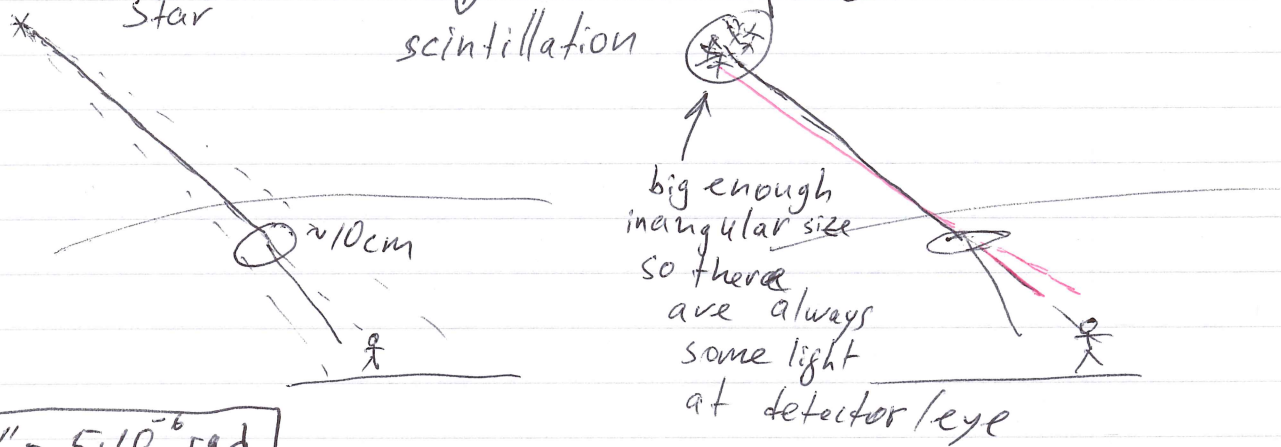


The atmosphere problem

Why star twinkle and planets don't
 star \updownarrow scintillation planet



$1'' = 5 \cdot 10^{-6} \text{ rad}$

Due to this effect best angular resolution is $0.25'' = 0.25 \cdot 5 \cdot 10^{-6} \text{ rad} \approx 1.25 \cdot 10^{-6} \text{ rad}$

can be mitigated with adaptive optics (≈ 10 years old)

* Closest star at $\approx 1\text{pc} \Rightarrow \theta \approx 1''$

recall $\frac{\lambda}{D} = \frac{10^{-6} \text{ m}}{10 \text{ m}} \approx 10^{-7} \text{ rad}$

so atmosphere nukes $\sqrt{10}$ factor of

We can also do detection with non optical λ : Radio, X-ray, γ -ray, infrared but atmosphere has only few windows of transparency



