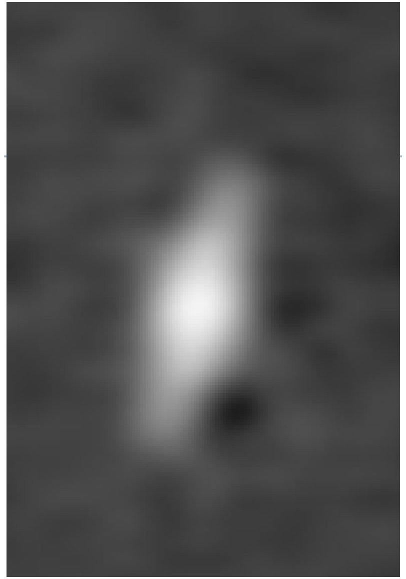


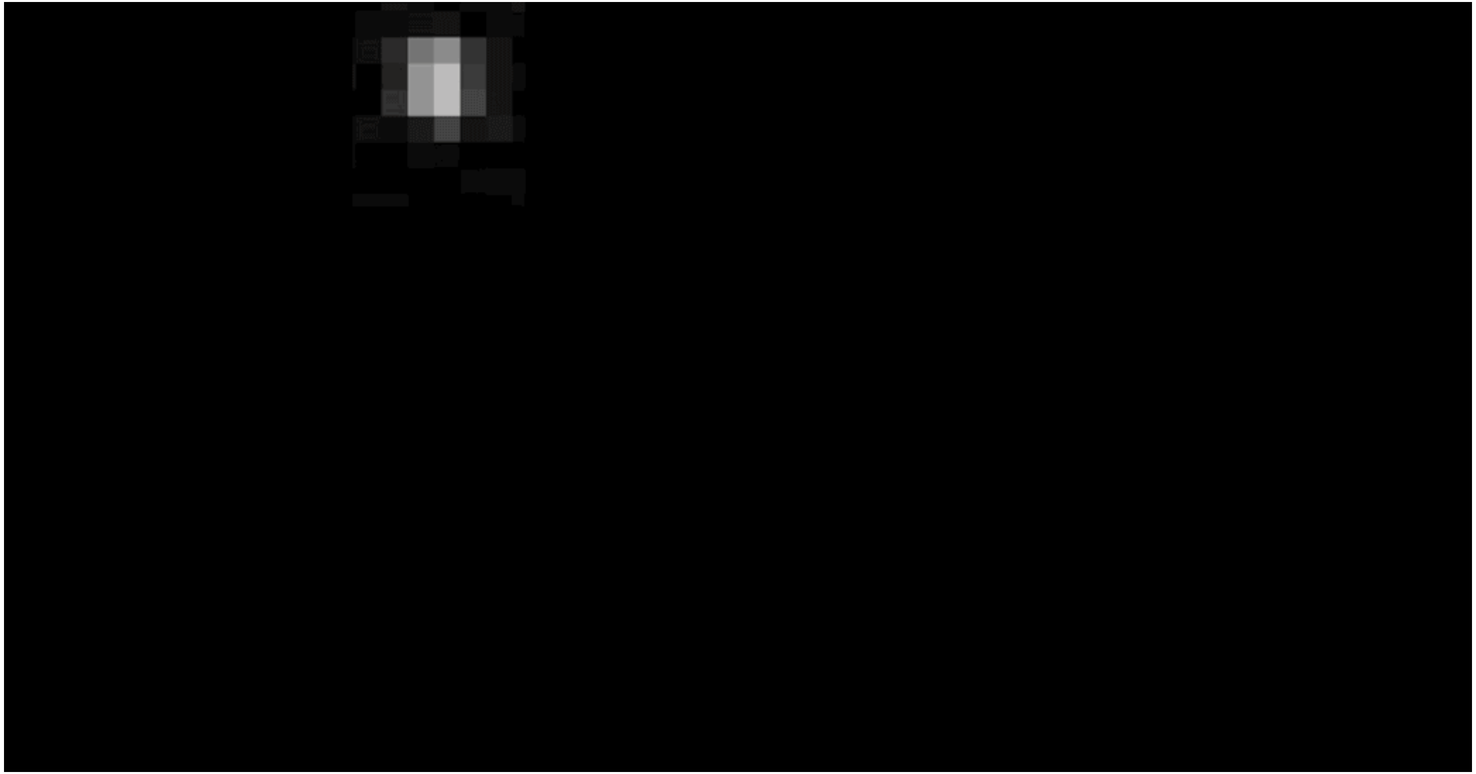
Interferometry 101

Gerard van Belle (Lowell Observatory)

Basic Science Motivation

Paul Signac, "Nice, Le Cours Saleya", 1922

Angular Resolution Makes Discoveries



Stellar Angular Sizes
(Back of the envelope)

- Use the sun as our prototype
- Solar vs. bright star apparent brightness:

$$V_\Theta - V \quad = -2.5\log(I_\Theta/I \quad)$$

$\rightarrow$ 2.5 × 10^{10} change in apparent brightness

- Since brightness scales with disk area:

$$\frac{I_\Theta}{I} = \frac{A_\Theta}{A} = \frac{\omega_\Theta}{\omega} = \left(\frac{\theta_\Theta}{\theta}\right)^2 \rightarrow \theta \quad = \theta_\Theta \times \sqrt{I \quad / I_\Theta}$$

- Since the sun is ~30' $\rightarrow$ θ_* = 12 mas
- Realized by Newton

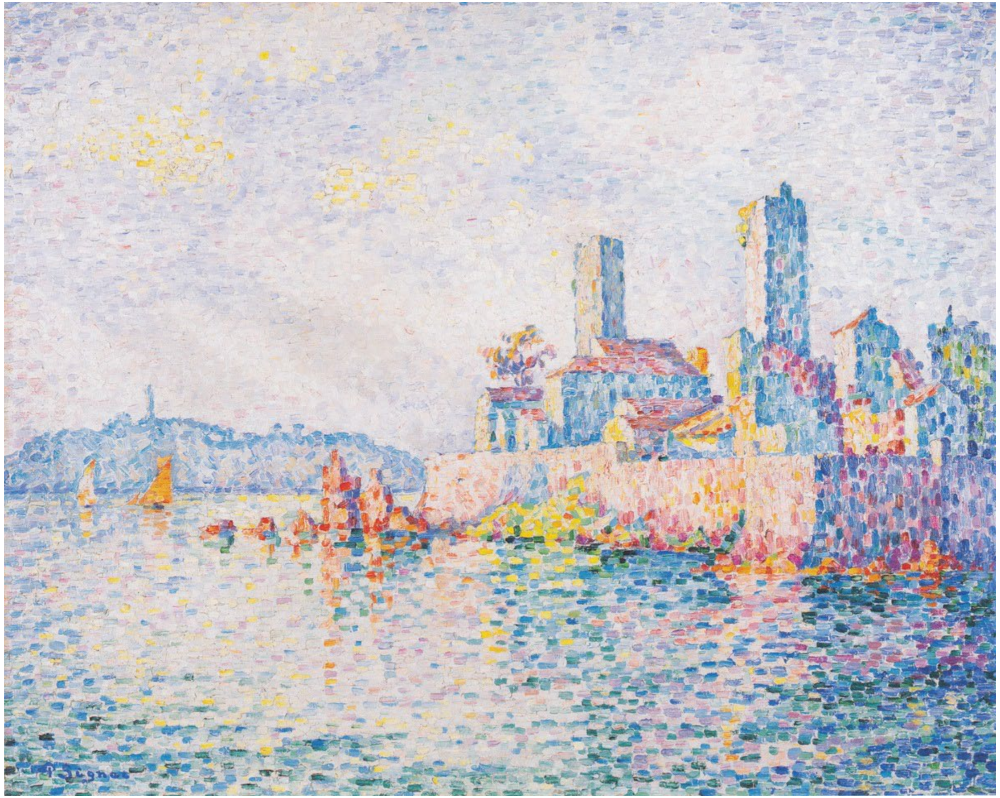
Interferometry: 'Silver Bullet Science'

- A very good analogy
  - Very expensive
  - Very hard to get to work
  - But, it gets results that are otherwise impossible
- And it's kind of magical

Interferometry: ‘Silver Bullet Science’

- Not something for everyone – sacrifices are made
  - Interferometers aren’t very sensitive
  - Interferometers don’t make ‘pretty pictures’
- But occasionally you have a werewolf to deal with

A Crash Course in Interferometry

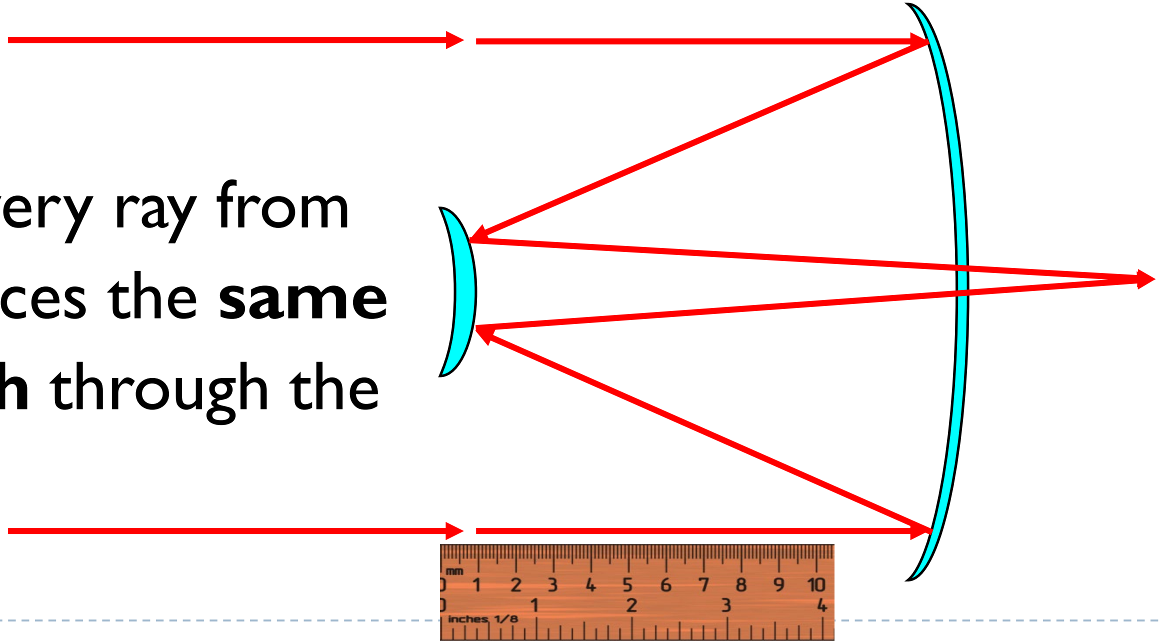


Paul Signac, "Antibes, die Türme", 1911

The Telescope: What's Happening Inside?

