Coronagraph Imaging of Planets and Debris Disks from a High-Altitude Balloon Platform

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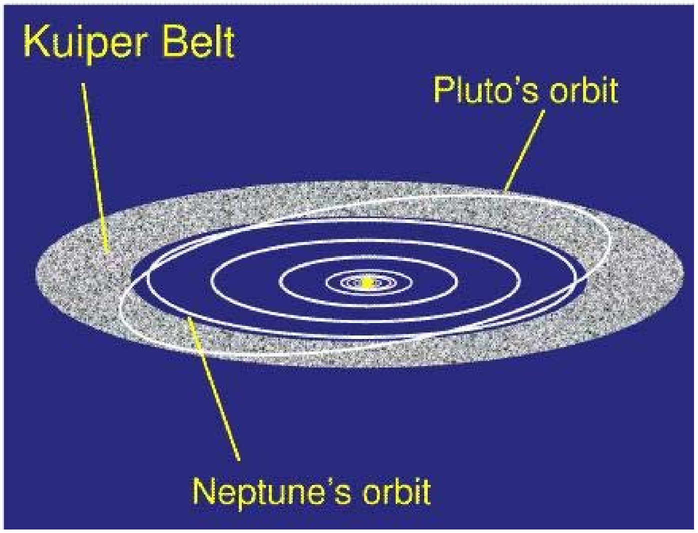
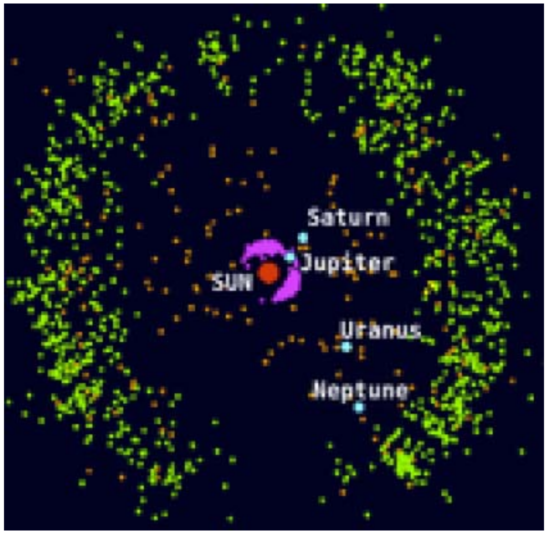
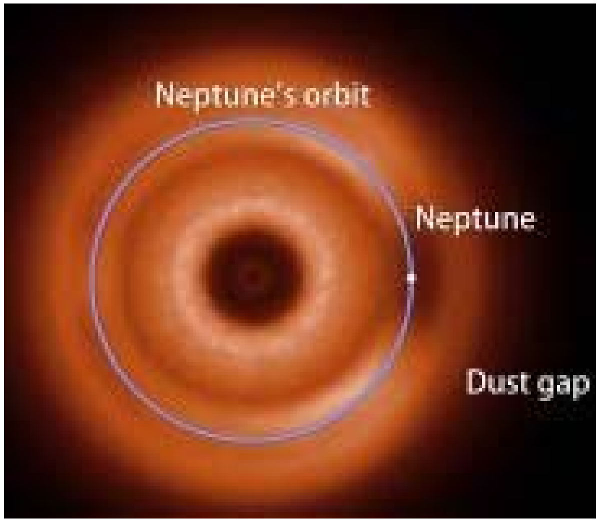
Debris disks: signposts of planets, asteroids, and comets

- *Debris disks* are rings of micron-size dust orbiting in the outer regions of planetary systems
- Asteroid and comet collisions, closer to the parent star, are the probable source of the dust
- Radiation pressure pushes this dust outward
- Planets shepherd and sculpt the dust into a ring
- The dust ring is bright enough to be imaged, brighter than the planets themselves
- *So debris disk images are our connection to as-yet unseen planets, comets, and asteroids*

