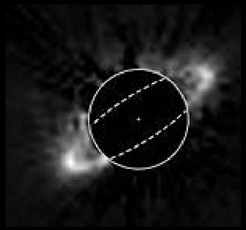
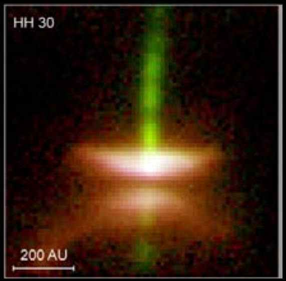
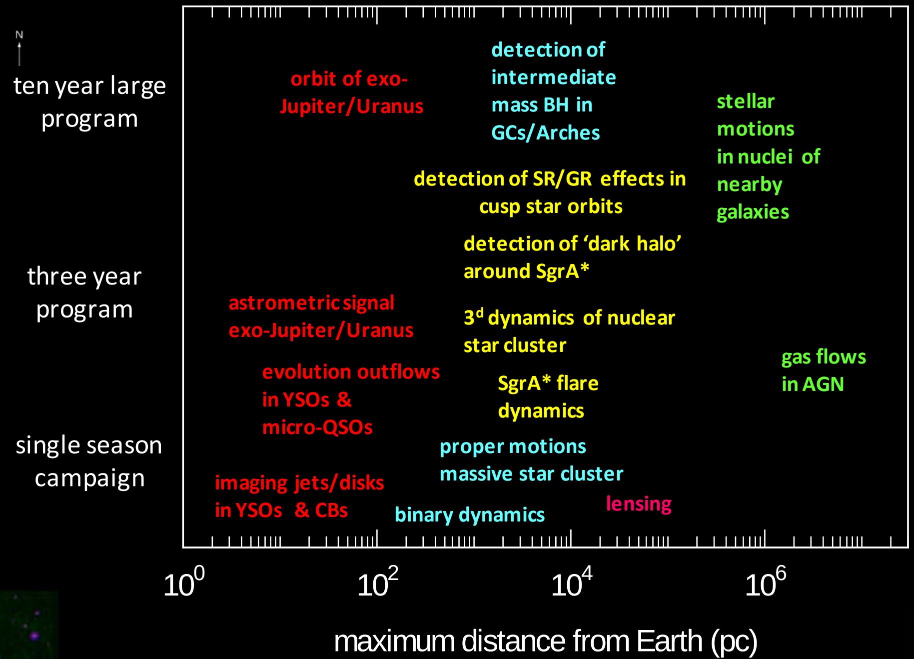
GRAVITY

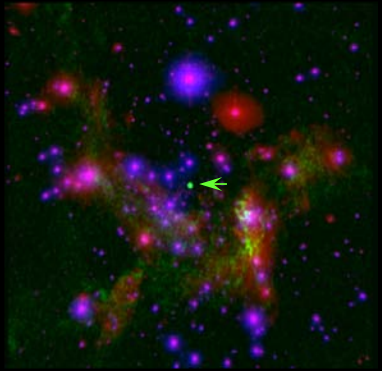
Frank Eisenhauer (Max-Planck-Institute for extraterrestrial Physics)
Ten Years of VLTI Conference, Garching, Germany, 26 October 2011

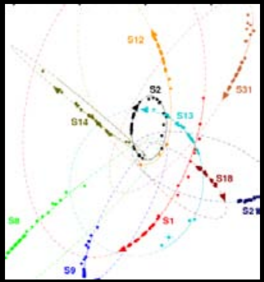
GRAVITY: Observing the Universe in Motion

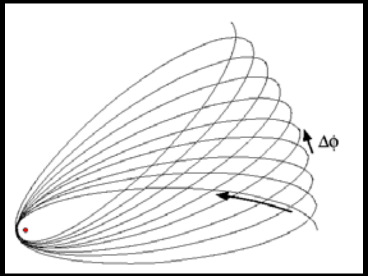


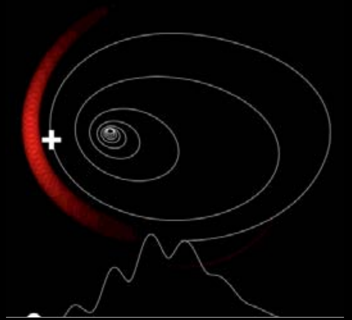












GRAVITY: Observing the Universe in Motion

GRAVITY: Observing the Universe in Motion

Frank Eisenhauer[1]
Guy Perrin[2,10]
Wolfgang Brandner[3]
Christian Straubmeier[4]
Karine Perraut[5]
António Amorim[6]
Markus Schöller[9]
Stefan Gillessen[1]
Pierre Kervella[2,10]
Myriam Benisty[3]
Constanza Araujo-Hauck[4]
Laurent Jocou[5]
Jorge Lima[6]
Gerd Jakob[9]
Marcus Haug[1]
Yann Clénet[2,10]
Thomas Henning[3]
Andreas Eckart[4]
Jean-Philippe Berger[5,9]
Paulo Garcia[6]
Roberto Abuter[9]
Stefan Kellner[1]
Thibaut Paumard[2,10]
Stefan Hippler[3]
Sebastian Fischer[4]
Thibaut Moulin[5]
Jaime Villate[6]
Gerardo Avila[9]
Alexander Gräter[1]
Sylvestre Lacour[2,10]
Armin Huber[3]
Michael Wiest[4]
Axelle Nolot[5]
Pedro Carvas[6]
Reinhold Dorn[9]
Oliver Pfuhl[1]
Eric Gendron[2,10]
Sarah Kendrew[3]
Senol Yazici[4]
Sonia Anton[6,8]
Yves Jung[9]
Markus Thiel[1]
Élodie Choquet[2,10]
Ralf Klein[3]
Paula Teixeira[6,9]
Philippe Gitton[9]
David Moch[1]
Frédéric Vincent[2,10]
Natalia Kudryavtseva[3]
Stefan Ströbele[9]
Eckhard Sturm[1]
Pierre Fédou[2,10]
Rainer Lenzen[3]
Paul Jolley[9]
Clemens Kister[1]
Vincent Lapeyrère[2,10]
Vianak Naranjo[3]
Christian Lucuix[9]
Reiner Hofmann[1]
Frédéric Chapron[2,10]
Udo Neumann[3]
Leander Mehrgan[9]
Oliver Hans[1]
Gérard Rousset[2,10]
Jose Ramos[3]
Marcos Suarez[9]
Reinhard Lederer[1]
Jean-Michel Reess[2,10]
Ralf-Rainer Rohloff[3]
Pierre Haguenauer[9]
Hendrik Bartko[1]
Arnaud Sevin[2,10]
Karl Wagner[3]
Jean-Louis Lizon[9]
Sebastian Rabien[1]
Claude Collin[2,10]
Gert Finger[9]
Richard Davies[1]
Daniel Rouan[2,10]
Markus Wittkowski[9]
Katie Dodds-Eden[1]
Denis Ziegler[2,10]
Frédéric Cassaing[7,10]
Henri Bonnet[9]
Mark Casali[9]
Reinhard Genzel[1]
Pierre Lena[2]

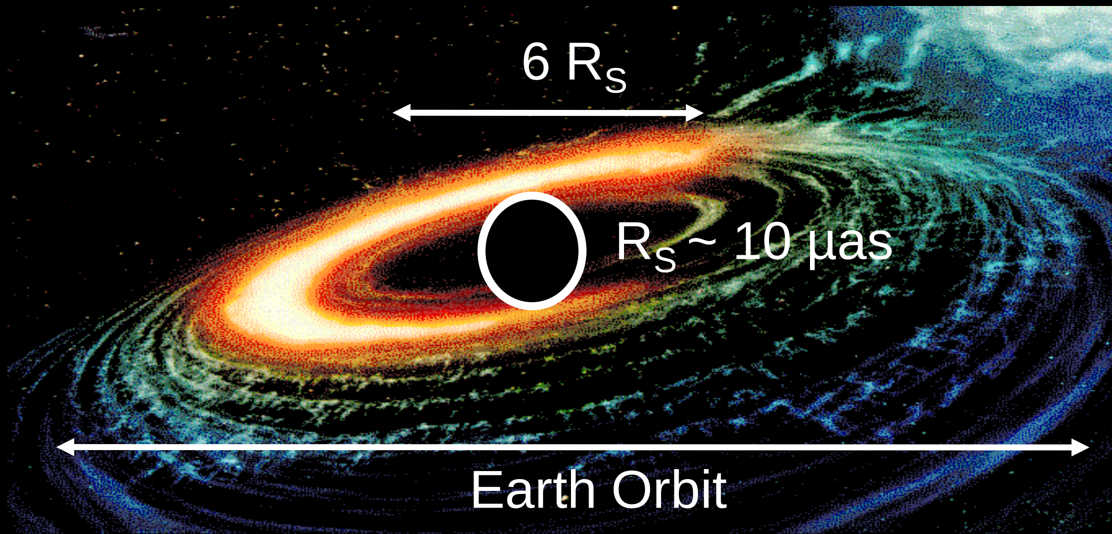
1 Max-Planck Institute for Extraterrestrial Physics, Garching, Germany
2 LESIA, Observatoire de Paris, CNRS, UPMC, Université Paris Diderot, Meudon, France
3 Max-Planck Institute for Astronomy, Heidelberg, Germany
4 Physikalisches Institut, University of Cologne, Germany
5 UJF–Grenoble 1/CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble, France
6 Laboratório de Sistemas, Instrumentação e Modelação em Ciências e Tecnologias do Ambiente e do Espaço (SIM), Lisbon and Porto, Portugal
7 ONERA, Optics Department (DOTA), Châtillon, France
8 Centro de Investigação em Ciências Geo-Espaciais, Porto, Portugal
9 ESO
10 Groupement d'Intérêt Scientifique PHASE (Partenariat Haute résolution Angulaire Sol Espace) between ONERA, Observatoire de Paris, CNRS and Université Paris Diderot

GRAVITY is the second generation Very Large Telescope Interferometer instrument for precision narrow-angle astrometry and interferometric imaging. With its fibre-fed integrated optics, wavefront sensors, fringe tracker, beam stabilisation and a novel metrology concept, GRAVITY will push the sensitivity and accuracy of astrometry and interferometric imaging far beyond what is offered today. Providing precision astrometry of order 10 microarcseconds, and imaging with 4-milliarcsecond resolution, GRAVITY will revolutionise dynamical measurements of celestial objects: it will probe physics close to the event horizon of the Galactic Centre black hole; unambiguously detect and measure the masses of black holes in massive star clusters throughout the Milky Way; uncover the details of mass accretion and jets in young stellar objects and active galactic nuclei; and probe the motion of binary stars, exoplanets and young stellar discs. The instrument capabilities of GRAVITY are outlined and the science opportunities that will open up are summarised.

Fundamental measurements over a wide range of fields in astrophysics

Much as long-baseline radio interferometry has tone, GRAVITY infrared (IR) astrometry, with an accuracy of order 10 microarcseconds and phase-referenced imaging with 4-milliarcsecond resolution, will bring a number of key advances (Eisenhauer et al., 2008). GRAVITY will carry out the ultimate empirical test to show whether or not the Galactic Centre harbours a black hole (BH) of four million solar masses and will finally decide if the near-infrared flares from Sgr A* originate from individual hot spots close to the last stable orbit, from statistical fluctuations in the inner accretion zone or from a jet. If the current hot-spot interpretation of the near-infrared (NIR) flares is correct, GRAVITY has the potential to directly determine the spacetime metric around this BH. GRAVITY may even be able to test the theory of general relativity in the presently unexplored strong field limit. GRAVITY will also be able to unambiguously detect intermediate mass BHs, if they exist. It will dynamically measure the masses of supermassive

