KIN/PFN/LBTI heritage and lessons learned

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Why Nulling?

- Goal: Improve contrast for faint dust & companion emission very close to bright stars
  - Work inside the few λ/D inner limit of coronagraphy

- For small stellar leaks, the "null depth", N, is given by

$$N = I_{min}/I_{max} = (1-V)/(1+V)$$

= ratio of the signal in the destructive & constructive interference states

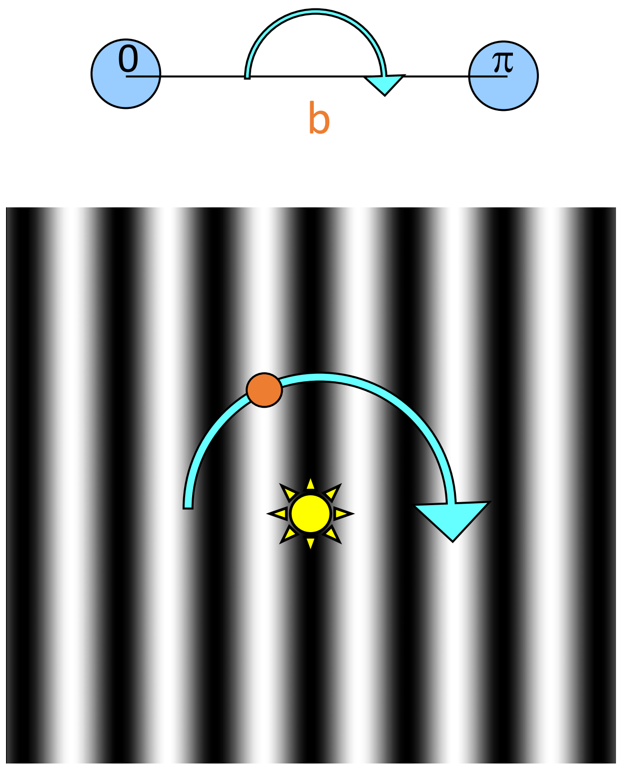
- For visibilities, V, ≈ 1, i.e., $V \approx 1 - \Delta V$

$$N \approx \Delta V/2 \qquad \textit{or} \qquad V \approx 1-2N$$

Aim to directly measure a small number (N)
instead of
delta from unity (V)

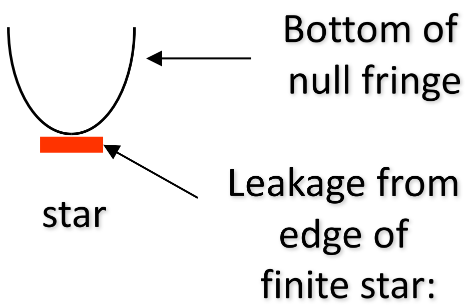
How?

- Antiphase a pair of apertures to center a dark interference fringe on a bright star
- Rotation of array (& fringes) modulates off-axis source signals



Bracewell (1978)

Stellar leak or null:

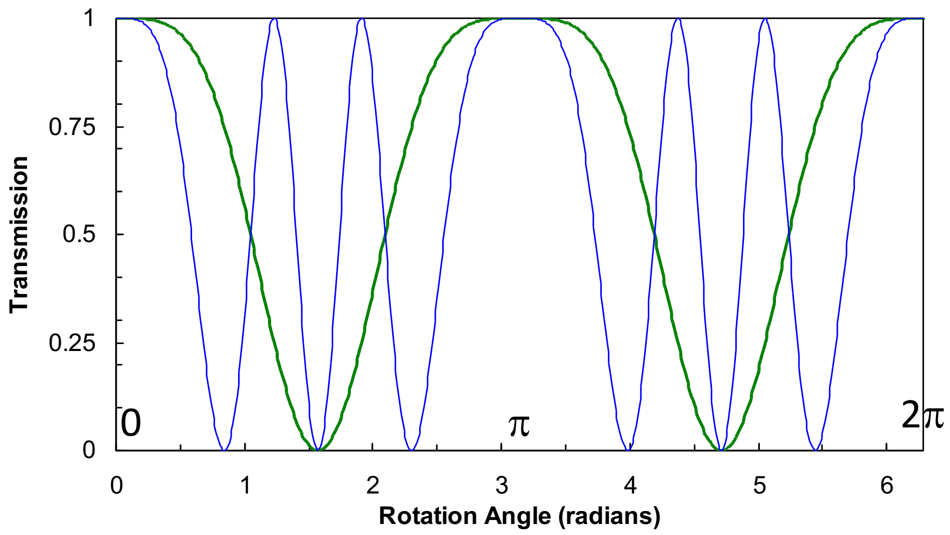


$$N = \frac{\pi^2}{16}\left(\frac{\theta_{dia}}{\lambda / b}\right)^2$$

Signals from off-axis sources:

Green: companion @ λ/2b

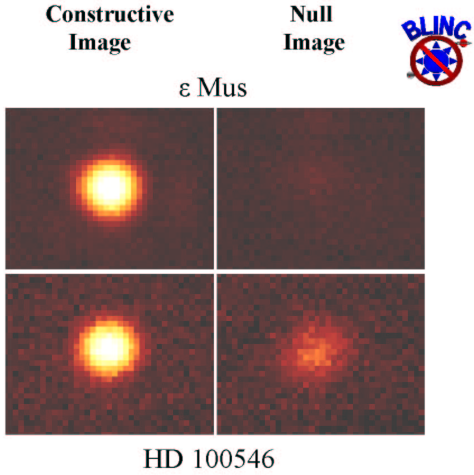
Blue: companion @ 3λ/2b



What Wavelength?

- Long (MIR) wavelengths:
  - High thermal background noise
    - to see faint emission, need to remove two stronger signals:
      - star & background
  - Ground-based goal: mainly warm exozodiacal emission in the habitable zone
  - Space: detection of thermal (habitable zone) exoplanet emission
- Short (NIR) wavelengths:
  - Only need to remove one bright emission source - the star
  - But phase phase stability is much worse
  - Goal: inner hot dust (or dust scattering) & hot companions

Nulling Experiments



		b/D	
• BLINC/MMT etc. (Univ. of Arizona) -	MIR		
• Keck Interferometer Nuller (JPL) -	MIR	85/4	LDLs
• Palomar Fiber Nuller (JPL) -	NIR	3.2/1.5	
• Large Binocular Telescope Int. (UofA) -	MIR	14/8	

Nulling with the Keck Interferometer

- Need to remove two different bright signals:
  - Strong (coherent) central star (few Jy)
  - Strong (incoherent & noisy) MIR background (10^3 Jy)

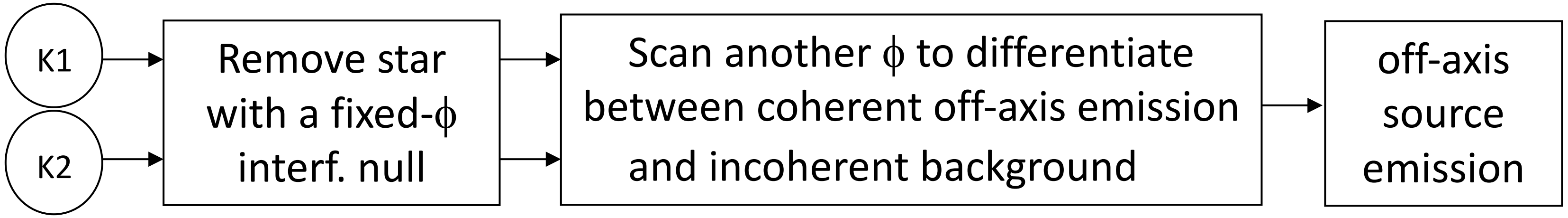
    ⇒ need two-step removal
- Nulling star requires fixed null phase

    ⇒ cannot scan null fringe
- Spatial chopping was not an option at Keck (need to use AO)

    ⇒ Use a two-stage interferometer

    – (phase chopping instead of sky chopping)

    ⇒ Need four input beams

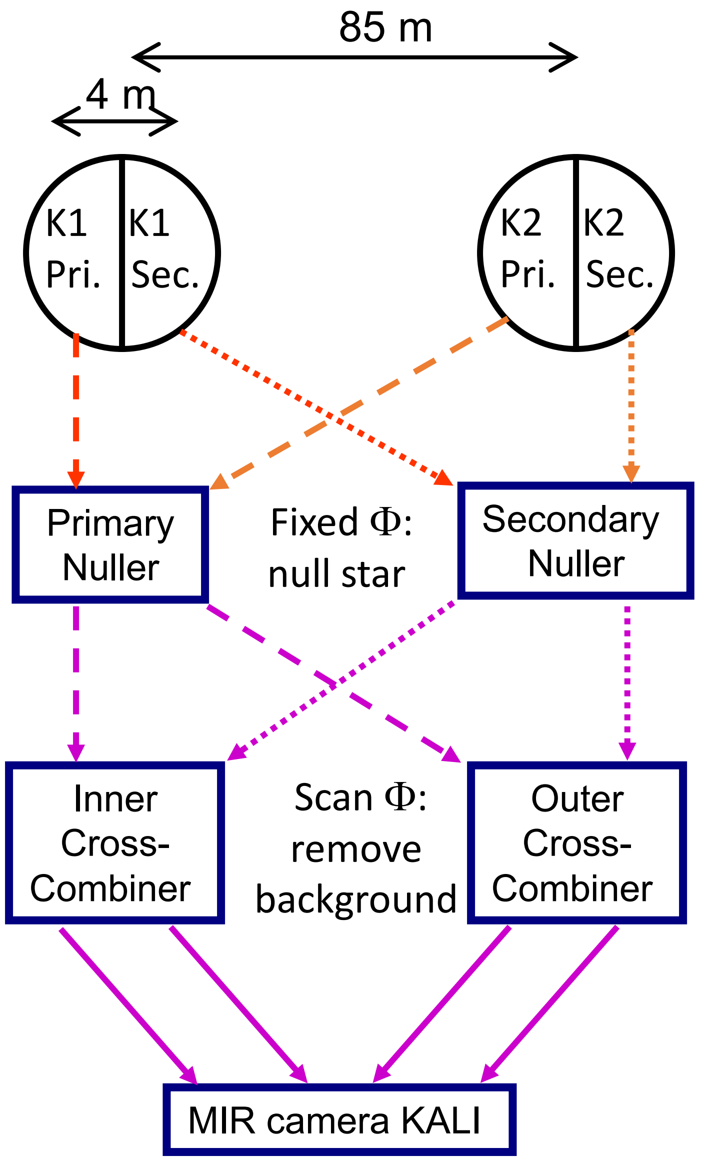


Colavita et al.; Serabyn et al.; Mennesson et al. papers

The Keck Interferometer Nuller (KIN)

Two stage interferometer:

- Split the two Keck apertures into 4 subapertures
- Null the star symmetrically (fixed phase):
  - Null on 2 parallel, long (85 m) baselines (~ 24 mas fringe)
- Interferometrically combine the 2 nulled outputs:
  - 4 m "cross-combiner" baseline across each aperture:
    - XC fringe spacing ~ 500 mas
  - Scan cross-combiner OPD:
    - Modulates & detects residual coherent emission
    - Incoherent background at d.c. not detected; but contributes noise
- Spatially filter the combined beams (pinhole, not SM fiber)
- Disperse & detect the 4 combined output beams:
- Subaps & pinholes define single-beam FOV: ~ 450 x 500 mas



The Null Measurement

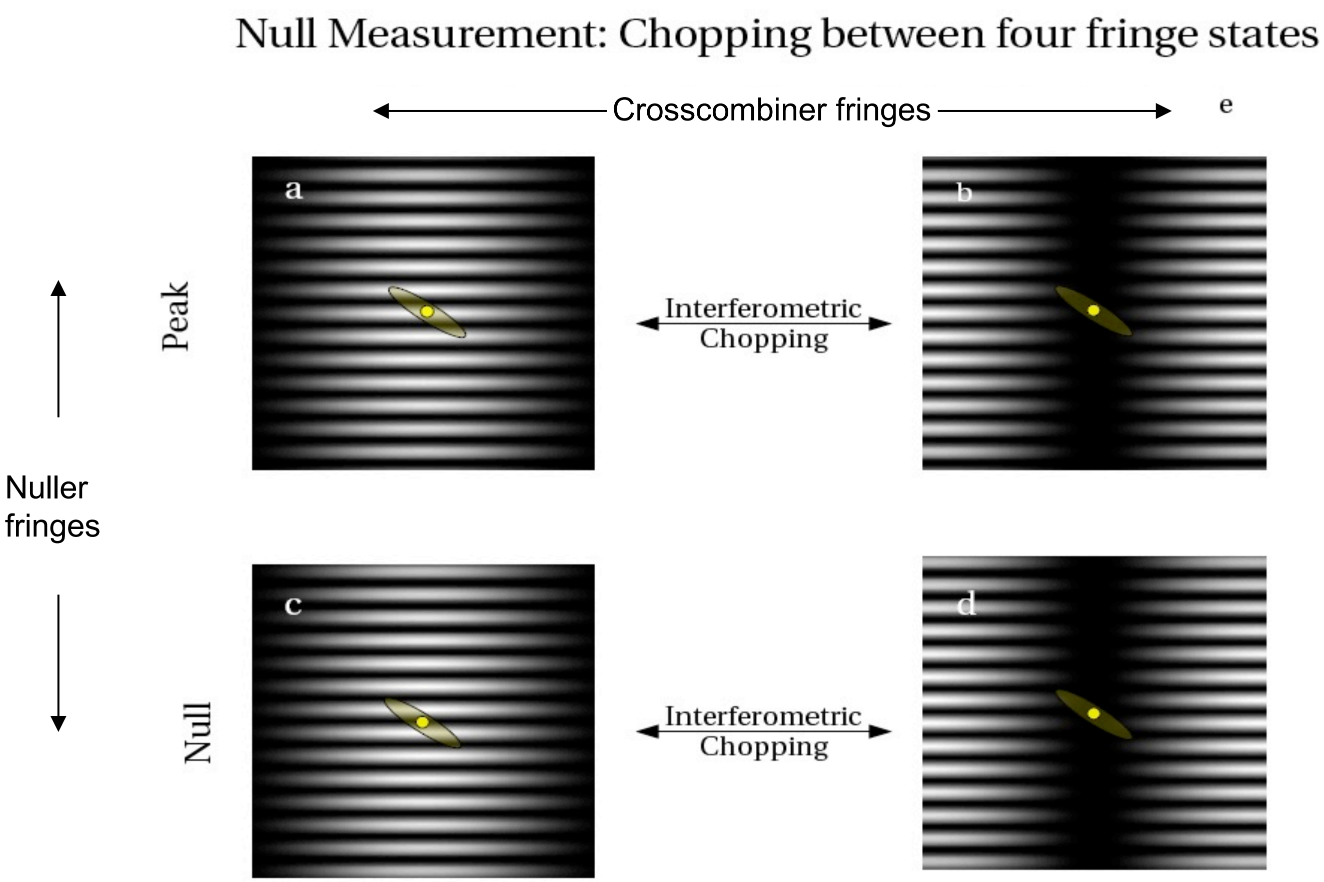
- KIN measures the integrated intensity transmitted by the nuller fringe pattern:

$$N = N_{star} + \int S(\theta,\varphi)\, t(\theta,\varphi)\, d\theta d\varphi \,/\, \int S(\theta,\varphi)\, d\theta d\varphi$$

given by

$$XC_{amp}(\text{destructive nuller state}) \,/\, XC_{amp}(\text{constructive nuller state})$$

