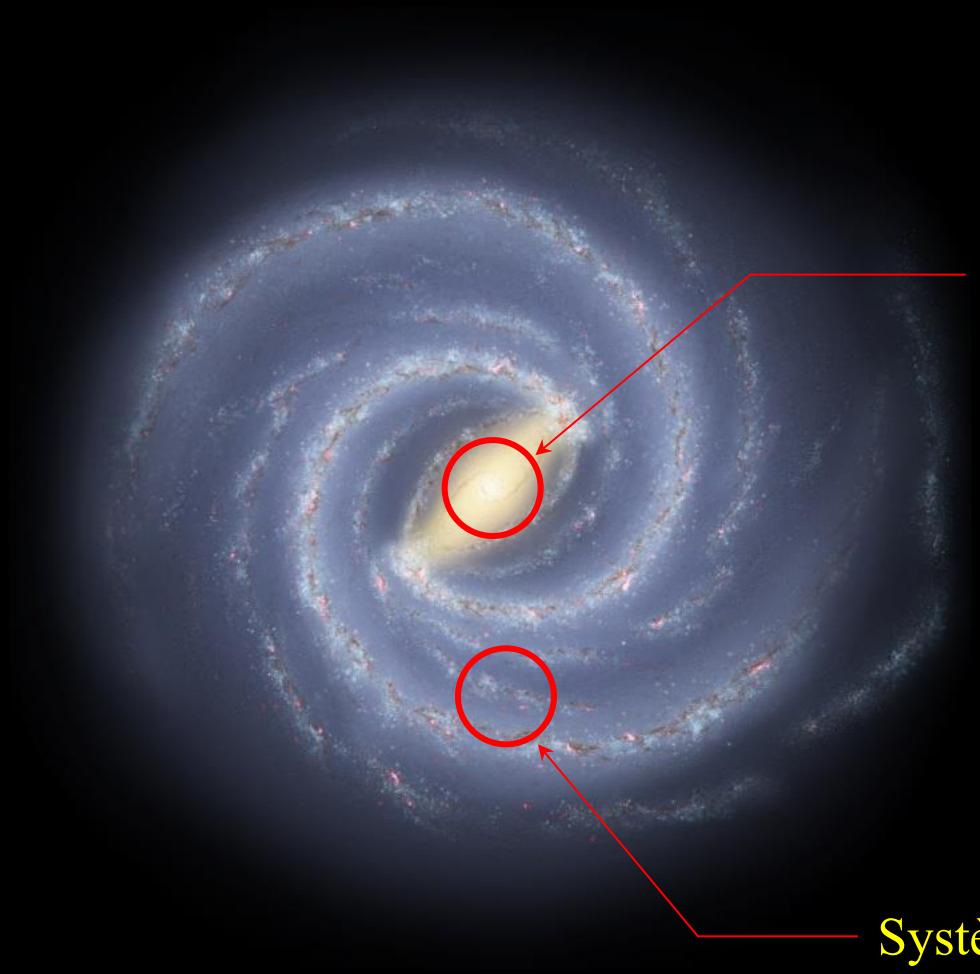
GRAVITY
2nd generation instrument for the VLTI

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 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

The Galactic center

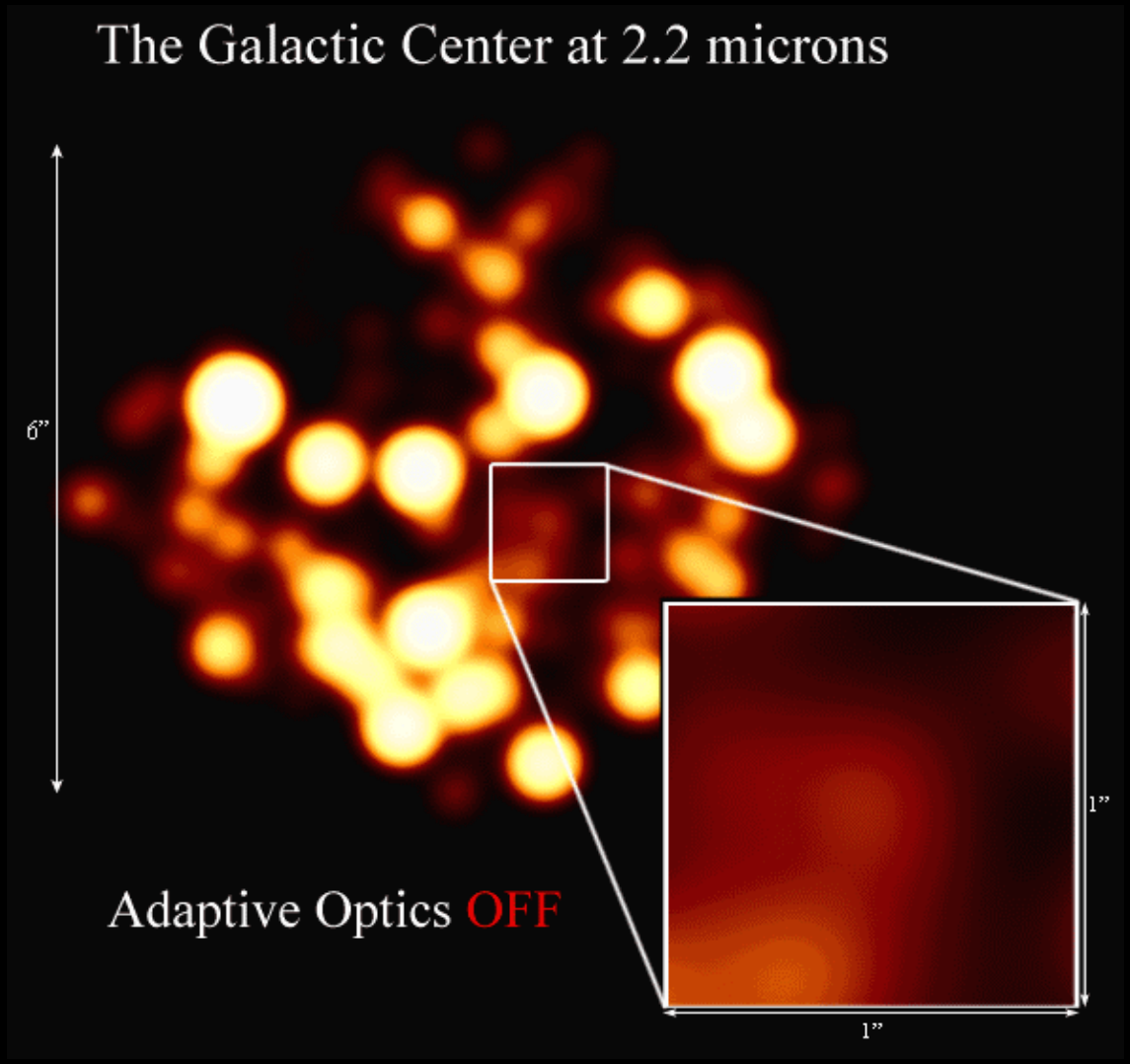


Diameter : 25 kpc
or 80 light-years


The galactic center as we see it

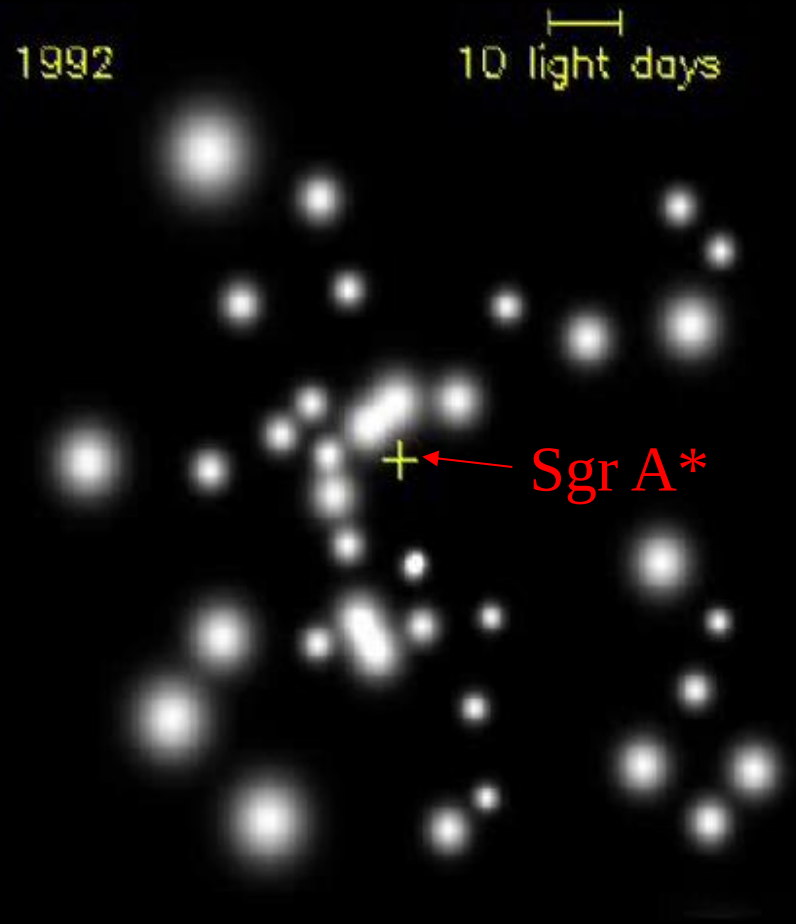

The Galactic center seen from
infrared space telescope Spitzer

with adaptive optics …



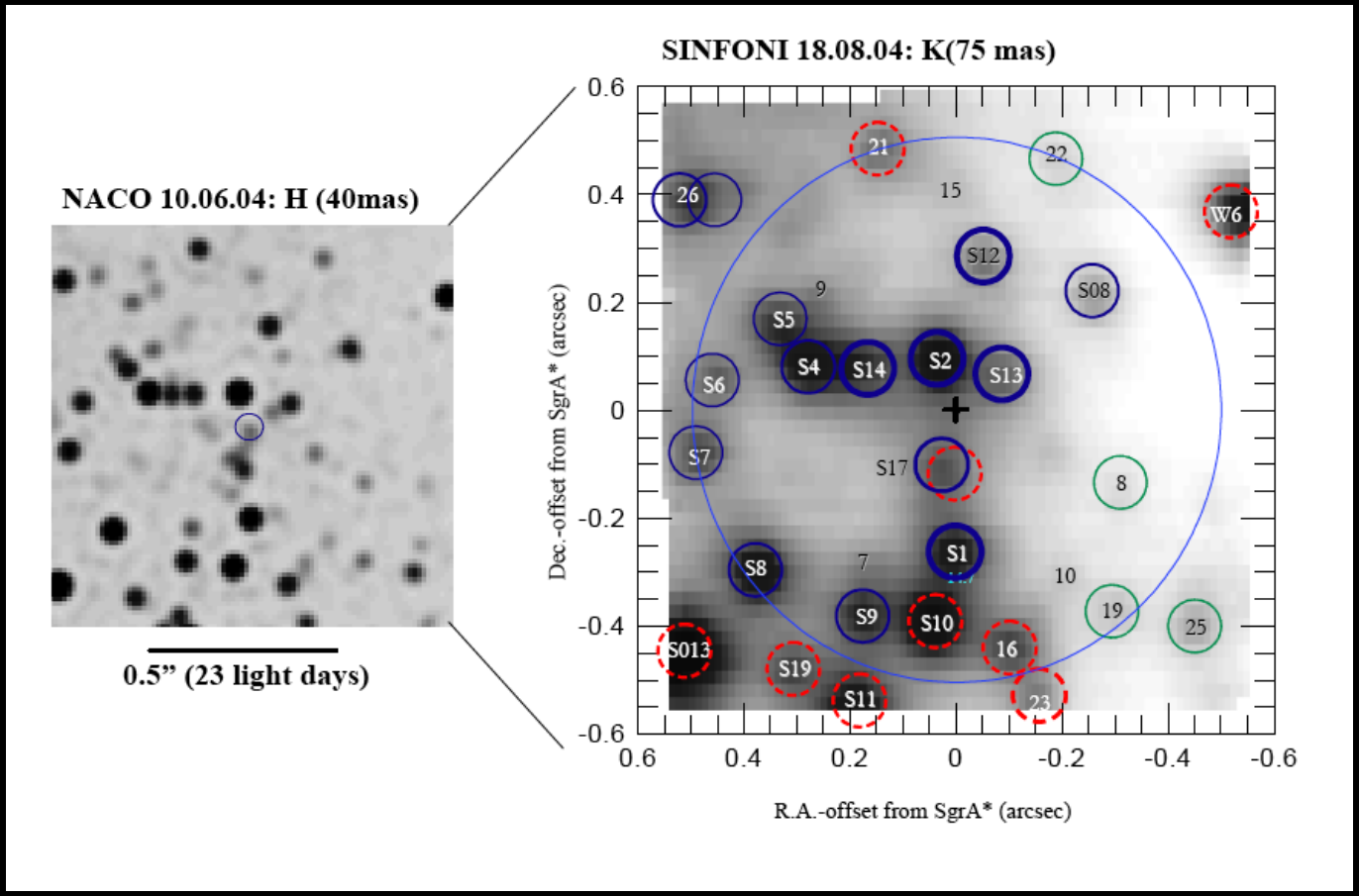
0,05 pc

Orbit of star S_2 observed with adaptative optics at VLT/NACO



Schödel et al. (2002)

We can do so with the many neighboring stars



Eisenhauer et al. (2005)

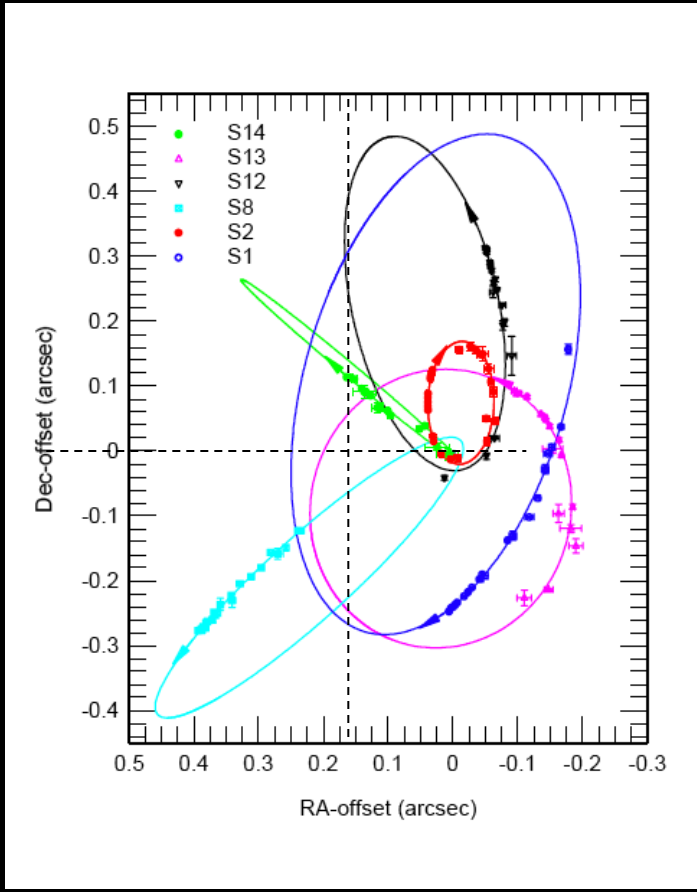
And get the mass of Sgr A*

3rd Kepler law:

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

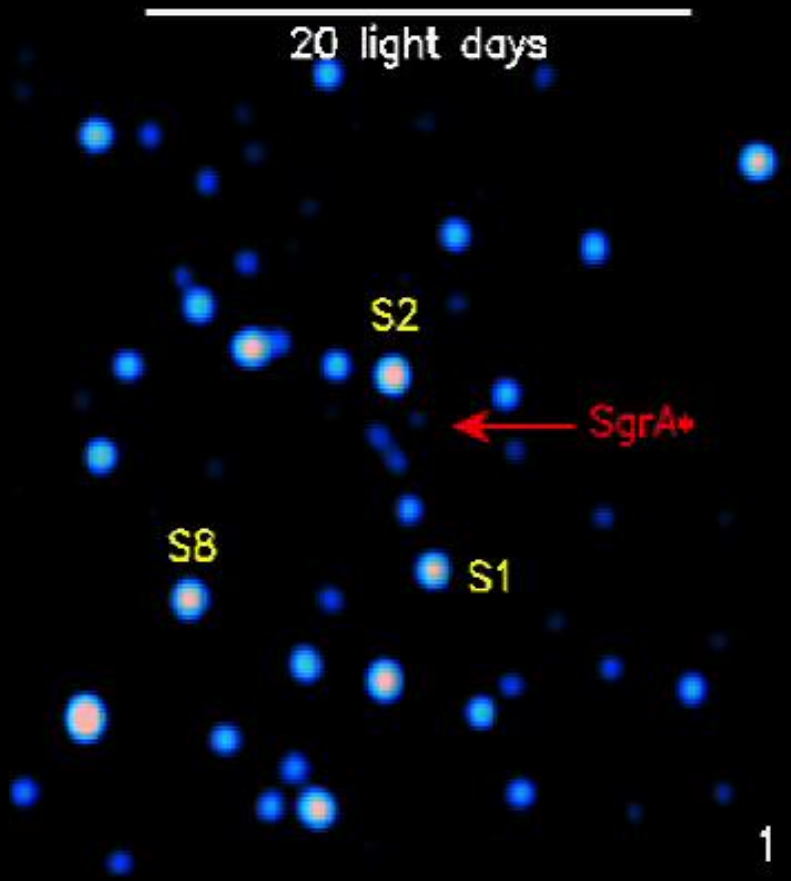
$M_{Sgr\,A^*} = 3{,}61 \pm 0{,}32 \cdot 10^6\ M_{Sun}$

(d = 7,62 ± 0,32 kpc)



Eisenhauer et al. (2005)

The flares of Sgr A*

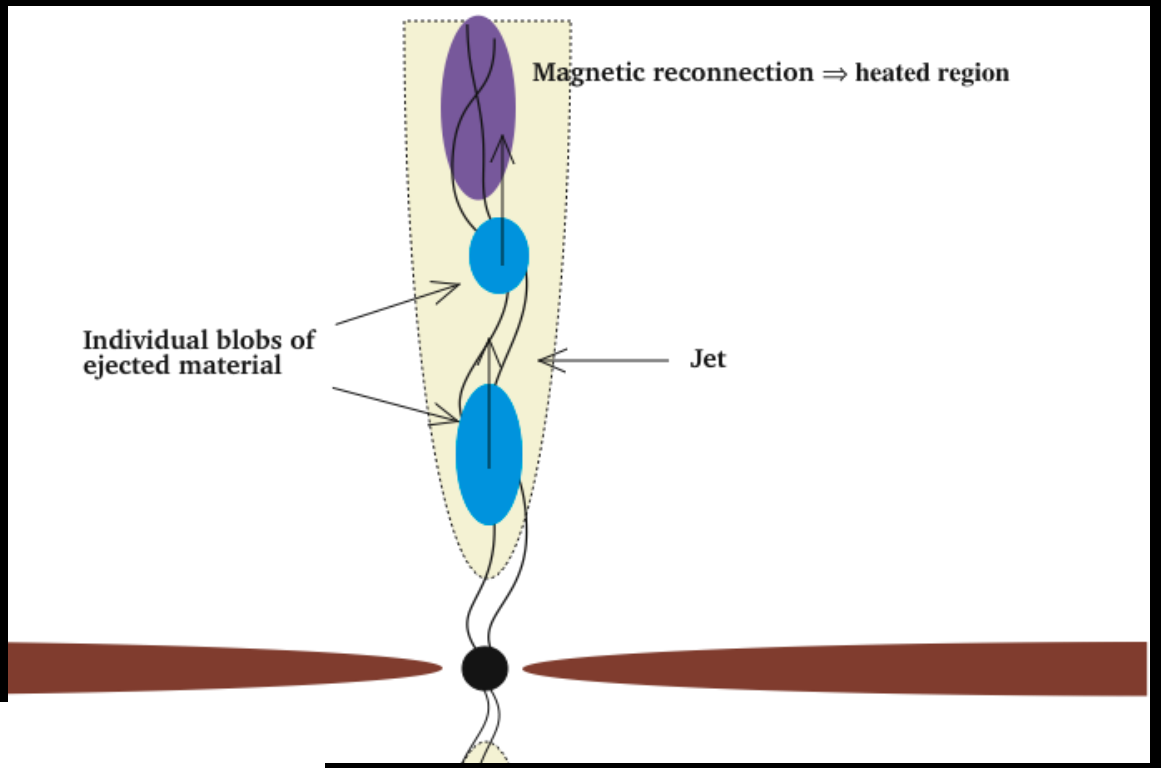


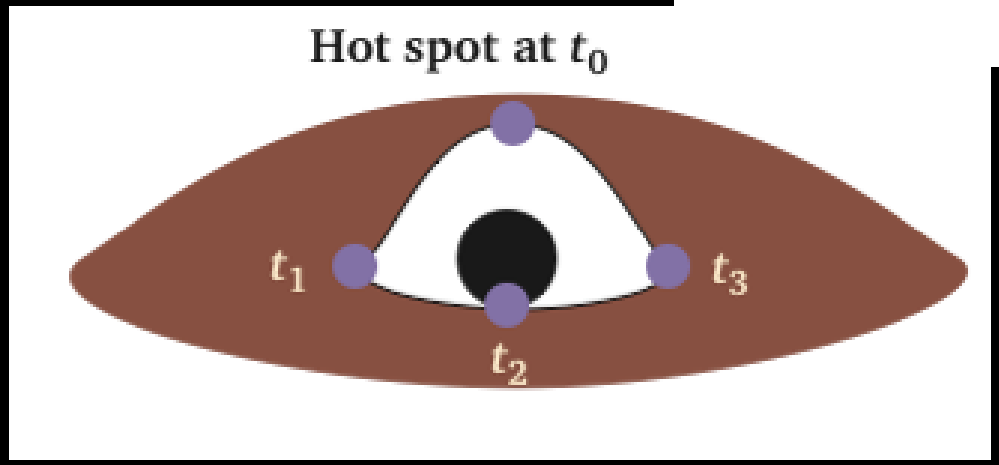
Genzel et al. (2003)

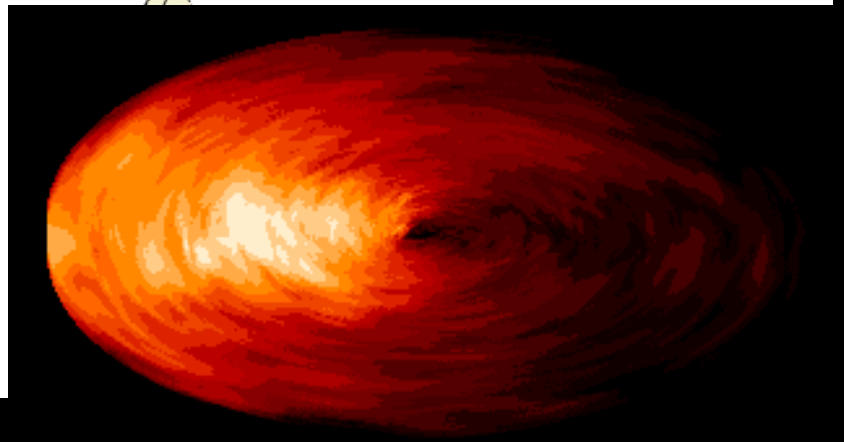
But what cause the flares?

Several possible scenarios :

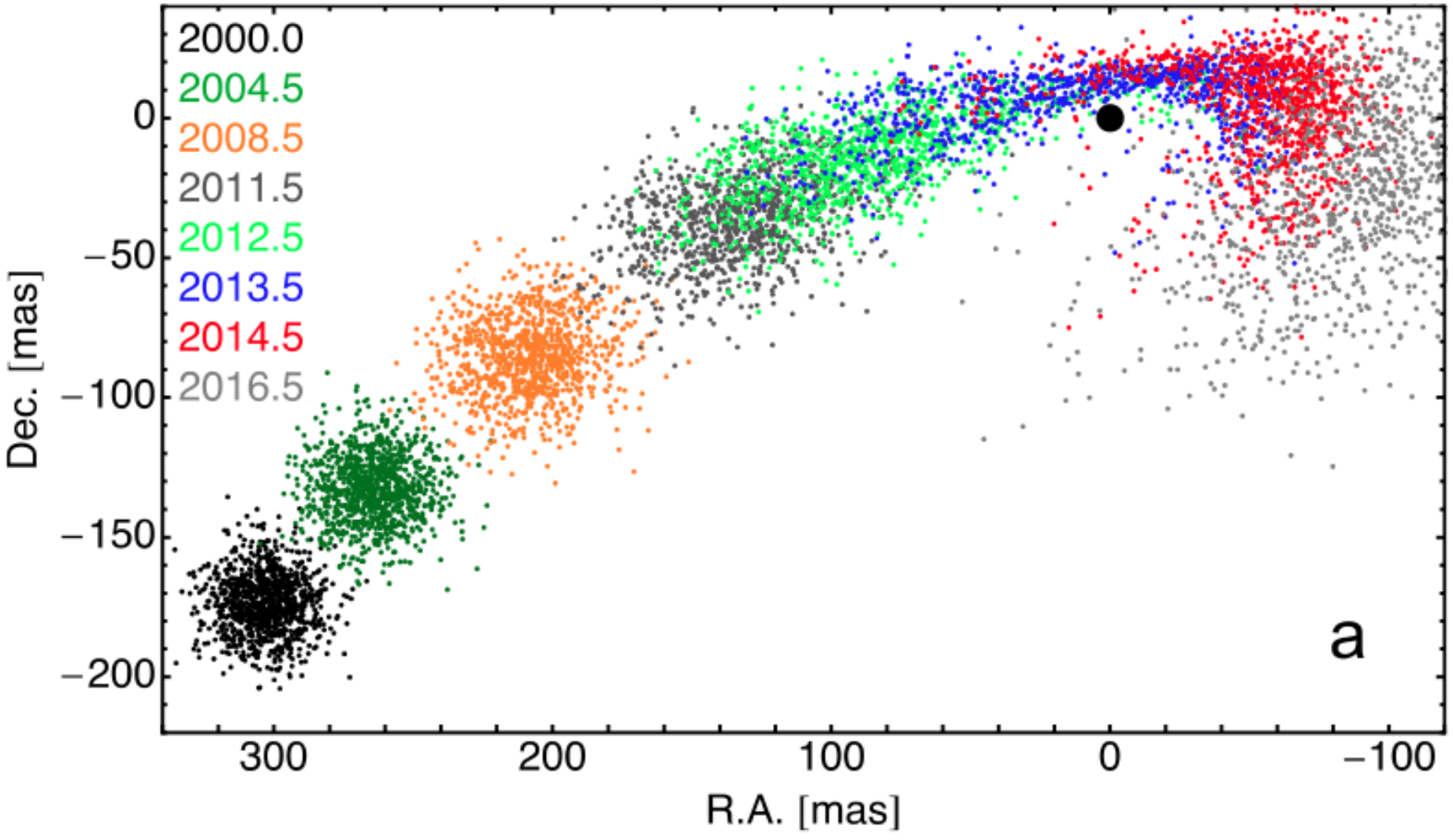
- magnetic reconnection within the jet
- Hot spot orbiting the black hole
- Fluctuations??

