Advances in “Amplitude” Interferometry

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Outline

- Science Motivations and Basic Principles
- Early optical interferometry experiments
  - Direct Detection, Intensity and Heterodyne (down-conversion) Interferometry
- Modern Era of Direct Detection Facilities
- Science Highlights
- Revival of Alternatives
  - Multiplexing, Wider bandwidths, Cherenkov Arrays
- Newest technique: Quantum "local oscillators"
- Future Facilities
- Discussion Points

Diffraction-*limited Imaging*

$$\Delta\theta \approx \frac{\lambda}{D}$$

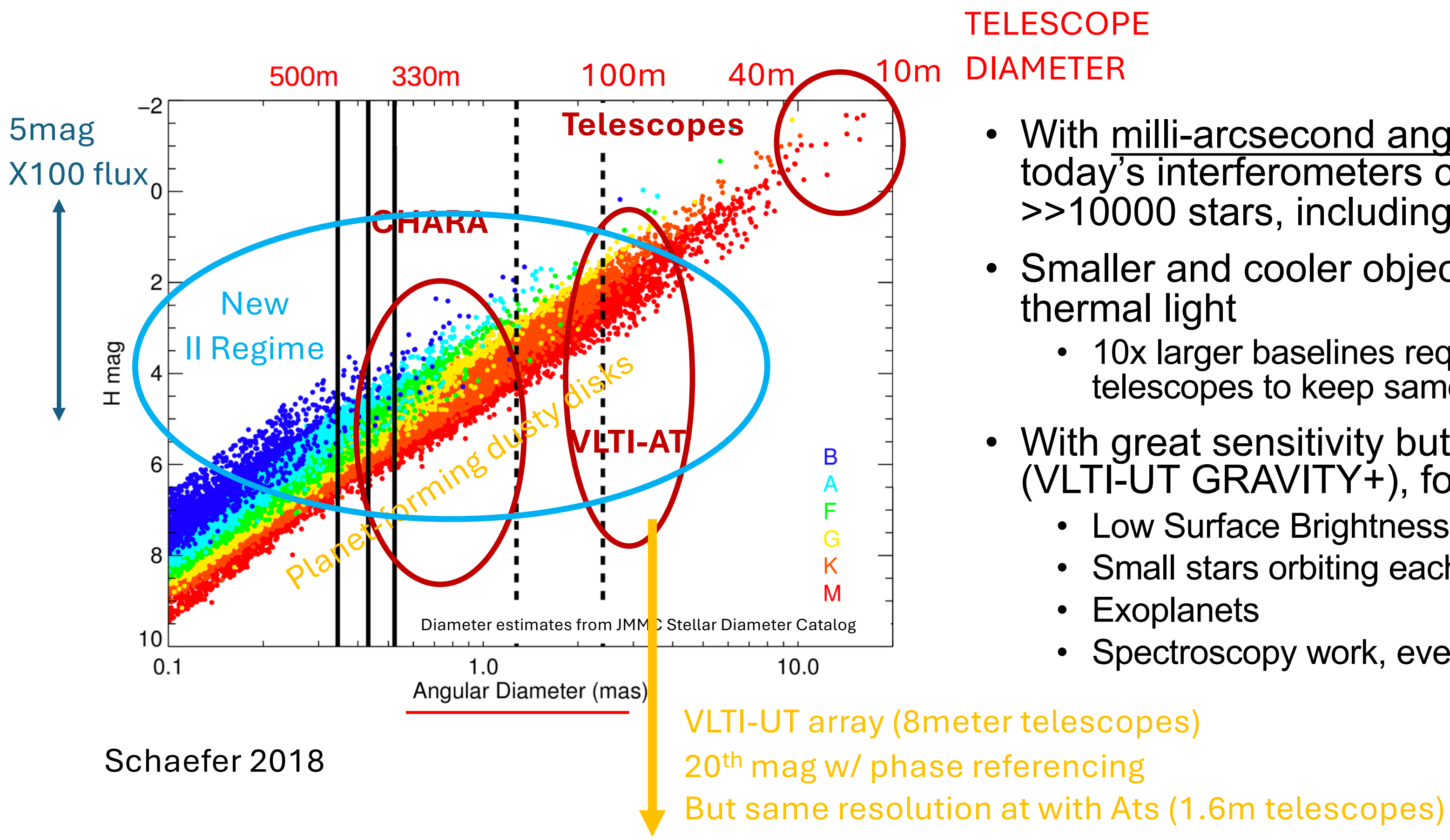
Wavelength of light

Diameter of telescope

Observatory	Wavelength	Diameter	Angular Resolution
James Webb Space Telescope	1.0 μm	6.5m	32 milliarcsecond (mas)
Keck Observatory	1.65 μm	10m	34 mas
E-ELT	1.65 μm	39m	9 mas

What stars can we resolve with current telescopes?

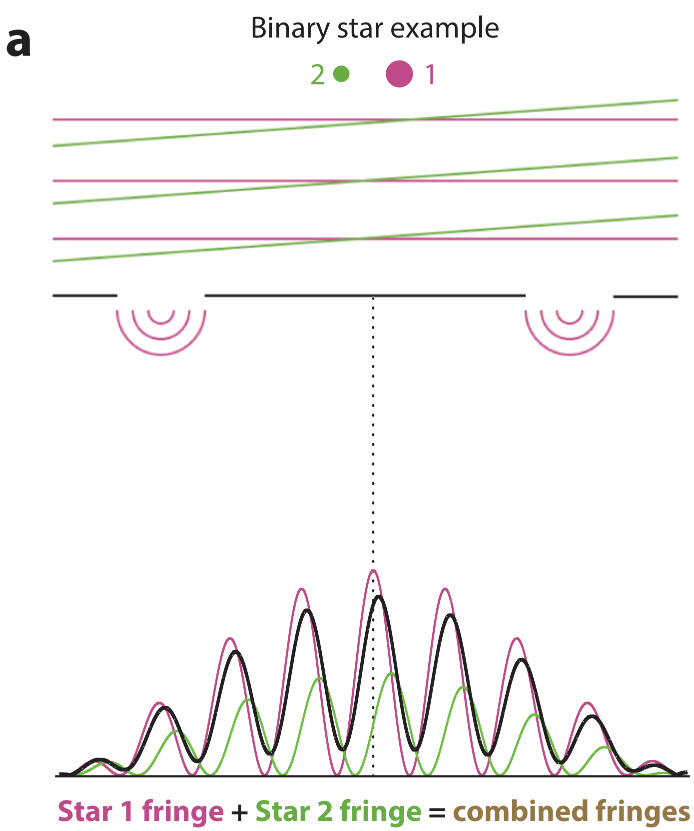
Stars in the Solar Neighborhood

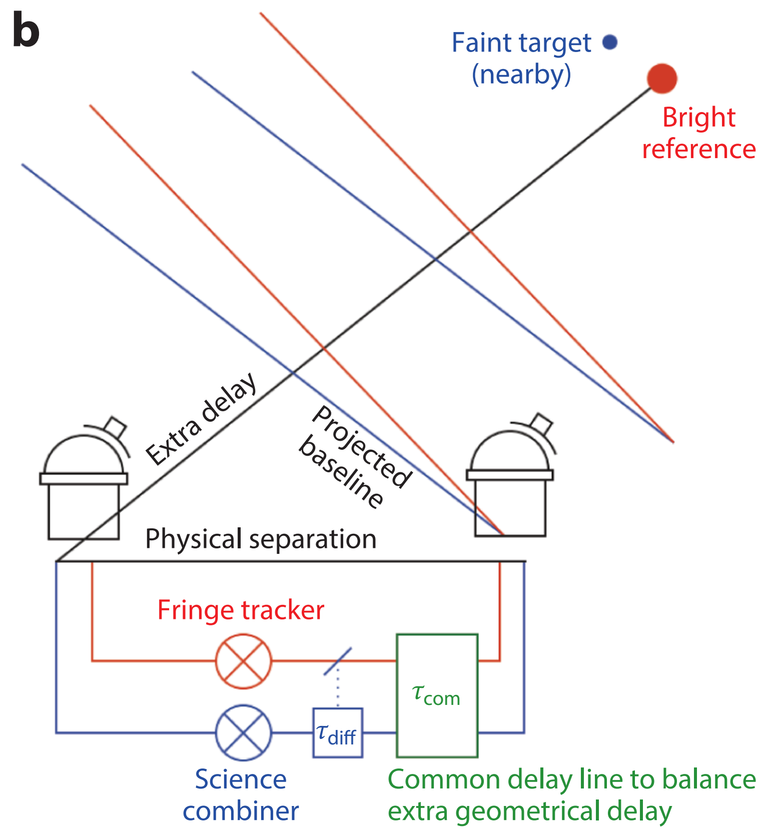


Schaefer 2018

- With milli-arcsecond angular resolution, today's interferometers can measure sizes of >>10000 stars, including most spectral types
- Smaller and cooler objects are fainter since thermal light
  - 10x larger baselines requires 10x larger diameter telescopes to keep same SNR
- With great sensitivity but short baselines (VLTI-UT GRAVITY+), focus on
  - Low Surface Brightness (dust)
  - Small stars orbiting each other (or black holes!)
  - Exoplanets
  - Spectroscopy work, even extragalactic

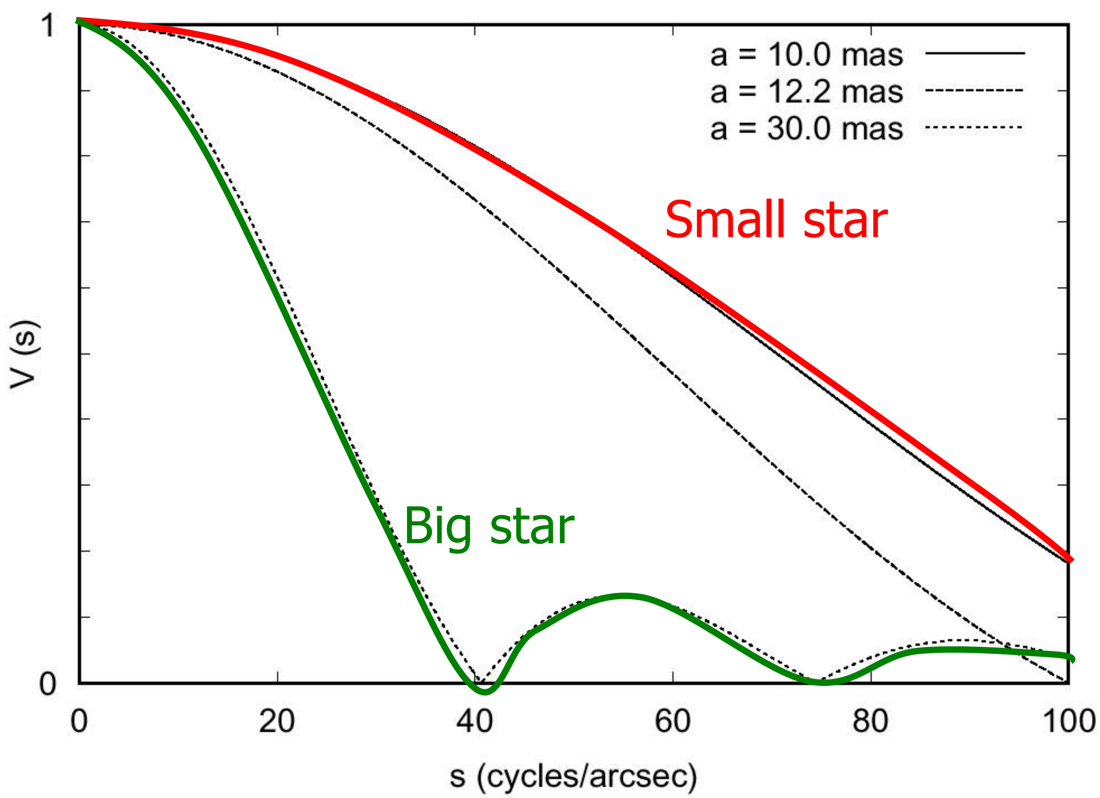
Basic Theory of Interferometry





Eisenhauer, Monnier & Pfuhl ARAA 2023

Examples of Visibilities: Stars



Baseline/wavelength

Uniform Disk:

$$V(s) = \left| \frac{2J_1(\pi a s)}{\pi a s} \right|$$

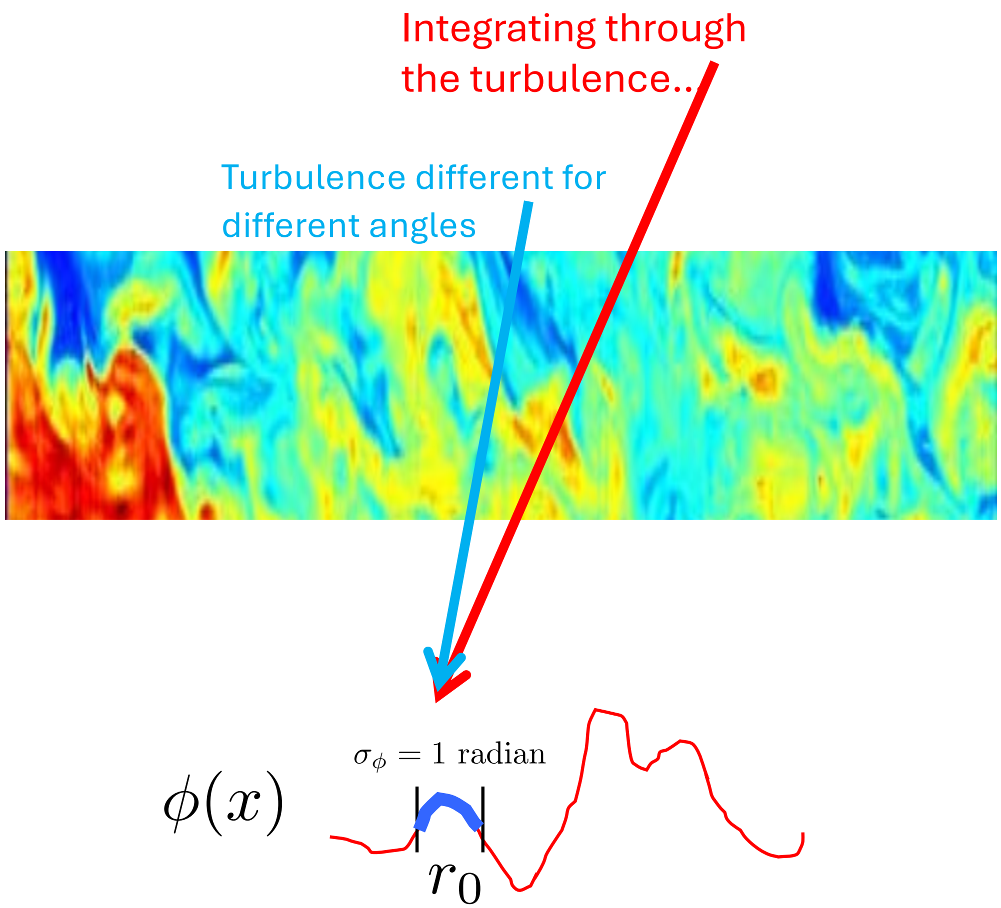
Low visibilities on long baselines can be tracked using "baseline bootstrapping" (not available for Intensity interferometry)

Note: 2nd lobe has 100x lower SNR in V2, requires 10^4 times longer integration

From the Michelson Summer School Notes 2000

Turbulence

- Coherence Length (r_0) of atmosphere:
  - ~20cm in visible
  - **~50cm** at 2.2 microns
  - Adaptive Optics needed for D>1m
- Coherent integration time
  - ~10 ms in visible
  - ~25 ms at 2.2 microns
- Field of view, isoplanatic patch
  - 5-10” in visible
  - 12-25” at 2.2microns
- Decoherence of fringes:
  - Ruins Fourier phase, except close phase
  - Limits dual-star fringe tracking, sky coverage
  - Limits astrometry precision drastically



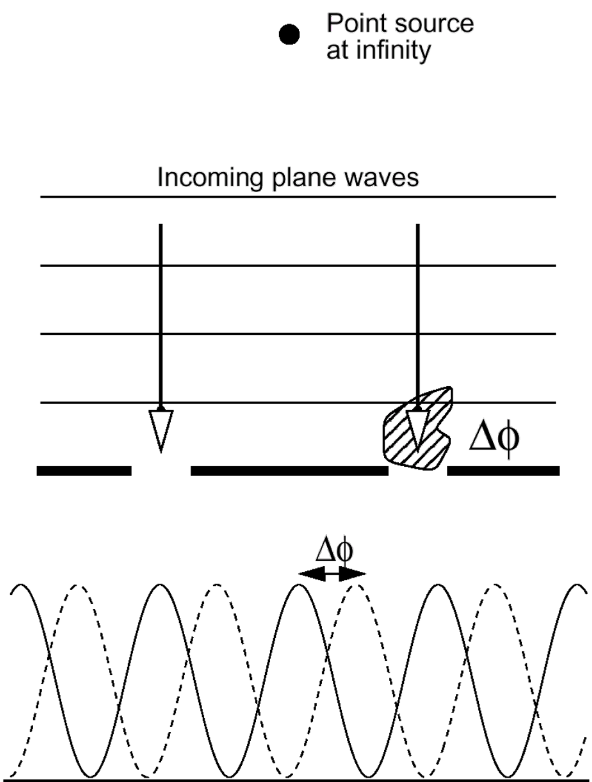
Atmosphere Corrupts the Phase

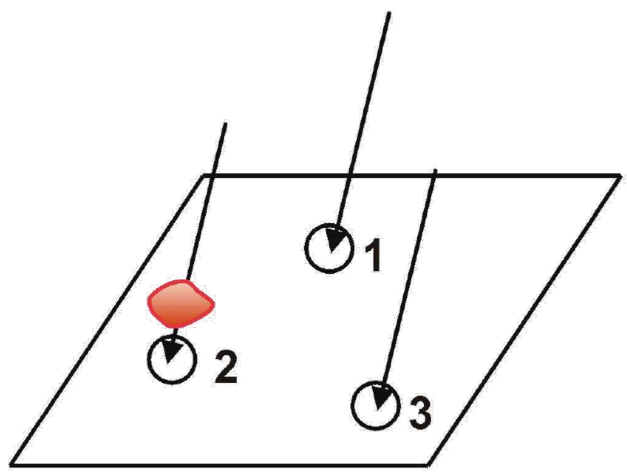
Science targets phases can be recovered by simultaneously measurements of a very nearby (bright) calibrator star

- Also allows long integrations to increase sensitivity!

Or, Closure phases are immune to phase variations above the telescopes

- cosine(cphase) available for intensity interferometry, but at very low SNR



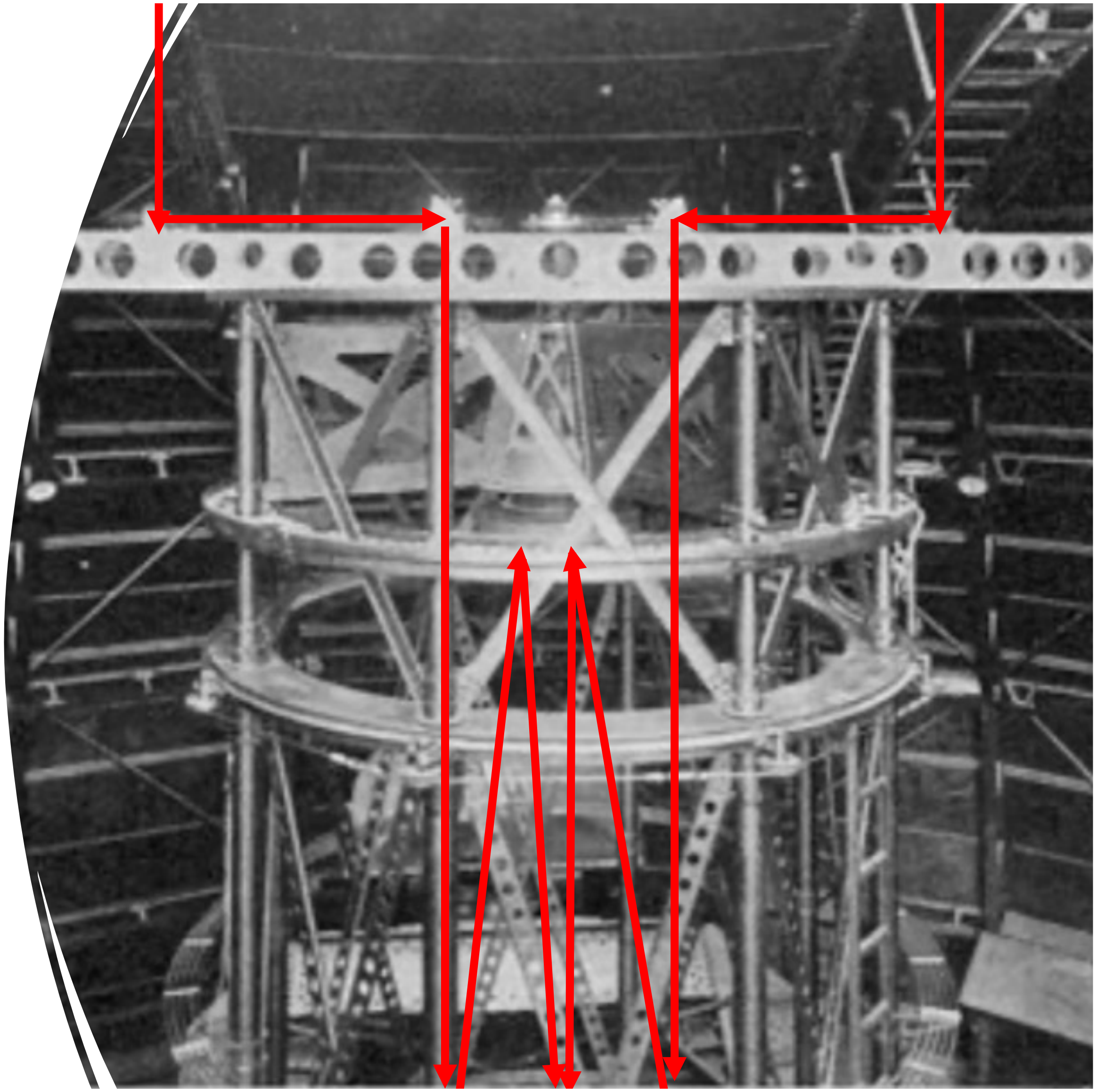


Observed		Intrinsic		Atmosphere
$\Phi(1\text{-}2)$	$=$	$\Phi_o(1\text{-}2)$	$+$	$[\phi(2)-\phi(1)]$
$\Phi(2\text{-}3)$	$=$	$\Phi_o(2\text{-}3)$	$+$	$[\phi(3)-\phi(2)]$
$\Phi(3\text{-}1)$	$=$	$\Phi_o(3\text{-}1)$	$+$	$[\phi(1)-\phi(3)]$

Closure Phase (1-2-3) $= \Phi_o(1\text{-}2)+\Phi_o(2\text{-}3)+\Phi_o(3\text{-}1)$

First Stellar Interferometry

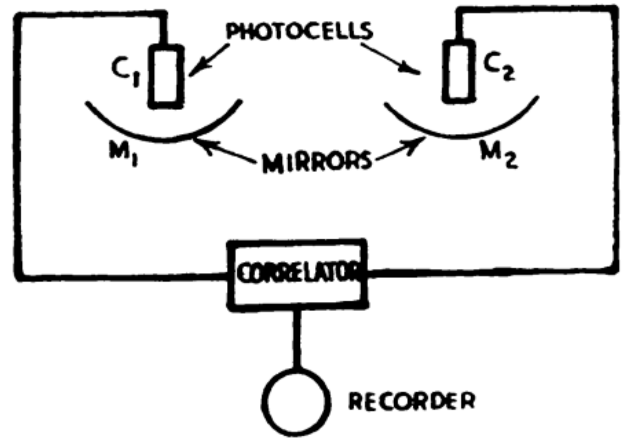
- Michelson and Pease (1921) resolved Betelgeuse and few other red giants using an interferometer installed on the top of the Mt. Wilson 100”
- Later attempts to go to longer baselines failed using separate telescopes



Intensity Interferometry

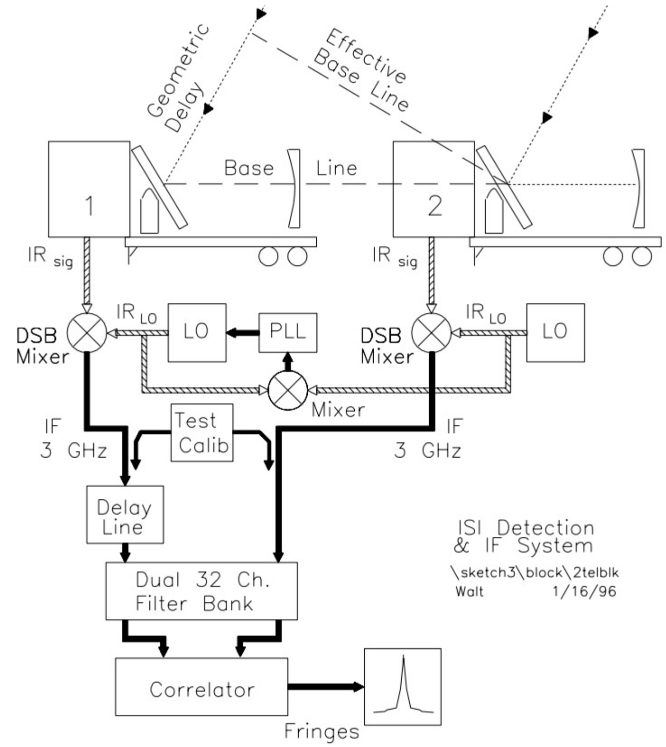
- Hanbury-Brown & Twiss (1956) showed intensity correlations between photons arriving at two separated detectors
  - Probability of detecting of a photon proportional to square of the classical electric field amplitude
- Narrabri Stellar Intensity Interferometry carried out important stellar diameter work (e.g.,Hanbury Brown, Davis & Allen 1974) that stands today
- SNR proportional to (square root of) electronic bandwidth (~GHz), not optical bandwidth (100 THz)
- Pros: can use light buckets, local detection of photons allowing (in principle) long baselines, interference in post-processing, no delay lines, can copy signals and interfere with as many telescopes needed w/o loss of SNR
- Cons: Poor sensitivity, SNR $\propto V^2$, narrow optical bandwidths, limited phase information