- Source model needed to estimate the total source flux



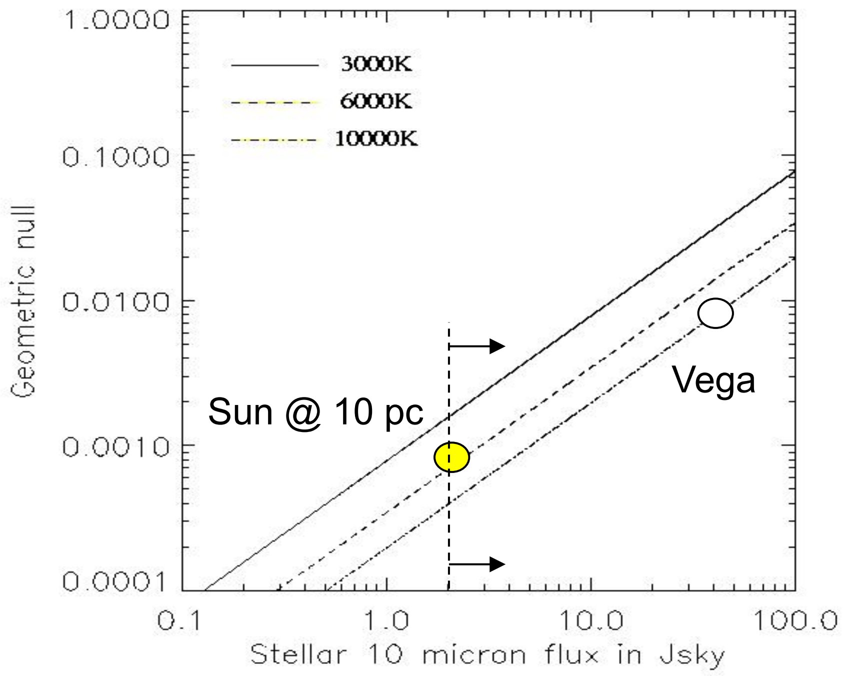
Stellar Null Leakage vs. Flux

$$N = \frac{\pi^2}{16}\left(\frac{\theta_{dia}}{\lambda / b}\right)^2$$

$\Rightarrow$ Both F_ν & N are $\propto \theta^2$

$\Rightarrow$ For a bb star of T > 4500K & flux density F_ν (Jy) (at bl=80m, λ=10 μm):

$N \sim 2F_\nu/T$

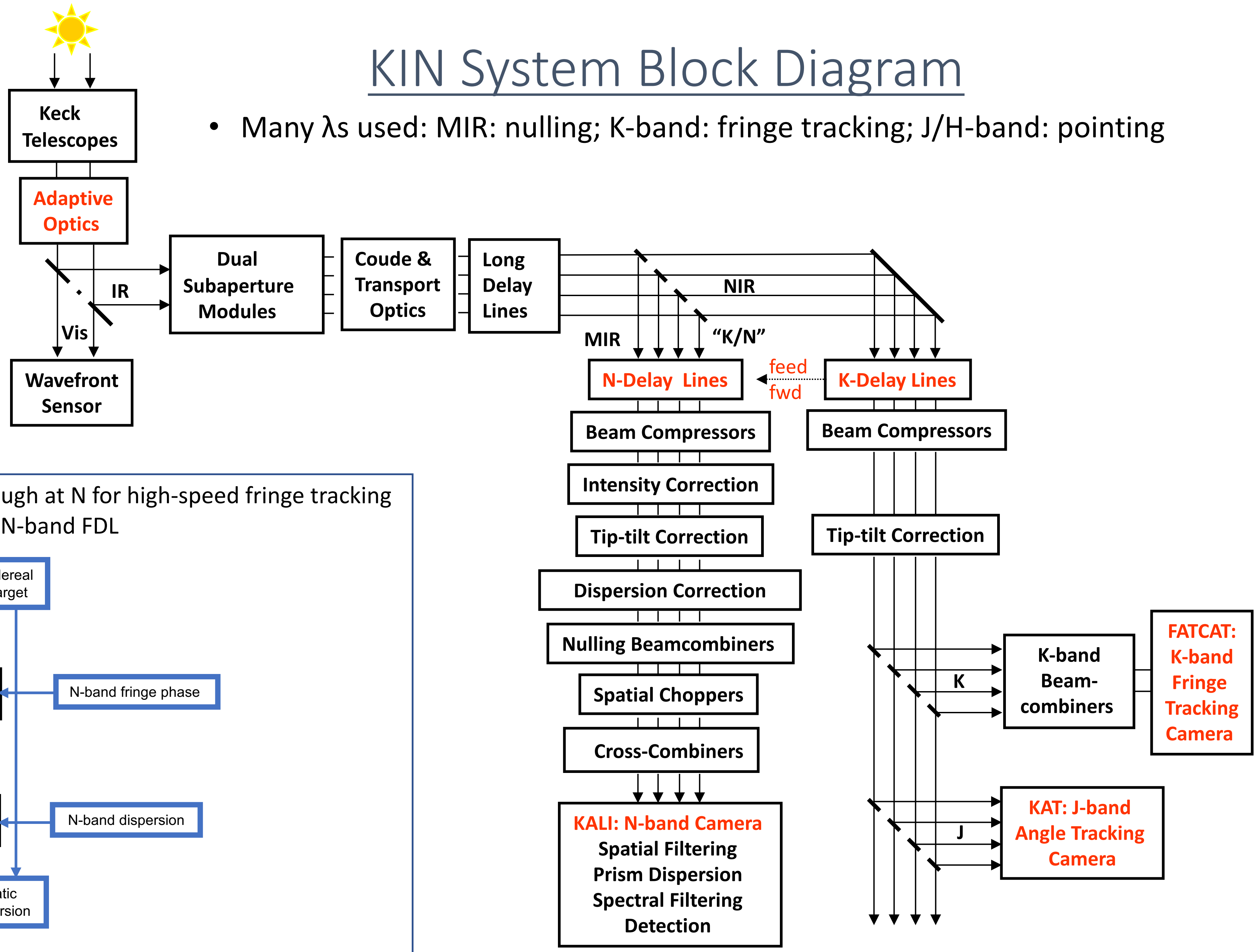


- Nearby A star nulls (e.g. Vega, Fomalhaut) $\approx 10^{-2}$
- Nearby G2 star nulls limited theoretically to > 10^{-3}

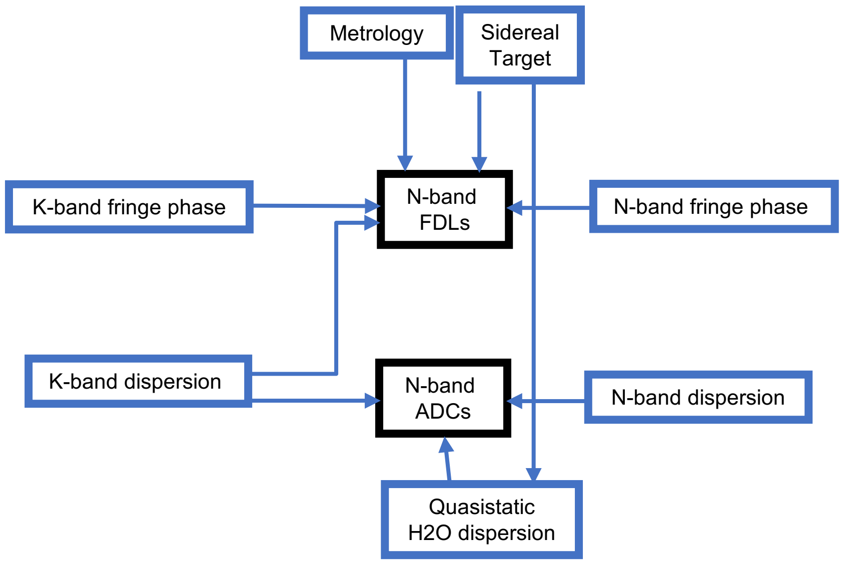
➔ need to calibrate with known stellar leakages (diameters)

KIN System Block Diagram

- Many λs used: MIR: nulling; K-band: fringe tracking; J/H-band: pointing

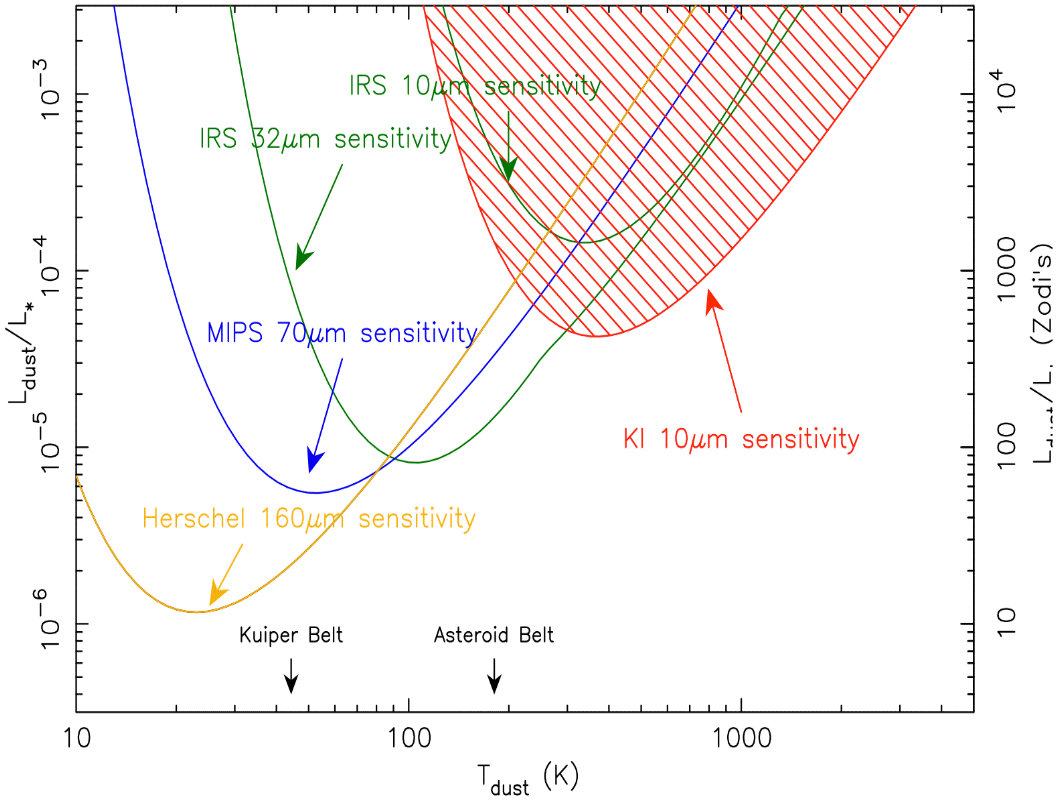


- Control: Sources not bright enough at N for high-speed fringe tracking
- K-band phase "fed-forward" to N-band FDL



KIN Results

- 47 nearby stars surveyed for exozodi @ 8.5 microns
- Final best calibrated null ~ 0.2 – 0.3%
  (Milan-Gabet et al. 2012; Mennesson et al. 2014)
- Upper limits are of order a few hundred hundred zodis

