The revival of Intensity Interferometry

Towards microarcsecond resolution

Etienne Lyard - Ecogia Science meeting - 18/11/2024

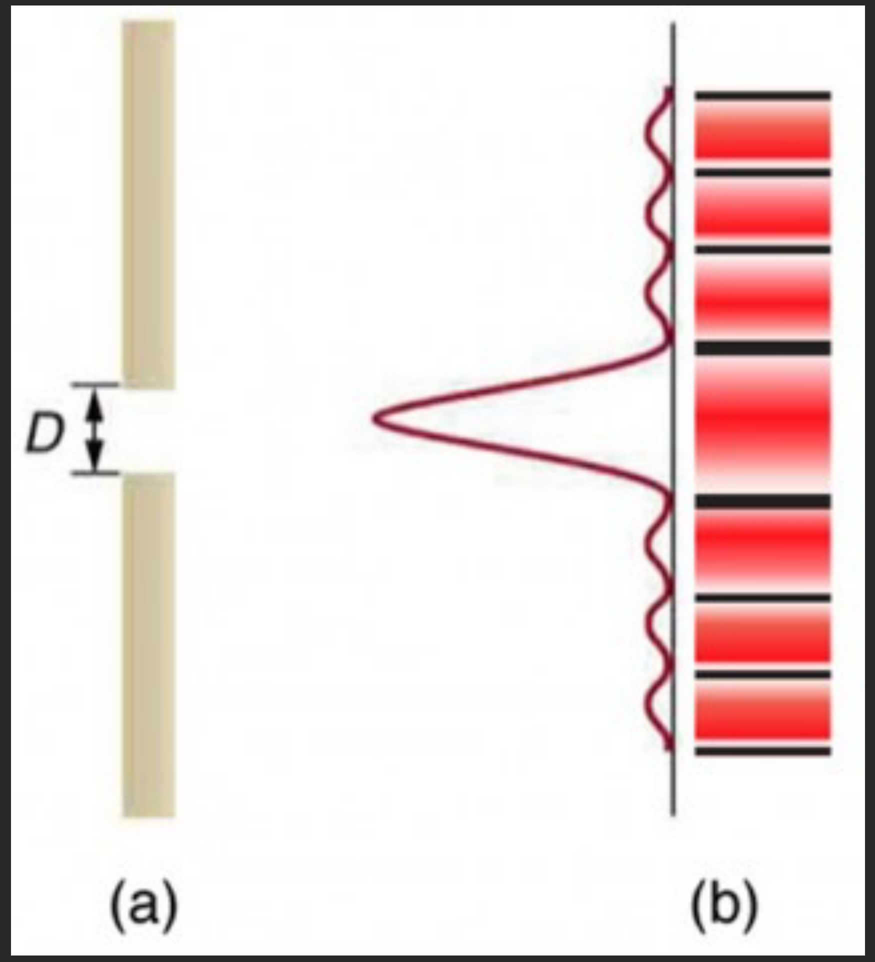
Content

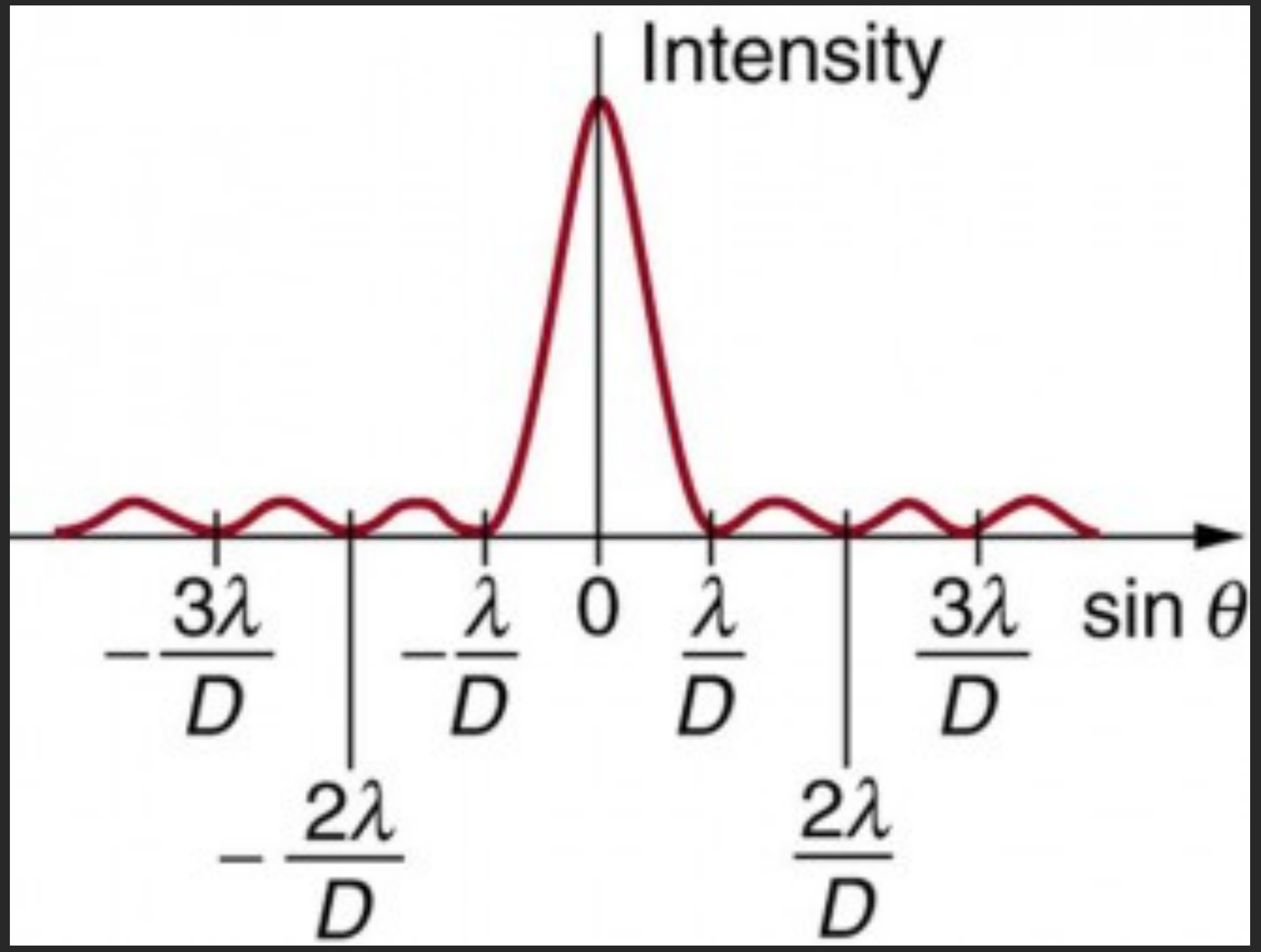
- Phase Interferometry
- Intensity Interferometry
- Quantum Interferometry
- Scientific Outlook

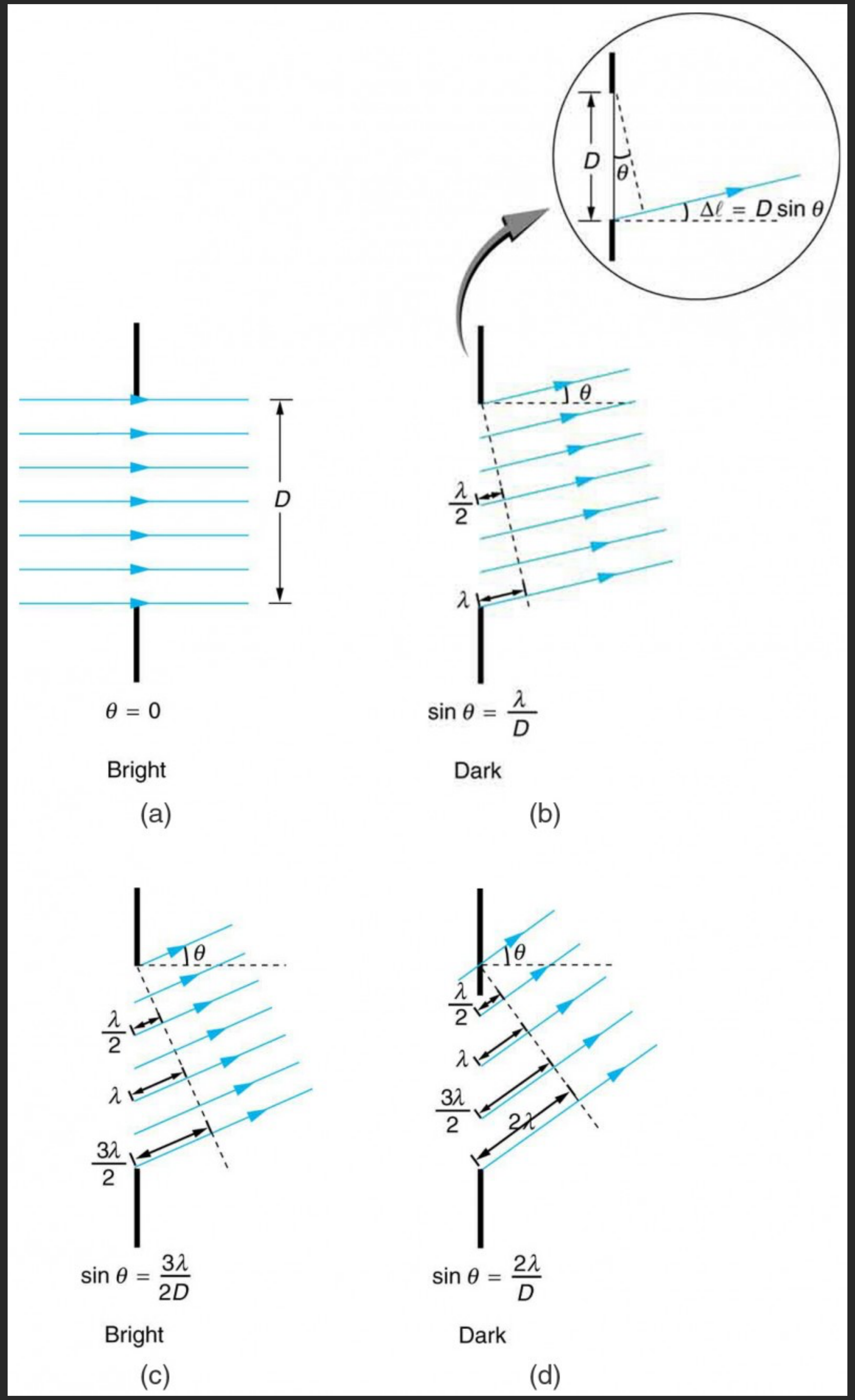
Phase Interferometry

General principle

- Single Slit Diffraction







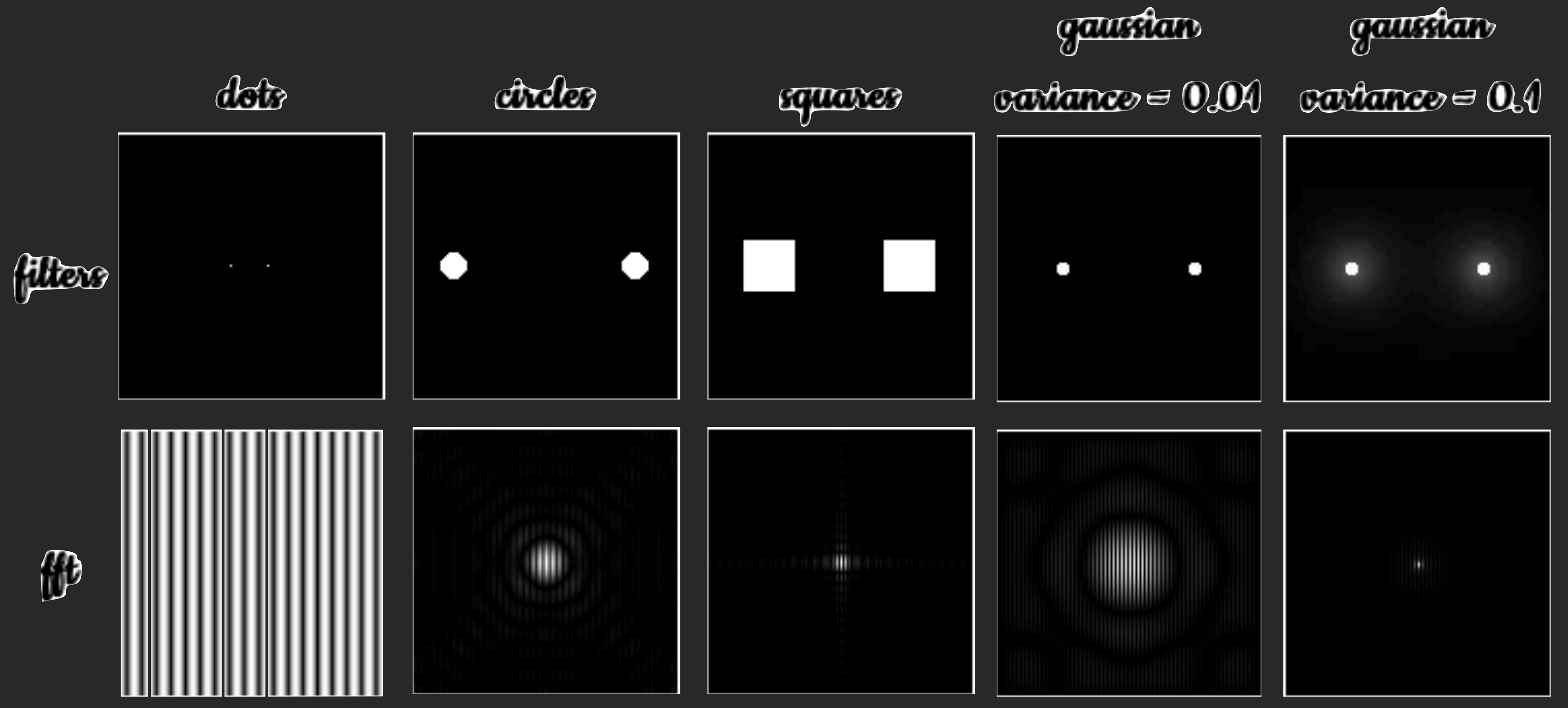
- Pattern only depends on λ and D
- Classical mechanics

https://courses.lumenlearning.com/suny-physics/chapter/27-5-single-slit-diffraction/

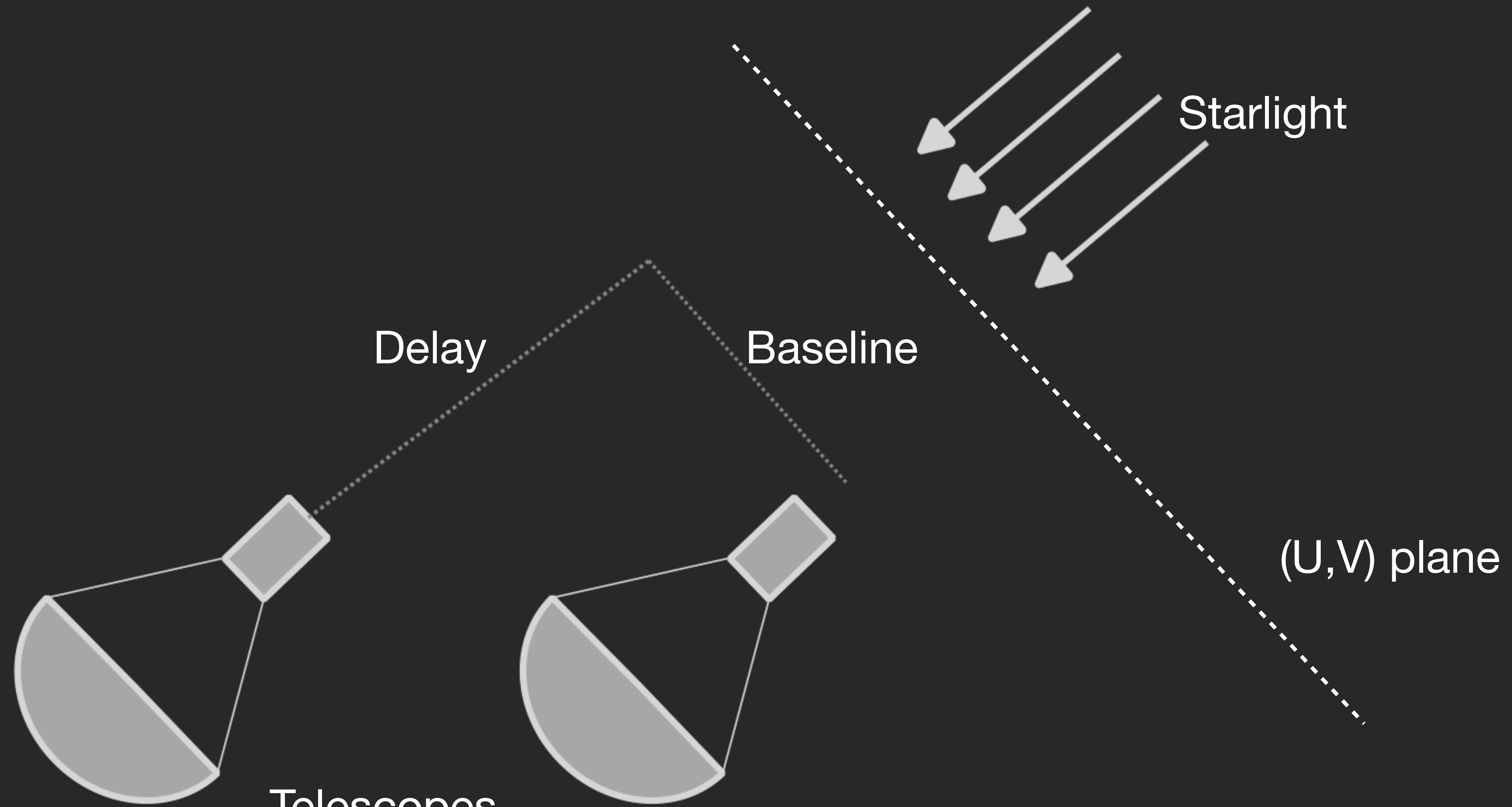
Phase Interferometry

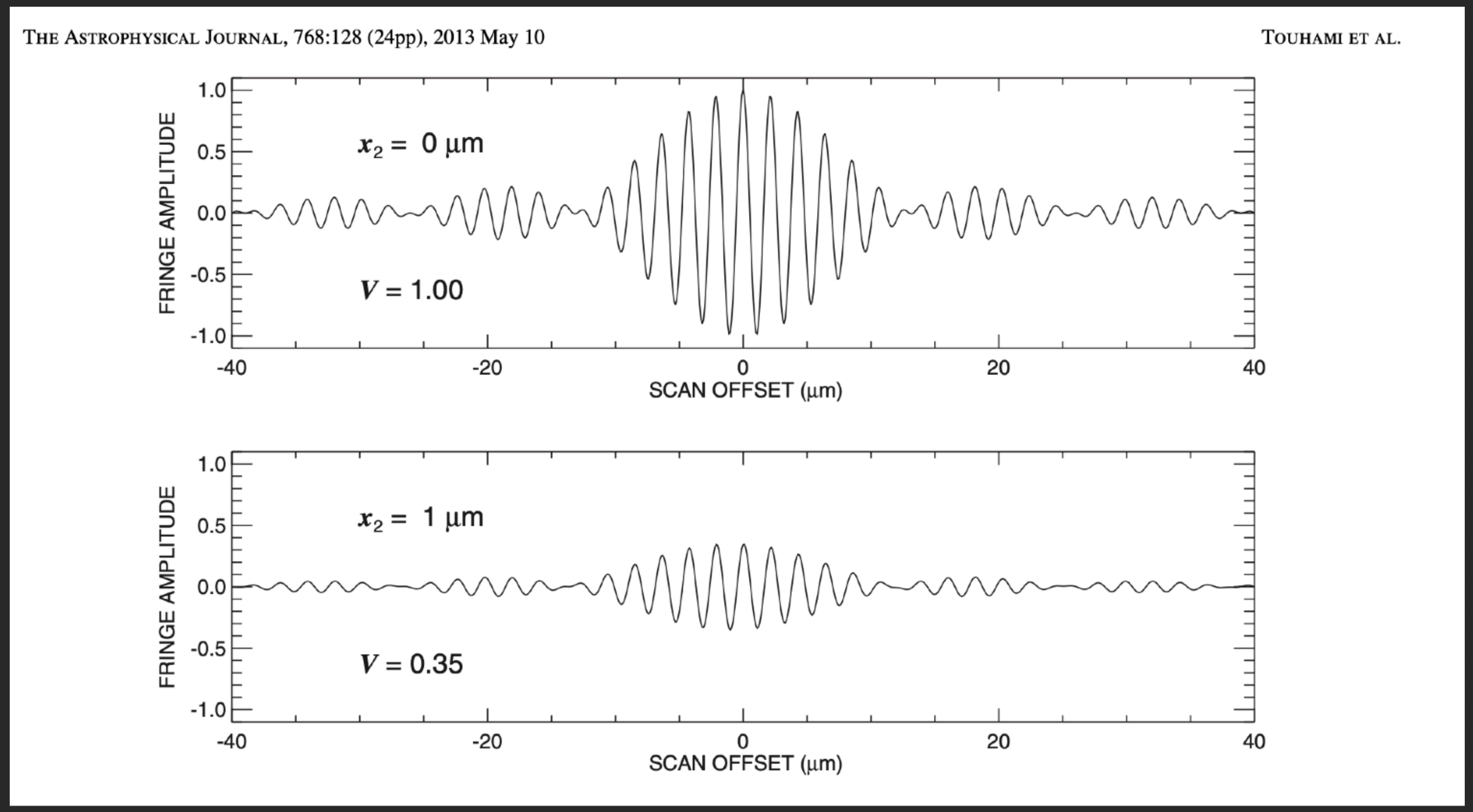
Van-Cittert-Zernik theorem

- The Fourier transform of the intensity distribution function of a distant, incoherent source is equal to its complex visibility
  - Distant sources appear to us as a collection of slits
- Putting several telescopes away from each other allow to probe the Visibility plane
  - Obtained Amplitude and phase is a measure of the Visibility plane at a given (U,V) separation of the telescopes



