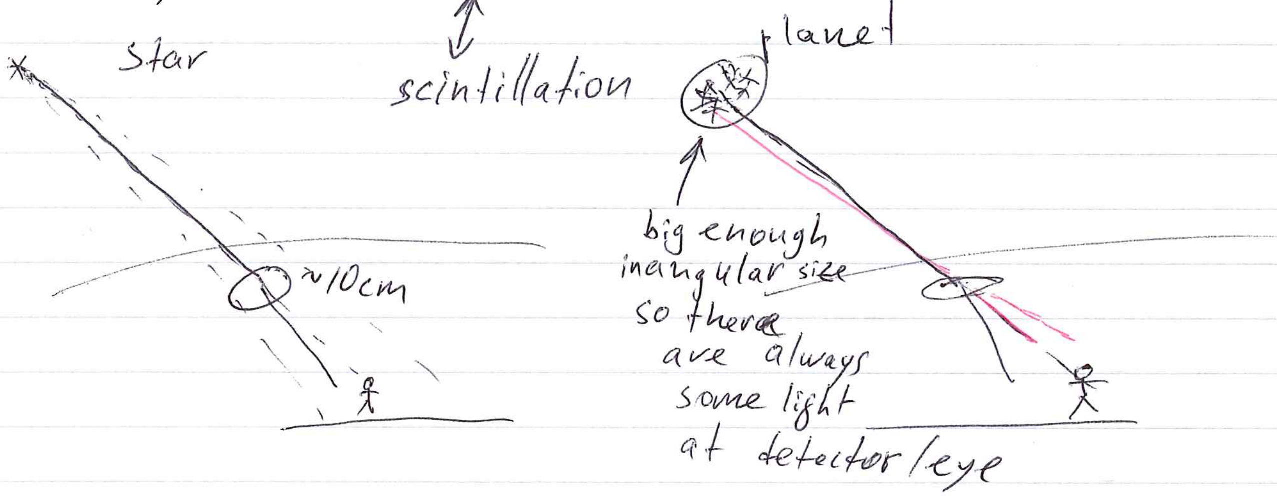
The atmospere problem

Why star twinkle and planets don't
↕
scintillation



Due to this effect best angular $\boxed{\text{resolution is } 0.25''} = 0.25 \cdot 0.5 \cdot 10^{-6}\ \text{rad} \sim$
$\simeq 1.25 \cdot 10^{-6}\ \text{rad}$

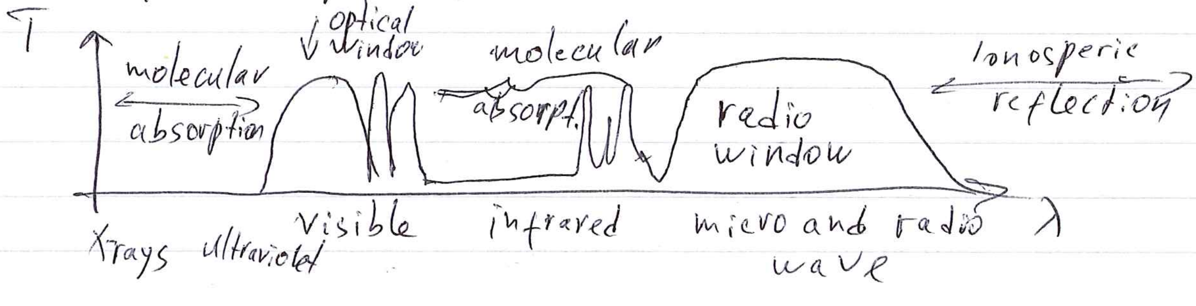
↕ can be mitigated with adaptive optics (≈ 10 years old)

