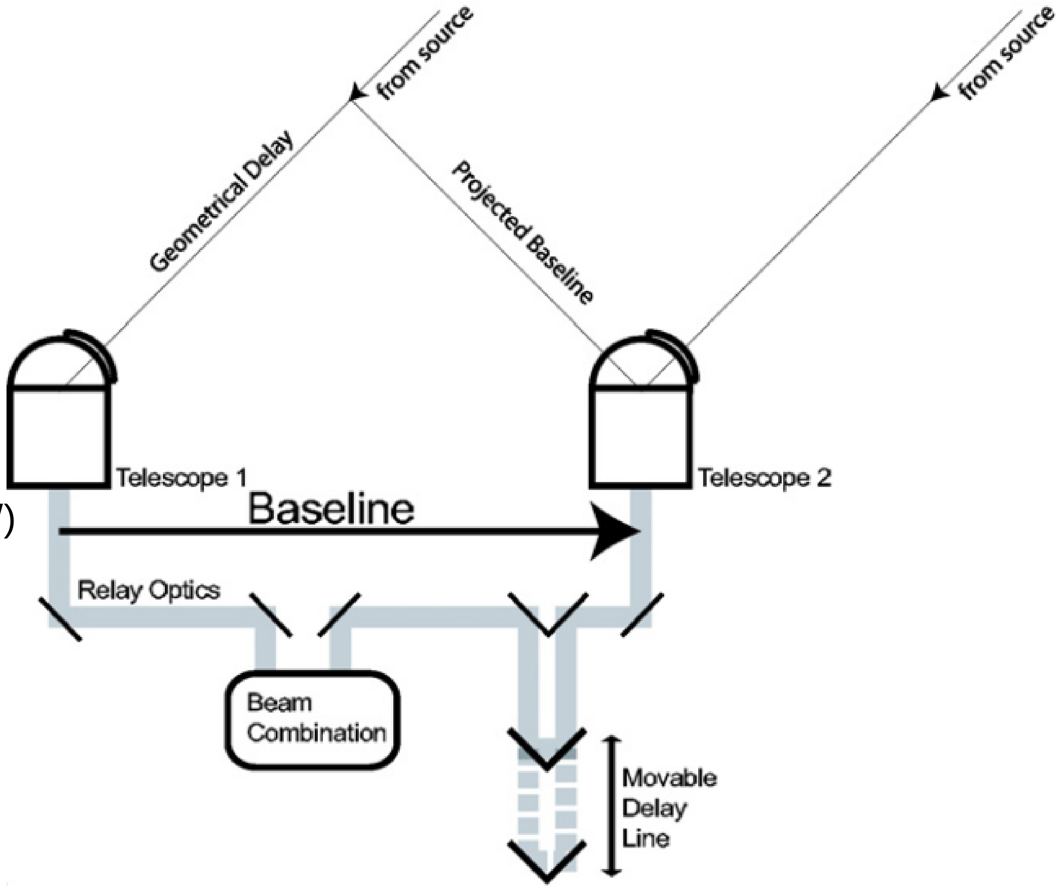
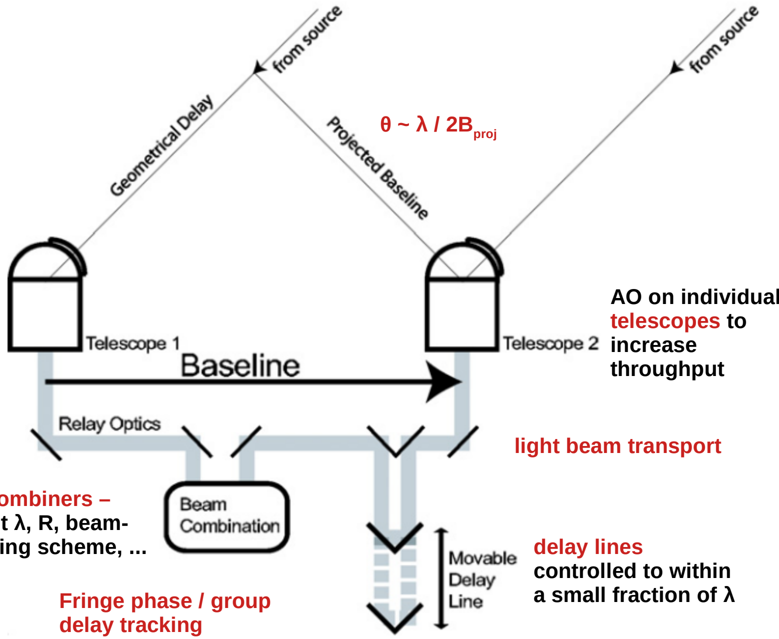
Optical Interferometry