albertyumol.github.io

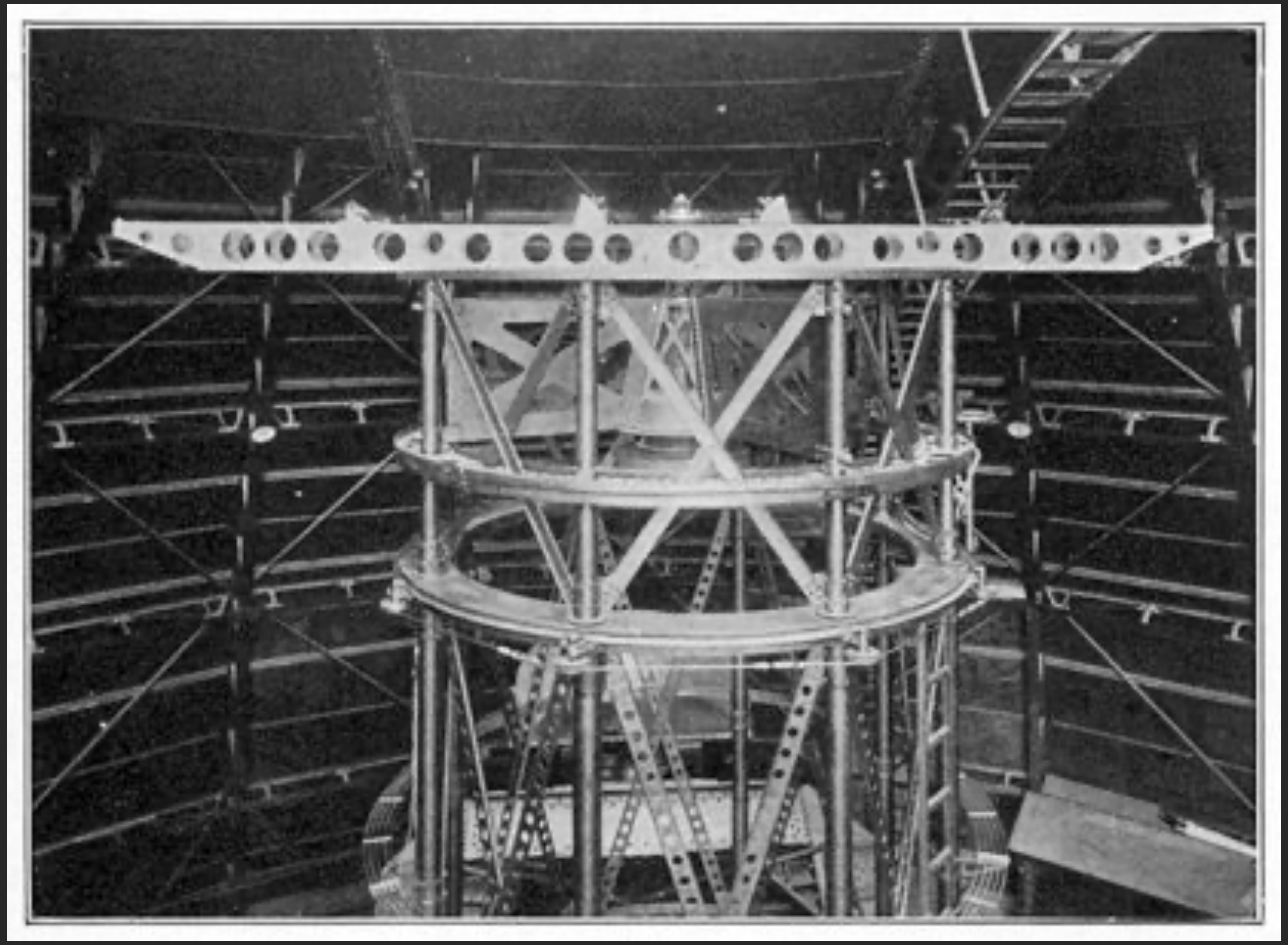


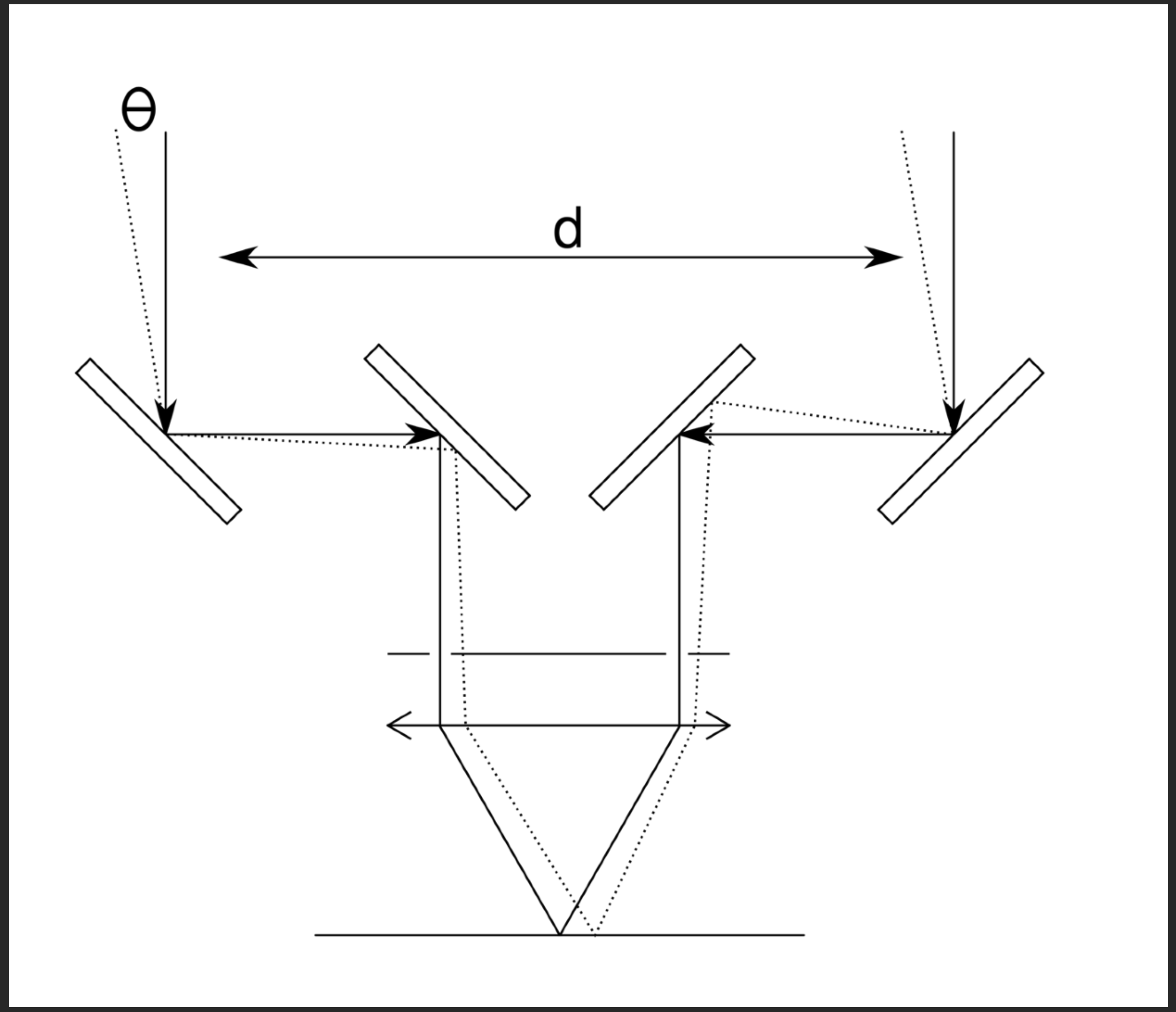


Phase Interferometry

Michelson Interferometer

- First realisation of the concept by Michelson himself and Pease in 1920
    - Measured Betelgeuse diameter at 47 marcs

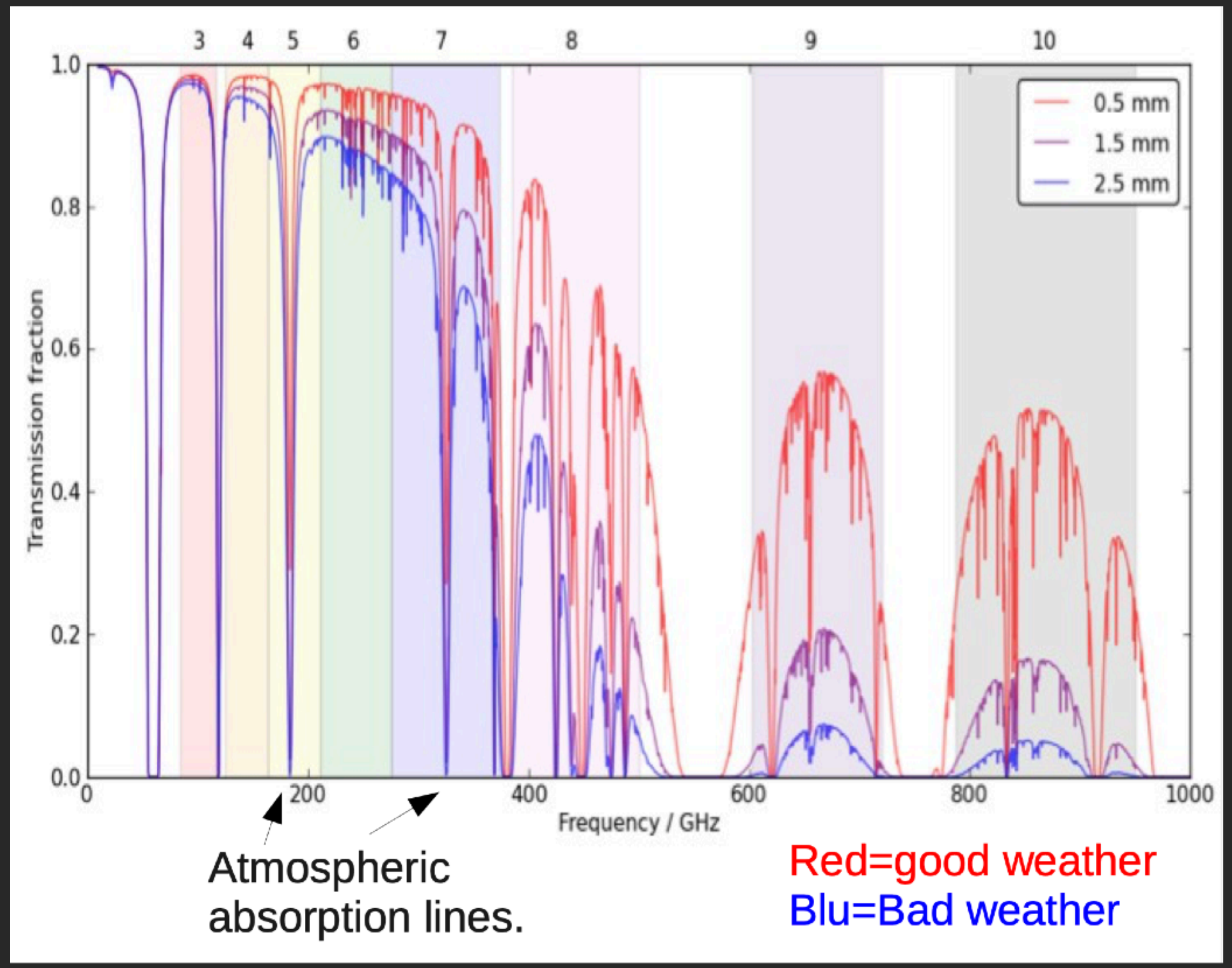




Phase Interferometry

Modern interferometers - Radio

- Sensitive to radio interference and atmosphere absorption
  - Remote locations
  - High-altitude



ALMA Bands and atmospheric absorption
E. Liuzzo 2018

MeerKAT / SKA Phase 1

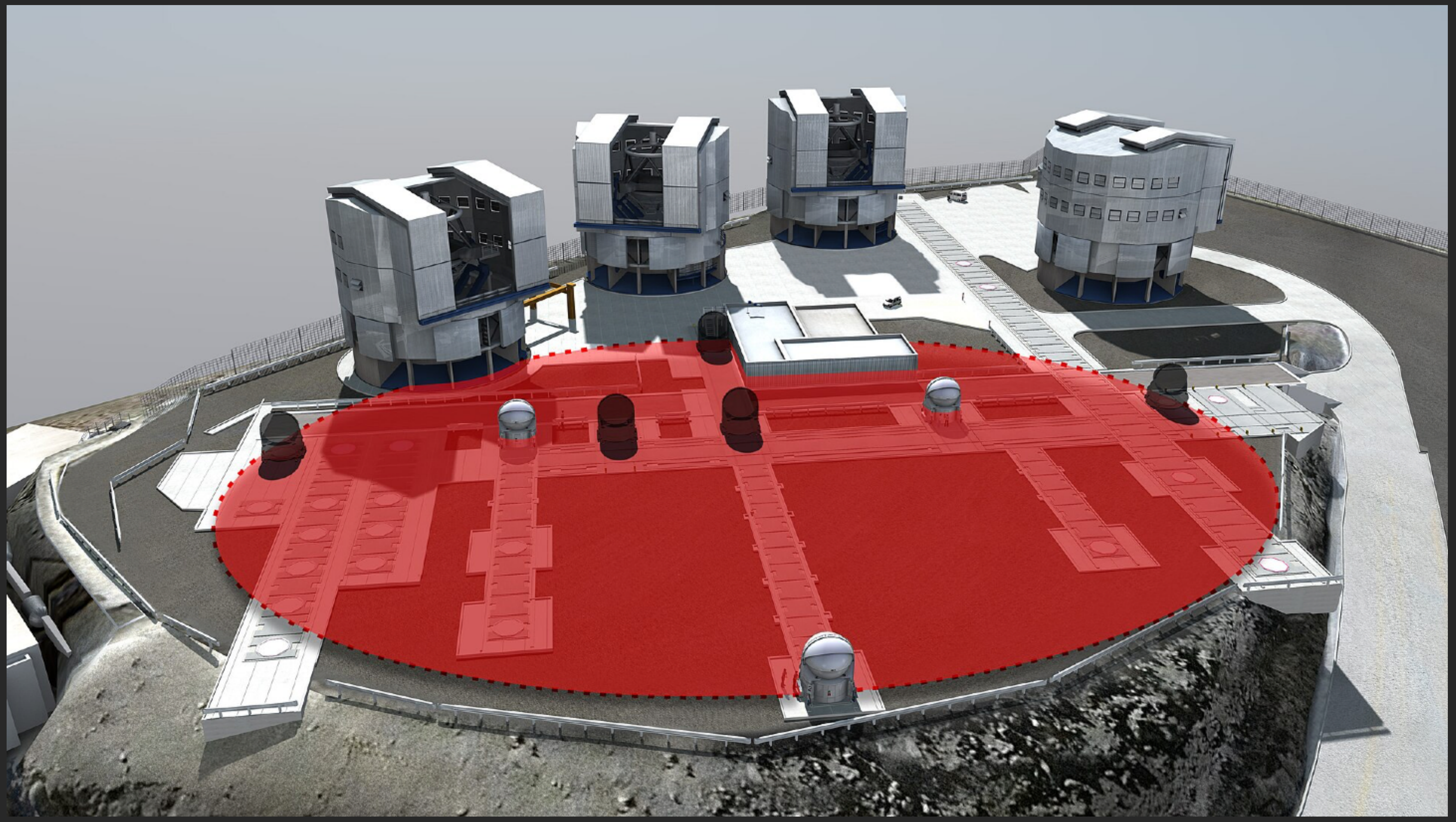
ALMA

VLA

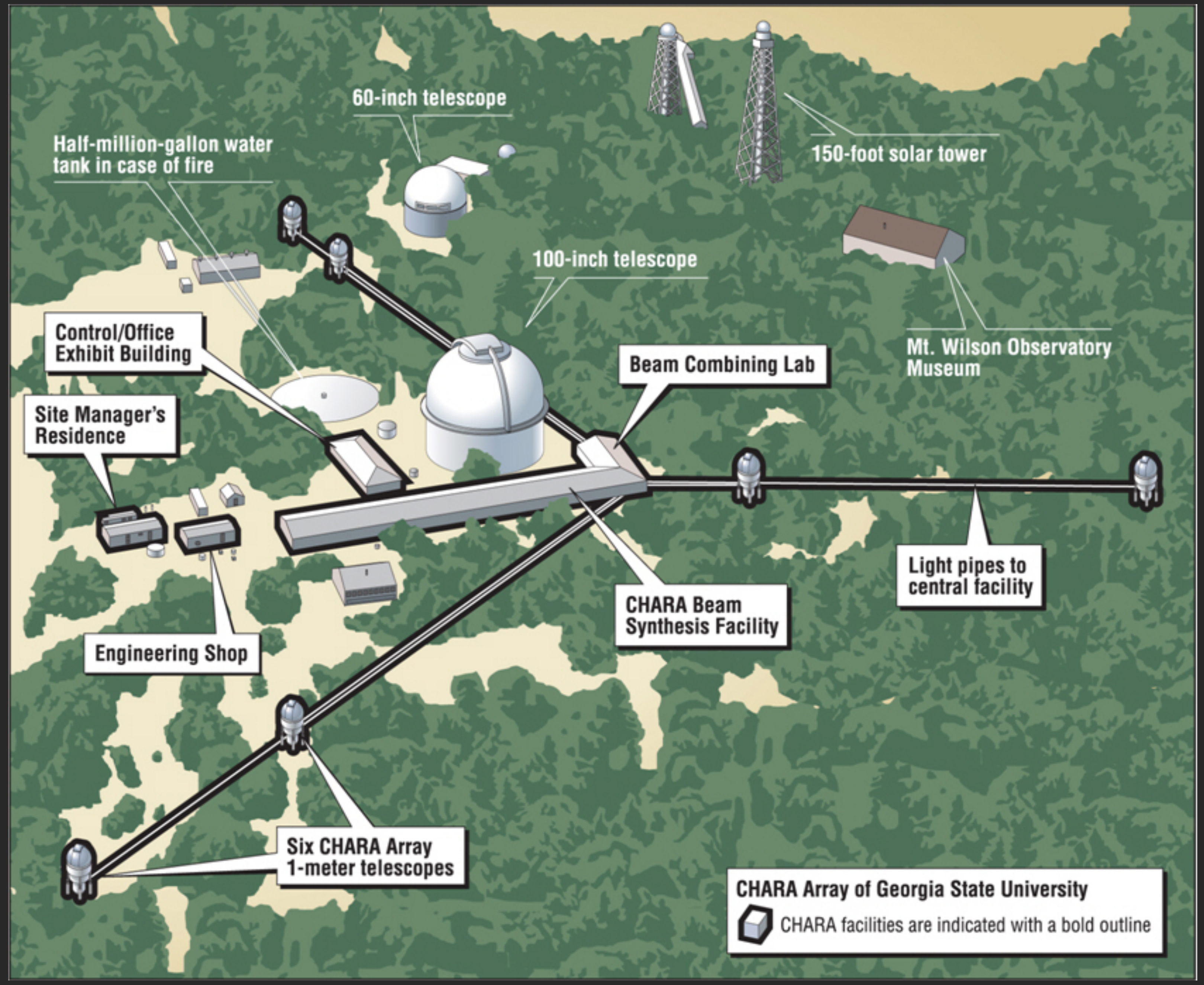
Phase Interferometry

Modern interferometers - Optical

- Optical interferometers difficult to build and operate because delays must be handled better than the wavelength of the light
    - Delay lines are modern marvels
    - Cost-limited to some hundreds of meters



VLTI and movable support telescopes

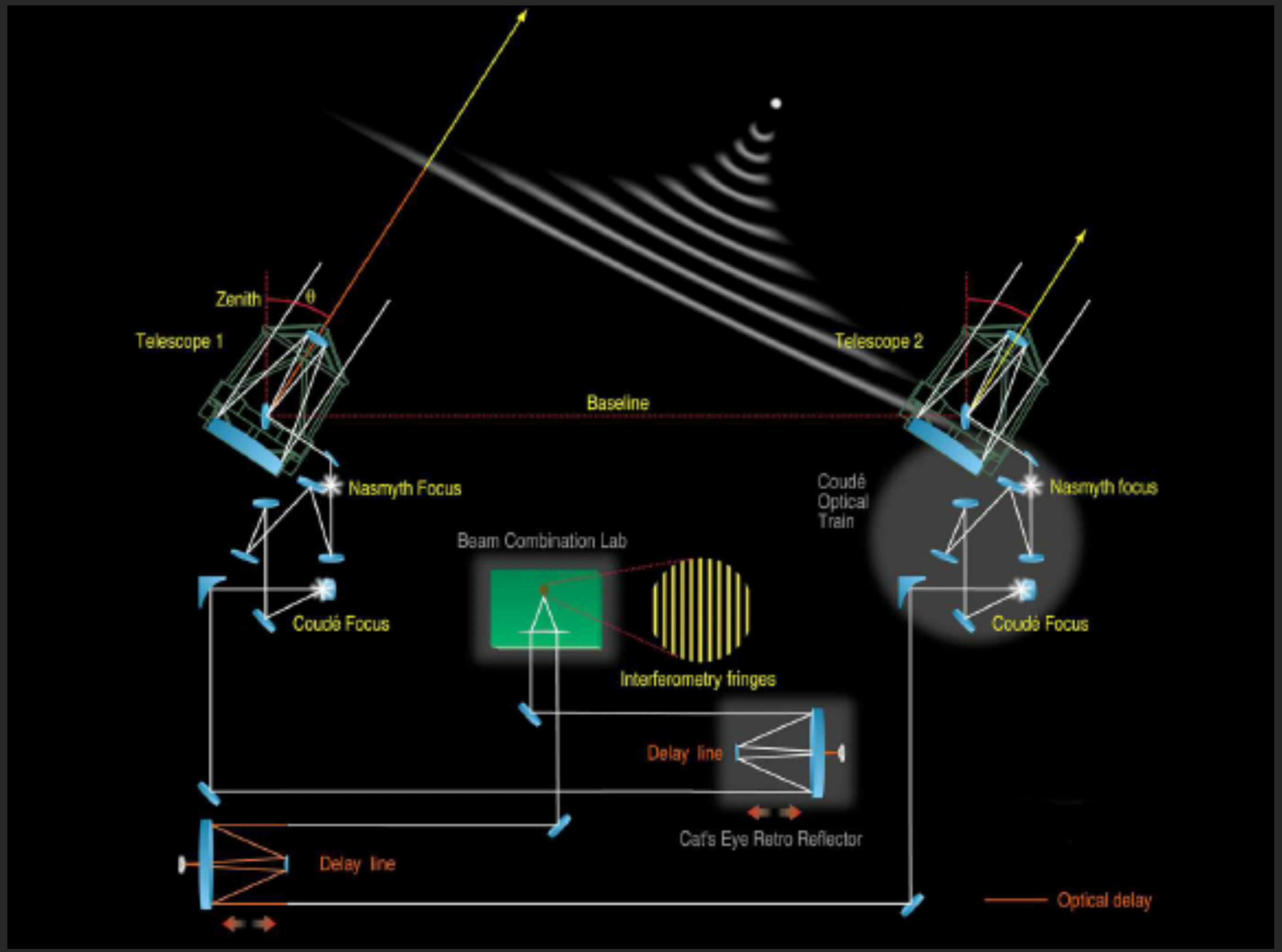


CHARA

Phase Interferometry

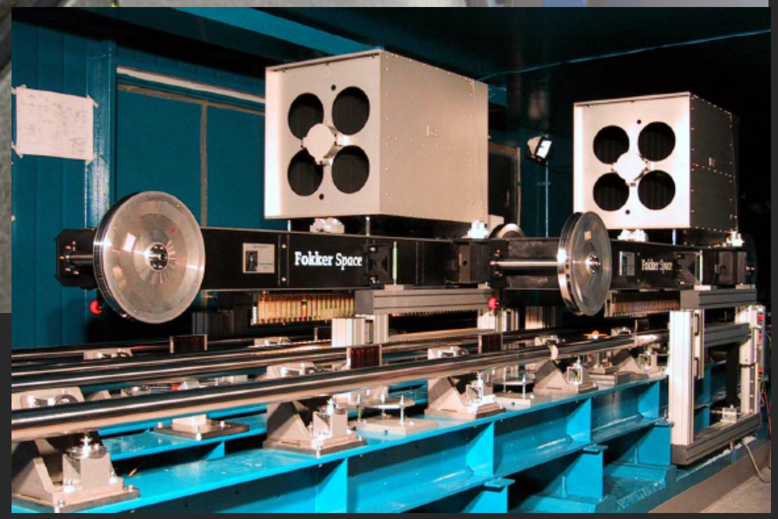
Challenging infrastructure

- $g^{(1)}$ is the correlation of the light's waveform itself
  - Only works for long-enough wavelength
  - Sampling + digital correlation in radio
  - Actual light correlation in optical



