An general introduction to optical stellar interferometry and VLTI in particular

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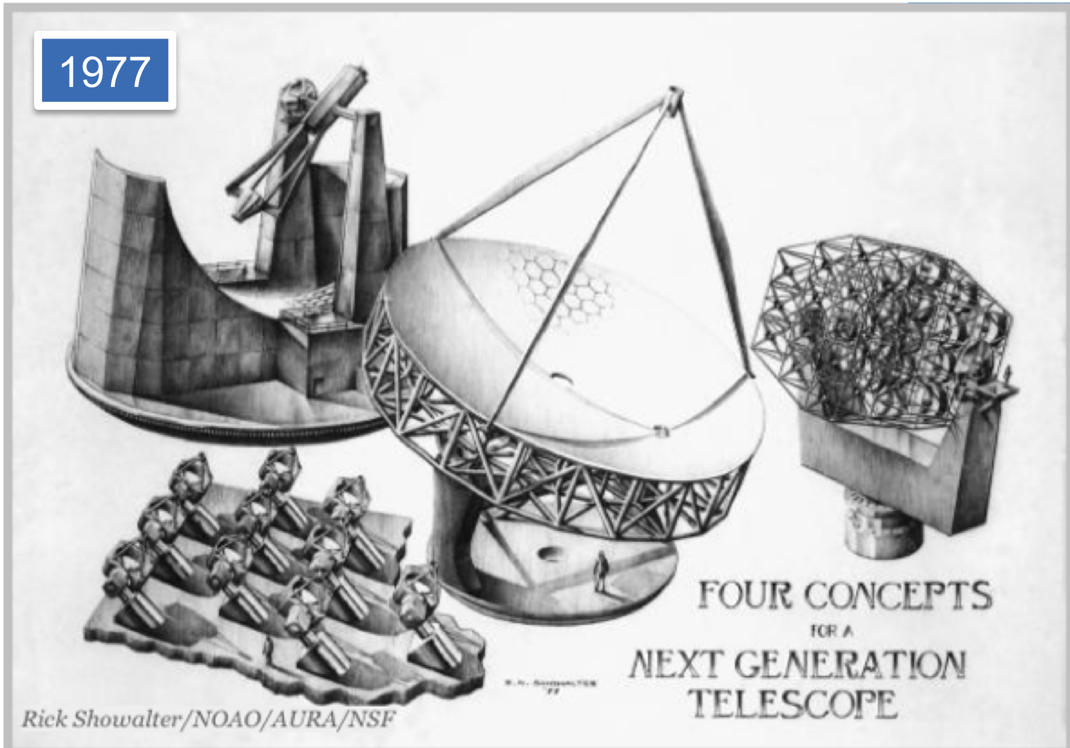
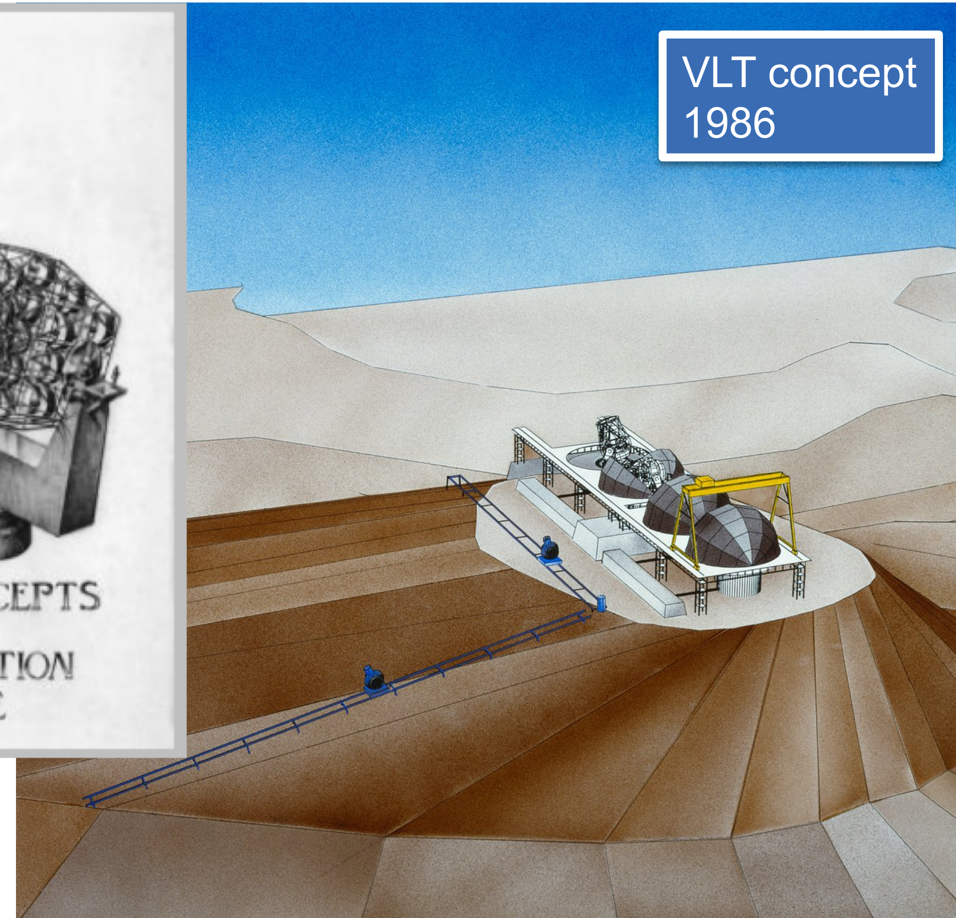
The Very Large Telescope ontop Cerro Paranal (Chile)

How did we get there?

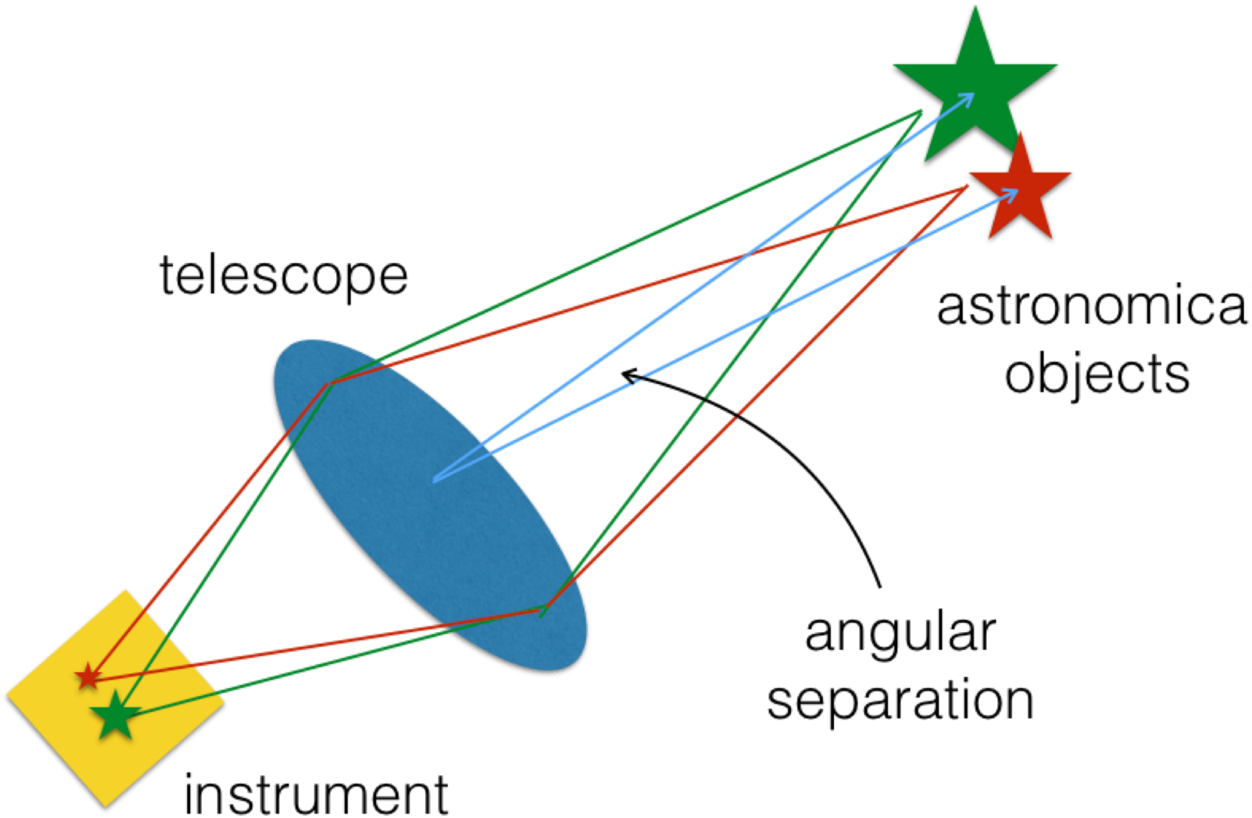




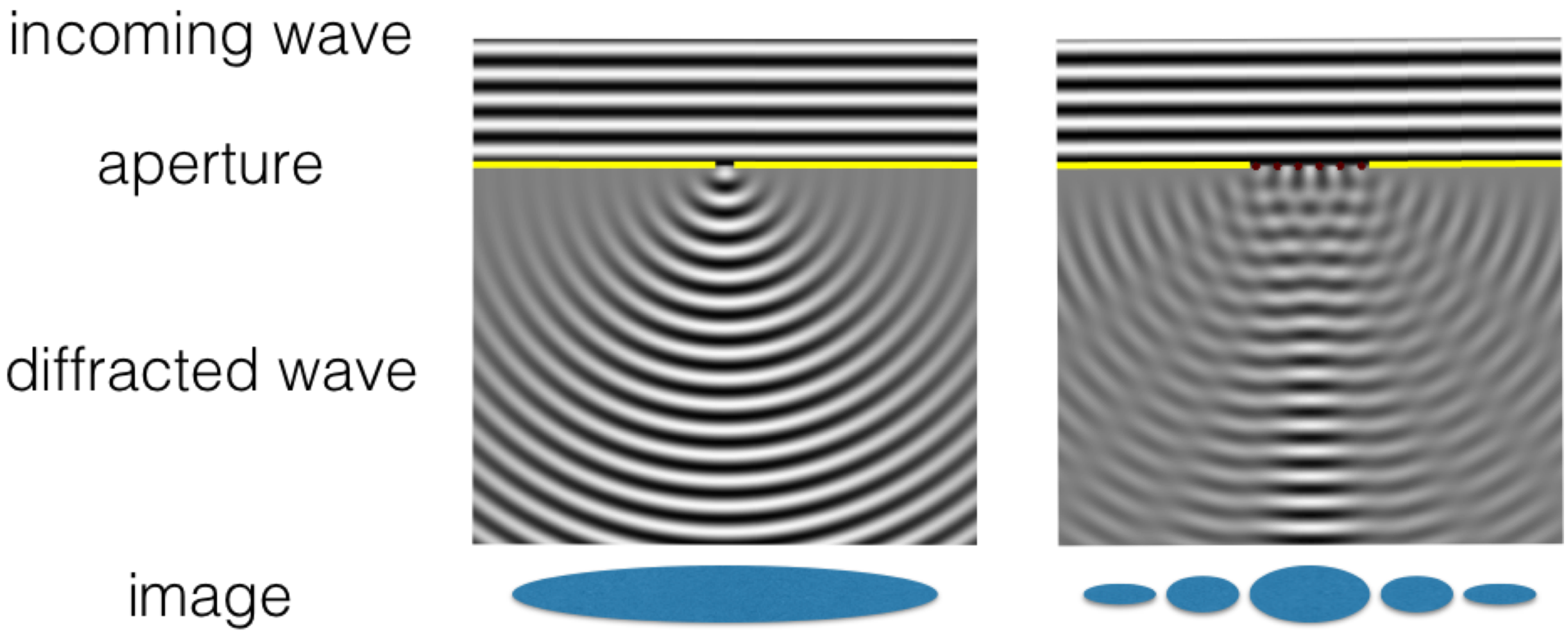
Considerations to build a telescope

- Collecting area
  - The larger the surface, the more sensitive the telescope
- Angular resolution
  - Smallest detail detectable
- Field of view
  - How many objects?

Angular separation

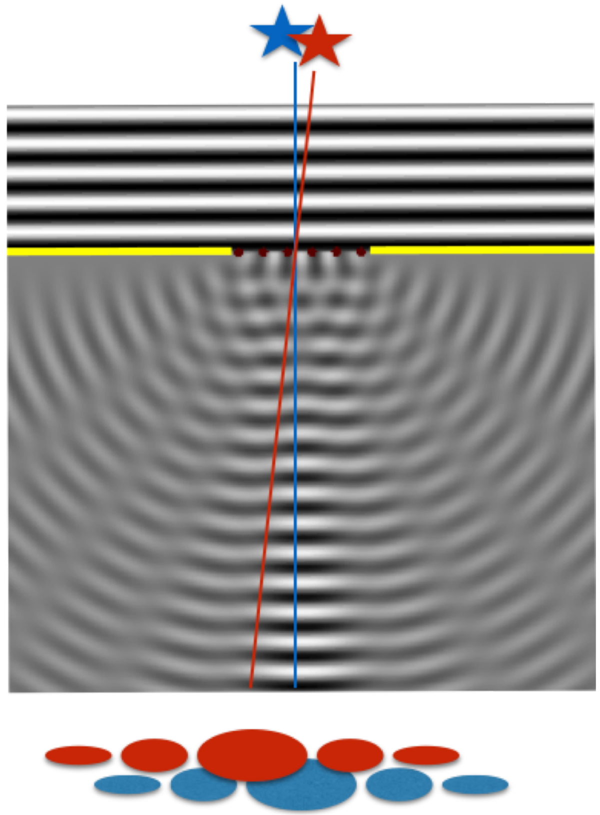


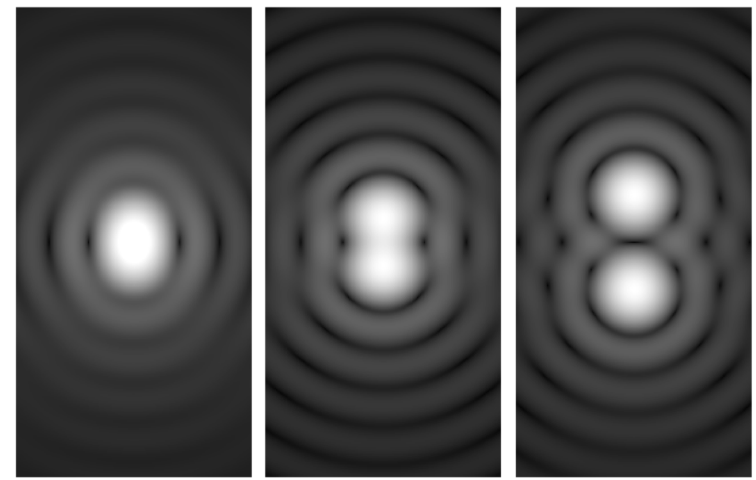
Diffraction in a telescope



http://en.wikipedia.org/wiki/Huygens%E2%80%93Fresnel_principle

Point spread function





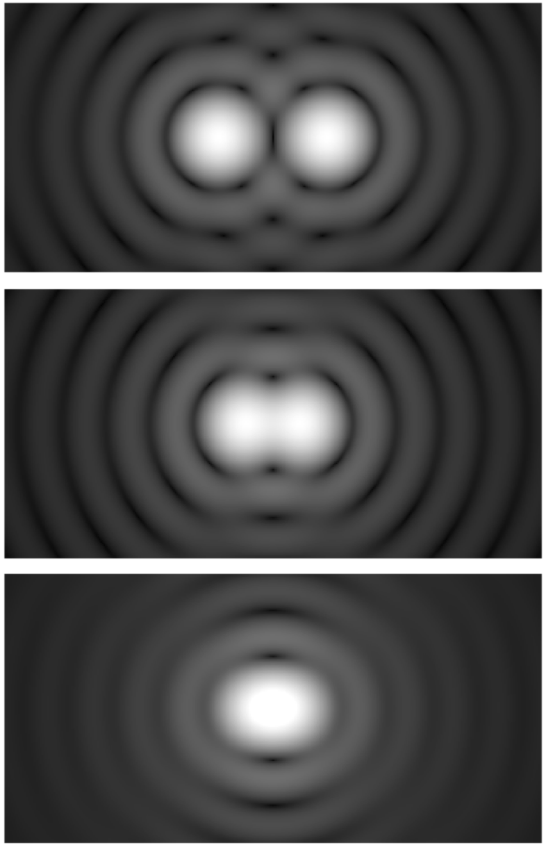
A circular aperture produces a so-called Airy pattern. Its first null has an angular radius of $1.22\lambda/D$

