Status of Nulling Interferometry in the US

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11 December 2012

Acknowledgments

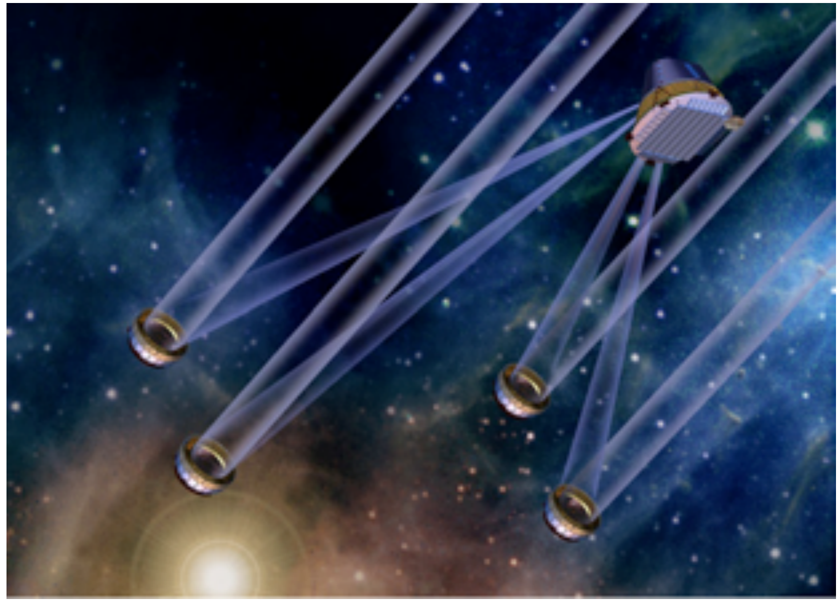
With help from:

Peter Lawson, Rafael Millan-Gabet, Phil Hinz, Stephen Rinehart, David Leisawitz, Gene Serabyn, Bruno Lopez, Denis Defrere

Summary of US Efforts

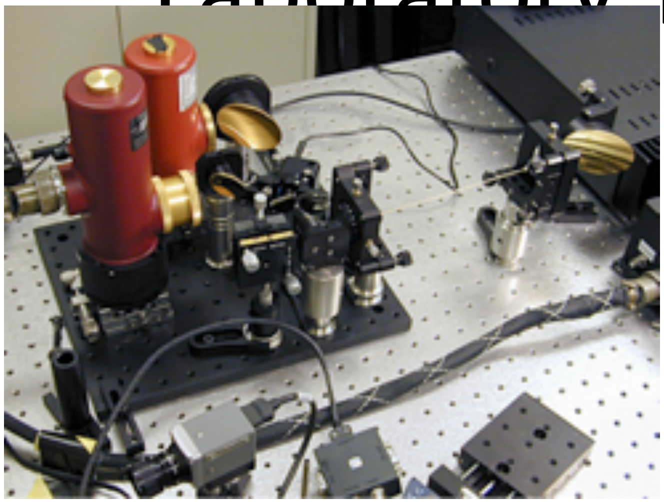
- JPL Testbeds for TPF-I
  - Milestones completed on null depth, stability, bandwidth, formation flying, planet detection
  - Milestone papers online at Exoplanet website
  - All work completed with testbeds, now inactive
- Keck Interferometer Nuller (KIN)
  - Used for Exozodi surveys on nearby stars with known excesses and without excesses
  - Used also for some general astrophysics
  - Keck Interferometer on hiatus until new funding is found after NASA stopped funding it
- Large Binocular Telescope Interferometer (LBTI)
  - Funded for next 5 years for Key Science project on a survey of nearby stars for exozodi
  - Competitively selected science team
  - N band -- mid-ir nuller, imaging (fizeau) combiner, aperture masks
  - K band pathlength sensing and compensation system built into nulling subsystem
  - L, M band near-ir fizeau combiner and aperture masks
- Rotating Palomar Fiber Nuller (PFN)

TPF-I Technology Goals and Accomplishments

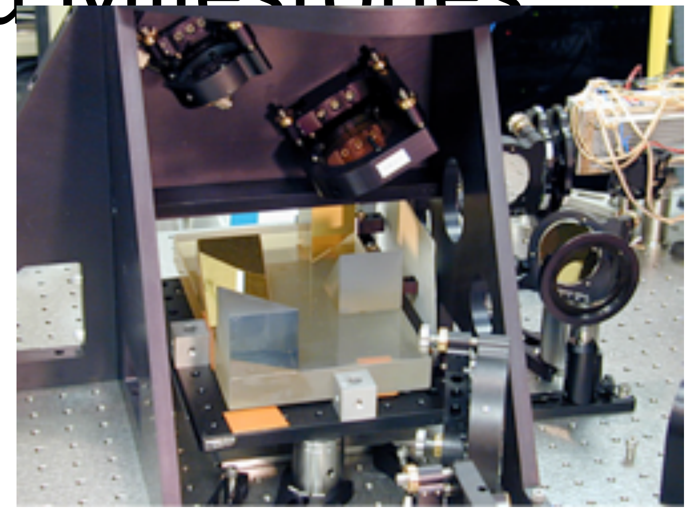


- Architecture
  - Adoption of Emma X-array by TPF-I and Darwin as basis for mission design
  - Demonstration of agreement between independent performance models of Emma X-Array and comprehensive target star catalog

Laboratory Testbed Milestones



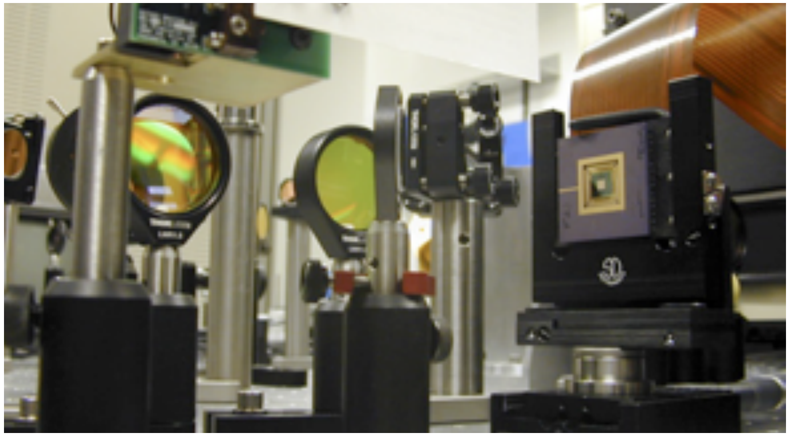
View of a chalcogenide glass fiber, in use within the Adaptive Nuller testbed. The fiber can be seen being fed by an off-axis parabola, to the right, prior to the spectrometer and single-pixel detector.



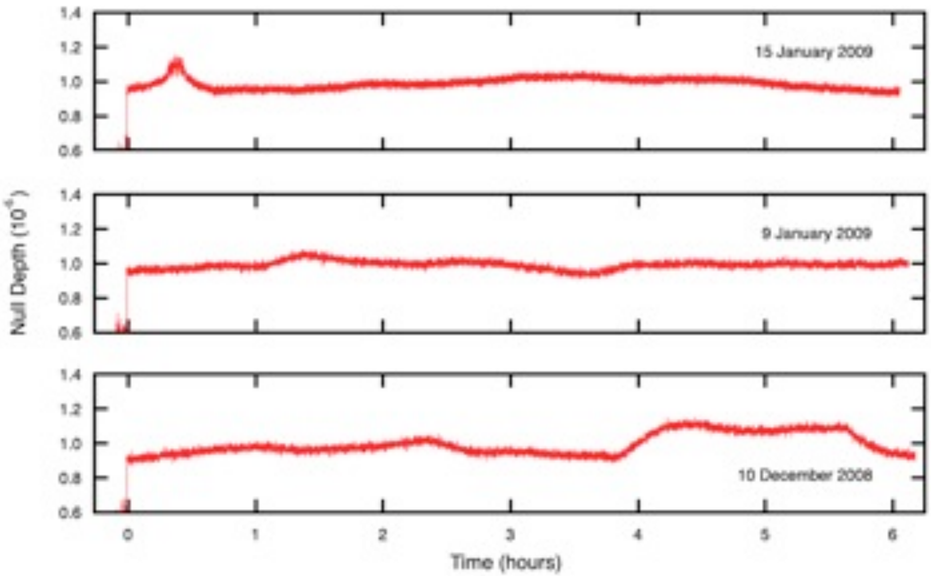
Side view of the periscope assembly of the Achromatic Nulling Testbed.

- MILESTONE #1 – Compensation of intensity and phase demonstrated by Adaptive Nuller testbed. Intensity compensated to 0.2% and phase to 5 nm rms across a 3 µm band centered at 10 µm
- MILESTONE #2 – Demonstration of precision formation flying maneuvers in a ground-based robotic testbed, with traceability to flight
- MILESTONE #3 – Demonstration of broadband nulling at the flight requirements of 1.0×10^{-5}, using 34% bandwidth centered at 10 µm. Monochromatic nulls demonstrated to 5×10^{-7}.
- MILESTONE #4 – Laboratory demonstration of detection of planet signal 10^{6} times fainter than a star while using array rotation, chopping, and averaging.

Adaptive Nuller Testbed



The Adaptive Nuller Testbed (AdN). The Adaptive Nuller demonstrated broadband nulling to the levels required for a flight mission. 1 x 10^-5 nulls were demonstrated using a bandwidth of 34% centered at a wavelength of 10 um. This photo shows a closeup of the Adaptive Nuller's deformable mirror, which performs the phase and intensity compensation.



