Terrestrial Planet Finder Mission

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# Terrestrial Planet Finder

## Nulling Interferometry

Robert O. Gappinger, Ph.D

Jet Propulsion Laboratory

California Institute of Technology

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# Outline

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- What is TPF?
- Infrared signatures
- What can we learn?
- Nulling interferometry
- Current nulling activities
- Summary

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# Terrestrial Planet Finder

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- With TPF we want to search for *earth-like* planets around nearby stars
- Why *earth-like* planets?
  - To what extent is our Solar System and our Earth unique?
  - Is life common or not?
- What is an *earth-like* planet?
  - A rocky planet of size similar to the earth
  - Not too small or the planet will lose its atmosphere
  - Not too big or it will be a gas giant
  - Not too hot or too cold, so liquid water is present
  - If possible, we would like to search for evidence of life
- The problem is that it is very hard to detect an earth-like planet!

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# What don't we know about Extra-Solar Planets

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- Key questions:
  - Are the planets *gaseous giants*, like Jupiter or Saturn?
  - Are they *rocky*, like the Earth?
  - What are their *ages*?
  - When did they form in relation to star and disk system?
  - To what extent does exo-zodiacal emission affect our ability to detect Earth-like planets?
- Basic facts we want to learn about a planet:
  - *Temperature*
  - *Radius*
  - *Mass* (known only within *sin i* ambiguity for presently known planets)
  - *Density*
  - Type of atmosphere and basic constituents

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# The Solar System Viewed from 10 pc

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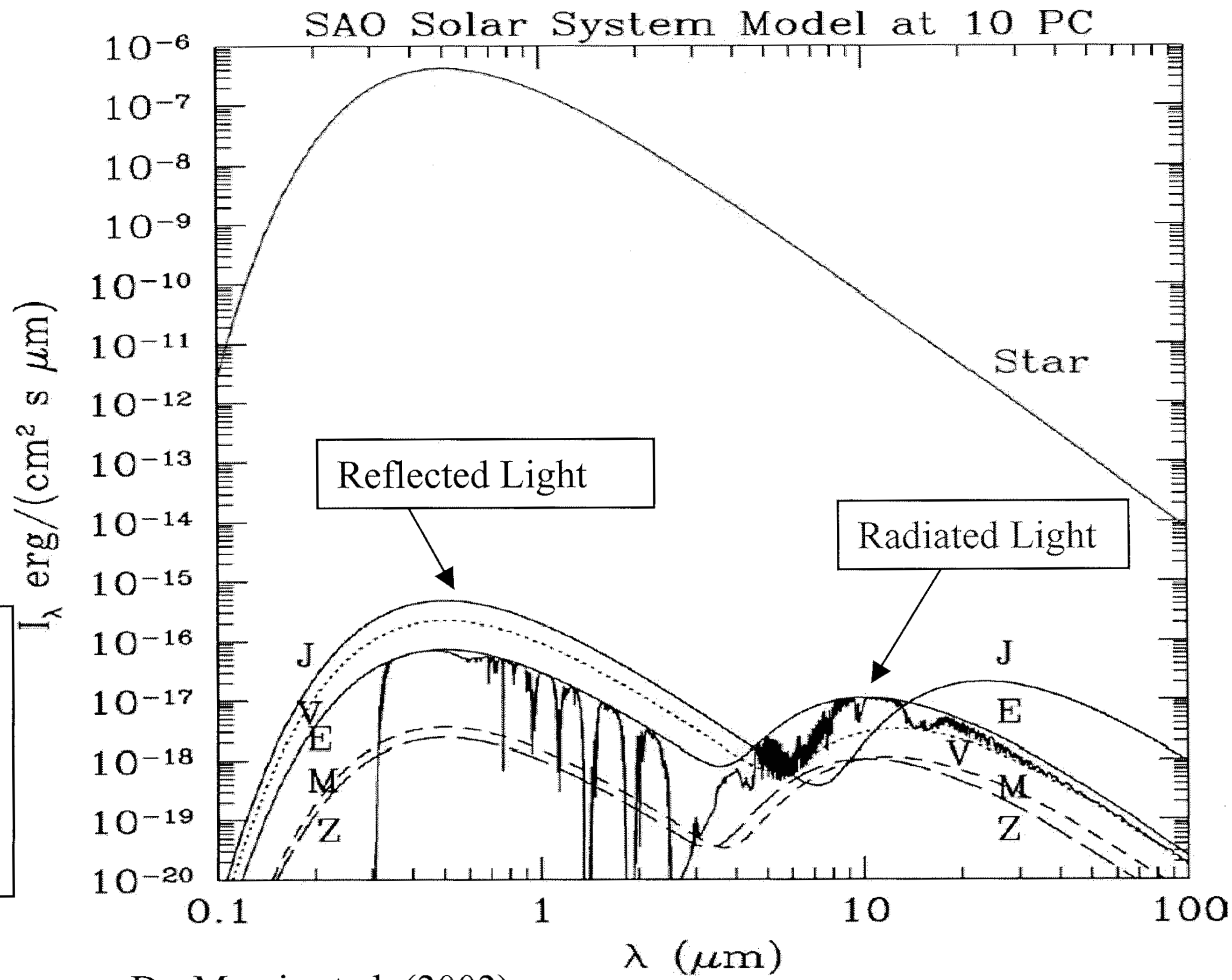
You can search for planets directly either from *reflected* starlight or *re-radiated* starlight

Notice that *different planets* have *different spectra* in the infrared




DesMarais et al. (2002)

