Interférométrie optique: les instruments et leurs spécificités

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Summary

1. Introduction on the principles
2. Back to the Object-Image relationship
3. The reality of Interferometry
4. The practice of interferometry
5. The instruments in operation
6. The future?

Introduction

Usual stellar physics

astrometry photometry
spectroscopy polarimetry

↓

Star are (almost) always considered as point-like source

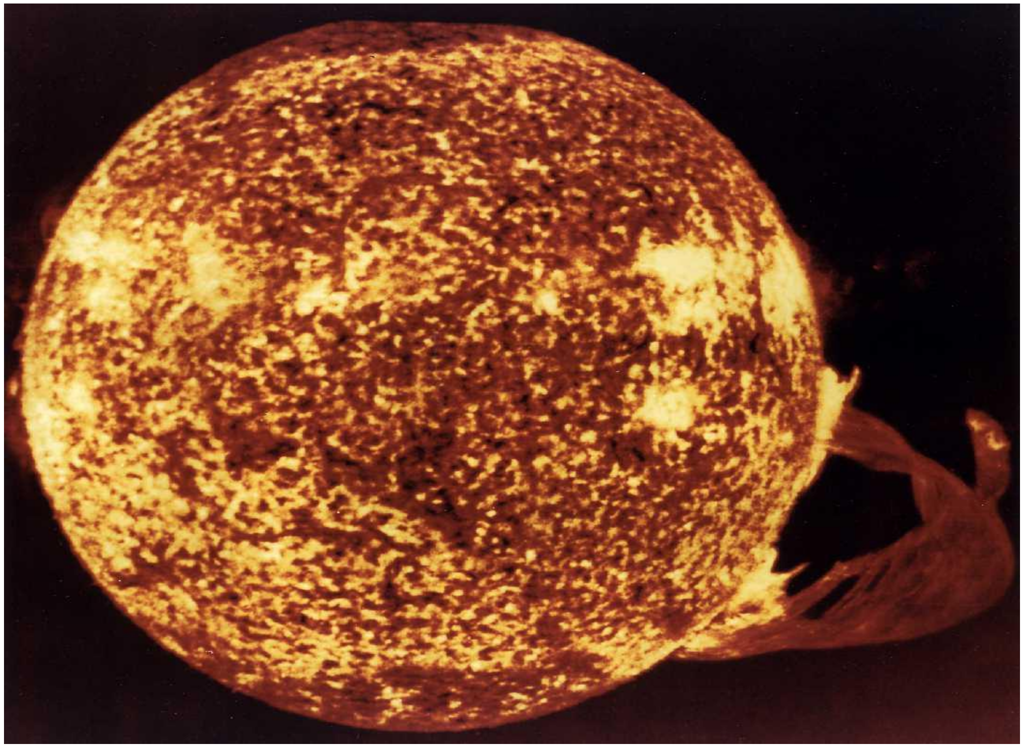
↓

No information on the brightness distribution

↓

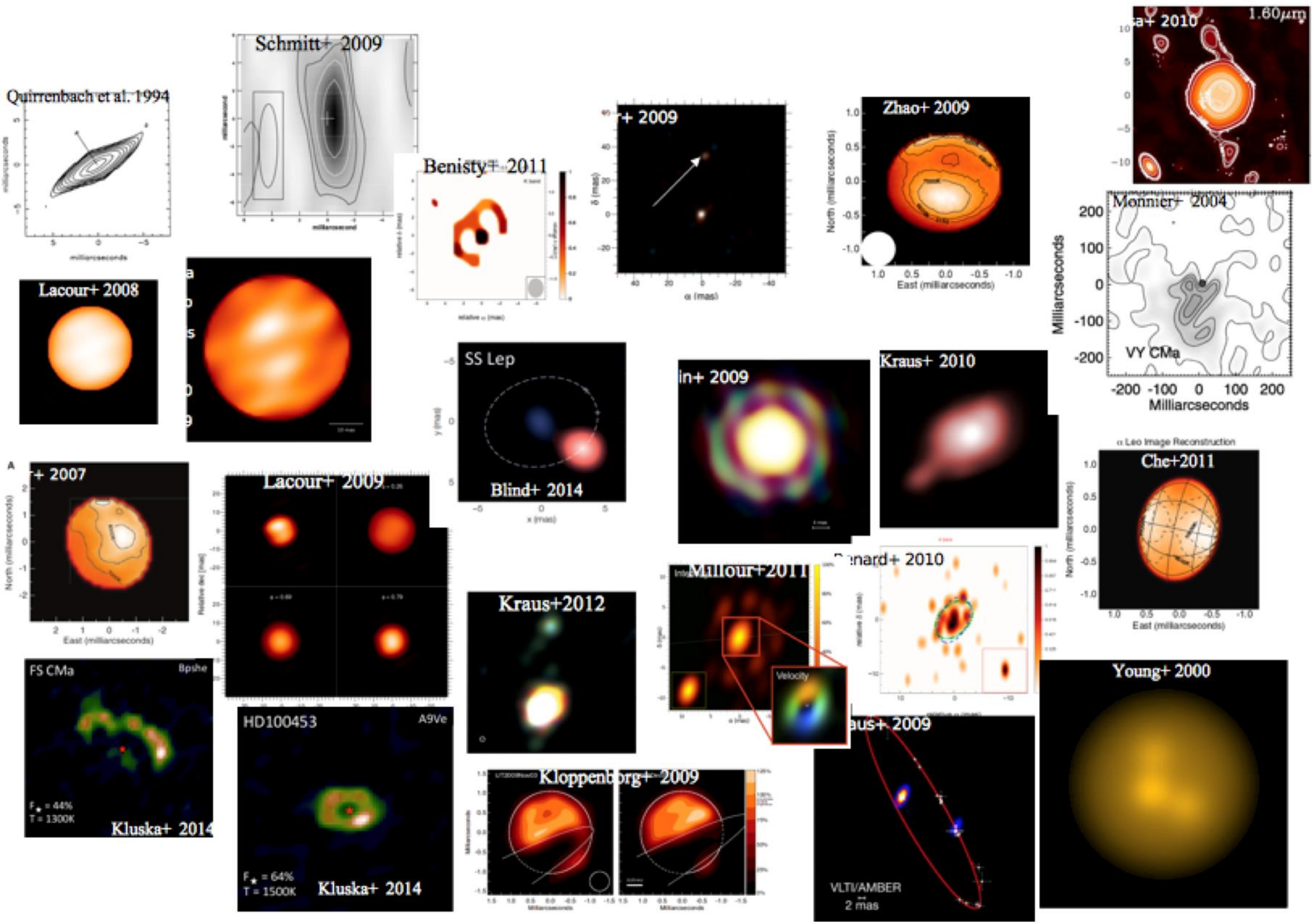
Scientific niche for the High Angular Resolution

Imaging stellar surfaces and environnements

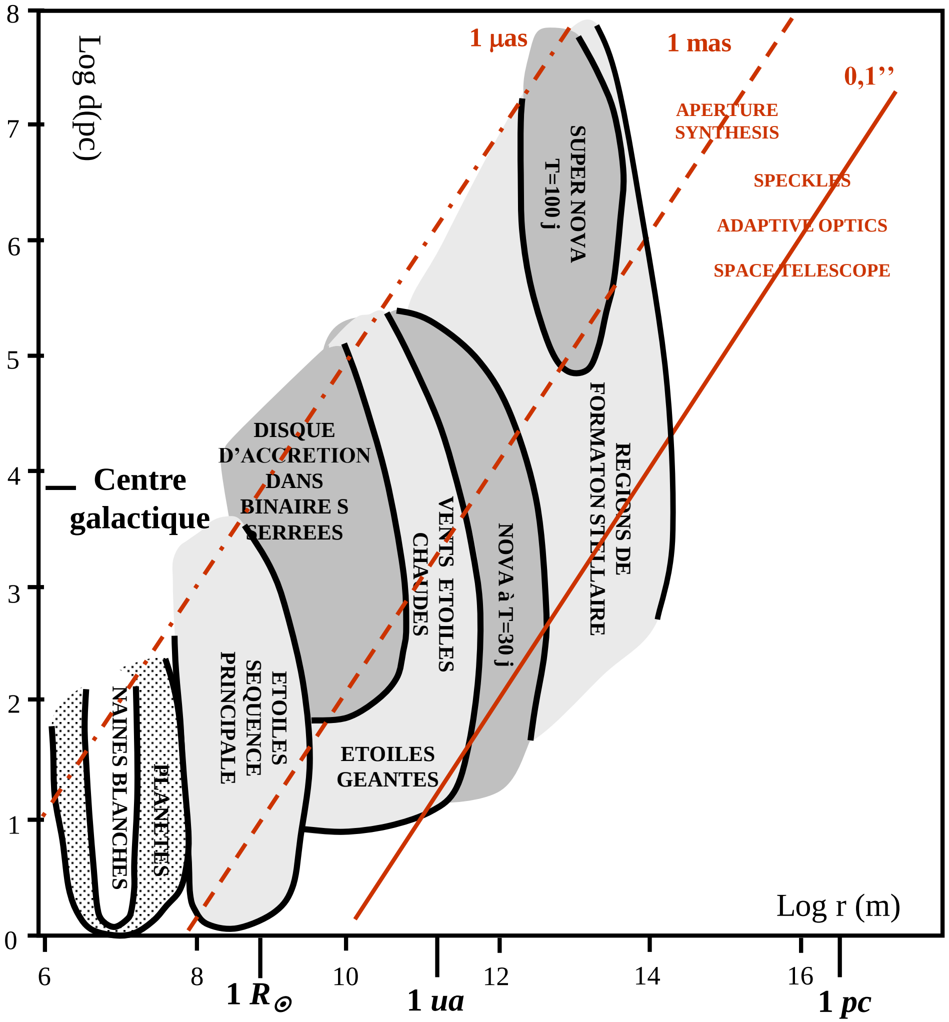


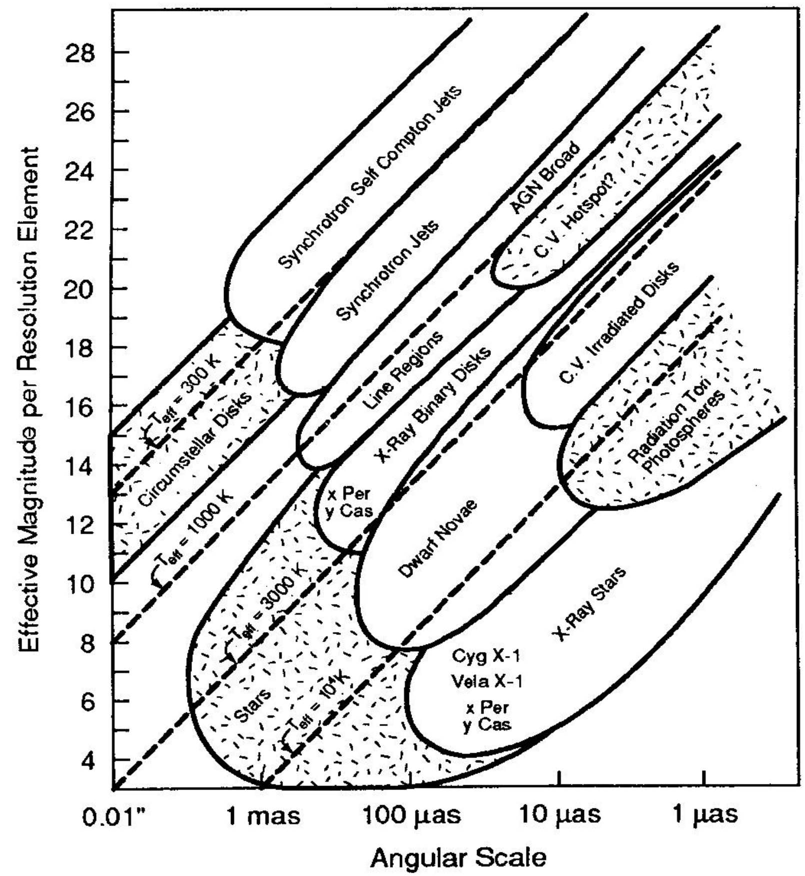
High resolution
- **spatial**
- **temporal**
- **spectral**

Needs for
- **field of view**
- **transfer function**

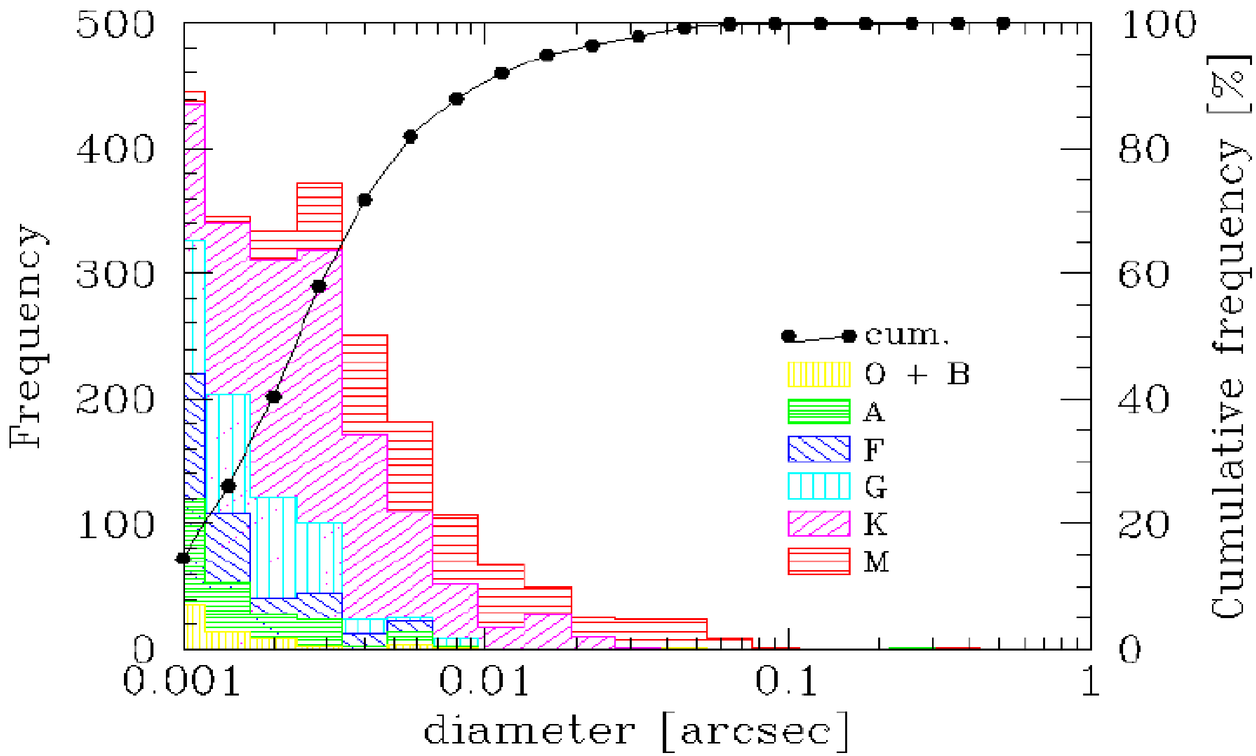

Schmitt+ 2009
Quirrenbach et al. 1994
Benisty+ 2011
+ 2009
Zhao+ 2009
a+ 2010
1.60μm
Monnier+ 2004
VY CMa
Milliarcseconds
Lacour+ 2008
SS Lep
Blind+ 2014
in+ 2009
Kraus+ 2010
+ 2007
Lacour+ 2009
α Leo Image Reconstruction
Che+2011
Kraus+2012
Millour+2011
Velocity
nard+ 2010
FS CMa
Bpshe
Kluska+ 2014
HD100453
A9Ve
Kluska+ 2014
Kloppenborg+ 2009
aus+ 2009
VLTI/AMBER
2 mas
Young+ 2000

Astrophysics sources and High Angular Resolution





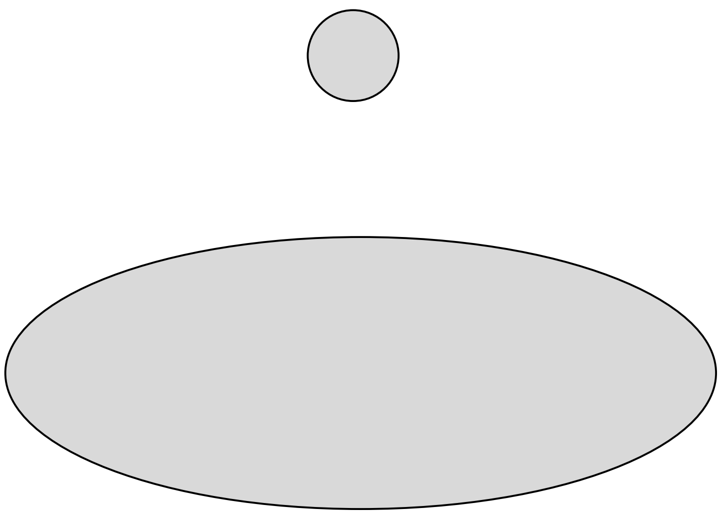
Distribution of stellar diameters



1309 sources
50 % < 2.5 mas
20 % > 5 mas
7% > 10 mas -> UT

How to measure a so small angular diameter?

Star at infinity
Angular diameter θ



Screen of radius r

Angular diameter θ ➔ solid angle $\Omega=\pi(\theta/2)^2$

Radius r ➔ Surface $S=\pi r^2$

Etendue of the beam

$$\varepsilon = S\Omega = \pi^2 r^2 (\theta/2)^2$$

Definition of coherence (Goodman)

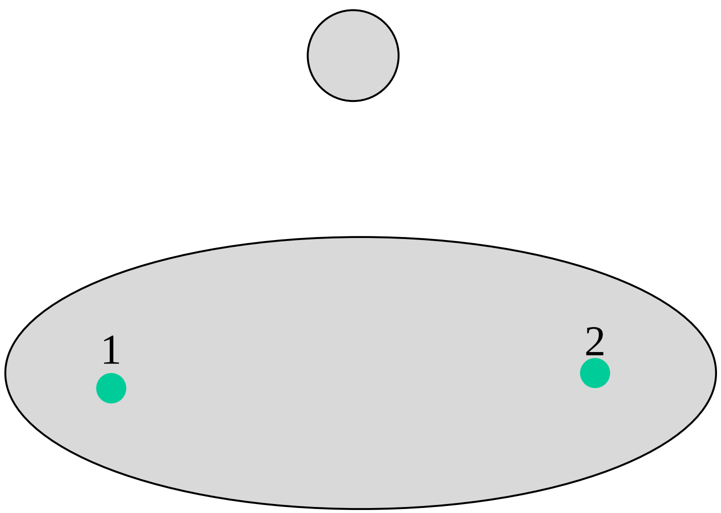
$$\varepsilon < \lambda^2$$

➔ $$r_c = \frac{\lambda}{\pi\left(\frac{\theta}{2}\right)}$$

N.A.: θ=10mas, λ=1µm ➔ r_c= 13m

Coherence & Van-Cittert Zernike Theorem

Star at infinity
Angular diameter θ



Screen of radius r

The coherence of the electromagnetic wave could be determined by the computation of the complex degree of mutual coherence between points 1 & 2 of the collecting area:

$$\Gamma_{12} = \frac{\left|\psi_1 \psi_2^*\right|}{\sqrt{\left|\psi_1\right|^2 \left|\psi_2\right|^2}}$$

V-CZ ➔ $$\Gamma_{12} = \frac{\left|\tilde{O}(B/\lambda)\right|}{\left|\tilde{O}(0)\right|}$$

Uniform Disk: $$\Gamma_{12} = \left|\frac{2J_1(\pi\theta B/\lambda)}{\pi\theta B/\lambda}\right|$$

Note: The definition of r_c (Goodman) corresponds at B where $\Gamma_{12}=0.5$
i.e. $\pi\theta B/\lambda=2$ ➔ $r_c=B=2\lambda/\pi\theta$ ➔ $\varepsilon=\lambda^2$.

How to measure a so small angular diameter (2)?

$$r_c = \frac{\lambda}{\pi\left(\frac{\theta}{2}\right)} \qquad \Gamma_{12} = \frac{\left|\psi_1 \psi_2^*\right|}{\sqrt{\left|\psi_1\right|^2 \left|\psi_2\right|^2}}$$

N.A.: θ=10mas, λ=1µm ➔ r_c= 13m
$\Delta\lambda$ = 0.1µm and $t_c.\Delta f$=1 ➔ $t_c=3.10^{-14}$s

With larger λ and fast detectors, it is possible to record the electromagnetic wave at two different locations and correlate them in a computer:

➔ Radio Interferometry (mm, cm wavelengths)
➔ Very Long Baseline Interferometry

With intermediate λ, small Δλ and fast detectors, one can create beating waves, record them and correlate them in a computer:

➔ Heterodyne Interferometry

Other cases: direct interferometry because (almost) no ways to record complex optical waves…

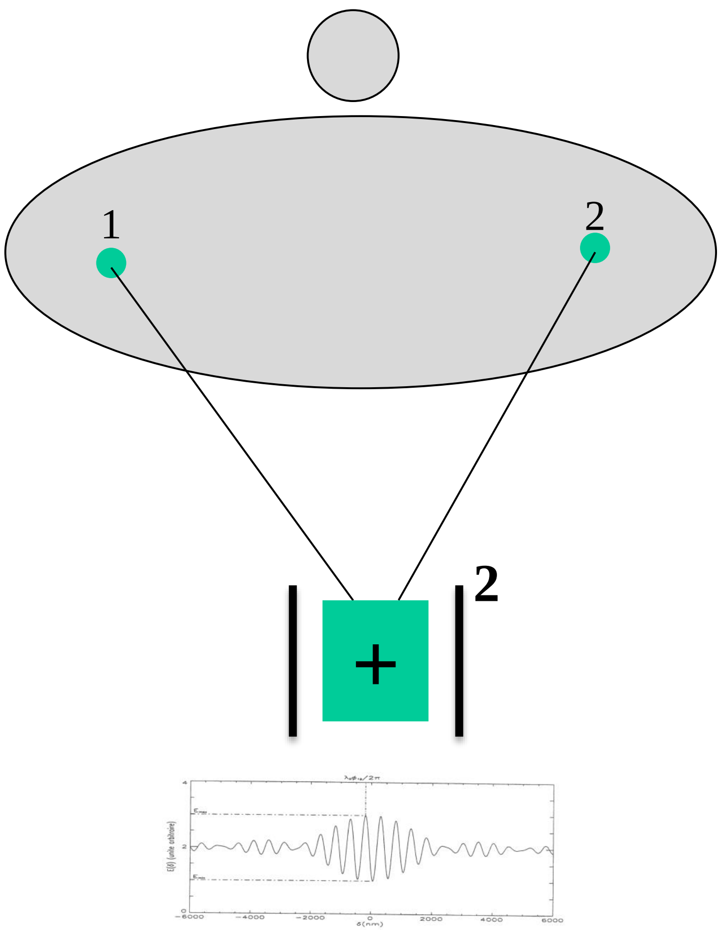
It could also be shown that the coherence between the two waves leads to a correlation between the fluctuation of intensities:

$$\left|\Gamma_{12}\right|^2 = \frac{\Delta I_1 \Delta I_2}{\overline{I_1}\,\overline{I_2}}$$

➔ Narrabri Intensity Interferometer but strong limitation in magnitude

The ideal interferometer
Young experiment with a star

Star at infinity
Angular diameter θ



$$I = \left|\Psi_1 + \Psi_2 e^{i\theta}\right|^2$$

$$I = \left|\Psi_1\right|^2 + \left|\Psi_2\right|^2 + 2\Psi_1\Psi_2^* \cos(\theta)$$

$$I = (I_1 + I_2) * \left(1 + \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} * \frac{\Psi_1\Psi_2^*}{\sqrt{\left|\Psi_1\right|^2\left|\Psi_2\right|^2}} * \cos(\theta)\right)$$

Photometric term: $\frac{2\sqrt{I_1 I_2}}{I_1 + I_2}$

Modulation term: $\frac{\left|\Psi_1\Psi_2^*\right| e^{i\phi}}{\sqrt{\left|\Psi_1\right|^2\left|\Psi_2\right|^2}}$

$$\gamma_{12} = \frac{\left|\Psi_1\Psi_2^*\right|}{\sqrt{\left|\Psi_1\right|^2\left|\Psi_2\right|^2}} = \frac{\left|\tilde{O}\left(\frac{B}{\lambda}\right)\right|}{\left|\tilde{O}(0)\right|}$$

Where are we?

- Notions
  - Coherence of a stellar wavefront
  - Fourier transform of the brightness distribution
  - Spatial frequencies of the source
- Method
  - Complex degree of mutual coherence
- This is really complicated…
- An other point of view: object-image relationship

Object-Image relationship

Brightness distribution in the image

$$I(\vec{\beta}) = H(\vec{\beta}) * O(\vec{\beta})$$

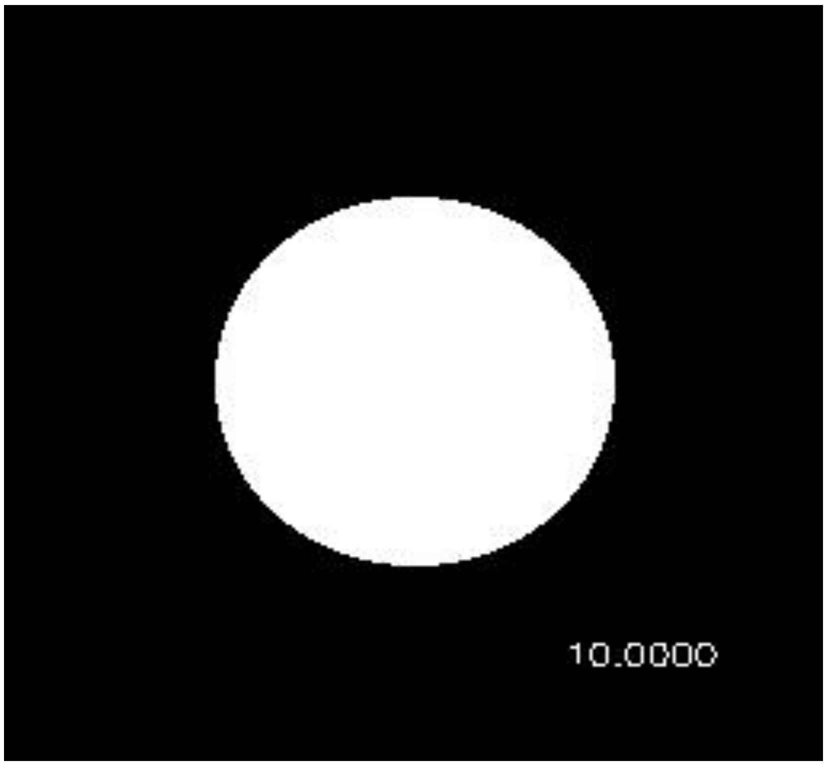
Spatial frequencies spectrum of the image

$$\tilde{I}(\vec{f}) = \tilde{H}(\vec{f}) \text{ x } \tilde{O}(\vec{f})$$

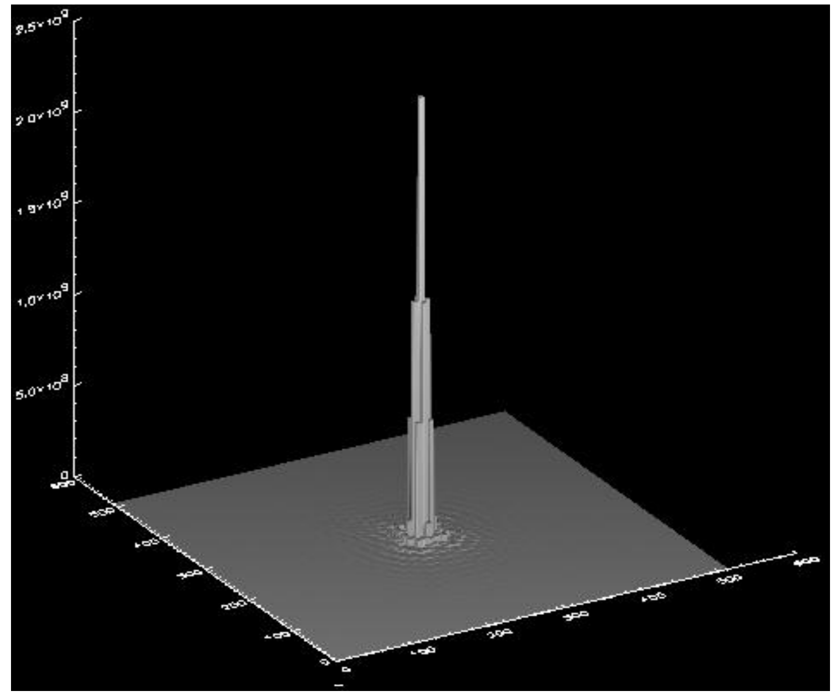
Modulation Transfer Function (MTF)

$$\left|\tilde{H}(\vec{f})\right| = AC[P(\lambda\vec{f})]$$

Telescope

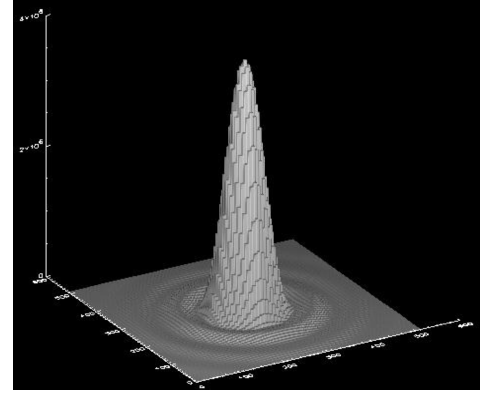


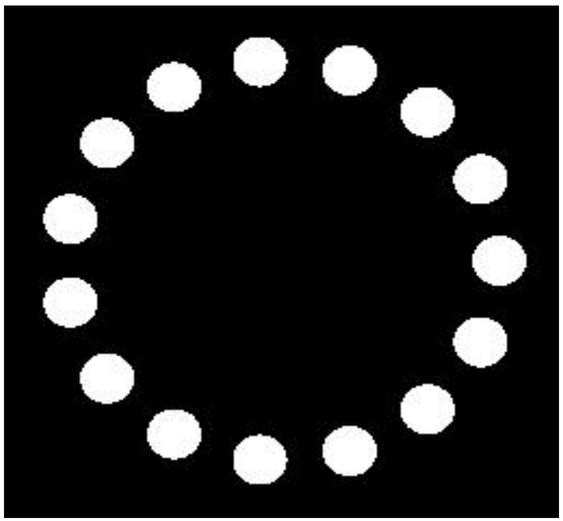
Pupil



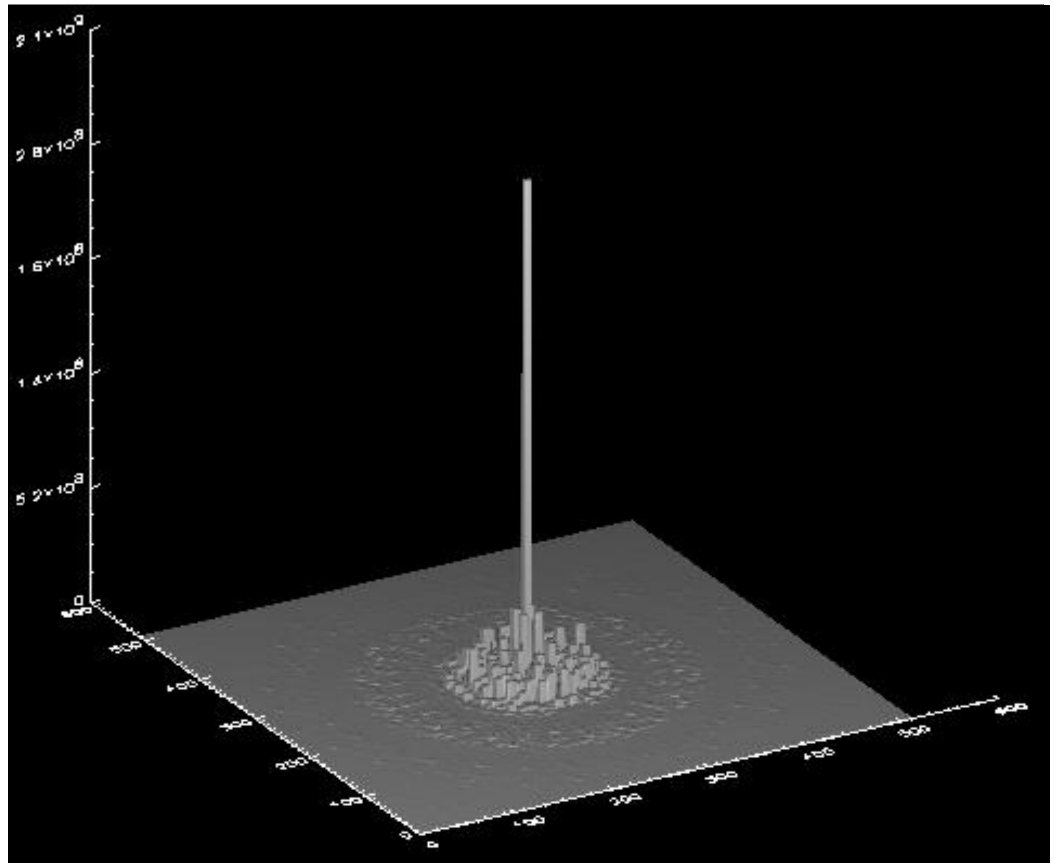
Point Spread Function

Interferometer

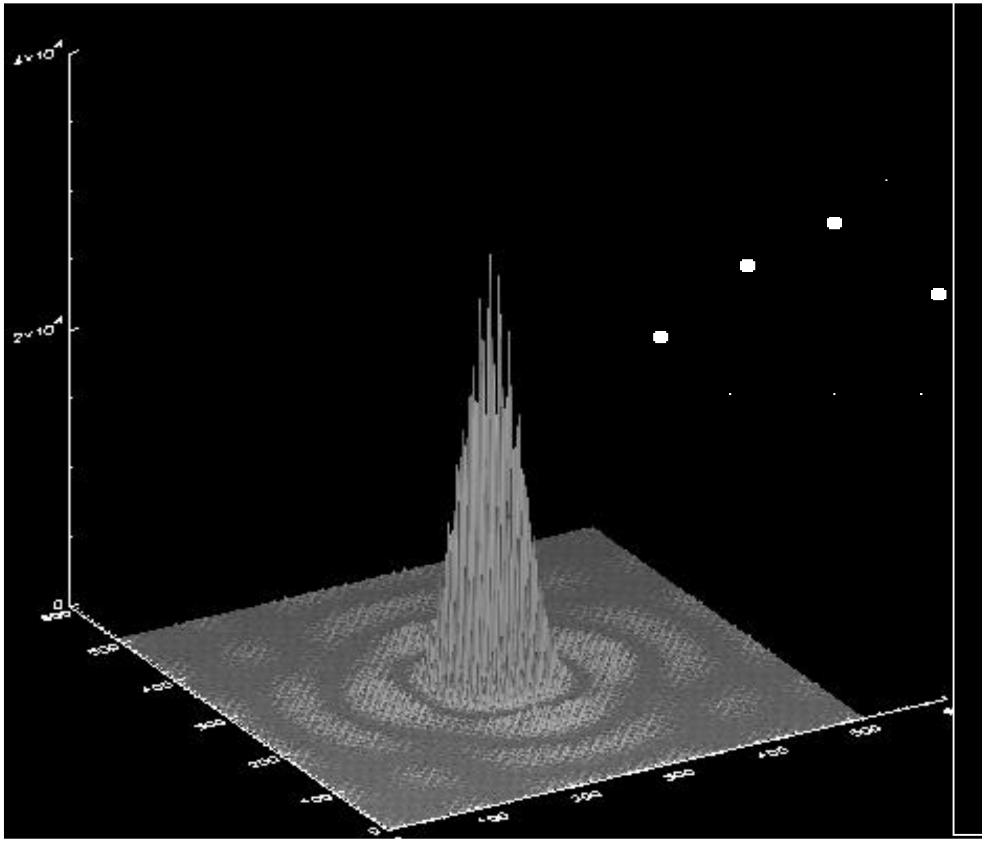




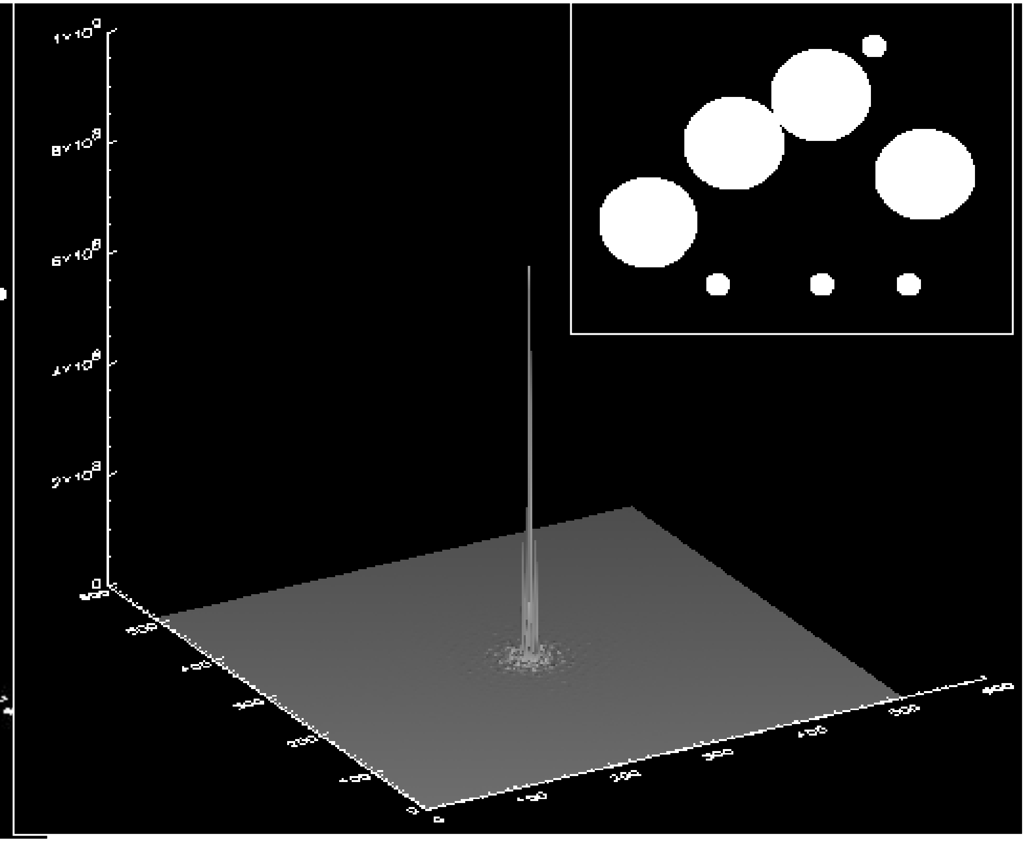
2345 Pupil



PSF: Importance of the combining scheme



4 UTs + 4 ATs Fizeau



4 UTs + 4 ATs densified

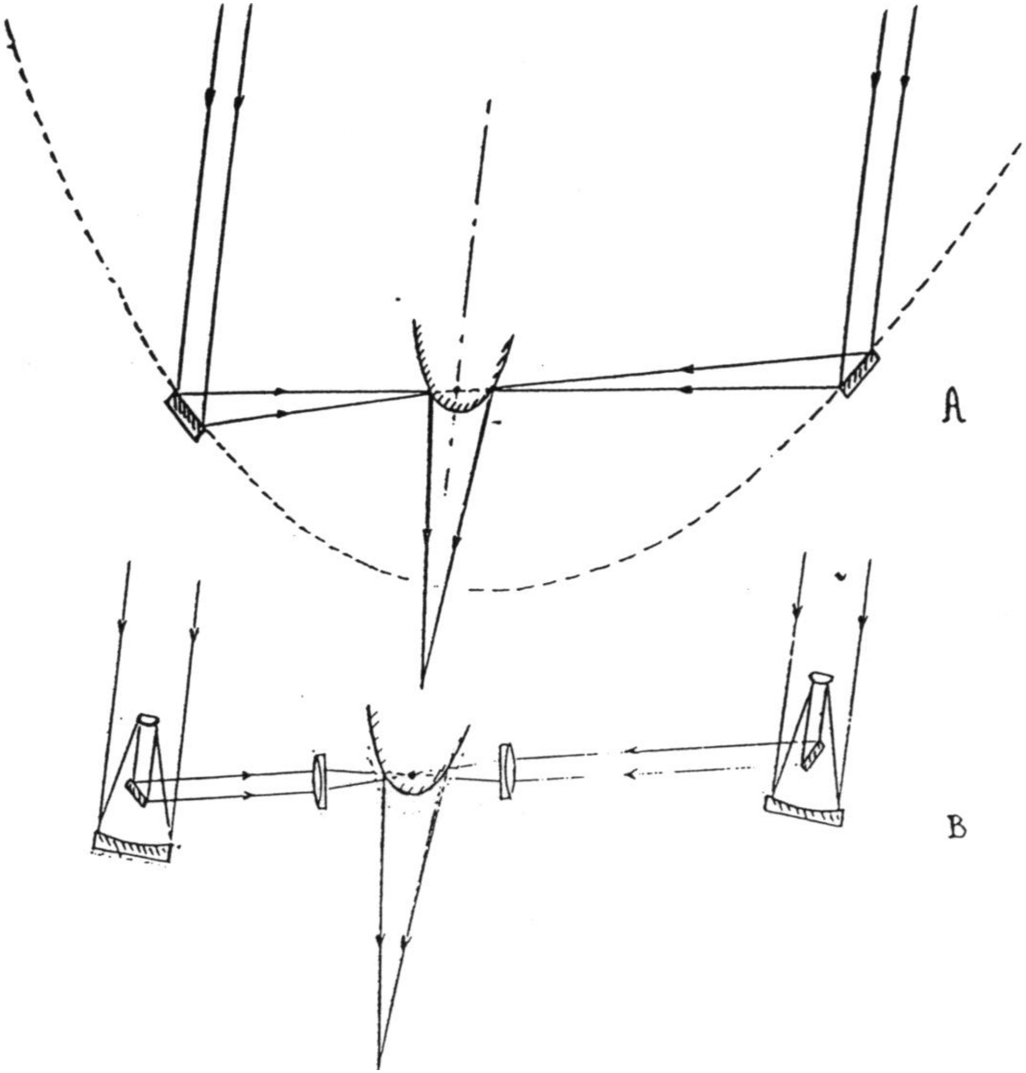
The (u,v) plane

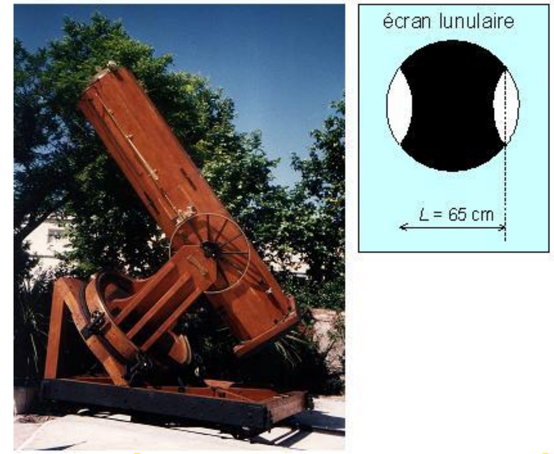
$$\left|\tilde{H}(\vec{f})\right| = AC[P(\lambda\vec{f})]$$

- The support of the MTF in the frequency plane is called the (u,v) plane.
- This is a function of
  - the input baseline
  - the latitude of the observatory
  - the target coordinates
  - the wavelength
  - the time

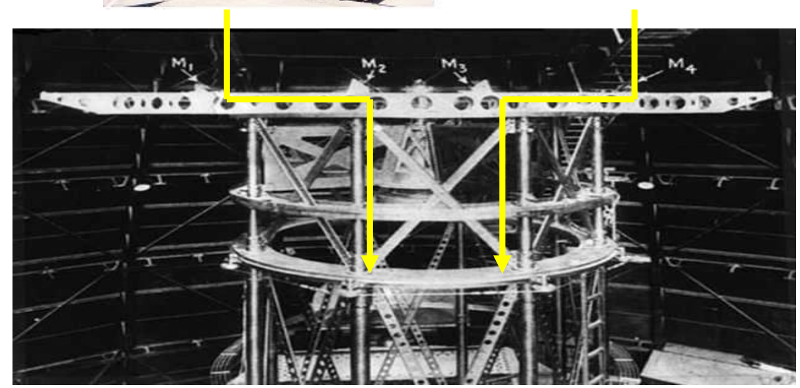
Some examples with a simulation tool: ASPRO2

Stephan, Michelson, Labeyrie





1874



1919

1974

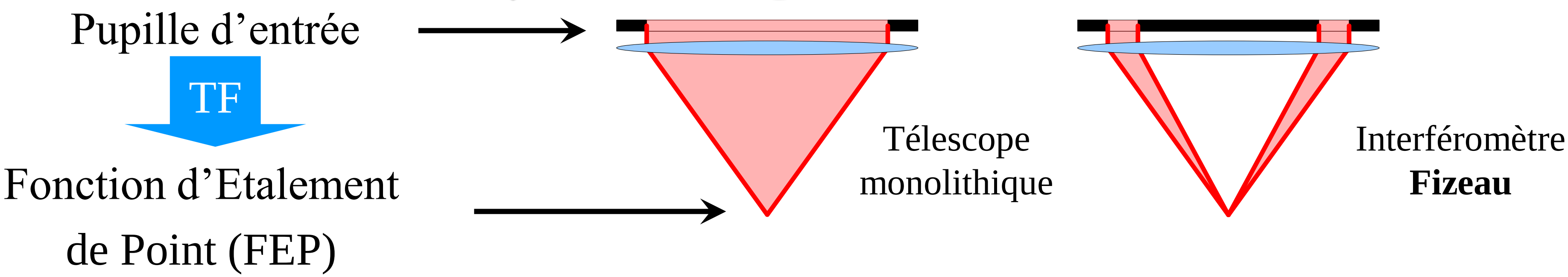
Where are we (2) ?

