GRAVITY
Stars orbiting the Galactic Black Hole

Stefan Gillessen
on behalf of
The GRAVITY collaboration

The mass measurement of Sgr A*,
the massive black hole candidate in the Galactic Center,
was honored with the Nobel prize

Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

$$R_S = \frac{2GM}{c^2}$$

How to find a black hole

1. Find an object that has an event horizon
2. Show that a certain amount of mass is confined to a volume smaller than R_S
3. Show that an object is unstable against its self-gravity

Note: Density is ill-defined for black holes

$$\rho \sim \frac{M}{\frac{4\pi}{3} R_S^3} \sim \frac{1}{M^2}$$

Black holes are astronomical objects

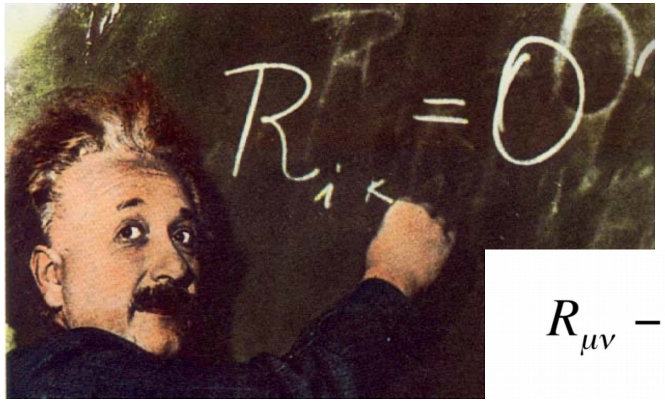
• 1kg:	$R_S = 10^{-27}$ m; (proton: 10^{-15} m)	$\rho = 10^{77}$ g/cm^3
• Earth:	$R_S = 1$ cm;	$\rho = 10^{27}$ g/cm^3
• Sun:	$R_S = 3$ km;	$\rho = 10^{16}$ g/cm^3
• Star cluster: (10^5 stars)	$R_S = 3 \times 10^8$ m; (distance to the moon)	$\rho = 10^6$ g/cm^3
• Galaxy (10^{11} stars)	$R_S = 3 \times 10^{14}$ m; (2000 AU)	$\rho = 10^{-6}$ g/cm^3 (thinner than air)

Types of black holes

- Particle physics scale ???
  - LHC, cosmic radiation
  - Should be bright & unstable due to their Hawking radiation
- Planetary mass – primordial black holes ??
  - primordial
- Stellar mass black holes($1 – 10\ M_{sun}$) ✓
  - End products of massive stars
- Intermediate mass black holes ($10^3 – 10^5\ M_{sun}$) ?
  - Primordial, or first generation of stars
- Supermassive black holes ($10^6 – 10^9\ M_{sun}$) ✓
  - in the center of galaxies
  - Quasars, Active Galactic Nuclei

A short history of black holes

1783 John Michell
Basic idea



1915 Albert Einstein:
General relativity

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} + \Lambda \, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

1916 Karl Schwarzschild
Black hole solution

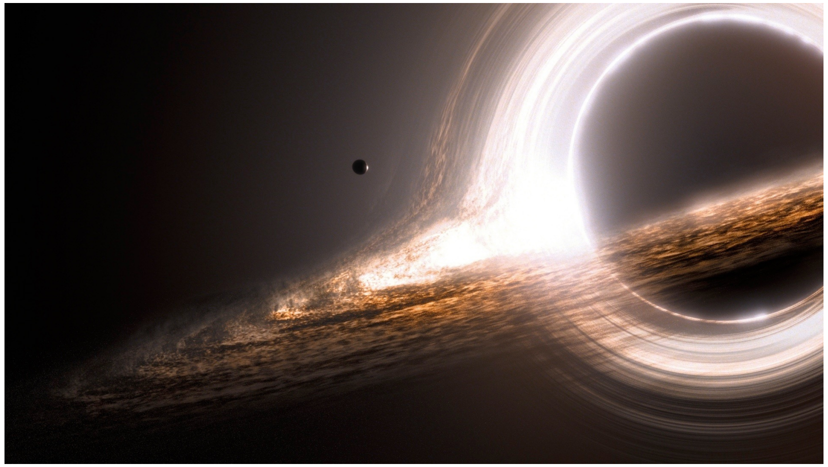
$$ds^2 = c^2 \left(1 - \frac{2GM}{c^2 r}\right) dt^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 - r^2 (d\theta^2 + \sin^2\theta d\phi^2)$$

1964 John Wheeler
"Black hole"

1969 Quasars speculated

1971 Cyg X-1's mass

2002 Galactic Center



PHILOSOPHICAL TRANSACTIONS

OF THE

ROYAL SOCIETY

OF

LONDON.

VOL. LXXIV. For the Year 1784.

PART I.

LONDON,

SOLD BY LOCKYER DAVIS, AND PETER ELMSLY, PRINTERS TO THE ROYAL SOCIETY.

MDCCLXXXIV.

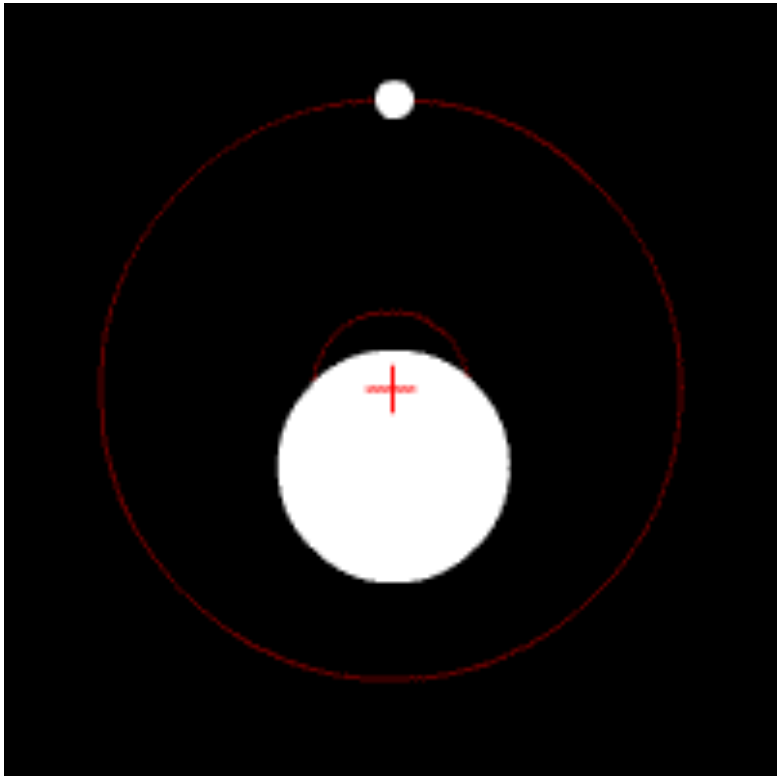
VII. *On the Means of diſcovering the Diſtance, Magnitude, &c. of the Fixed Stars, in conſequence of the Diminution of the Velocity of their Light, in caſe ſuch a Diminution ſhould be found to take place in any of them, and ſuch other Data ſhould be procured from Obſervations, as would be farther neceſſary for that Purpoſe. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendiſh, *Eſq. F. R. S. and A. S.* p. 35

16. Hence, according to article 10, if the ſemi-diameter of a ſphære of the ſame denſity with the ſun were to exceed that of the ſun in the proportion of 500 to 1, a body falling from an infinite height towards it, would have acquired at its ſurface a greater velocity than that of light, and conſequently, ſuppoſing light to be attracted by the ſame force in proportion to its vis inertiæ, with other bodies, all light emitted from ſuch a body would be made to return towards it, by its own proper gravity.

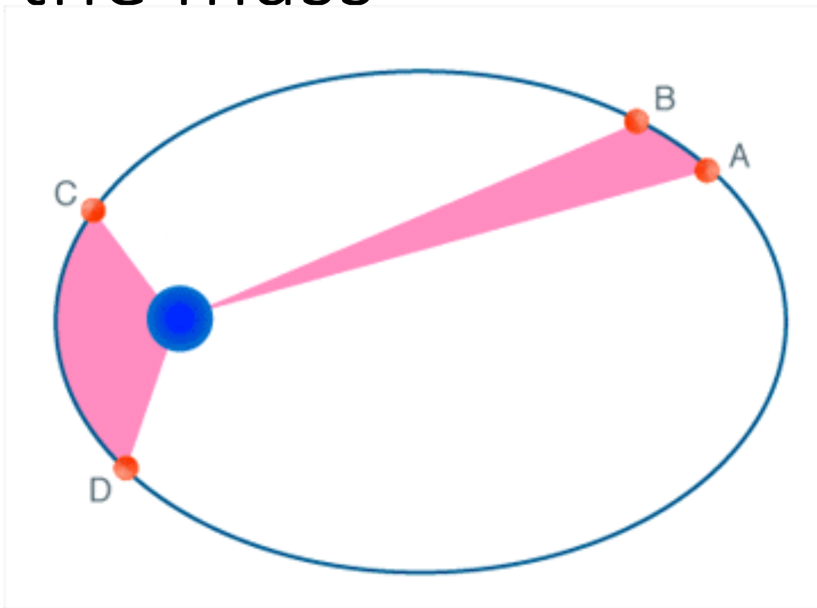
Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

Unseen mass can shake a visible object

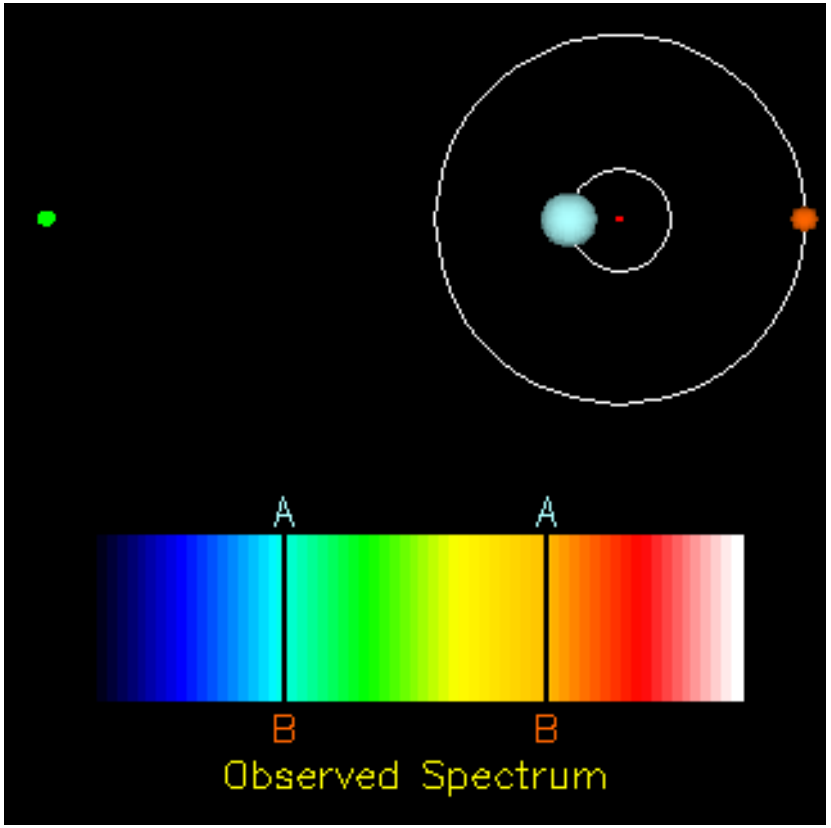


Kepler ellipses yield the mass

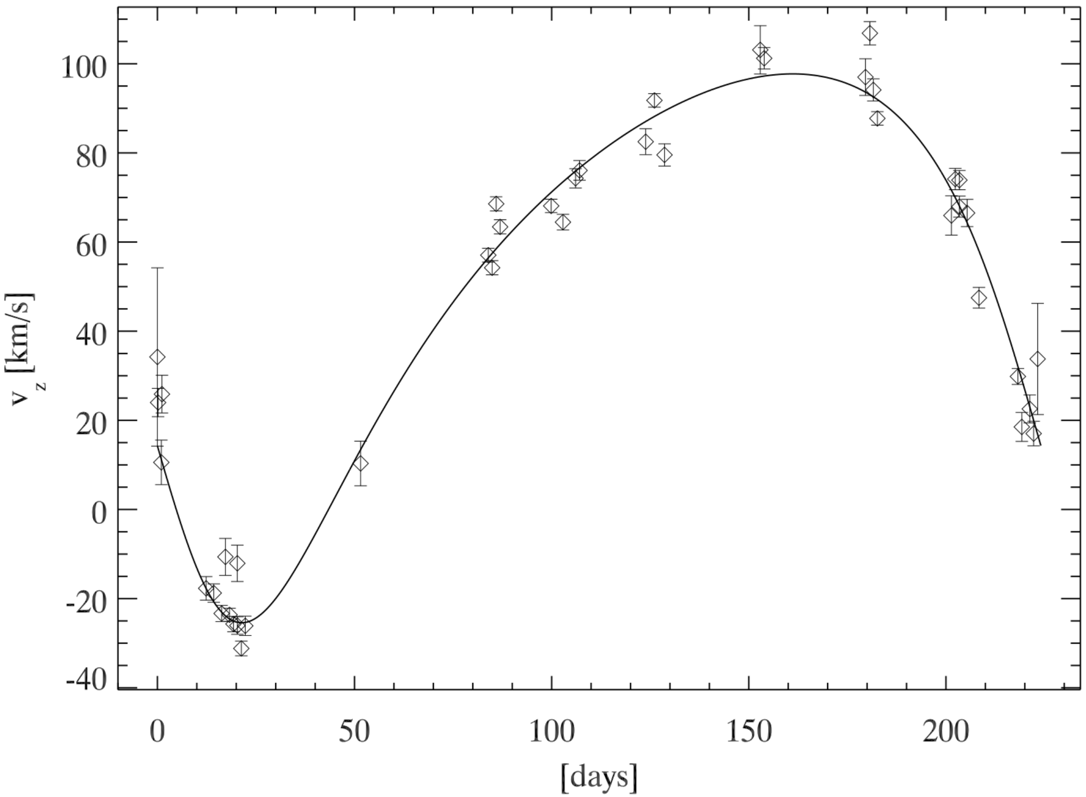


$$M = \frac{4\pi^2}{G}\,\frac{a^3}{T^2}$$

Most successful route:
Radial velocity measurements using the Doppler effect

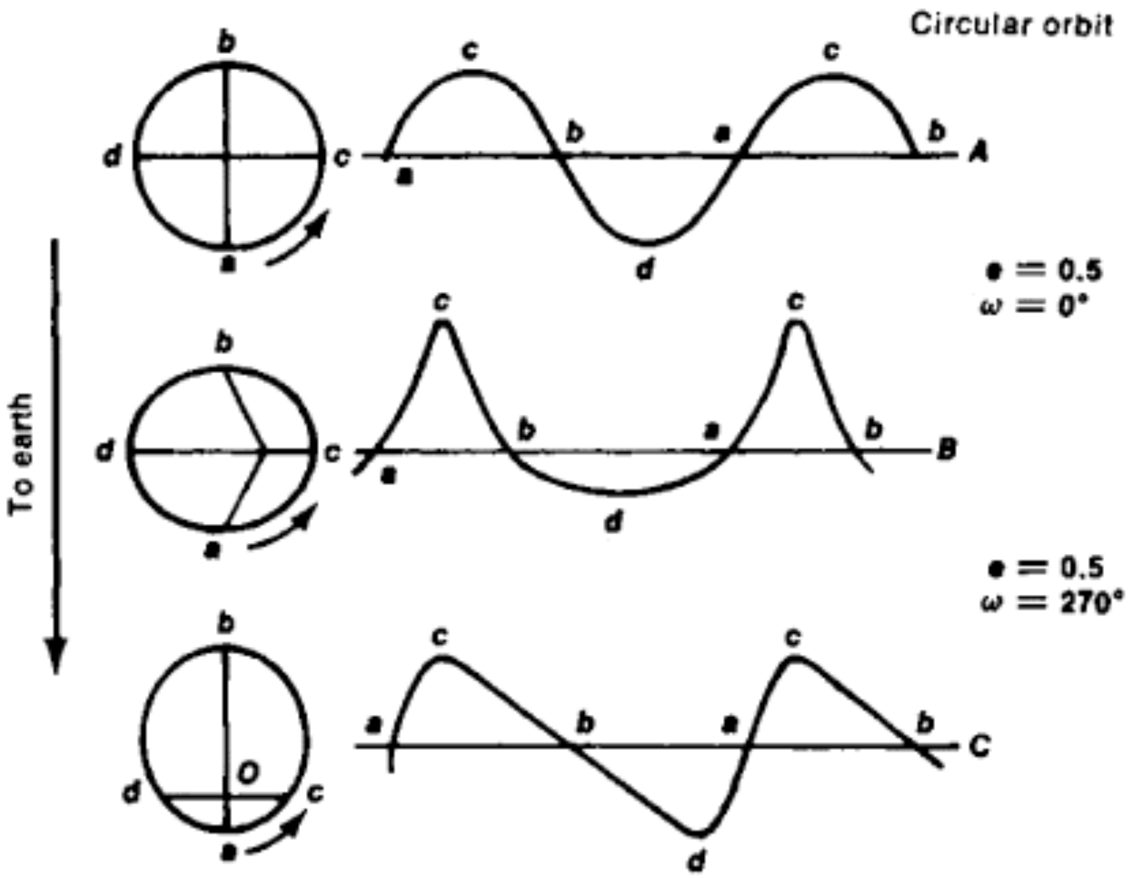


A typical example



Pfuhl et al. 2014

Shape and orientation of the orbit matter



Determine the orbital elements

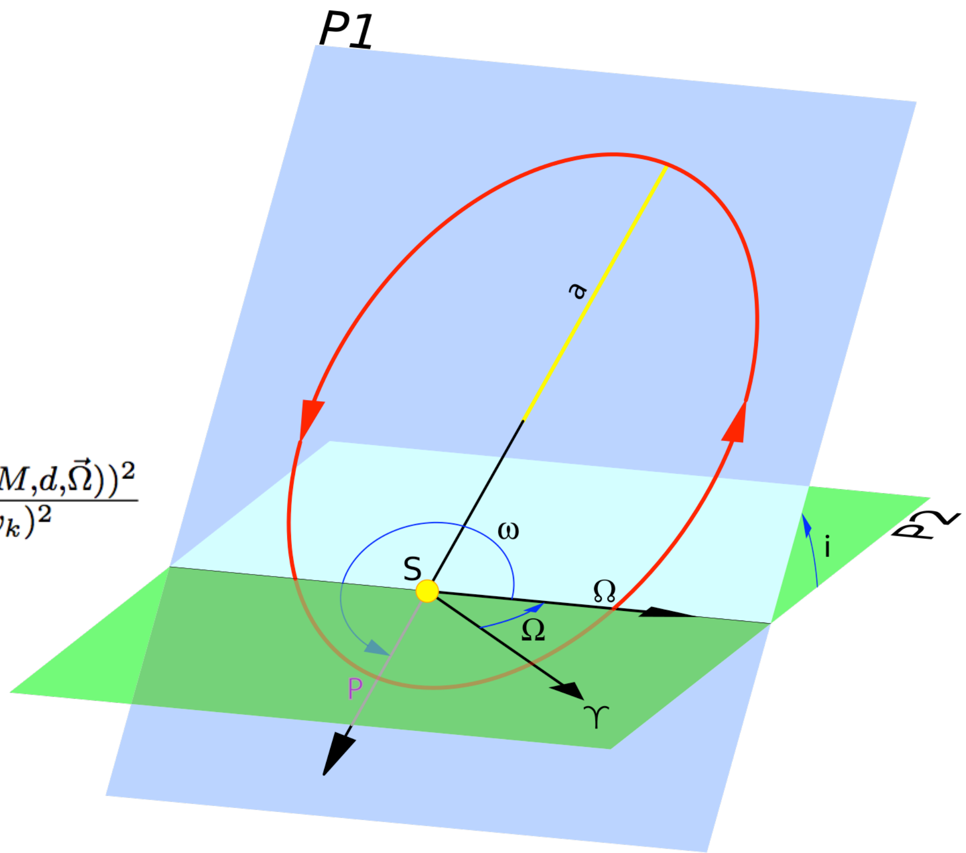
$$\{v_k \pm \Delta v_k\}$$

$$\vec{\Omega} = \{a, e, i, \Omega, \omega, t_0\}$$

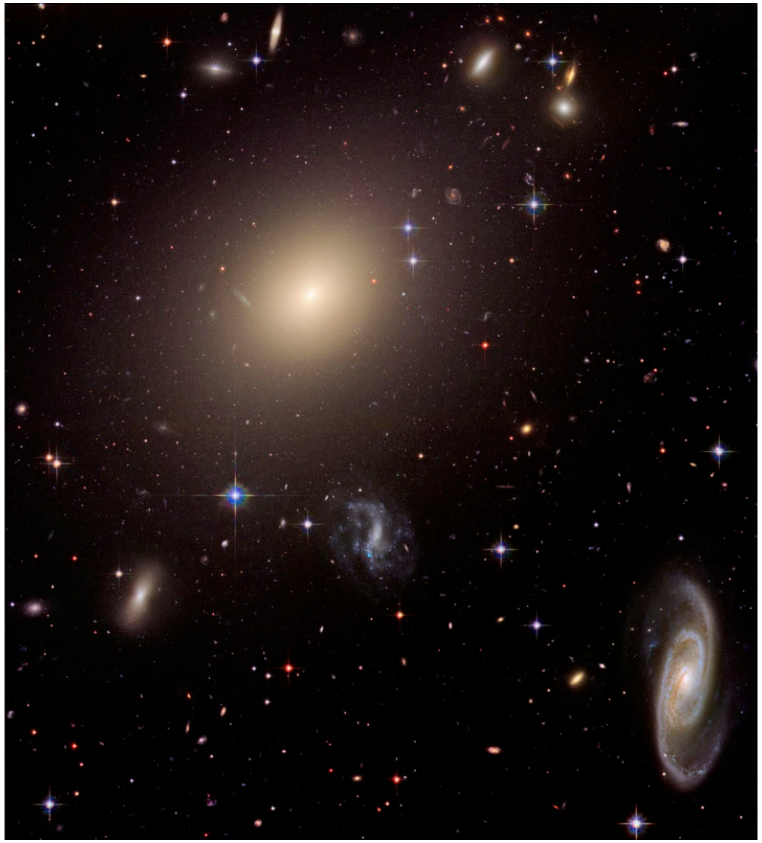
$$v(t) = v(t; M, d, \vec{\Omega})$$

$$\chi^2(M, d, \vec{\Omega}) = \sum_{k=1}^{\max} \frac{(v_k - v(t; M, d, \vec{\Omega}))^2}{(\Delta v_k)^2}$$

$$\min \big|_{(M,d,\vec{\Omega})} \; \chi^2(M, d, \vec{\Omega})$$



More difficult:
Unresolved stellar system



You can measure:

- Projected light profile
  ➔ proxy for $n(R)$
- Radial velocity profile
  ➔ $v(R)$, $\sigma(R)$

Solution: Jeans modeling

Distribution function: $$f = f(\vec{x}, \vec{v}, t)$$

"How many stars are at any given time
at a certain position with a certain velocity"

Number density of particles: $$n(\vec{x}, t) = \int f(\vec{x}, \vec{v}, t)\, d^3v$$

Mean velocity: $$\langle v \rangle = \int v\, f\, d^3v$$

Solution: Jeans modeling

Full differential: $$\frac{d\,f}{d\,t} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial x}\frac{\partial x}{\partial t} + \frac{\partial f}{\partial v}\frac{\partial v}{\partial t}$$

Newton's law: $$\frac{\partial v}{\partial t} = a = -\frac{\partial \Phi}{\partial x}$$

yields: $$\frac{d\,f}{d\,t} = \frac{\partial f}{\partial t} + v\,\frac{\partial f}{\partial x} - \frac{\partial \Phi}{\partial x}\frac{\partial f}{\partial v}$$

$$\frac{\partial f}{\partial t} + \vec{v}\;\nabla f - \nabla\Phi\,\frac{\partial f}{\partial \vec{v}}$$

Solution: Jeans modeling

Collisionless, incompressible system:

"CBE" $$0 = \frac{\partial f}{\partial t} + \vec{v}\,\nabla f - \nabla\Phi\,\frac{\partial f}{\partial \vec{v}}$$

$\int \mathrm{CBE}\, d^3v$ yields continuity equation: $$0 = \frac{\partial n}{\partial t} + \frac{\partial (n \cdot \langle \vec{v} \rangle)}{\partial \vec{x}}$$

$\int v\, \mathrm{CBE}\, d^3v$ yields Jeans equation

$$-\nabla\Phi = \frac{\partial \langle \vec{v} \rangle}{\partial t} + \langle \vec{v_i} \rangle \frac{\partial \langle \vec{v} \rangle}{\partial x_i} + \frac{1}{n}\nabla(n\,\sigma^2)$$

Velocity dispersion appears here, because:

$$\langle v^2 \rangle = \langle v \rangle^2 + \sigma^2$$

Solution: Jeans modeling

Simplest case: steady state, spherical symmetric, non-rotating system:

The potential is Newtonian $\Phi(r) = \frac{G\,M(r)}{r}$

Only radial part of Jeans equations survives, and many terms are 0:

$$-\frac{d\Phi}{d\,r} = \frac{1}{n}\frac{d\,(n\sigma^2)}{d\,r}$$

Integrating:

$$n(r)\sigma^2(r) = \int_r^{\infty} n(r')\frac{d\Phi(r')}{d\,r'}d\,r'$$

Solution: Jeans modeling

Slight complication: We measure **projected** values only

$$r^2 = R^2 + z^2 \qquad \Sigma(R) = \int_{-\infty}^{\infty} n(R,z)dz$$

change of variables z ➔ r

$$\Sigma(R) = \int_R^{\infty} \frac{r}{\sqrt{r^2 - R^2}} n(r)\, dr$$

Similar for velocity dispersion

$$\Sigma(R)\sigma_P^2(R) = \int_R^{\infty} \frac{r}{\sqrt{r^2 - R^2}} n(r)\sigma^2(r)\, dr$$

Some maths ...

$$\sigma_P^2(R) = G\, \frac{\int_R^{\infty} (r^2 - R^2)^{1/2}\, r^{-2}\, M(r) n(r) dr}{\int_R^{\infty} (r^2 - R^2)^{-1/2}\, r\, n(r) dr}$$

Now we can “Jeans model”

1. Define your model

$$M(r) = M_{\rm central} + 4\pi \int_0^r r^2 \rho(r) dr$$
$$\rho(r) = \rho_0 \, r^\gamma$$
$$n(r) \propto r^\Gamma$$

1. Determine $n(r)$ from $\Sigma(R)$,
   i.e. fit Γ to reproduce measured density profile

2. Remaining free 3 parameters: $M_{\rm central}$, ρ_0, γ.

3. For each set of these 3, one can evaluate $\sigma_P^2(R)$

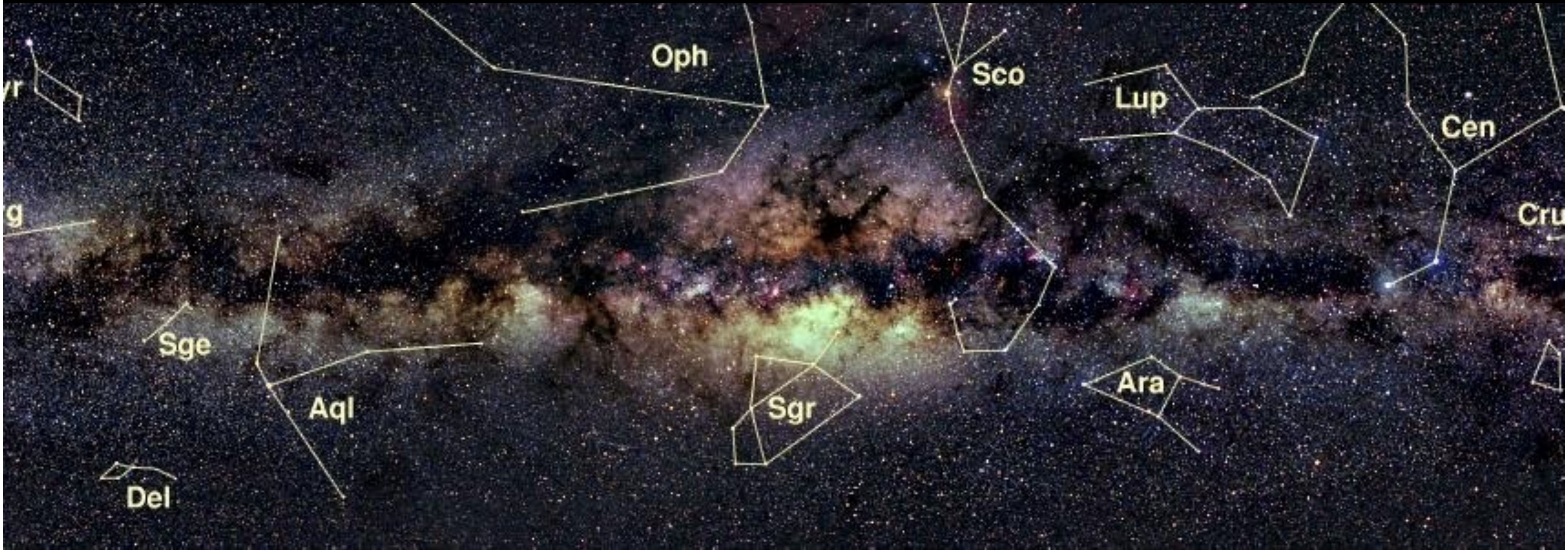
4. Minimize χ^2 to measured values of $\sigma_P(R_k)$

5. You have determined M(r) !

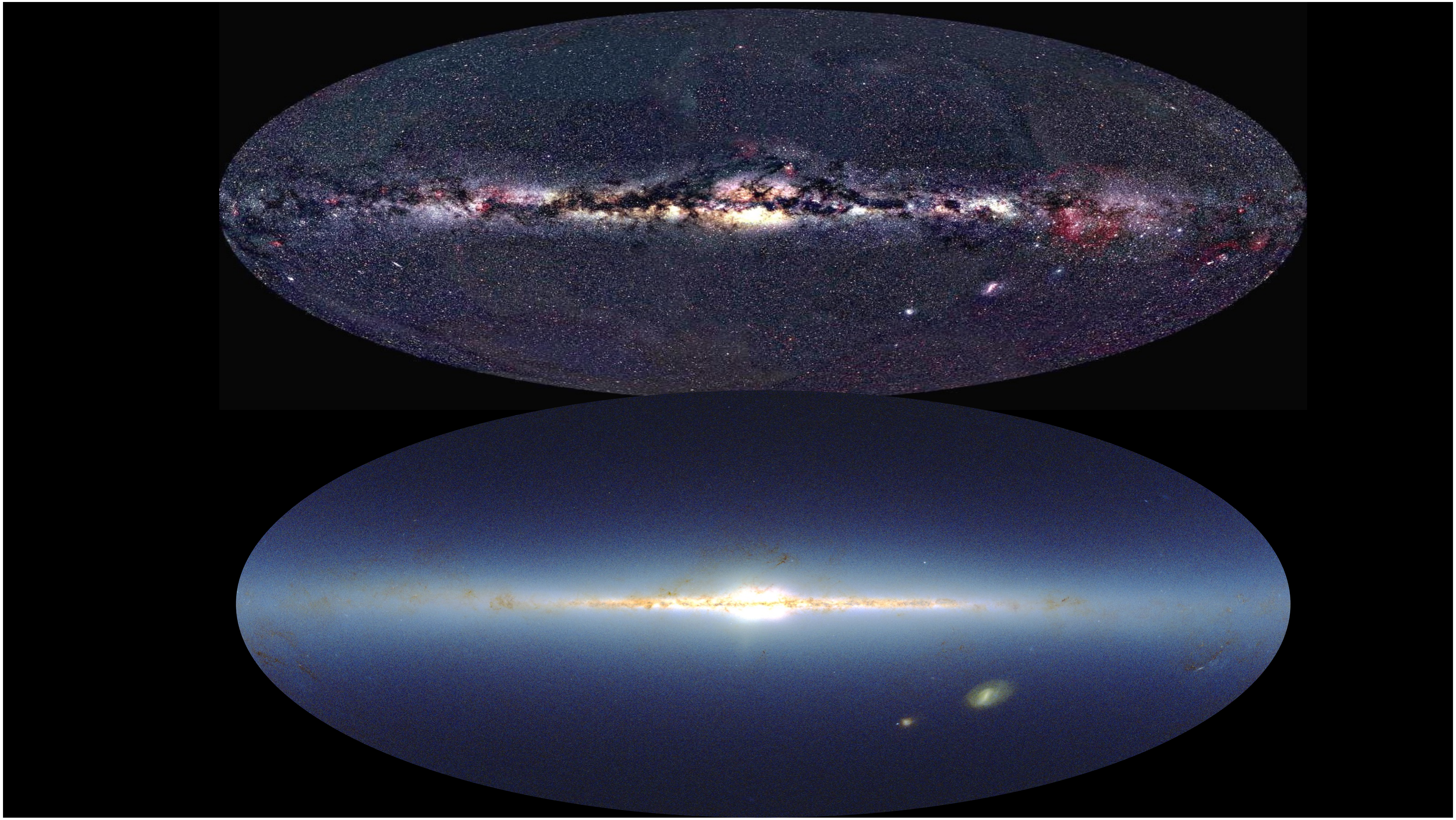
Outline

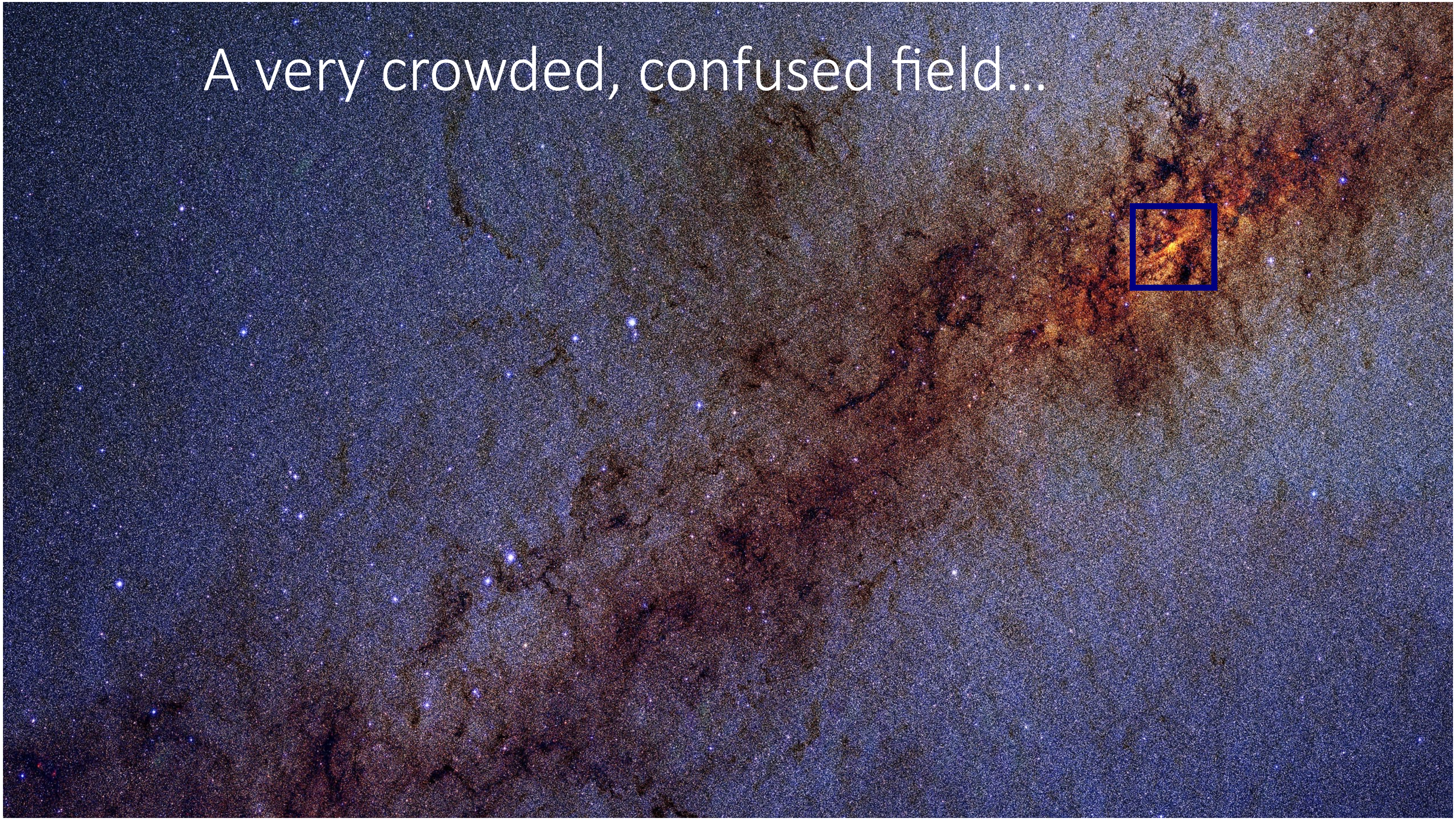
- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

The Galactic Center is highly obscured

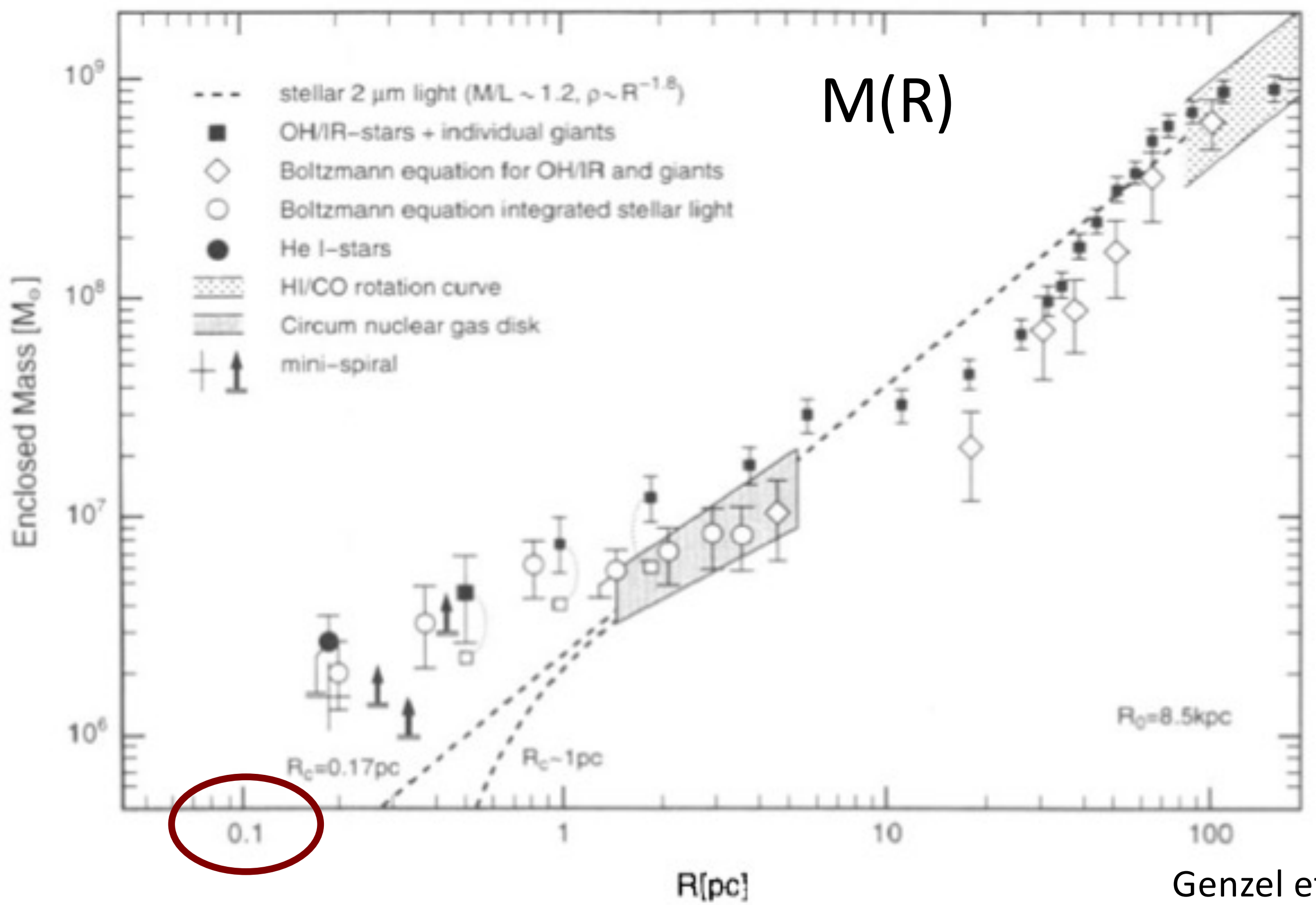


Using infrared light allows one to look through the dust



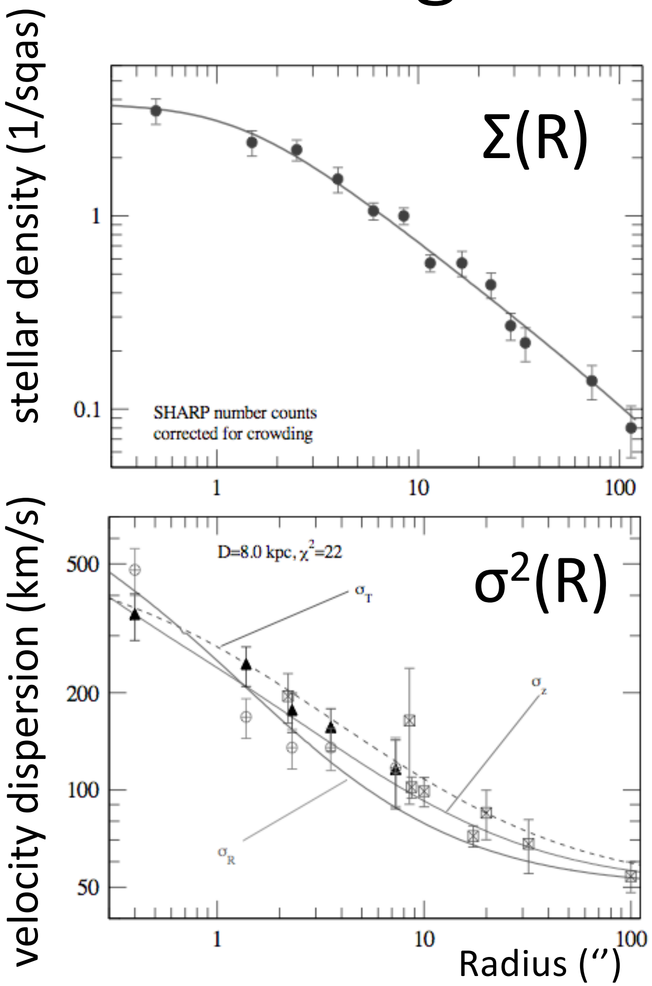

A very crowded, confused field…

Jeans modeling in the Galactic Center – 1990's

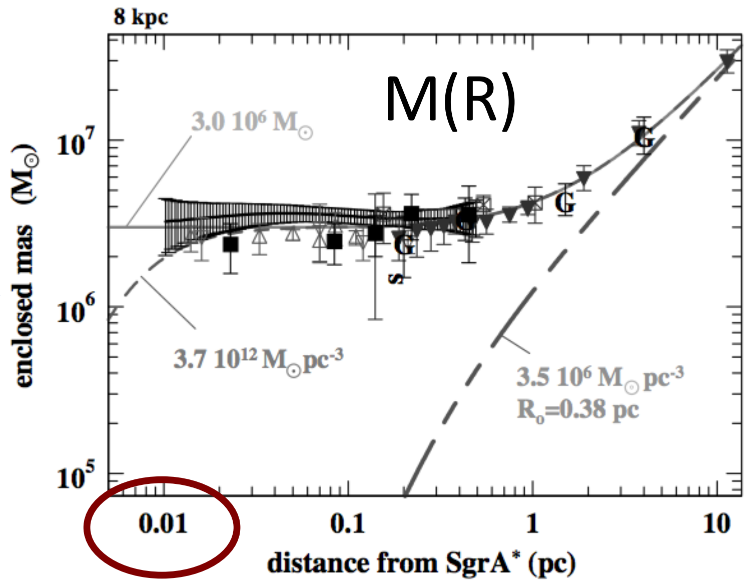


Genzel et al. 1994

Jeans modeling in the Galactic Center – 2000



cluster + central mass

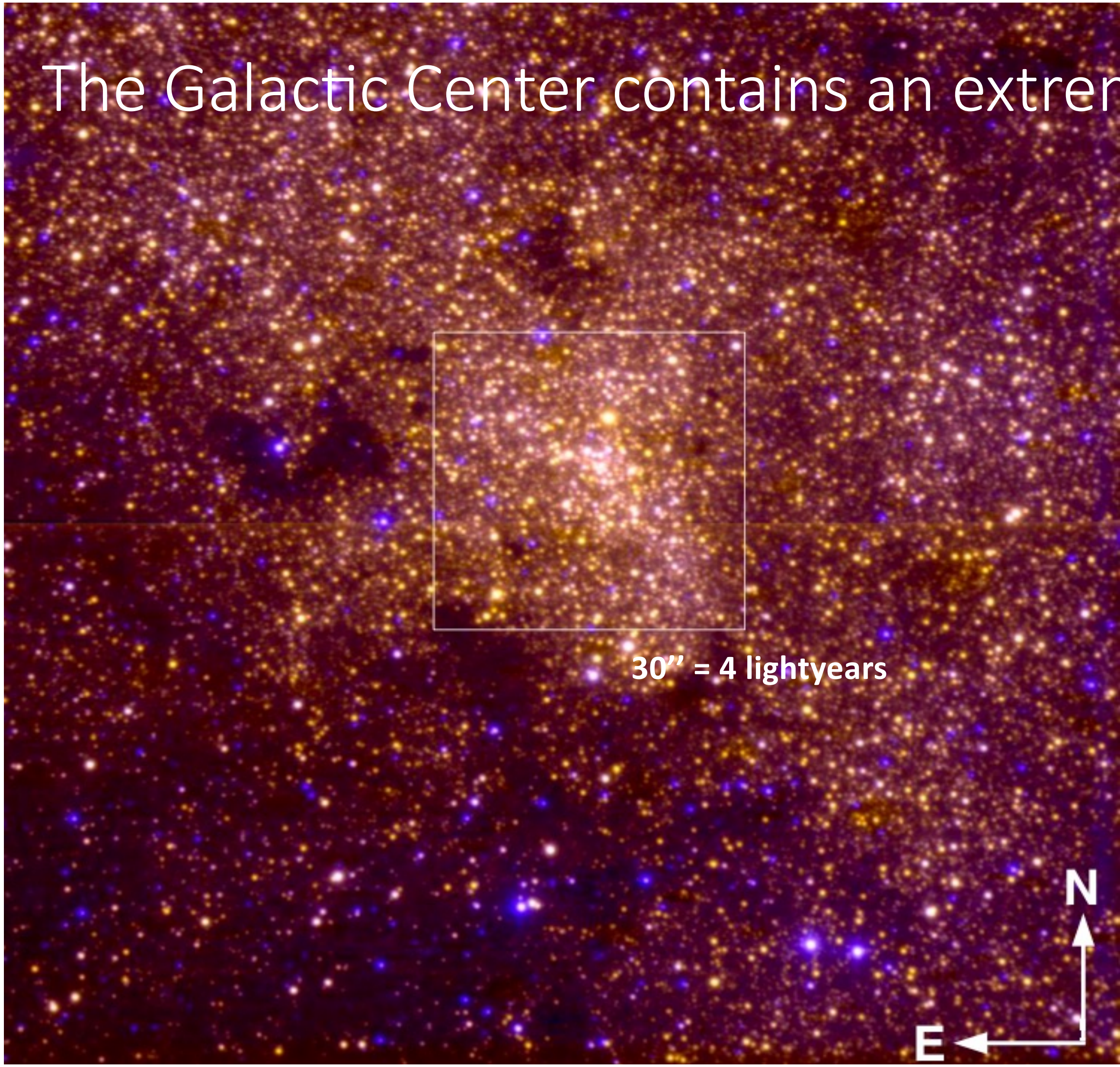


Genzel et al. 2000

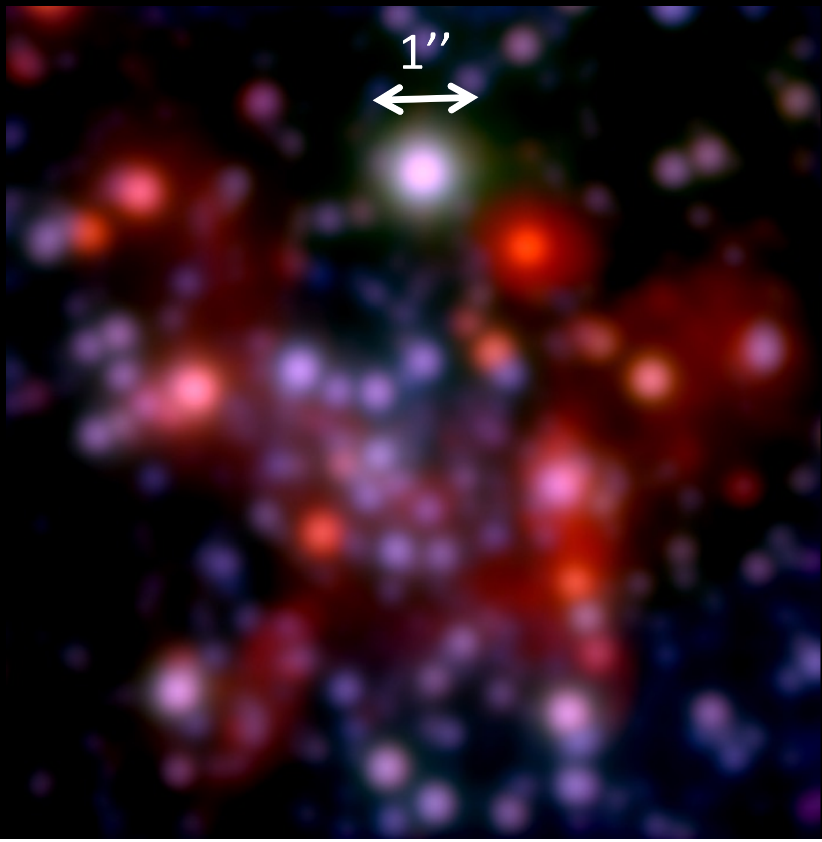
Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