- Our parallel rays enter and bounce around – **in a very special way**

- Every path of every ray from the star traces the **same pathlength** through the telescope

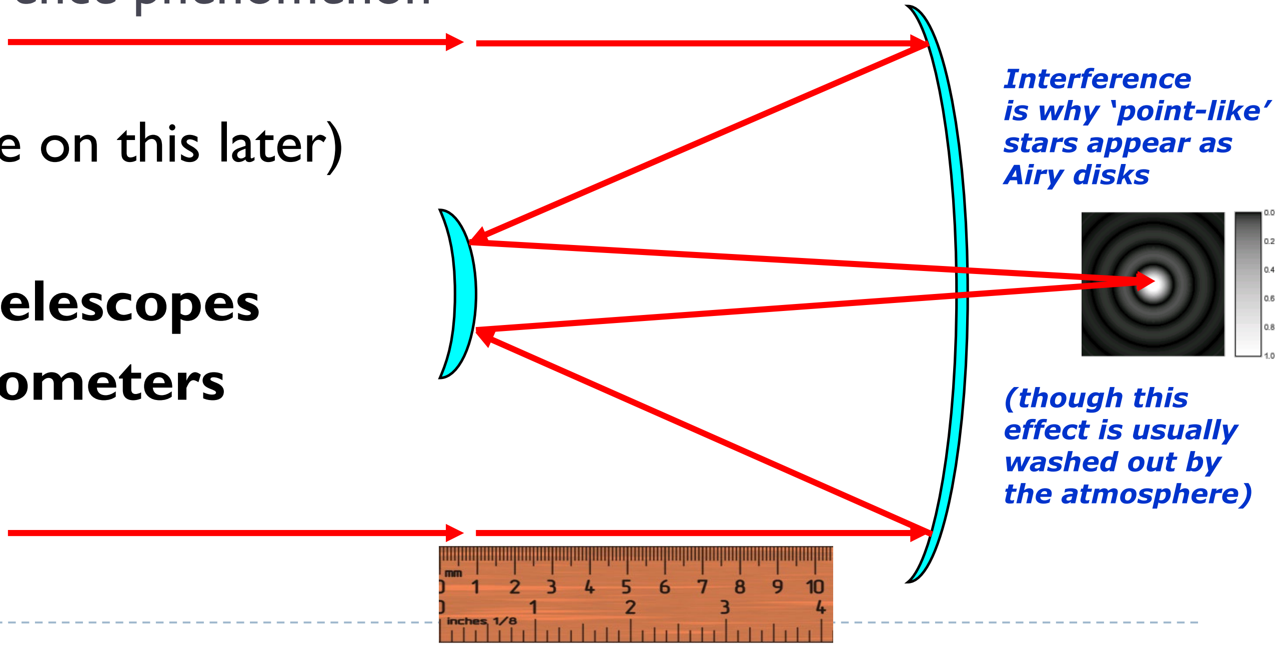


The Telescope: What's Happening Inside?

- When light rays from a source satisfy this pathlength condition, the can form an image
  - This is an 'interference phenomenon'

(more on this later)

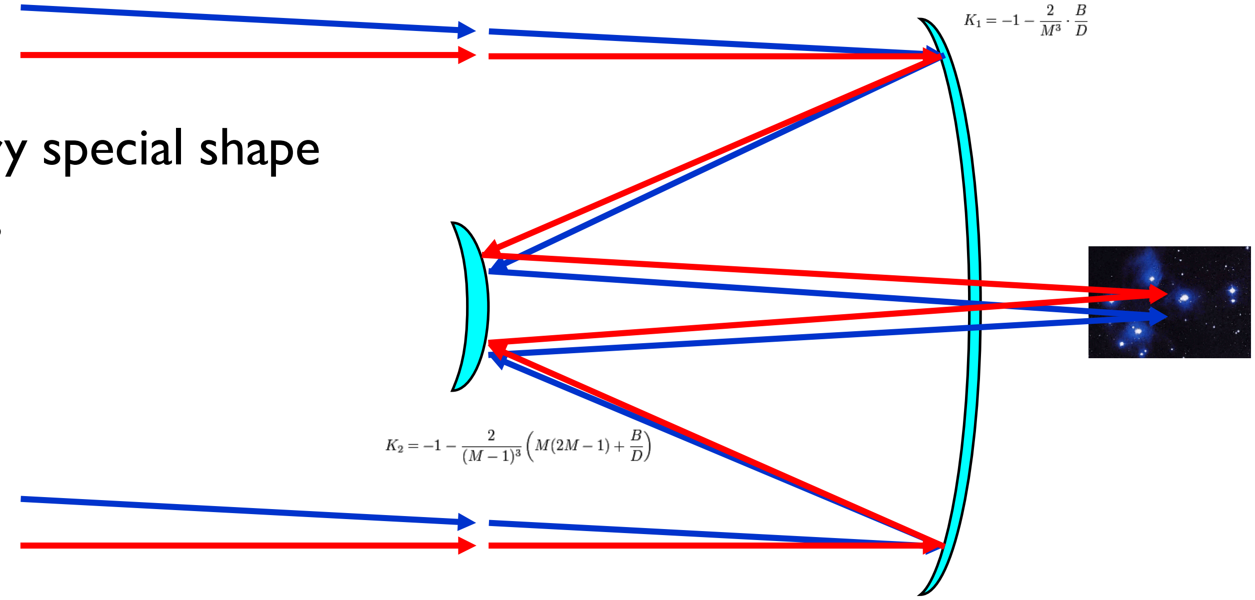
- Special secret: **all telescopes are interferometers**



The Telescope: What's Happening Inside?

- This **pathlength condition** is true for other nearby stars in the field of view of the telescope, at slightly different angles

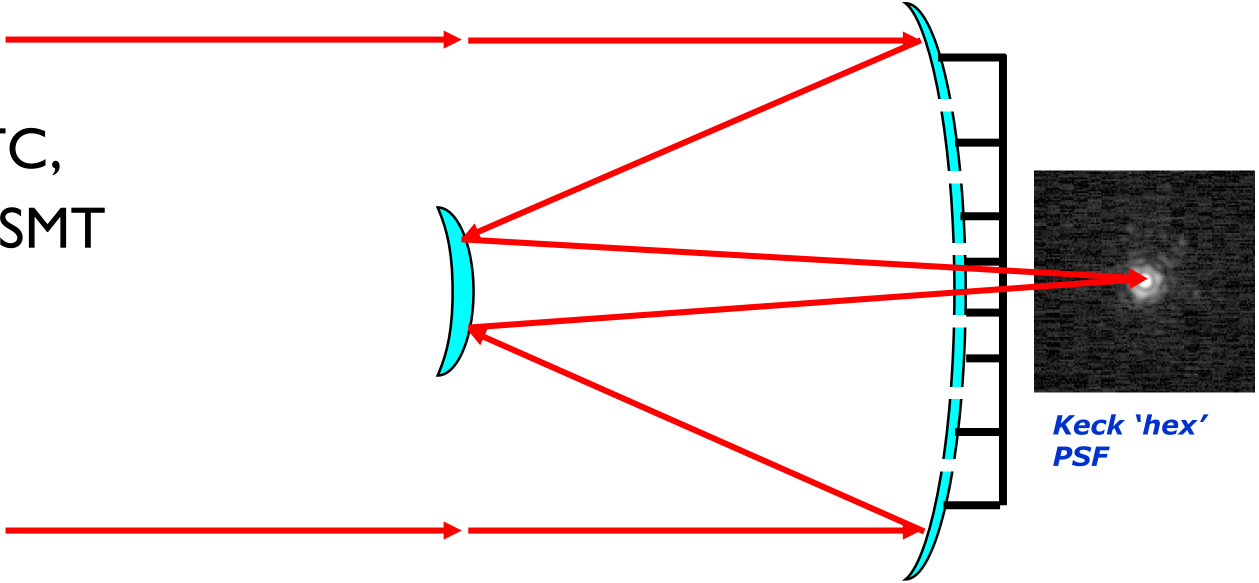
- This dictates the very special shape of the mirrors



In the Pursuit of Clever (at the risk of Stupid)

- Here's a neat trick: satisfy the pathlength condition with separate pieces of glass for your primary mirror

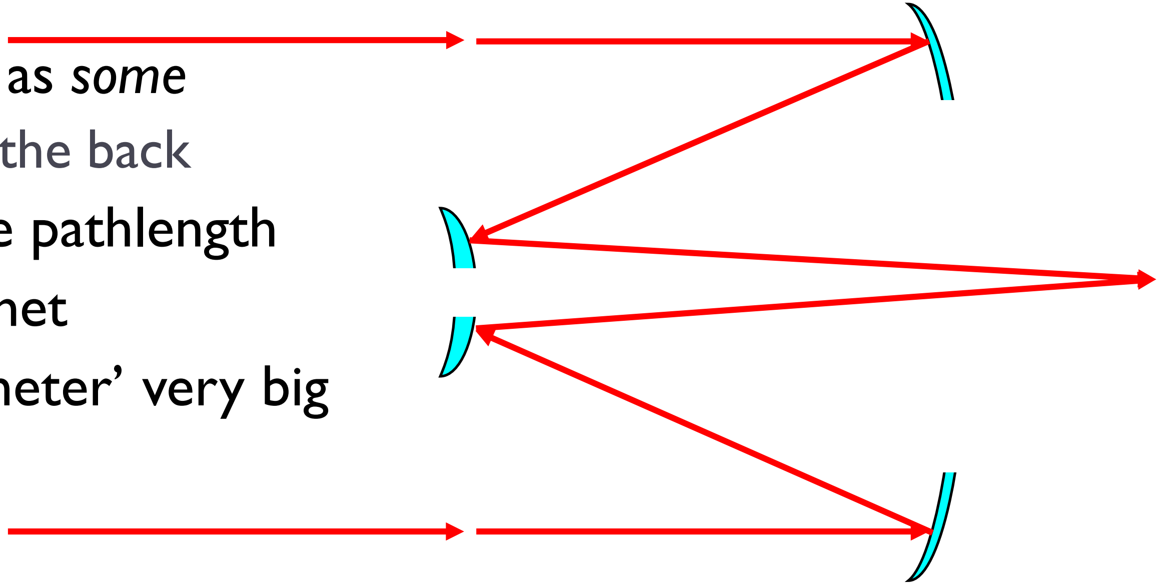
- Examples: Keck, GTC,
  E-ELT, TMT, GSMT



Cracking the Resolution Problem

- Taking the neat trick even further: really chop up your telescope into a **long baseline interferometer**

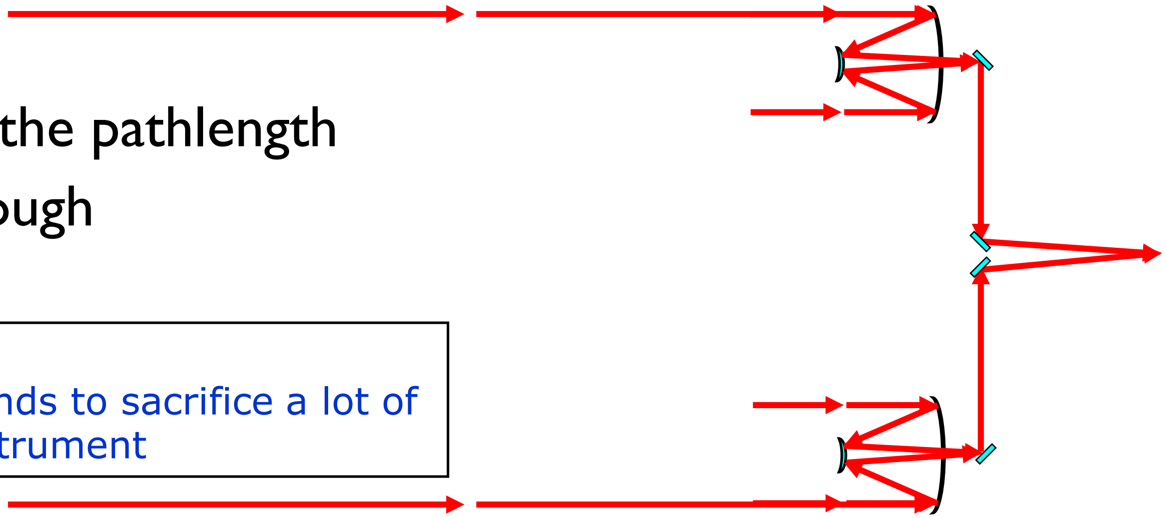
- This works as long as *some* light is getting to the back end, and if the pathlength condition is met
- Can make the 'diameter' very big