Star size diameters

Betelgeuse ↙ larger than Earth orbit

$$R_{st} = 1000 R_{\odot} = 10^3 \cdot 7 \cdot 10^8 \text{ m}$$



$$\text{distance } b = 200 \text{ pc} = 200 \cdot 3 \cdot 10^{16} \text{ m}$$

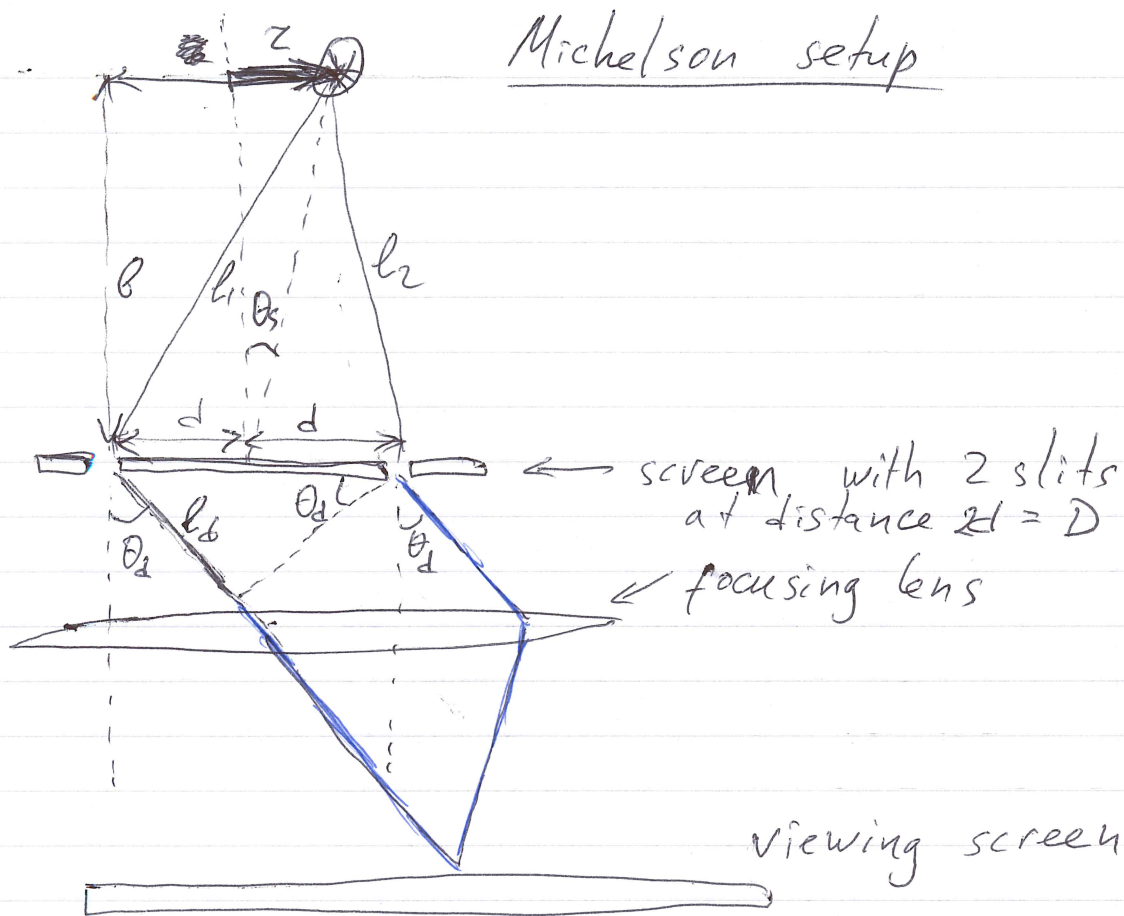
$$\theta_{\text{disk}} = \frac{R_{st}}{b} = \frac{7 \cdot 10^{11}}{6 \cdot 10^{18}} \approx 10^{-7} \text{ rad}$$

So it can be done with telescopes with ϕ of about 5-10 m

But the atmosphere ruins it.

The answer is differential measurements

Michelson setup



We are concerned with interference so total path difference between path 1 and 2 is $\Delta l = l_1 + l_2 - l_3$

↑ due to diffraction

note that blue parts are equal (lens ~~is~~ focusing property) for beams which are parallel.

$$l_1 = \sqrt{b^2 + (d+z)^2}$$

$$l_2 = \sqrt{b^2 + (d-z)^2}$$

$$l_d = 2d \cdot \sin \theta_d$$

$$\Delta l = l_1 + l_d - l_2 =$$

$$= \sqrt{b^2 + (d+z)^2} + 2d \sin \theta_d - \sqrt{b^2 + (d-z)^2} =$$

$$= \left| \begin{array}{l} b \gg z, \\ b \gg d \end{array} \right| \approx b \left(1 + \frac{(d+z)^2}{2b^2} \right) + 2d \sin \theta_d$$

$$= b \left(1 + \frac{(d-z)^2}{2b^2} \right) =$$

$$= \frac{2dz}{b} + 2d \sin \theta_d =$$

$$= \left| \begin{array}{l} \text{recall } \frac{z}{b} = \theta_s \text{ angle to the star,} \\ 2d = D \text{ separation between slits} \end{array} \right|$$

