Nulling Interferometry

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Outline of Talk

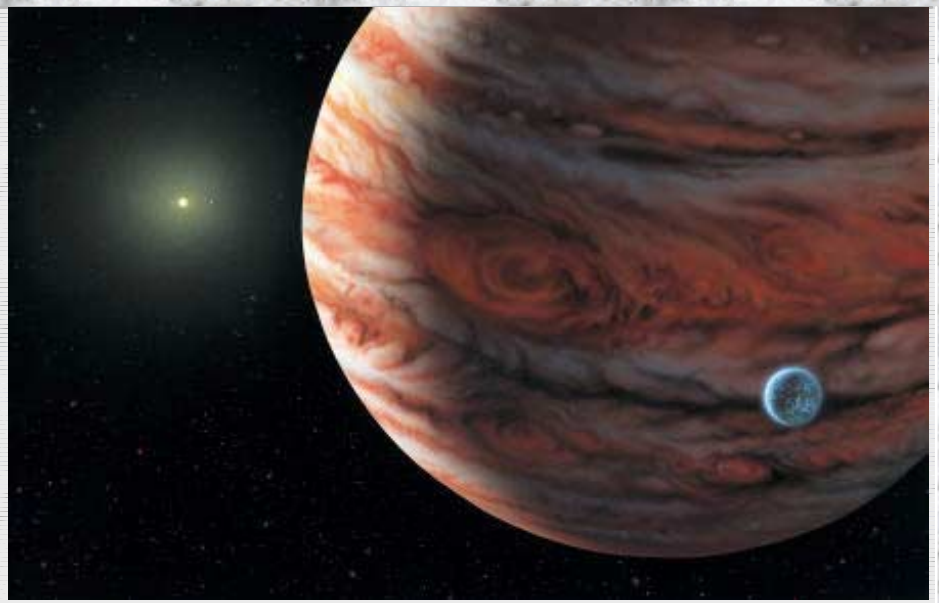
- Motivation for Nulling
- Techniques
- Historical Development of Nulling
- Conclusions

Good Reference Papers

- Serabyn, E. “Nulling Interferometry and Planet Detection”, Michelson Sum. School, 1999, Ch 16, ed. By P. R. Lawson.
- Baudoz, P. et al., “Achromatic Interfero Coronography I” and “II”, 2000, Astron. & Astrophy. Supp., 141 & 145.
- Serabyn, E. & Colavita, M. M., “Fully Symmetric Nulling Beam Combiners”, 2001, Applied Optics, 40.

Motivation

- Detection of extrasolar giant planets and ultimately Earth-like planets
- Identify habitable planets in other stellar systems
- Other science **-YSOs, evolved stars, AGN**



Planet Detection

- Earth-Sun separation = 1 AU & Saturn-Sun separation = 10 AU

at 10 pc this corresponds to 100 & 1000 mas respectively

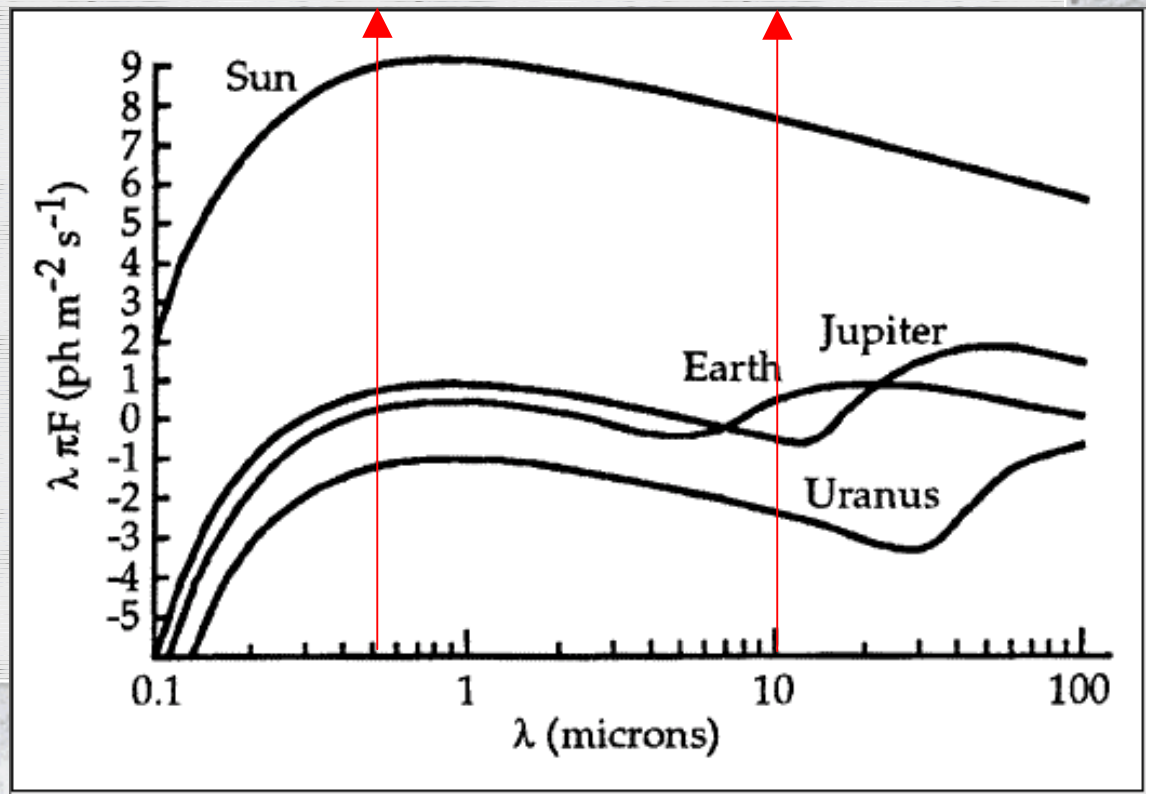
- λ/D for $\lambda = 0.5\ \mu m$ for 1 & 10 m telescopes = 100 & 10 mas
- PSF sidelobe peaks fall off @ θ^{-3} for circular aperture
  - drops off to $10^{-9 \rightarrow -10}$ at several hundred λ/D

    by apodizing aperture can be reduced to tens of λ/D
- if diffraction were entire issue, we'd detect Jupiters @ 10 pc

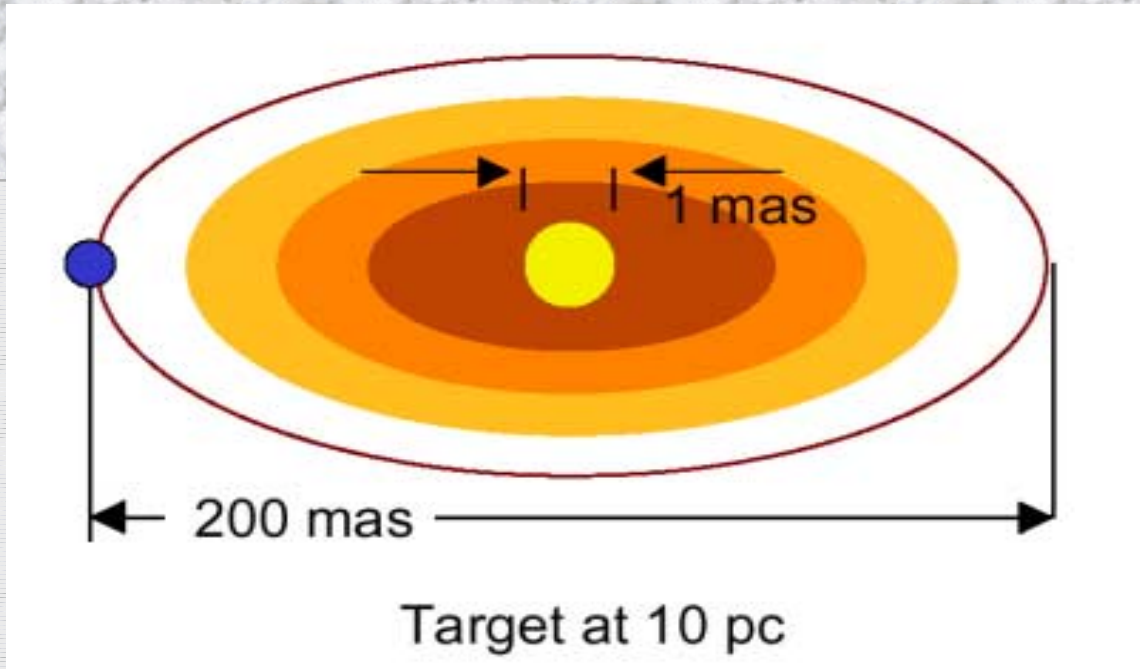
with HST ➔ wavefront irregularities producing scattered light

Contrast Issues

- Earth-Sun contrast at 0.5μm – $10^{-9 \rightarrow -10}$
- Earth-Sun contrast at 10.0μm – 10^{-6}



Exozodiacal Emission in Orbital Plane of Target Stellar System



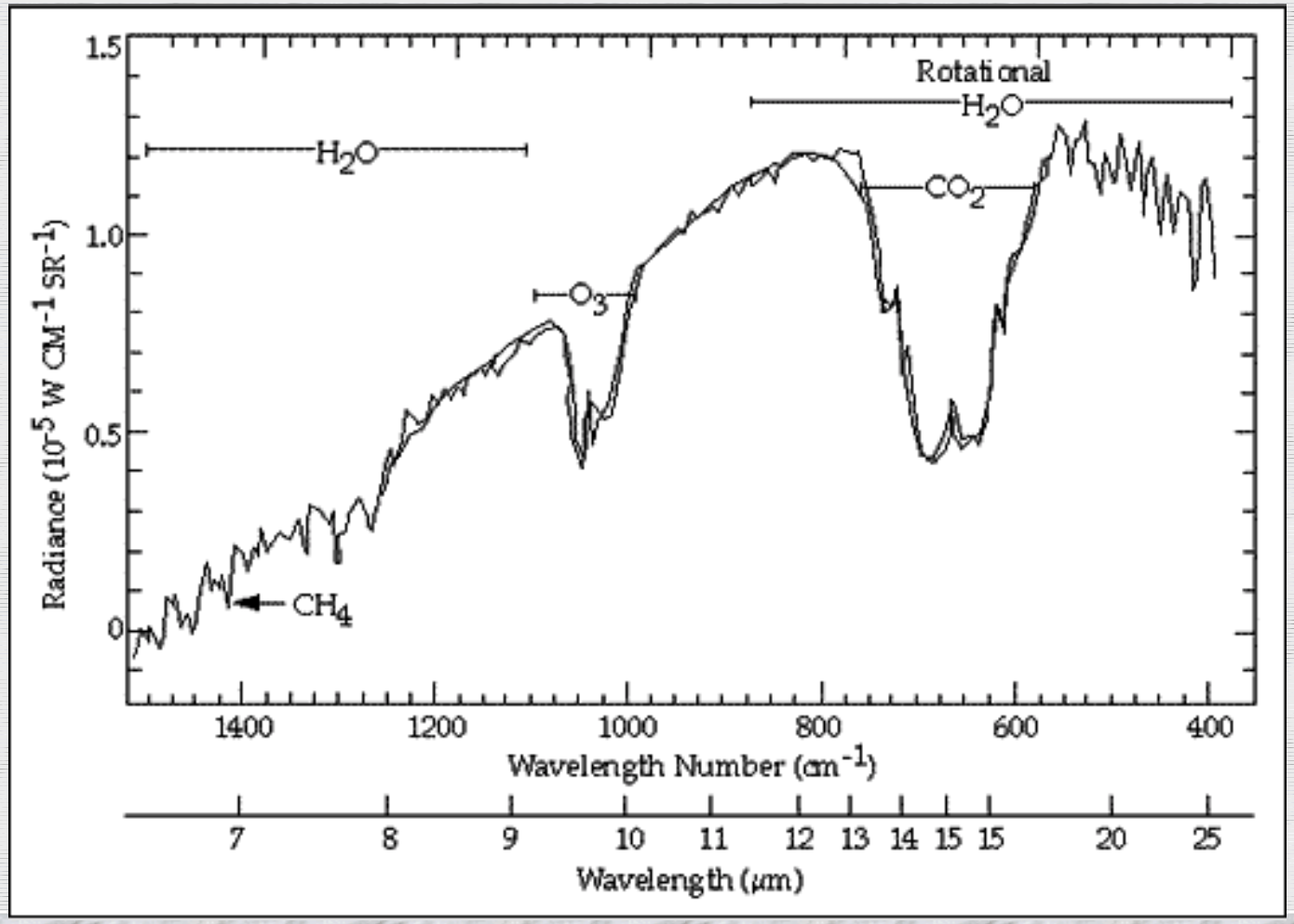
--disk's integrated thermal emission is likely to exceed gas giant planet's by orders of magnitude