Cracking the Resolution Problem

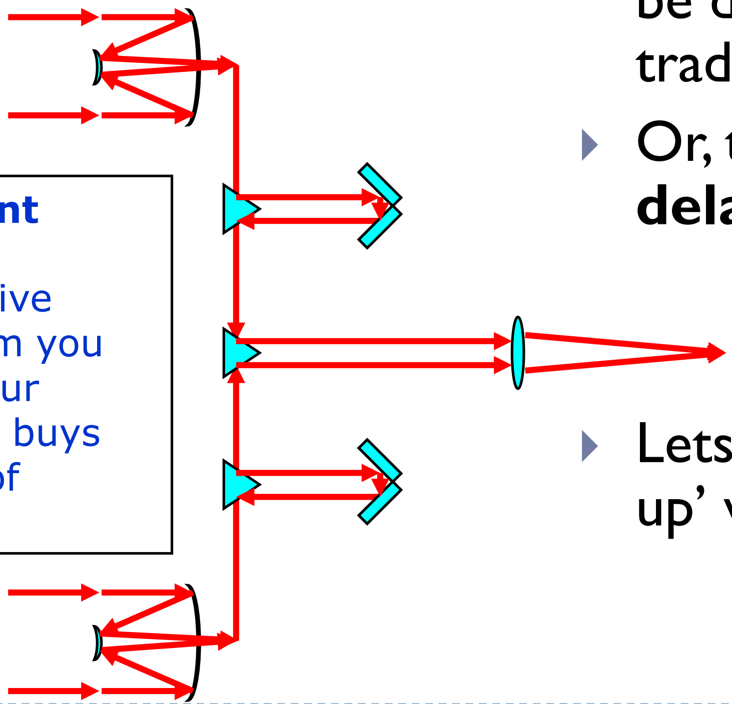
- Taking the neat trick even further: really chop up your telescope by making it **many telescopes**

- Still have to satisfy the pathlength condition, though



Important caveat:
Doing things this way tends to sacrifice a lot of 'field of view' of your instrument

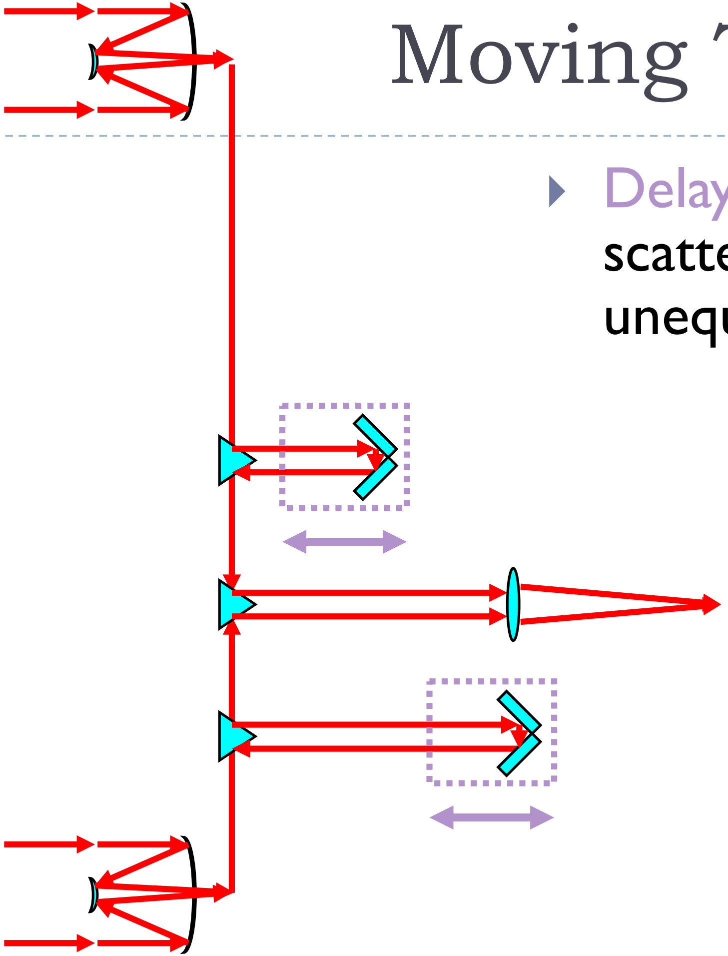
Cracking the Resolution Problem



Important caveat:
Every active subsystem you add to your telescope buys you lots of problems

- Meeting the pathlength condition can be done through static means (the traditional approach)
- Or, this can be done actively with **delay lines**
- Lets light from one telescope 'catch up' with light from another

Moving Things Around



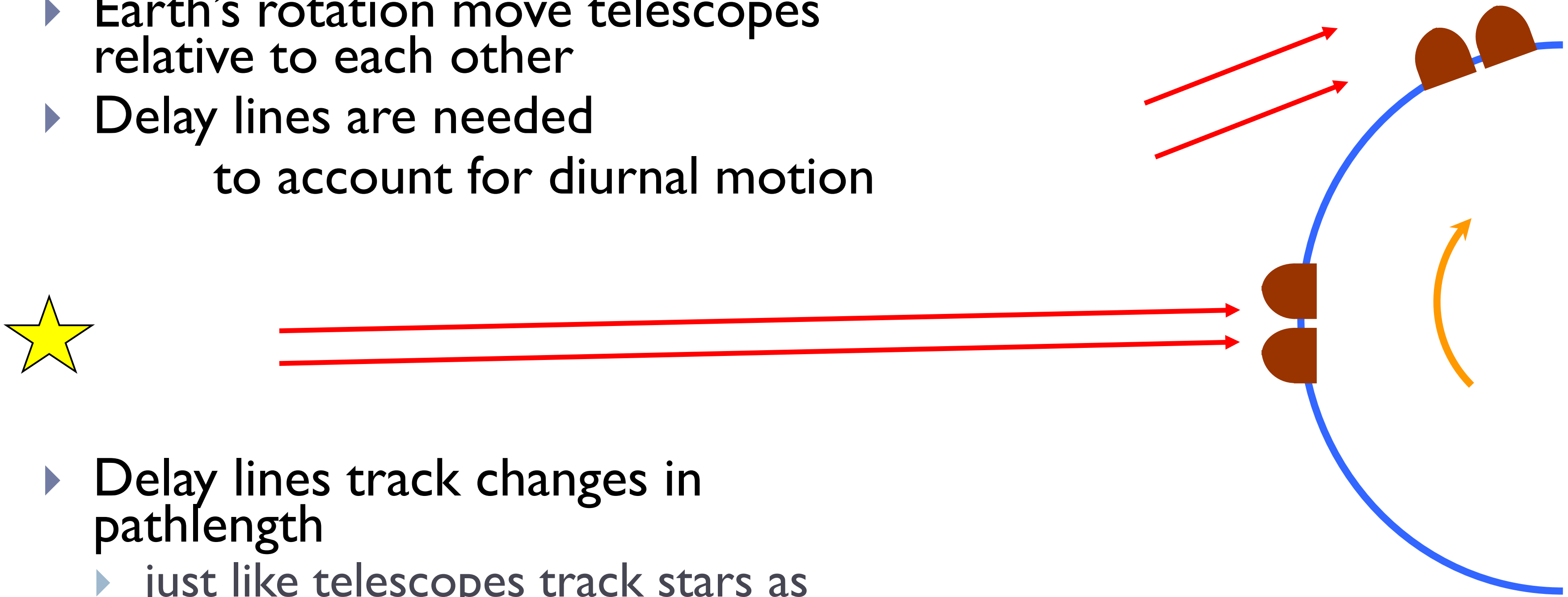
- Delay lines let you have telescopes scatter across the landscape at unequal distances

Examples: IOTA, NPOI, VLTI

Things Move Around On Their Own

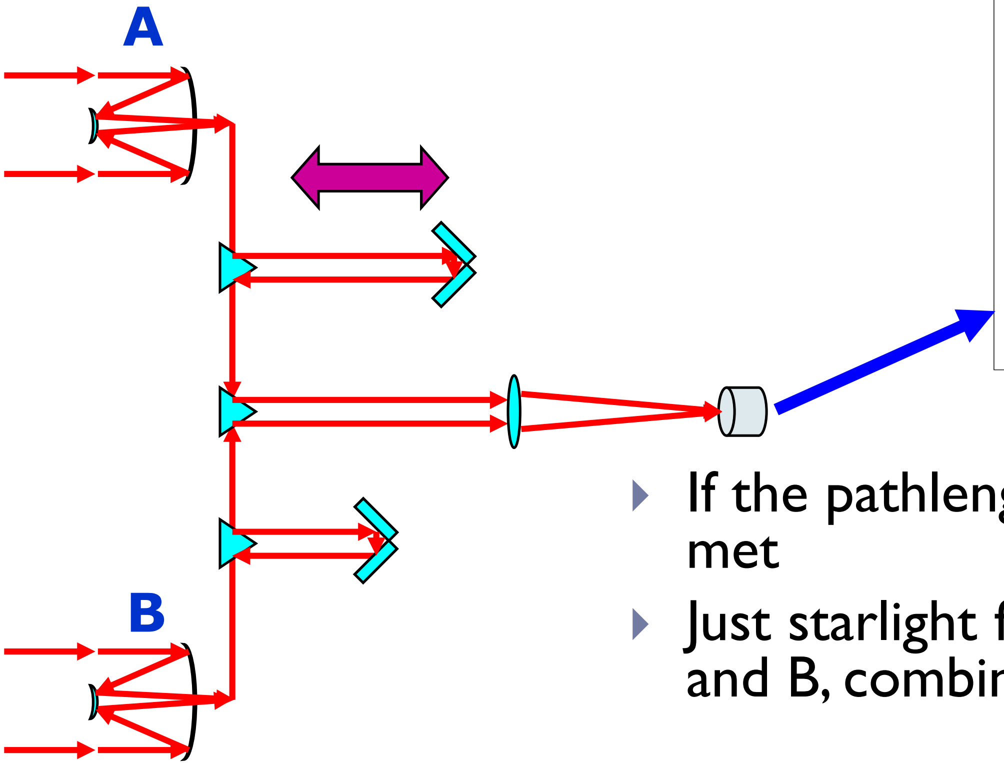
- Earth's rotation move telescopes relative to each other
- Delay lines are needed

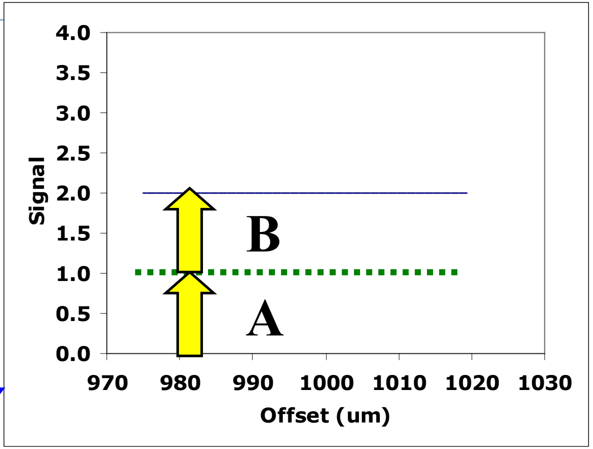
  to account for diurnal motion



- Delay lines track changes in pathlength
  - just like telescopes track stars as they move across the sky