Broadband nulling data from the Adaptive Nuller. A total of 16 hours of data are shown from three separate 6-hour experiments. Each data set shows an average null depth better than 1 x 10^−5. This level of starlight suppression would dim the starlight so that it is fainter than the glow of a typical exozodiacal cloud that might surround a target system.

Planet Detection Testbed

Overview of the Planet Detection Testbed (PDT). This testbed includes a 4-beam nulling beam combiner to emulate the system complexity of the Emma X-Array. In laboratory experiments with the PDT, planet signals a million times fainter than a star have been detected.

The PDT completed Milestone #4 in October 2009. An example dataset is shown on the next slide.

The criteria for the milestone were as follows:

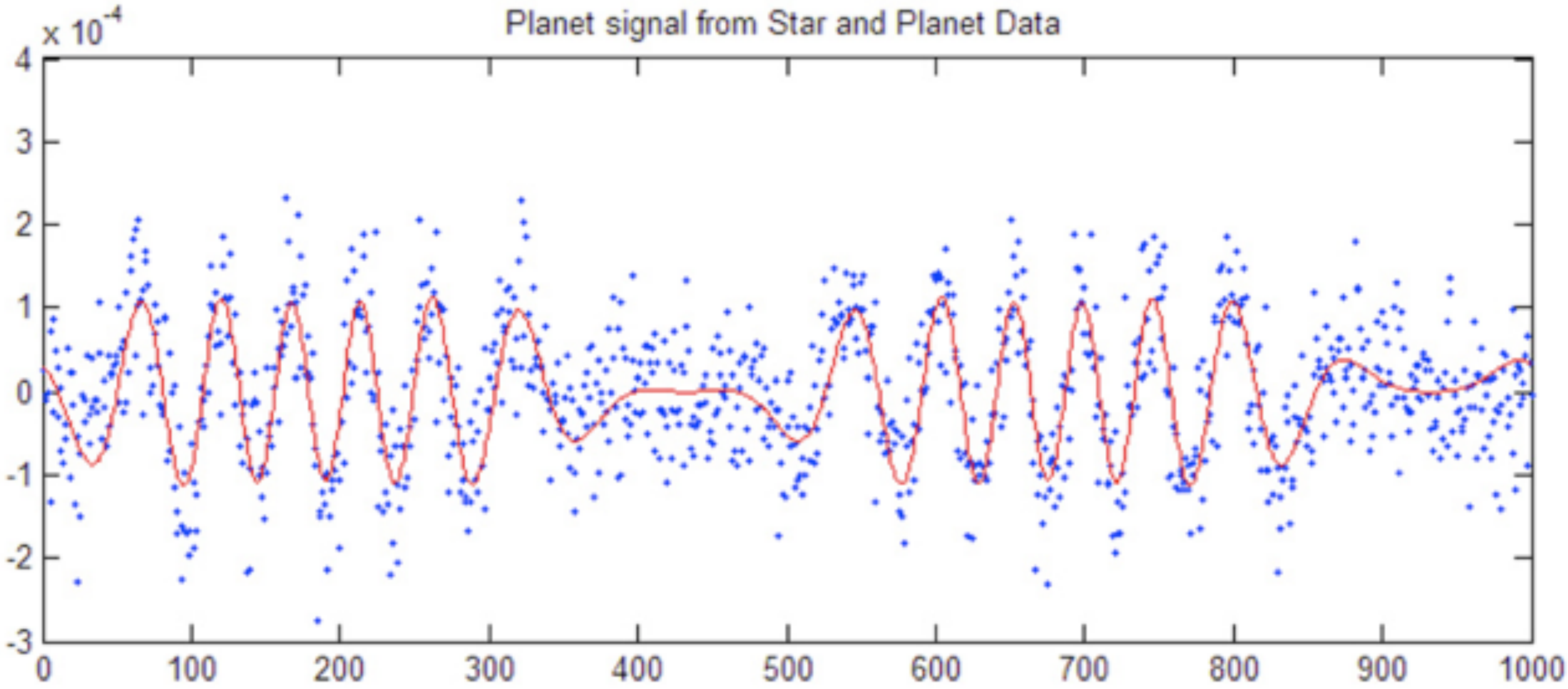
1. Detect a planet at a contrast of 10^{-6} relative to the star at a signal to noise ratio of ≥ 10.

2. Show residual starlight suppression from phase chopping, averaging and rotation ≥ 100.

3. The tests in (1) and (2) must each run for a total duration of 10,000 s and may include one or more planet rotations at timescales ≥ 2, 000 s.

4. The tests in (1) and (2) must be satisfied simultaneously on three separate occasions with at least 48 hours between each demonstration.

PDT, continued



Planet signal detected with the Planet Detection Testbed, from experiments on 10 July 2009. The null depth was 7.4×10^{-6}, the planet/star contrast was 4.4×10^{-7}, and the planet is detected with a signal-to-noise of 16.4. The best-fit fringe pattern is shown for reference. Rotation, chopping, and averaging here provides an additional factor of 250 in noise suppression.

Miscellaneous Accomplishments

- Autonomous rendezvouz and docking maneuvers in space by DARPA's Orbital Express and ESA's Autonomous Transfer Vehicle, Jules Verne.

- Mid-IR spatial filter developments
  - Chalcogenide fibers (NRL) – 20 cm long – 30 dB (factor of 1000) rejection of higher order modes, efficiency 40% accounting for throughput and Fresnel losses. Good single mode behaviour at 10 µm, fibers good to at least 11 µm. These fibers were used in the Achromatic Nulling Testbed and Adaptive Nulling Testbed.
  - Silver Halide fibers (Tel Aviv) – 10-20 cm long, demonstrated 42 dB rejection (16,000) of higher order modes with losses of 12 dB/m. Silver halide fibers useable to 18 µm. Testing only done at 10 µm.

Many papers

- Publications available and displayed on JPL Exoplanet website or through ADS
- Testbed papers – Gappinger, Martin, Booth, Peters are lead authors on main papers
- Fibers – Kzendzov

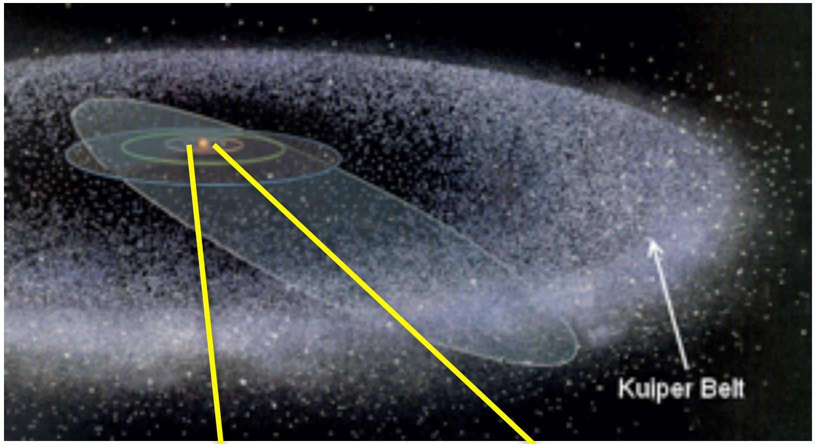
Exozodis

- Debris disk: dust generated by collisions in asteroid and Kuiper belts and by comet outgassing. The inner component (<5AU) is called zodiacal cloud.

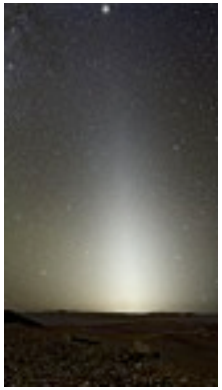
- Extra-solar analogs are common, but due to observational limitations we know a lot more about outer, colder dust (exo-Kuipers) than about debris dust in the planet formation zone.

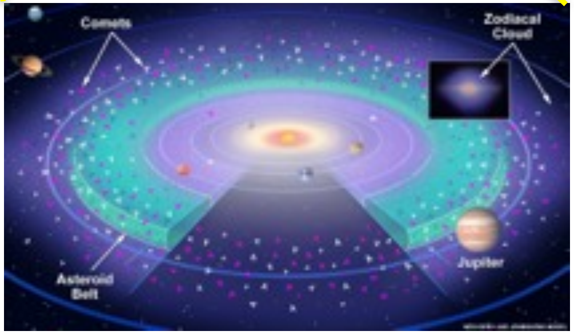
- Zodiacal dust reflects planetary system formation history and current dynamical state.
- But, could be a major hindrance to the direct detection of exo-Earths (noise + confusion).