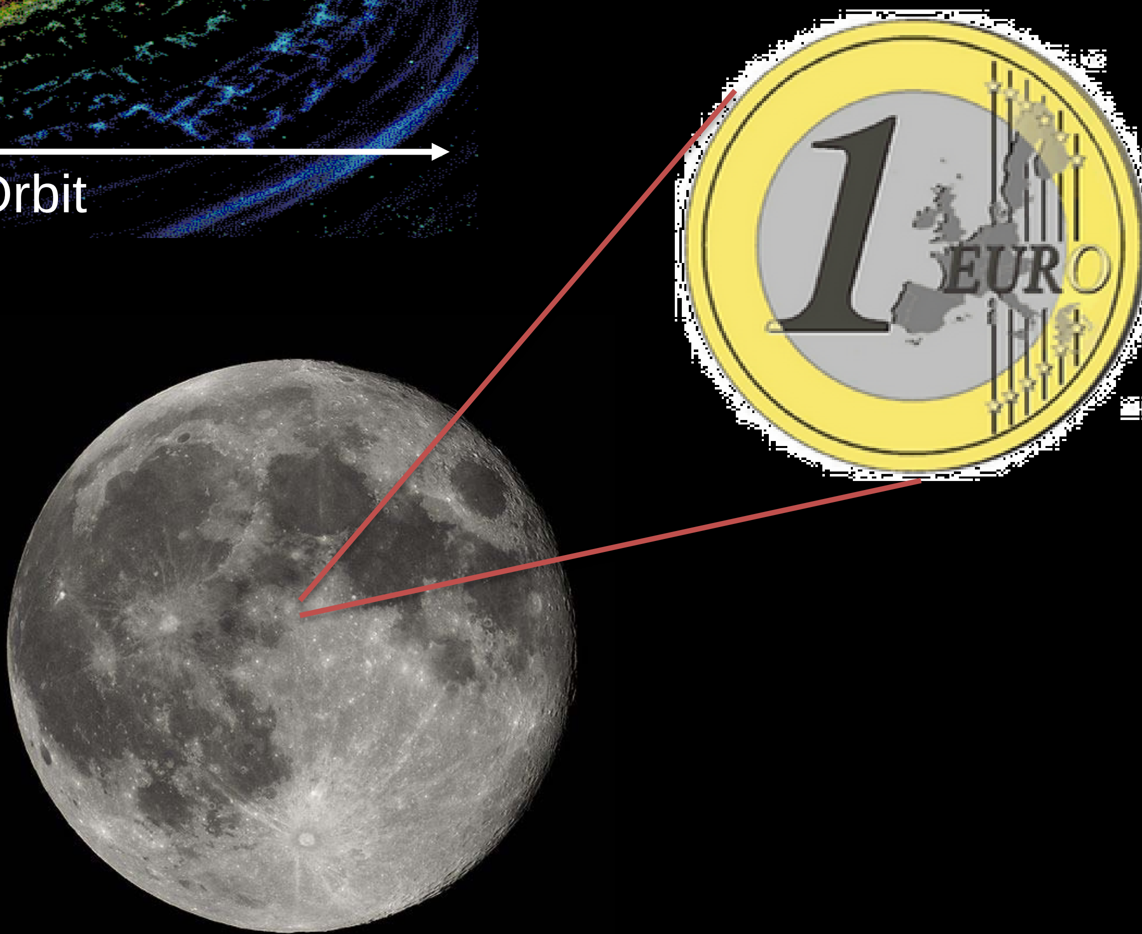
Setting the Scale – just to scare …



1 Schwarzschild radius

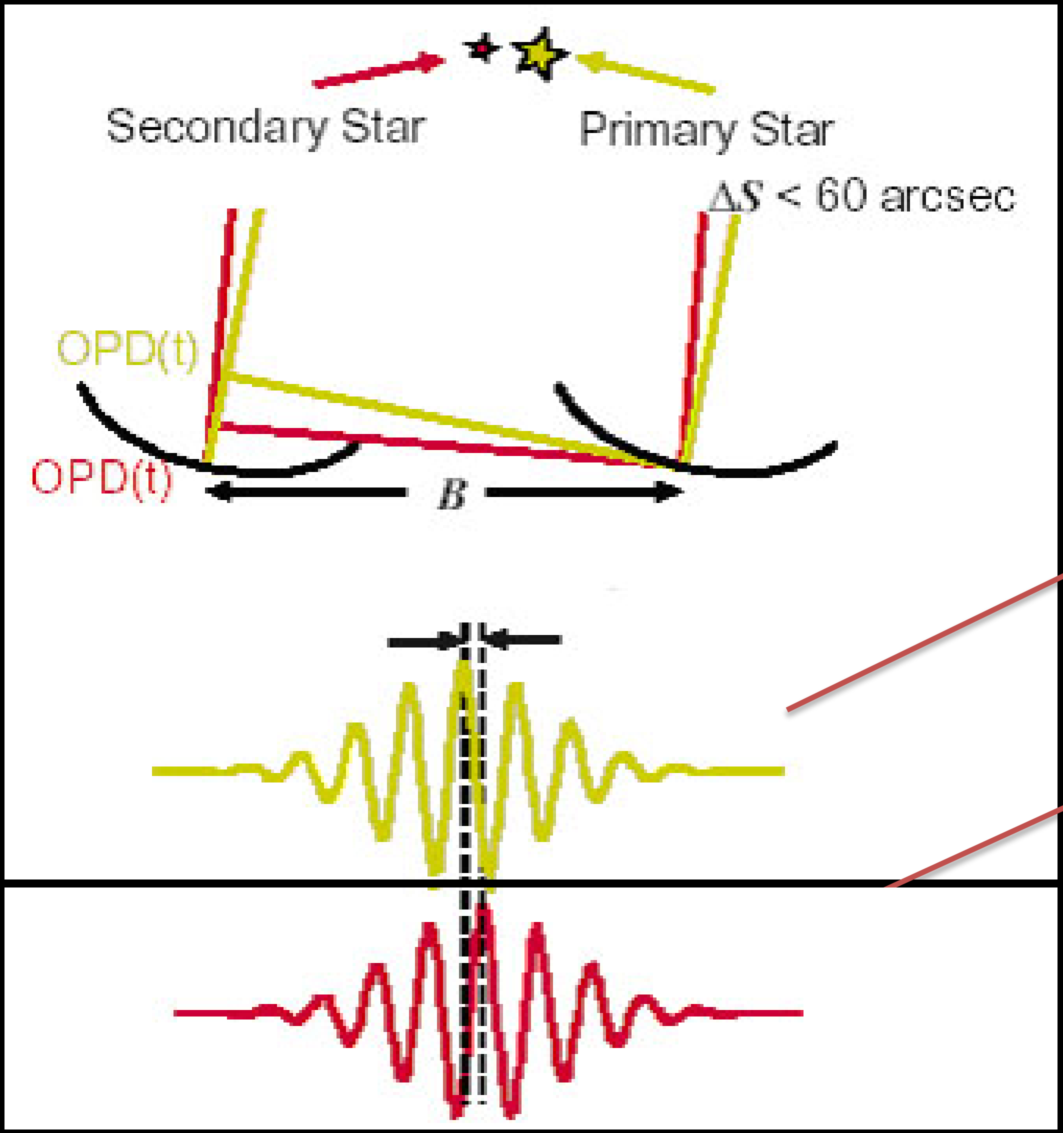
=

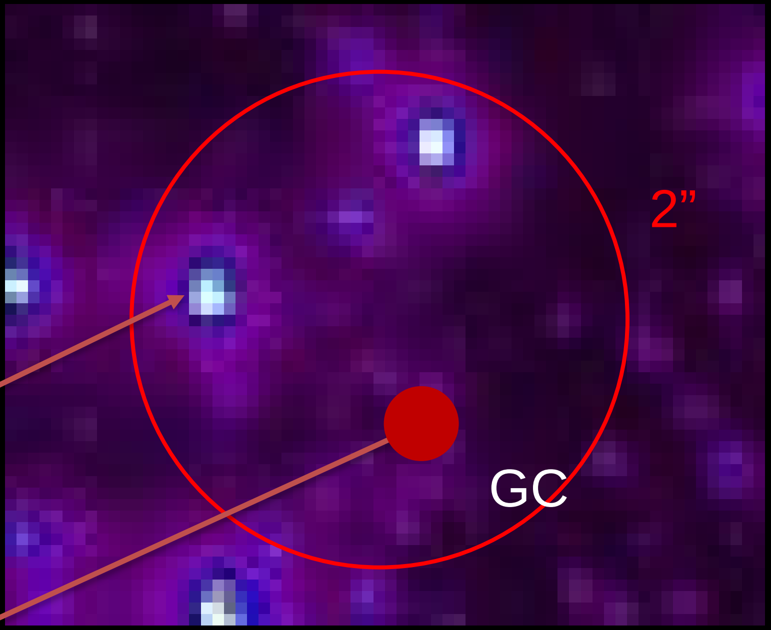
a coin on the moon



Phase Referenced Imaging & Astrometry

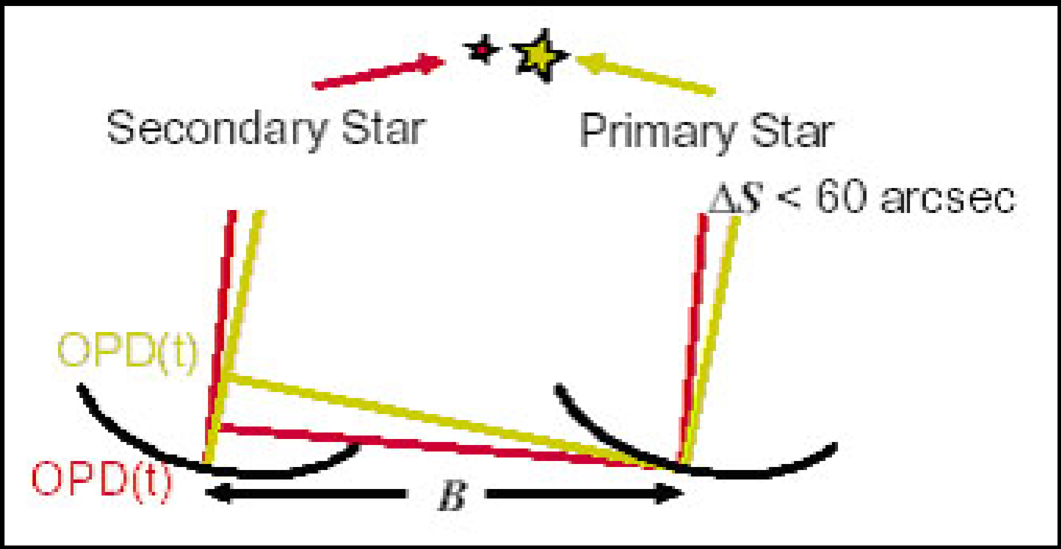
$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$

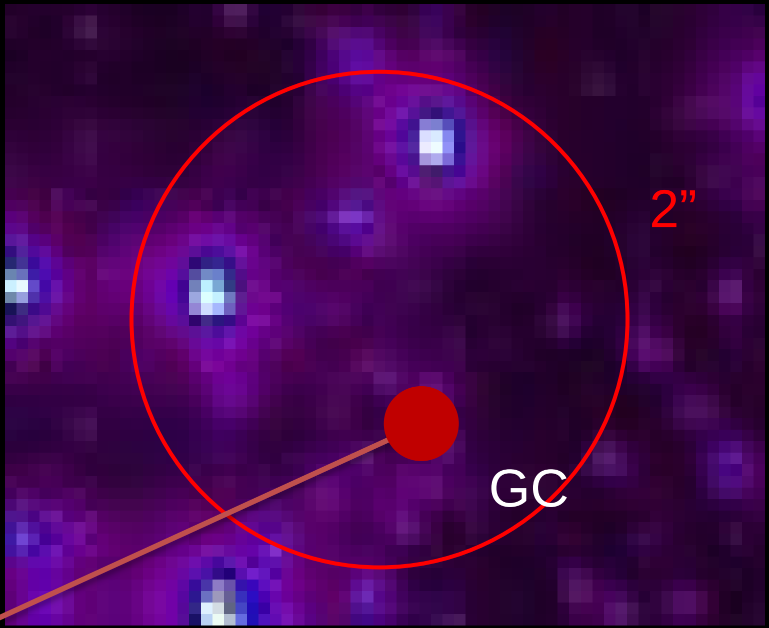


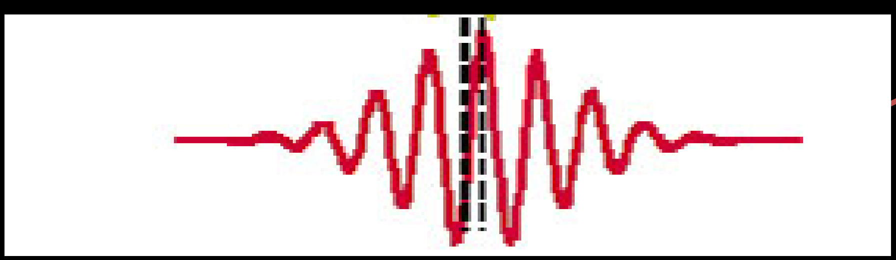


Phase Referenced Imaging & Astrometry

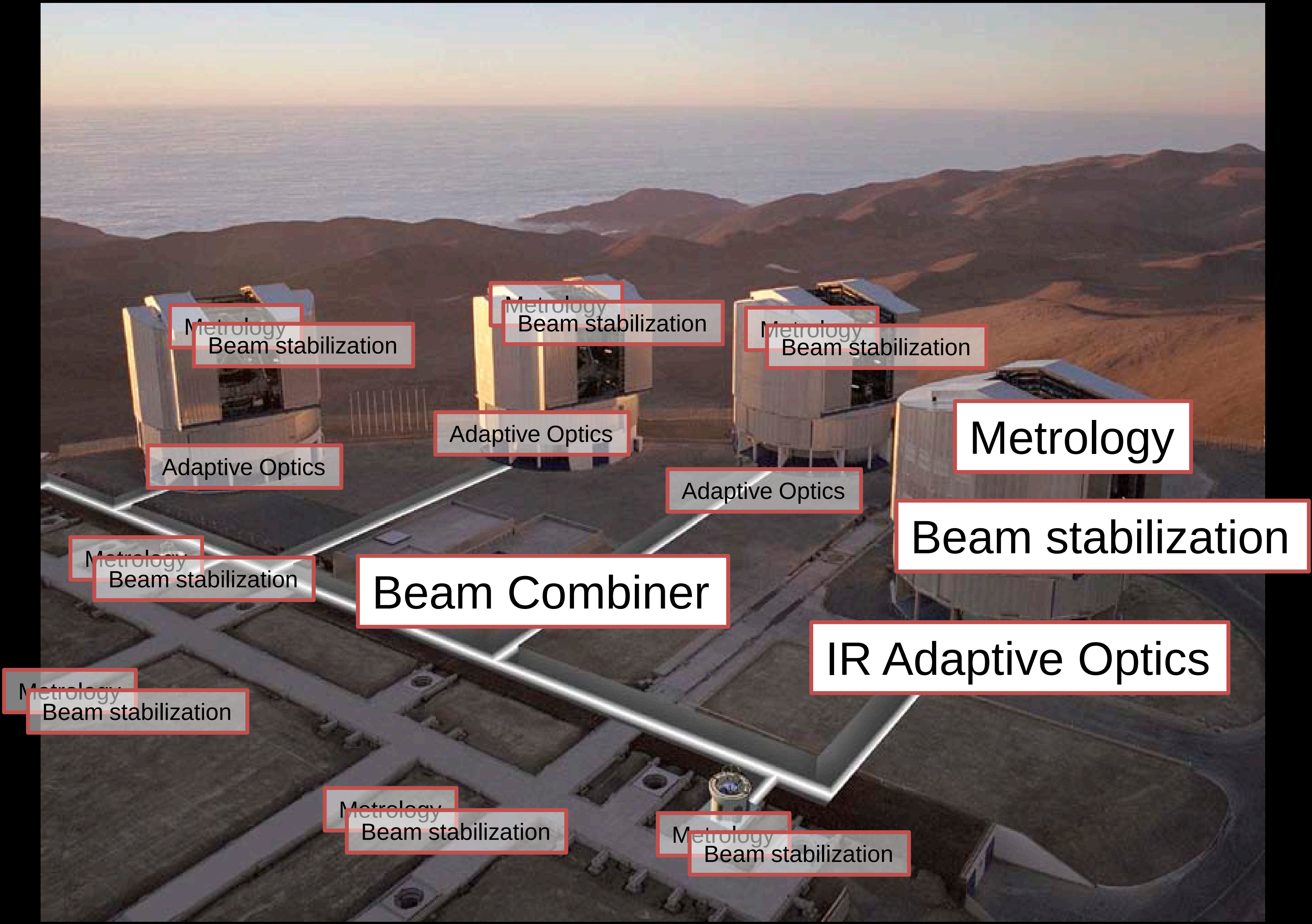
Contrast (B) <-> FourierTransform (Image)



