# The Past, Present and Future of Nulling Interferometry

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# Outline

- Past
- Present
- Future

# A recent mass extinction event

- In the distant past (*ca*. 2000), infrared nulling interferometry space mission concepts were abundant:
  - e.g., TPF-I, Darwin, FKSI, the visible nuller
- With the passage of time, visible-wavelength concept species (such as internal and external coronagraphy) came to dominate the landscape
- Questions:
  - Is there an environmental niche in which nulling can once again thrive?
  - What have we learned about nulling with ground-based systems (BLINC, KIN, PFN, LBTI) since then?
- A (small) exoplanet program study was initiated to summarize the current state of nulling and where it might go next:

  "Revisiting Nulling Interferometry Space Mission Concepts"

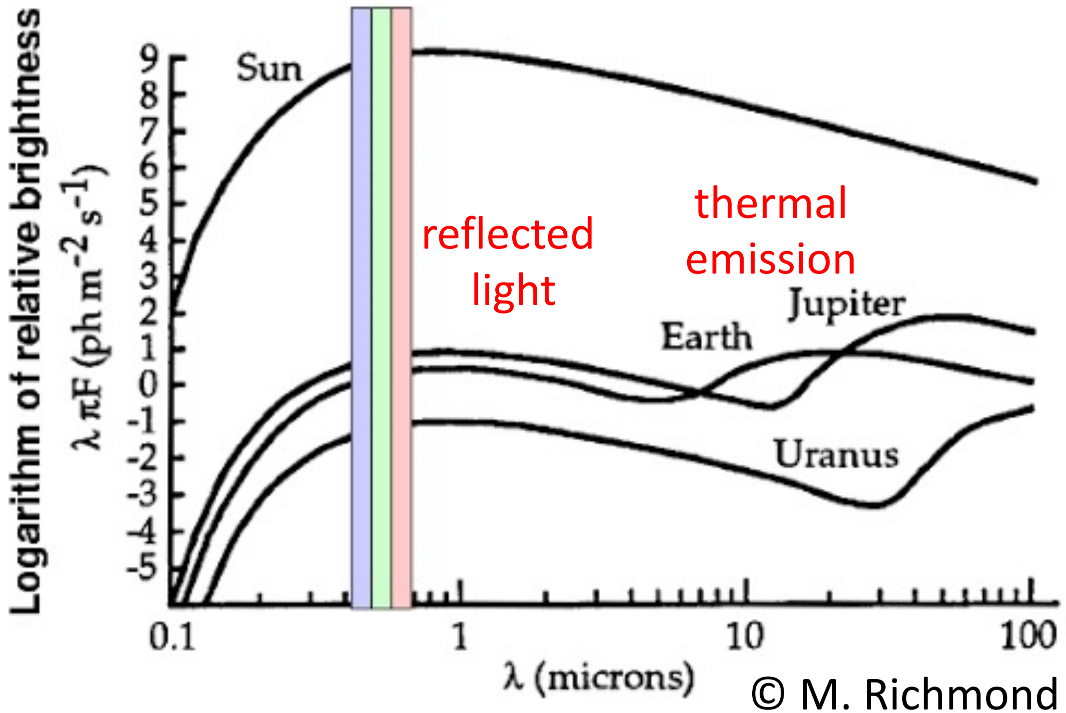
  PI – B. Mennesson, with E. Serabyn & S. Martin

# “Revisiting Nulling Interferometry Space Mission Concepts” Task List

- Task 0: Science goals, objectives, and measurement capabilities beyond HabEx/LUVOIR in the ELT/TMT era (with Danchi & Stark of Goddard))
- ***Task 1*: Collect and summarize key nulling and interferometry lessons learned since the TPF-I concept work, from the Keck, Palomar and LBTI nullers, from nulling results in the lab (e.g., PDT/fiber nuller/grating nuller) and from recent high contrast interferometry (GRAVITY)**
- Task 2: Consider the application of higher spectral resolution techniques, such as molecular mapping, to MIR nulling
- Task 3: Revisit (and potentially modify) the TPF-I Emma baseline mission concept
- Task 4: Identify Tech Gaps for several possible mission scenarios
- Task 5: Identify Candidate Technologies to be developed to close these gaps
- Task 6: Monitor European progress in order to position NASA as an essential collaborator to their efforts to develop a future mission (or to a mission concept from the US side)

- **TODAY: focus mostly on Task 1 – lessons learned**

# Why nulling interferometry? Infrared spectra of exoplanets

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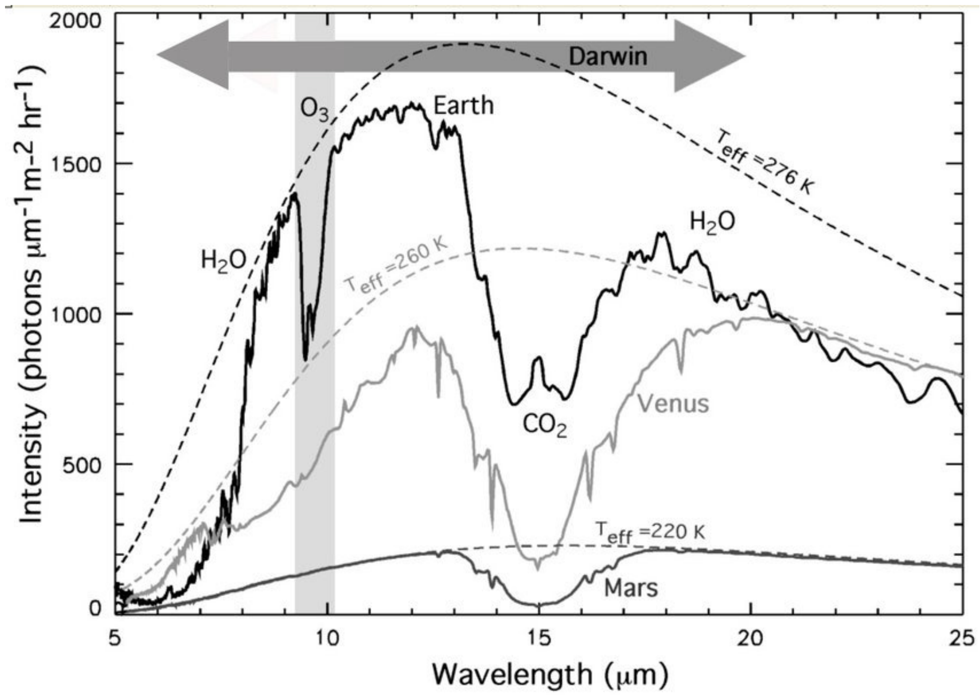



Cockell et al. 2009; Astrobiology

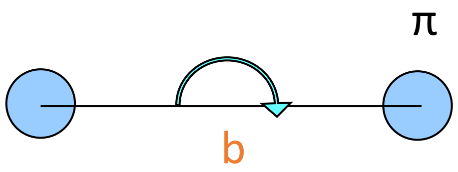
Advantages of long wavelength spectra:
Much easier contrast
Contain important spectral features of relevant molecules

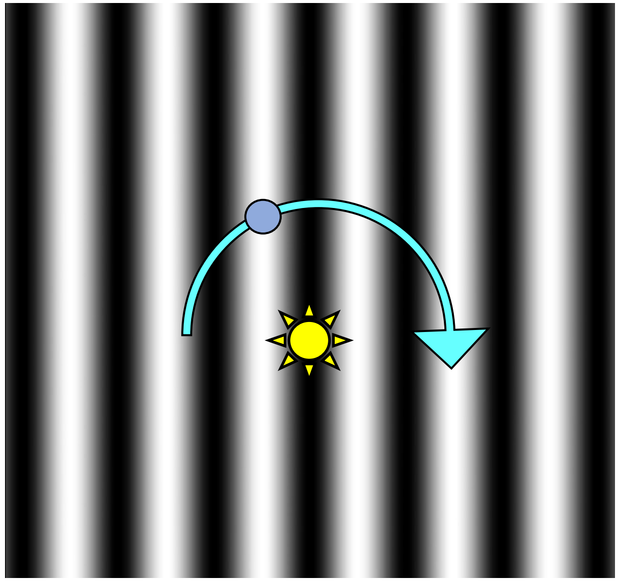
Disadvantages of long wavelengths:
Need large optics or long interferometric baselines
High background noise calls for cooled optics

# What is Nulling Interferometry?

- Need to reduce starlight in the thermal IR, just as for visible/near-IR coronagraphy (but less)
- But large MIR wavelengths imply large optics or more likely, multiple telescopes with large separations

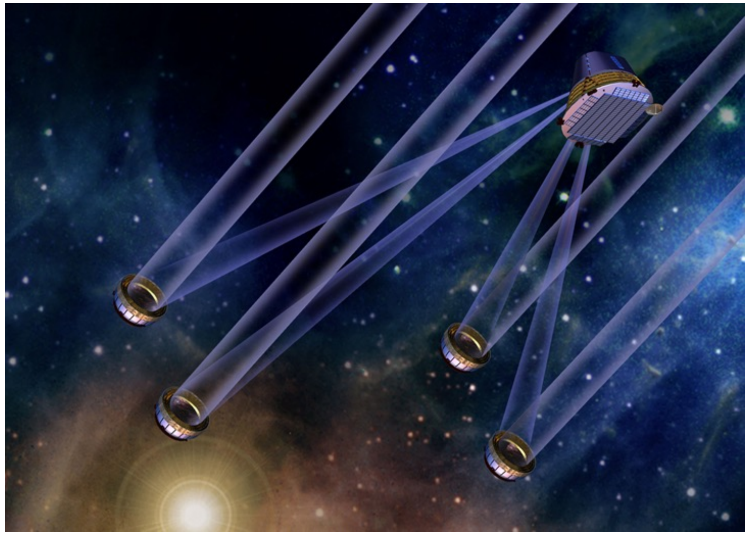
- Simplest case: anti-phase a pair of separate collecting apertures to center a dark interference fringe on a star (Bracewell 1978)



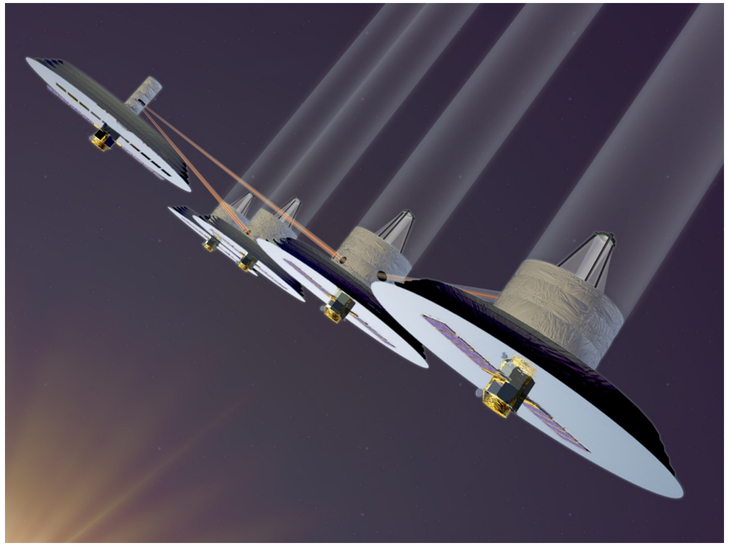



- Quick comparison of high-contrast techniques:
  - Nulling interferometry: phase a small number of separate large tel. apertures to generate a dark fringe
  - Coronagraphy: phase a large number of  small deformable-mirror subapertures (within a single large telescope aperture) to generate a dark hole.

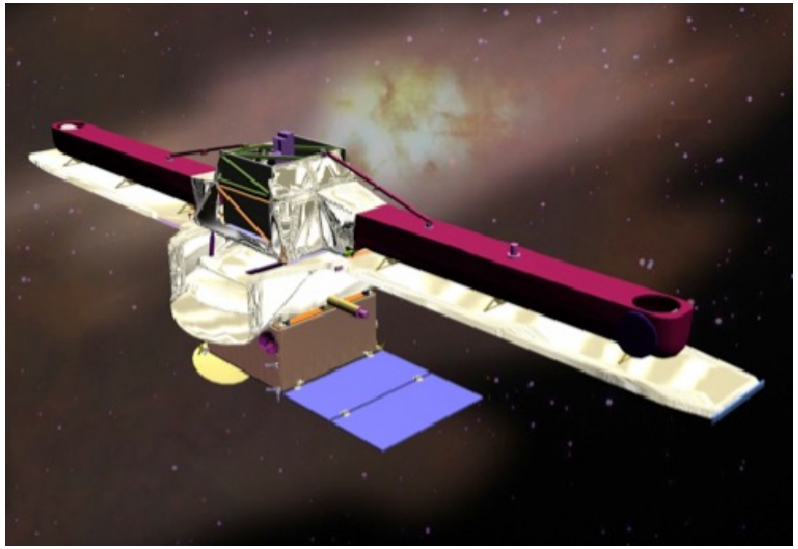
# Earlier nulling interferometry mission concepts (I): thermal-infrared; multiple, separated apertures



Darwin/Emma (Europe)



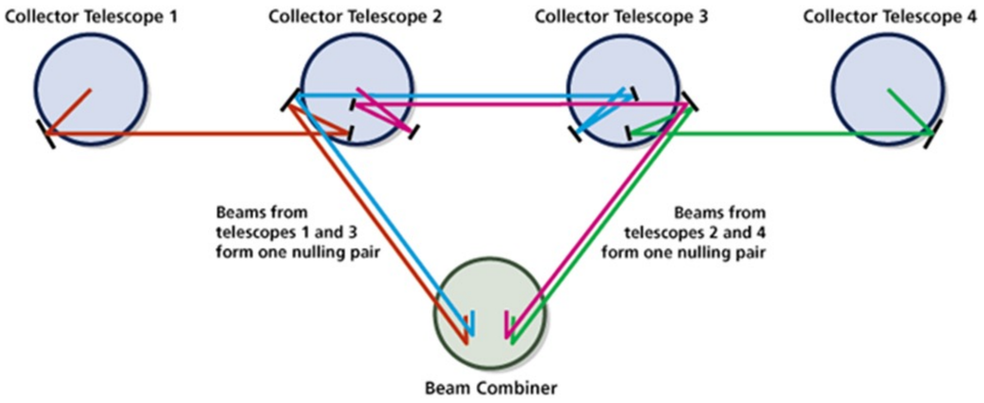
TPF-I (NASA)



simpler 2 telescope case: FKSI (Danchi et al.)

