Whither Nulling Interferometry?

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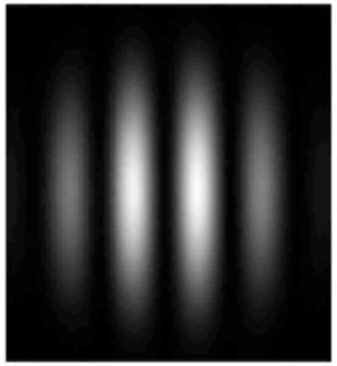
Why Nulling?

- Improve contrast for dust & companions inside the few λ/D coronagraphic IWA

    - usually not as deep as coronagraphy

central
dark fringe



- For small stellar leaks, the "null depth" is set by the fringe minimum:

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

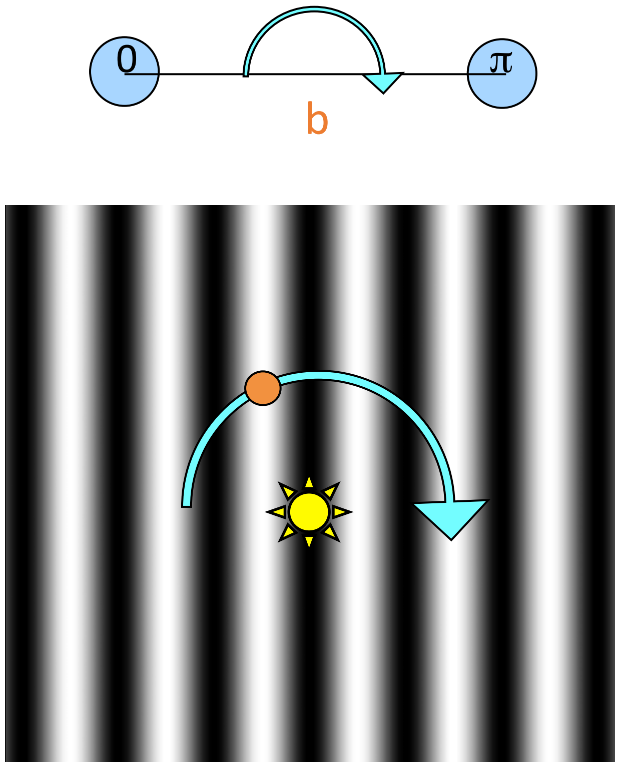
= ratio of the destructive & constructive interference signals

- Directly measure a small quantity (N) instead of a small deviation from unity (V)

    - for $V \approx 1$, and defining $\Delta V = 1 - V$, $\qquad N \approx \Delta V/2$

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

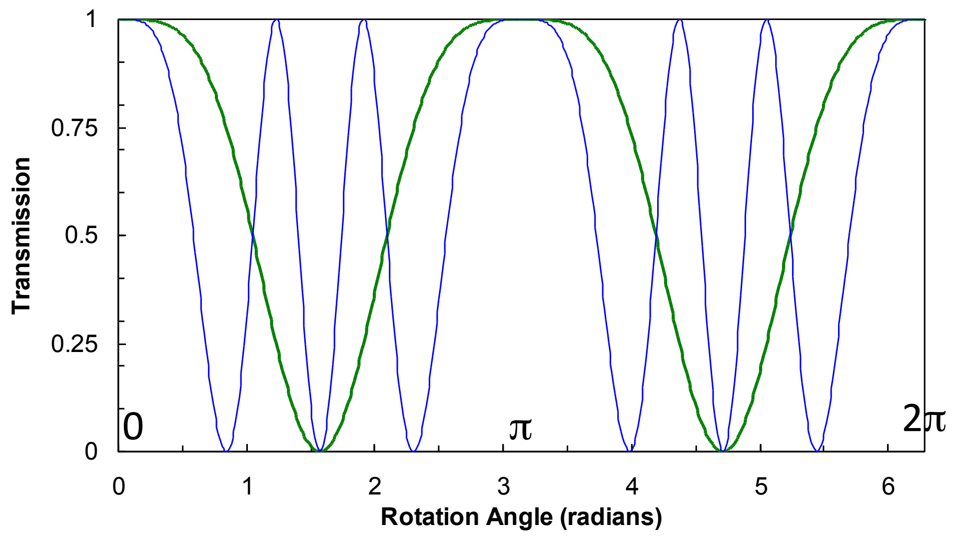


Bracewell (1978)

Signals from off-axis sources:

Green: companion @ $\lambda/2b$

Blue: companion @ $3\lambda/2b$



Science Goals

- Original goals (Bracewell; TPF-I; Darwin):
  - Terrestial exoplanets in the thermal IR (MIR)

- But
  - High thermal background noise
    - to see faint emission, need to remove two stronger signals:

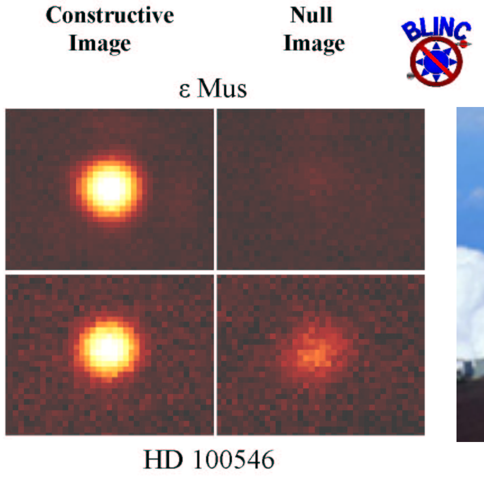
      \- stellar flux & thermal background
  - Ground-based: mainly exozodi levels of nearby stars, protostellar disks

- Shorter wavelengths (NIR):
  - Only need to remove one bright emission source - the star
  - But worse phase stability
  - Hot inner exozodi (visibility deficit stars), inner protostellar disks,inner exoplanets

On-sky Nulling Experiments to date

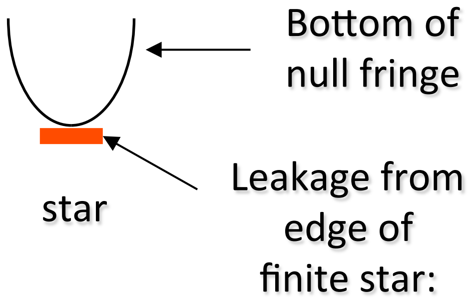
		b/D (meters)
• BLINC/MMT etc. (Univ. of Arizona) -	MIR	
• Keck Interferometer Nuller (JPL) -	MIR	85/4
• Palomar Fiber Nuller (JPL) -	NIR	3.2/1.5
• Large Binocular Telescope Int. (UofA) -	MIR	14/8

- Future: Subaru (integrated optics), VLT/HI5...



Stellar Leakage:
sometimes two apertures are not enough:

Stellar leak or null:



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

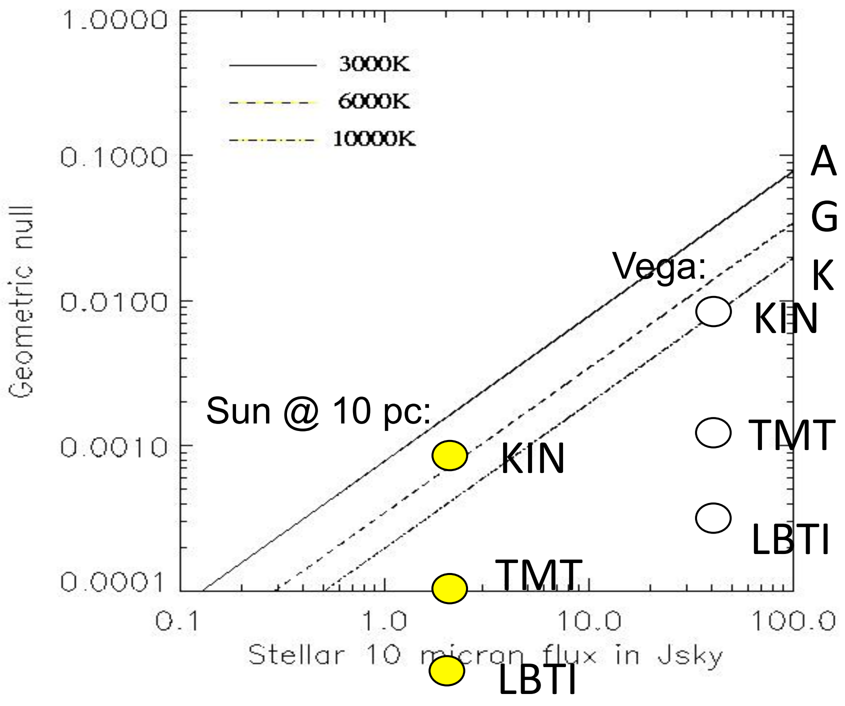
- Stellar null degrades for longer b

IWA = λ/4b

N = $(\pi^2/256)\,(\theta_{dia}/\mathrm{IWA})^2$

- Null gets worse for smaller IWA

(wide fringes for deep nulls; narrow fringes for small IWA)



Both F_ν & N are $\propto \theta^2$

For KIN, for a blackbody star of T > 4500K & flux density F_ν (Jy):

$N \sim 2F_\nu/T$

- Nearby A stars (e.g. Vega, Fomalhaut) ≈ 10^{-2} to few 10^{-4}
- Nearby G2 star ≈ 10^{-3} to few 10^{-5}

➔ calibration with known stellar leakages needed to further reduce star

Thermal-IR Nulling from the Ground

- Need to remove two bright signals:
    - star & background

- Nulling starlight requires fixed null phase

  ⇒ cannot scan null fringe when one is nulling the star

  ⇒ nulling does not remove the background

- Some type of modulation required to remove background:
    - LBTI uses dual chopping secondary mirrors
    - KIN: used phase chopping instead of sky chopping: a 2-stage interferometer with 4 input beams

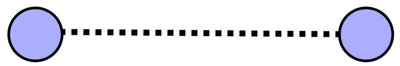
- Larger number of apertures:
    - Can produce deeper nulls
    - Can also allow modulation to remove backgrounds

Deeper Nulls: Binomial Nulling Array Configurations

Woolf, Angel et al.