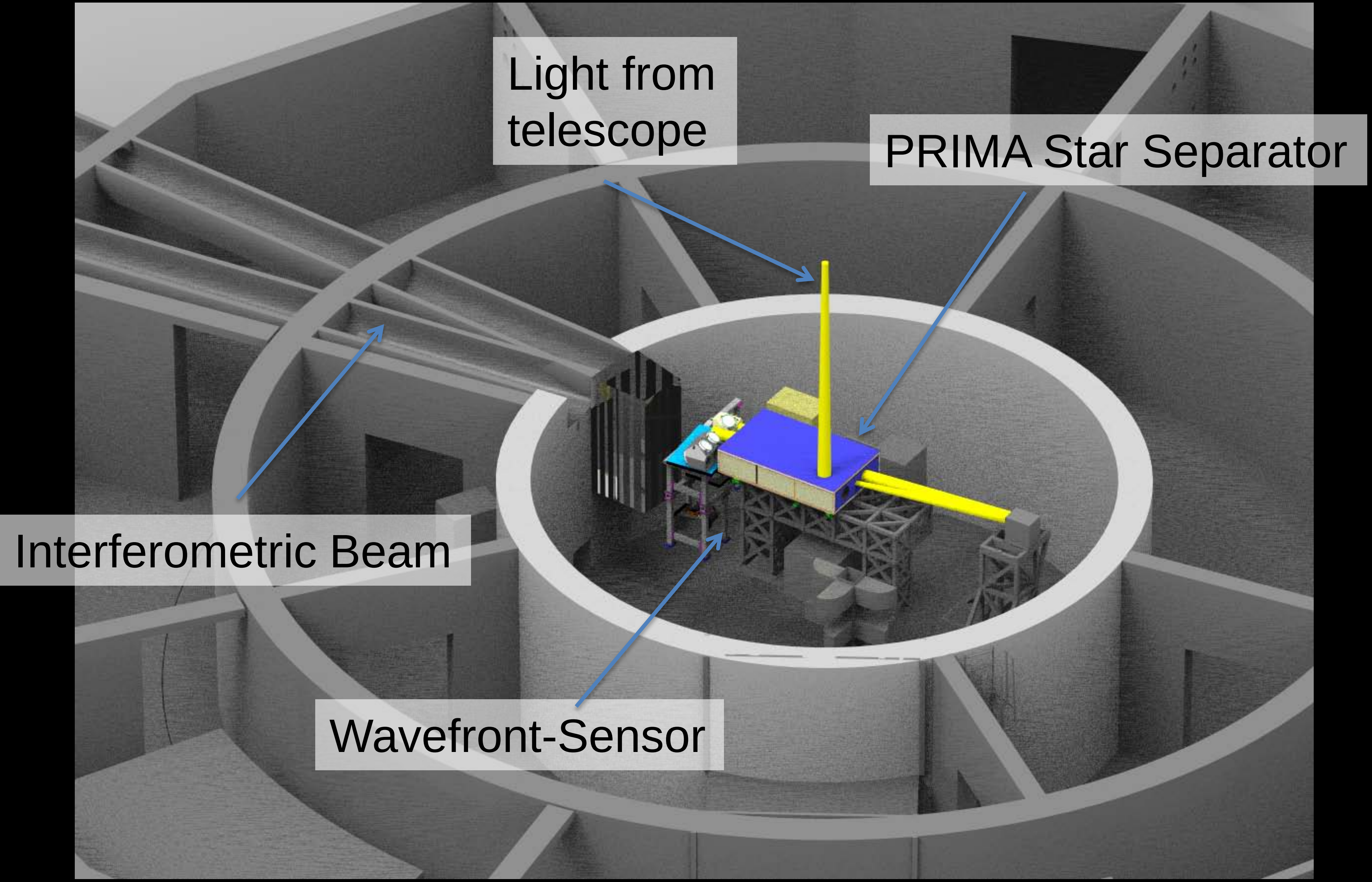




GRAVITY Astrometry & Imaging



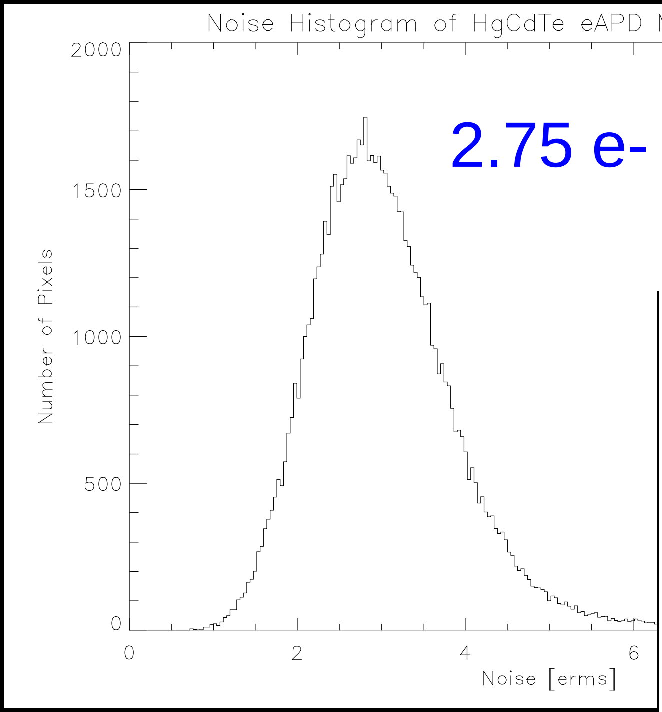
Adaptive Optics



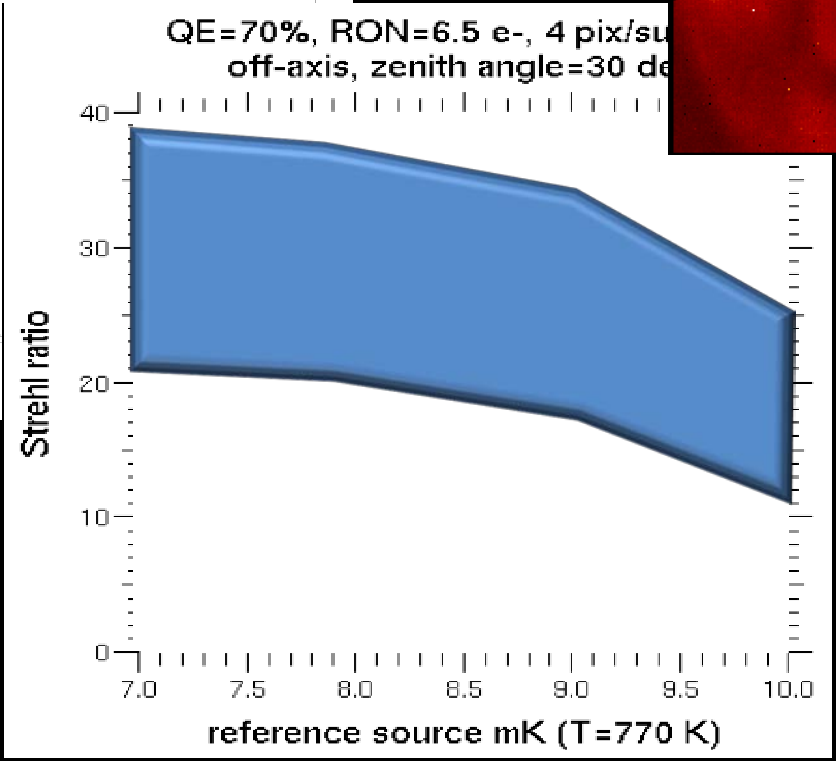
Brander, Hippler et al., Clenet et al. 2010

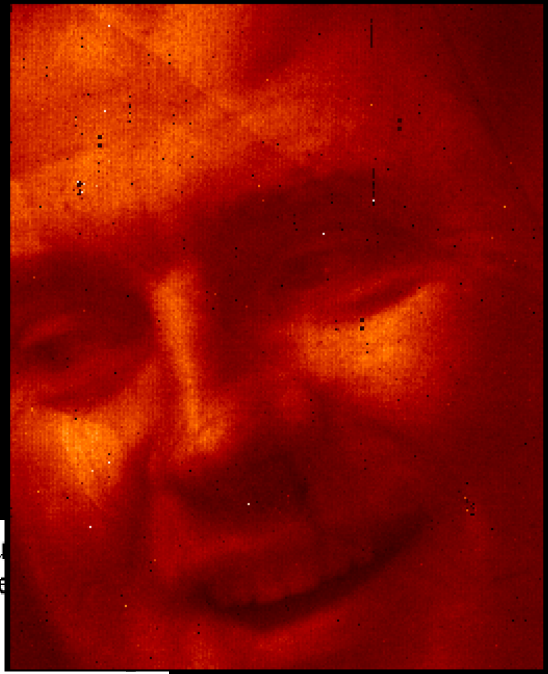
Adaptive Optics and Fringe Tracking Detectors

SELEX / ESO development of Infrared Avalanche Photo Diode array:



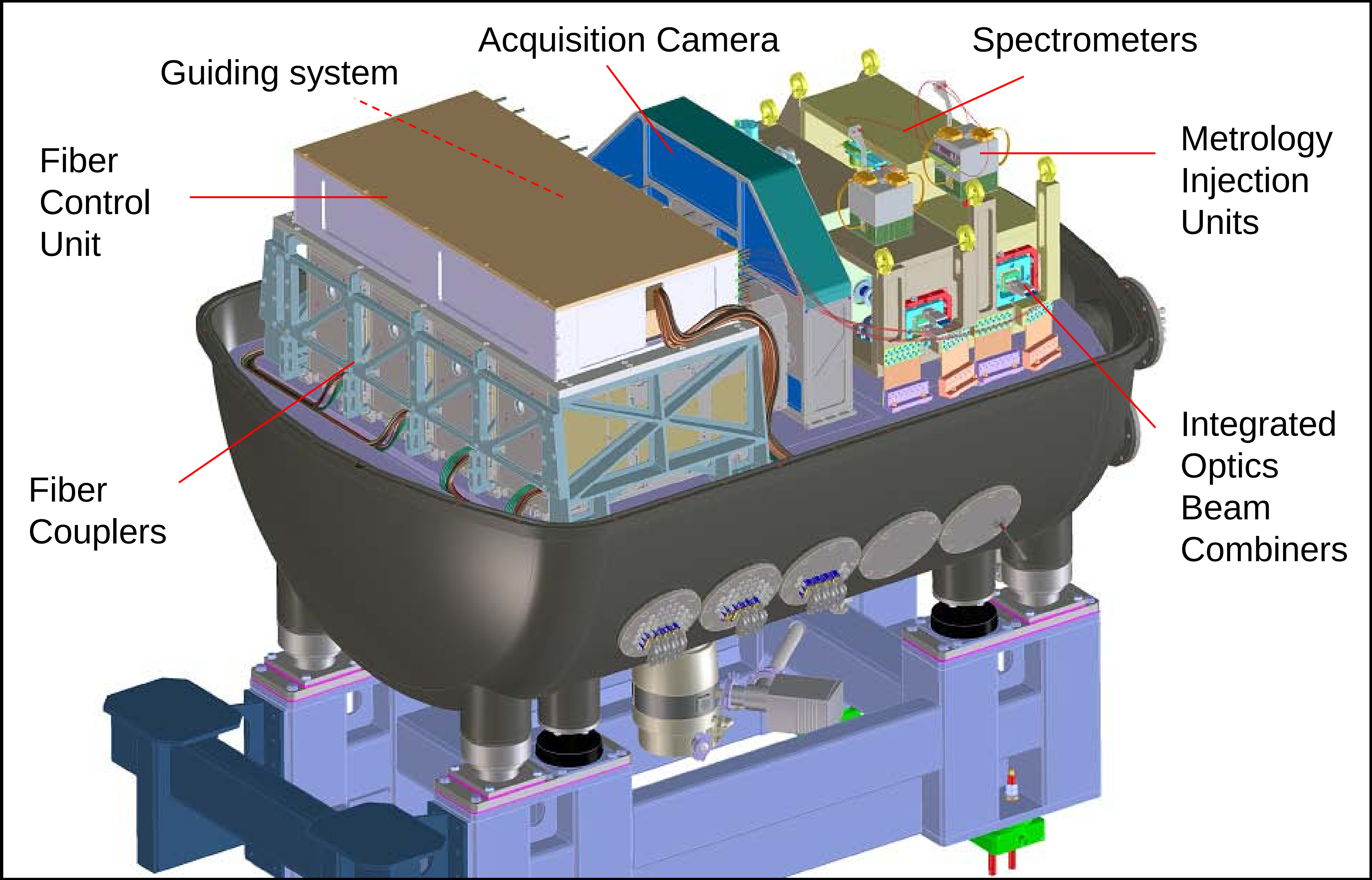
Finger et al. 2010





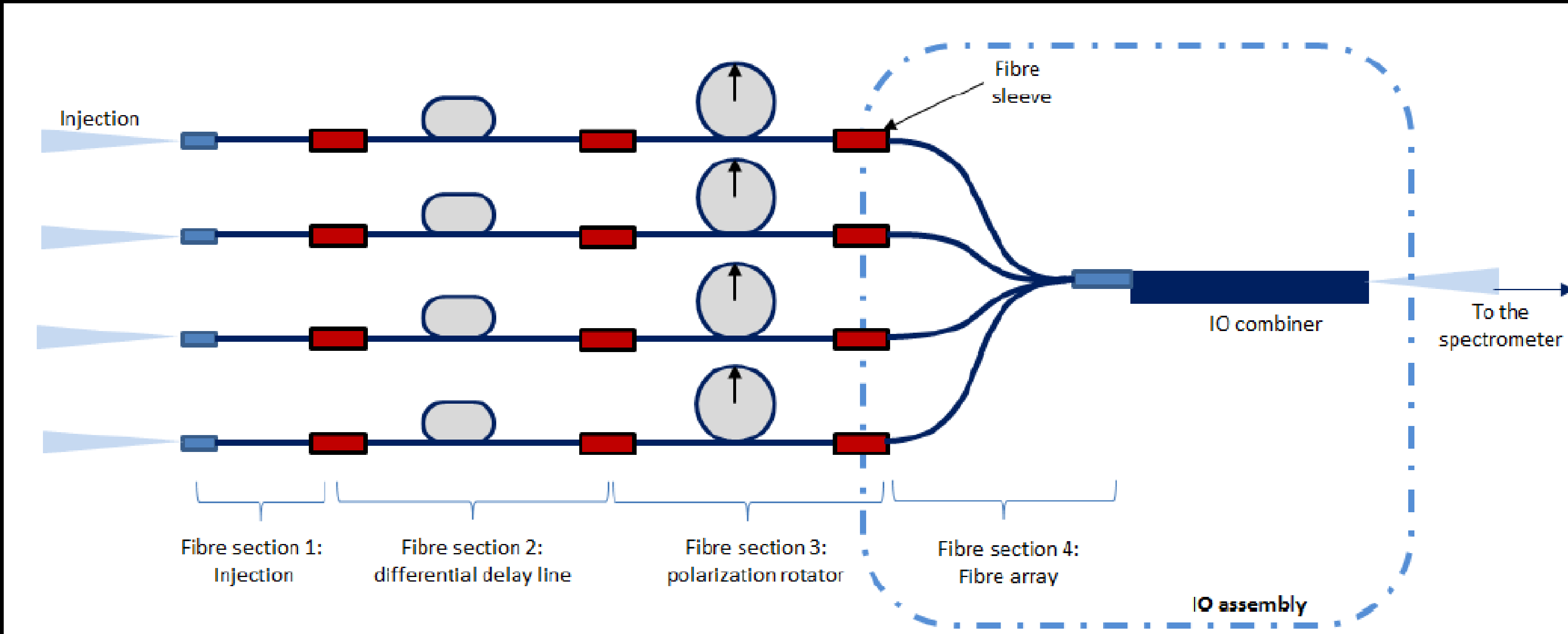
Brander, Hippler et al., Clenet et al. 2010

Beam Combiner Instrument



Haug, Thiel et al.