e.g. int. th. em. from 1 zodi is 10^{-4} of Sun's at 10 μm

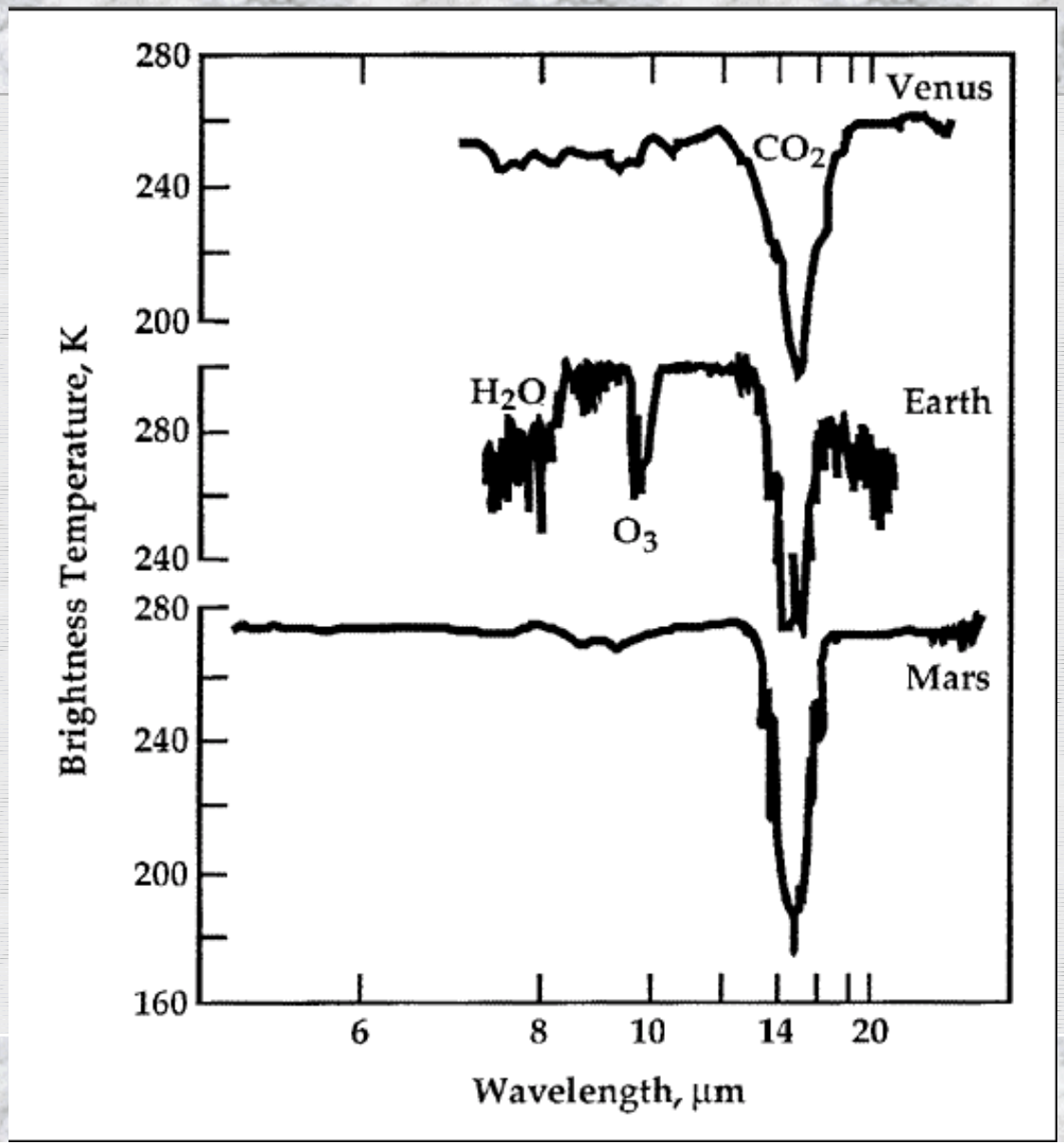
-- 10^{2} greater than Jupiter

-- 10^{3} greater than Earth

Biomarkers

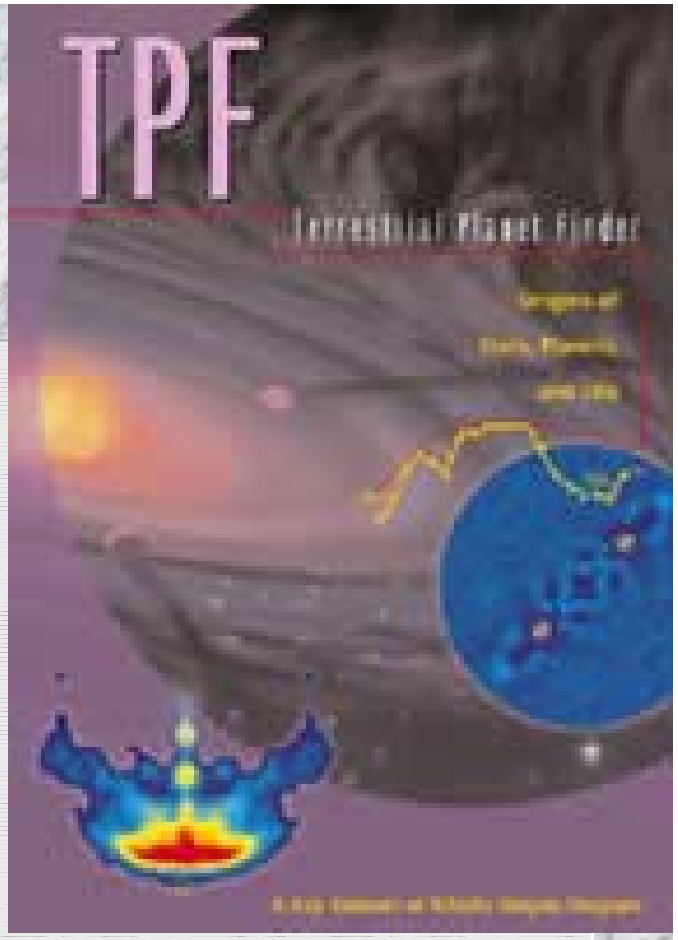

Rotational
H_2O
H_2O
CO_2
O_3
CH_4
Radiance (10^{-5} W CM^{-1} SR^{-1})
1.5
1.0
0.5
0
1400
1200
1000
800
600
400
Wavelength Number (cm^{-1})
7
8
9
10
11
12
13
14
15
15
20
25
Wavelength (μm)

Comparison to Other Planets



Missions

- Terrestrial Planet Finder (TPF) - NASA/Origins/JPL/CIT
  - goals search for habitable planets and life outside solar system
  - architecture: optical coronagraph or large-baseline IR interferometer
  - architecture - 2006; launch 2012-15
  - Keck Interferometer Nuller is part of precursor studies



Missions (cont)

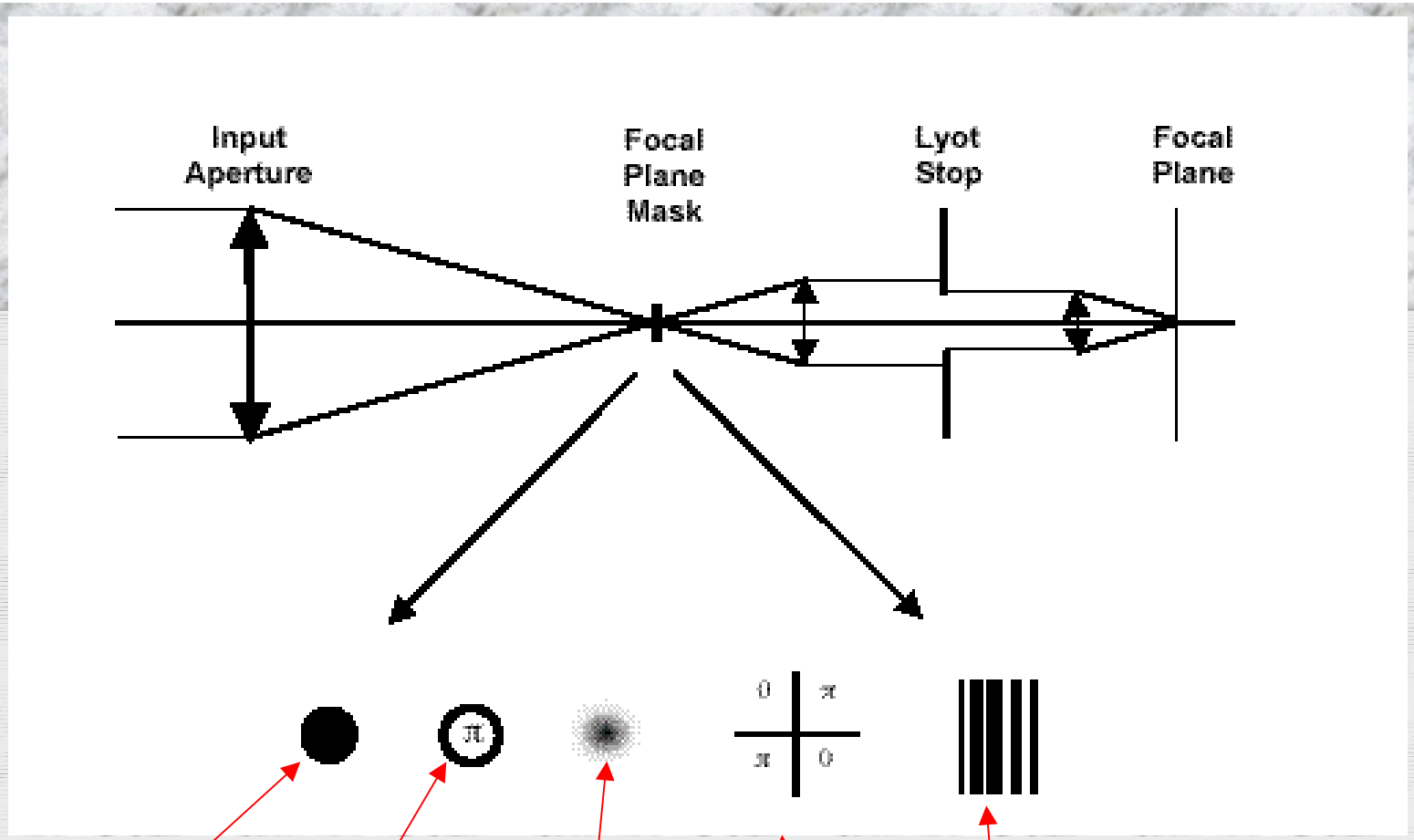
- DARWIN - ESA
  - goals detect and characterize Earth-like planets through nearby star survey
  - six 1.5m telescopes in L2 orbit operating in IR
  - launch 2014
  - VLTI Nuller (ESO) is part of precursor studies
  - SMART-2 demonstrate formation flying