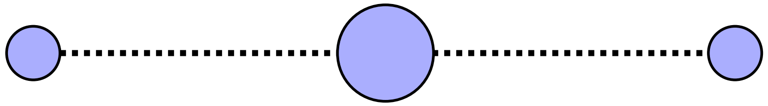
θ^2 null

Amplitudes 1:-1



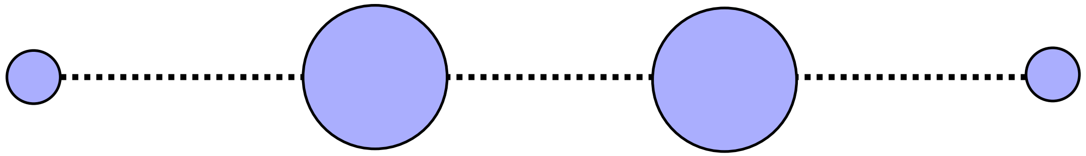
θ^4 null

Amplitudes 1:-2:1



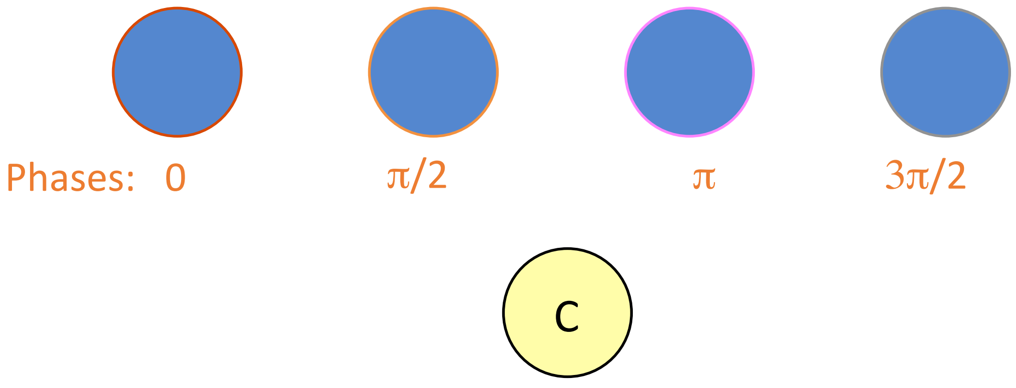
θ^6 null

Amplitudes 1:-3:3:-1

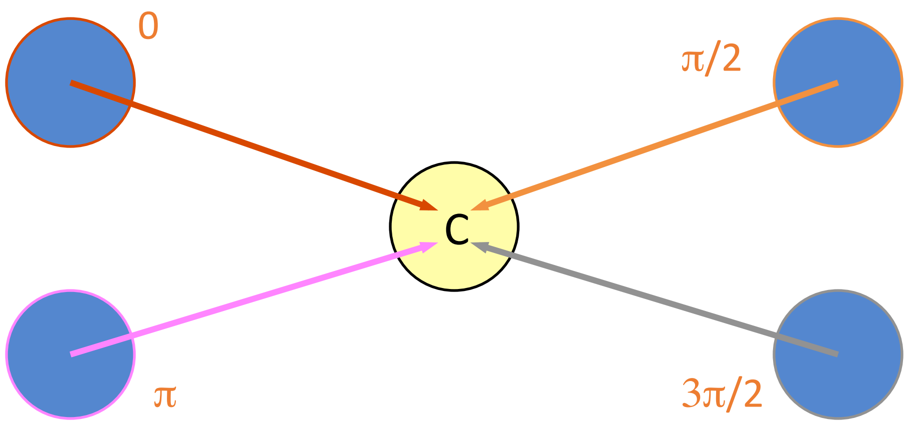


- As the number of telescopes grows, the order of the null grows,
  - but, non-identical field amplitudes are required.
- Very expensive with independent spacecraft;
  - but OK as subapertures within large single-aperture telescopes

Single-Baseline Nullers with modulation: Dual chopped nullers



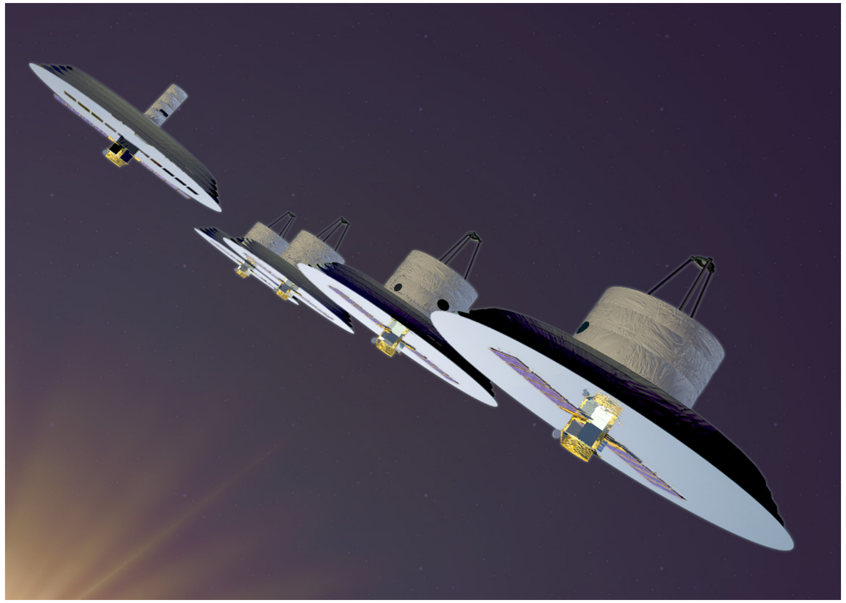
Dual-chopped Bracewell nuller



X-Array

O. Lay et al.

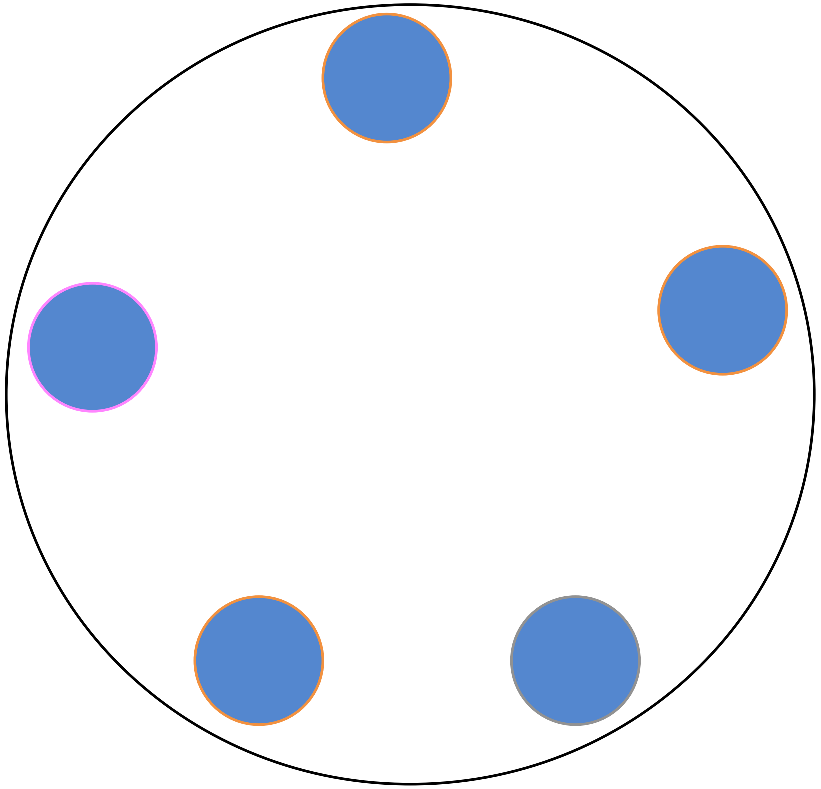
TPF-I:



- Amplitudes all the same
- Raw nulls not so deep
  - reduce residue by phase chopping between nullers
- Can separate stellar null depth and resolution (IWA)

Circular Nuller Designs (Darwin)

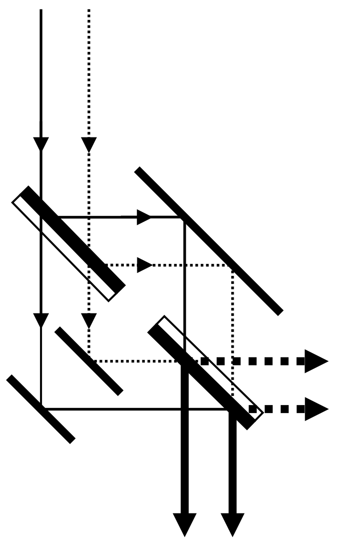
- Fits nicely within a large aperture telescope



Mennesson, Marriotti

General Beamcombiners for 2,3,4 Telescopes

2



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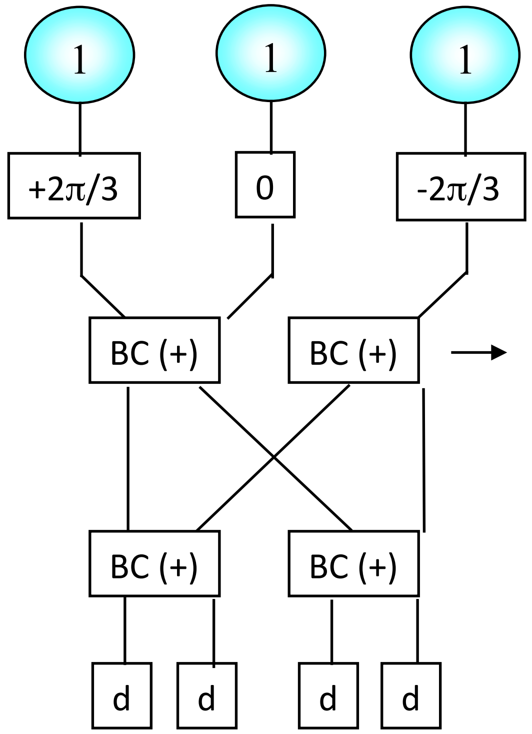