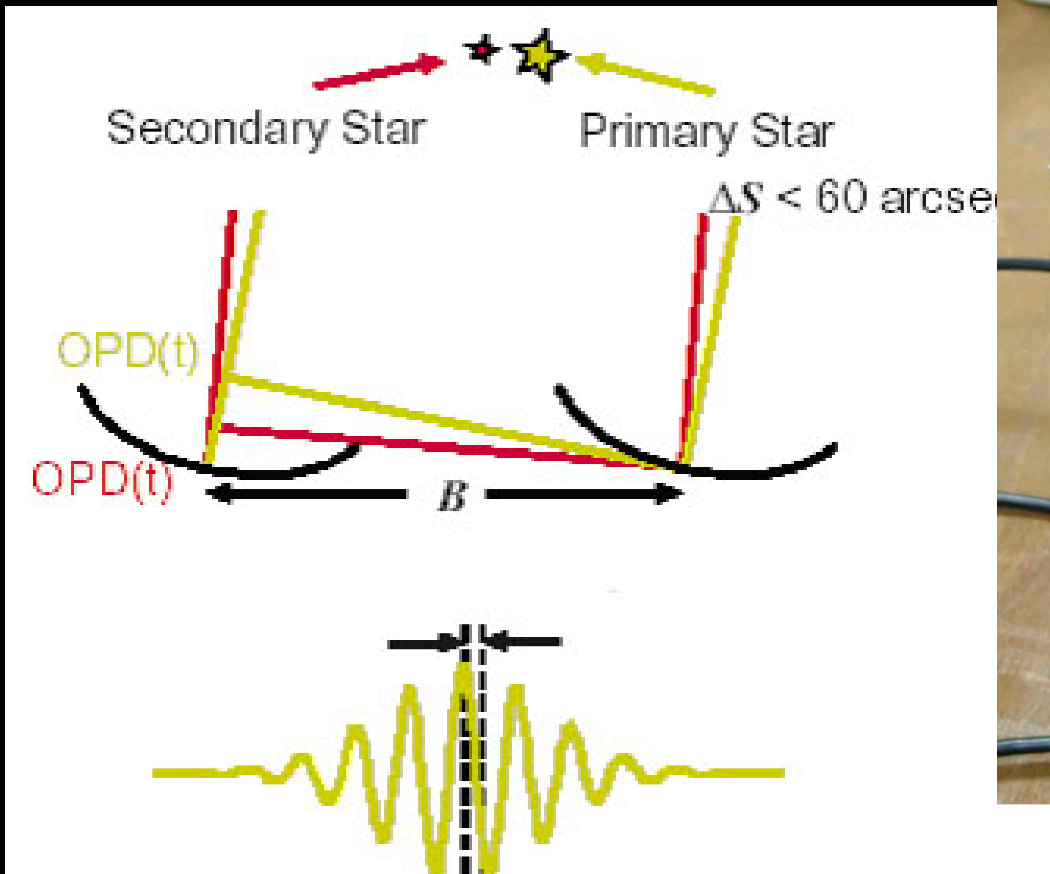
Single Mode Instrument

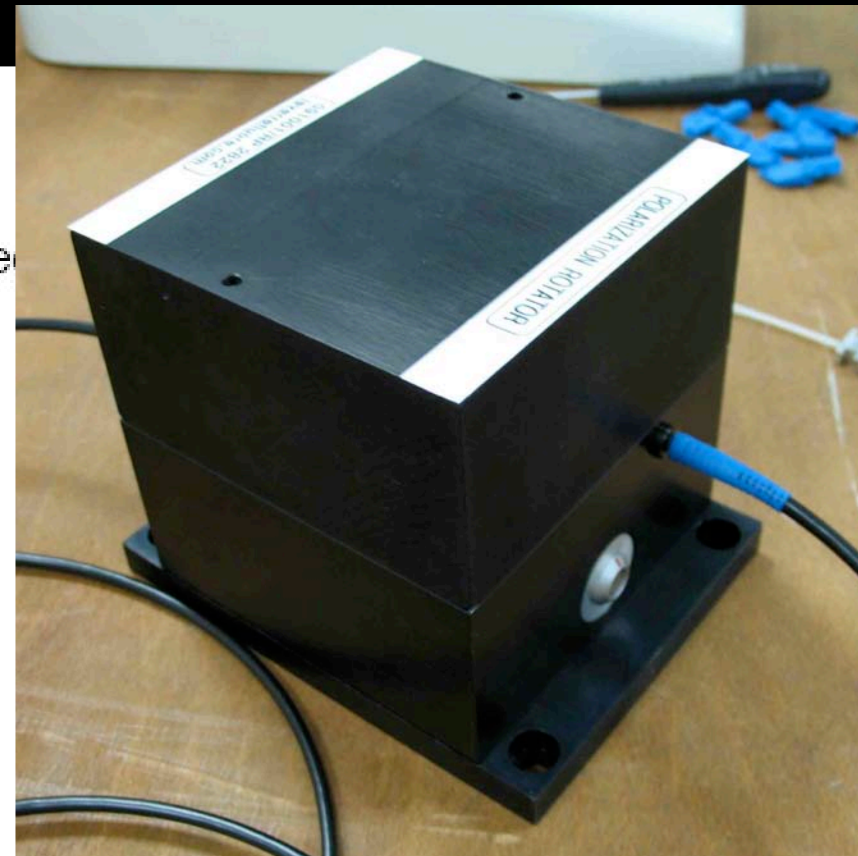


Fluoride glass fibers (OHANA)
- optimum throughput in K-band
- possibility to measure in unpolarized light = sensitivity

Perrin, Perraut, Jacou et al.

Fiber control

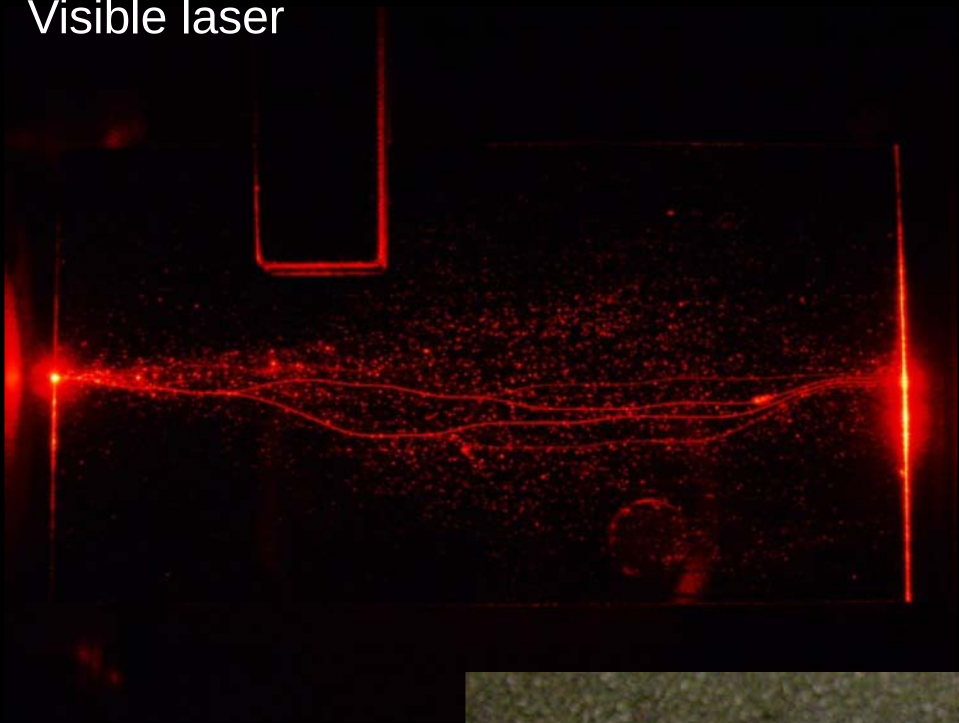




Perrin et al.

Integrated Optics

Visible laser

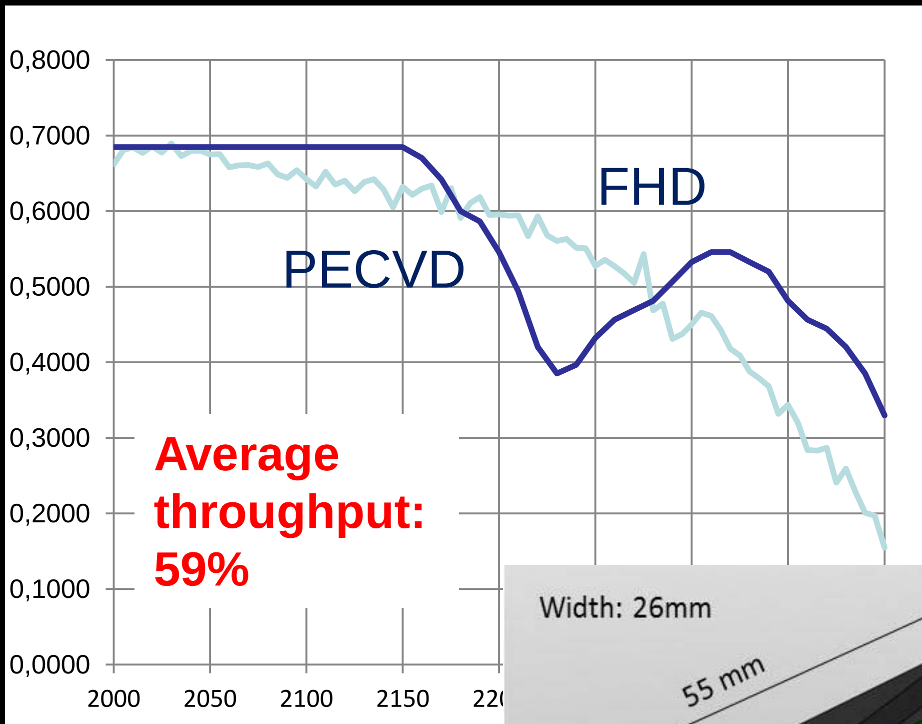


Optical equivalent of electronic integrated circuits

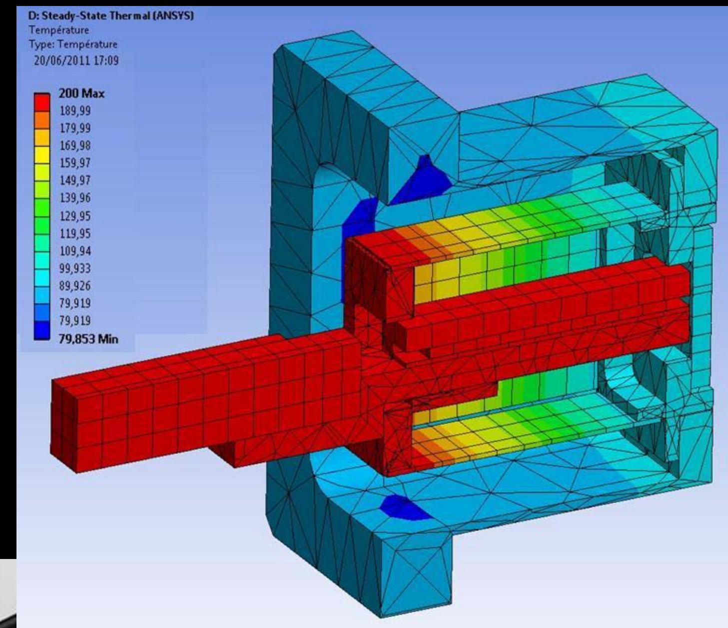
Jacou et al. 2010, Perraut et al.