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

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

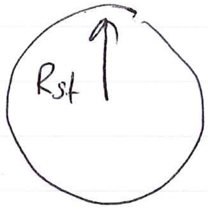
so atmospere nukes factor of 10

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



Star size diameters

Betelgeuse — larger then Earth orbit



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

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

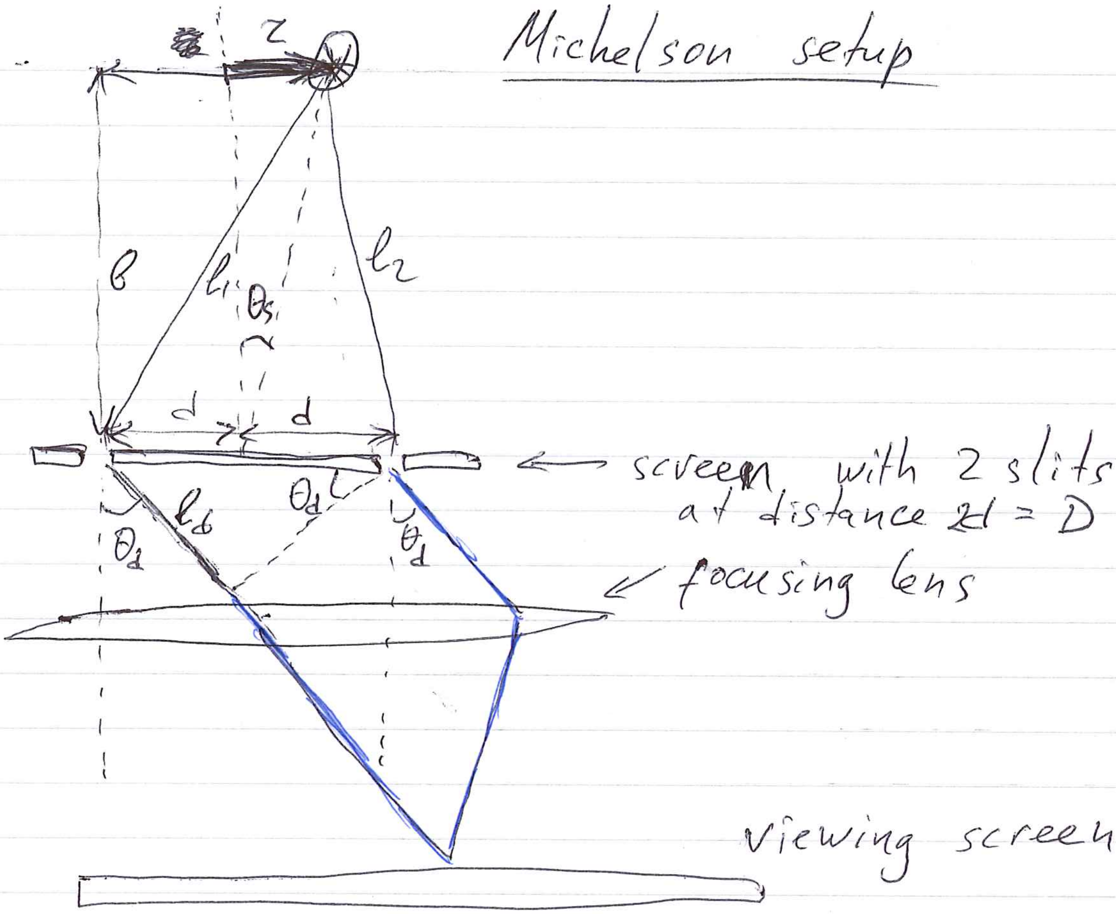
$$\theta_{disk} = \frac{R_{st}}{\ell} = \frac{7 \cdot 10^{11}}{6 \cdot 10^{18}} \simeq 10^{-7} \text{ m}$$

So it can be done with telescopes with ∅ of about 5÷10 m

But the atmosphere ruins it.

The answer is differential measurements

Michelson setup



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

↑ due to difraction

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

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

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

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

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

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

$$= \Big/ \begin{matrix} b \gg r, \\ b \gg d \end{matrix} \Big/ \simeq b\left(1 + \frac{(d+r)^2}{2b^2}\right) + 2d\sin\theta_d - b\left(1 + \frac{(d-r)^2}{2b^2}\right) =$$

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

$$= \Big/ \text{recall } \frac{r}{b} = \theta_s \text{ angle to the star,} \quad 2d = D \text{ separation between slits} \Big/$$

$$\boxed{\Delta l = \theta_s \cdot D + D\sin\theta_d}$$

condition for interference maxima

$$\Delta l = \lambda \cdot m$$

—— // —— minima

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

Let's be concerned with maxima only

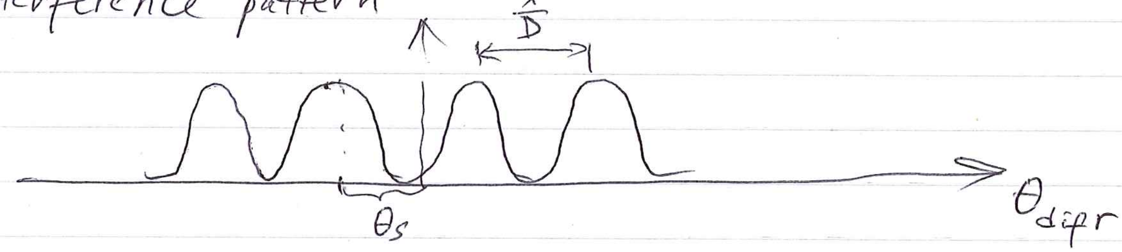
$$\Delta l = \theta_s D + D \sin\theta_d = \lambda m$$