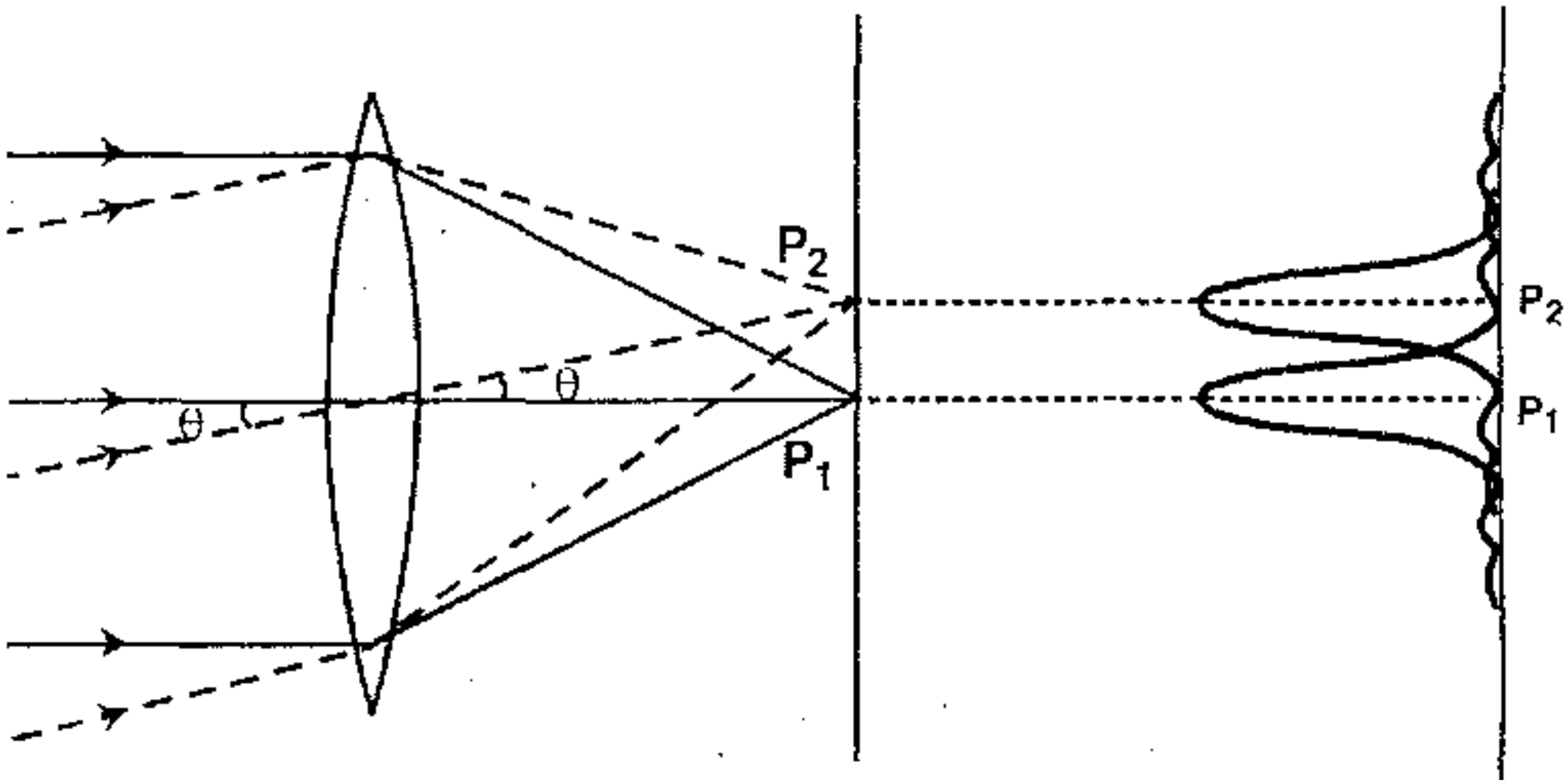
The Galactic Center contains an extremely dense star cluster



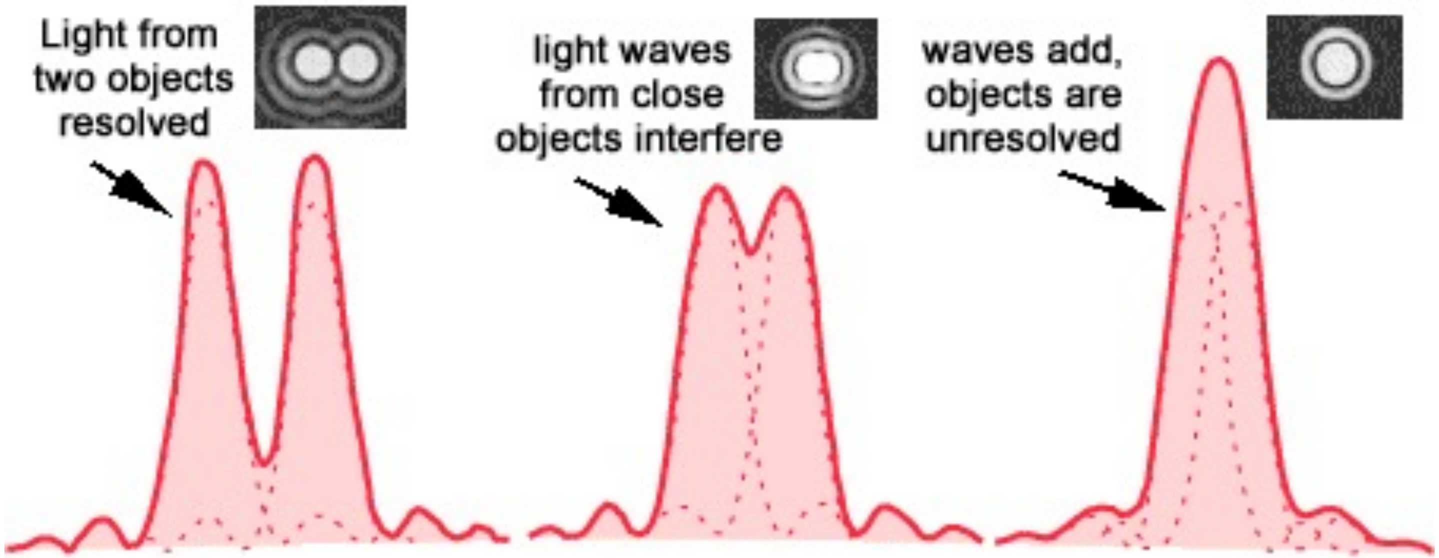
The central 20’’: Not very sharp



Why are the point-like stars not images as points?



Objects are resolved when they are further apart than 1.22 × λ / D



Rayleigh criterion: $\theta > 1.22 \times \lambda / D$

$\lambda = 2\mu m$; $D = 8m$ should be: $\theta = 0.05''$

but we observe $\theta = 1''$?!

The "Seeing" smears out the images

That is severely limiting

Light wavefronts are aberrated

Wavefront error
for telescope diameter D:

$$\sigma^2 = 1.030\left(\frac{D}{r_0}\right)^{5/3}$$

complete decorrelation: $\sigma^2 = 1$ rad ➔ $D \approx r_0$

Turbulence limits the resolution of a telescope to an effective size of r_0.

$R \sim \lambda/r_0$ instead of $R \sim \lambda/D$.

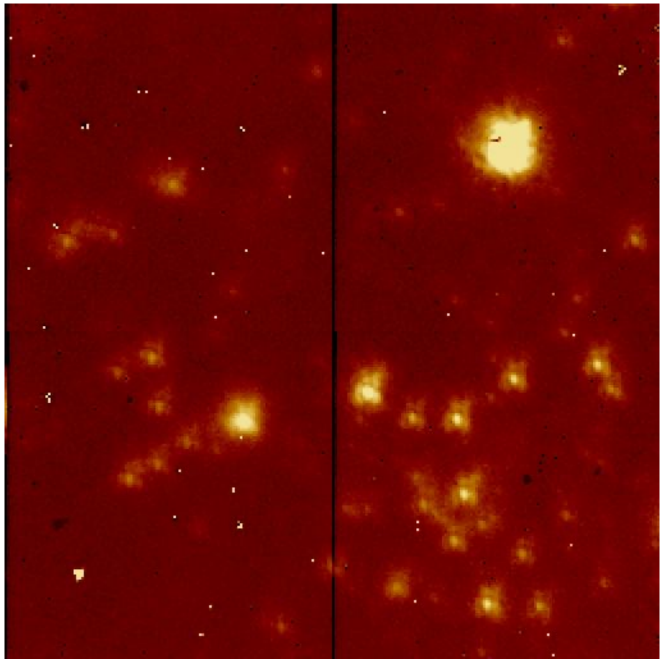
$\lambda = 2.2\mu m$, $\theta = 1''$

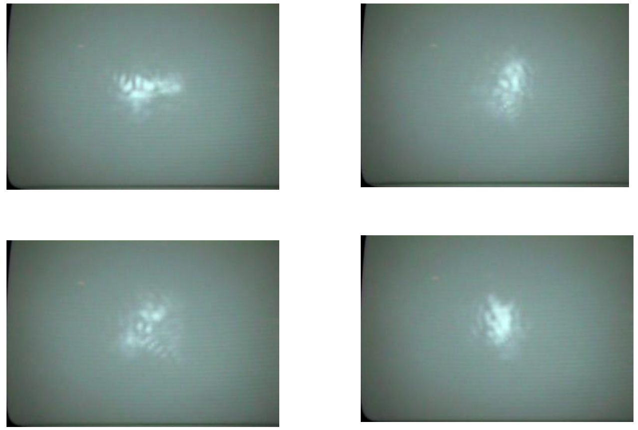
⬇

$r_0 = 40$ cm

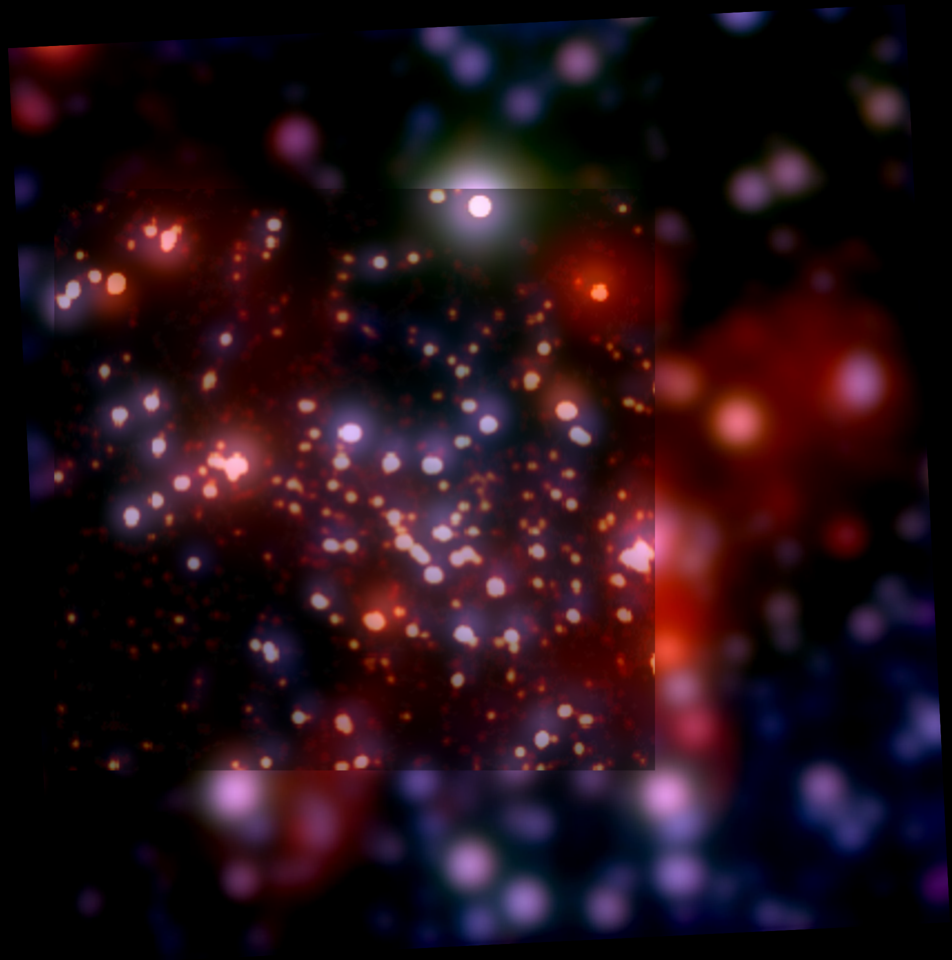

La Silla, Chile
© Serge Brunier

1992 - 2001: Speckle-Imaging



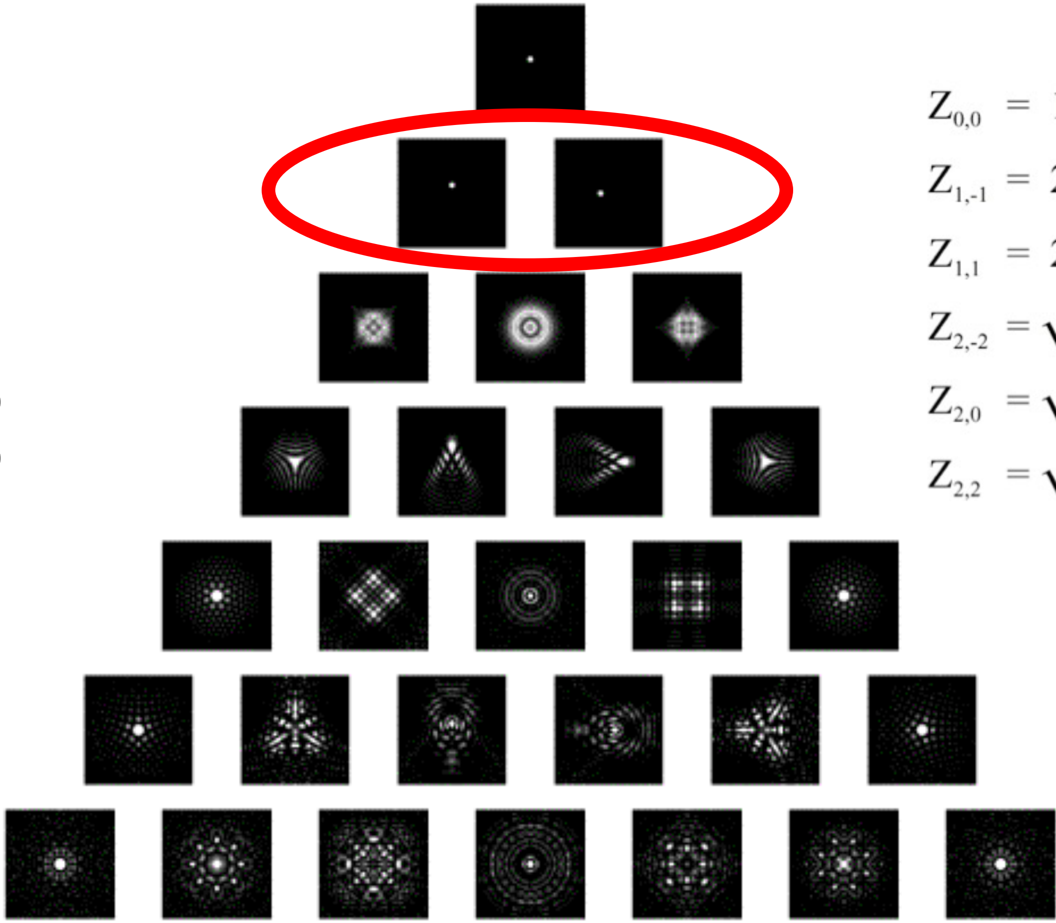


From seeing-limited to to diffraction-limited



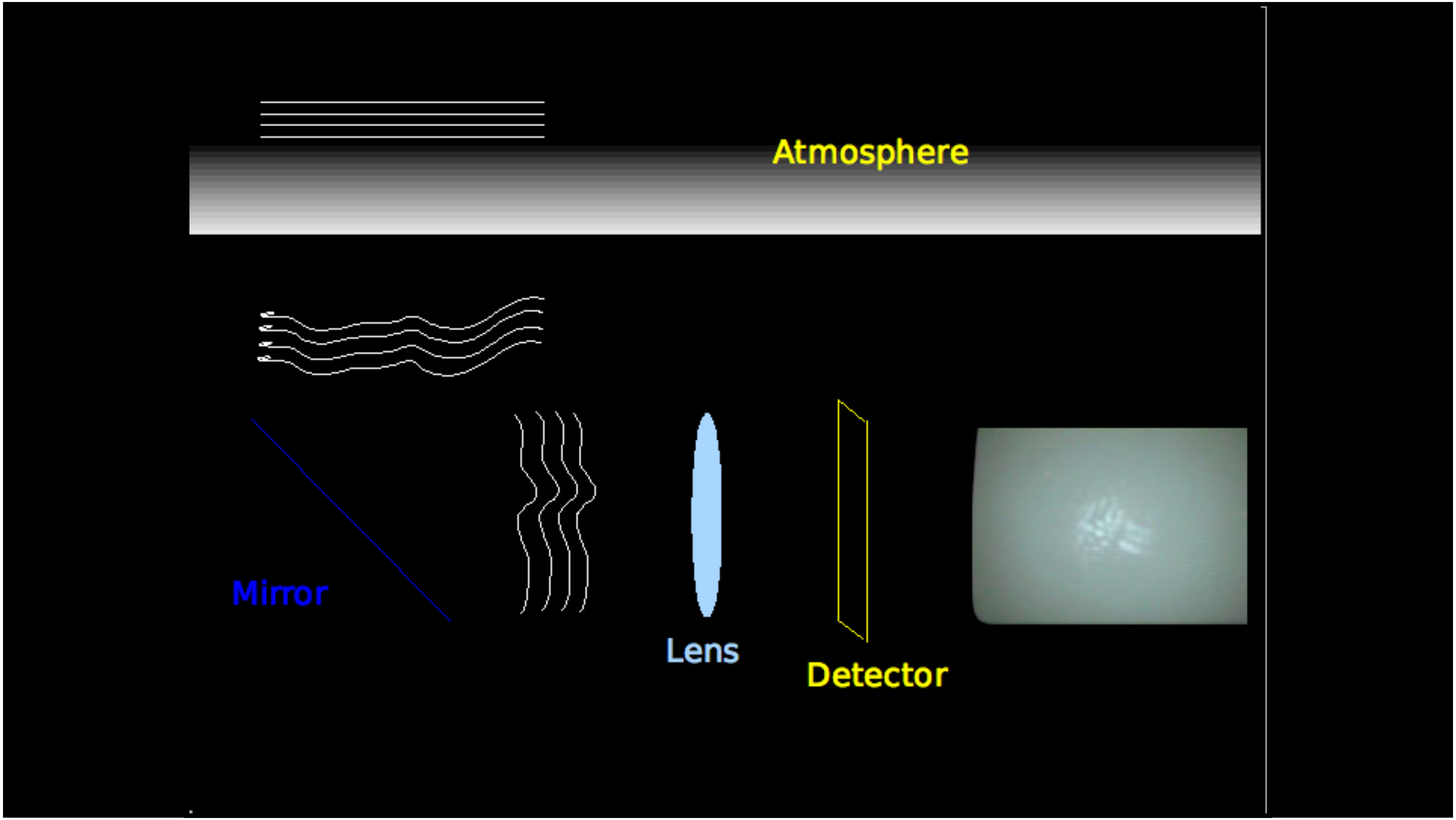
“Simple shift and add” only corrects two terms of wavefront aberrations

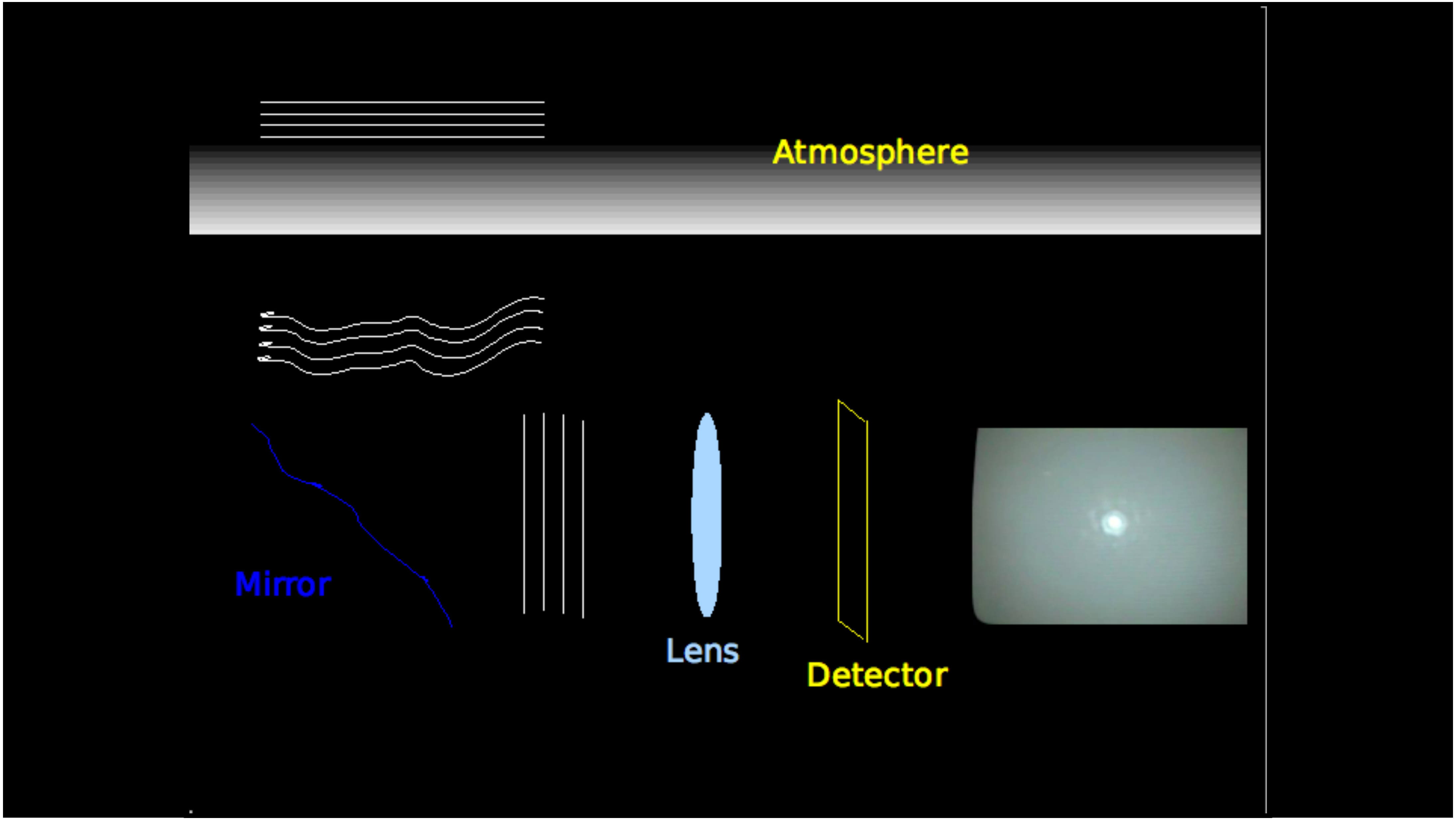
=



$Z_{0,0} = 1$	piston
$Z_{1,-1} = 2\, r \sin\theta$	tip/tilt
$Z_{1,1} = 2\, r \cos\theta$	tip/tilt
$Z_{2,-2} = \sqrt{6}\, r^2 \sin 2\theta$	astigmatism
$Z_{2,0} = \sqrt{3}\, (2r^2 - 1)$	focus
$Z_{2,2} = \sqrt{6}\, r^2 \cos 2\theta$	astigmatism

“Zernike” polynomials

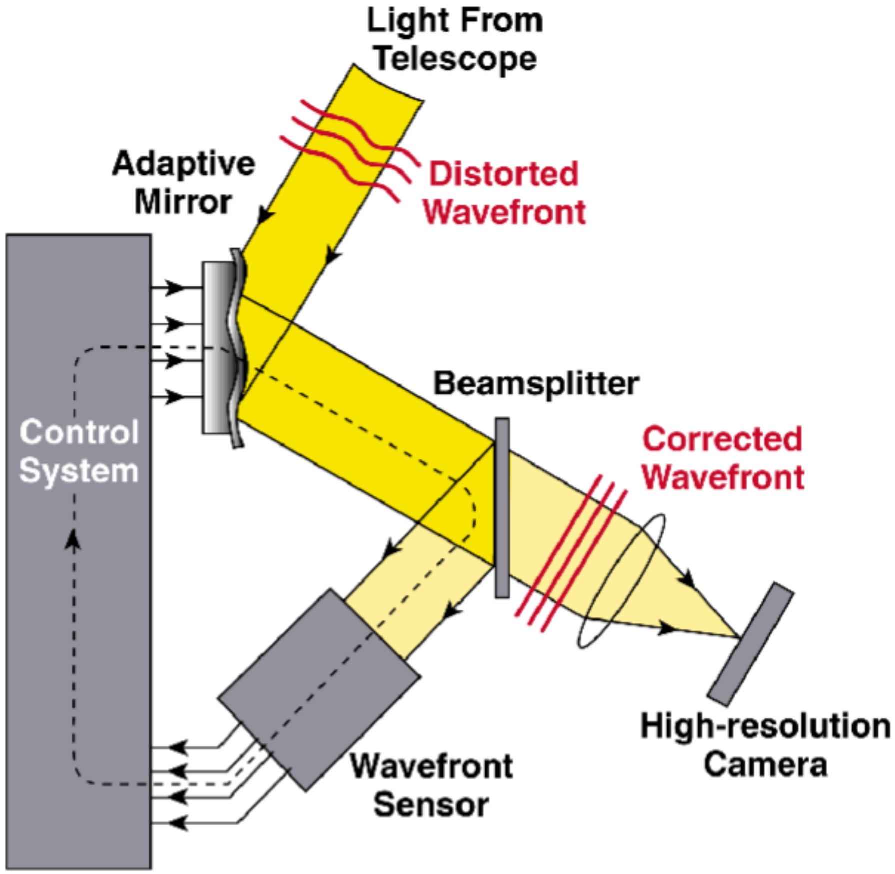

Atmosphere
Mirror
Lens
Detector



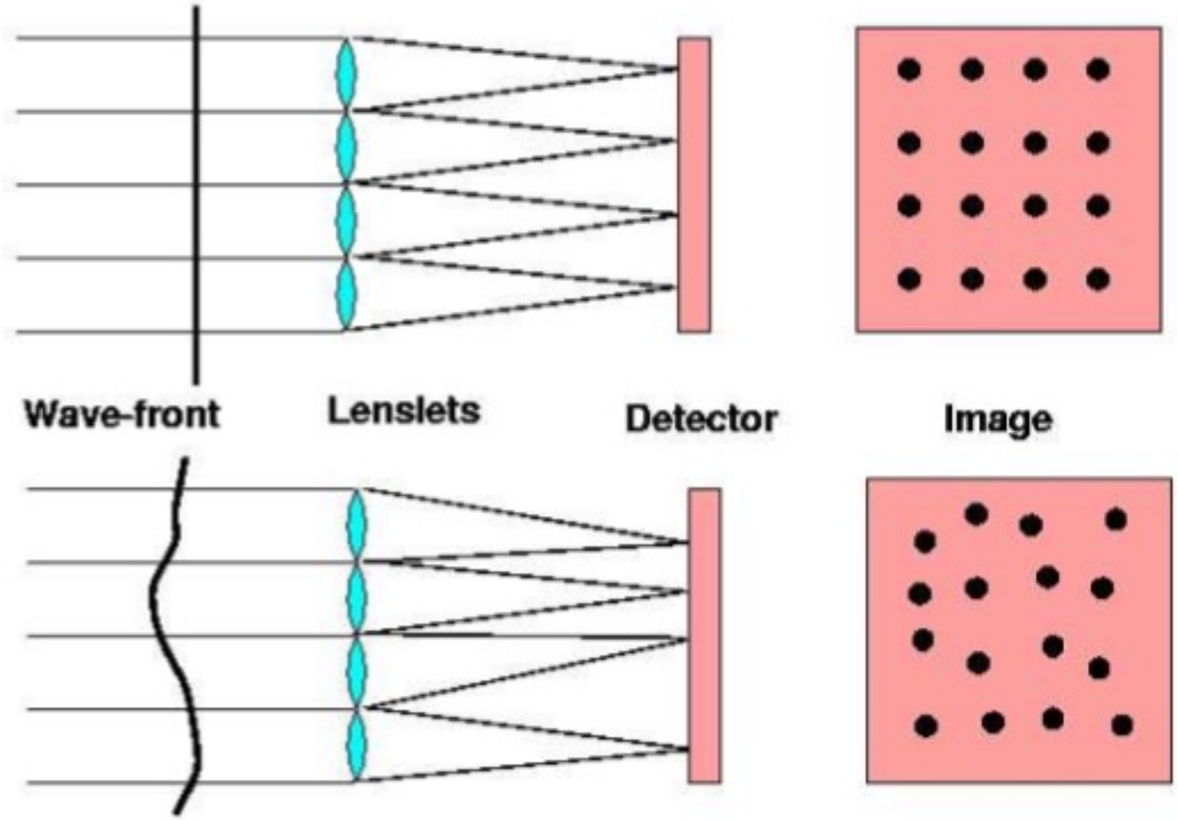
Atmosphere
Mirror
Lens
Detector

We need… An Adaptive Optics system

τ_0

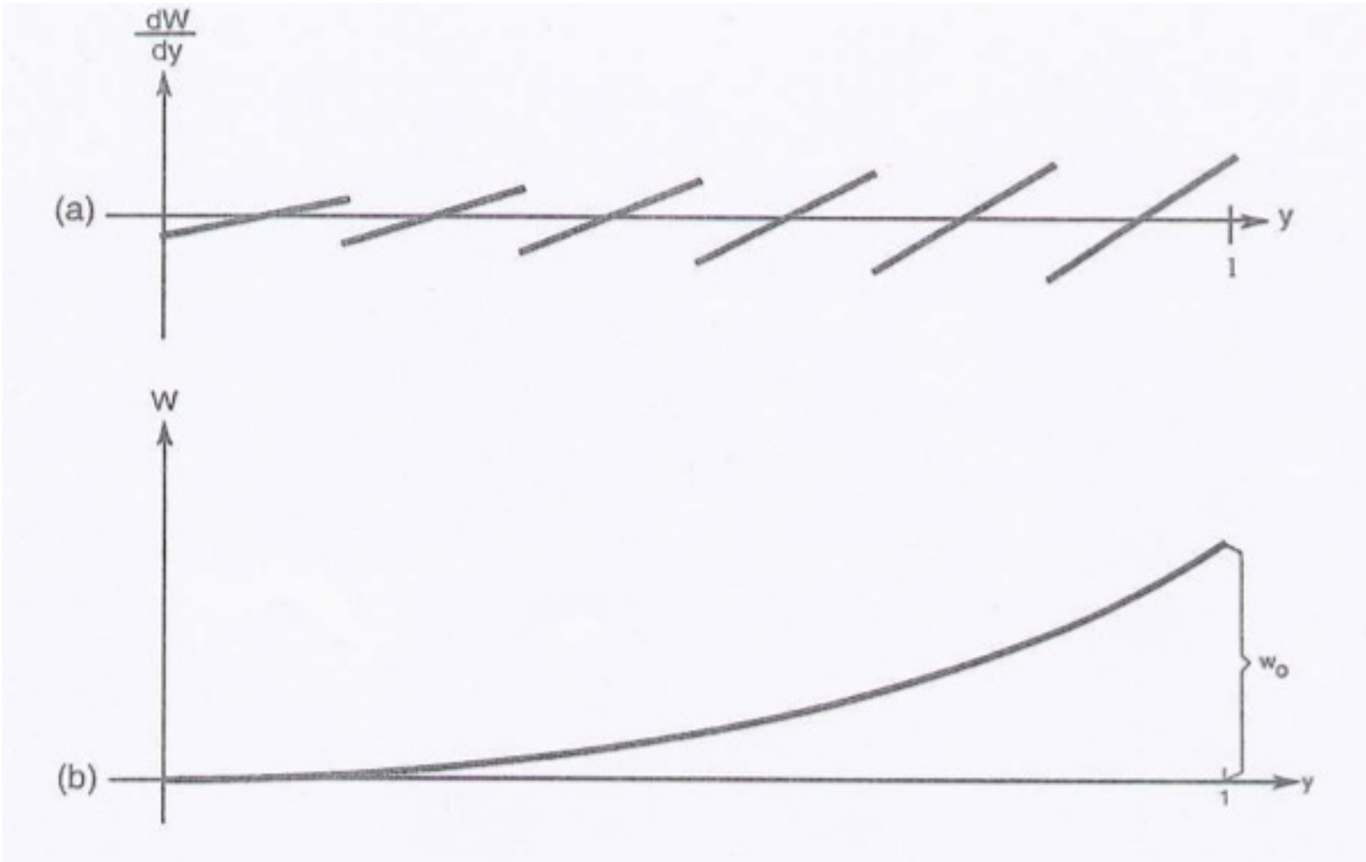


Shack-Hartmann-WFS: samples **slope** of wave front

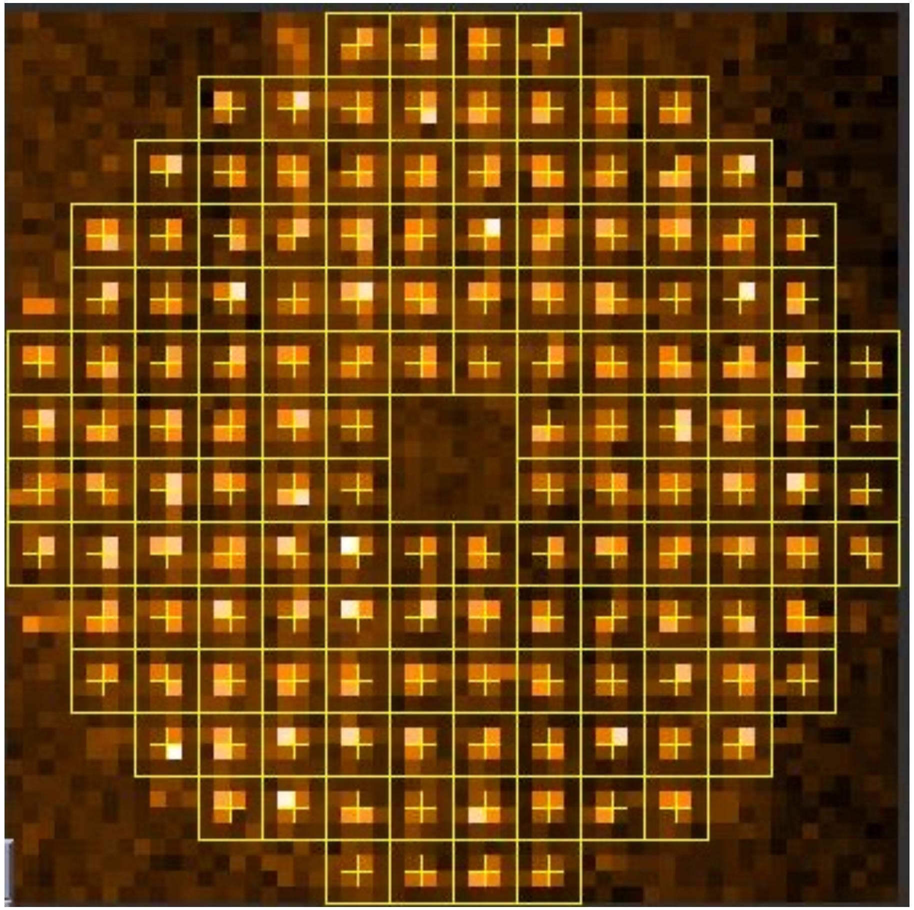


r_0 / D

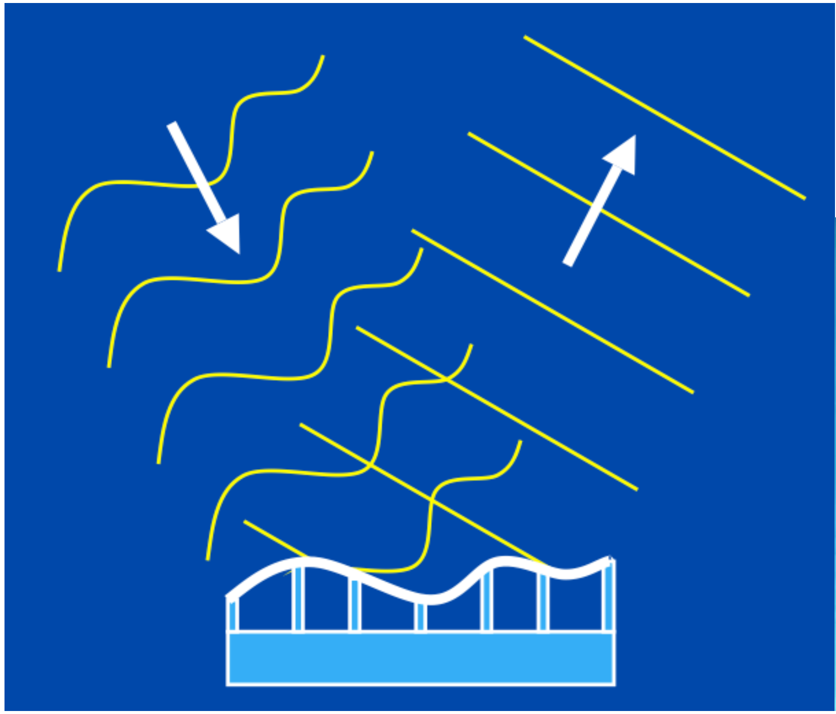
From slopes to the wavefront

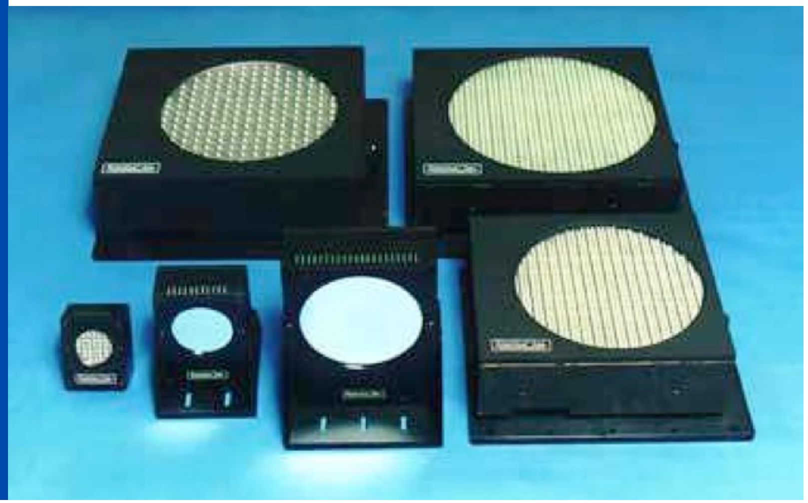


A real world detector: NACO-WFS



Deformable Mirrors





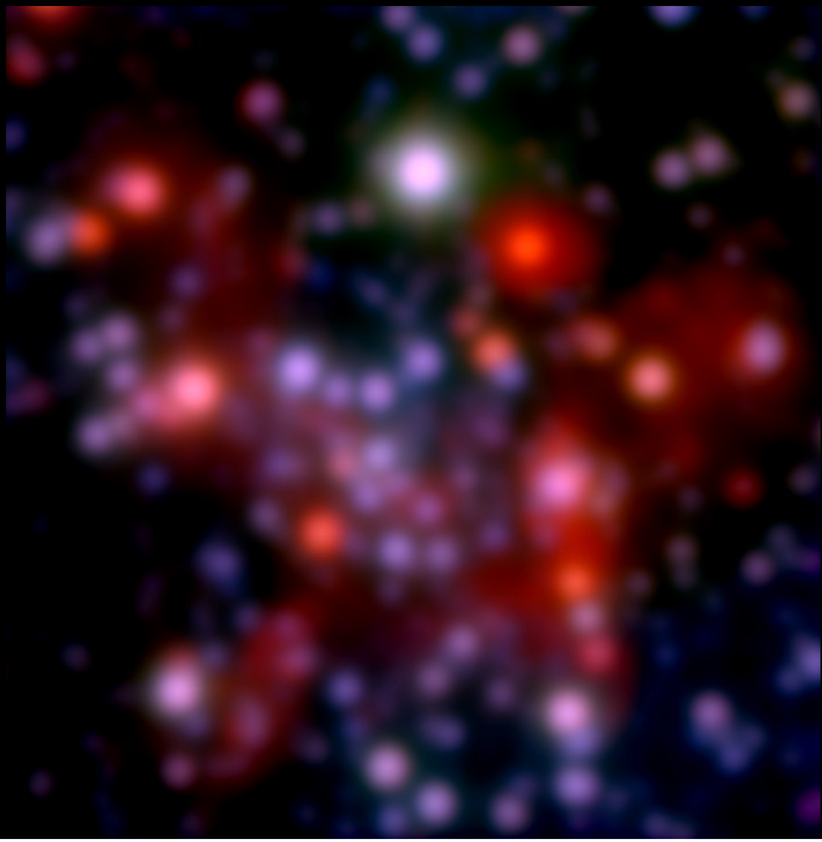
Paranal, Chile

NACO & SINFONI: For almost 20 years the Adaptive optics instruments at the VLT

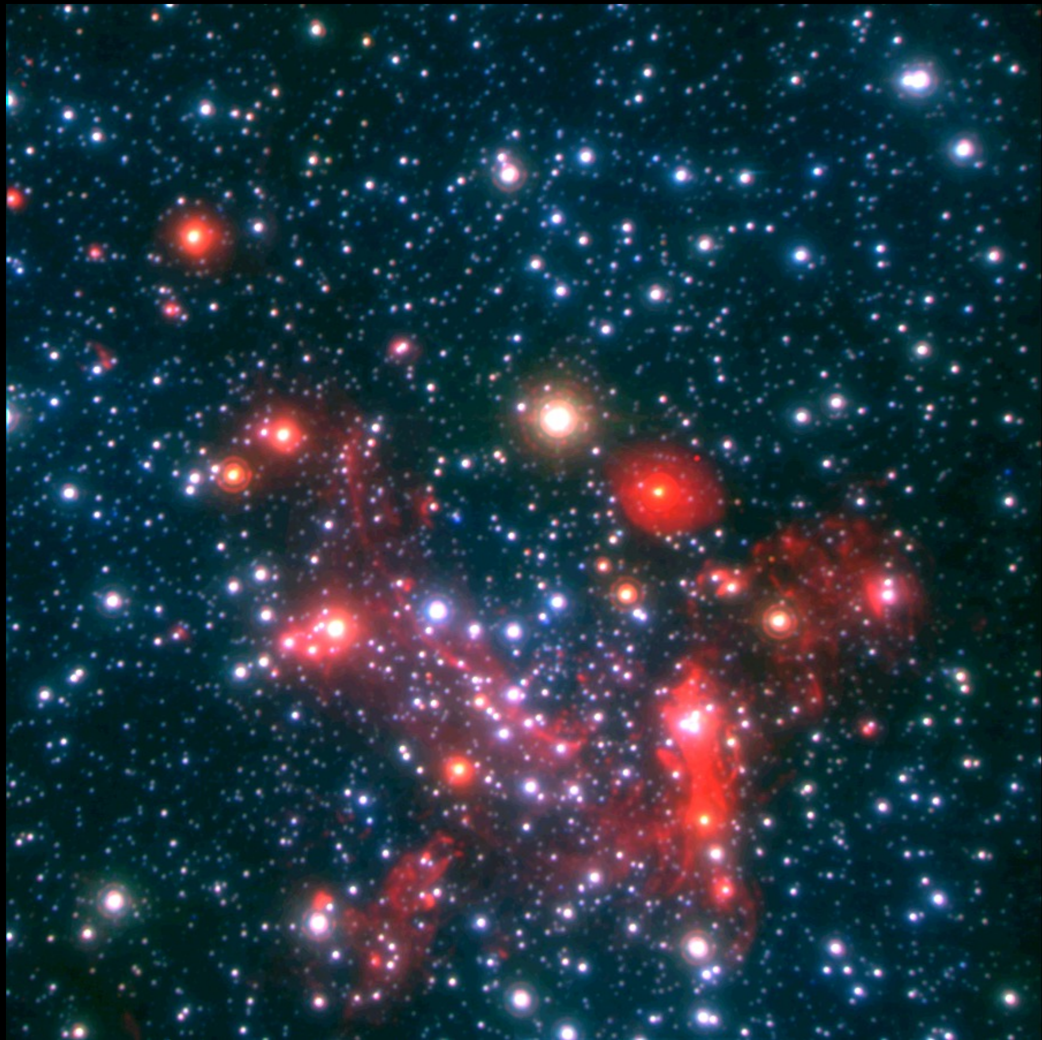
NACO (2002 – 2019):
Astrometry with 300 µas

