Title: GRAVITY - Exploring Physics Close to the Galactic Center Black Hole with Infrared Interferometry

Date: Nov 12, 2014 11:10 AM

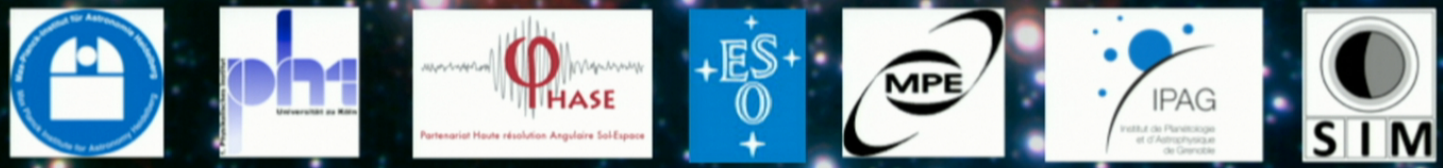
URL: http://pirsa.org/14110091

Abstract: GRAVITY is a new instrument combining the four 8m ESO Very Large Telescopes in Chile. Other than the BlackHoleCam / EHT with its focus on imaging the shadow of the black hole against the surrounding accretion flow, the goal of GRAVITY is to measure dynamical processes in the immediate vicinity of the black hole, for example the motion of matter close to the last stable orbit and relativistic effects in stellar orbits. Our presentation covers the experimental and astrophysical aspects of this project and highlights the complementarity with the submm interferometry to overcome the degeneracies in modelling the observations.

GRAVITY
Exploring Physics Close to the Galactic Center Black Hole with Infrared Interferometry

Stefan Gillessen,
replacing Frank Eisenhauer

Eisenhauer, Perrin, Brandner, Straubmeier, Rousselet-Perraut, Amorim, Abuter, Genzel, Kervella, Böhm, Eckart, Jocou, Garcia, Accardo, Pfuhl, Paumard, Deen, Wank, Moulin, Gordo, Delplancke-Stroebele, Gillessen, Lacour, Henning, Wiest, Magnard, Anugu, Finger, Blind, Clénet, Hippler, Yazici, Ventura, Lima, Garcia, Burtscher, Gendron, Huber, Lazareff, Gitton, Kok, Rousset, Klein, Monin, Jakob, Sturm, Habois, Laun, Benisty, Jochum, Haug, Fedou, Lenzen, Kern, Kellner, Lapeyrere, Neumann, Lizon, Wieprecht, Chapron, Panduro, Mehrgan, Ott, Dembet, Ramos, Schöller, Lippa, Sevin, Rohloff, Stroebele, Weber, Collin, Salzinger, Suarez, Valles, Haussmann, Ziegler, Scheithauer, Wittkowski, Hans, Azouaoui, Yang



GRAVITY

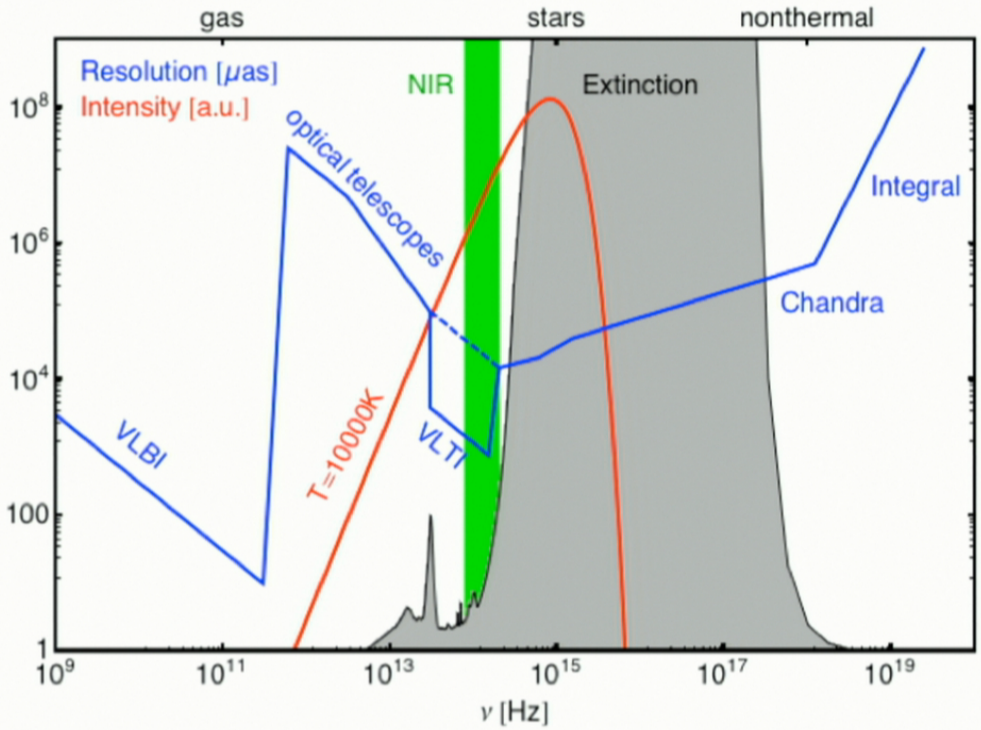
Exploring Physics Close to the Galactic Center Black Hole with Infrared Interferometry

Frank Eisenhauer

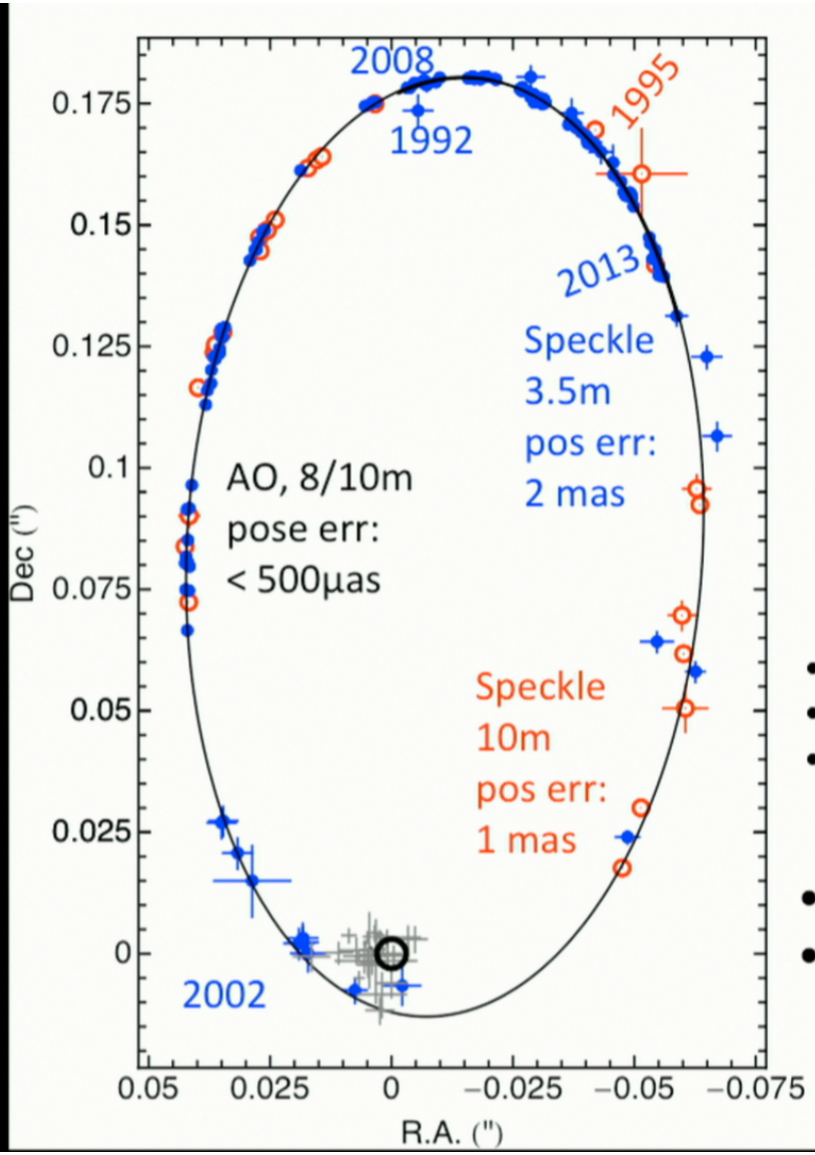
Eisenhauer, Perrin, Brandner, Straubmeier, Rousselet-Perraut, Amorim, Abuter, Genzel, Kervella, Böhm, Eckart, Jocou, Garcia, Accardo, Pfuhl, Paumard, Deen, Wank, Moulin, Gordo, Delplancke-Stroebele, Gillessen, Lacour, Henning, Wiest, Magnard, Anugu, Finger, Blind, Clénet, Hippler, Yazici, Ventura, Lima, Garcia, Burtscher, Gendron, Huber, Lazareff, Gitton, Kok, Rousset, Klein, Monin, Jakob, Sturm, Habois, Laun, Benisty, Jochum, Haug, Fedou, Lenzen, Kern, Kellner, Lapeyrere, Neumann, Lizon, Wieprecht, Chapron, Panduro, Mehrgan, Ott, Dembet, Ramos, Schöller, Lippa, Sevin, Rohloff, Stroebele, Weber, Collin, Salzinger, Suarez, Valles, Haussmann, Ziegler, Scheithauer, Wittkowski, Hans, Azouaoui, Yang

Philae landed!

The near-infrared is a sweet spot



- can see stars good tracers for gravity
- interferometry feasible



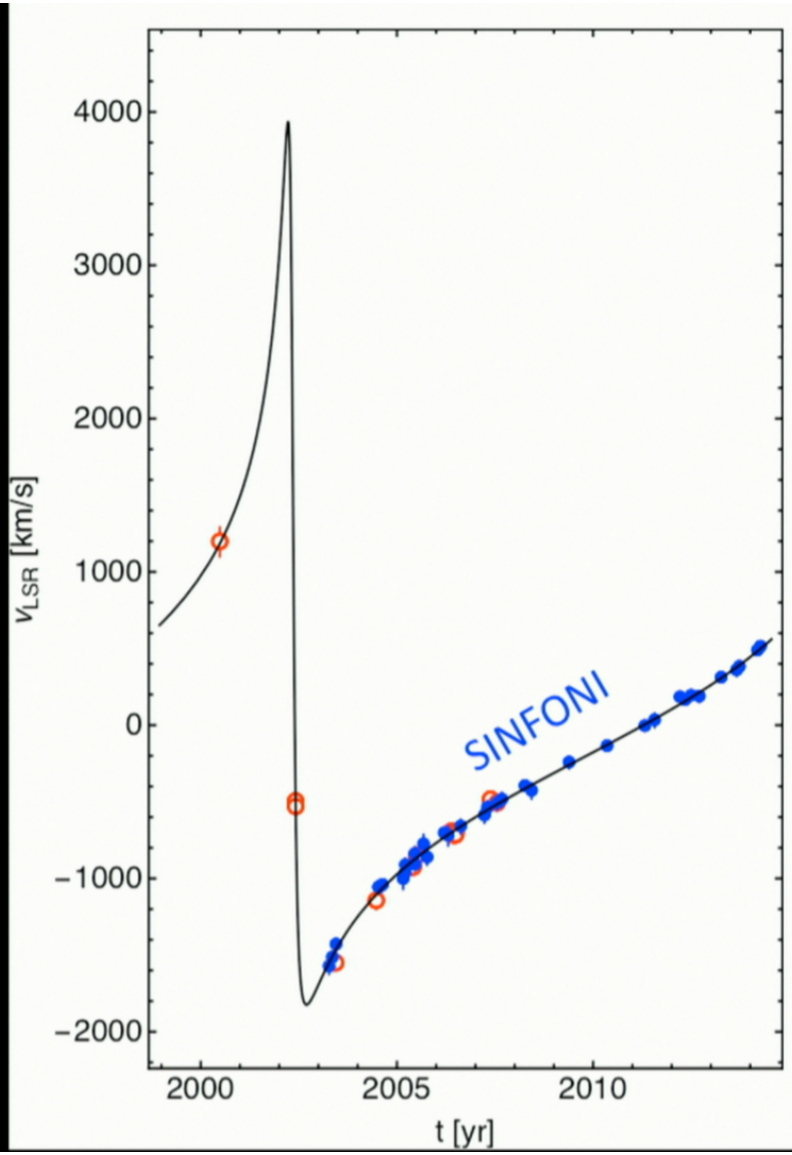
S2: the showcase star

VLT & Keck data suitably combined

(Gillessen et al. 2009ab, Ghez et al. 2008, newer data)

- period: 15.9 years
- semi major axis: 125 mas
- eccentricity 0.88

- $M = 4.30 \pm 0.06 \pm 0.35 \times 10^6\ M_\odot$
- $R_0 = 8.28 \pm 0.15 \pm 0.30$ kpc



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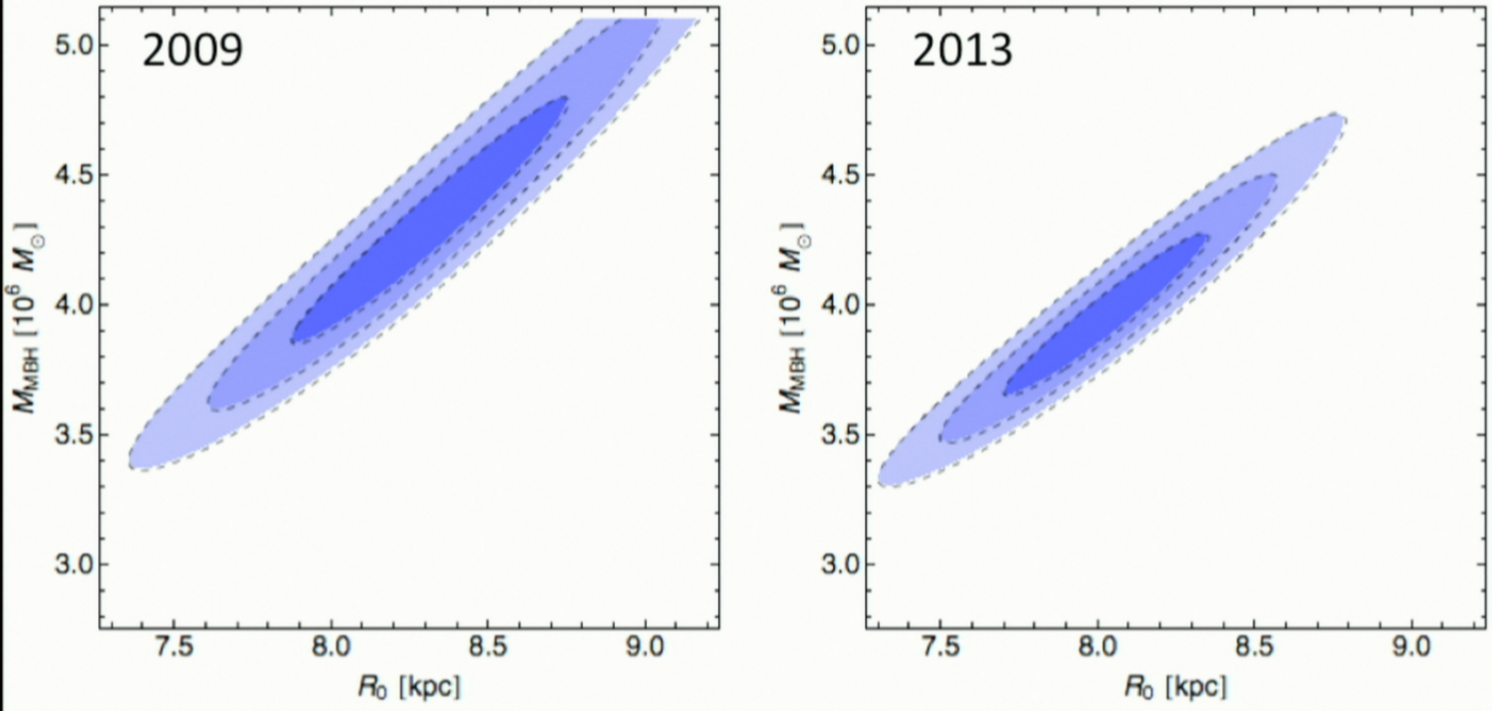
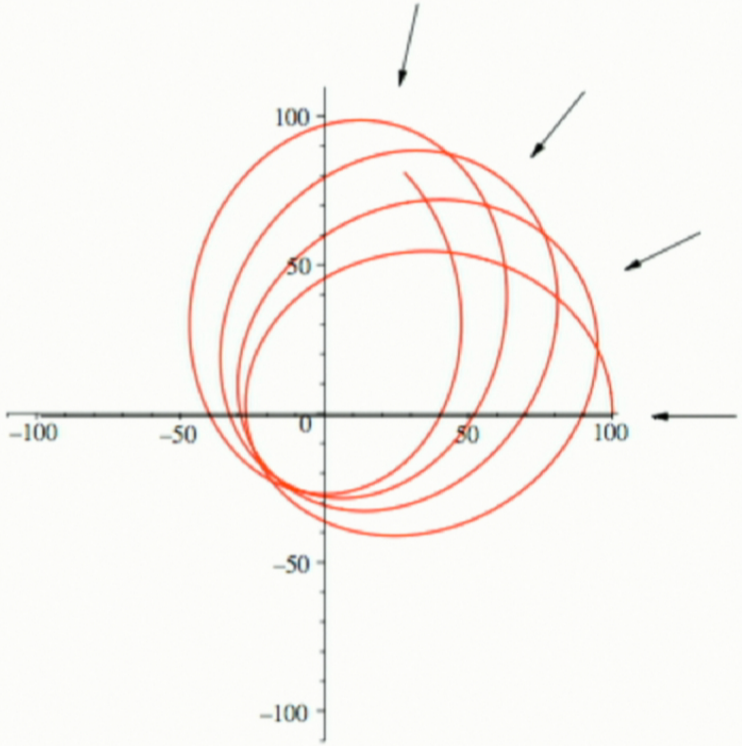
Mass and distance are highly correlated



We cannot measure the pericenter shift – not yet

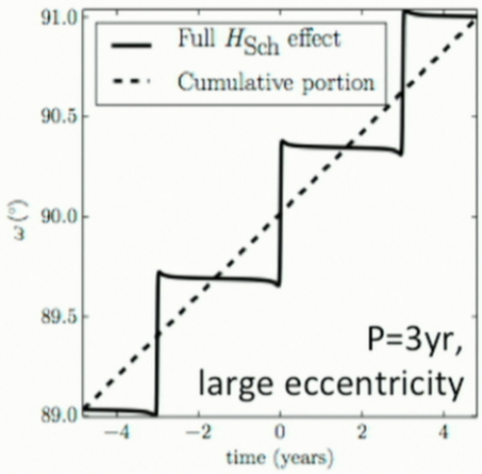


Rubilar & Eckart (2001)

expected:
$\Delta\omega = 0.22°$ per revolution
(16 years)

