

GRAVITY

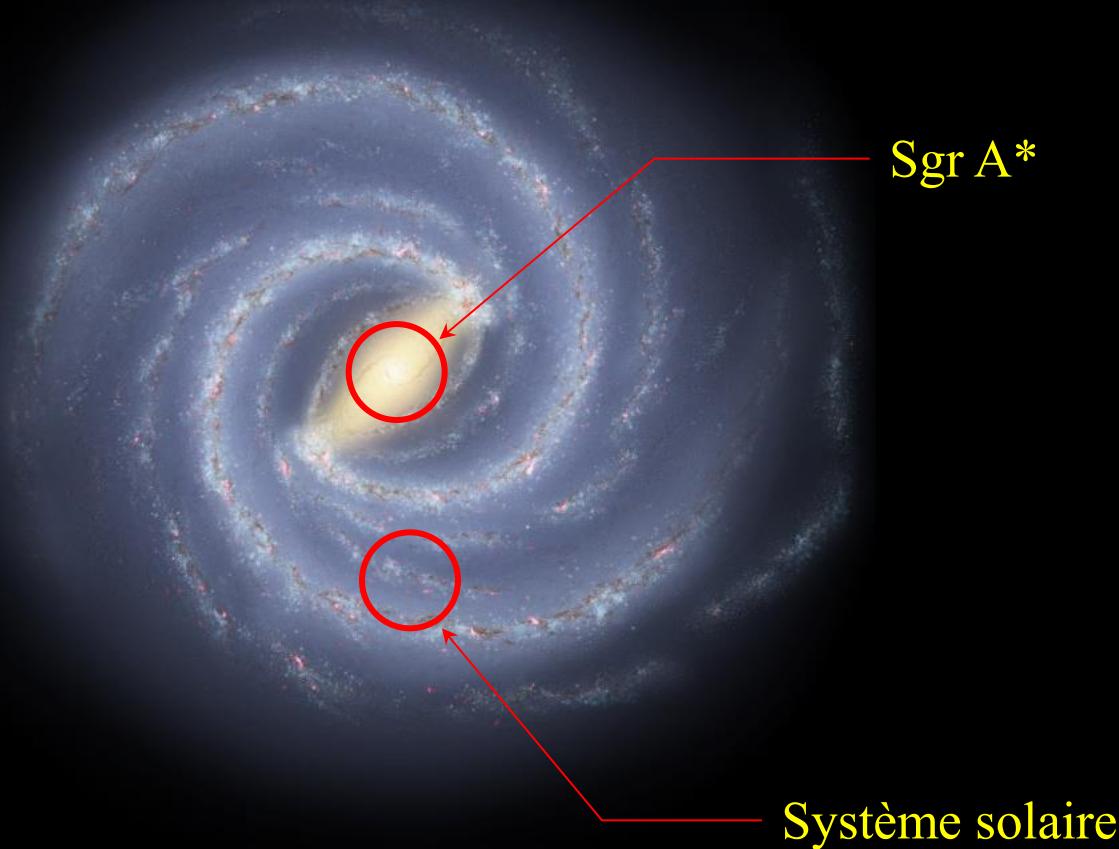
2nd generation instrument for the VLTI

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 Férou, 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



The Galactic center

Diameter : 25 kpc
or 80 light-years





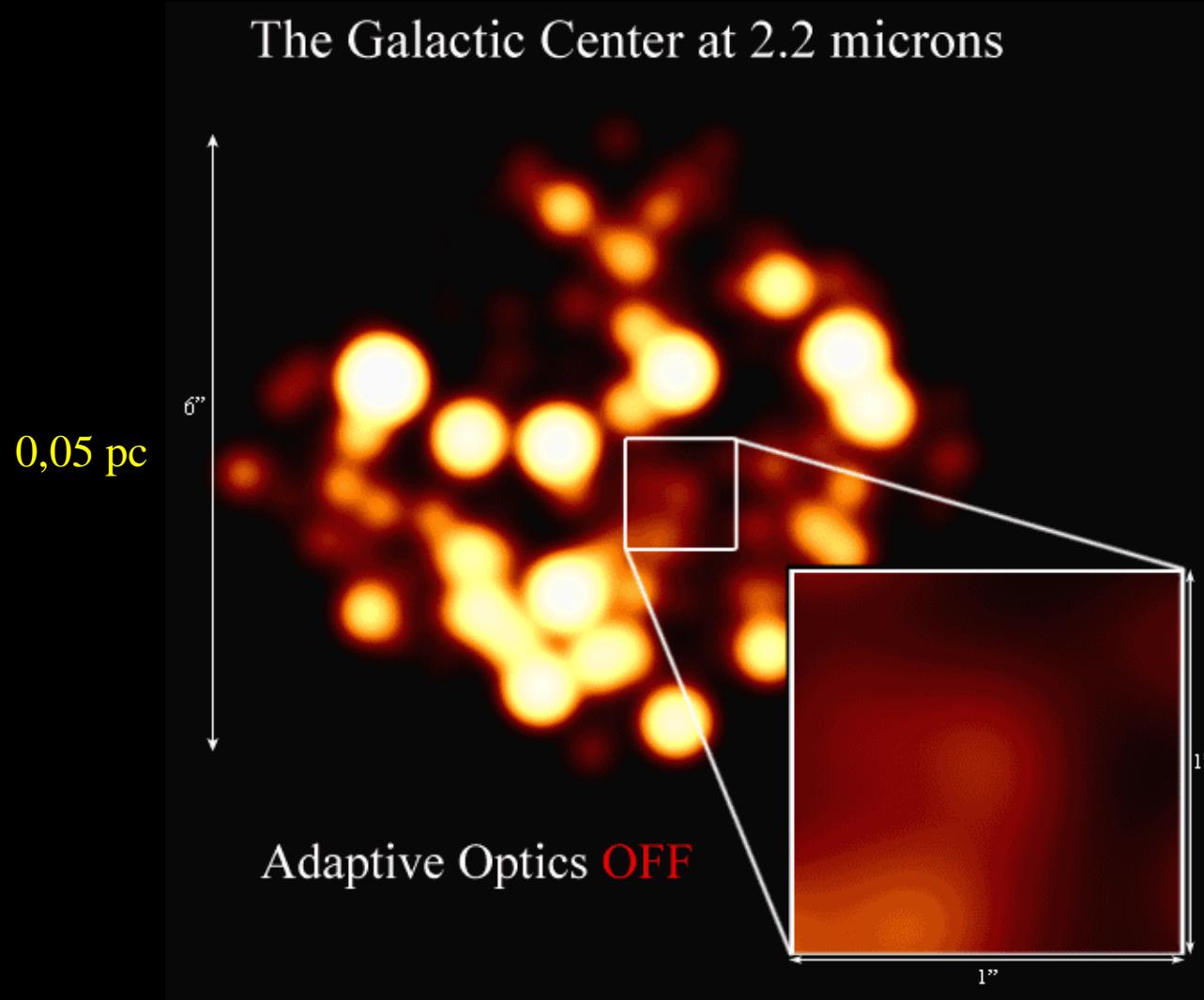
The galactic center as we see it

25.09.2013

OHP : Optical interferometers

The Galactic center seen from infrared space telescope Spitzer

with adaptive optics ...



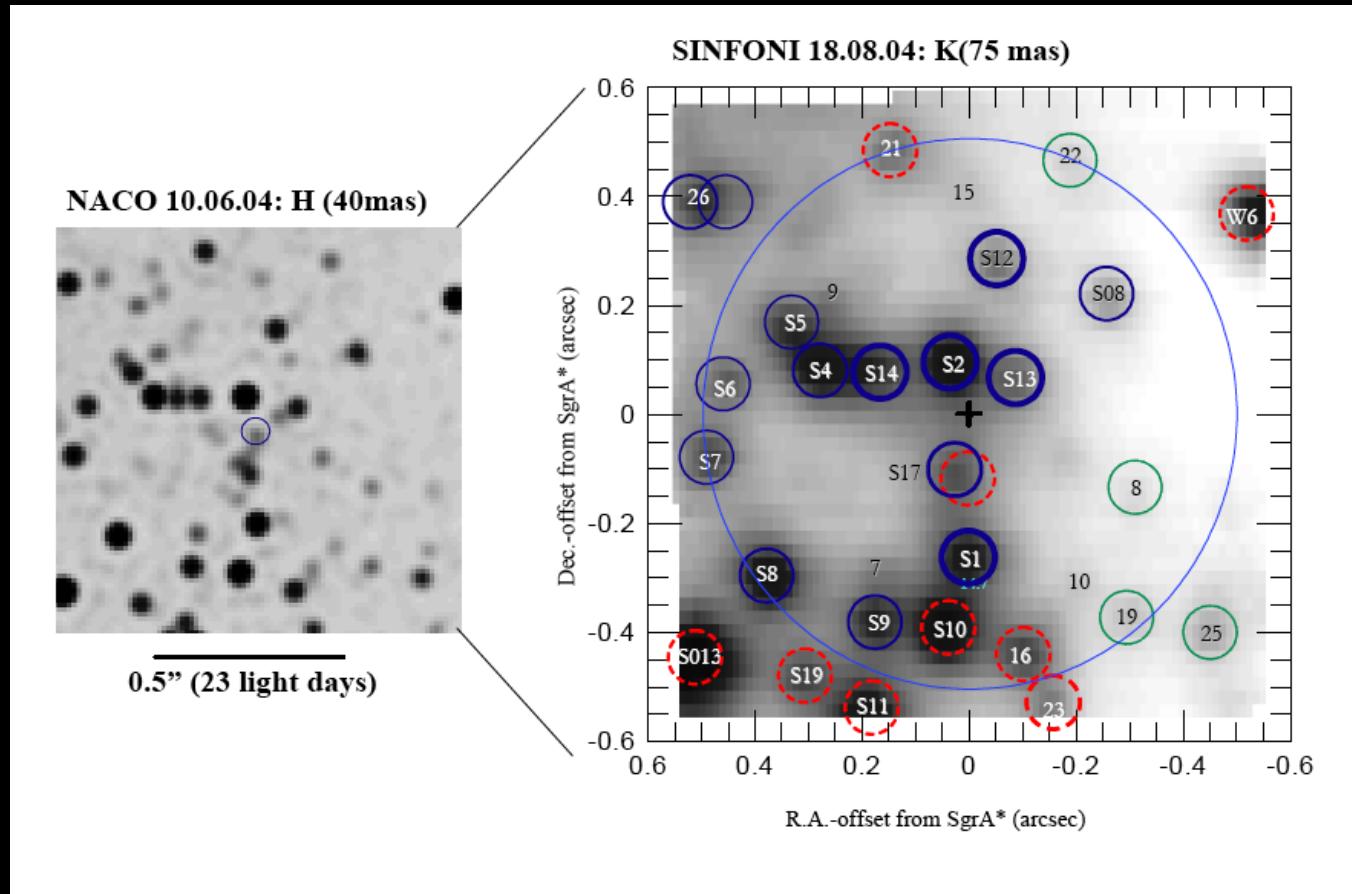
Orbit of star S₂ observed with adaptative optics at VLT/NACO

1992 10 light days

+ ← Sgr A*

Schödel et al. (2002)

We can do so with the many neighboring stars



And get the mass of Sgr A*

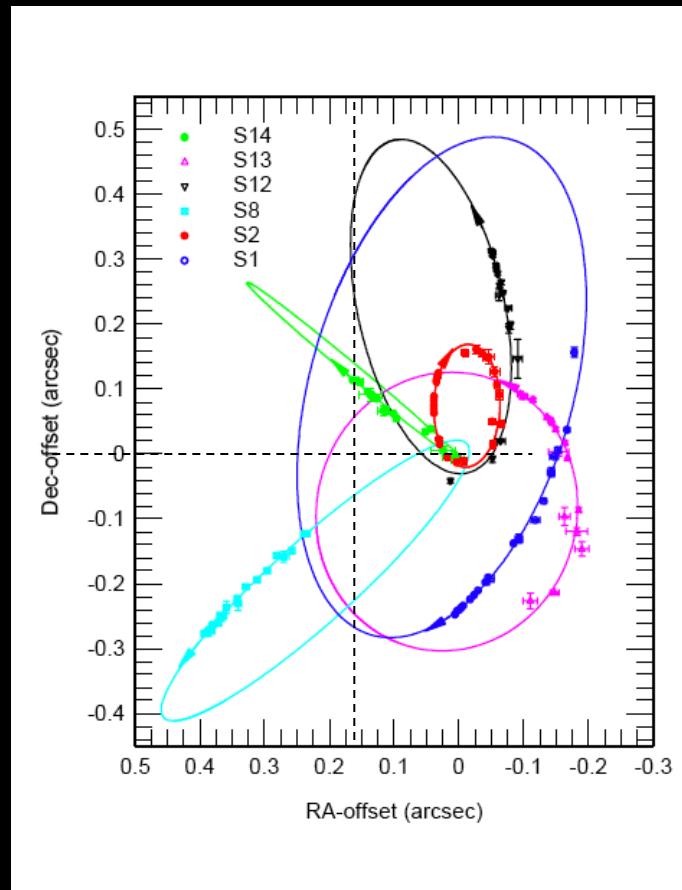
3rd Kepler law:

$$\frac{a^3}{T^2} = \frac{GM_{\text{Sgr A}^*}}{4\rho^2}$$



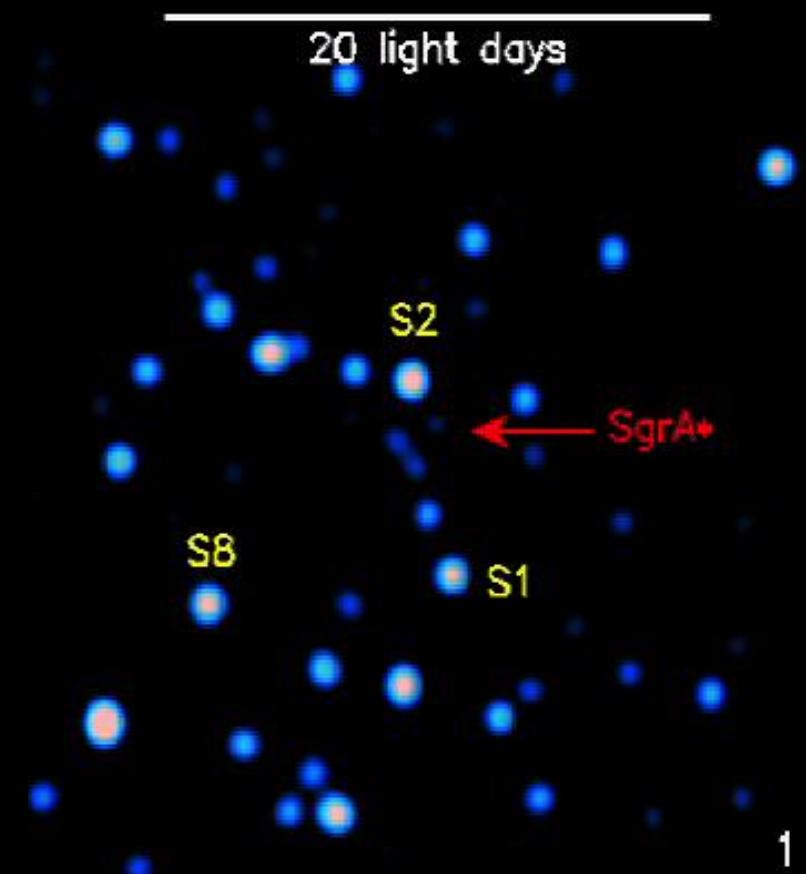
$$M_{\text{Sgr A}^*} = 3,61 \pm 0,32 \times 10^6 M_{\text{Sun}}$$

$$(d = 7,62 \pm 0,32 \text{ kpc})$$



Eisenhauer et al. (2005)

The flares of Sgr A*

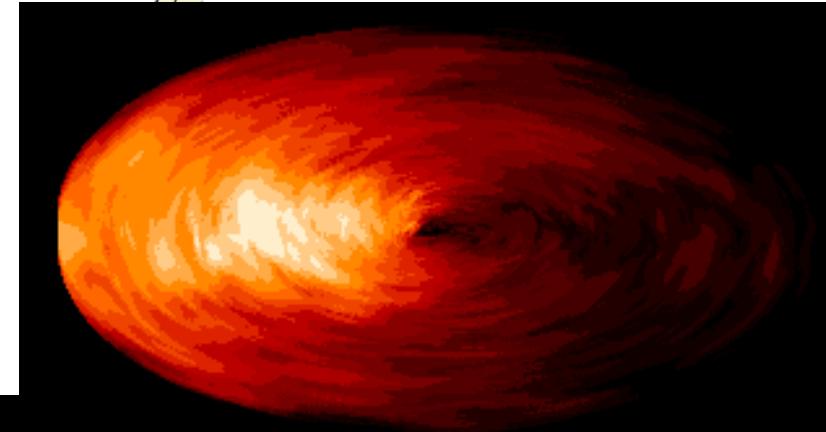
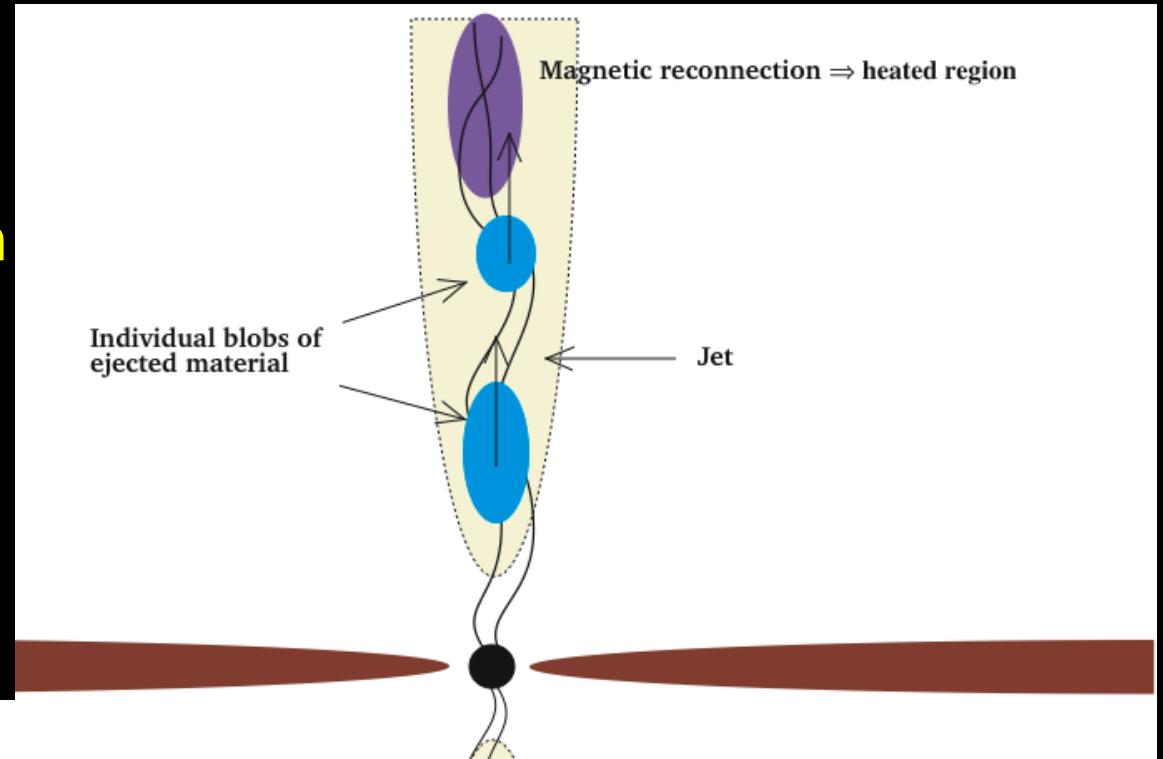
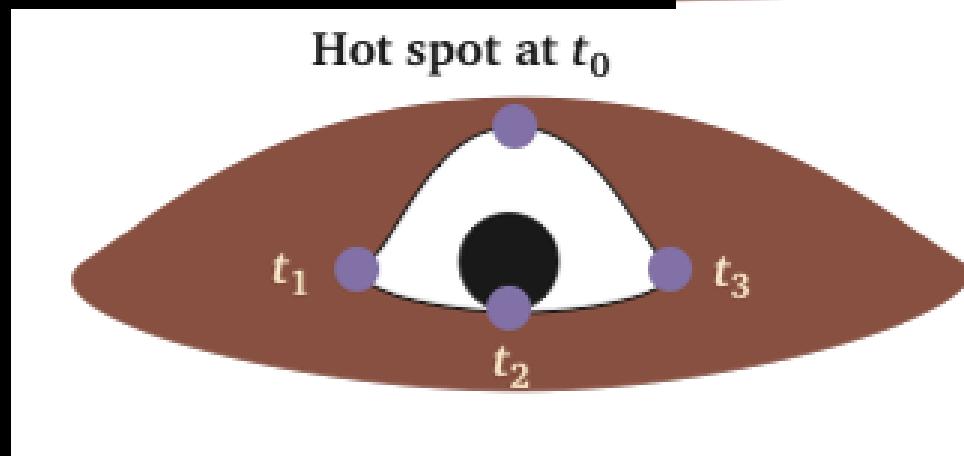


Genzel et al. (2003)

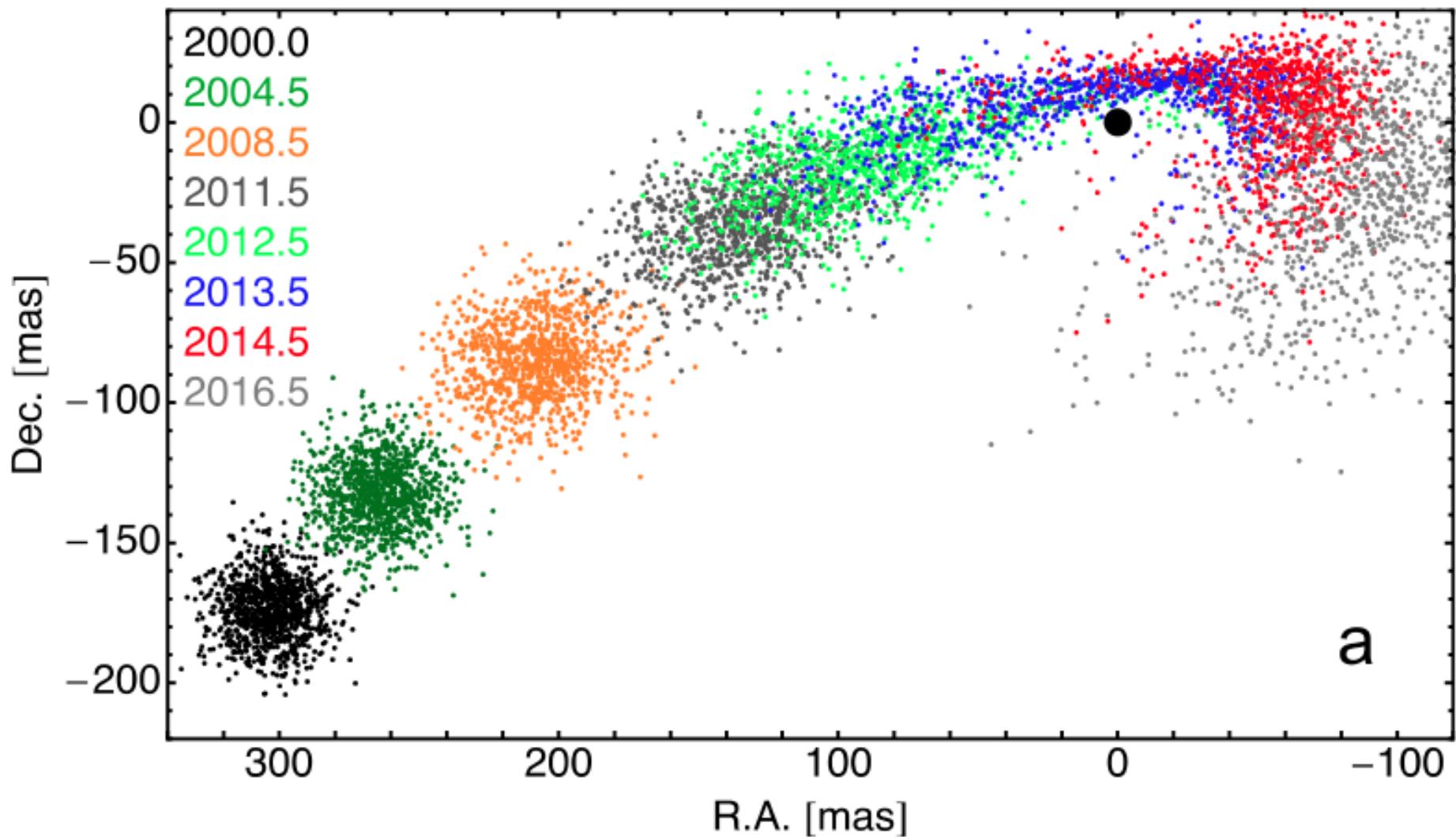
But what cause the flares?

