Challenges and Advantages of Interferometry from the Ground

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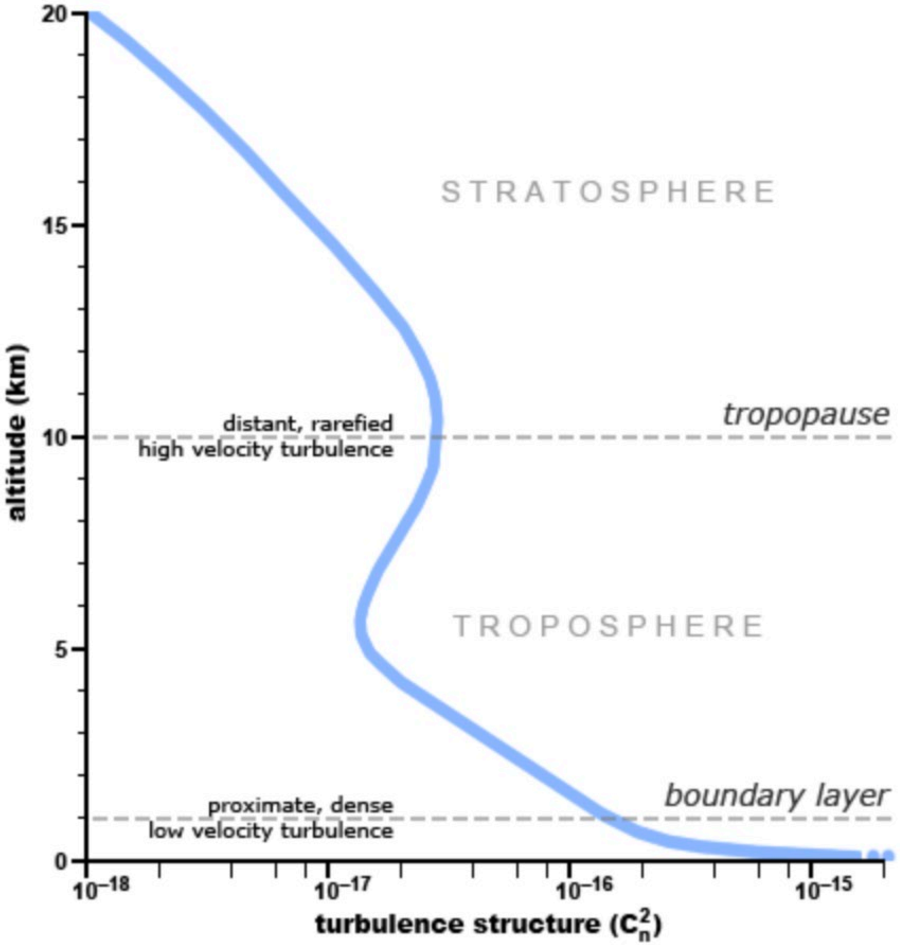
The biggest challenge is the turbulent atmosphere

- Four categories of turbulence
  - Instrument
  - Surface (ground - 200 m) turbulence with a diurnal cycle
  - Geographic turbulence, independent of landscape above 4 km with minimum 5-9 km
  - High atmosphere, jet stream 10-15 km

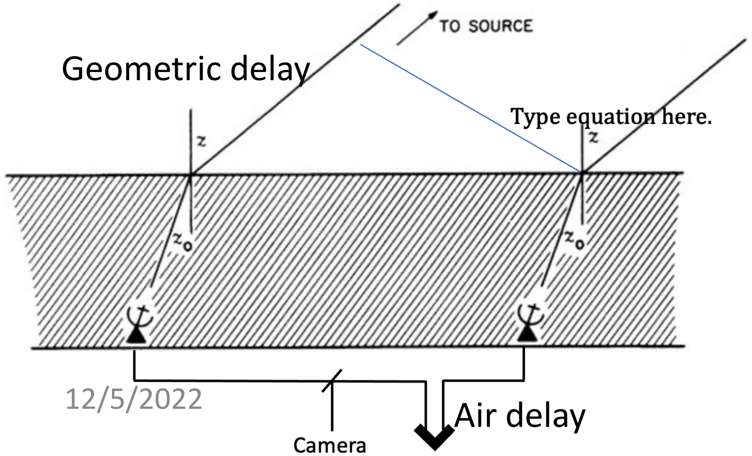
All these categories of turbulence, except for stratospheric layers above 20 km, are problematic for interferometry to varying degree



The Hufnagel Valley model for the strength of turbulence with altitude

Challenges from the still atmosphere

- Absorption
  - Index $n = n_R + jn_I$
  - Scattering at short wavelengths
  - Absorption from induced polarity in molecules (N_2, O_2, CO_2, H_2O) at optical IR wavelengths
  - Absorption due to permanent dipole of H_2O at longer wavelengths
- Propagation Delay
  - Longitudinal and angular dispersion