RECENT results across the world for Cherenkov Arrays, such as MAGIC and VERITAS

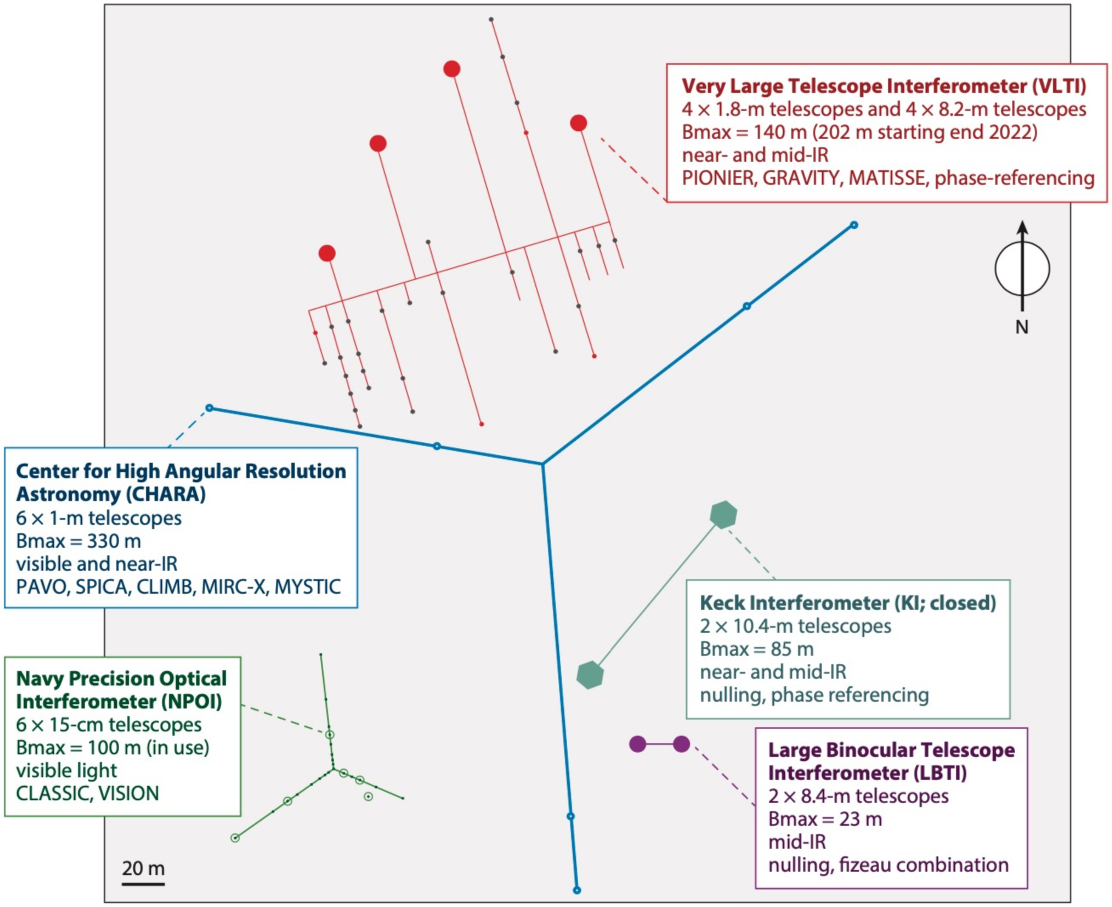


Heterodyne (down-conversion) Interferometry

- Common in radio to mix sky signal with a ``local oscillator (LO)" to shift the spectrum to lower frequencies
  - Final Frequency: True frequency – LO frequency ("beat note")
- Charles Townes UCB (and Jean Gay, Côte d'Azur)) developed infrared "heterodyne" stellar interferometry
  - LO = CO2 laser at 11microns; Kitt Peak McMath + ISI @ Mt. Wilson
  - Major contributions to evolved star science, e.g., Danchi et al. 1994
- Unavoidable quantum fluctuations of LO ("shot noise") introduce extra background: $T_{bg} \approx h\nu/k$
  - ~1400K at 10μm, 14000K at 1μm (!)
  - SNR related to electronic bandwidth, not optical bandwidth
- Pros: Local detection, interference in post-processing possible, no topical delay lines, can copy signals and interfere with as many telescopes needed w/o loss of SNR
- Cons: Poor sensitivity, quantum shot noise, narrow bandwidths, need to coherently distribute the LO between telescopes

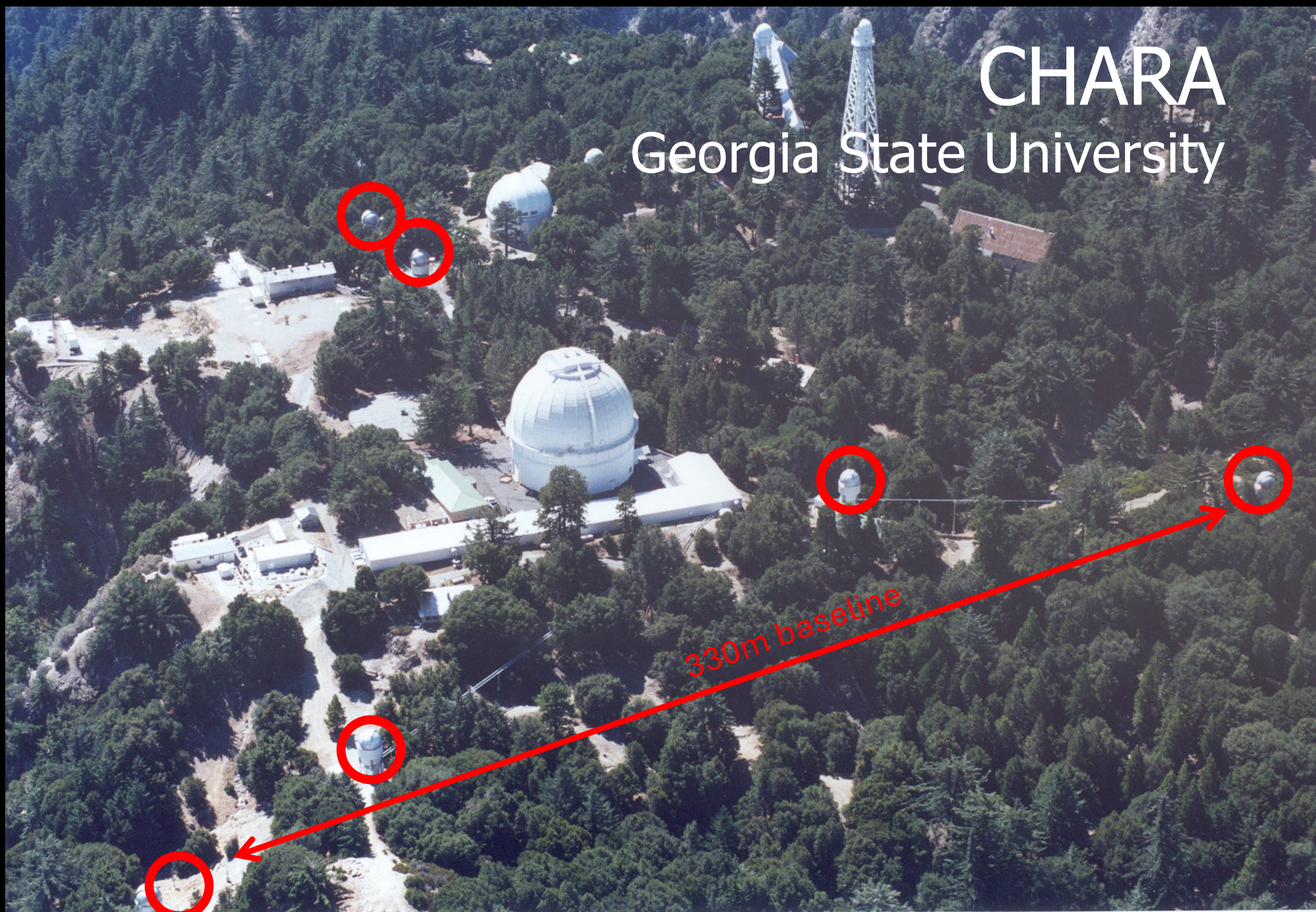


Current Optical/Infrared Interferometers



Eisenhauer, Monnier & Pfuhl ARAA 2023

- Center for High Angular Resolution Astronomy (CHARA)
  – 6Tx1m, 330m (mag 7.5)
- Very Large Telescope Interferometer
  - 4Tx1.8m, 200m (mag 9)
  - 4Tx8m, 140m **(mag 20 !)**
- Navy Precision Optical Interferometer
  - 6Tx15cm, 100m (mag 6)
- Large Binocular Telescope Interferometer
  - 2Tx8.4m, 23m nulling



Visible combiners:

- PAVO (2T)
- SPICA (6T)

IR combiners

- CLASSIC (2T)
- CLIMB (3T)
- MIRCX (6T, J+H)
- MYSTIC (6T, K)

Very Large Telescope Interferometer (VLTI)

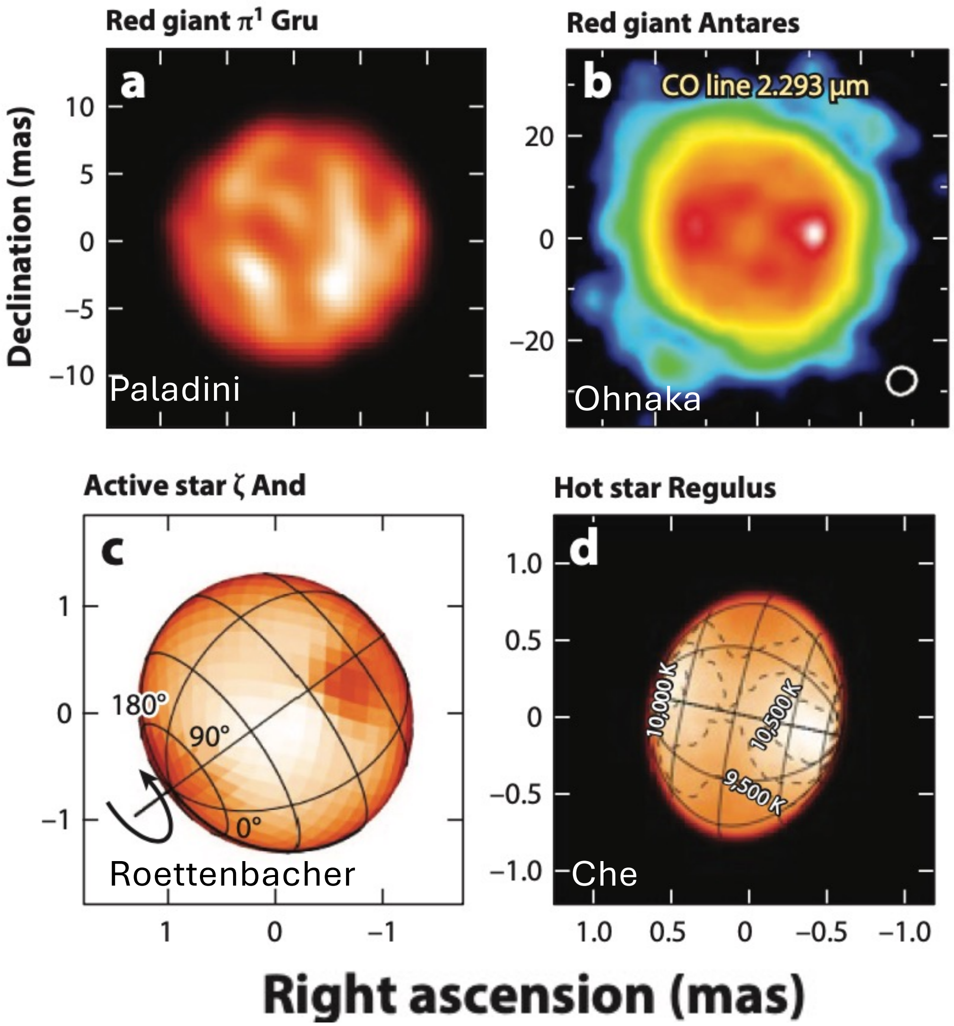
GRAVITY Combiner

- Uses all four 8m VLT Telescopes
  - Baselines up to 140m
- K band (2.2 microns) Integrated Optics Combiner
- Infrared APD Arrays (320x256)
  - <1e– read noise at >khz rates
- Phase referencing within 3”
  GRAVITY Wide expands this to 30”
  & GRAVITY+ extends sensitivity (phase ref star 9^{th}->13^{th}) using laser guide stars

Also: PIONIER combiner (H band) and MATISSE (3-12microns)

