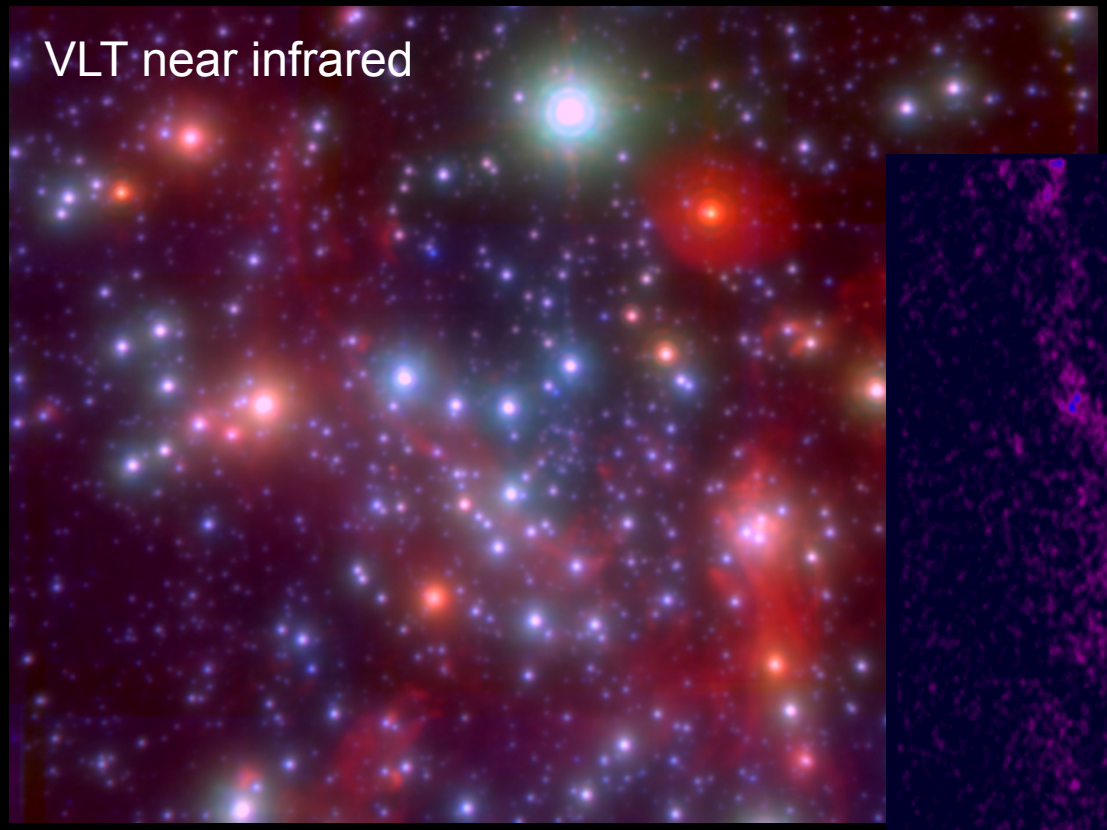
The MPE galactic center team: Reinhard Genzel, Frank Eisenhauer, Stefan Gillessen, Katie Dodds-Eden, Tobias Fritz, Oliver Pfuhl, Thomas Ott

Infrared observations and interferometry of Sgr A*

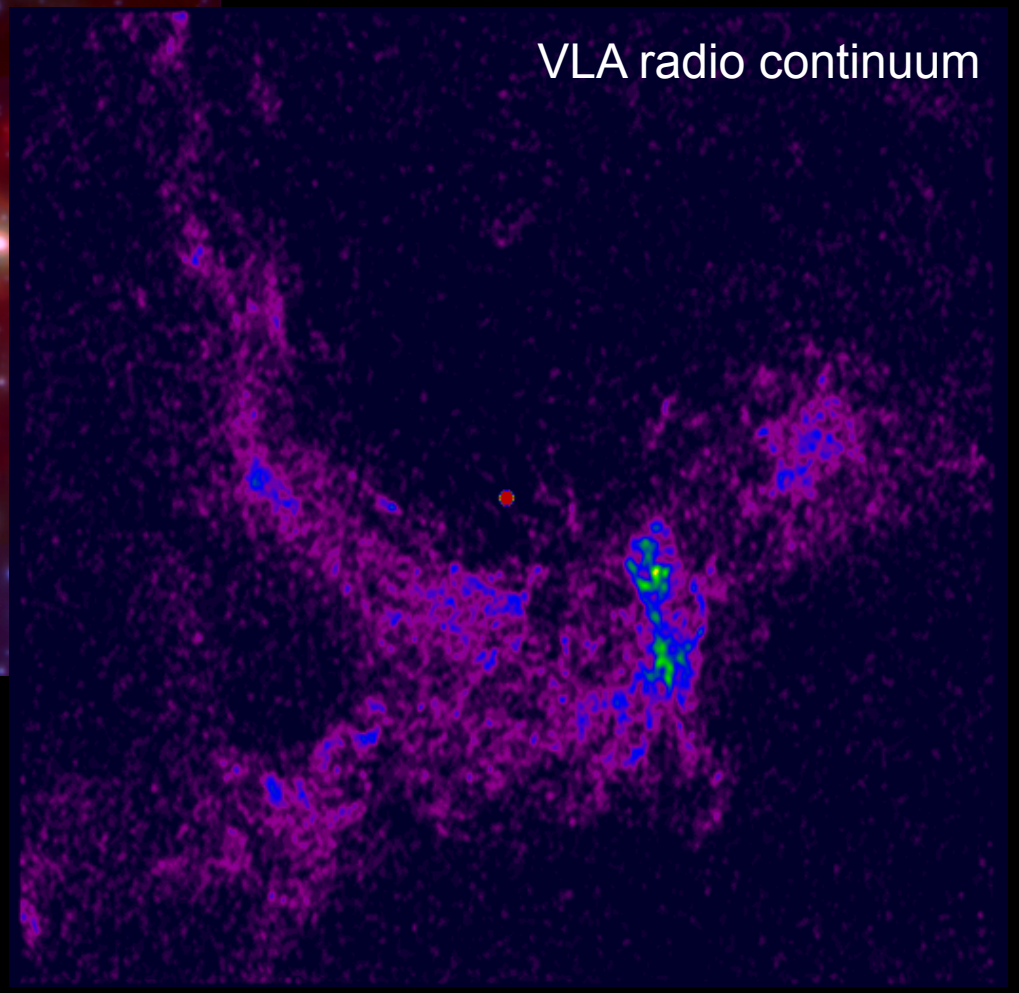
The GRAVITY team: Frank Eisenhauer, Guy Perrin, Wolfgang Brandner, Christian Straubmeier , Karine Perraut , Antonio Amorim , Markus Schöller, Reinhard Genzel, Pierre Kervella , Myriam Benisty, Sebastian Fischer , Laurent Jocou, Paulo Garcia, Gerd Jakob, Stefan Gillessen, Yann Clénet , Armin Boehm, Constanza 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

From stars to black holes: mm-VLBI with ALMA and other telescopes
Frank Eisenhauer (MPE), Garching, Germany, 27 June 2012

A perfect synergy between infrared and radio …



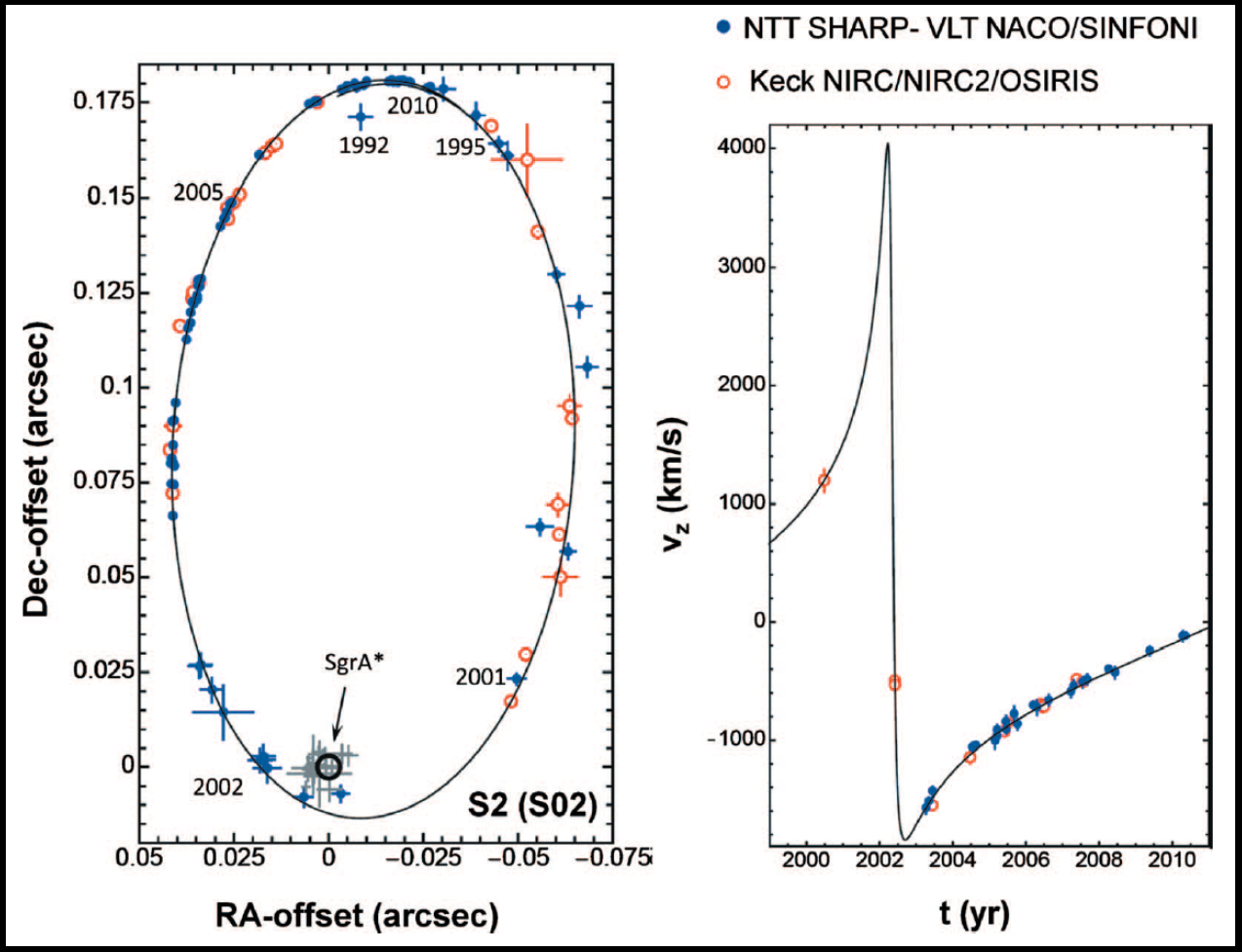
Courtesy of ESO / MPE



Lo & Claussen 1983, Ekers et al. 1983, Zhao et al 2009, Yusef-Zadeh et al. 2010

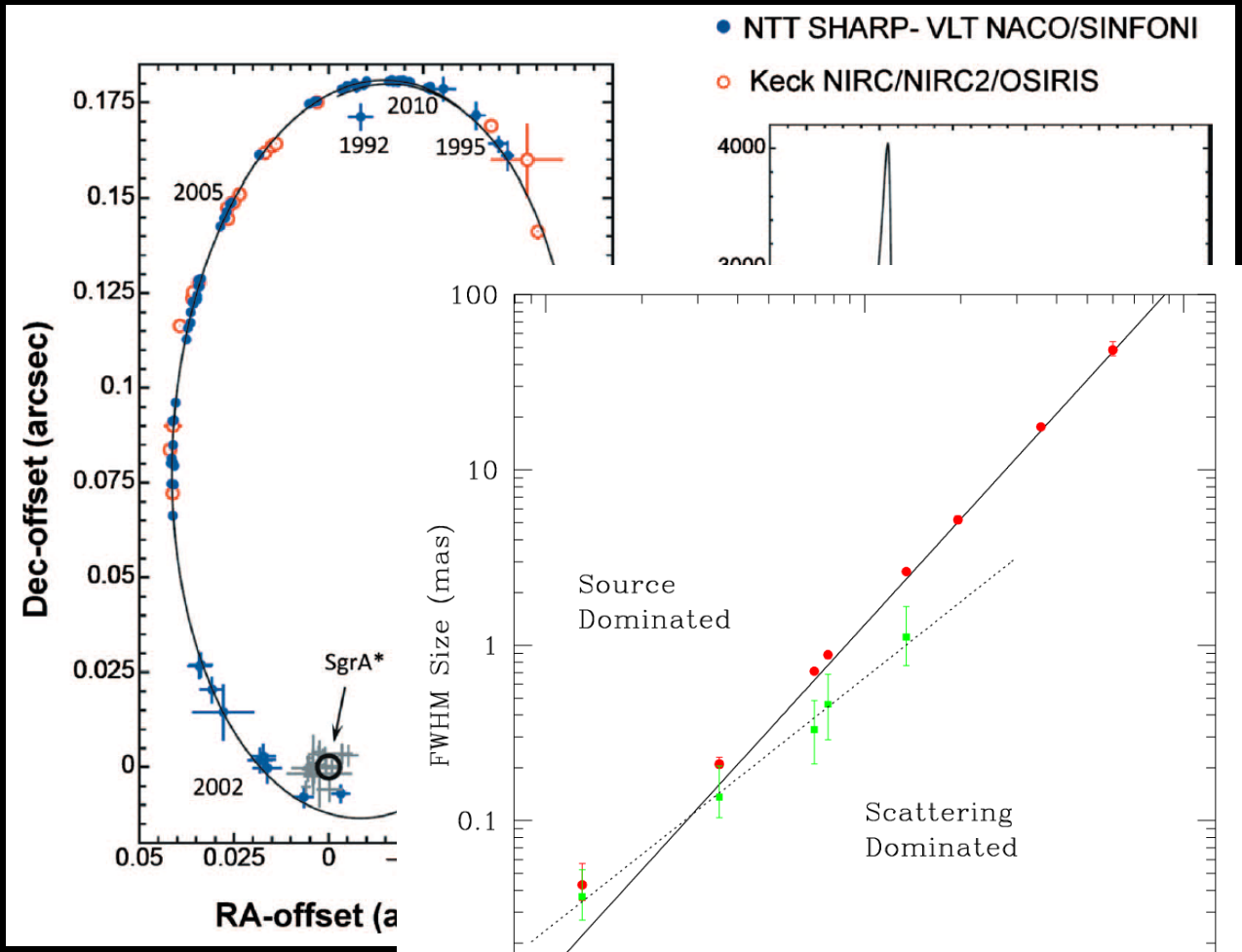
For more references see recent review by Genzel, Eisenhauer, Gillessen et al. 2010, RevModPhys

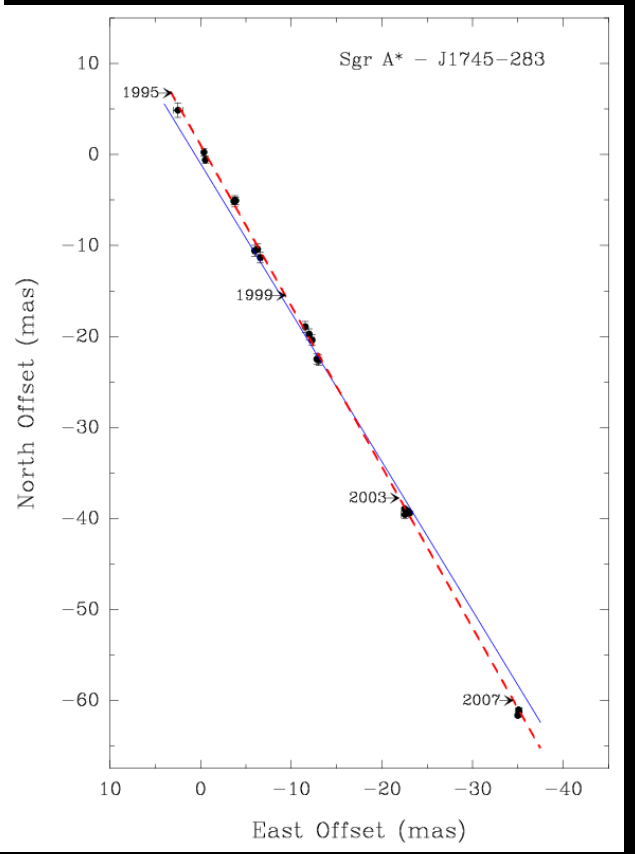
… best evidence for super-massive black holes