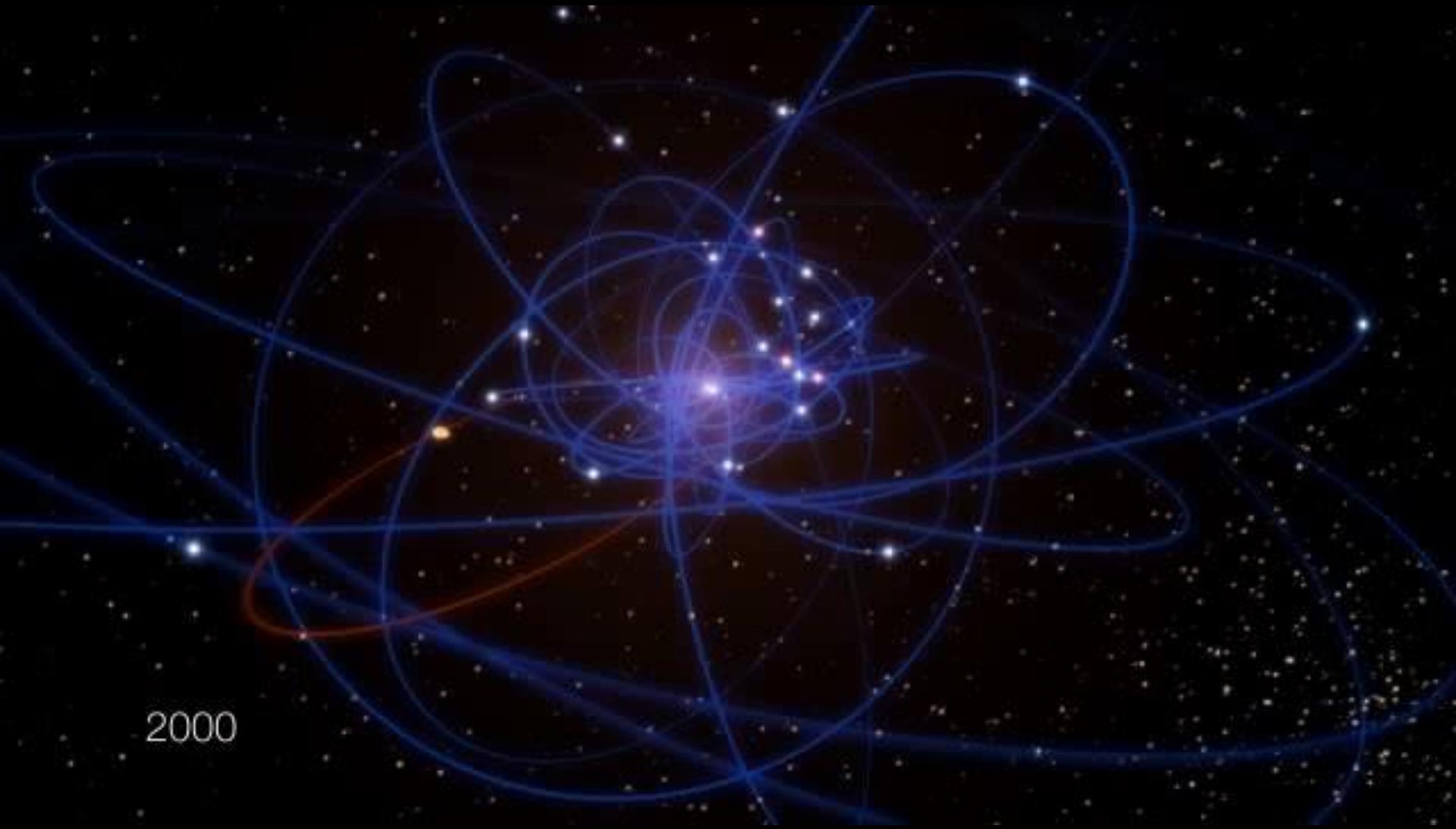
Several possible scenarios :

- magnetic reconnection within the jet
- Hot spot orbiting the black hole
- Fluctuations??



A cloud is coming





2000

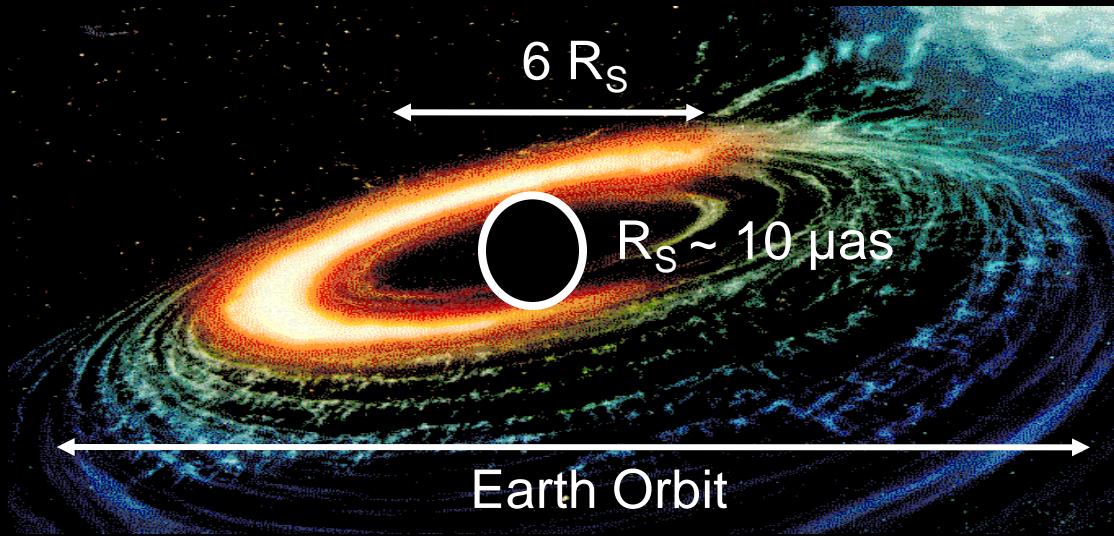
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Credits: Schartmann, ESO, Berry, NASA, Broderick

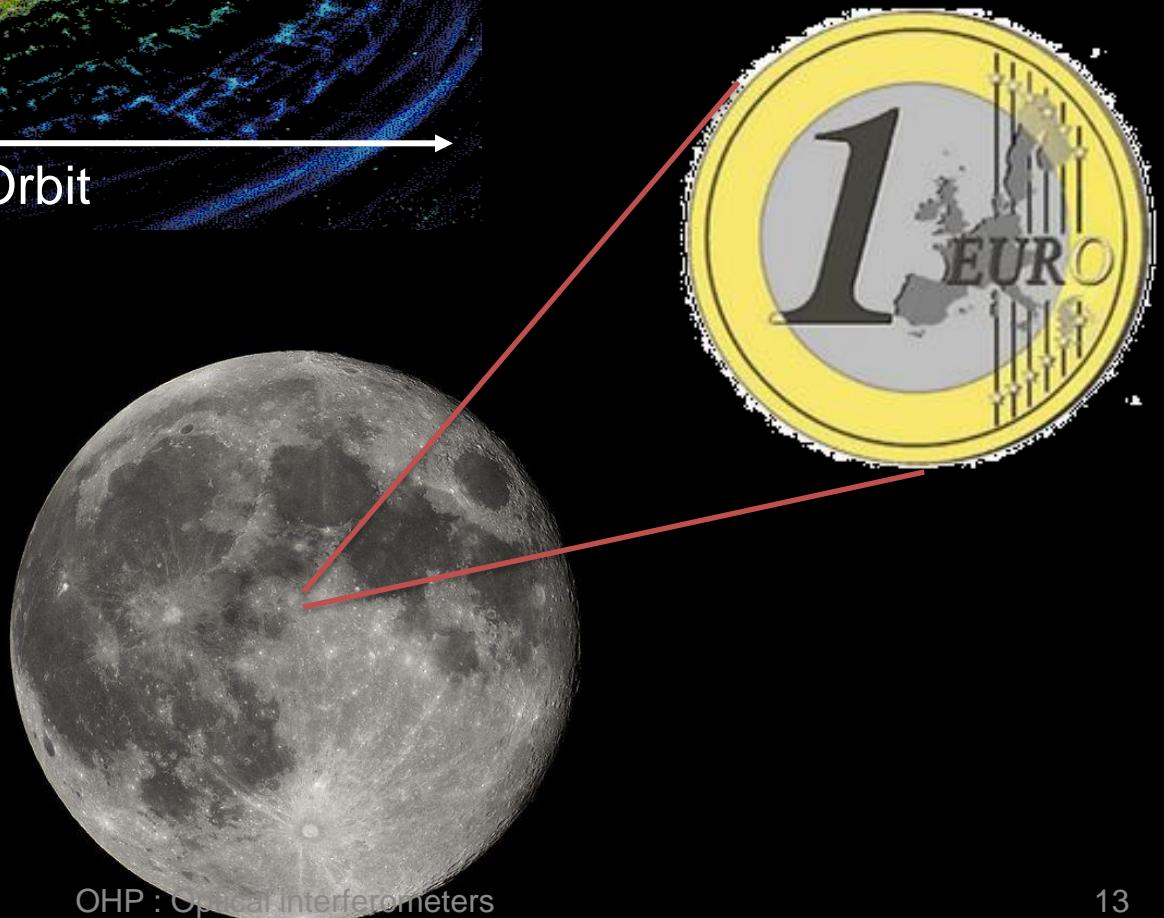
OHP : Optical interferometers

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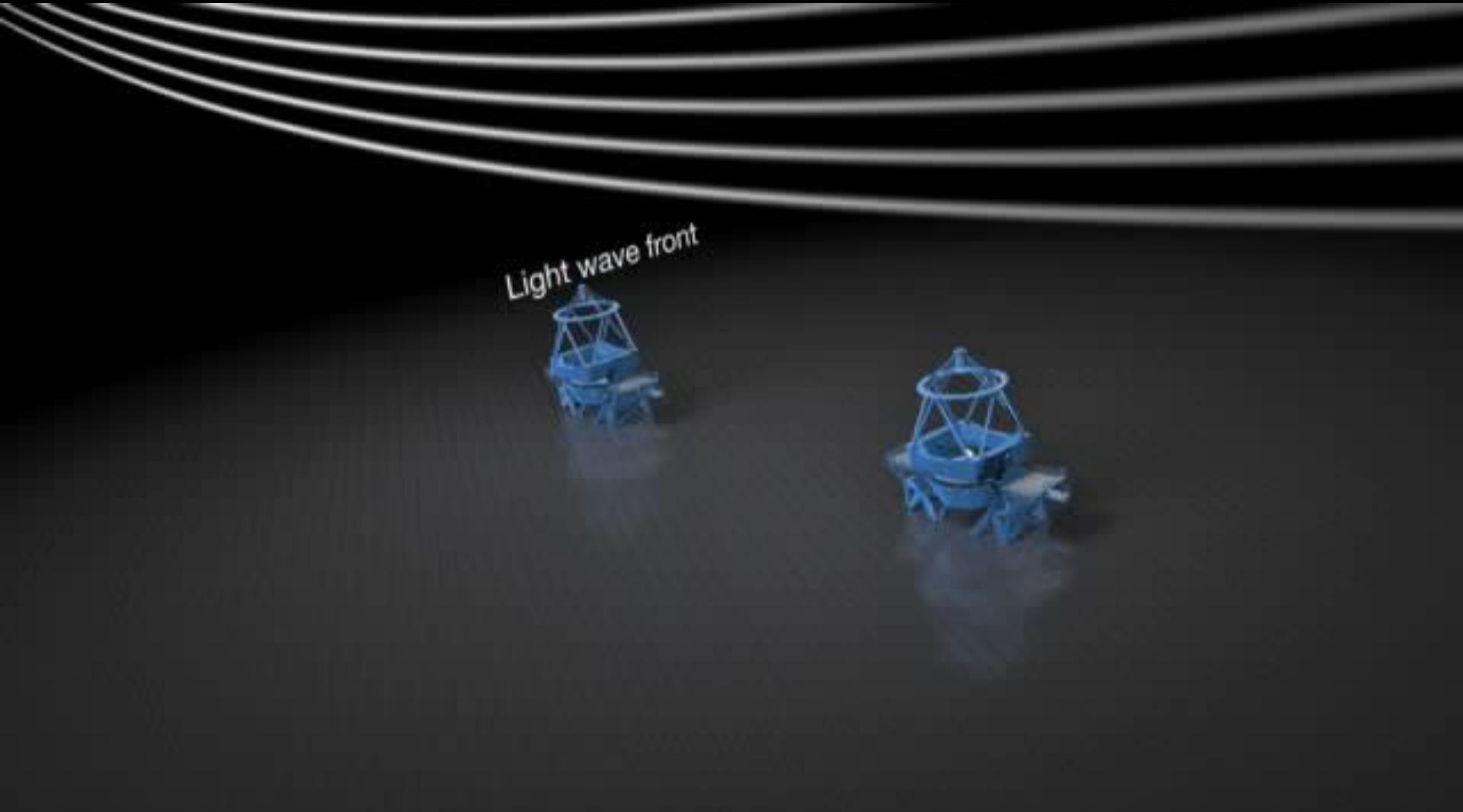
Setting the scale – just to scare ...



1 Schwarzschild radius
=
a coin on the moon



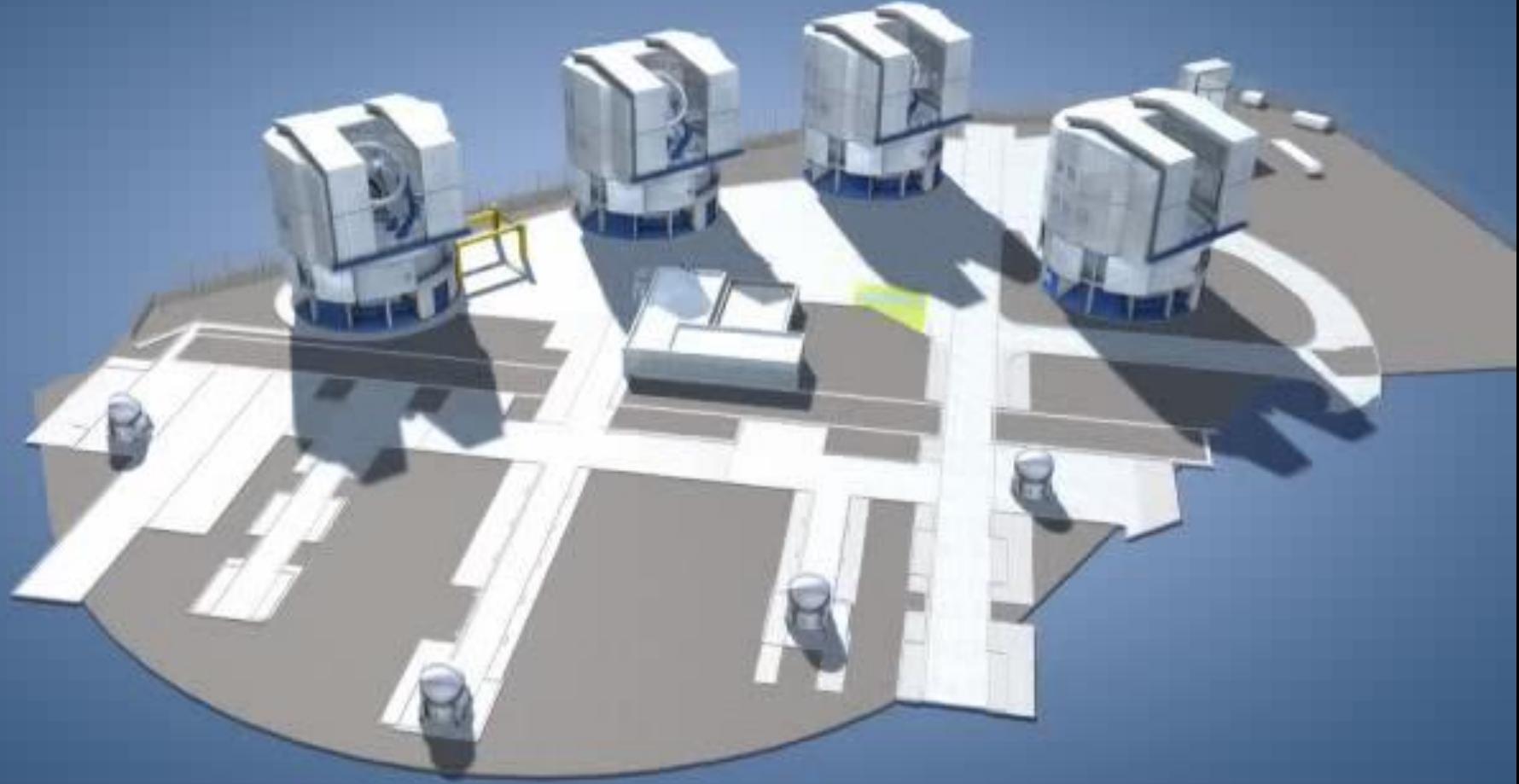
Interferometry



A diagram illustrating optical interferometry. Two blue wireframe models of astronomical telescopes are positioned on a dark surface. A curved white line, labeled "Light wave front", originates from the left telescope and curves upwards and to the right, passing between the two telescopes. The second telescope is oriented towards the end of the wave front.

Light wave front

GRAVITY @ ESO VLT



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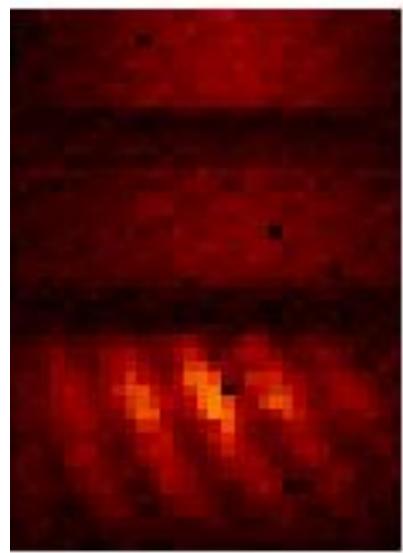


Courtesy of ESO

Setting the scale – ... maybe not that scary



5 nm @ 100m
=
a coin on the moon



Interferometry

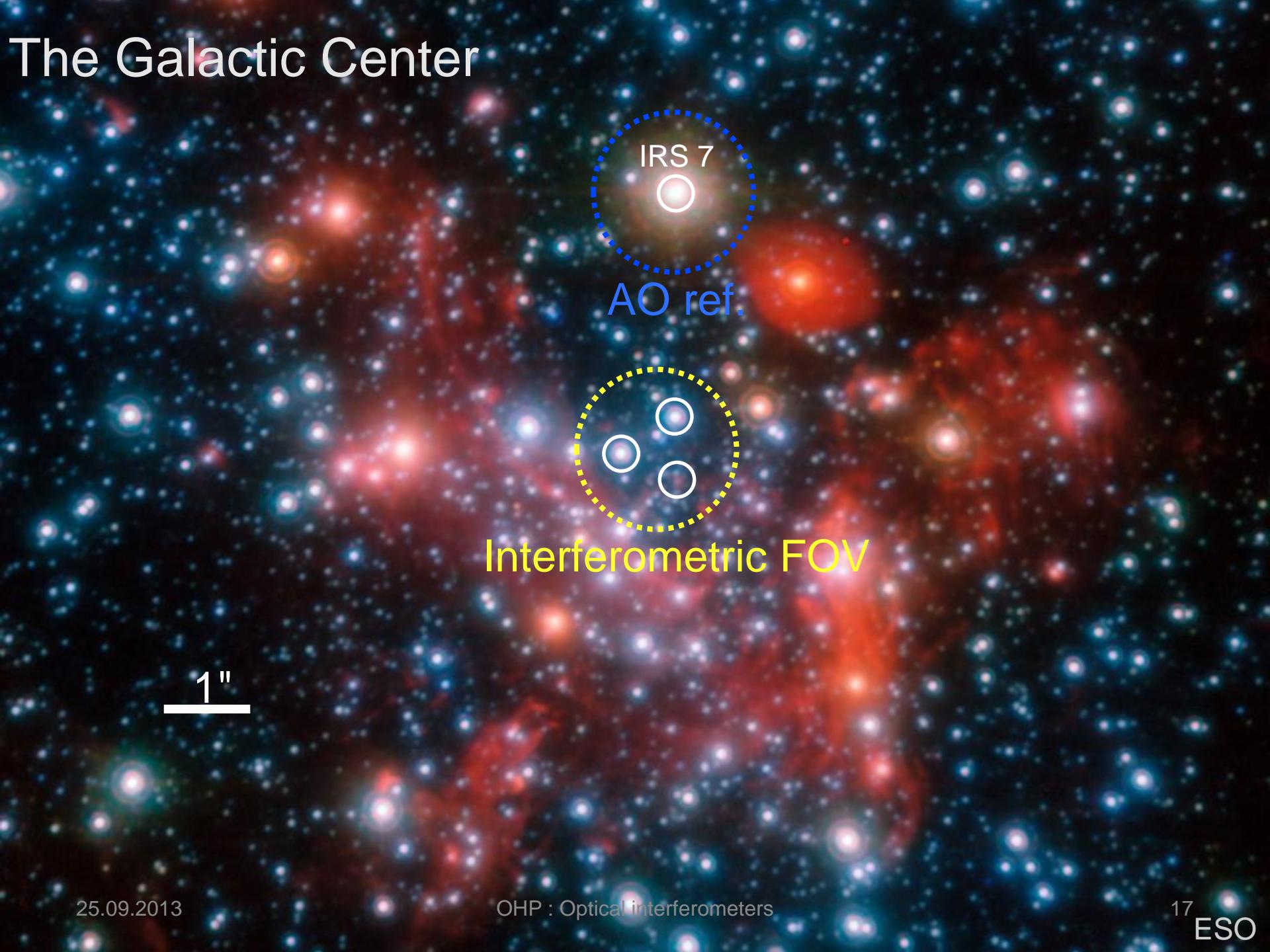
25.09.2013



OHP : Optical Interferometers

The Galactic Center

1''



IRS 7

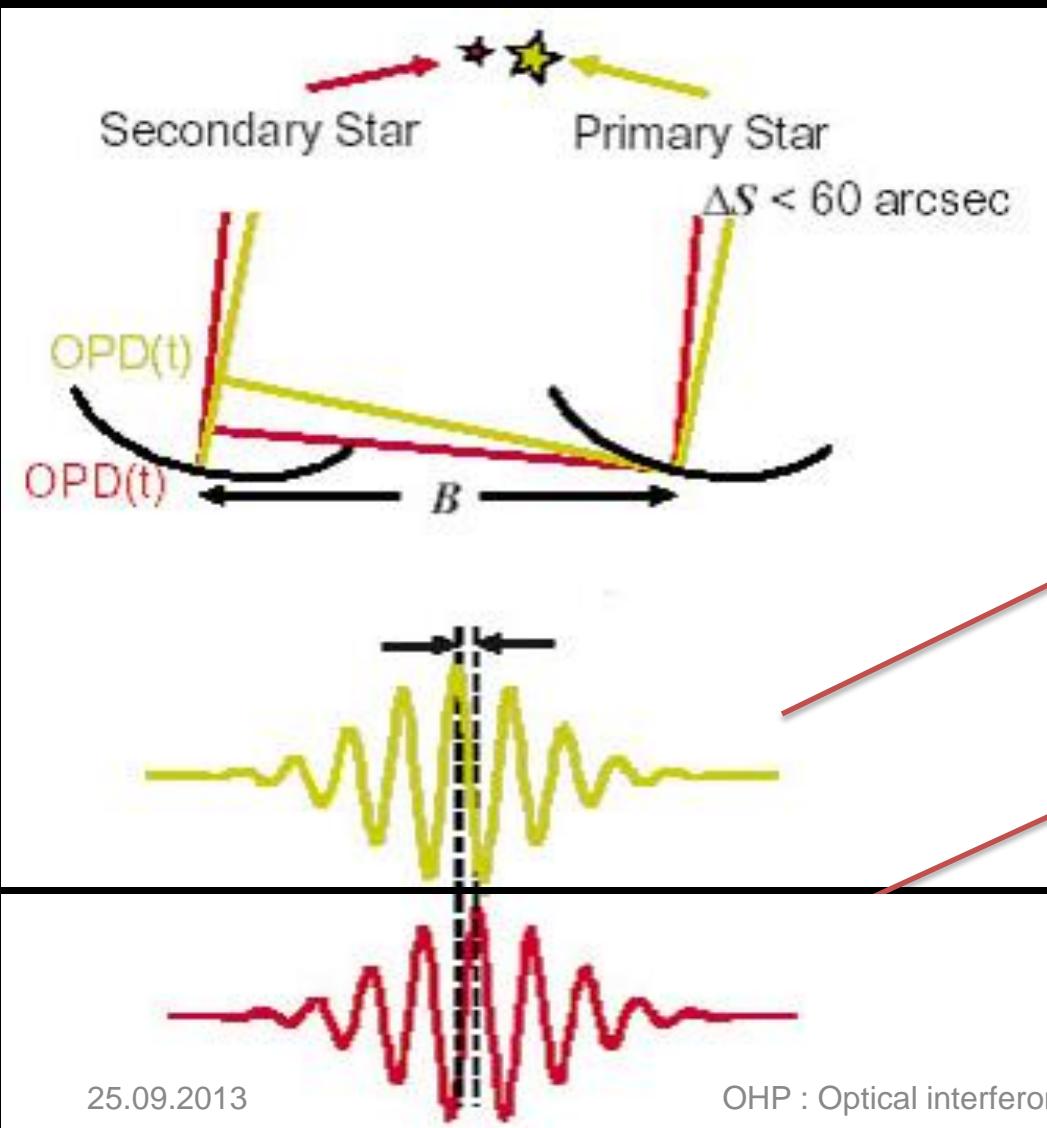
AO ref.