Techniques for Extrasolar Planet Detection

- Coronography
  - focal plane mask and a pupil (Lyot) stop
  - filter focal plane PSF
  - modify (attenuate) aperture plane distribution
  - few airy rings
- Nulling Interferometry
  - wavefronts arr. at two separate pupils are superposed & subtracted in pupil plane
  - modify aperture plane field
  - spatially filter (single mode)
  - PSF central lobe

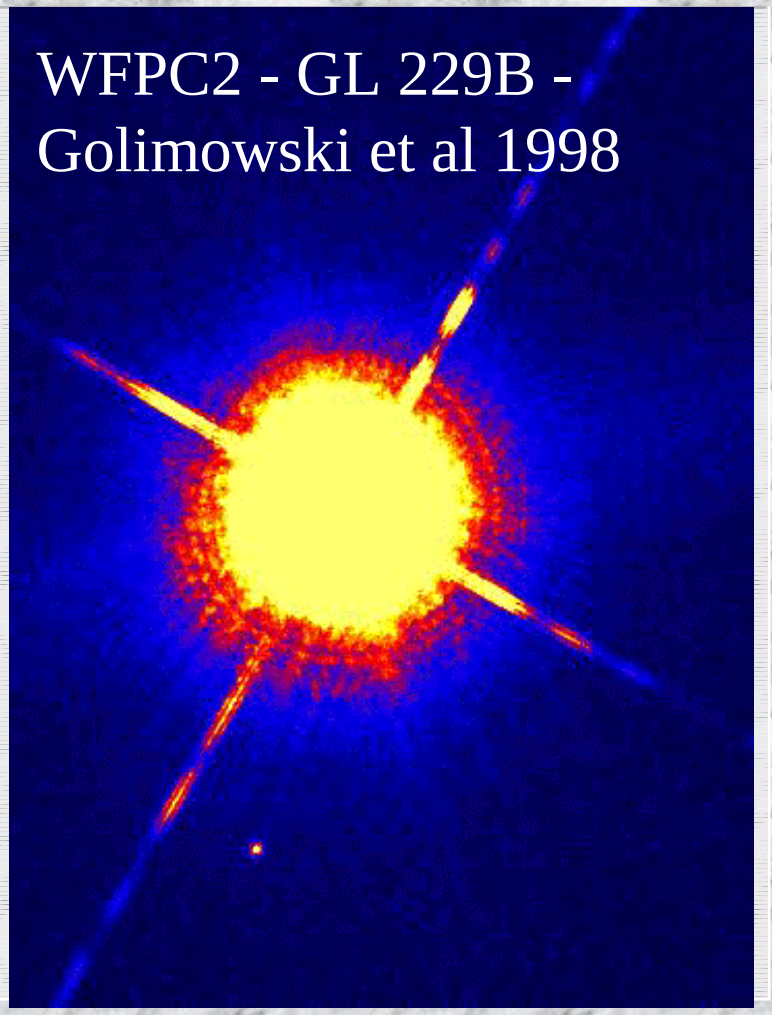
Coronography

- First developed in 1939 by Lyot for studying stellar corona
- Used on stars to study circumstellar disks (β Pic) and substellar mass companions (GL 229B)
- Coupled with AO to take advantage of sharper PSFs
- Focal plane mask (opaque or phase) to suppress stellar flux
- Undersized Lyot stop to suppress high spatial-frequency PSF wings and improve contrast
- Removes energy through absorption


Input
Aperture
Focal
Plane
Mask
Lyot
Stop
Focal
Plane
π
0
π
π
0
opaque mask
phase mask +π
graded opacity mask
4-quad. phase mask
band-limited opaque mask

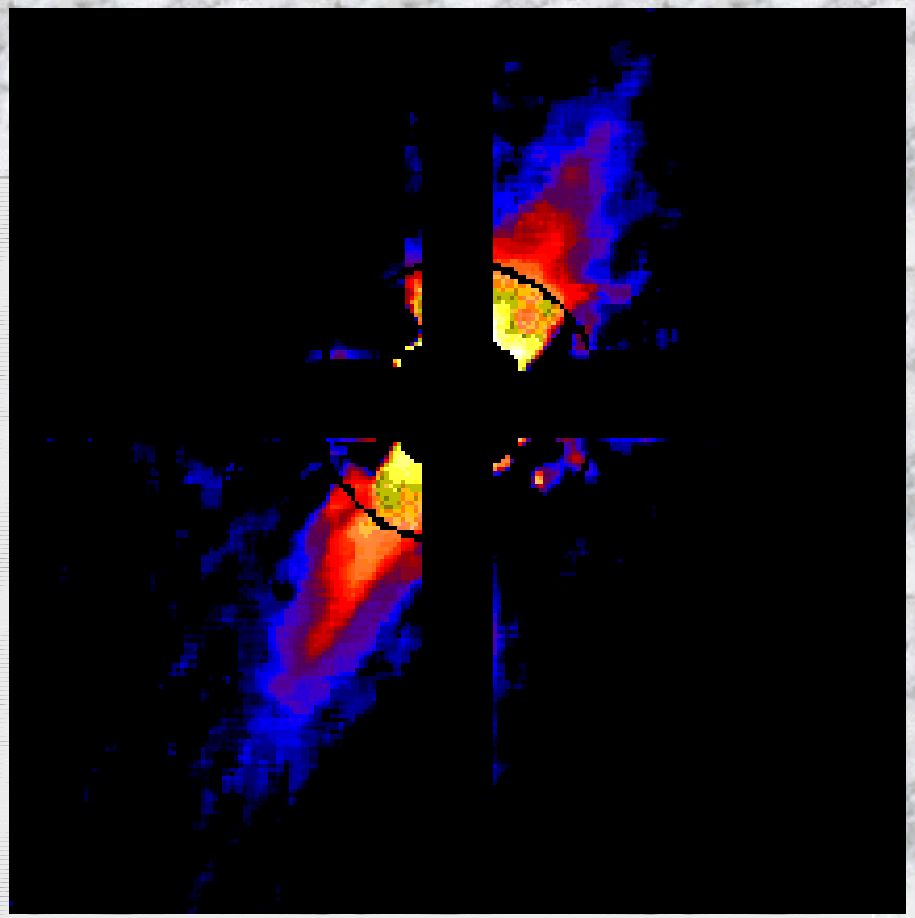
Examples

- HST image of GL 229A and B – about 7” separation at 6 pc from Earth
- See need for Lyot pupil mask to suppress diffraction spikes and scattered light in order to see much closer to parent star



WFPC2 - GL 229B - Golimowski et al 1998

•Suppression of diffraction spikes and scattered light allows for resolution of many intensity levels of β Pic disk (analogous to our exozodi disk)

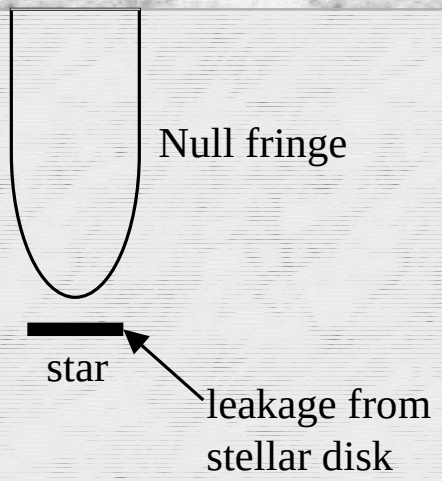


β Pic - ADONIS Coronagraph - Mouillet et al. 1996

Nulling Interferometry

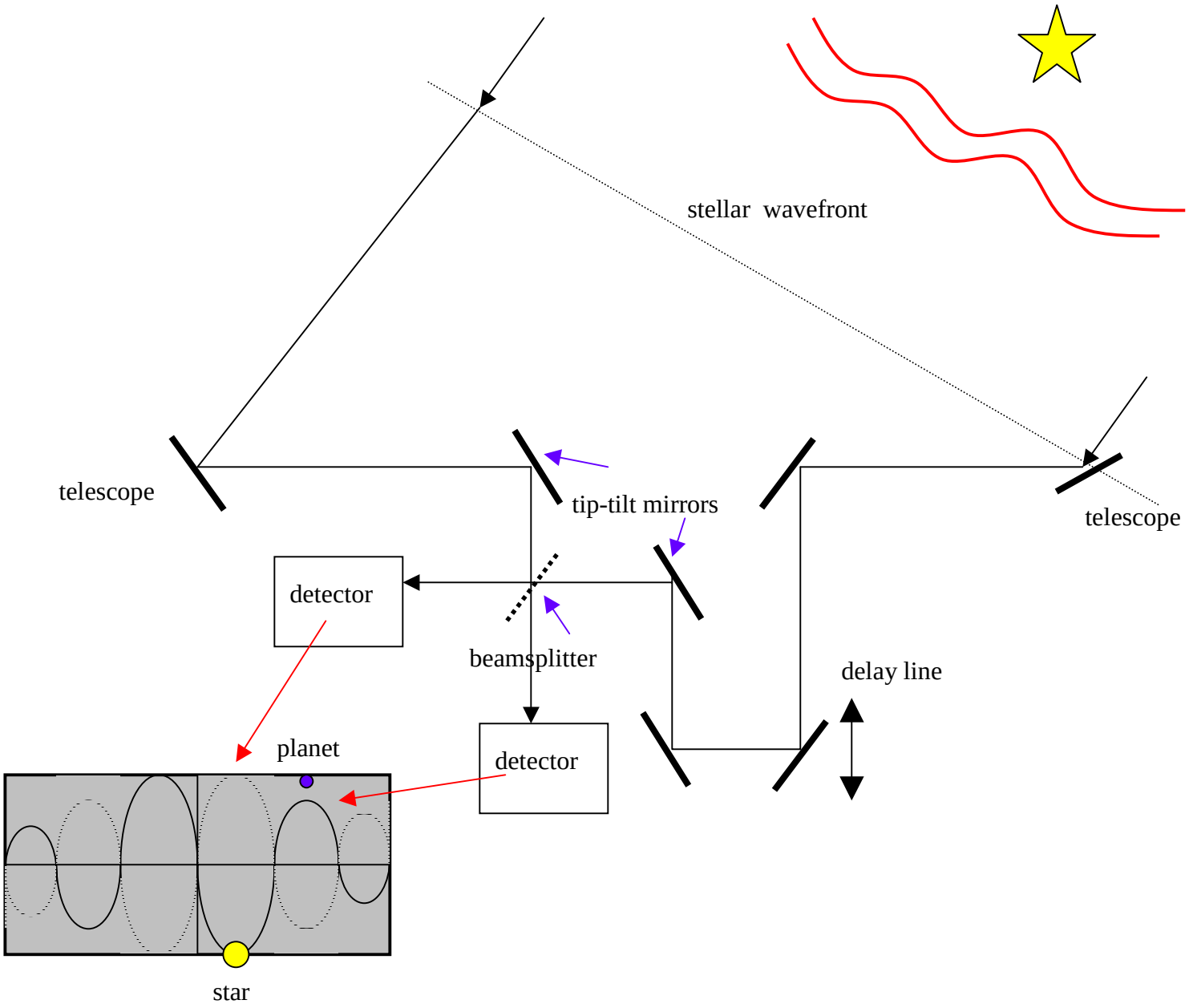
- First described by Bracewell (1978) and expanded upon by Bracewell & MacPhie (1979)
- Several groups using variations of technique for future telescope applications (KI, LAOG, LBT, OCA, VLTI)
- Demonstrations at ground-based observatories
  - splitting doubles
  - studying circumstellar material (YSOs and evolved stars)
- Planned implementation on DARWIN and possibly TPF after further large-observatory proof of concept