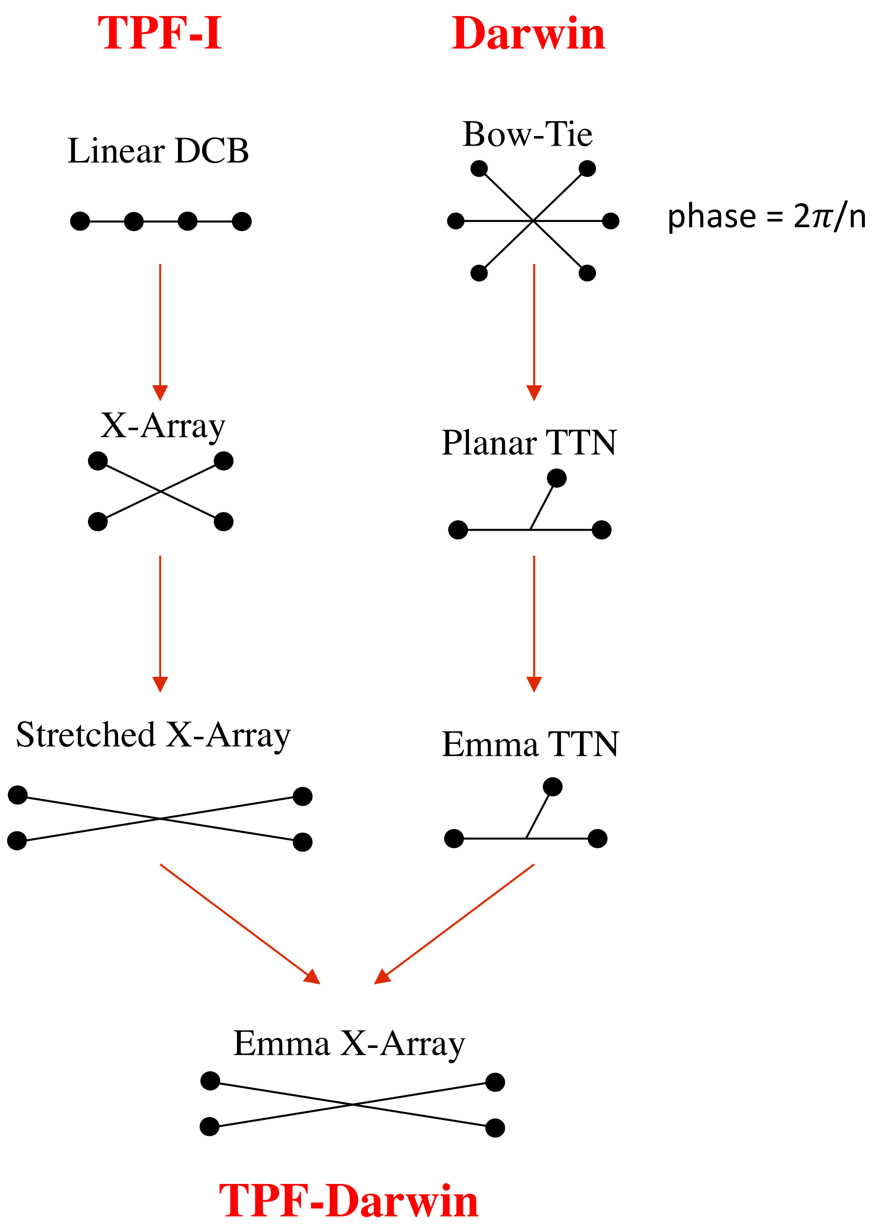
Beam combination and path-length matching:

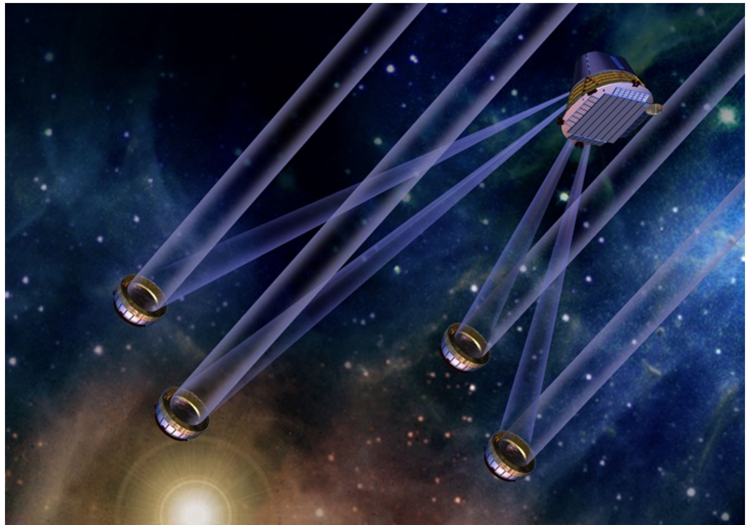
(1 & 3 pass through 2 before combining)



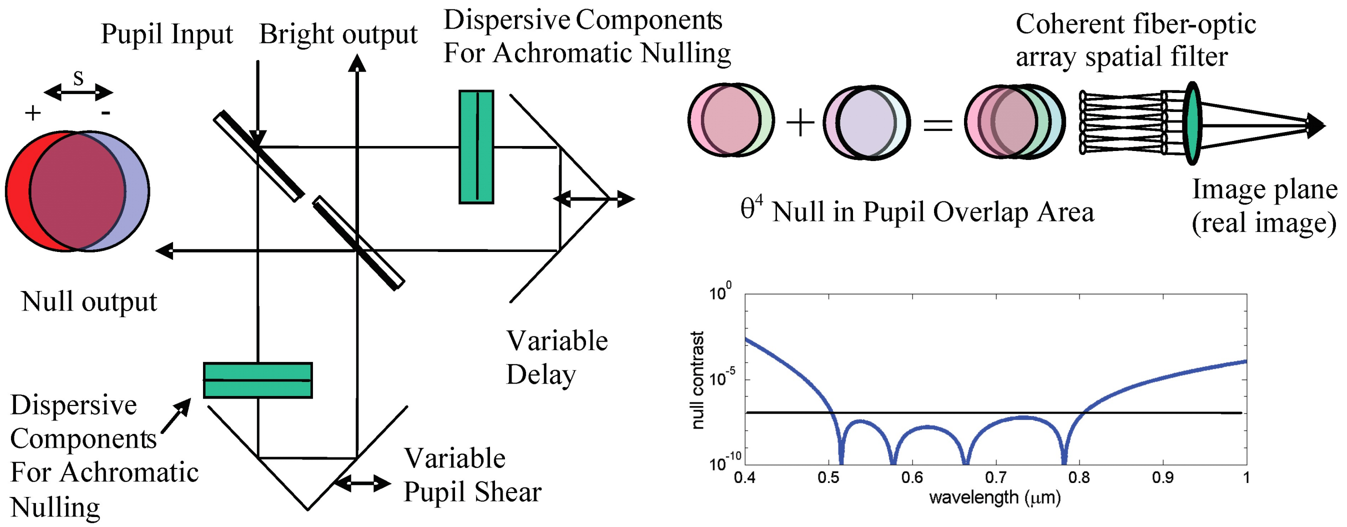
# Evolution and natural selection

evolving toward the best solution:

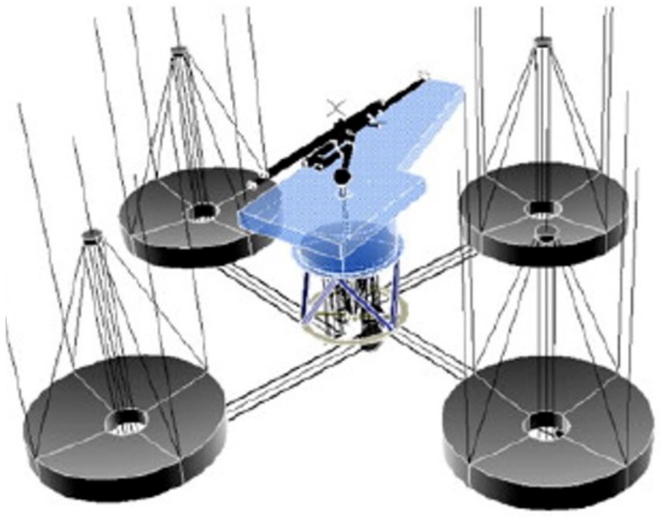


# Previous nulling interferometry mission concepts (II): Visible $\lambda$ allows single aperture approaches




Levine et al. 2003



DAVINCI

Woodruff et al. 2010

# Nulling systems & missions had/have two main flavors

- Mid-IR multi-aperture nulling: thermal exoplanet spectra (including terrestrial exoplanets)
  - long baselines needed for long wavelengths imply well-separated multiple apertures
  - cryogenic
  - potential space missions: TPF-I, Darwin, FKSI
  - ground-based systems deployed: Keck Interferometer, LBTI

- NIR/visible wavelength nulling: reflected-light exoplanets & very hot exoplanets
  - multiple subapertures within a single large telescope aperture
    (“sub-aperture” or “cross-aperture” nulling)
  - can reach smaller angles than a coronagraph on the same telescope
  - potential space missions: visible-light TPF, DAVINCI, Habex, LUVOIR
  - ground-based demo system: Palomar Fiber Nuller (PFN): two successive APRA awards to JPL
  - lab demo: Visible Nuller TDEM project at Goddard

- Both flavors of nulling are potentially useful to future NASA space missions

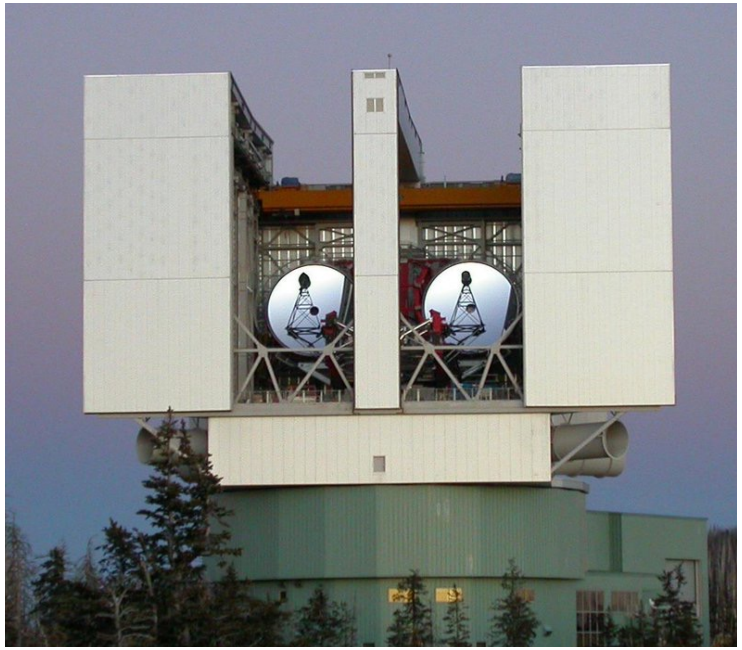
# Implementations (Lab & Sky)

- Lab Work in US and Europe aimed ultimately at TPF-I and Darwin (PDT at JPL)
- In the US, precursor on-sky observations of exozodiacal light:
  - BLINC, KIN, PFN, LBTI
    - Mostly in the MIR (N band = 10 microns)
    - Note: Europe also had an early on-sky interfero-coronagraph experiment
- PFN demonstrated on-sky nulling also feasible at $\lambda$s as short as the NIR

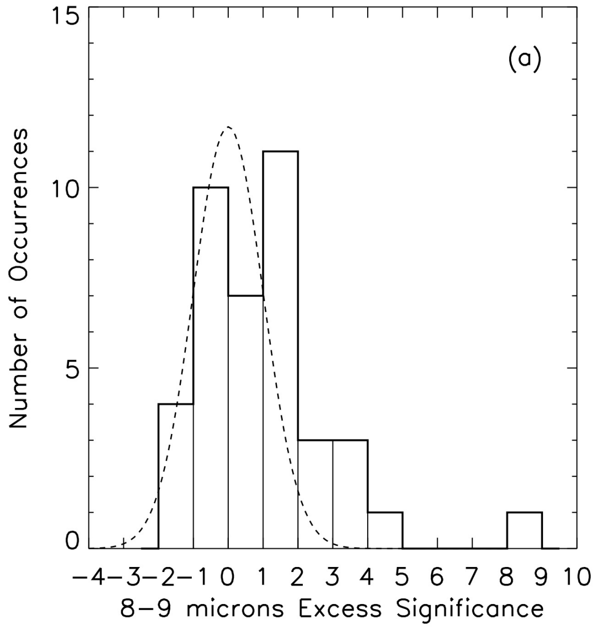
# The On-sky Mid-infrared Nullers: Exozodiacal Fluxes