- Lecture 1
  - Basic principles and History
  - Atmospheric turbulence and how to overcome it
  - Subsystems of an interferometric observatory – CHARA and VLTI
  - Interferometric observables
- **Lecture 2**
  - Science case – classical Be stars
  - OIFITS format
  - JMMC tools for interferometry (https://www.jmmc.fr/)
- Lecture 3
  - Parametric fitting of interferometric data with PMOIRED (https://github.com/amerand/PMOIRED)



Optical Interferometry



$\theta \sim \lambda / 2B_{proj}$

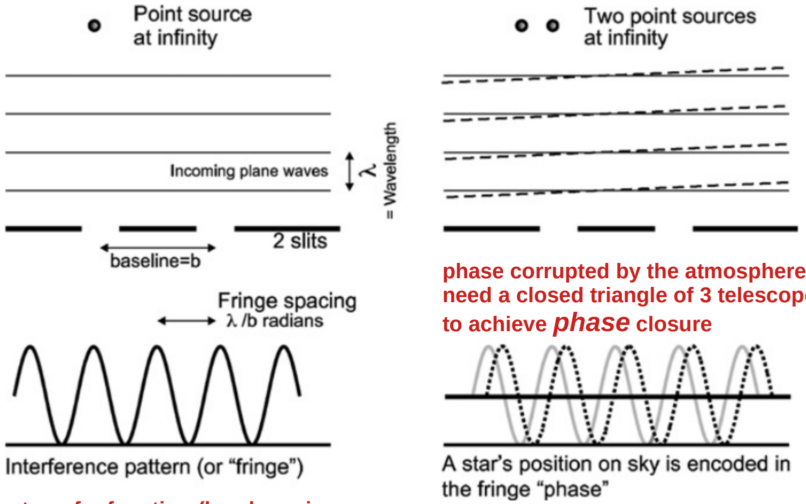
AO on individual telescopes to increase throughput

light beam transport

beam combiners – different λ, R, beam-combining scheme, ...

delay lines controlled to within a small fraction of λ

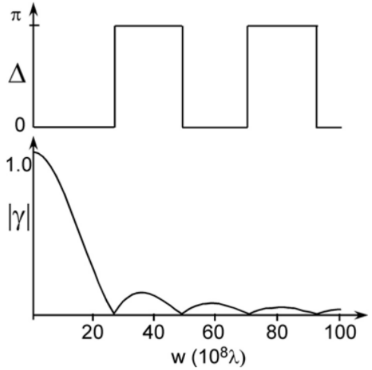
Fringe phase / group delay tracking



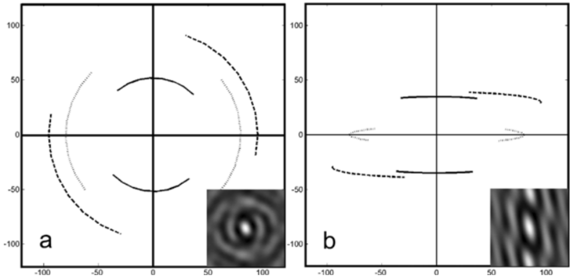
phase corrupted by the atmosphere – need a closed triangle of 3 telescopes to achieve ***phase*** closure

need to monitor transfer function (by observing calibrators with known diameters) to calibrate science target ***visibility***

