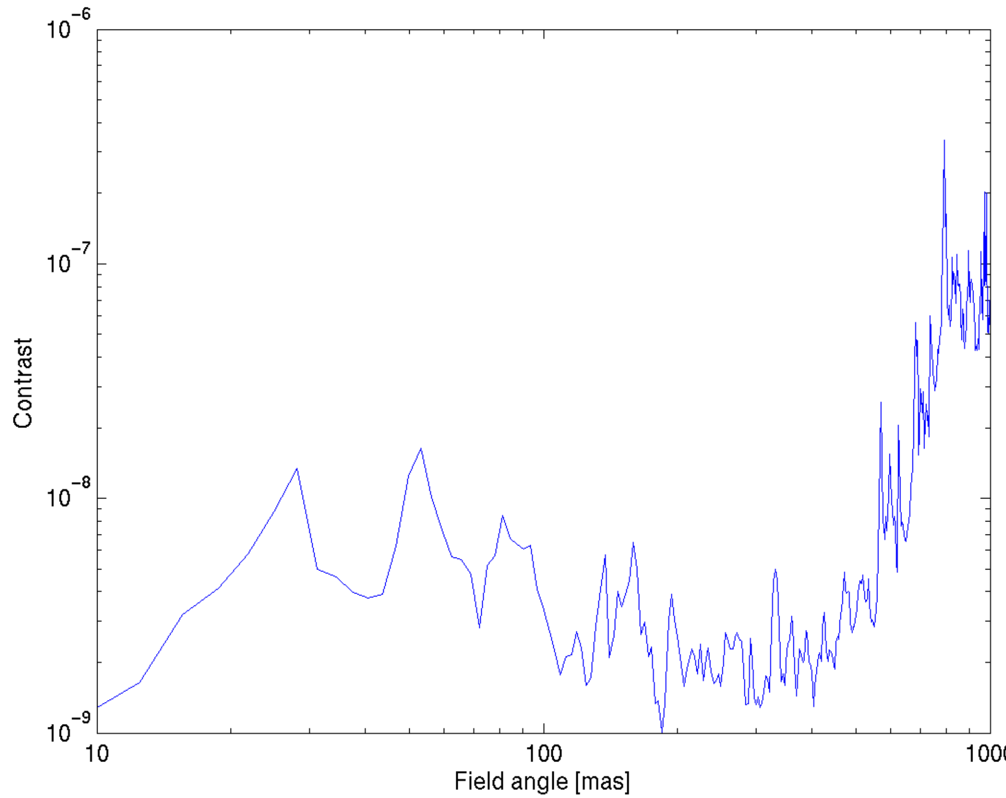
- We want to make sure that the telescope design does not fundamentally limit the achievable contrast
- We desire quick, analytic relations with which to predict contrast
- Example: contrast dependence on segment aberrations