$$\Delta l = \theta_s \cdot D + D \sin \theta_d$$

condition for interference maxima

$$\Delta l = m \lambda$$

— | — minima

$$\Delta l = \frac{\lambda}{2} + m \lambda$$

Let's be concerned with maxima only

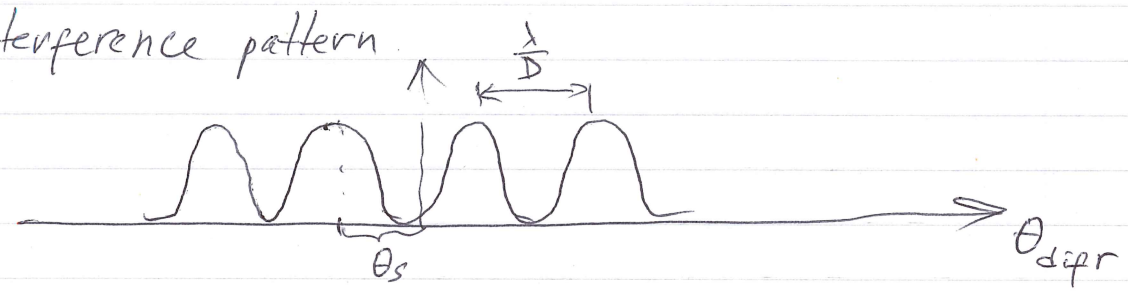
$$\Delta l = \theta_s D + D \sin \theta_s = \lambda m$$

$$\sin \theta_{\max} = \frac{\lambda m}{D} - \theta_s$$

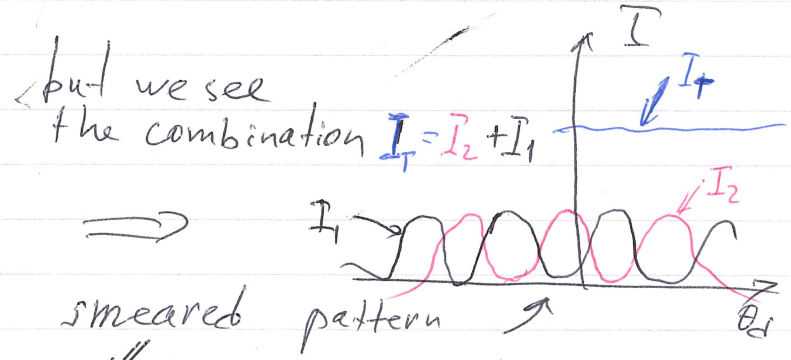
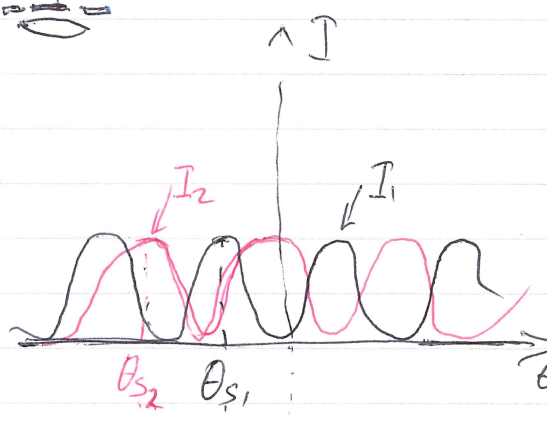
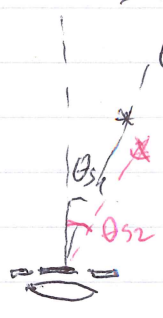
$\theta \ll 1$

$$\theta_{\max} = \frac{\lambda}{D} m - \theta_s$$

interference pattern



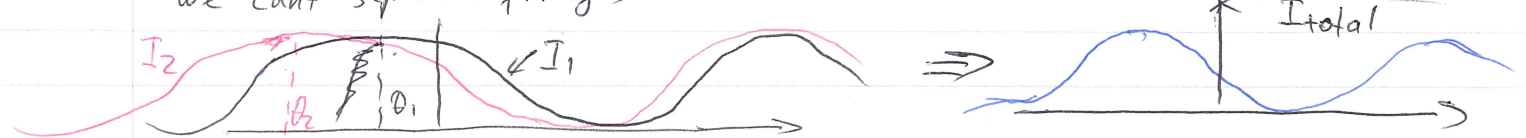
Suppose we are observing two stars at θ_{s1} and θ_{s2} . Each of the stars will form the following patterns on the screen



