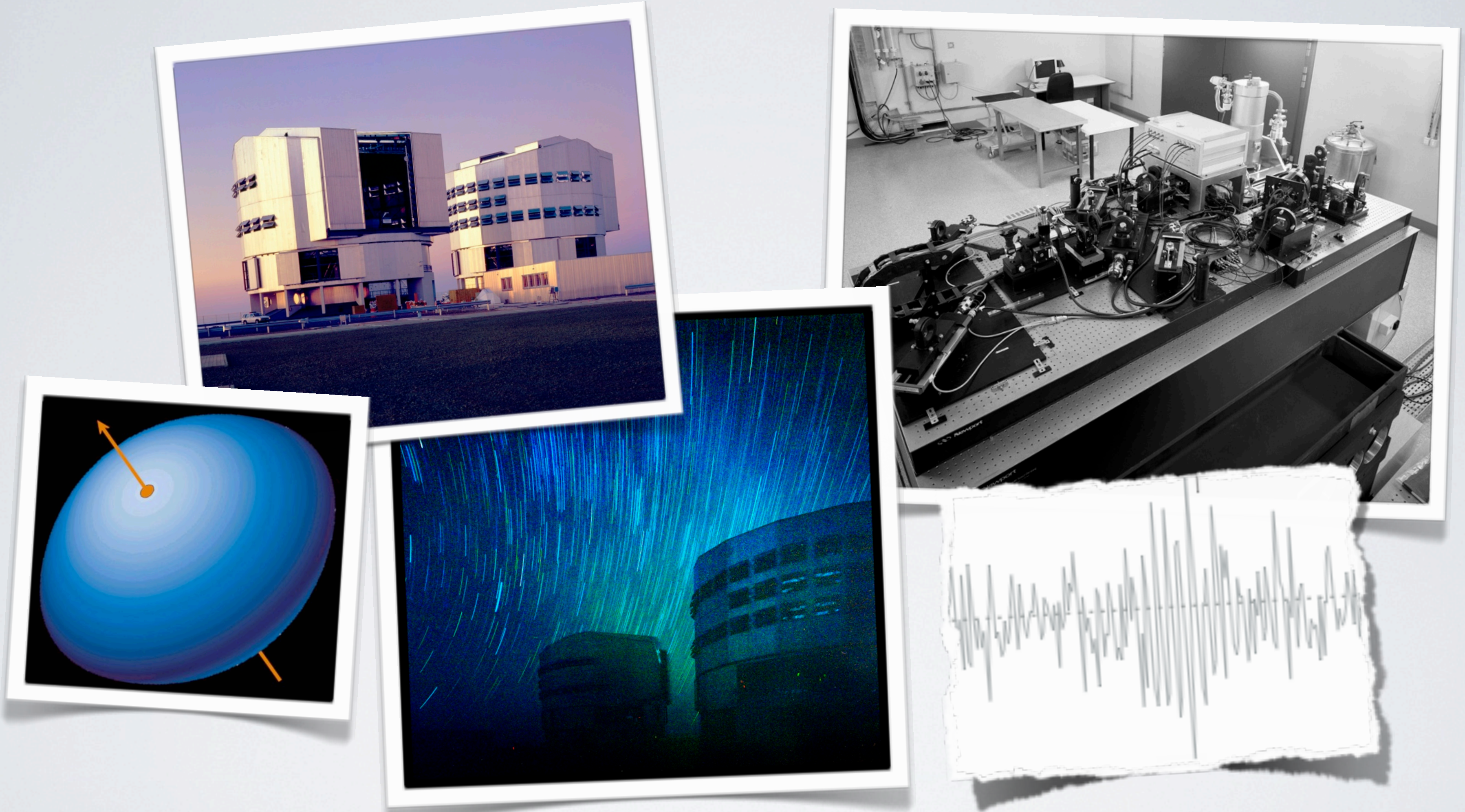
THE CARTOGRAPHY OF THE SUN AND THE STARS

INTERFEROMETRY TO DETERMINE STELLAR SHAPES (1/2)



Pierre KERVELLA
pierre.kervella@obspm.fr

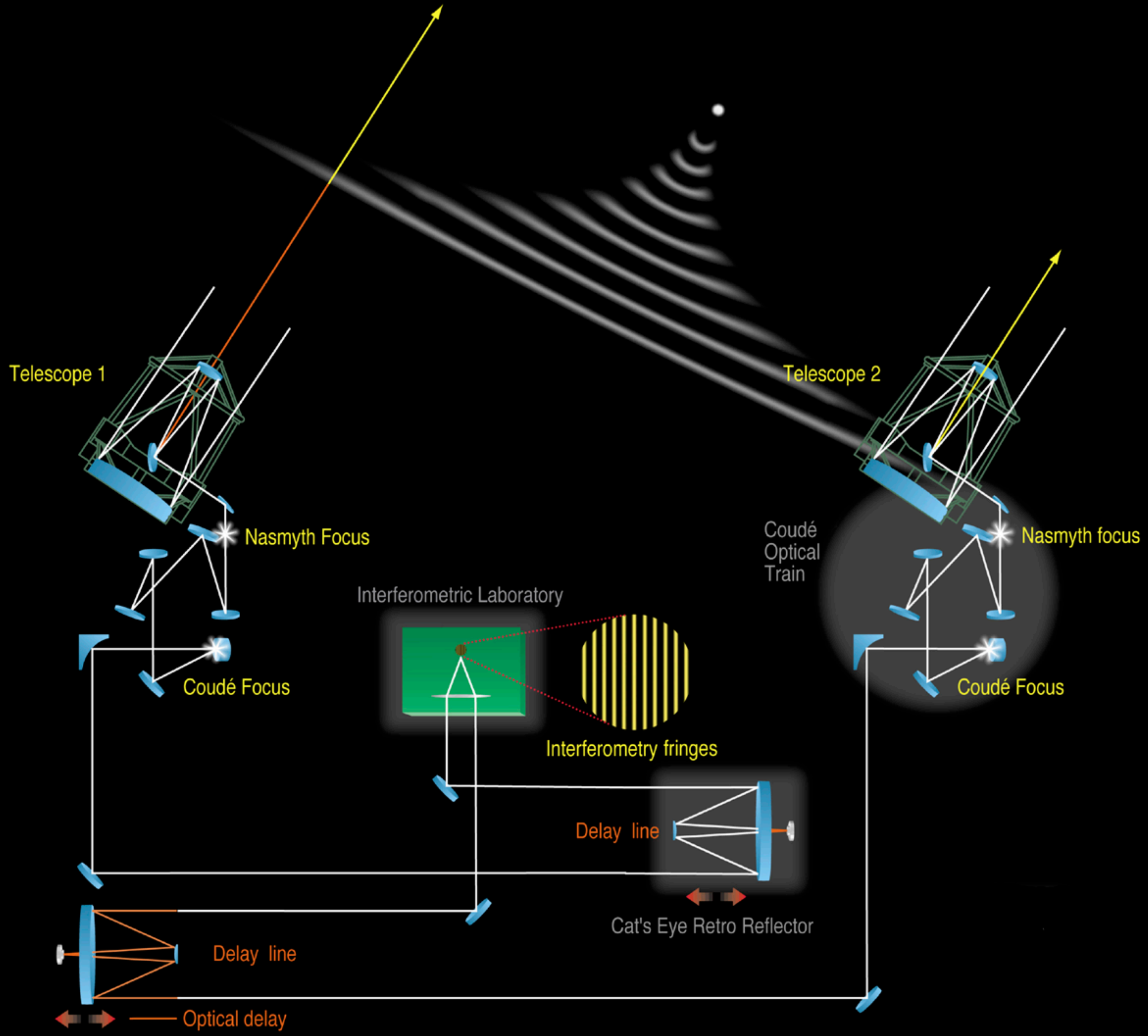
PRELIMINARY REMARKS

- Do not hesitate to ask questions
- Practical approach of observation and data analysis, with a focus on model fitting
  - exercises this afternoon on real data
- The objective of this course is that you understand the method and the possibilities of interferometry

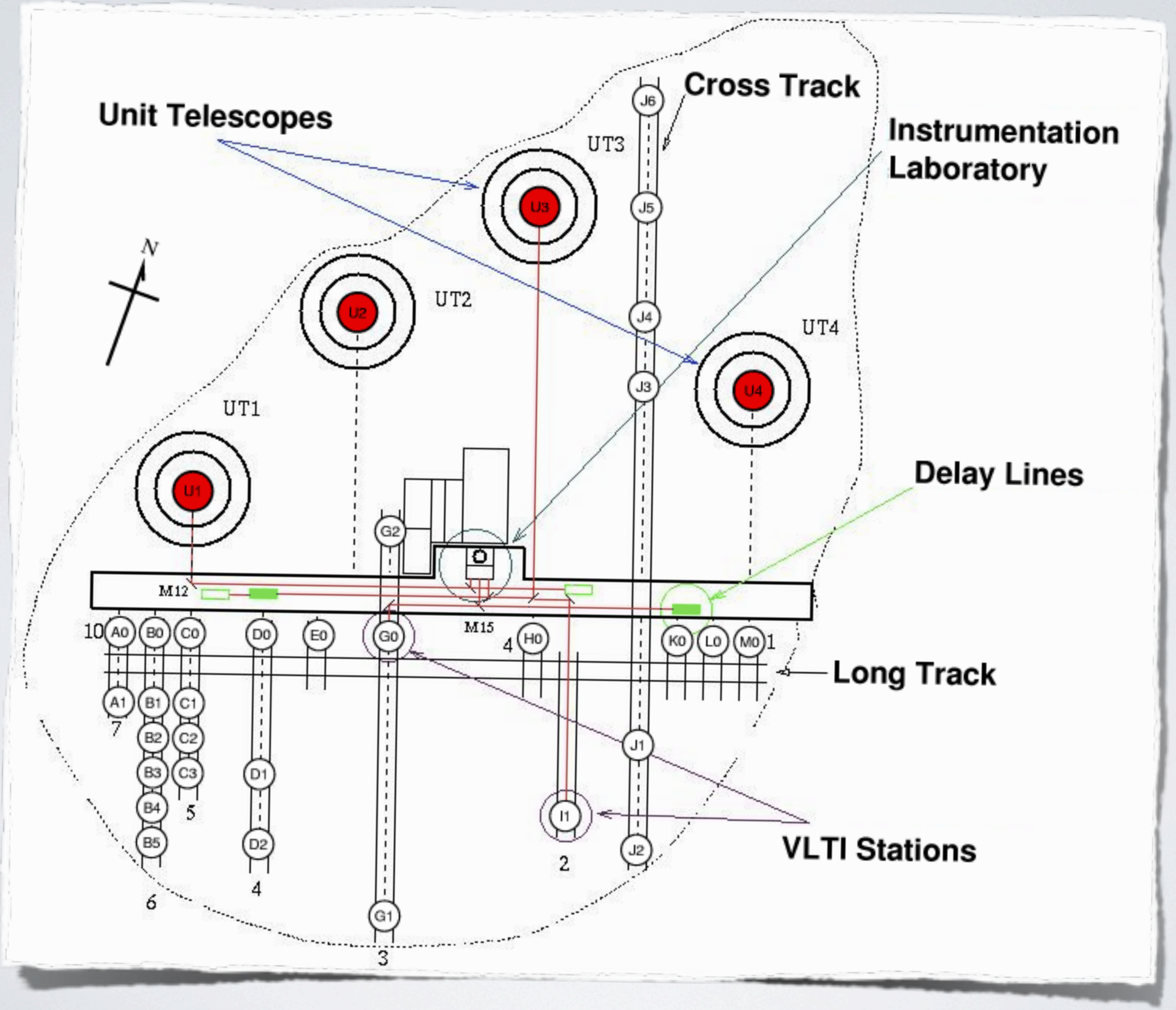
Brief presentation of VLTI

Observations of Achernar

Analysis of VINCI and PIONIER data


Telescope 1
Telescope 2
Nasmyth Focus
Nasmyth focus
Coudé Optical Train
Interferometric Laboratory
Coudé Focus
Coudé Focus
Interferometry fringes
Delay line
Cat's Eye Retro Reflector
Delay line
Optical delay

PARANAL OBSERVATORY



Unit Telescopes

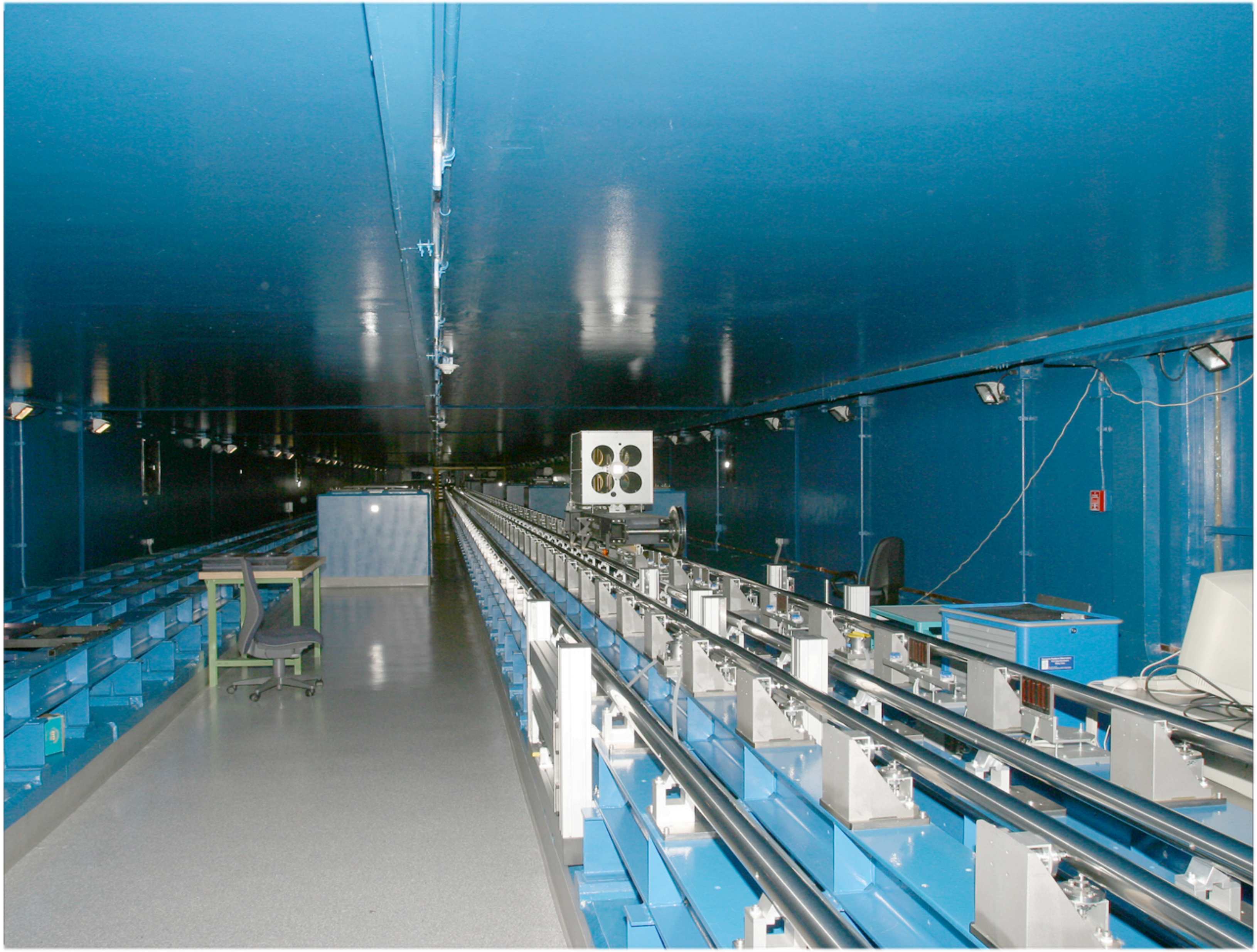
Cross Track

Instrumentation Laboratory

Delay Lines

Long Track

VLTI Stations




Fokker Space

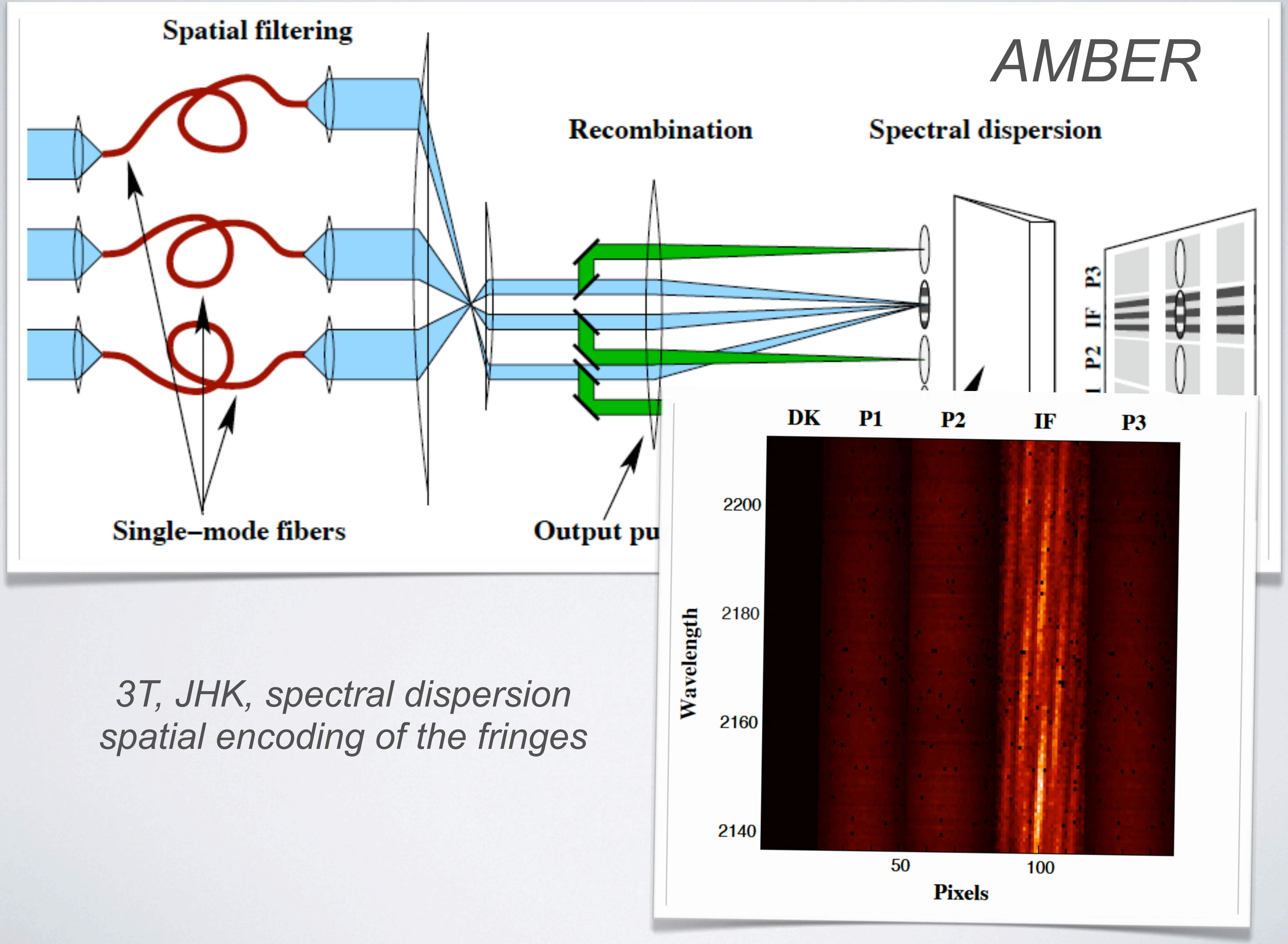
VLTI INSTRUMENTATION (1)

- **VINCI:** decommissioned in 2008
  - recombination of 2 telescopes in the K band (2,2 μm) or H band (1,6 μm)
  - beam spatial filtering and recombination using single-mode fibers
  - temporal modulation of the optical path difference (OPD)
  - squared visibility V^2 integrated over the band
- **AMBER:** operational (offerred), filtering using fibers, spatial modulation of the OPD
  - 3-telescope instrument, in H (1,6 μm) and K (2,2 μm) bands
  - spectral resolution $\Delta\lambda/\lambda$ of 35 (LR), 1500 (MR) and 10000 (HR)
  - measurement of 3 visibilities and 1 closure phase
- **MIDI:** operational (offered)
  - 2 telescopes, thermal infrared domain : N (8-13 μm) band
  - spectral resolution R=30 or R=320
  - temporal modulation of the OPD
  - measurement of one $V(\lambda)$ of the differential phase $\phi(\lambda)$ over the N band

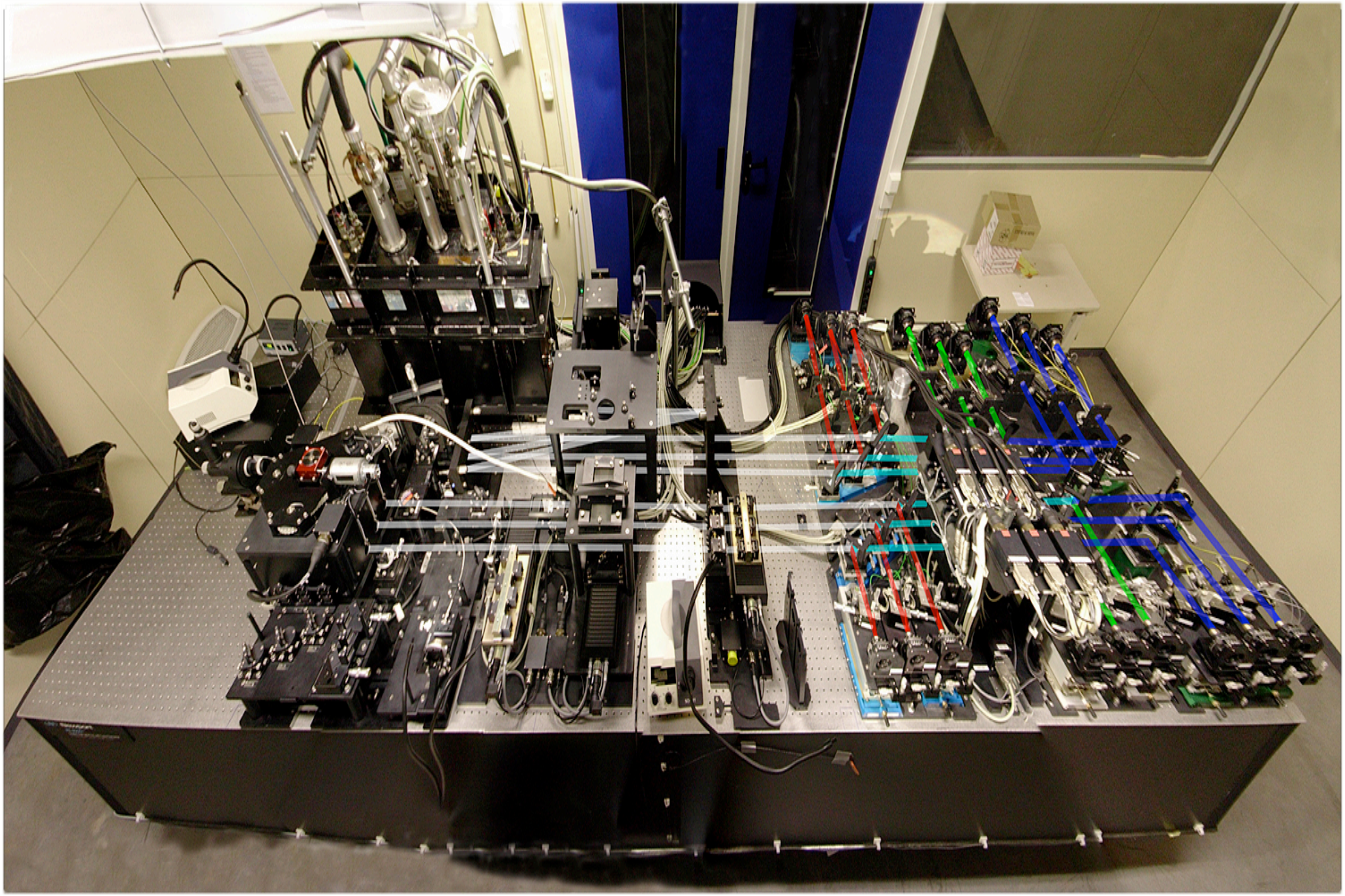
VLTI INSTRUMENTATION (2)