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

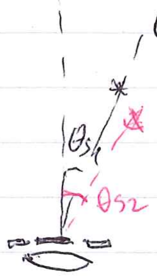
$\theta \ll 1$

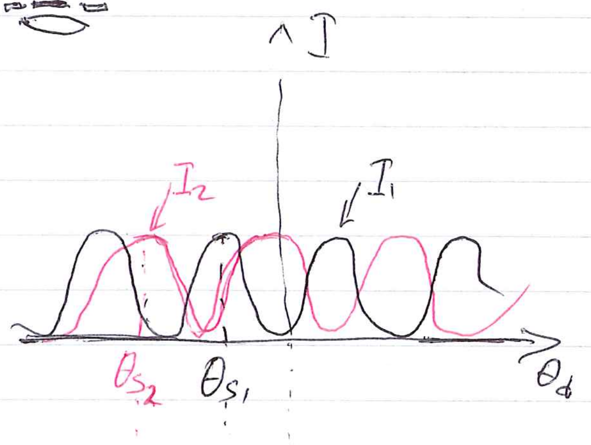
$$\theta_{max} = \frac{\lambda}{D} m - \theta_s$$

interference pattern



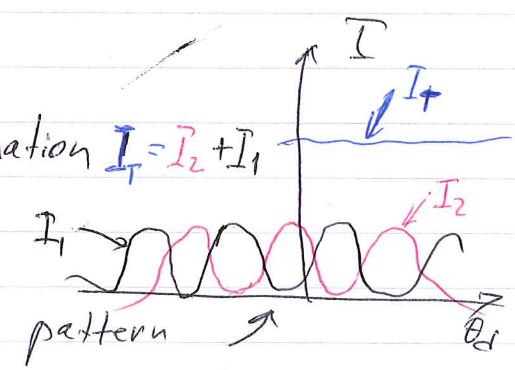
Suppose we are observing two stars at θ_{s_1} and θ_{s_2}. Each of the stars will form the following patterns on the screen





but we see the combination $I_T = I_2 + I_1$

$\Longrightarrow$

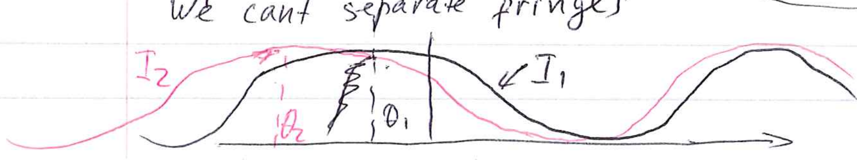


smeared pattern

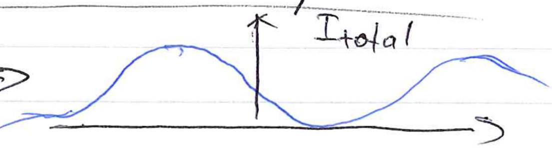
$$\boxed{\theta_{s_2} - \theta_{s_1} = \frac{\lambda}{D}}$$

resolution of this Michelson setup

if we decrease D: we cant separate fringes



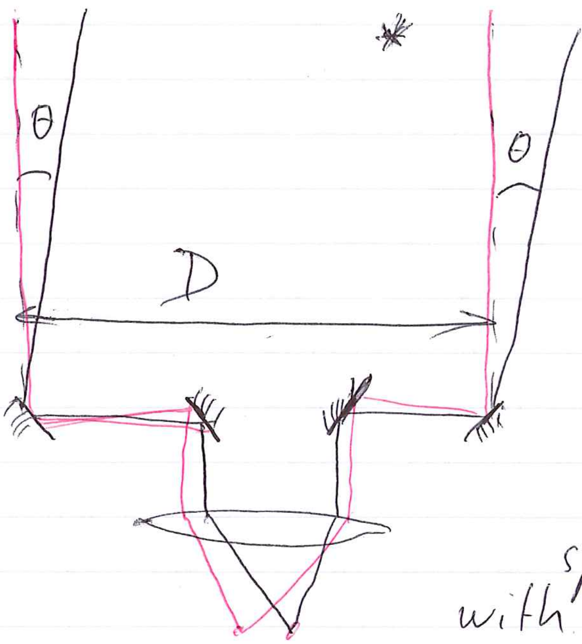
$\Longrightarrow$



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

But we've got an advantage: contrast of the pattern (i.e. do we see fringes or not) is ~~[illegible]~~ not affected by the atmospere 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 allignment i.e. position of reflected spot need to be controlled with better than λ precision

