The Galactic Center

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MPE Garching

with slides from R. Genzel, S. Gillessen, O. Pfuhl, and the MPE GC group (mpe.mpg.de/ir/GC)

ESO/Y. Beletsky

The Galactic Center

1. Seminar: strong gravity around Sgr A* (30.05)

2. Low-luminosity accretion onto Sgr A* (31.05)

3. Resolving a black hole event horizon (today)
   i. How do we know Sgr A* is a black hole?
   ii. Getting to the event horizon with interferometry

About the lectures

- Selected topics: highly biased
- Please ask questions!

- ~1 interactive Q / lecture:
  ~10 mins to think/calculate, discuss, share

About the lectures

- pdf of slides online: mpe.mpg.de/~jdexter/GCslides

- Further reading: Genzel+2010, Morris+2012, Falcke & Markoff 2013

The Galactic Center

2. Low-luminosity accretion theory
(why is Sgr A* so faint?)

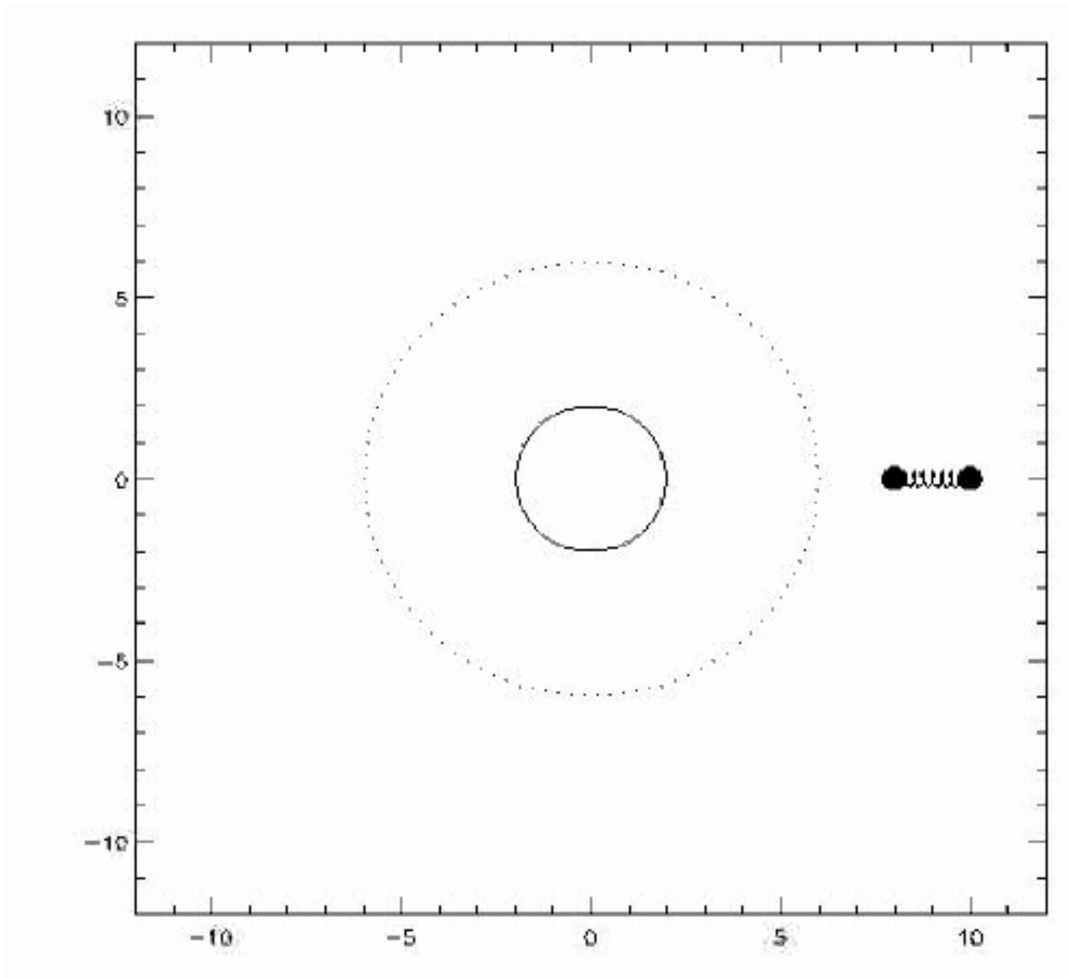
Review

Sgr A* is faint because

- Gas supply (stellar winds) is not large enough
- A tiny fraction of gas supplied reaches the black hole!
- The accretion flow is inefficient at radiating away its gravitational binding energy

How does gas fall into a black hole?

- Weakly magnetized gas: field is dragged along, restoring force when stretched (torque!)



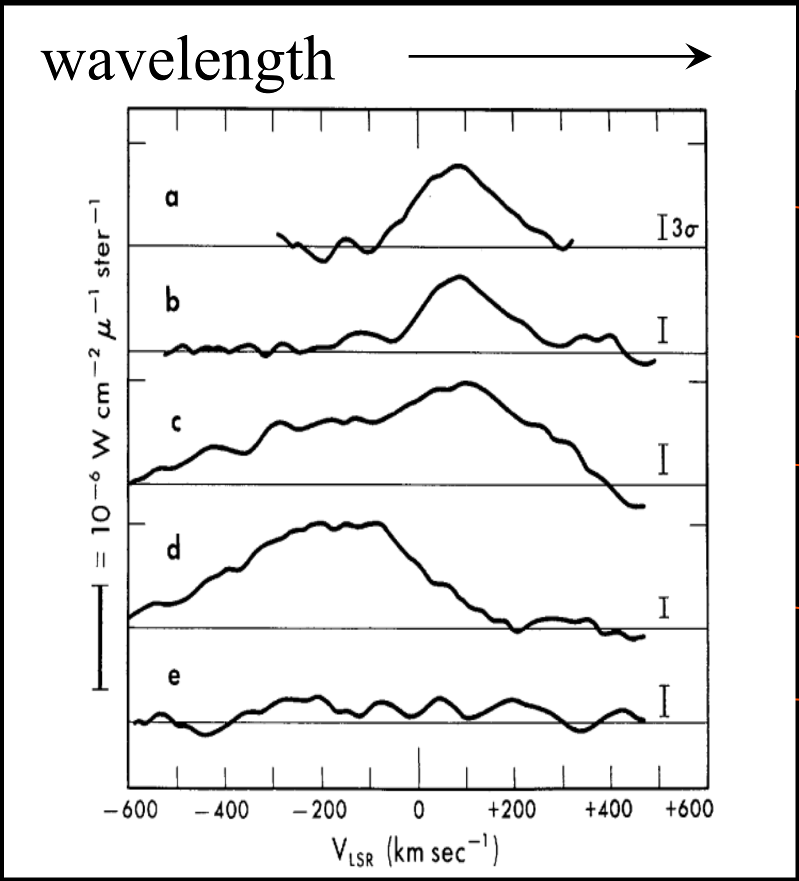
The Galactic Center

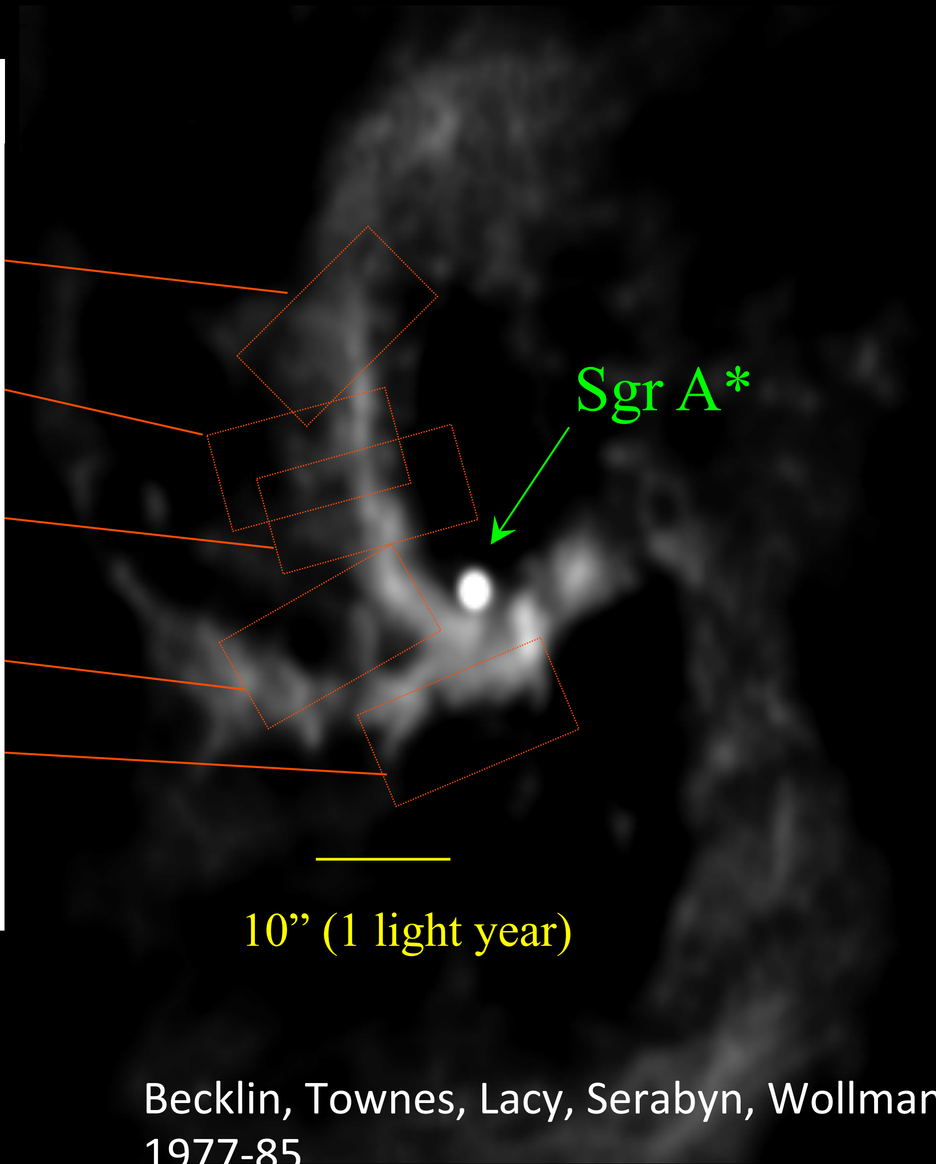
3. Resolving a black hole event horizon

Black hole sphere of influence

- Measure: (x,y), v_z, (v_x, v_y)
- At what scale do we see effects of a black hole on stars?
- When $M_*(>r) = M_{BH}$:
  - $G\ M_{BH} / R > \sigma_*^2$
  - $R < GM_{BH} / \sigma_*^2$; $\sigma_* \sim 100$ km / s
    $R \sim 2$ pc $(M_{BH} / 4 \times 10^6\ M_{sun})$
- Need to go to central parsec to look!

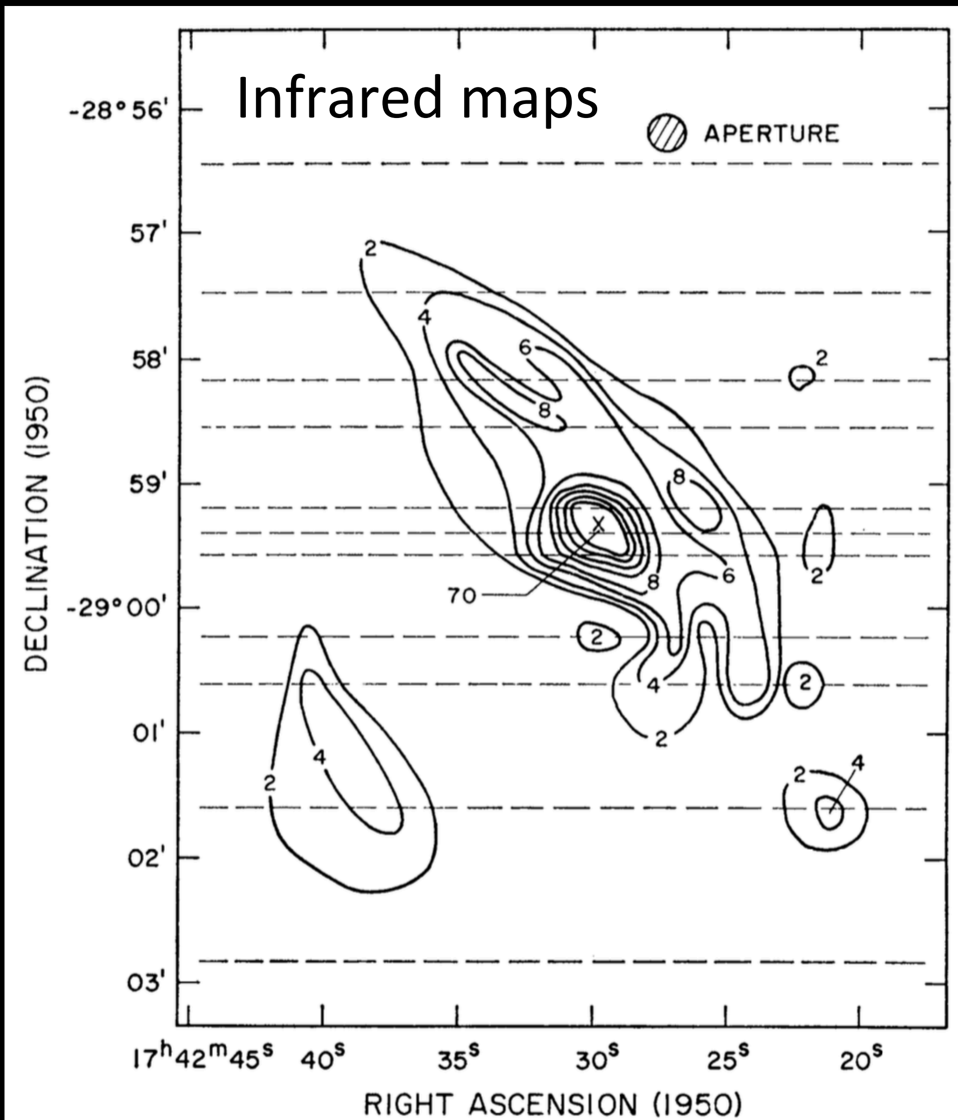
Large gas velocities around Sgr A*



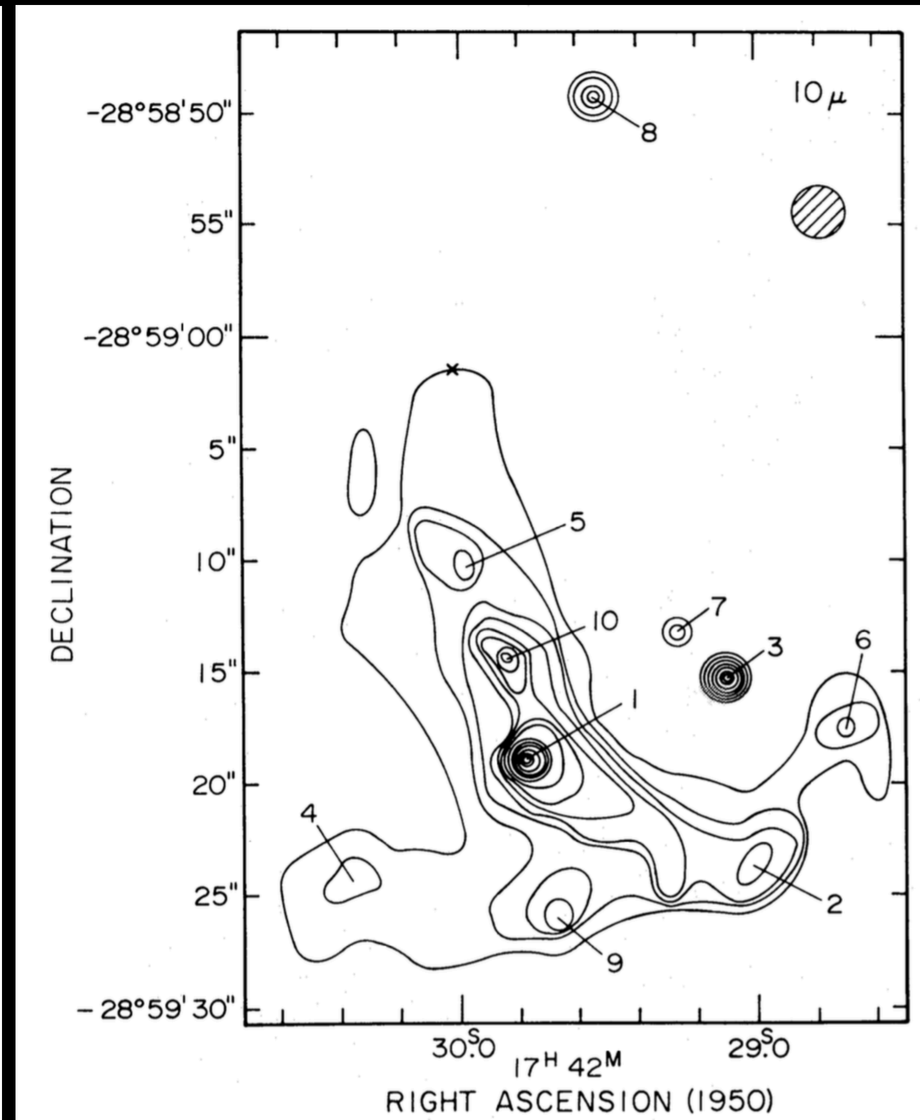


Becklin, Townes, Lacy, Serabyn, Wollman
1977-85

Stars in the Galactic center



Becklin & Neugebauer 1968

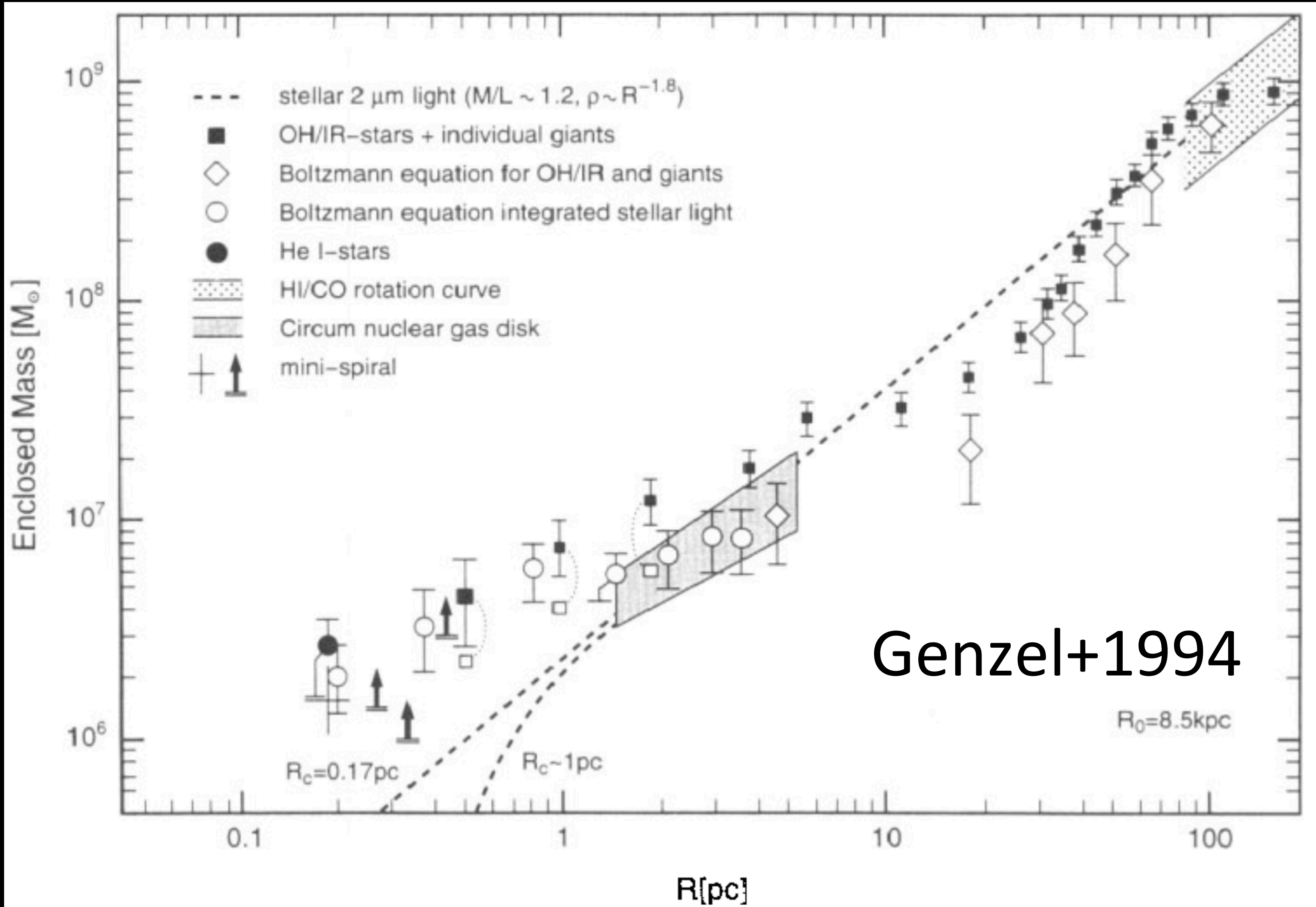


Becklin+1978

Galactic center
nuclear star cluster

ESO/R. Schödel

A concentrated dark mass measured from gas and stars

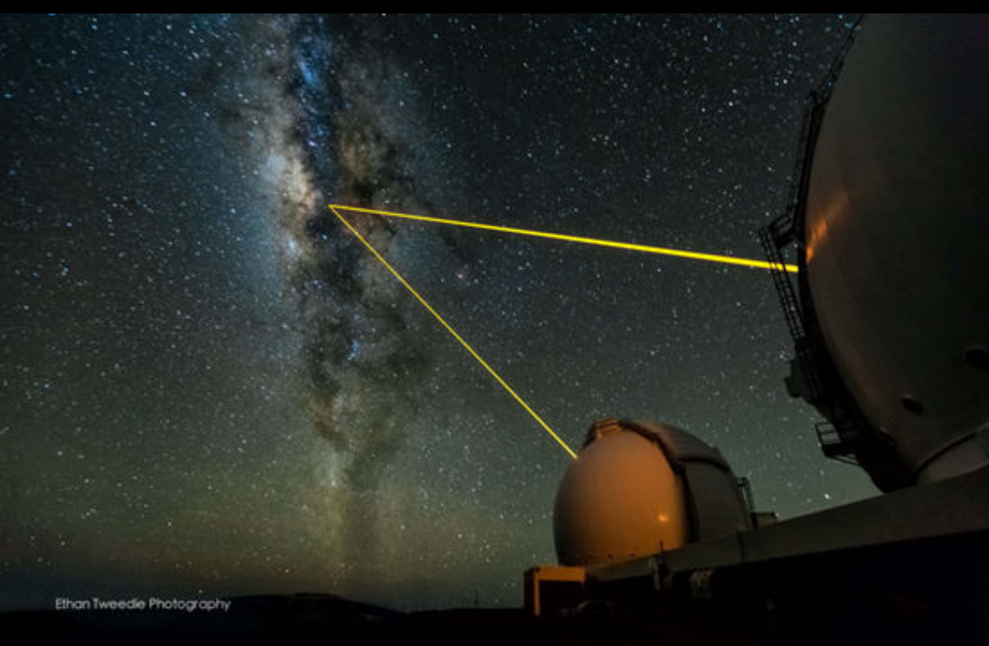


Genzel+1994

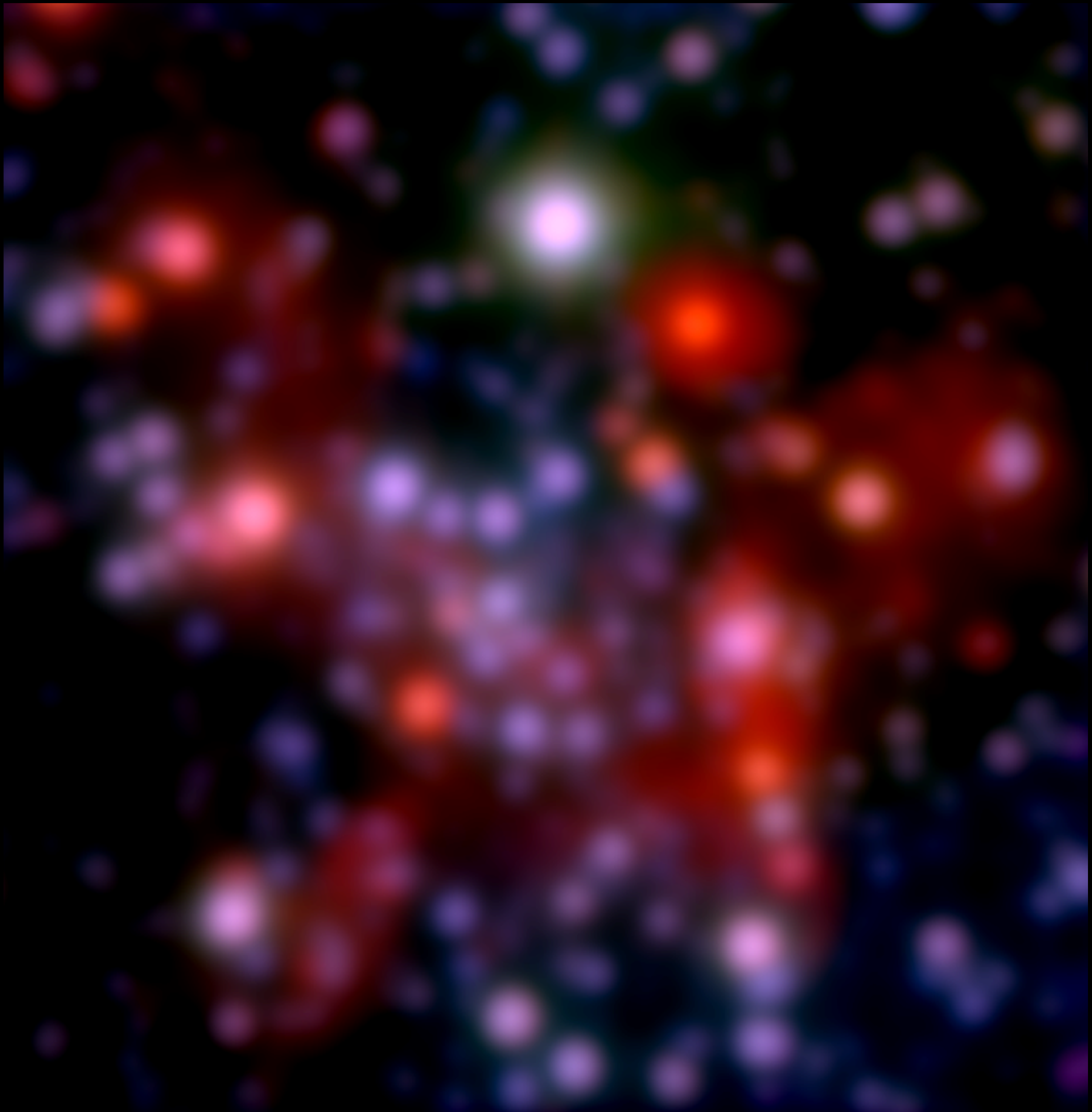
Big telescopes and adaptive optics

- Diffraction limit: $\vartheta_{min} \sim \lambda/B$
- 8-10m telescopes can resolve ~ 50 mas: in GC ~ 2 mpc!