Edgeworth-Kuiper Belt: our own debris disk





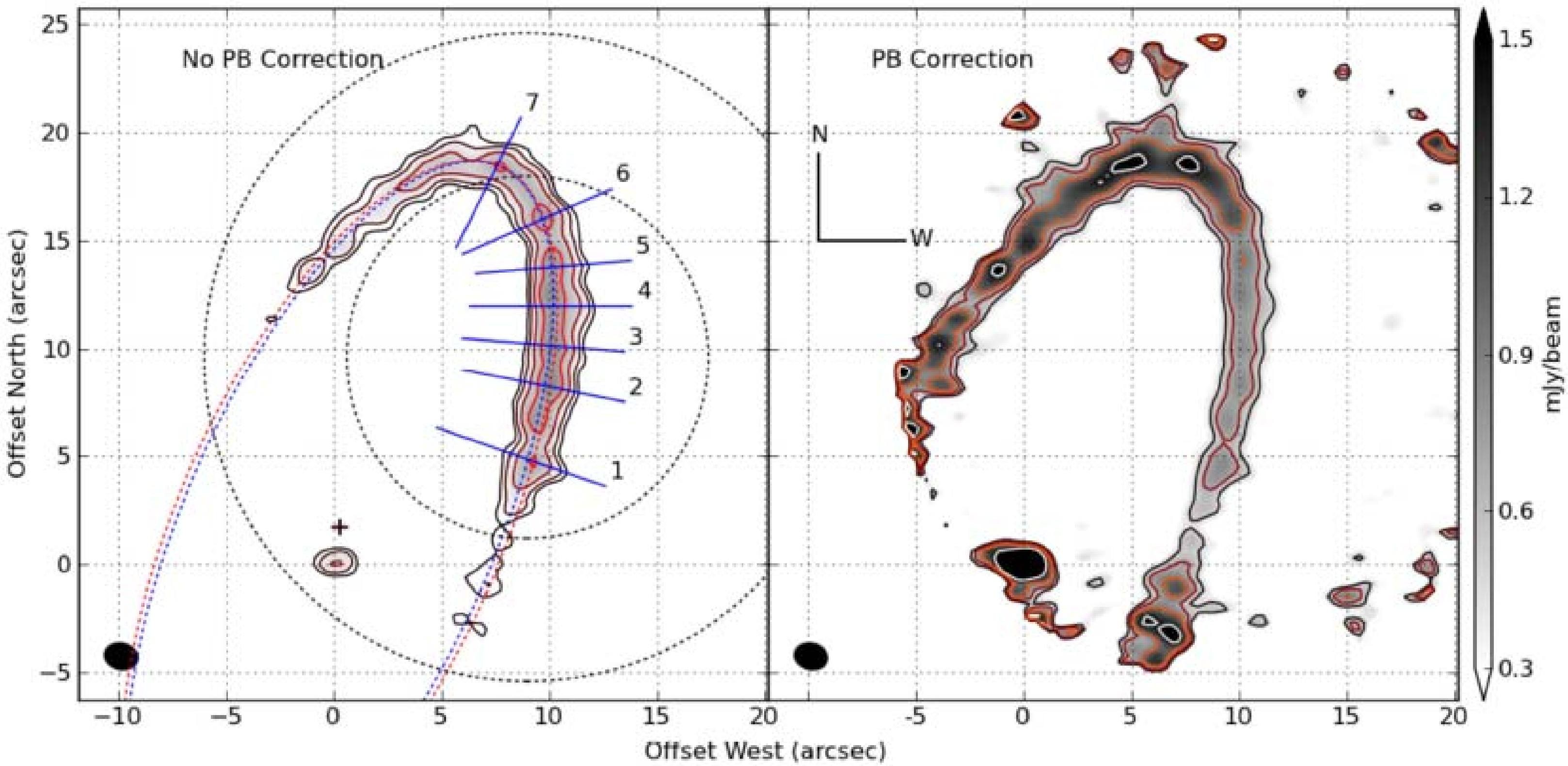


- (left) EKOs and dust occupy ~circular orbits just beyond Neptune
- (center) ~1000 EKOs are known, incl. Pluto, but 10^9 are suspected
- (right) Simulations show that dust must accumulate along with the EKOs, shepherded by Neptune, in 30-50 AU ring
- Pioneer 10 & 11 found dust impacts from 3-50 AU
- Luminosity of EKB is ~10^{-7}, roughly same as zodiacal light
- Mass of EKB is ~0.1 Earth