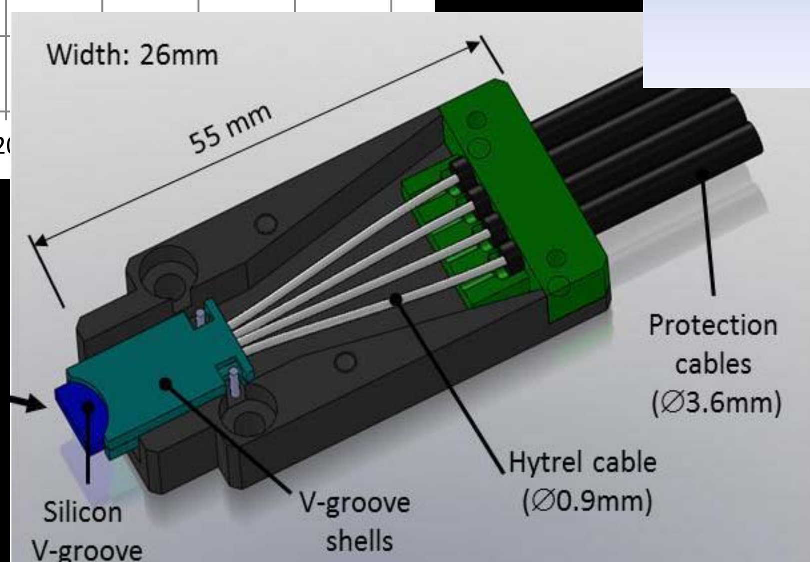
Integrated Optics

K-band operation



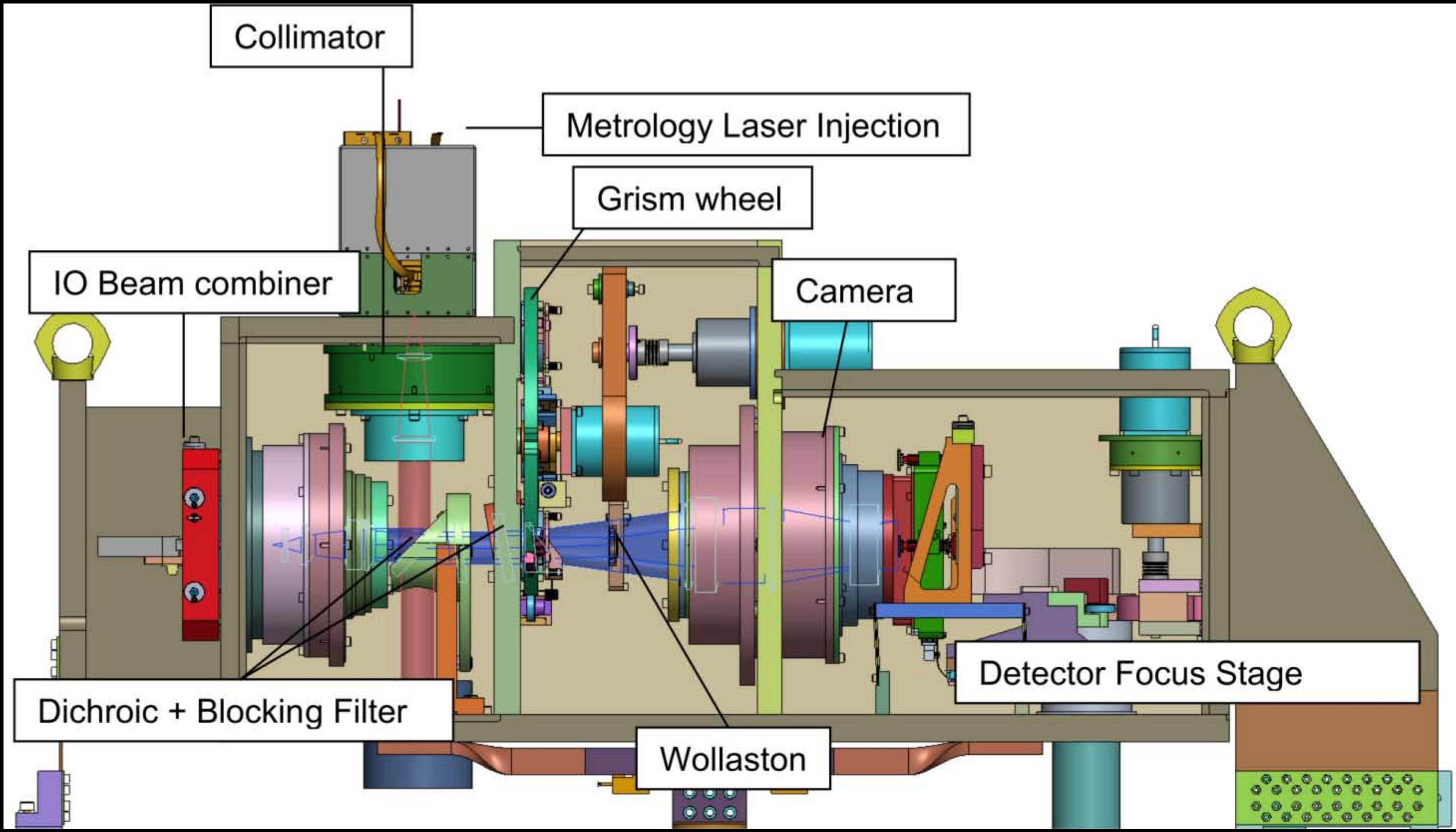
Cryogenic operation





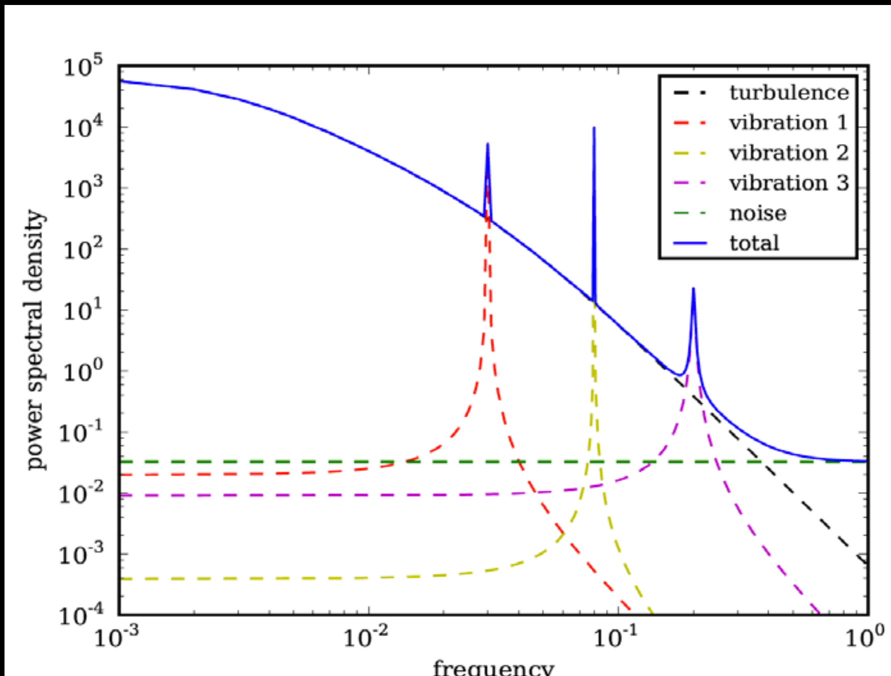
Jacou et al. 2010,
Perraut et al.

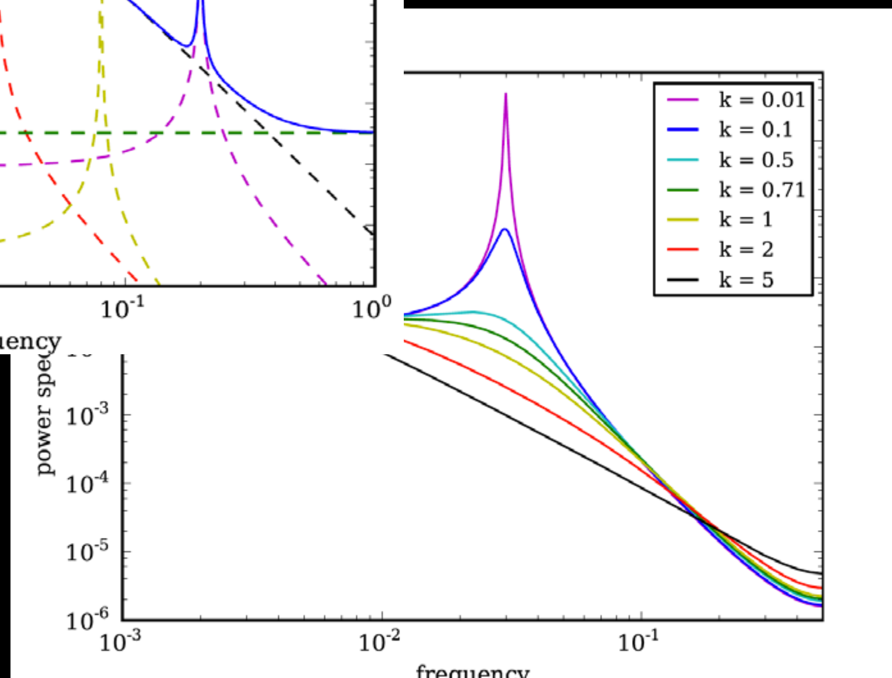
Spectrometers

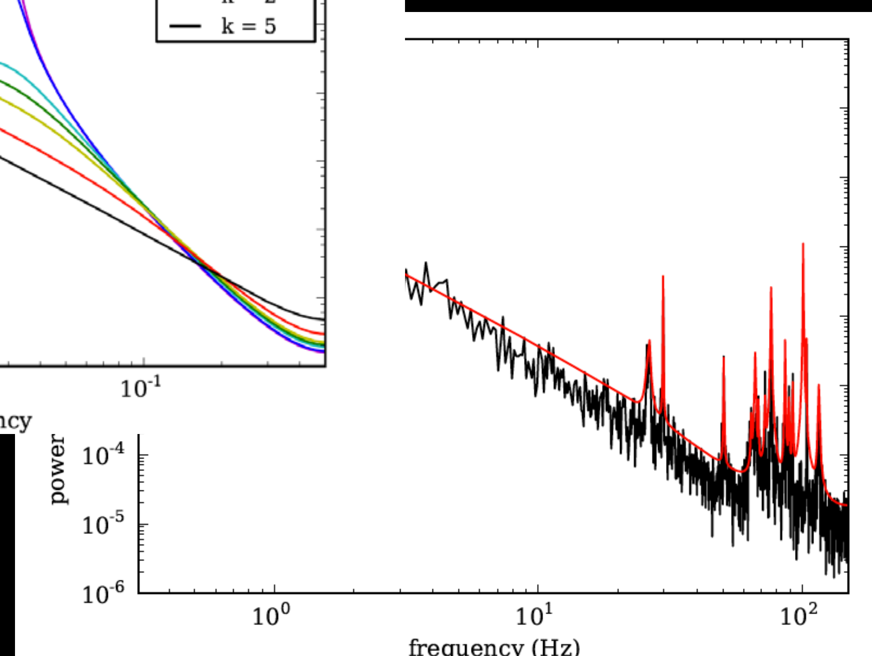


Straubmeier et al. 2010

Fringe Tracker – Kalmann Control



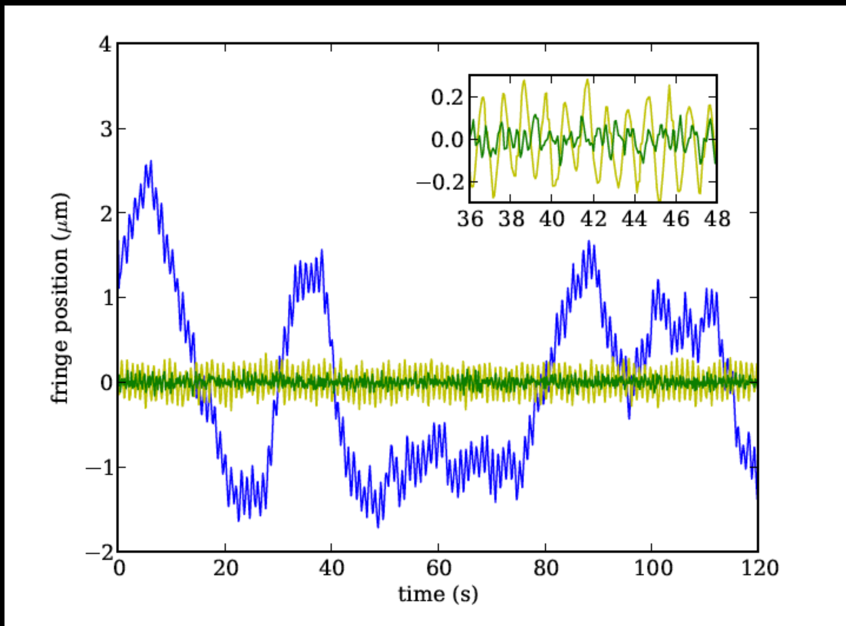


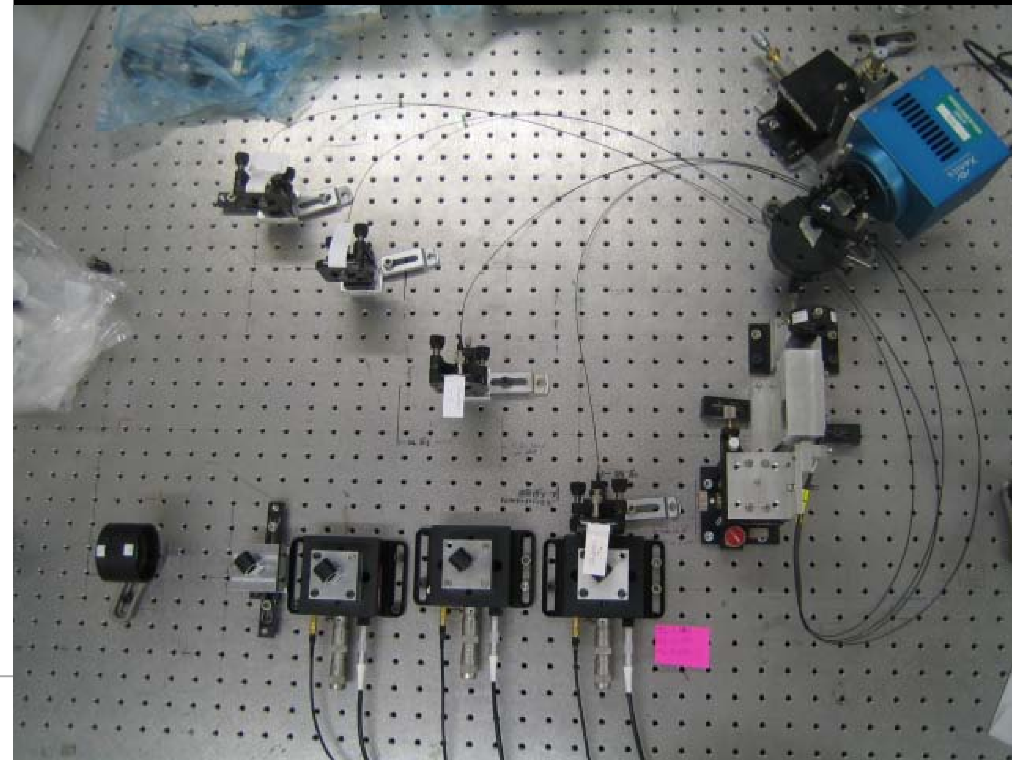


Menu, Choquet , Fedou,
Dembet, et al.