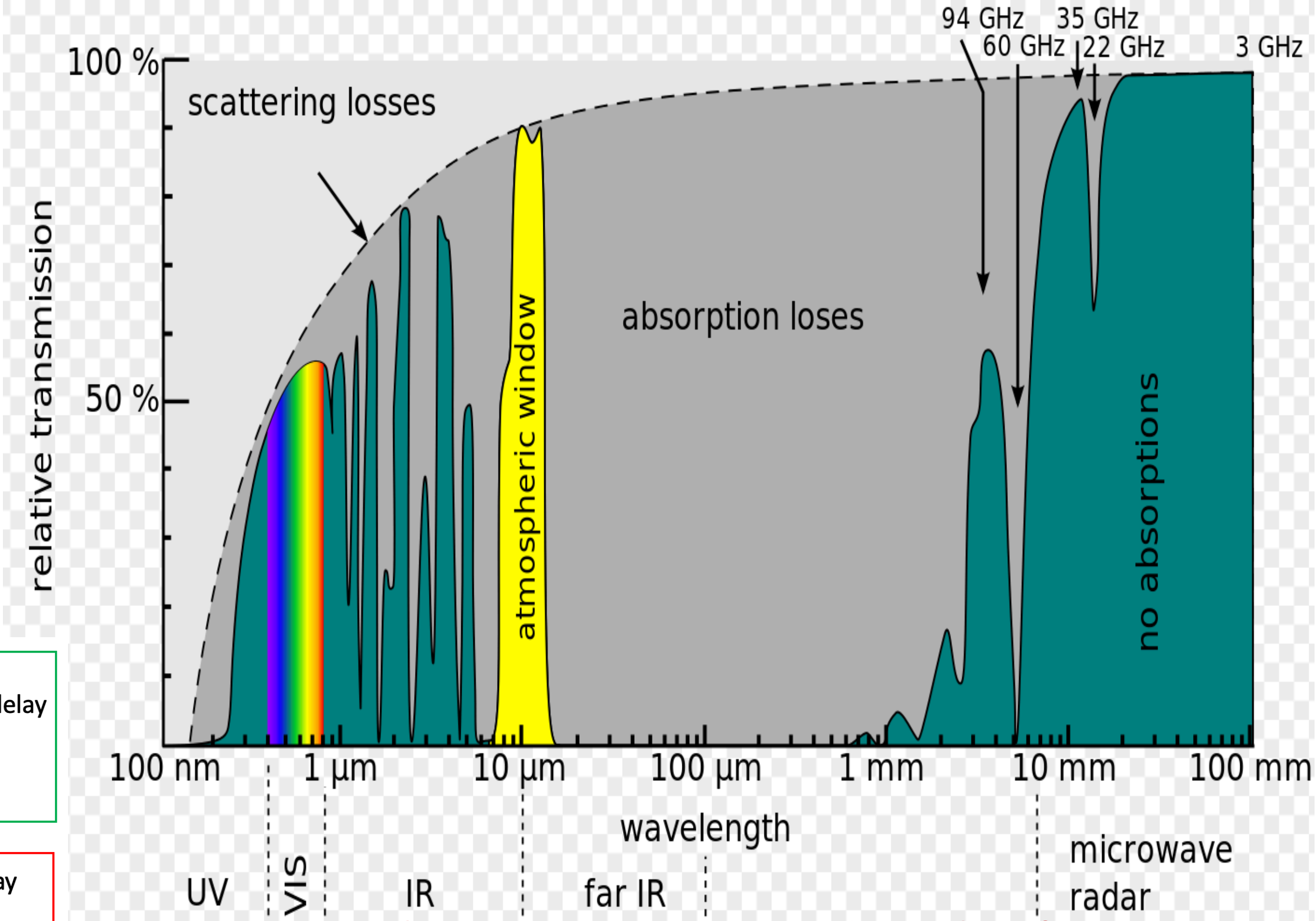


One Color propagation delay

$$L = 10^{-6}\int N(s)ds$$

Two color dispersive delay

$$L_B - L_R = 10^{-6}\int ds\, N_B(s) - N_R(s)$$



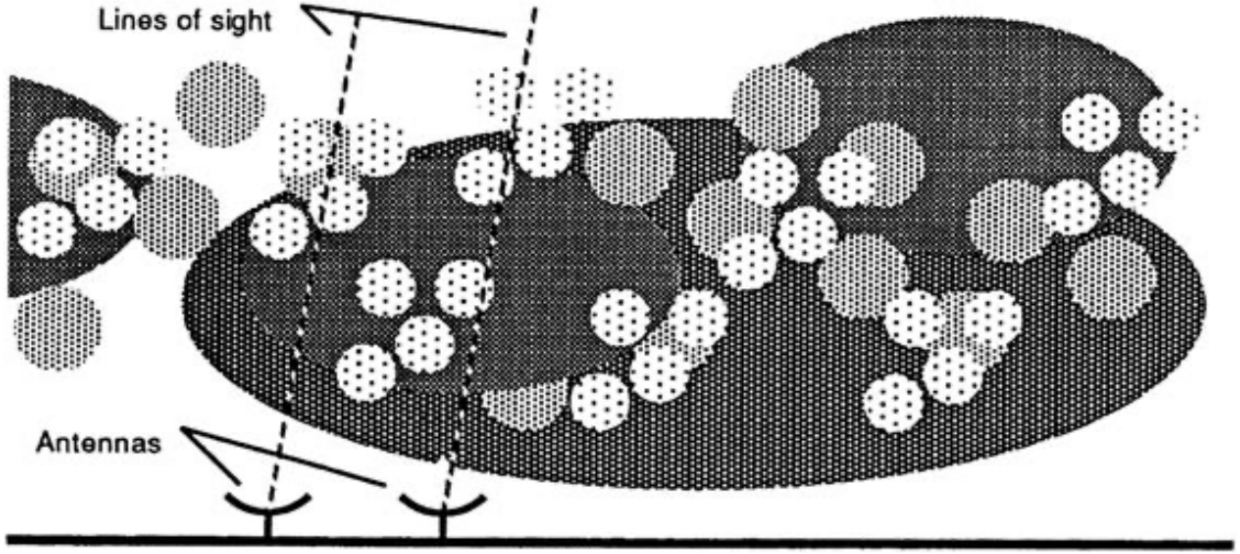
Results in transmission windows, but finite absorption within these windows gives strong sky background in the MIR