SINFONI (2003 – 2019):
Spectroscopy with 7 km/s

Really a big step forward: AO



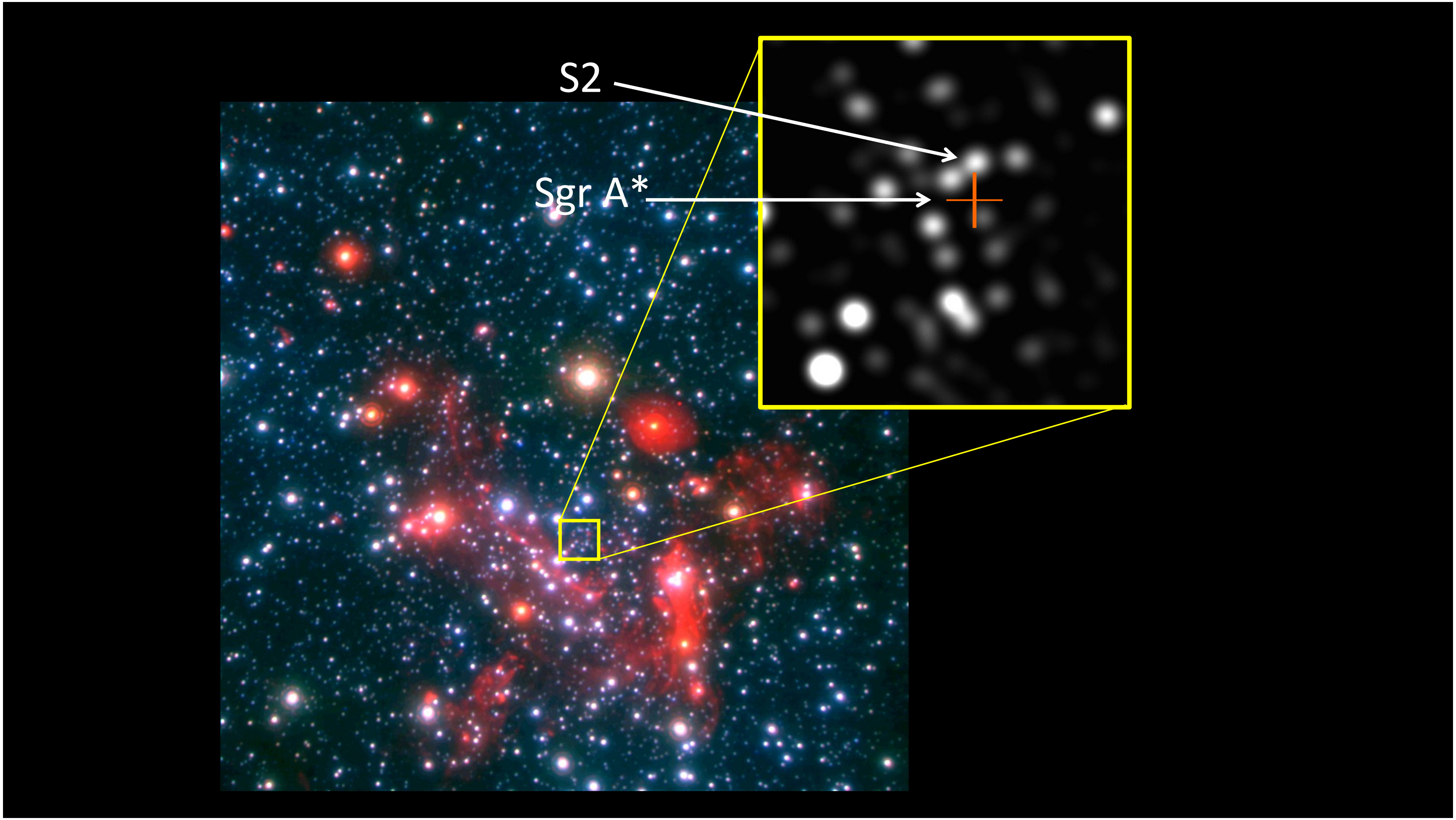
Strehl ratio
40%



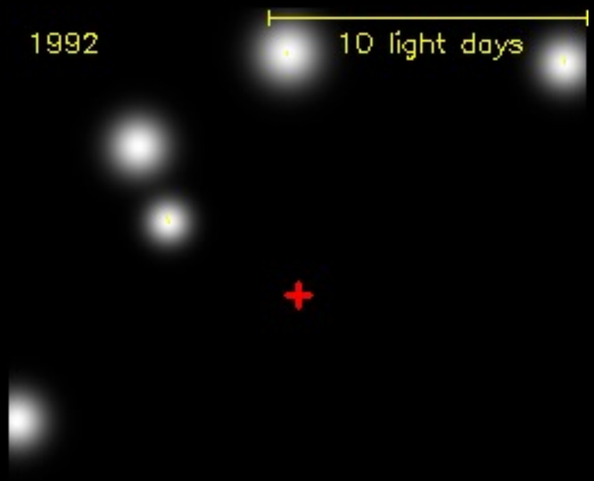
NACO,
HKL color composite

Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)


S2
Sgr A*

The stars move on Keplerian ellipses

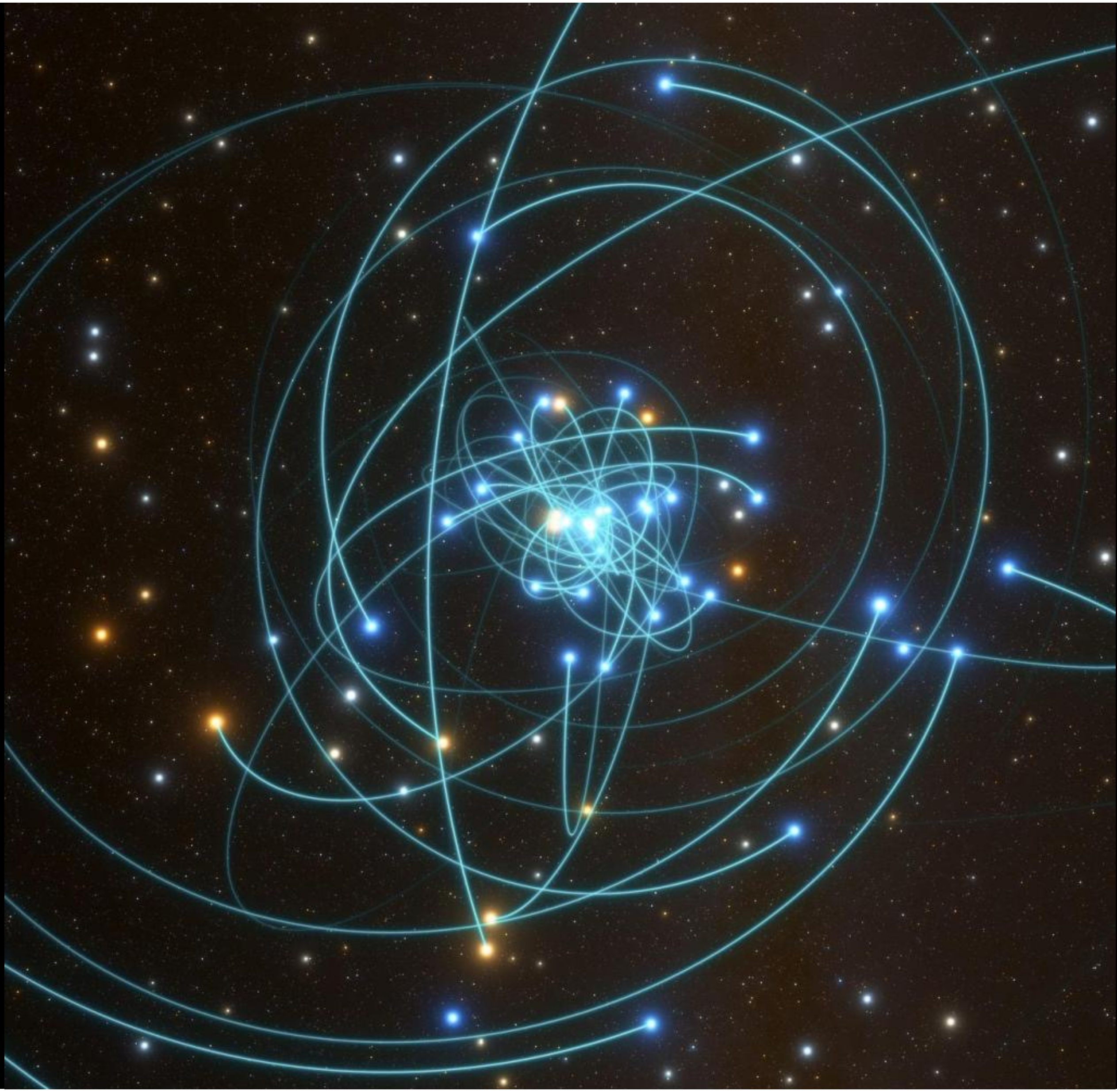


Resulting mass:

$$M = \frac{4\pi^2}{G}\frac{a^3}{P^2}$$

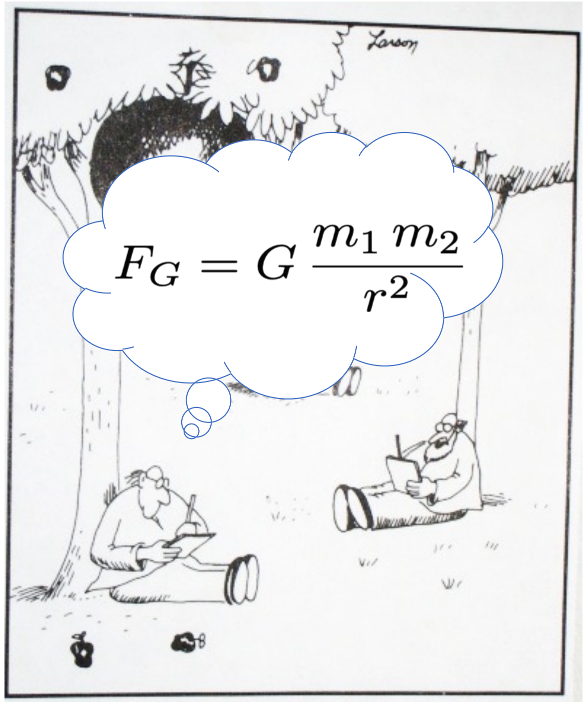
$$M = \frac{4\pi^2}{6.67\times10^{-11}\,\frac{\mathrm{Nm}^2}{\mathrm{kg}^2}}\frac{(125''\times 8.3\,\mathrm{kpc})^3}{(16\mathrm{yr})^2} = 4.3\times10^6\,M_\odot$$

WOW!



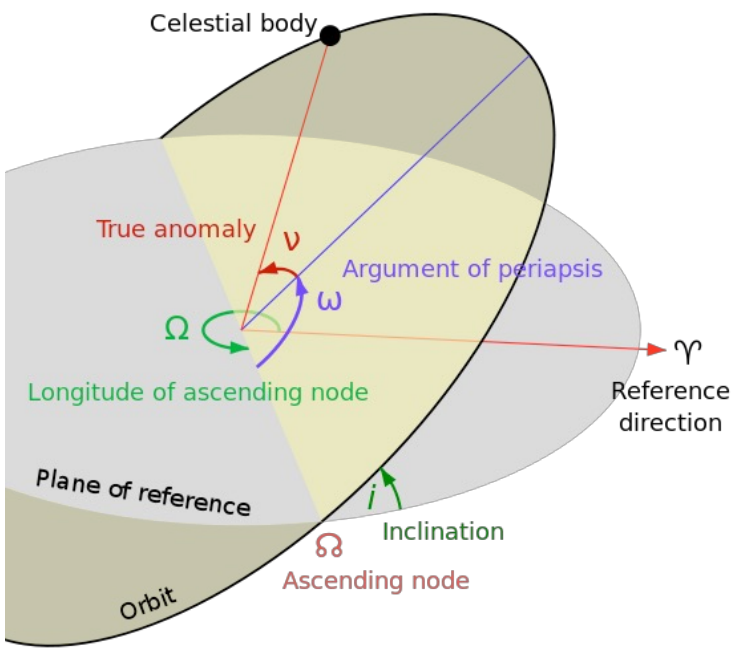
Currently known: around 50 orbits

Newton would have understood this but he had no chance to see it



"Nothing yet. ... How about you, Newton?"

How to measure stellar orbits



- 6 orbital elements:
  (a, e, i, ω, Ω, t)
- Need 6 dynamical quantities
- more if information on potential needs to be inferred

- Imaging data:
  x, y, v_x , v_y
- Spectroscopy:
  v_z

- At least one more number needed: an acceleration
  - a_{2D} from imaging
  - $a_z = dv_z / dt$ from spectroscopy

Determine the orbital elements and black hole parameters

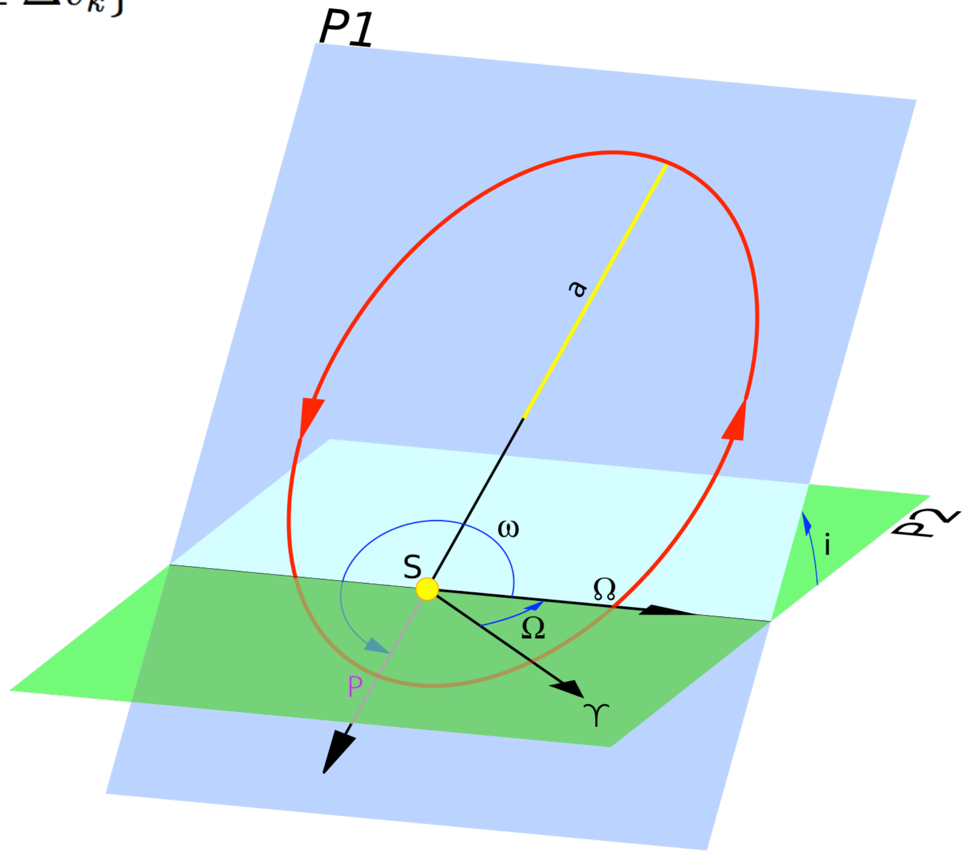
$$\{x_j \pm \Delta x_j,\ y_j \pm \Delta y_j,\ v_k \pm \Delta v_k\}$$

$$\vec{\Omega} = \{a, e, i, \Omega, \omega, t_0\}$$

$$x(t) = x(t; M, d, \vec{\Omega})$$
$$y(t) = y(t; M, d, \vec{\Omega})$$
$$v(t) = v(t; M, d, \vec{\Omega})$$

$$\chi^2(M, d, \vec{\Omega}) =$$
$$\sum_{j=1}^{\max} \frac{(x_j - x(t;M,d,\vec{\Omega}))^2}{(\Delta x_j)^2} +$$
$$\sum_{j=1}^{\max} \frac{(y_j - y(t;M,d,\vec{\Omega}))^2}{(\Delta y_k j)^2} +$$
$$\sum_{k=1}^{\max} \frac{(v_k - v(t;M,d,\vec{\Omega}))^2}{(\Delta v_k)^2}$$

$$\min\big|_{(M,d,\vec{\Omega})}\ \chi^2(M, d, \vec{\Omega})$$

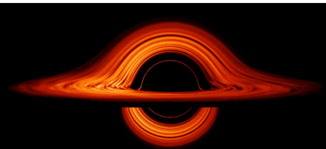


Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

Why we are sure  Sgr A* is a black hole

Eckart & Genzel 1996, Ghez+ 1998, 2003, 2005, Schödel+ 2002, Eisenhauer+ 2005, Gillessen+ 2009, 2017, Böhle+ 2016, GRAVITY Coll 2018, 2022

Reid & Bruntthaler 2004, 2020

mass

IR
stellar orbits
$4.3 \times 10^6 M_\odot$
± 0.3%

VLBA :
radio Sgr A*
$> 1 \times 10^6 M_\odot$

position

IR + VLA

mass and
radio Sgr A*
coincide

Reid+ 2007
Plewa+ 2015

faintness

radio + IR

Sgr A*
cannot have
a surface

Broderick & Narayan 2006
Broderick+ 2009

size

IR + X-ray
timescales
≈ 0.1 AU

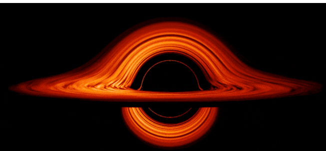
VLBI /EHT
0.4 AU

GRAVITY
flares
0.5 AU

Baganoff+ 2001, Genzel+ 2003, Dodds-Eden+ 2009

Doeleman+ 2008, Akiyama+ 2022,

GRAVITY Coll. 2018b

Why we are sure  Sgr A* is a black hole

Eckart & Genzel 1996, Ghez+ 1998, 2003, 2005, Schödel+ 2002, Eisenhauer+ 2005, Gillessen+ 2009, 2017, Böhle+ 2016, GRAVITY Coll 2018, 2022

Reid & Brunthaler 2004, 2020

mass

IR
stellar orbits
$4.3 \times 10^6\, M_\odot$
$\pm$ 0.3%

VLBA :
radio Sgr A*
$> 1 \times 10^6\, M_\odot$

position

IR + VLA

mass and radio Sgr A* coincide

Reid+ 2007
Plewa+ 2015

faintness

radio + IR

Sgr A* cannot have a surface

Broderick & Narayan 2006
Broderick+ 2009

size

IR + X-ray timescales
≈ 0.1 AU

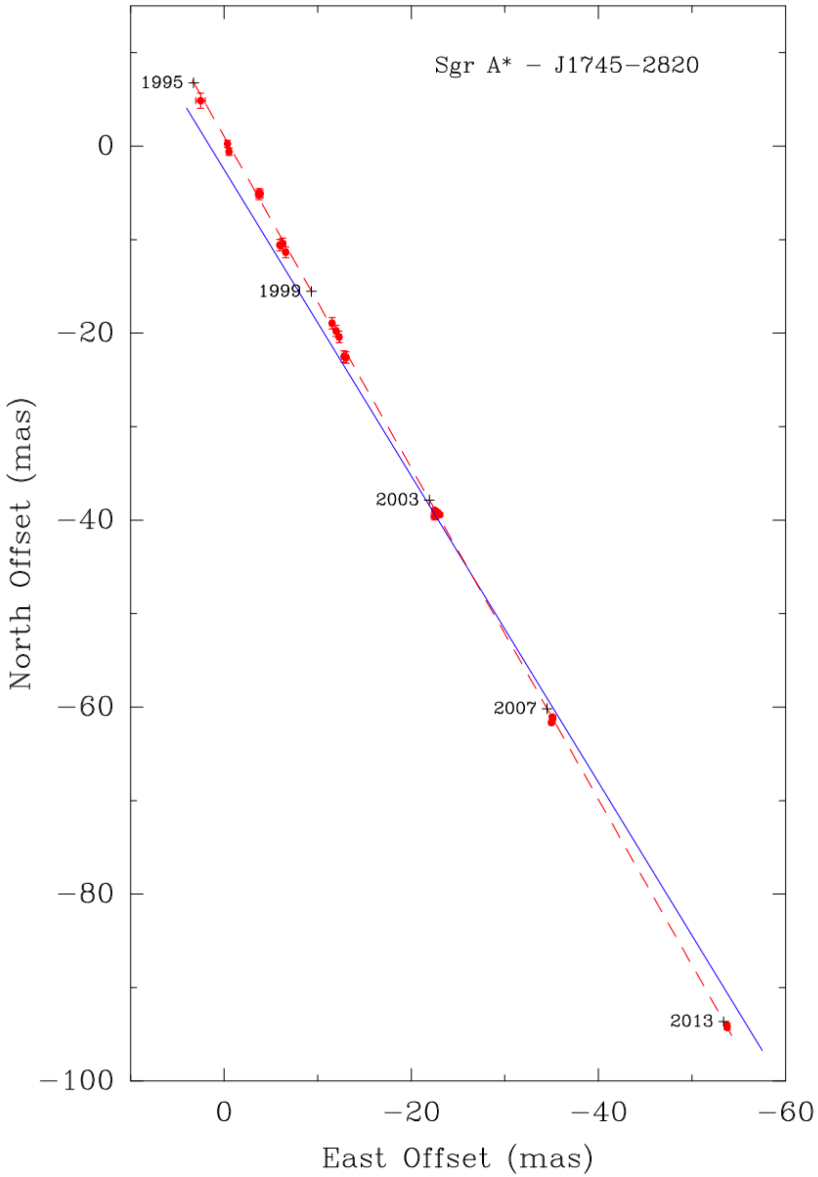
VLBI /EHT
0.4 AU

GRAVITY flares
0.5 AU

Baganoff+ 2001, Genzel+ 2003, Dodds-Eden+ 2009

Doeleman+ 2008, Akiyama+ 2022,

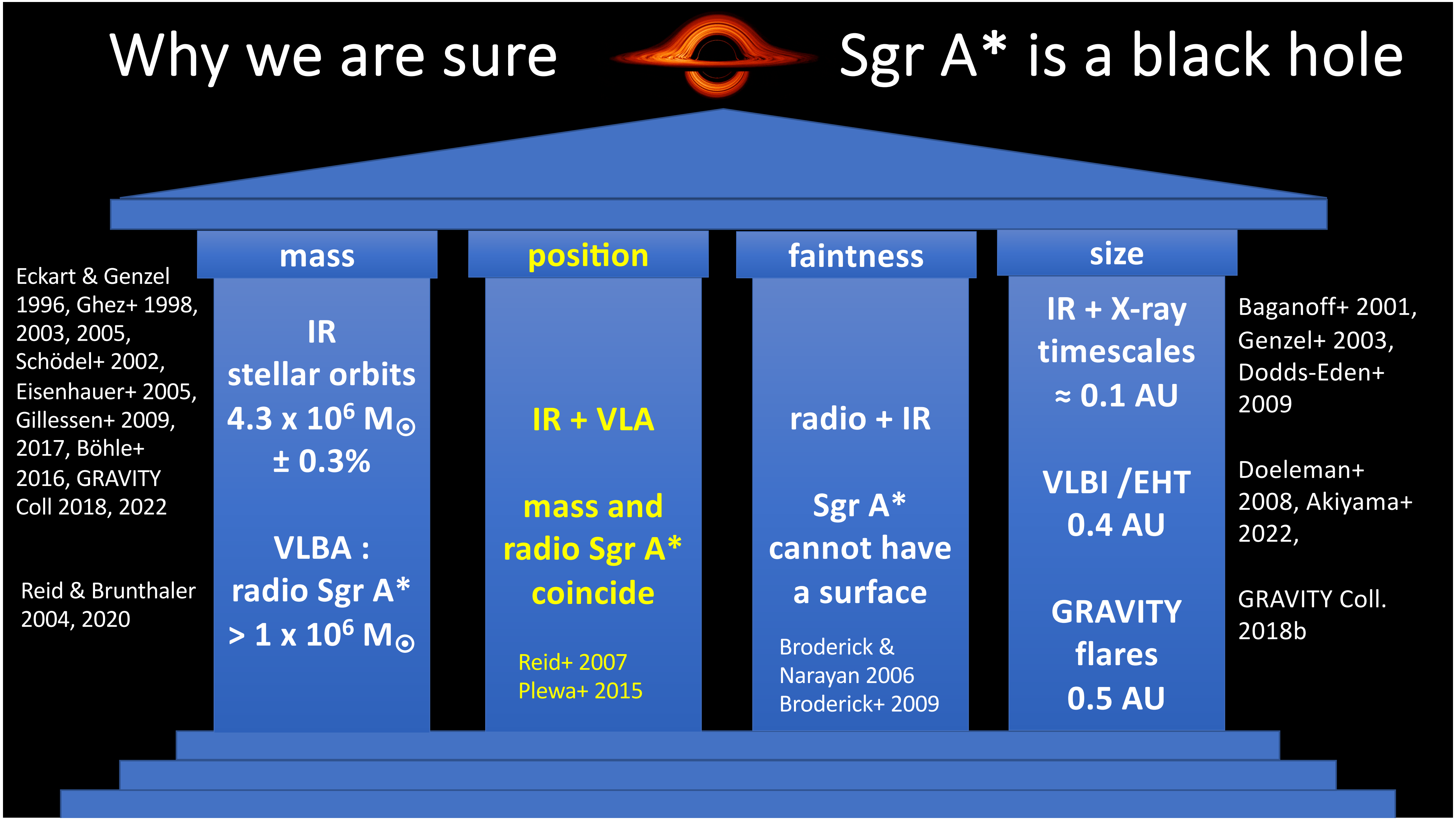
GRAVITY Coll. 2018b



Sgr A* must be very heavy

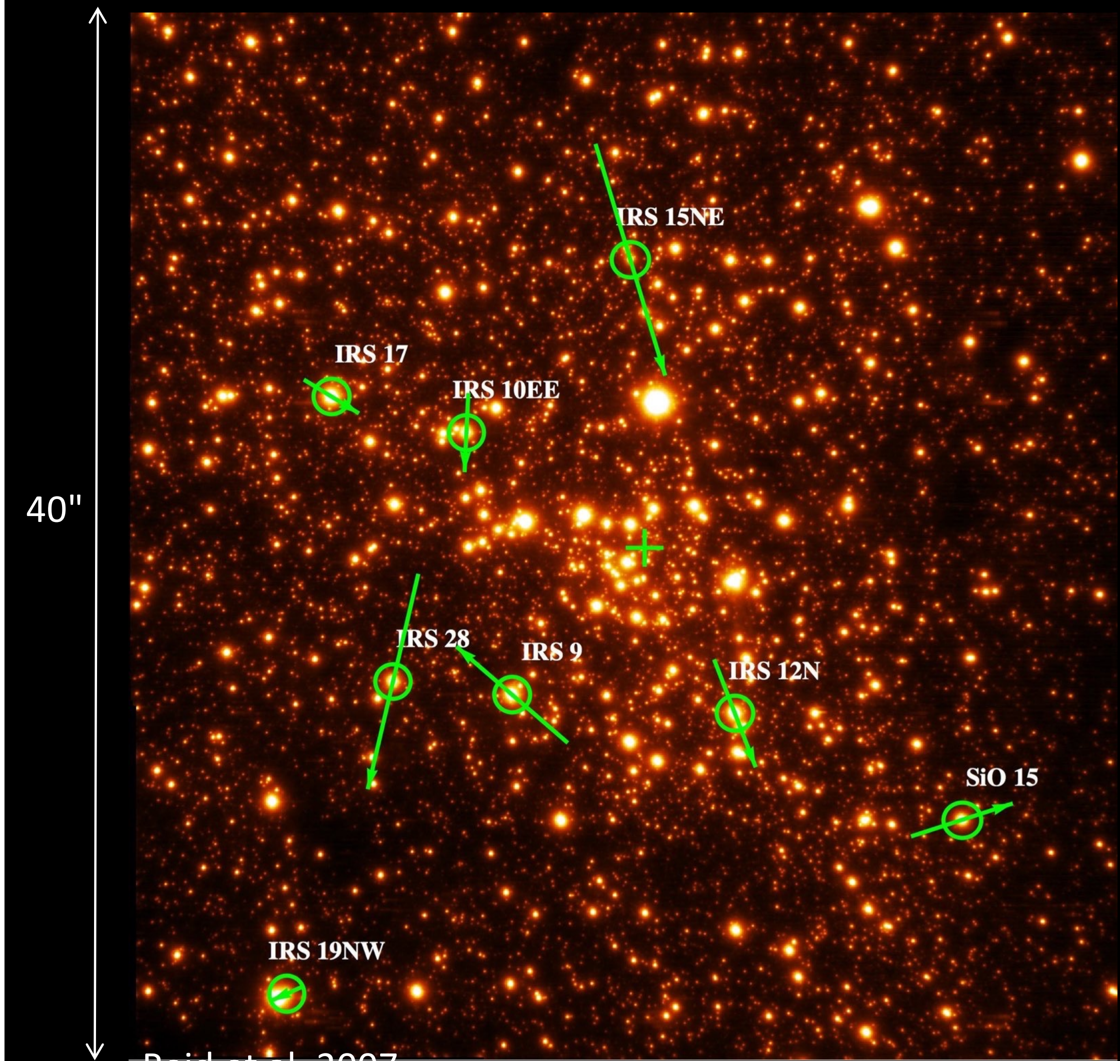
- perfectly linear motion
  - reflex motion of Sun (~200 km/s)
- intrinsic motion
  - gal. l : -7.2 ± 8.5 km/s
  - gal. b: -0.4 ± 0.9 km/s
- Sgr A* is much heavier than surrounding stars
  - mass > $10^6\,M_\odot$

Reid 2007, 2020



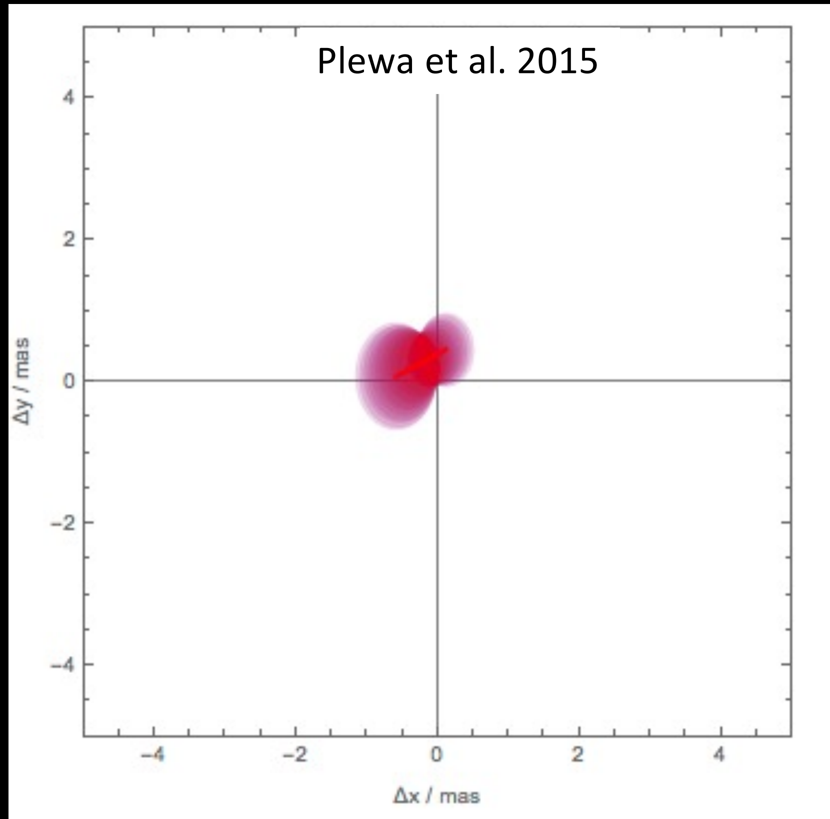
Why we are sure Sgr A* is a black hole
mass
position
faintness
size
Eckart & Genzel 1996, Ghez+ 1998, 2003, 2005, Schödel+ 2002, Eisenhauer+ 2005, Gillessen+ 2009, 2017, Böhle+ 2016, GRAVITY Coll 2018, 2022
Reid & Bruntháler 2004, 2020
IR
stellar orbits
4.3 x 10^6 M☉
± 0.3%
VLBA :
radio Sgr A*
> 1 x 10^6 M☉
IR + VLA
mass and radio Sgr A* coincide
Reid+ 2007
Plewa+ 2015
radio + IR
Sgr A* cannot have a surface
Broderick & Narayan 2006
Broderick+ 2009
IR + X-ray timescales
≈ 0.1 AU
VLBI /EHT
0.4 AU
GRAVITY flares
0.5 AU
Baganoff+ 2001, Genzel+ 2003, Dodds-Eden+ 2009
Doeleman+ 2008, Akiyama+ 2022,
GRAVITY Coll. 2018b

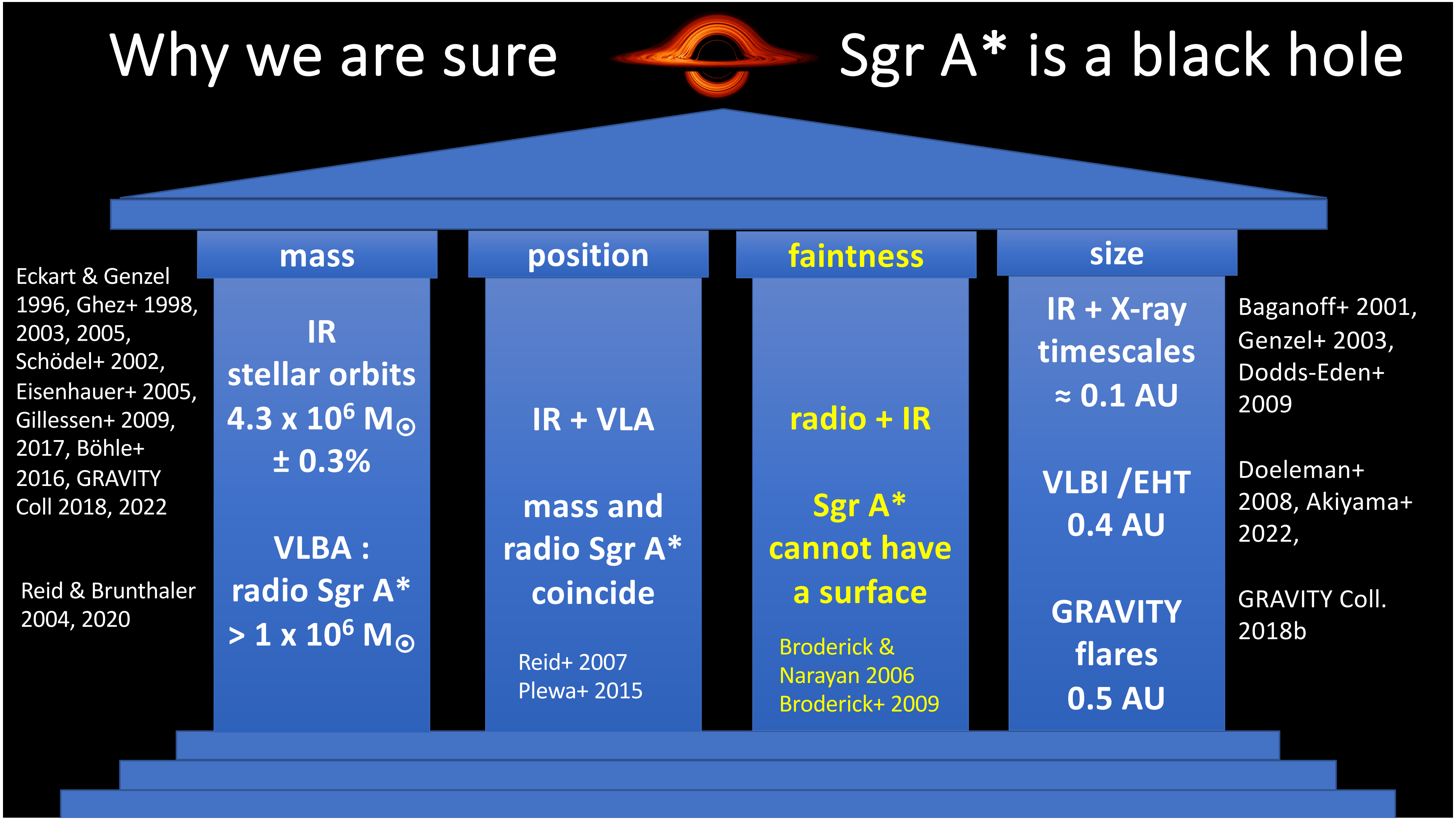
The positions of mass & radio-Sgr A* agree to within 1 mas



Reid et al. 2007

- Sgr A*
  - radio source
- SiO maser stars
  - IR sources
  - radio sources




Why we are sure Sgr A* is a black hole
mass
position
faintness
size
Eckart & Genzel 1996, Ghez+ 1998, 2003, 2005, Schödel+ 2002, Eisenhauer+ 2005, Gillessen+ 2009, 2017, Böhle+ 2016, GRAVITY Coll 2018, 2022
Reid & Brunthaler 2004, 2020
IR stellar orbits
4.3 x 10^6 M☉ ± 0.3%
VLBA : radio Sgr A* > 1 x 10^6 M☉
IR + VLA
mass and radio Sgr A* coincide
Reid+ 2007
Plewa+ 2015
radio + IR
Sgr A* cannot have a surface
Broderick & Narayan 2006
Broderick+ 2009
IR + X-ray timescales ≈ 0.1 AU
VLBI /EHT 0.4 AU
GRAVITY flares 0.5 AU
Baganoff+ 2001, Genzel+ 2003, Dodds-Eden+ 2009
Doeleman+ 2008, Akiyama+ 2022,
GRAVITY Coll. 2018b