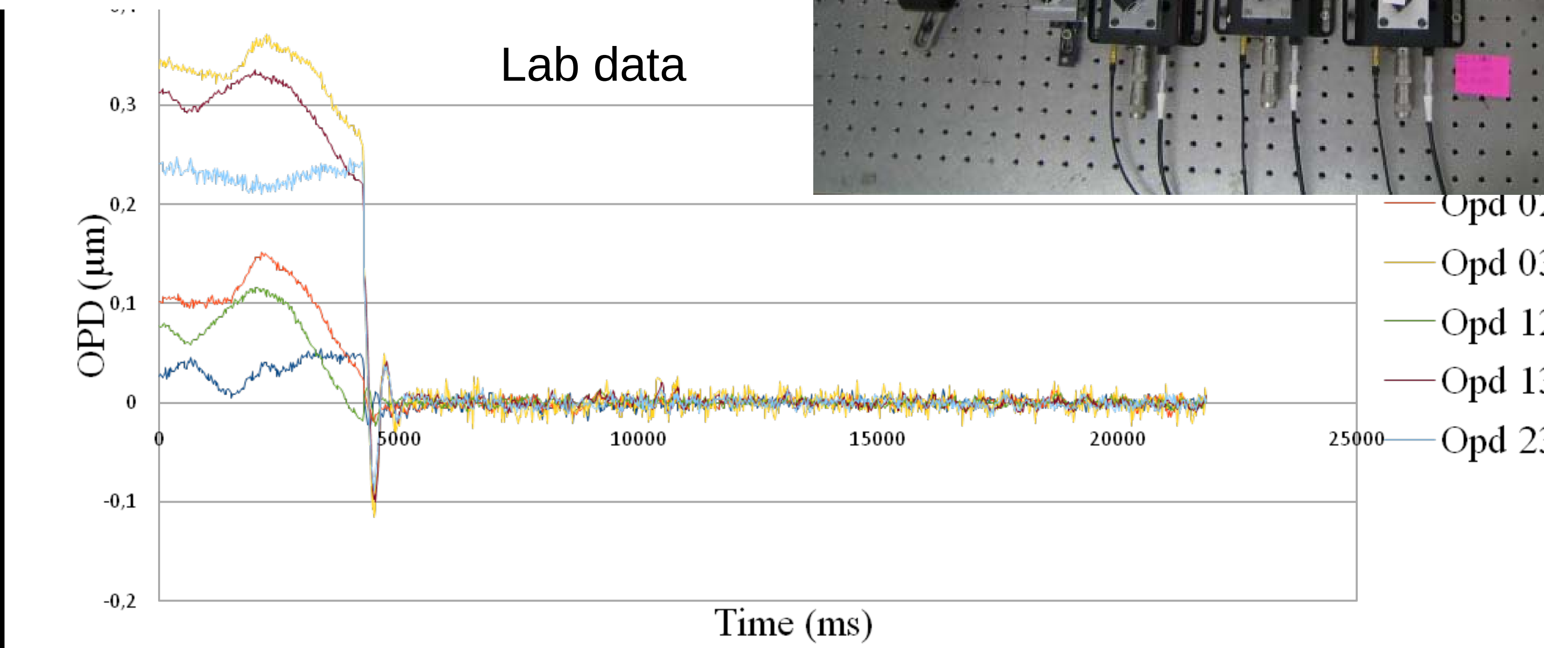
Fringe Tracker

Fringetracking testbed @ LESIA





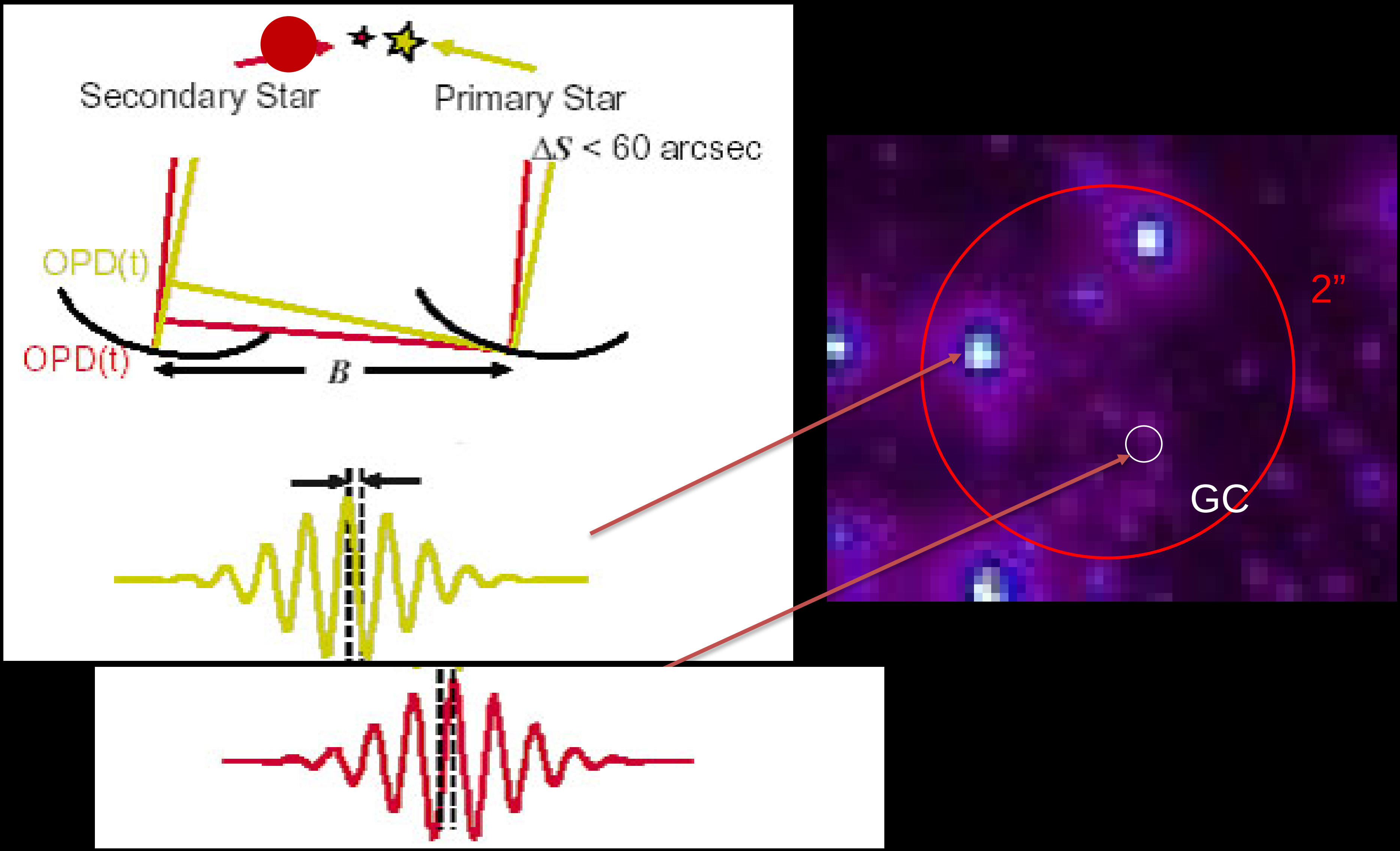
Lab data



Choquet et al. 2010

Narrow Angle Astrometry

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



Interferometric Astrometry

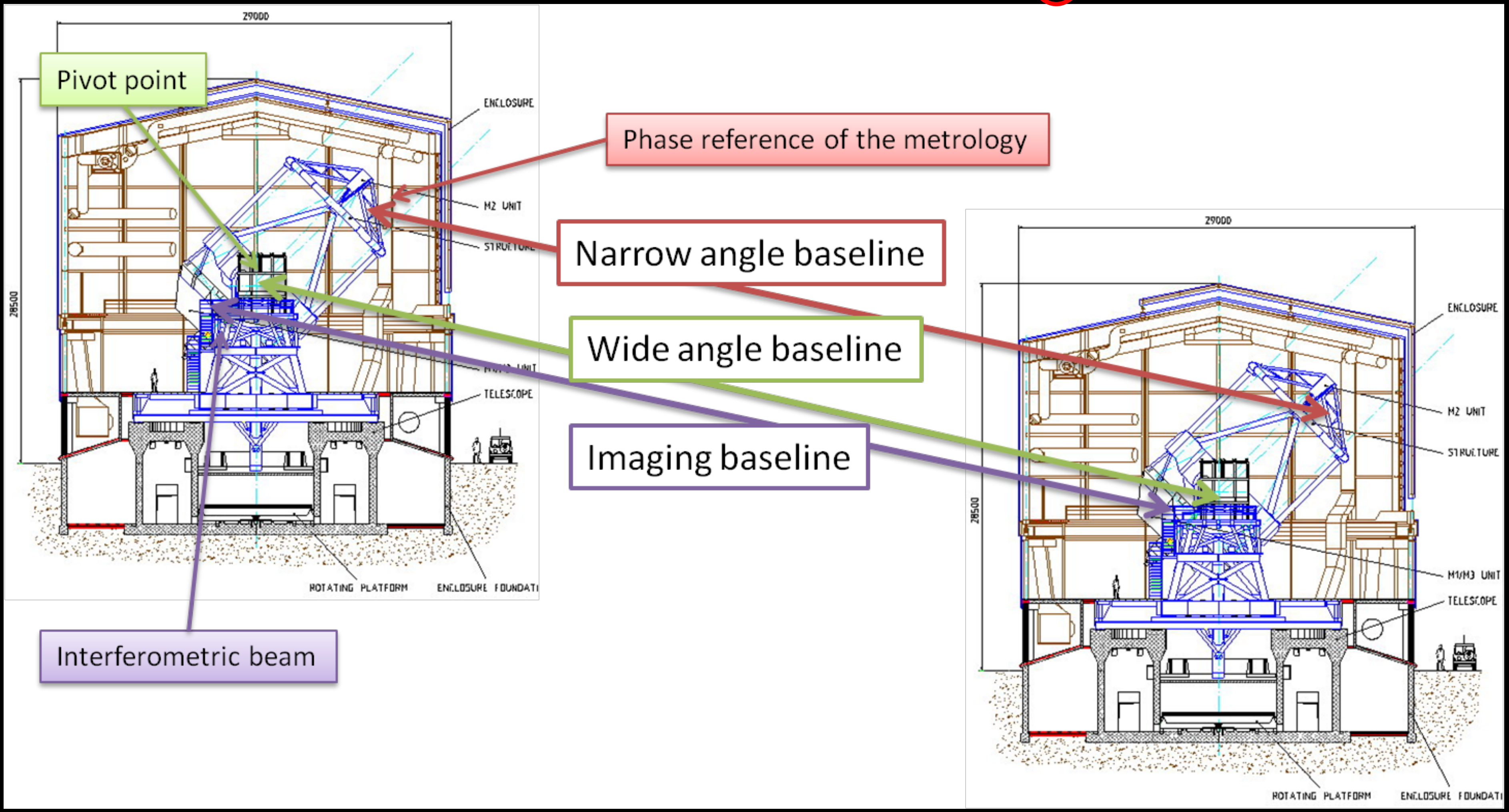
5 nm ←

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

500 µm 10 µas

Interferometric Baseline

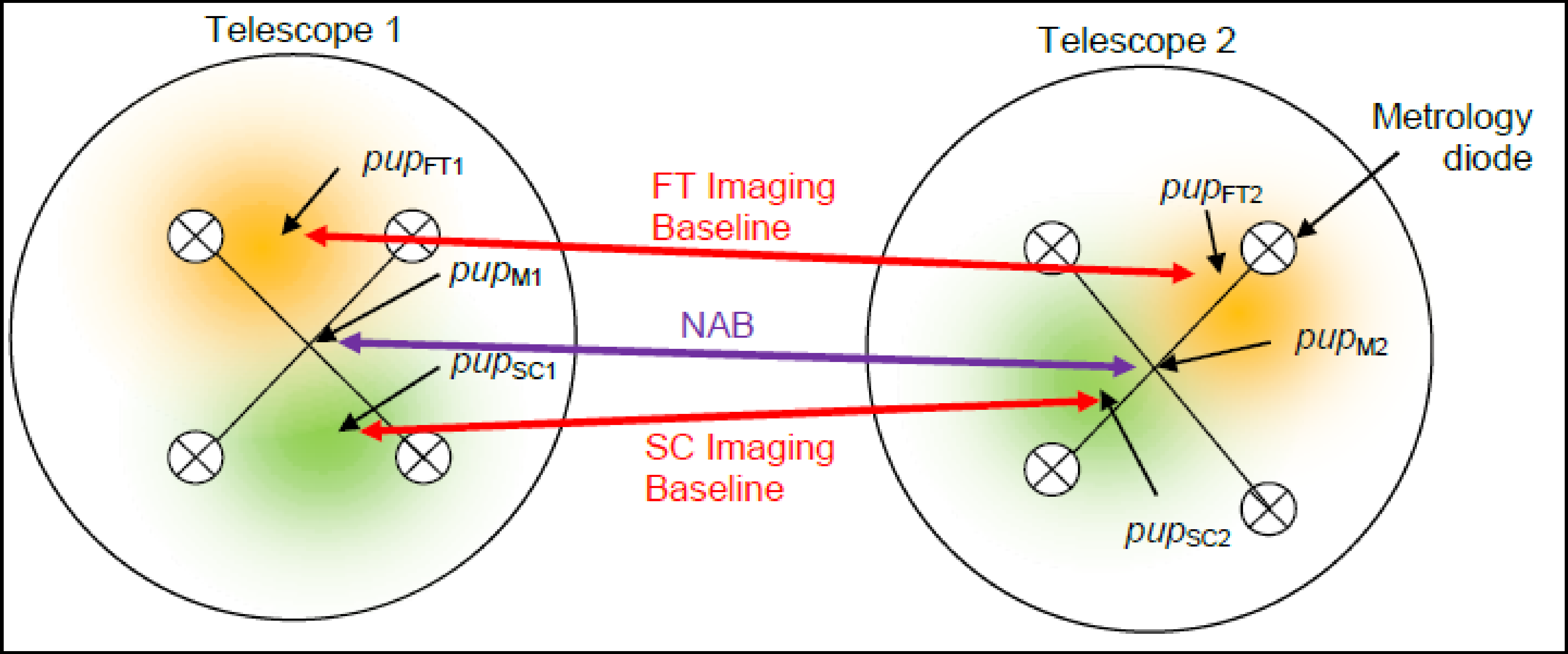
$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$



Lacour et al.

Interferometric Baseline

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



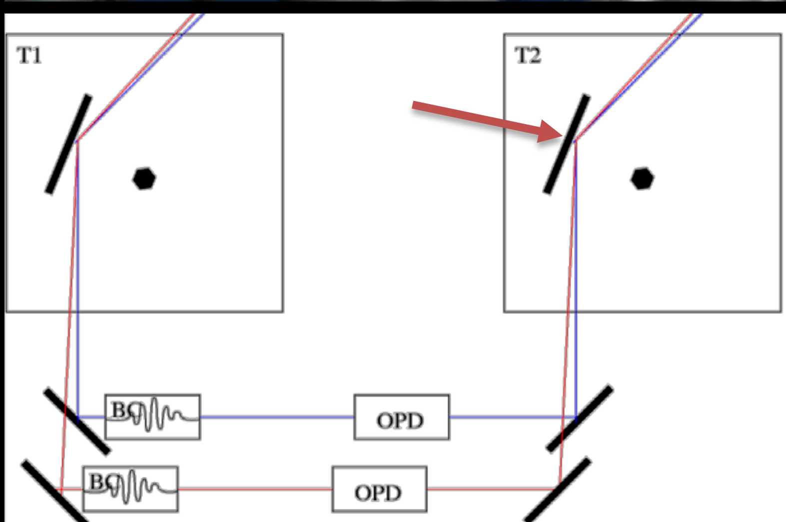
Lacour et al.

Narrow Angle Baseline

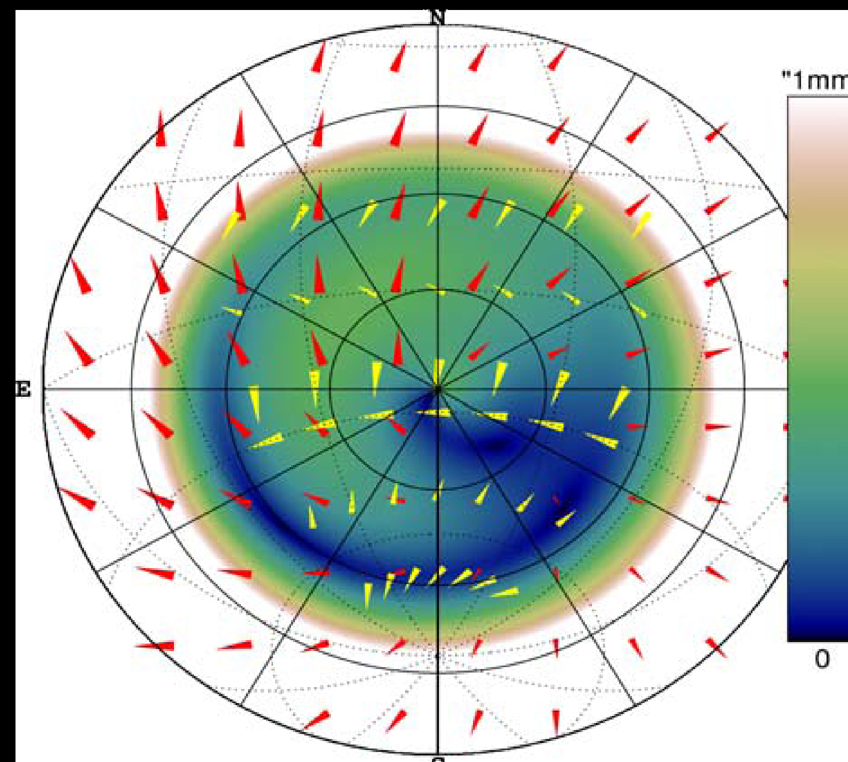
$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$

500 µm

Stable realization of the narrow angle baseline



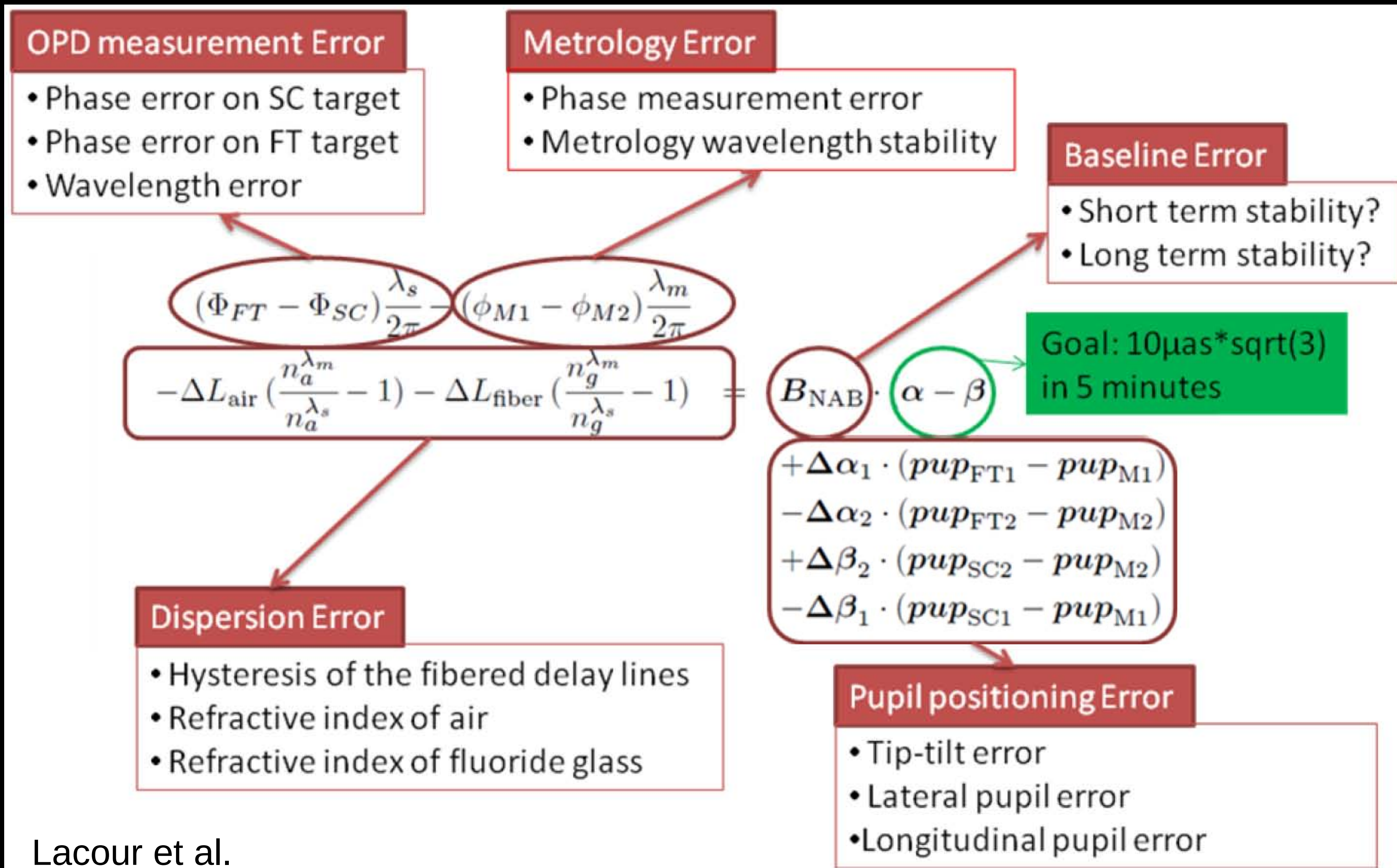
Calibration of the narrow angle baseline



Lacour, Kervella et al.