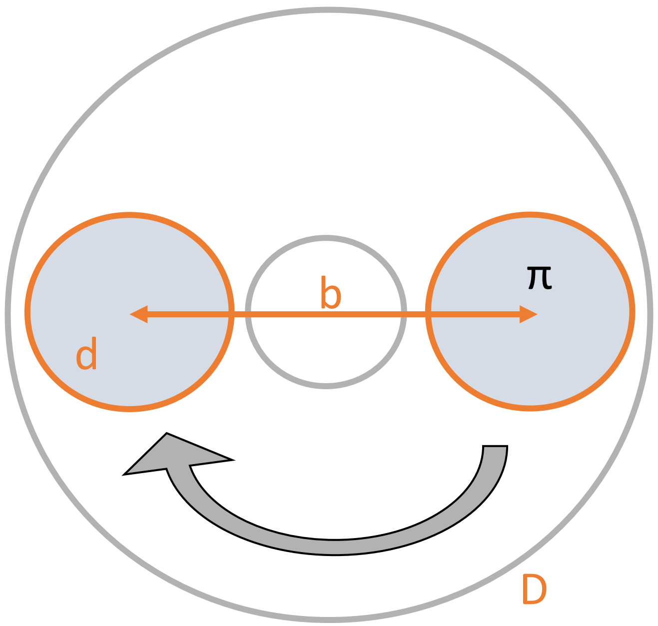


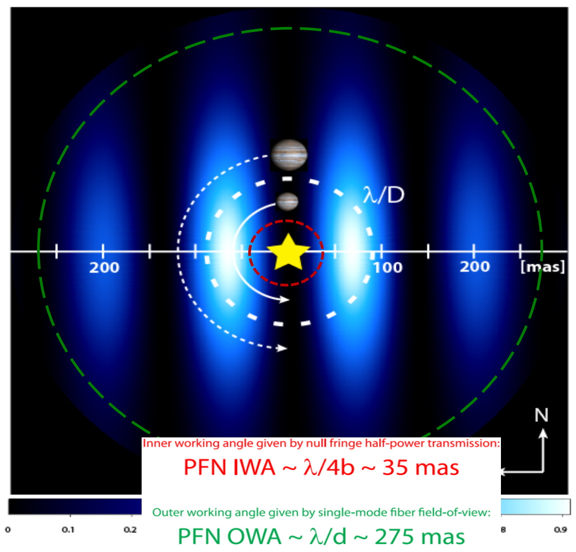
Conclusions & Lessons Learned from the KIN

- Beam geometry:
  - Single aperture beam small
  - Fringe pattern: null fringe too narrow (too much stellar leak)
  - Long baseline fringes too narrow (integrate over many fringes)
  - Limited baseline rotation capability (Earth rotation)
- Beamtrain:
  - High beam emissivity & low transmission,
  - Residual beam shear between sub-aps
  - Coherent background beam emissivity (coherent emissivity crosstalk)
  - H_2O residual dispersion in unbalanced atmospheric paths → nulls vary across passband
- Four beams used instead of two:
  - Optomechanical complexity
  - Operational complexity – few people could run it

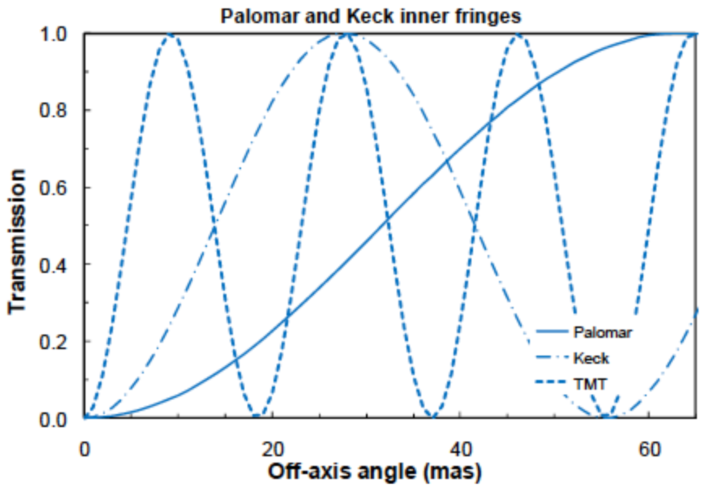
A Rotating-Baseline Nuller, a la Bracewell/TPF-I: The Palomar Fiber Nuller

- Generate one (or more) baselines between sub-apertures on a large telescope
  - Rotate the baseline(s) to modulate the signals from off-axis sources (via K mirror)
  - Small IWA (< λ/D) provides a very unique coronagraphic IWA
- Uses the facility ExAO system as the first-level fringe tracker (no delay lines needed)





Why: small inner working angle



IWA ~ $\lambda/4b = \lambda/4(D-d) \rightarrow \frac{1}{4}\,\lambda/D$

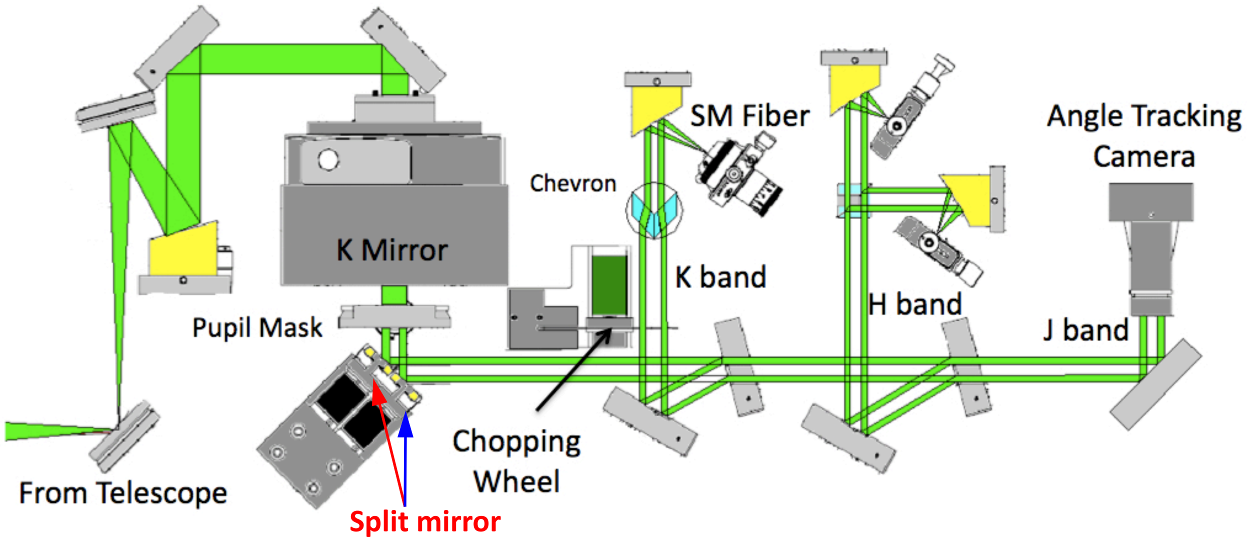
OWA_{SM} ~ $\lambda/2d \rightarrow D/2d\,(\lambda/D) \rightarrow 5/3(\lambda/D)$ @ Palomar

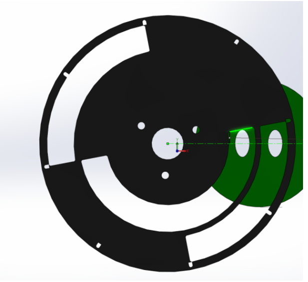
Operates entirely inside normal coronographic IWA

	IWA	λ/D
Palomar:	33 mas	90 mas
Keck:	13 mas	45 mas
TMT:	4 mas	14 mas

The Palomar Fiber Nuller (PFN)

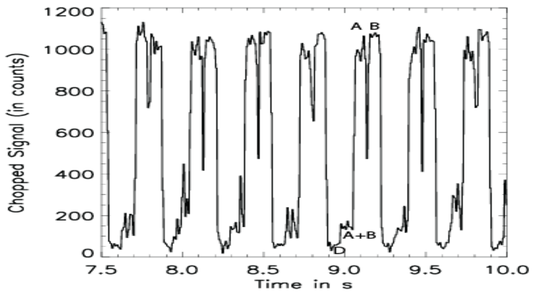
Serabyn, Mennesson, Martin, Liewer, Loya, Hanot, Kuhn



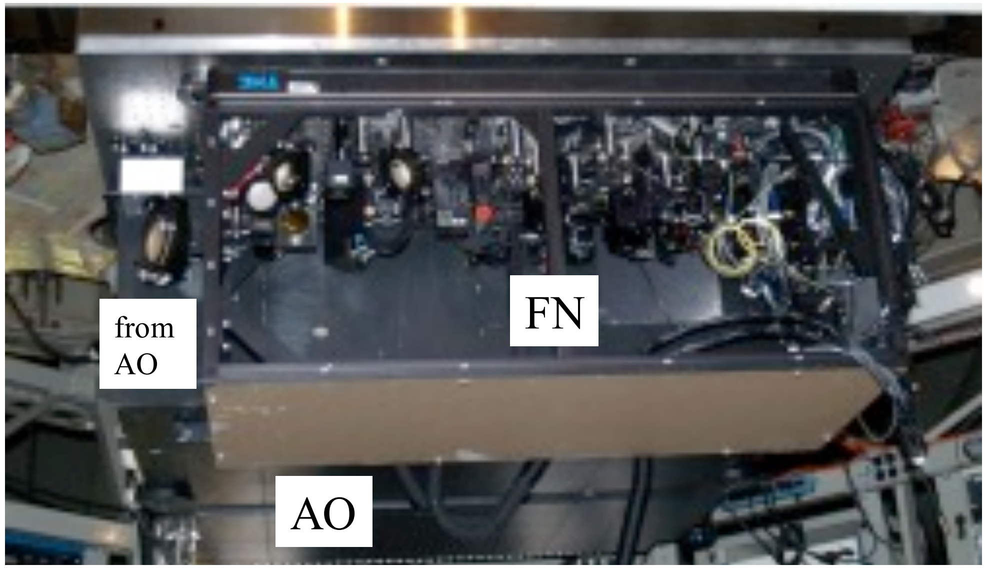


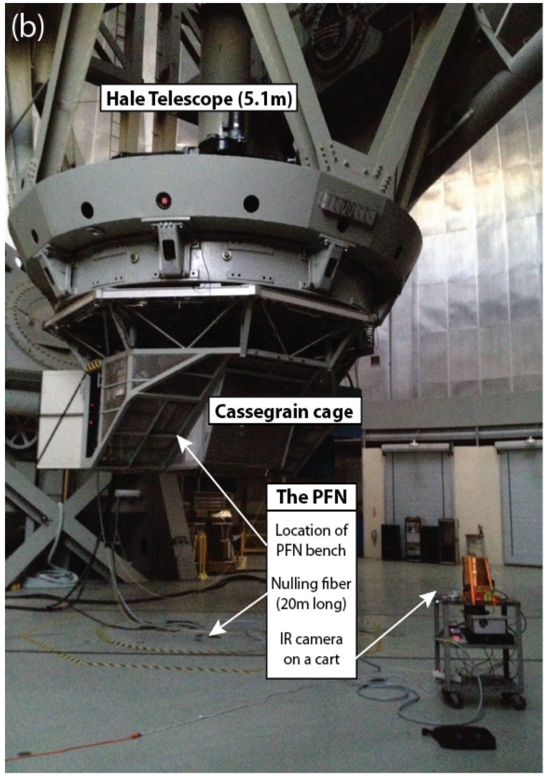
mask

Rapid calibration:
Measure A-B, A, B, dark



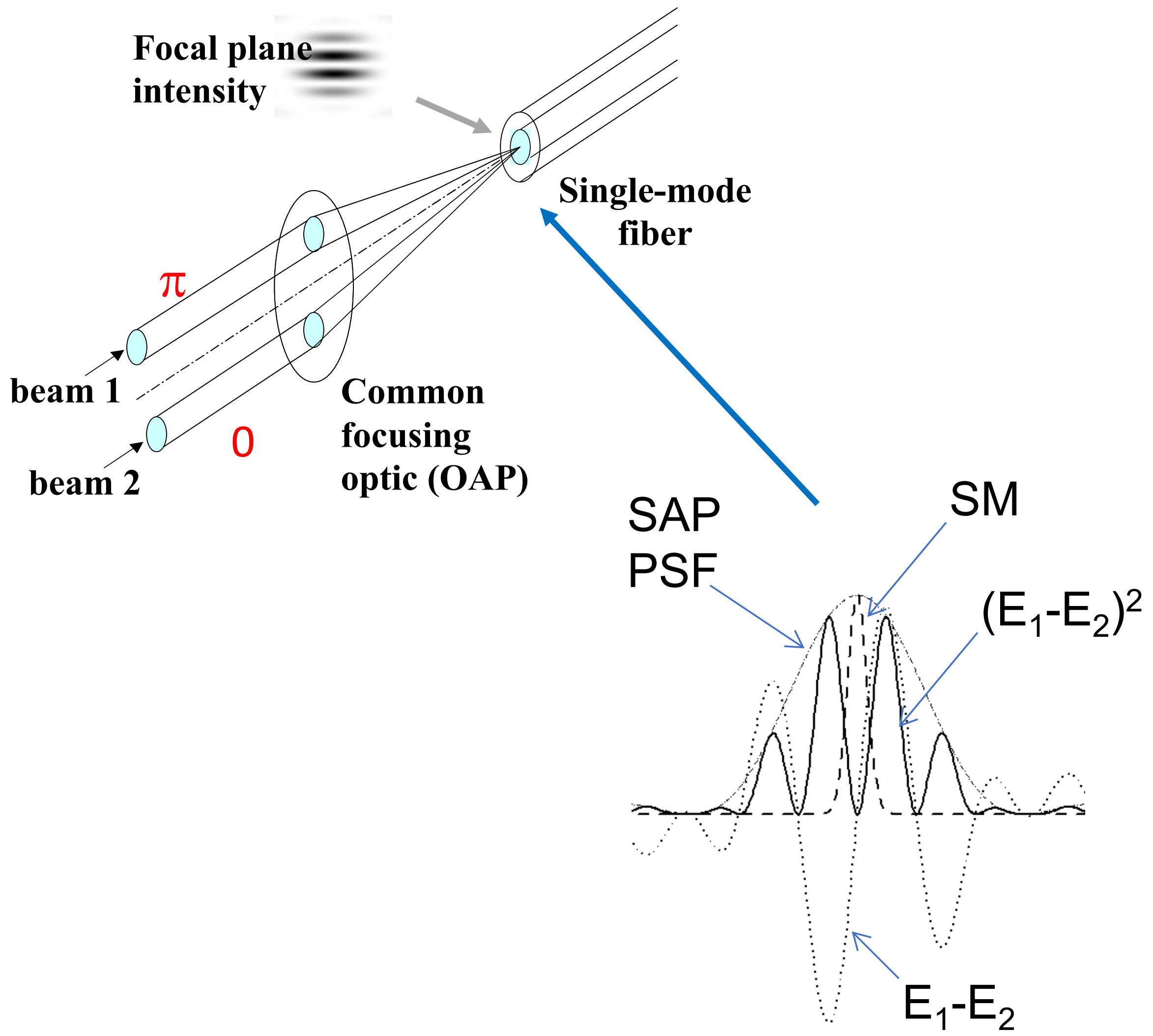
- **Palomar ExAO:** stabilizes OPD (~200 – 250 nm rms)
- **Split mirror:** OPD scans and fine OPD matching
- **Pupil Mask:** two elliptical holes on primary image
- **Pupil shear:** match beam intensities
- **K-mirror:** baseline rotation
- **Choppier wheel:** rapid calibration
- **Dispersion correction:** increased injection and BW
- **IR SM fiber combiner**