Schödel *et al.* 2003, Eisenhauer *et al.* 2005,
Ghez *et al.* 2005, 2008, Gillessen *et al.* 2009a,b

… best evidence for super-massive black holes

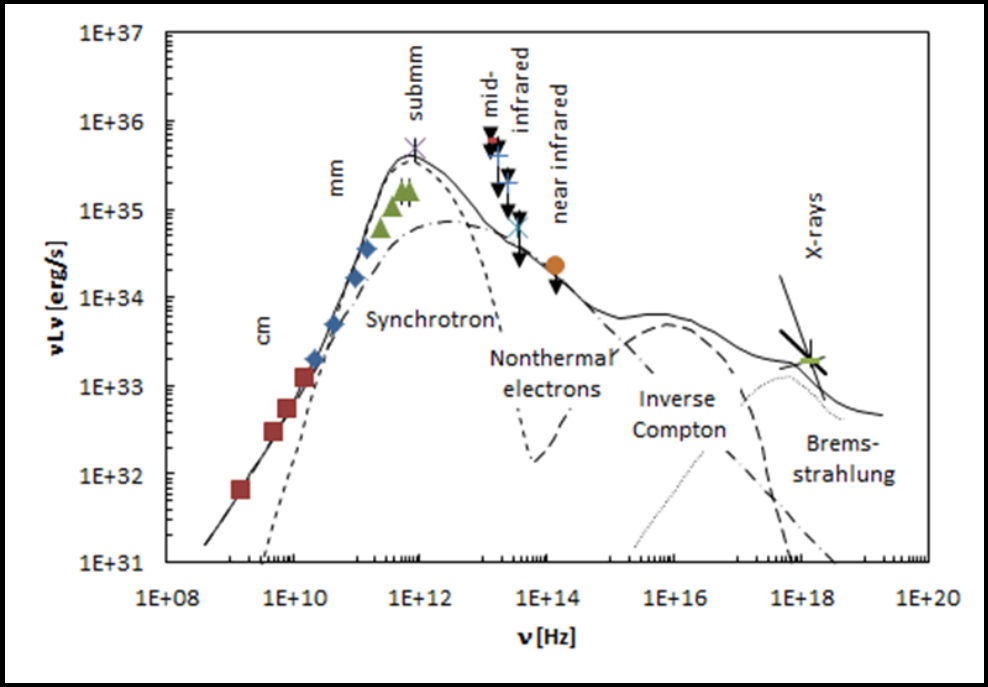




Krichbaum et al. 1998, Bower *et al.* 2004, 2006, Shen *et al.* 2005, Doeleman *et al.* 2008

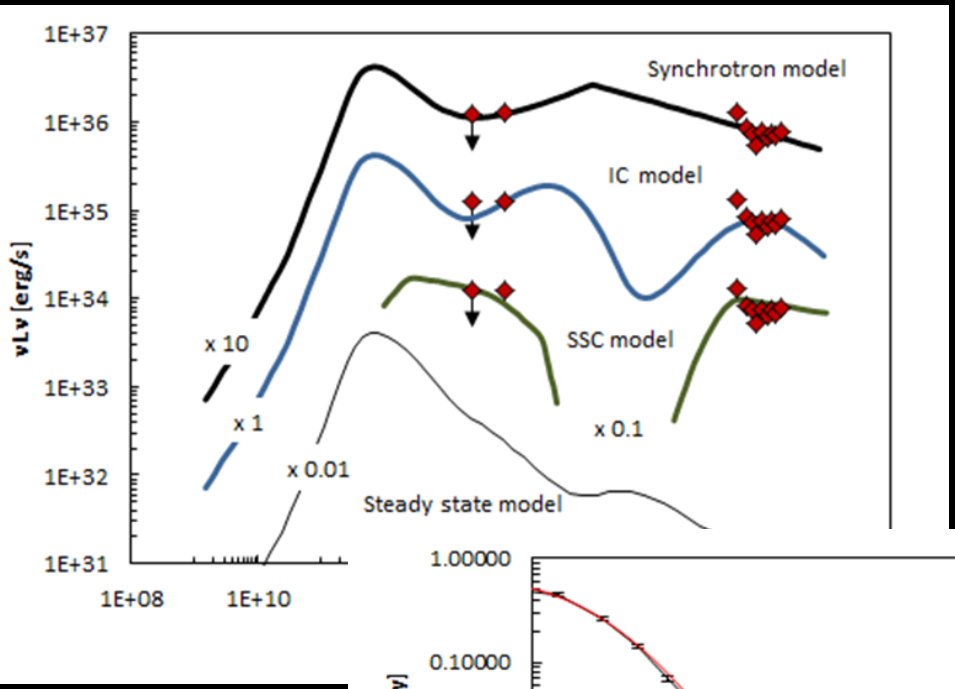
Reid and Brunthaler 2004, Reid 2009

… and combined information about the accretion

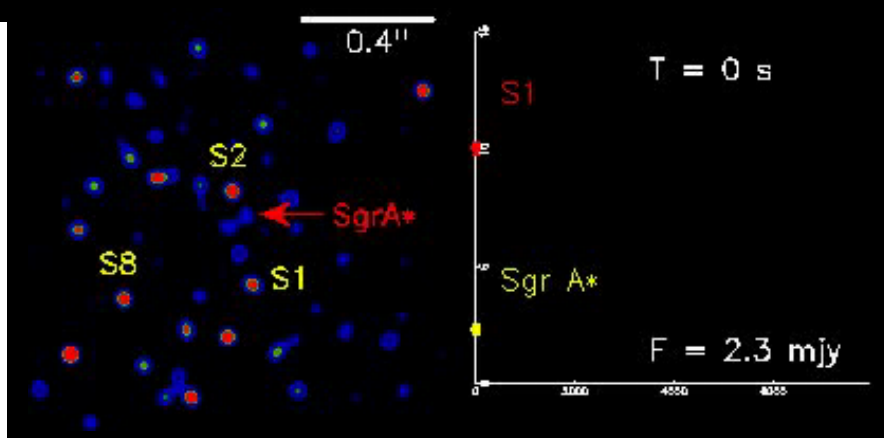


Zhao et al. 2001, Falcke et al. 1998, Zylka et al. 1995, Serabyn et al. 1997, Cotera et al. 1999, Gezari 1999, Schödel et al. 2007, Hornstein et al. 2002, Baganoff et al., 2003, Yuan et al. 2003

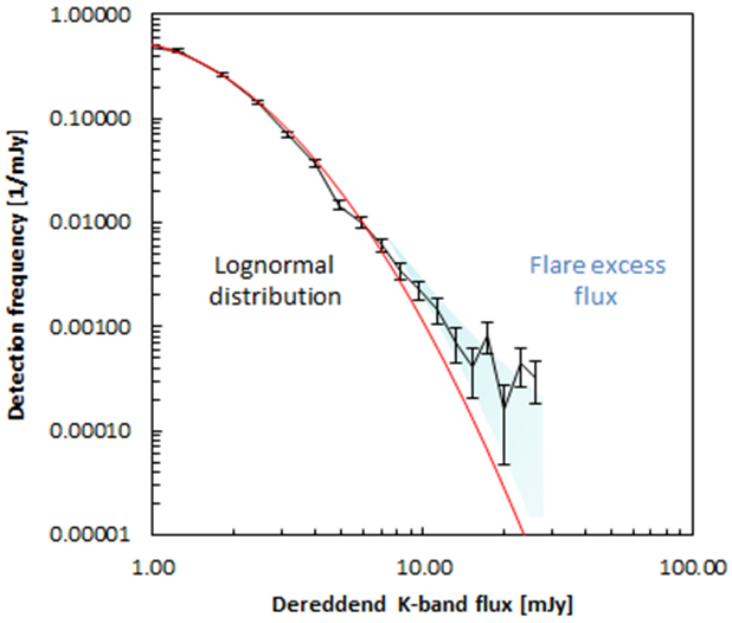
… and its flares from non-thermal electrons

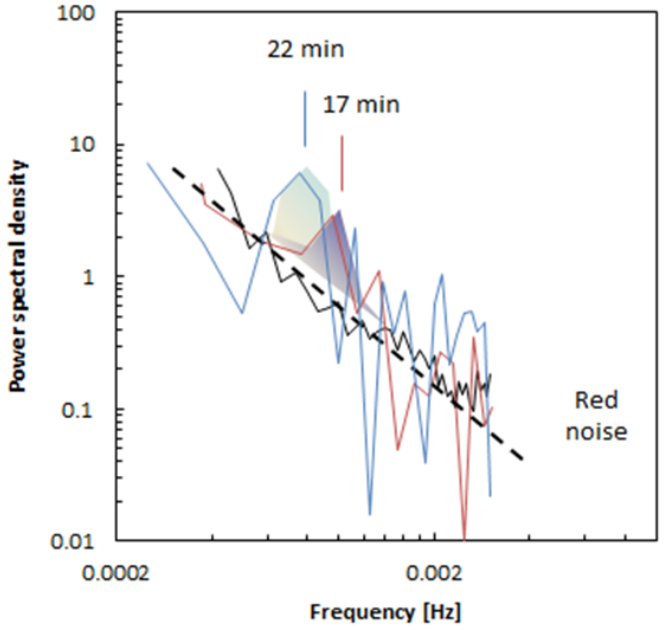


Sabha et al. 2010
Dodds Eden et al. 2009



Genzel et al. 2003, Eckart et al., Ghez et al.

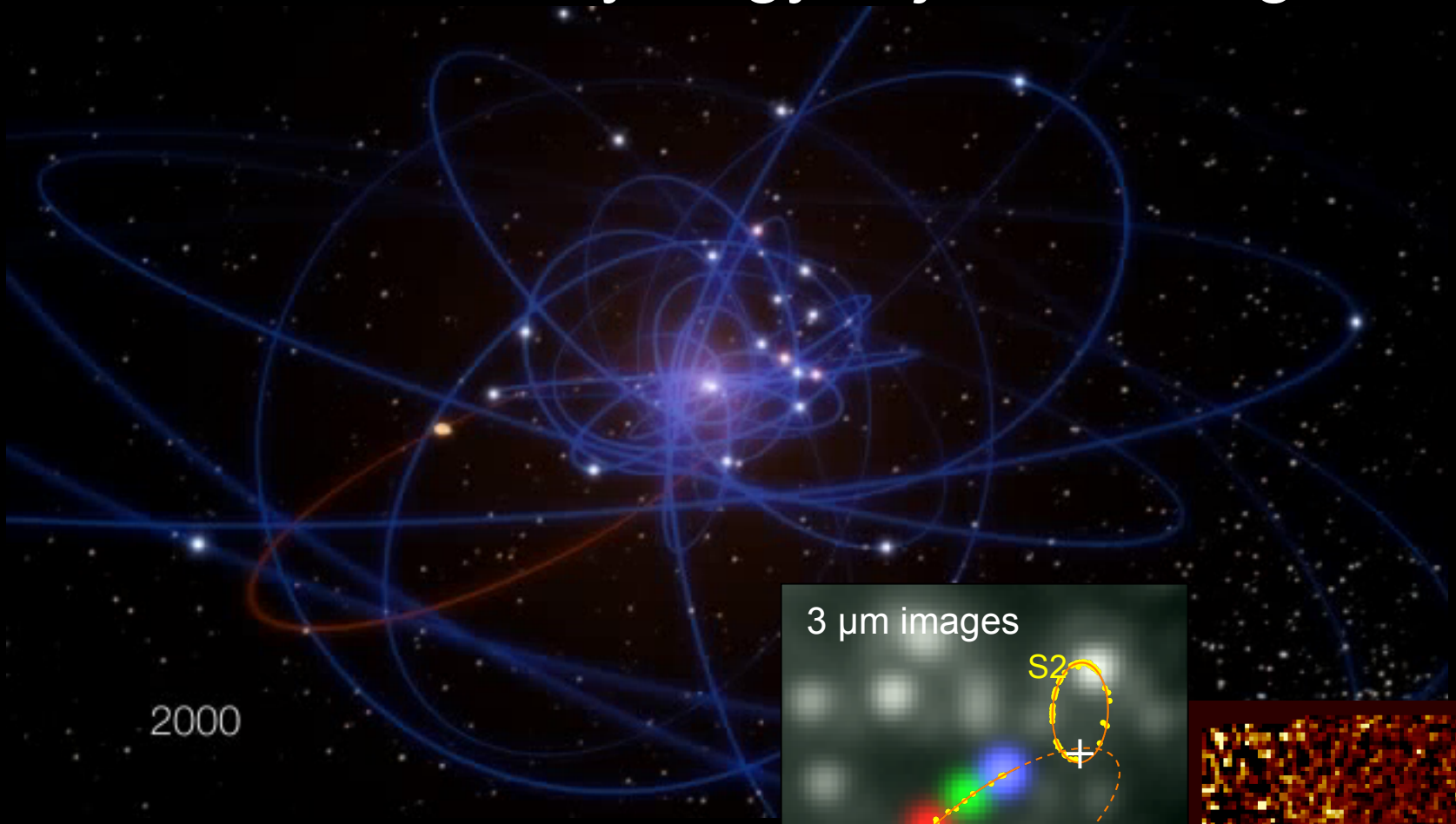




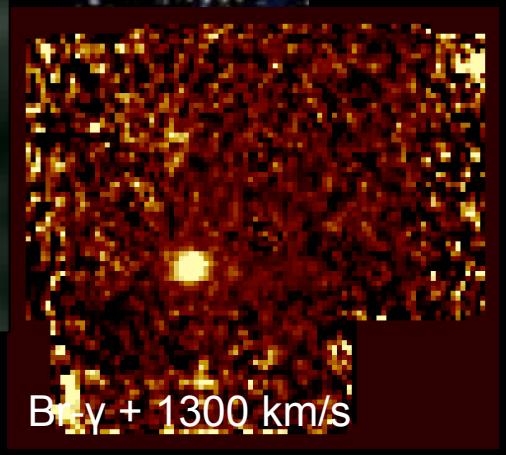
Dodds-Eden et al. 2010

Genzel et al. 2003, Do et al. 2006, Trippe et al. 2007

The next synergy is just arriving …



Credits: Schartmann / ESO



Gillessen et al. 2011, Burkert et al. 2012, Schartmann et al. 2012

But on the black hole itself …

… we hardly know even a single quantity:

Mass

$$M_\bullet = 4.30 \pm 0.20 \pm 0.30 \times 10^6\,\mathrm{M}_\odot$$

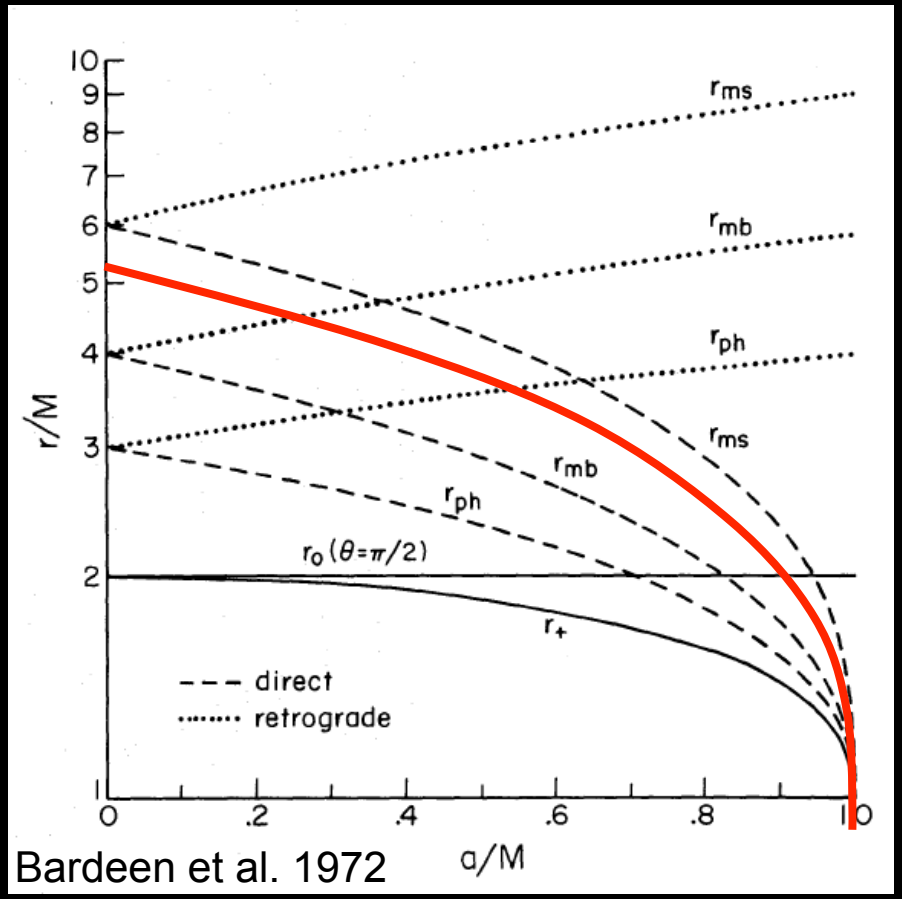
… luckily there is only one other quantity missing …