- D: diameter of the telescope
- λ: wavelength of observation

Order of magnitudes

- 1.22λ/D = 8.4e-8 radians for an D=8m telescope in the visible (λ=550nm)
- Unit of small angle is the arcsecond (“)
  - 1” = π/180/3600 = 4.85e-6 radian
  - 1mas = 0.001” = 4.85e-9 radian
- 1.22λ/D = 0.017” (=17mas) for an D=8m telescope in the visible (λ=550nm)

Point Spread Function

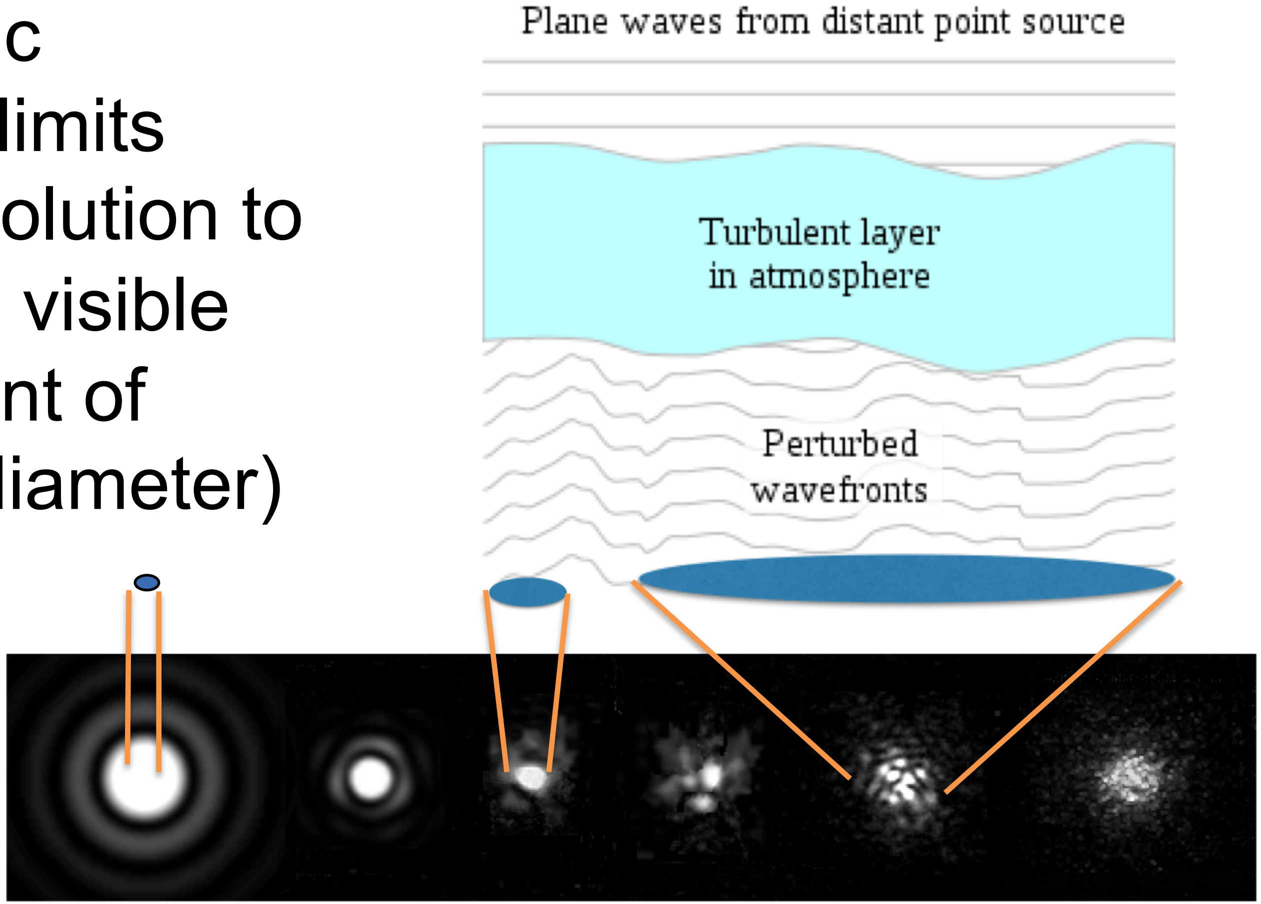


How good is 1” resolution?

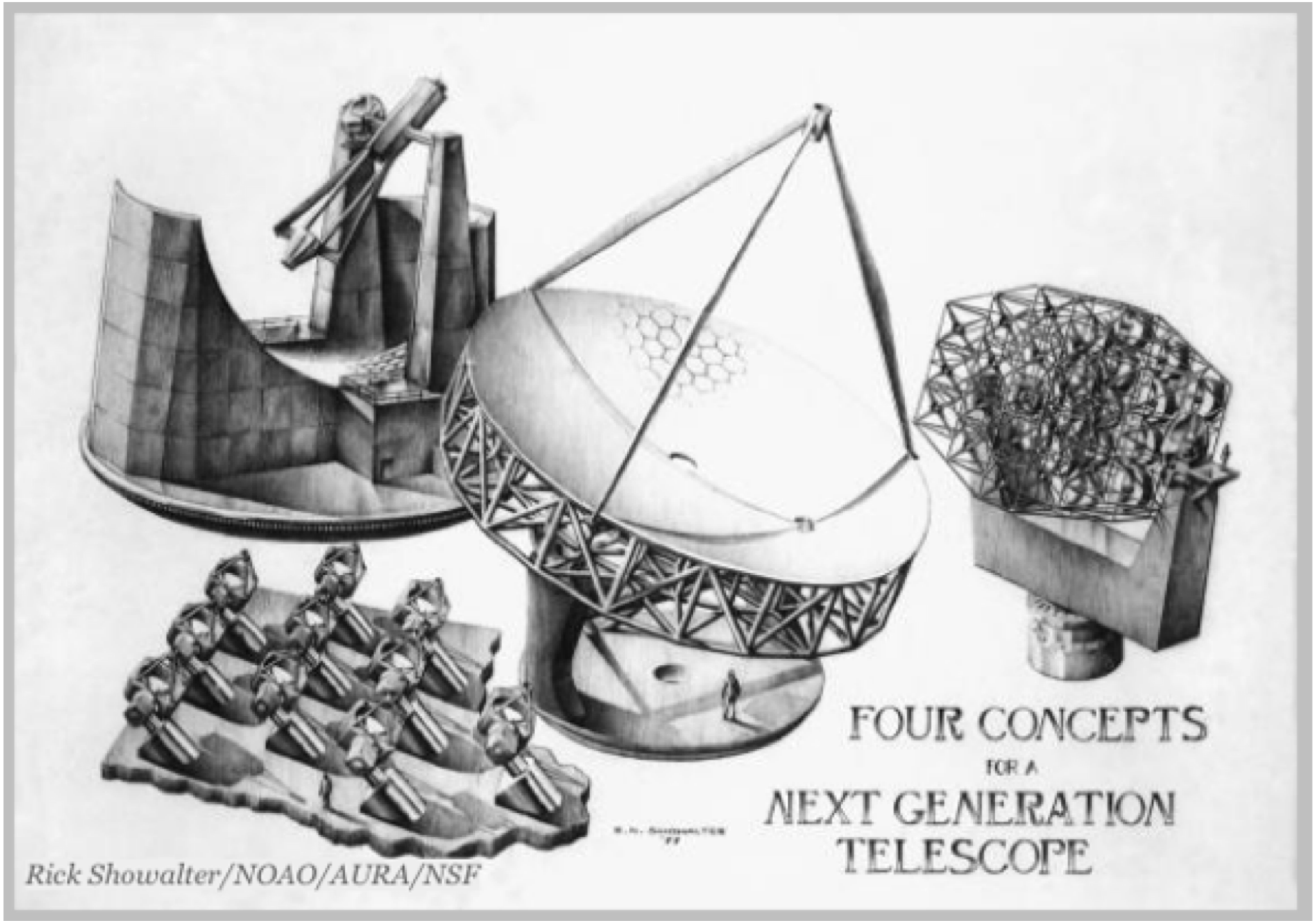
- By definition,
  - 1 astronomical unit (150×10^6km) seen from a distance of 1 parsec (~3.2 light years)
- From the closest star (proxima Cen, d=1.3pc):
  - The Sun appears 0.007”=7mas
  - Sun-Earth distance is ~0.8”
- Closest star forming regions at d~140pc:
  - 1” is 140AU ~ 3x Pluto’s orbit
  - 0.017” is 2.4AU ~ asteroid belt

Atmospheric effects

- Atmospheric turbulence limits angular resolution to ~0.5” in the visible (independent of telescope diameter)



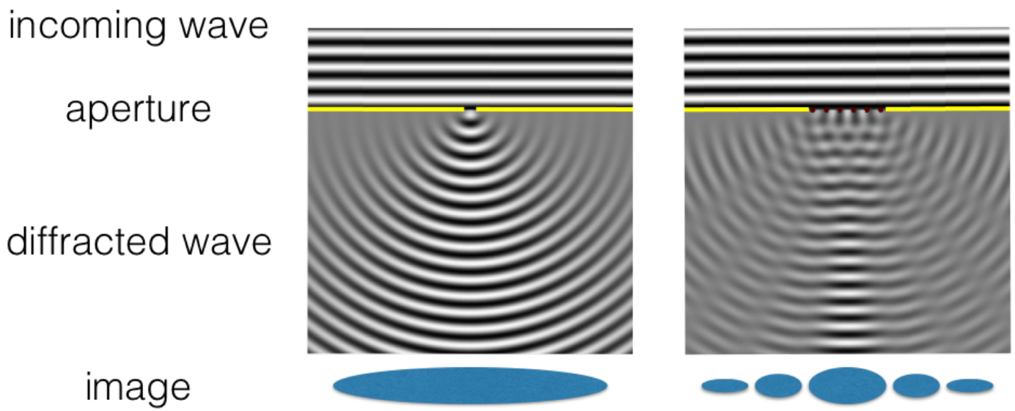
The highest angular resolution?

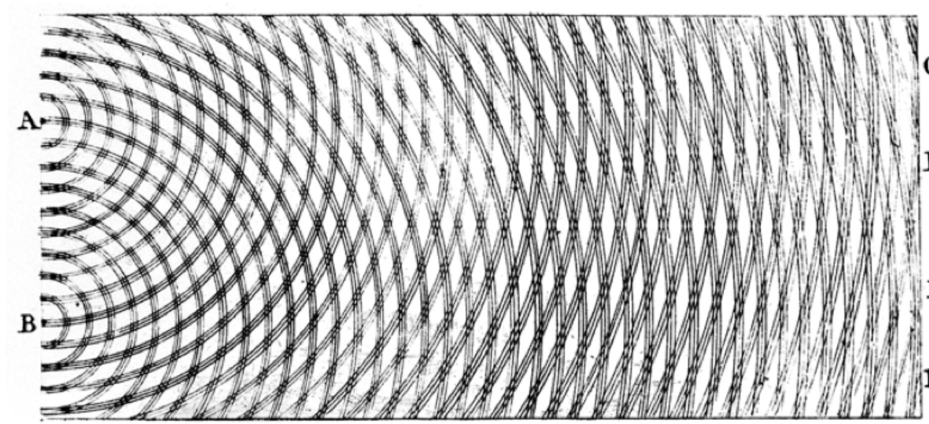


Reaching higher angular resolution

- How do we free ourselves of atmospheric seeing?
  - Adaptive optics
- How do we go beyond the limitation of the single aperture telescope?