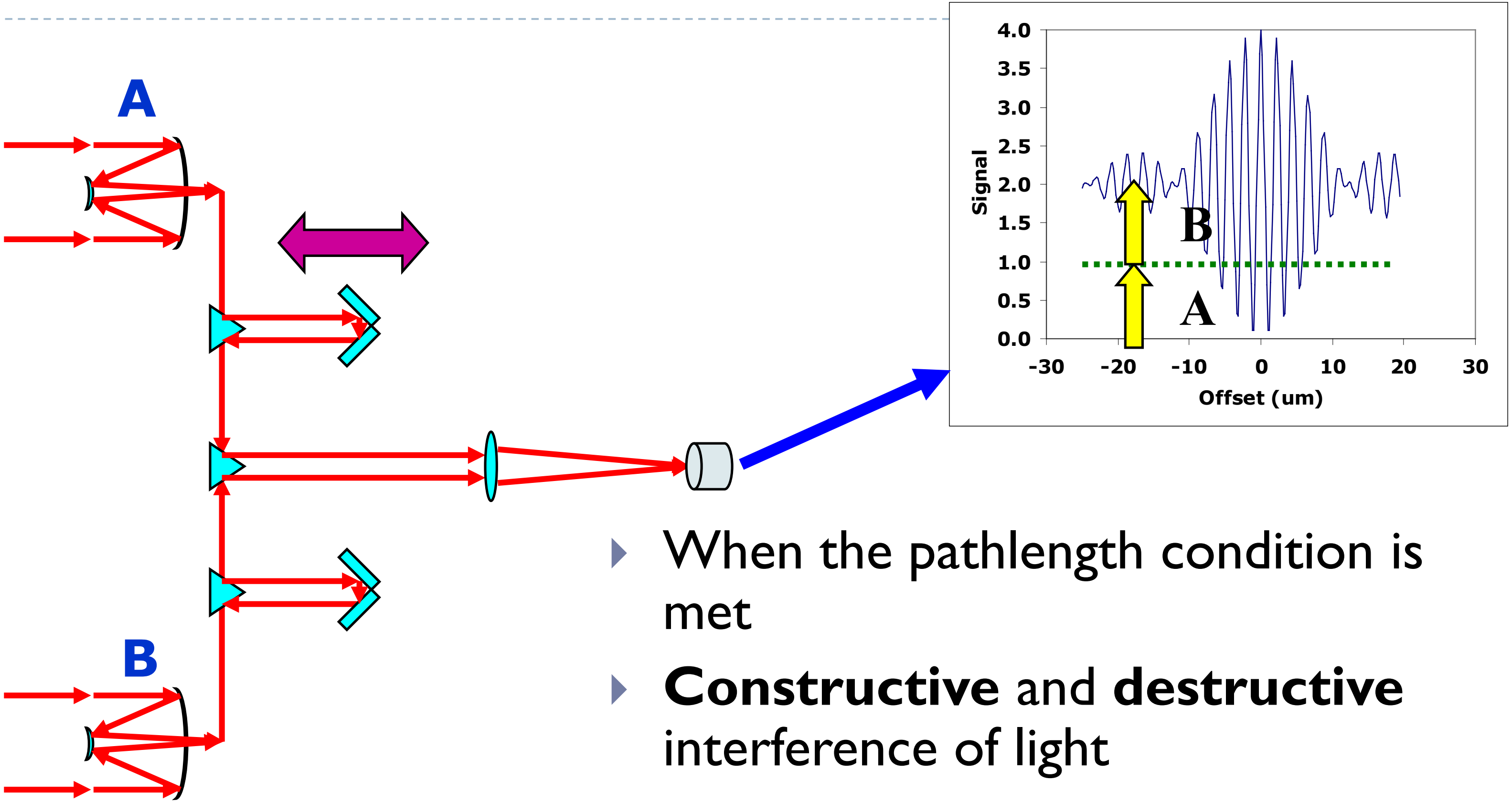
What Does an Interferometer 'See'?





- If the pathlength condition is not met
- Just starlight from telescope A, and B, combined

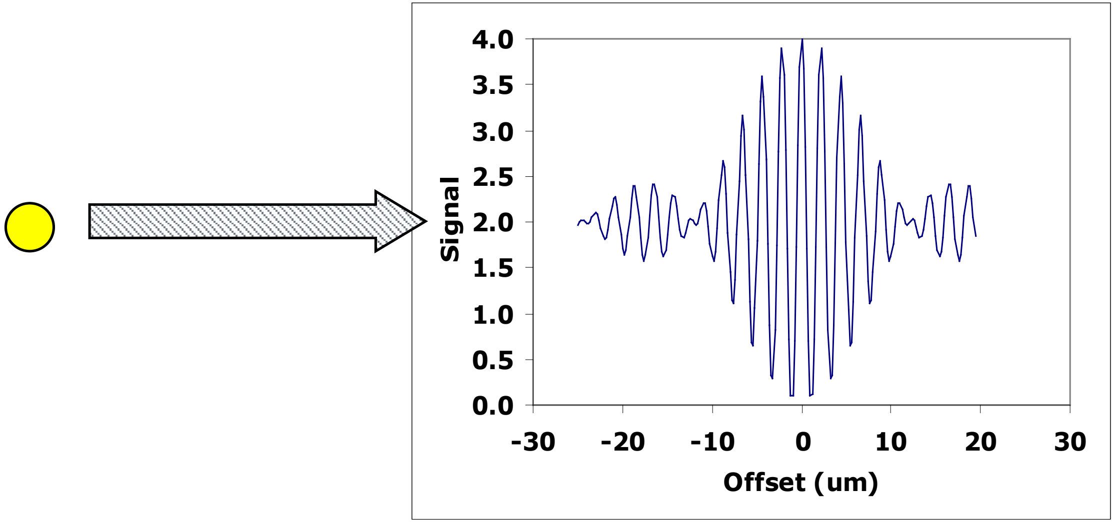
What Does an Interferometer 'See'?



- When the pathlength condition is met
- **Constructive** and **destructive** interference of light

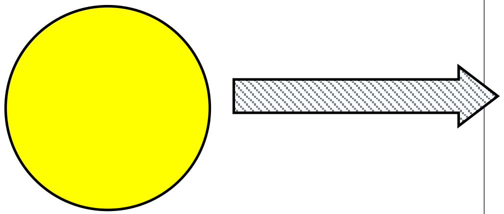
Observing Small Stars

- For a very small – **point-like** – star, fringes will be high contrast
- By 'very small', I mean $\vartheta < 0.25$mas

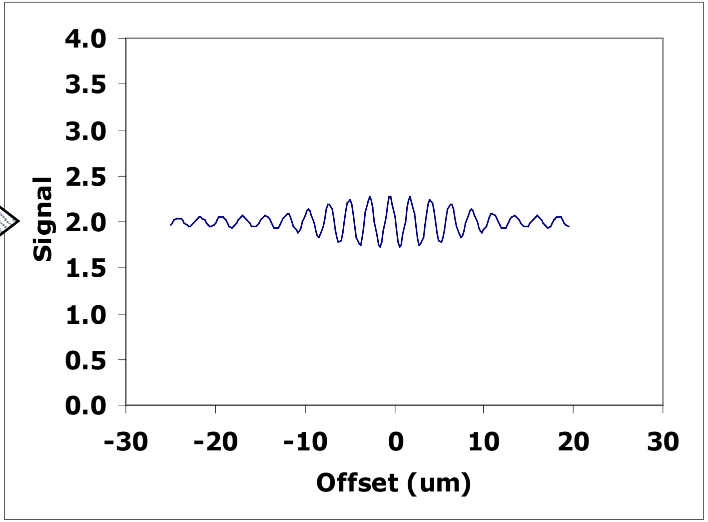


Observing Large Stars

- For a large – **resolved** – star, fringes will be high contrast
- By 'large', I mean $\vartheta \approx 0.5\text{-}3$ mas (in the case of NPOI)

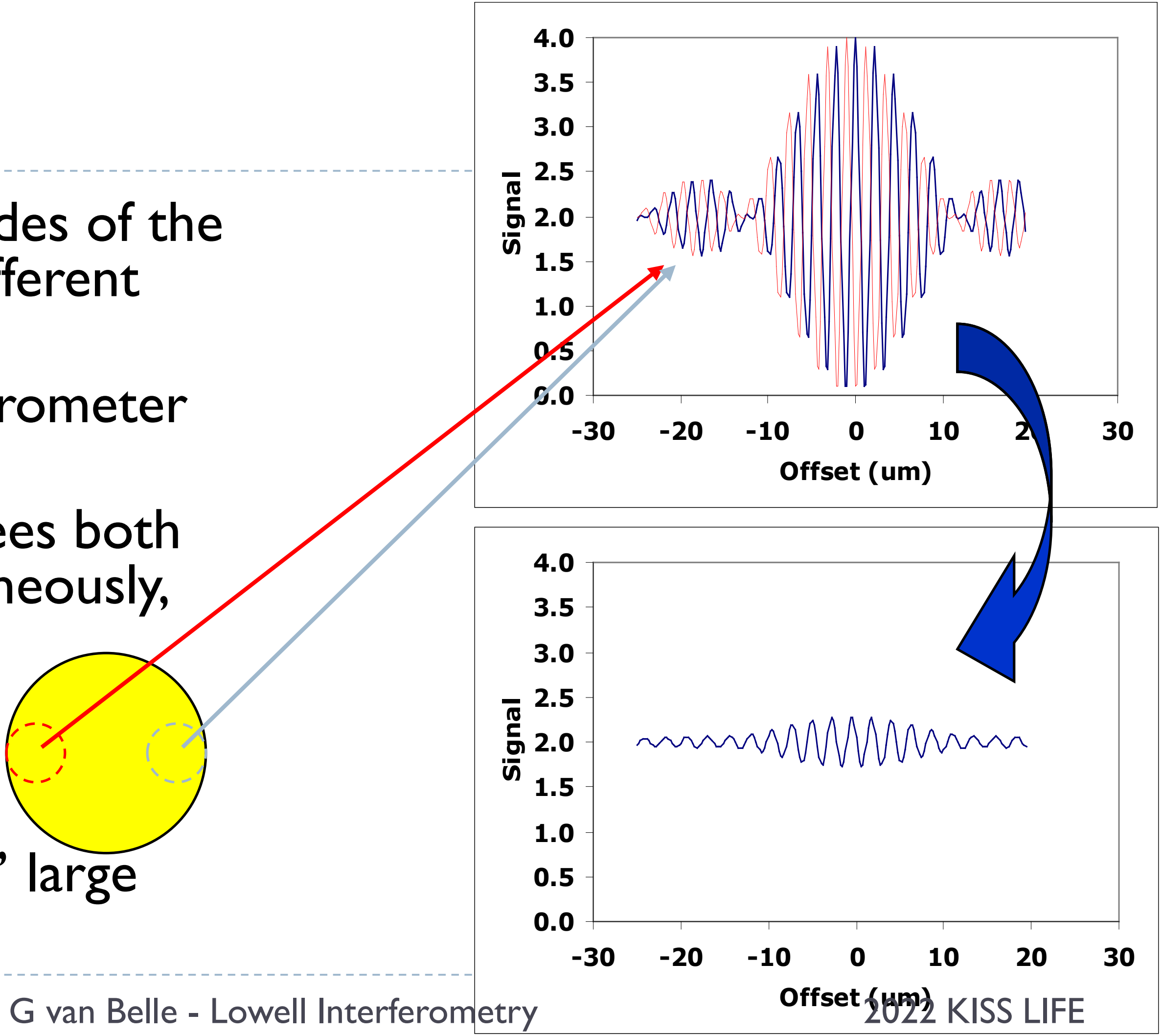


Viola! This could be useful.