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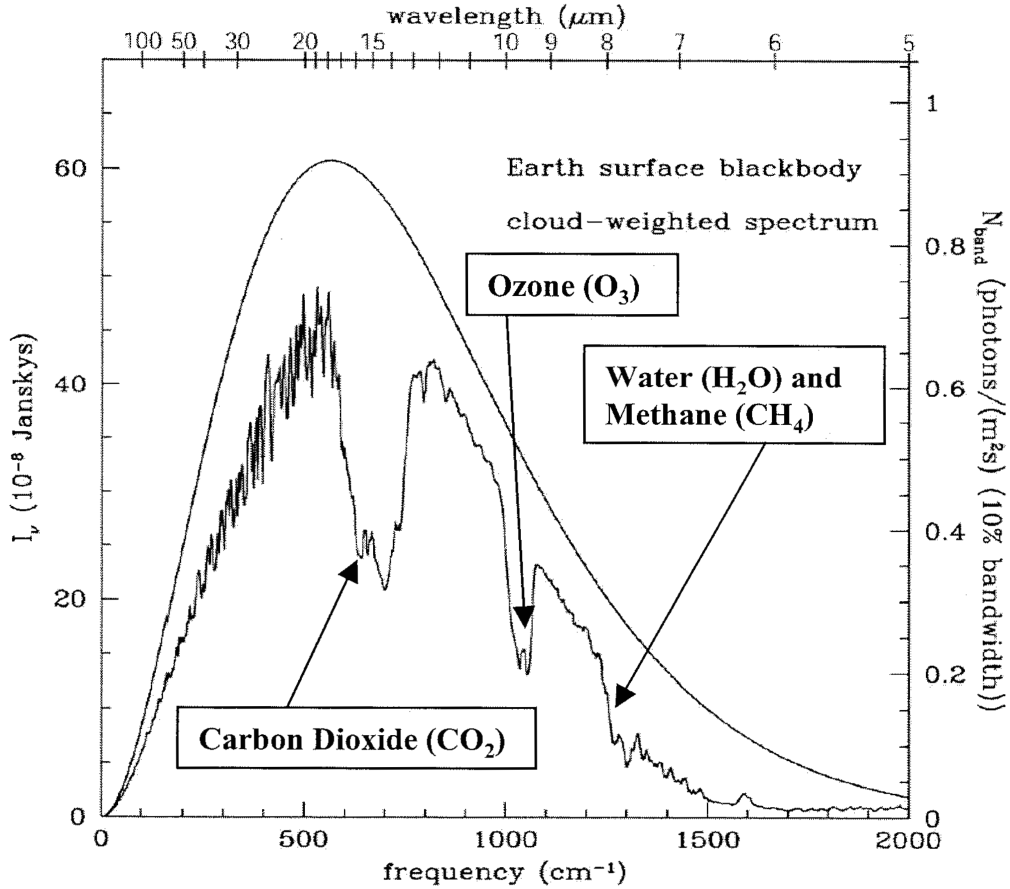
# Earth's IR Spectrum Compared to Blackbody




- Molecules in the Earth's atmosphere change the spectrum substantially away from a blackbody curve.
- Different molecules have different characteristic atmospheric features, which have widths on the order of ½ micron, and large depths.

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# IR Spectral Indicators of Life

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- Desire to observe simultaneously both:
  - Oxidized species such as $O_3$, $CO_2$, $NO_2$, $SO_2$
  - And Reduced species such as $CH_4$, $NH_3$, $H_2S$
- Ozone and Methane are probably best IR indicators of life
- Ozone is an essential indicator of oxygen content in the atmosphere
- Direct detection of water at 6.3 microns is highly desirable
- These considerations suggest mid-infrared wavelength coverage from 6 microns to 17 microns is needed for best results

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# Detecting Earth-like Planets is Difficult

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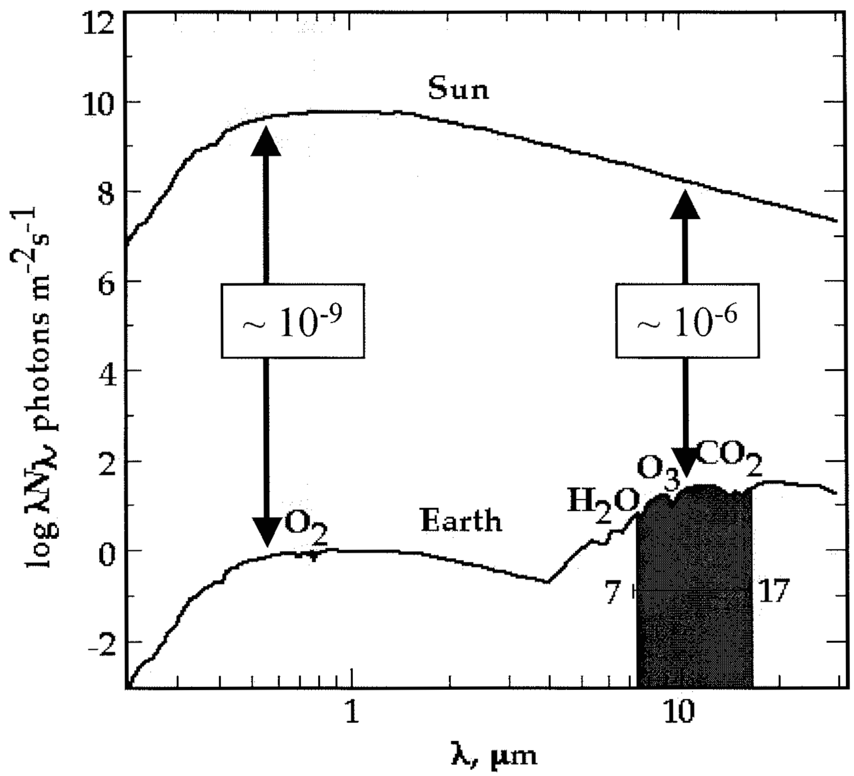
- Detecting light from planets beyond solar system is hard:
  - Earth sized planet emits few photons/sec/m$^2$ at 10 $\mu$m
  - Parent star emits $10^6$ more
  - Planet within 1 AU of star
  - Dust in target solar system $\times$300 brighter than planet
- Finding a firefly next to a searchlight on a *foggy night*

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# How to obtain physical information from infrared data

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- If you *detect* the planet at *two different wavelengths* (measure the flux at those wavelengths) you can get the *temperature* (color temperature)
- From the *measured fluxes* and *color temperature* you can determine the *radius* of the planet (photometric size from the infrared flux method)
- If you *track the planet with time*, and measure the orbit, you eliminate the *sin i* ambiguity, and improve the estimate of the *mass* (for presently known planets)
  - From the *mass* and the *radius*, estimate *density*
  - *(May already have some masses from SIM)*
- If you measure at a modest spectral resolution, you can determine what molecules and their abundance, temperature and density are present in the atmosphere
  - Ultimately need radiative transfer models

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# Why IR Interferometry and Nulling?