Diffraction of partial apperture

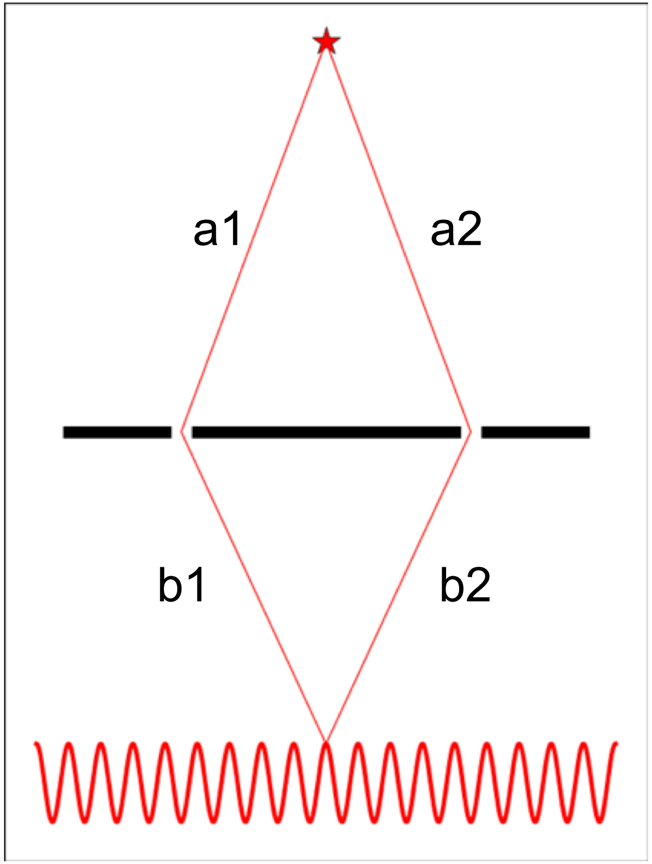




"On the Theory of Light and Colours"
Thomas Young, 1801

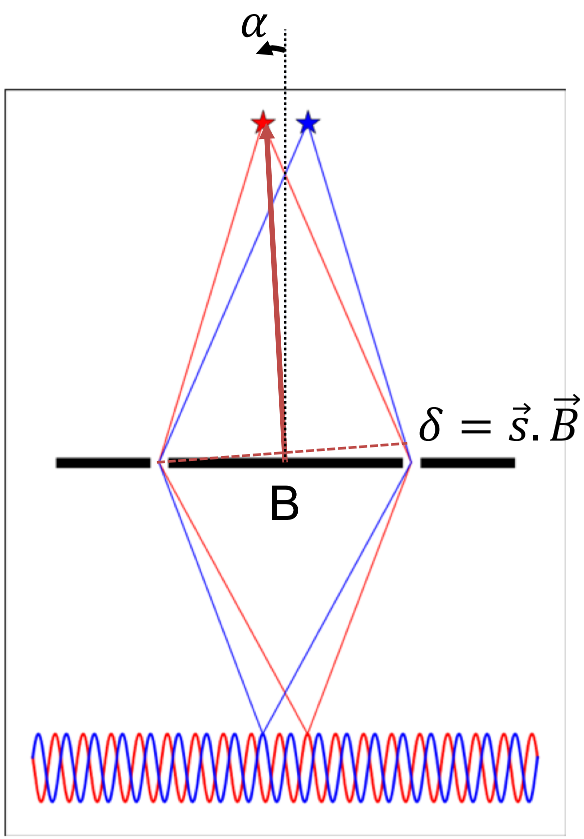
Young's double slit experiments

- a1+b1 – a2+b2: optical path difference
- In phase: White fringe
  - $(a1+b1-a2-b2)\%\lambda = 0$
- Out of phase: Dark fringe
  - $(a1+b1-a2-b2)\%\lambda = \lambda/2$
- http://www.falstad.com/ripple/

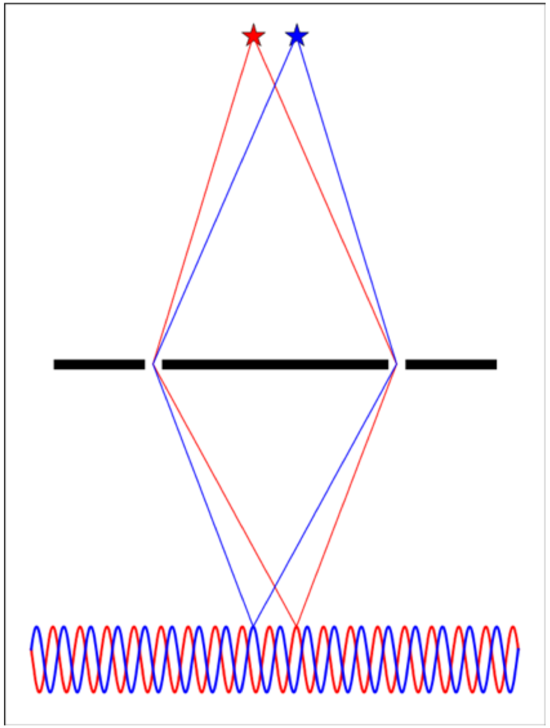


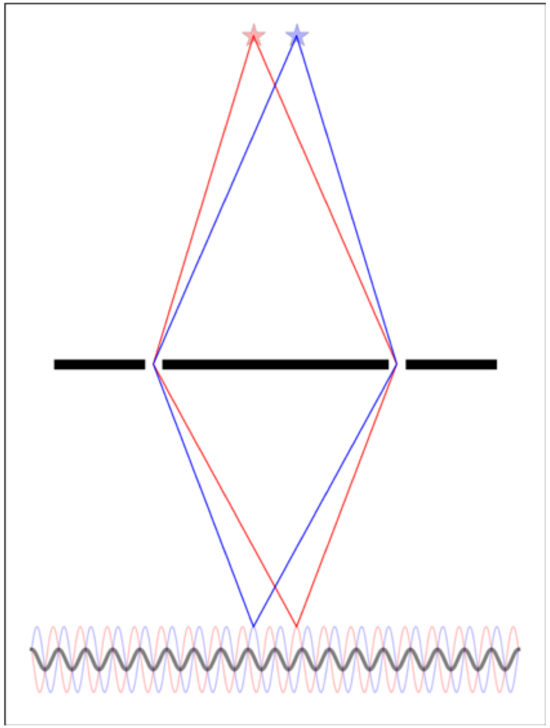
Spatial information in fringes

- $\vec{s}$ direction to the object
- Optical path difference
  - $\vec{s}.\vec{B} = \mathrm{B}.\sin(\alpha) \approx \alpha B$
- Phase of the fringes contains information about $\vec{s}$ (α)
- 1 Fringe corresponds to $\vec{s}.\vec{B}(\approx \alpha B) = \lambda \Rightarrow \alpha \approx \lambda/B$
- Phase of the fringes: $2\pi\alpha B/\lambda$



Object's geometry affects the phase and amplitude of the fringes





Fringe patterns for each point in the object add up in the focal plane and produce a fringe pattern with reduced contrast:

resolved <> reduced fringe contrast

Proper formulation

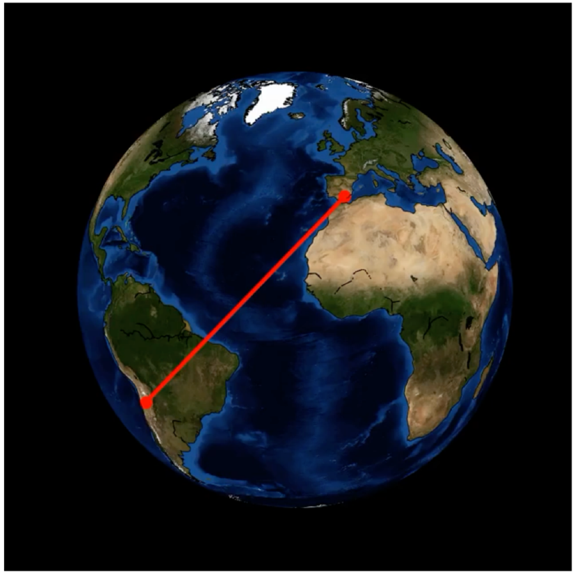
- The fringes' amplitude and phase is called the **complex visibility**
- Baseline vector $\vec{B} = (u, v)$ [same unit as λ]
- Pointing vector $\vec{s} = (x, y)$ [in rad]
- The complex visibility is the normalized Fourier transform of the image I(x,y):

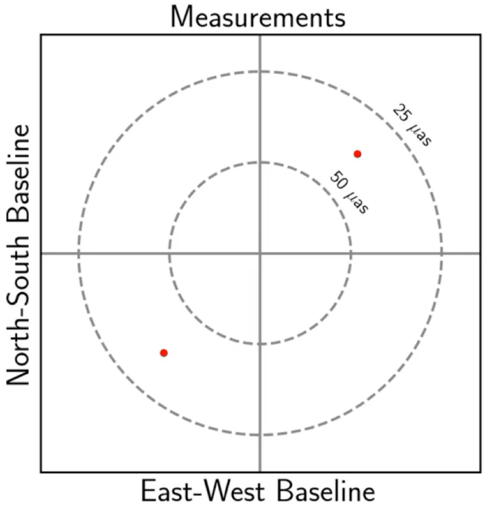
$$V(u,v,\lambda) = \frac{\iint I(x,y) e^{-2\pi i (xu+yv)/\lambda} dx dy}{\iint I(x,y) dx dy}$$

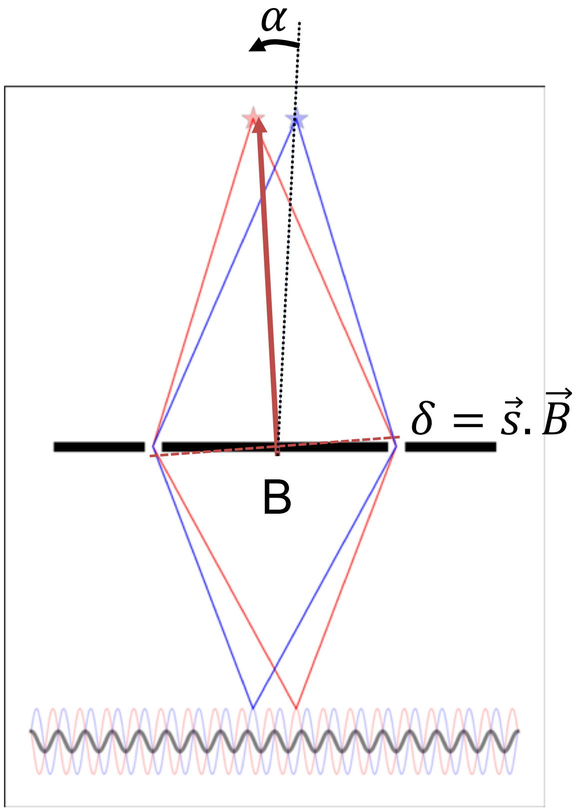
[Van Cittert – Zernike Theorem]

Single baseline gives very limited information

- Binaries separated by α, 2α, 3α, … have same fringe pattern for a given B
- Image is 2D and baseline is 1D







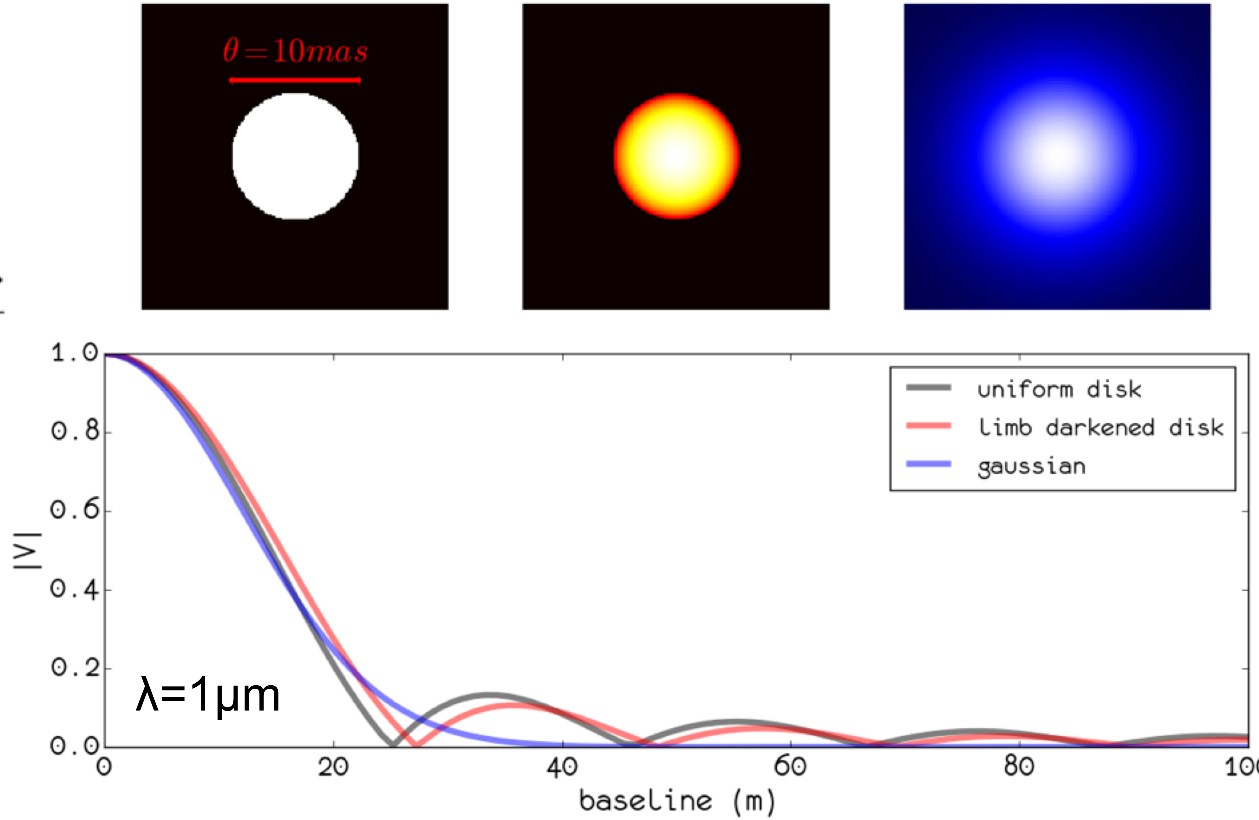
Centro-symmetric images

For a centro-symmetric image, Fourier transform becomes an Hankel transform:

$$V(B,\lambda) = \frac{\int I(r,\lambda) J_0(rB/\lambda) r dr}{\int I(r,\lambda) dr}$$

Case for a uniform disk:

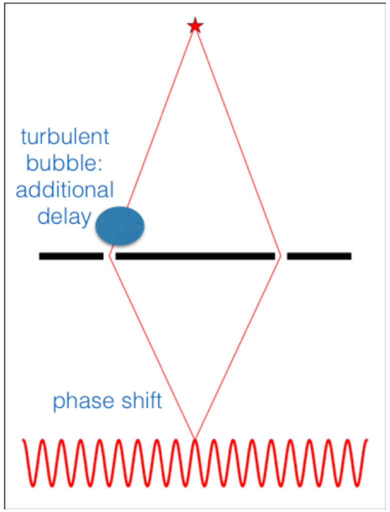
$$V_{\mathrm{UD}} = 2\frac{J_1(x=\pi B\theta/\lambda)}{x}$$

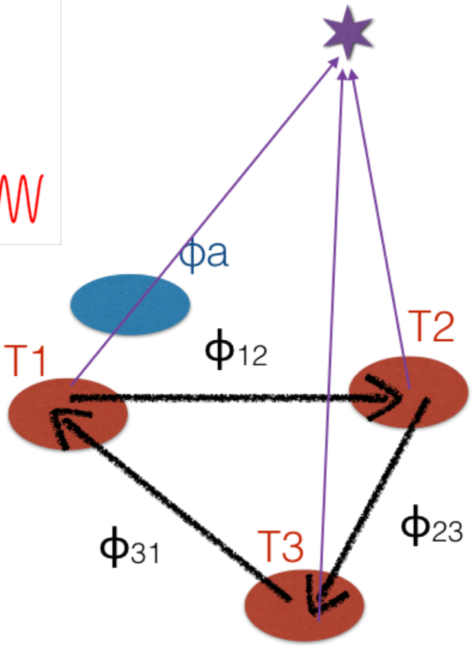


Recover the phase information

- The atmosphere induces phase jitter >> 2π
- Sum of phases in a triangle are immune to the turbulence: closure phase

$$CP = (\phi_{12}+\varphi_a) + \phi_{23} + (\phi_{31}-\varphi_a)$$
$$= \phi_{12} + \phi_{23} + \phi_{31}$$