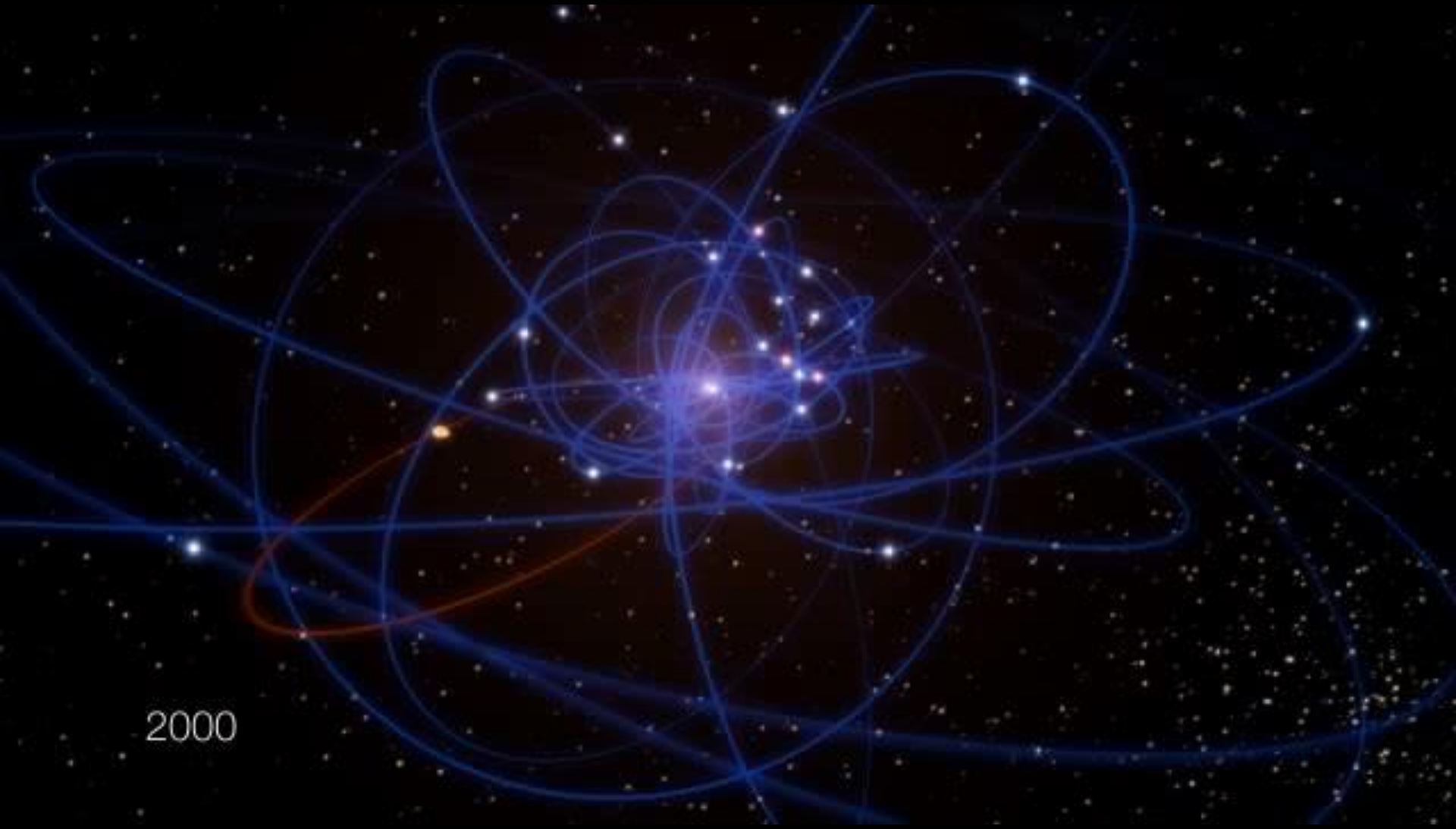






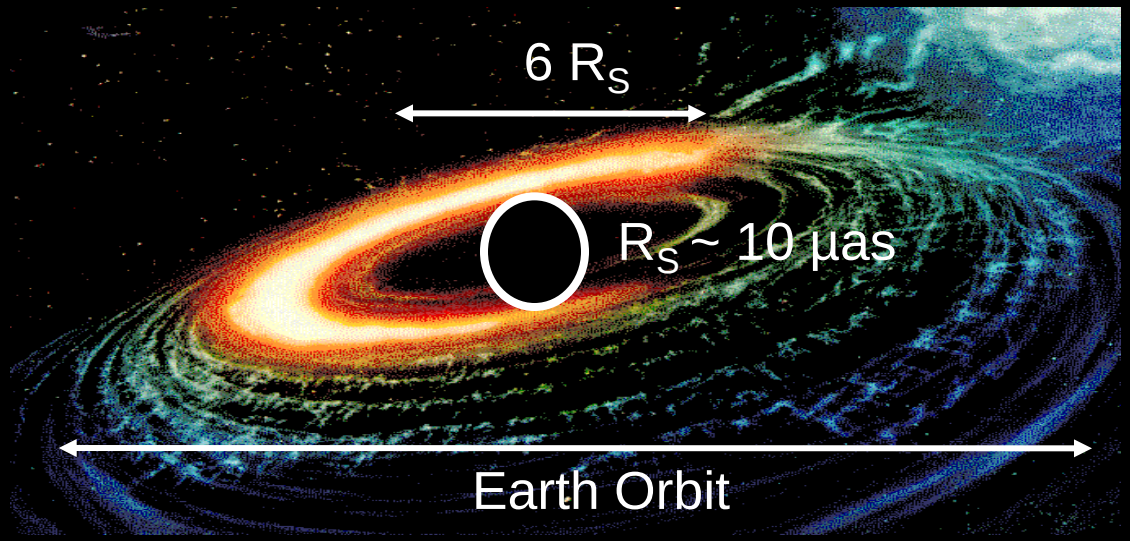
A cloud is coming





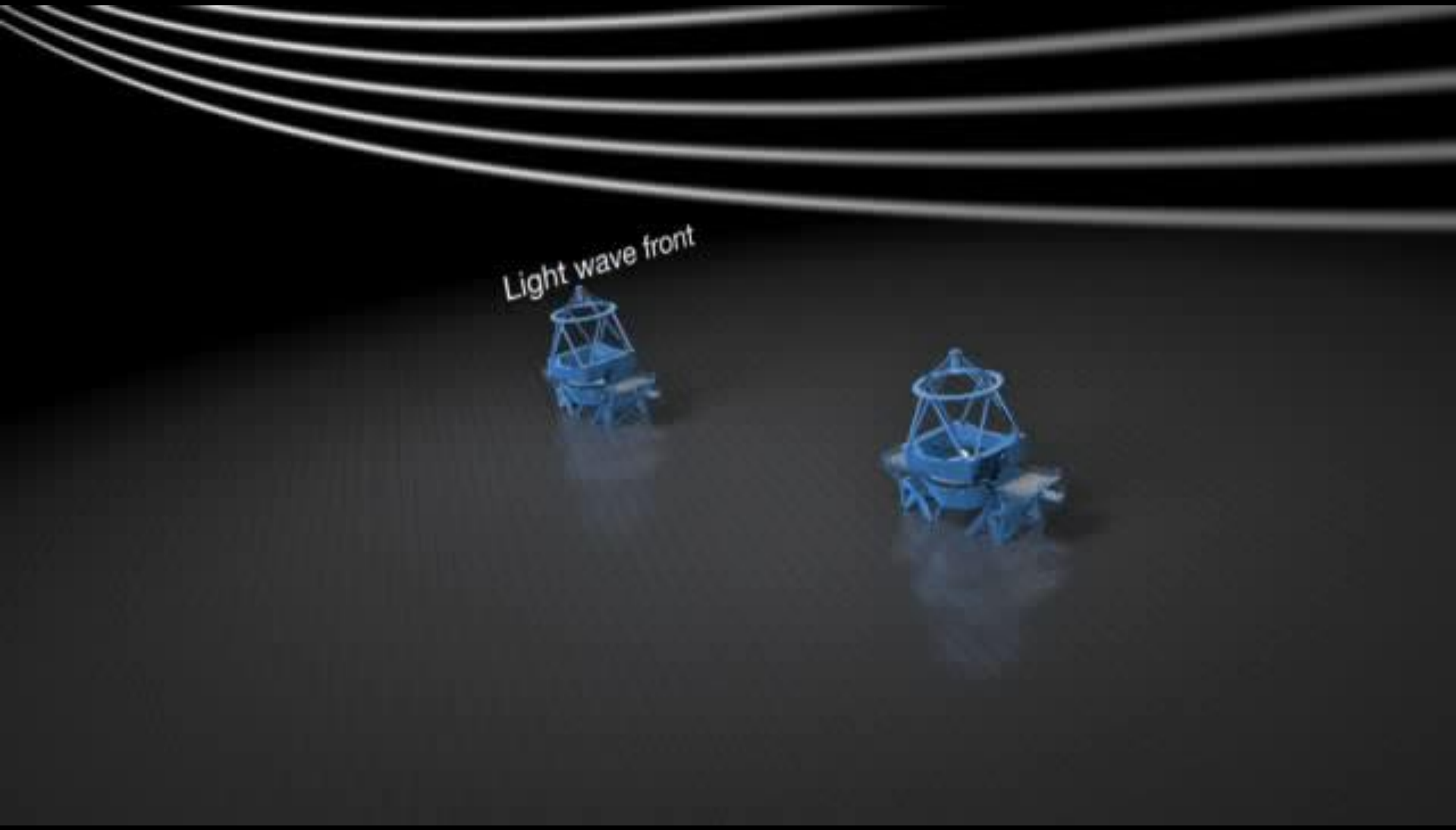
Credits: Schartmann, ESO, Berry, NASA, Broderick

Setting the scale – just to scare …



1 Schwarzschild radius
=
a coin on the moon

Interferometry

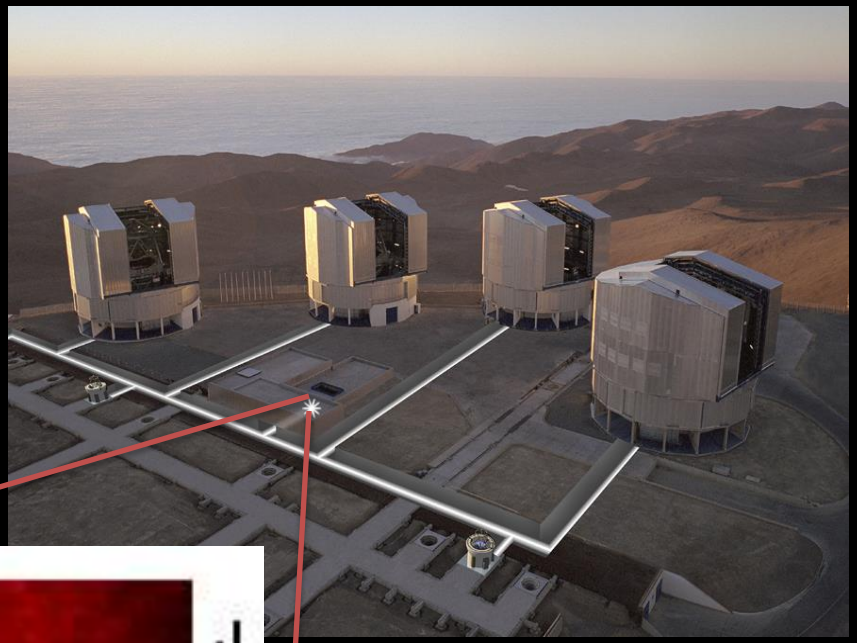


Courtesy of ESO

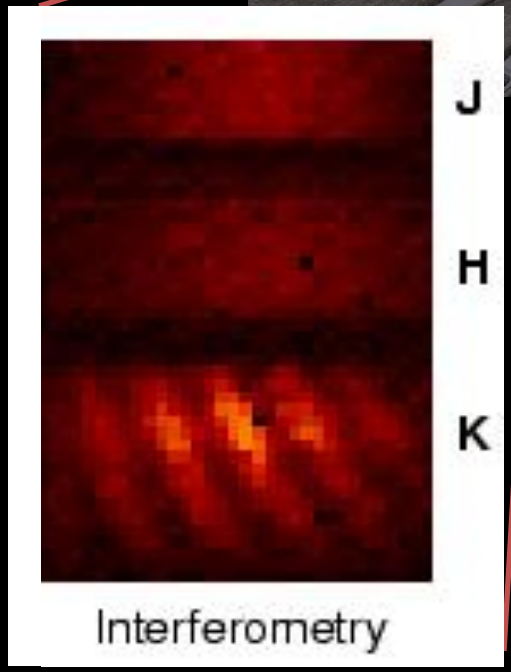
GRAVITY @ ESO VLTI

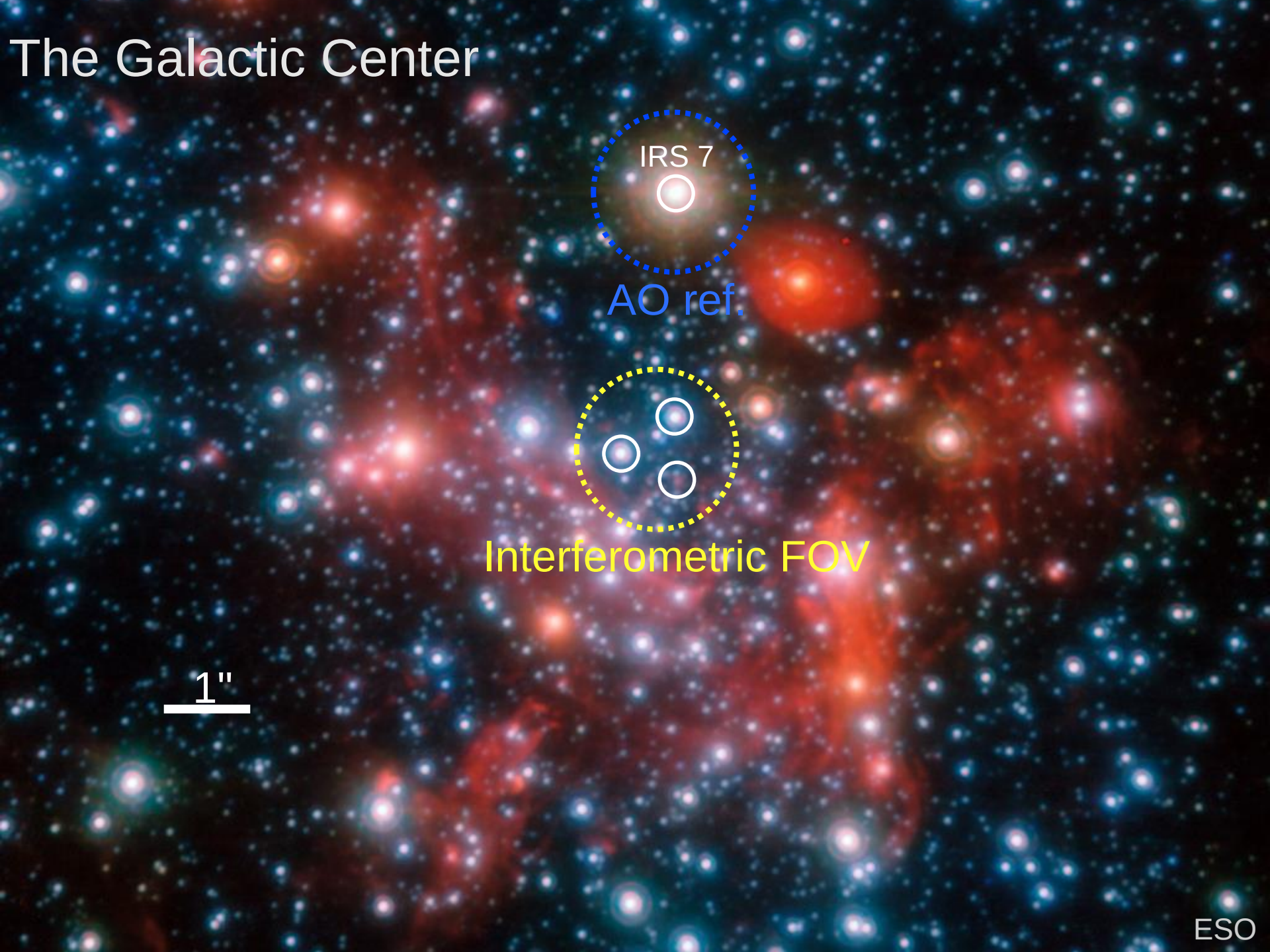
Courtesy of ESO

Setting the scale – … maybe not that scary



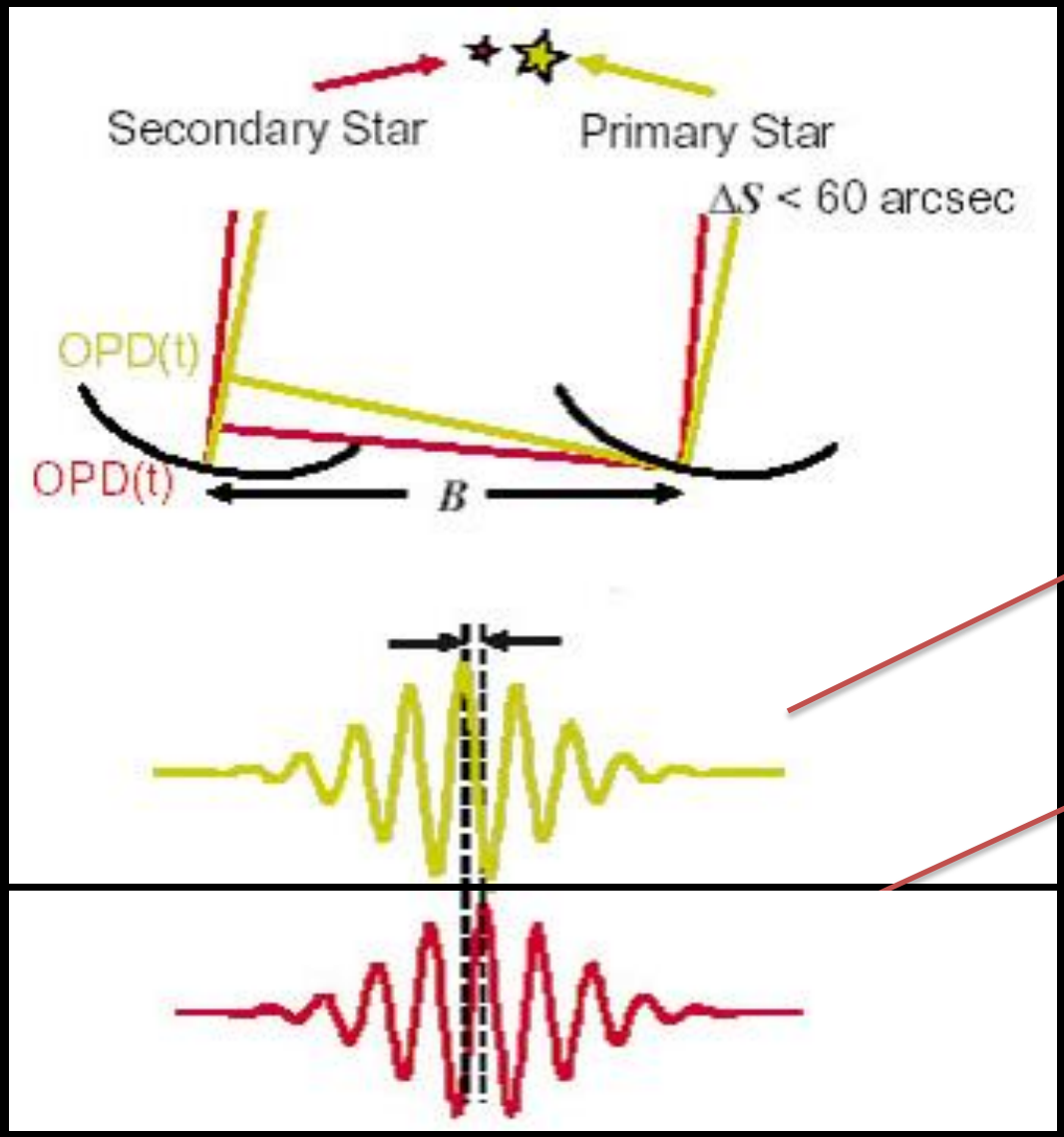
5 nm @ 100m
=
a coin on the moon




The Galactic Center
IRS 7
AO ref.
Interferometric FOV
1"
ESO

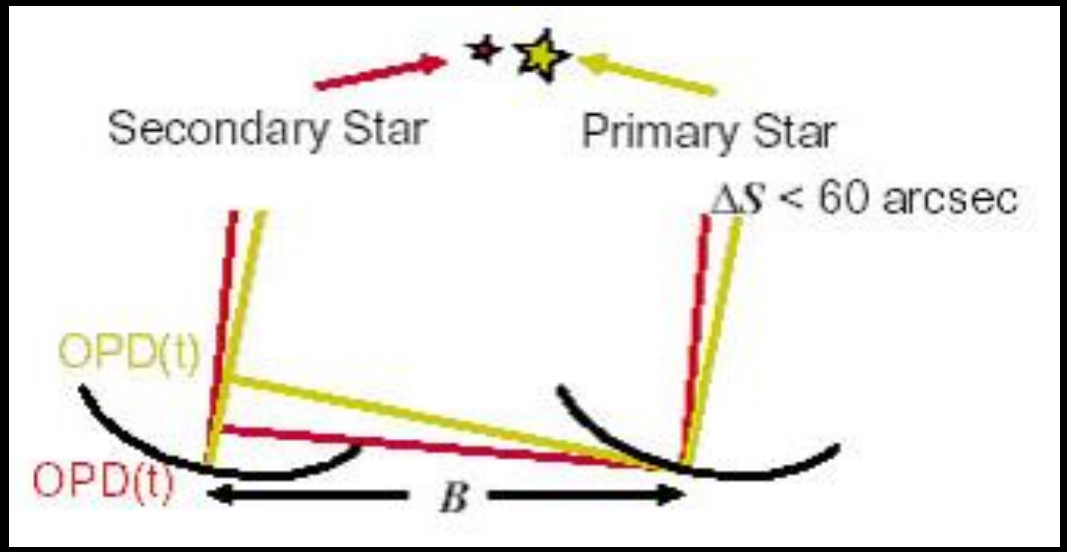
Phase referenced imaging & astrometry

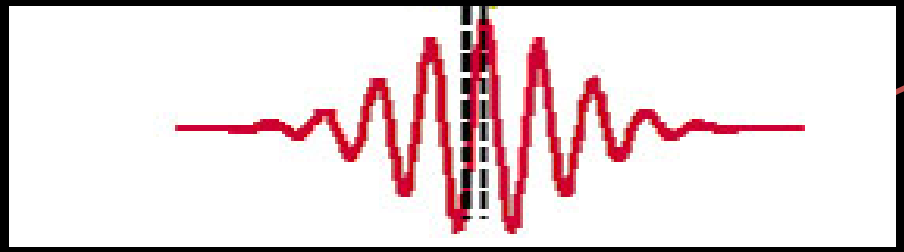
$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$