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- Interferometry is a technique that gives us the highest spatial resolution at a particular wavelength, compared to a classical filled aperture telescope
- Resolution is important because the planets are close to their stars, typically 1 AU for an earth-like planet around a G2 dwarf star like the Sun
- At a distance of 10 pc, this gives angular resolution requirement of ~ 0.1 arcsec, or 0.03 arcsec at 30 pc
- An IR interferometer with modest baselines matches these requirements very well --
  - Resolution of an interferometer is ~ $\lambda/2B$
  - Then if $\lambda \sim$ 6-17 $\mu$m a baseline of 30 m gives a resolution of about 0.04-0.12 arcsec
- Infrared signal of planet is expected to be less dependent on orbital phase of planet than at visible wavelengths
- Nulling is a method to reduce the star flux by a large amount and has been proven in the laboratory

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# What kind of spectral resolution is needed?

- *Narrowest* feature in 10 μm band is about 0.5 μm wide, *typical* features around 1 μm wide
- Sample with about 2 resolution elements across the features:
  - Implies $\Delta\lambda \sim 0.25\text{-}0.5$ μm
  - Resolution R is $\lambda/\Delta\lambda \sim 10/0.25 - 10/0.5 \sim 20\text{-}40$
- We picked R~25-30 as a good round number

# A simple interferometer

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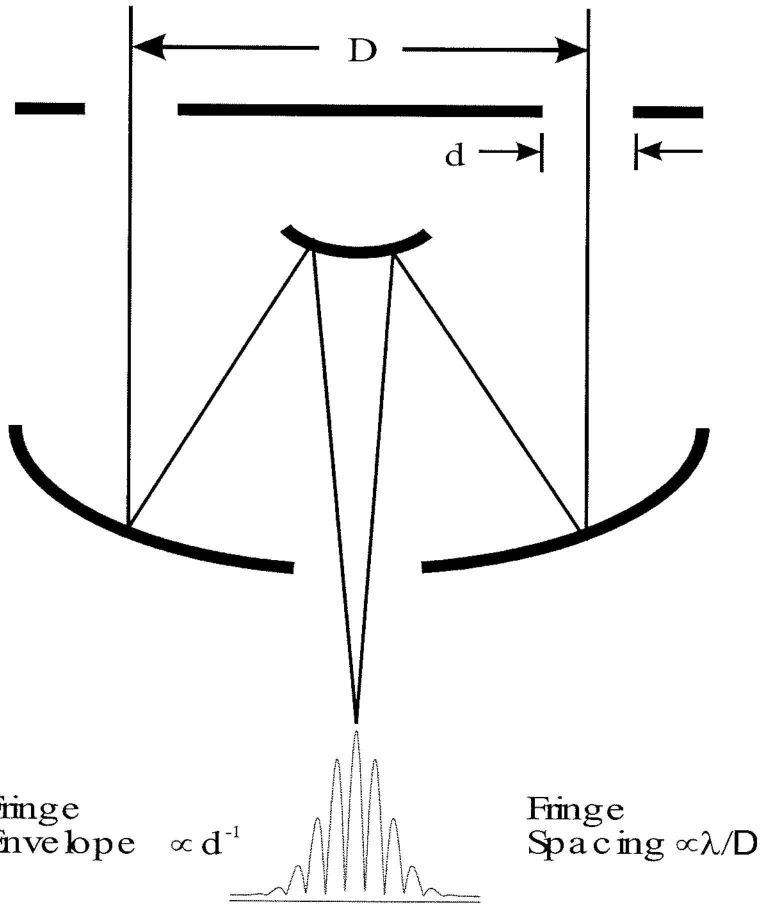
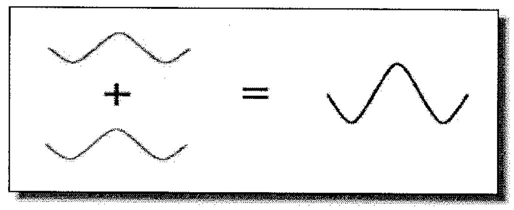
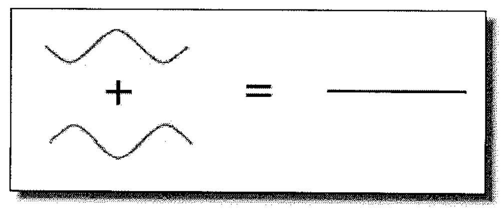
Simplest Interferometer -- Aperture Masking




- You get a peak when pathlengths are equal on both sides -- "white light fringe"




- You get a null when pathlengths differ by one half a wavelength -- a "dark fringe"