if we decrease D , we can't separate fringes

$$\theta_{s2} - \theta_{s1} = \frac{1}{2D} \lambda$$

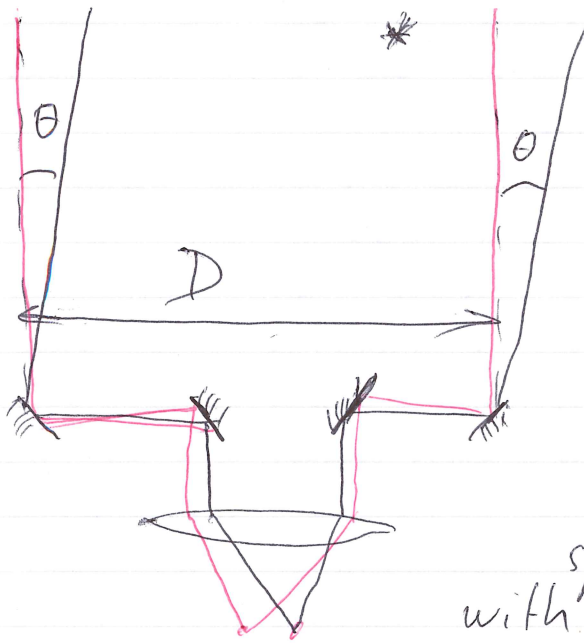
resolution of this Michelson setup



Wait a second our resolution is still no better than one of original telescope, i.e. $\sim \lambda/D$

But we've got an advantage: contrast of the pattern (i.e. do we see fringes or not) is ~~not~~ not affected by the atmosphere any more.

But there is one more trick to use



so we can separate slits by a larger distance.

It sounds easier than it is:

We need to move mirrors without affecting their alignment

i.e. position of reflected spot need to be controlled with better than λ precision

So at the time of Michelson the largest telescope ~~was~~ had $\phi \approx 5$ m, Michelson used $D = 6$ m (recall it need to be scanned!)

In 1891 Jupiter moons diameters

In 1920, ~~he~~ he measured diameter of the Betelgeuse star with it angular size $\approx 0.044''$. Note a difference that a star can be considered as bunch of point sources * * * * *

