Astrometry in the Galactic Centre

Thibaut Paumard

GRAVITY project scientist
LESIA – CNRS / Observatoire de Paris
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Outline

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Seemingly clear and falsely simple definition

According to wikipedia:

Astrometry is the branch of astronomy that involves precise measurements of the positions and movements of stars and other celestial bodies.

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- Measure position: in which coordinates?
- Position: 2D ? 3D?
- Movement: relative to what?
- Precise: what does it mean?

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Not addressed by the definition

- For what purpose?
- How is it done?

Dream and reality

Dream

Real 3D position and "Movements", i.e. ideally predictions for

- 3D position;
- 3D velocity;
- (3D acceleration...)

at any past and future date.

Reality

3 per epoch:

- α, right ascension
- δ, declination

Usually relative to some reference source;

- v_r, radial velocity

using spectroscopy, usually relative to Earth.

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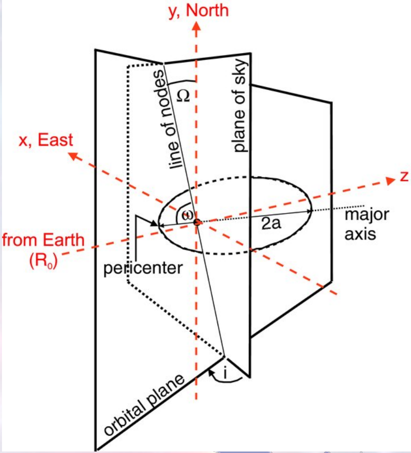
Example: orbital motion

Star orbital parameters:

6 parameters, e.g. initial position and velocity, or

- position angle of line of nodes;
- inclination of orbital plane;
- angle yielding direction of major axis;
- semi-major axis;
- excentricity;
- elongation at given date.



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Parameters of massive particle

- 3D position and velocity (assuming isolated!);
- mass.

Total 13 parameters in Newtonian case.

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Rotating black-hole

- Orientation of spin axis (2 angles);
- Spin parameter.

Total: 16 in GR black-hole.

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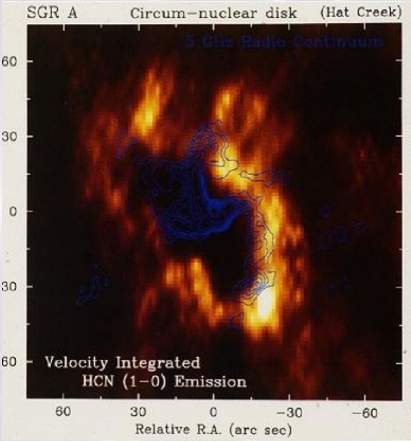
More for alternative theory



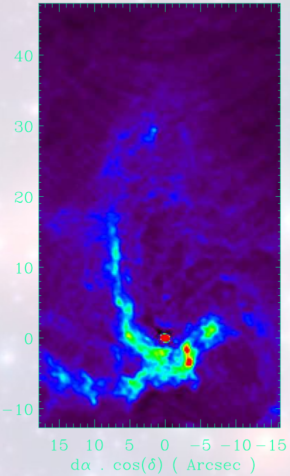
Blitz et al.

Constituents of central parsecs

- The CND (torus of molecular gas);
- Sgr A Ouest (the Minipiral, dust+ionised gas) + Sgr A* (the SMBH);
- The nuclear cluster of early type stars;
- The S cluster;

Key questions

- Formation of massive stars
- mechanisms involved in starburst galaxies and AGNs
- black-hole physics



Roberts & Goss '93, VLA H92α

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NACO H, K', L

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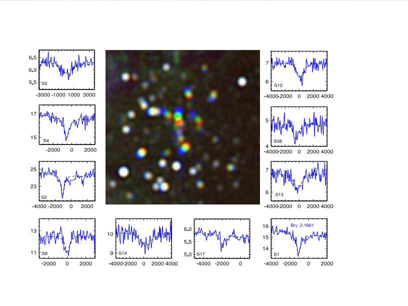

NACO 3 epochs, SINFONI spectra

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In the context of the Galactic Center

Goal and mean

Relate the components observed at various wavelength;

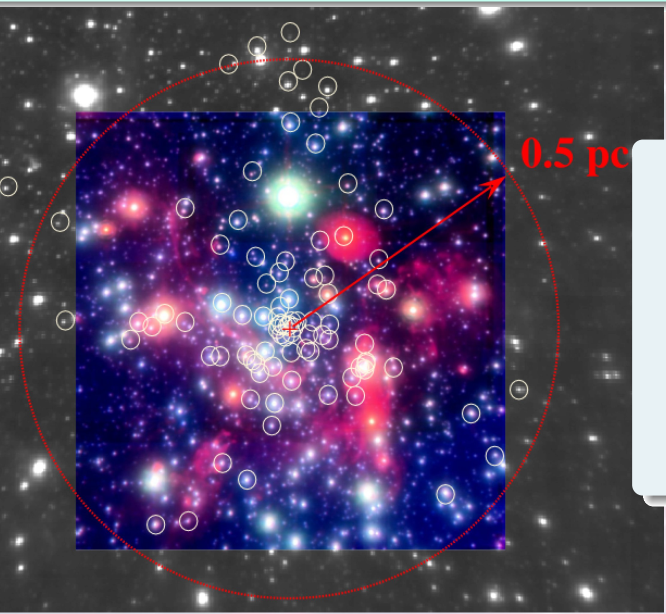
- 3D structure and kinematics;
- Interactions;

Reference frame

Sgr A* is a natural reference (everything rotates around it!), but not bright in the infrared:

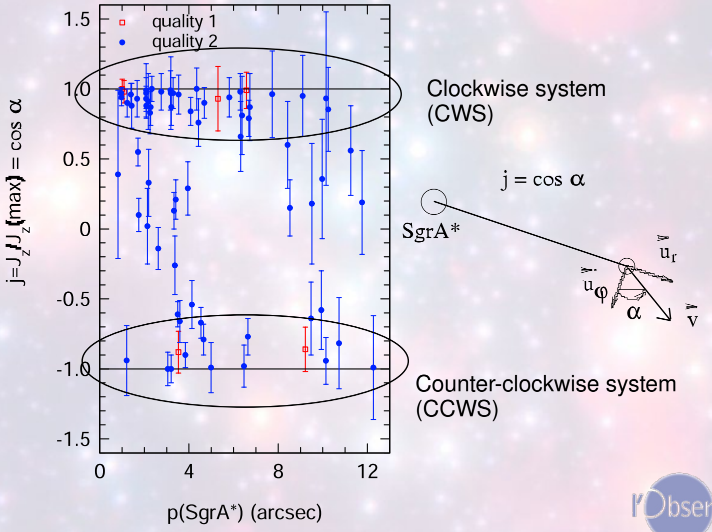
- need intermediate references (e.g. masers, stars associated with radio emission;
- beware of nasty effects (image distorsions...)
- some instrumental effects are time-dependent.

