Planetary System Instrument

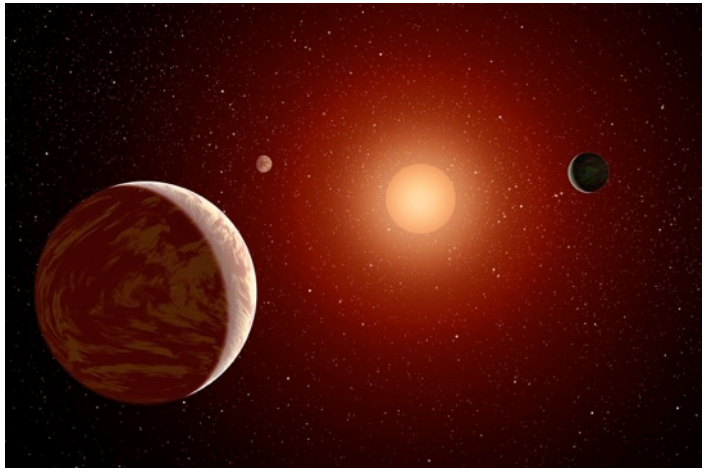
A second-generation TMT instrument concept

Ben Mazin and Mike Fitzgerald

for the PSI Collaboration

Large Apertures are Vital for Direct Imaging of Exoplanets

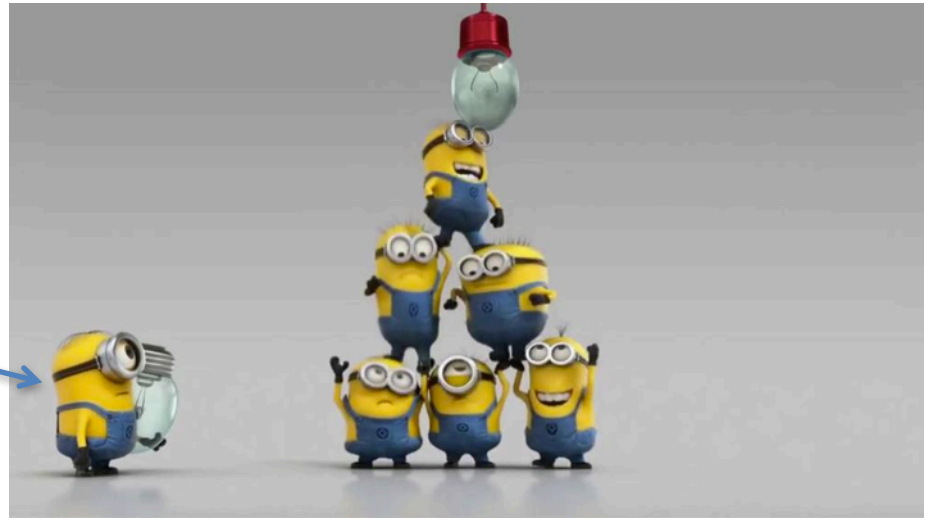
- GPI/SPHERE/SCExAO/P1640 show planets are rare past 10 AU
- Going inside 10 AU pushes us to large aperture and short wavelengths for a small IWA
  - 2 λ/D for TMT at 1.3 micron = 10 mas!
  - 0.1 AU at 10 pc
    - M star habitable zones at 10^{-8} contrast ratios
    - 275 M stars within 10 pc
    - 22 G stars within 10 pc
  - 1 AU at 100 pc
    - Gas Giants at high spectral resolution
  - 4.5 AU at 450 pc (Orion)
    - Planet formation



M star habitable zone
Image Credit: NASA/JPL-Caltech

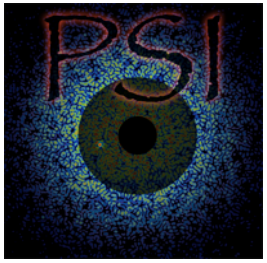
We Rebooted the PSI Team!

- We began forming a team in 2015 to study a TMT instrument for these science goals
  - Building off (and including many people) from the 2006 PFI study



Bruce

2015 Workshop at UCLA



Design Study and Roadmap Teams

Scope	DMs (Actuator Count, #, Loc.)	Coronagraph	Wavelength Coverage and Spectral Resolution	Laser Mode
Mike F.	Bruce M.	Dimitri M.	Ben M.	Christoph B.
Bruce M.	Don Gavel	Olivier G.	Heather K.	Jessica L.
Ben M.	Mitch T.	Bruce M.	Andrew H.	
Mitch T.	Dimitri M.	Gene S.	Quinn K.	
			Jonathan F.	