No-Hair theorem: once in a stable condition after formation, a black hole has only three independent physical properties:

Spin

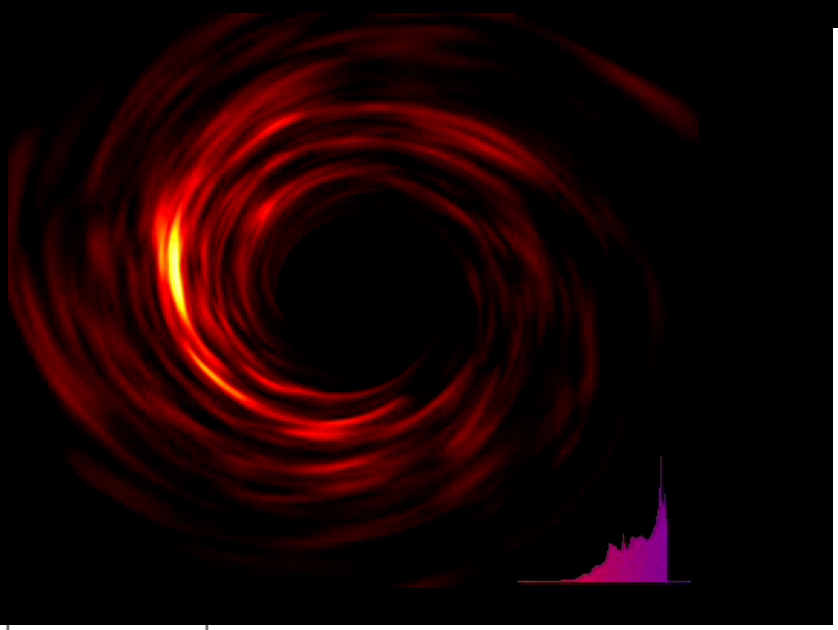
(Electric charge)

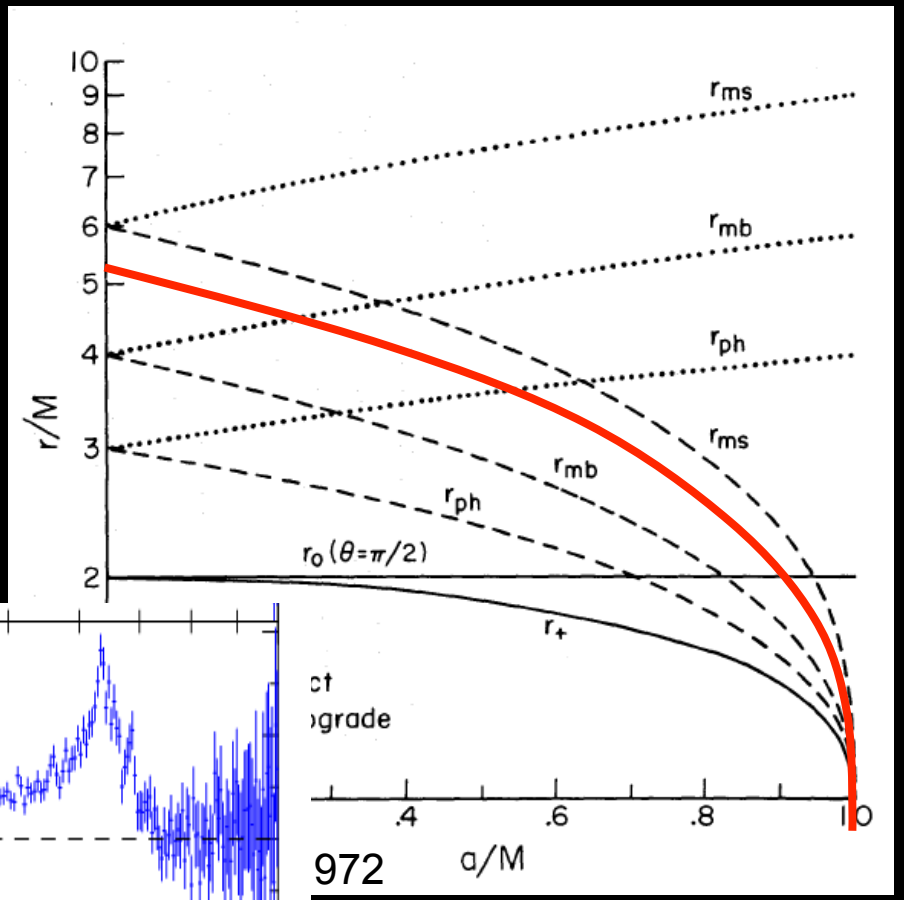
Spin measurements from the last stable orbit …

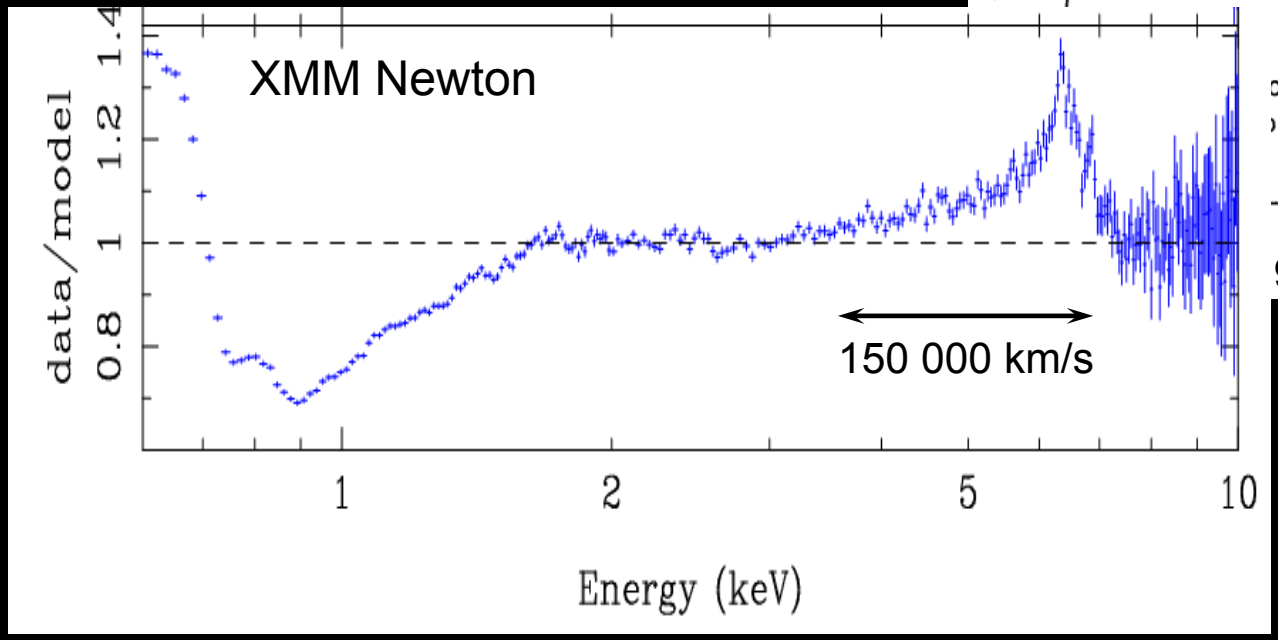


Bardeen et al. 1972

… with X-rays …

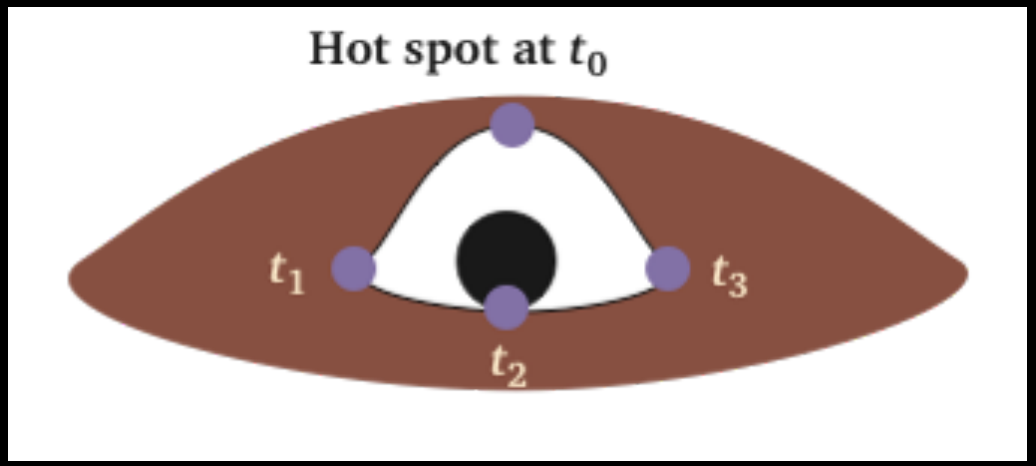


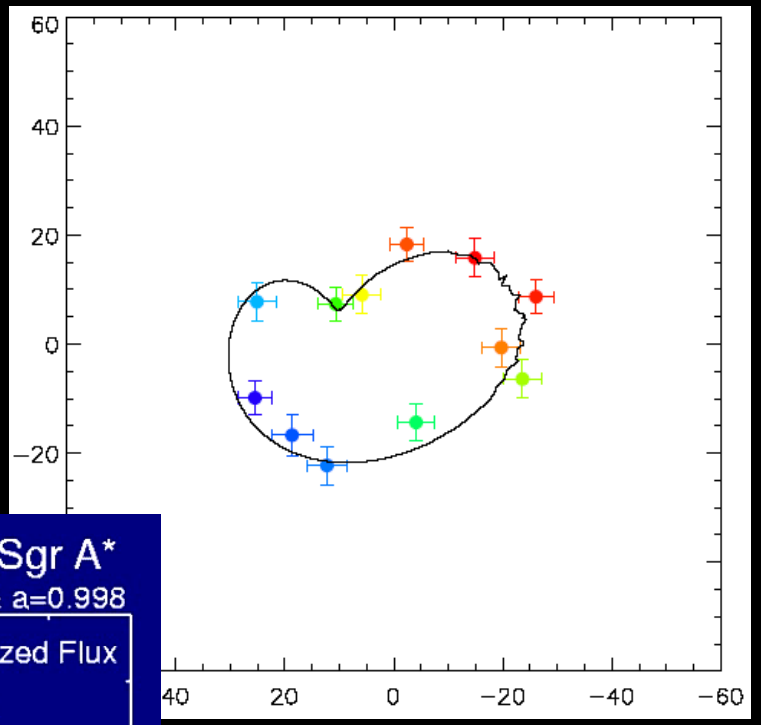




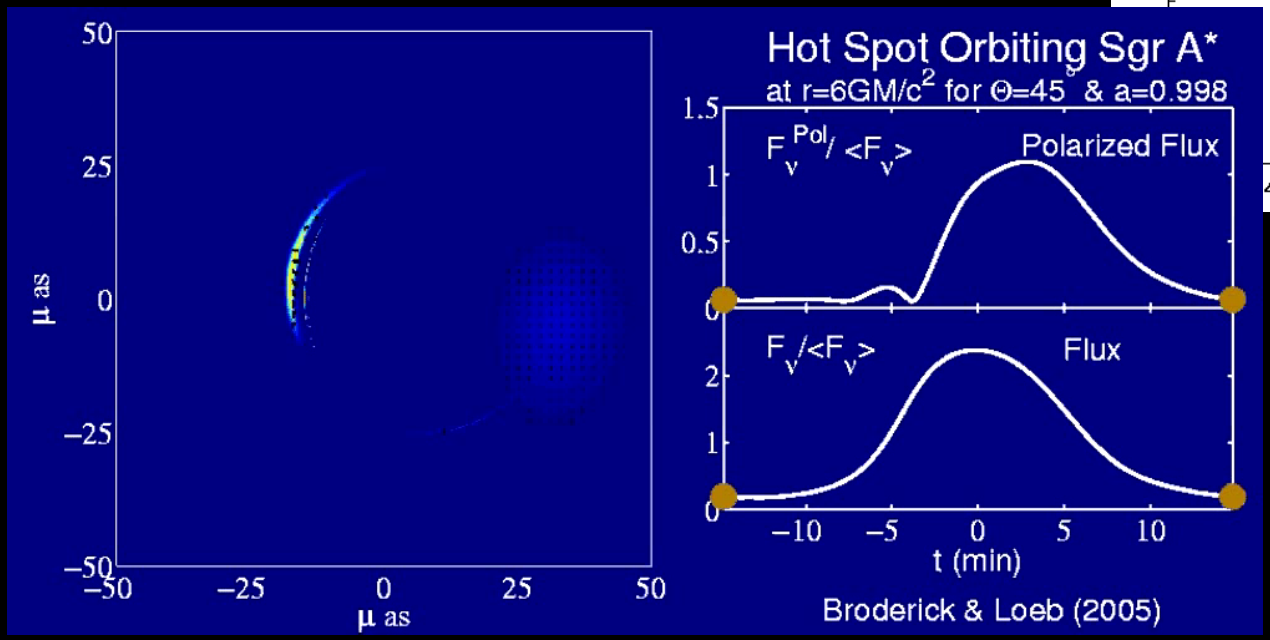
Tanaka, Nandra et al 1997-99, Fabian et al. 2002, Nandra et al. 2007, Reynolds et al. 2011