Interferometric FOV

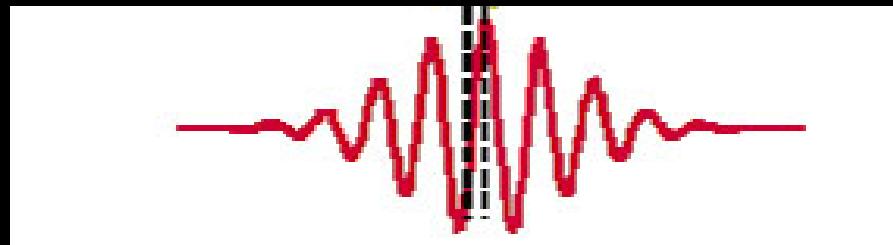
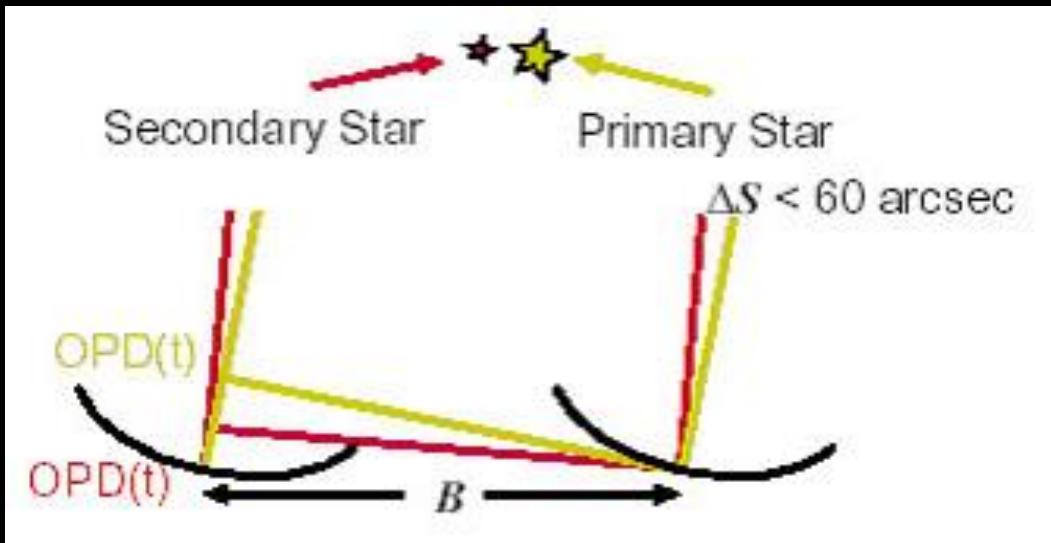
Phase referenced imaging & astrometry

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

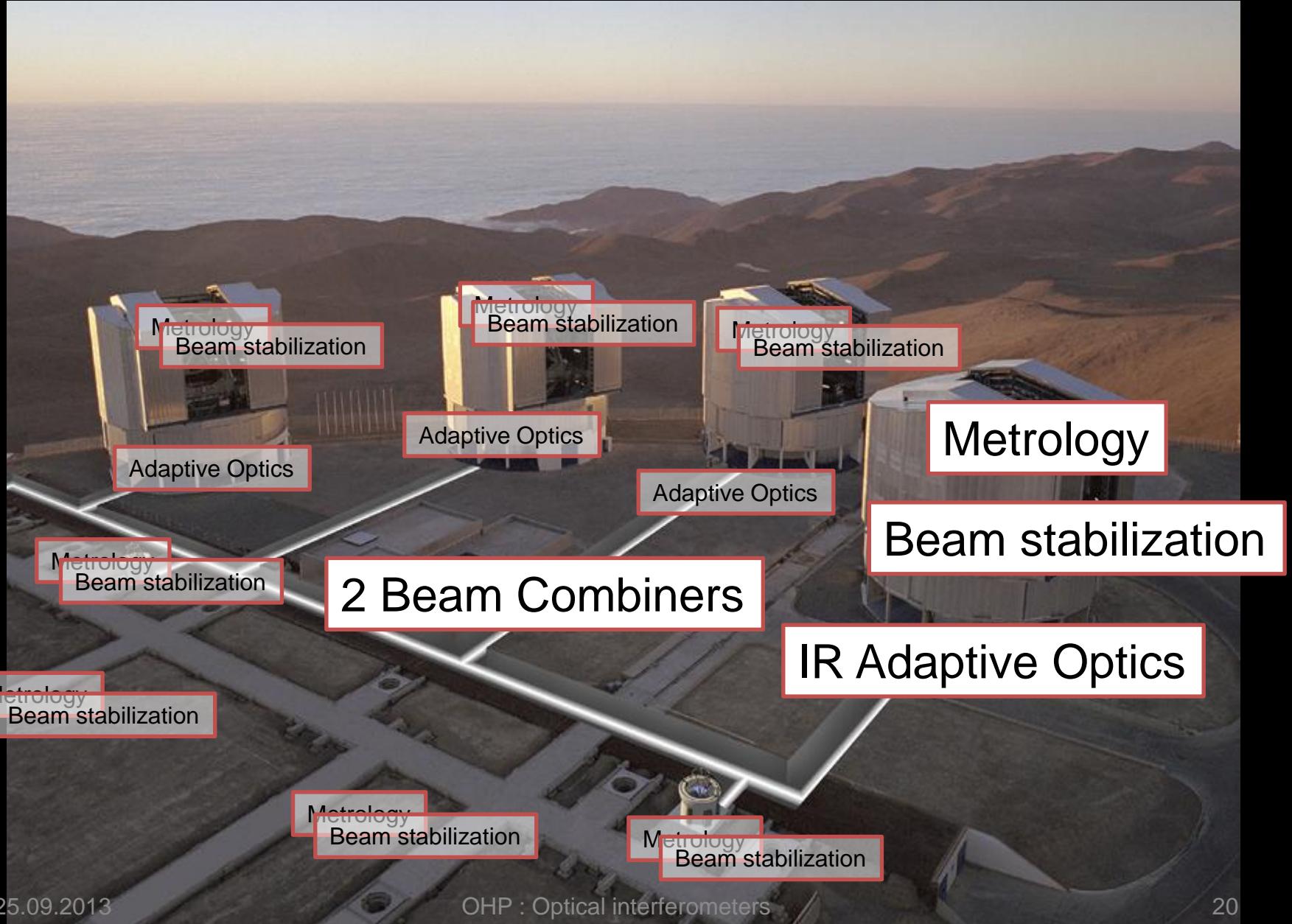


Phase referenced imaging & astrometry

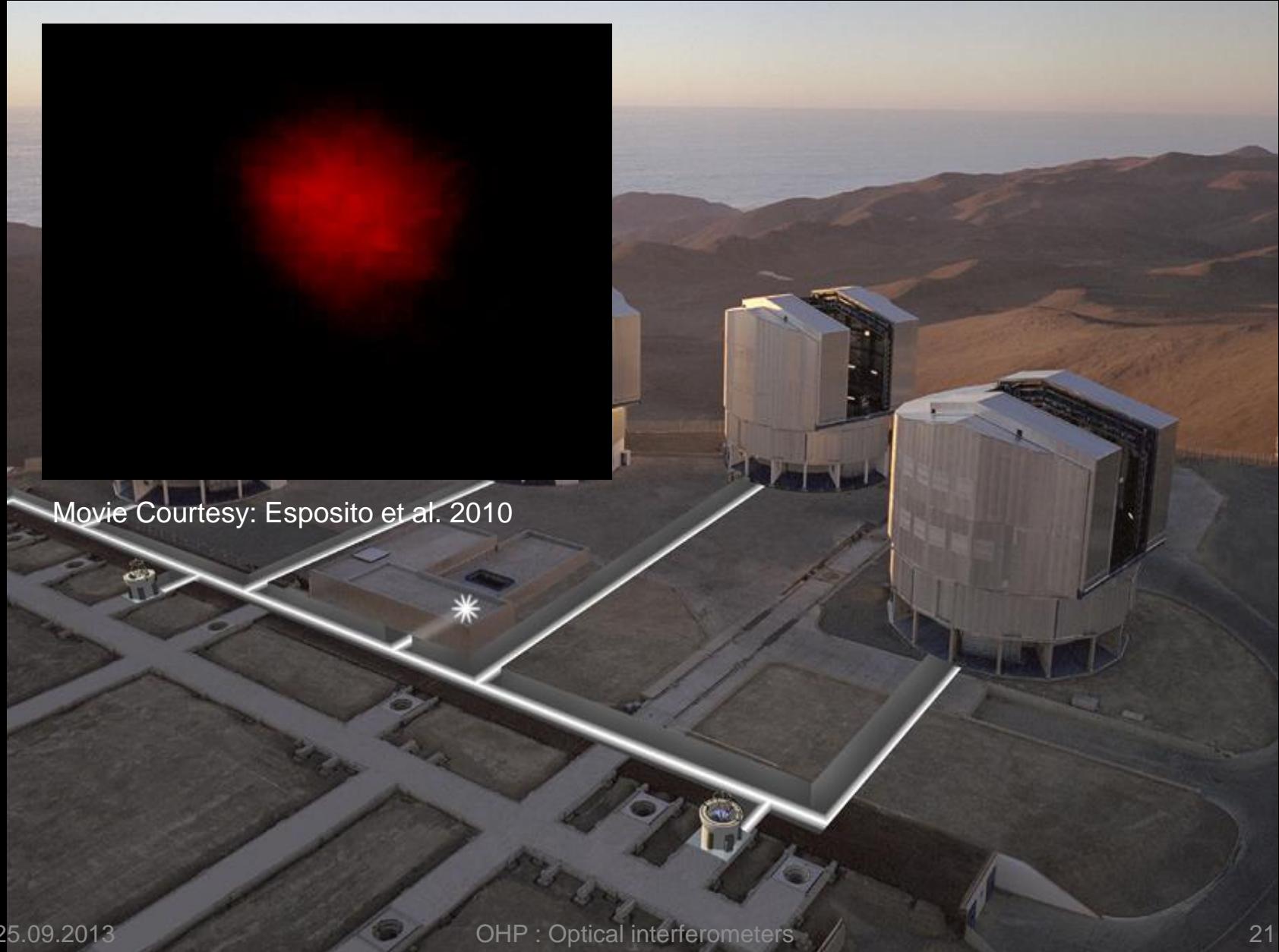
Contrast (B) <-> FourierTransform (Image)



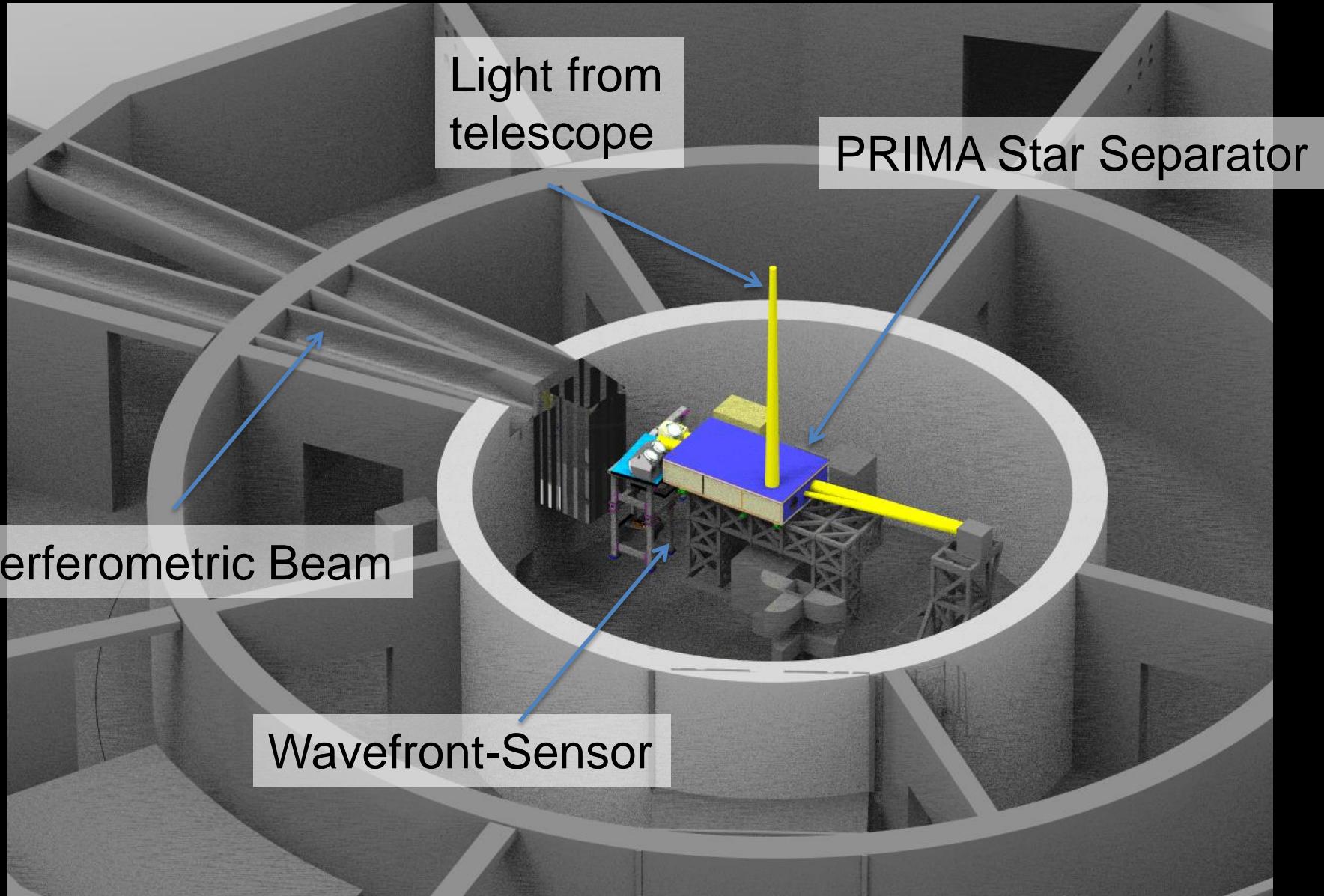
GRAVITY astrometry & imaging



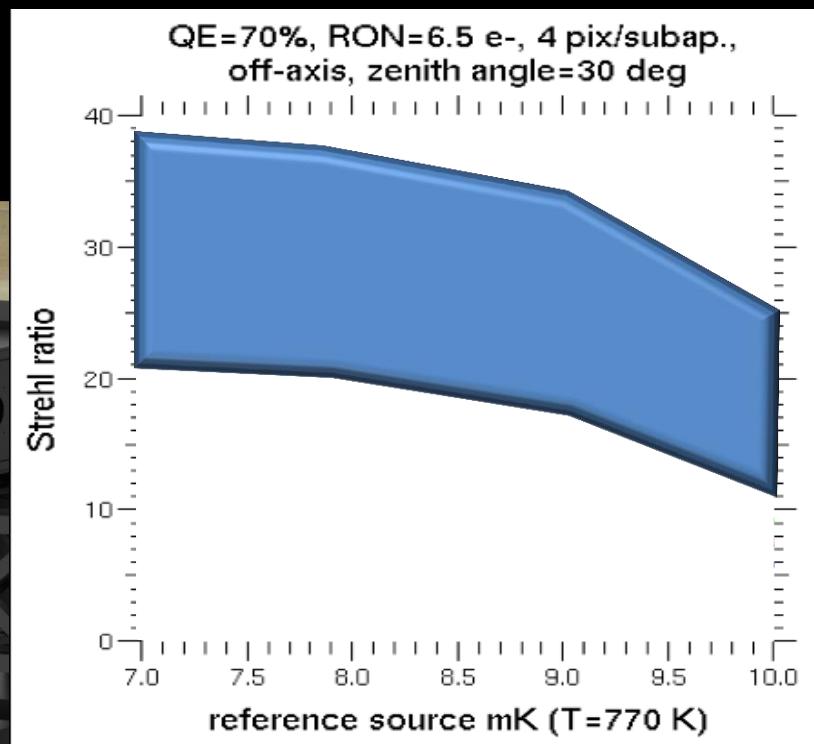
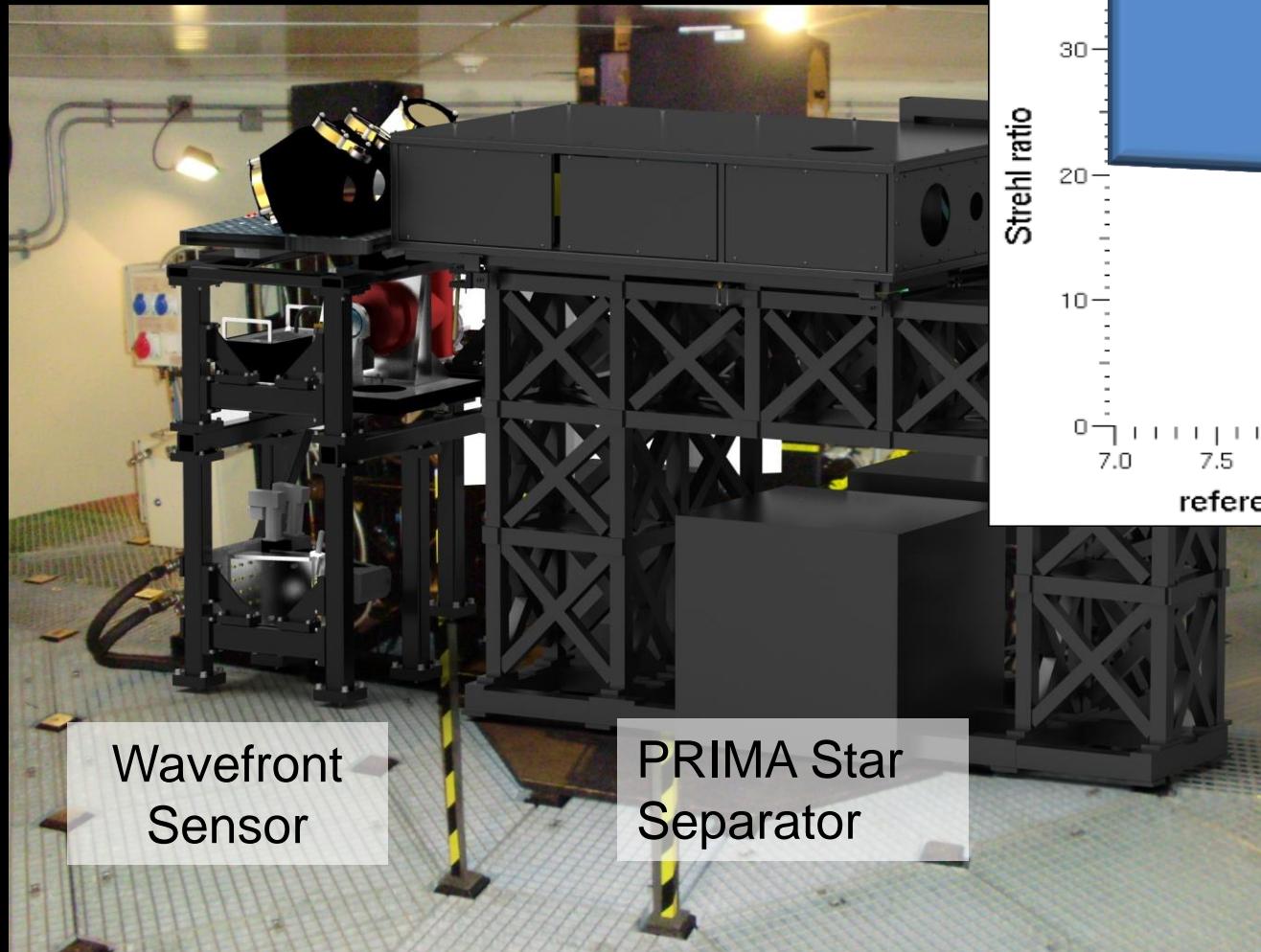
GRAVITY adaptive optics



GRAVITY adaptive optics

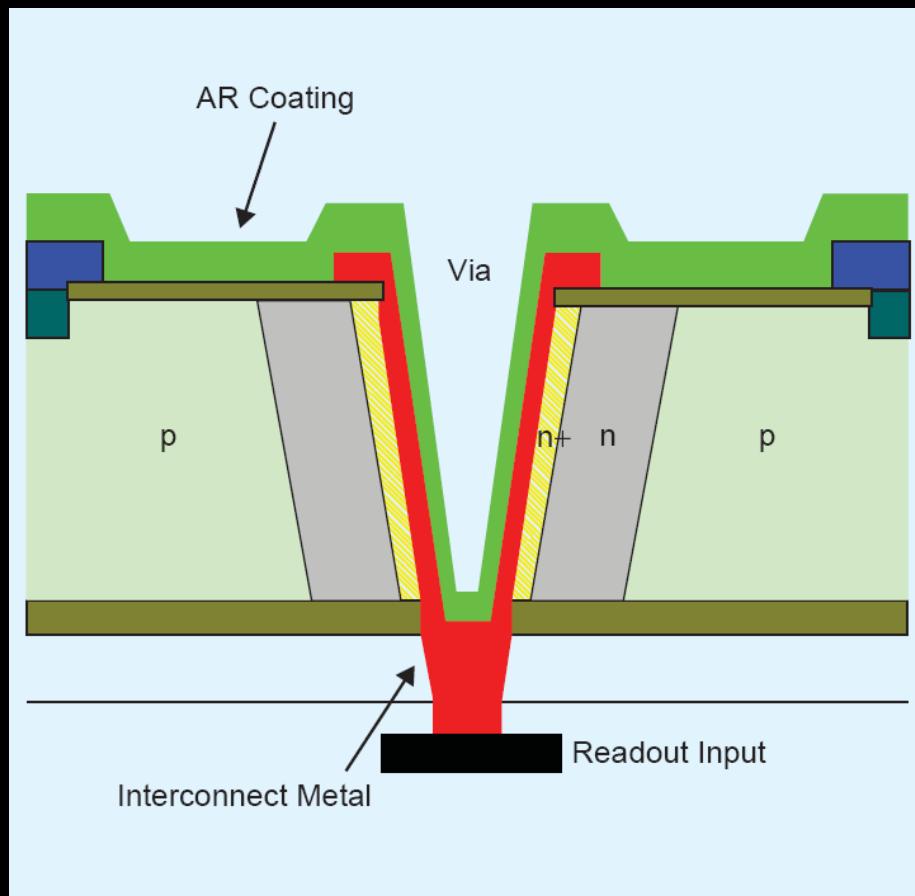
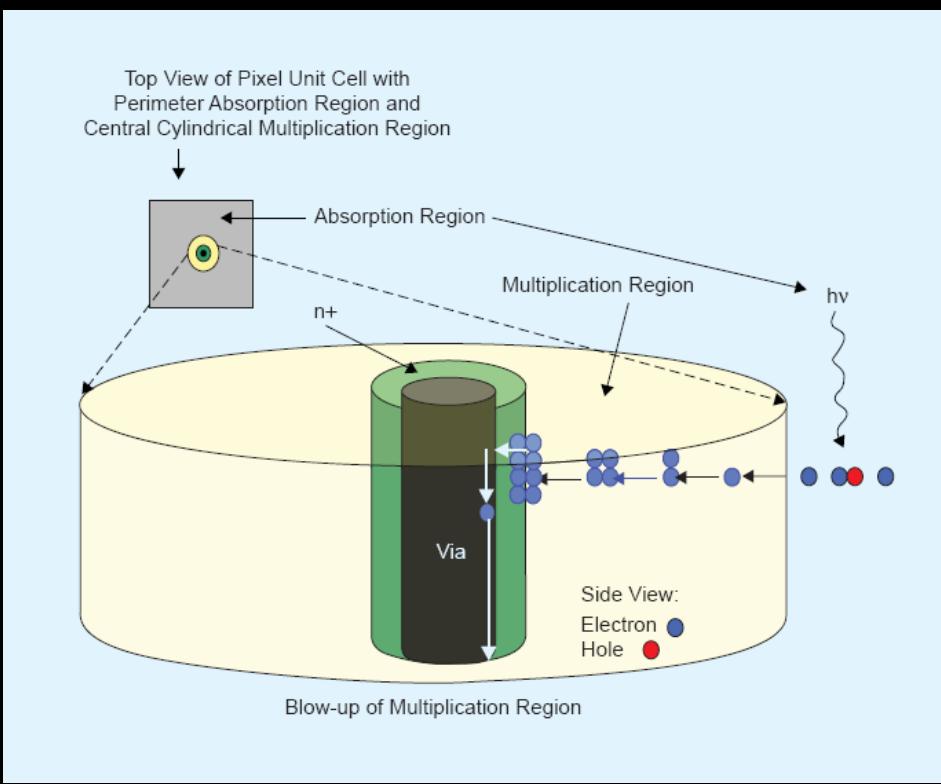