PSI Collaboration

Performance Estimating Tool:
Ian Crossfield, Olivier Guyon, Christian Marois, Mitch Troy, Ben Mazin

Stra
Ben
Mike
Chaz
Chris
Dimi
Jessi
Mike
Bruce Macintosh
Norio Narita
G. Vashist

Organizers:
Mike Fitzgerald
Ben Mazin

Wes T.	Ian C.	Dimitri M.			
Bruce M.	Andy S.	Jonathan F.			
Bjorn B.	G.V.				
Norio N.	Shelly W. for link to IRIS				

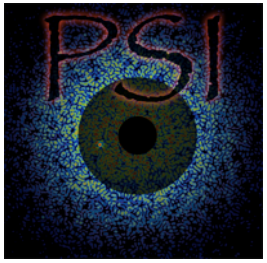
Room to Grow!

Science Goals

- After discussions at the workshop, the team converged on the following primary science goals we expect to be most relevant in the TMT era:
  - Discover and Characterize Rocky Planets and look for Life
    - Extreme Contrast (10^{-8}) at 2 λ/D with spectroscopy to resolve bio-signature gasses, especially in M dwarf habitable zones
      - Finding life outside the solar system would be one of the most profound scientific discoveries in history, and we have a clear path forward. We have to try!
  - Understand the Atmosphere and Formation of Gas Giants
    - High spectral resolution at more modest contrast
    - Broad wavelength coverage
- Secondary Science Goals
  - Disks
  - Planet Formation
  - Exozodical Light

Exoplanet Science Capabilities

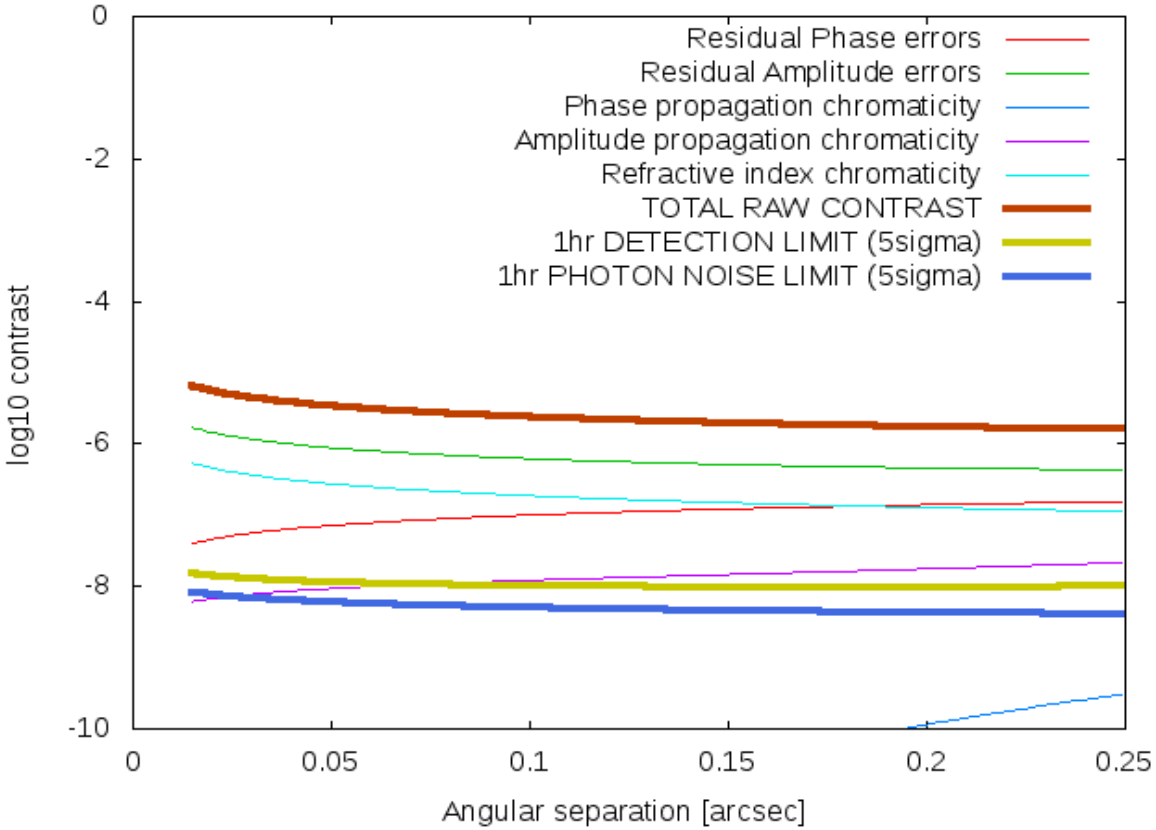
Capability	JWST	WFIRST	TMT PSI
Reflected Light Rocky Planets	✖	✖	
Reflected Light Neptunes	✖	Imaging Low res. spec	✔
Reflected Light Jovians	✖	Imaging Low res. spec	✔
Thermal Jovians	Transit spec Very wide sep. imaging	✖	✔
Thermal Neptunes	Transit spec Very wide sep. imaging	✖	✔
Thermal Rocky	Transit spec	✖	Super Earths