Back to turbulence: the clear turbulent atmosphere causes phase and amplitude fluctuations

- Which lead to coherence limitations
  - Coherent aperture size (r_0)
  - Maximum coherent integration time ($< r_0/V$)

$$N \times r_o^2 \times \frac{r_o}{V} \gg 1$$

  - Vmag < 10
  - Scales as $\lambda^{18/5}$

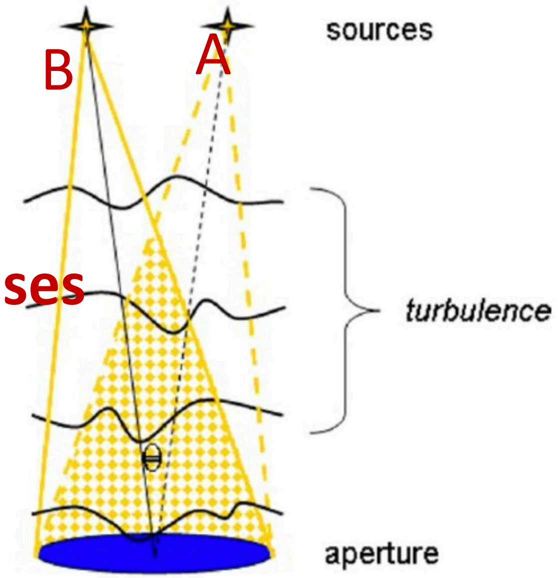


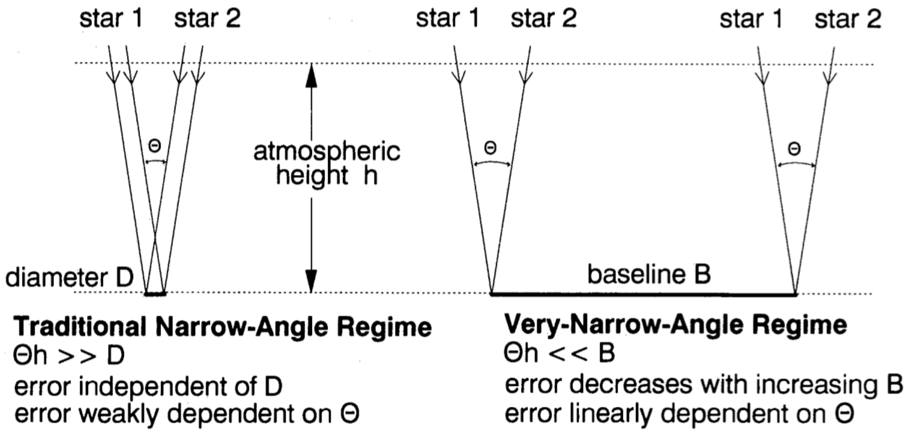
A cartoon representation of a two element interferometer beneath a tropospheric screen with irregularities of various sizes. Energy enters at the largest scales and then cascades down to smaller scales.

Overcoming coherence limitations with interferometric phase referencing

- Short coherence times limits phase tracking interferometers even on 8-10 m class telescopes to K < 11
- Off axis phase tracking or phase referencing can be implemented to realize coherence times of ~ minutes
    - Implemented on PTI, Keck, PRIMA for long baseline narrow angle astrometry
    - Scientifically exploited for the first time on VLTI-GRAVITY

Src A and B within an isoplanatic angle, (few arcsec) then phases are correlated

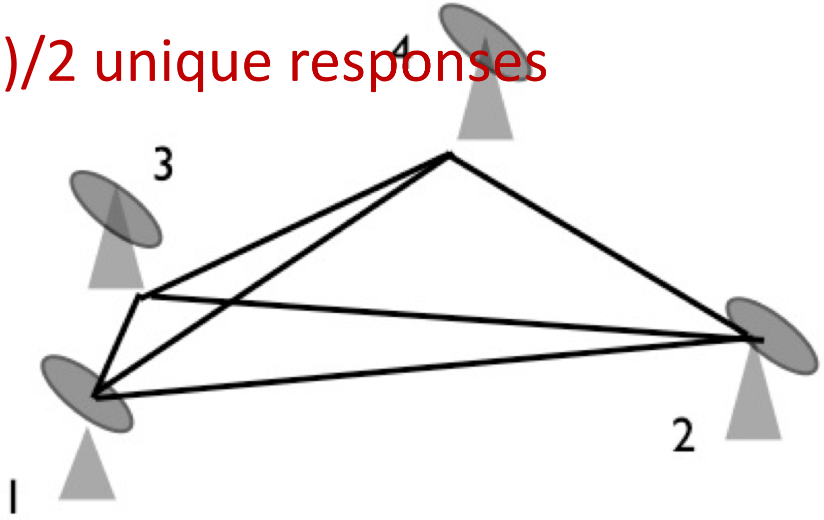




NA Astrometry Shao & Colavita 1992

N-Element interferometers can measure closure quantities that are independent of the atmosphere