Concept



$$N = \{\pi\theta_{dia} / \ 4\lambda/b\}^2$$

- Combine light at OPD=0
- Electric field vectors 180° out of phase
- Off-axis emission from sources near constructive fringe maxima transmitted
- Null depth: ratio of transmitted powers
- Unwanted energy is reflected into bright outputs
- Trick: dual polarization and achromatic simultaneously


stellar wavefront
telescope
tip-tilt mirrors
telescope
detector
beamsplitter
delay line
planet
detector
star

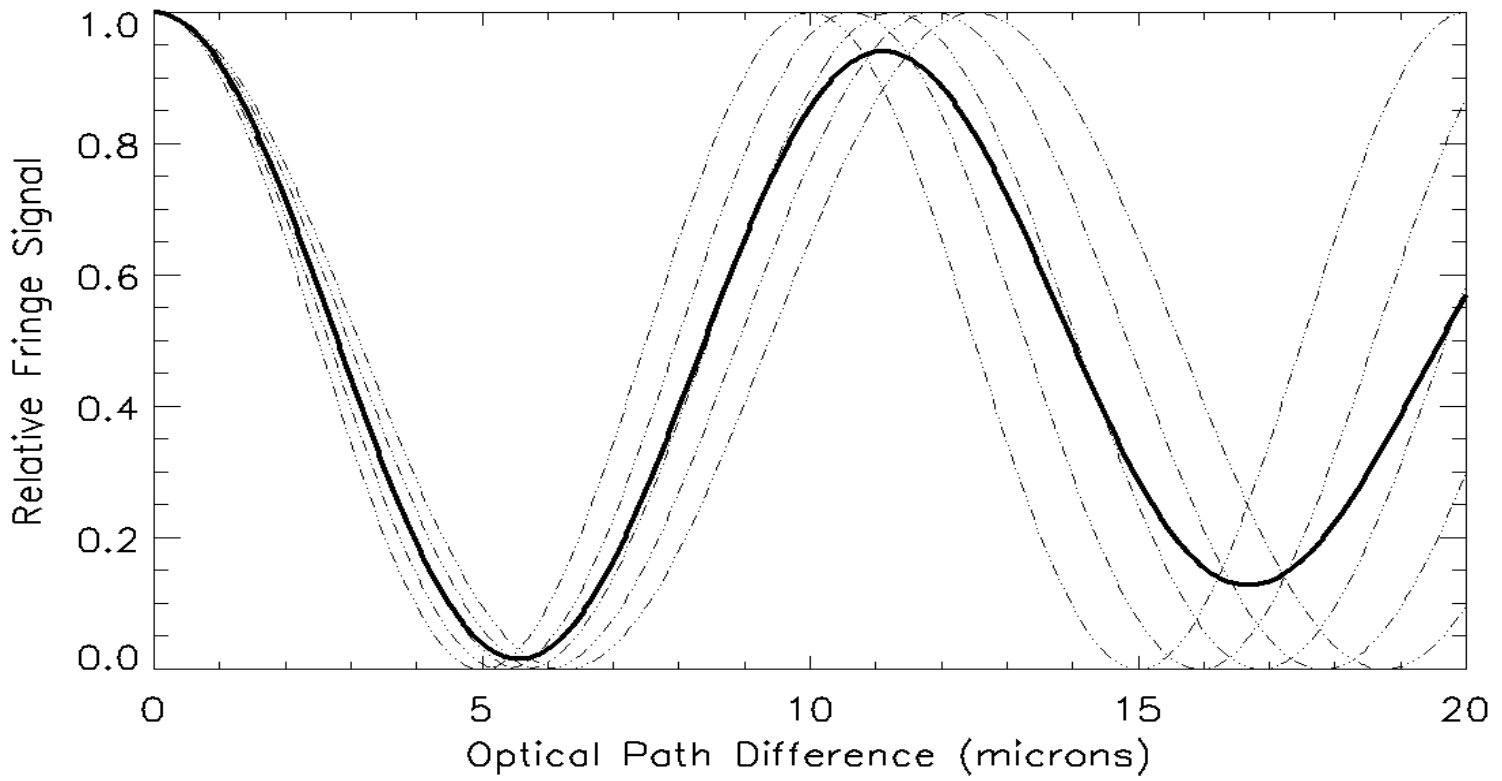
Wrinkle...

- Original concept by Bracewell & MacPhie (1979) won't work (they added flipped electric fields at a beam splitter)
  - stellar cancellation must be very deep (10^6 planets, $10^{3\text{-}4}$ exozodis)
  - achromatic deep nulls not possible with completely symmetric standard stellar interferometer as beam splitter outputs are not equivalent
    - introduction of $\lambda/4$ average offset optimizes cancellation...but it is ***chromatic***

Other approaches

We need the complement to the standard Michelson interferometer, wherein an ideal achromatic fringe at zero OPD is formed by subtracting two incident electric fields

- relative flip of electric-field vectors
  - intrinsically achromatic
  - three different variants here (rotational shearing, cat's eye & fully symmetric)
- phase retardation approach
  - light at each wavelength is delayed by exactly the distance to arrive 180° out of phase

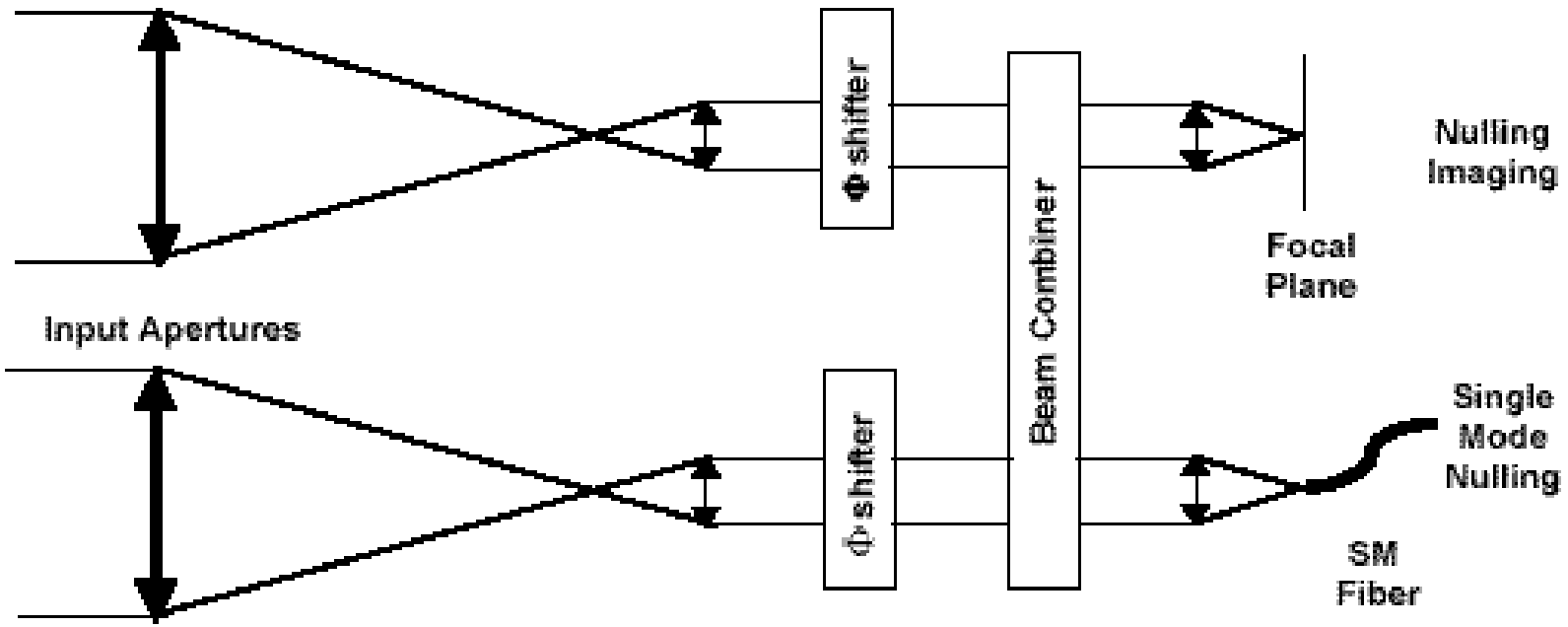


- "white light" fringe is average of chromatic fringe positions
  - compensate for color differences across band and find way to balance beam intensities without introducing further chromaticities or other errors

Requirements for Stability

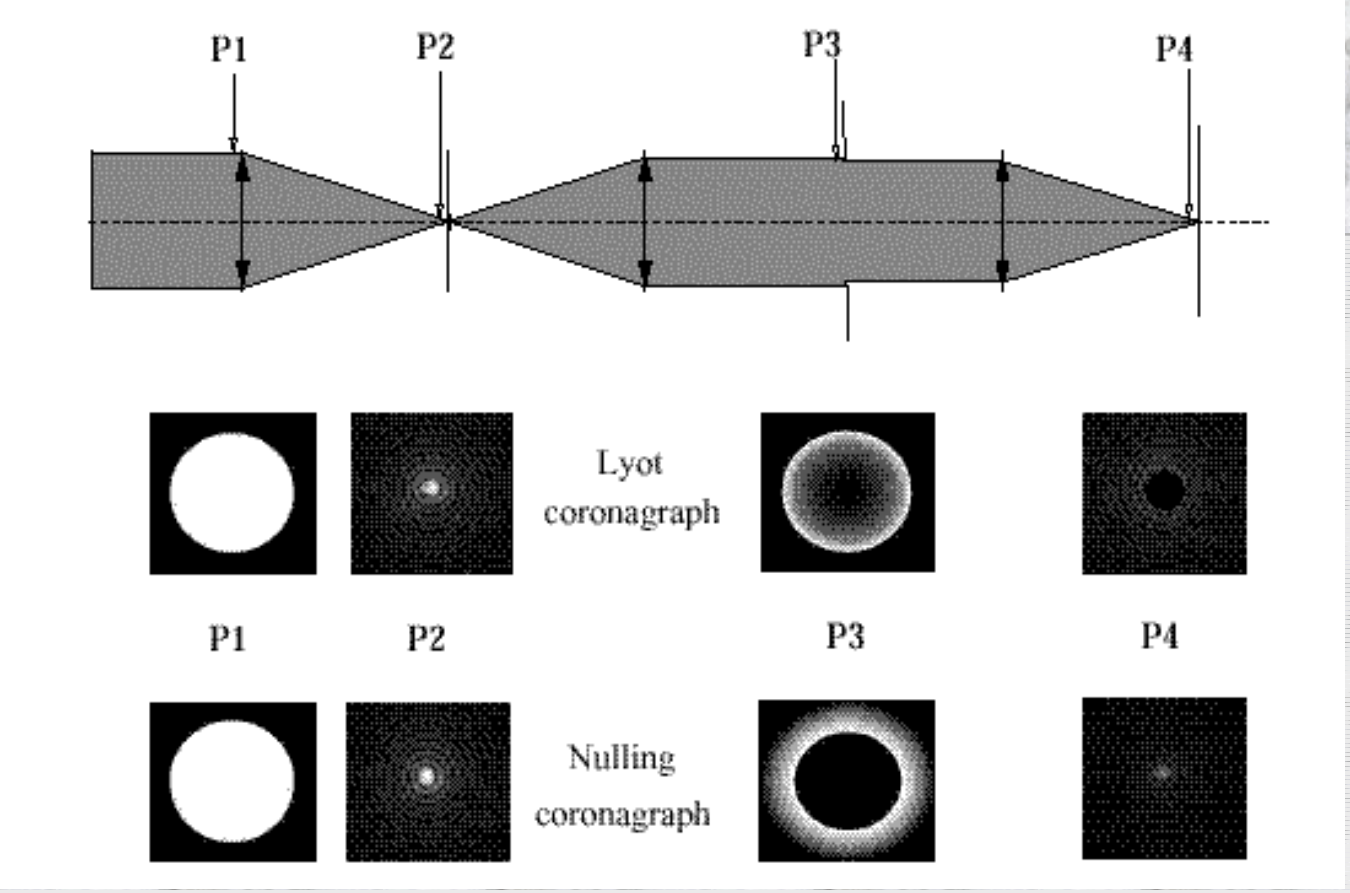
- For given polarization state match to $2\sqrt{N}$
  - beam intensities — pointing offsets or obscurations
  - E field rotation angles — image rotation
  - phase delays — optical delay lines
- For 10^{-6} nulls
  - better than 10^{-3} match on all components