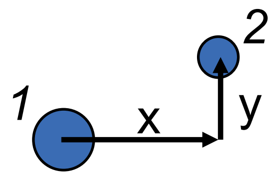




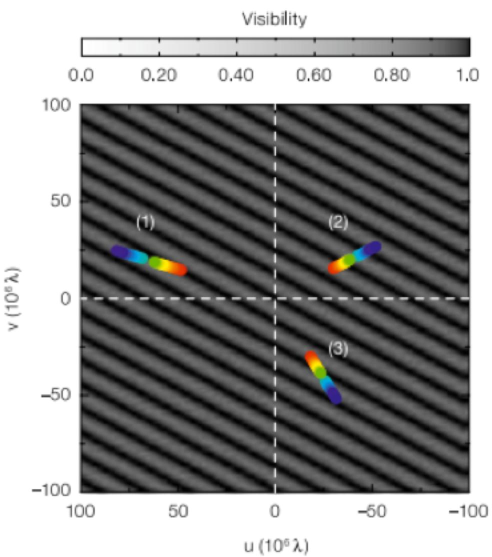
Binary star

The Fourier transform is linear:

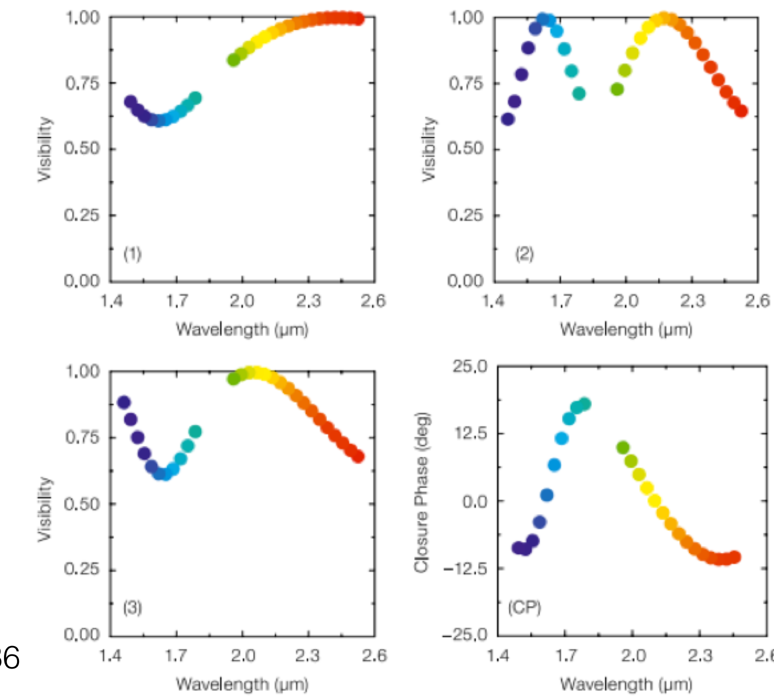
$$V = \frac{f_1 V_1 + f_2 V_2 e^{-2i\pi(ux+vy)/\lambda}}{f_1 + f_2}$$



3 Telescopes with several spectral channels (e.g. VLTI/AMBER) allow to un-ambiguously measure a binary separation and flux ratio.

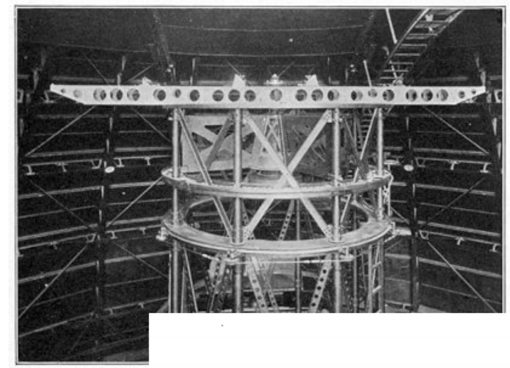


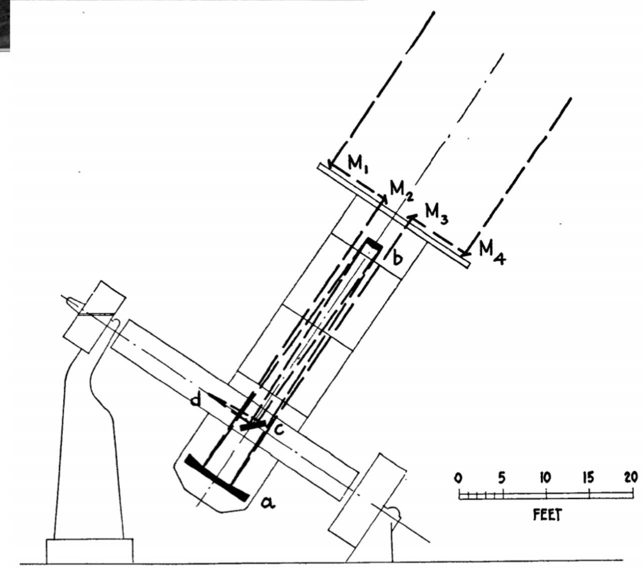
Kraus+ 2009 The Messenger 136



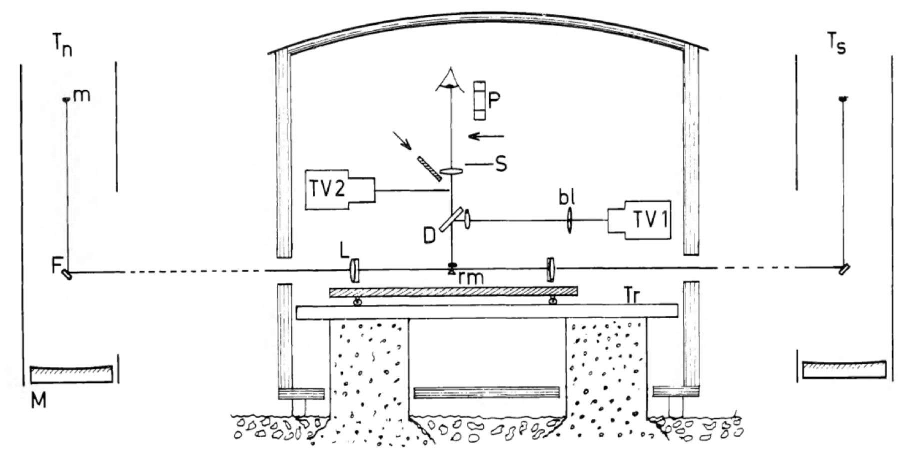
Early history

- H. Fizeau (1868): first idea of stellar interferometry
- E. Stéphan (1874): upper limit of size of stars using 65 cm telescope
- A. Michelson & F. Pease (1921): measure the first angular diameter of a star (Betelgeuse) using a 6 m interferometer
  http://articles.adsabs.harvard.edu/pdf/1921ApJ....53..249M





1970's: The rebirth



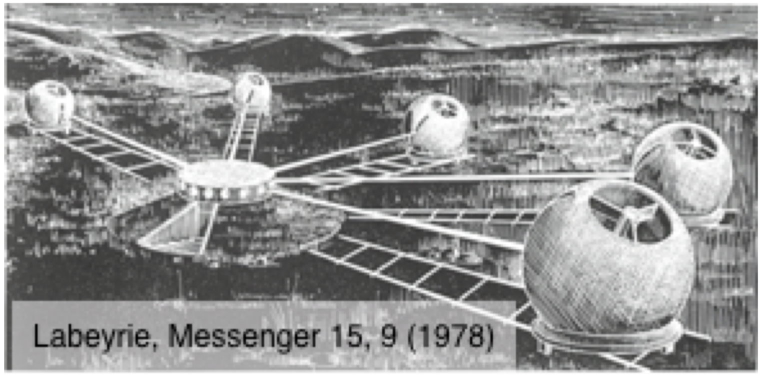
A. Labeyrie 1975: first fringes combining separate telescopes

http://articles.adsabs.harvard.edu/pdf/1975ApJ...196L..71L

Late 1970's at ESO: what to build after La Silla's 3.6m?

- 1977: ESO will build a 16m Telescope (or 4x8m, or 16x4m)
- 1981: ESO conference "Scientific Importance of High Angular Resolution at Infrared and Optical Wavelengths"
- 1986: decision to build four 8m Telescopes with 3 modes:
  - Standalone
  - Incoherent
  - Coherent

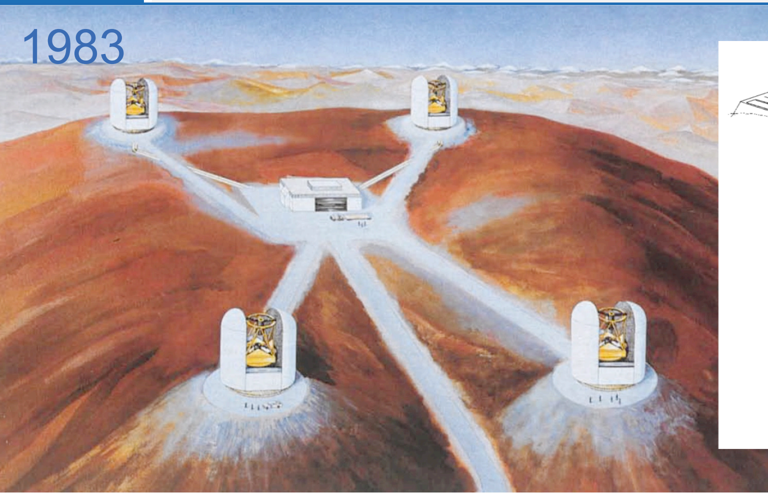
"While the concensus viewpoint seemed to support the view that the emphasis for post-conventional telescopes should lie in the incoherent addition of more photons from bigger systems, a strongly vocal minority was clearly convinced that techniques using phase information should not be neglected"
Messenger p2, #12 (1978)



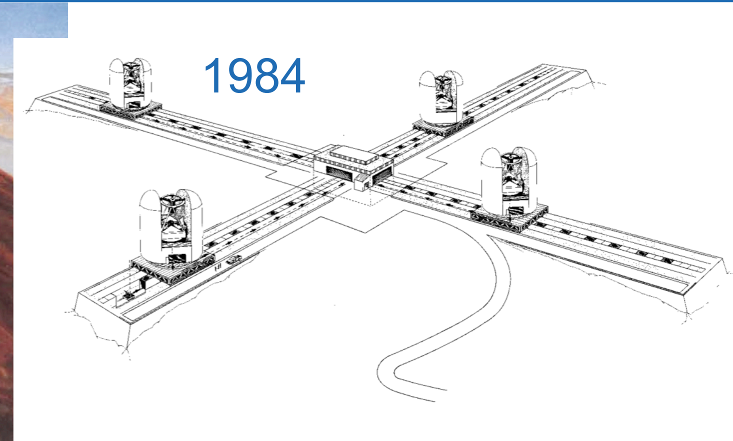
Labeyrie, Messenger 15, 9 (1978)