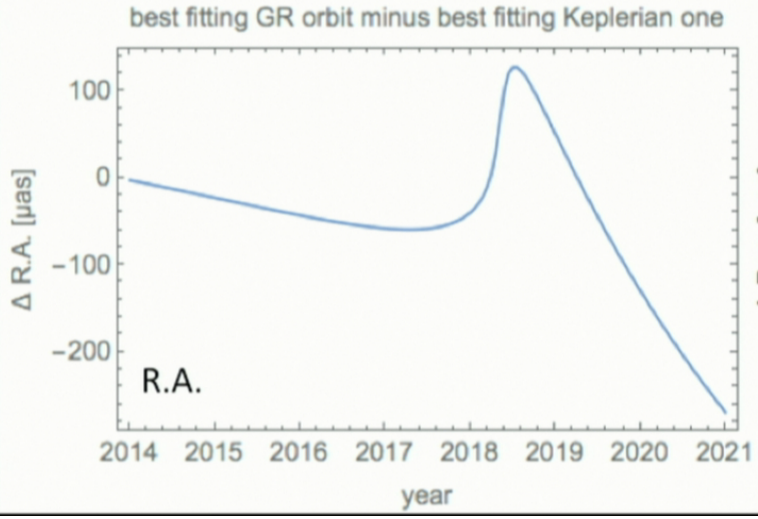
measurement error:
around that

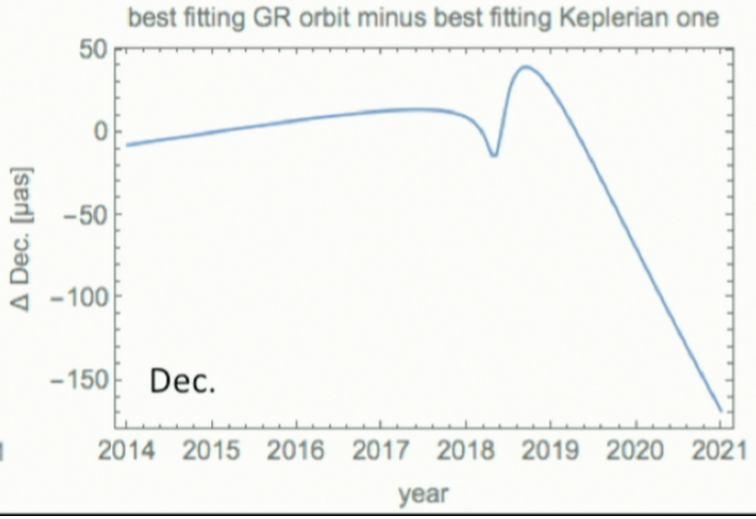
Precession "ticks"



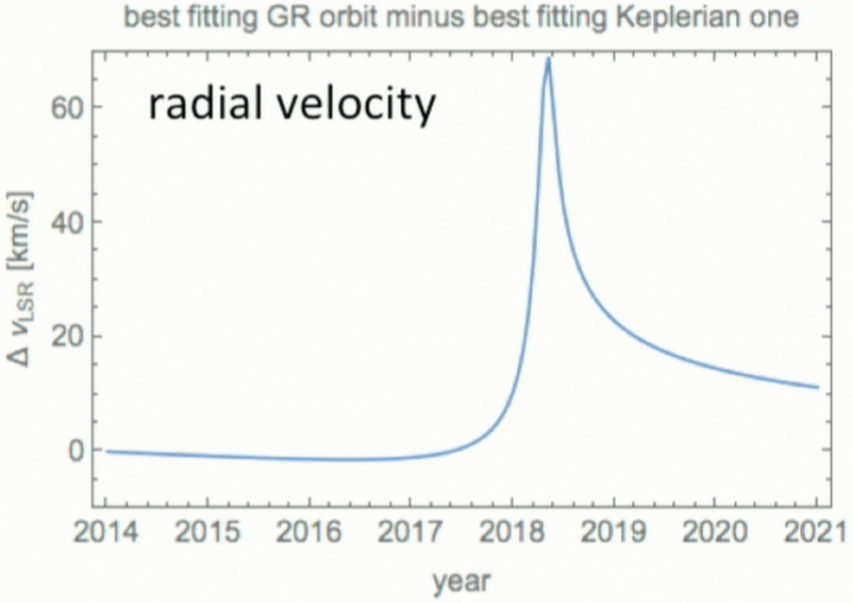
Angelil & Saha (2014)

Precession will be detected after next pericenter passage





Gravitational redshift: well within reach



- typical measurement error (SINFONI): 25km/s

Imagine we could zoom in further

Expected in central 100 mas:

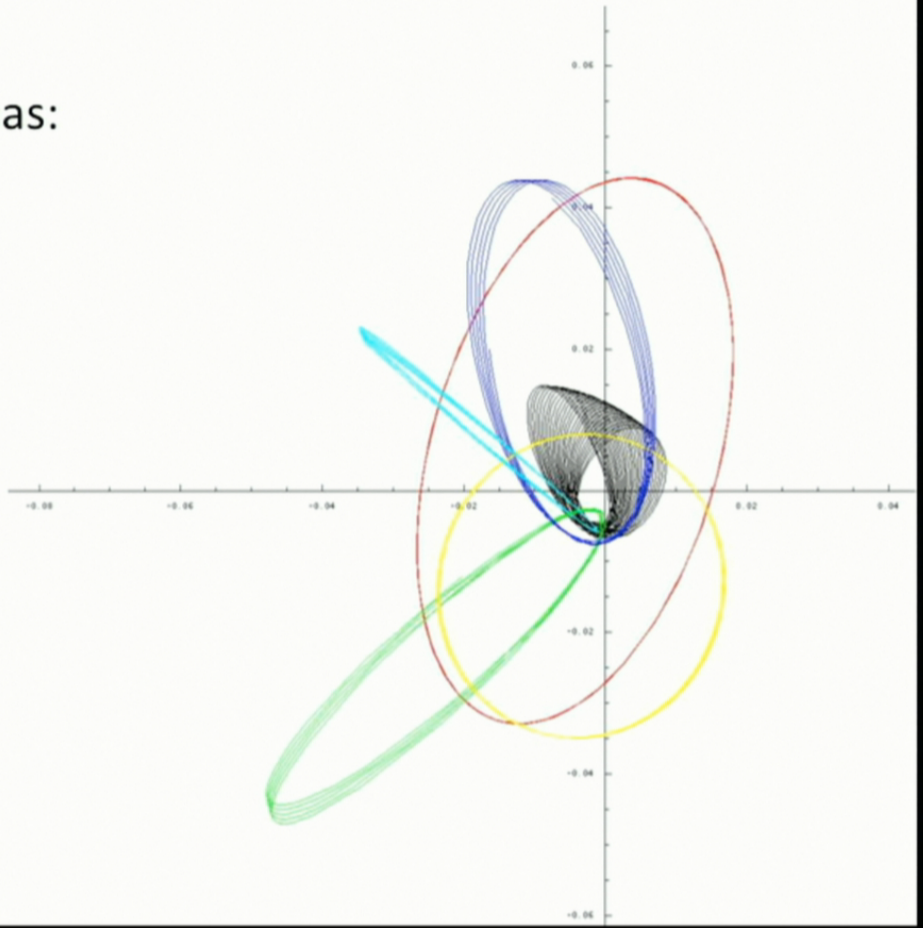
- 2 .. 10 stars
- K = 17 .. 19 mag

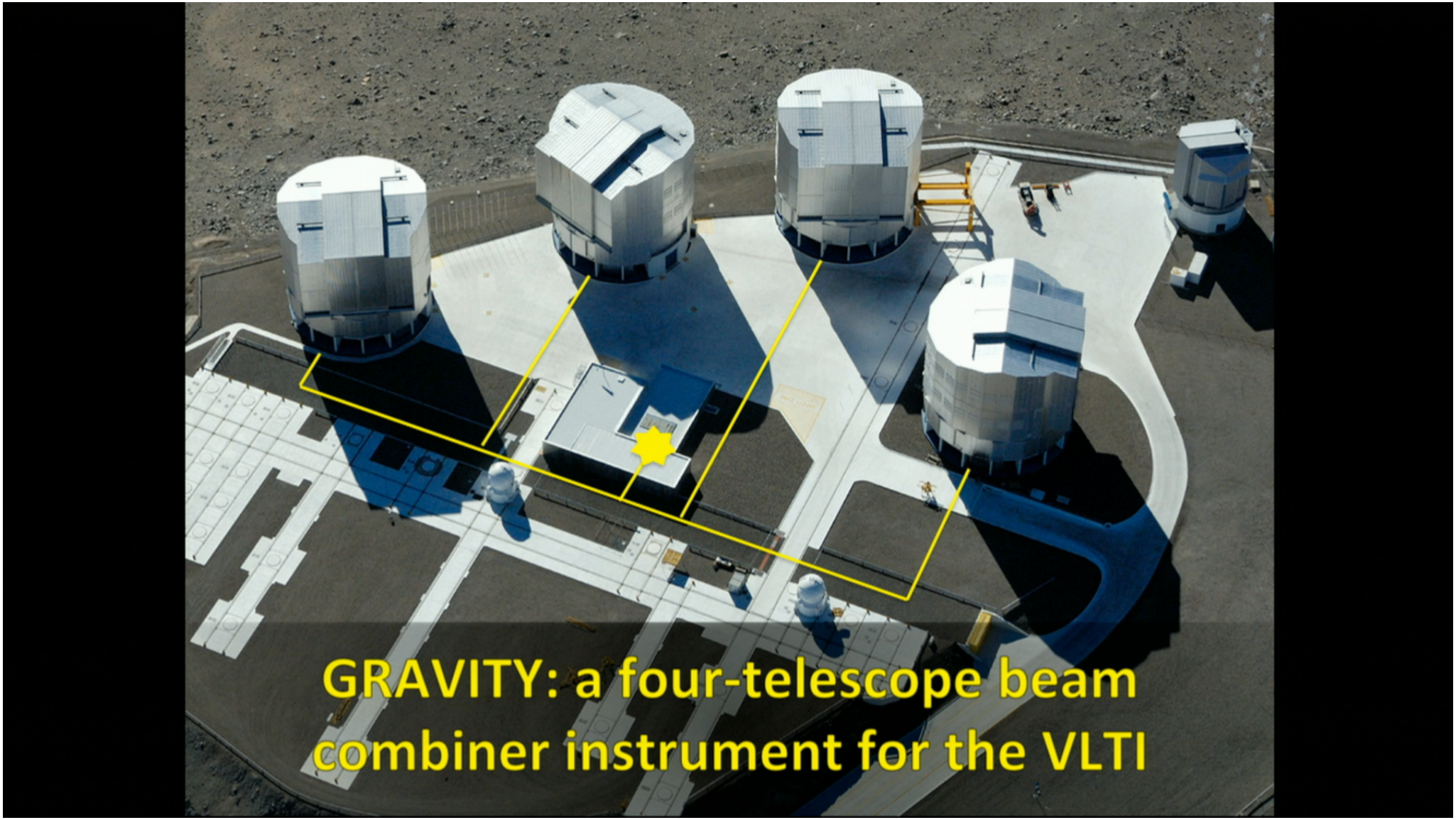
Orbital Period:

- 1 year

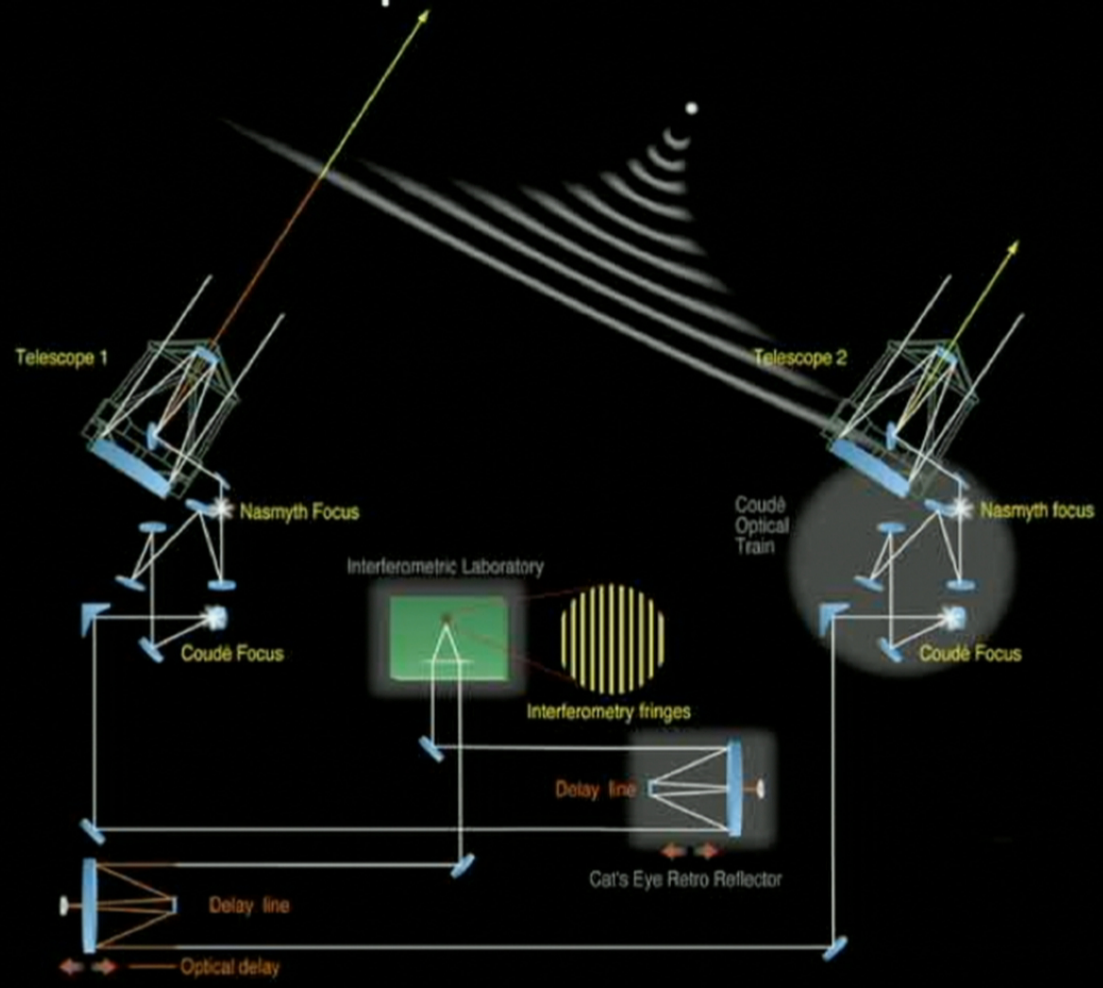
Precession:

- few ° per year



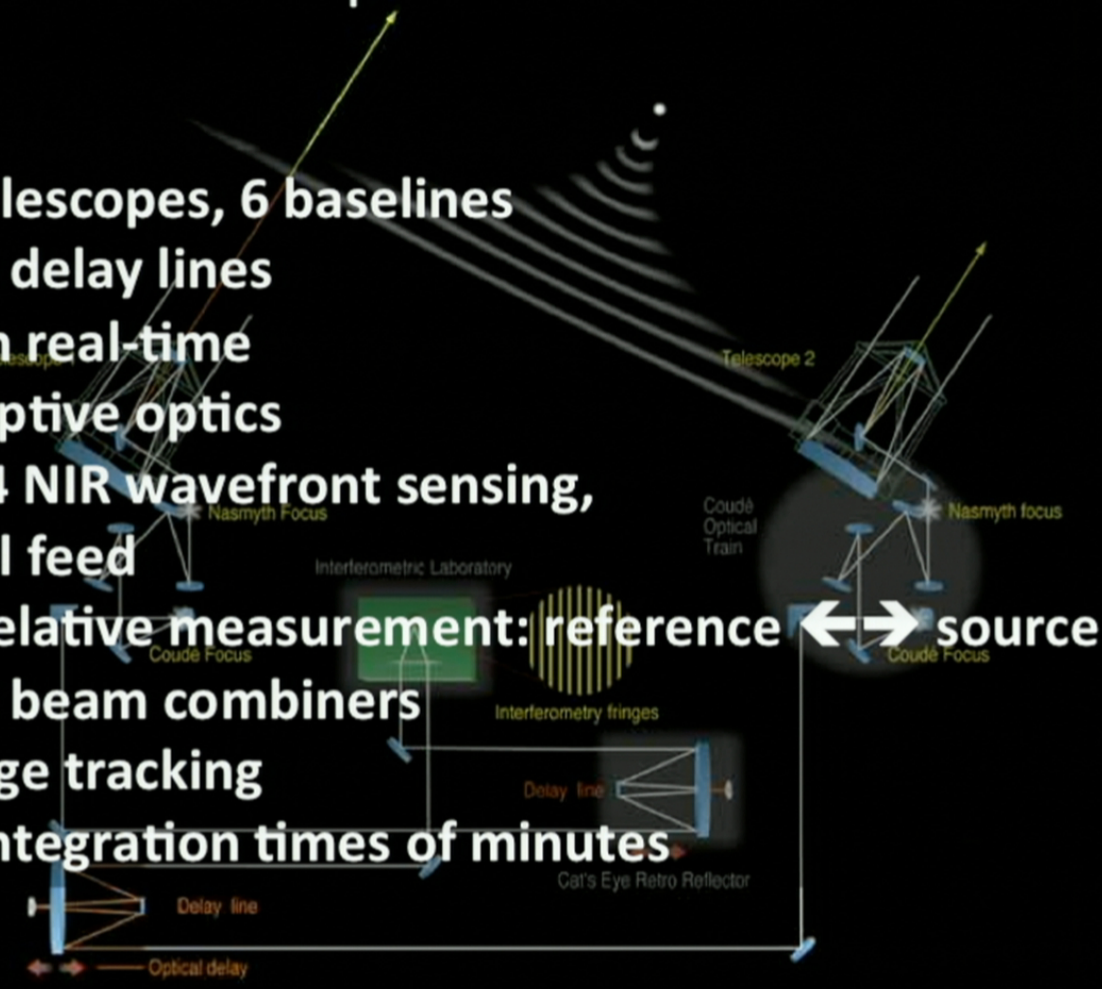

GRAVITY: a four-telescope beam combiner instrument for the VLTI

A complicated machine

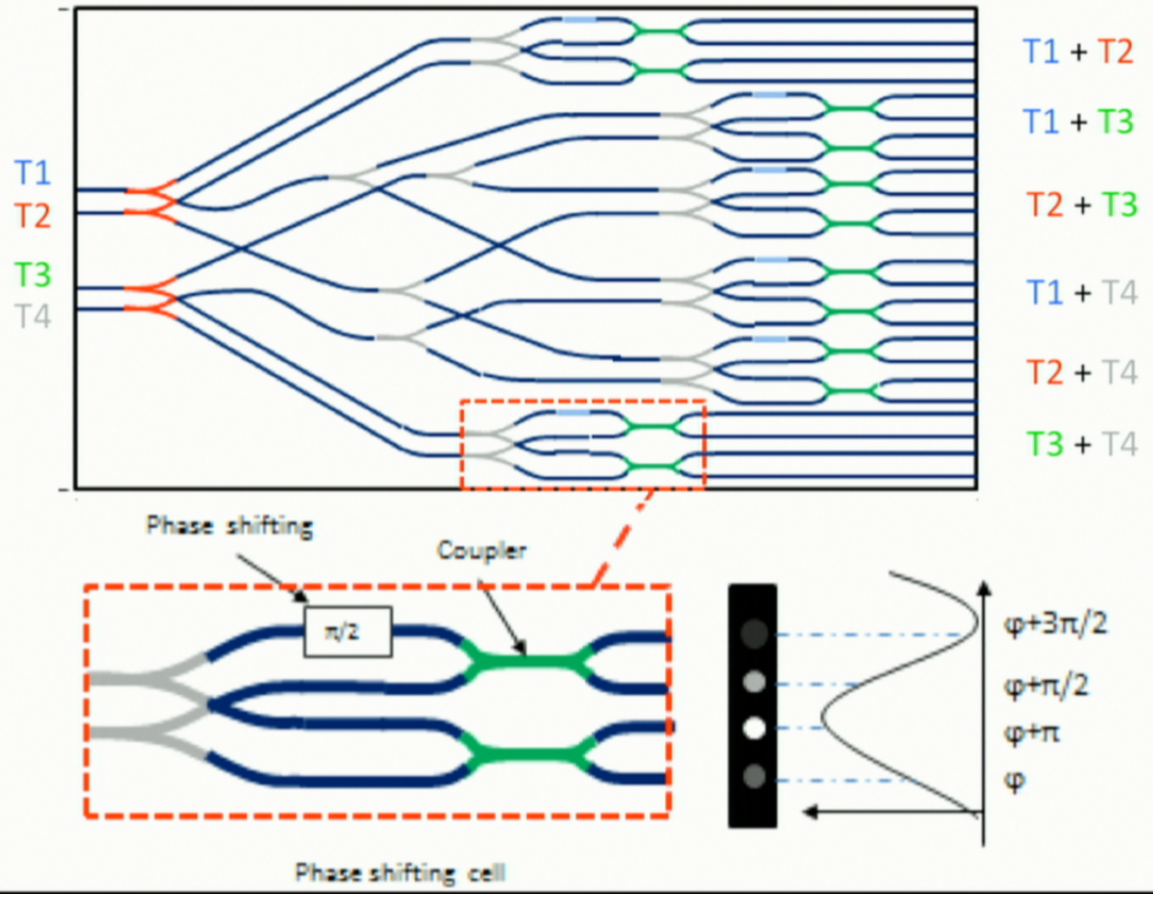


A complicated machine

- 4 telescopes, 6 baselines
  - 4 delay lines
  - in real-time
- adaptive optics
  - 4 NIR wavefront sensing,
- dual feed
  - relative measurement: reference ↔ source
  - 2 beam combiners
- fringe tracking
  - integration times of minutes



At the heart of GRAVITY: Integrated optics beam combiner



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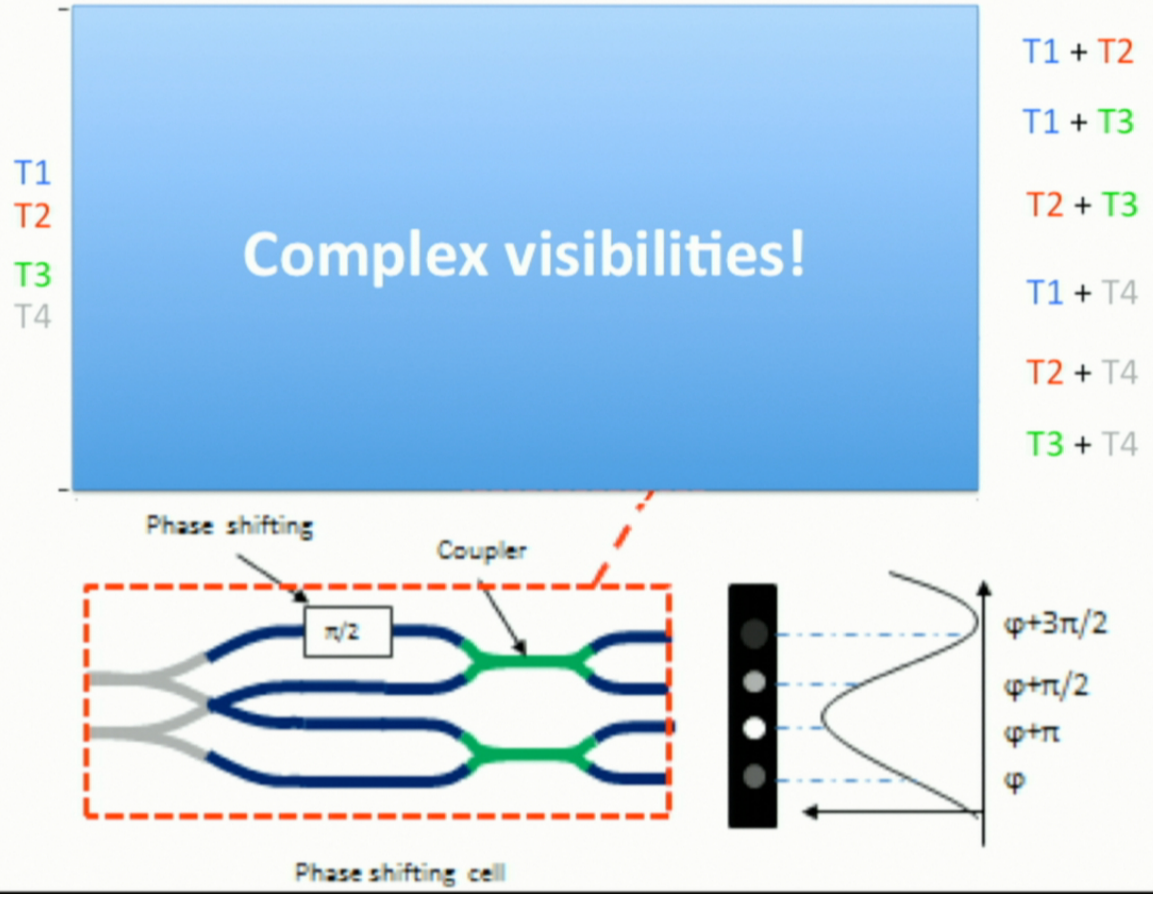
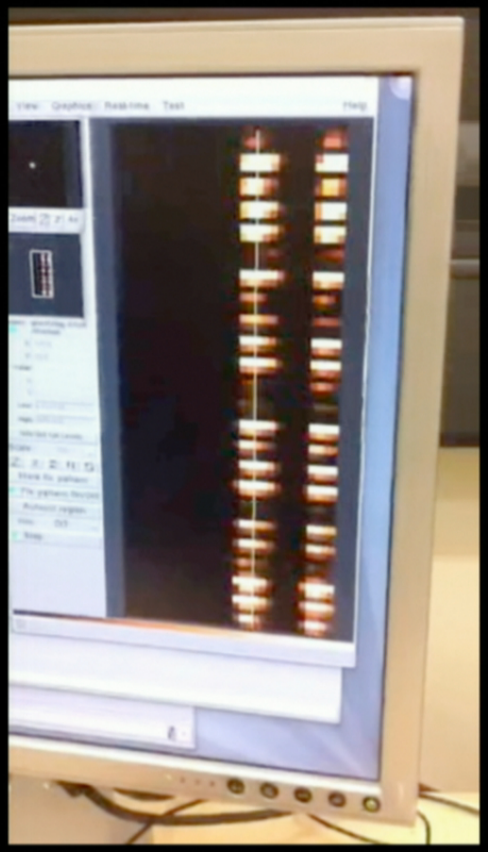


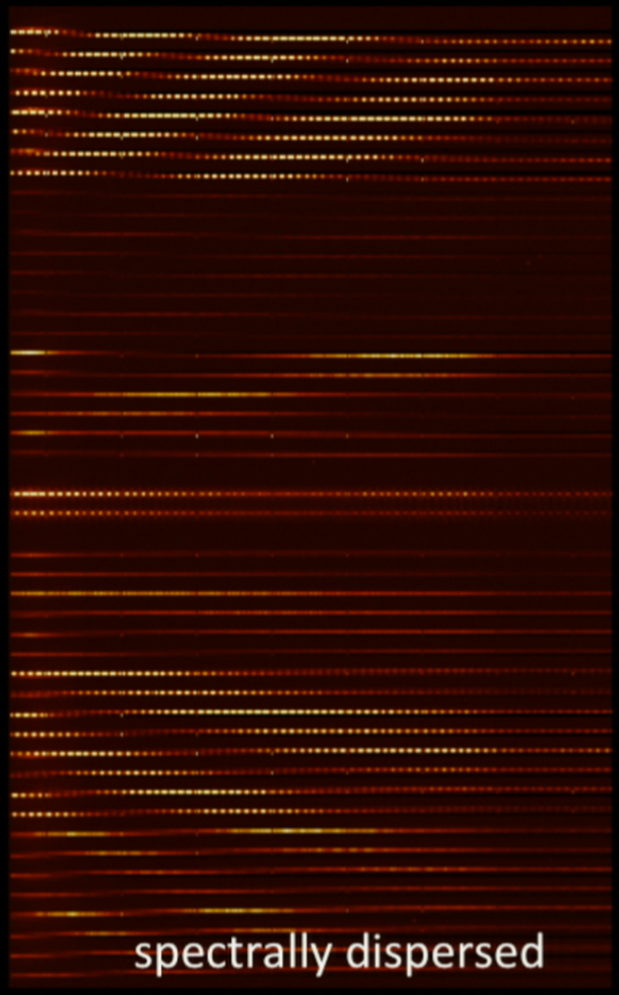
Fringes in the lab

undispersed

Fringes in the lab

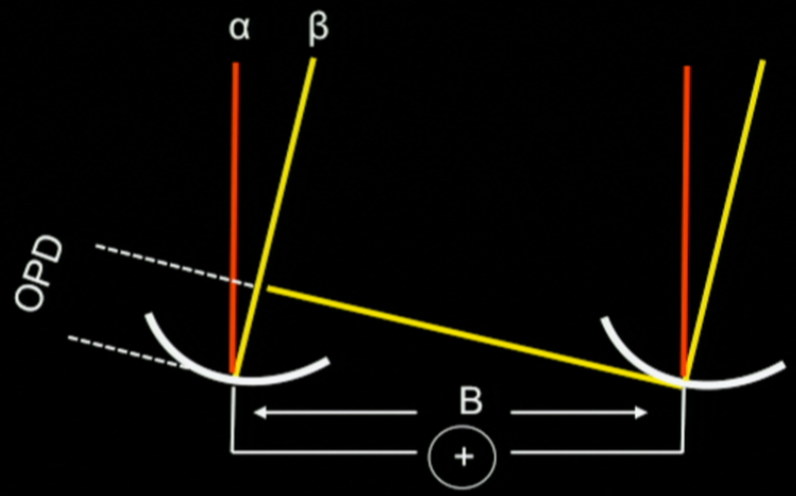


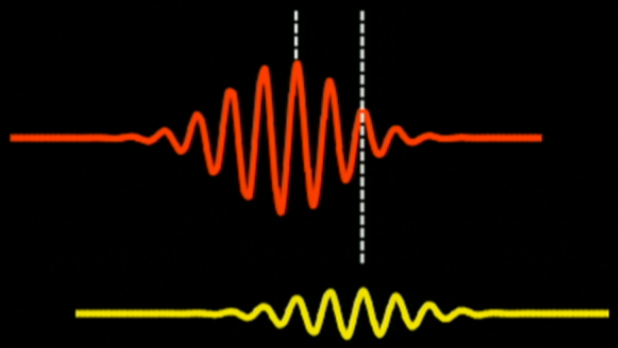
undispersed

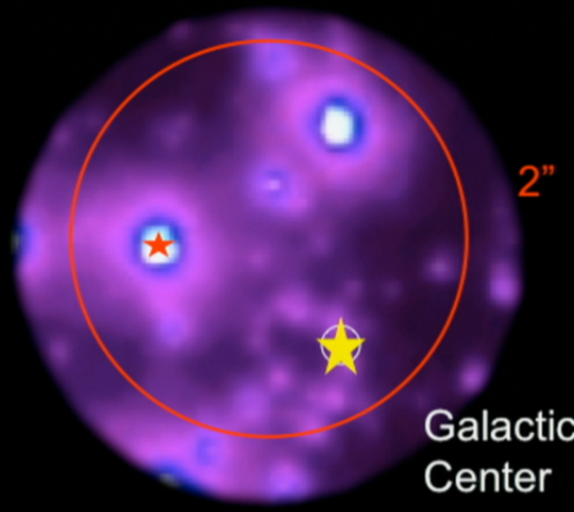


spectrally dispersed

Phase Referenced Imaging and Astrometry







Phase reference

Science object

Principle: easy
Implementation: difficult

$$OPD = B_{\mathrm{NAB}} \cdot (\alpha - \beta)$$

Lacour et al. 2014

Principle: easy
Implementation: difficult

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?

Goal: 10µas*sqrt(3) in 5 minutes

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

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

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

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. 2014

Simulations show:
GRAVITY can observe stars within 100mas of Sgr A*

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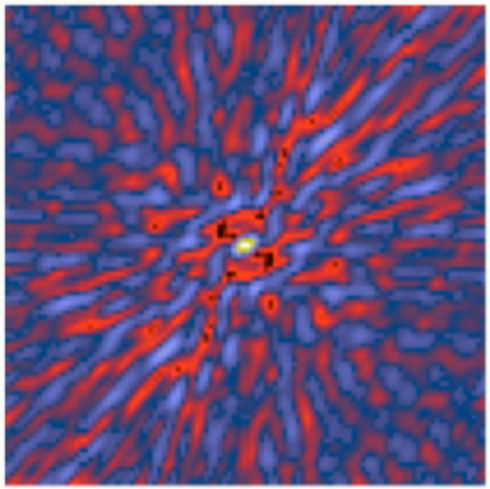
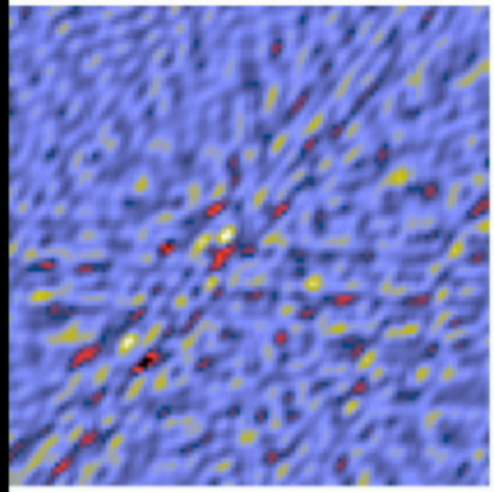
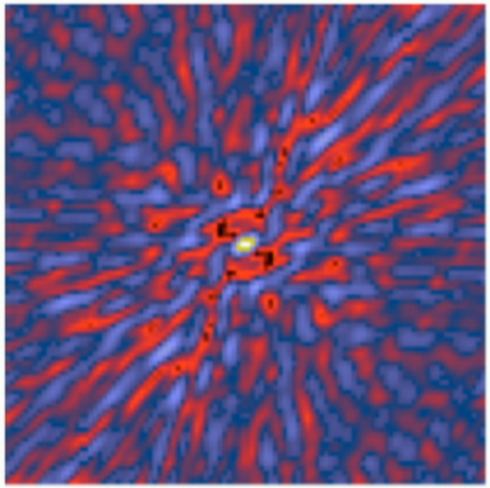


PSF: 4 UTs, K, 9 hrs

Simulations show: GRAVITY can observe stars within 100mas of Sgr A*



Simulated Image



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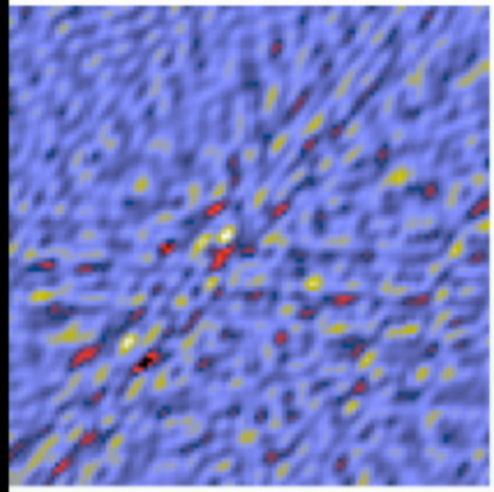
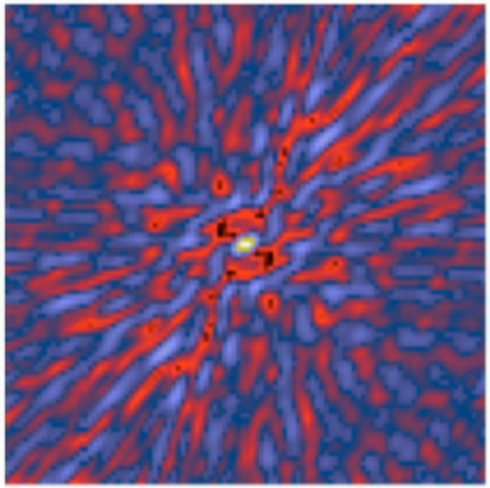
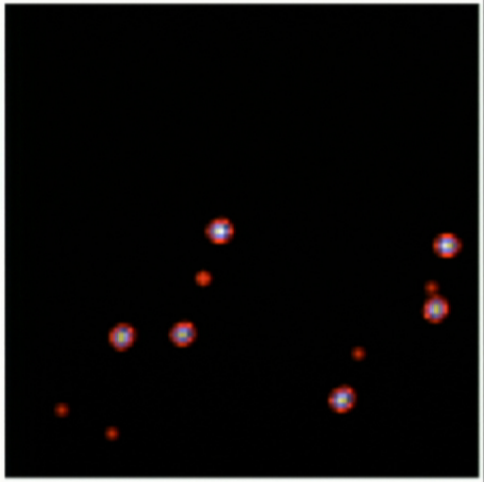