The VLTI and its subsystems A. Glindemann et al. 2003

1/4 of the ALMA Correlator (3000 FPGAs in 32 racks)



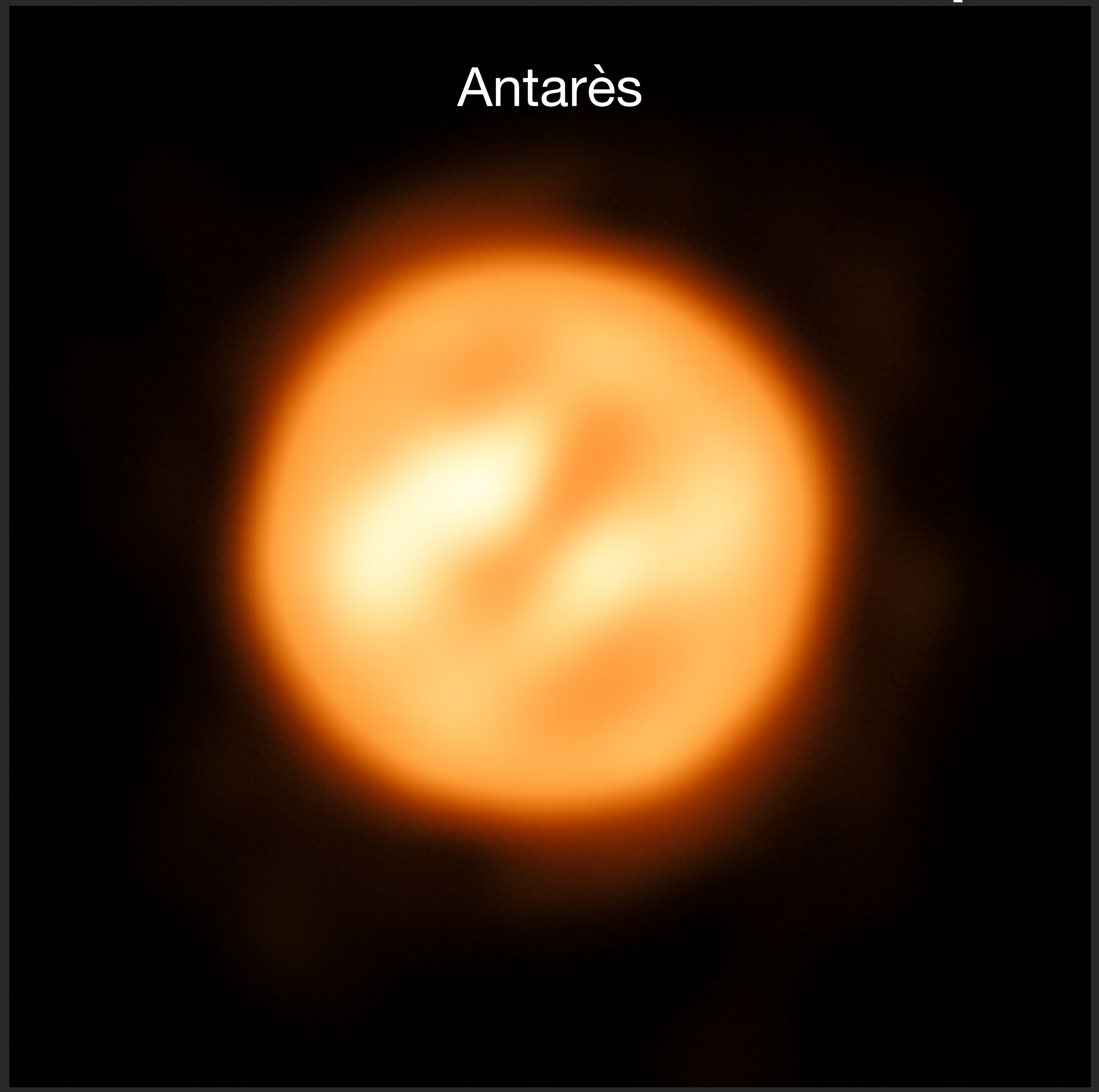
The VLTI delay lines - ESO

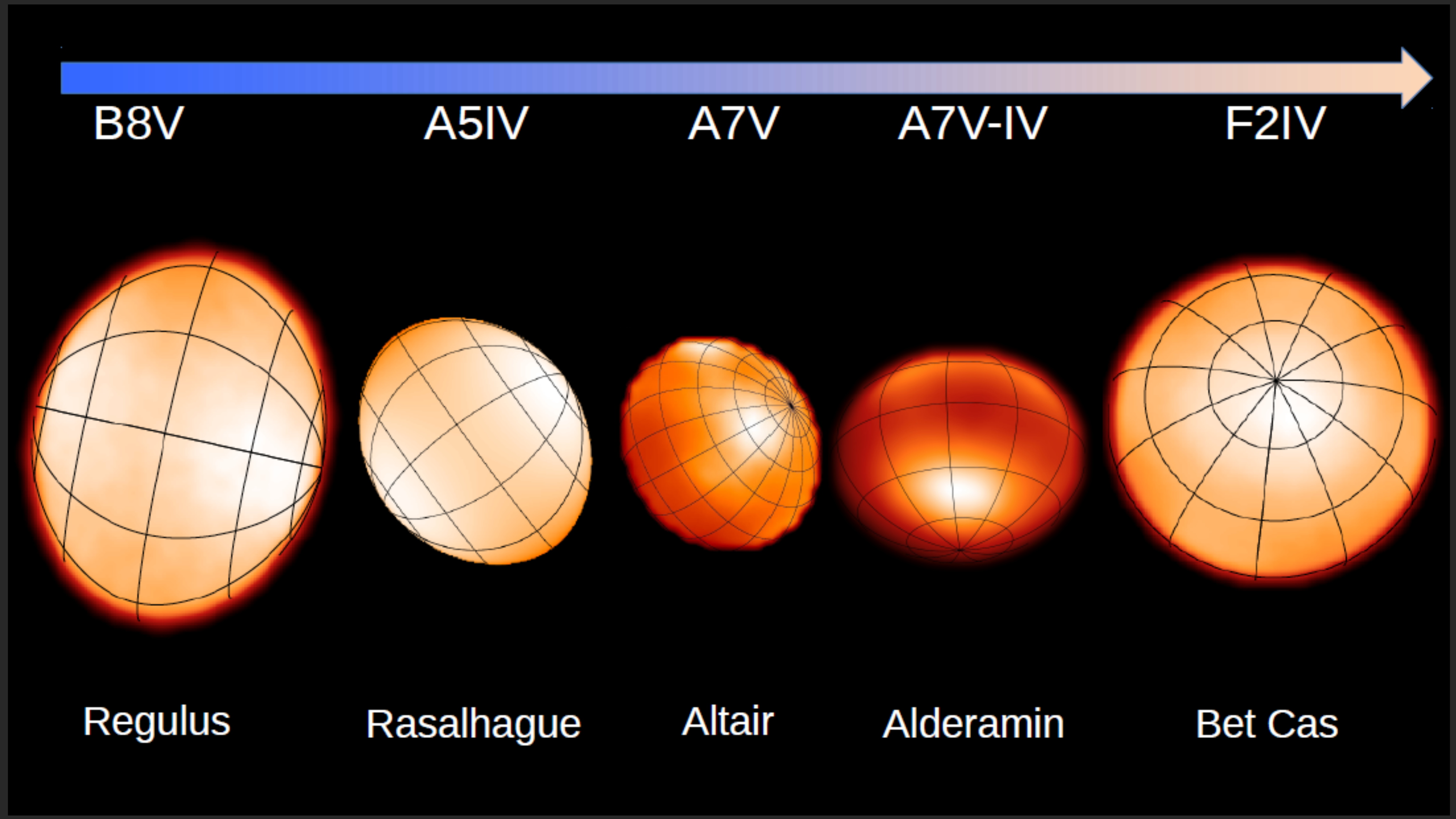
Phase Interferometry

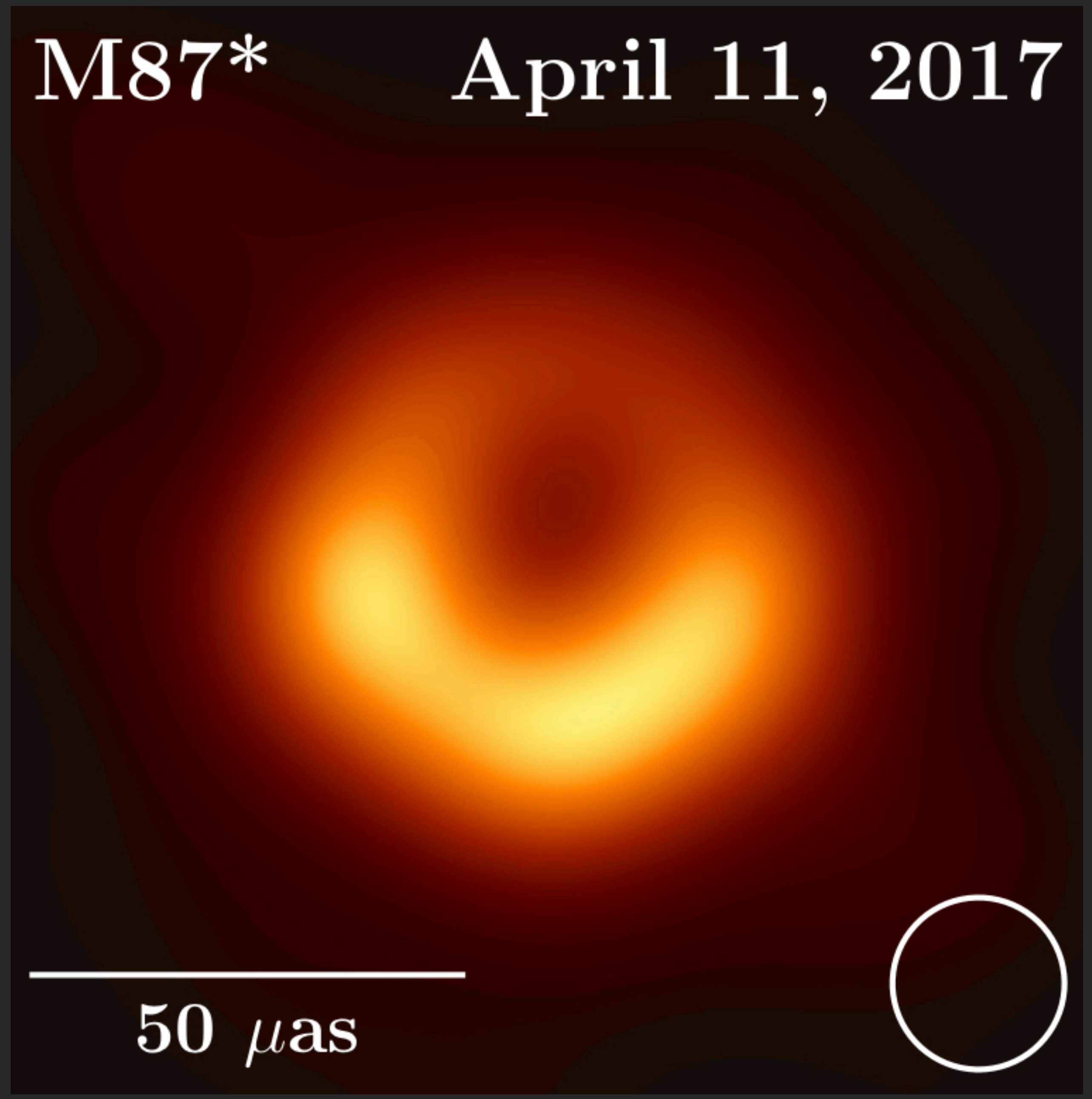
Unparalleled resolution: 30 to 5000x better than JWST !!