GRAVITY adaptive optics



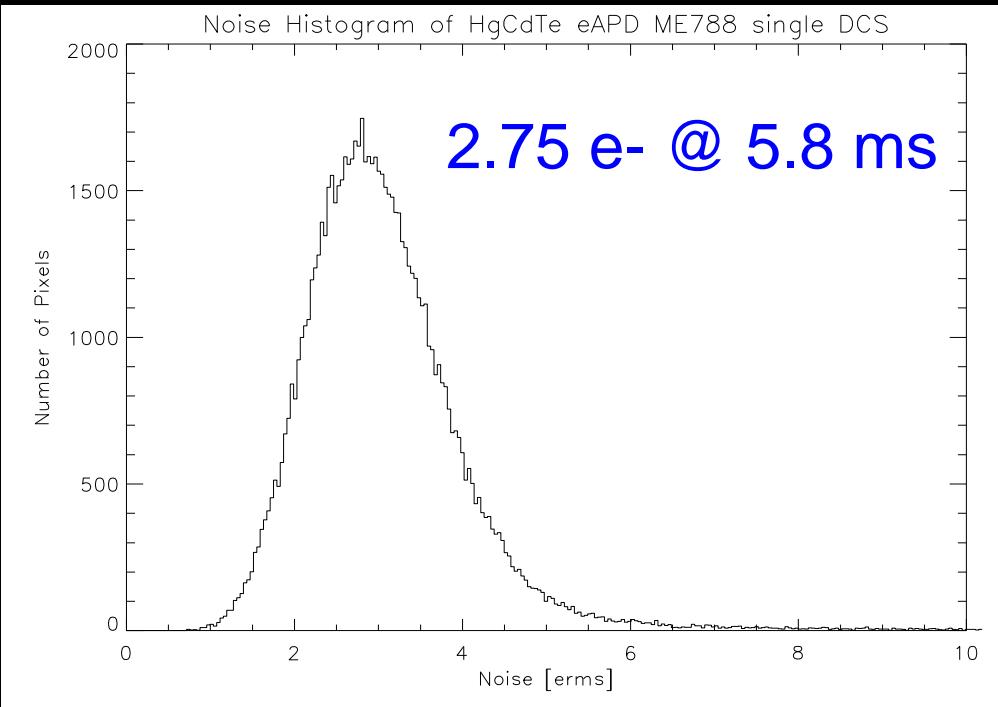
Adaptive optics and fringe tracking Detectors

SELEX / ESO development of Infrared
Avalanche Photo Diode array:



Adaptive Optics and Fringe Tracking Detectors

SELEX / ESO development of Infrared
Avalanche Photo Diode array:



Finger et al. 2010

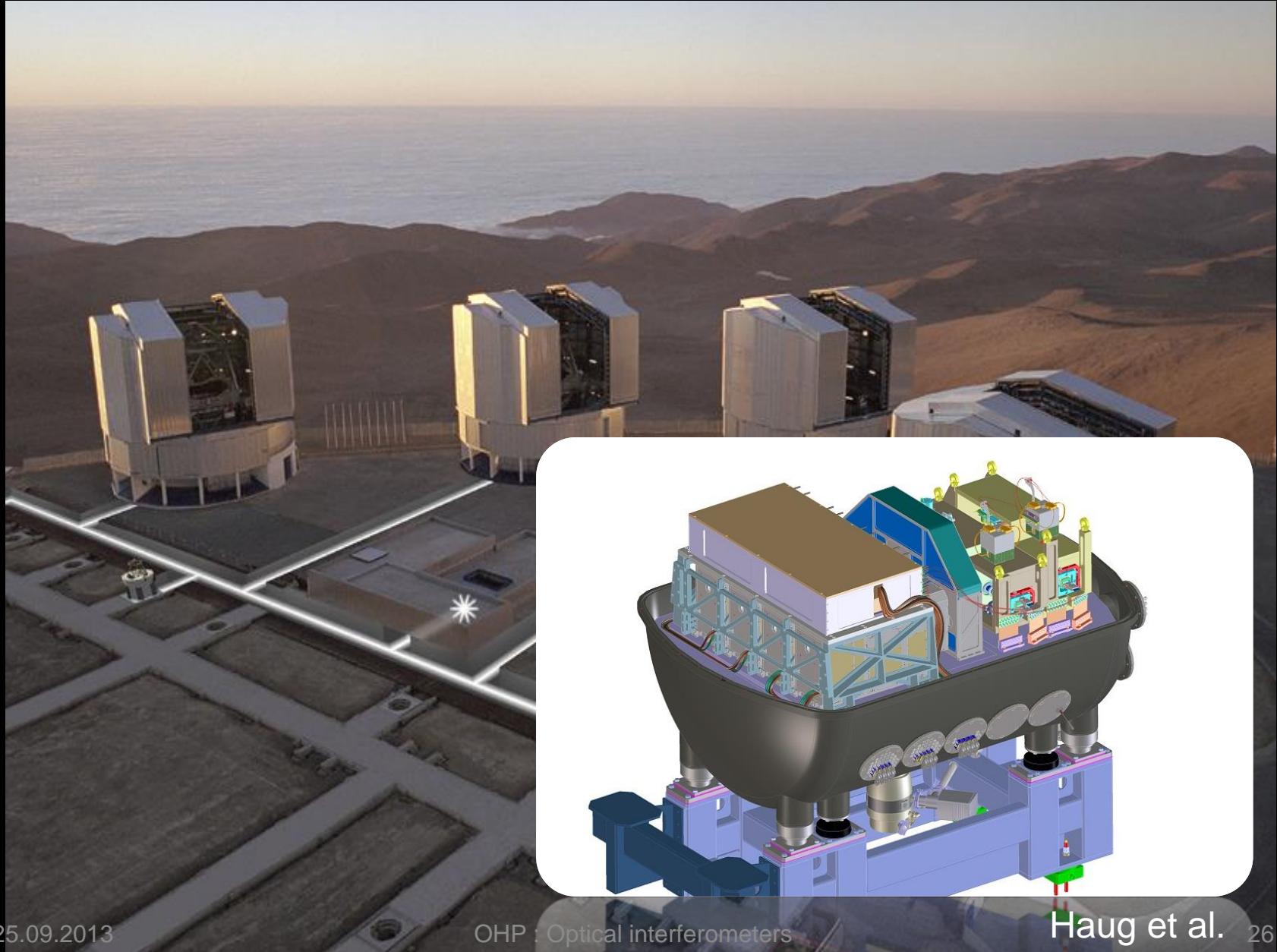
Brander, Hippler et al.,
Clenet et al. 2010

OHP : Optical interferometers

25/02/2018

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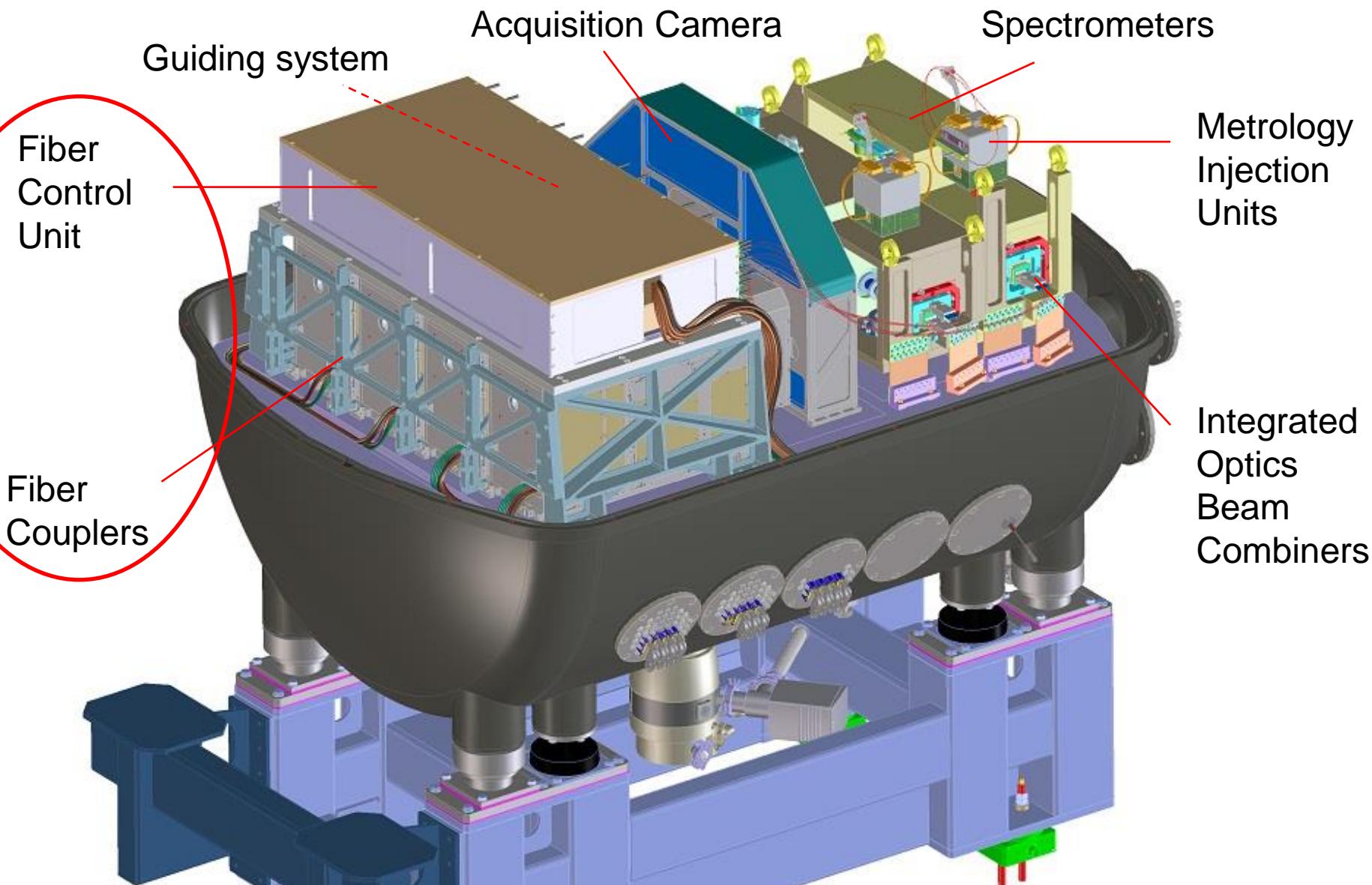
GRAVITY beam combiner



Beam Combiner Instrument



1 - Fiber Control Unit



Single mode interferometer

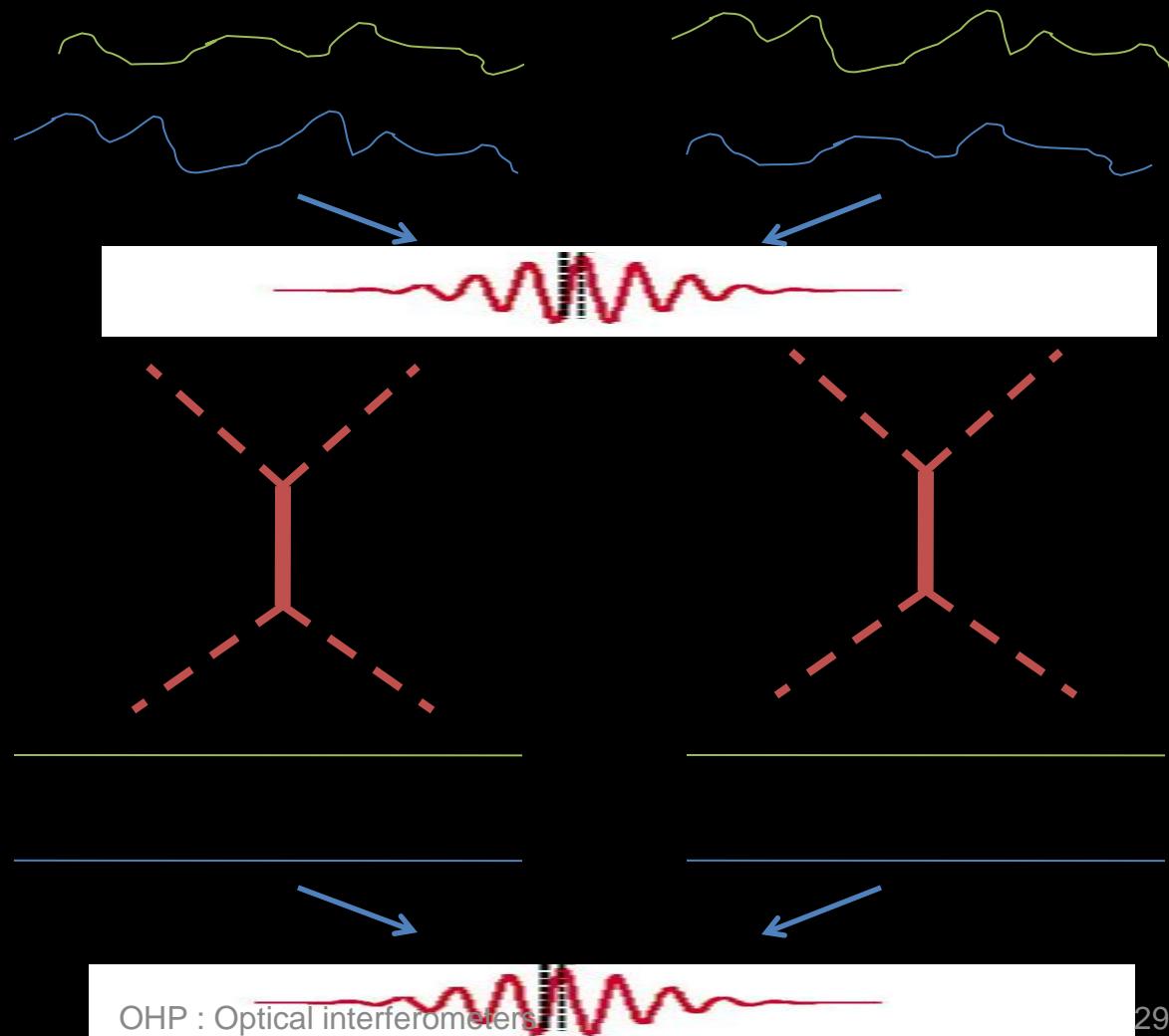
Most important quantities for interferometry is well measured phase and calibrated contrast, not flux

Distorted Waves

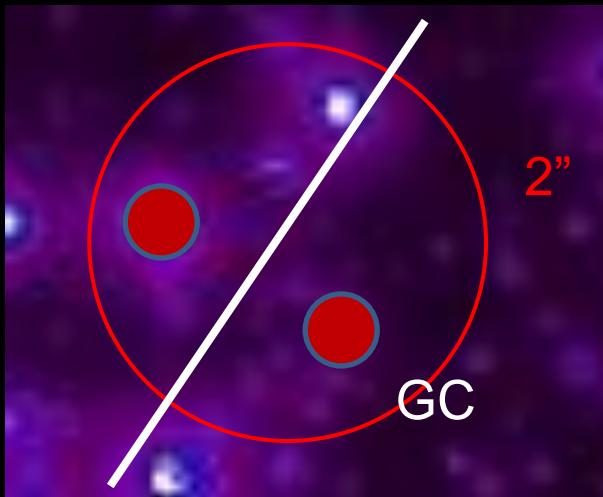
Constant flux, but
variable contrast

Single mode fiber
“Low pass filter”

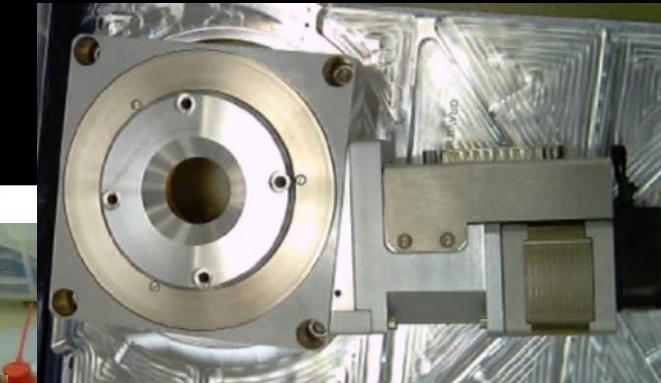
Variable flux, but
constant contrast



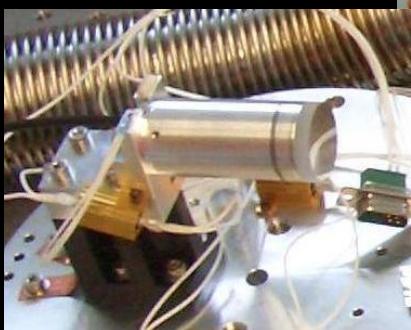
Fibercoupler



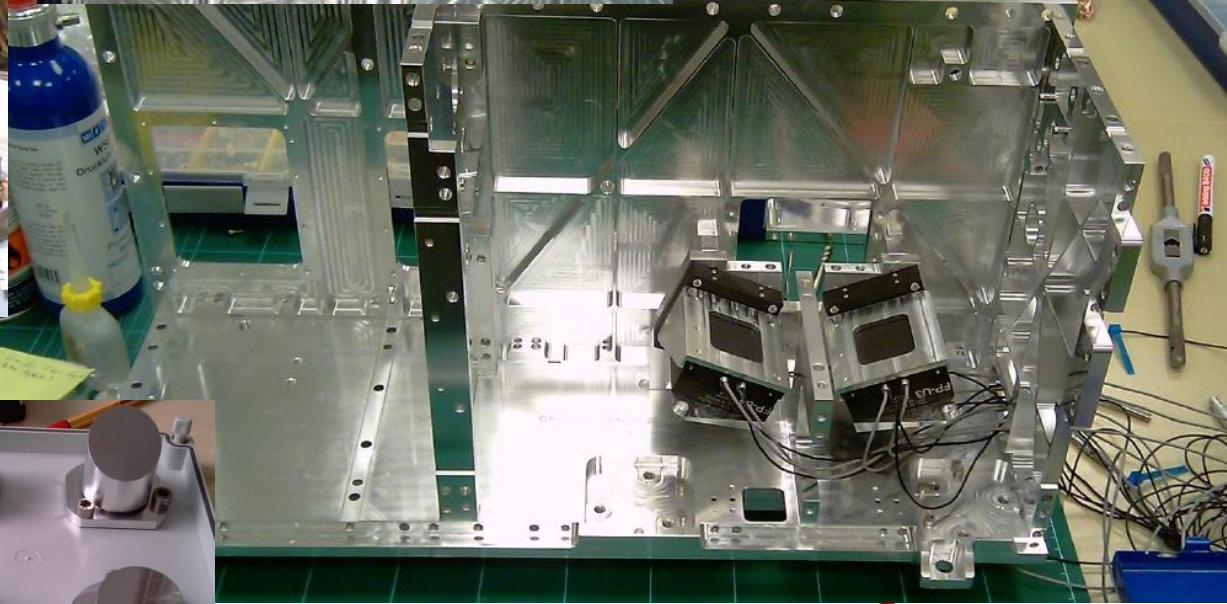
Rotation Stages



Shutters



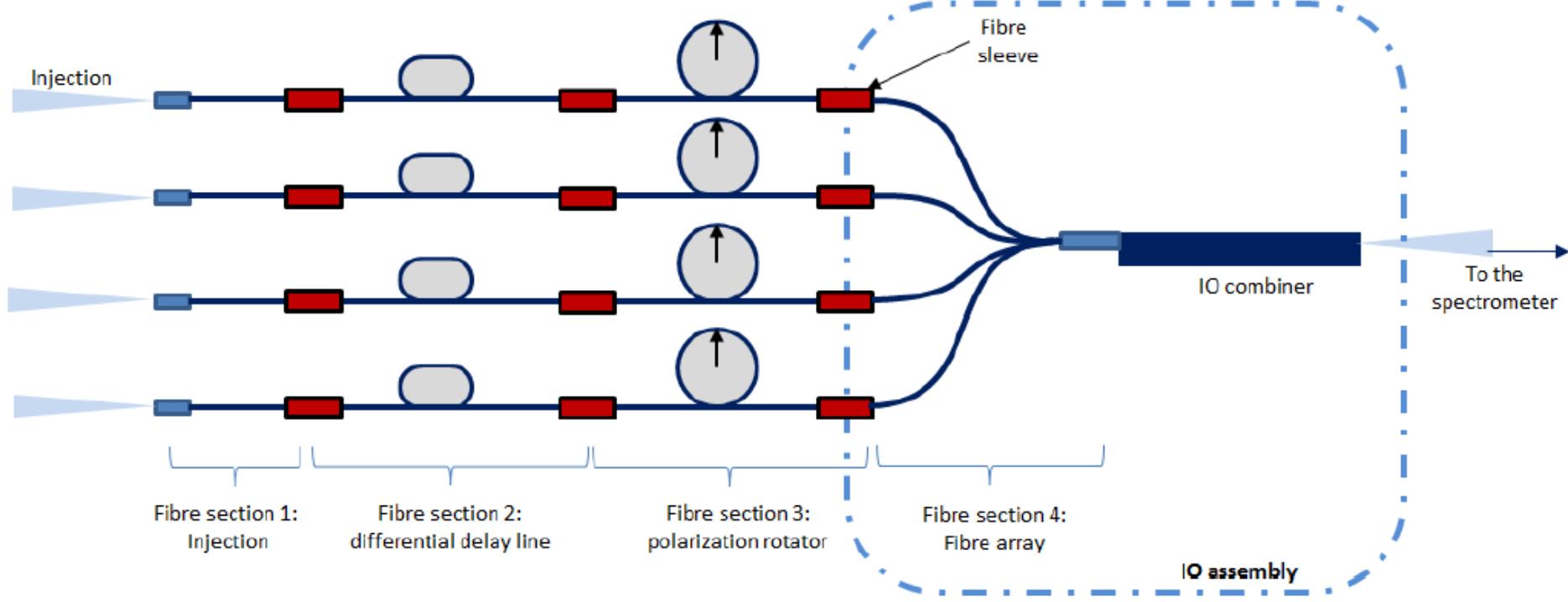
Tip-Tilt-Piston-Actuator



Pupil-Actuator



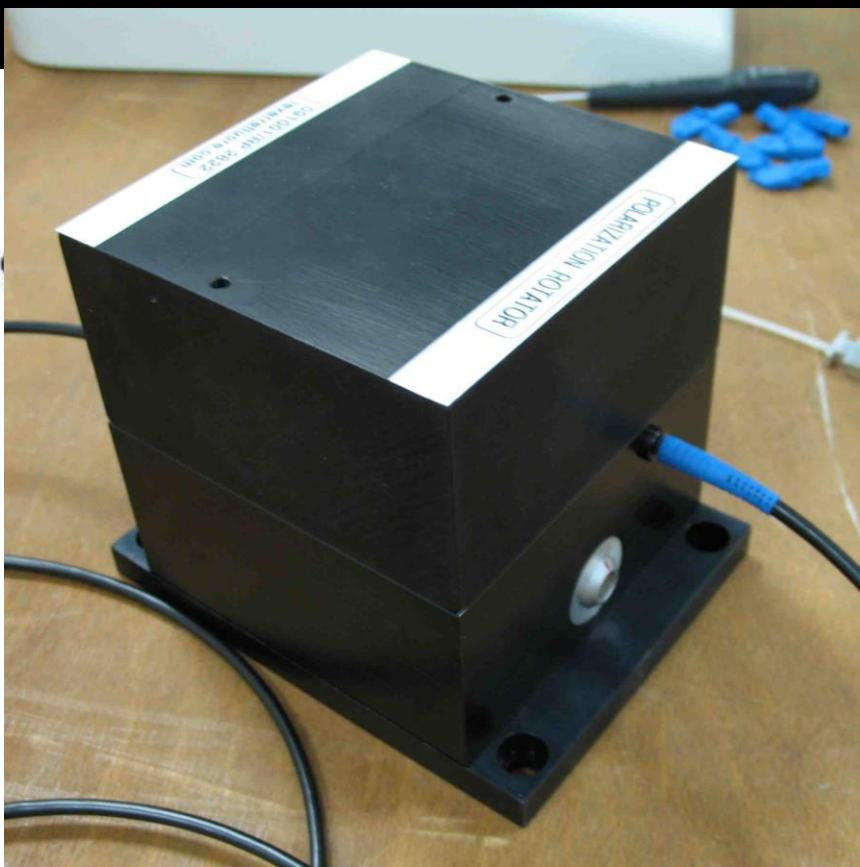
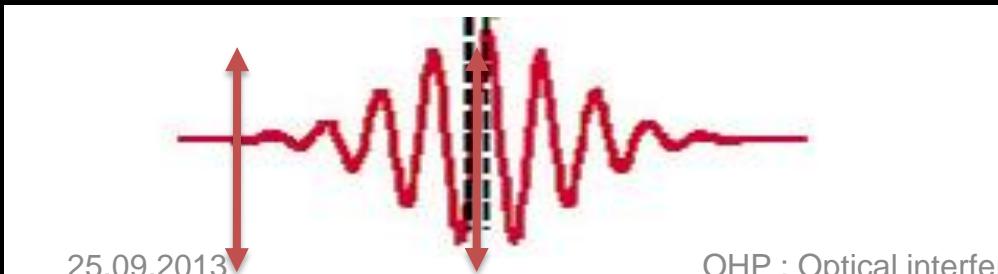
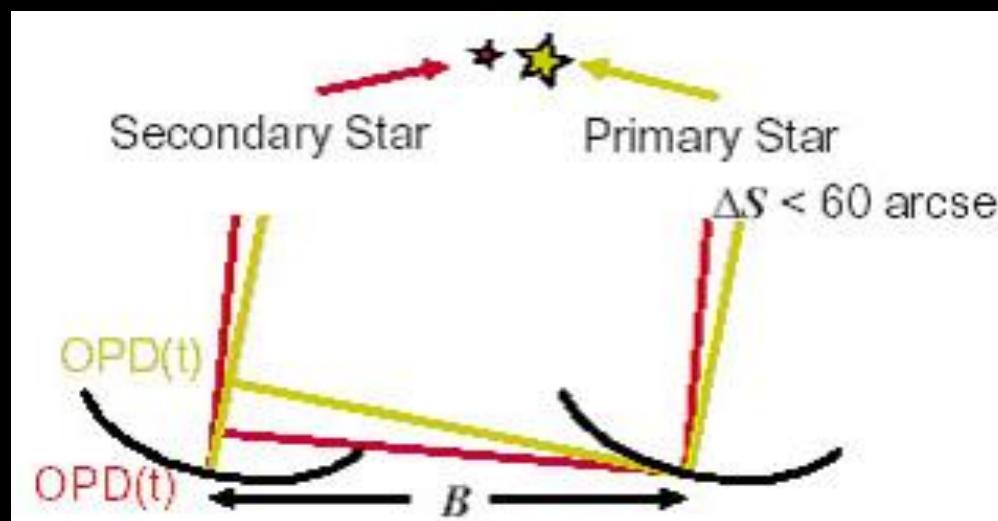
Single Mode Instrument