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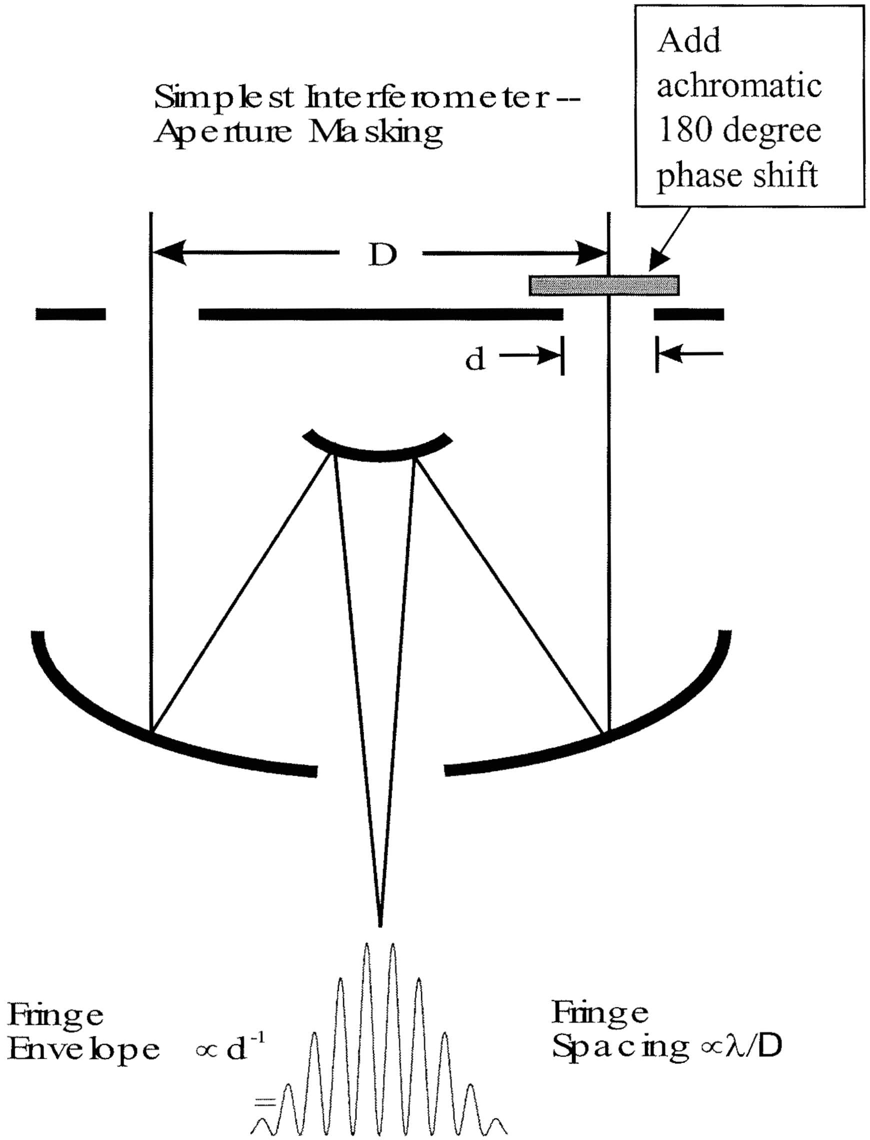
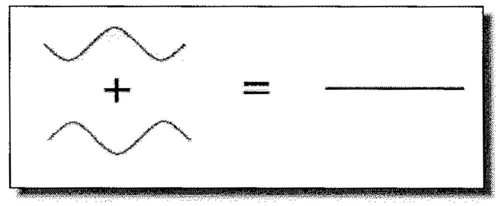
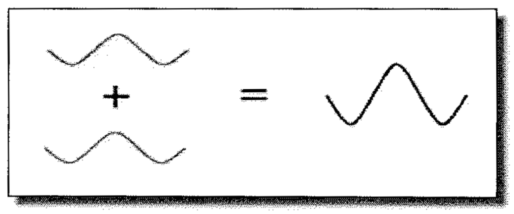
# A simple nulling interferometer




•You get a null when pathlengths are equal on both sides -- "white light null fringe"




•You get a peak when pathlengths differ by one half wavelength -- a "bright fringe"

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# A Simple Example of an Interferometric Detection of a Planet

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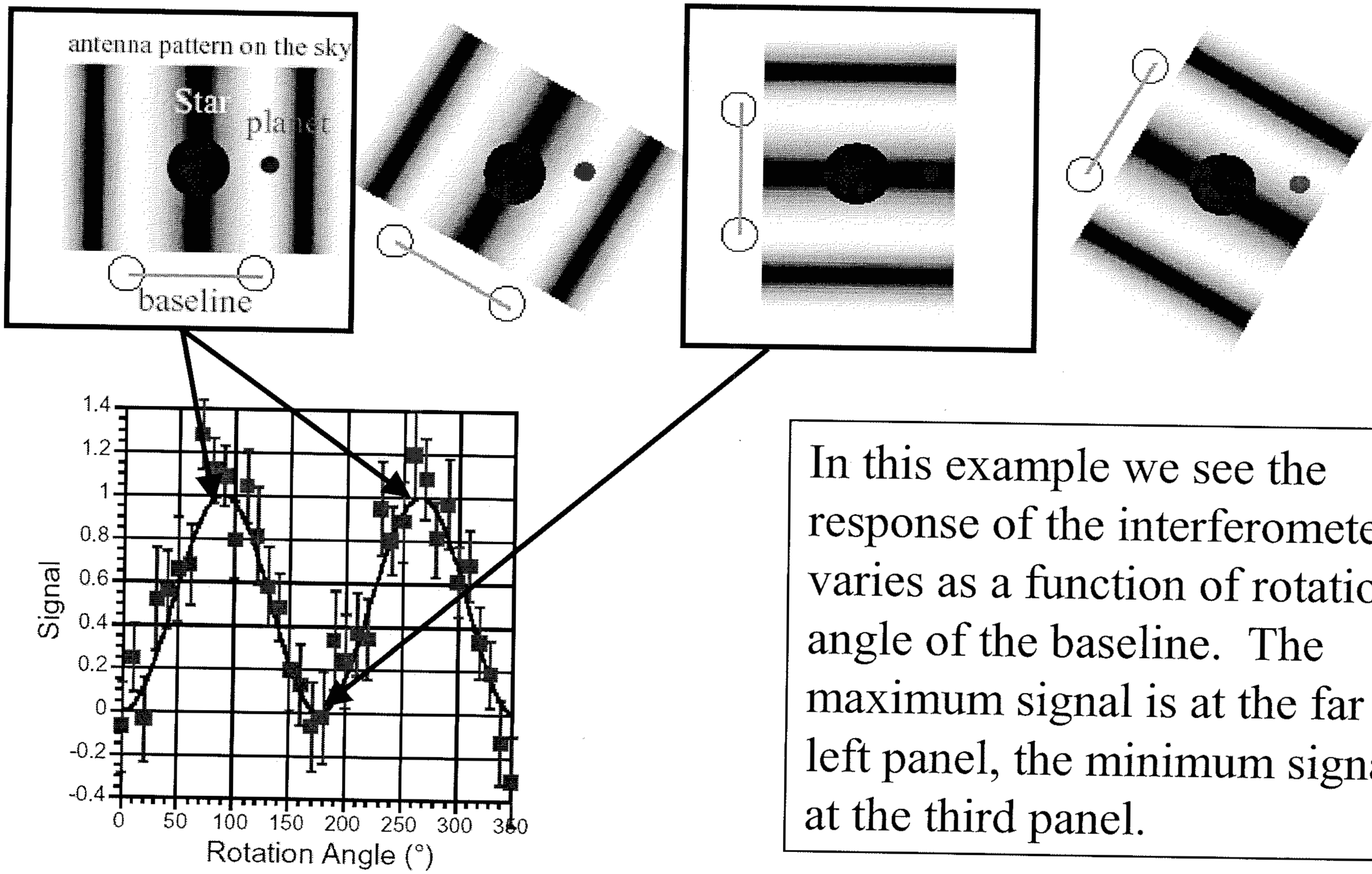
## Interferometric Exo-Planet Detection




In this example we see the response of the interferometer varies as a function of rotation angle of the baseline. The maximum signal is at the far left panel, the minimum signal at the third panel.