Jet Propulsion Laboratory
California Institute of Technology

Simulation procedure

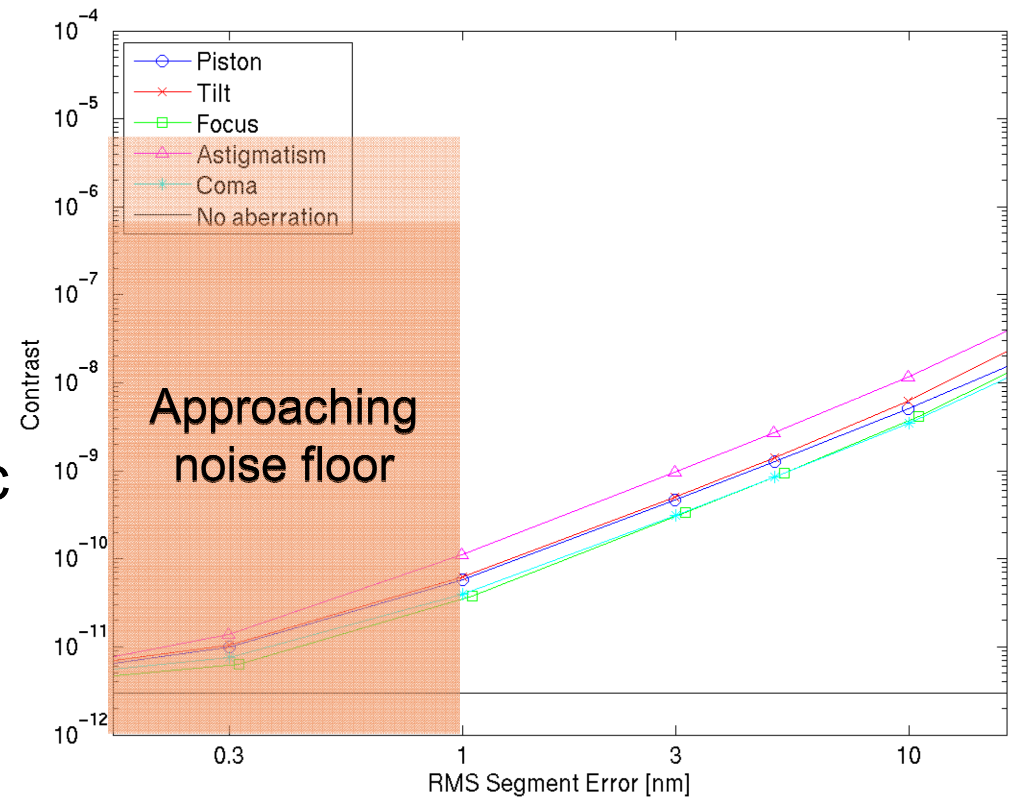


- Apply a single segment aberration (e.g., piston)
- Correct the aberrated wavefront
- Null the corrected wavefront
- Form H band image an measure contrast
- Rinse and repeat



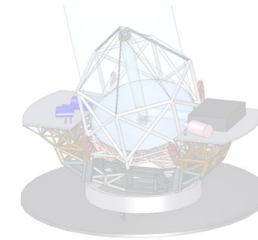
Contrast dependence

- Dependence of contrast on wavefront error
- Curve-fit
- Build a set of parametric fits for each aberration



THIRTY METER TELESCOPE

Contrast calculator spreadsheet

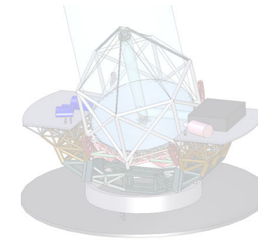


$$C = \sum_n c_n \sigma_n^2$$

Aberration	nm RMS	Contrast
Piston	10	4.62E-09
Tilt	10	4.61E-09
Focus	10	3.06E-09
Astigmatism	10	8.31E-09
Coma	10	2.45E-09
Trefoil	10	8.98E-09
Spherical	10	7.97E-09
Secondary Astig	10	5.76E-09
Tetrafoil	10	15.29E-09
		61.05E-09

Jet Propulsion Laboratory
California Institute of Technology

Contrast predictions

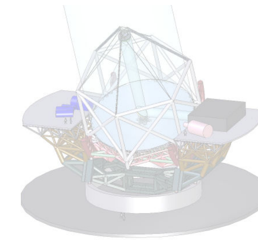


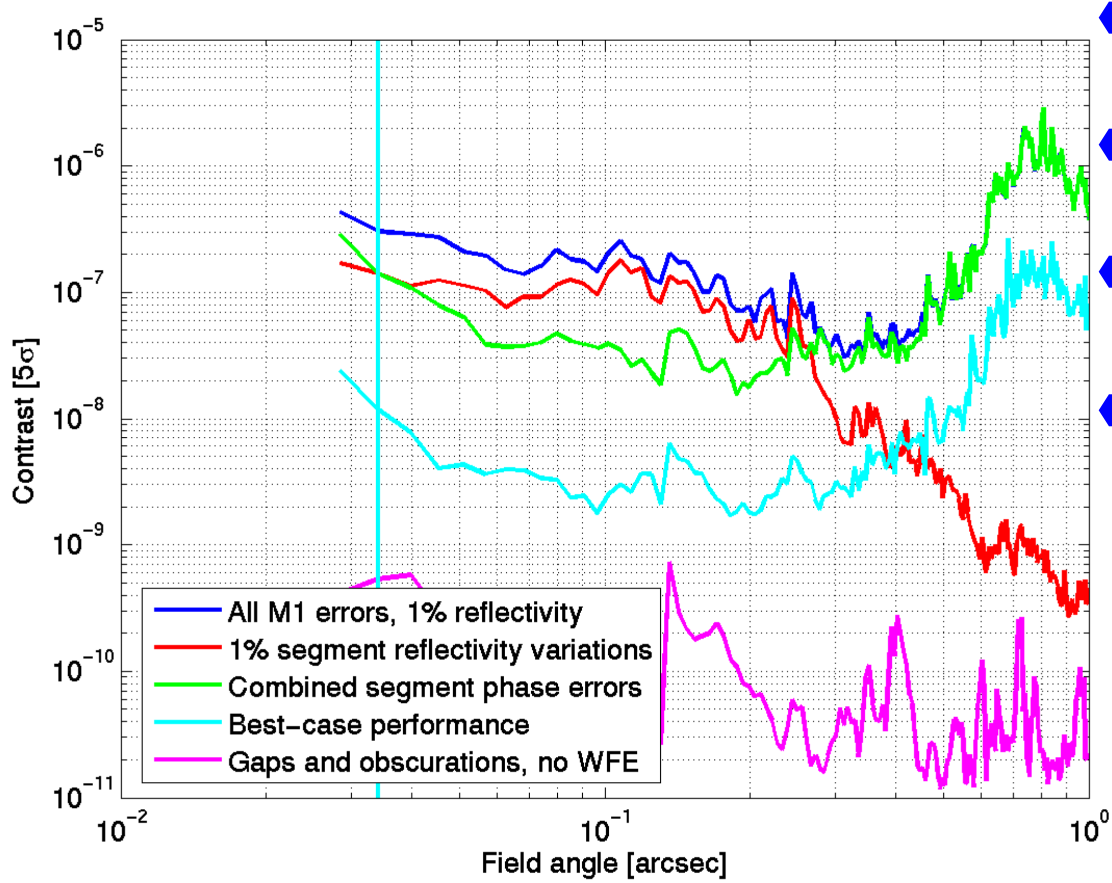
	Linear Model	End-to-end simulation	Error Factor
Unwarped segments	1.2×10^{-7}	2.5×10^{-7}	2.1
Warped segments	2.0×10^{-8}	4.5×10^{-8}	2.3
Alignment errors	1.0×10^{-8}	1.3×10^{-8}	1.3
Combined	3.0×10^{-8}	5.6×10^{-8}	1.9