each baseline measures one Fourier component of the sky brightness distribution



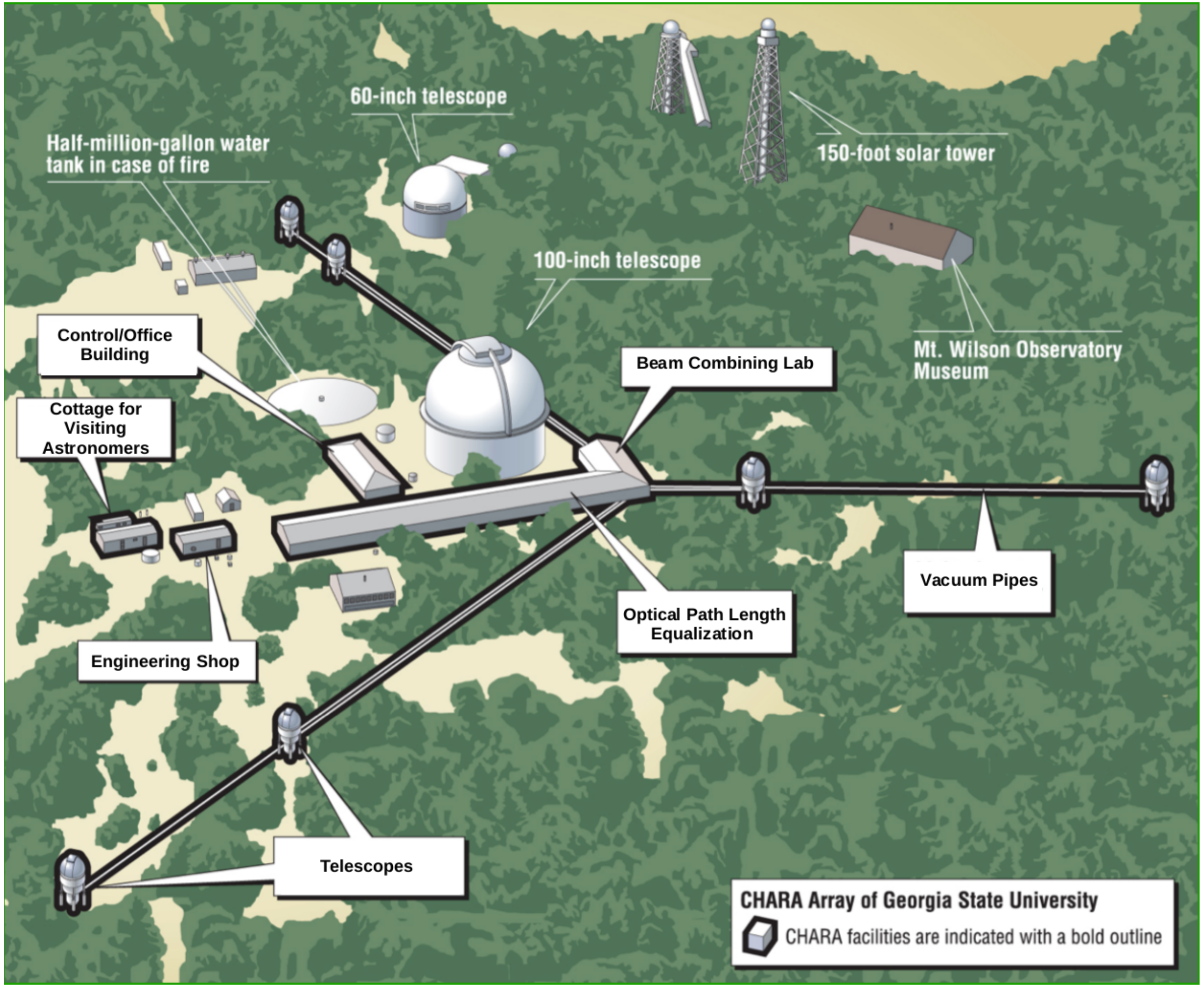
spatial frequency (baseline)



baselines fill the uv-plane as the Earth rotates

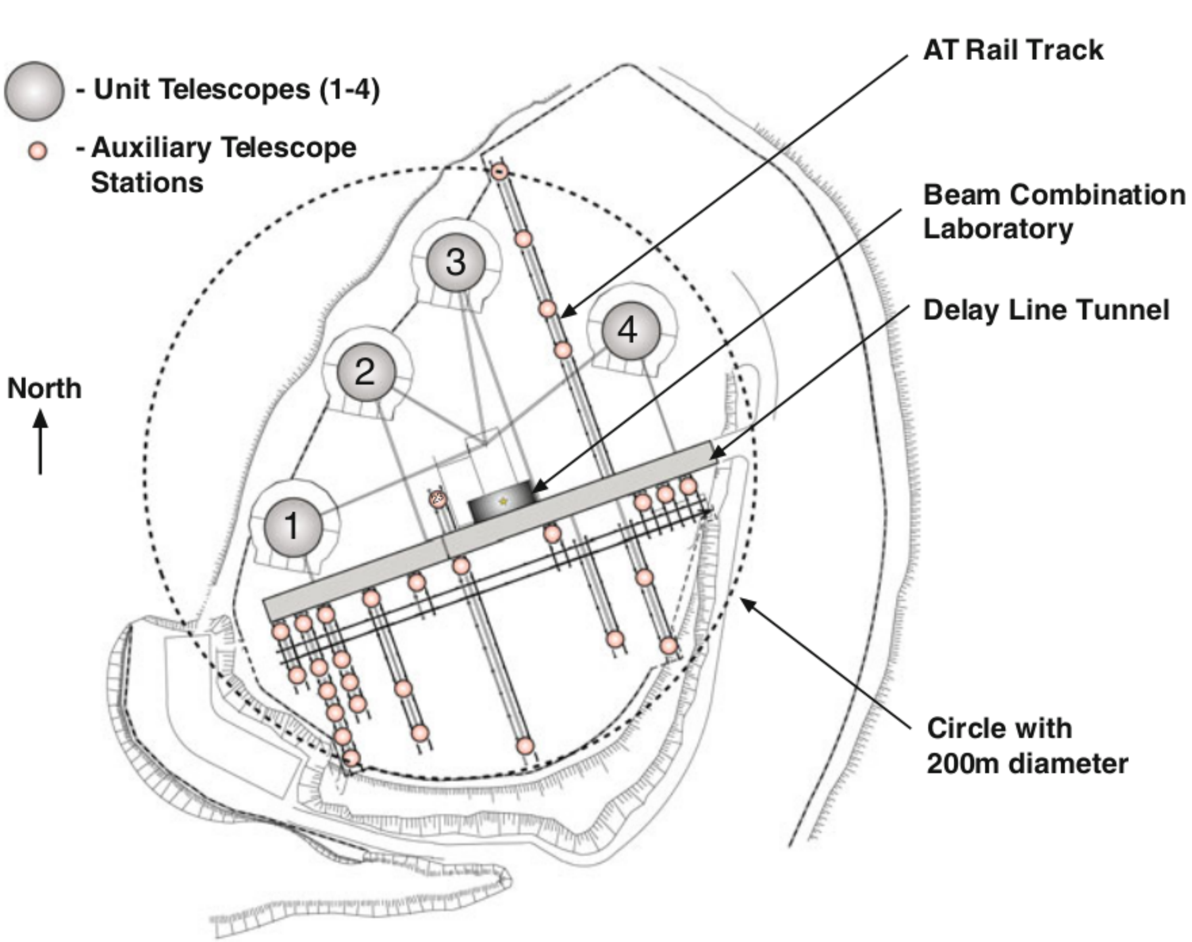
- **Size measurement / photocenter displacement**
- **Detection of companions**
- **Geometrical model-fitting**
- **Model-independent image reconstruction**