Refs.: http://www.solstation.com/stars/kuiper.htm ; Vitense etal , A&A (2010, 2012); Kirov etal, ApJ (2008)

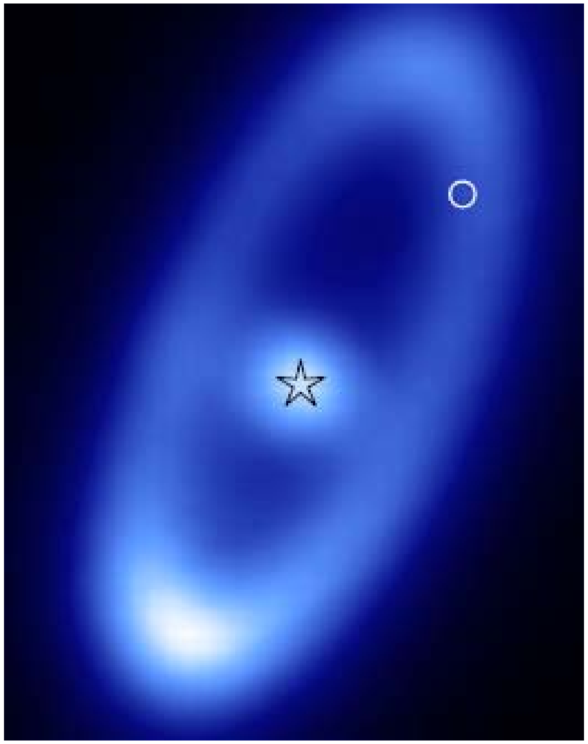
Fomalhaut's debris disk: ALMA detection

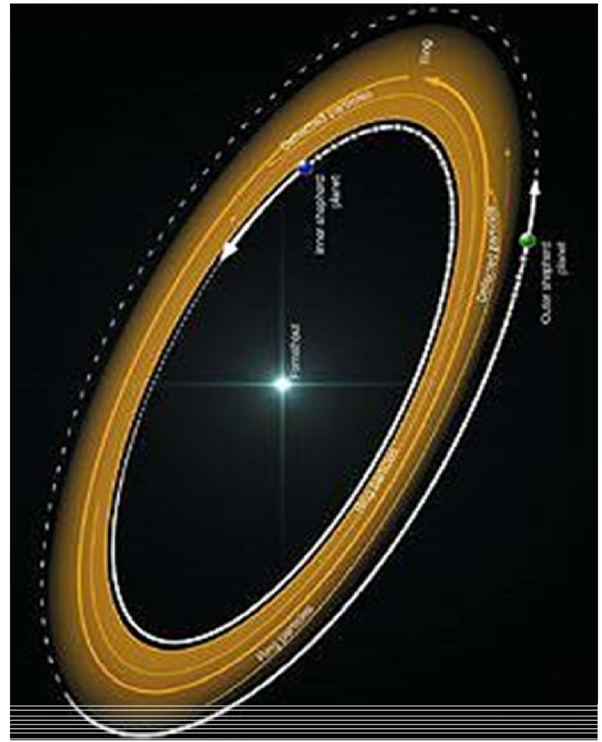
- ALMA detection at 850 μm finds sharp-edged ring at ~140 AU
- Ring width is 13-19 AU
- 2 shepherd planets suffice, with, e.g., each < 3 Earths



Boley etal, astroph (2012)

Fomalhaut's debris disk: Herschel detection





- (left) Herschel 70-µm image
- (right) Schematic of belt & 2 shepherd planets

Ref.: Acke etal A&A (2012)