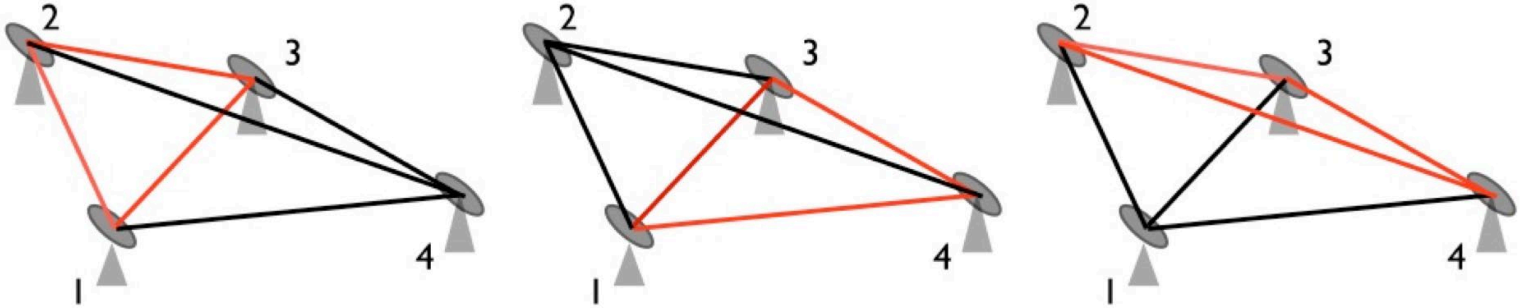
N(N-1)/2 unique responses



Ratio of observables = (N-2)/N
= 33% (N=3)
~ 100 % (N = large)

⇒In general the reliability of closure phase imaging favors large N-arrays for more robust calibration and better uv-coverage. This may be easier done from the ground than space.

(N-1)(N-2)/2 unique closure phases



Ground based mid-IR nulling measurements for Exo-zodiacal Light

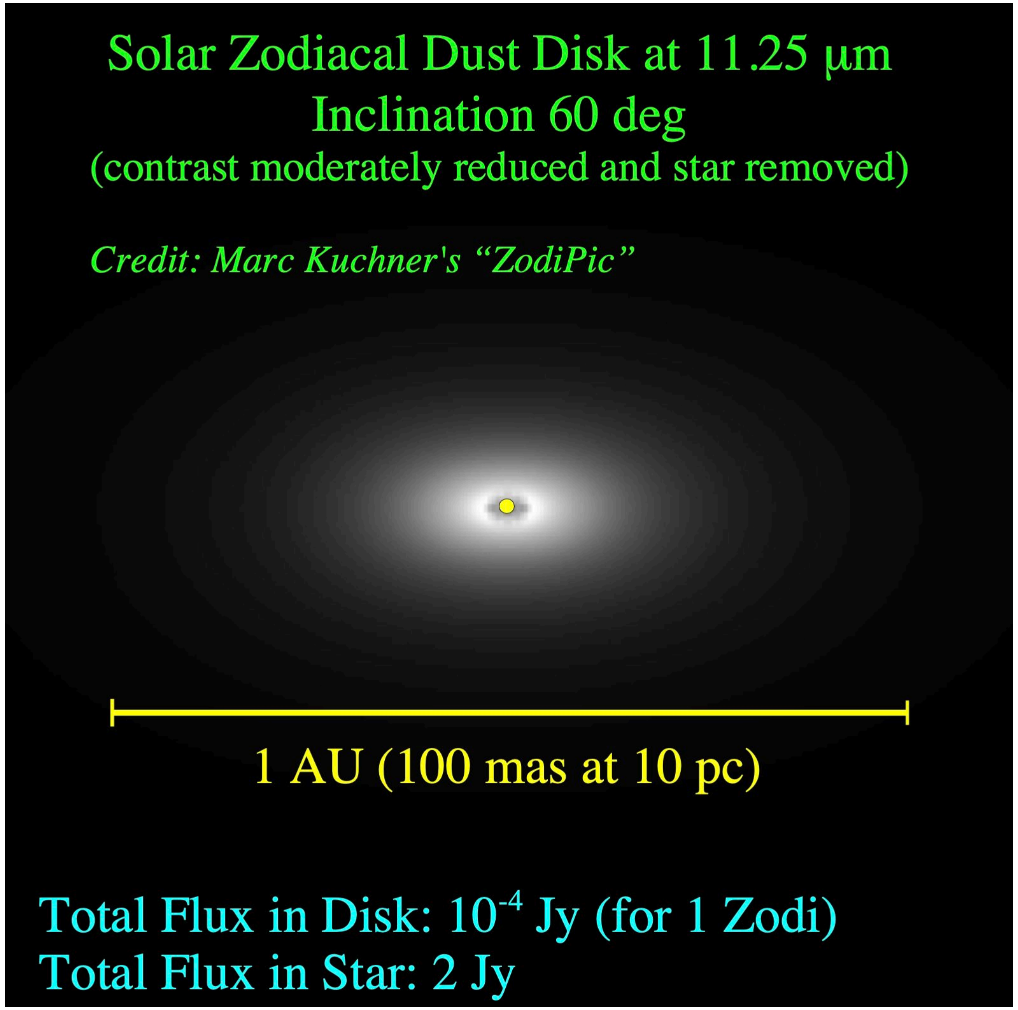
- Contrast for 1 ExoZodi ~ 5e^{-5}
- Equivalent to measuring a traditional visibility to about 100 ppm

$$Null = \frac{1 - V}{1 + V}$$

$$\frac{\delta V}{V} = 10^{-4}$$

- In practice ground-based Nullers have achieved dV/V ~ 5-10 x 10^{-4} at 0.1”