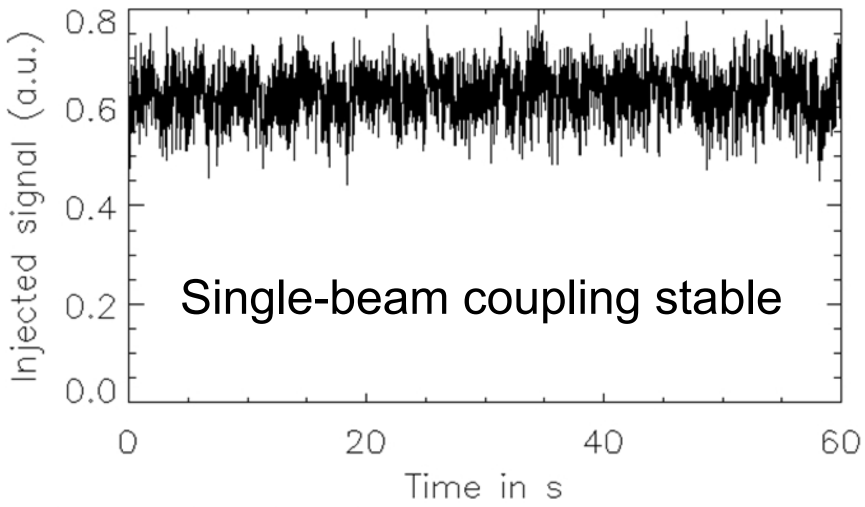
Mennesson et al., Serabyn et al., Martin et al.

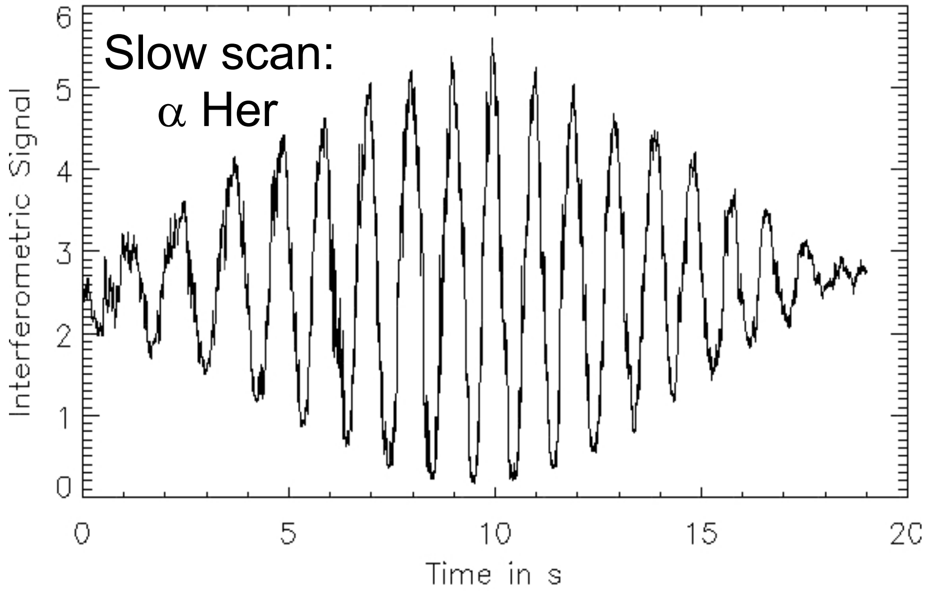
Keeping it Simple: Single-Mode Fiber Combiner



Behind ExAO system →

- Fiber coupling very stable:
- Fringes very stable



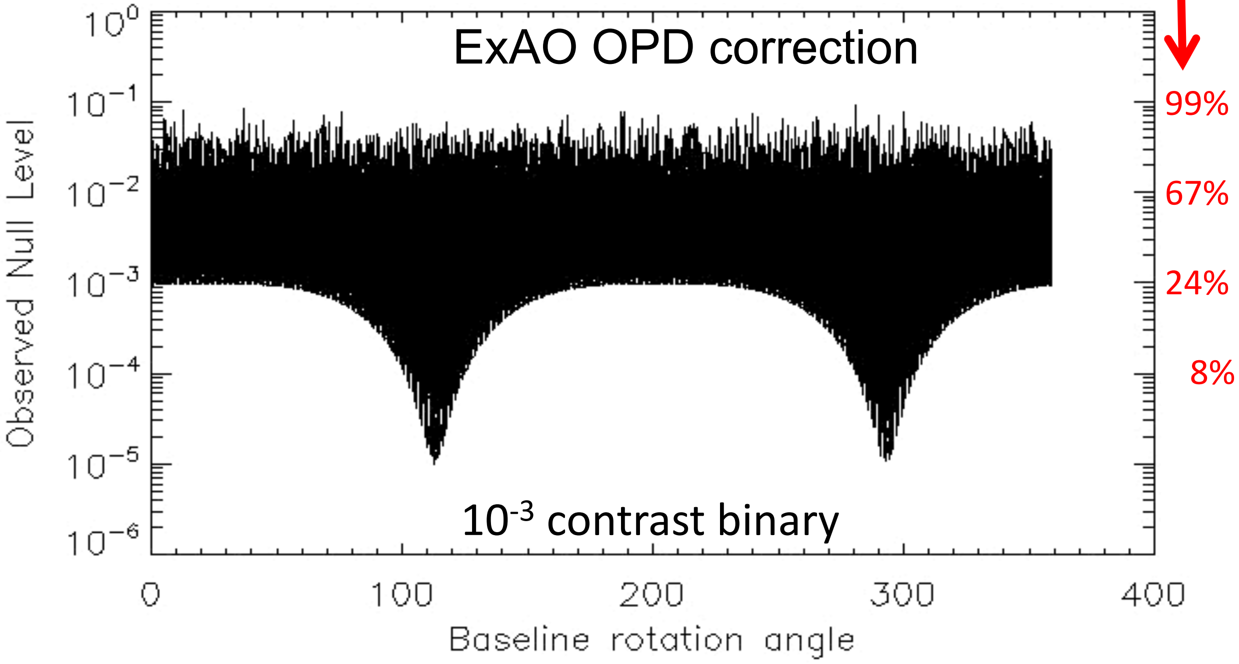


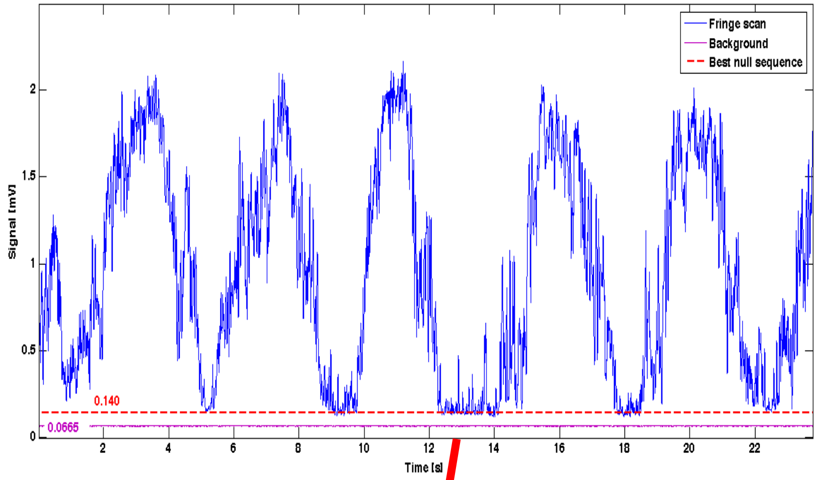
Null depth not super-stable

- Stabilize only well enough to stay near the right fringe minimum with ExAO
  - ExAO allows a larger amount of time to be spent near null
  - Can enable ~ 10^{-4} null depth meas. on very bright stars

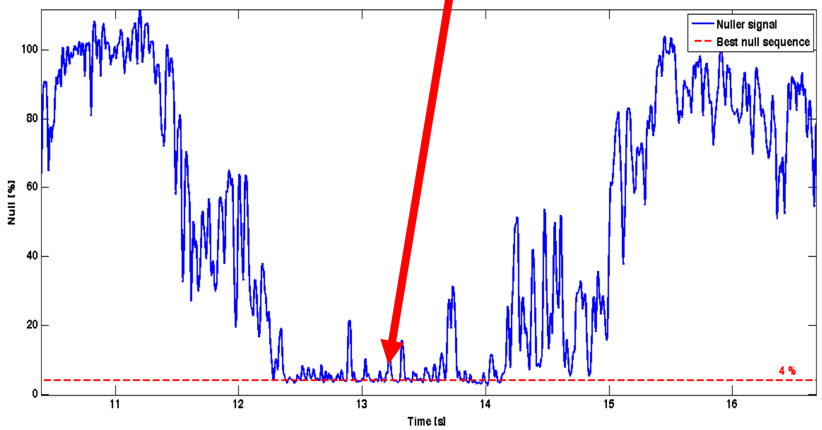
Stellar diameter measurement:

Model one baseline rotation with K-band nuller





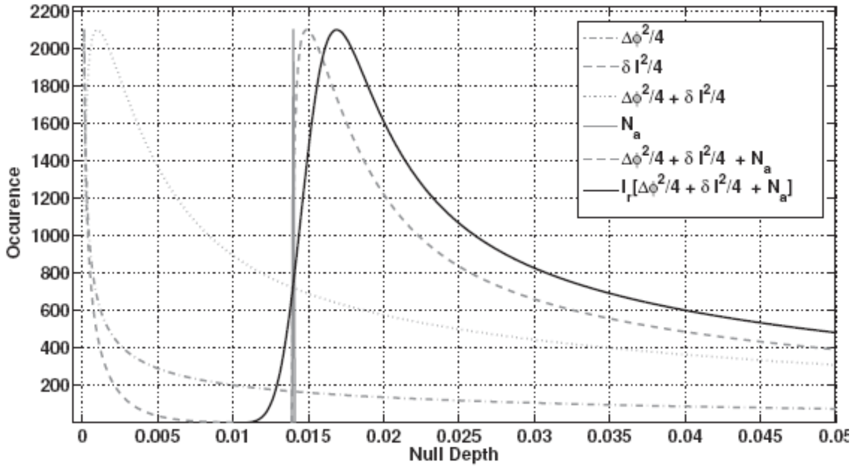
Alpha Her
Diam ~32 mas
Null ≈ 0.04%

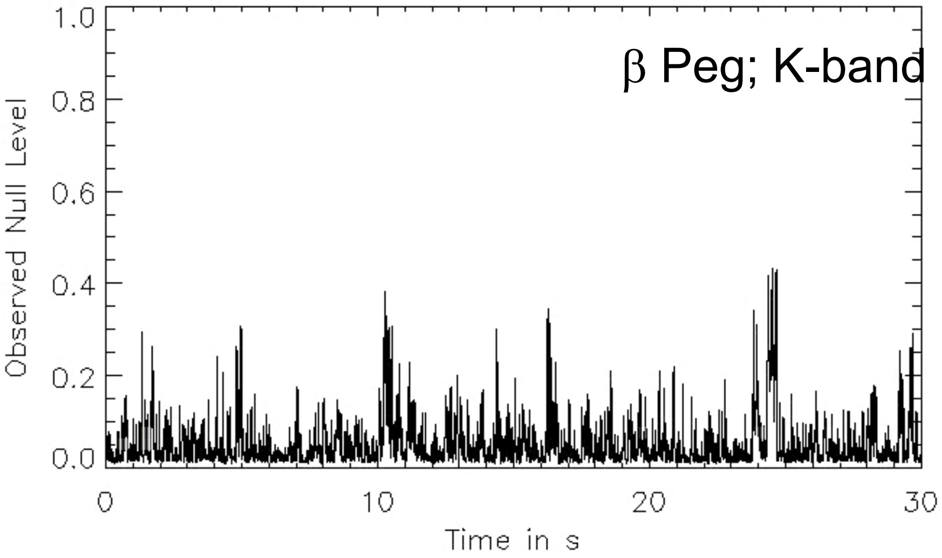


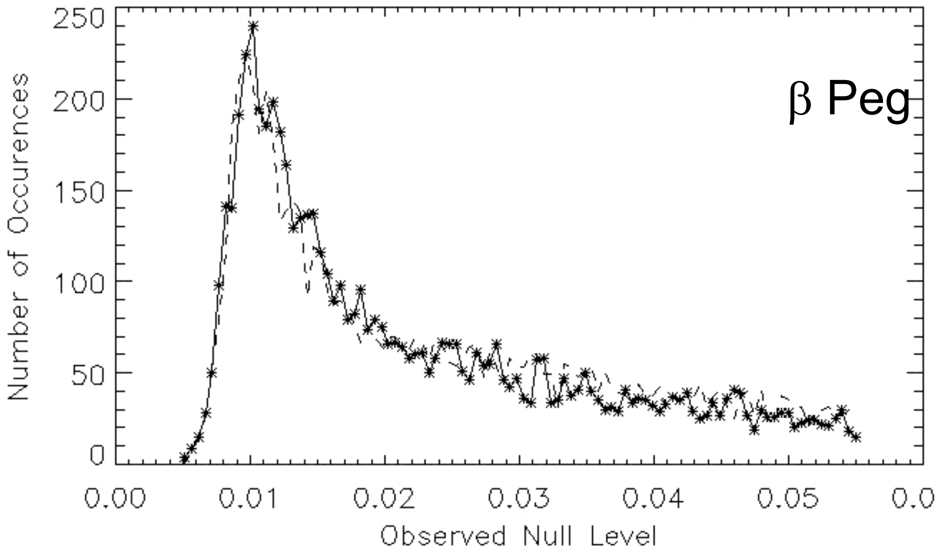
Null depth seen in raw fringe scan via flat fringe minima
But, N not given by "mean null level"