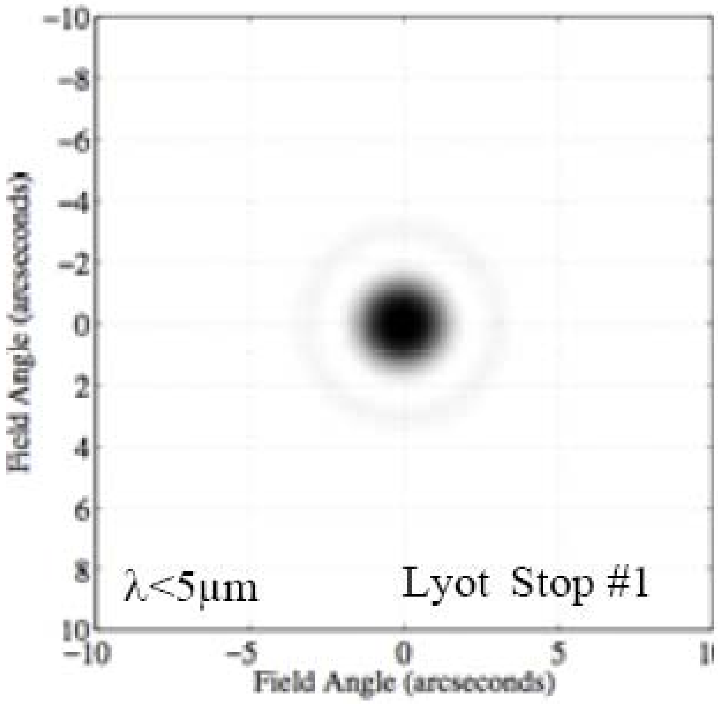
Science from visible & thermal images

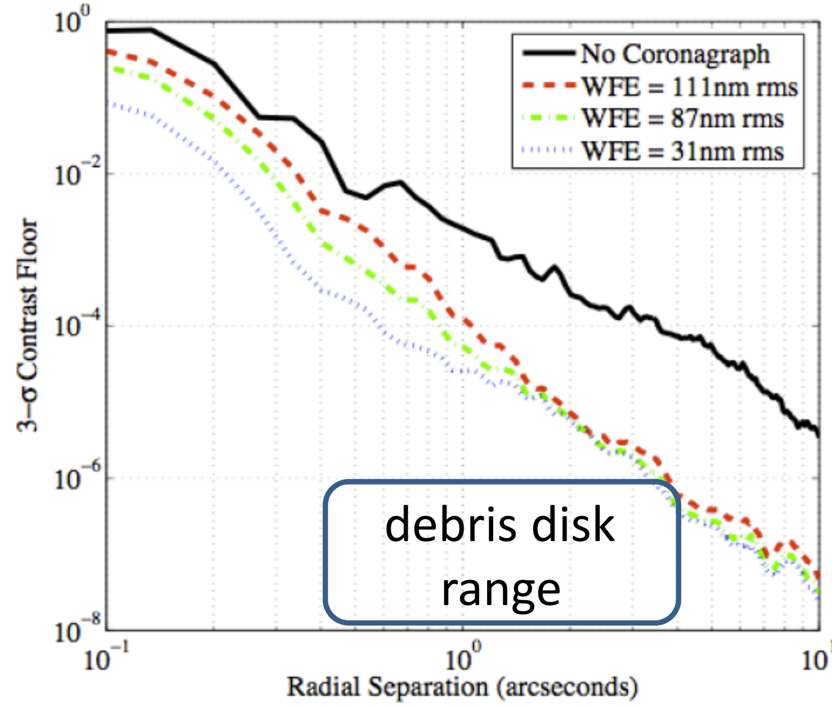
- Thermal flux → # grains * area/grain * σT^4
- Thermal spectrum → T → size (star-belt separation, AU)
- Visible image size → location of comet/asteroid source of grains
- Visible image shape → width/warp → shepherd planet locations
- Visible image shift → massive planet
- Visible image brightness → # grains * area/grain * albedo→albedo
- Visible image color → type of material, size of grain, weathering
- Visible image numbers → relative history of planetary systems