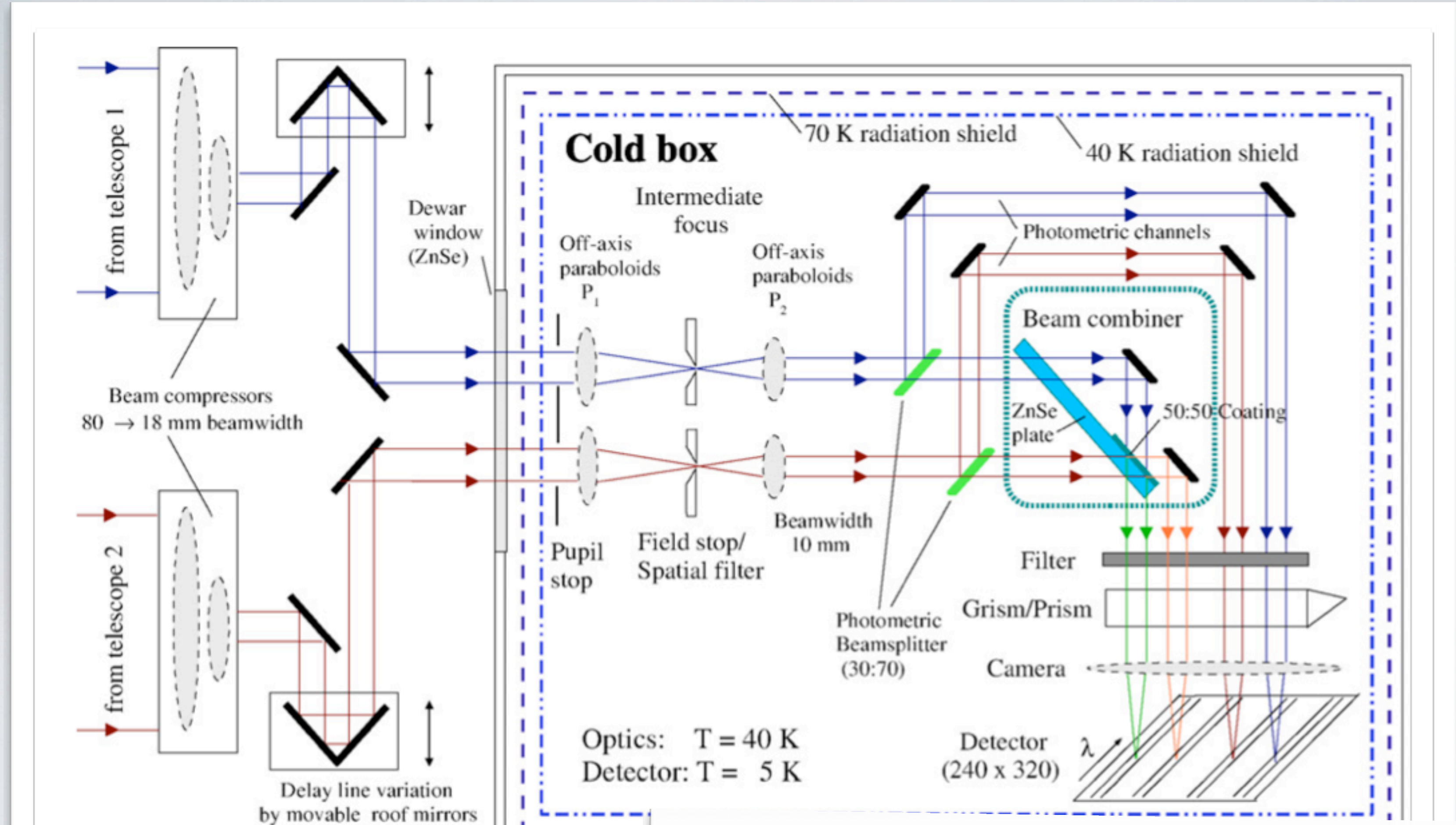
- **PIONIER:** visitor instrument, operational since 2010
  - recombination of **4 telescopes** in the H band (1,6 μm)
  - uses an integrated optics component for the recombination of the four beams
  - temporal modulation of the OPD
  - measurement of the visibility on 6 baselines and 3 closure phases with a low spectral resolution

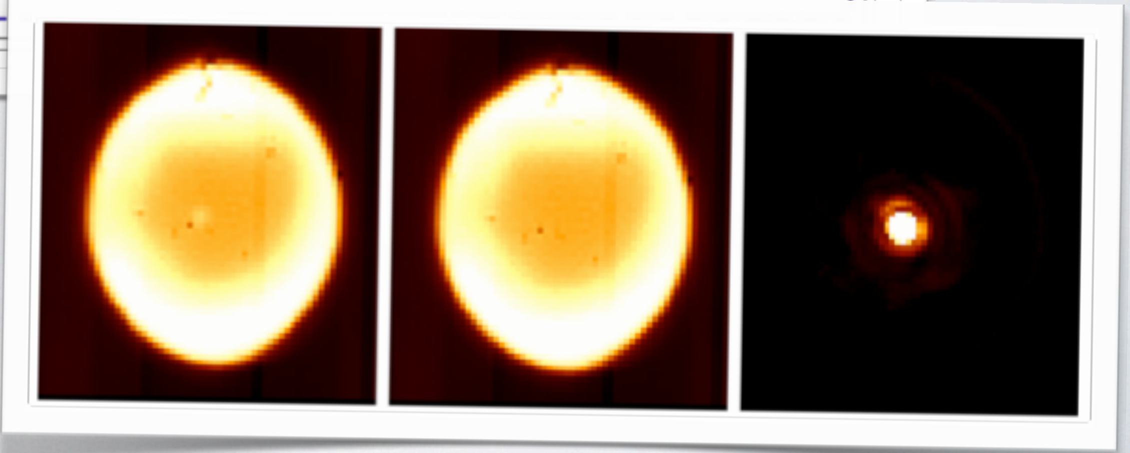
AMBER



3T, JHK, spectral dispersion
spatial encoding of the fringes

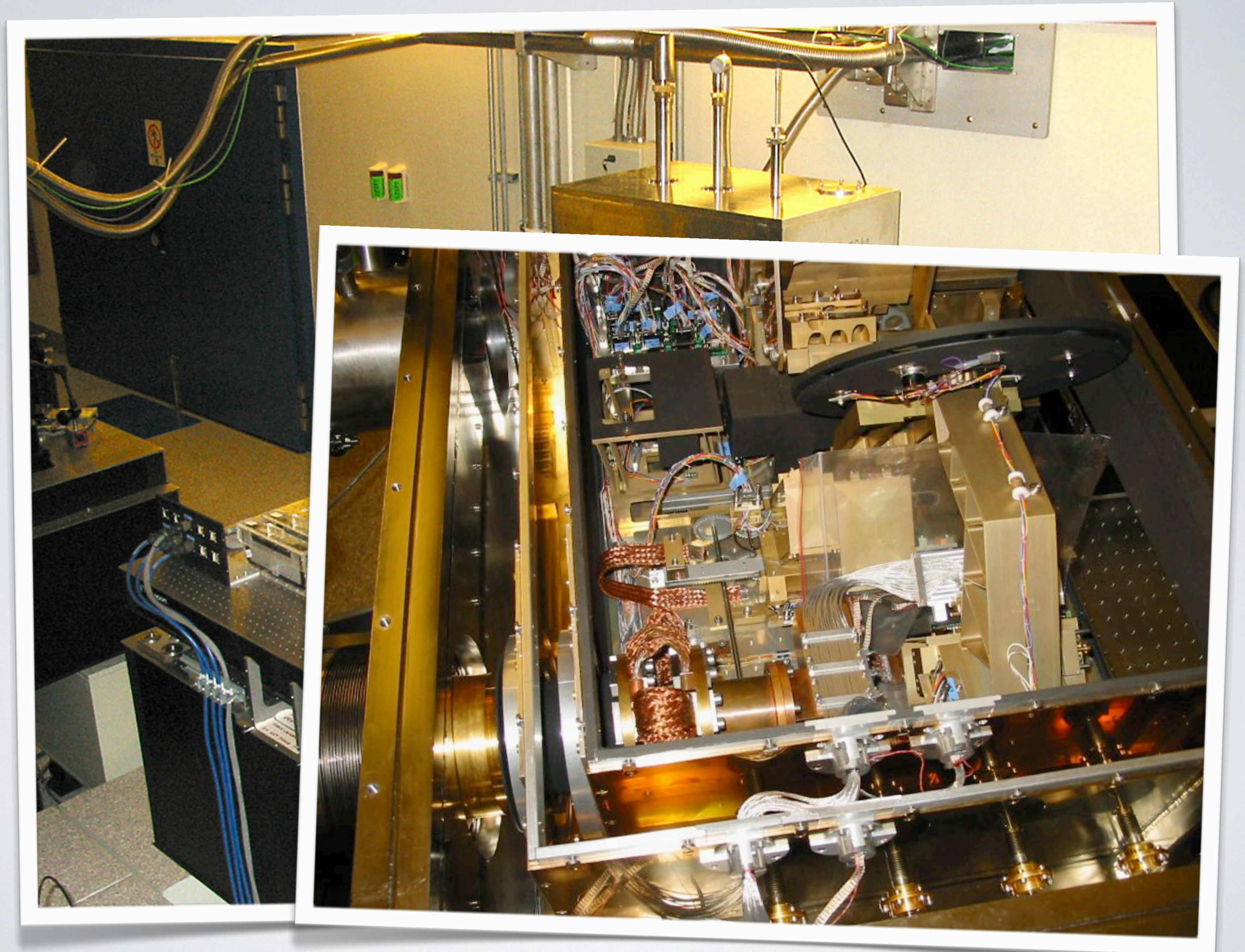




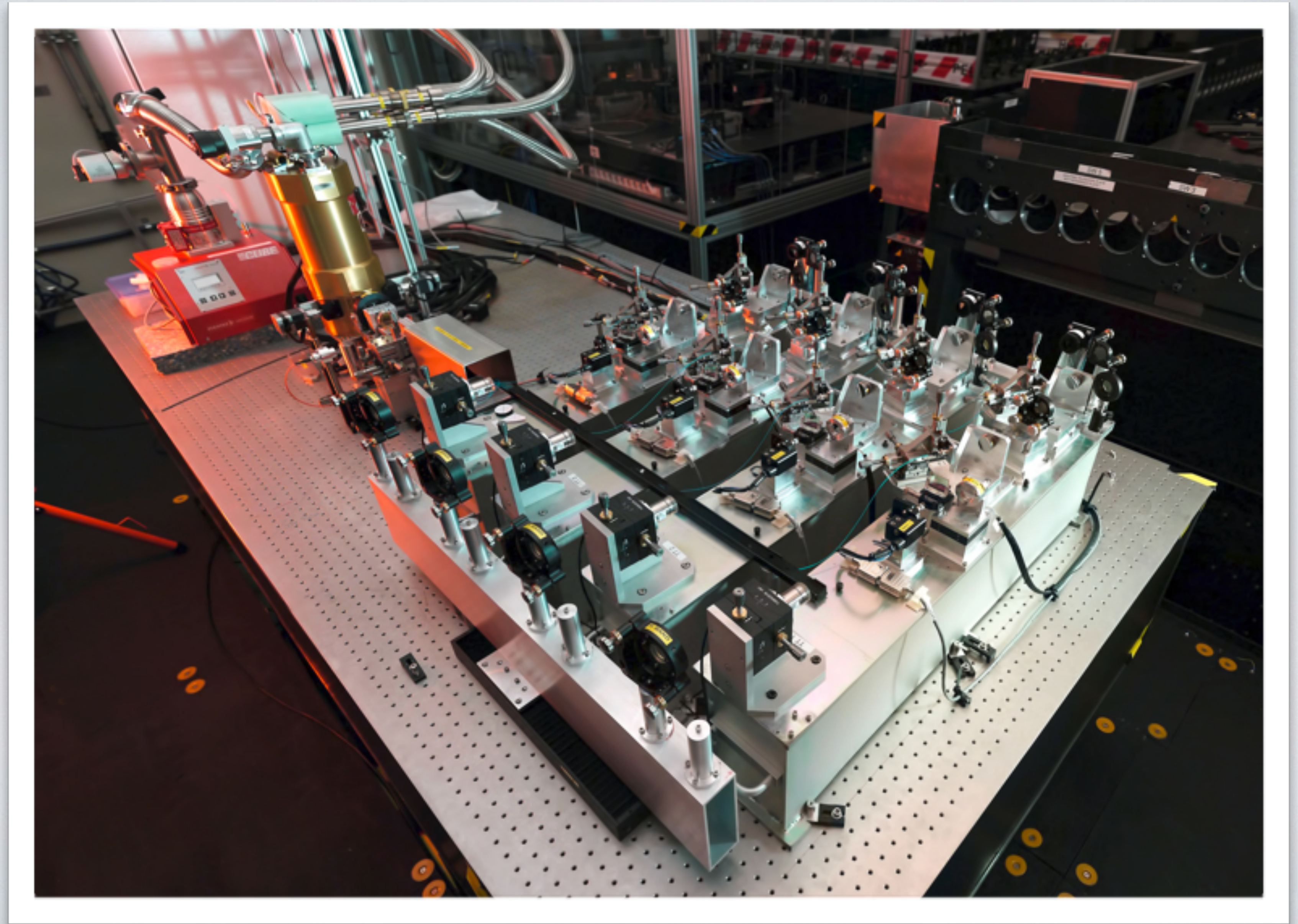


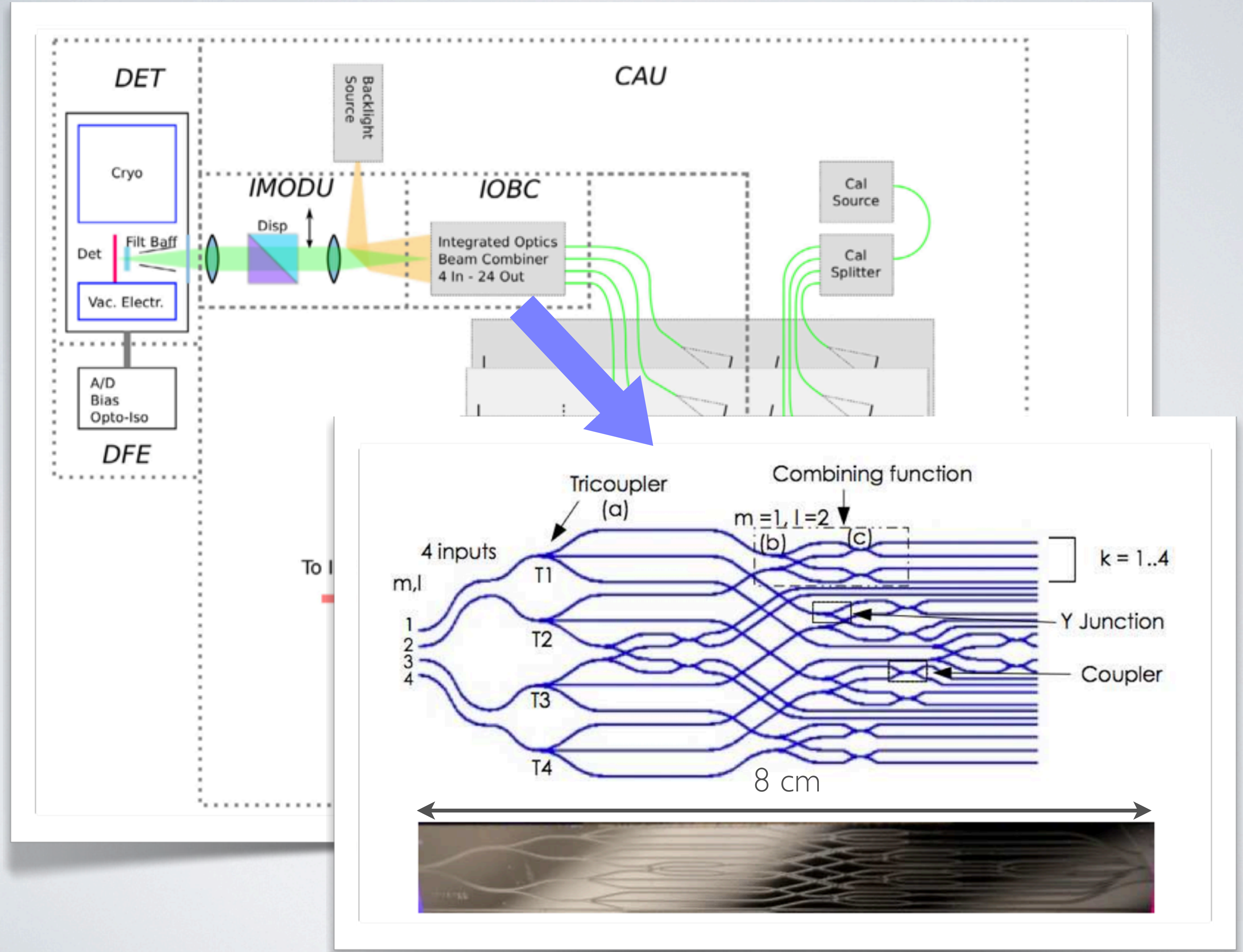
MIDI

2T, 10 µm, spectral dispersion
Temporal coding of the fringes



PIONIER

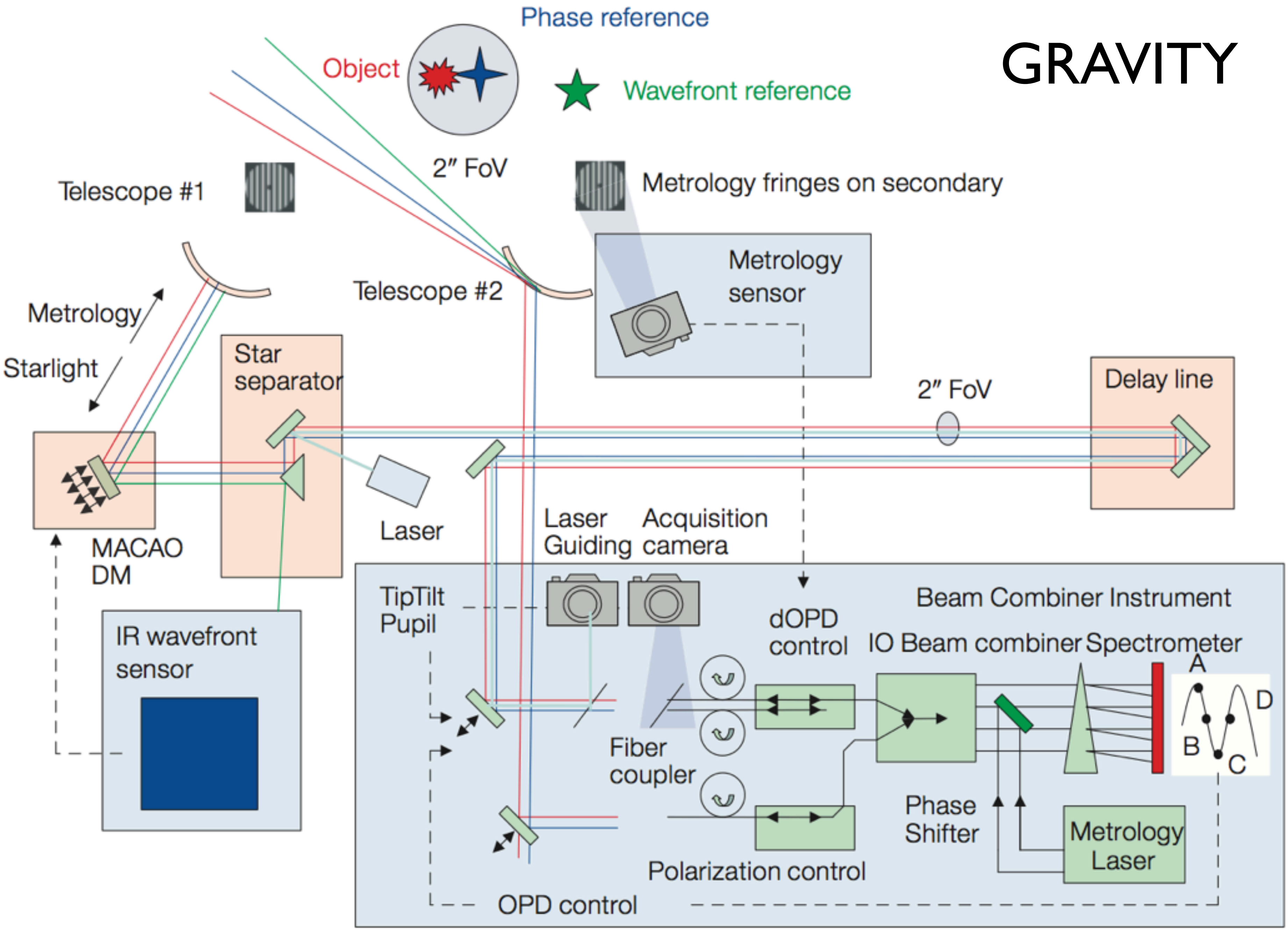



DET
CAU
Backlight Source
Cryo
Det
Filt Baff
Vac. Electr.
IMODU
Disp
IOBC
Integrated Optics Beam Combiner 4 In - 24 Out
Cal Source
Cal Splitter
A/D Bias Opto-Iso
DFE
To I
Tricoupler (a)
Combining function
m =1, l =2
(b)
(c)
4 inputs
m,l
1
2
3
4
T1
T2
T3
T4
k = 1..4
Y Junction
Coupler
8 cm

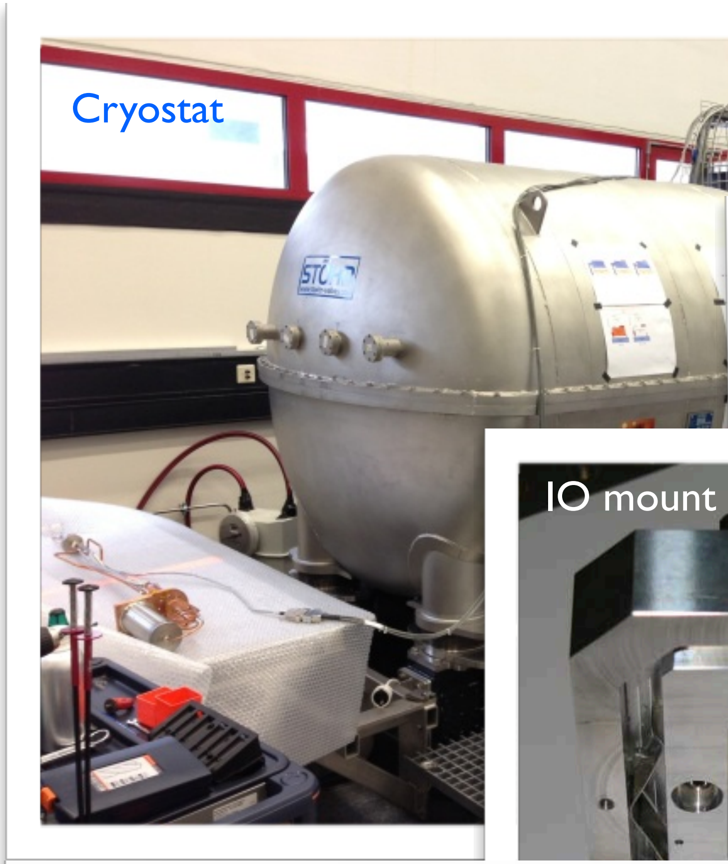
SECOND GENERATION VLTI INSTRUMENTS (2015+)