Why is This?

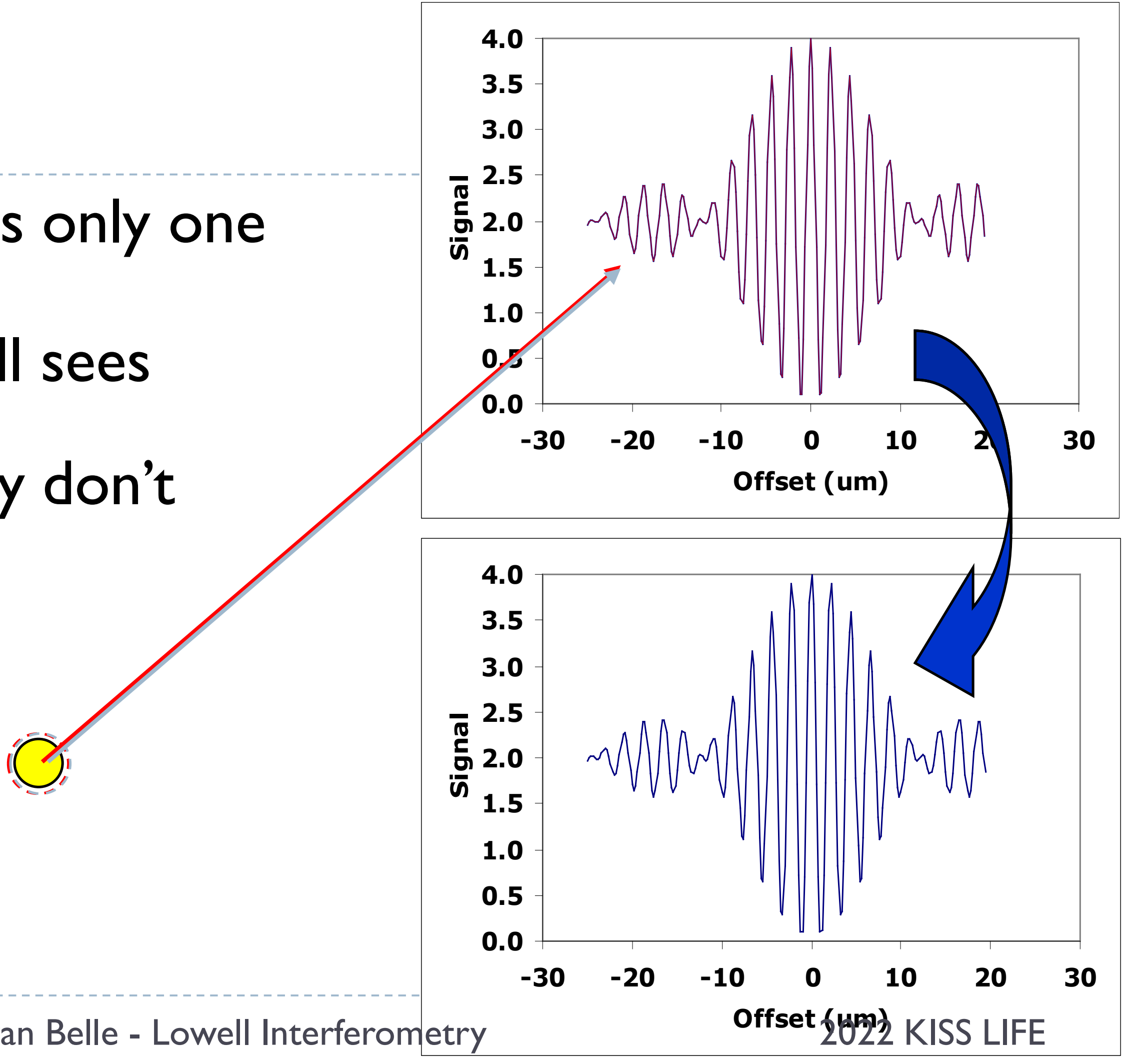
- Light from different sides of the star correspond to different pathlengths
- Optical path = interferometer pointing
- The interferometer sees both fringe packets simultaneously, overlapping



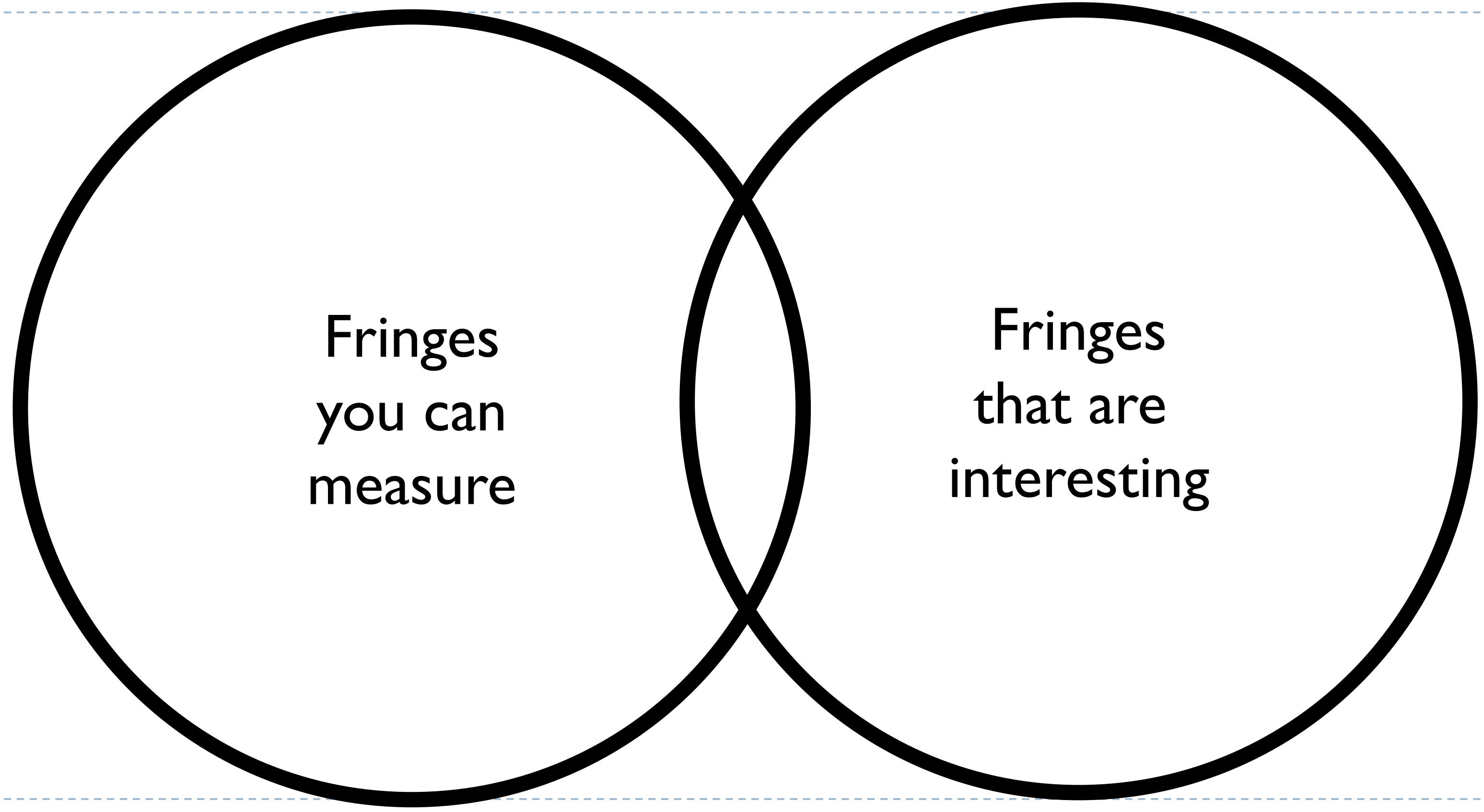
- NB. can ‘**overresolve**’ large sources

Why is This?

- For a small star, there is only one pathlength
- The interferometer still sees both fringe packets simultaneously, but they don't smear each other out



Mozurkewich's Law



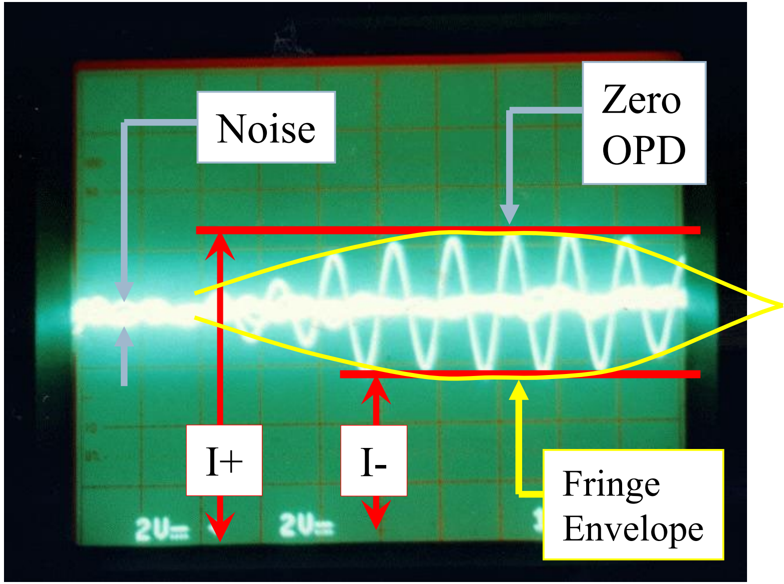
Mozurkewich's Corollary to Mozurkewich's Law

- "Determine what it is that you *can* measure,
  and declare it is therefore interesting."

What does a Fringe *Actually* Look Like?