For planets $\frac{\delta V}{V} = 10^{-6}$



Solar Zodiacal Dust Disk at 11.25 μm
Inclination 60 deg
(contrast moderately reduced and star removed)

Credit: Marc Kuchner's “ZodiPic”

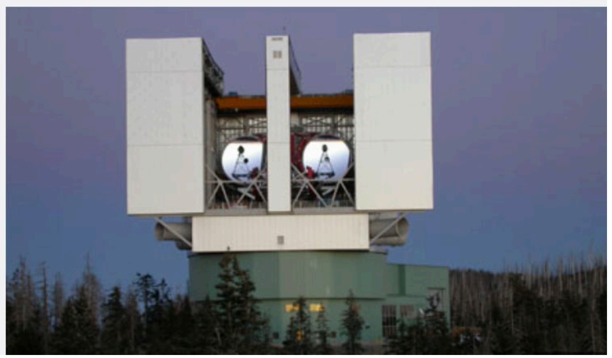
Total Flux in Disk: 10^{-4} Jy (for 1 Zodi)
Total Flux in Star: 2 Jy

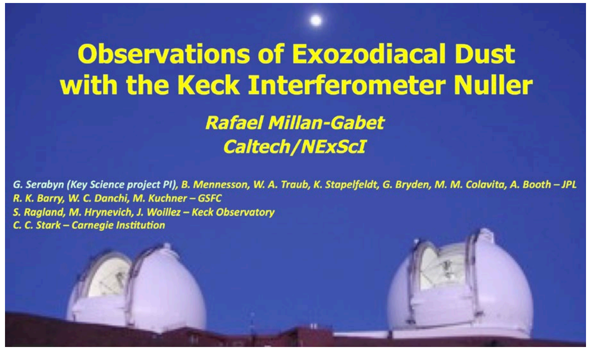
Mid-IR Nulling Limitations are analogous to those for coronagraphy

- Raw null depths are limited by E-field phase and amplitude fluctuations

$$N_{raw} \sim \frac{\varepsilon^2}{4} + \frac{\varphi^2}{4} + myriad\ other\ terms$$

$$\varphi < \ 2\ \times 10^{-2}\ radians\ or\ 30\ nm\ RMS$$





Observations of Exozodiacal Dust
with the Keck Interferometer Nuller

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G. Serabyn (Key Science project PI), B. Mennesson, W. A. Traub, K. Stapelfeldt, G. Bryden, M. M. Colavita, A. Booth – JPL
R. K. Barry, W. C. Danchi, M. Kuchner – GSFC
S. Ragland, M. Hrynevich, J. Woillez – Keck Observatory
C. C. Stark – Carnegie Institution

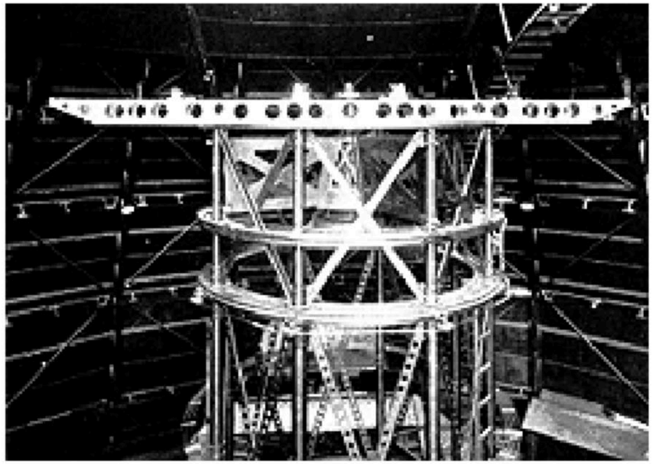
- Background rates are huge. Raw null depths can also be limited by improper calibration of background fluctuations

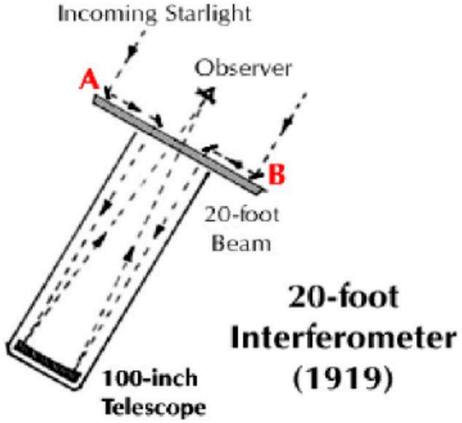
$$N_{raw} \sim \frac{\varepsilon^2}{4} + \frac{\varphi^2}{4} + \boxed{\frac{\gamma B}{N}} + (myriad - 1)\ other\ terms$$