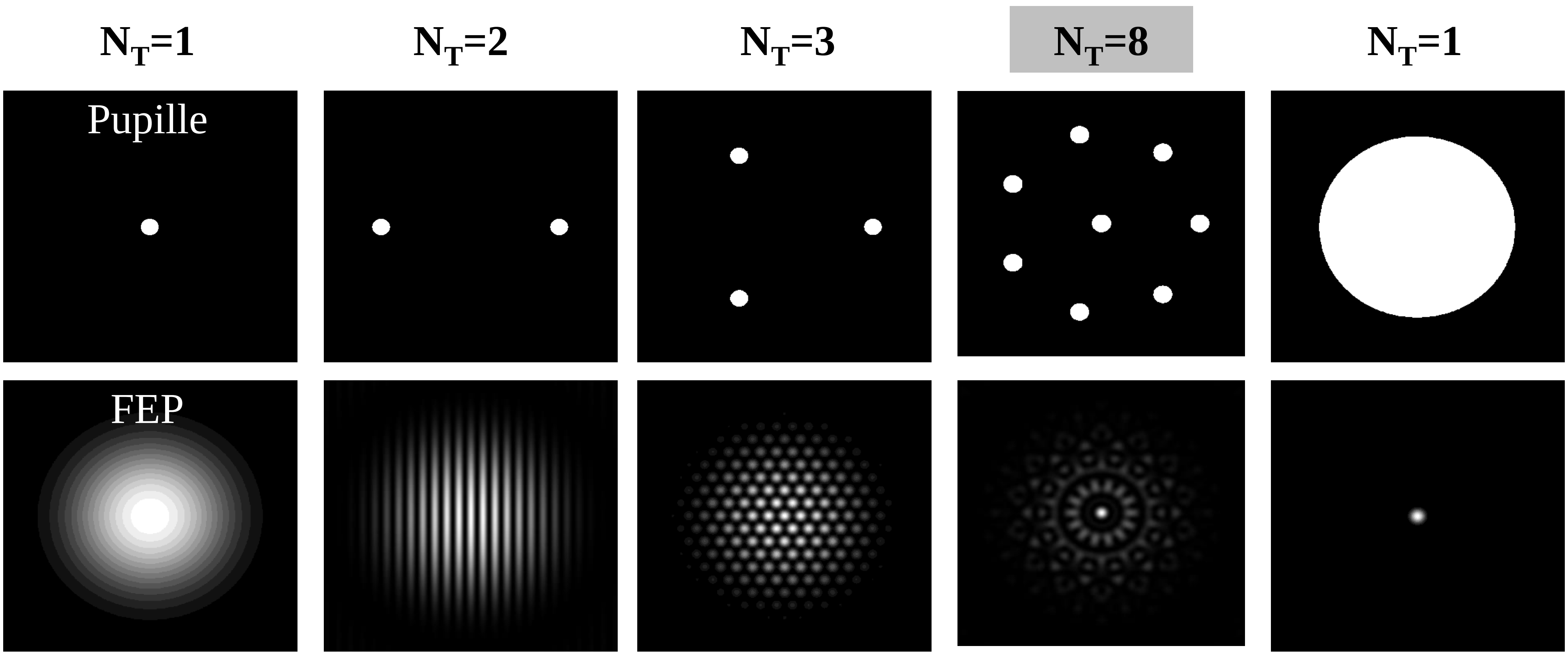
Conceptually speaking, Interferometry is really simple in fact, it's just an imaging technique!

And yes, direct imaging is possible!

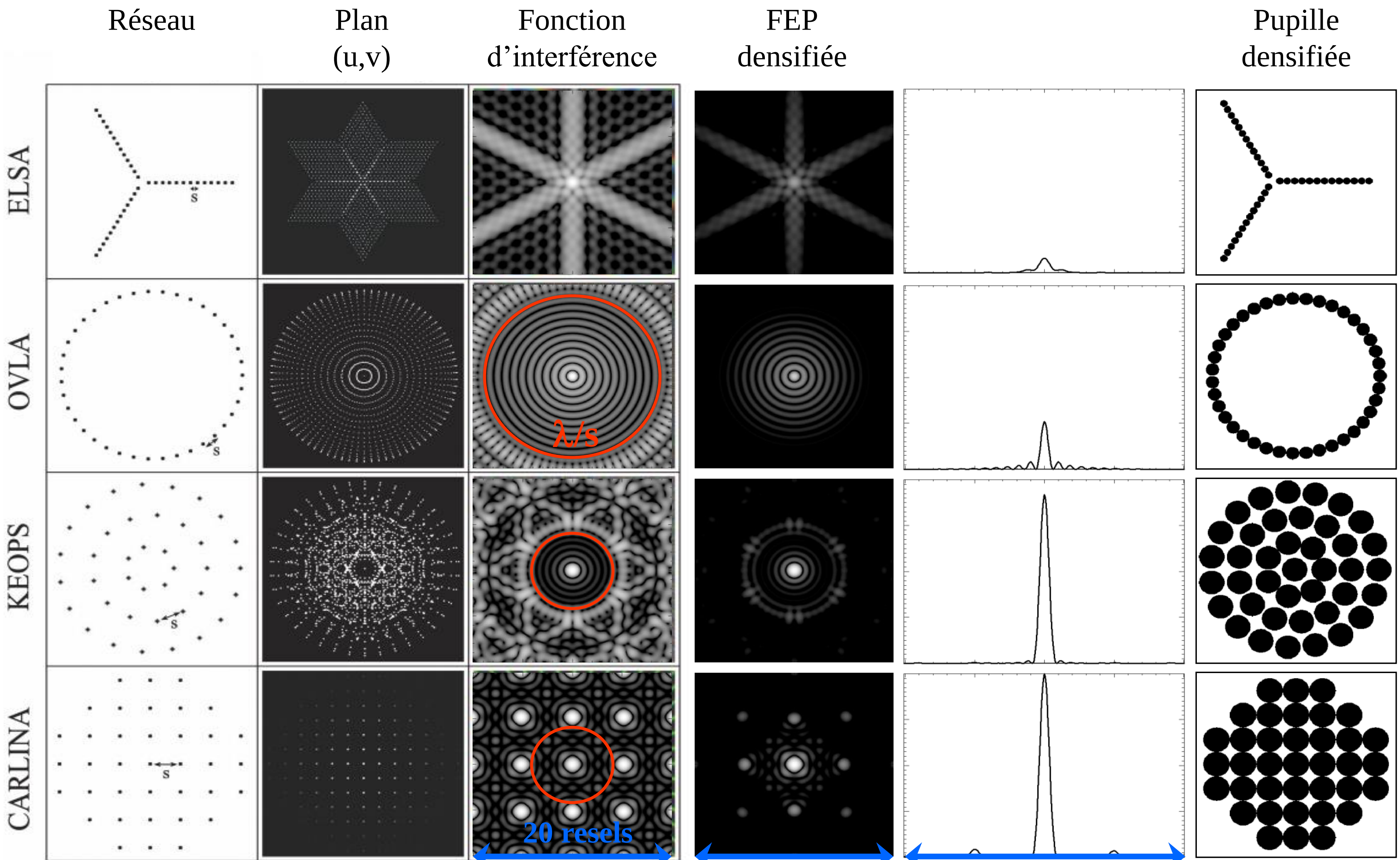
F. Patru, PhD

Pupil-Image relation

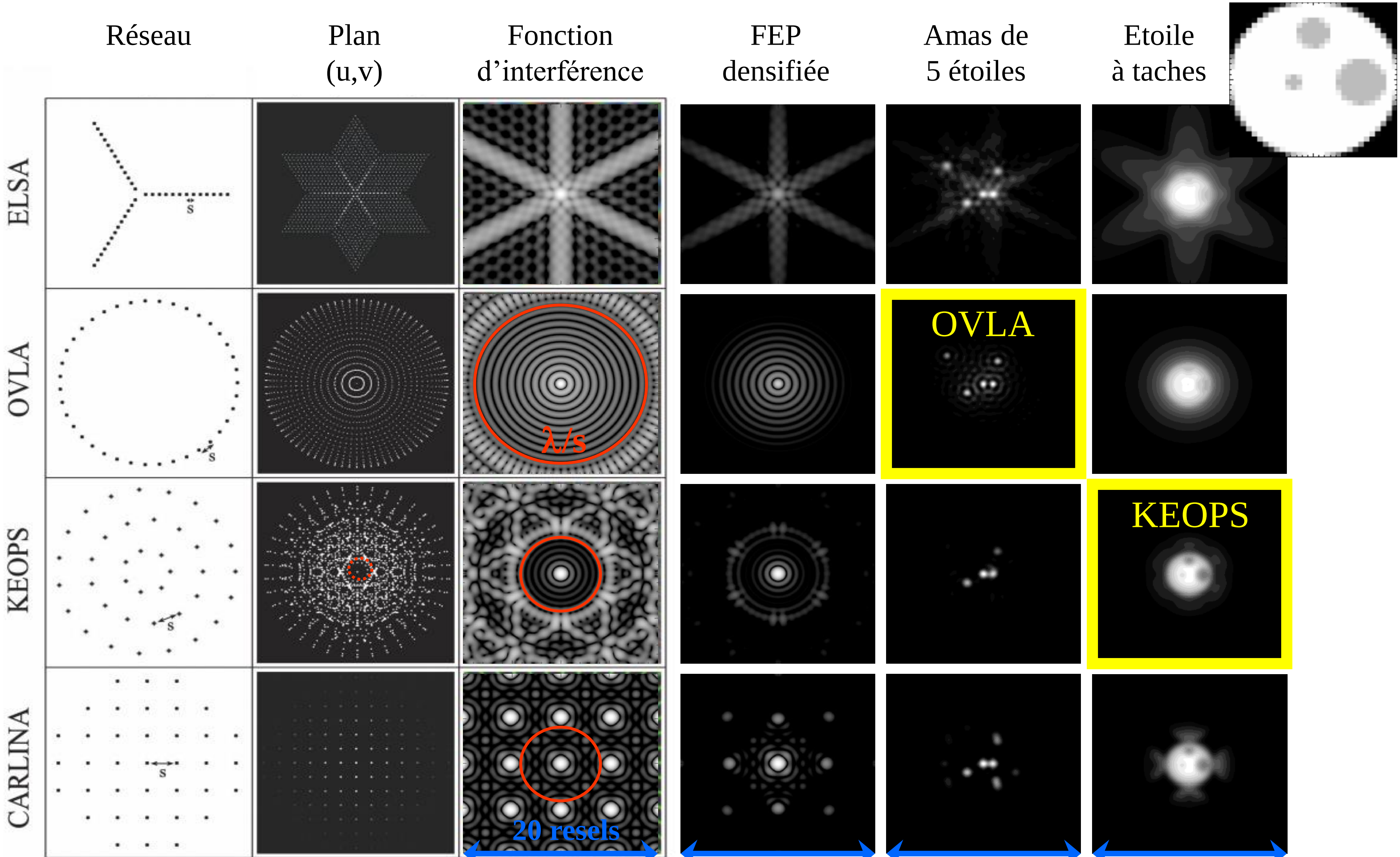




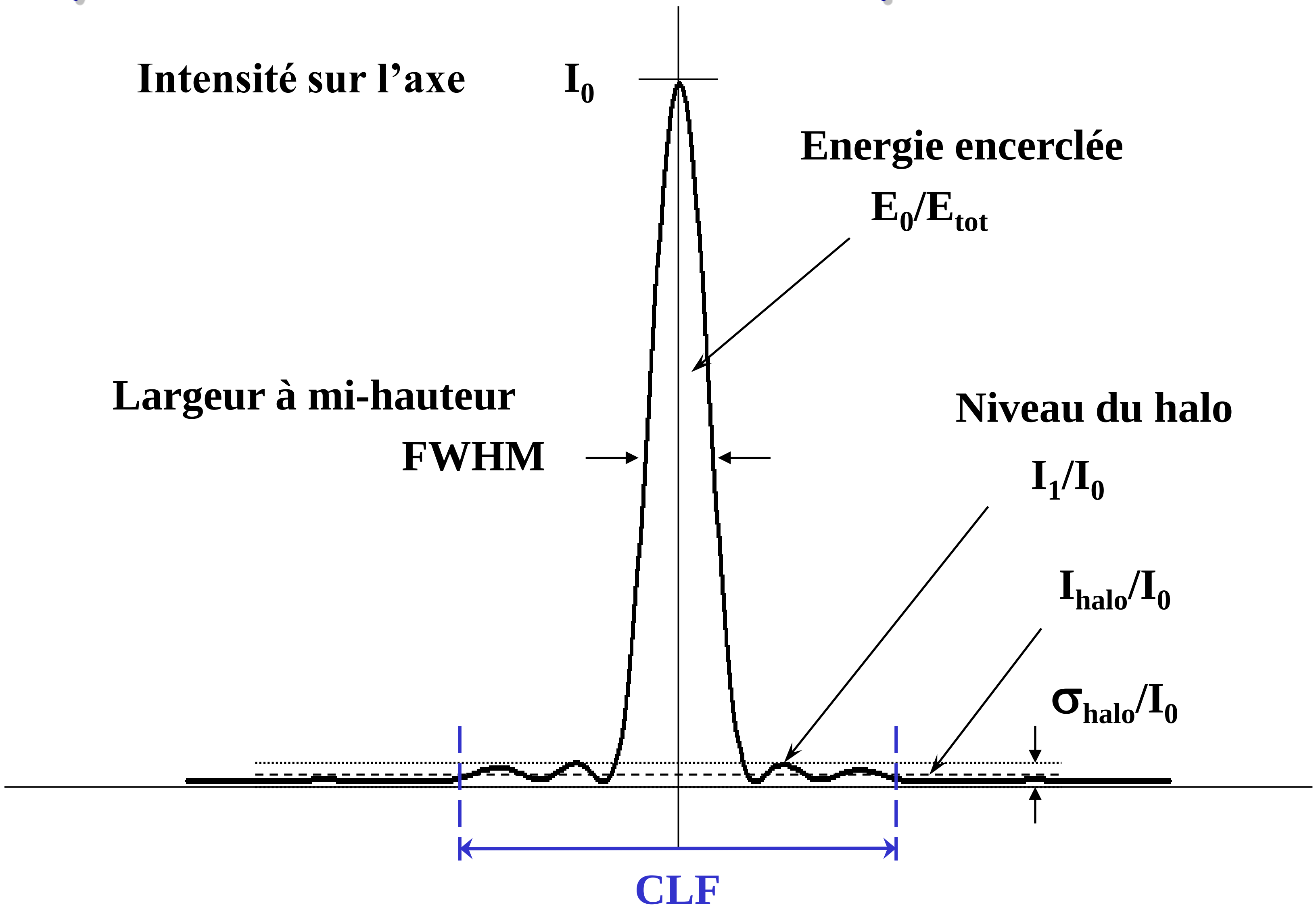
Geometry of the input pupil



Direct imaging exemples



Quality criteria in the Point Spread Function



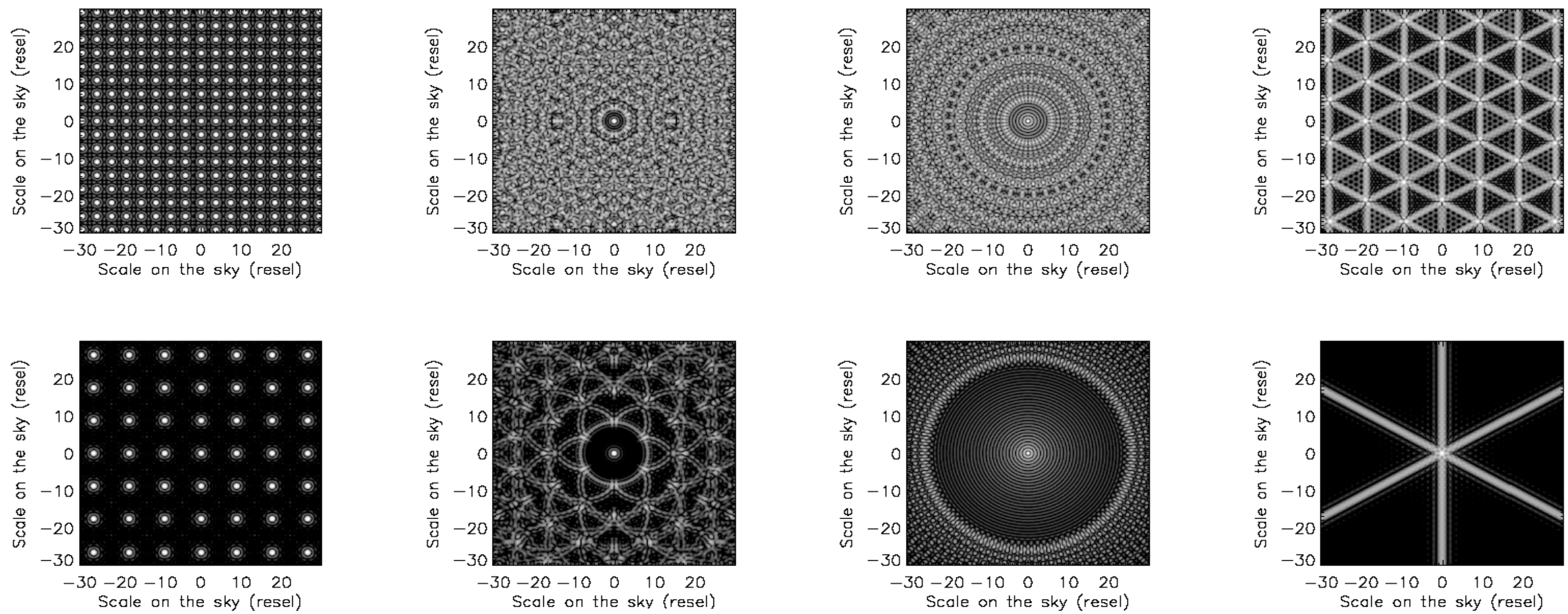
Quality versus number of sub-pupils

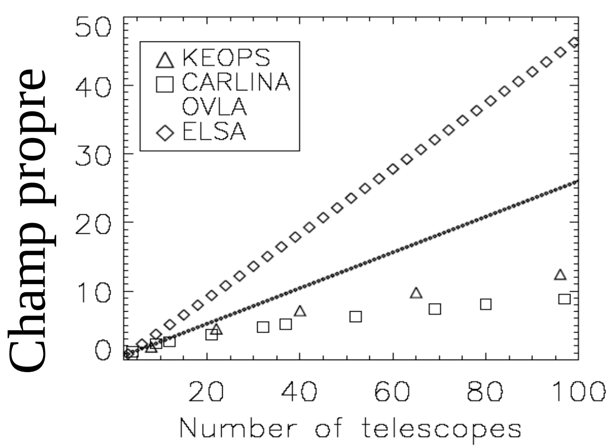
Fonction d'interférence

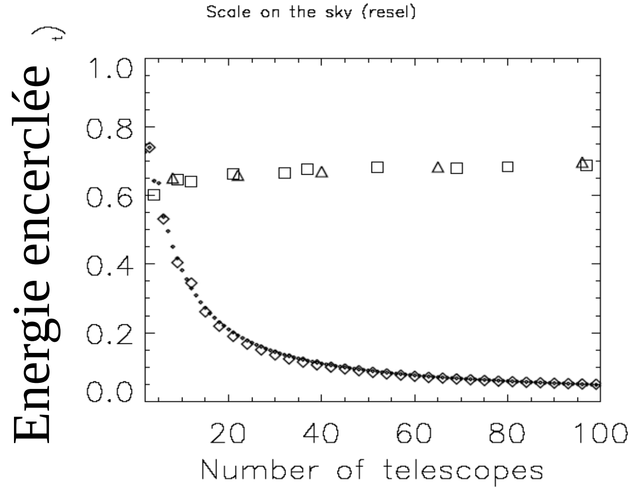
CARLINA | KEOPS | OVLA | ELSA

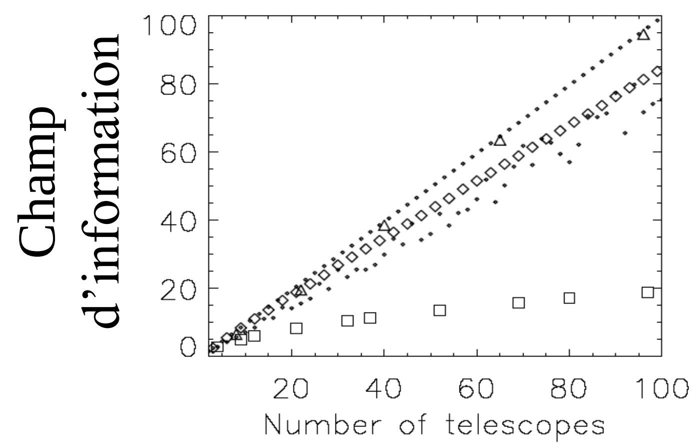
20 ouvertures

100 ouvertures









Where are we (3) ?

Ok Interferometry is, conceptually speaking, not different as any imaging telescope but…

Why has it been so difficult to get first images? And why do we continue to speak of fringes and visibilities?

Again a coherence problem…

but also a budget issue!

Coherence in reality

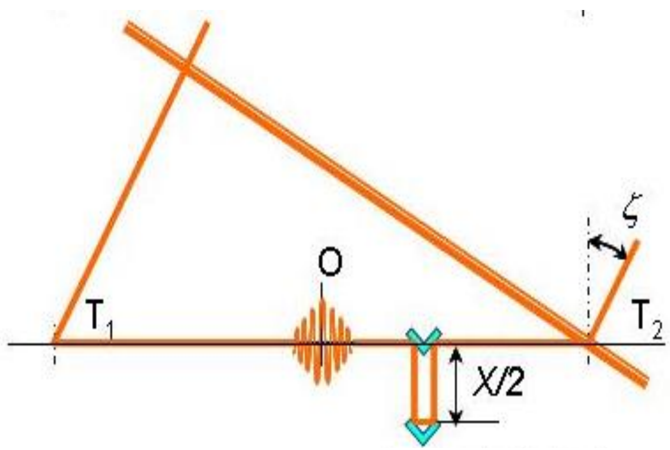
$$r_c = \frac{\lambda}{\pi\left(\frac{\theta}{2}\right)} \qquad \Gamma_{12} = \frac{\left|\psi_1 \psi_2^*\right|}{\sqrt{\left|\psi_1\right|^2 \left|\psi_2\right|^2}} \qquad I = \left|\Psi_1 + \Psi_2 e^{i\theta}\right|^2$$

N.A.: θ=10mas, λ=1µm ➔ r_c= 13m

Δλ=0.1µm and t_cΔf=1 ➔ $t_c=3.10^{-14}$s

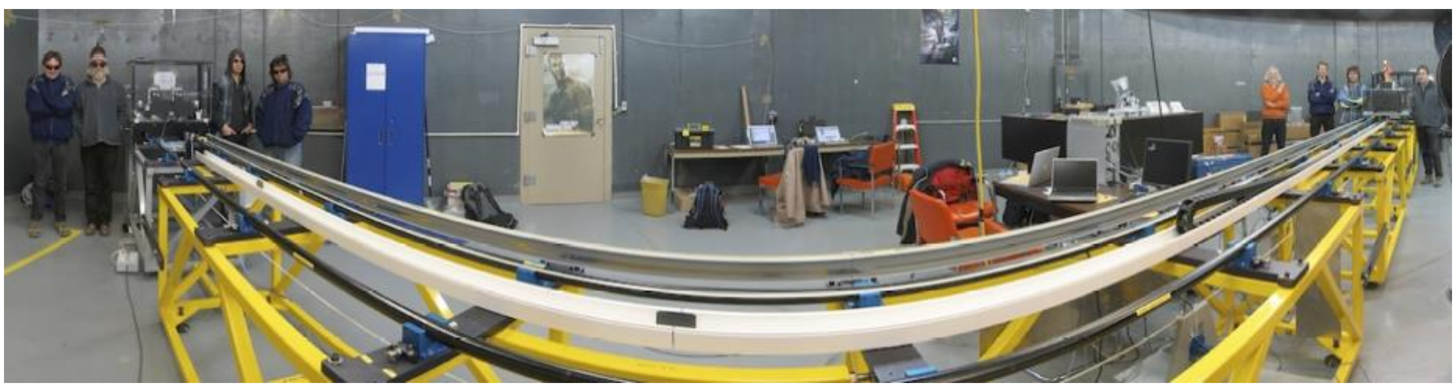
lc=c.tc=λ²/Δλ=R.λ ➔ **l_c=10µm**

First difficulty: equalizing the optical paths



Delay lines

Exemples of delay lines

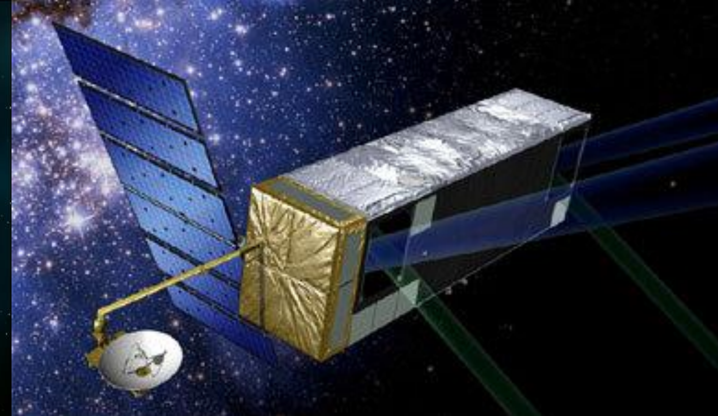


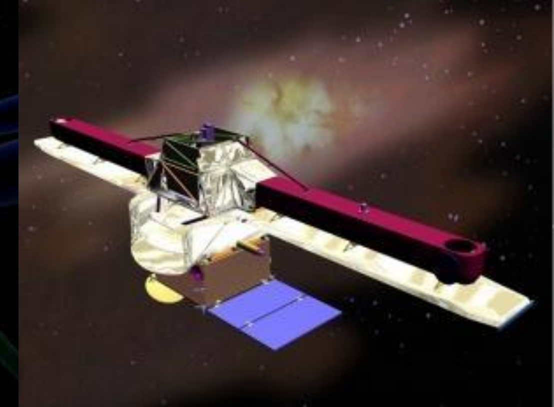
Second main difficulty: the atmospheric turbulence

- After passing through the turbulent atmosphere, the coherence is reduced:
  - Spatially: r_0 = 10cm
  - Temporarily t_0 = 5ms
  - Spectrally $\Delta\lambda$ = 30nm in the visible

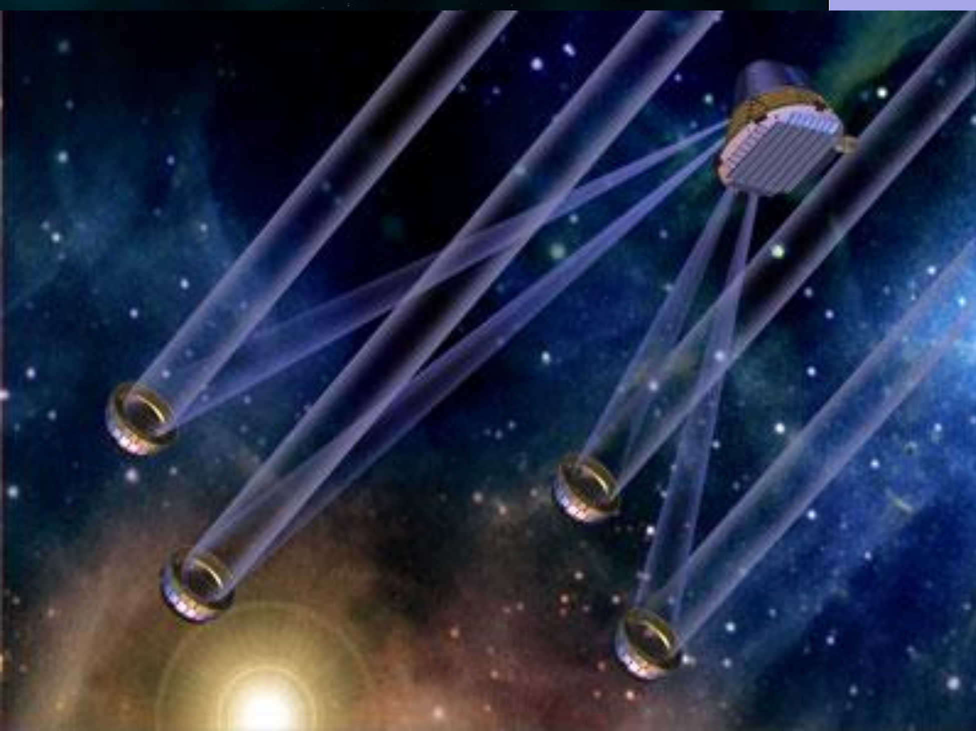
- Note
  - hypervolume of coherence ≈ $(\text{turbulence})^4$!

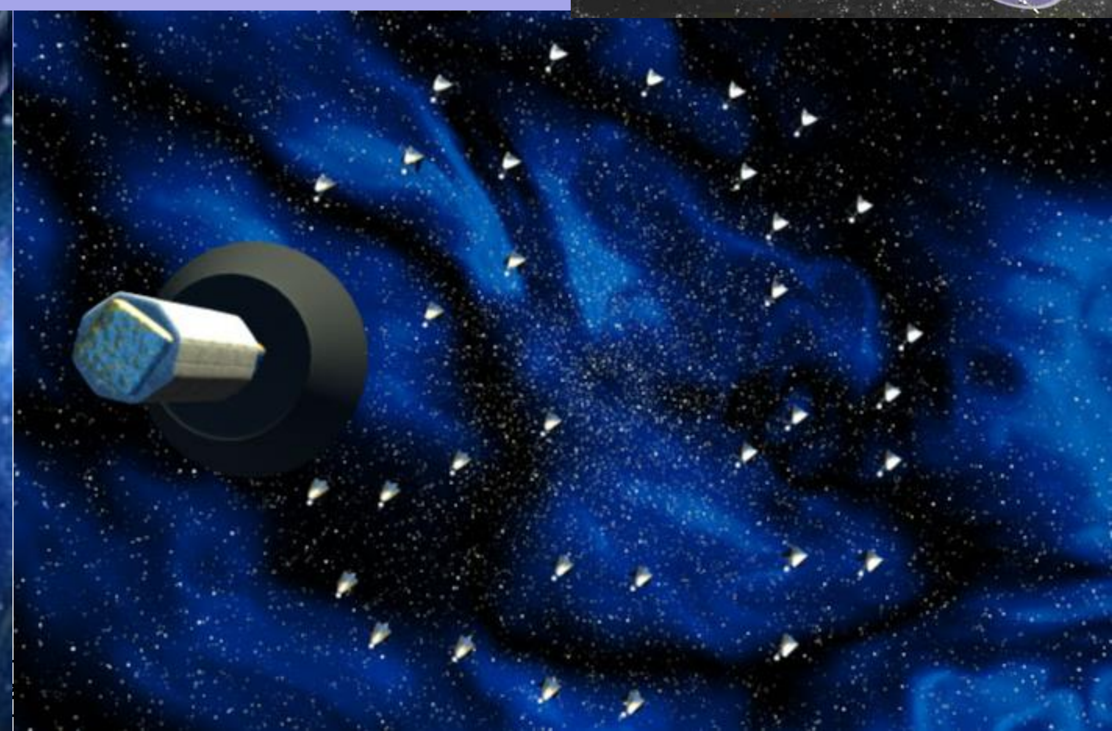
- Solutions
  - Space
  - Cophasing devices
  - Correct sampling of the corrugated wavefront





SPACE PROJECTS

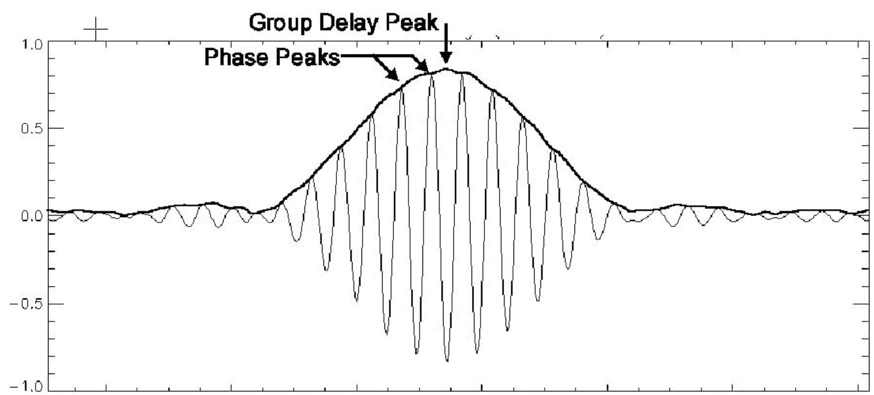




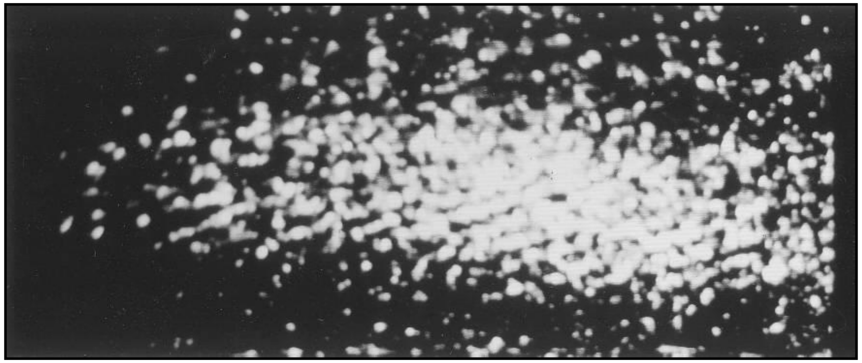
Cophasing devices (1)

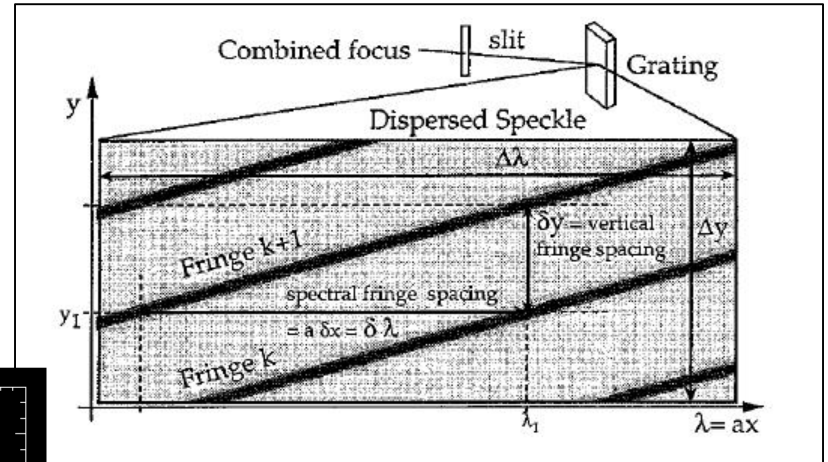
$$I = (I_1 + I_2) * \left(1 + \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} * \frac{\Psi_1 \Psi_2^*}{\sqrt{|\Psi_1|^2 |\Psi_2|^2}} * \cos(\theta) \right)$$

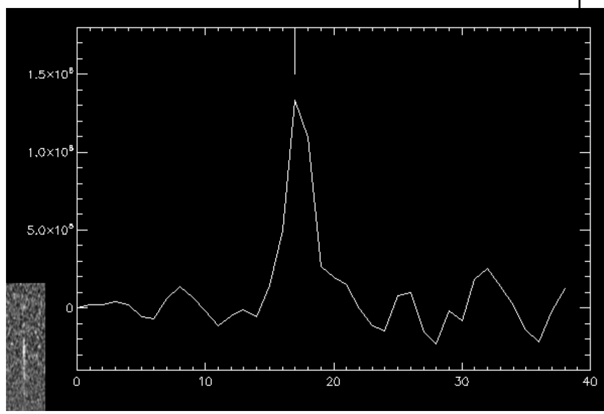
But θ contains a modulation term + a random atmospheric term

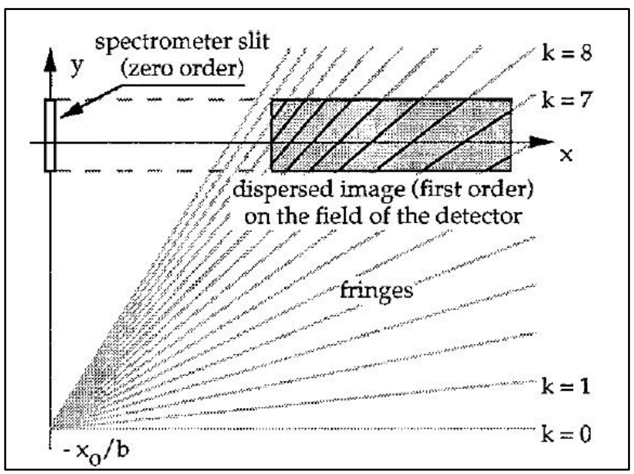


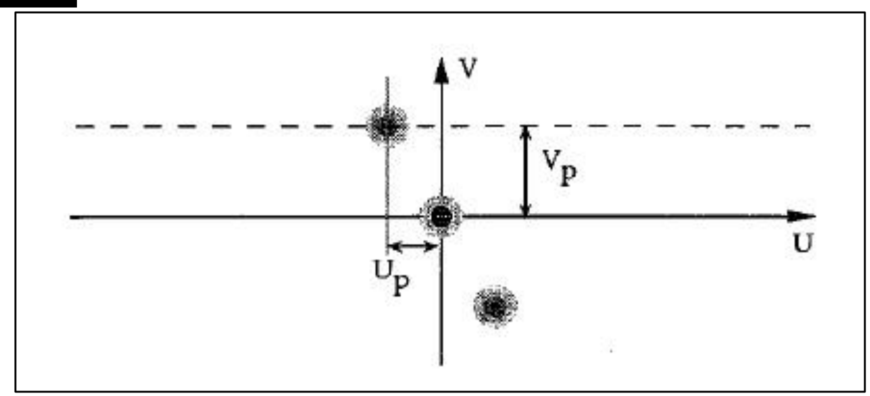
Cophasing devices, dispersed fringes (2)











Cophasing: does-it work?

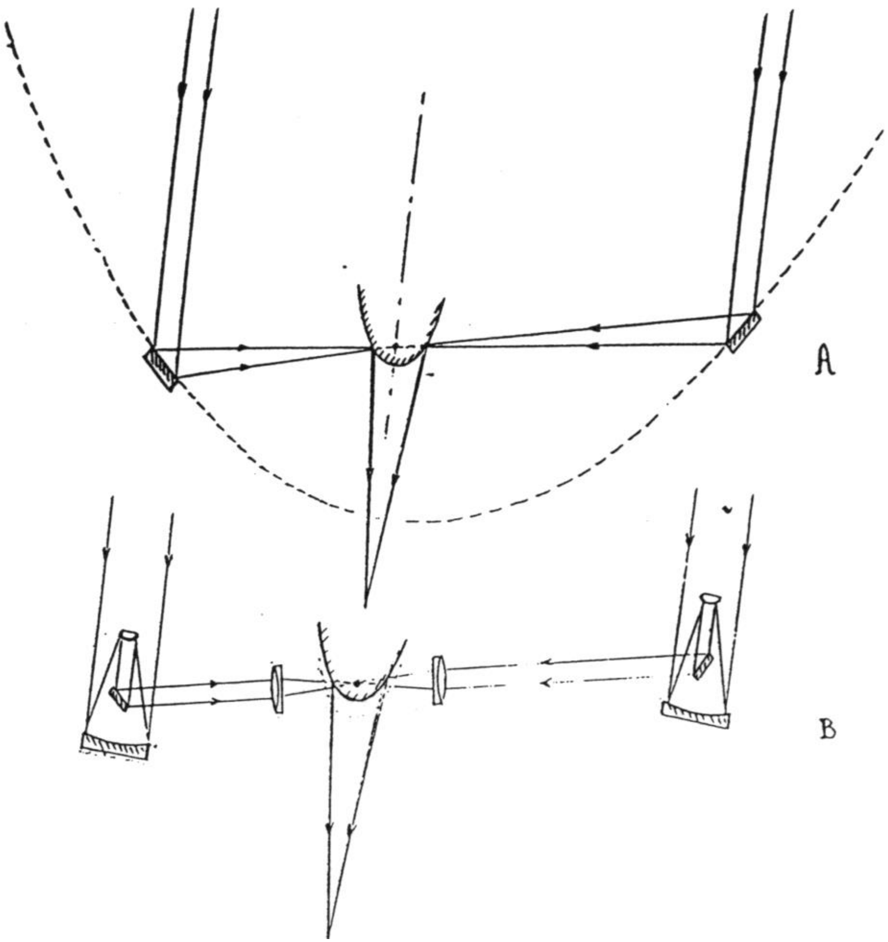
- Yes of course ➔ GRAVITY is able to make long integrations of the fringe signal. But this is very recent and for the moment quite exceptional

➔ Short exposures are mandatory otherwise the high spatial frequency information is blurred and the image quality is lost

⇔ a telescope without AO but in speckle interferometry mode

➔ Strong limitations in sensitivity, signal to noise ratio.