Measurement of Null Depth from Statistics of the Null: The Null Self-Calibration Algorithm

- One-sided fluctuations near null because N $\propto \varphi^2$
    - Can invert null depth fluctuations
        - Analytically in simple cases
    - $p(N)dn=p(\varphi)d\varphi$; assume Gaussian fluctuations
        - Use statistics in reality
    - Model null distribution to recover astrophysical null
- Relaxes stabilization requirements significantly
    - Enables nulling at shorter wavelengths
    - Analogous to dark speckle techniques

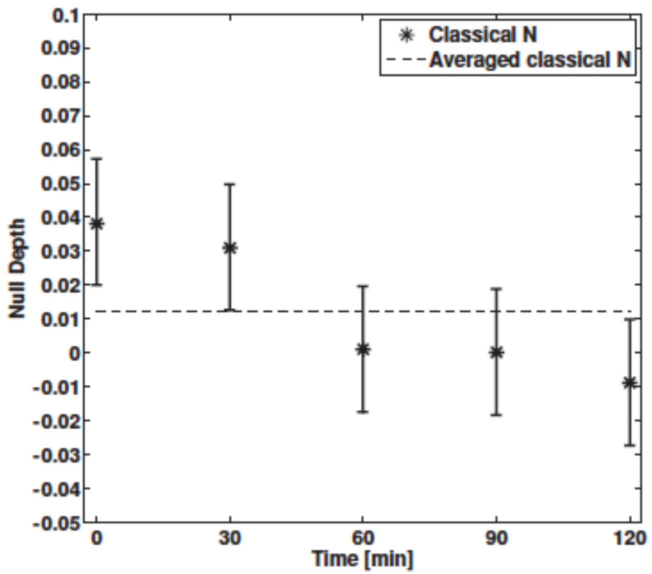


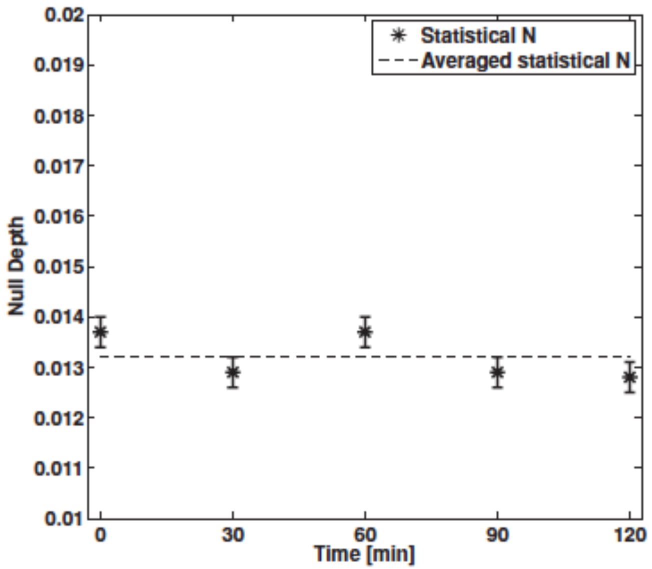


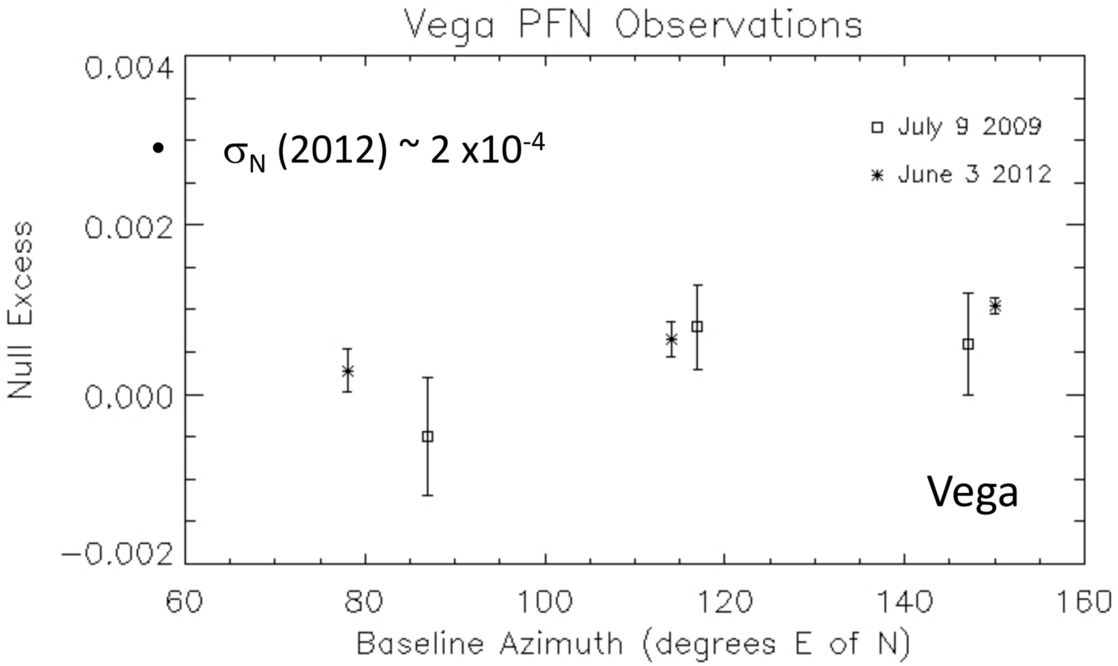


Hanot et al. 2011

Accuracy Improvement with Null Self-Calibration





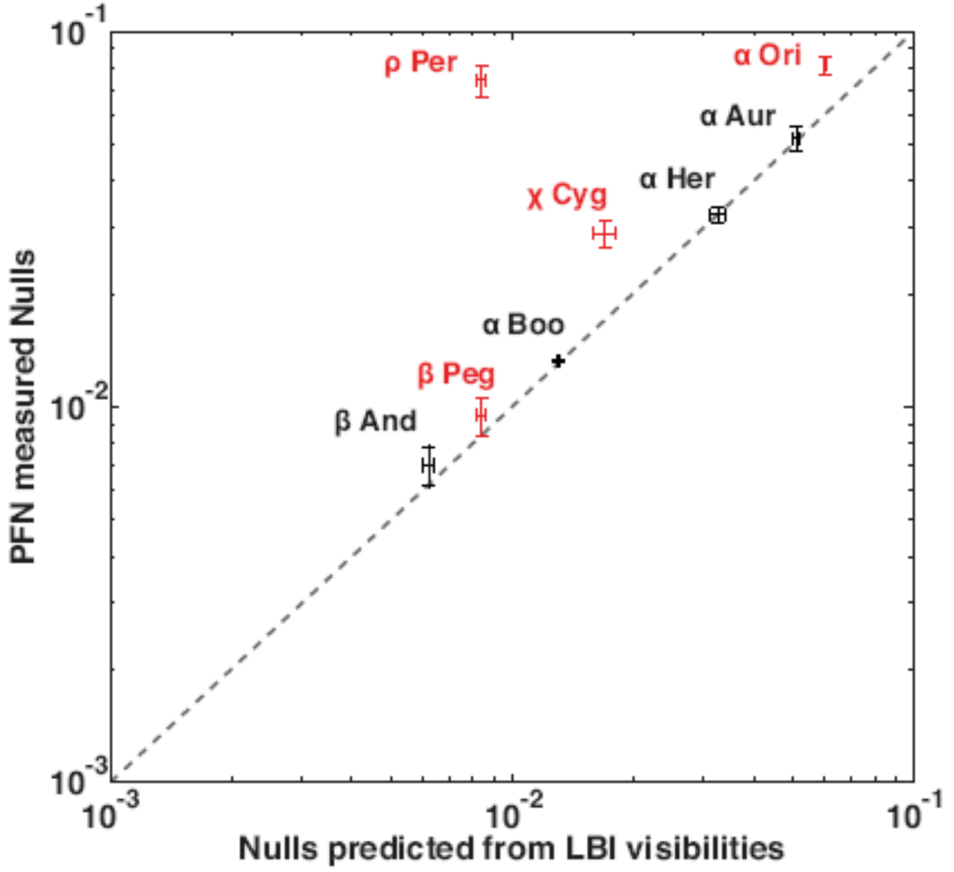


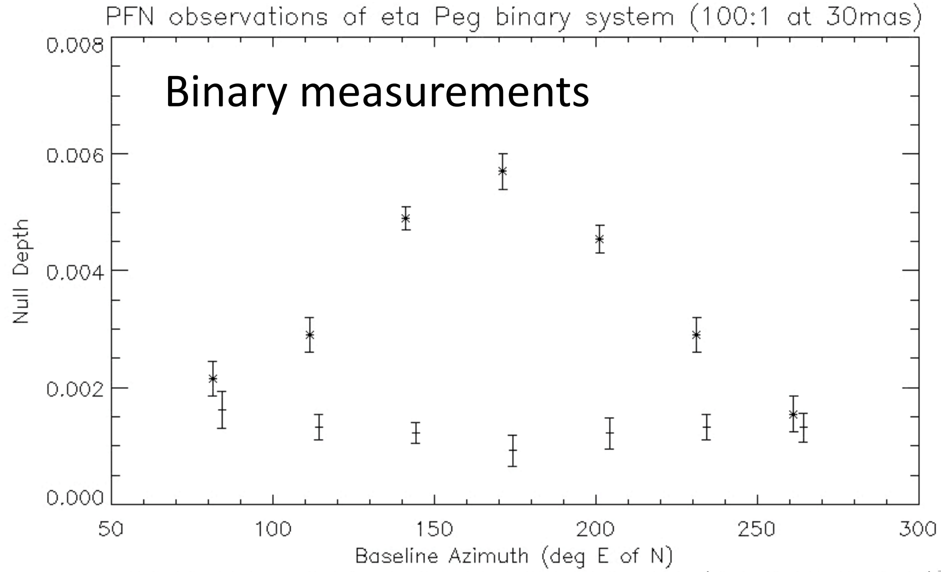
NSC yields an order of magnitude
Improvement in null depth accuracy!

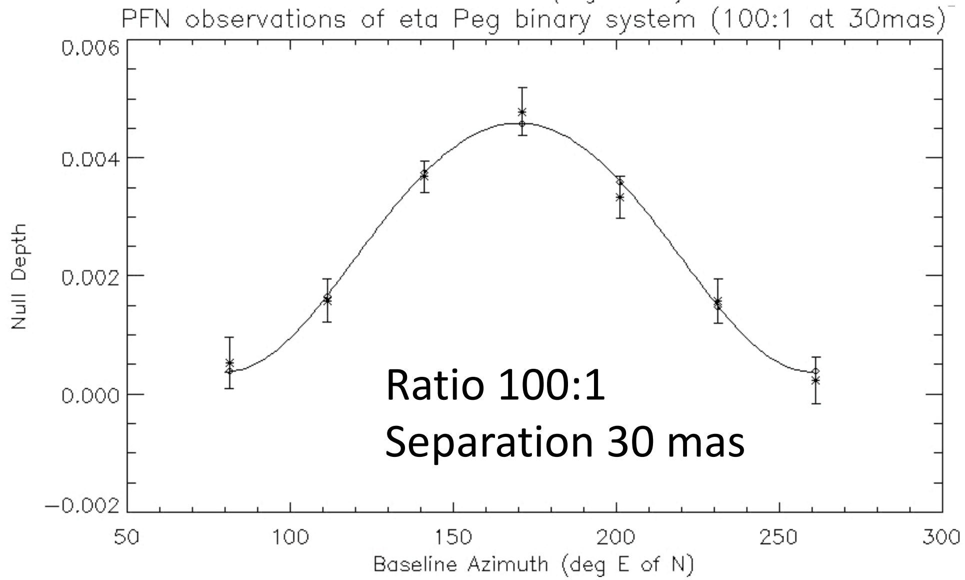
Stellar Measurements with the PFN's 3.2 m baseline

- High accuracy (a few 0.01 % to 0.1%) has enabled measurements of stellar diameter and binary separation with a very short baseline!

Giant diameter measurements







- A bigger telescope & baseline would help!

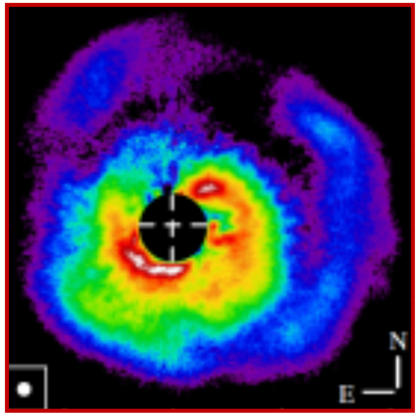
This is what TPF-I/Darwin aimed at doing!