$\simeq$ 100 early type stars within a 0.5 pc radius



- About 100 early type stars detected
- 5 elements per star: 2D pos, 3D vel.
- Many stars, few elements $\Rightarrow$ statistical study

The OB stars are mostly on projected tangential orbits



The early-type stars live in two disks

$$\vec{v} = \begin{pmatrix} v_x = v \sin\theta \cos\varphi \\ v_y = v \sin\theta \sin\varphi \\ v_z = v \cos\theta \end{pmatrix}, \quad \vec{n} = \begin{pmatrix} \sin i \cos\Omega \\ -\sin i \sin\Omega \\ -\cos i \end{pmatrix}$$

$$\vec{v} \perp \vec{n} \Leftrightarrow \vec{n} \cdot \vec{v} = 0 = \sin i \cos\Omega \sin\theta \cos\varphi - \sin i \sin\Omega \sin\theta \sin\varphi - \cos i \cos\theta$$

$$\Leftrightarrow \operatorname{cotan}\theta = \tan i \cos(\Omega + \varphi).$$

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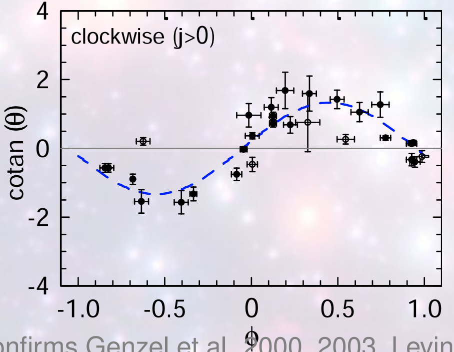

confirms Genzel et al. 2000, 2003, Levin & Beloborodov 2003, Tanner et al. 2006

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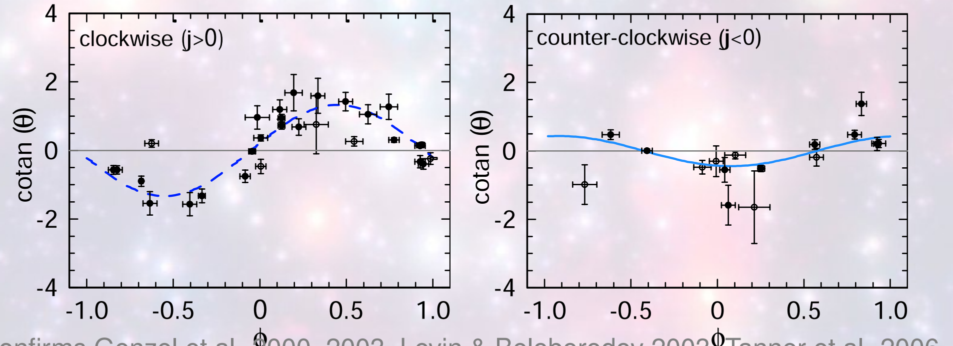

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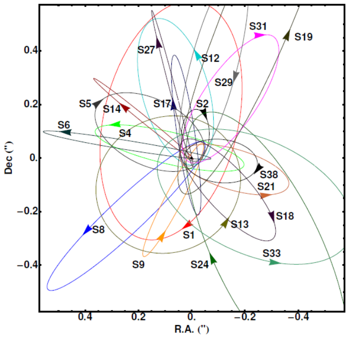
The early type stars orbit Sgr A* in one (or two) disks

Interpretation

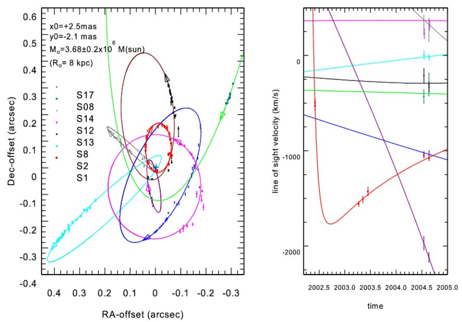
The Early type stars have been formed in an event of star formation, about 2 – –6 Myr ago, in a gaseous disk.

For inner stars: accelerations yield full orbits



S-stars cluster (Gillessen et al. 2009): size = 1" ≈ 0.05 pc

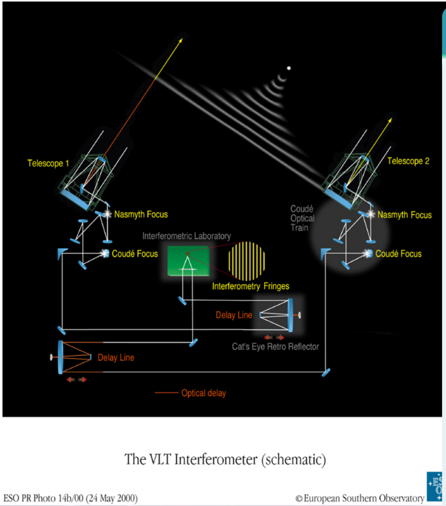
3D structure of orbits



Schödel et al. 2003, Ghez et al. 2003, Eisenhauer et al. 2005

Schödel et al. 2003, Ghez et al. 2003, ... *Gillessen et al. 2009*...

Interferometre = hardware Fourier Transform



$S(x, y) \mapsto \widehat{S}(u, v)$

- fringes from two telescopes $\mapsto$ sample $\widehat{S}$ at one (u,v) point;
- (u, v) determined by $\vec{B}_{\rm sky}$, λ;
- $\vec{B}_{\rm sky}$ set by position of the two telescopes, position of the source, and sidereal time;
- $\widehat{S}$ is complex: visibility V, phase ϕ;
- sufficient (u, v) coverage allows image reconstruction (finding S);
- each ϕ measurement gives very accurate 1D astrometry.

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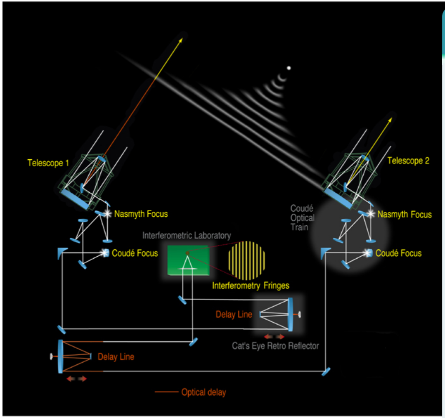

The VLT Interferometer (schematic)

ESO PR Photo 14b/00 (24 May 2000)

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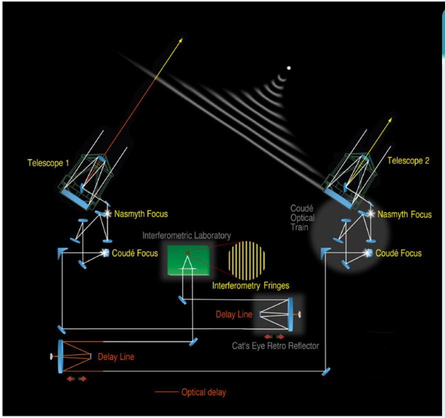

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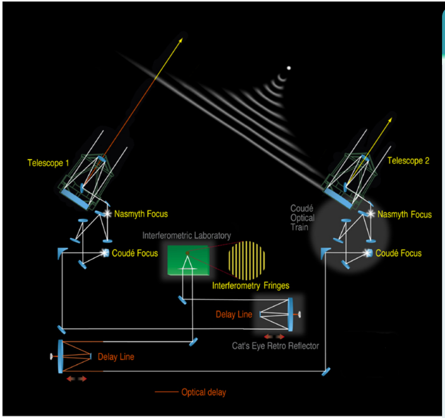