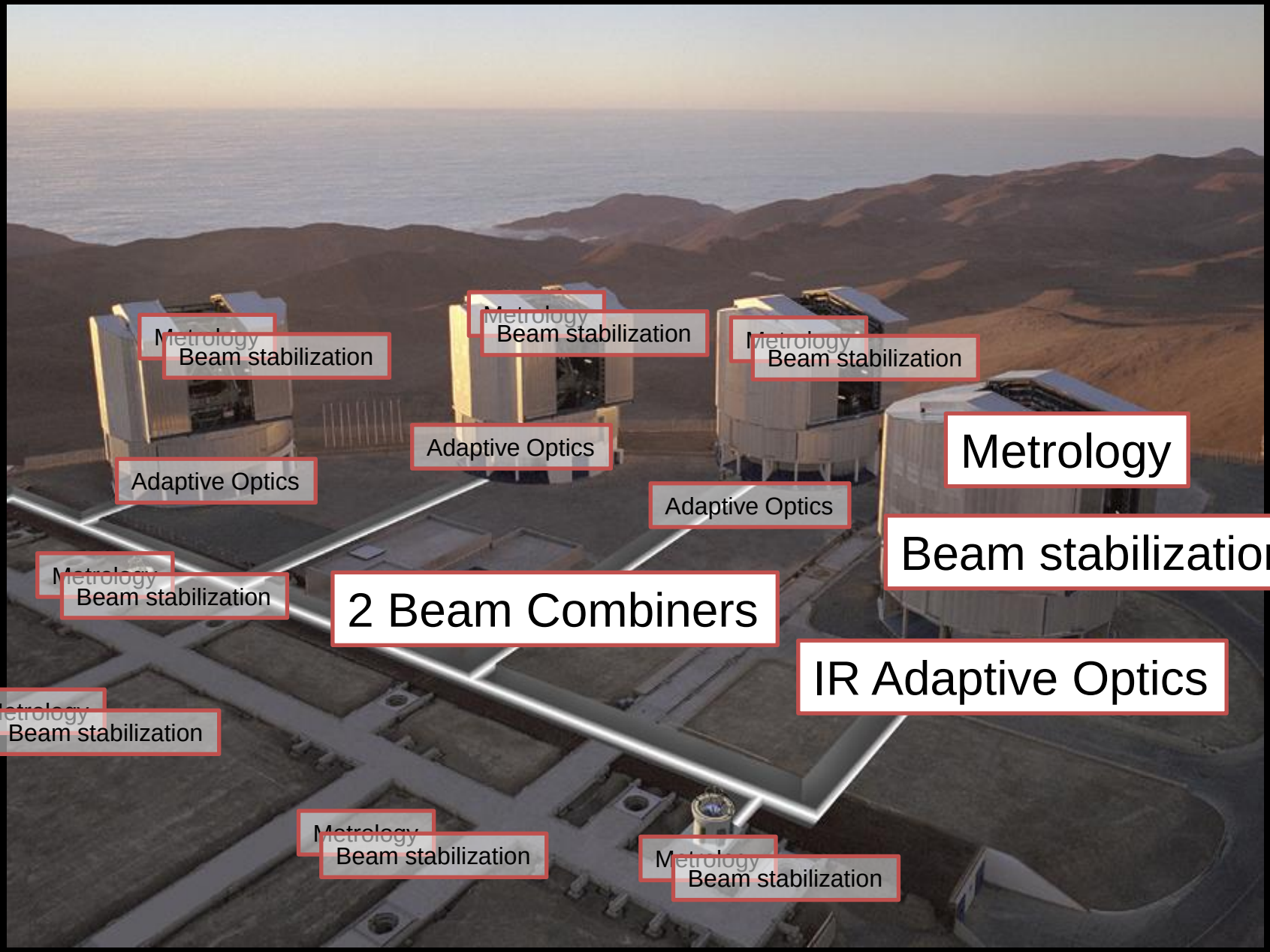
Phase referenced imaging & astrometry

Contrast (B) <-> FourierTransform (Image)

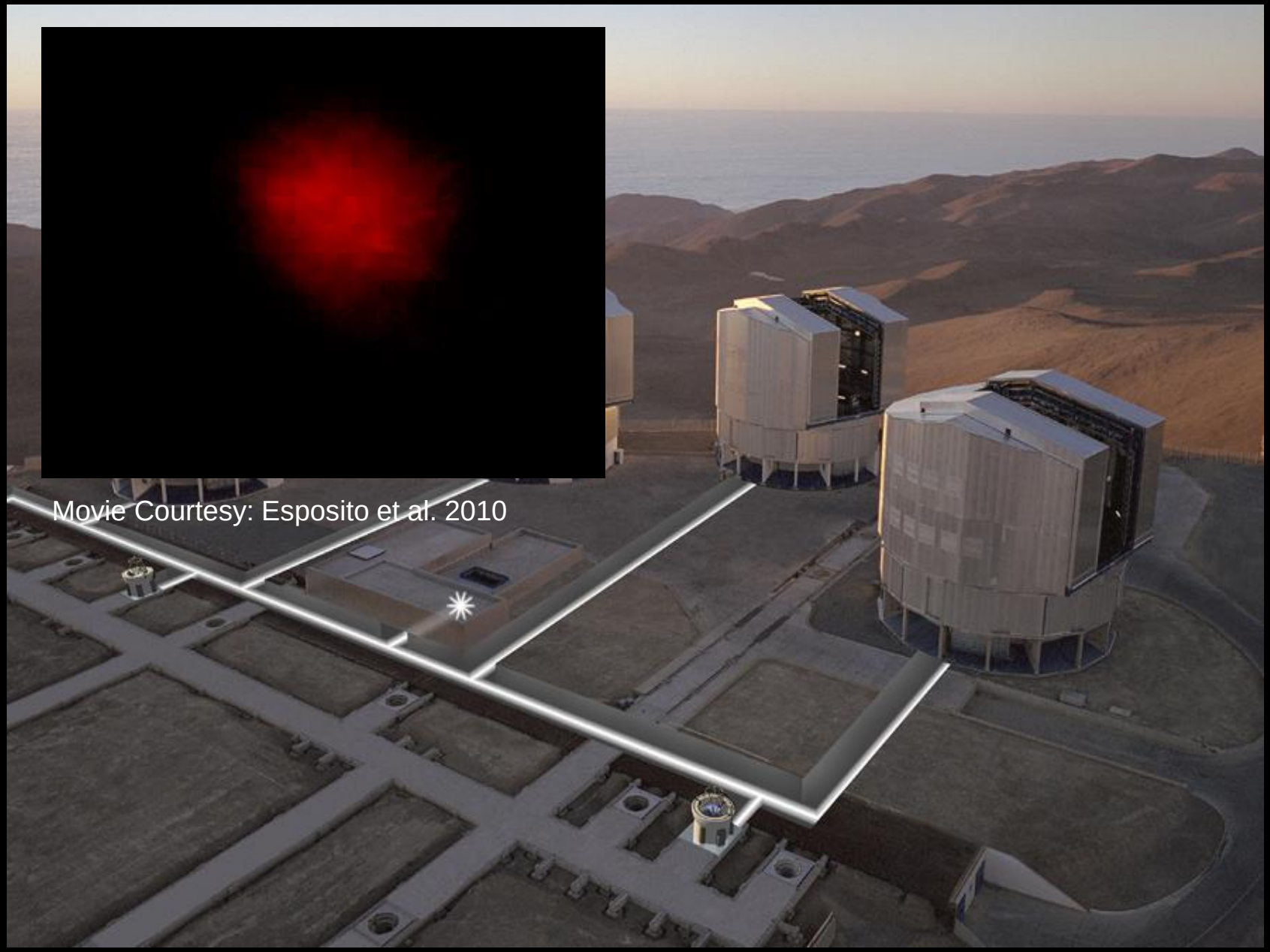




GRAVITY astrometry & imaging

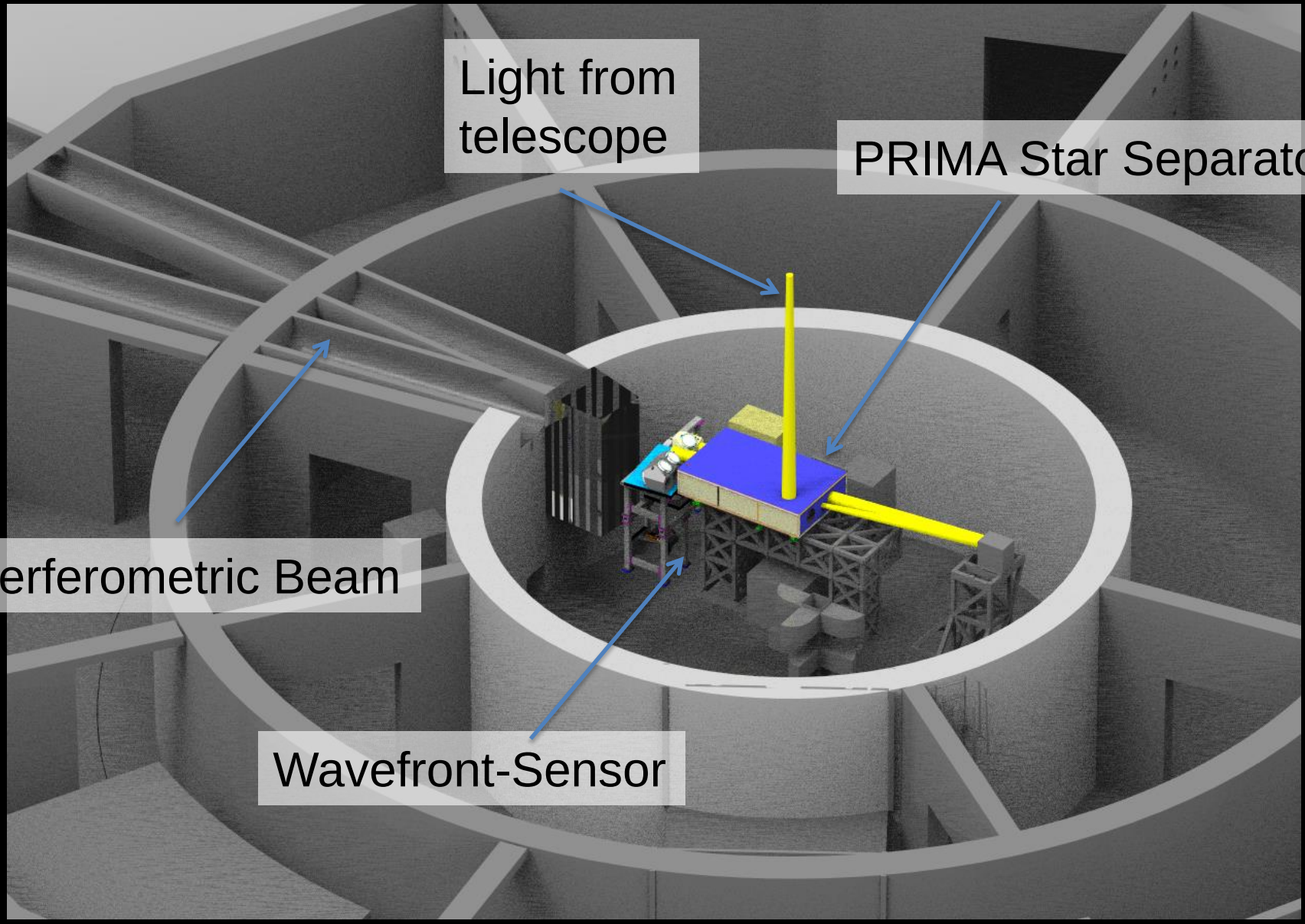


GRAVITY adaptive optics



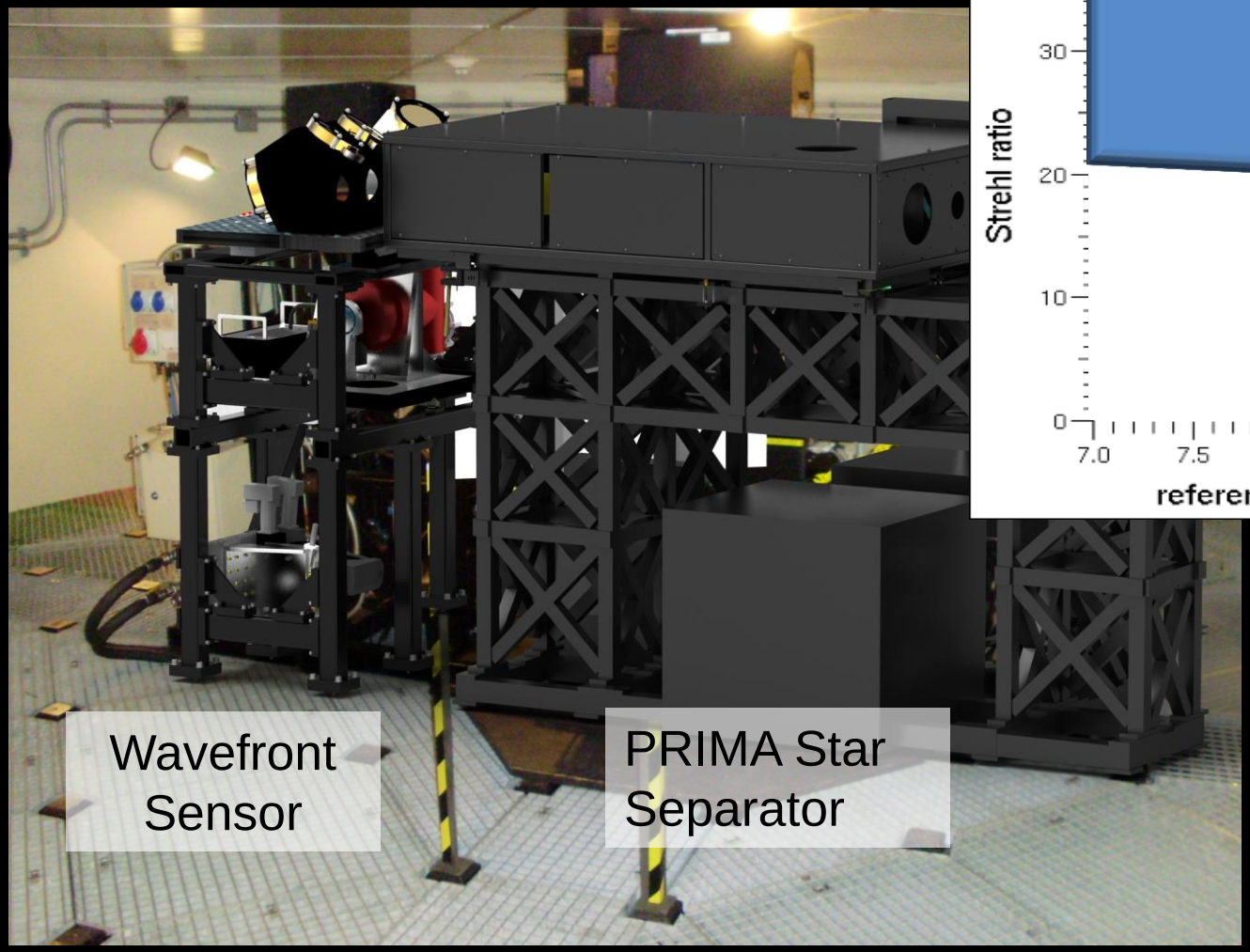
Movie Courtesy: Esposito et al. 2010

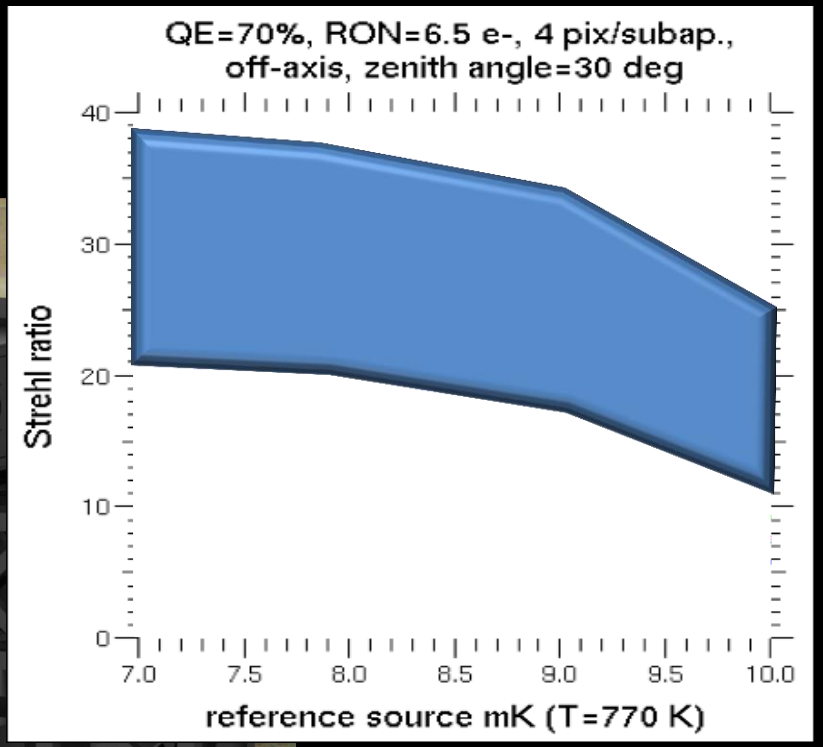
GRAVITY adaptive optics



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

GRAVITY adaptive optics

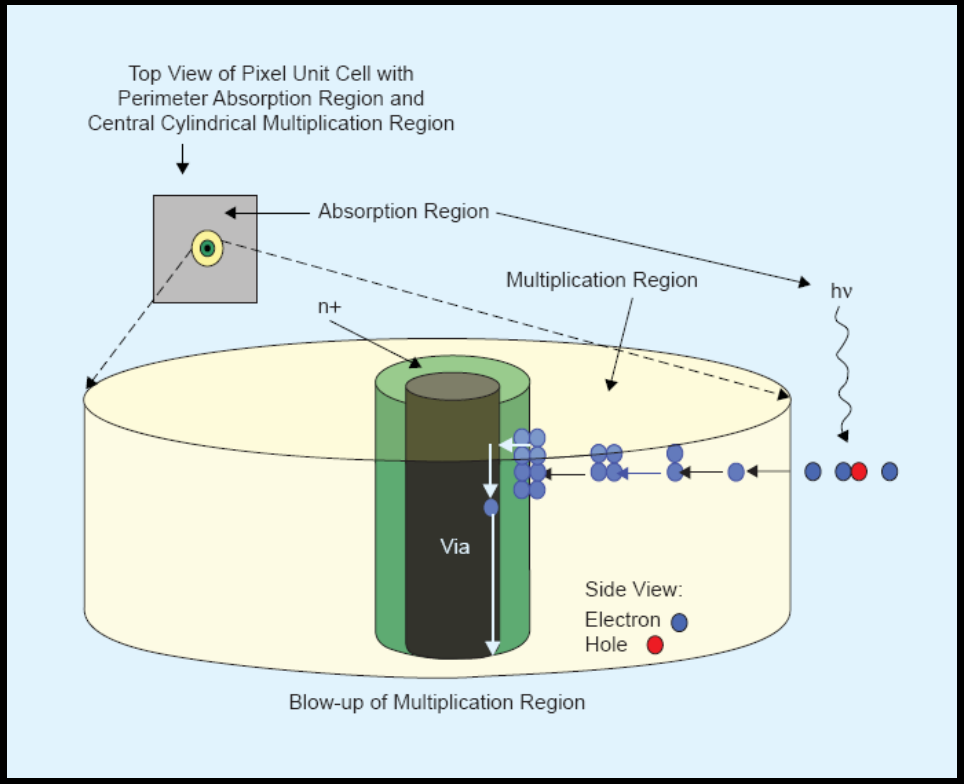


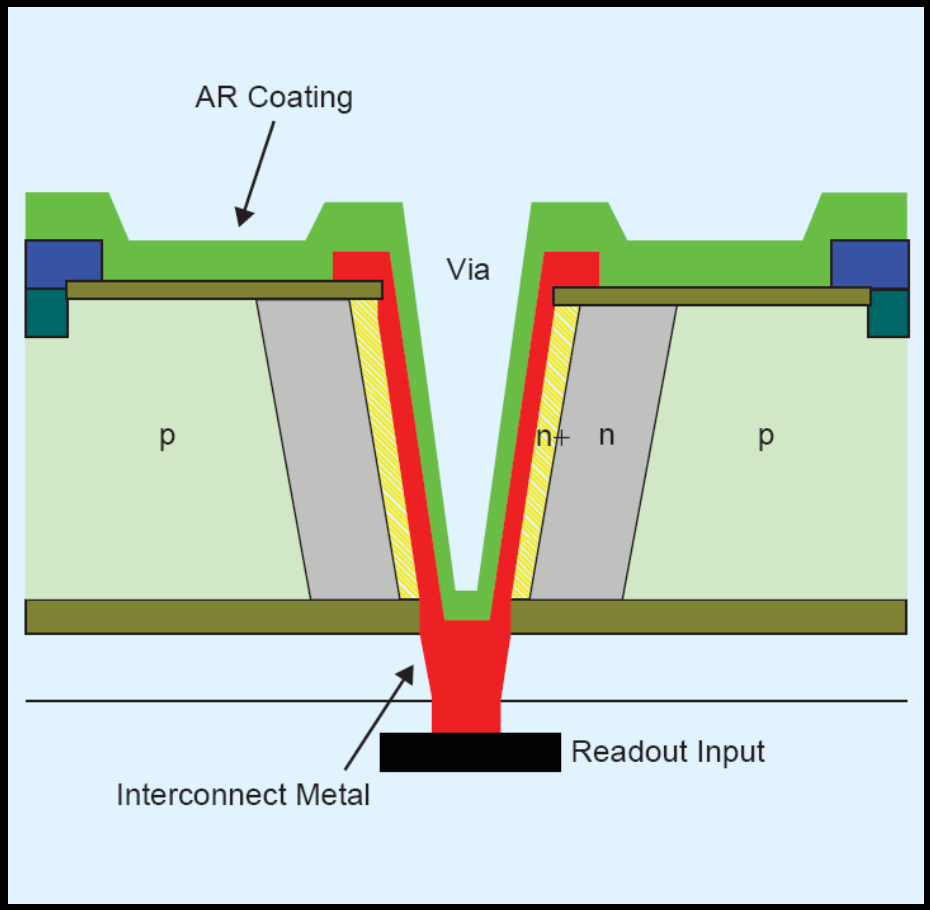


Brander, Hippler et al., Clenet et al. 2010

Adaptive optics and fringe tracking Detectors

SELEX / ESO development of Infrared Avalanche Photo Diode array:

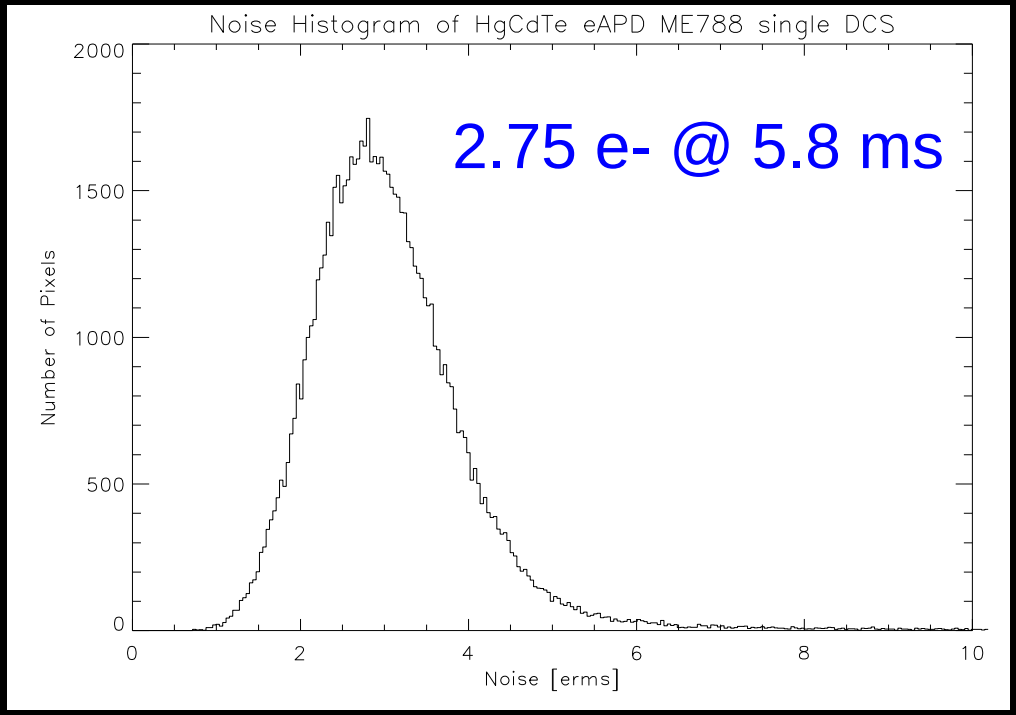




Beck et al. 2010

Adaptive Optics and Fringe Tracking Detectors

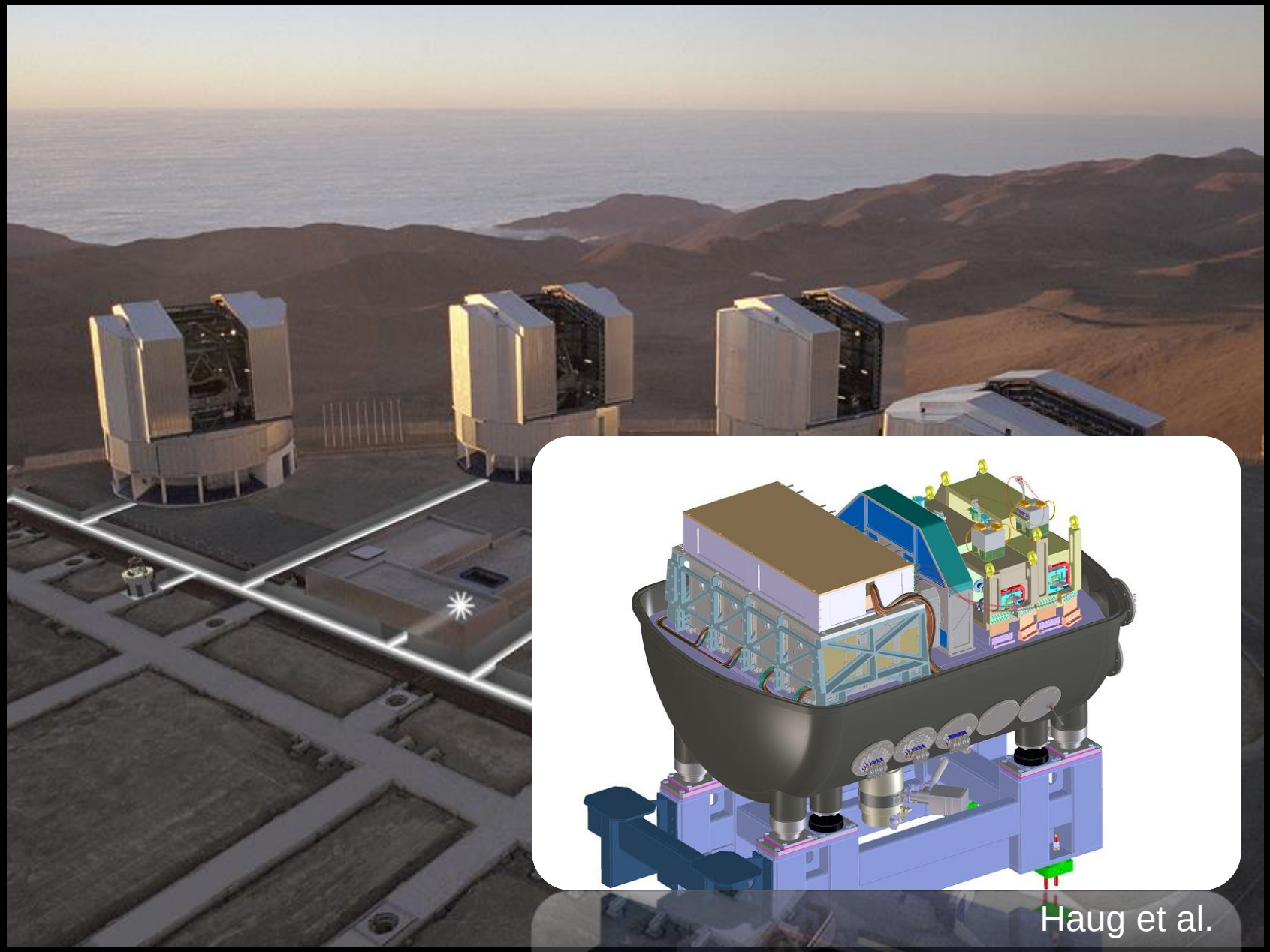
SELEX / ESO development of Infrared Avalanche Photo Diode array:



Finger et al. 2010

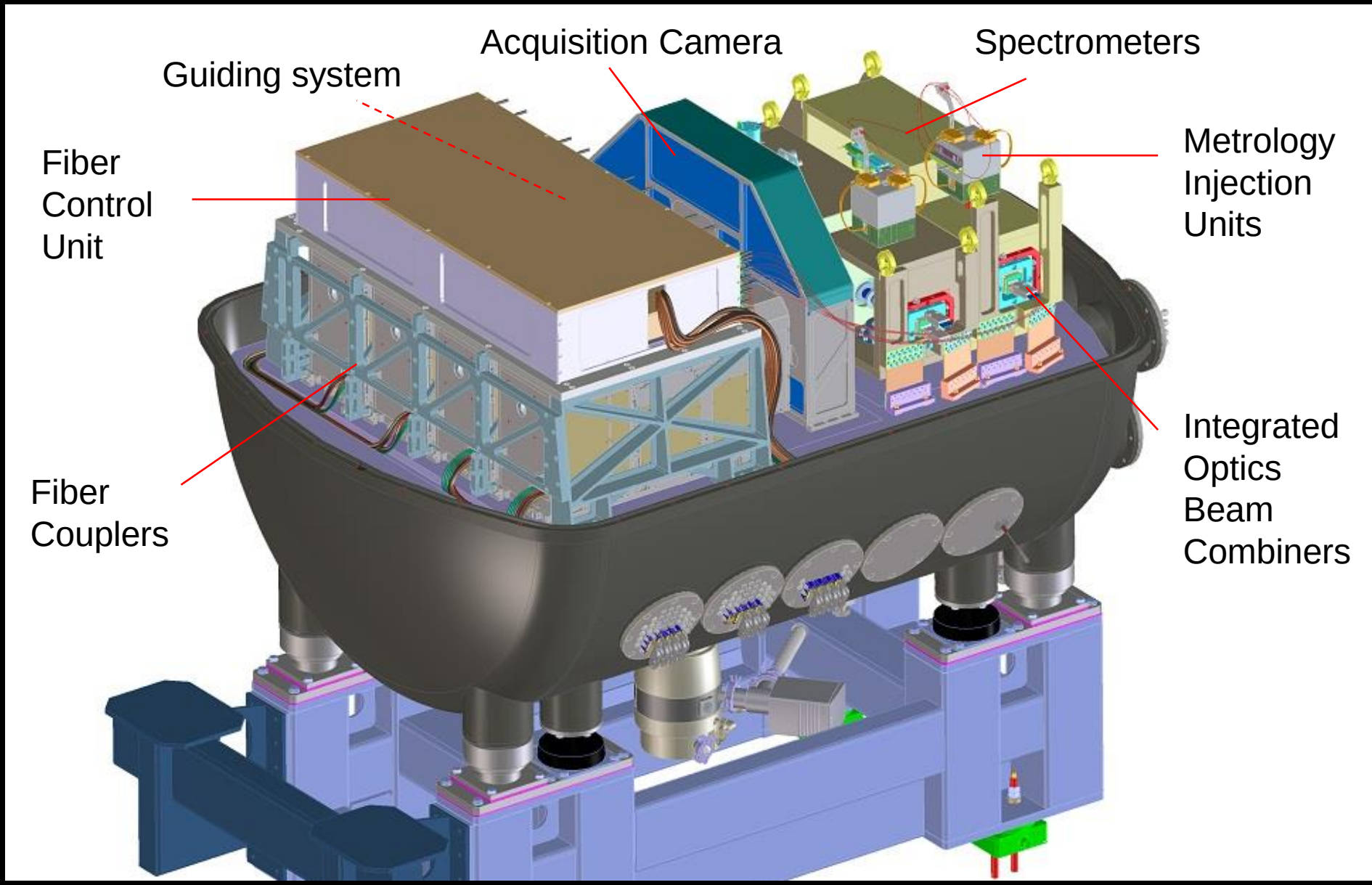
Brander, Hippler et al.,
Clenet et al. 2010

GRAVITY beam combiner



Haug et al.

Beam Combiner Instrument



Haug, Thiel, Hausmann et al.

Beam Combiner Instrument

Haug, Thiel, Hausmann et al.

Single mode interferometer

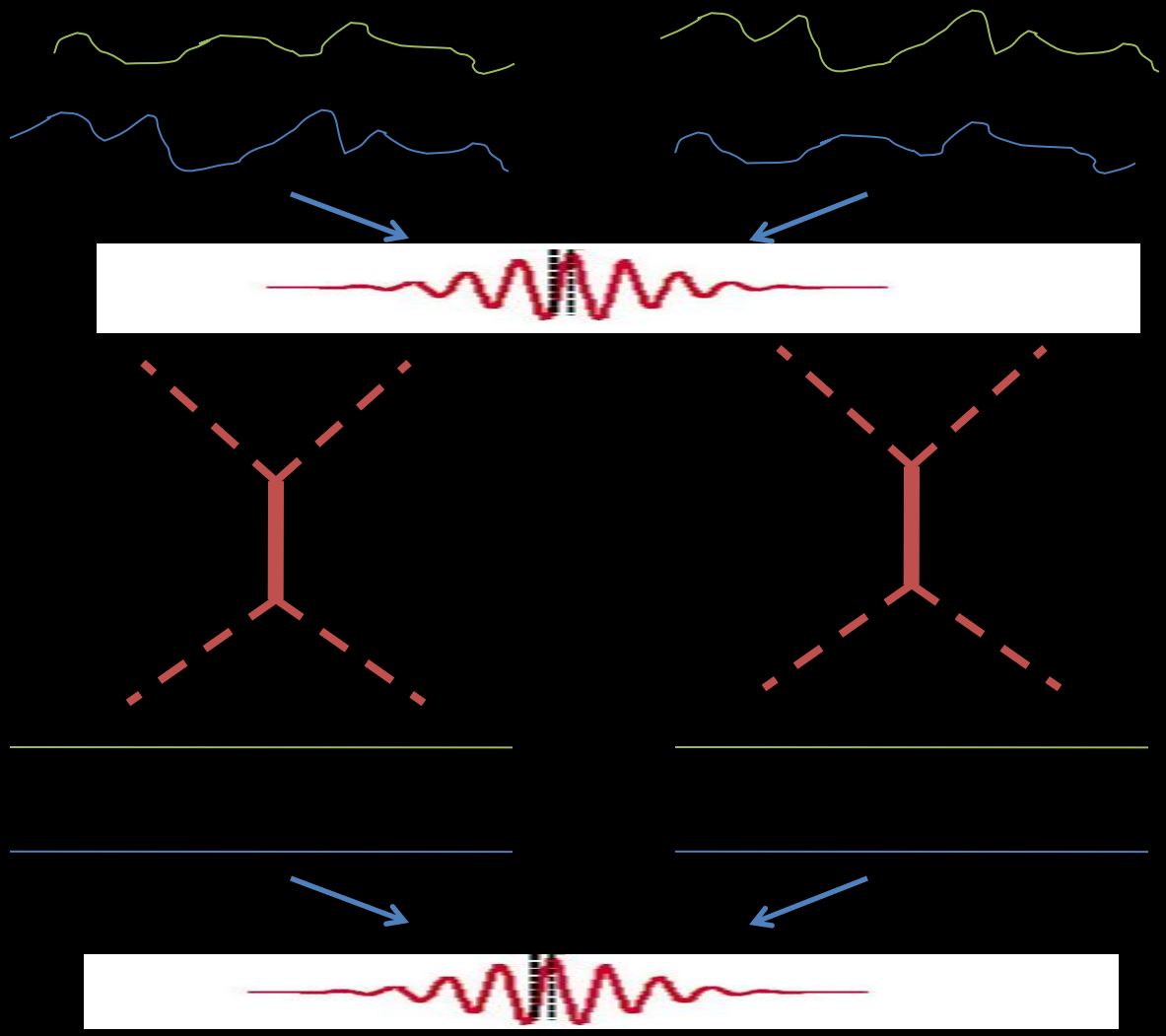
Most important quantities for interferometry is well measured phase and calibrated contrast, not flux

Distorted Waves

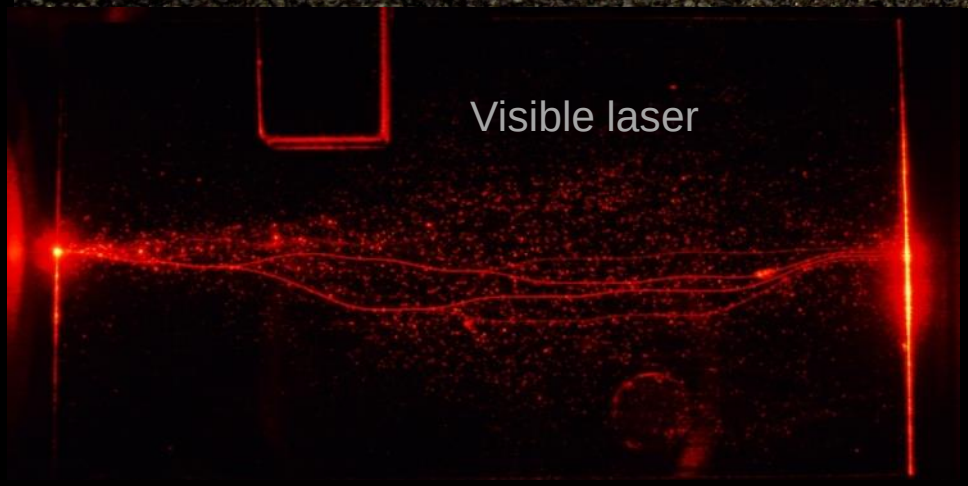
Constant flux, but variable contrast

Single mode fiber
“Low pass filter”

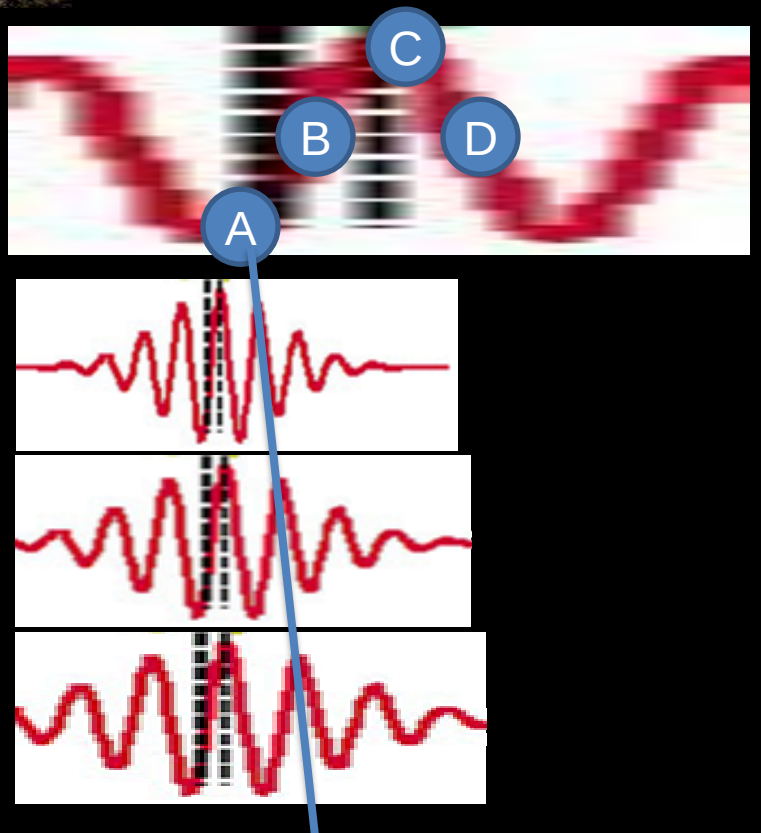
Variable flux, but constant contrast



Integrated optics feeding spectrometer



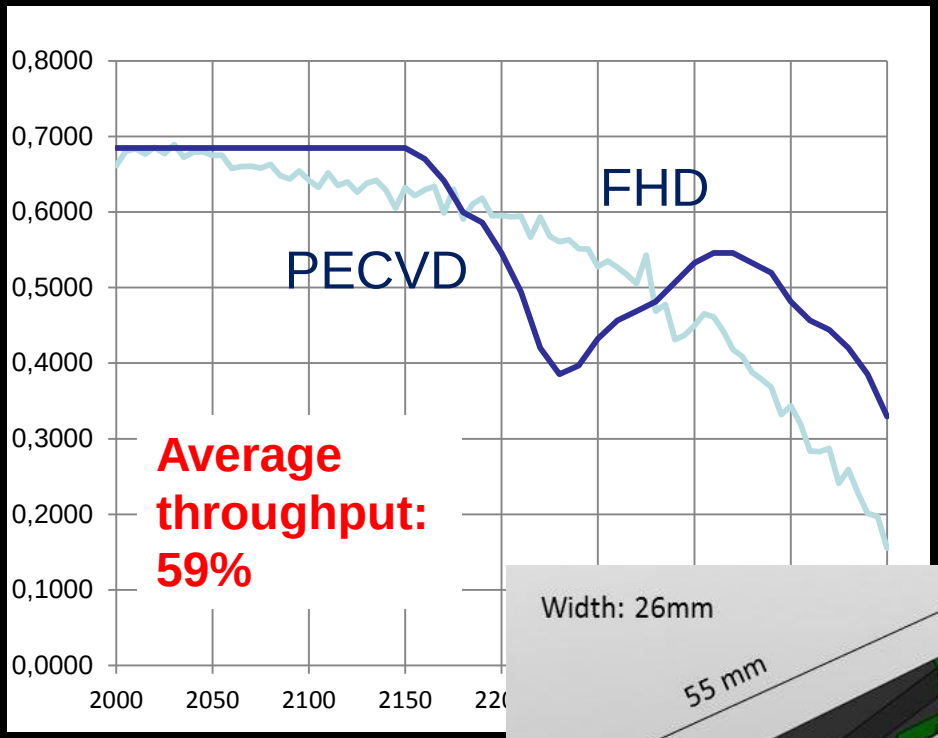
Jacou et al. 2010, Perraut et al.



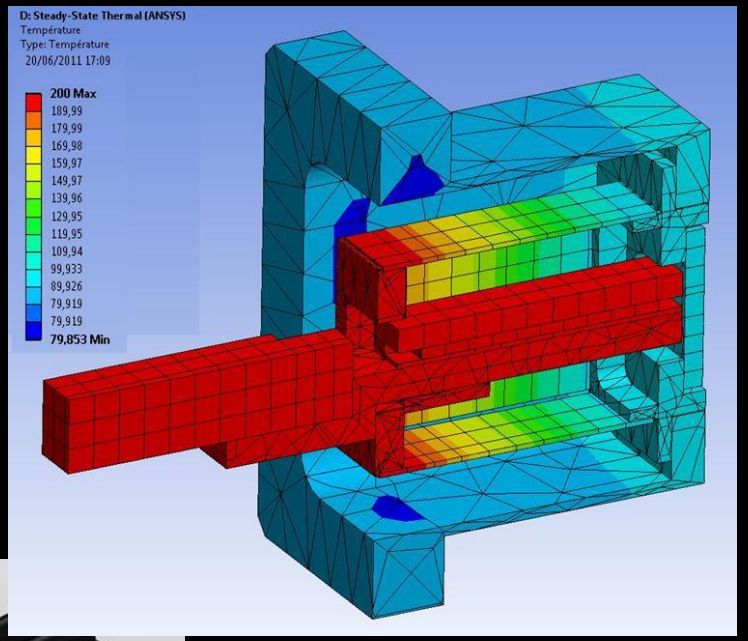
Straubmeier et al. 2010

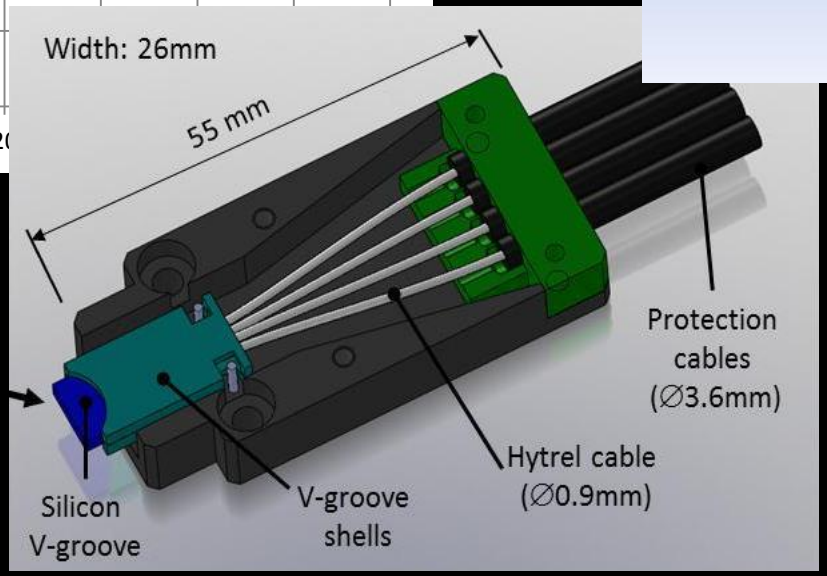
Integrated Optics

K-band operation



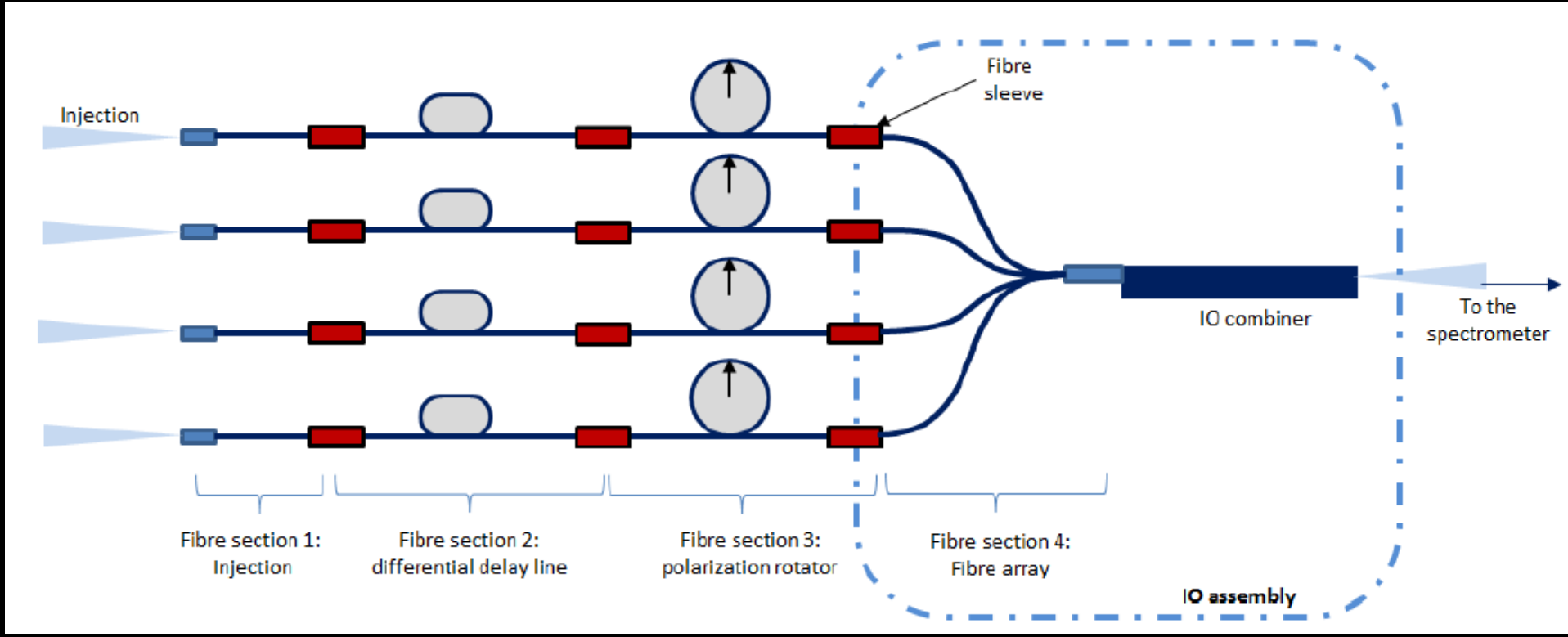
Cryogenic operation





Jacou et al. 2010,
Perraut et al.

Single Mode Instrument

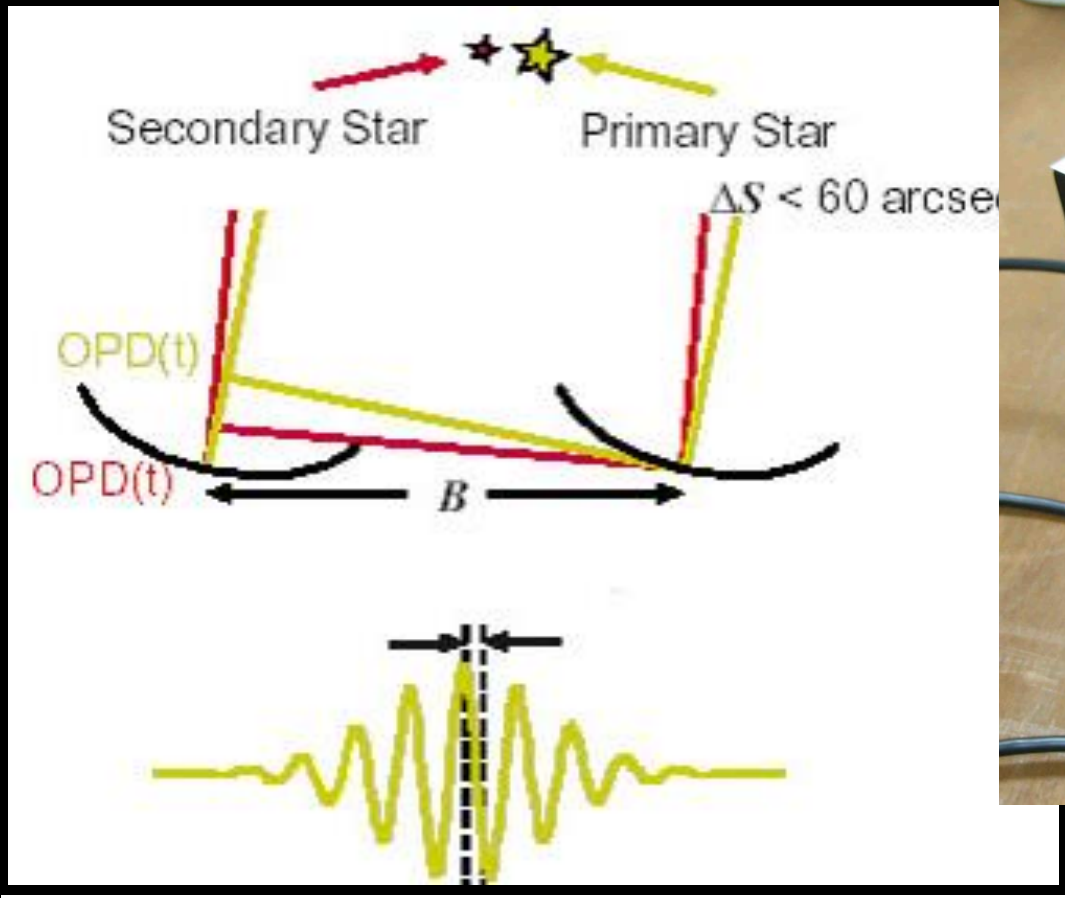


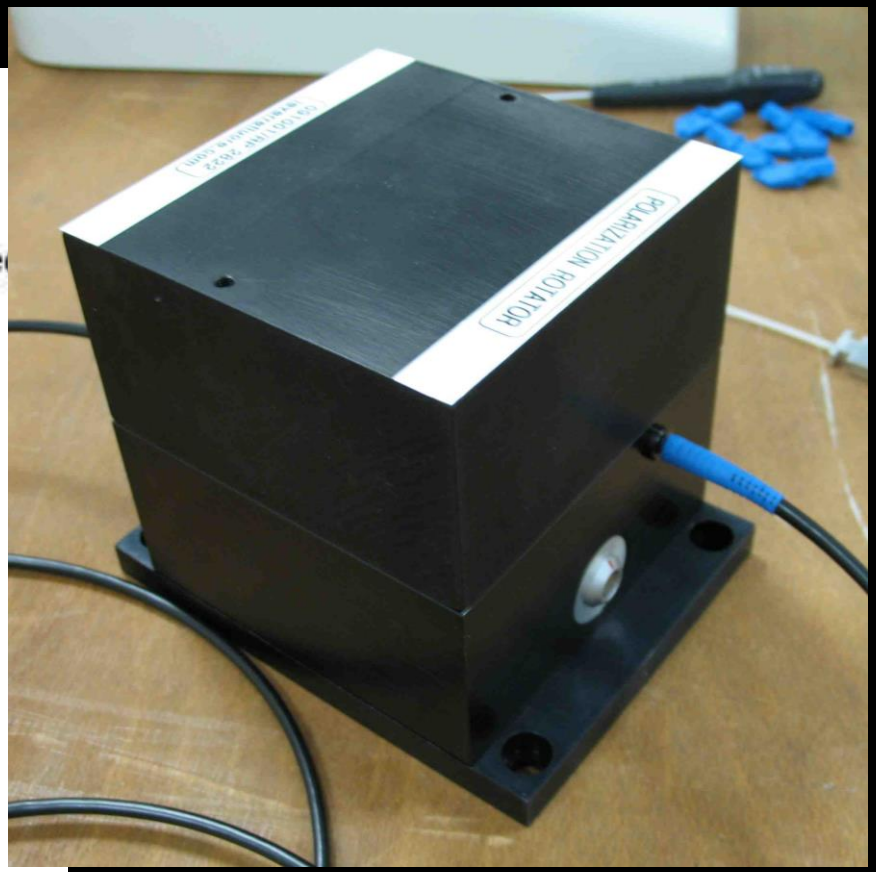
Fluoride glass fibers (OHANA)

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

Perrin, Perraut, Jacou et al.