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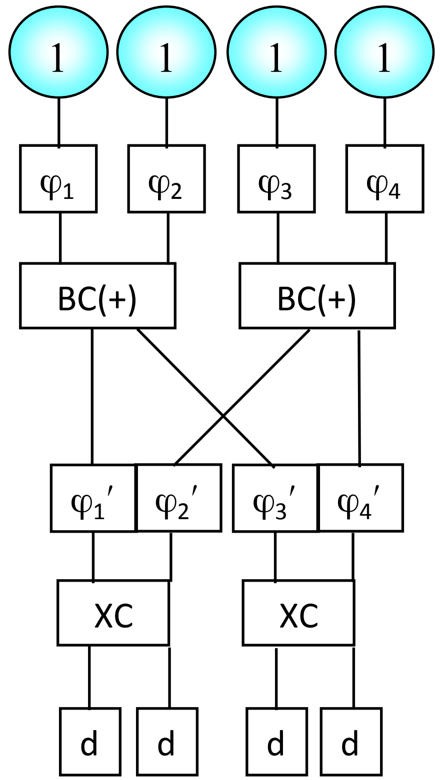
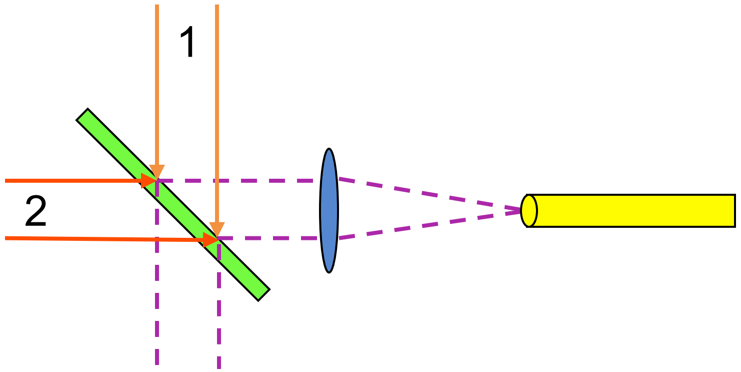
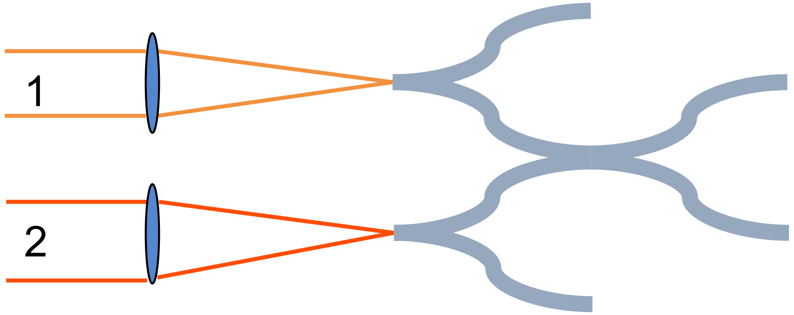


Serabyn et al.

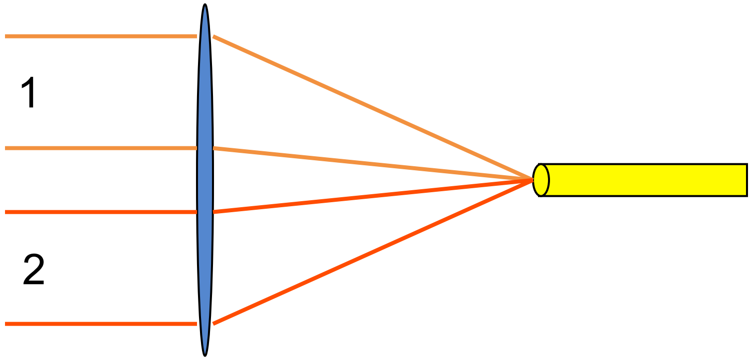
Simpler Beam Combiners



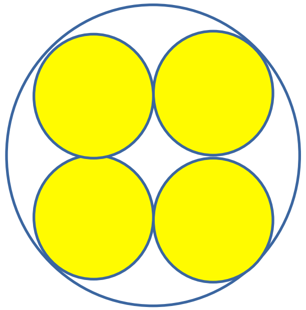
Classical free-space beam combination
Fiber acts only as a spatial filter



Combine fields inside fibers or integrated optics
The fibers act as spatial filters and combiners
(Also act as splitters for power monitoring)
(FLUOR: Coude du Foresto 1998)



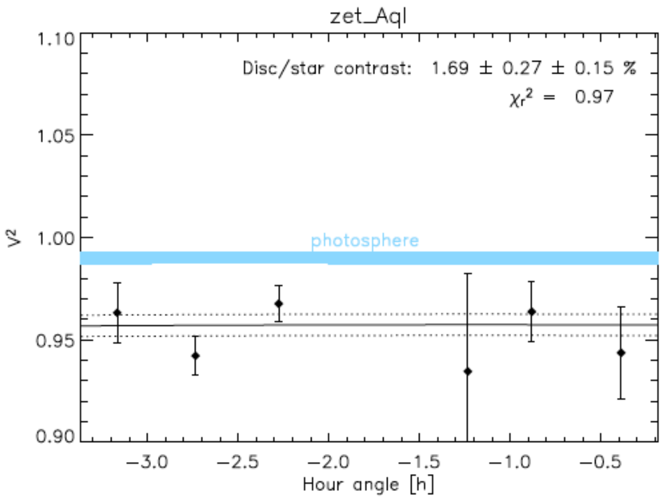
Combine free space fields via coupling to fiber mode
Fiber is both spatial filter & beam combiner
(Haguenauer and Serabyn 2006)



Fiber combination adapts easily to combine n beams
(Wallner et al. 2004)

Fibers available mostly for shorter wavelengths!

Nulling at shorter (NIR) wavelengths

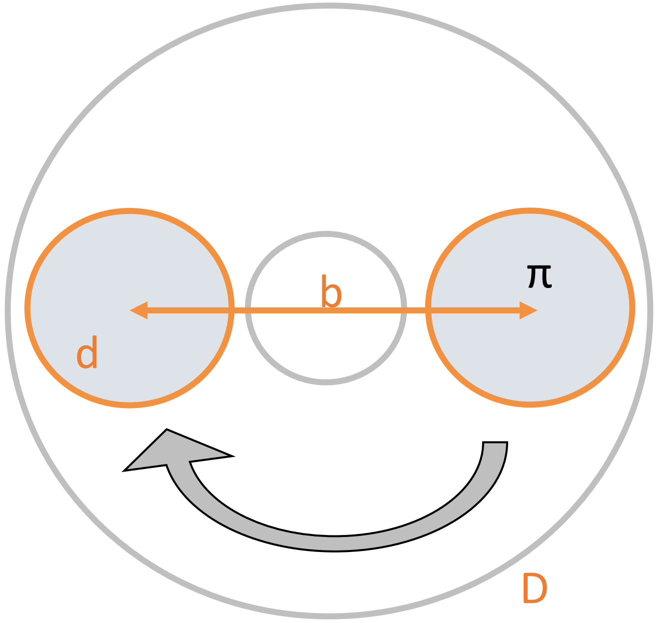


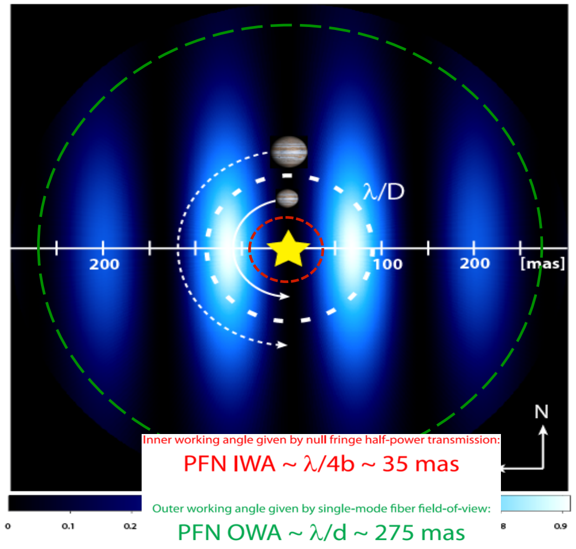
Hot inner exozodi; Absil et al. (2008)

- Why?
  - Science: Hot dust and inner (hot) exoplanets
- Why not?
  - Phase fluctuations much worse
- How:
  - Much lower background than MIR
  - Phase stability: use ExAO system on a single ap. telescope as cross-ap. fringe tracker
  - Use SM fiber for higher order WF error removal
  - Calibrate null-depths rapidly with spinning wheel (faster than chopping secondary)
  - Most important: Null self-calibration algorithm

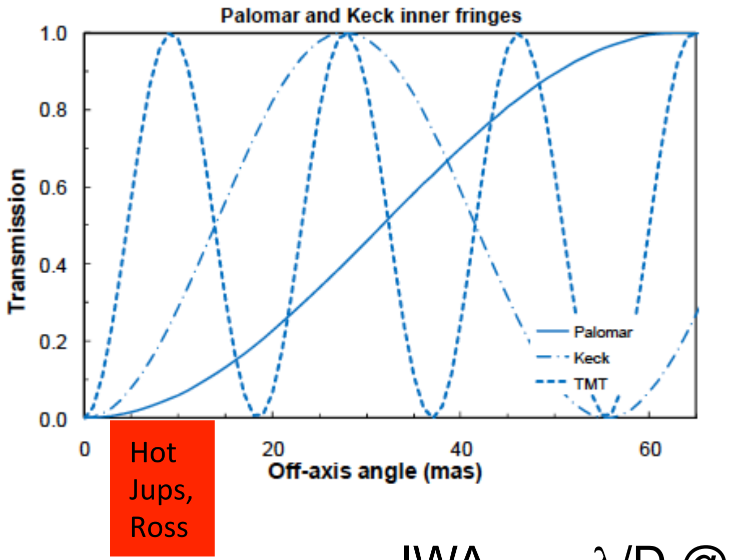
A rotating baseline nuller on a single aperture telescope

- 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), a la Bracewell
  - Small IWA (< λ/D) provides a very unique coronagraphic IWA





