High Contrast Interferometry: Nulling Interferometry and Differential Phase

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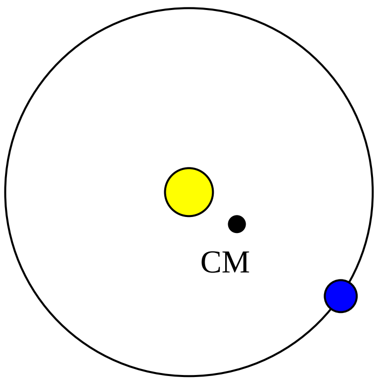
Outline

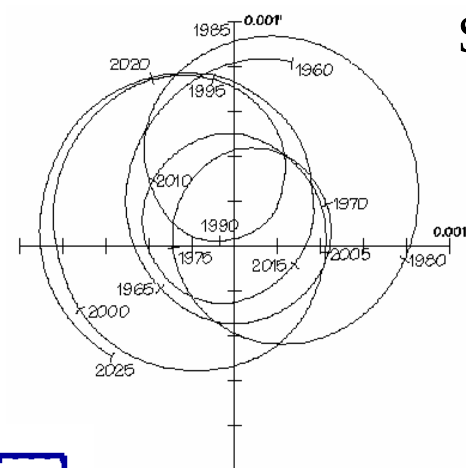
- Extrasolar Planets and Exozodiacal Disks in the Infrared
- Two Interferometric Direct Detection Methods
- Differential Phase
- Nulling Interferometry
- The Keck Interferometer Nuller: A Few System Level Issues
- Future Plans: Nulling from Space

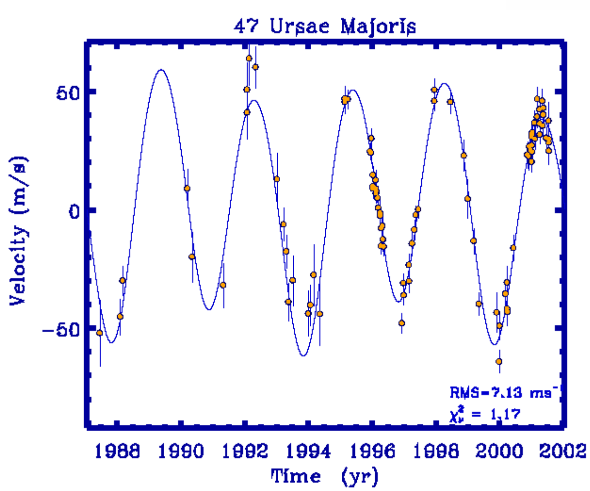
Extrasolar Planets and Exozodiacal Disks in the Infrared

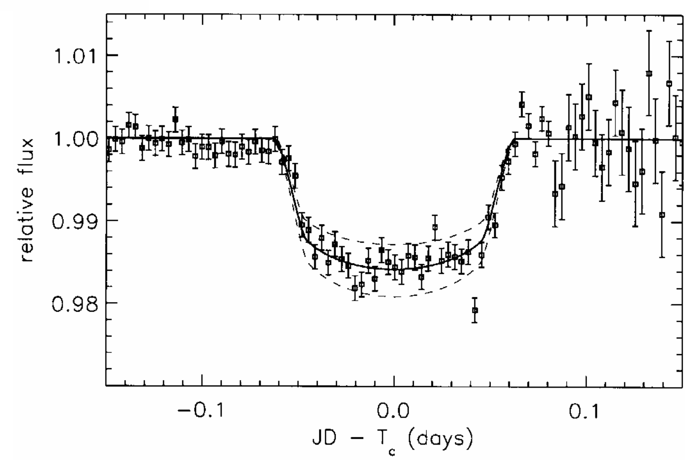
Planet Detection Methods: Indirect

- **Indirect Methods**: perturbations to stellar parameters:
  - Stellar Velocity → Radial Doppler Shifts
  - Stellar Position → Astrometry
  - Stellar Intensity → Transits, Microlensing, Spectrum Modification









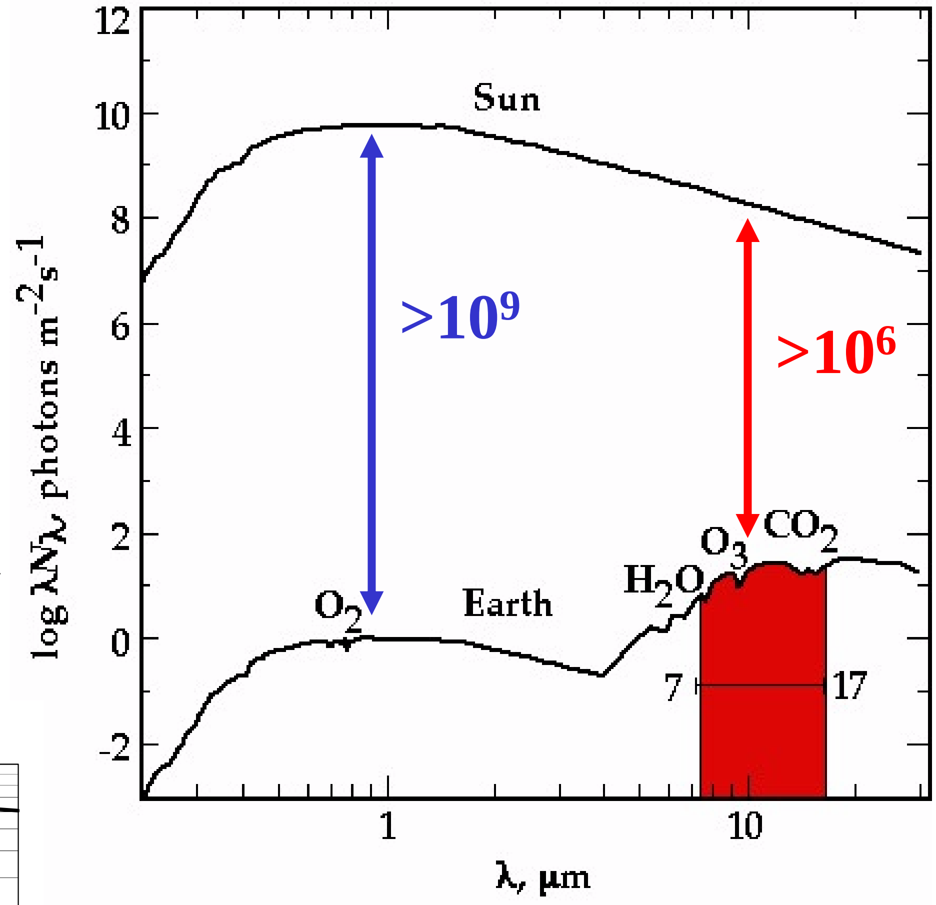
Problem I: Small Angular Scales

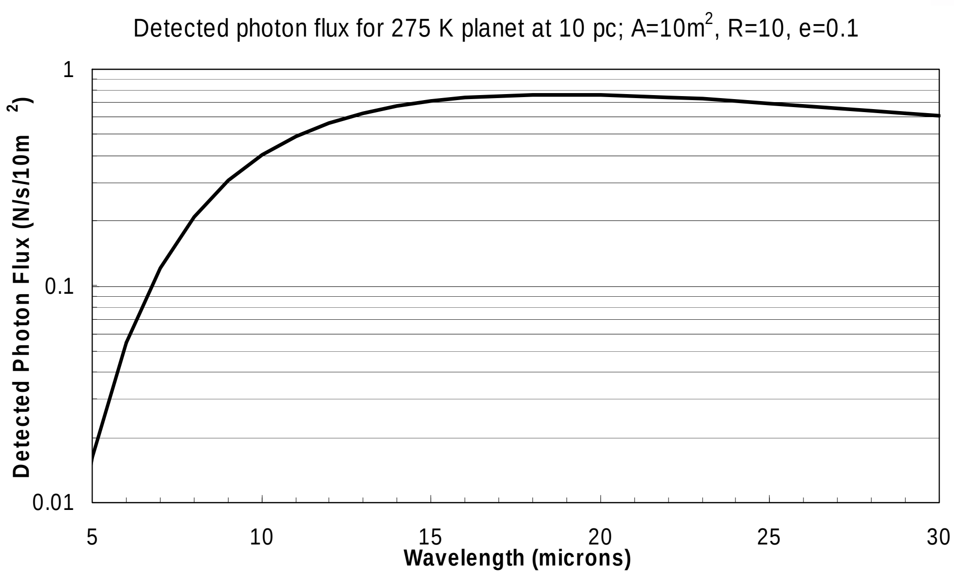
Earth Orbital Radius at 10 pc ⇔ 0.1 arc seconds
Saturn Orbital Radius at 10 pc ⇔ 1 arc second

- To see terrestrial planets in the "habitable zones" of nearby stars, need to be able to observe to within about 50 milli-arc seconds of bright stars

Problem II: High Contrast Ratio

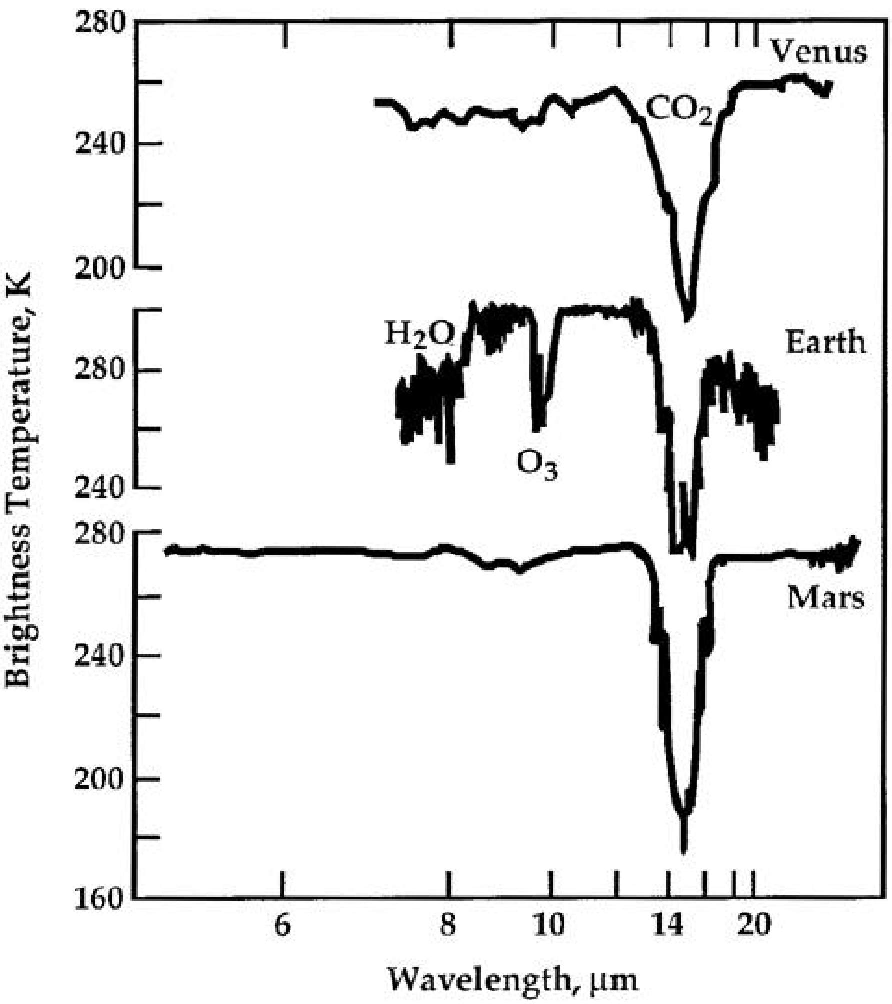
- **Terrestrial Planets:**
  - Reflected optical flux
    = a few 10^{-10} of star
  - Thermal emission contrast
    = a few 10^{-7} of star
  - Fluxes are faint, but detectable
  - But diffracted/scattered stellar light, and zodiacal & exozodical emission are much brighter





The Payoff: Mid-Infrared Planetary Spectroscopy of Terrestrial Planets

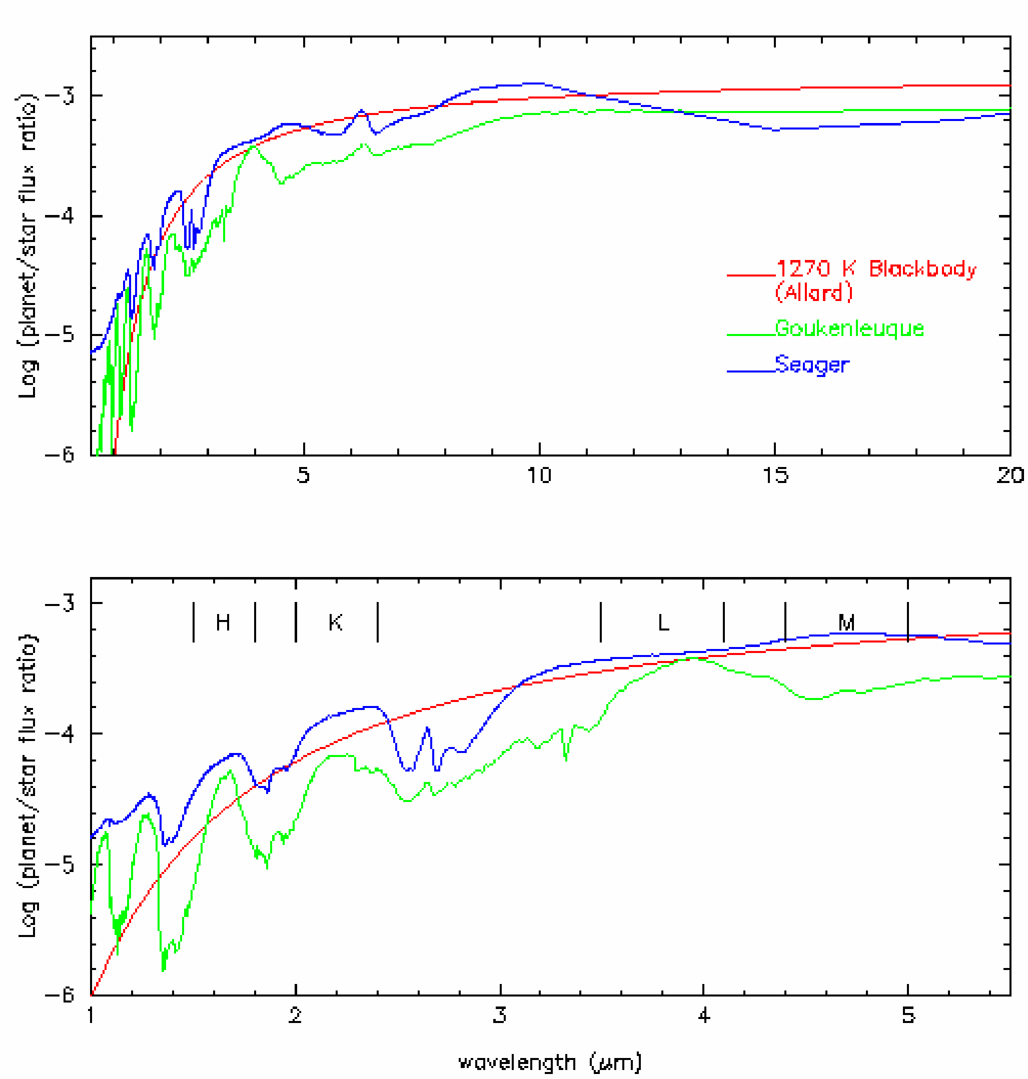
- Presence of a terrestrial planet atmosphere: CO_2
- Search for H_2O: precondition for life?
- Search for life: nonequilibrium species - O_2 , or O_3 as surrogate, perhaps CH_4
- Giant planet atmospheres



Jovian Planets & Hot Jupiter spectra

- **Jovian analogs:**
  Comparable contrast:
  larger, but farther out and cooler
- **Young Jupiters:**
  Bright, but need nearby young stars
- **Hot Jupiters:**
  Much brighter:
  contrast ≈ 10^{-3} to 10^{-4} in the IR
  But much closer in:
  need high angular resolution

Contrast changes from ≈ 10^{-3} to 10^{-4} across NIR



Problem III: Not Just Stars and Planets

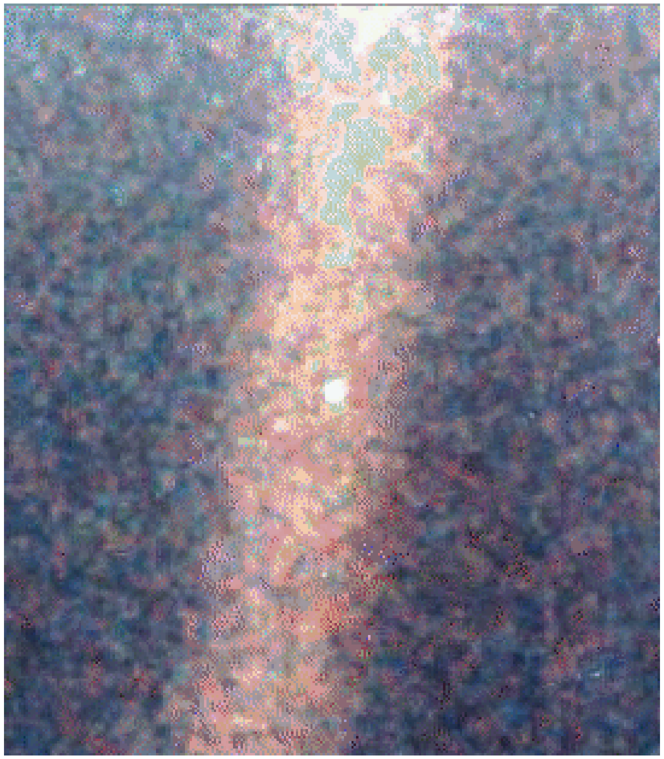
- Distance = 10 pc; λ = 10 μm;

- Signal strengths:

	MIR flux
G2 star	2.2 Jy
Exozodiacal emission (1 Zodi)	200 μJy
Jupiter	2 μJy
Earth	0.3 μJy