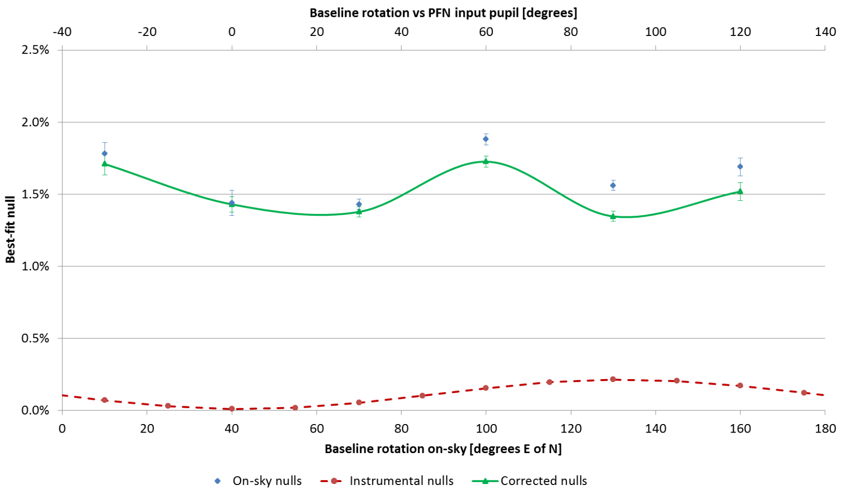
PFN Dust Observations

- AB Aur:

Herbig Ae/Be pre-main sequence star
Mass: 1.5-10 Msun
Age: 1-4 MYr
Dist: 144 pc

Hashimoto 2011 – Subaru

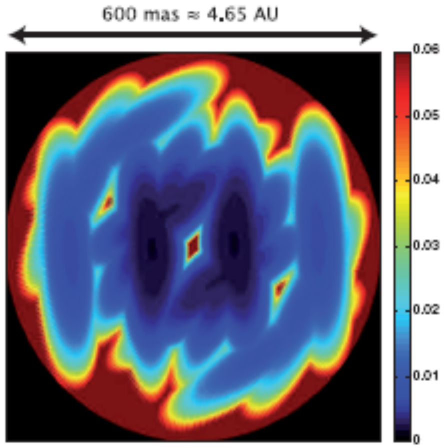


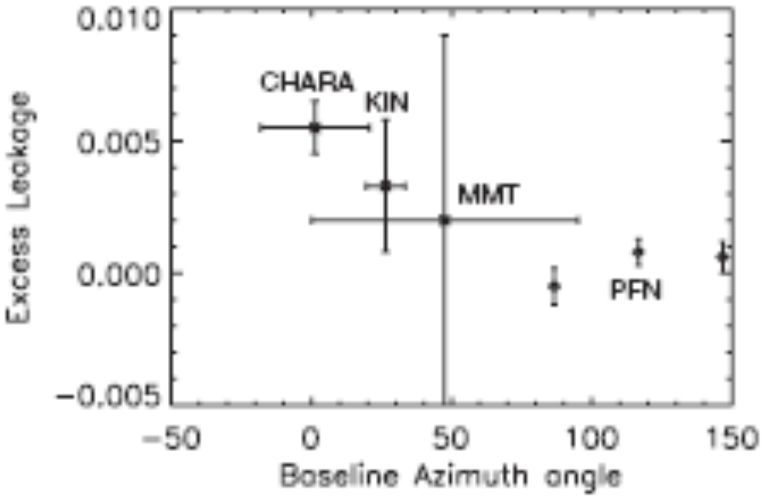


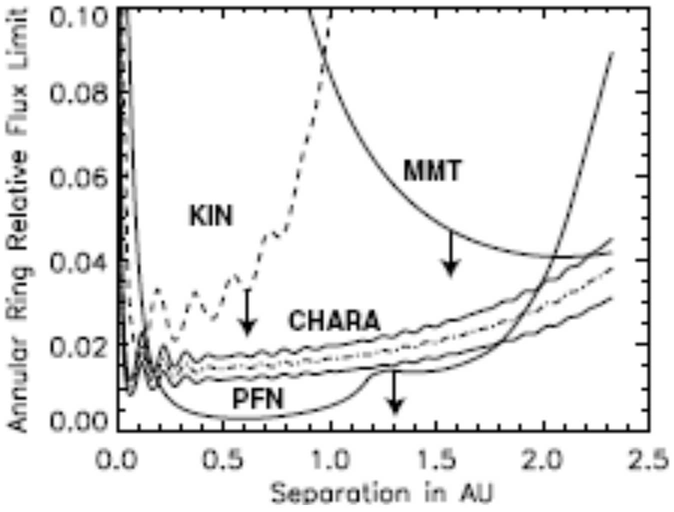
Kuhn et al.

Bright inner dust:
Inner spiral or companion?

- Vega: shortest baseline obs., but deepest limits (Mennesson et al. 2011)







- Hot inner dust sources: Mini-survey carried out of Absil detections (~ 10 stars): detection limits of N ~ 0.2%
  - Preliminary conclusion is that 2 micron dust is at small radii (in preparation)

The Palomar Fiber Nuller: Performance & Limitations

- High-accuracy NIR nulling (N ~ few 10-4 to 10-3 or so at K_s) enabled by:
  - Lower background than MIR
  - Use of ExAO as cross-aperture fringe tracker
  - SM fiber for WF error term removal
  - Rapid null-depth calibration
  - Null self-calibration algorithm
- Limitations to PFN:
  - Baseline a bit too short
  - Null fringe too broad to see very close in
  - Phase stability is relaxed, but need to make sure that one is on correct fringe
  - Atmospheric refraction for non-horizontal baselines
  - Atmospheric dispersion
  - Integration time a bit too long (> 5 msec to date)
- A nuller on a larger single-aperture telescope could be interesting (esp. TMT/ELT)

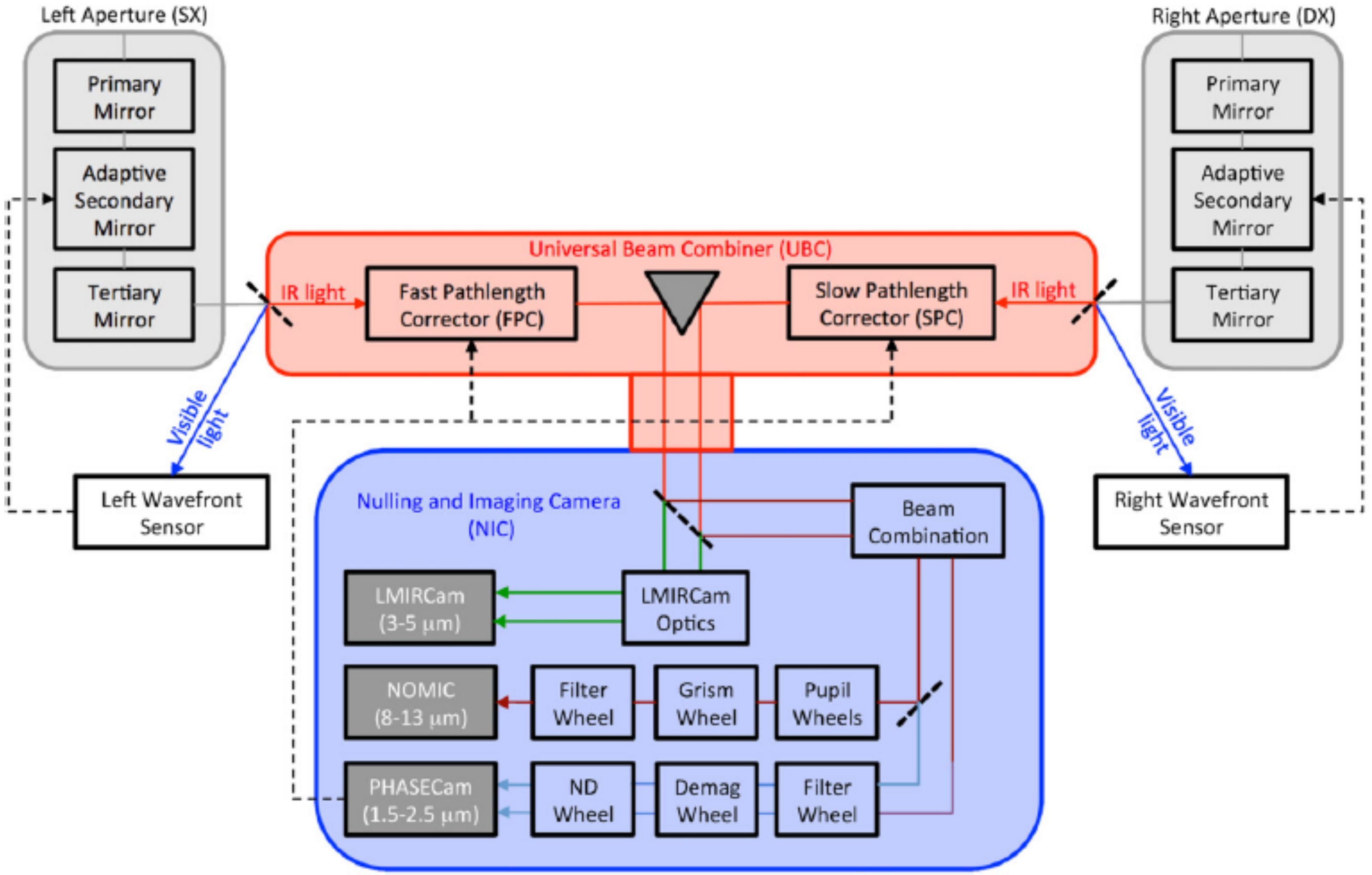
LBTI Nulling

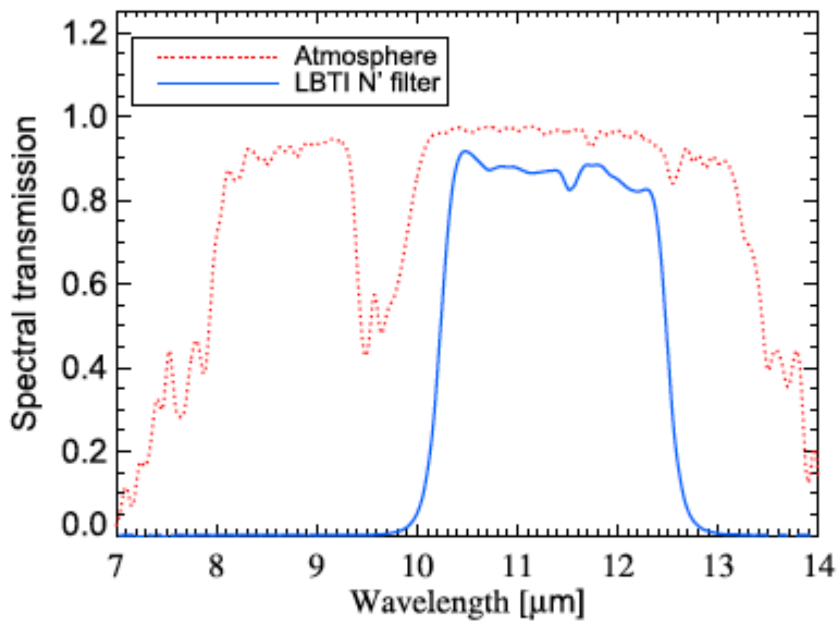
Hinz et al., several

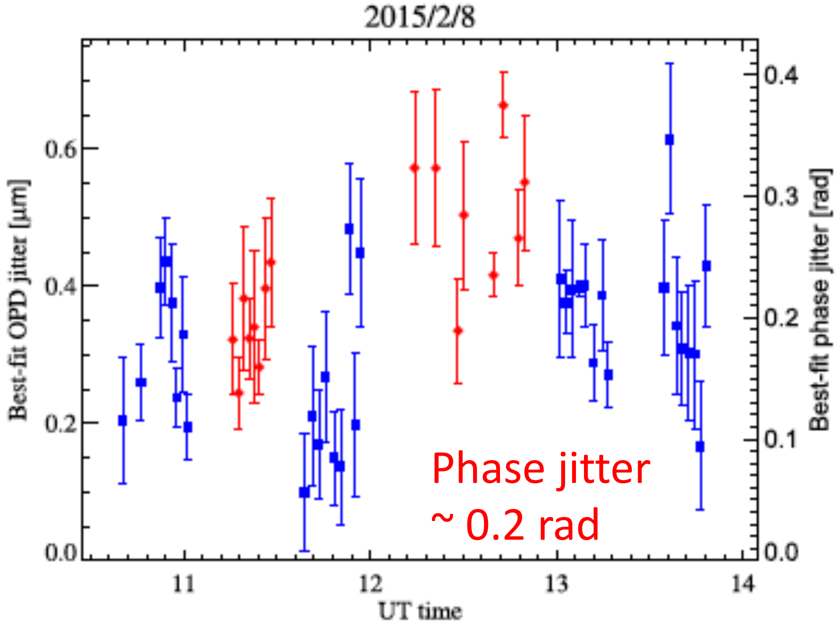
- Beam train limitations largely removed:
  - Emissivity much lower
  - No correlated coherent emissivity from optics
  - Shear much easier to deal with, with a pair of round beams
- Greatly reduced H_2O dispersion:
  - common mount
  - horizontal baseline
- Using nulling self-calibration
- Spatial filtering not used

The LBTI MIR Nuller

(Defrere et al. 2016)