Outer Solar System …



Inner Solar System …



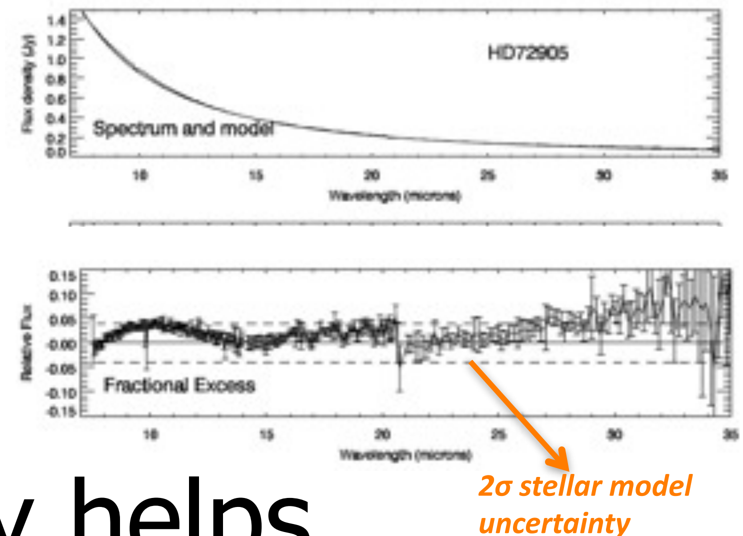


Zodi light seen from Paranal

Exozodis are difficult to detect

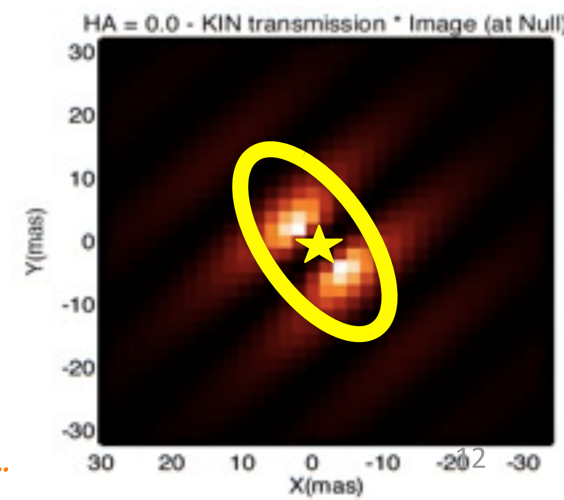
- The dust emission is faint and close to the star.
- Unresolved photometry is the most common method.
- Even with infinite photometric accuracy, limited to ~1% best case relative photometry by ability to predict the stellar MIR flux (~300 zodi, 1σ).

Spitzer/IRS – Beichman et al. 2006



Interferometry helps

- Spatially separate the signal from the star and the surrounding disk.
- 2 main methods:
    - NIR high-accuracy visibility (CHARA/FLOUR, VLTI/PIONIER).
    - MIR Nulling (MMT/BLINC, KIN, LBTI).
- Free of modeling assumptions on the stellar spectrum.

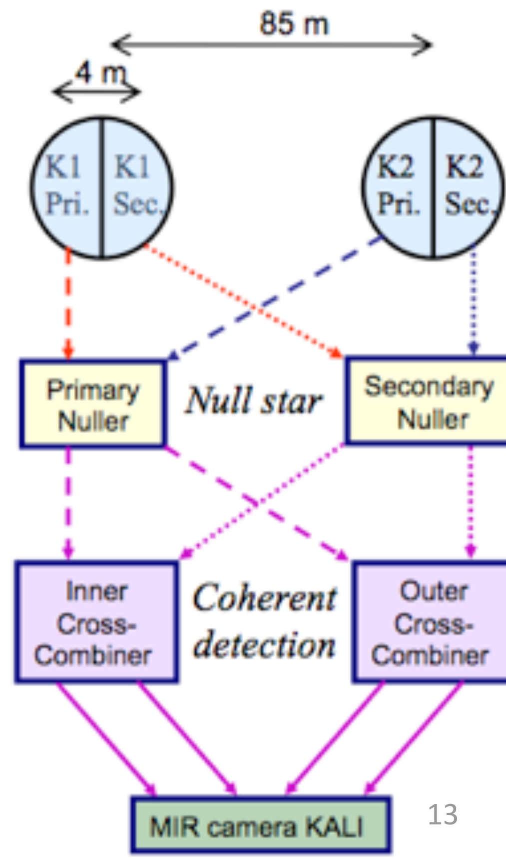


See refs. by: Ciardi, Absil, Di Folco, Defrere, Smith, Akeson, Liu, Stock, Stark, Millan-Gabet, Mennesson etc …

The Keck Interferometer Nuller

- Spectral band: 8 – 13 µm (R~25).
- Sensitivity: 1.5 Jy @ 10µm
- **Resolution (λ/2B) = 10 mas @ 8.5µm**
- FOV: 0.1 AU – 4 AU @ 10 pc ➔ sensitive to inner dust.
- Double-nuller architecture:
  - DC signal ➔ AC signal.
  - Allows accurate visibility measurements in spite of large thermal background.
- σ(Leak) = 0.003 (typical) corresponds to σ(Vis) = 0.006 (0.6%, much better than standard MIR interferometry!
- **Translates to σ(zodi) = 160.**

Note: the unit "zodi" refers to a scaled zodiacal-twin disk (see discussion of units in Roberge et al 2012).



Instrument details: Colavita 2009. Theory: Serabyn 2012

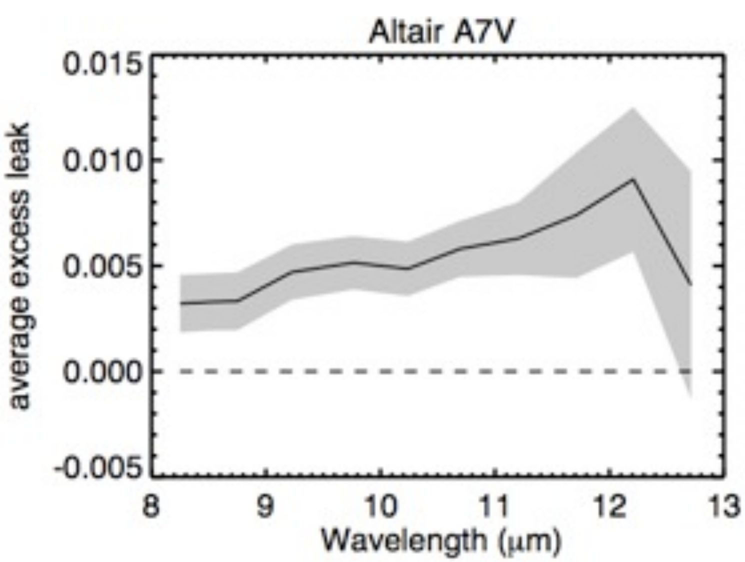
KIN exozodi surveys

- **Three NASA Key Science projects (2008-2009):**
  - **23 mostly FGK stars with no previously known dust (PI: Serabyn 2008-2009)**
  - **19 mostly early type stars with previously known cold dust (PIs: Hinz & Kuchner 2008-2009)**
- **One additional PI program (Mennesson 2010-2011):**
  - **6 mostly early type stars suspected to have very hot/close-in dust (from the Absil et al. survey at CHARA).**

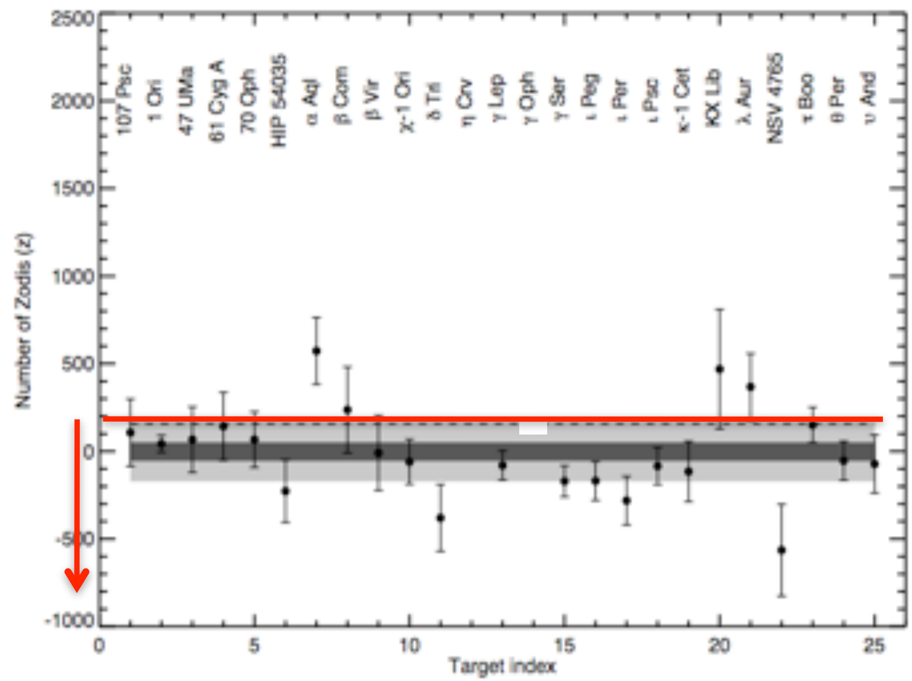
Analysis of stars with a priori no dust

(Millan-Gabet, Serabyn, Mennesson et al. 2011)

- 23 FGK stars.
- Only one shows dust at marginal detection level (Altair – but later, NIR excess also detected by