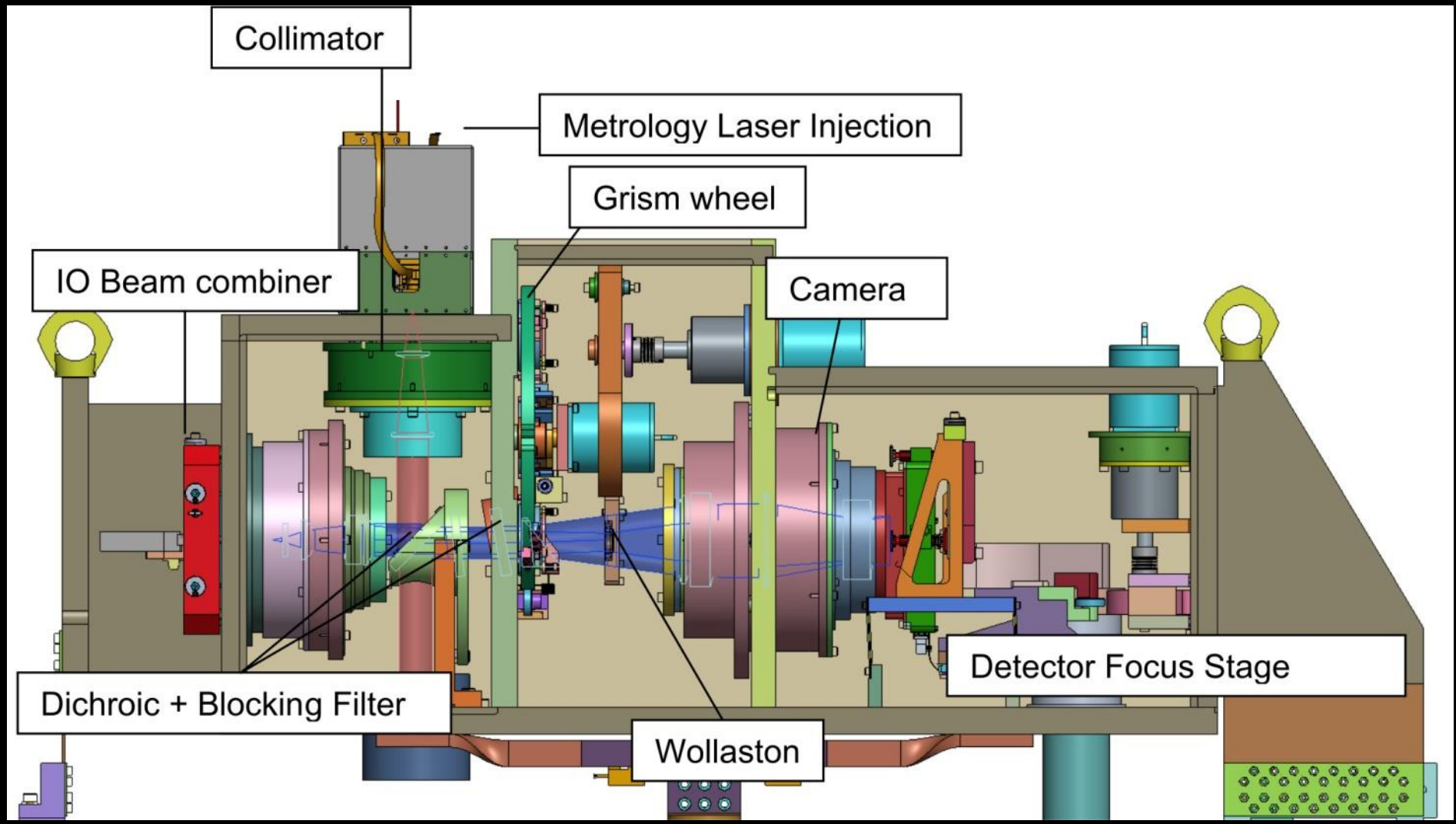
Adjusting the path length and polarization





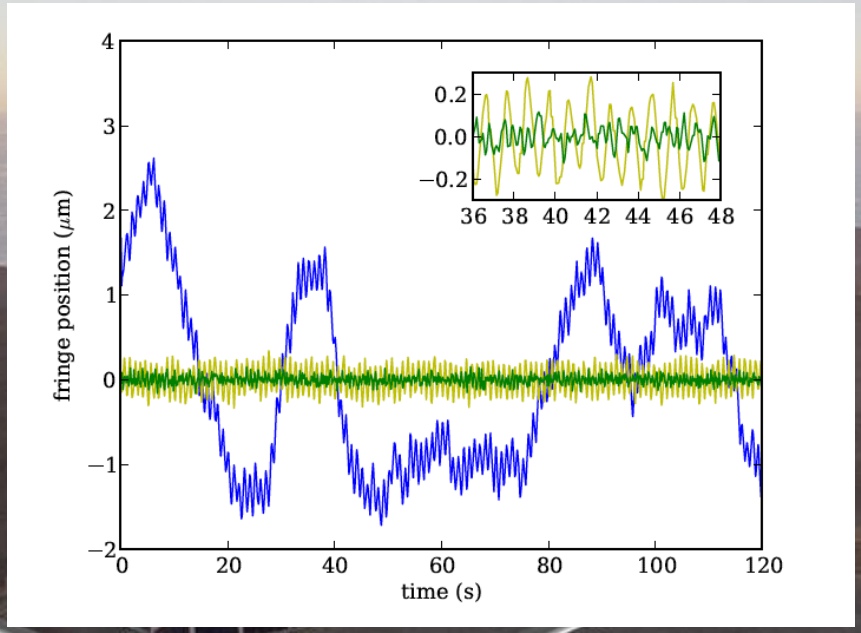
Perrin et al.

Spectrometers



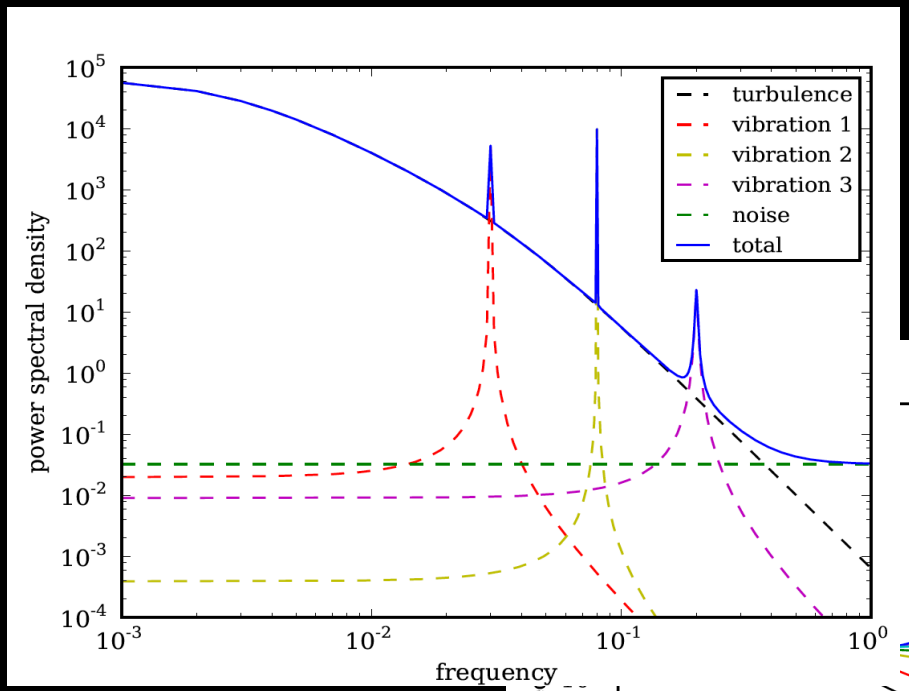
Straubmeier et al. 2010

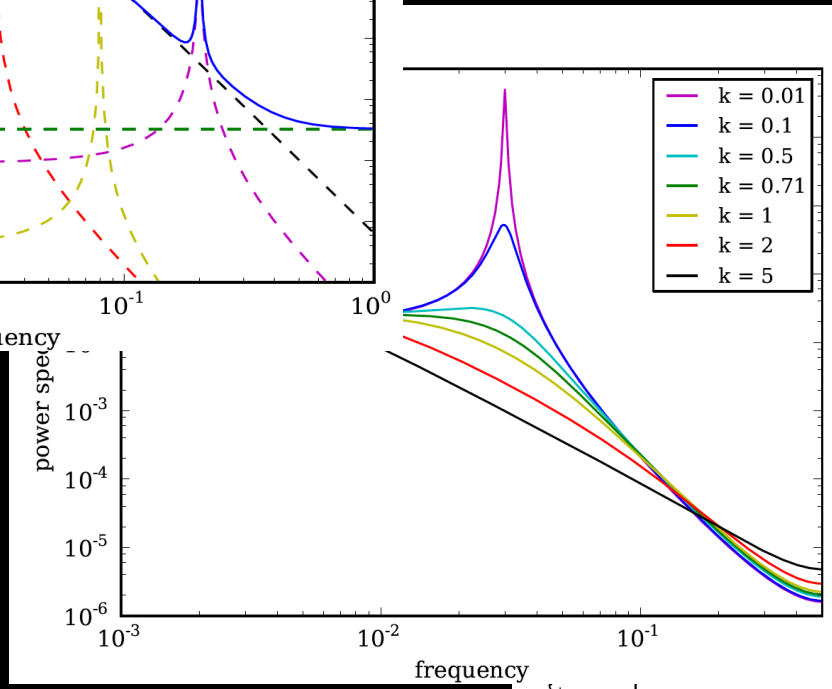
GRAVITY fringe tracking

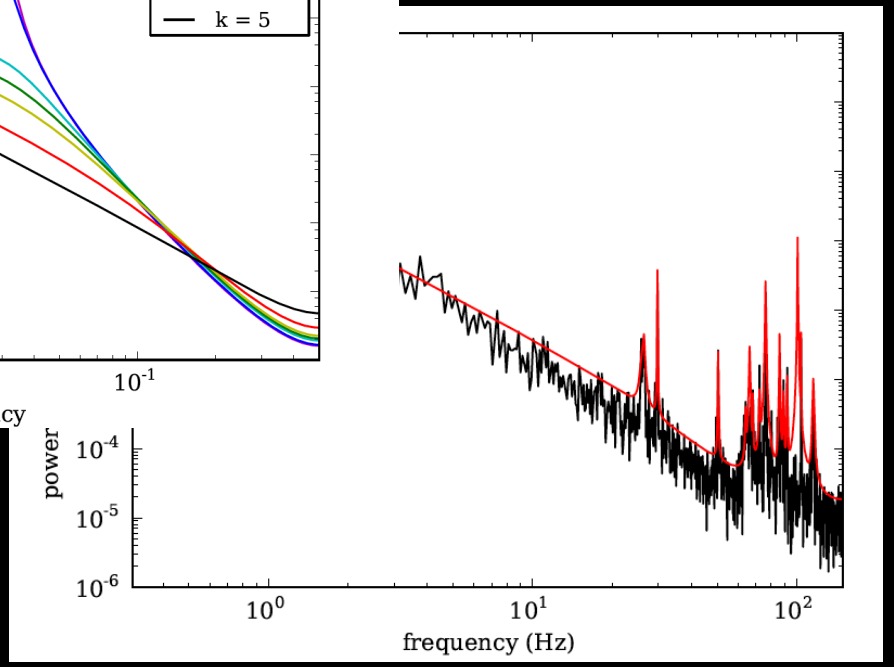


Choquet et al. 2010

Fringe Tracker – Kalmann Control

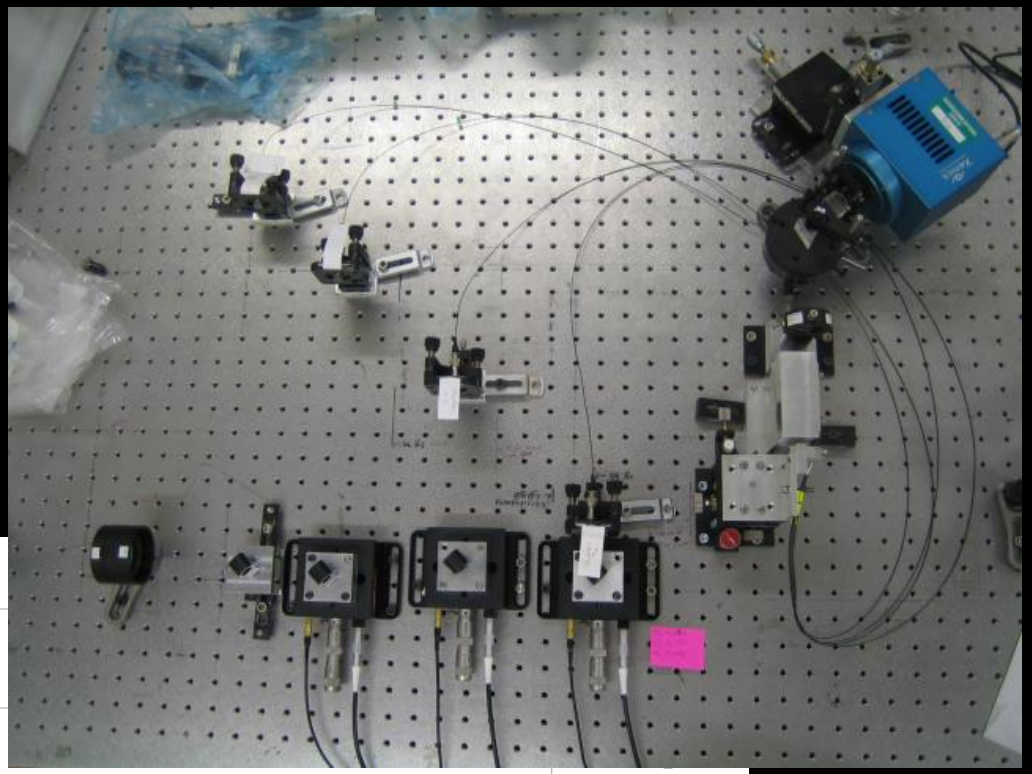


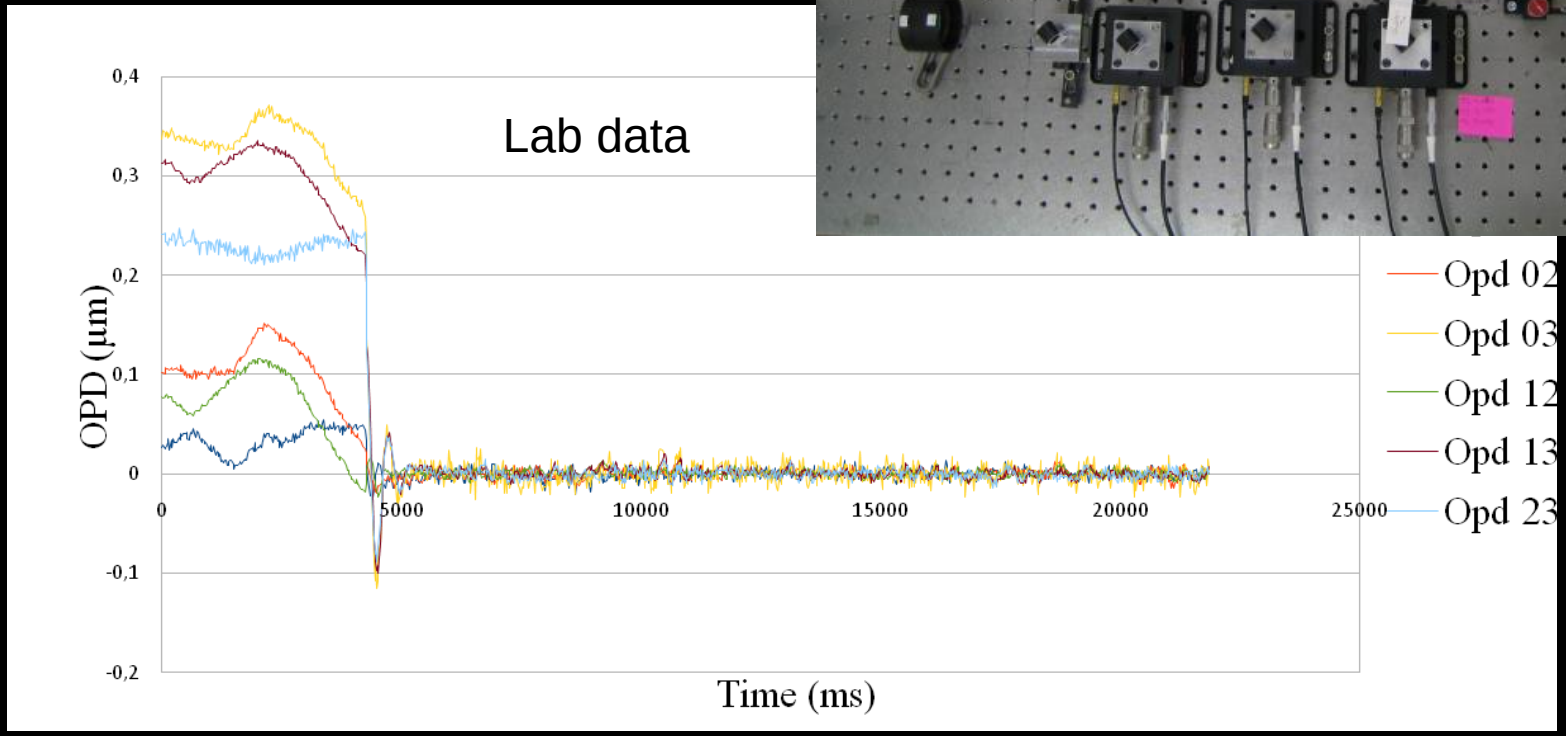




Menu, Choquet , Fedou, Dembet, et al.

Fringe Tracker - testbed

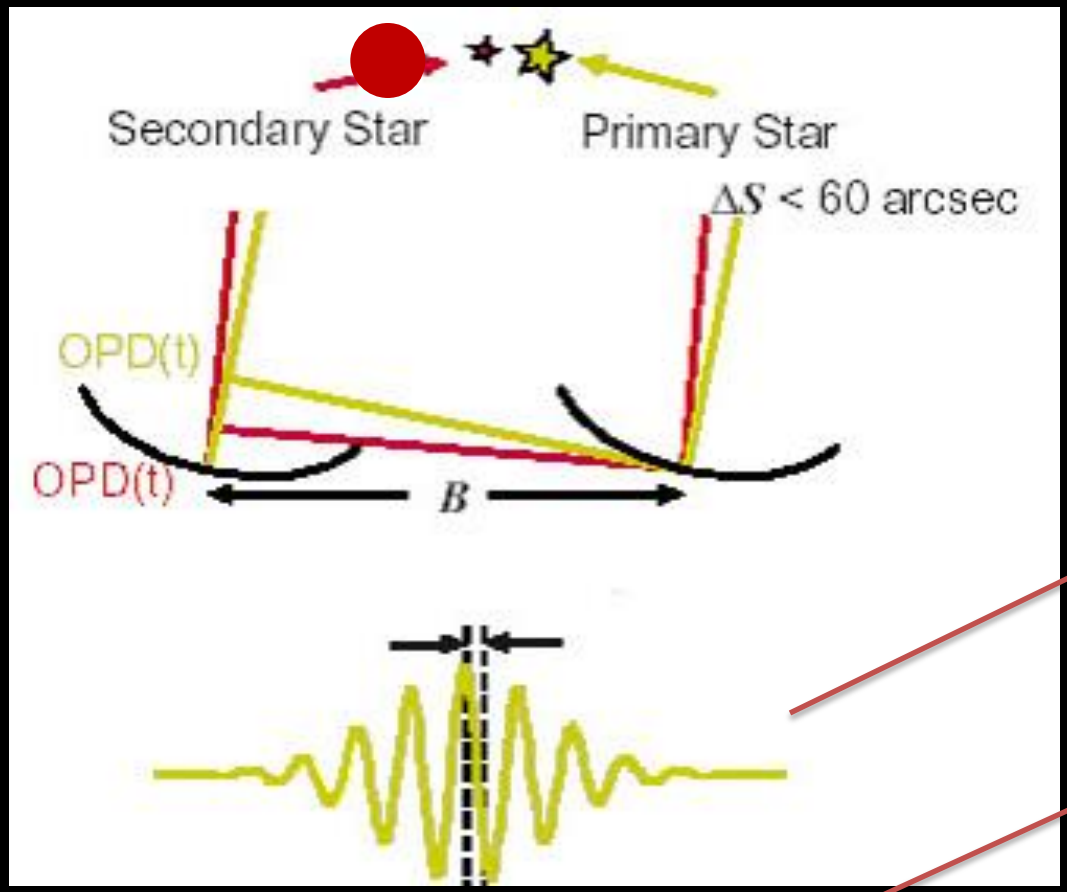




Choquet et al. 2010

Interferometric astrometry

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



Interferometric astrometry

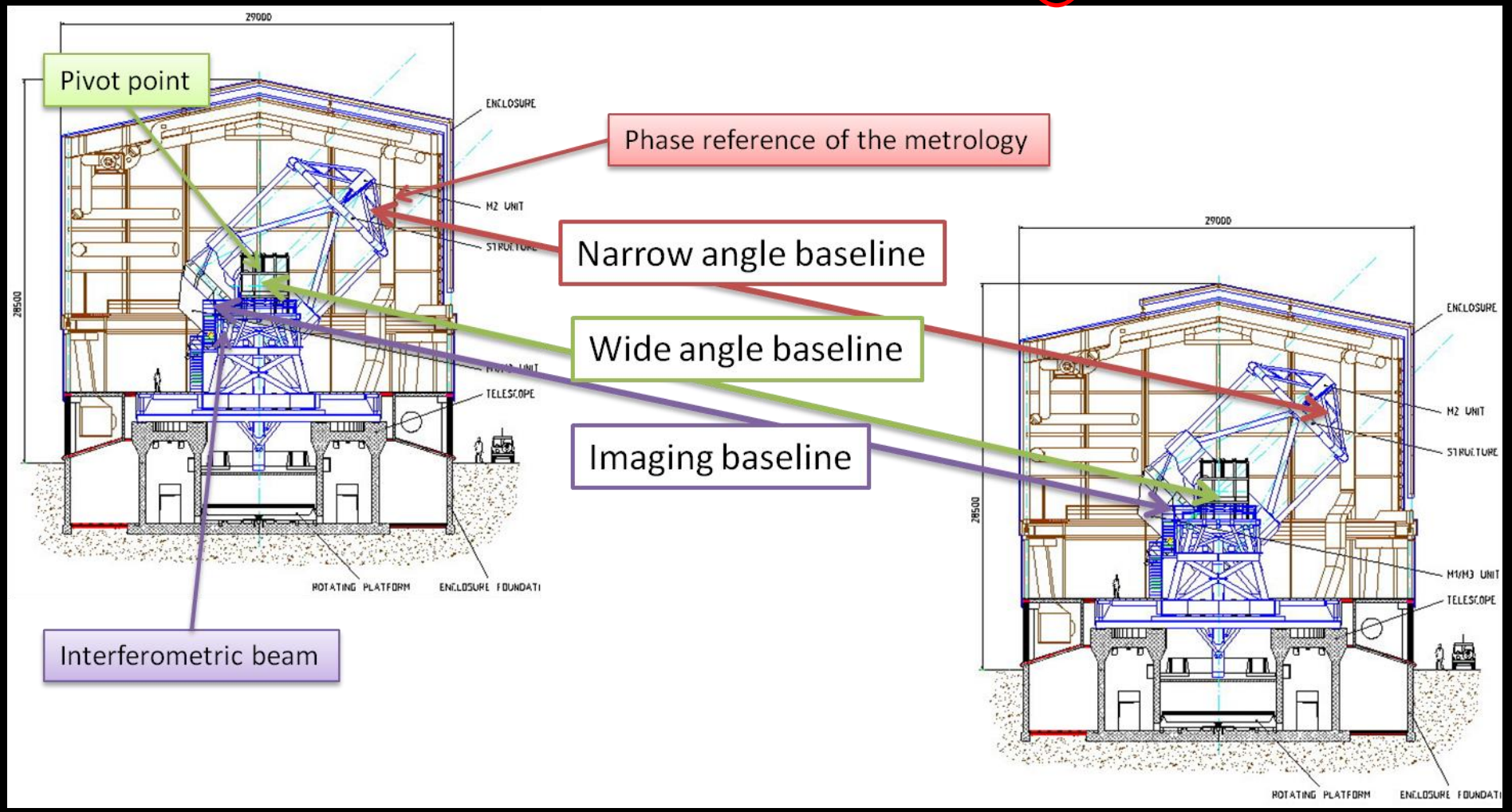
5 nm ←

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

500 µm 10 µas

Interferometric baseline

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



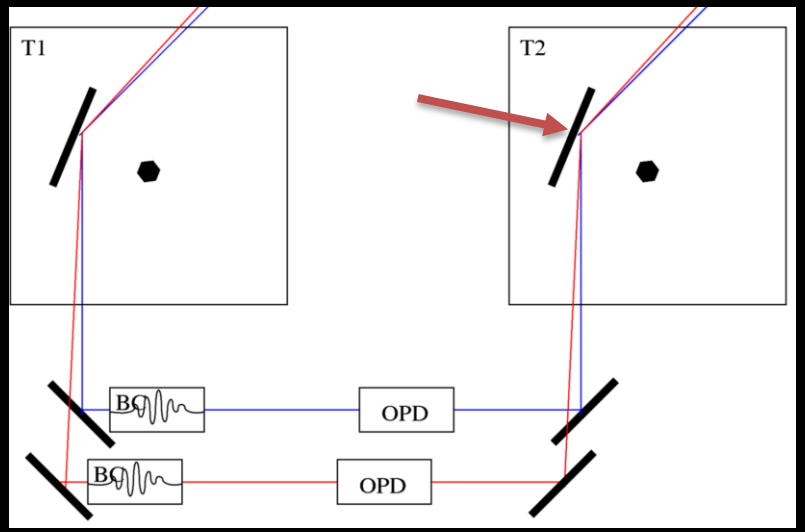
Lacour et al.