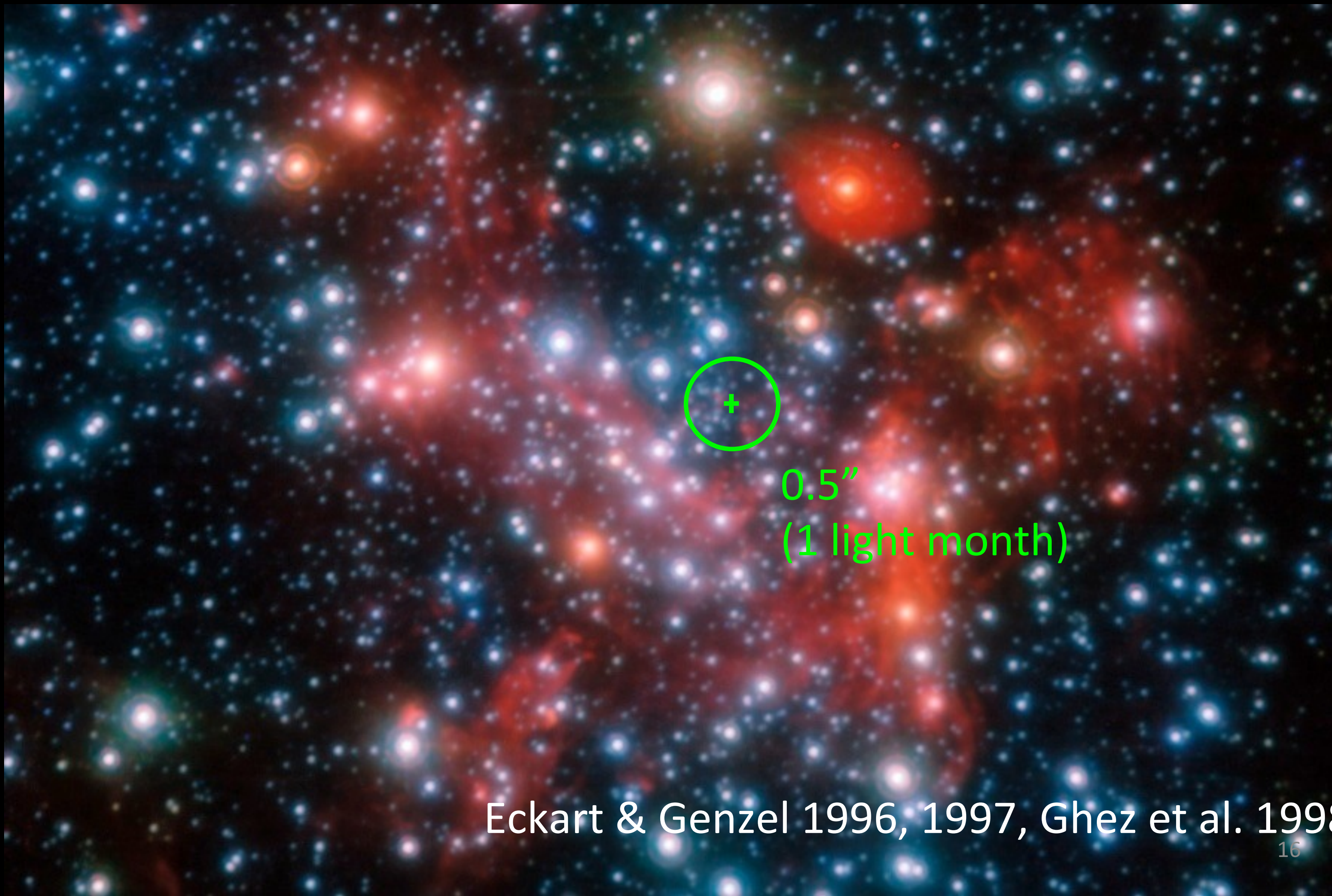
Keck



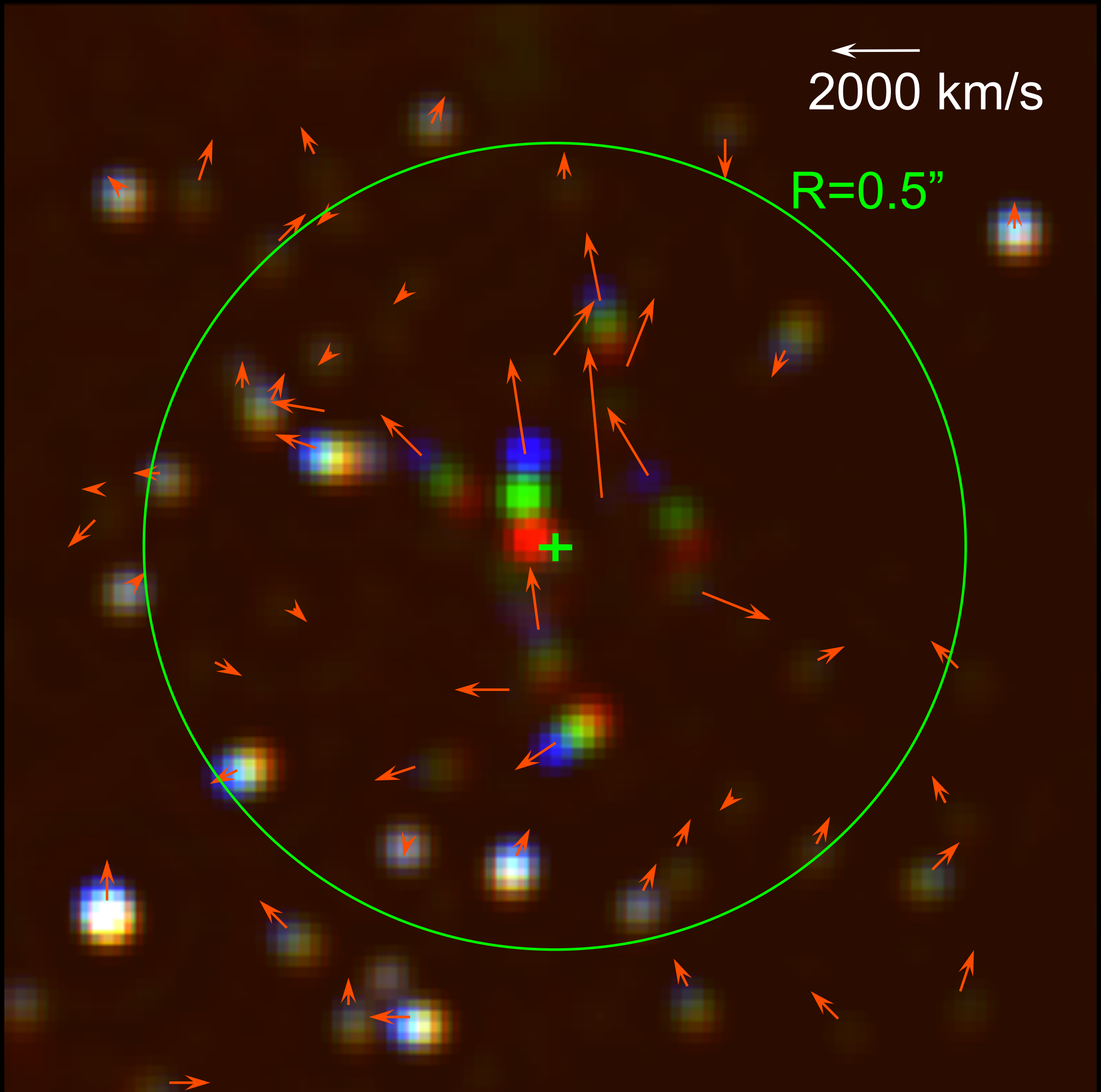
without adaptive optics



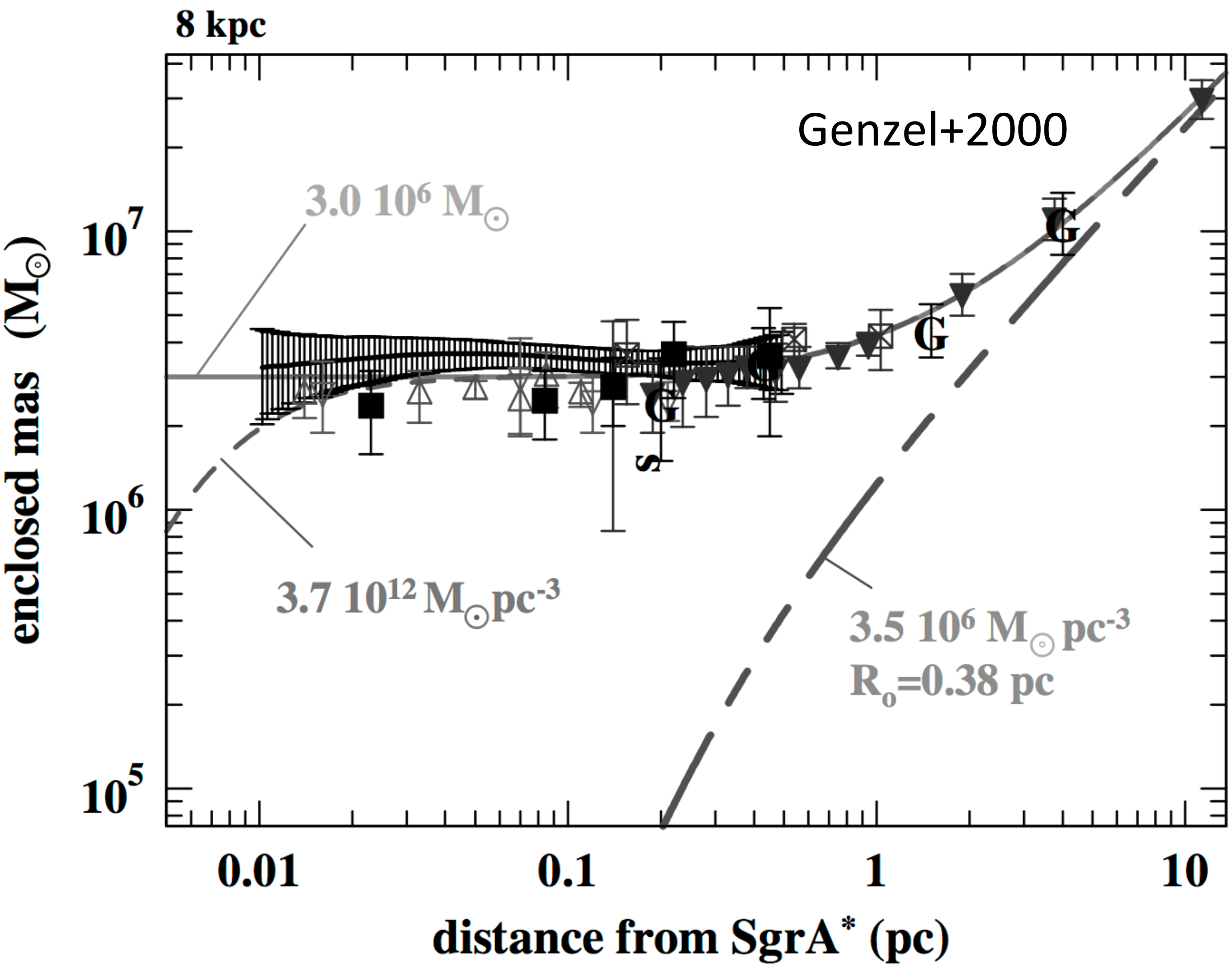
Motions of stars around Sgr A*



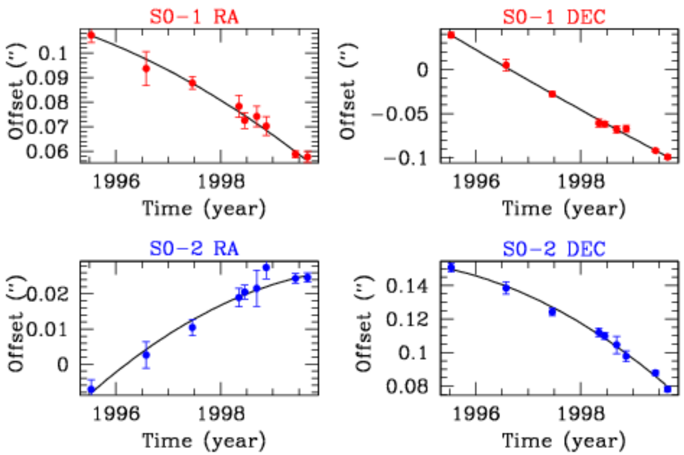
The S stars

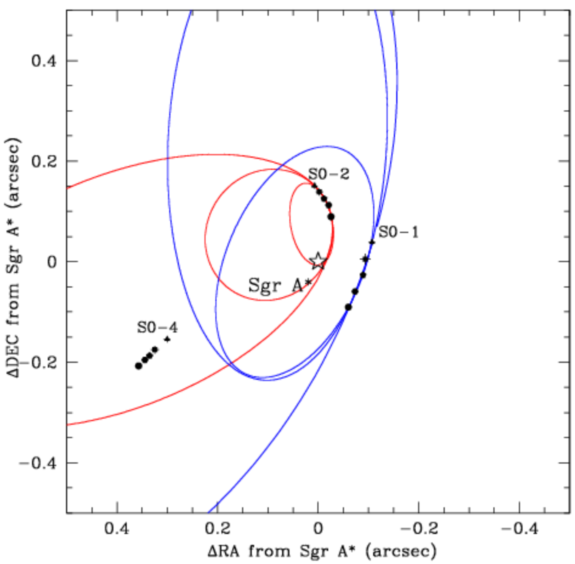


Enclosed mass from proper motions

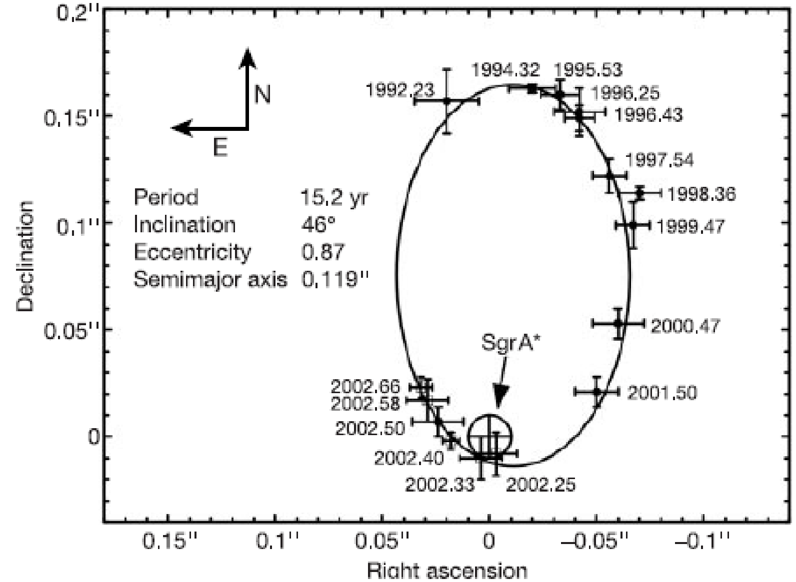


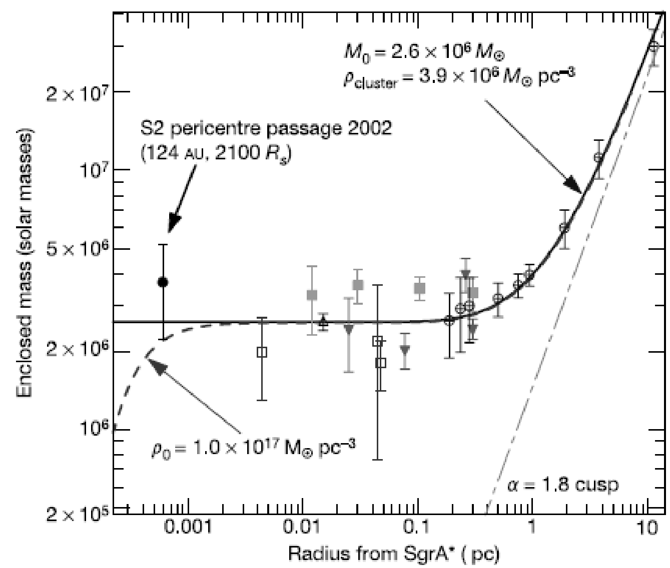
Accelerations and the first orbit





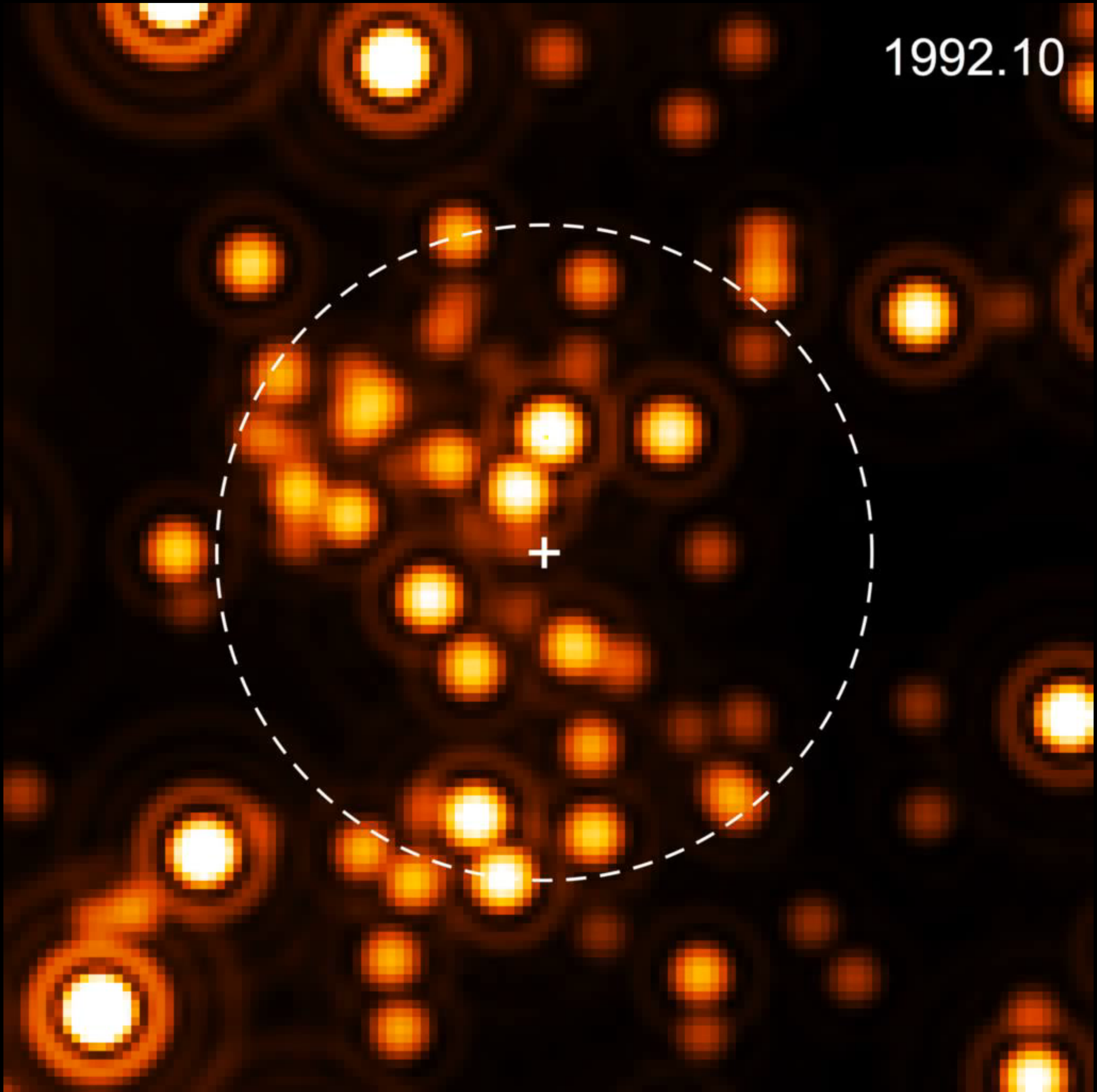
Ghez et al. 2000 (Nature): first accelerations

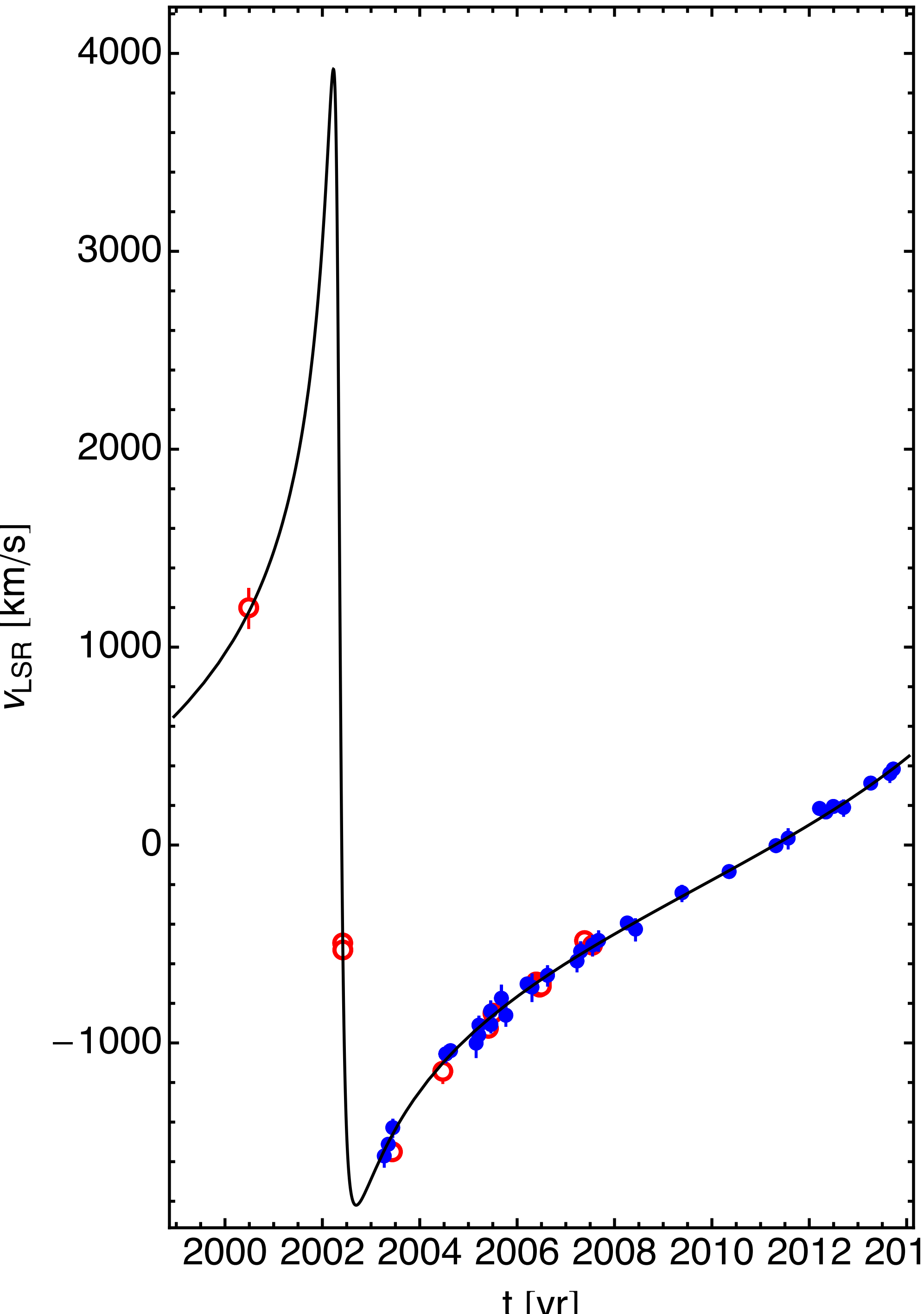




Schoedel 2002 (Nature): first orbit

The S stars 20 years later





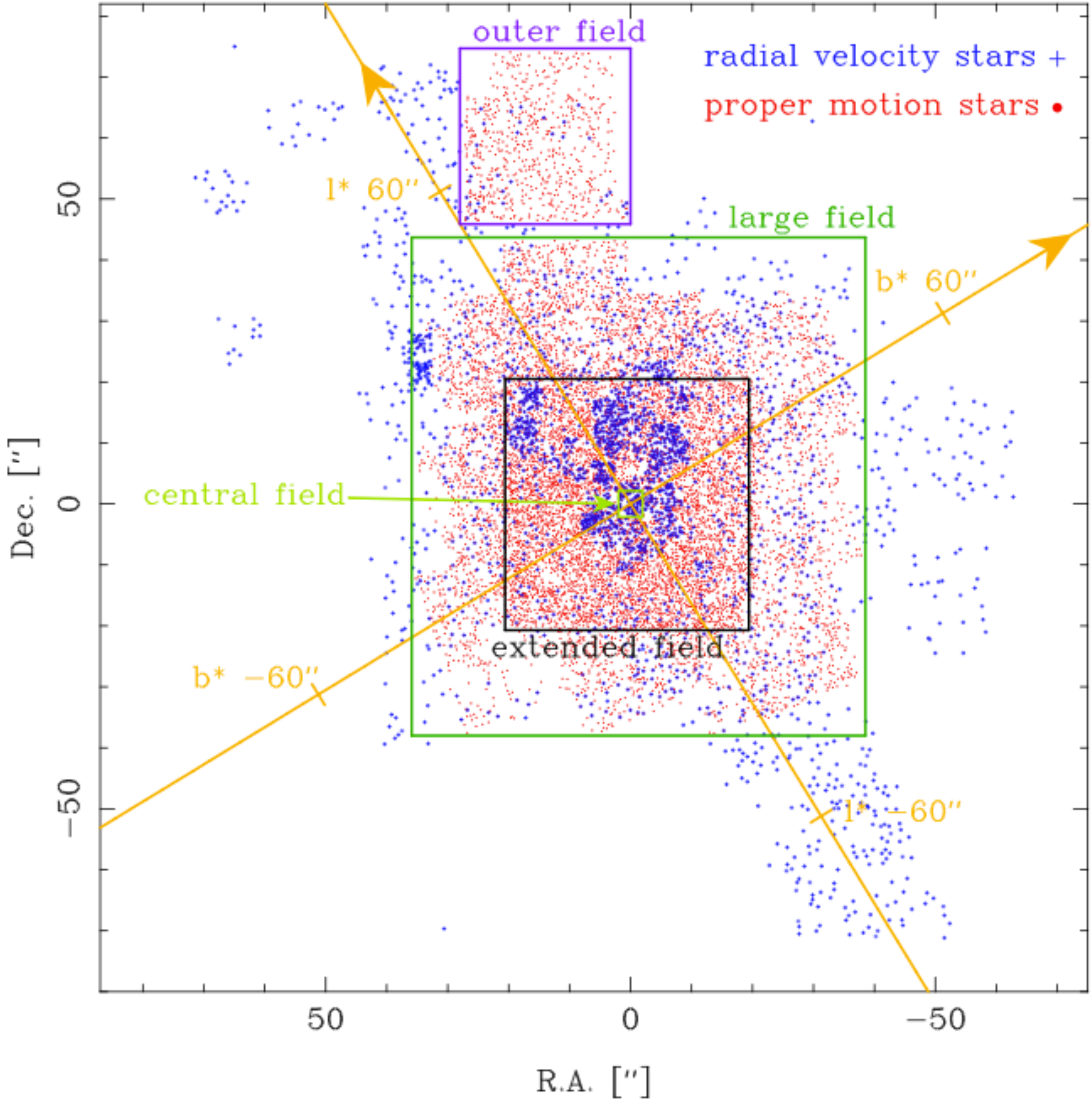
S2: the showcase star

VLT Keck

(Gillessen et al. 2009ab, Ghez et al. 2008, Gillessen+2017)