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# TPF Interferometer Nulling Requirements

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- TPF Interferometer will need deep and stable interferometric nulling, over a broad MidIR bandwidth, for long observation periods, at cryogenic temperatures to detect planets.
  - Specifically:
    - Null Depth: $10^{-6}$
    - Null Stability: $10^{-7}$
    - Optical Bandwidth: 7 – 12 um (50%)
    - Operating Temperature: 77K
    - Observation Period: 1000 – 10,000 sec (~20 min – ~2.5 hours)
    - Off-axis planet flux: $10^{-5}$
- The Achromatic Nulling Testbeds is demonstrating progress toward this ultimate milestone
- Here's how we're doing it…

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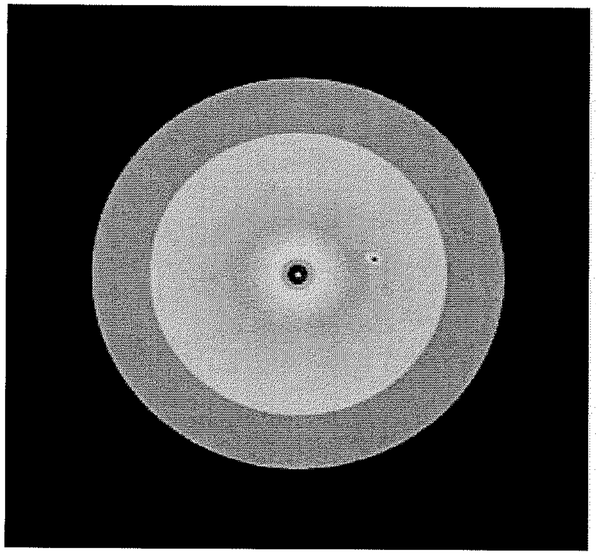
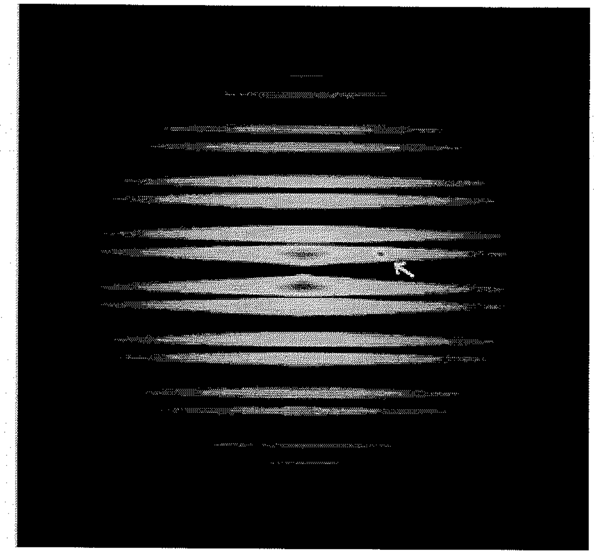
# Ultimate Nulling Capabilty





| Objective | TPF Flight | Testbed |
|---|---|---|
| Null depth | $10^{-5}$ | $10^{-6}$ |
| Null stability | $10^{-8}$ | $10^{-7}$ |
| Timescales | $10^{4}$ s | $10^{3}$-$10^{4}$ s |
| Temperature | 40 K | 77 K |