… in the infrared





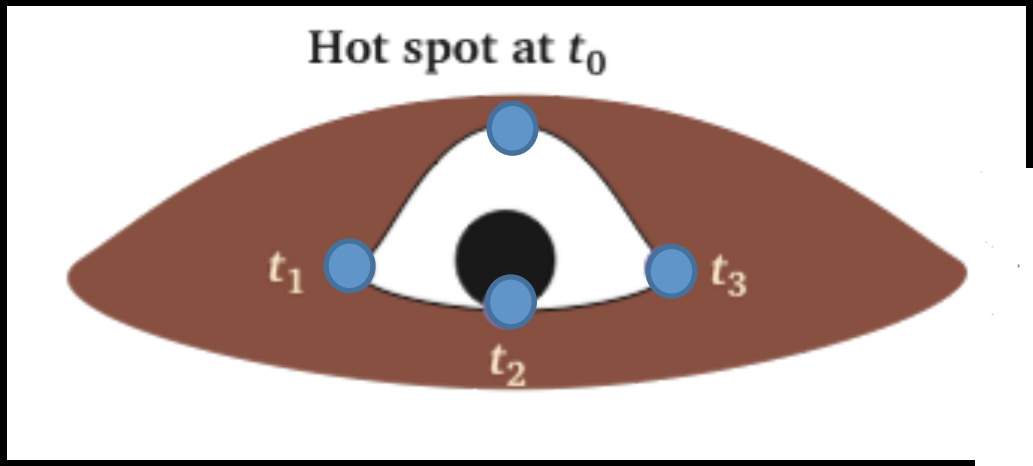
Paumard et al. 2005



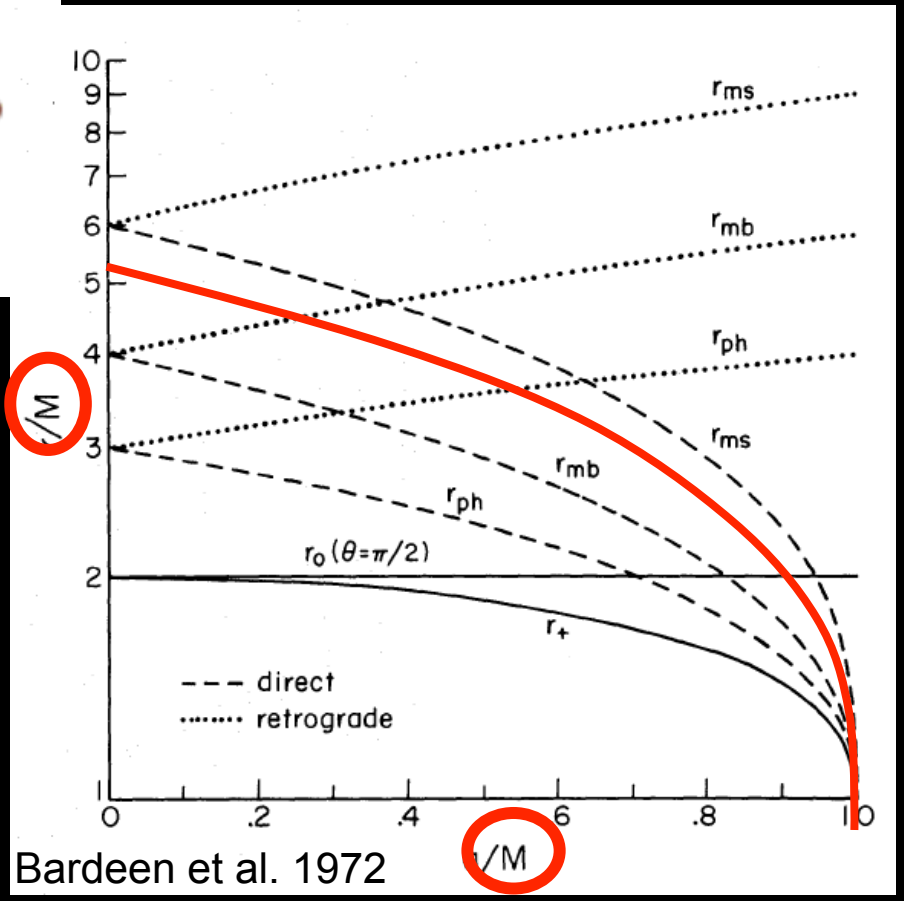
Broderick & Loeb 2005

Last stable orbit spin measurement is difficult …

Need to be on last stable orbit



Need to know mass



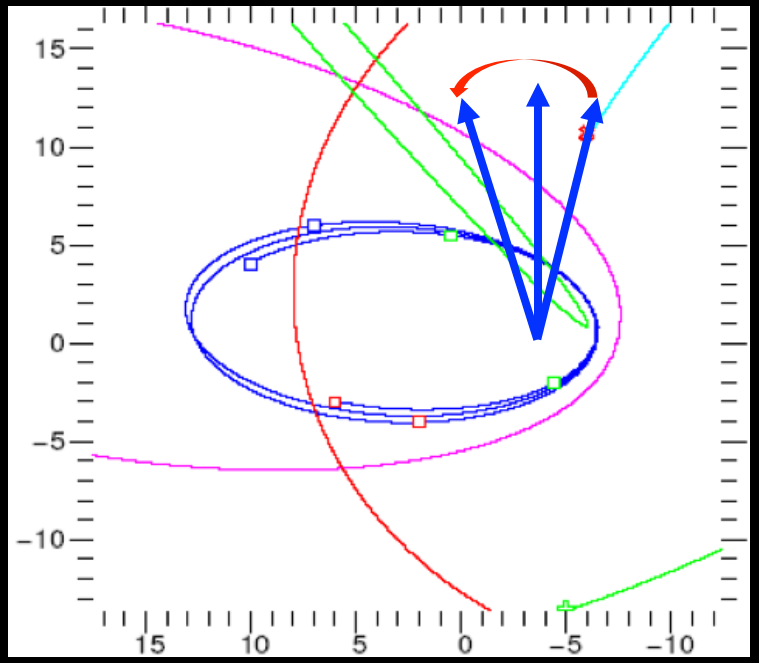
Bardeen et al. 1972

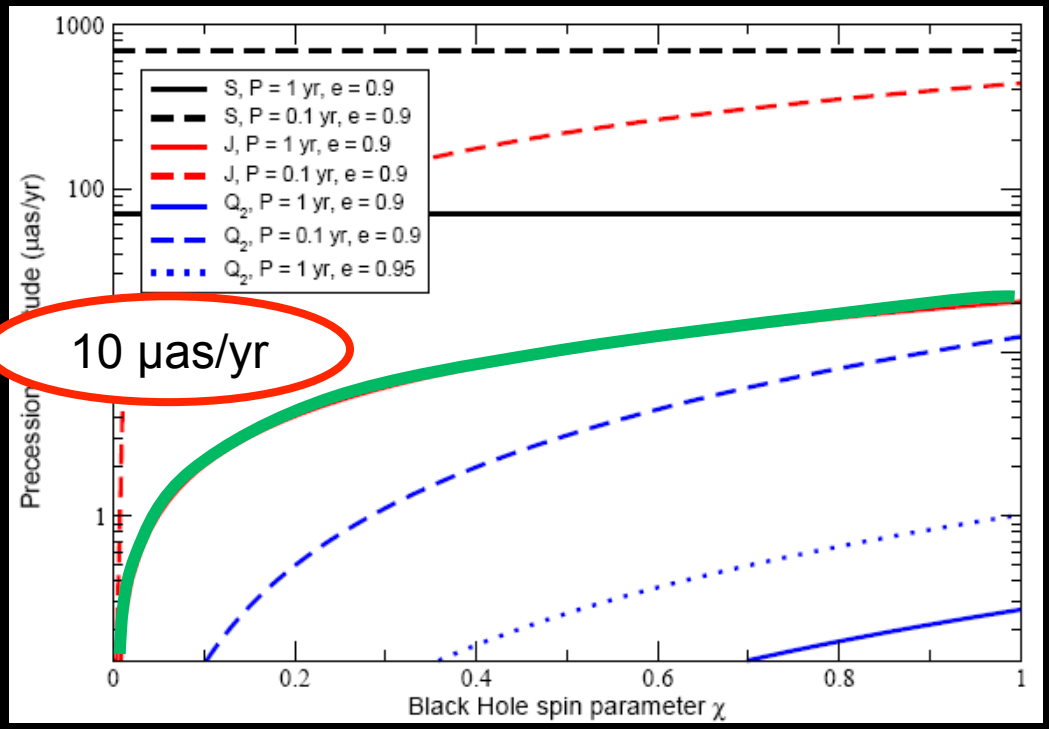
Spin measurement from Lense Thirring effect