800x smaller

40mas







VLTI
res. 3.5 mas

Chara
res. 0.2 mas

EHT
res. 0.019 mas

Phase Interferometry

Angular resolution

6’830’000 mas

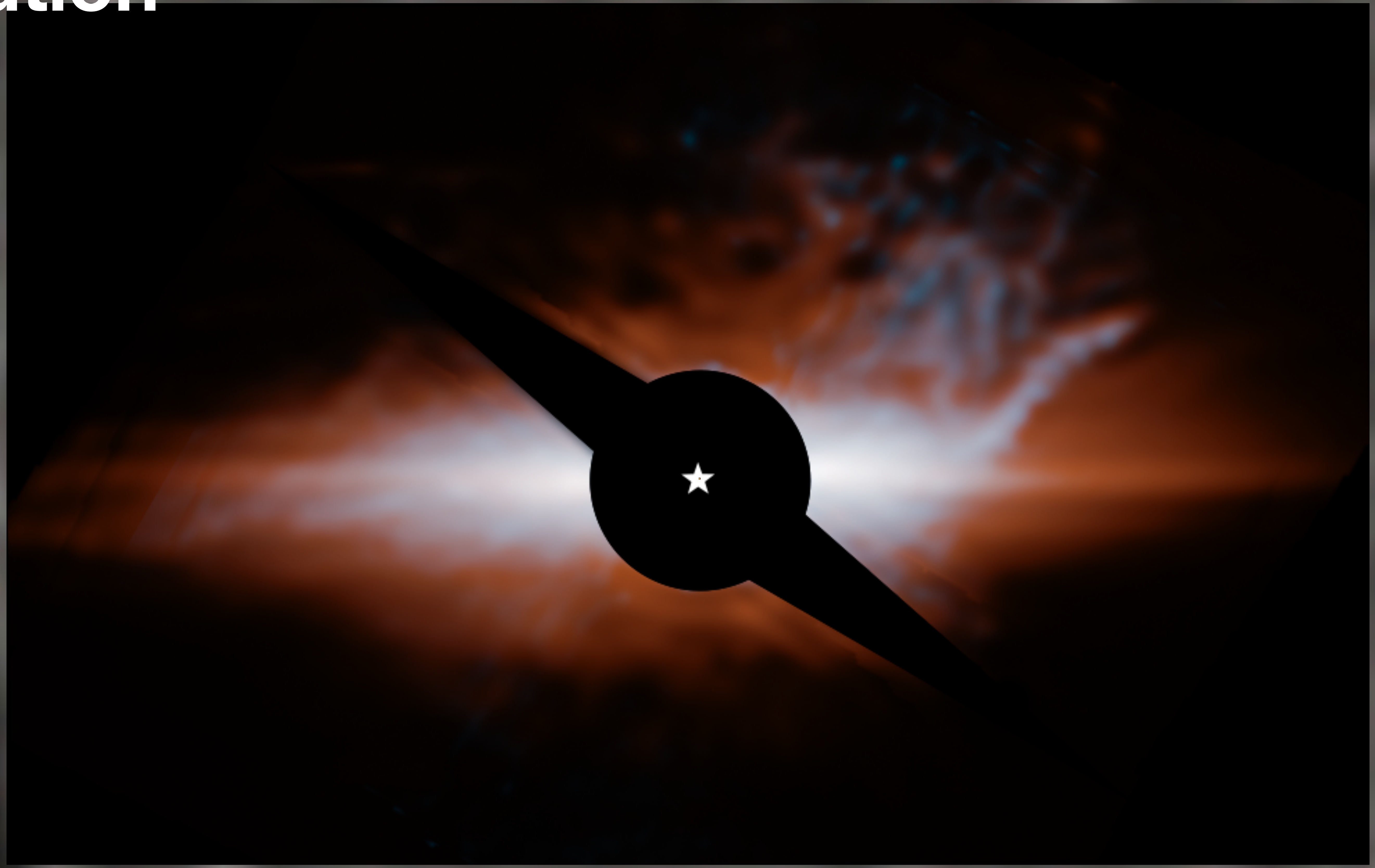
Phase Interferometry

Angular resolution

Phase Interferometry

Angular resolution

Beta Pictoris
JWST - MIRI
2024



68’300 mas

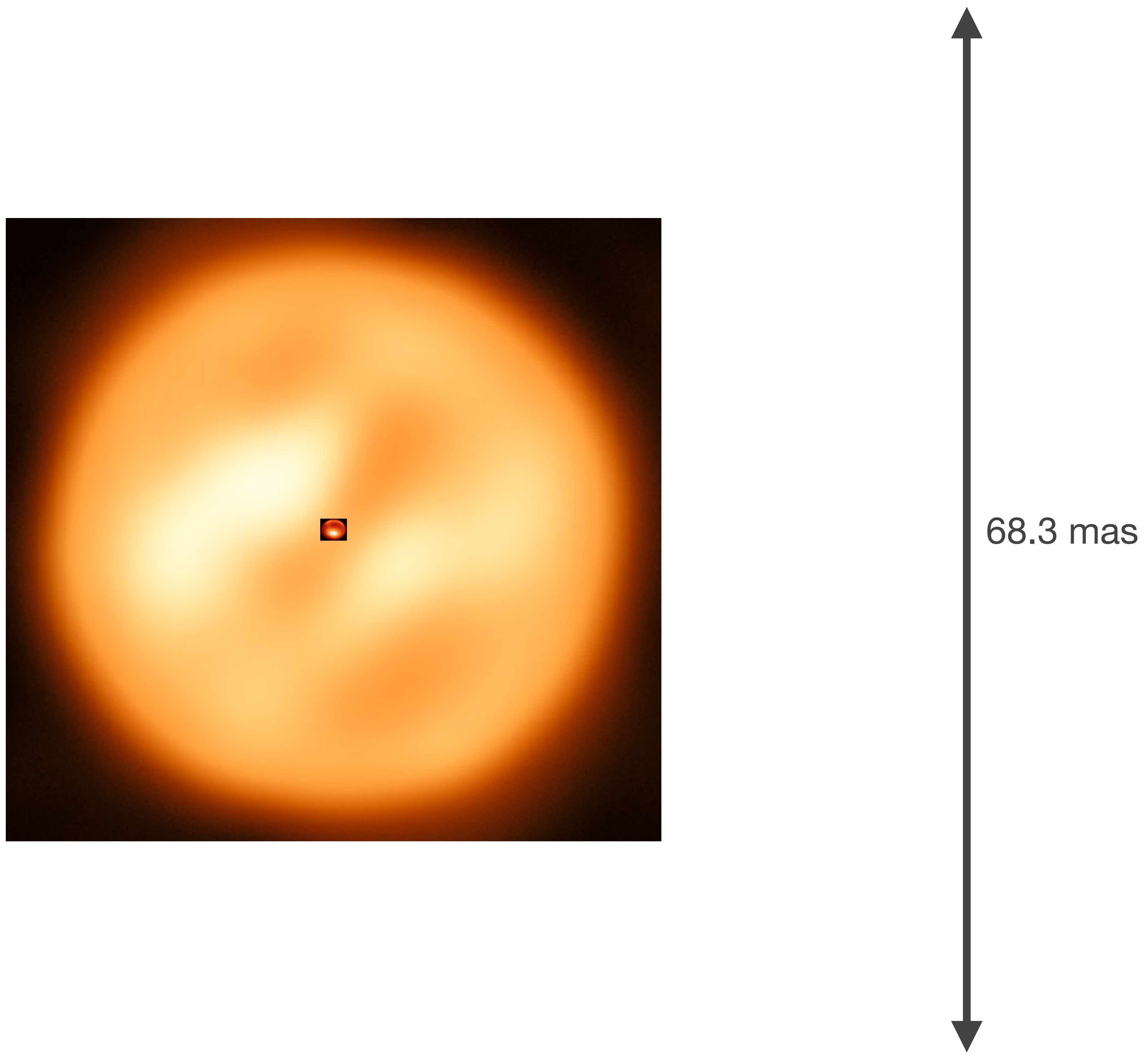
Phase Interferometry

Angular resolution

Phase Interferome

Angular resolution

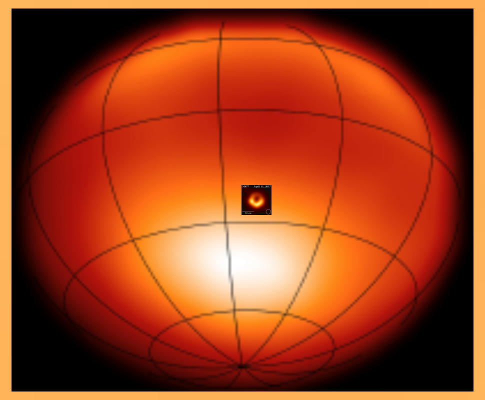
Antarès



Phase Interferometry

Angular resolution

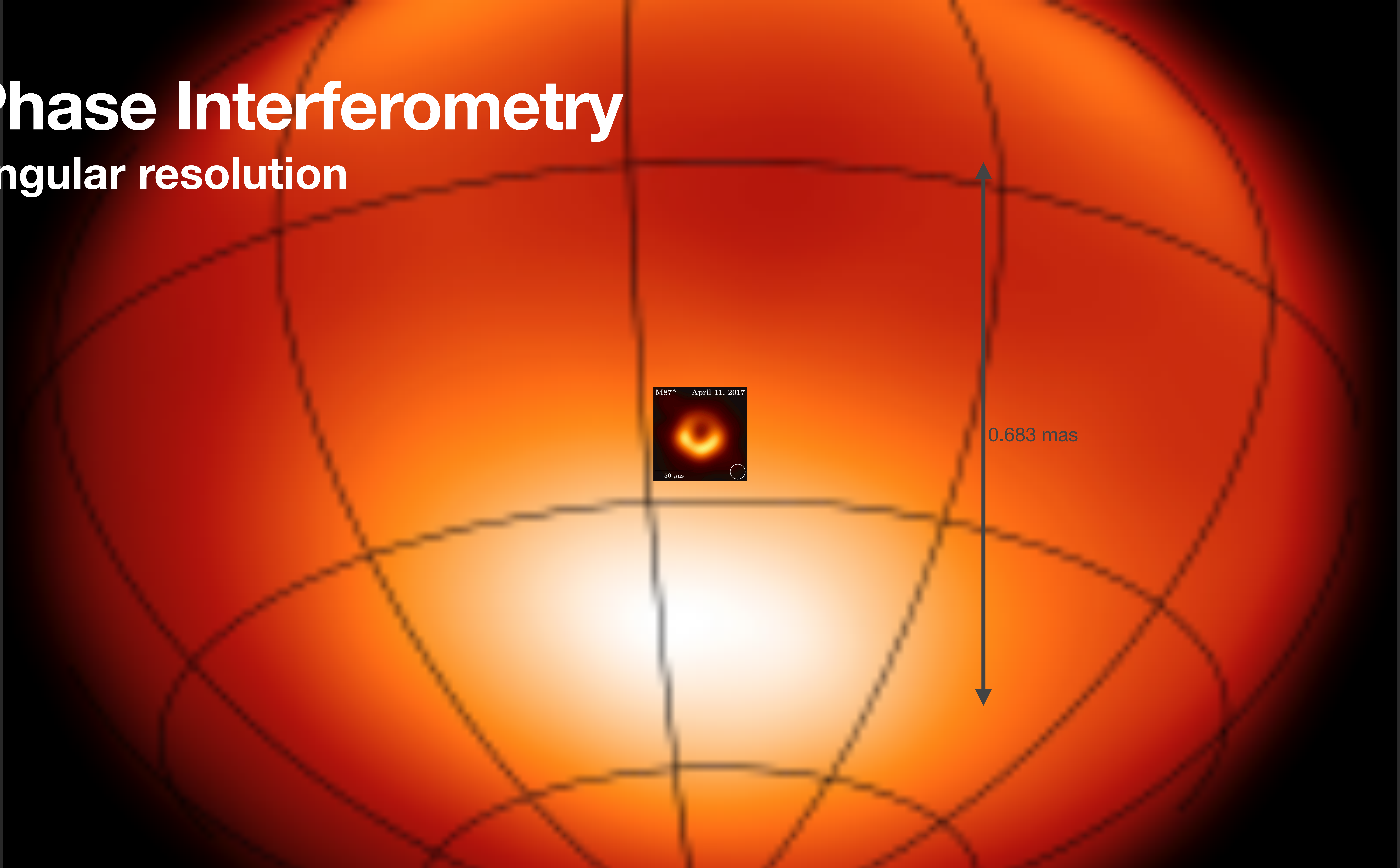
Alderamin



6.83 mas

Phase Interferometry

Angular resolution



Phase Interferometry

Limitations in angular resolution

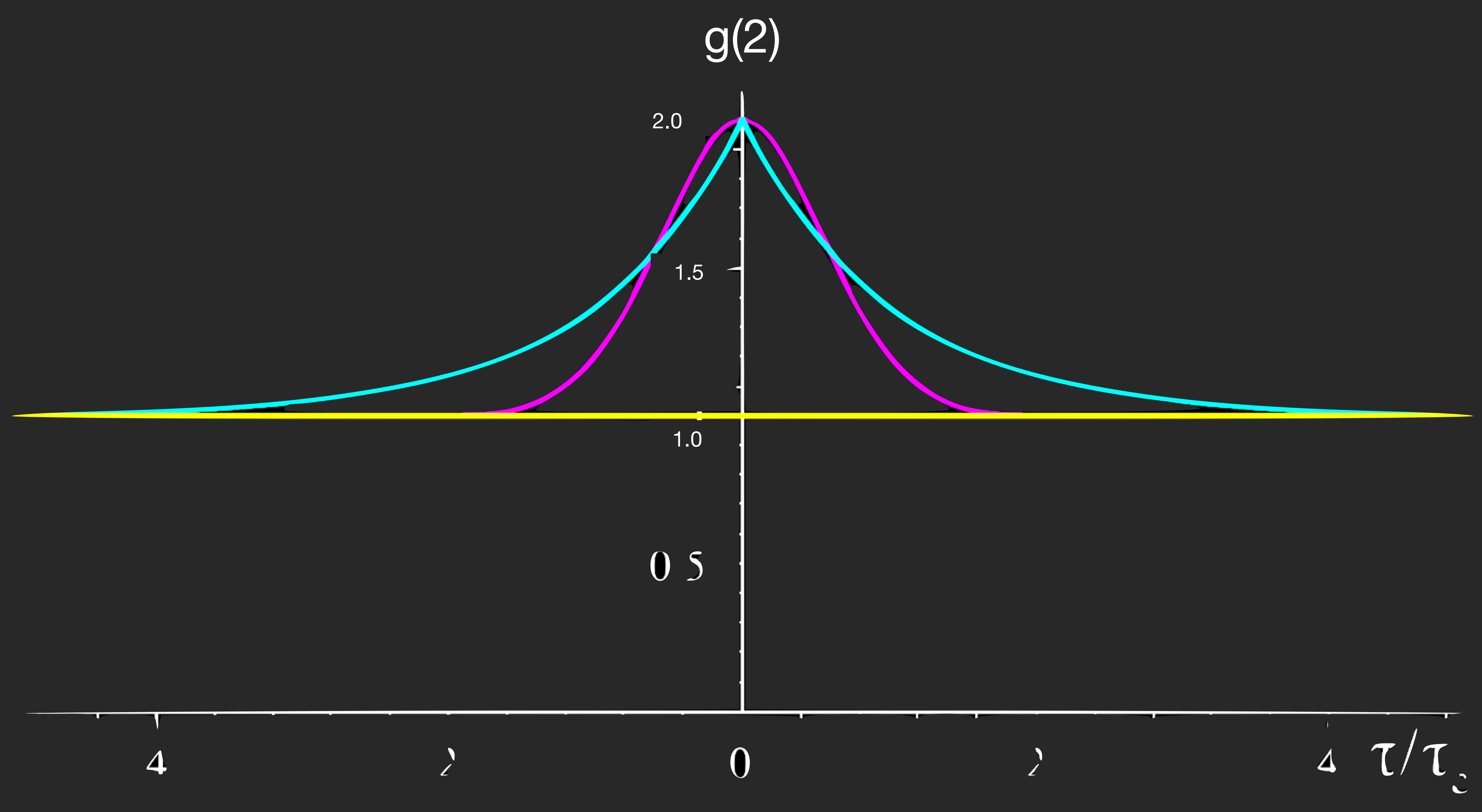
- Cost
  - No new optical facility likely to be built in the foreseeable future
  - Delay lines become increasingly more difficult to build at longer distances
- Radio interferometers already utilise the whole Earth for long baselines
- How can we go further ?
  - Go for shorter wavelength
    - —> Intensity Interferometry !

Intensity Interferometry

Measure $g^{(2)}$

- Second-order correlation of light
    - The correlation of the light intensity: the HBT effect
- Only works for chaotic light-sources
    - Can be explained classically or via quantum interpretation
    - Quantum interpretation also work for fermion’s anti-bunching
- Community was skeptical at that time

$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$



Plot of g(2) as a function of the delay normalized to the coherence length t/tc. Yellow curve is for a coherent state (ideal laser or single frequency). Cyan is for Lorentzian chaotic light. The magenta curve is for Gaussian chaotic light.

Wikipedia

Intensity Interferometry

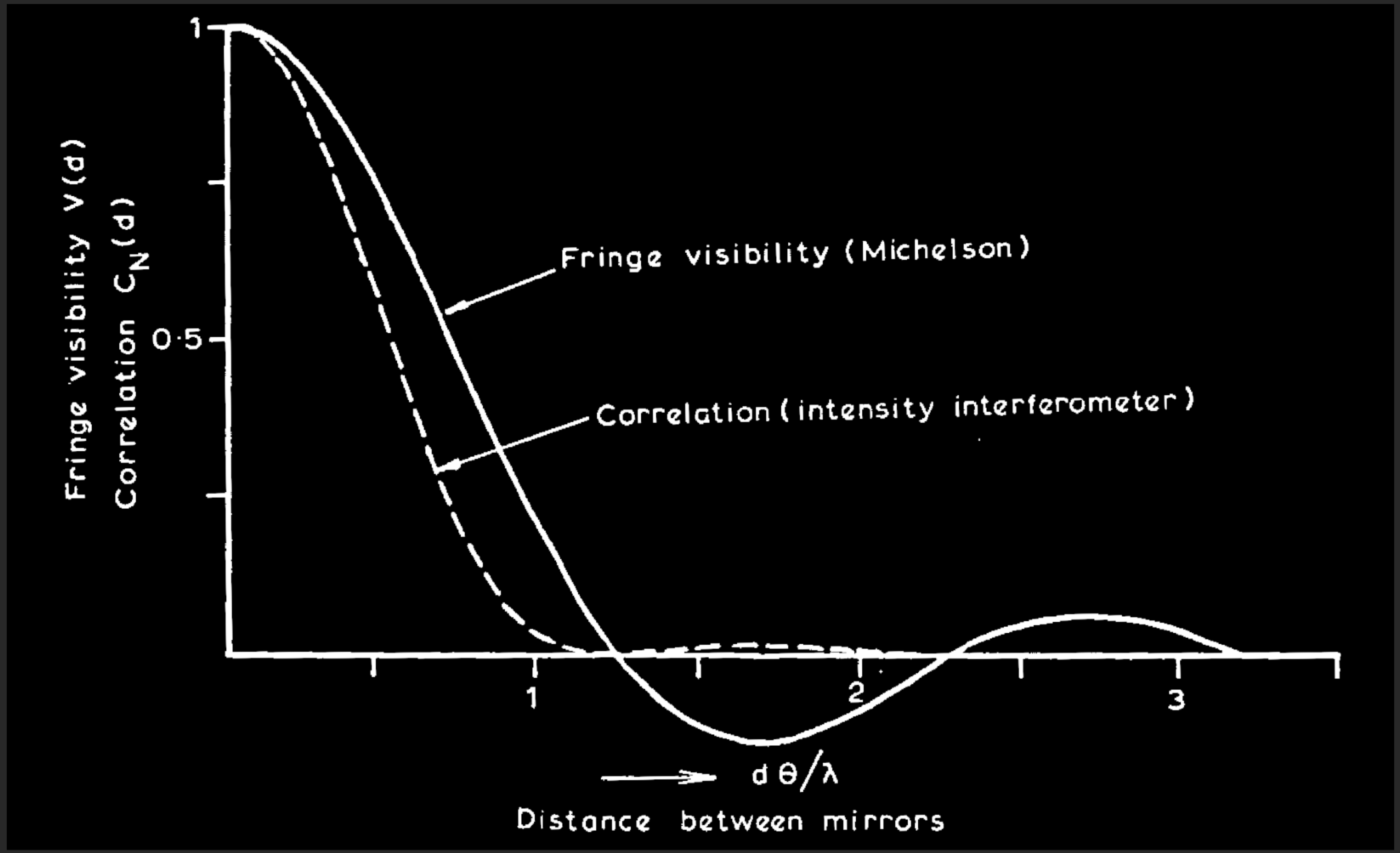
Probe Visibility squared

$$g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2$$

- Works at any wavelength
  - As long as flux is workable
- Insensitive to atmosphere
  - For reasonable baselines

$$\mathrm{SNR} = \frac{\Phi}{1 + B/\Phi} A_{\mathrm{eff}} |V(\overrightarrow{x_1} - \overrightarrow{x_2})|^2 \left(\frac{t_{\mathrm{obs}}}{\Delta t}\right)^{1/2} N_{\mathrm{chan}}^{1/2}$$

  - Narrow-bands
  - BIG telescopes
  - Fast sampling
  - Many channels



The Intensity Interferometer, R. Hanbury Brown

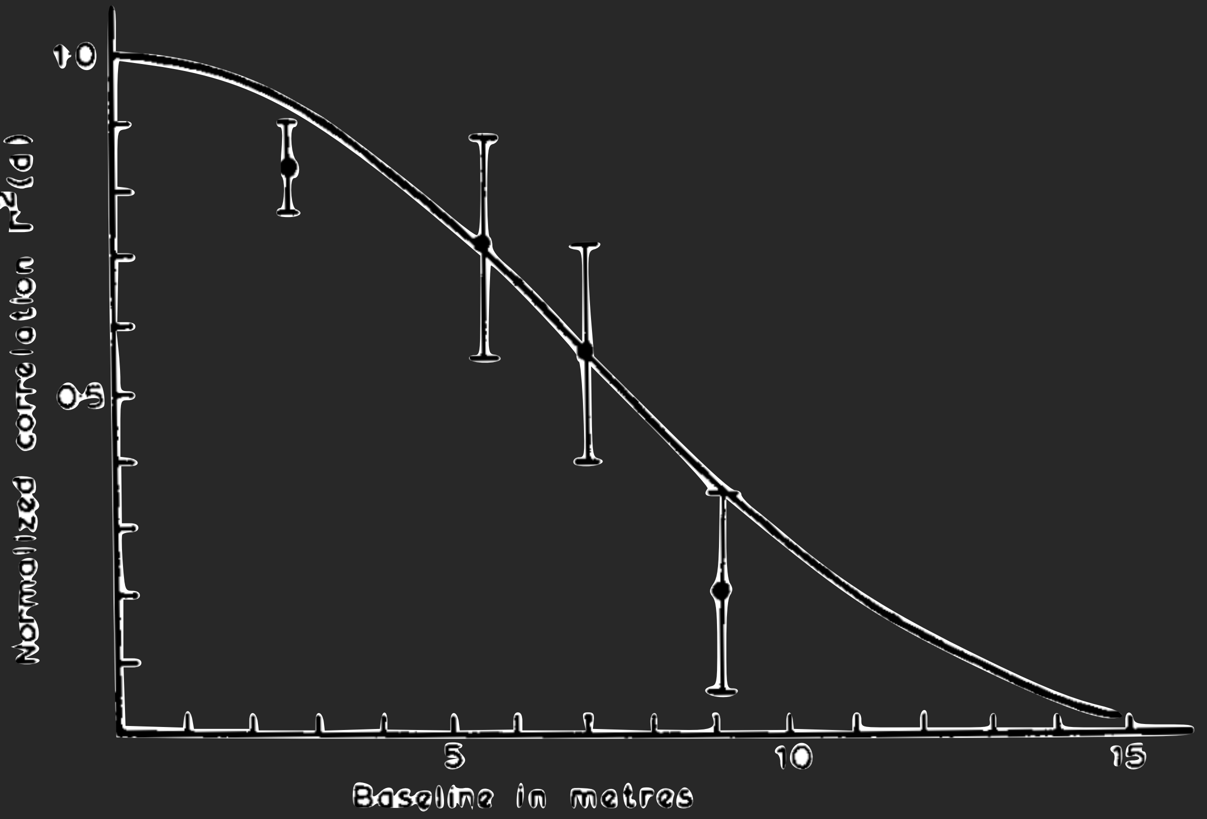
Intensity Interferometry

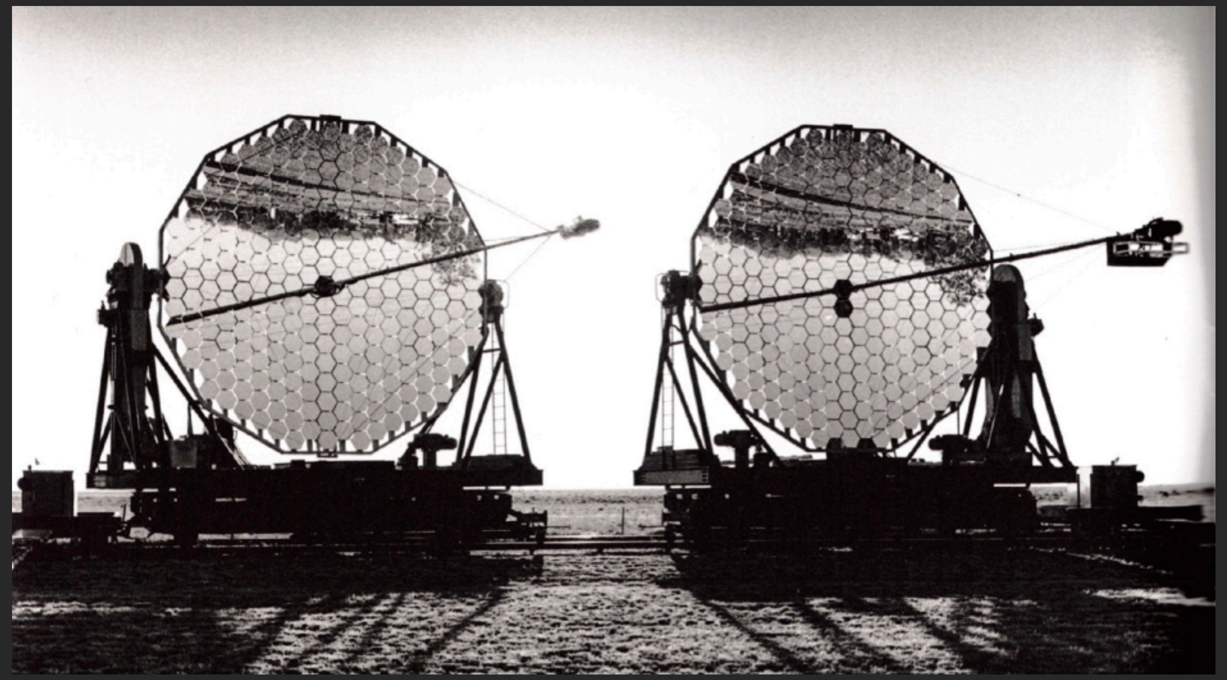
Where it all began

- The Narrabri stellar interferometer
  - Analog correlator !

Jodrell Bank - 1956

Narrabri control room





Narrabri stellar interferometer - 1972

ATNF Daily Astronomy Picture - 07/11/2018

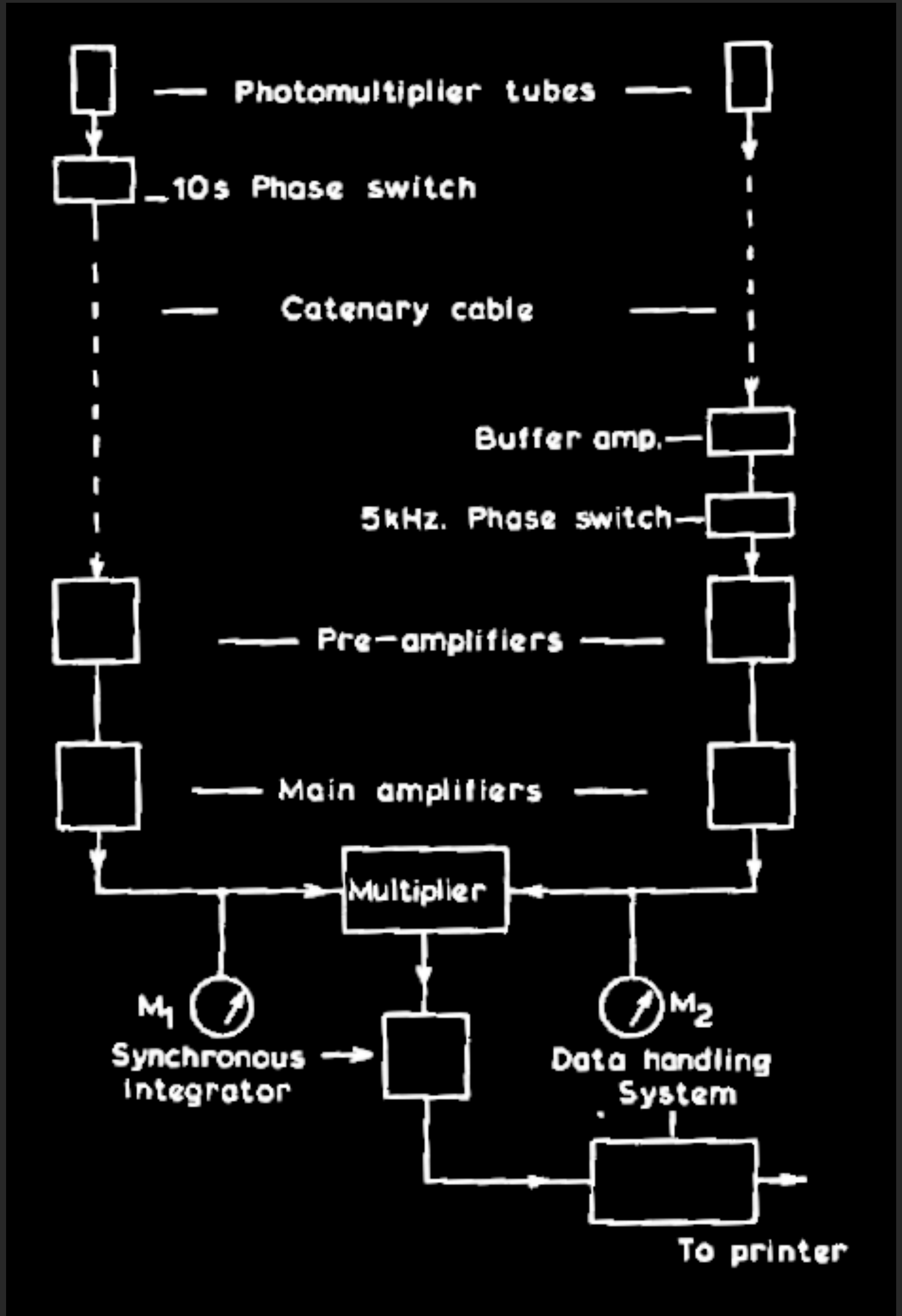
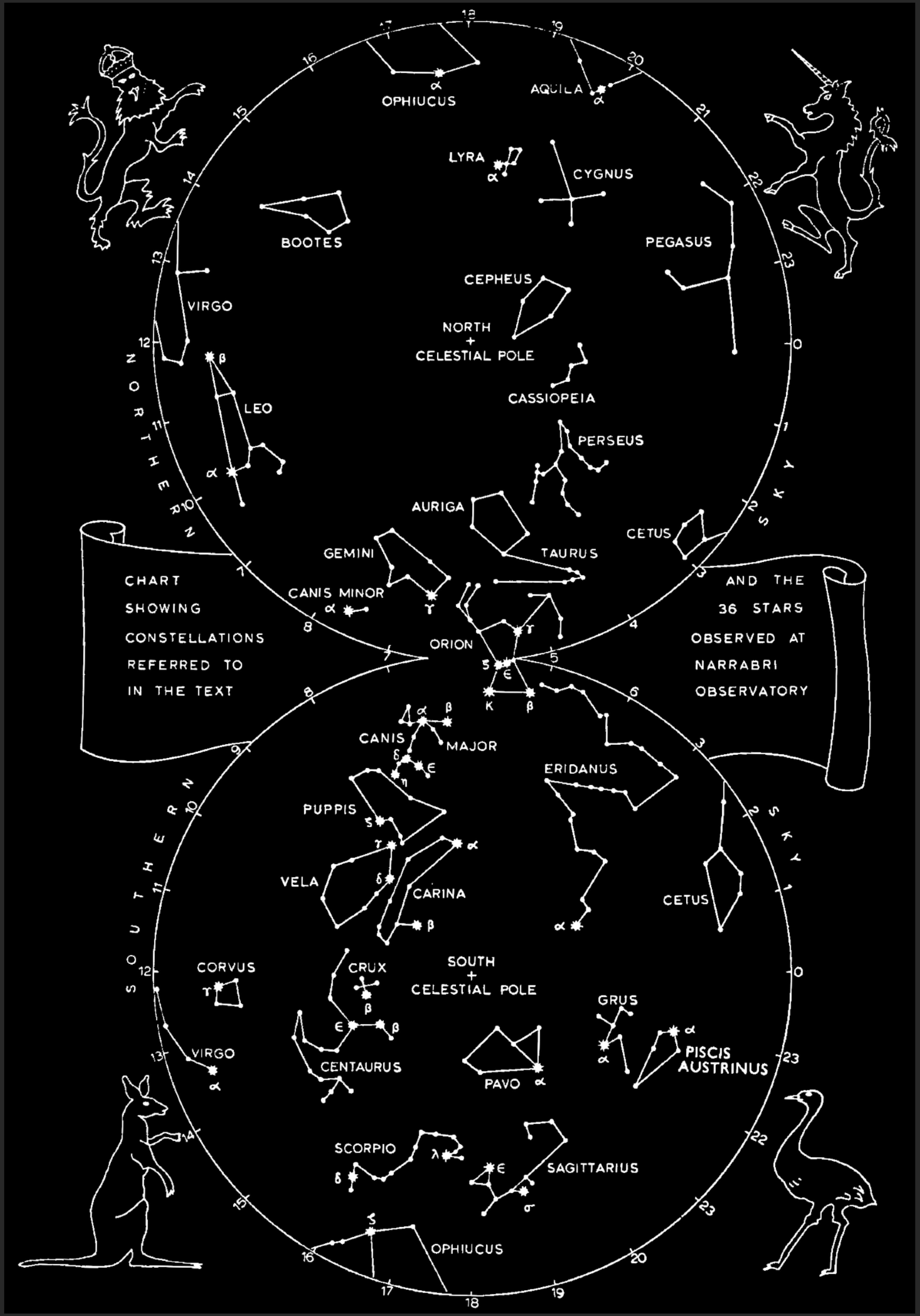


Fig. 8.8. Outline of the correlator.