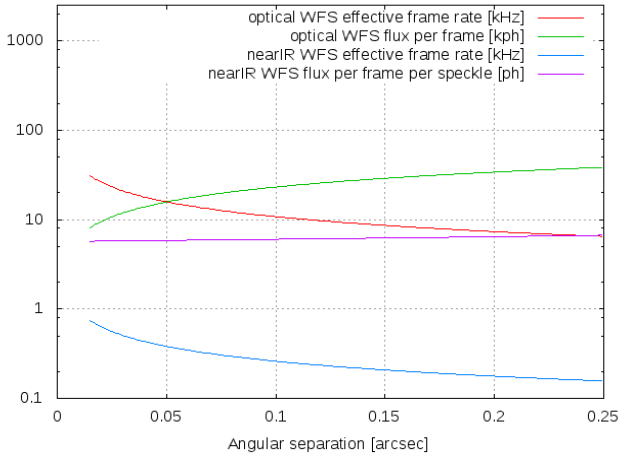


Extreme Contrast

- Extreme Contrast (10^{-8}) at ~2 λ/D is challenging
  - Requires "raw" contrast ~10^{-5}
    - Post-processing of science frames yields further improvements of up to 1000x, down to photon shot noise
  - Advanced coronagraphs (PIAA, VV)
  - Fast, low latency AO systems
  - Near-IR wavefront sensing (chromatic effects)
    - Fast focal plane speckle nulling
      - Demonstrations on Palomar and Subaru this year!
  - Accurate PSF calibration
- We aim to demonstrate this contrast level on 8-10 m telescopes in the next several years
  - See Olivier Guyon's talk on Thursday morning

Photon Noise Limit





Calculations and plots from O. Guyon

300Hz speckle control loop (~1kHz frame rate) is optimal
Residual speckle at ~1e-6 contrast and fast → good averaging to detection limit at ~1e-8