- 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



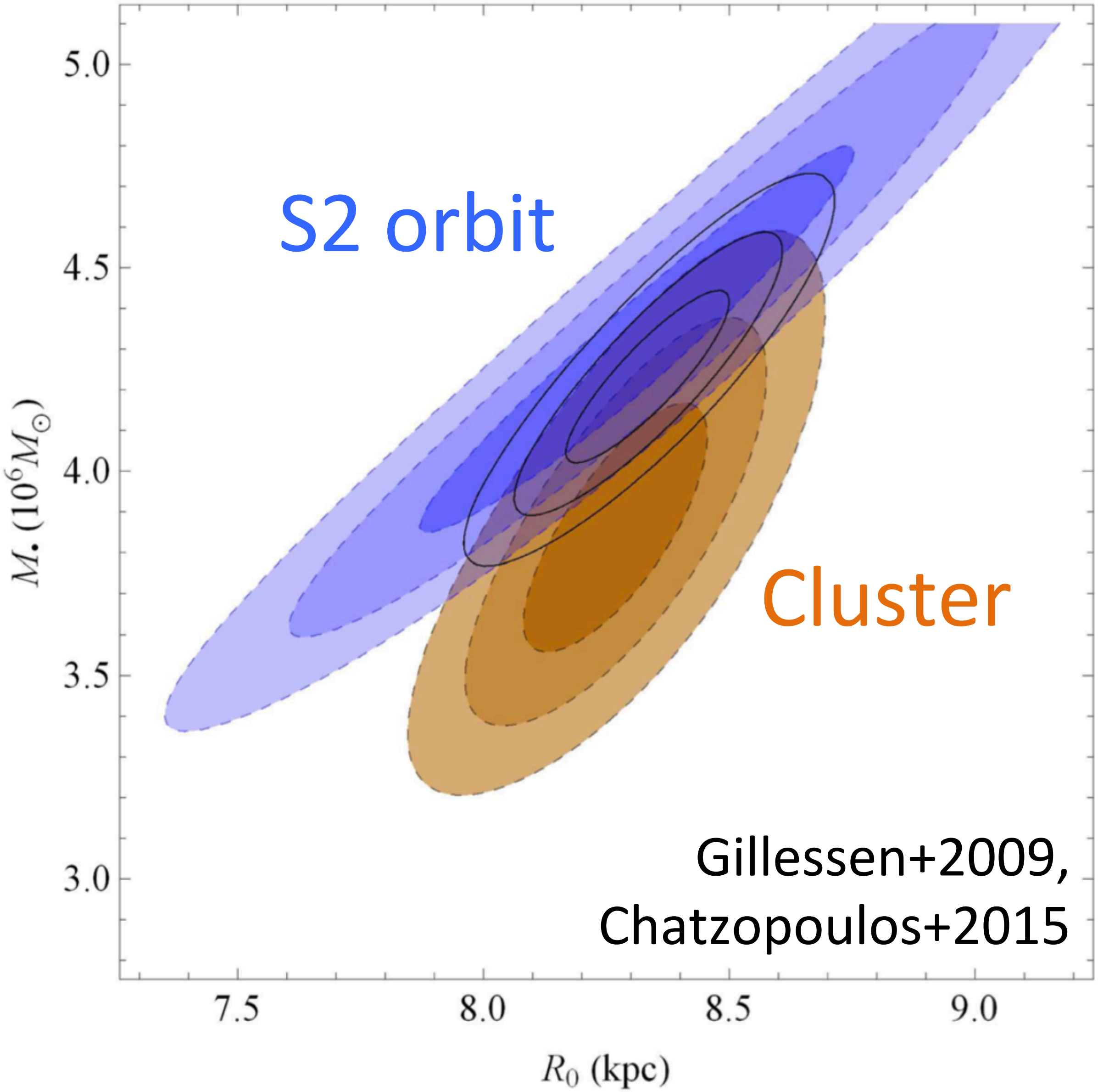
Nuclear cluster : A huge data set

> 10000 proper motions

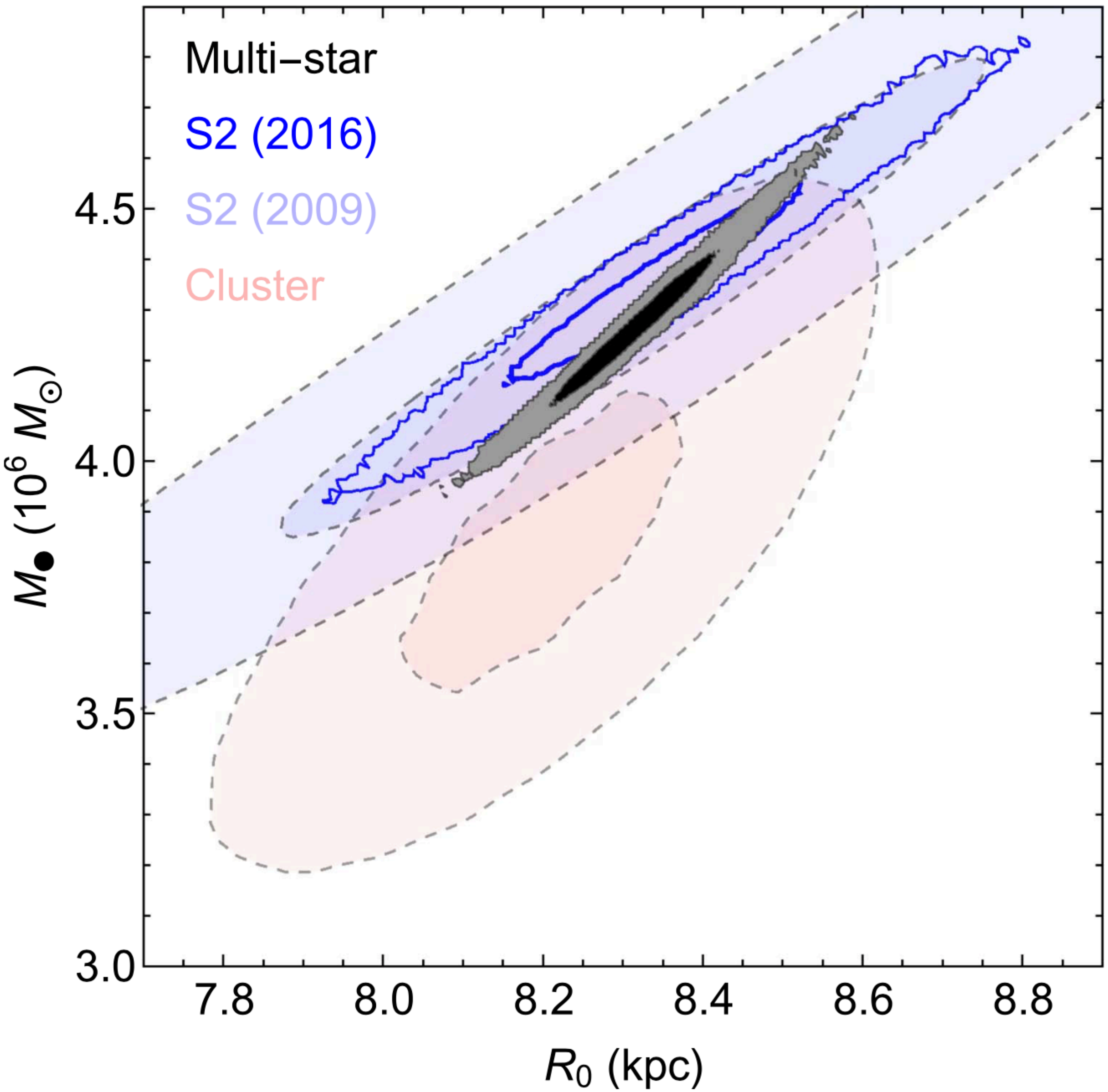
> 2500 radial velocities

Fritz+ 2014

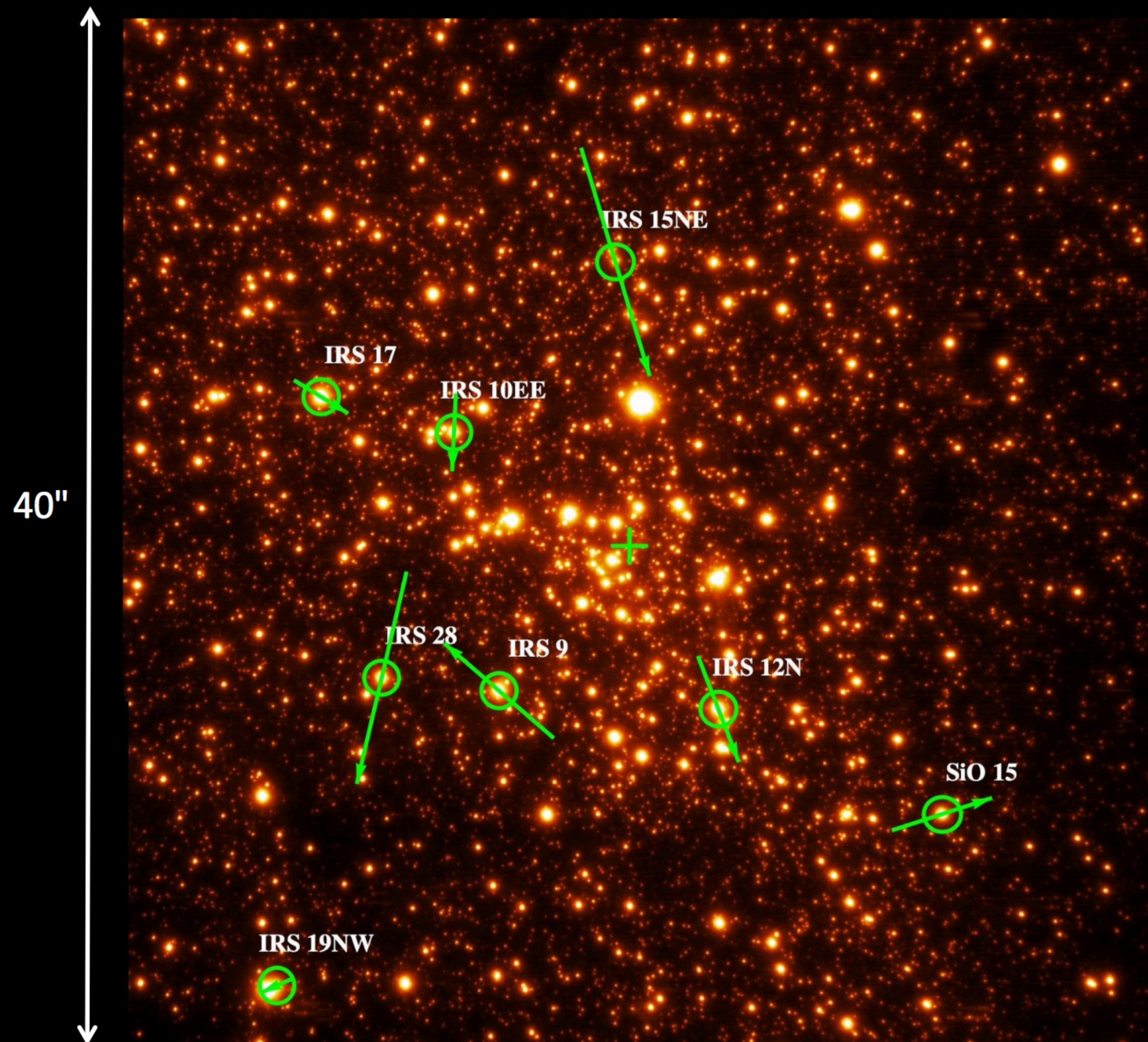
Mass and distance to Sgr A*



Mass and distance to Sgr A*



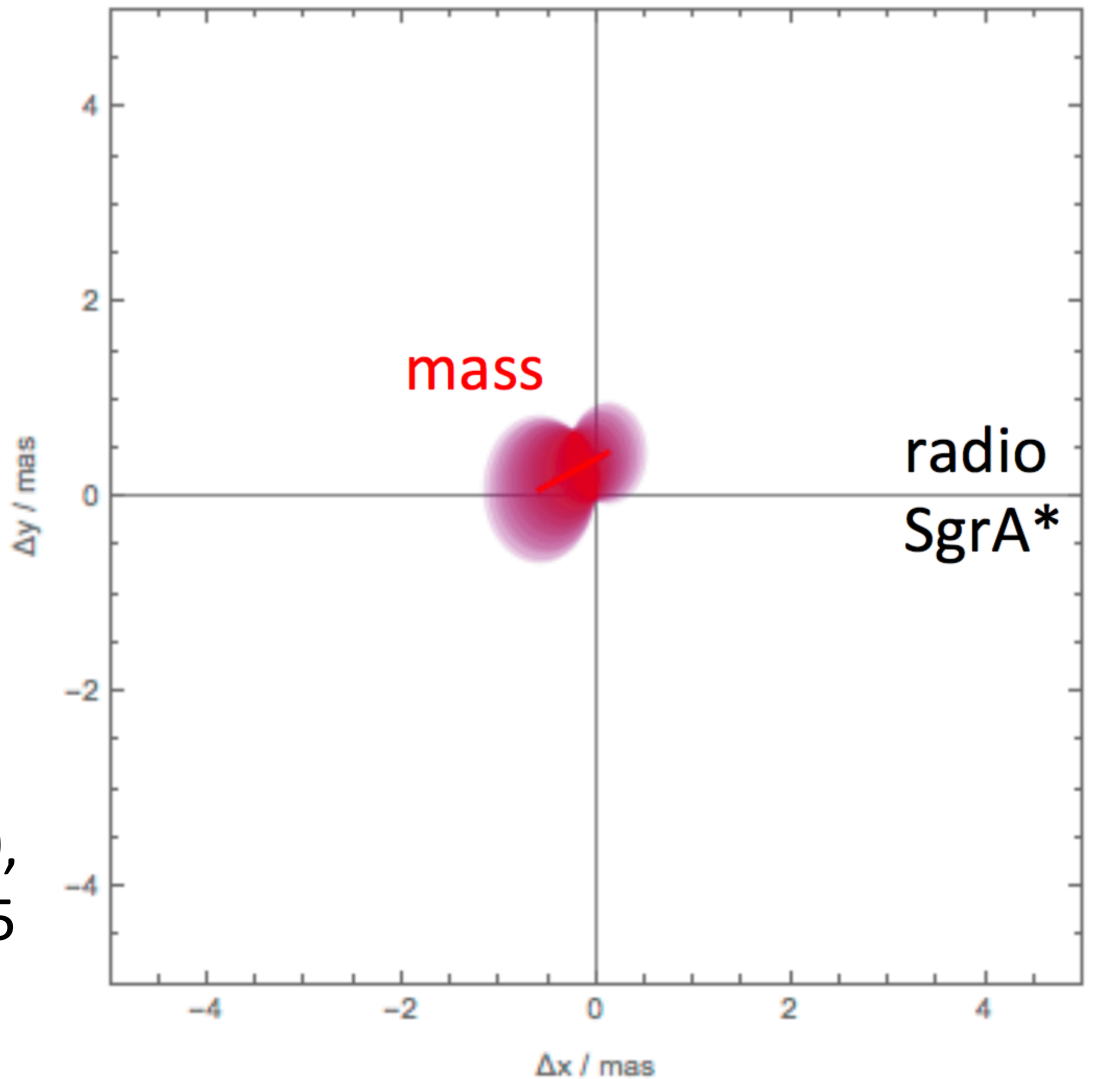
We can also locate the mass



- SiO maser stars
  - IR sources
  - radio sources
- Sgr A*
  - radio source
- Masers et "large" distances
- Positional accuracy
  - intrinsic: < mas
  - emission from outer atmosphere: up to ~mas

Reid et al. 2007

The mass is < 1 mas from Sgr A*

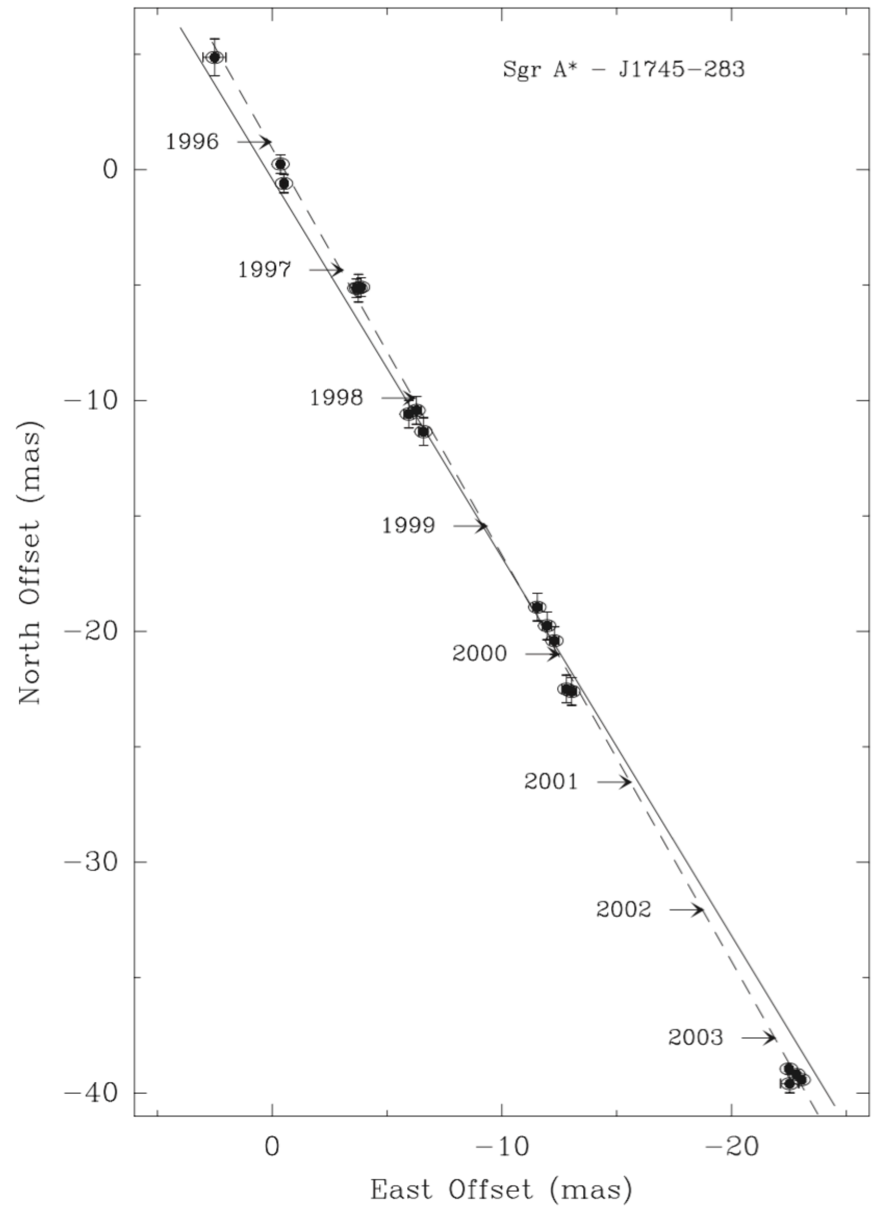


Yelda+2010,
Plewa+2015

Most or all of the mass is Sgr A*

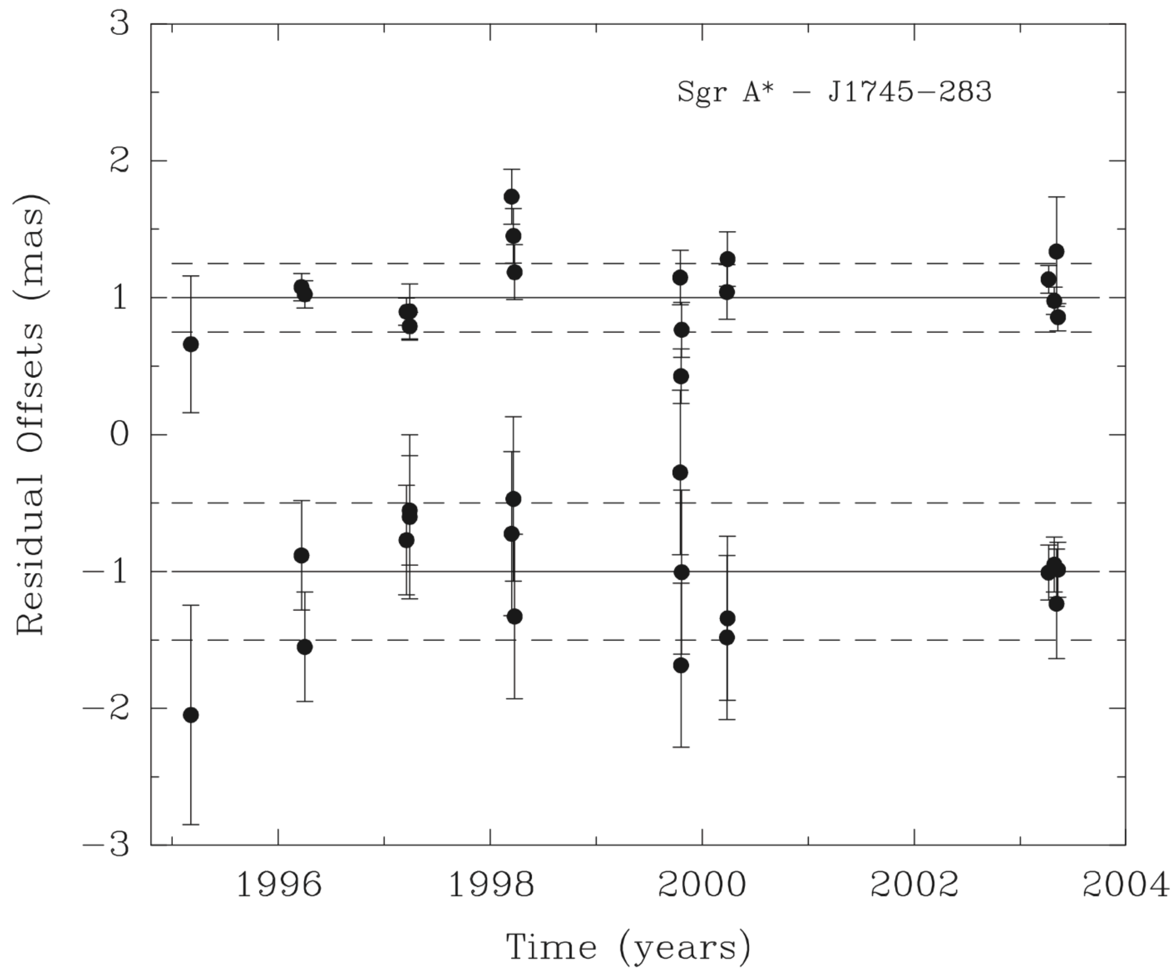
- Motion of radio Sgr A* relative to background AGN
  (Reid & Brunhalter 2004)

- Dashed line: motion of sun through Galaxy



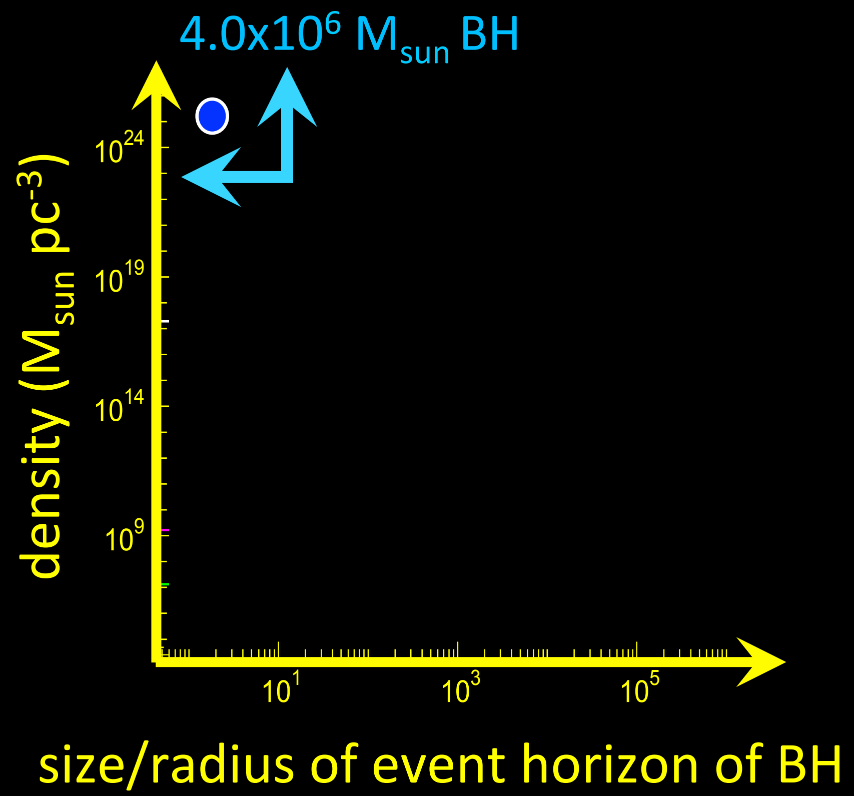
Most or all of the mass is Sgr A*

- Residual: Sgr A* is not moving!
- Radio source: > 10% of central mass



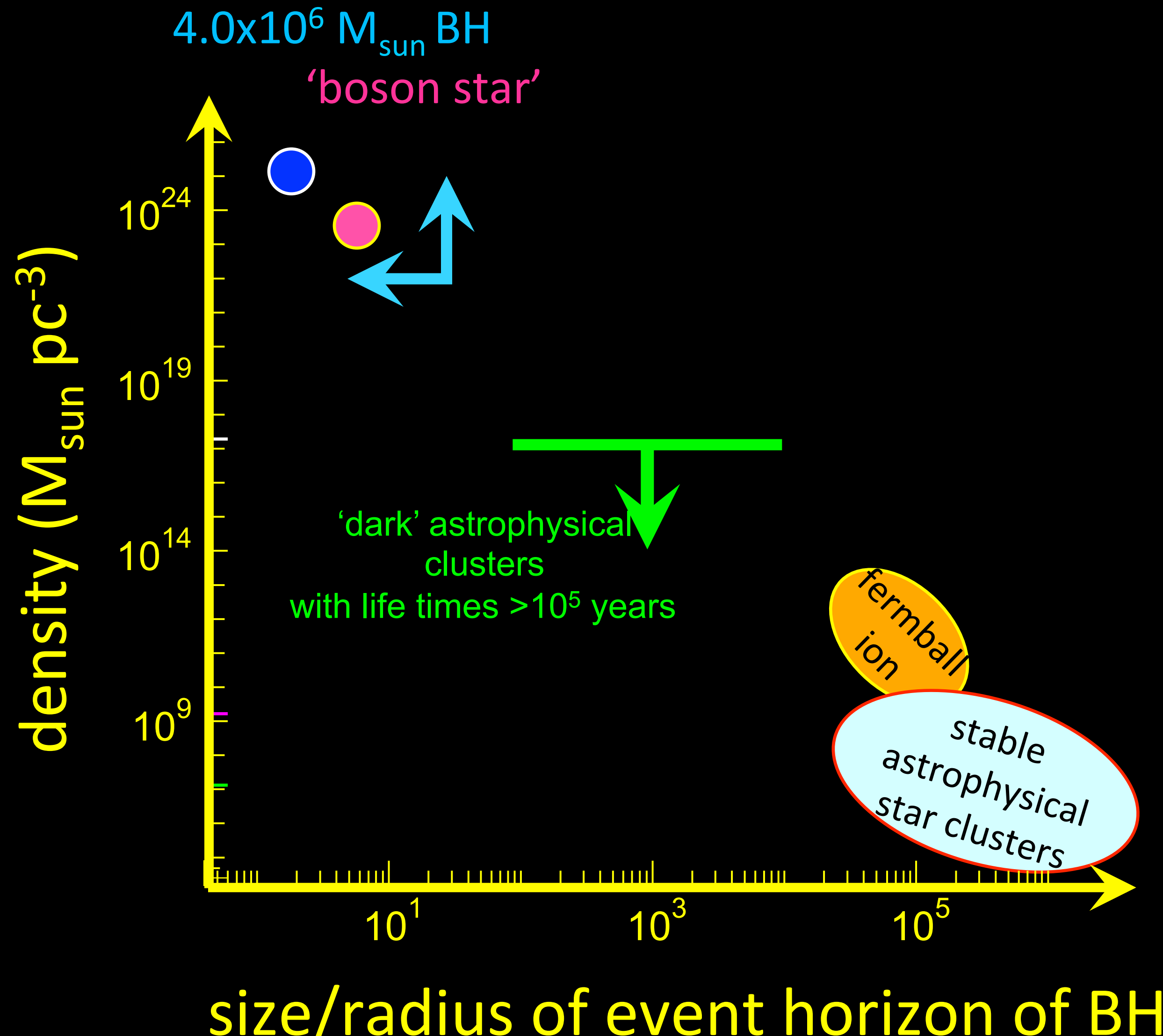
Limits on the density of Sgr A*

- 4.0×10^6 M_{sun} inside of S2
  (Schödel+ 2002, Gillessen+ 2009)
- > 10% of this is Sgr A*
  (Reid & Brunthaler 2004)
- Sgr A* radio size: ~4 R_s
  (Bower+ 2006, Doeleman+ 2008)