The CHARA Array



- Six 1-m fixed telescopes with TelAO in Y-shaped configuration
- B_{min} = 33 m; B_{max} = 330 m
- θ ~0.2 mas in *R* to ~0.5 mas in *H*
- Vacuum beam relay pipes & LabAO before optical lab
- Beam combiners
  - Classic/CLIMB – 2T/3T in *K’* band
  - PAVO – 2T in *R* band
  - MIRC-X and MYSTIC – 6T simultaneously in *H* and *K* band
  - SPICA – 6T visible (commissioning)
  - SILMARIL – 3T H & K (commissioning)
- Decommissioned beam combiners
  - VEGA – 2T in visible
  - FLUOR – 2T in *K’* band

VLTI



- Four 8-m fixed telescopes or four 1.8-m movable telescopes
- B_{min} ~ 11 m, B_{max} ~ 200 m
- θ ~1 mas in *H, K,* ~3 mas in *L*, *M*
- Enables dual-field observations
- Beam combiners
  - PIONIER – 4T in *H* band
  - MATISSE – 4T in *LMN* bands
  - GRAVITY – 4T in *K* band with dual-field mode – great boost in sensitivity
  - GRAVITY+ – Upgrade of observatory infrastructure and UT telescope AO (in progress)
- Decommissioned beam combiners
  - AMBER – 3T *K* band
  - MIDI – 2T *N* band
  - VINCI – VLTI commissioning instrument

Interferometric observables

From the interference pattern on the detector, we measure proxies of the complex visibility:

- Visibility modulus |V| / visibility squared V^2
  - The basic observable for all beam combiners
  - Size and point-symmetric shape of the object
  - Visibility decreasing with increasing baseline – object angularly resolved
- Closure phase CP / T3PHI
  - At least 3T beam combiner needed
  - Deviations from point symmetry when deviating from 0 degrees
- Differential Phase DPHI
  - High spectral resolution needed - VEGA, SPICA, AMBER, MATISSE, GRAVITY
  - The phase within a spectral line normalized to the surrounding continuum – e.g. a star that appears as a point source in the continuum, but the line emission from its circumstellar environment is resolved
- Differential visibility
  - Similar to DPHI but for visibility

Resources

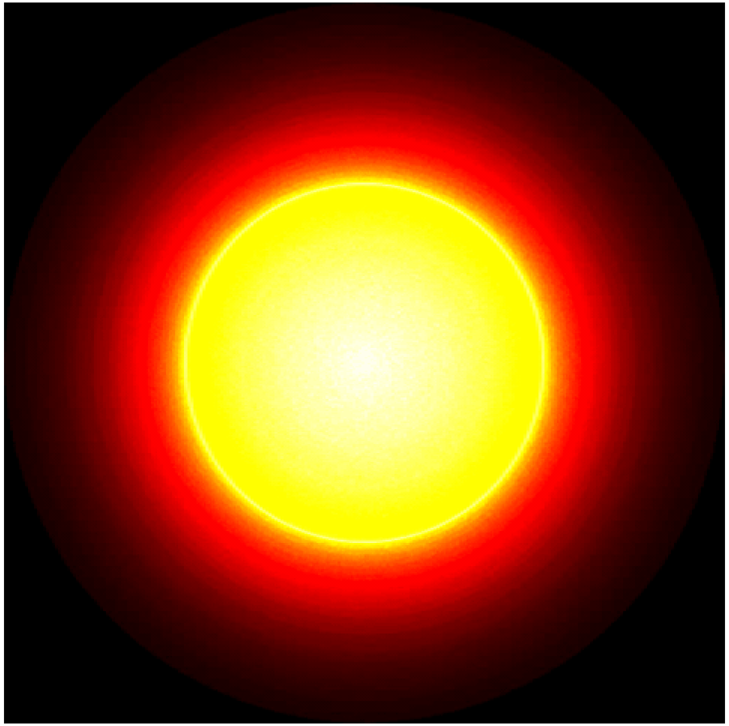
- VLTI schools - materials now available for the 2024 school at https://vltischool2024.sciencesconf.org/
- ESO/CHARA website, instrument manuals, reduction pipeline cookbooks, …
- VLTI Expertise centers, ESO Helpdesk