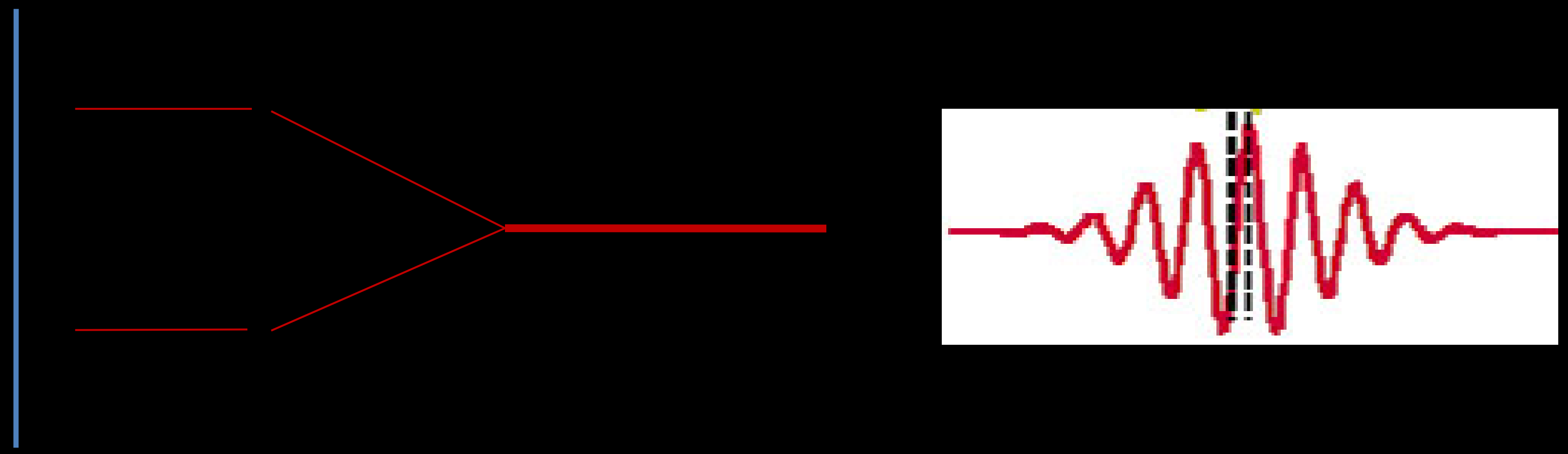
Interferometric Astrometry

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

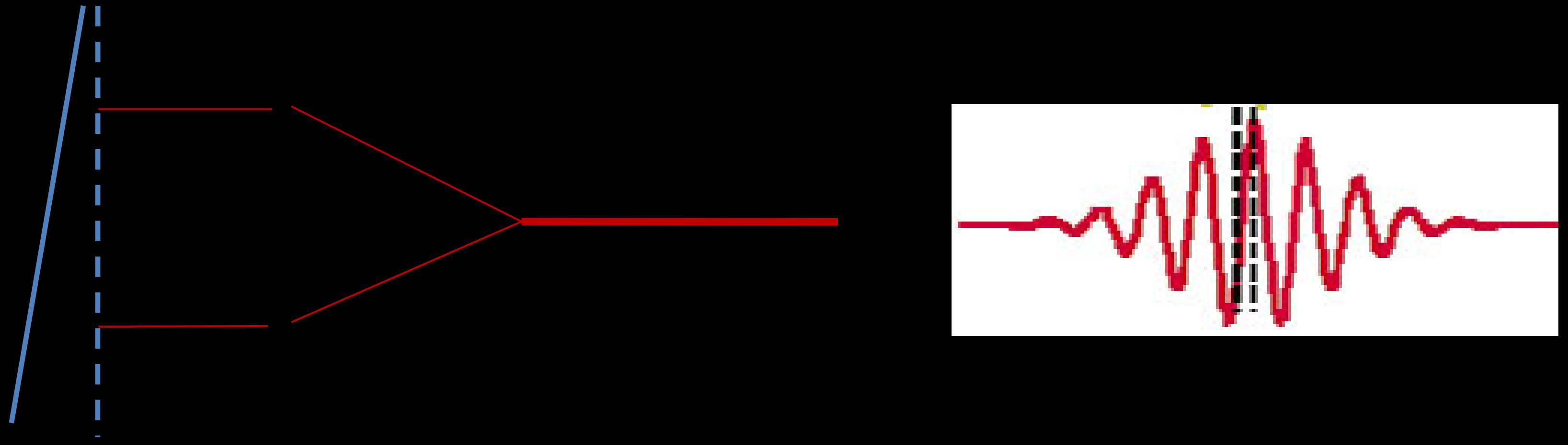


Pupil Errors

For perfect tip-tilt correction



For simultaneous tilt error



Interferometric Astrometry

FT/SC differential pupil error

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

Lateral pupil error

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

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

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

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

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

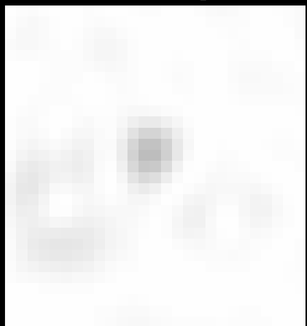
Control pupil such that fiber pupils are fixed on metrology reference

Minimize Tip/Tilt and guiding errors

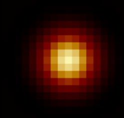
Lacour et al.