Imaging Stars

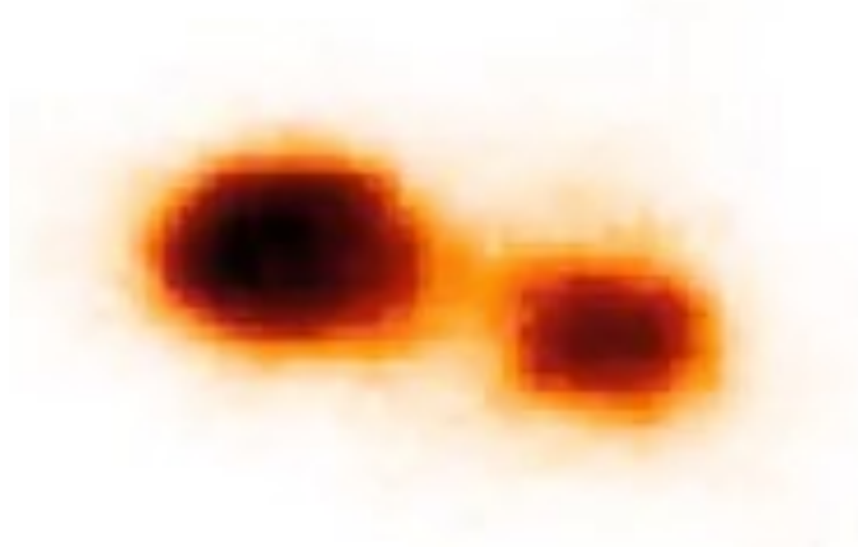
Eisenhauer, Monnier & Pfuhl ARAA 2023



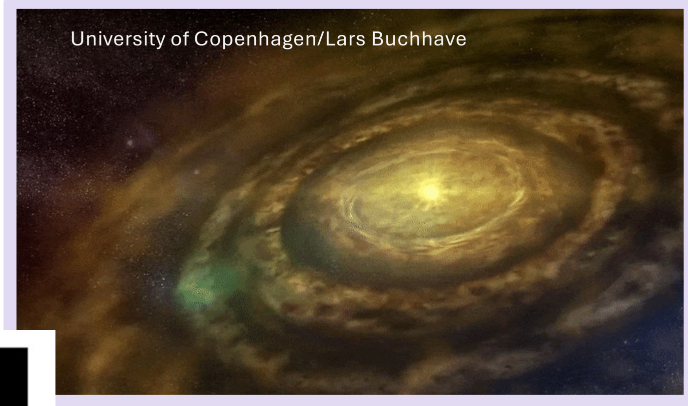
β Lyr

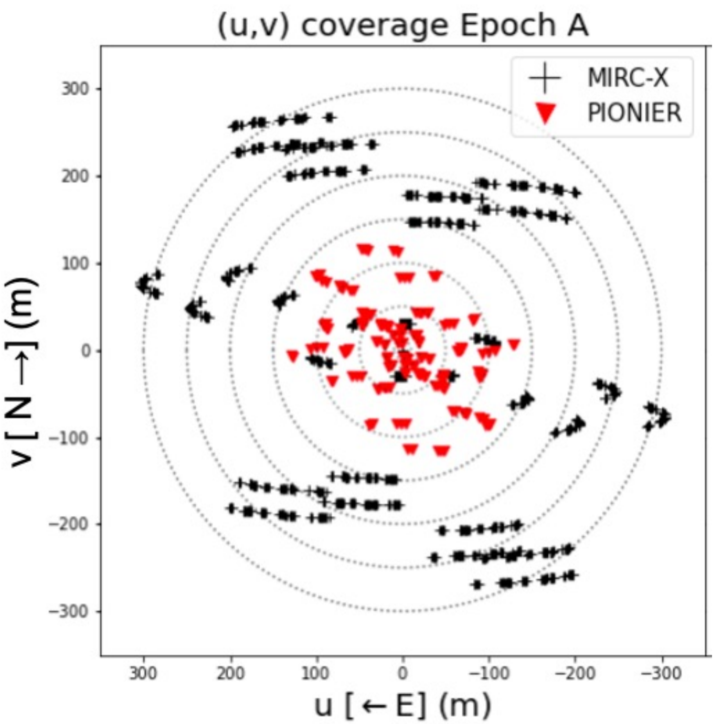
Interacting binary separation 1mas

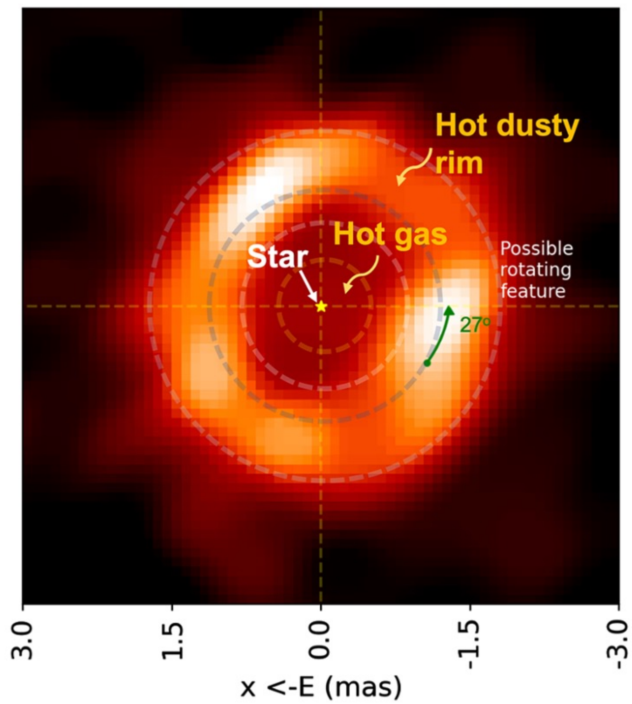
(Zhao et al)



Imaging Planet-forming Disks

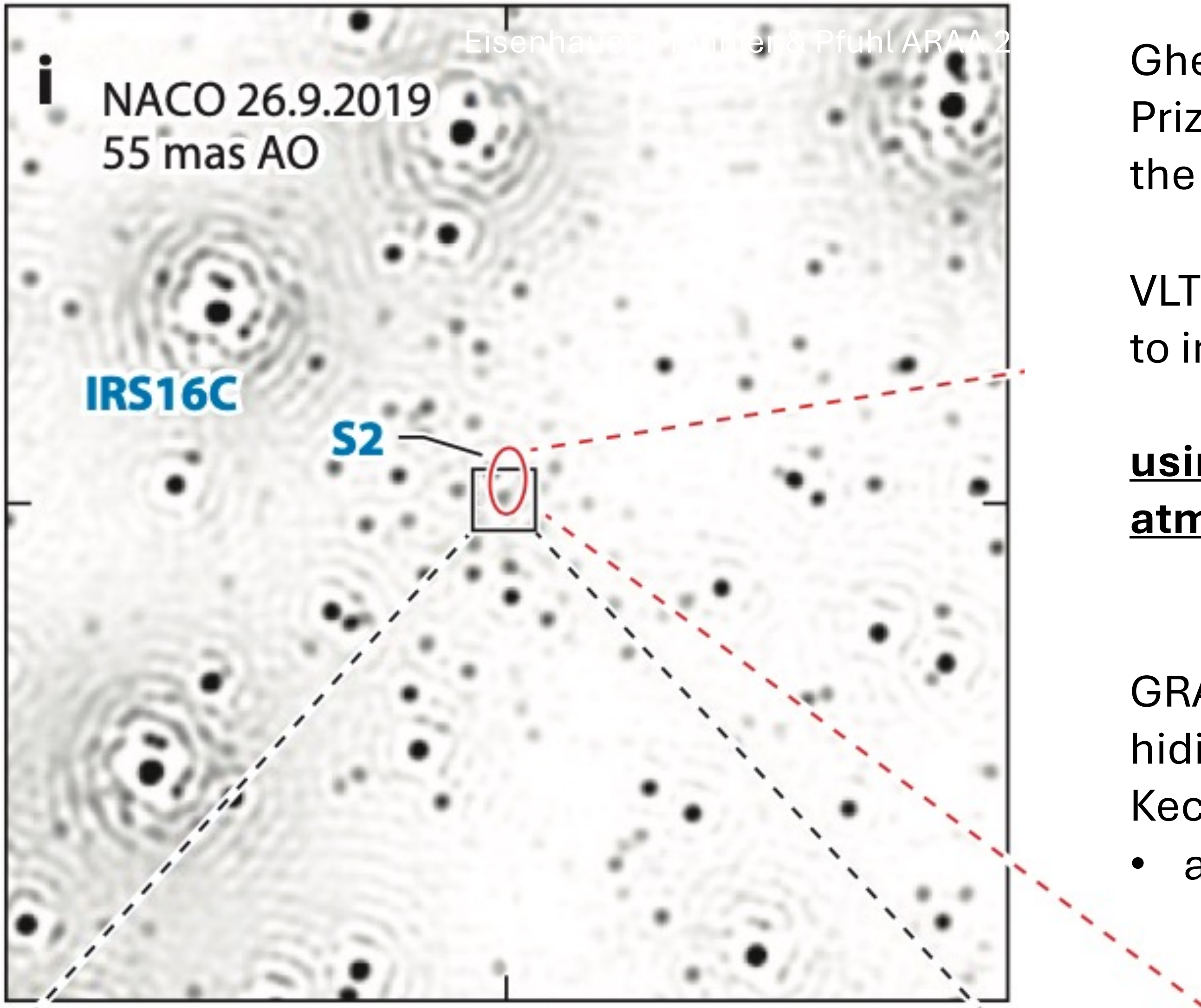






3mas diameter hot dust ring around v1295 Aql

Ibrahim et al. 2023



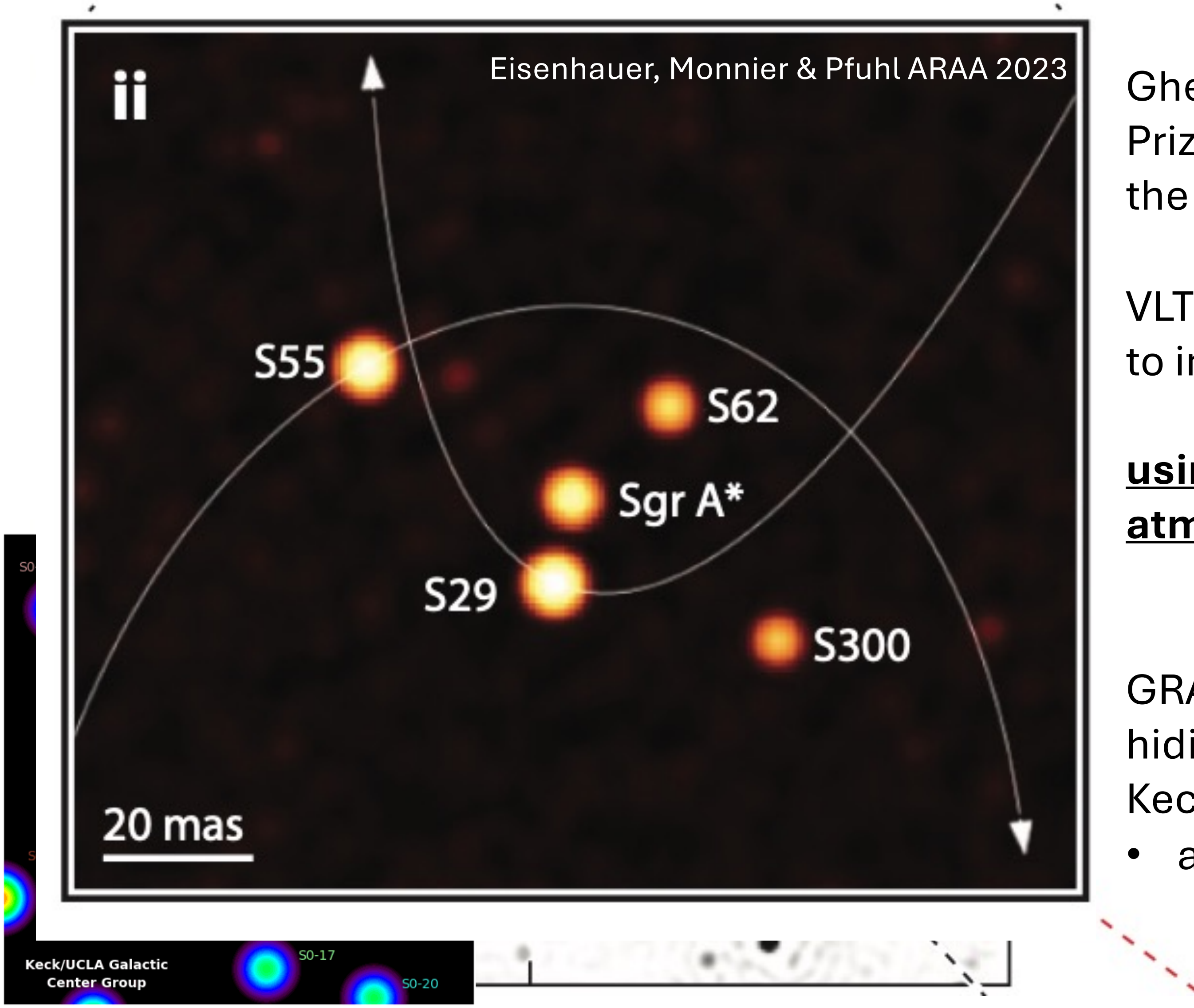
Ghez and Genzel won 2020 Nobel Prize for studies of stars orbiting the Galactic Center

VLTI-GRAVITY instrument designed to improve angular resolution

<u>using bright nearby star to track atmospheric turbulence!</u>

GRAVITY discovered more stars hiding “inside” one pixel of Keck/VLT!