- Constructive & destructive interference of light
- Fringe **contrast** or **visibility**:

$$V = \frac{I^+ - I^-}{I^+ + I^-}$$



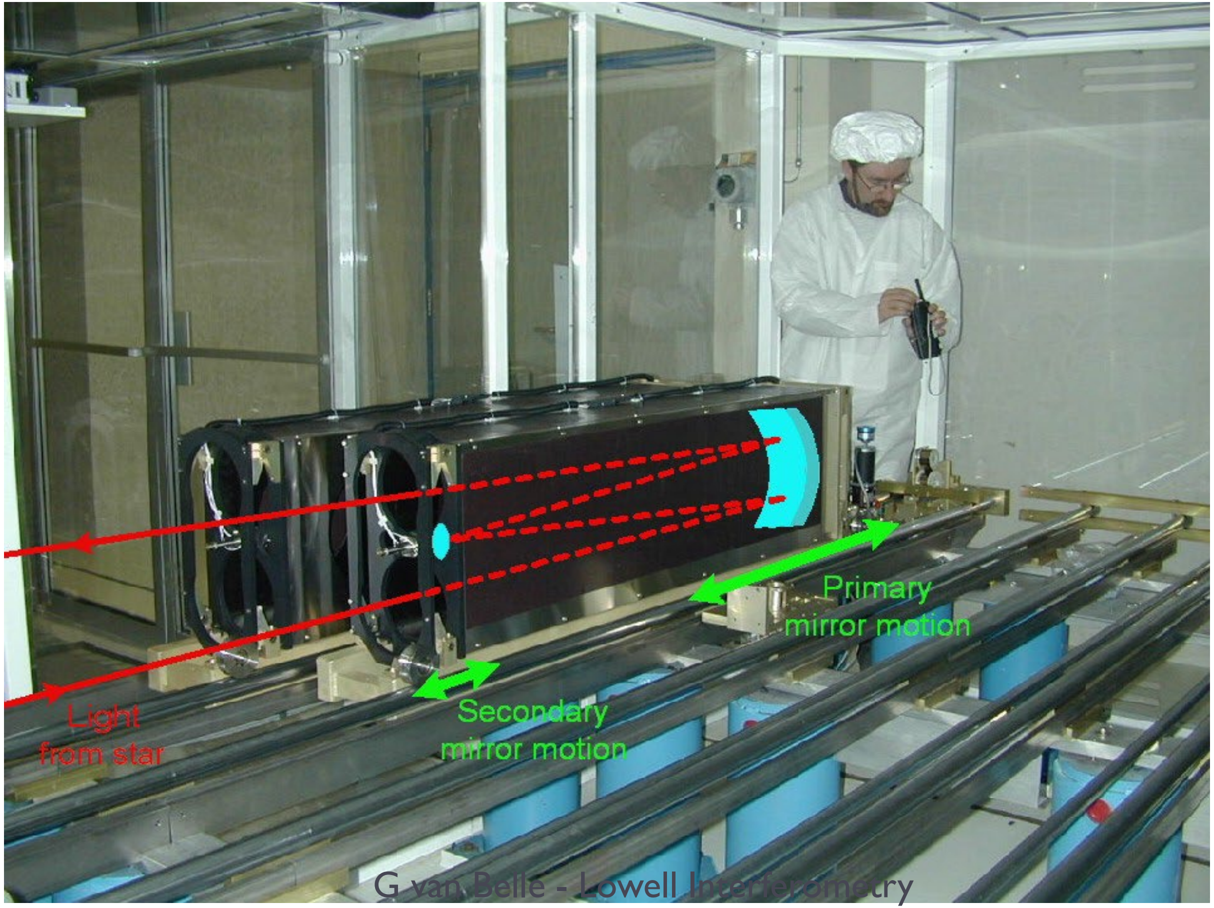
Actual starlight fringes from IOTA - β And
Photo credit: R.R. Thompson

Interferometric Arrays

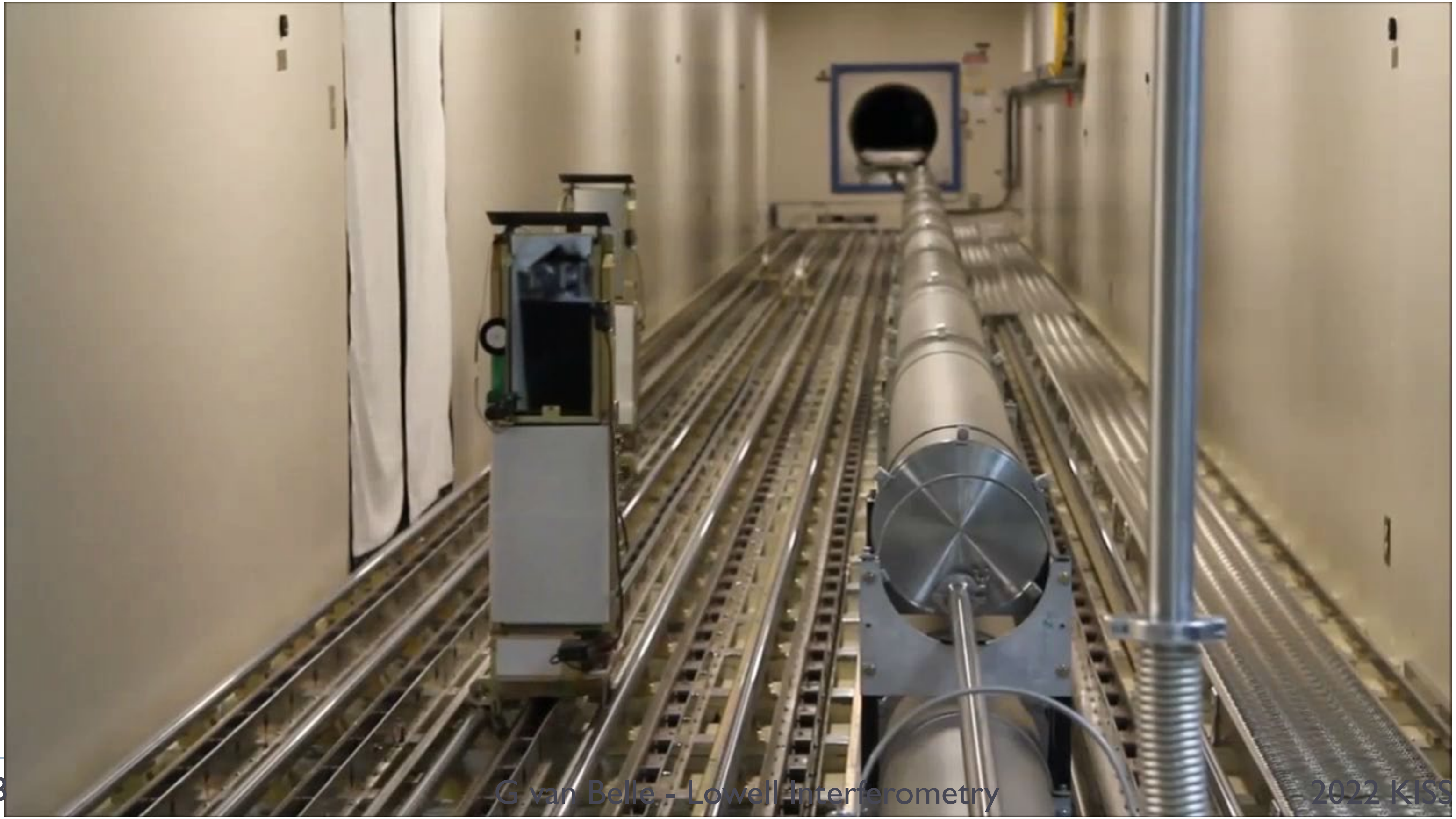
- Use multiple telescopes as a single telescope
- Break the resolution limit without breaking the bank
- Already an established technique for radio wavelengths
  - But much more difficult in the visible
  - Radio: **Detect-and-mix**
  - Optical: **Mix-and-detect**

← Charlie Townes:
"It's because the value of ħ is what it is."

Delay Lines at Keck



Keck in Motion

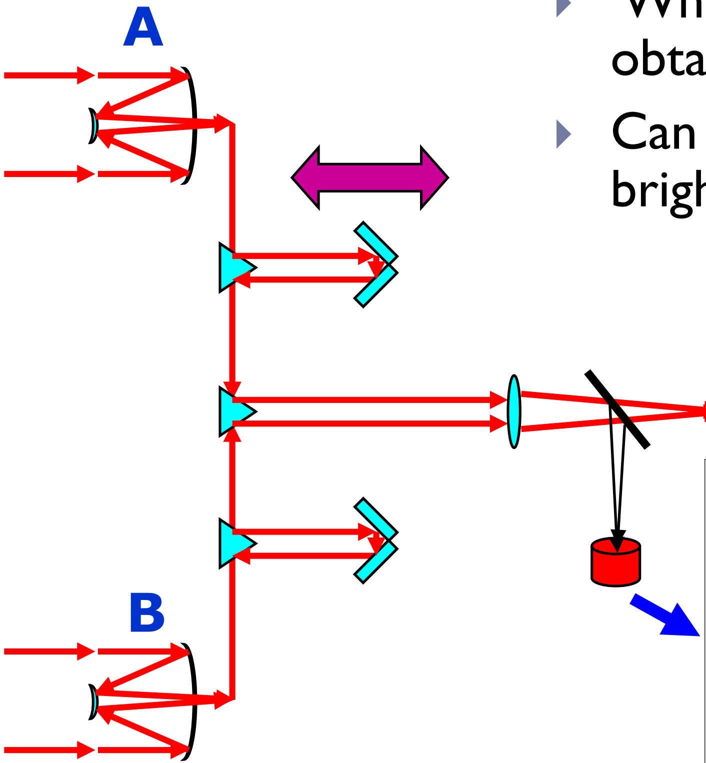


Techniques: Differential Phase & Baseline Bootstrapping

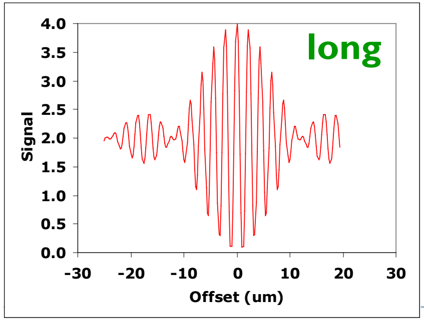
Paul Signac, "La Corne D'or, Les Minarets", 1907

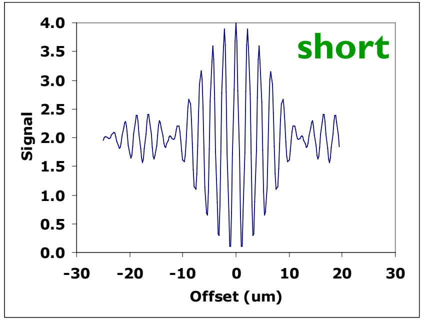
Differential Phase (aka Wavelength Bootstrapping)

- ‘White light’ phasing means fringes obtainable at all wavelengths
- Can track at wavelengths where object is bright, science at interesting wavelengths



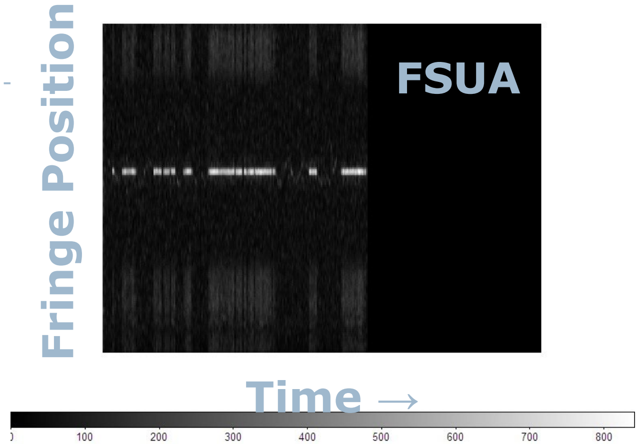
Example: PRIMA+MIDI, CHARA (many modes), Gravity+MATISSE (proposed)