The Intensity Interferometer, R. Hanbury Brown

Intensity Interferometry

36 stellar radii measured



Intensity Interferometry

Then nothing for 50 years….

Intensity Interferometry

SII Rebirth

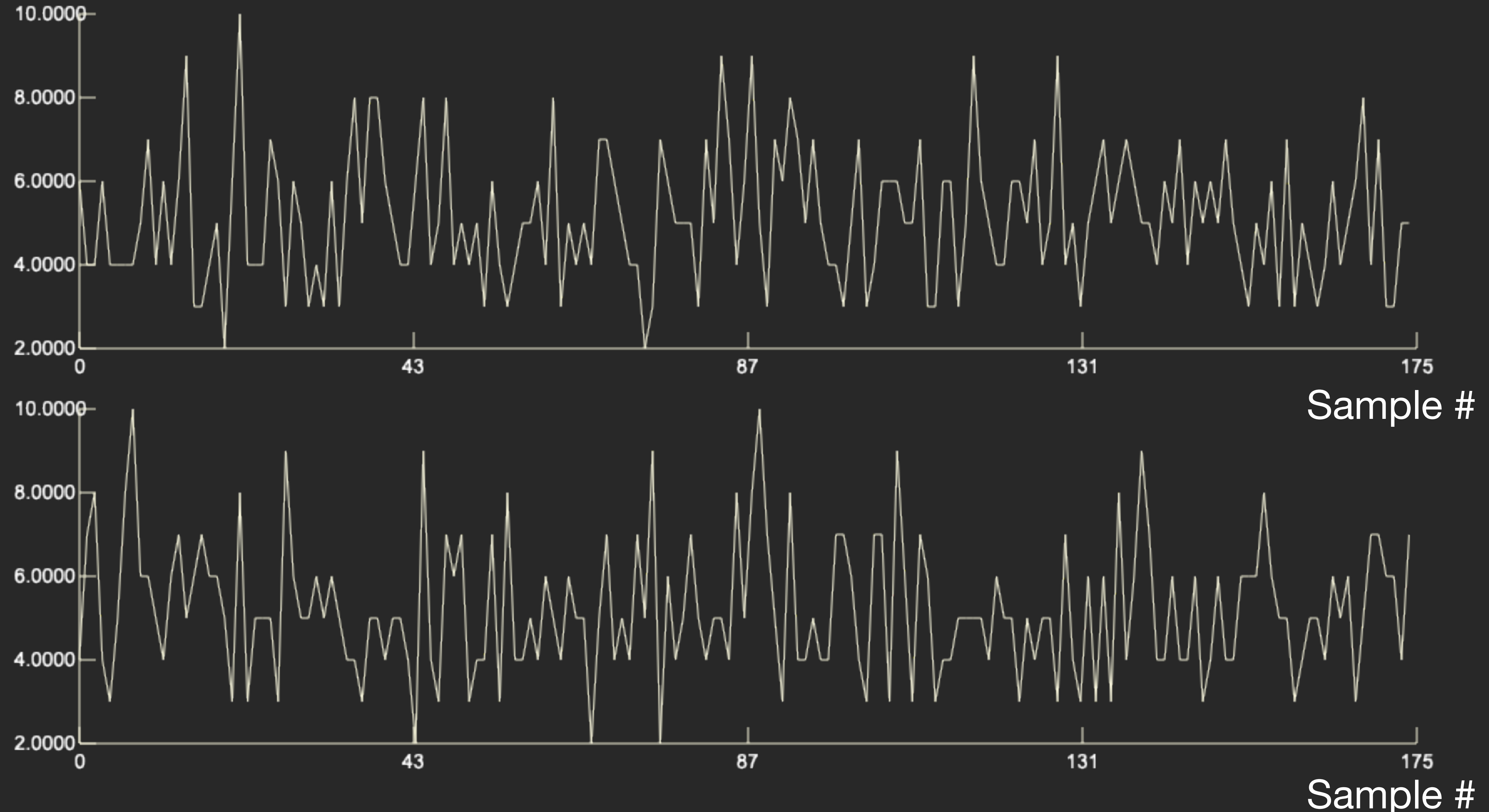
- Cherenkov telescopes !
  - BIG light-collection area
  - Fast sampling

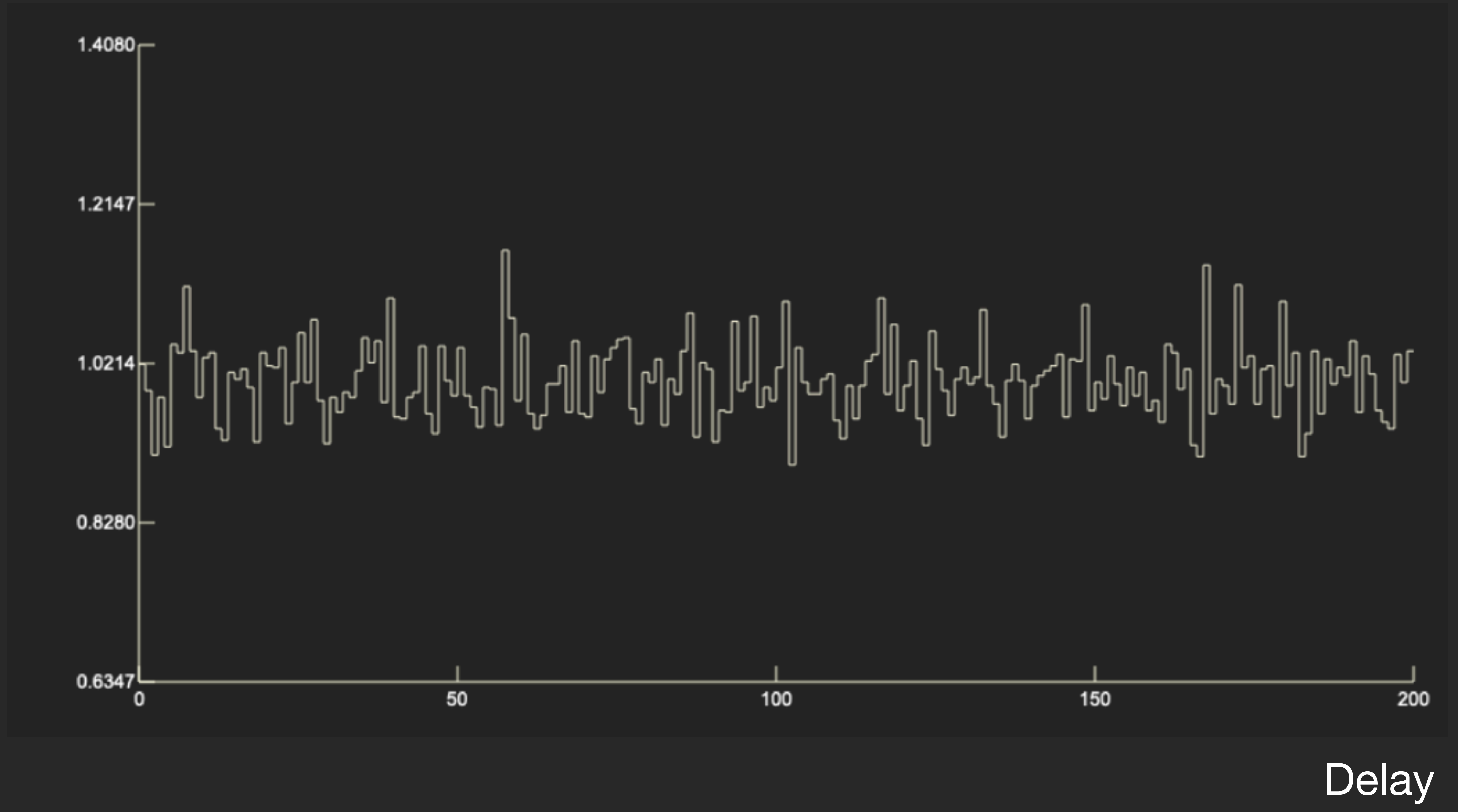
Intensity Interferometry

Intensity regime

- Photons are sampled via fast ADCs

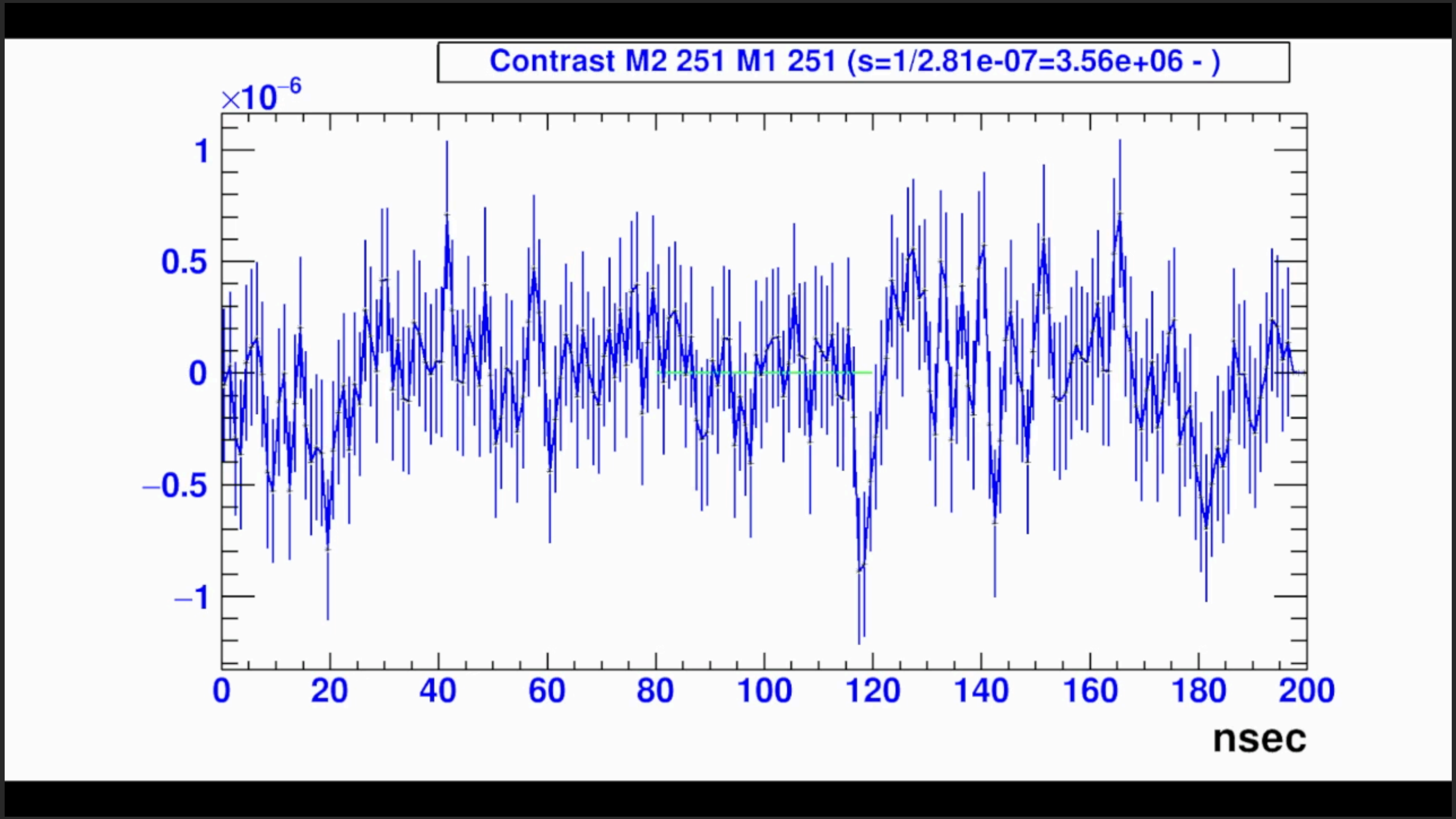
- Correlation produced from waveforms





Intensity Interferometry

Correlation in action



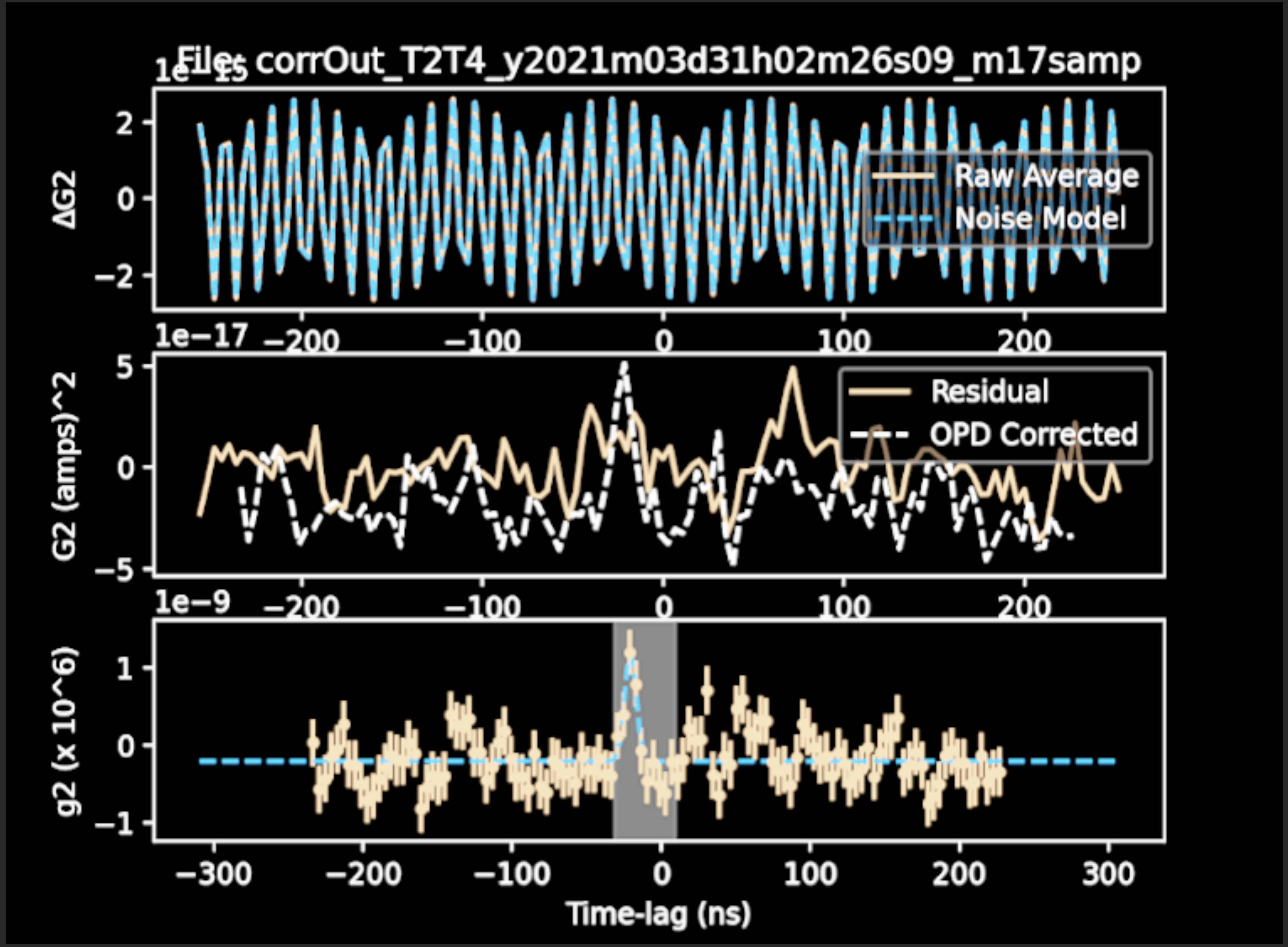
Adhara - MAGIC 1 + MAGIC 2 - 4 minutes Exposure

Intensity Interferometry

Veritas

- FPGA-based readout and correlation
  - offline
  - CPU-based correlation since recently

A. Archer

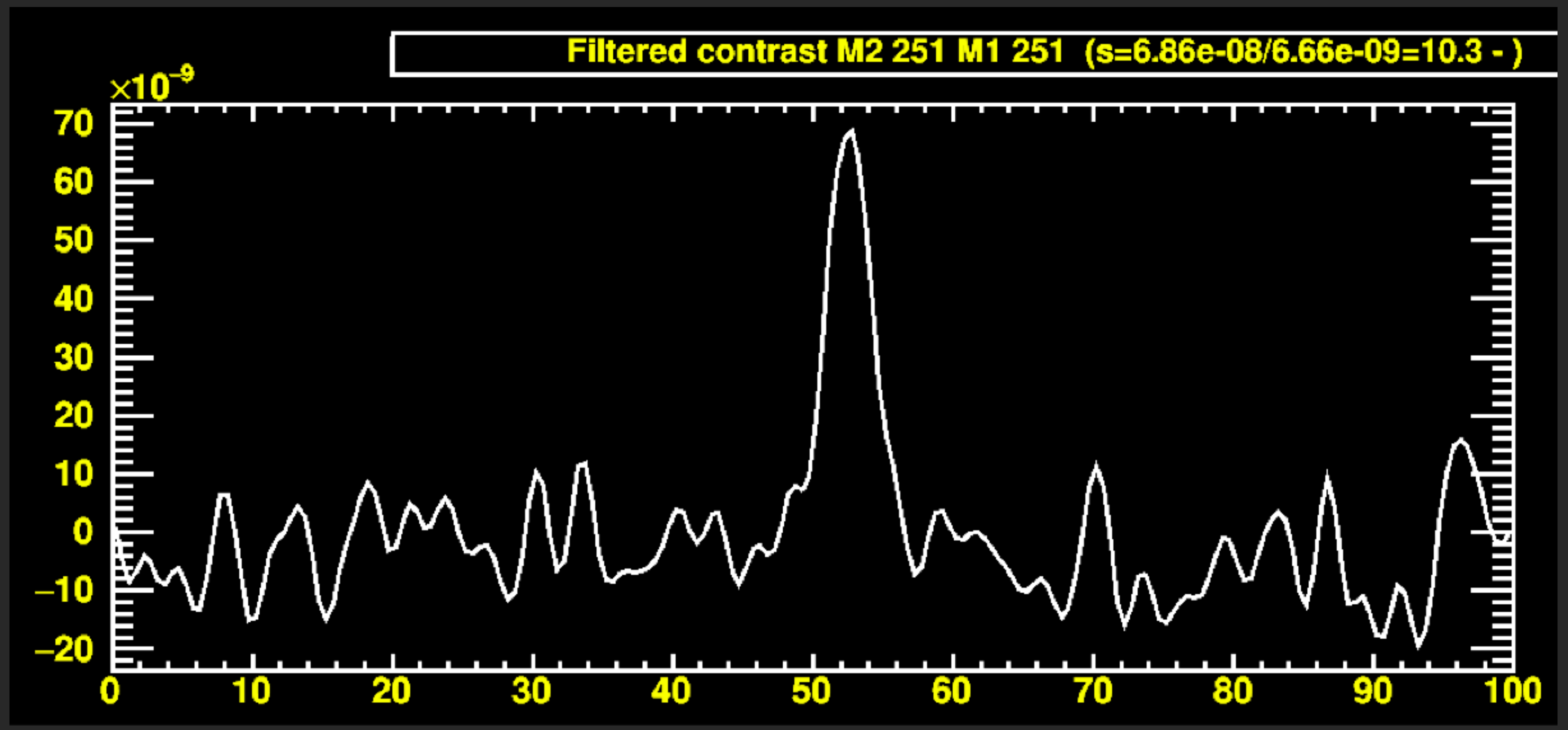


VERITAS collab.