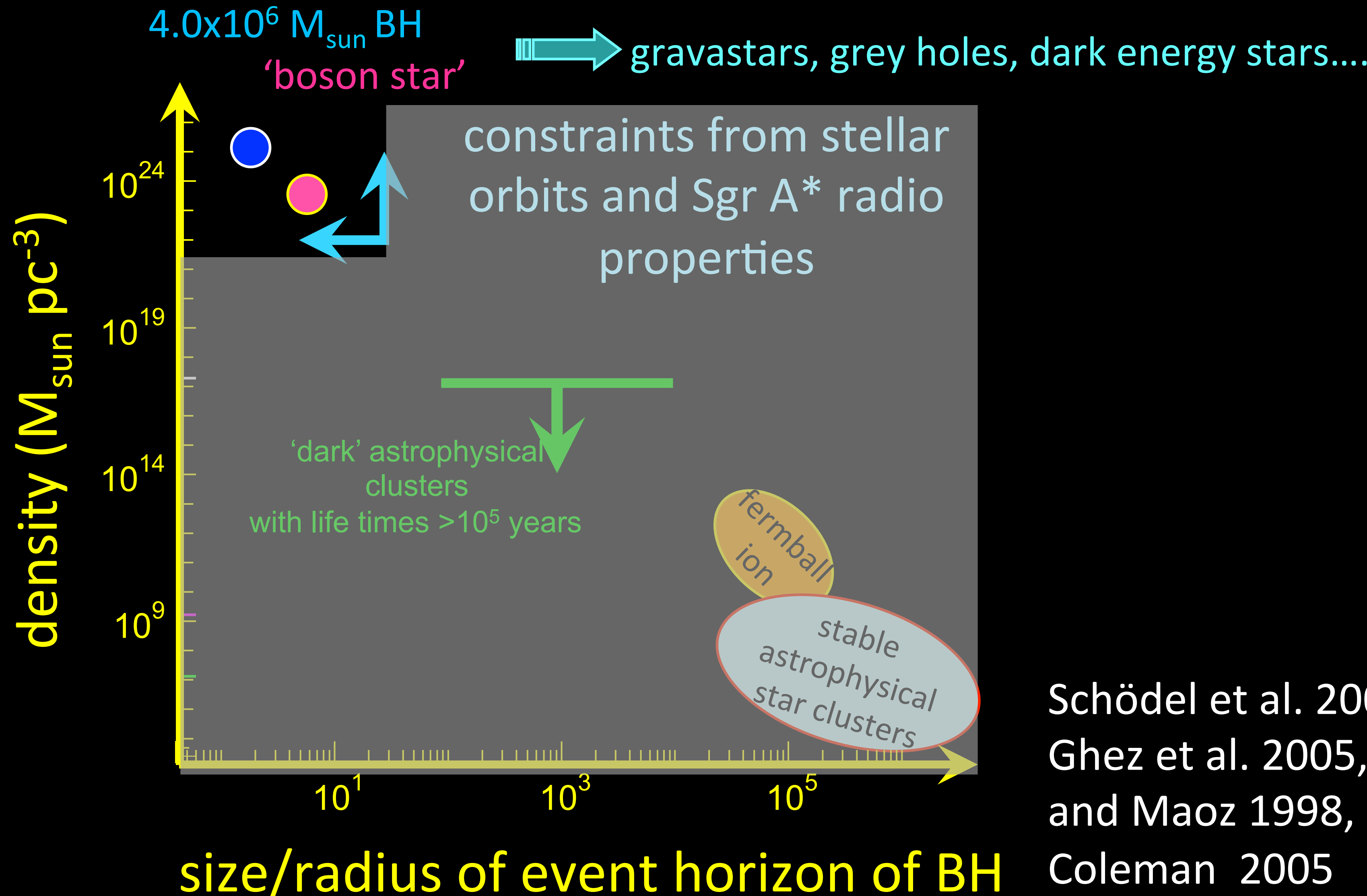
- density: ~10^{-2} of black hole

Is Sgr A* a black hole?



Schödel et al. 2003,
Ghez et al. 2005,
and Maoz 1998,
Coleman 2005

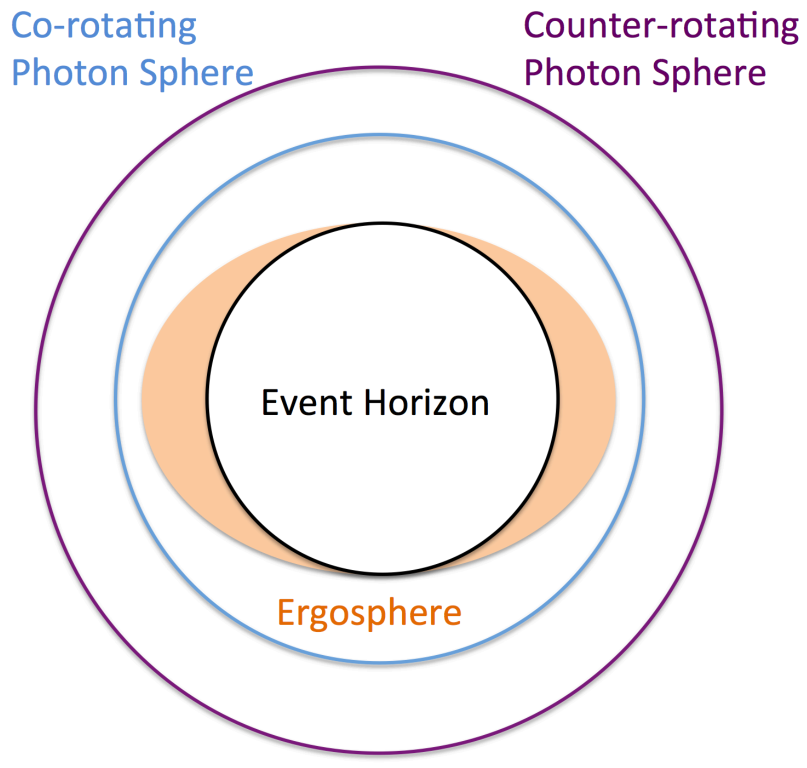
Is Sgr A* a black hole?



Schödel et al. 2003, Ghez et al. 2005, and Maoz 1998, Coleman 2005

Black hole

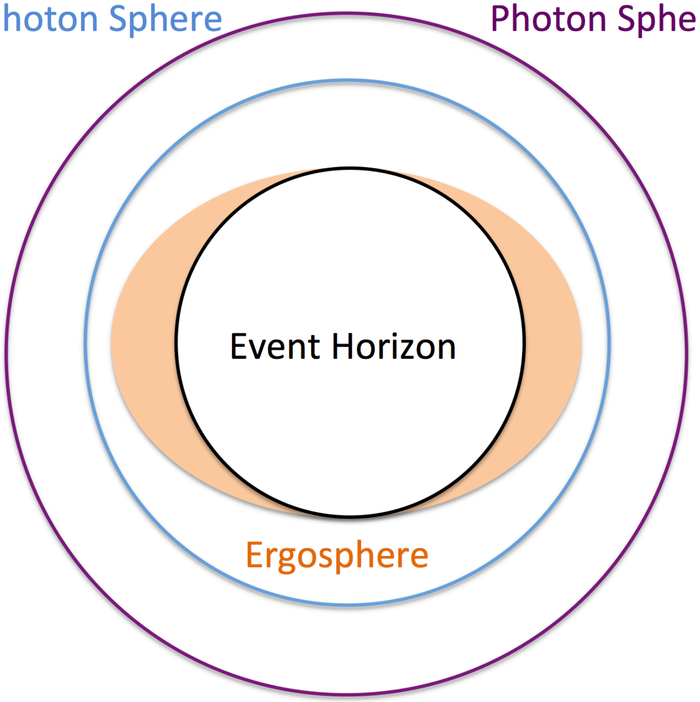
- Event horizon: $R_S = 2\ GM/c^2 = 2\ R_g$
- Innermost stable circular orbit: 1-9 R_g
- Circular photon orbit: 1-4 R_g

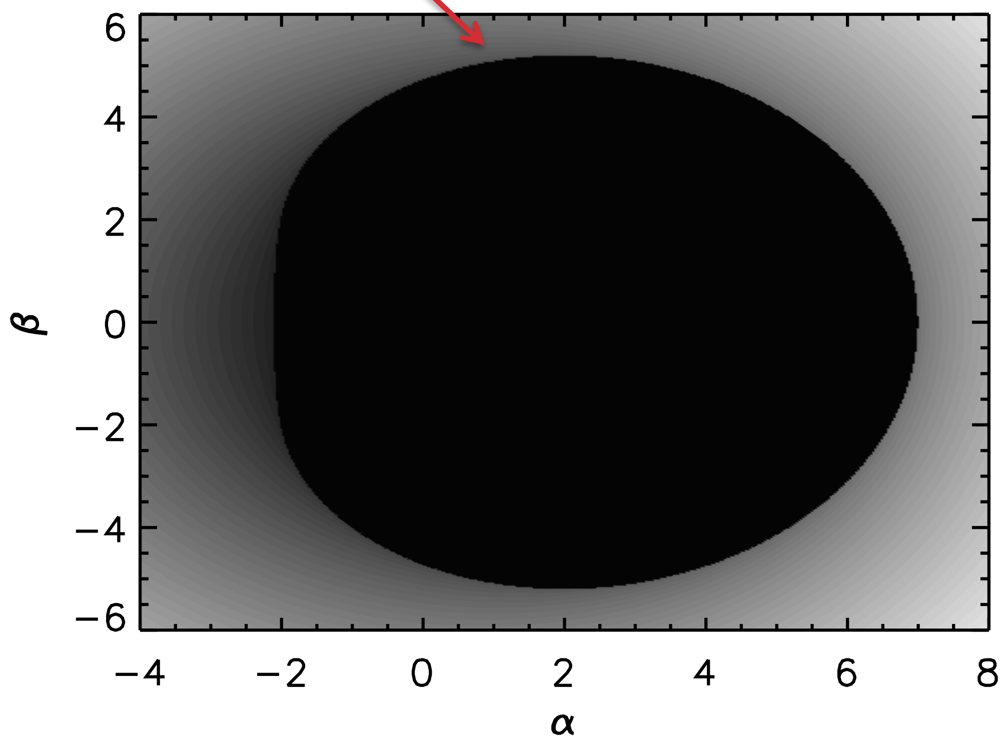


Black hole shadow

Shadow inside photon orbits

Size: ~10 R_g

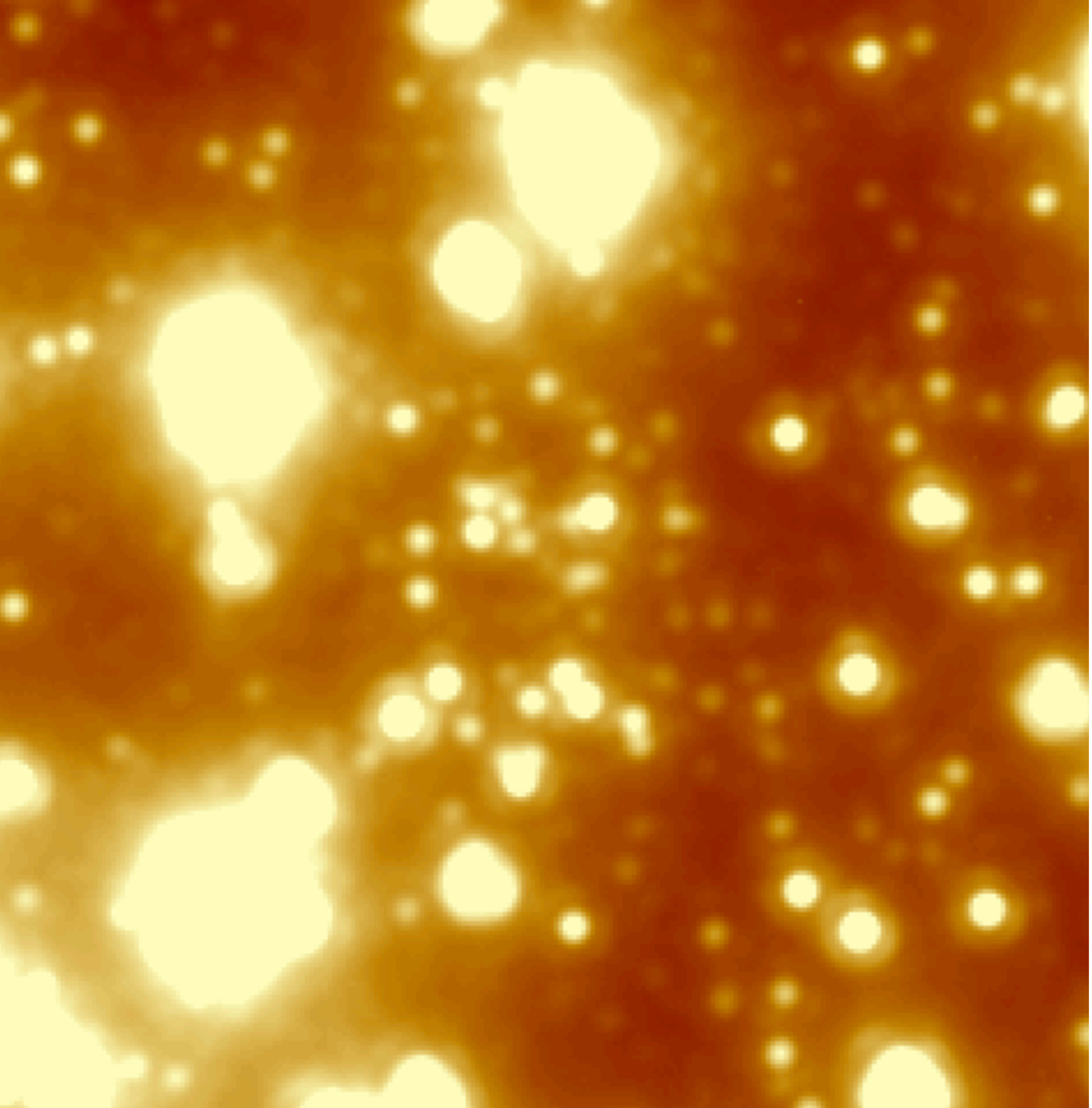




Bardeen (1973); Dexter & Agol (2009)

Q: resolving the BH shadow of Sgr A*

- $R_g = GM / c^2$, $M = 4x10^6 M_{sun}$, D = 8 kpc
- How large is 10 R_g in angular size on sky?
- How large of a telescope do we need to resolve that size at wavelengths of:
  - 1 mm (radio)?
  - 2 micron (IR)?
  - 1 nm (X-ray)?
- Think/calculate, share, then discuss!

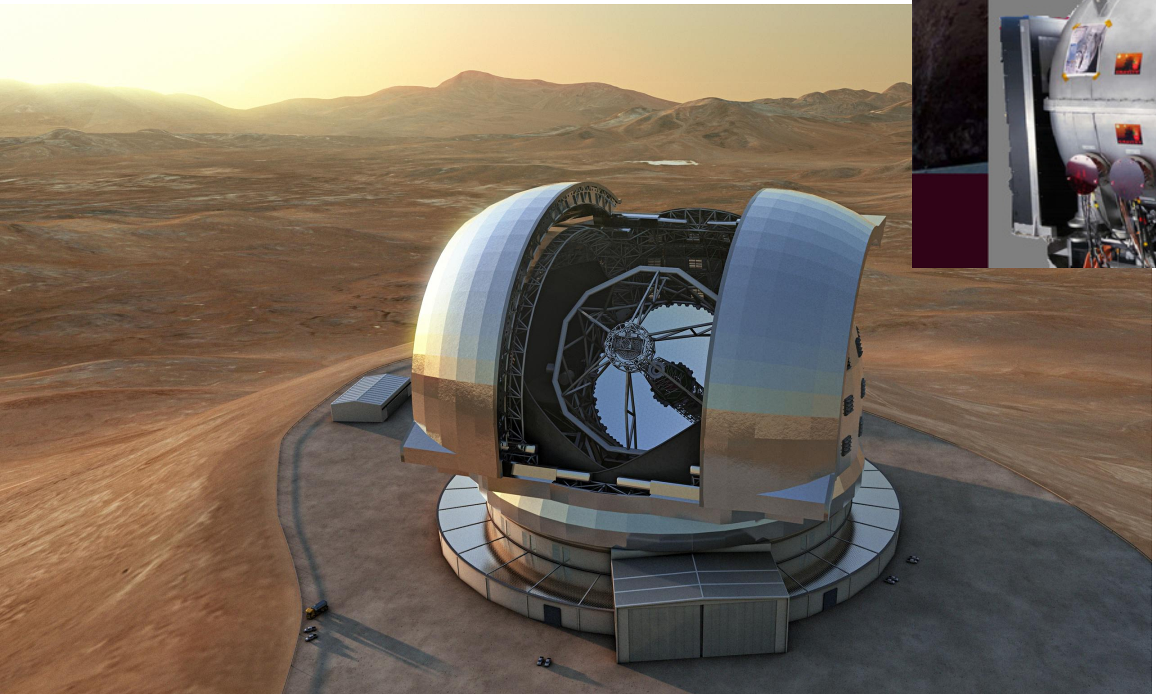


Current images limited by confusion: “halo noise” prevents detection of faint stars

Solution: higher spatial resolution

Discovering new S stars

- VLTI GRAVITY
- 30m telescopes (GMT, TMT, ELT)



Interferometry basics

- The electric field measured at Earth is the Fourier transform of the emitted radiation pattern from a source on the sky

$$E(\mathbf{r}, \theta, t) = E(\theta, t) e^{2\pi i\, \theta \cdot \mathbf{r}/\lambda}$$

$$E(\mathbf{r}, t) = \int E(\theta, t) e^{2\pi i \theta \cdot \mathbf{r}/\lambda} d^2\theta$$

Morales & Wyithe 2010

Interferometry basics

- The quantity of interest is the intensity, not the electric field

$$I(\theta) = \langle E(\theta, t) E^*(\theta, t) \rangle_t = \langle |E(\theta, t)|^2 \rangle_t$$

$$I(\mathbf{u}) = \langle E(\mathbf{r}, t) * E^*(\mathbf{r}, t) \rangle_t$$

$\mathbf{u} = \Delta \mathbf{r}$

Interferometry basics

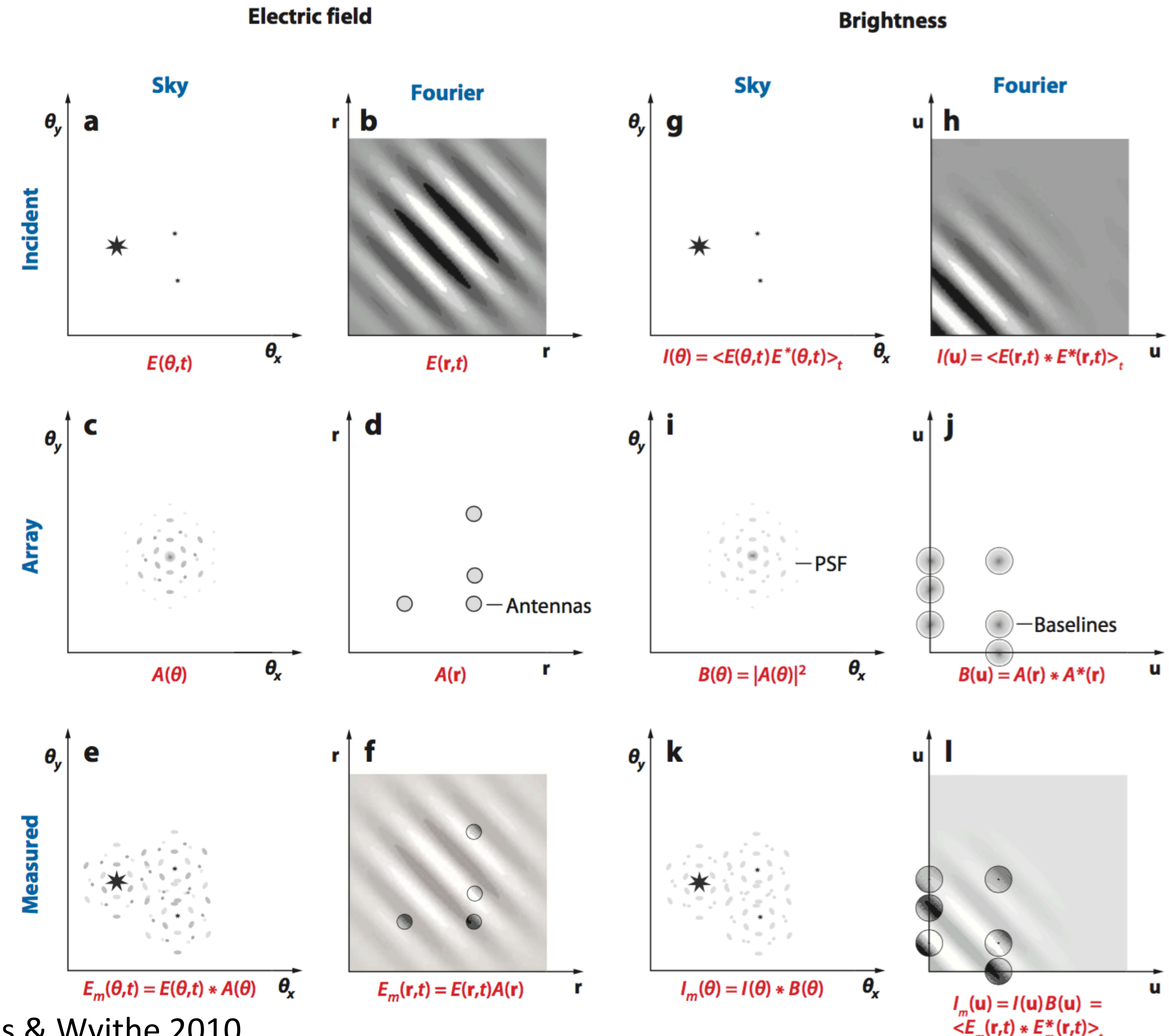
- Use the convolution theorem:

$f * g = F^{-1}\{F(f)\ F(g)\}$

"complex visibility"

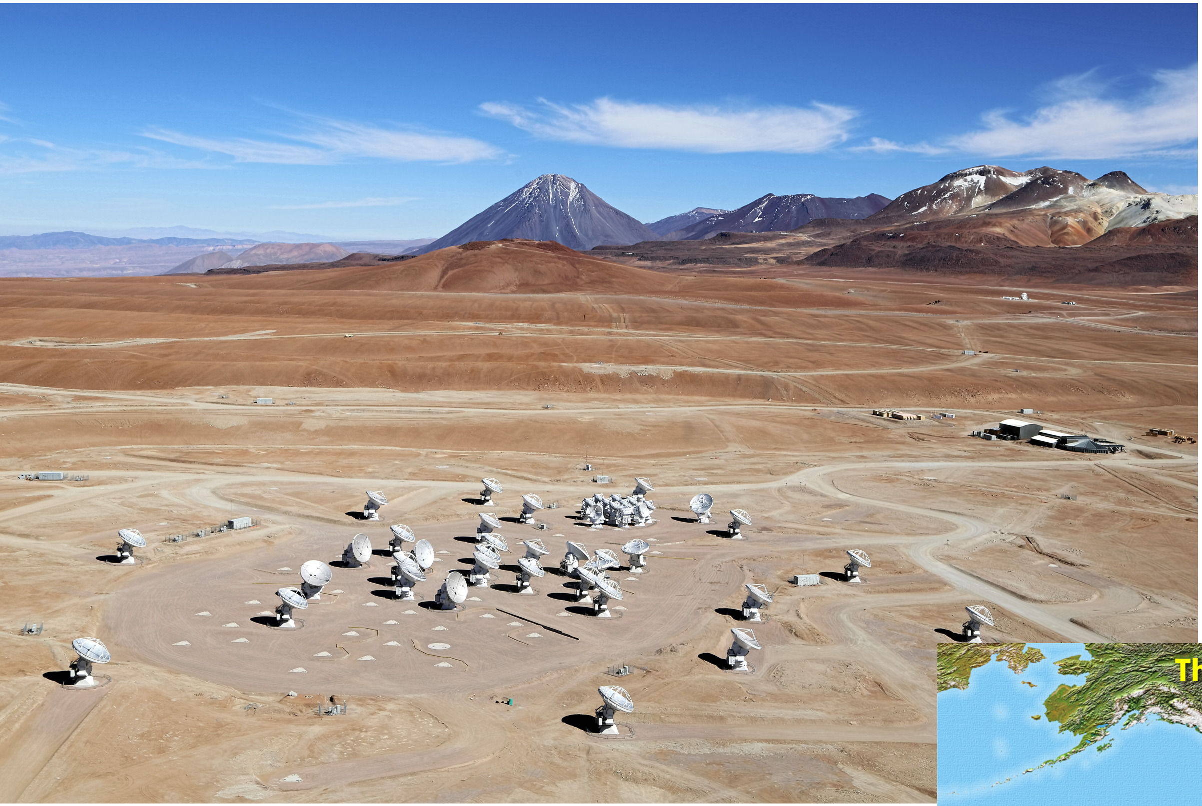
$$I(\mathbf{u}) = \int I(\theta) e^{-2\pi i \theta \cdot \mathbf{u}/\lambda} d^2\theta$$

Interferometers measure the Fourier transform of the source image using telescope pairs