Converging on a design

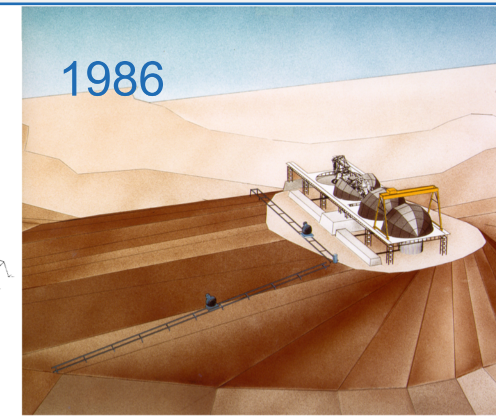
1983



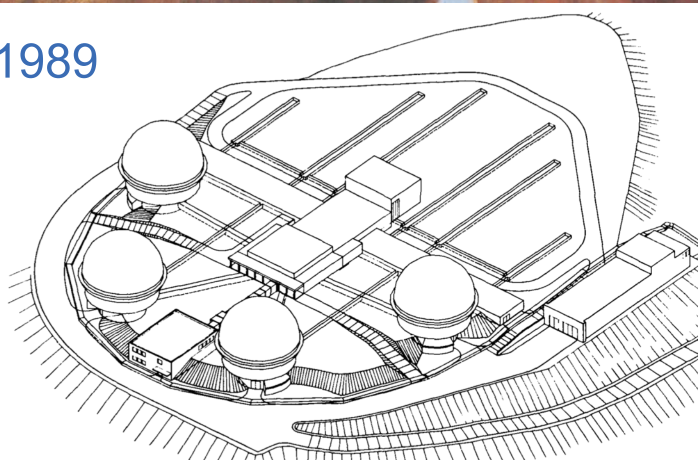
1984

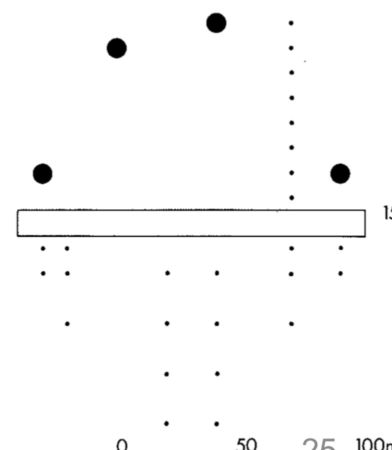


1986

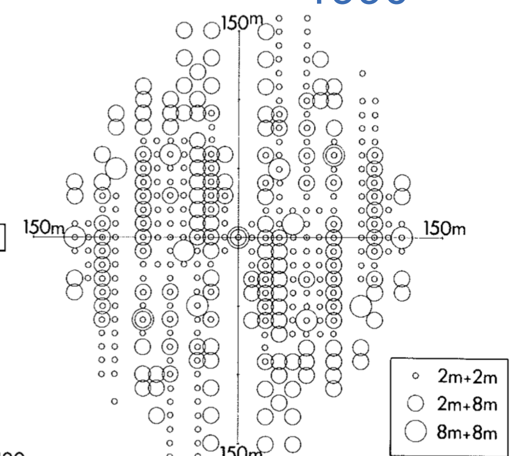


1989



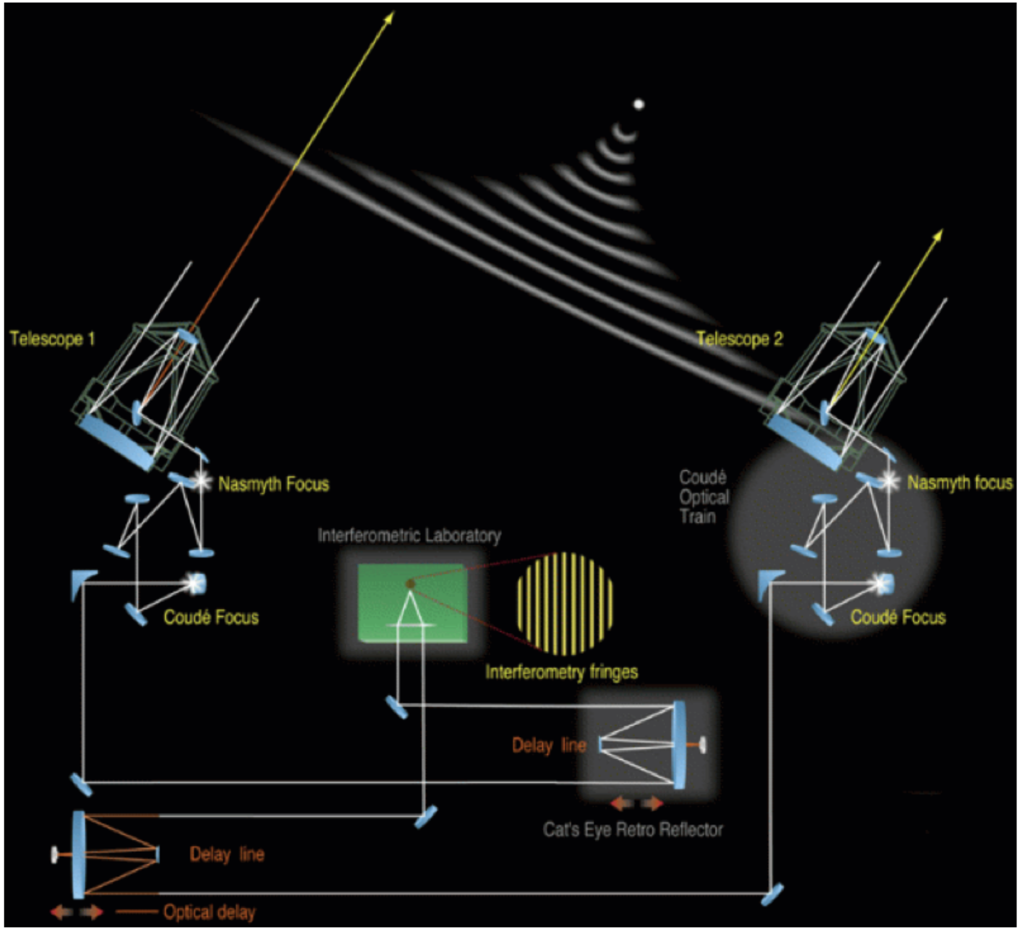


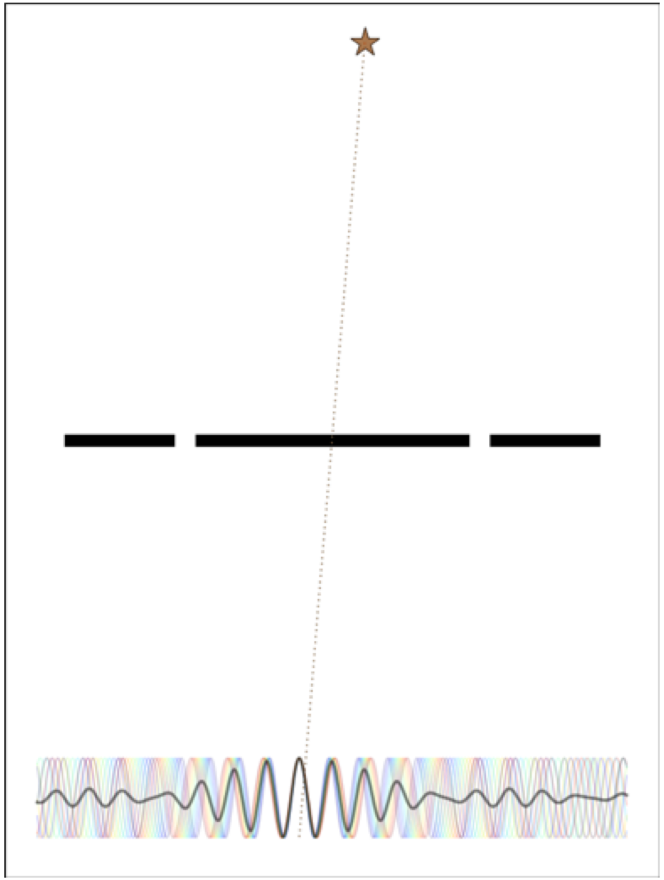
1990




B ~ 140m
λ ~ 2.2μm
λ/B ~ 3mas

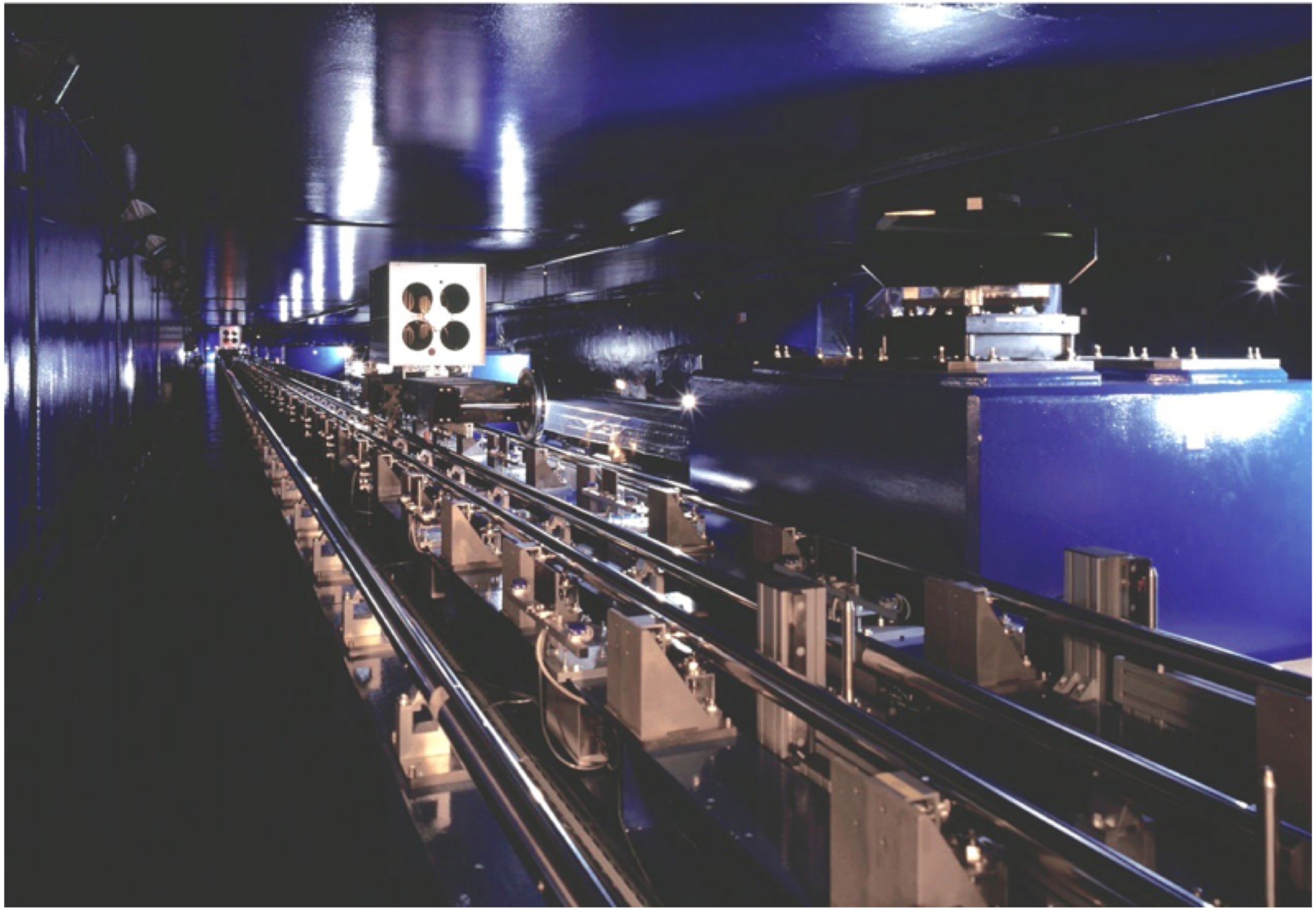
Principles of operations



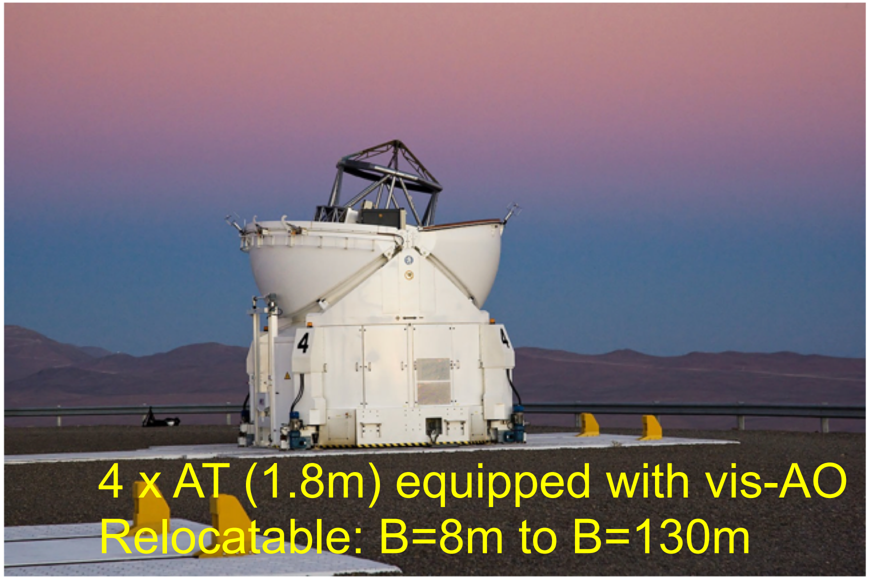


Coherence is only a few λ

Delay Line



Telescopes


4 x AT (1.8m) equipped with vis-AO
Relocatable: B=8m to B=130m


4 x UT (8.2m)
equipped with vis and nir AO

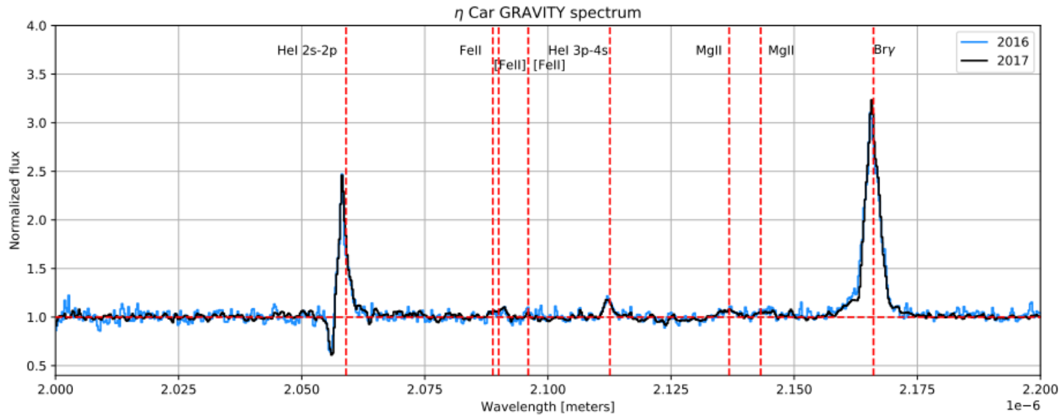
VLTI instruments (4T)

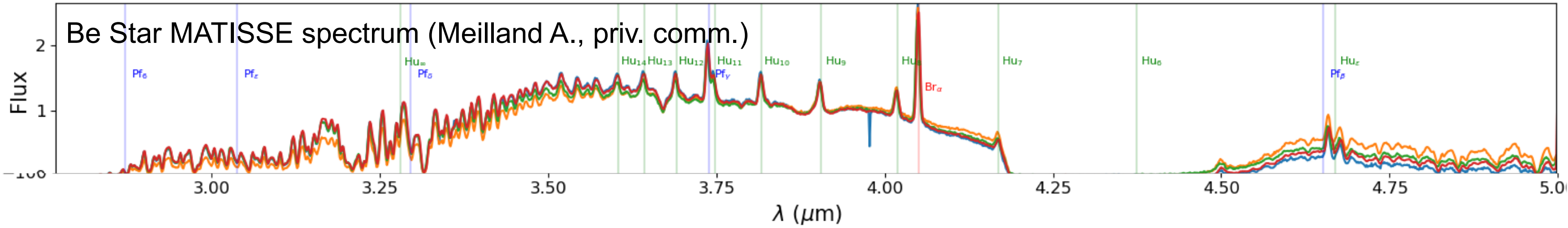
https://www.eso.org/sci/facilities/paranal/instruments.html

- PIONIER
  - H band (λ~1.6μm), R~50
- GRAVITY
  - K band (λ~2.2μm), R~20, 500 and 4000
  - Fringe tracker (up to 2” off-axis)
- MATISSE
  - L,M,N bands (λ~3 to 12μm), R~30, 500, 1000 amd 3500
  - GRAVITY as a fringe tracker

Spectral capabilities

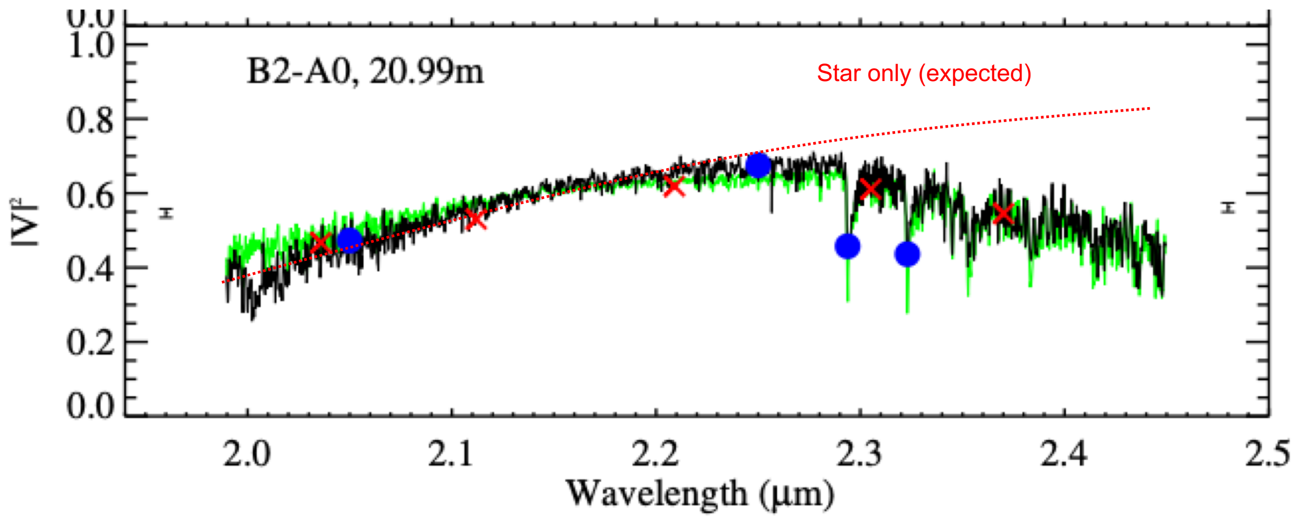
Eta Car (LBV) GRAVITY spectrum (Gravity Collaboration 2018)