# A quick review of nulling (I)

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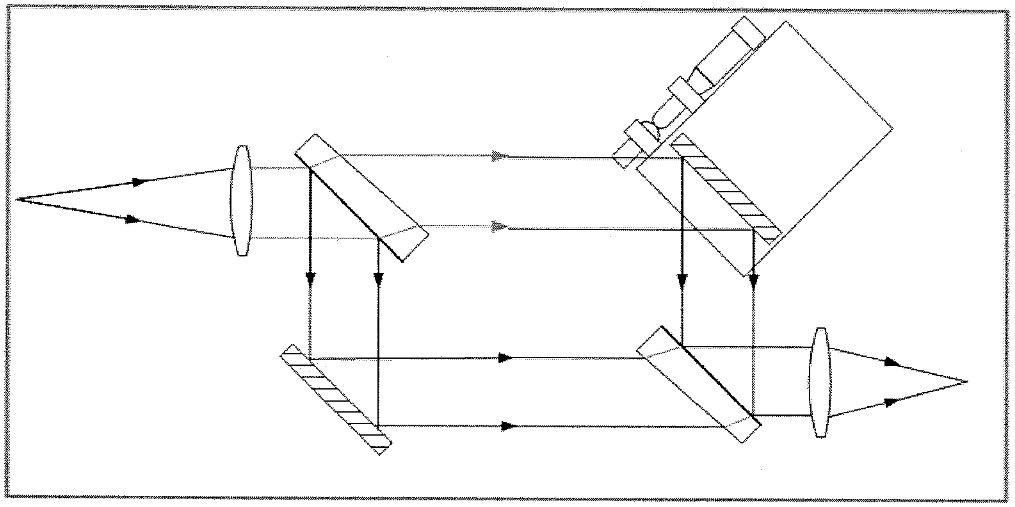
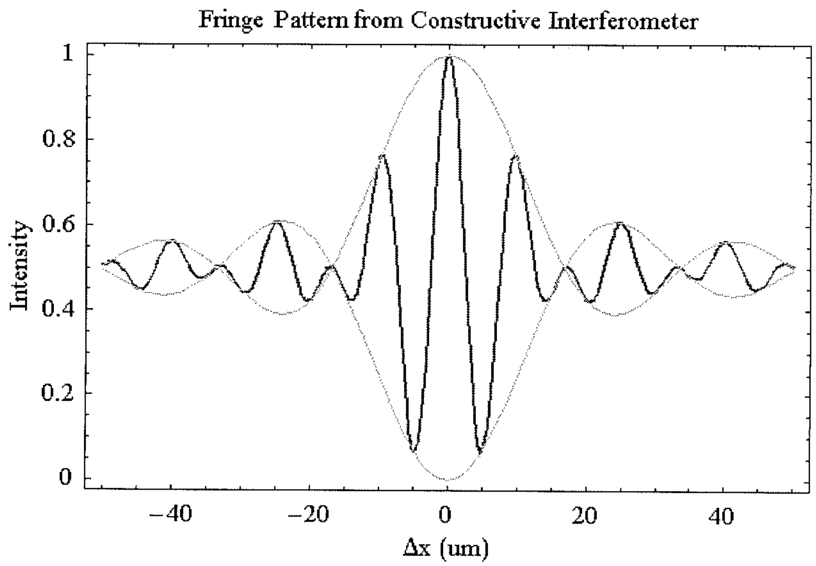
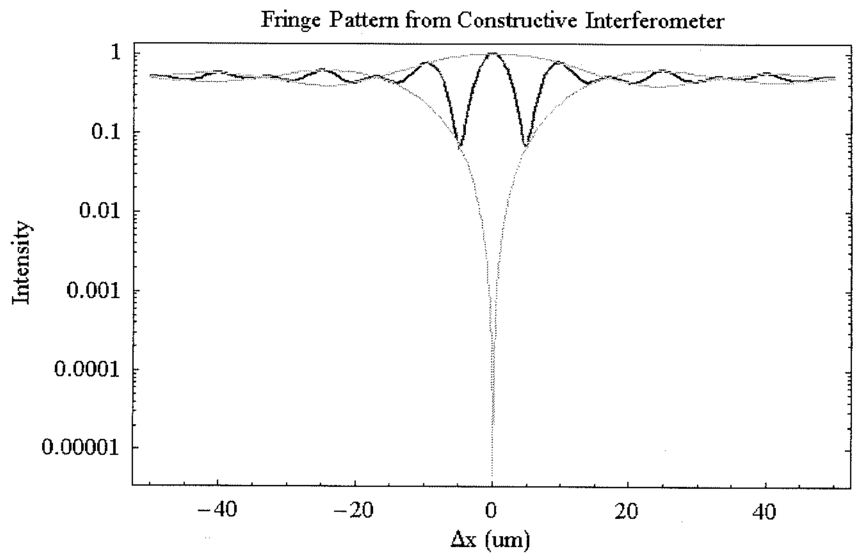


**Constructive Interferometer**

$$I(\Delta x) = \frac{Io}{2}\left[1 + Cos(\frac{2\pi}{\lambda}\Delta x)\right]$$



# A quick review of nulling (II)

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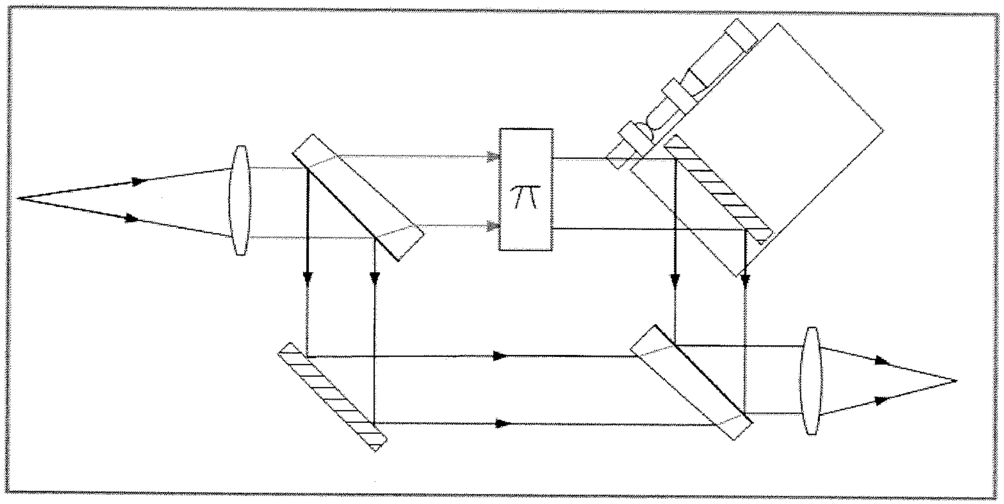


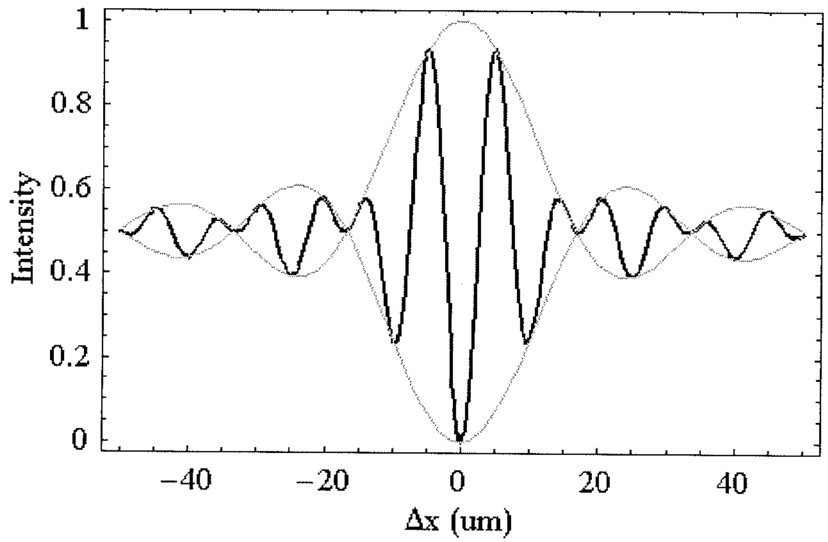

**Nulling Interferometer**

Achromatic!