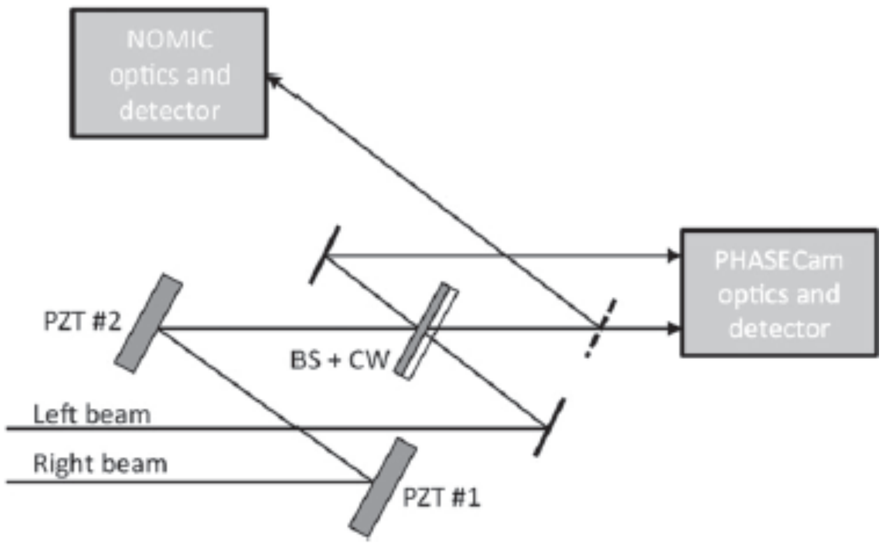


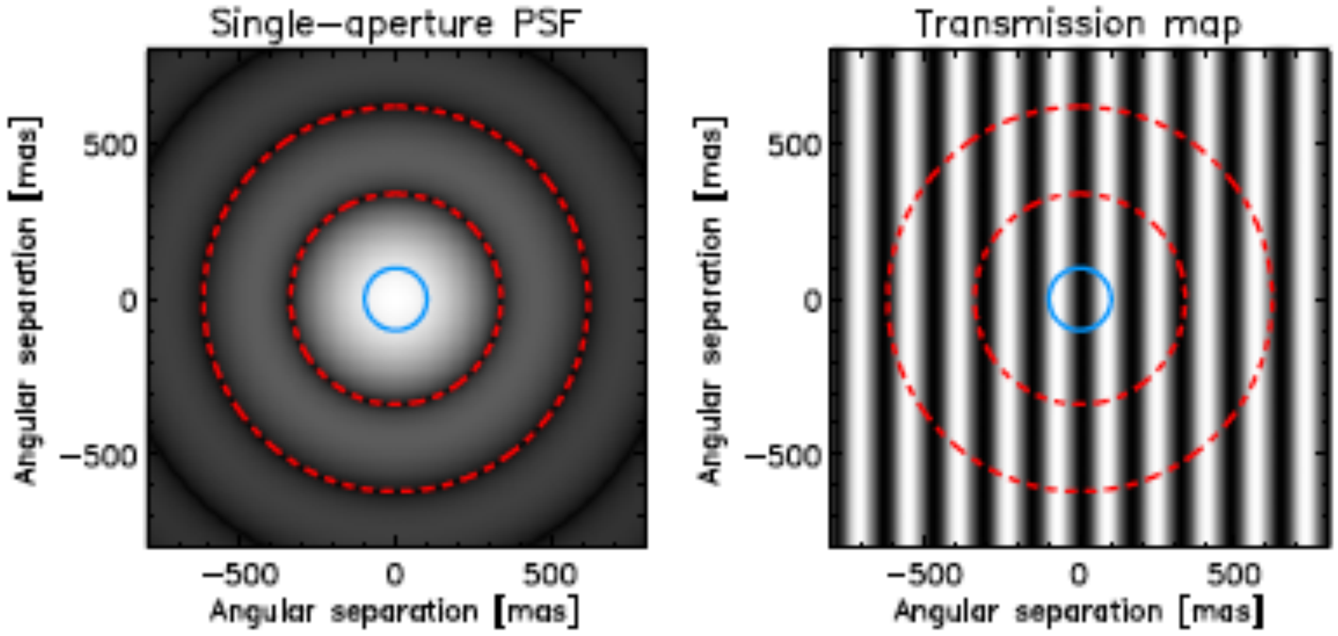




The LBTI Beamcombiner and Fringes

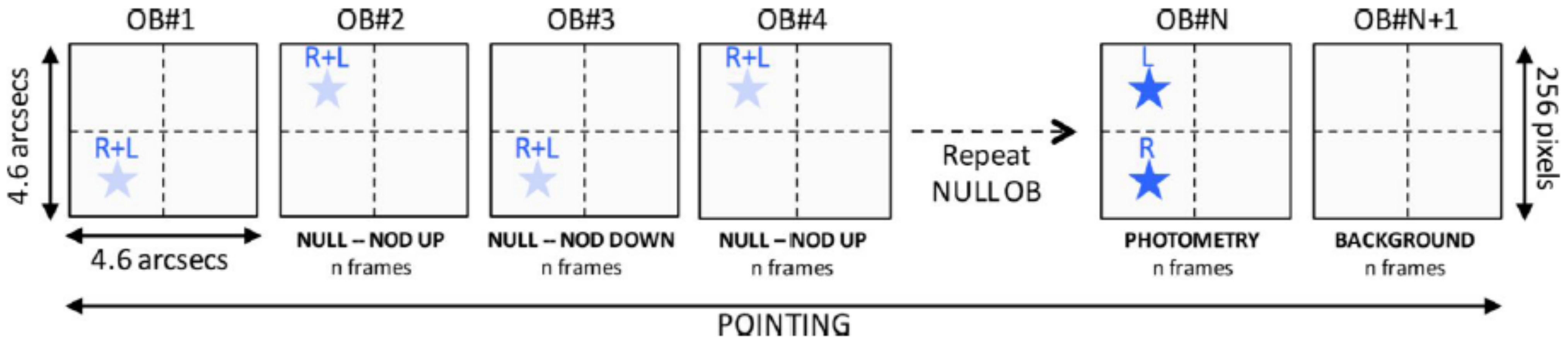
simple & cold



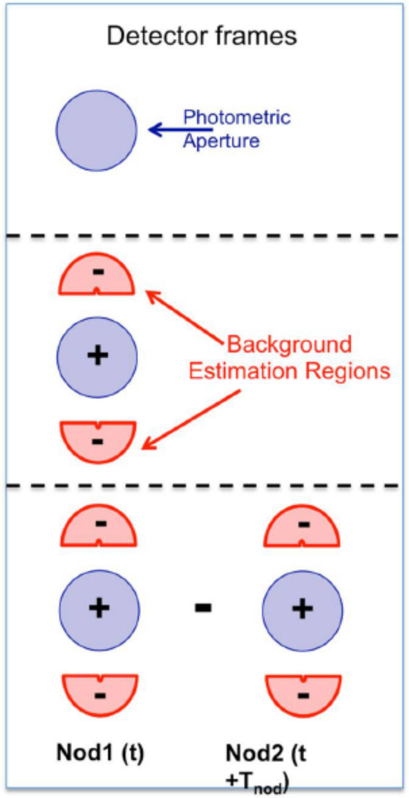


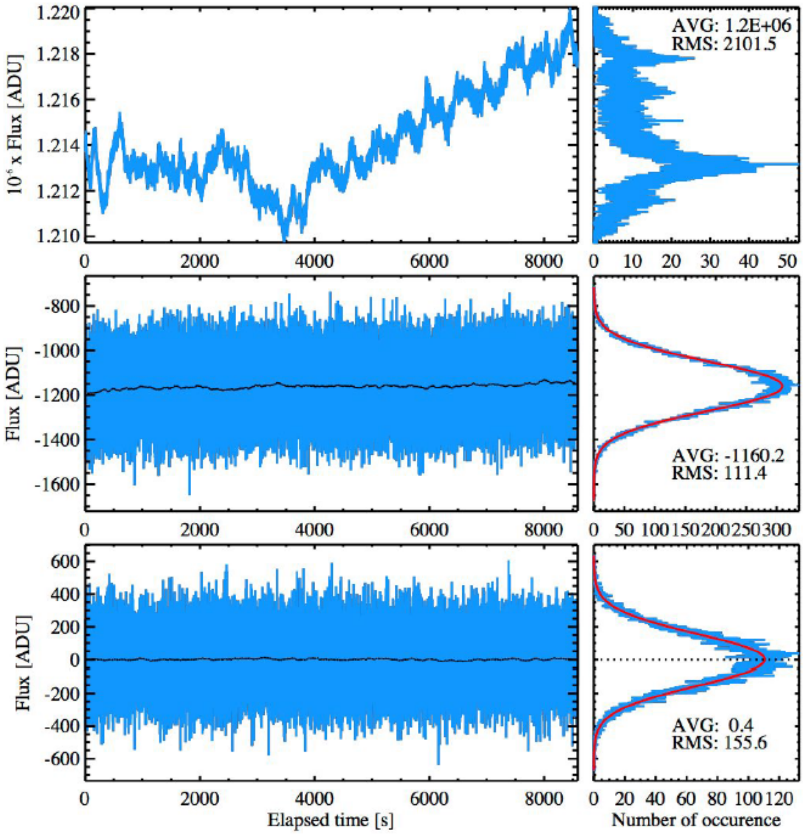
(Defrere et al. 2016)

Background removal with spatial nodding/chopping

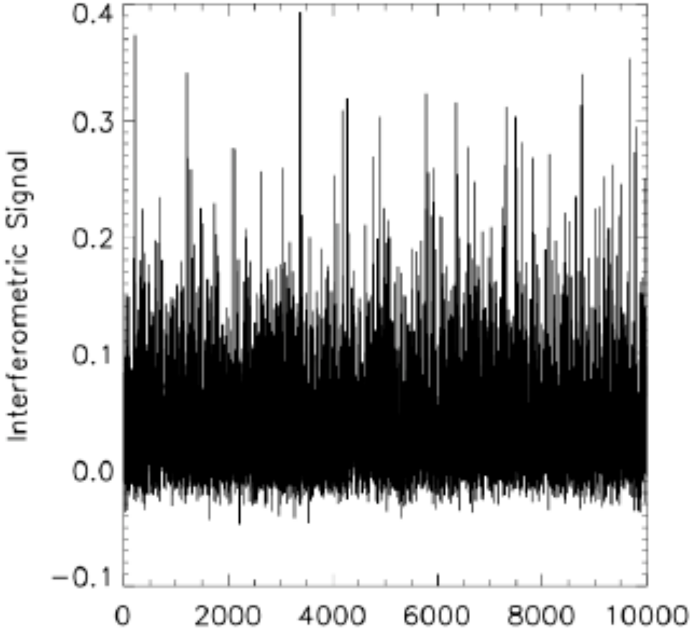


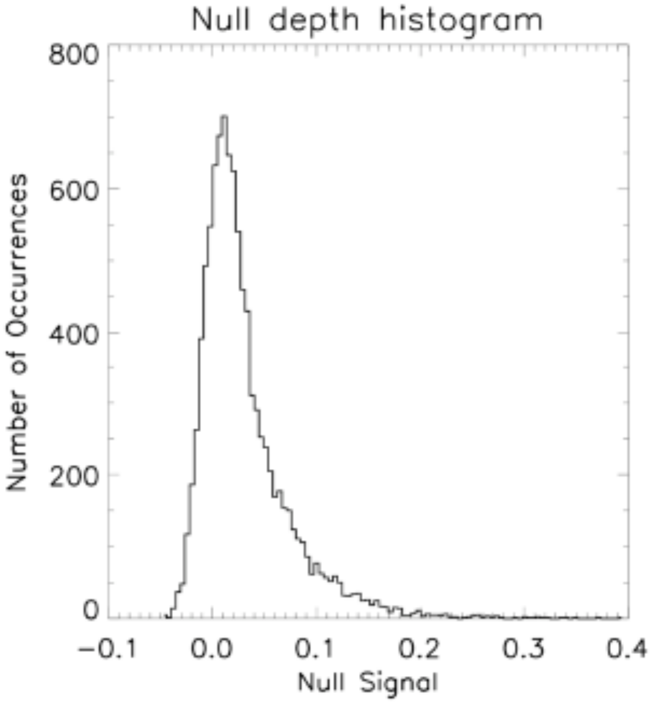
- Background >> star
- Need to remove background to a few ppm
- Need to null to a few 10^{-4} to get to tens of zodi range