Morales & Wyithe 2010

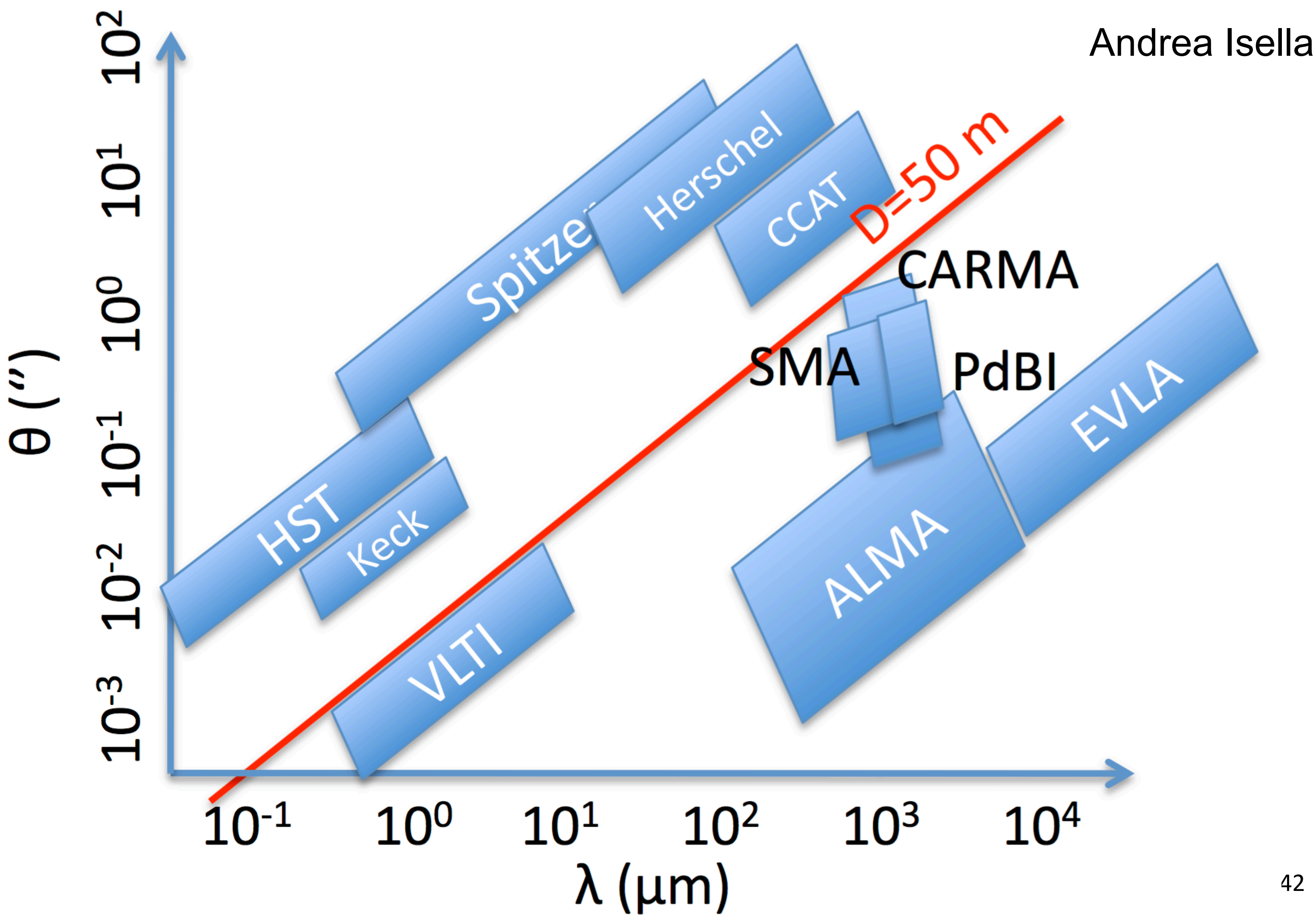
“Connected element” vs. VLBI



ALMA

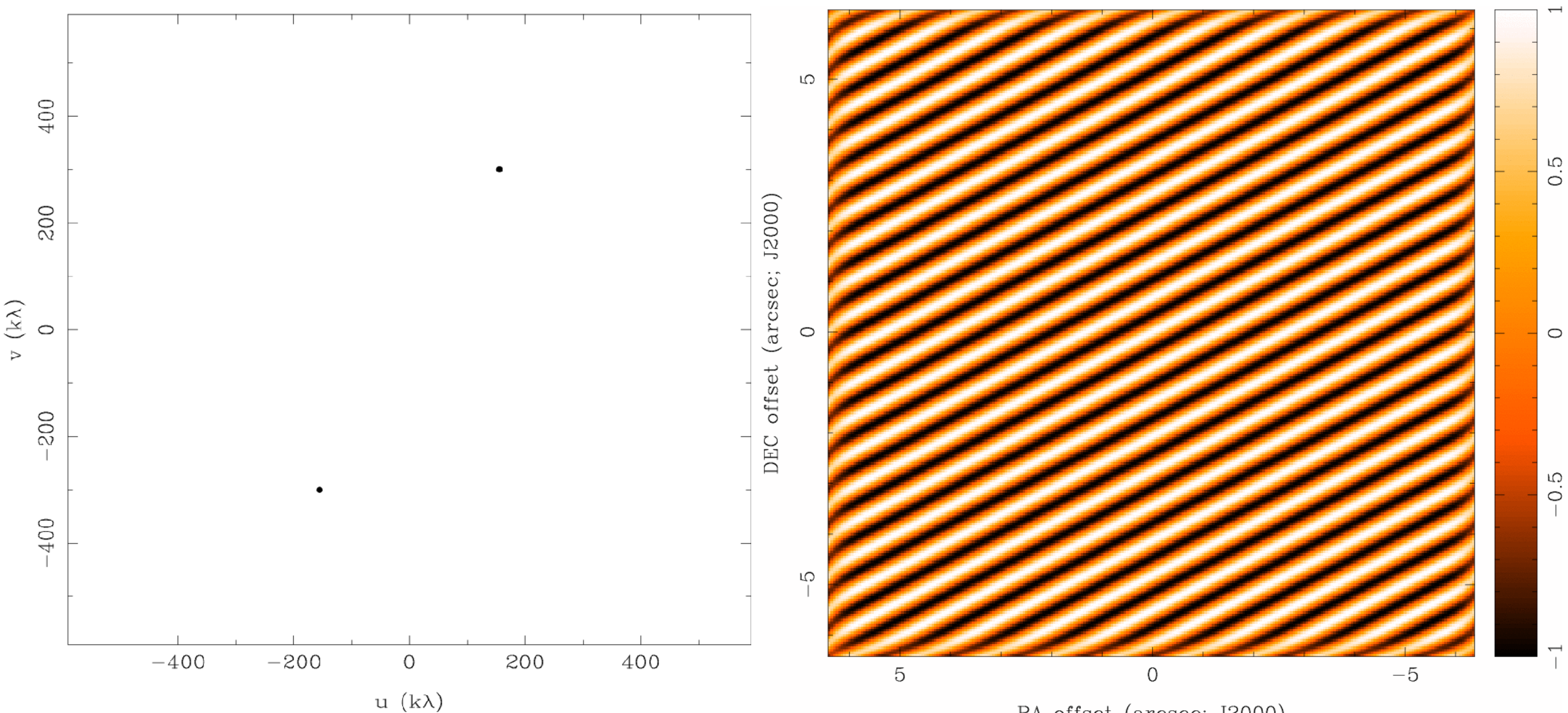
VLBA

Interferometry for high resolution



Effects of a sparse *uv* coverage

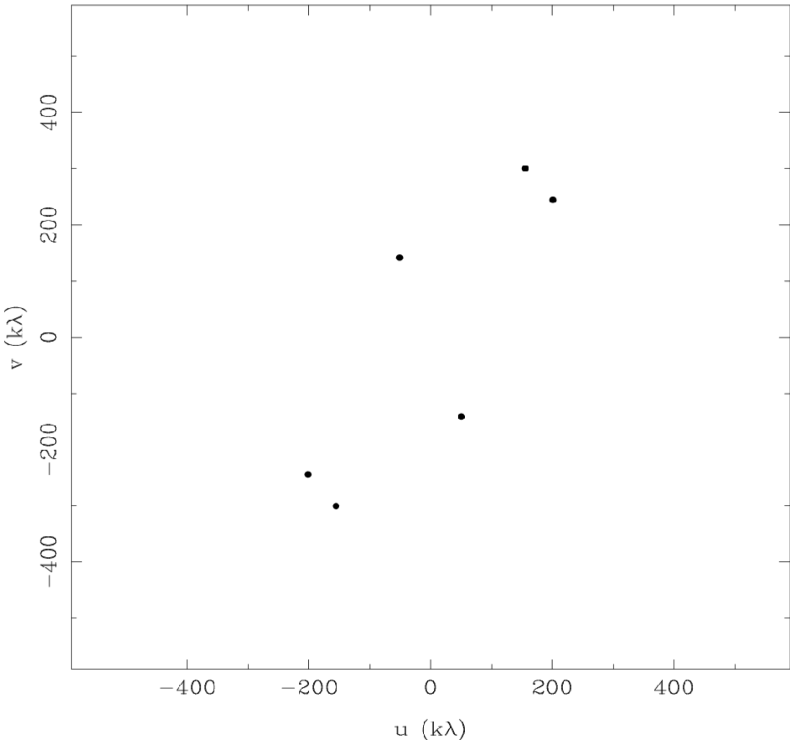
Synthesized Beam (i.e.,PSF) for 2 Antennas

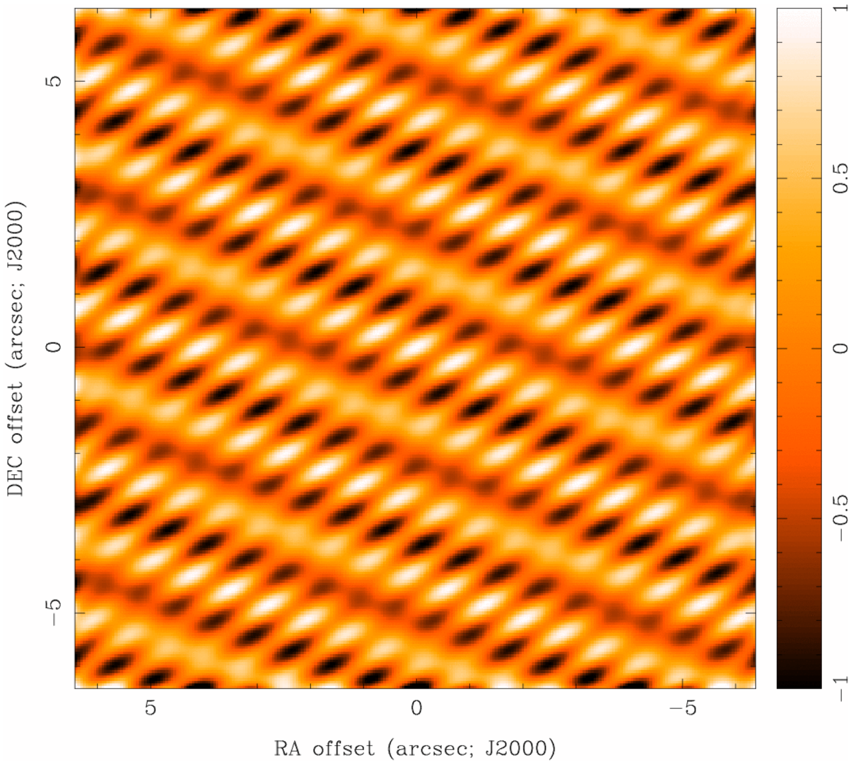


Andrea Isella
https://science.nrao.edu/opportunities/courses/casa-caltech-winter2012/Isella_Radio_Interferometry_Basics_Caltech2012.pdf

Effects of a sparse *uv* coverage

3 Antennas





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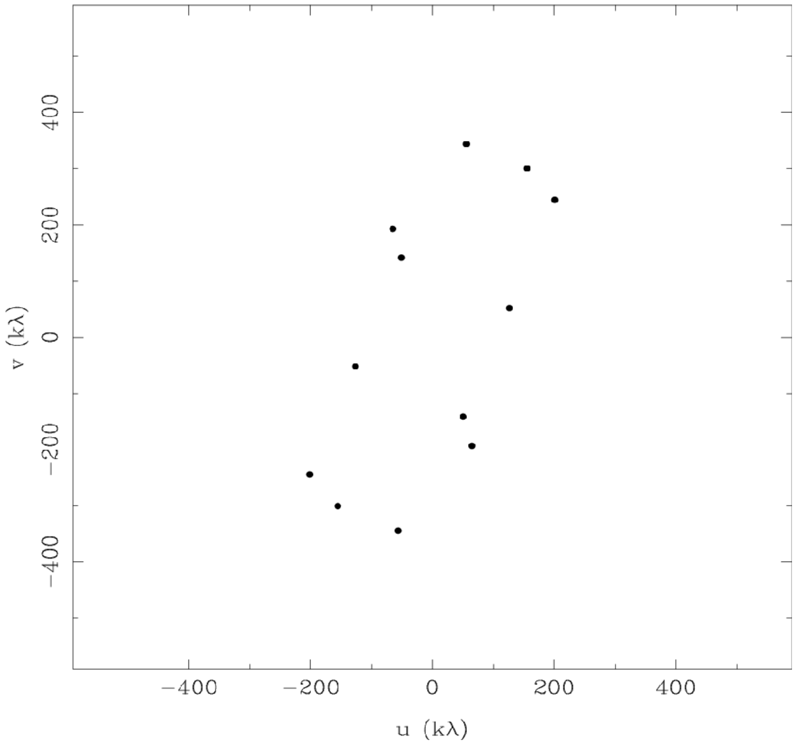
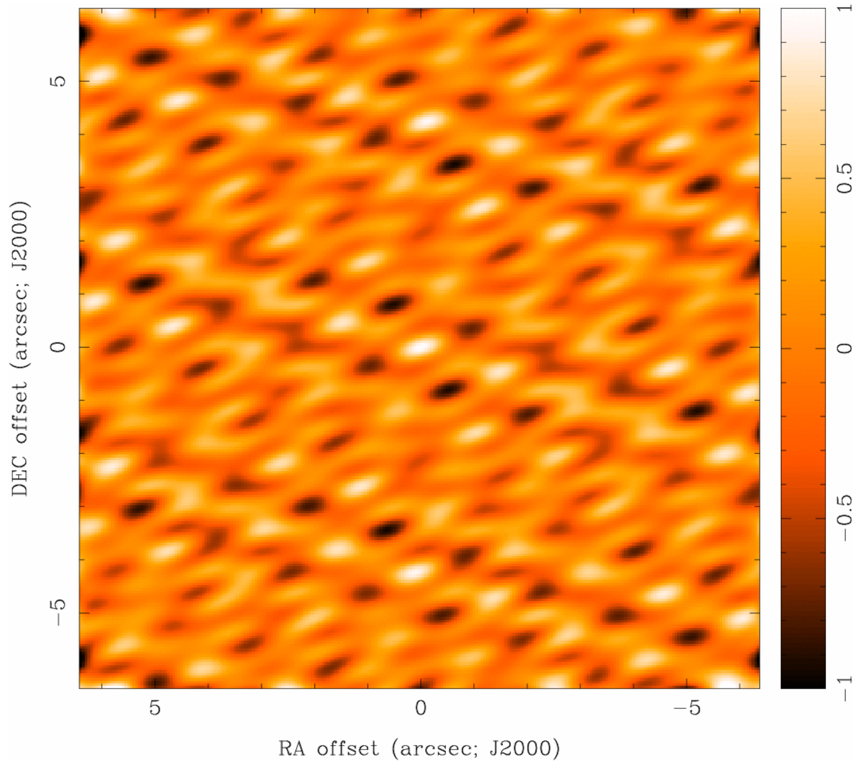
Effects of a sparse *uv* coverage

4 Antennas





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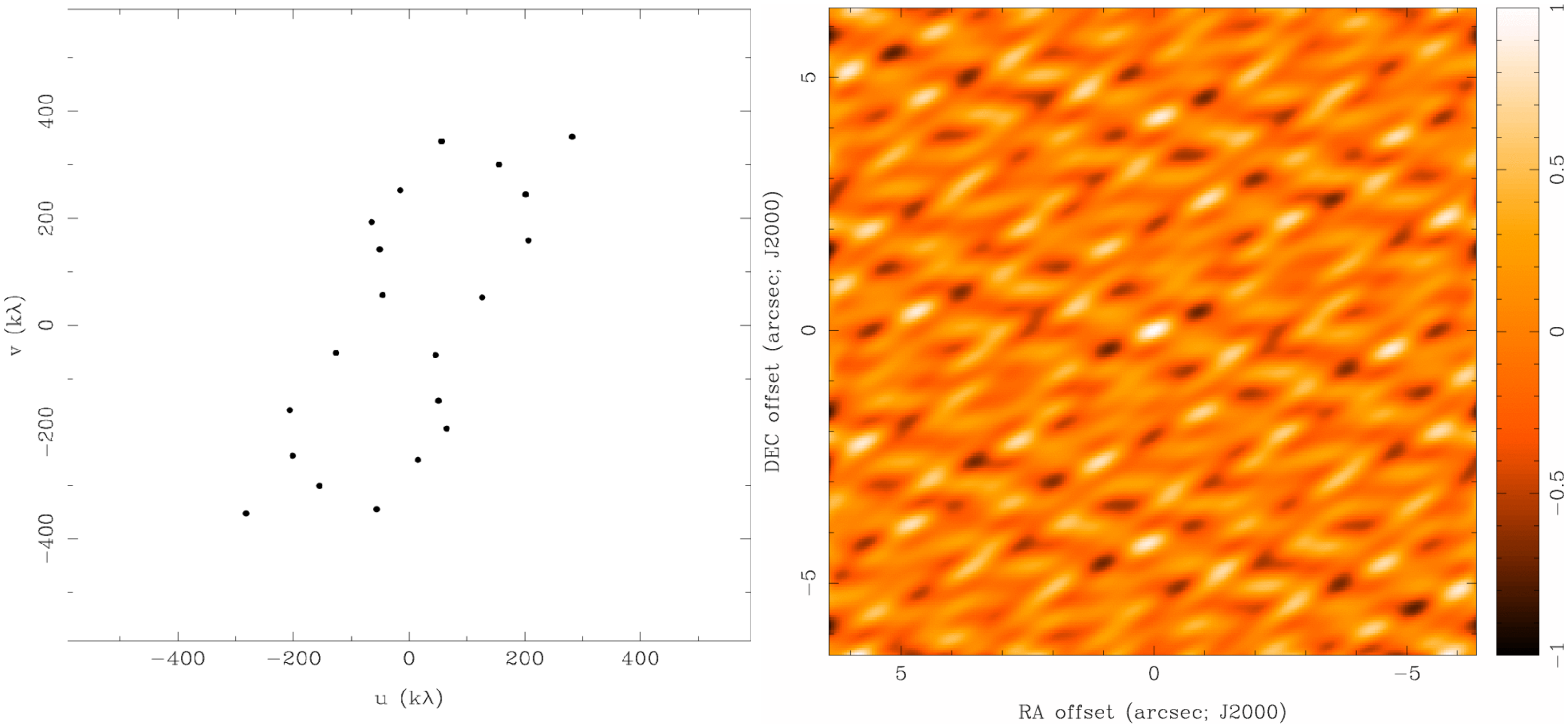
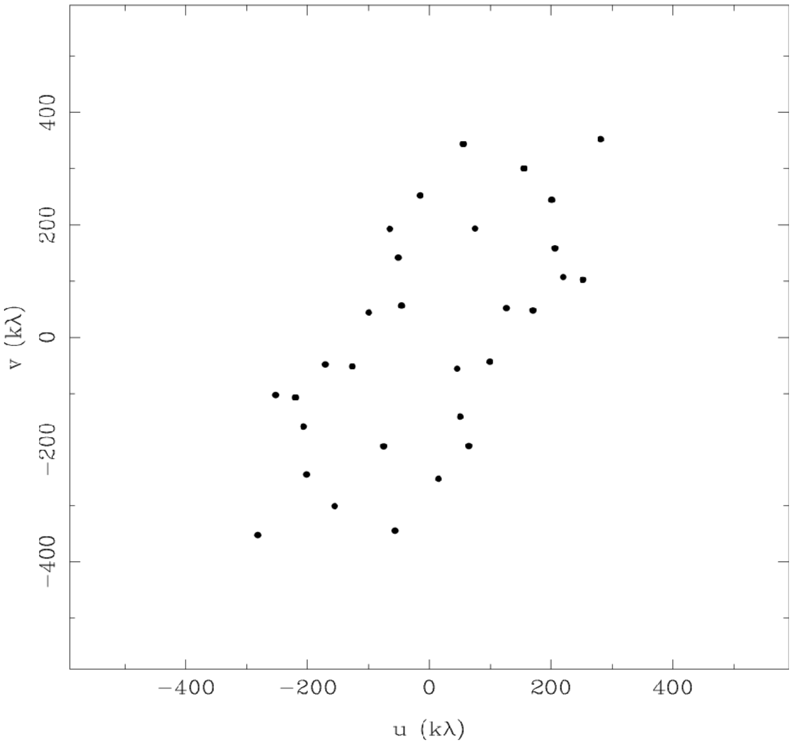
Effects of a sparse *uv* coverage

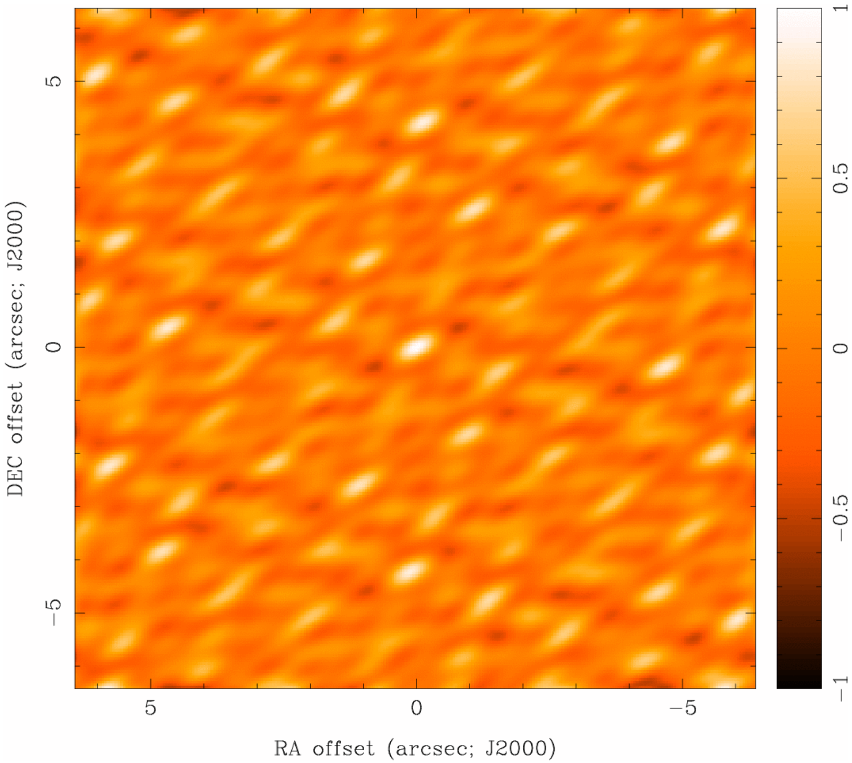
5 Antennas



Effects of a sparse *uv* coverage

6 Antennas





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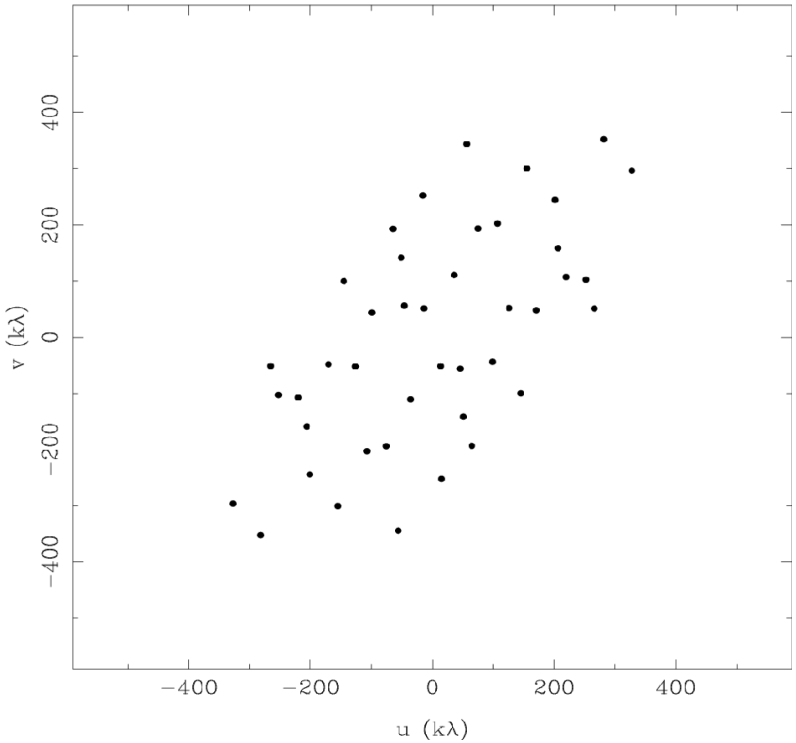
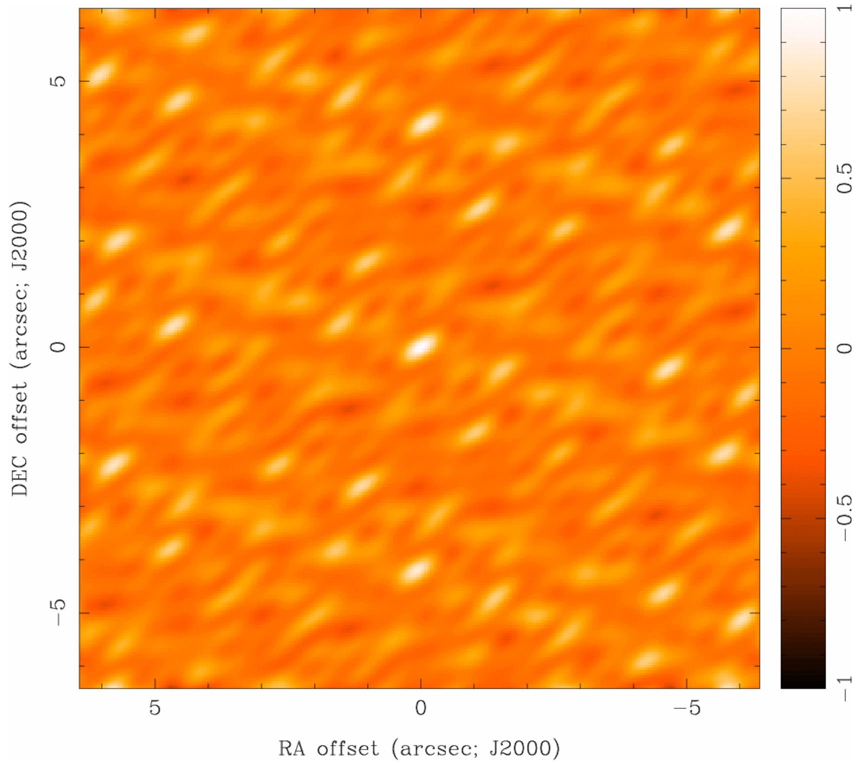
Effects of a sparse *uv* coverage

7 Antennas





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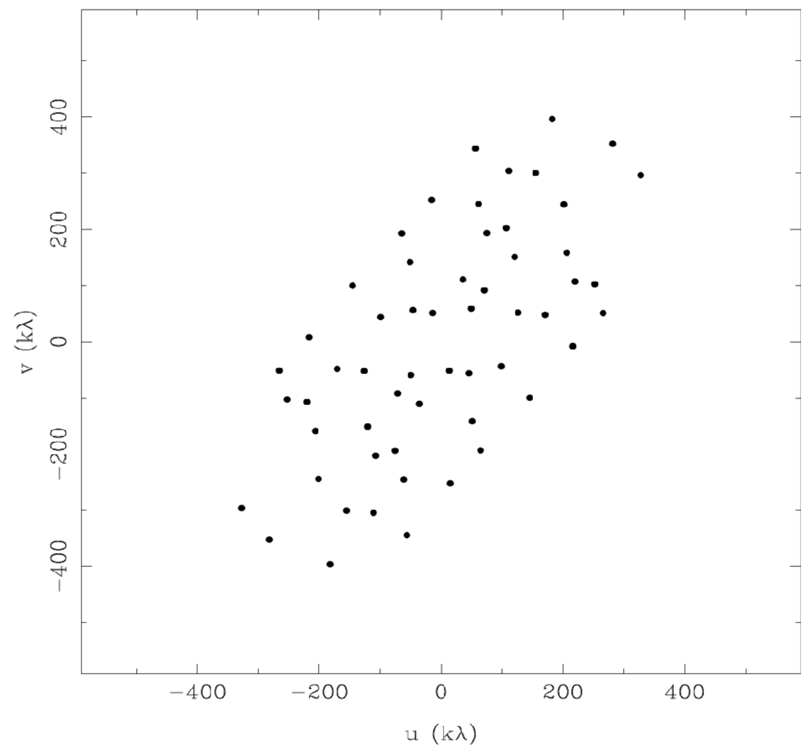
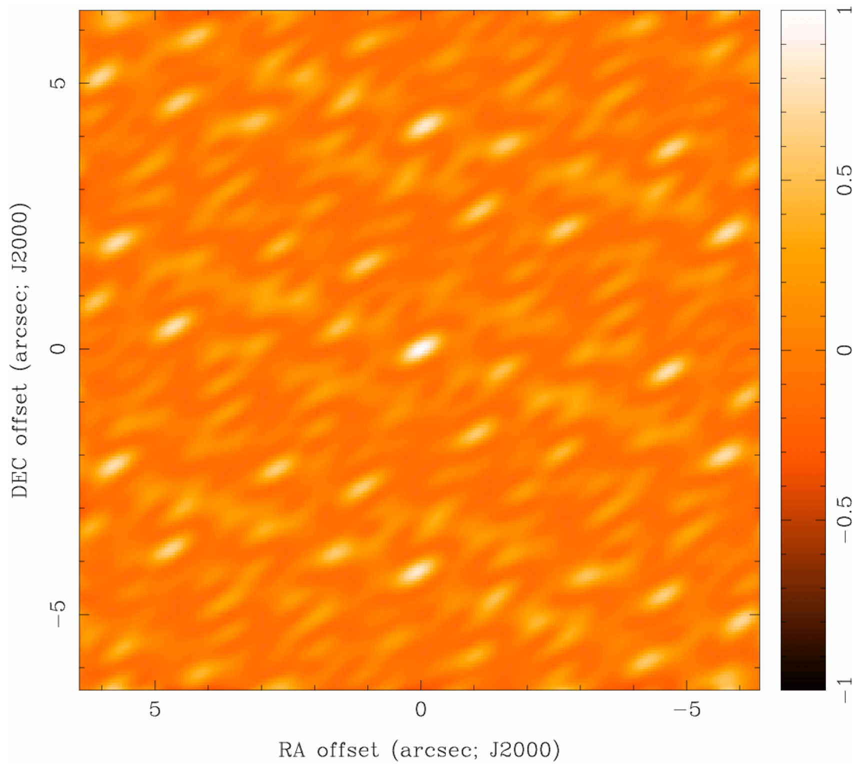
Effects of a sparse *uv* coverage