- Background fluxes:

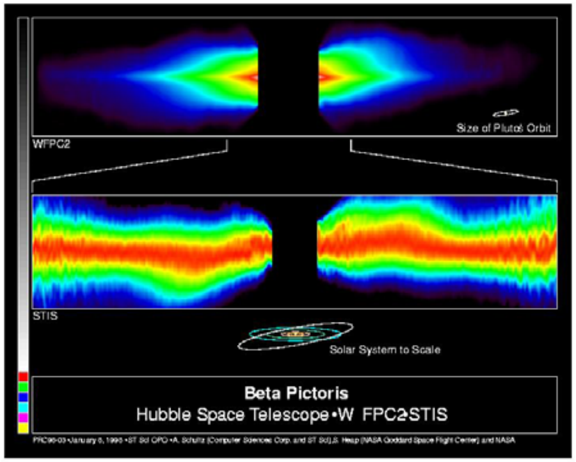
	MIR flux
Zodiacal emission	800 μJy
Sky (emissivity = 0.1)	30 Jy



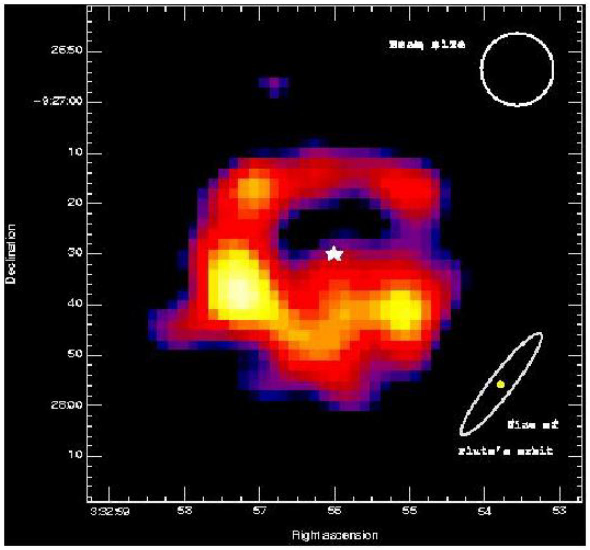
- **Integrated exozodiacal emission may be much brighter than 10 μm planetary emission**

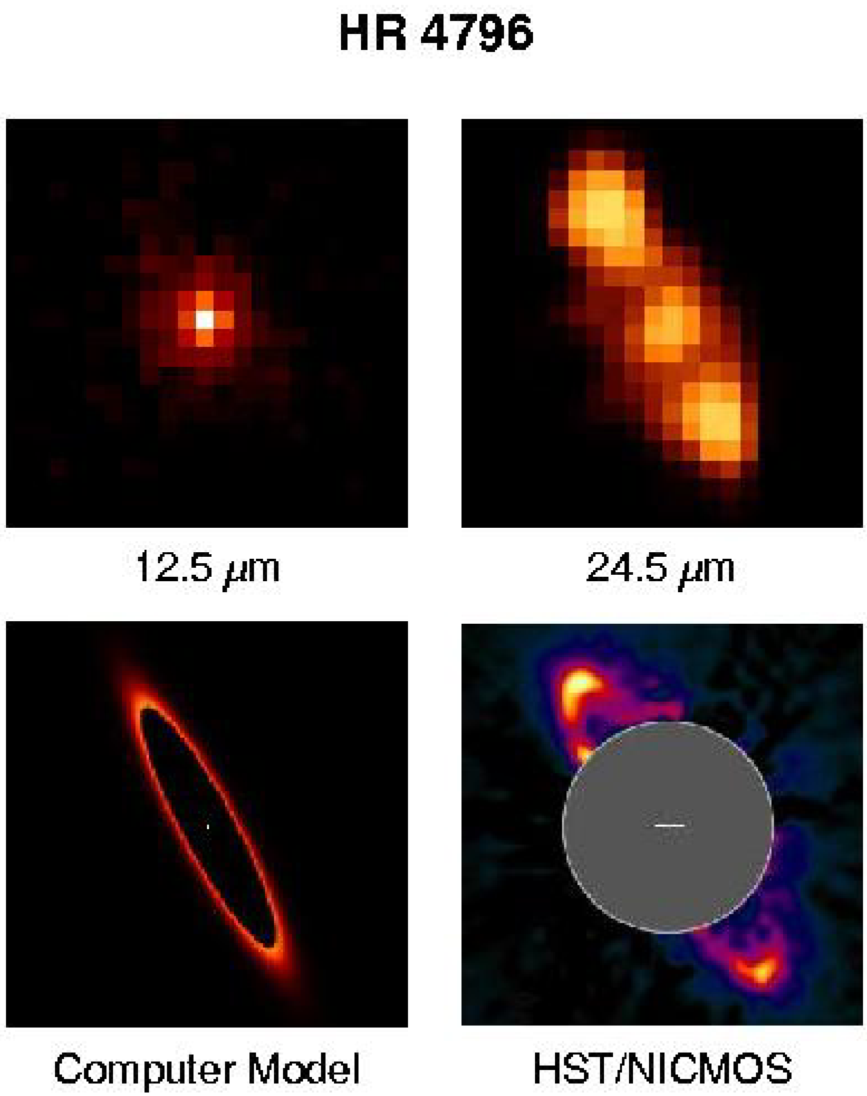
Dust Disks around Nearby Stars

Optical,
β Pic



Submm,
Vega





- Cold dust primarily at > 30 AU, Kuiper-belt-like radii; not zodiacal disks
- Exo-zodiacal disks much closer in; how bright are they for typical stars?

Interferometry Science Goals

- NIR:
  - Bright hot Jupiters:

    Large NIR spectral slope suggests differential measurement vs. wavelengths: differential phase
- MIR:
  - Contrast ratio OK on exozodiacal dust and hot Jupiters:
  - Null star out and measure fluxes directly

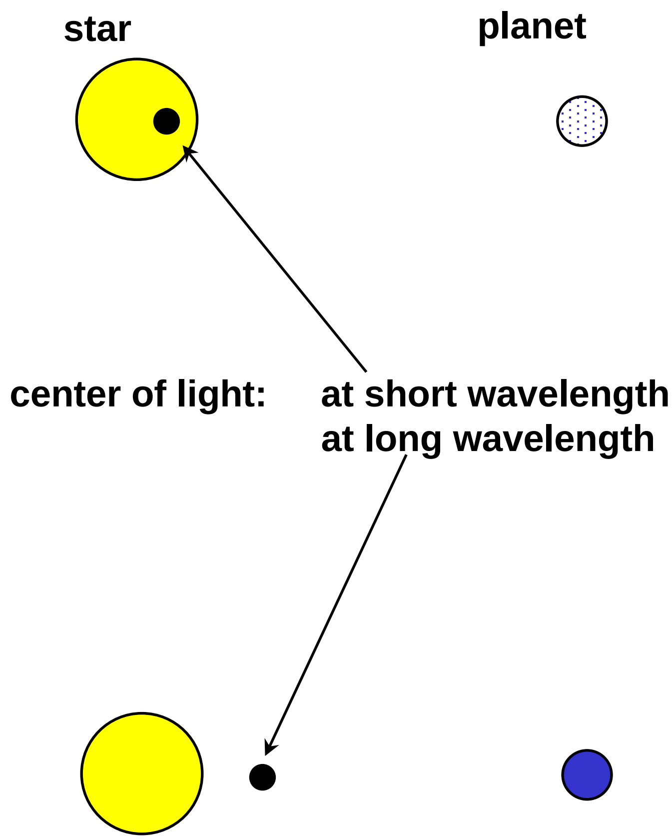
Staged Development of Nulling Interferometry

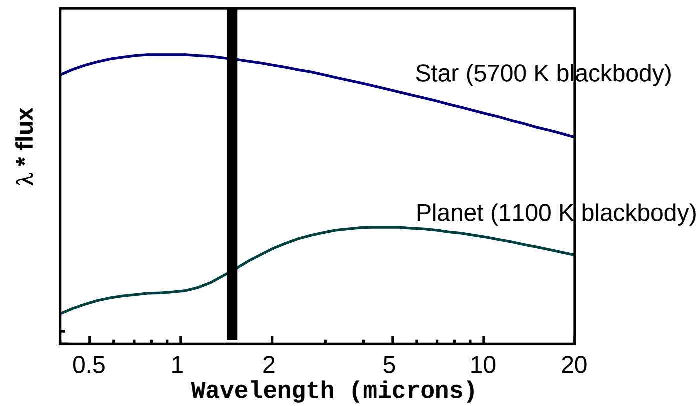
- Ground-based nullers on large-telescope interferometers (Keck, LBT, VLTI):
  - lower contrast sufficient to detect exo-zodiacal disks and perhaps super-bright planets
- Spaced-based nullers:
  - Higher contrast and stability to detect terrestrial planets (TPF_n, DARWIN)

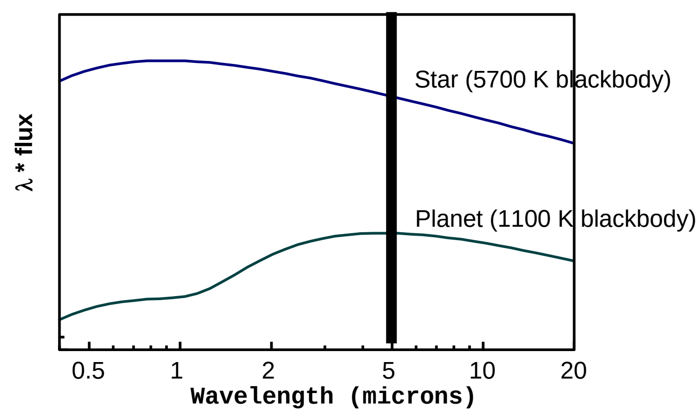
Interferometric Direct Detection Methods

Detection of Hot Jupiters with Differential Phase

Convert intensity ratio to phase shift for binaries with **different spectra**

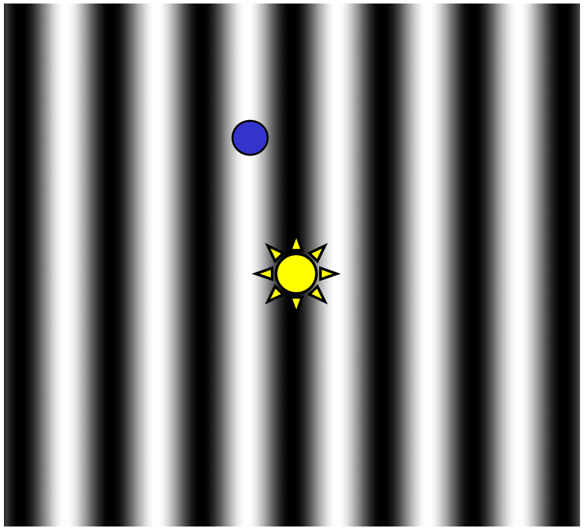






Nulling Interferometry

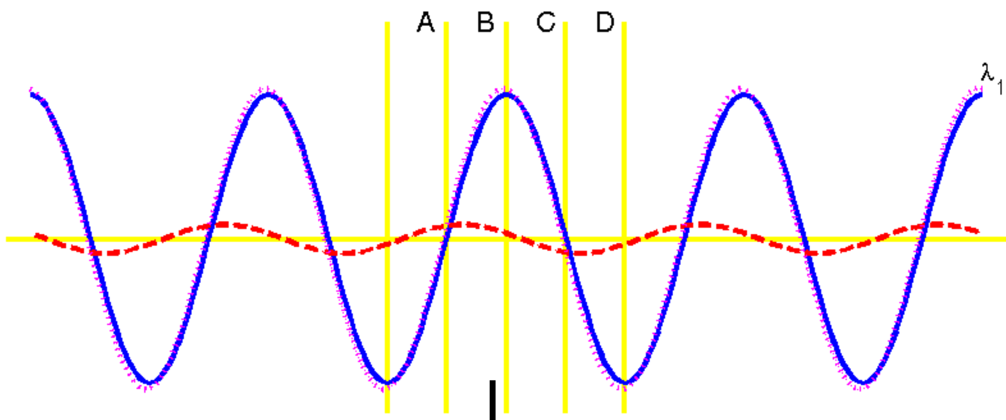
- Place destructive interference fringe across star
- Detect off-axis planets or disk emission through constructive fringes



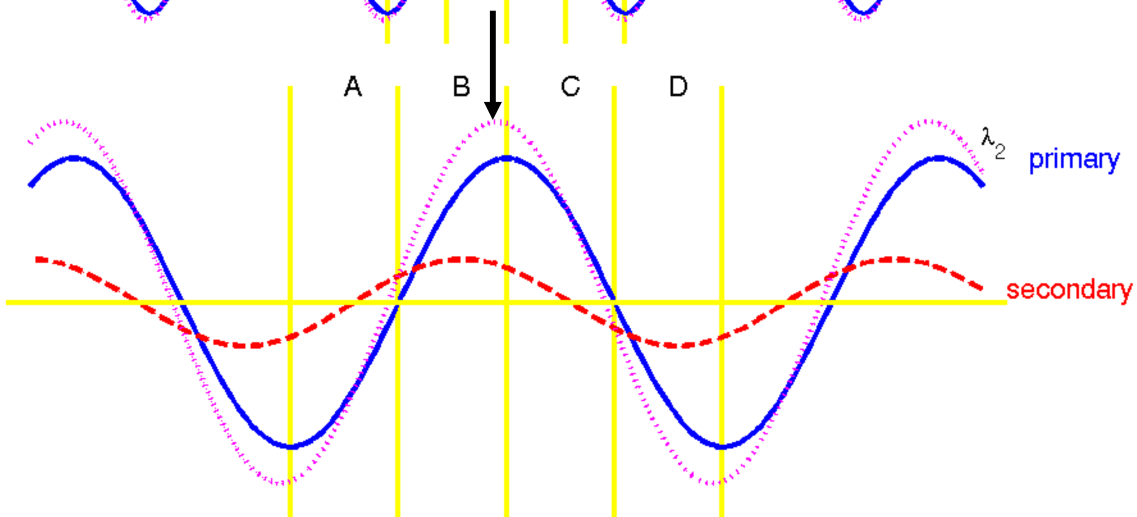
Differential Phase

DP fringes

Faint secondary



Not quite so faint secondary



- Fringe phase is a function of λ if the two sources have different spectra

DP signal

- Combined signal = $A+Be^{i\phi}$, with $B<<A$ and $\phi=kb\theta$
- $\tan\psi = B\sin\phi / (A+B\cos\phi) \approx B\sin\phi / A$
- $\mathrm{Max}(\psi) \approx B/A$

  $\approx 10^{-4}$ radians at 2 μm

  $\approx 3 \times 10^{-4}$ radians at 4 μm
- Differential Phase = $\psi_1 - \psi_2 \approx B_1/A_1 - B_2/A_2$
  is roughly the difference in the planet/stellar flux ratio at the two wavelengths, 1 & 2
- Size of DP = few tenths of milliradians at most
  - requires relative phases to about 100 picometers

Expected DP for known Hot Jupiters

Star	T_{star}	Semi-major axis (mas)	T_{planet}	Max DP H-K (mrad)	Max DP K-L (mrad)
HD 187123	5830	0.9	1290	0.09	0.18
τ Boo	6600	2.7	1540	0.10	0.33
HD 209458	6025	0.9	1200	0.04	0.10
HD 75289	6030	1.6	1350	0.10	0.24
51 Peg	5750	3.3	1230	0.06	0.25
υ And	6300	3.9	1480	0.09	0.23
HD 217017	5570	3.5	980	0.03	0.19

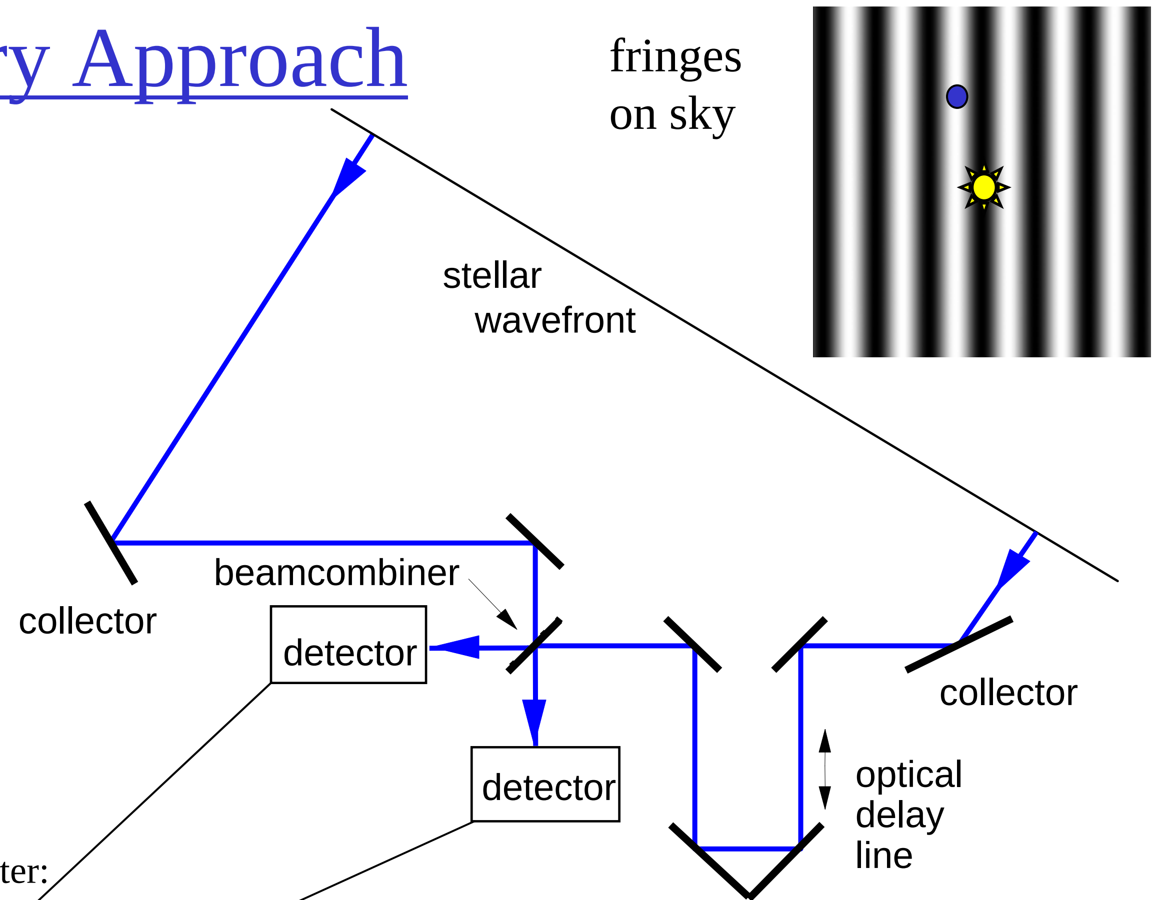
Calibration Procedure

- Use zero DP star to accurately calibrate DP phase
- Build highly accurate/linear fringe scanner with metrology to linearize scan
- Water vapor fluctuations on a good night on Mauna Kea produce a DP signature 1000 times larger than the astrophysical signal
- Use known spectrum of water refractivity to distinguish between water and astrophysical signal