Fluoride glass fibers (OHANA)

- optimum throughput in K-band
- possibility to measure in unpolarized light = sensitivity

Adjusting the path length and polarization

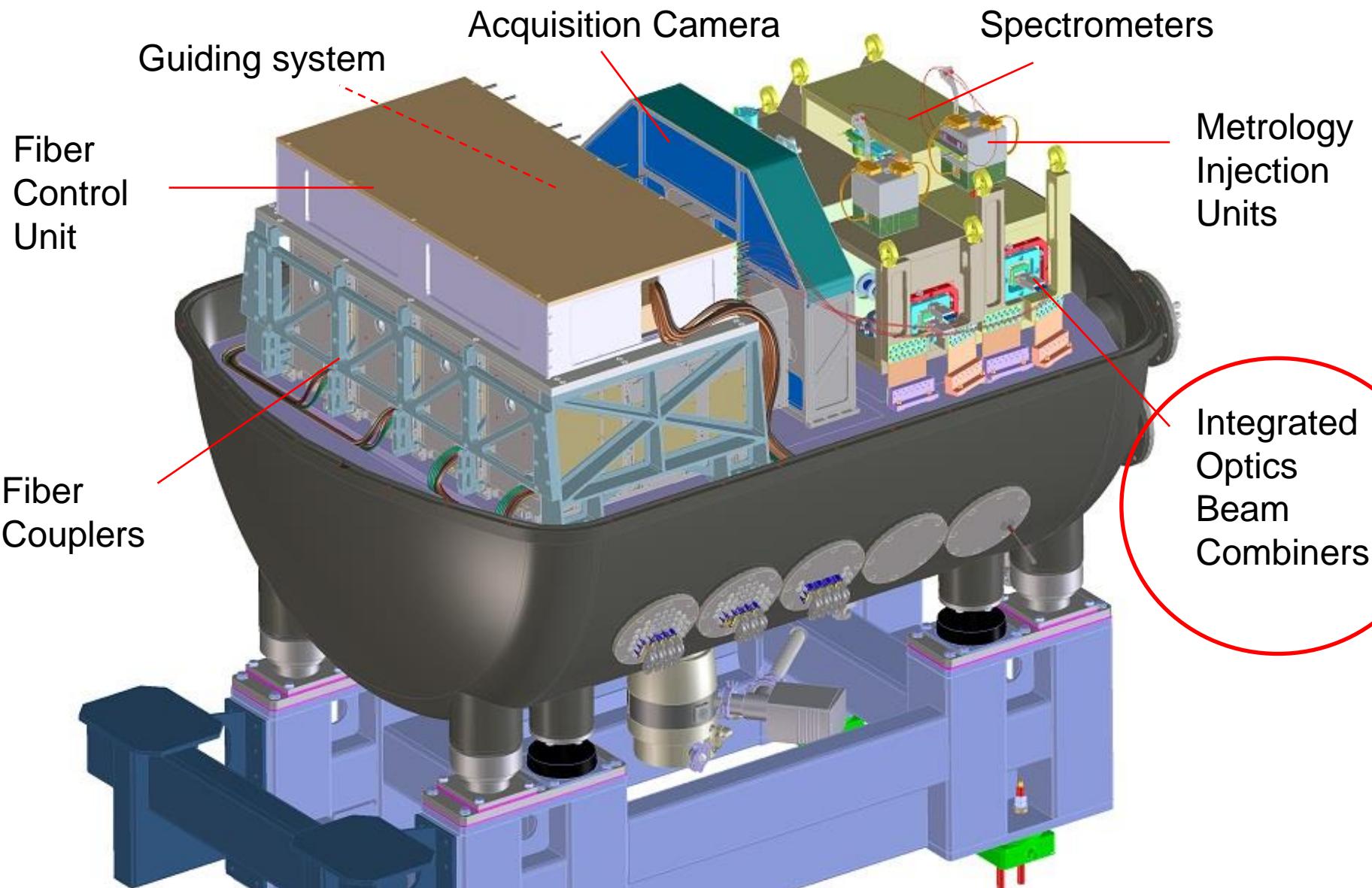


Perrin et al.

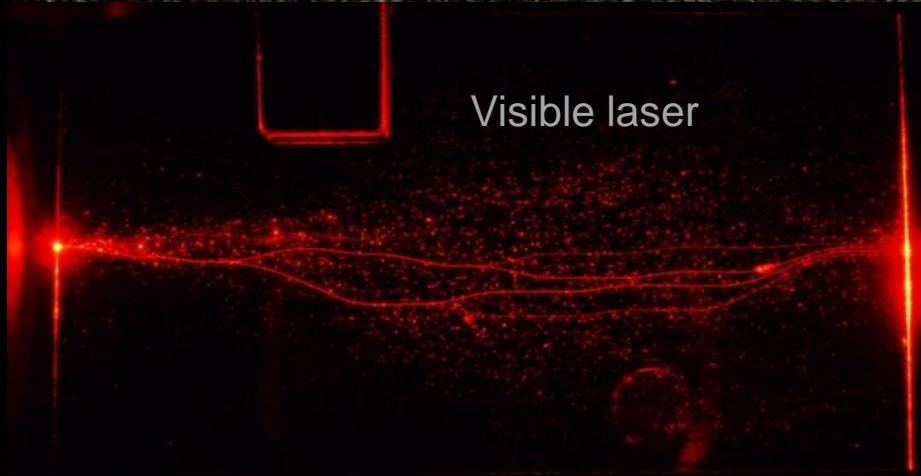


25.09.2013 OHP : Optical interferometers

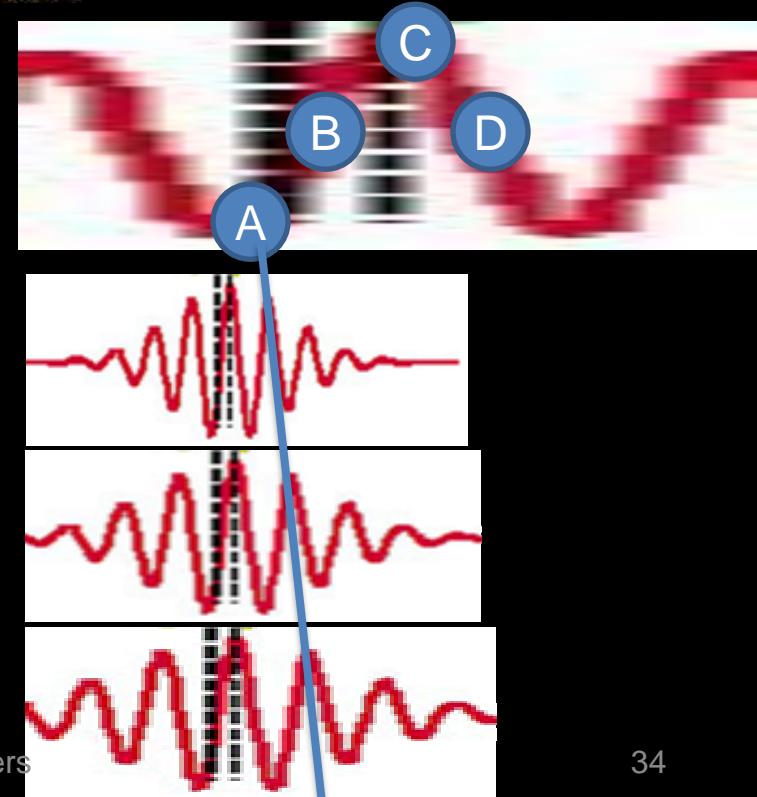
2 – Combiner optics



Integrated optics feeding spectrometer

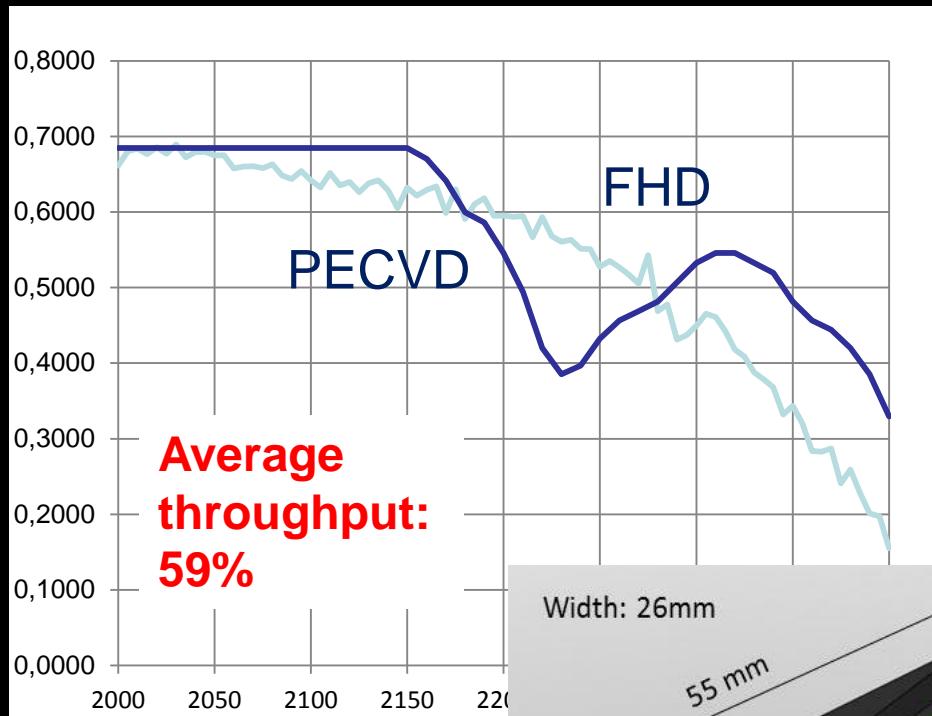


Jacou et al. 2010, Perraut et al.

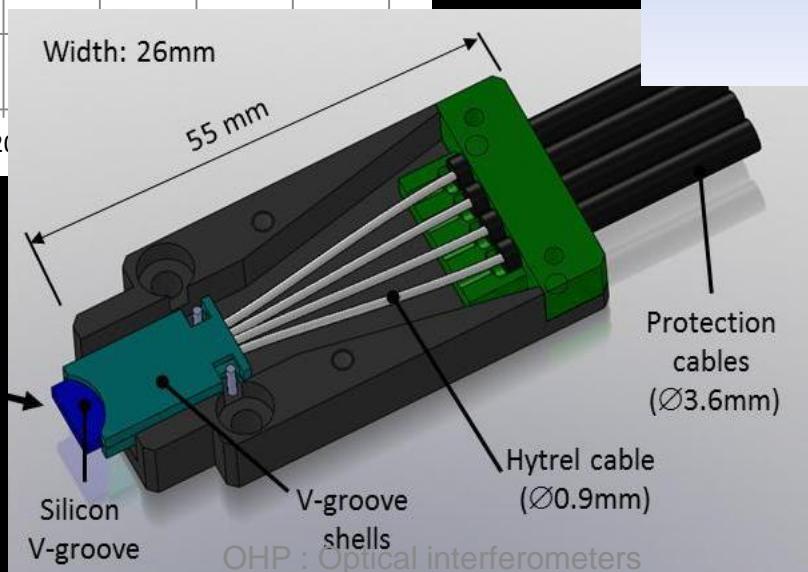
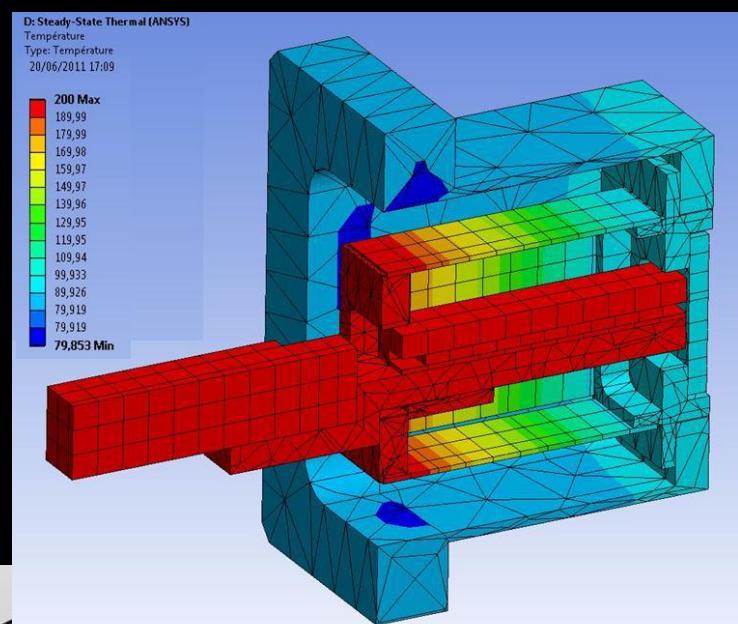