Small inner working angle



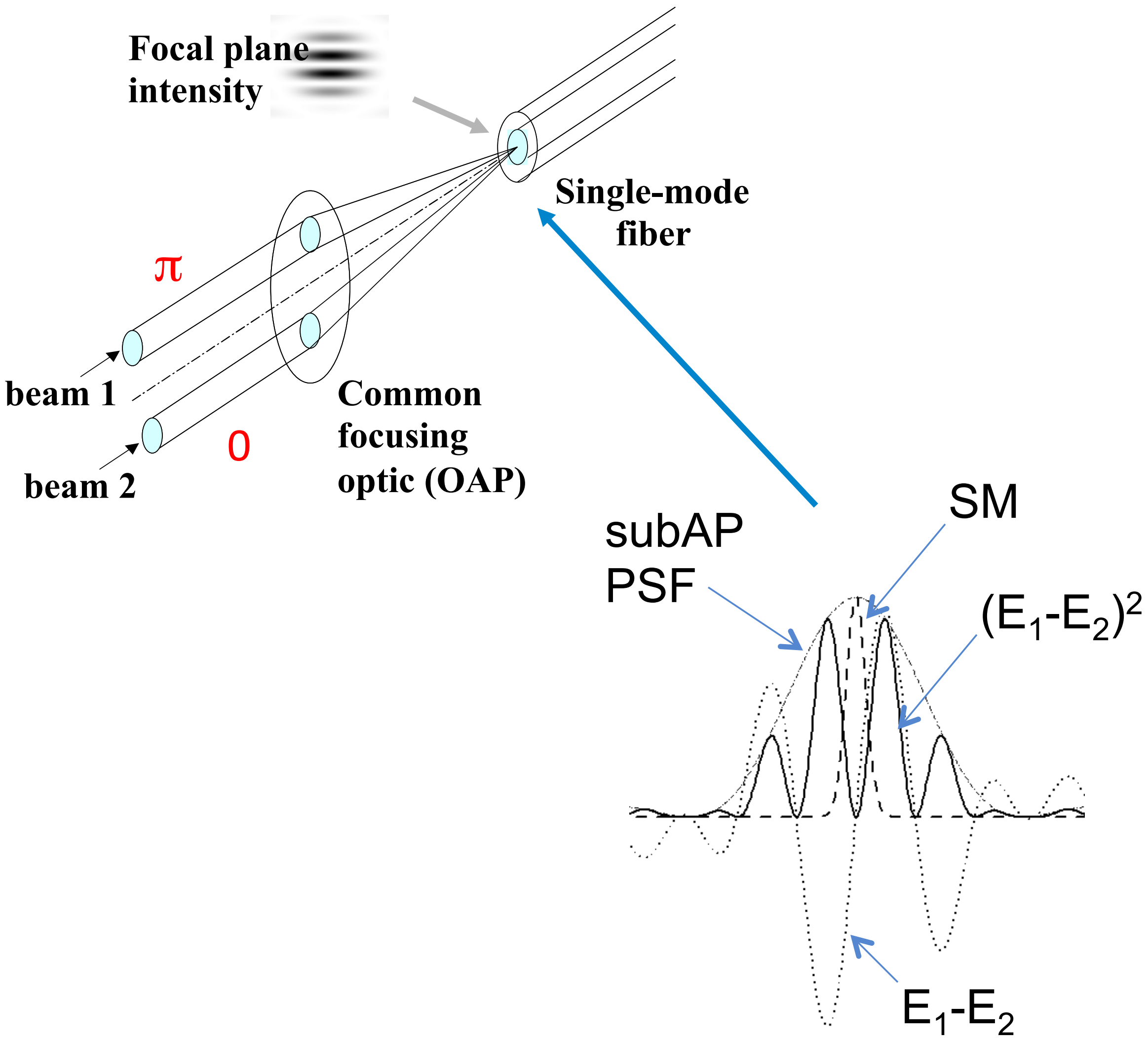
IWA ~ $\lambda/4b = \lambda/4(D-d) \rightarrow \frac{1}{4}\,\lambda/D$

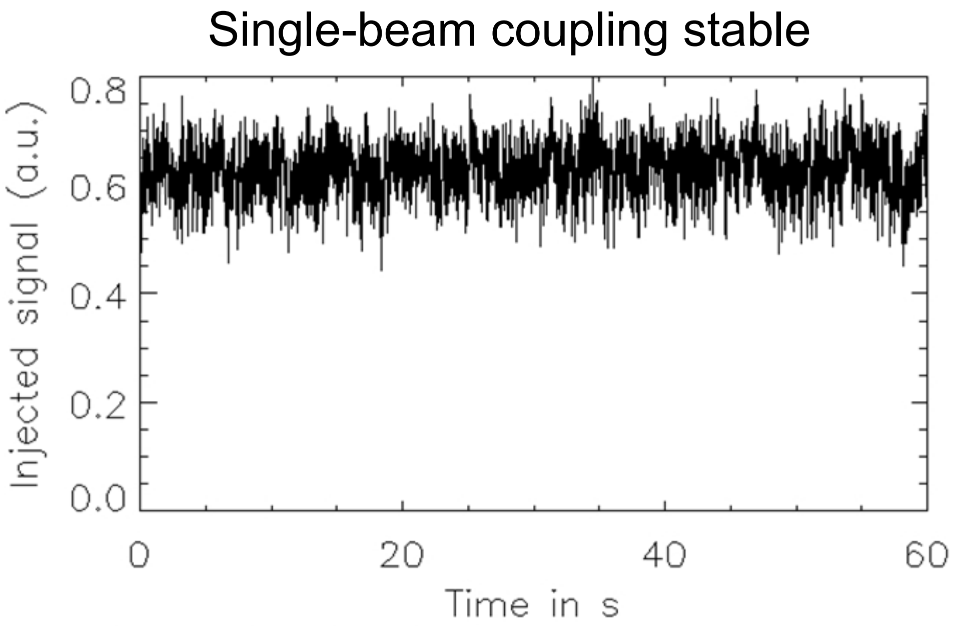
OWA_{SM} ~ $\lambda/2d \rightarrow D/2d\ (\lambda/D) \rightarrow 5/3(\lambda/D)$ @ Palomar

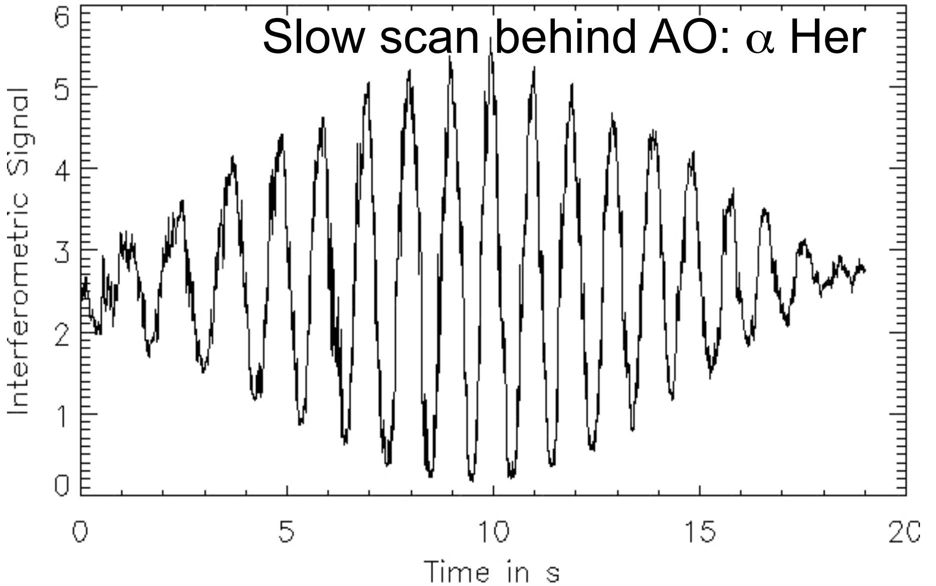
Operates entirely inside normal coronographic IWA

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

Coupling and stability behind ExAO



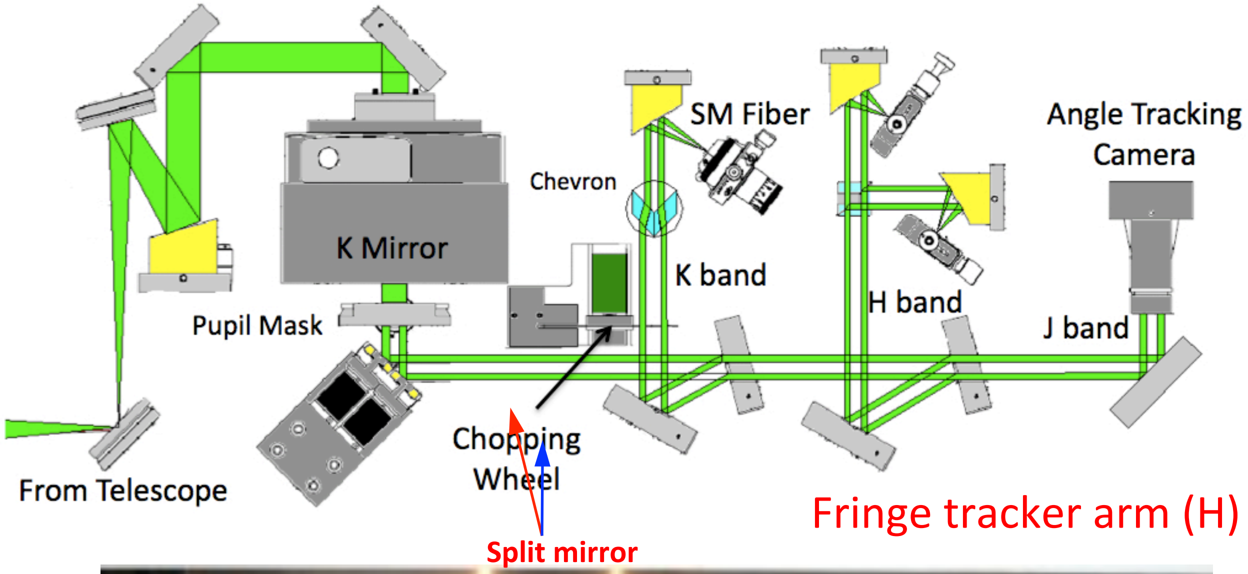




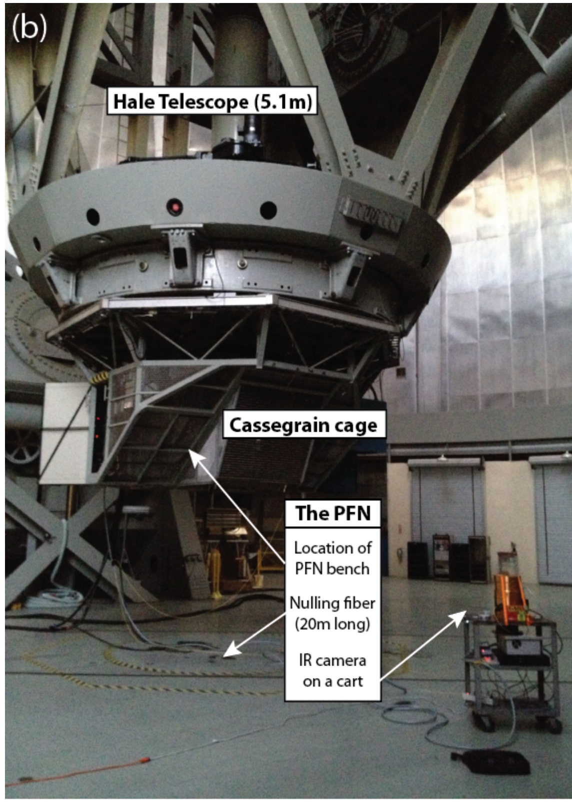
In future, can also potentially move to integrated optics