Simulated Image

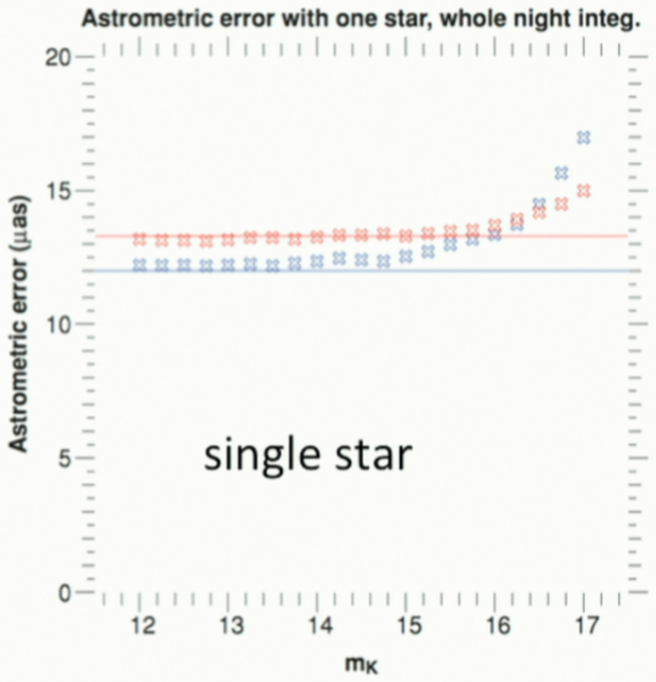


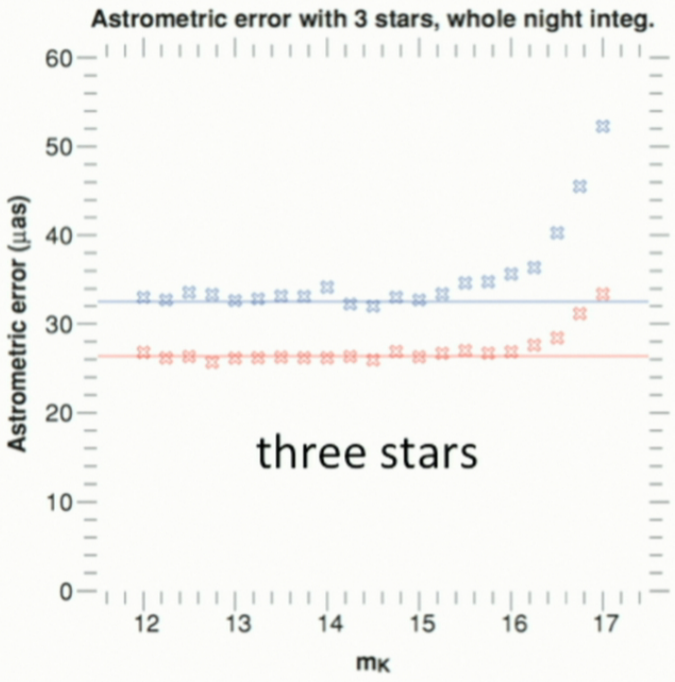
PSF: 4 UTs, K, 9 hrs

Cleaned image



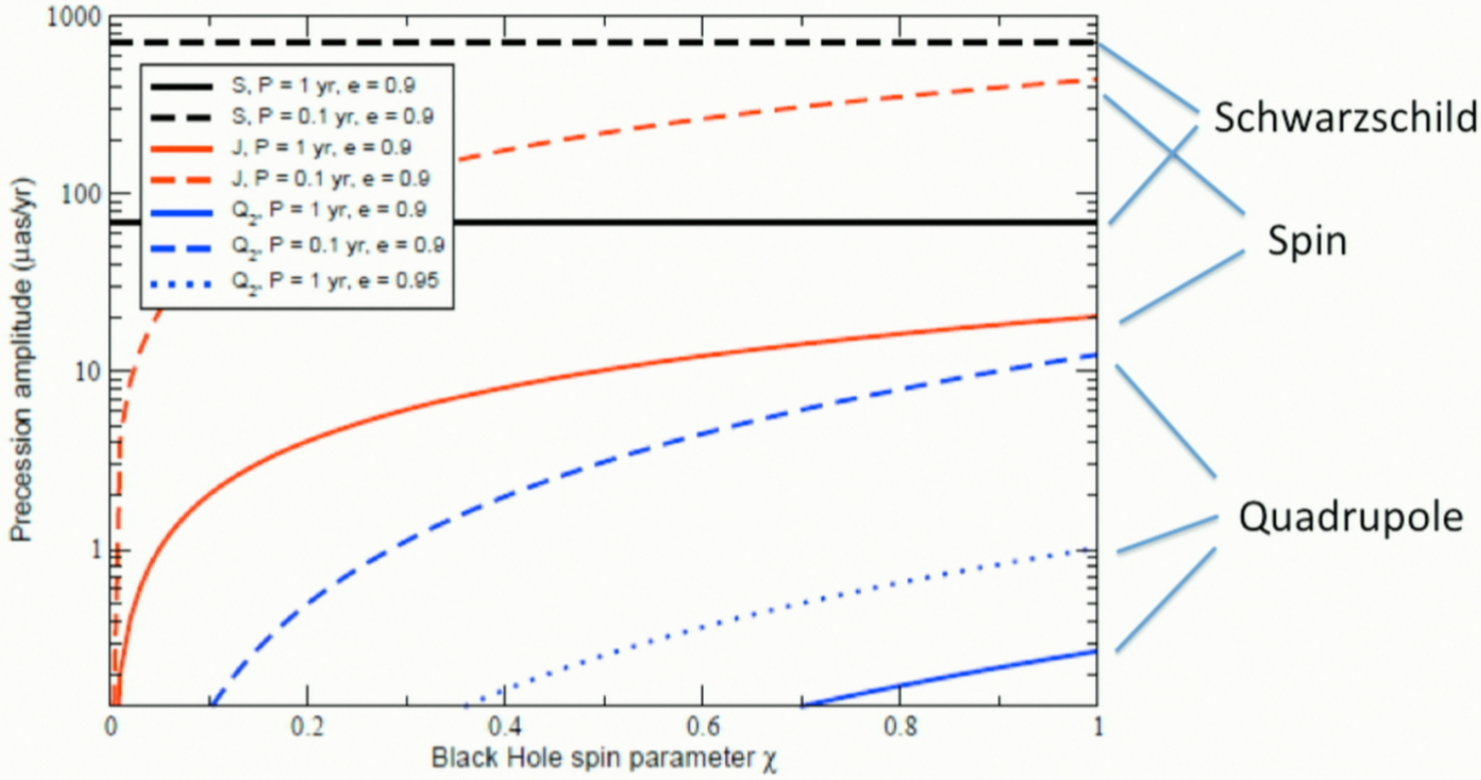
Astrometry at the 10μas level





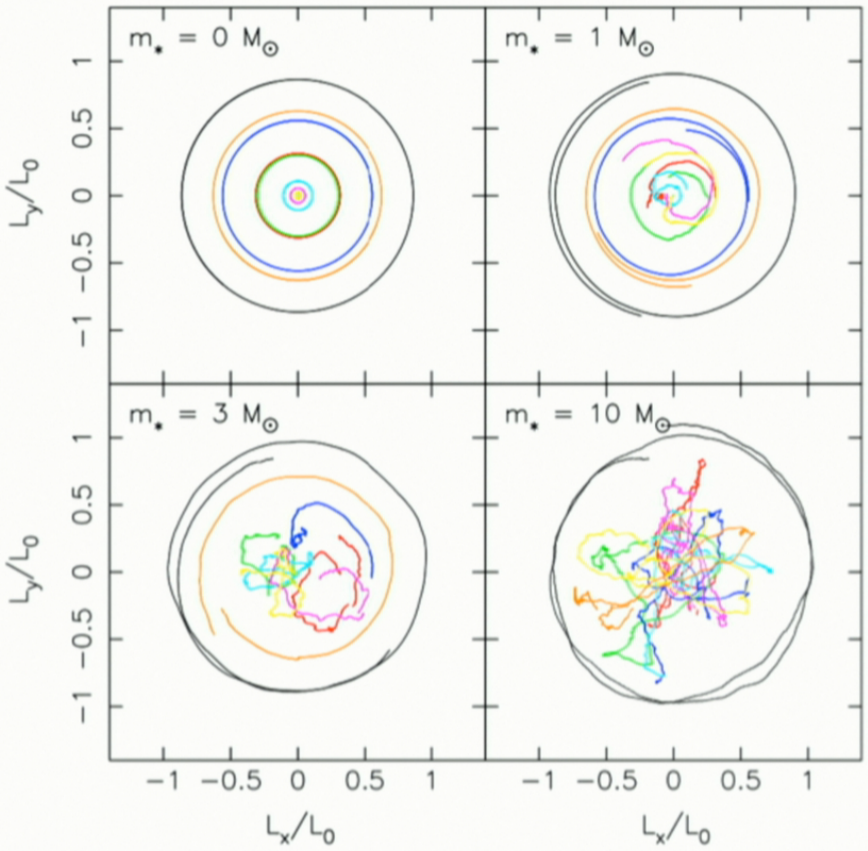
Vincent et al. 2011

Higher order effects of the metric are hard to detect



Will 2008

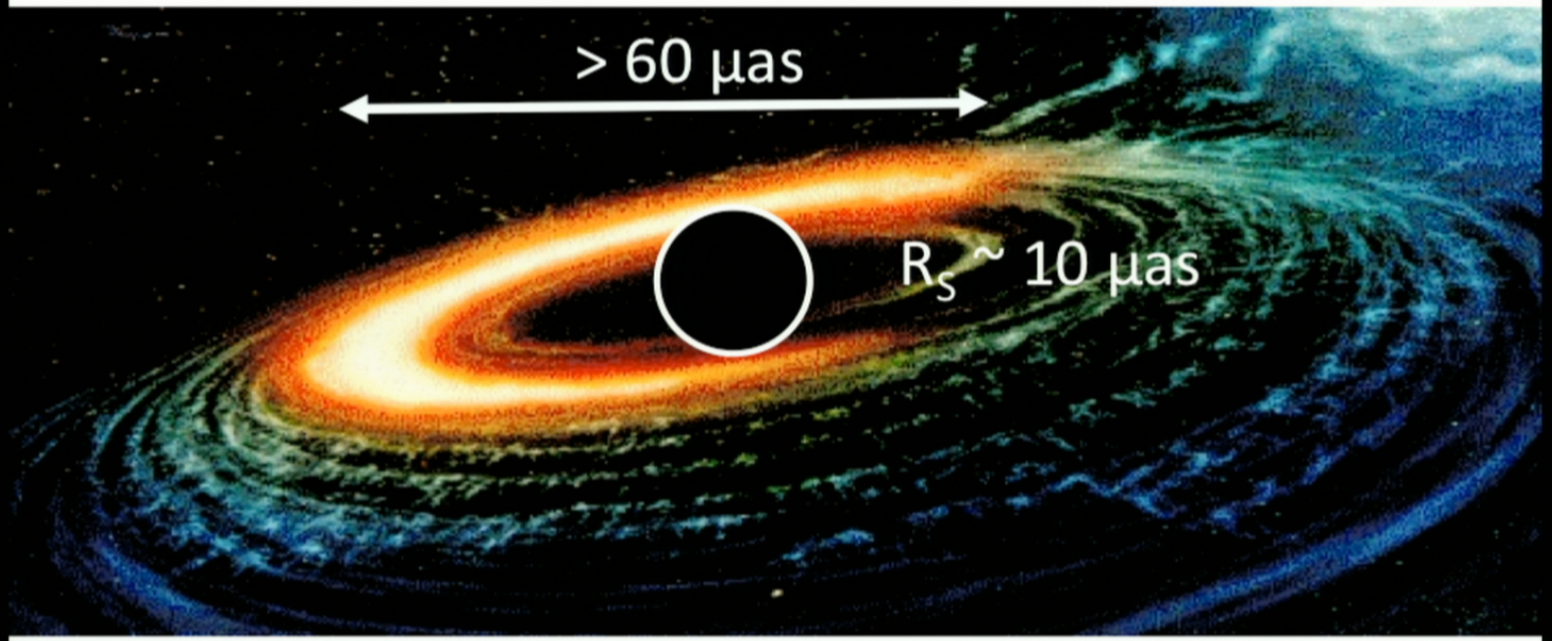
Newtonian precession will be a nuisance



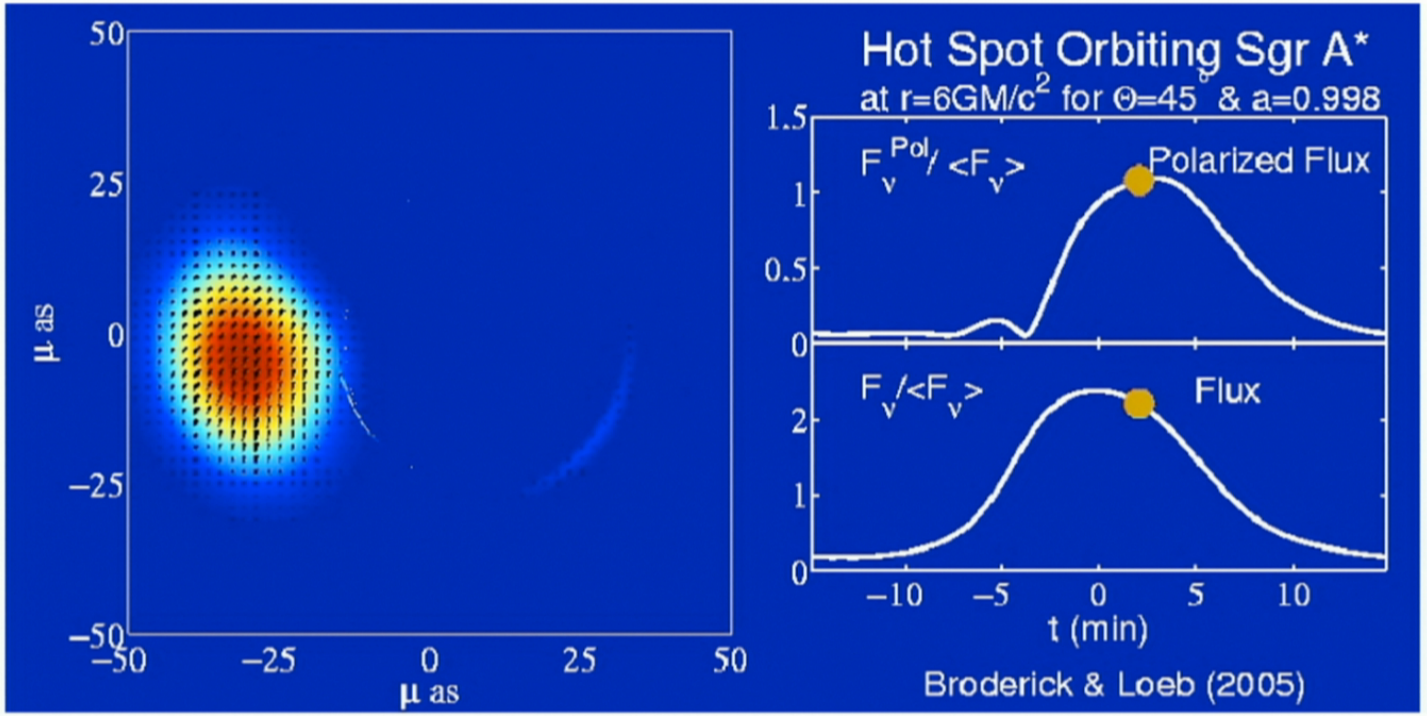
stars perturb each other's orbits

Merritt et al. 2010

10μas is the event horizon scale for Sgr A*
Flares orbit with amplitudes > 50μas



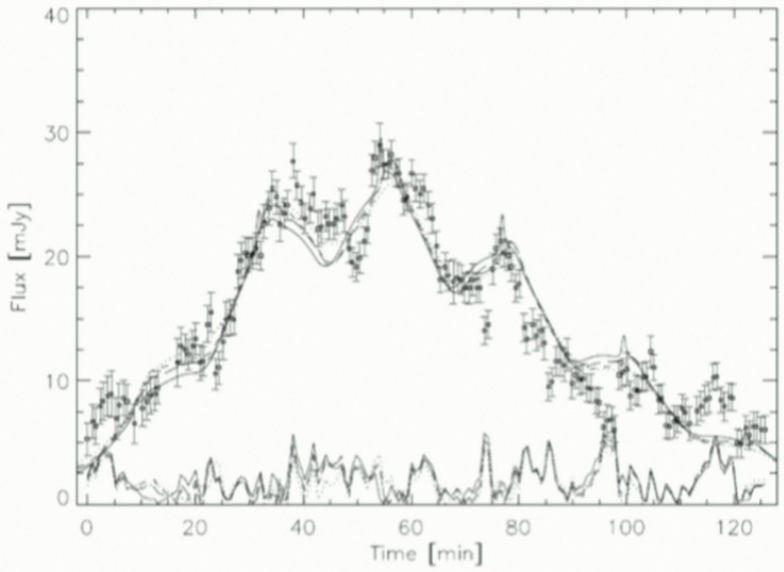
The relativistic view of an orbiting hot spot



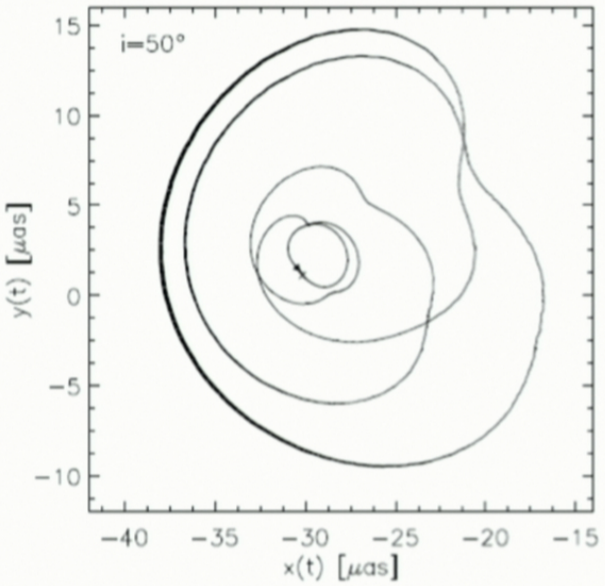
Broderick & Loeb 2005

What data will we have?