Sgr A* should be bright - but is not

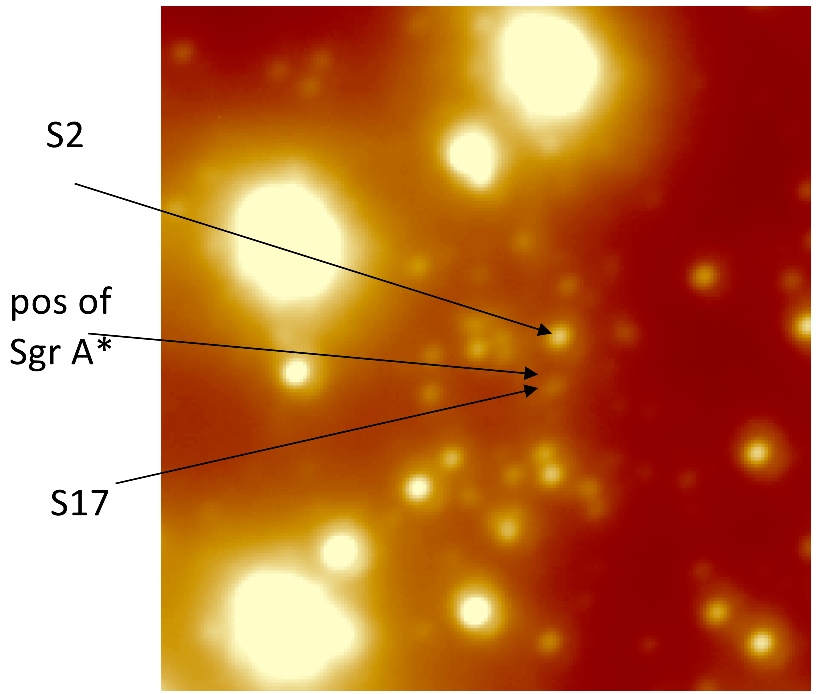
Limit: Eddington luminosity

radiation pressure = gravitation

$$L_{Edd} = \frac{4\pi G m_p c}{\sigma_T} M$$

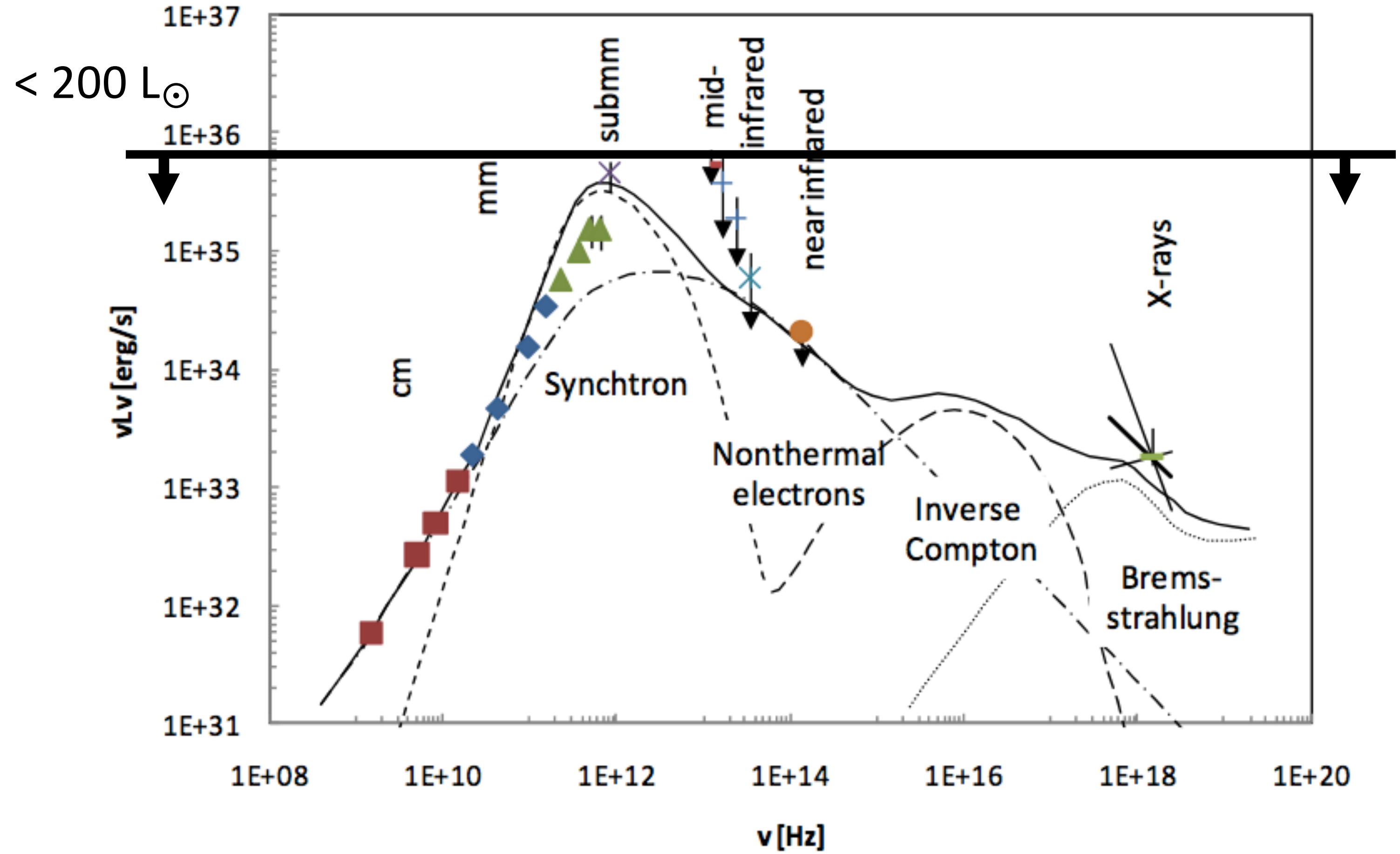
$L = \eta \times 5 \times 10^{44}$ erg/s

$= \eta \times 10^{11} L_\odot$



Sgr A* is dim at all wavelengths:
$\eta \sim 10^{-8}$

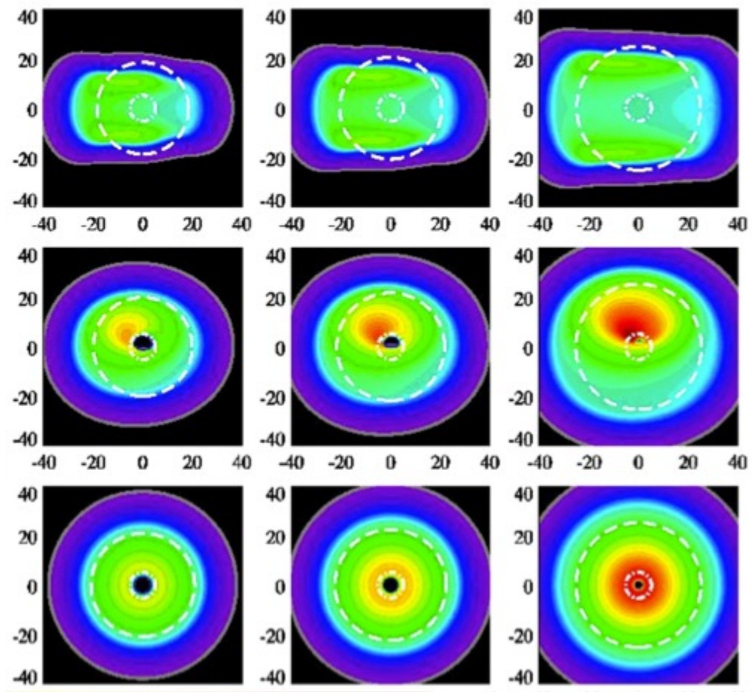
Genzel et al. 2010



Radiatively Inefficient Accretion Flow

low L/L_{Edd} is a combination of:

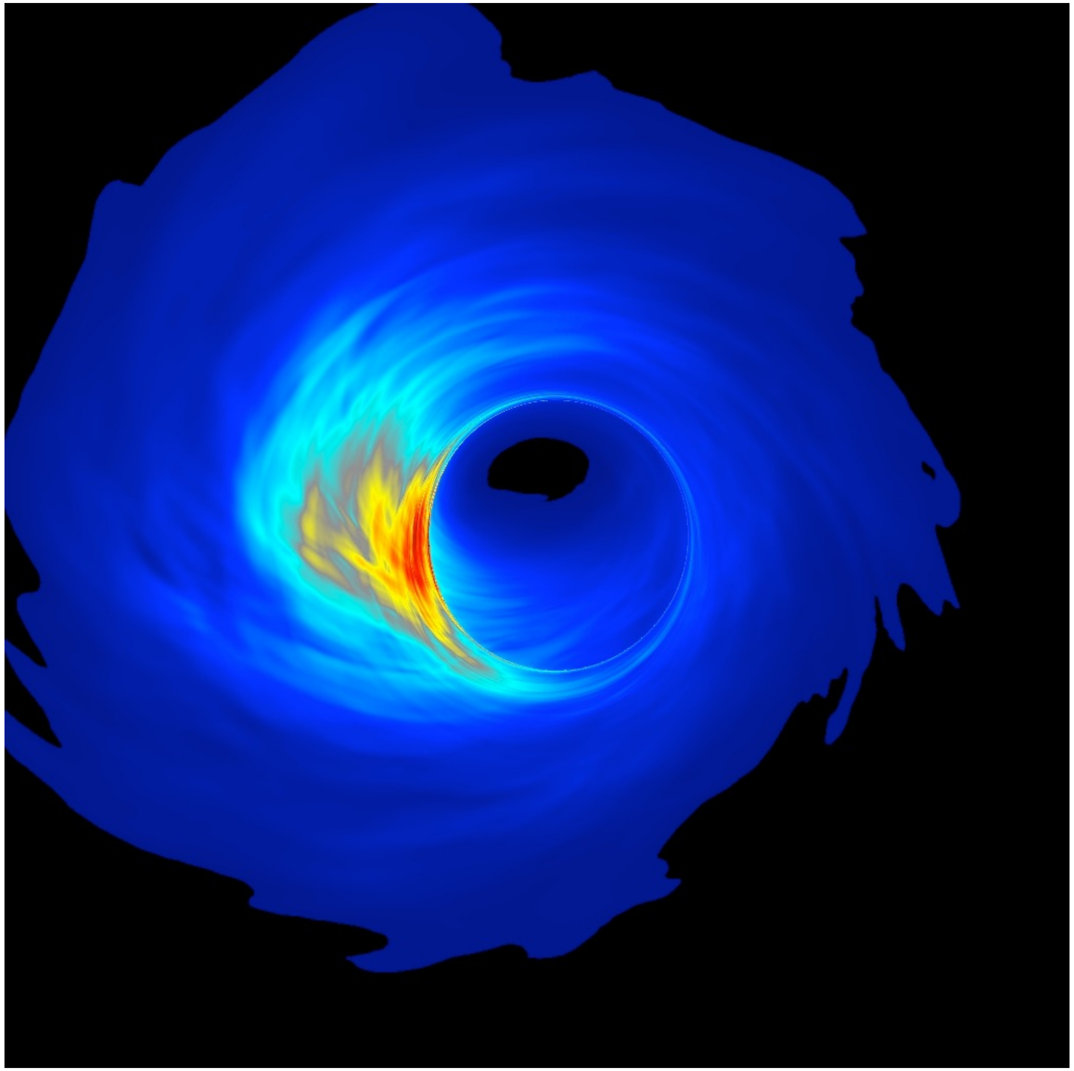
- low accretion rate at Bondi radius
- low efficiency angular momentum transport
- low efficiency energy transfer protons to electrons
- most of the gas arriving at a few R_s ejected back out



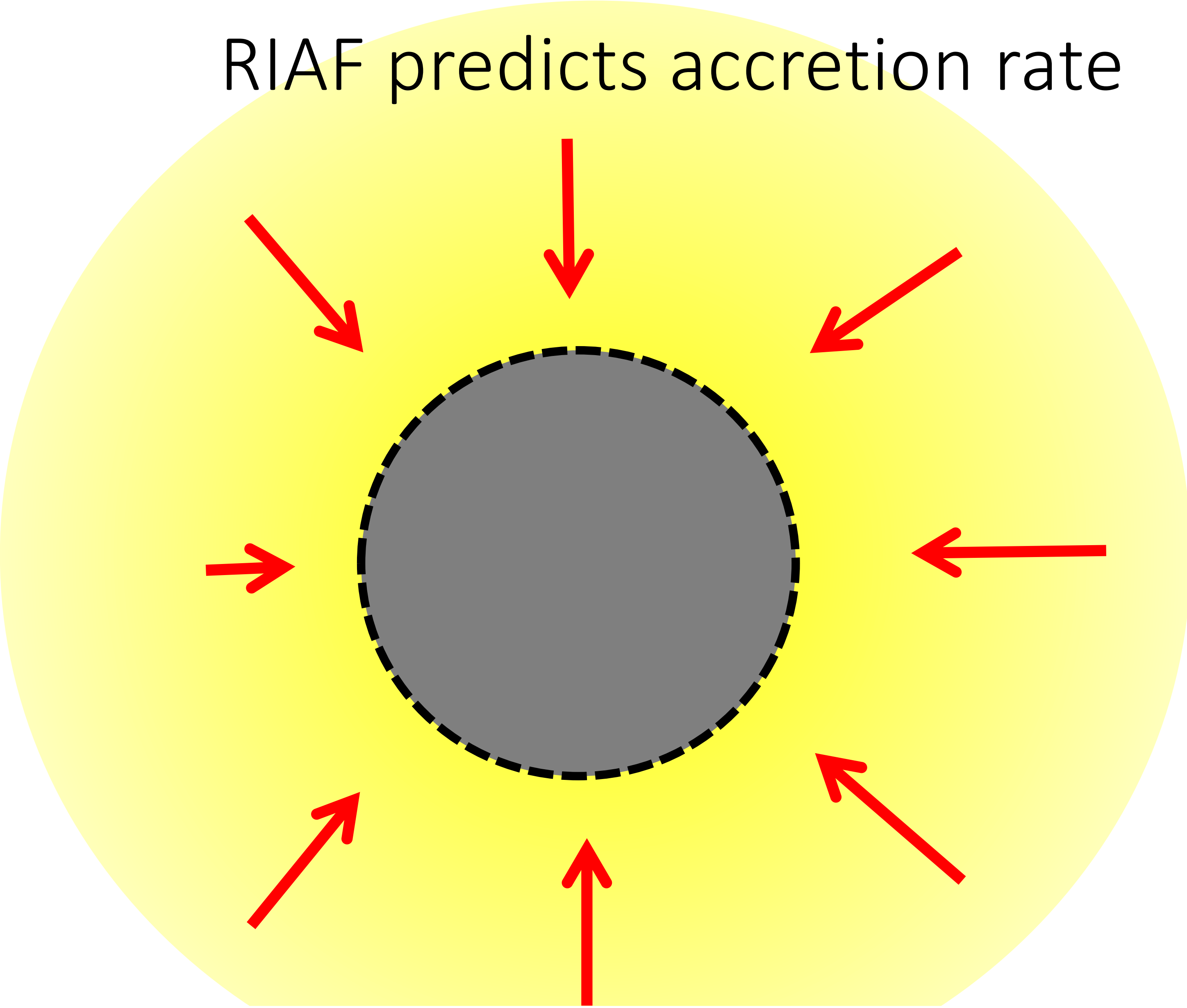
Yuan et al. 2009

Begelman, Bower, Blandford, Cuadra, De Villers, Falcke, Hawley, Krolik, Liu, Melia, Markoff, Marrone, Narayan, Quataert, Rees, Revnitsev , Stone, Wang, Yuan 1995-2013

MHD simulation with GR ray-tracing



RIAF predicts accretion rate



accretion flow

radio emission:
RIAF

accretion rate:
~ 5 x 10^{-8} $M_\odot$/yr

99% of that
reaches
“surface”

Assume, material is crashing onto surface

$$P = \sigma A T^4$$

$$P = \dot{M} c^2$$

constant

area

temperature

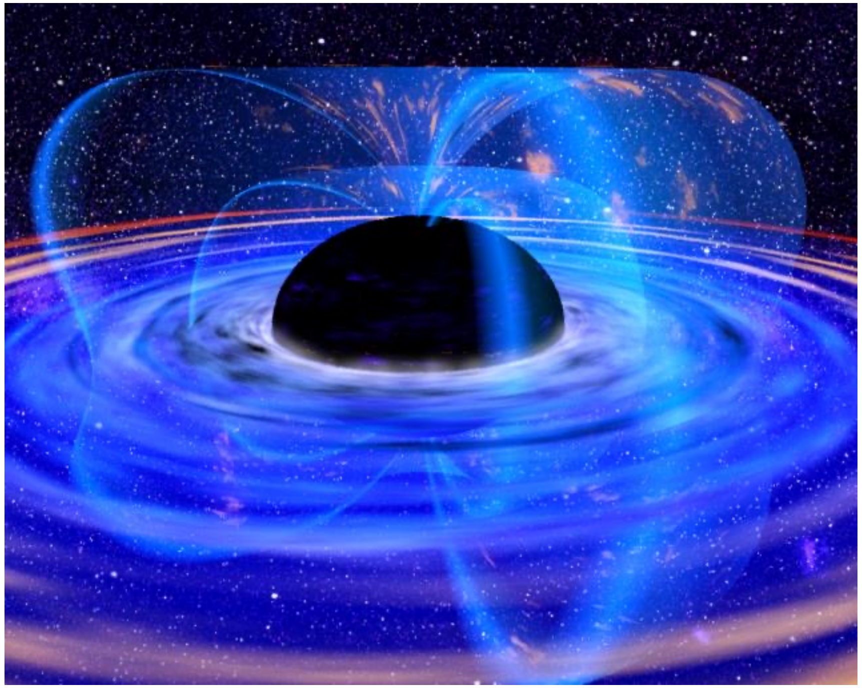
Accretion Rate

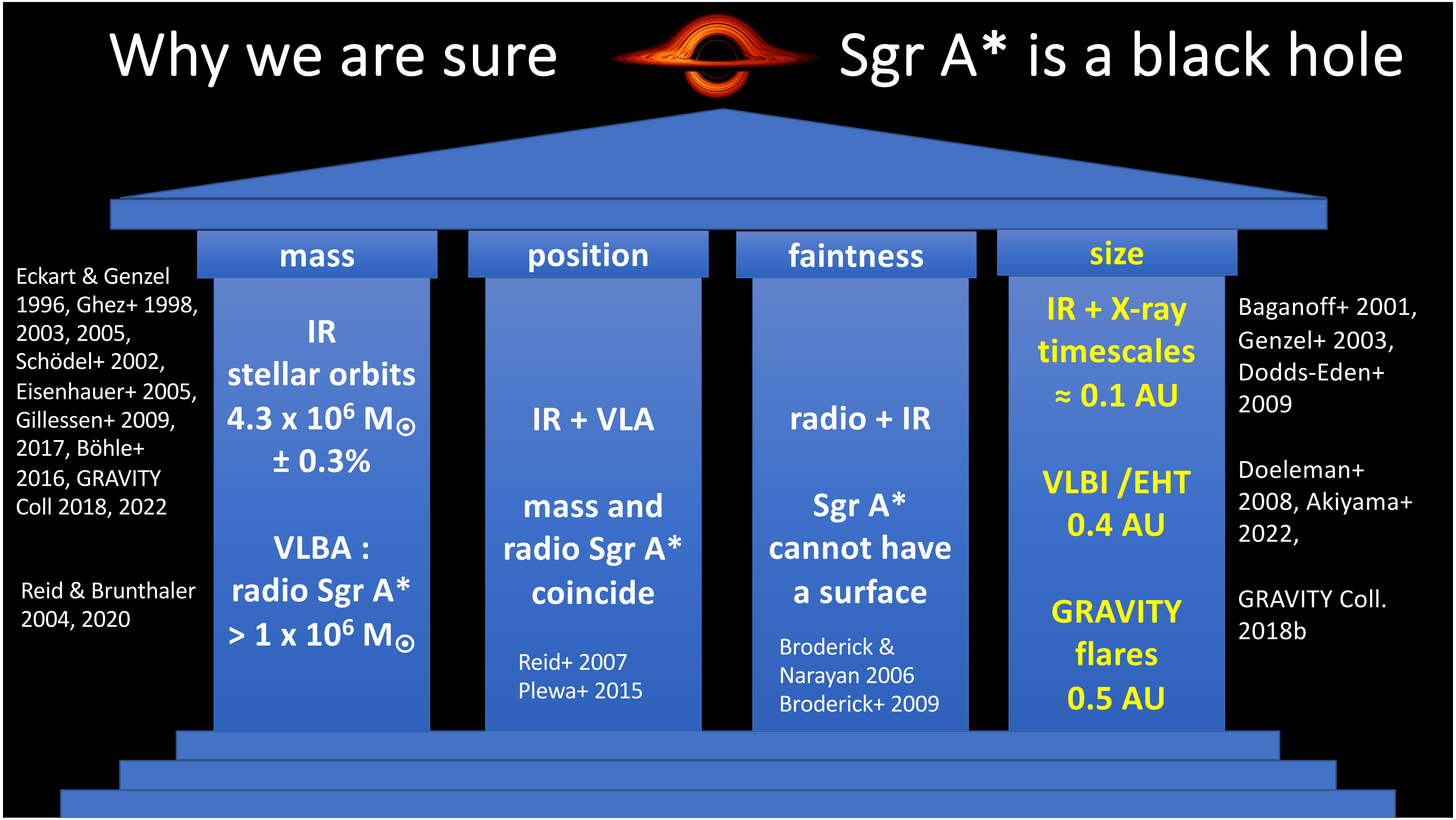
measured size
< 4 Rs

20000 K

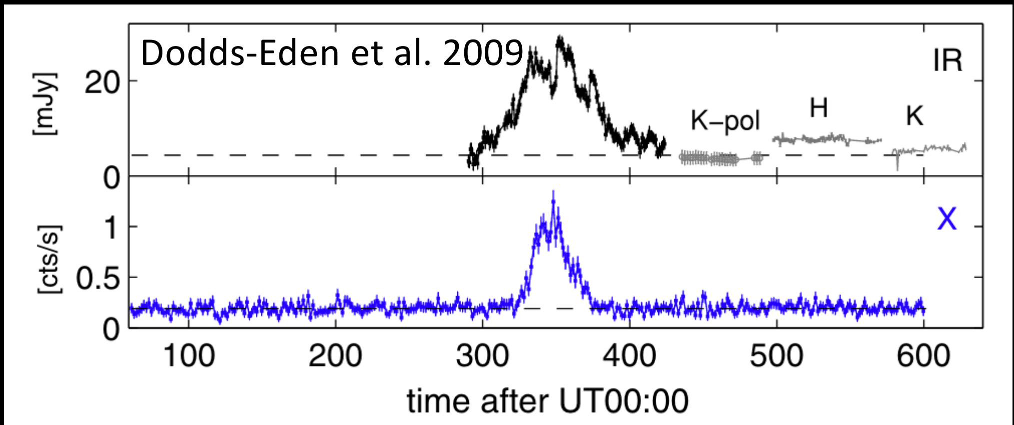
Sgr A* has an event horizon

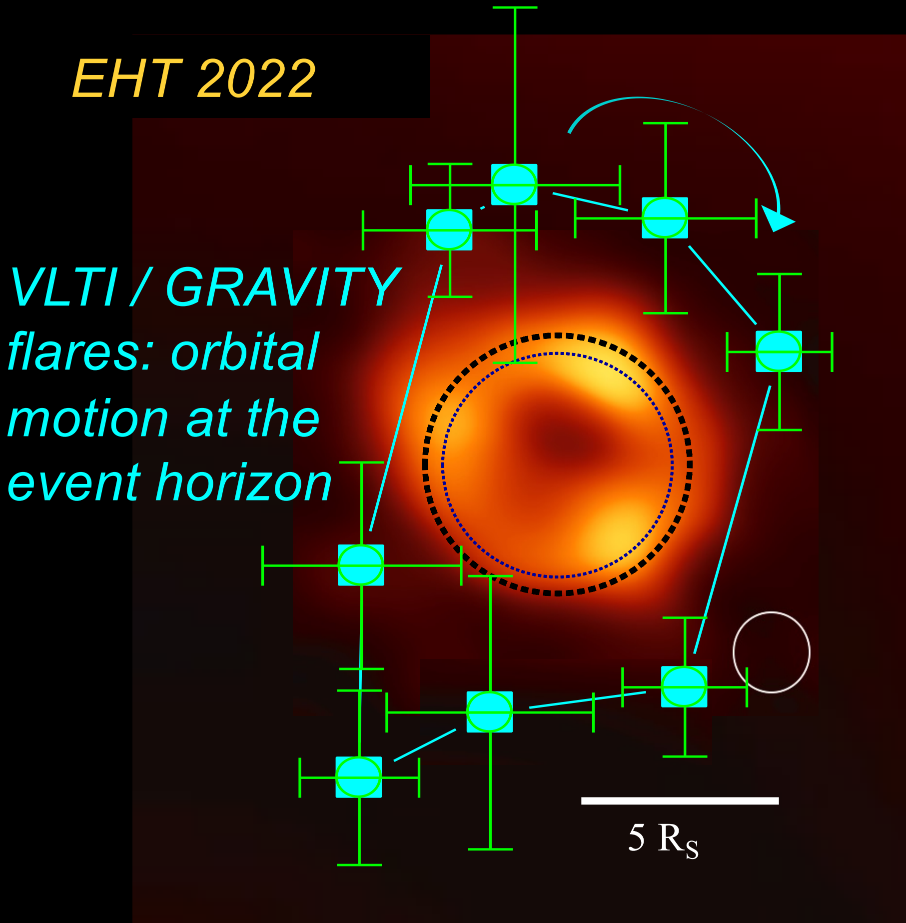
- Hot surface: 20000 K
  - infrared light
- Size: 1/10 Earth orbit
  - like a normal star
  - extremely luminous
- But normal stars can be seen
- Sgr A* cannot have a surface




Why we are sure Sgr A* is a black hole
mass
IR
stellar orbits
4.3 x 10^6 M☉
± 0.3%
VLBA :
radio Sgr A*
> 1 x 10^6 M☉
Eckart & Genzel 1996, Ghez+ 1998, 2003, 2005, Schödel+ 2002, Eisenhauer+ 2005, Gillessen+ 2009, 2017, Böhle+ 2016, GRAVITY Coll 2018, 2022
Reid & Brunthaler 2004, 2020
position
IR + VLA
mass and radio Sgr A* coincide
Reid+ 2007
Plewa+ 2015
faintness
radio + IR
Sgr A* cannot have a surface
Broderick & Narayan 2006
Broderick+ 2009
size
IR + X-ray timescales ≈ 0.1 AU
VLBI /EHT 0.4 AU
GRAVITY flares 0.5 AU
Baganoff+ 2001, Genzel+ 2003, Dodds-Eden+ 2009
Doeleman+ 2008, Akiyama+ 2022,
GRAVITY Coll. 2018b

Sgr A* is very compact



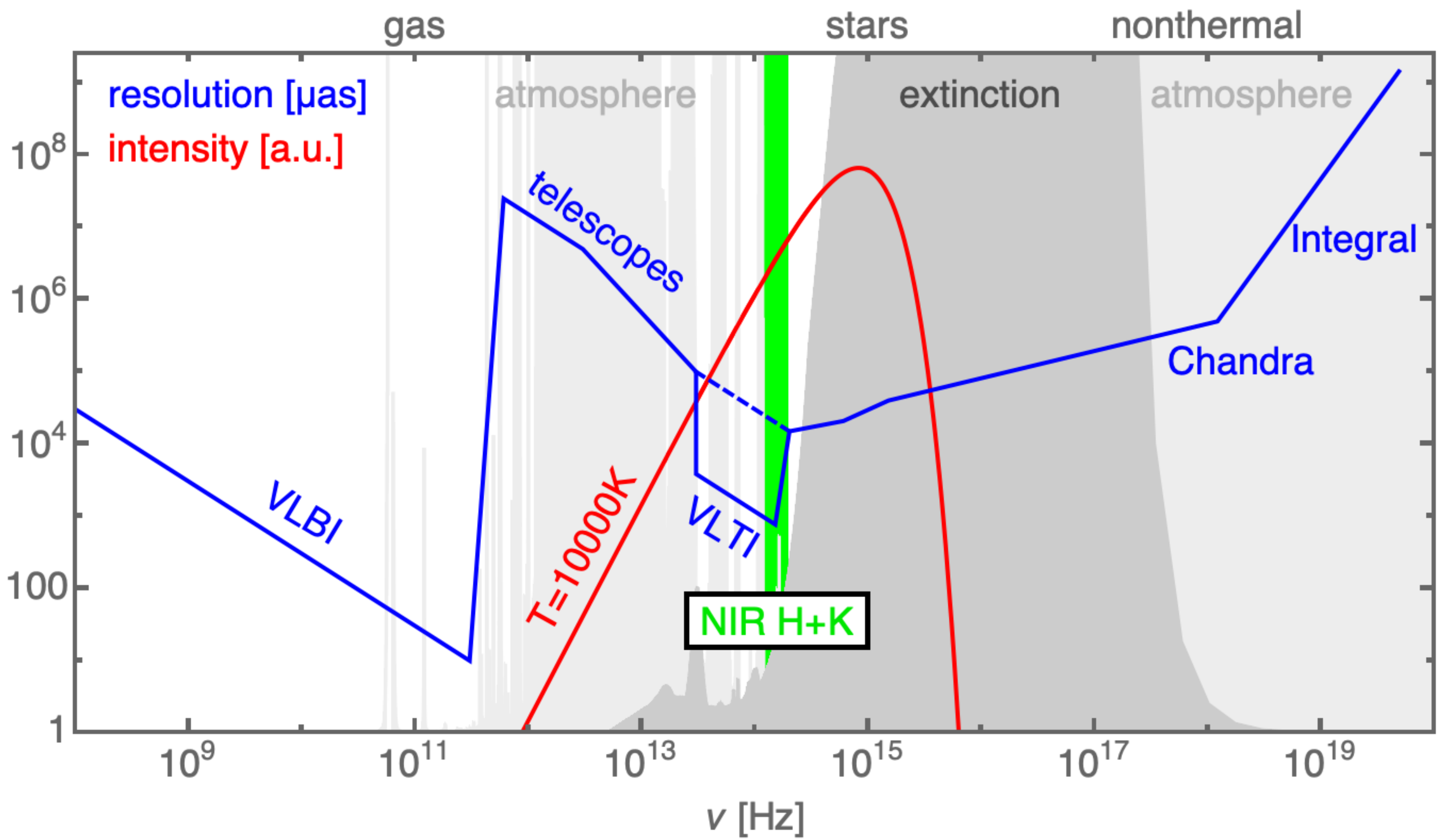


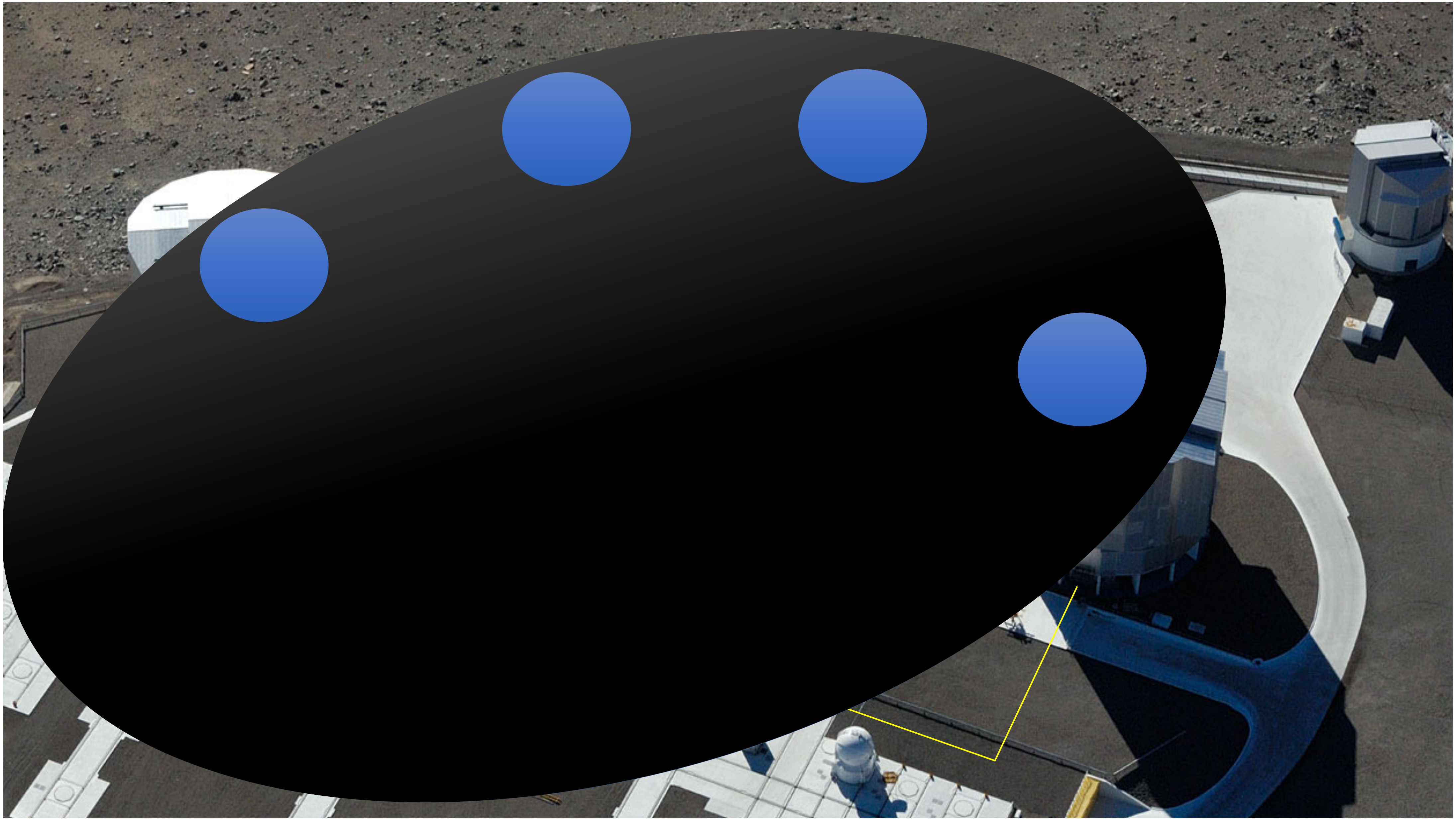
Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

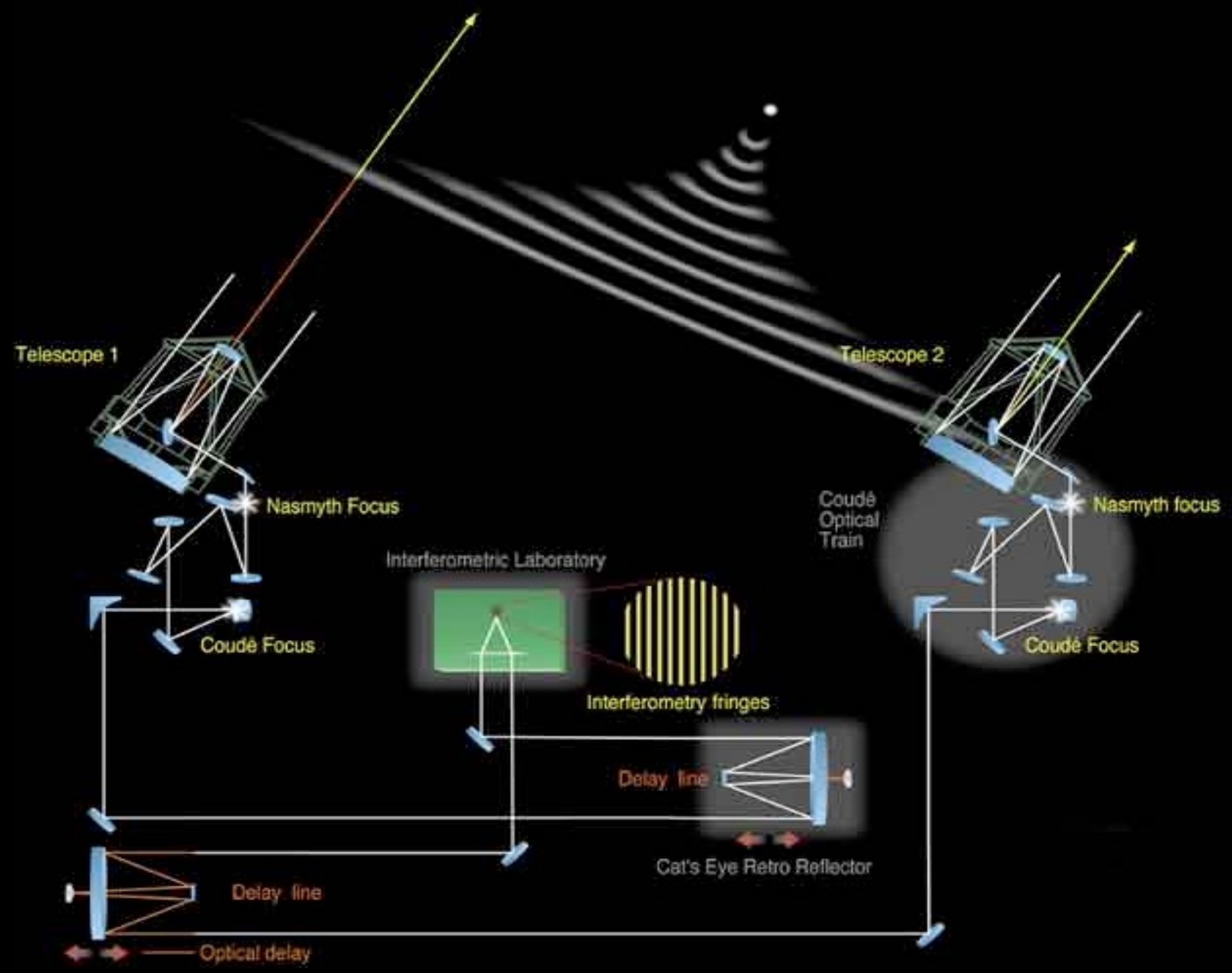

How to zoom in further ?

The sweet spot in wavelength: The near-infrared





But: Optical interferometry is hard



Online cophasing to nano-meters

MPE

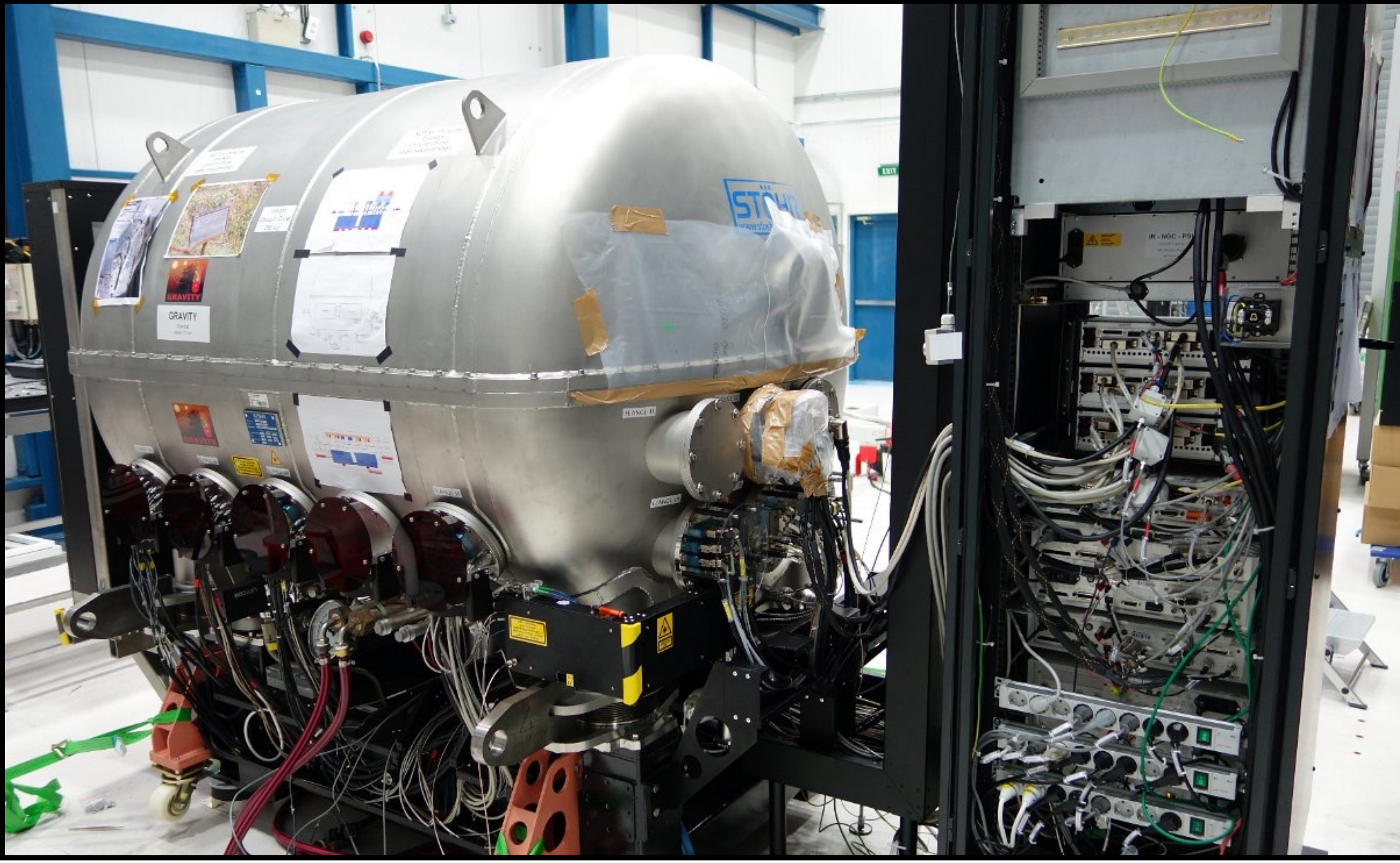
PHASE
Partenariat Haute résolution Angulaire Sol-Espace

IPAG
Institut de Planétologie
et d'Astrophysique
de Grenoble

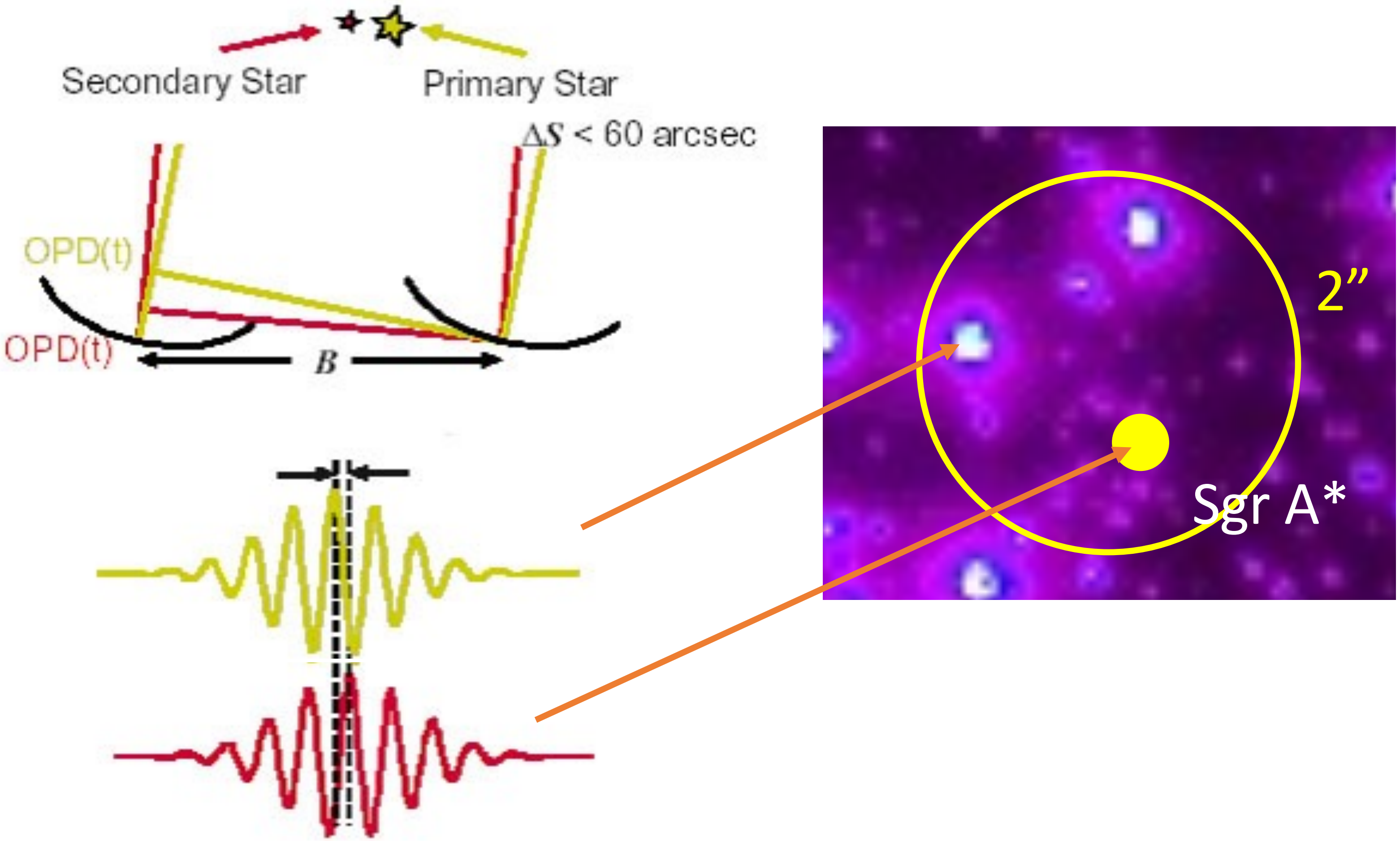
SIM

ESO

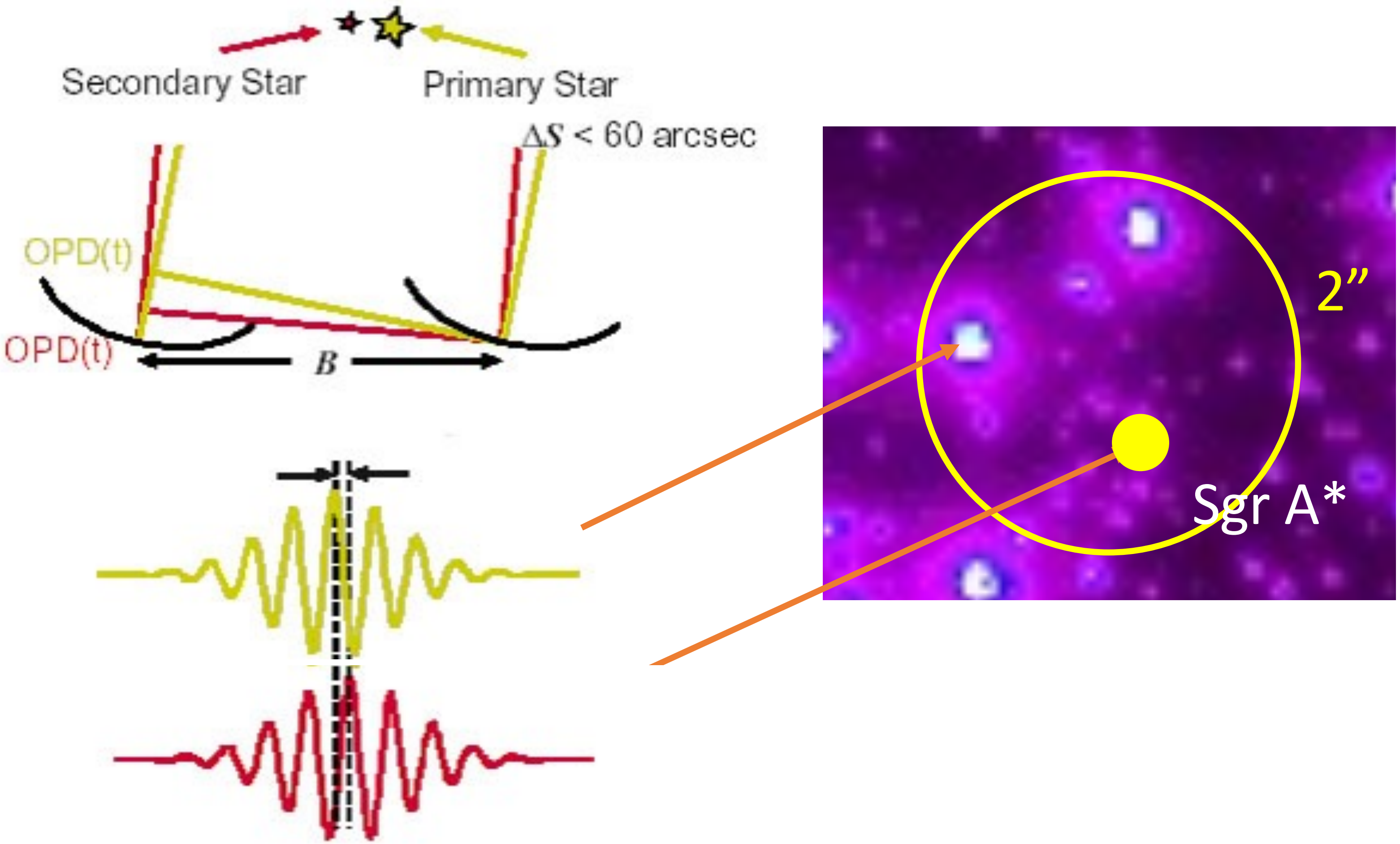
Dual feed, 4-telescope, adaptive optics-assisted, fringe-tracking beam combiner instrument