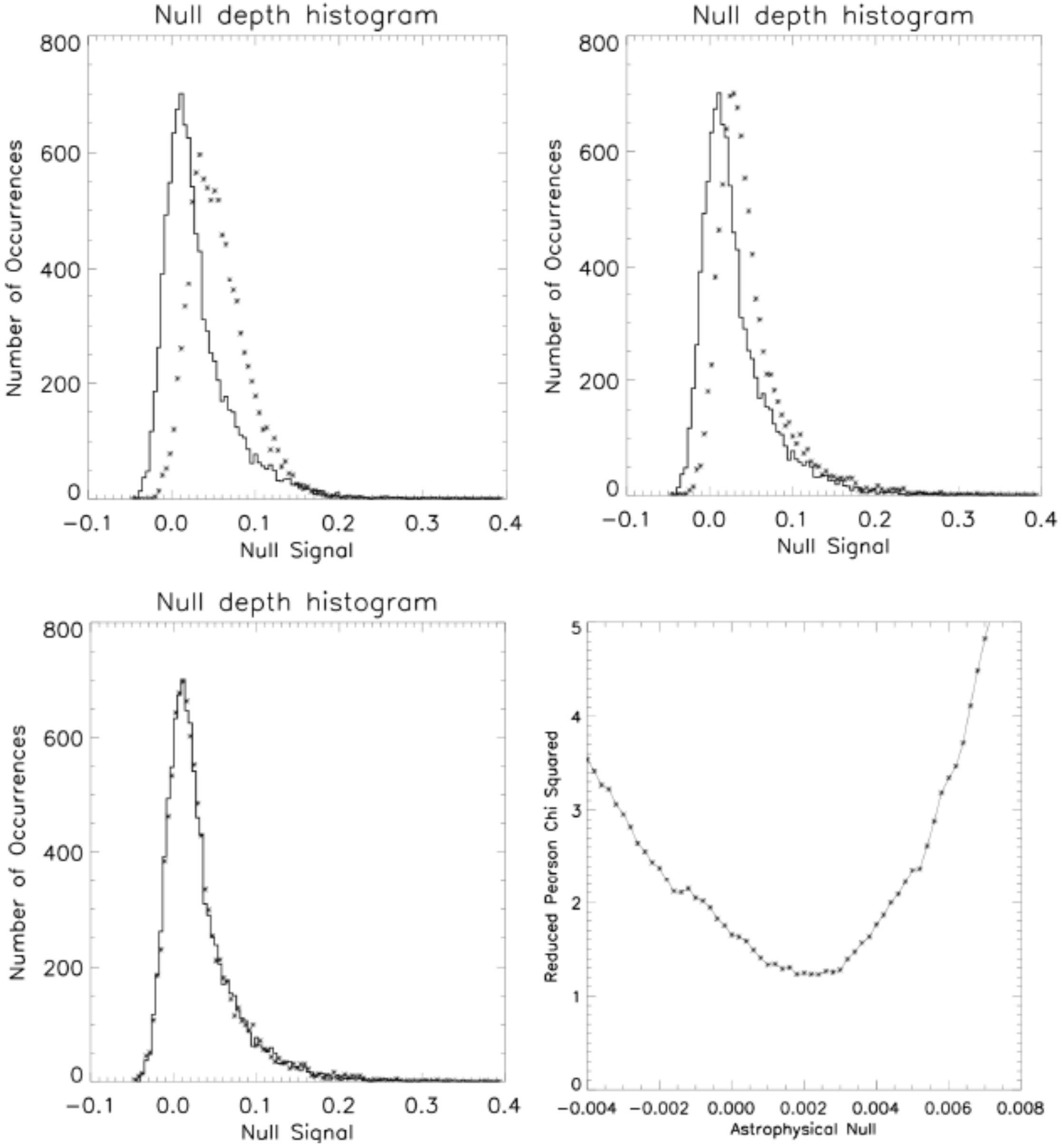




Null Self-Calibration employed for LBTI data reduction







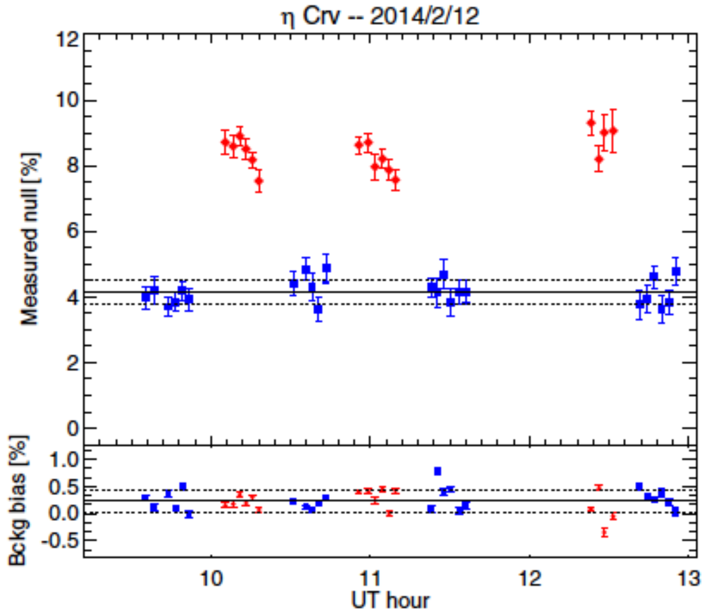
Defrere et al. (2016)

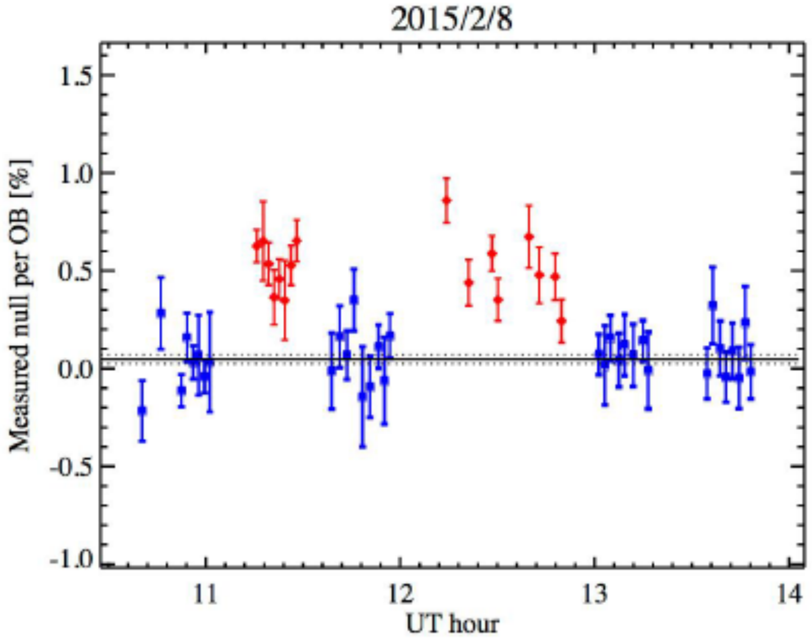
Mennesson et al. (2016)

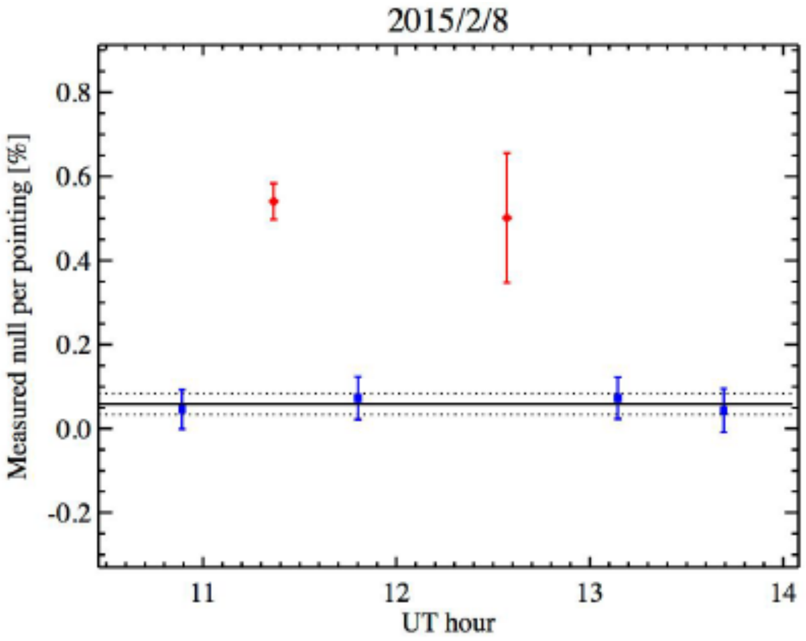
High Nulling Data Quality

η Crv

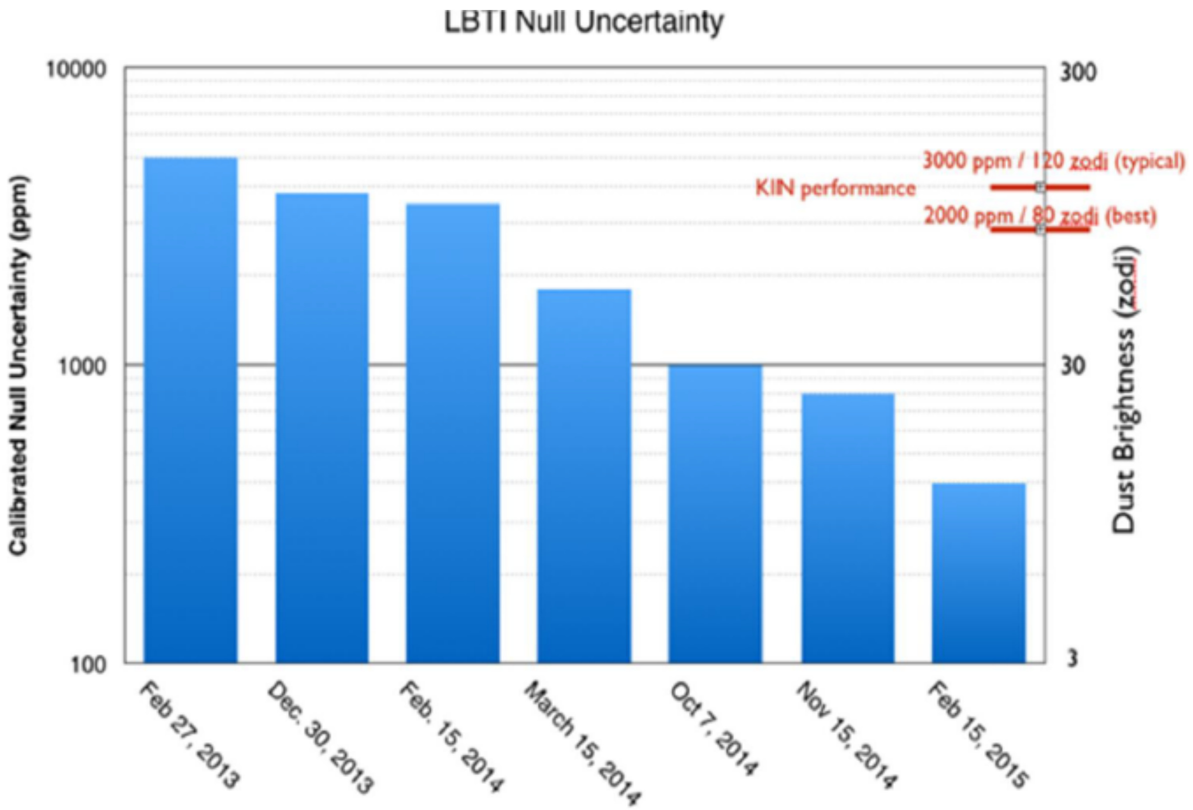
Defrere et al. (2016)

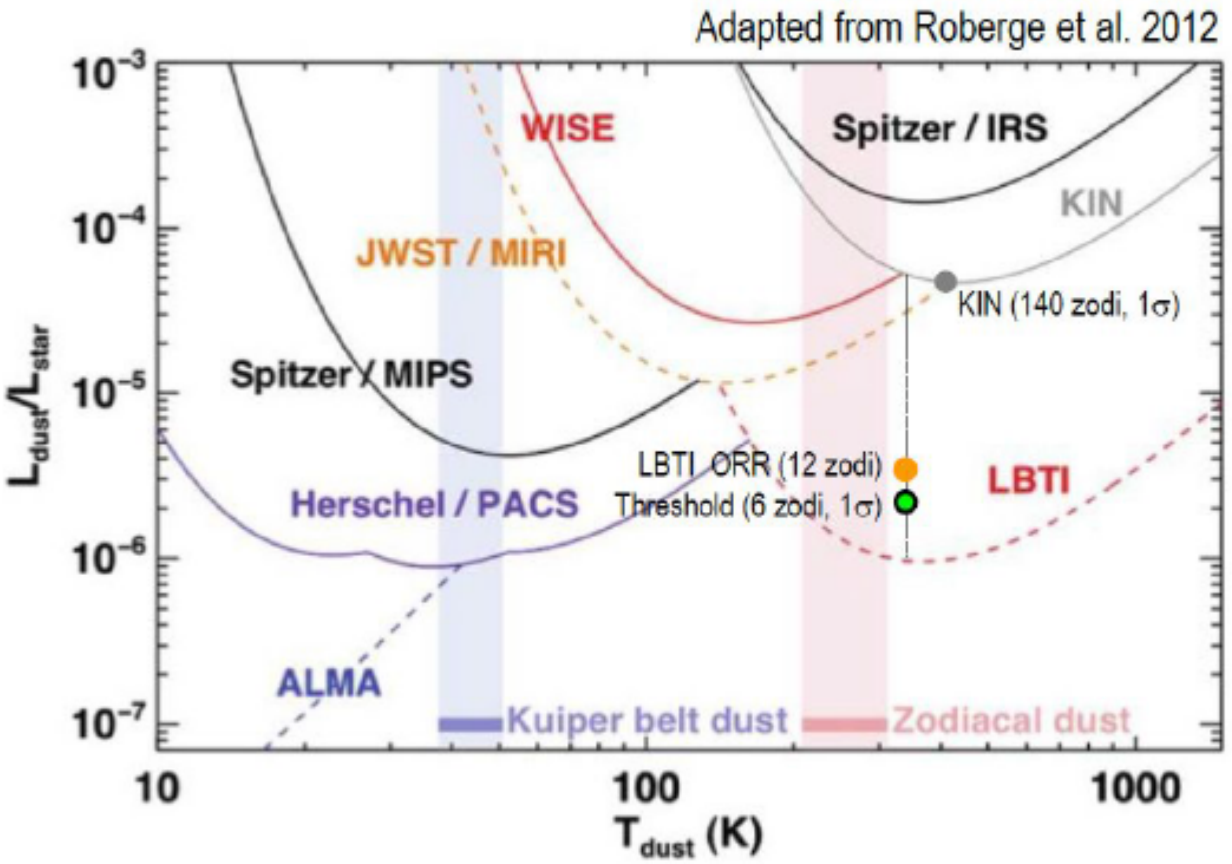






Performance History and Goals





Danchi et al. 2016

LBTI Nulling

- Nulls to 5 x 10^{-4} @ 11 microns
  - Almost 10x better than Keck
    - 10x lower background
    - Null self-calibration
- Limitations:
  - Background and background bias fluctuations between on & off beams
    - Background varies spatially & temporally
    - Nod period of ~ once per minute too slow
  - Fringe pattern – broad null fringe

Overall Lessons Learned

- Minimize complexity
- Low emissivity extremely important in the MIR
  - (order of magnitude lower at LBTI)
- Non-interferometric solutions for background removal good
- b/D can be very constraining on a single baseline
  - Long baselines → high stellar leak
  - Short baselines → can't get close to center
  - (TPF/Darwin solved this (on paper) with multiple baselines)
- Nulling self-calibration has enabled high accuracy nulling in both the NIR & MIR
  - Dispersed nulling and very rapid readout would help get the most out of NSC
- There is still great potential for high-accuracy NIR nulling/visibility measurements