So at the time of Michelson the largest telescope ~~[illegible]~~ had $\varnothing \simeq 5$ m, Michelson used $D = 6$ m (recall it need to be scaned!)
In 1891 Jupiter moons diameters
In 1920, ~~[illegible]~~ He measured diameter of the Betelgeuse star with it angular size $\approx 0.047''$. Note a difference that a star can be considered as bunch of point sources * * * * * ... *

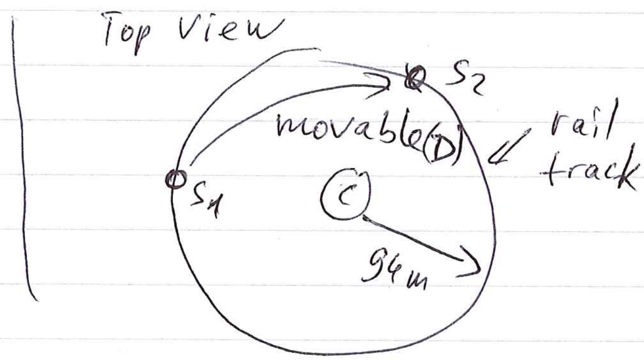
Beyond standard telescope resolution, and mitigation of atmospheric effect.

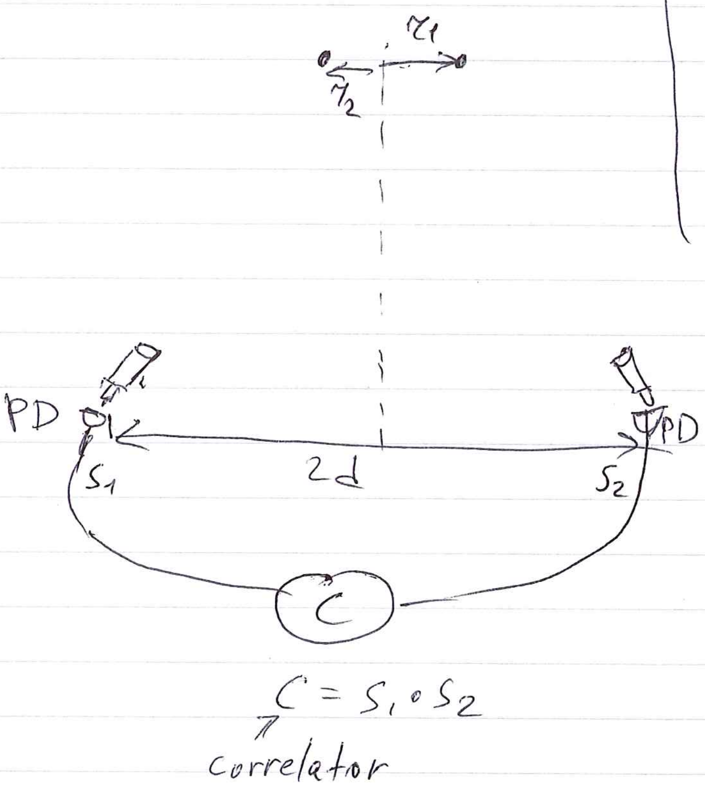
Key idea: we will do differential measurement, so objects might appear to shift/woble/twinkle but resulting measurement will not

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

The next idea we will use <u>intensity</u> (vs more well known field) <u>interferometer</u>

Manbury, Brown, and Twiss experiment 1956





← two separated telescope collected light, they do not need to be good. HBT used war time (WWII) search light ($\emptyset = 165$ cm, $f = 65$ cm)

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

So for the first source signal from 1st detector

$$S_1 = \underset{\downarrow \text{star 1}}{I_1(t)}$$

on a 2nd detector it is $S_2 = I_1(t - \Delta l_1/c)$

$$\Delta l_1 = D \cdot \frac{r_1}{f} \quad \text{(see Michelson exp.)}$$

Similarly for the 2nd star

So
$$S_1 = I_1(t) + I_2(t)$$
$$S_2 = I_1\left(t - \frac{\Delta l_1}{c}\right) + I_2\left(t - \frac{\Delta l}{c}\right)$$

