# Overview of Optical Interferometry and Facilities

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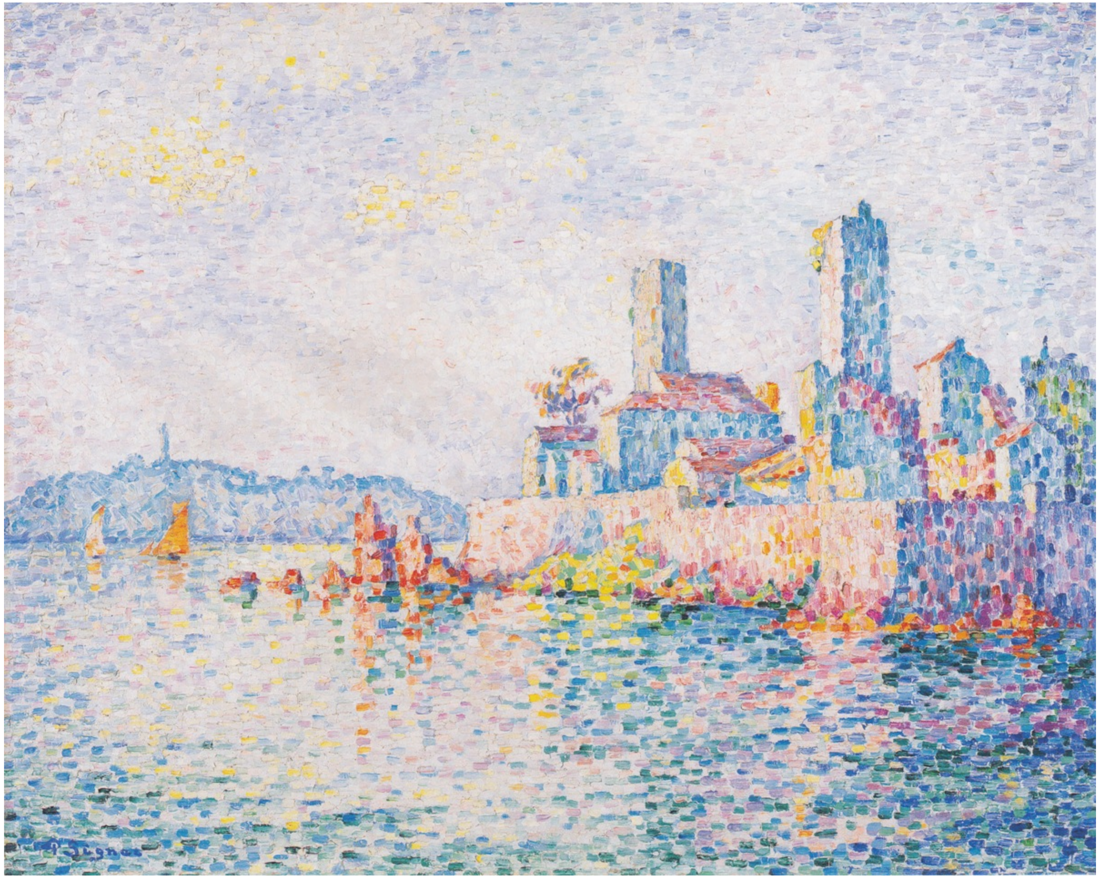
SPACE, LLC

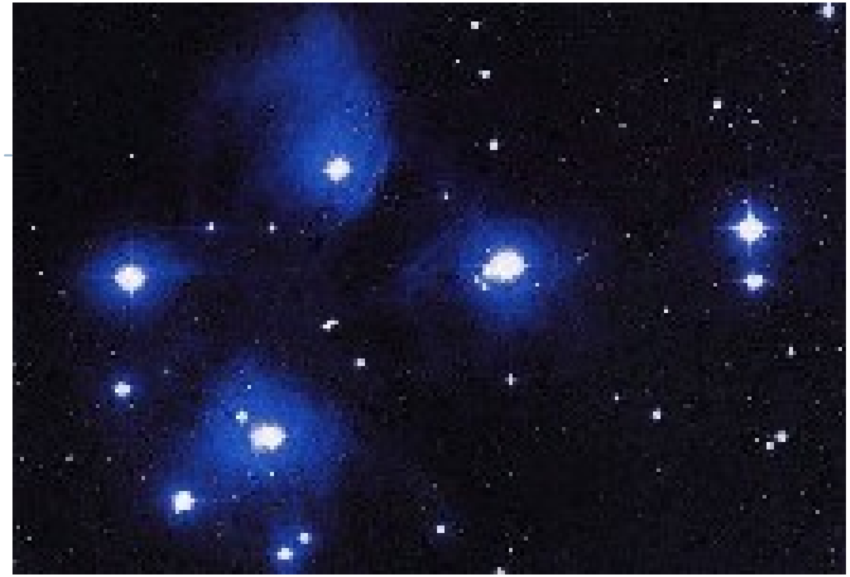
# A Little About Interferometry in the Optical



*Paul Signac, “Antibes, die Türme”, 1911*

# Stellar Angular Sizes

## (Back of the envelope)



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

$$V_{\Theta} - V_{*} = -2.5 \log \left( I_{\Theta} / I_{*} \right)$$

→ $2.5 \times 10^{10}$ change in apparent brightness

- Since brightness scales with disk area: $\dfrac{I_{\Theta}}{I_{*}} = \dfrac{A_{\Theta}}{A_{*}} = \dfrac{\omega_{\Theta}}{\omega_{*}} = \left( \dfrac{\theta_{\Theta}}{\theta_{*}} \right)^{2} \rightarrow \theta_{*} = \theta_{\Theta} \times \sqrt{I_{*} / I_{\Theta}}$

- Since the sun is ~30’ → $\theta_*$ = 12 mas
- Realized by Newton

# Optical 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

# Optical Interferometry: ‘Silver Bullet Science’

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

# Interferometry

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Andreas Glindemann

Principles of Stellar Interferometry

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Peter A. Schuller

Optical Long-Baseline Interferometry

Concept, Implementation, Calibration, and Application in Astronomy

VDM Verlag

ntroduction to Optical Stellar Interferometry

A. Labeyrie, S. G. Lipson, and P. Nisenson

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Practical Optical Interferometry

Imaging at Visible and Infrared Wavelengths

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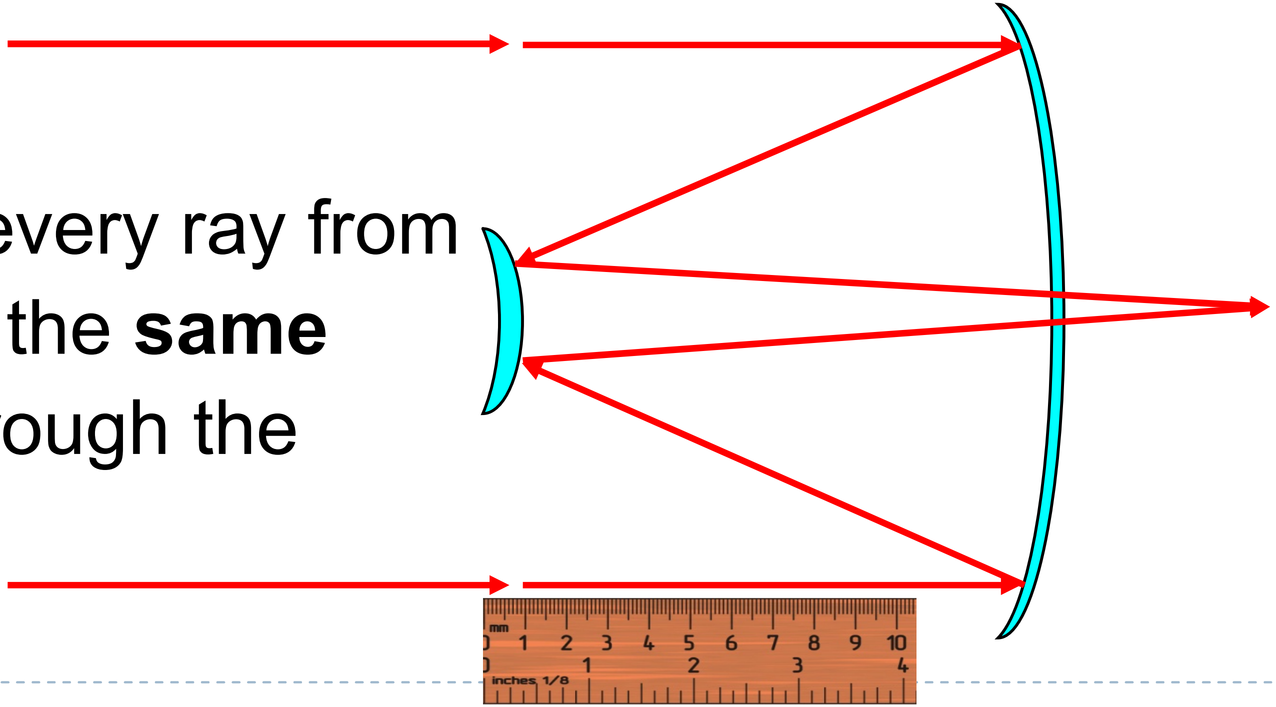
# The Telescope: What's Happening Inside?

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



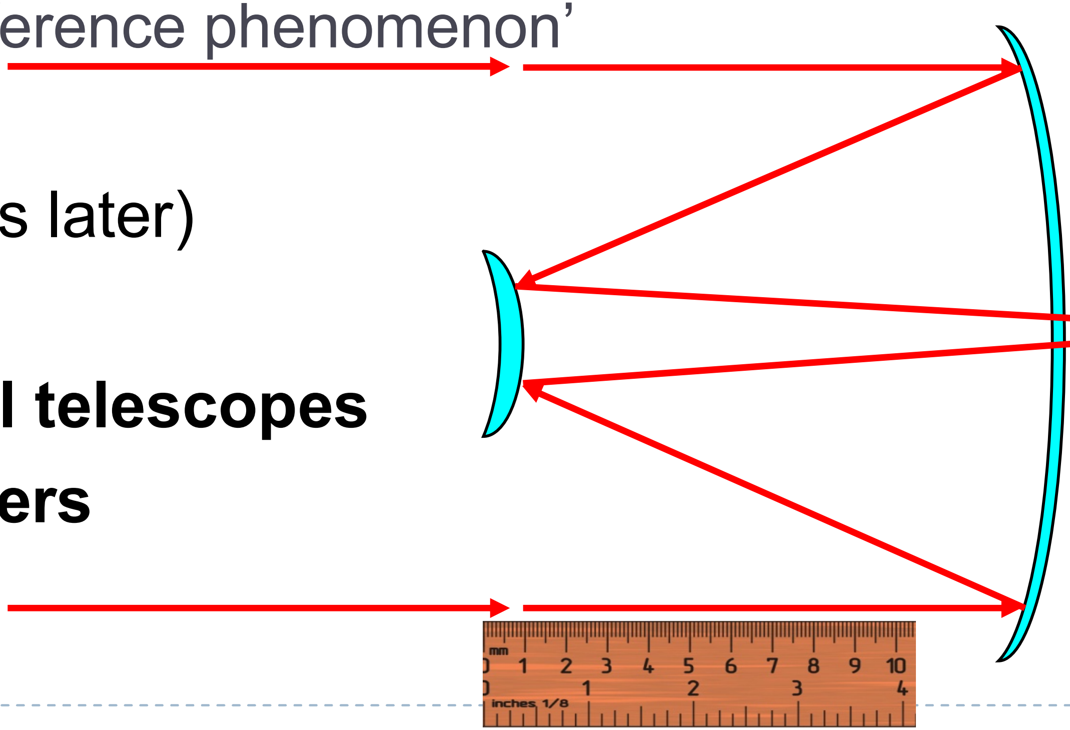
- Every path of every ray from the star traces the **same pathlength** through the telescope

# The Telescope: What's Happening Inside?

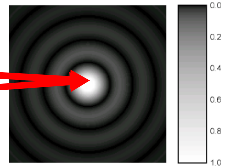
- When light rays from a source satisfy this pathlength condition, the can form an image
  - This is an 'interference phenomenon'

(more on this later)

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



***Interference is why 'point-like' stars appear as Airy disks***

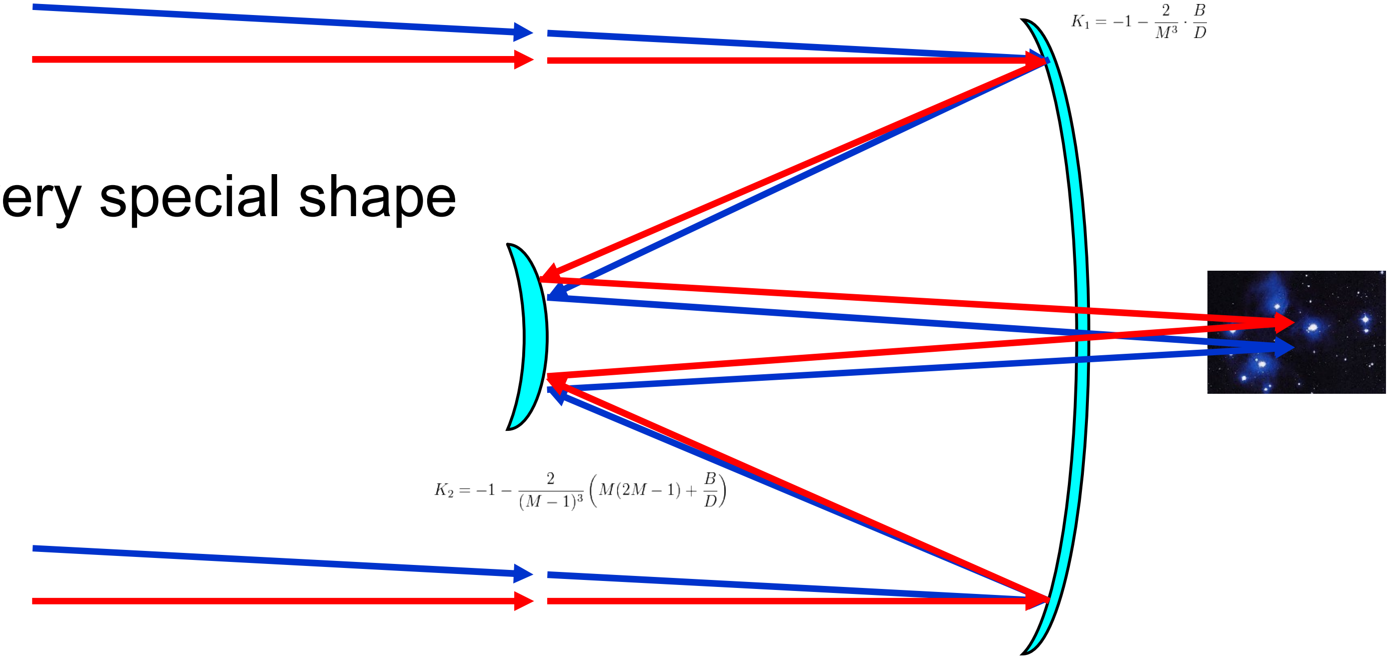


***(though this effect is usually washed out by the atmosphere)***

# 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

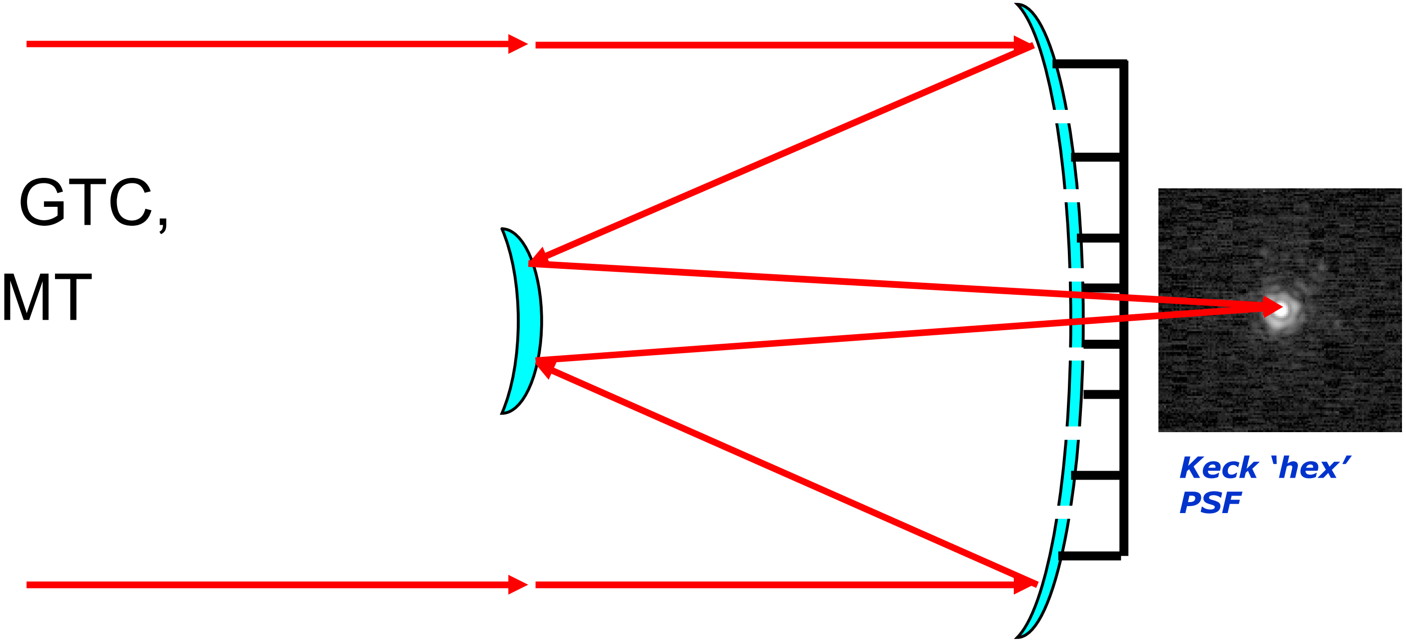
- This dictates the very special shape of the mirrors