Precession of the angular momentum vector around the spin of the black hole

$$\dot{\Theta}_J \approx 0.847\,\chi P^{-4/3}(1-e^2)^{-3/2}$$

Will 2008

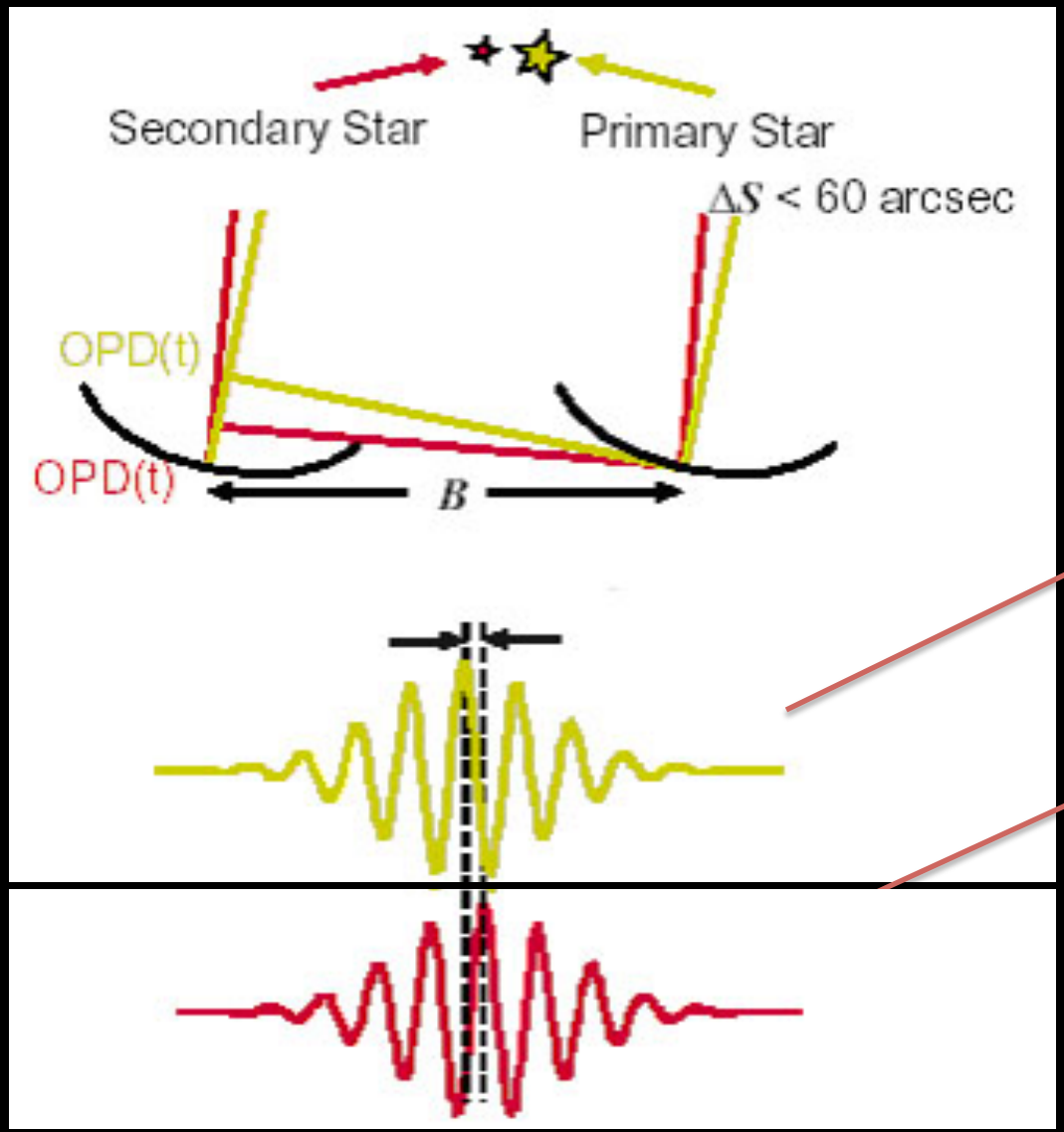


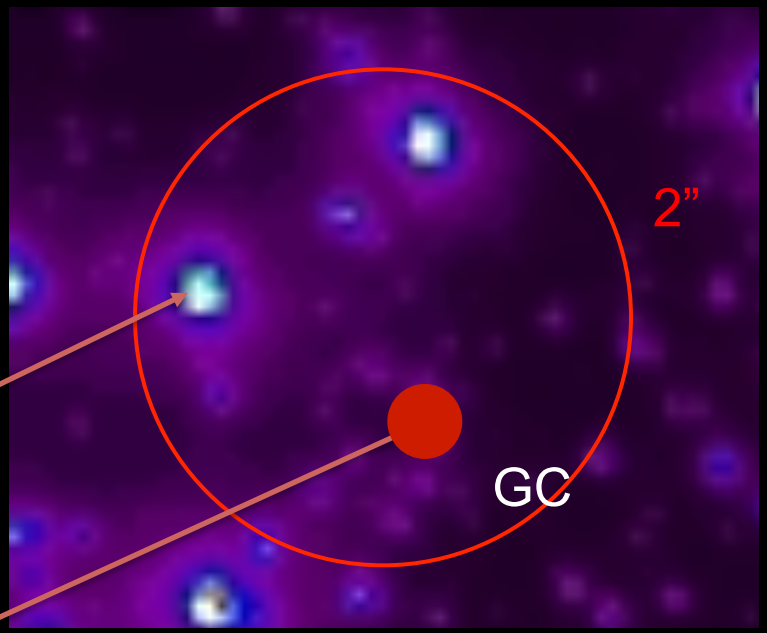


Phase referenced imaging & astrometry

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

500 µm 10 µas

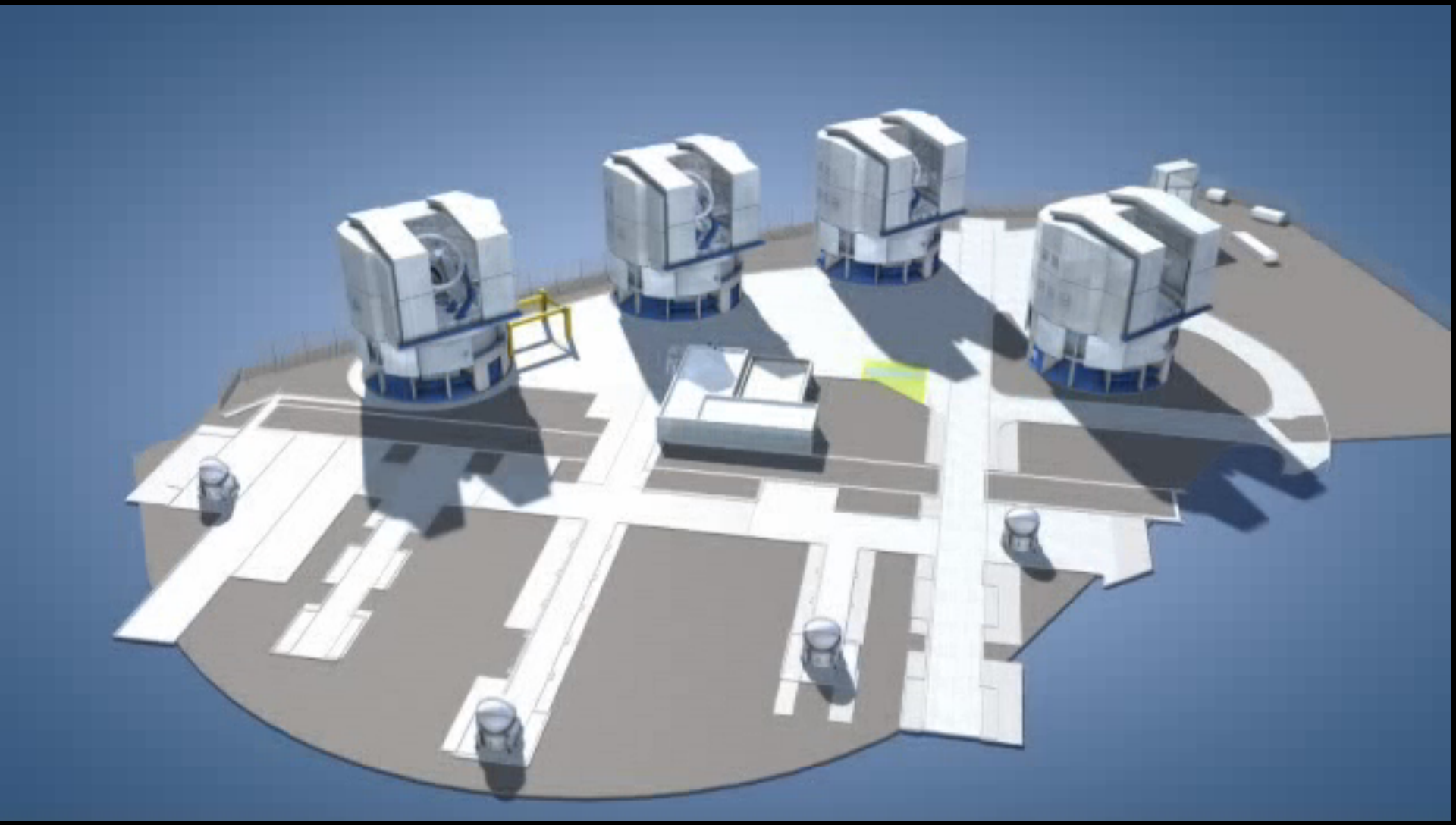




PRIMA @ VLTI

Delplancke 2008

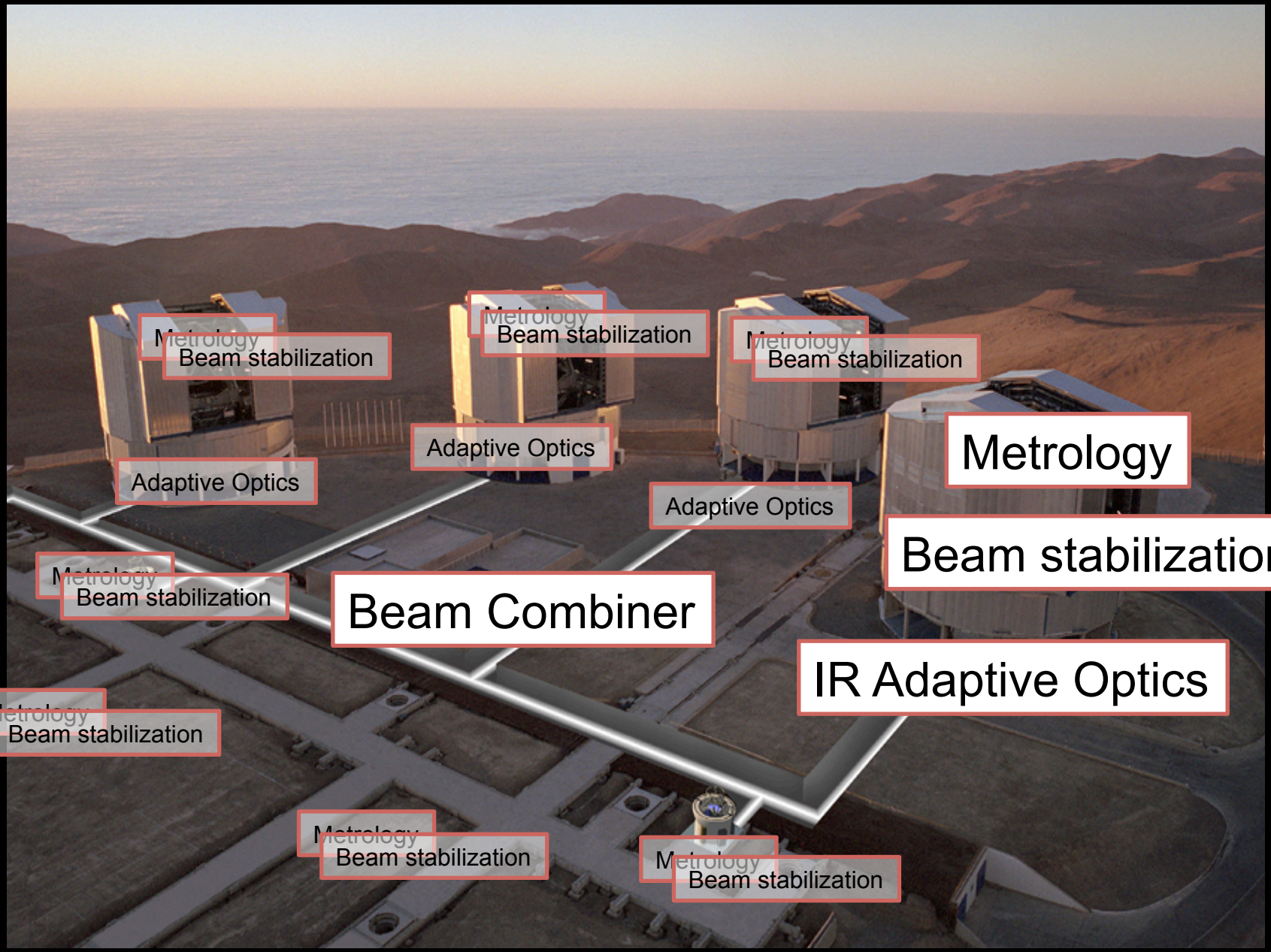
GRAVITY @ ESO VLTI



Eisenhauer et al. 2011

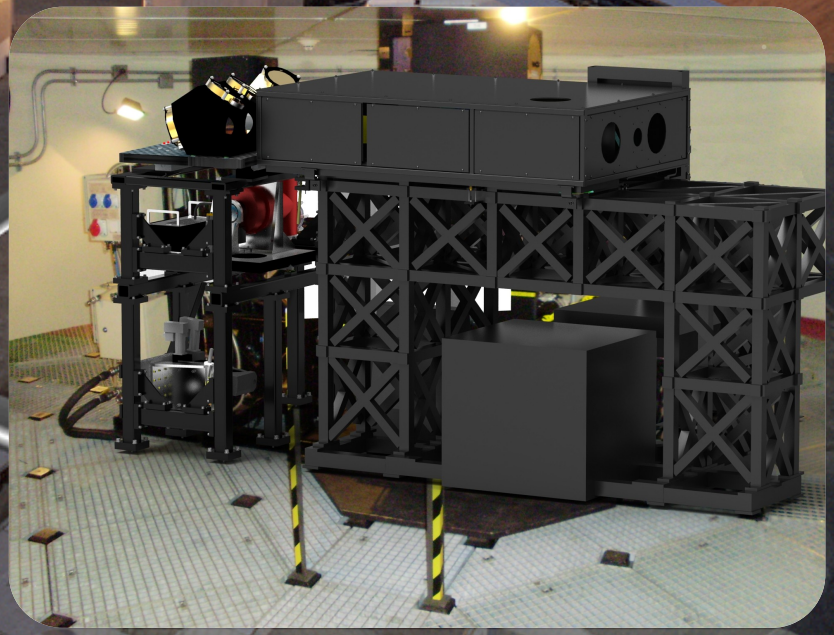
Courtesy of ESO

GRAVITY astrometry & imaging



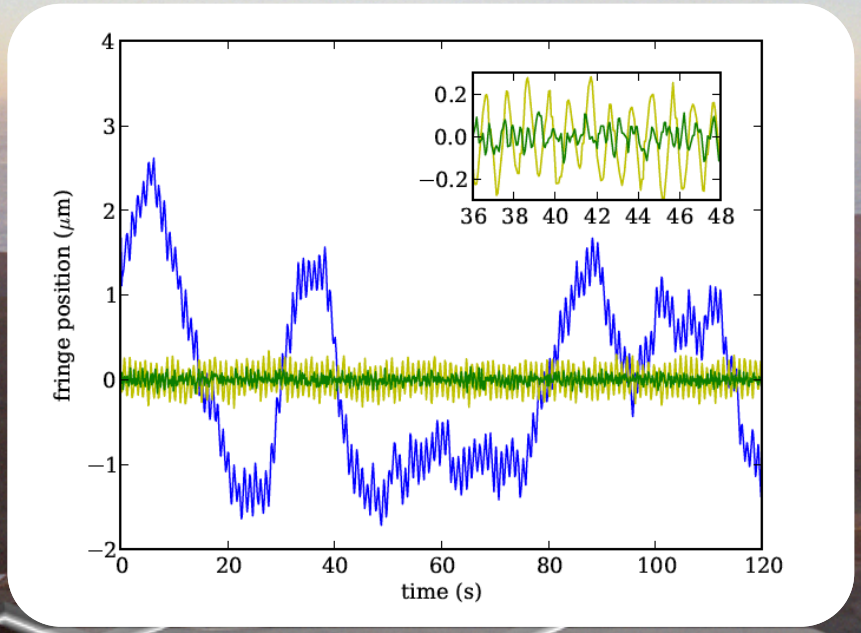
GRAVITY adaptive optics

Movie Courtesy: Esposito et al.



Brandner et al., Clenet et al.

GRAVITY beam combiner & fringe tracking



Choquet et al.

Haug et al.

Single mode interferometer

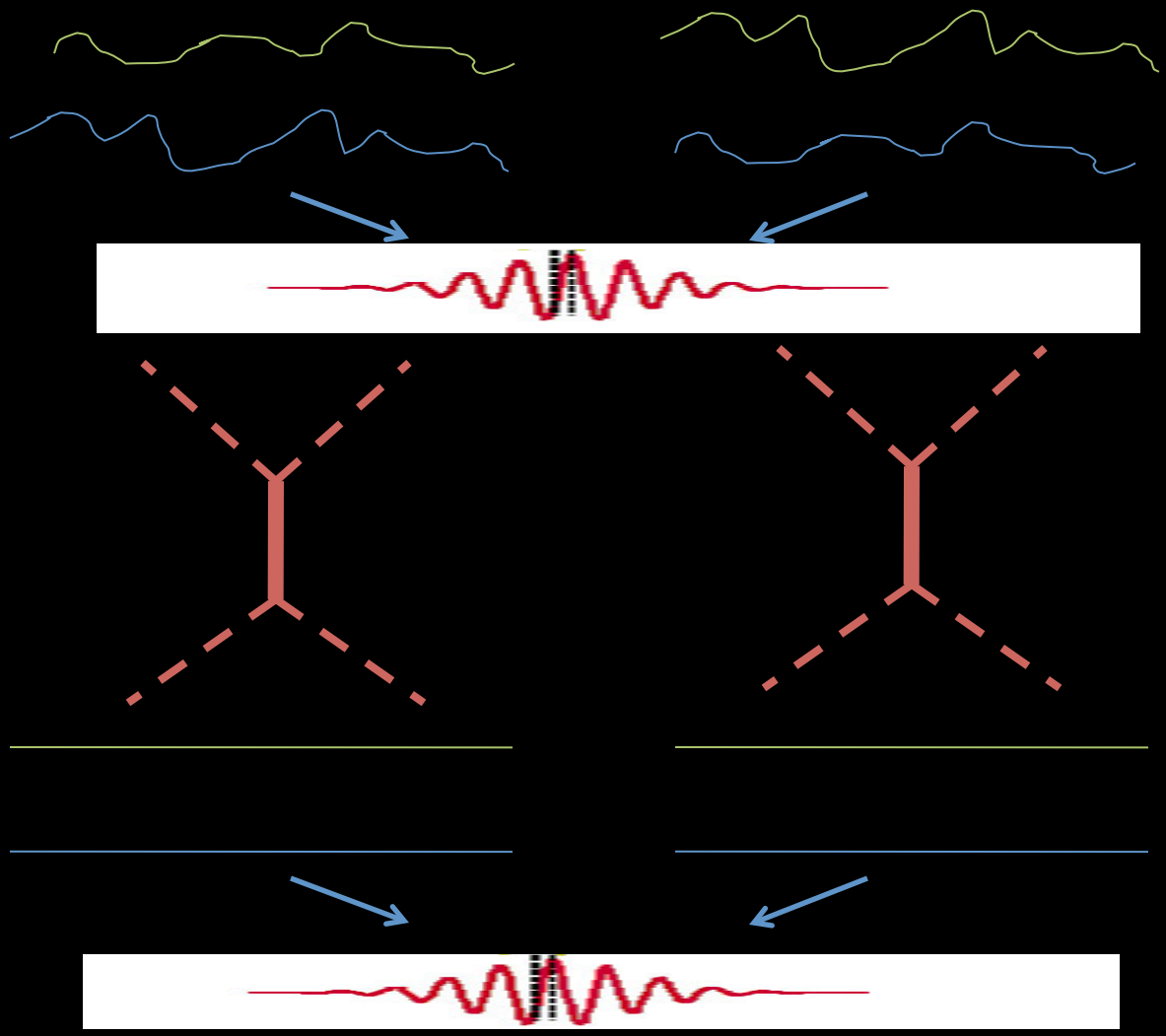
Most important quantities for interferometry is well measured phase and calibrated contrast

Distorted Waves

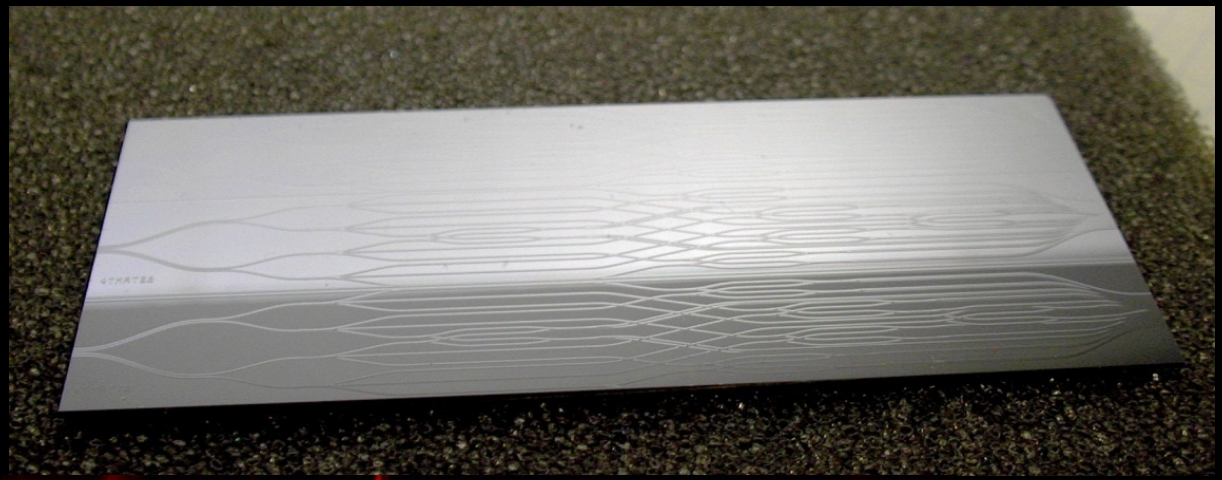
Constant flux, but variable contrast

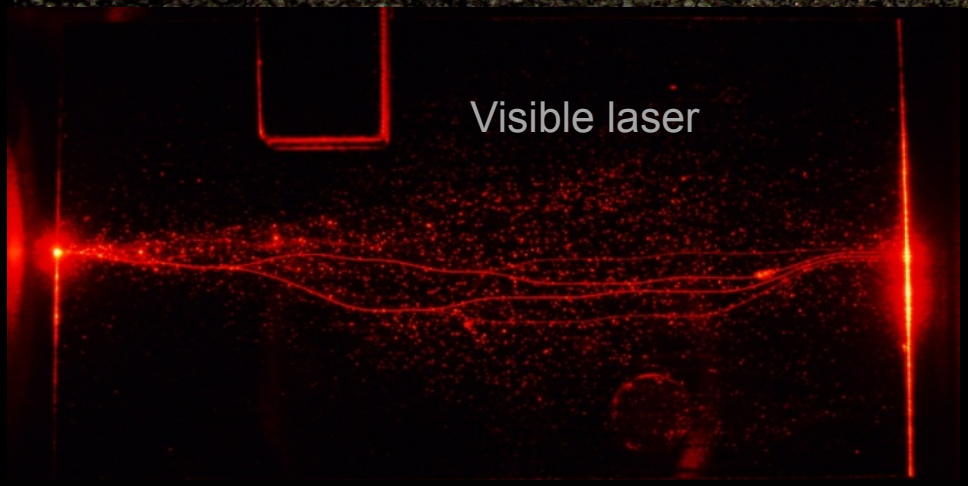
Single mode fiber
“Low pass filter”