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

$$= \langle (I_1(t) + I_2(t)) \cdot \left(I_1\left(t - \overset{\tau_1}{\frac{\Delta l_1}{c}}\right) + I_2\left(t - \overset{\tau_2}{\frac{\Delta l_2}{c}}\right)\right) \rangle$$

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

$$+ \cancel{\langle I_1(t) \cdot I_2(t - \tau_2) \rangle} + \cancel{\langle I_2(t) I_1(t - \tau_1) \rangle}$$

const → const

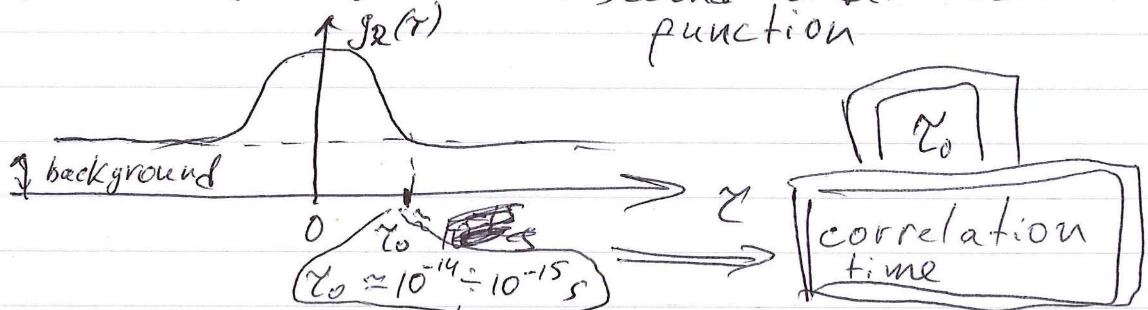
uncorrelated sources

Note $\langle .. \rangle = \frac{1}{T} \int_1^T .. \, dt$

We assume that all light sources have the same g_2 behavior

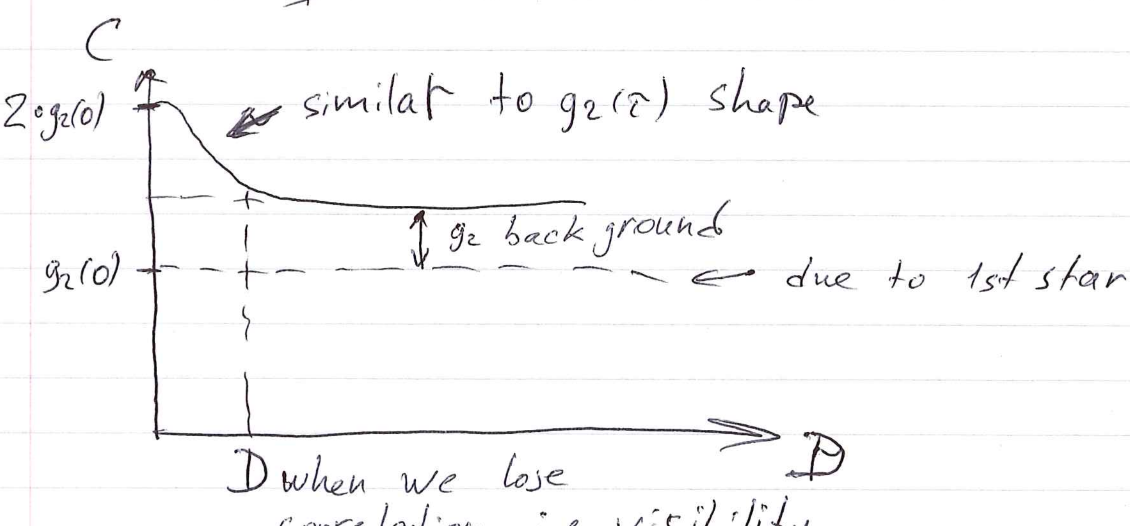
So $\quad C = g_2(\tau_1) + g_2(\tau_2)$

A typical thermal light source has the following $g_2(\tau)$ ← second order correlation function



let's for simplicity chose $\tau_1 = 0$
then $\tau_1 = 0$ ← always

no we move detectors to change D



D when we lose correlation, i.e. visibility

$$D \Leftrightarrow \frac{\Delta \ell_2}{c} = \tau_0$$

star separation

$$\Rightarrow \frac{D \cdot r_2}{\ell\, c} = \tau_0 \Rightarrow \boxed{r_2 = \tau_0 \cdot c \cdot \frac{\ell}{D}}$$

Note that angular resolution $\boxed{\theta_s = \frac{r}{\ell} = \frac{c\tau_0}{D}}$ D is limitless;