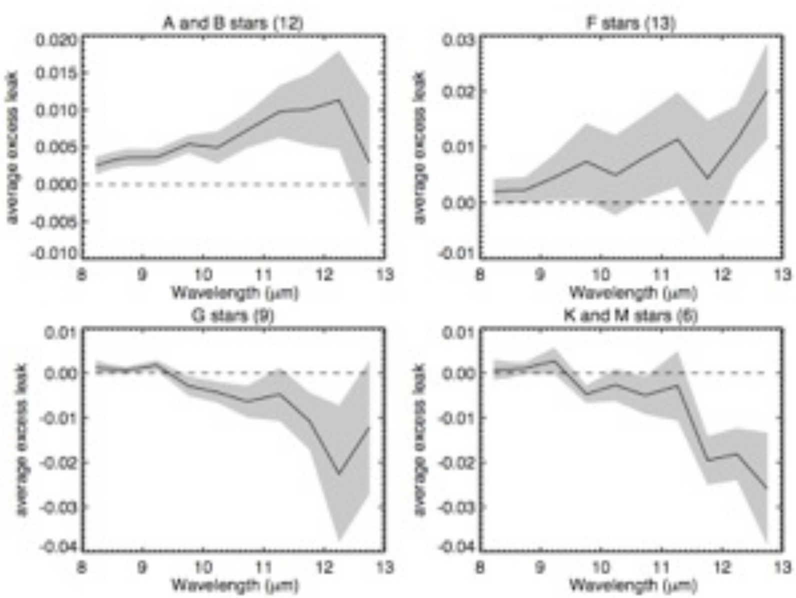
600 +/- 200 solar zodi

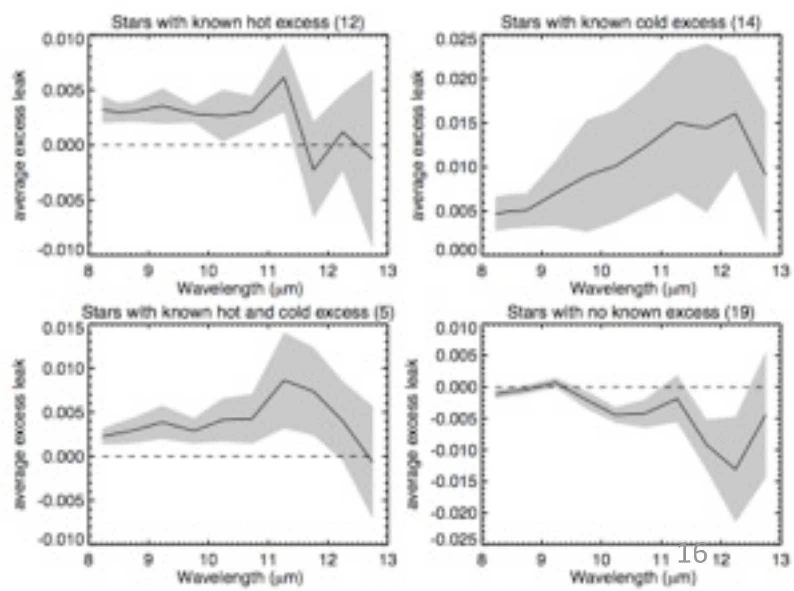


150 zodi 3σ upper limit for the *class*

Analysis of stars with previously known dust

- **14 single stars with previously known cold (far IR) excess:**
  - 4 detected by KIN: Fomalhaut, ζ Lep, γ Oph and η CrV.
    (+ 5 more marginal detections)
- **12 single stars with known hot (NIR) excess (CHARA/FLUOR):**
  - stars with only hot excess, do not tend to show KIN excess - 3 of 8 and with only very weak excess.
- Complete sample: 40 single stars, look for trends with:
  - **Spectral type: more KIN detections for A stars. disk difference or age effect?**
  - Presence of cold/hot dust: hot dust appears to have physically different origin.
- **Produce "top-10" list of cleanest stars (<100 zodi), as input to the next survey.**





Conclusions so far

- We are learning very interesting things with NIR and MIR interferometry.

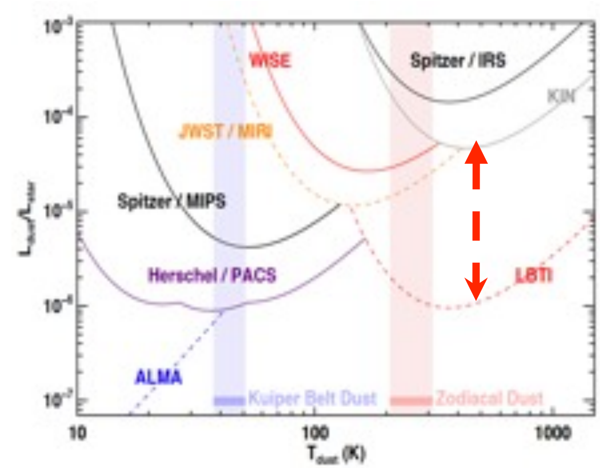
- The sensitivity of current exozodi finders, 300-1000 zodi 3σ, is not adequate to assess whether exozodis in the 10–100 zodi range (problematic for direct exo-Earth detection & characterization missions from space) are common or not.

- Need dedicated effort with x10 or more improvement.

The Large Binocular Telescope Interferometer (LBTI)

- **PI: Phil Hinz, U. Arizona.**
- NASA-funded instrument **for the LBT:**
  - **8-13 µm / 3-5 µm.**
  - **Nulling, Fizeau and aperture masking interferometry.**
- **Currently in commissioning.**
- **Expected** ultimate nulling performance: **noise equivalent 10 zodi (3σ).**

Roberge et al. ExoPAG report 2012

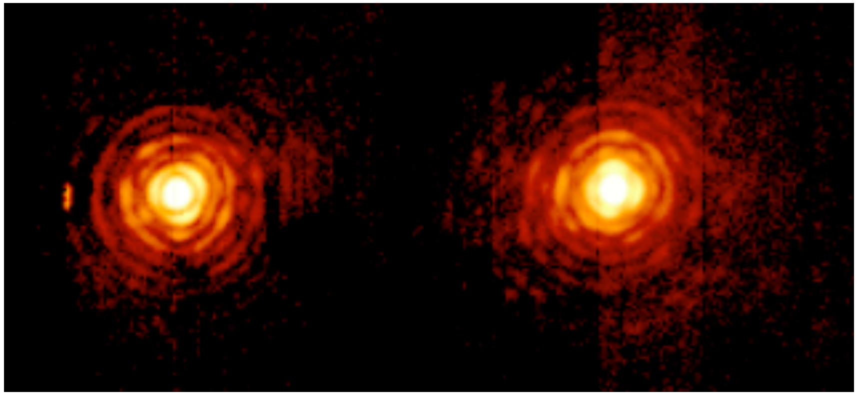


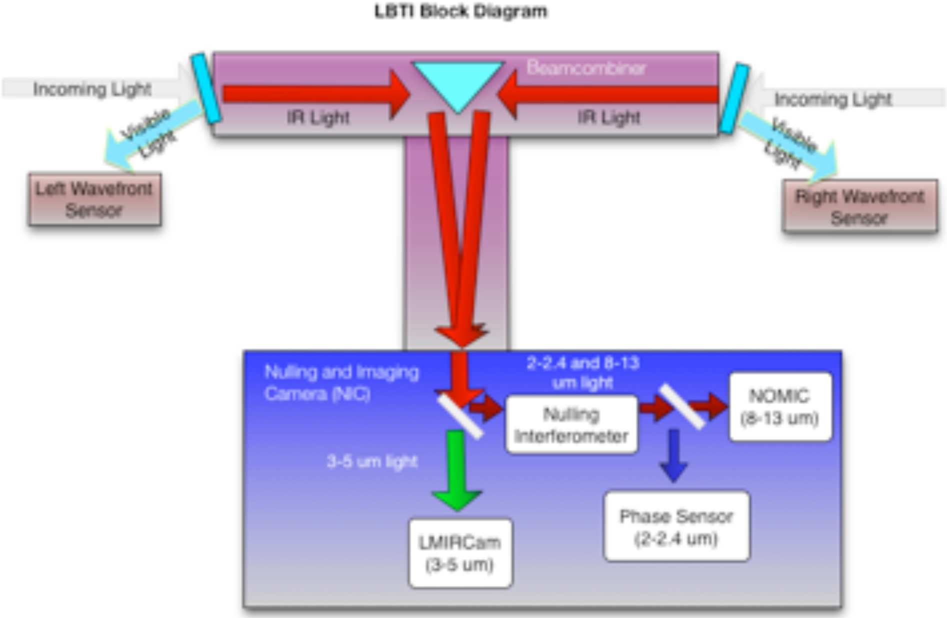
Exozodi key science survey:

- 50-100 nearby Sun-like stars.
- Competitively selected science team.
- Reconnaissance of specific exo-Earth detection targets + statistical constraints on the exozodi "luminosity function".

LBTI main features

- Sensitivity: two 8.4 m telescopes.
- Resolution: Bmax = 22.7 m.
- Leverages secondary deformable mirror to achieve diffraction limited wavefronts.
- Relatively simple beam train + cooled optics beam combiner, allows high sensitivity in the MIR.