Intermediate case between coronography and (SM) nulling removes spatial filter, allowing access off axis – with a subsequent reduction in capabilities and null depth {in some sense the complement of phase coronography}



Current nulling developments...

entrance pupil plane *focal plane* *2nd pupil plane* *2nd focal plane*

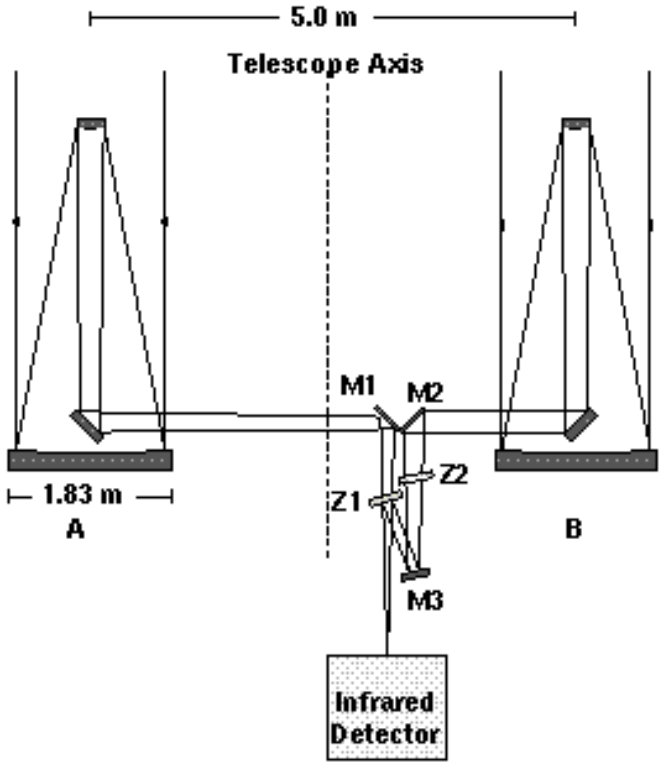


- Direct imaging through phase shift starlight cancellation
  - no rotation about optical axis
  - complete Fourier plane sampling
  - NOT an interferometric nuller

Guyon et al. 1999, PASP, 111

Beam Splitter Nuller – Phase Retardation

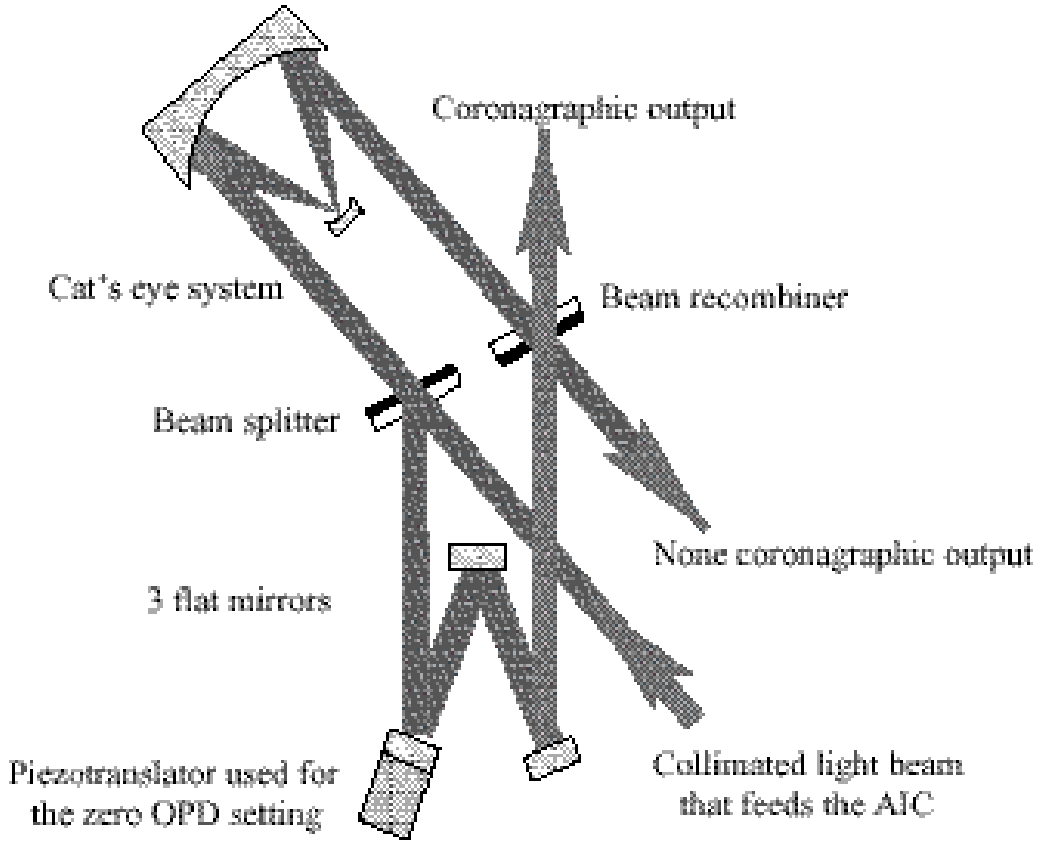
- Schematic of MMT nuller
  - telescopes co-mounted
  - no DL
  - low thermal emission
  - unmatched reflections close to normal to reduce polarization effects
  - phase shift achieved by 42μm air path difference



Hinz et al. 1998, Nature, 395

Achromatic interfero coronograph

- Michelson Interferometer with cat's eye mirror
  - introduces 180° phase shift and pupil rotation
  - central source is obscured
  - two images of off-axis sources
  - close sensing at fraction of Airy radius

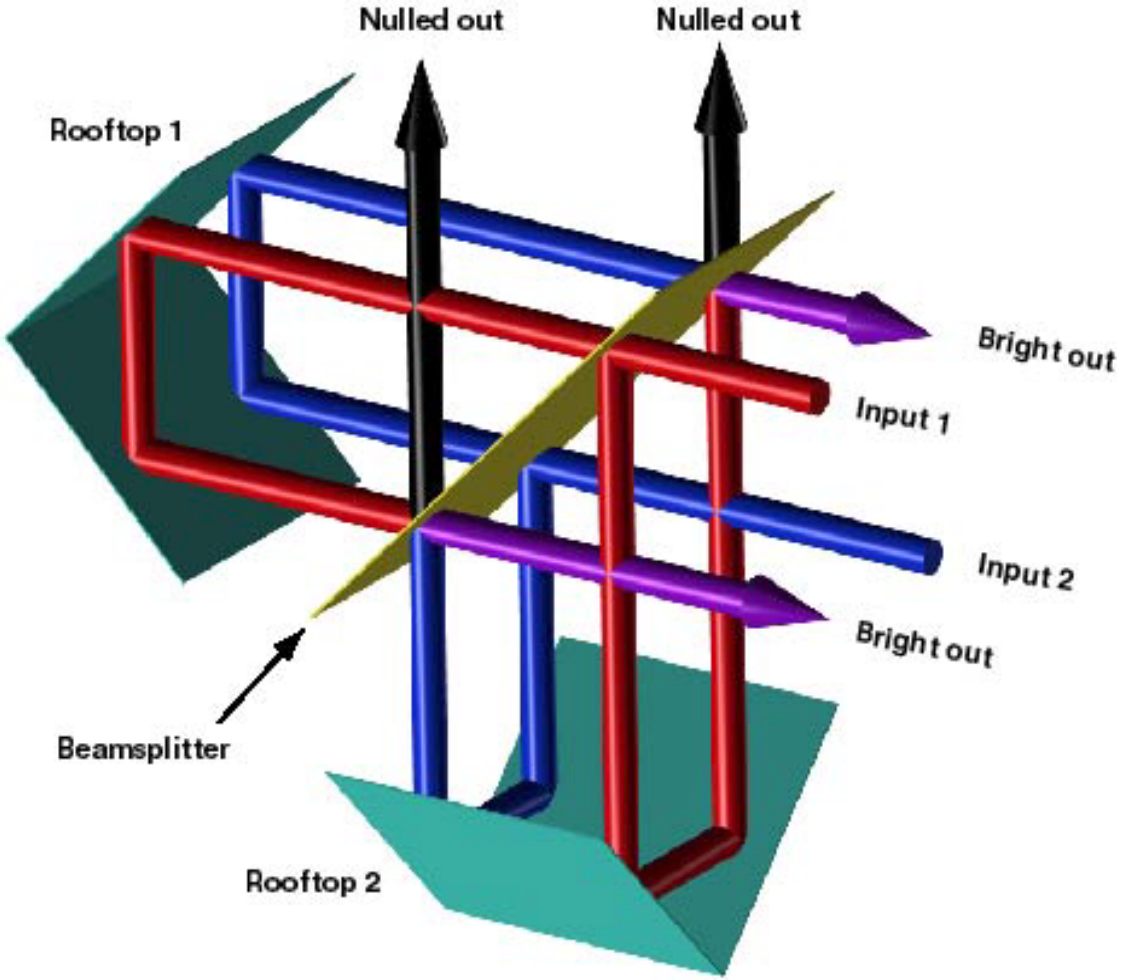


Baudoz et al. 2000, A&A, 141 & 145.