# 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

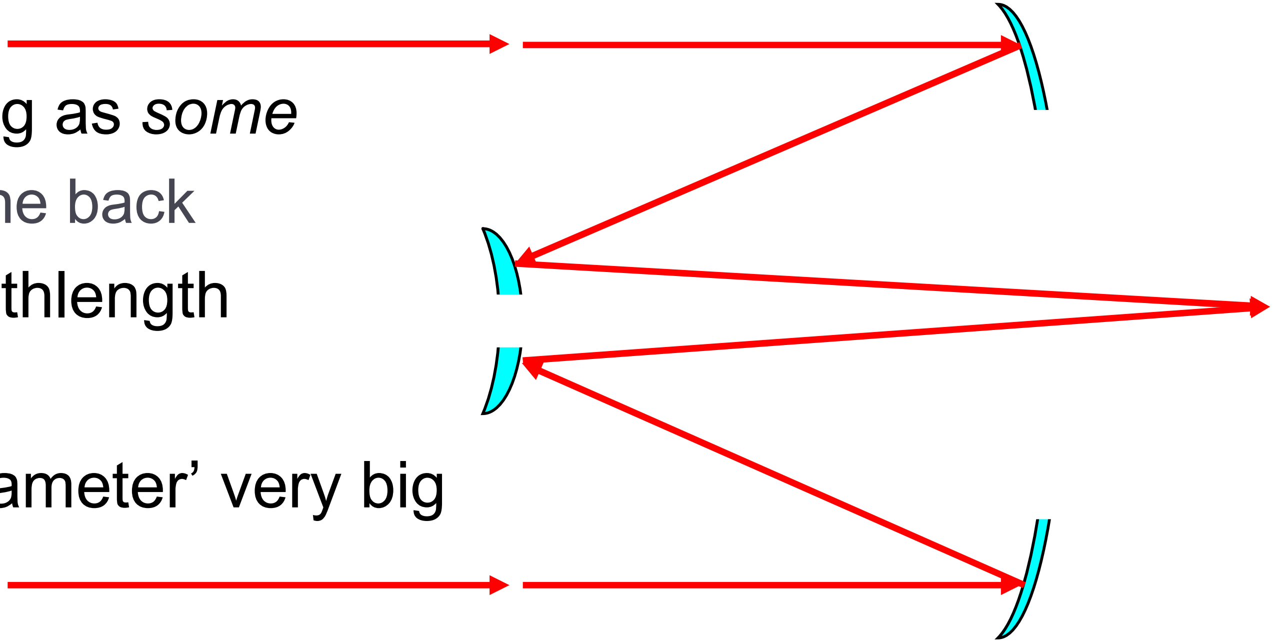
- Examples: Keck, GTC, E-ELT, TMT, GSMT



***Keck ‘hex’ PSF***

# Cracking the Resolution Problem

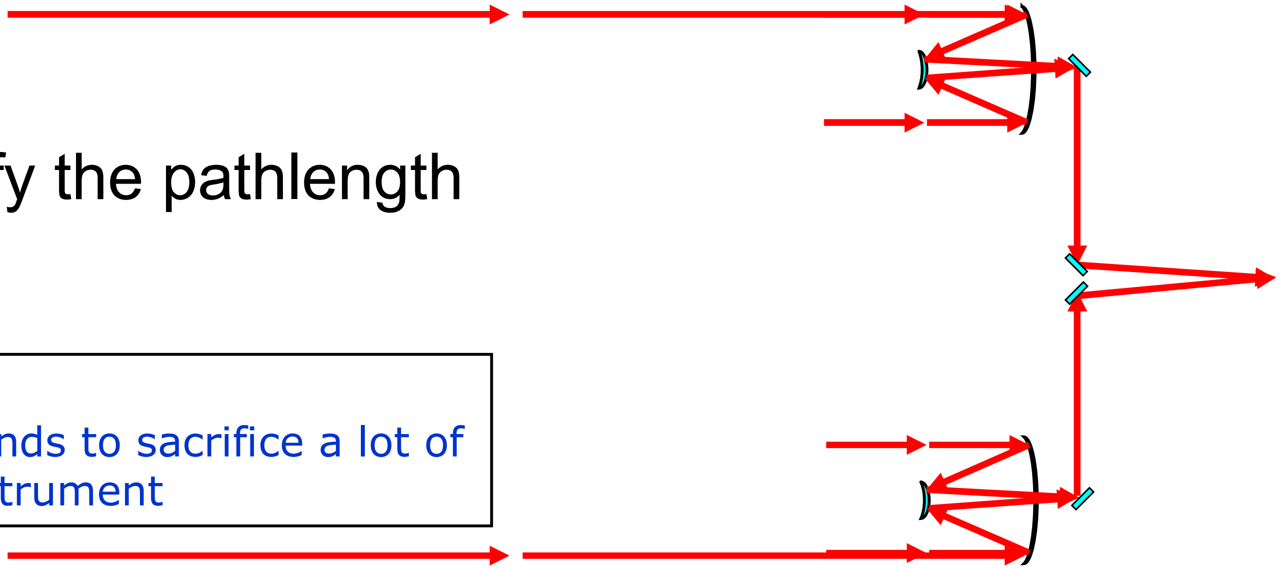
- Taking the neat trick even further: really chop up your telescope into a **long baseline interferometer**



- 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

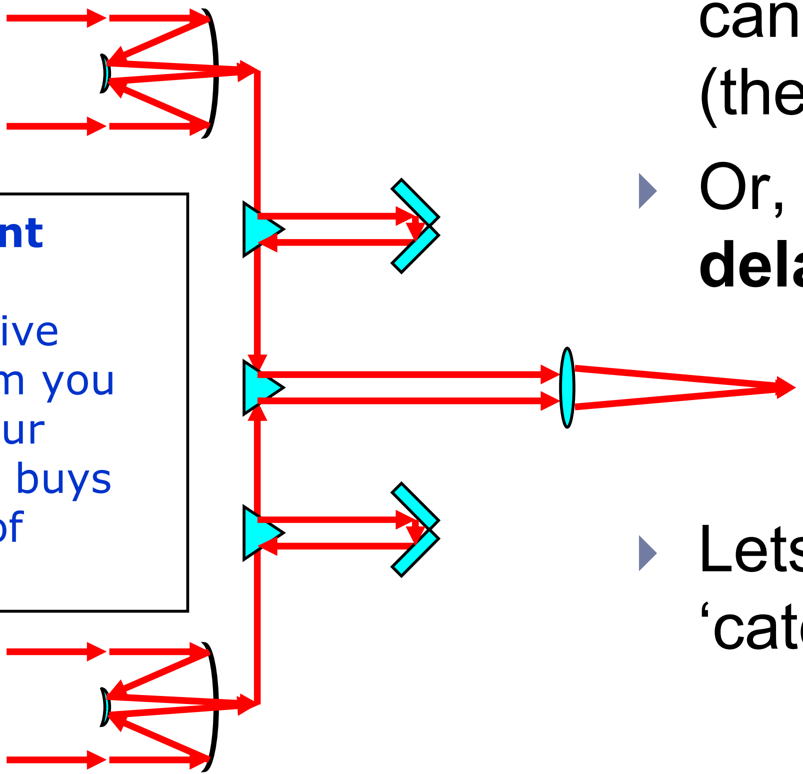
- Taking the neat trick even further: really chop up your telescope by making it **many telescopes**



- Still have to satisfy the pathlength condition, though

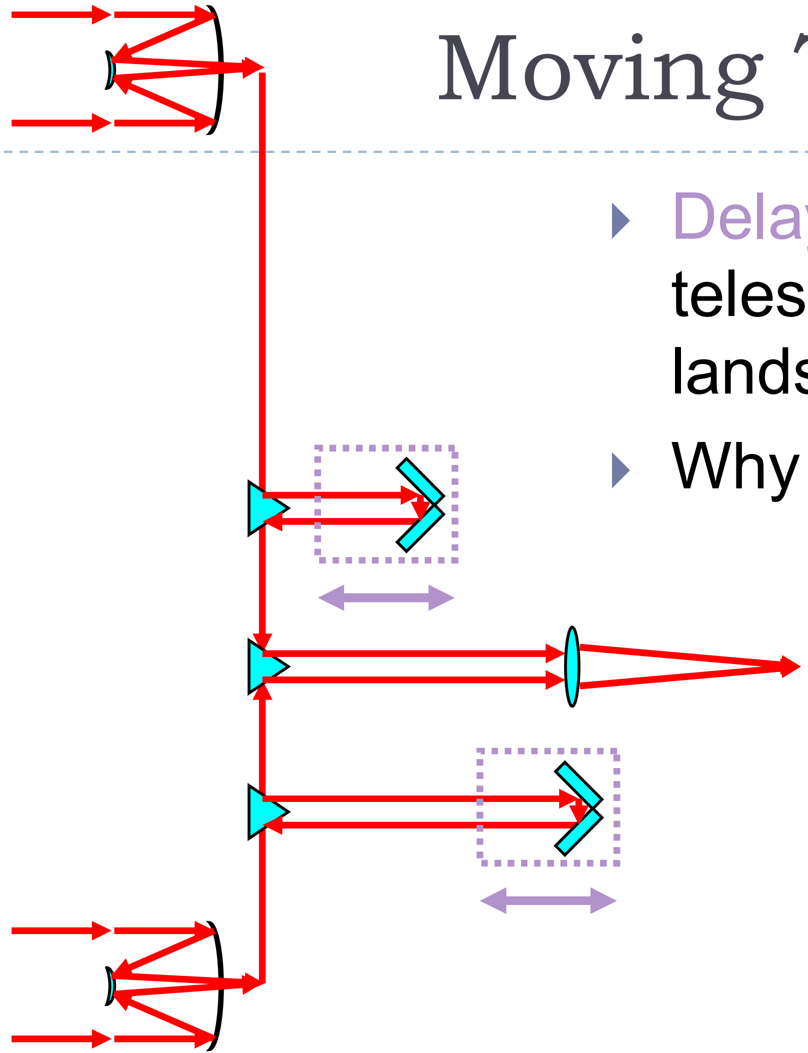
**Important caveat:**
Doing things this way tends to sacrifice a lot of 'field of view' of your instrument

# 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



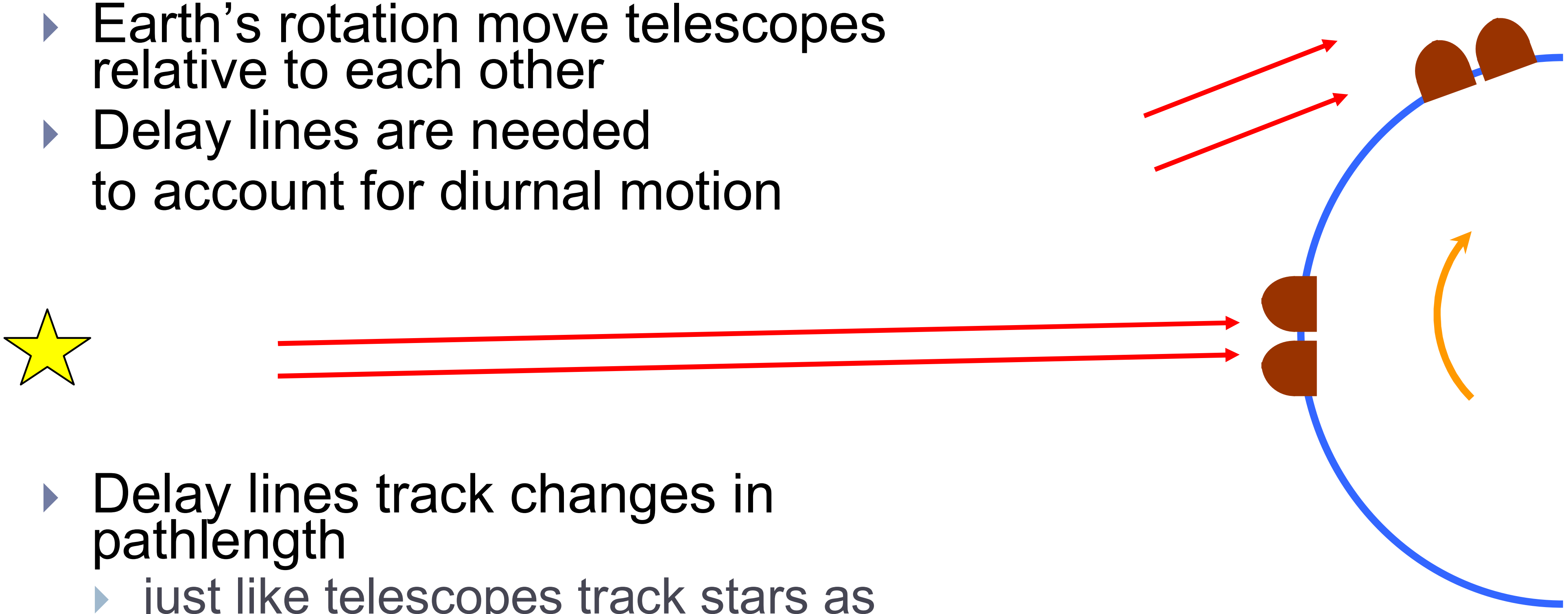
# Moving Things Around

- Delay lines let you have telescopes scatter across the landscape at unequal distances
- Why not fix things in place?

# Things Move Around On Their Own

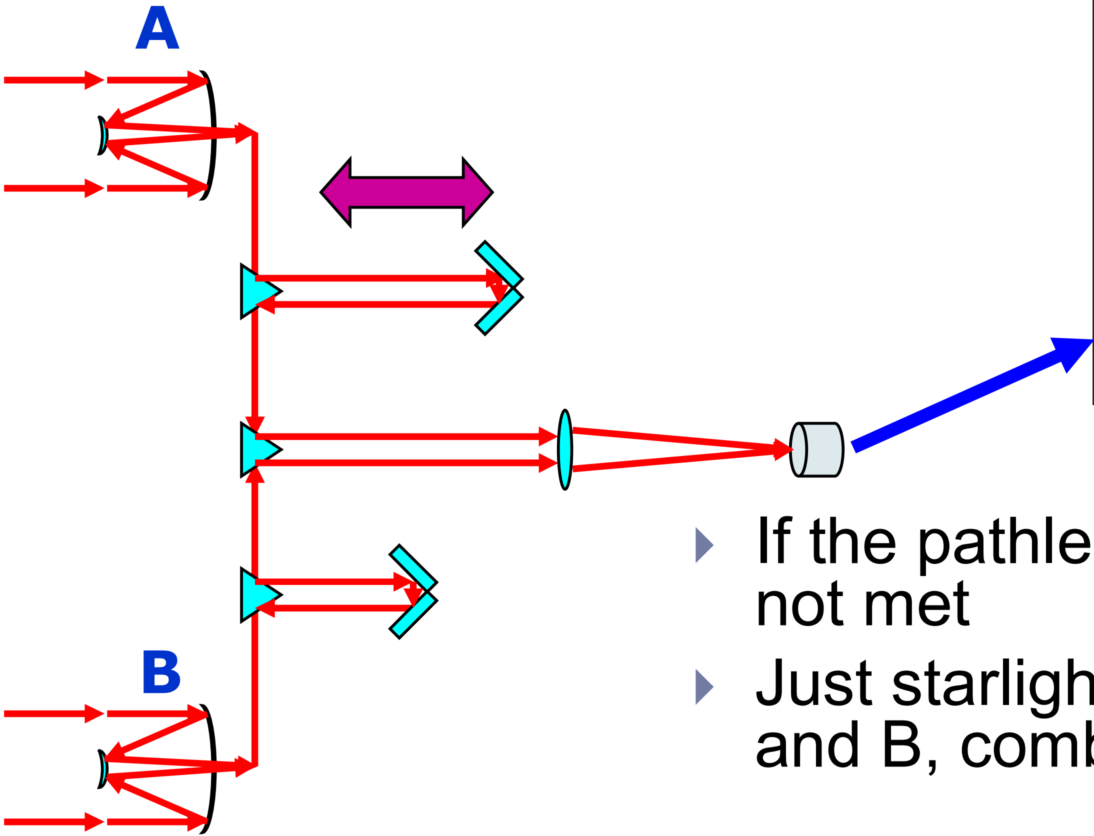
- Earth's rotation move telescopes relative to each other
- Delay lines are needed

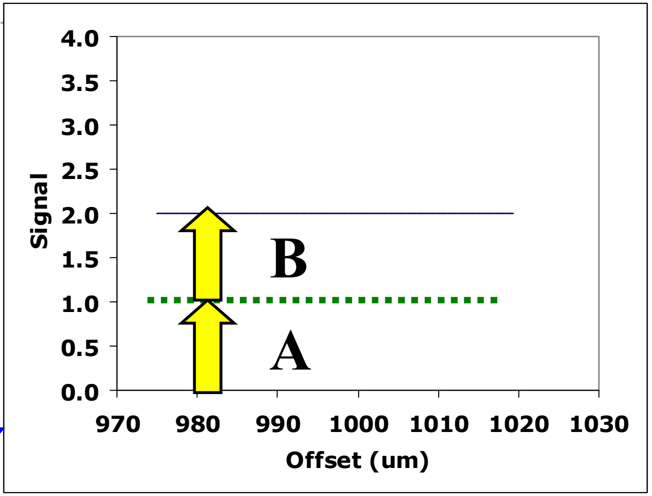
  to account for diurnal motion



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

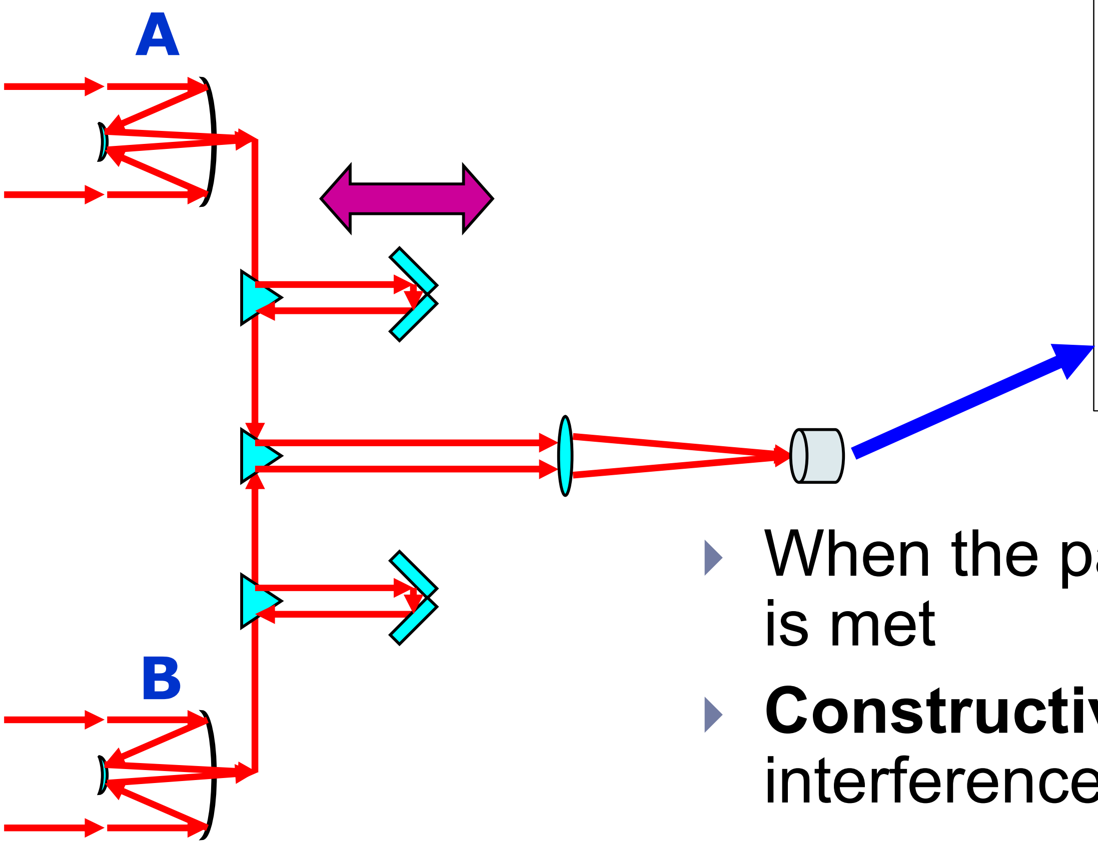
# What Does an Interferometer ‘See’?