We have developed a Systems Engineering tool that can quickly calculate tradeoffs between segment aberrations and PFI contrast!

TMT THIRTY METER TELESCOPE

Contrast From Segmented Errors



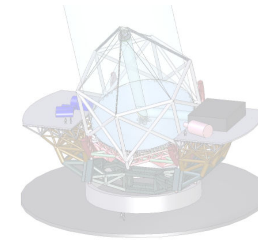


- Amplitude errors dominate and will be controlled
- Segment aberrations dominant error term
- Contrast is:
  - 5.6 X 10^{-8} from 3-10 λ/D
- If WH performed at theoretical limits the telescope would not impact achievable contrast
  - 6.6 X 10^{-9} from 3-10 λ/D

Jet Propulsion Laboratory
California Institute of Technology

THIRTY METER TELESCOPE

Future of PFI

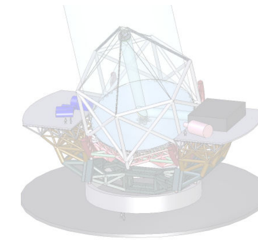


- Probably not a TMT first-light instrument
- Gemini Planet Imager: an excellent pathfinder
- Perhaps on-sky before the end of next decade
- An exciting expansion of exoplanetary research!

Jet Propulsion Laboratory
California Institute of Technology

THIRTY METER TELESCOPE

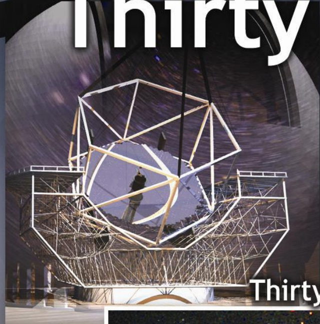
Acknowledgements



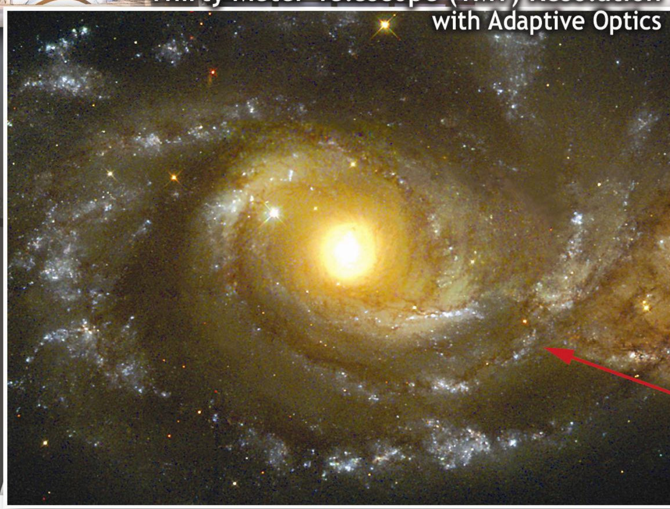
- Prof. Graham and the Berkeley Astronomy Department, for inviting me to come speak
- The PFI and TMT teams for the many slides I borrowed from past presentations and reports
- The authors gratefully acknowledge the support of the TMT partner institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the Association of Universities for Research in Astronomy (AURA), the California Institute of Technology and the University of California. This work was supported, as well, by the Canada Foundation for Innovation, the Gordon and Betty Moore Foundation, the National Optical Astronomy Observatory, which is operated by AURA under cooperative agreement with the National Science Foundation, the Ontario Ministry of Research and Innovation, and the National Research Council of Canada.