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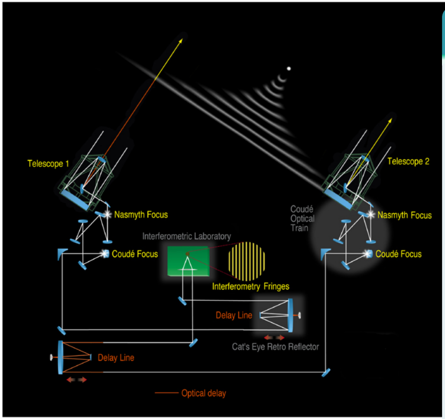

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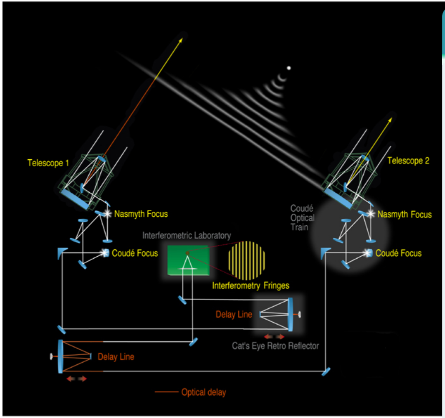

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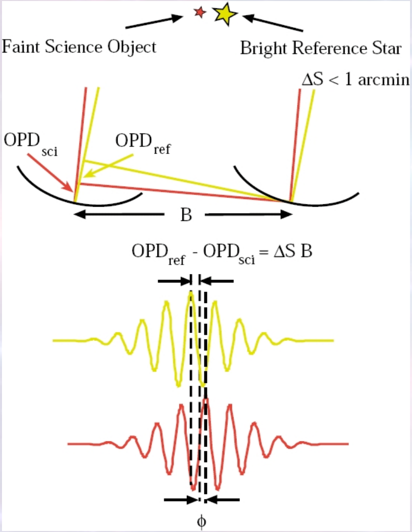
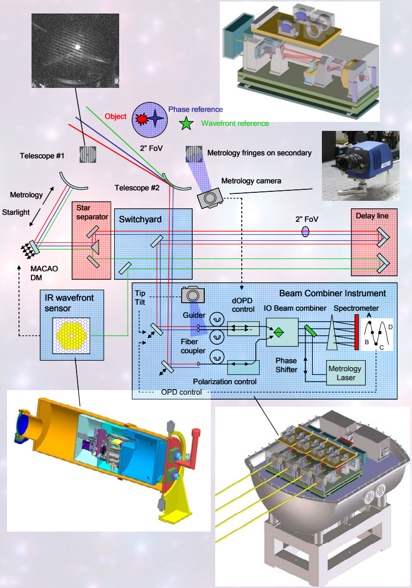
Imaging @ 1 mas, astrometry @ 10 μas



(Glindemann & Lévêque 2000)

- $B = 100$-m baseline;
- reference–science objects distance: $\Theta = 1.2''$;

$\Rightarrow$ 1 $R_S = 10$ μas accuracy in $t = 65$ s integration time!



GRAVITY, 2nd generation instrument for the VLTI

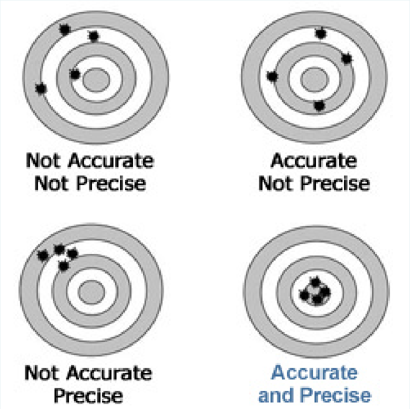
- H+K AO;
- fringe-tracker (+phase reference);
- extremely sensitive.

$\Rightarrow$ lock on 3 different sources!

Operating modes

- AO: $K < 10$;
- Fringe-tracking: $K < 10$;
- Science: $K < 16$ (17);
- Baseline: 100m (UTs);
- K band, $R = 22, 500$ and 4000.

Precision vs. accuracy



Need a very well known ref. frame for long-term accuracy

GRAVITY is very precise

- motion during 1 night at 10μas level;
- long-term accuracy affected by e.g.
  - changes in the instrument (relocations...)
  - changes in the reference stars!
- long-term accuracy: pessimistic 100 μas, better with proper calibration.

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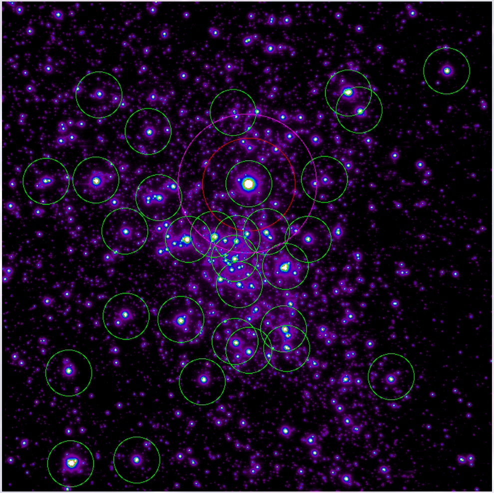


MPE data

Fringe-tracker limit

- ≥ 1 AT reference ($K \lesssim 7$);
- ≥ 30 UT refs. ($K \lesssim 10$);
- Green: 2" UT field-of-view
- Red: 4" AT field-of-view

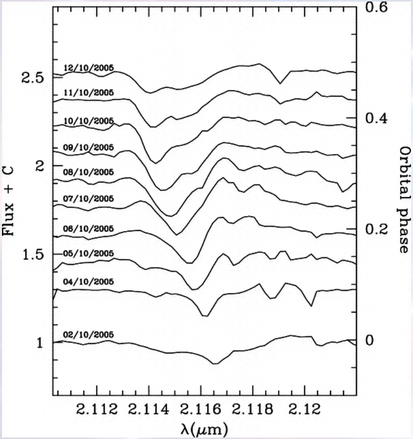
Within those fields:

- limit: $K < 19$;
- high-accuracy astrometry;
- spatially resolved spectroscopy...

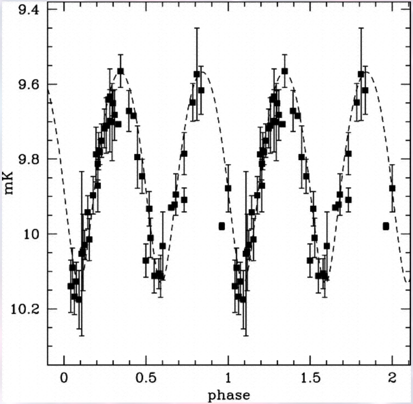
Between those fields:

If one common $K < 15$ star: common astrometric solution.