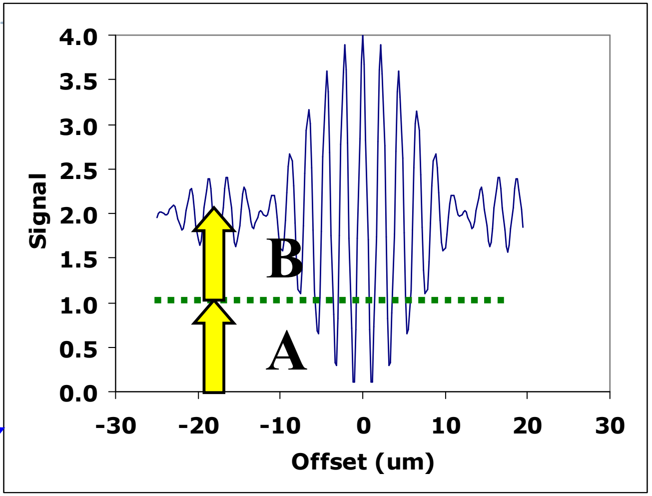




- If the pathlength condition is not met
- Just starlight from telescope A, and B, combined

# What Does an Interferometer ‘See’?

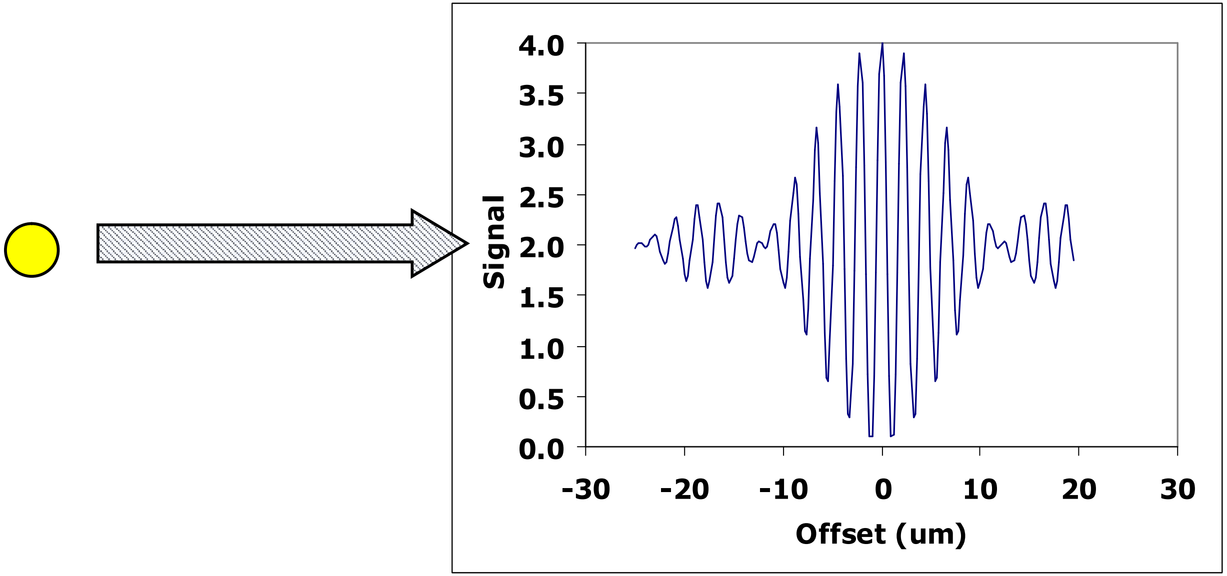




- When the pathlength condition is met
- **Constructive** and **destructive** interference of light

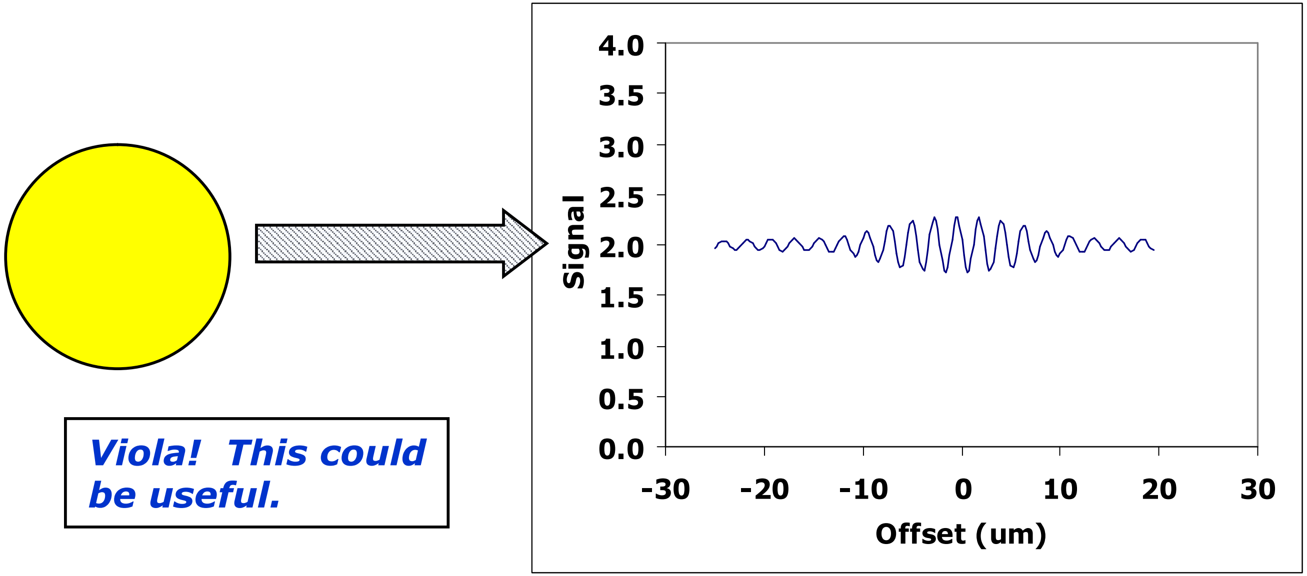
# Observing Small Stars

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



# Observing Large Stars

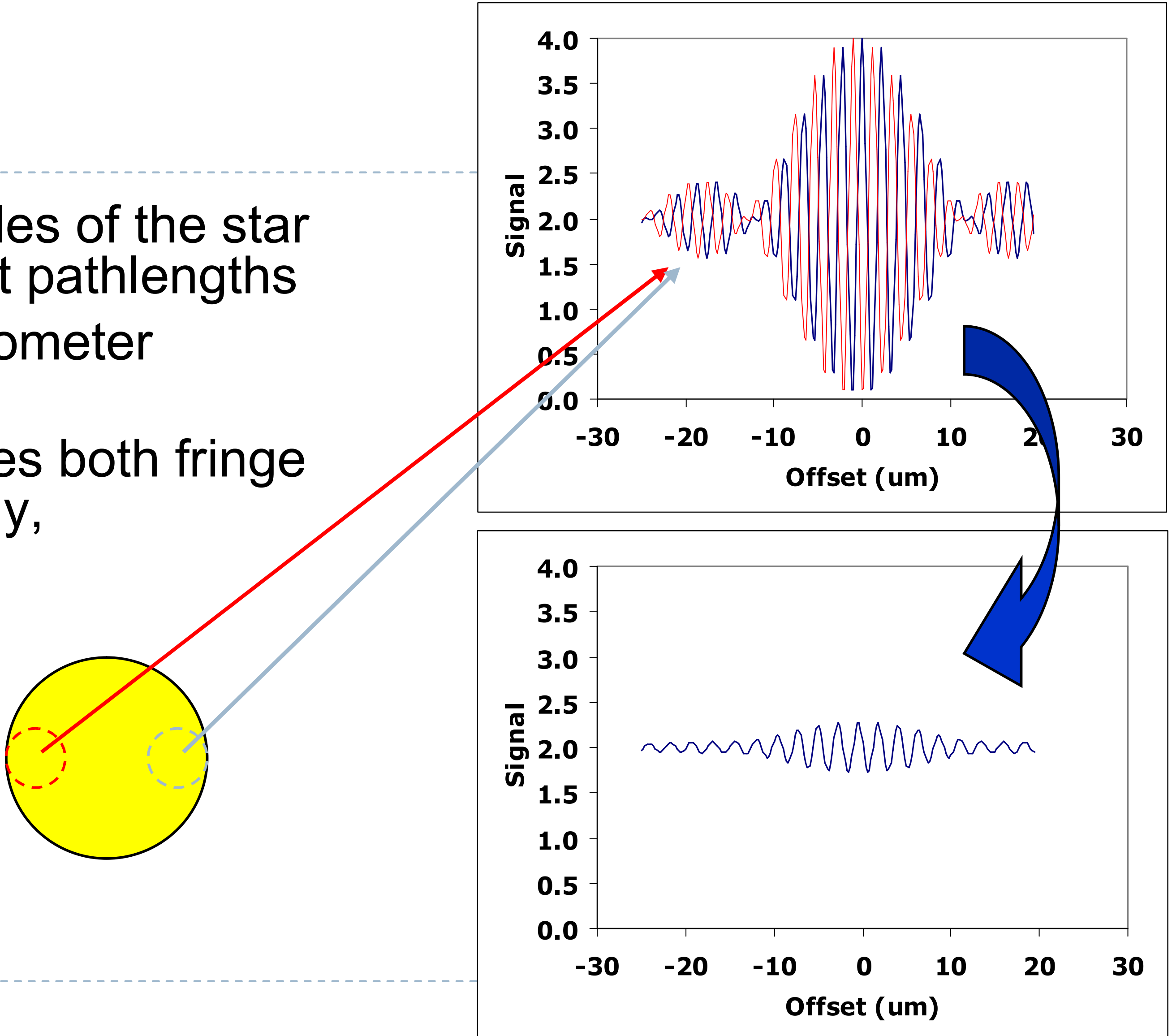
- For a large – **resolved** – star, fringes will be high contrast
- By ‘large’, I mean $\theta \approx$ 0.5-3 mas (in the case of NPOI)



***Viola! This could be useful.***

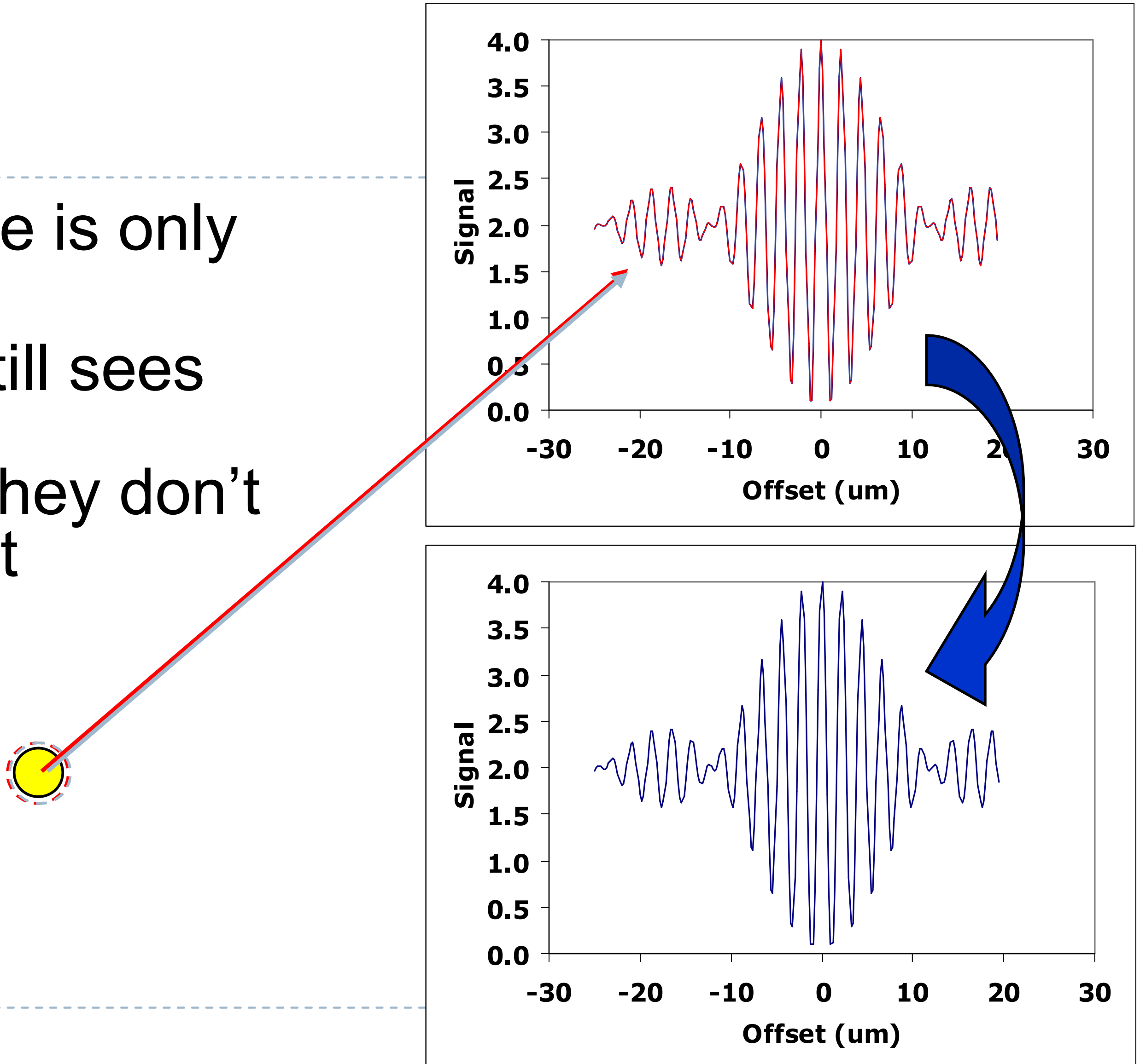
# Why is This?

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



# Why is This?

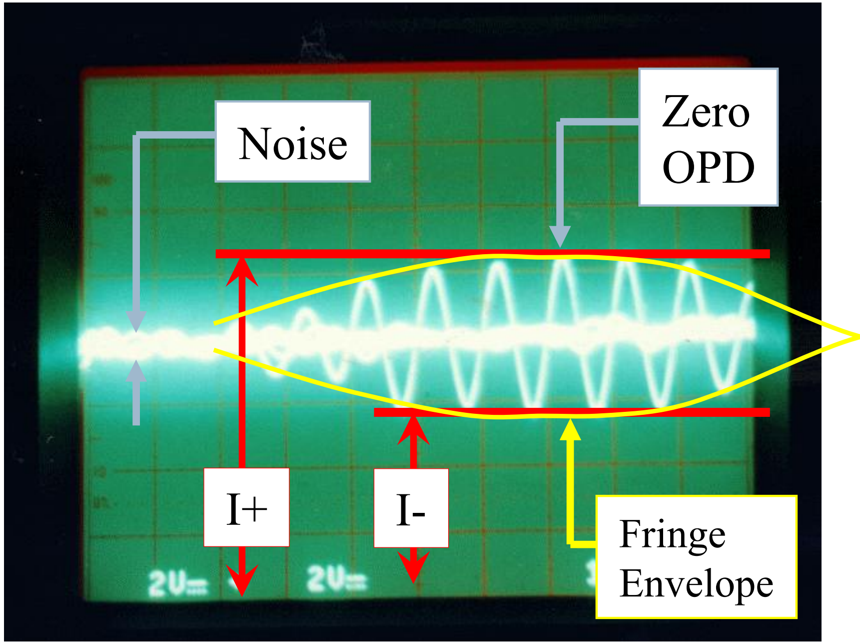
- For a small star, there is only one pathlength
- The interferometer still sees both fringe packets simultaneously, but they don’t smear each other out



# 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

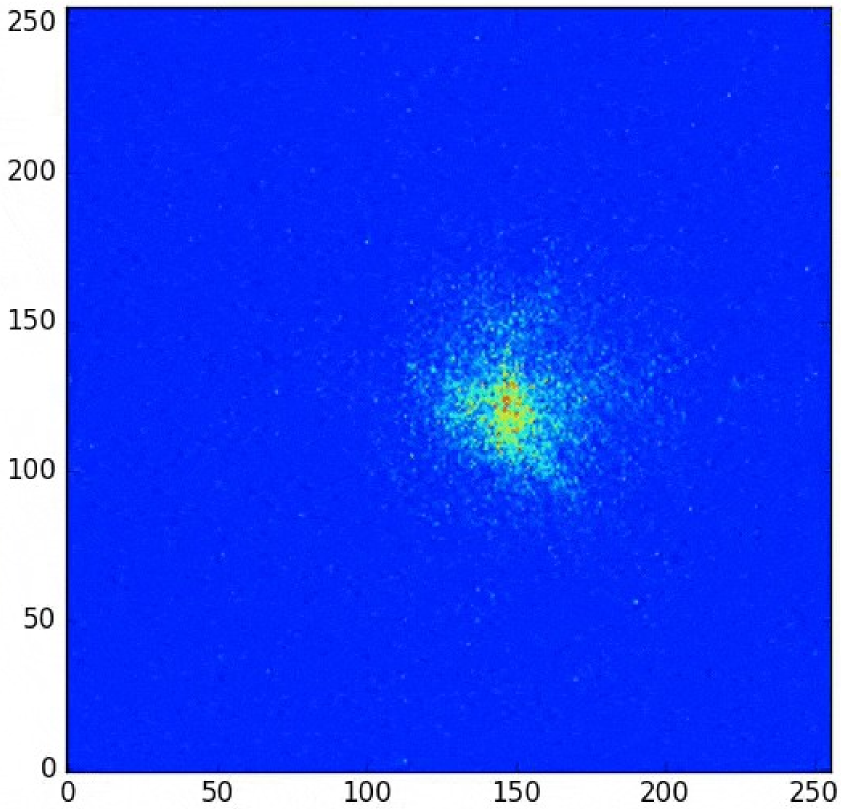
# Interferometric Arrays

- 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**

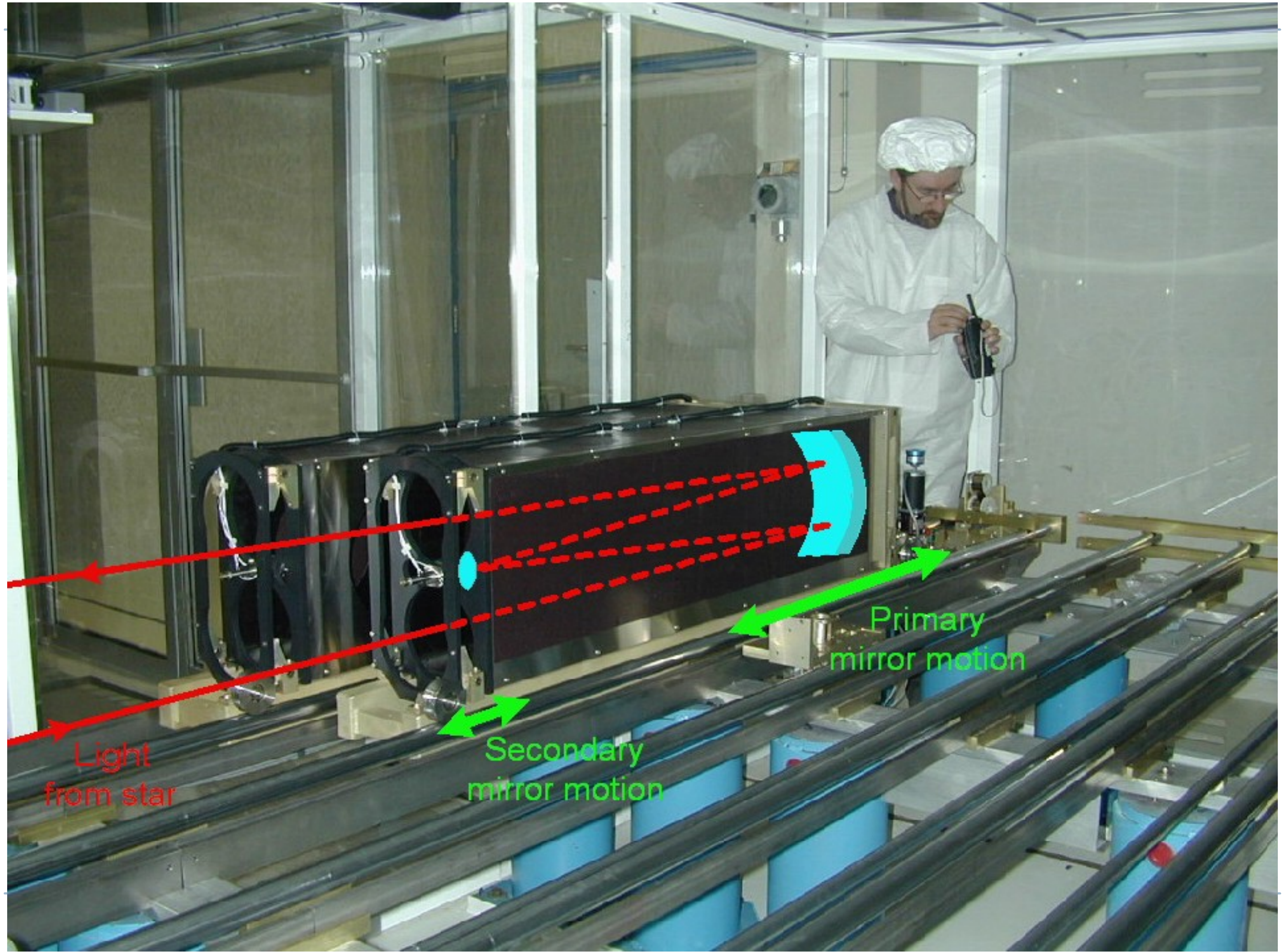
← **Charlie Townes:**
"It's because the value of $\hbar$ is what it is."