Jet Propulsion Laboratory
California Institute of Technology

Thirty Meter Telescope (TMT)

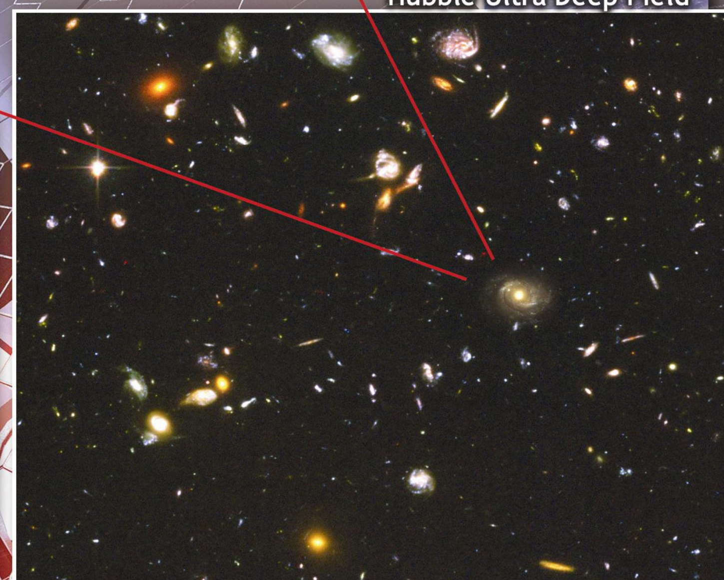


Thirty Meter Telescope (TMT) Resolution with Adaptive Optics



HST Resolution

Hubble Ultra Deep Field

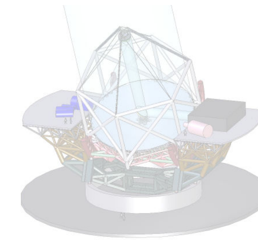


Shown here is an example of the angular resolution that TMT will have with its adaptive optics system, comparing it to the resolution of the Hubble Space Telescope. With adaptive optics, TMT will be diffraction limited for wavelengths of 1μm and longer. This resolution will greatly enhance the sensitivity of TMT in the infrared.

Currently in the design phase, the Thirty Meter Telescope (TMT) project is a collaboration between the University of California, the Associated Universities for Research in Astronomy, and the Association of Canadian Universities for Research in Astronomy and Caltech.