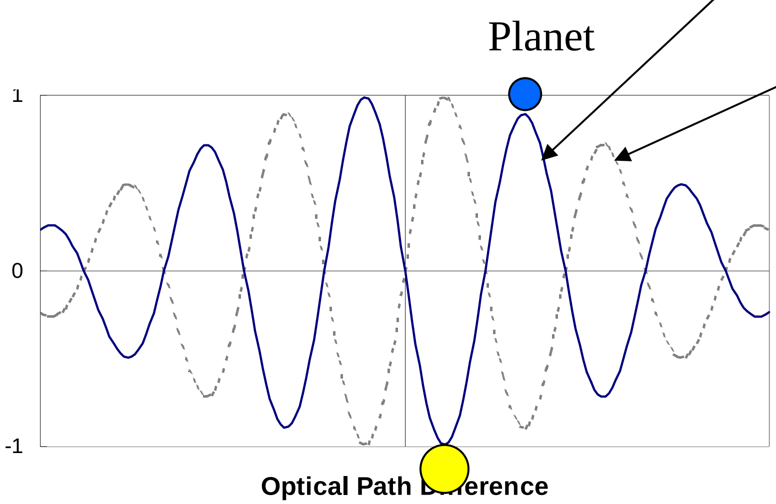
Nulling Interferometry

Nulling Interferometry Approach

- Star: destructive interference
- Off-axis planets constructive
- Need very deep, achromatic destructive interference fringe



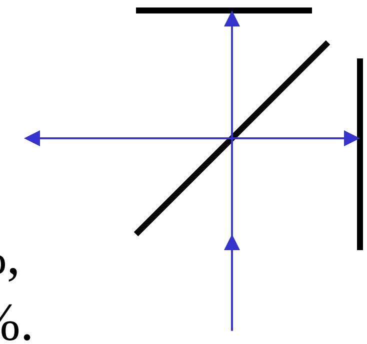
Detector outputs with single-pass beamsplitter:



Achromatic Destructive Interference

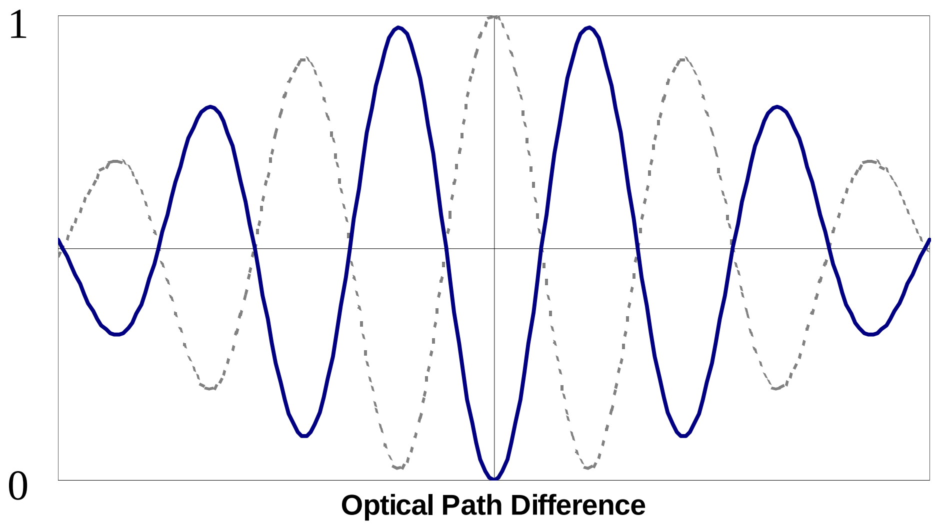
- Normal ``constructive" 2-beam interferometer: $I_{\text{out}} = I_{\text{in}}(1+V\cos\varphi)/2$
- Bandwidth limitation to destructive interference minima:

$$\frac{I_{\min}}{I_{\max}} = \frac{1}{2}\left(1-\operatorname{sinc}\frac{\pi}{2}\frac{\Delta\lambda}{\lambda}\right)$$



- For bandwidths of 5, 10, 20, 30, 40, and 50%,
  the deepest cancellation is 0.05, 0.2, 0.8, 1.8, 3.2, and 5%.

- Deeper cancellation requires an achromatic approach,
  e.g. a relative field flip, a double-pass beam-splitter, etc.



$$I_{\text{out}} = I_{\text{in}}(1-V\cos\varphi)/2$$

Nulling Basics

- Introduce a wavelength-independent phase shift of 180 degrees between the two arms of an interferometer. Converts the central maximum to an achromatic destructive interference minimum (null):

  $$I_{out} = I_{in}(1 - V\cos\phi)/2.$$

  Here I_{out} is the *total* output power (for 2 input beams).

- Null depth definition: $$N \equiv I_{min} / I_{max}$$

- For visibilities close to 1, $$N = (1 - V\cos\phi)/2$$

- For V=1 and small phi, $$N = (\phi / 2)^2$$

General achromatic nulling requirements

- Desire $E_1 - E_2 = 0$
- High degree of **symmetry** and **stability** required:

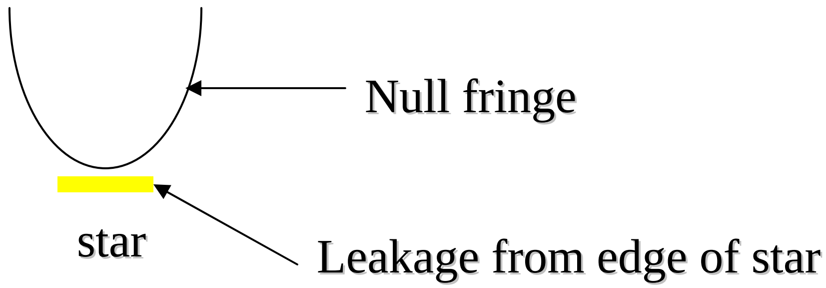
- **E** fields in the two input beams oppositely oriented
- Equal field amplitudes
- Zero relative path difference
- Simultaneous zero of OPD for both polarizations
- Simultaneous cancellation at all wavelengths in the passband
- Simultaneous zero of OPD across aperture:

  Surfaces typically limit null depth to ≈ 1- Strehl ratio, or few %

  ⇒ wavefront cleanup with single mode spatial filter required

- Small stellar angular diameter (singler baseline):

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



EQUATIONS FOR NULL DEPTH IN THE PRESENCE OF ERRORS

Instantaneous null depth for broadband plane waves from a disk-like source (aberrations not included):

$$\mathrm{N(t)} = \frac{1}{4}\left[(\Delta\phi_{\mathrm{c}}(\mathrm{t}))^2 + \langle(\Delta\phi_{\lambda}(\mathrm{t}))^2\rangle + \frac{\pi^2}{4}\left(\frac{\theta_{\mathrm{dia}}}{\lambda_{\mathrm{sh}}/\mathrm{b}}\right)^2 + \frac{1}{4}(\Delta\phi_{\mathrm{s-p}})^2 + \alpha_{\mathrm{rot}}^2 + (\delta\mathrm{I}(\mathrm{t}))^2 \right]$$

Time-average null in the presence of active OPD matching and intensity matching:

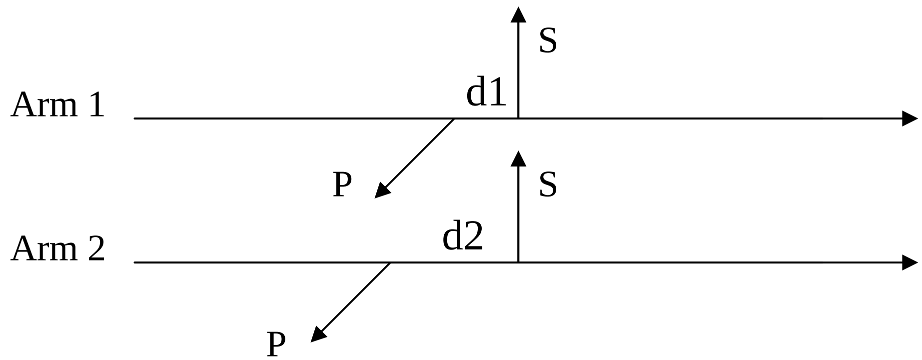
$$\overline{\mathrm{N}} = \frac{1}{4}\left[\sigma_{\phi}^2 + \langle(\Delta\phi_{\lambda})^2\rangle + \frac{\pi^2}{4}\left(\frac{\theta_{\mathrm{dia}}}{\lambda_{\mathrm{sh}}/b}\right)^2 + \frac{1}{4}(\Delta\phi_{\mathrm{s-p}})^2 + \alpha_{\mathrm{rot}}^2 + \sigma_{\mathrm{I}}^2 \right]$$

Root mean square (rms) fluctuation of the null:

$$\sigma_{\mathrm{N}} = \sqrt{\frac{\sigma_{\phi}^4 + \sigma_{\mathrm{I}}^4}{8}}$$

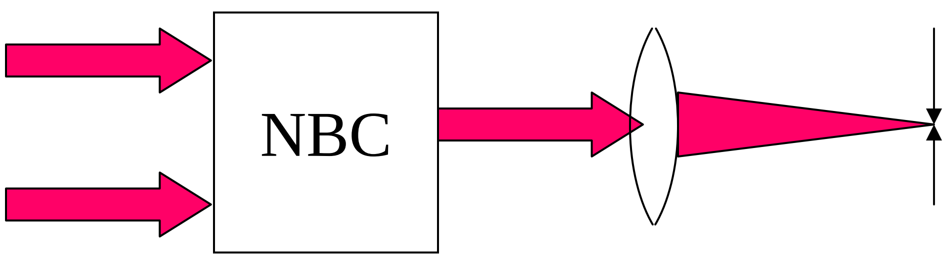
Keck requirements from null depth

	Constraint	N=1e-4
Differential Image Rotation	$\theta < 2\sqrt{N}$	$< 1°$
Throughput Asymmetries	$\frac{I_{diff}}{\bar{I}} < 4\sqrt{N}$	$< 4\%$
Strehl Fluctuations (1-S)	$\frac{\sigma_I}{\bar{I}} < 2\sqrt{N}$	$< 2\%$
Optical Path Errors	$x < \frac{\lambda}{\pi}\sqrt{N}$	< 32 nm
Feed Forward Time	$\frac{t_{ff}}{t_{02}} < \left(2\sqrt{N}\right)^{6/5}$	< 0.7 msec
Differential s-p Polar. Delay	$\Delta < 4\sqrt{N}$	< 2.3



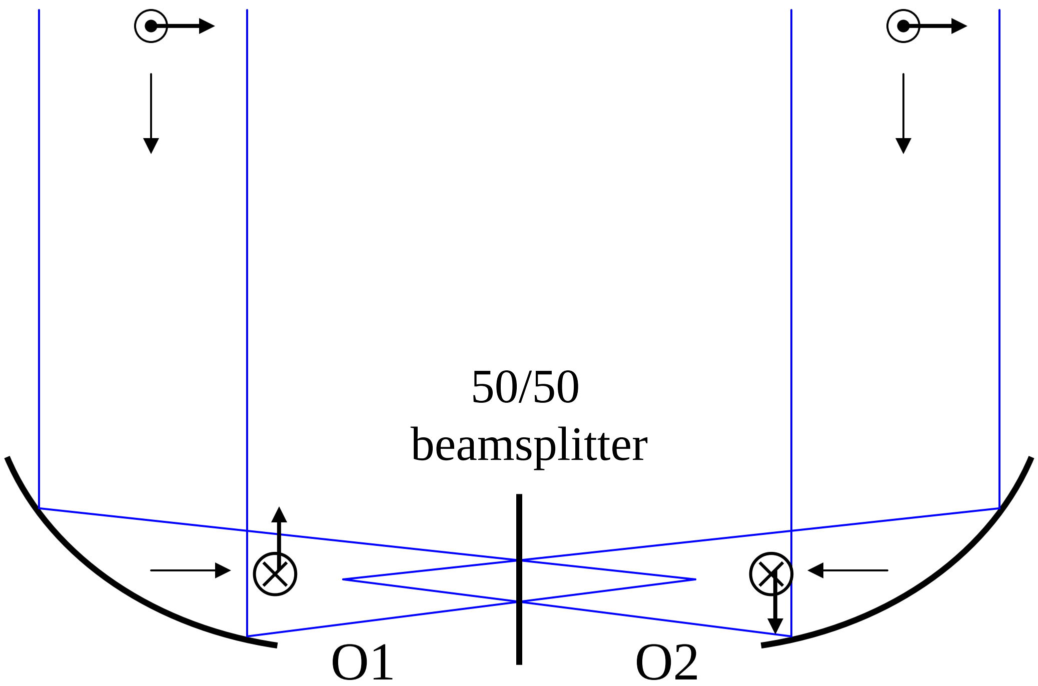
Wavefront Cleanup

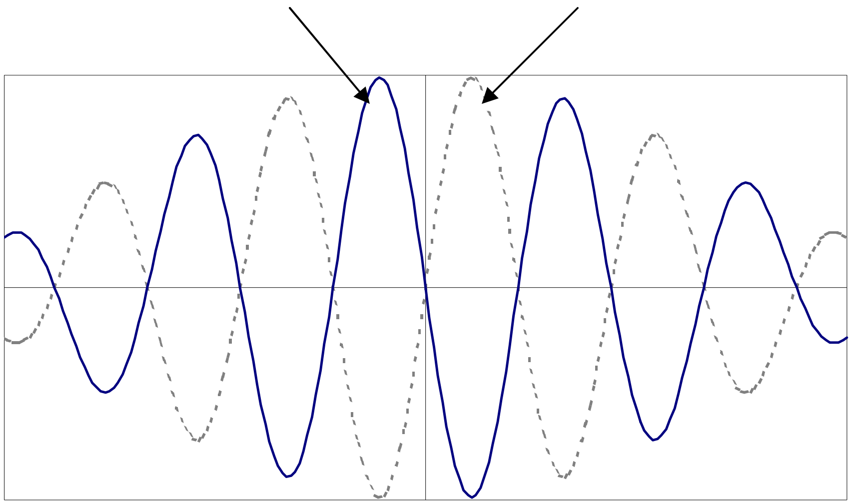
- Aberrated wavefronts prohibit simultaneous field cancellation across the wavefront. N limited to about 1-S.
- Wavefront cleanup required for deep nulls
- Effected by means of a spatial filter in output focal plane
- Only the point-spread function core is transmitted
- Limits nulling to a single spatial mode of the telescope