- as faint as K 19th mag



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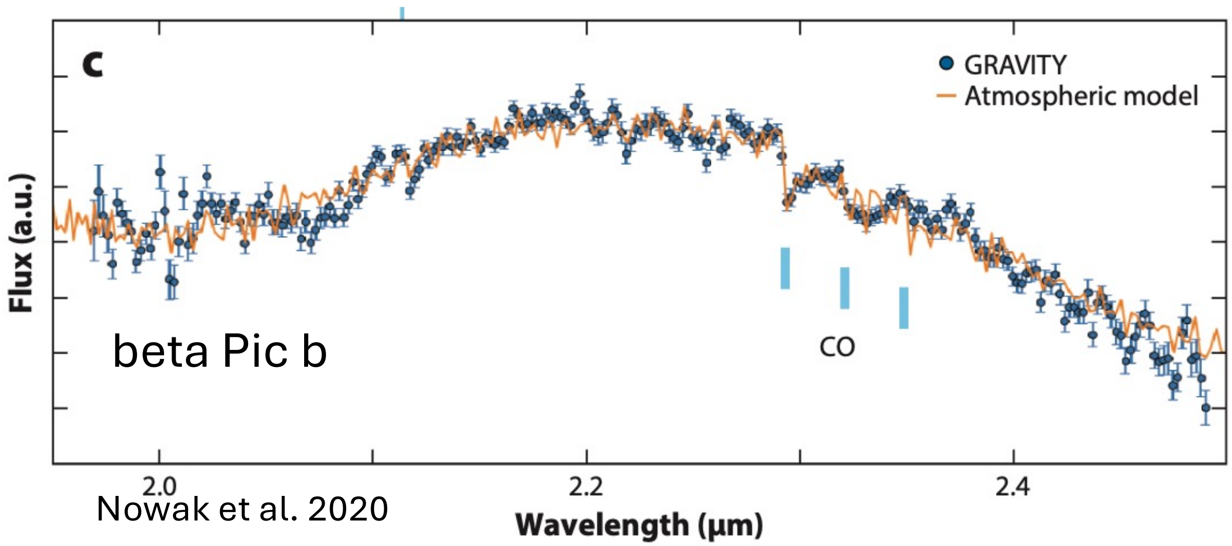
Exoplanets with Interferometry

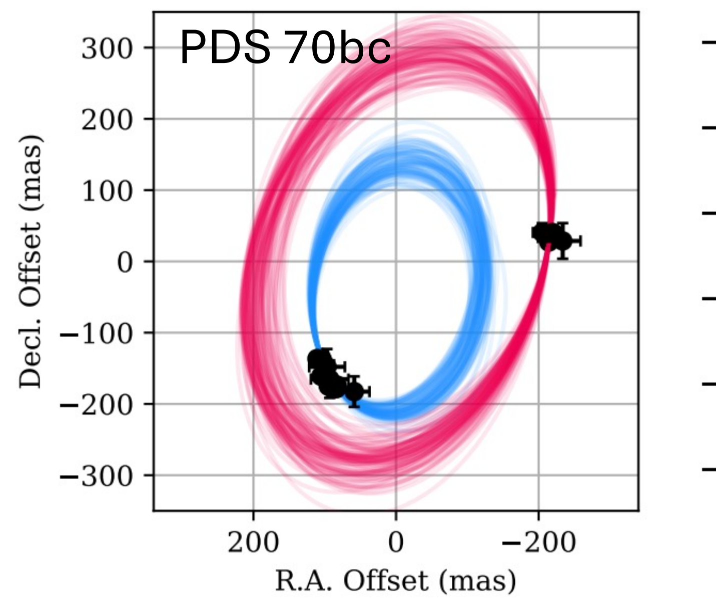
VLTI/GRAVITY can track on bright exoplanet host stars and use other fiber focus on an exoplanet

- Works on known AO-found exoplanets
- AND new GAIA planets inferred from astromet



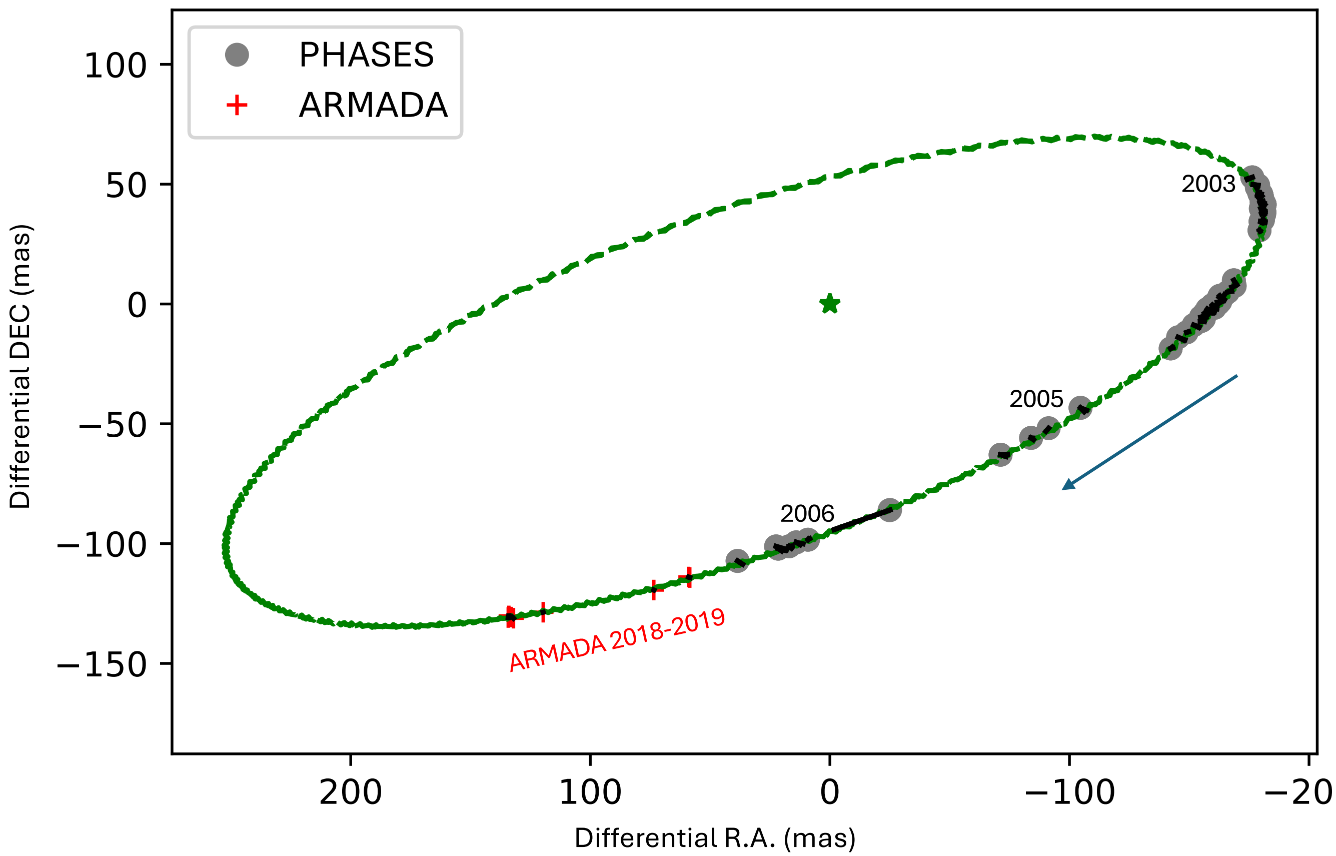
Nowak et al. 2020

10-50x better astrometry than adaptive optics to allow orbits to be constrained!



Wang et al. 2023

CHARA/MIRCX can do extremely precise differential astrometry between close binaries

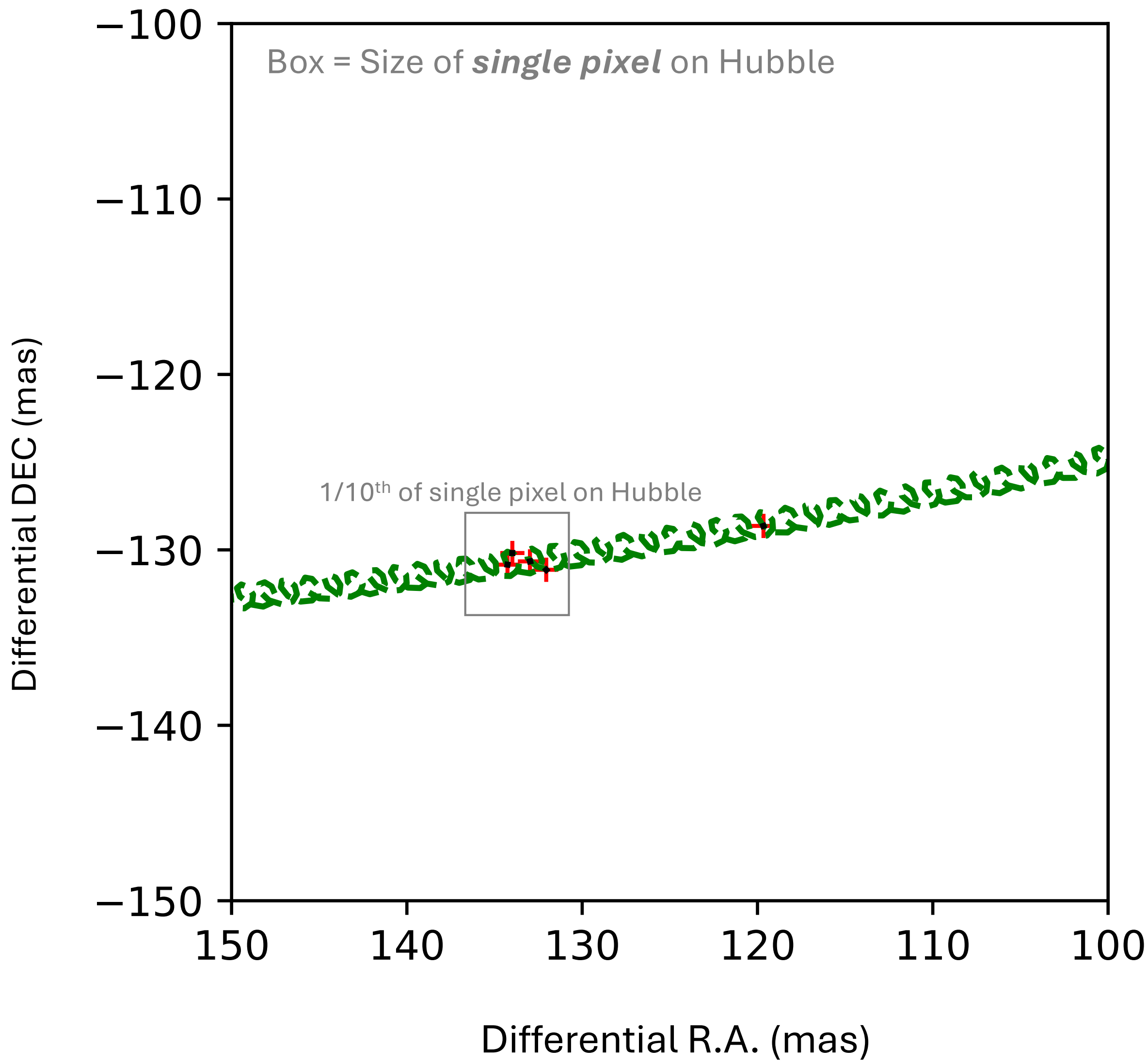


Kappa Peg

Known triple system: Muterspaugh et al (2010)