Light curve



Centroid track



Hamaus et al. 2009

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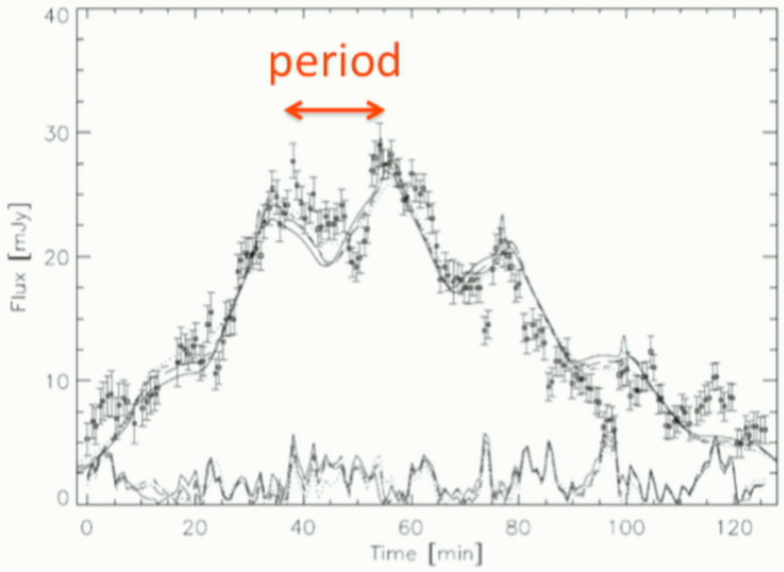

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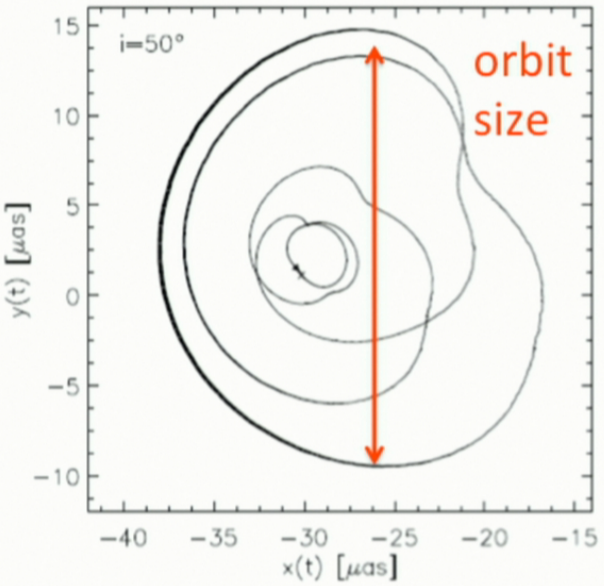

Hamaus et al. 2009

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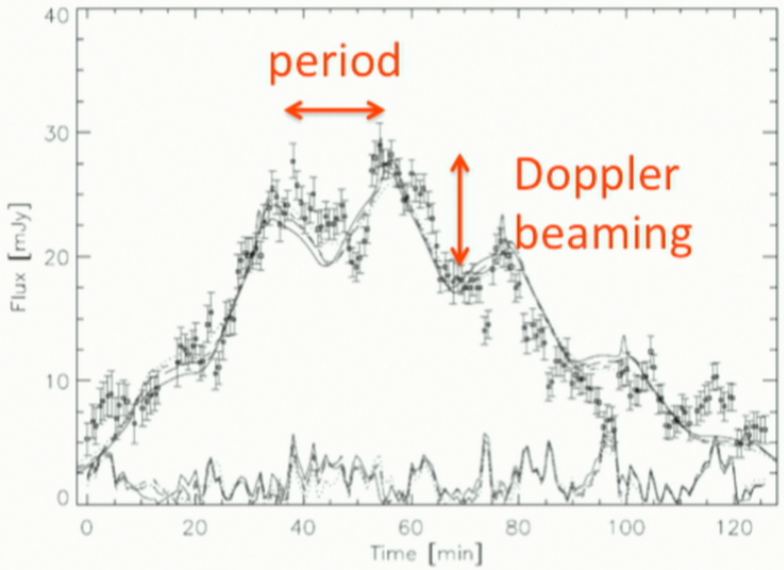

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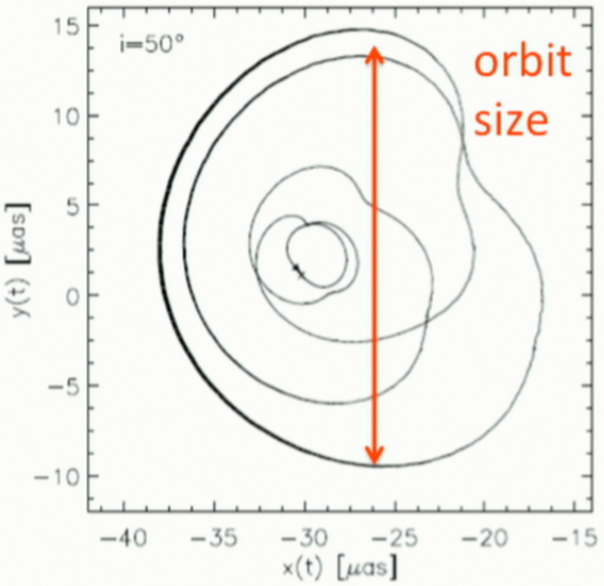
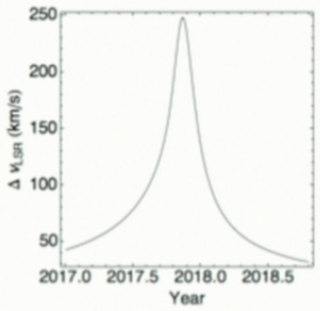


Hamaus et al. 2009

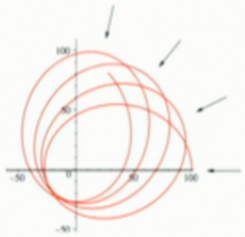
➔ Spin, Radius, Inclination

A ladder of relativistic effects



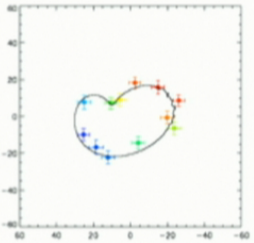
β^2 effects in radial velocities

1



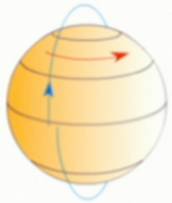
relativistic prograde precession

2



black hole spin from flares

3



Lense-Thirring precession

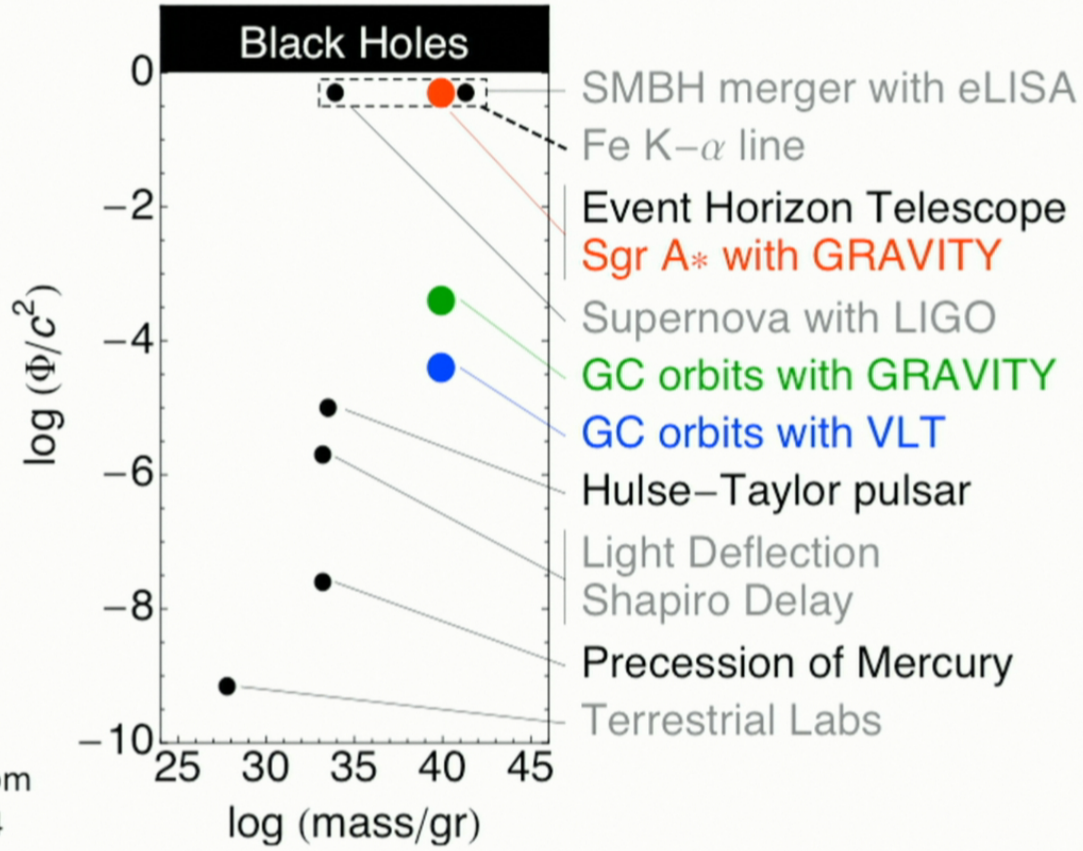
4

Quadrupole moment of metric

5

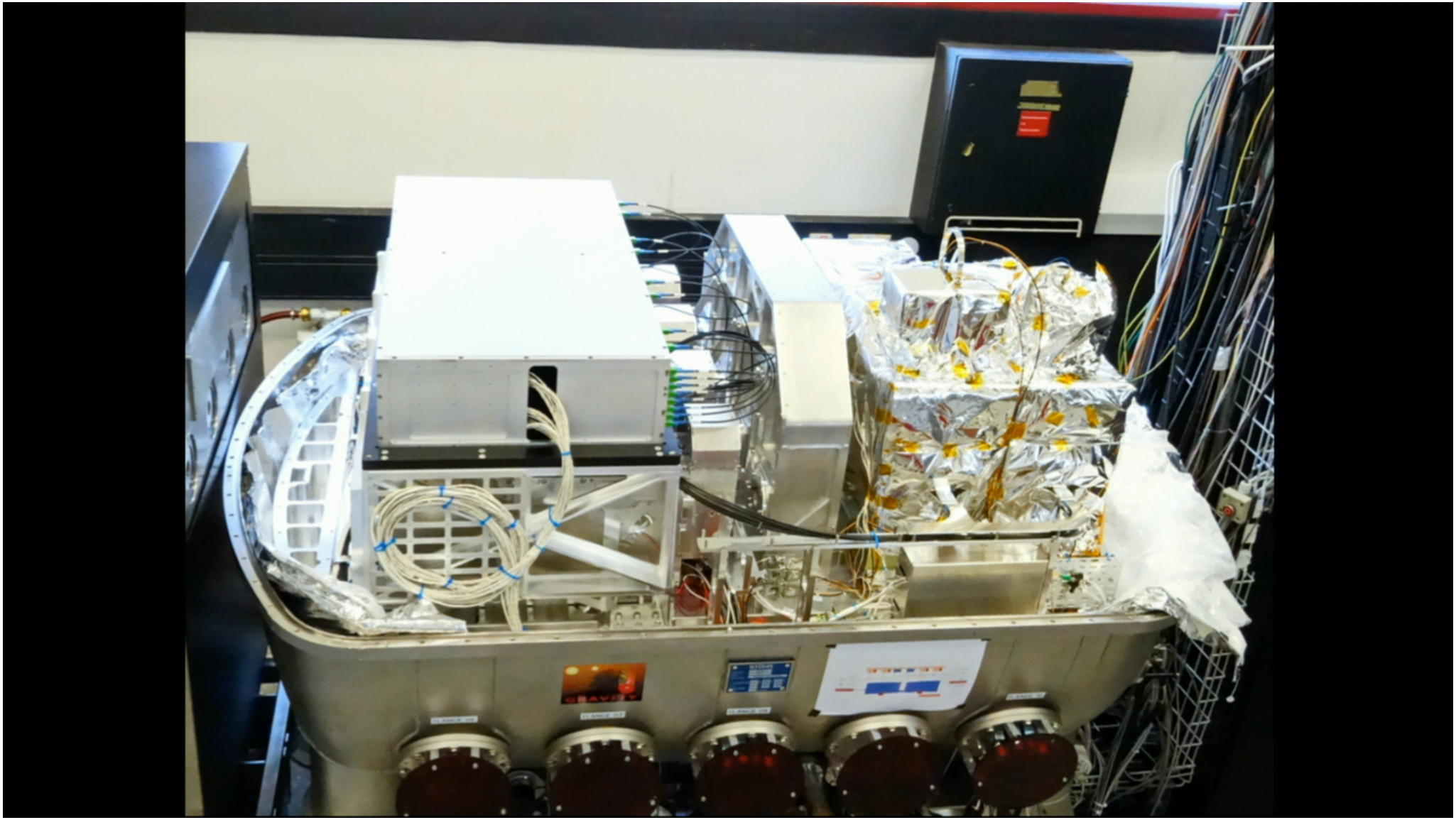
more challenging

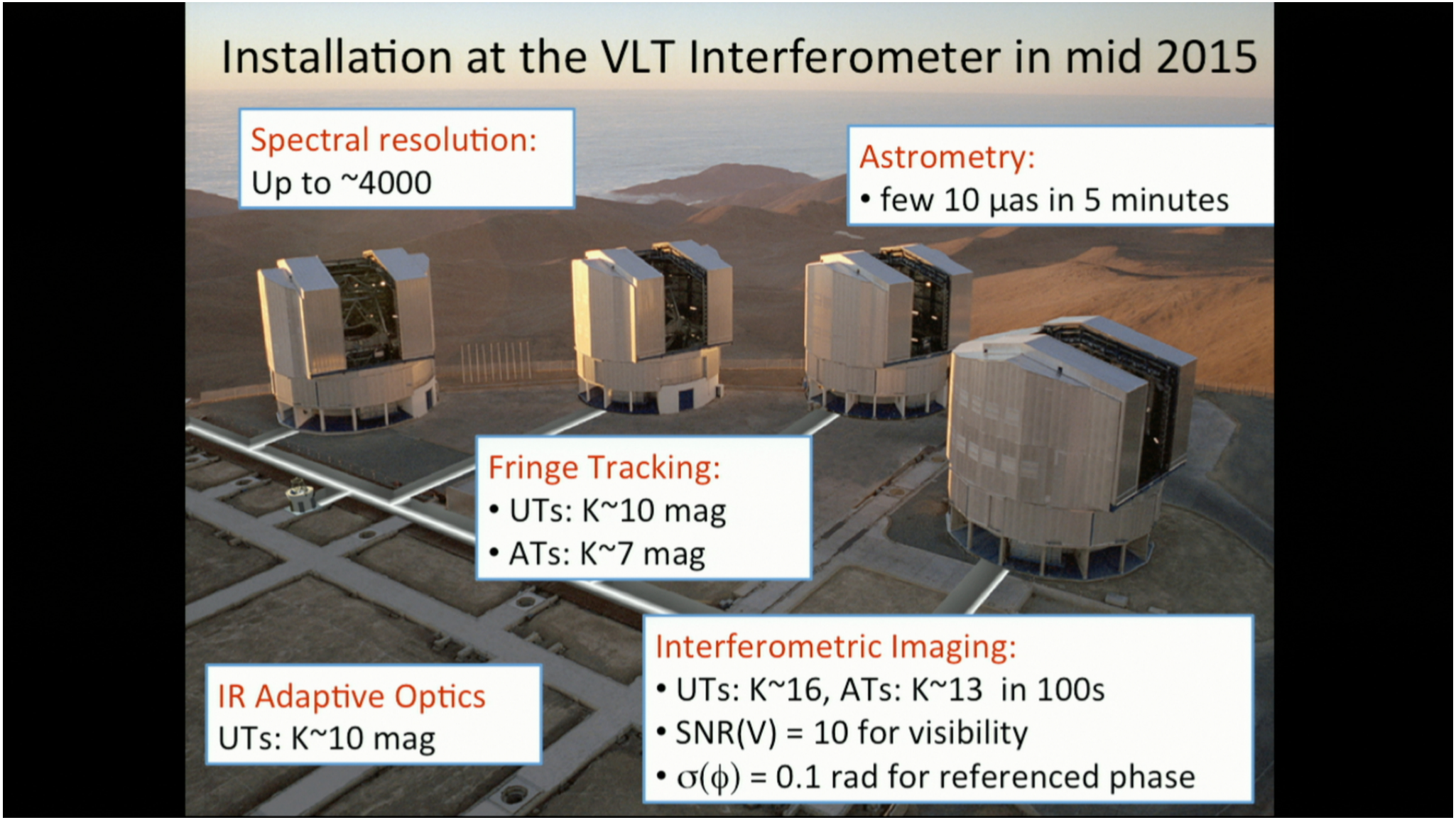
Comparison with other gravity experiments



adapted from Psaltis 2004

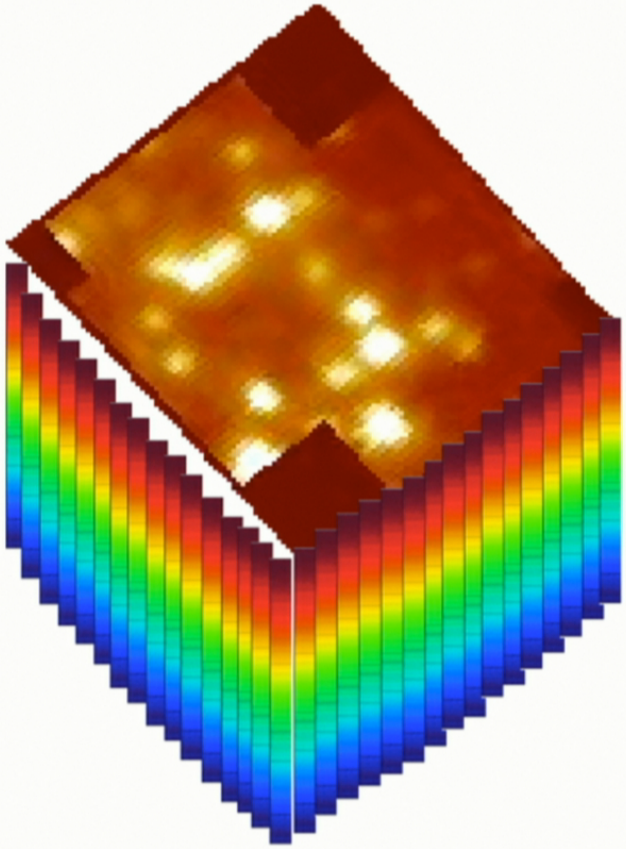

GRAVITY keeps us busy!