Variable flux, but constant contrast

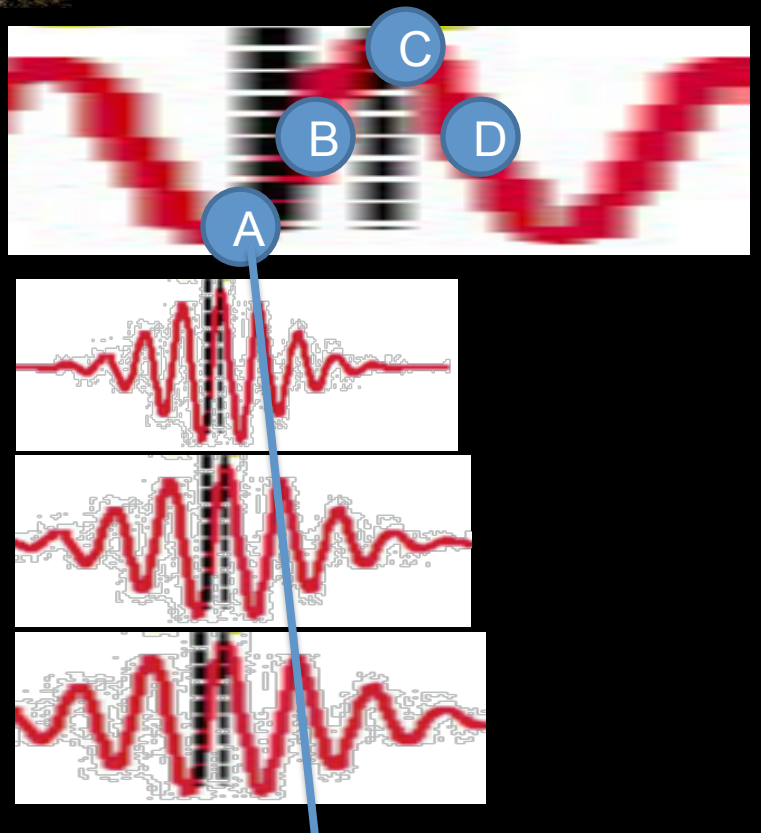


Integrated optics feeding spectrometer





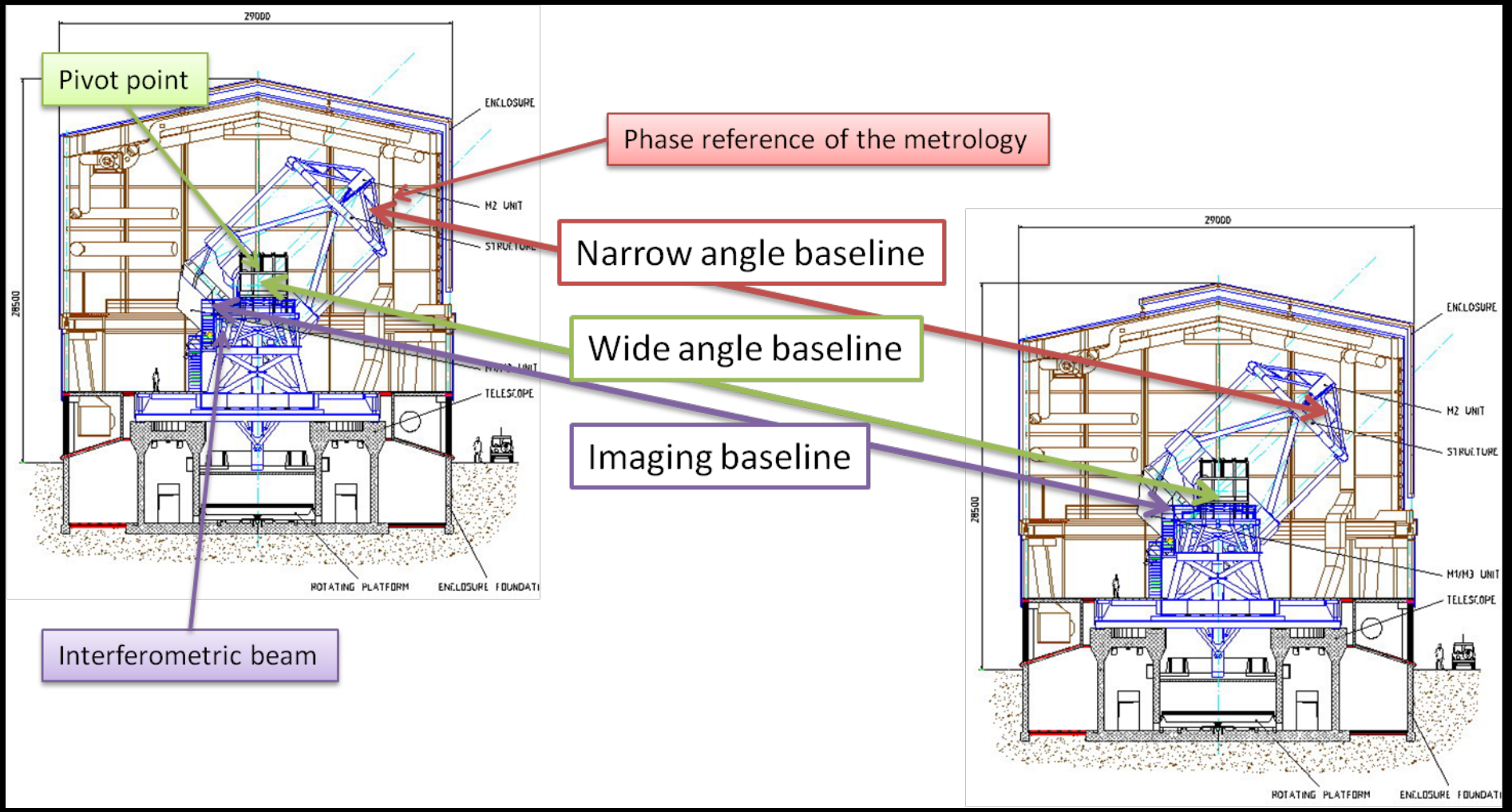
Jacou et al., Perraut et al., Perrin et al.



Straubmeier et al.

Interferometric baseline

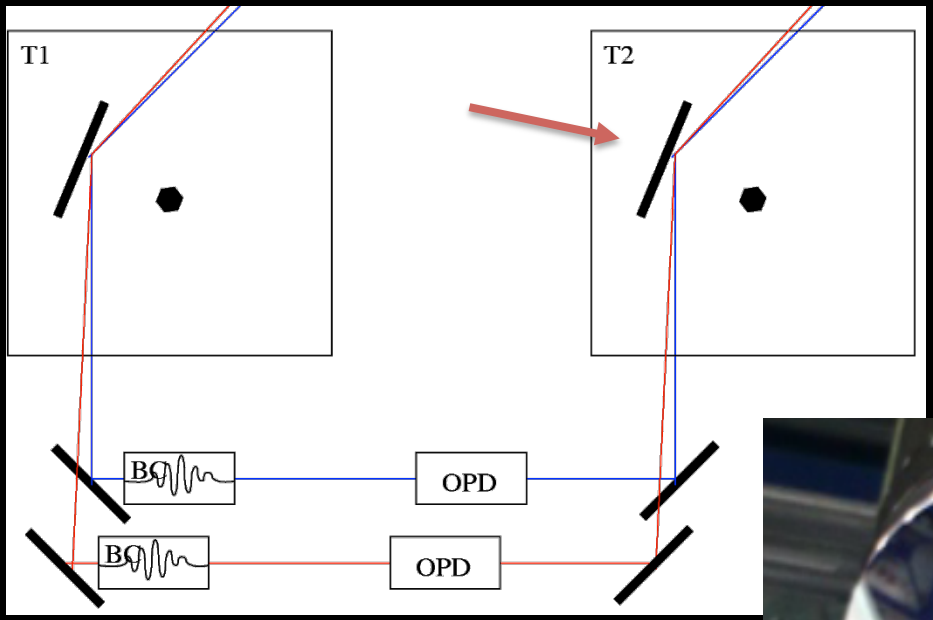
$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$



Lacour et al.

GRAVITY narrow angle baseline and metrology

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

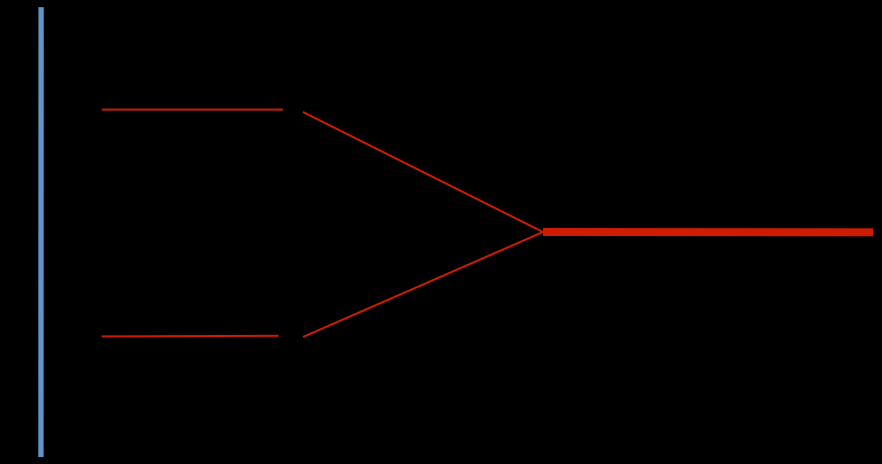


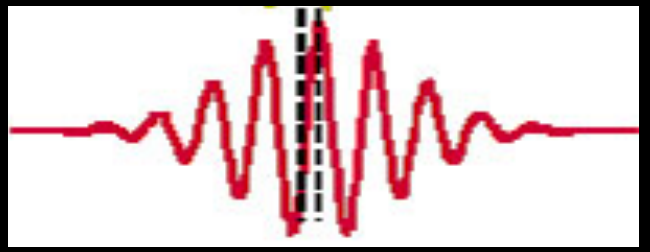
Stable realization of the narrow angle baseline

Gillessen, Bartko, Rabien et al.

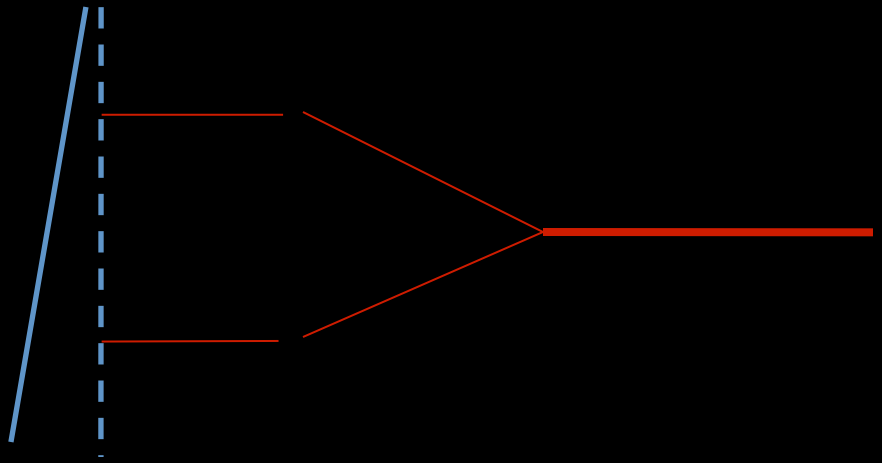
Pupil and tilt errors

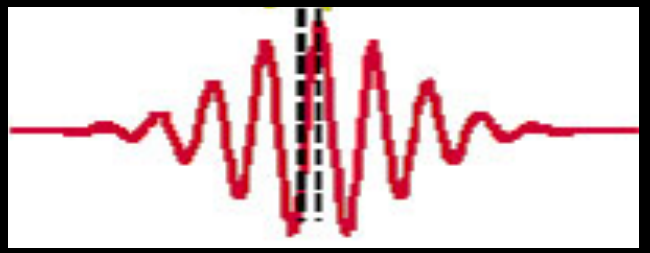
For perfect tip-tilt correction





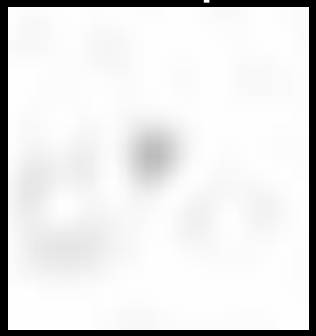
For simultaneous tilt error

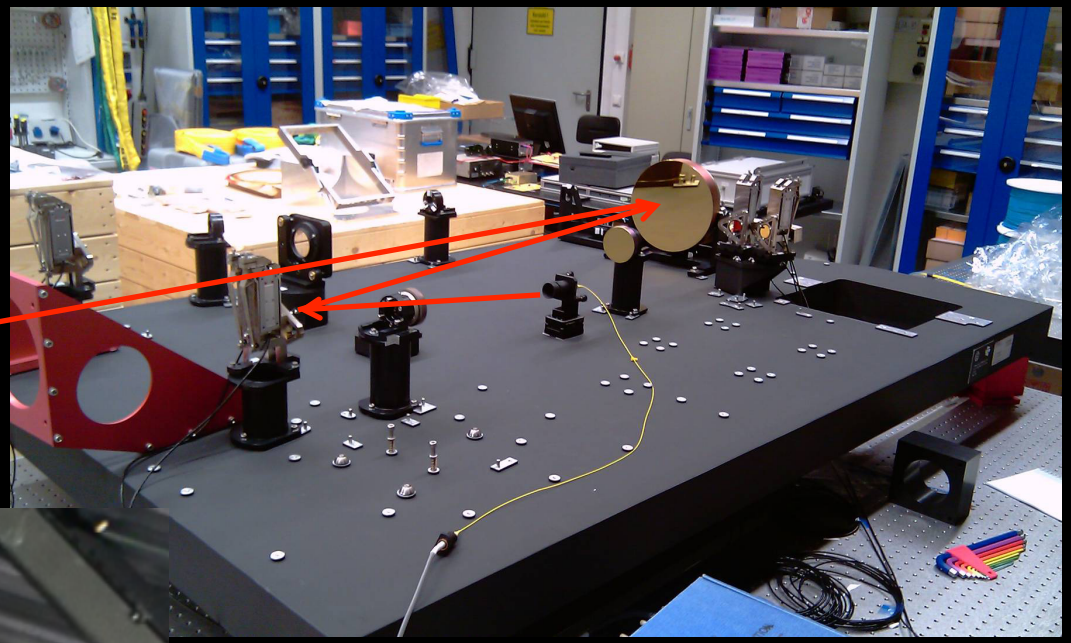


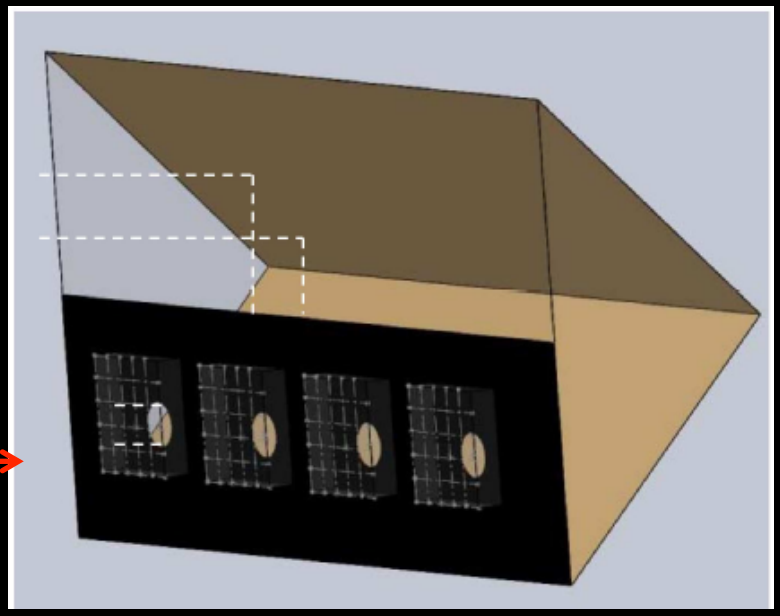


GRAVITY tip/tilt and pupil control

Atmosphere VLTI Tunnel

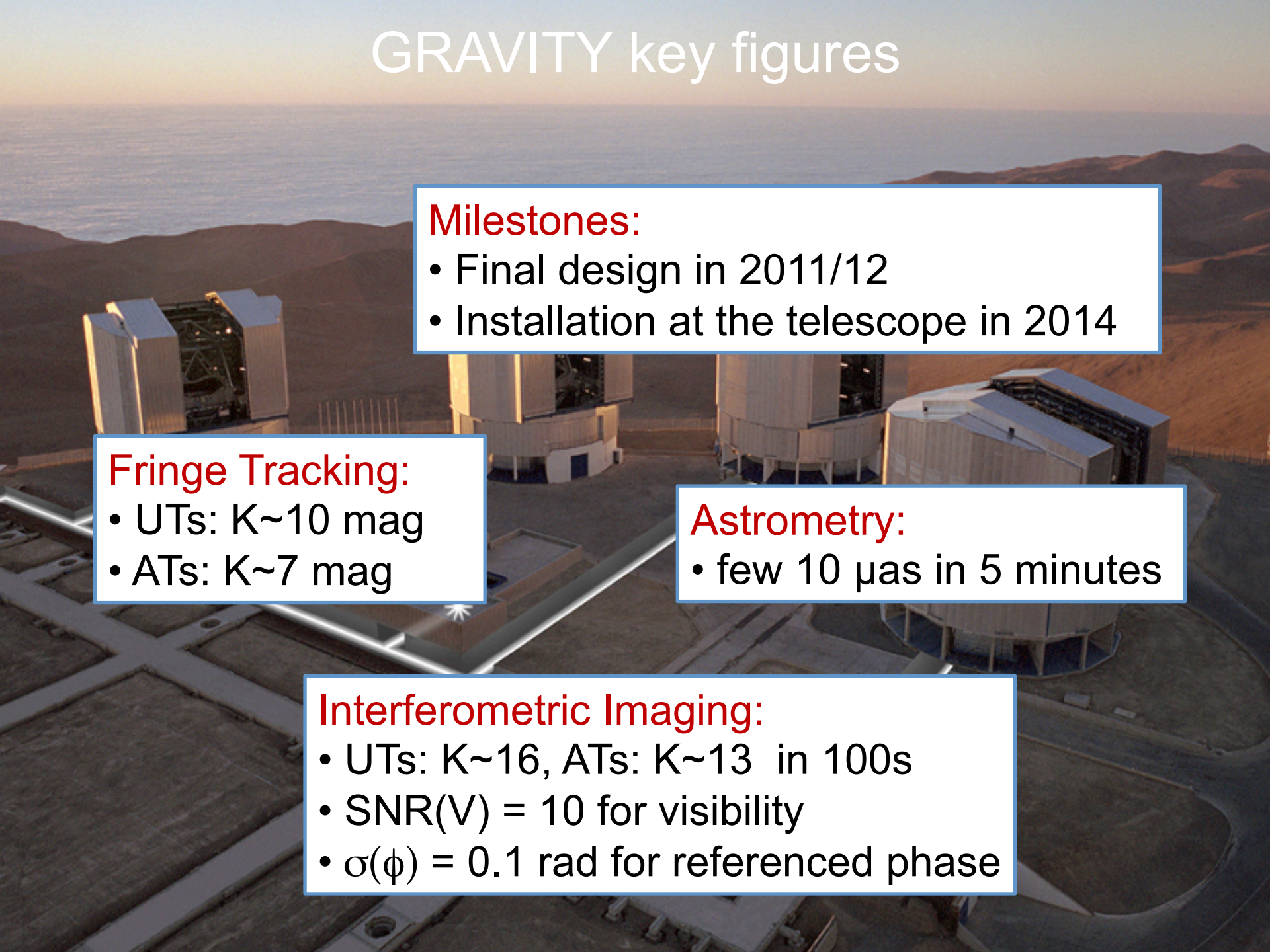






Pfuhl et al., Amorim et al.