The Palomar Fiber Nuller (PFN)

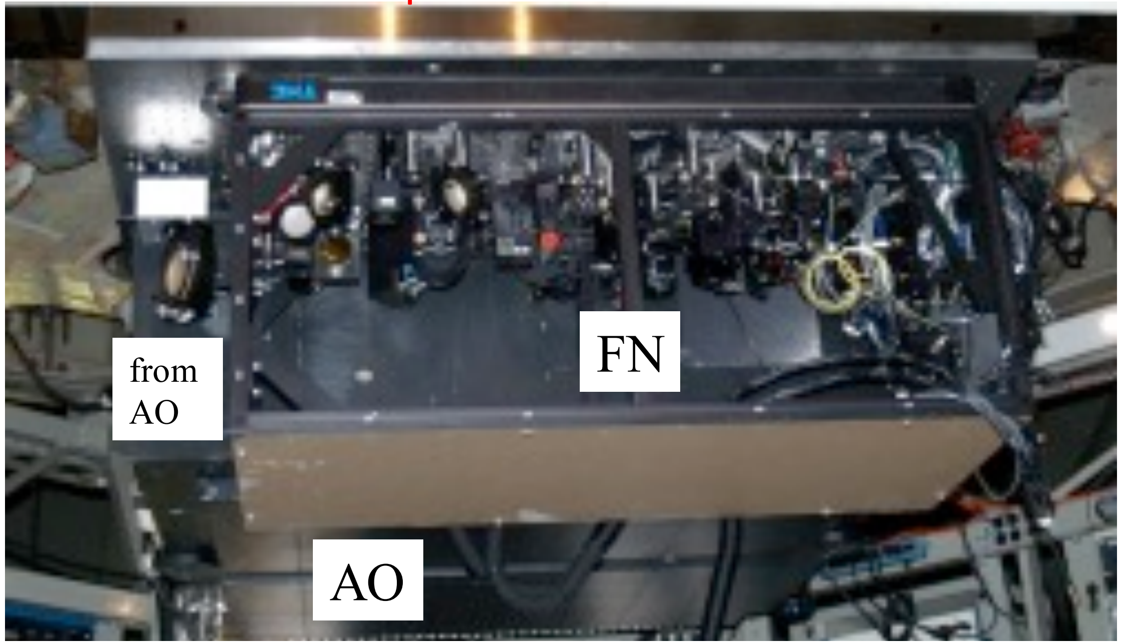
Serabyn, Mennesson, Martin, Liewer, Loya, Kuhn, Hanot papers



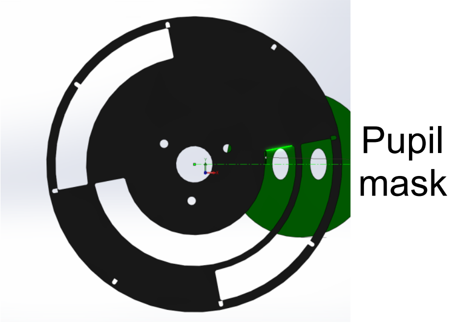
- **K-mirror:** baseline rotation
- **Pupil mask:** two elliptical holes at primary image
- **Pupil shear:** match beam intensities
- **Split mirror:** OPD scans and fine OPD matching
- **Chopper wheel:** rapid calibration
- **Chevron:** dispersion correction & pupil compression
- **IR SM fiber combiner**



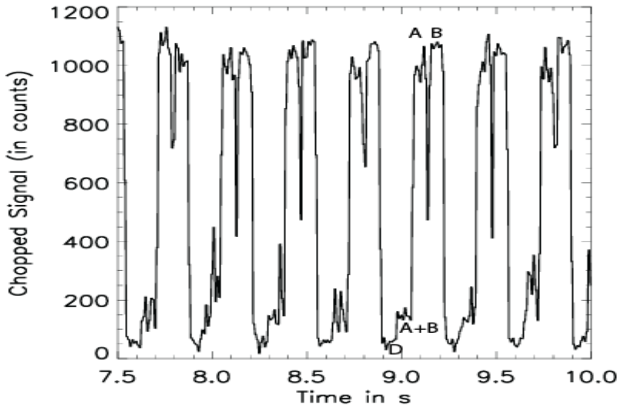
Fringe tracker arm (H) not needed



Rapid calibration: Sequentially measure A-B, A, B, dark



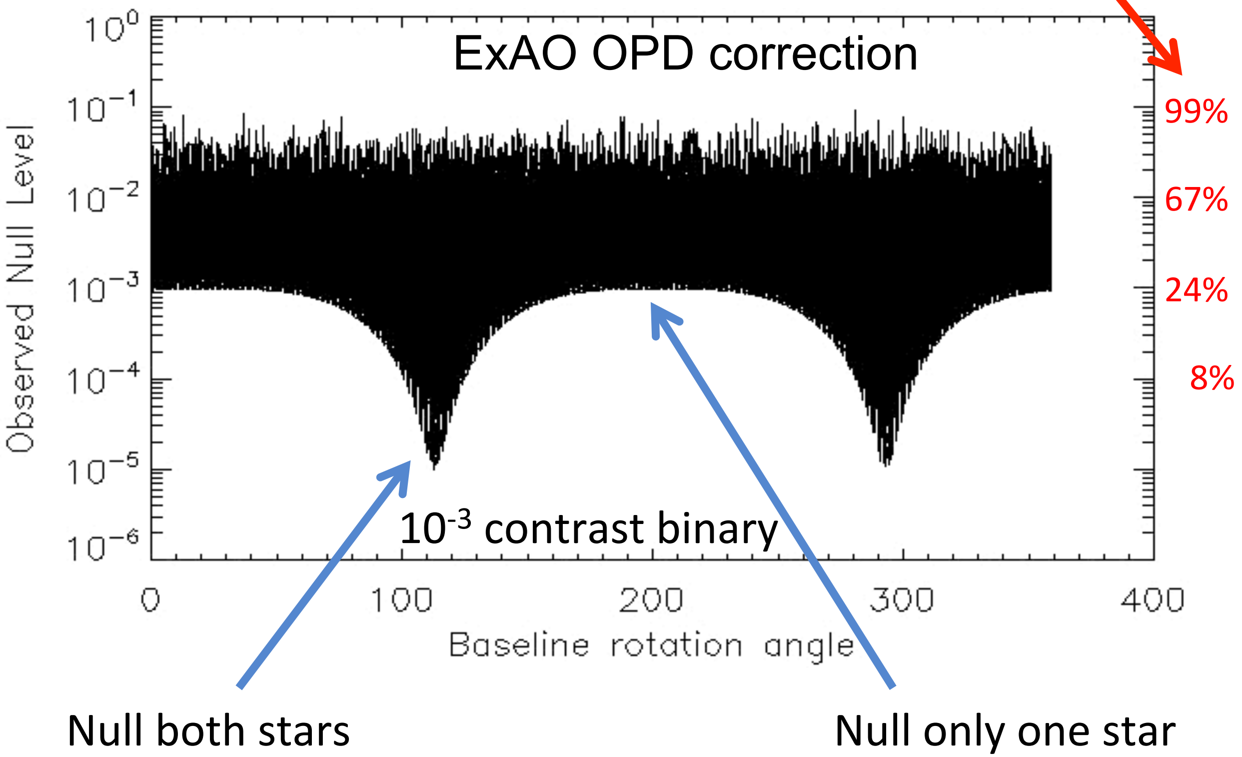
Chopper wheel



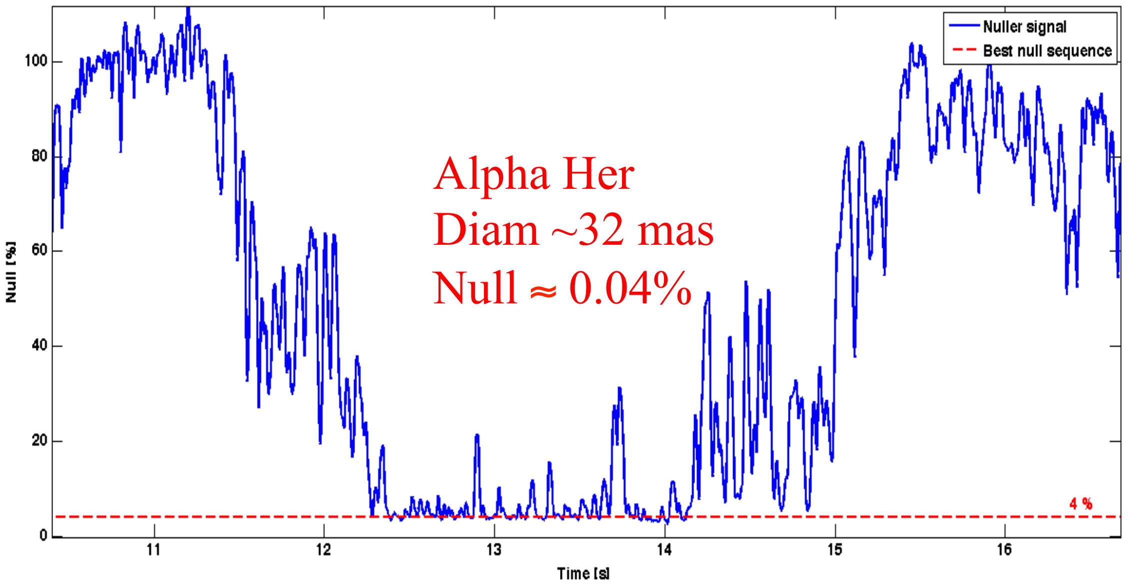
Even behind ExAO, null depth not very stable