# Limitations of Terrestrial Observing

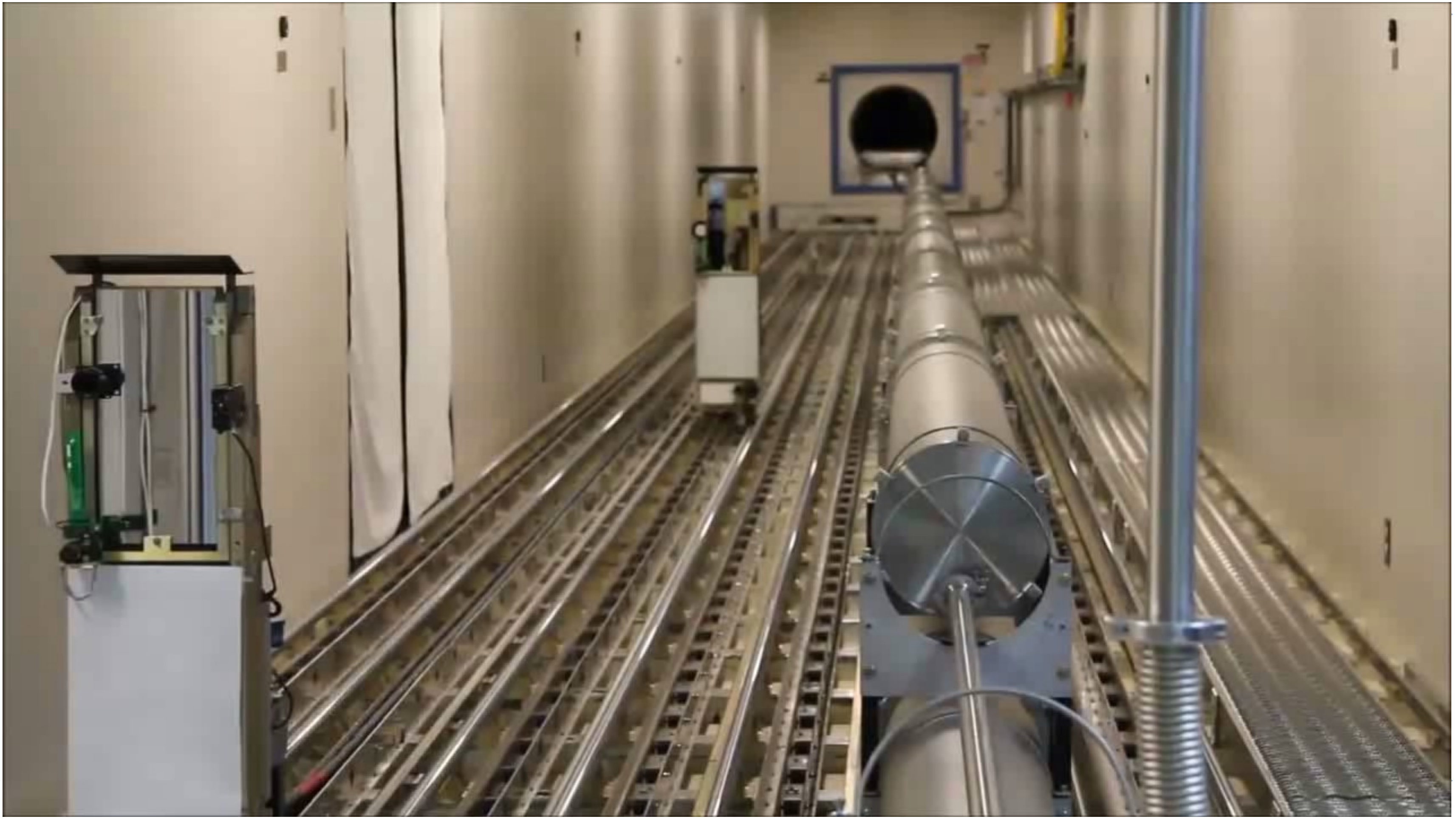
- Short coherence times
  - ~1ms in the visible
  - *Much longer in the radio*
- Have to use some of the object light to track in real time
- Wavefront is corrupted
  - Have to use more of the object light to correct
- *Sensitivity is limited*



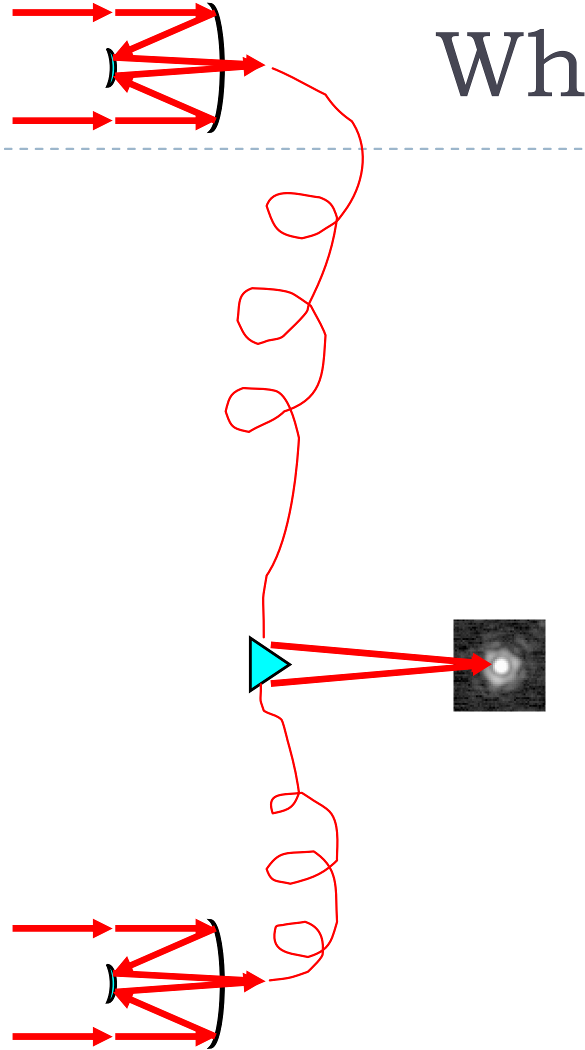
# Delay Lines at Keck



# Keck in Motion



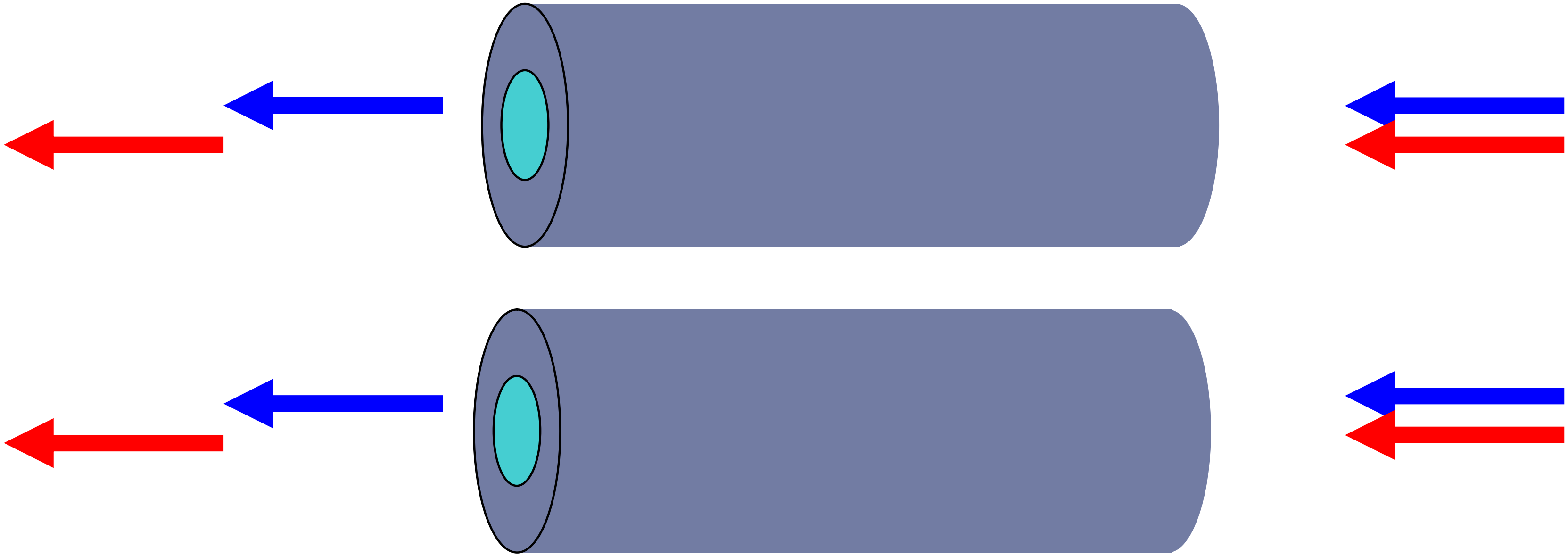
# Why not use fibers?



- Current technology Single mode, polarization maintain fibers let you **RELAY** light from telescopes to lab
- Hasn't solved **DELAY** problem.
  - **Why?**