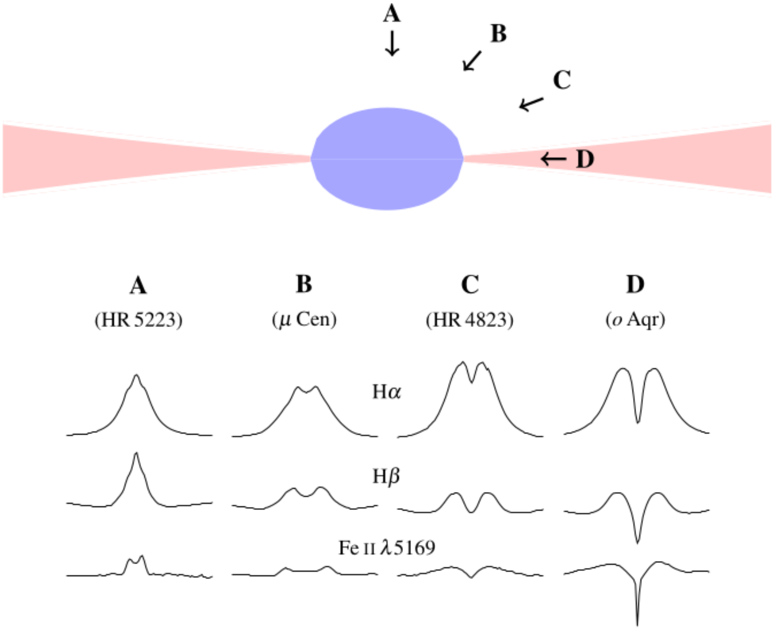
Science cases

- Measurement of stellar diameters – *UD > 0.2 mas*
- Mapping of astrometric orbits of multiple star systems – *orbit sizes from ~1 to ~50 mas*
- Imaging of surfaces of stars with large angular diameters – *UD > 2 mas*
- Circumstellar environments – Be stars, YSOs, evolved stars, … - *spectro-interferometry*
- Resolving Active Galactic Nuclei, inner parts of YSOs – *pushing the boundaries, GRAVITY+*

Classical Be stars

- Rapidly rotating and non-radially pulsating main-sequence B-type stars with ionized, gaseous decretion disks in Keplerian rotation
- Many Be stars are post-mass-transfer binaries with faint, stripped companions





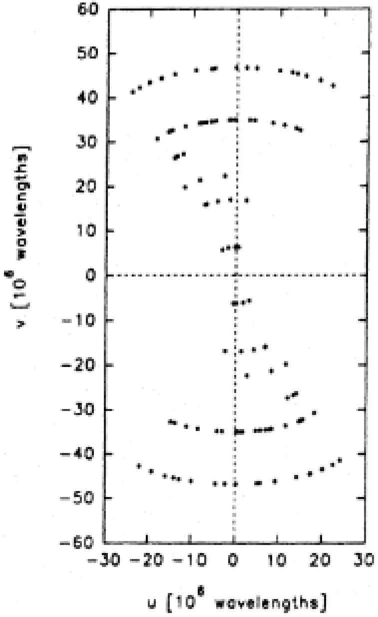
Struve 1931,
Rivinius+ 2013

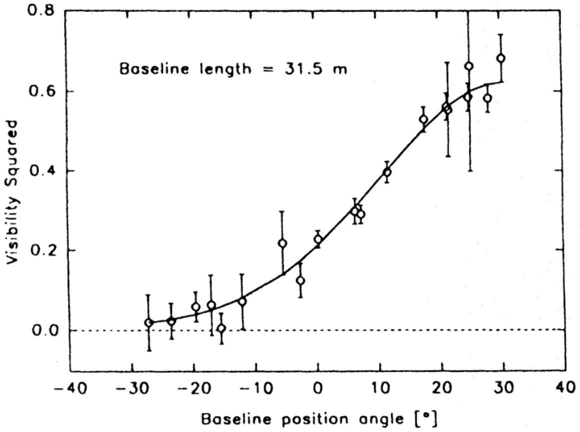
Ideal targets for optical interferometry