Achromatic nulling

The Role of Beamsplitters

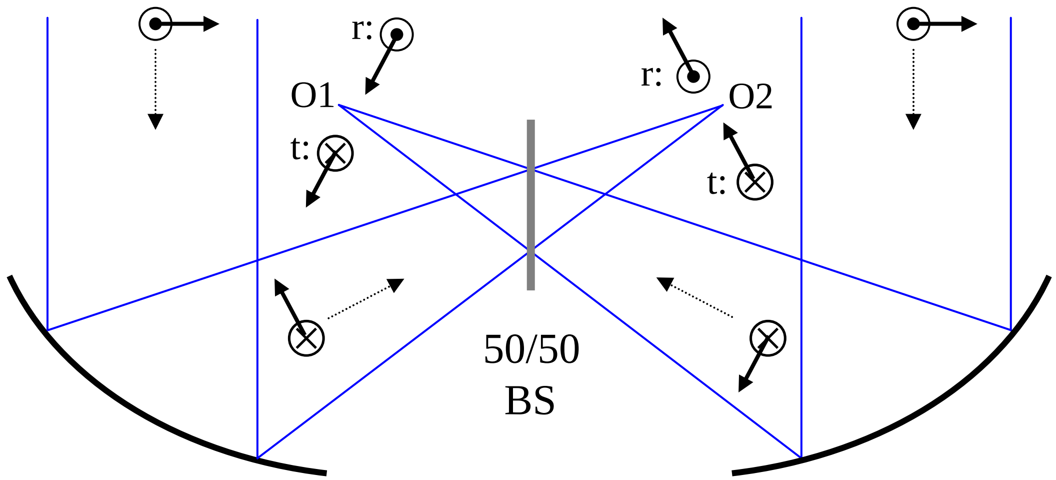


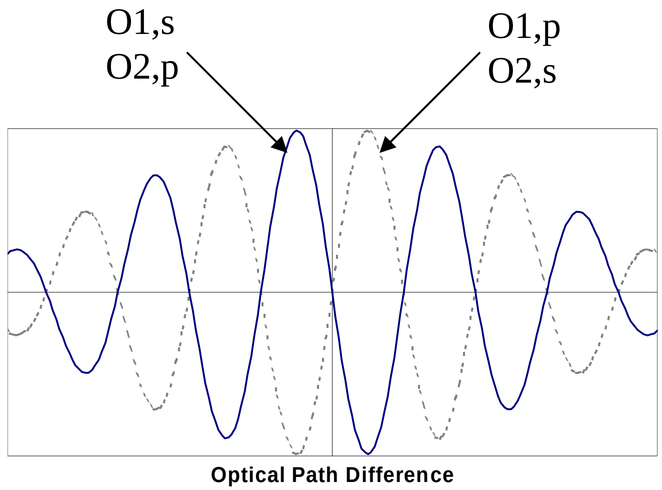


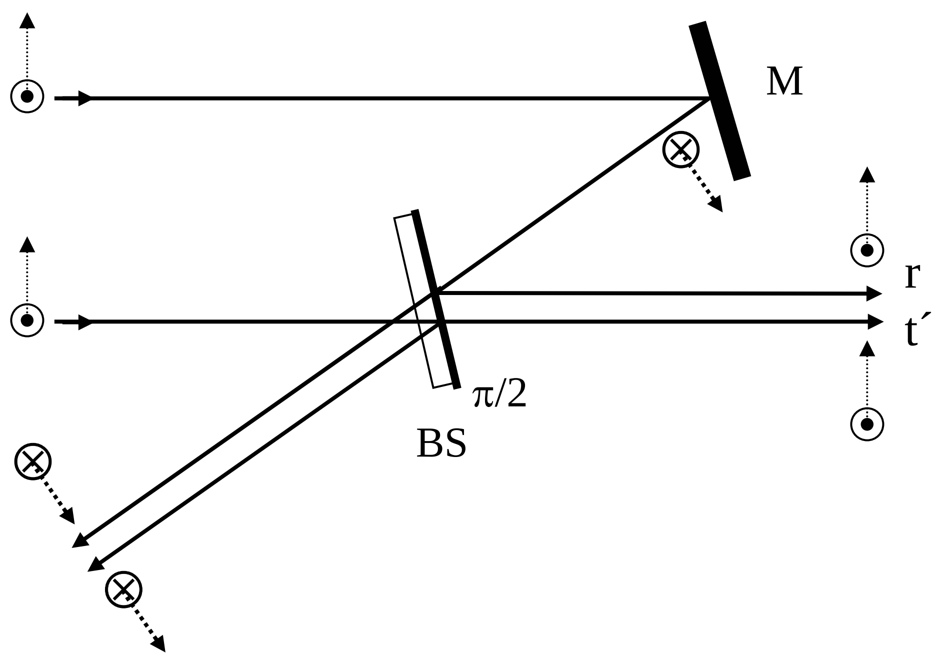
- Symmetric layout:
  - ⇒ at zero OPD equal powers to O1 & O2
  - ⇒ complementary fringes at O1 & O2
  - ⇒ no null at Zero OPD
  - ⇒ π /2 phase shift between r & t waves at b.s.

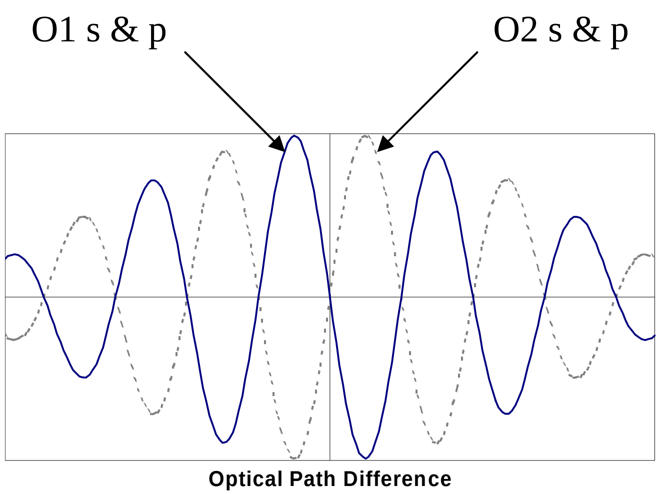
- Best cancellation at finite OPD
  - ⇒ cancellation is chromatic
- 2 polarizations yield fringes out of phase by π
  - ⇒ fringe patterns cancel completely
- Need to break symmetry with one extra reflection

Need to Break the Symmetry







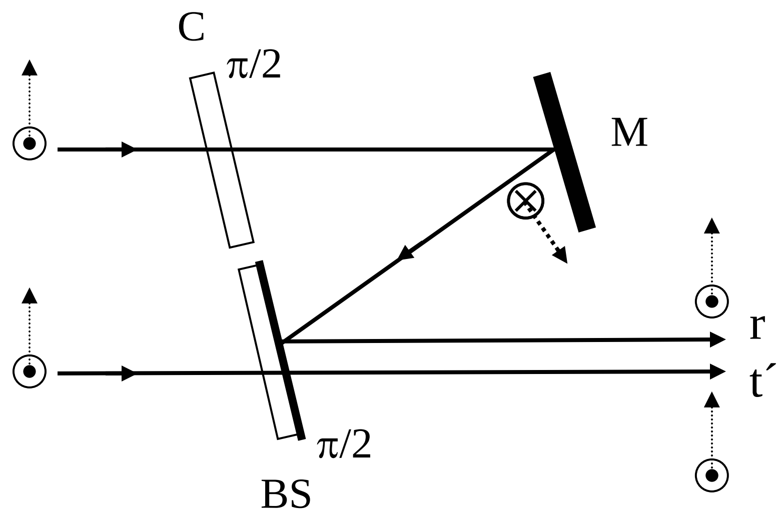


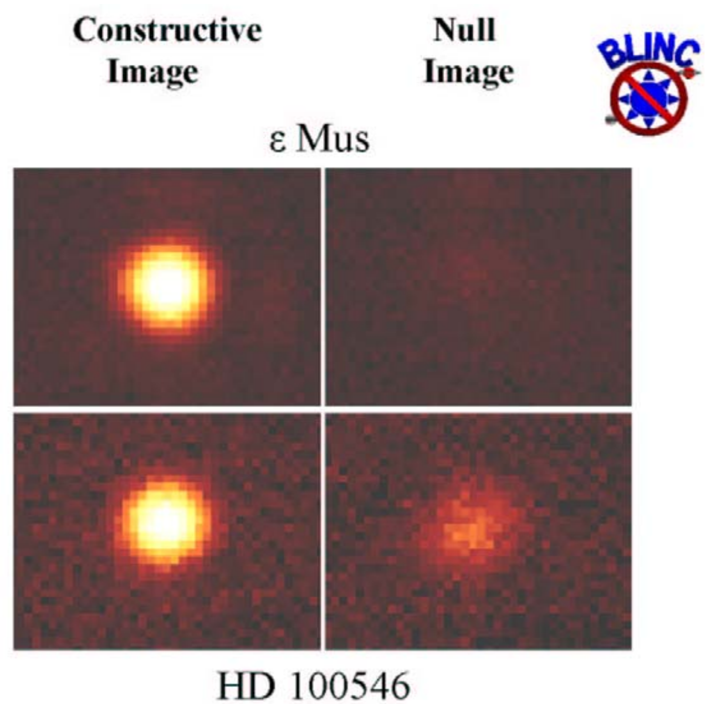
And Add an Additional π/2 Phase Shift

- Extra mirror in one arm phases both polarizations
- Ideal BS: phase(r) – phase(t) = ± π/2
- Thickness difference between BS & comp can give another π/2 phase shift

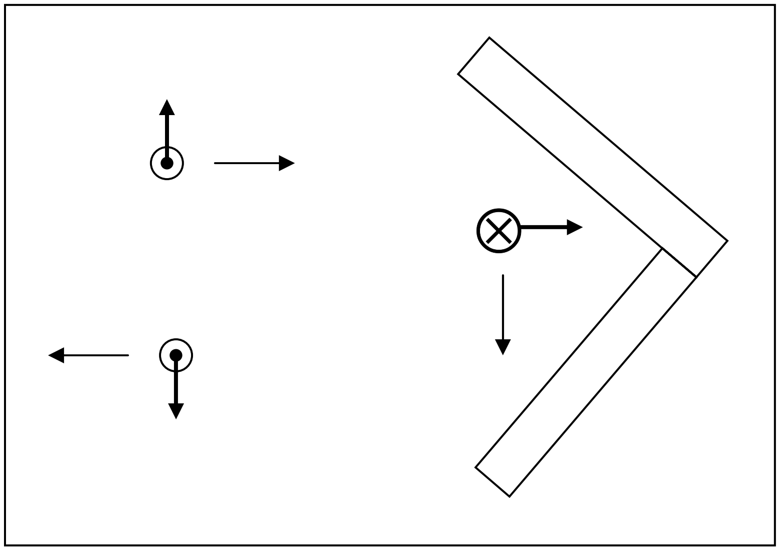
- Has been taken to telescopes (UofA)
  - Stellar null depths ≈ 0.04
  - Dust shells detected

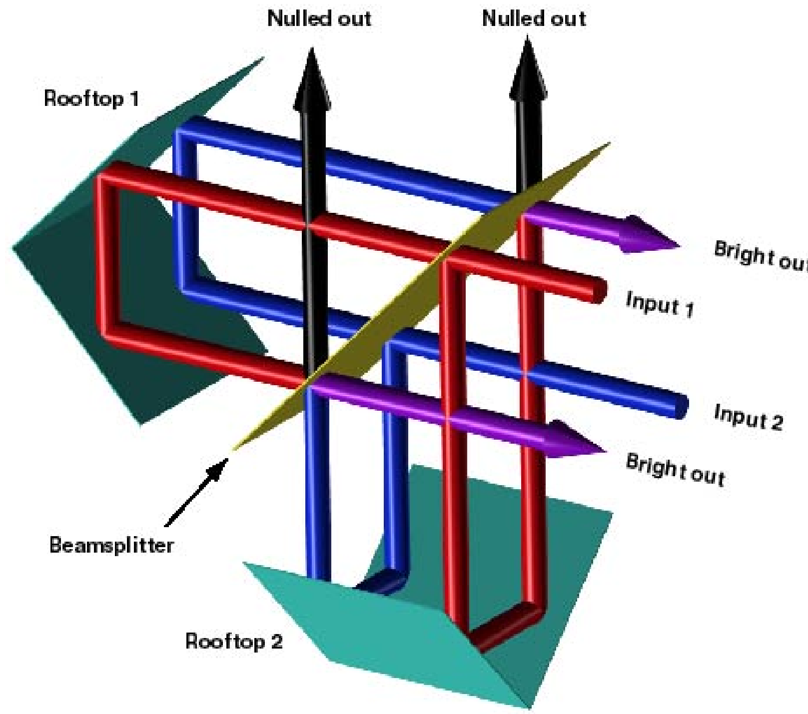
- But still has residual asymmetries:
  - Need amplitude match: r = t
  - Need ideal phase condition to be met: phase(r) – phase(t) = ± π/2
  - Unbalanced AR traversals present (symmetric "sandwich" beamsplitter removes this problem)



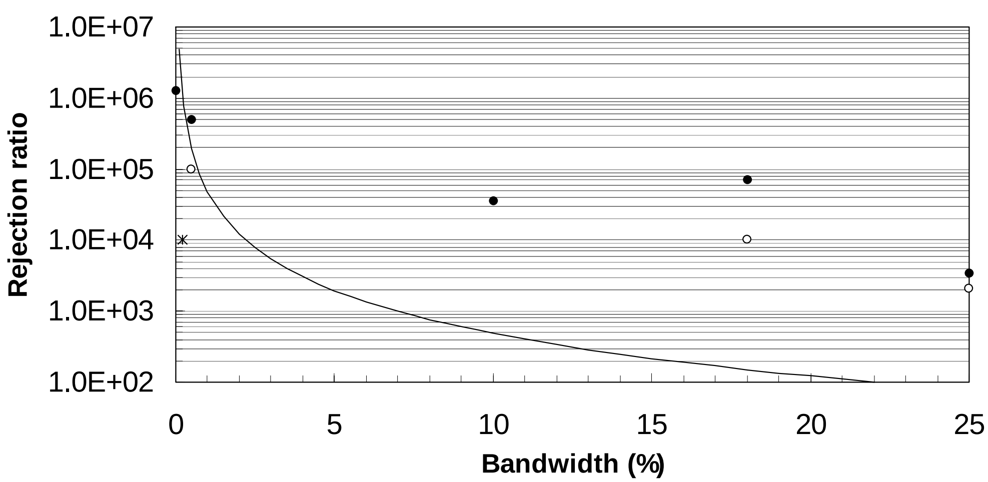


Or flip the field: rotational-shearing interferometer

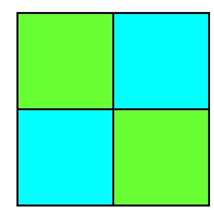




Laboratory single-pol results at JPL (IR & opt):

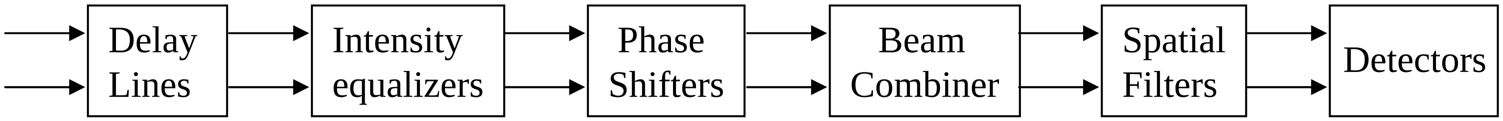


- ≈balanced nulling outputs: $rt - r't \approx 0$
- But:
  - r is not identical to r′
  - Unbalanced AR coating passes
  - Not completely symmetric
  - Want 4-quadrant BS:

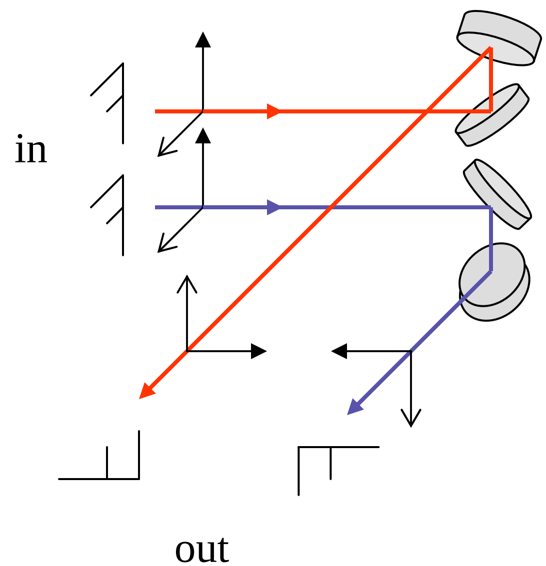


The Ideal Nuller: Completely Symmetric

- Goals:
  - completely symmetric (except for field reversal)
  - separable functionalities
- Elimination of residual asymmetries:
  - Unbalanced mirror reflections
  - Asymmetric beamsplitter coating passes
  - Unequal substrate passes
  - Unequal numbers of antireflection coating passes
- Dual-polarization operation
- Broadband operation
- Separation of Nuller Functions:
  - Field reversal
  - Phase shifting
  - Beam combination



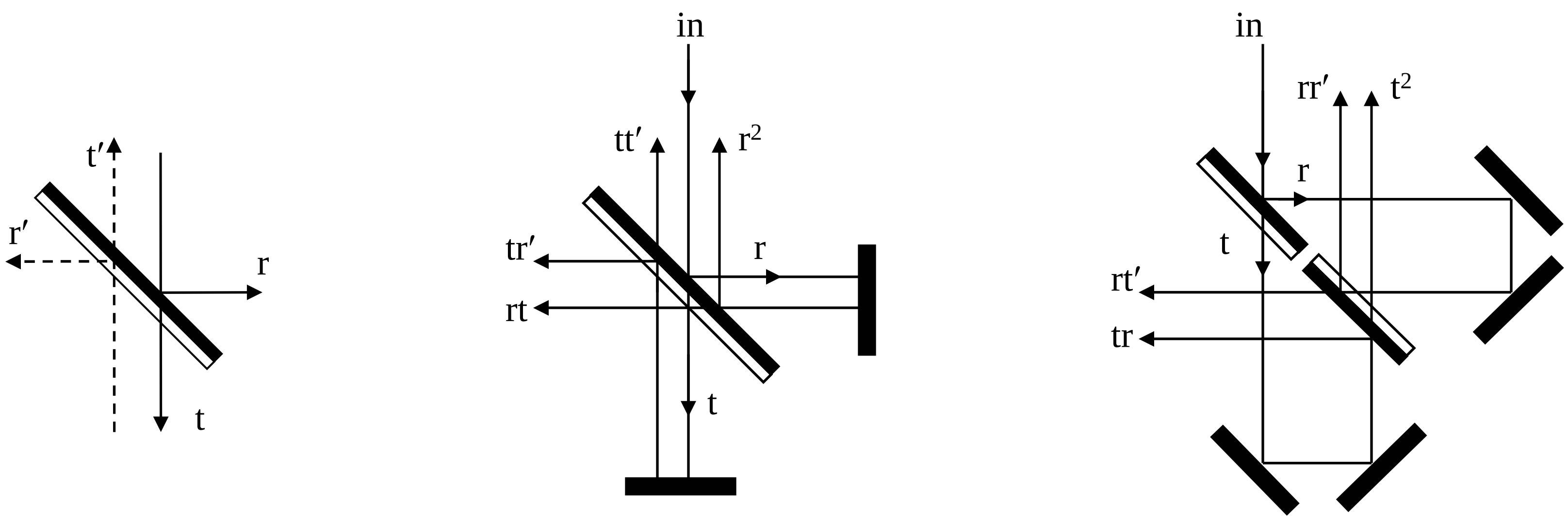
Achromatic field-flip
with inverted right-angle periscope pair



1s and 1p reflection
per polarization

- Output fields and images rotated 180º
- Allows field flip prior to constructive beam combiner
- Achromatic, polarization-independent field reversal