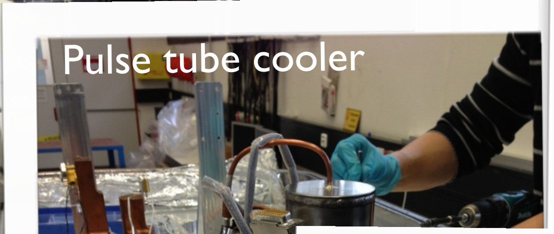
- **GRAVITY:** 4T beam combiner with dual field (2,2 µm)
  - Ultra-high accuracy narrow-angle astrometry (10 µas)
  - Spectro-interferometric imaging R=30 to 4000 (K band)
  - MPE Garching/Observatoire de Paris/U. Cologne/...
  - Primary objective: the Galactic Center
  - Many other applications !
- **MATISSE:** 4T recombiner in the thermal infrared domain
  - Follow-up of the successful MIDI instrument
  - Observatoire de la Côte d'Azur/MPIA/MPIfR/...
  - Objectives: young stellar objects, planetary formation, evolved stars

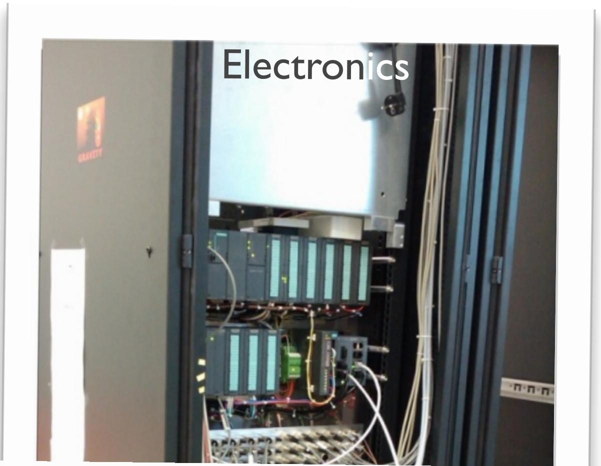
GRAVITY



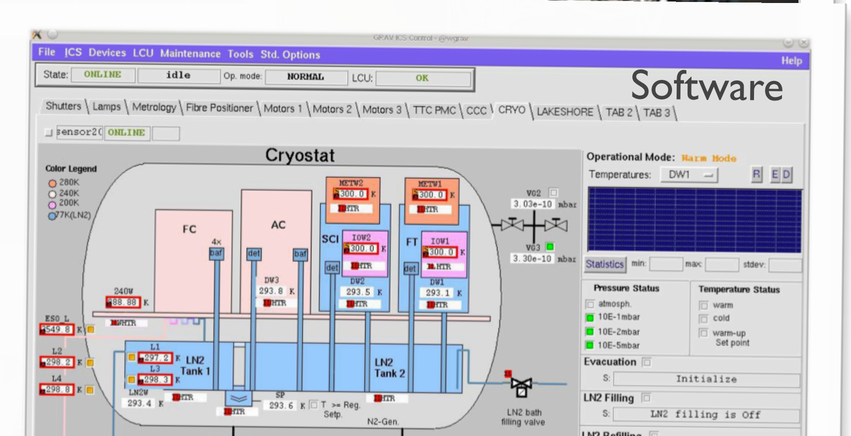
Eisenhauer et al. (2011, ESO Messenger, 143, 14)


Cryostat


Pulse tube cooler


Electronics


IO mount


Software

GRAV ICS Control - @wgrav

State: ONLINE idle Op. mode: NORMAL LCU: OK

sensor2(ONLINE

Operational Mode: Warm Mode

Temperatures: DW1

Pressure Status
- ☐ atmosph.
- 🟩 10E-1mbar
- 🟩 10E-2mbar
- 🟩 10E-5mbar

Temperature Status
- ☐ warm
- ☐ cold
- ☐ warm-up Set point

Evacuation ☐ S: Initialize

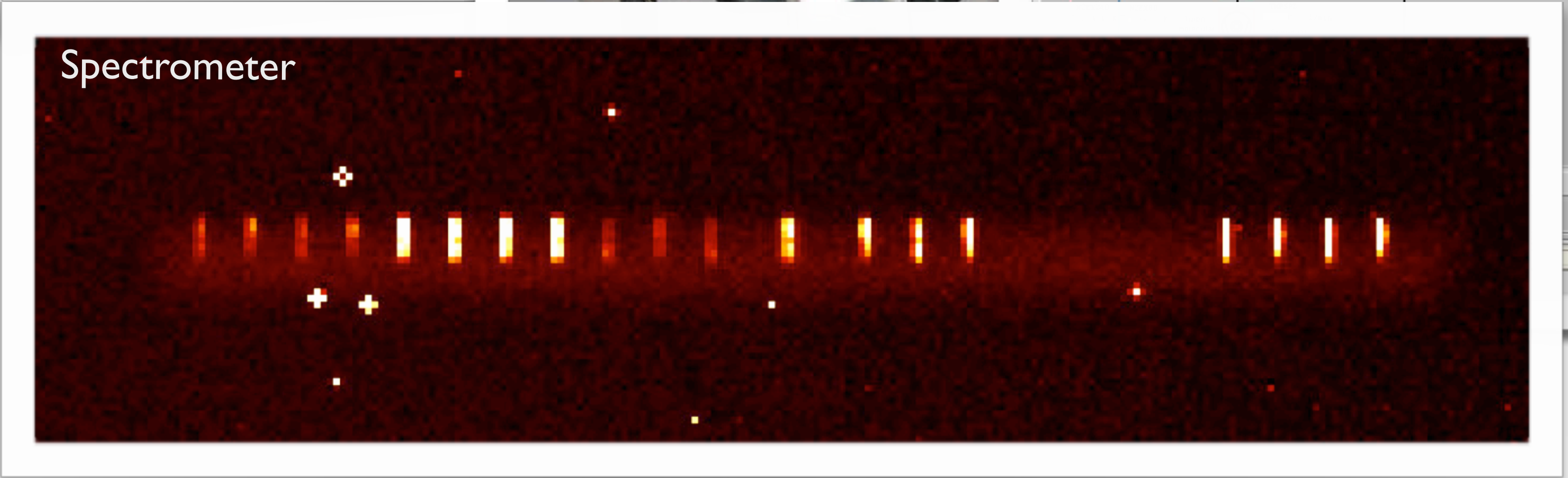
LN2 Filling ☐ S: LN2 filling is Off

LN2 Refilling ☐ S: LN2 Refilling is Off

SP Regeneration ☐ S: Initialize

Warm-Up ☐ S: Initialize

Re-Pressurization ☐ S: Re-Pressurization is Off

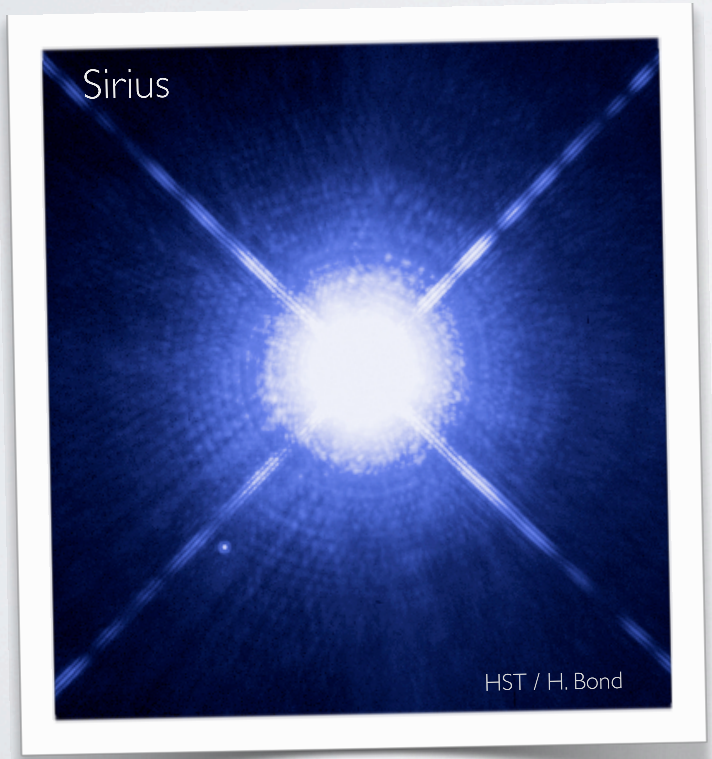

Spectrometer

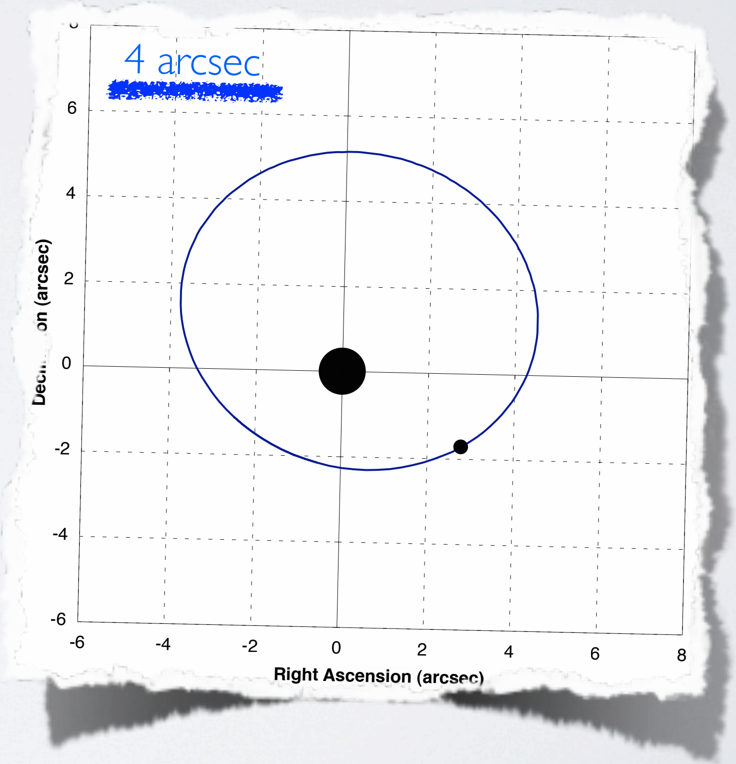
PERFORMANCES

- 4 telescopes, 3 closure phases, dual field capability
- Angular resolution: 3 mas (set by VLTI baselines), super-resolution possible
- R=4000 observations possible up to FT limiting magnitude (m_K=10)
- With suitable m_K<10 reference within 2" (UTs) or 6" (ATs), *observations up to m_K=19* are possible

ASTROMETRY WITH GRAVITY

- Astrometry and spectro-imaging up to separations of 6" and $m_K = 19$ if nearby phase reference with $m_K < 10$ is available





SCHEDULE

- Start: 2004
- PDR: 2009
- FDR: 2011
- PA Europe: September 2014
- First light: Early 2015
- First science operations: End 2015

PRACTICAL EXAMPLE: OBSERVATIONS OF ACHERNAR WITH VINCI

ACHERNAR

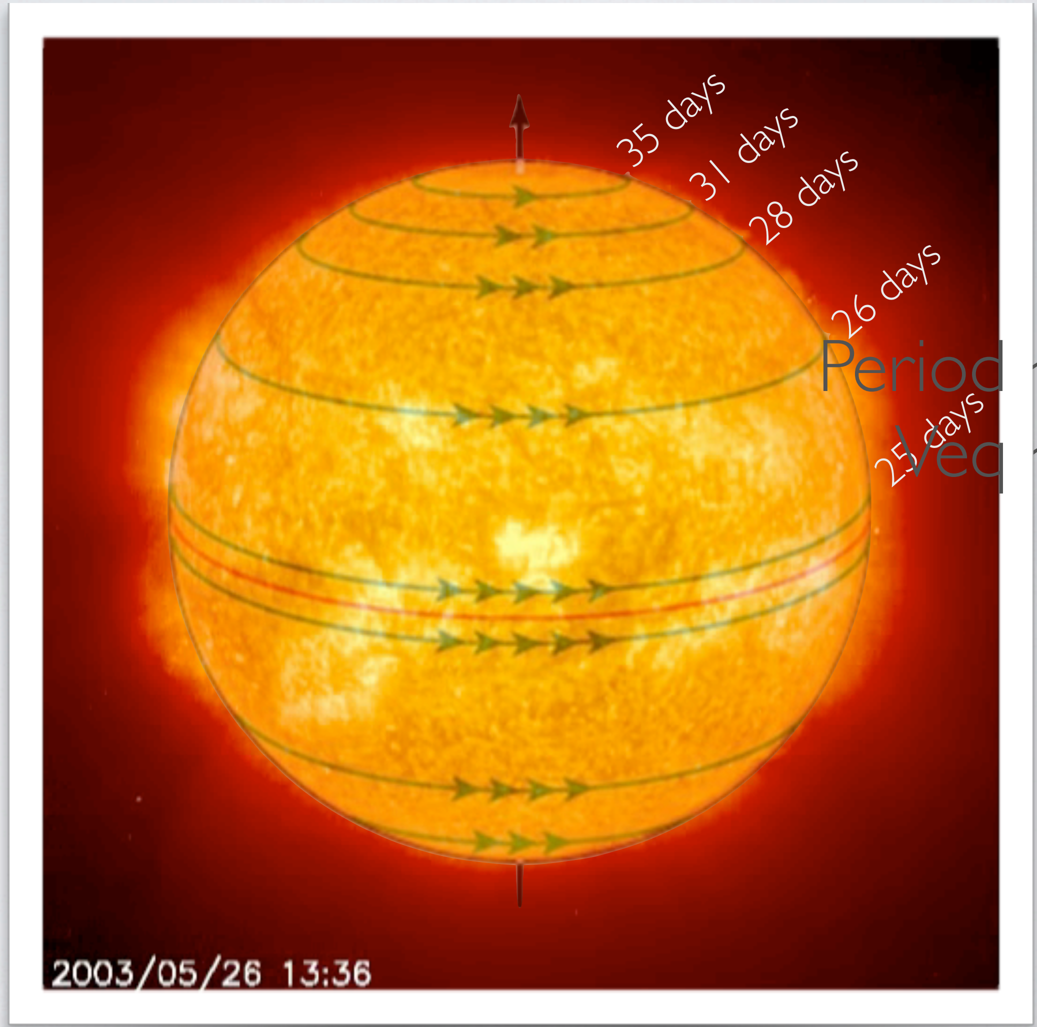
- 9th brightest star (m_V=0.50)
- *Be* star (B3Vpe)
- Effective temperature ~ 15 000 K, Luminosity ~ 3000 L_{sun}
- d = 44 +/- 1 pc
- M ~ 6 M_{sol}, R ~ 9 R_{sol}
- Theta(mas) = 9.305 * D(Dsol)/d(pc) > angular diameter ~2 mas
- In the infrared (2 µm), baseline to resolve Achernar ~200 m
- Projected rotational velocity:

$$\theta \propto \left(\frac{\lambda}{B}\right)$$

v.sin i = 225 km/s

Is it possible to know the rotation period ?