8 Antennas





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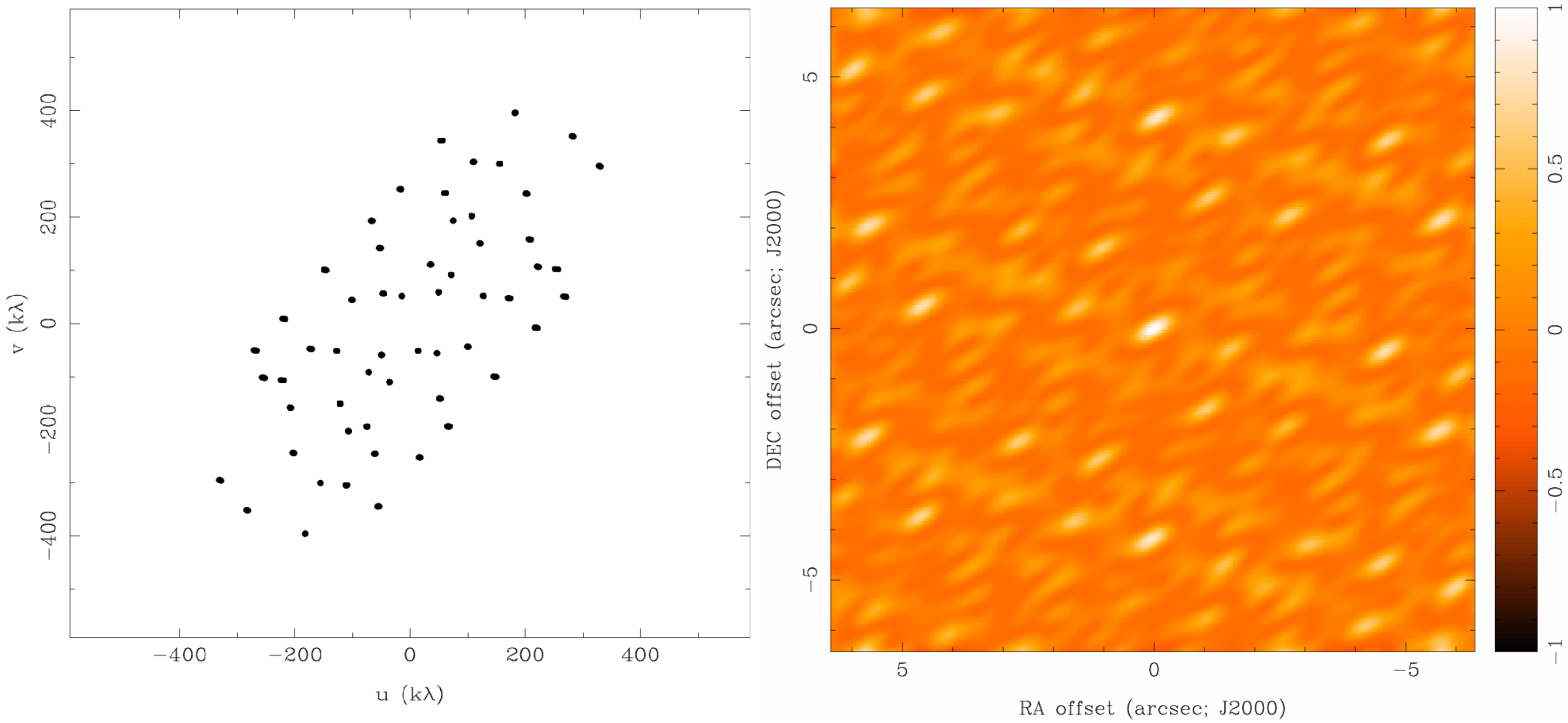
Effects of a sparse *uv* coverage

8 Antennas x 6 Samples



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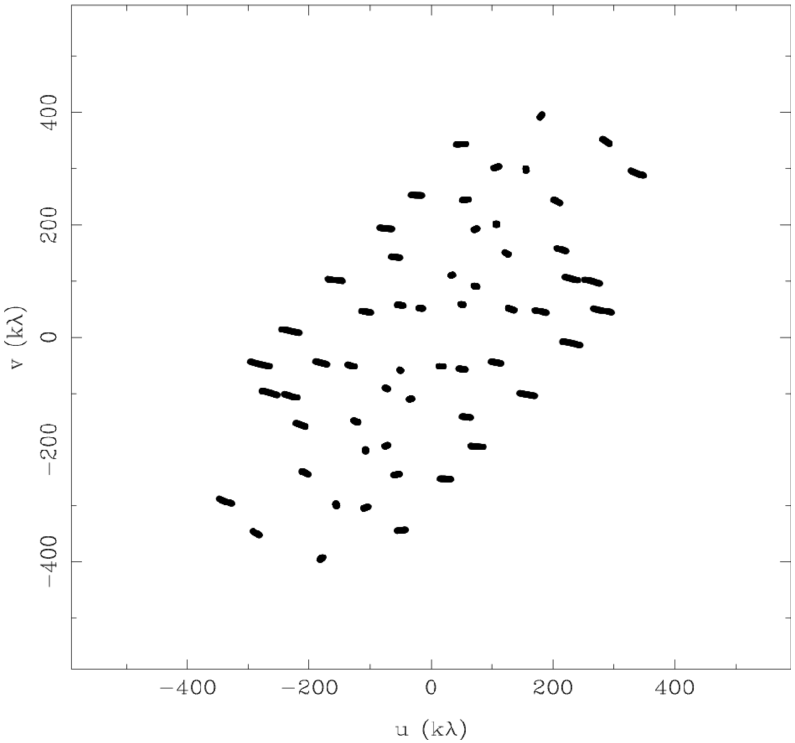
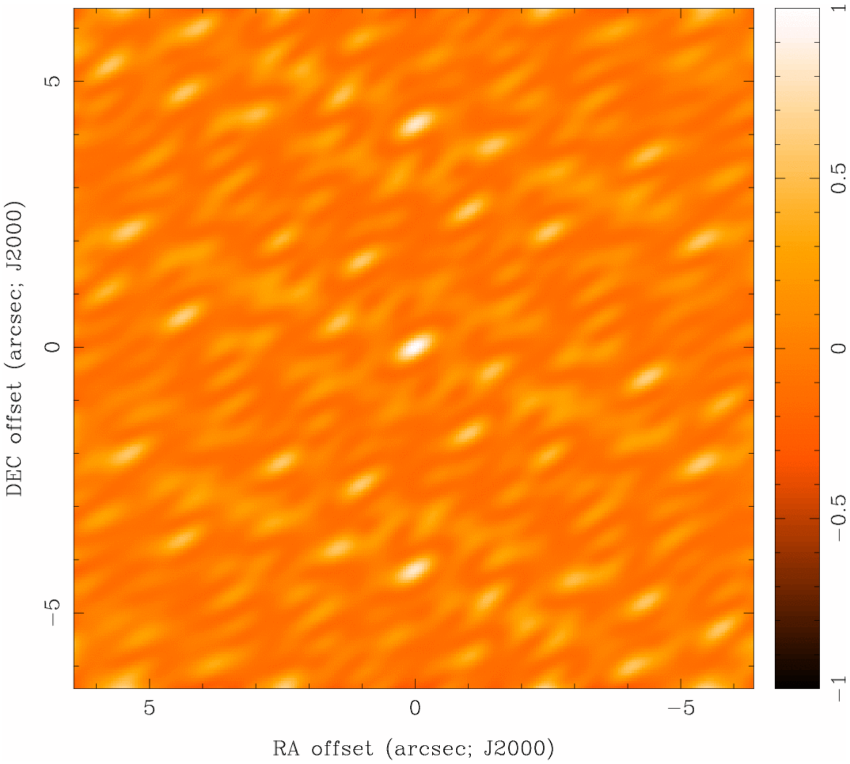
Effects of a sparse *uv* coverage

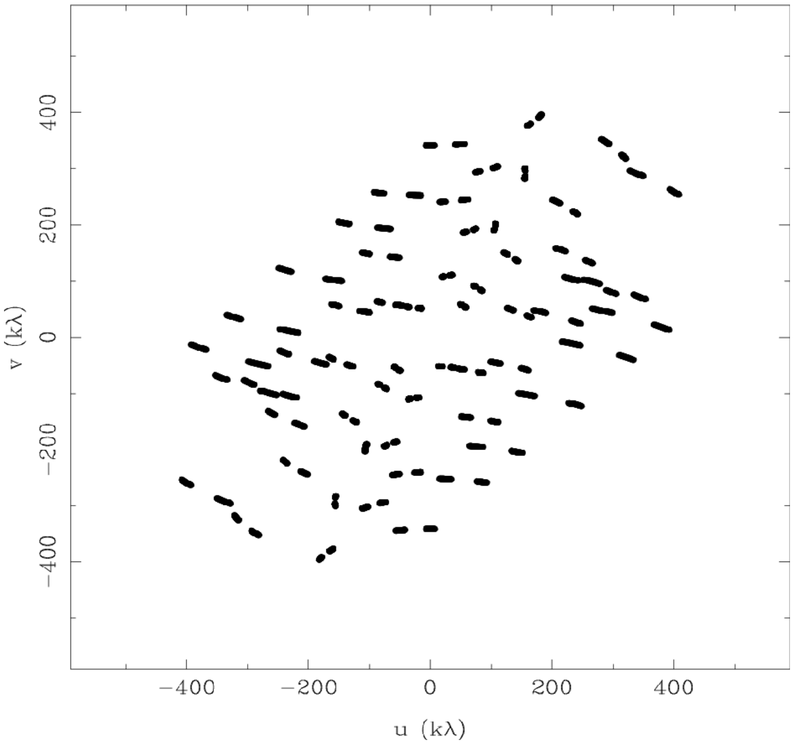
8 Antennas x 30 Samples

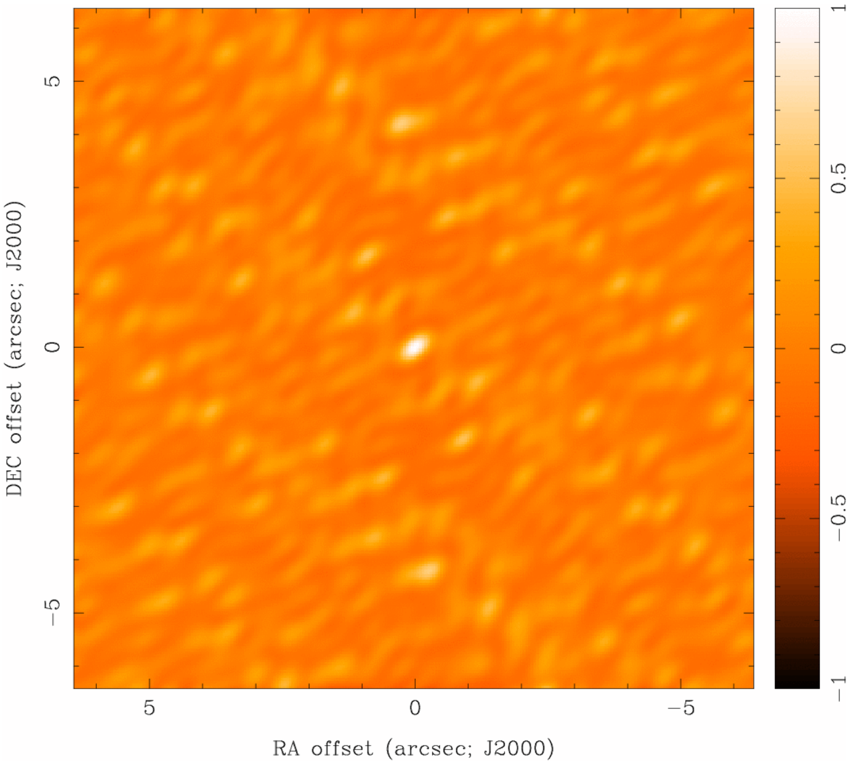




Effects of a sparse *uv* coverage

8 Antennas x 60 Samples





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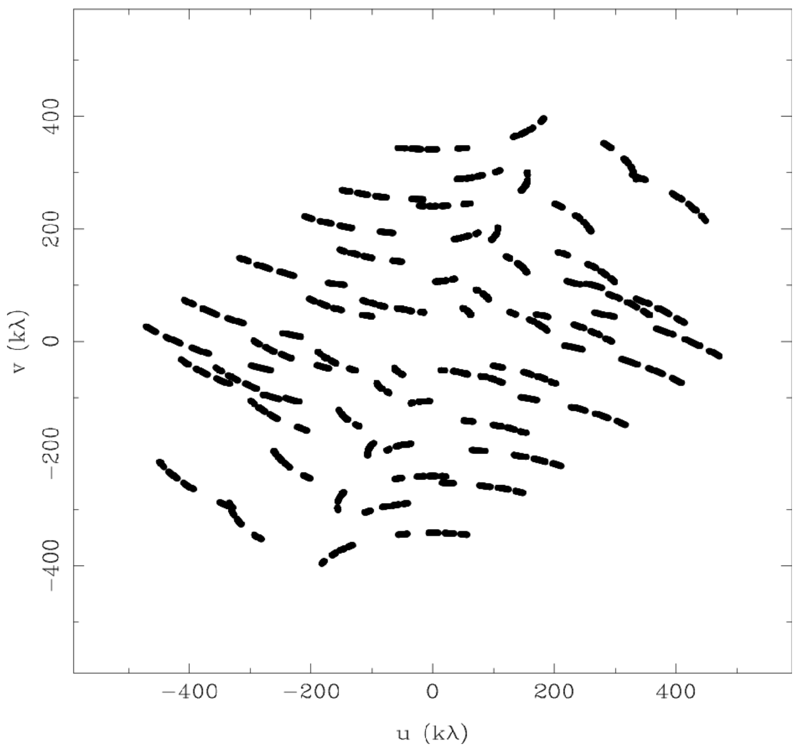
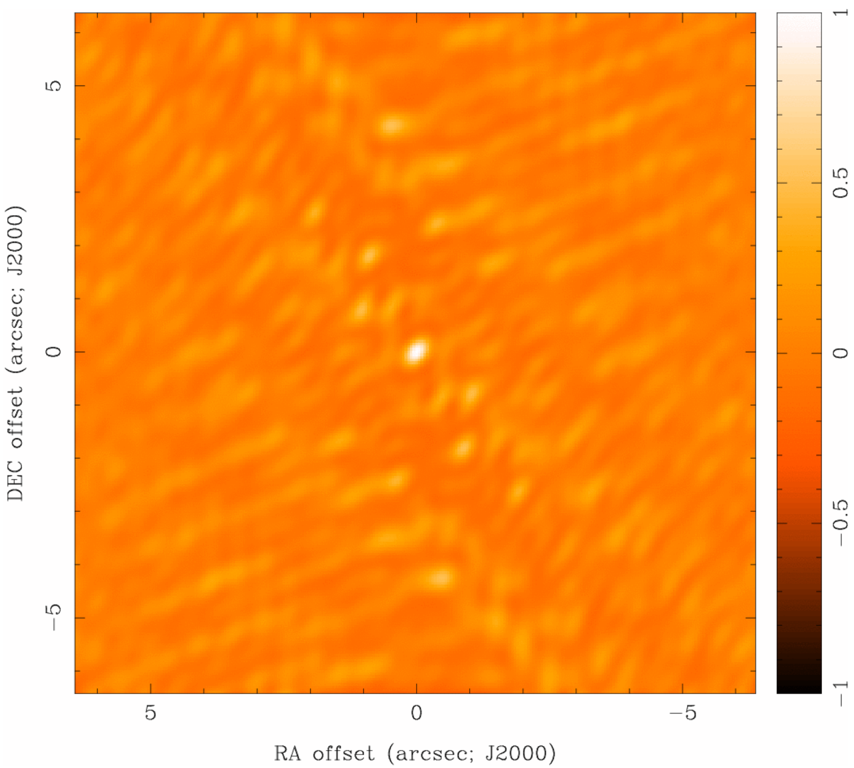
Effects of a sparse *uv* coverage

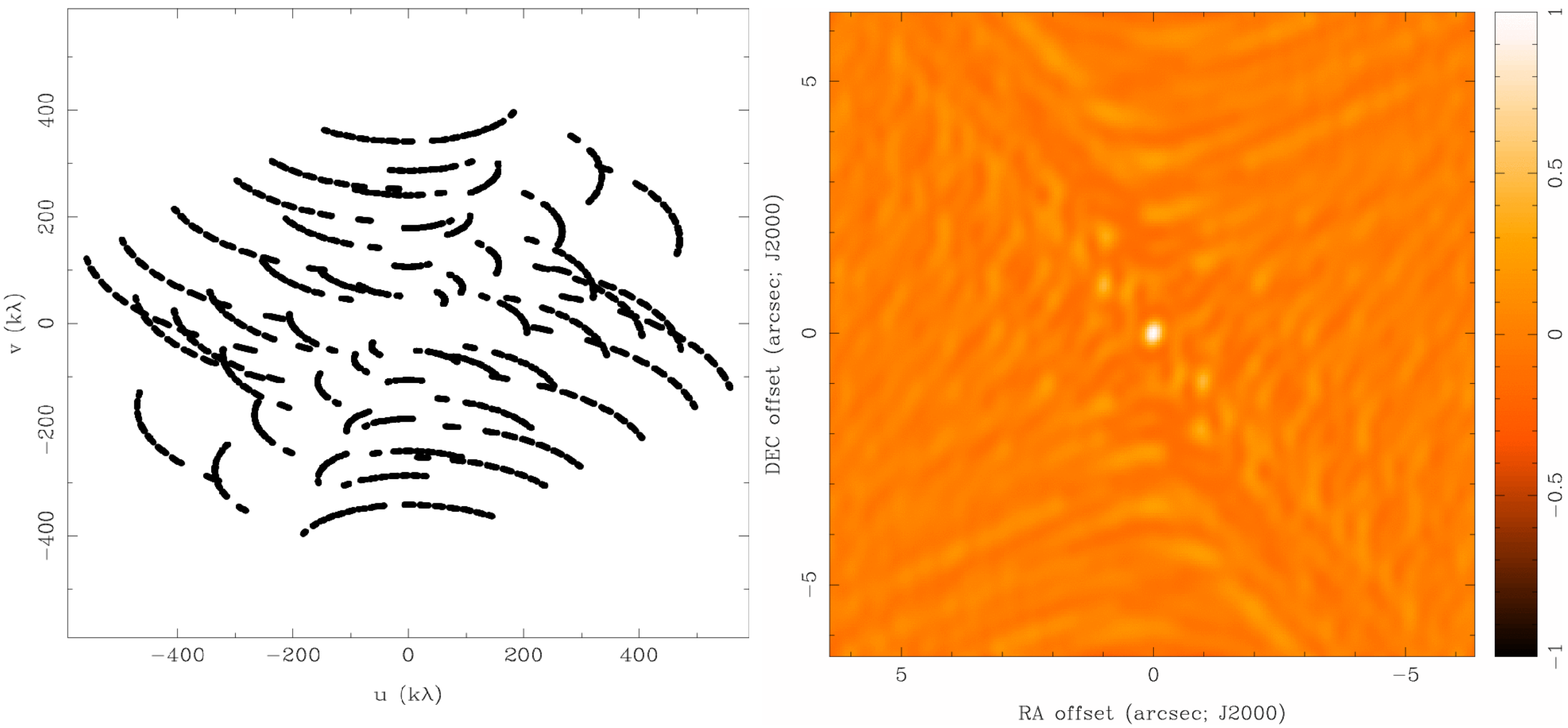
8 Antennas x 120 Samples





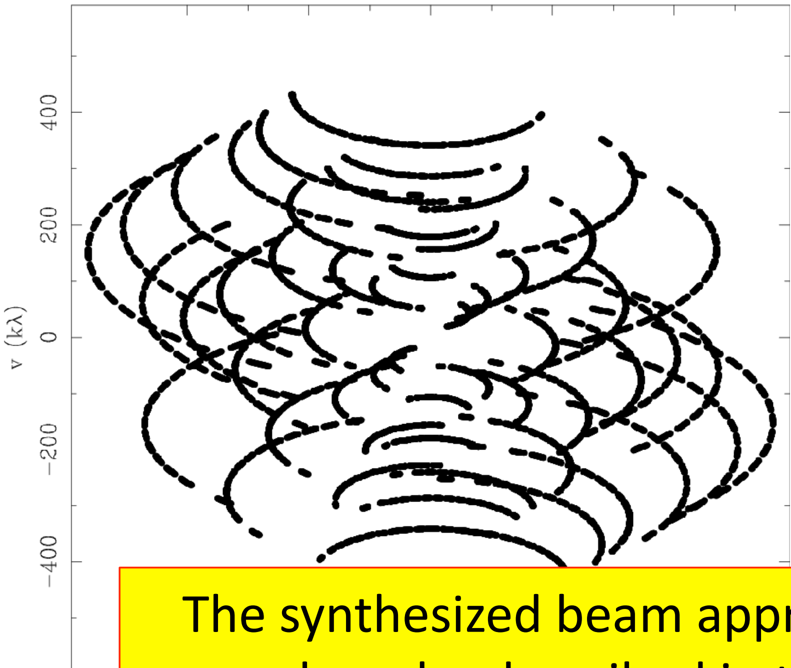
Effects of a sparse *uv* coverage

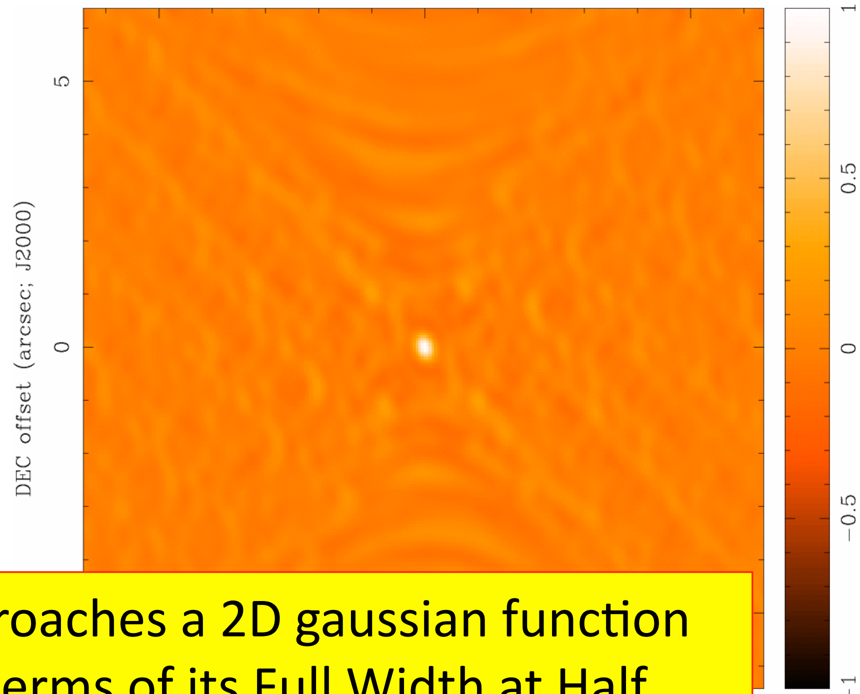
8 Antennas x 240 Samples



Effects of a sparse *uv* coverage

8 Antennas x 480 Samples





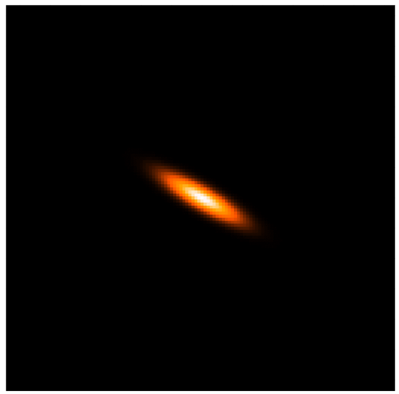
The synthesized beam approaches a 2D gaussian function and can be described in terms of its Full Width at Half Maximum (FWHM) and Position Angle (PA)

2D Fourier Transform Pairs

T(x,y)