Integrated Optics

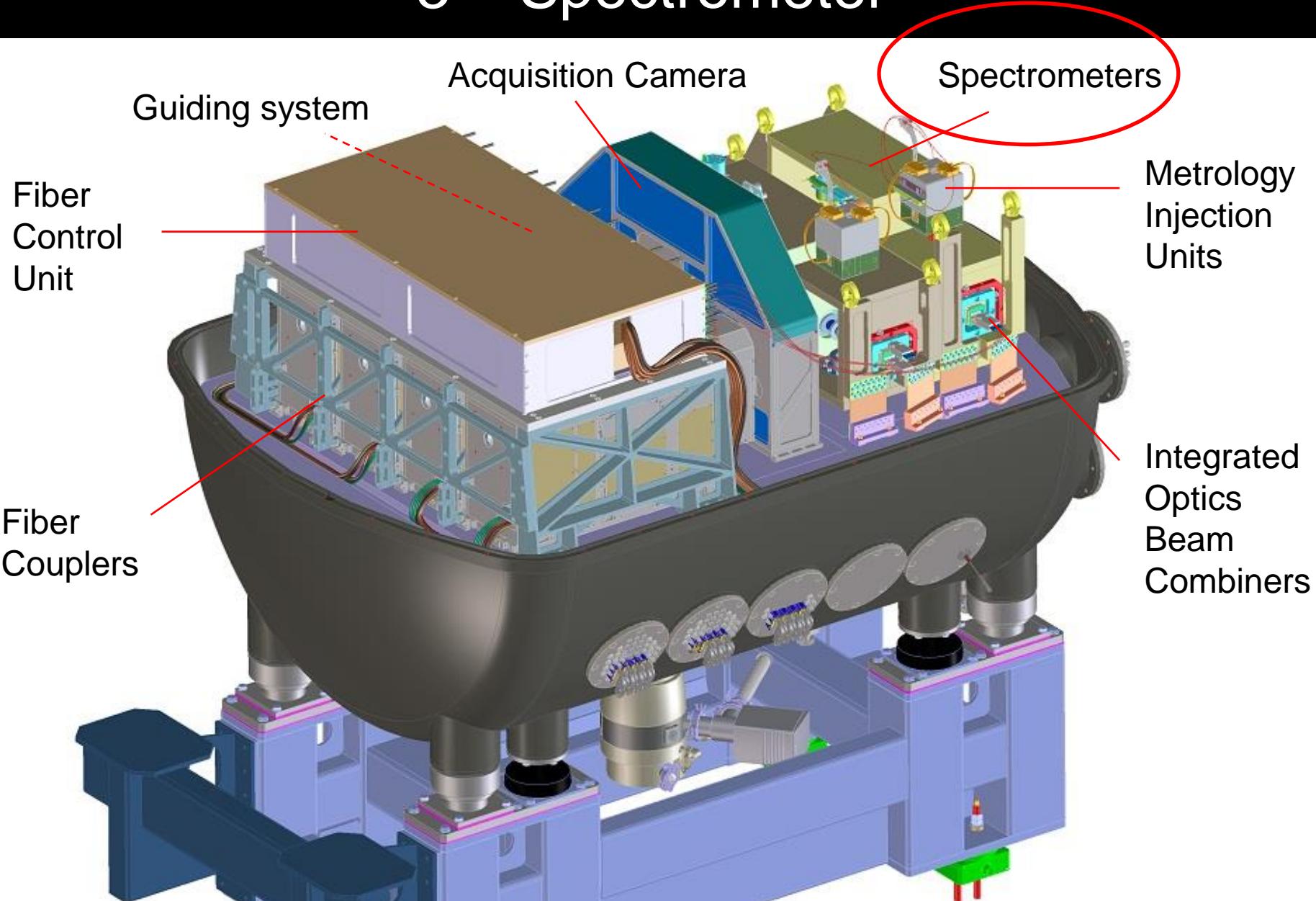
K-band operation



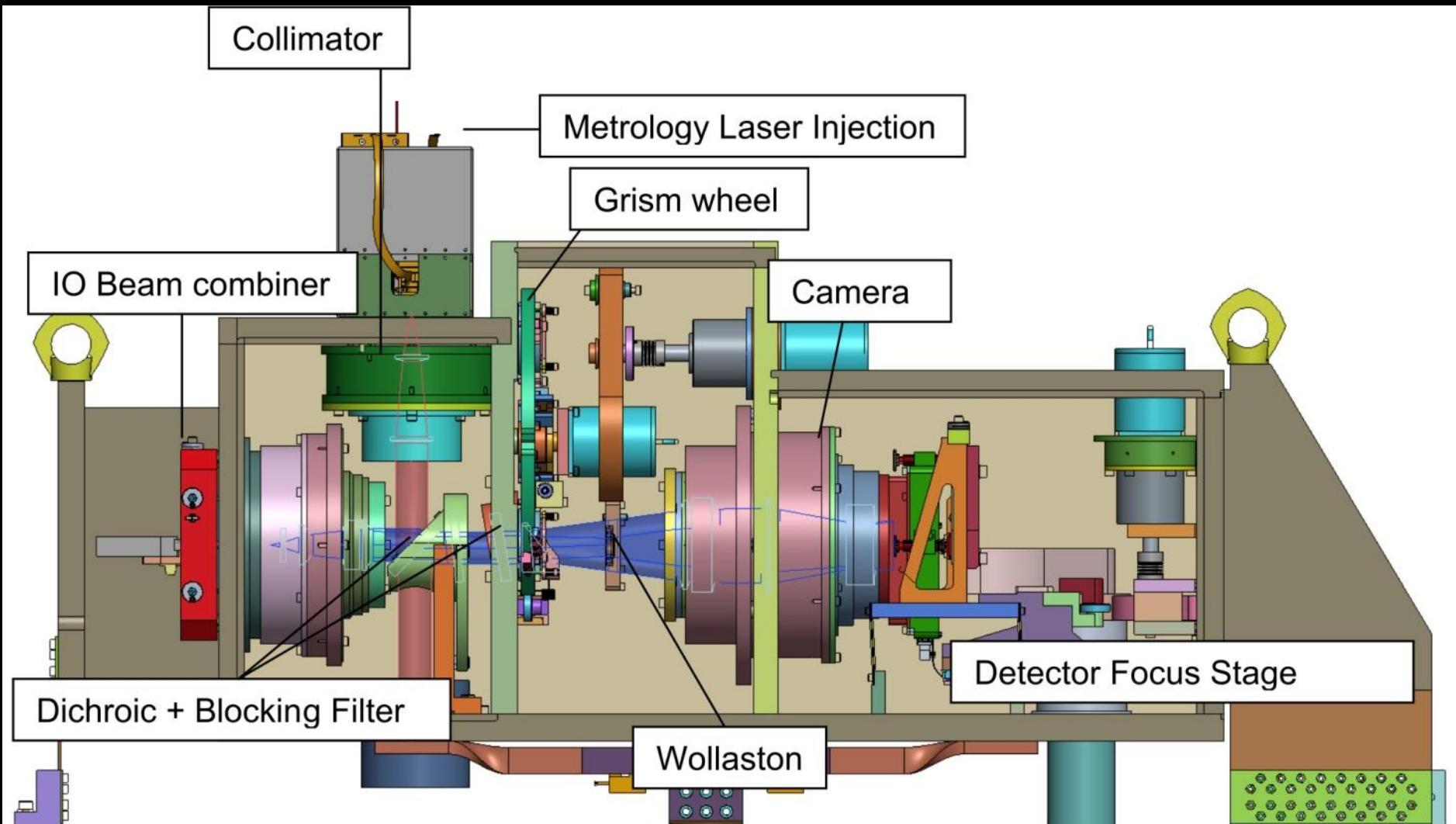
Cryogenic operation



3 – Spectrometer

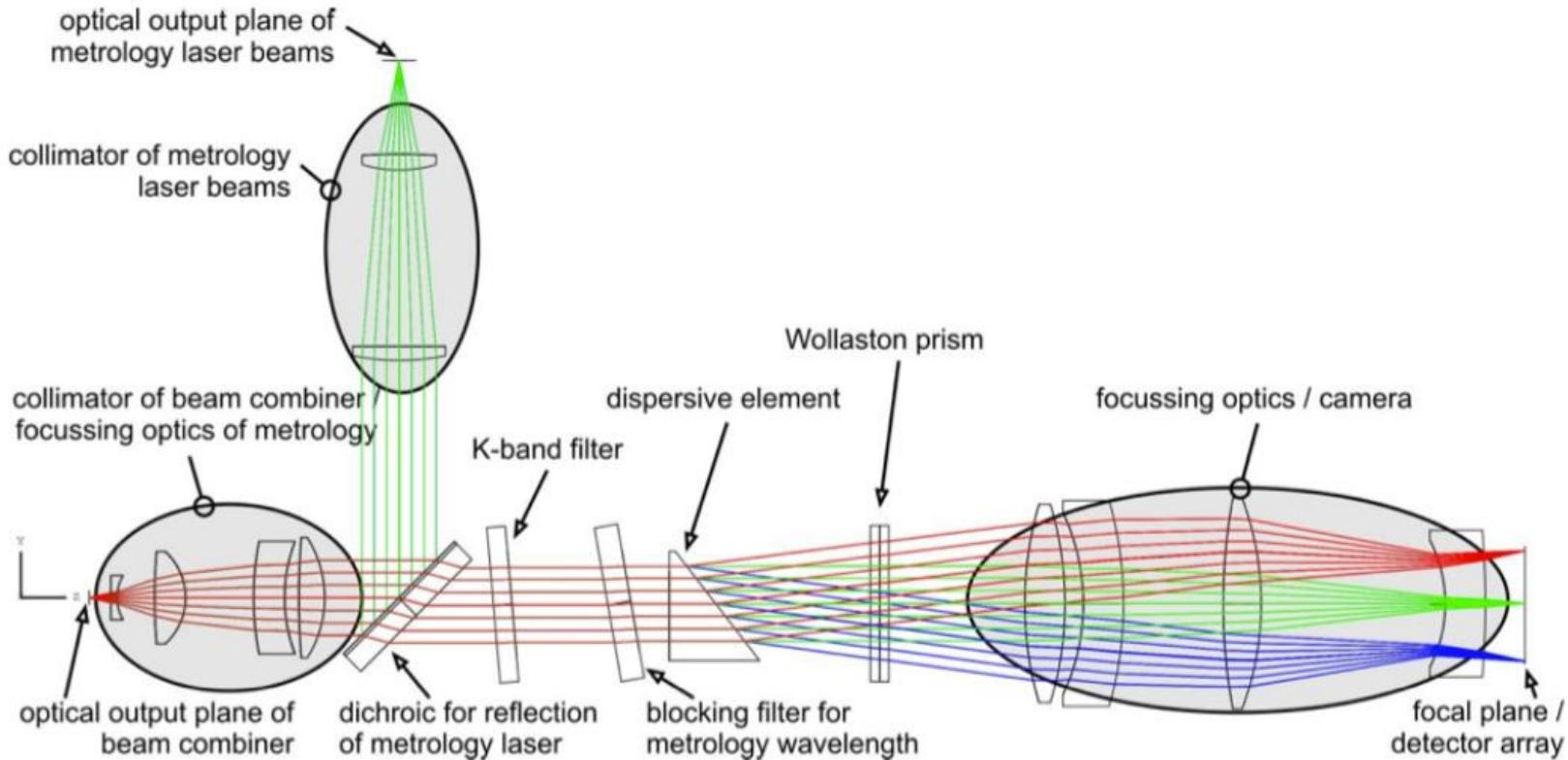


Spectrometers

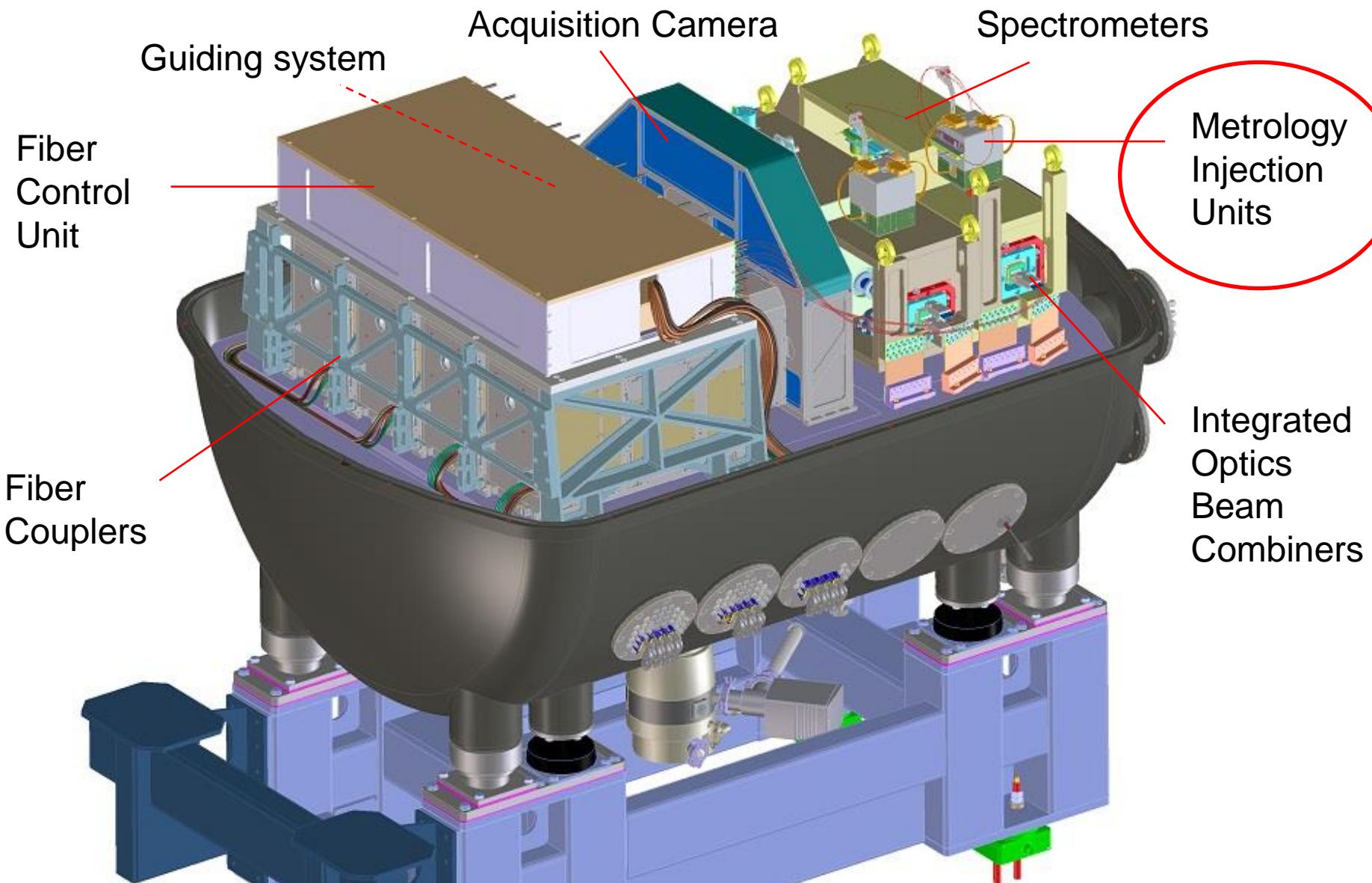


Spectrometers

Collimator

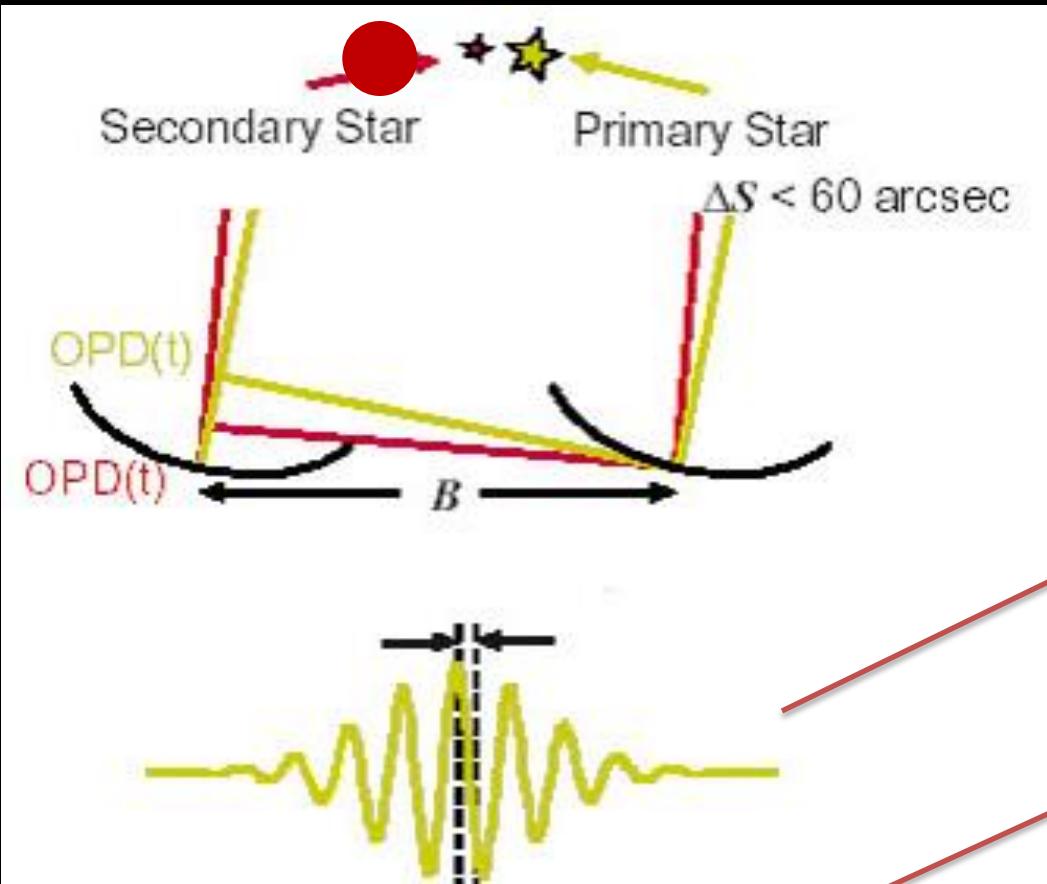


4 – Metrology



Interferometric astrometry

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



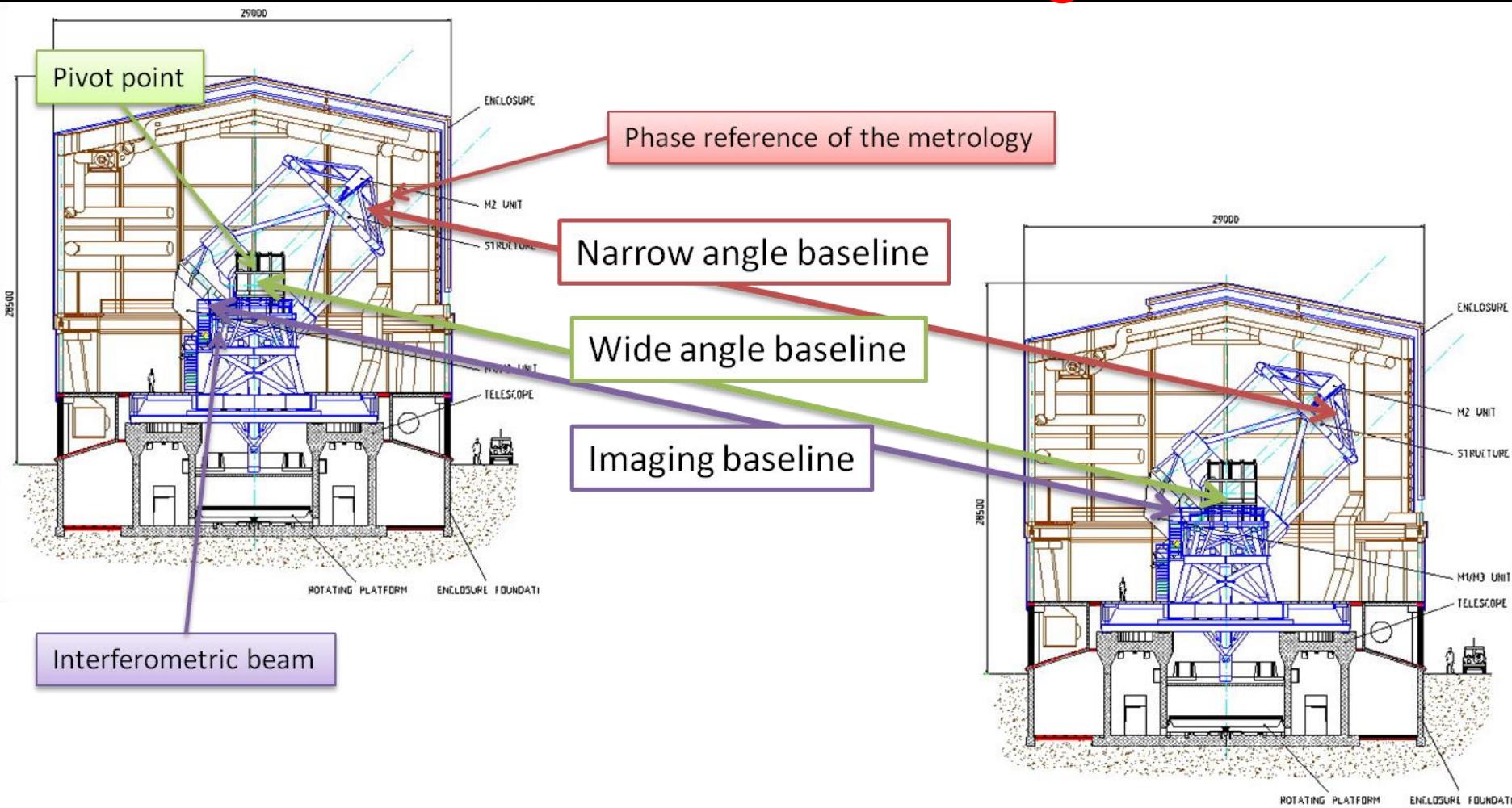
Interferometric astrometry

$$5 \text{ nm} \leftarrow \delta OPD = \vec{B} \cdot \vec{\alpha} - \vec{B} \cdot \vec{\beta} = \vec{B} \cdot (\vec{\alpha} - \vec{\beta})$$

500 μm 10 μas

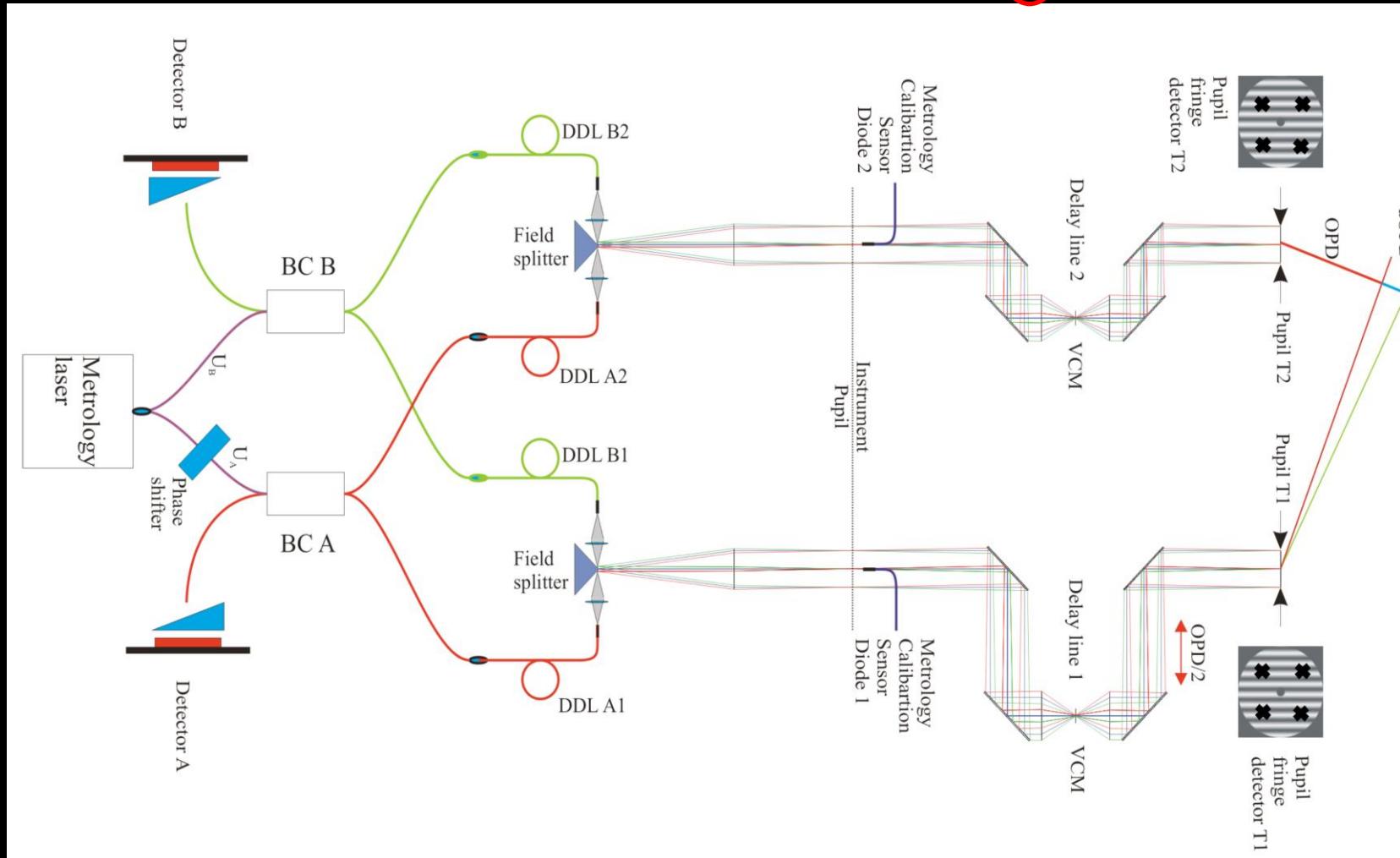
Interferometric baseline

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



Interferometric baseline

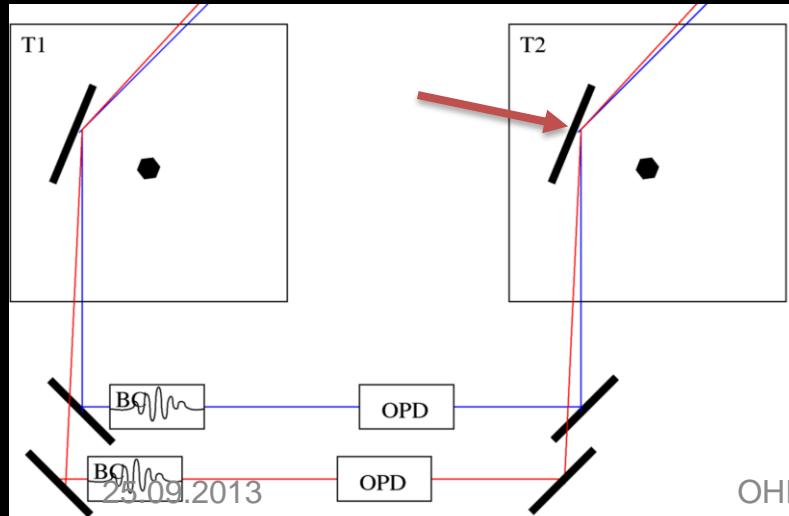
$$\delta OPD = \vec{B} \cdot \vec{\alpha} - \vec{B} \cdot \vec{\beta} = \vec{B} \cdot (\vec{\alpha} - \vec{\beta})$$



GRAVITY narrow angle baseline and metrology

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

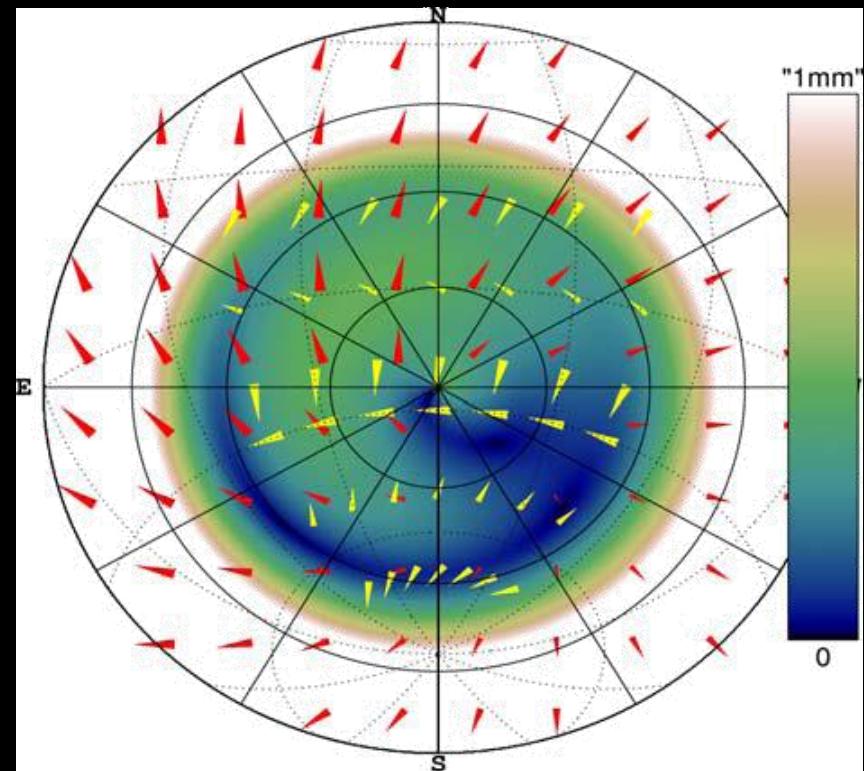
Stable realization of the narrow angle baseline



OHP : Optical interferometers

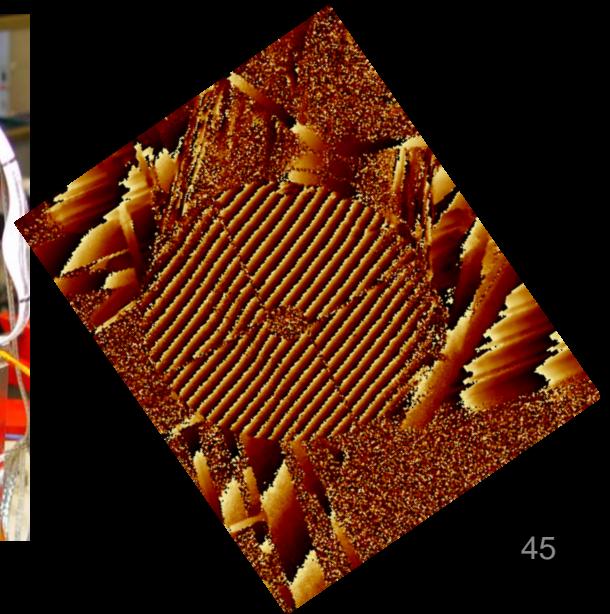
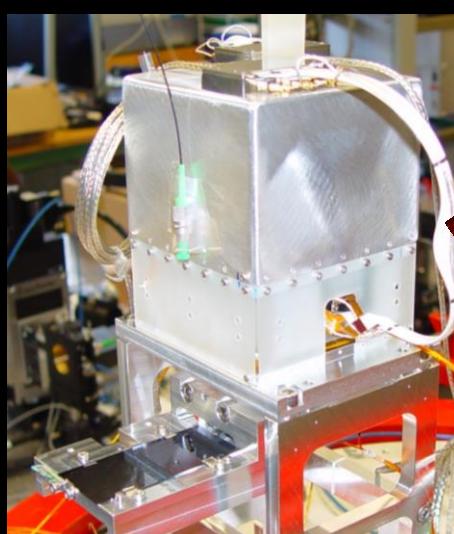
500 μm