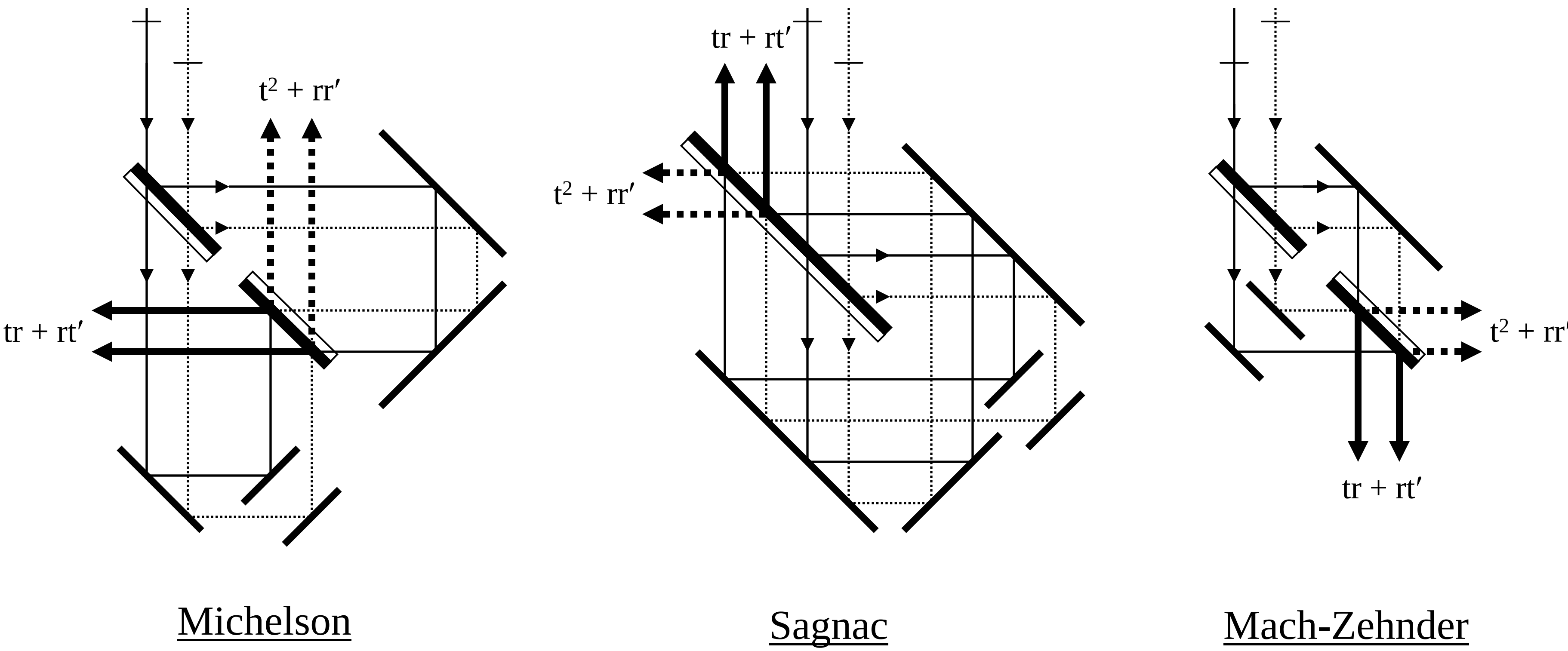
Perfect addition with a reciprocal beamsplitter pair



(a) **(b)** **(c)**

- Generally r ≠ t, so single pass beamsplitters are typically not very symmetric.
- Double pass: generally rt - r′t ≈ 0, but not = 0; However, rt′ - rt is identically zero.
- Reversed pair of beamsplitters yields a perfectly symmetric, constructive combiner.
- Reversed beamsplitter pairs provide this perfect constructive interference
  independent of polarization, wavelength, and angle-of-incidence
- Such a combiner needs to be preceded by a nearly-perfect field reversal.

Perfectly-symmetric, constructive 2-beam combiners

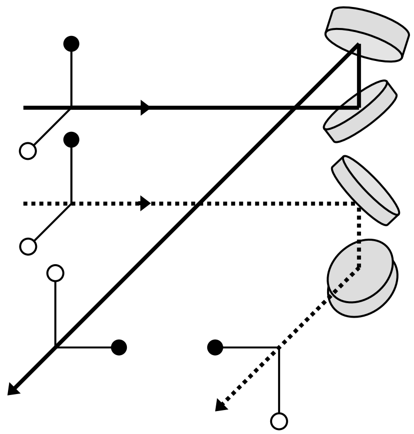


For nulling, precede these with a field reversal.

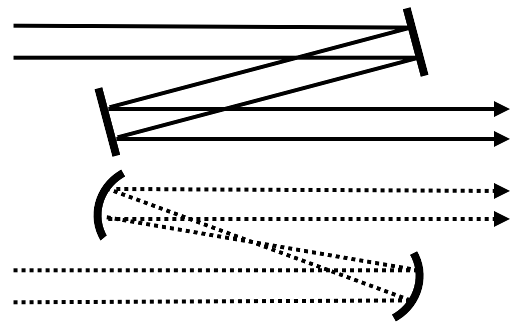
Beamsplitter Symmetry

- Coatings are not a big issue in symmetric double-pass configurations:
  - Balanced outputs have $rt - r't = 0$
  - Phase effects cancel: $\Phi(rt) = \Phi(r't)$
- On the other hand, BS-pair symmetry is important:
    - Coating variations
    - Substrate thickness matching
    - Substrate uniformity
    - Alignment matching
- Substrate wedge angle does break symmetry slightly

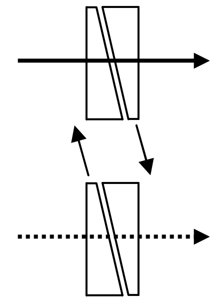
Field-reversal stages:



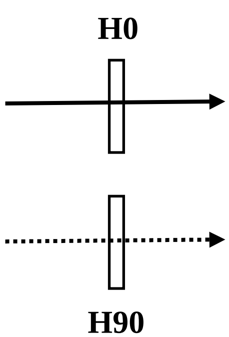
Right Angle Periscopes



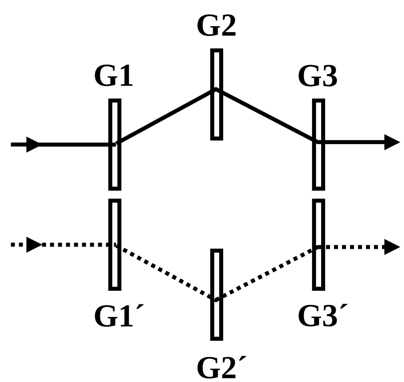
Extra Focus



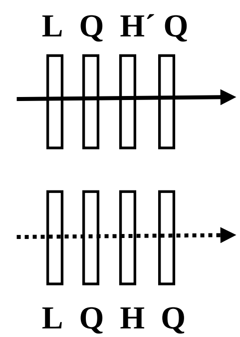
Dielectric Phase



Half Wave Plates

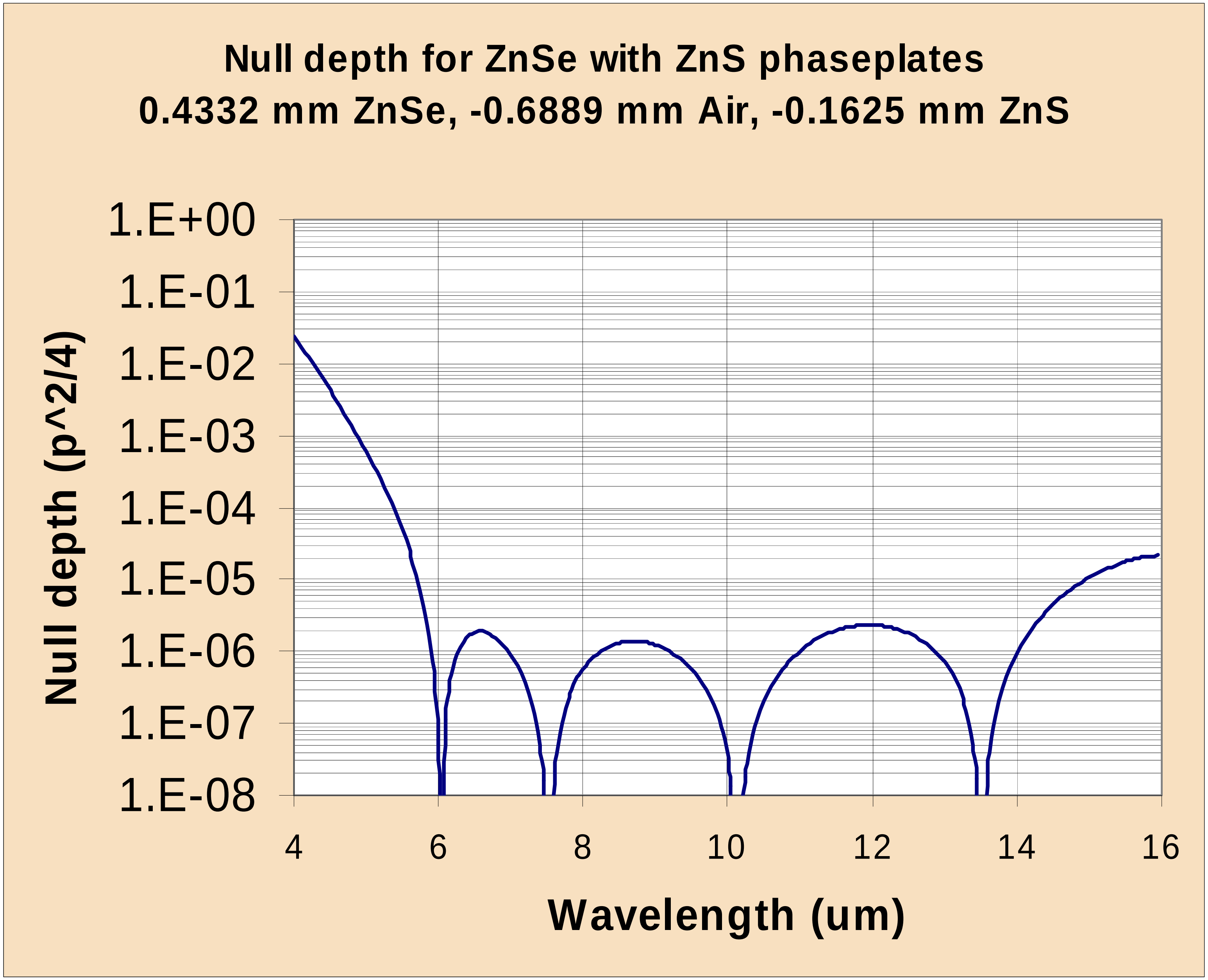


Grating Phase



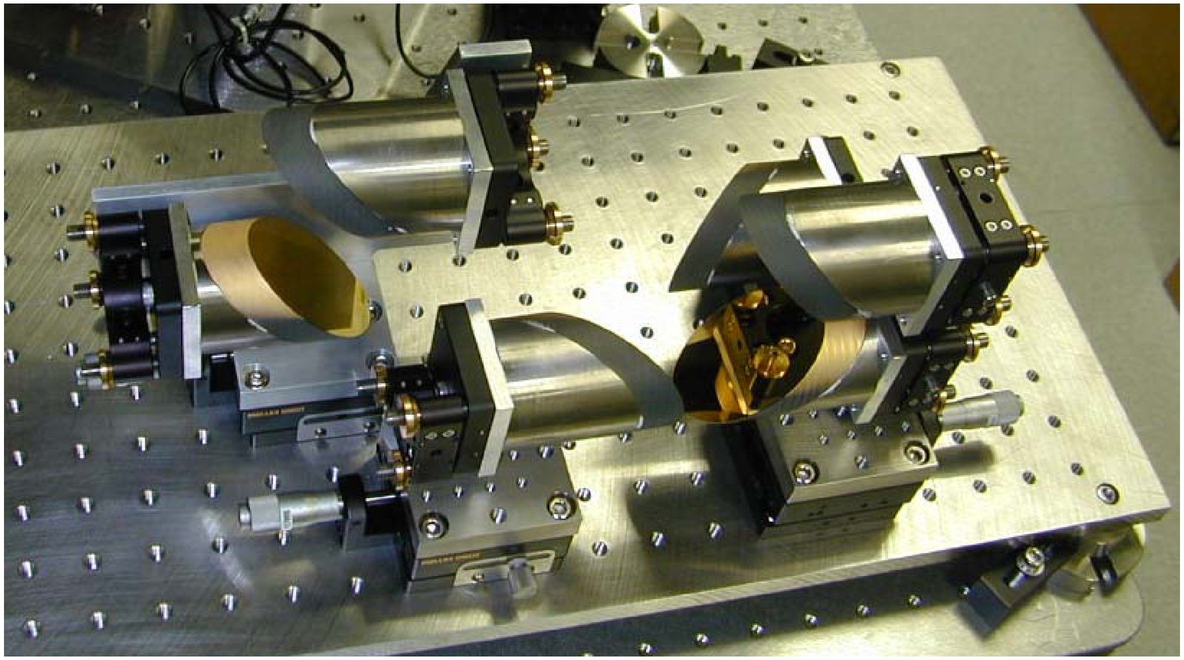
Pancharatnam Phase

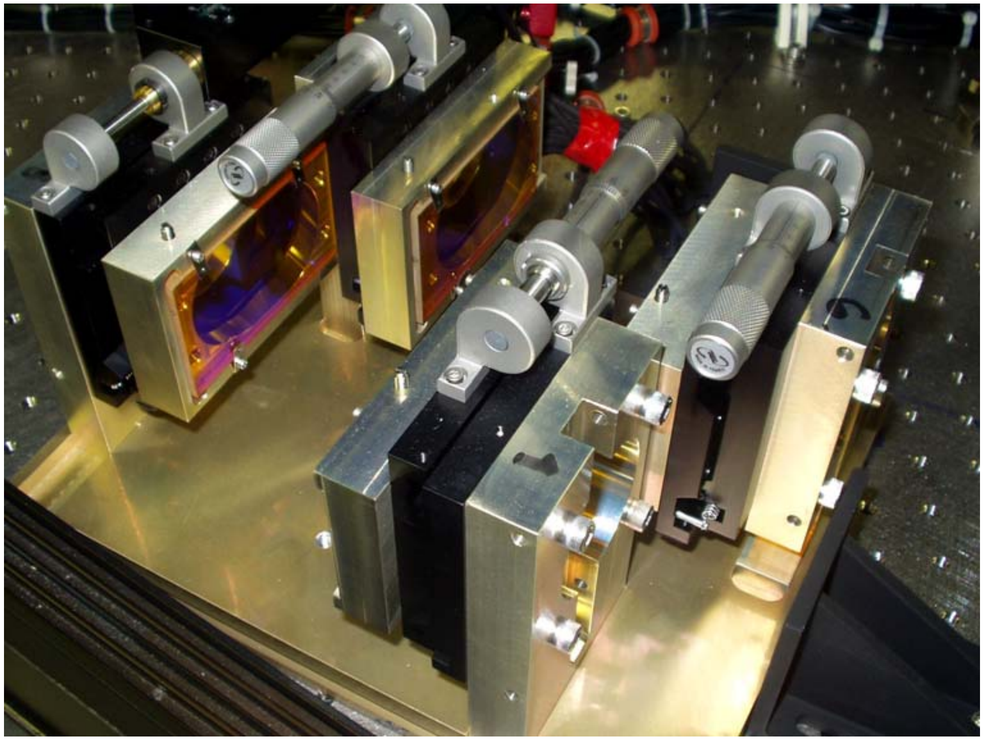
- Not all fully symmetric; some are lossy; some work with single-polarization; but all these approaches now work in principle
- The Keck Nuller needs dielectric phase plates to counteract atmospheric effects anyway, so they will be used for the nulling field reversal also.