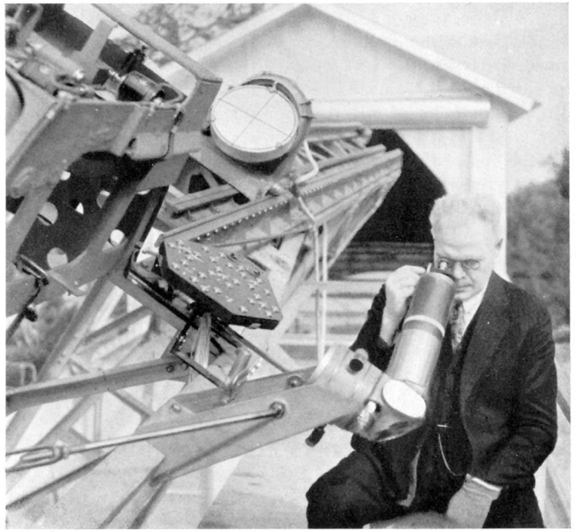
PPM knowledge of background rates after chopping
B = 100 x N

- Raw null depths are also limited by dispersion, water-vapor seeing

Hundred years of stellar interferometry from Mt. Wilson







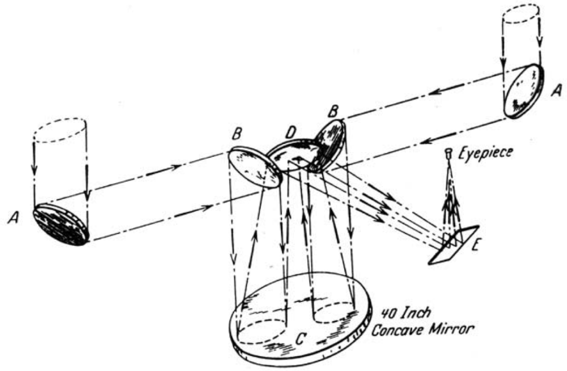


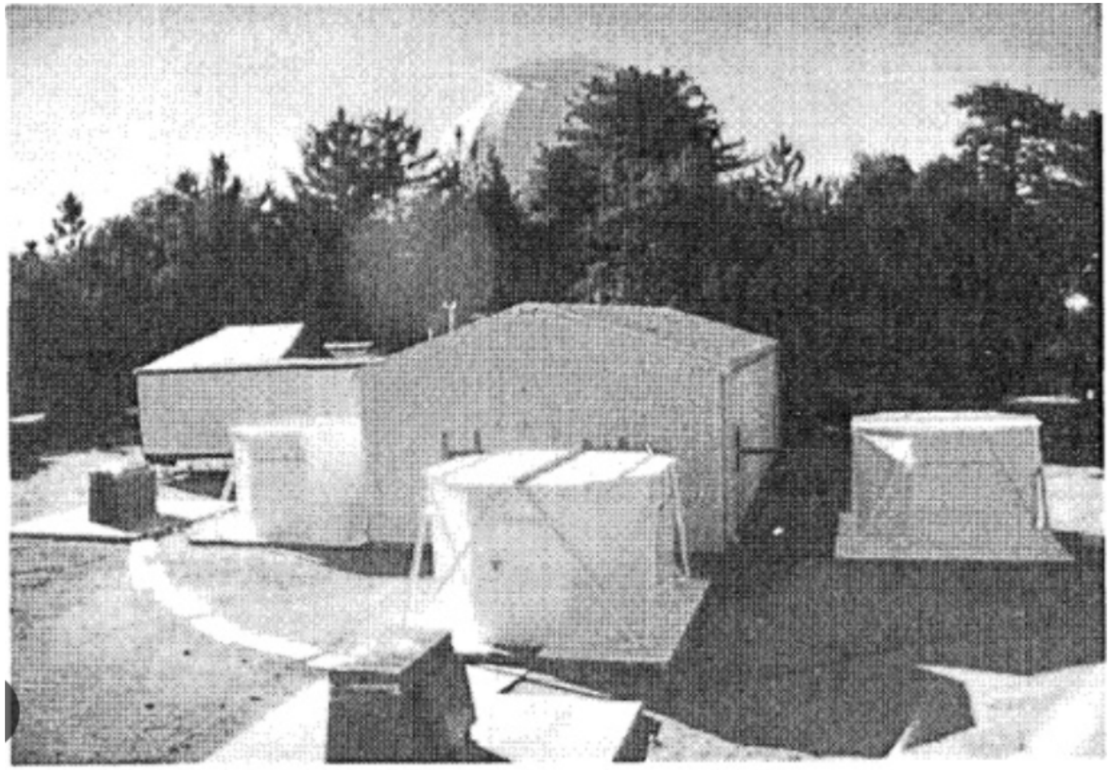
Abb. 8. Diagram of light path in 50 foot interferometer.