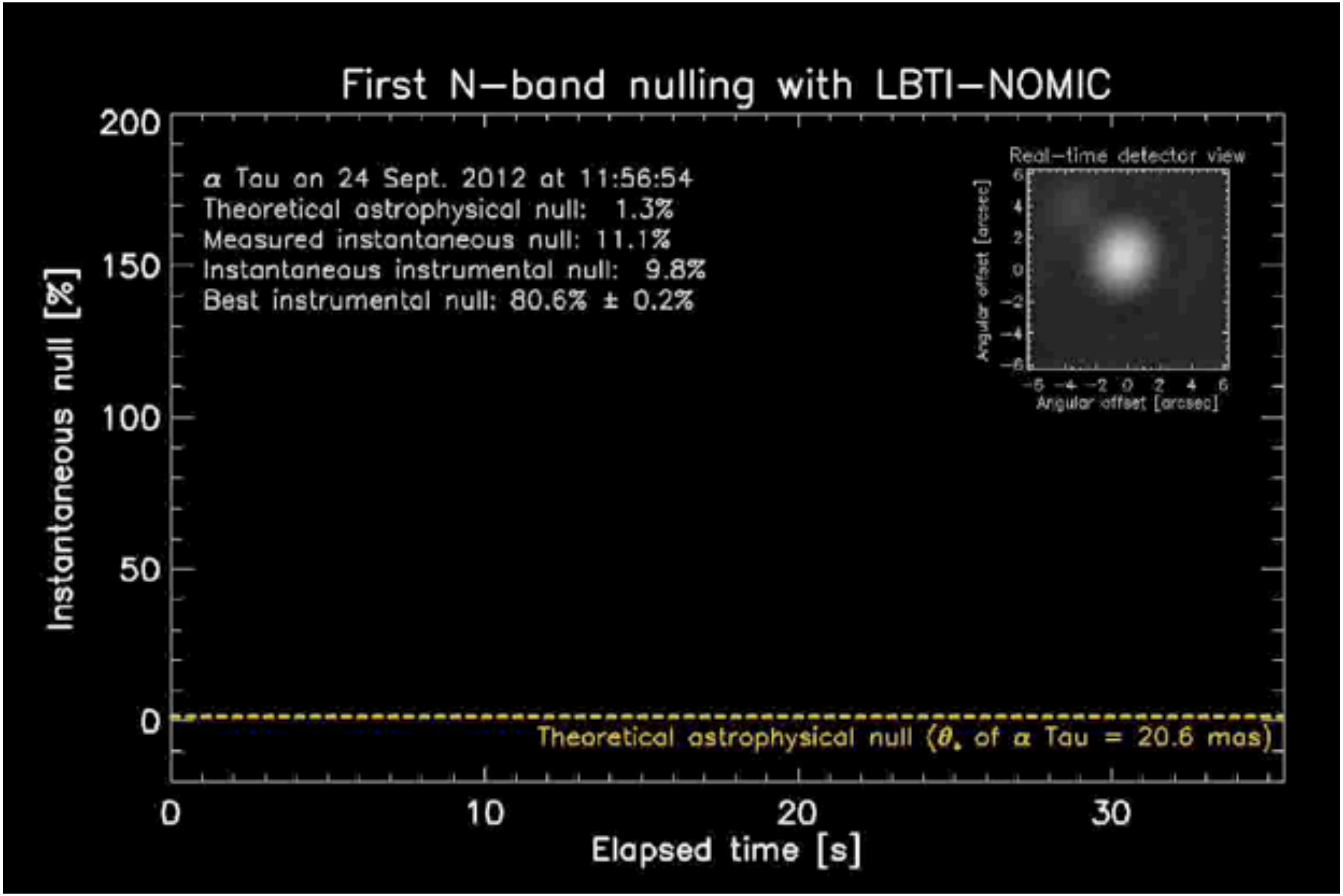
LBTI status

- September 2012:
  - first N-band nulling observations
  - Open-loop (no tip/tilt nor phase control)
  - Best null depth of 4.0% +/- 1.0%

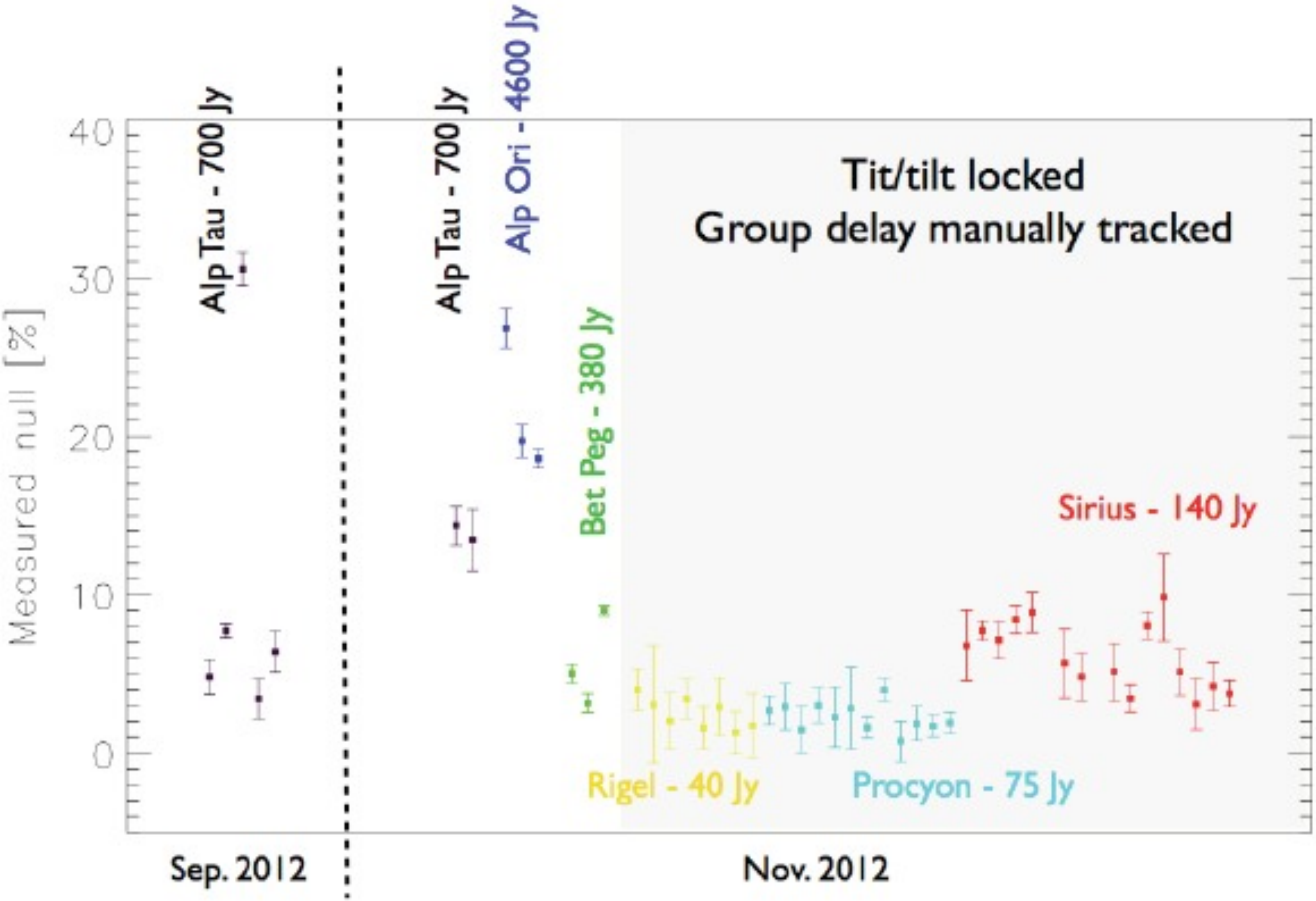
- November 2012
  - Successfully performed coordinated chopping on sky
  - Took simultaneous science measurements in both N and L bands
  - Successfully tested out tip-tilt control.
  - Tested phase control (up to 35Hz)
  - Took nulling data on calibrators with tip-tilt locked (group delay manually tracked)
  - Best null depth of 1.0% +/- 0.5%

First nulling data sequence

September 2012 – Alpha Tau



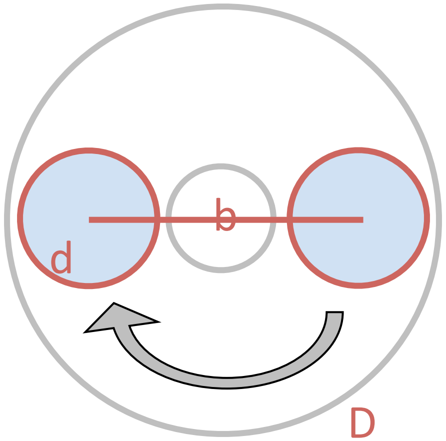
Overview of nulling data



The Rotating Palomar Fiber Nuller

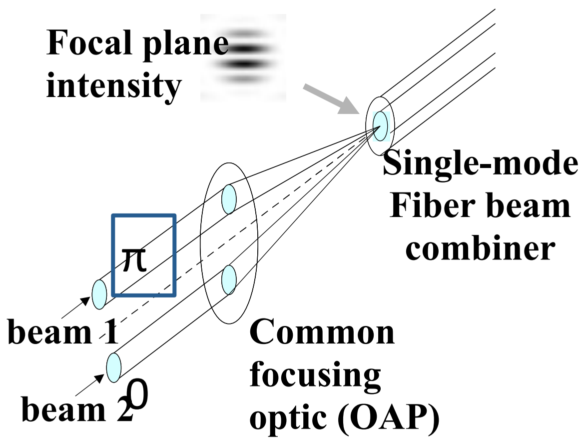
E. Serabyn, B. Mennesson, J. Kuhn, S.R. Martin, K. Liewer, F. Loya et al.

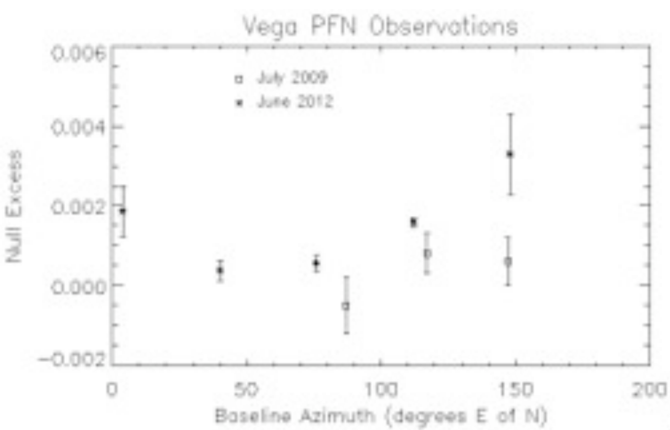
A rotating baseline nuller



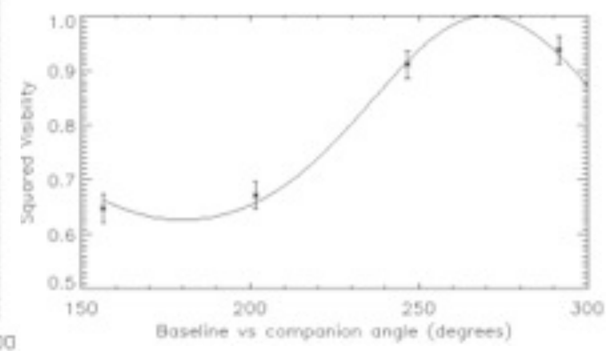
On the telescope

Simple beam combiner



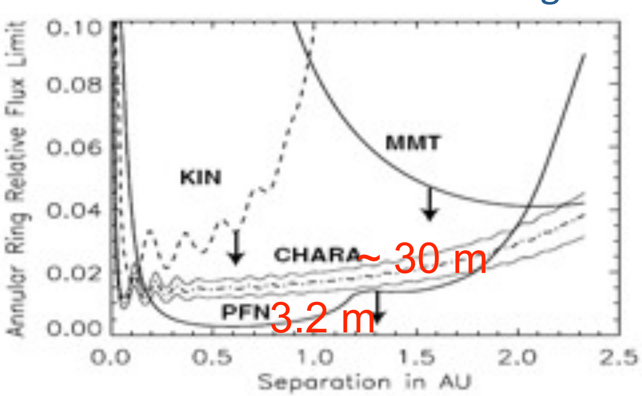


null depth accuracy ~ 0.02%
(at 2 μm)