TMT PSI Targets

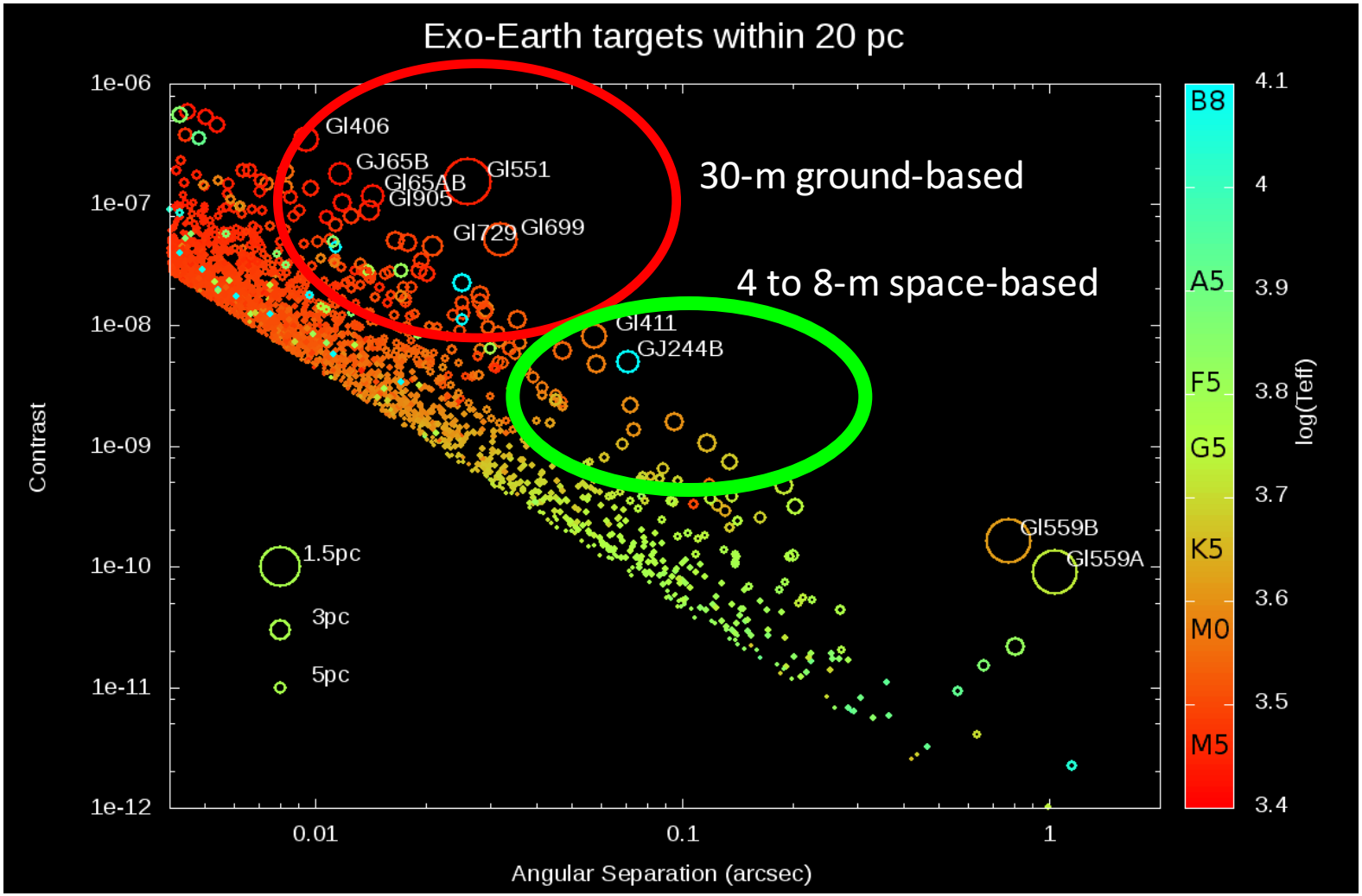


Figure from
O. Guyon

High Spectral Resolution

- High resolution spectra of Gas Giants possible for transiting planets or with Doppler spectroscopy

- A moderate resolution spectrograph (R~5000) would allow the detailed study of old Gas Giants in more distant orbits