THIRTY METER TELESCOPE

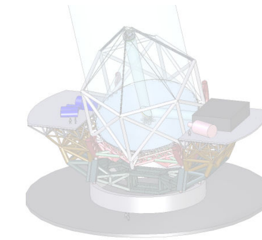
Backup

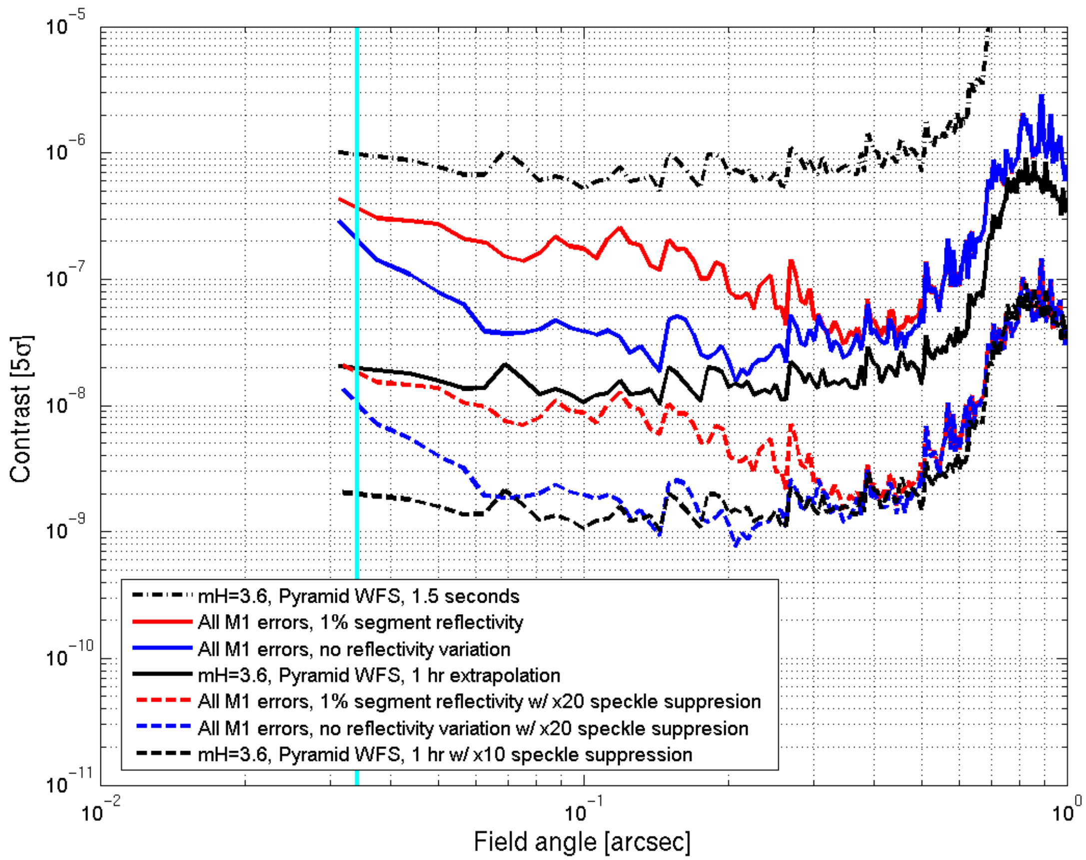


Jet Propulsion Laboratory
California Institute of Technology

TMT
THIRTY METER TELESCOPE

Telescope Errors Dominate PFI Contrast



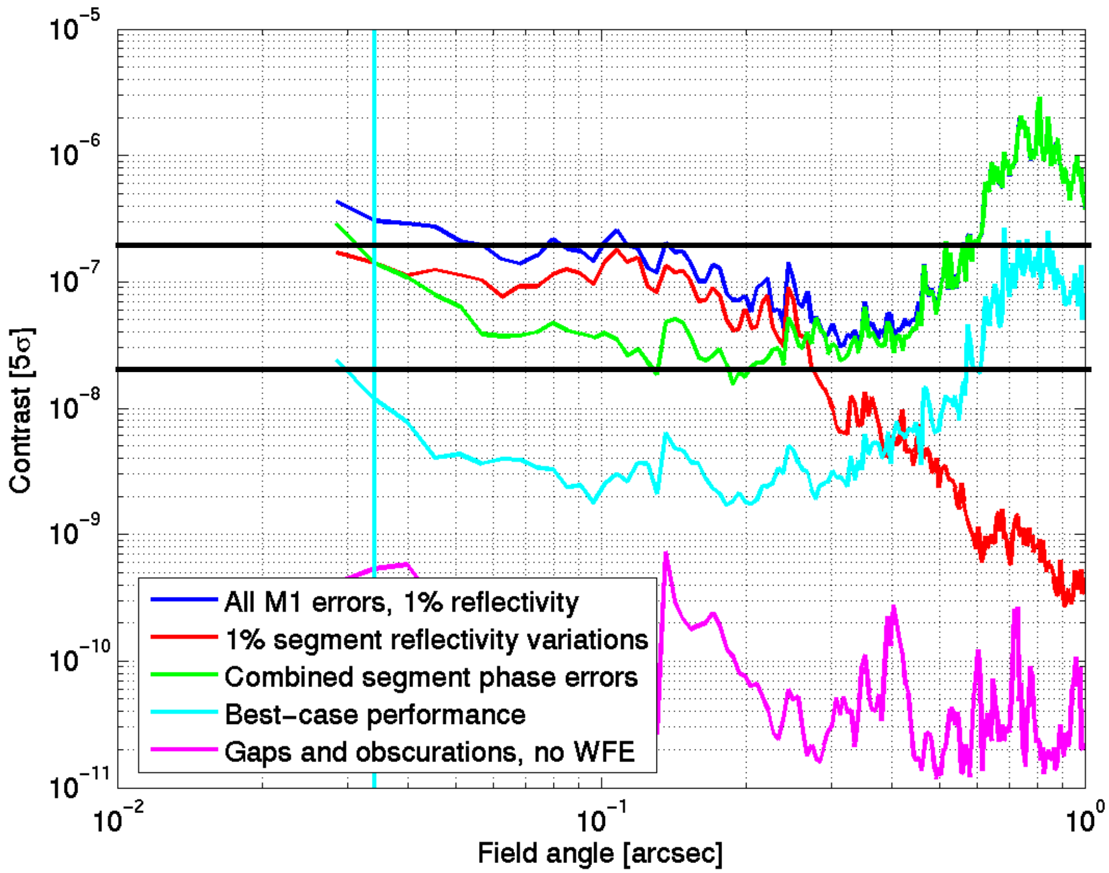


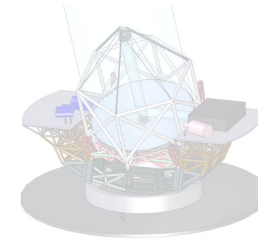
- At > 5λ/D the telescope and PFI contrast limits are the same.
- The telescope limits PFI performance from 3 to ~5λ/D
- If the WH perform as intended then the telescope will not limit PFI contrast

Jet Propulsion Laboratory
California Institute of Technology

Contrast From All M1 Errors

TMT
THIRTY METER TELESCOPE

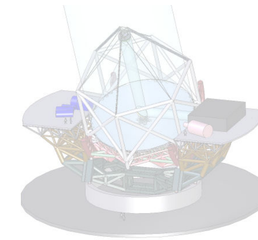




- Amplitude errors dominate and will be controlled
- Segment aberrations dominant error term
- Contrast is:
  - 1.4 x 10^{-7} at 3λ/D
  - 5.6 X 10^{-8} from 3 to 10 to λ/D
- If WH performed at theoretical limits the telescope would not impact achievable contrast
  - 1.0 x 10^{-8} at 3λ/D
  - 6.6 X 10^{-9} from 3 to 10 to λ/D