- ExAO stabilizes only enough (~100 nm) to stay near fringe minimum
  - allows a larger amount of time to be spent near null
  - Can enable ~ 10^{-4} null depth meas. on very bright stars

Binary: model of one baseline rotation with K-band nuller



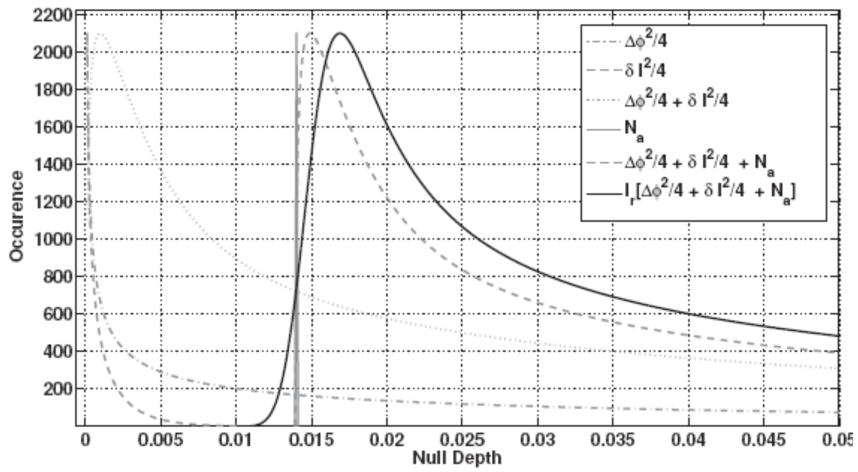
Stellar diameter measurement from null:

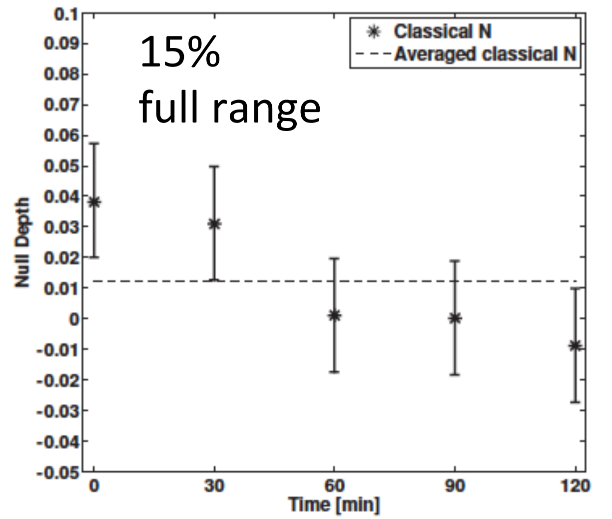


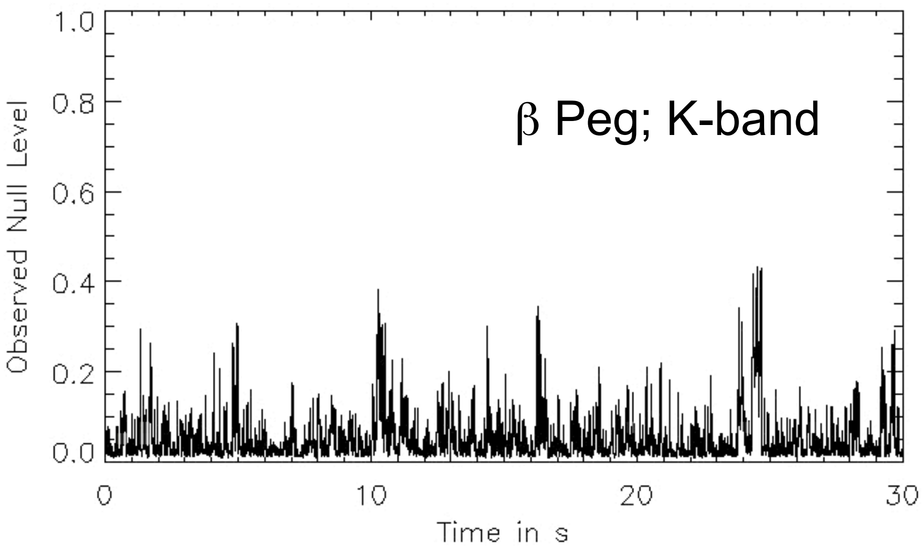
Null is NOT given by "mean null level"

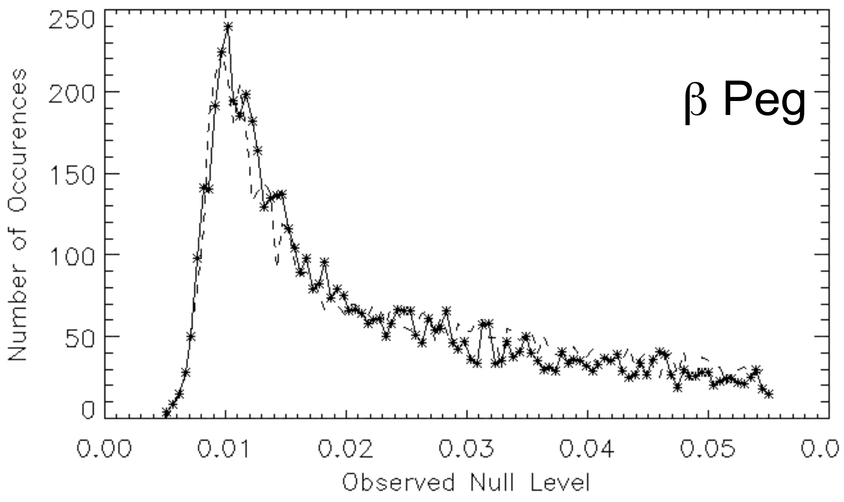
Measurement of Null Depth from Statistics of the Null: The Null Self-Calibration Algorithm

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

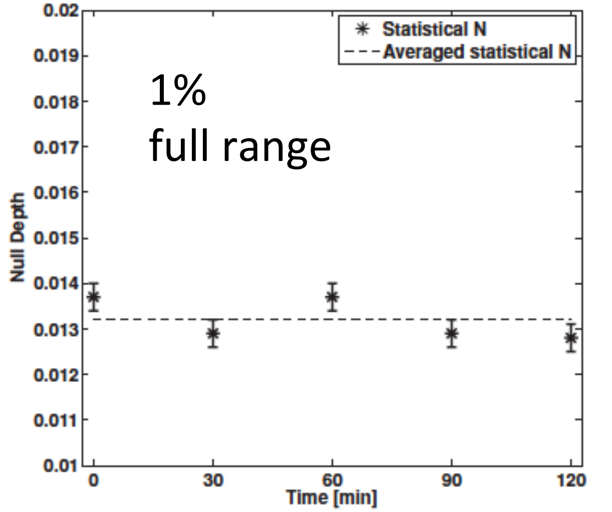








Hanot et al. 2011

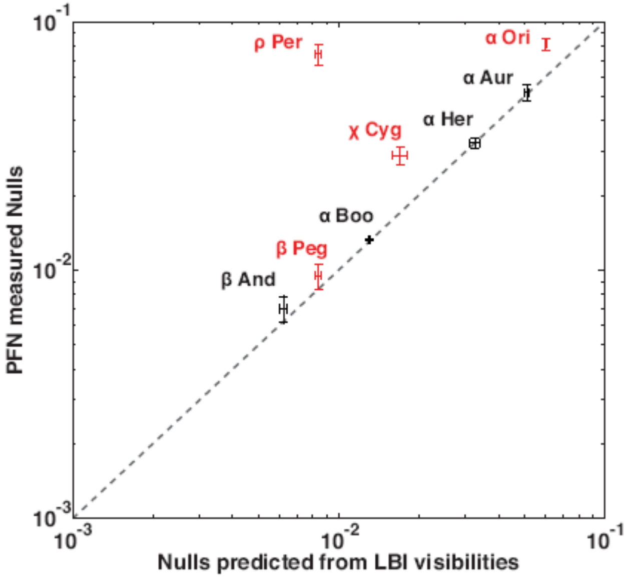


NSC yields > an order of magnitude Improvement in null depth accuracy!

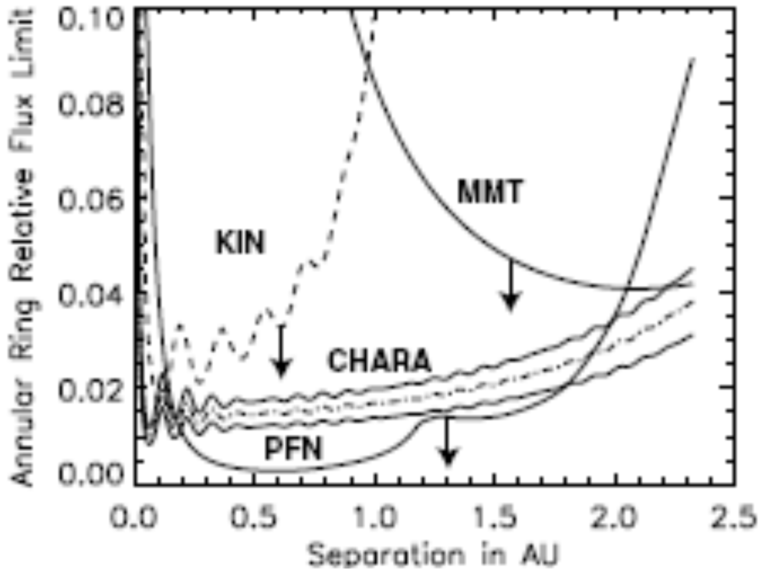
PFN: Measurements with a 3.5 m baseline

- High accuracy (a few 0.01 % to 0.1%) enables measurements with a very short baseline!