Null depth for ZnSe with ZnS phaseplates
0.4332 mm ZnSe, -0.6889 mm Air, -0.1625 mm ZnS
Null depth (p^2/4)
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
4
6
8
10
12
14
16
Wavelength (um)

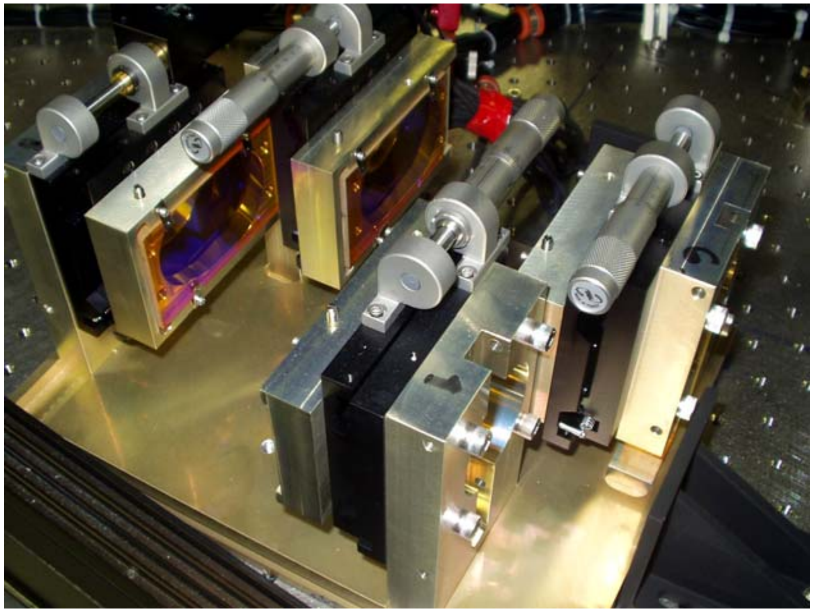
Field Flippers in the lab

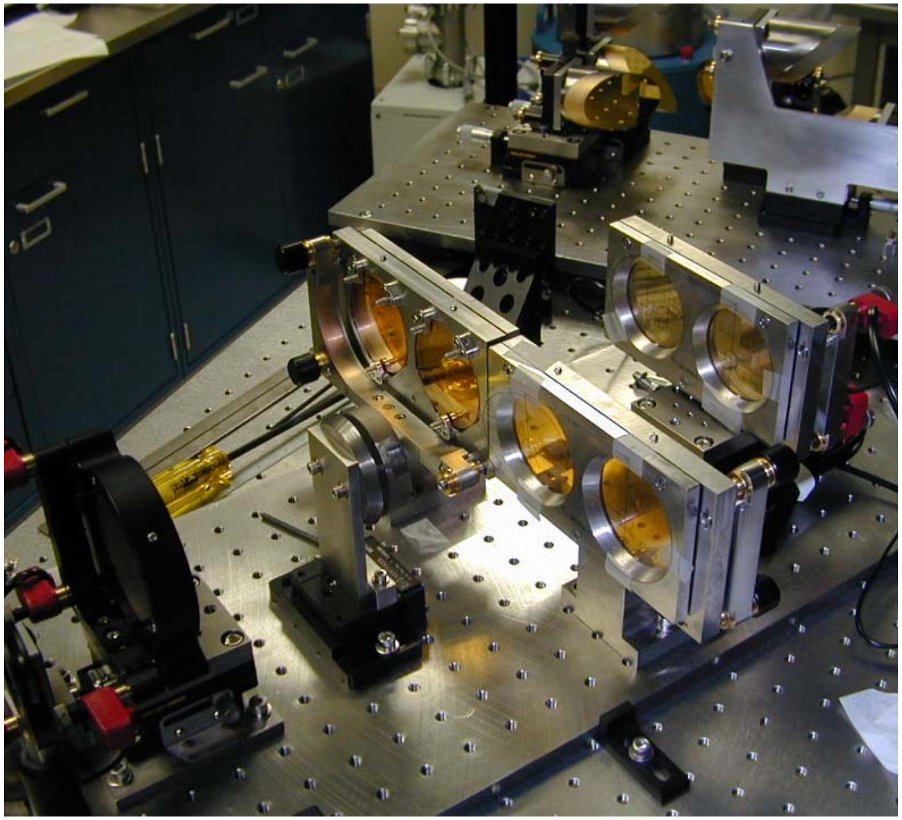
- Periscopes
- Dielectric prisms





The Keck and TPF mid-infrared MMZ nullers

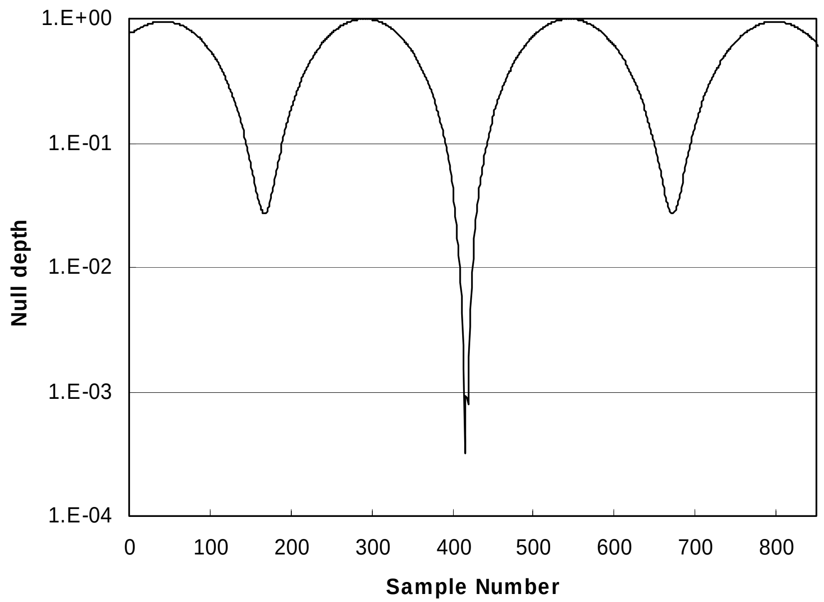


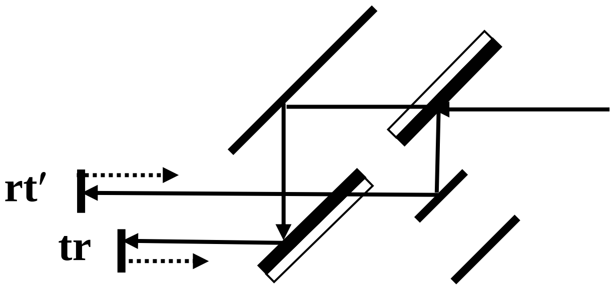


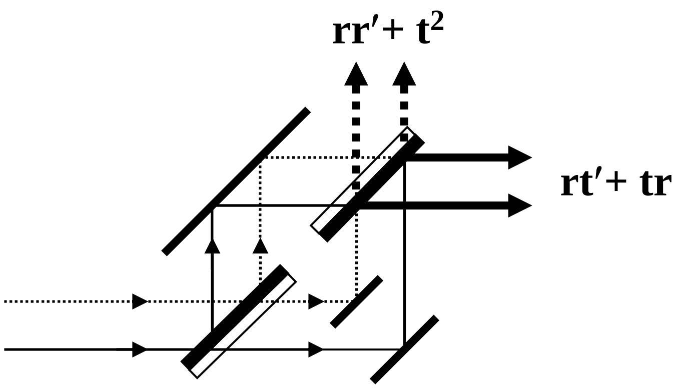
- Field reversal by dielectric plates
- Beam combination with MMZ

Laboratory Nulling Results at JPL

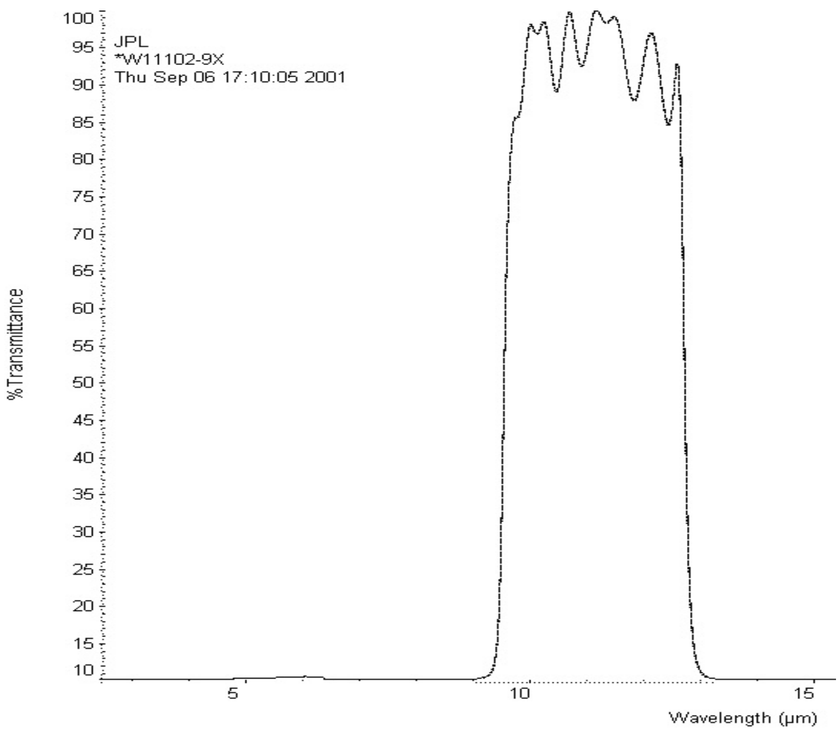
- Sources: CO_2 laser and thermal filament
- Room temperature optics
- Dielectric field flip and MMZ nuller
- Detector so far: single-pixel LN_2 MCT
- Single-pixel detector as the spatial filter
- Null optimization by equalization of symmetric off-center fringes
- No intensity control needed yet
- Dual polarization results for white light
- Required symmetric beams generated by reverse pass through nuller





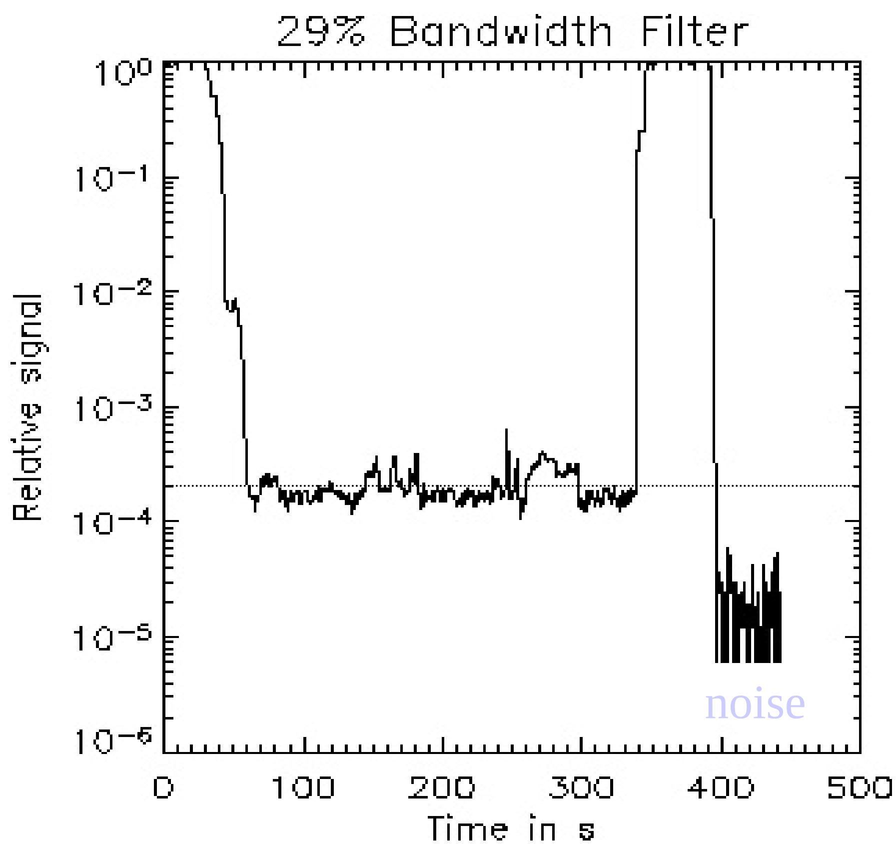


Dual Polarization Non-stabilized White Light Nulls on the Keck Nulling Beam Combiner



29% bandwidth filter

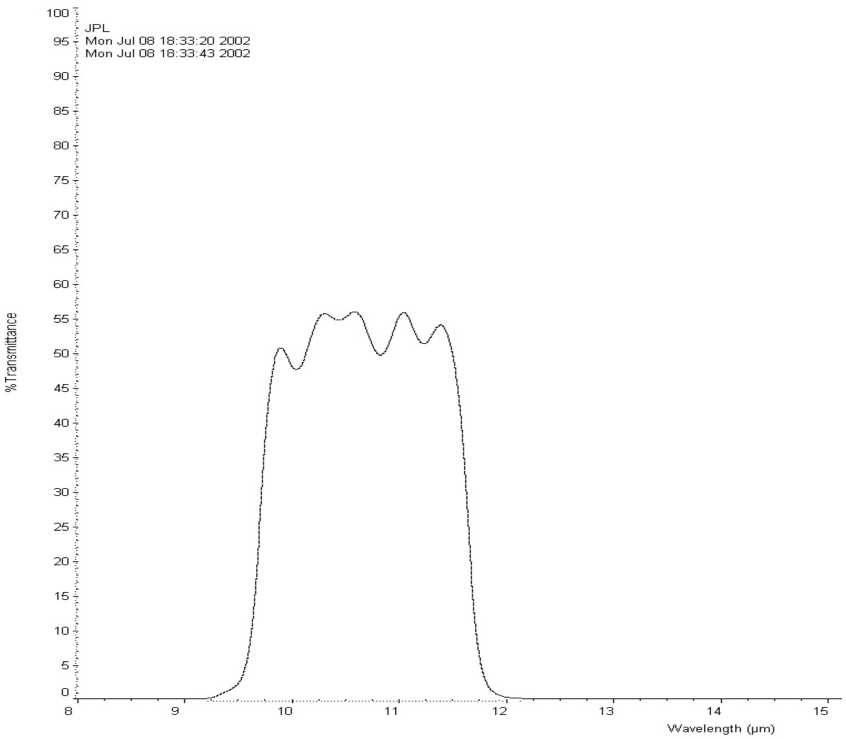
Half max points: 9.2-12.35 µm



> 5000 “steady state”

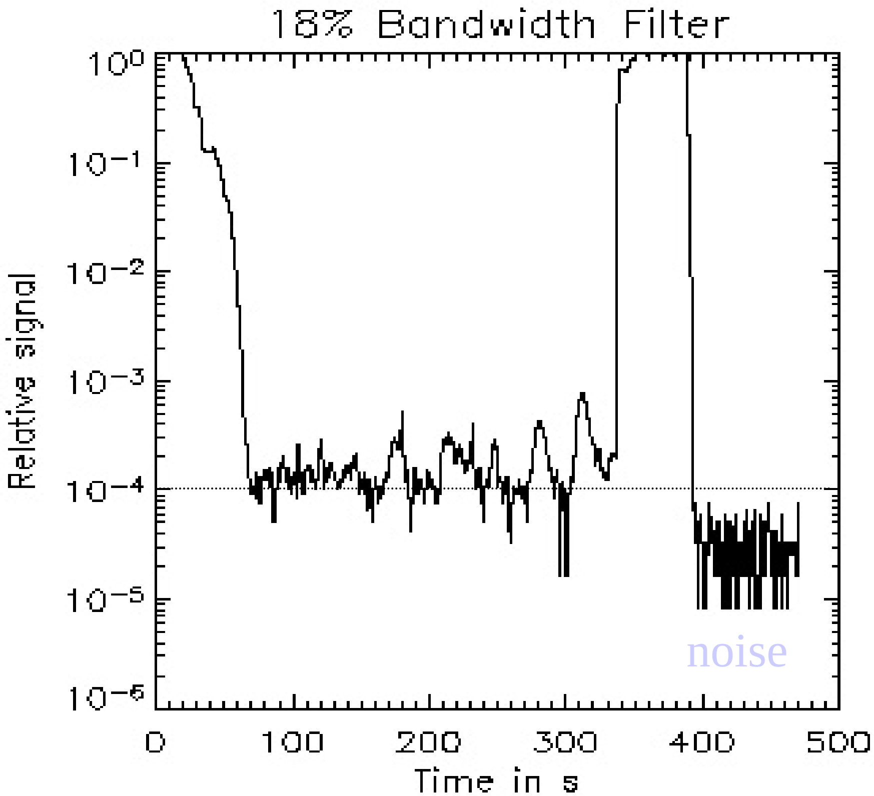
> 6000:1 transients

Dual Polarization Non-stabilized White Light Nulls on the Keck Nulling Beam Combiner: II