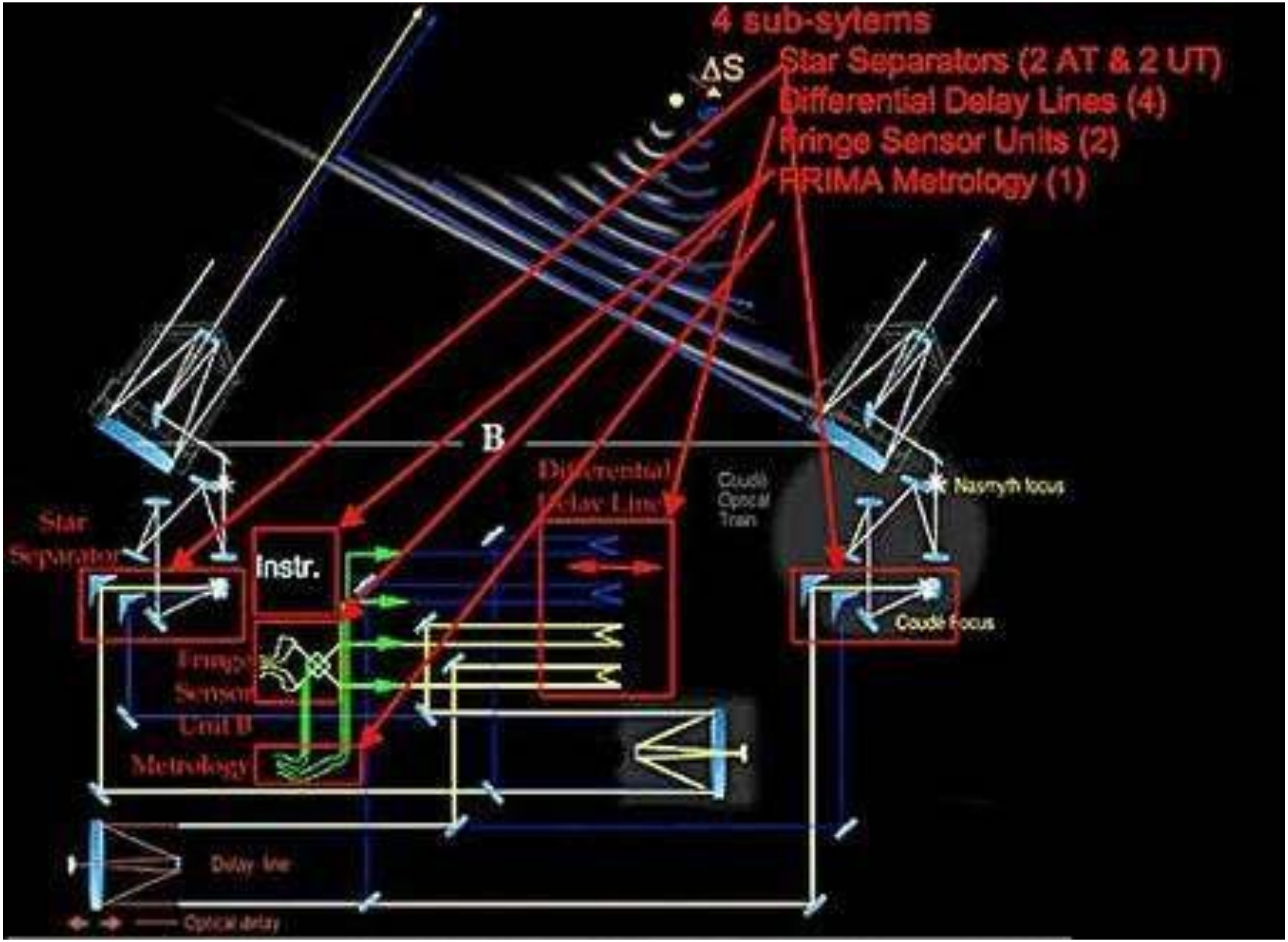
Interferometer=telescope? Not exactly in fact



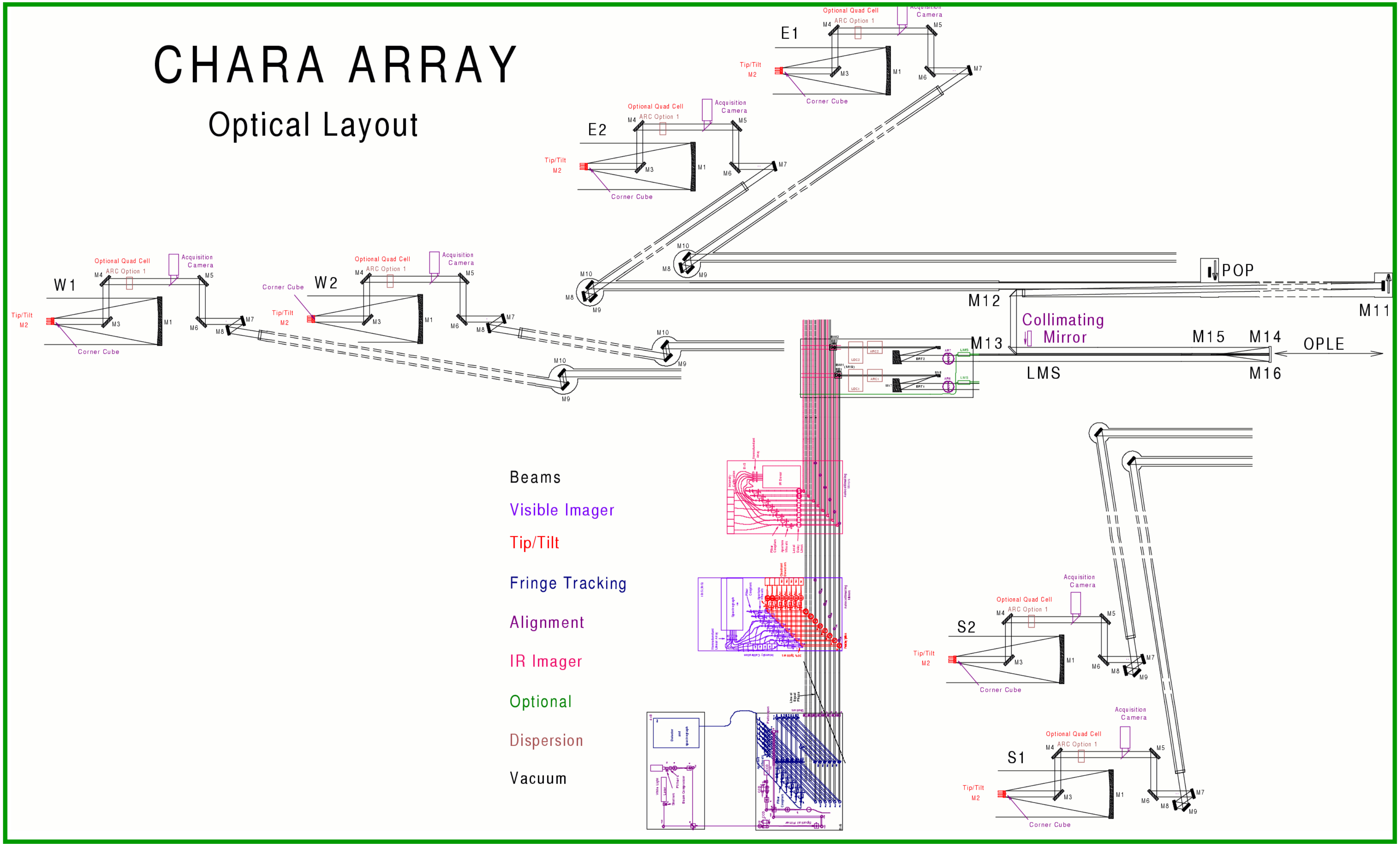
- The pupil plane is made of independent subpupils
  - Control of the position of the subpupils
  - Control of the tip/tilt of the subpupils
  - Control of the piston between the subpupils
  - ➔ AO for an interferometer
- The pupil plane is not perpendicular to the direction of pointing
  - Delay
  - Atmospheric dispersion
  - Fresnel diffraction

➔ Complex optical interfaces between the collection of the waves and the interferometric focus.

VLTI


4 sub-sytems
ΔS
Star Separators (2 AT & 2 UT)
Differential Delay Lines (4)
Fringe Sensor Units (2)
PRIMA Metrology (1)
B
Differential Delay Line
Coudé Optical Train
Nasmyth focus
Star Separator
Instr.
Coudé Focus
Fringe Sensor Unit B
Metrology
Delay line
Optical delay

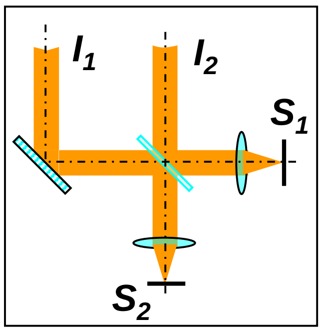
CHARA


CHARA ARRAY
Optical Layout
E1
E2
W1
W2
S1
S2
Optional Quad Cell
ARC Option 1
Acquisition Camera
Tip/Tilt M2
Corner Cube
M1
M3
M4
M5
M6
M7
M8
M9
M10
POP
M11
M12
M13
Collimating Mirror
M15
M14
M16
OPLE
LMS
Beams
Visible Imager
Tip/Tilt
Fringe Tracking
Alignment
IR Imager
Optional
Dispersion
Vacuum

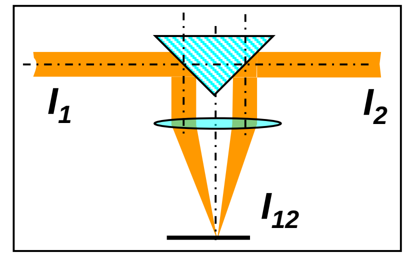
Encoding of fringes

$$I = \left|\Psi_1 + \Psi_2 e^{i\theta}\right|^2$$

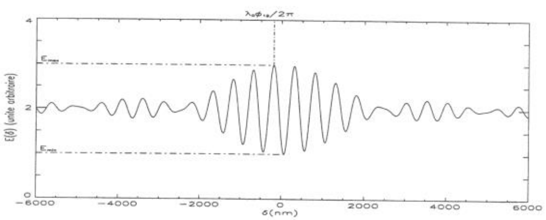
Coaxial



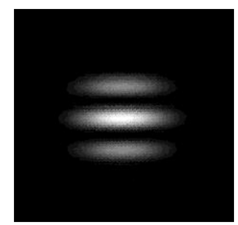
Multi-axial



Temporal sampling



Spatial sampling



Measuring the fringe contrast

$$I = (I_1 + I_2) * \left(1 + \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} * \frac{\Psi_1 \Psi_2^*}{\sqrt{|\Psi_1|^2 |\Psi_2|^2}} * \cos(\theta) \right) \quad \text{with } \theta(\text{t}) \text{ or } \theta(\text{x})$$

Contrast of the interference figure (with $I_1=I_2$)

$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{|\Psi_1 \Psi_2^*|}{\sqrt{|\Psi_1|^2 |\Psi_2|^2}}$$

But this is practically not possible because of the fast turbulence motion

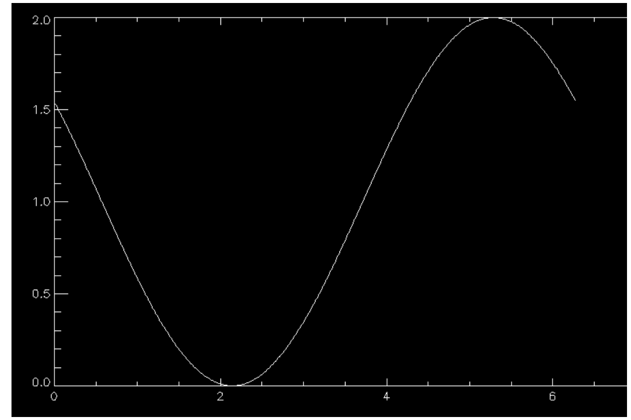
C is measured through the Fourier Transform of the image

$$\left|\tilde{I}\right|^2 = 1 + \frac{C^2}{4} \delta(\pm f), \; f \text{ being the frequency of the modulation}$$

More details in Roddier & Léna, 1994, Journal of Optics

A short digression…

I=1+Vcos(wt+ϕ)



$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{(1+V)-(1-V)}{(1+V)+(1-V)} = \frac{2V}{2} = V$$

$$I_A = I(0-\pi/2), I_B = I(\pi/2-\pi), I_C = I(\pi-3\pi/2), I_D = I(3\pi/2-2\pi)$$

$$\mathcal{V} = \frac{\pi}{\sqrt{2}} \frac{\sqrt{(I_A - I_C)^2 + (I_B - I_D)^2}}{I_{\text{tot}}}$$

Both methods are equivalent to a Fourier transform in fact!

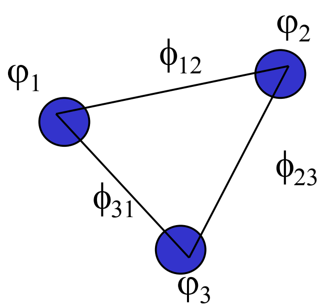
Measuring the phase

$$I = (I_1 + I_2) * \left(1 + \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} * \frac{\Psi_1 \Psi_2^*}{\sqrt{|\Psi_1|^2 |\Psi_2|^2}} * \cos(\theta) \right) = (I_1 + I_2) * \left(1 + \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} * \frac{|\Psi_1 \Psi_2^*|}{\sqrt{|\Psi_1|^2 |\Psi_2|^2}} * \cos(\theta + \phi) \right)$$

1) Differential phase:

$$\left\langle \tilde{I}_{\lambda_1} \tilde{I}^*_{\lambda_2} \right\rangle_{\frac{\vec{B}}{\lambda}} \Rightarrow \frac{\left| \tilde{O}_{\lambda_1}\left(\frac{\vec{B}}{\lambda}\right) \right|}{\left| \tilde{O}_{\lambda_2}\left(\frac{\vec{B}}{\lambda}\right) \right|} \text{ et } Arg\left(\tilde{O}_{\lambda_1}\left(\frac{\vec{B}}{\lambda}\right) \right) - Arg\left(\tilde{O}_{\lambda_2}\left(\frac{\vec{B}}{\lambda}\right) \right) = \phi_{B,\lambda_2} - \phi_{B,\lambda_1}$$

2) Phase closure:



$$\text{Baseline 12: } \Psi_{12} = \Phi_{12} + \varphi_1 - \varphi_2$$
$$\text{Baseline 23: } \Psi_{23} = \Phi_{23} + \varphi_2 - \varphi_3$$
$$\text{Baseline 31: } \Psi_{31} = \Phi_{31} + \varphi_3 - \varphi_1$$

$$with\ \Phi_{ij} = Arg\left(\tilde{O}\left(\vec{B}_{ij} / \lambda \right) \right) \text{ and } \varphi_i \text{ the turbulent phase on pupil i}$$

Closure phase equation: $\mathbf{\Psi_{12} + \Psi_{23} + \Psi_{31} = \Phi_{12} + \Phi_{23} + \Phi_{31}}$

Interferometric data

Visibility

$$V^2 = \left| \frac{\tilde{O}\left(\frac{B}{\lambda}\right)}{\tilde{O}(0)} \right|^2$$

Differential phase

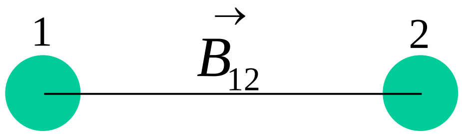
$$Arg\left(\tilde{O}_{\lambda_1}\left(\frac{\vec{B}}{\lambda}\right)\right) - Arg\left(\tilde{O}_{\lambda_2}\left(\frac{\vec{B}}{\lambda}\right)\right)$$

Phase closure

$$\Psi_{12} + \Psi_{23} + \Psi_{31} = \Phi_{12} + \Phi_{23} + \Phi_{31}$$

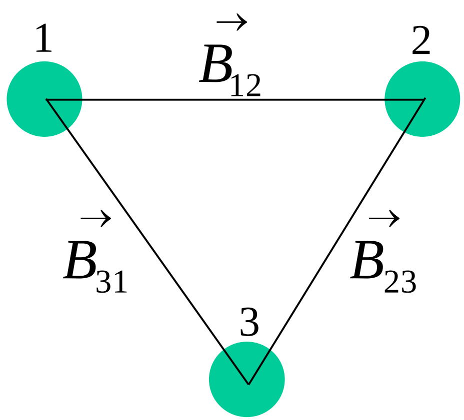
Number of observables

2 telescopes interferometer



$$\left|\tilde{O}(\vec{B}_{12}/\lambda)\right|^2$$

3 telescopes interferometer



$$\left|\tilde{O}(\vec{B}_{12}/\lambda)\right|^2$$

$$\left|\tilde{O}(\vec{B}_{23}/\lambda)\right|^2$$

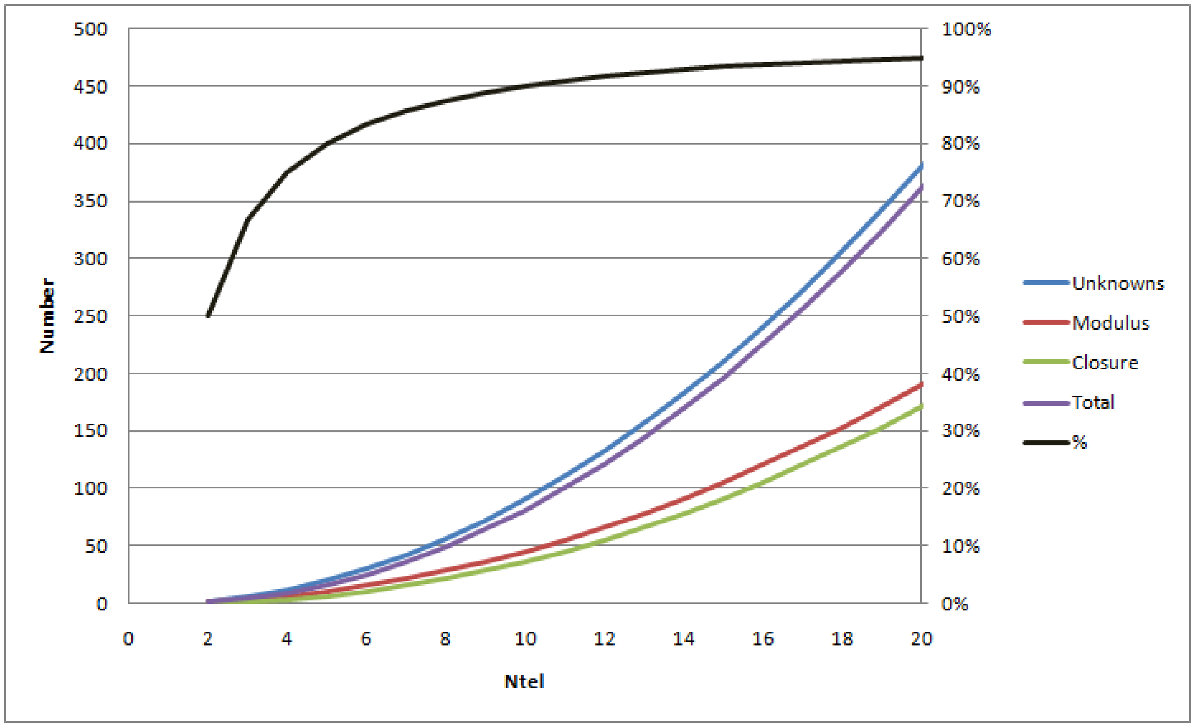
$$\left|\tilde{O}(\vec{B}_{31}/\lambda)\right|^2$$

$$Arg(\tilde{O}(\vec{B}_{12}/\lambda)) + Arg(\tilde{O}(\vec{B}_{23}/\lambda)) + Arg(\tilde{O}(\vec{B}_{31}/\lambda))$$

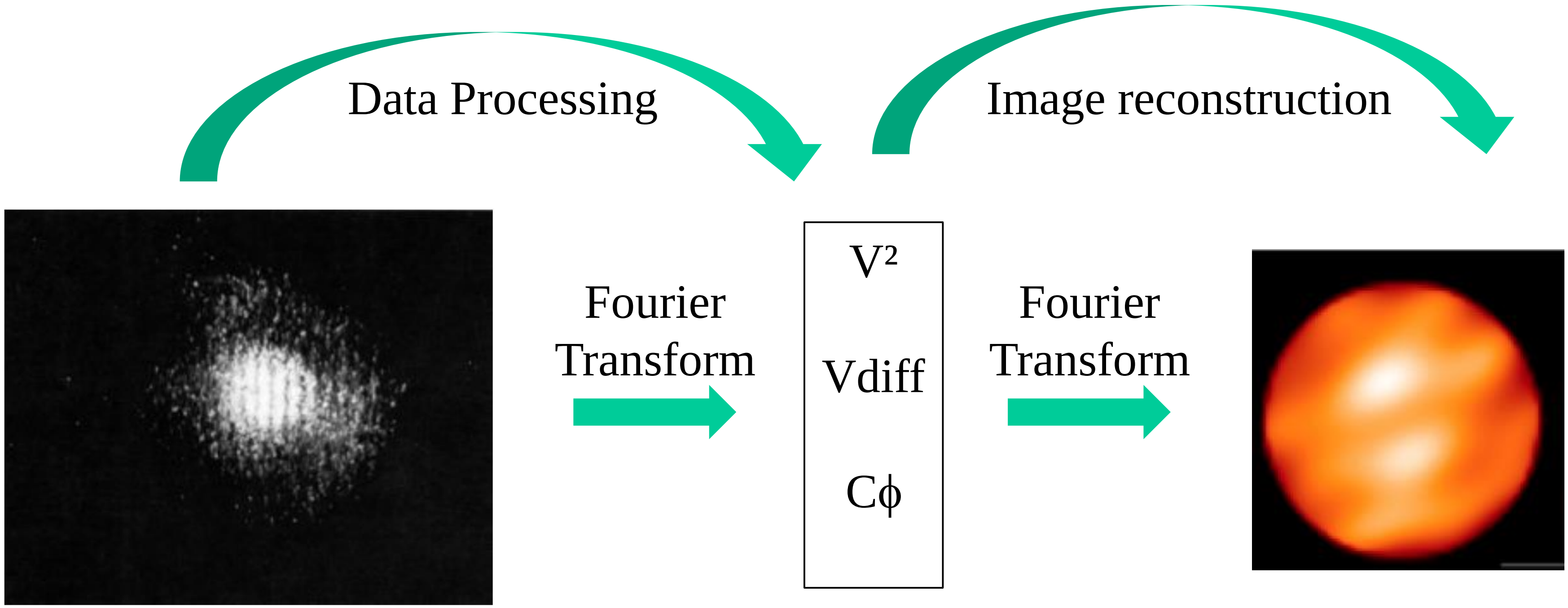
Generalization

An interferometer with n telescopes produces

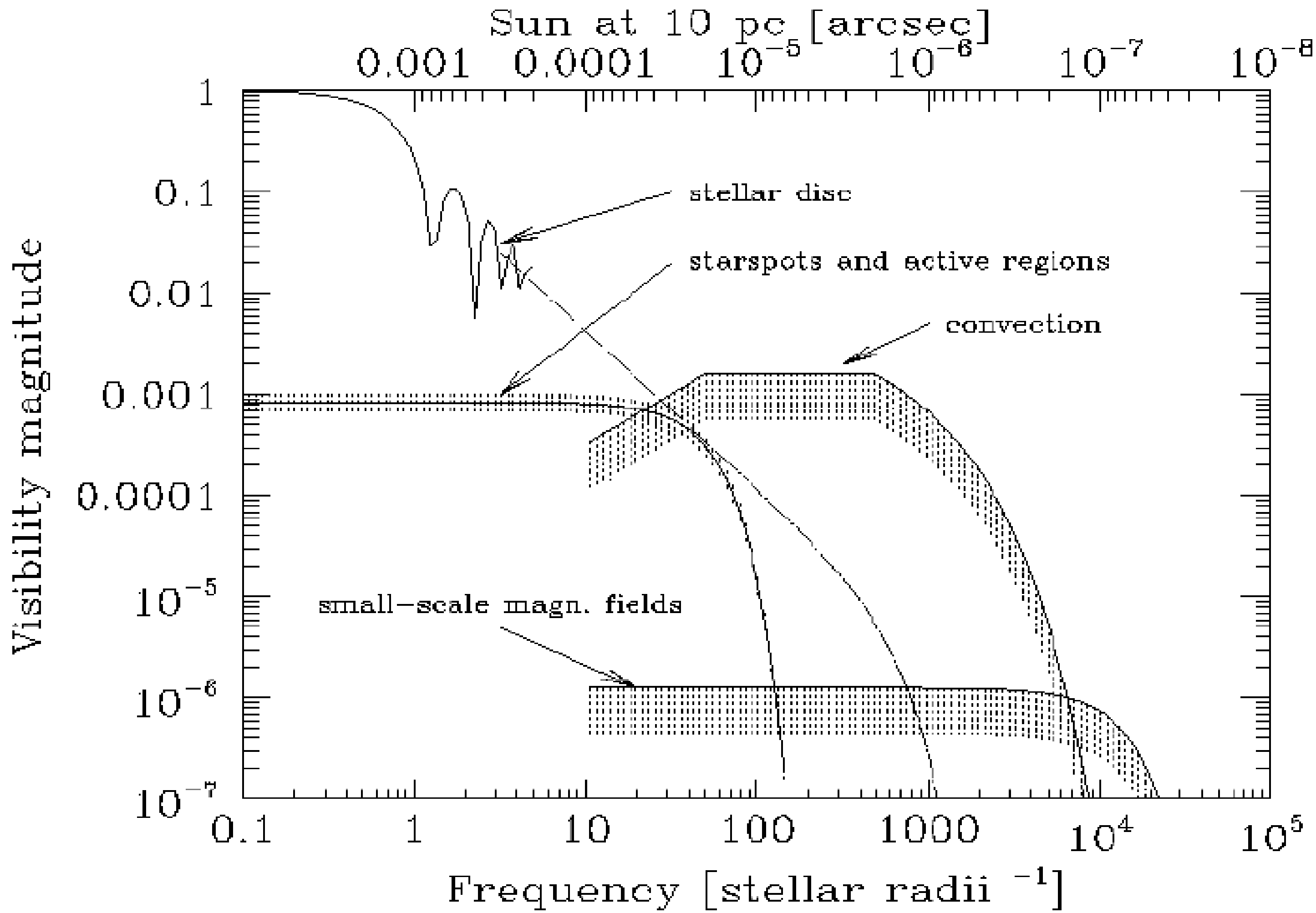
- n(n-1)/2 bases, so [n(n-1)/2] complex quantities, so **n(n-1) unknowns**
- **n(n-1)/2 modulus** measurements
- **(n-1)(n-2)/2 closure phase** measurements



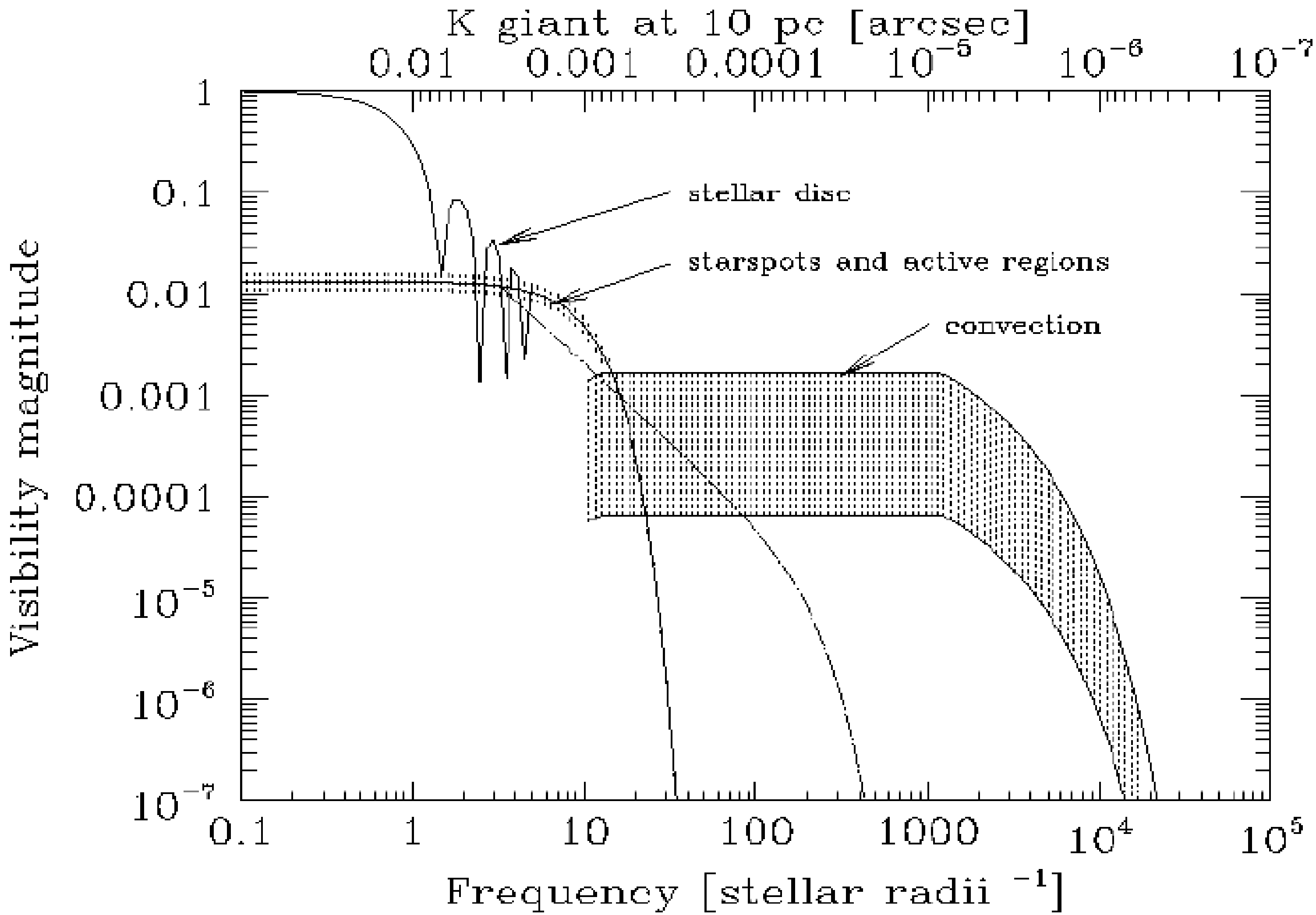
But do not remember that an interferometer is a direct imaging telescope!



Visibility of a solar type star (1 RΘ) at 10 pc ?

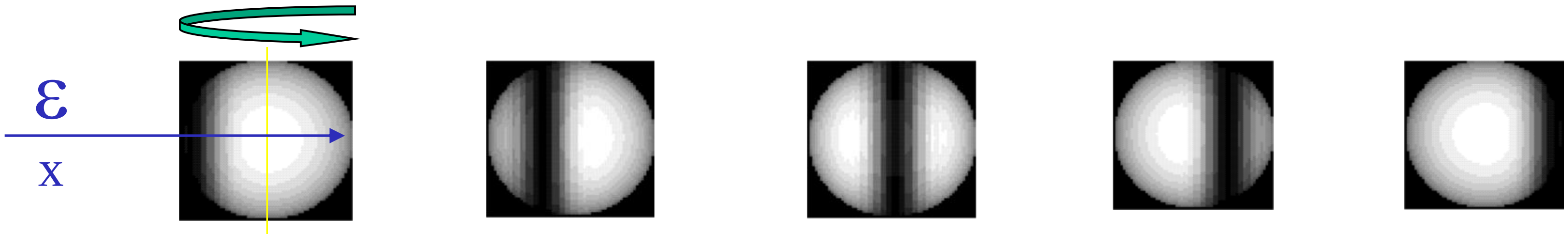


And a K giant (25 $R_\odot$) at 10 pc ?

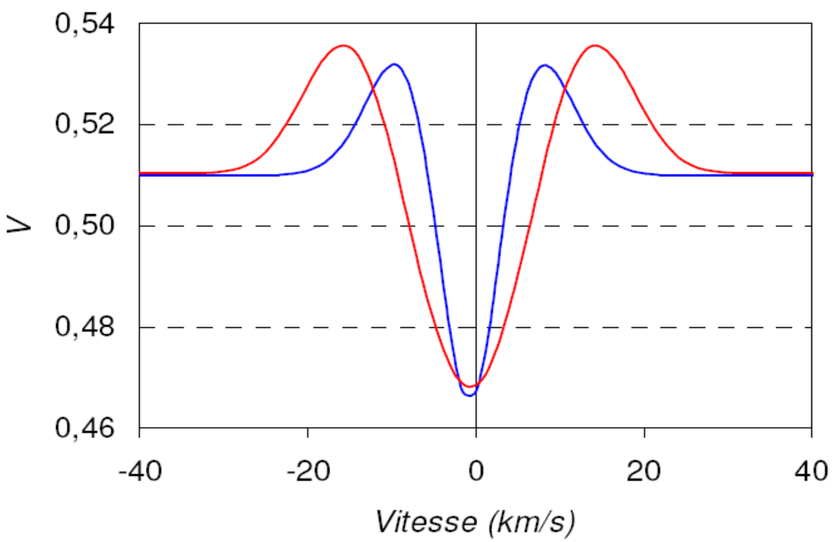


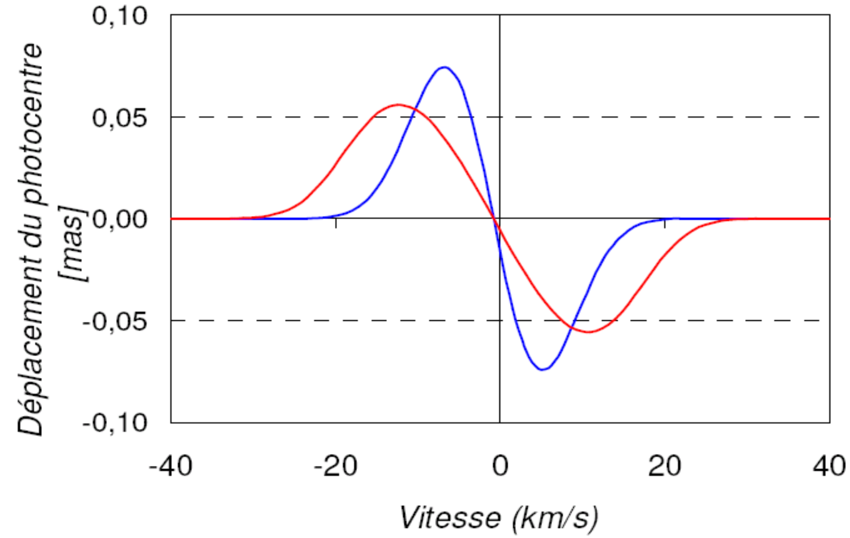
Example of differential phase measurements

$V_{rot}\sin i$



$V_{rot}\sin i$ *10 or 20 km/s*





Different ways of considering interferometric observations

Everything is in $\frac{\vec{B}_p}{\lambda}$

- Spatial frequency sampling *(base, wavelength)*
- Spectral sampling
- Field sampling
- Time sampling
- Polarisation sampling

➔ Complementary data are usually considered

Some exemples of preparation tools

JMMC

ASPRO2

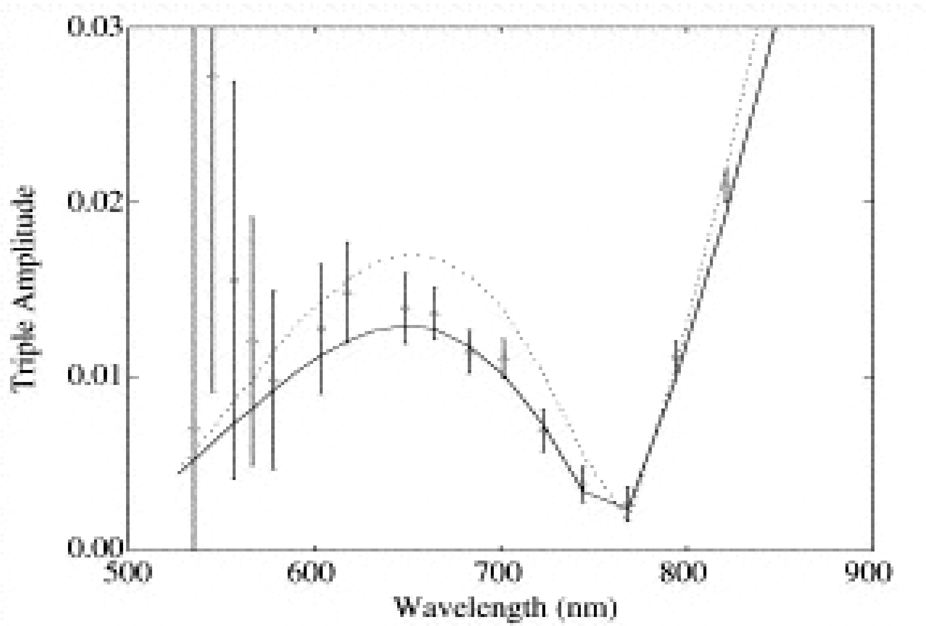
NexSCI

VMT

Publications and science database: JMMC-BIBDB

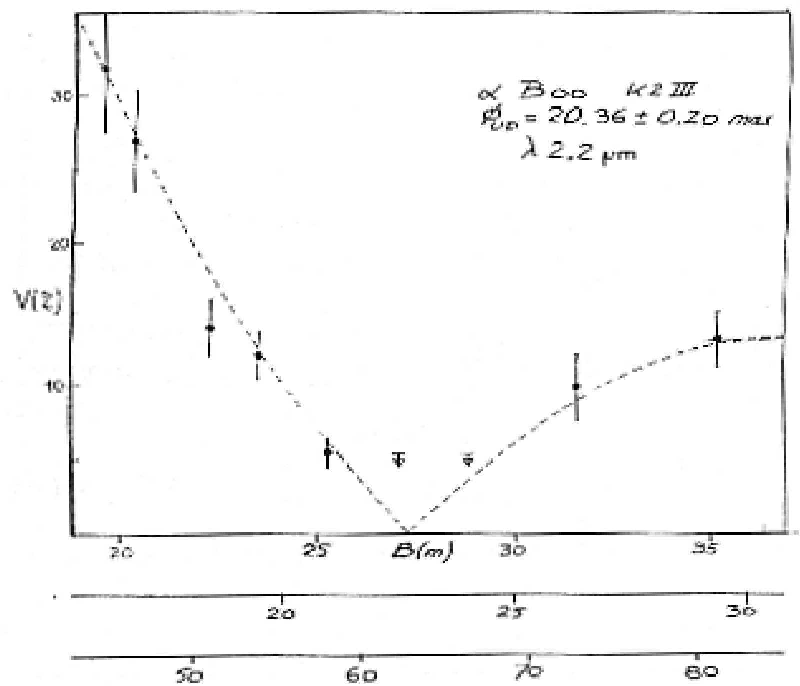
Limb darkening measurements

α Cas



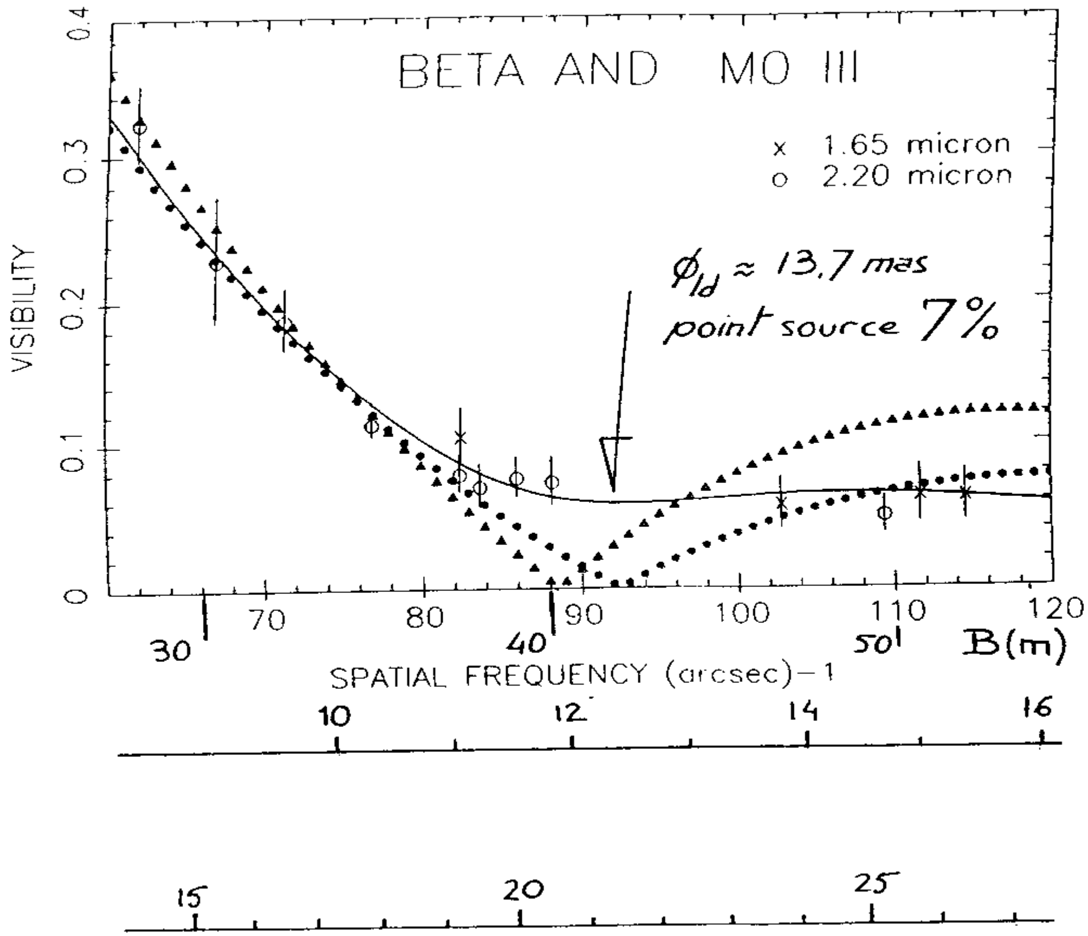
Hajian et al. 1998, ApJ,496, 484 (NPOI)

α Boo



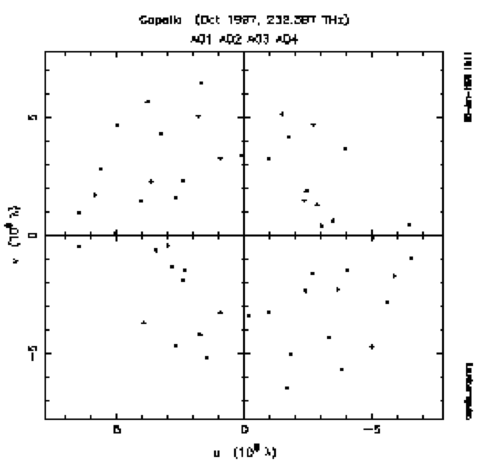
Di Benedetto & Foy 1986, A&A, 166, 204, (I2T)

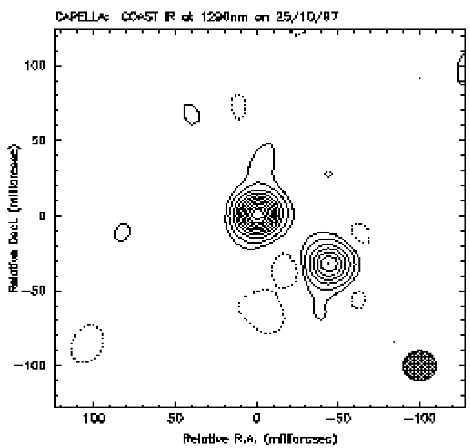
Stellar structure detection



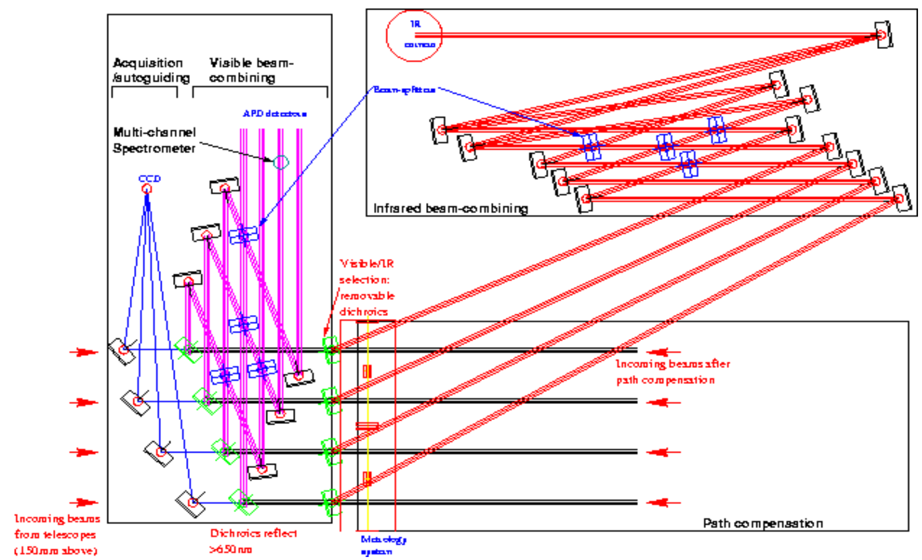
Di Benedetto & Bonneau, 1990, A&A, 358, 617

COAST (Cambridge, MRAO)