Michelson & Pease 1921

50-foot Interferometer, Pease 1930

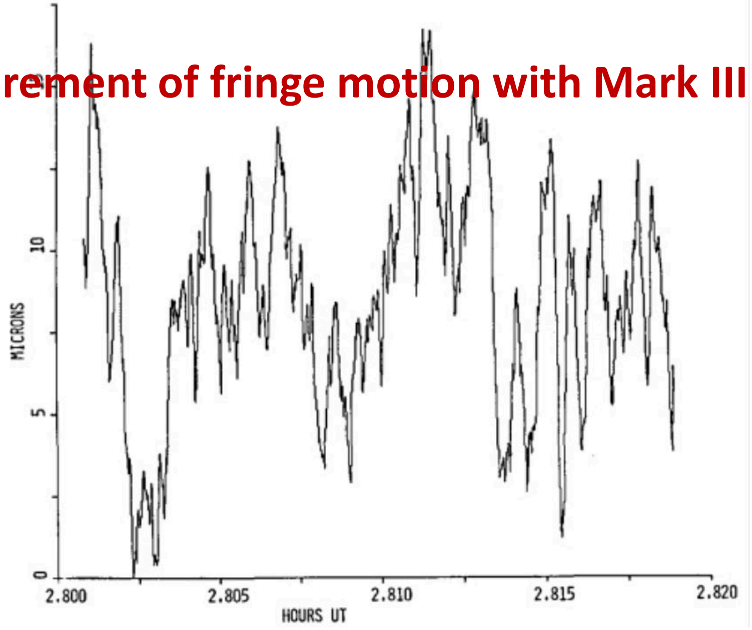
	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010	2020
Michelson & Pease	▨										
Pease		▨									
Mark I, II, III							▨				
Infrared Spatial Interferometer							▨	▨	▨		
CHARA									▨	▨	▨
Hanbury Brown & Twiss					▨	▨					
Labyrie I2T						▨					

Mt. Wilson centric developments over 100 years (dates in crude lumps of ~10 years)

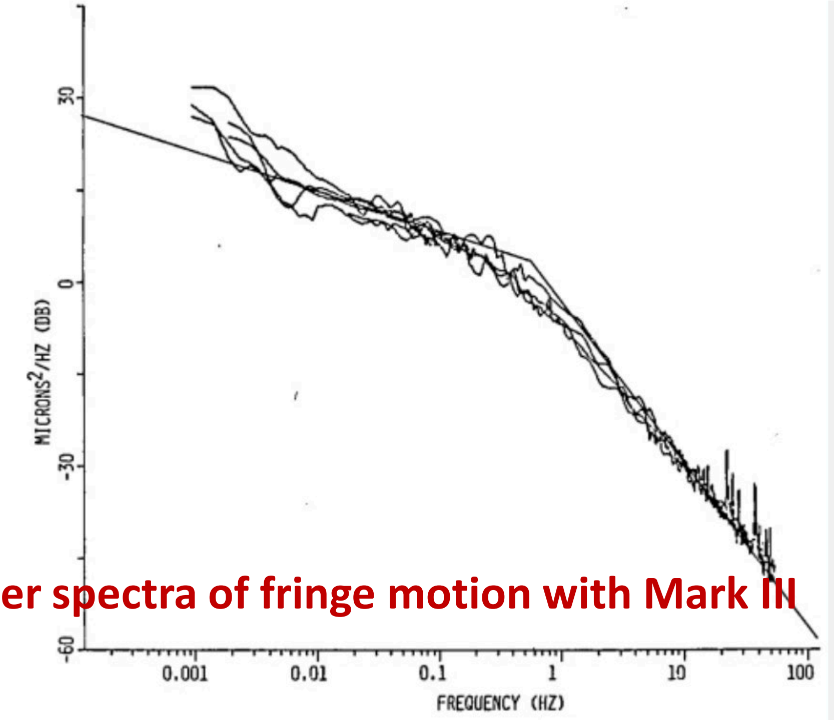


Mark I, II, and III stellar interferometers on Mt. Wilson (1979 – 1995) relied on significant advances in optics, electronics, computing, lasers, etc.

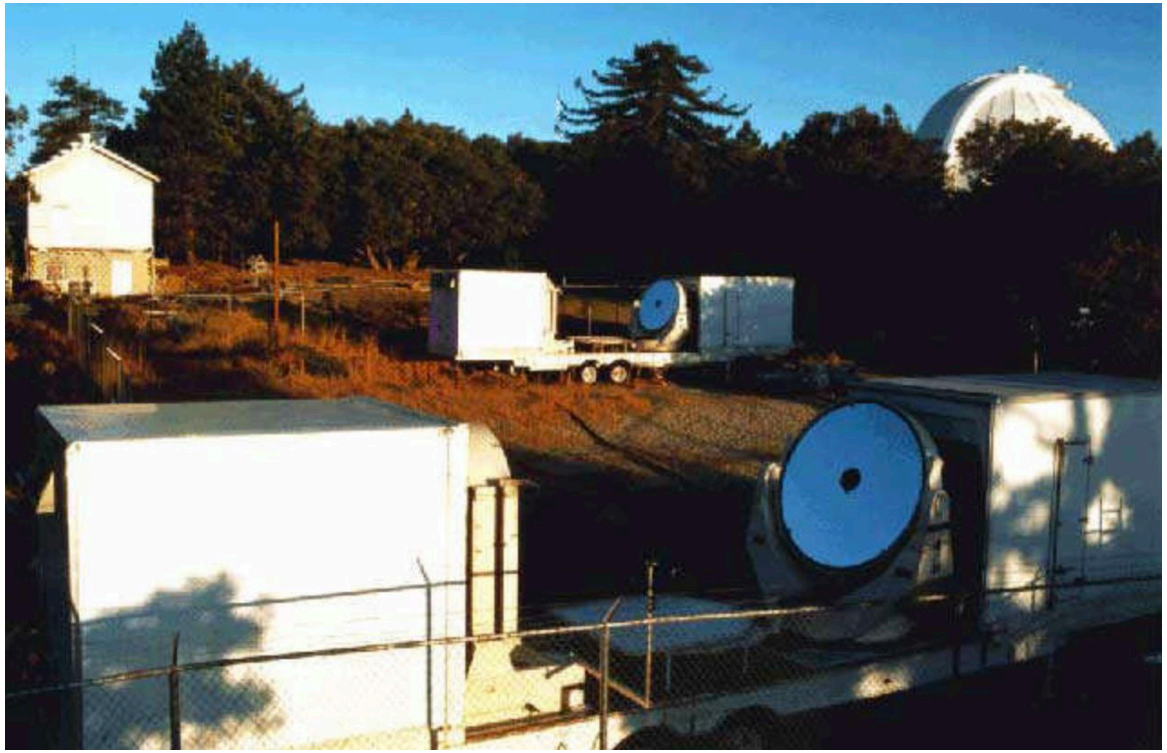
Mark I demonstrated phase tracking (Shao & Staelin 1977)
Mark II demonstrates a fast delay line (Shao et al. 1984)
Mark III show 2-color astrometric measurement (Shao et al. 1988)