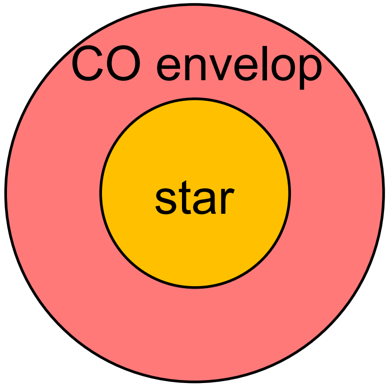


Differential visibilities

CO lines in Mira-type star (Wittkowski+ 2018)

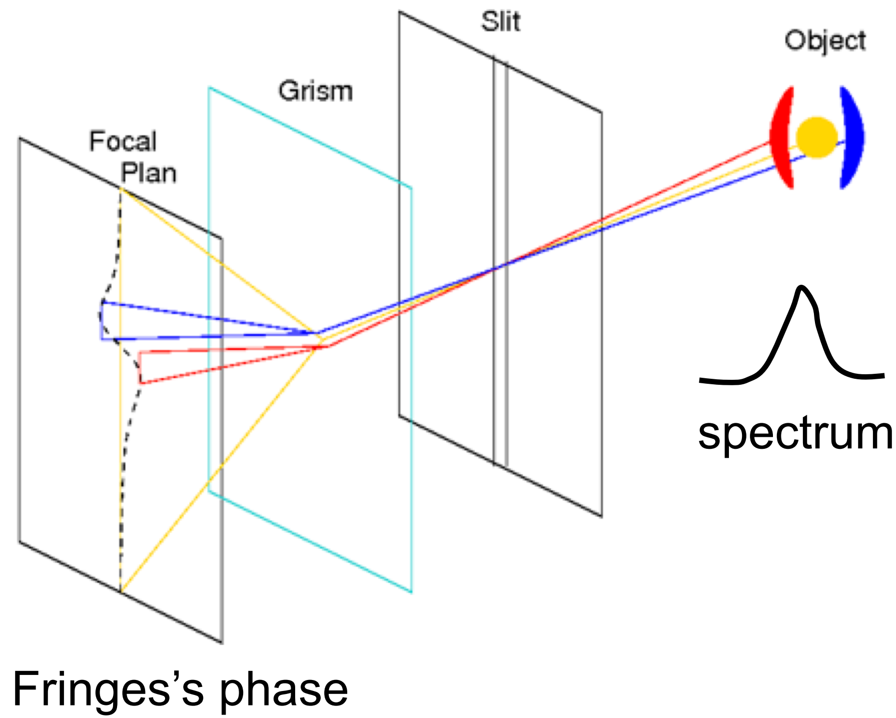


Visibility drops in a line -> object is larger



Differential phases

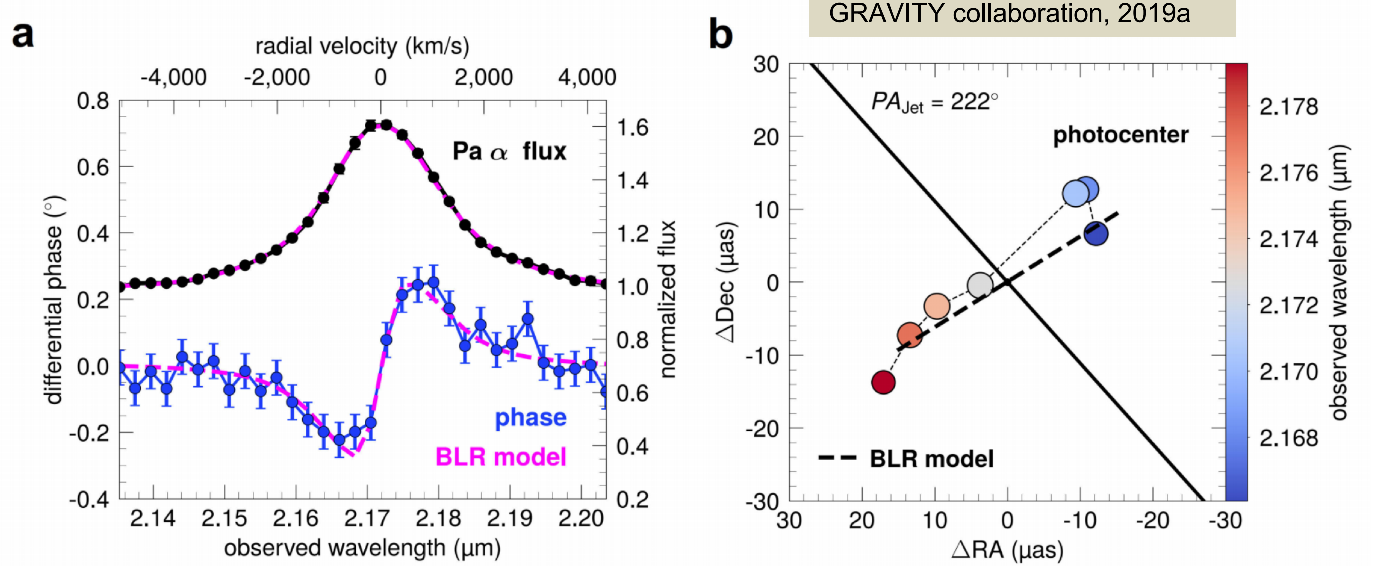
- Spectro-interferometry gives complementary information to spectroscopy
- Fringes' contrast drops as object gets resolved
- Fringes differential phase follow the photocenter



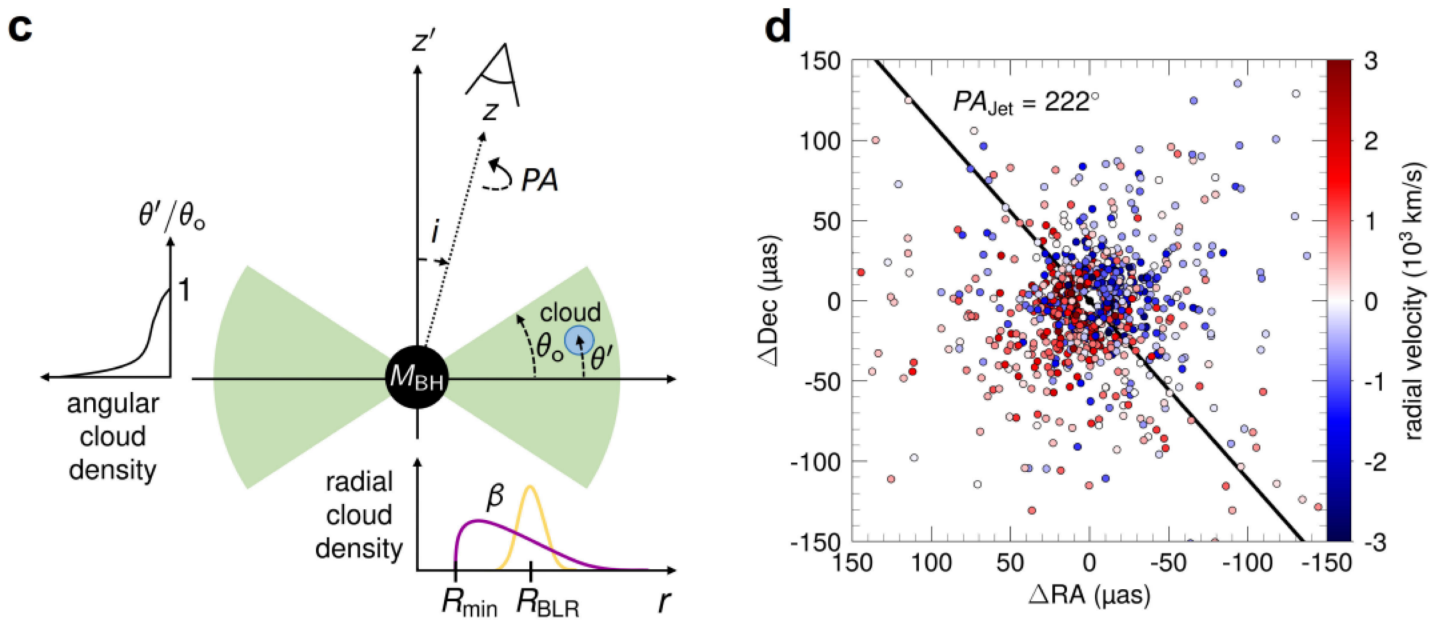
Differential phase application

- Measuring the orbital motion of the Broad Line Region in the quasar 3C273 ($z=0.158$)
- Knowing the distance, the mass of the central object can be estimated: $2.6\pm1.1\ 10^8\ M_\odot$

GRAVITY collaboration, 2019a



3C273 modeling

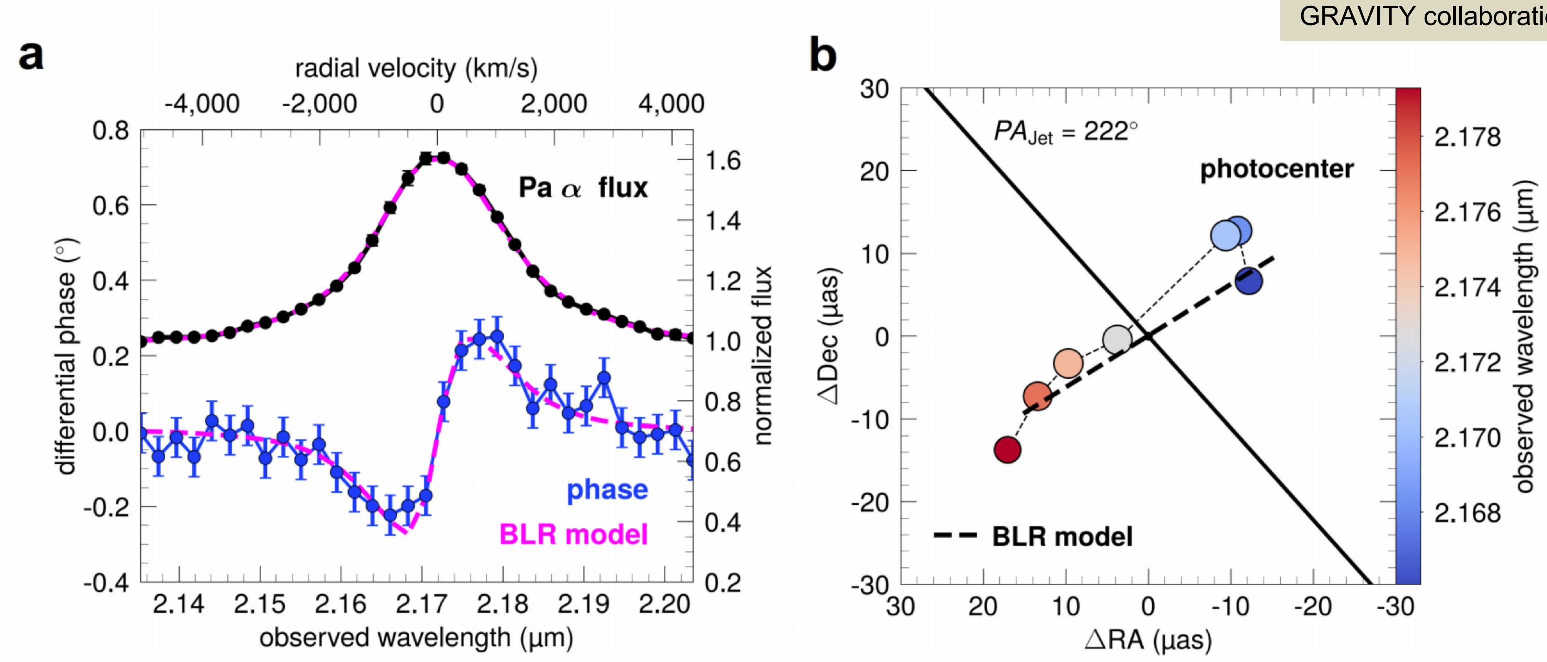


GRAVITY collaboration, 2019a

Beating the diffraction?

- BLR of 3C273 found to be 46±10μas
- λ/B = 2.2μm/140m ~ 3.2mas

GRAVITY collaboration, 2019a

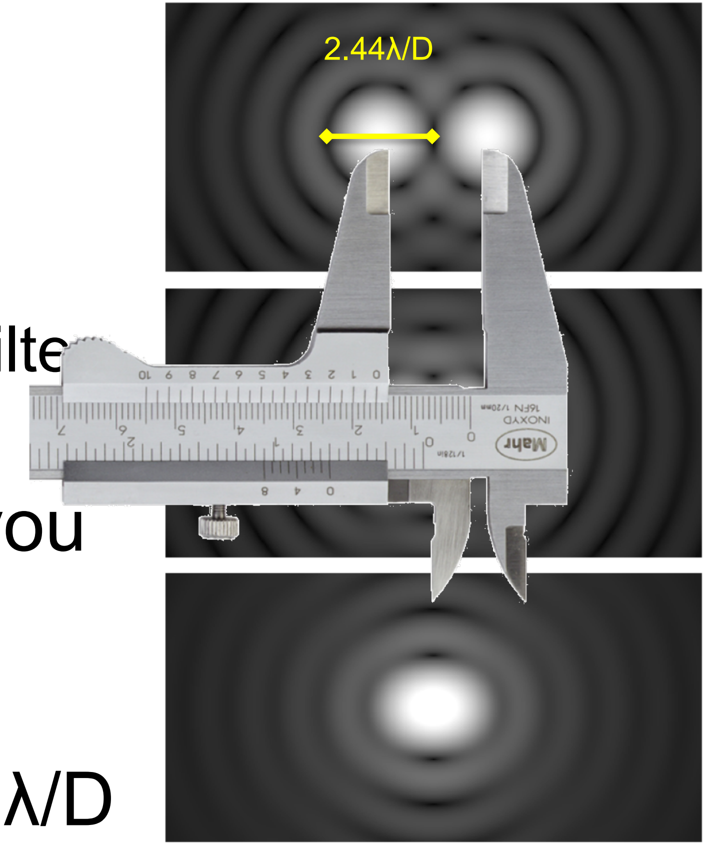


Beating the diffraction?