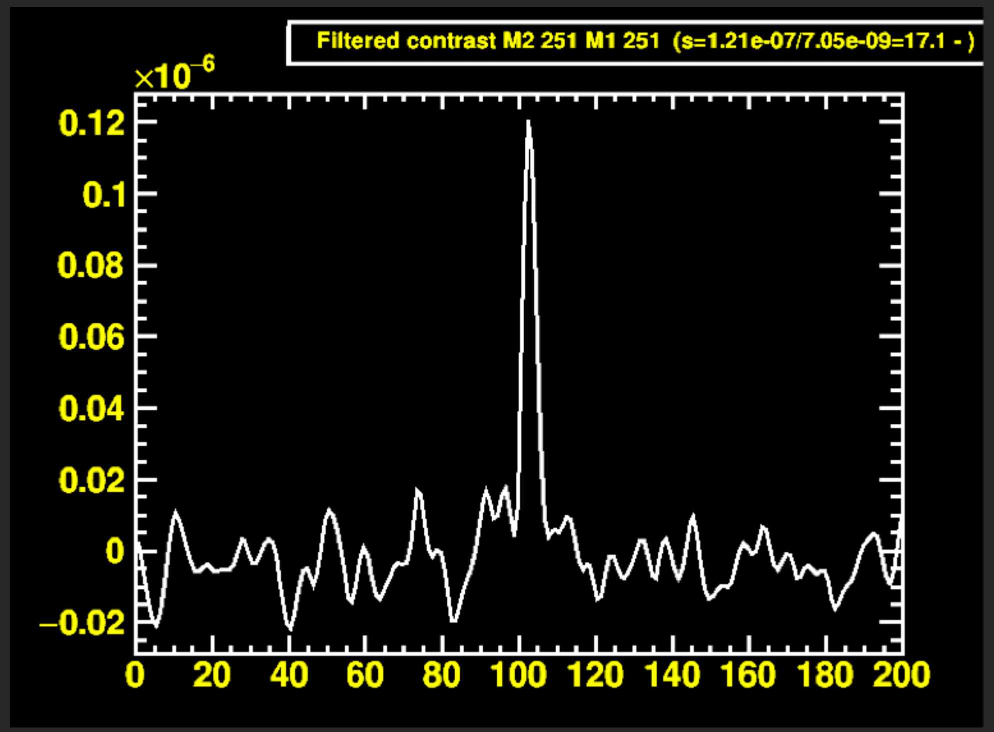
Intensity Interferometry

MAGIC experiment + LST1

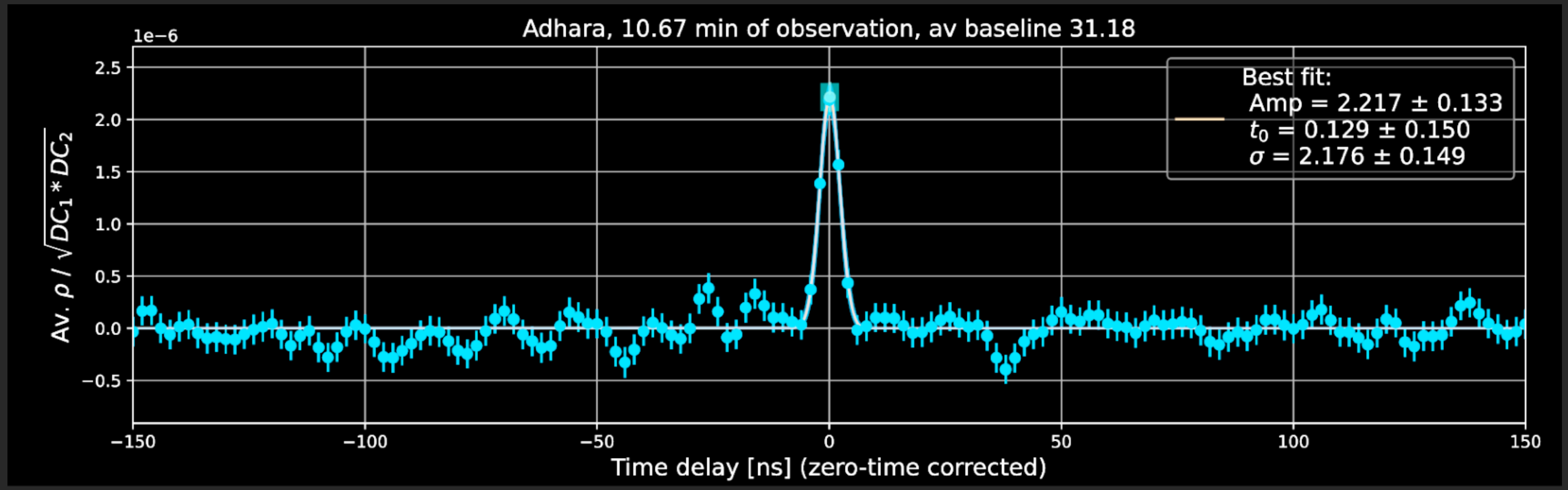
- FADC readout, GPU correlation
  - online
- FPGA-based readout and correlation



Eta-Ori - 140 mins - 2 GSPS



Mirzam - 105 mins - 1 GSPS

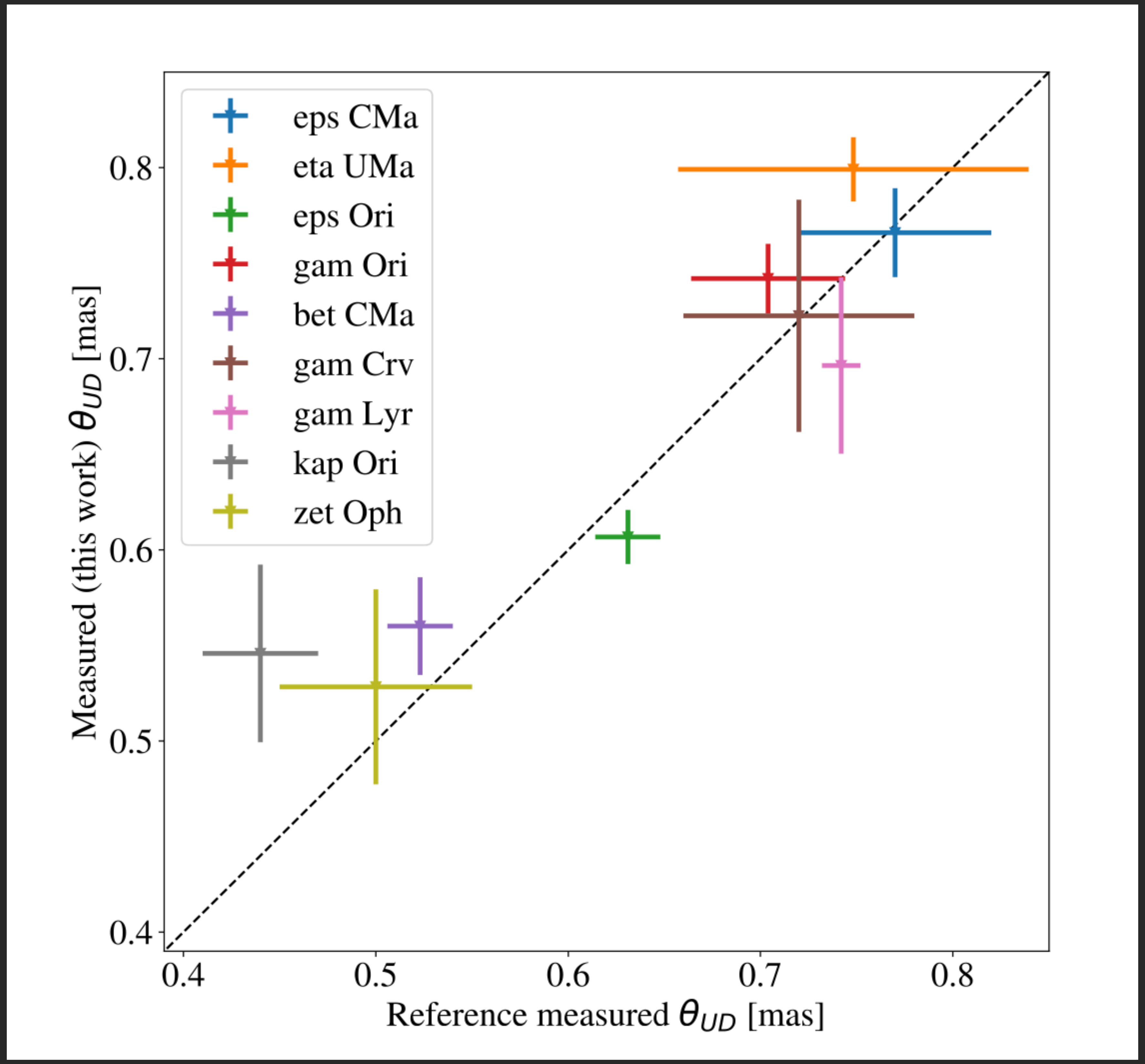


T. Hasan - MAGIC collab.

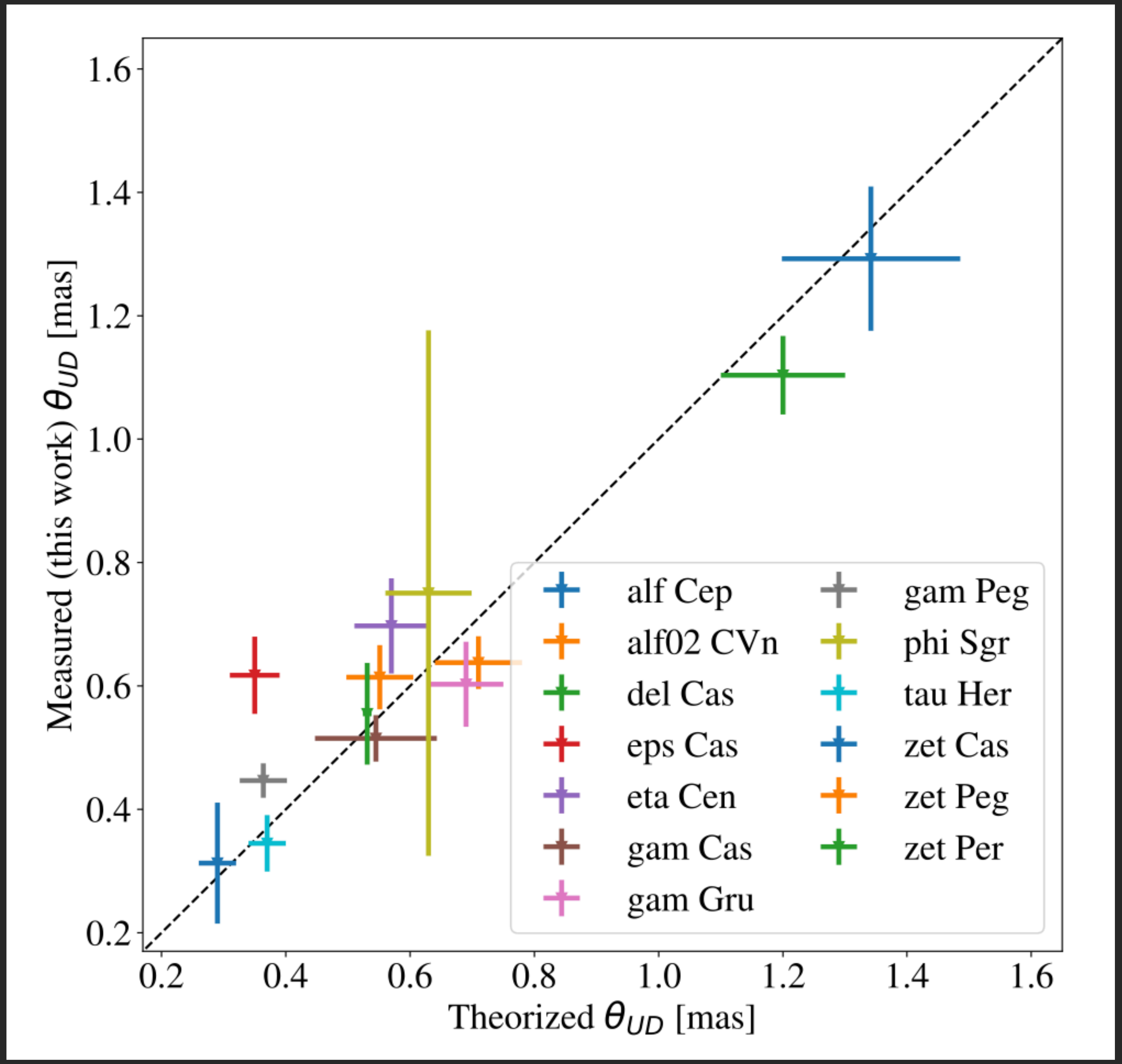
Urs Leutenegger

Intensity Interferometry

MAGIC experiment results



9 Previously measured stellar diameters



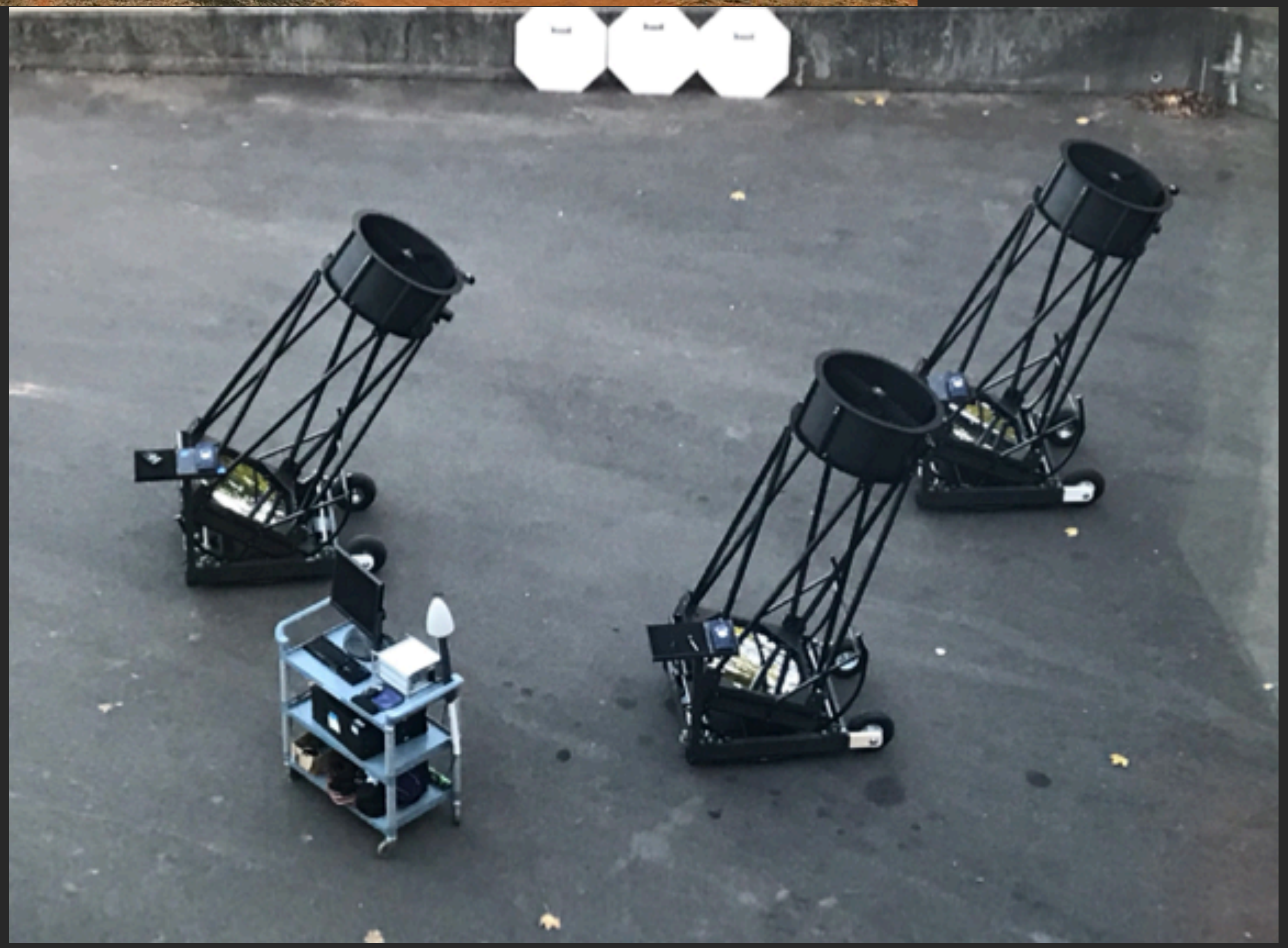
13 Newly measured stellar diameters

T. Hasan et al. 2024

Intensity Interferometry
More experiments

- H.E.S.S. stellar interferometer
  - Acquires zero-baseline always

- Using photon-counting devices
  - SCSI - Southern Connecticut Stellar Interferometer



  - I2C - Intensity Interferometry at Calern
    - More recently at Paranal support telescopes

Intensity Interferometry

Limitations in source magnitude

- Many photons needed to obtain good SNR
- Current telescopes somewhat limited to Mag 3 / Mag 4
  - Dimmer targets possible only if exposure time significantly increases
- No dedicated facility limits observation opportunities
  - Dim, non-spherical sources basically out-of-reach
- Telescopes already pretty big
  - Up to 23 m !
- Improve time resolution
  - -> Go quantum
  - R. Walter's QUASAR Project
    - https://data.snf.ch/grants/grant/216669

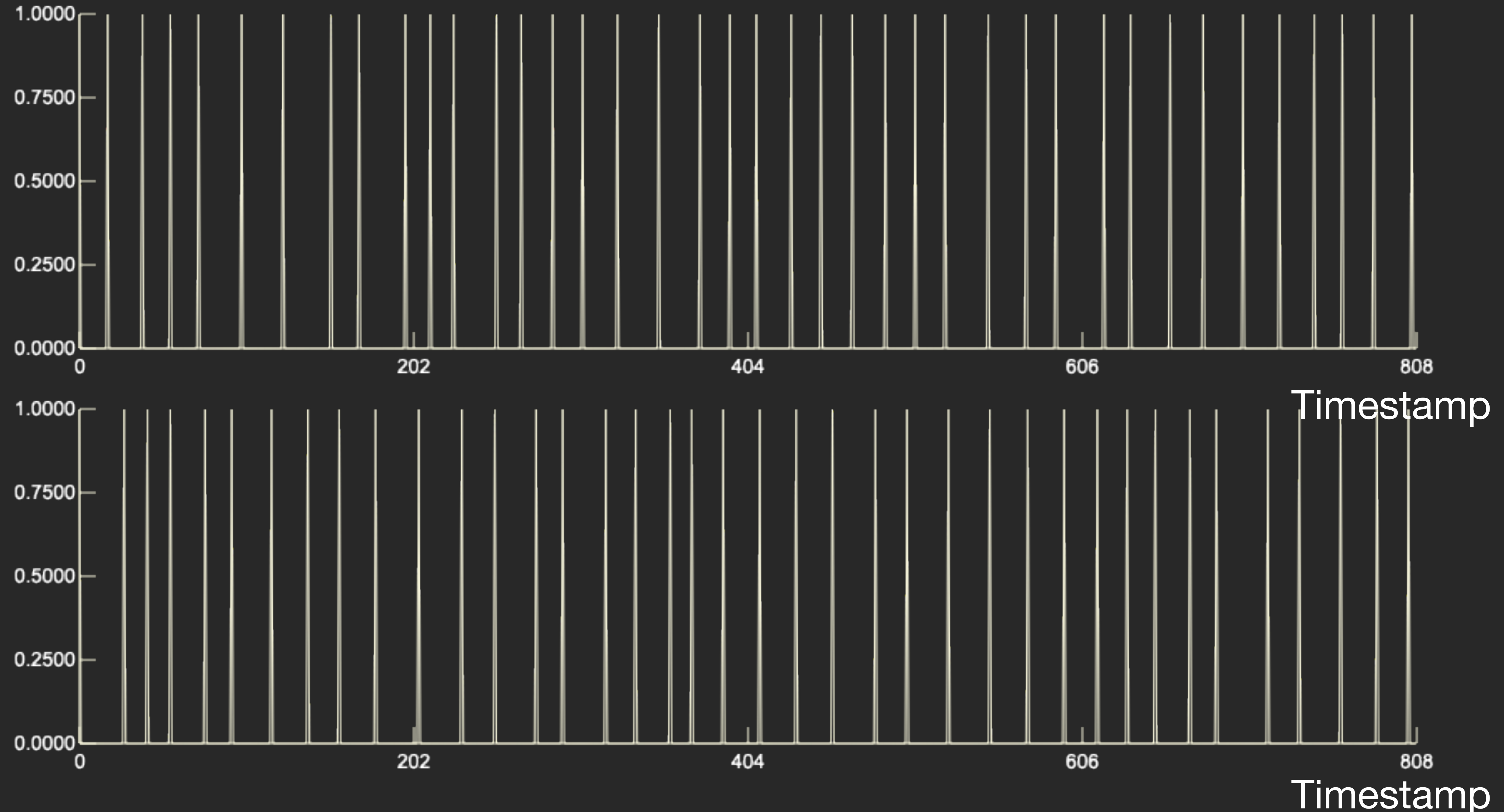
$$\mathrm{SNR} = \frac{\Phi}{1 + B/\Phi} A_{\mathrm{eff}} \,|\, V(\vec{x_1} - \vec{x_2}) \,|^2 \left(\frac{t_{\mathrm{obs}}}{\Delta t}\right)^{1/2} N_{\mathrm{chan}}^{1/2}$$