Imaging telescopes for debris disks

- Ground-based: impossible for all but Fomalhaut (speckles)
- Hubble: limited to handful of bright disks with contrast > 10^{-7}
- Spitzer: combined-light thermal photometry only
- JWST: difficult (see next chart)
- Balloon-borne coronagraph: promising (see charts after next)

JWST imaging of debris disks





- (left) NIRCAM occulter 1.25 arcsec radial sombrero, with F480M
- (right) 3-σ envelope to the azimuthally averaged contrast, for no coronagraph (black), and for occulter (colors)
- Result: The contrast & radius of known and expected debris disks is *outside the range of sensitivity of JWST*

Ref.: adapted from Green et al, SPIE (2005)

Zodiac II: Example of a feasible coronagraph on a balloon platform

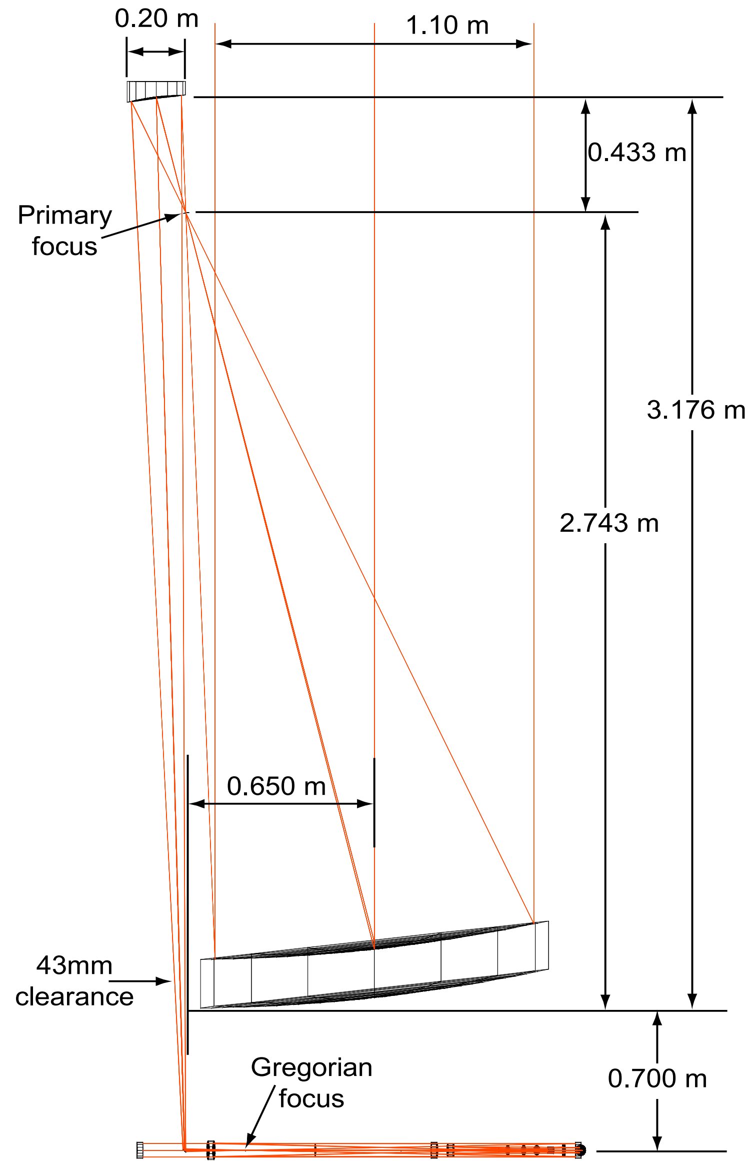
We show here the 1.1-m diameter version of Zodiac II.

A mini-Zodiac should have nearly comparable performance.