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

Back to astrophysics – Galactic Center

The nature of flares and the properties of the black hole

Probing general relativity and relativistic stellar systems

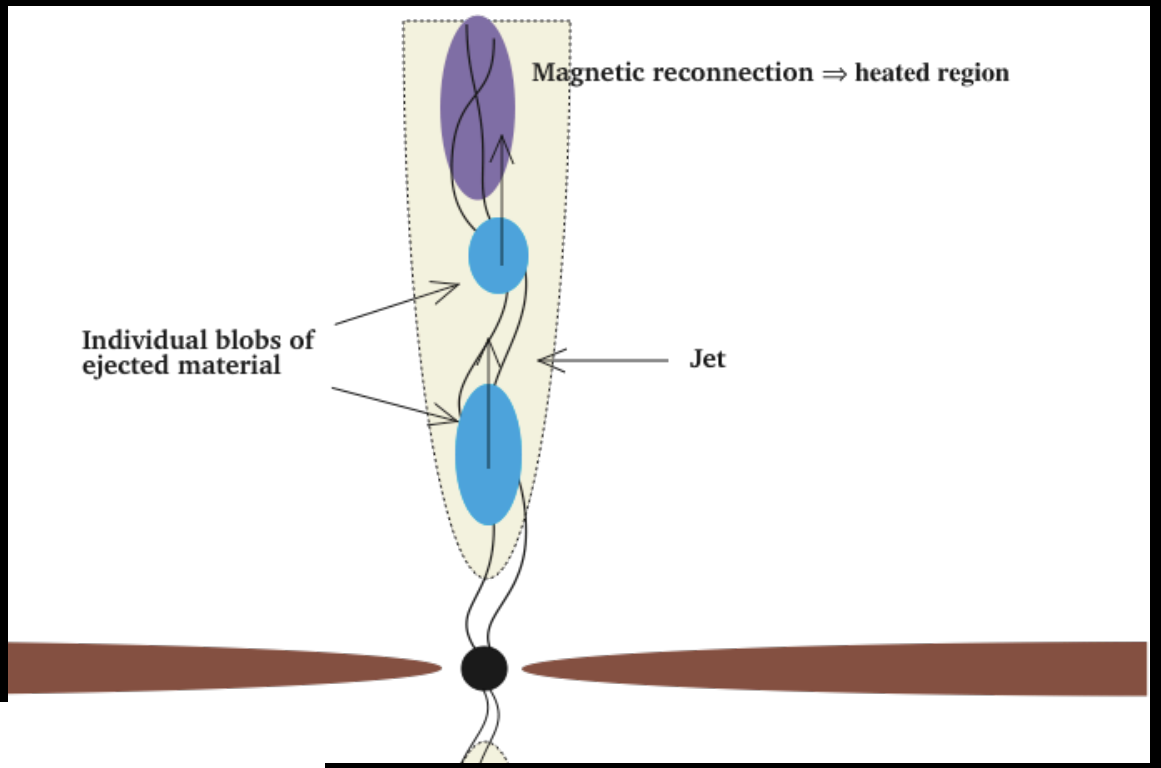
Resolving the Paradox-of-Youth

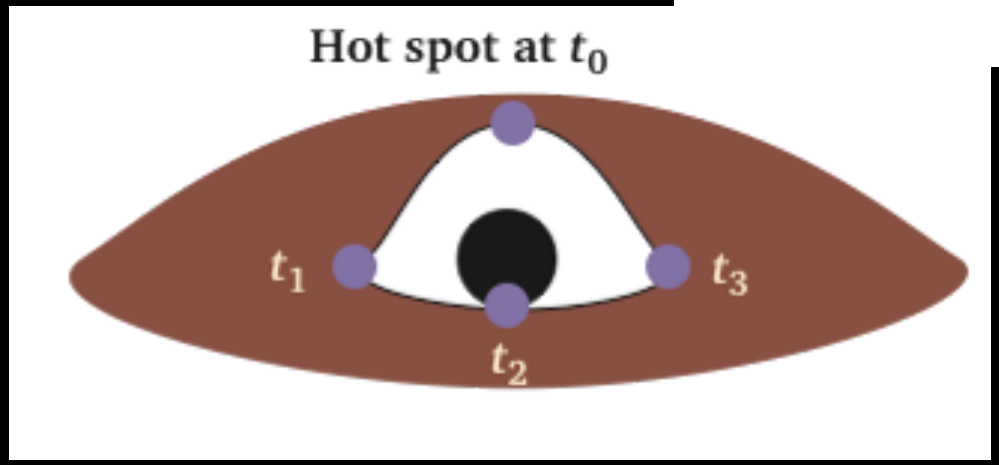
The nature of flares

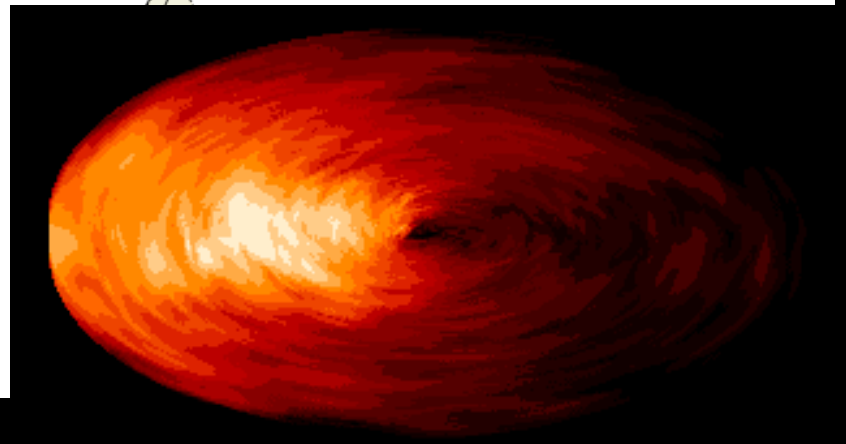
Three competing scenarios

- Jet
- Orbiting hot spot
- Statistical fluctuations

Let's have a look

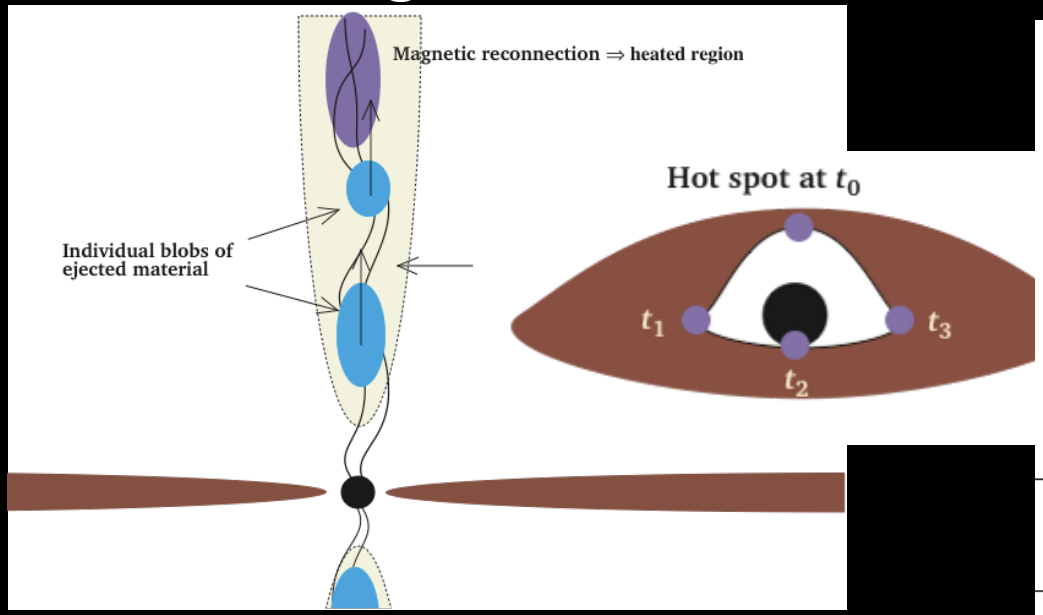


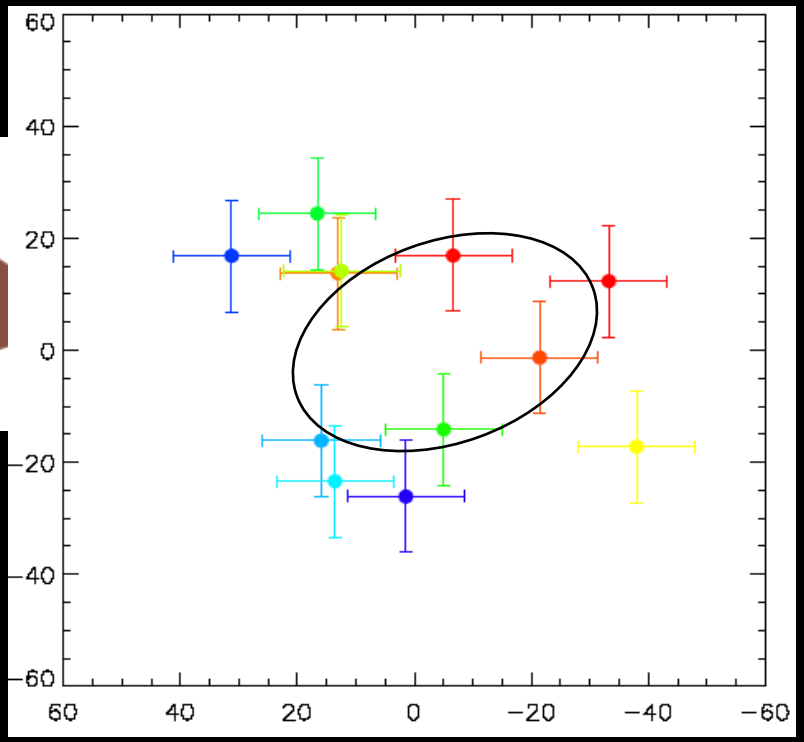




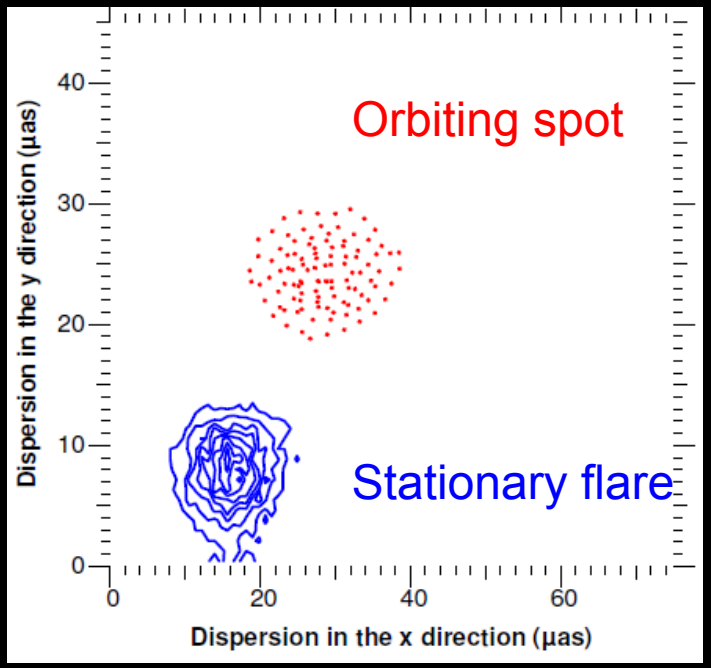
Chan et al. 2009

Probing the nature of flares with GRAVITY





Paumard et al. 2005

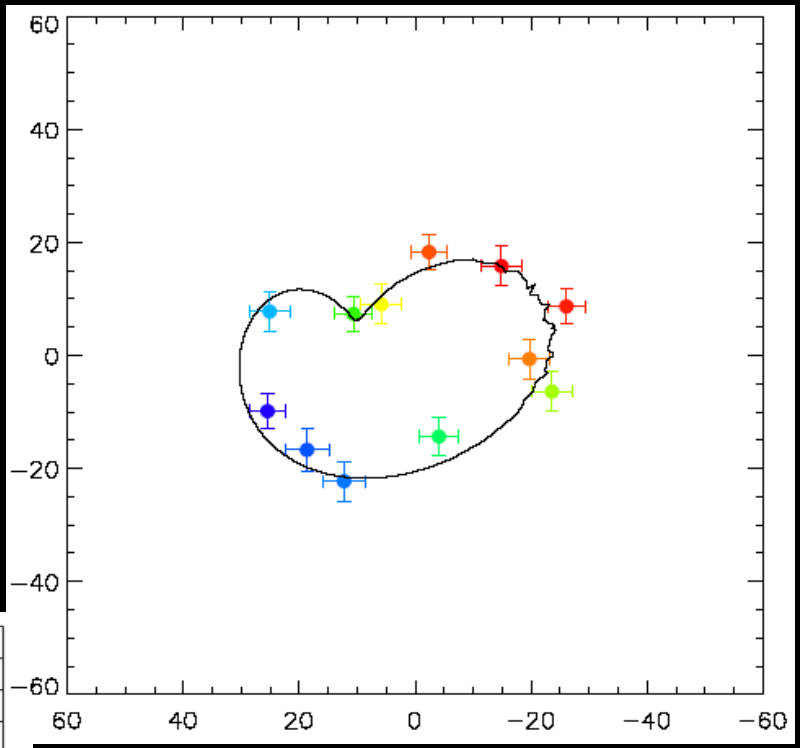


Vincent et al. 2010

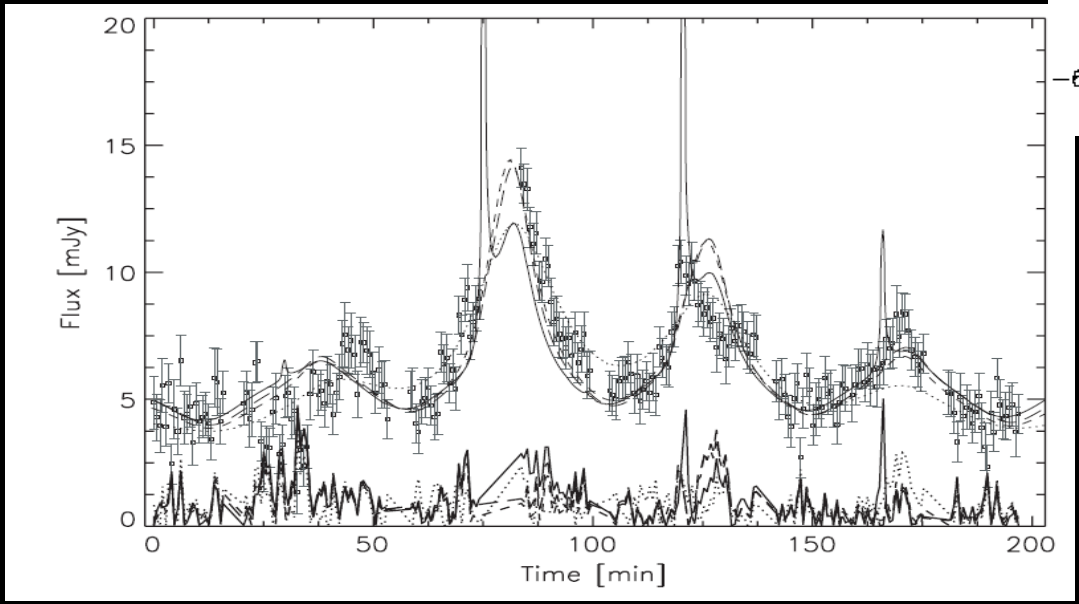
Probing the spin and its inclination

"Coherently"
add flares

Simultaneously
fit light curve
and orbit

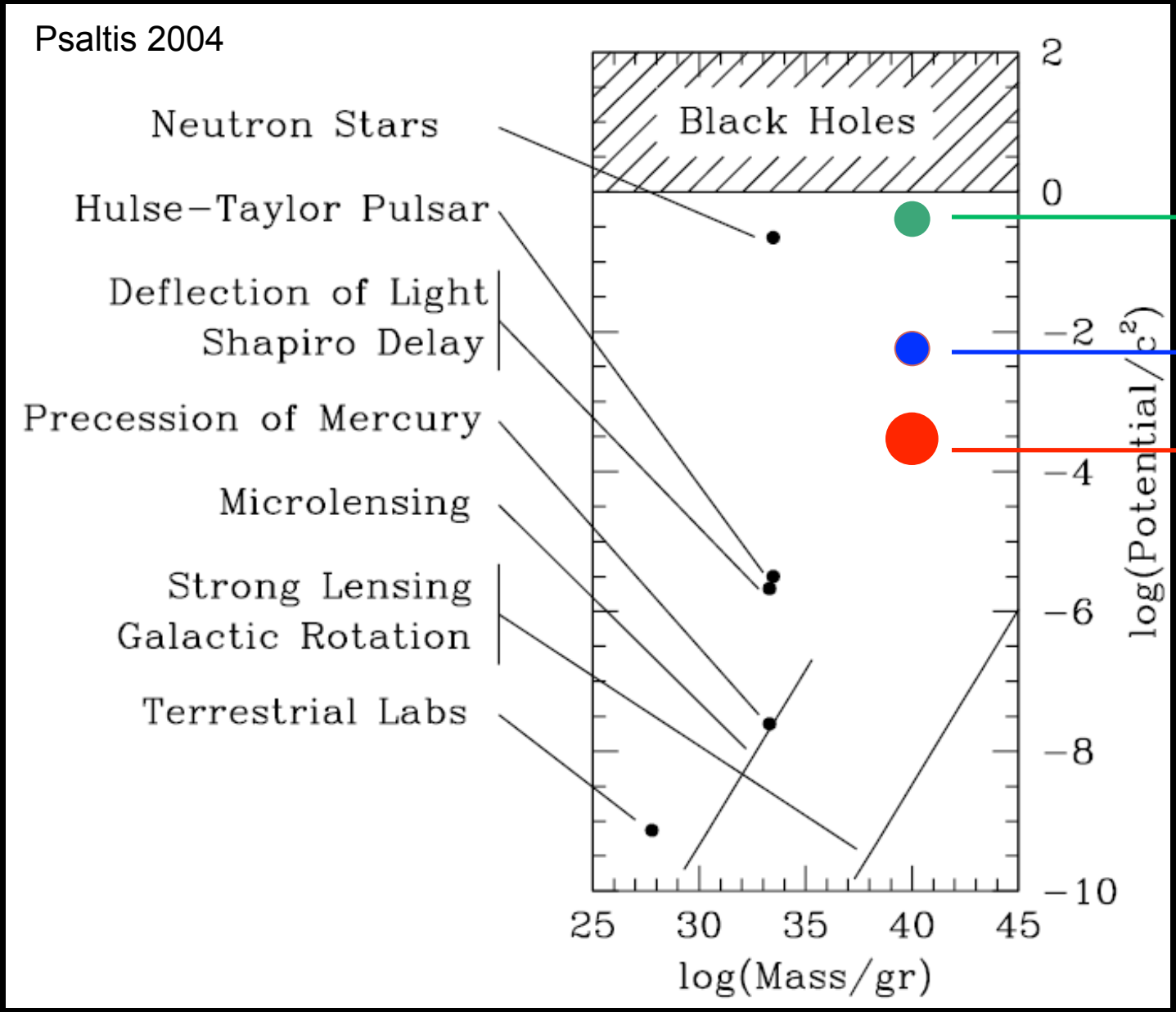


Paumard et al. 2005



Hamaus et al. 2009, Mayer et al. 2010

Probing General Relativity



Galactic center

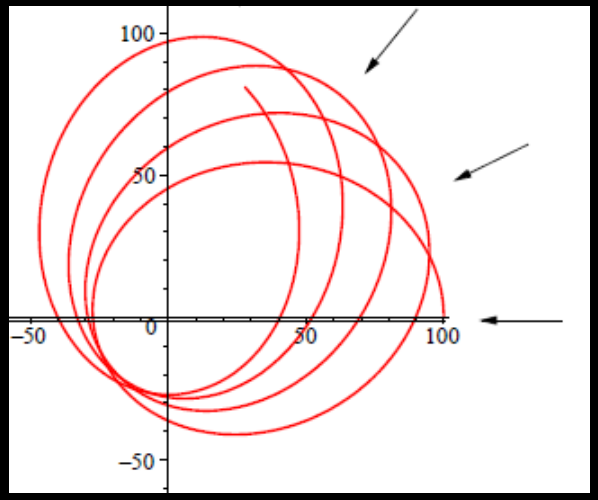
flares

central cusp

S-star orbits

β^2 general relativistic effects in S-star orbits

Periastron shift



Jaroszynski 1998, Fragile & Mathews 2000, Rubilar & Eckart 2001, Weinberg et al. 2005

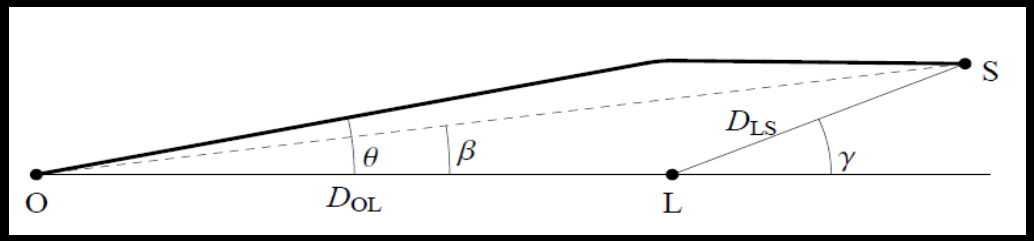
Einstein Equivalence Principle

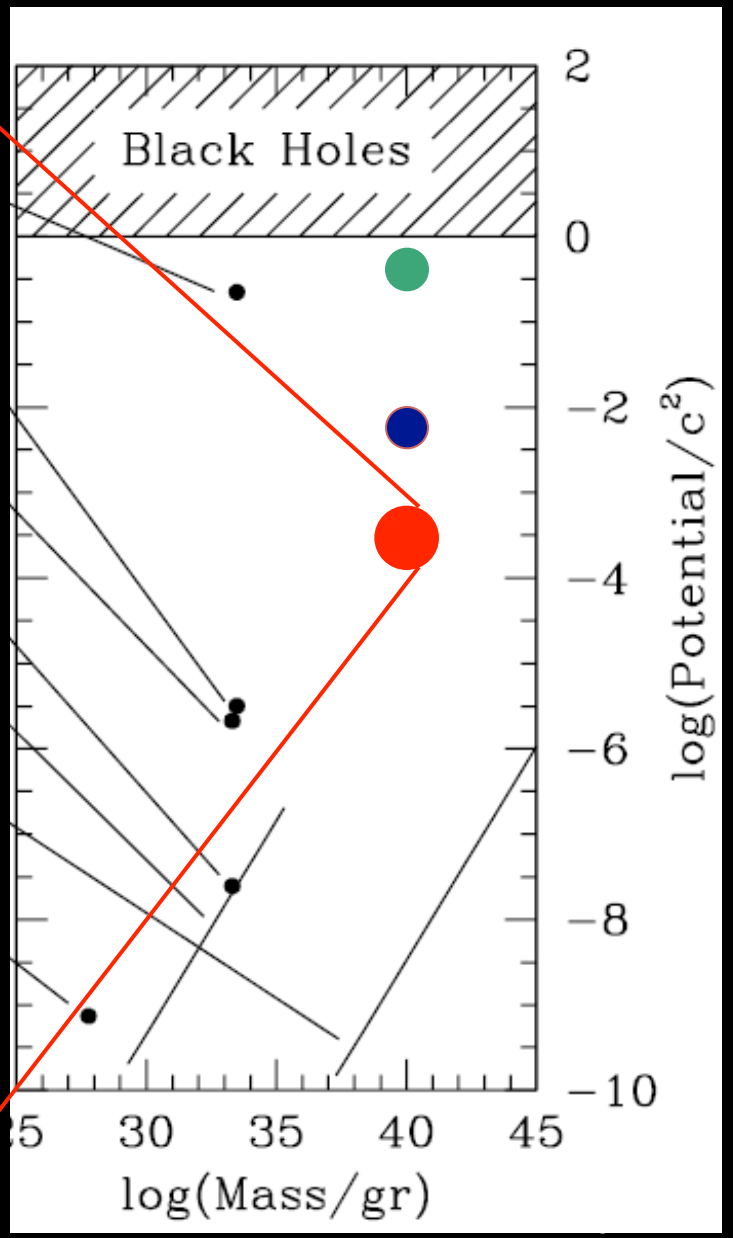
$$\frac{\nu_0}{\nu} = (1 + v_{\rm los})\left(1 + \frac{2}{r}\right).$$

Angélil & Prasenjit 2011, Zucker et al. 2006