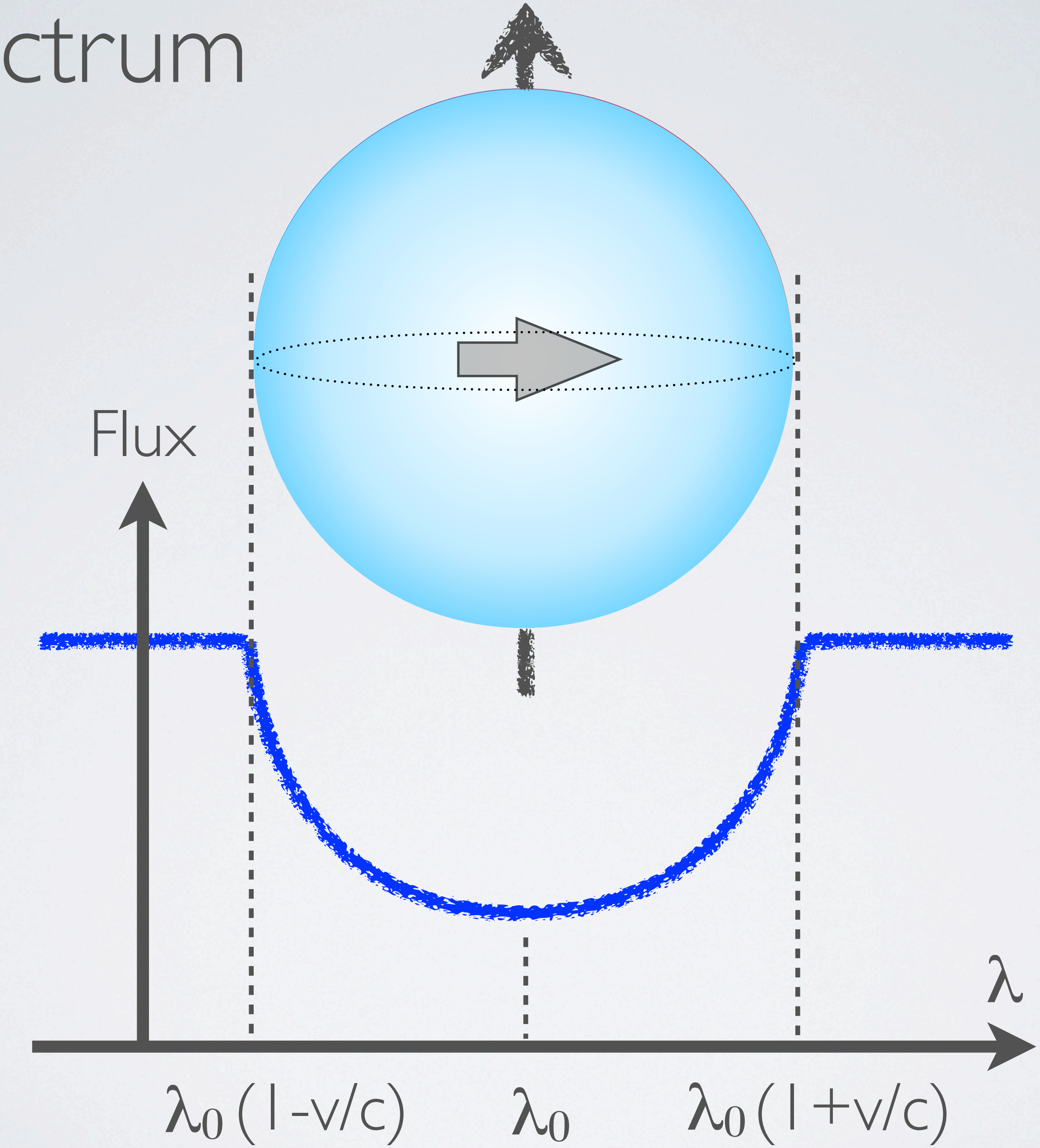
SOLAR ROTATION

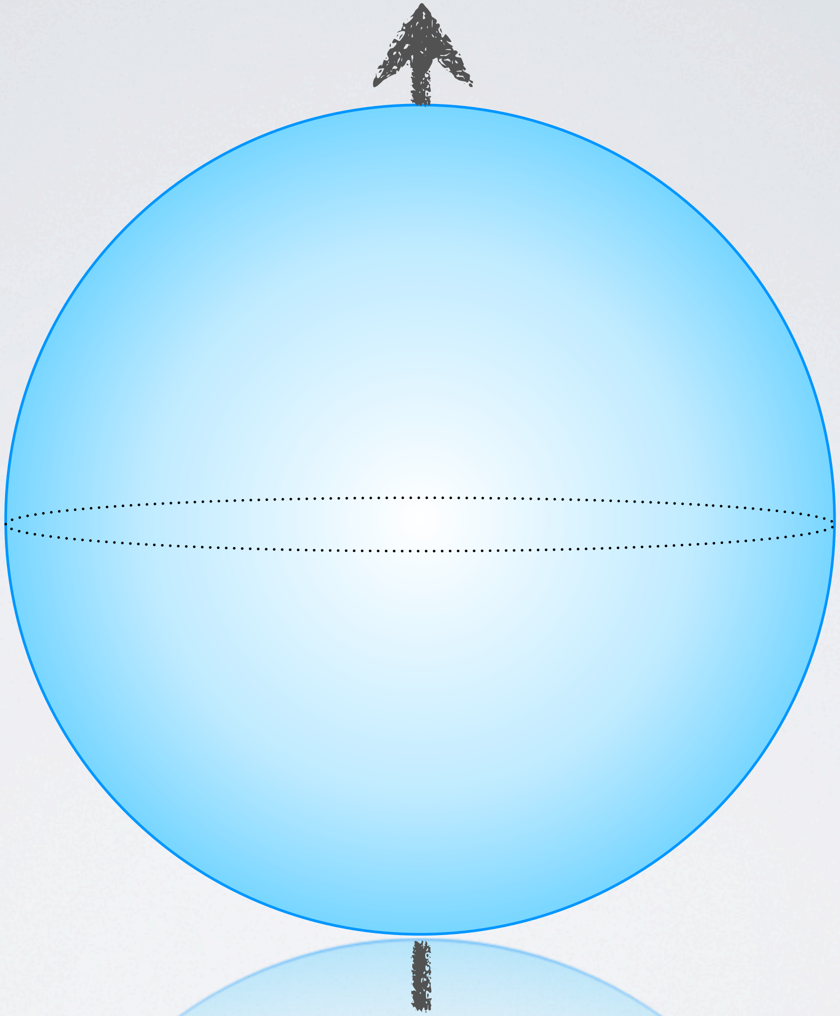


Period ~ 1 month

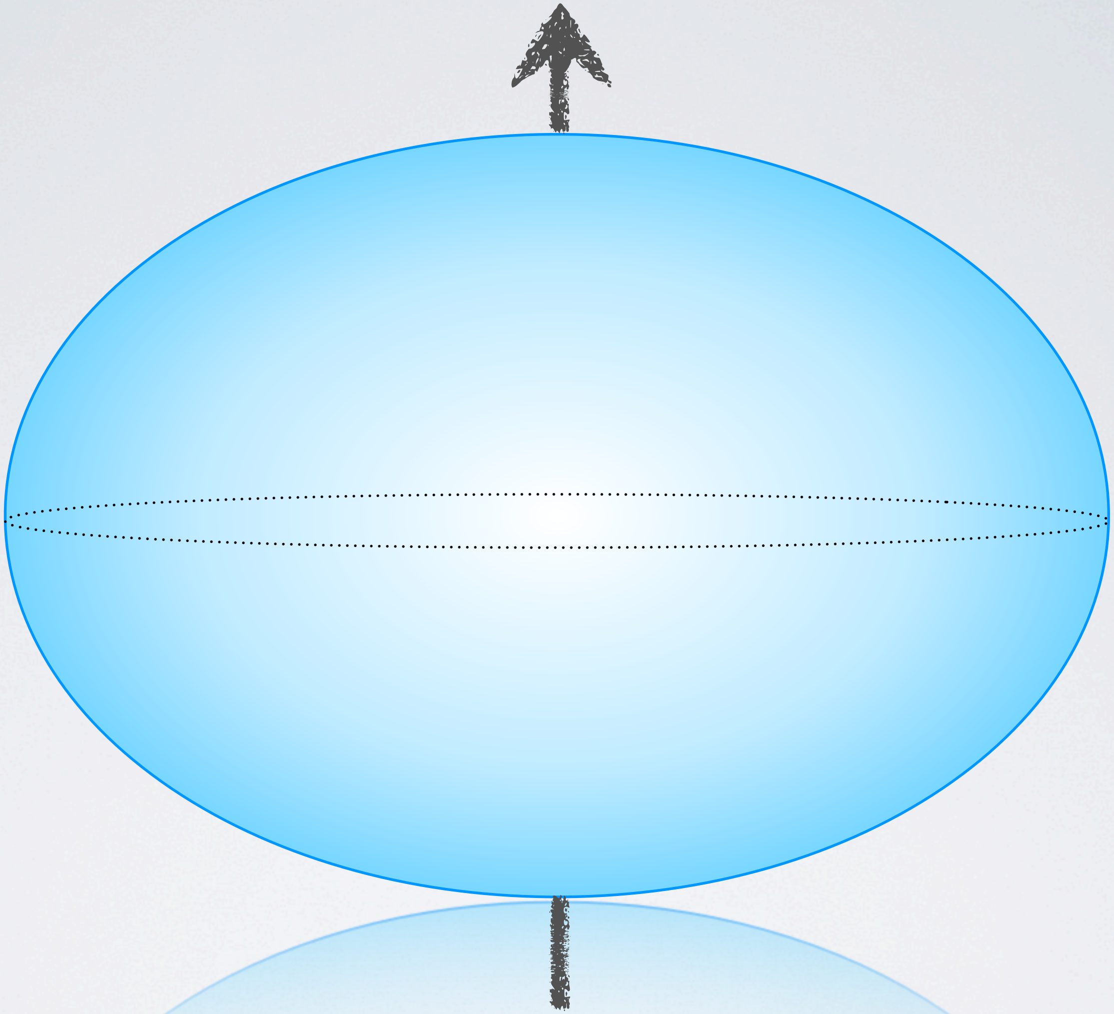
Veq ~2 km/s

Spectrum



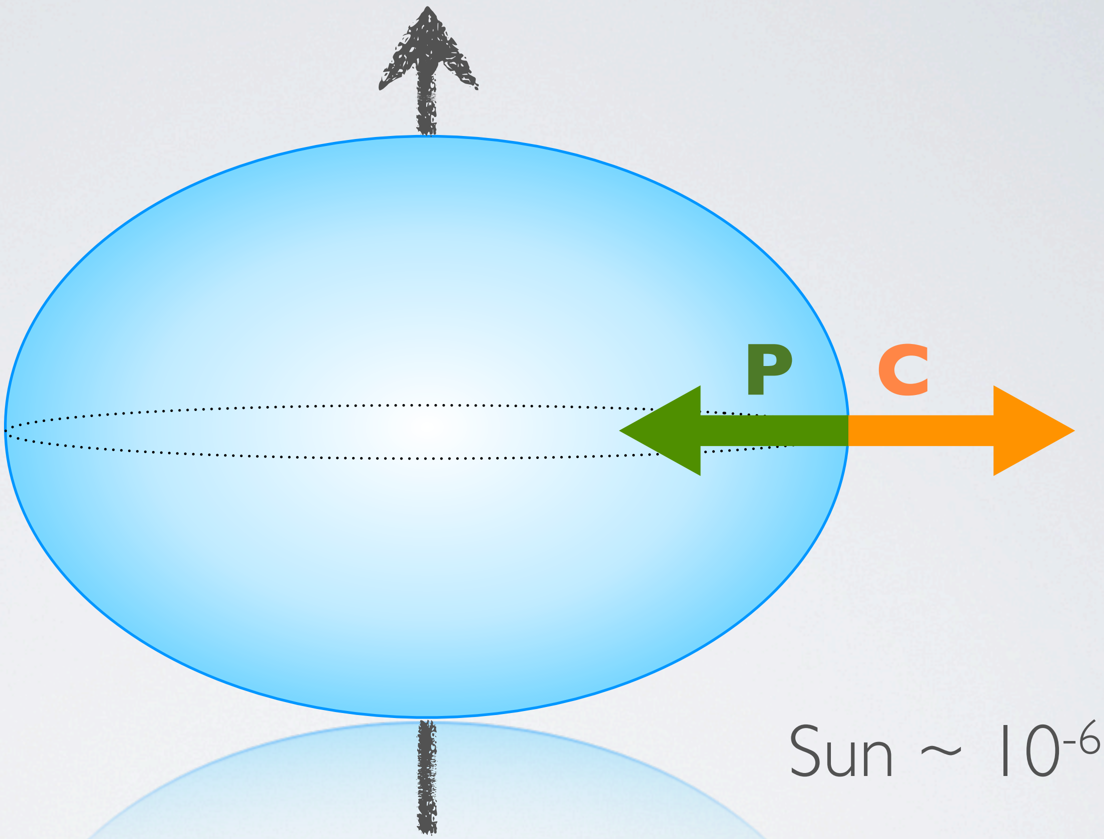


Slow rotation



Rapid rotation

FLATTENING

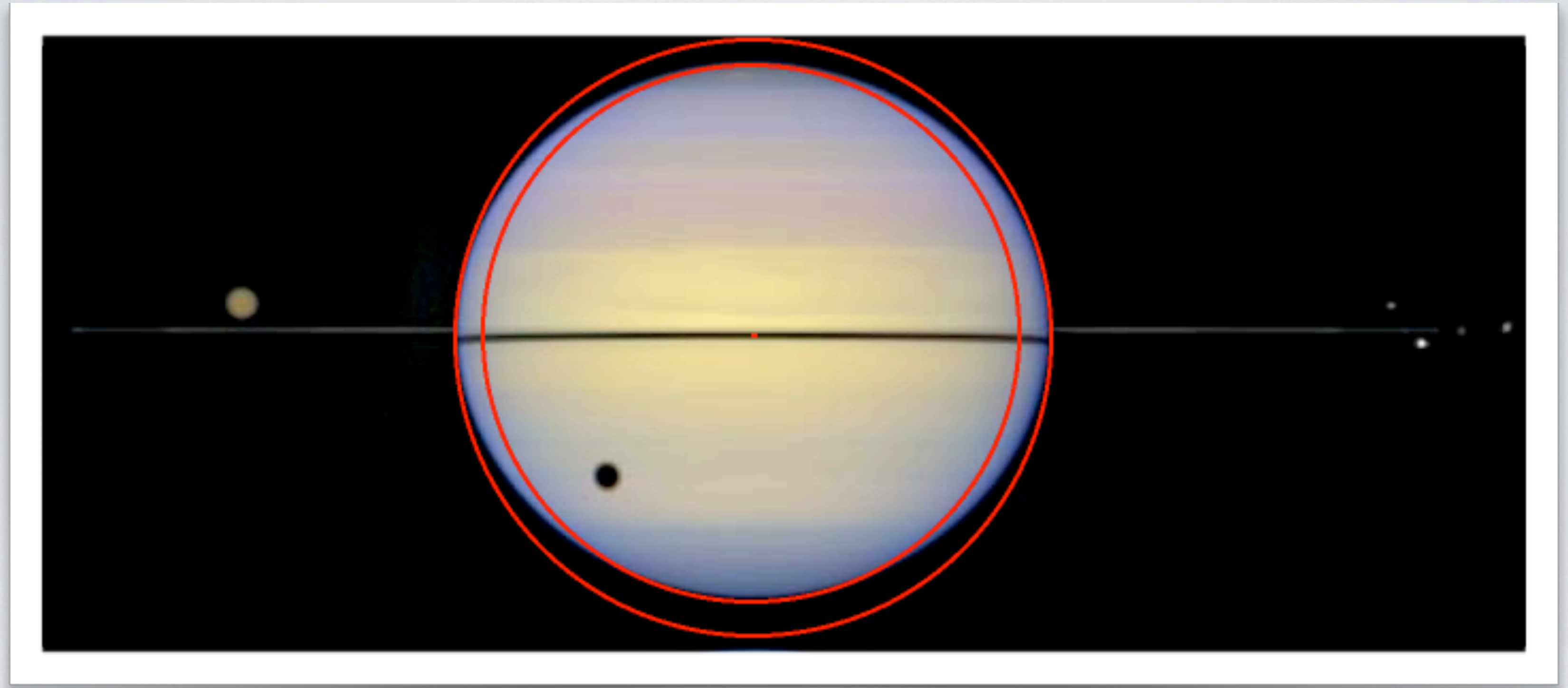


Sun ~ 10^{-6}

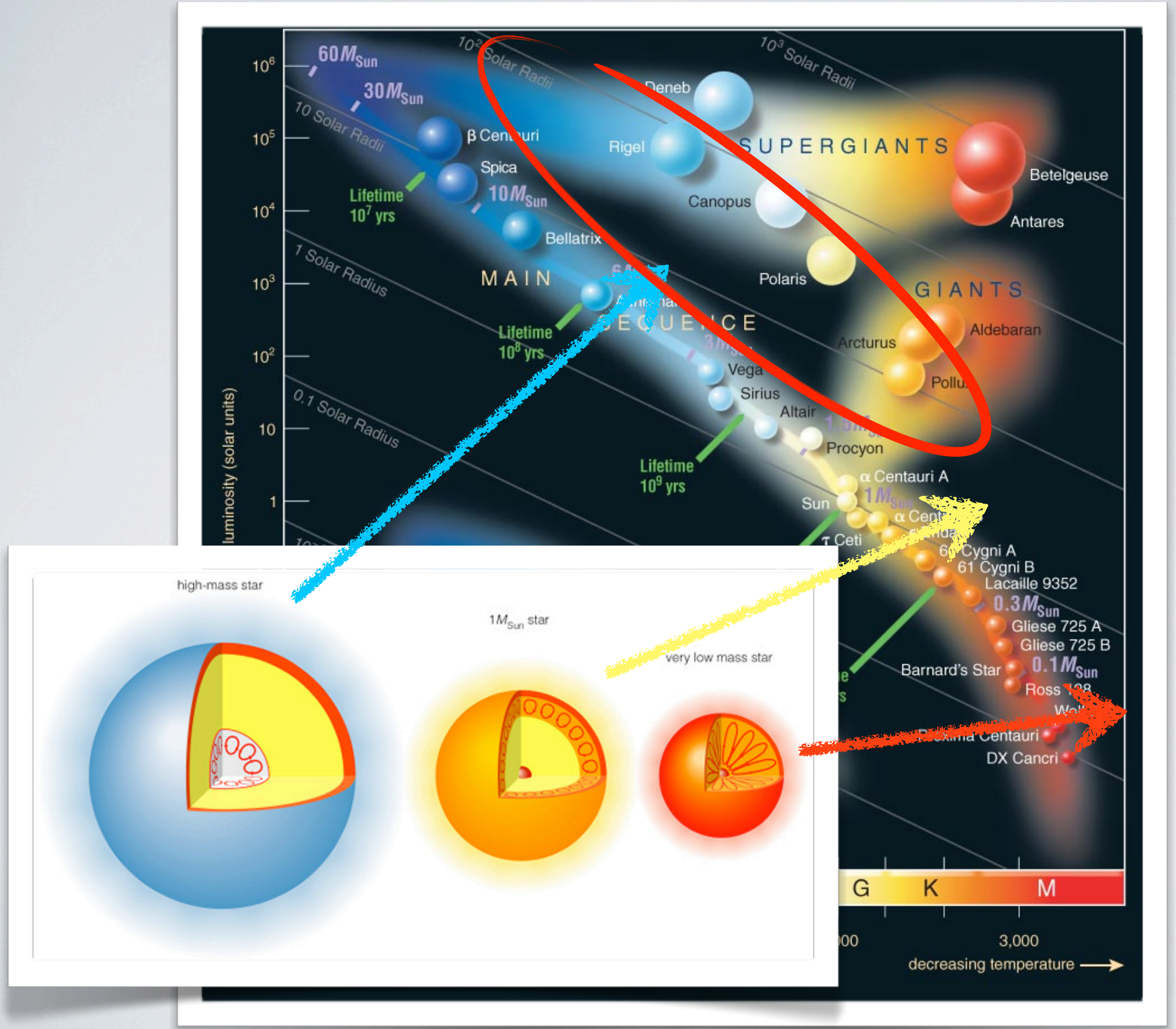
$$f = \frac{R_{eq} - R_{pol}}{R_{pol}} \sim \frac{1}{2}\frac{C}{P} = \frac{1}{2}\left[\frac{m\omega^2 R}{GMm/R^2}\right] = \frac{3}{8\pi G}\boxed{\frac{\omega^2}{\rho}}$$

What is the critical rotation velocity ?

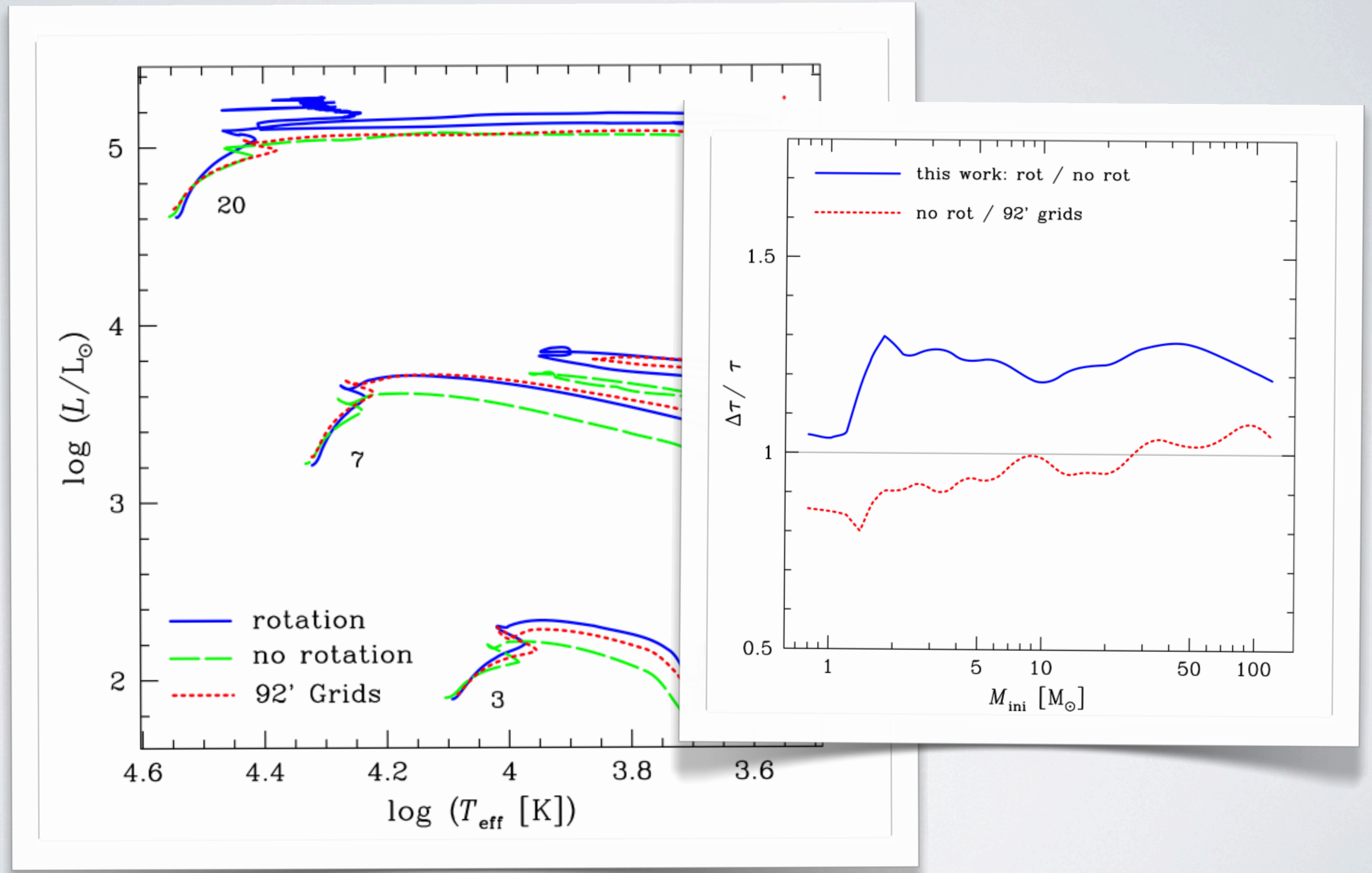
(Huygens approximation)



HST / Karkochka et al.

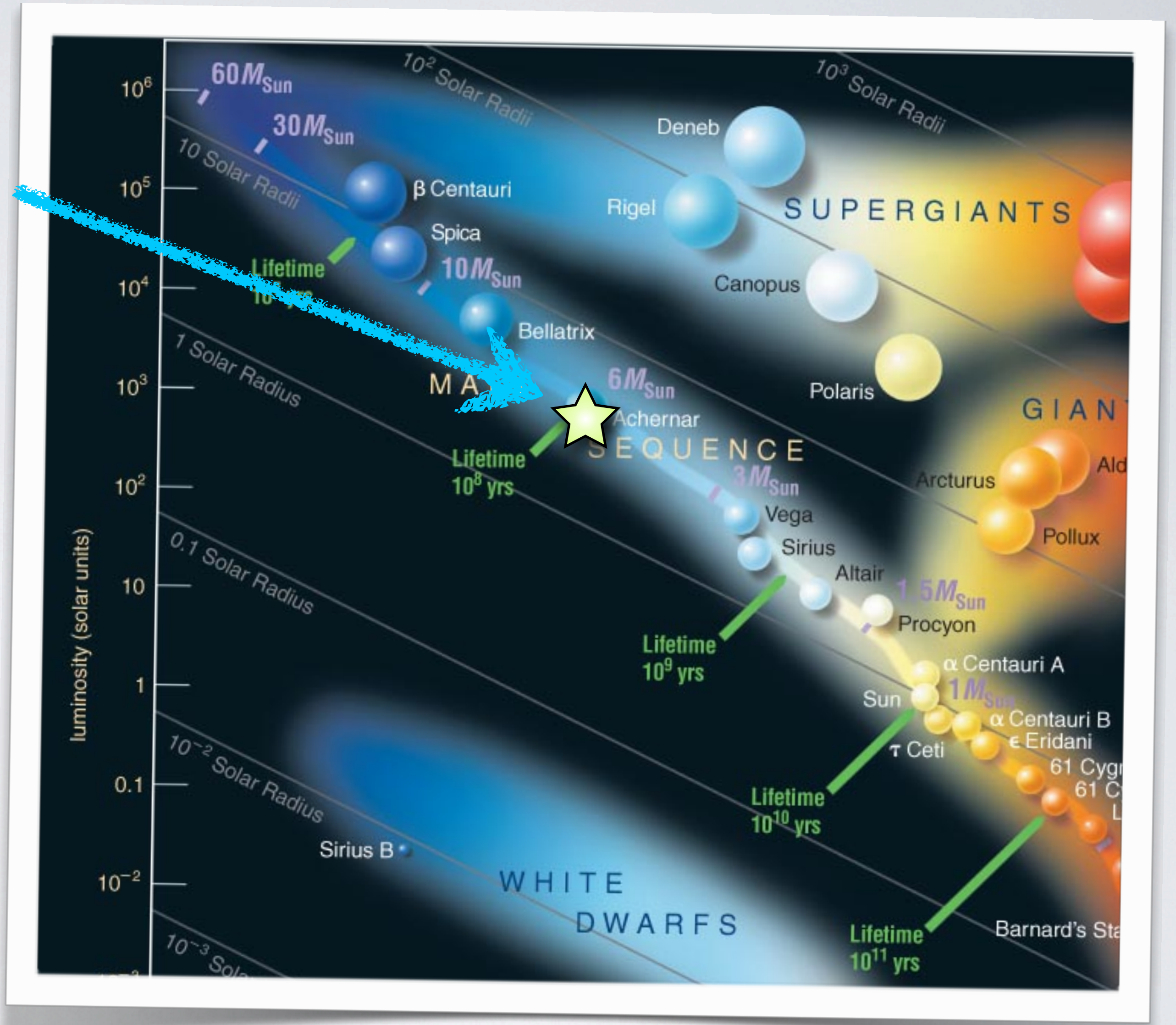

10^6
10^5
10^4
10^3
10^2
10
1
luminosity (solar units)
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
Deneb
Rigel
β Centauri
Spica
Canopus
Bellatrix
Polaris
SUPERGIANTS
Betelgeuse
Antares
GIANTS
Aldebaran
Arcturus
Pollux
MAIN SEQUENCE
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Vega
Sirius
Altair
Procyon
α Centauri A
Sun
1 M_{Sun}
α Centauri B
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
0.3 M_{Sun}
Gliese 725 A
Gliese 725 B
Barnard's Star
0.1 M_{Sun}
Ross 128
Proxima Centauri
DX Cancri
G
K
M
3,000
decreasing temperature →
high-mass star
1 M_{Sun} star
very low mass star

STELLAR EVOLUTION



Ekström et al. 2012, A&A, 537, A146

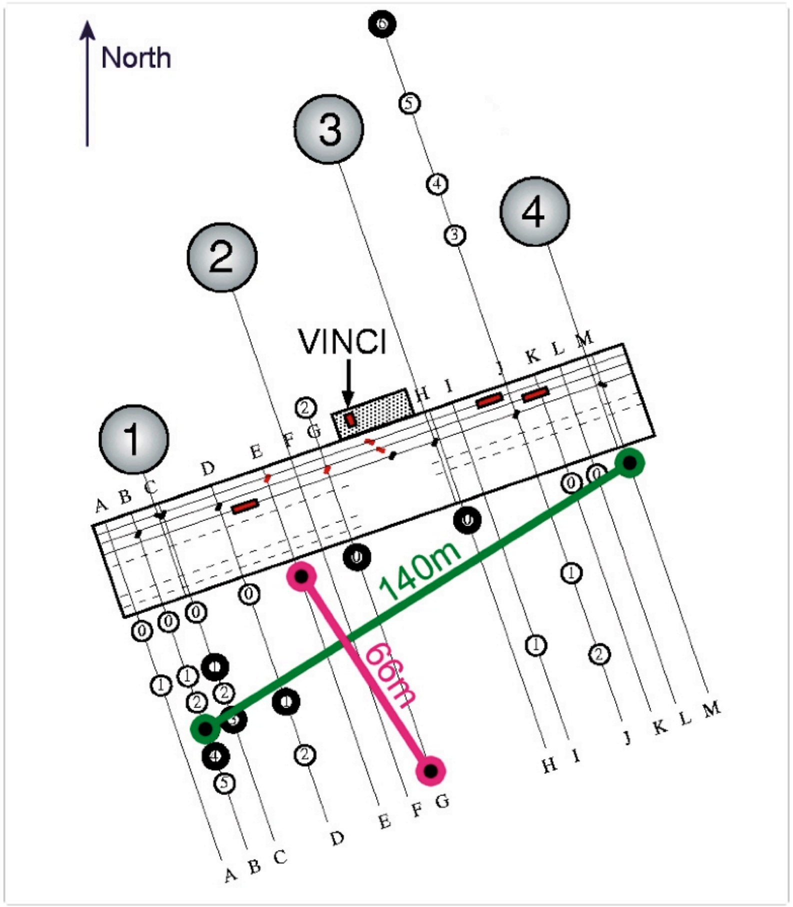
Achernar B3Ve



VLTI-VINCI OBSERVATIONS

- Achernar was among the first stars observed with the VLTI in 2001-2002
- Recombination of 2 telescopes
- 2 perpendicular baselines + efficient supersynthesis