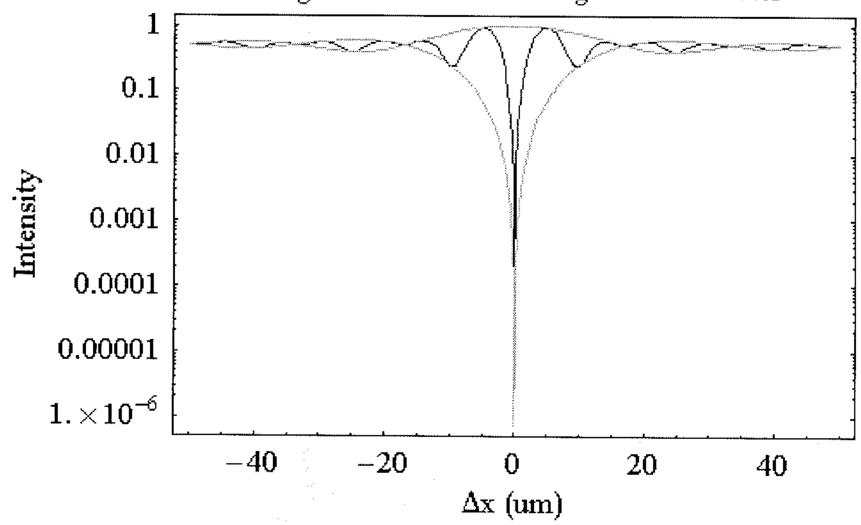
$$I(\Delta x) = \frac{Io}{2}\left[1 + Cos(\frac{2\pi}{\lambda}\Delta x + \pi)\right]$$

$$I(\Delta x) = \frac{Io}{2}\left[1 - Cos(\frac{2\pi}{\lambda}\Delta x)\right]$$

Fringe Pattern from Nulling Interferometer




Fringe Pattern from Nulling Interferometer

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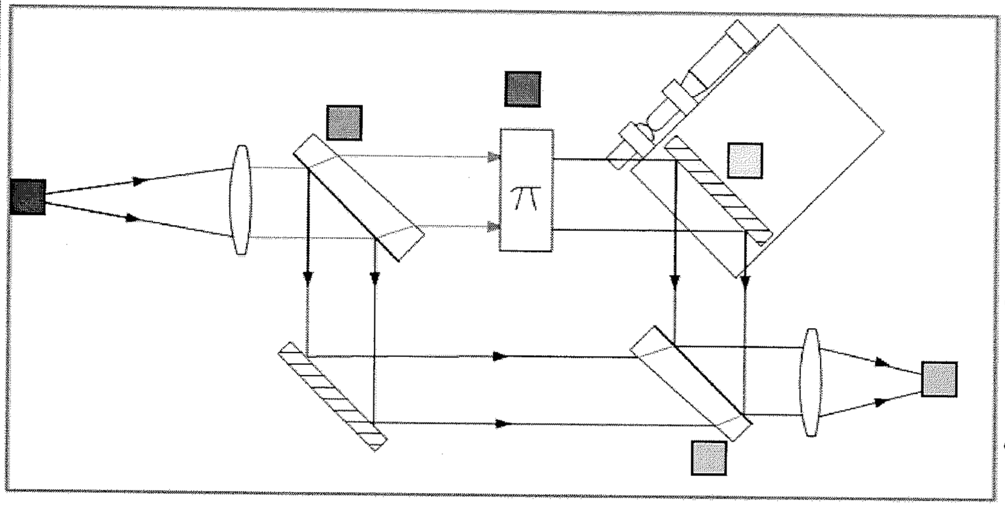
# Key Components of a Nulling Interferometer




**Nulling Interferometer**

- Source and single mode filter
- Source Split
  - Planet Light Injection
- Achromatic Field Flip
  - Or Pseudo-achromatic
- Path length control
  - Air Delay
- Recombination
- Output single mode filter and detector
- Ancillary:
  - Chopper
  - Shutters

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# Warm Achromatic Nulling Testbed

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- Demonstrate the physics of deep nulling under moderately easy conditions
  - 300K Work environment
  - Table top experiment
  - Preliminary motion control with off-the-shelf components
- Will be limited in the performance by the detector
  - Primarily a problem for white light observations
    - Difficult to get bright broadband IR source
- Deep laser nulling has been accomplished
- White light observations with bandwidths of 20% - 30% are currently under investigation

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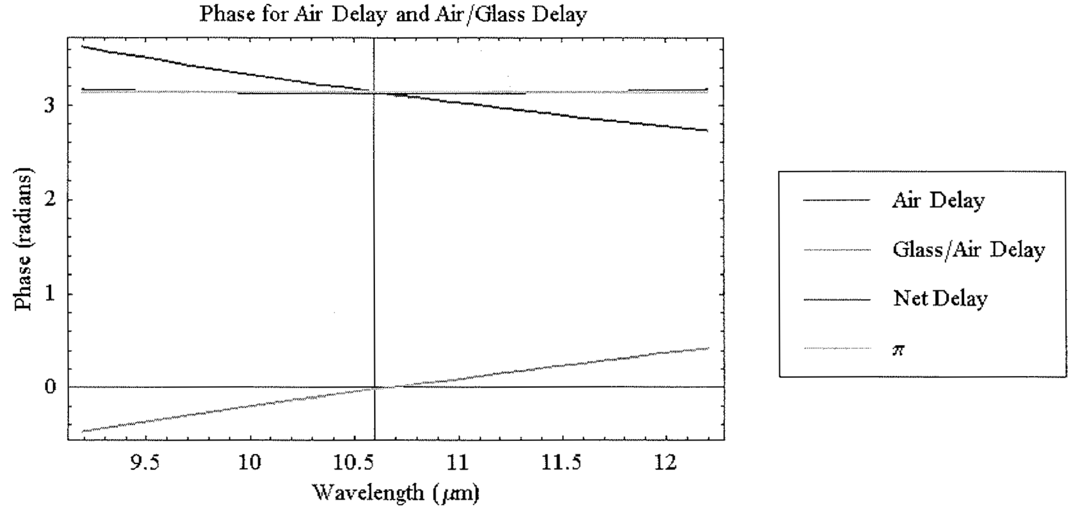
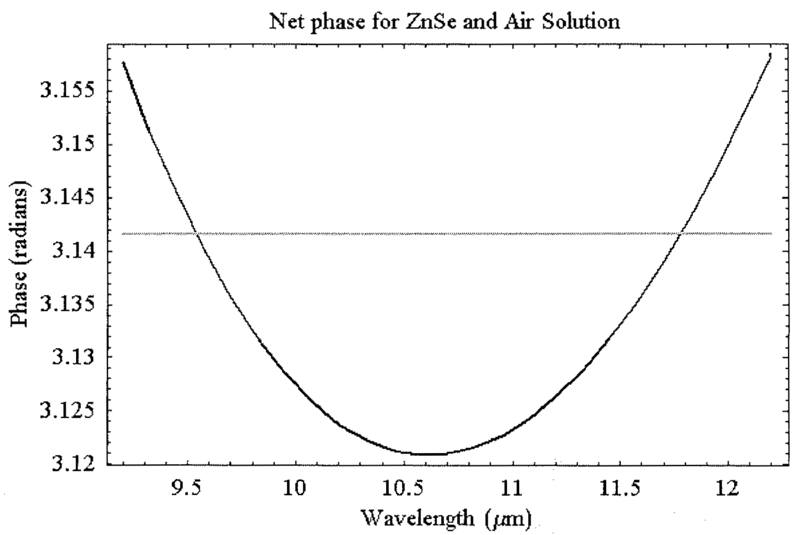
# Nulling with Phase Plates