GRAVITY narrow angle baseline and metrology

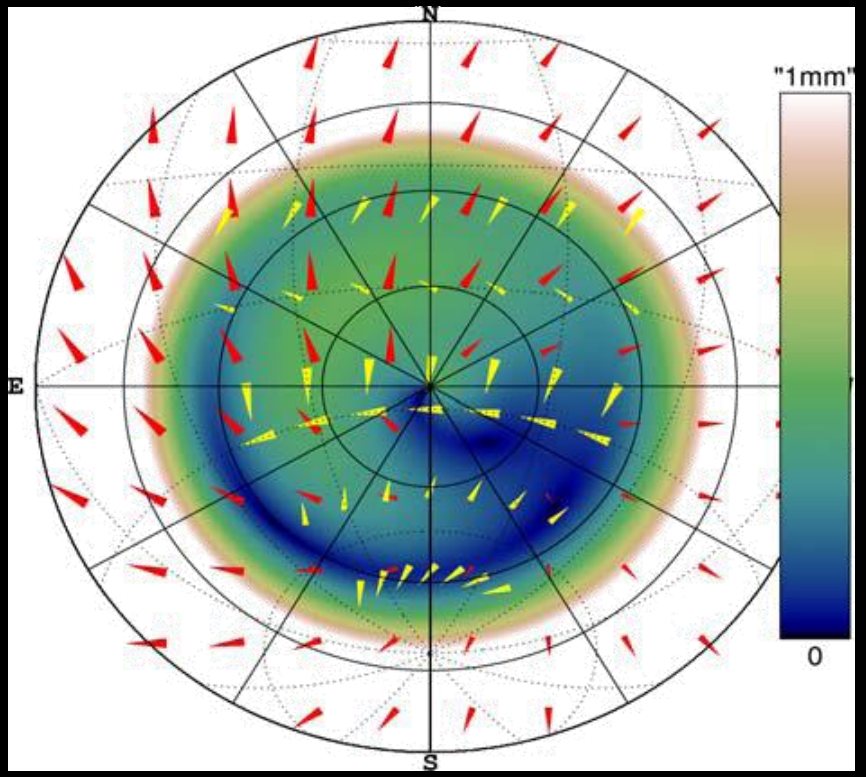
$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$

500 µm

Stable realization of the narrow angle baseline



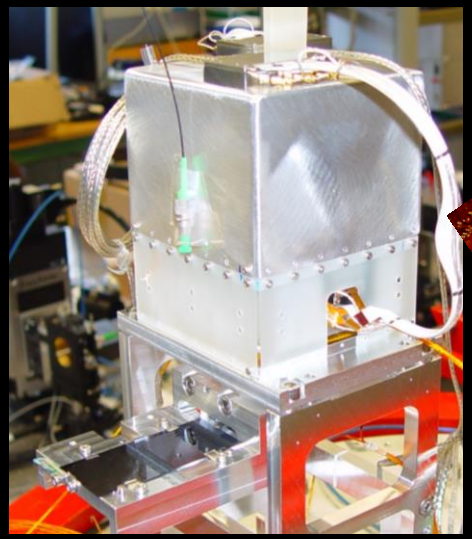
Calibration of the narrow angle baseline

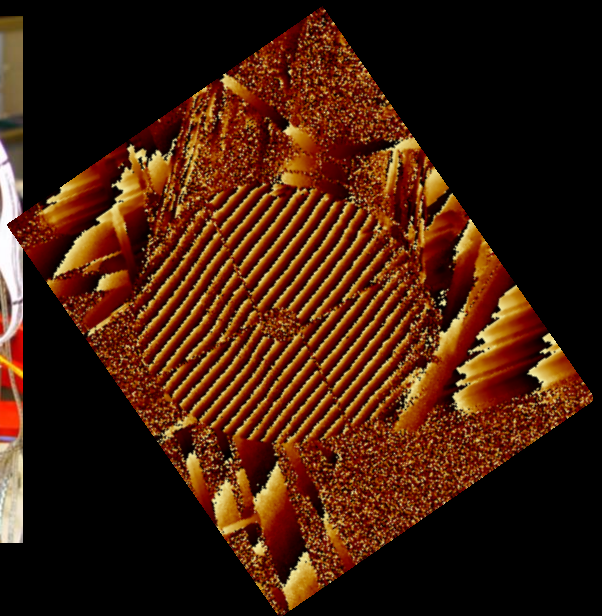


Lacour, Kervella et al.

Laser Metrology

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

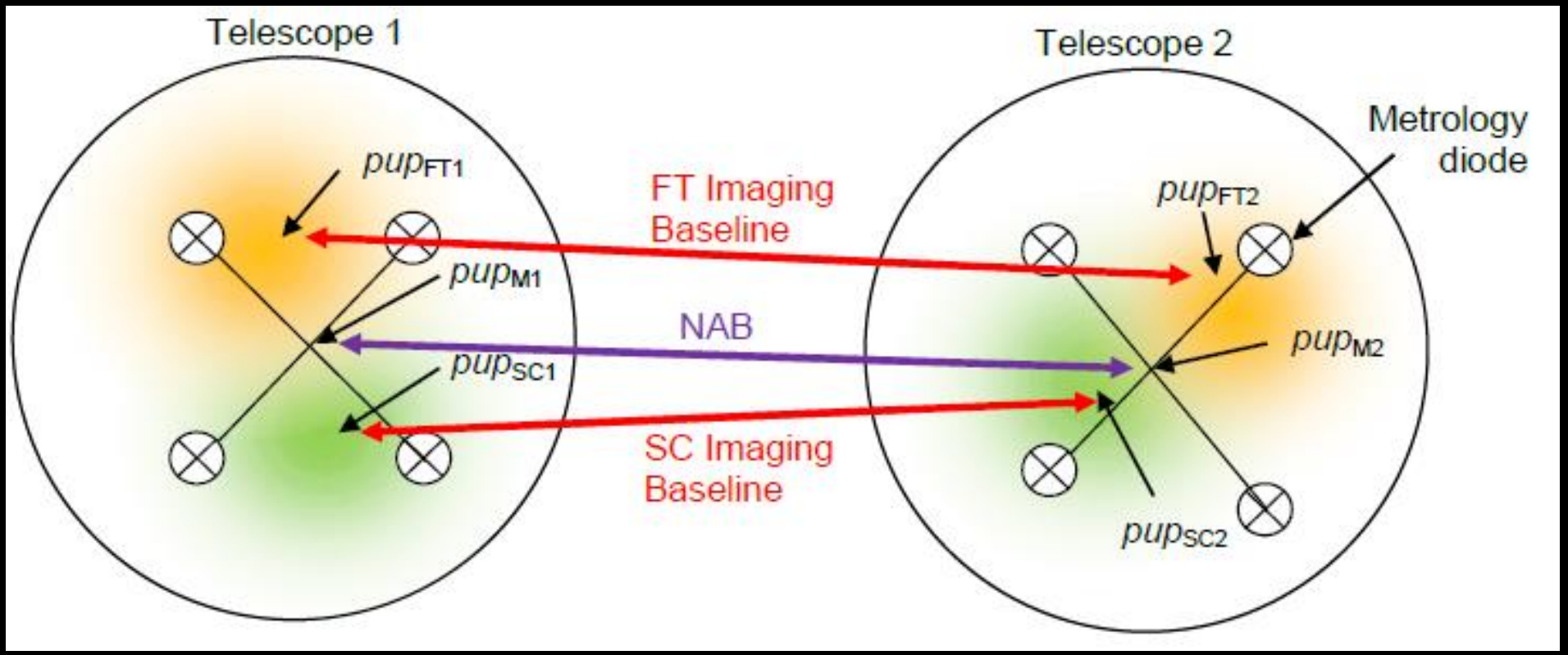




Rabien et al. 2008, Bartko et al. 2010, Gillessen et al.

Interferometric Baseline

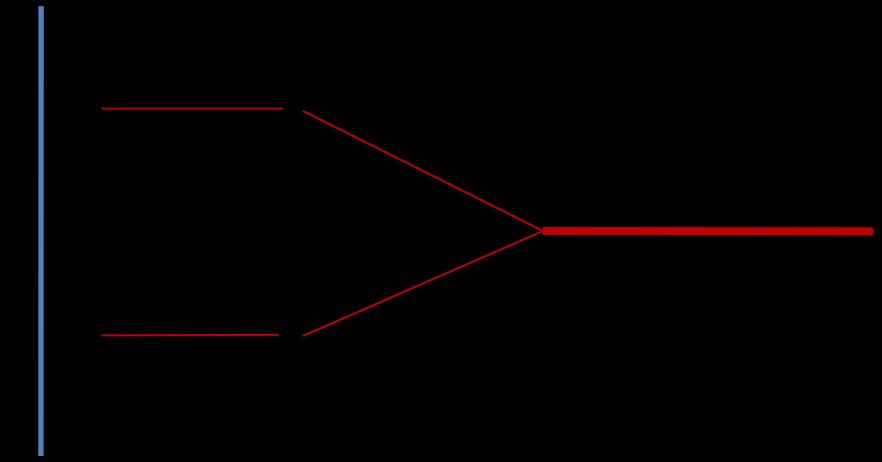
$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$

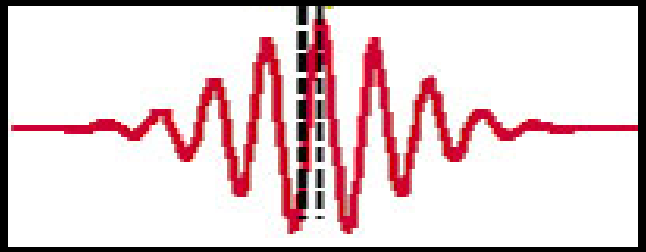


Lacour et al.

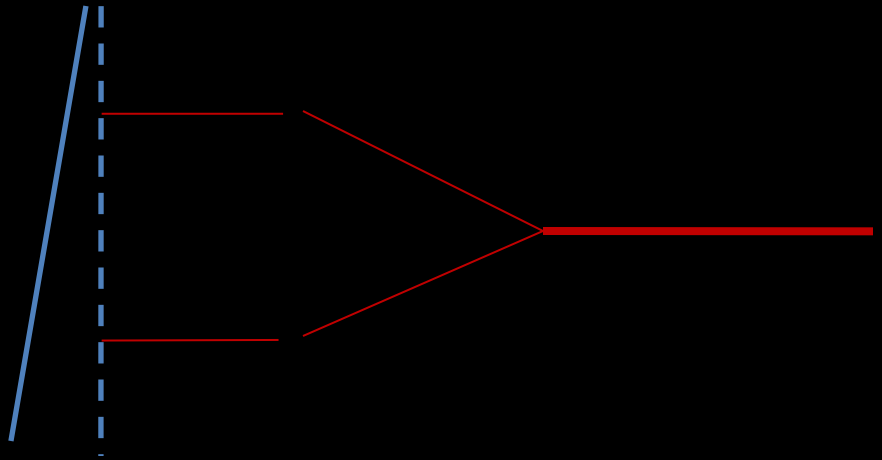
Pupil and tilt errors

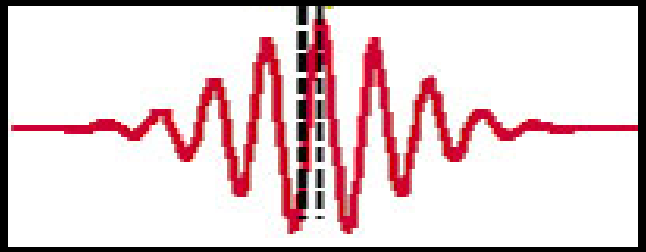
For perfect tip-tilt correction





For simultaneous tilt error





Interferometric Astrometry

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

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?

$$(\Phi_{FT} - \Phi_{SC})\frac{\lambda_s}{2\pi} - (\phi_{M1} - \phi_{M2})\frac{\lambda_m}{2\pi}$$

$$-\Delta L_{\text{air}}\left(\frac{n_a^{\lambda_m}}{n_a^{\lambda_s}} - 1\right) - \Delta L_{\text{fiber}}\left(\frac{n_g^{\lambda_m}}{n_g^{\lambda_s}} - 1\right) = B_{\text{NAB}} \cdot (\alpha - \beta)$$

Goal: 10µas*sqrt(3) in 5 minutes

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

Dispersion Error

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

Pupil positioning Error

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

Lacour et al.

Interferometric Astrometry

FT/SC differential pupil error

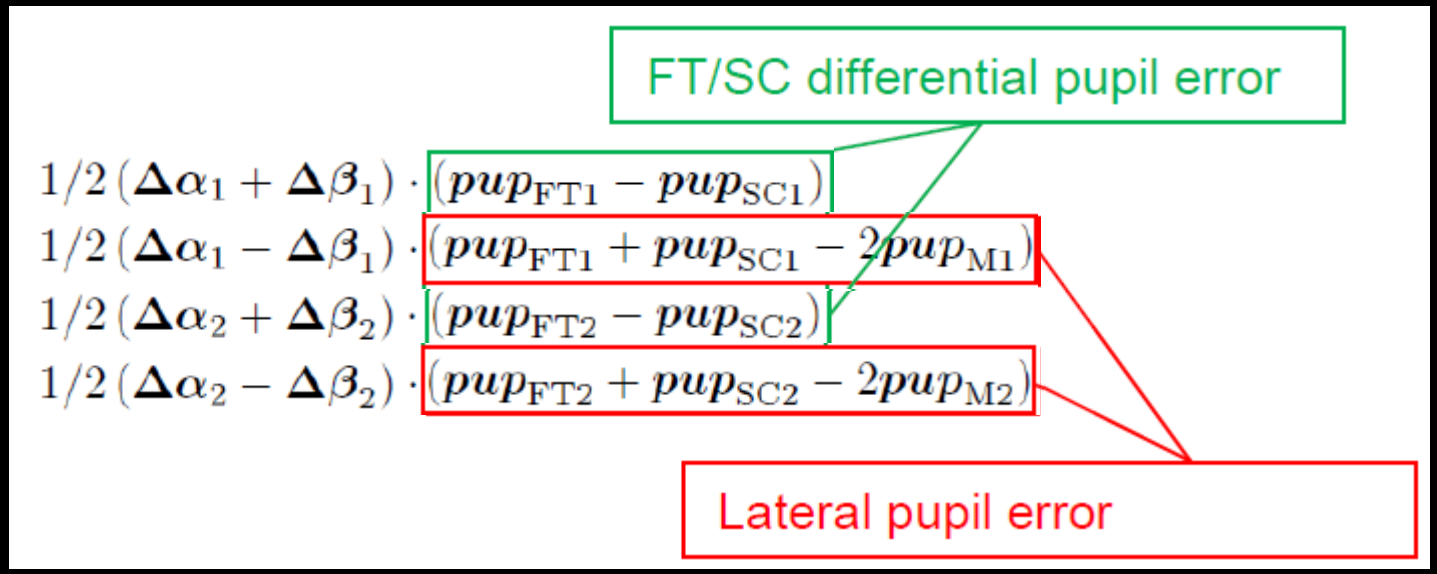
$$1/2\,(\Delta\alpha_1 + \Delta\beta_1)\cdot(pup_{\mathrm{FT1}} - pup_{\mathrm{SC1}})$$
$$1/2\,(\Delta\alpha_1 - \Delta\beta_1)\cdot(pup_{\mathrm{FT1}} + pup_{\mathrm{SC1}} - 2pup_{\mathrm{M1}})$$
$$1/2\,(\Delta\alpha_2 + \Delta\beta_2)\cdot(pup_{\mathrm{FT2}} - pup_{\mathrm{SC2}})$$
$$1/2\,(\Delta\alpha_2 - \Delta\beta_2)\cdot(pup_{\mathrm{FT2}} + pup_{\mathrm{SC2}} - 2pup_{\mathrm{M2}})$$

Lateral pupil error

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

Lacour et al.

Interferometric Astrometry



Align your fibers (angles) well, and actuate both pupils with the same actuator
-> Telescope pointing error / common tip/tilt

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

Acquire well, and actuate tip/tilt of both fibe
-> Pupil error does not hurt too much

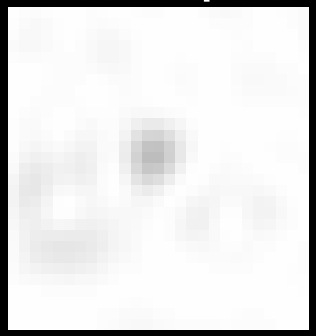
Control pupil such that fiber pupils are fixed on metrology reference

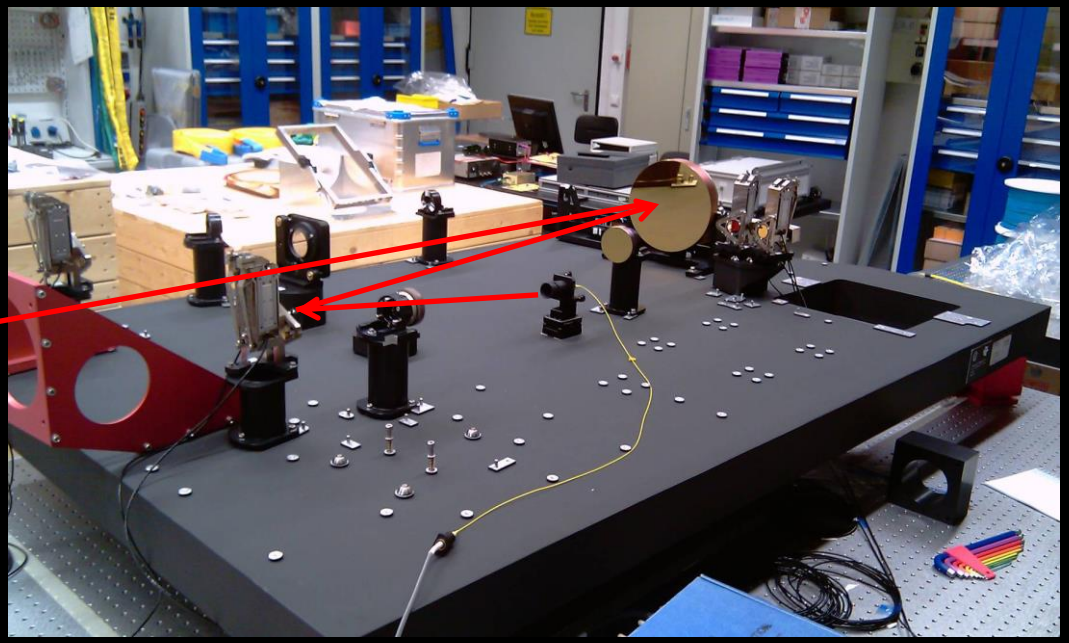
Minimize Tip/Tilt and guiding errors

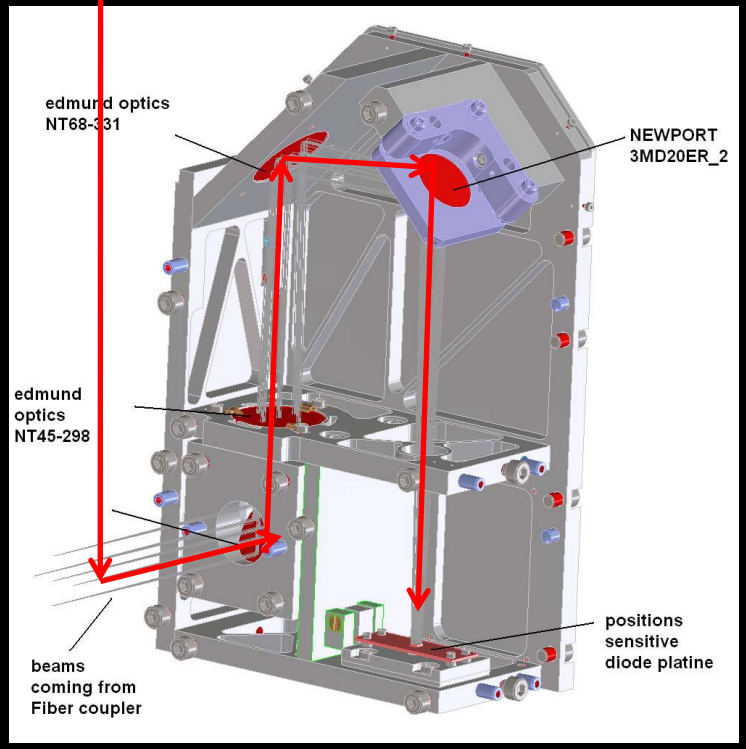
Lacour et al.

GRAVITY Tilt Control

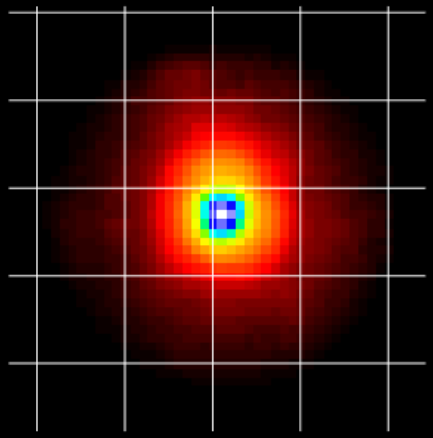
Atmosphere VLTI Tunnel





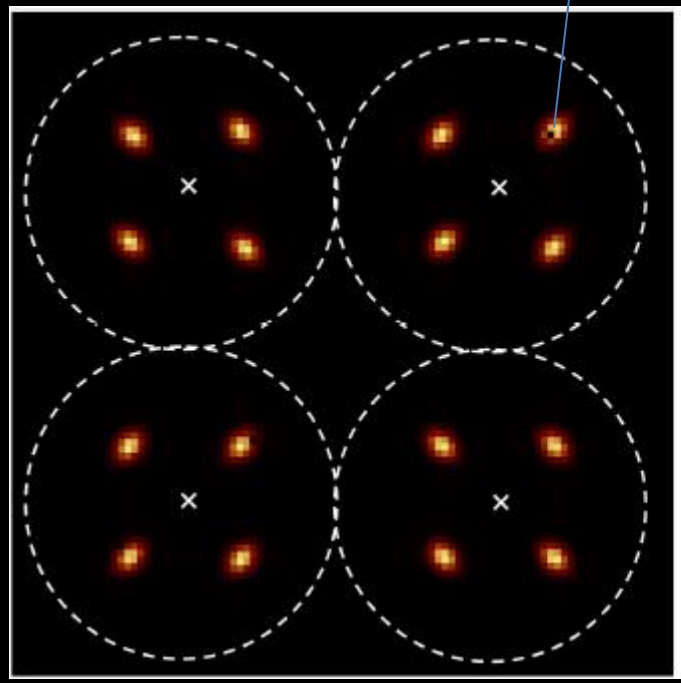


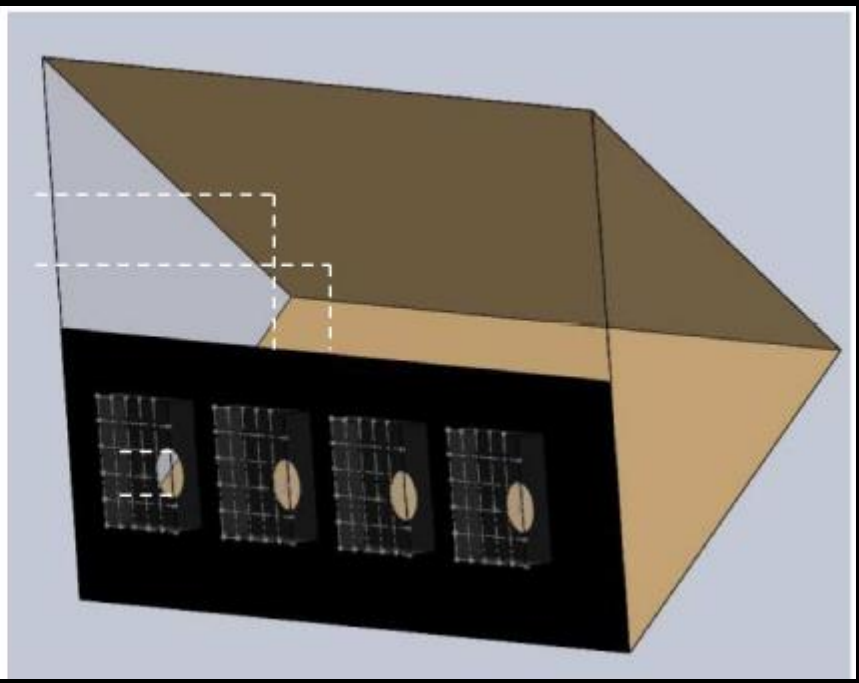
Acquisition and guiding camera



Pfuhl et al., Amorim et al. 2010,

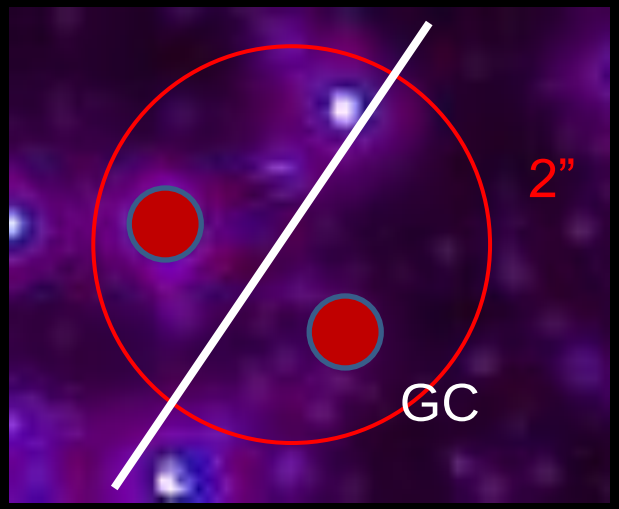
GRAVITY Pupil Control



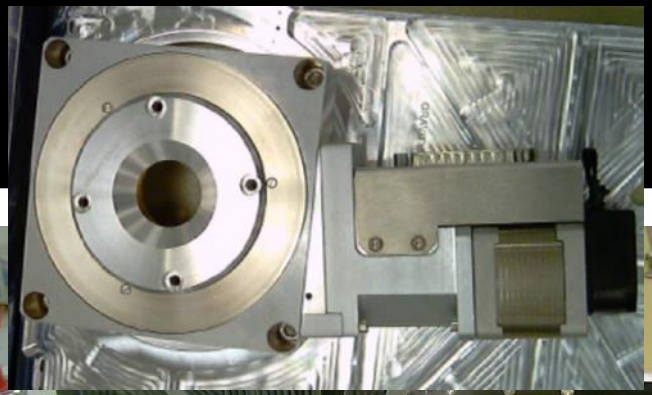


Amorim et al. 2010, Pfuhl et al.