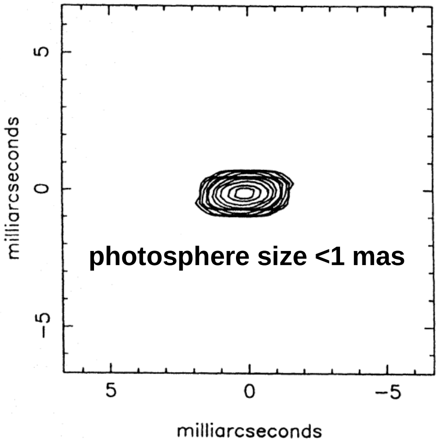
- Disk size and shape from visibility measurements
- Disk asymmetries and companion detection from closure phases
- Disk kinematics and extent from differential visibilities and phases across emission lines (Hα and Brγ)

Be star interferometric milestones

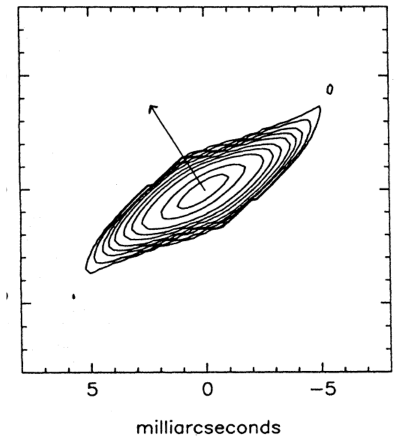
- **ζ Tau disk imaged by MkIII Optical Interferometer** (Quirrenbach+ 1994)







25 nm channel centered at 550 nm – point-source

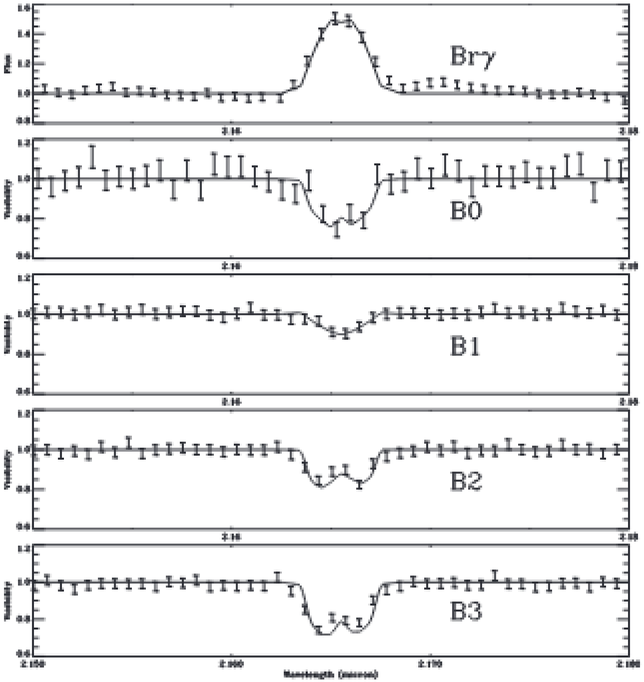


Hα line - 1-nm wide centered at 656 nm

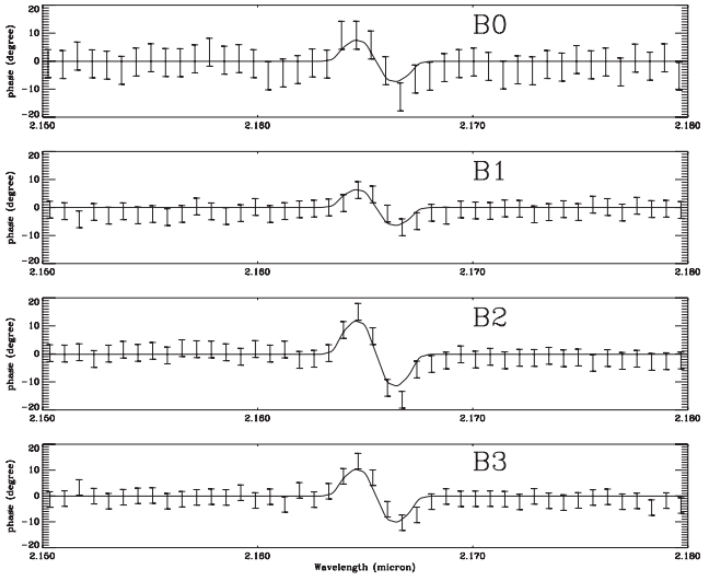
Be star interferometric milestones

- **Keplerian rotation of α Ara disk from VLTI/AMBER spectro-interferometry** (Meilland+ 2007)

Differential visibility



Differential phase



Evidence for Keplerian rotation in ‘S-shaped’ profile

Be star interferometric milestones

- **First detection of a stripped companion orbiting a Be star with CHARA/MIRC** (Mourard+ 2015)