GCIRS 16SW: eclipsing, equal-mass, contact binary Martins et al. (2006), Peeples et al. (2007)



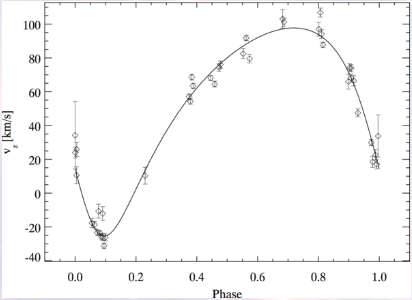
Spectroscopy



Photometry

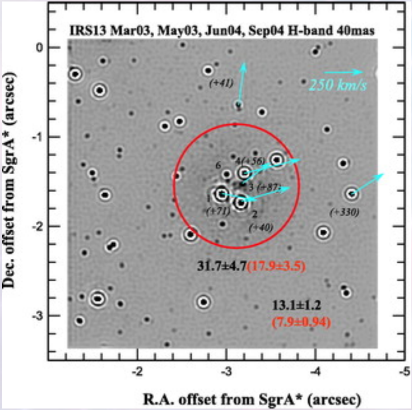
$P = 19.45$ d, $\theta_{\text{sep}} \sin(i) = 132.8 \pm 4.4 R_{\odot} \simeq 77\ \mu$as

GCIRS 16NE: long-period binary Pfuhl et al. (2014)



- primary $\simeq 50 M_\odot$;
- secondary $\simeq 30 - 50 M_\odot$;
- $a \sin(i) \simeq 144\ \mu$as
- GRAVITY: full orbit within 1 yr!

GCIRS 13E: the cluster within Maillard et al. (2003), Paumard et al. (2006), Fritz et al. (2013)



- many objects within 1″
- fairly high velocity dispersion

⇒ intermediate mass black-hole?

- but claims that some objects may be just dust
- needs higher resolution spectro-imaging!
- Hooray for GRAVITY!

The binary fraction in the GC

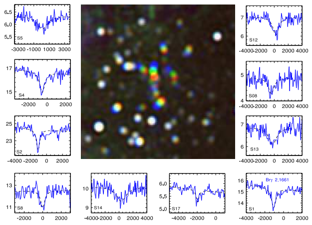
- radial velocities and eclipses: only high inclinations, small separations.
- GRAVITY:
  - direct imaging at 4 mas resolution,
  - differential astrometry continuum–spectral feature,
  - astrometry at 10 μas

  yields census of binary fraction at lower *i*, larger *a*.

Other multiple systems

- Several “co-moving groups”;
- GCIRS 13E: several early type stars within 1$''$;
- Hypothesized to harbour an IMBH.

The Cusp or S Star Cluster



3-epoch NACO imaging
SINFONI spectra

1 light-month

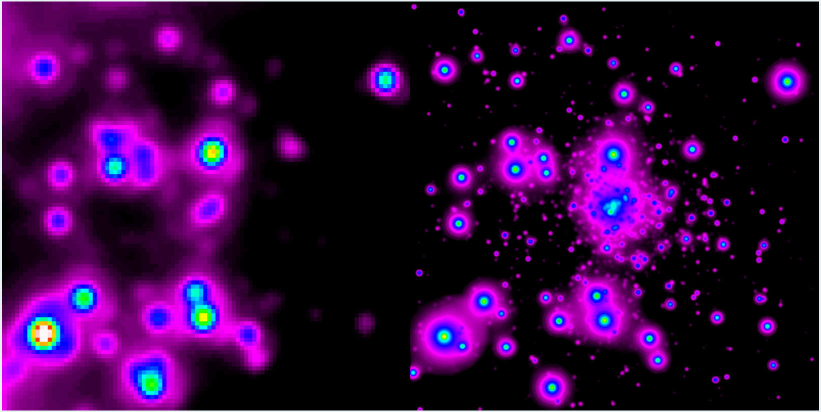
- (too) many OB stars;
- excentric orbits;
- S2: 15-year period, 1% light-speed;
- Keplerian orbits to within uncertainties.

Limitations

- spatial crowding;
- astrometric precision.

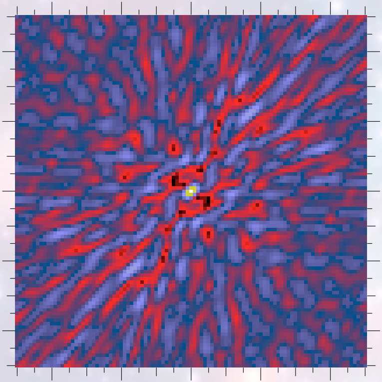
Overcome spatial crowding

Trippe et al. simulated field for E-ELT/MICADO (1″ × 1″)



VLT (8 m) E-ELT (42 m)

PSF: 3 (V, φ) sets, K-band, 4 UTs

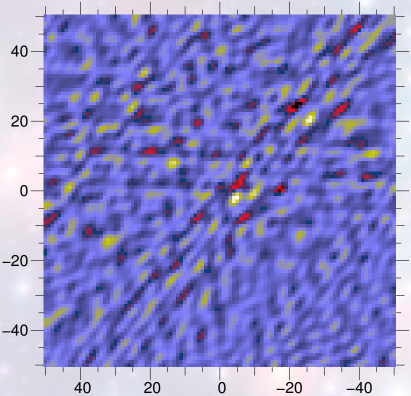


100 mas field-of-view

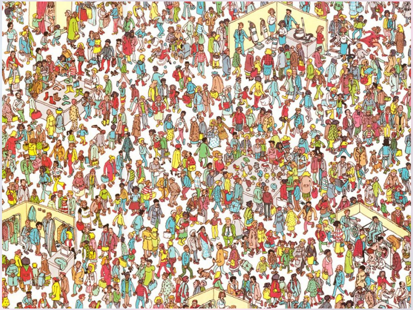
Assumed constraints

- 3h per observation;
- 5 spectral elements in the K band;
- dynamic range: $\simeq$ 1 mag;
- error on visibility:1%;
- error on phase: 2°.

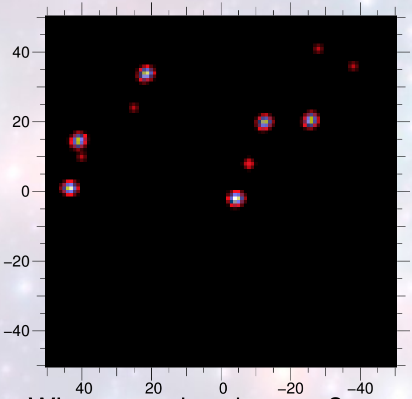
Synthesised image



Where are the six stars?

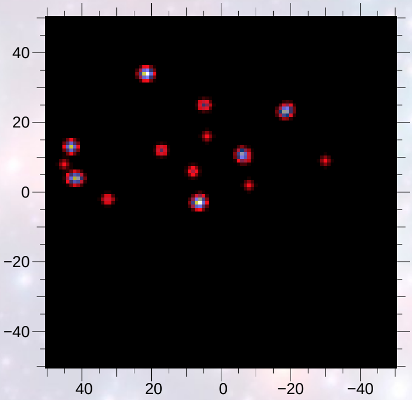


Synthesised image, cleaned



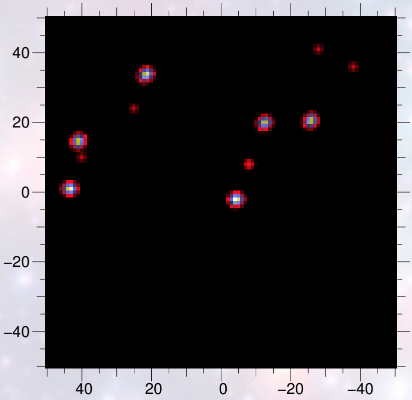
Where are the six stars?