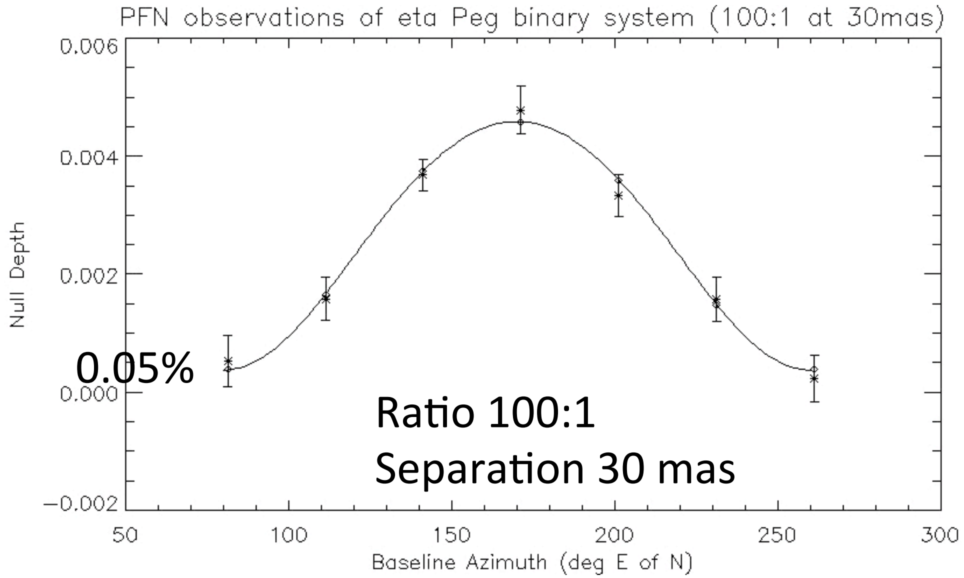
Giant star diameters:



Exozodi dust:



Companion detection:



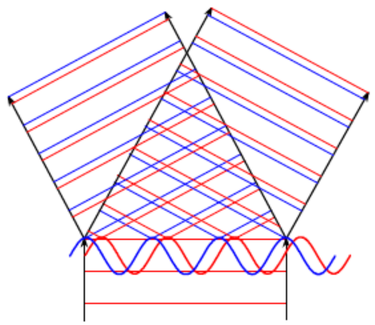
This is what TPF-I/Darwin aimed at doing!

- Hot inner dust: Mini-survey carried out of Absil detections (~ 10 stars): detection limits of N ~ 0.2%
  - Preliminary conclusion is that 2 micron dust is at very small radii (in preparation)
- Bigger telescope & baseline needed to go further

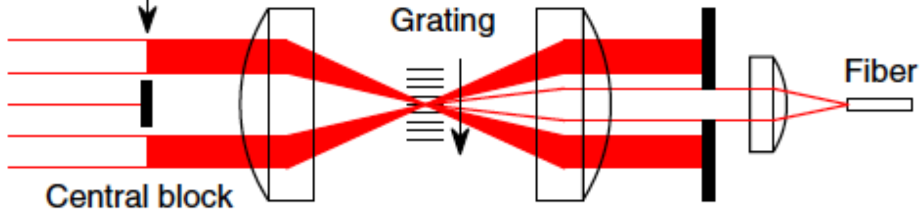
Simplified nulling optics for the future: the grating nuller (achromatic fringes), etc.

No beamsplitters
Drop-in optics

Grating nuller:
Martin et al. 2017



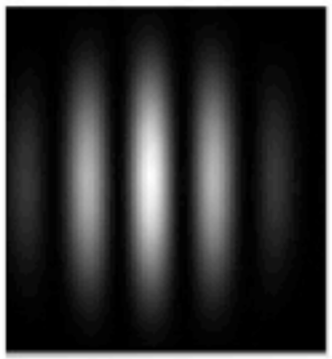
Phase shift by lateral motion of grating

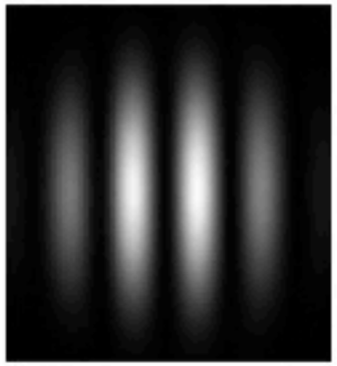


Null zeroth order with lateral grating shift

Liquid crystal phase shifters:

Constructive fringe





Dark fringe

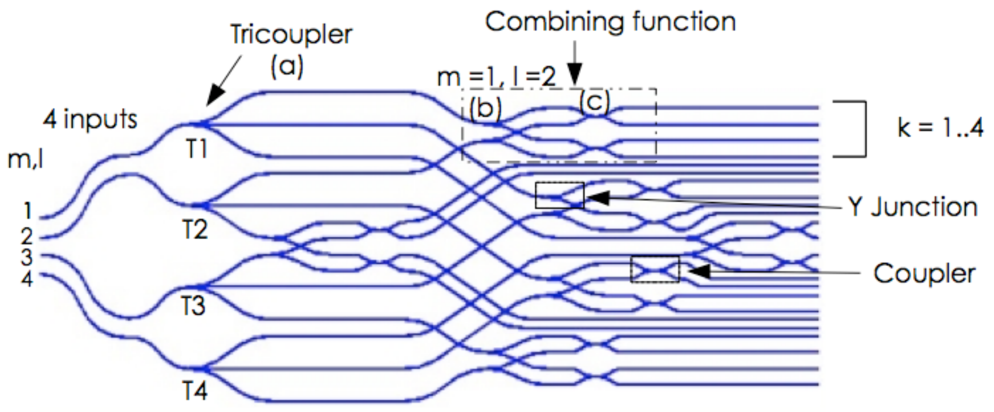
...Vortex nulling...

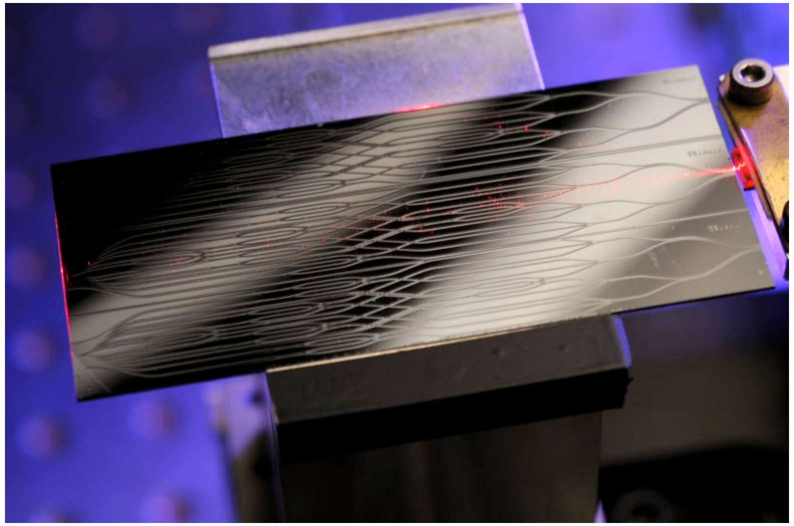
Or, Integrated Optics Beam Combiner: e.g., PIONIER

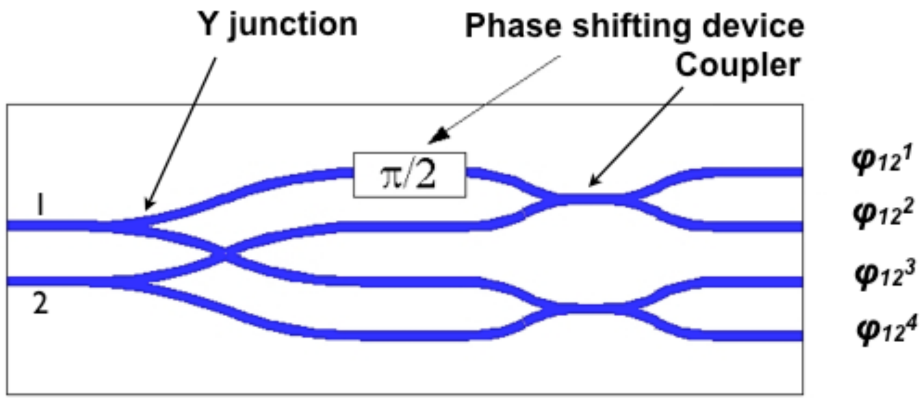
4 input beams (6 baselines)→ 24 output beams

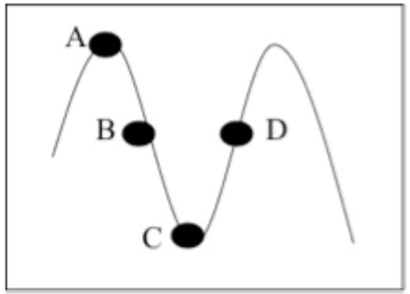
Includes 4 quadrature phases for each baseline

(Berger et al., Kern et al. 2011)









$\varphi_{12}^2 = \varphi_{12}^1 + \pi$

$\varphi_{12}^3 = \varphi_{12}^1 + \pi/2$

$\varphi_{12}^4 = \varphi_{12}^3 + \pi = \varphi_{12}^2 + \pi/2$

Need to show deep suppression

Nulling Lessons Learned

- Minimize complexity
- Low emissivity extremely important in the MIR
- Background removal (chopping) if possible
- b/D can be very constraining on a single baseline
  - Long baselines (KIN) → high stellar leak
  - Short baselines (PFN) → can't get close enough to center
  - TPF-I/Darwin solved this (on paper) with multiple baselines; can implement on large telescopes
  - TMT: just right?