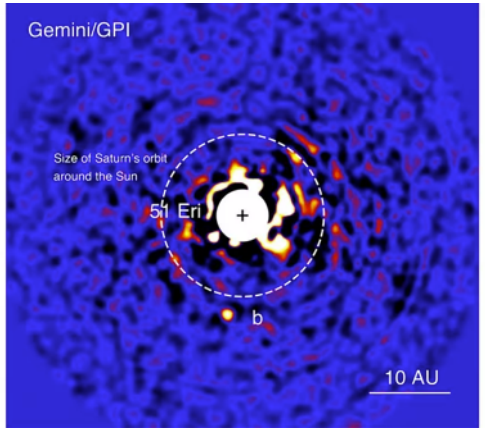
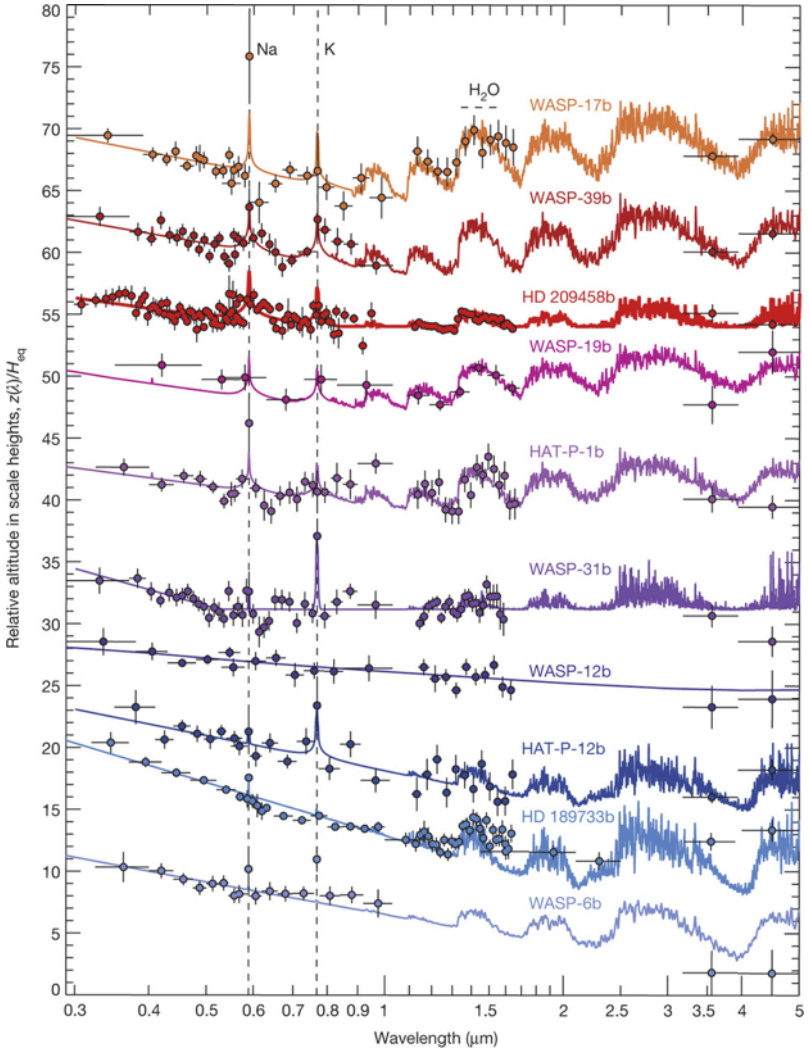


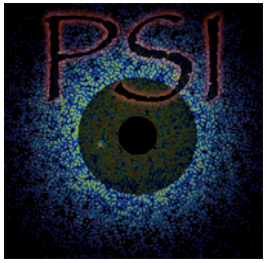
Image Credit: J. Rameau and C. Marois

Broad Wavelength Coverage

- Broad wavelength coverage required to break degeneracies in atmospheric models
- Coverage out to 5 microns gives the most information
- Coronagraphy over very wide bands is very challenging and may require multiple coronagraphs
  - Possible complementarity with MICHI