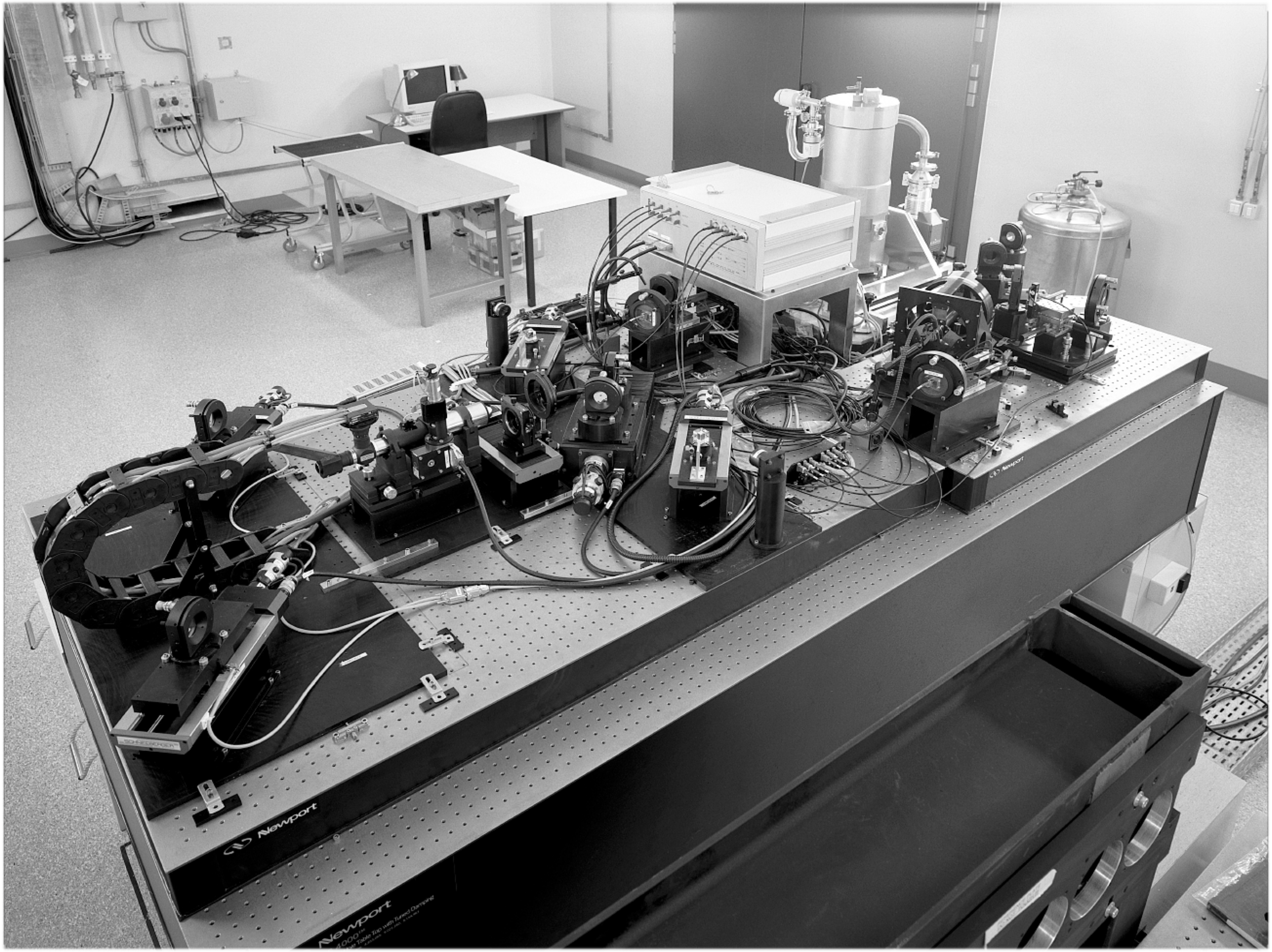
What is the maximum distance at which it is possible to resolve completely a star identical to the Sun with the VLTI ? (B=140m, λ=1.6 µm)



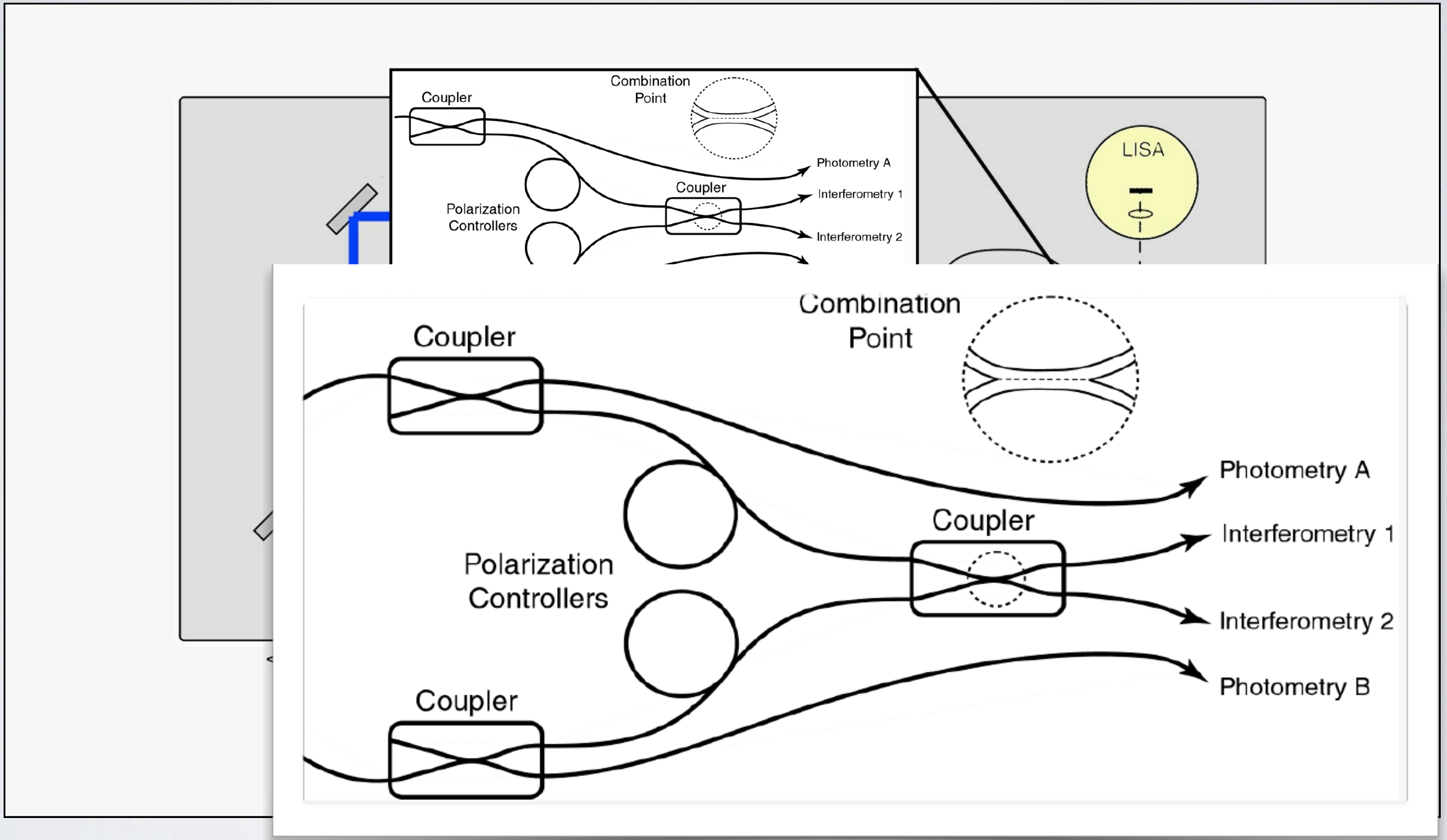
Resolution 1.6 µm/ 202m = 2.3 mas = the Sun at 4.1 pc = parallax > 247mas

33 stars in the Gliese catalogue, but most of them are very small (red dwarfs)

But it is possible to resolve bigger stars at larger distances ! *Achernar* for example...


Newport
Newport
Newport

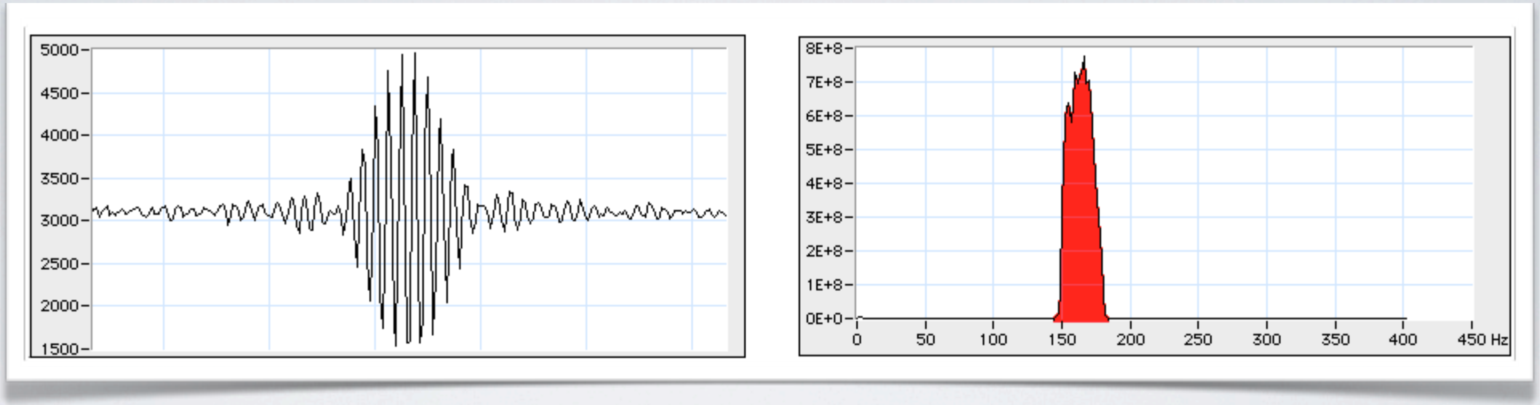
PRINCIPLE OF VINCI



What is the overall photometric efficiency of the VLTI + VINCI ?
(22 mirors in each "arm", injection in fibers, K band filter, camera...)

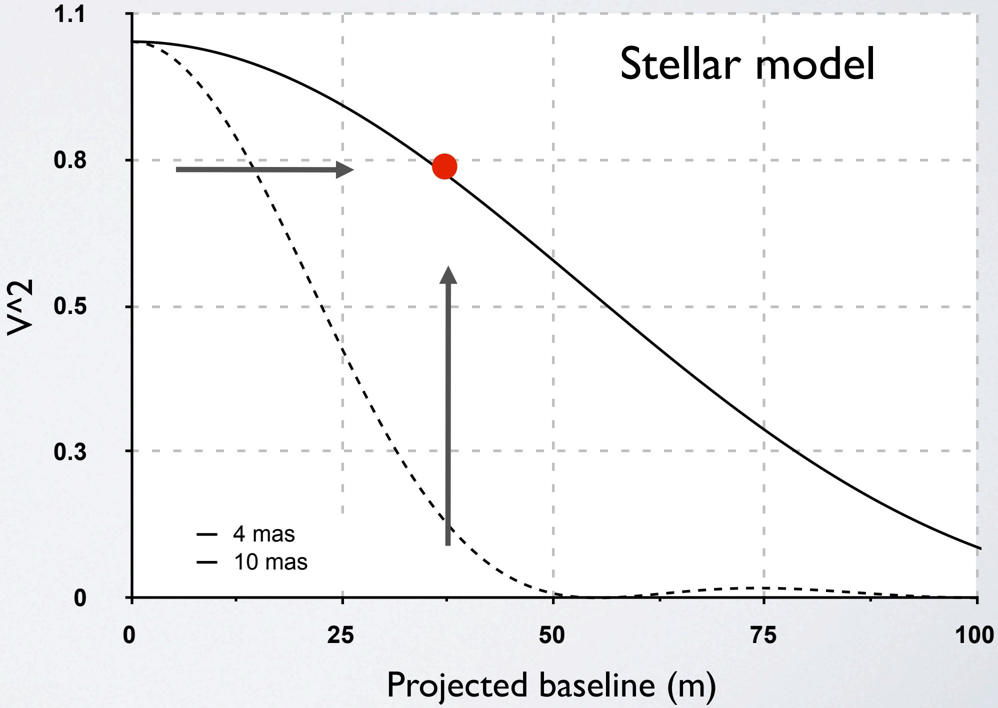
MEASUREMENT OF THE COHERENCE FACTOR

Estimator used in VINCI



Calibration of the interferometric efficiency of the system:

Observation of a calibrator star with a known visibility



ANALYSIS OF VINCI OBSERVATIONS

1. Presentation of the observations
2. Raw data reduction
3. Visibility calibration
4. Visibility model fitting
5. Interpretation of the results

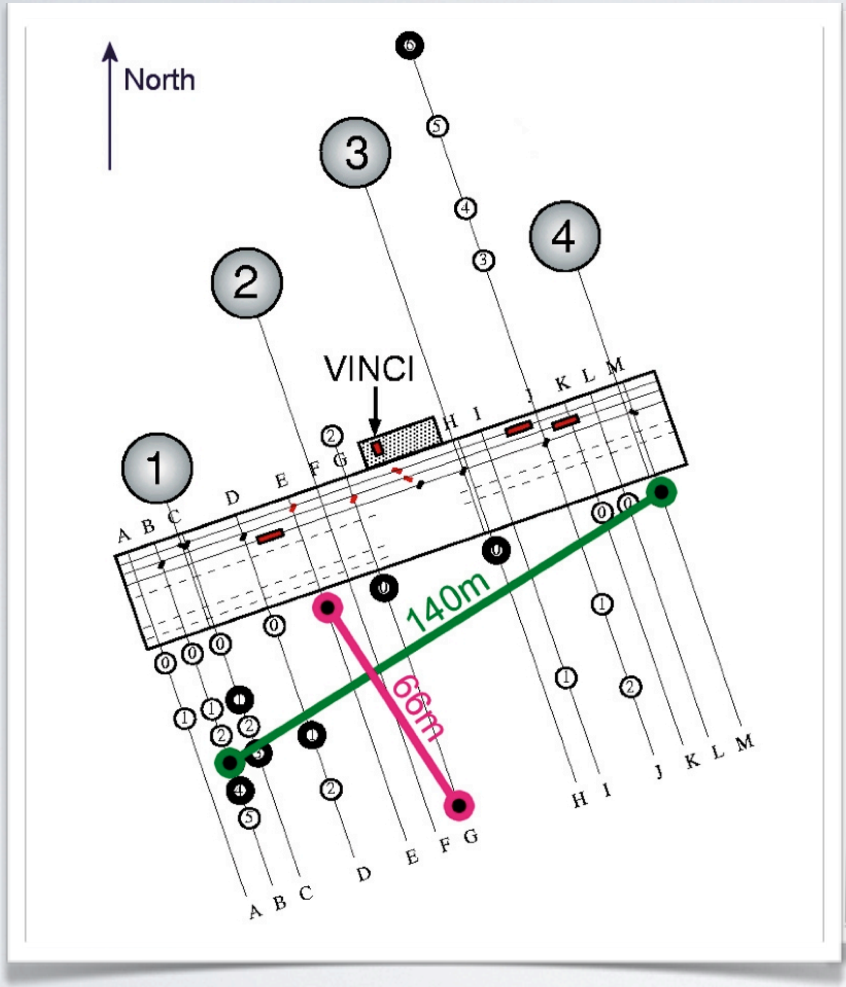
OVERVIEW OF THE OBSERVATIONS

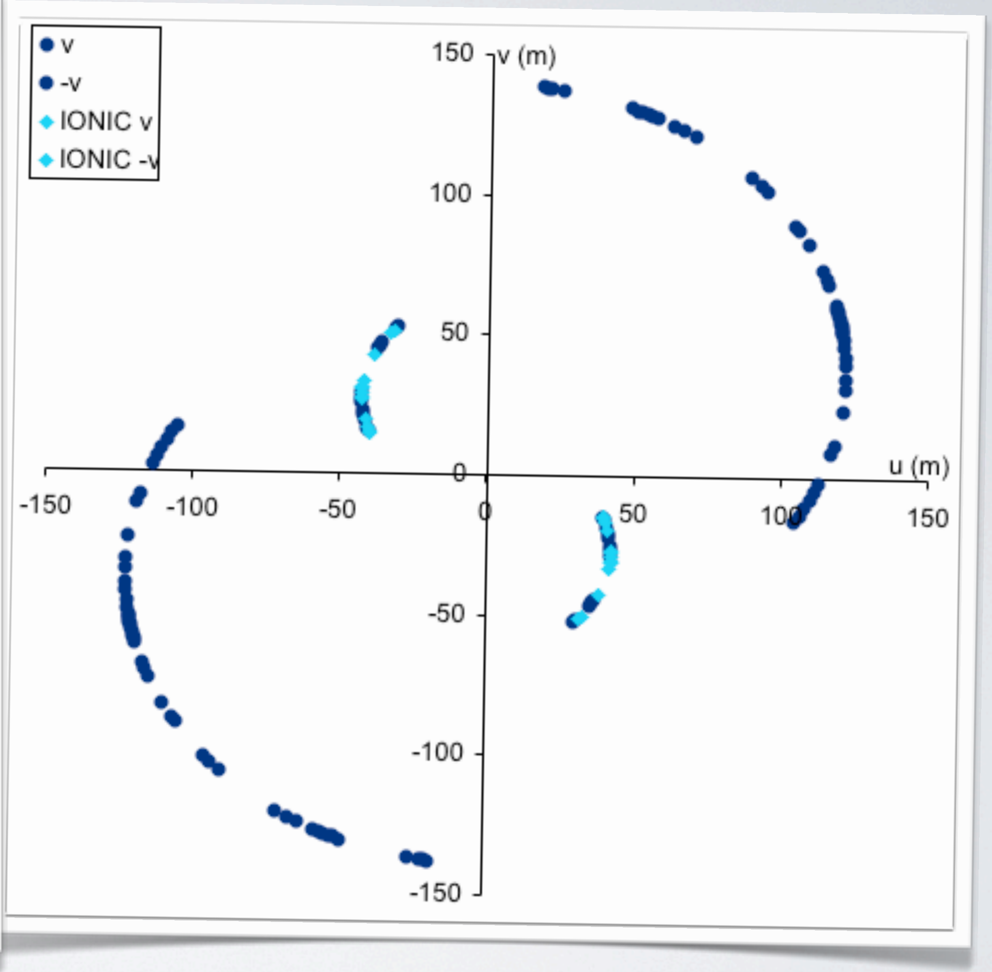
- Pairs of Achernar + calibrator observations
  - estimation of the transfer function of the VLTI
  - 4 distinct calibrators

- **60 V^2 mesurements** in the K band (over 16 nights)
- **14 V^2 mesurements** in the H band (over 7 nights)

- Supersynthesis
  - Achernar = dec -60 deg ⇒ supersynthesis is efficient
  - observations at different hour angles
  - variable projected baseline

SUPERSYNTHESIS

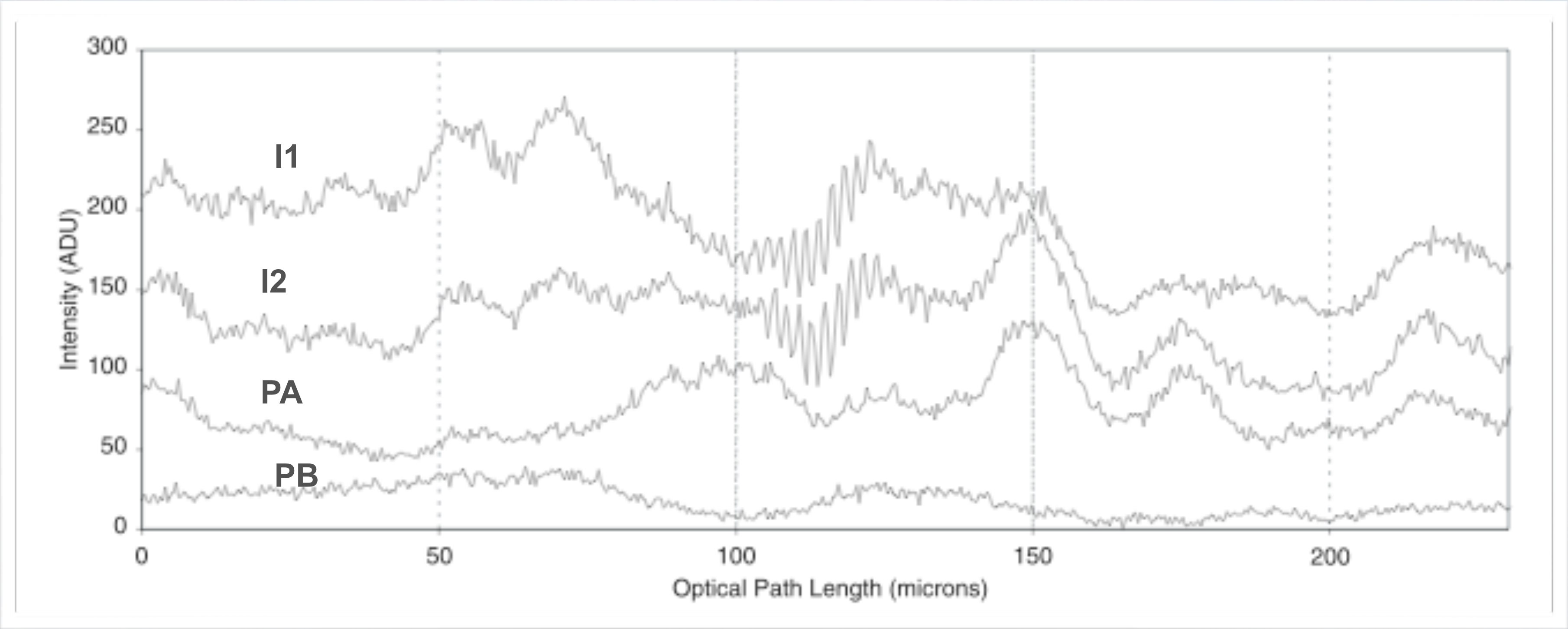




- Almost complete coverage in azimuth

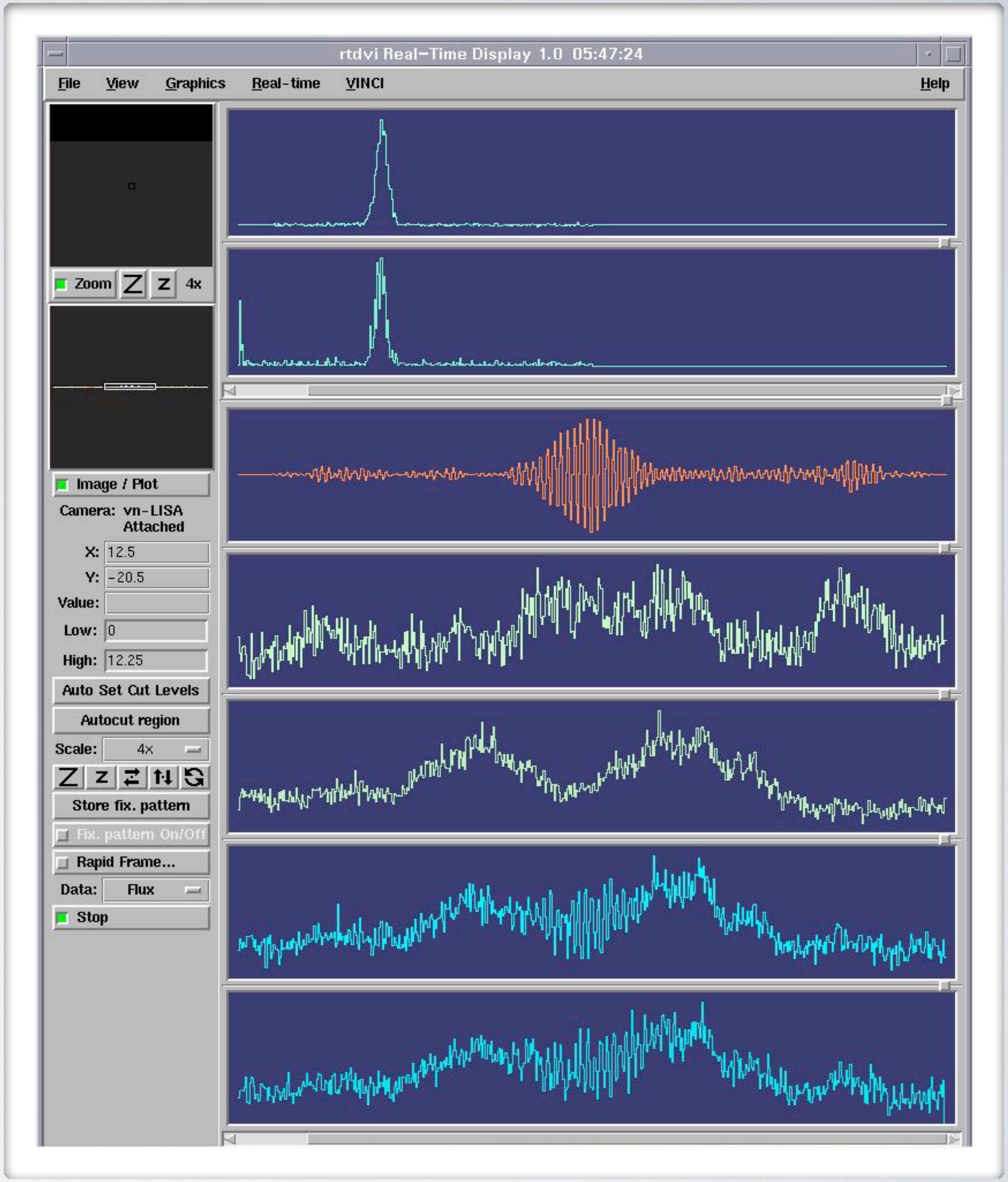
RAW DATA PRODUCED BY VINCI

- The raw data contain 4 signals:
  - two photometric signals PA and PB
  - two interferometric signals I1 and I2



IN REAL TIME...