Measurement of fringe motion with Mark III



Power spectra of fringe motion with Mark III

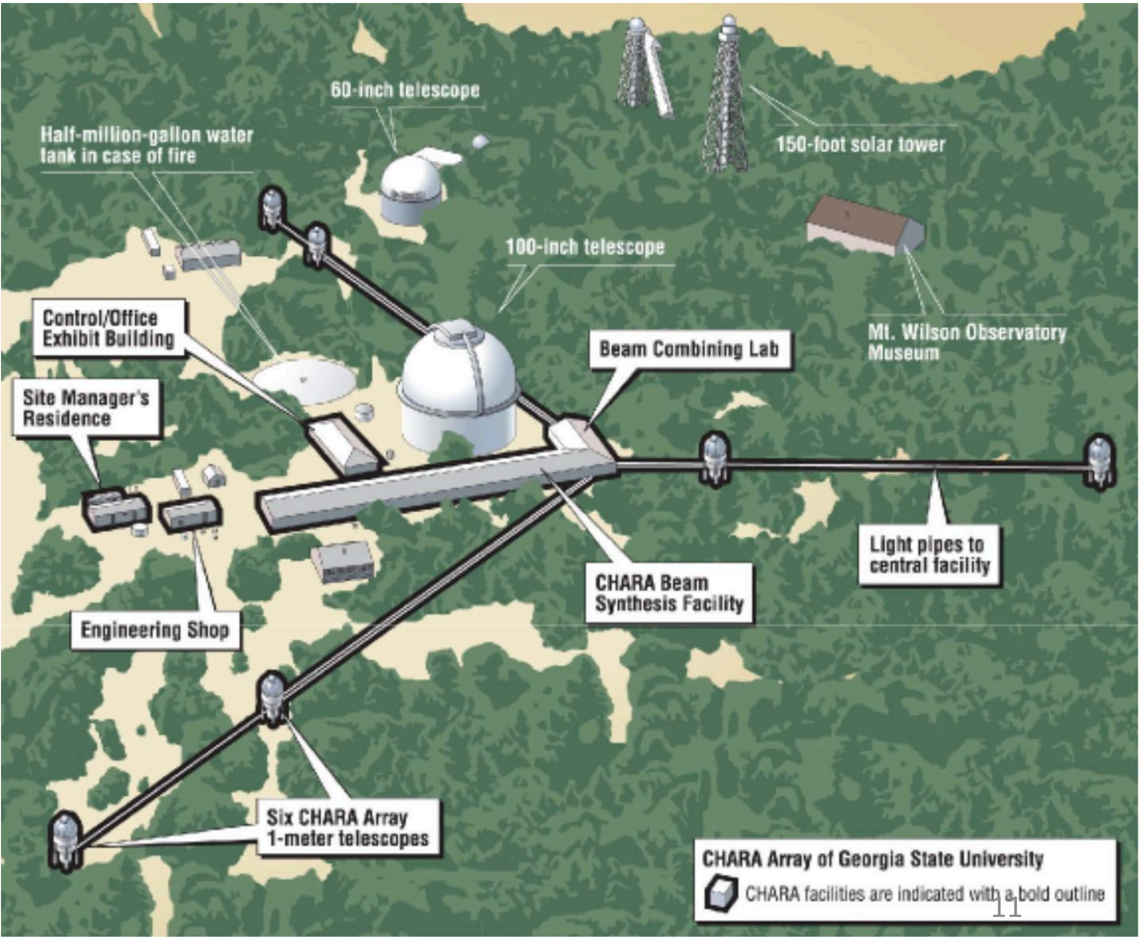


Infrared Spatial Interferometer
11 um heterodyne detection with CO2 laser LO
and BW = 3 GHz
1988 –

E.g. Sutton et al. 1988; Hale et al. 2000

CHARA Array 1999 –
Six 1-m telescopes, max 330 m baseline

Major US optical interferometry facility and testbed for technologies



New challenges for ground based interferometry

- The desire for large baseline interferometric arrays
  - Photonic combiners in the mid IR bands
  - Fiber transport and fiber delay lines
    - Fibers are strongly dispersive media
    - Apart from silica, and perhaps ZBLAN glass, transmission in fibers is poor. Hollow core technologies?
  - For ultra long baselines
    - Broadband heterodyne photonic receivers
    - Time transfer for syncing LOs
    - LOs
    - Computing, UHS data recording etc.