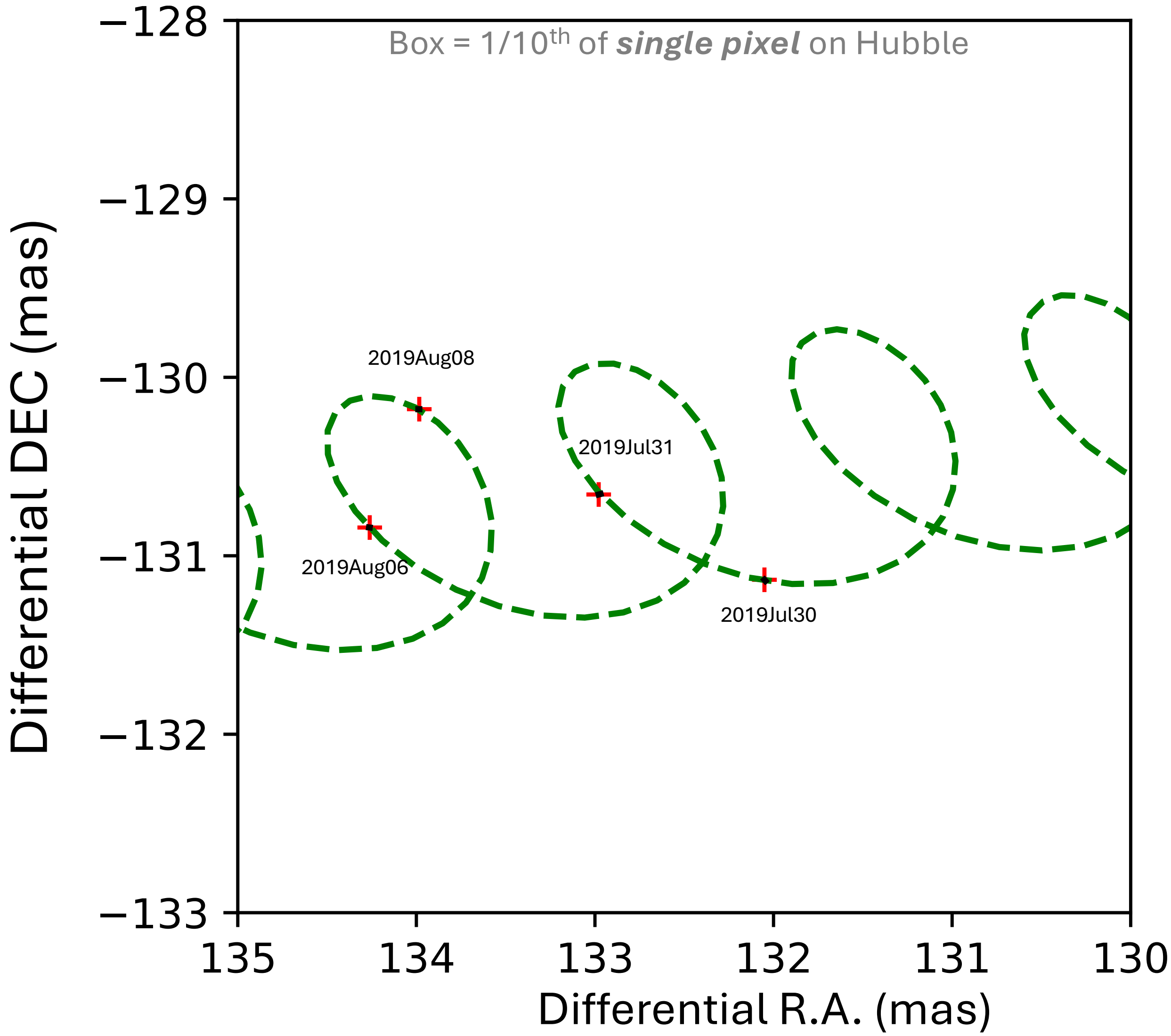
Gardner et al (2021a)

Kappa Peg



Box = Size of ***single pixel*** on Hubble
1/10th of single pixel on Hubble
−100
−110
−120
−130
−140
−150
Differential DEC (mas)
150
140
130
120
110
100
Differential R.A. (mas)

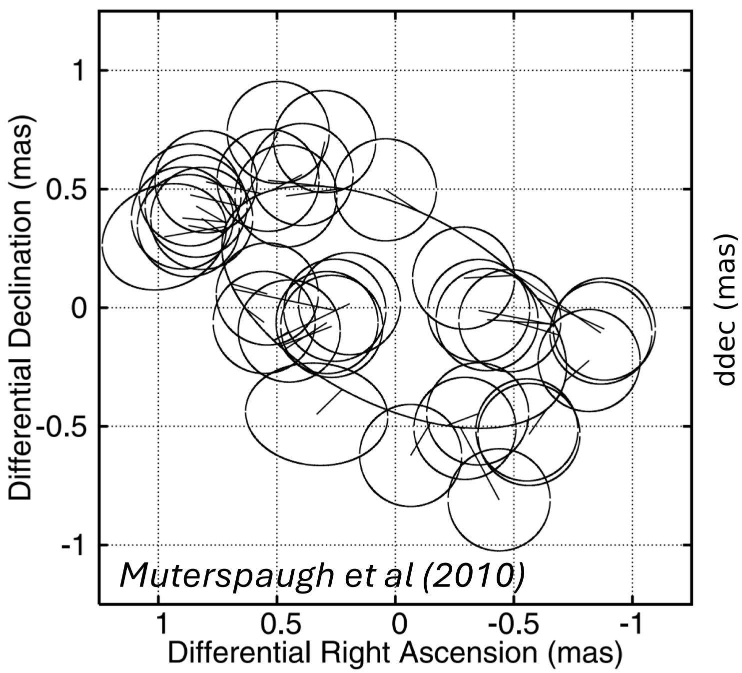
Kappa Peg


Box = 1/10th of *single pixel* on Hubble
2019Aug08
2019Jul31
2019Aug06
2019Jul30
−128
−129
−130
−131
−132
−133
135
134
133
132
131
130
Differential DEC (mas)
Differential R.A. (mas)

Kappa Peg

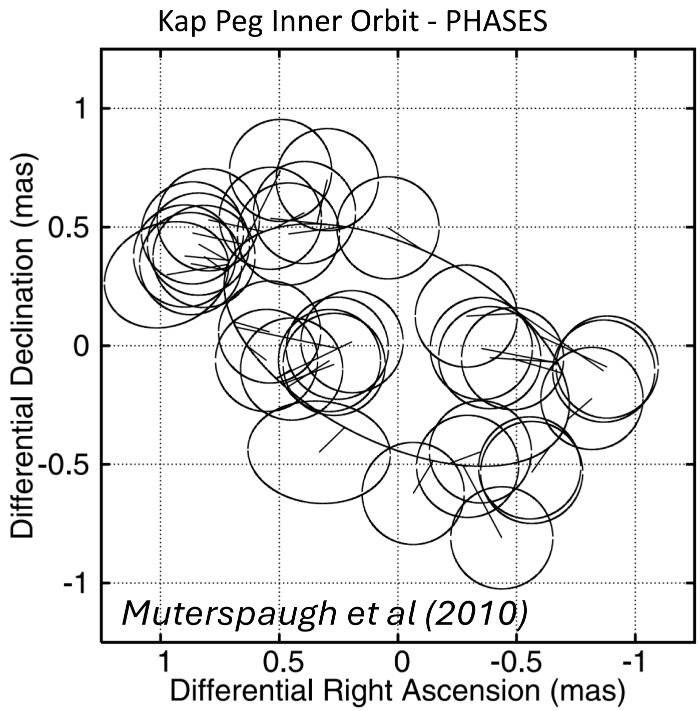
Box = 1/50th of ***single pixel*** on Hubble

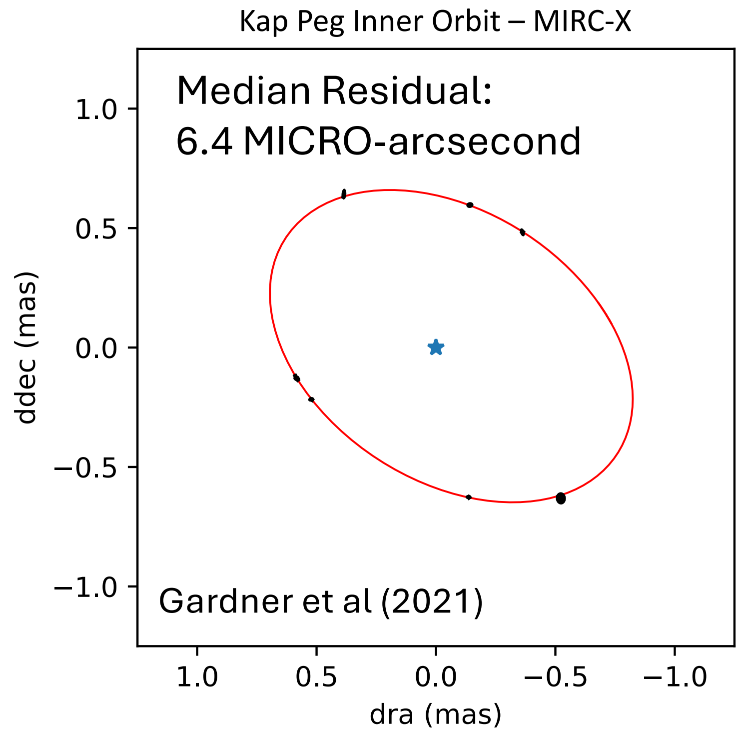
Kap Peg Inner Orbit - PHASES



Kappa Peg

Box = 1/50th of ***single pixel*** on Hubble



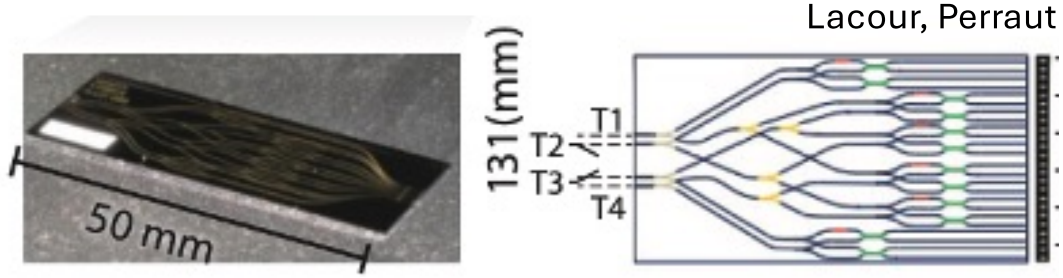


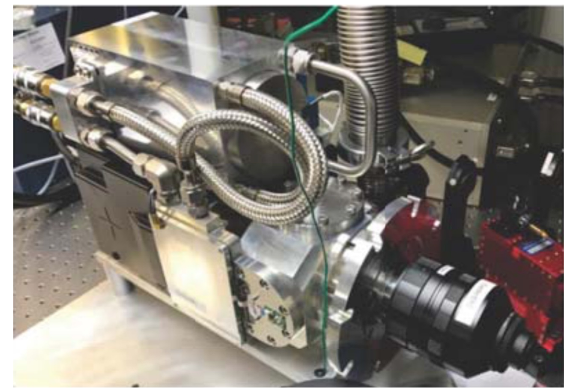
CHARA/MIRC astrometric precision is better than GAIA and can reveal giant exoplanets in theses systems

Technology

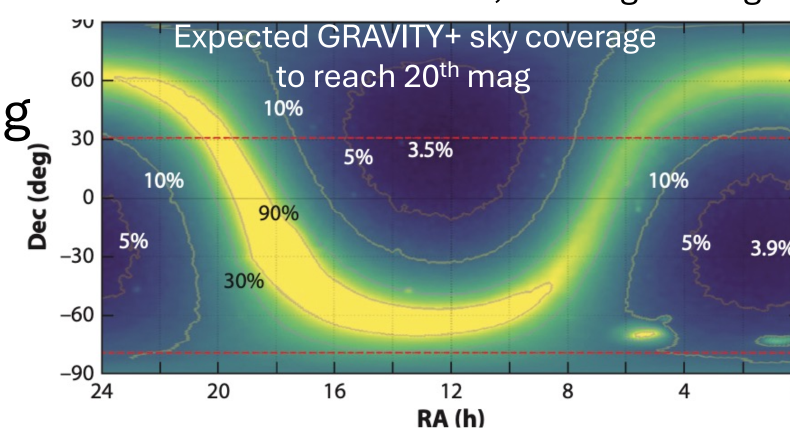
- Laser Metrology
- Single-mode Fibers for Spatial Filtering
- Integrated Optics Beam Combination
- e-APD NIR camera
  - <1 e- read noise at >2khz
- Dual-star phase referencing
- Laser Guide Star Adaptive Optics