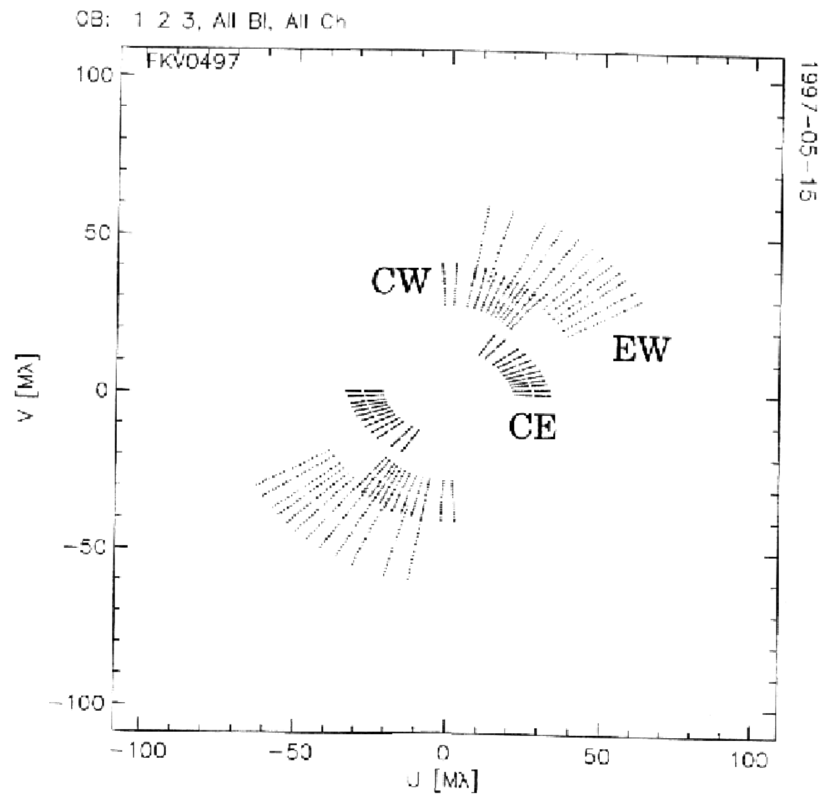




First reconstructed image: Capella



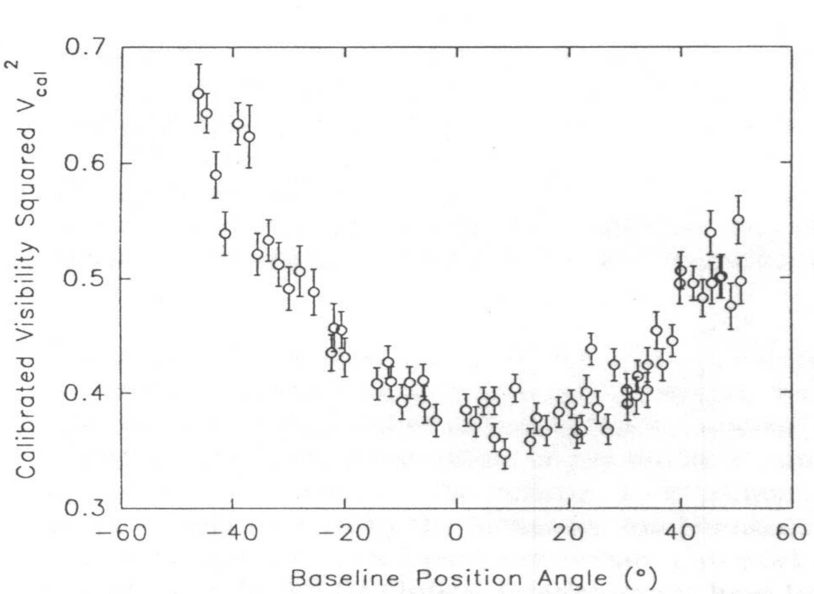
Sampling the (u,v) plane



NPOI observation of the binary star mizar

Supersynthesis effect

γ Cas

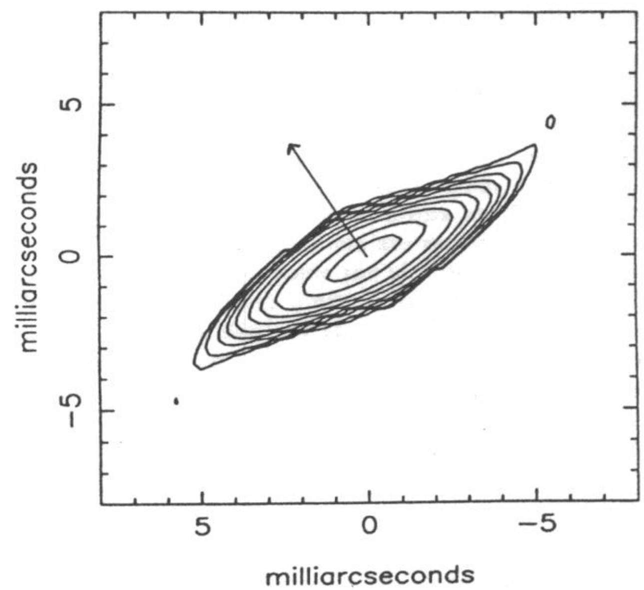


Non-spherical envelope

(Quirrenbach et al. 1993, ApJ, 416, L25)

e=0.74, Major axis= 3.2 mas

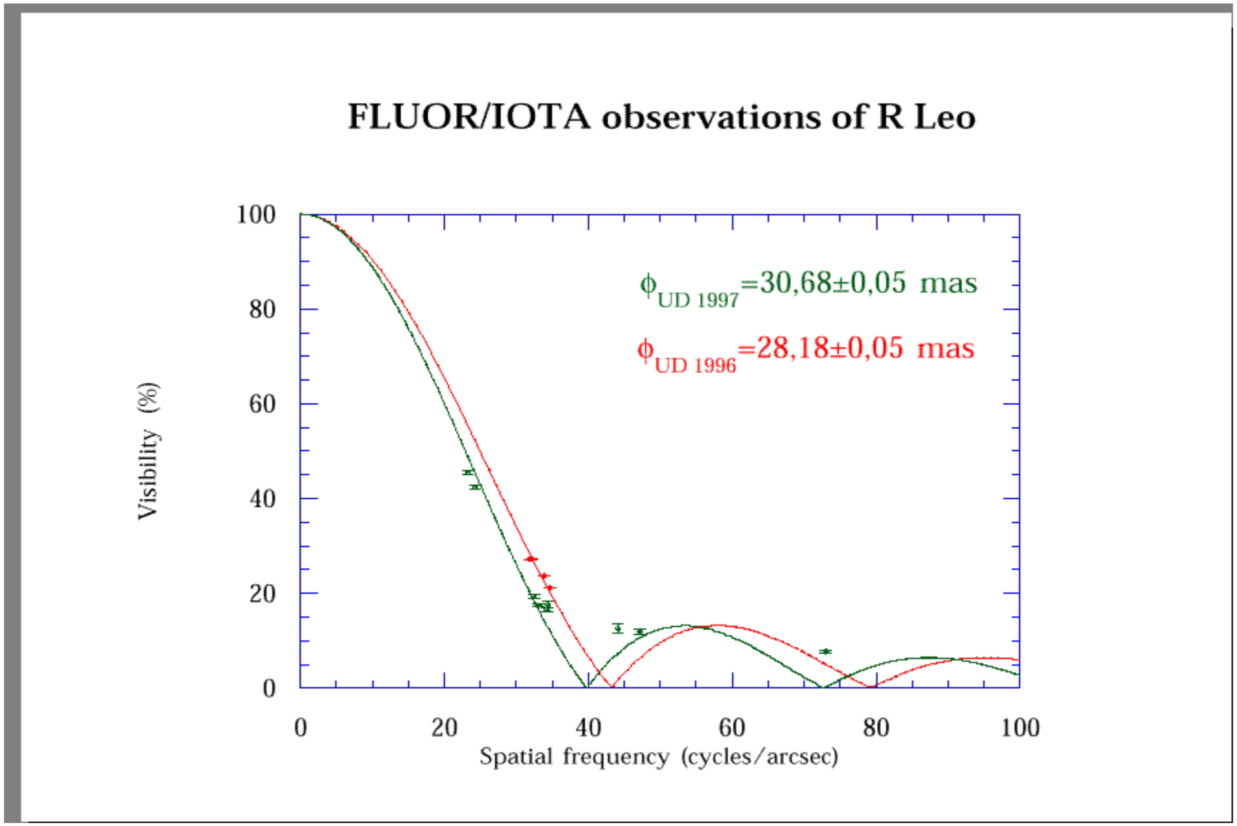
ζ Tau



Flattened envelope

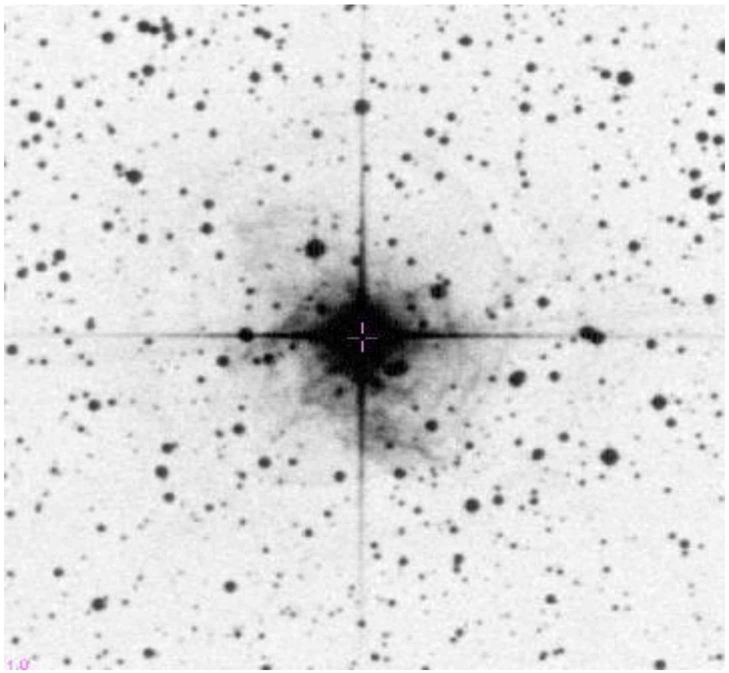
(Quirrenbach et al., A&A, 283, L13)

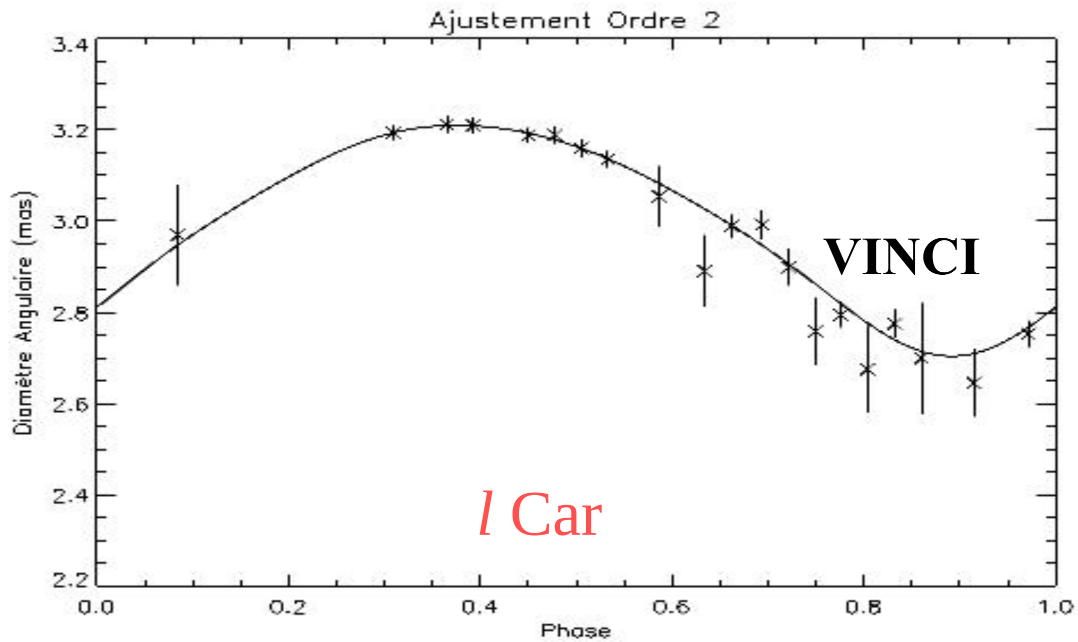
Time sampling



Variation of the angular diameter of R Leo as a function of time IOTA/FLUOR

Cepheids stars





Calibration of the measurements

- On a point-like source, V^2=1 in theory, much less in actual conditions
- 1/2 to 2/3 of the observing time is spent on calibrators.

$$V^2_{m,cal} = V^2_{th,cal} x T^2$$

$$==> \quad V^2_{th,target} = V^2_{m,target} x \frac{V^2_{th,cal}}{V^2_{m,cal}}$$

$$V^2_{m,target} = V^2_{th,target} x T^2$$

- What is a good calibrator? σV^2_{th} and σV^2_m

SearchCal getCal

Starting the interpretation

- Calibrated visibilities and limited (u,v) coverage.
- Interferometric measurements are usually stored in OIFITS file (international norm for data exchange).

Model fitting is a first step solution

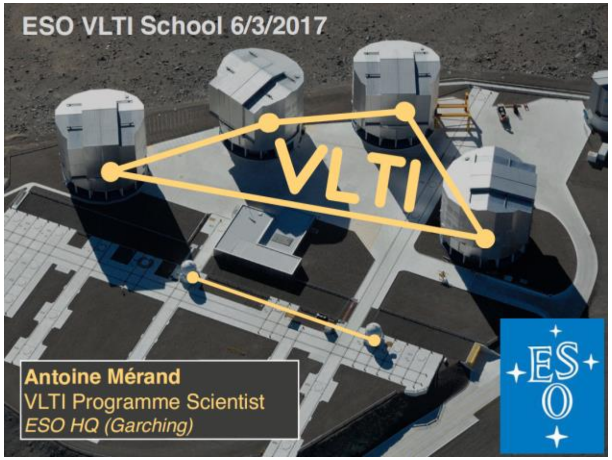
LITPRO (JMMC)

More elaborated models are usually necessary

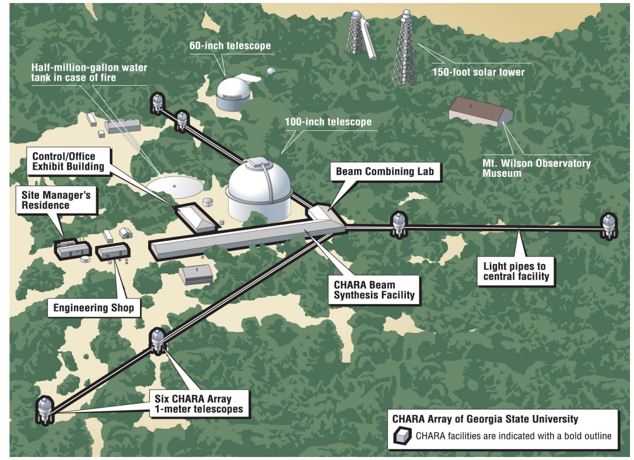
Image reconstruction

Now the reality

ESO/VLTI



CHARA



NPOI

MROI


Anderson Mesa
437m (17,200″)
Navy Precision
Optical Interferometer

NPOI: The Basics

NPOI Array Center

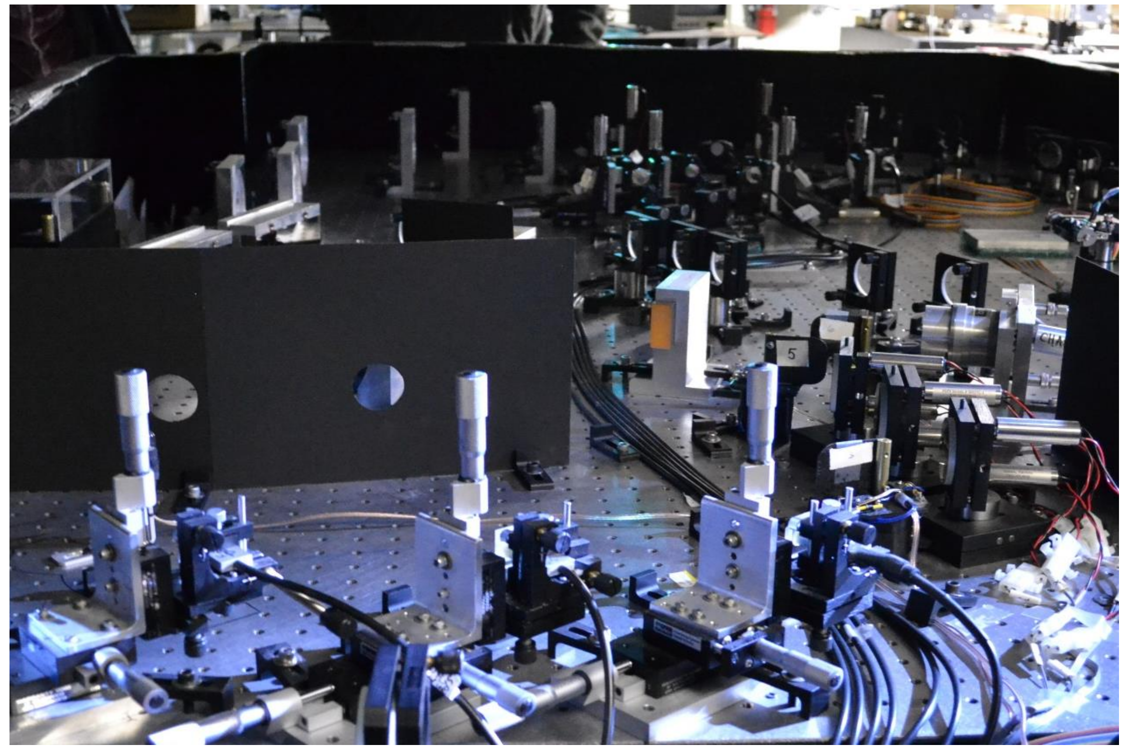
- NPOI = Navy Precision Optical Interferometer
  - Major funding by Oceanographer of the Navy and Office of Naval Research
  - Additional instrument funding from National Science Foundation

60

- NPOI is collaboration between US Naval Observatory (USNO), Naval Research Lab (NRL) & Lowell Observatory
- Lowell is both a science partner, and a contractor to USNO (infrastructure & ops) & NRL (site projects)

NPOI Current Performance

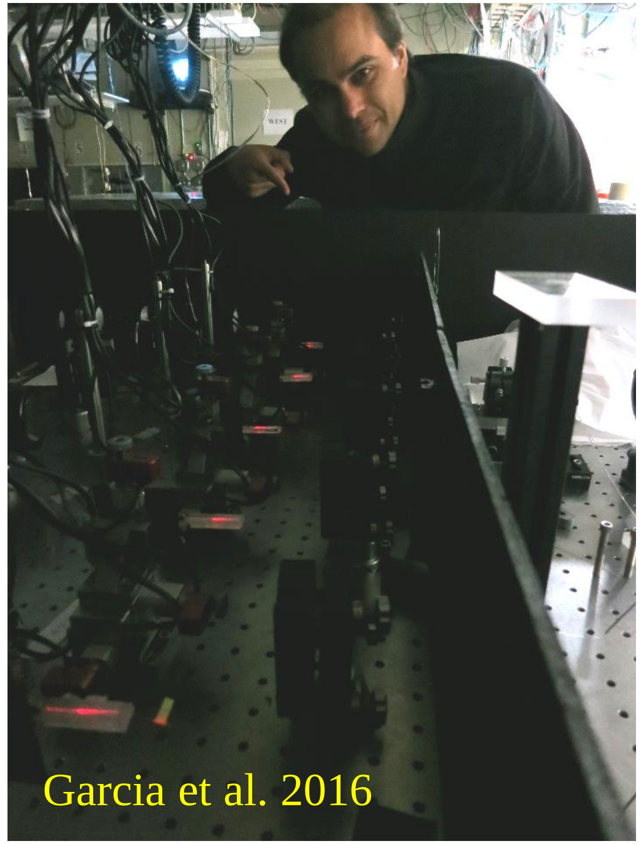
- 'Classic' Combiner
  - APD-based temporally modulating combiner
  - Spectral resolution: R=40 (16 channels) over 550-850nm
  - Collects *many* N-way permutations
    - 1/3 of data dropped
  - Sensitivity limit of $m_V \approx 5.5$



Armstrong et al. 1998, 2013

NPOI Current Performance

- VISION
  - EMCCD-based spatially modulating combiner
  - Spectral resolutions: R=200, 1000 over 570-850nm
  - Collects *all* N-way permutations
  - Automatic data pipeline adapted from MIRC
  - Sensitivity limit of $m_V \approx 6$



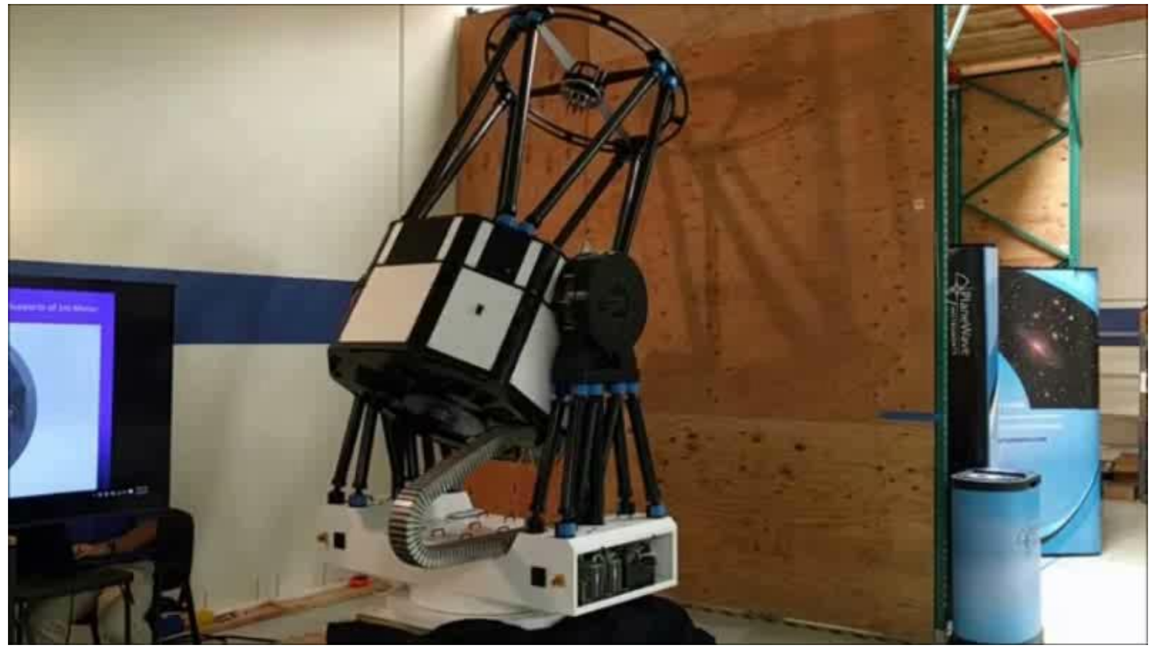
Garcia et al. 2016

Current Infrastructure

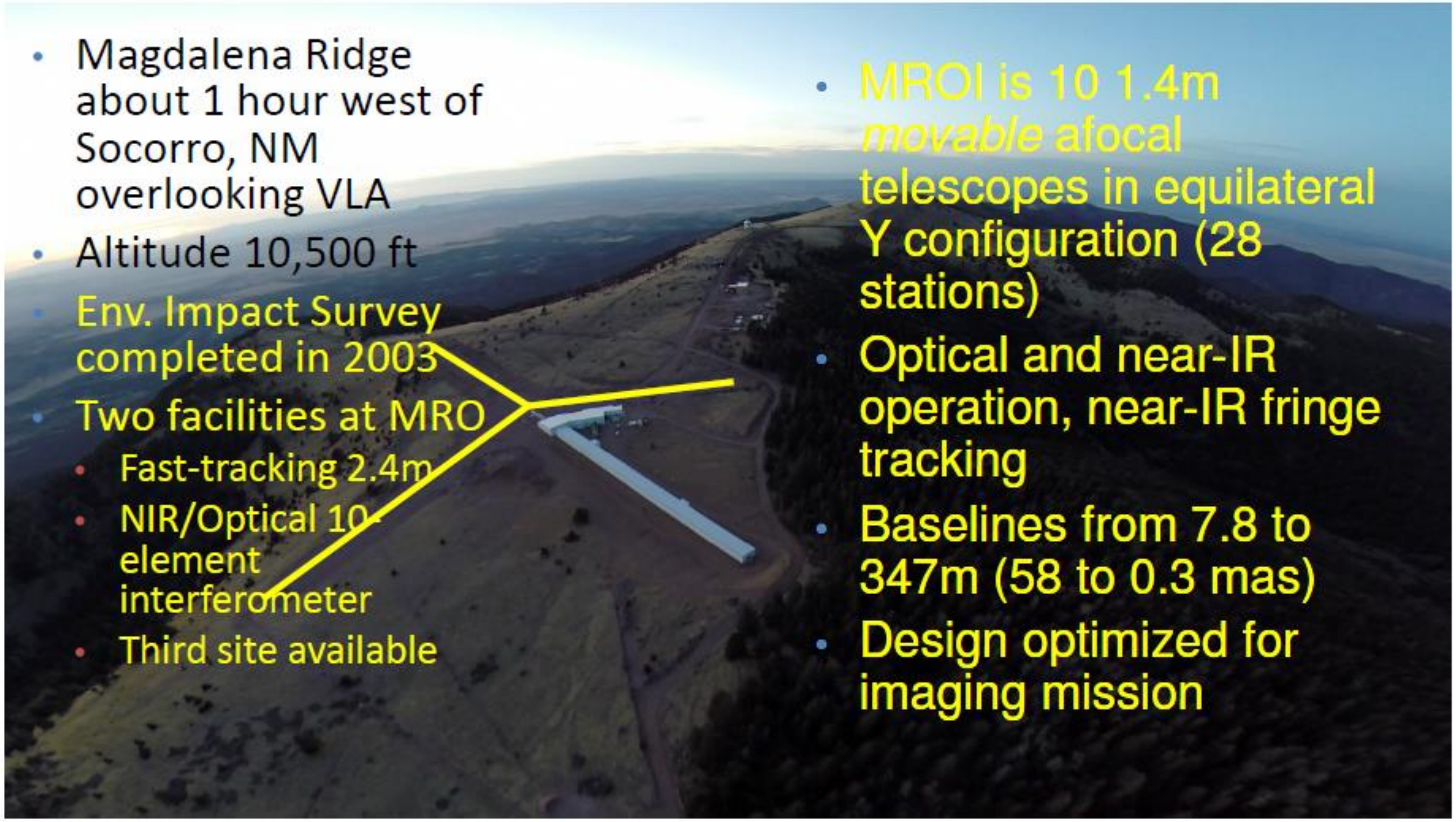
- Siderostats
  - Six 12-cm 'imaging' apertures
  - Four 12-cm 'astrometric' apertures
- FDLs
  - Six variable optical delay lines
- LDLs
  - Not yet online
  - Limits sky coverage
- Astrometric metrology
  - Mothballed

Large Apertures for NPOI

- NRL support for development of geosat imaging technology
  - Capital construction for 3×1.0 m telescopes
- New large model from PlaneWave Instruments for 1.0 m
  - Robust, turnkey operations
  - CDK700 proven with MINERVA and other projects
- 70× increase in collecting area: Δm of up to +4.5mag



Overview of the Observatory



- Magdalena Ridge about 1 hour west of Socorro, NM overlooking VLA
- Altitude 10,500 ft
- Env. Impact Survey completed in 2003
- Two facilities at MRO
  - Fast-tracking 2.4m
  - NIR/Optical 10-element interferometer
  - Third site available

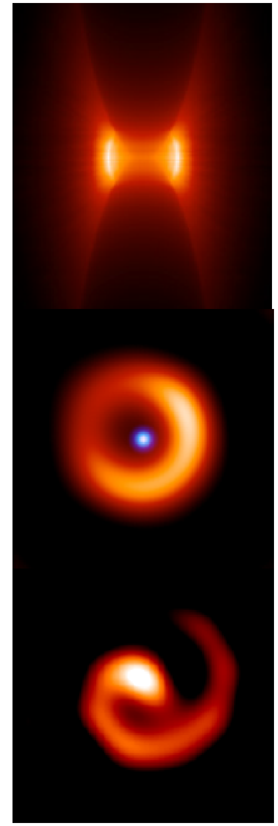
- MROI is 10 1.4m *movable* afocal telescopes in equilateral Y configuration (28 stations)
- Optical and near-IR operation, near-IR fringe tracking
- Baselines from 7.8 to 347m (58 to 0.3 mas)
- Design optimized for imaging mission

MROI Science Case

- AGN:
  - Verification of the unified model.
  - Determination of nature of nuclear/extra-nuclear starbursts.
  - H =14 gives >100 targets.

- Star and planet formation:
  - Protostellar accretion, imaging of dust disks, disk clearing as evidence for planet formation.
  - Emission line imaging of jets, outflows and magnetically channeled accretion.
  - Detection of sub-stellar companions.

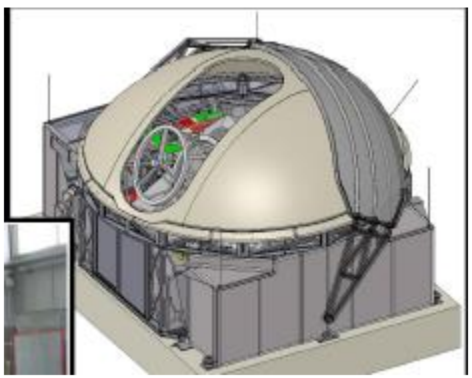
- Stellar accretion and mass loss:
  - Convection, mass loss and mass transfer in single and multi-star systems.
  - Bipolarity and collimation of circumstellar material, wind and shock geometries, interacting binary systems
  - Pulsations in Cepheids, Miras, RV Tauris, etc.



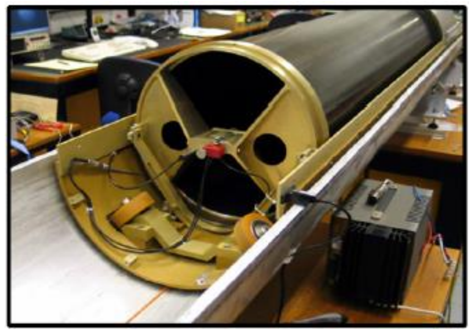
MROI current situation

1st telescope Nov. 16

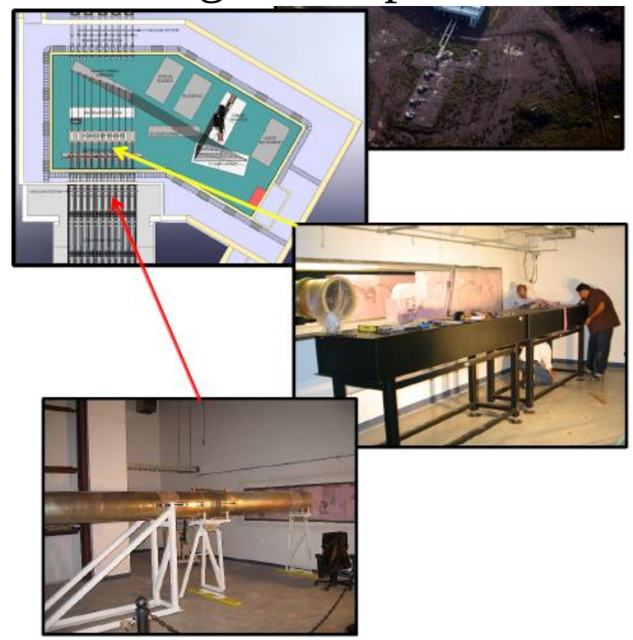
1st Dome Nov. 17



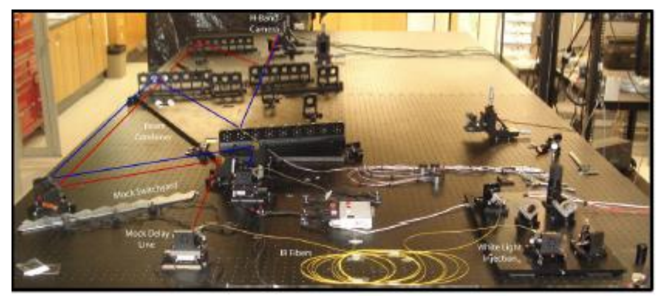
1st cart delivered



Building in completion



Prototype of fringe tracker



Timeline for Future Development

- Funding under $25M cooperative agreement with AFRL supports deploying first 3 telescopes
- First telescope and enclosure deployed on array arms next spring – will characterize light into beam combining facility
- Fringes anticipated in 2019 and three-telescope measurements in 2020
- More funding needed to complete 10 telescope facility – looking to NSF, alumni, philanthropy
- Costs are ~$8M per "beamline" – looking for partners for new beamlines as well as operations

ESO/VLTI Paranal Observatory

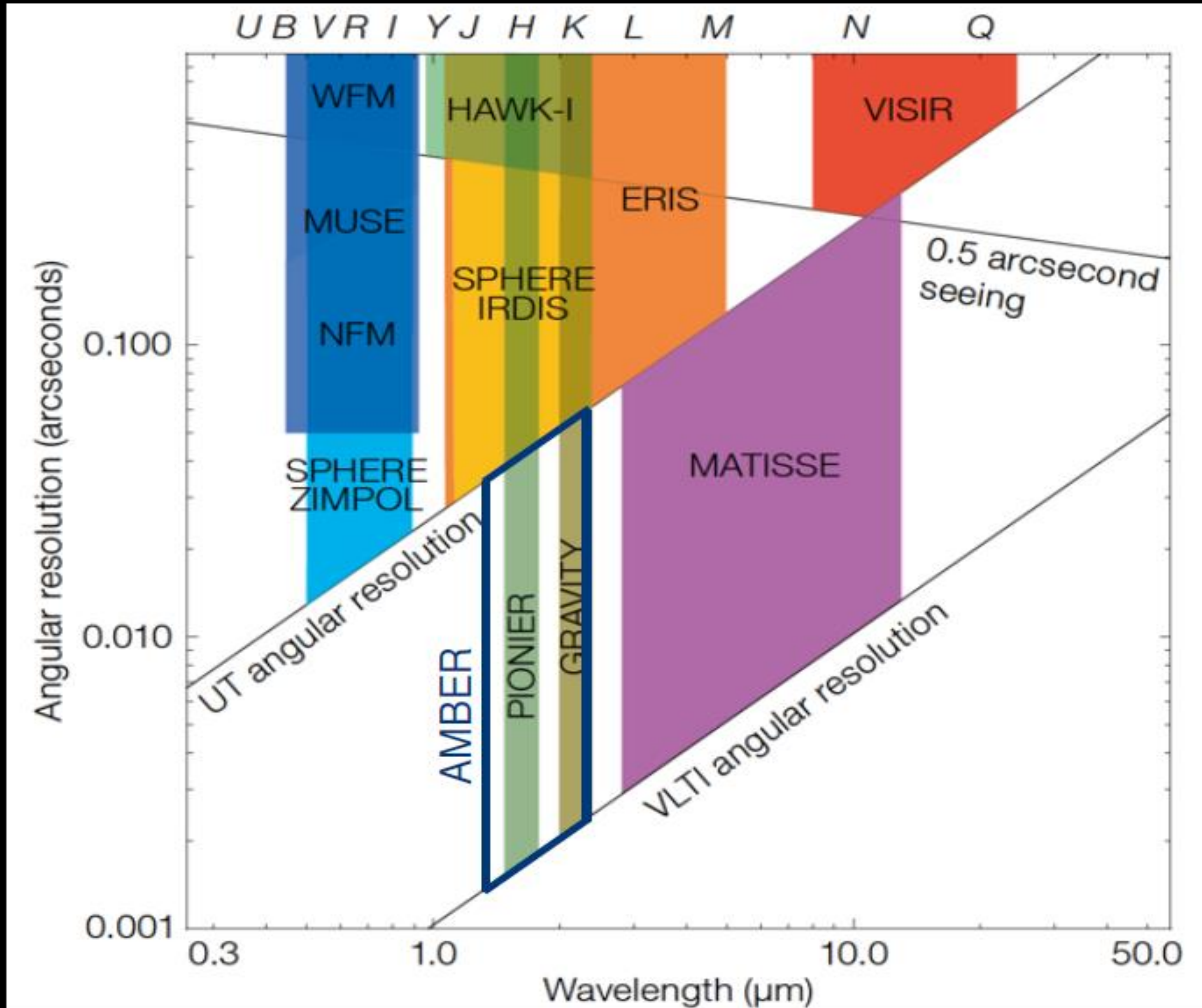
- Up to 4 telescopes simultaneously
- UTs (8.2m) and movable ATs (1.8m)
- Wavelength coverage from 1.5µm to 12µm
- Baselines from 11m to 140m
- Angular resolution in the 0.001" (1mas) regime

Instrument overview

	AMBER	PIONIER	GRAVITY	MATISSE
# of combined telescopes (ATs or UTs)	3	4	4	4
Spectral range and resolution	H-K (35,1500,12000)	H (none,30)	K (22,500,4000)	L,M,N (30-5000)
Fringe tracker	FINITO		Dedicated internal FT (on/off-axis)	GRA4MAT

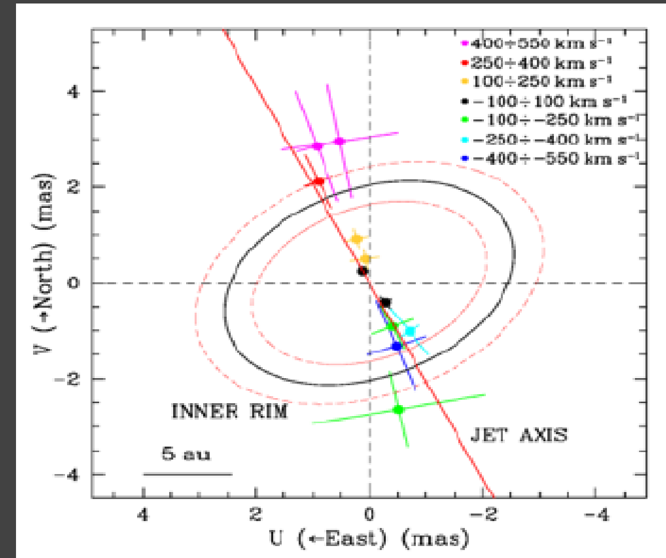
\+ astrometry offered in the near-future

Instrument spatial resolution and spectral coverage

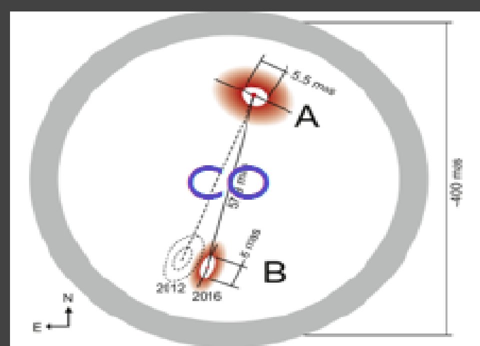


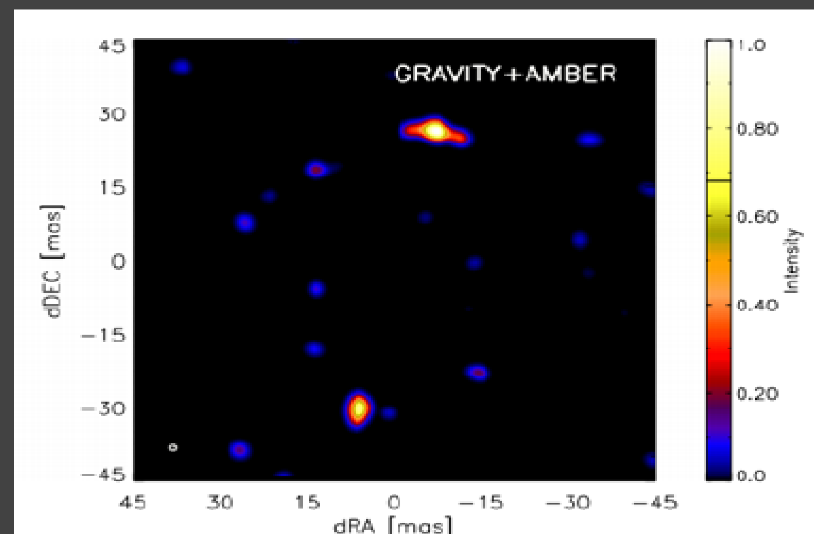
Massive YSOs

- AMBER resolves a jet for IRAS 13481-6124
- AMBER+GRAVITY image a of Massive YSO binary



Caratti o Garatti+ 2016

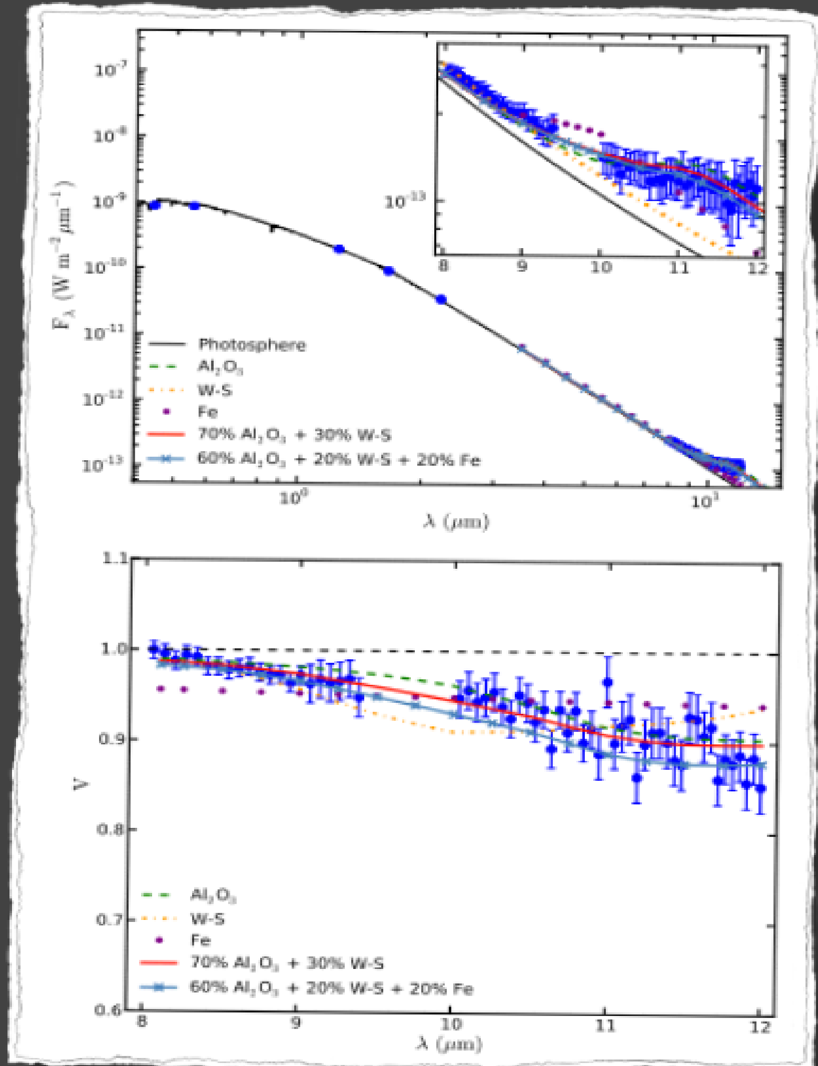




Kraus+ 2017

Cepheids' mass loss

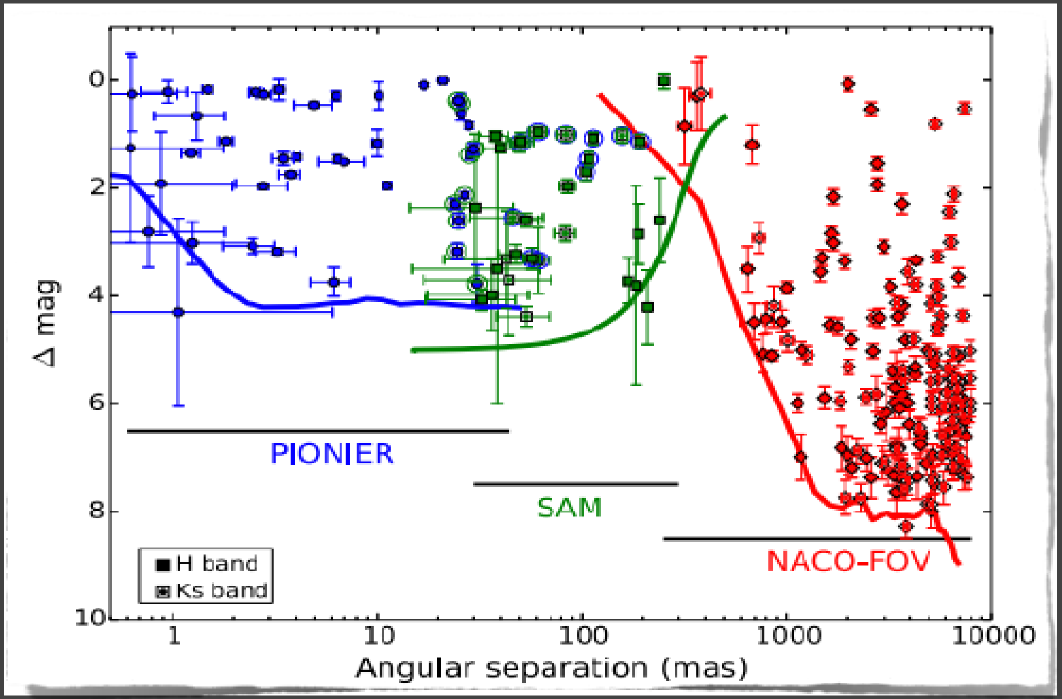
- MIDI resolved known IR excess
- Modelled using DUSTY code
- Mineralogy not well constrained yet (MATISSE)



Gallenne et al. (2013)

Binarity of massive stars

- ~45% of O stars are in multiple systems according to RV
- PIONIER+NACO survey showed 100% of O stars are in multiple systems



Sana + 2014

Interacting Binary

Image reconstruction (PIONIER)

unexpected mass ratio (fact. of 2)

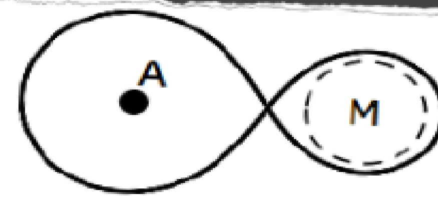
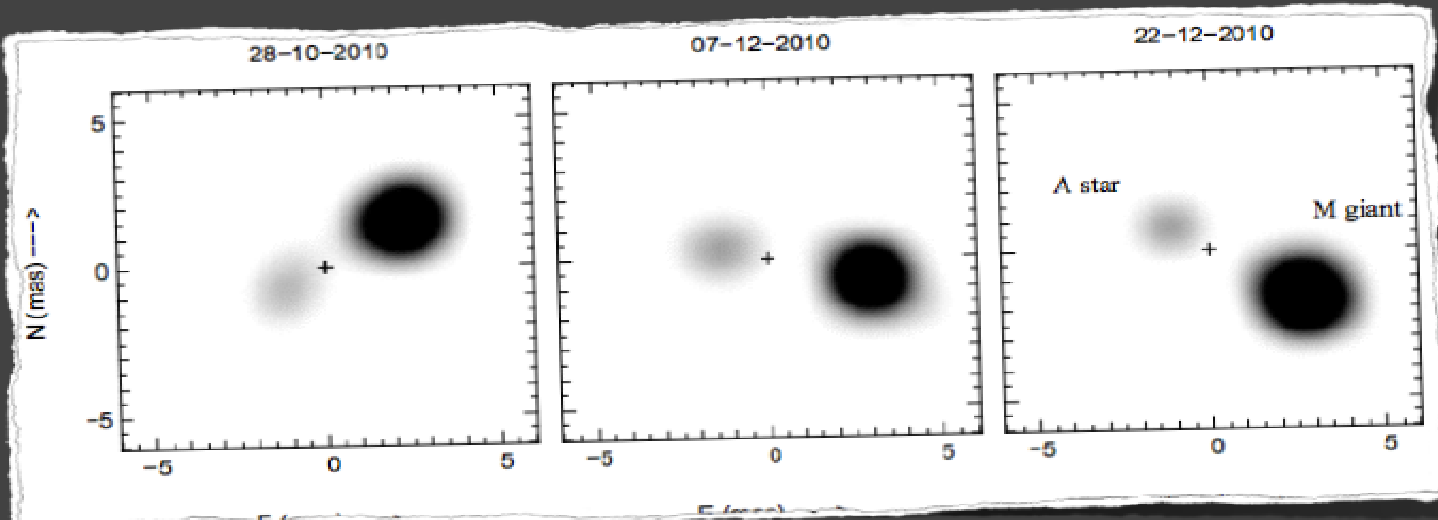


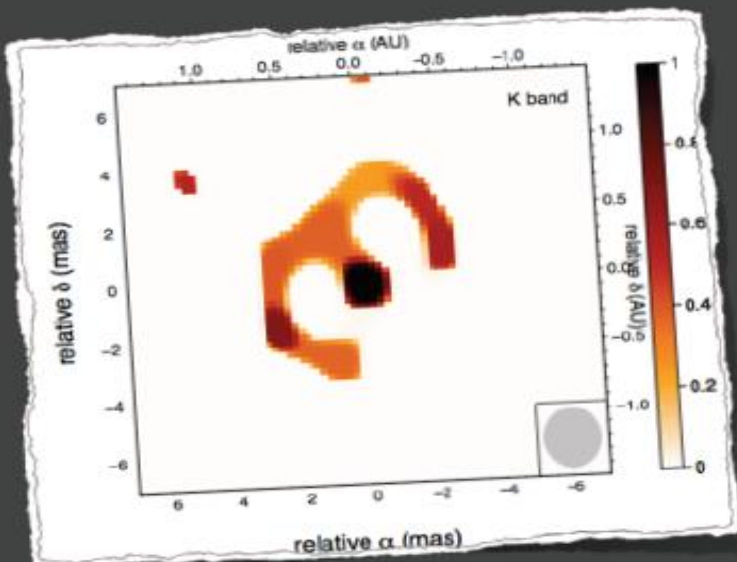
Fig. 5. Representation of the modified Roche equipotential (solid line) for a mass ratio $1/q = 2.2$. The limb-darkened diameter of the M giant is the dashed line, while the A star one is the dark dot.