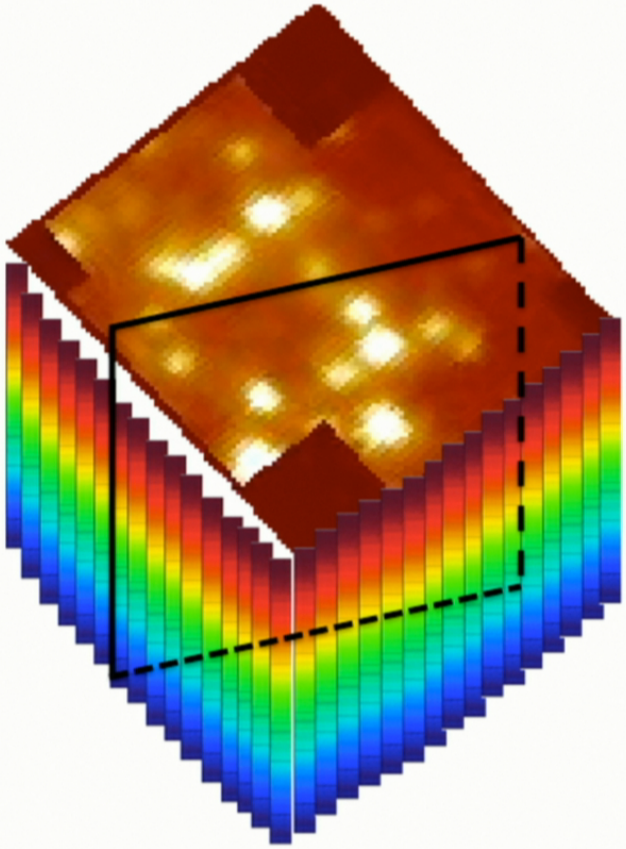

Installation at the VLT Interferometer in mid 2015
Spectral resolution:
Up to ~4000
Astrometry:
• few 10 μas in 5 minutes
Fringe Tracking:
• UTs: K~10 mag
• ATs: K~7 mag
IR Adaptive Optics
UTs: K~10 mag
Interferometric Imaging:
• UTs: K~16, ATs: K~13 in 100s
• SNR(V) = 10 for visibility
• σ(ϕ) = 0.1 rad for referenced phase

Let me also comment on G2

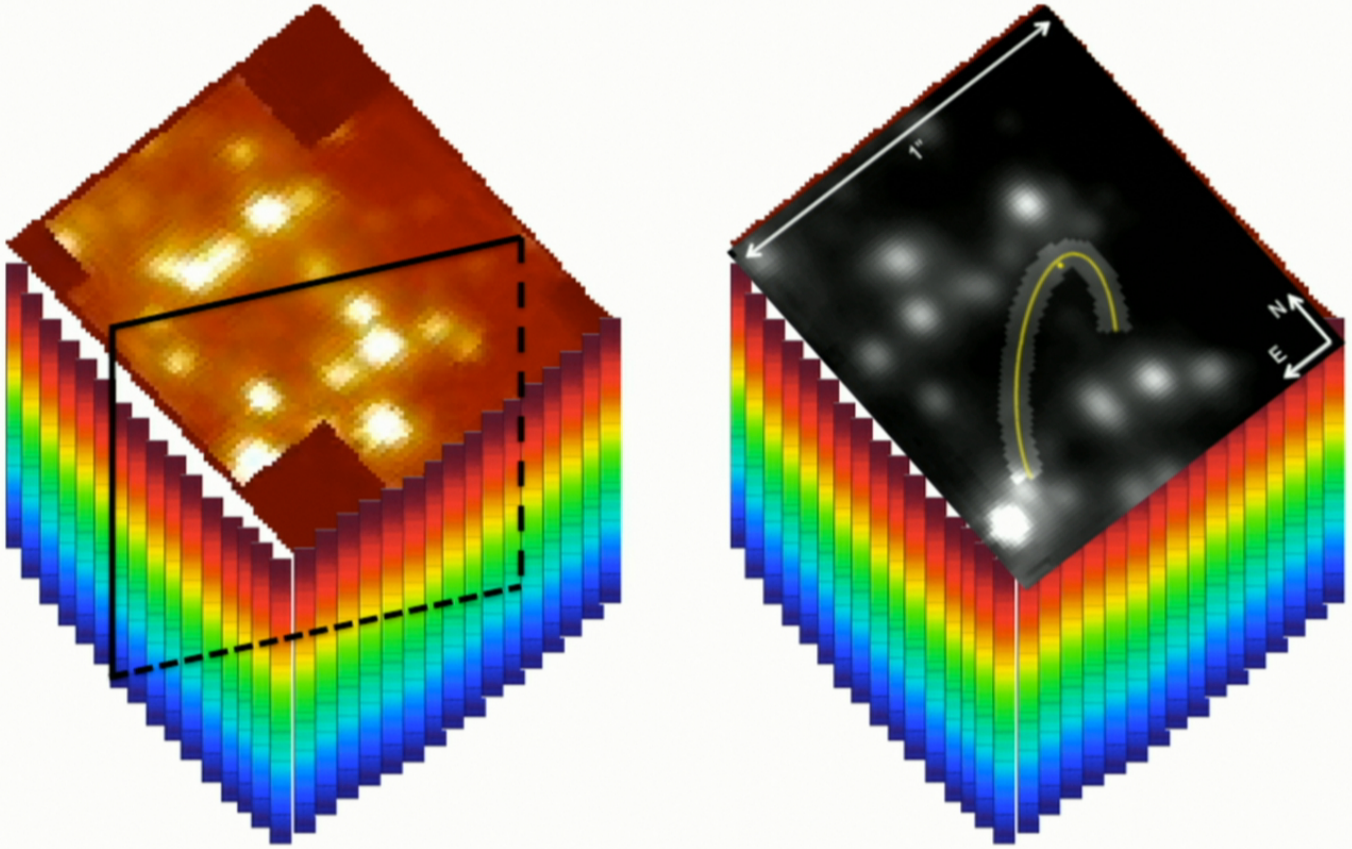
Position – Velocity - Diagram



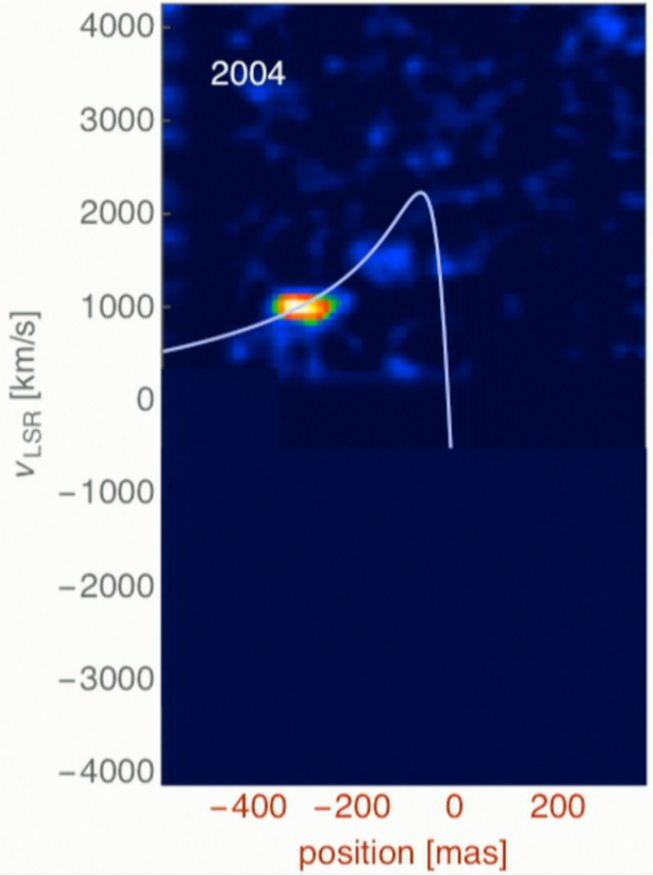
Position – Velocity - Diagram



Position – Velocity - Diagram



The tidal shear is developing in front of our eyes



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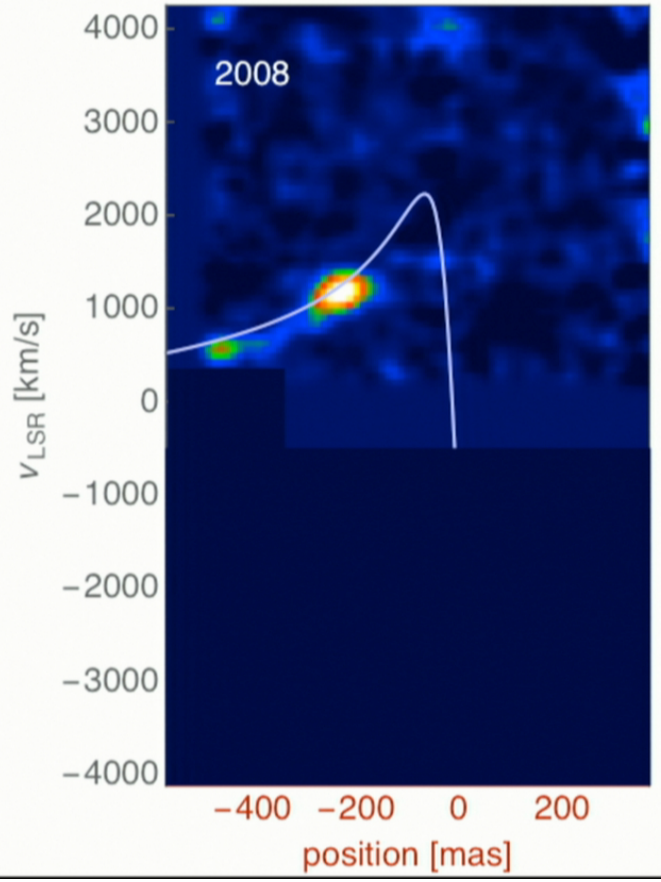

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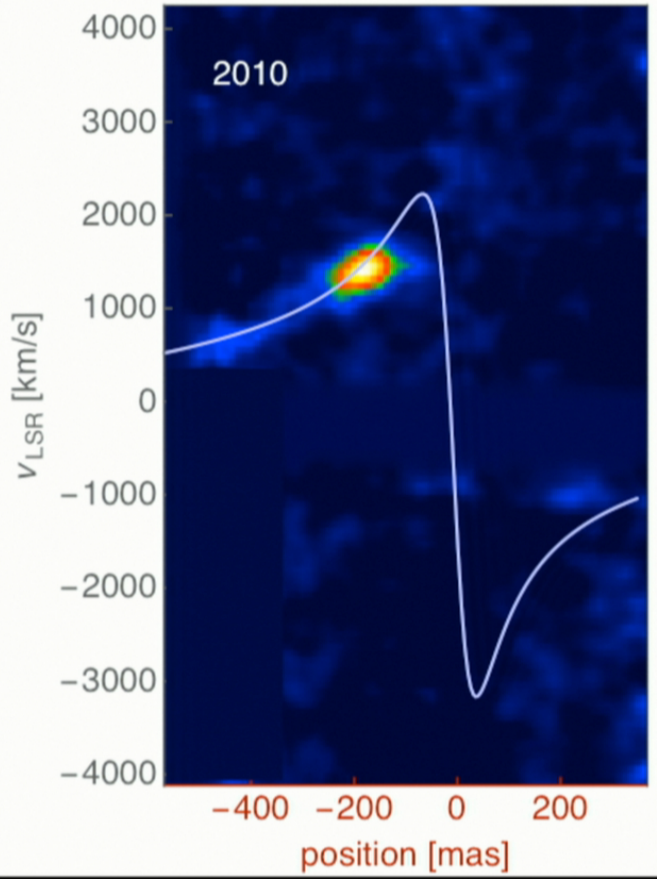

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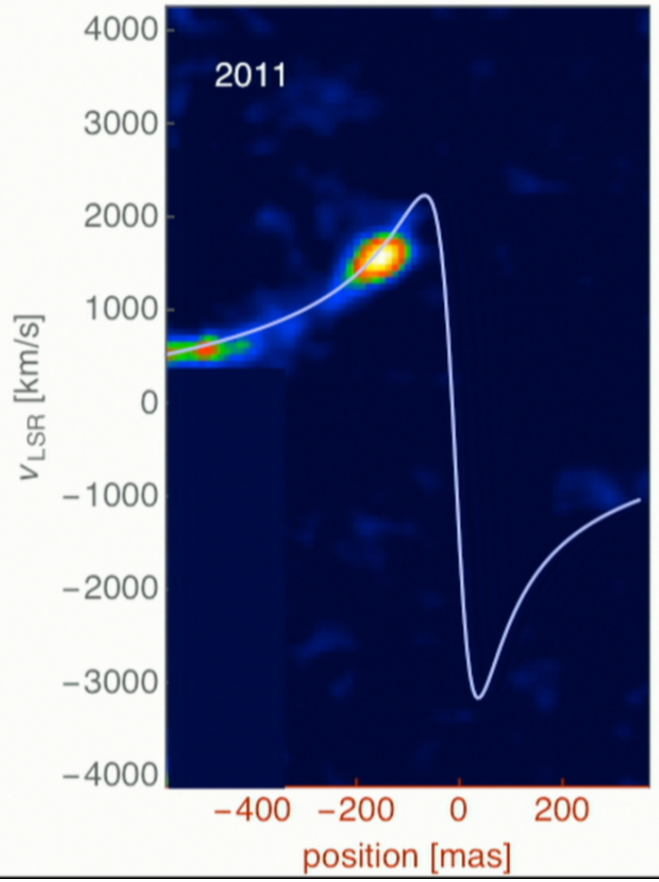

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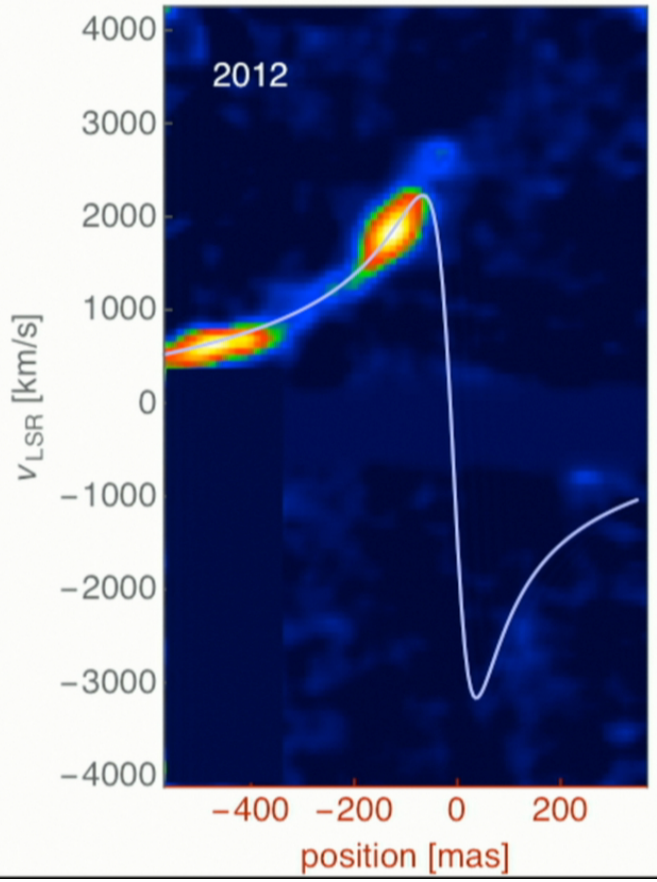

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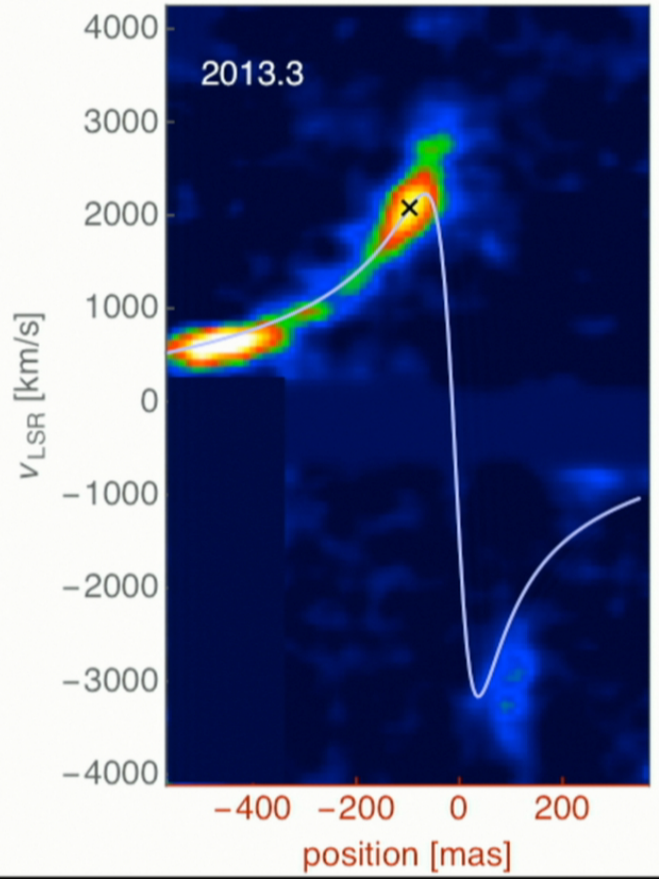

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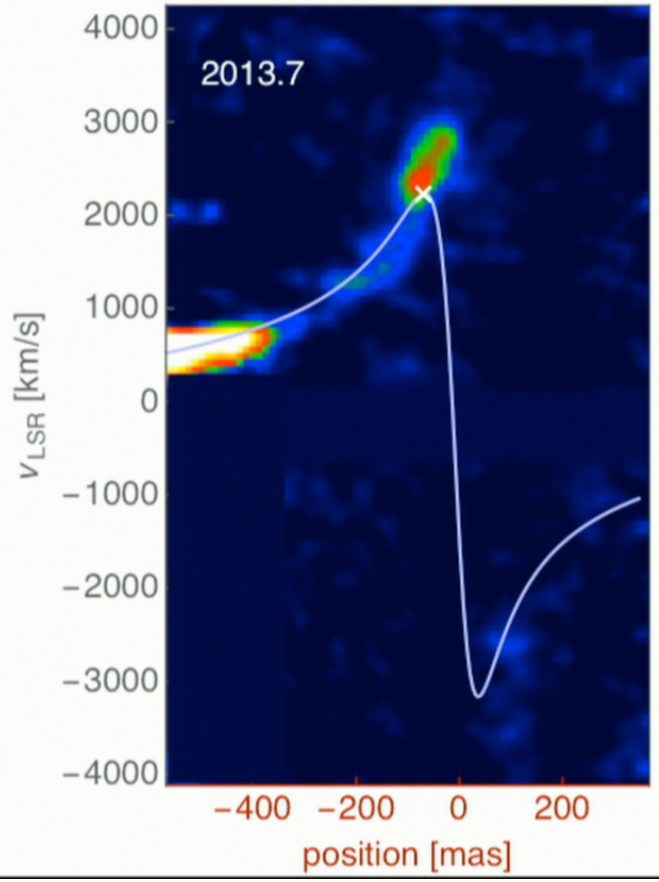

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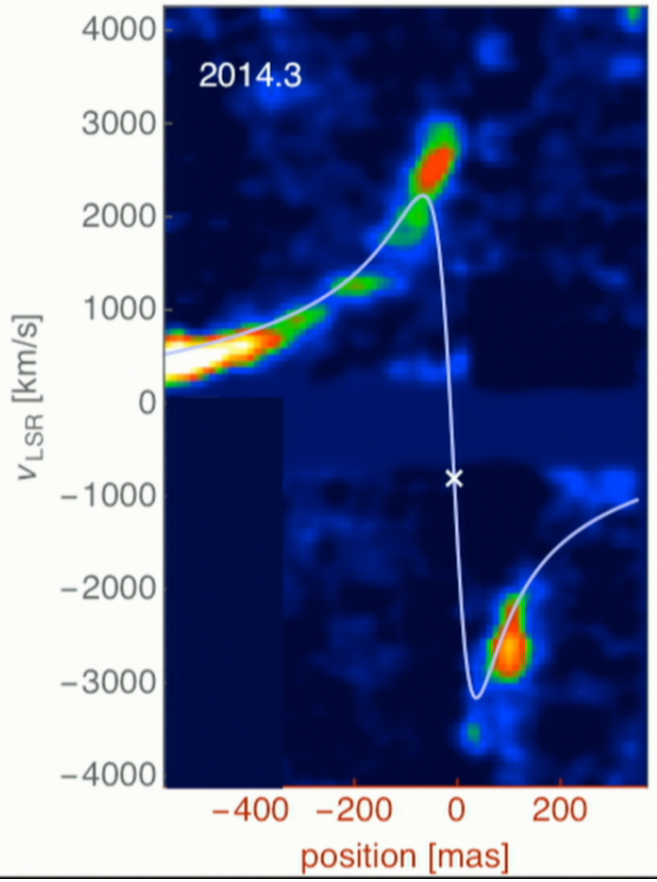