# An Approach: Fibers

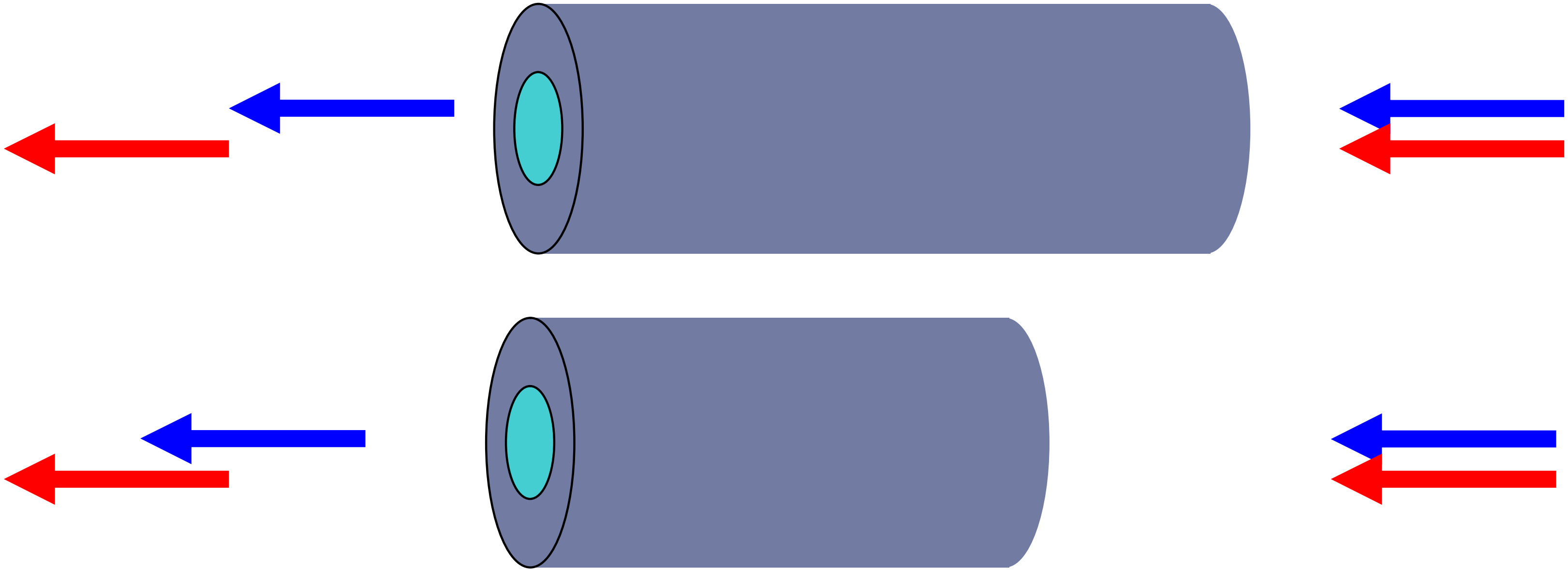
- This works for beam RELAY



Works if fibers are **exactly** the same length

# A Bad Approach: Fibers

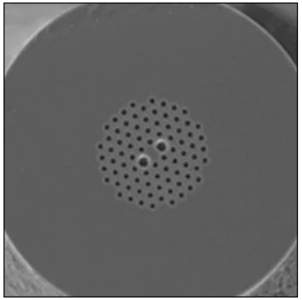
- This DOES NOT work for beam DELAY

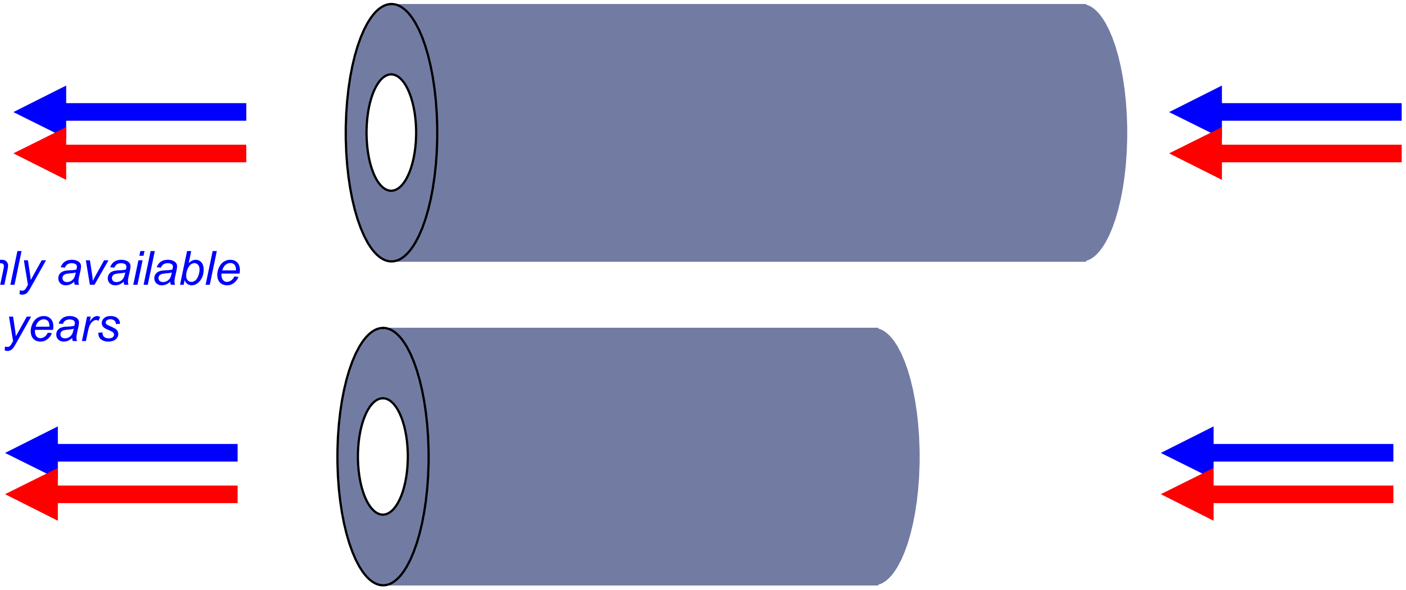


Inner glass has wavelength-dependent speed of light

# A New Approach: Hollow-Core Fibers

- This *will* work for beam DELAY

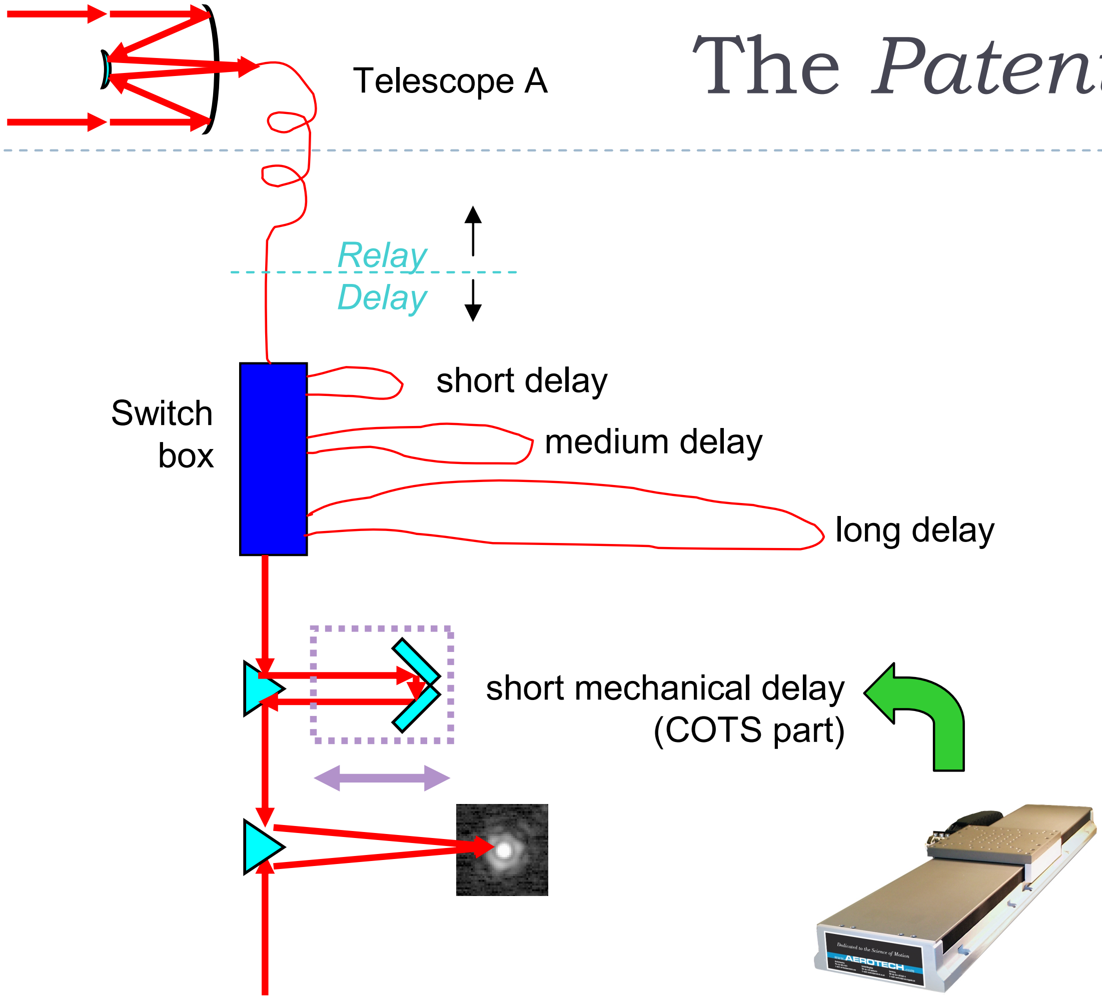




*These fibers only available for the last few years*

Inner hollow has wavelength-*independent* speed of light

# The *Patent Pending* New Idea



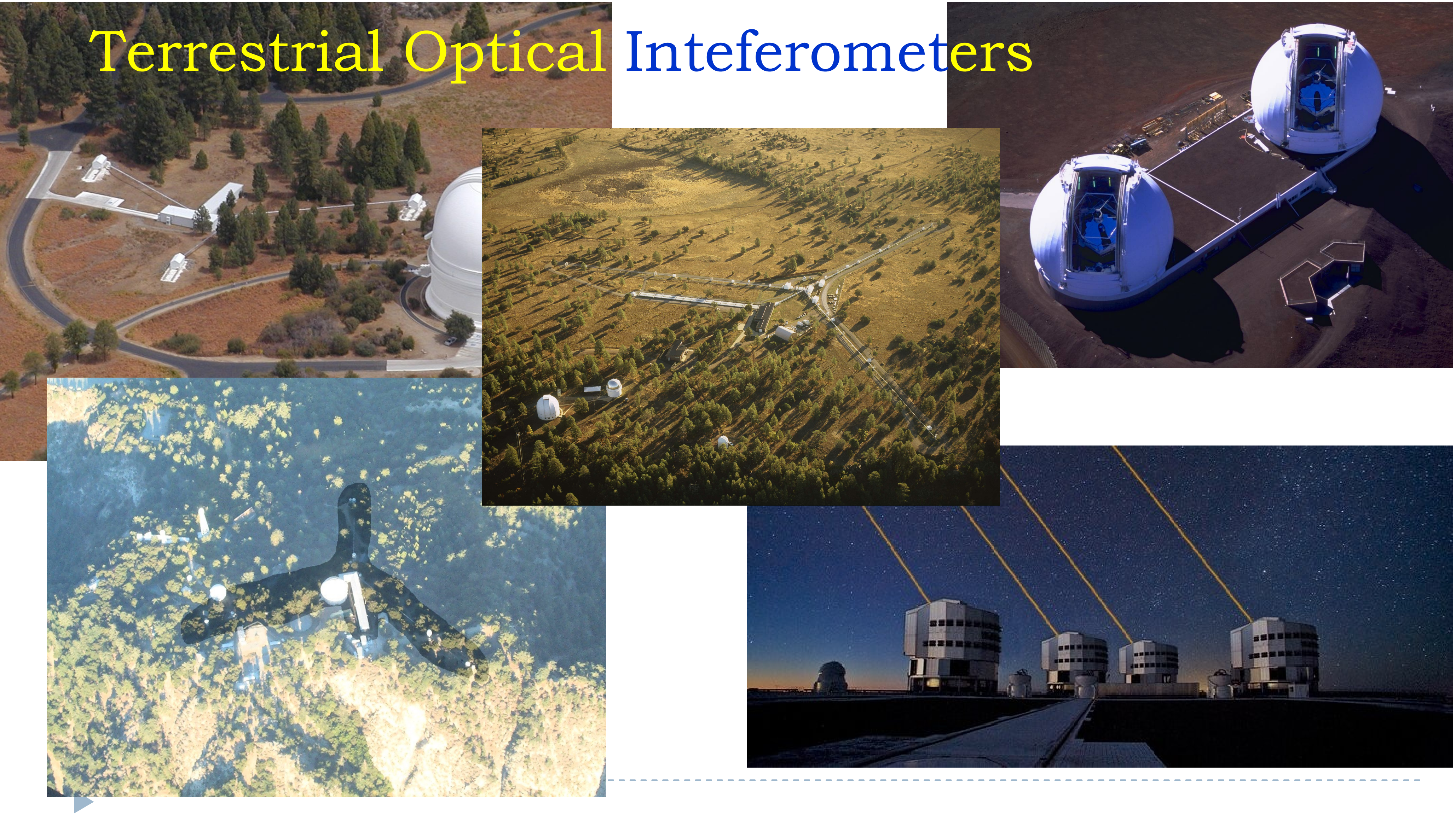
- Fiber Delay lines do most of the work in 'chunks'
  - Does not require a dedicated building to get >100m of delay
- A short mechanical delay line takes care of the rest
  - Commercial-off-the-shelf part
  - Short range: optics can be small

# 300-foot Delay lines at CHARA

# The Facilities

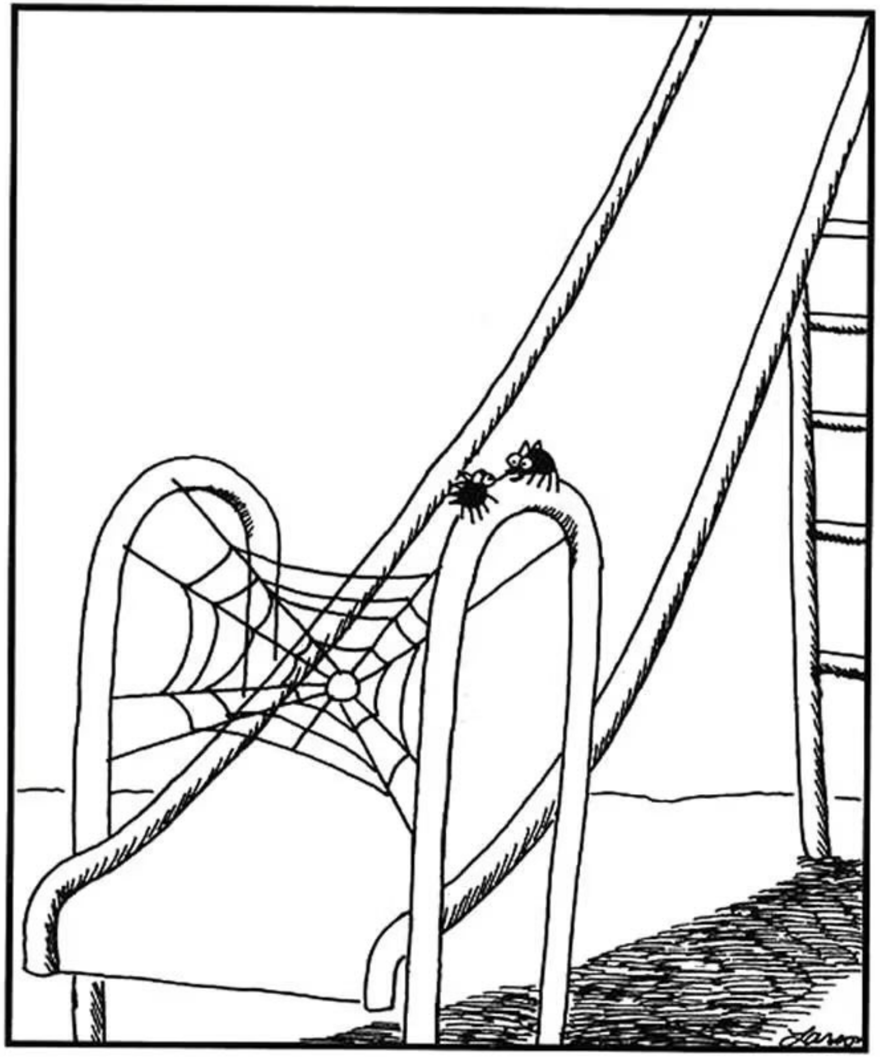
*Paul Signac, “La Corne D'or, Les Minarets”,*

# Terrestrial Optical Inteferometers



# What Optical Interferometers Really Look Like

**(apologies to Gary Larson)**



"If we pull this off, we'll eat like kings."

# Science:
The Palomar Testbed Interferometer

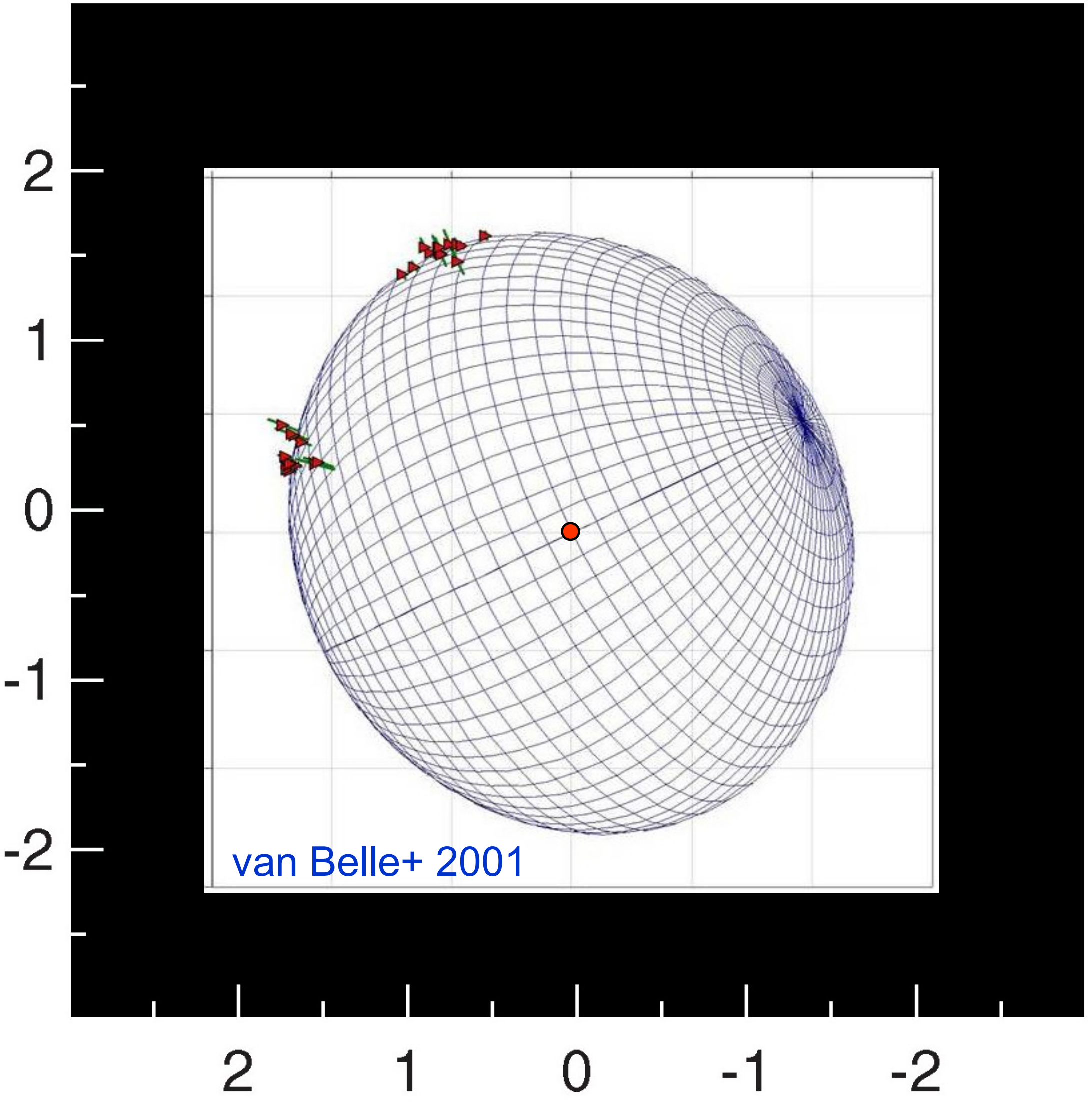
**Notable catalog of achievements**

- First direct measurement of rotational oblateness in rapid rotator Altair (van Belle et al 2001 ApJ 559 1155)
- Dual-star wide-angle astrometry at the 100uas level (Shao et al AAS 195 8714)
- Detection of Vega dust disk (Ciardi et al. 2001)
- Narrow-angle astrometry at the 10uas level and detection of planetary-mass objects (Muterspaugh et al 2010 AJ 140 1657)
- Giant star linear sizes and temperatures (van Belle et al 2021 ApJ 922 163)
- Supergiant linear sizes and temperatures (van Belle et al 2009 394 1925)
- Carbon star sizes & oblateness (van Belle et al 2013 ApJ 775 45)

**Photo Credit:** Gerard van Belle

# Altair: the Prototype Rapid Rotator

- v sin i ~210 km/s
- Spinning every 12 hours
- Leads to:
    - ~20% oblateness
    - Gravity darkening



van Belle+ 2001

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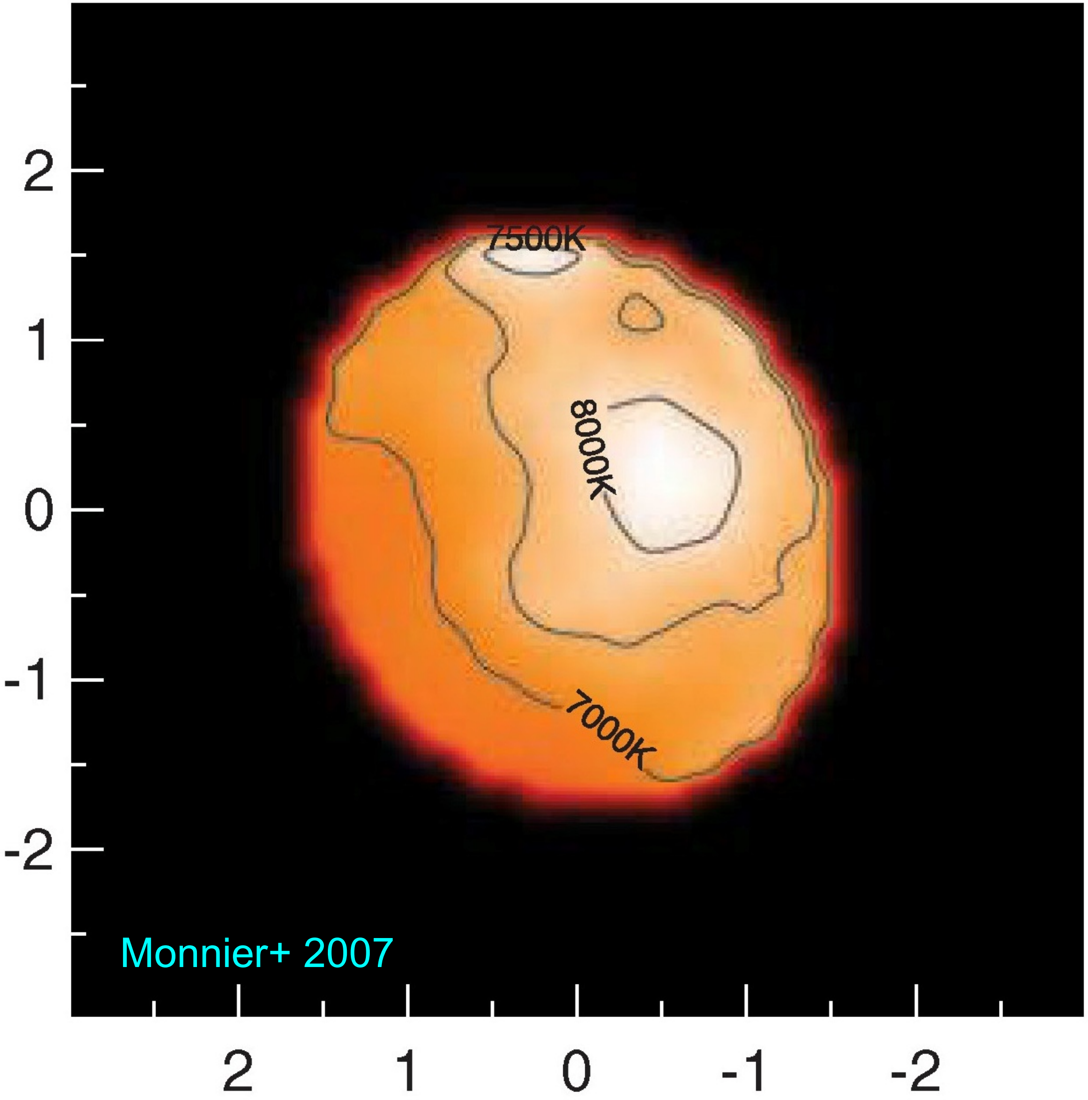
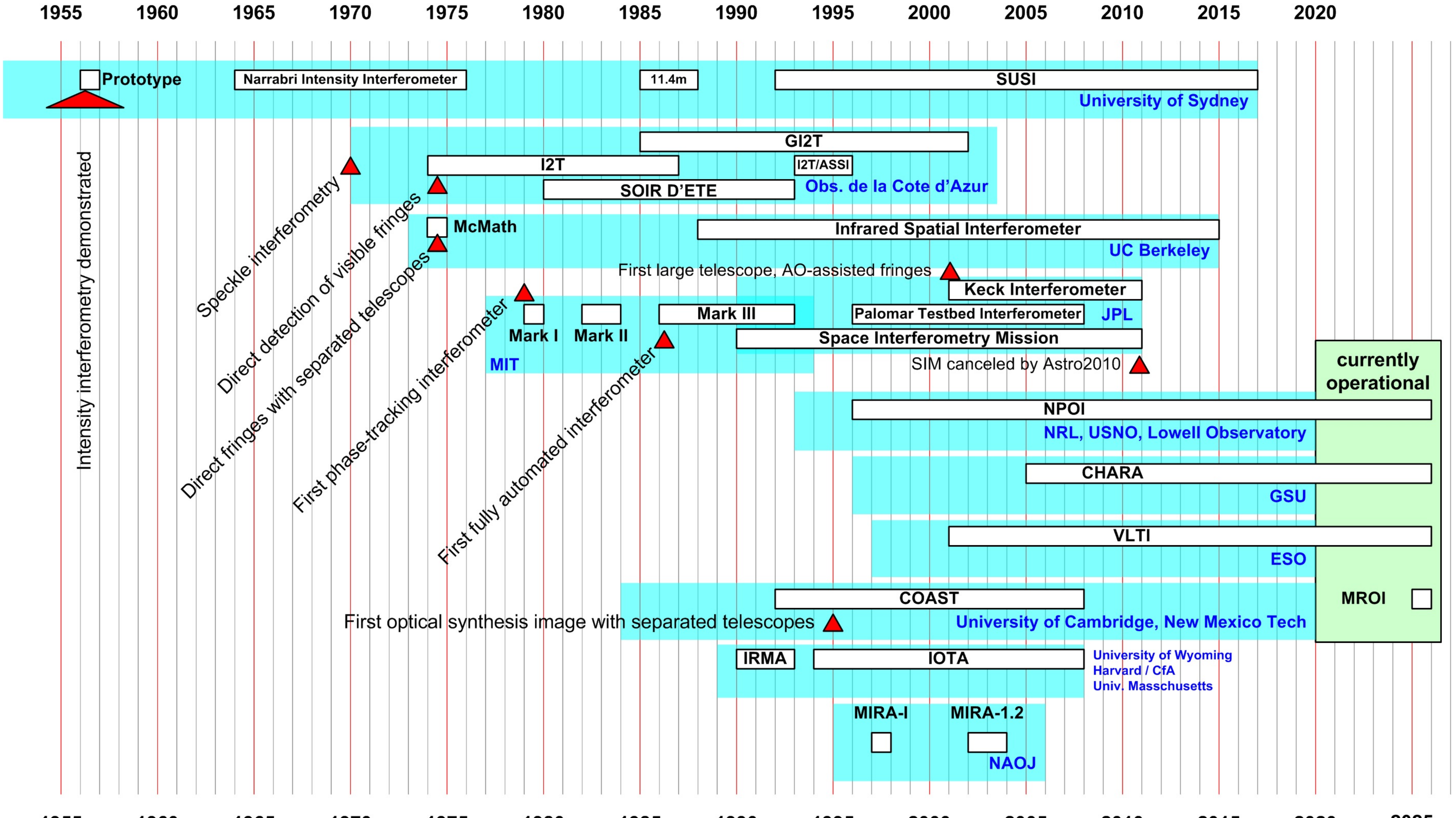