Phase referenced imaging

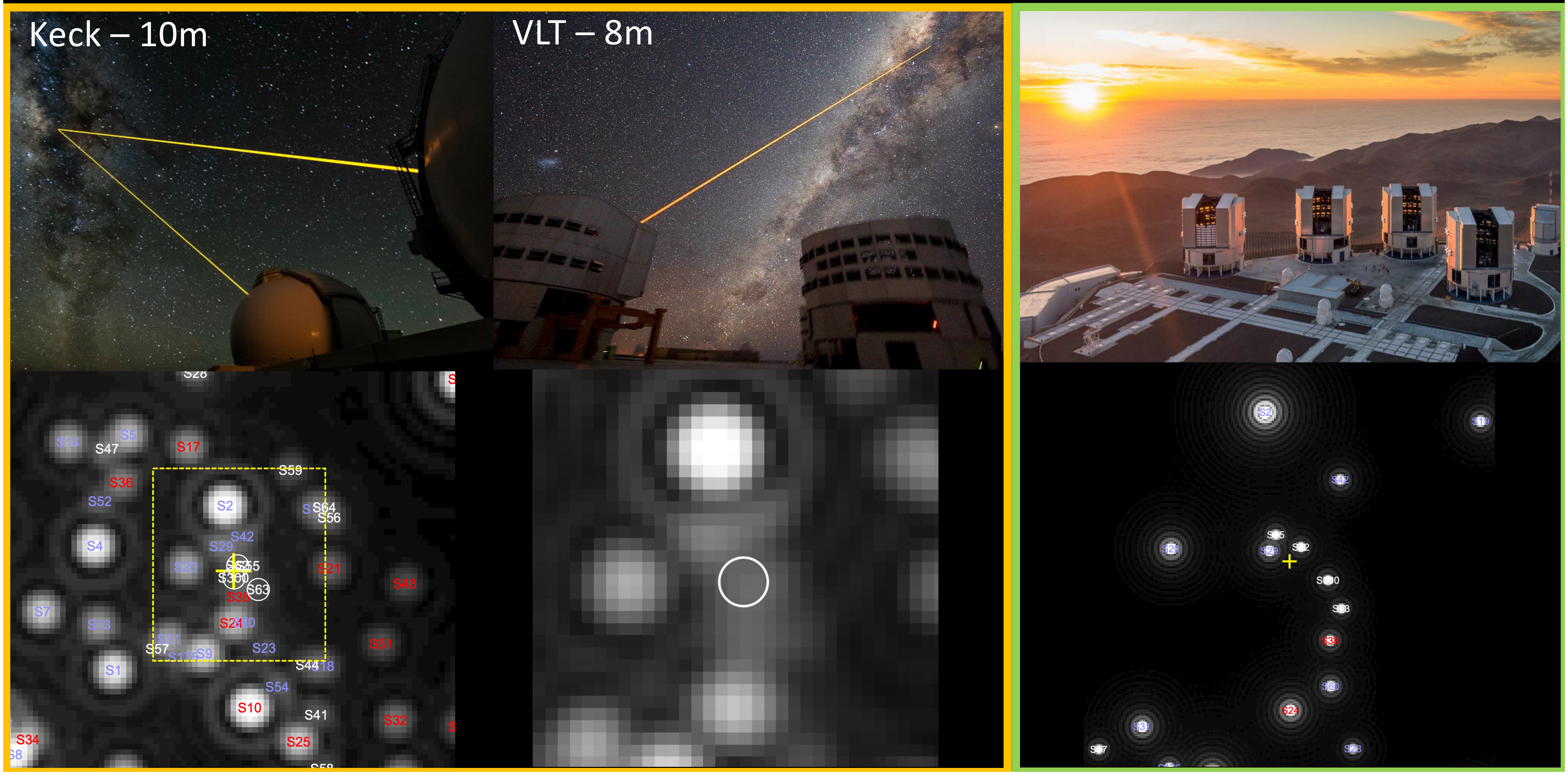


Dual beam astrometry



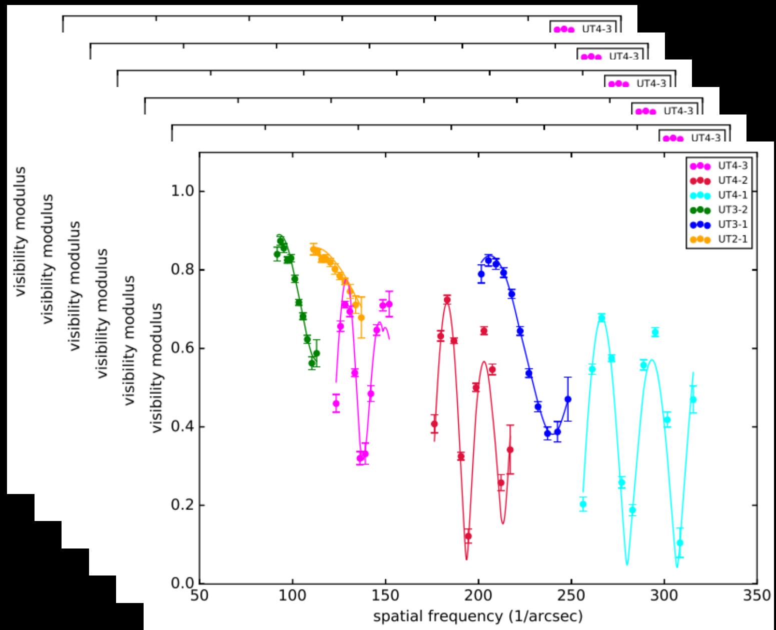

S2
200 mas

Laser guide star adaptive optic is 15x less sharp



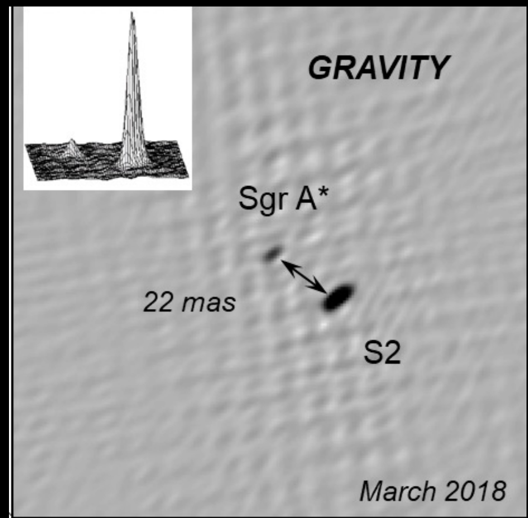
GRAVITY interferometry of Sgr A* and S2

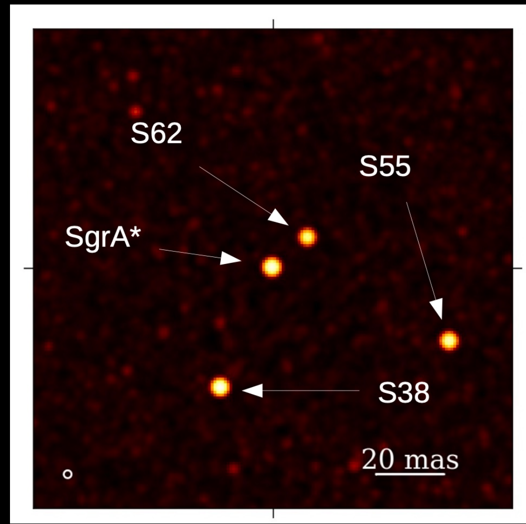
Fringe contrast and phase



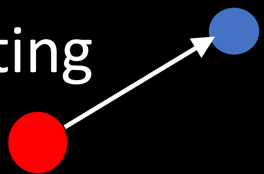
Images

GRAVITY coll. 2017, 2018a





Model fitting

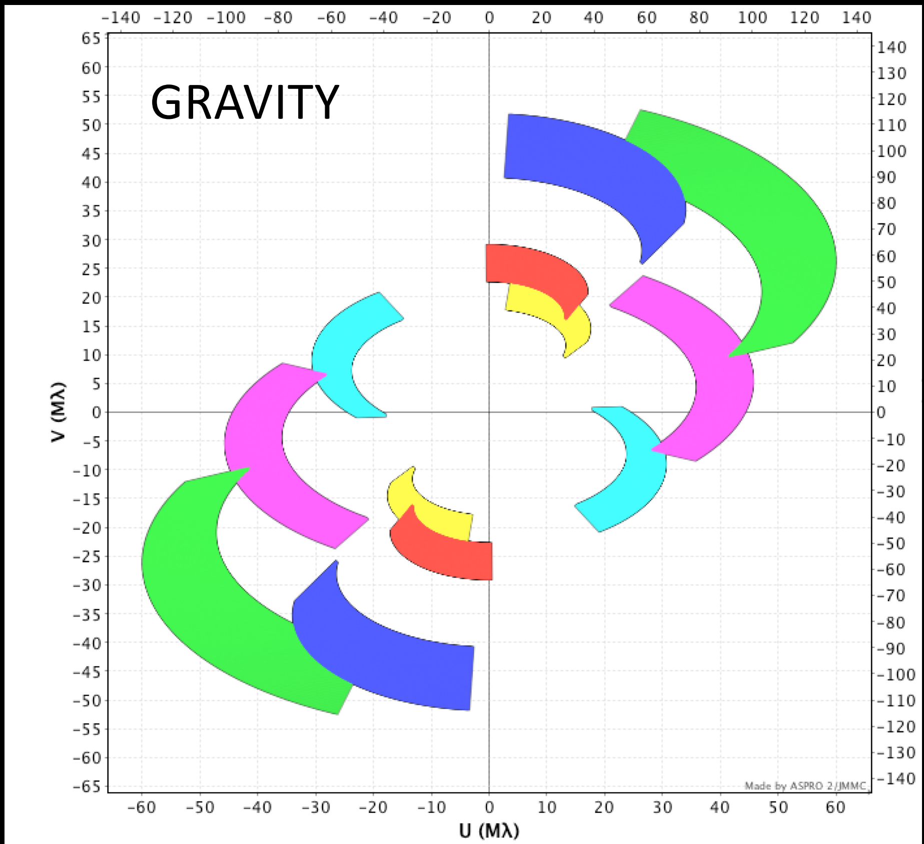


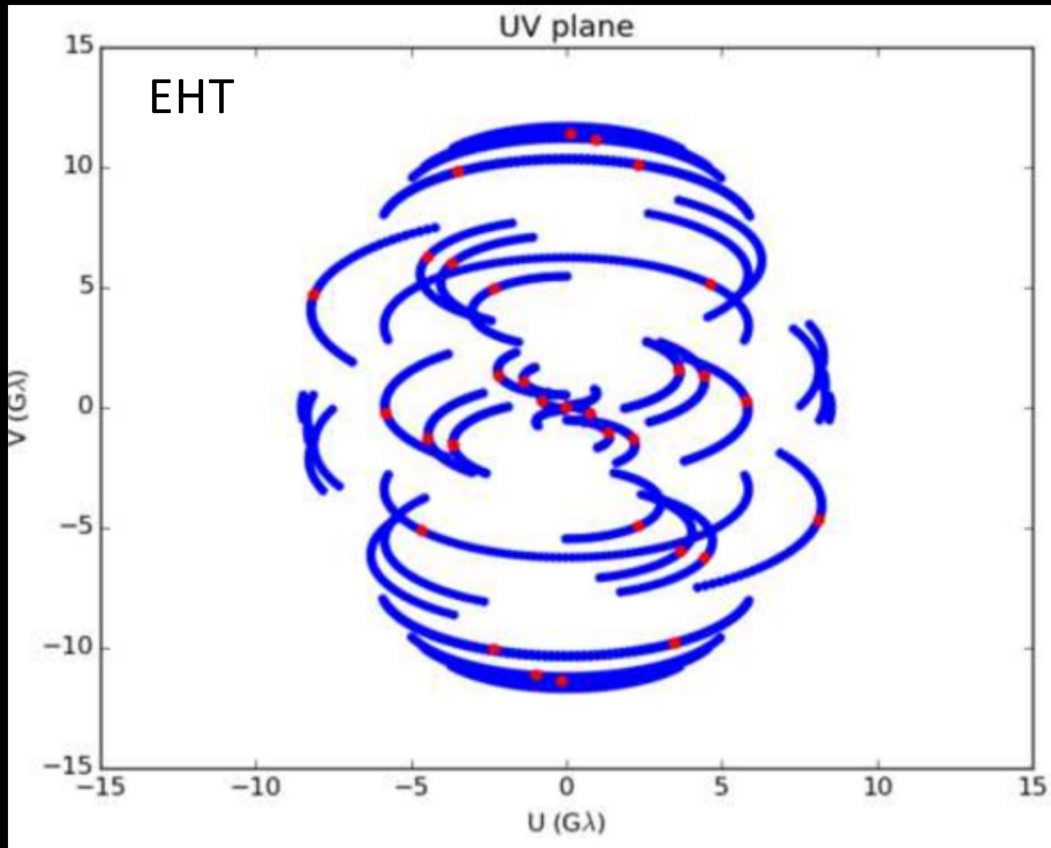
Source & instrument model:

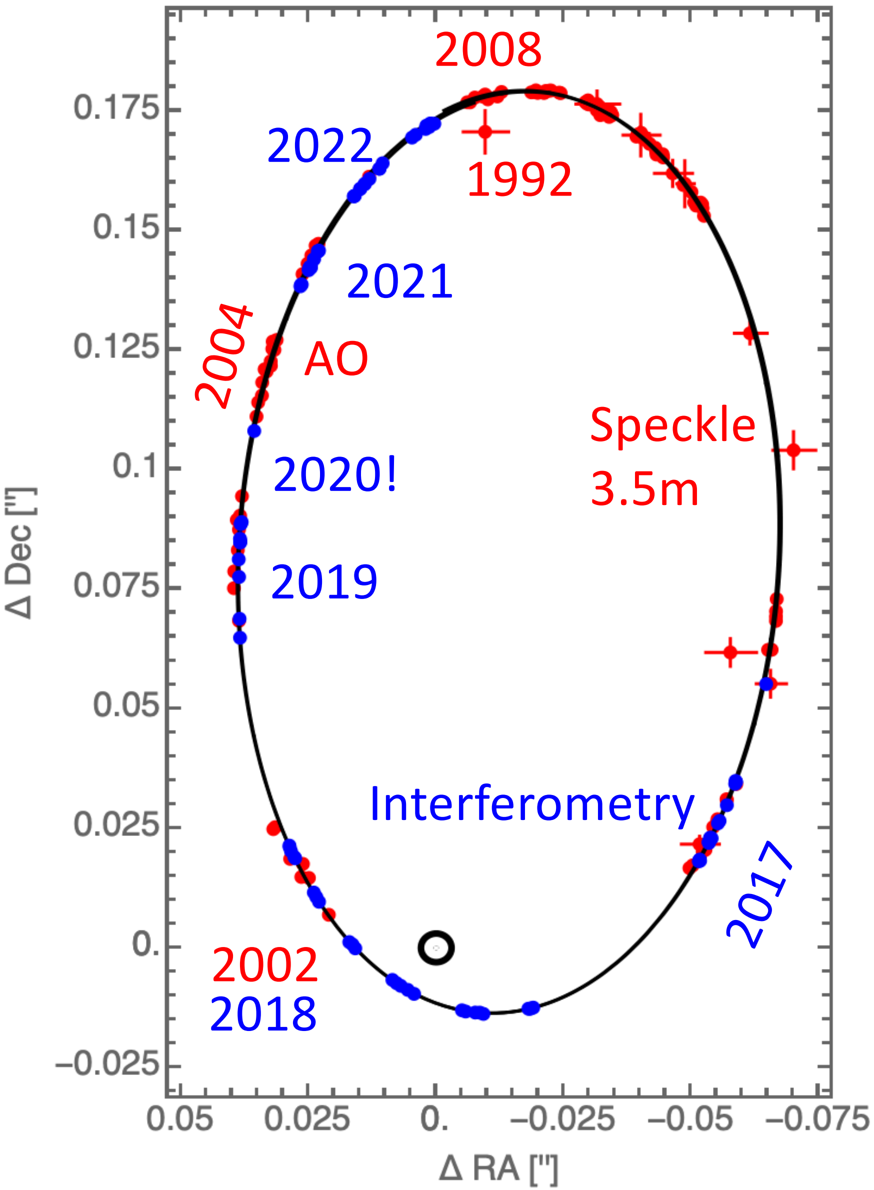
- Separation vector
- Brightness-ratio
- source colors

- Bandwidth smearing
- Injection per telescope

UV coverage good even with 6 baselines - due to the 20% width of the K-band







S2: the showcase star

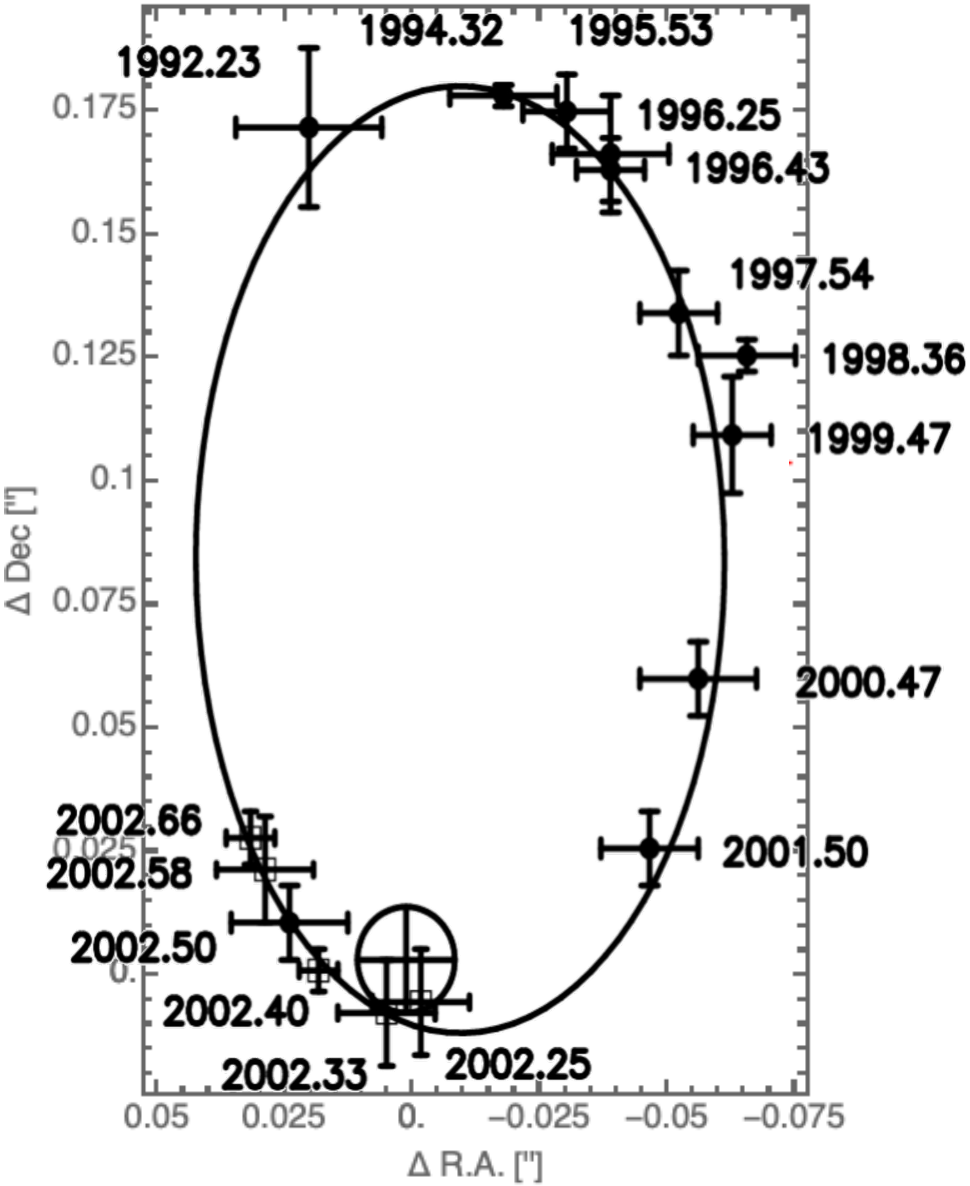
Adaptive Optics &
Interferometry data

(Gillessen et al. 2017, Boehle et al. 2016, GRAVITY collaboration 2018a, 2019a, 2020, 2021, 2022)

- period: 16 years
- semi major axis: 125 mas
- eccentricity 0.88

- angular momentum and energy have errors of 0.2%

- pericenter: 19 May 2018



S2: the showcase star

Adaptive Optics &
Interferometry data

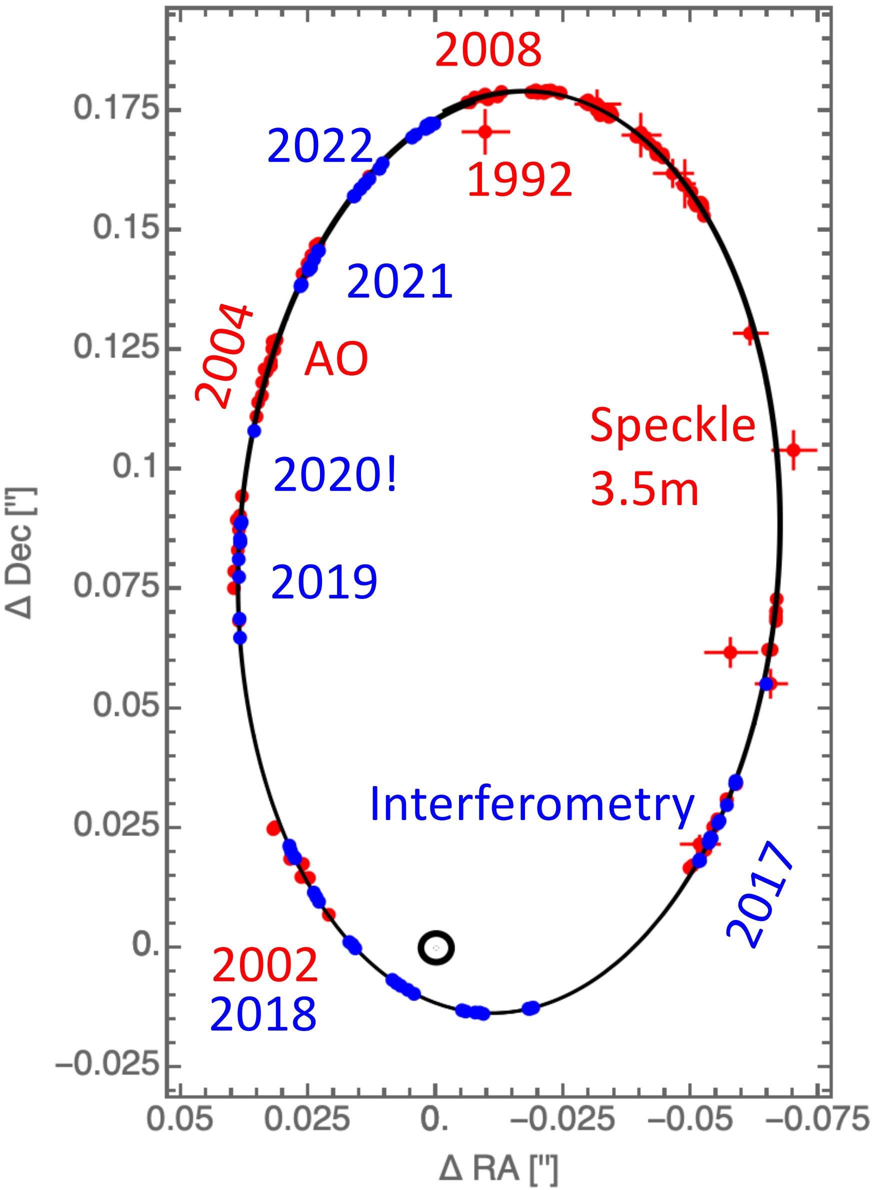
(Gillessen et al. 2017, Boehle et al. 2016, GRAVITY collaboration 2018a, 2019a, 2020, 2021, 2022)

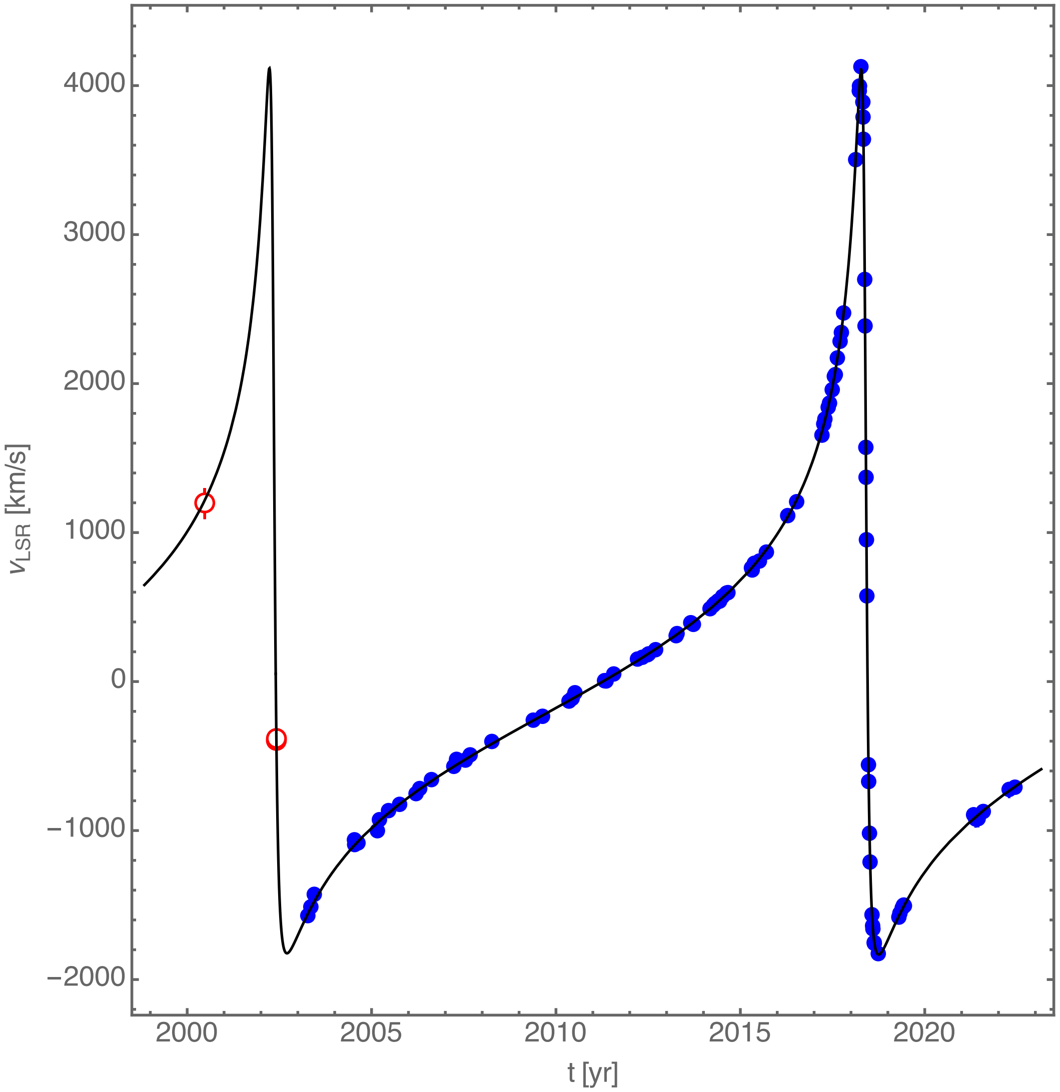
- period: 16 years
- semi major axis: 125 mas
- eccentricity 0.88

- angular momentum and energy have errors of 0.2%

- pericenter: 19 May 2018

The S2 orbit is very fruitful



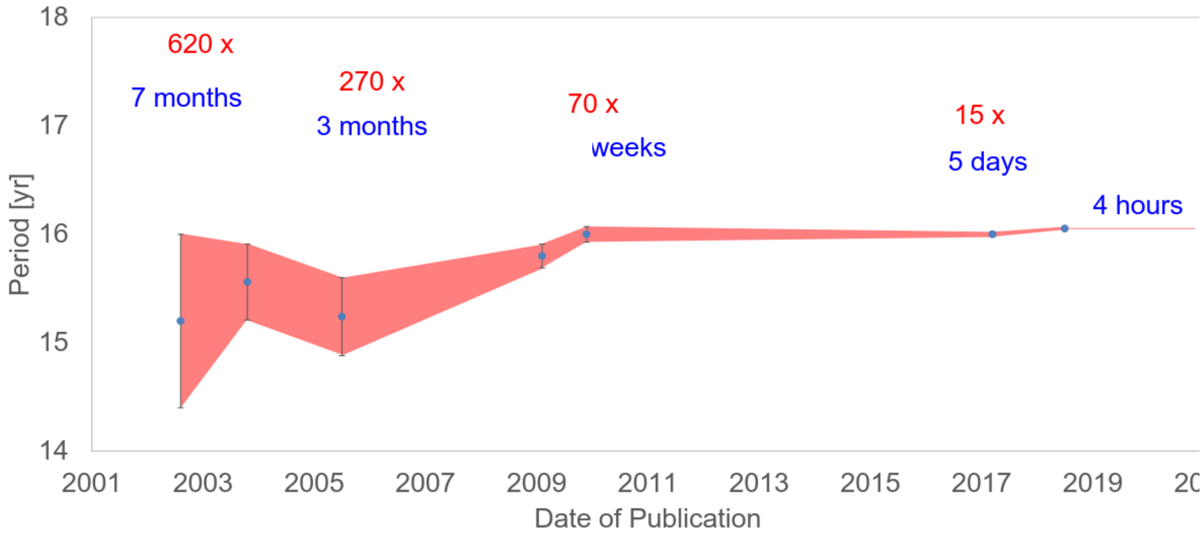


The S2 orbit is very fruitful

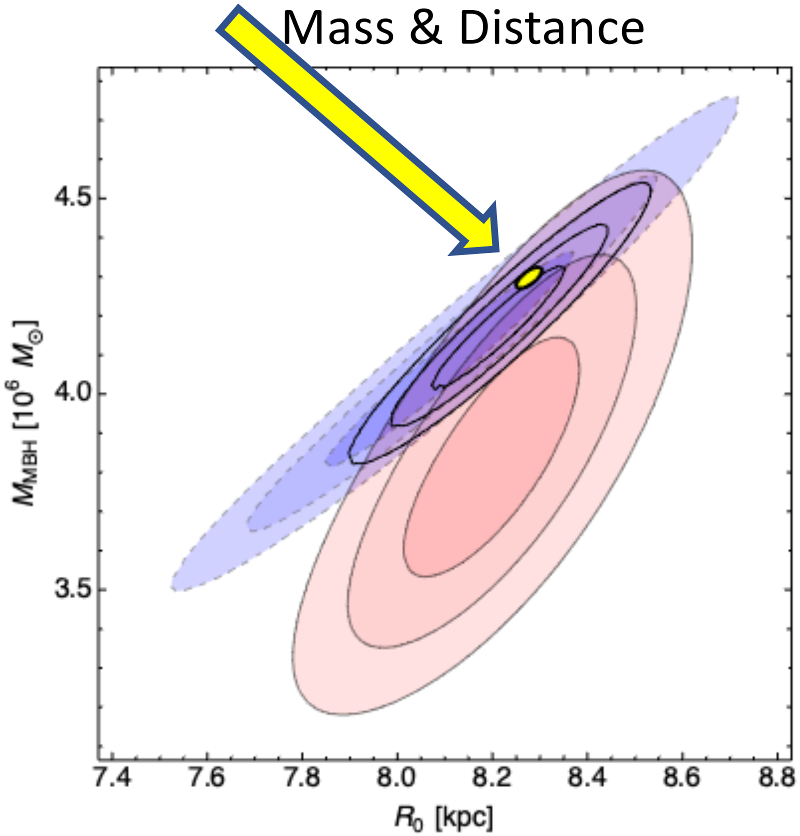
- geometric distance
- relativistic redshift
- test of equivalence principle
- relativistic precession
- limits on extended mass

Improvements by orders of magnitudes

Orbital Period



Mass & Distance



Images: Positions, proper motions, angular velocity in mas/yr
Spectra: Radial velocity in km/s

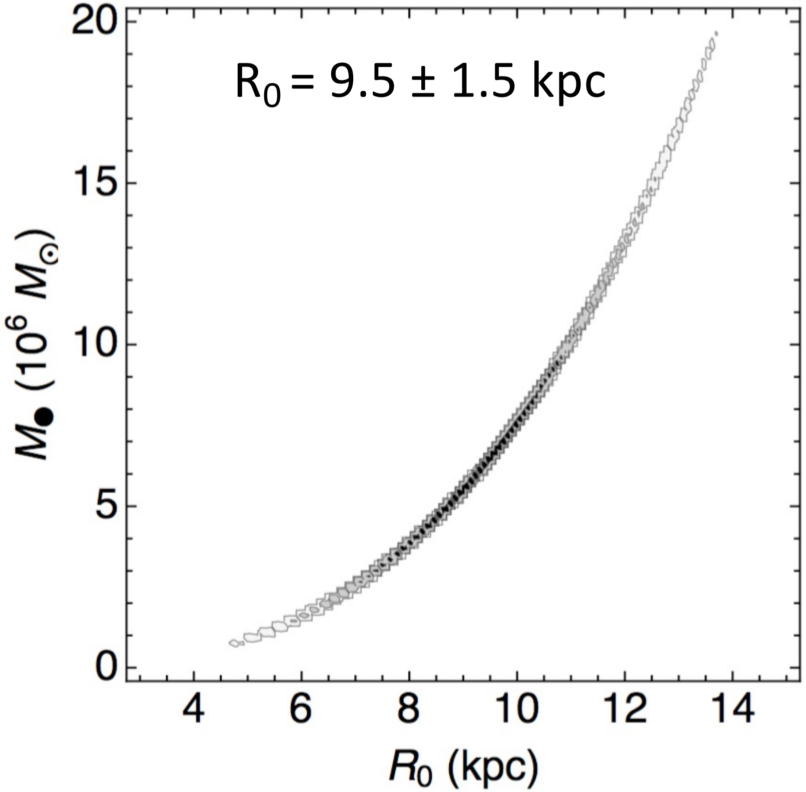
Conversion of angles to absolute length: **The distance**

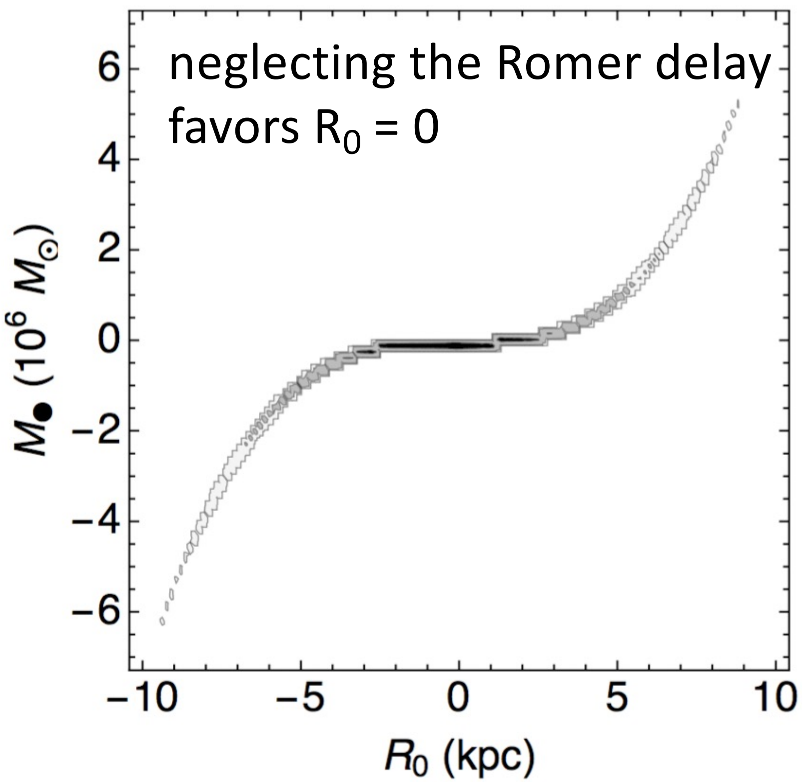
Outline

- Part I   The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II   Errors, Fitting and all that
- Part III   Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

We can measure R_0 **without** radial velocities

via the Romer delay in the astrometry



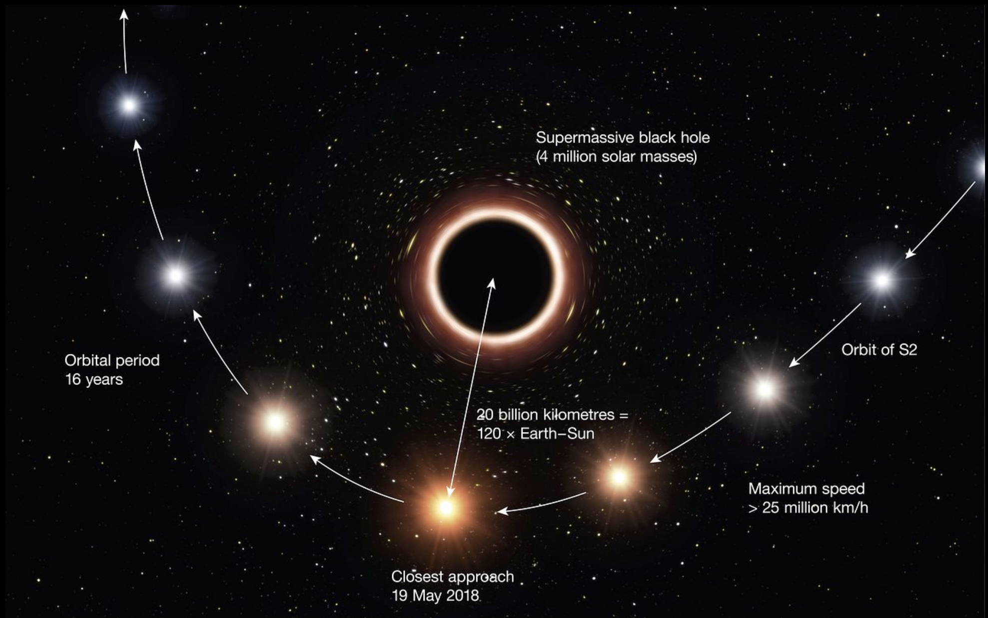


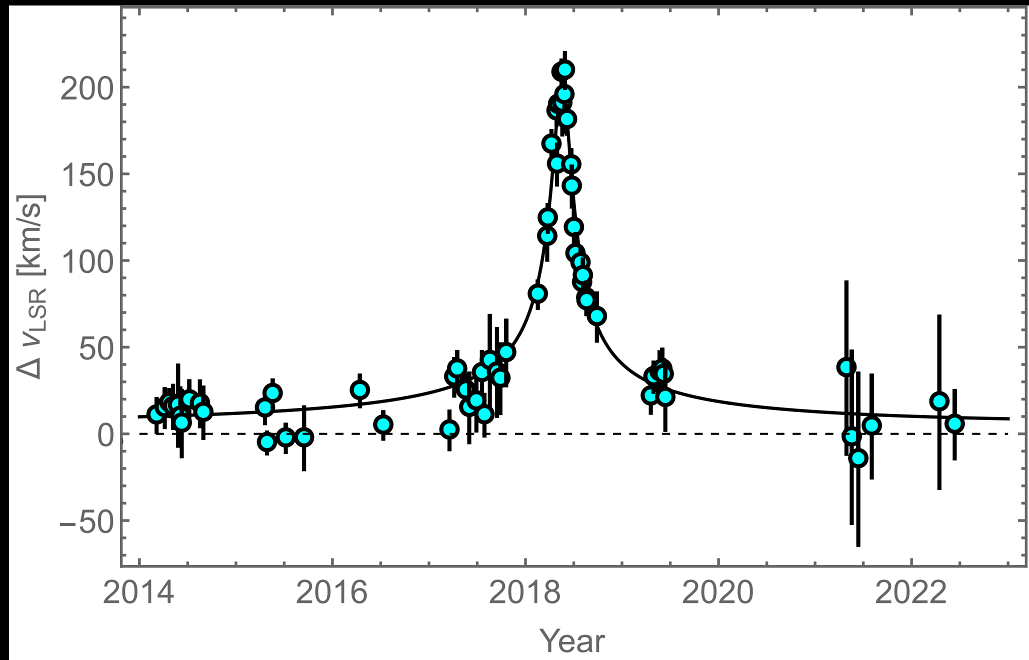
Anglada-Escudé & Torra 2006, GRAVITY collaboration 2019a

At closest approach of 120 AU, S2 reached 8000 km/s

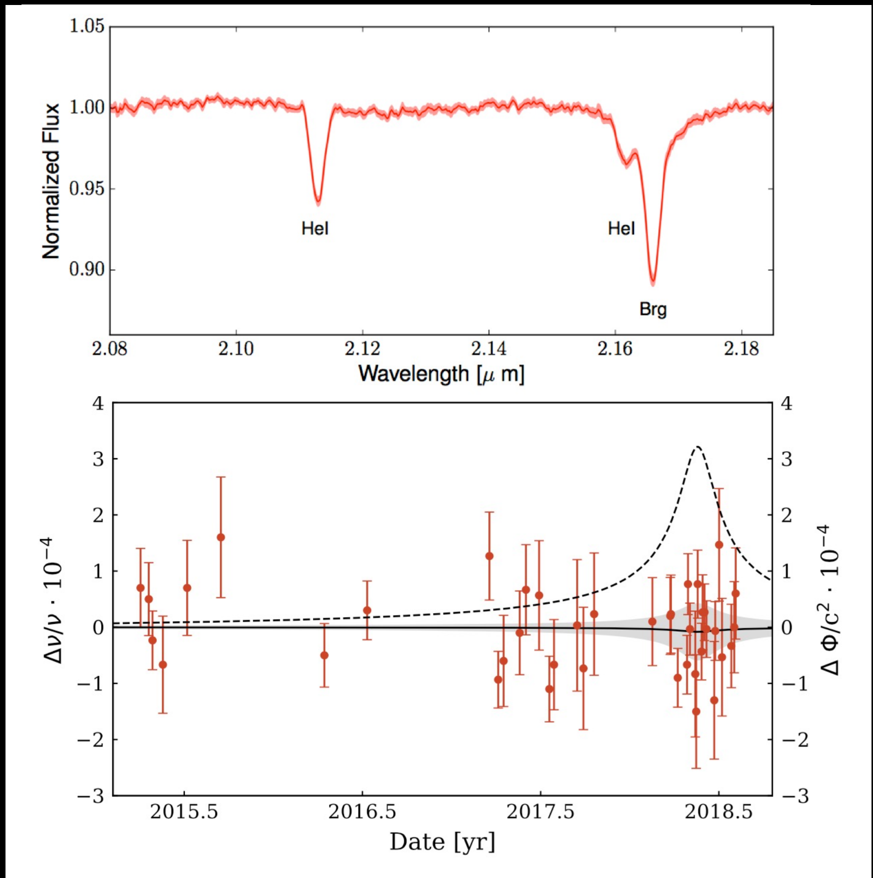
- **transverse Doppler effect**
- **gravitational redshift from Sgr A***