Lacour, Perraut





Selex, First Light Imaging

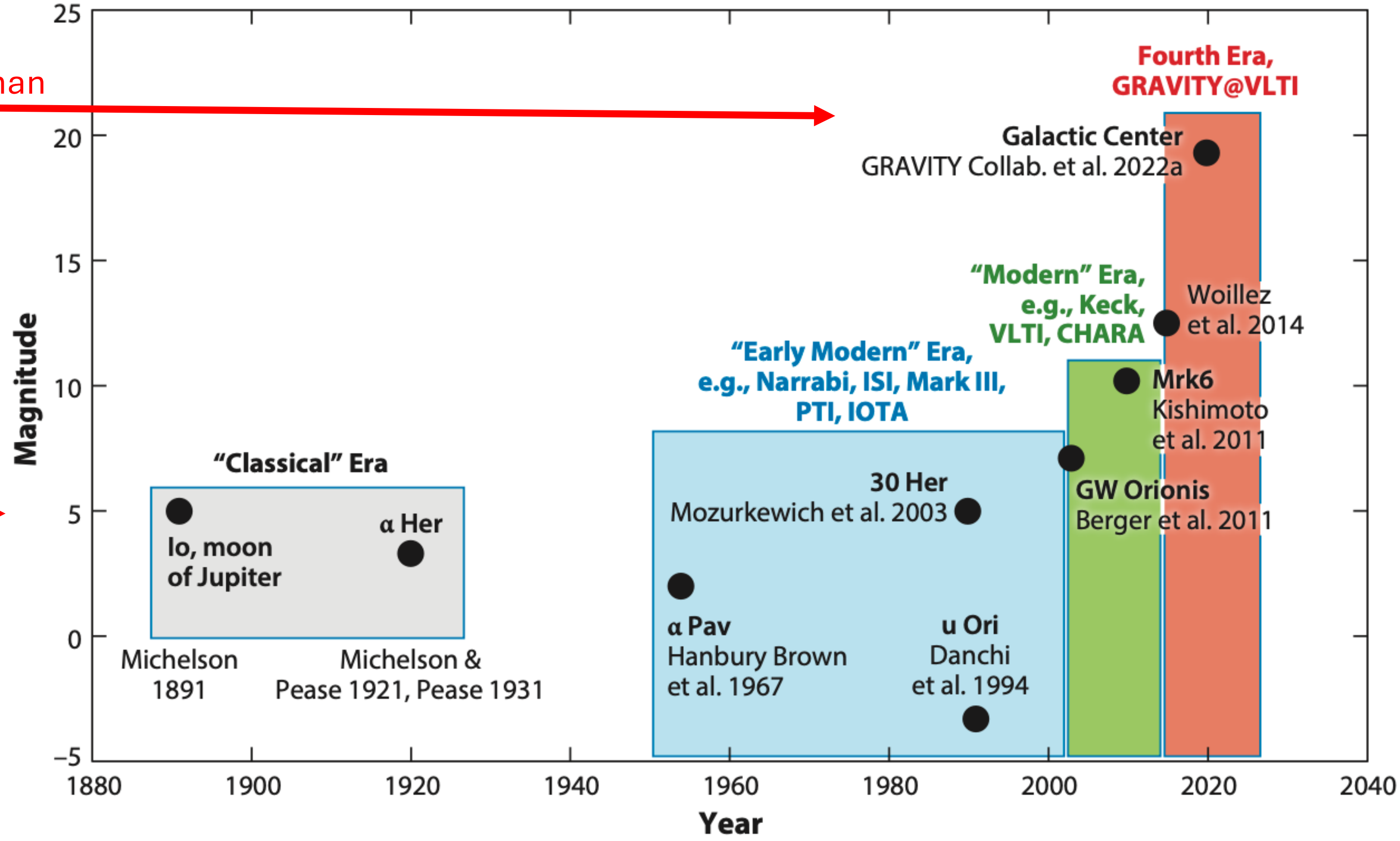


History of Sensitivity Improvements

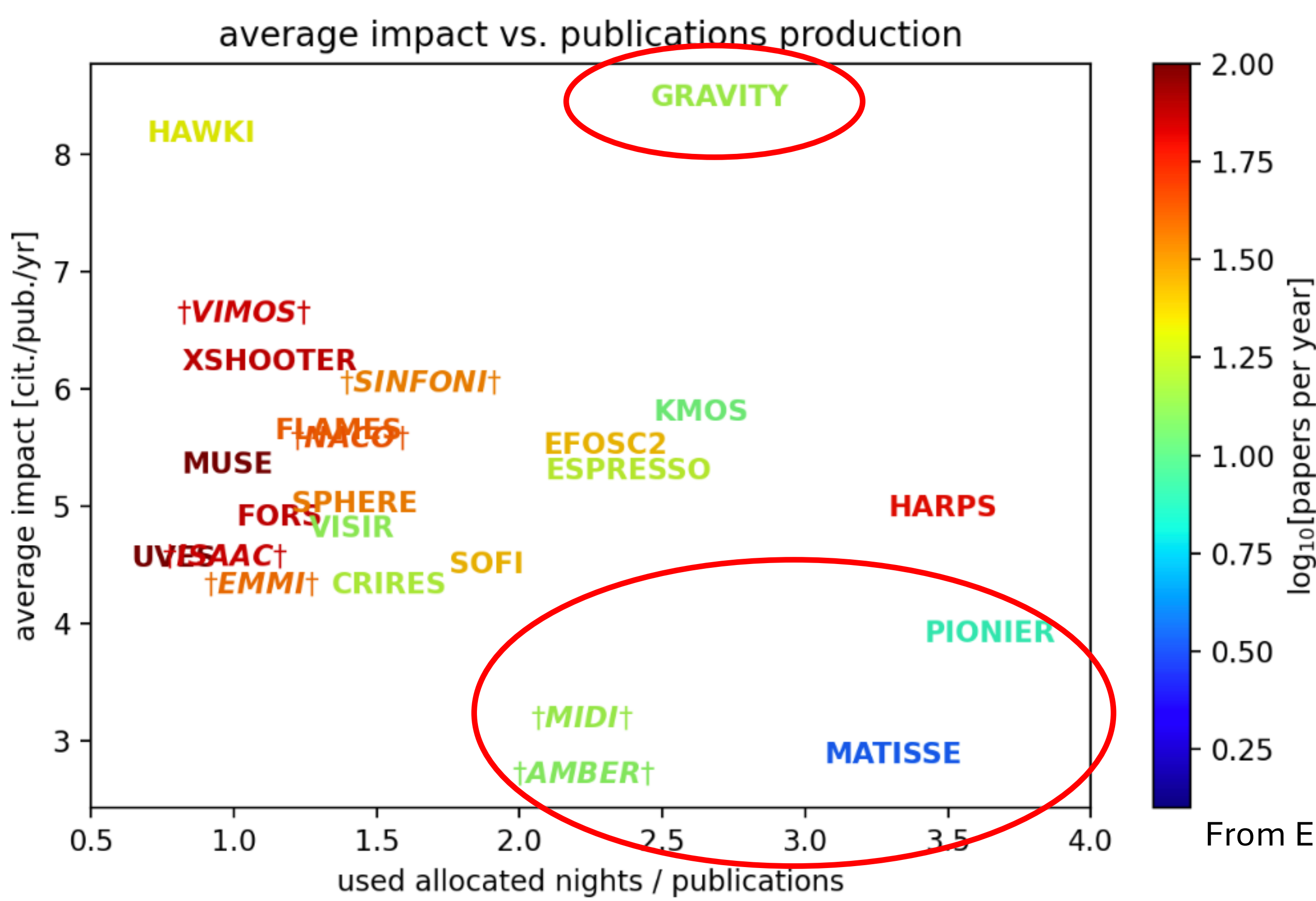
Eisenhauer, Monnier & Pfuhl ARAA 2023

20th mag with
phase referencing
(1million x fainter than
naked eye,
50000x better than
CHARA)

Naked eye



Sensitivity matters….



From ESO VLTI Program Scientist
Antoine Merand

Revival of Alternatives

Interest in intensity and down-conversion interferometry has been renewed, fueled by technical advances:

- High-QE (large bandwidth, short time) single-photon detectors
  - In arrays !
- Laser combs
- Multiplexing wider bandwidths, broadband digitizers >100GHz
- Phase-stabilized visible/IR lasers
- Ultra-high reflectivity coatings (99.9999% over broad bands)
- Up-conversion
- Astrophotonics, new fibers, accessible foundries, telecom synergy
- Mature Cherenkov array facilities

Many of these technologies have Quantum Synergies – a welcome new source of funds for Tech Development!

Quantum Local Oscillator

PRL 109, 070503 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

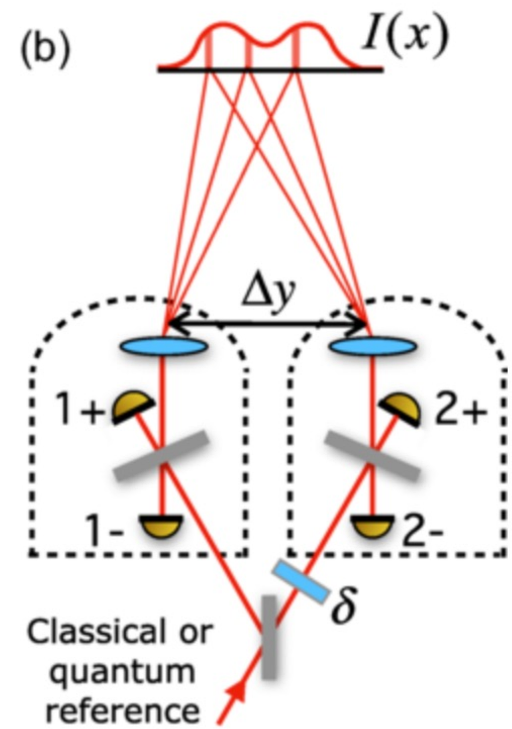
Longer-Baseline Telescopes Using Quantum Repeaters

Daniel Gottesman, Thomas Jennewein,
Sarah Croke

Modelled after Gottesman et al. 2012

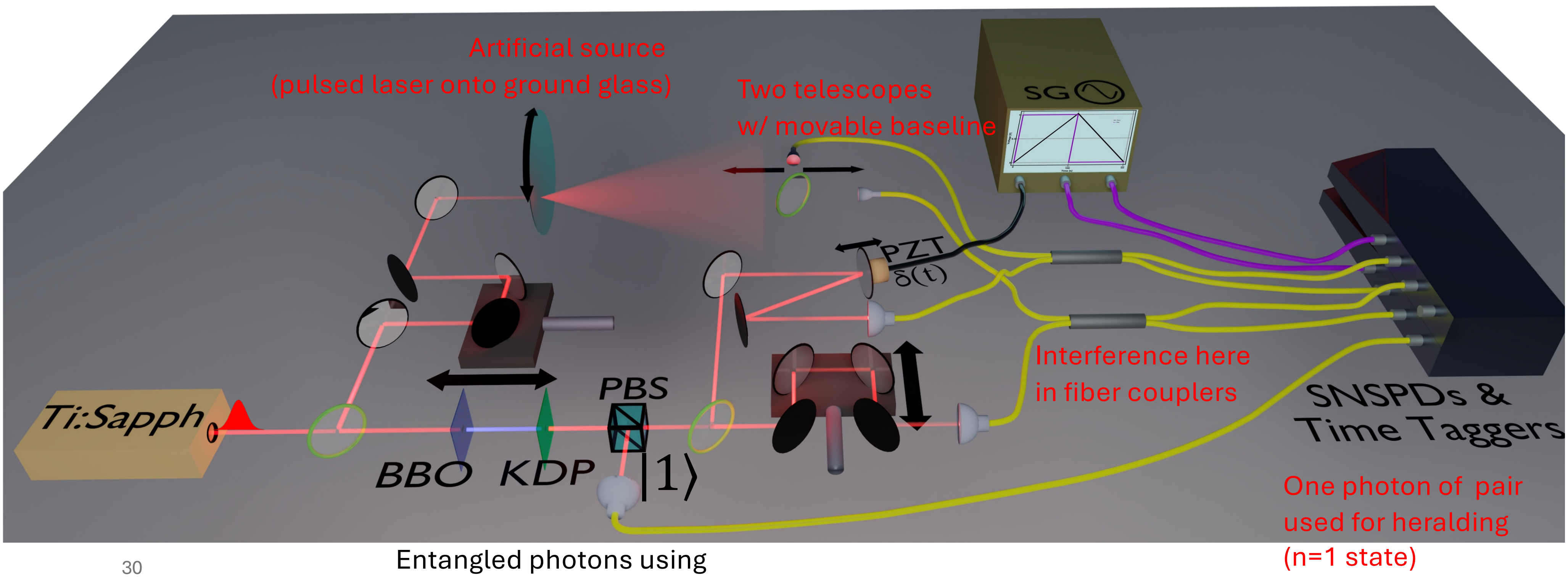
Use entangled photon source to create a single photon (n=1) state

- Acts as a local oscillator with no extra photon noise
- First lab test Brown et al. 2023
  - See next slides…
- Pros: Local detection, no excess shot noise
- Cons: Narrow bandwidths, need to distribute QLO
- <u>Awaiting Quantum network or long-lived Quantum Memories to be ‘better’ than direct-detection</u>



Demonstrating <u>table-top interferometric imaging</u> using a path-entangled single photon towards quantum telescopy (Brown et al. PRL 2023)

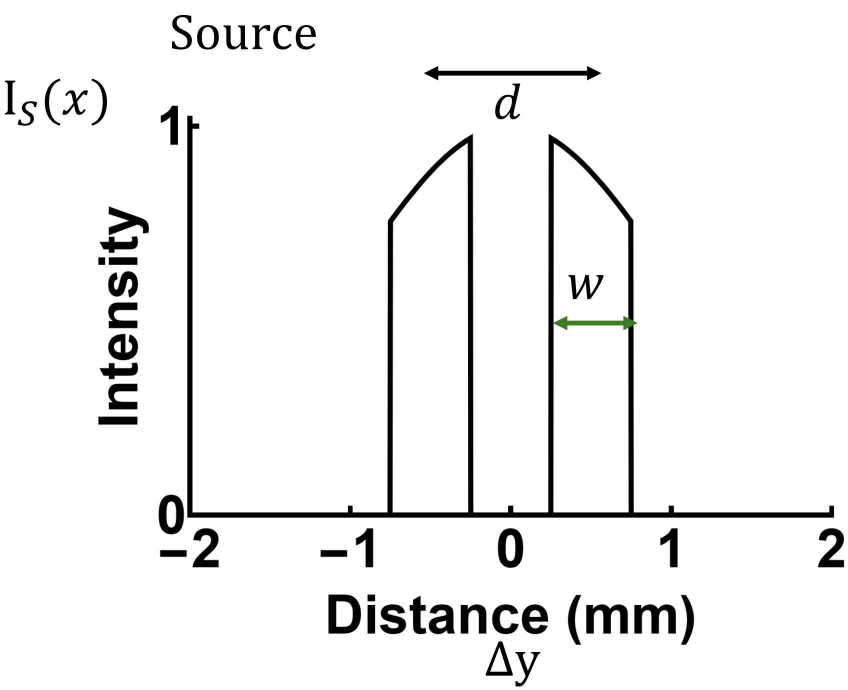
<u>Matthew Brown</u>, Markus Allgaier, Valerian Thiel,
Michael Raymer, and Brian Smith (U. Oregon), John Monnier (U. Michigan)