I(θ)

elliptical Gaussian



⇌

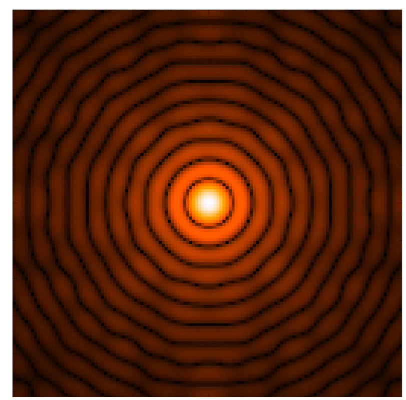
|V(u,v)|

I(u)

elliptical Gaussian

Disk

⇌

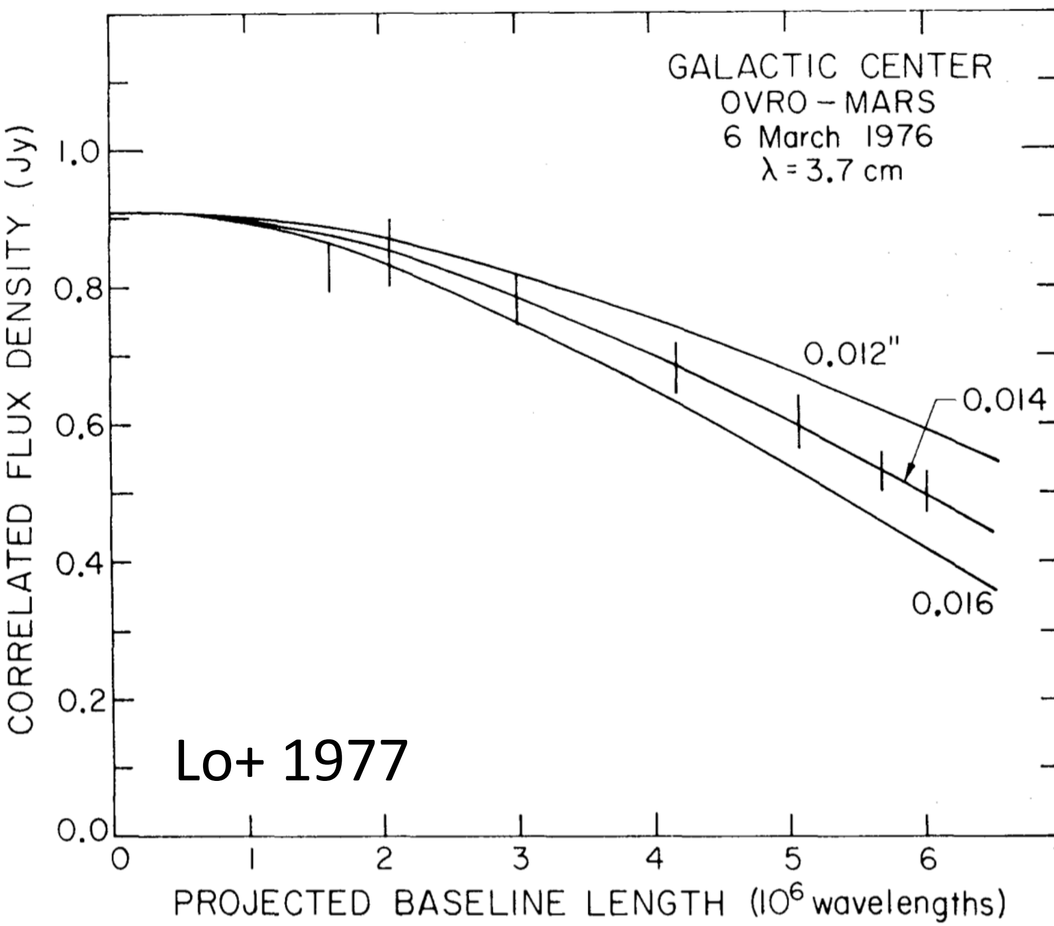


Bessel

sharp edges result in many high spatial frequencies

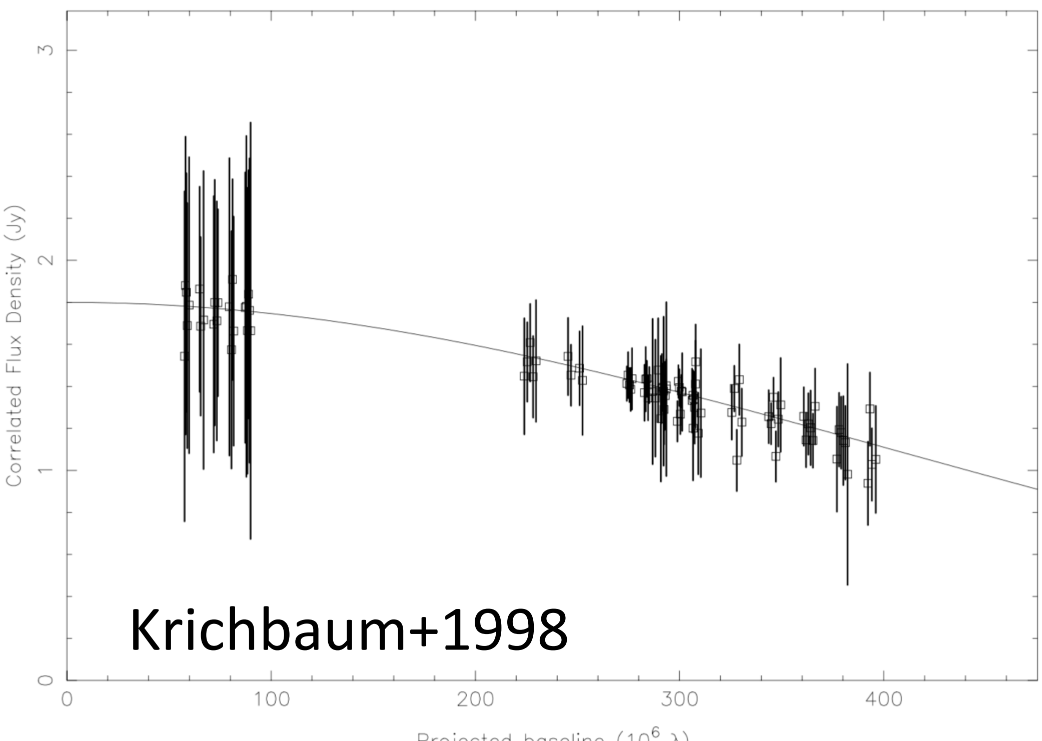
Interferometry of Sagittarius A*

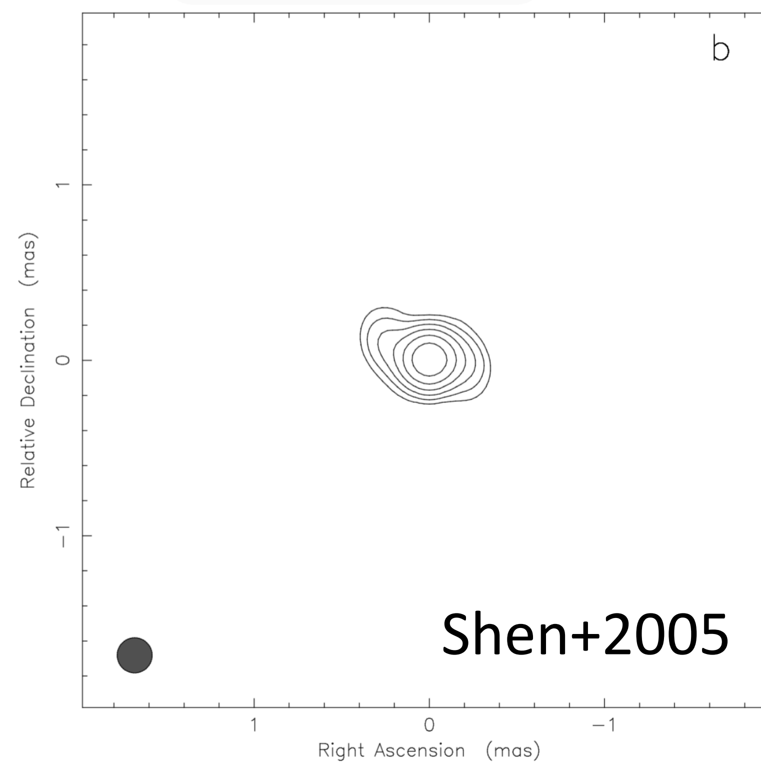
- A compact radio source at the very center
  (Balick & Brown 1974)



Push to higher resolution, shorter wavelength

- VLBI observations
  (Lo, Moran, Krichbaum, Bower, …)
- Atmosphere changes every ~10-100s





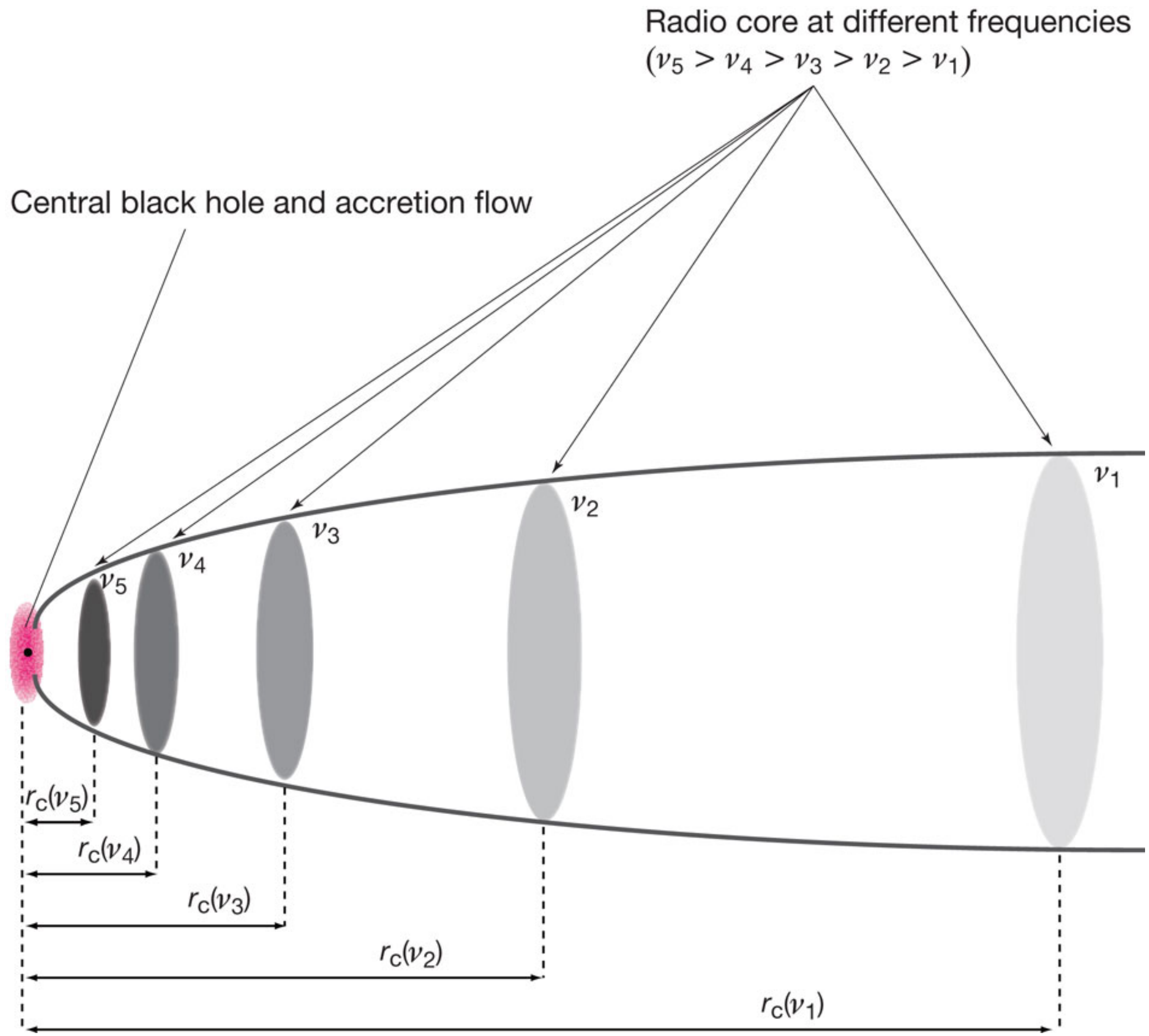
Viewing the shadow of Sgr A*

Falcke, Melia, Agol 2000

- Spatial resolution: $\lambda/B \sim 10$ μas with $B \sim 10000$ km: need $\lambda \sim 1$mm
- Interstellar scattering $\sim \lambda^2$, $\theta_{SC} \sim 10$ μas λ_{mm}^2
- Synchrotron self-absorption: $\tau < 1$ at $\lambda < 1$mm

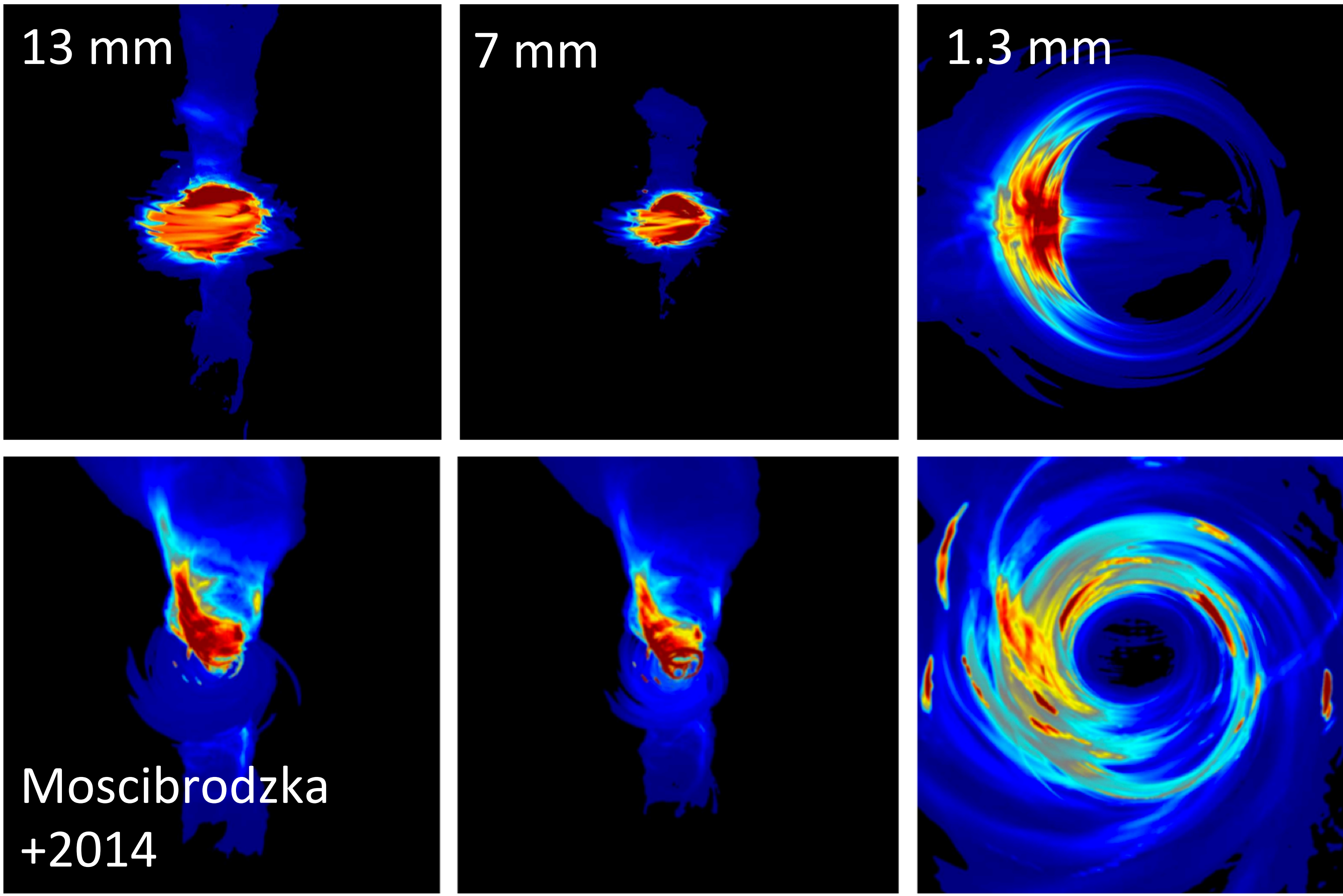
Viewing the shadow of Sgr A*

- Synchrotron self-absorption: $\tau < 1$ at λ<1mm

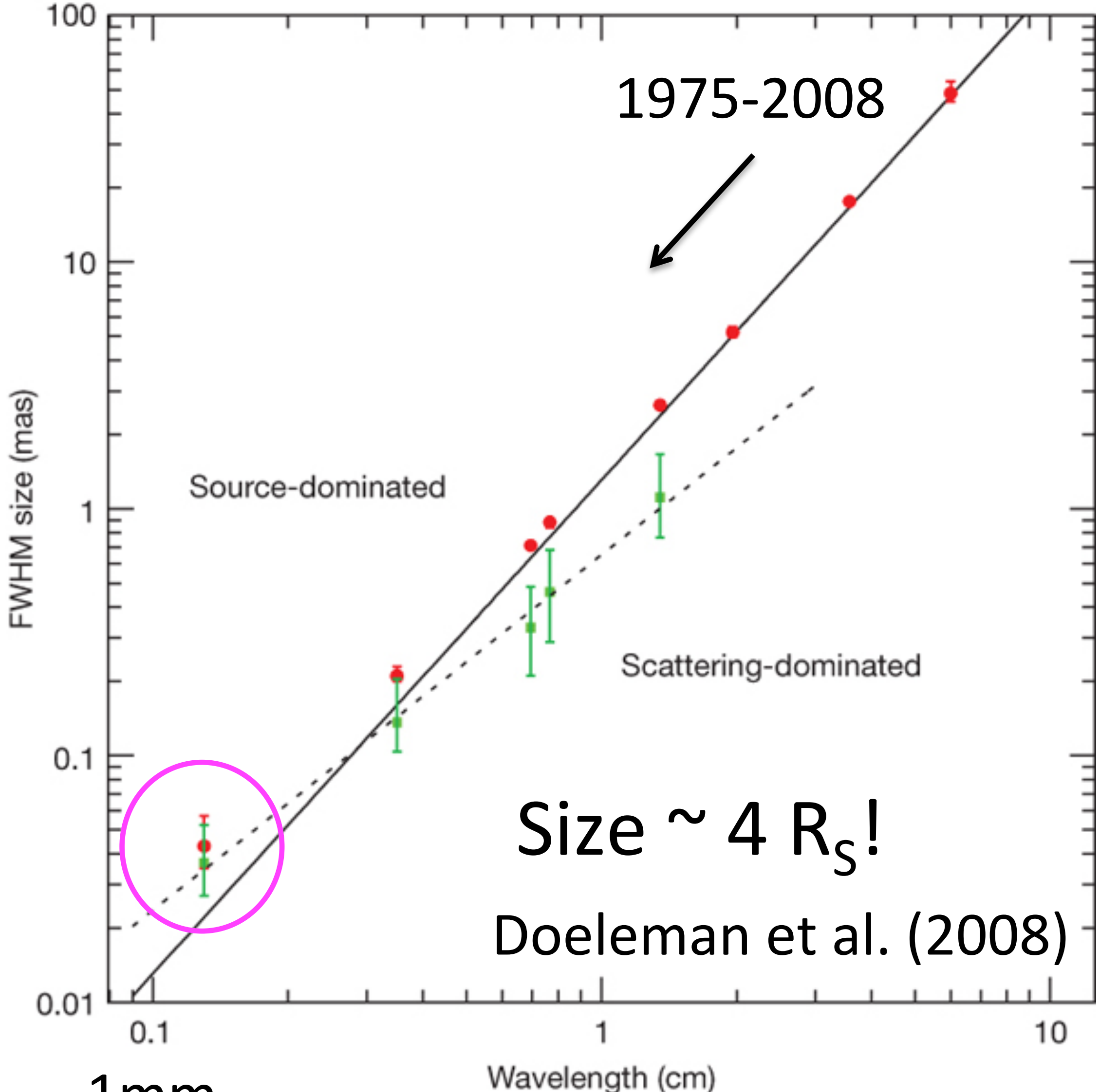


Viewing the shadow of Sgr A*

- Synchrotron self-absorption: $\tau < 1$ at $\lambda<1mm$



The radio size of Sgr A*



Size (mas)

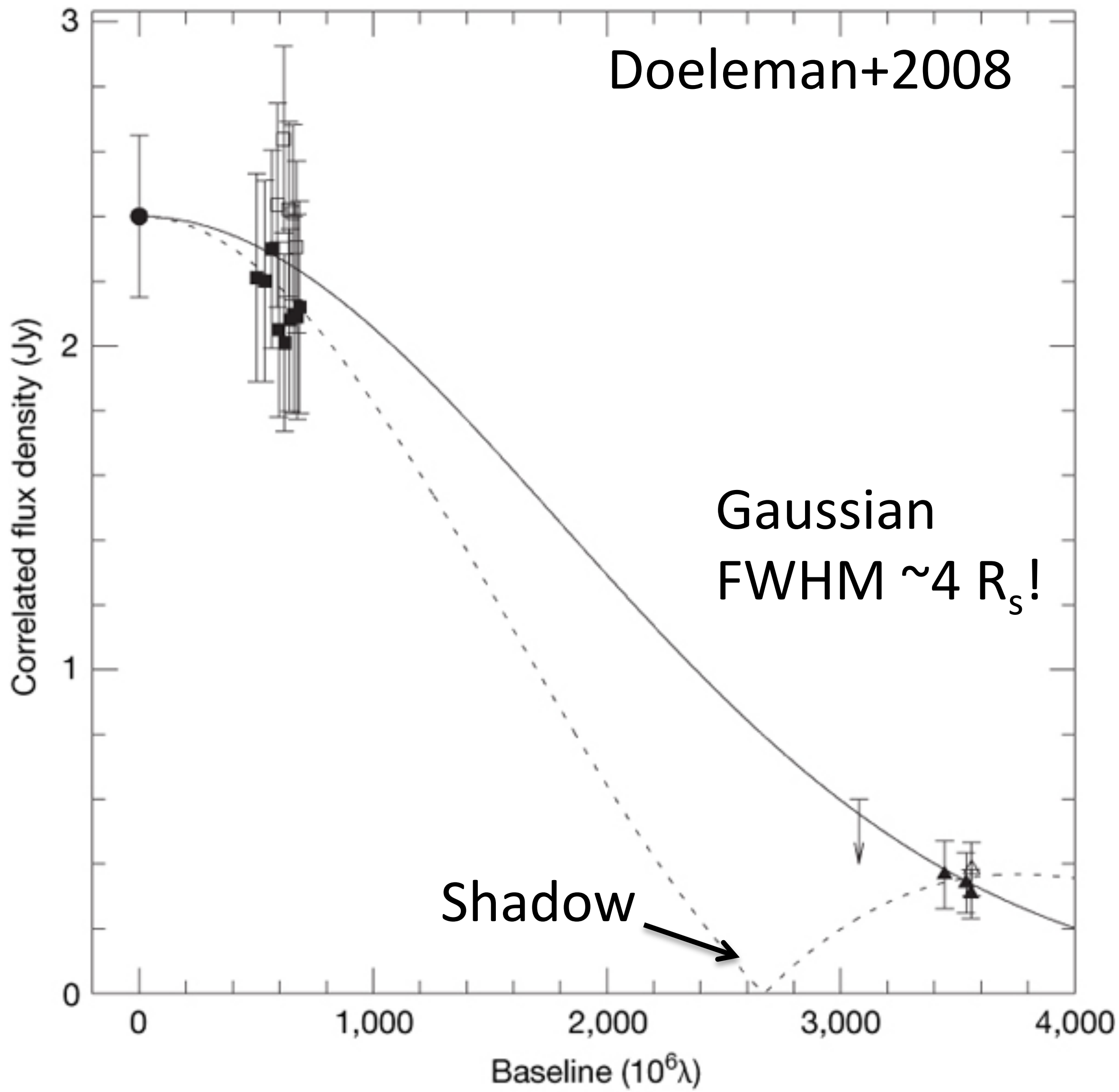
Size ~ 4 R_S!

Doeleman et al. (2008)

1mm

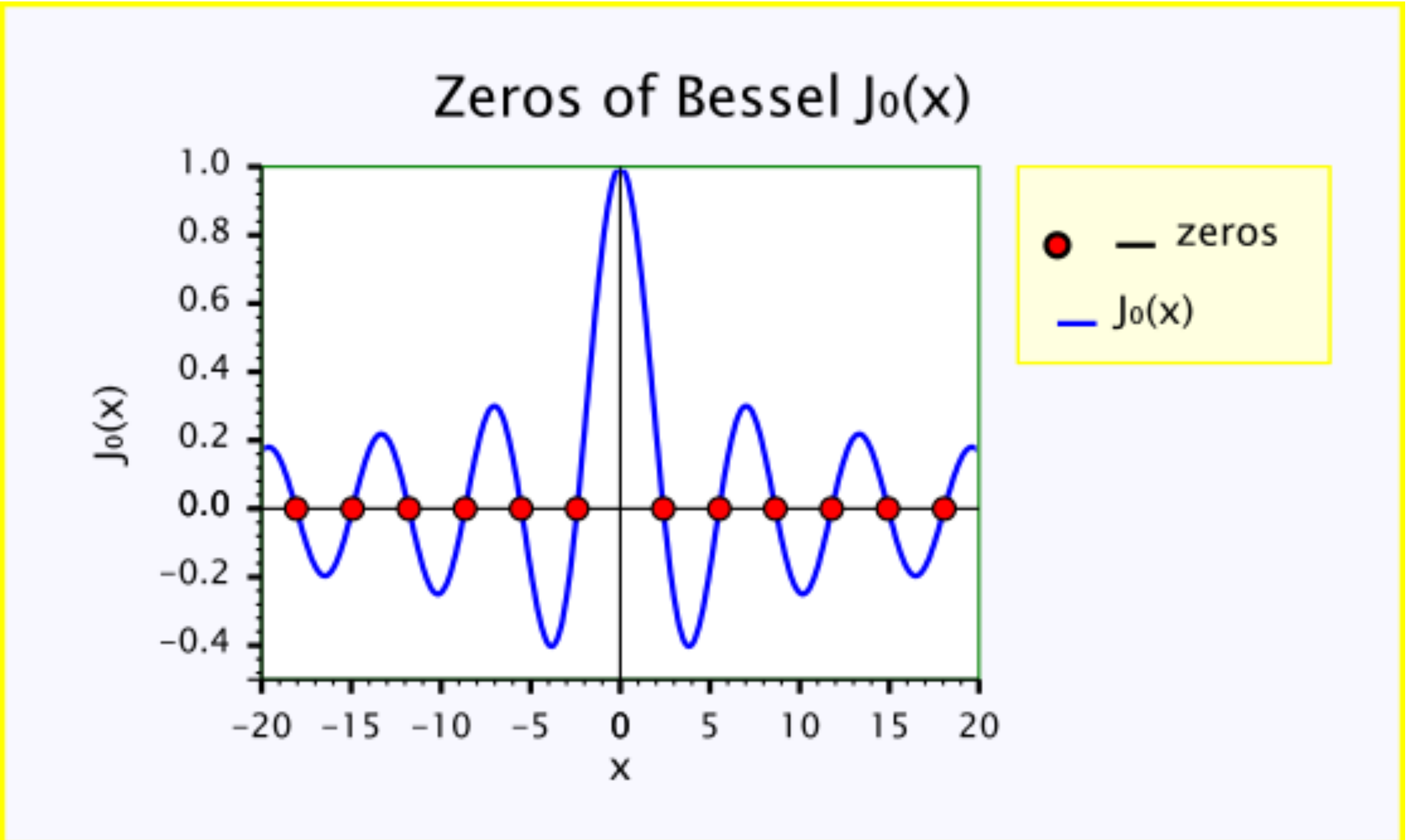
Wavelength (cm)

First 1.3mm VLBI data



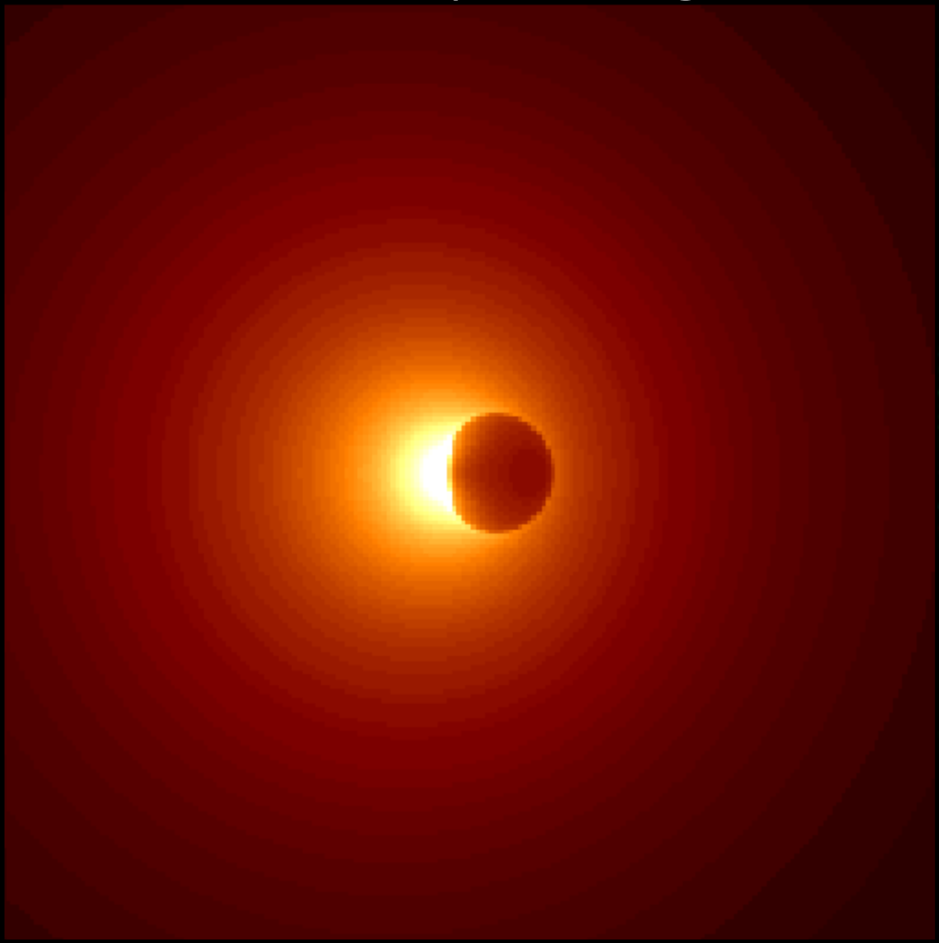
Black hole shadow as a “null”

- I(theta) ~ delta(r-r0), I(**u**) = J_0(2piur$_0$)
- Shadow: r_0 ~ 25 μas, zero at u ~ 3000 Mλ



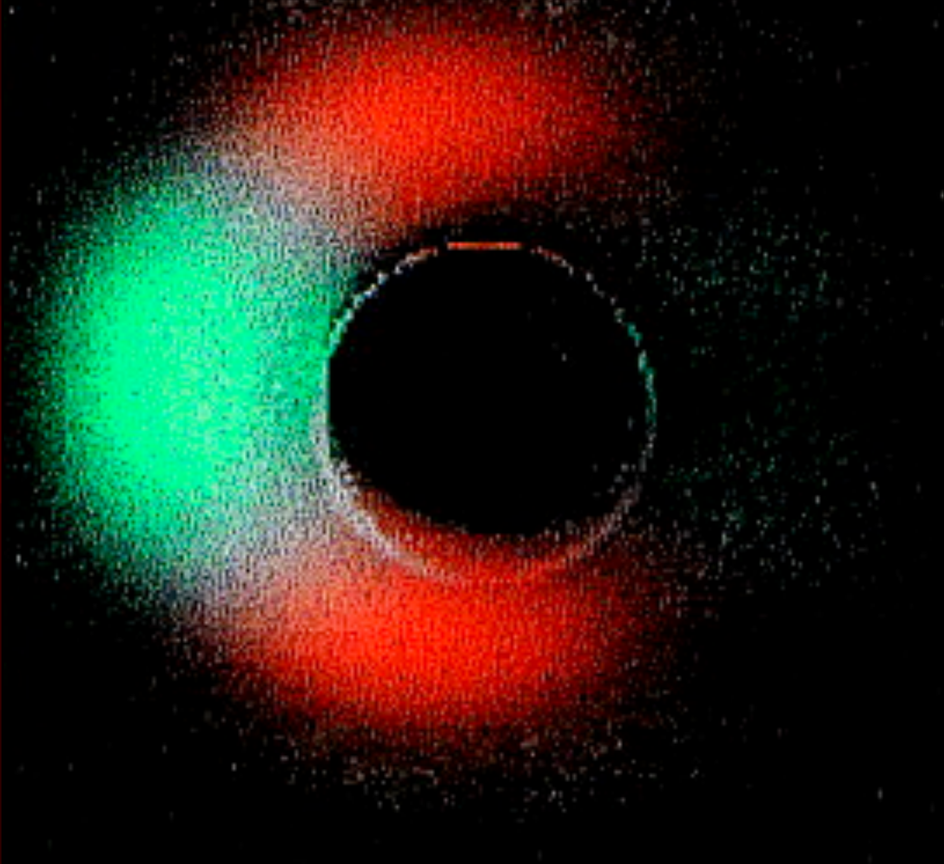
Black hole images

Orbital motion, spherical gas dist.