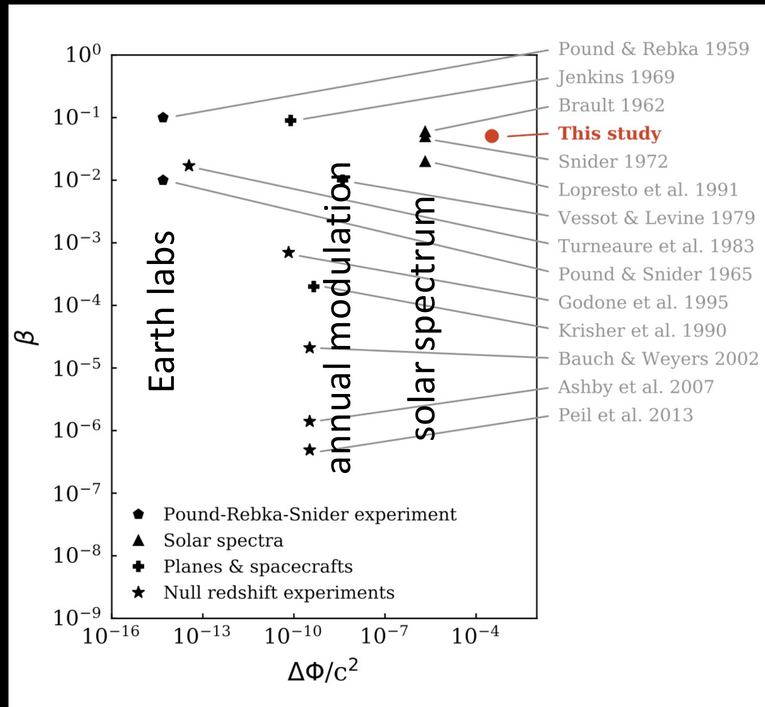
GRAVITY Coll. 2018a





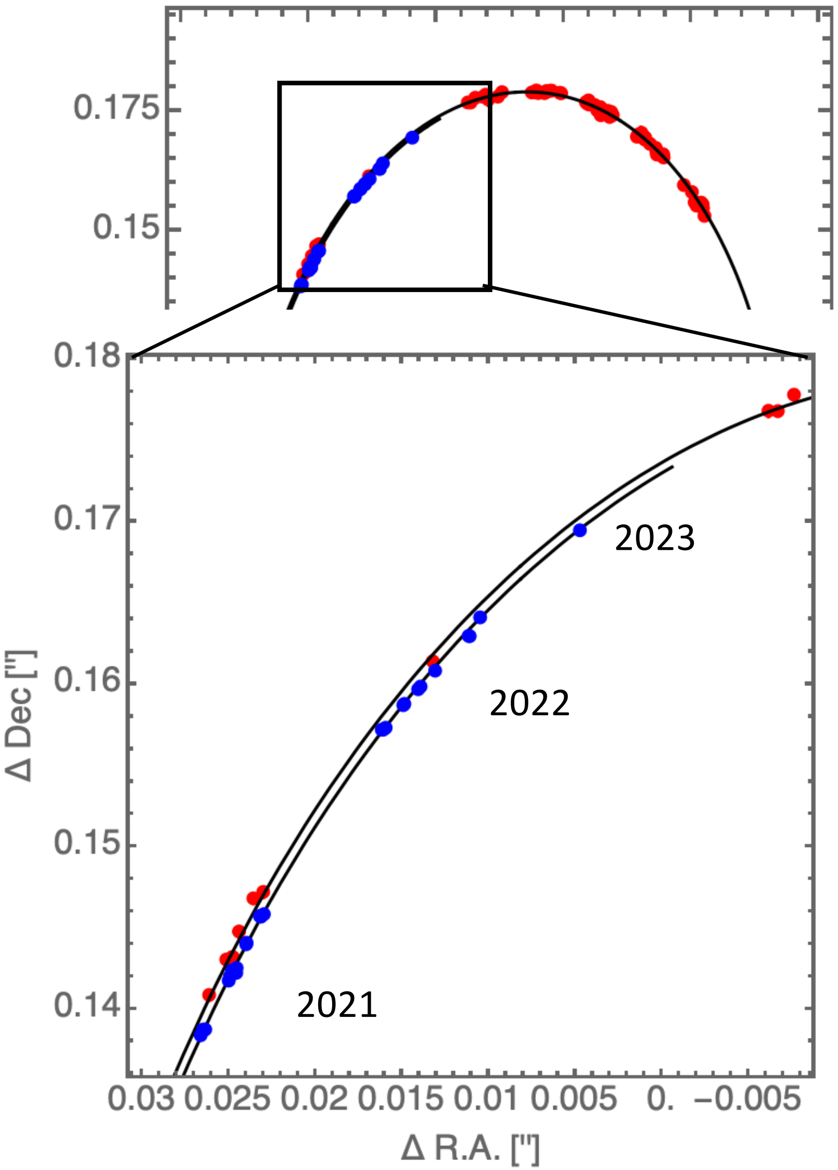
Comparing the redshift for two atomic lines tests the equivalence principle

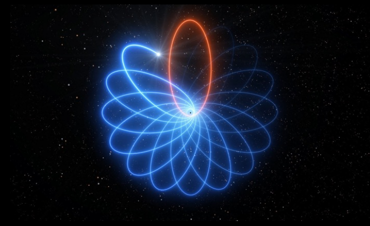


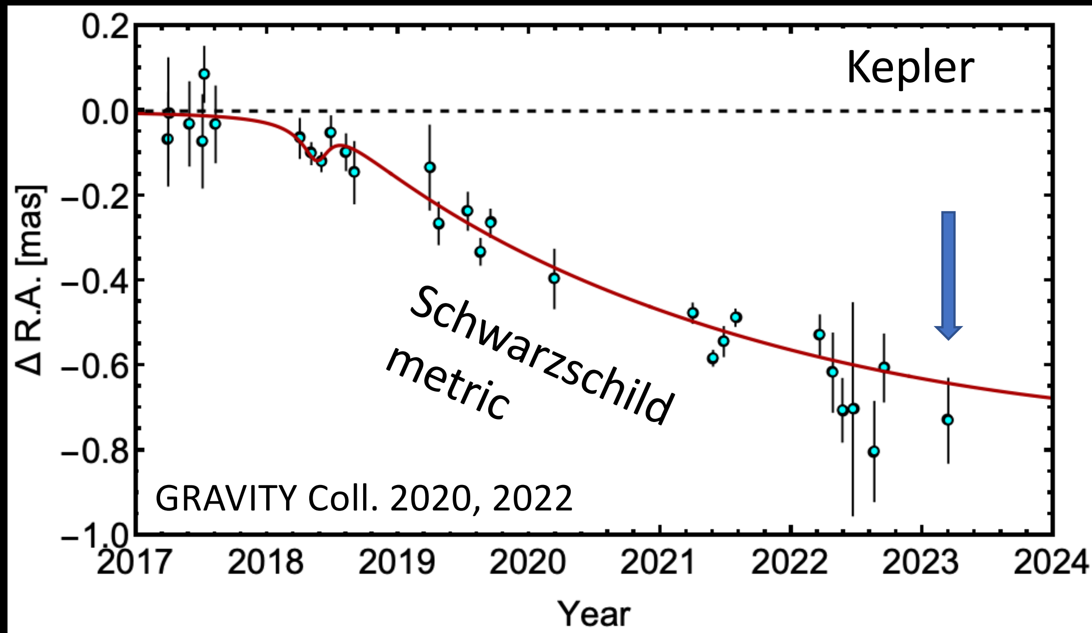


GRAVITY Coll. 2019

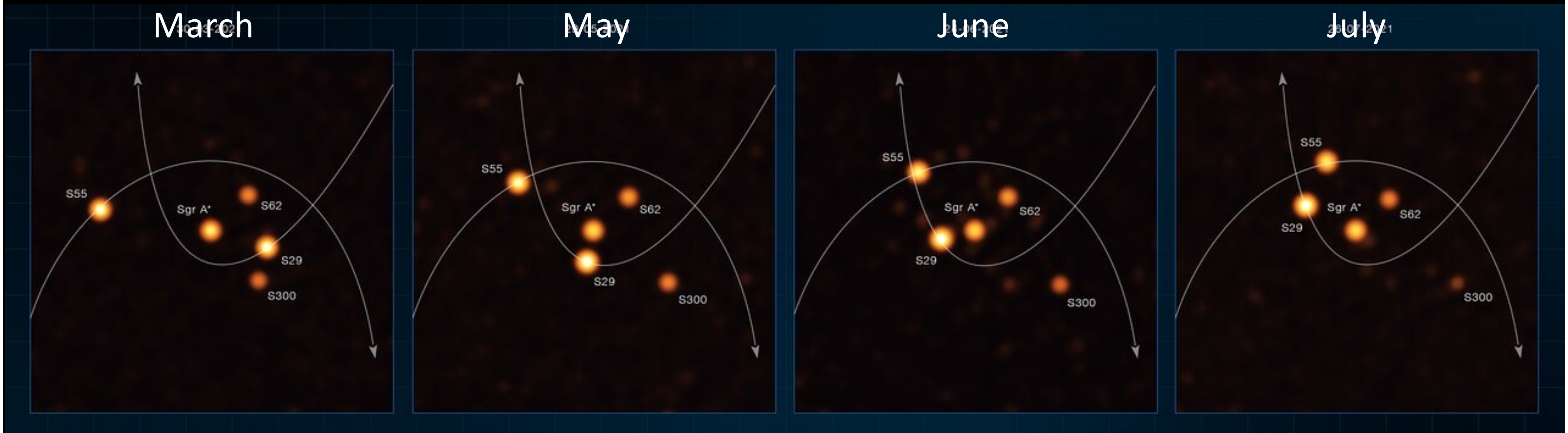
The Schwarzschild precession is detected at >10σ



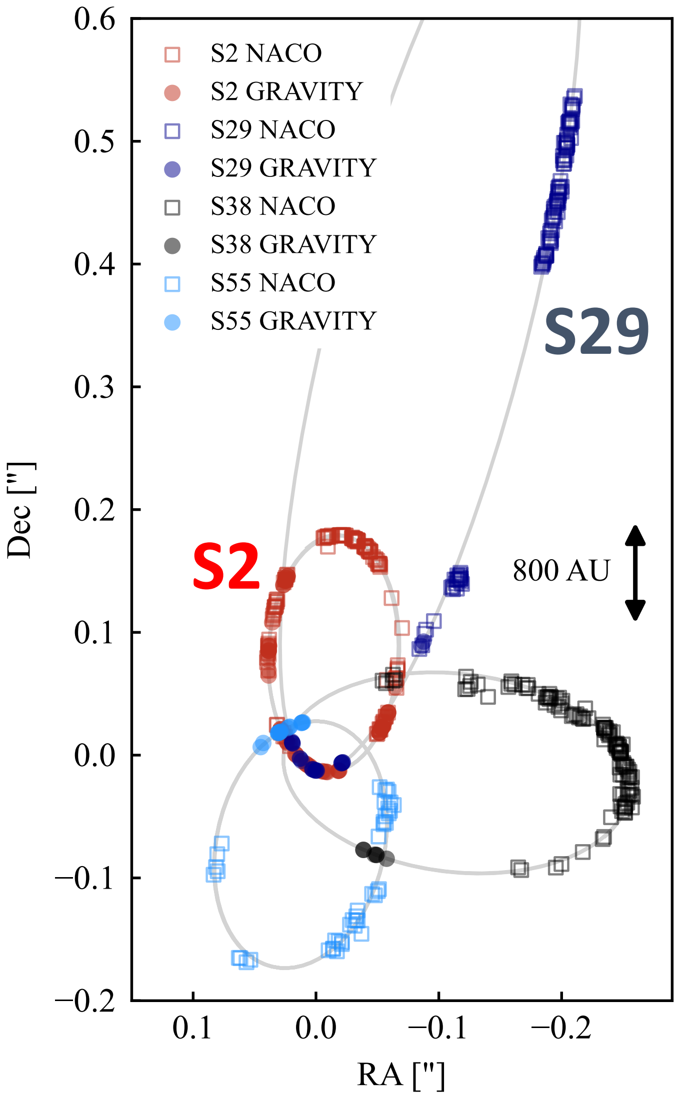




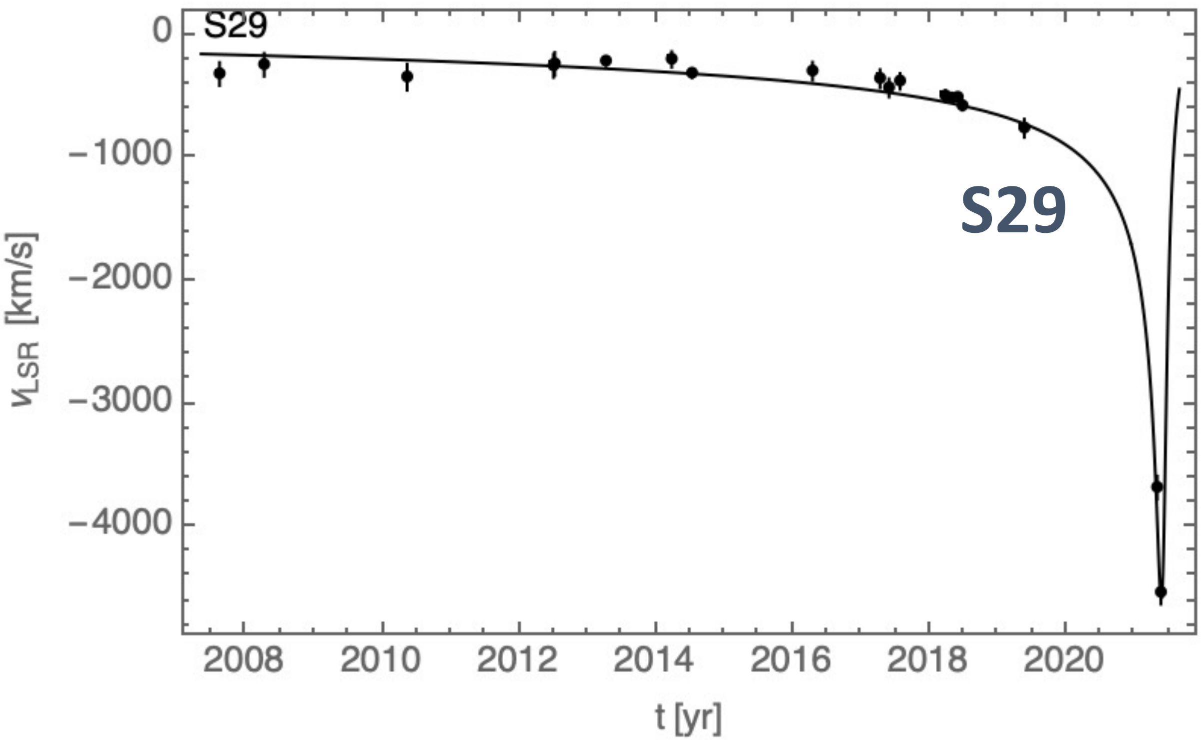
New since 2021:
GRAVITY astrometry of more stars
(S29, S38, S42, S55, …)



GRAVITY collab. 2022a,b

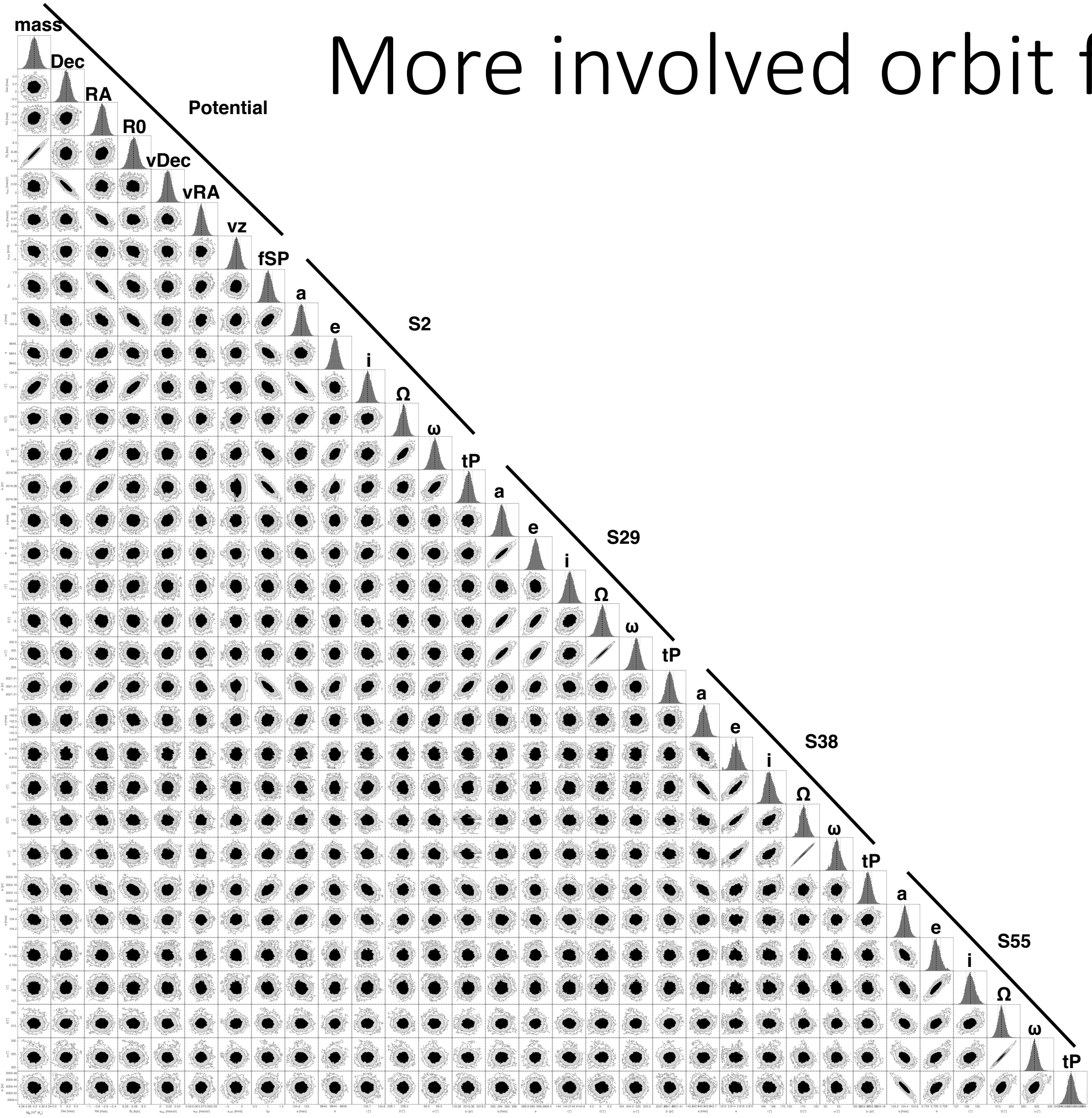


We had previous coverage for these stars

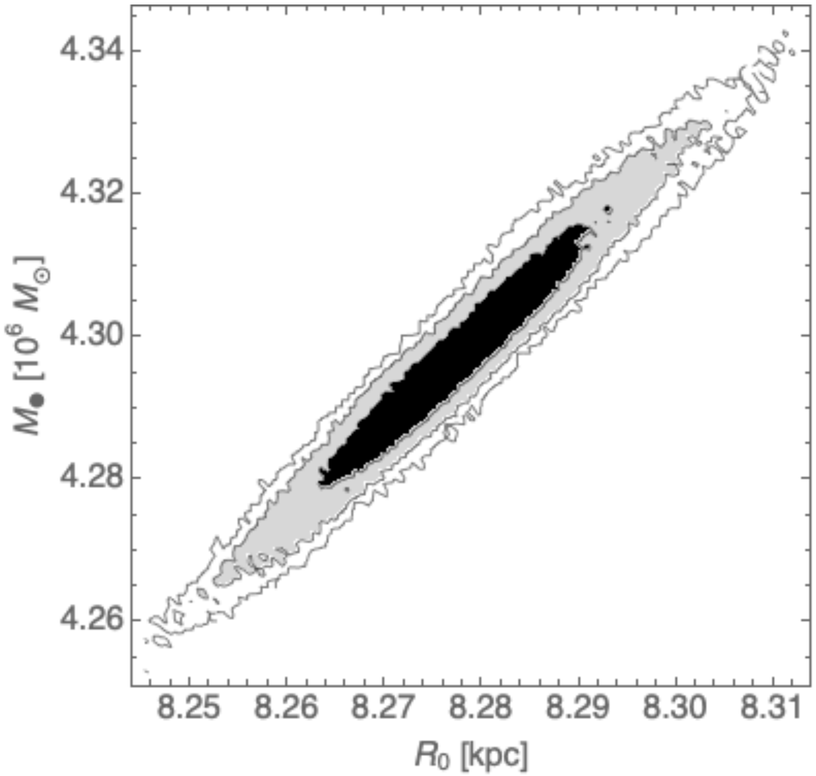


GRAVITY collab. 2022a

More involved orbit fit…



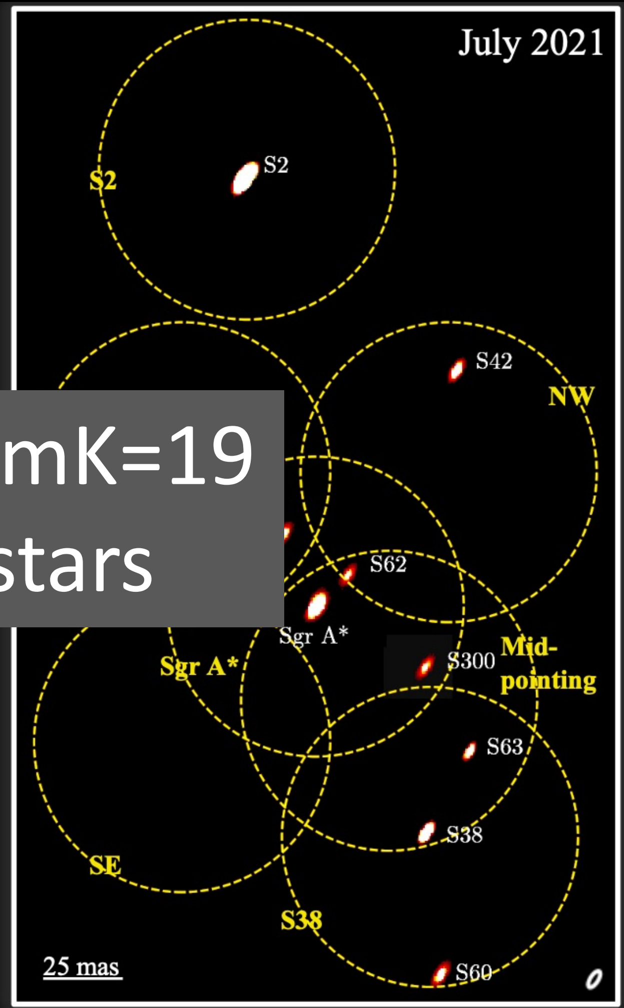
$R_0 = 8.277 \pm 0.009_{stat} \pm 0.035_{sys}$ kpc
$M = 4.297 \pm 0.012_{stat} \pm 0.040_{sys} \times 10^6 M_\odot$



GRAVITY collab. 2022a

Imaging at milli-arcsec resolution

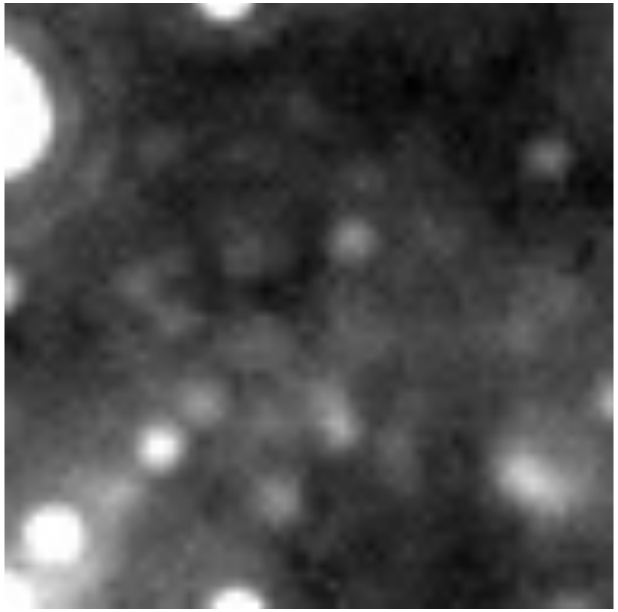
- Tracking stars down to mK=19
- Discovering new, faint stars

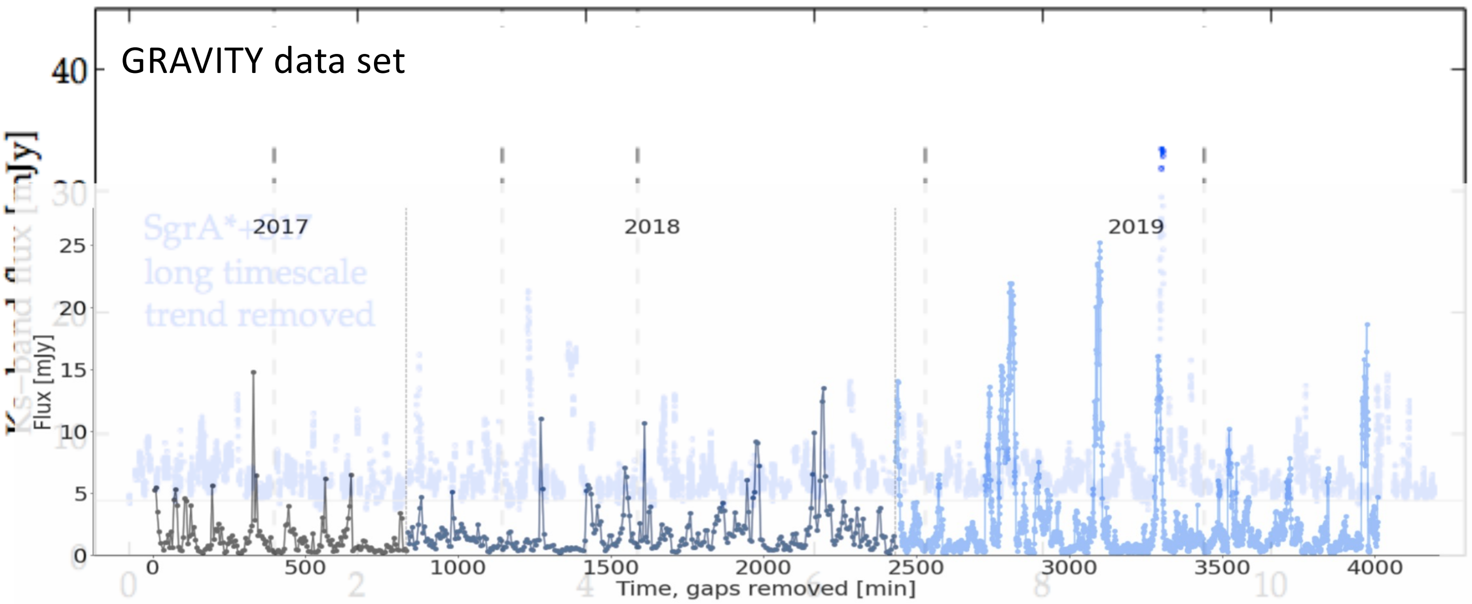


Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - (A funny gas cloud)

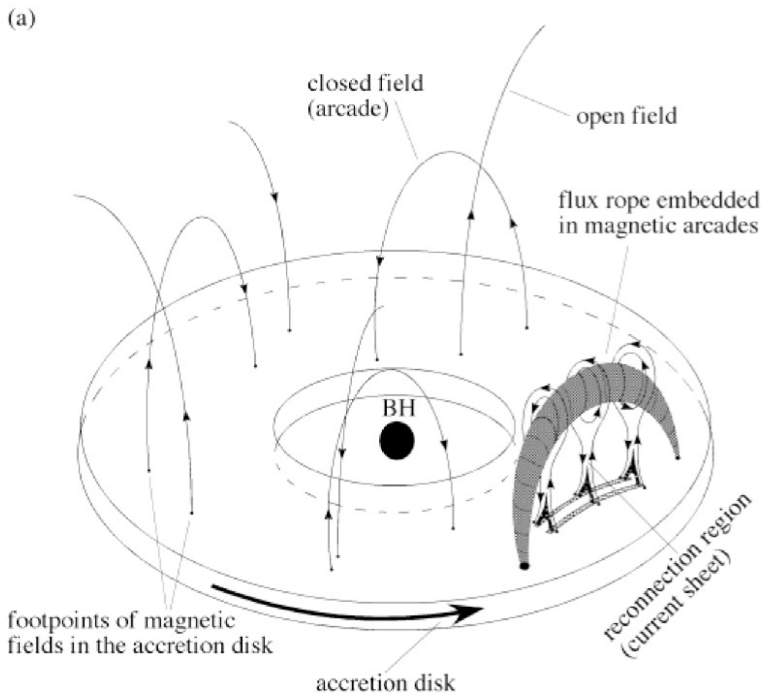
Sgr A* is flaring in the infrared

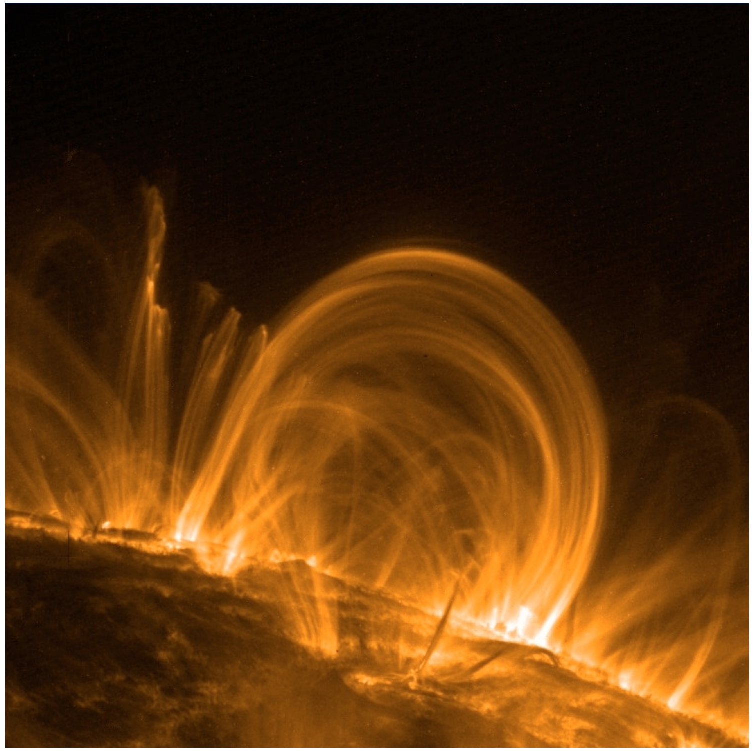




Genzel et al. 2003, Dodds-Eden et al. 2011, Witzel et al. 2012, 2018, GRAVITY coll. 2020b

Speculation: An analog to solar flares

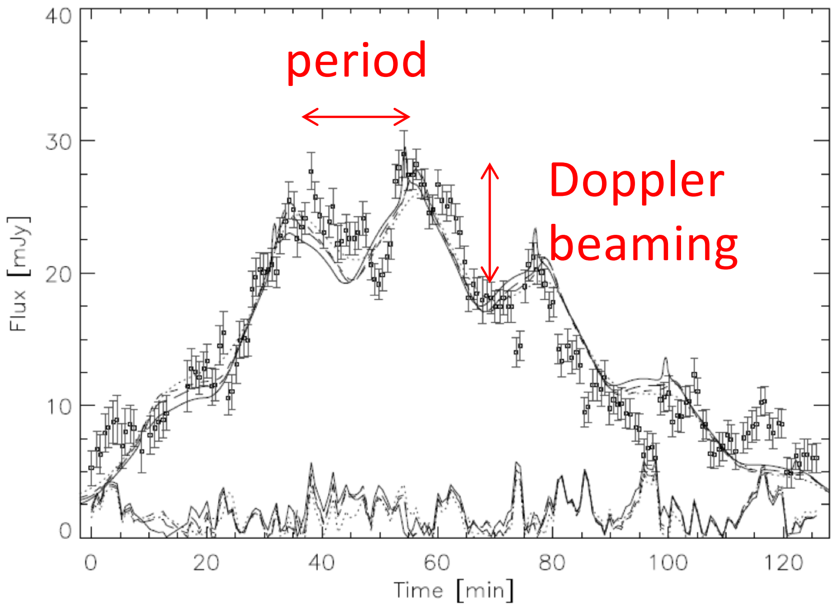




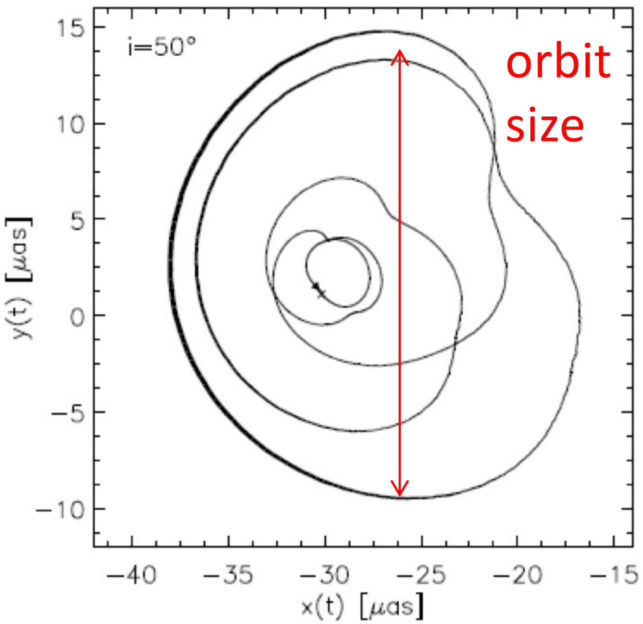
Yuan et al. 2009

What can one learn from flare orbits?

Light curve



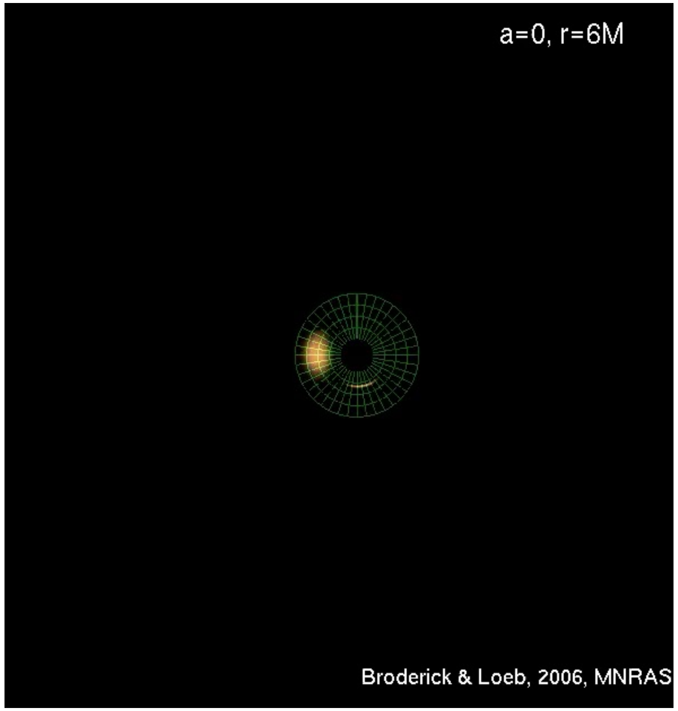
Centroid track



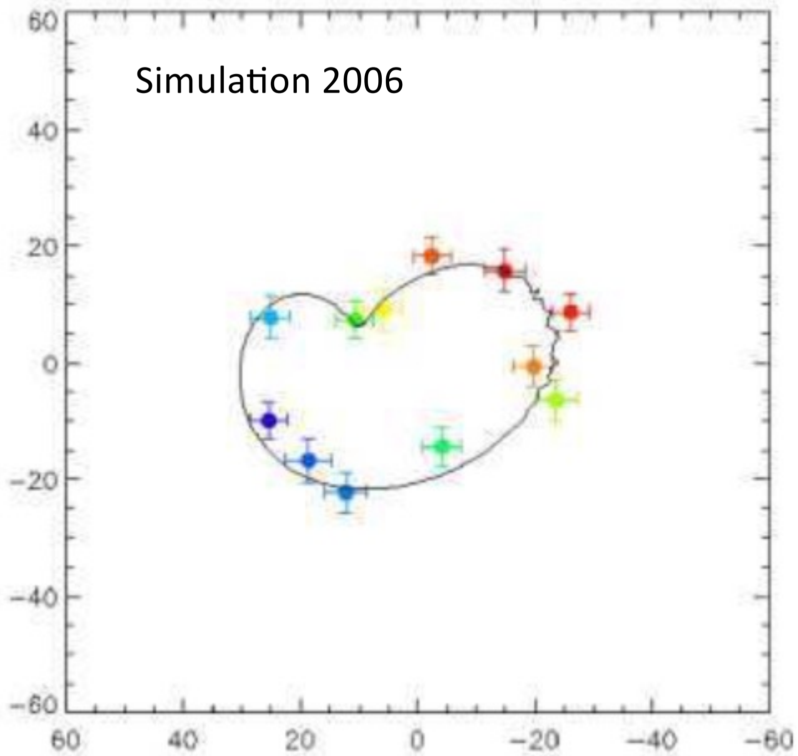
Hamaus et al. 2009

➔ Radius, **Inclination**, **Spin**

The flares should orbit at a few 10µas radius - in reach for GRAVITY astrometry

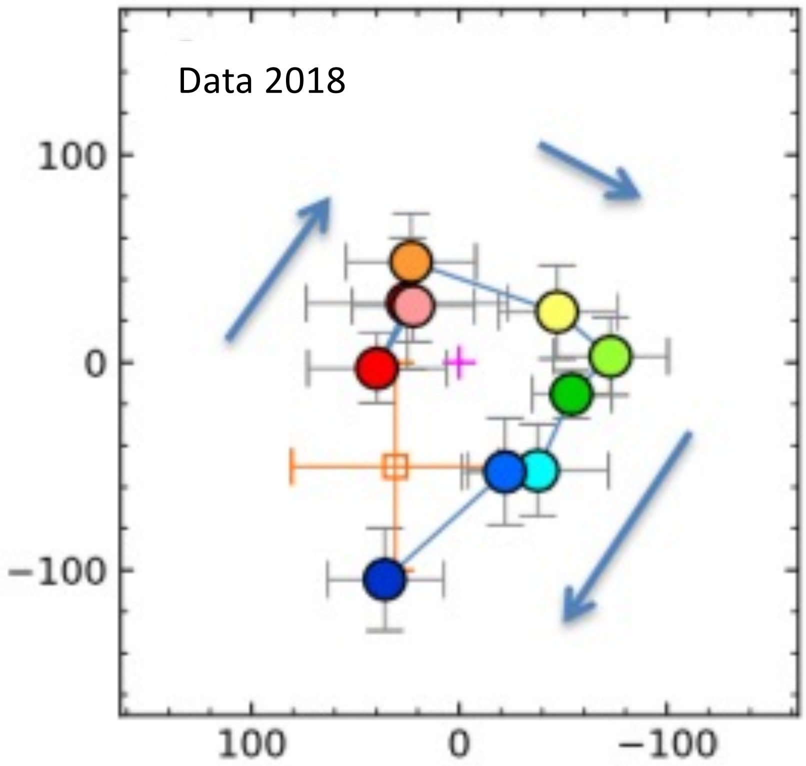


Broderick & Loeb 2005, 2006

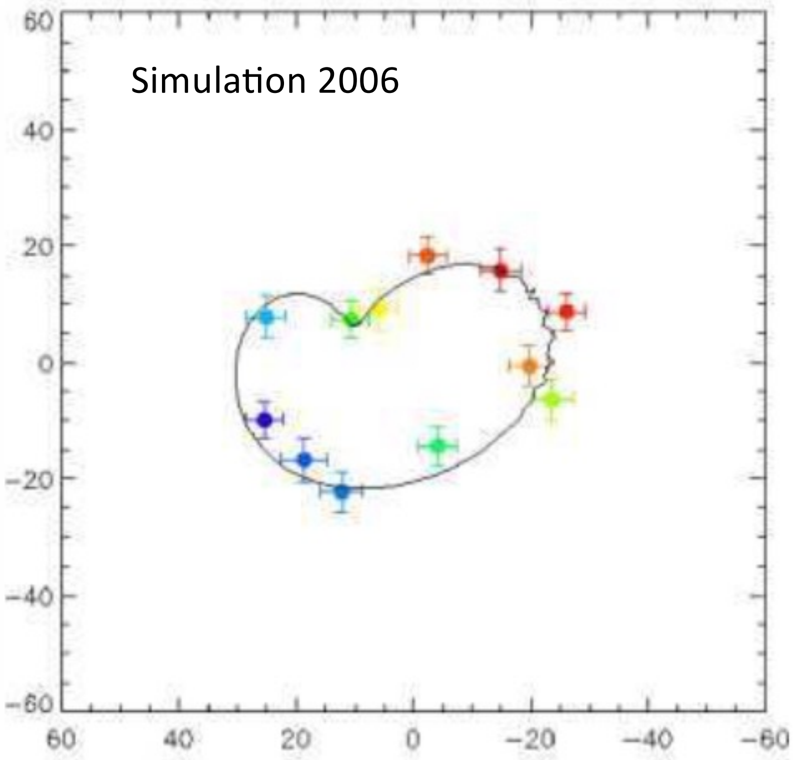


GRAVITY science proposal 2006

GRAVITY observations 2018: Orbiting hot spots (4x)