companion detection

dust measurements: Vega



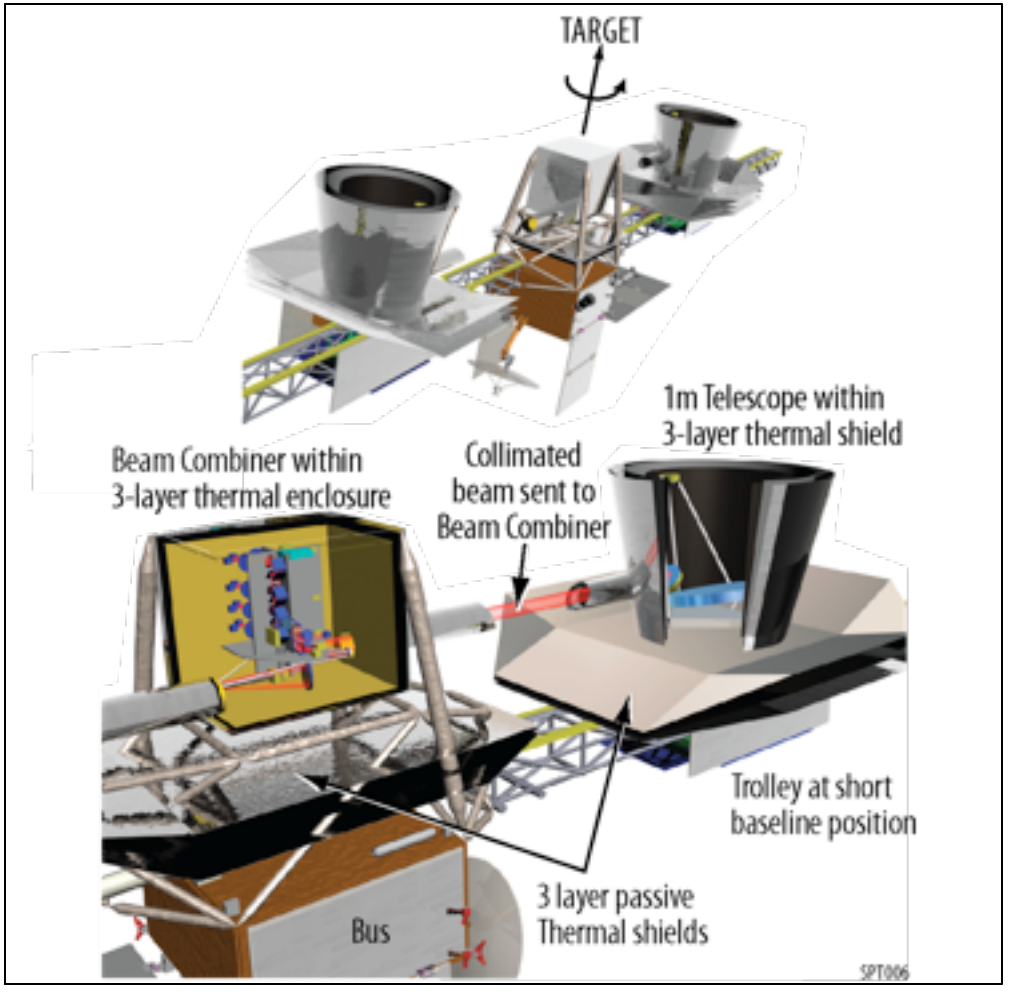
Non-nulling but relevant projects

- SPIRIT/WIIT Testbed
  - PI, D. Leisawitz, GSFC
- BETTII balloon borne FIR interferometer on a boom
  - PI, S. Rinehart, GSFC

The Space Infrared Interferometric Telescope (SPIRIT)

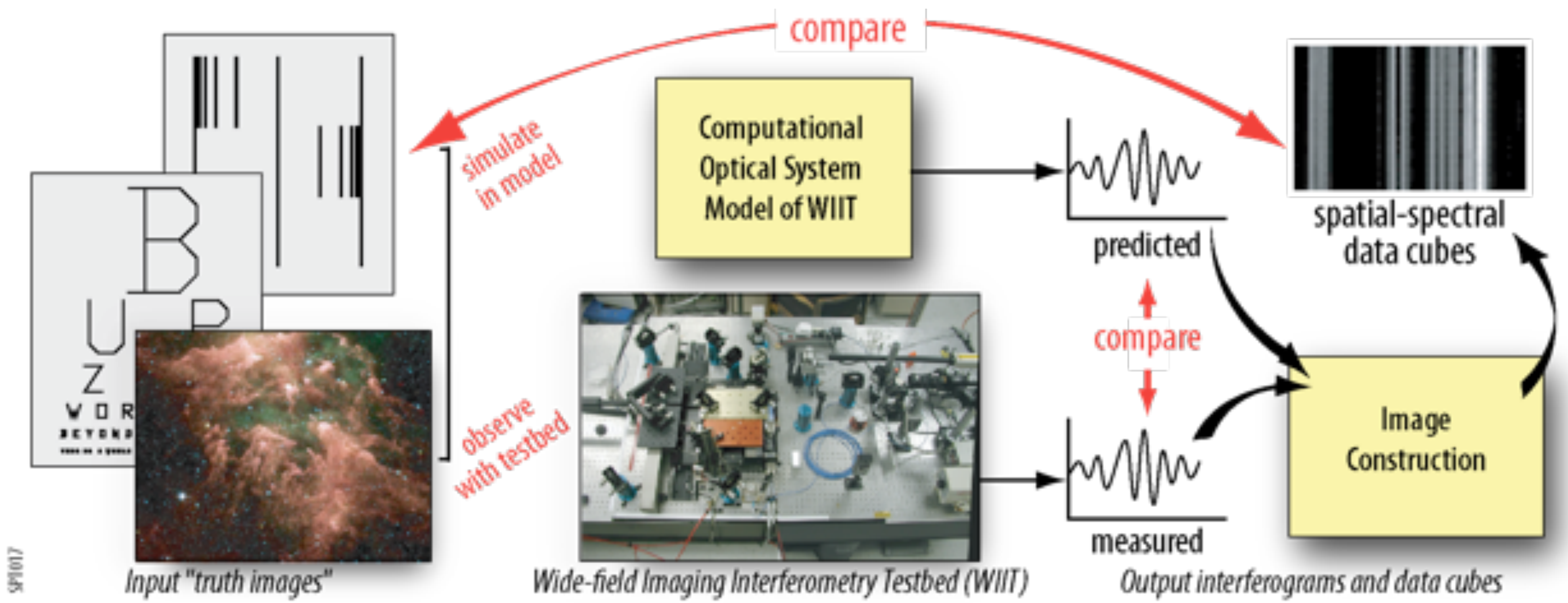
SPIRIT is needed to address science goals prioritized by the Decadal Survey:

- Discover how the conditions for habitability arise during planetary system formation
- Find and characterize exoplanets by measuring their sculpting effects on protoplanetary and debris disks
- Study the formation, merger history, and star formation history of galaxies