Monnier+ 2007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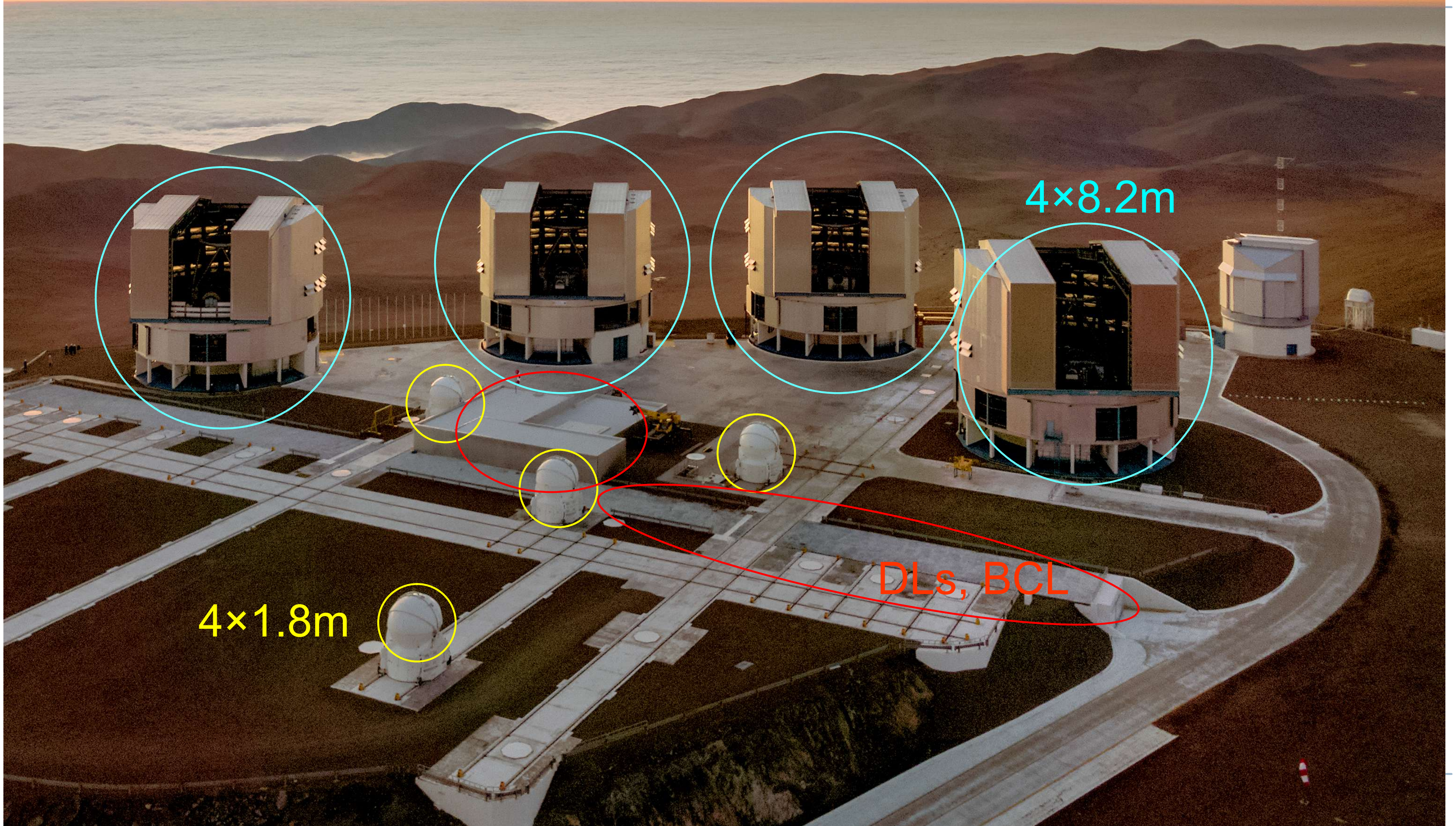
2020
Prototype
Narrabri Intensity Interferometer
11.4m
SUSI
University of Sydney
Intensity interferometry demonstrated
GI2T
I2T
I2T/ASSI
SOIR D'ETE
Obs. de la Cote d'Azur
Speckle interferometry
Direct detection of visible fringes
McMath
Infrared Spatial Interferometer
UC Berkeley
Direct fringes with separated telescopes
First large telescope, AO-assisted fringes
Keck Interferometer
First phase-tracking interferometer
Mark I
Mark II
Mark III
Palomar Testbed Interferometer
JPL
Space Interferometry Mission
MIT
First fully automated interferometer
SIM canceled by Astro2010
currently operational
NPOI
NRL, USNO, Lowell Observatory
CHARA
GSU
VLTI
ESO
COAST
MROI
First optical synthesis image with separated telescopes
University of Cambridge, New Mexico Tech
IRMA
IOTA
University of Wyoming
Harvard / CfA
Univ. Masschusetts
MIRA-I
MIRA-1.2
NAOJ

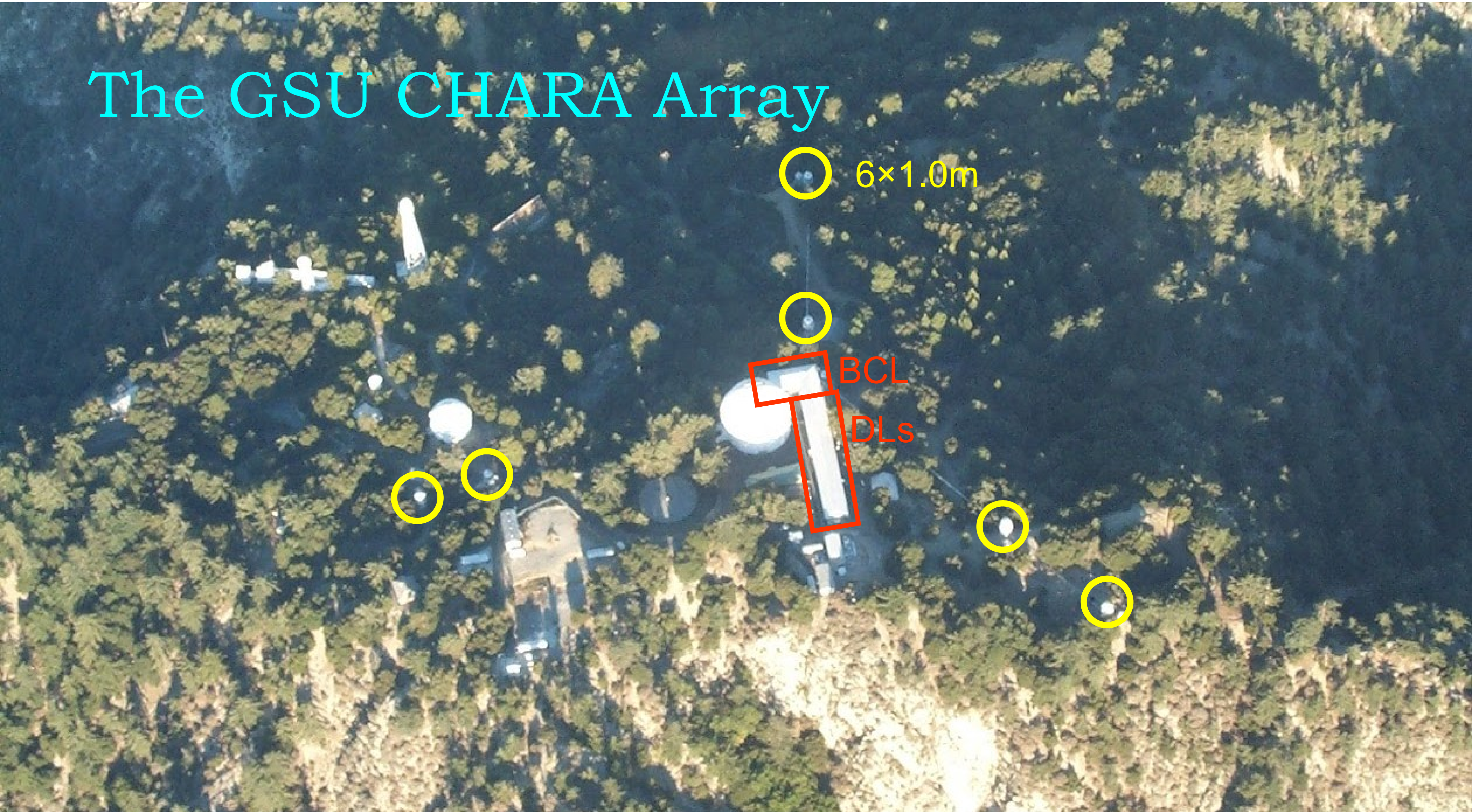
# VLTI

# VLTI

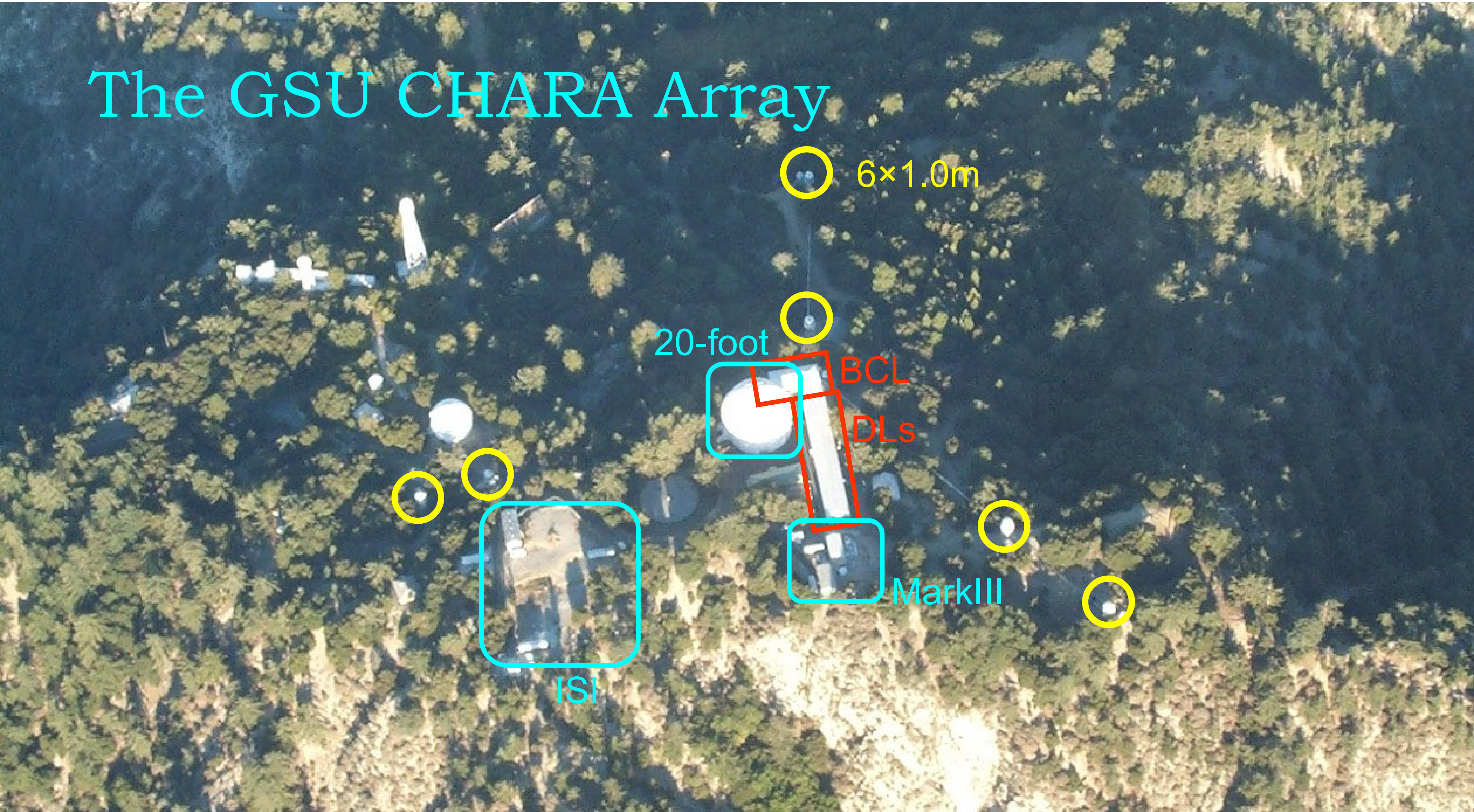


# The GSU CHARA Array

# The GSU CHARA Array



# The GSU CHARA Array

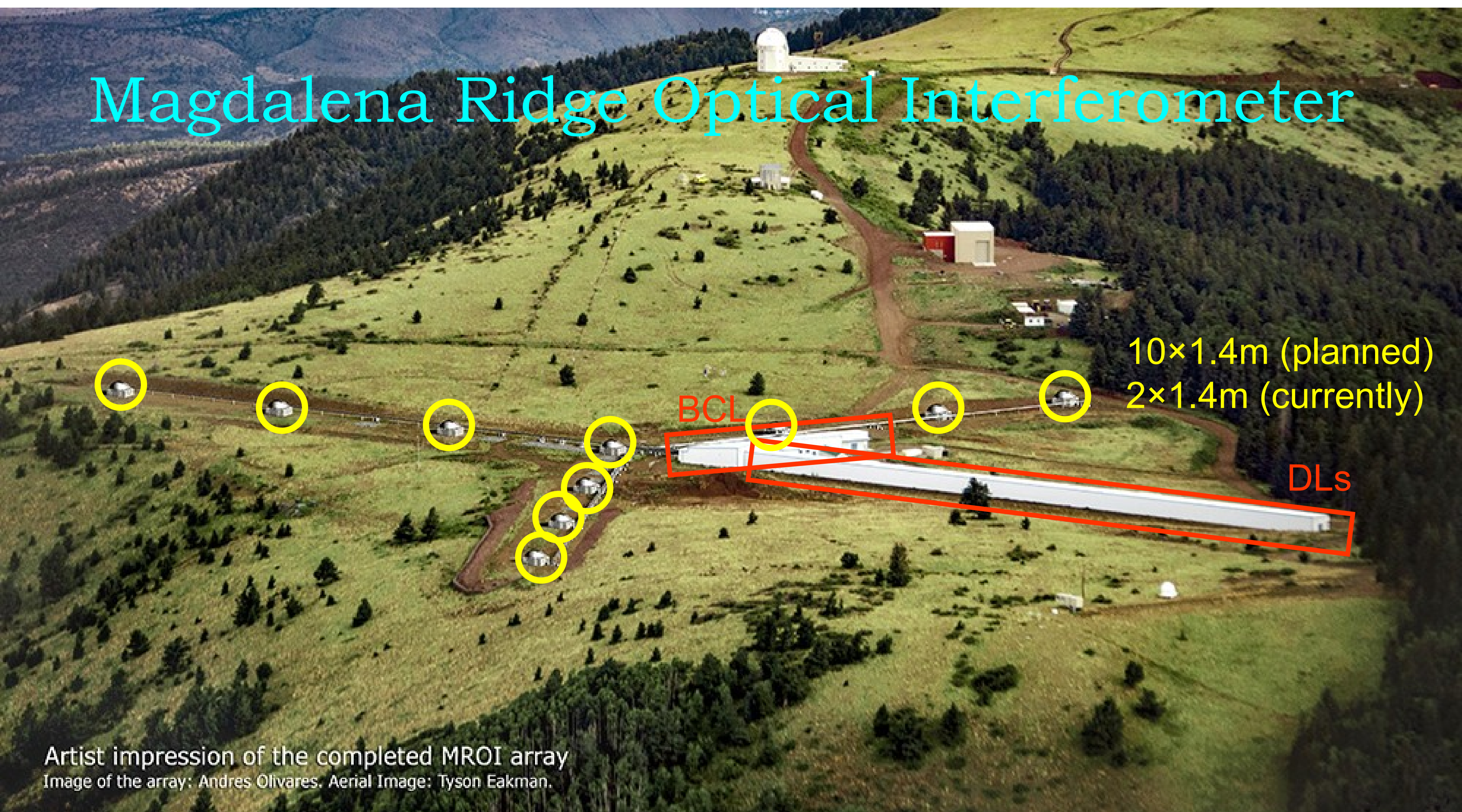


# Magdalena Ridge Optical Interferometer

Artist impression of the completed MROI array

Image of the array: Andres Olivares. Aerial Image: Tyson Eakman.

# Magdalena Ridge Optical Interferometer



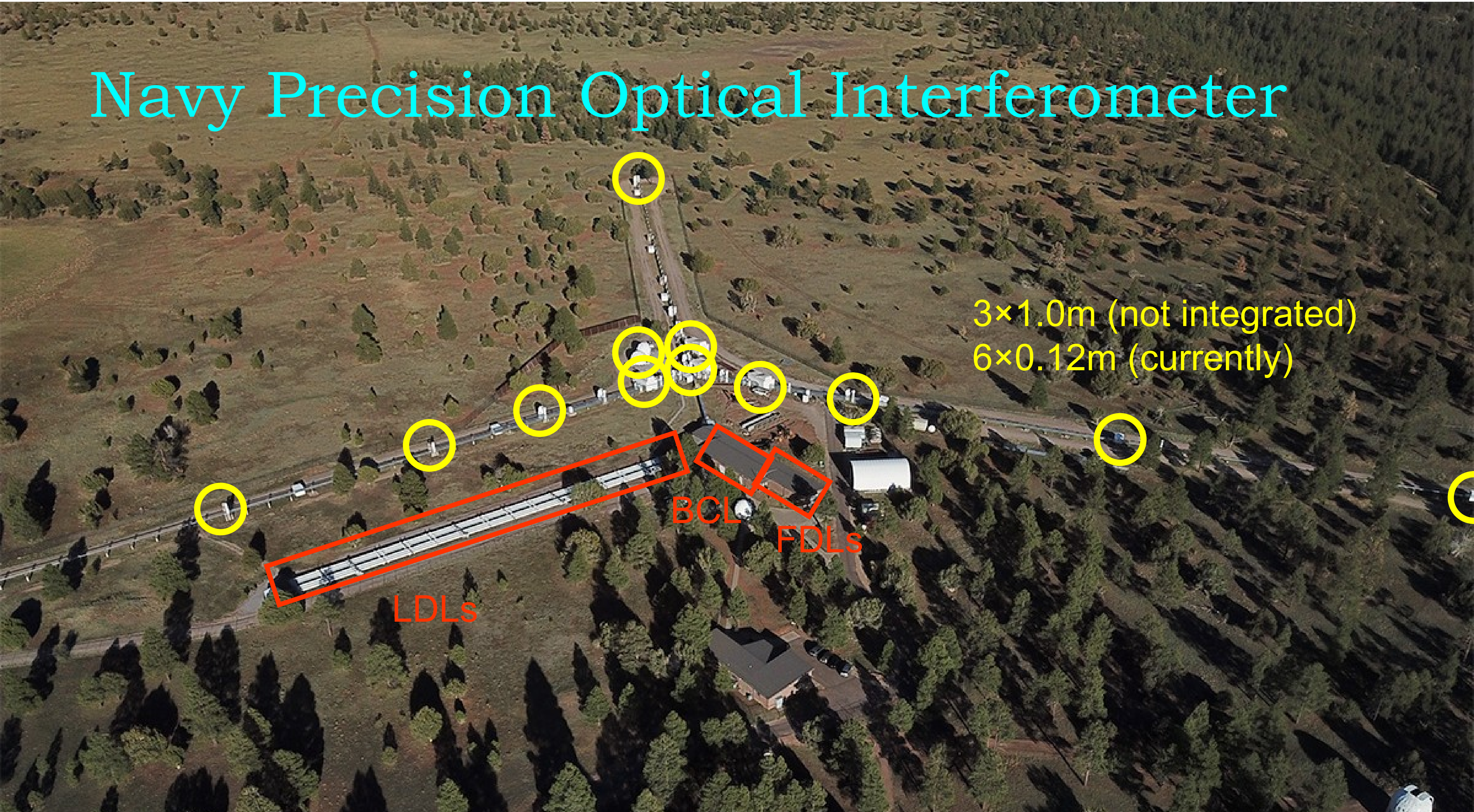
10×1.4m (planned)
2×1.4m (currently)

Artist impression of the completed MROI array

Image of the array: Andres Olivares. Aerial Image: Tyson Eakman.