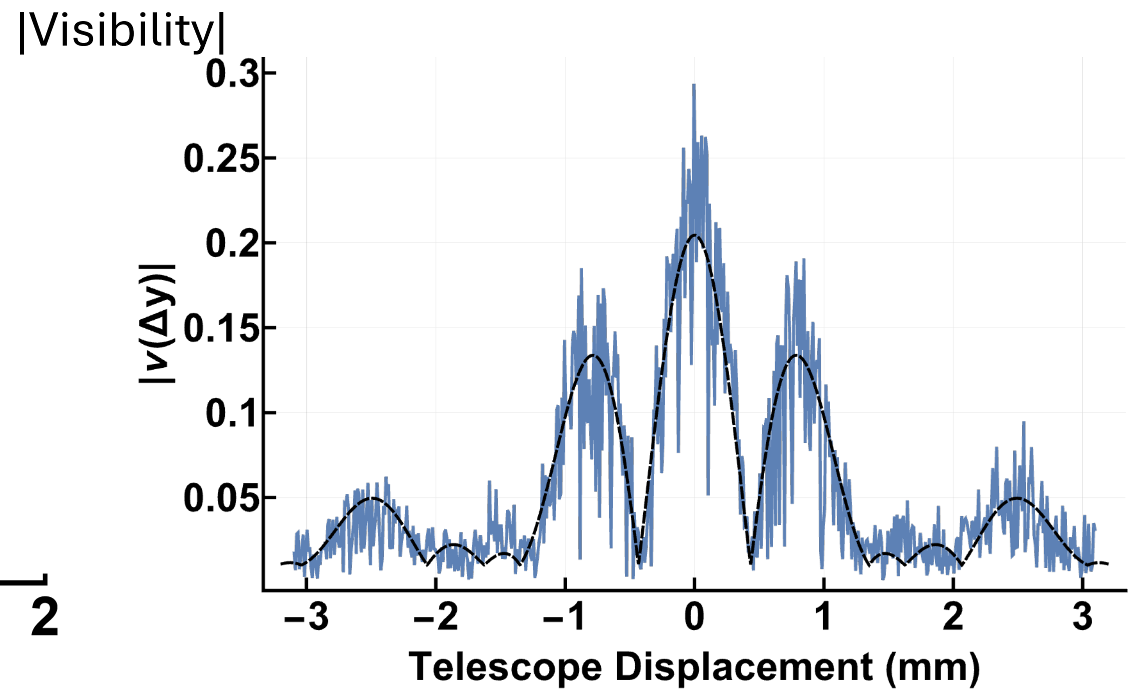


Entangled photons using
Spontaneous Down-Conversion

Brown et. al., Phys. Rev. Lett. 131, 210801

Results: 1mm Double Slit using laser source



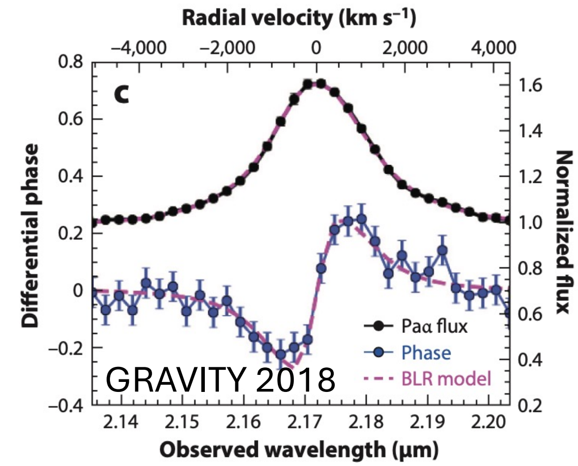


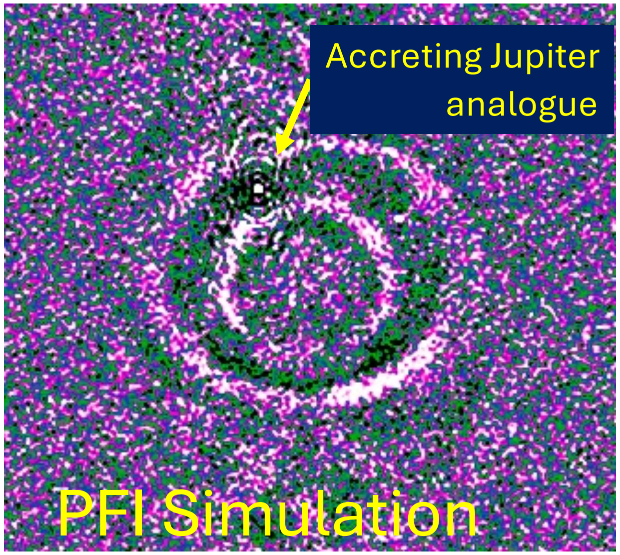
Fringes with Sun are planned next

Future Directions

- CHARA seeking bigger telescopes and (limited) longer baselines
  - Visible AO systems
  - Movable fiber coupled telescope (up to km or so baseline)
- VLTI upgrades
  - GRAVITY+ instrument will open-up the extragalactic sky to interferometry
  - Nulling interferometry mode for exoplanets
- MRO Interferometer with first light 2024
- Cherenkov Telescope Array (CTA – when?) and others reviving I.I.
  - How will new I.I. improve upon CHARA?
- Planet Formation Imager (PFI) could image planets as they form
  - requires 12x8m mid-IR telescopes over 2km ($$$)
- Big Fringe Telescope (van Belle)
  - 16x0.5m telescopes, 2.2km for imaging bright stars and binaries
- Space Interferometry
  - Large Interferometer for Exoplanets (LIFE)
  - Smaller space pathfinders under development too (US, Japan)
  - Lunar arrays being explored

Kinematics of Quasar/AGN
Broad Line Regions for a large samples





Large Interferometer for Exoplanets (LIFE)

- Mid-infrared Nulling to measure spectra of Earth-like planets
- Being studied as potential ESA Mission
- Complements NASA Habitable Worlds Observatory (HWO)
  (and probably easier)

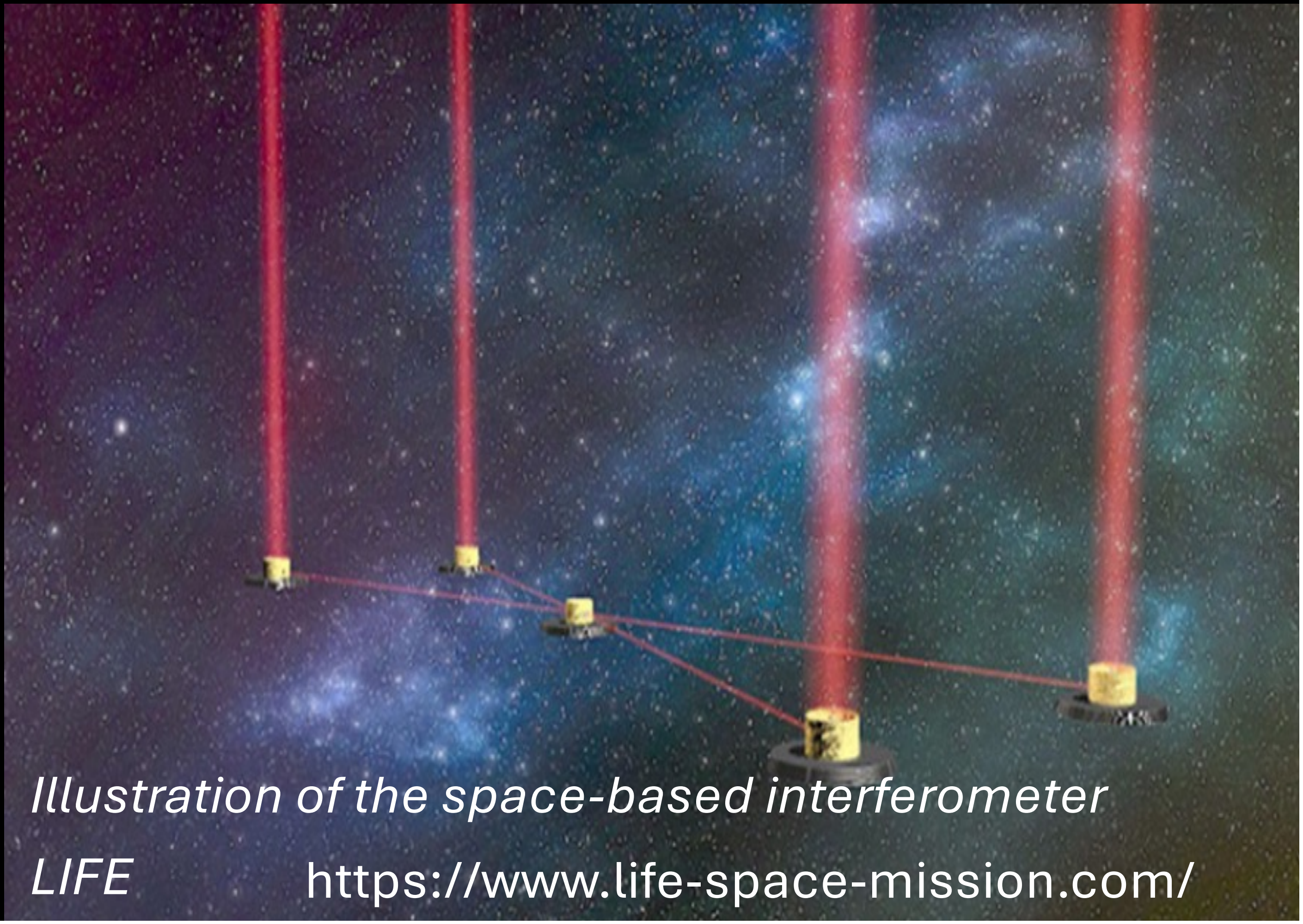


Illustration of the space-based interferometer LIFE https://www.life-space-mission.com/

Discussion Points for Workshop

Long (>350m) baselines with Amplitude Interferometers are not being actively developed (unfortunately)

- No engineering problems for baselines up 10km but they don't exist so an opening for intensity interferometer
- Too expensive for the required large telescopes and infrastructure, for a narrow science case

Ultra Long Baselines (>10km) require >>10m diameter telescopes since targets resolved

Impossible to compete with VLTI for baselines < 200m

- 20th mag is 100000x fainter than conventional intensity interferometry limits

Imaging anything but binary stars means sources have low visibilities

- Makes limb-darkening and phase retrievals with intensity interferometry impractical

Wide-field astrometry is very difficult from ground

- Turbulence introduces large jitter
- Dual-star modules introduce differential effects that are hard to control at necessary level (e.g., dual star HBT idea)

Multiplexing spectrum is critical for sensitivity boosting though not easy for II,HI, QI

- Time-tagging photons for Intensity Interferometer is far more tractable than fully digitizing bandwidth needed in heterodyne
- Energy-resolved detectors are not there yet; echelle spectroscopy requires good image quality
- Will new technology funding from 'Quantum' change this situation?

Science Goals and Long-term Vision for Intensity Interferometry

- What can I.I. do that CHARA/VLTI can't?
  - I would urge not to just repeat the same measurements on same stars that have been done already -- but just slightly bluer. Push for something grander
- Narrow-band methods should develop narrow band science cases: Spectroscopy of winds (Wolf-Rayet, O-stars, mass-loss)
  - Could be done with current arrays with modest multiplexing
- What are best wavelength ranges for HBT? Definitely blue? Infrared? Both?
- CTA could synthesize large aperture (>100m effective diameter) and go for long 5-20km baselines – CTA (100m)+ VLT (16m) + ELT (39m) triangle

Quick Overview of Methods

Method	Advantages	Disadvantages
Intensity Interferometry	Easiest to implement *no delay lines, beam transfer Can use low-quality telescopes Very long baselines possible	Narrow Bandwidths Require 2 photons, so far less sensitive
”Heterodyne” Interferometry (down-conversion) *Mixing CW laser with star	Electronic/digital delay lines Can split signals for a large N tells Improved using combs	Narrow bandwidths High shot-noise (h nu) Need to distribute LOs (?)
“Direct Detection” Interferometry	Broad bandwidths Optimal combination for SNR Benefits from photonics revolution	Complex infrastructure Low throughput Expensive (per photon) Limited to B~300m for now
Up-conversion via non-linear optics	Avoids heterodyne shot noise Opens some wavelength ranges	Narrow bandwidths Low efficiency Niche use case
Quantum-enhanced Interferometry (e.g, Brown 2023 and others)	Has some advantages of Heterodyne Less (or no) shot-noise penalty	Narrow bandwidths Need to distribute quantum resources