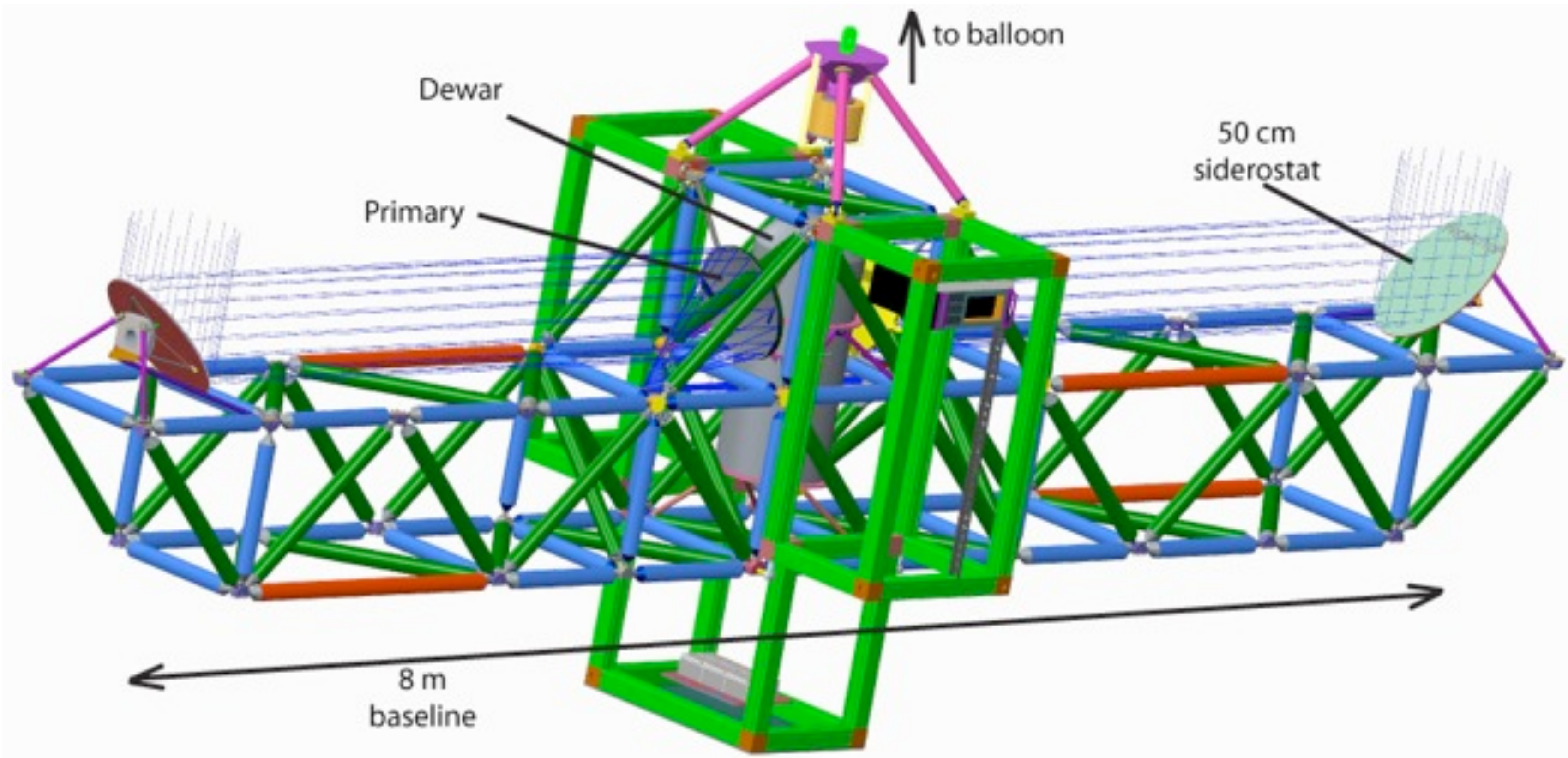
Wide-field spatio-spectral interferometry

The ultimate acceptance test for wide-field spatio-spectral interferometry for space flight application is demonstrated excellent agreement between synthesized hyperspectral cubes and observed, astronomically realistic "truth images," and a quantitative accounting for any differences in terms of understood instrumental effects.



ROSES APRA project at GSFC, D. Leisawitz, PI

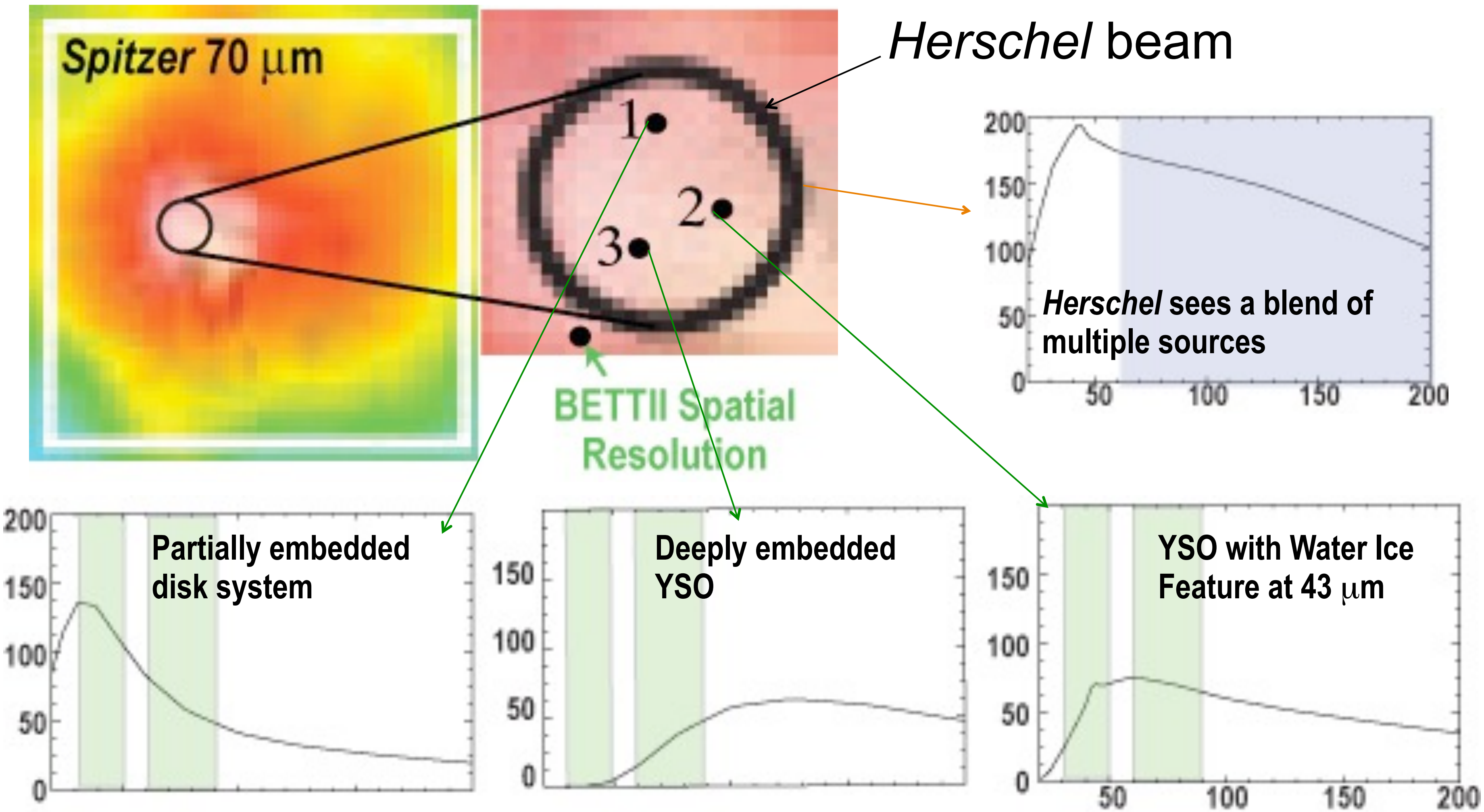
BETTII



8-meter interferometer providing 0.5" resolution at 40 microns
Wavebands of 30-50 and 60-90 microns
Spectral resolution of up to R=200, using Double-Fourier interferometry
~2' field-of-view
Carbon-fiber structure is stiff, light, and has good thermal properties

ROSES APRA funded project,
S. Rinehart, PI

Science With BETTII

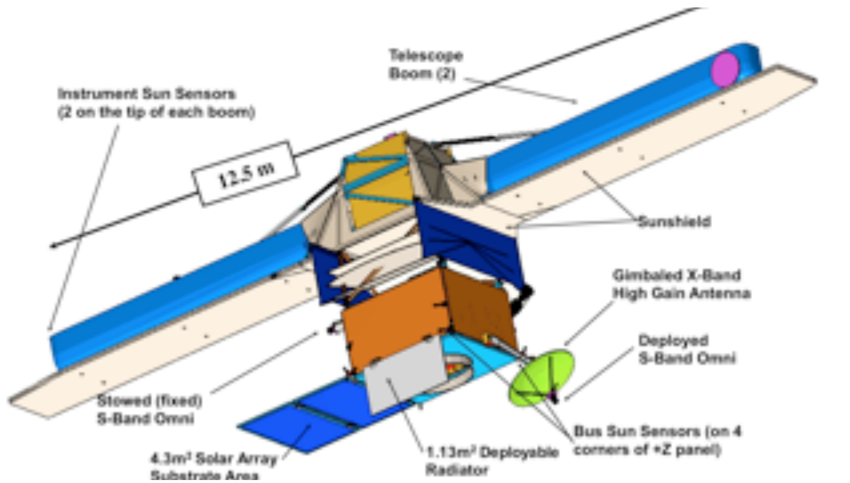


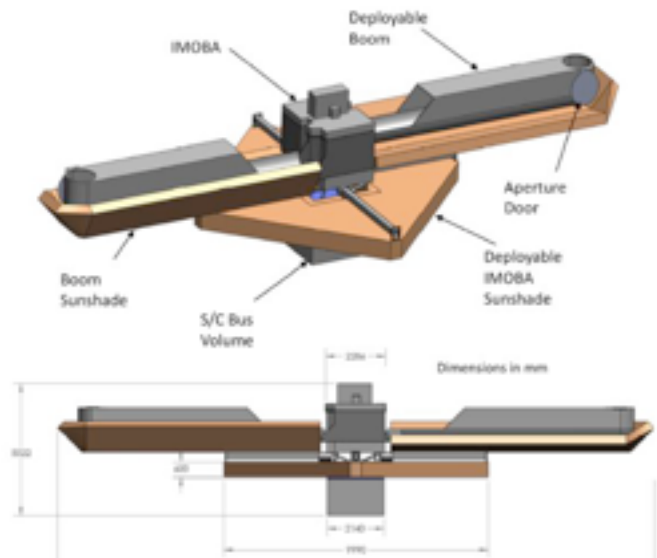
FKSI

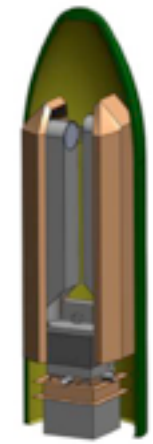
- Most recent work in 2009-2010 time frame – mission design studies:
  - Center wavelength from 5 to 10 um
  - Baseline from 12.5 m to 20 m
  - Mirror diameter from 0.5 m to 1.0 m
  - Passive cooling to 40 K
  - JWST cryocooler for detectors operating at longer wavelengths
  - Did performance calculations to see how many super-Earths and Earth-sized planets could be detected
  - Work was published in SPIE in 2010, and other conference proceedings
- Currently working with **PERSEE** for FKSI related issues:
  - Test imaging capabilities with realistic scene consisting of star, planet, and exozodi, but the current plan is to generate transmission maps, which is equivalent
  - Test of pathlength control for realistic boom and reaction wheel noise sources