Lensing

Bozza & Mancini 2012





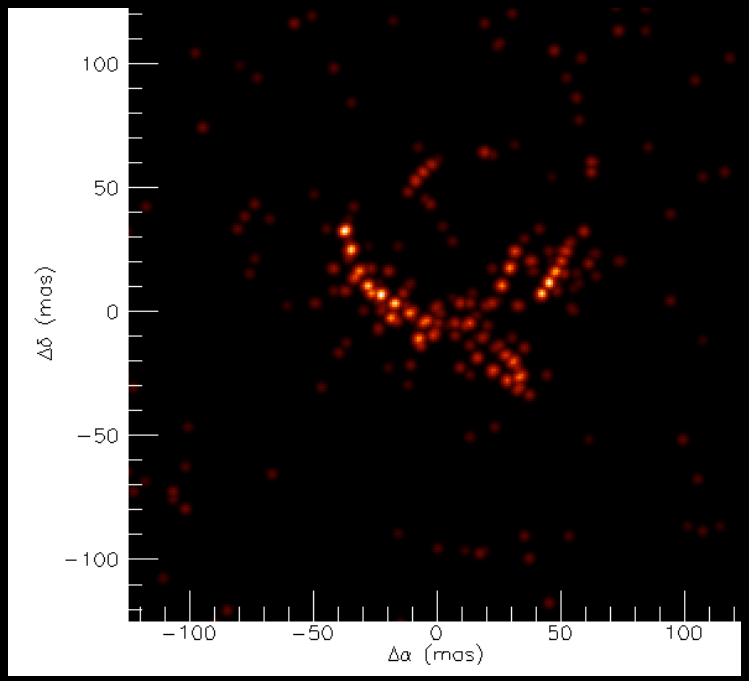
Lense Thirring precession and no-hair theorem

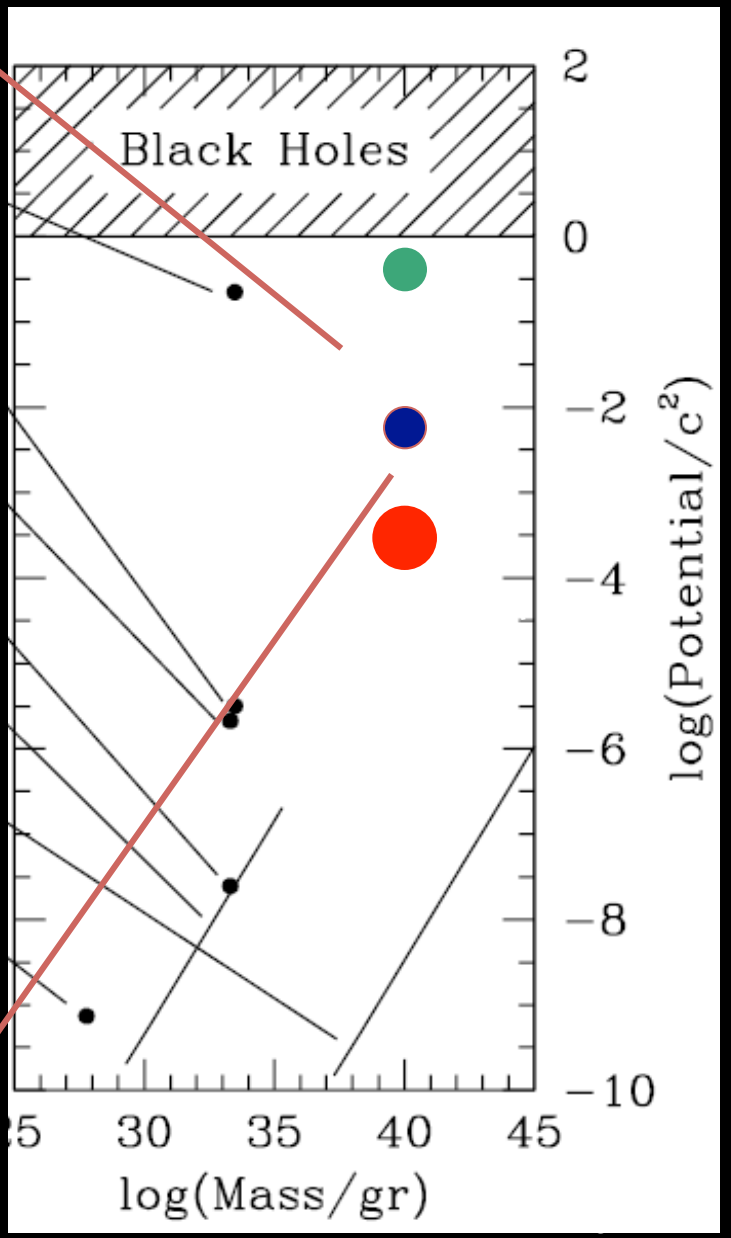
Precession of the angular momentum vector and quadrupole moment

$$\begin{aligned}\dot{\Theta}_J &\approx 0.847\,\chi P^{-4/3}(1-e^2)^{-3/2}\,,\\ \dot{\Theta}_{Q_2} &\approx 9.68\times 10^{-3}\,\chi^2 P^{-5/3}(1-e^2)^{-2}\end{aligned}$$

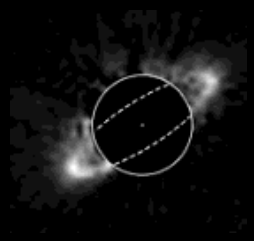
$$\begin{aligned}\sin i\Delta\Omega &= \sin\alpha\sin\beta(A_J - A_{Q_2}\cos\alpha)\\ \Delta i &= \sin\alpha\cos\beta(A_J - A_{Q_2}\cos\alpha)\end{aligned}$$

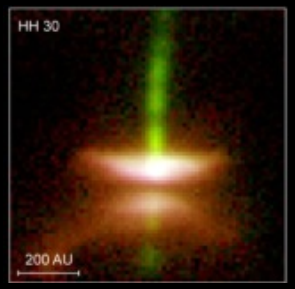
Will 2008, Merritt et al. 2009





GRAVITY: Observing the Universe in Motion





ten year large program

three year program

single season campaign

orbit of exo-Jupiter/Uranus

detection of intermediate mass BH in GCs/Arches

stellar motions in nuclei of nearby galaxies

detection of SR/GR effects in cusp star orbits

detection of 'dark halo' around SgrA*

astrometric signal exo-Jupiter/Uranus

3d dynamics of nuclear star cluster

evolution outflows in YSOs & micro-QSOs

SgrA* flare dynamics

gas flows in AGN

proper motions massive star cluster

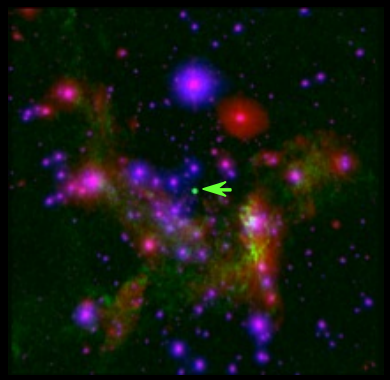
imaging jets/disks in YSOs & CBs

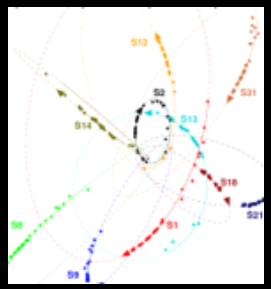
binary dynamics

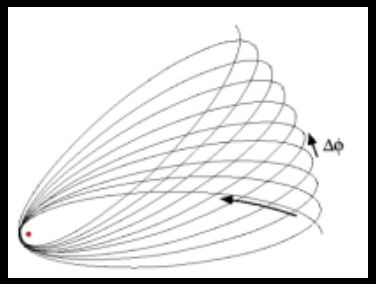
lensing

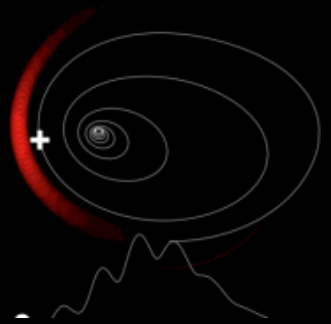
10^0 10^2 10^4 10^6

maximum distance from Earth (pc)









Thank you very much for your attention