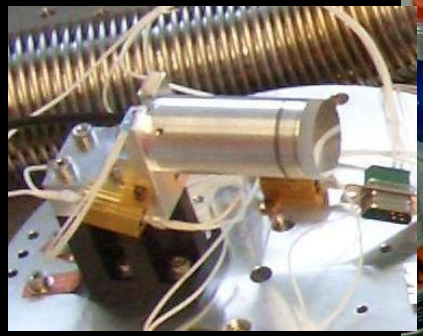
Fibercoupler



Rotation Stages



Shutters



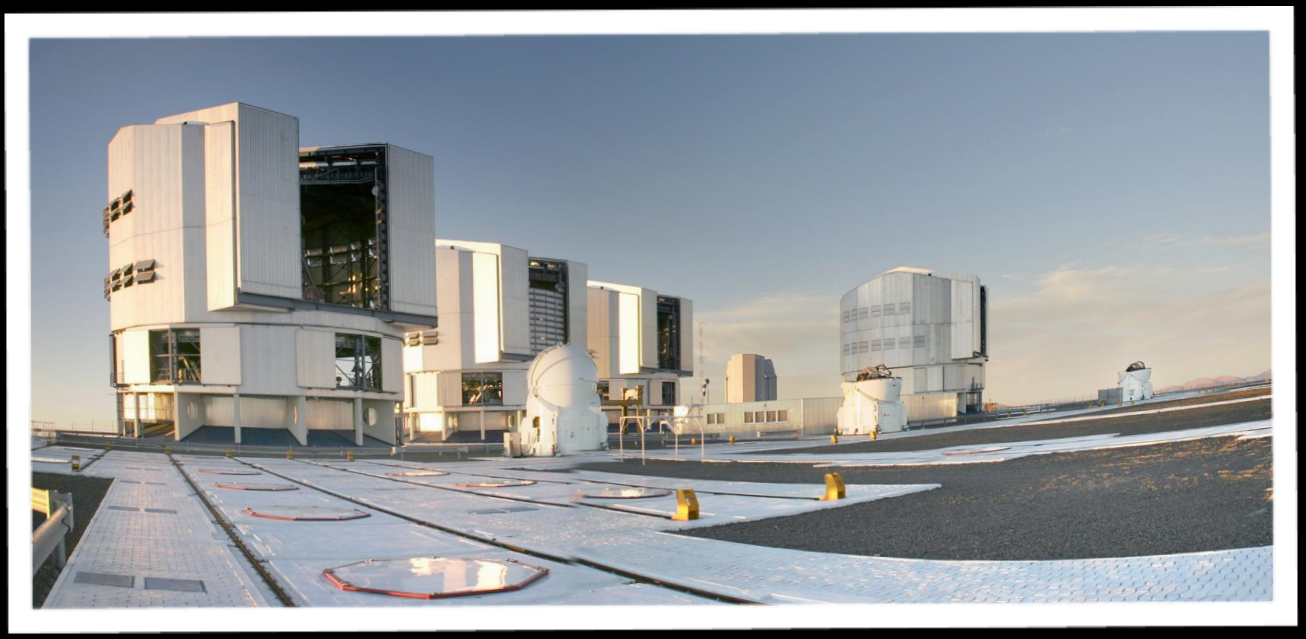
Tip-Tilt-Piston-Actuator

Pupil-Actuator

Pfuhl et al. 2010

X,Y,Z Stages

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



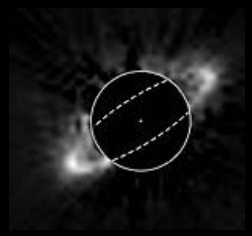
Overview

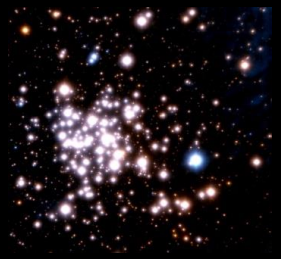
- Primary science case: the Galactic Center
- 4-telescope beam combiner for the VLTI
- K band (full)
- 3 spectral resolutions (R=22, 500, 4000)
- single and dual field (< 2" or 6" separation)
- dual field astrometry
- m_K~10 limiting magnitude of fringe tracker
- m_K~19 for science combiner