# Navy Precision Optical Interferometer

# Navy Precision Optical Interferometer



3×1.0m (not integrated)
6×0.12m (currently)

# Let's Go to Space!

*Ferdinand du Puigaudeau, "The Bourg de Batz Church under the Moon"*

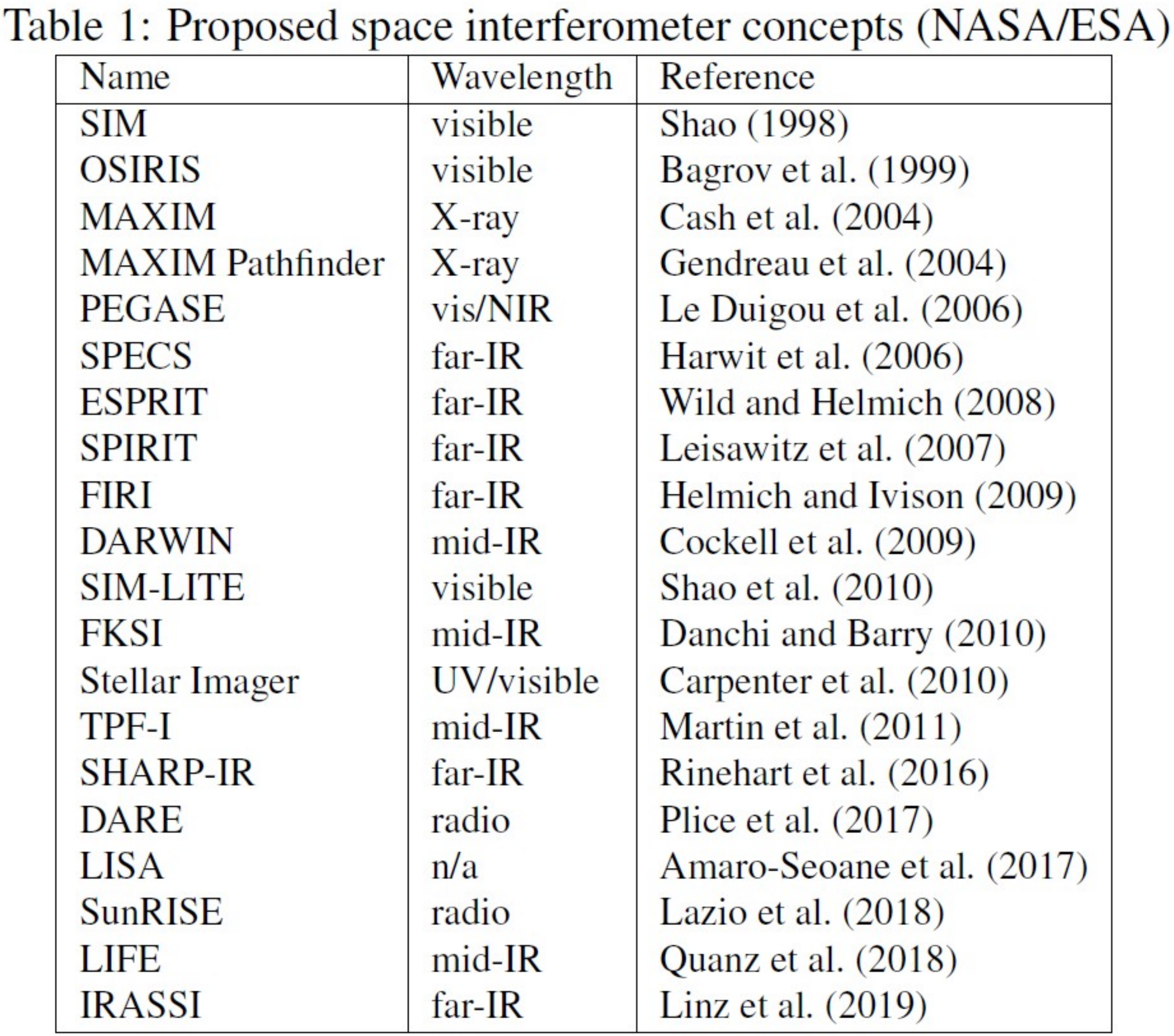
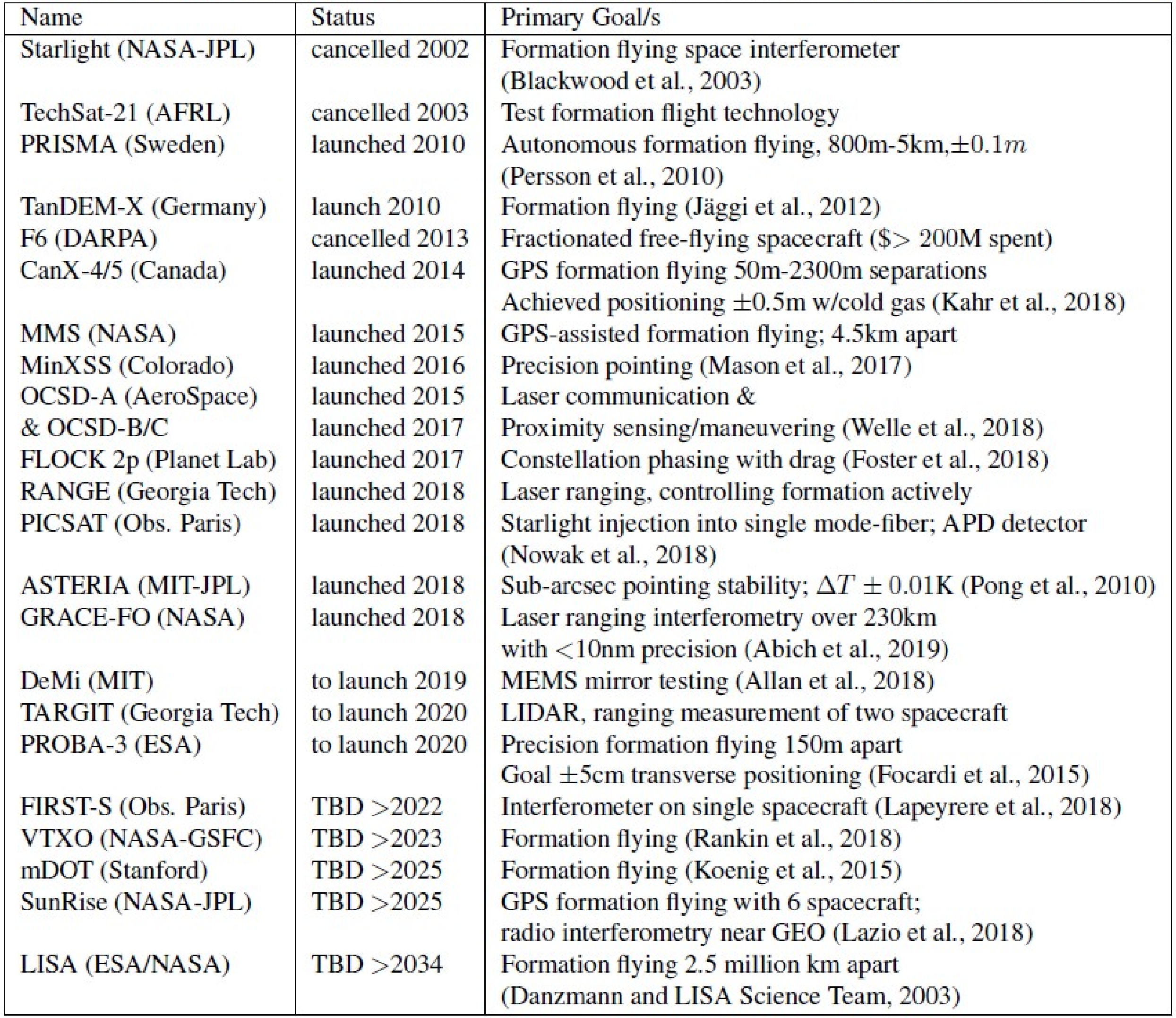


Table 1: Proposed space interferometer concepts (NASA/ESA)

| Name | Wavelength | Reference |
|---|---|---|
| SIM | visible | Shao (1998) |
| OSIRIS | visible | Bagrov et al. (1999) |
| MAXIM | X-ray | Cash et al. (2004) |
| MAXIM Pathfinder | X-ray | Gendreau et al. (2004) |
| PEGASE | vis/NIR | Le Duigou et al. (2006) |
| SPECS | far-IR | Harwit et al. (2006) |
| ESPRIT | far-IR | Wild and Helmich (2008) |
| SPIRIT | far-IR | Leisawitz et al. (2007) |
| FIRI | far-IR | Helmich and Ivison (2009) |
| DARWIN | mid-IR | Cockell et al. (2009) |
| SIM-LITE | visible | Shao et al. (2010) |
| FKSI | mid-IR | Danchi and Barry (2010) |
| Stellar Imager | UV/visible | Carpenter et al. (2010) |
| TPF-I | mid-IR | Martin et al. (2011) |
| SHARP-IR | far-IR | Rinehart et al. (2016) |
| DARE | radio | Plice et al. (2017) |
| LISA | n/a | Amaro-Seoane et al. (2017) |
| SunRISE | radio | Lazio et al. (2018) |
| LIFE | mid-IR | Quanz et al. (2018) |
| IRASSI | far-IR | Linz et al. (2019) |

Table 2: Missions developing enabling technology for formation flying space interferometry



| Name | Status | Primary Goal/s |
|---|---|---|
| Starlight (NASA-JPL) | cancelled 2002 | Formation flying space interferometer<br>(Blackwood et al., 2003) |
| TechSat-21 (AFRL) | cancelled 2003 | Test formation flight technology |
| PRISMA (Sweden) | launched 2010 | Autonomous formation flying, 800m-5km,±$0.1m$<br>(Persson et al., 2010) |
| TanDEM-X (Germany) | launch 2010 | Formation flying (Jäggi et al., 2012) |
| F6 (DARPA) | cancelled 2013 | Fractionated free-flying spacecraft (\$> 200M spent) |
| CanX-4/5 (Canada) | launched 2014 | GPS formation flying 50m-2300m separations<br>Achieved positioning ±0.5m w/cold gas (Kahr et al., 2018) |
| MMS (NASA) | launched 2015 | GPS-assisted formation flying; 4.5km apart |
| MinXSS (Colorado) | launched 2016 | Precision pointing (Mason et al., 2017) |
| OCSD-A (AeroSpace) | launched 2015 | Laser communication & |
| & OCSD-B/C | launched 2017 | Proximity sensing/maneuvering (Welle et al., 2018) |
| FLOCK 2p (Planet Lab) | launched 2017 | Constellation phasing with drag (Foster et al., 2018) |
| RANGE (Georgia Tech) | launched 2018 | Laser ranging, controlling formation actively |
| PICSAT (Obs. Paris) | launched 2018 | Starlight injection into single mode-fiber; APD detector<br>(Nowak et al., 2018) |
| ASTERIA (MIT-JPL) | launched 2018 | Sub-arcsec pointing stability; $\Delta T \pm 0.01$K (Pong et al., 2010) |
| GRACE-FO (NASA) | launched 2018 | Laser ranging interferometry over 230km<br>with $<$10nm precision (Abich et al., 2019) |
| DeMi (MIT) | to launch 2019 | MEMS mirror testing (Allan et al., 2018) |
| TARGIT (Georgia Tech) | to launch 2020 | LIDAR, ranging measurement of two spacecraft |
| PROBA-3 (ESA) | to launch 2020 | Precision formation flying 150m apart<br>Goal ±5cm transverse positioning (Focardi et al., 2015) |
| FIRST-S (Obs. Paris) | TBD $>$2022 | Interferometer on single spacecraft (Lapeyrere et al., 2018) |
| VTXO (NASA-GSFC) | TBD $>$2023 | Formation flying (Rankin et al., 2018) |
| mDOT (Stanford) | TBD $>$2025 | Formation flying (Koenig et al., 2015) |
| SunRise (NASA-JPL) | TBD $>$2025 | GPS formation flying with 6 spacecraft;<br>radio interferometry near GEO (Lazio et al., 2018) |
| LISA (ESA/NASA) | TBD $>$2034 | Formation flying 2.5 million km apart<br>(Danzmann and LISA Science Team, 2003) |

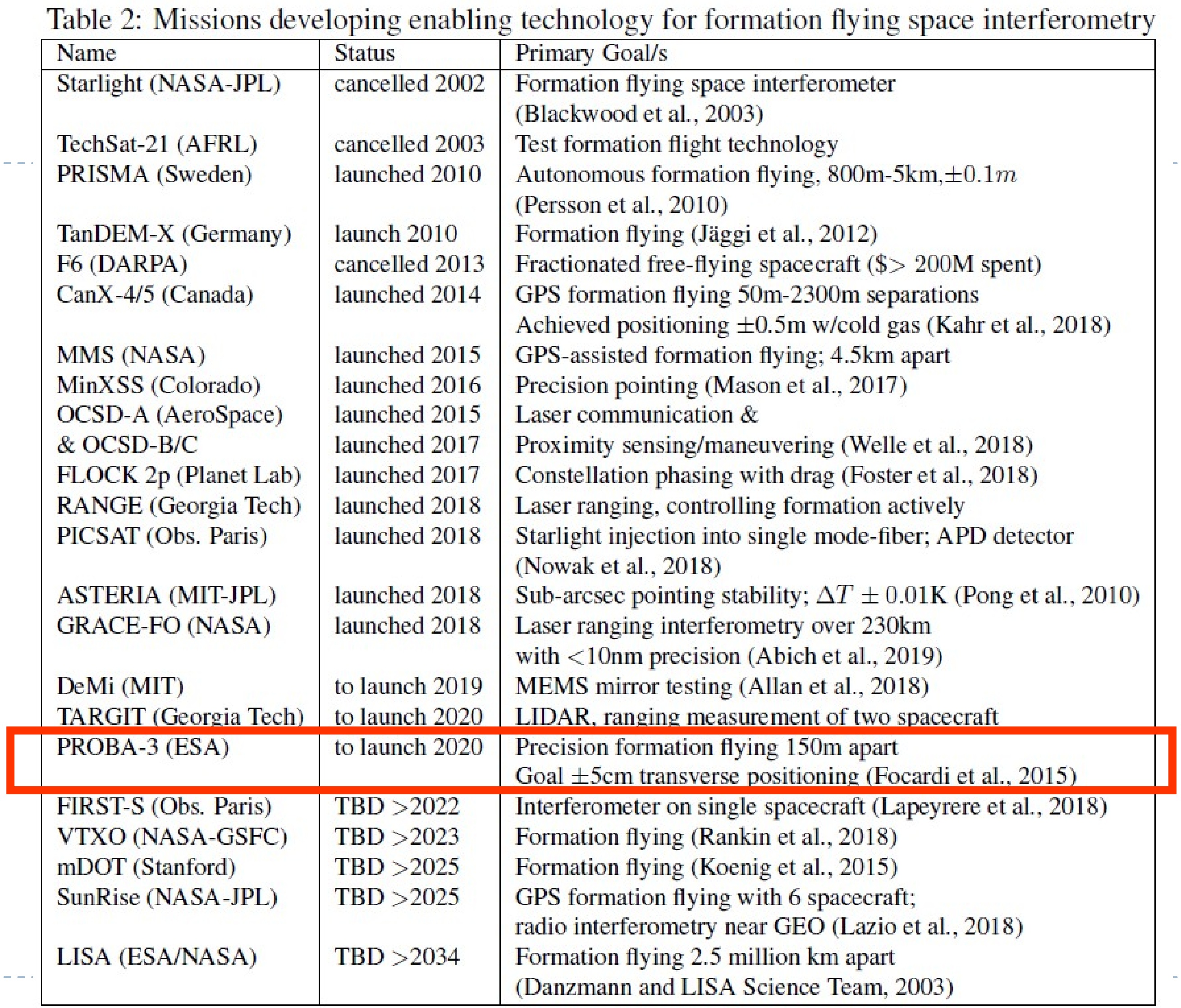


Table 2: Missions developing enabling technology for formation flying space interferometry

| Name | Status | Primary Goal/s |
|---|---|---|
| Starlight (NASA-JPL) | cancelled 2002 | Formation flying space interferometer<br>(Blackwood et al., 2003) |
| TechSat-21 (AFRL) | cancelled 2003 | Test formation flight technology |
| PRISMA (Sweden) | launched 2010 | Autonomous formation flying, 800m-5km,±0.1$m$<br>(Persson et al., 2010) |
| TanDEM-X (Germany) | launch 2010 | Formation flying (Jäggi et al., 2012) |
| F6 (DARPA) | cancelled 2013 | Fractionated free-flying spacecraft ($> 200M spent) |
| CanX-4/5 (Canada) | launched 2014 | GPS formation flying 50m-2300m separations<br>Achieved positioning ±0.5m w/cold gas (Kahr et al., 2018) |
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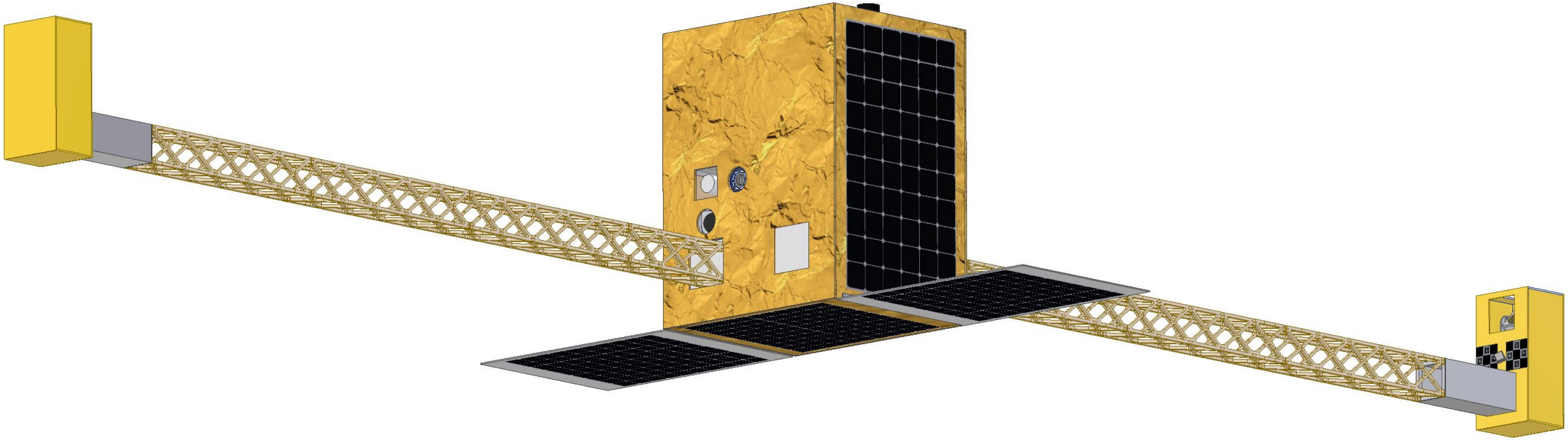
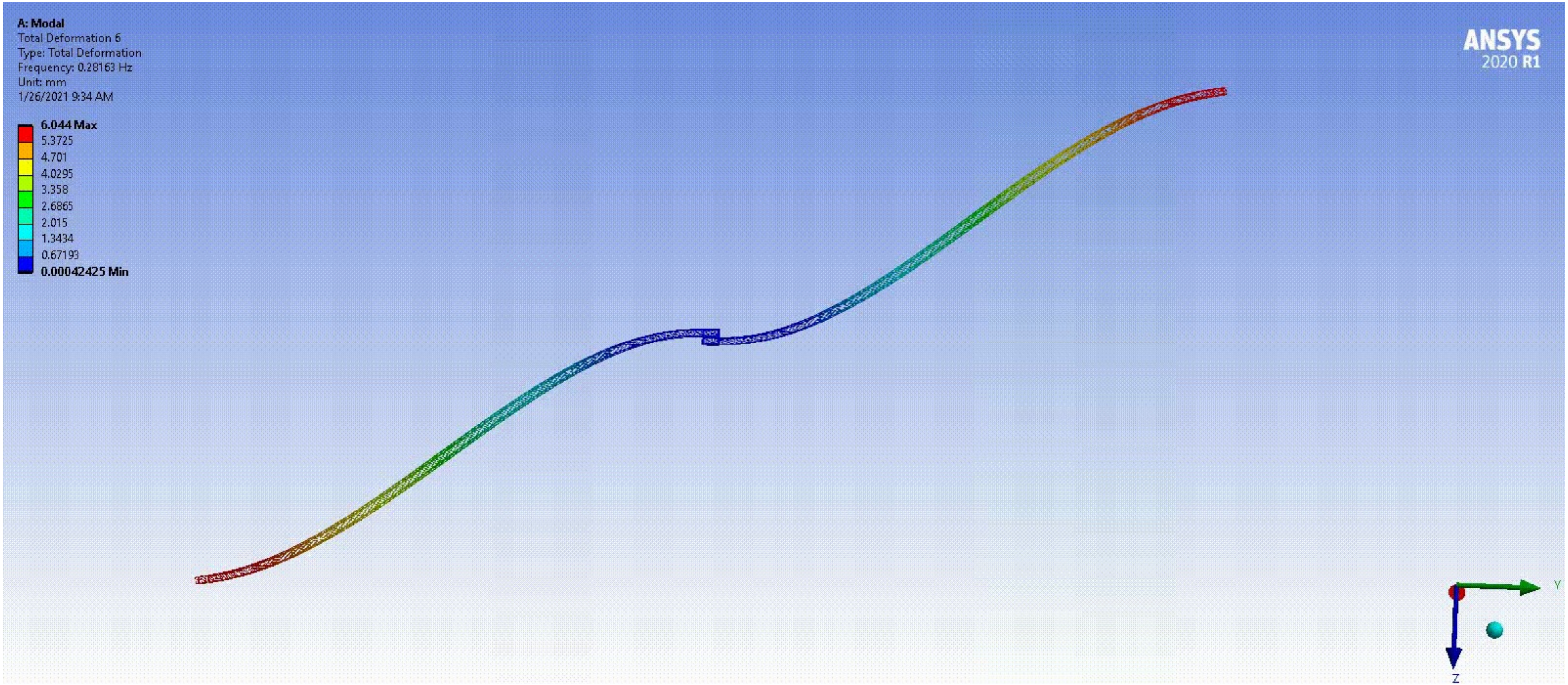
Actual launch: 2024
$200M