- Nulling self-calibration (NSC) has enabled high accuracy nulling in both the NIR & MIR
  - In use at PFN, LBTI, Subaru
  - 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

The future?: Nulling on large single aperture telescopes (Keck, GMT, TMT, ELT)

- NIR nulling on a larger single-aperture telescope could be quite interesting:
  - Simplified nulling optics
  - Integrate nuller into the AO system
  - Good baseline range possible
  - Good stellar rejection possible
  - Multiple baselines easy to implement within a large single-aperture telescope
  - Make use of fibers, integrated optics...
  - Nulling self-calibration (~ dark speckle)
  - Combine nulling with closure phase?

- To enable:
  - Innermost Hot jup spectroscopy & innermost exozodi structure in to a few mas

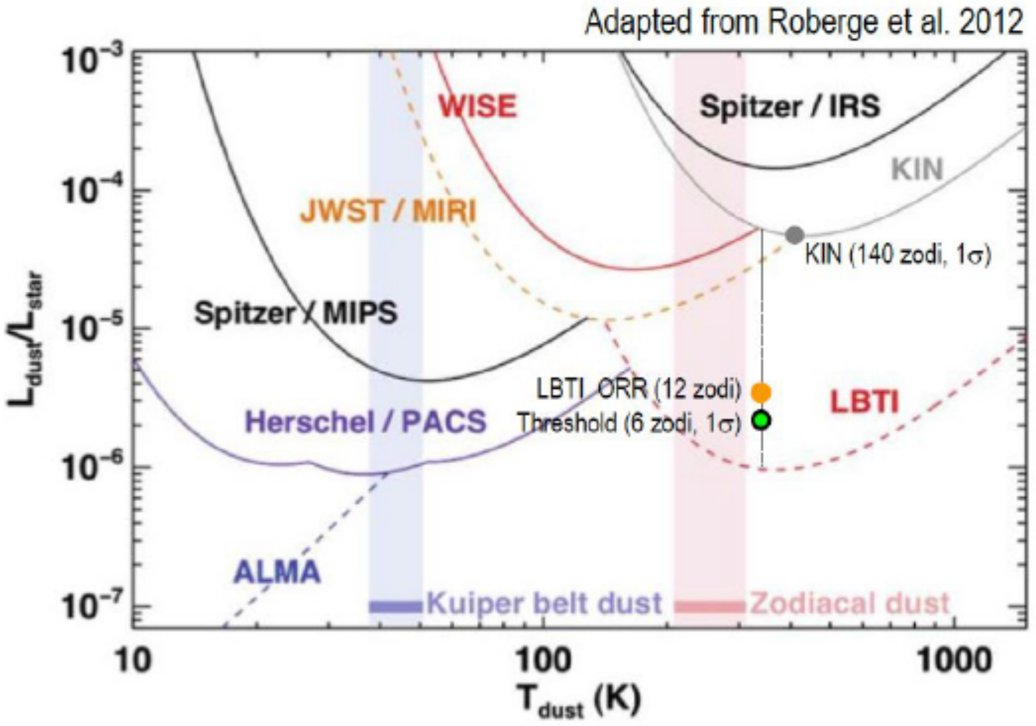
Fini

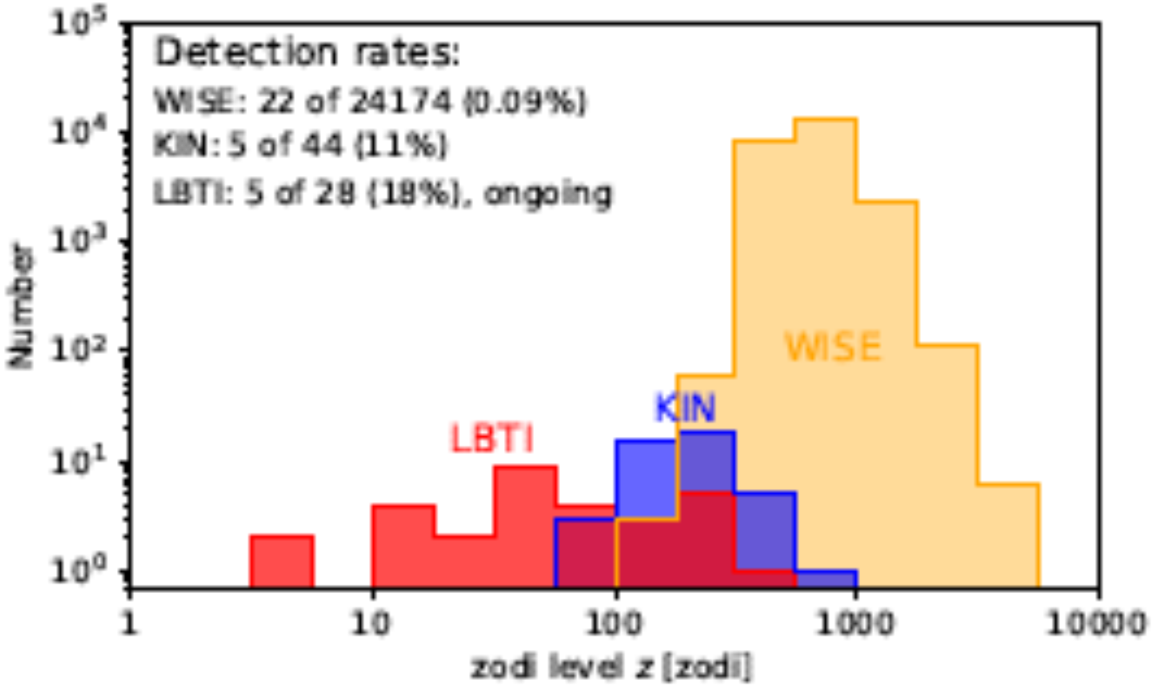
MIR nulling: KIN/LBTI differences

• Configuration:	Independent telescopes vs. common mount
• Baseline:	85 m vs. 14 m
• Modulation:	Interferometric phase chopping vs. spatial chopping
• Subapertures:	4 vs. 2
• Emissivity:	high vs. low
• Spatial filtering:	Partial vs. none (inside vs. outside λ/D)
• Data reduction:	Prior to vs. apres nulling self-calibration

MIR Nulling Results

- KIN: 47 stars; final best calibrated null ~ 0.2 – 0.3%; Upper limits a few hundred hundred zodis (Milan-Gabet et al. 2012; Mennesson et al. 2014)
- LBTI: about an order of mag deeper
    - Accuracy improvement due to lower emissivity and use of statistical nulling self-calibration technique



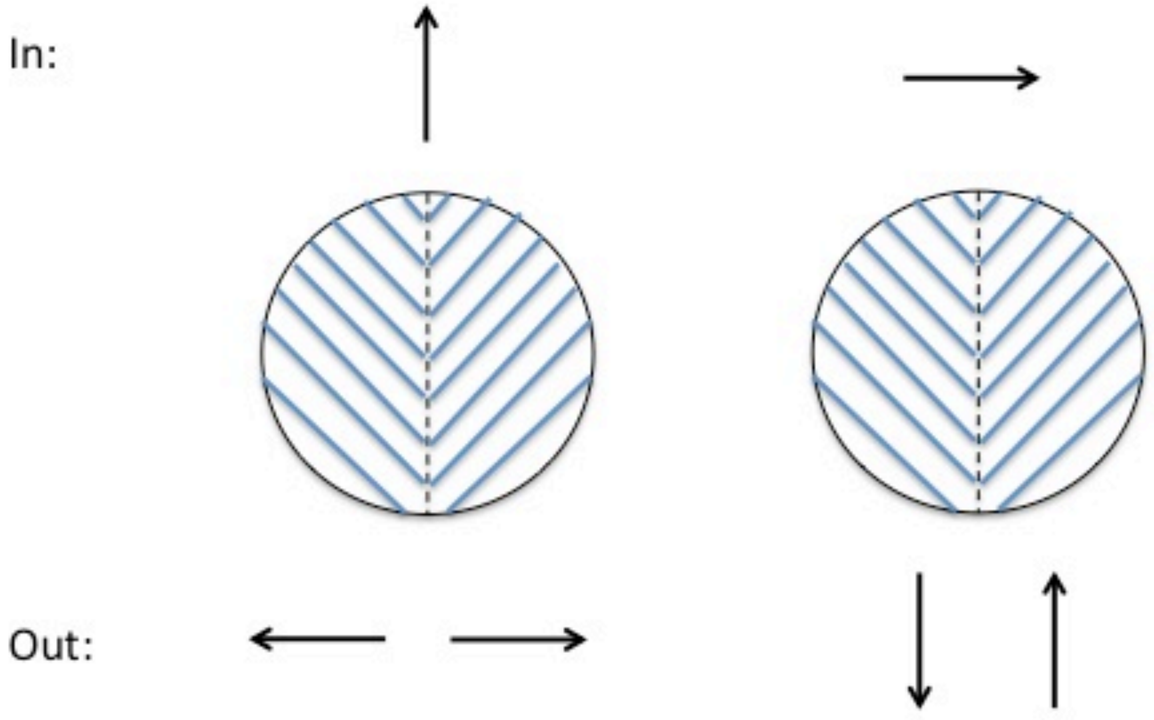


The Future: Simplicity
e.g., Crossed Half-Wave Plate Nuller

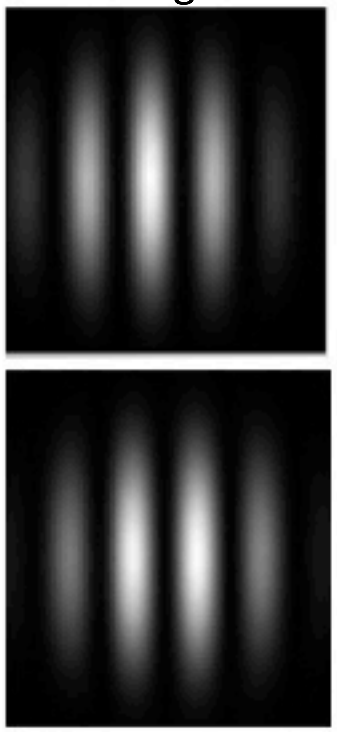
Time to move to a larger telescope (longer baselines)

Need simplified nulling arrangements: need to be efficient!

Want drop-in optics for existing coronagraphic benches



Constructive fringe



Dark fringe