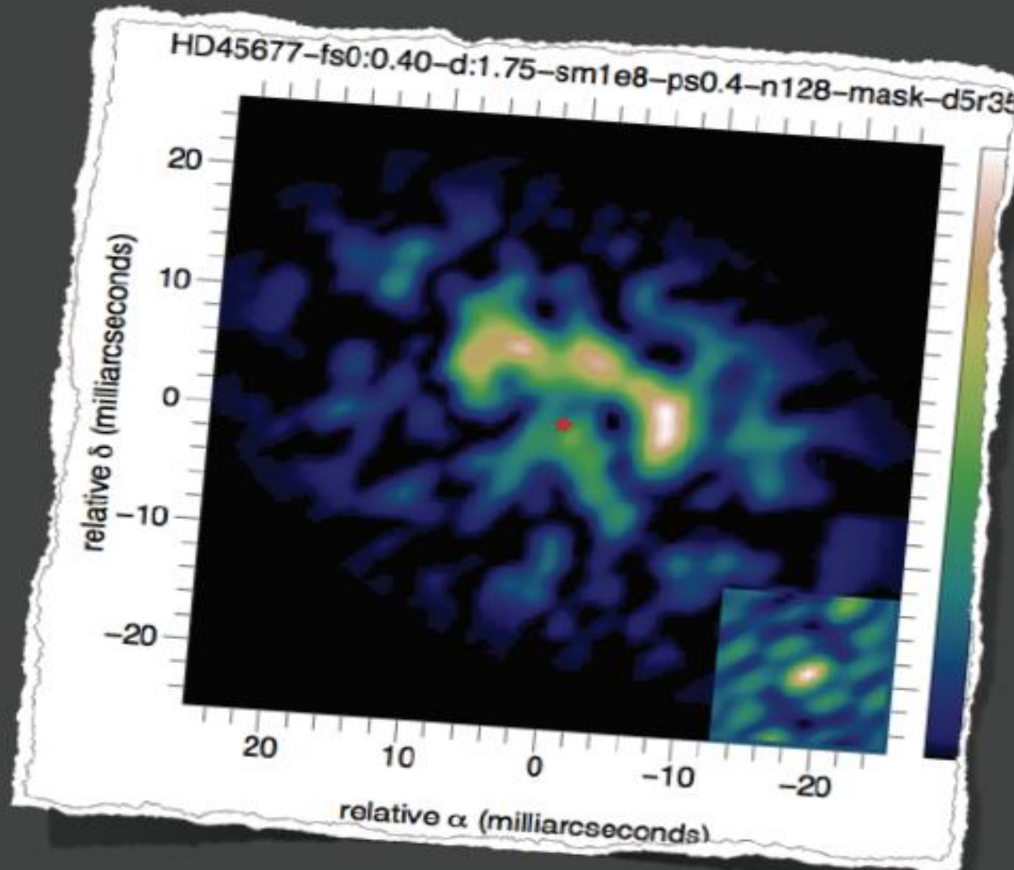
Blind, Boffin et al. (2011)

Disks & young stars

- Disk inner rim reconstructed images
- "the first AU"



Benisty et al. (2011): AMBER

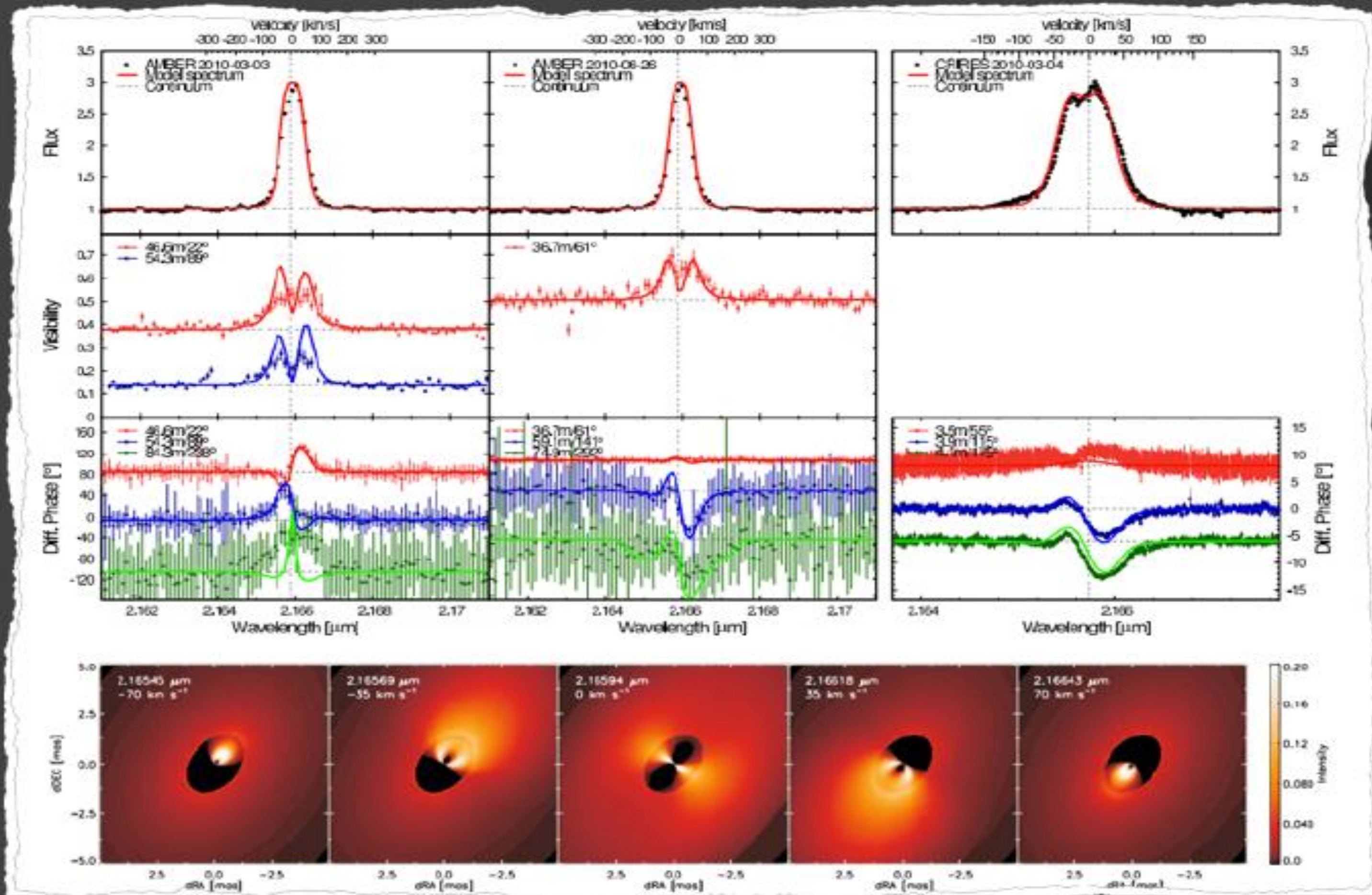


Kluska et al. (in prep): PIONIER

Be stars

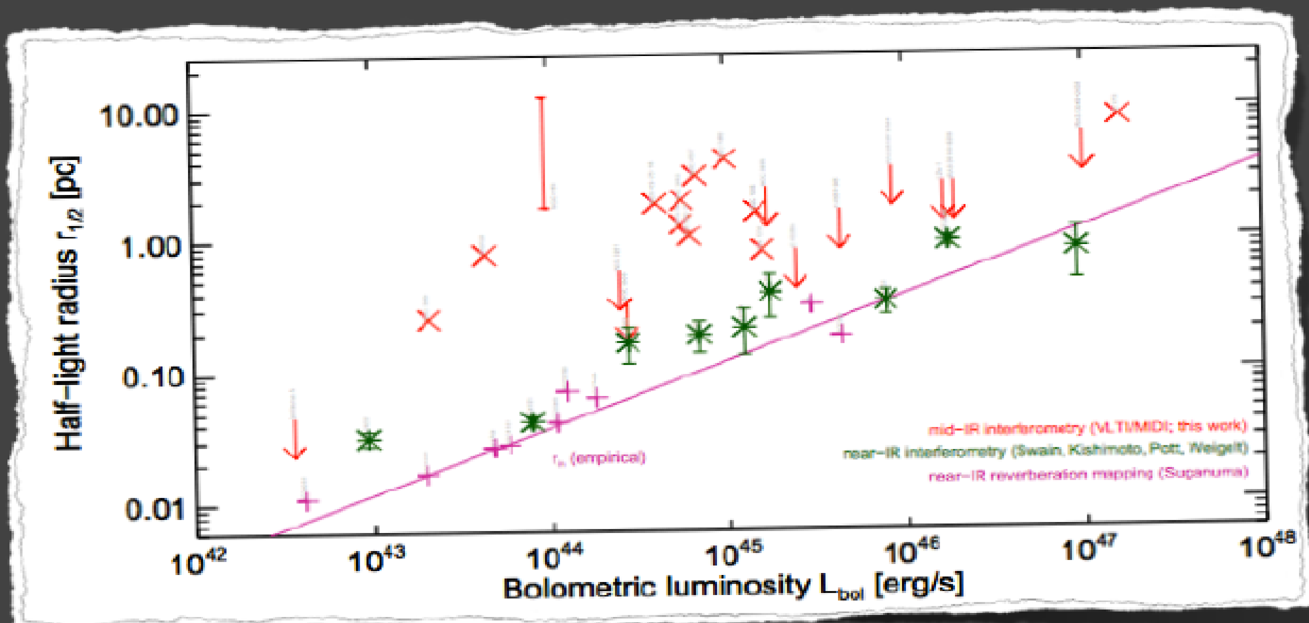
(Keplerian) disks and companions

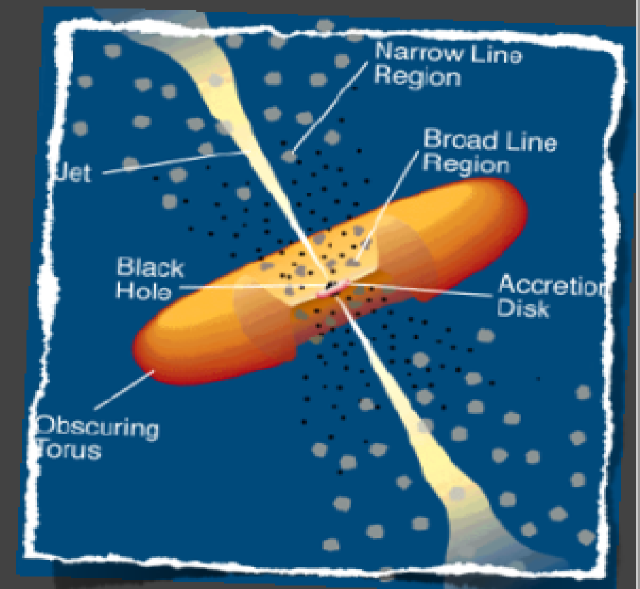
Kraus et al. 2012



AGNs

- No morphological differences between type 1 and type 2 (!)
- Radius/Luminosity relation





Burtscher et al. 2013 (MIDI)

The GRAVITY instrument in short

Very challenging science cases

Demanding requirements

- High sensitivity in K-band: **K ~ 10** (fringe tracking)
  K ~ 16 (long-integration imaging)
- Astrometry at **10-µas** accuracy → control of aberrations, image and pupil positioning and control, metrology, … **at nm-level!**

Technical challenges
Innovative R&D

- Fast low-noise detectors
- Ultra-stable metrology laser
- **Integrated optics combiners**

Key-figures

- A cryostat of **2.3 tons**
- **2-m long** and **diameter of 1.5-m**
- **Under vacuum**
- Controlled temperatures : **80, 200, 240 K**

Le consortium GRAVITY

Frank Eisenhauer, Guy Perrin, Wolfgang Brandner, Christian Straubmeier , Karine Perraut , Antonio Amorim , Markus Schöller, Reinhard Genzel, Pierre Kervella , Myriam Benisty, Sebastian Fischer , Laurent Jocou, Paulo Garcia, Gerd Jakob, Stefan Gillessen, Yann Clénet , Armin Boehm, Constanza Araujo-Hauck, Jean-Philippe Berger, Jorge Lima, Roberto Abuter, Oliver Pfuhl, Thibaut Paumard, Casey P. Deen, Michael Wiest , Thibaut Moulin, Jaime Villate, Gerardo Avila, Marcus Haug, Sylvestre Lacour , Thomas Henning, Senol Yazici , Axelle Nolot , Pedro Carvas, Reinhold Dorn, Stefan Kellner, Eric Gendron, Stefan Hippler, Andreas Eckart , Sonia Anton, Yves Jung, Alexander Gräter, Élodie Choquet , Armin Huber, Narsireddy Anugu , Philippe Gitton, Eckhard Sturm, Frédéric Vincent , Sarah Kendrew, Stefan Ströbele, Clemens Kister, Pierre Fédou, Ralf Klein, Paul Jolley, Magdalena Lippa, Vincent Lapeyrère, Natalia Kudryavtseva, Christian Lucuix, Ekkehard Wieprecht, Frédéric Chapron, Werner Laun, Leander Mehrgan, Thomas Ott, Gérard Rousset , Rainer Lenzen, Marcos Suarez, Reiner Hofmann, Jean-Michel Reess, Vianak Naranjo, Pierre Haguenauer, Oliver Hans, Arnaud Sevin , Udo Neumann, Jean-Louis Lizon, Markus Thiel, Claude Collin , Jose Ricardo Ramos, Gert Finger, David Moch, Daniel Rouan, Ralf-Rainer Rohloff, Markus Wittkowski, Richard Davies, Denis Ziegler , Karl Wagner, Henri Bonnet, Katie Dodds-Eden, Frédéric Cassaing, Pengqian Yang, Florian Kerber, Sebastian Rabien, Nabih Azouaoui, Frederic Gonte, Josef Eder, Vartan Arslanyan, Willem-Jan de Wit, Frank Hausmann, Roderick Dembet, Luca Pasquini, Harald Weisz, Pierre Lena, Mark Casali, Bernard Lazareff, Zoltan Hubert, Jean-Baptiste Le Bouquin

7 institutes over 4 countries
Whole project: ~10 M€ and 160 FTE
INSU/CNRS : 1.5 M€ and ~55 FTE
Duration ~ 10 years

GRAVITY science cases

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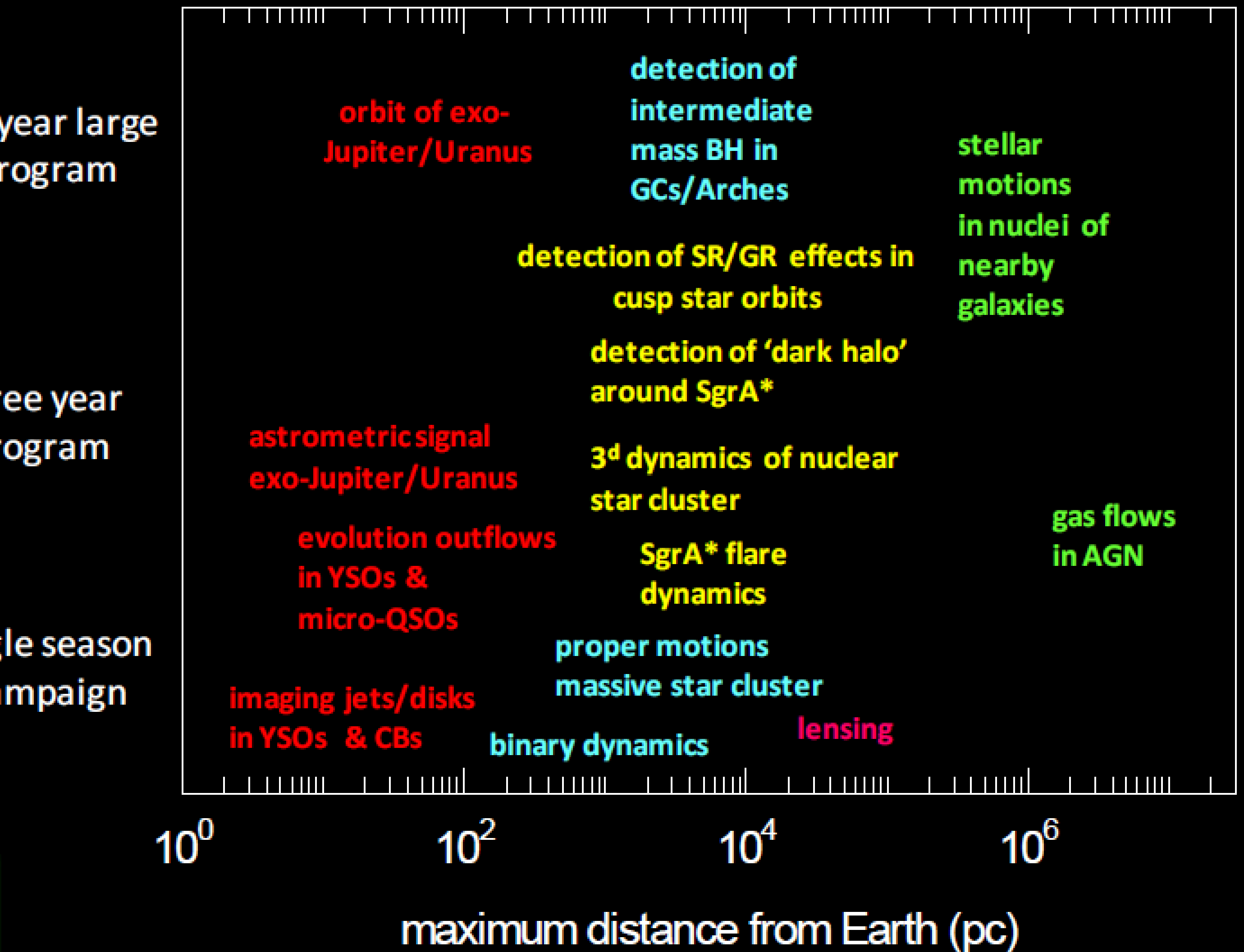
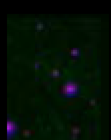
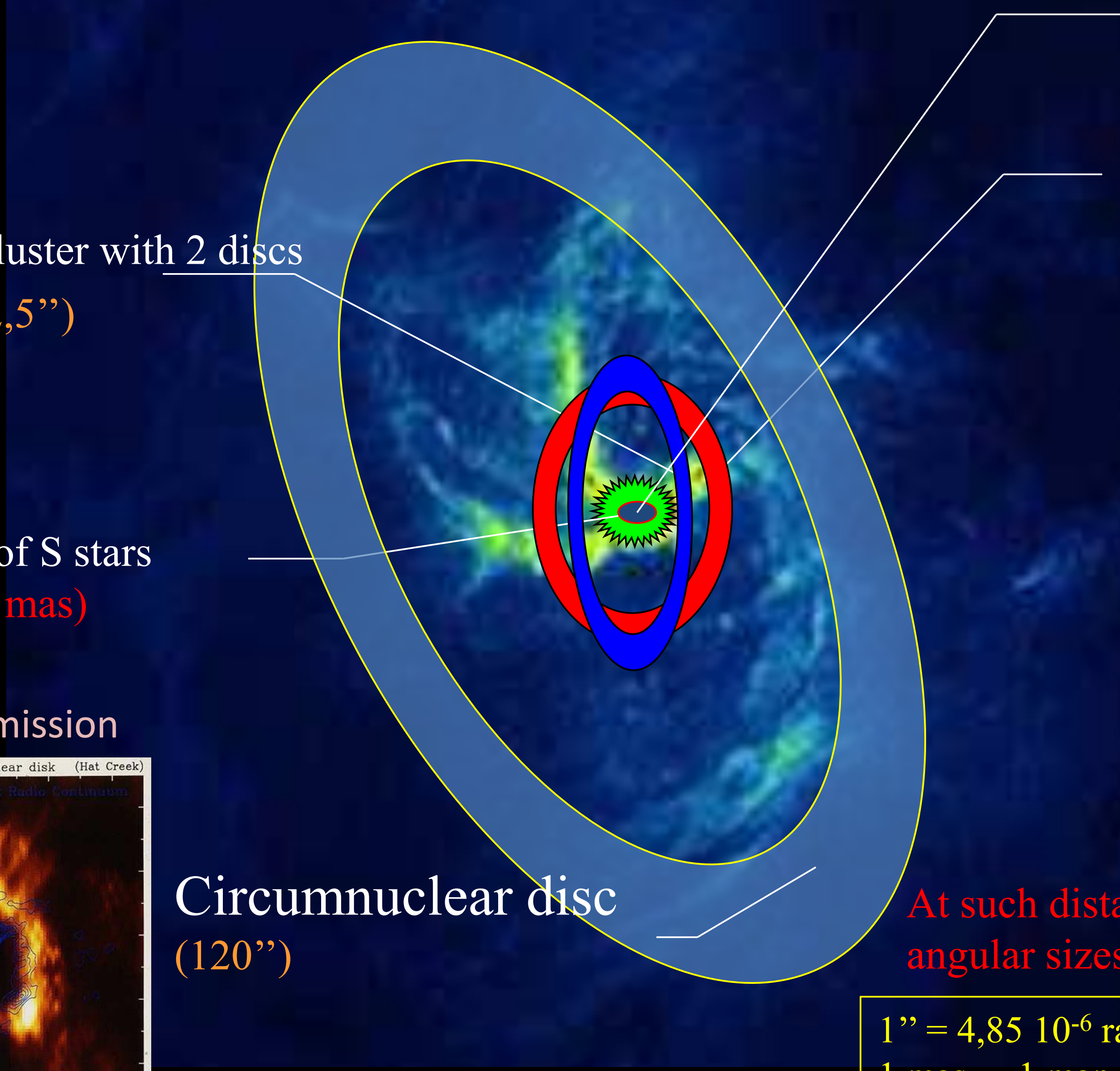
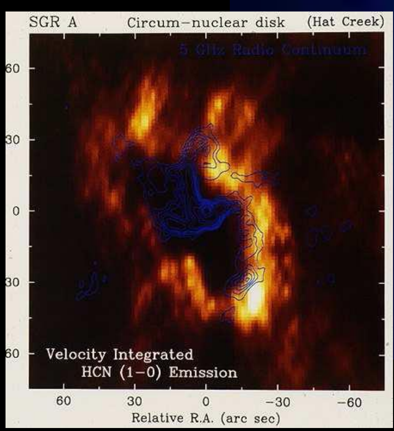




Sgr A* and the Galactic Center



Radio emission

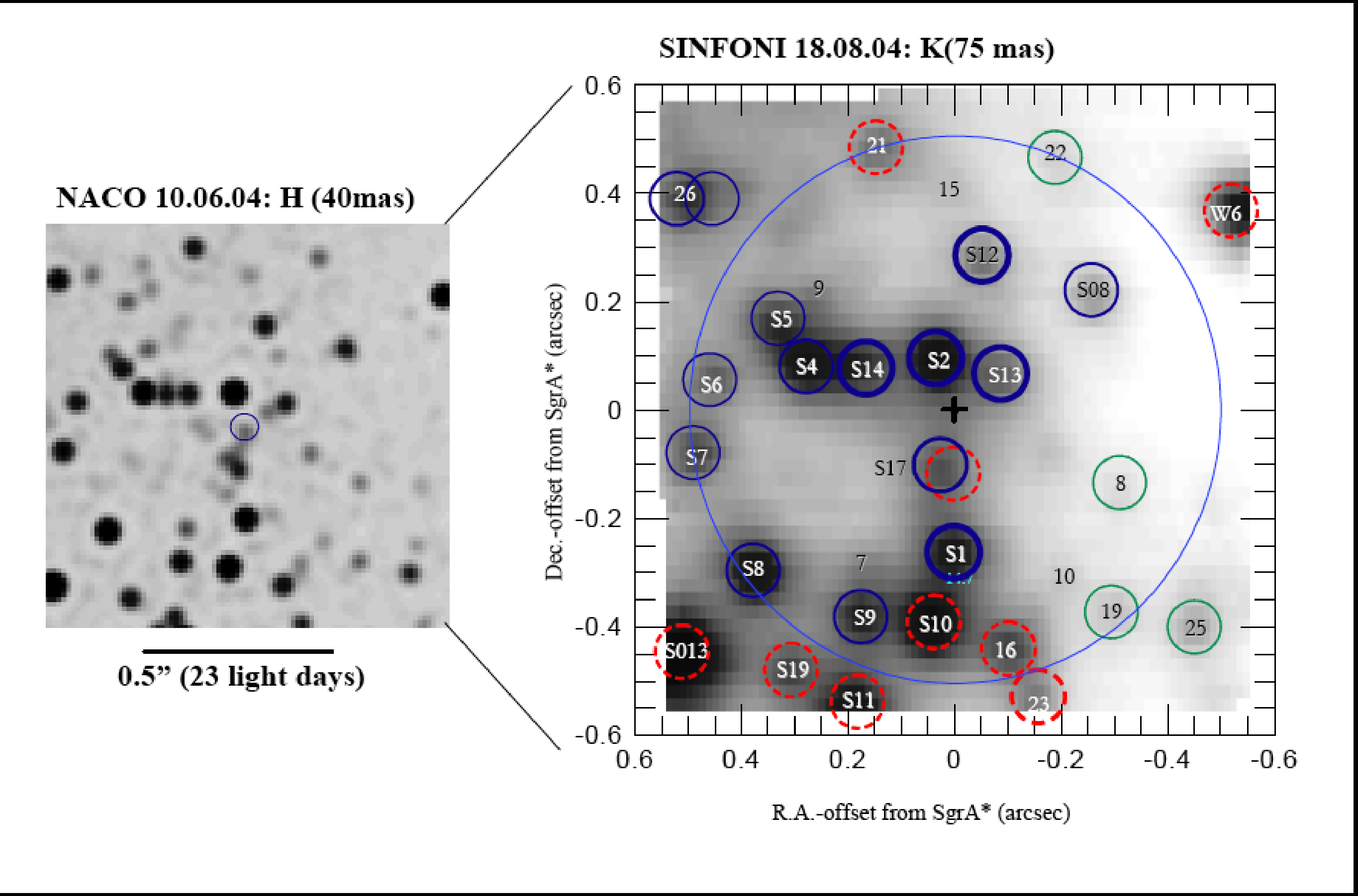


At such distances, one consider angular sizes

1” = 4,85 10^{-6} rad = 1 man at Paris
1 mas = 1 man on the Moon
20 μas = 1 hair at Paris

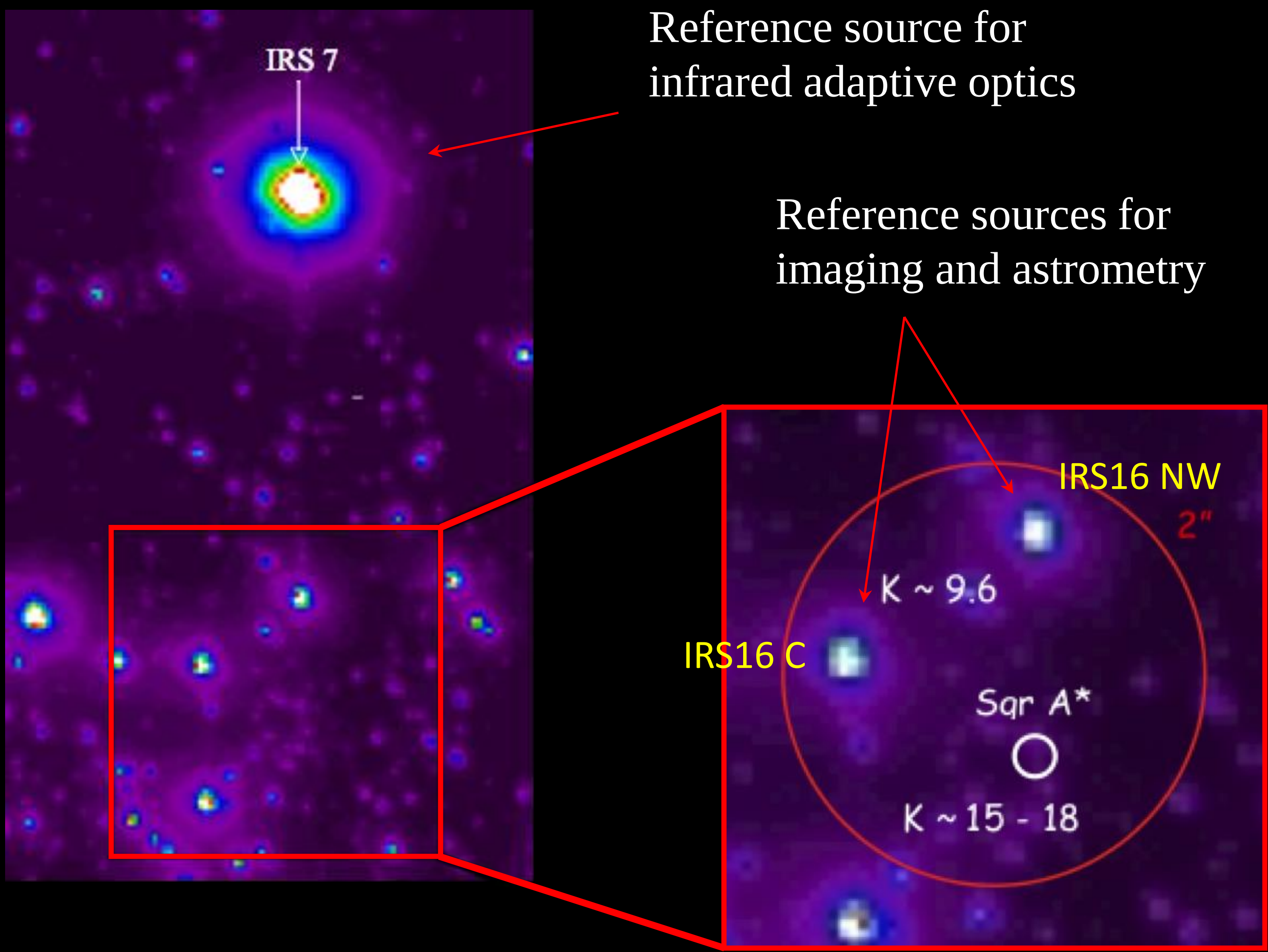
The Galactic Center: a very star-crowded field

Observation in the near-infrared by adapative optics and spectroscopy at the VLT

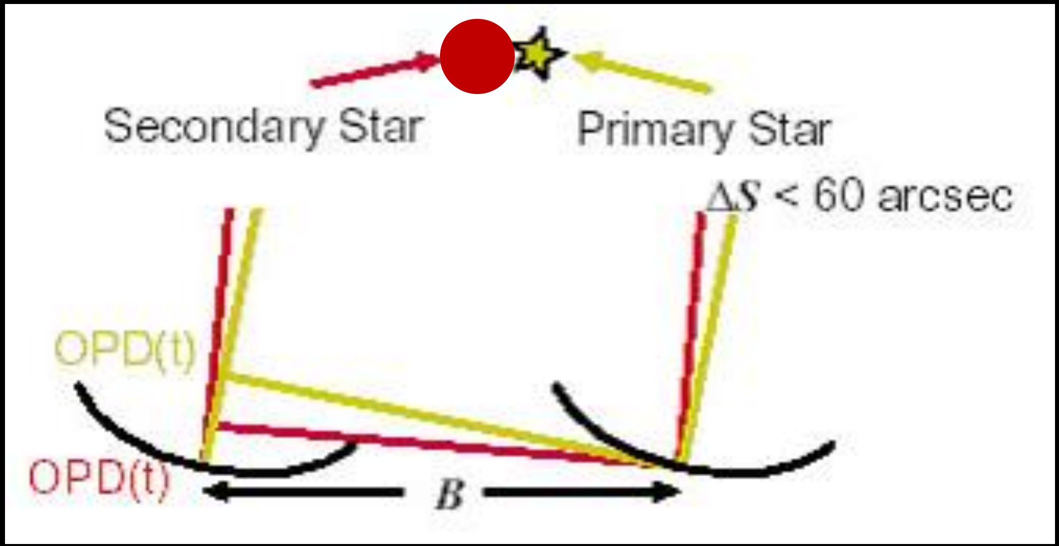


Eisenhauer et al. (2005)

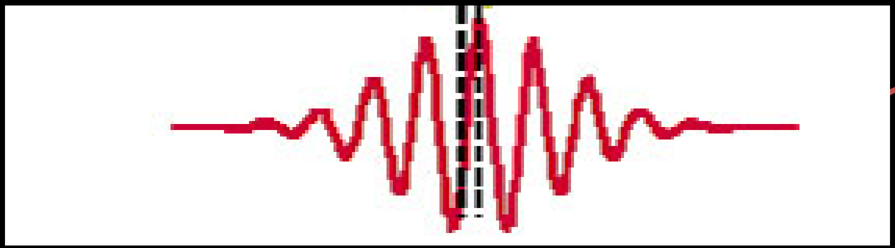
Two GRAVITY modes

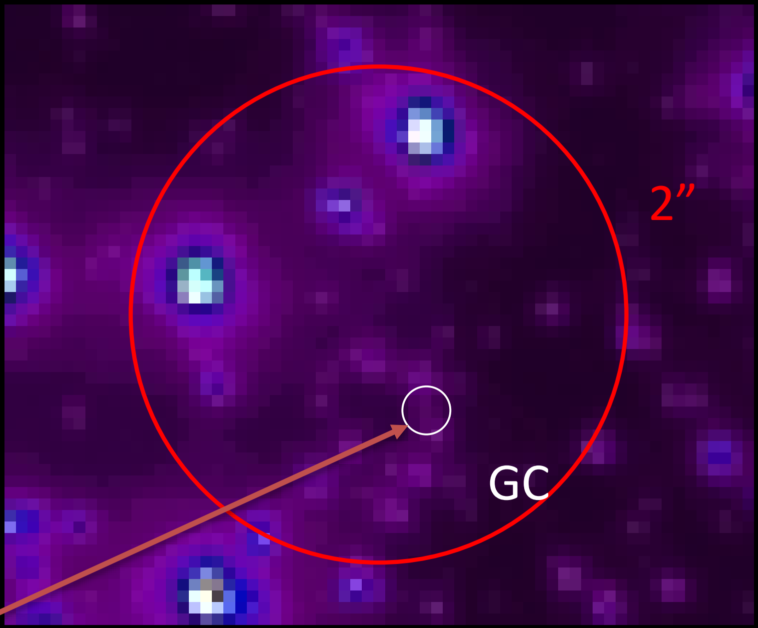


The GRAVITY imaging mode



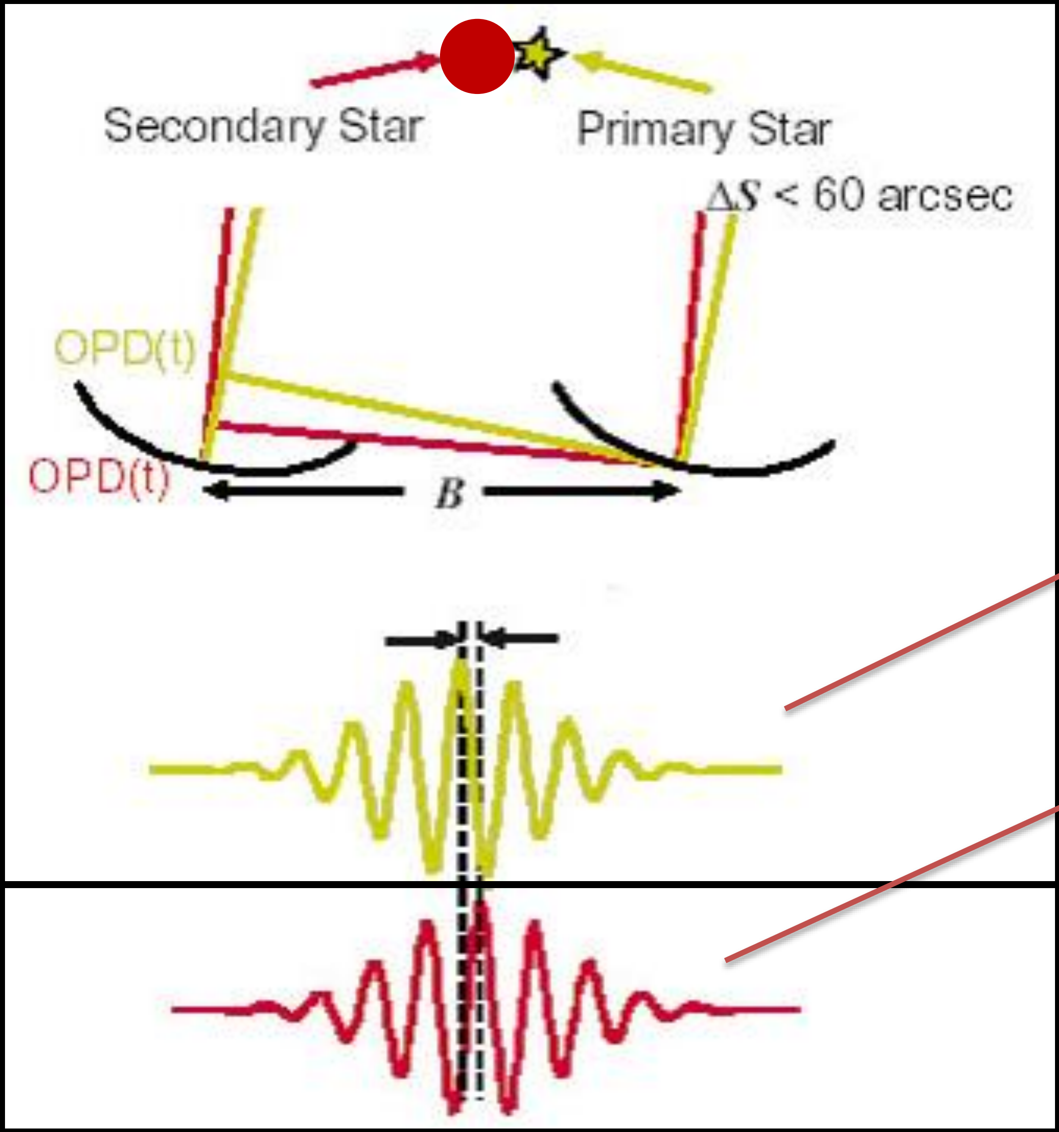
Contrast (B) ↔ F. T. (Object)

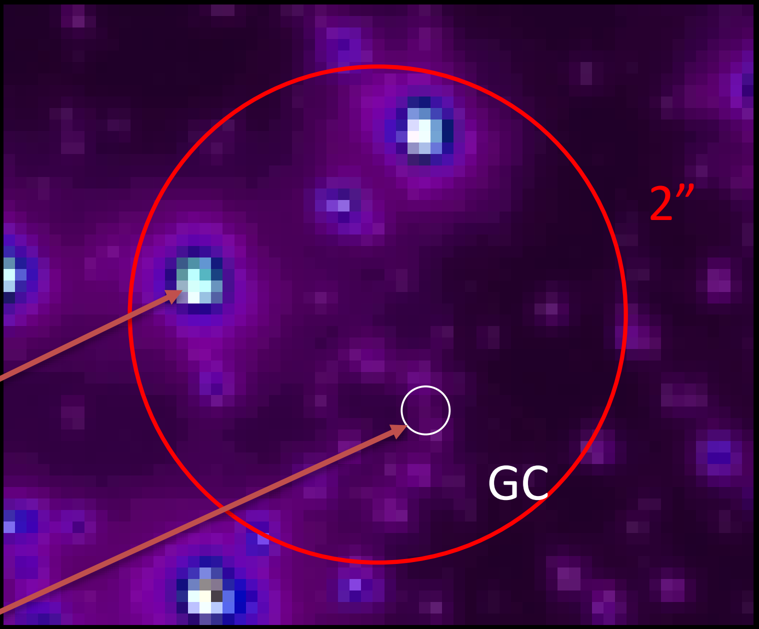




The GRAVITY astrometric mode

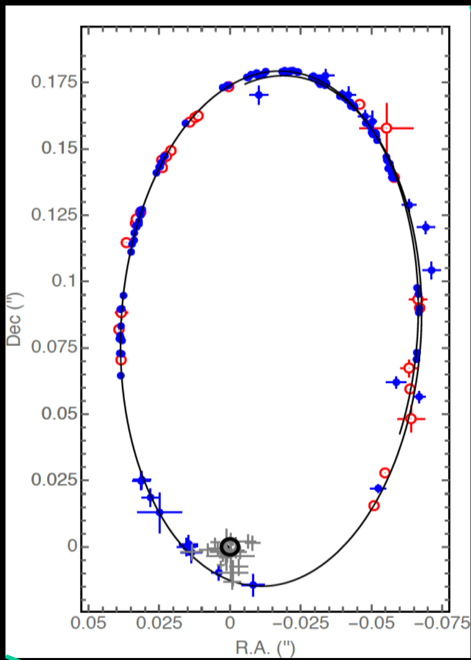
$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$