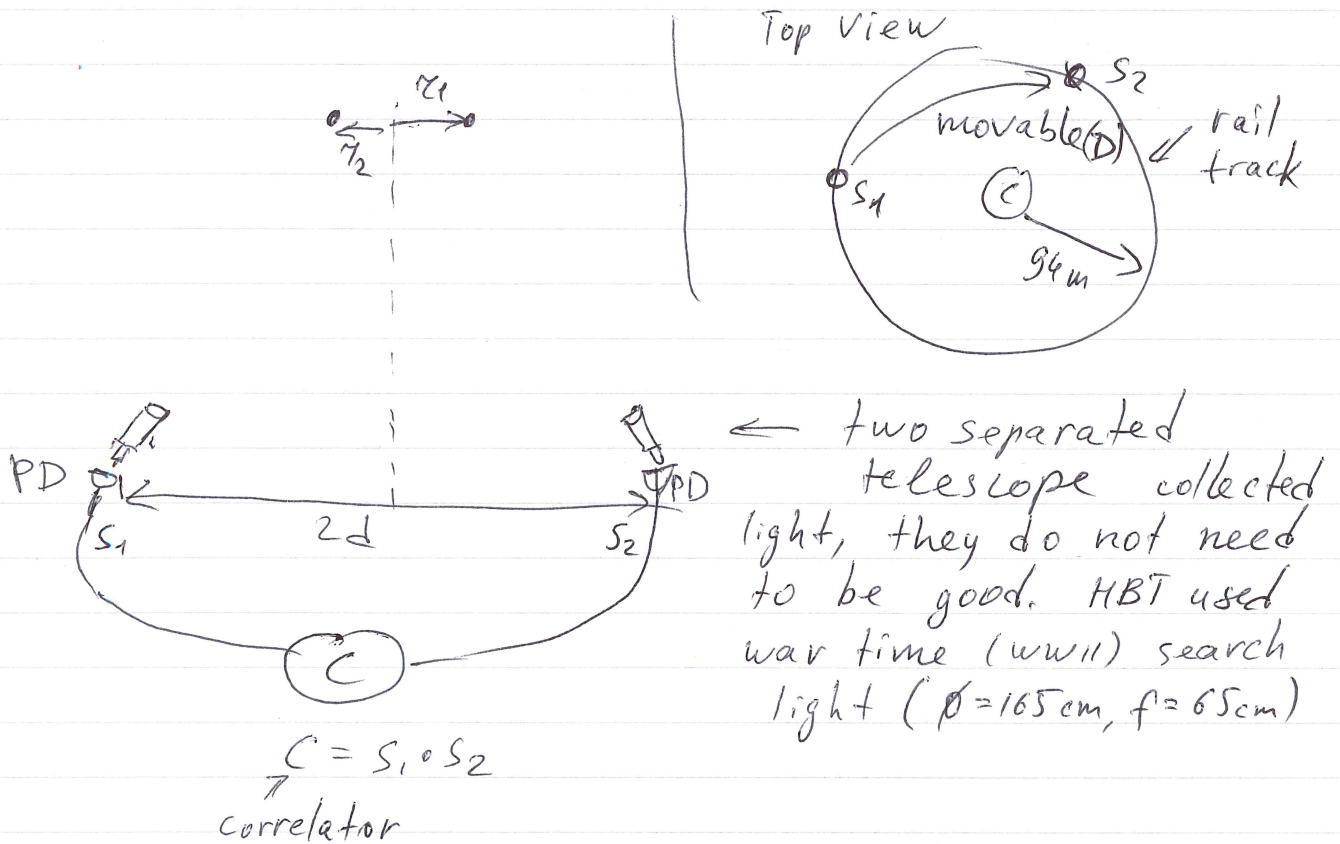
Beyond standard telescope resolution,
and mitigation of atmospheric effects.

Key idea: we will do differential measurements,
so objects might appear to shift/wobble/twinkle
but resulting measurement will not

Alignment problems limit practical size of D , setups with $D=18$ m are known though.

The next idea we will use intensity (vs. more well known field) interferometer

Hanbury Brown and Twiss experiment 1956



light ~~intensity~~ seen by one detector is delayed with respect to the other one due to optical path difference Δl

So for the first source signal from 1st detector

$$S_1 = I_1(t)$$

on a 2nd detector it is $S_2 = I_1(t - \Delta l/c)$

$$\Delta l_1 = D \cdot \left(\frac{z_1}{\rho} \right) \approx D \theta_{z_1} \quad (\text{see Michelson exp.})$$

Similarly for the 2nd star

$$S_1 = I_1(t) + I_2(t)$$

$$S_2 = I_1(t - \frac{\Delta l_1}{c}) + I_2(t - \frac{\Delta l_2}{c})$$

$$C = \langle S_1 \circ S_2 \rangle =$$

$$= \langle (I_1(t) + I_2(t)) \circ (I_1(t - \frac{\Delta l_1}{c}) + I_2(t - \frac{\Delta l_2}{c})) \rangle$$

$$= \langle \underbrace{I_1(t) I_1(t - \tau_1)}_{g_2(\tau_1)} \rangle + \langle \underbrace{I_2(t) I_2(t - \tau_2)}_{g_2(\tau_2)} \rangle$$

$$+ \langle I_1(t) \circ I_2(t - \tau_2) \rangle + \langle I_2(t) \circ I_1(t - \tau_1) \rangle$$