- Constructive port used to control OPD through servo-loop
- Light beams are from AO system

Rotational Shearing Interferometer

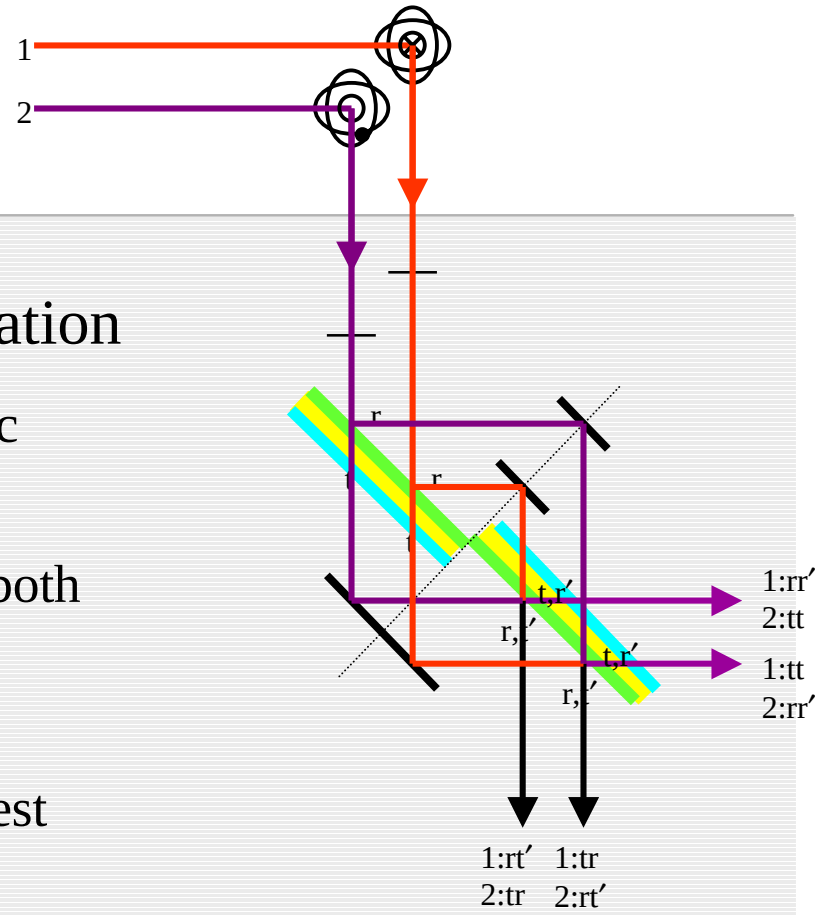
- Michelson Interferometer with rooftop mirrors
  - •introduces 180° phase shift and pupil rotation
  - •double-pass of beam splitter leads to 4 outputs – 2 nulled, 2 bright
  - •significant asymmetry exists: light of given polarization. undergoes 2 s reflections on one arm, 2 p on other



Serabyn, 1999, MSS Notes and Ap. Op., 38.

- •corrected through introduction of properly oriented 45° mirrors out front
- •path-length control through paired outputs

Fully Symmetric Nulling Beam Combiner



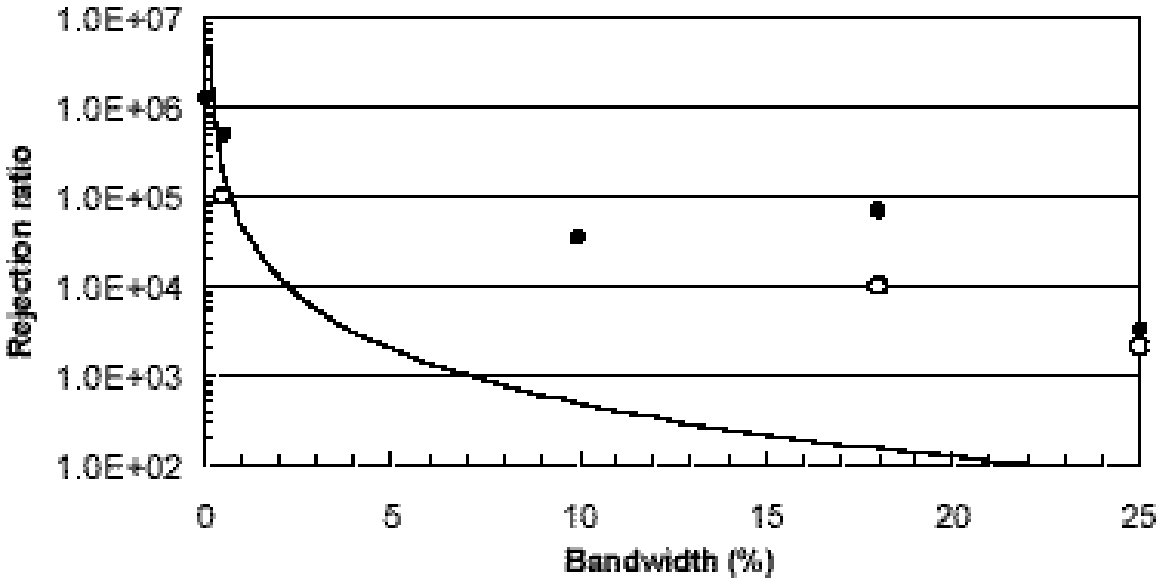
- Modified Mach-Zehnder configuration
  - separate field-flip and interferometric combination functions
  - perfectly symmetric with respect to both beam-splitter encounters and mirror reflections
  - M-Z physically symmetric with fewest optics and simplest layout
  - requires introduction of path-length offset prior to beam combination

Serabyn & Colavita, 2001, Ap. Op., 40.

Laboratory Results

- Optical version of RSI for SIM testbed
  - single-mode, single polarization null
  - >10^{-6} transient nulls
  - 7x10^{-5} average controlled null at 18% BW

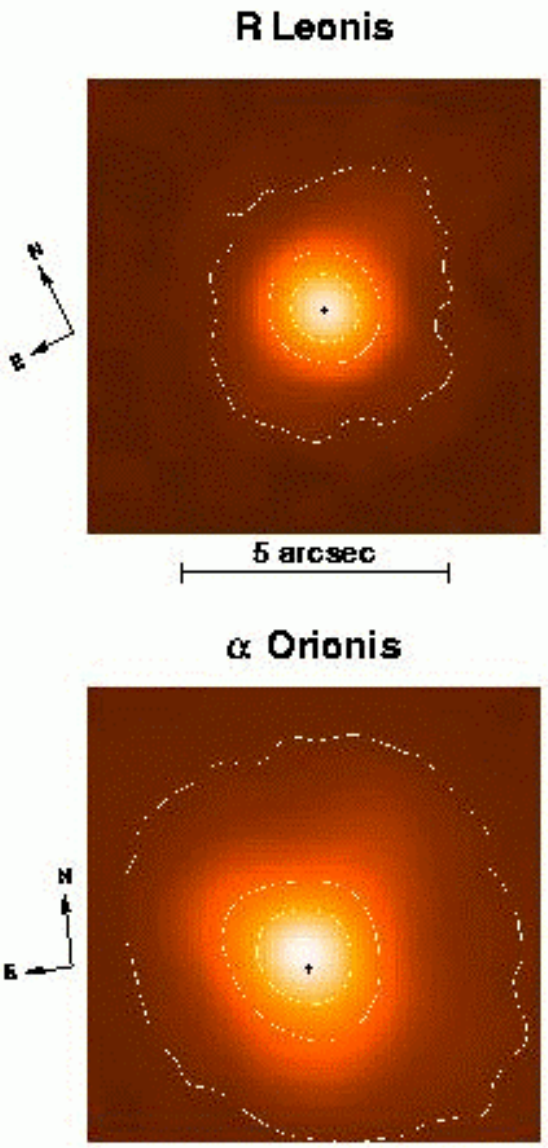
- Obtained 17000:1 Null in MIR with this configuration using laser diode source



Wallace, Hardy & Serabyn, 2000, Nature, 406.

Observatory Results

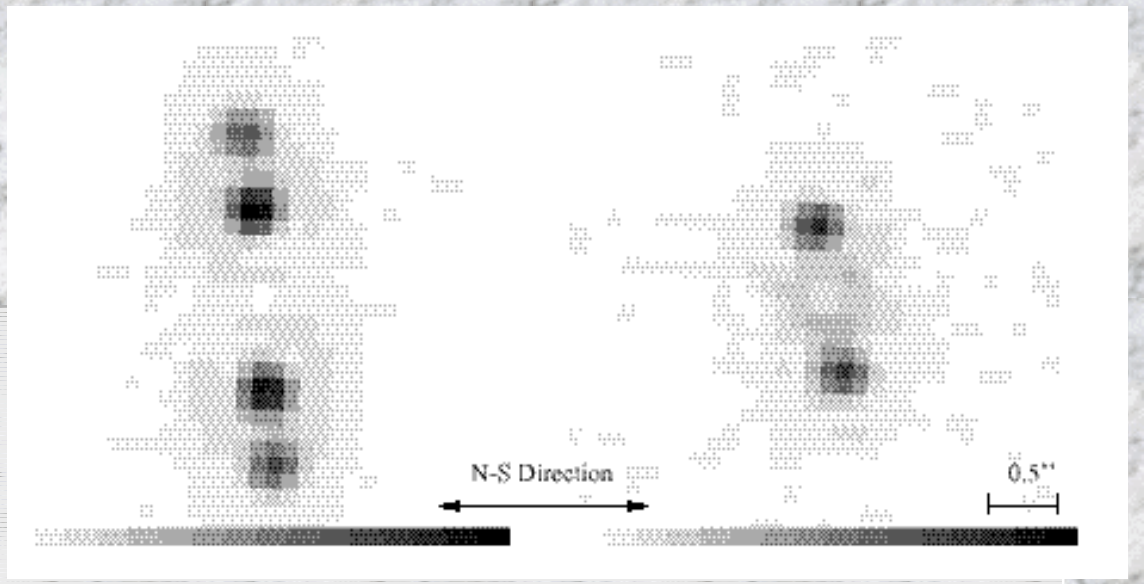
- Phase retardation using MMT @ 10μm
  - Real-time observation of image with path length adjustment of beamsplitter
  - Atmospheric turbulence introduces path-length changes for null
  - Averaged null images of evolved stars (contours are 1, 10 & 20%) and + marks centroid of stellar emission
  - Nulls are 24% and 36% of integrated flux of brightest images, respectively



Hinz et al., 1998, Nature, 395.

Observatory Results

•AIC @ Ob. de Haute Provence (OHP) behind AO system – 1.5m scope @ 2.2 μm



Baudoz et al., A&A, 2000, 145

- •AO system switching between blind acquisition and view mode to correct for pointing offsets
- •record images in on and off-axis (4-5 Airy rings) positions to obtain nulling and photometric information
- •Image of double HD211673 off and on-axis: separation is 1.4 Airy rings (530 mas) and $\Delta K = 0.36$ mag
- •Based on performance, should achieve $\Delta K=5.0$ @ 800 mas separation and detections for smaller mag differences as close as 110 mas

My Favorite Nuller...