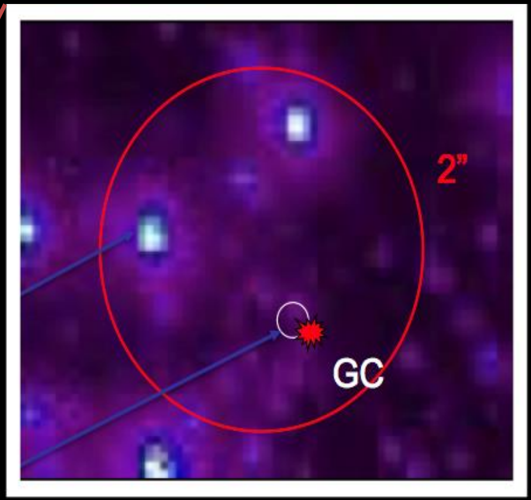


The GRAVITY tour

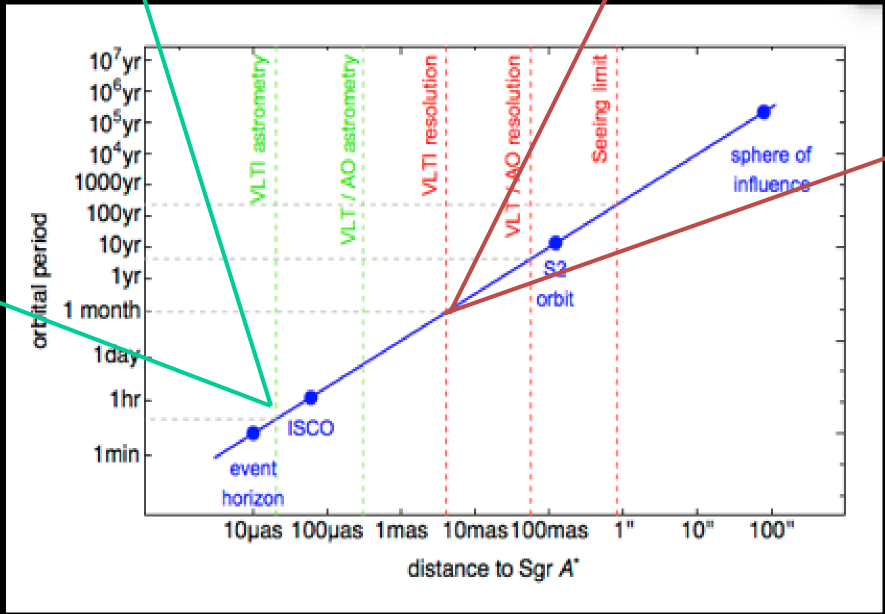
First results on the Galactic Center



Astrometry



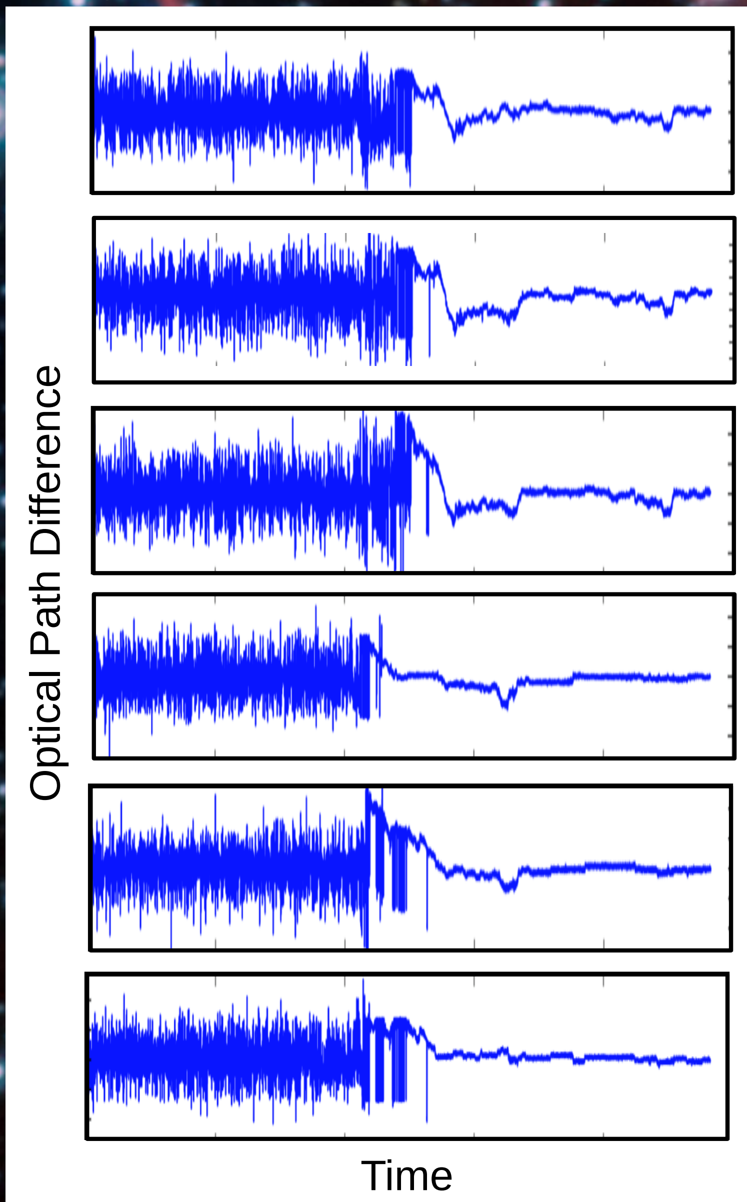
Imaging

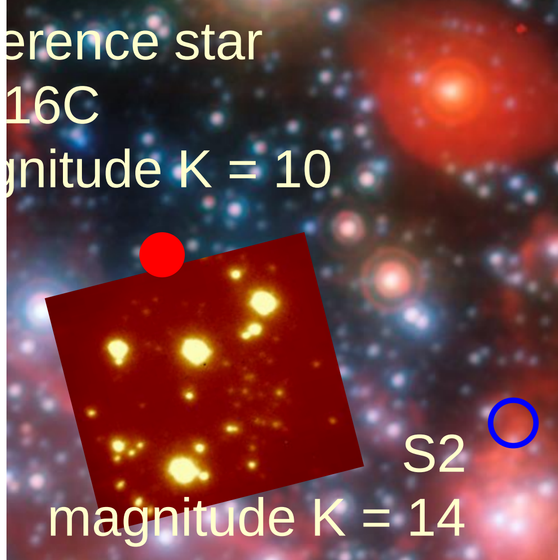


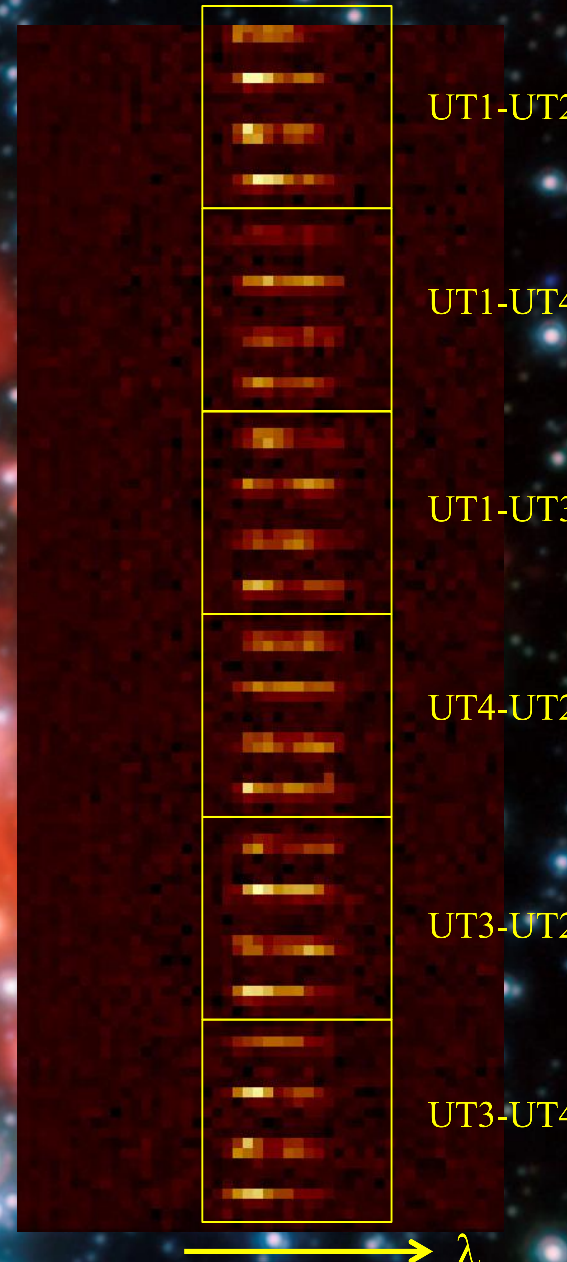
First observations of the Galactic Centre

(2016, May 17th)

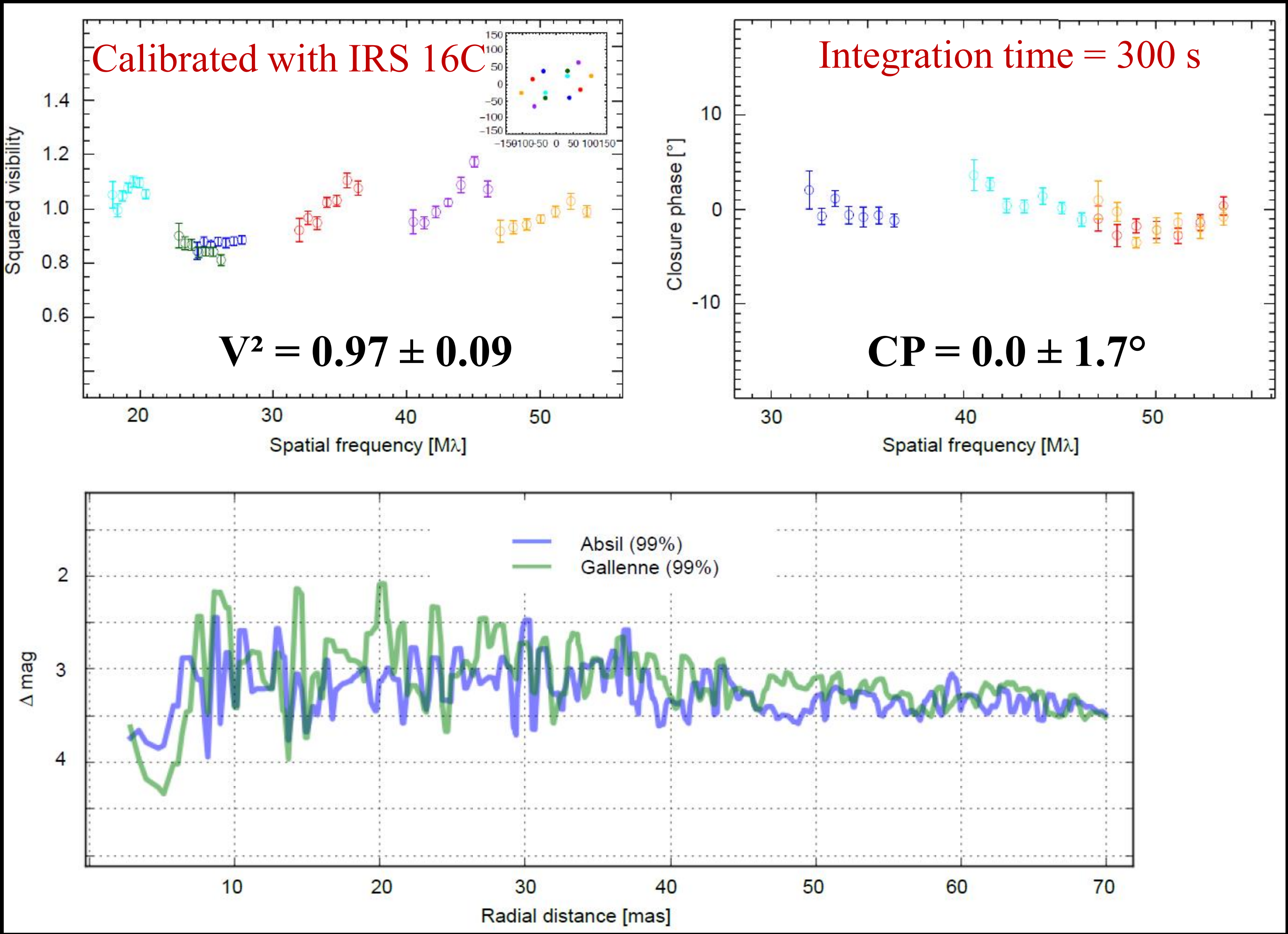
Fringe tracking on IRS16C (λ/10 rms)



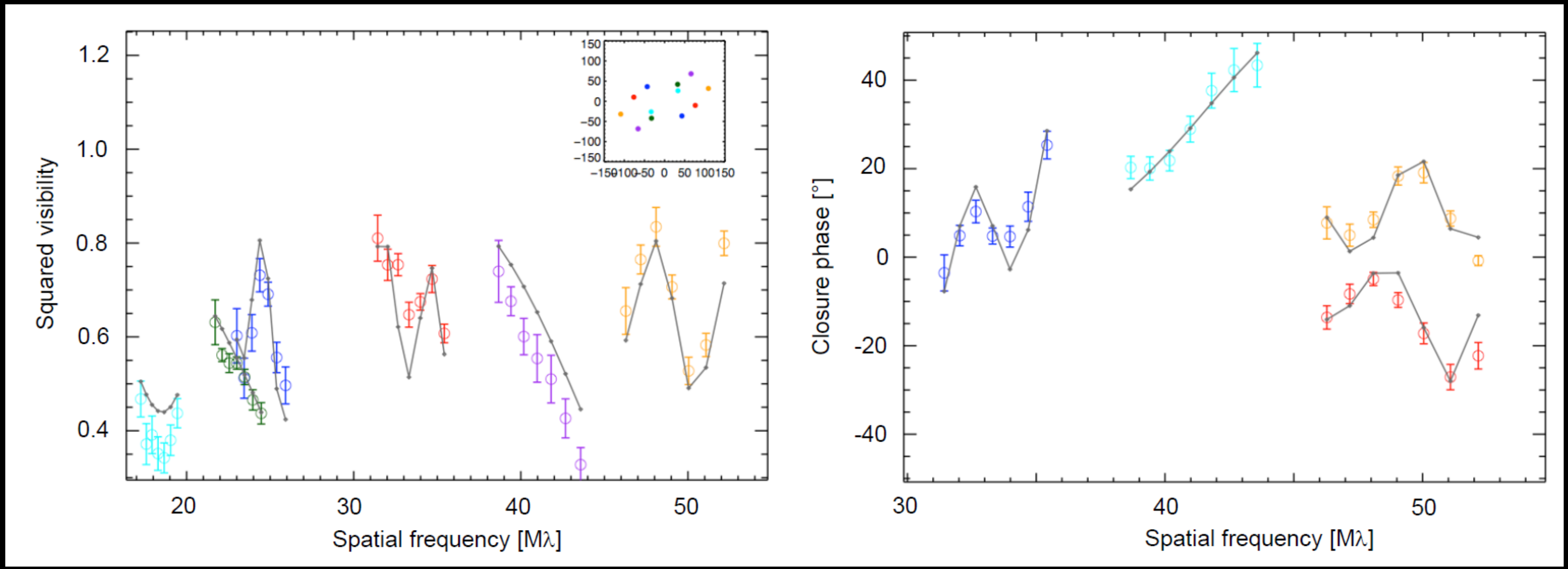


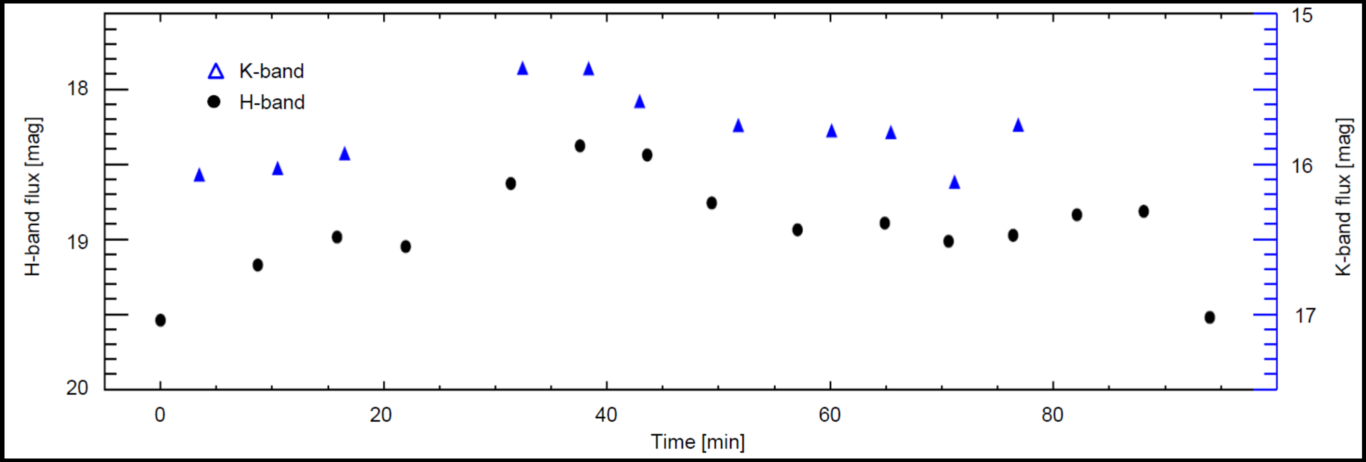


No stars brighter than mK = 17.1 mag near S2

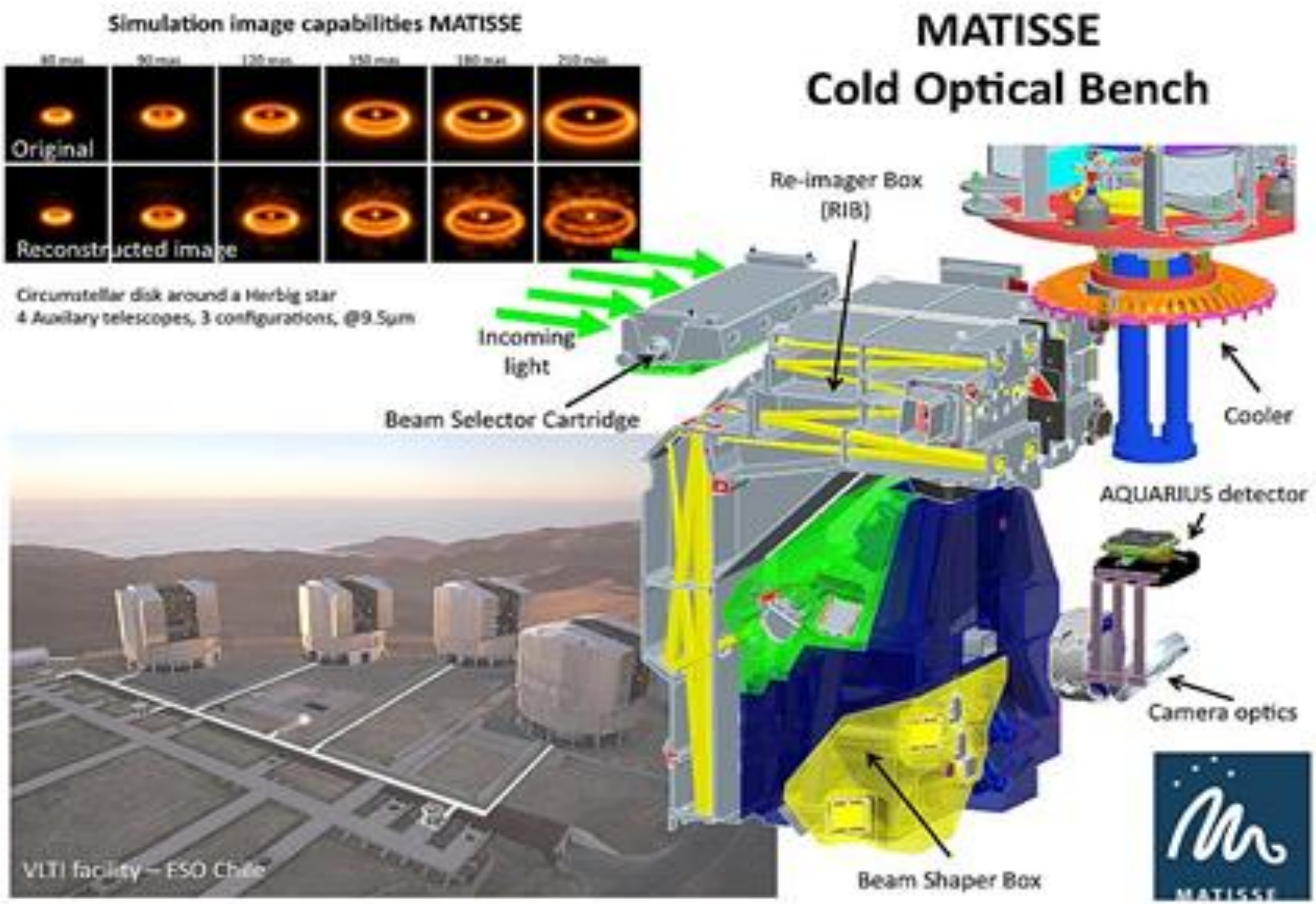


First detection of Sgr A* in infrared interferometry





[GRAVITY Collaboration – Abuter et al., A&A, 602, A94]

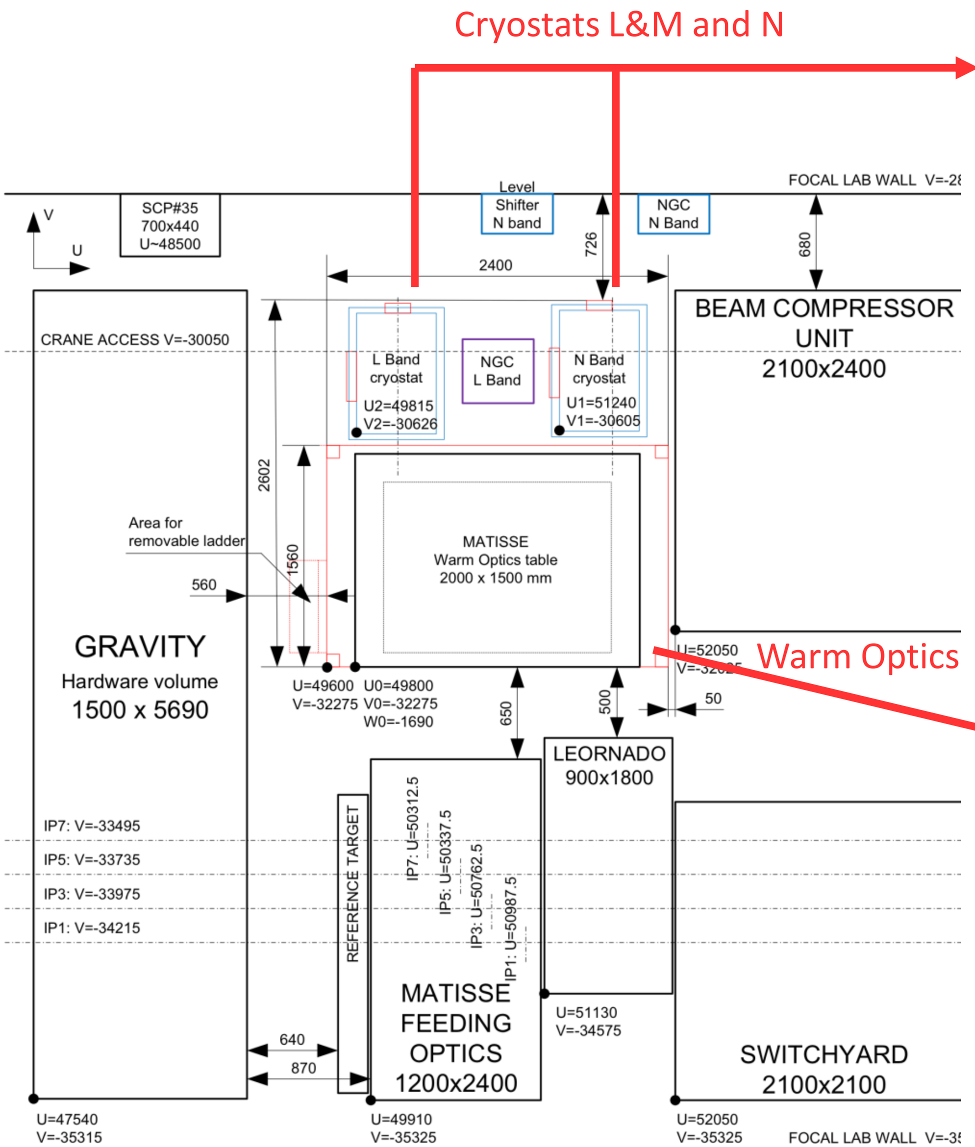


Simulation image capabilities MATISSE
Original
Reconstructed image
Circumstellar disk around a Herbig star
4 Auxilary telescopes, 3 configurations, @9.5µm
MATISSE
Cold Optical Bench
Re-imager Box
(RIB)
Incoming
light
Beam Selector Cartridge
Cooler
AQUARIUS detector
Camera optics
Beam Shaper Box
VLTI facility – ESO Chile

Consortium

	Observatoire Côte d'Azur Laboratoire Lagrange Université de Nice IPAG & CEA Saclay (France) *	Science – General concept & system – Management – Warm Optics – Control Command –Data reduction -Assembly, Integration, Tests - Commissioning
	Université de Leiden ** ASTRON (Netherlands)	Science – Cold optics – Interfaces
	Max Planck Institüt Heidelberg (Germany)	Science – Cryogenics – Electronics
	Max Planck Institüt Bonn (Germany)	Science – Detector – Image reconstruction
	Université Vienne (Austria) Université de Kiel (Germany)	Science
	European Southern Observatory (Germany)	Science- Detector – Infrastructure and VLTI logistics

MATISSE in the VLTI focal lab.



Observation of the inner protoplanetary disk regions

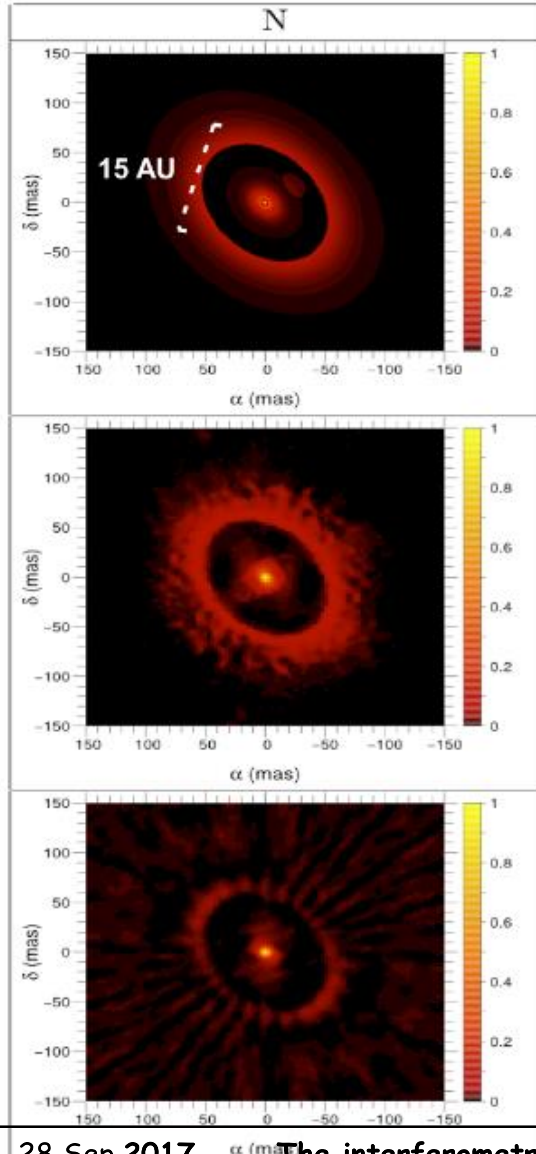
Analytical model of HD100546 disk + gap + clump

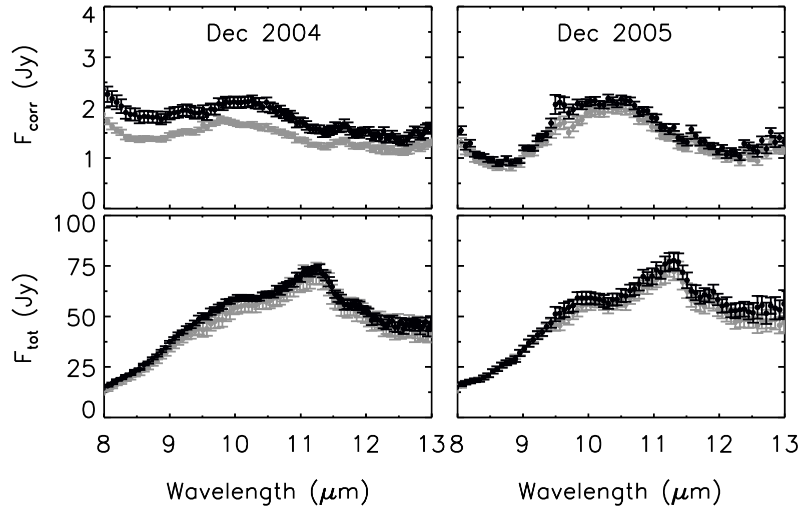
Reconstructed N band image (AT: 1.8m VLT telescope)

3 nights

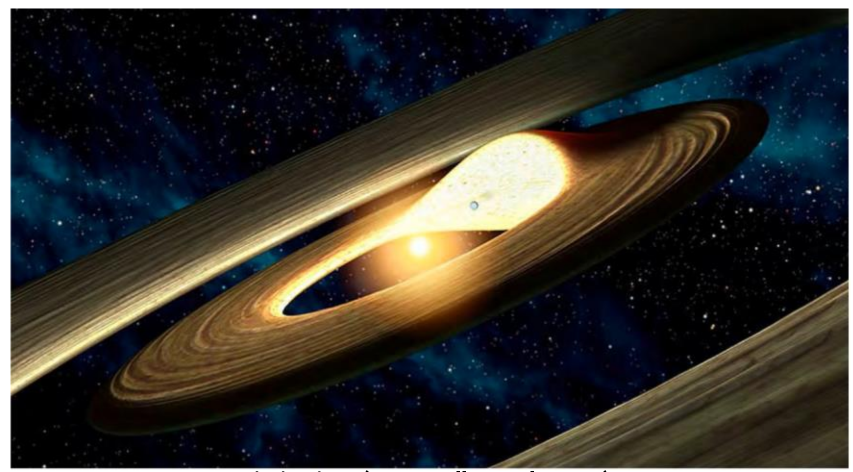
Reconstructed N band image (UT: 8m VLT telescope)

1 night





Panic et al. 2014



Artistic view (Muzerolle et al. 2009)

MATISSE – Current status

- PAE (Preliminary Acceptance Europe) from 20 Jun 2017 to 12 Sep: green light for the transport to Paranal
- Departure from Nice on 4&11 Oct 2017
- Arrival at Paranal: end of October
- 1st light around Feb. 2018
- Commissioning >Feb/Mar 2018

NSF

NOAO

Georgia State University

Observatoire de la CÔTE d'AZUR

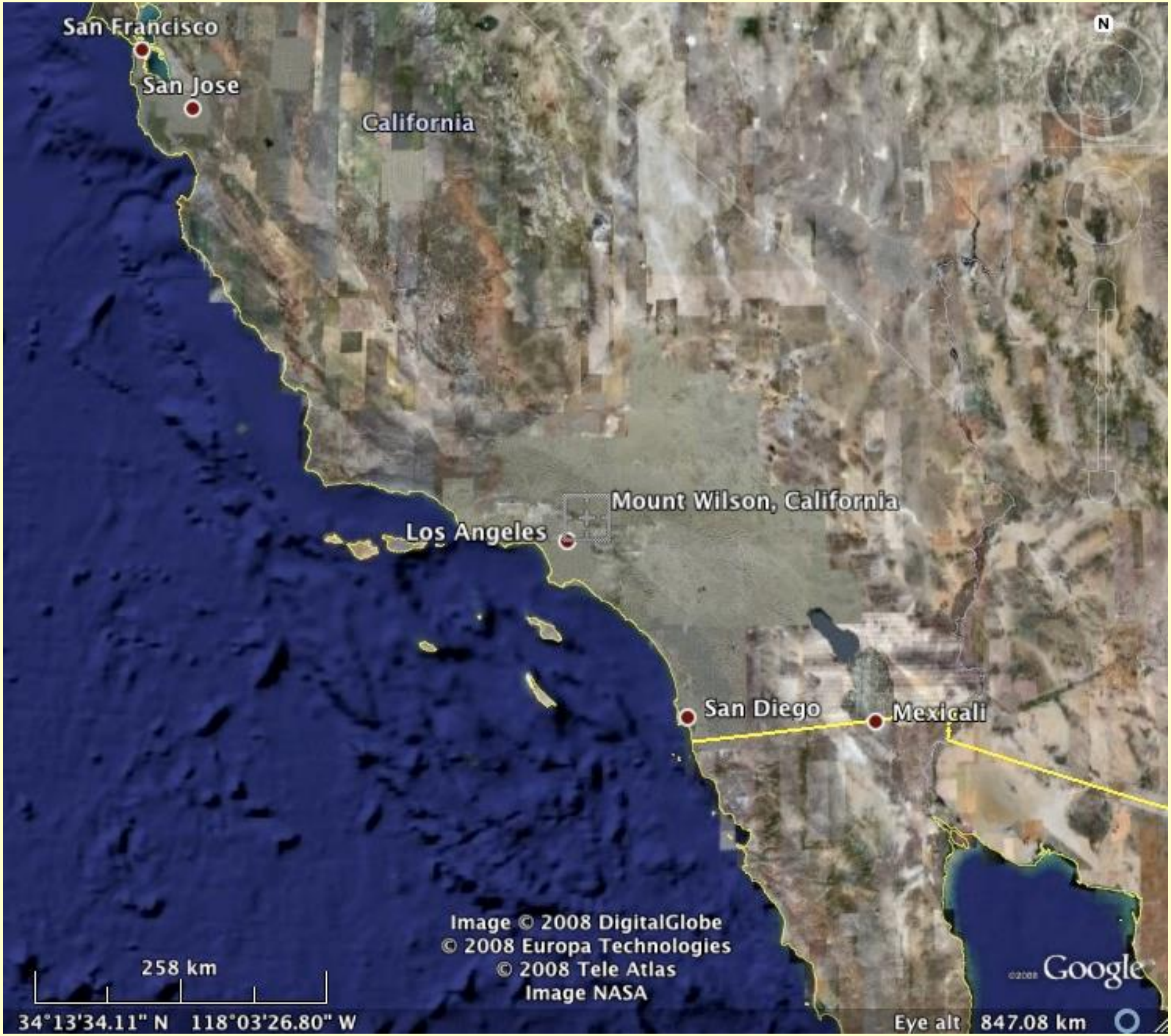
NExScI
NASA Exoplanet Science Institute

l'Observatoire de Paris | LESIA

SYDNEY UNIVERSITY STELLAR INTERFEROMETER
SUSI
AUSTRALIA

THE UNIVERSITY OF MICHIGAN
ARTES · SCIENTIA · VERITAS
1817

The CHARA Collaboration


San Francisco
San Jose
California
Mount Wilson, California
Los Angeles
San Diego
Mexicali
Image © 2008 DigitalGlobe
© 2008 Europa Technologies
© 2008 Tele Atlas
Image NASA
258 km
34°13'34.11" N 118°03'26.80" W
Eye alt 847.08 km
Google

First science publication….. 5 years later!

FIRST RESULTS FROM THE CHARA ARRAY. I. AN INTERFEROMETRIC AND SPECTROSCOPIC STUDY OF THE FAST ROTATOR α LEONIS (REGULUS)

H. A. McAlister, T. A. ten Brummelaar, D. R. Gies,[1] W. Huang,[1] W. G. Bagnuolo, Jr.,
M. A. Shure, J. Sturmann, L. Sturmann, N. H. Turner, S. F. Taylor,
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erika@chara.gsu.edu, ogden@chara.gsu.edu

S. T. Ridgway
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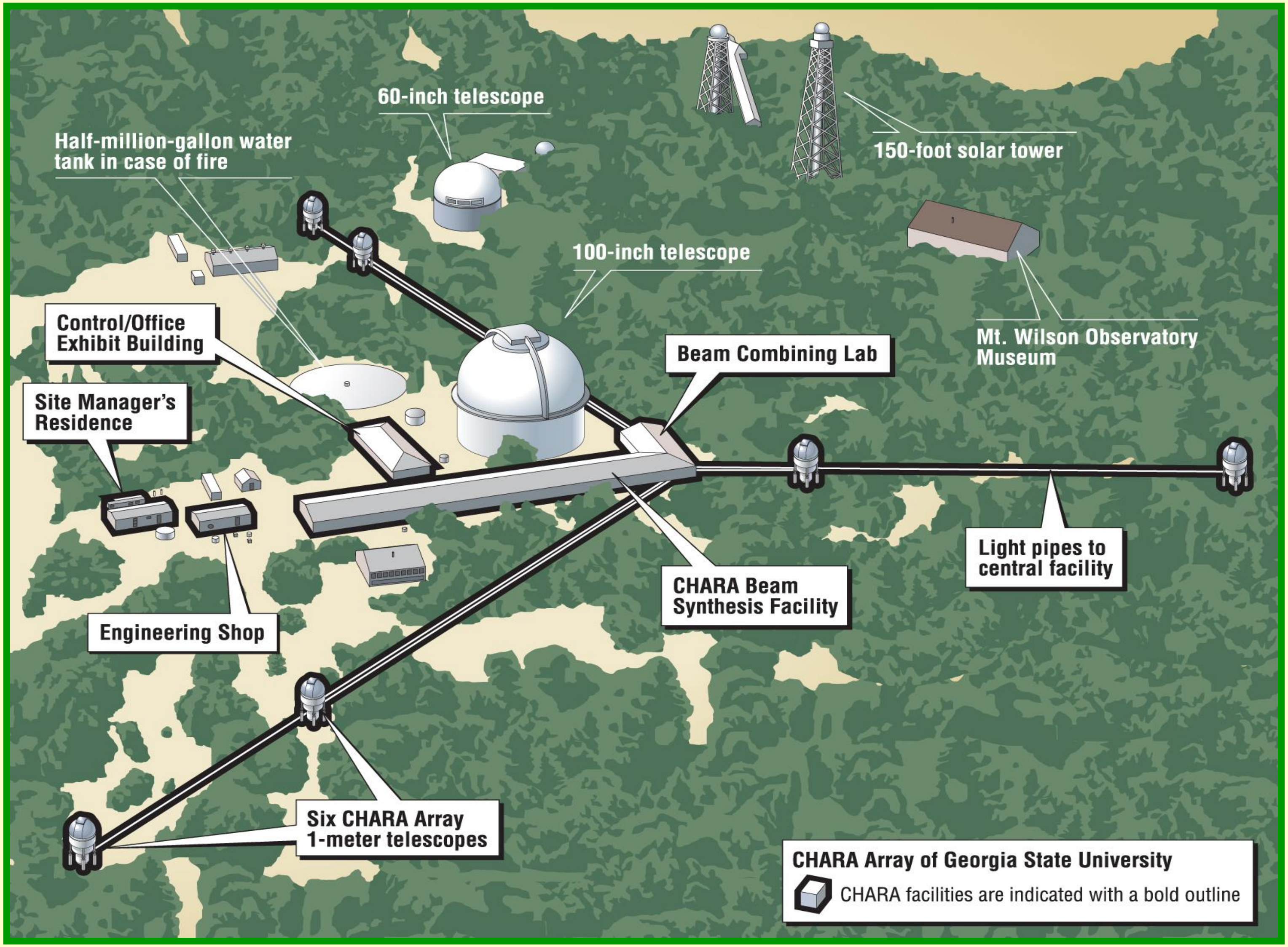
Received 2004 November 15; accepted 2005 January 10

ABSTRACT

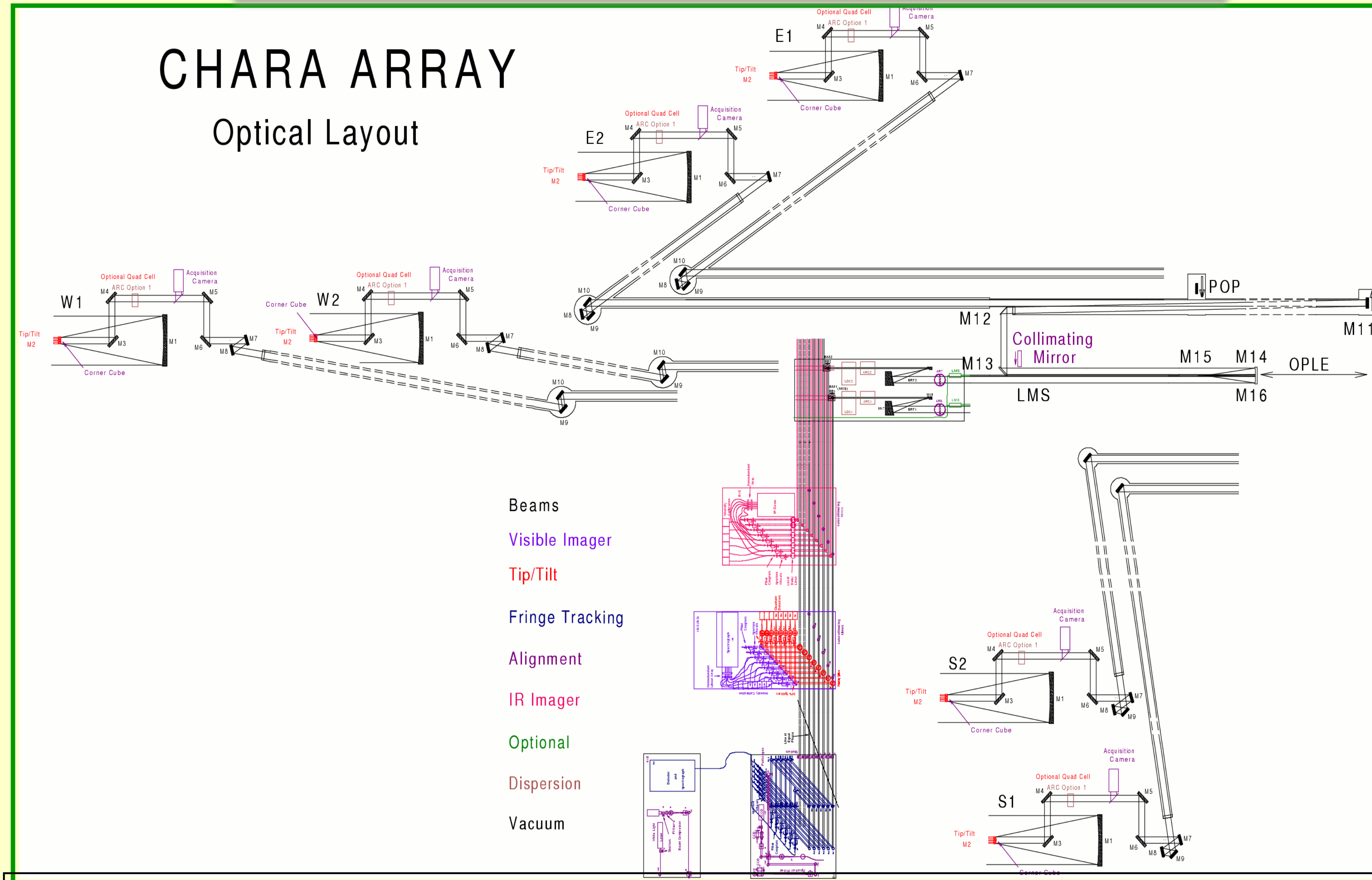
We report on *K*-band interferometric observations of the bright, rapidly rotating star Regulus (type B7 V) made with the CHARA Array on Mount Wilson, California. Through a combination of interferometric and spectroscopic measurements, we have determined for Regulus the equatorial and polar diameters and temperatures, the rotational velocity and period, the inclination and position angle of the spin axis, and the gravity darkening coefficient. These first results from the CHARA Array provide the first interferometric measurement of gravity darkening in a rapidly rotating star and represent the first detection of gravity darkening in a star that is not a member of an eclipsing binary system.