- 2 to 10 interferograms per second
- One observation with 500 interferograms takes ~**5 minutes**
- A calibrator star is observed before and after the scientific target



Camera: vn-LISA Attached

X: 12.5

Y: -20.5

Value:

Low: 0

High: 12.25

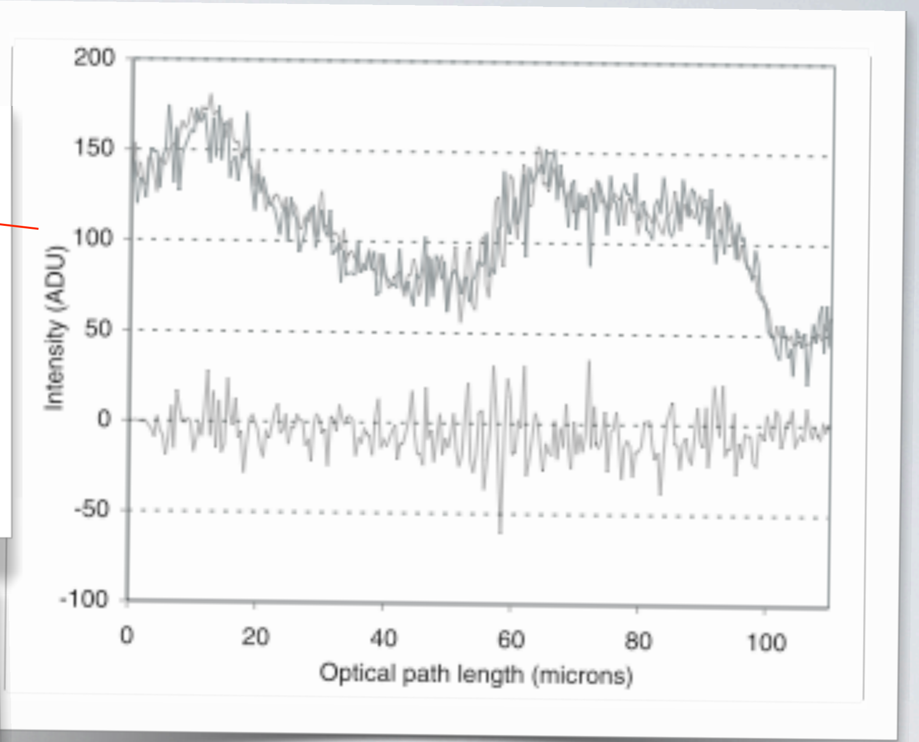
Scale: 4x

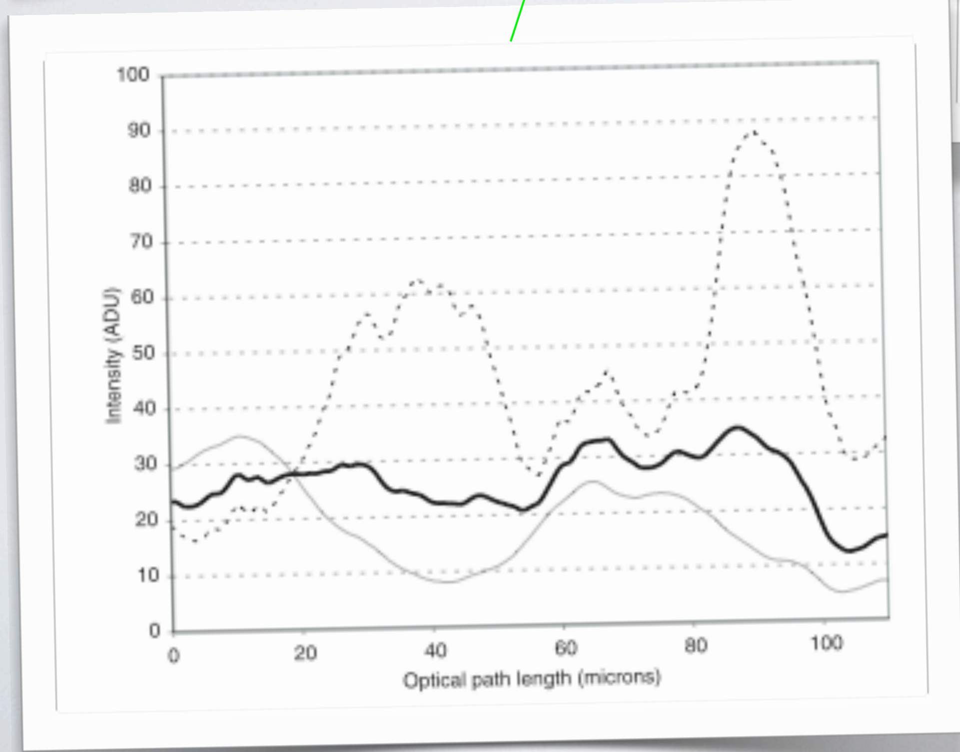
Data: Flux

NORMALIZATION

$$I_{1\,\mathrm{cal}} = \frac{1}{2\sqrt{\kappa_{1,\mathrm{A}}\,\kappa_{1,\mathrm{B}}}}\,\frac{I_1 - \kappa_{1,\mathrm{A}}P_\mathrm{A} - \kappa_{1,\mathrm{B}}P_\mathrm{B}}{[\sqrt{P_\mathrm{A}\,P_\mathrm{B}}]_\mathrm{Wiener}}$$

$$I_{2\,\mathrm{cal}} = \frac{1}{2\sqrt{\kappa_{2,\mathrm{A}}\,\kappa_{2,\mathrm{B}}}}\,\frac{I_2 - \kappa_{2,\mathrm{A}}P_\mathrm{A} - \kappa_{2,\mathrm{B}}P_\mathrm{B}}{[\sqrt{P_\mathrm{A}\,P_\mathrm{B}}]_\mathrm{Wiener}}.$$



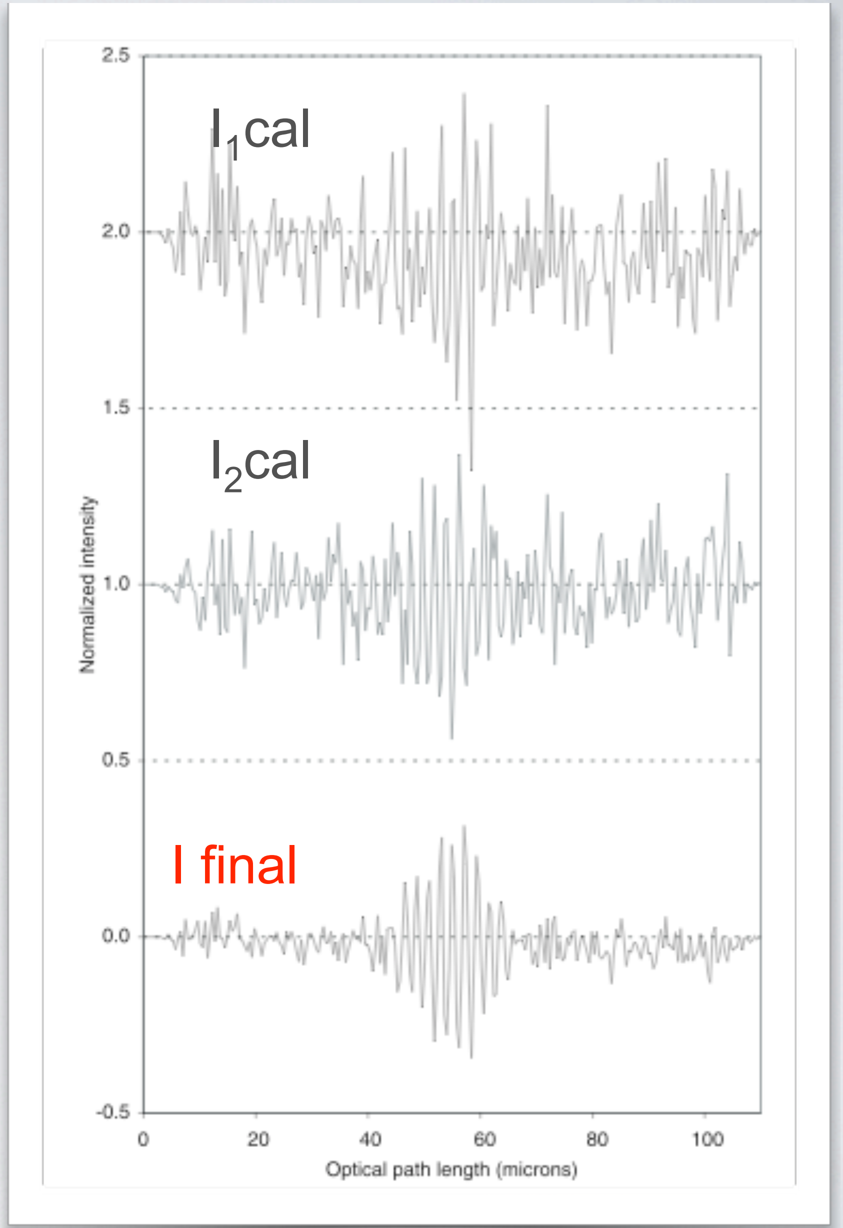


correction of almost all the atmospheric perturbations of the fringe signal

SUBTRACTION OF THE NORMALIZED SIGNALS

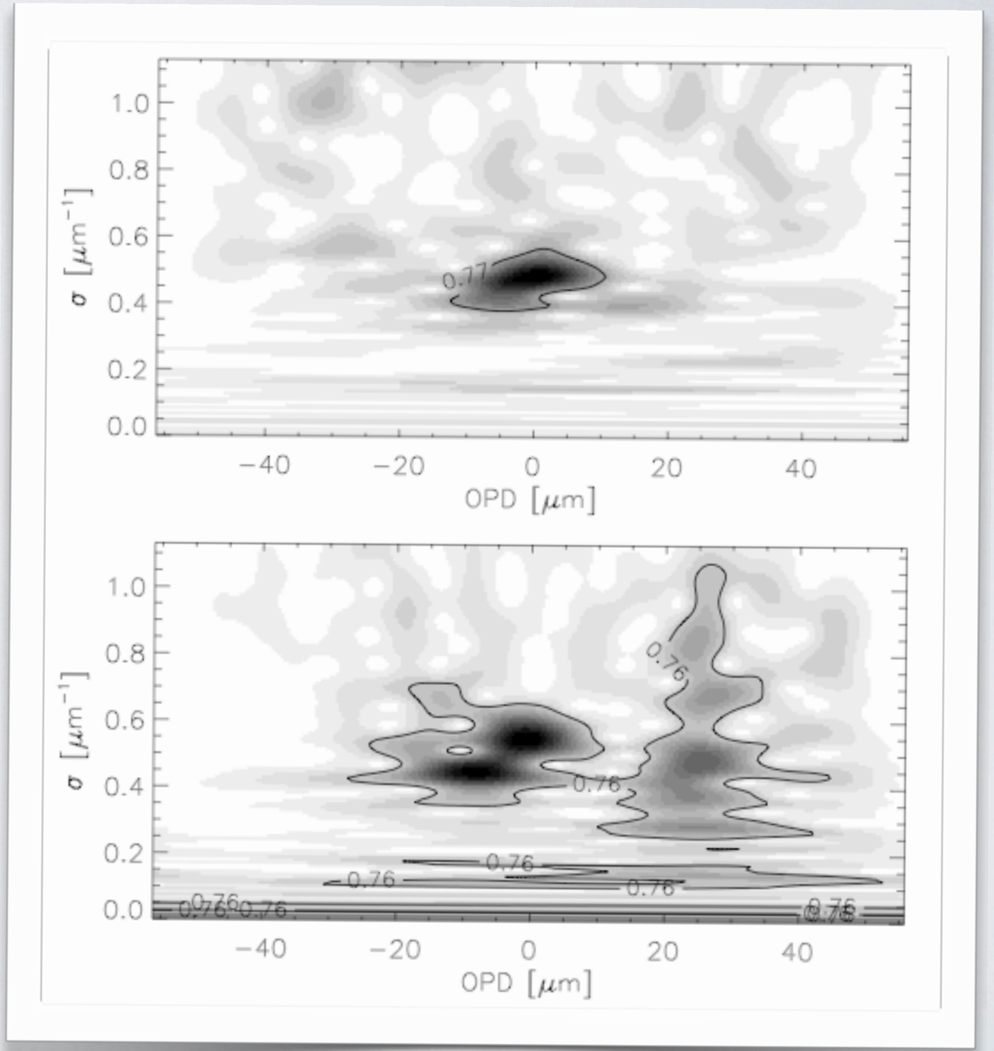
$$I = \frac{I_{1\,\mathrm{cal}} - I_{2\,\mathrm{cal}}}{2}.$$

- to remove the correlated noises introduced during the subtraction and normalization



SELECTION OF THE INTERFEROGRAMS

- Wavelet transform
  - time-frequency analysis
- Gives the possibility to reject the interferograms affected by the *atmospheric piston*

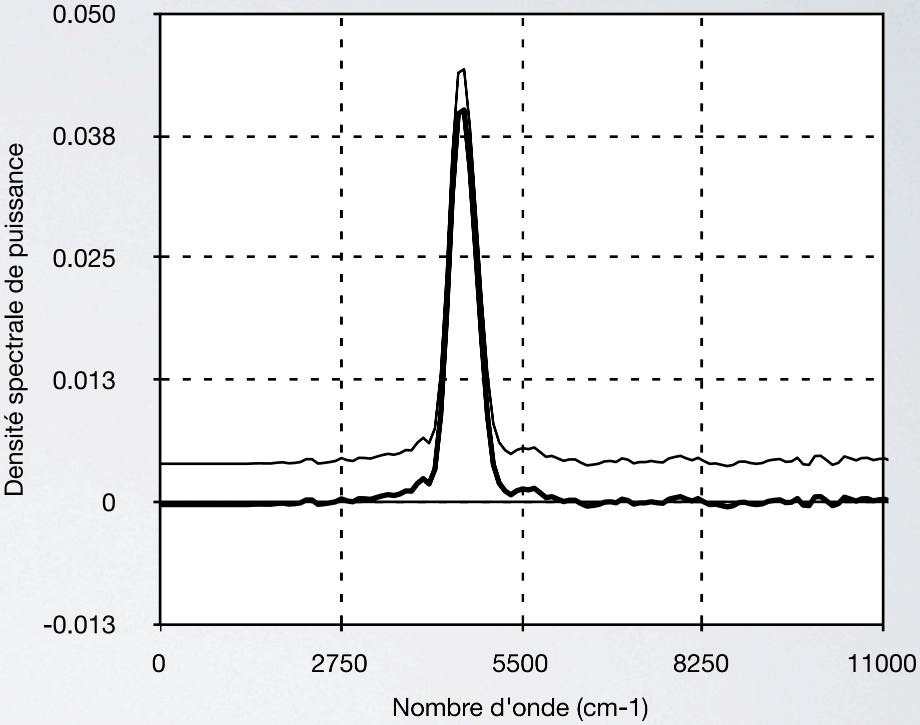


INTEGRATION OF THE MODULATED POWER

Power spectral density of the wavelet transform, projected on the frequency axis over the fringe extension in OPD

The power spectrum of the fringes does not show residuals around the fringe peak.

The integration of the fringe peak gives the squared coherence factor μ^2



What is the origin of the power spectrum "background" that we have to subtract before integrating the fringe peak ?

VISIBILITY CALIBRATION TRANSFER FUNCTION

- The efficiency of the interferometer + atmosphere is not perfect, and it does not transmit 100% of the modulation of the fringes

- This loss of modulation must be measured and corrected

- We therefore observe a star with a known angular diameter, the *calibrator*

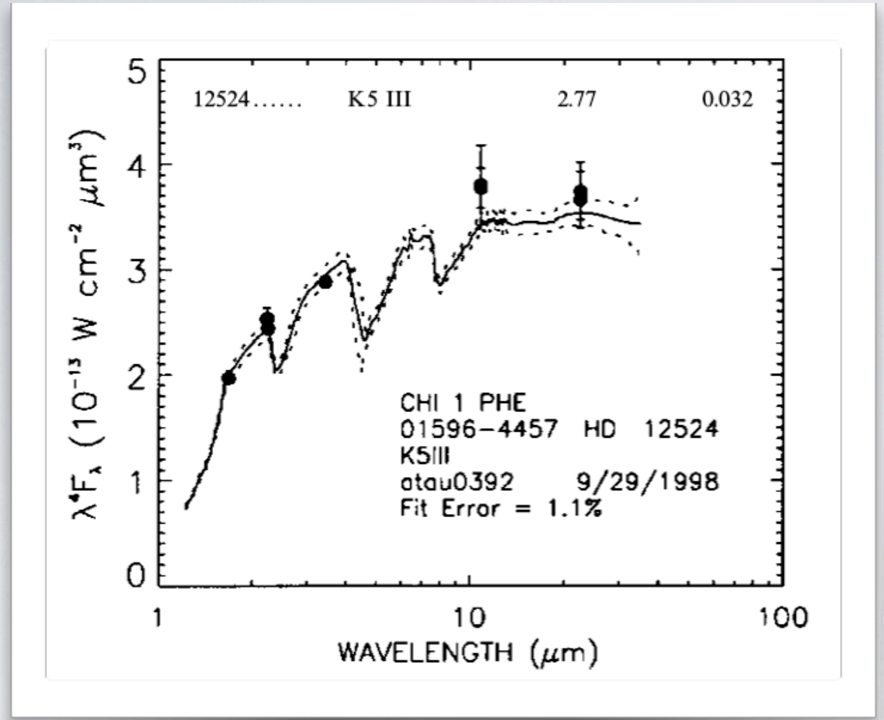
- Knowing the expected visibility, we can estimate precisely the transfer function **T^2**, and corrext the instrumental squared coherence factor **μ^2** or the source

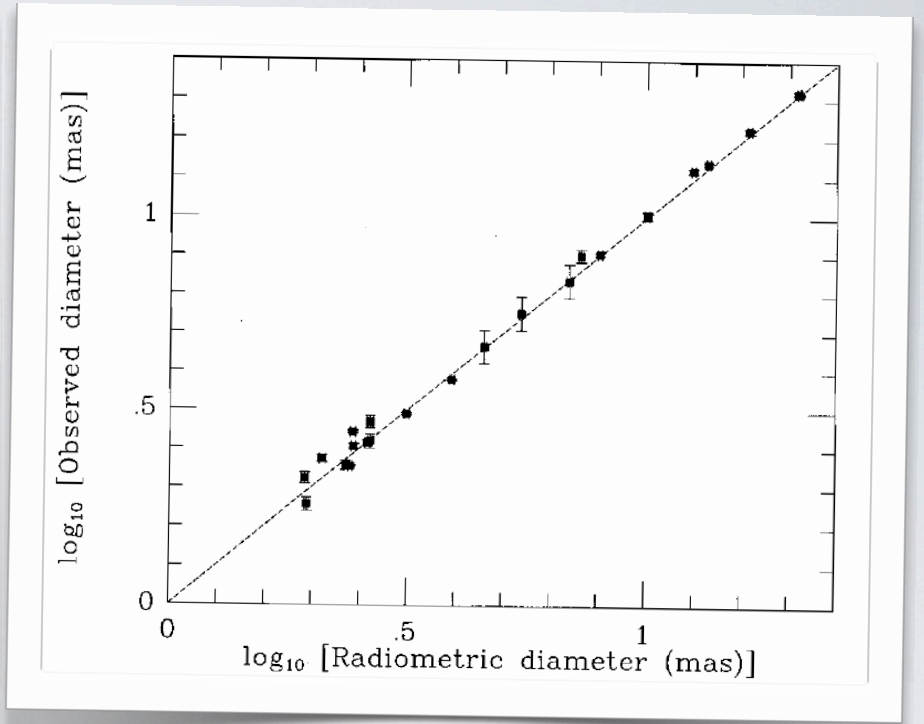
$$T^2 = \frac{\mu^2_{\text{calib}}}{V^2_{\text{calib}}}$$

$$V^2_{\text{source}} = \frac{\mu^2_{\text{source}}}{T^2}$$

How can we predict the size of a calibrator ?

SIZE OF THE CALIBRATOR





- Calibrator χ Phe: θ_{LD} = 2.77 +/- 0.03 mas, θ_{UD} = 2.69 +/- 0.03 mas

  Linear limb darkening correction in the K band : θ_{DA}/θ_{DU} = 1.03, (T_{eff}=4000 K, log g=2)
- Beware of binary stars and fast rotators...