Enhanced FKSI Design

Original Design







FKSI-2 in Atlas V Fairing

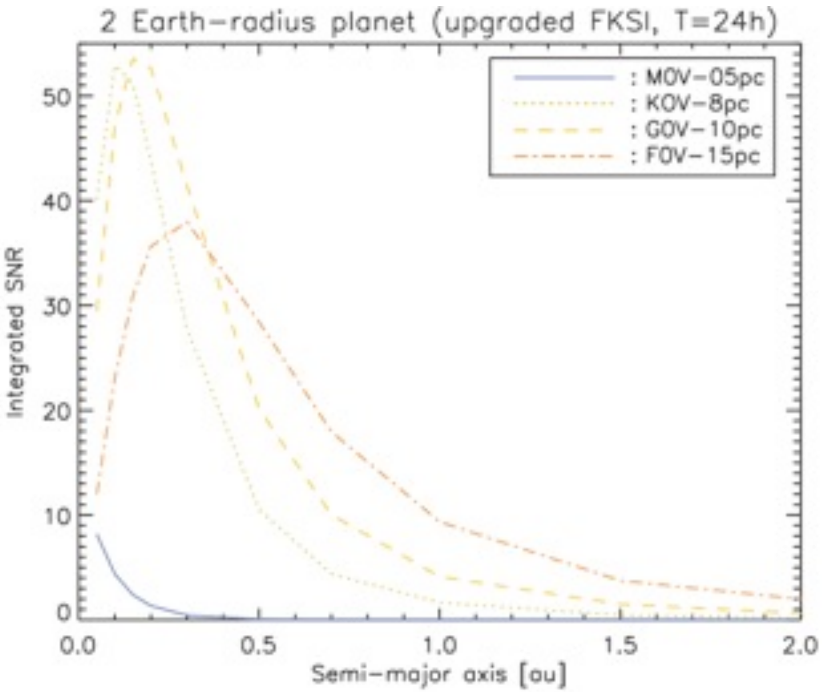
Basic Assumptions:	
SNR = 5 for detection	
SNR = 10 for spectroscopy	(R = 20 at 10 μm)
3 sets of observations per star (visits)	
< 2 years total	
< 7 days total per star	
T_{earth} = 288 K	
Earth albedo = 0.3	
Inclination angle of planet orbit = 45°	
Sunshade FOR = ± 45°	
1 SSZ emission from observed system's dust disk	

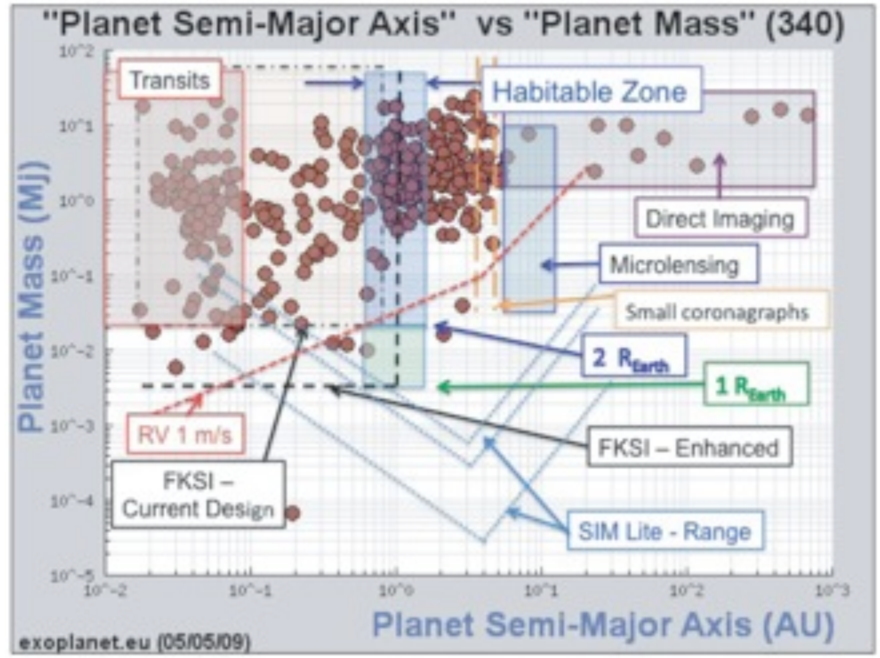
Enhanced "D" Design					
Tel = 1 m					
R_{Planet}	Total	N_F	N_G	N_K	N_{Spec}
1 R_{Earth}	4	0	1	3	4
2 R_{Earth}	34	6	16	12	16
Tel = 1.5 m					
1 R_{Earth}	15	0	7	8	4
2 R_{Earth}	95	35	48	12	27
Tel = 2.0 m					
1 R_{Earth}	29	3	14	12	12
2 R_{Earth}	138	65	61	12	43

Results of simulations using the TPF performance simulator of Dubovitsky & Lay for an enhanced FKSI but with 1-, 1.5-, and 2-m diameter telescopes. N_x is the number of 1 or 2 R_{Earth} exoplanets detected in the population of F, G and K dwarf stars within 30 pc. N_{spec} are the number of these target planets for spectroscopic characterization of the atmosphere.

Barry, Danchi, Lopez, et al.
Pathways Towards Habitable Planets
ASP Conference Series, Vol. 430, 2010
Vincent Coud´e du Foresto, Dawn M. Gelino, and Ignasi Ribas, eds.

Enhanced FKSI Exoplanet Discovery Space





Simulations of FKSI performance with 1-2 m class telescopes at 40K and a 20-m baseline demonstrate that many 2 Rearth super-Earths and a few Earth-twins can be discovered and characterized within 30 pc of the Sun.

Discovery space for exoplanets for FKSI and other mission concepts and techniques

Details in Danchi, Barry SPIE 2010, and Astro2010 contribution

Concluding Remarks

- TRL levels
  - Basic components for starlight suppression at TRL 4. TRL 5 requires testing in a relevant environment. Maybe LBTI qualifies since it cryogenic.
  - Pinholes for spatial filtering at TRL 5, but single mode fibers are at TRL 4, they need to be tested cryogenically
- For testbeds
  - Could proceed with brassboard designs
  - System level demonstrations
  - Cryotesting of complete nulling systems (i.e., like a cooled version of Planet Detection Testbed)
  - Integrated optics versions of nuller components
- Some current issues in the US
  - Since 2010 in the US the focus has been on an optical flagship coronagraphic mission. The 2.4 m NRO telescope is being seriously considered and an SDT has been commissioned to think about this. Such a mission could be WFIRST plus a coronagraph, internal or external, most likely internal.
  - What about the IR? We are discussing the possibility of PROBE scale missions like was agreed upon by the Exoplanet Community Forum and book in 2009.
  - There was a disconnect between the community and the writers of the Astro2010

Some Ideas on a Forward Path

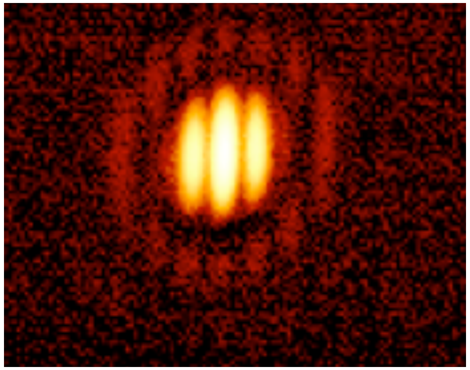
- Work on medium scale mission concepts based on FKSI
  - Continue work with PERSEE
  - Look into ways to better have US and Europe work together on mission concept design and planning :

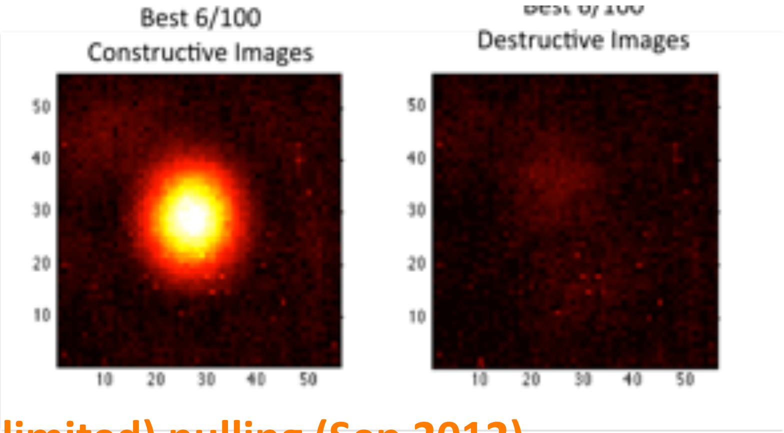
  Plan for instance to a contribution to the CNES Prospective Workshop of 2014 (idea of R&D …).
  - Coordination of proposal efforts
  - Participation in US ExoPAG
  - Develop an organization of framework to move forward
- French + other European participation in LBTI, especially broader science program with Aperture Masking, Fizeau Imaging, in support of MATISSE …

Backup

Status

10 µm Fizeau fringes.





Open-loop (seeing limited) nulling (Sep 2012).