Jet Propulsion Laboratory
California Institute of Technology

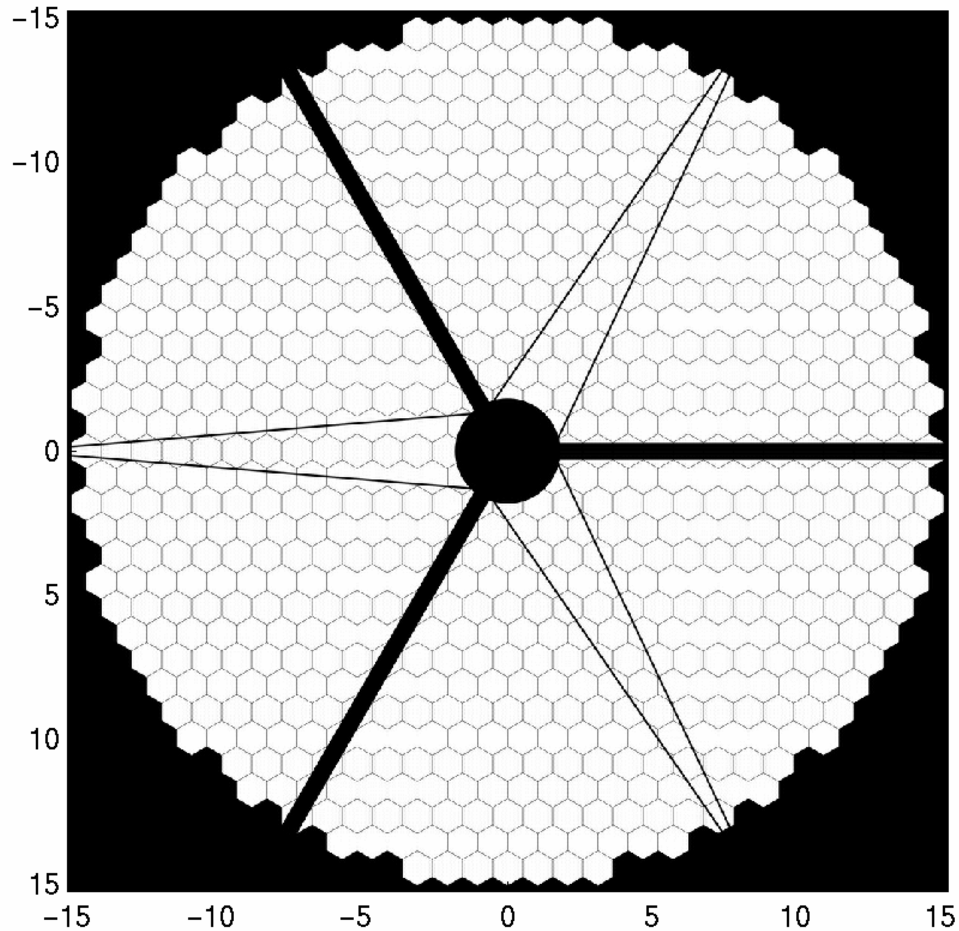
THIRTY METER TELESCOPE



Conclusions

- The telescope will not limit contrast at the 10^{-8} level
  - The relatively small segment gaps do not limit contrast
  - The large obscurations from the secondary and supports do pose a challenge
    - The nuller is able to suppress this diffraction
  - Segment-to-segment reflectivity variations are an issue
    - Will require amplitude control using a 2nd DM
  - Performance of warping harnesses is the key driver in the performance
- Future work:
  - Investigation and understanding of expected segment aberrations as well as alternate control algorithms (Chanan 6267-79)
  - Build a first order model to predict contrast based on segment Zernikes
  - Investigation of dynamic effects (tip/tilt and segment vibrations)