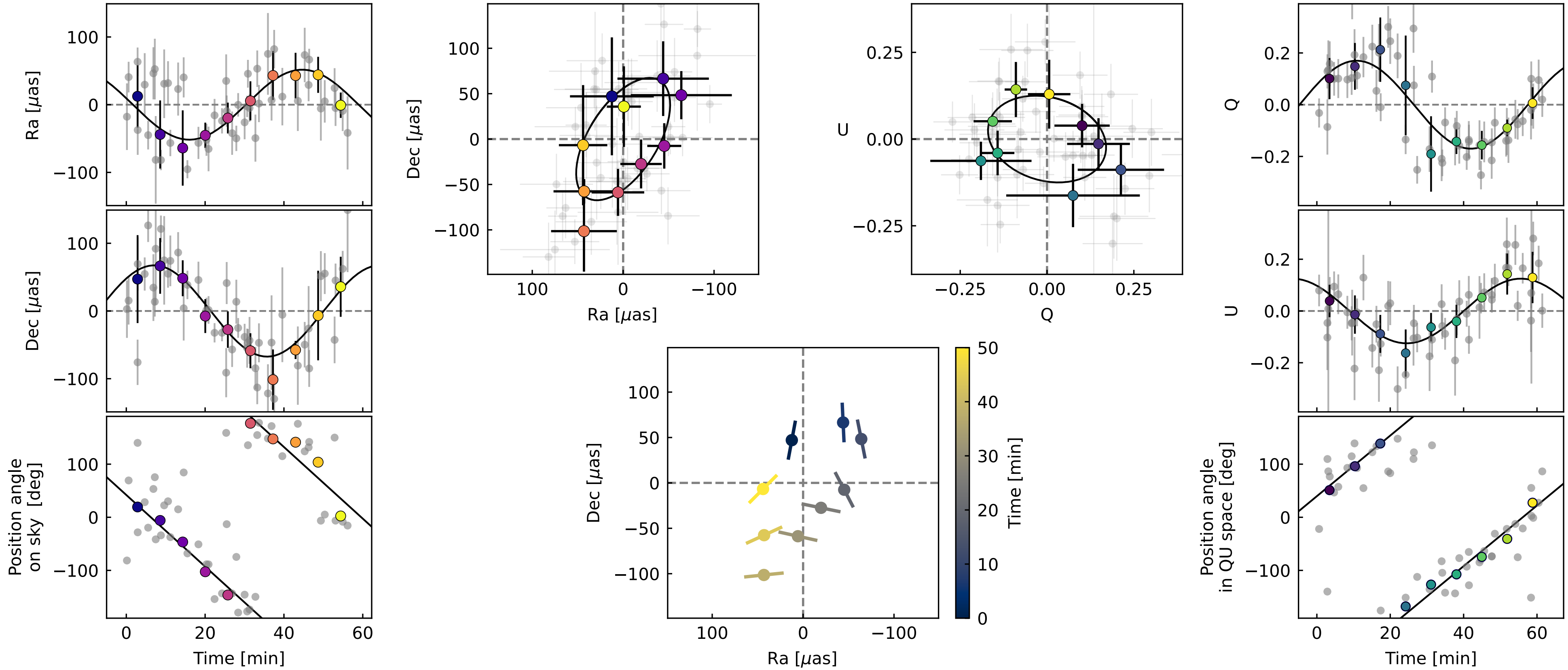


GRAVITY collaboration 2018b

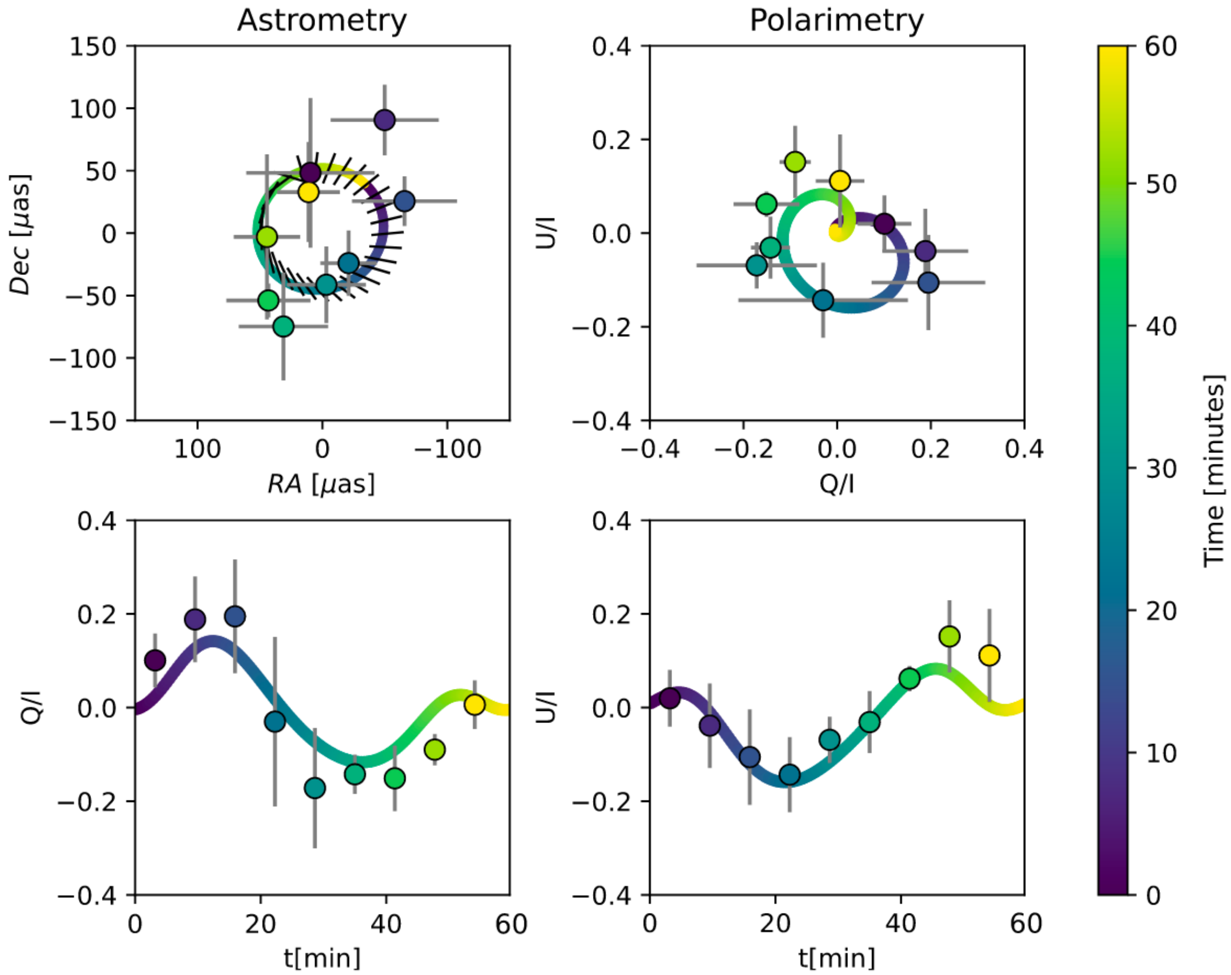


GRAVITY science proposal 2006

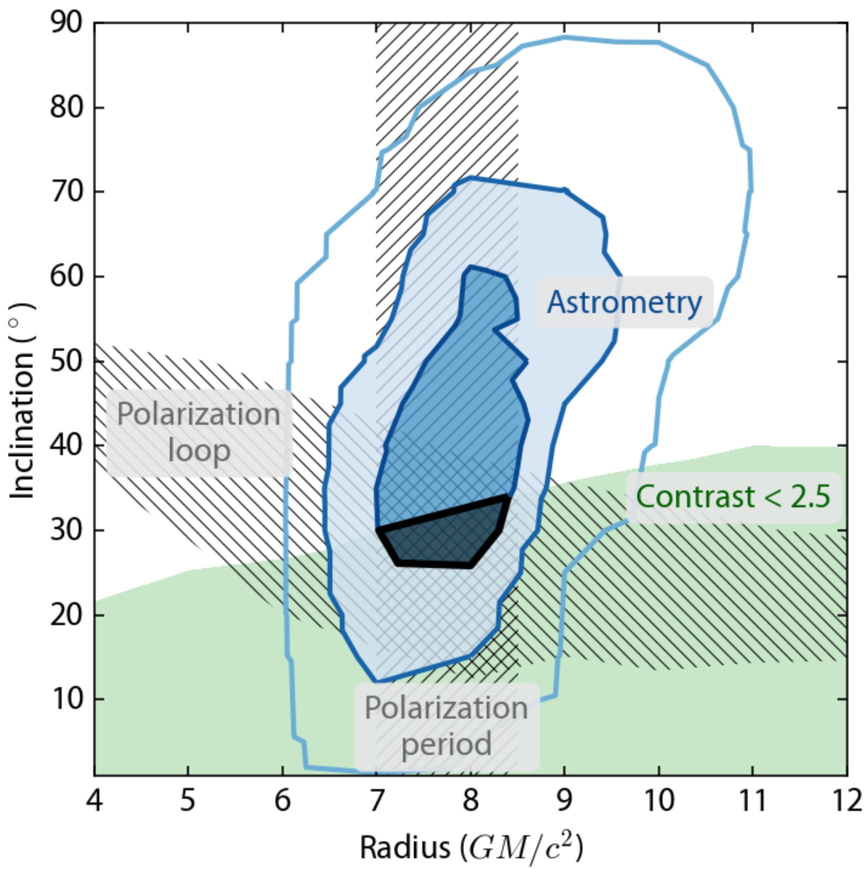
Status 2023: 4 flares with astrometric loop
6 flares with polarimetric loop



An orbiting, polarized hot spot can describe the data

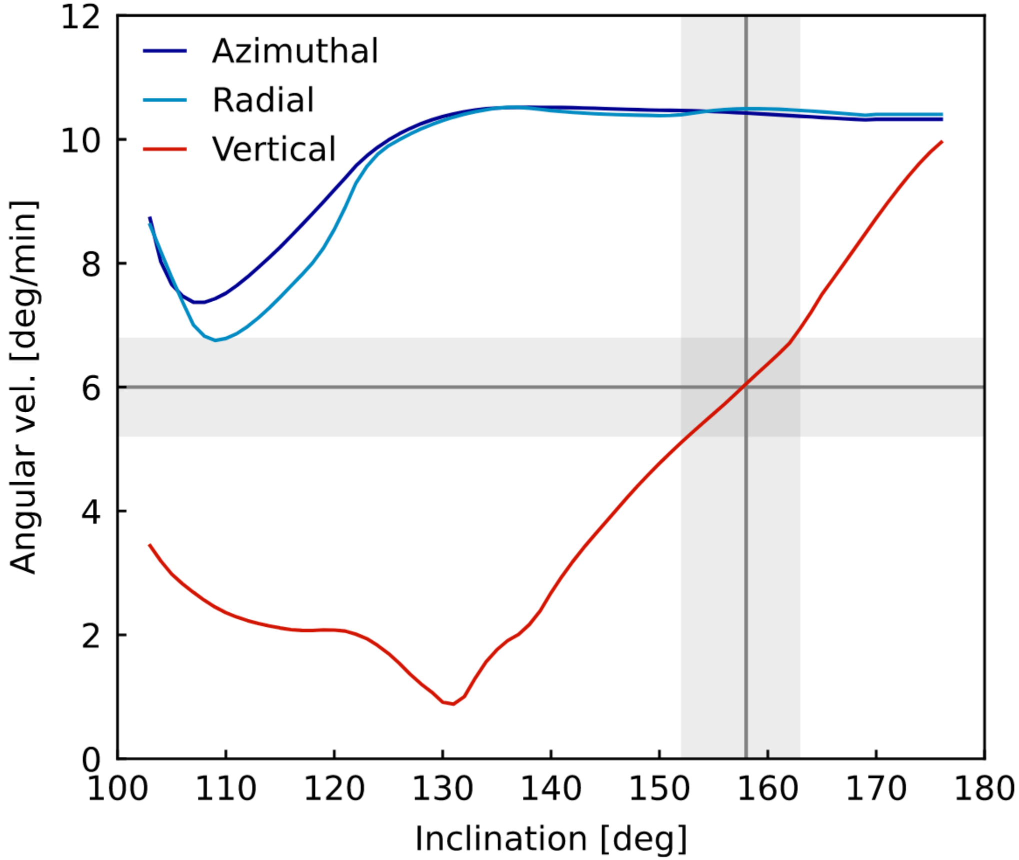


A face-on view and a vertical magnetic field for SgrA* is favored

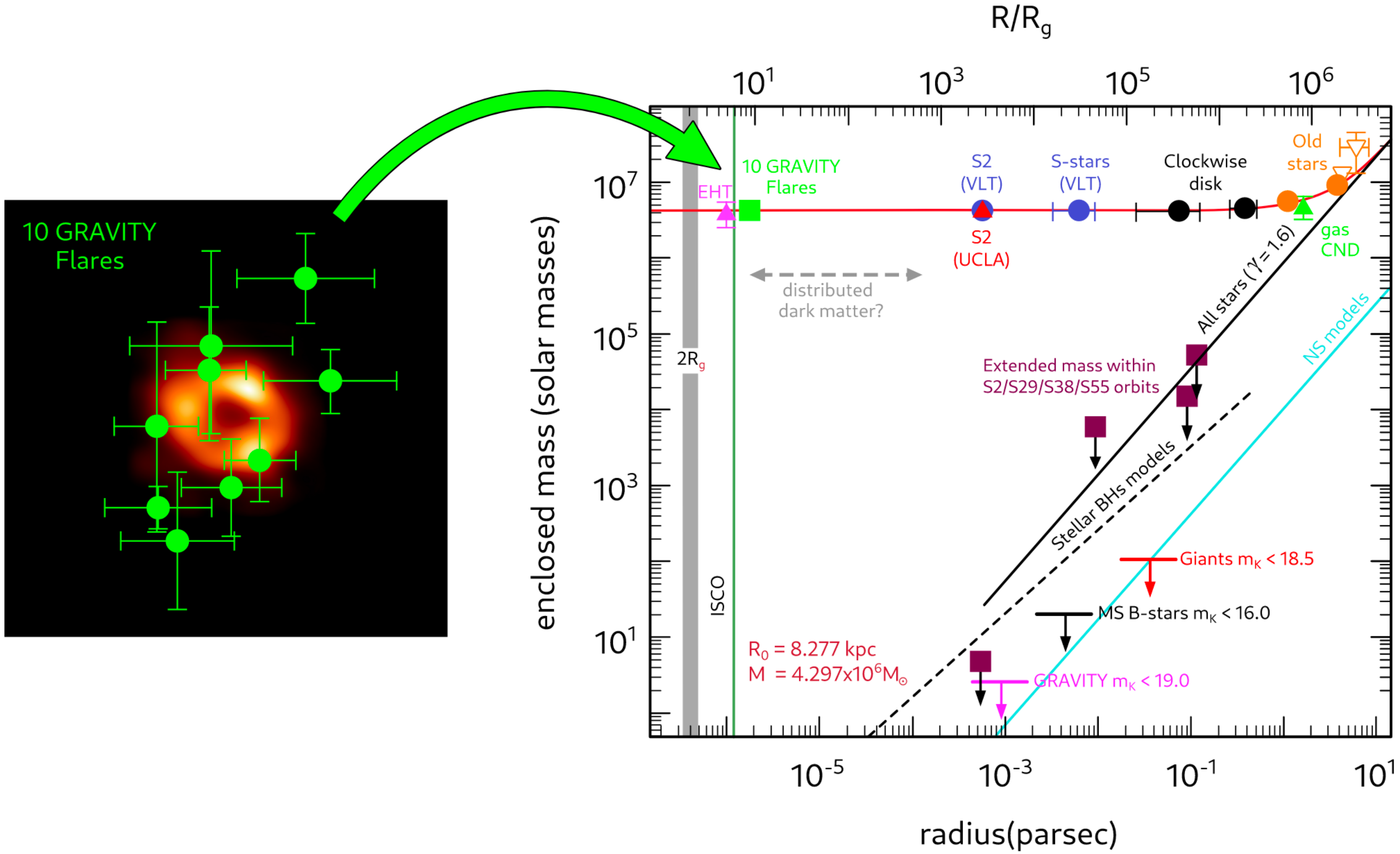


GRAVITY collaboration 2018b

Key for the inclination:
Angular velocity of polarization vector rotation

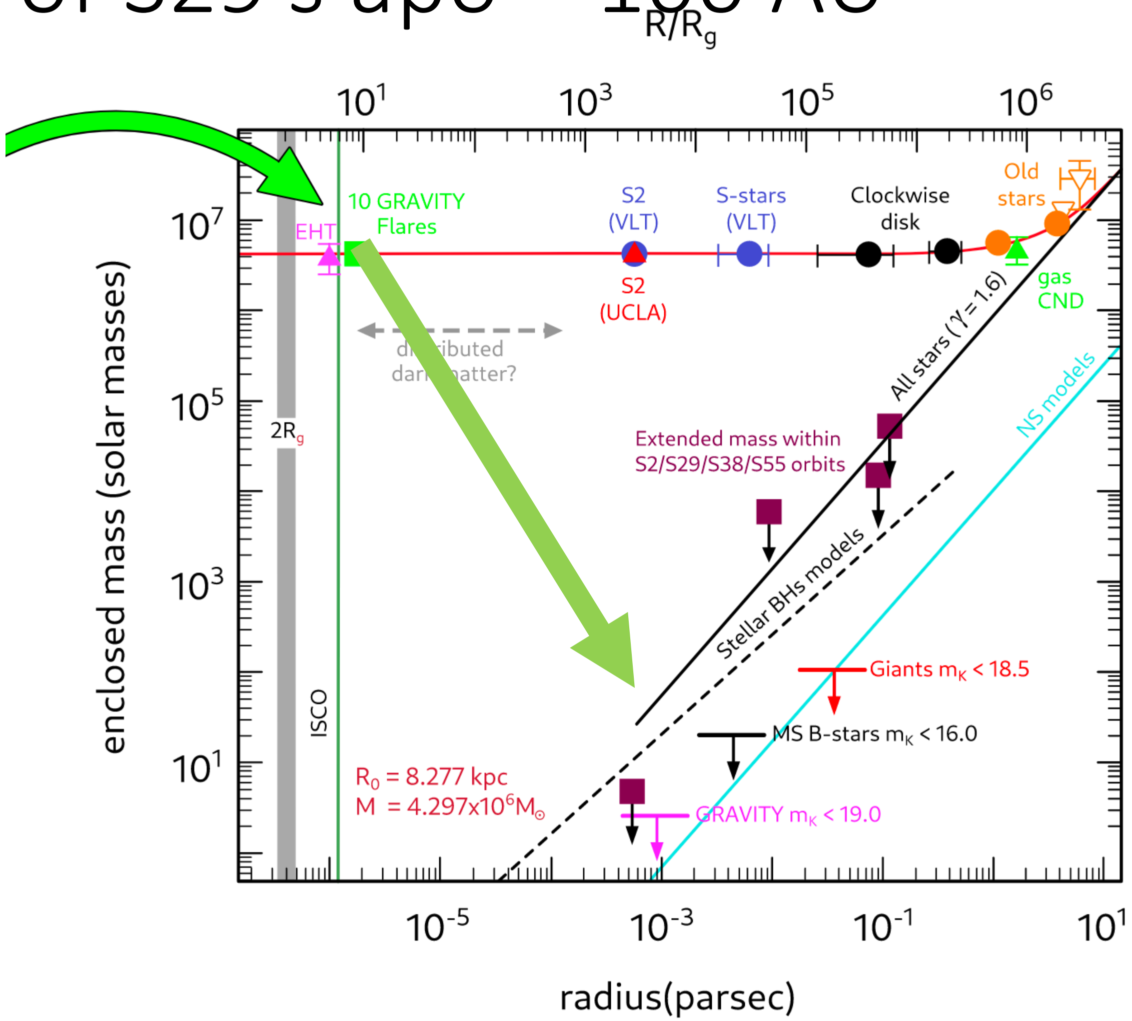


Period known, radius known ➡ mass known

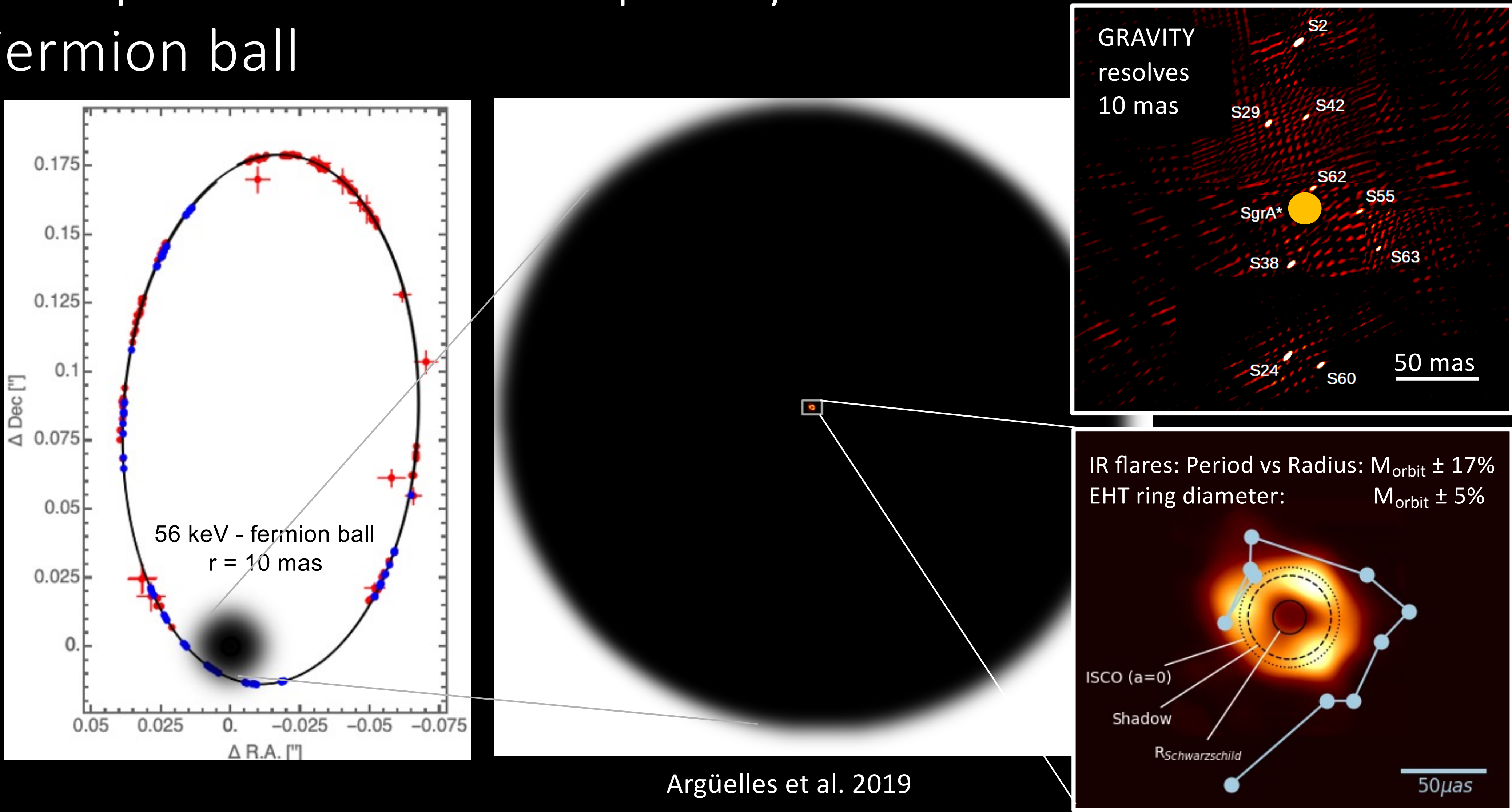


99.9% of the mass of Sgr A* is inside of S29's apo = 100 AU

At most
~ 0.1% ~ 4000 $M_\odot$
can be in an extended configuration

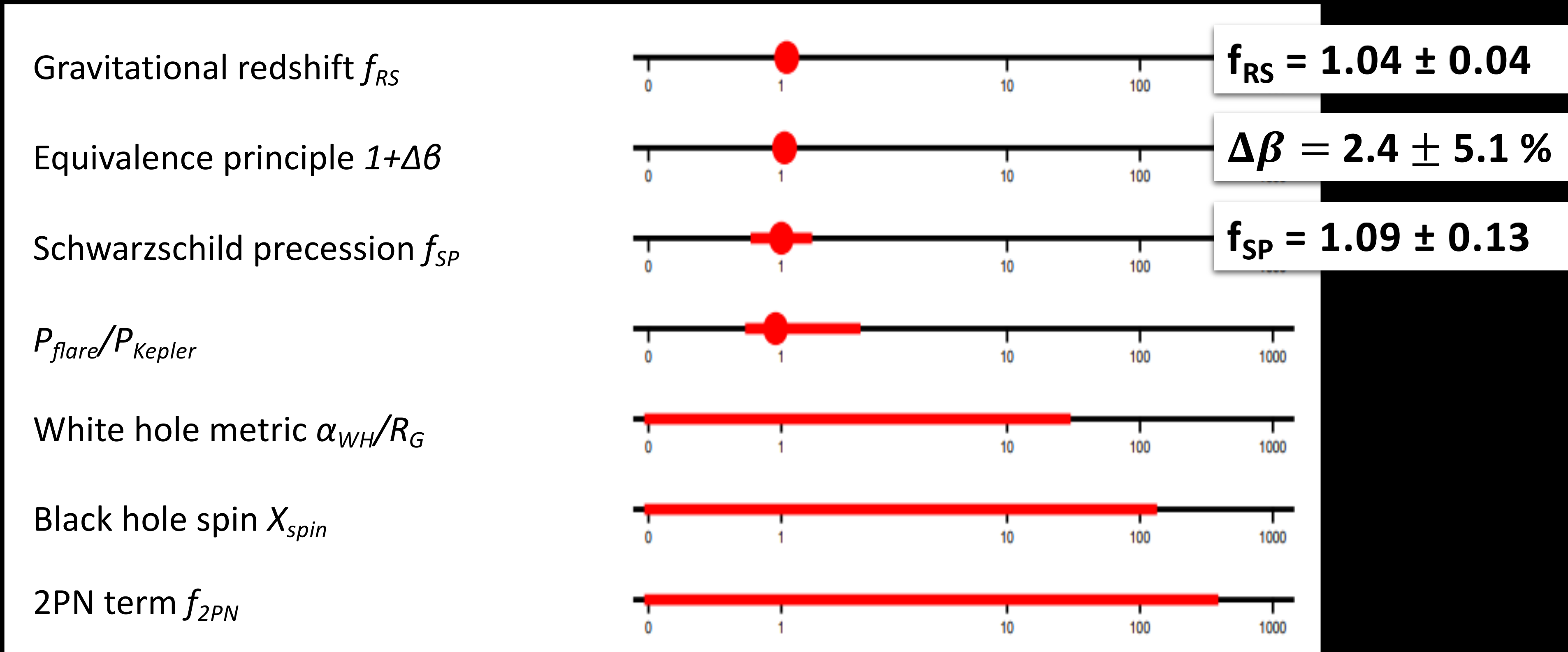


Example of a model completely ruled out: Fermion ball



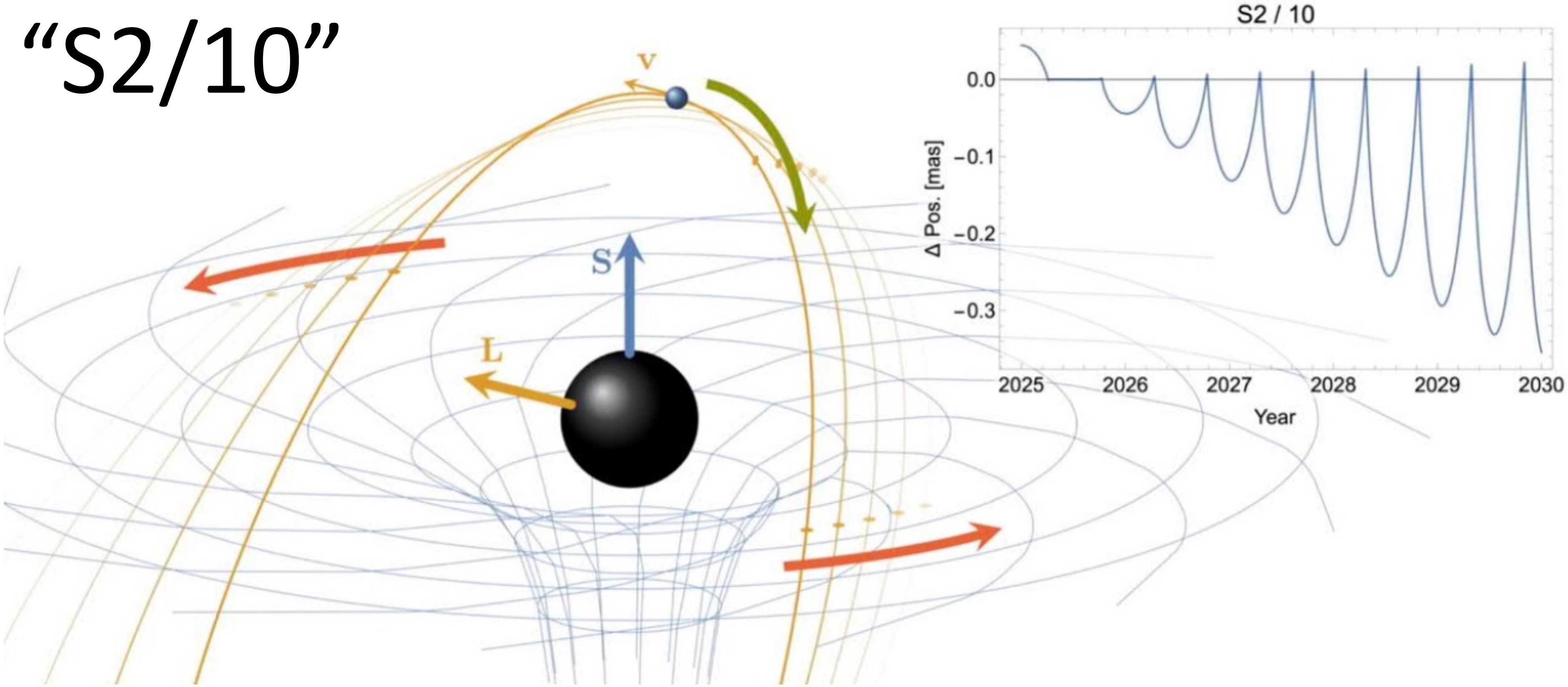
Argüelles et al. 2019

GRAVITY- starting to set limits

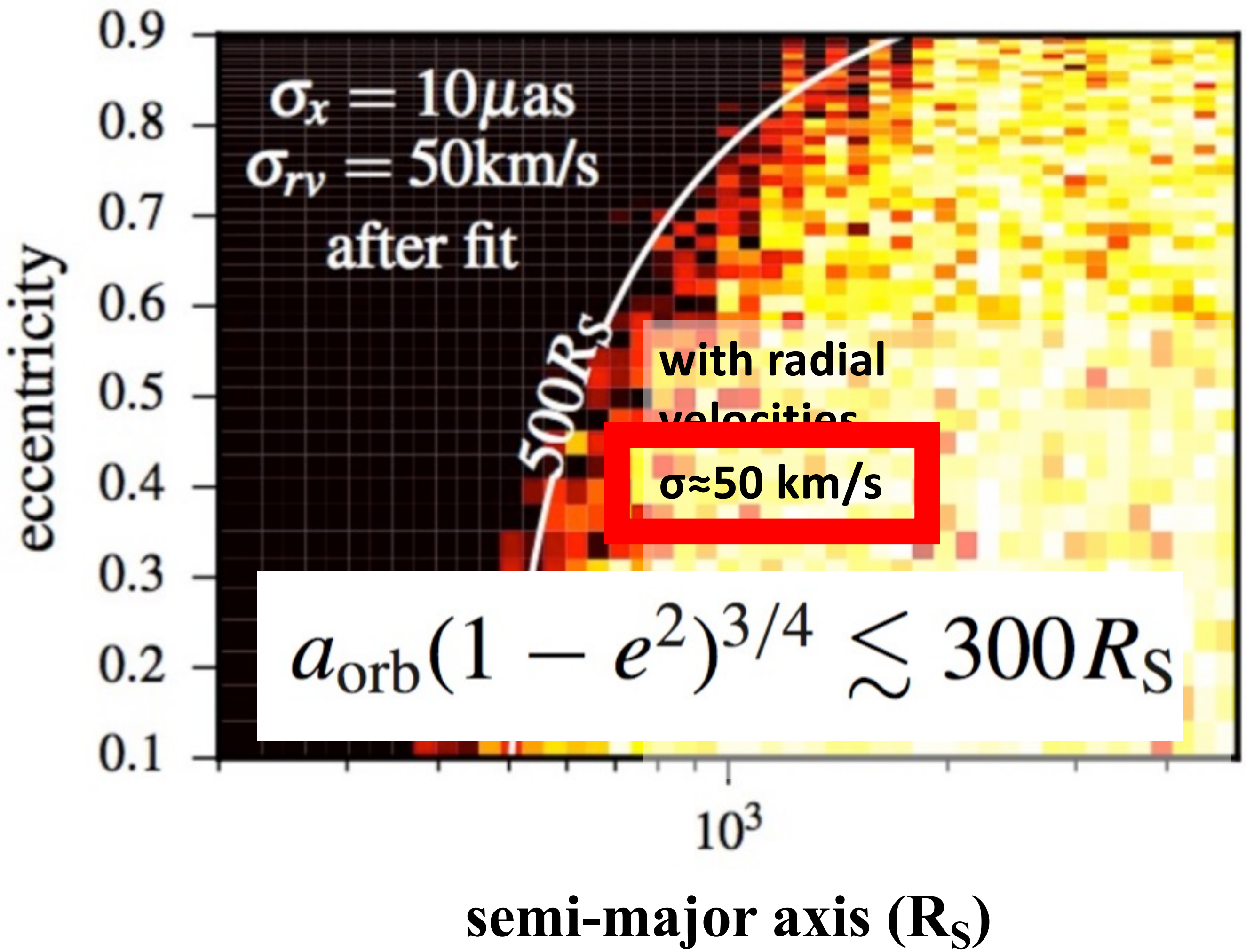


How far can we get in the Galactic Center?

"S2/10"



What star is needed to detect the spin?



Spin effects: r^{-3}

➔ stars further in

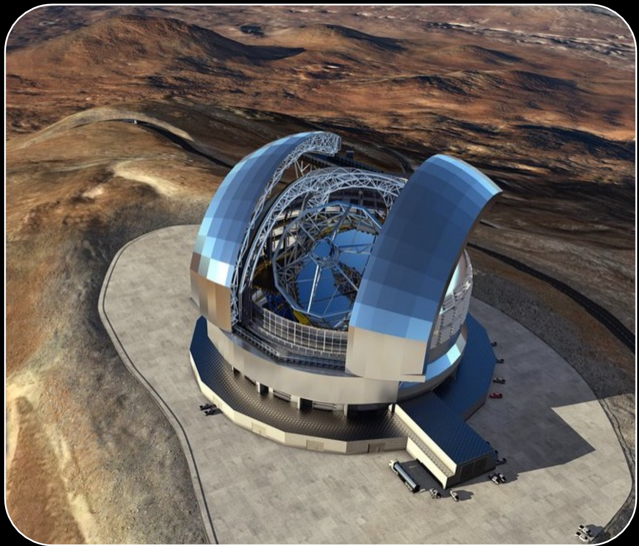
➔ astrometry harder, spectroscopy easier

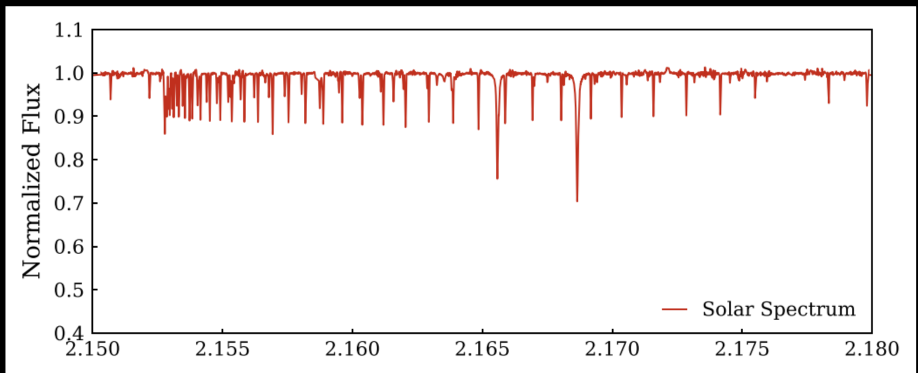
- very conservative radial velocity error
- we don't need to limit us to one star

Waisberg et al. 2018

Medium-term goal: The spin of Sgr A*

ELT Spectroscopy

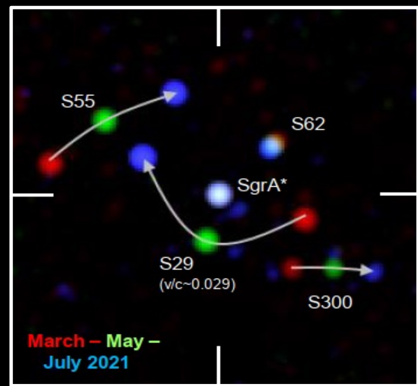




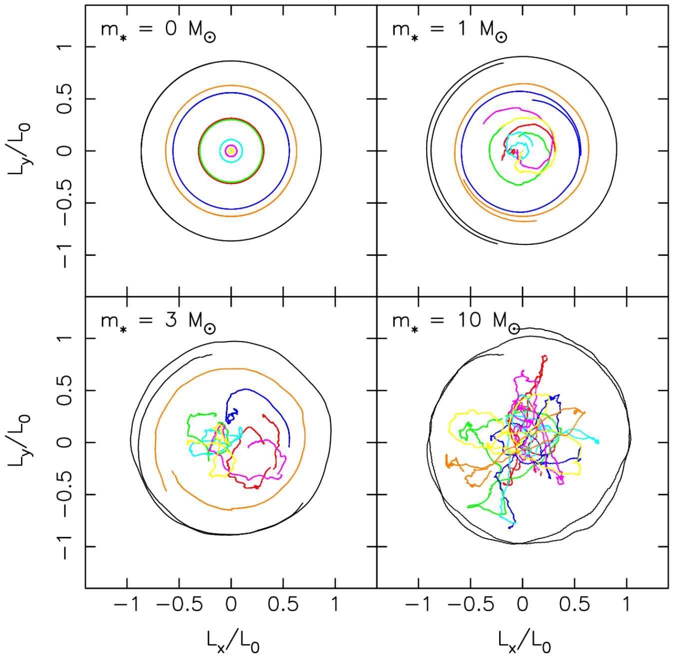
Deep Interferometric Imaging

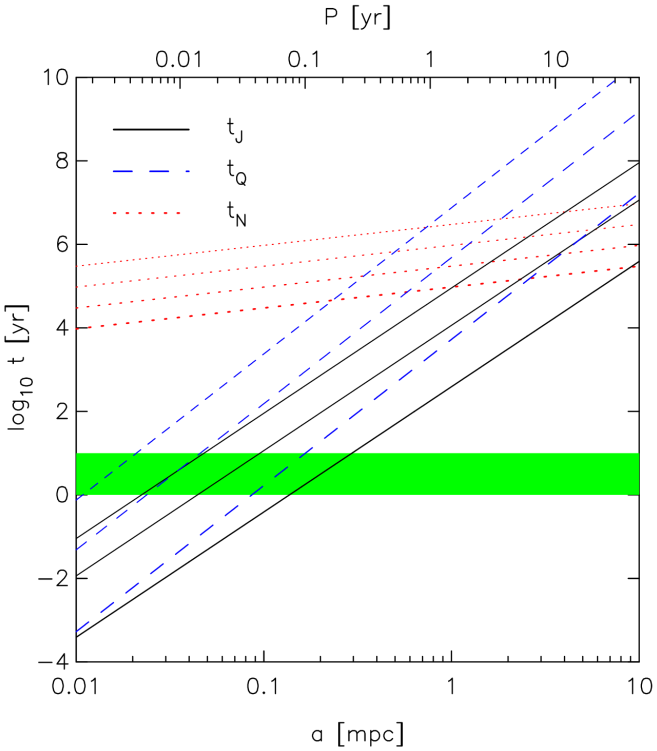
Δv < 1 km/s

mK > 21



Theoretical arguments were too pessimistic

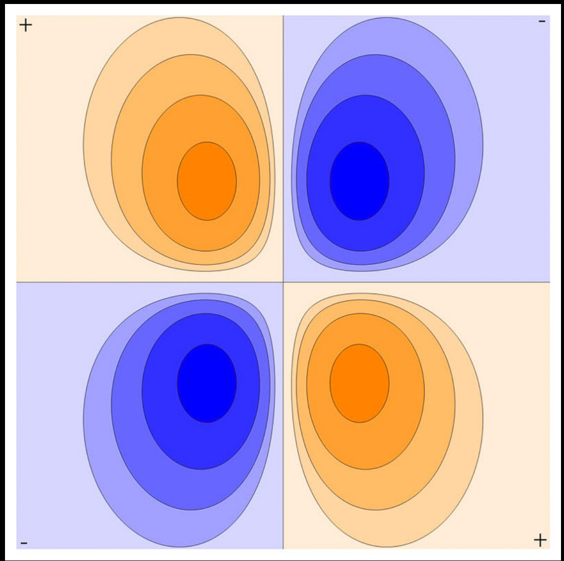




Merritt+ 2010

- arguments based on time-averaged changes
- but observers see “abrupt” changes
- “if a change happens at peri-center, it was the MBH”

Longer term goal: No-hair theorm



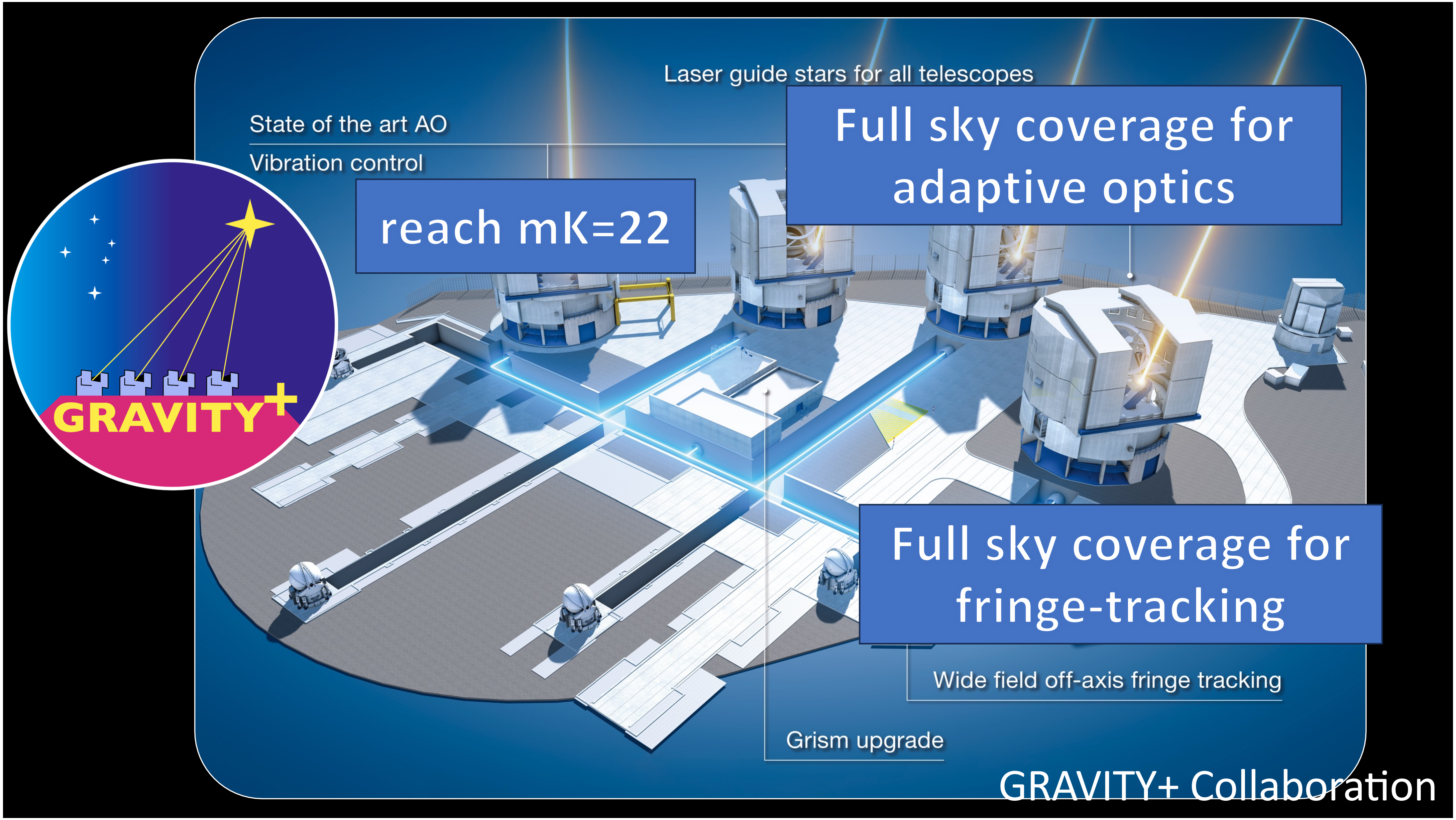
Will 208

$$\boldsymbol{a} = -\frac{M\boldsymbol{x}}{r^3} + \frac{M\boldsymbol{x}}{r^3}\left(4\frac{M}{r} - v^2\right) + 4\frac{M\dot{r}}{r^2}\boldsymbol{v}$$
$$- \frac{J}{r^3}[2\boldsymbol{v}\times\hat{J} - 3\dot{r}\boldsymbol{n}\times\hat{J} \ldots$$
$$+ \frac{3}{2}\frac{Q_2}{r^4}[5\boldsymbol{n}(\boldsymbol{n}\cdot\hat{J})^2 - 2(\boldsymbol{n}\cdot\hat{J})\hat{J} - \boldsymbol{n}],$$

In general relativity:
$Q_2 = -J^2/M$

Quandrupole moment: observational quantity

Rad err [km/s]	Schwarz-schild	Lense-Thirring	Lensing & Delay	Quad-rupole
10	0.6%	3%	-	-
1	0.4%	0.7%	35%	-
0.1	0.02%	0.04%	4%	11%