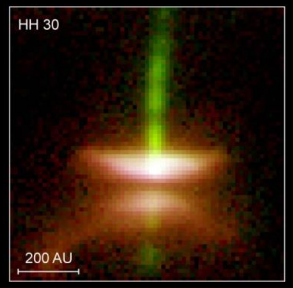
Performances

- 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 ~19* are possible

Observing the Universe in motion



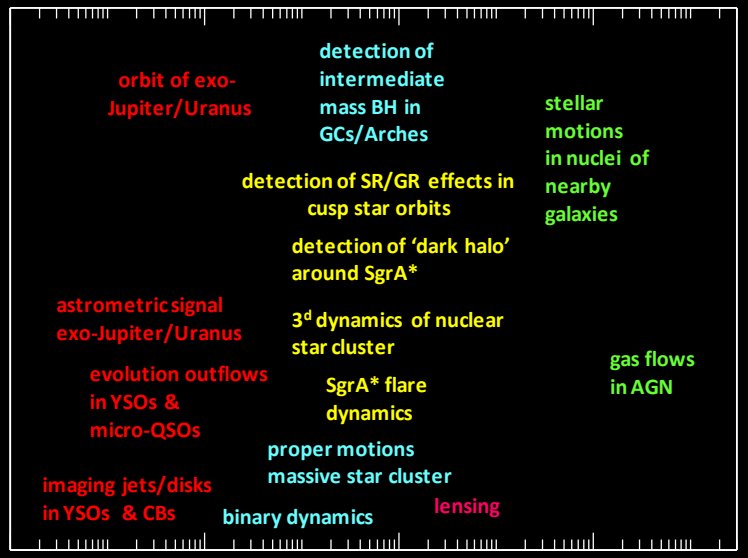


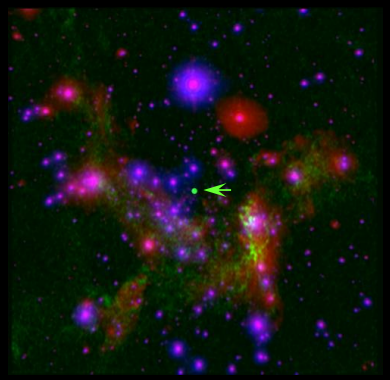


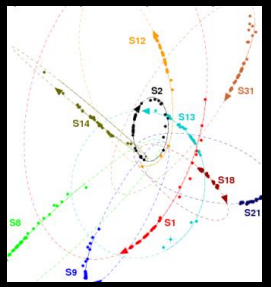
ten year large program

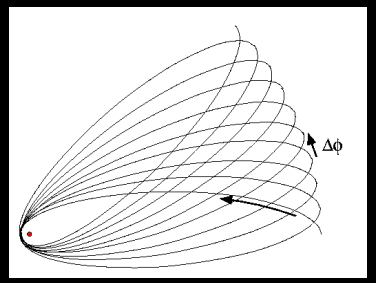
three year program

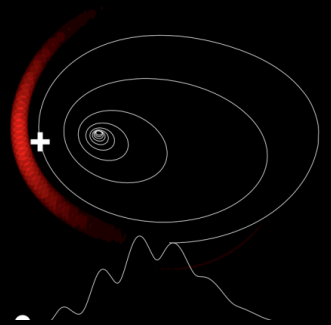
single season campaign





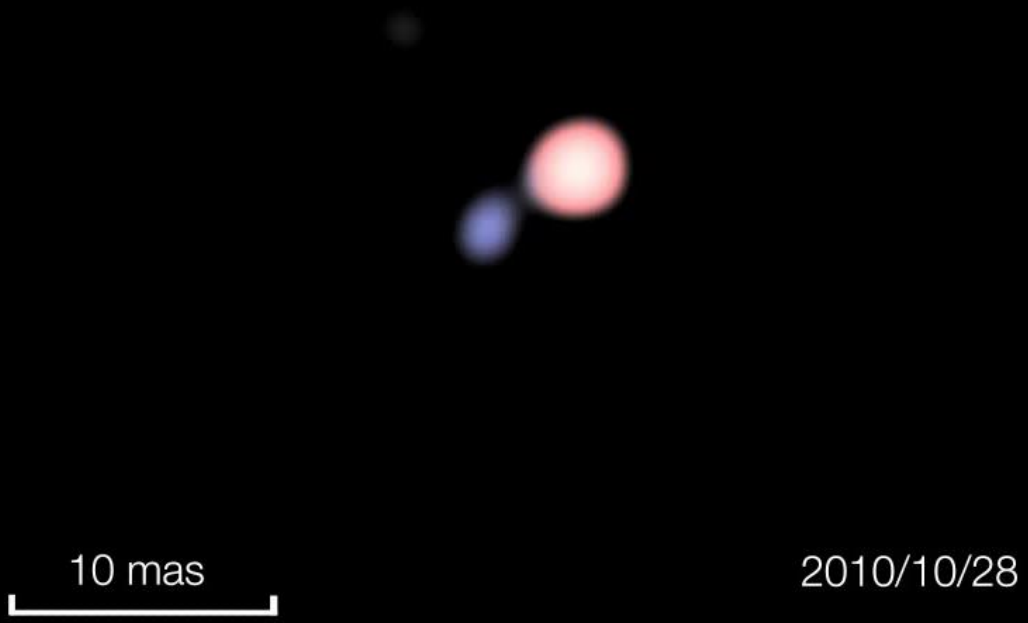






Observing the Universe in motion

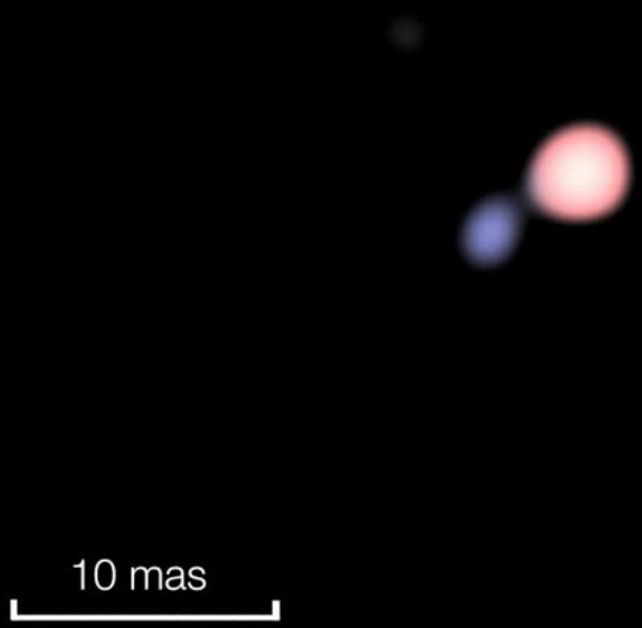
SS Leporis



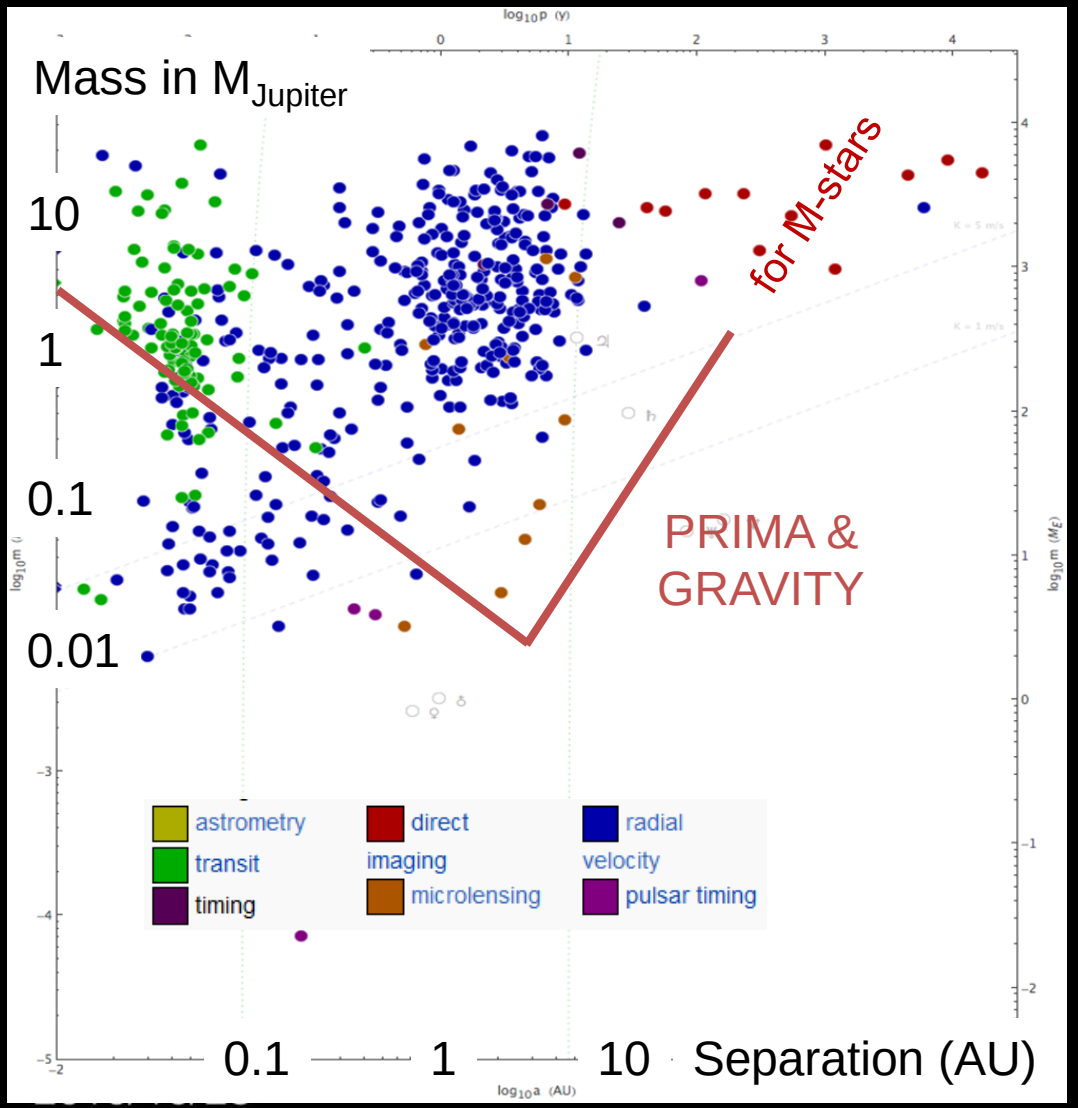
Blind et al. 2012, ESO

Observing the Universe in motion

SS Leporis



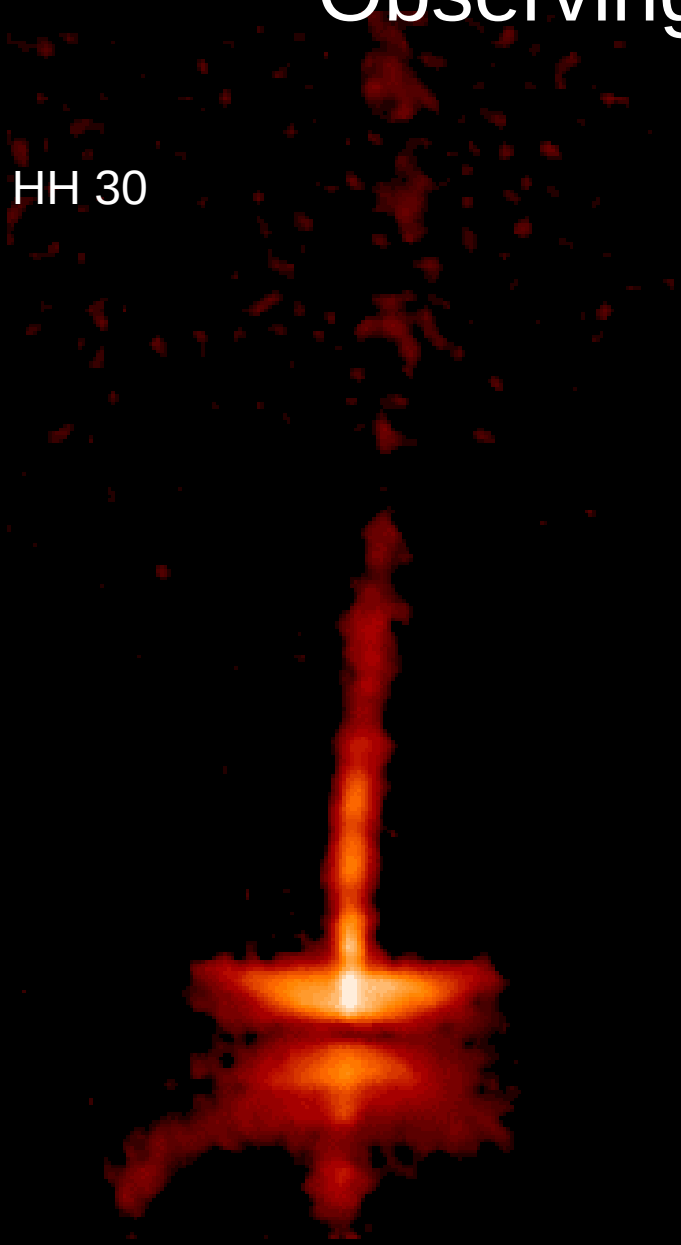
Blind et al. 2012, ESO



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

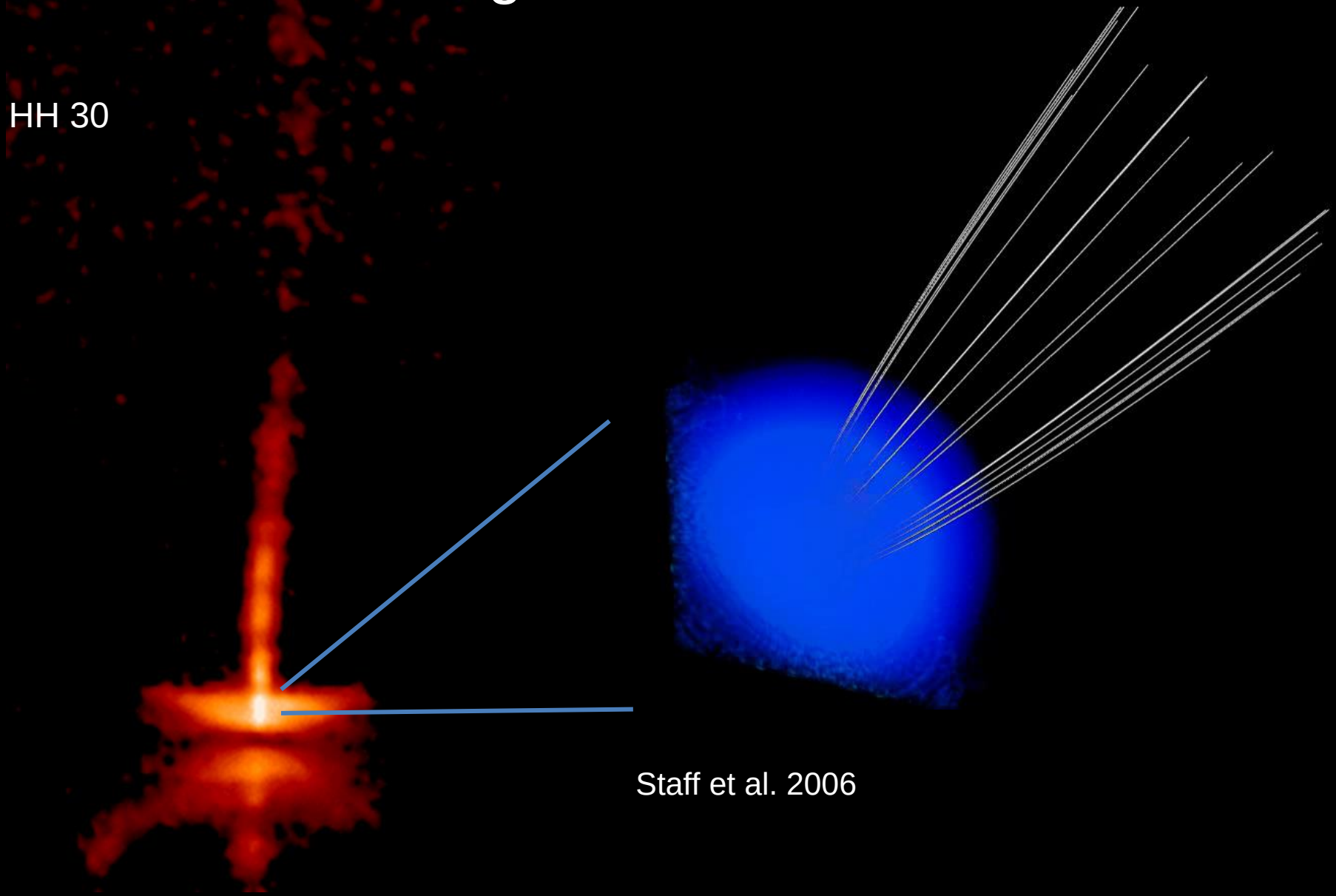
Observing the Universe in motion

HH 30



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

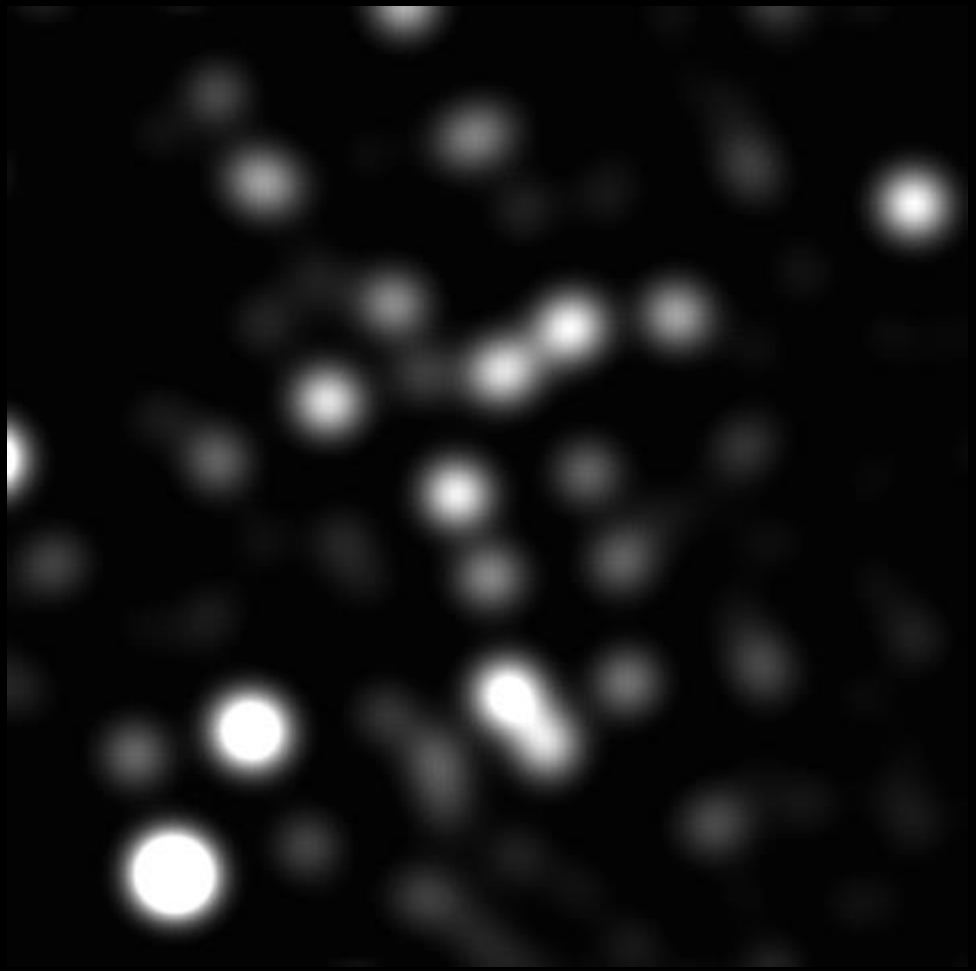
Observing the Universe in motion



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

Observing the Universe in motion

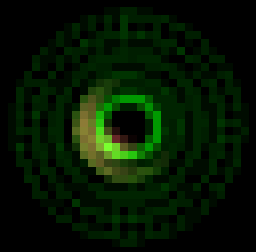
Galactic Center



NTT/VLT observations

Observing the Universe in motion

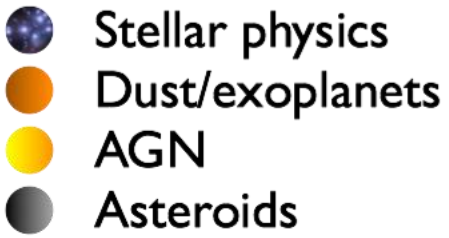
Galactic Center

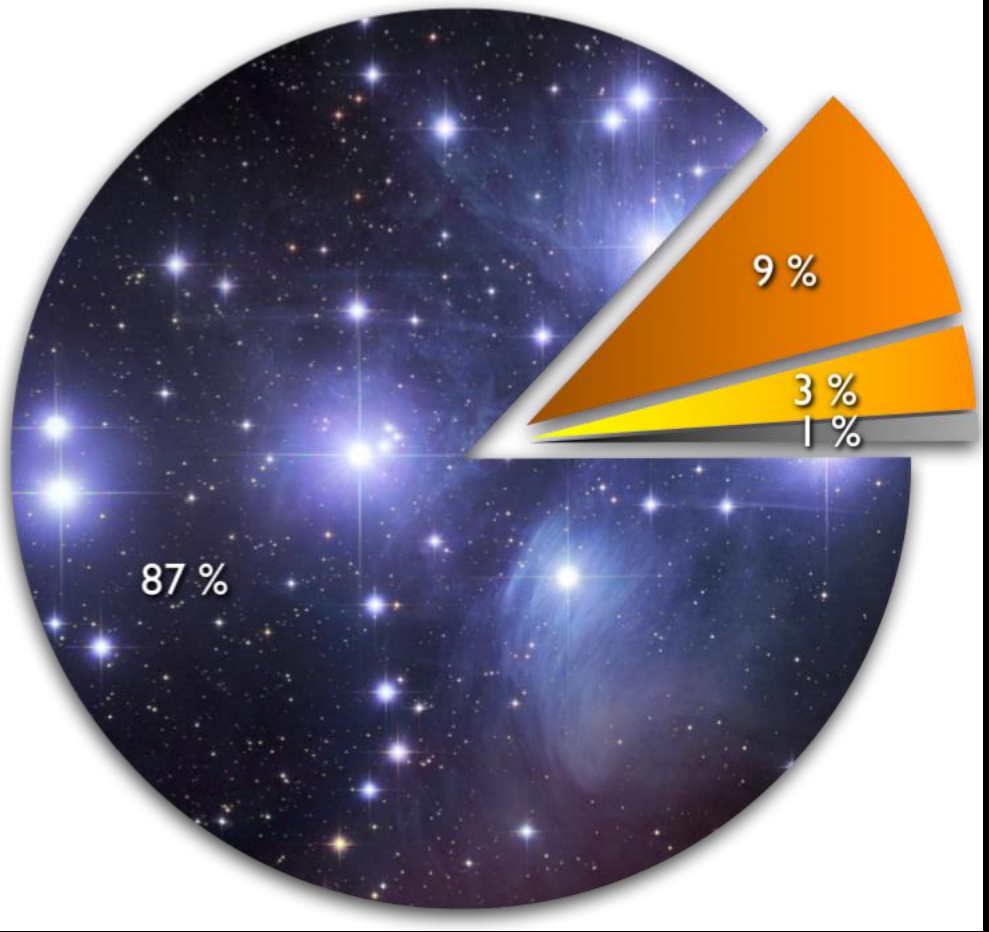


Gillessen et al. 2011, Burkert et al. 2012, Schartmann et al. 2012, Credits: ESO, Berry/NASA, Broderick

Stellar Physics & Interferometry

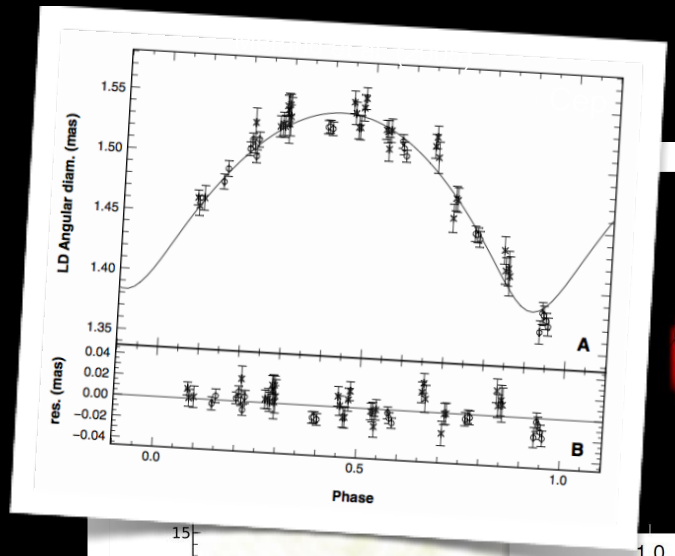
Publications in optical / infrared interferometry (1998-2013)

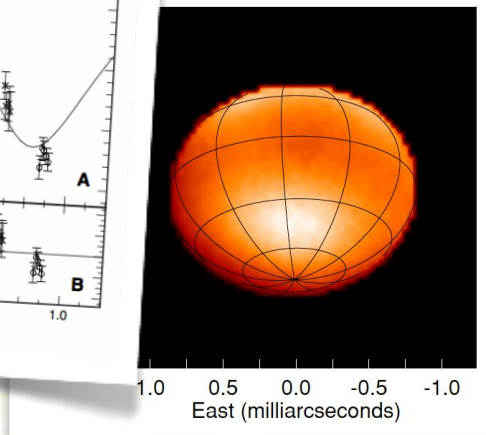


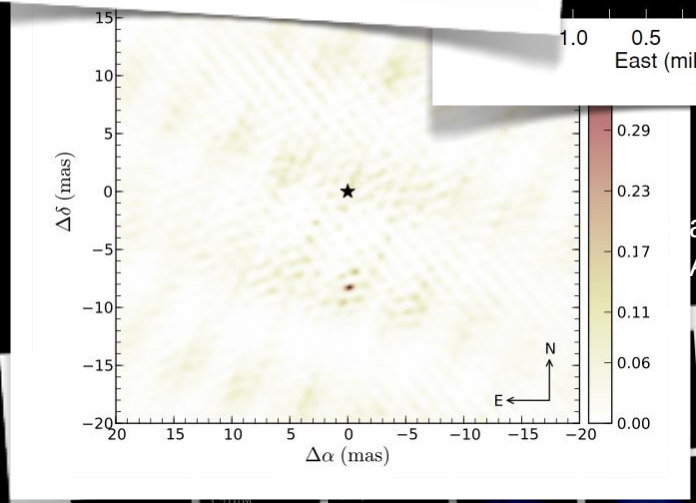


http://apps.jmmc.fr/bibdb/

- 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)







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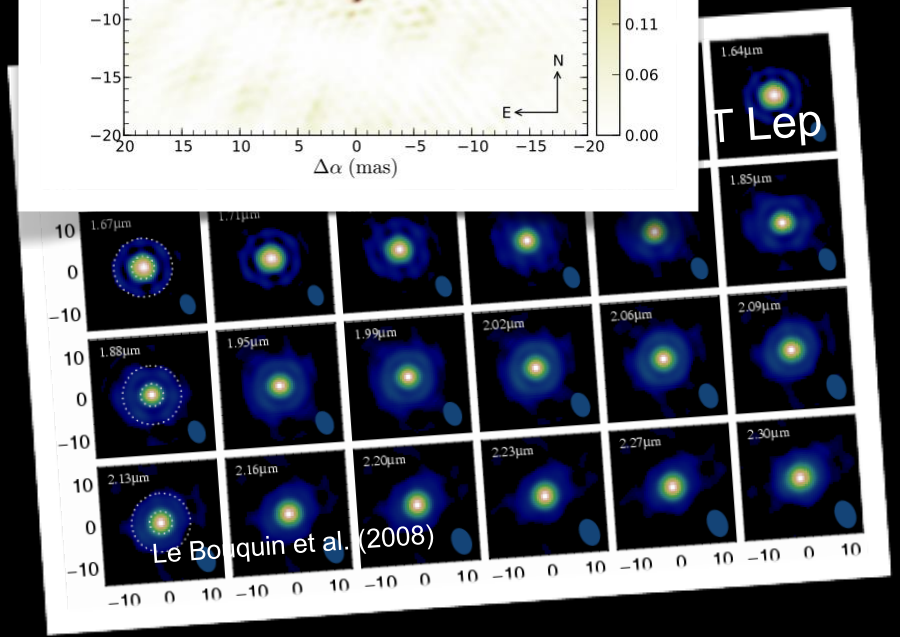
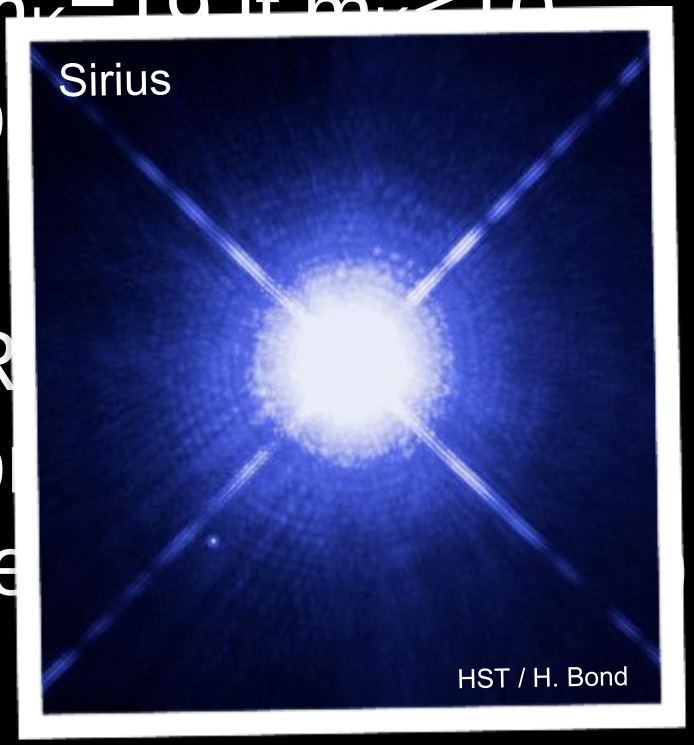
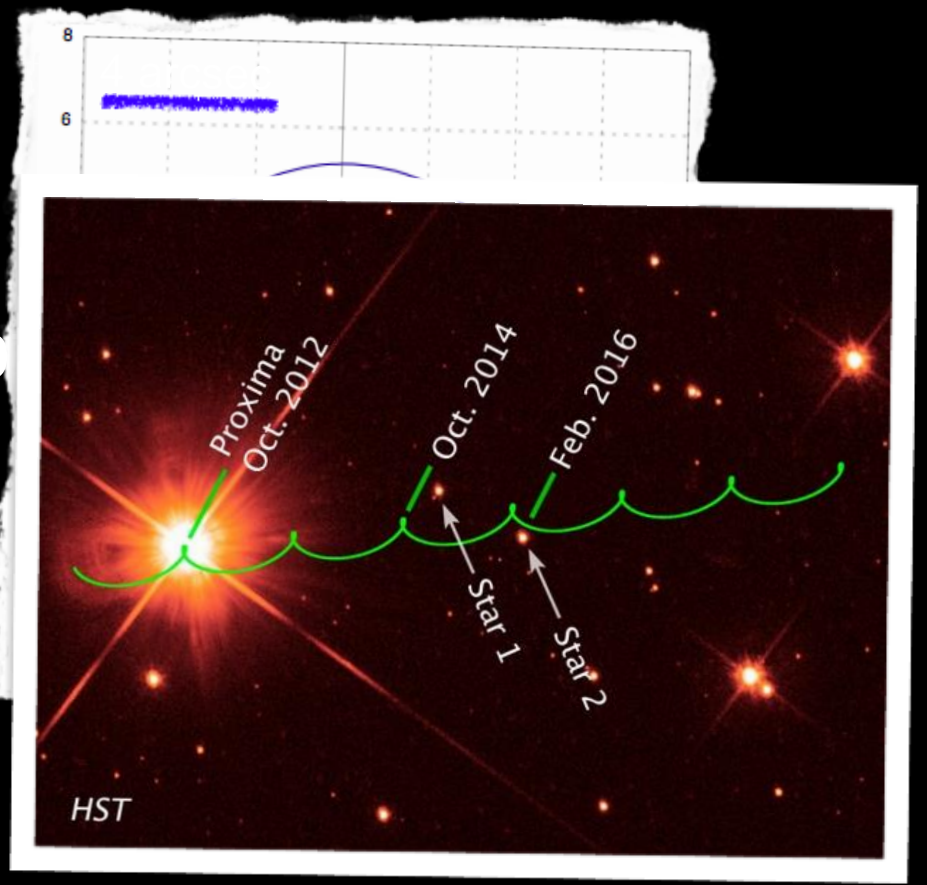


Le Bouquin et al. (2008)

Astrometry

- Astrometry and spectro-imaging up to 6" separation and m$_K$=19 if m$_K$<10
- R
  o
  b
  re

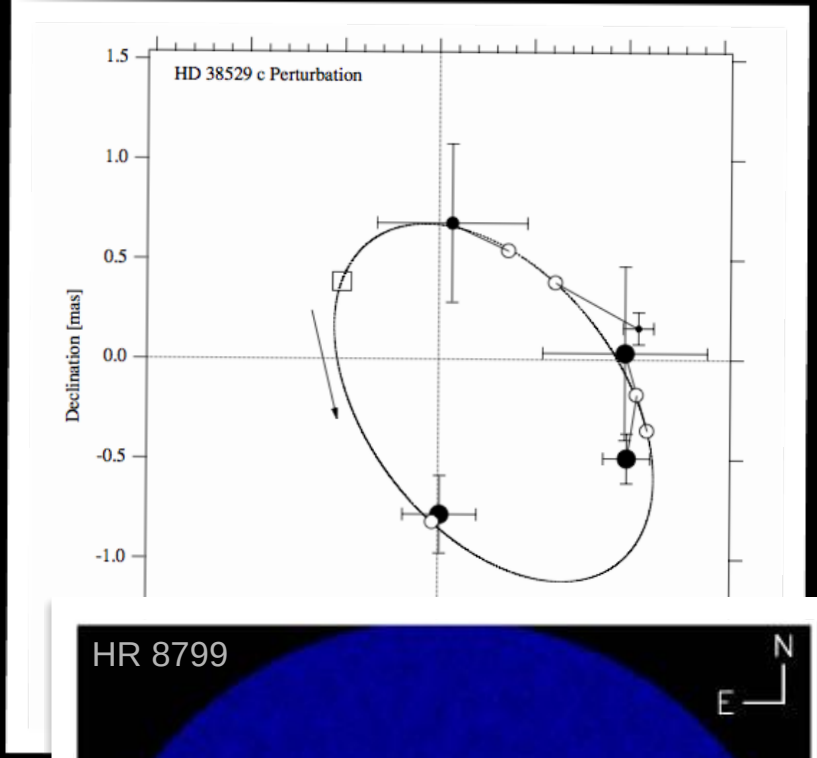


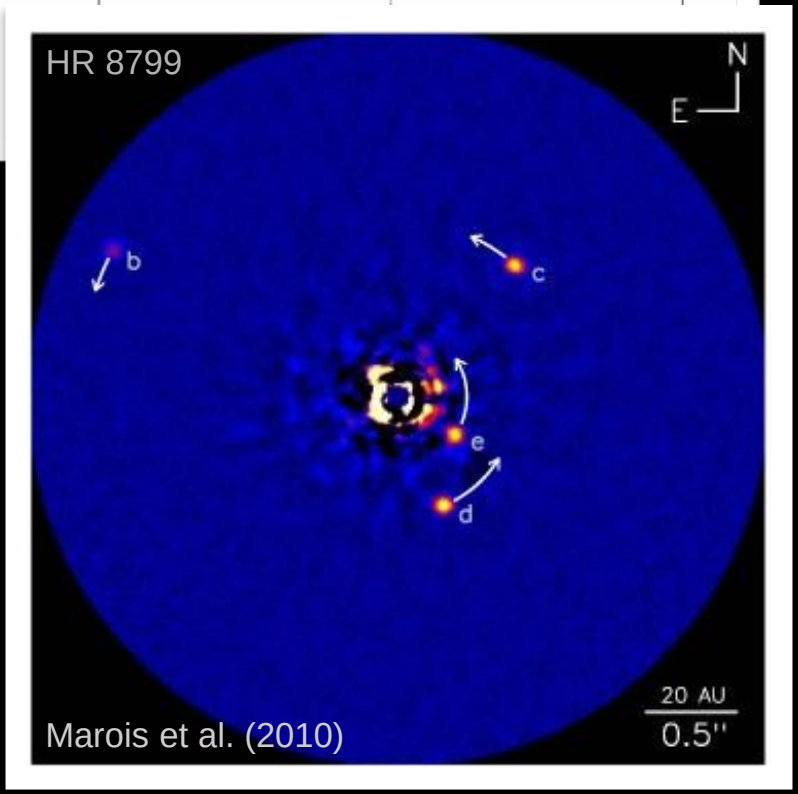


Exoplanets

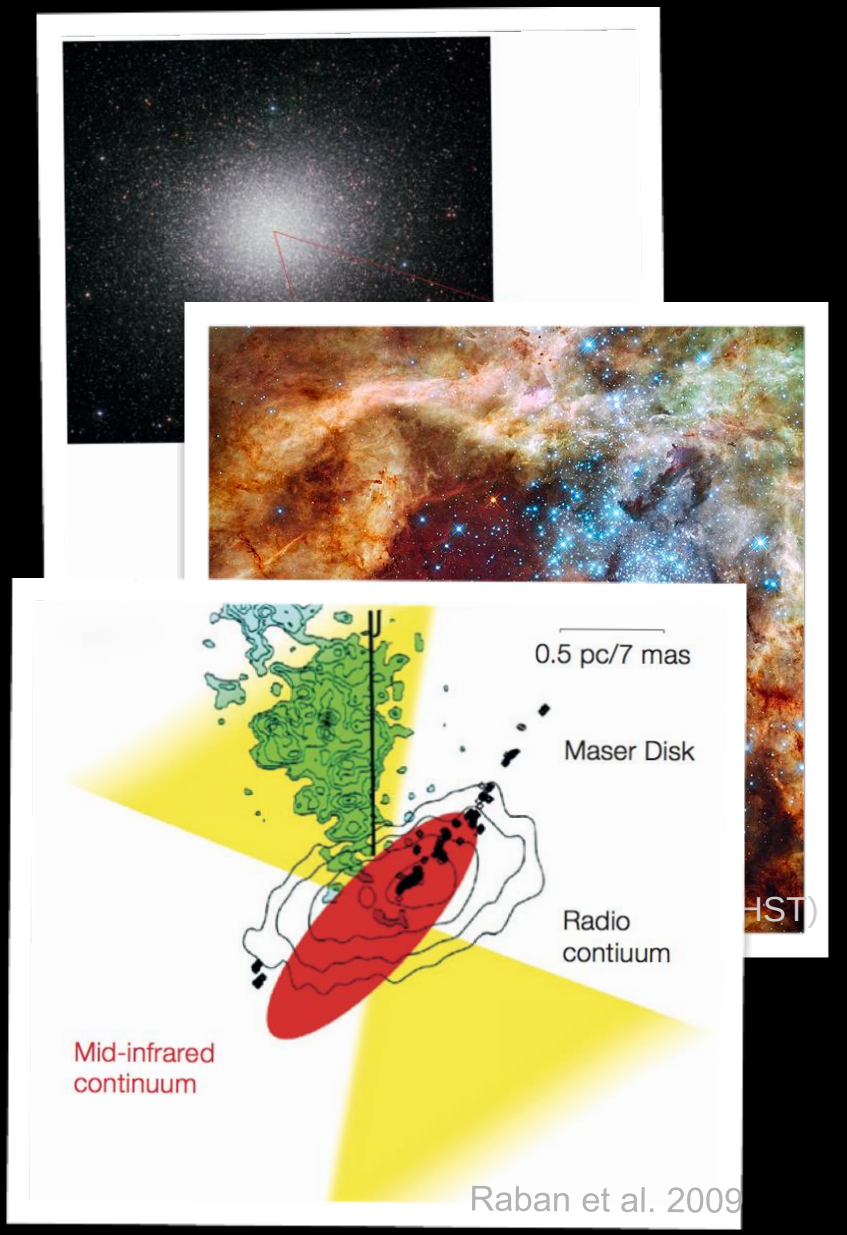
- Astrometric wobble of star ➠ Planet mass

- Displacement of spatially resolved planets relative to their star ➠ Moons





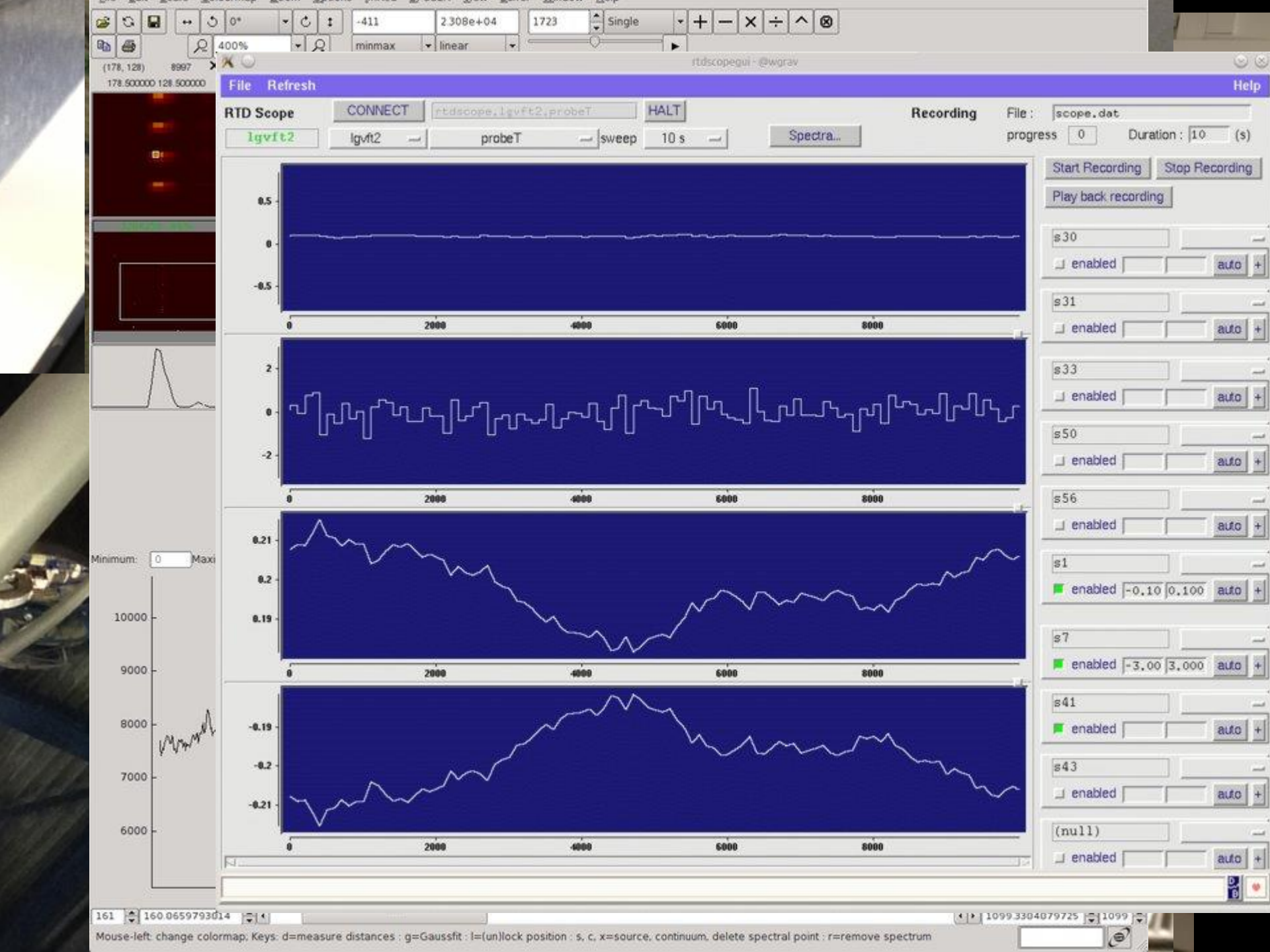
- Astrometry of stars near globular cluster cores
- Brightest stars in the Magellanic Clouds and their surroundings
- Spectro-imaging of AGN cores (including spectro-astrometry)



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)


rtdscopegui - @wgrav
File Refresh Help
RTD Scope
CONNECT
rtdscope,lgvft2,probeT
HALT
Recording
File : scope.dat
progress 0
Duration : 10 (s)
lgvft2
lgvft2
probeT
sweep 10 s
Spectra...
Start Recording
Stop Recording
Play back recording
s30
s31
s33
s50
s56
s1
s7
s41
s43
(null)
enabled
auto
-0.10
0.100
-3.00
3.000
Minimum:
Maxi
Mouse-left: change colormap, Keys: d=measure distances : g=Gaussfit : l=(un)lock position : s, c, x=source, continuum, delete spectral point : r=remove spectrum