3 months proper motion



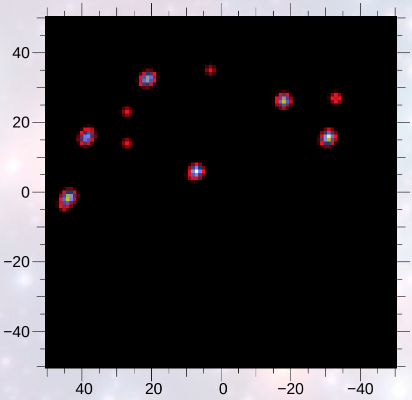
May (2 (V, φ) sets)

3 months proper motion



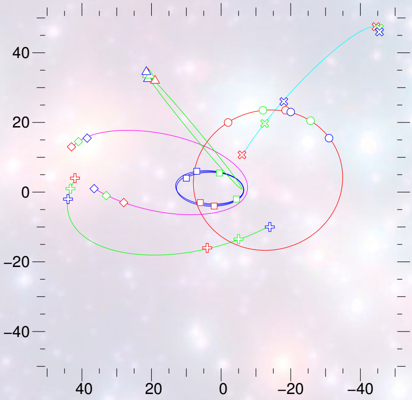
June (3 (V, φ) sets)

3 months proper motion



July (2 (V, φ) sets)

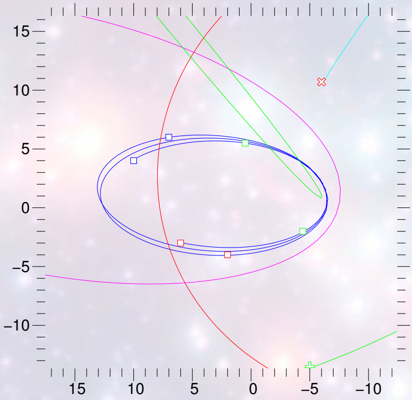
2 seasons proper motion



Relativistic precession within 2 years!

- Here: Crude measured astrometry + input orbits.
- Real model fitting somewhat complex (Römer effect, lensing effects): use GYOTO.

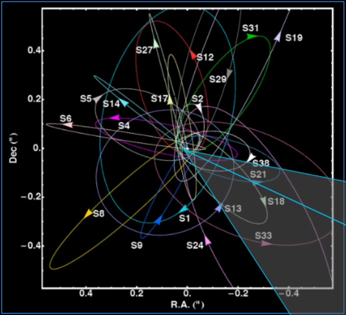
2 seasons proper motion



Relativistic precession within 2 years!

- Here: Crude measured astrometry + input orbits.
- Real model fitting somewhat complex (Römer effect, lensing effects): use GYOTO.

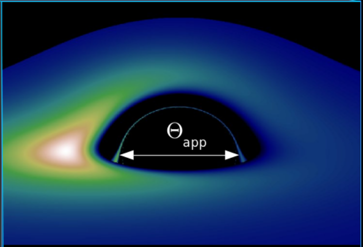
1. The Galactic Center and GRAVITY



Gillessen S., et al. ApJ, 692, 1075 (2009)

S cluster → Orbit of S2

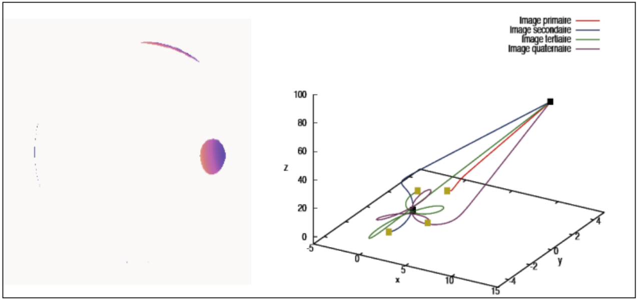
$M_0 = 4.31 \pm 0.6 \times 10^6\, M_\odot$



Simulated image by GYOTO, of an accretion disk around a Schwarzschild black hole

Apparent size of a Schwarzschild black hole seen from the Earth (D ≈ 8 kpc): $\Theta_{app} \approx 53\ \mu as$ (> 10 µas)

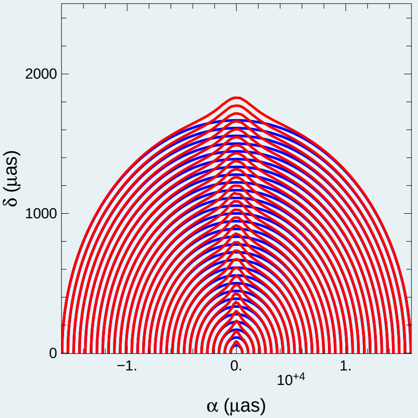
Largest black hole candidate



Lensing effects of a moving star on the ISCO with ā=0.9(PhD of Frédéric Vincent).

Beware of lensing effects

Appearance of circular orbits at 84° inclination



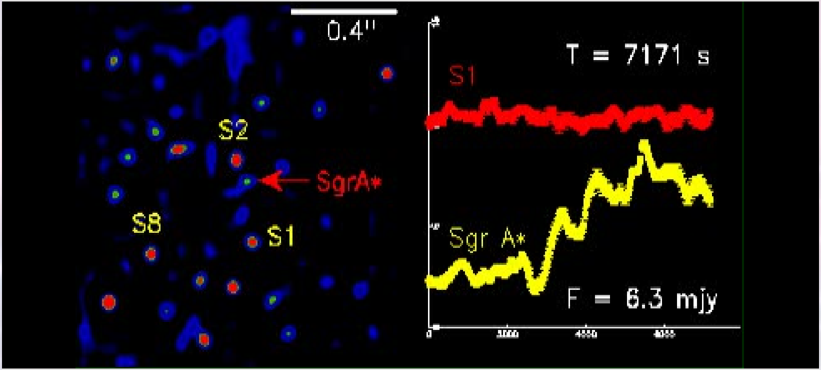
At the 10μas scale, lensing effects matter

- 5μas everywhere in the plane of Sgr A*;
- $>$ 100 μas when nearly aligned behind Sgr A*;
- error on major axis $\simeq$ 10μas everywhere in the central parsec.

(Bozza et al. 2012, Grould et al. 2015)

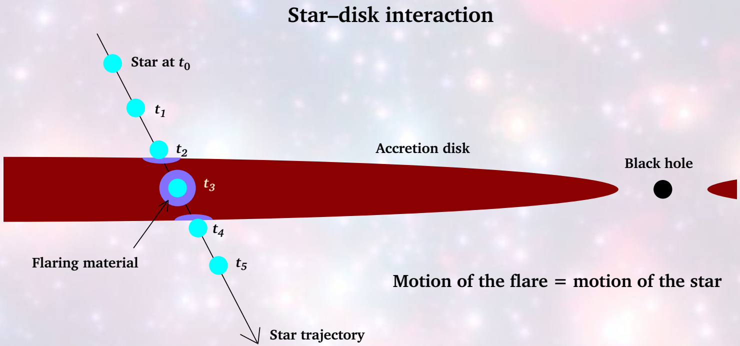
That's why we said apparent 2D and real 3D!