- Differential phase is measured better than 0.1º
- 360º of phase corresponds to 1 wavelength
- Differential phase is measured better than λ/3600
- Actual resolution for 0.1º is λ/B/3600 ~ 1µas

Diffraction limit

- Definitions for a telescope of diameter D:
  - Airy pattern first null at radius 1.22λ/D
  - Aperture is a lowpass (spatial) filte of cutoff λ/D
- Limitation depends how well you know / sample your PSF
- Telescopes can achieve differential astrometry << 1.22λ/D



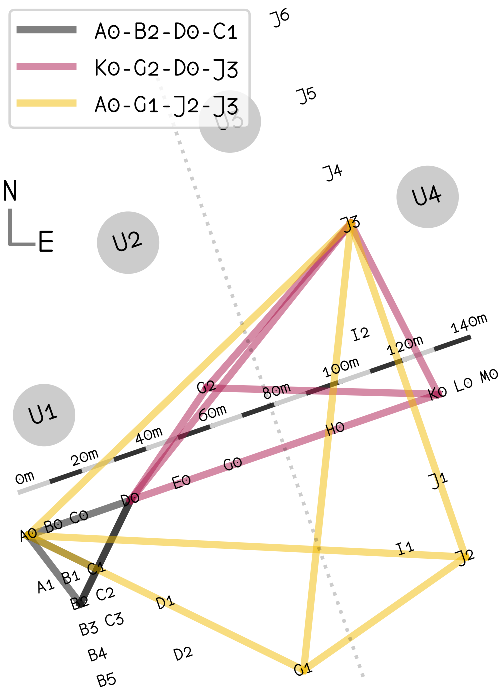
Imaging reconstruction

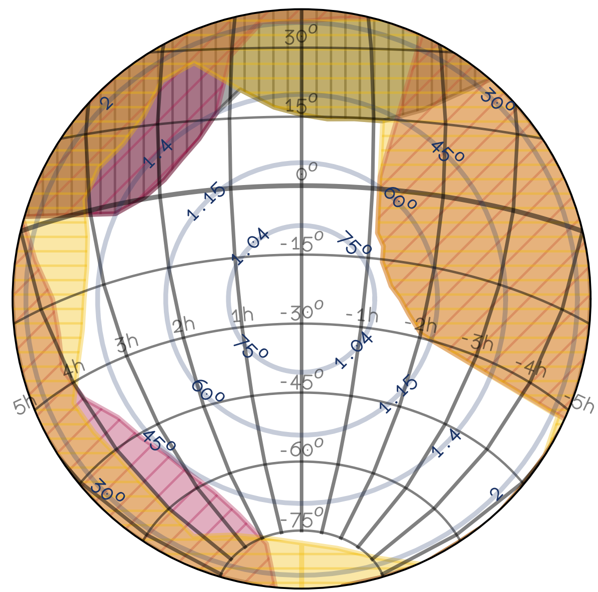
- Full aperture == low pass filter (up to λ/D)
- In practice, (u,v) plane is sparsly filled
  - nT = n(n-1)/2 baseline, (n-1)(n-2)/2 closure phases
- Visibility interpolation and regularisation (priors) are needed:
  - edge-preserving smoothness, total variation, maximum entropy, etc.
- Very useful when the morphology is not well known complex
- Limitations:
  - Largest to smallest scales: λ/B_{max} -> λ/B_{min}
  - Number of pixels ~ $(B_{max}/B_{min})^2$
  - Dynamic range ~ 1/precision on Visibility

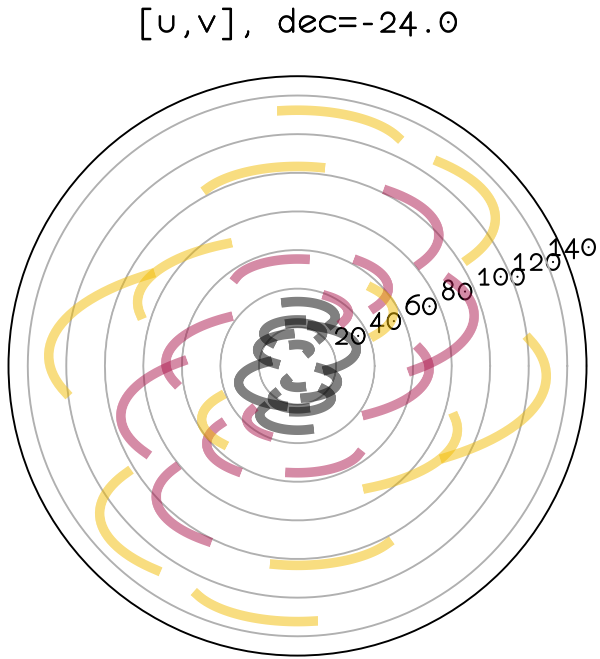
Imaging at VLTI

Moveable telescopes in three 4T configurations

B_{min}=8m to B_{max}=130m → ~16x16 image

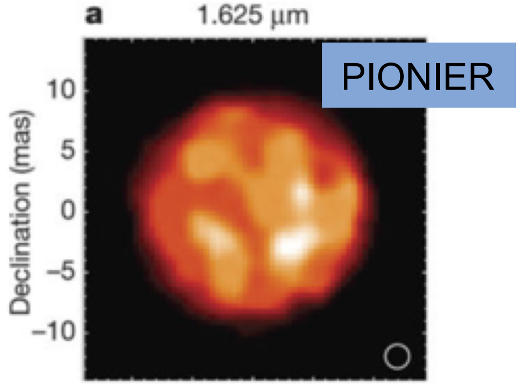




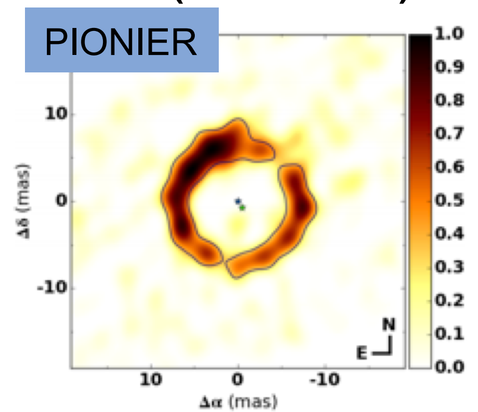


Some VLTI images

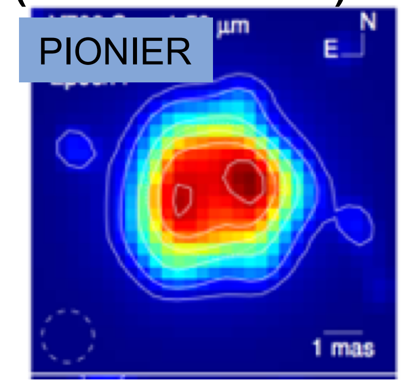
AGB pi[1] Gru (Paladini+ 2018)



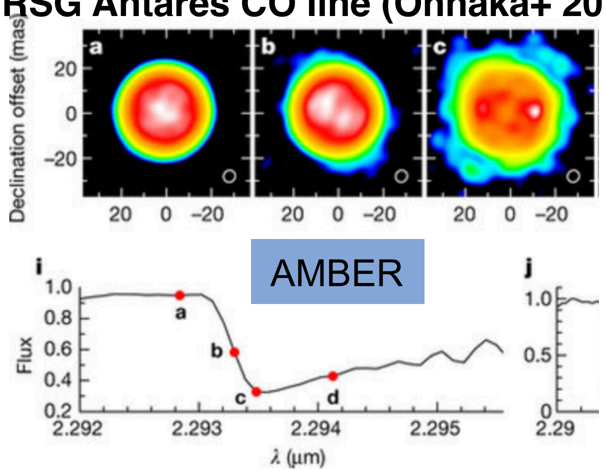
post-AGB IRAS 08544-4431 (Hillen+ 2016)

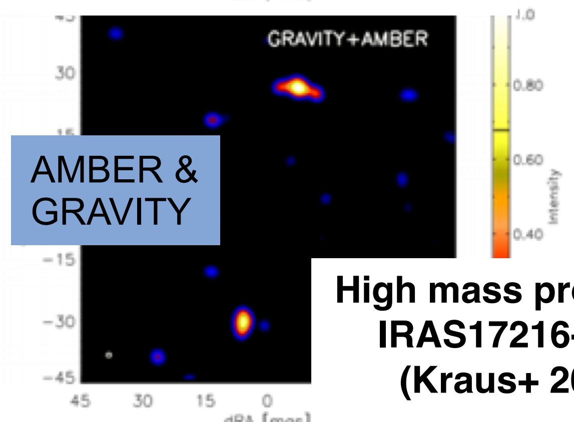


YHG V766 Cen (Wittkowski+ 2017)



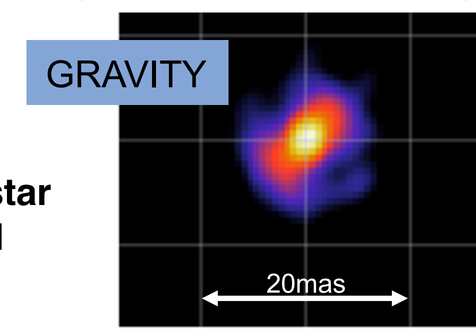
RSG Antares CO line (Ohnaka+ 2017)





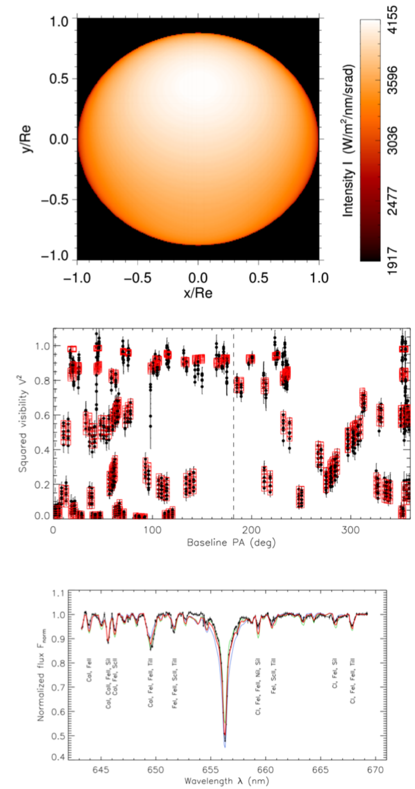
High mass proto-star IRAS17216-3801 (Kraus+ 2017)

LBV Eta Car, HeI line (GRAVITY Collab 2018)

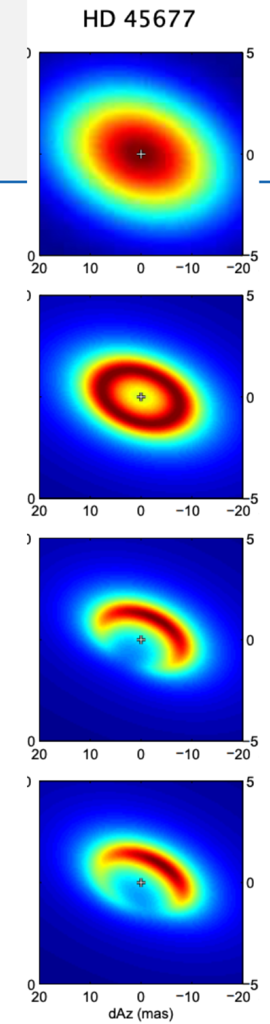


Do I always need imaging?

- Different approaches:
  - Morphological fit
  - Physics based model (simulation)
- Additional observables very useful (photometry, spectroscopy…)
- Visibilities can be modelled and parameters fitted



Synthetic image, visibilities and spectra for a fast rotating star (Domiciano de Souza+ 2018)

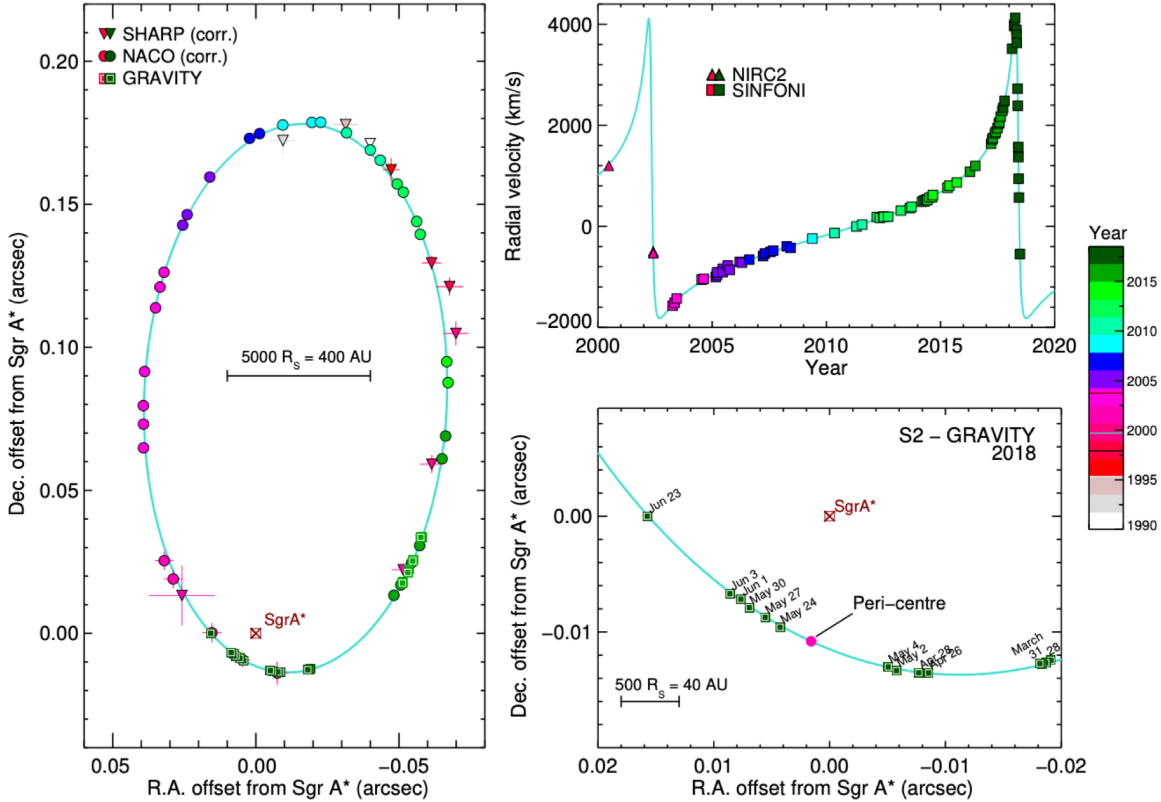


modeling disks images using simple analytical functions (Lazareff+ 2017)

Galactic Centre

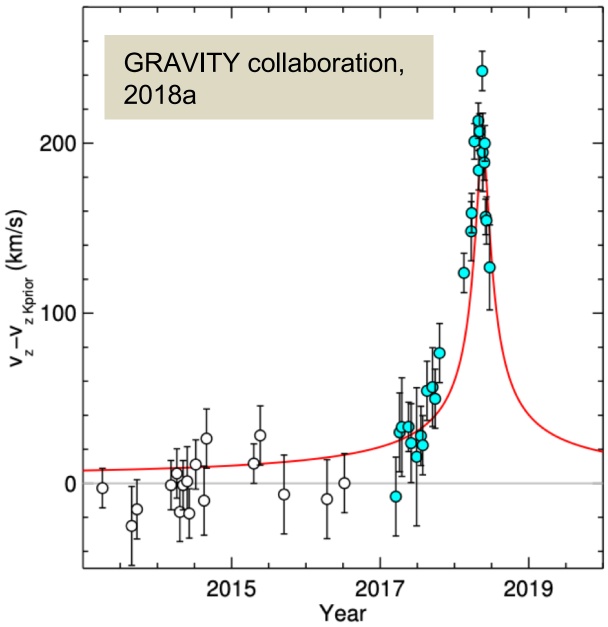
- Resolving a binary in astrometry and radial velocity gives the mass and the distance
- Best distance and mass to the Galactic Centre