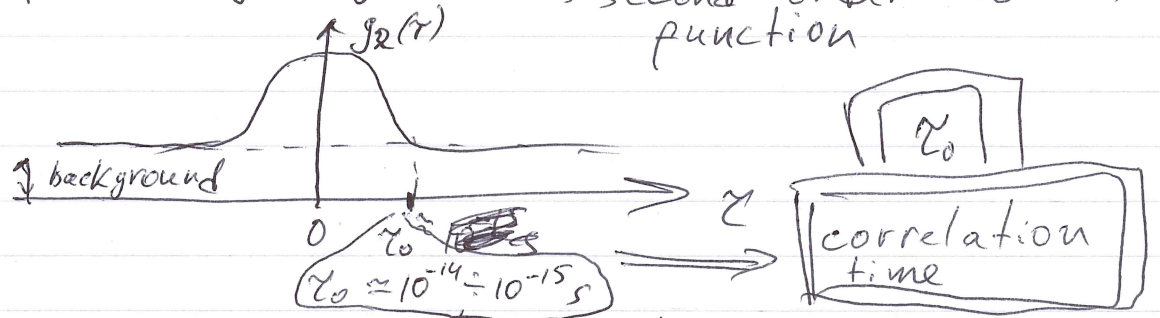
→ const → const
uncorrelated sources

Note $\langle \dots \rangle = \frac{1}{T} \int_0^T \dots dt$

We assume that all light sources have the same g_2 behavior

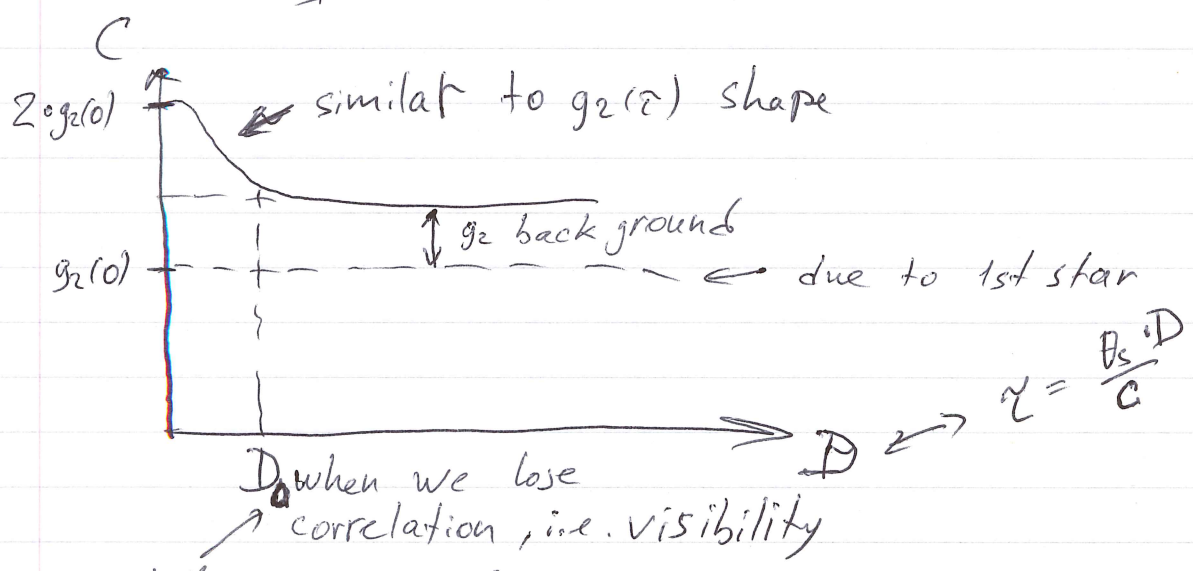
So $C = g_2(r_1) + g_2(r_2)$

A typical ^{thermal} light source has the following $g_2(r)$ ← second order correlation function



Let's for simplicity chose $r_1 = 0$
 then $r_2 = 0$ ← always, i.e. $\theta_{star_1} = 0$

no we move detectors to change D



when we lose correlation, i.e. visibility

$D \Leftrightarrow \frac{\Delta r_2}{c} = \tau_0$

$\Rightarrow \frac{D \cdot r_2}{\delta c} = \tau_0 \Rightarrow$

star separation

$r_2 = \tau_0 \cdot c \cdot \frac{\theta}{D_0}$

Note that angular resolution

$\theta_s = \frac{r}{\delta} = \frac{c \tau_0}{D_0}$

D is limit less,