# Flying an Interferometer in Space

## *Lowell – Redwire Optimast NASA SBIR study*





**A: Modal**
Total Deformation 6
Type: Total Deformation
Frequency: 0.28163 Hz
Unit: mm
1/26/2021 9:34 AM

# Optical Arrays on the Moon?

- Lunar surface access is rapidly becoming more tenable
- Very small apertures can surpass very large apertures on the ground

# Long Coherence Times

- No atmosphere
  - No atmospheric coherence time limit
  - Need to be mindful of instrumental coherence time
- A 2" aperture has greater sensitivity than an 8m VLTI aperture after first second of integration; 300+ sec possible
- Free vacuum → clean beam propagation, no vacuum machinery

# Lester (2006)

“The only thing the moon has to offer astronomy is

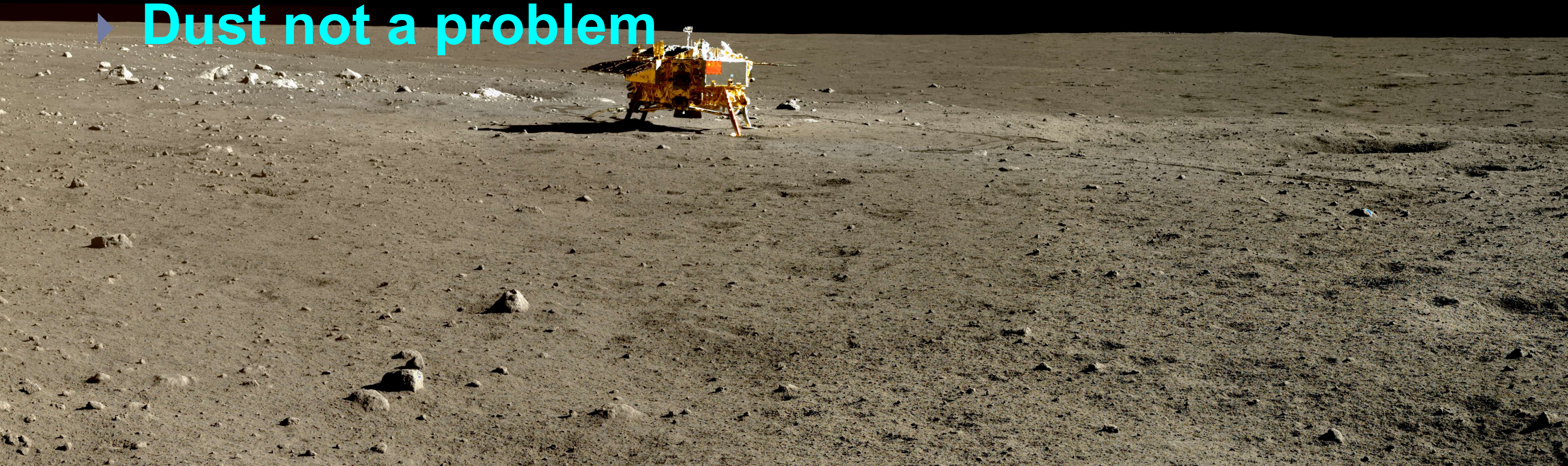
**dust**

and **gravity**”

(slightly paraphrased)

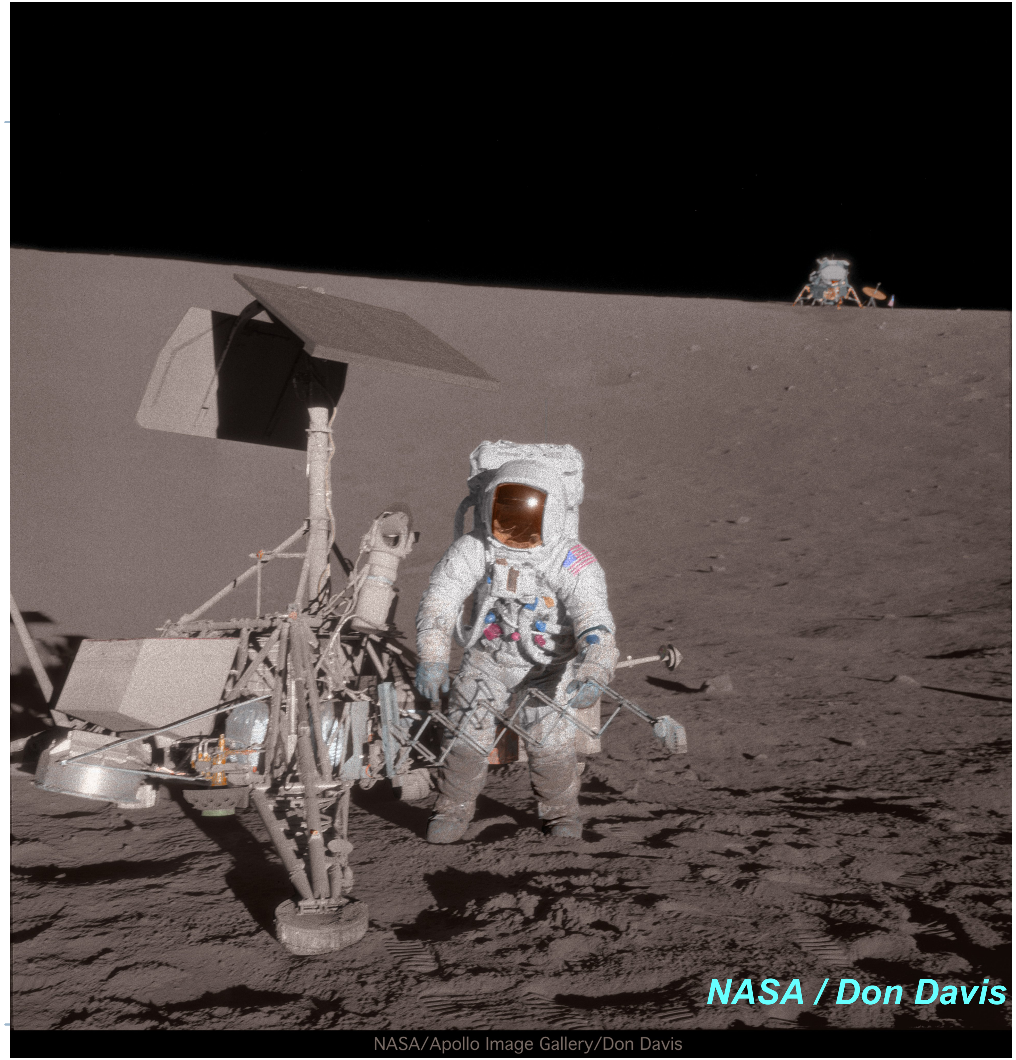
# Dust: LUT on board Chang'e-3 Lander

- UV telescope with **years** of operations (2015 - 2018+)
  - For sunrise & sunset, a shutter aperture was closed
- **Dust not a problem**



# Gravity

- It's not a bug, it's a **feature**
    - Eg. Surveyor 3, Apollo 12: 180m baseline, stable relative position for the past 50 years
    - Nearly perfect for large optical interferometers
    - Formation flying is unsolved, expensive
- Gravity makes stationkeeping **trivial**
- Lunar surface provides stable platform



*NASA / Don Davis*

NASA/Apollo Image Gallery/Don Davis

Keck
INSTITUTE FOR SPACE STUDIES

# Astronomical Optical Interferometry from the Lunar Surface

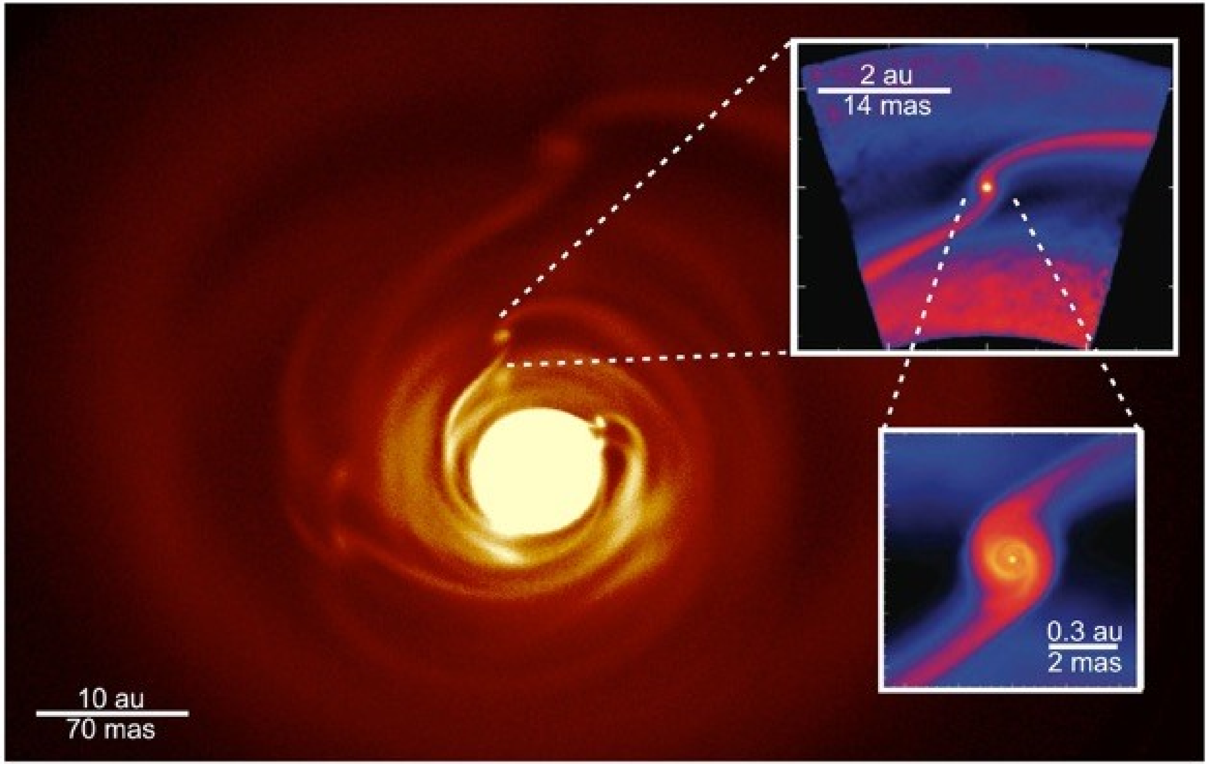
November 18 - 22, 2024

# Back to Earth & Conclusions

*Paul Signac, "Port St. Tropez", 1899*

# Planet Formation Imager

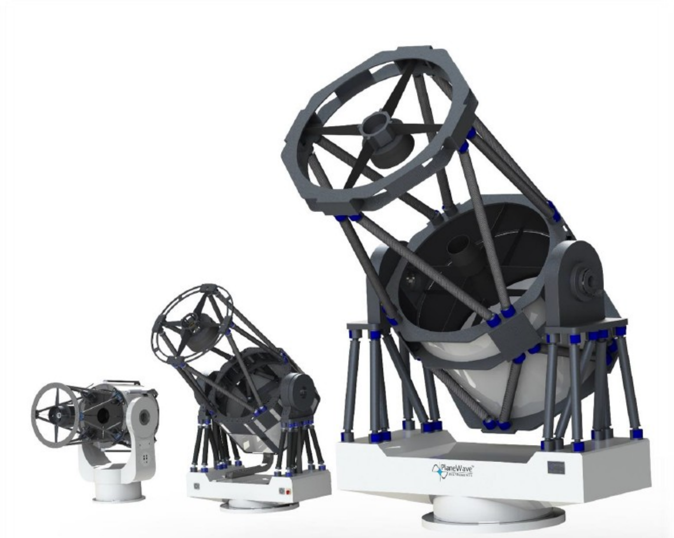
- 12×3m terrestrial telescopes
- Baselines to 1.5km
- 3.5-13μm: 0.08-0.25au at 140pc
- Hill spheres in PPDs



# Optical Telescopes: Commodity Items

- Telescopes 0.5 m and up *used* to be bespoke items, now COTS
- Typical prices:
  - 0.5m: $65k
  - 0.7m: $235k
  - 1.0m: $600k
  - 2.0m: ~$2.5M?
- See van Belle, Meinel & Meinel (2004) for cost ~ $D^{2.5}$ scaling

PW2000
Size Comparison to PW1000 & CDK700

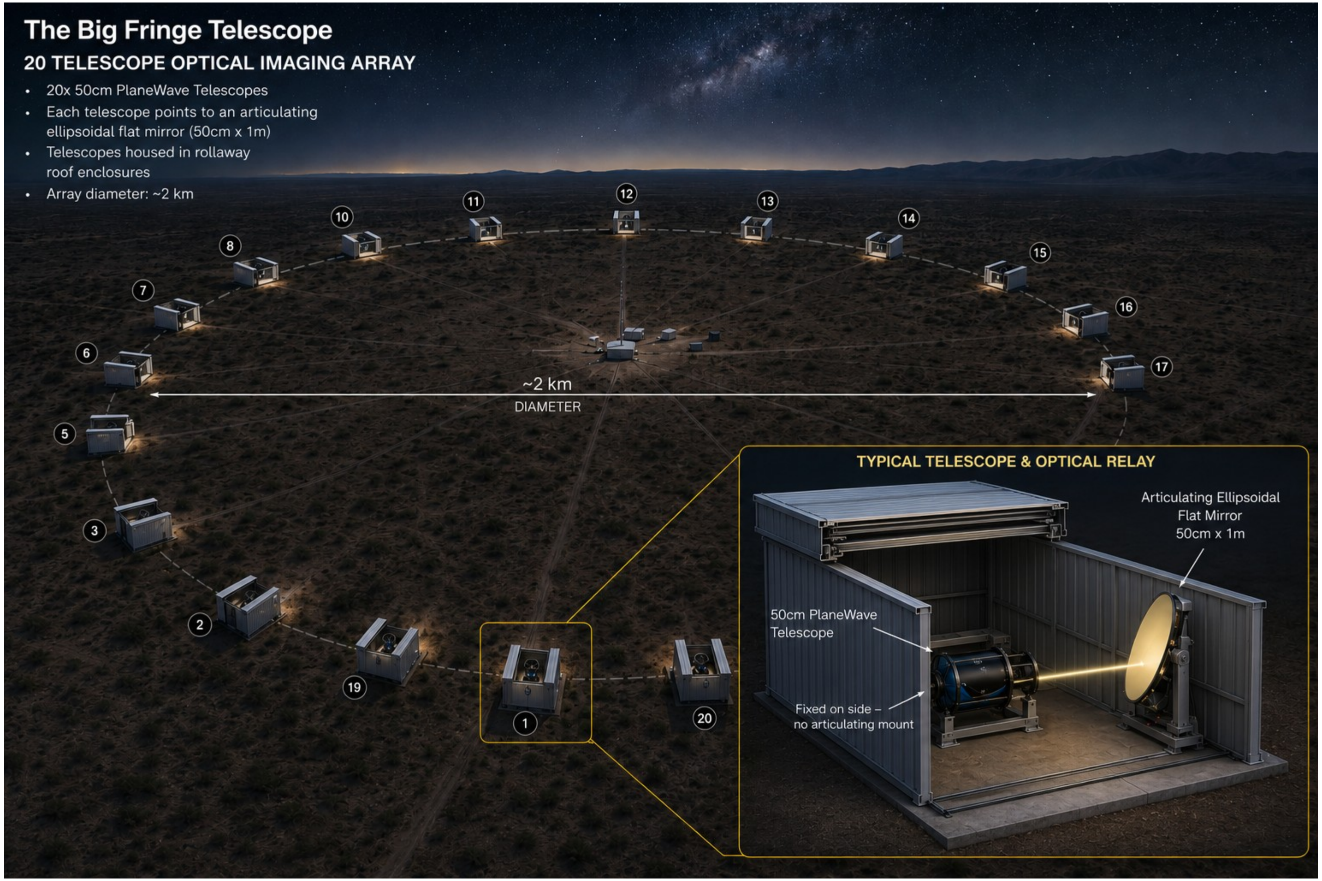


# COTS and NPOI Upgrade

- Off-the-shelf 1.0m's are now available at the array

# BFT (Big Fringe Telescope)

- COTS parts
- Fiber beam relay
- Next-gen delay lines
- Stellar 'snapshot' surface imaging
  - Butterfly diagrams of spots
  - Exoplanet transit movies



**The Big Fringe Telescope**

**20 TELESCOPE OPTICAL IMAGING ARRAY**

- 20x 50cm PlaneWave Telescopes
- Each telescope points to an articulating ellipsoidal flat mirror (50cm x 1m)
- Telescopes housed in rollaway roof enclosures
- Array diameter: ~2 km

# Decadal 2030 & Optical Interferometry

- Coming up sooner than you think!
- Ground-based
  - enhancements of CHARA, MROI
  - new possibilities: PFI, BFT
- Space-based
  - Formation flying vs. Lunar-based
  - Imaging, nulling, 0.1uas exoplanet astrometry