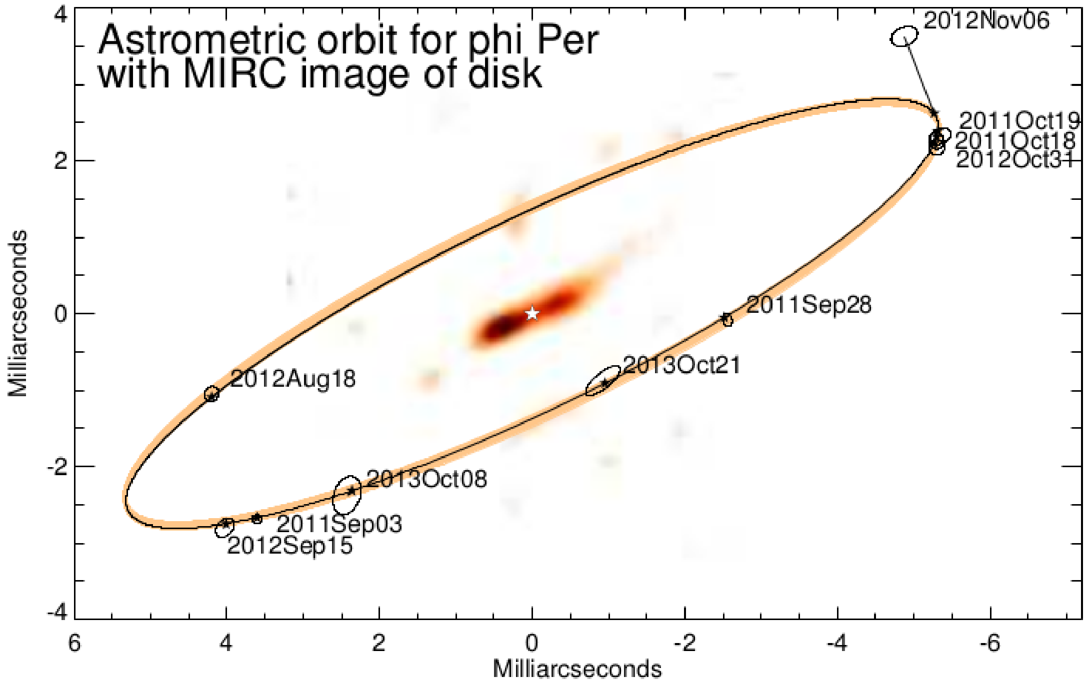


Table 6. Position of the companion as a function of the RJD as detected in the various MIRC data sets.

RJD	Phase	Separation	PA	$\sigma_{\rm major}$	$\sigma_{\rm minor}$	PA(σ)
55 807.91	0.62	4.50	126.7	0.07	0.06	84
55 832.86	0.81	2.56	268.2	0.09	0.06	18
55 852.87	0.97	5.75	293.1	0.11	0.10	12
55 853.76	0.98	5.83	293.5	0.14	0.10	298
56 158.02	0.38	4.34	104.0	0.10	0.09	330
56 185.81	0.60	4.90	124.8	0.14	0.10	318
56 231.77	0.96	5.73	292.3	0.10	0.10	291
56 237.61	0.01	6.08	306.6	0.18	0.12	292
56 573.86	0.66	3.39	134.4	0.26	0.17	340
56 586.76	0.76	1.27	226.6	0.28	0.10	309

Parameter	Value
$T_{\rm RV\ min}$ (RJD)	56 110.03 ± 0.08
P (d)	126.6982 (fixed)
a (mas)	5.89 ± 0.02
e	0 (fixed)
i (°)	77.6 ± 0.3
ω(°)	0 (fixed)
Ω(°)	−64.3 ± 0.3
γ (km s^{-1})	−2.2 ± 0.5
K_a (km s^{-1})	10.2 ± 1.0
K_b (km s^{-1})	81.5 ± 0.7
M_{a+b} ($M_\odot$)	10.8 ± 0.5
M_a ($M_\odot$)	9.6 ± 0.3
M_b ($M_\odot$)	1.2 ± 0.2
d(pc)	186 ± 3