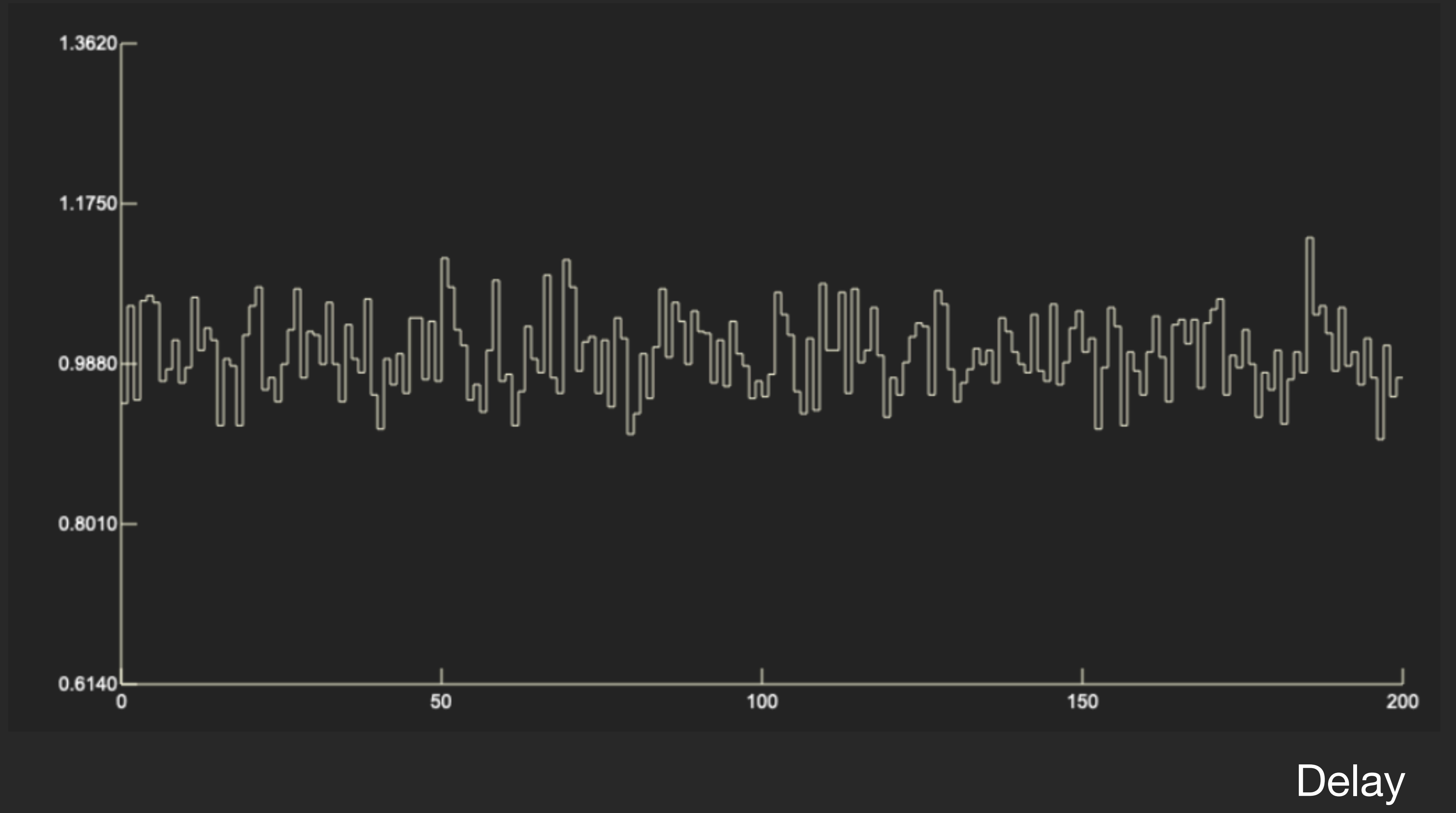
Quantum Interferometry

Photon counting regime

- Photons are timestamped via single-photon-counting devices

- Histogram produced from timestamps



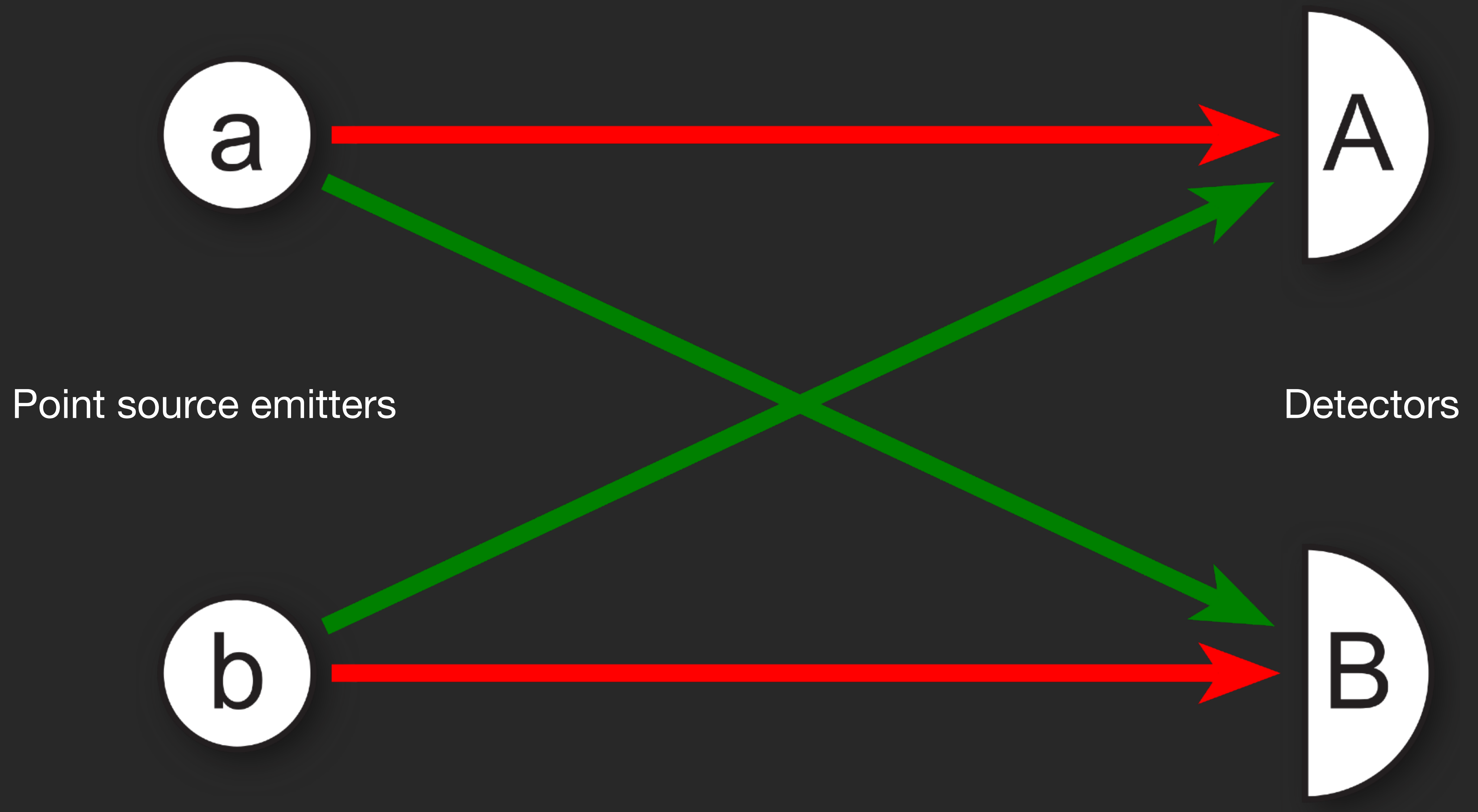


Quantum Interferometry

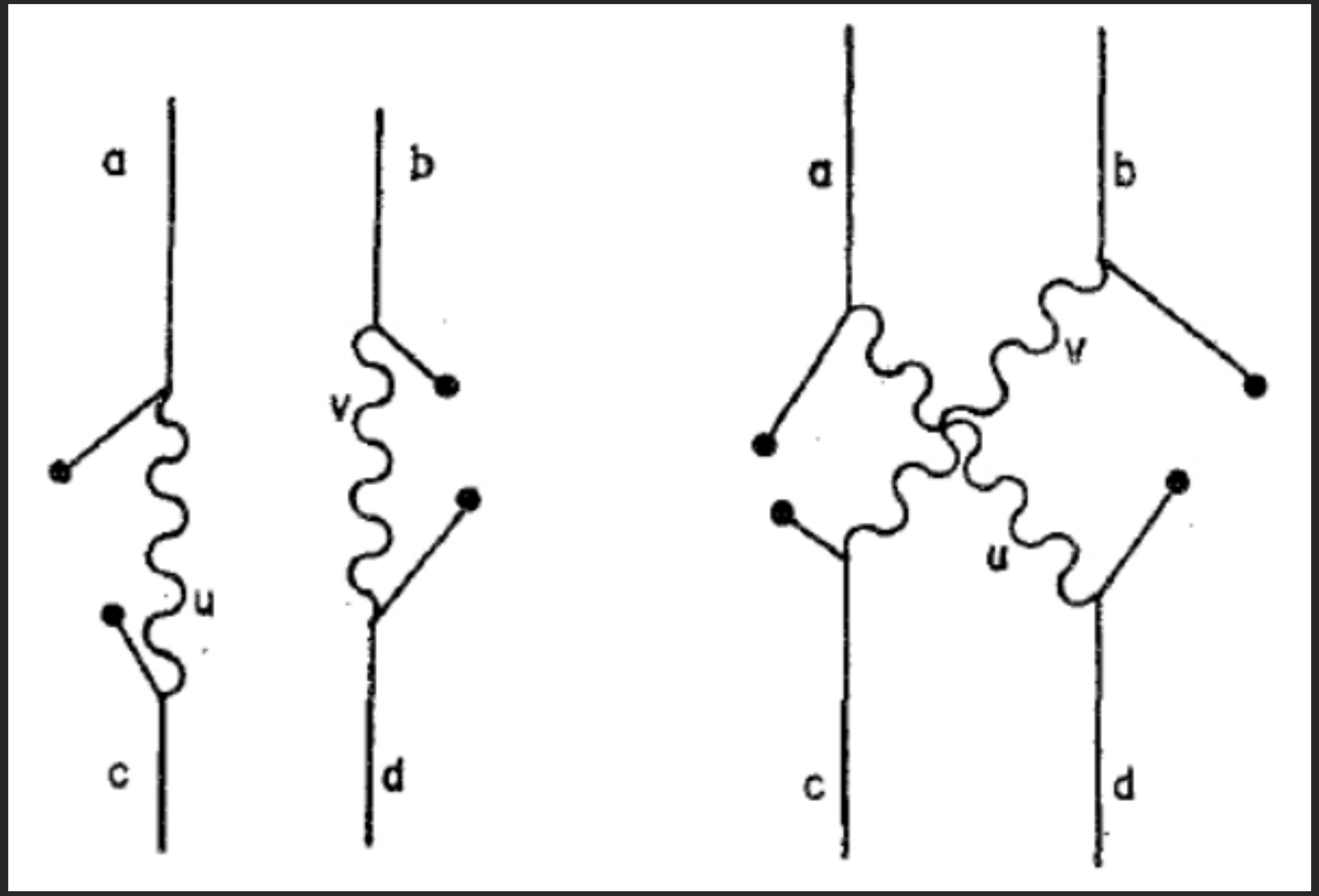
Why does photon counting work ?

- Hanbury Brown and Twiss effect
  - Wave-particle duality
  - Bunching of Bosons, anti-bunching of Fermions
- Nobel prize to Roy J. Glauber in 2005

- Theorised independently by
  - Fano in 1961
  - Glauber in 1963
- Ugo Fano had passed away in 2001



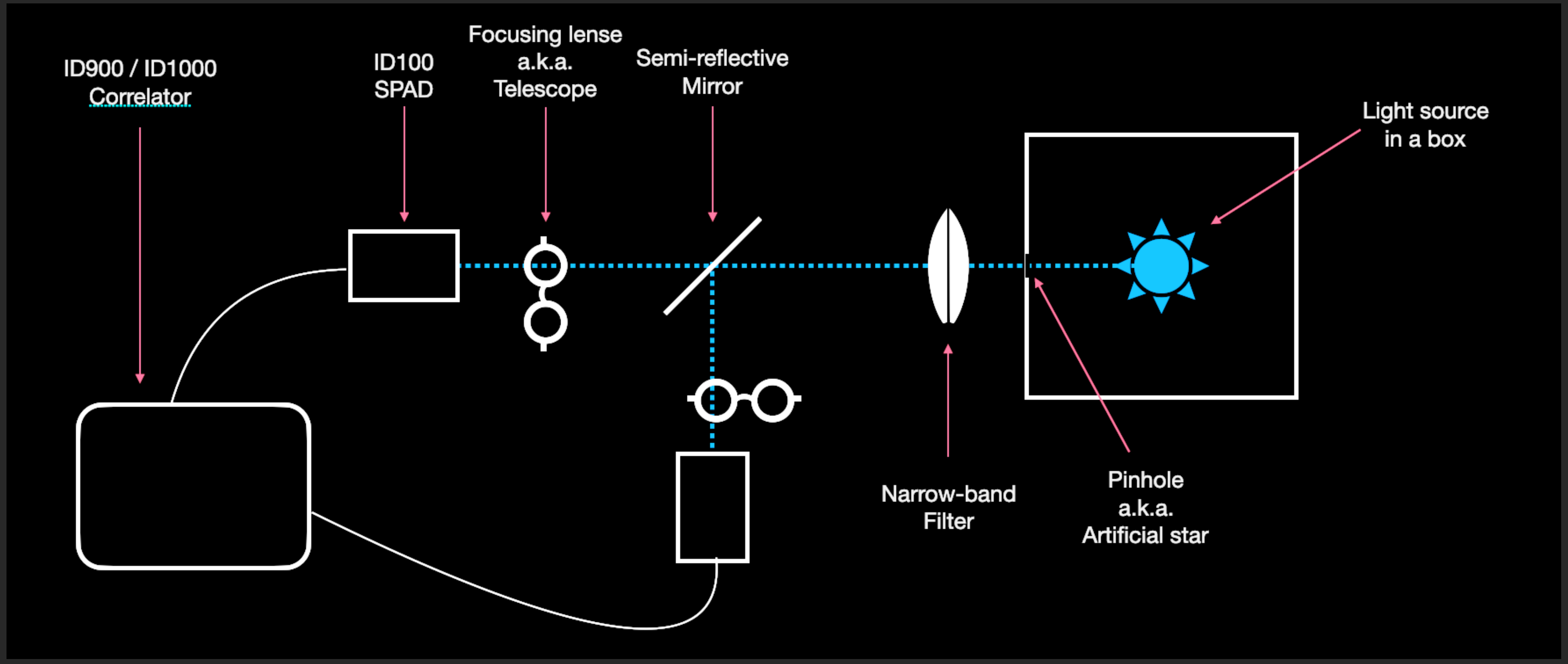
Wikipedia

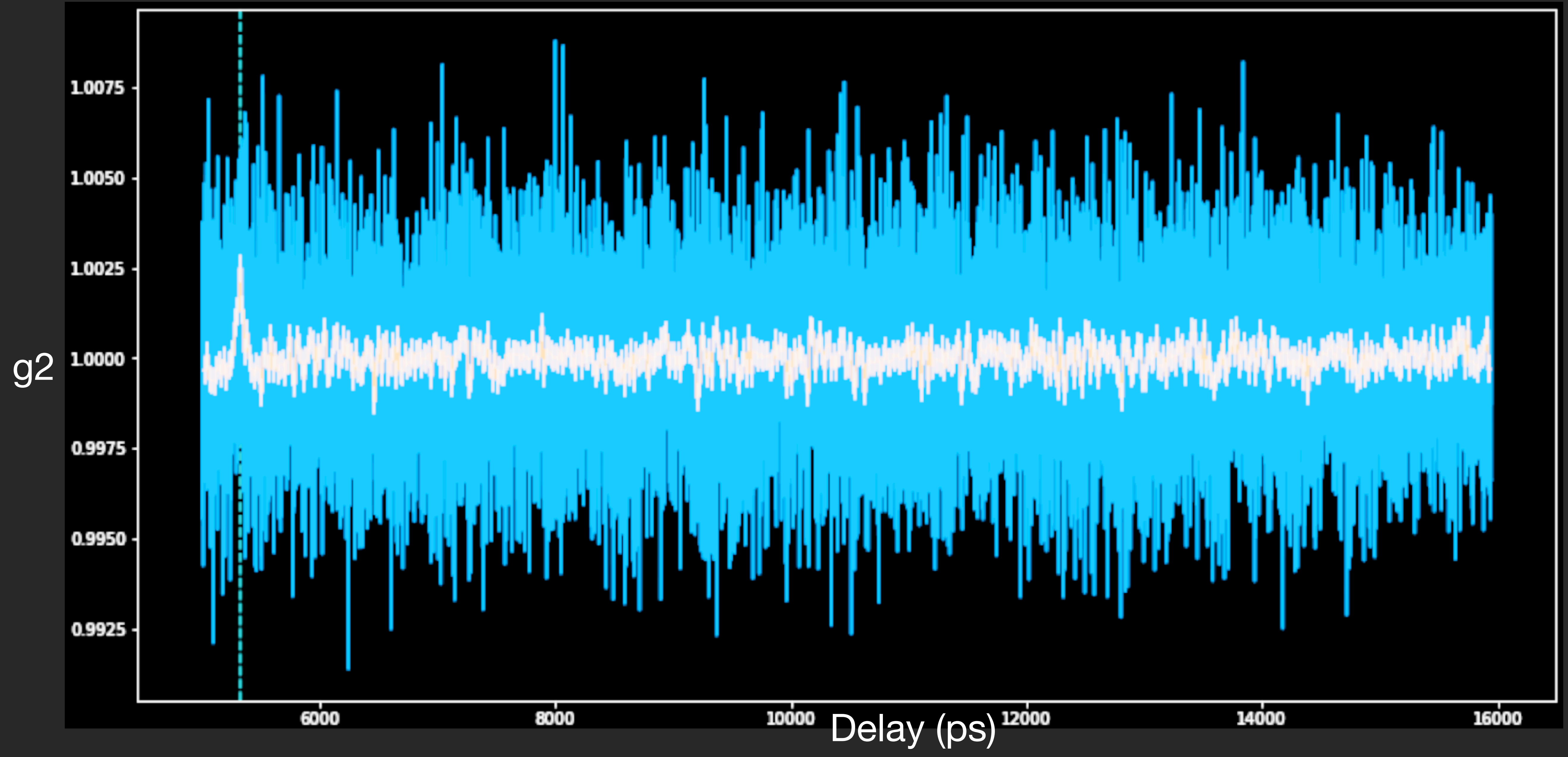


Quantum Interferometry

Photon counting in the lab

- IDQ ID1000 correlators
  - Online histograming
  - Correlated noise to be taken care of
- SPADs
  - Resolution better than 100ps
- $g^{(2)}$ is the small peak on the left
  - Usually very small as even narrow filters (1nm) produce very short coherence time
  - $\tau = \frac{1}{\Delta\nu} \approx \frac{\lambda^2}{c\Delta\lambda} < 1\text{ps}$

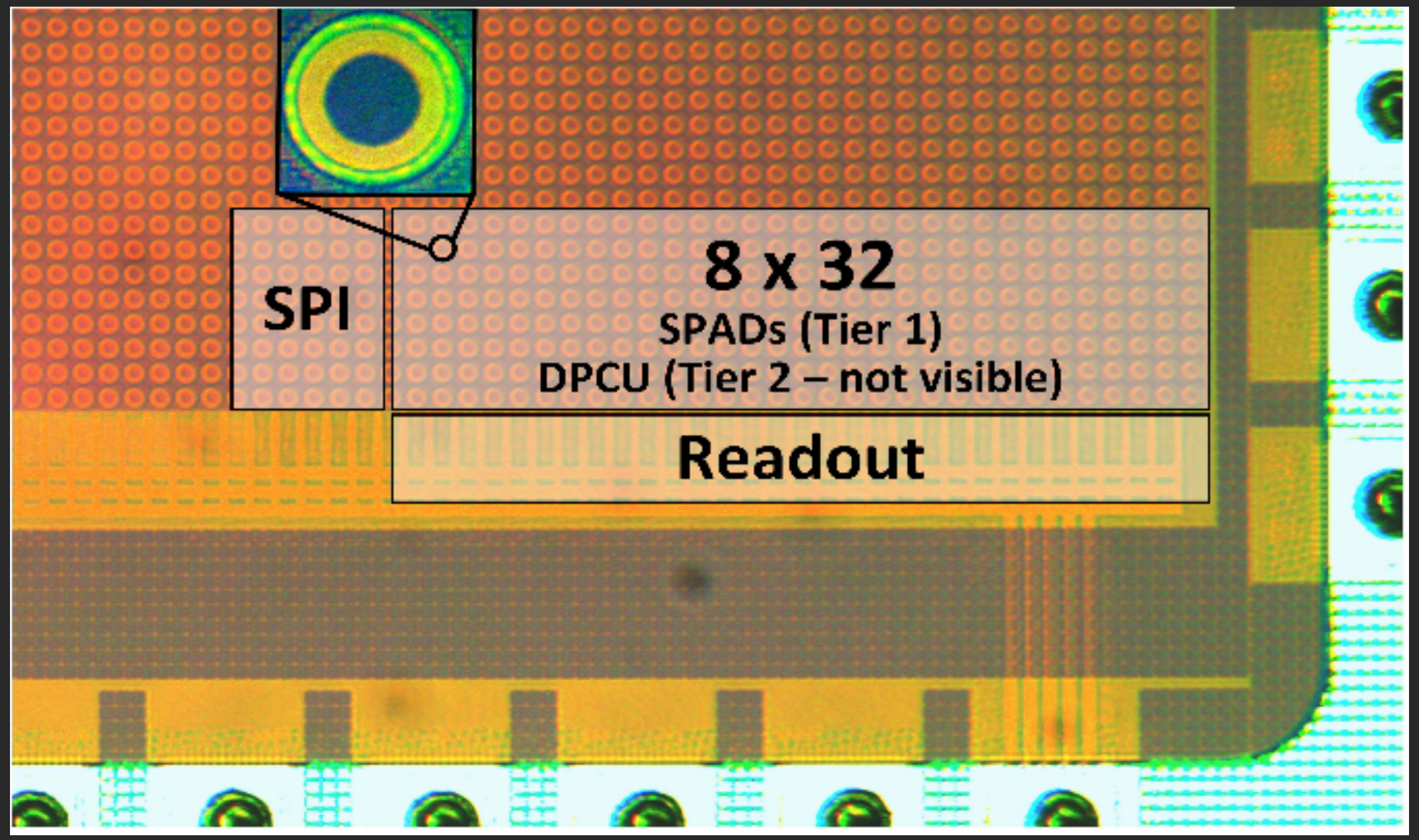




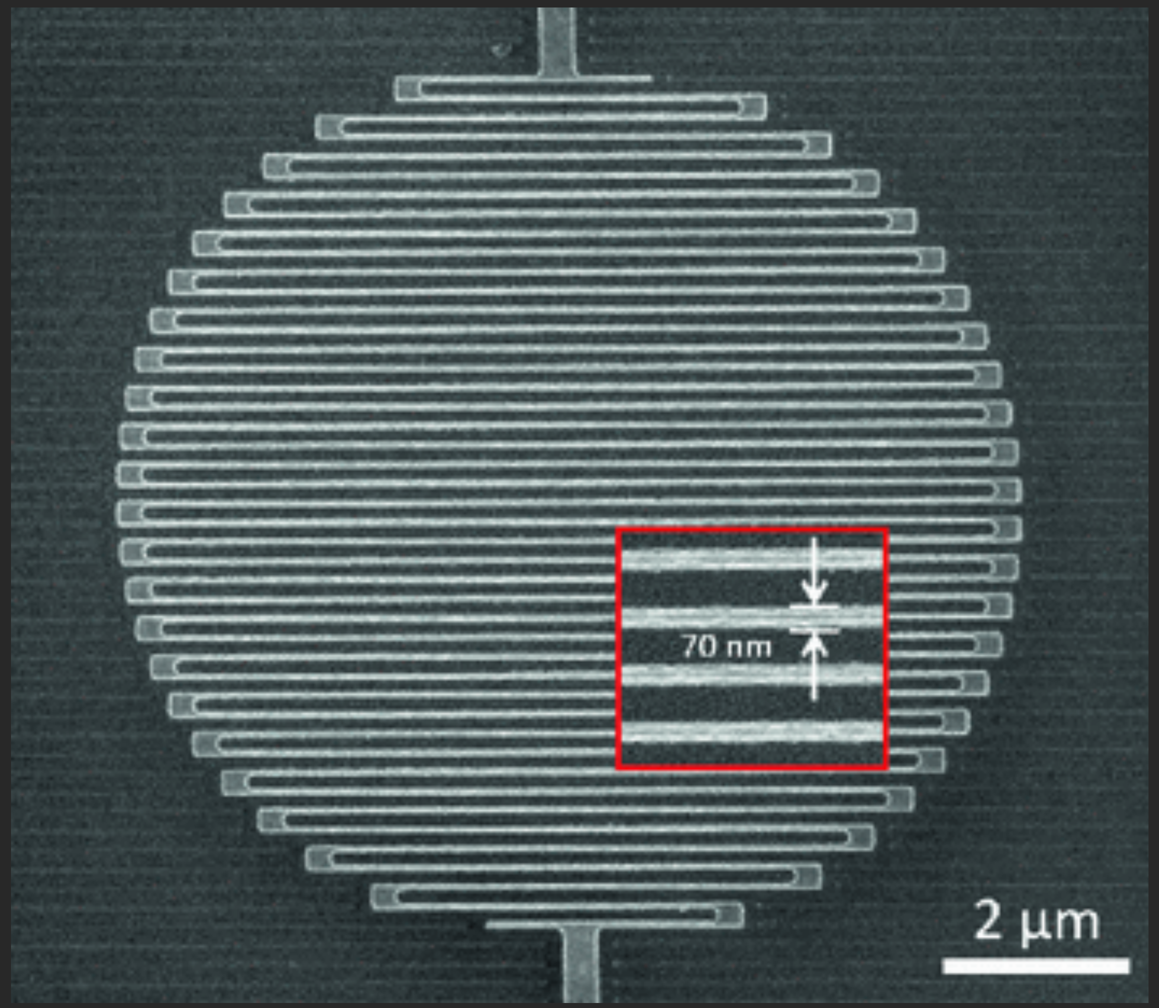
Quantum Interferometry

Photon counting at telescopes

Becker & Hickl GMBH



E. Charbon et al.



F. Najafi et al.

- Various devices tested by various groups
- Performances vs constraints under evaluation
  - Hybrid Single-Photon Detectors
  - Single Photon Avalanche Diods
  - Super-conducting nano-wires
- Arrays of detectors look promising

$$\mathrm{SNR} = \frac{\Phi}{1 + B/\Phi} A_{\mathrm{eff}} \, |V(\vec{x_1} - \vec{x_2})|^2 \left(\frac{t_{\mathrm{obs}}}{\Delta t}\right)^{1/2} N_{\mathrm{chan}}^{1/2}$$