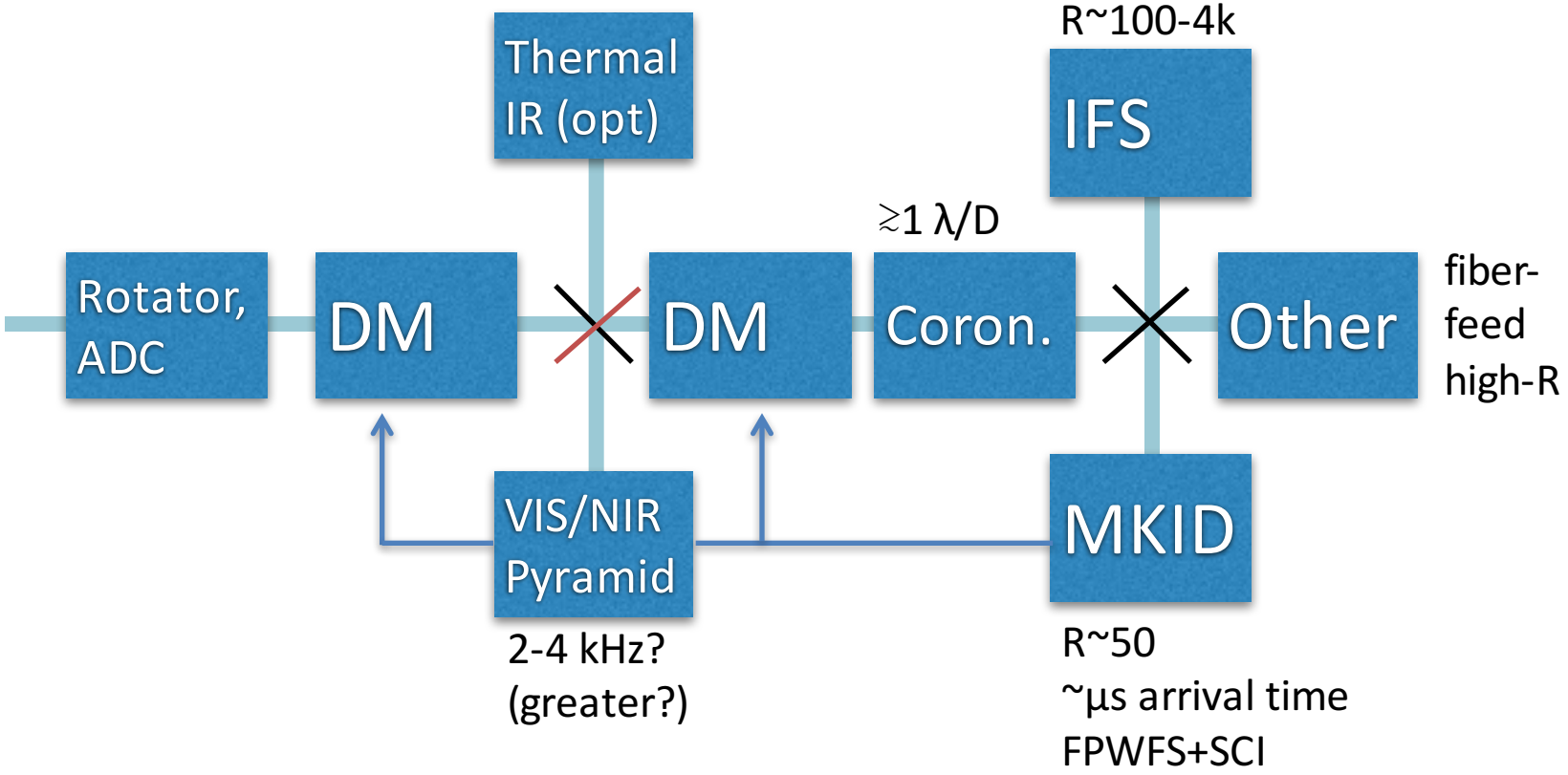
Sing et al. 2016



Surprising Agreement

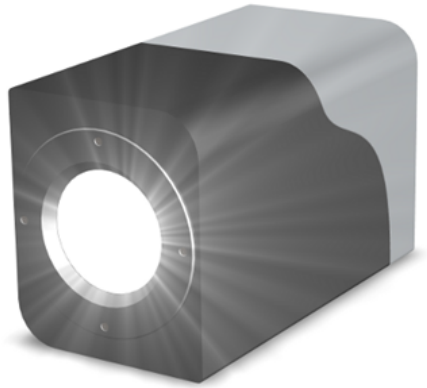
- The team converged without dissent on a design featuring high order AO, a very fast visible wavefront sensor, and advanced coronagraph feeding a variety of instruments
- A modular design with well documented interface requirements is preferred
  - Allows different institution to build different modules
    - Field rotator, ADC, DM, WFS, IFS, fiber feed, etc.
  - Allows future upgradeability
    - Important in this field as technology changes fast

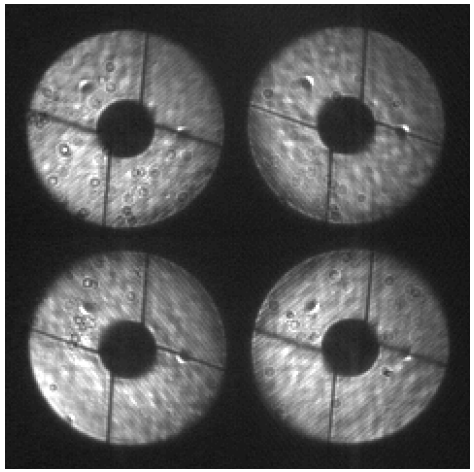
Modular System Architecture

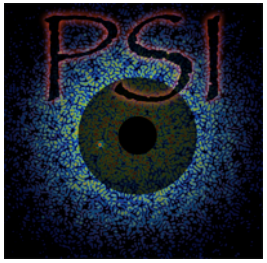


Technology Roadmap AO/Deformable Mirrors

- The deformable mirror needed for PSI does not currently exist
  - 120x120 actuator, 10 micron stroke, fast response time
  - There are promising new technologies, including ALPAO DM
  - Shared interest with E-ELT
  - Funding and Development is needed!
- Wave Front Sensors
  - Pyramid WFS working in the field (SCExAO, Mag-AO)