Working with interferometric data – OIFITS format

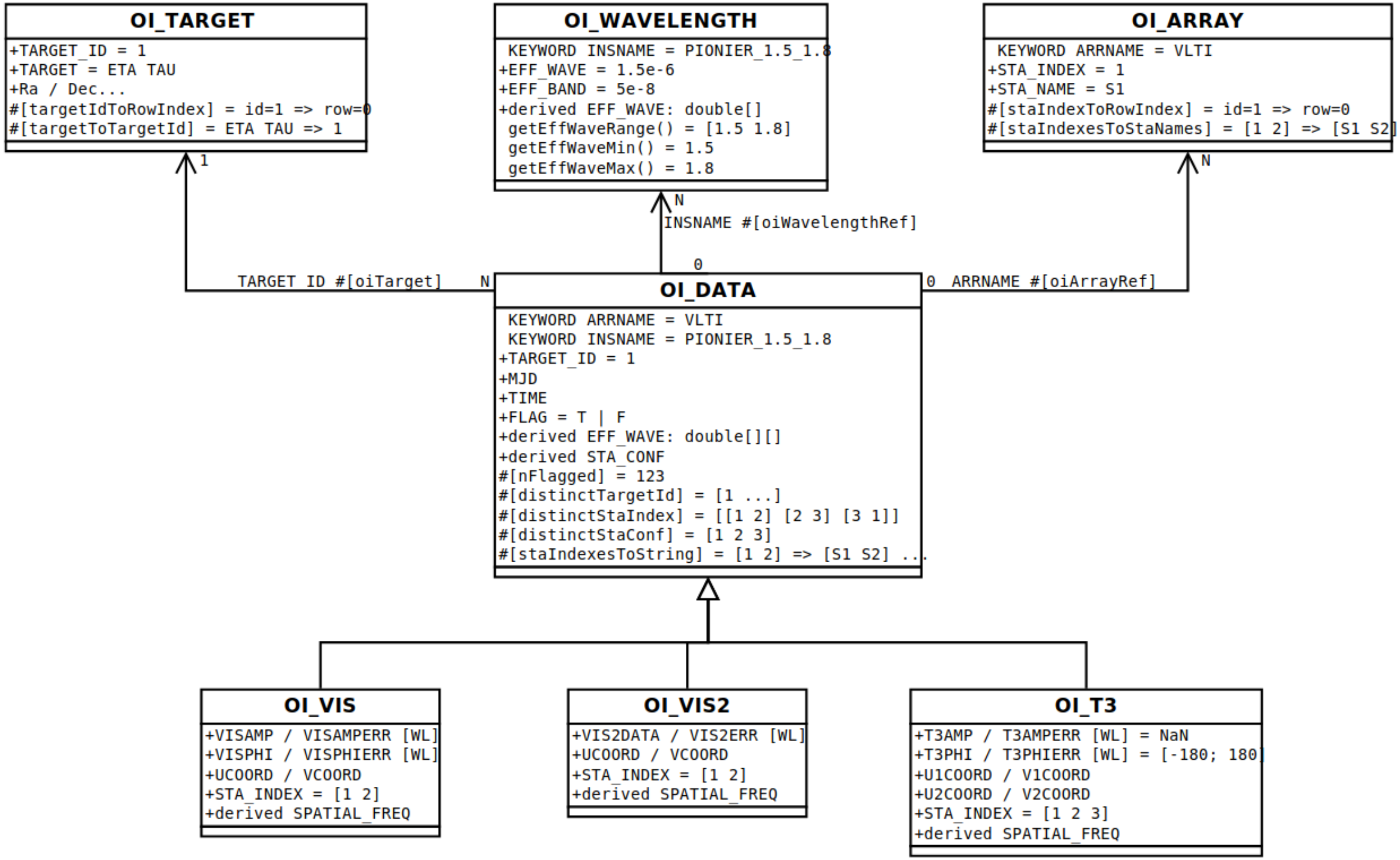
- Interferometric data come in standardized OIFITS format - *.oifits (https://arxiv.org/pdf/1510.04556)
  - Can be manipulated with standard software tools such as Python/Astropy – *fitsheader*, *fitsinfo, fitscheck, fitsdiff*
  - ESO qfits library – *dfits and fitsort*

Table 1. OIFITS version 1 tables and their main use.

HDU[1]	Intent	Multiplicity
(Header)	(Mostly empty)	
OI_TARGET	"Objects" positions (and effective cross-index)	1
OI_ARRAY	Geometry of telescope positions, aperture size	0..N
OI_WAVELENGTH	Observing wavelengths (and instrument identification tag)	1..N
OI_VIS2	V^2 observables (baselines)	0..N
OI_T3	phase closures (triplets of baselines)	0..N
OI_VIS	Differential Phases etc...	0..N

1: Header Data Unit, the highest level component of the FITS file structure (binary tables for OIFITS)

Working with interferometric data – OIFITS format



JMC tools

- Interoperable Java tools
- **Aspro2** – Planning observations, checking observability, *uv* coverage
- **GetStar** – Get star info such as size estimates based on spectro-photometry and distance
- **SearchCal** – search the database of interferometric calibrators for your science target
  - Need to calibrate system visibility (response to a point source / source of a known size) – this is a function of seeing, zenith angle, time, ...
- **OiDB** – Optical interferometry Data Base including reduced, calibrated and published data (Haubois+ 2014)
- **OIFits explorer** – Plot data from OIFITS files
- LITPro – geometrical model fitting of interferometric data, for this we will use **PMOIRED** instead
- Oimaging – model-independent imaging of data with good *uv* coverage