The flares



3 models

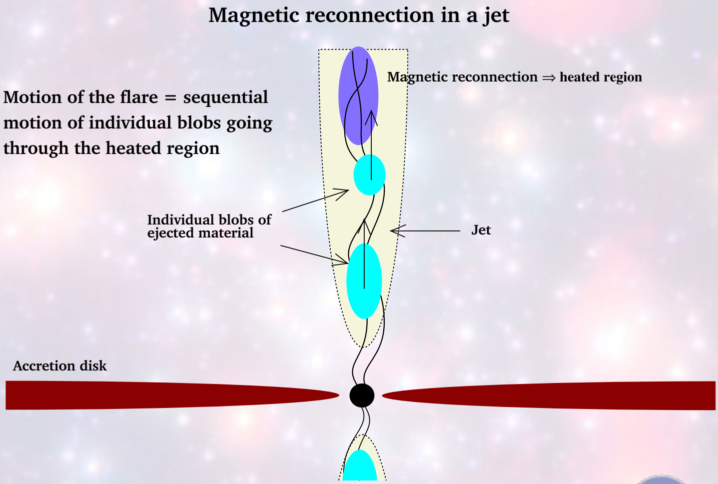
Nayakshin et al. (2004)



Keplerian velocity: $v \simeq \left(\frac{r}{R_S}\right)^{-1/2} \times 10\ \mu\mathrm{as\ min}^{-1}$

3 models

Markoff et al. (2001)

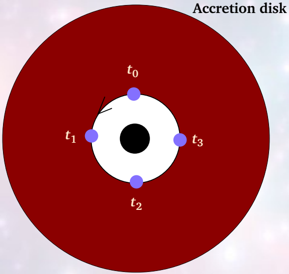


$c \simeq 15\ \mu\text{as min}^{-1}$

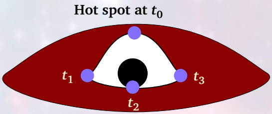
3 models

Yuan et al. (2004)

Hot spot on the last stable orbit



Last stable orbit seen from above

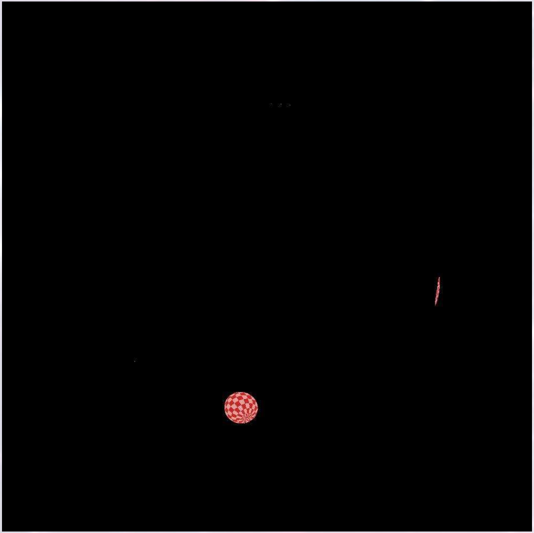


Last stable orbit seen at high inclination

Motion of the flare =
orbital motion of the clump

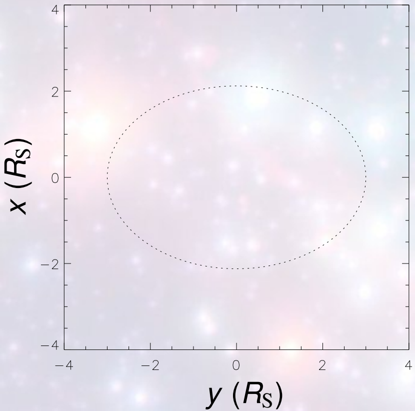
on average = 0

"Blob" on the LSO



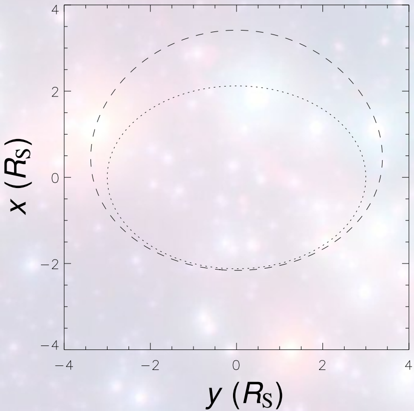
- $R_{\rm blob} = 0.25 R_{\rm S}$;
- $d = 3 R_{\rm S}$ (ISCO);
- Schwarzschild metric (Kerr also computed);
- $i = 45°$ (80°, 90°).

Astrometric model, $i = 45^\circ$



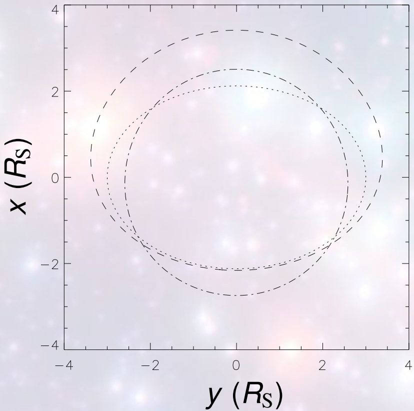
A circle with an inclination of 45º

Astrometric model, $i = 45^\circ$



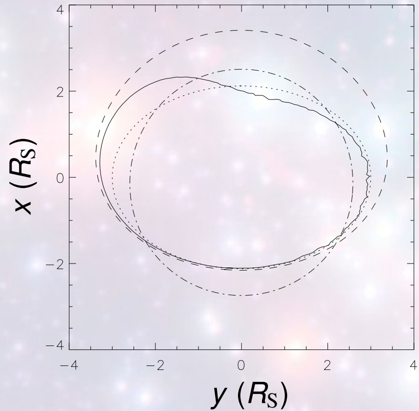
Track of the primary image: projected circle, lensed