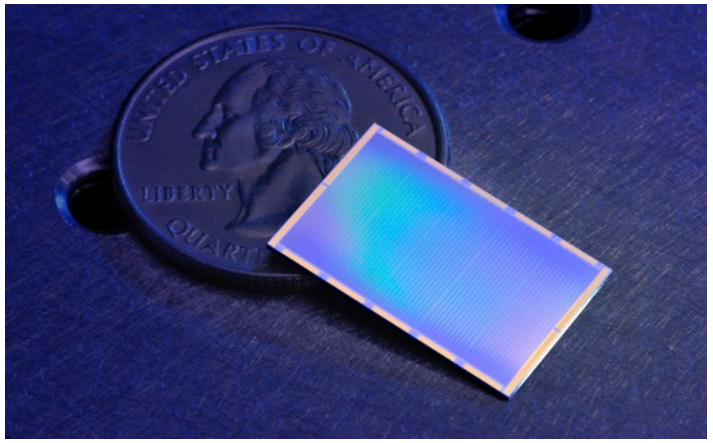


Technology Roadmap Coronagraphs

- Advanced coronagraphs (PIAA, Vector Vortex, etc.) are fairly mature and on sky
- Improvements are useful but not required
  - Wider bandwidth
  - Higher throughput
  - Better raw contrast at low IWA (LOWFS)

Technology Roadmap Detectors

- Need detectors for WFS, Speckle Nulling Camera, IFS, etc.
  - EMCCD cameras (O-CAM) operating at 3.7 kHz are on sky now
  - SAPHIRA arrays in the near-IR are also coming online and growing
  - MKIDs coming this year for Palomar and Subaru
- The detectors we need will likely be ready with continued development



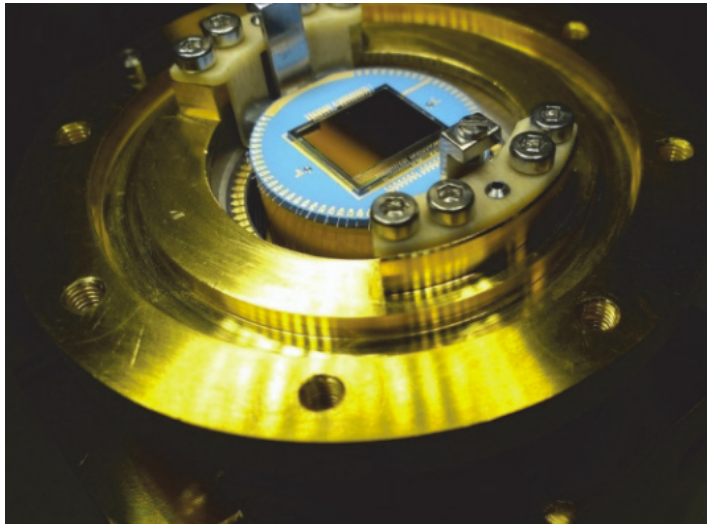
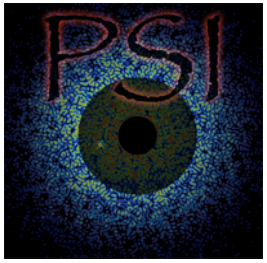
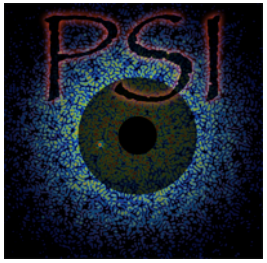


Image Credit: Top, Mazin Lab Bottom: First Light Imaging



Technology Roadmap Precursors

- The instrument we converged on looks a lot like SCExAO+MEC
- Many lessons (i.e., low wind condition) can only be learned on sky – precursor development is vital!
- SCExAO+MEC with the addition of a new woofer DM could potentially evolve into a visiting TMT instrument for use at first light
  - Risk mitigation for a second generation instrument
    - Telescope vibration environment
      - Big deal on Subaru/Gemini/VLT
    - Designs for a segmented primary
    - Designs robust against segment problems
    - Processing algorithms



Next Steps

- UCO funding secured for Mike and me to visit potential partners for team building this fall
- UCO funding secured for another workshop this winter to further develop science case and system architecture
  - Contact bmazin@ucsb.edu if interested in attending
- Draft technology roadmap to assist in funding technology priorities
- Propose to TMT feasibility study in 2017
- Work with government and private partners to look for funding
  - Breakthrough Starshot