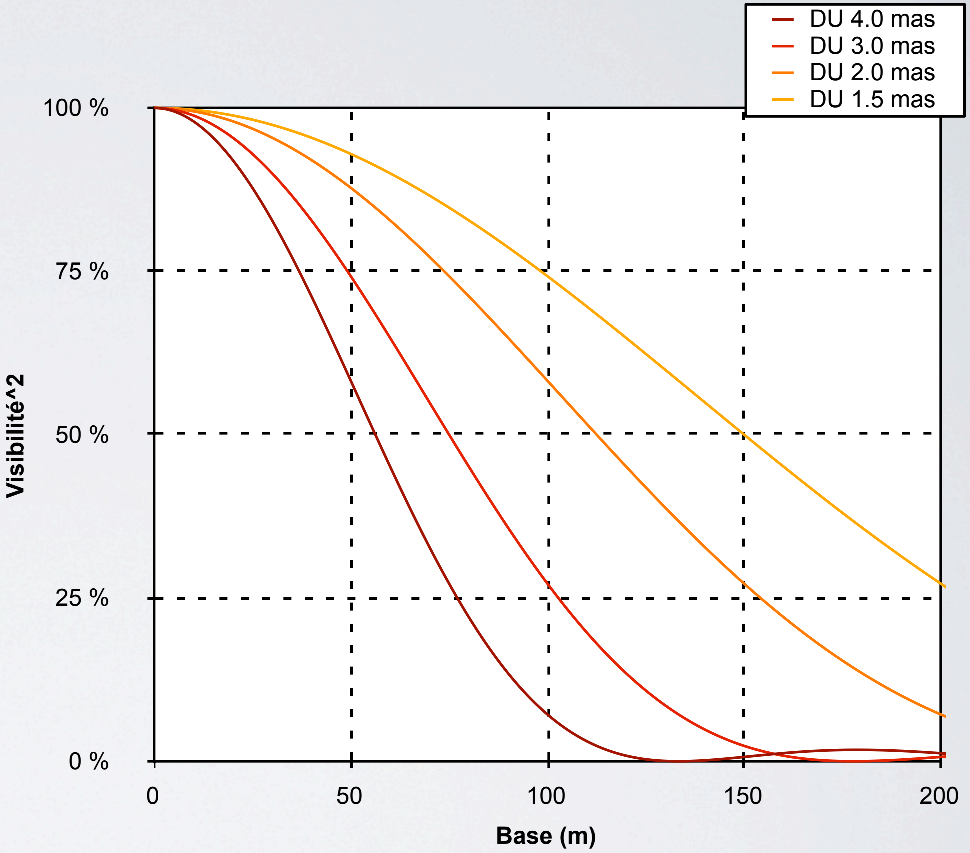
VISIBILITY MODEL

For Achernar, our goal is to measure the shape of its distorted photosphere

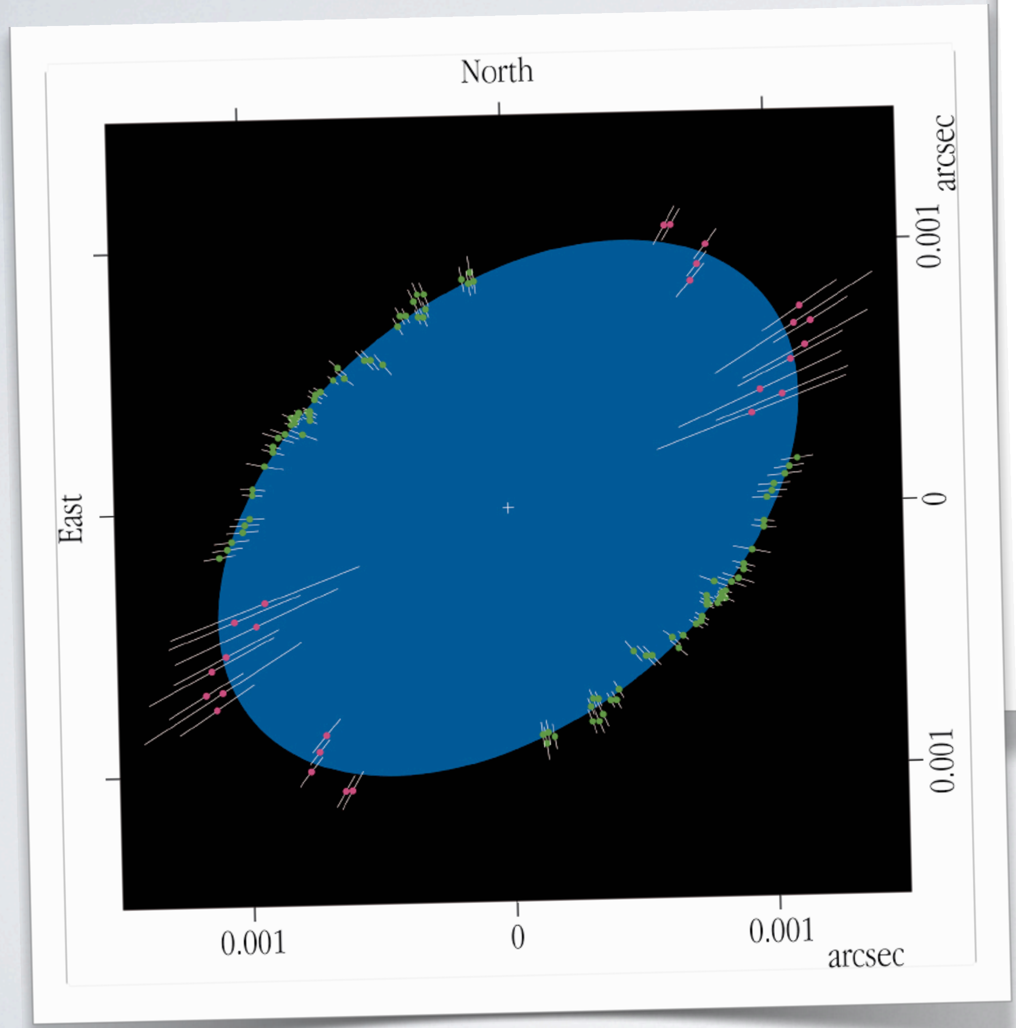
- First step: *uniform circular disk* size as a function of azimuth

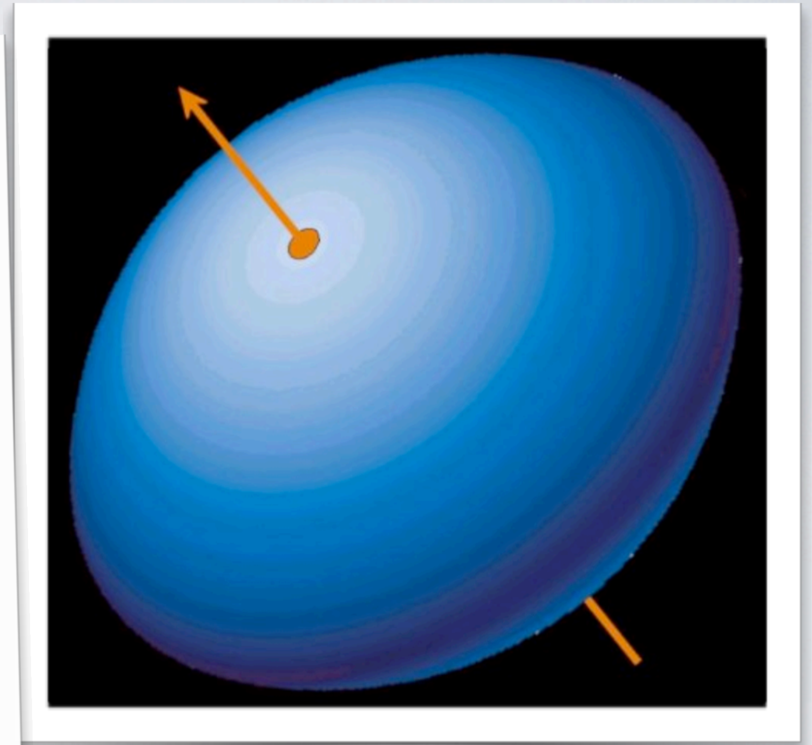
$$V\left(S = \frac{B}{\lambda}\right) = \frac{2J_1(\pi \O_{UD} S)}{\pi \O_{UD} S}$$

- Second step: a *uniform ellipse* model



FIRST STEP: UNIFORM DISK SIZE FUNCTION OF AZIMUTH

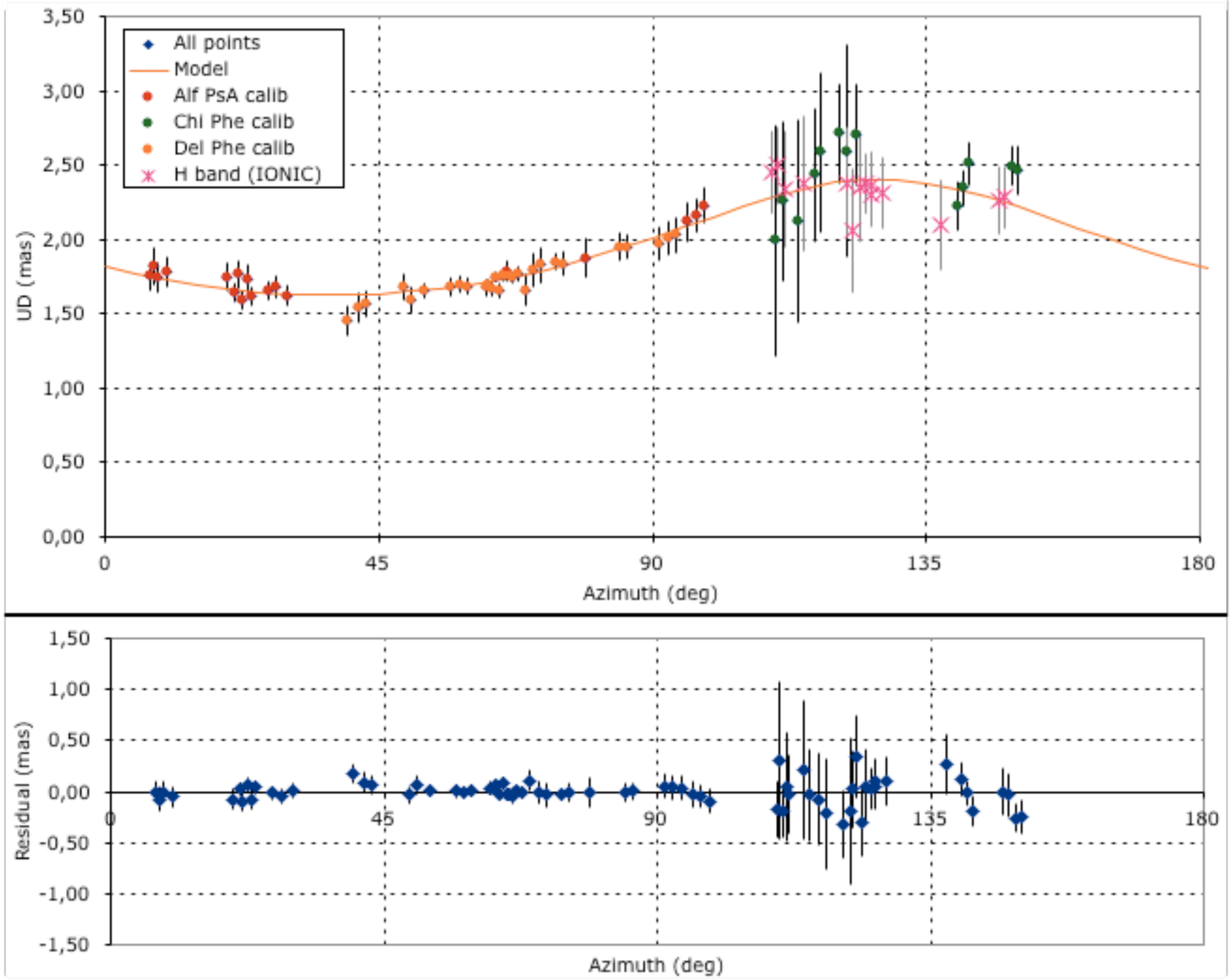




a/b ~ 1,56

Physical model not flat enough ?

DIFFERENT CALIBRATORS



SECOND STEP: ELLIPSE MODEL

- Ellipse model:

$$\theta_{DU}(Az) = \frac{1}{\sqrt{\left(\frac{\cos(Az-\alpha)}{2a}\right)^2 + \left(\frac{\sin(Az-\alpha)}{2b}\right)^2}}$$

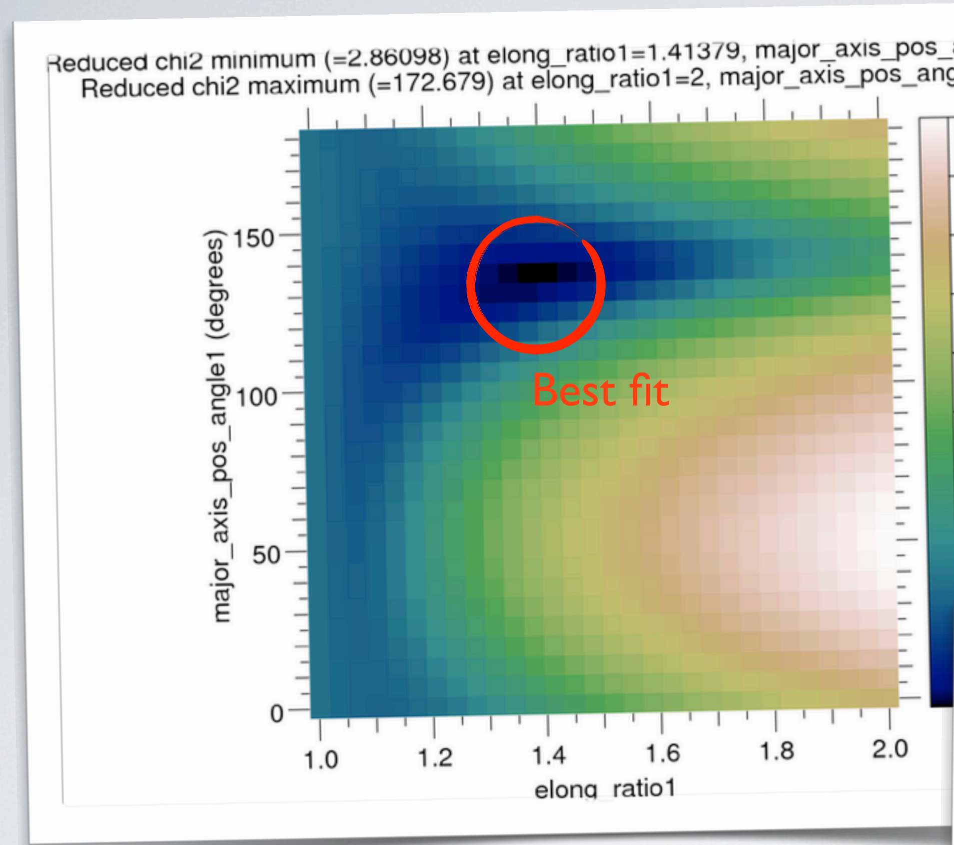
- Fit of the parameters α, a, b

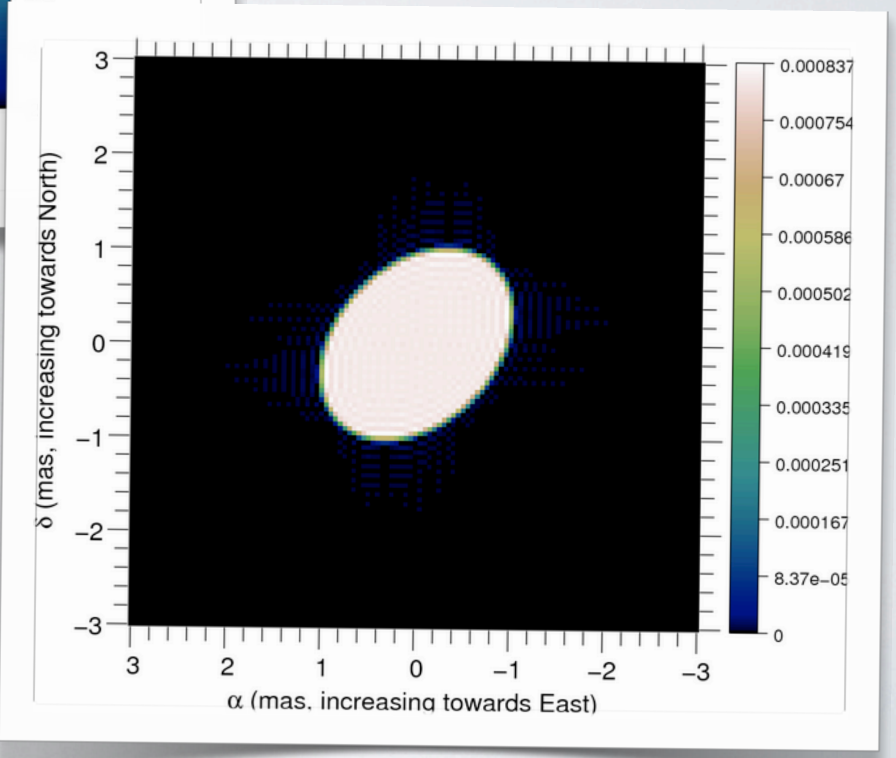
- Minimization of the following quantity:

$$\chi^2(\alpha,a,b) = \sum_i \frac{\left(V_i^2{}_{\text{mesuré}} - V^2{}_{\text{modèle}}(Az_i)\right)^2}{\sigma_i^2\left(V^2\right)}$$

How are the error bars computed ?

General method: $\chi^2 = \chi^2$ minimum + 1





Adjustment using LITpro:

a/b = 1.41

INTERPRETATION

What do you think of the derived flattening ?
Does it agree with the Huygens approximation for Achernar (1.34) ?

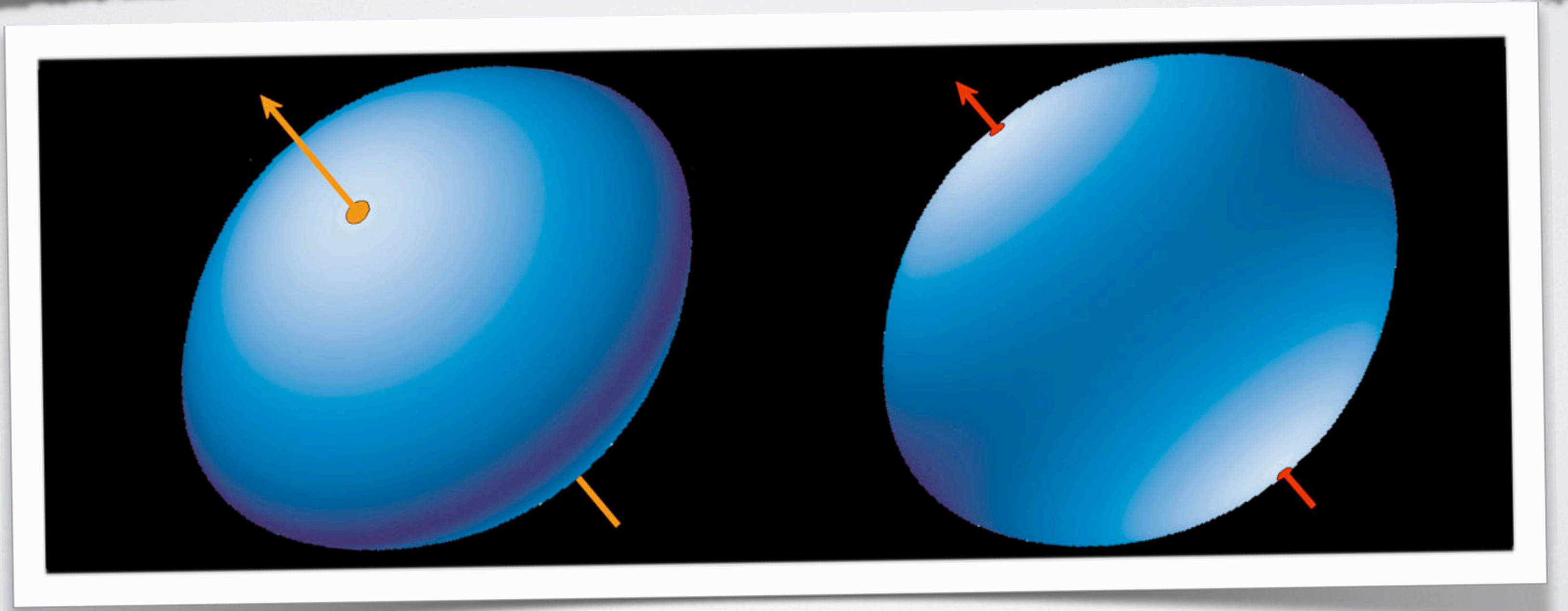
Mass	6	Msol		
Equatorial radius	9.2	Rsol		
Equatorial velocity	280	km/s		
Msol	2.00E+30	kg		
Rsol	7.50E+08	m		
G	6.67E-11	SI		
Period	1.55E+05	s	1.79	days
omega	4.06E-05	rad/s		
Density	8.72E+00	kg/m3		
Flattening	**1.34**			

- Additional phenomena:
  - Von Zeipel effect
  - differential rotation
  - circumstellar material
  - ...

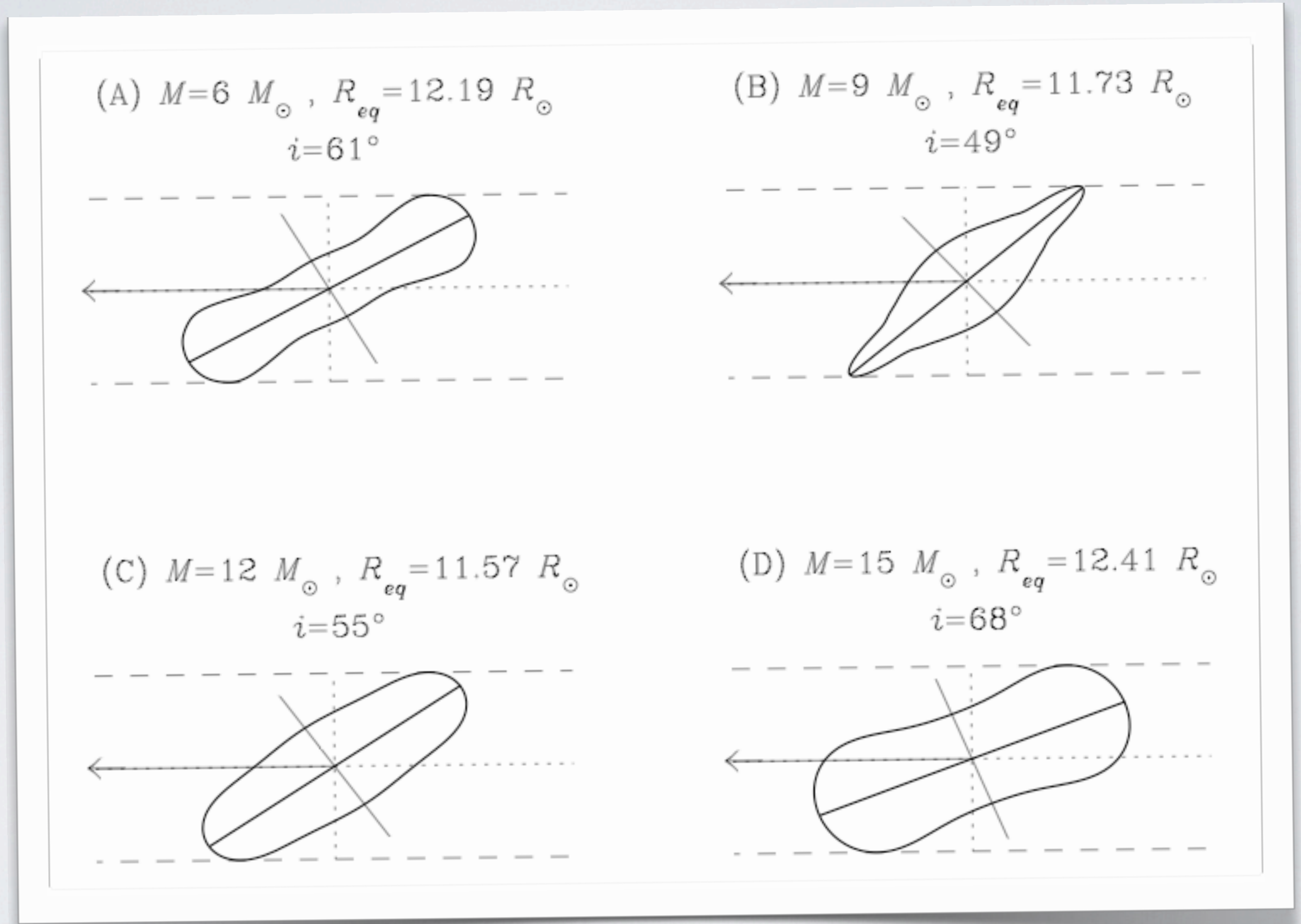
GRAVITY DARKENING

In a uniformly rotating star, the emerging radiative flux is proportional to the local effective gravity $(g_{\mathrm{eff}})^{1/4}$.