Need to remove both the star and the thermal background flux

KIN: 4-subaperture, dual-chopped-nuller; somewhat similar to TPF-I



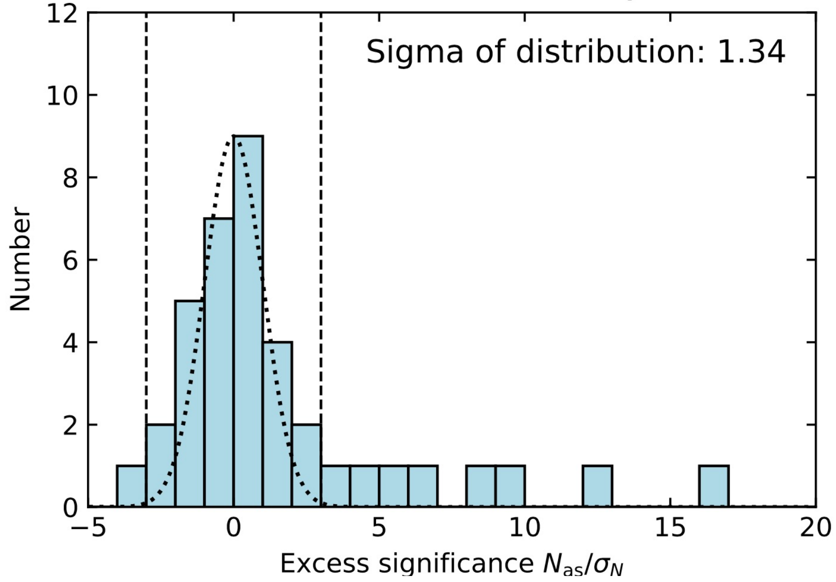
LBTI:
dual-aperture Bracewell nuller; spatial chopping




Menneson et al. 2014

limits set on
avg. exozodi level;

also
several detections




Ertel et al. 2020

# Near-IR: The Palomar Fiber Nuller

- Nulling has mostly been applied at long, i.e., MIR, wavelengths, because of the high phase stability needed
- The Palomar Fiber Nuller (PFN) was built to:
  - develop techniques to enable nulling at shorter wavelengths (NIR)
  - demonstrate the use of nulling baseline rotation to detect companions, as envisioned for space-based nullers
  - demonstrate on-sky the use of a single-mode (SM) fiber in beam-combination/nulling
  - demonstrate IWAs smaller than coronagraphs
  - look for hot inner dust

Succeeded in first four; inner dust seen in AB Aur, limits in Vega

several Martin et al., Mennesson et al. and Serabyn et al papers

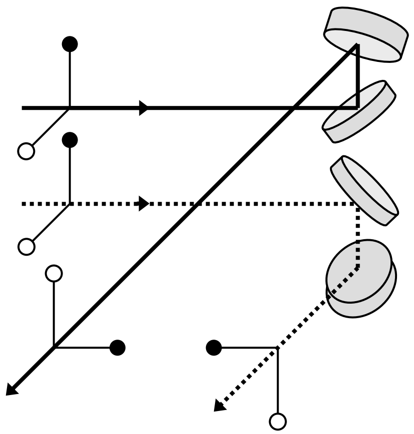
# Summary of Previous On-Sky Nulling Experiments

| | when | type | wavelength | baseline (m) | approx. IWA (mas) | ~ best nulls |
|---|---|---|---|---|---|---|
| • BLINC | (late 90s) | Cross-aperture | 10 $\mu$m | ~ 4 | 125 | |
| • KIN | (20-aughts) | Separated-ap | 10 $\mu$m | 85 | 6 | $10^{-3}$ |
| • PFN | (early 20-teens) | Cross-aperture | 2 $\mu$m | 3.5 | small baseline, but good IWA 33 | $3 \times 10^{-4}$ |
| • LBTI | (late 20-teens) | Separated-ap | 10 $\mu$m | 14.4 | 35 | $3 \times 10^{-4}$ |

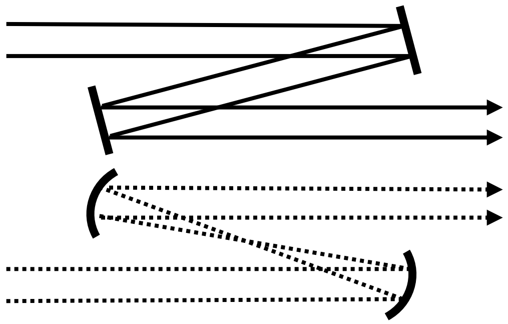
Note: the KIN and PFN contrasts are inside the central $\lambda$/D single-mode

# The Details: Nulling Subsystems

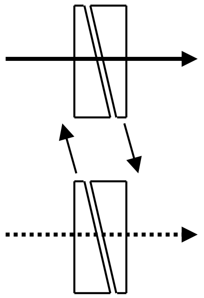
# Many ways to null achromatically (broadband) had been known or proposed



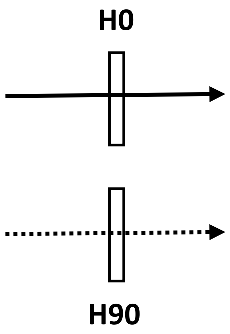
Field flip with Right Angle Periscopes



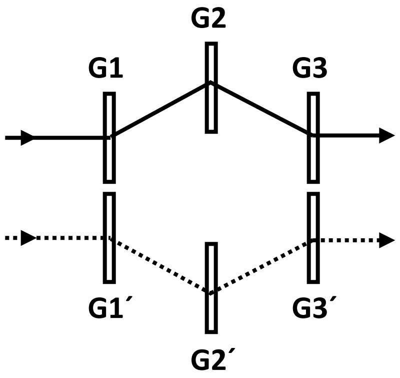
Gouy phase field flip



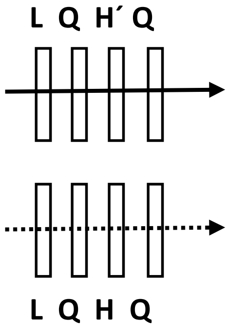
Dielectric Phase Shift




Half Wave Plate Phase shift




Lateral Grating Phase



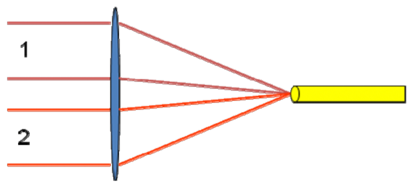

Pancharatnam Phase

Serabyn (2003)

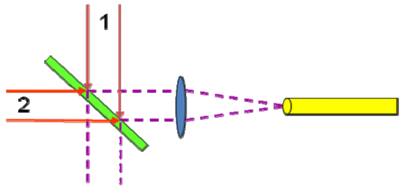
# Simplicity: the Fiber Nuller

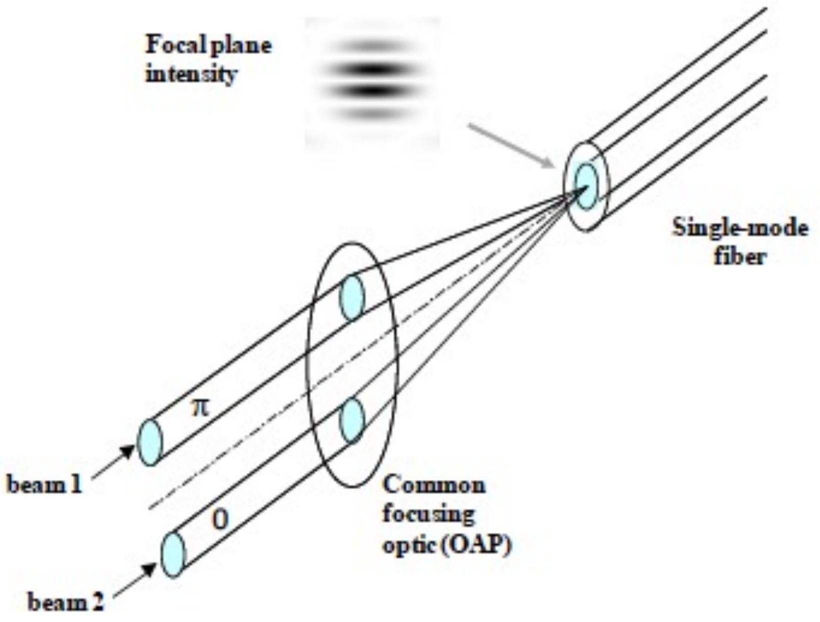
- Can use a single mode fiber as the actual beamcombiner (in addition to being a spatial filter)
- Multi-axial beam-combination (Fizeau combination)
- Just needs a phase shifter up front to make a nuller
- Achieved close to $10^{-6}$ visible nulls in the lab (Haguenauer & Serabyn 2006)
- Well-suited to cross-aperture nulling

multi-axial:

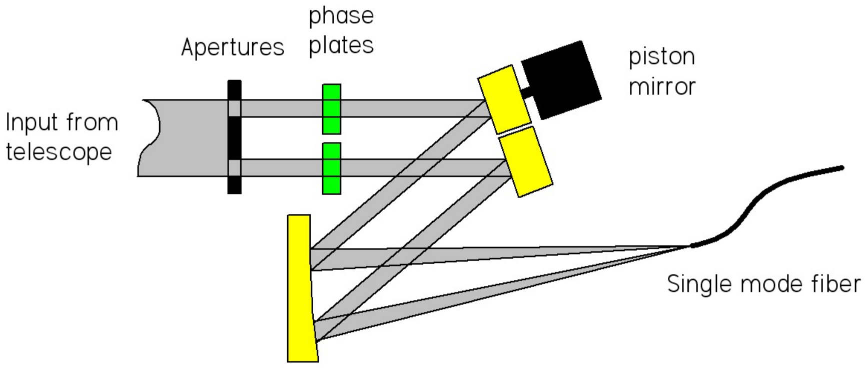



coaxial:




Wallner et al 2004; Haguenauer & Serabyn 2006




PFN implementation

Martin et al 2008

# Nulling Systems (Lab)

# JPL's Achromatic Nuller Testbed tested MIR nulling techniques

Gappinger et al. 2009

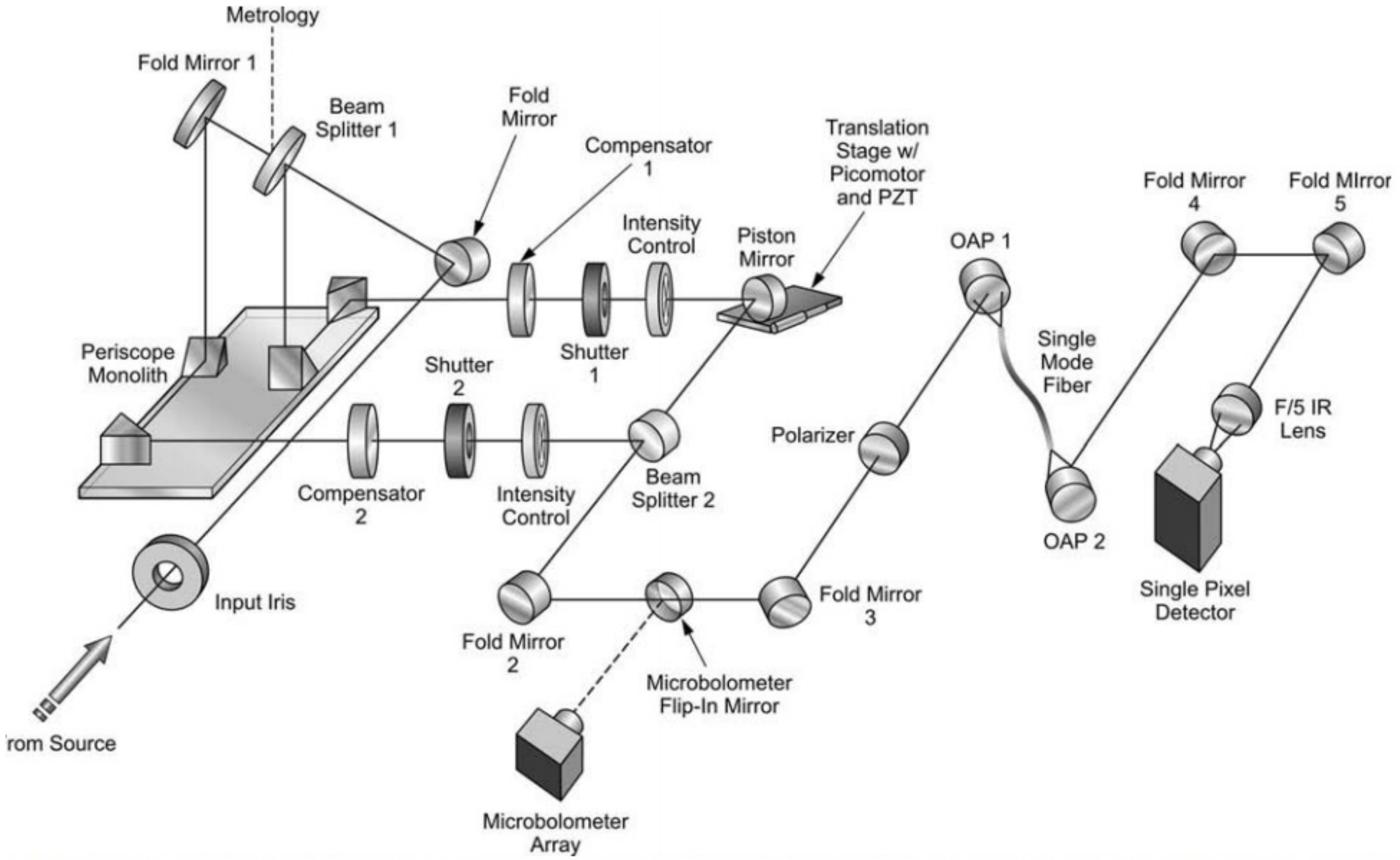
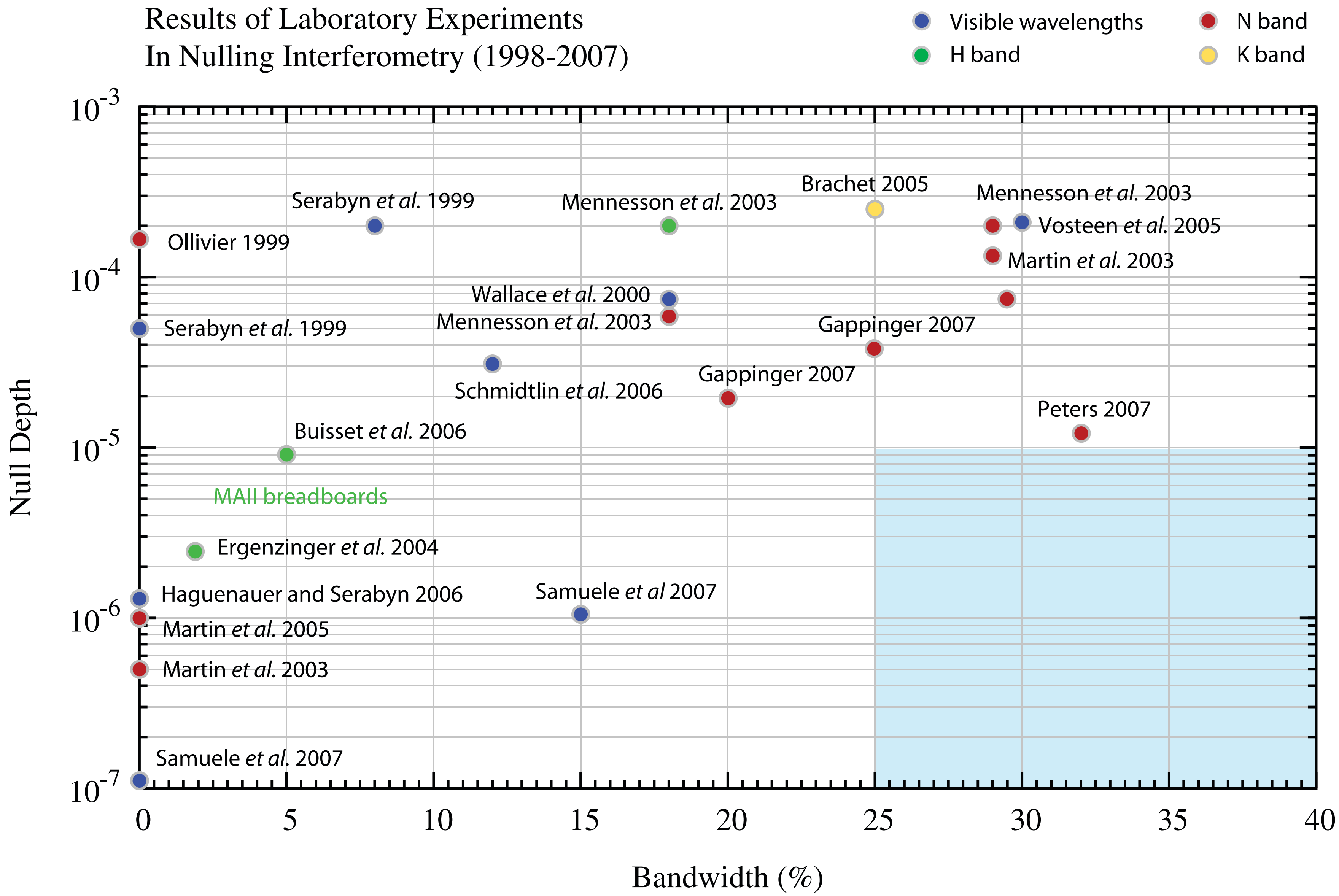



**Table 1. Experimental Results for Various Achromatic Nulling Testbed Architectures**

| Phase Delay Method | Nulling Bandwidth | Polarization | Null Depth (rms) |
|---|---|---|---|
| Single Glass | 30% | Dual | $8.8 \times 10^{-5}$ |
| Dual Glass | 30% | Dual | $9.1 \times 10^{-5}$ |
| Through Focus | 25% | Dual | $6.7 \times 10^{-4}$ |
| Periscope | Laser (10 μm) | Dual | $1.1 \times 10^{-5}$ |
| Periscope | Laser (10 μm) | Single | $3.3 \times 10^{-6}$ |
| Periscope | 20% | Single | $2.0 \times 10^{-5}$ |
| Periscope | 25% | Single | $4.0 \times 10^{-5}$ |

# Representative Summary of Lab Null Depths Achieved




bandwidth degrades nulls ➔ dispersed nulling necessary

Lawson et al. 2007

# Correcting Broadband Nulls in the presence of errors: the Adaptive Nuller

uses a deformable mirror (DM)to null (phase) each channel across a dispersed band (the spectrum is on the DM)

**Table 1. Comparison of Flight Requirements with Pre-Phase A Testbed Specifications and Actuals**

| Parameter | Flight Performance | Achromatic Nulling Tesbed[1,2] | Planet Detection Testbed | Adaptive Nuller[3] |
|---|---|---|---|---|
| **Null depth** | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ |
| **Amplitude control** | 0.13% | Derived | 0.12% | 0.2% (static) |
| **Phase control** | 1.5 nm | Derived | 2 nm | 5 nm (static) |
| **Stability timescale** | 50,000 s + | 21,600 s | 5,000 s | 21,600 s |
| **Bandwidth** | 7–17 µm | 25 % (8.3–10.7 µm) | $\lambda = 10.6$ µm | 30 % (8.2–11.6 µm) |

[1] The Milestone #3 criteria are listed here: mean null $\leq 1 \times 10^{-5}$, bandwidth $\geq$ 25% (with actual bandwidth of the testbed noted in parentheses), measurements to span $\geq$ 6-hour.

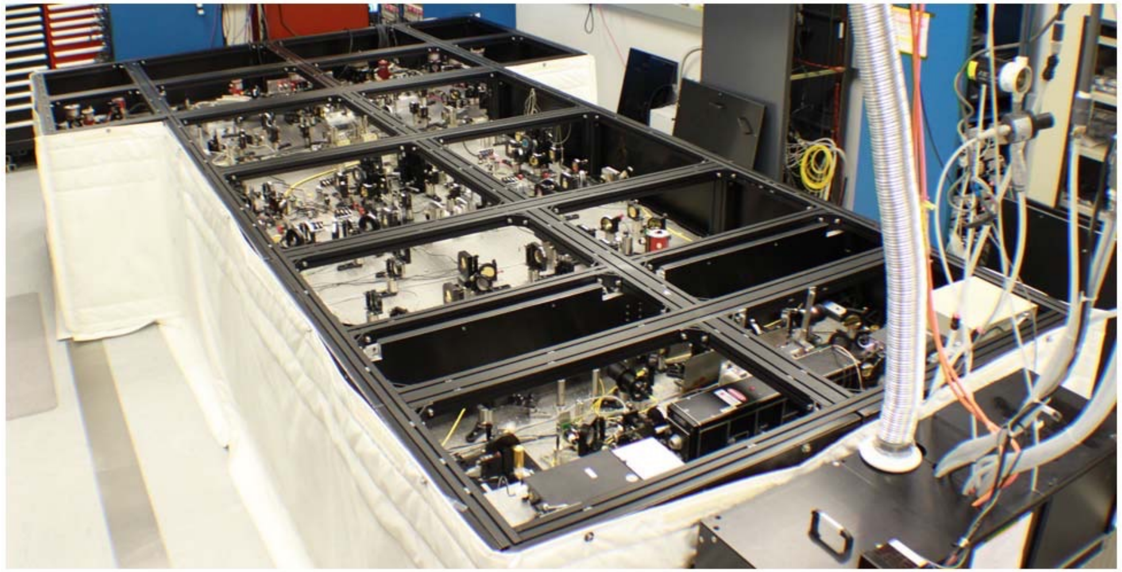
[2] The final results from the Achromatic Nulling Testbed are given in the paper by Gappinger et al. (2009).

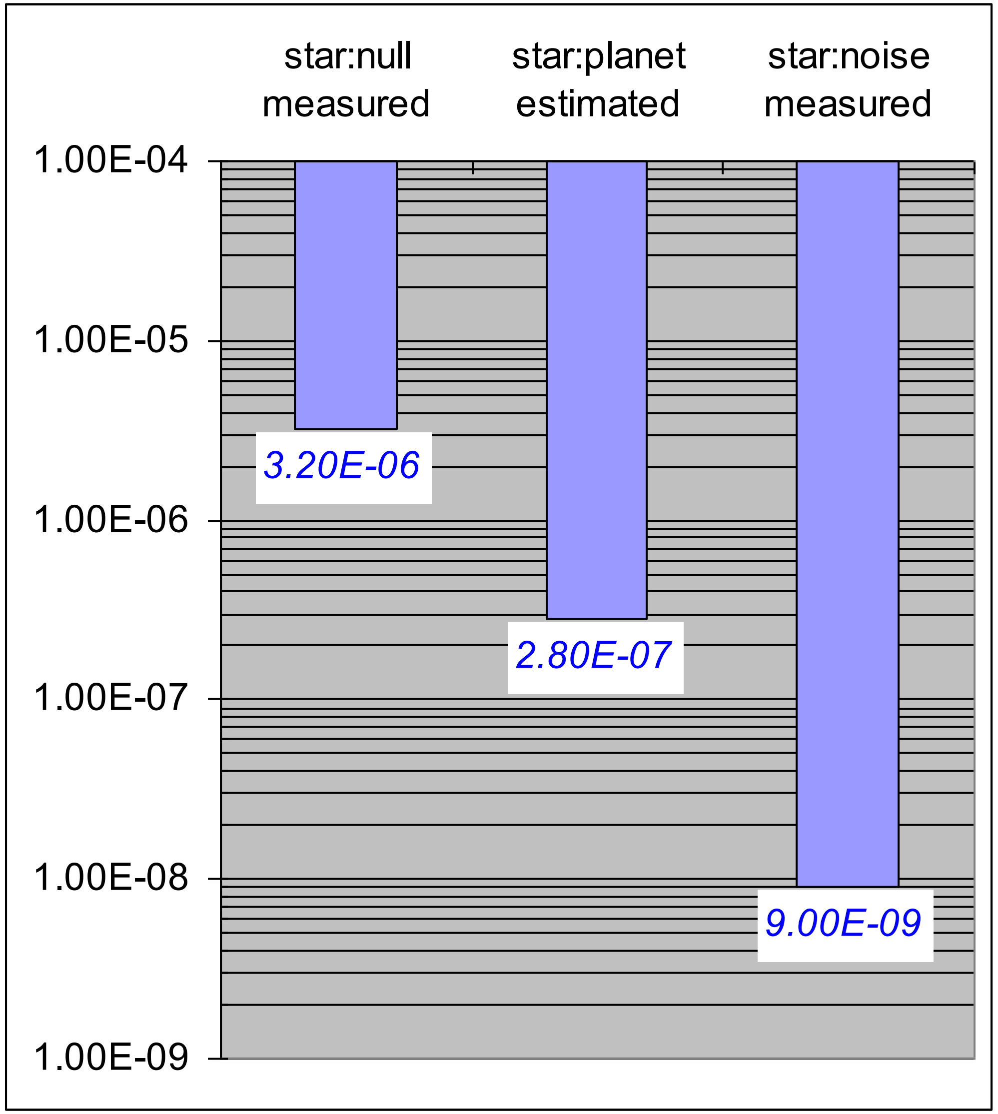
[3] The Milestone #1 criteria are listed here (with actual bandwidth noted in parentheses). Further details can be found in the paper by Peters et al. (2008). Note the specifications of the Adaptive Nuller are compatible with the Milestone #3 criteria.

Broadband Starlight Suppression Demonstration;
Exoplanet Interferometry Technology Milestone #3 Report;
Peters et al.