Subject headings: infrared: stars — stars: fundamental parameters — stars: individual (α Leonis, Regulus) — stars: rotation — techniques: interferometric

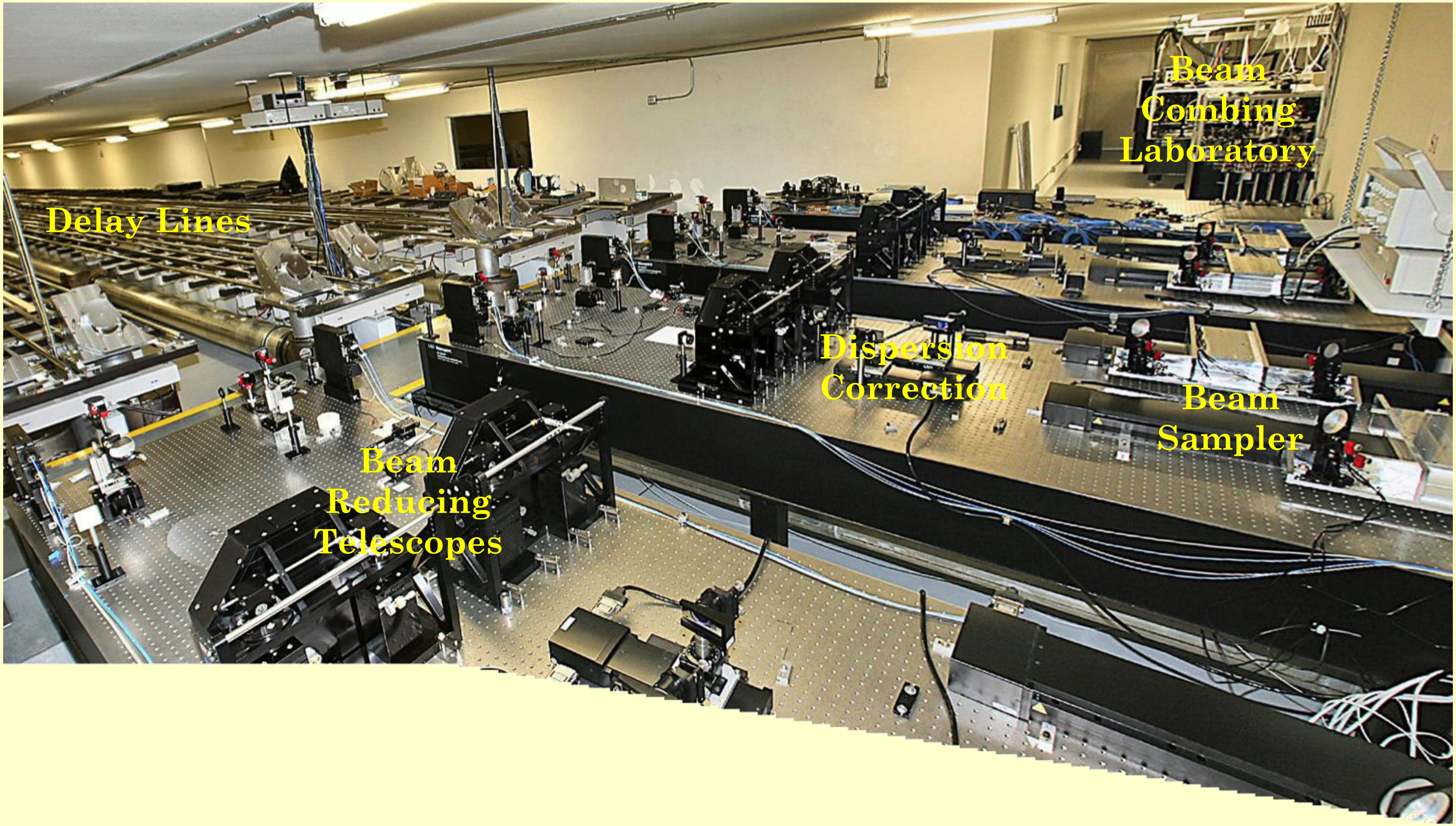
Layout of the CHARA Array



Overall Optical Layout

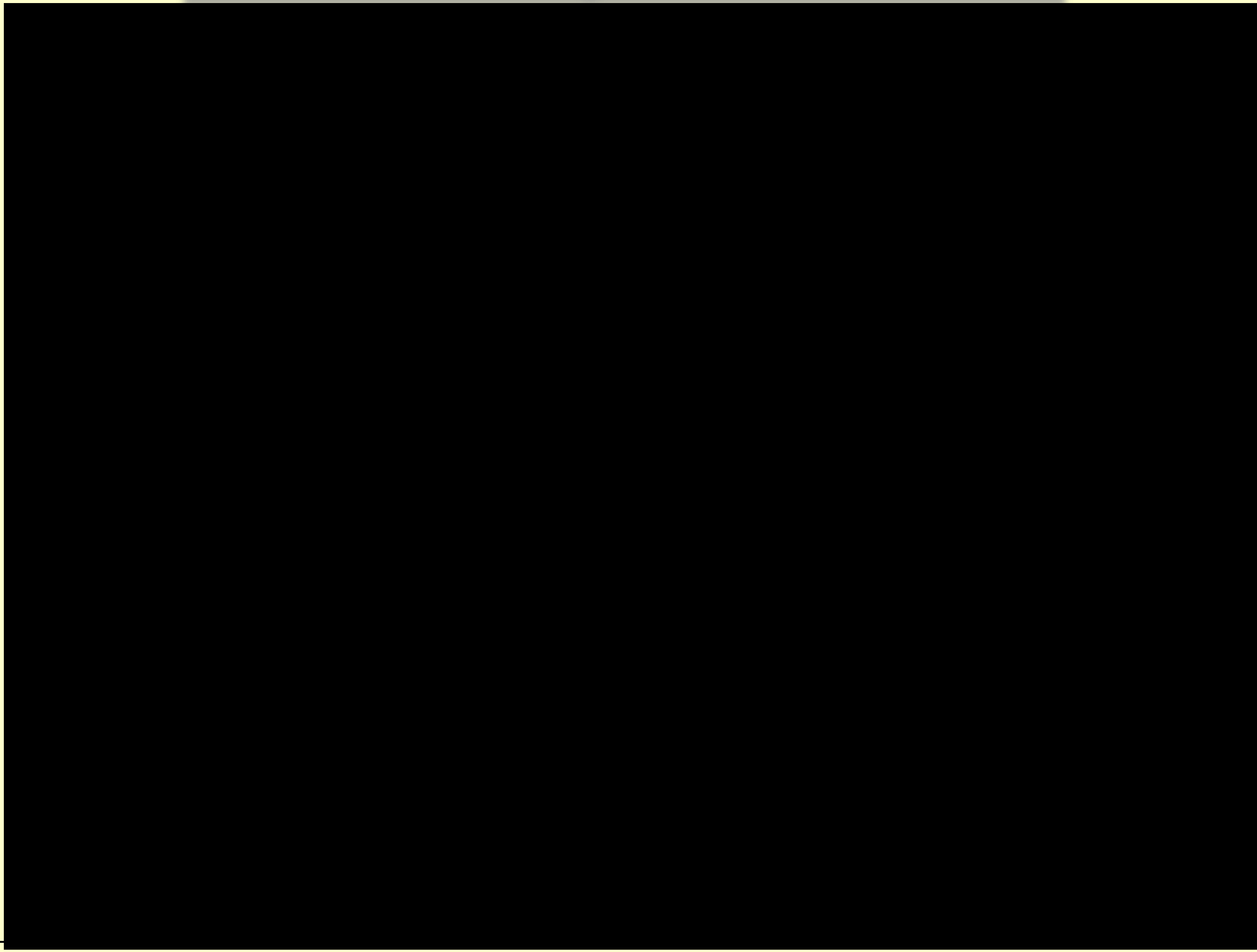


Optics Laboratory



The 30 second CHARA tour.

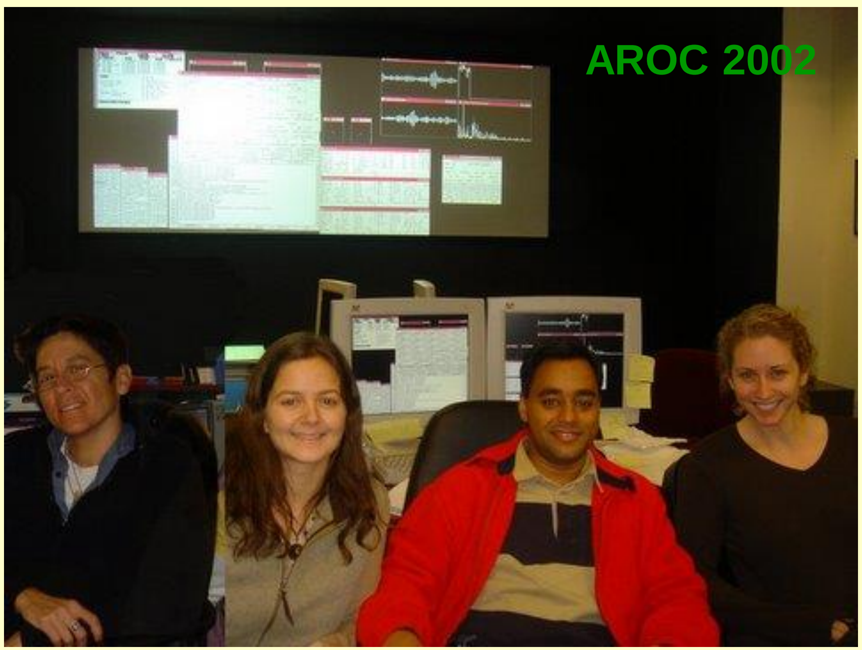
Delay Lines



"Beam Combiners are us"

- CHARA CLASSIC – 2 way open air J, H & K
- CHARA CLIMB – 2x3 way open air J, H & K
- FLUOR – 2 way fiber based K band
- MIRC – 6 way fiber based imager J, H & K
- VEGA – 4 way open air V,R,I R=30000
- PAVO – 3 way aperture plane V,R,I
- CHAMP – 6 beam fringe tracker J, H & K
- More to come... (CIMB++, MIRCx, MYSTIC, FRIEND++…..)

ROCMI 2006

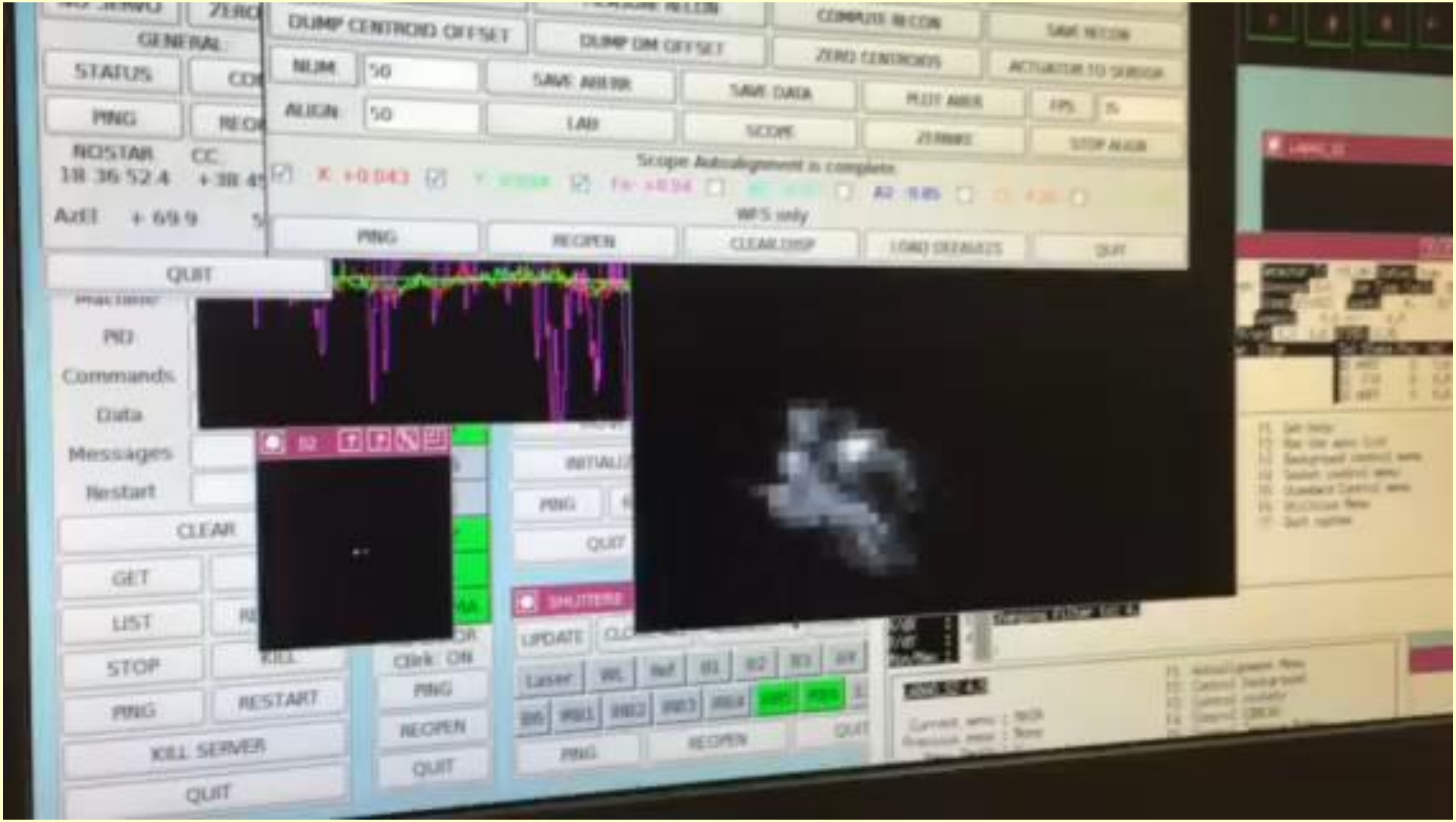


The CHARA Adaptive Optics Program

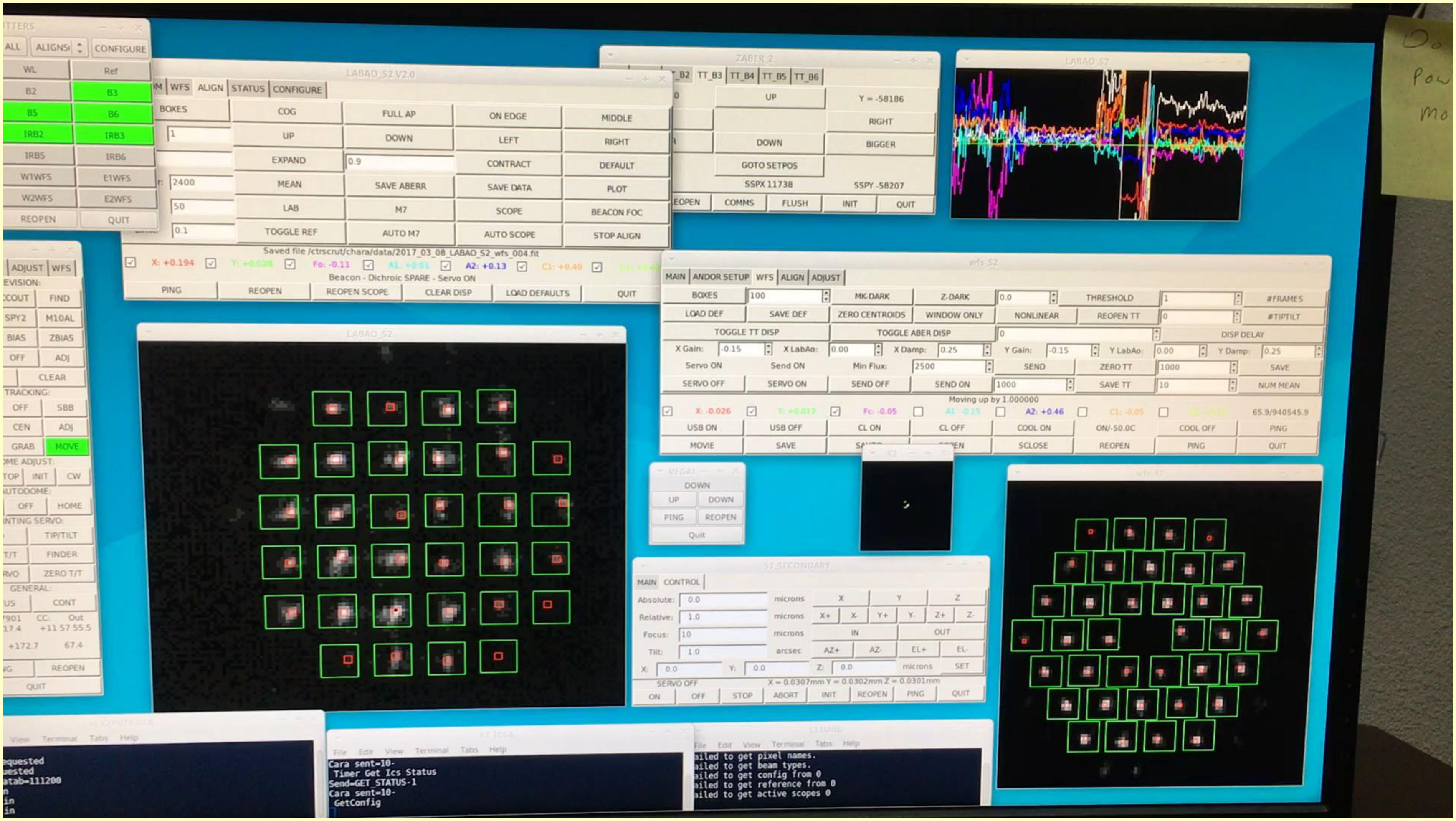
- The CHARA Adaptive Optics Program is broken into 2 Phases.
- This is purely an artifact of funding realities.
- Phase I (NSF/ATI), which includes Wave Front Sensors for each telescope and non-common-path AO systems for the laboratory, was funded in 2010 and is now nearing completion.
- Phase II (NSF/MRI), which includes deformable mirrors for each telescope, began in mid-2015.

The program is fully funded.

CHARA-AO Program First On Sky Test



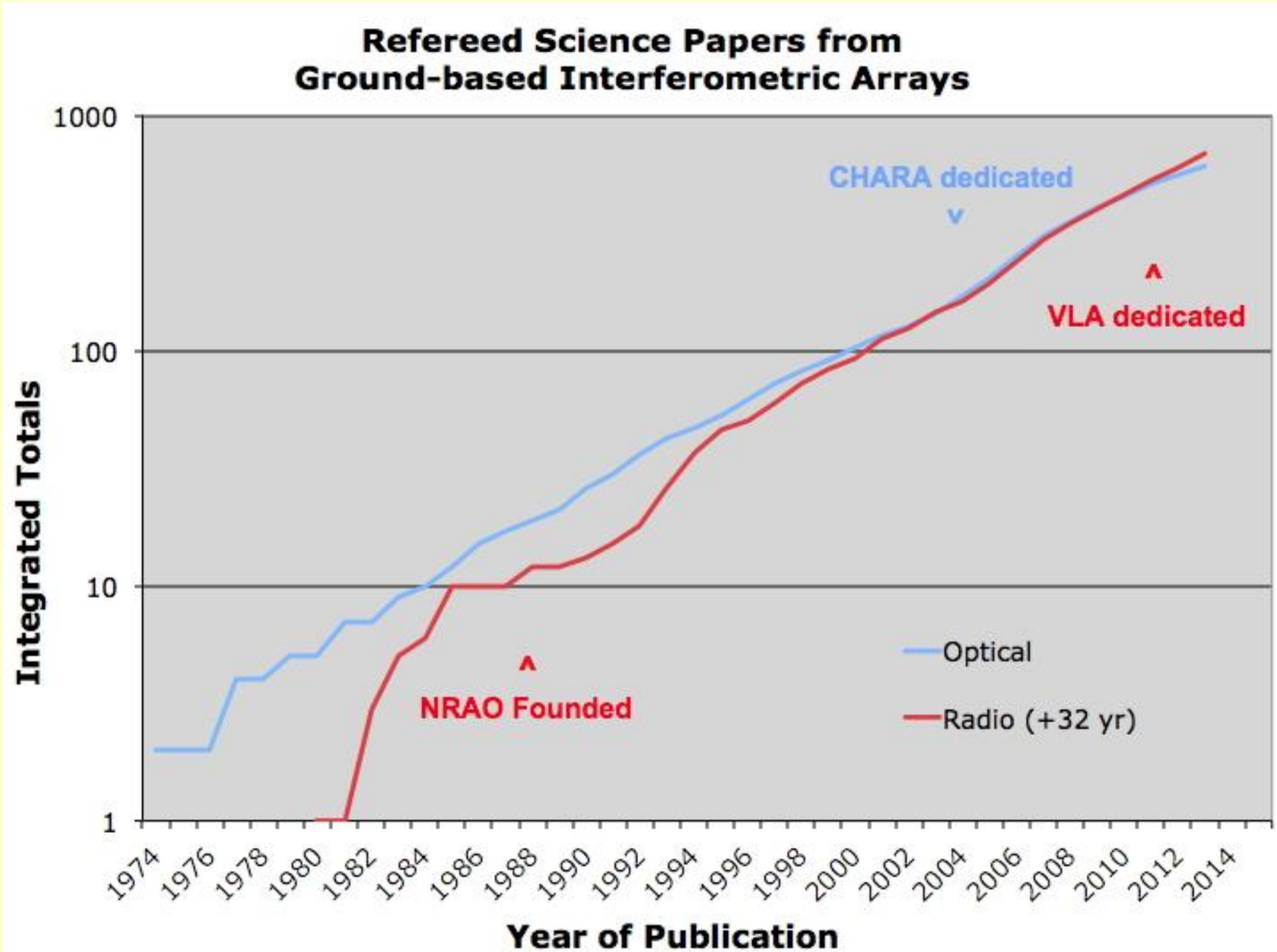
The CHARA Array Adaptive Optics Program



Enabling Milliarcsecond Astrophysics: Open access for the CHARA Array

- The NSF/MSIP program is a response to the previous decadal report that stated that the NSF needs to direct more funding to mid-scale programs, including new instruments, access to existing instruments, and access to existing data archives.
- Our proposal has been funded for $4M over 5 years to provide 50-75 nights per year of open access to the CHARA Array through the NOAO TAC process.

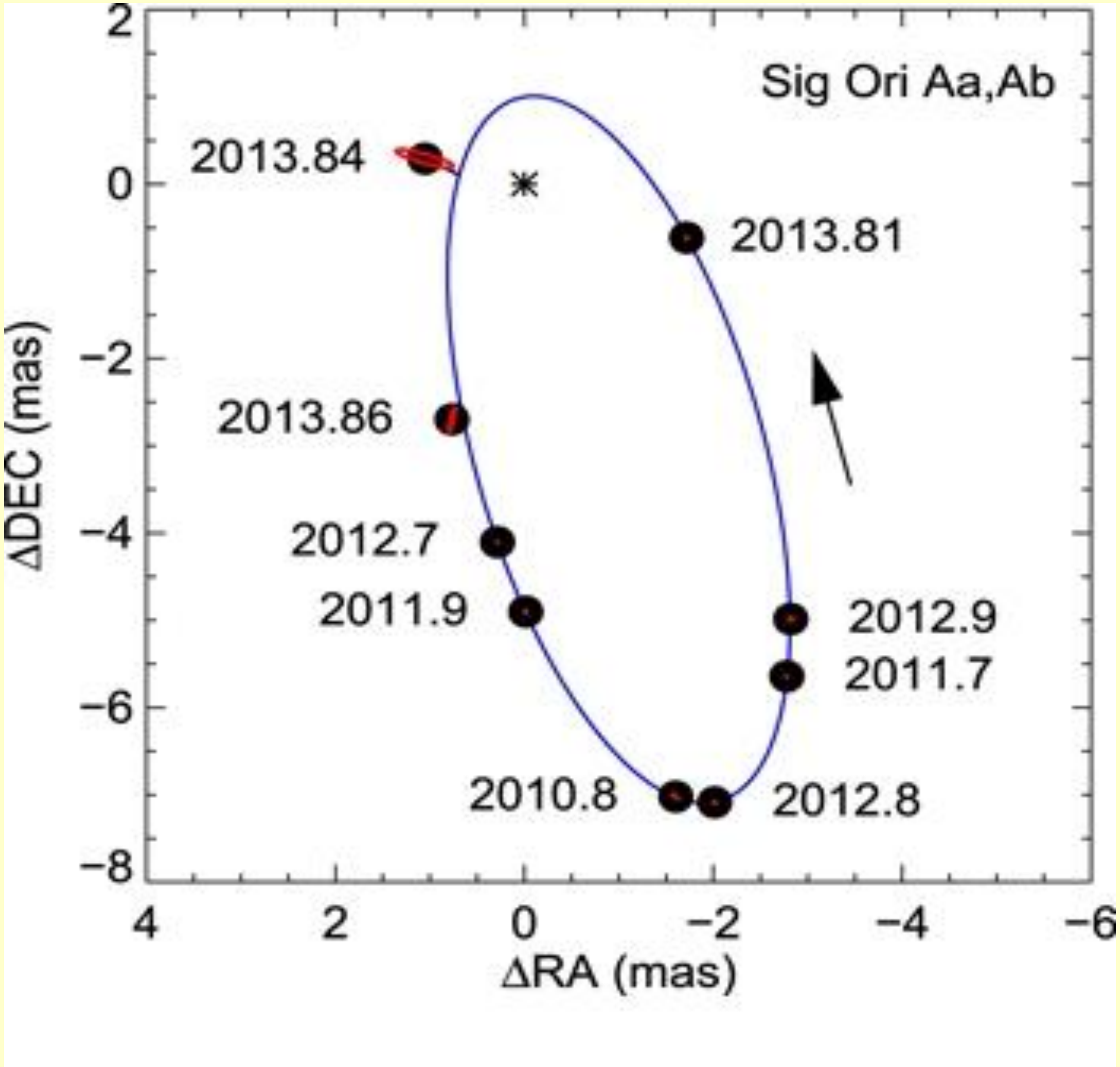
Proposal focus A – "Optical Interferometry is not as obscure or as difficult as many believe."



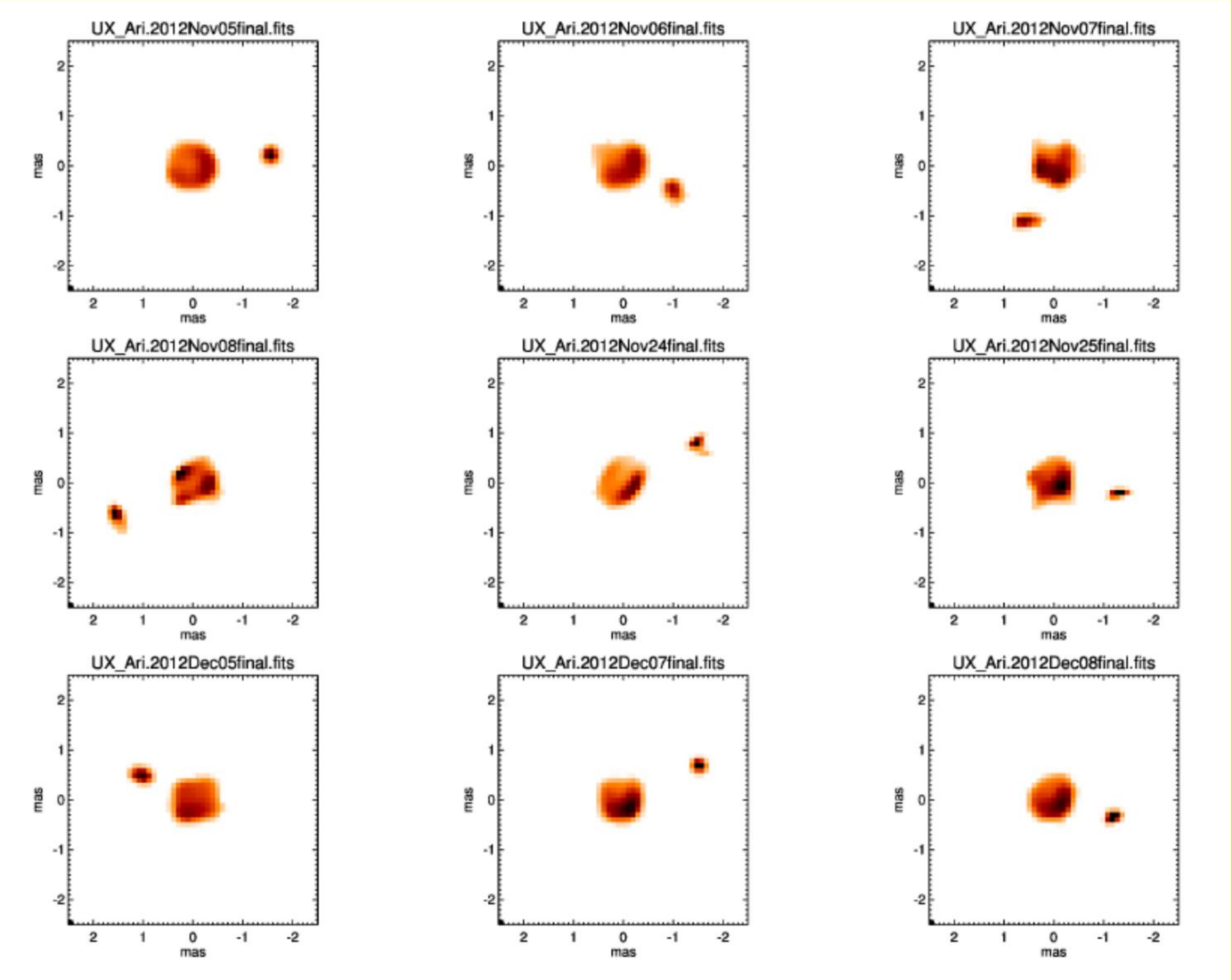
Stellar Diameters – Our bread and butter science

- The fundamental properties of stars are not really very well known, and certainly poorly measured until quite recently.
- Basic parameters like size, temperature and luminosity can now be directly measured for a large range of stellar types.
- Imaging stellar surfaces is now routine.

Orbit of sigma Ori (Schaefer et al.)

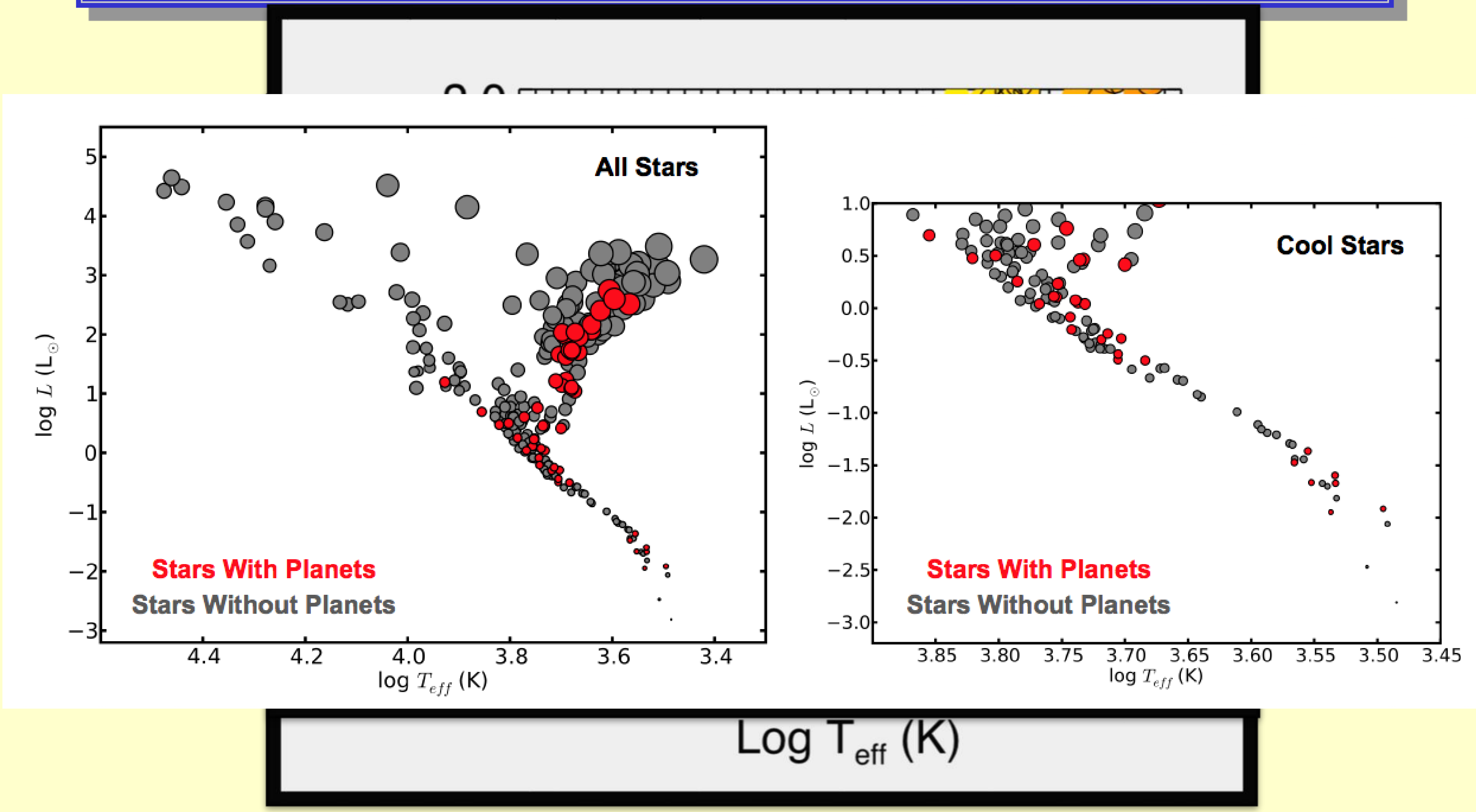


The Orbit of UX Arietis – Hummel et. al.



An Interferometric HR Diagram

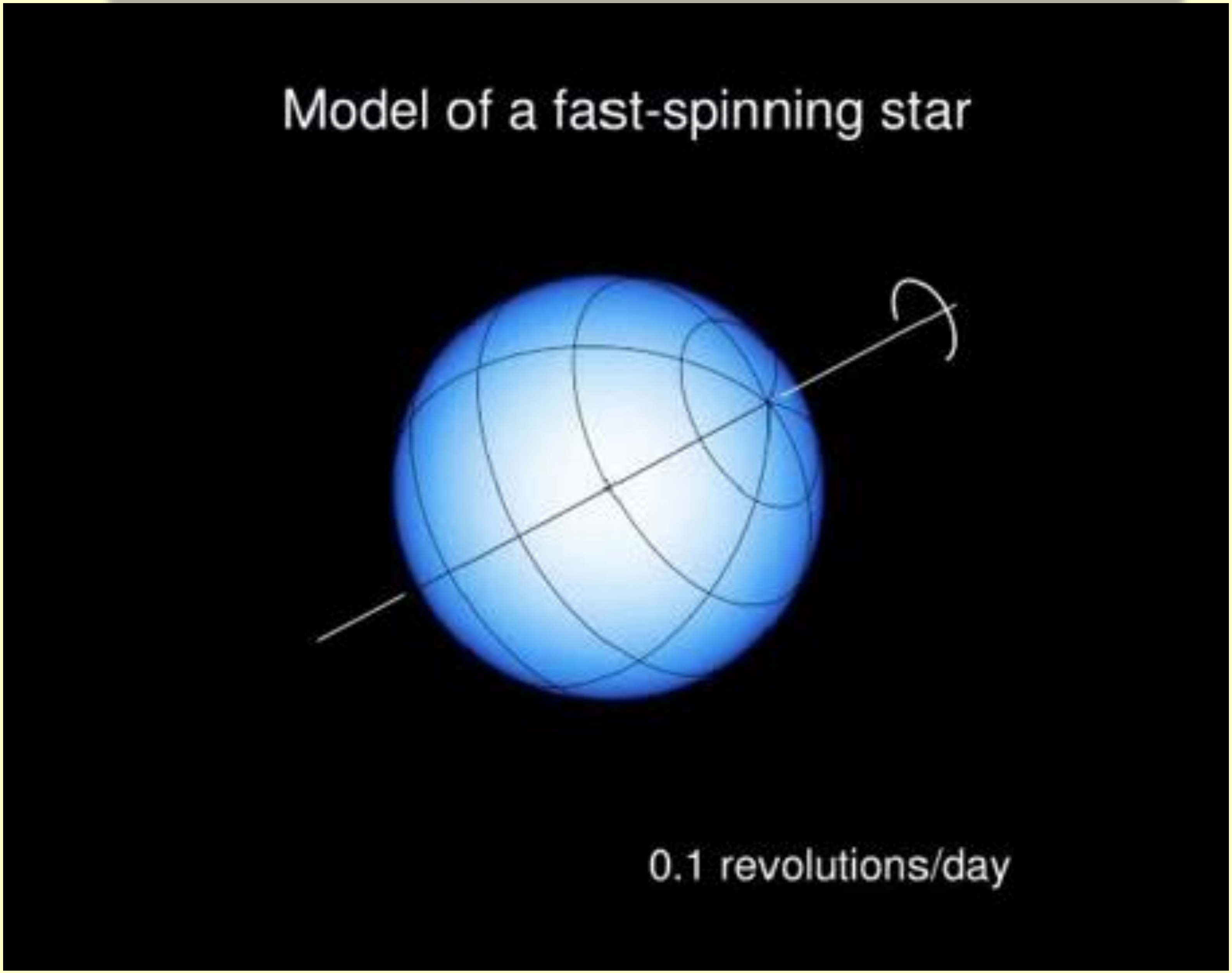
Compliments of Tabetha Boyajian and Kaspar von Braun



More recent data showing the stars known to have planets. / **Measurements are all from the CHARA Array.**

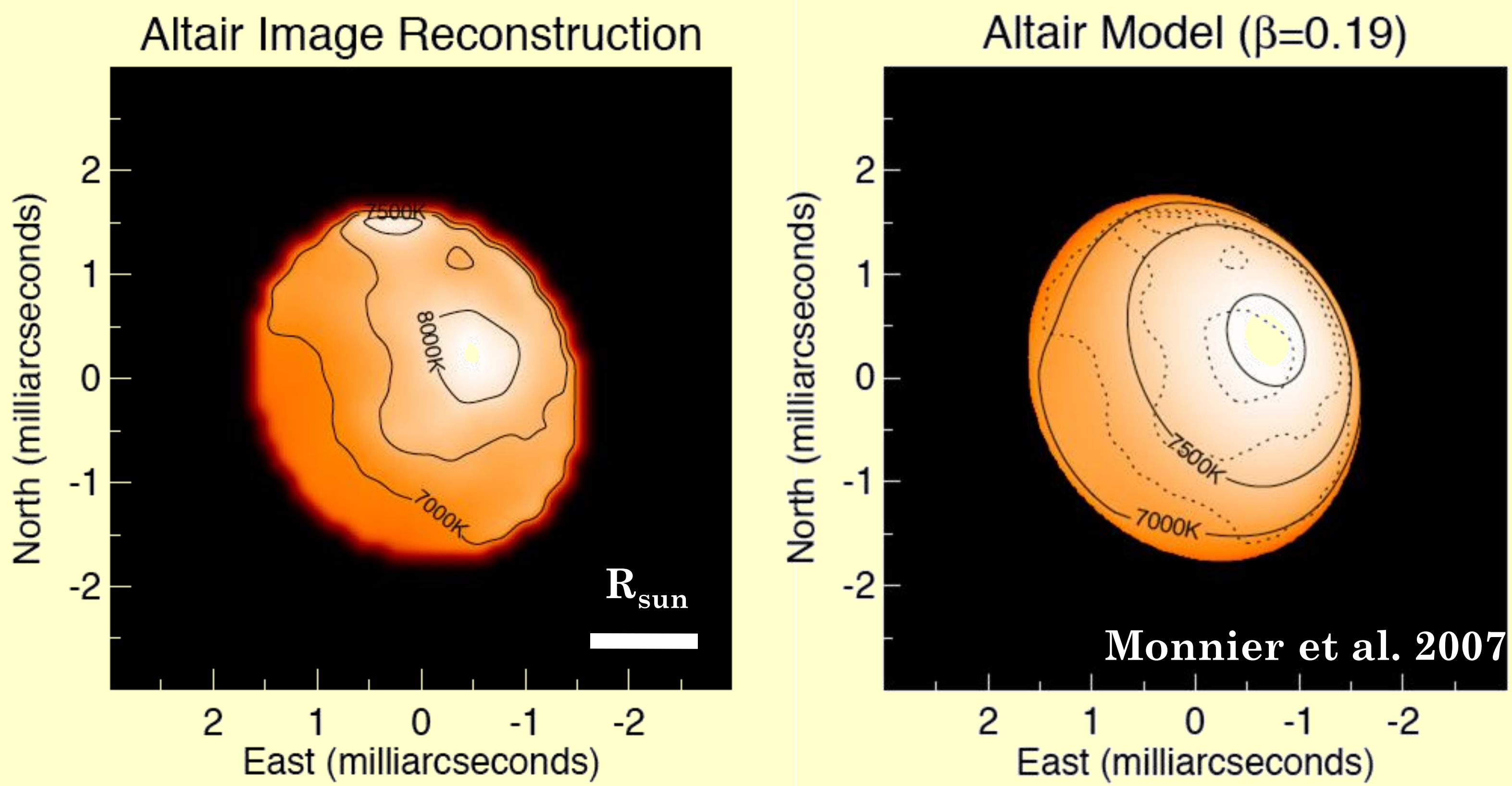
These data from 2009/2014

Rotating Stars Are Oblate:

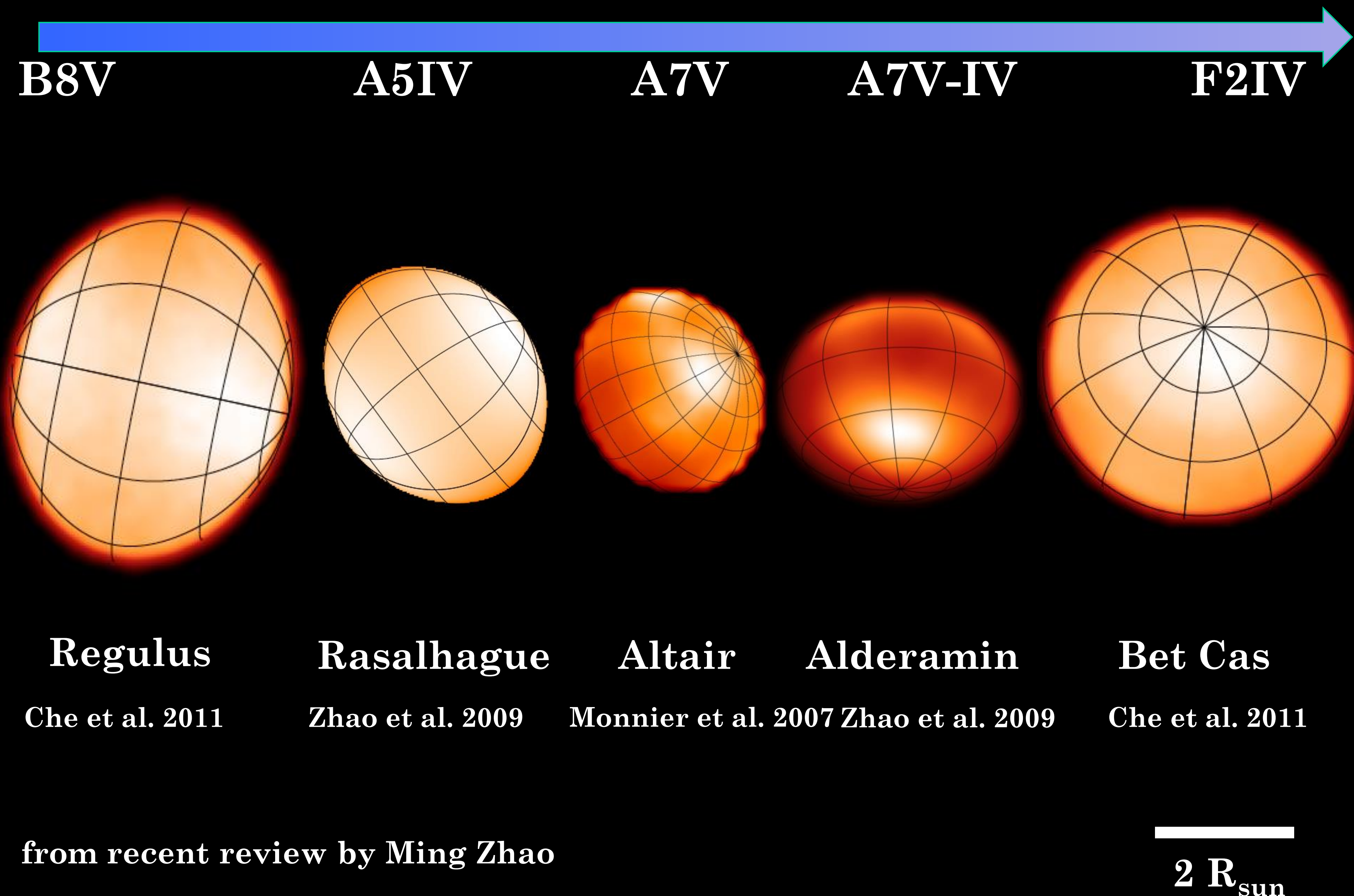


First image of a main-sequence star
(besides the Sun…)

- Altair (a Aql, V=0.7)
  - Nearby hot star (d=5.1pc, SType A7V, T=7850 K)
  - Rapidly rotating (v sin i = 240 km/s, ~90% breakup)



MIRC Observations of Rapid Rotators



from recent review by Ming Zhao

Imaging spots is hard because the dynamic range is large.