- Keck Interferometer Nuller
  - MIR nulling beam combiner using subapertures of 2 Keck 10 m telescopes
  - MMZ configuration, with metrology and path length control
  - fringe position feed-forward from K band
  - atmospheric dispersion compensators used to introduce field-flip (rather than periscopes)
  - MIR emission detected by KALI camera – 4 beams

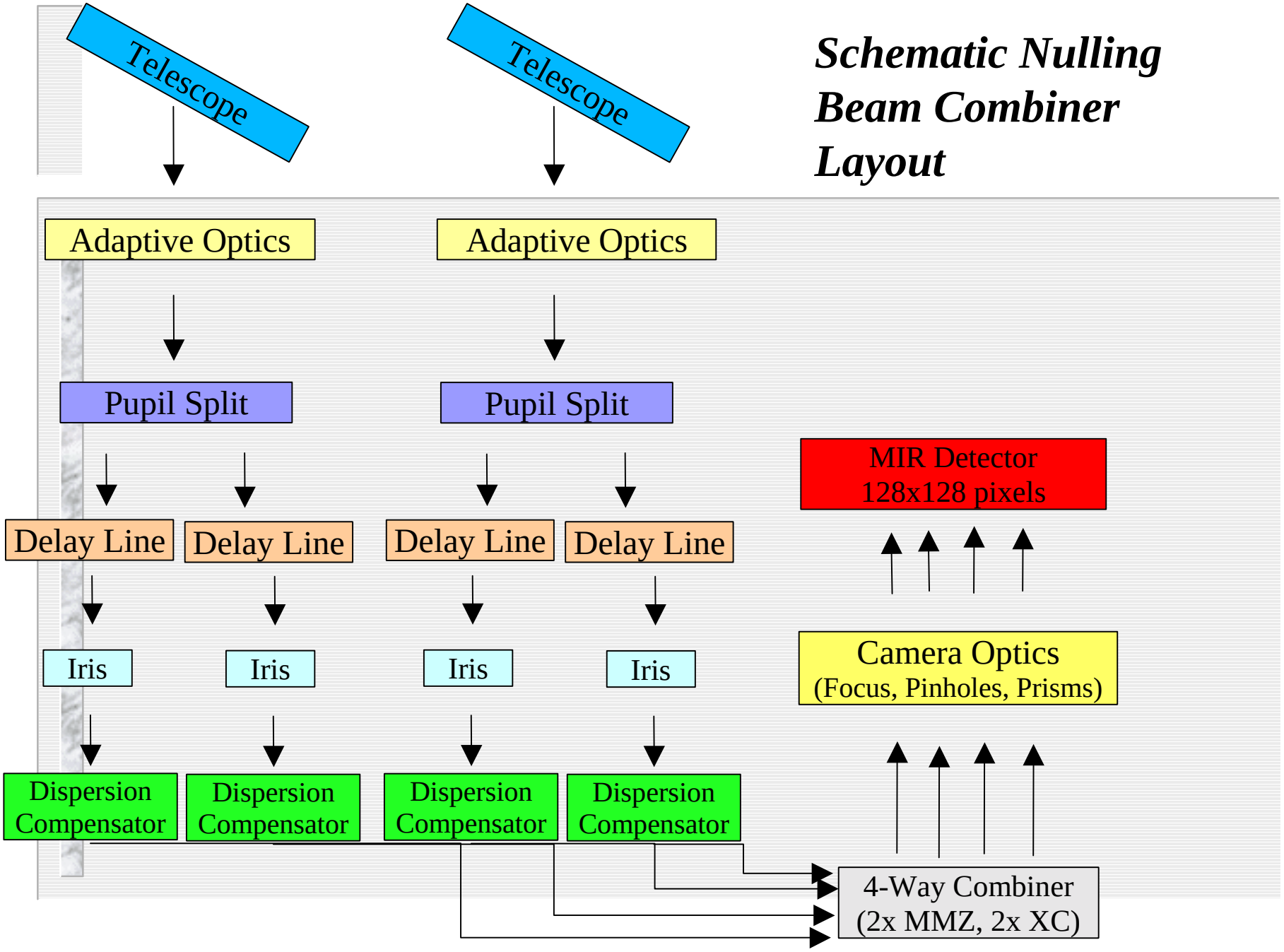
Keck Interferometer

- Built by JPL for NASA Origins Science
- Operation by CARA and ISC

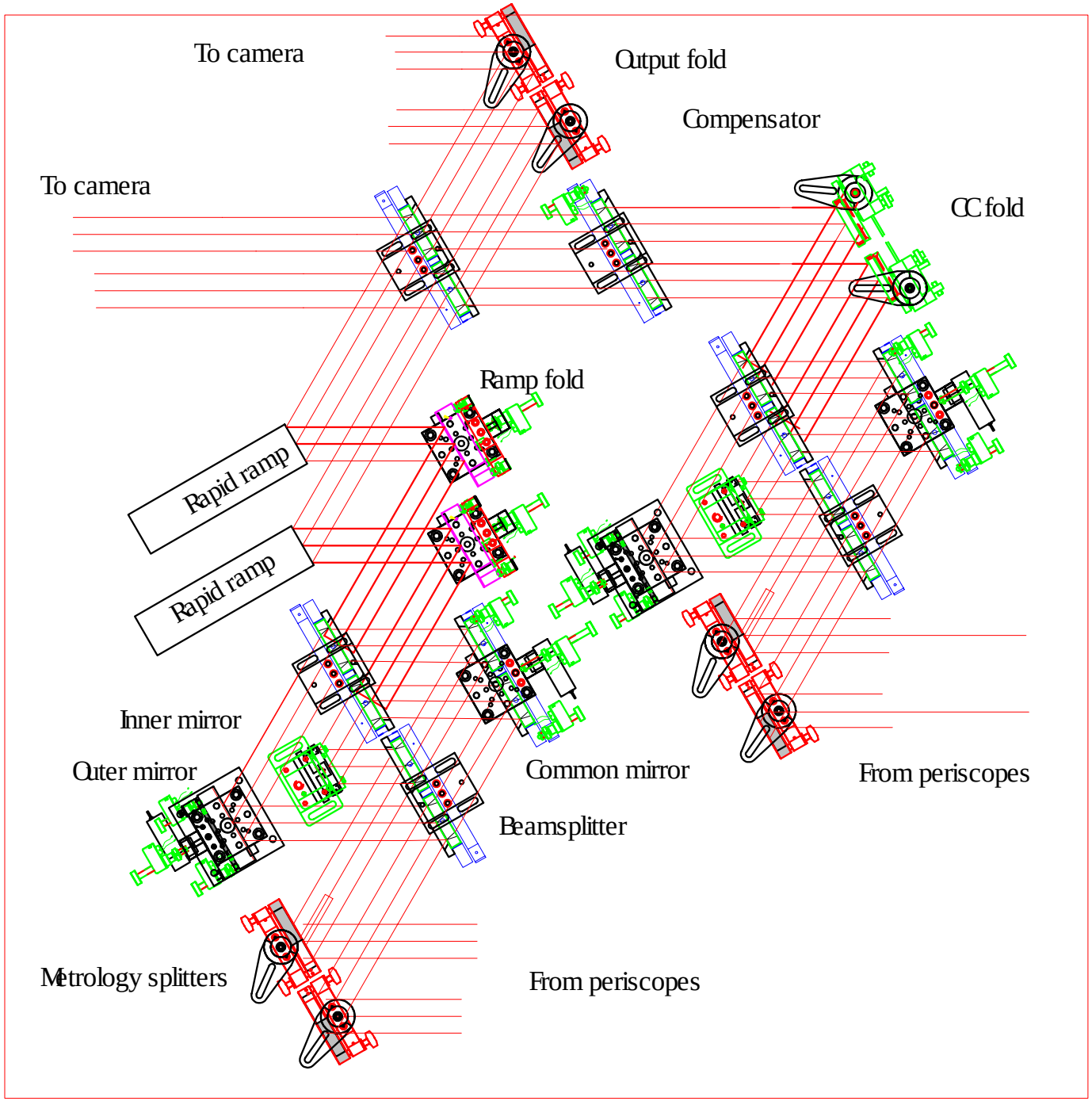
Three Origins-based Key Projects:

- Nulling to detect exozodiacal dust signatures
- Differential Phase measurements to identify giant gas planets
- Dual-star astrometry to find planetary companions