Instrument

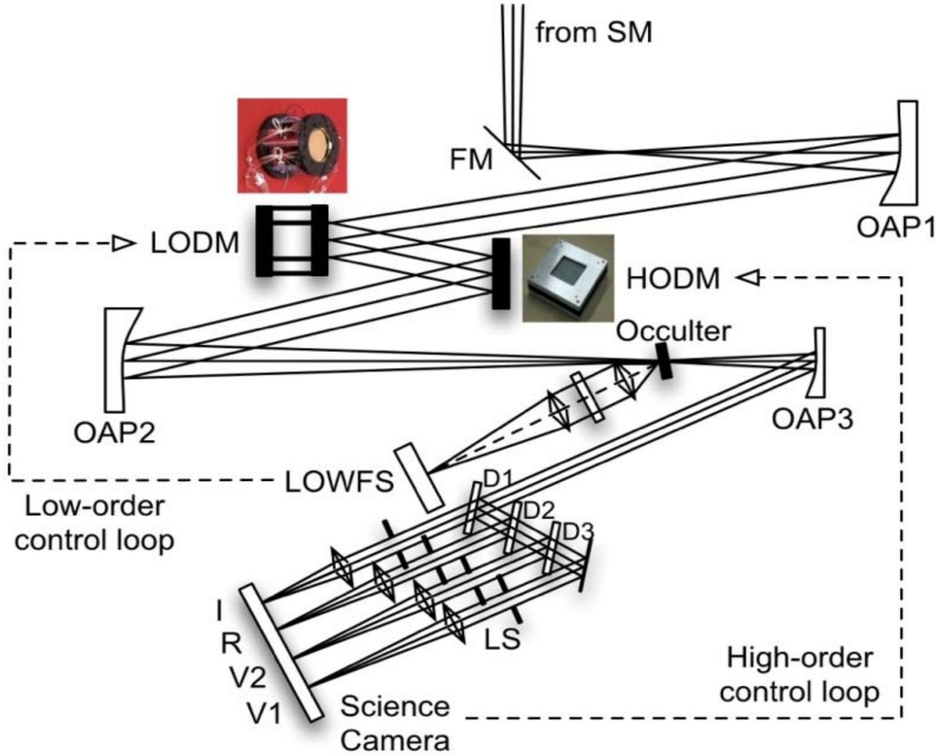
- 1.1-m diameter telescope, for angular resolution and collecting power
- Imaging coronagraph, to keep bright star from flooding disk image: final contrast 10^{-8}
- Visible wavelength operation, to see reflected light from disk: 500-990 nm
- Four spectral bands, to measure disk color
- Stratospheric balloon platform, to get above Earth's turbulence: 35 km
- Multi-hour integration times, to capture faint disk images: 4 flights,

  25 targets
- No current or planned facility can match Zodiac II on debris disks, by factor of 100



Coronagraph

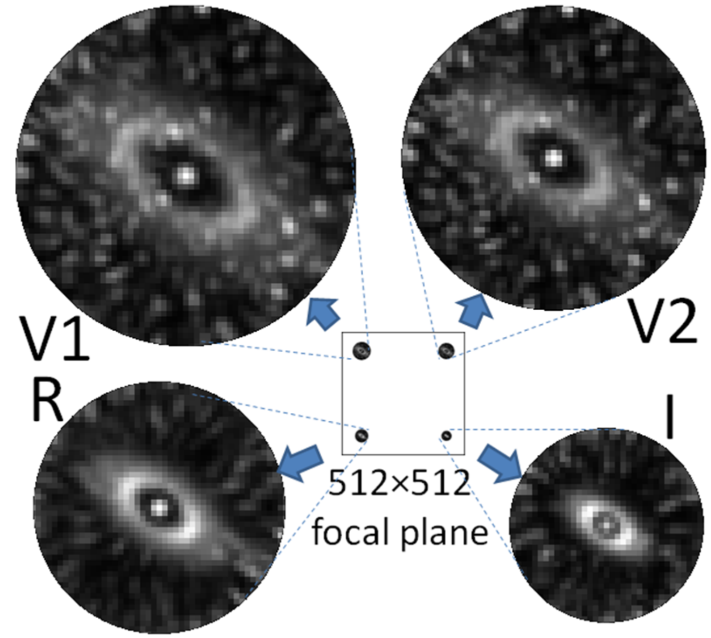
Coronagraph schematic showing optical path and control loops