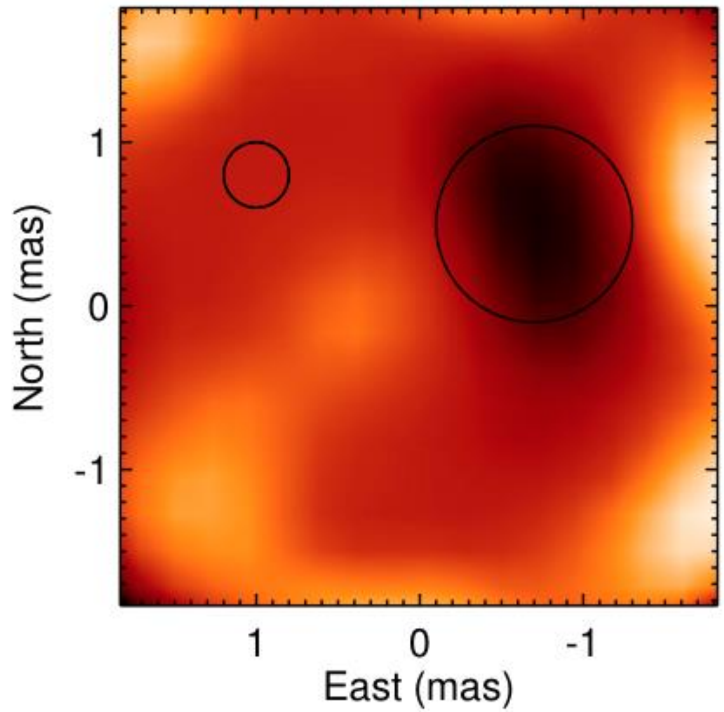
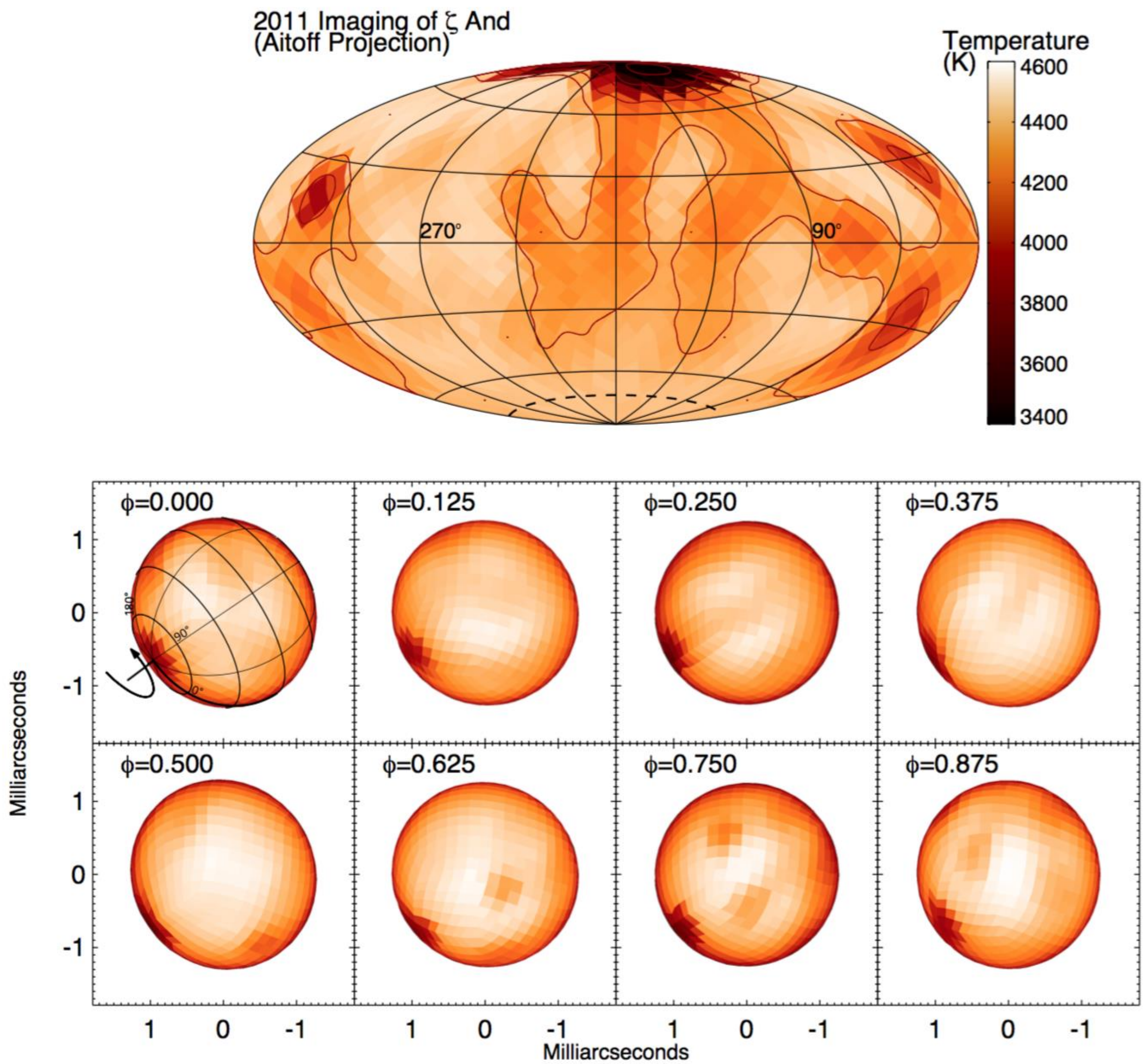


Figure 10. diameters e ... ngular

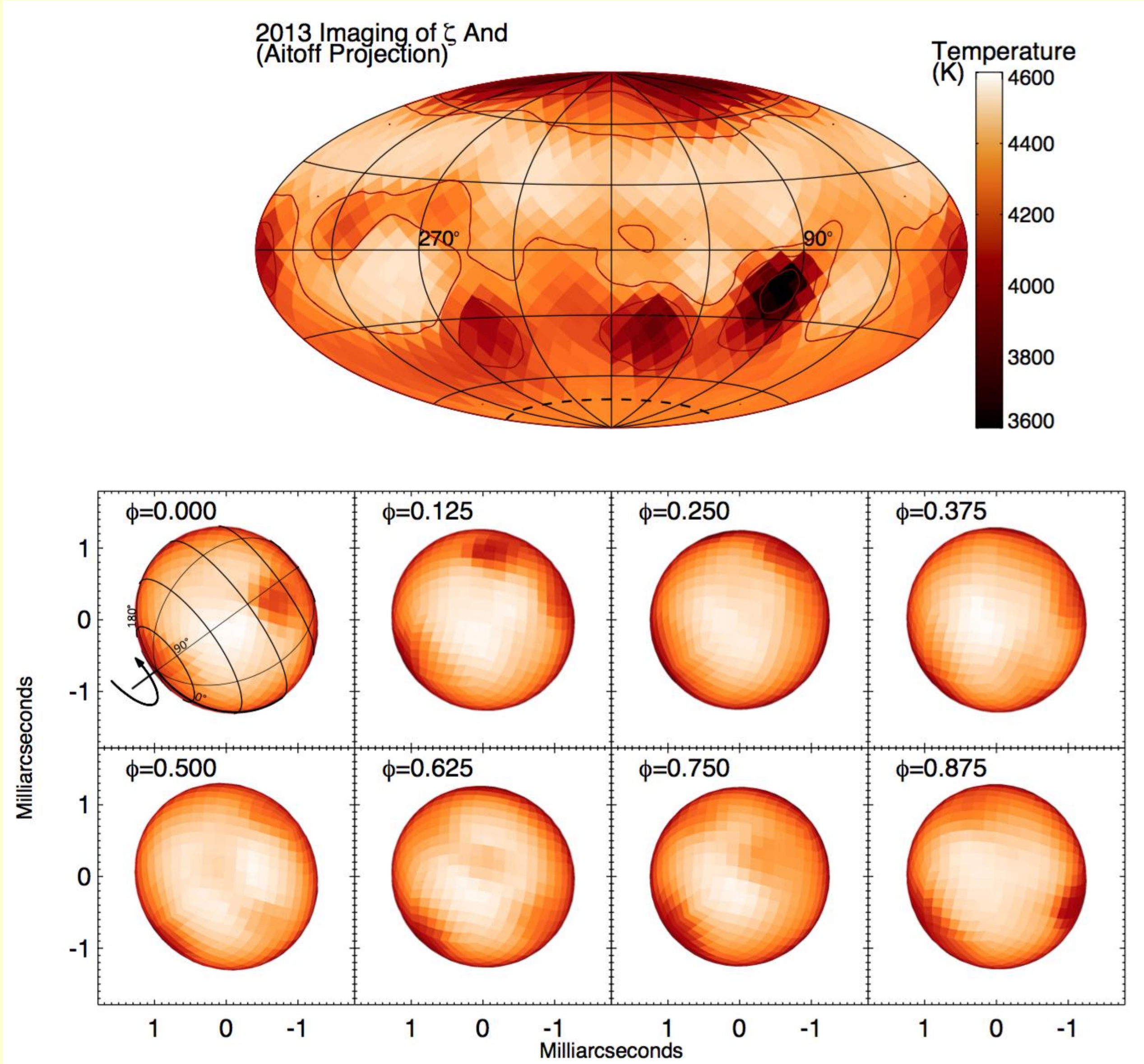
FIG. 2.— Shown is a closeup of the SQUEEZE reconstruction for the Sep 2^{th}, 2011 data near an apparent starspot. The black circle on the right shows the aperture used to extract starspot properties from reconstructed image. The black circle on the left shows the aperture over the "quiet" photosphere. The "quiet" photosphere is defined as a part of the stellar surface devoid of flux gradients. The size of the aperture is identical to the minimum achievable angular resolution.

Parks et al. 2015

Spotted K giant ζ Andromeda (Roettenbacher et al. 2015)

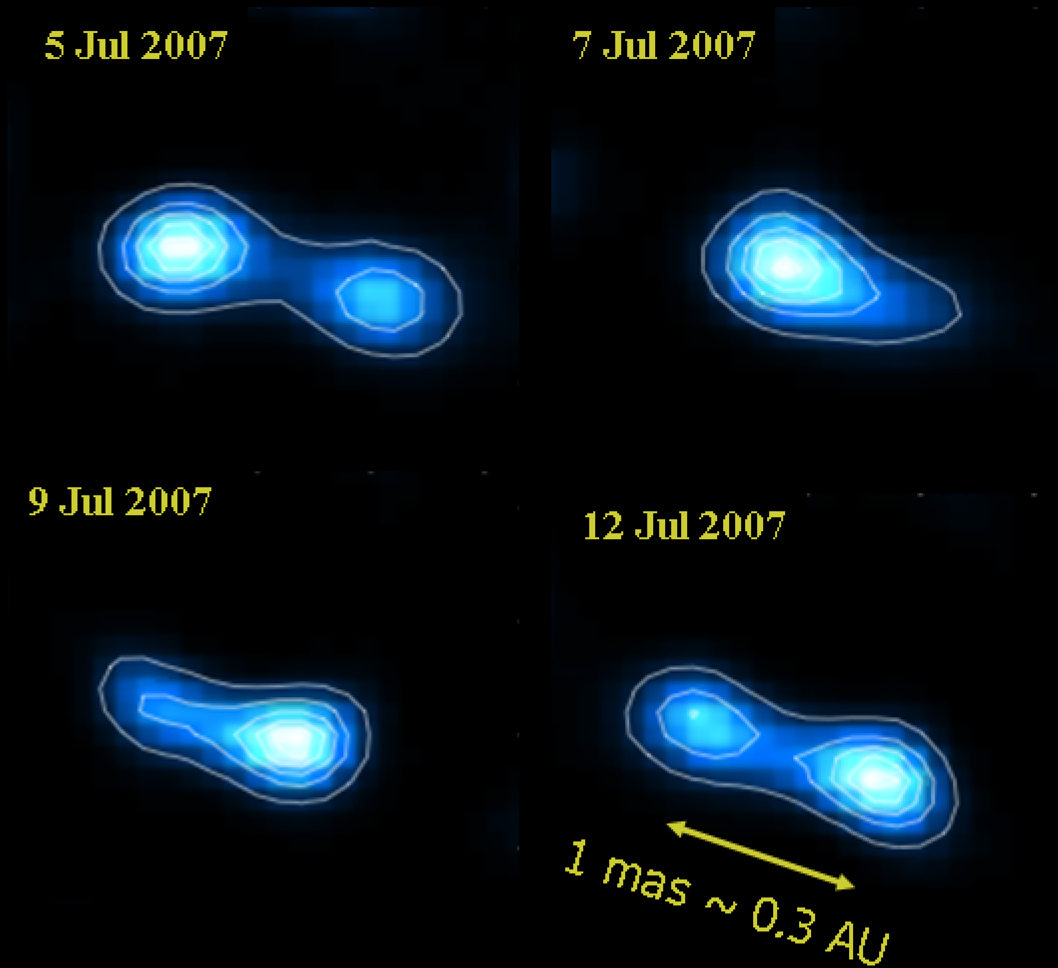


Spotted K giant ζ Andromeda (Roettenbacher et al. 2015)

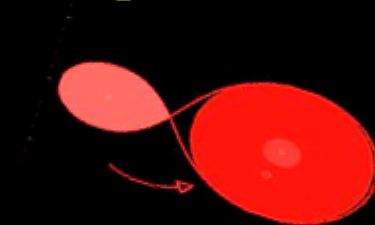


βLyrae – First Imagery: 4-frame movie

Zhao et al. ***Science*** *2007.*

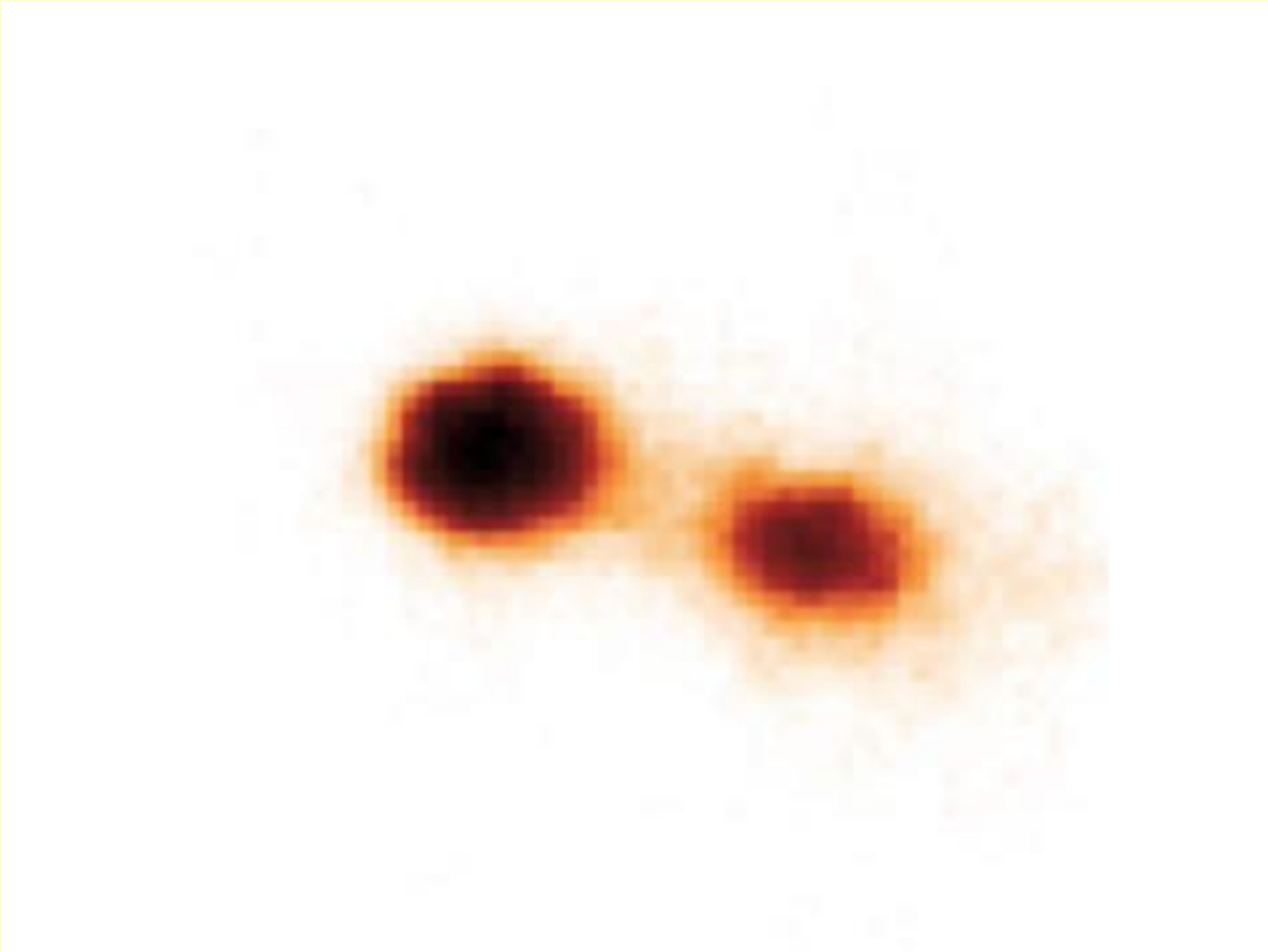


Four images are consistent with model and show hints of mass exchange.

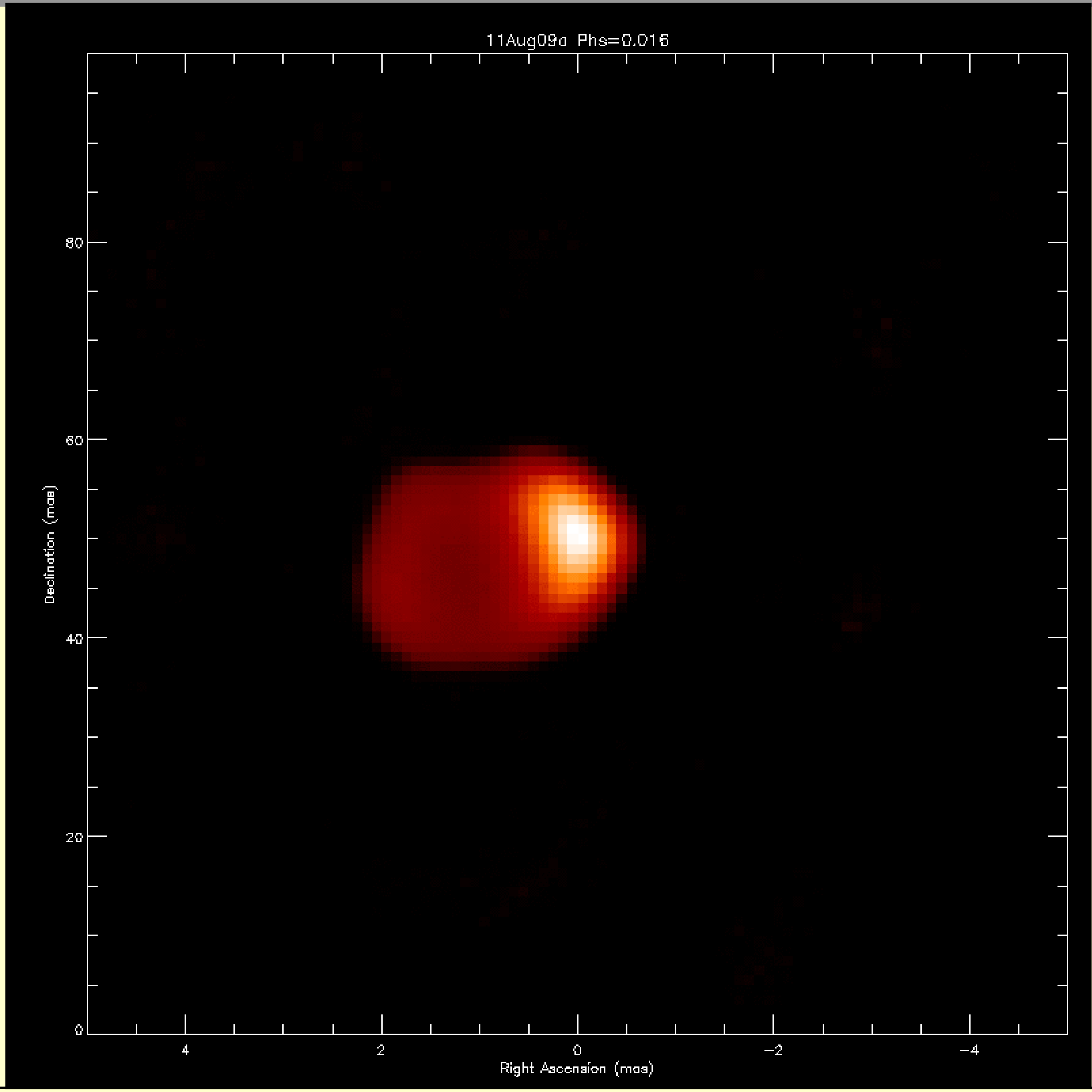


Model of
Linnell *et al.*
1988

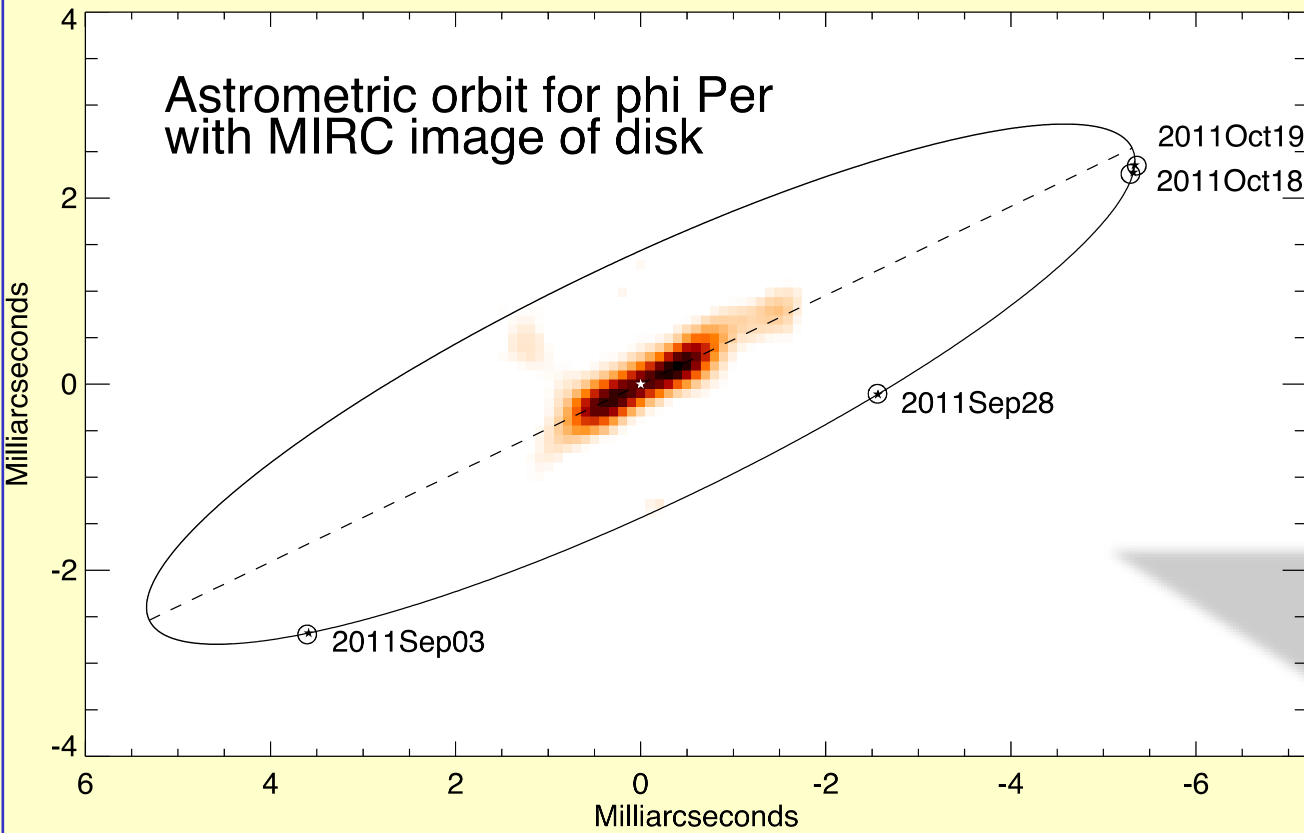
β Lyrae – The Movie

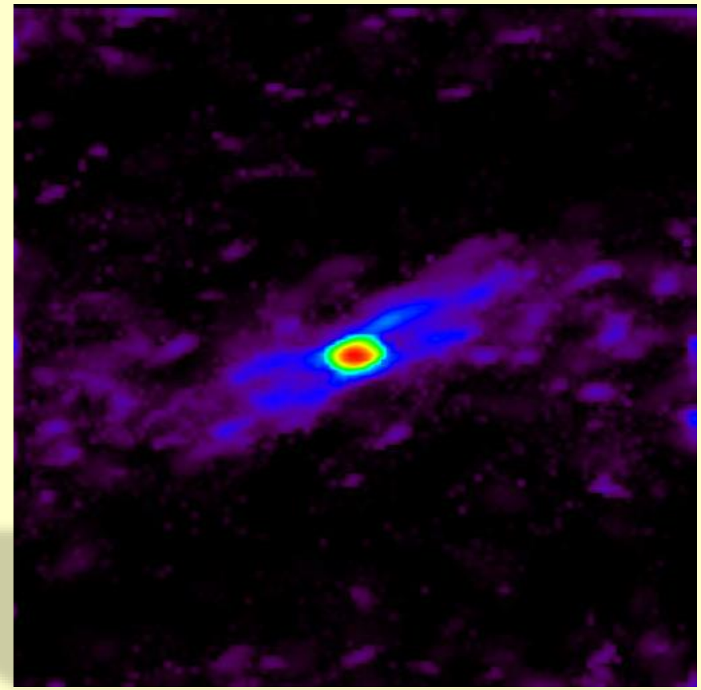


Algol the Movie: Baron et al 2011.



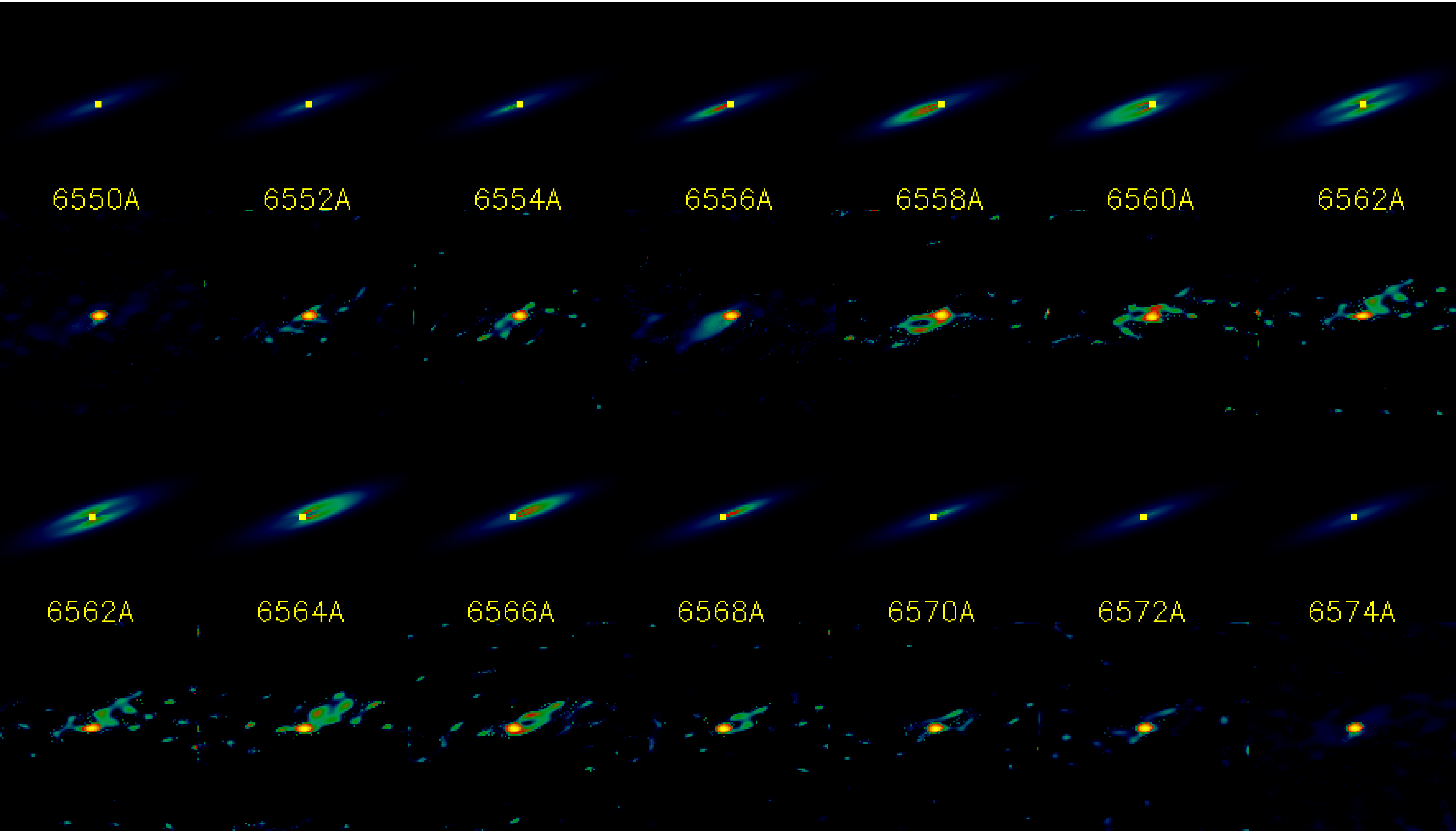
Imaging a Be Star disk and the orbit its faint companion



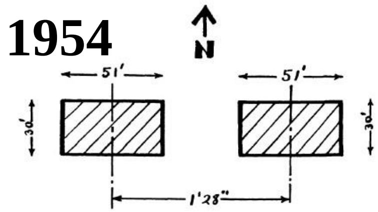


VEGA 4T

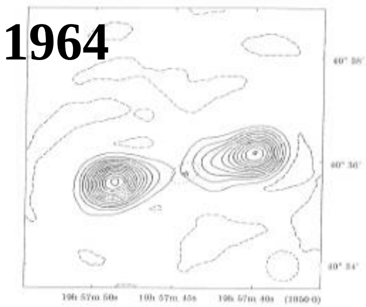
And even more … spectral imaging



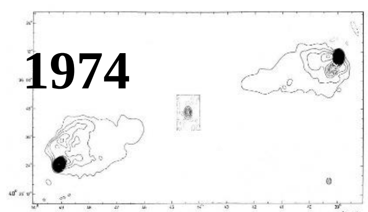
La radio source Cygnus-A au cours du



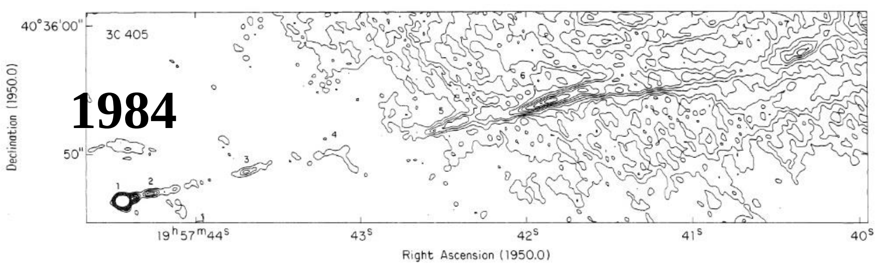
Jennisson et al., 1954



Ryle et al., 1964



Hargrave and Ryle 1974



Perley et al., 1984

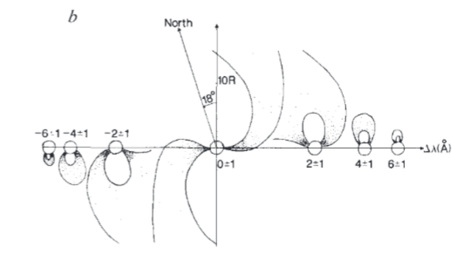
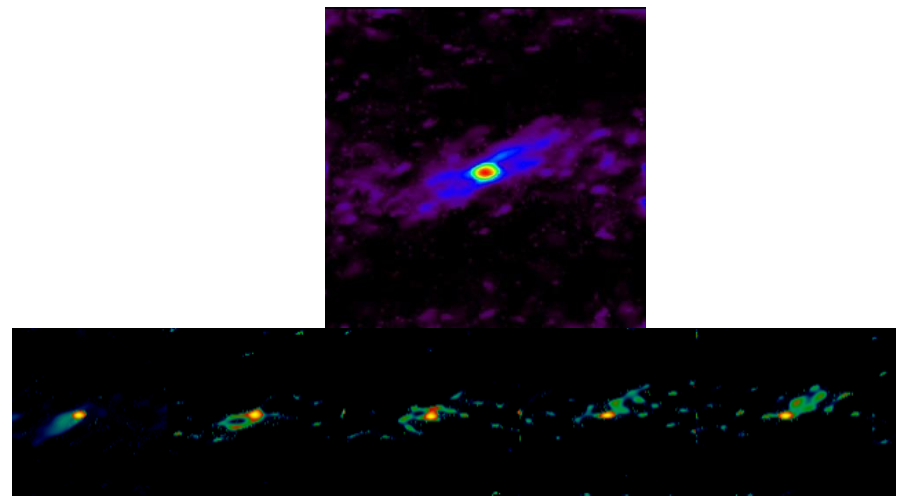


FIG. 2 The rotating hydrogen disk of γ-Cas, according to the model of

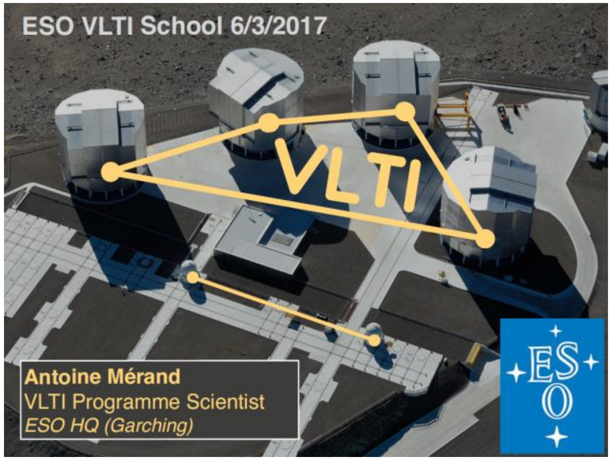
γ Cas, GI2T 1989



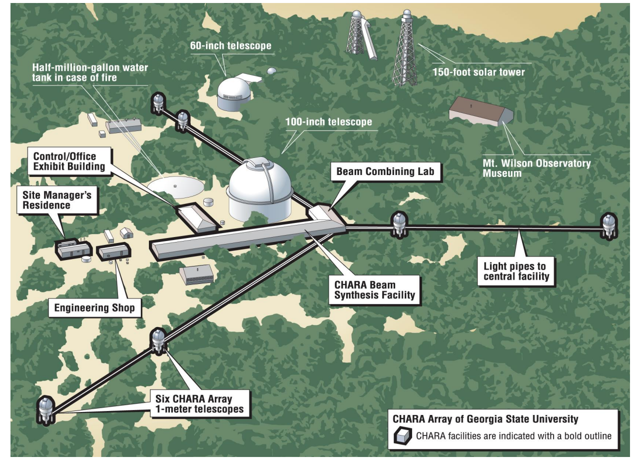
ϕ Per, VEGA 2015

Today the reality … and tomorrow?

ESO/VLTI



CHARA



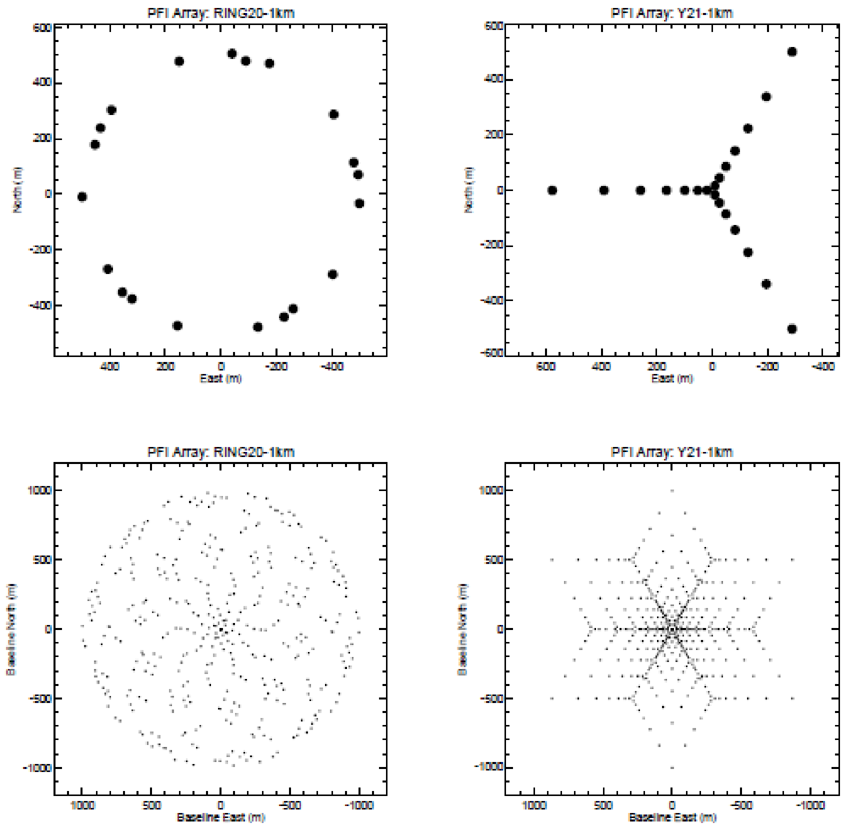
NPOI

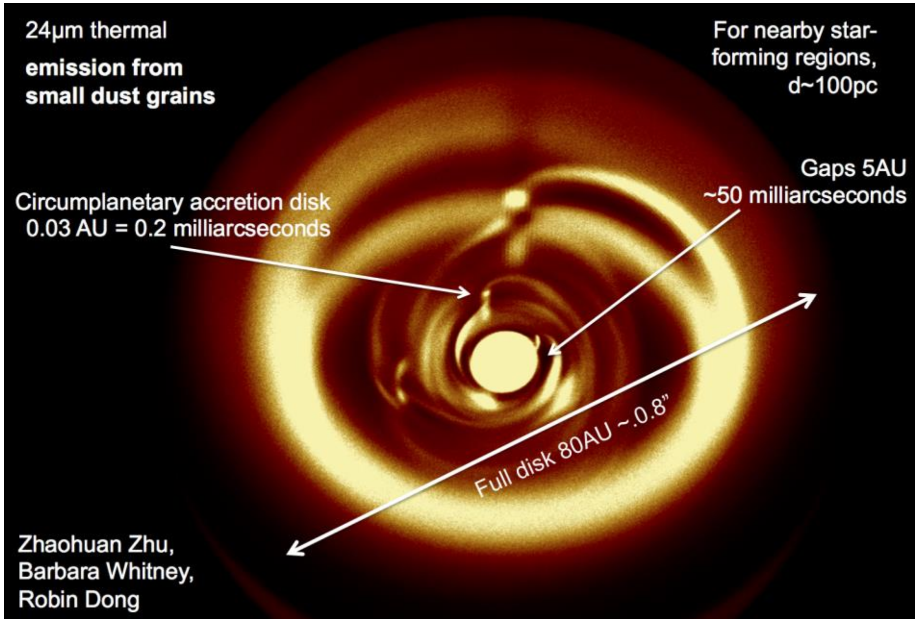
MROI

Planet Finder Imager studies ?

Table 1. Four Example PFI Arrays are explored in this report.

Shorthand Name	Array Shape Shape	Number of Telescopes	Maximum Baseline (m)	Minimum Baseline (m)	Max Spanning Baseline (m)
RING20-1km	Ring array	20	1000	42	300
RING20-5km	Ring array	20	5000	209	1500
Y21-1km	Y array	21	1000	33	187
Y21-5km	Y array	21	5000	165	935





Probably necessary to change our approach?

The optical interferometers are really complex machines
The extension of the current concepts to ~optical ALMA is not obvious

What are the other possibilities:

- Intensity interferometers?
- Space?

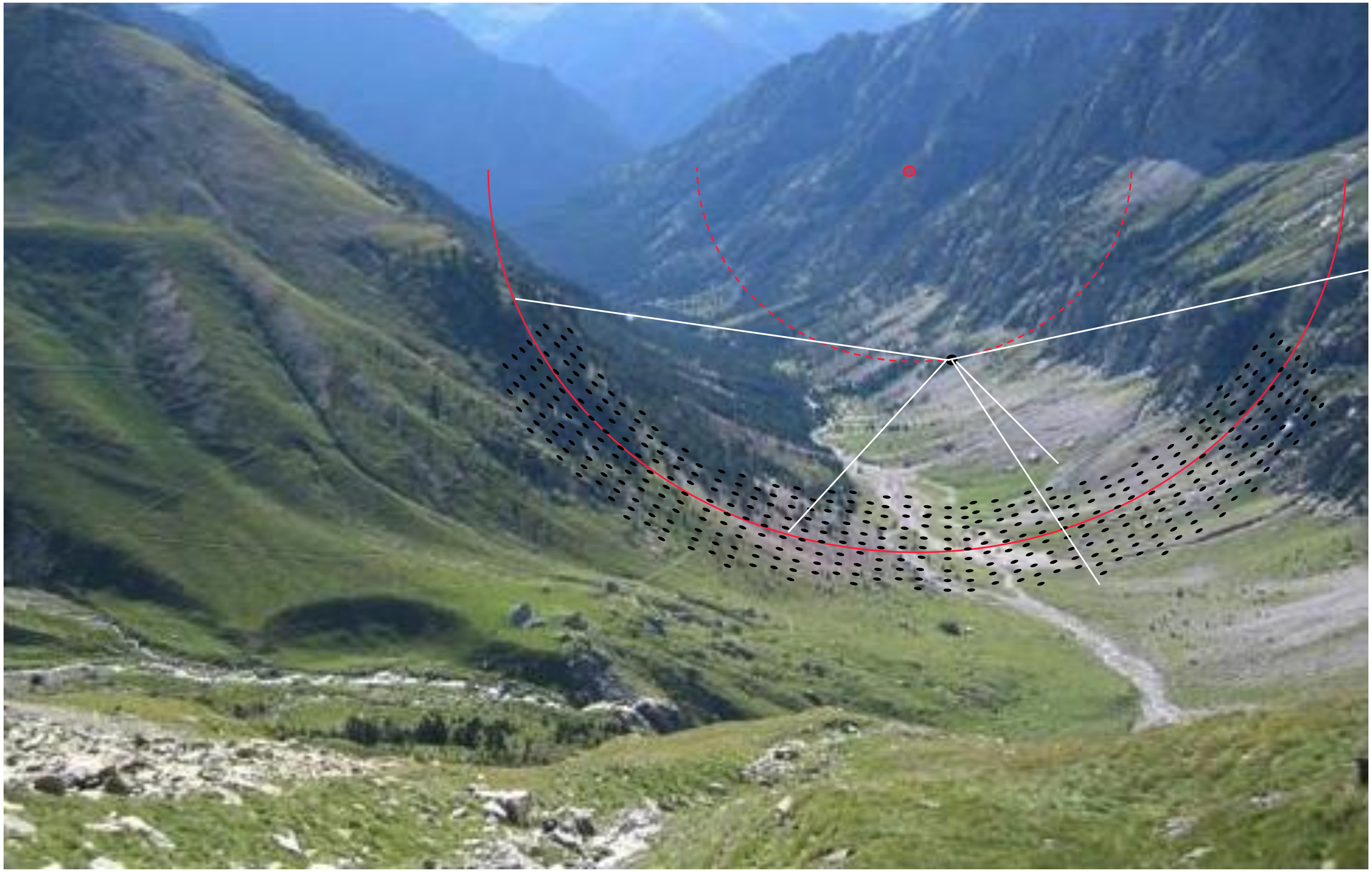
A more direct ‘direct imaging interferometer’: Optical Arecibo?

An optical version of Arecibo or of the new FAST radiotelescope?

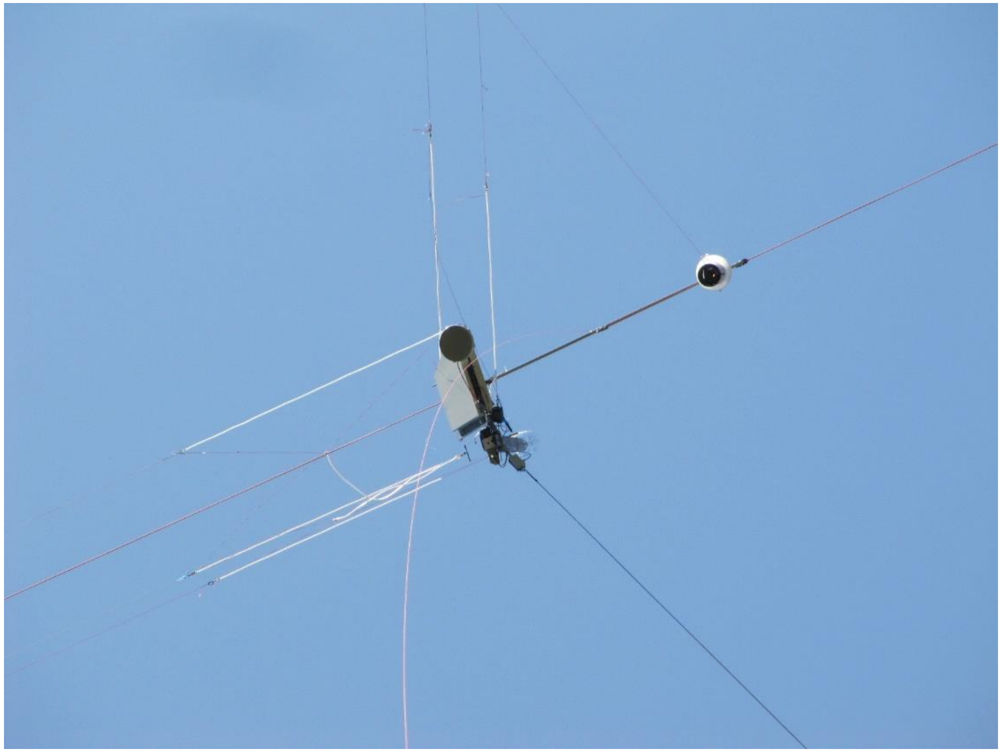
- No delay lines needed
- But moving focal optics

Cables for shape adjustment,
activable for a sliding
paraboloidal deformation

Construction of a 57m hypertelescope in the southern Alps, France



Preliminary results



focal gondola, 101m high, computer-driven

- 2015: Vega image obtained at coudé from one sub-aperture
- 2017: Full validation of the tracking and orientation, new optical bench with embarked cameras. More tests to come…