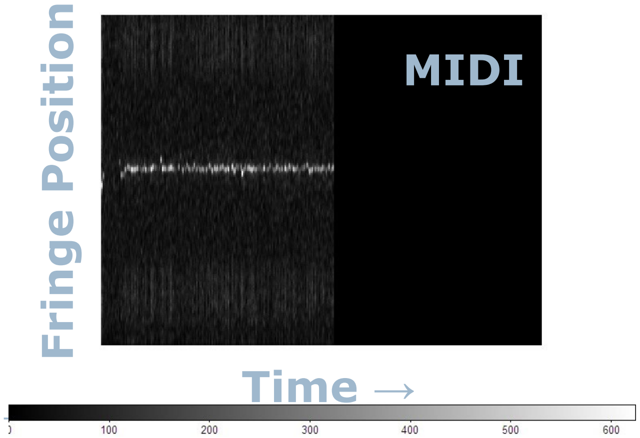




Differential Phase demo

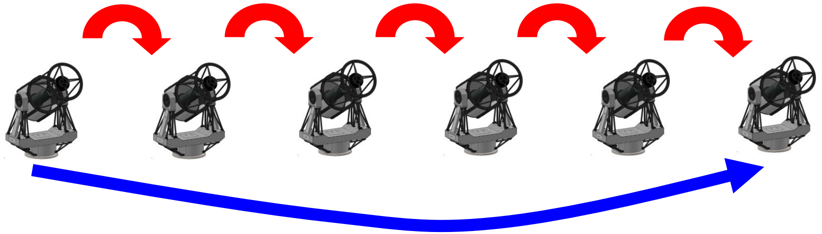
- PRIMA+MIDI demonstration (2009)
  - FTK errors reduced by order of magnitude
  - Sensitivity >>3x MIDI-alone limit
- Technique proposed in 1992 as method to detect 'hot Jupiters' by Colivta & Shao
  - Not pursued, everyone 'knew' that Jupiters would be neither hot nor close to host star





Baseline (+wavelength) Bootstrapping

- Fringe amplitude decreases with increasing baseline
- Can phase on multiple short baselines
- Long baseline phasing then comes 'for free'
- Can phase unit baselines at longer wavelengths for increased fringe amplitude, too
- A way to beat 'Mozurkewich's Law'



Example: NPOI (newClassic, NIR-FTK)

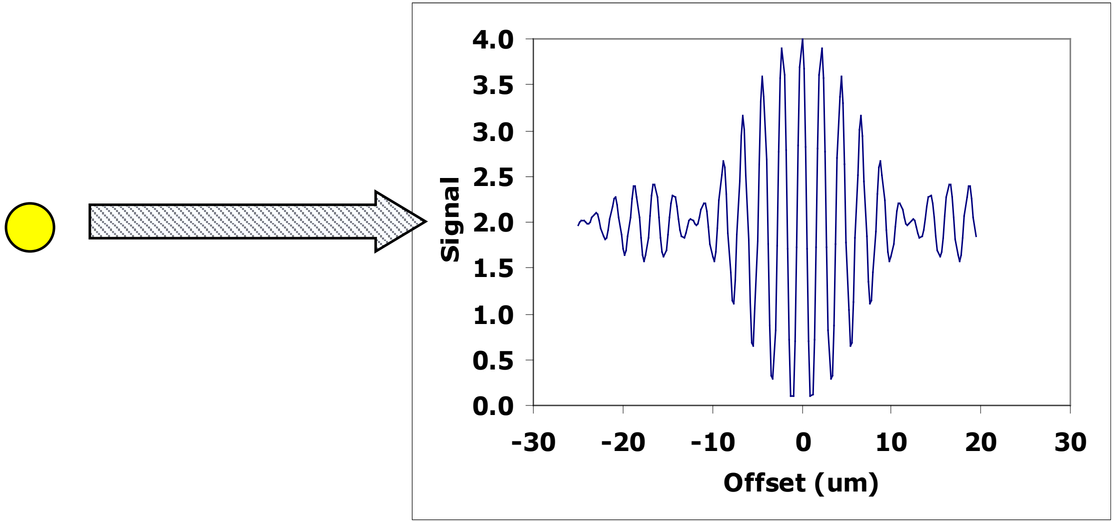
Technique: Nulling

Paul Signac, "La Corne D'or, Les Minarets", 1907

Nulling

- Pair-wise beam combiners typically have two outputs: one constructive, one destructive

Constructive side

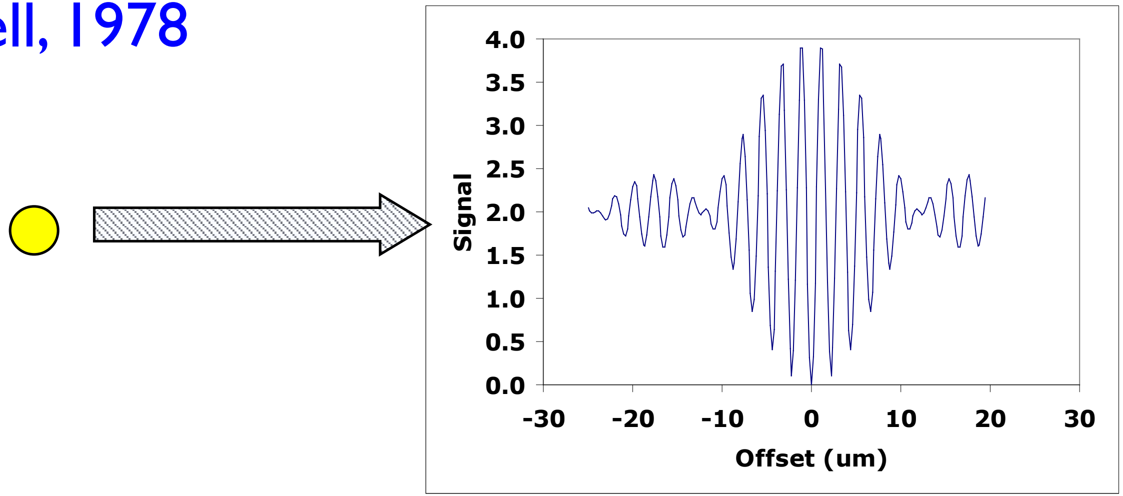


Nulling

- Pair-wise beam combiners typically have two outputs: one constructive, one destructive

Bracewell, 1978

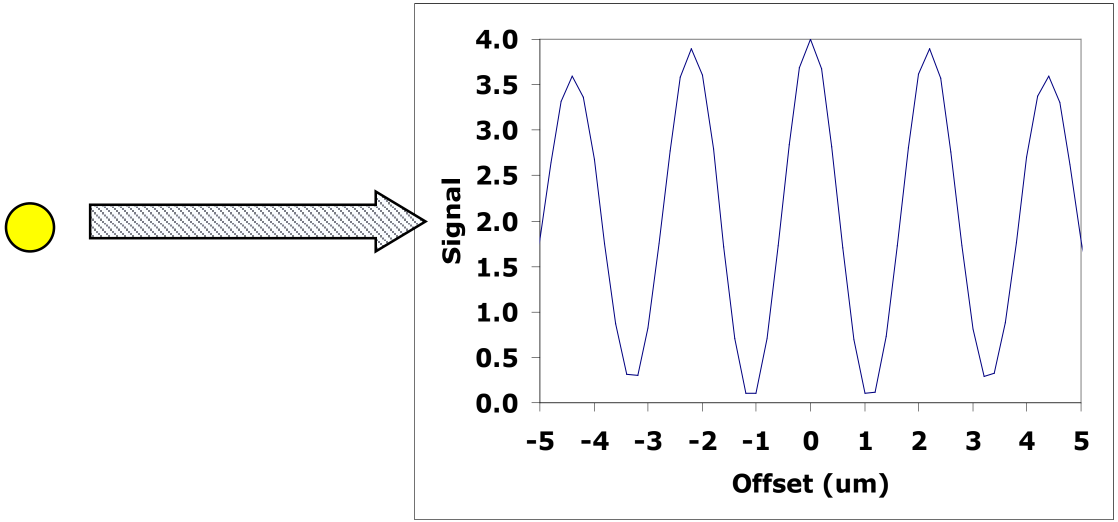
Destructive side



Nulling (zoom)

- Pair-wise beam combiners typically have two outputs: one constructive, one destructive

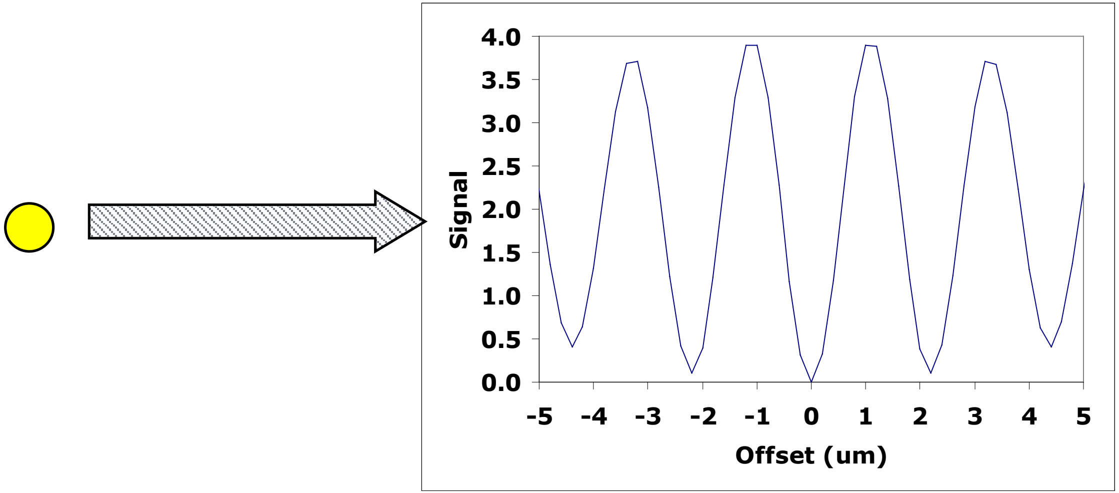
Constructive side



Nulling (zoom)

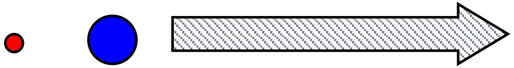
- Pair-wise beam combiners typically have two outputs: one constructive, one destructive

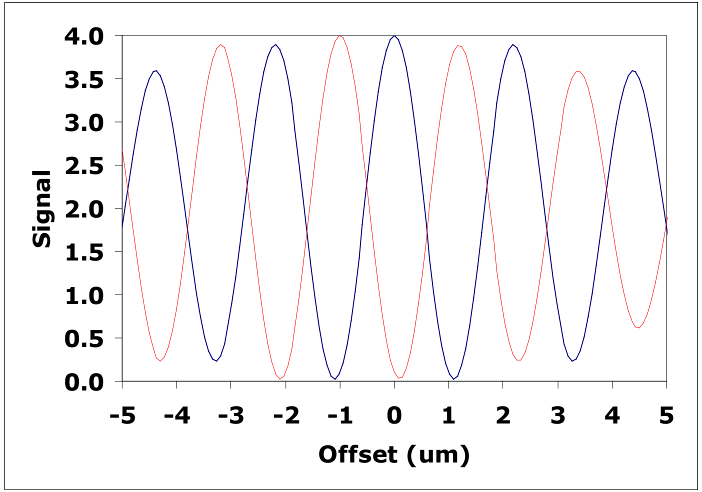
Destructive side



Nulling (two body case)

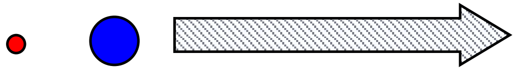
- Null out starlight, but keep planet light constructively interfering



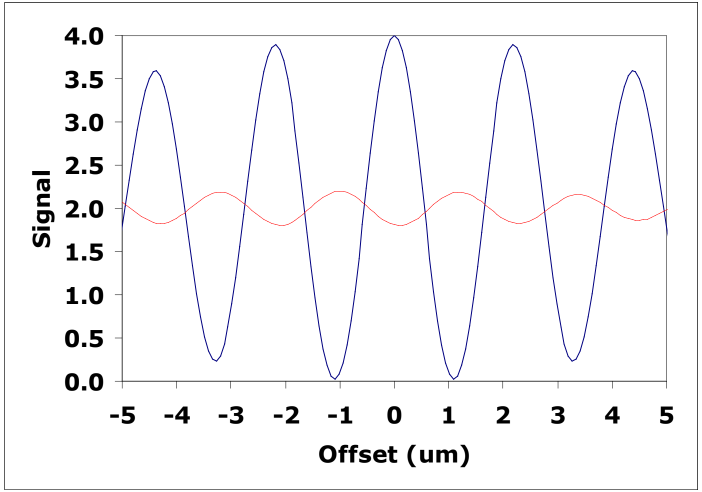


Nulling (star + planet)