- The low-order modes are measured by a LOWFS using light reflected off the occulter. These modes are corrected by the LODM.
- The high order deformable mirror is adjusted based on science camera images of the residual speckles.
- Dichroics (D1, D2, D3) split the beam into 4 wavelength bands that pass through individual Lyot stops (LS) before reaching the single science camera.

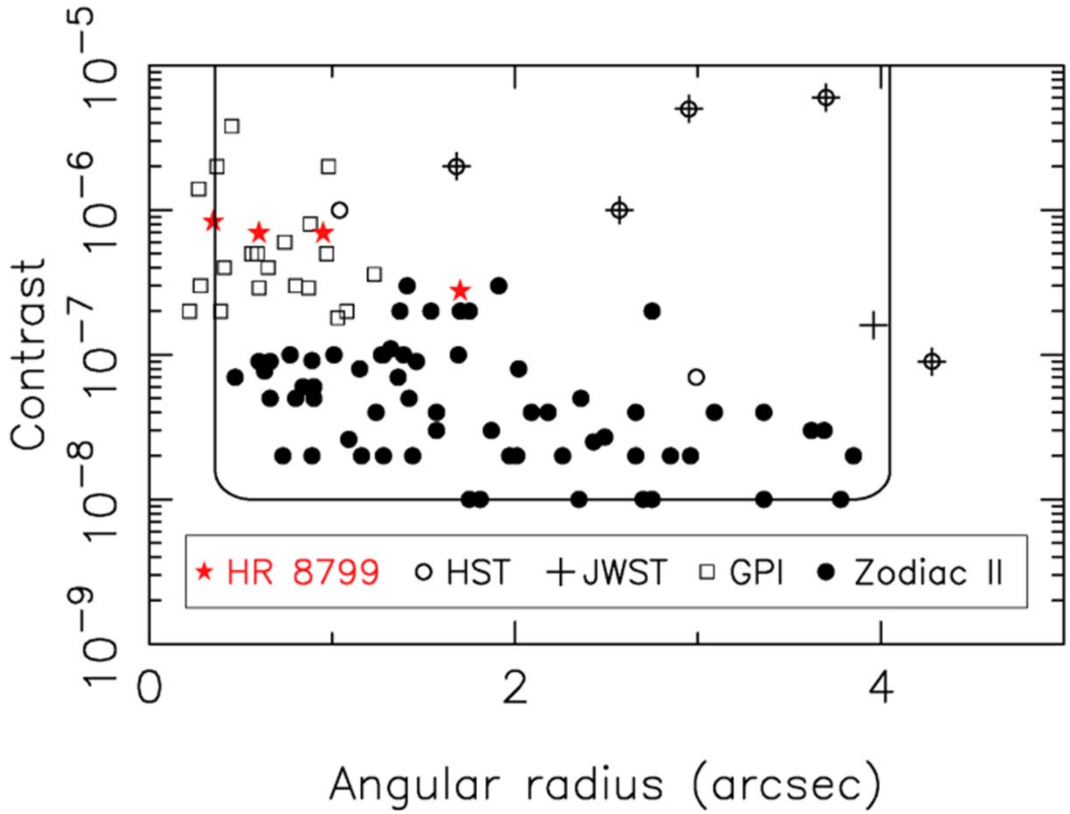
Focal plane simulation

Band	Central Wavelength	Bandwidth (FWHM)	D_{Lyot}/D_{tel}
V1	520 nm	10%	0.65
V2	580 nm	10%	0.58
R	700 nm	20%	0.48
I	900 nm	20%	0.37