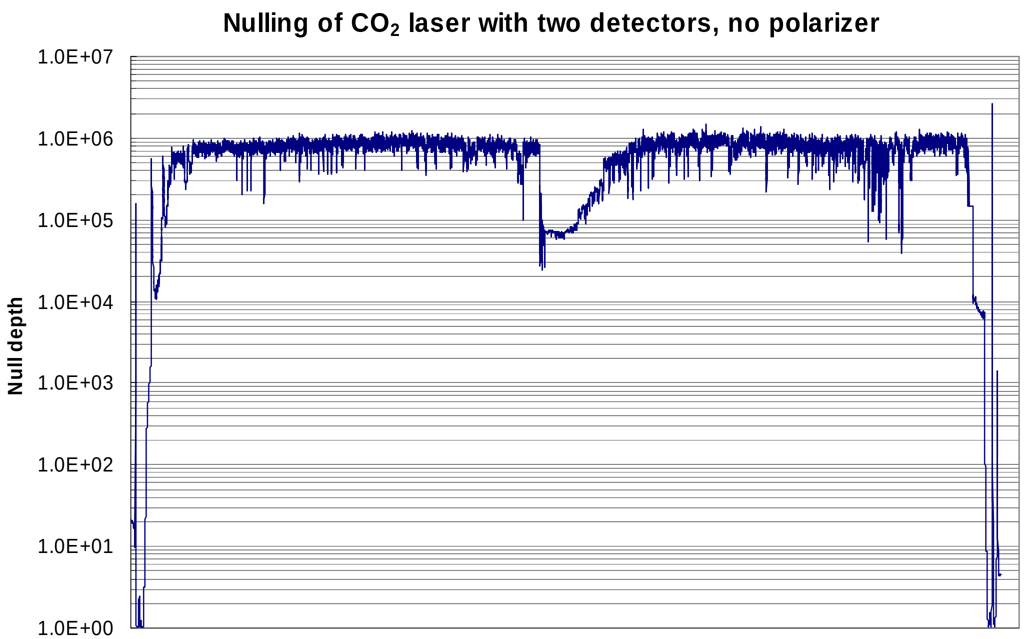
18% bandwidth

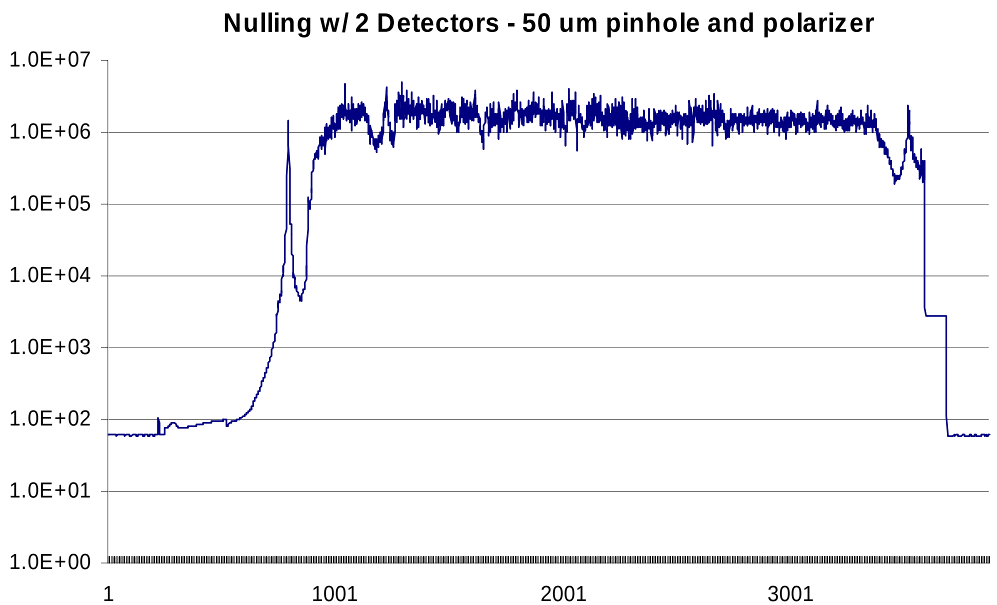
Half max points: 9.7-11.65 microns



> 10,000:1

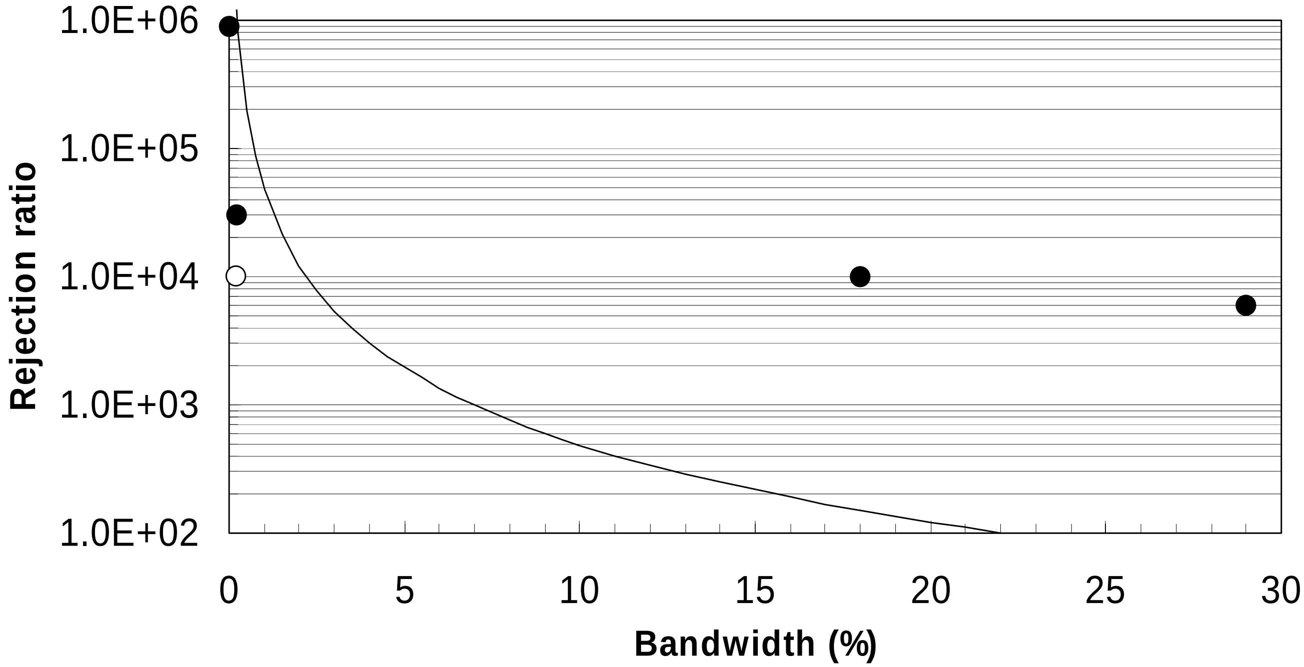
CO_2 laser nulling on the TPF nuller





> 1,000,000:1

MIR Lab Nulling Results: Summary



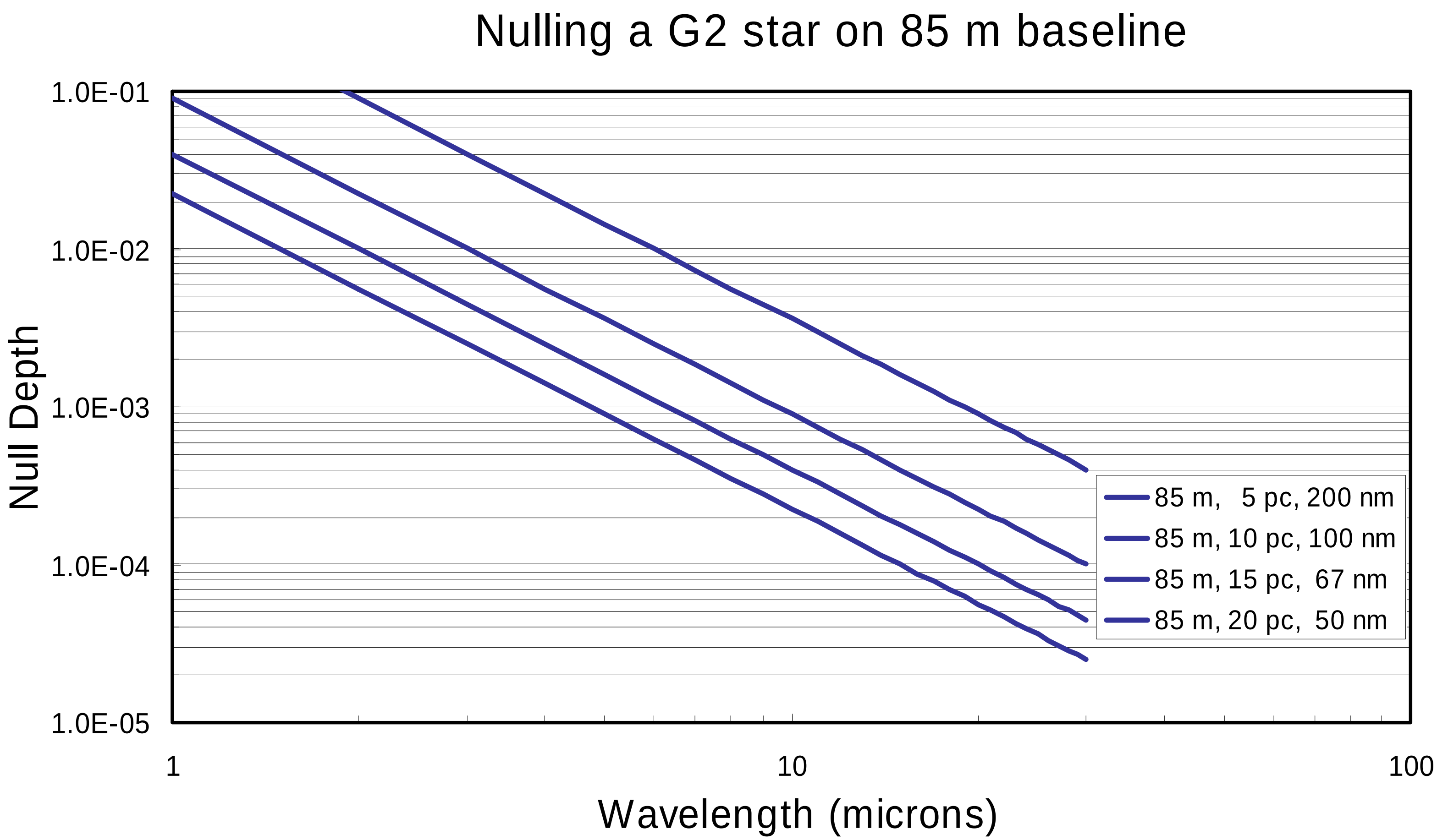
- 29% BW; dual-polarization, WL nulls > 6,000:1
- 18% BW, dual-polarization, WL nulls > 10,000:1
- Keck WL performance goal of 10,000:1 for about 20% BW has been met
- Monochromatic CO_2 laser nulled to 1,000,000:1

The Keck Interferometer Nuller: A Few System Level Issues

The Keck Interferometer

- Interferometry with the two 10-m Keck telescopes
- NASA-funded joint project between JPL and CARA
- Broad range of science capabilities, including nulling & DP

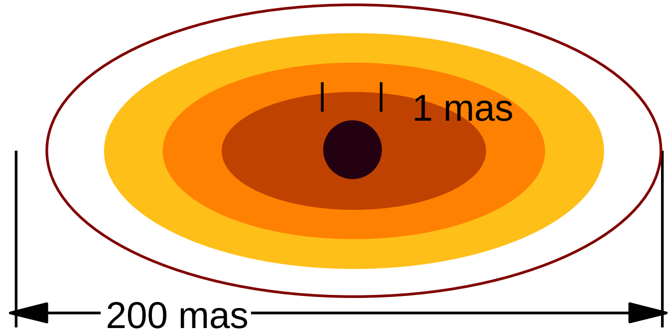
Stellar null depths vs. wavelength,



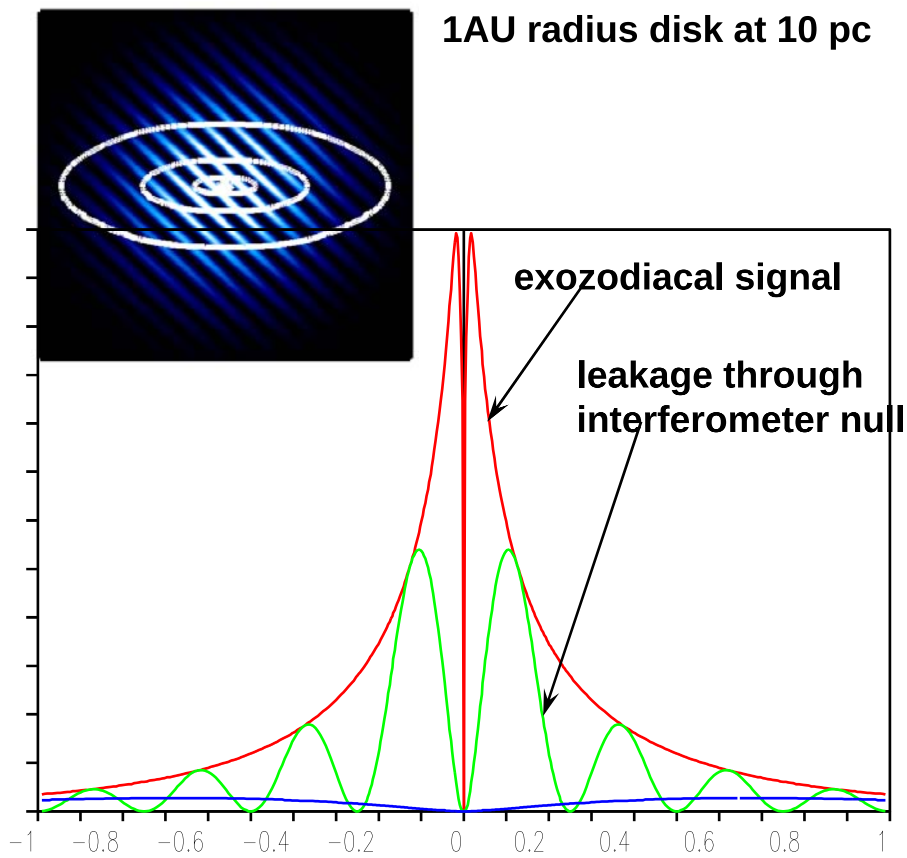
To achieve the baseline-limited null, require: $\sigma_x < b\theta_d/4$

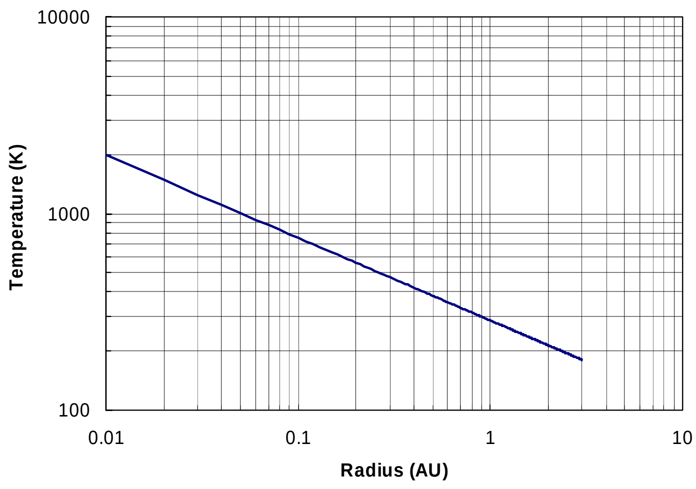
Detection of Exozodiacal Dust using Nulling

- Characterization of the exozodiacal emission level around nearby stars: a necessary preliminary to TPF
  - Keck goal: 10-solar-system equivalent zodiacal dust disk
- Two beam scales (at 10 μm)
  - Aperture/ SM beam: λ / diameter = 200 mas
  - Interferometer: λ / baseline = 25 mas



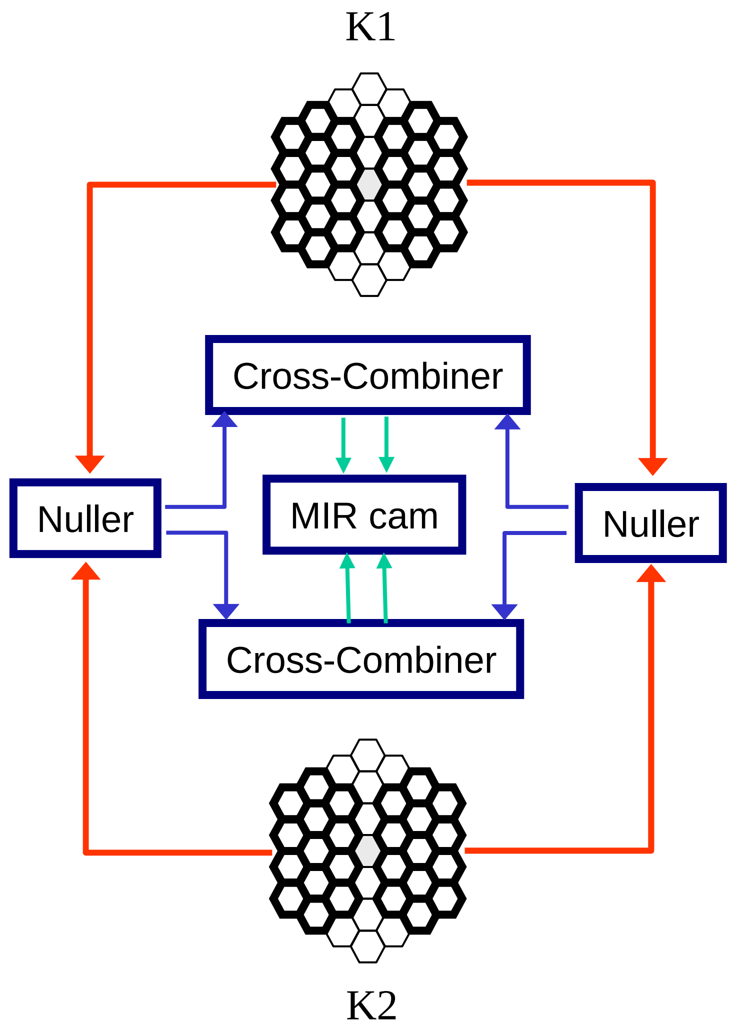
1AU radius disk at 10 pc



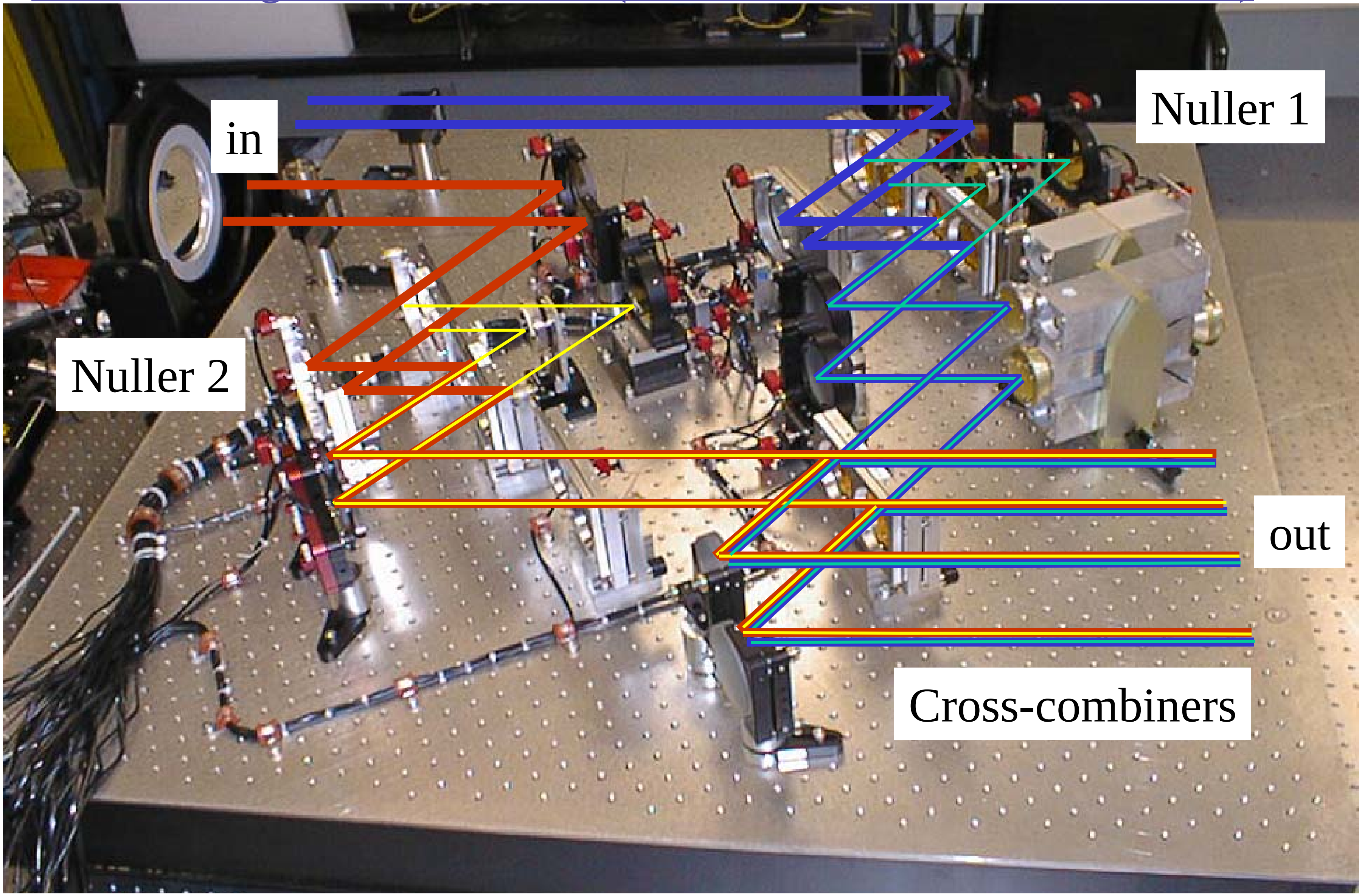


Keck Nulling Approach: Dual-baseline Nulling

- Need to remove both star and thermal background
- Dual-baseline nulling
  - Send two beams to basement from each telescope
- Null star on each of two K1-K2 baselines
- Perform standard OPD-scan interferometry on the two nulled outputs
  - Use rapid OPD scan between the two nulled beams to measure exozodi fringe
- MIR OPDs stabilized by fringe tracking at 2 mμ