Calibration of the narrow angle baseline

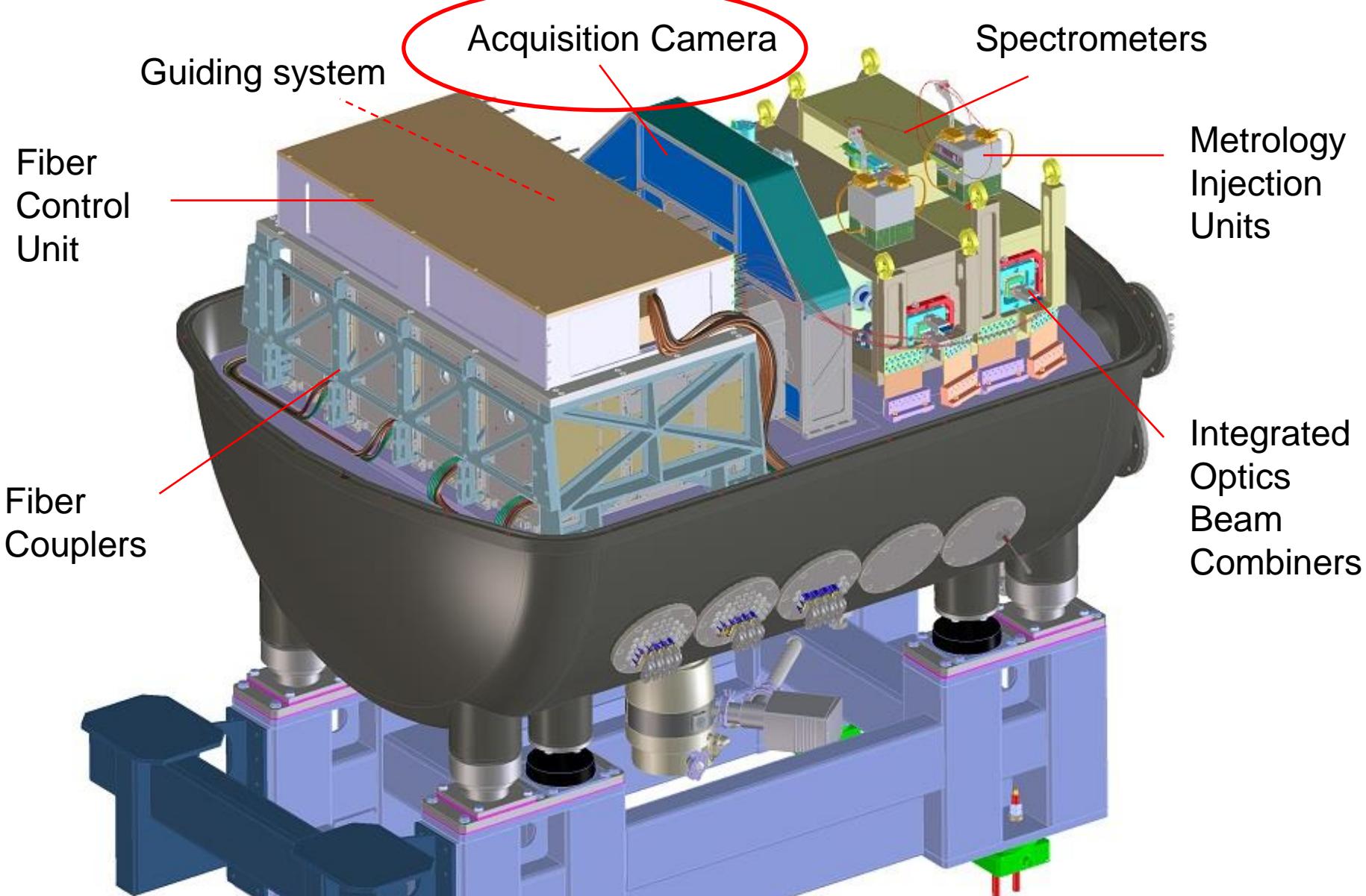


Laser Metrology

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

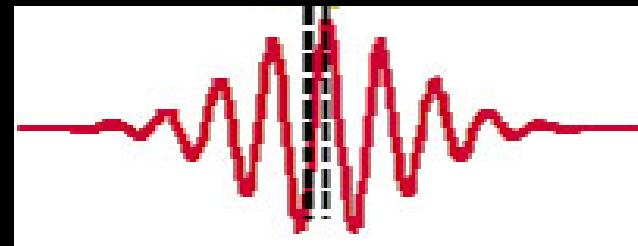
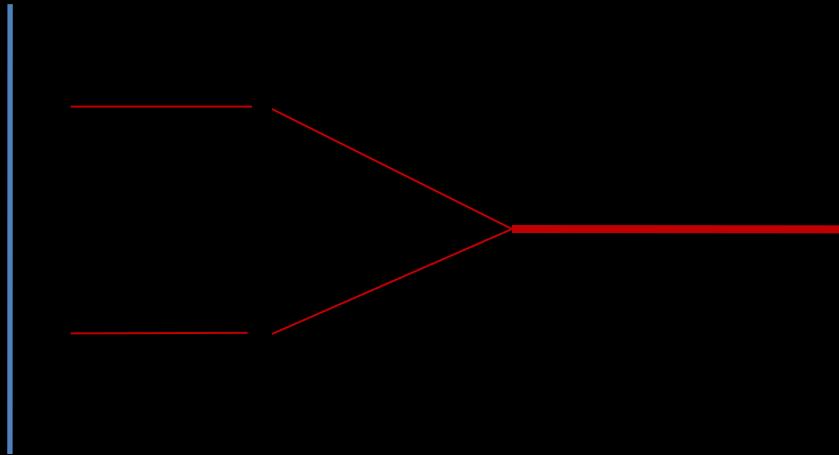


5 – Acquisition Camera

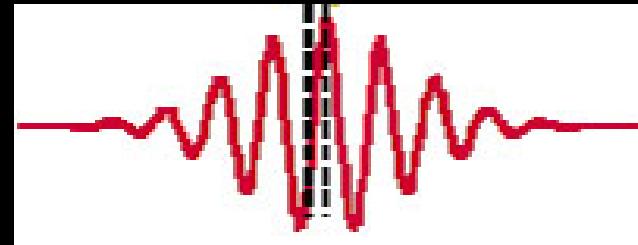
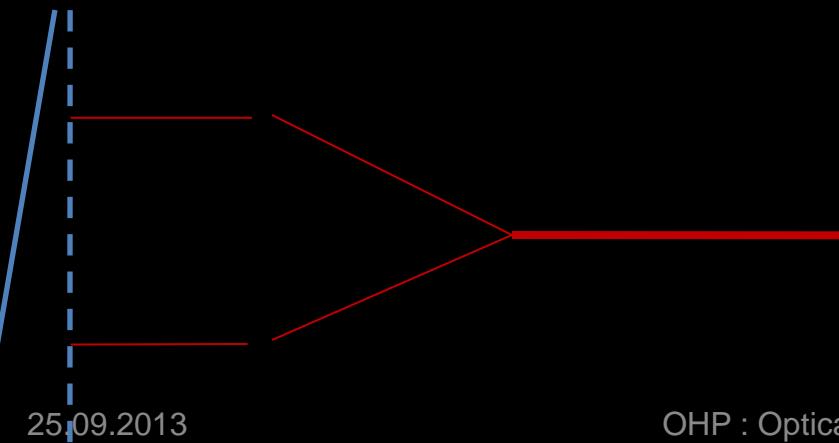


Pupil and tilt errors

For perfect tip-tilt correction



For simultaneous tilt error



Interferometric Astrometry

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

OPD measurement Error

- Phase error on SC target
- Phase error on FT target
- Wavelength error

Metrology Error

- Phase measurement error
- Metrology wavelength stability

Baseline Error

- Short term stability?
- Long term stability?

$$(\Phi_{FT} - \Phi_{SC}) \frac{\lambda_s}{2\pi} - (\phi_{M1} - \phi_{M2}) \frac{\lambda_m}{2\pi} = -\Delta L_{air} \left(\frac{n_a^{\lambda_m}}{n_a^{\lambda_s}} - 1 \right) - \Delta L_{fiber} \left(\frac{n_g^{\lambda_m}}{n_g^{\lambda_s}} - 1 \right)$$

Dispersion Error

- Hysteresis of the fibered delay lines
- Refractive index of air
- Refractive index of fluoride glass

$$B_{NAB} \cdot \vec{\alpha} - \vec{\beta}$$

Goal: $10\mu\text{as} * \sqrt{3}$
in 5 minutes

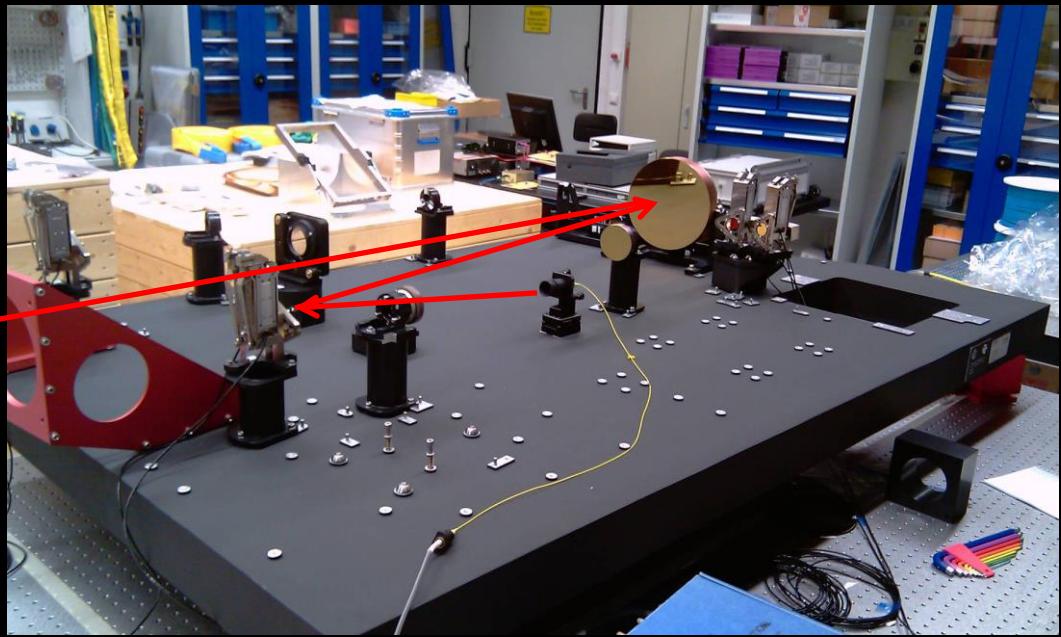
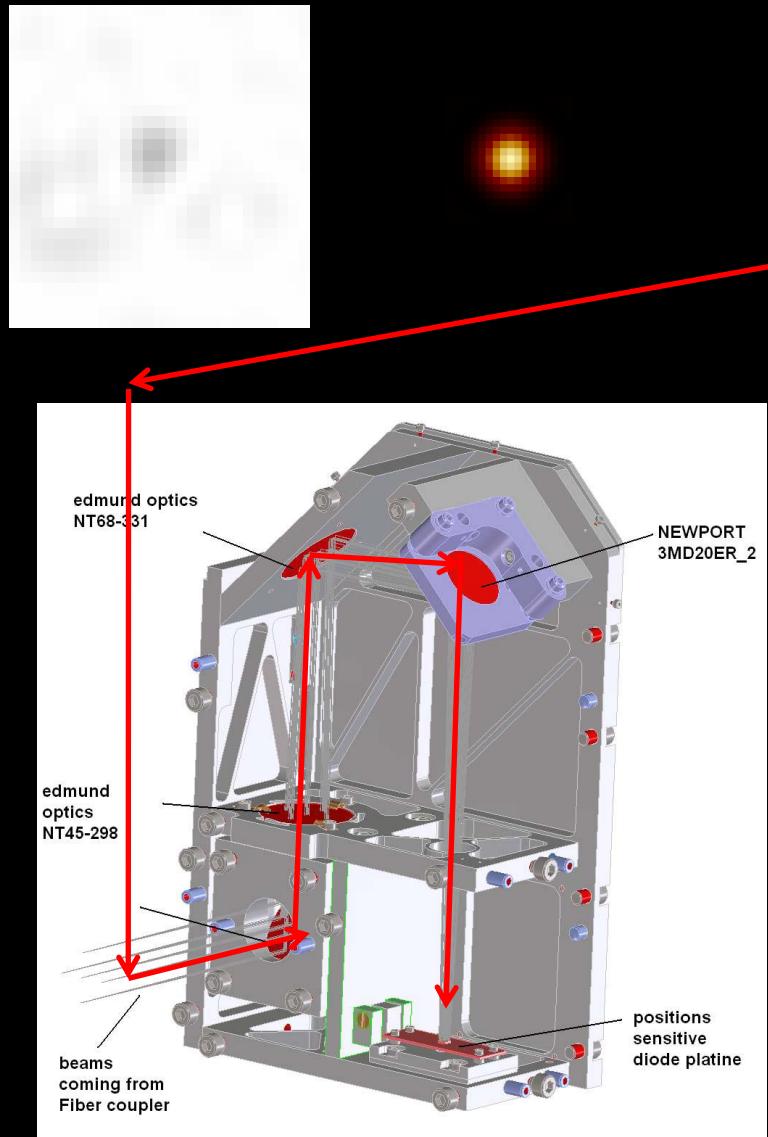
$$+ \Delta\alpha_1 \cdot (pup_{FT1} - pup_{M1}) \\ - \Delta\alpha_2 \cdot (pup_{FT2} - pup_{M2}) \\ + \Delta\beta_2 \cdot (pup_{SC2} - pup_{M2}) \\ - \Delta\beta_1 \cdot (pup_{SC1} - pup_{M1})$$

Pupil positioning Error

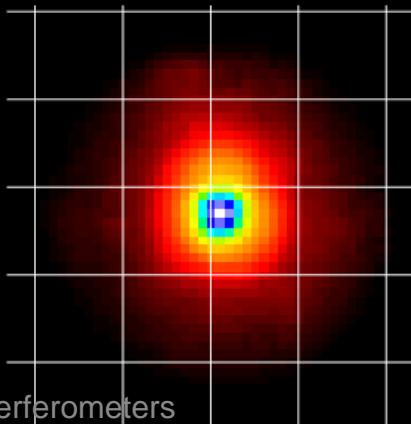
- Tip-tilt error
- Lateral pupil error
- Longitudinal pupil error

GRAVITY Tilt Control

Atmosphere VLT Tunnel

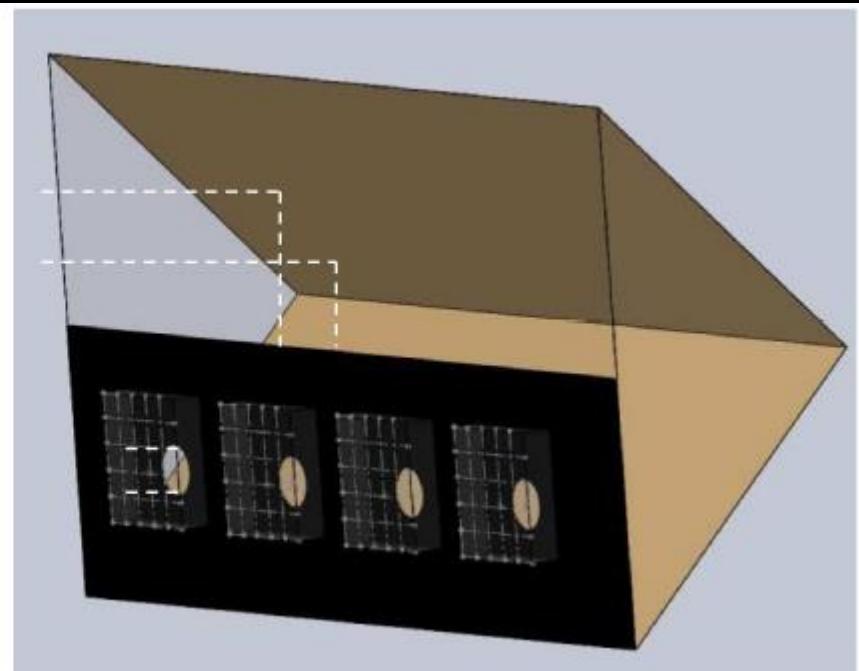
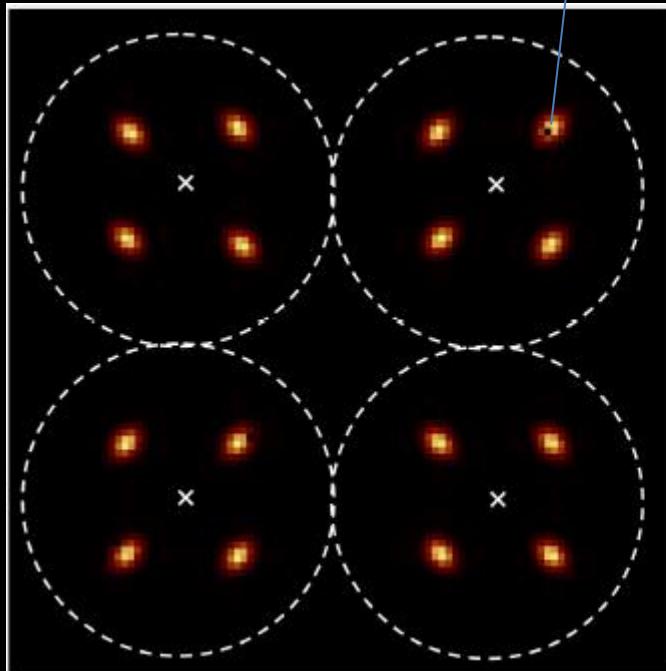


Acquisition and
guiding camera



OHP : Optical interferometers

GRAVITY Pupil Control



25.09.2013

Amorim et al. 2010, Pfuhl et al.

OHP : Optical interferometers

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Back to astrophysics – Capablities and scientific prospects of the VLTI-GRAVITY instrument



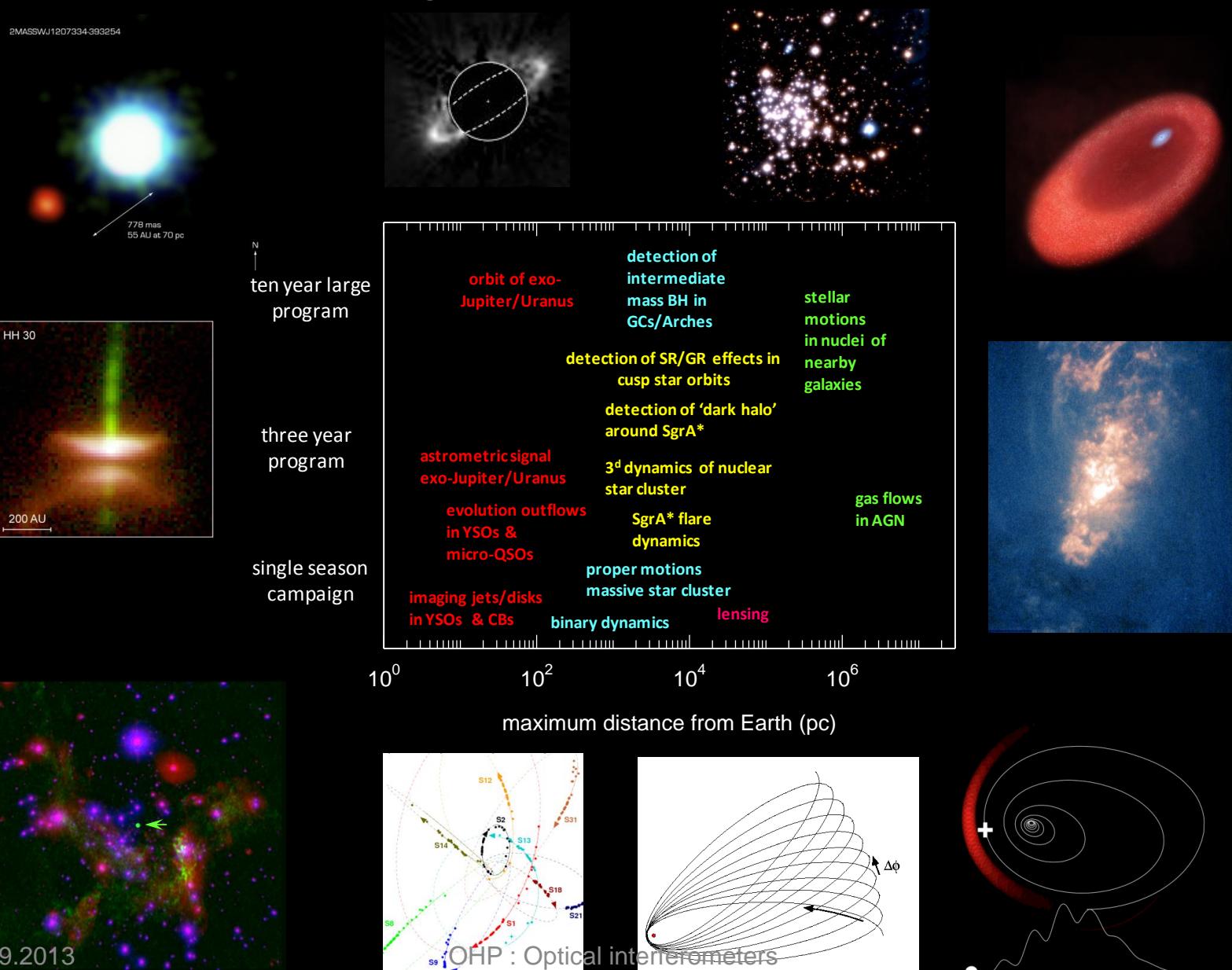
Overview

- Primary science case: the Galactic Center
- 4-telescope beam combiner for the VLTI
- K band (full)
- 3 spectral resolutions ($R=22, 500, 4000$)
- single and dual field (< 2" or 6" separation)
- dual field astrometry
- $m_K \sim 10$ limiting magnitude of fringe tracker
- $m_K \sim 19$ for science combiner

Performances

- 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 $m_K \sim 19$* are possible

Observing the Universe in motion



Observing the Universe in motion

SS Leporis



10 mas

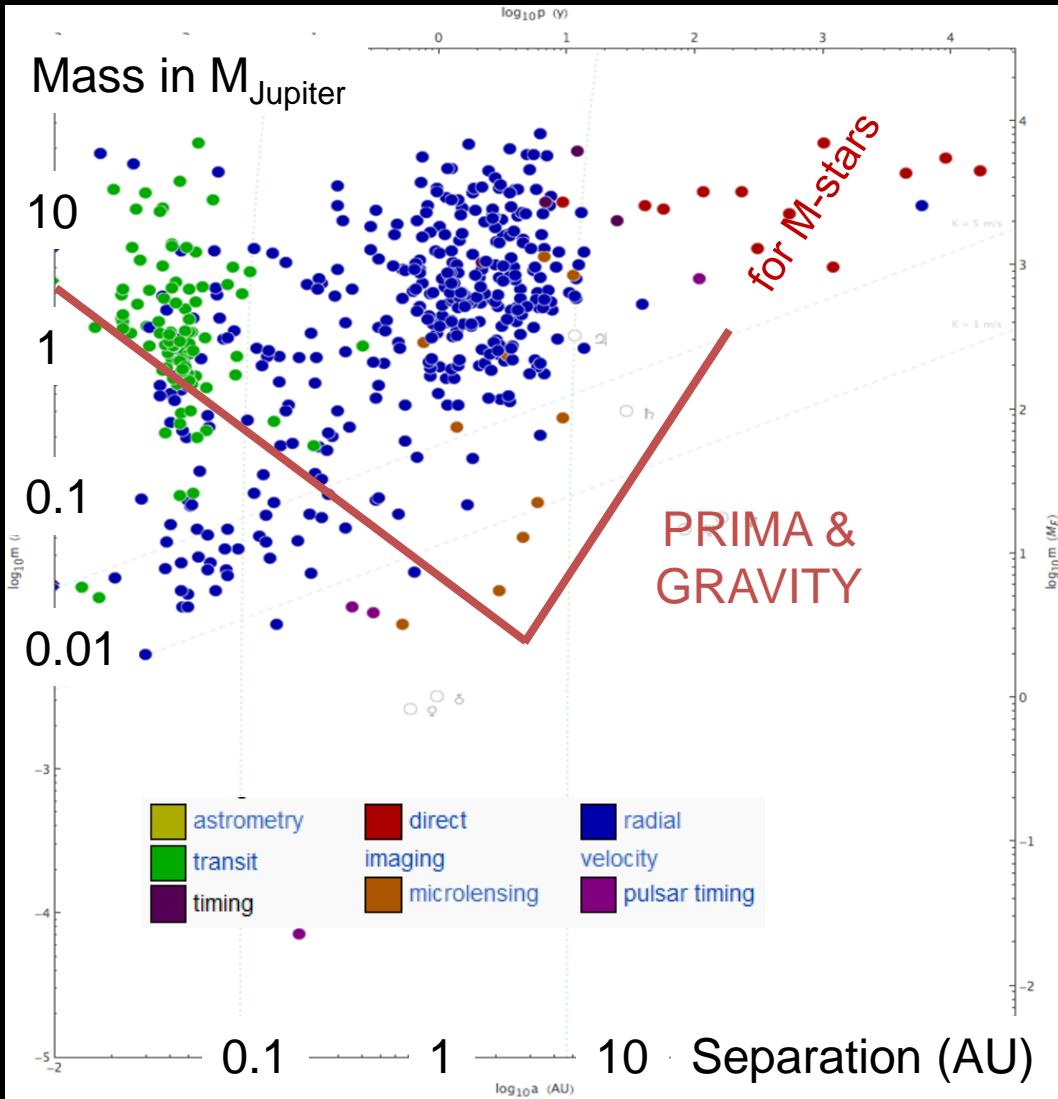
2010/10/28

Observing the Universe in motion

SS Leporis



10 mas

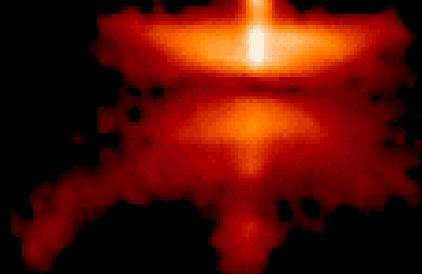


From Wikipedia (exoplanet discovered through 2010-10-03)