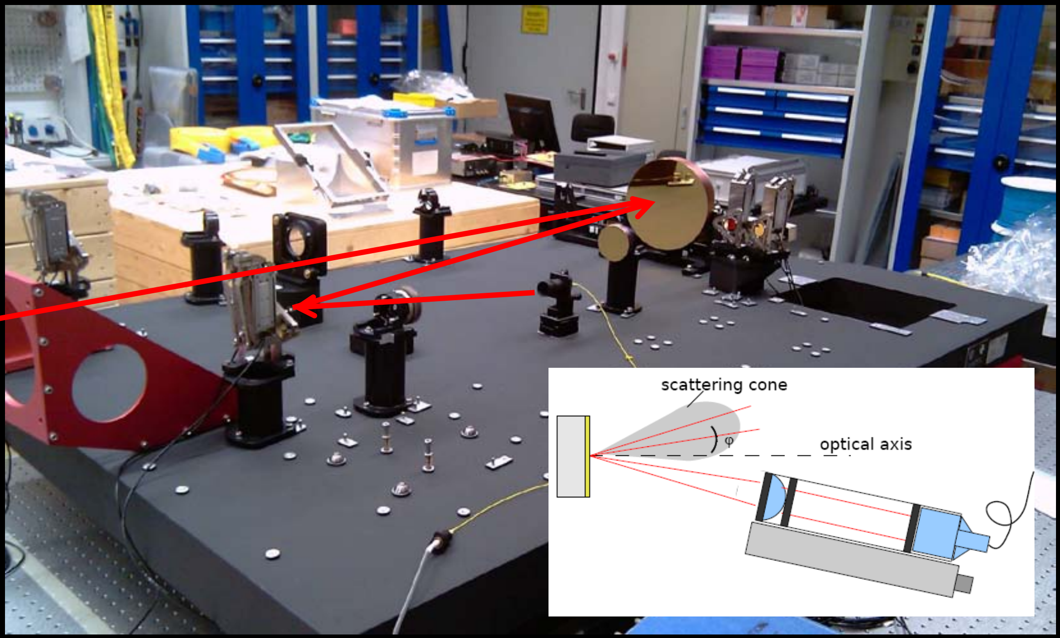
Tilt Control

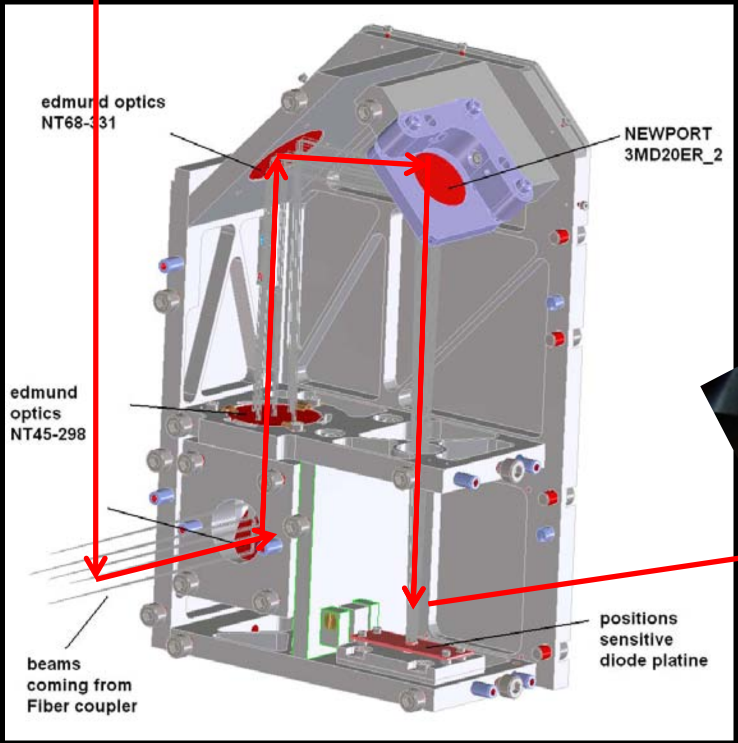
Atmosphere

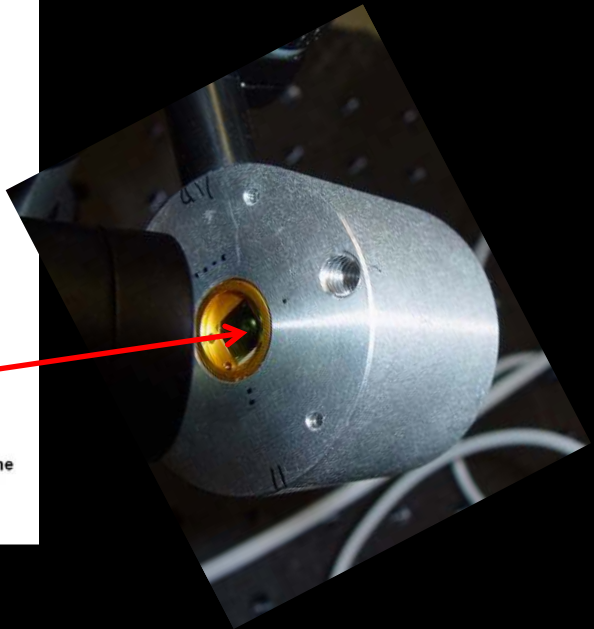


VLTI Tunnel

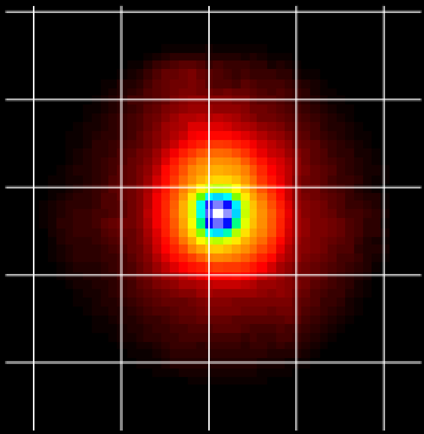






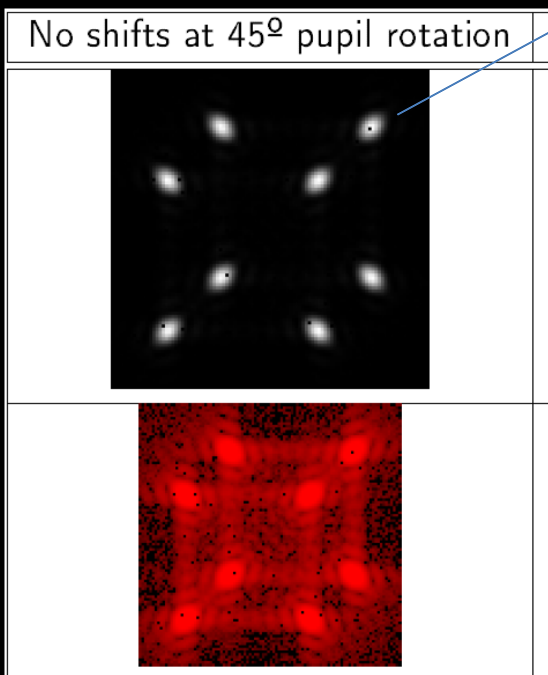


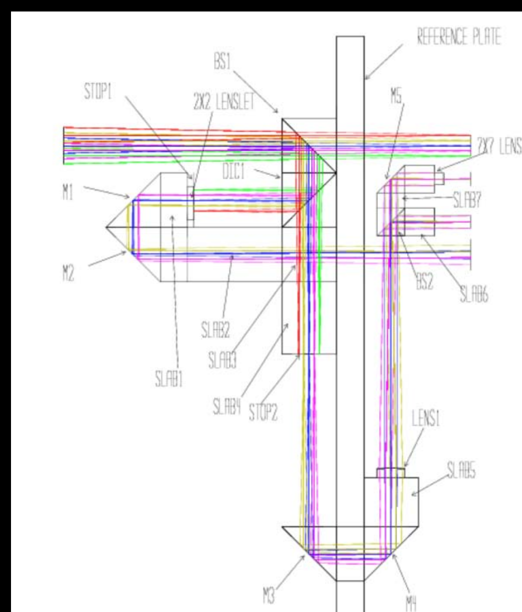
Acquisition and guiding camera

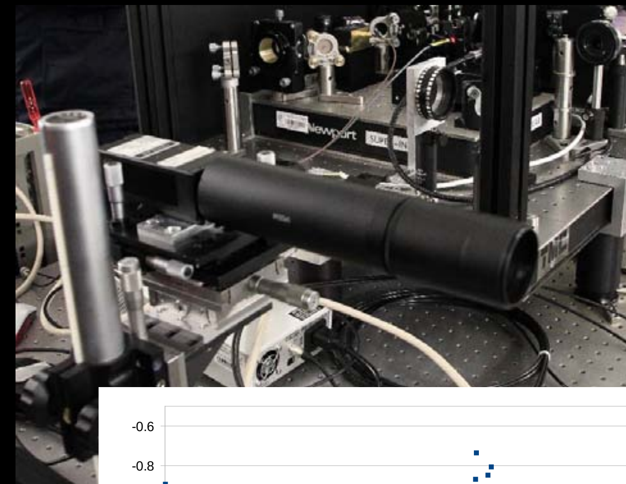


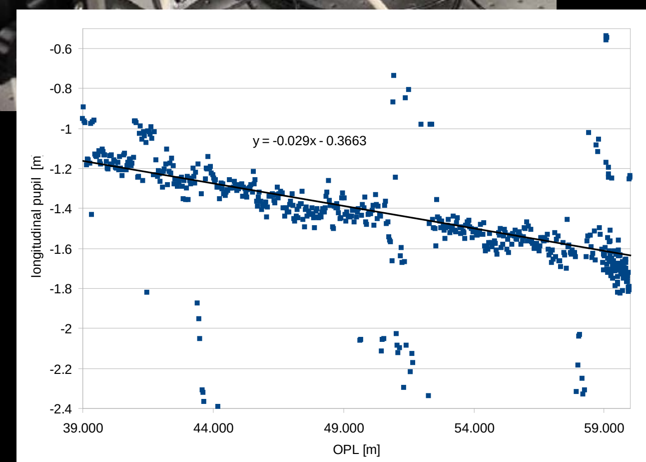
Pfuhl et al., Amorim et al. 2010,

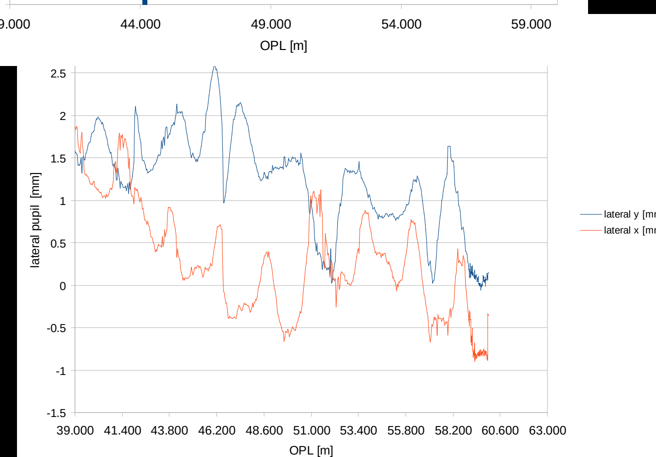
Pupil Control





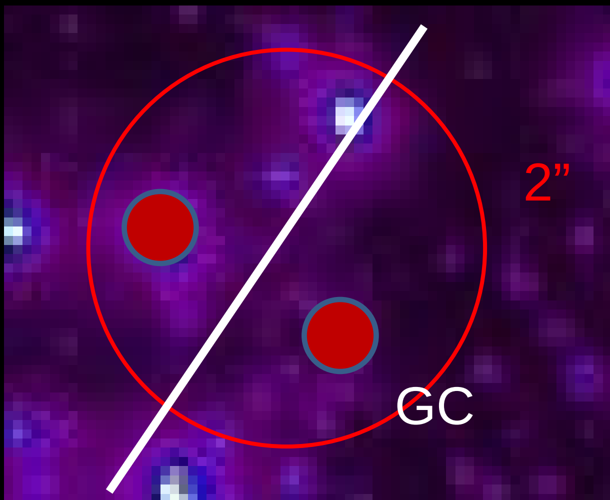




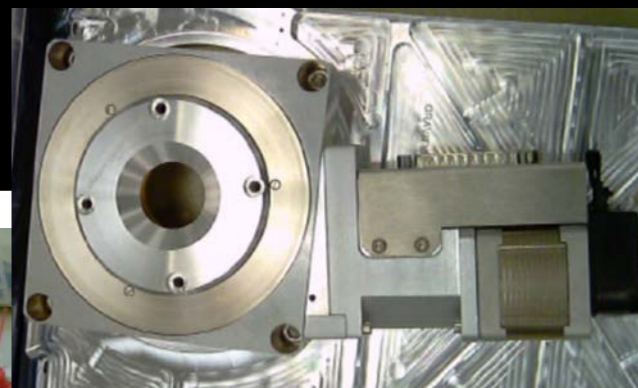


Amorim et al. 2010, Pfuhl et al.

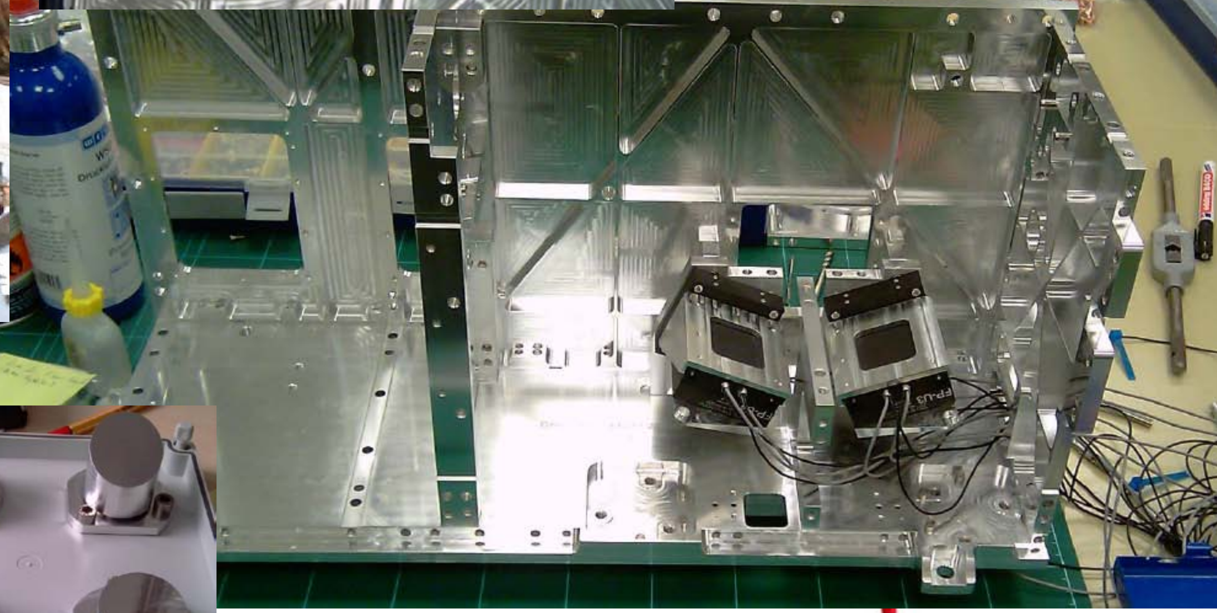
Fibercoupler

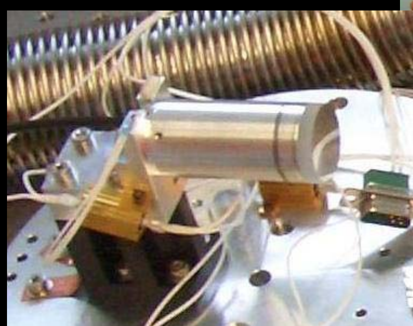


Rotation Stages



Shutters





Tip-Tilt-Piston-Actuator

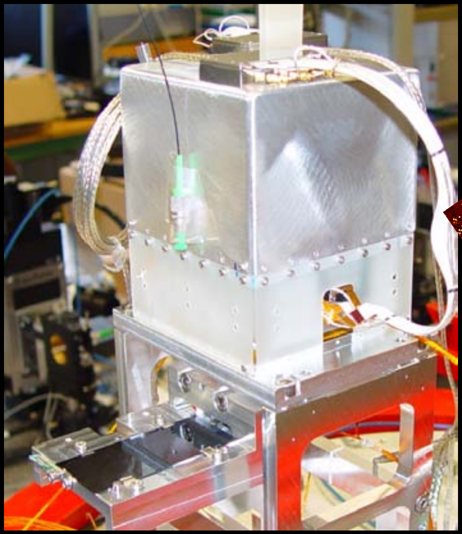
Pupil-Actuator

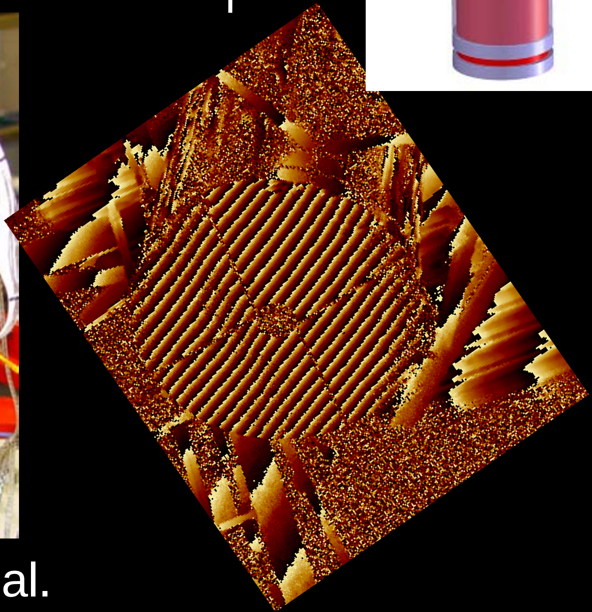
Pfuhl et al. 2010

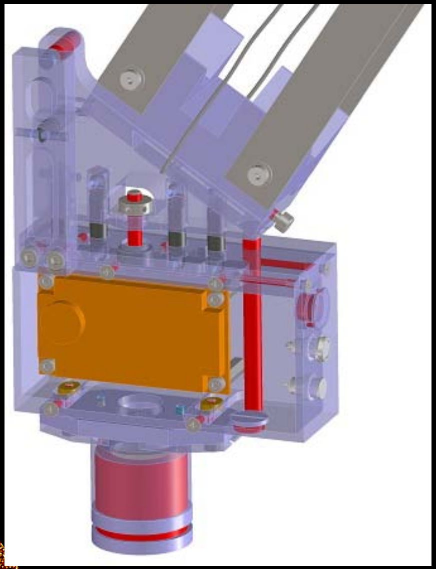
X,Y,Z Stages

Laser Metrology

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

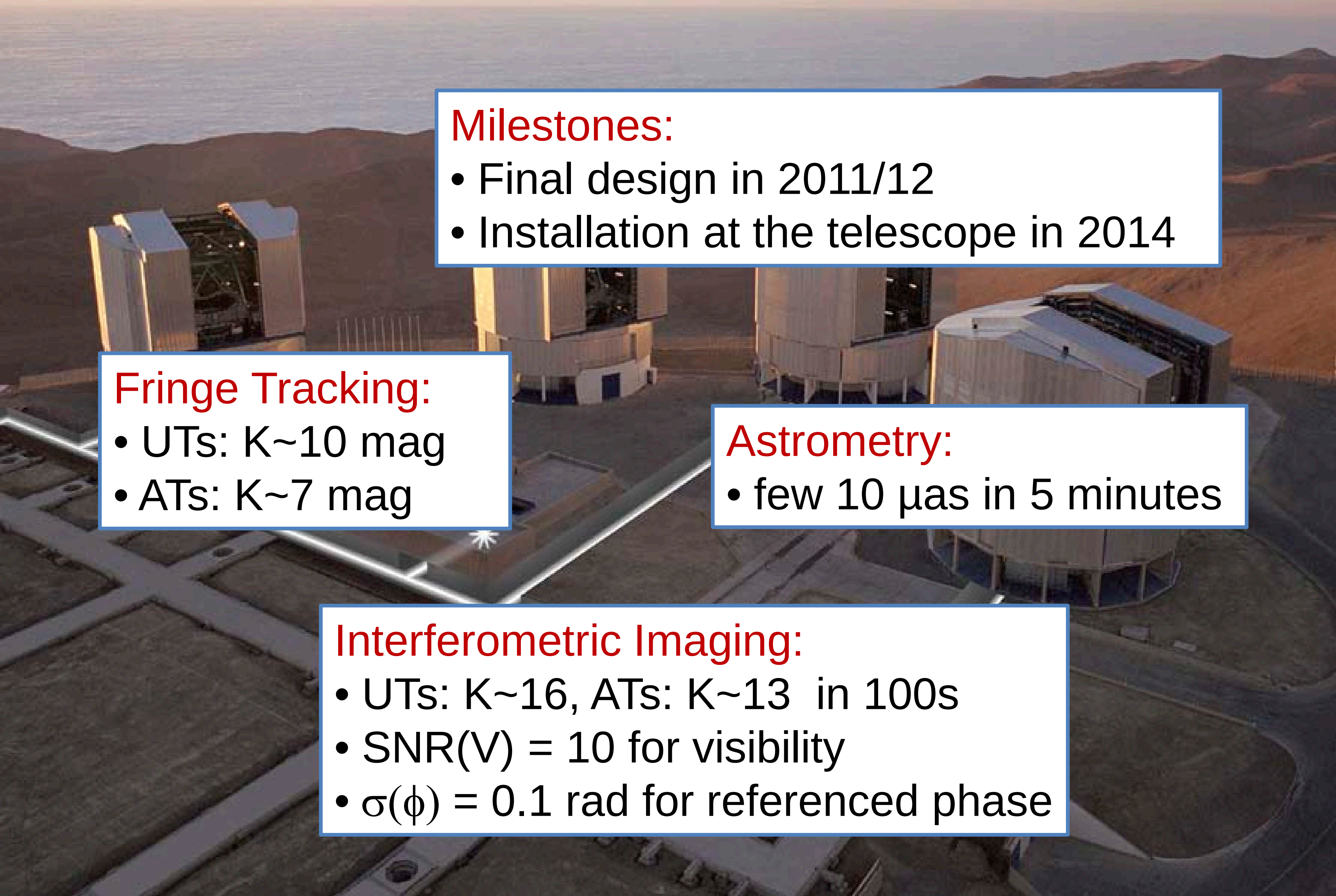






Rabien et al. 2008, Bartko et al. 2010, Gillessen et al.

GRAVITY Key Figures



Milestones:
- Final design in 2011/12
- Installation at the telescope in 2014

Fringe Tracking:
- UTs: K~10 mag
- ATs: K~7 mag

Astrometry:
- few 10 µas in 5 minutes

Interferometric Imaging:
- UTs: K~16, ATs: K~13 in 100s
- SNR(V) = 10 for visibility
- $\sigma(\phi)$ = 0.1 rad for referenced phase

Thank you very much for your attention