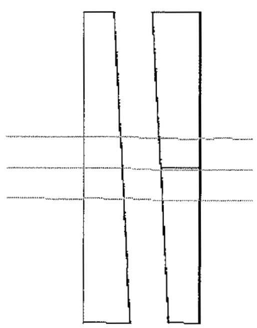
- Pseudo-achromatic Field Flip

$$\varphi(\lambda) = \sum_i \frac{2\pi}{\lambda} n_i(\lambda) t_i = \pi$$

- Setup for 9.3 to 12 micron bandwidth gives null depth 4.8 $10^{-5}$
- Prisms add -76.2 micron ZnSe in one telescope beam
- Delay line adds +188.3 micron air in one telescope beam



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# Warm Achromatic Nuller: Current Status

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- Achieved 1,000,000:1 null with a laser
- Achieved 10,000:1 null for 30% bandwidth infrared source
- Building 3 testbeds to pursue 100,000:1 null for 20% bandwidth IR source

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# Achromatic Nulling Testbed

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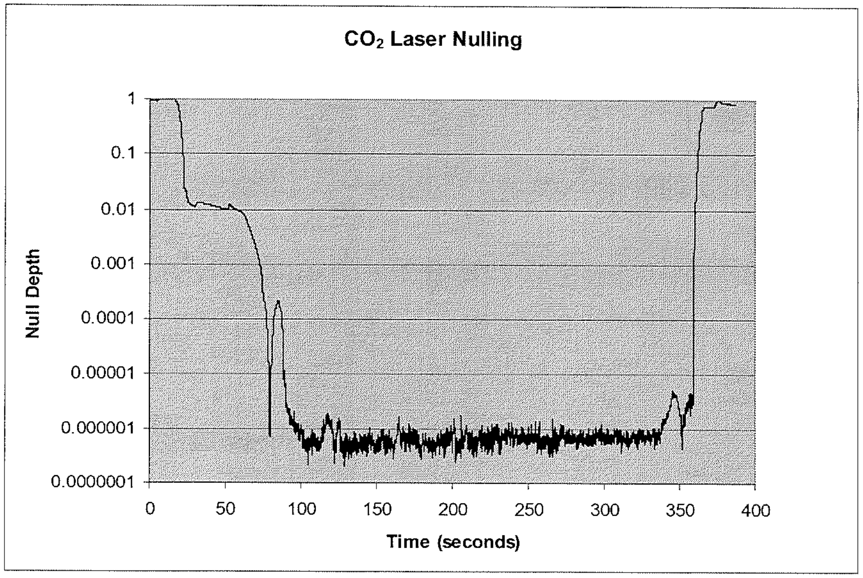
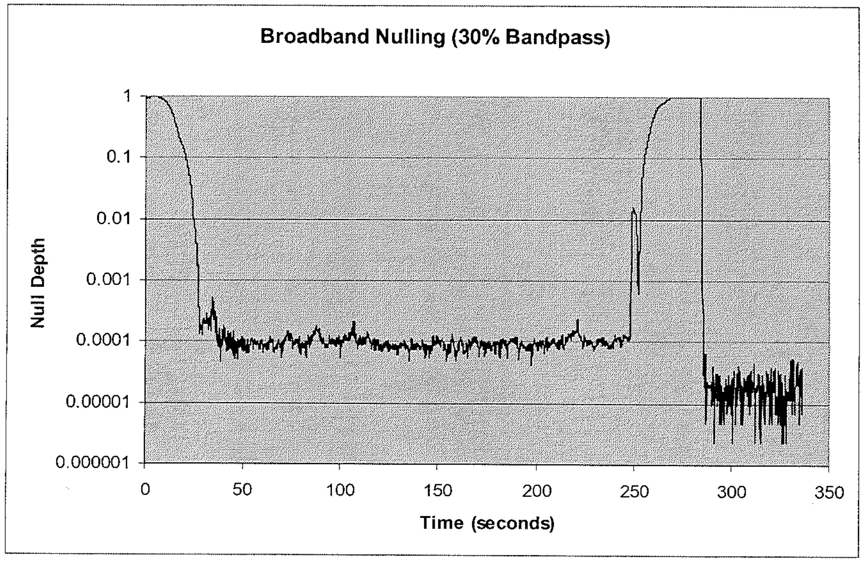
- $10^{-6}$ Null depth with 10.6 um laser

- $10^{-4}$ Null depth with 30% BW at 10um

  Goal is $10^{-5}$ Null with 25% BW

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# Summary

- Nulling interferometry will allow parent star to be dimmed sufficiently to detect planet
- Laboratory results are showing progress toward ultimate null depth requirements
- Current experiments are limited by detector noise
  - Need brighter source

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