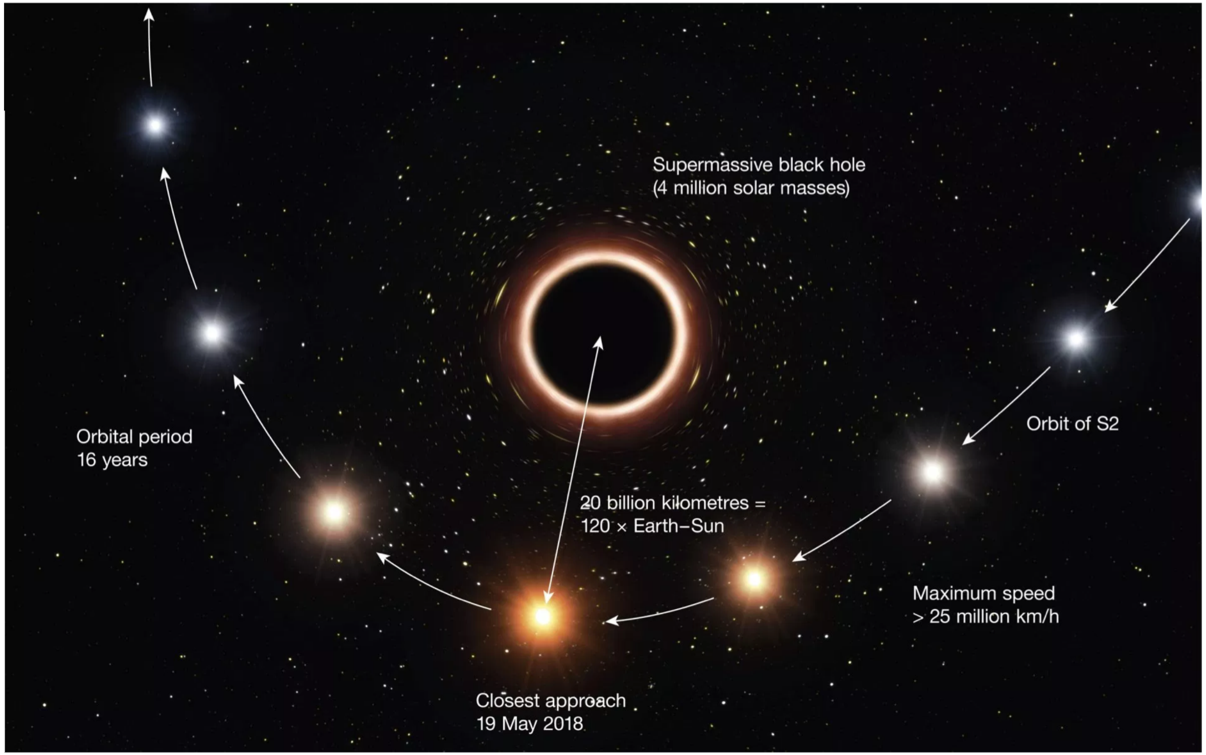
GRAVITY collaboration, 2018a



Detection of gravitational reddening around Sgr A*

Radial velocity deviation to the apparent orbit:



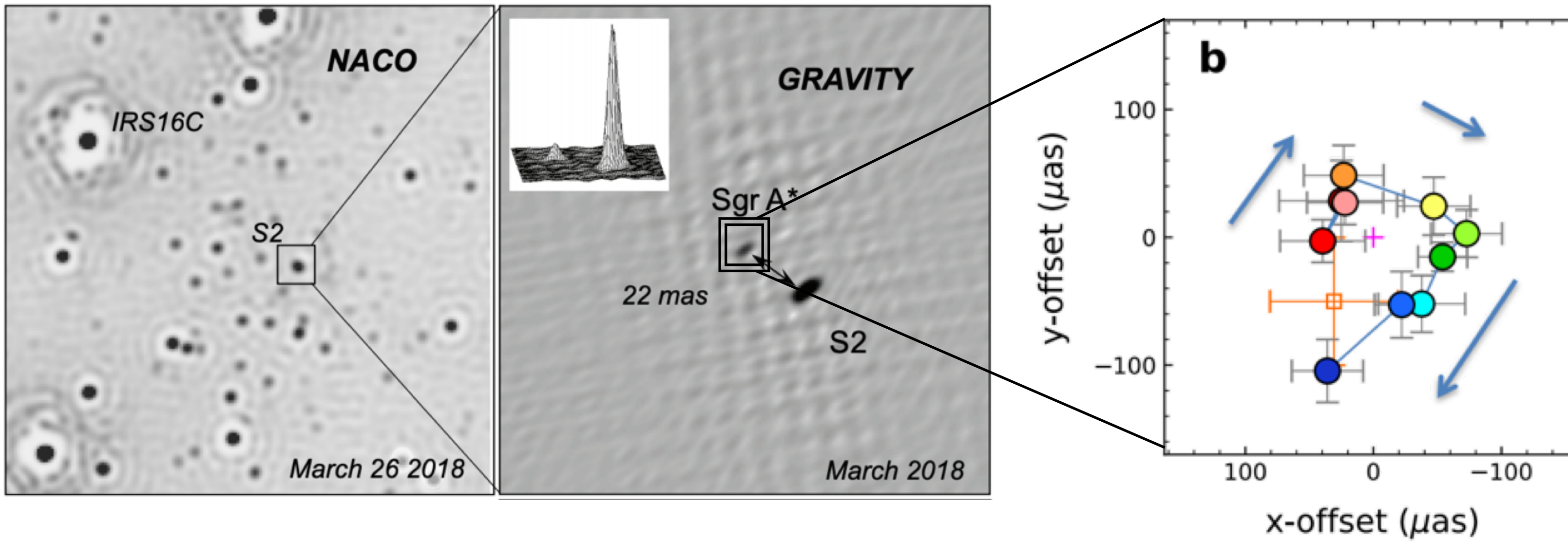


Credit: ESO/M. Kornmesser

Detection of LSCO around Sgr A*

GRAVITY collaboration, 2018a

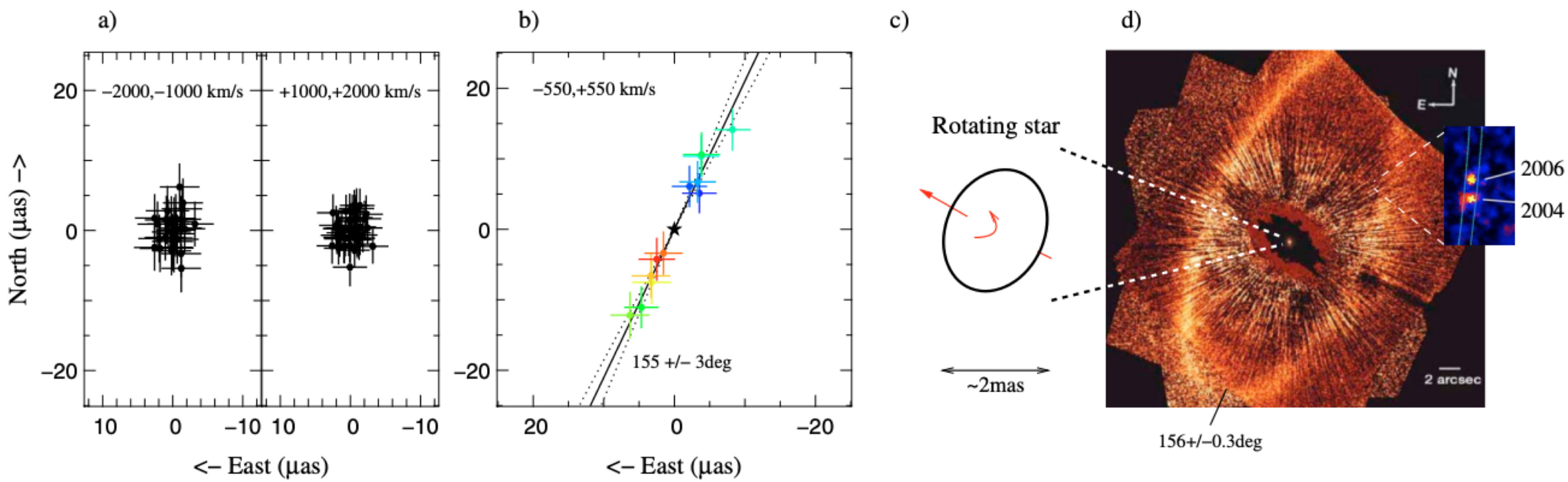
GRAVITY collaboration, 2018b



Material falling on the last stable circular orbit around the black hole

Spin orbit alignment

Is a star co-rotating with the debris disk and planets?

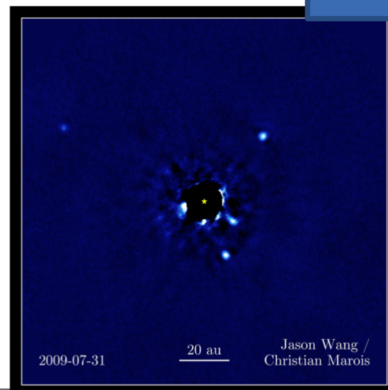


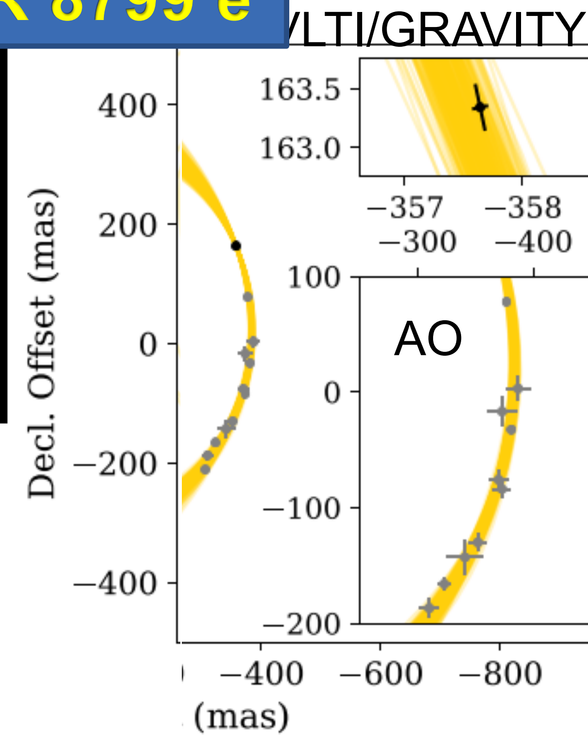
Le Bouquin+ 2009

Spectroscopy and astrometry of exoplanets

100x improvement on astrometry and spectral resolution compared to AO

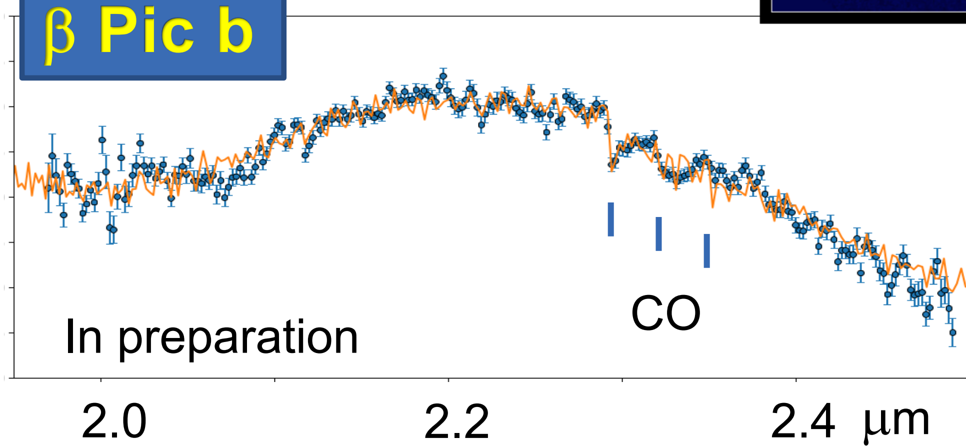
HR 8799 e





GRAVITY Collaboration+ 2019

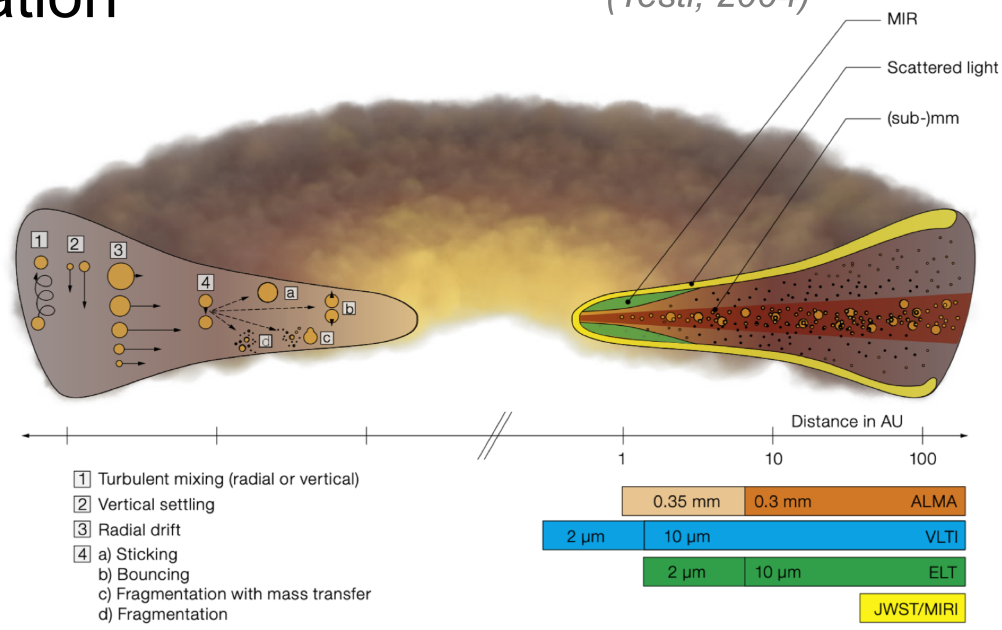
β Pic b



Complementarity

- AO imaging, ALMA
  - probes (slightly) larger scales
  - Inner/outer disk orientation (warping)
- Spectroscopy
  - Localise processes
  - binaries
- SED
  - $L \propto R^2 T_{\mathrm{eff}}^4$

Protoplanetary disk (Testi, 2004)



Why Optical Interferometry?

- Unmatched angular resolution
  - Imaging with ~1mas resolution (λ/B)
  - High angular astrometry (can be <<λ/B, ~50µas)
  - Spectroscopic capabilities
- Limitations:
  - Sensitivity compared to imaging / spectroscopy
  - Dynamic range of few 100
  - Field of View == diffraction limit of the telescope (UTs~50mas; ATs~250mas)

To go further

- 2020 VLTI School (to be announced)
  - http://www.european-interferometry.eu/training
- Introduction from a past School:
  - https://arxiv.org/abs/1907.07443