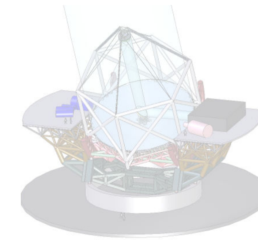
Segmentation and Obscuration of Pupil



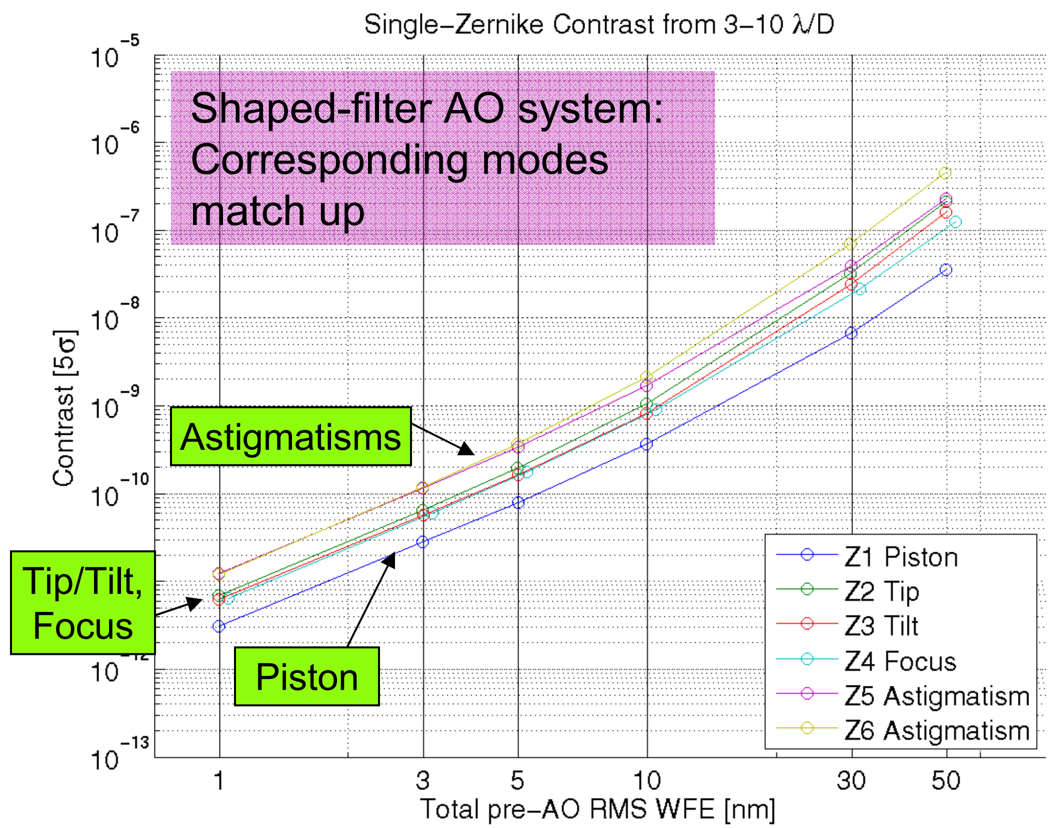
- 738 Segments
- Segments are 0.6 m on a side
- 4 mm gaps
- Central obscuration: 3.65 m circle
- 3-50 cm compression supports
- 6-10 mm support cables

THIRTY METER TELESCOPE

Similar-Zernike Discrepancy

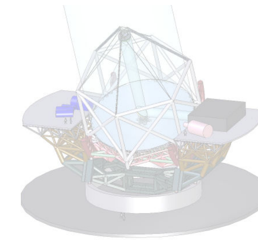


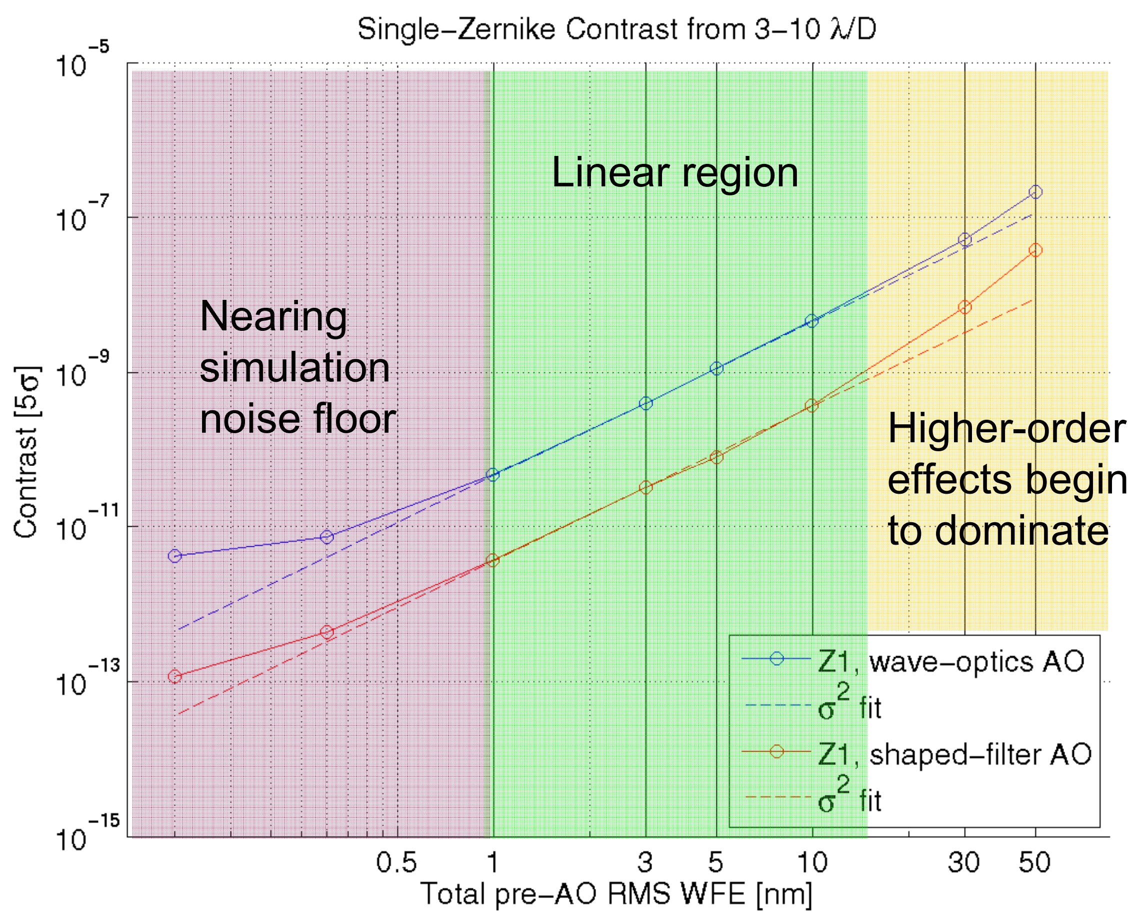
- Contrary to expectations, the contrast dependencies of similar segment aberrations (tip/tilt, astigmatisms) do not match up
- Using an idealized filtering AO system (removes all aberrations up to the AO's controllable bandpass) eliminates this discrepancy in the linear regime (see figure at right)
- Suggestion: difference is due to AO system, either
  - Wavefront Sensing
  - Wavefront Control
- Conclusion: while we would like to understand this effect, it does not prevent us from making effective contrast predictions