- Four Zodiac II bands are recorded onto a single CCD camera
- Images are scaled to give 2.5 pixel per FWHM in each image
  - R- and I-band images smaller than the V-band images
- Simulated disk structure (assumed two belts) surrounding a V=6 star
  - 1 hour of -1-minute-long integrations
  - Disk can be seen within each of the circular dark holes

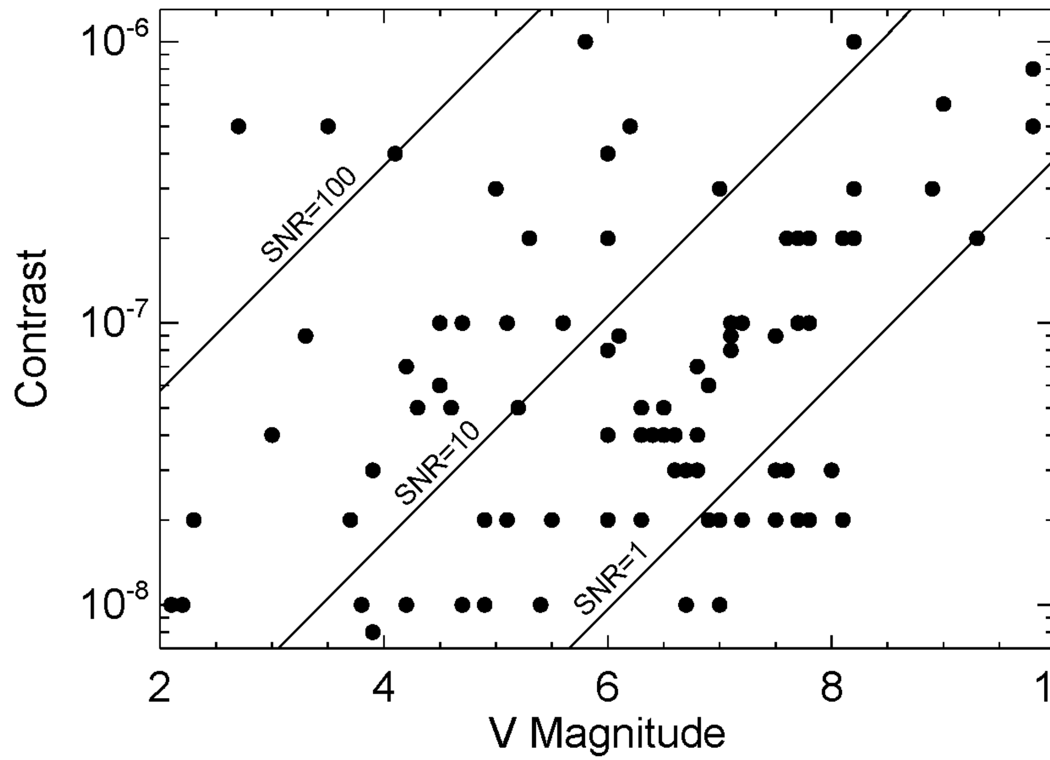
Predicted debris disc sizes and contrasts



- 89 target debris disks for Zodiac II shown in the the U-shaped area
  - Complete list derived from Spitzer data
  - Inner angular limit of the U is for V1-band; outer limit is for I-band
- Zodiac II contrast and angular resolution open up a large discovery space

Sensitivity

- SNR per resolution element
- 1 hour integration
- V1 (520 nm) band



Signal-to-noise ratio (SNR) for our target debris disks vs. stellar magnitude and disk contrast

Thank you!

Further references:

1. S. Wolf, et al, Circumstellar disks and planets, science cases for next-generation optical/infrared long-baseline interferometers, A & A (2012)

2. O. Absil and D. Mawet, Formation and evolution of planetary systems: the impact of high angular resolution optical techniques, A & A (2010)

3. G. Bryden, et al, Zodiac II: debris disk science from a balloon, SPIE (2011)