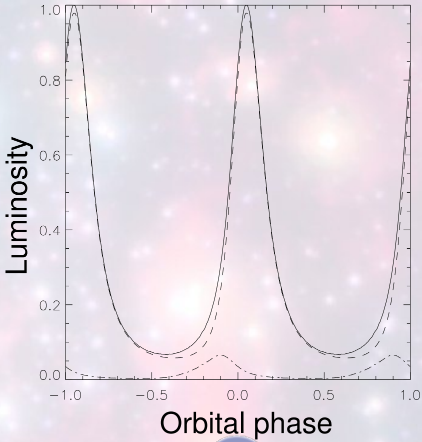
Astrometric model, $i = 45^\circ$



Track of the secondary image: almost a face-on circle

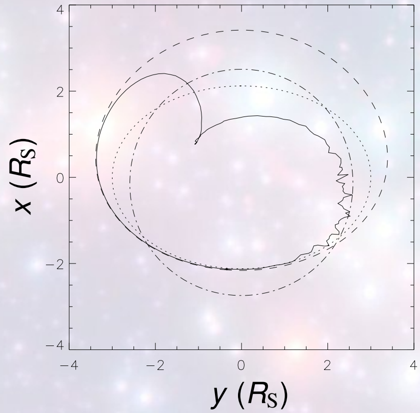
Astrometric model, $i = 45^\circ$

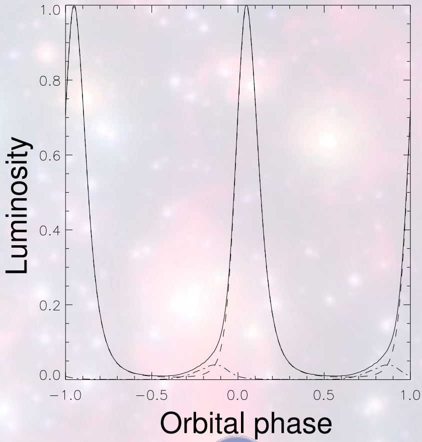




Global centroid, lensing + beaming (or $\nu L_\nu \propto \nu^0$)

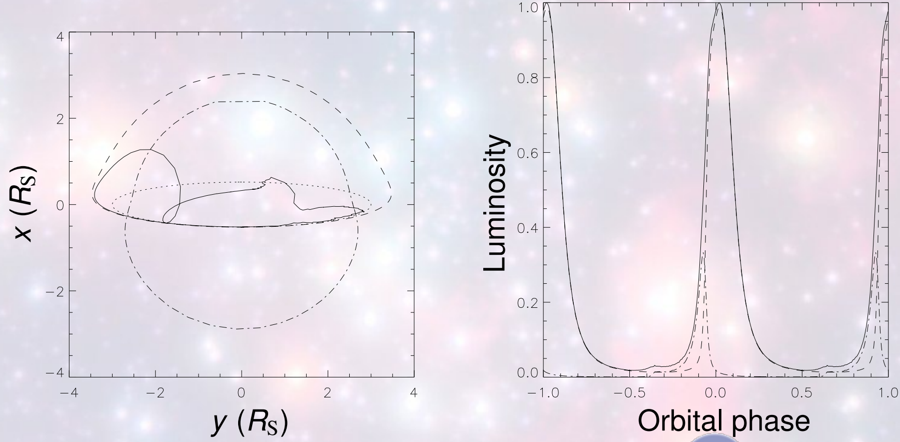
Astrometric model, $i = 45^\circ$





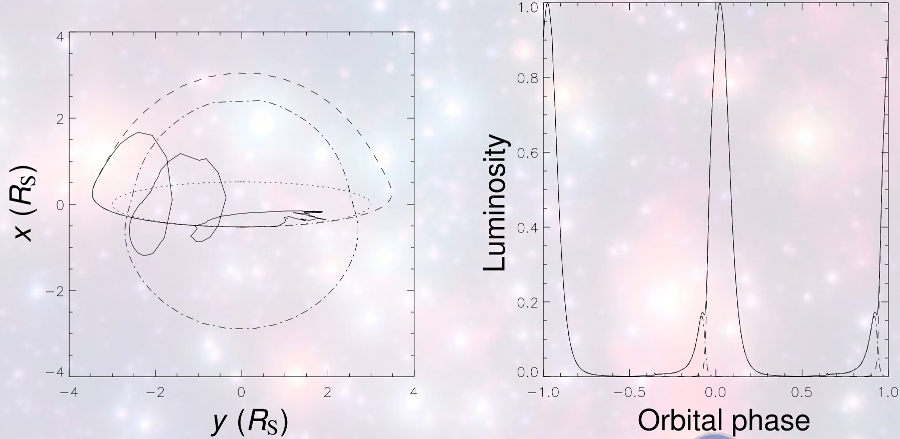
Global centroid, lensing + beaming + doppler ($\nu L_\nu \propto \nu^{-3}$)

Astrometric model, $i = 80°$



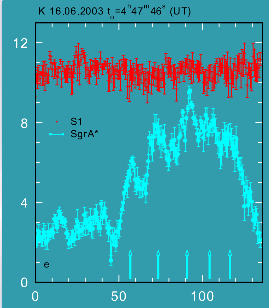
Global centroid, lensing + beaming (or $\nu L_\nu \propto \nu^0$)

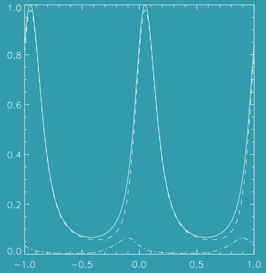
Astrometric model, $i = 80^\circ$



Global centroid, lensing + beaming + doppler ($\nu L_\nu \propto \nu^{-3}$)

The light-curves don't fit



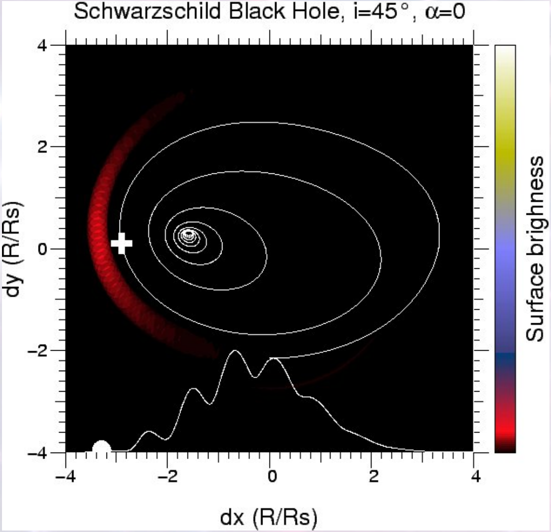


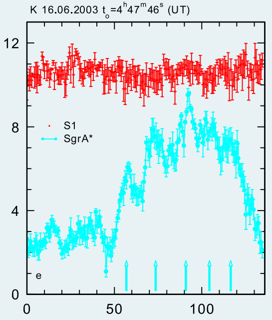
- (Overall raise and decay;)
- low contrast;
- time-variable contrast;

$\Rightarrow$ extended component.

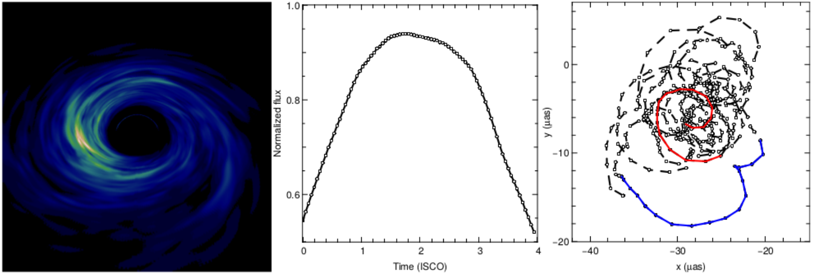
Must include arc spreading from the hot spot.