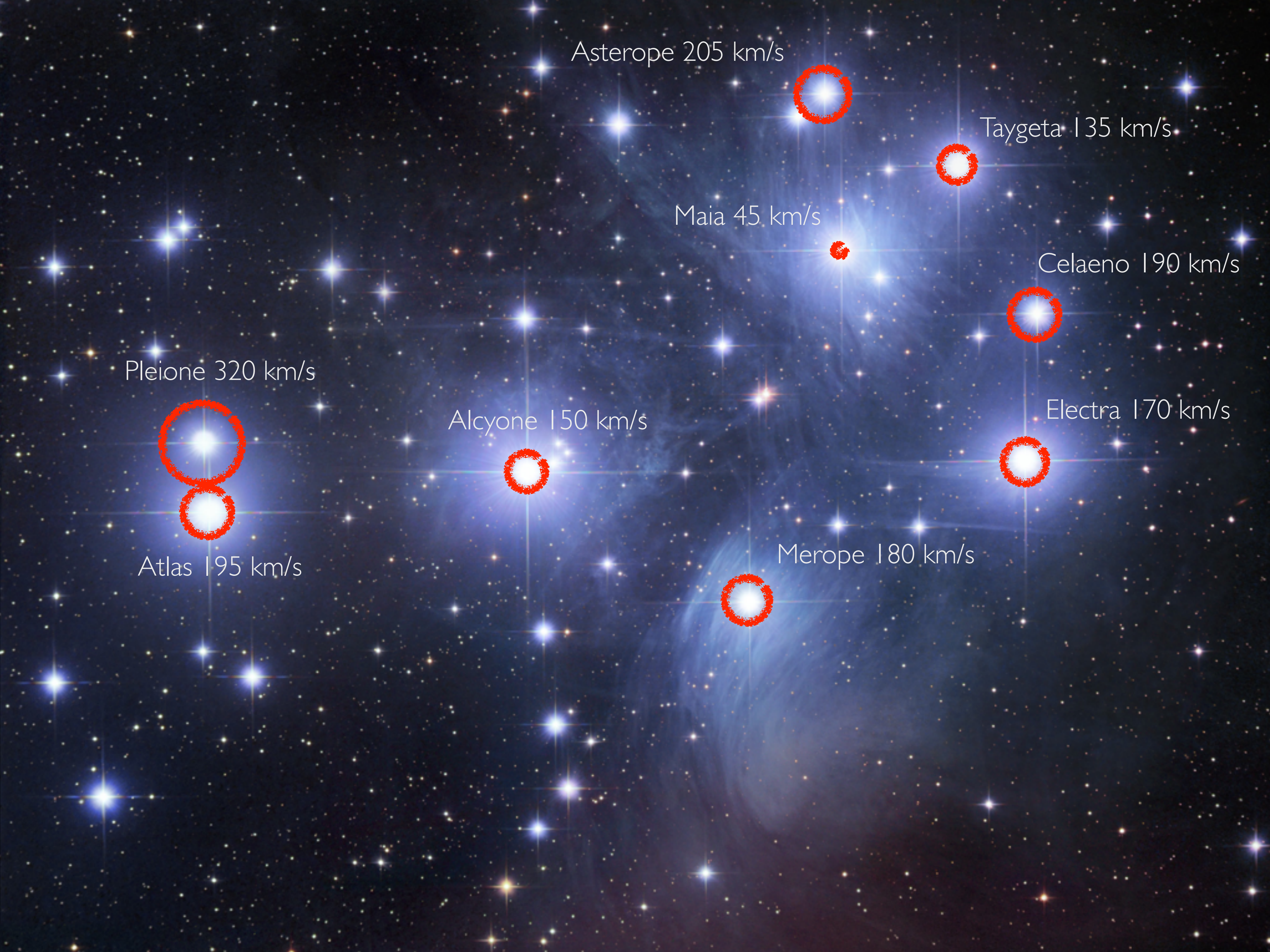
H. Von Zeipel 1924, MNRAS, 84, 665

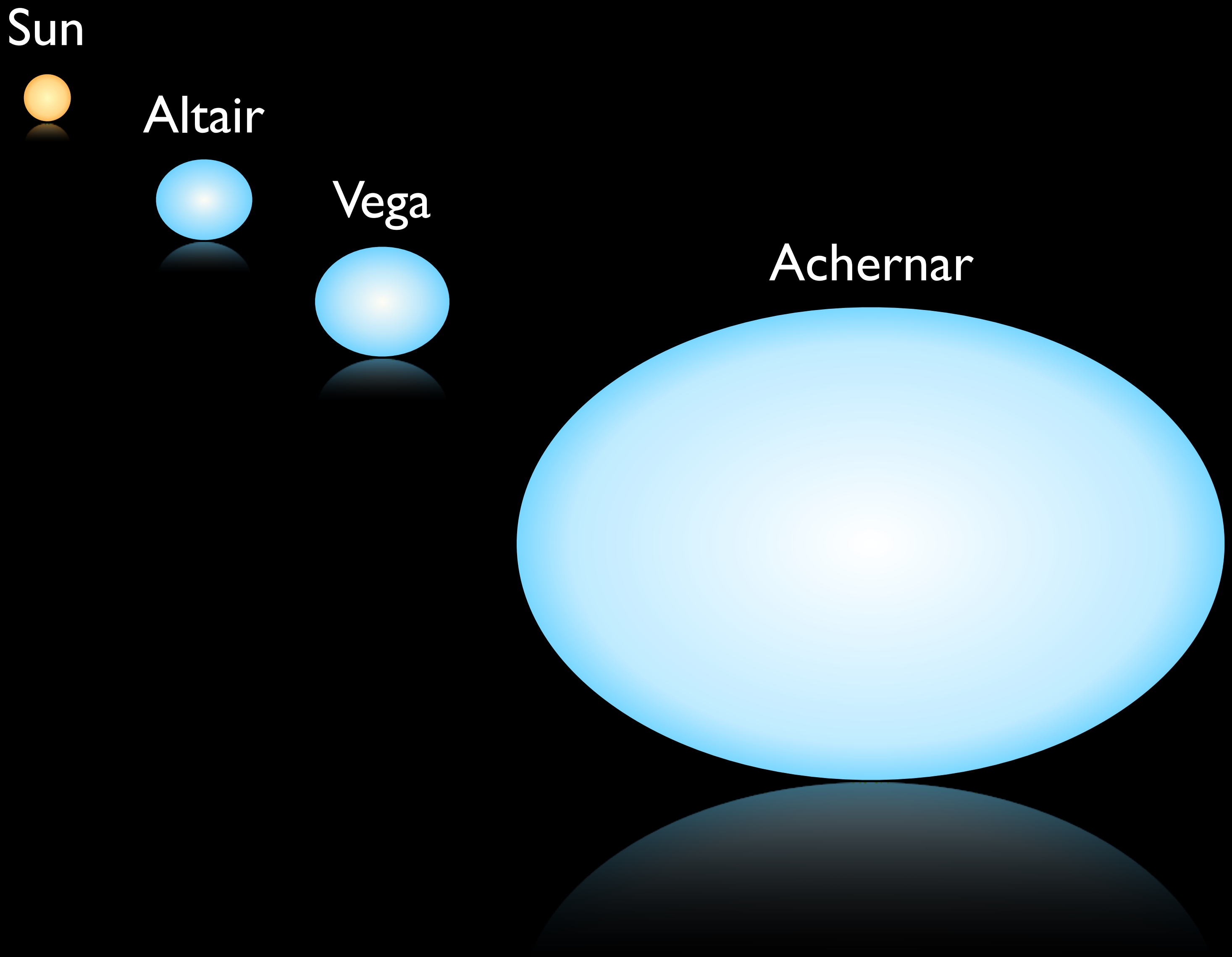


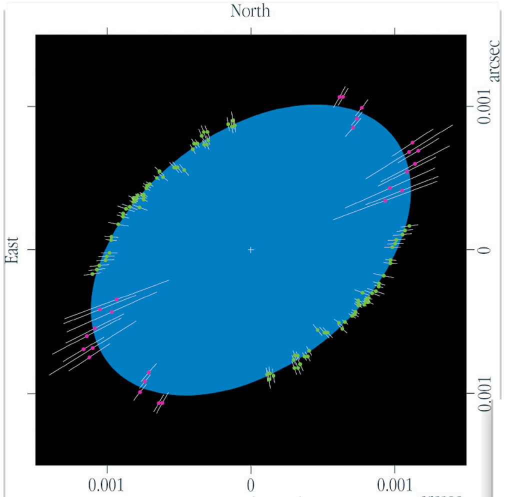
MODELS WITH DIFFERENTIAL ROTATION



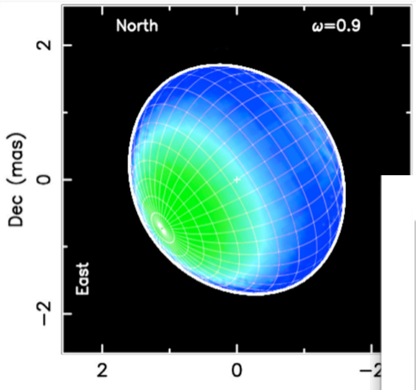
Jackson et al. (2004)


Asterope 205 km/s
Taygeta 135 km/s
Maia 45 km/s
Celaeno 190 km/s
Pleione 320 km/s
Alcyone 150 km/s
Electra 170 km/s
Atlas 195 km/s
Merope 180 km/s

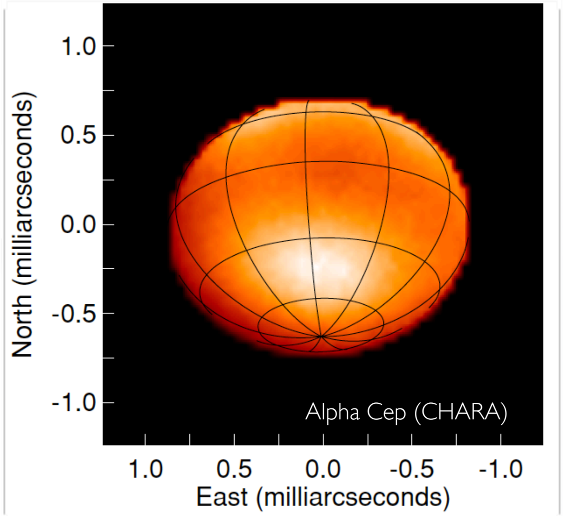

Sun
Altair
Vega
Achernar



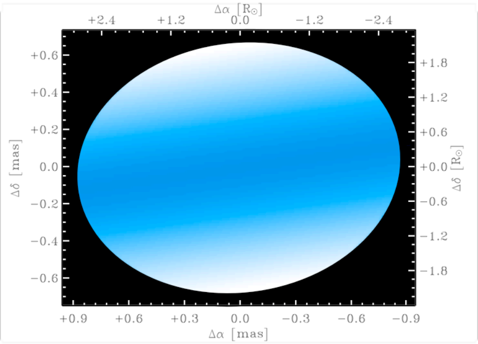
Achernar (VLTI)



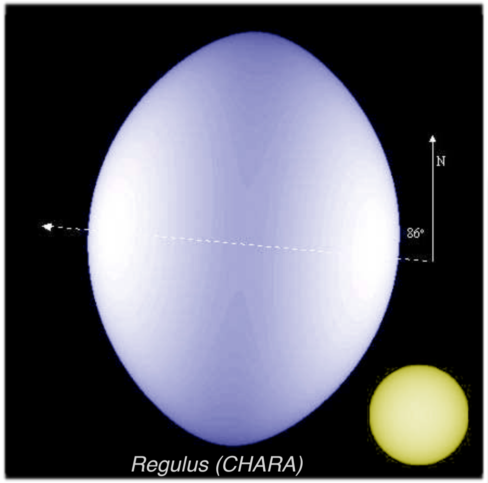
Altaïr (NPOI)



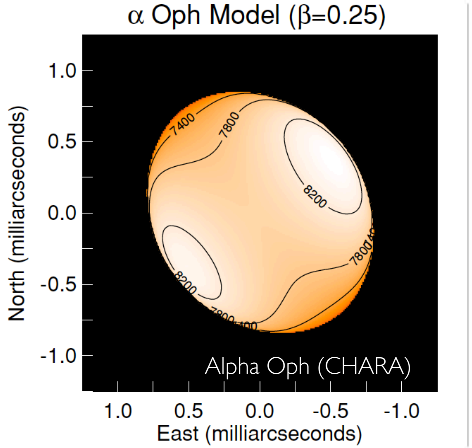
Alpha Cep (CHARA)



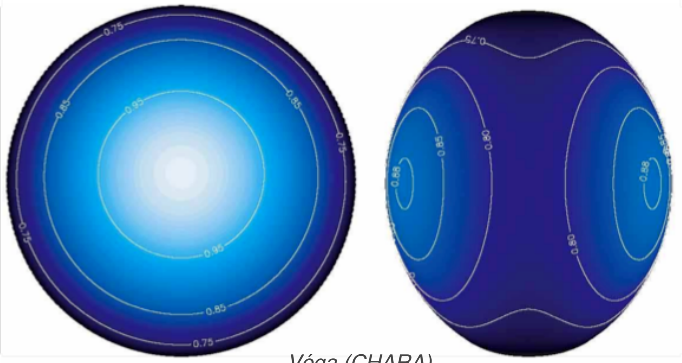
Alderamin (CHARA)



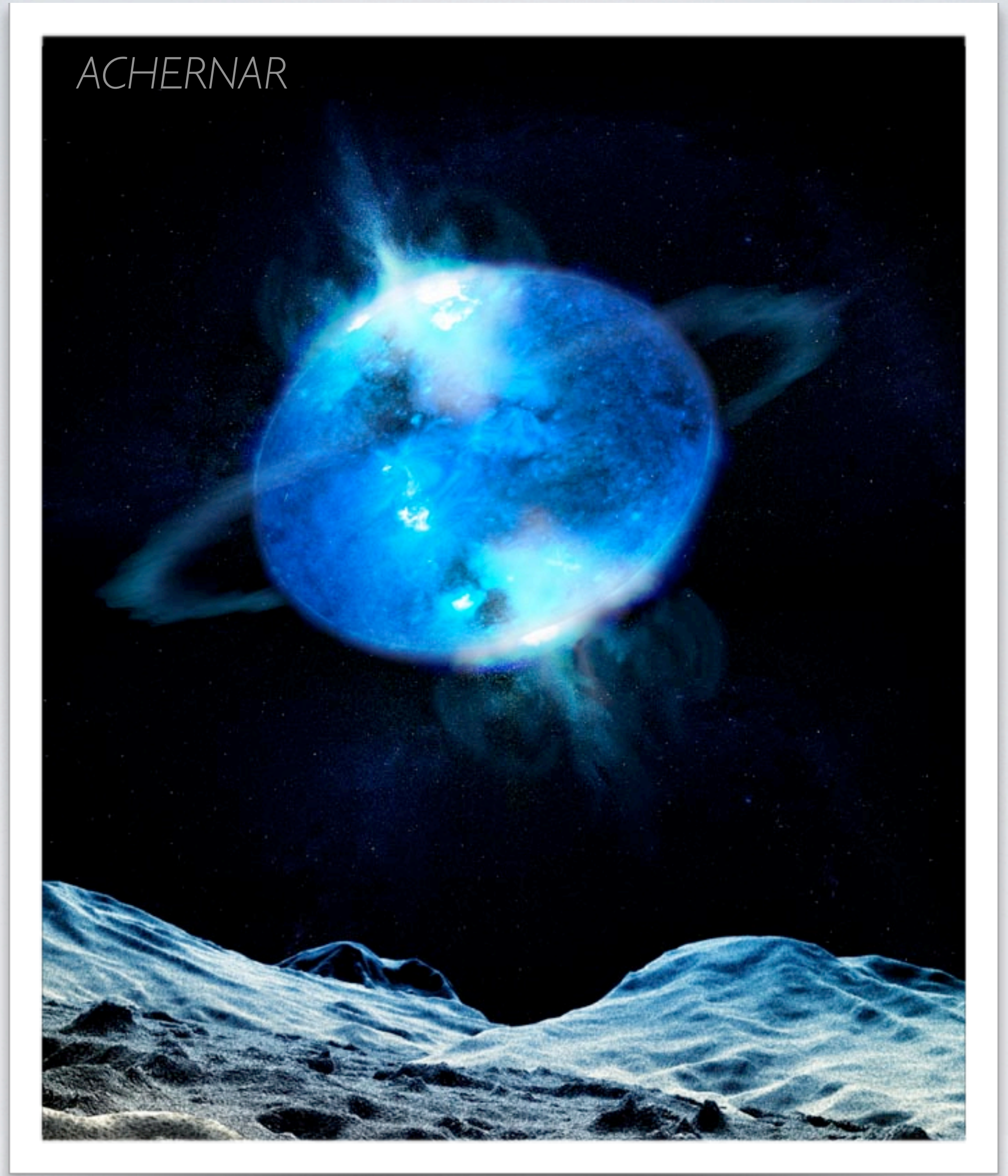
Regulus (CHARA)



Alpha Oph (CHARA)

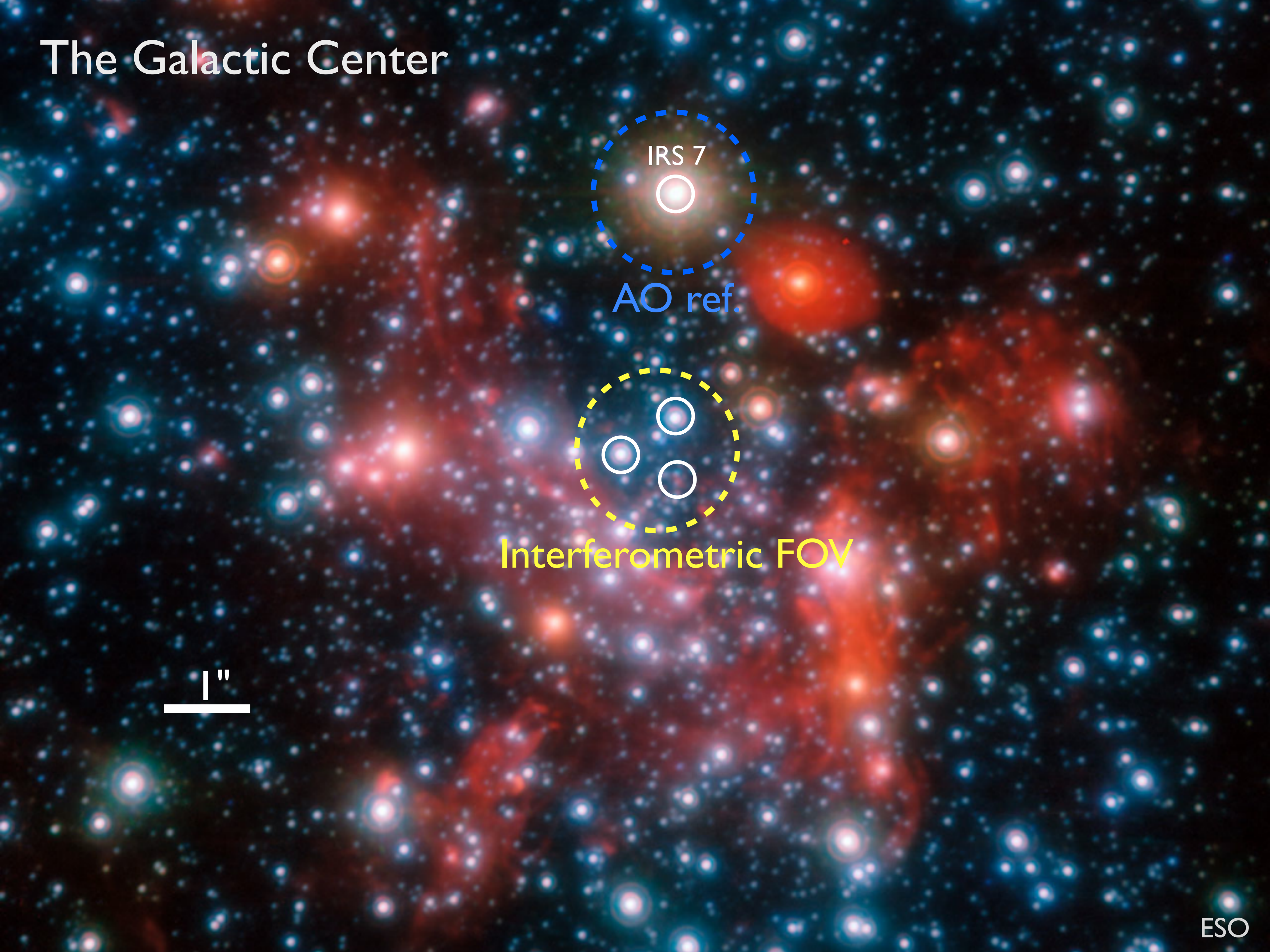


Véga (CHARA)



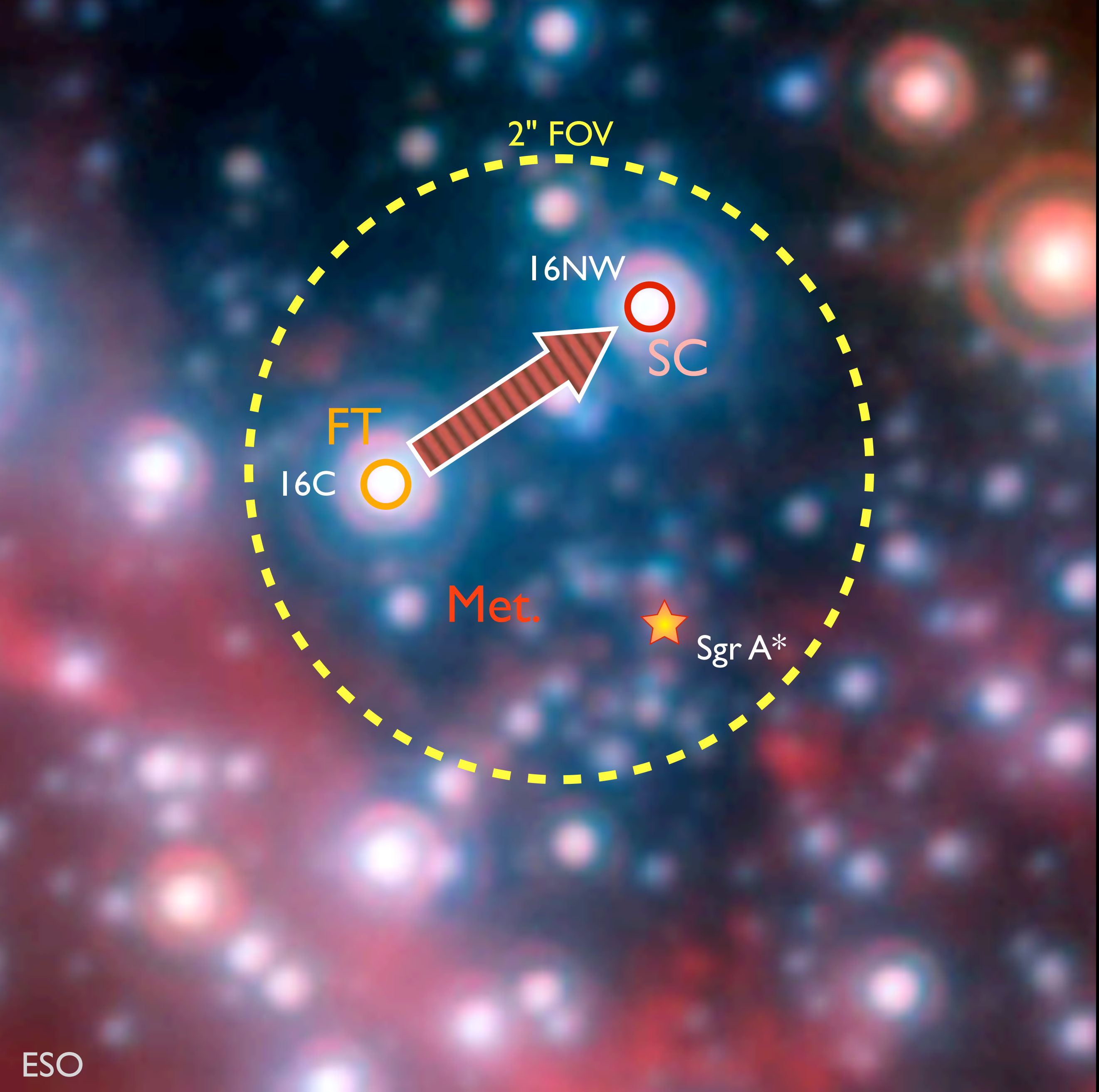
Is it a reasonable image ?

The Galactic Center



ESO

The Galactic Center



ESO

Fringe Tracker

Science Combiner

Phase

+ Metrology

- Imaging
- Astrometry

Galactic Center

1.

2.