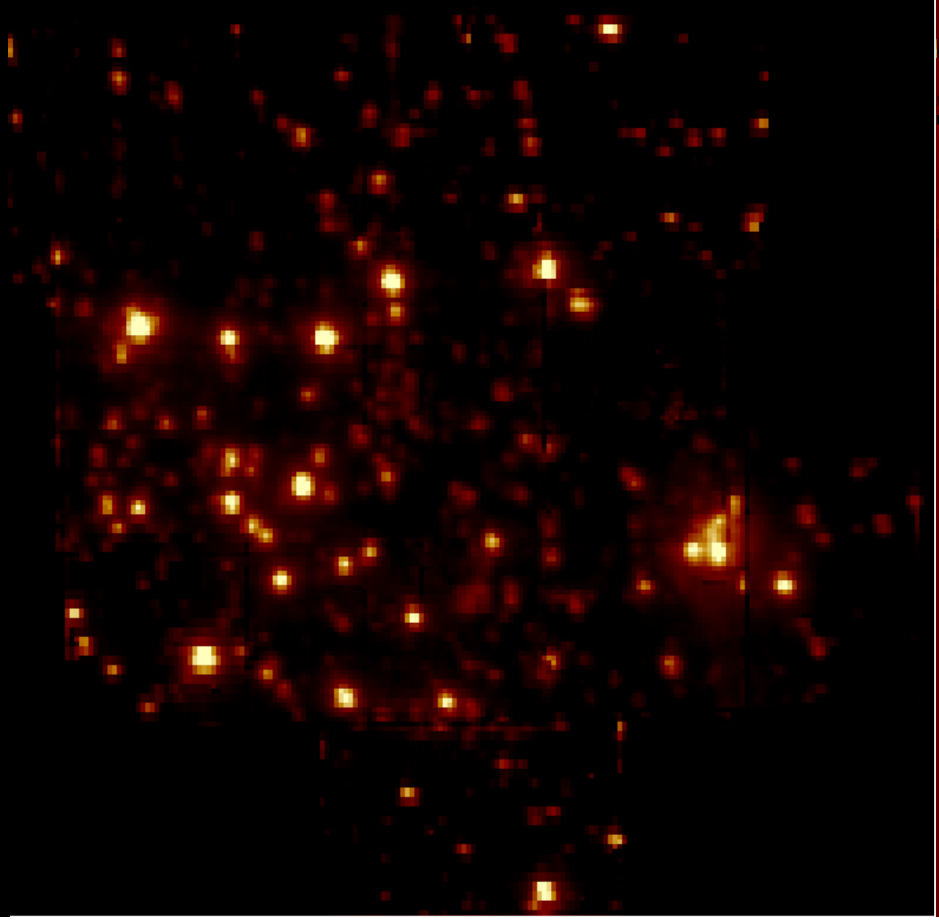
Laser guide stars for all telescopes
State of the art AO
Vibration control
reach mK=22
Full sky coverage for adaptive optics
GRAVITY+
Full sky coverage for fringe-tracking
Wide field off-axis fringe tracking
Grism upgrade
GRAVITY+ Collaboration

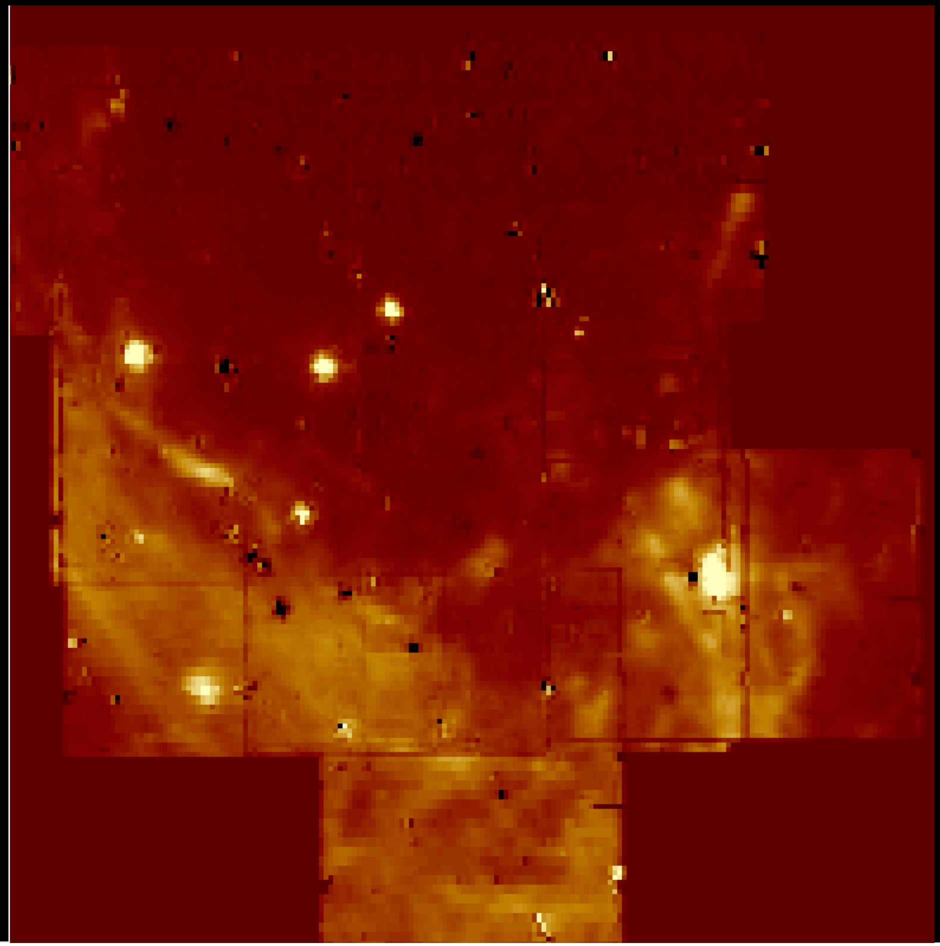
Outline

- Part I The mass of Sgr A*
  - Astronomical black holes
  - Measuring mass
  - Infrared observations
  - Adaptive Optics
  - Stellar Orbits
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A*
  - Interferometry
  - Testing General Relativity in the Galactic Center
  - SgrA* flares
  - A funny gas cloud

The Galactic Center is gas rich

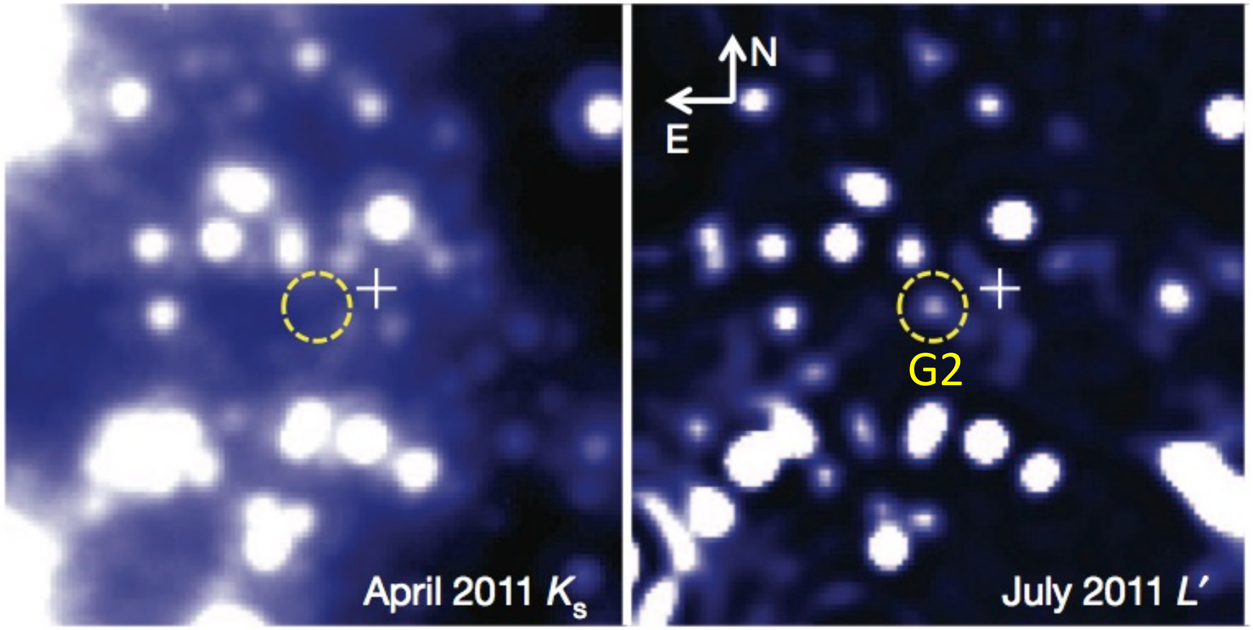
ERIS, 100mas, 2.166µm, R=11200

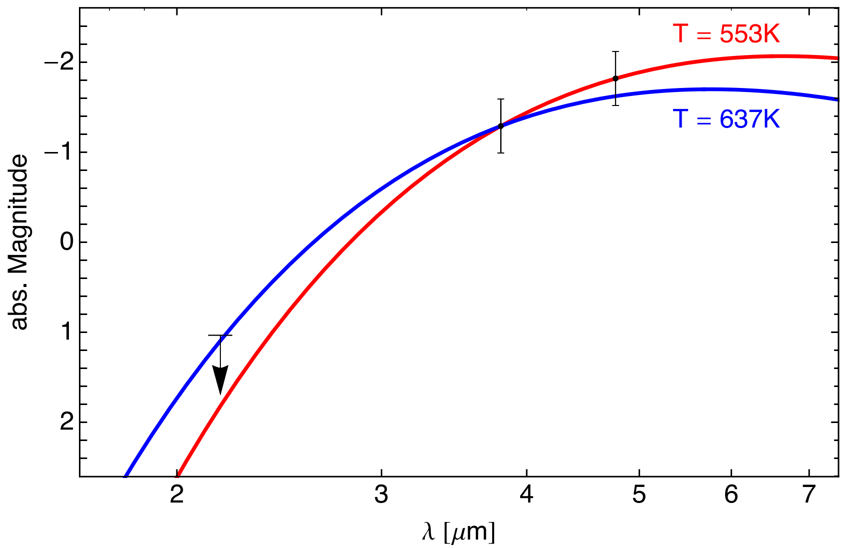




A cool object: G2 - T = 600 K

Gillessen et al. 2012



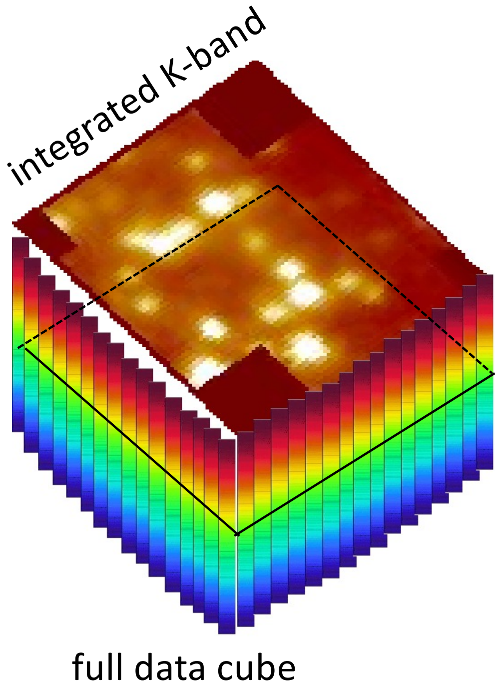


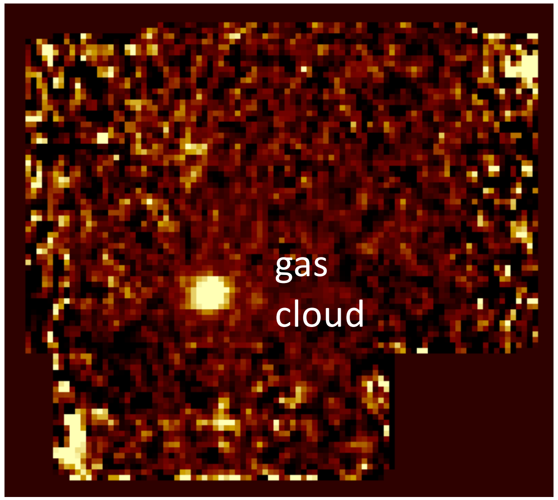
2.15 µm

3.8 µm

G2 is a dusty, ionized gas cloud

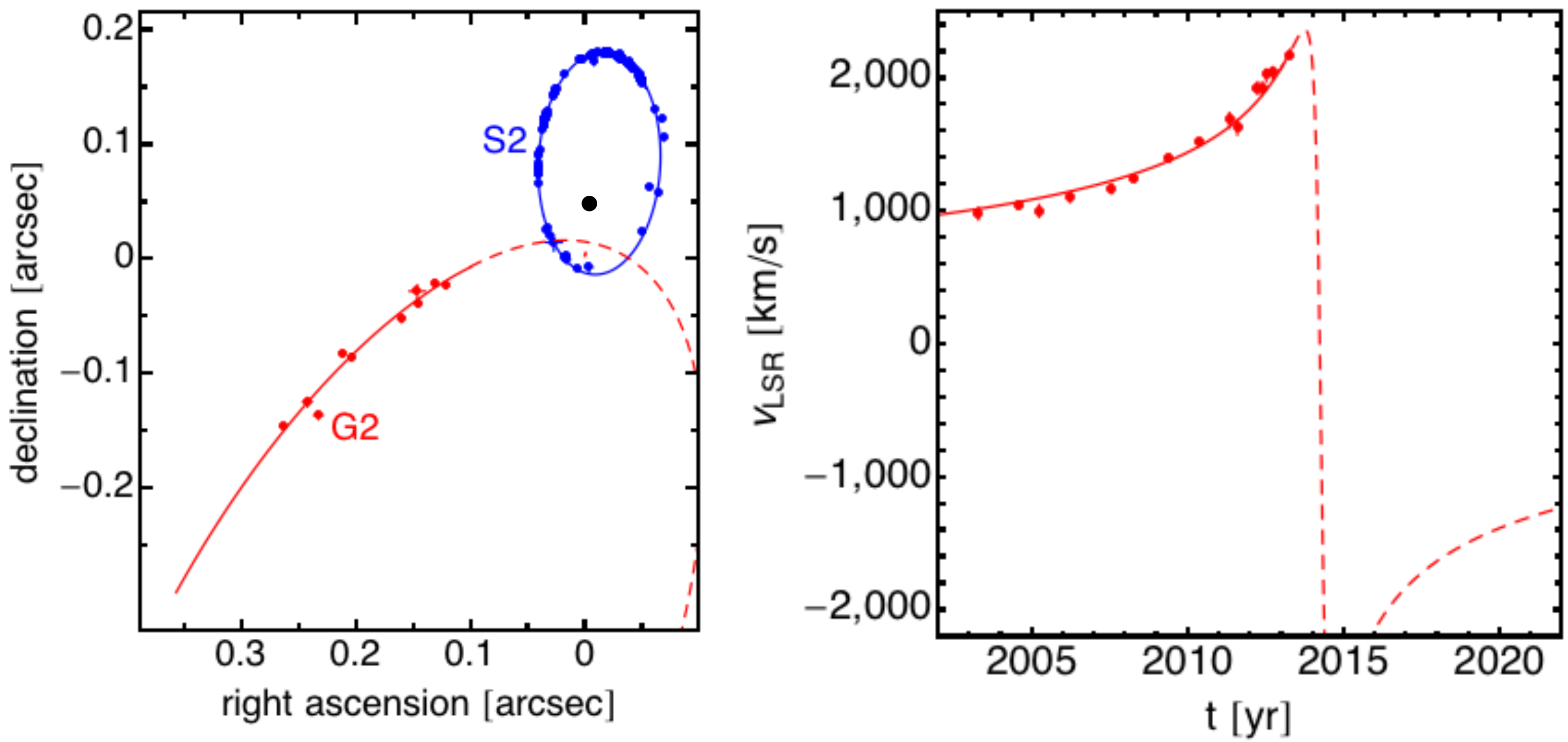
Integral-field spectroscopy: SINFONI





channel map at
Br-γ + 1300 km/s
(2.175 μm)

G2 has an interesting orbit



- pericenter 2014 @ 2000 R_S
- highly eccentric

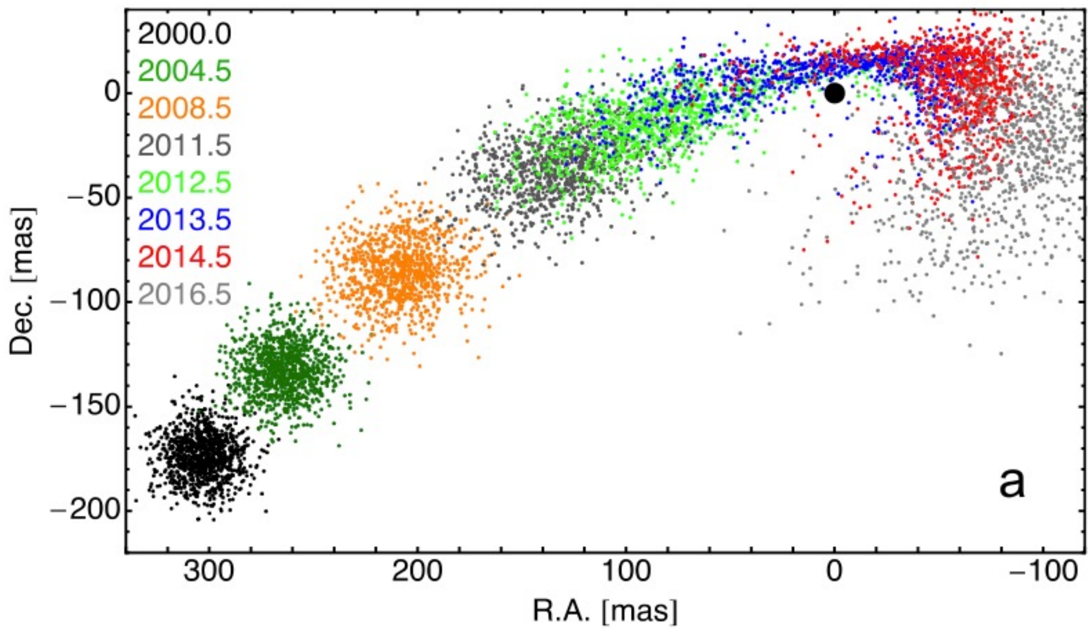
Phifer et al. 2013
Gillessen et al. 2013

For the gas dynamics the source model does not matter

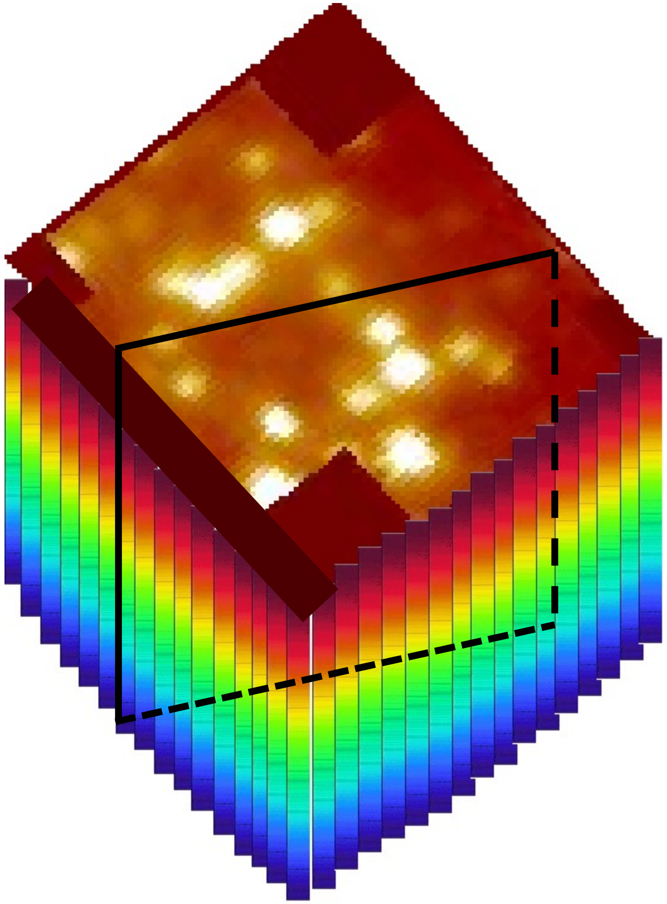
Gravitationally binding G2's gas in the tidal field of Sgr A*: M >> 100M$_\odot$

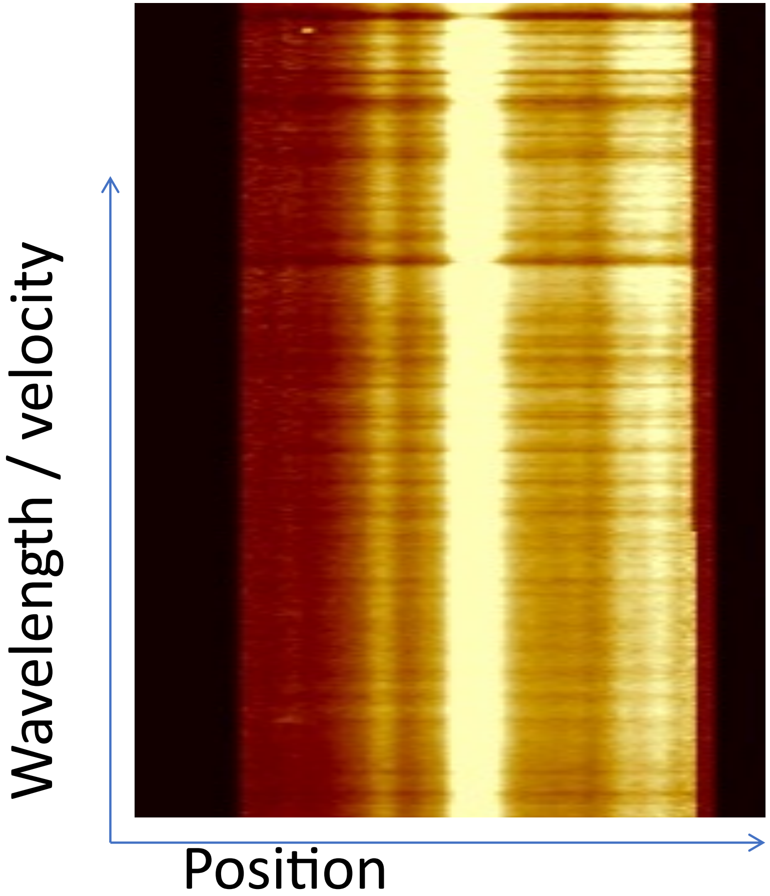
The gas that we see cannot be bound to any central object

We should see G2 tidally evolve

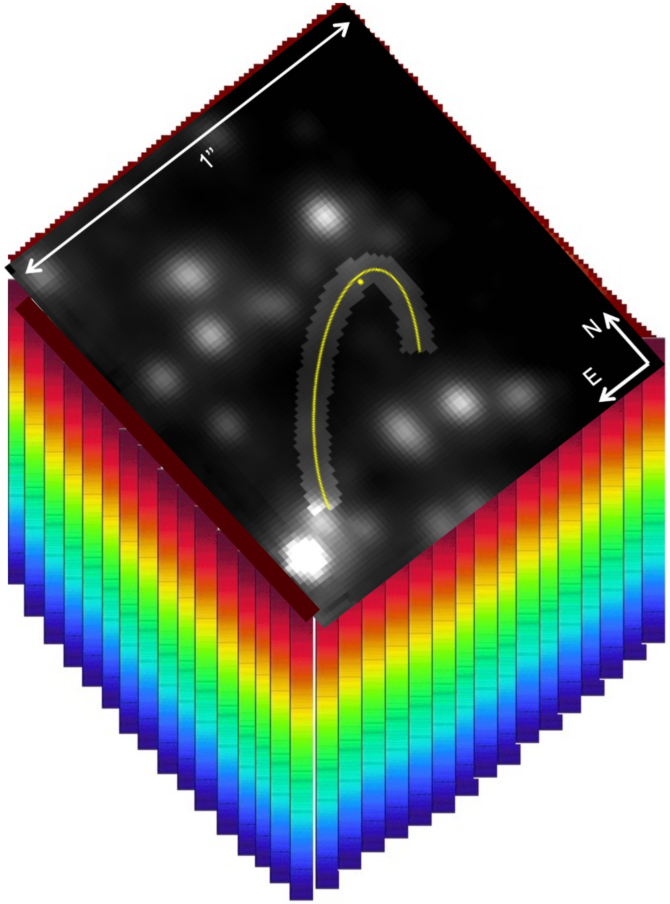


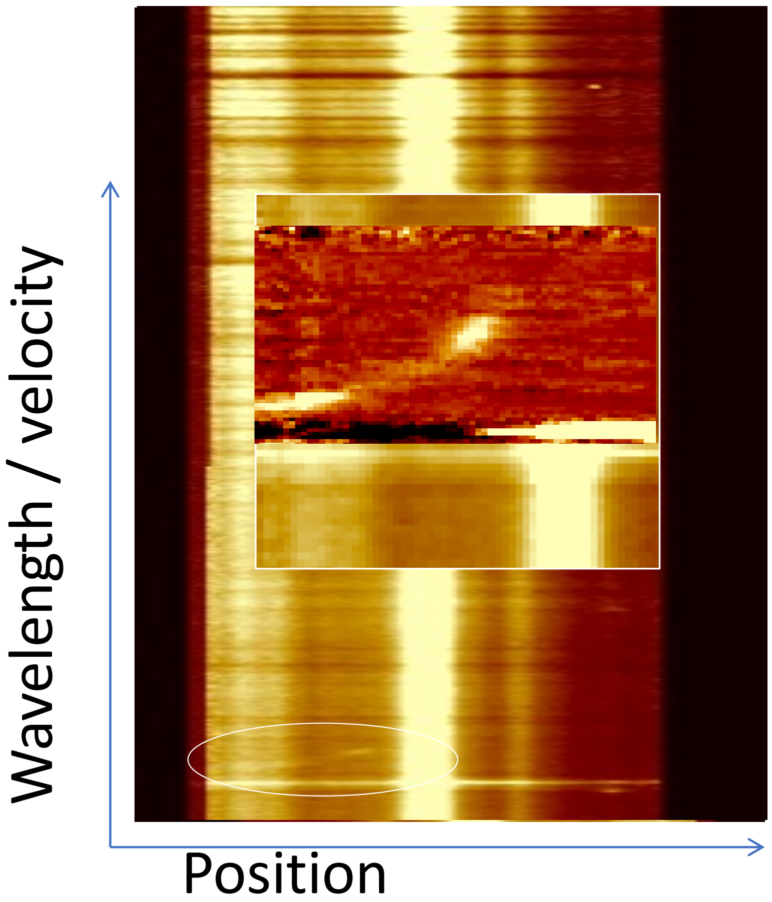
Position – Velocity - Diagram





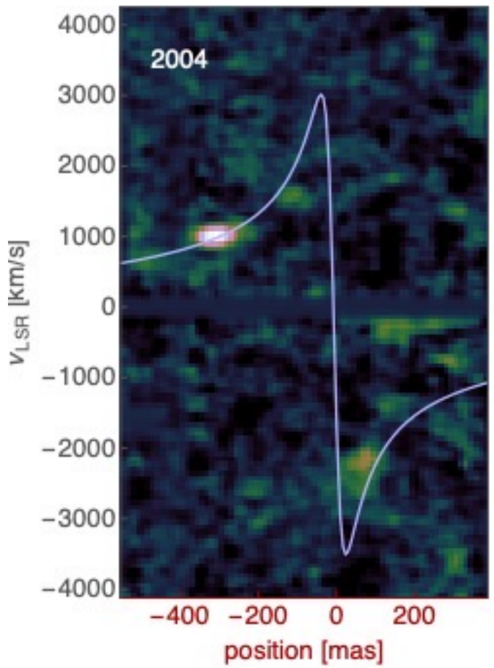
Position – Velocity - Diagram



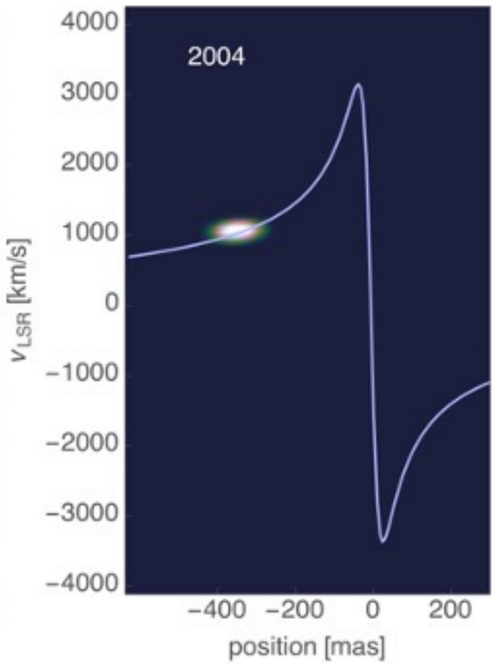


Too beautiful to watch: The tidal evolution of G2

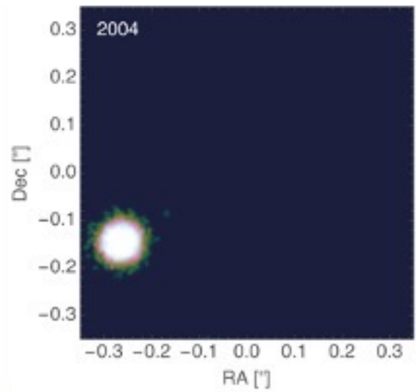
2004



the actual data
PV



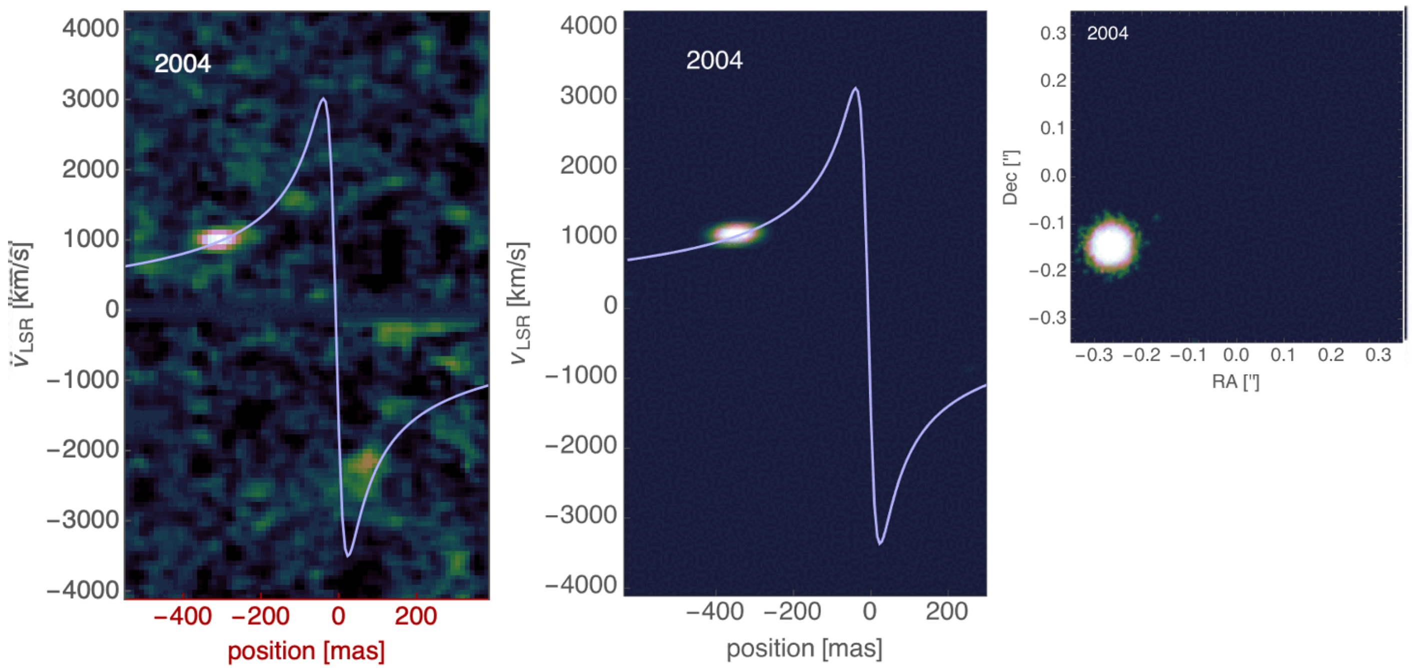
ensemble of
test particles - PV



ensemble of
test particles – RA/Dec

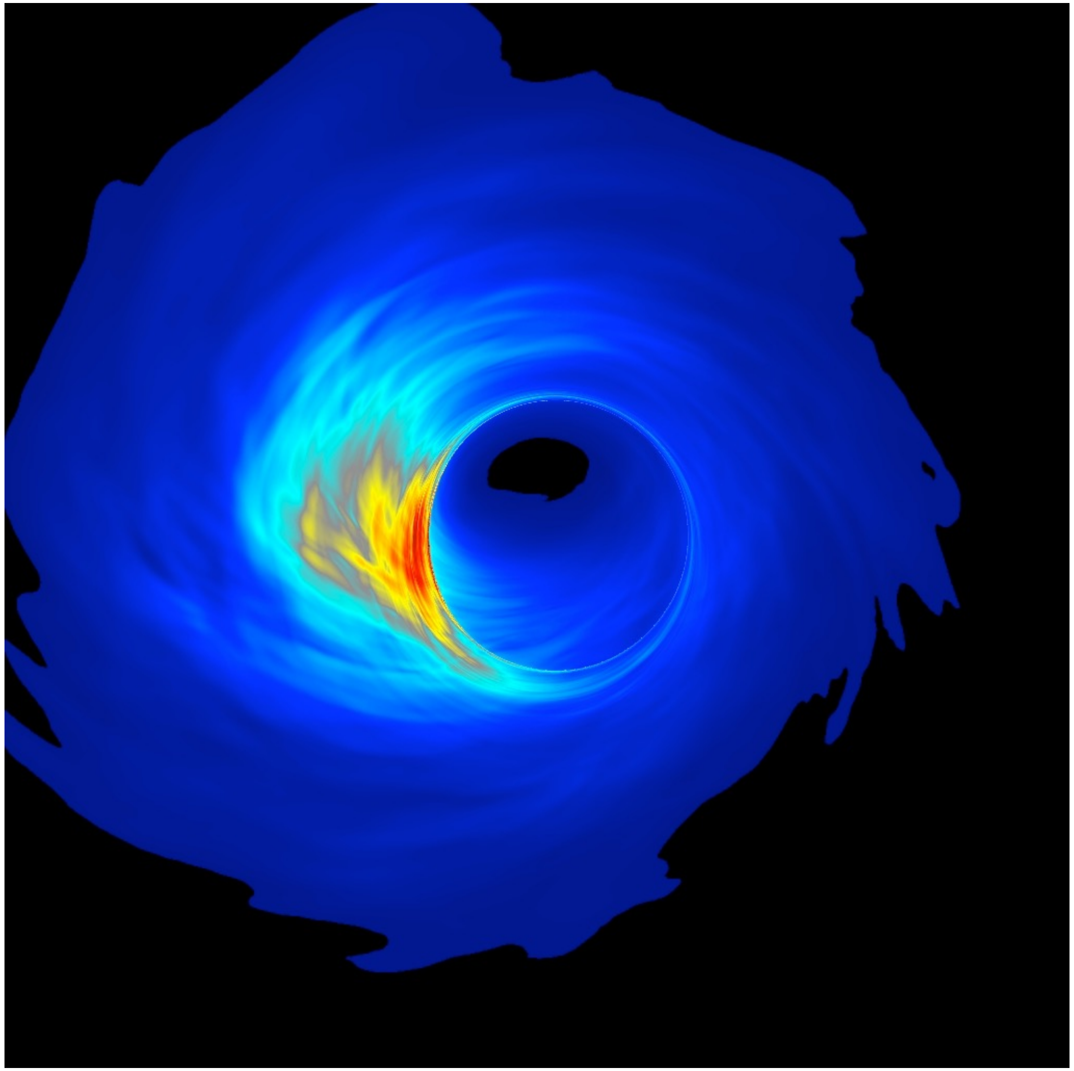
Too beautiful to watch: The tidal evolution of G2

2004

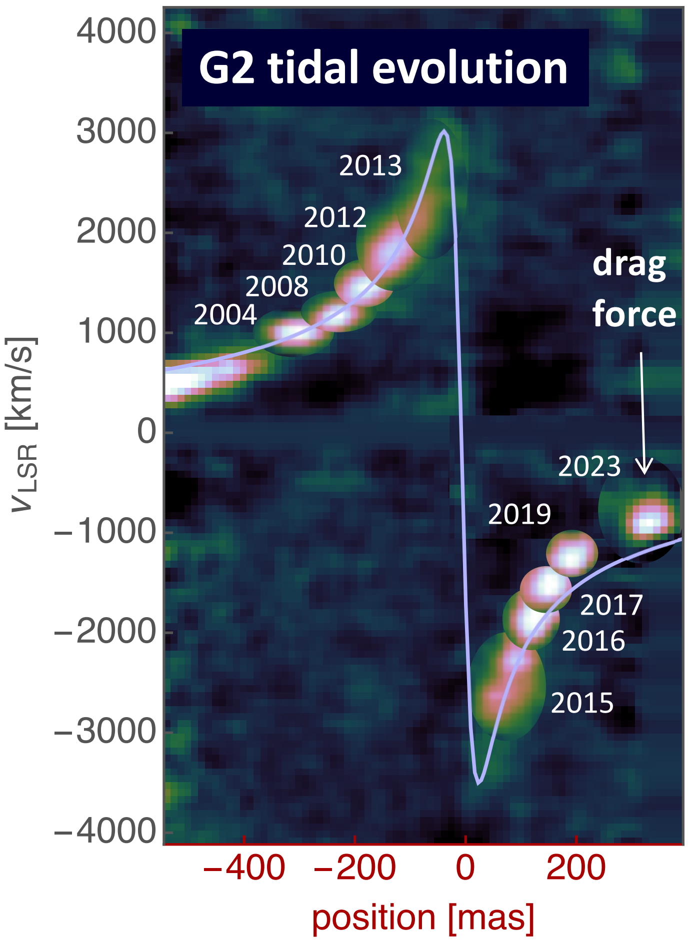



MailOnline

Missing: Interaction with Accretion Flow

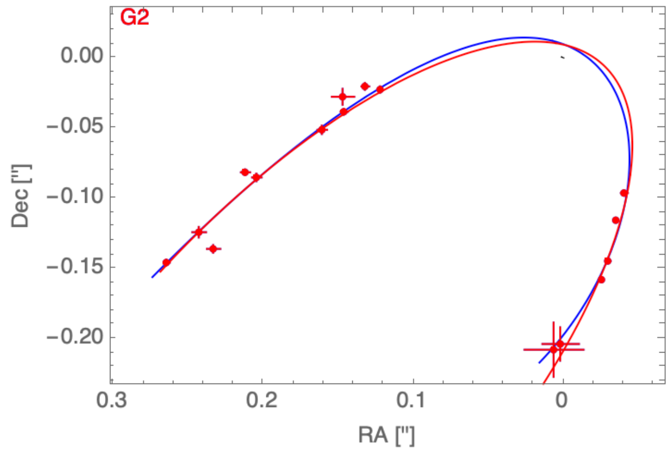


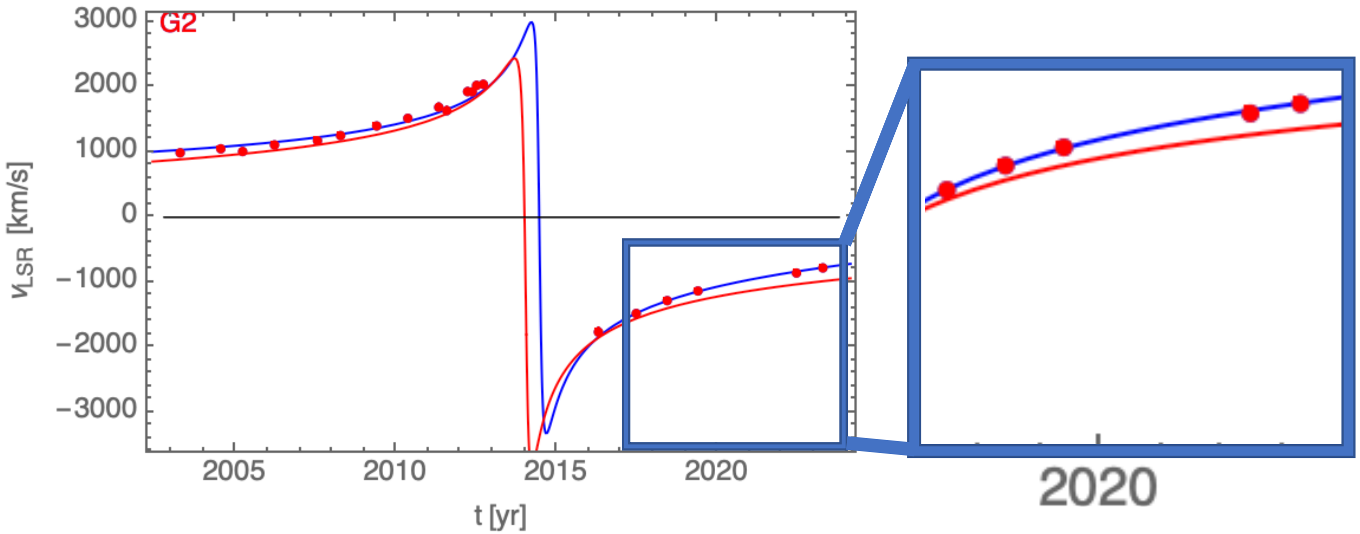
The G2 data since 2017 show a deceleration



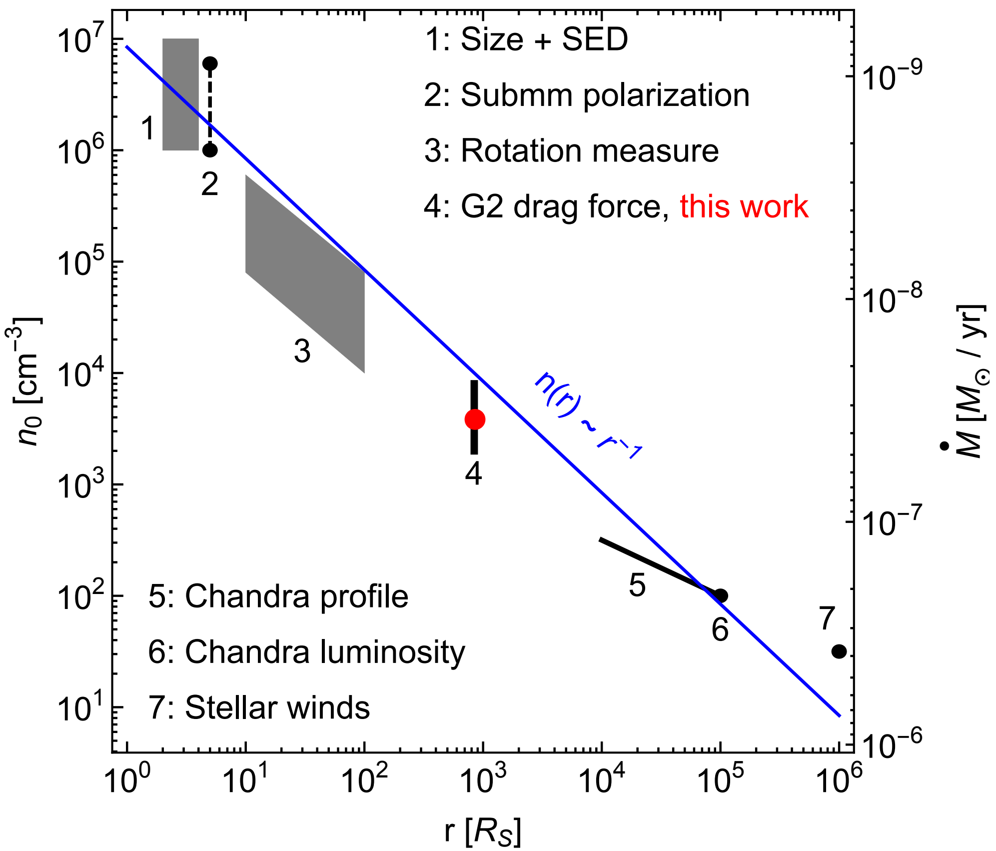
$$F_{\text{drag}} \propto s^2 \rho(r) v^2$$

$$\rho(r) \propto r^{-1}$$





A very valuable constraint of the accretion flow density



1: One zone models using size & SED
(Doeleman et al. 2008,
Bower et al. 2015,
von Fellenberg et al. 2018)
2: Agol 2000,
Quataert & Gruzinov 2000a
3: Bower et al. 2003,
Marrone et al. 2006, 2007
5: Wang et al. (2013)
6: Baganoff et al. (2003)
7: Quataert et al. (2004)

Outline

- Part I The mass of Sgr A*
  - Astronomical black holes …….. stellar and massive
  - Measuring mass …….. orbits, Jeans-modeling
  - Infrared observations …….. see through the dust
  - Adaptive Optics …….. see sharp – diffraction limit
  - Stellar Orbits …….. measure the 4.3 million M_{sun}
- Part II Errors, Fitting and all that
- Part III Testing the black hole paradigm
  - The black hole nature of Sgr A* …….. mass, size, position, faintness
  - Interferometry …….. breaks the diffraction limit
  - Testing G.R. in the Gal. Center …….. redshift, precession, … spin?
  - SgrA* flares …….. accretion flow geometry
  - A funny gas cloud …….. accretion flow density


Thanks to the
GRAVITY team