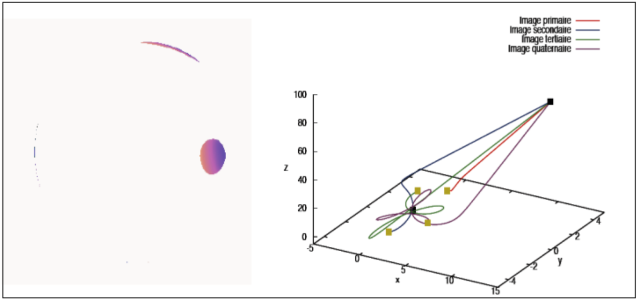
“Arc” on the LSO



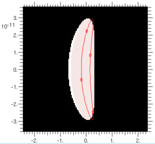


- $\alpha = 0$;
- $i = 45°$.





Lensing effects of a moving star on the ISCO with ā=0.9(PhD of Frédéric Vincent).



Vincent et al. 2014, MNRAS 441:3477

Hot spot

- **Hot spot**

  [Genzel et al., 2003]

- **Rossby wave**

  [Tagger & Melia, 2006; Falanga et al., 2007]

Weather forecasting

- **Red noise**

  [Do et al., 2009]

Ejection

- **Plasmon**

  [Van der Laan, 1966; Yusef-Zadeh et al., 2006]

- **Jet**

  [Falcke & Markoff, 2000; Markoff et al., 2001]

Three astrometric classes of models

- Hot-spot like, **equatorial plane** [hot-spot, Rossby wave]
- Weather forecasting, **equatorial plane** [red noise]
- Ejection, **out of the equatorial plane** [plasmon,jet]

Question

- Can GRAVITY distinguish these classes?

Three models

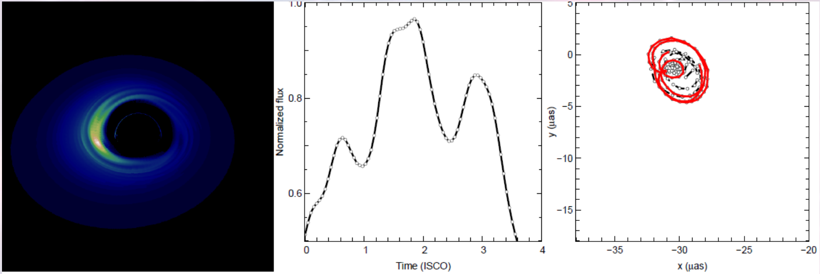
- **Rossby wave**: hydro, 2D disk, pseudo-Newtonian potential, synchrotron emission [P. Varniere]
- **Red noise**: MHD, 3D vertically-averaged disk, pseudo-Newtonian potential, Novikov-Thorne emission [P. Armitage]
- **Ejected blob**: MHD, axisymmetric 3D blob ejection, pseudo-Newtonian potential, synchrotron emission [F. Casse]

Observation simulation

- Using **GYOTO** to ray-trace light curves
- Using **GRAVISIM** to simulate GRAVITY data

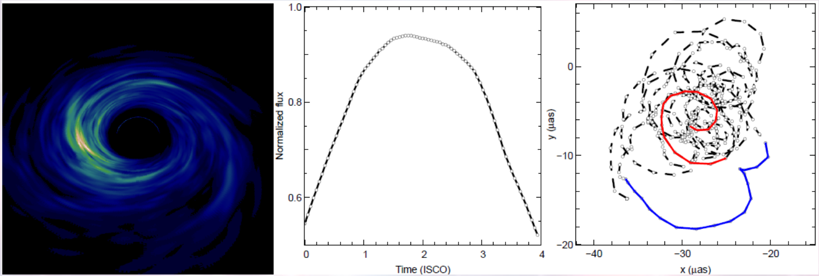
`gyoto.obspm.fr`

Rossby wave instability



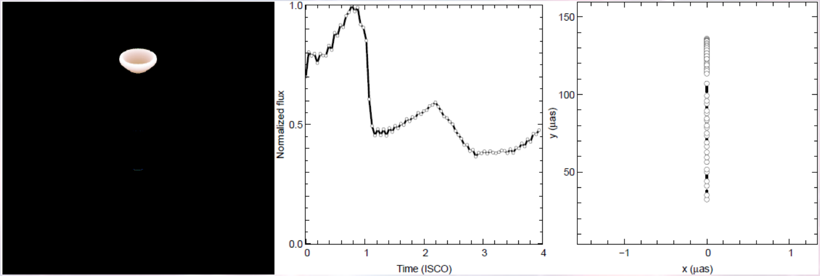
- Like little-contrasted hot-spot;
- Contained in disk;
- Orbital motion.

Red noise (a.k.a. disk meteorology)



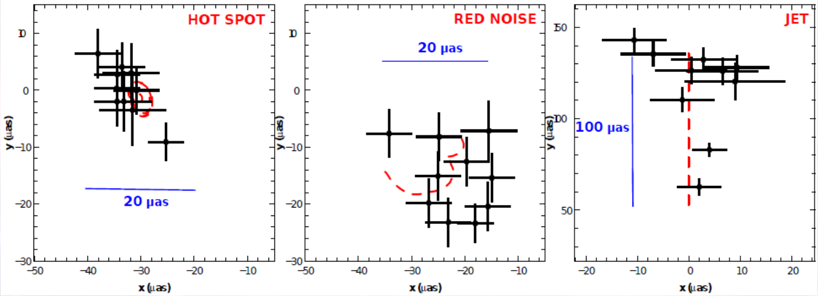
- Like many random hot-spots;
- Contained in disk;
- Orbital motion.

Ejected plasmon

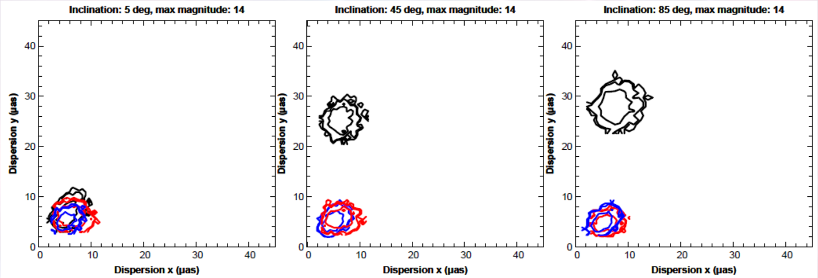


- Like spot-in-jet;
- In jet, not in disk;
- Axial motion.

Comparison (1 night)



Comparison (statistical)



- RWI (“hot spot”) and red noise identical;
- Jet-like model is very different.

Outline

Conclusion

- Imaging and astrometry of stars at the parsec scale:
  - Stellar physics on individual stars;
  - Binary fraction, comoving groups;
  - Complete mass-function to subsolar;
  - Astrometric accelerations up to several arcseconds;
  - Solid reference frame for the following:
- Astrometry of the S-stars and central 60 mas:
  - Relativistic orbits;
  - Lensing effects;

  $\Rightarrow$ constrain metric around Sgr A*;

  $\Rightarrow$ weigh nuclear cluster and dark matter halo;
- Astrometry of the flares of Sgr A*:
  - 10 μas astrometry $\Rightarrow$ nature of flares;
  - probe spacetime at a few $R_{\rm S}$;
- GRAVITY currently being integrated in Paranal