# Planet Detection Testbed (PDT) lab measurements

- $CO_2$ laser (Martin et al. 2010)
- Used 4 beam phase chopping nuller for the last factor of a few hundred



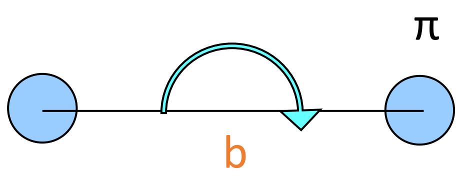



- As discussed below, NSC algorithm and GRAVITY instrument provide comparable level of “extra” rejection without hardware complexity

# On-sky nullers again

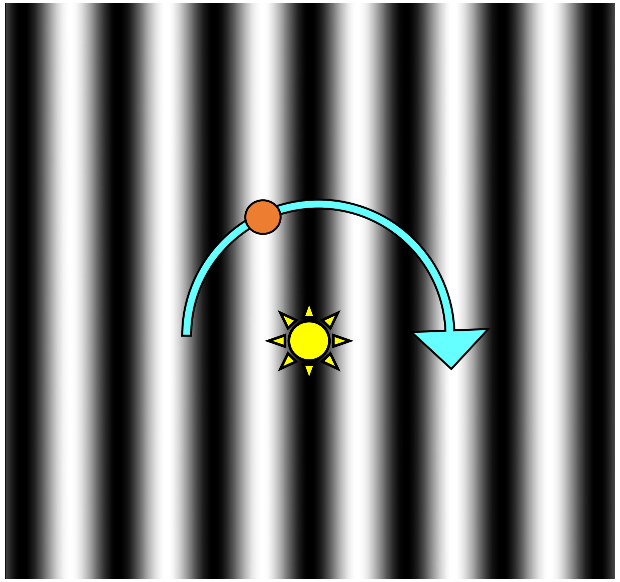
# The PFN: a Rotating Nulling Interferometer a la Bracewell

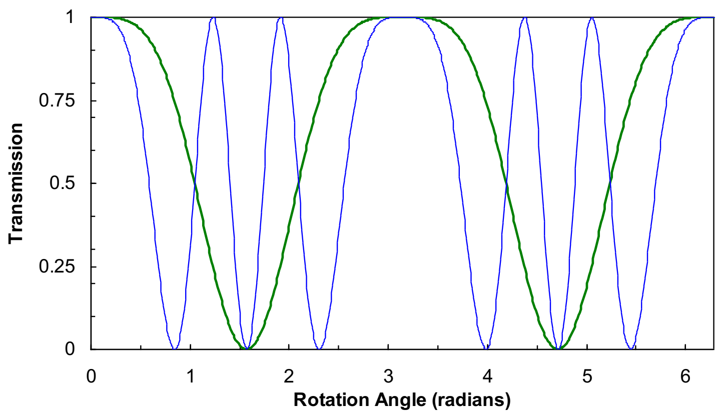
- Anti-phase a pair of apertures to center a dark interference fringe on a star
- Rotate baseline to modulate off-axis emission
- Deduce companion location from the modulation freqs. & phases

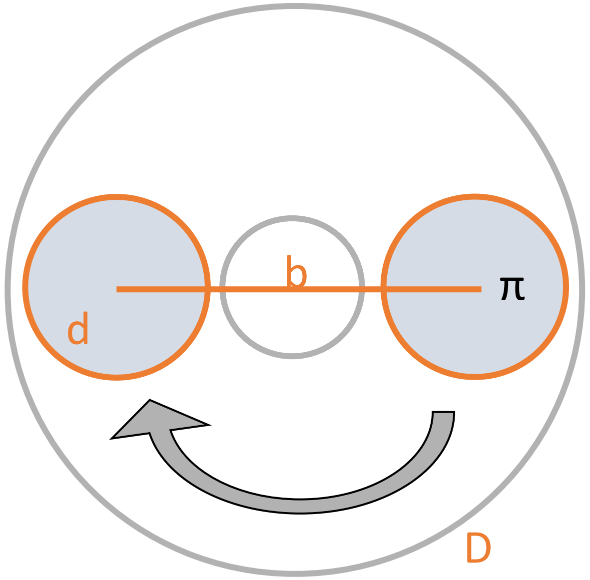



<u>Demonstrate it as a single aperture rotating nuller:</u>

- 2 subapertures within a large telescope aperture
- Rotating the pupil (K-mirror) rotates the baseline
- Use the AO system as the fringe tracker



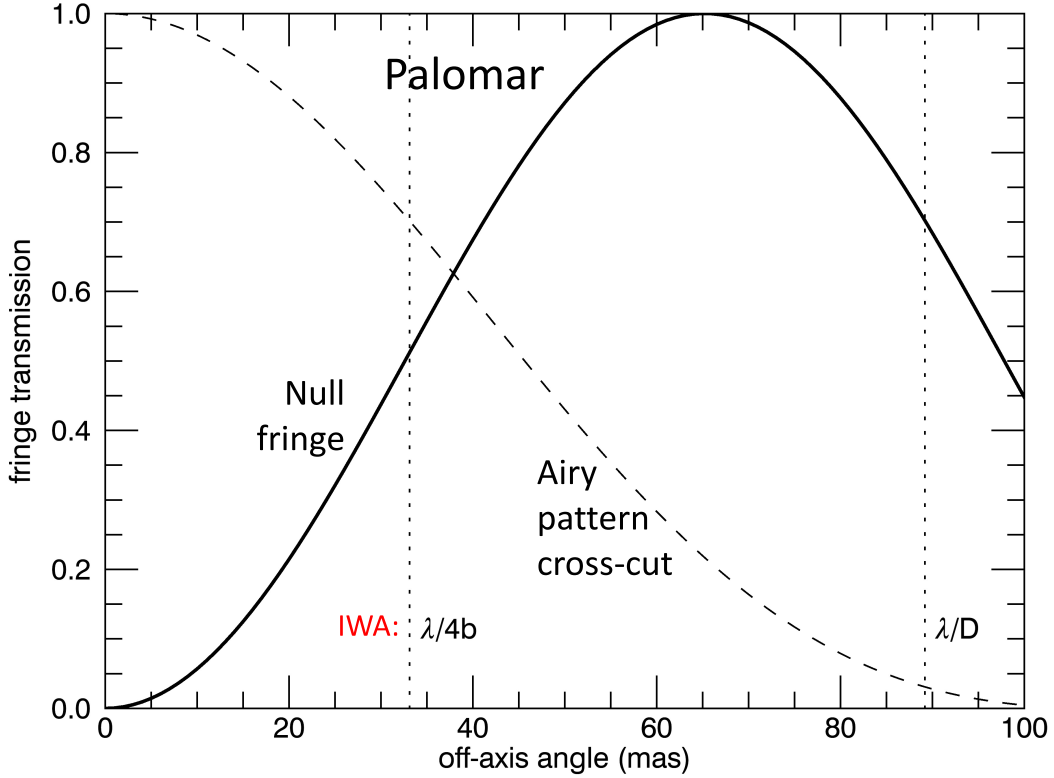


# A cross-aperture nuller is a very small-IWA coronagraph

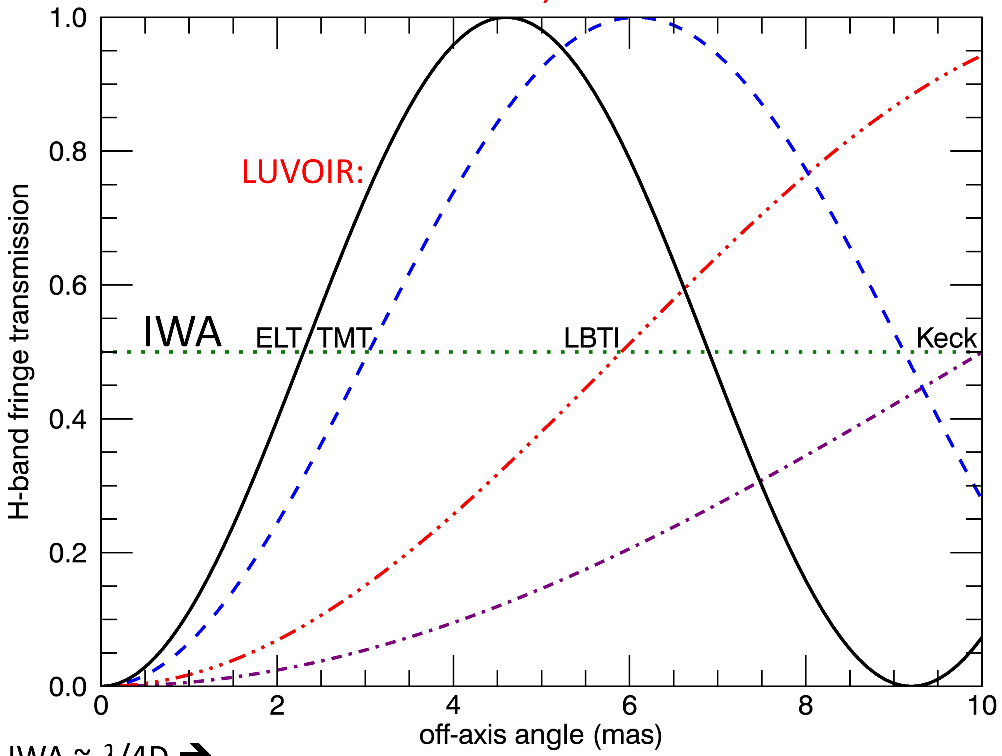
A cross-aperture single-baseline nuller has an IWA = $\lambda/4b$ ~ 1/4 - 1/3 $\lambda$/D

- can observe up to ~ an order of magnitude closer to stars than a full-ap coronagraph (IWA ~ 2 – 4 $\lambda$/D)
- But, high phase stability needed at short wavelengths




Serabyn, Mennesson, Martin 2020, SPIE

H-band for all but LUVOIR; LUVOIR at 0.56 microns




- IWA ~ $\lambda$/4D ➔

~ 2 – 4 mas on 30m telescopes (H & K)

~ 6 – 13 mas at Keck & LBTI (H & K)

~ 2 mas for LUVOIR in the visible: equivalent to ELT/TMT at H-band

<u>science:</u>

long term trend RV, refl light exopl, BDs, spec binaries, hot Jups, hot dust,

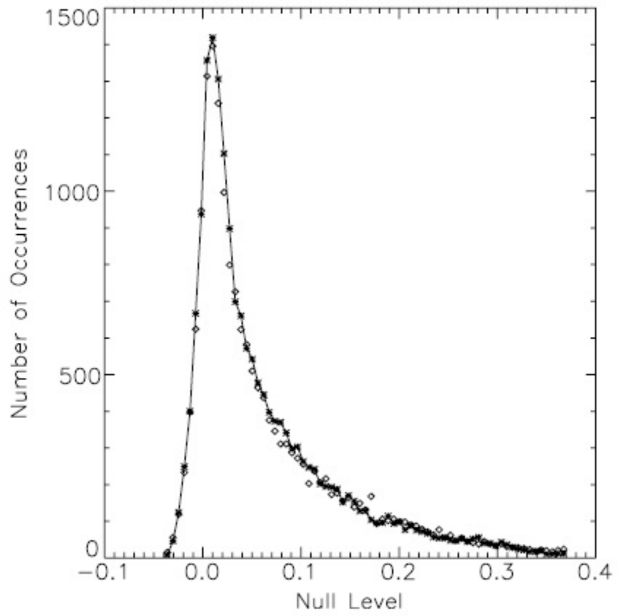
# Enabling nulling at short wavelengths:
# **The Null Self-Calibration Algorithm**

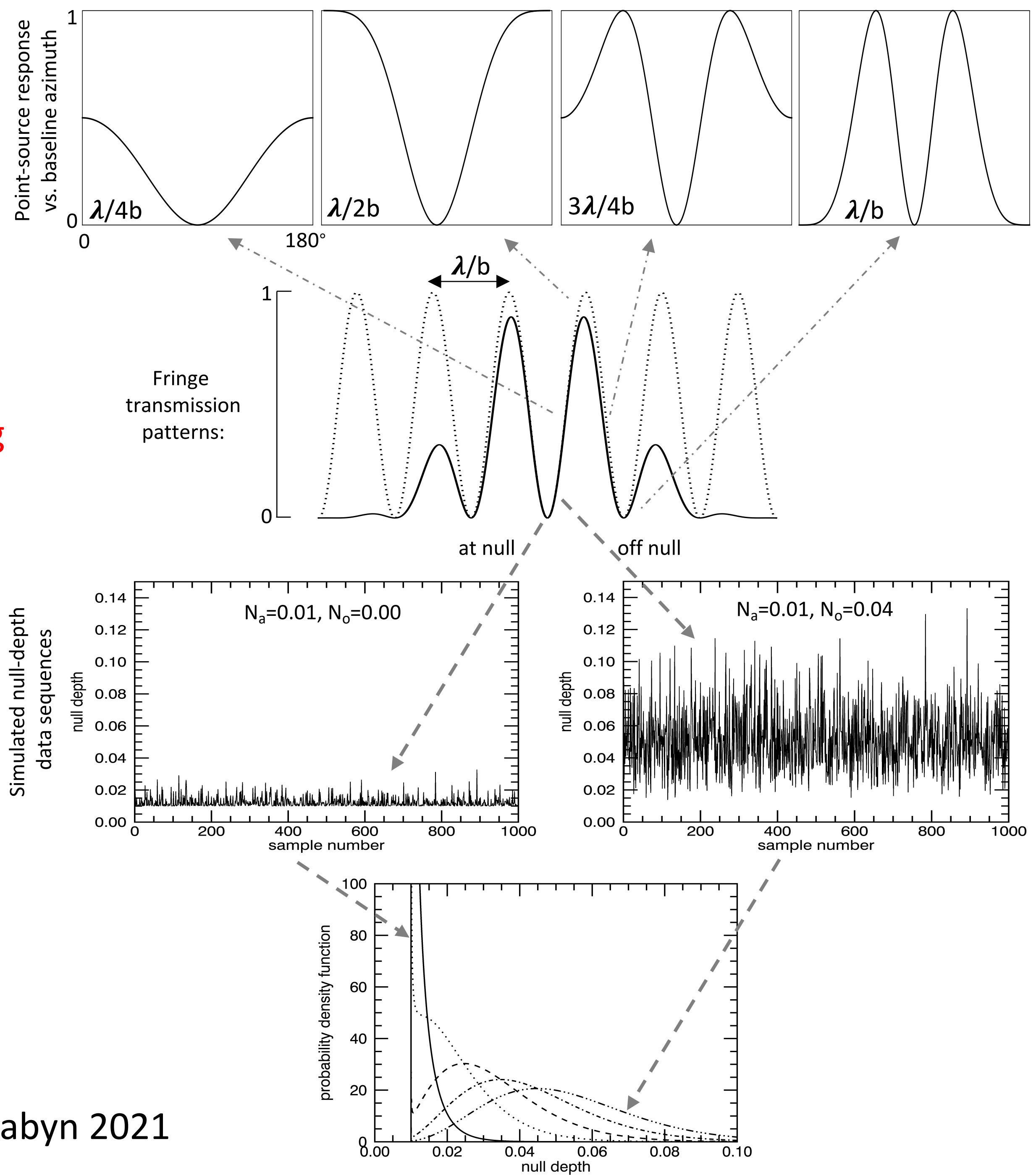
- The null-depth depends quadratically on phase:

  ➔ the fluctuation spectrum can be used to extract the astrophysical null depth in the presence of imperfect phase

- i.e., fit the observed phase fluctuation spectrum to extract the true astrophysical null depth
- Relaxes phase-stabilization requirement by up to 2 orders of mag
  - Adaptive optics is the only “fringe tracker” needed
  - Don’t need a high-accuracy fringe tracker

Vega:



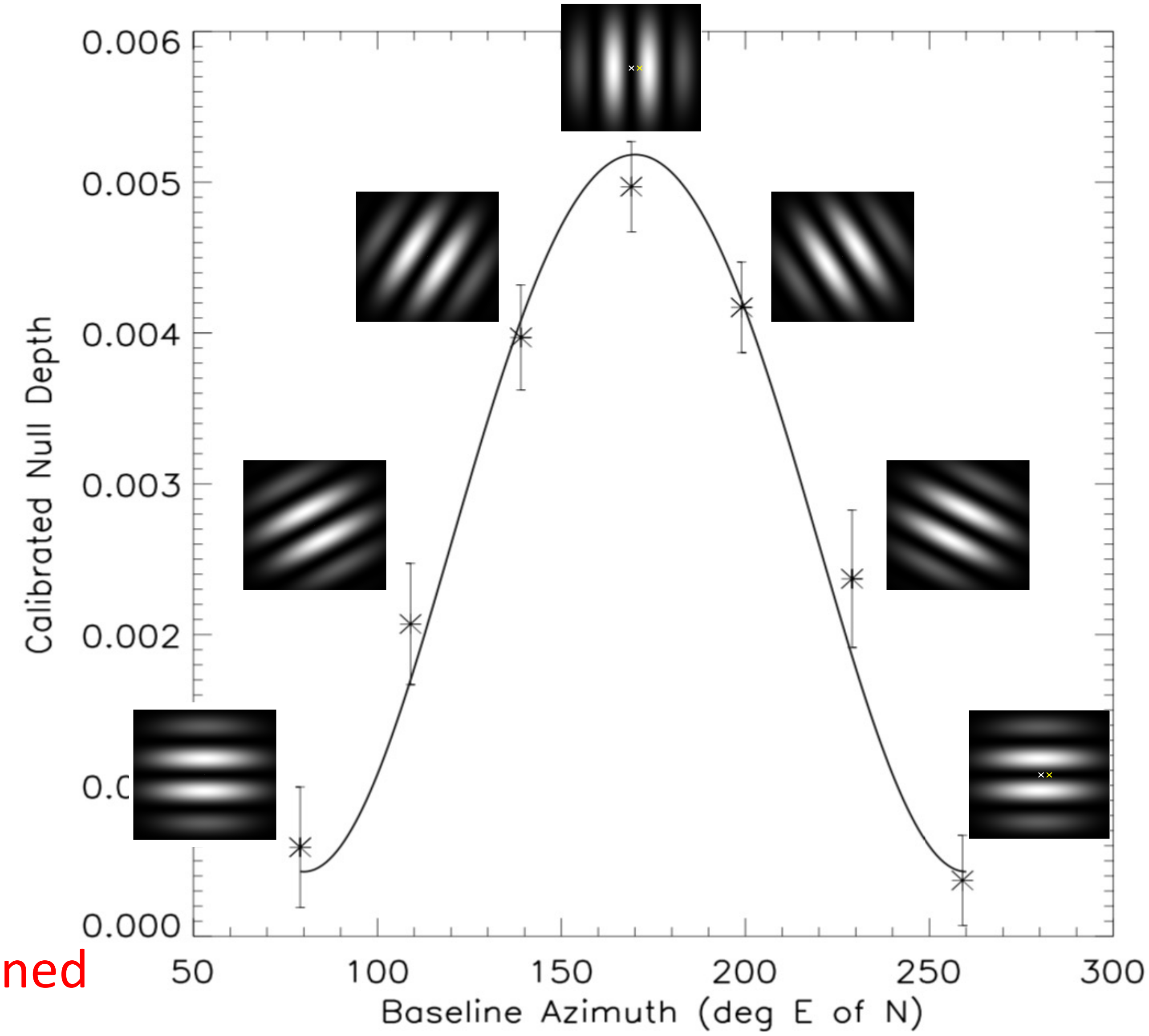

Hanot et al. 2011; Mennesson et al. 2011; Serabyn et al. 2019; Serabyn 2021

# How well does it work? Companion detection w. PFN ($K_s$): the η Peg spectroscopic binary

- Full null-depth rotation curve measured (180° baseline rotation using K-mirror)
- Detected sec. star 1% of primary flux at ~$\lambda$/3D
- 5 x $10^{-4}$ offset at the bottom of rotation curve gives primary star diameter
- Null depth errors ~ 3 x $10^{-4}$

➔ on-sky NIR nulling clearly feasible

➔ First demo of companion detection using baseline rotation as Bracewell and TPF envisioned




Serabyn et al. MNRAS 2019 & OPN 2019

# LBTI: Background Estimation (9.8 to 12.4 um):

- Large thermal background at LBTI (~ the detected flux of a 100 Jy star)
  - Measured thermal background (and detector time-variable mean bias) reaches a relative accuracy (over 90 min) of $3 \times 10^{-6}$ (Mennesson et al. 2016, SPIE), by using:
    - Background subtraction from off-source detector region
    - Periodic telescope nodding to measure offset between the two regions
- For a space mission with 40K telescopes, the thermal background is many orders of magnitude lower, making a $3 \times 10^{-6}$ relative estimation error completely negligible
  - Quiet MIR detectors then become very important:
    - Fluctuations of the detector output bias signal (such as the low frequency drift seen in the Aquarius detector) will NOT reduce when going to space and may still be an issue
    - Accurate characterization of mid-IR detector spatial-temporal drifts, or better detectors, will be required for future missions, as well as the development of mitigation strategies

# Astrophysical null estimation at LBTI (9.8 to 12.4 um):

- NSC algorithm also allowed LBTI to reach null depth accuracies ~ 3 x $10^{-4}$ (1-sigma) (Ertel et al. 2020)
- Similar accuracy with (PFN) or without (LBTI) SM fiber so far (but different wavelengths)
- Performance limited mostly by detectors, thermal background and atmospheric dispersion:
    - Background (and detector bias) estimation errors & background photon noise
    - Residual errors in NSC (non single-mode behavior, non gaussian OPD, inaccurate estimate of phase jitter within single integration)
    - Any time variability of the intra band dispersion from calibrator to target
        - LBTI mount implies no longitudinal dispersion, but there might be differential time-variable effects between water vapor columns above each aperture

- Key potential improvements to LBTI MIR nulling:
    - MIR Detector with reduced low-frequency detector-bias fluctuations vs space and time
    - MIR Detector with lower read noise to allow shorter integrations and spectrally dispersed measurements, helping reduce finite spectral bandwidth and finite integration effects
    - LBTI measurements might be improvable by a factor of 2 to 3 before reaching the background-limited photon noise limit

# Comparison of past on-sky nullers

| | KIN | LBTI | PFN |
|---|---|---|---|
| Separate telescopes? | Yes | Yes | No |
| Number of beams | 4 | 2 | 2 |
| Common telescope mount? | No | Yes | Yes |
| Interferometric mode | Michelson | Michelson | Fizeau |
| Baseline rotation? | Earth rotation | Earth rotation | Unrestricted baseline rotation |
| Long Delay lines? | Yes | No | No |
| Waveband | MIR N-band | MIR N-band | NIR $K_s$-band |
| Fringe tracking | Shorter (NIR) wavelengths | Shorter (NIR) wavelengths | Extreme (VIS) AO system |
| Modulation | Phase scan | Spatial nodding | Chopper wheel |
| Calibration | Reference stars | Reference stars | Reference stars only needed below ~ $10^{-3}$ |
| Beam combiner geometry | Co-axial | Co-axial | Multi-axial |
| Beam combining element | Dual beamsplitter | Single beamsplitter | Single-mode fiber |
| Dispersion compensator | Glass | Glass | Glass |
| Dispersion compensator phase shift | $\pi$ | $\pi/2$ | $\pi$ |
| Disp. comp. glass shape | Wedges | Flat | Chevron |
| Glass thickness modulation | Translation | Static | Rotation |
| Spatial filtering | Pinhole | Aperture photometry | Single-mode fiber |
| Number of spectral channels | ~ 10 | 1 | 1 |
| Data product | Fringe scan intensities | Images | Single-mode intensity measurements |
| Data reduction | Visibility determination | Null self-calibration | Null self-calibration |
| Dominant noise terms | Thermal background | Thermal background & low frequency detector noise | Phase jitter within single exposures and variable dispersion effects |

Serabyn, Mennesson, Martin; 2020 SPIE

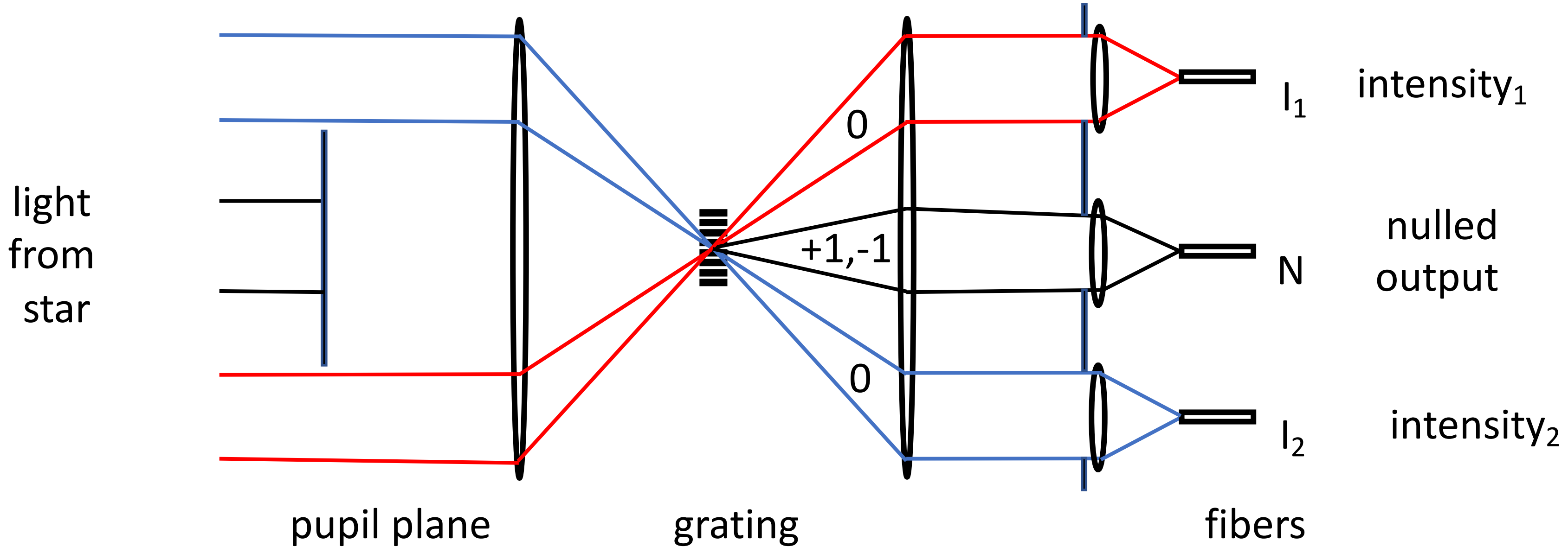
# Lessons learned from Past Nulling Experiments