Jet Propulsion Laboratory
California Institute of Technology

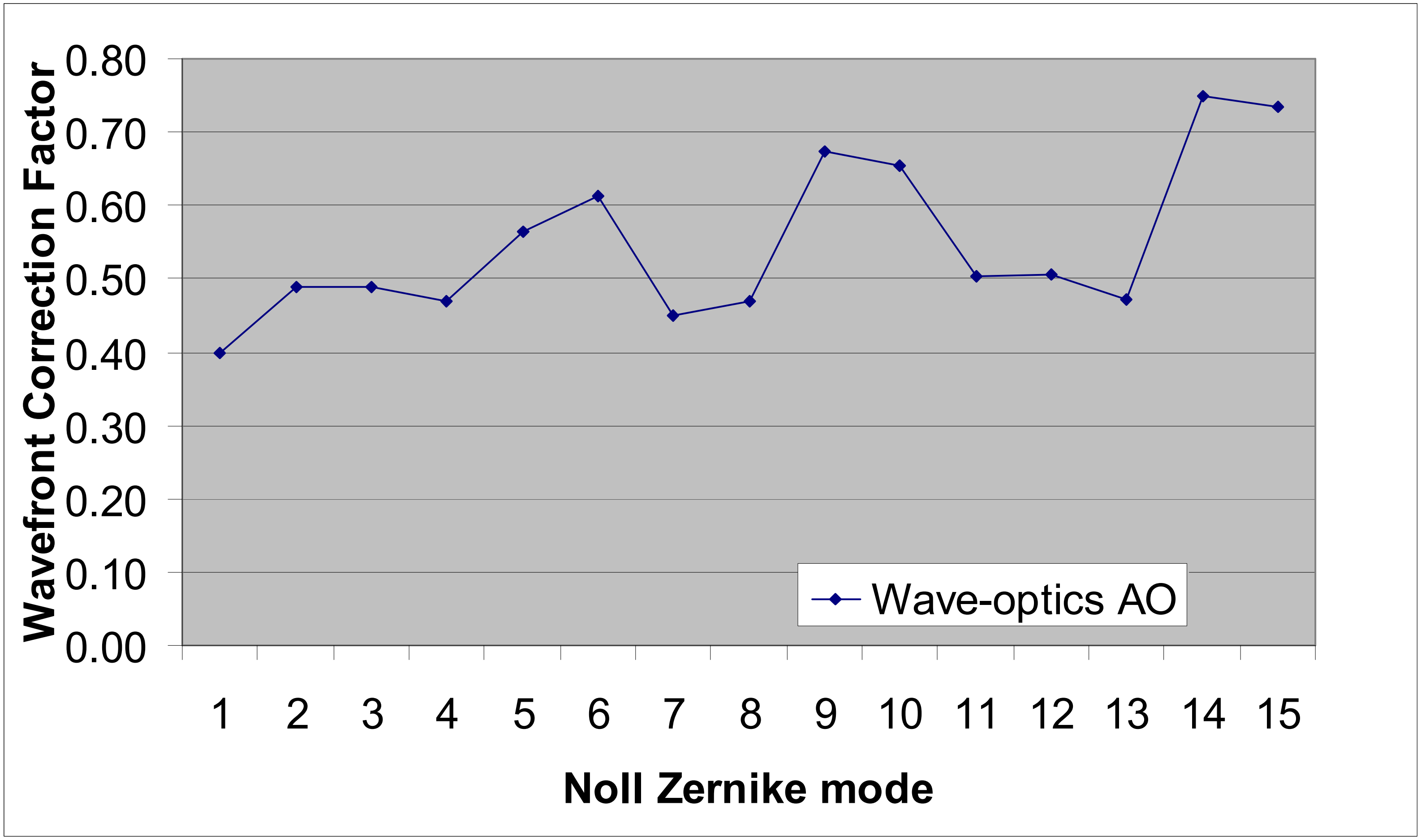
Comparison of AO Effects





TMT
THIRTY METER TELESCOPE

Wavefront Correction Factors



Jet Propulsion Laboratory
California Institute of Technology