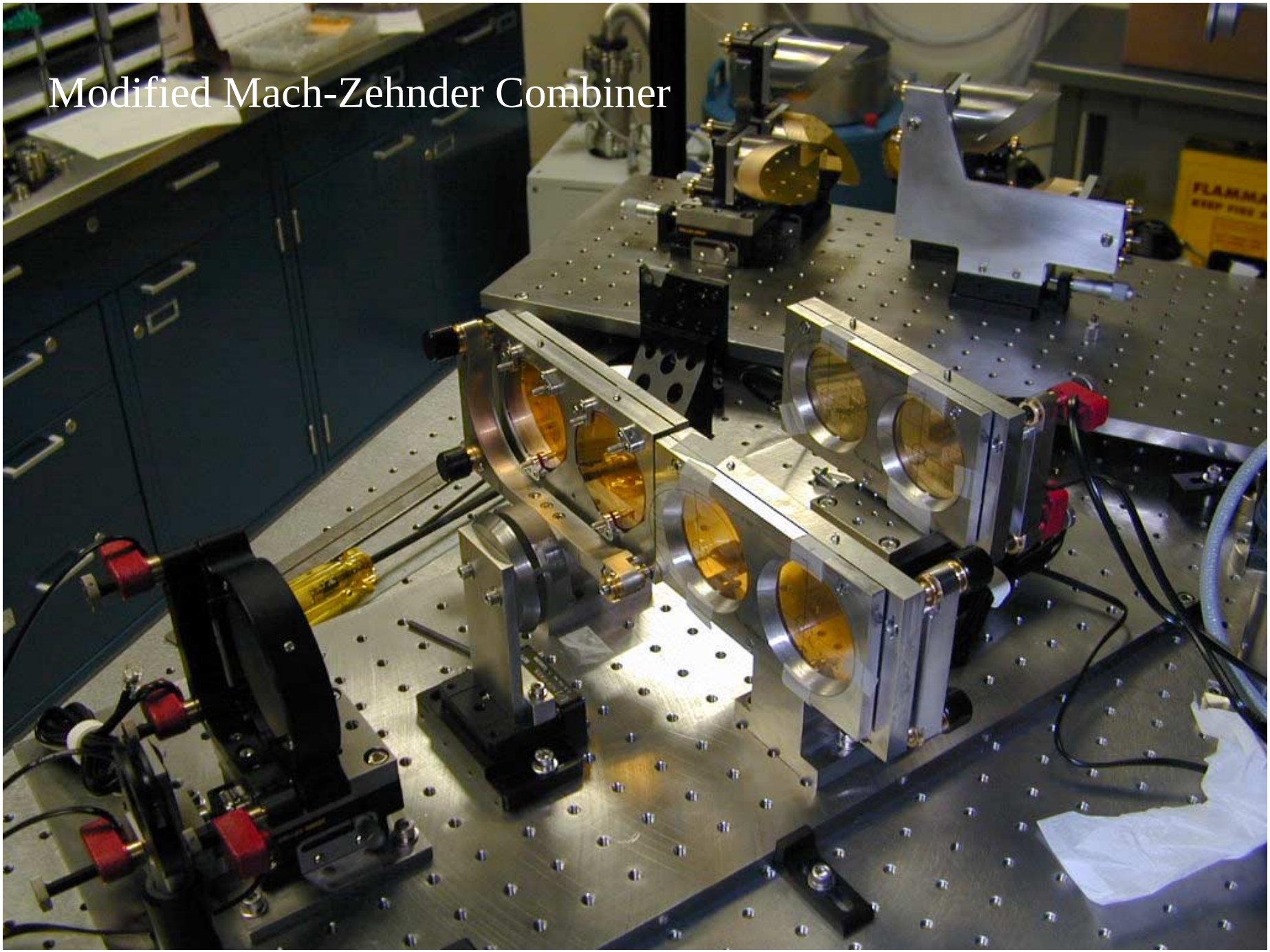
Schematic Nulling Beam Combiner Layout



MMZ and Cross-Combiner Table Layout

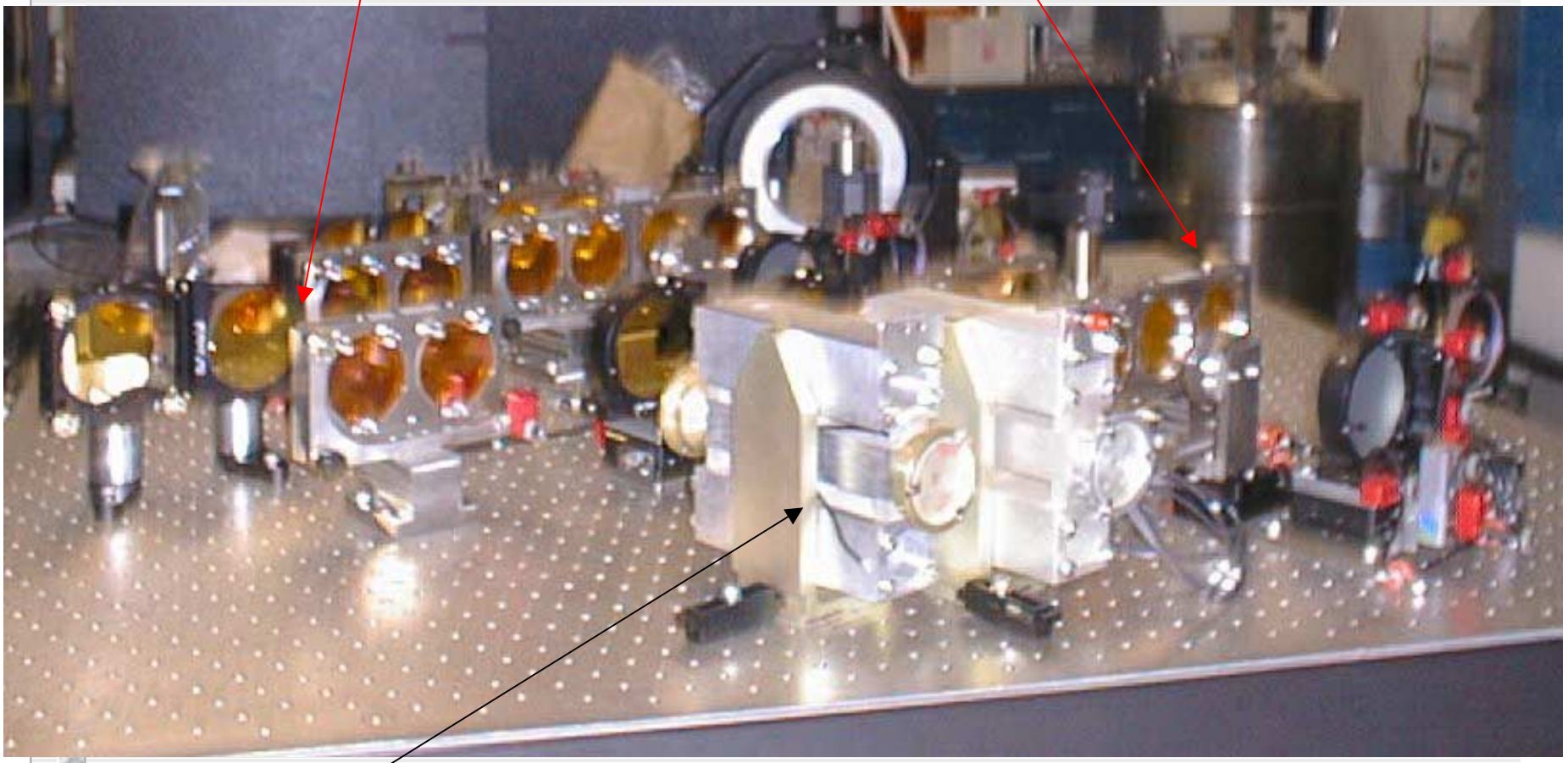


Modified Mach-Zehnder Combiner



Cross-combiners

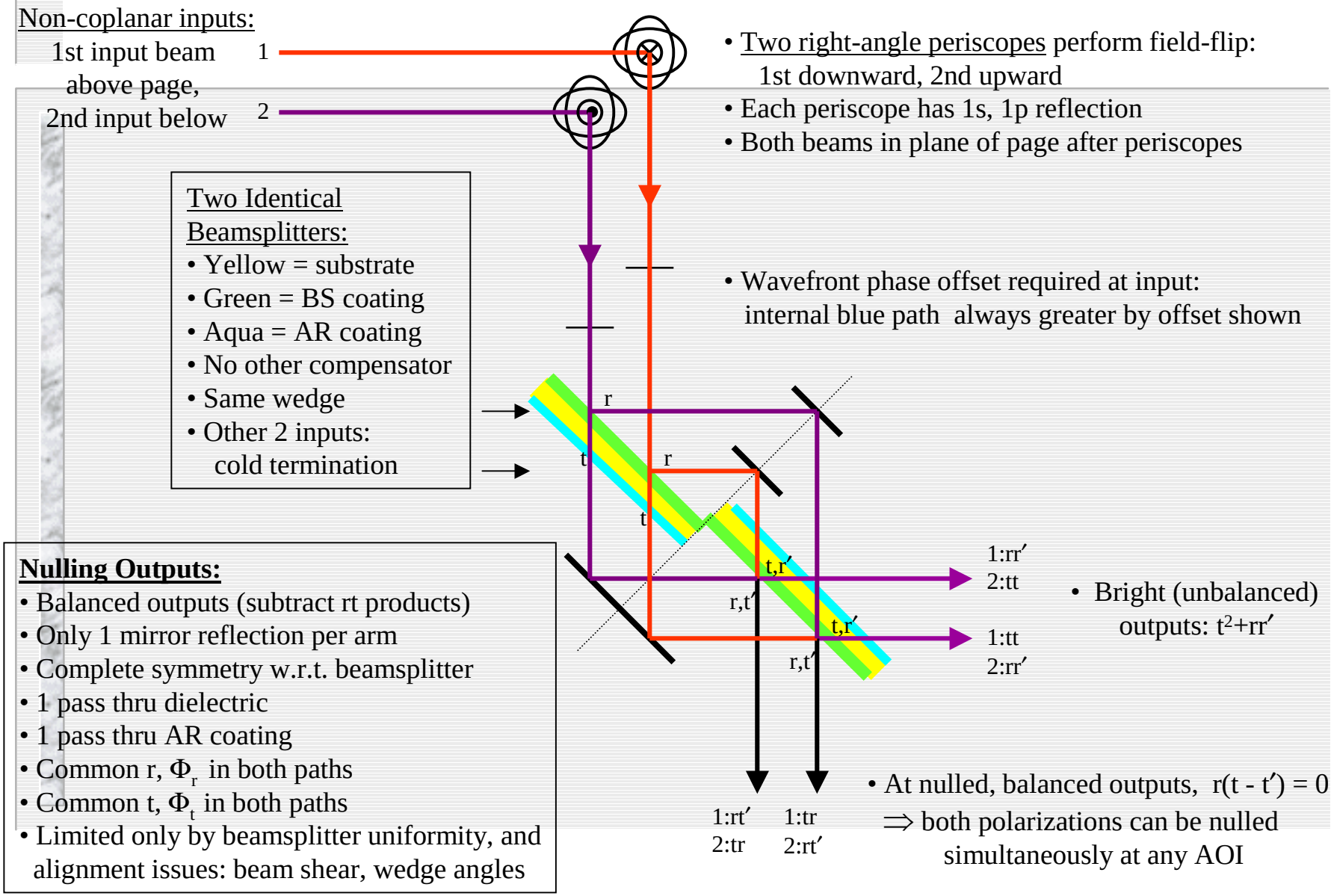
Modified Mach-Zehnder combiners



Rapid ramp actuators

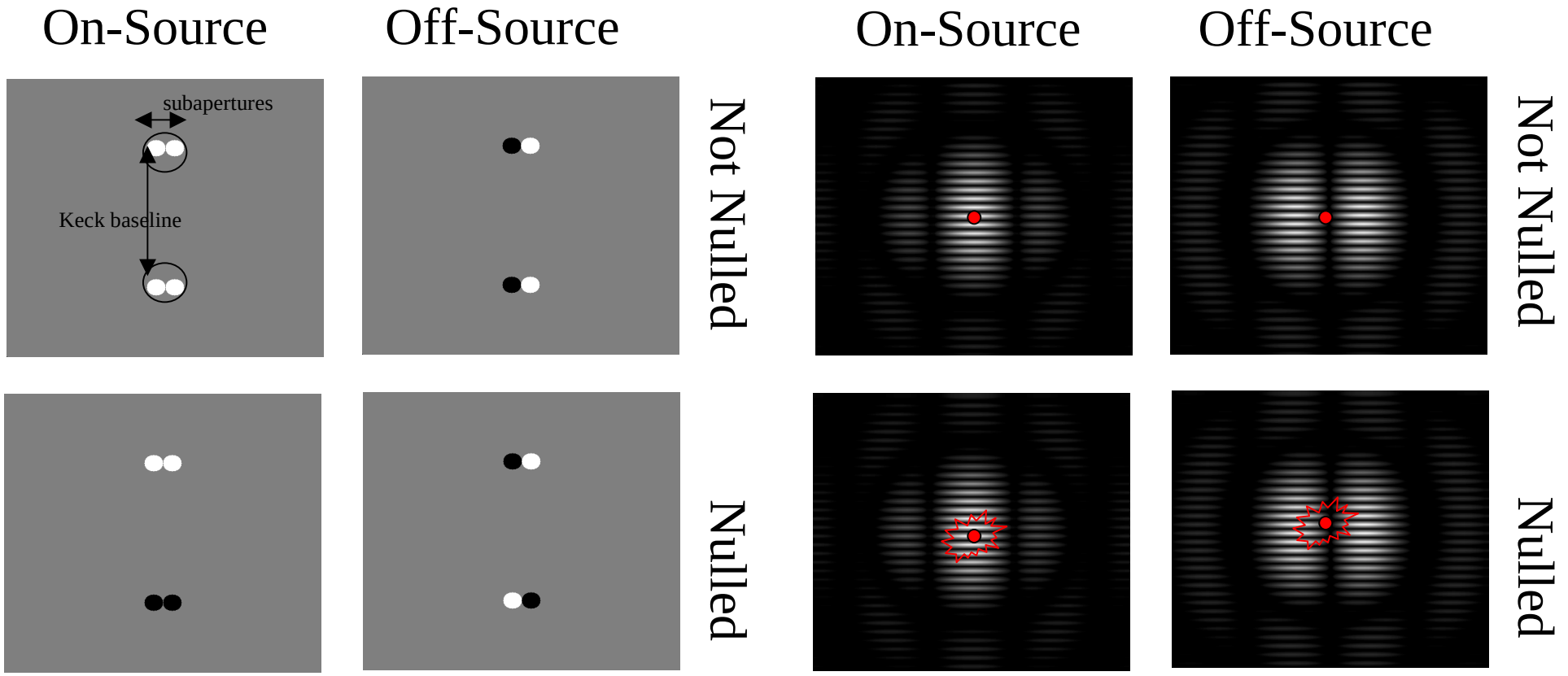
New Nulling Configuration:

Field-flip prior to beam combiner, followed by modified Mach-Zehnder interferometer



Nulling Outputs:

- Balanced outputs (subtract rt products)
- Only 1 mirror reflection per arm
- Complete symmetry w.r.t. beamsplitter
- 1 pass thru dielectric
- 1 pass thru AR coating
- Common r, Φ_r in both paths
- Common t, Φ_t in both paths
- Limited only by beamsplitter uniformity, and alignment issues: beam shear, wedge angles



white = 0° black = 180°

Not nulled = bright KK fringe On-source = bright aperture fringe

Nulled = dark KK fringe Off-source = dark aperture fringe

Summary and Conclusions

- Nulling interferometry holds best hope for studying exozodiacal and exoplanetary candidates for arbitrary distances (although there are coronography advocates)
- Next decade we expect exciting results from ground-based interferometers in preparation for space-based missions

Stay tuned.....

Acknowledgements

- E. Serabyn, B. Mennesson, C. Koresko & P. Lawson for suggestions on what to present
- WWW for many pictures
- ADS abstracts for text
- G. van Belle for computer use

References

- Serabyn, 2002, IEEEAC, “Comparison of High Dynamic Range Near-Neighbor Detection Approaches for TPF”
- All other references listed within text of presentation