(Serabyn, Mennesson & Martin SPIE 2020)

1. Important to match interferometric baseline length to the science desired (no choice at KI or Palomar)
2. Slow telescope nodding OK to remove background fluctuations at required level (every 1-2 minutes at LBTI)
3. A common mount (sub-ap nulling) eliminates a few issues (symmetry easy; no long DL or long. dispersion)
4. Minimize number of warm reflections
5. Inherently achromatic nuller most valuable for space (atmosphere dominates on ground systems)
6. Simplicity is good, if and when possible: e.g. 2 beams; single beamsplitter or fiber combiner (no beamsplitter)
7. Modal filtering is potentially less important that previously assessed; still open
   - Situation has changed b/c of active WFC in space – high Strehls
   - Trade between DM (WFC complexity and larger FOV) vs. SM fiber (throughput and FOV losses)
8. Stability over-rated! Phase control accuracy (and mean null depth) are determined by the need to reduce starlight photon noise below other noise contributors (exozodi, solar zodi), not by the planet to star flux ratio
9. NSC takes care of the calibration of phase & intensity fluctuations, allowing the removal of null instability noise (so far for a 2 beam nuller).
10. Much easier to null at short wavelengths than thought
11. “Better” MIR detectors required for space:
    - lower low frequency drift & read noise to allow shorter integrations & background limited spectral dispersion
12. NSC allows simultaneous nulling across a spectrally dispersed band
13. Coaxial nullers seem to reach deeper nulls than multi-axial nullers

# Potential Future Steps: The Grating Nuller

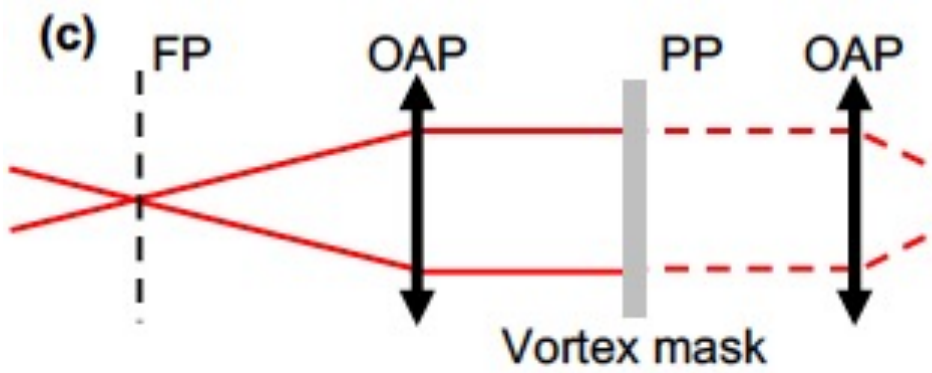
- A grating can by itself serve as the beam combiner, phase shifter and baseline rotator
  - Grating can combine +1 and -1 orders from opposite sides of the aperture
  - Shifting grating laterally provides phase shifting
  - Rotating the grating rotates the baseline
- Baseline scales with wavelength (for small angles), yielding achromatic on-sky fringes
- Coaxial beamcombiner worked better than PFN multi-axial b.c. by about a factor of 10

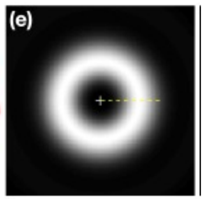



Martin et al. (2017)

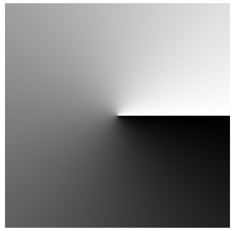
# Future Steps: The Vortex Fiber Nuller

- Uses continuous phase wrap around 1 aperture instead of fixed phase shift between 2 subapertures
- IWA intermediate between single-baseline nulling and coronagraphy; bridges the two techniques
- Angular discrimination possible with polarizers
- To go on sky at Keck in Nov. 2021 (Mawet group)



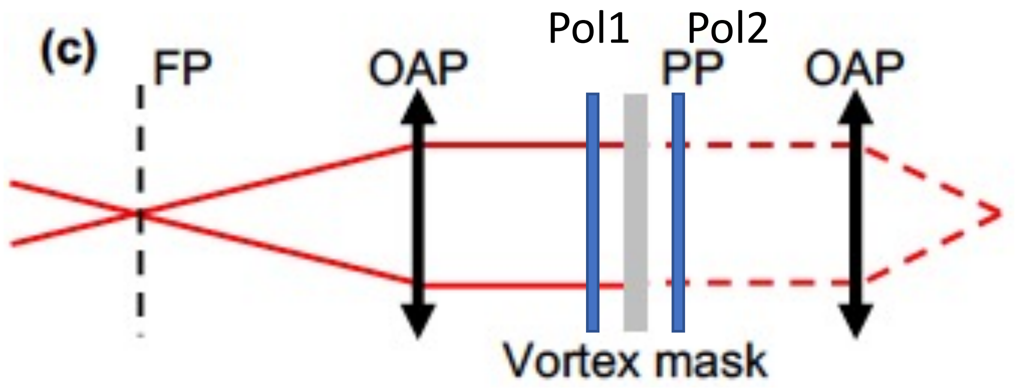




Ruane et al. 2019

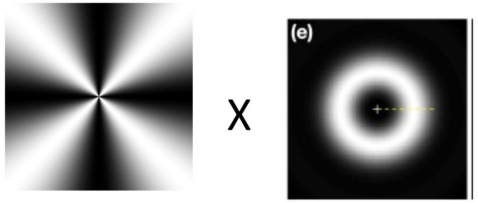


continuous vortex phase

stellar output intensity does not couple to SM fiber



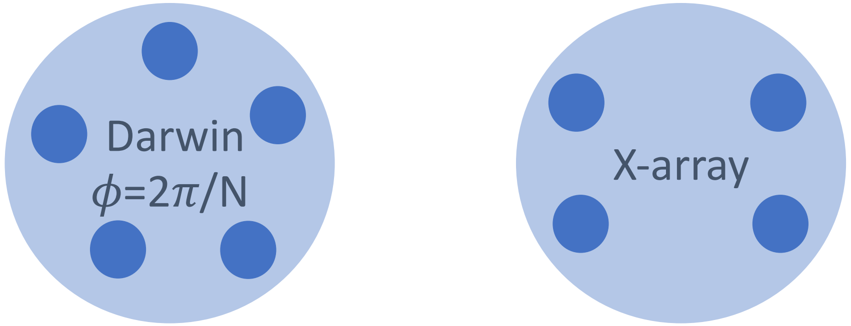

Angular response is the product of the two terms




Serabyn et al. 2020

# Sub-aperture nulling can enable multi-aperture nulling on large telescopes such as TMT and LUVOIR

- Stellar rejection degrades with longer nulling baselines
  - null depth proportional to $b^2$
- For deeper starlight rejection on large telescopes, can use higher order nulling or phase chopping
  - Both require more than two subapertures
  - More complex beamcombiners unless multi-axial b.c.




- More complex beamcombiners (e.g., on TMT/ELT/Habex/LUVOIR) are much easier/cheaper than multiple telescopes in space, such as TPF-I and Darwin

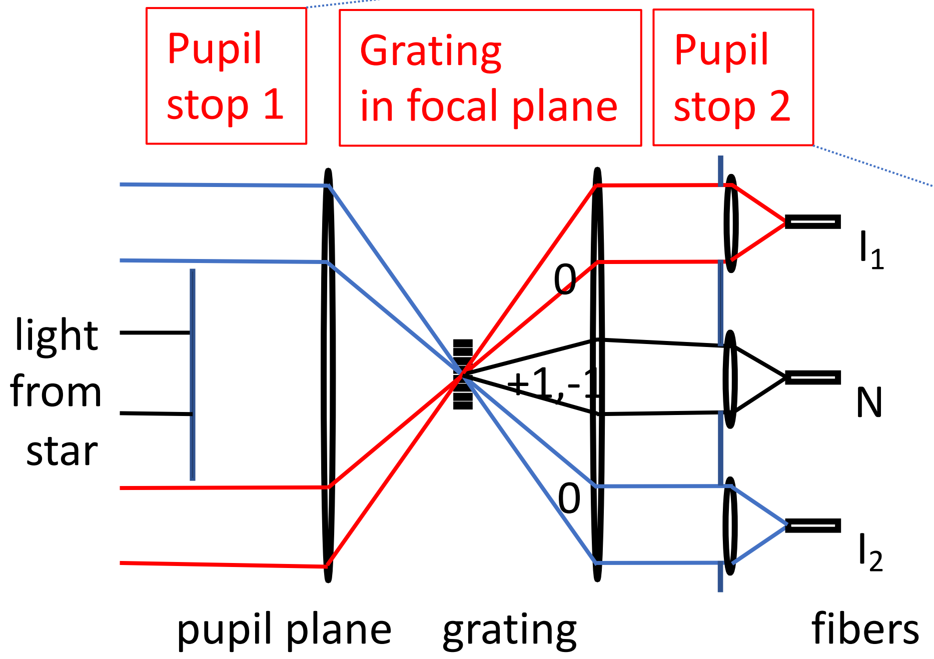
➔For smaller IWA, should consider a visible nuller or vortex nuller on Habex/LUVOIR (NIR for TMT)

(Note: A vortex nuller is the smooth limit of the Darwin or Angel-cross “stepped phase around a circle” approach)

# Implementing Future Nullers Easily:
# Future Nullers can be Subsumed into Coronagraphic Benches

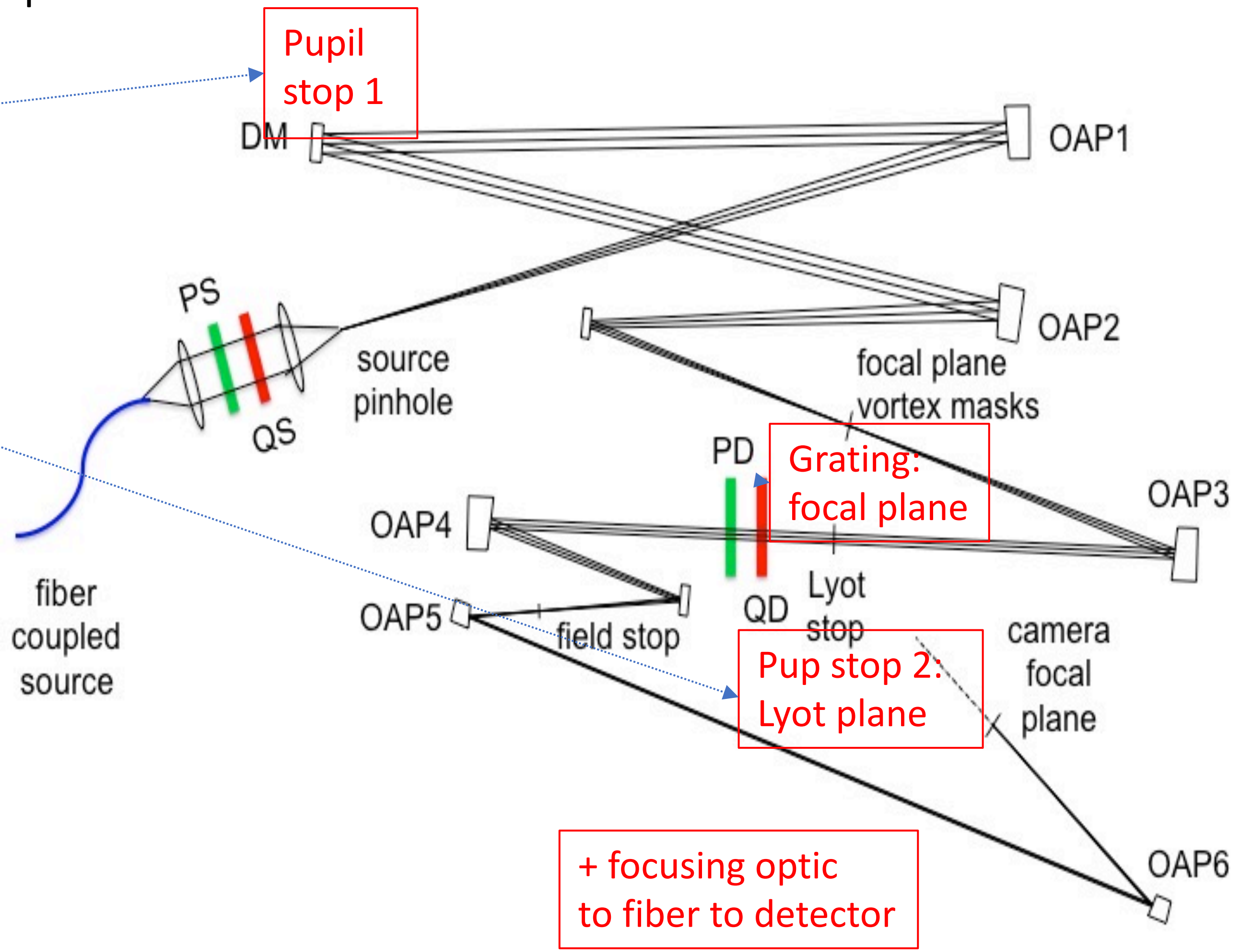
- Nullers can be implemented on coronagraphic benches:
- i.e., insert "nulling masks" into coron. focal plane and pupil plane