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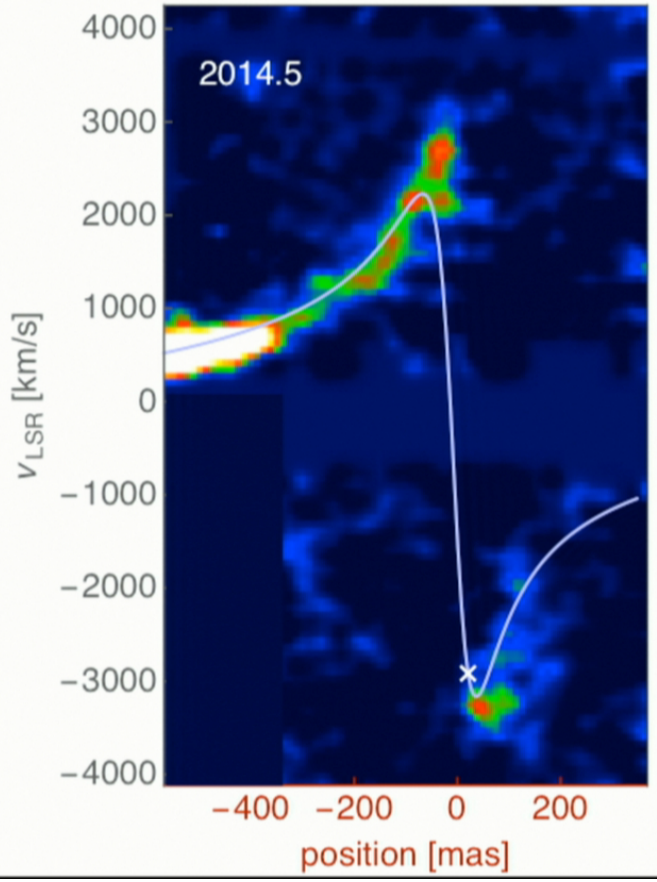

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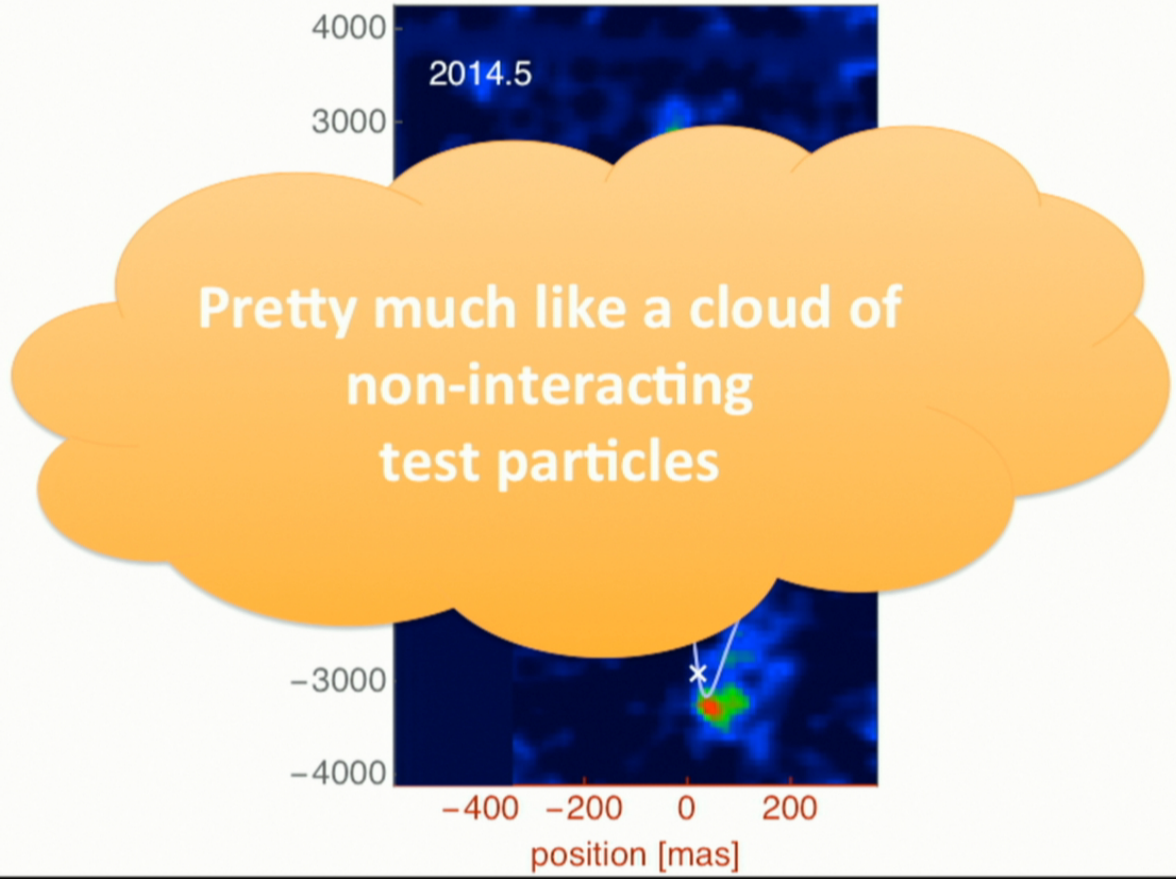
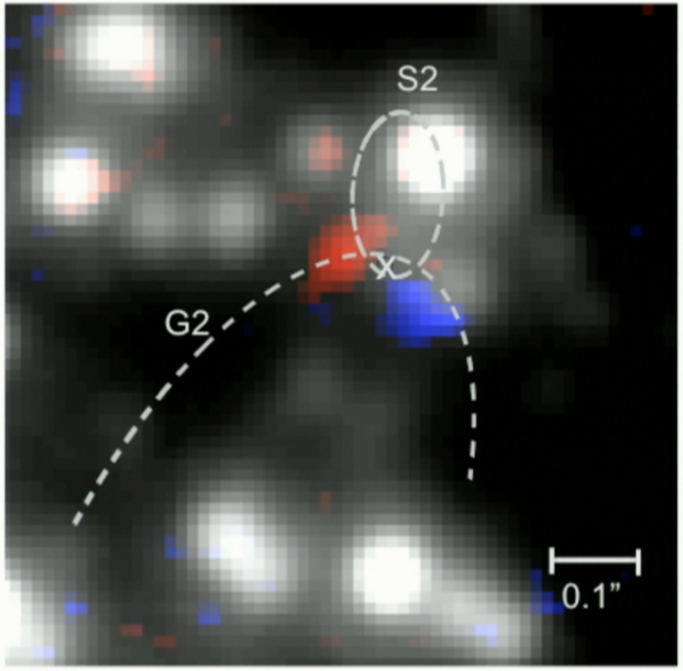


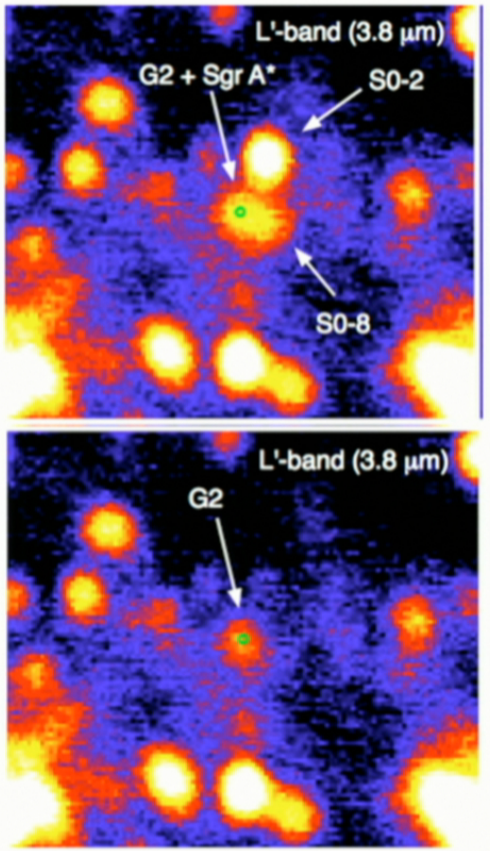
Pretty much like a cloud of non-interacting test particles

2014: Two views of the same object



VLT, Br-γ, gas emission

Pfuhl et al.2014, Witzel et al. 2014



Keck, 3.8μm, dust emission

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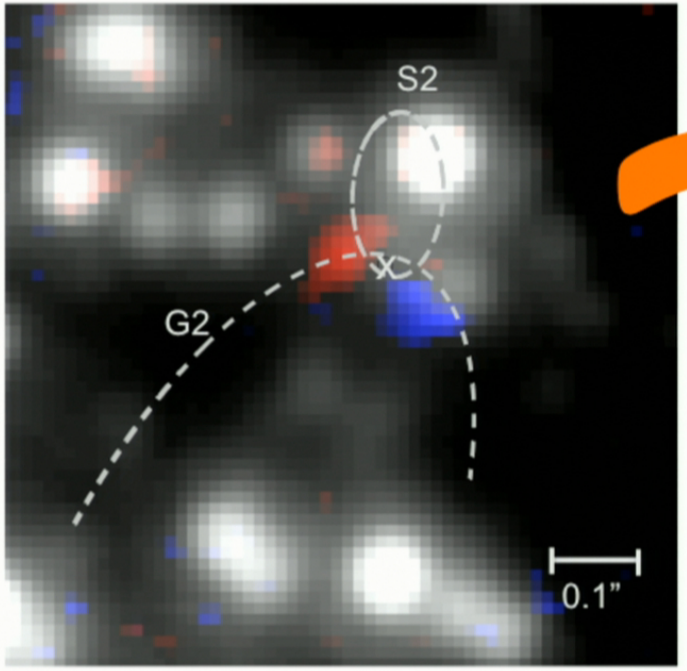

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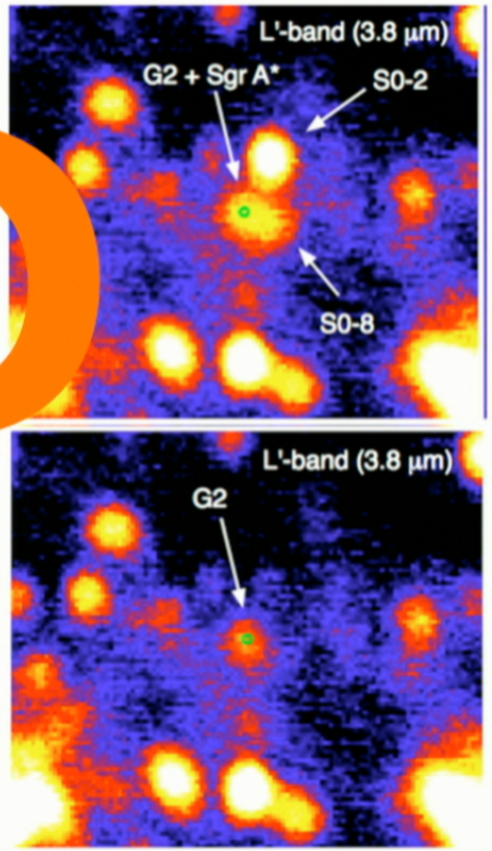
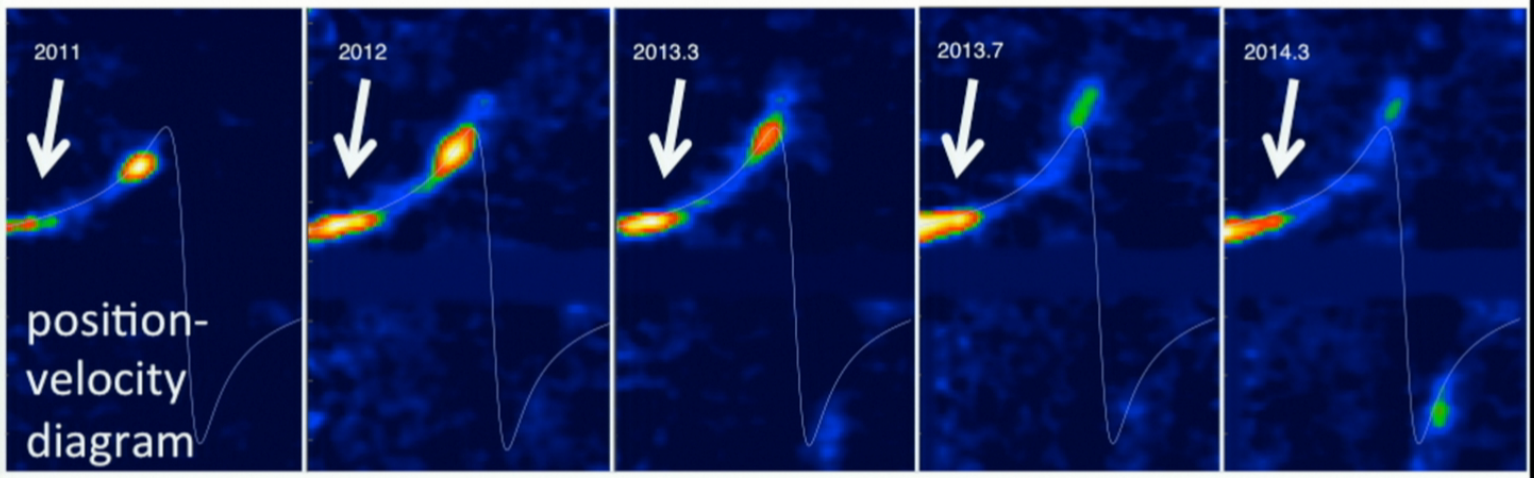
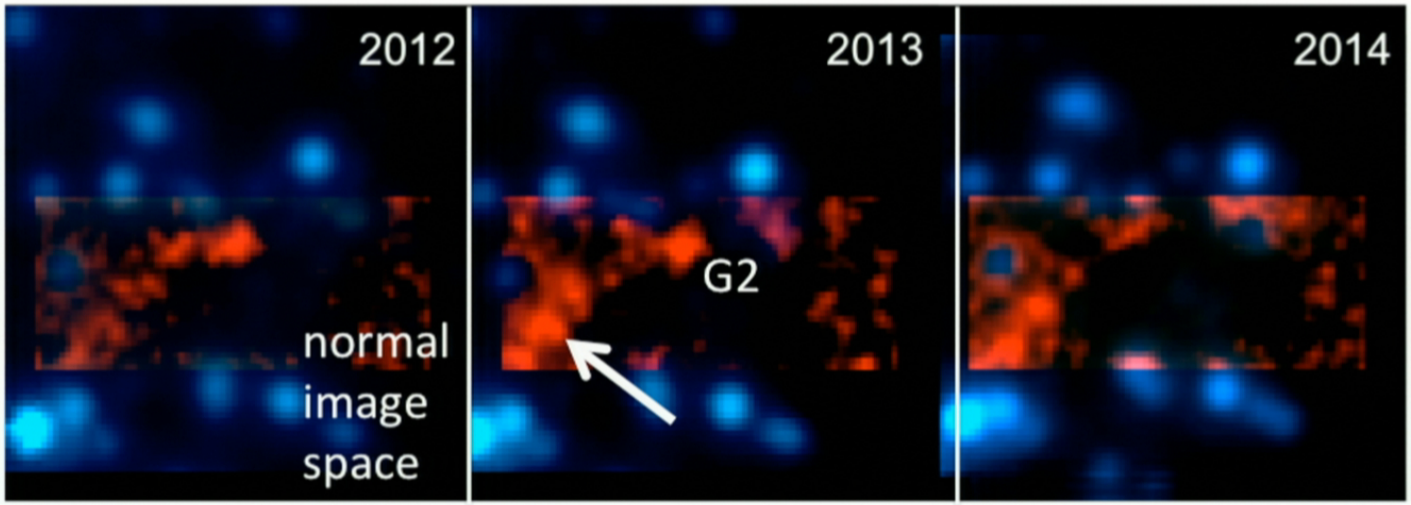


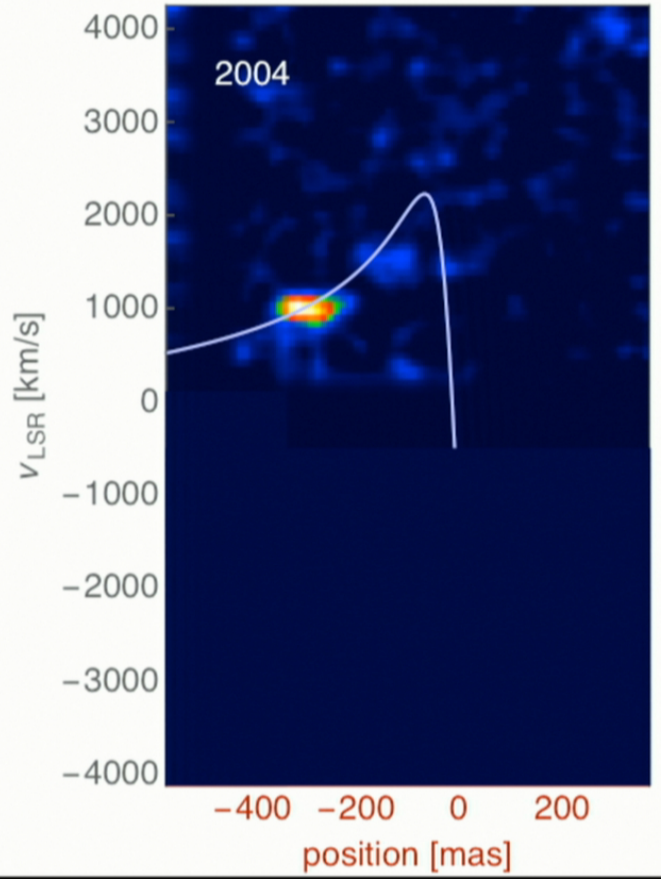
Keck, 3.8μm, dust emission

A tail is following G2





There is even gas preceding G2



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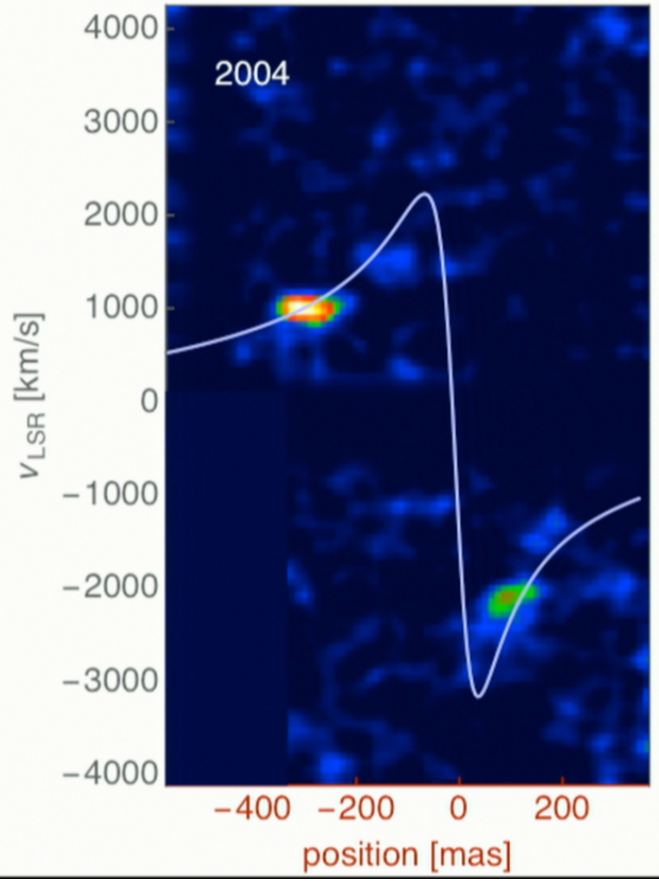