OHP : Optical interferometers

Observing the Universe in motion

HH 30



25.09.2013

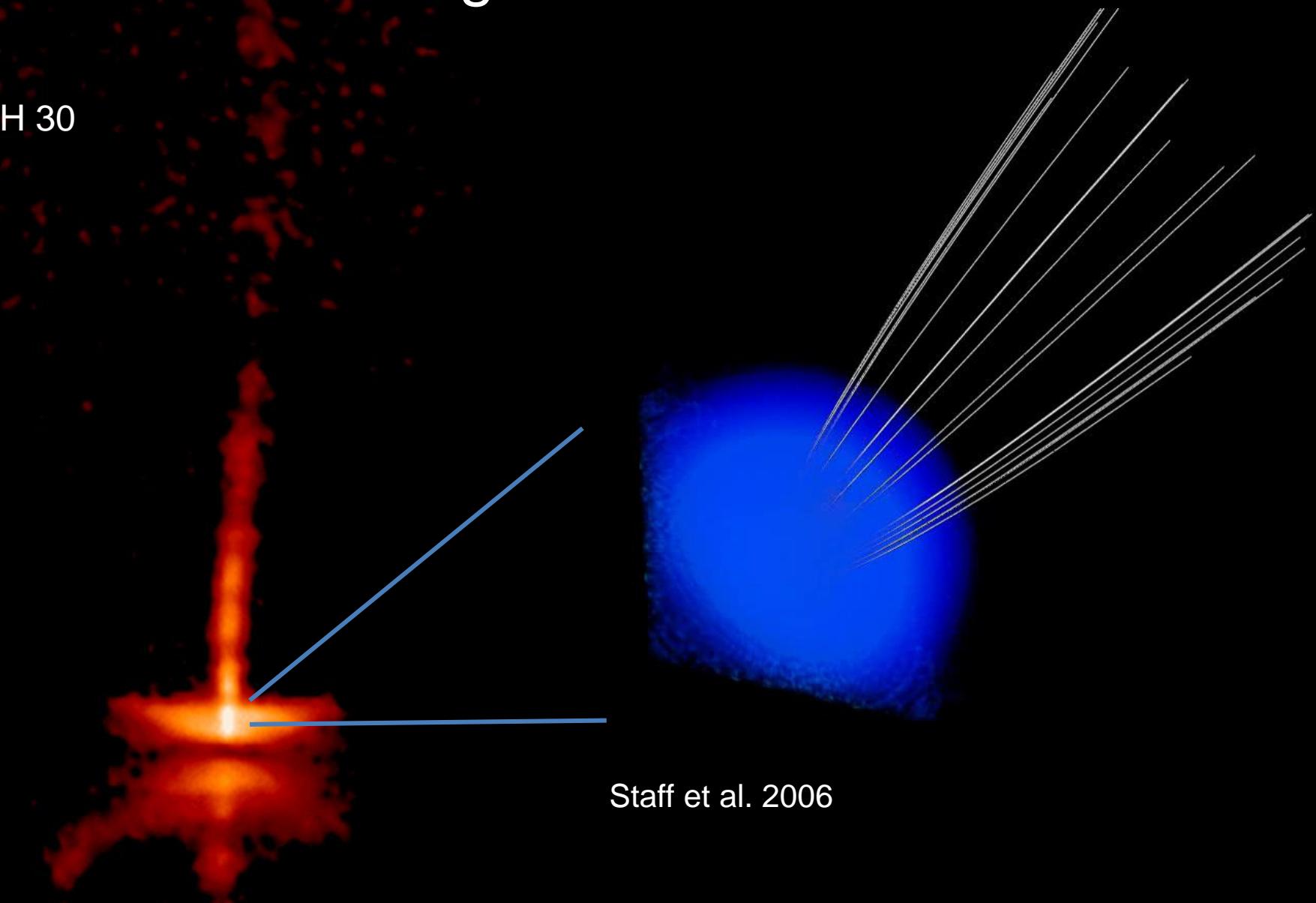
Credits: Watson, Stapelfeldt, Krist, Burrow, ESA STScI

OHP : Optical interferometers

57

Observing the Universe in motion

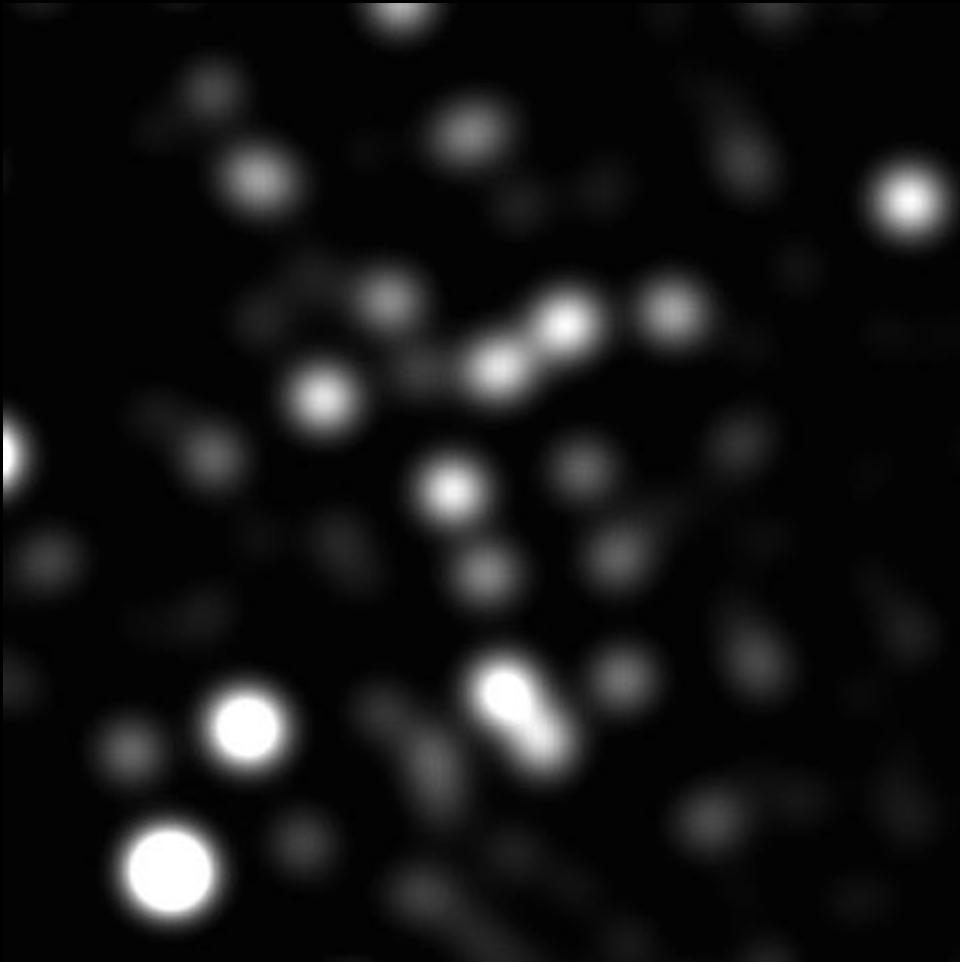
HH 30



Staff et al. 2006

Observing the Universe in motion

Galactic Center



25.09.2013

NTT/VLT observations

OHP : Optical interferometers

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Observing the Universe in motion

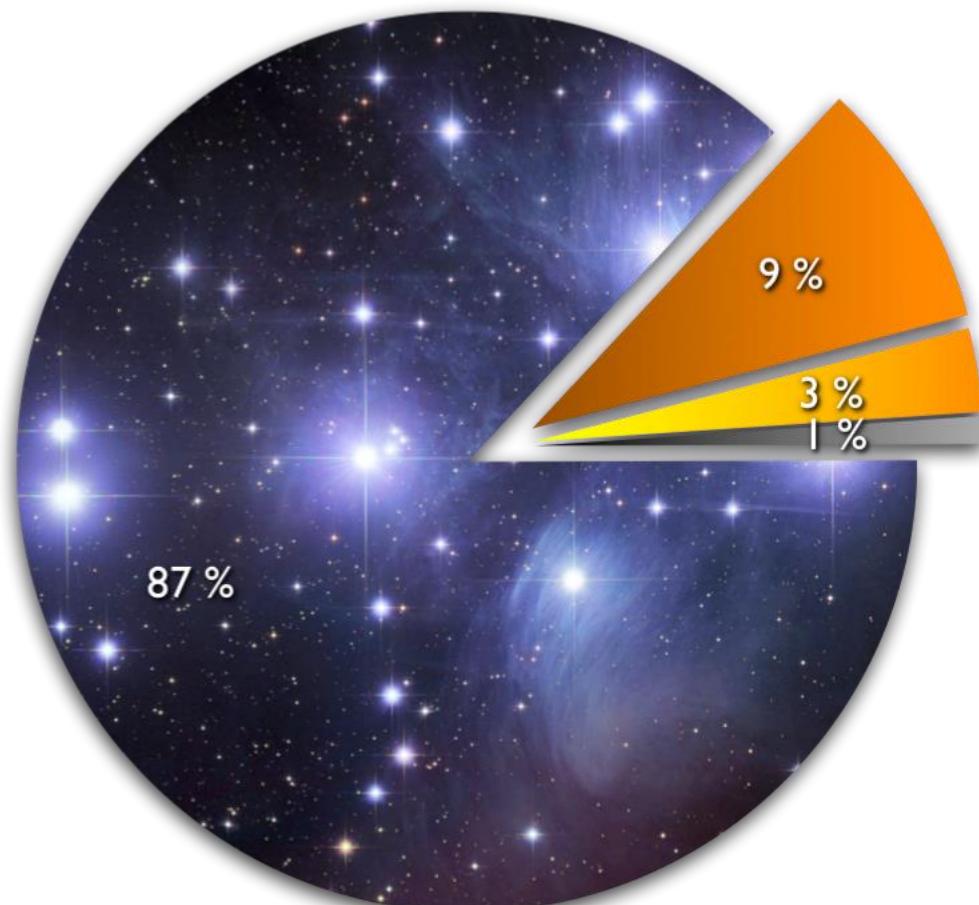
Galactic Center



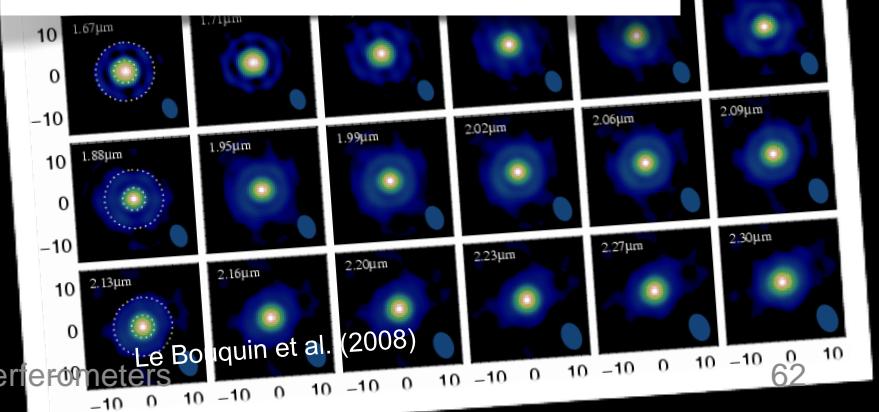
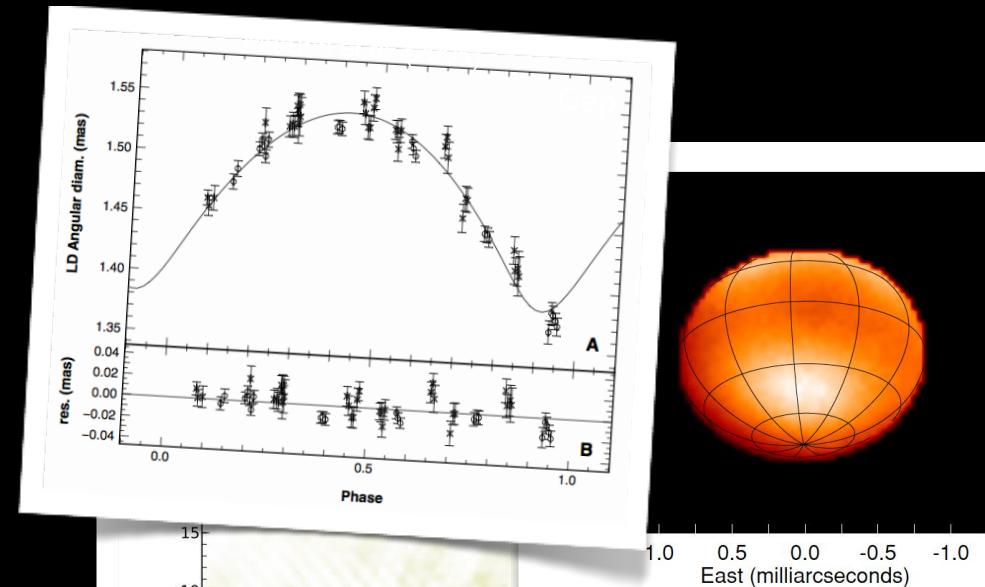
Stellar Physics & Interferometry

Publications in
optical / infrared
interferometry
(1998-2013)

- Stellar physics
- Dust/exoplanets
- AGN
- Asteroids

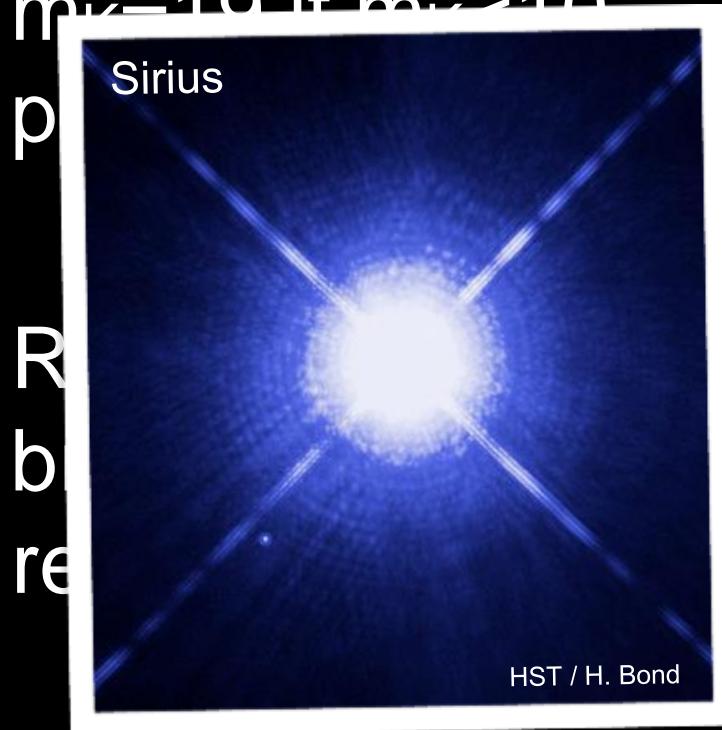


- 4T interferometry (like PIONIER), with spectral resolution (like AMBER)
- Single field sensitivity ~ PIONIER
- Spectro-imaging of stellar surfaces and environments at spectral resolution 4000
- Within a single field of view (60 / 250 mas)

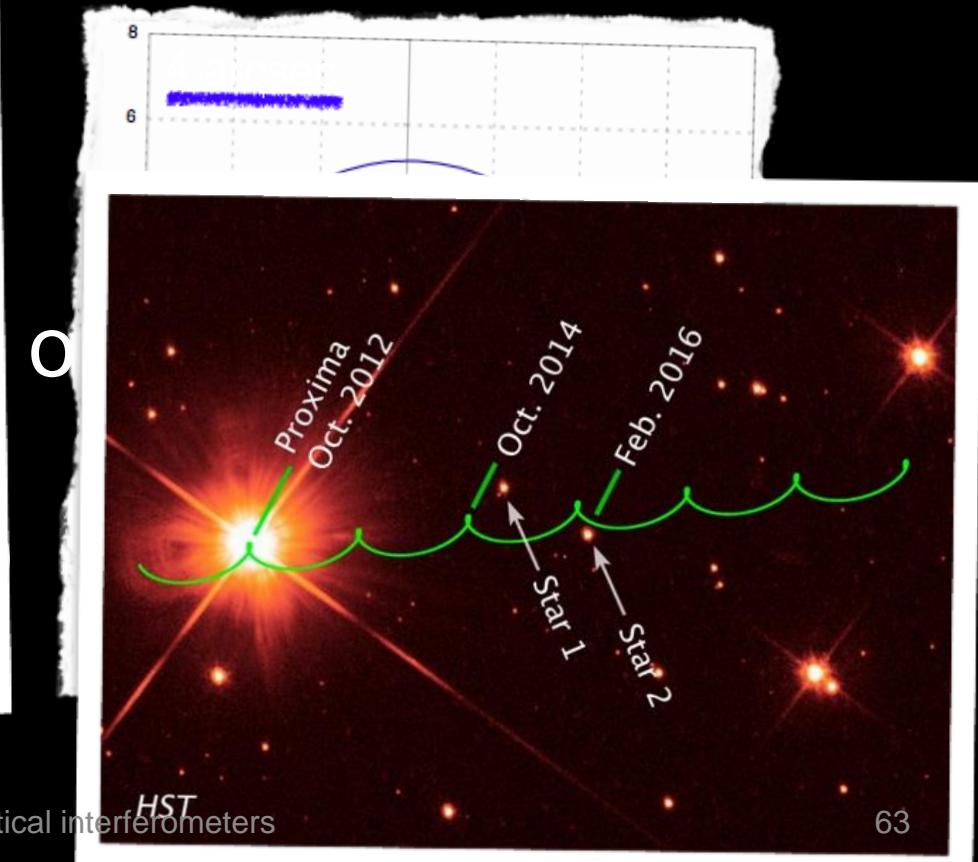


Astrometry

- Astrometry and spectro-imaging up to 6" separation and $m_1 = 10$ if $m_2 < 10$

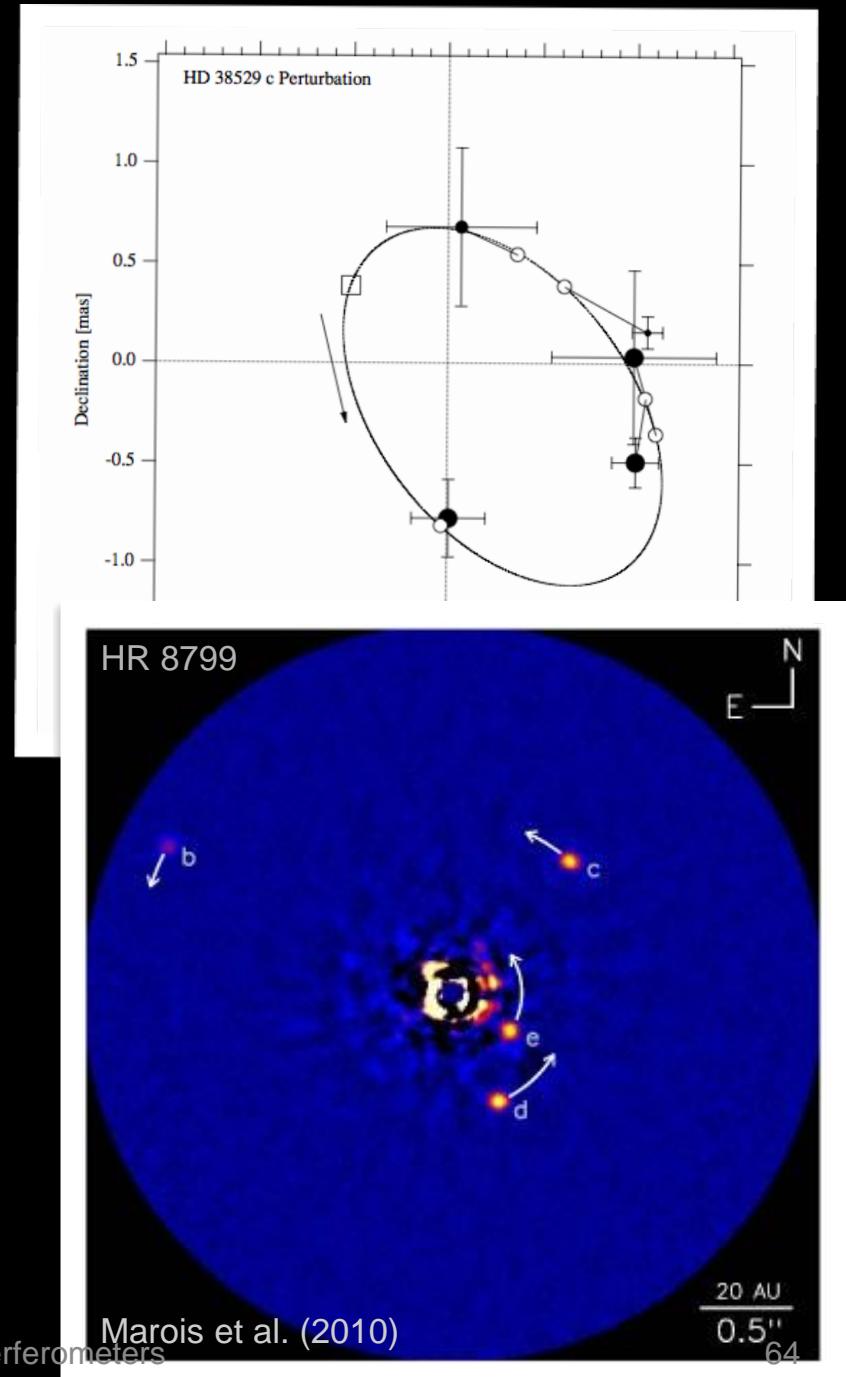


- Radial velocity measurements

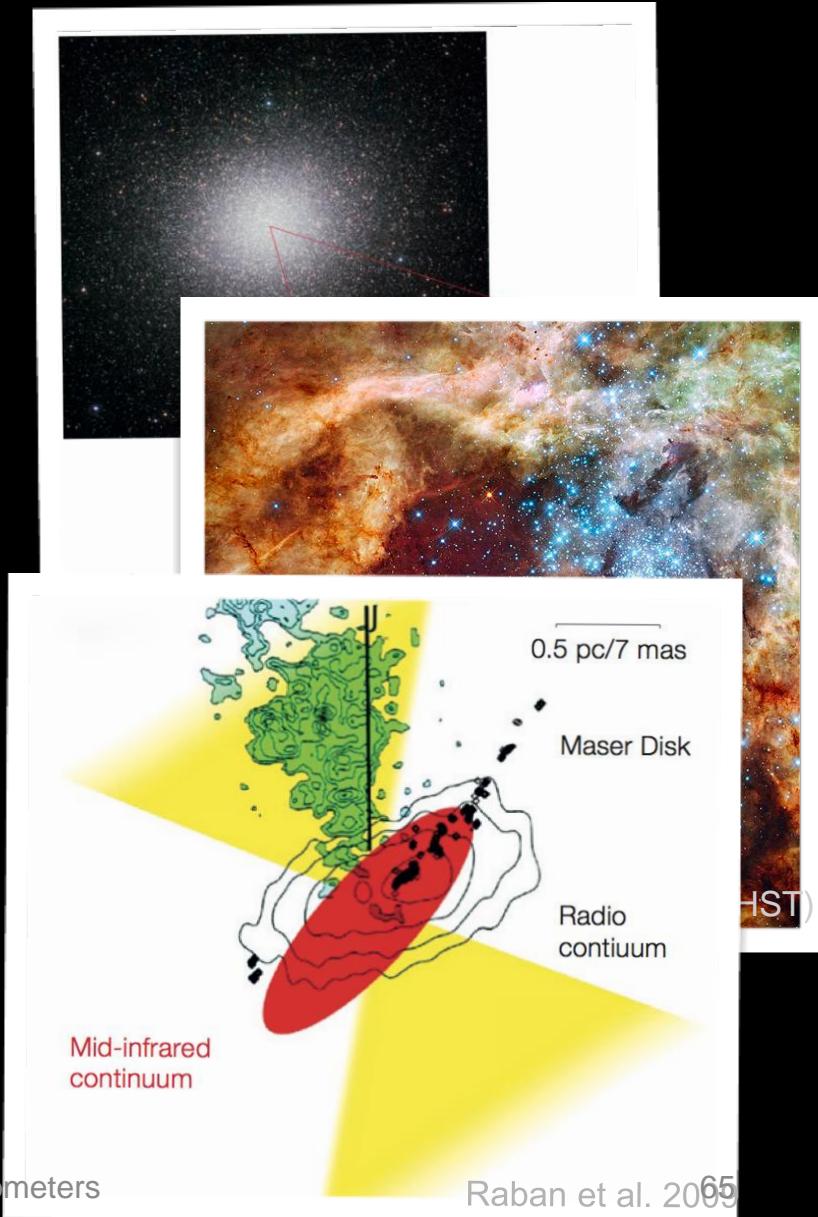


Exoplanets

- Astrometric wobble of star \rightarrow Planet mass
- Displacement of spatially resolved planets relative to their star \rightarrow Moons



- Astrometry of stars near globular cluster cores
- Brightest stars in the Magellanic Clouds and their surroundings
- Spectro-imaging of AGN cores (including spectro-astrometry)



Schedule

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

STATUS OF THE INSTRUMENT (pictures only)