## Grating nuller layout:




Serabyn et al. 2020

## Coronagraph layout:



# Potential Future Steps: Dispersed Nulling

- Dispersed Nulling:
  - Null several spectral channels across the observation band simultaneously
  - Use null self-calibration algorithm (instead of adaptive nulling) to remove phase offsets from null in each channel
  - Can provide spectra of companions and dust
- The ideal nulling system would combine PFN (nulling at angles $<\lambda/D$ using NSC) and GRAVITY (dispersion) attributes
  - i.e., dispersed nulling within the stellar point spread function core

| | **GRAVITY @ VLTI** | **PFN** | **Ideal** |
|---|---|---|---|
| Spatial | $> \lambda/D$ | $< \lambda/D$ | $< \lambda/D$ |
| Spectral | Dispersed interferometry | Single channel | Dispersed interferometry |
| Stellar rejection | Spatially off the star | Stellar nulling | Stellar nulling |

# ESO GRAVITY: not a nuller (yet) but very impressive results

*No existing coronagraph can detect beta pic c.*
*First direct detection of an exoplanet previously detected by RV !!*

A&A 642, L2 (2020)
https://doi.org/10.1051/0004-6361/202039039


Astronomy & Astrophysics

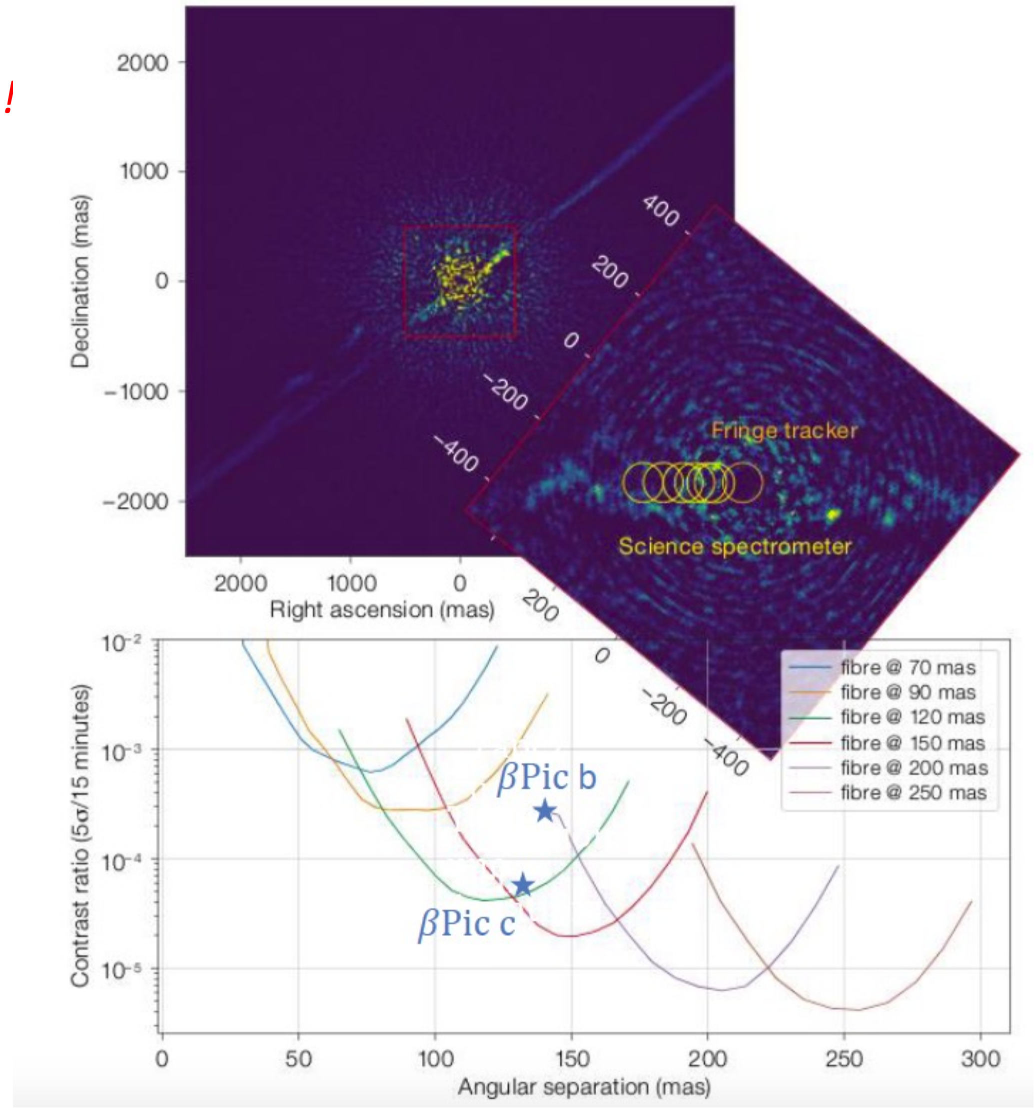
Letter to the Editor

## Direct confirmation of the radial-velocity planet $\beta$ Pictoris c

M. Nowak[1,2], S. Lacour[3,7], A.-M. Lagrange[4], P. Rubini[24], J. Wang[10], T. Stolker[27], R. Abuter[7], A. Amorim[16,17], R. Asensio-Torres[6], M. Bauböck[5], M. Benisty[4], J. P. Berger[4], H. Beust[4], S. Blunt[10], A. Boccaletti[3], M. Bonnefoy[4], H. Bonnet[7], W. Brandner[6], F. Cantalloube[6], B. Charnay[3], E. Choquet[9], V. Christiaens[13], Y. Clénet[3], V. Coudé du Foresto[3], A. Cridland[18], P. T. de Zeeuw[18,5], R. Dembet[7], J. Dexter[5], A. Drescher[5], G. Duvert[4], A. Eckart[15,21], F. Eisenhauer[5], F. Gao[5], P. Garcia[17,28], R. Garcia Lopez[19,6], T. Gardner[12], E. Gendron[3], R. Genzel[5], S. Gillessen[5], J. Girard[11], A. Grandjean[4], X. Haubois[8], G. Heißel[3], T. Henning[6], S. Hinkley[26], S. Hippler[6], M. Horrobin[15], M. Houllé[9], Z. Hubert[4], A. Jiménez-Rosales[5], L. Jocou[4], J. Kammerer[7,25], P. Kervella[3], M. Keppler[6], L. Kreidberg[6,23], M. Kulikauskas[20], V. Lapeyrère[3], J.-B. Le Bouquin[4], P. Léna[3], A. Mérand[7], A.-L. Maire[22,6], P. Mollière[6], J. D. Monnier[12], D. Mouillet[4], A. Müller[6], E. Nasedkin[6], T. Ott[5], G. Otten[9], T. Paumard[3], C. Paladini[8], K. Perraut[4], G. Perrin[3], L. Pueyo[11], O. Pfuhl[7], J. Rameau[4], L. Rodet[14], G. Rodríguez-Coira[3], G. Rousset[3], S. Scheithauer[6], J. Shangguan[5], J. Stadler[5], O. Straub[5], C. Straubmeier[15], E. Sturm[5], L. J. Tacconi[5], E. F. van Dishoeck[18,5], A. Vigan[9], F. Vincent[3], S. D. von Fellenberg[5], K. Ward-Duong[29], F. Widmann[5], E. Wieprecht[5], E. Wiezorrek[5], J. Woillez[7], and the GRAVITY Collaboration

*(Affiliations can be found after the references)*

Received 27 July 2020 / Accepted 26 August 2020




A very large team working on interferometry in Europe!



Bet Pic c is directly detected at a < $10^{-4}$ flux ratio at only 130 mas from the star !

# GRAVITY Exoplanet Observations: Lessons Learned

- VLTI Gravity exoplanet observations are based on dual-field interferometry:
  (pioneered long ago by JPL at PTI & Keck)
  - Planet is off-axis by more than a diffraction beam width (2.3 lam/D for beta Pic c)
  - The planet signal is interferometrically modulated vs wavelength (& baseline)
  - Really a photometric observation taking advantage of off-axis starlight reduction and the high frequency modulation of the planet signal
- Like the PFN, GRAVITY can detect companions 1% of the residual starlight signal
  - GRAVITY beta pic c is ~ 1% of the residual starlight (~ 1%) at its location
  - PFN mean null ~ 10%; but can detect to .05%
- Plans for GRAVITY+
  - Improve throughput (MPIA working on it)
  - Nulling !!! (proposals: Mennesson XRP 2020, 2021; Nowak MPIA proposal)
  - Apply NSC technique to spectrally dispersed data
  - Extend to on-axis observations, accessing the small angles where exoplanets actually are

# Comparison of Nullers & GRAVITY

Gravity not a nuller; looks outside lambda/D

| | KIN | LBTI | PFN | GRAVITY |
|---|---|---|---|---|
| Separate telescopes? | Yes | Yes | No | Yes |
| Number of beams | 4 | 2 | 2 | 4 |
| Common telescope mount? | No | Yes | Yes | No |
| Interferometric mode | Michelson | Michelson | Fizeau | Michelson, in Dual Field |
| Baseline rotation? | Earth rotation | Earth rotation | Unrestricted baseline rotation | Earth rotation |
| Long Delay lines? | Yes | No | No | Yes |
| Waveband | MIR N-band | MIR N-band | NIR $K_s$-band | NIR K-band |
| Fringe tracking | Shorter (NIR) wavelengths | Shorter (NIR) wavelengths | Extreme (VIS) AO system | NIR K-band on-axis starlight |
| Modulation | Phase scan | Spatial nodding | Chopper wheel | Spatial Nodding |
| Calibration | Reference stars | Reference stars | Reference stars only needed below $\sim 10^{-3}$ | Central star |
| Beam combiner geometry | Co-axial | Co-axial | Multi-axial | Co-axial |
| Beam combining element | Dual beamsplitter | Single beamsplitter | Single-mode fiber | Single-mode fiber and photonic component |
| Dispersion compensator | Glass | Glass | Glass | None except telescope ADC |
| Dispersion compensator phase shift | $\pi$ | $\pi/2$ | $\pi$ | None (not a nuller) |
| Disp. comp. glass shape | Wedges | Flat | Chevron | N/A |
| Glass thickness modulation | Translation | Static | Rotation | N/A |

# Summary

- Many advances made (NSC algorithm) and many lessons learned (phasing, detector and background)
  - both for separated aperture and sub-aperture nullers.
- NSC enables short wavelength (NIR/Vis) nulling, making a sub-aperture nuller on Habex/LUVOIR (or TMT/ELT) a nearer term option (than an IR interferometer in space) worth considering
- A key advantage of NSC is that using spectral dispersion, not all wavelengths need to null at the same time or at the same OPD, but very deep nulls can still be measured in each spectral bin.
- Both the PFN and GRAVITY were able to detect faint sources 10 to 100 times fainter than the mean residual starlight level (Q factor of 0.01 to 0.1).
- To boost faint source detectability:
  - PFN used broad-band data recorded at high temporal resolution (5 ms)
  - GRAVITY used spectrally dispersed data (R=4500) and long individual exposures (10s+).
  - The trade between temporal & spectral resolution for optimum nulling accuracy will be explored in our current study
- On a given telescope, a nuller can observe closer to the center than a classical coronagraph
  - Need to push nulling to deeper levels:
  - Co-axial nullers such as the grating nuller have been found to reach deeper lab contrasts than multi-axial nullers

# "Revisiting Nulling Interferometry Space Mission Concepts" Task List

- Task 0: Science goals, objectives, and measurement capabilities beyond HabEx/LUVOIR in the ELT/TMT era (Danchi/Stark)
- ***Task 1*: Collect and summarize key nulling and interferometry lessons learned since the TPF-I concept work: From the Keck, Palomar and LBTI nullers, from nulling results in the lab (e.g., PDT/ Grating nuller) and from high contrast interferometry with GRAVITY**
- Task 2: Consider the application of higher spectral resolution techniques, such as molecular mapping, to MIR nulling
- Task 3: Revisit (and potentially modify) the TPF-I Emma baseline mission concept
- Task 4: Identify Tech Gaps for several possible mission scenarios
- Task 5: Identify Candidate Technologies to be developed to close these gaps
- Task 6: Monitor European progress in order to position NASA as an essential collaborator to their efforts to develop a future mission (or to a mission concept from the US side)

- **TODAY: focused mostly on Task 1 – lessons learned**

# Interferometry Initiative Overall Schedule (FY 21)

| LEAD | TASKS | FY21 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | O | N | D | J | F | M | A | M | J | J | A | S |
| Danchi | ***Task 0: Revisit TPF-I Science Goals*** | | | | | | KD | | | | | | |
| Serabyn | ***Task 1: Collect and summarize lessons learned since TPF-I*** | | | | KD | | | | | | | | |
| Roudier | ***Task 2: Consider the application of High Spectral Resolution Observations*** | | | | | | KD | | | | | | |
| Mennesson | ***Task 3: Define Strawman DRM*** | | | | | | | | | | KD | | |
| Serabyn | ***Task 4: Identify Technology Gaps*** | | | | | | | | | | | KD | |
| Martin | ***Task 5: Identify Candidate Technologies to fill Gaps*** | | | | | | | | | | | | KD |
| Mennesson | ***Task 6: LIFE mission concept collboration*** | | PD | | PD | | PD | | PD | | PD | | PD |

*KD: Key Deliverable*

*PD: Periodic Deliverable*