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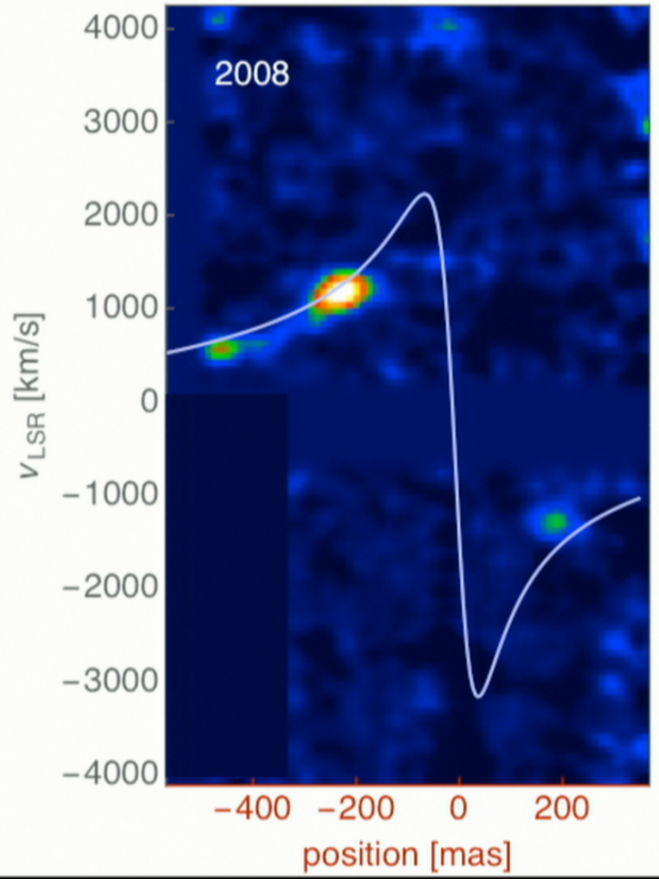
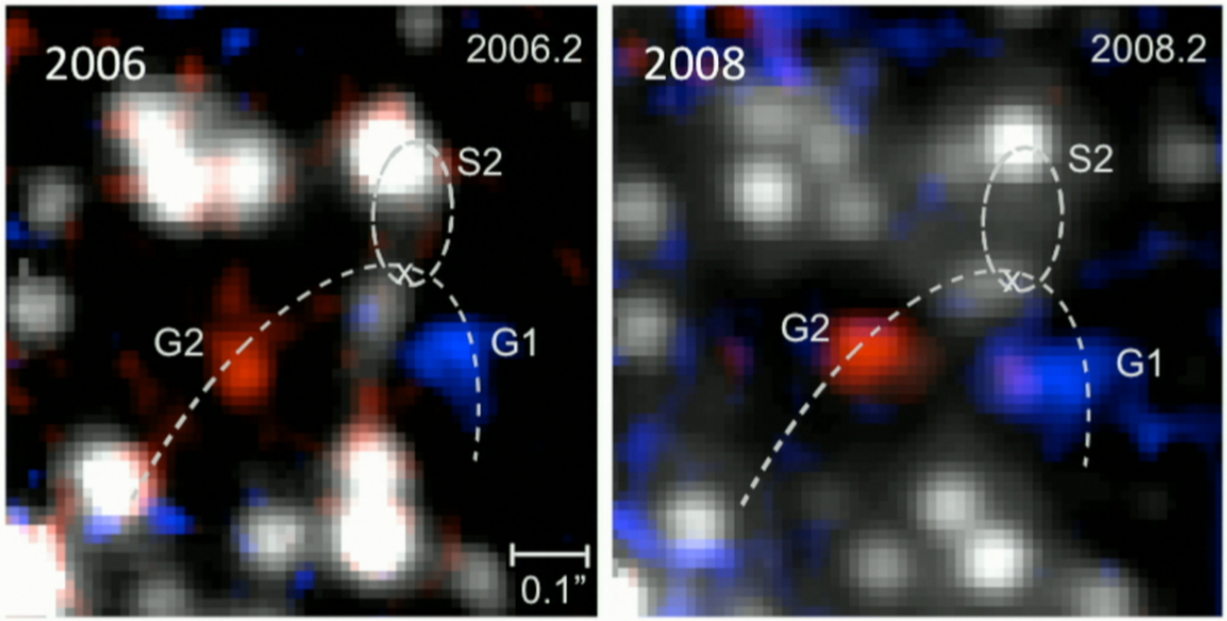
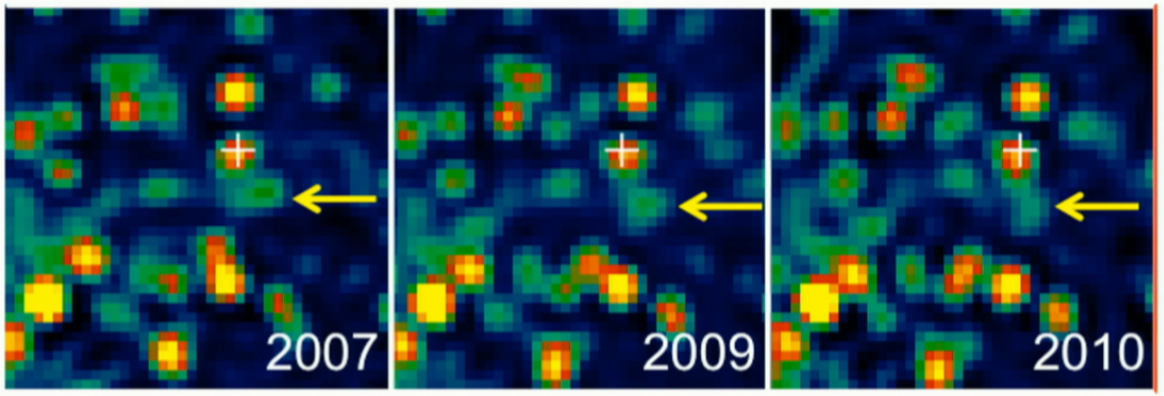


G2: red-shifted gas
G1: blue-shifted gas

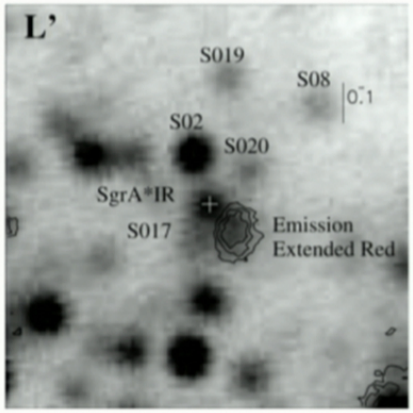


Pfuhl et al. 2014

G1 has a well-known L'-band counterpart



VLT



Keck

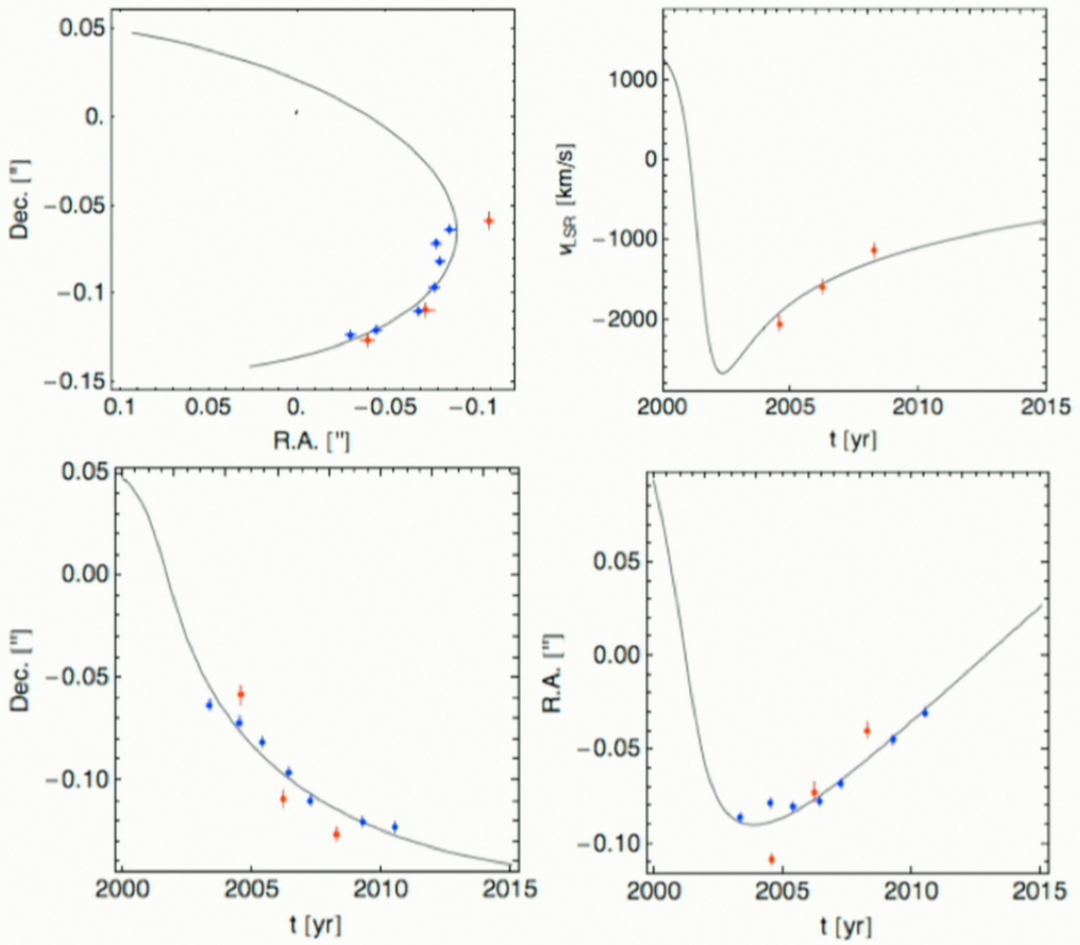
Clénet et al. 2005, Ghez et al. 2005
"a nearby [...], extended, very red source, which we suggest arises from a locally heated dust feature."

We can get an orbit for G1

NACO
L'-band
dust emission

SINFONI
Br-γ
gas emission

Pfuhl et al. 2014



The G2 and G1 orbits are coplanar - and the orientation of the ellipse agrees as well

	semi-major axis	eccentricity	pericenter time	inclination	pos. angle. asc. node	long. pericenter
G2	1.05 ± 0.25 "	0.976 ± 0.007	2014.25 ± 0.06	118 ± 2 °	82 ± 4 °	97 ± 2 °
G1	0.36 ± 0.16 "	0.860 ± 0.050	2001.57 ± 0.40	108 ± 2 °	69 ± 5 °	109 ± 8 °

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Simple idea: G1 was on the same orbit as G2 before its pericenter, but experienced a drag force due to ram pressure

$$\frac{\vec{F}}{m} = -\frac{GM}{r^2}\vec{e_r} - \alpha\,\rho\,v^2\vec{e_v}$$

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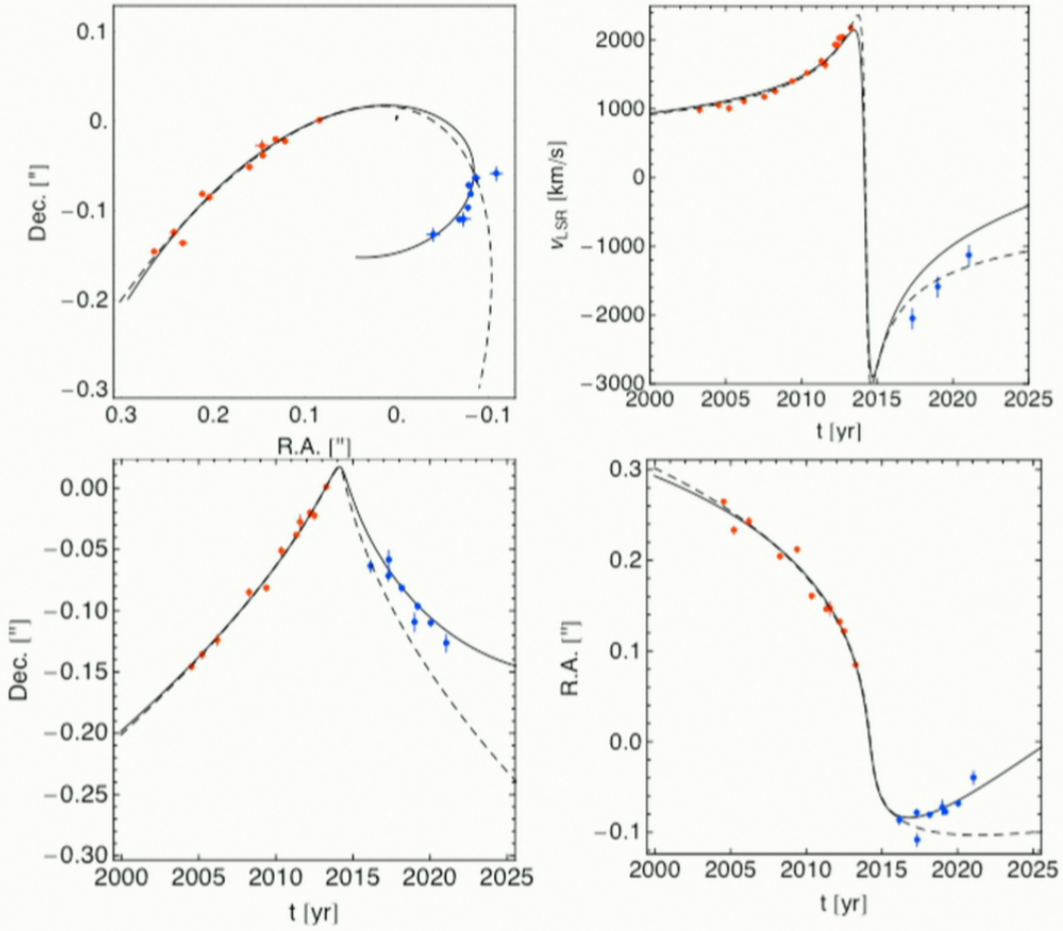
Test this: Advance G1 data by $\Delta\, t_{peri}$ to the future and solve for combined data set

The simple drag force model describes the combined data surprisingly well

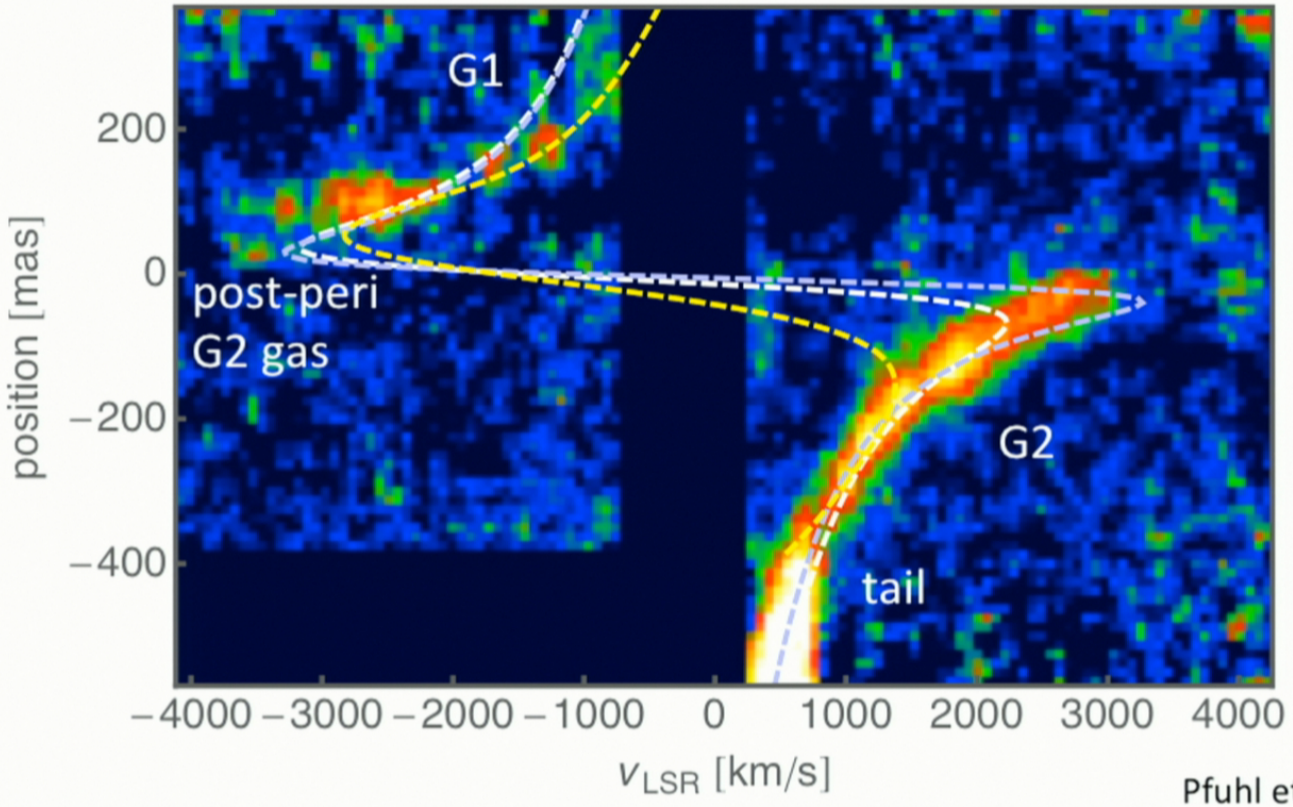
G2 data

G1 data



Pfuhl et al. 2014

G2 – a knot in a much longer gas streamer



Pfuhl et al. 2014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