Keck nulling beam-combiner (2 nullers and 2 cross combiners)

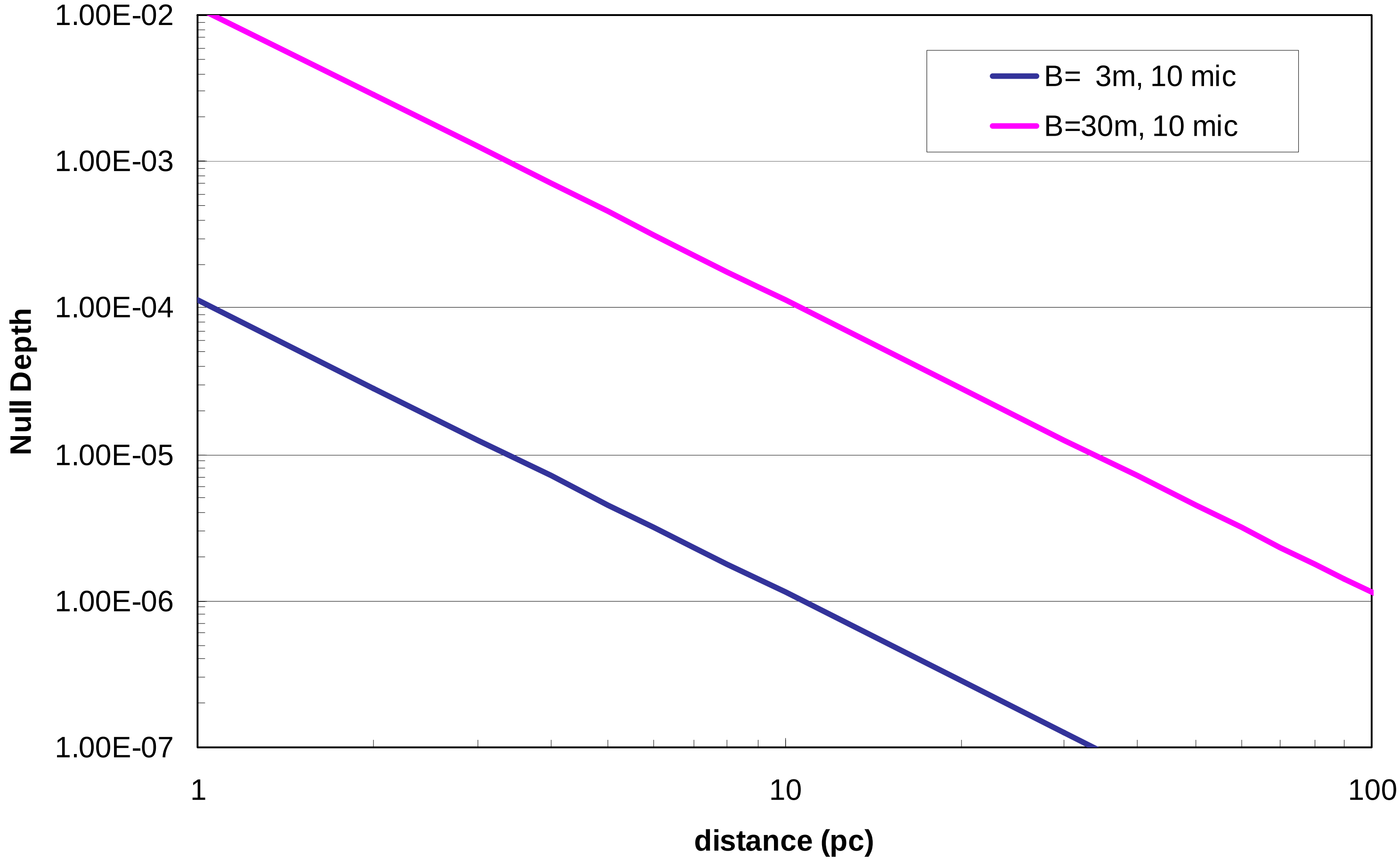


Keck Interferometer Status and Near-Term Schedule

– Visibility mode functional
– Nulling beamcombiner breadboard functional at JPL
– The nuller is scheduled to ship to Keck toward the end of the year
– Shared risk science team in place
– Differential Phase next priority

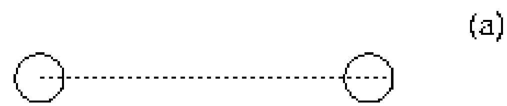
Future Plans:
Nulling from Space

Nulls vs. baseline length

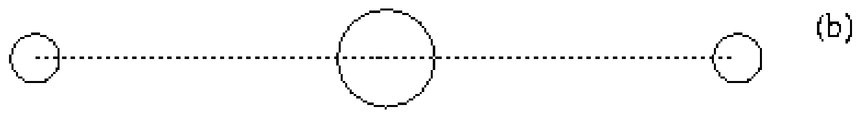


- For a single nulling baseline, the null depth degrades as $baseline^2$
- Cannot reach 10^{-6} nulls with baselines above a few meters
- But then the broad null wipes the inner planets out as well

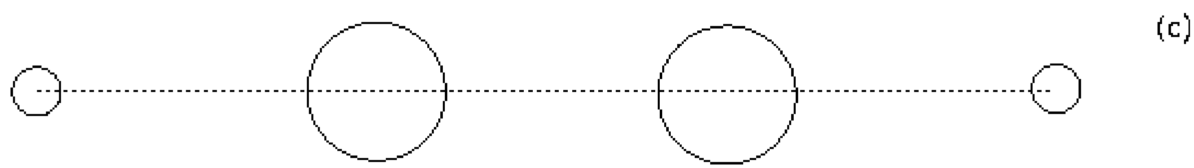
One Dimensional Nulling Interferometer Configurations for Broader Nulls



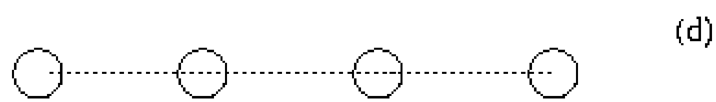
- Single-baseline "Bracewell"
  1:-1,
  θ^2 null



- Degenerate Angel cross (DAC)
  -1:2:-1,
  θ^4 null



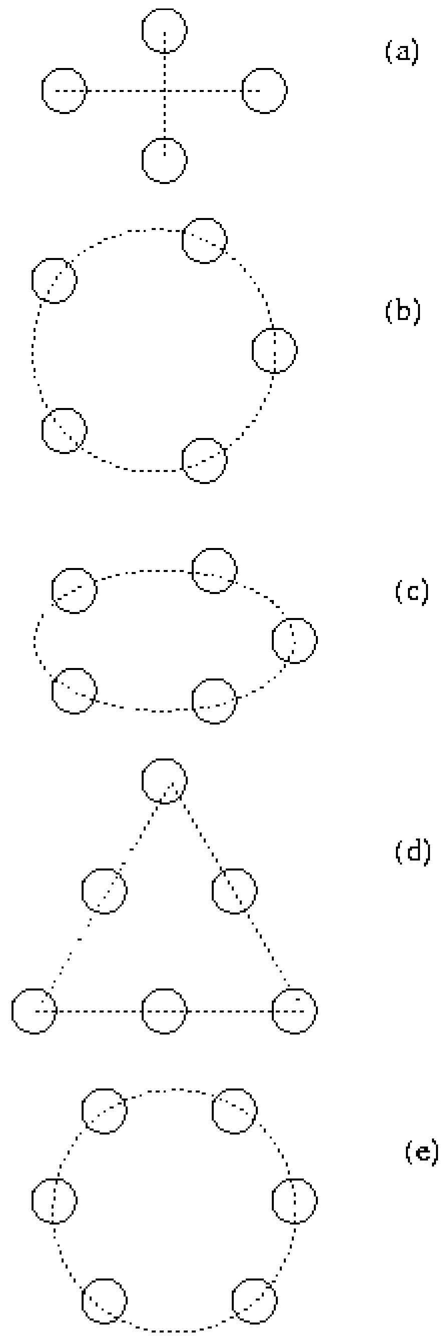
- OASES
  -1:3:-3:1,
  θ^6 null



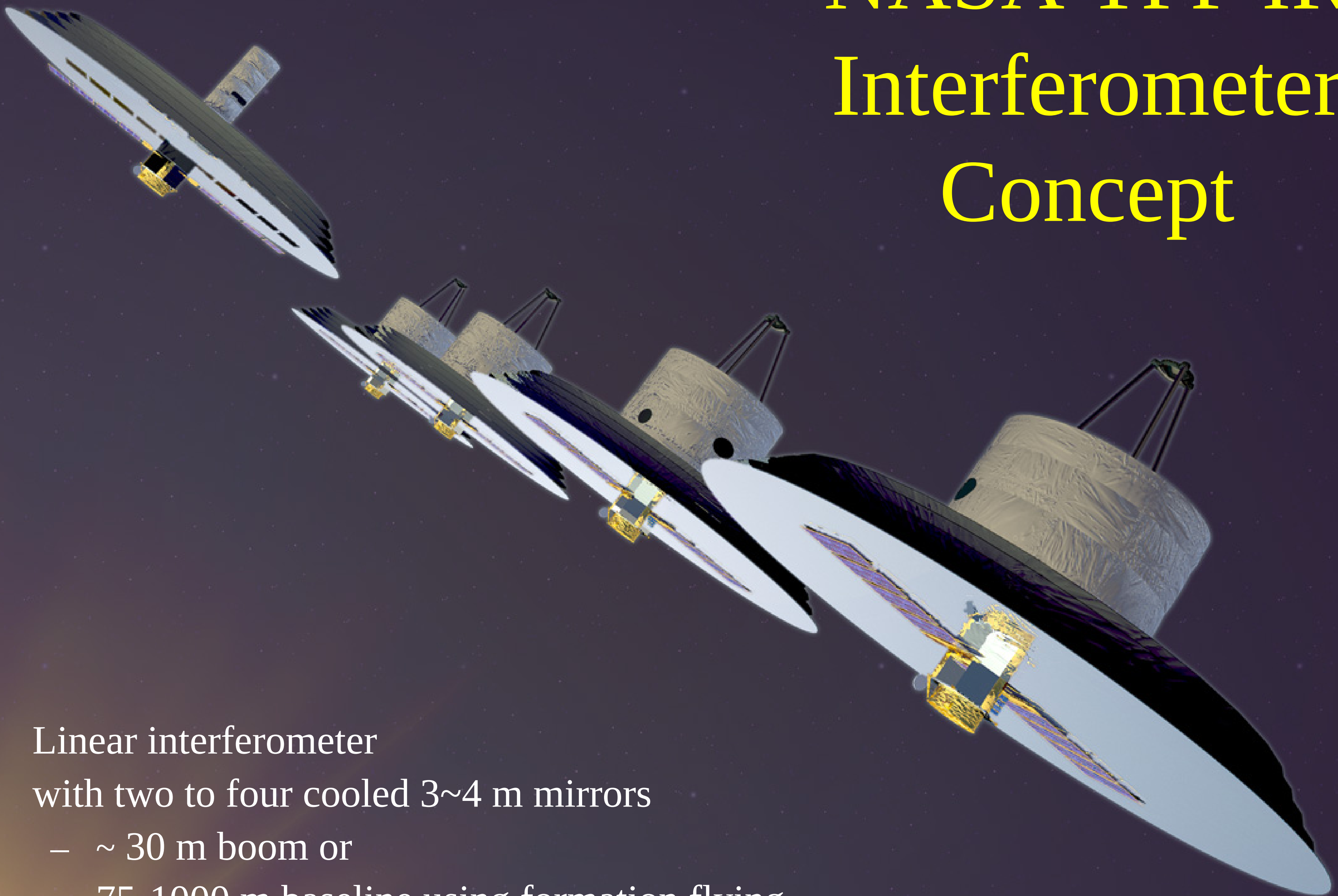
- Chopped "Bracewell"
  -1:-1:1:1,
  θ^2 nulls,
  θ^3 residue after phase chopping
  Removes symmetric exozodiacal signal

Two Dimensional Nulling Interferometer Configurations

- a) Angel cross - asymmetric to wash out transmission zeros upon array rotation
- b) Five on a circle - odd symmetry yields different responses to exoplanets and exozodi
- c) Five on an ellipse - combines advantages of a & b
- d) Six on a triangle (Marriotti configuration) - triple DAC with phase chopping
- e) Six on a hexagon (Laurance configuration) - dual-bent-OASES (or other) with phase chopping
- Problems: many spacecraft, complex beam combiners, sharing telescopes between nullers

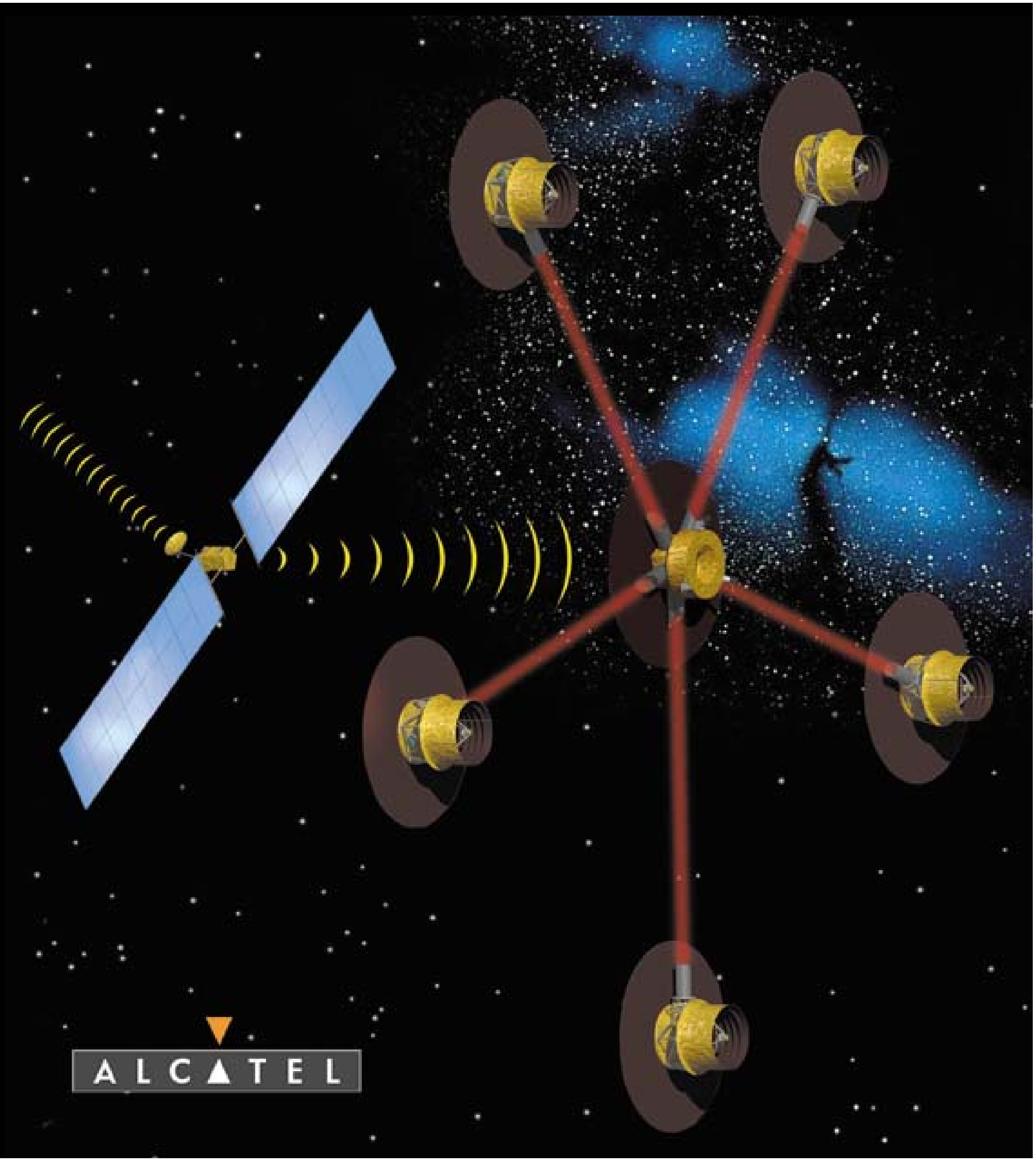


NASA TPF IR Interferometer Concept



- Linear interferometer
  with two to four cooled 3~4 m mirrors
  - ~ 30 m boom or
  - 75-1000 m baseline using formation flying
- Operate at 1 AU for 5 years to survey 150 stars

ESA Darwin Concept



Five to six cooled telescopes arranged on a circle