- Null out starlight, but keep planet light constructively interfering – planet is typically much dimmer, though



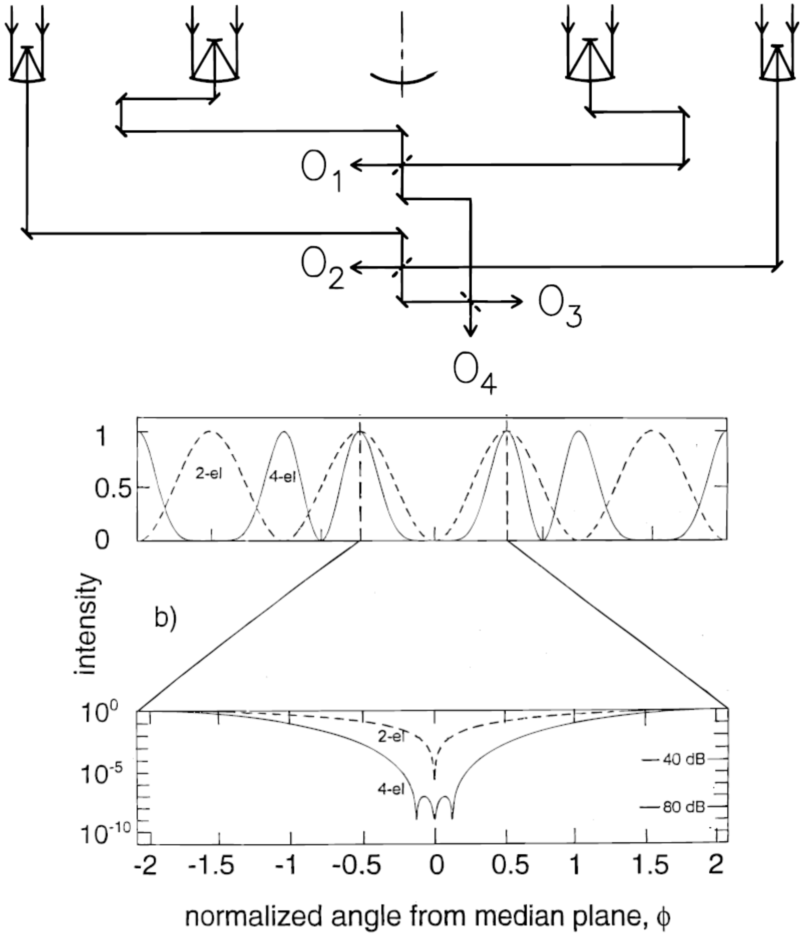
Examples: Keck Nuller, LBTI



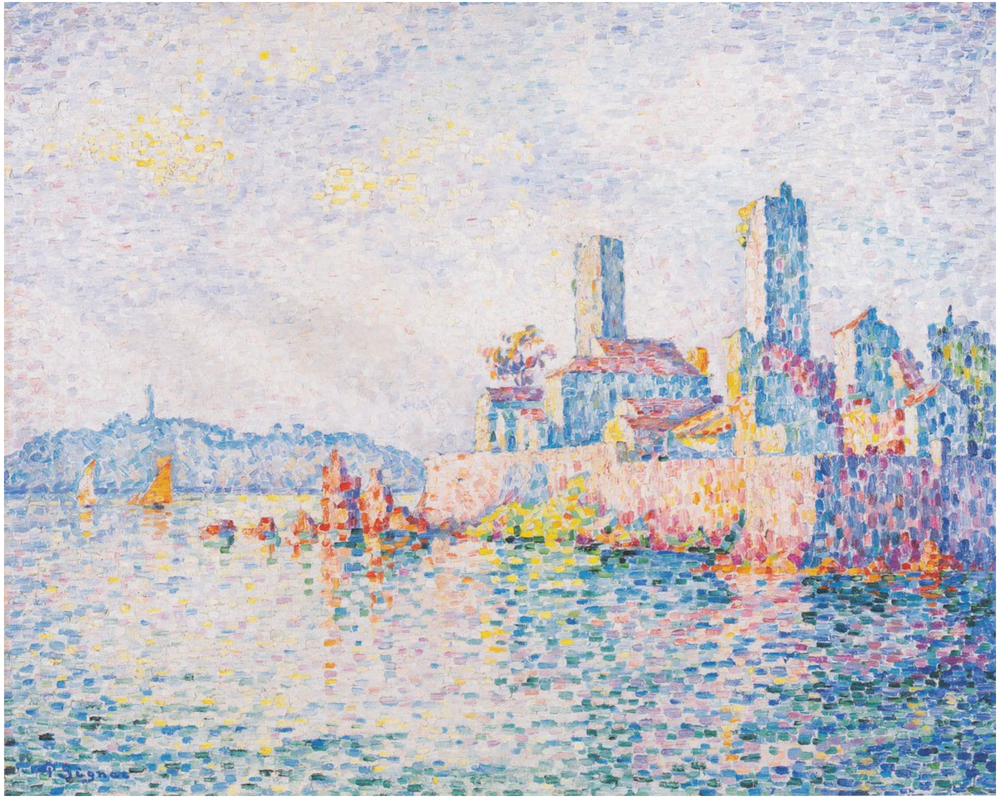
Nulling, Double Bracewell

- Going from two to four apertures for a 'double Bracewell'
- Wider, deeper null

Angel & Woolf, 1997



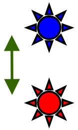
Technique: Astrometry

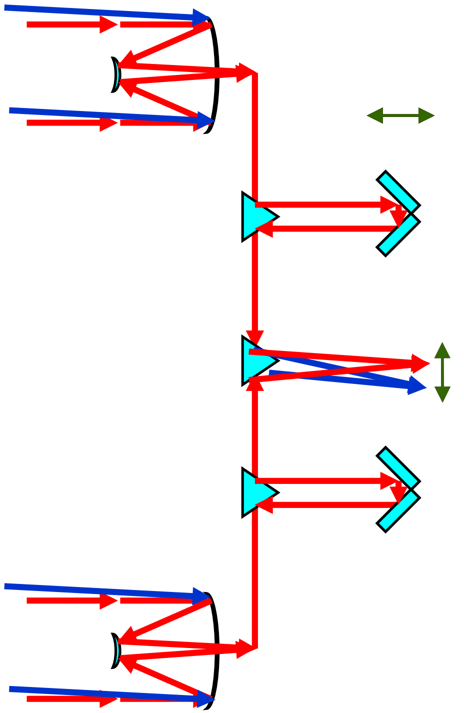


Paul Signac, "Antibes, die Türme", 1911

Astrometry: Simple in Principle

- Two angularly separated objects
- Fringe peaks show up separated in delay space
- Scanning in delay to detect, measure peak separation
- Linear separation → angular separation

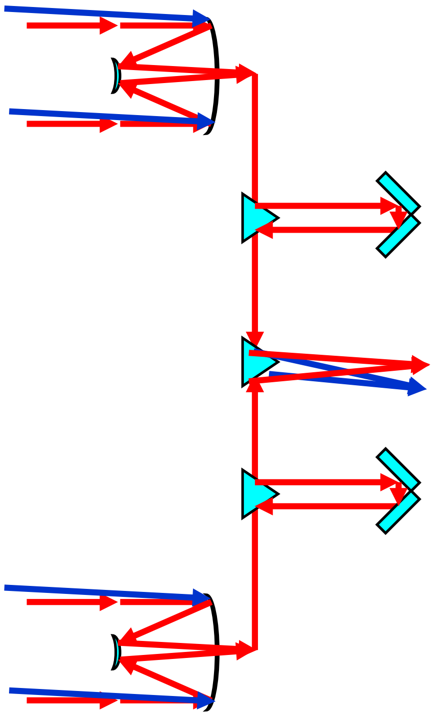




(NB. This is the 'narrow angle' variant)

Astrometry: Insanely Hard in Practice

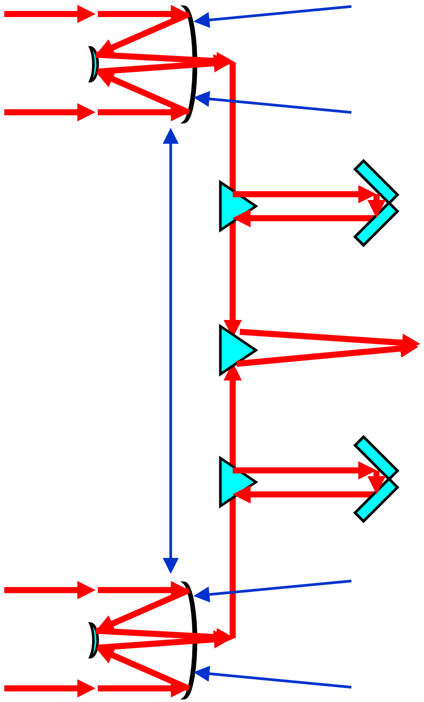
- Where to separate beams?
  - Back end
  - Field separator at telescopes
- What baseline does each star 'see'?
- Differences in delay space: separation or something else?
  - Pathlength monitoring: how to do?



Example: PTI, VLTI+PRIMA, VLTI+Gravity CHARA+Armada, VLTI+Gravity-Wide

Astrometry: Insanely Hard in Practice

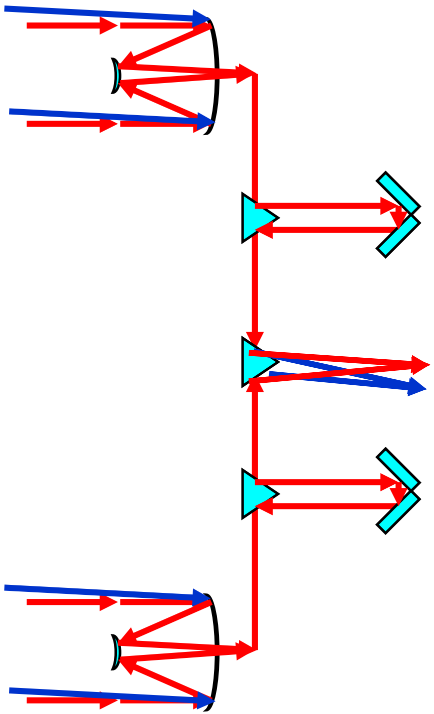
- 'Wide angle' Variant
- Monitor telescope positions (~um), all pathlengths with laser metrology (~nm) (blue)



Example: NPOI

Phase Referencing: Same Basic Architecture

- For 'bright-faint' imaging
  - Use bright object to phase array, 'stare' at dim object
  - Only need to track fringes to optical tolerances (~10nm)
  - Baseline knowledge only needed to a ~few mm
- Eliminates significant amounts of metrology
- Limited on ground to atmospheric isoplanatic angle



Example: VLTI+Gravity 'imaging'

Questions?

Paul Signac, "Port St. Tropez", 1899

Food for Thought

- ‘You are allowed one miracle per mission’ - Chas Beichman

- Each one of these is a *separate* miracle: Interferometry, formation flying, nulling