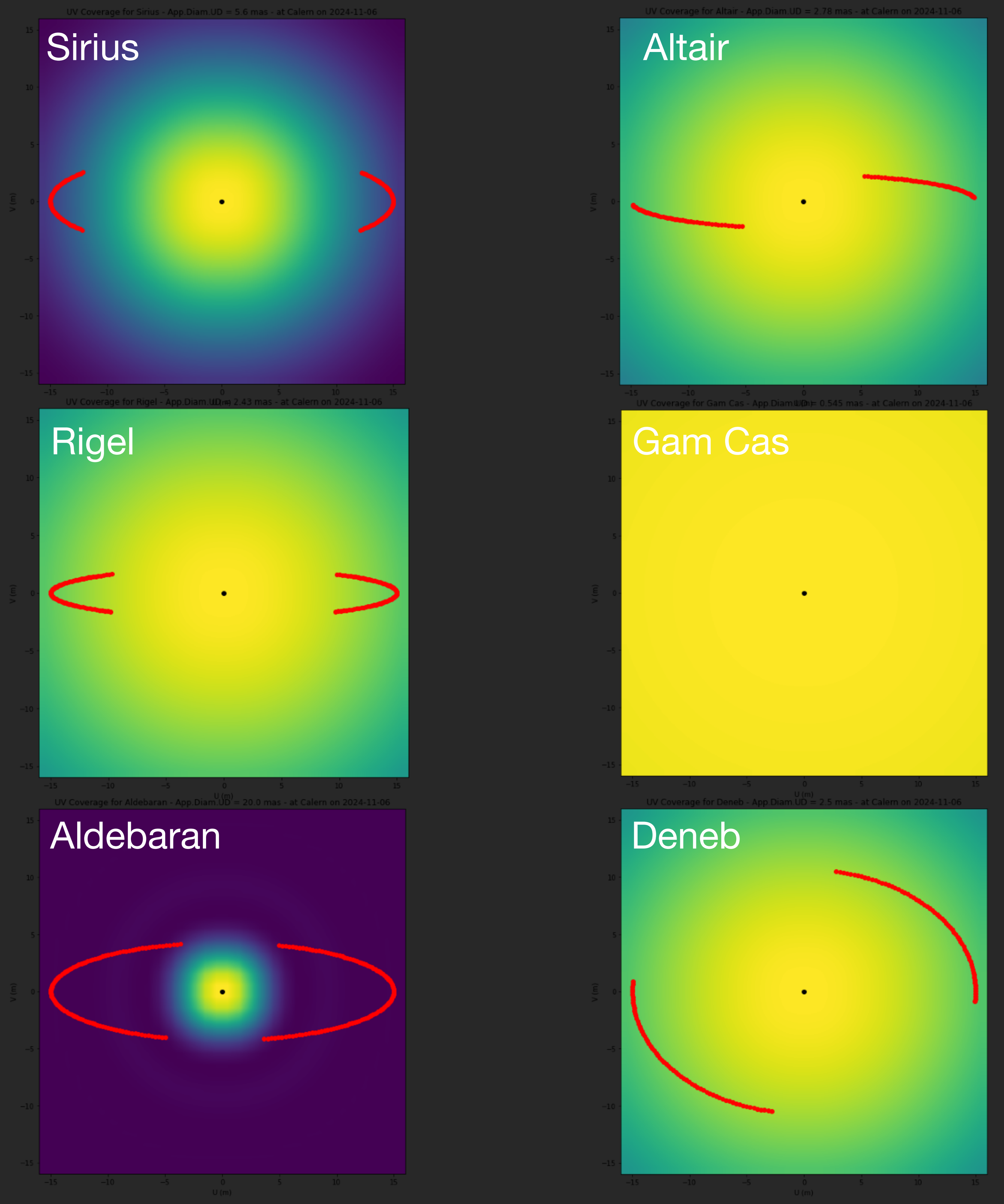
Quantum Interferometry

Next steps

- Measure $g^{(2)}$ at a telescope with SPADS
  - Looking at a bright calibrator
- Zero-baseline obtained recently
  - From Skinakas observatory

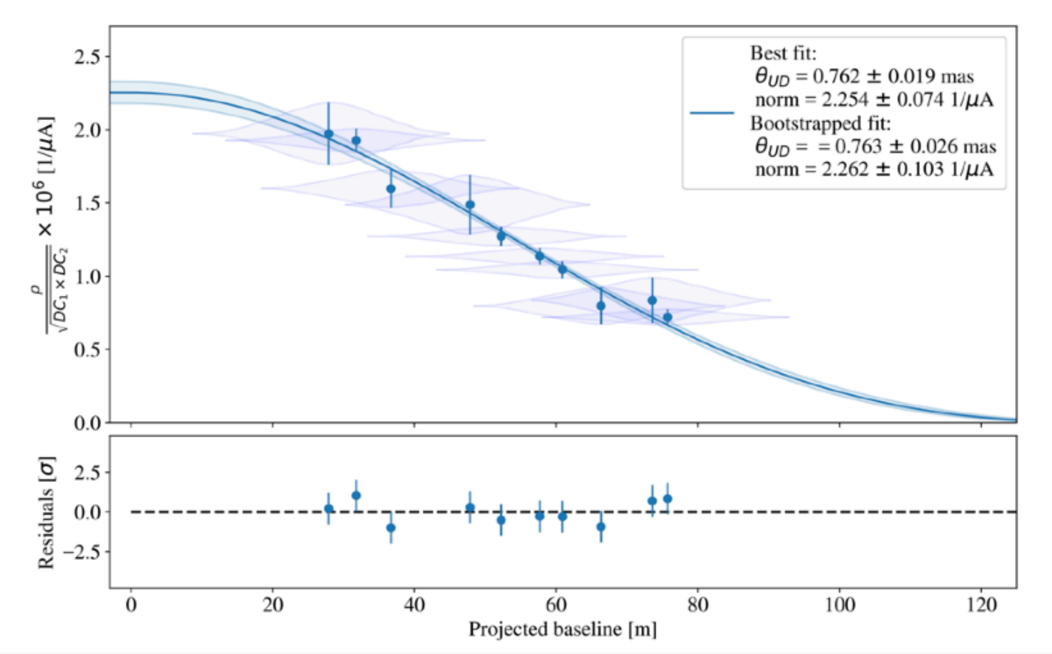
- Cross-baseline signal yet to be seen
  - Will hopefully happen at Nice observatory
  - 2x 1m telescopes - 15m baseline

UV tracks for a single night of a few bright stars seen from C2PU observatory

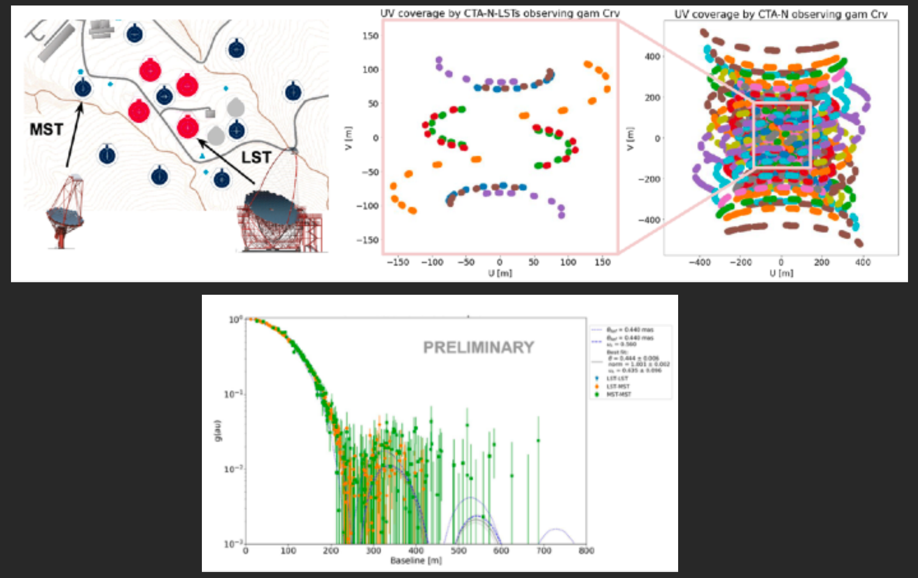


Intensity Interferometry

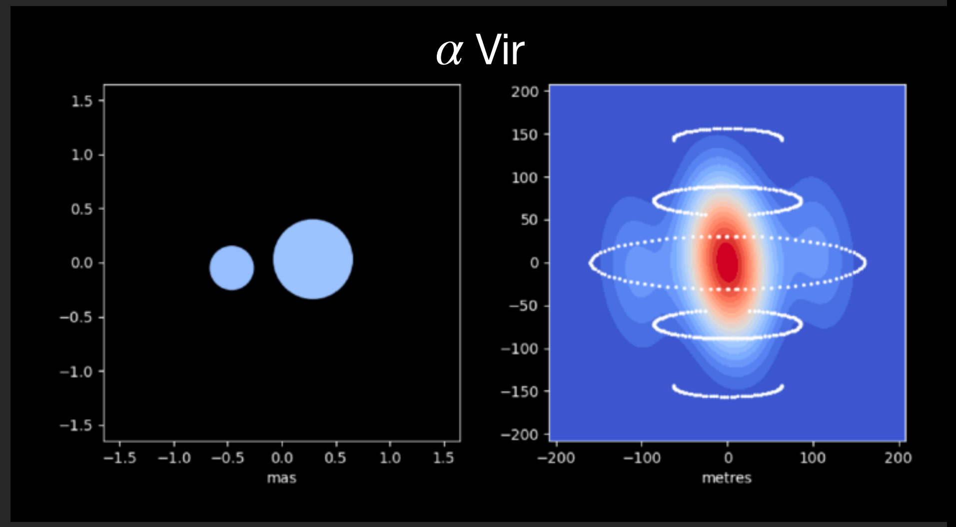
Science Outlook



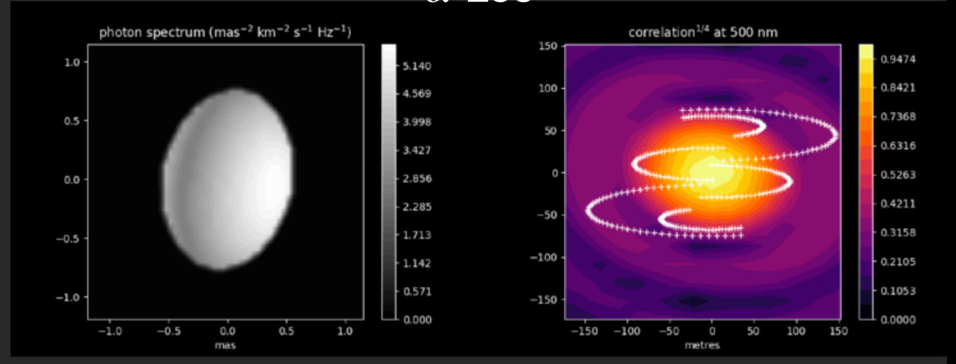
Measurement of the Stellar diameter of Adhara - T. Hassan et al. 2024



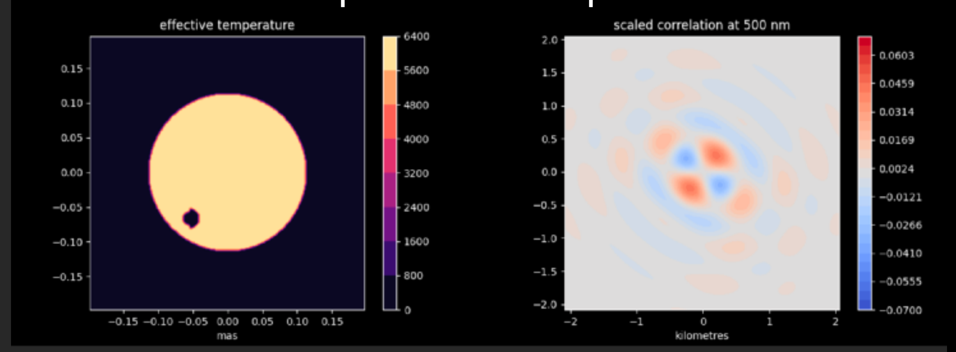
Limb darkening with CTAO North - J. Biteau et al. 2024

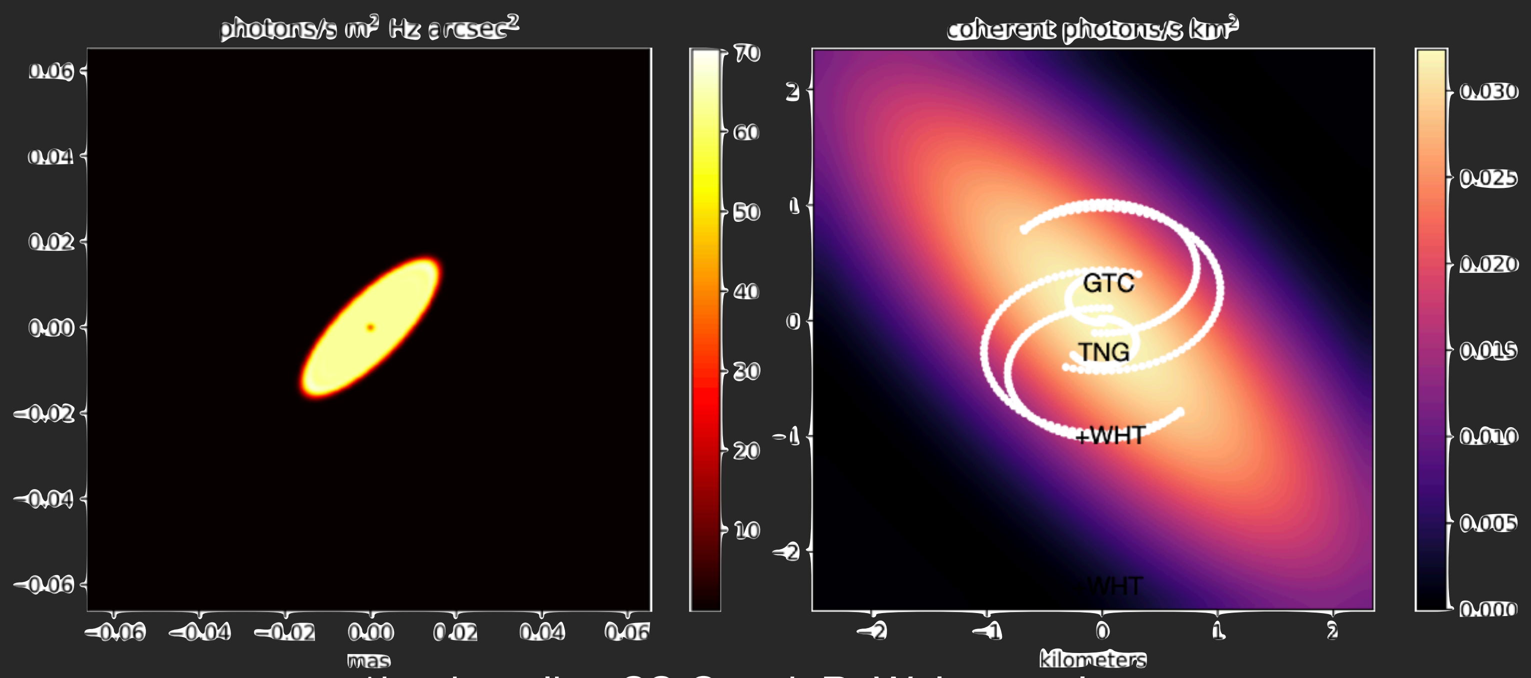


α Leo



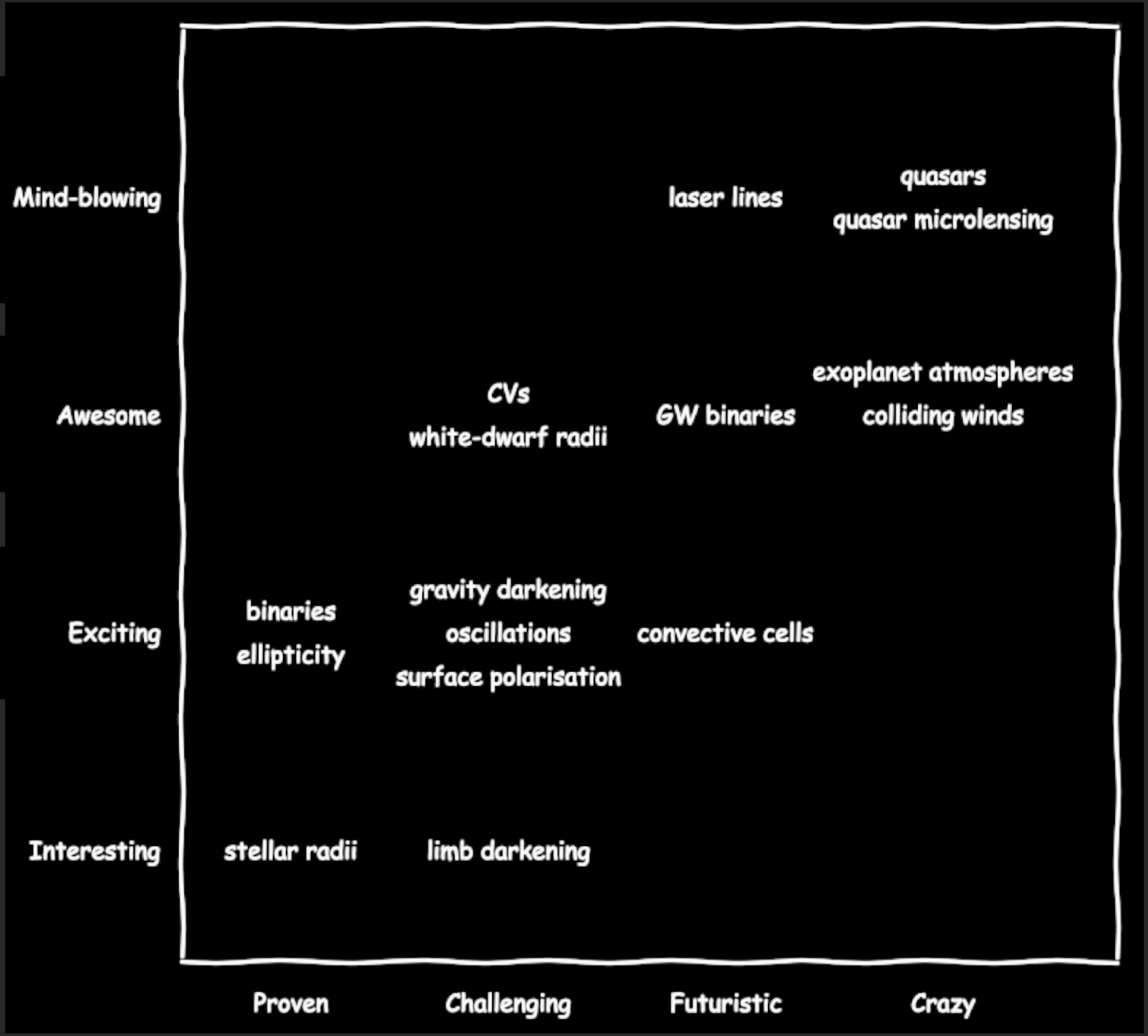
Exoplanet atmosphere





1km baseline SS Cygni R. Walter et al.

P. Saha et al. - SII workshop Porquerolles 2024



Summary

- Phase interferometry has reached maturity
  - No significant improvement in angular resolution foreseen over the coming decades
  - Many targets within the reach of existing facilities
- Intensity interferometry can improve the angular resolution by a factor 100
  - At visible wavelengths
- Many challenges to overcome
  - Picosecond time resolution
  - Light focusing from big instruments
  - Picosecond synchronisation over long distances
  - Yet undiscovered issues
    - Sub-mm metrology over kilometre baselines