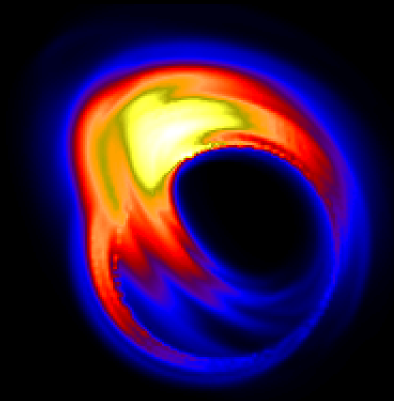
Falcke, Melia & Agol (2000)

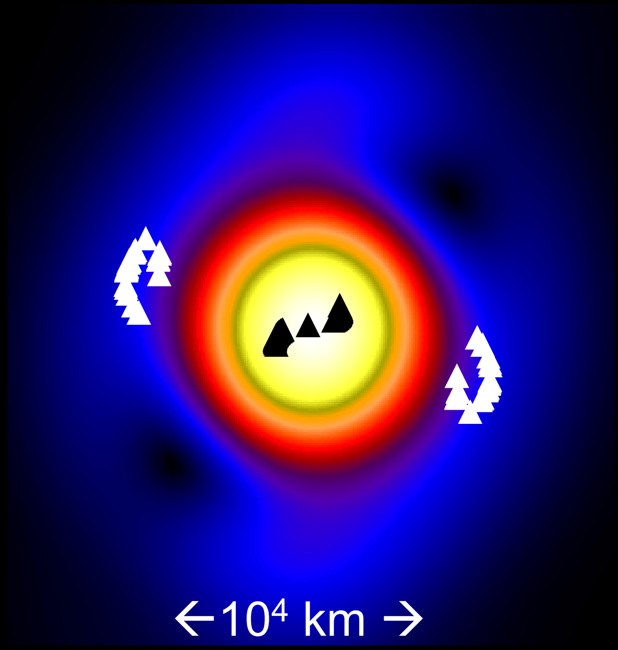
Orbital motion, gas torus, inclined to observer

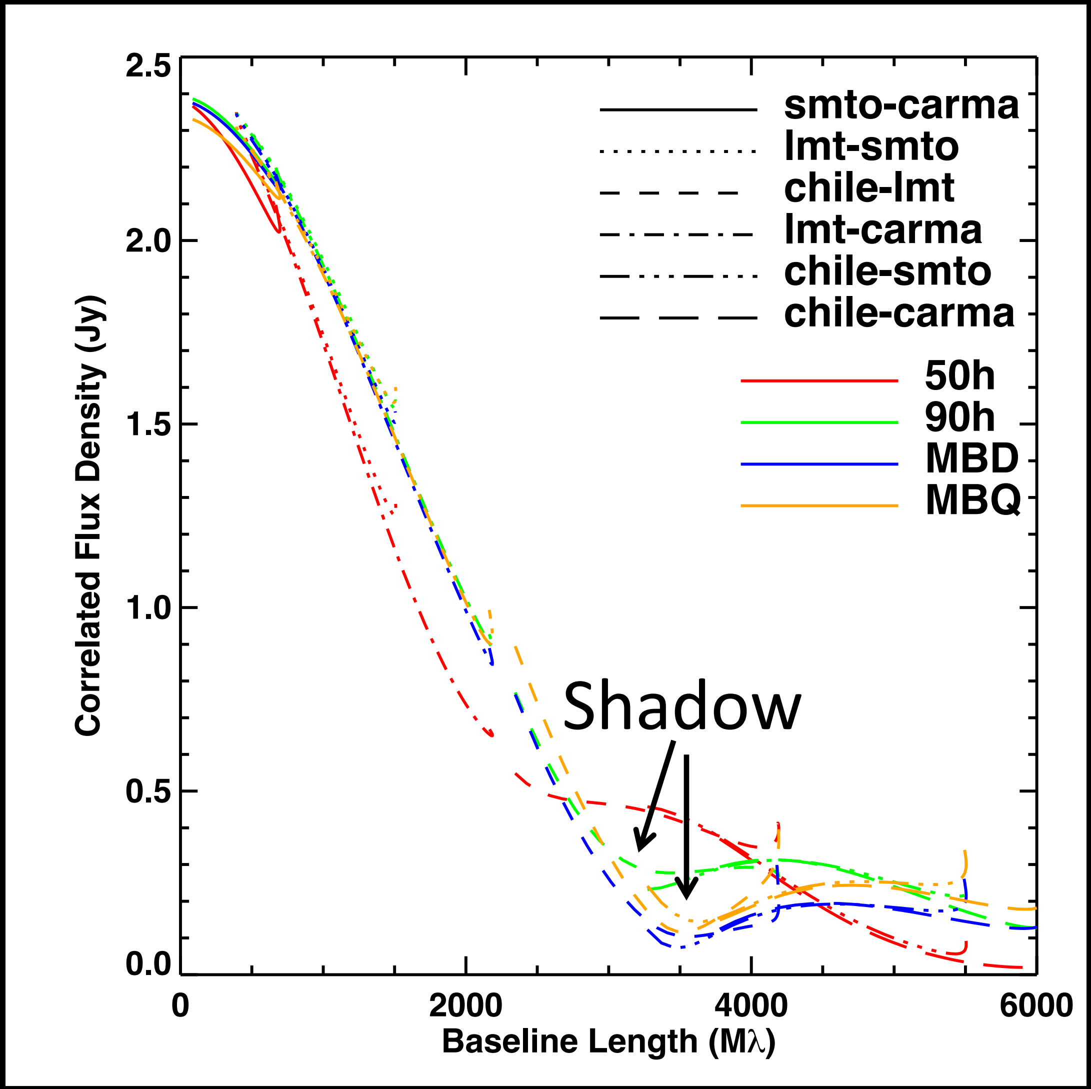


Bromley, Melia & Liu (2001)

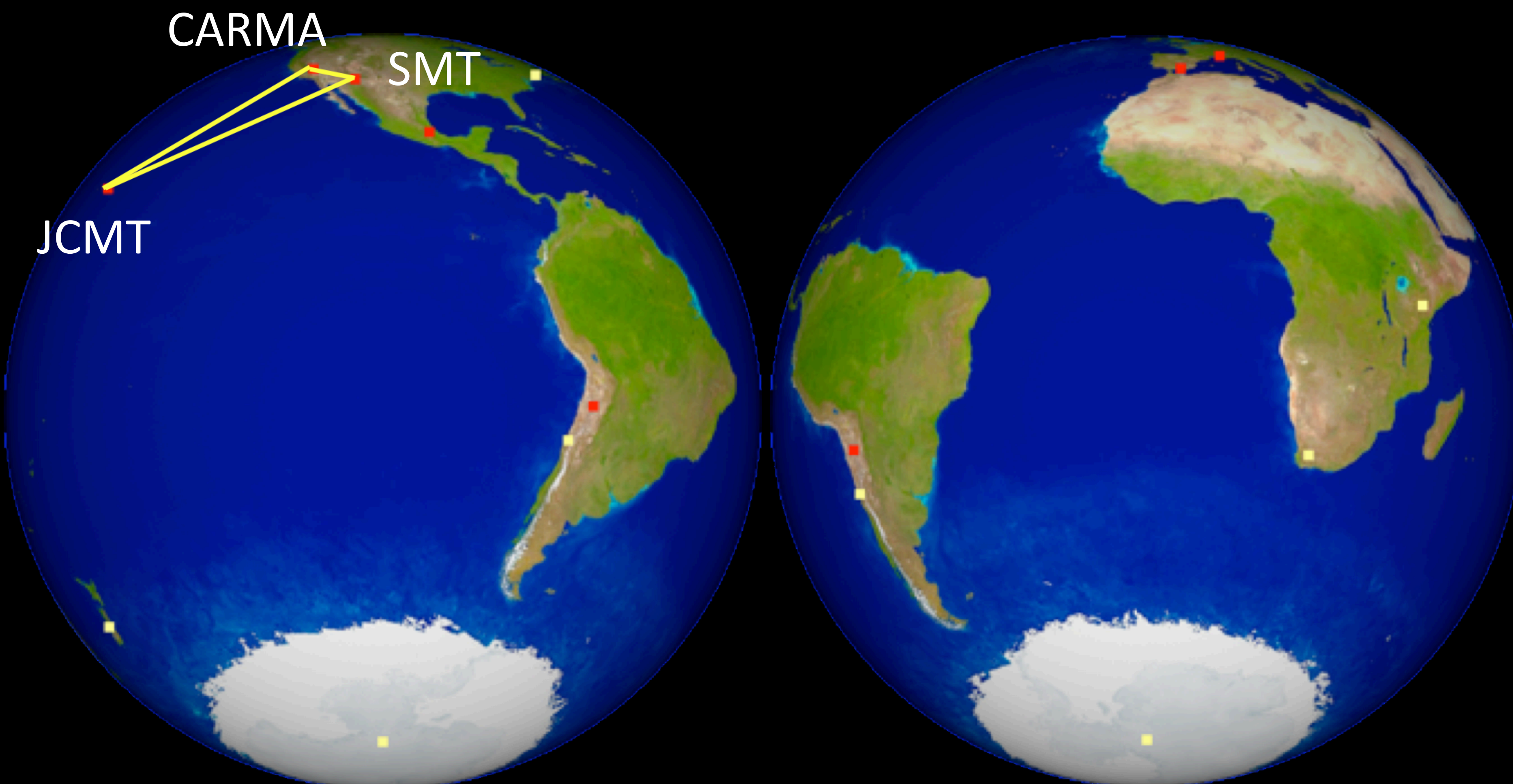
Crescent image BH shadows



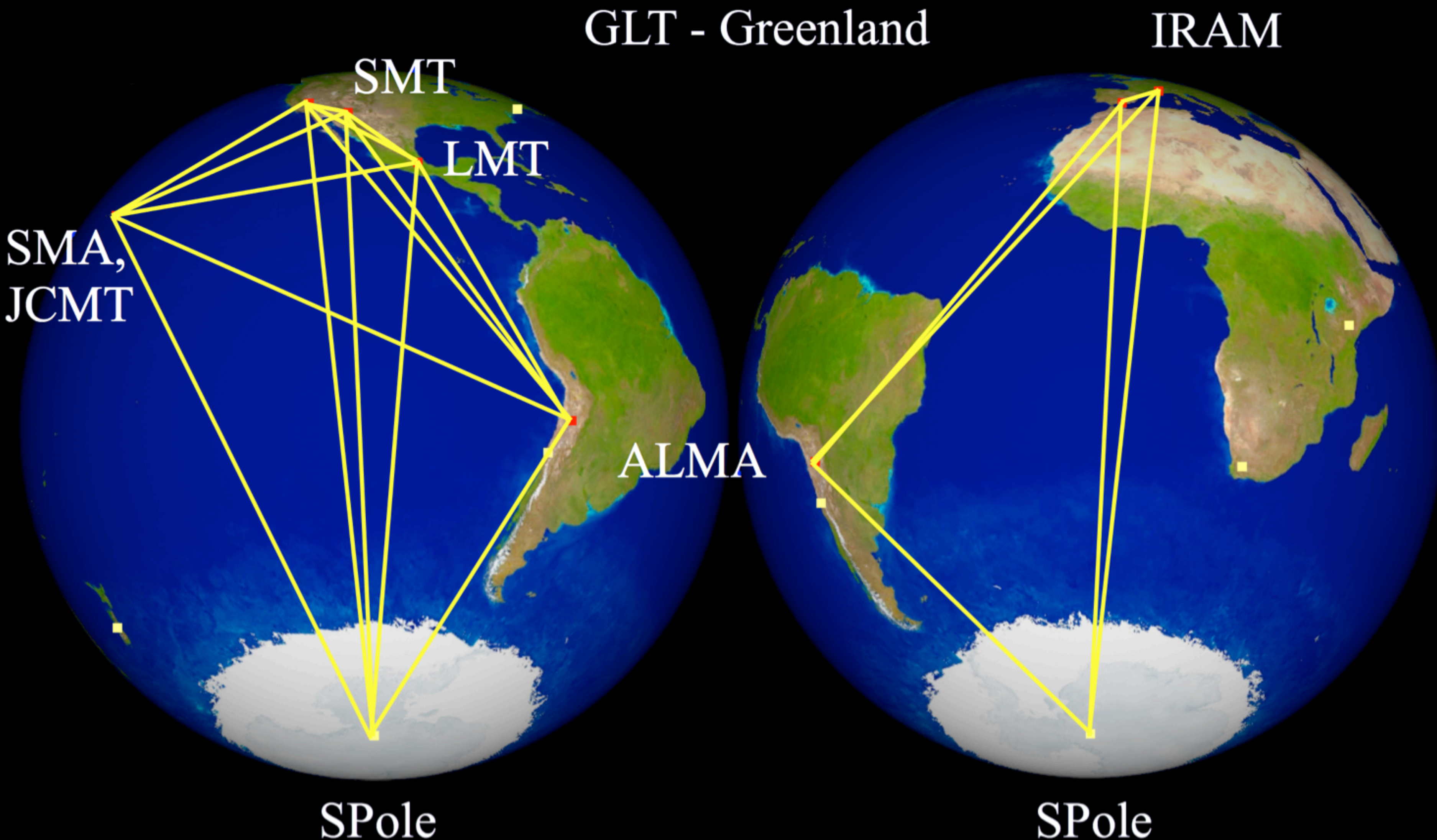




Event Horizon Telescope 2007



Event Horizon Telescope 2017



M87 imaging with EHT+ALMA

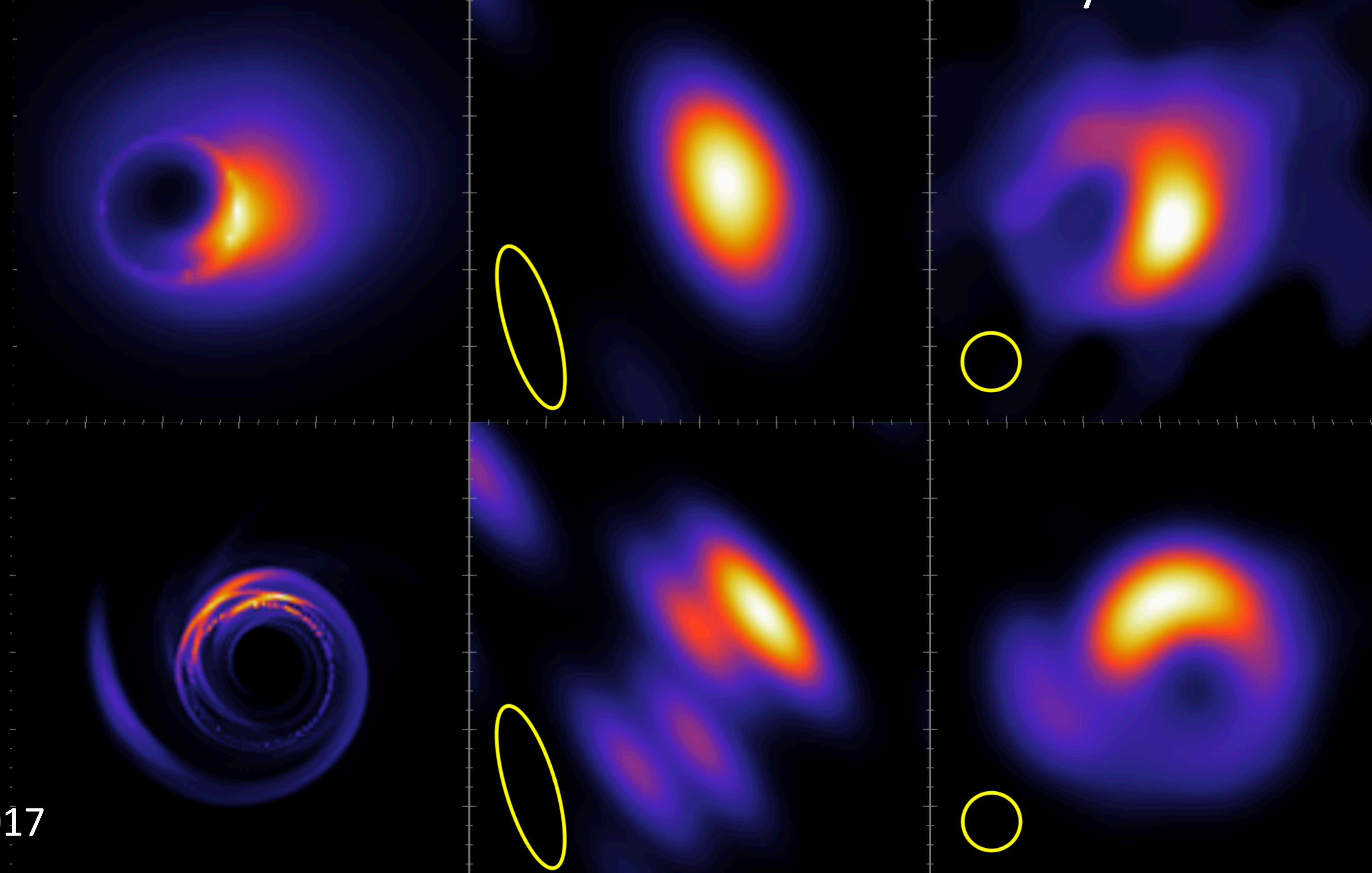
Akiyama+2017

Forward jet

Broderick+2009,
Lu+2012

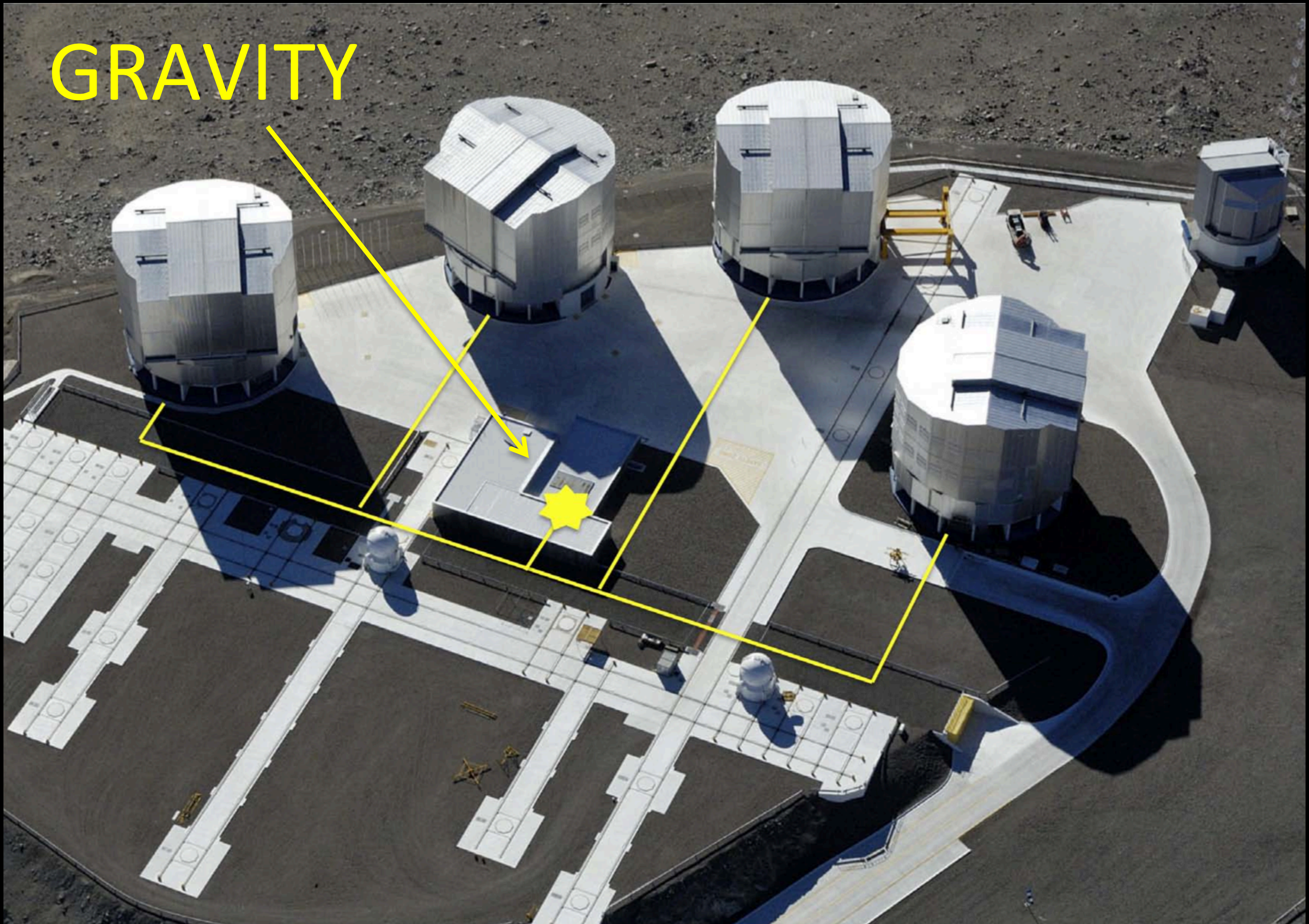
Counter jet

Dexter+2012,
Moscibrodzka+2017



Original | EHT 2013 | EHT 2017

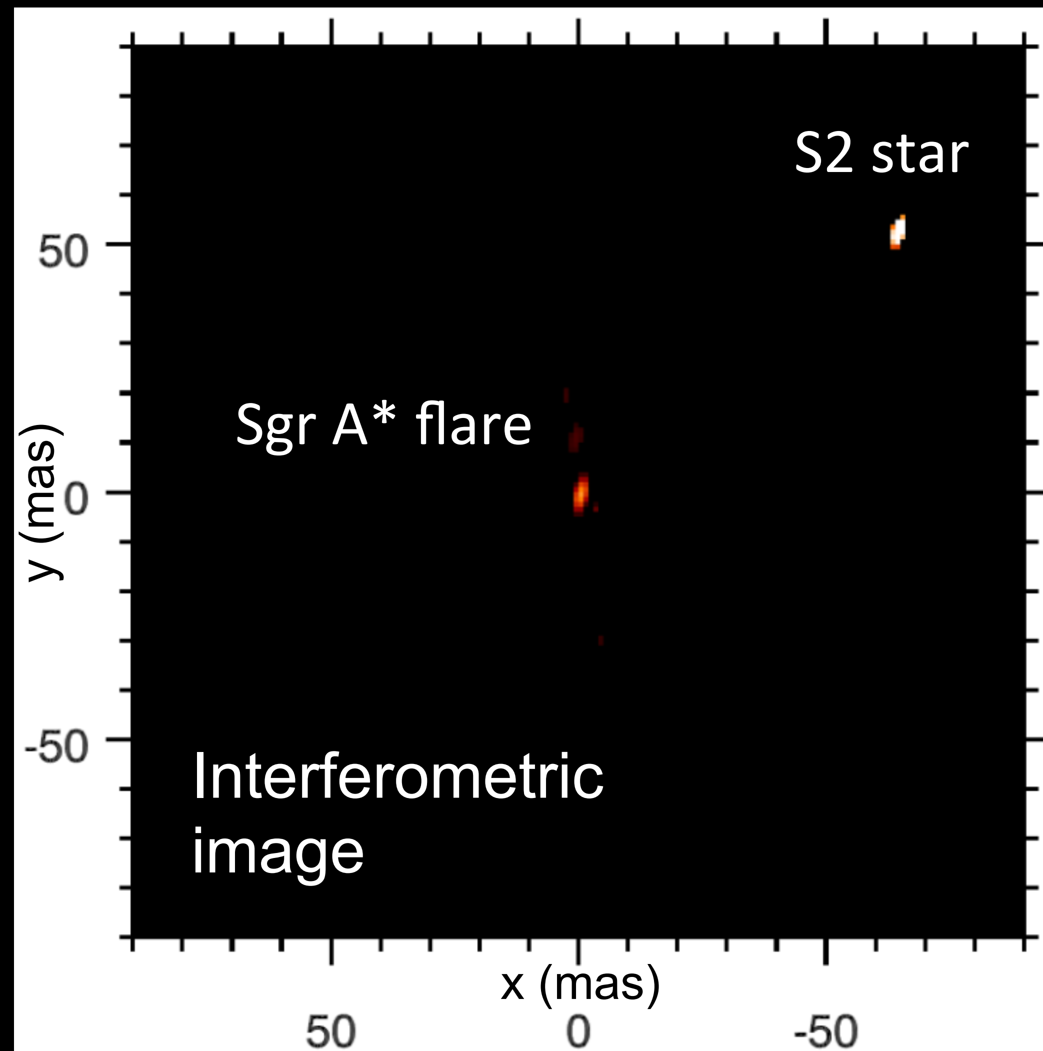
VLTI GRAVITY:
4 telescope optical interferometry



GRAVITY image of the Galactic center

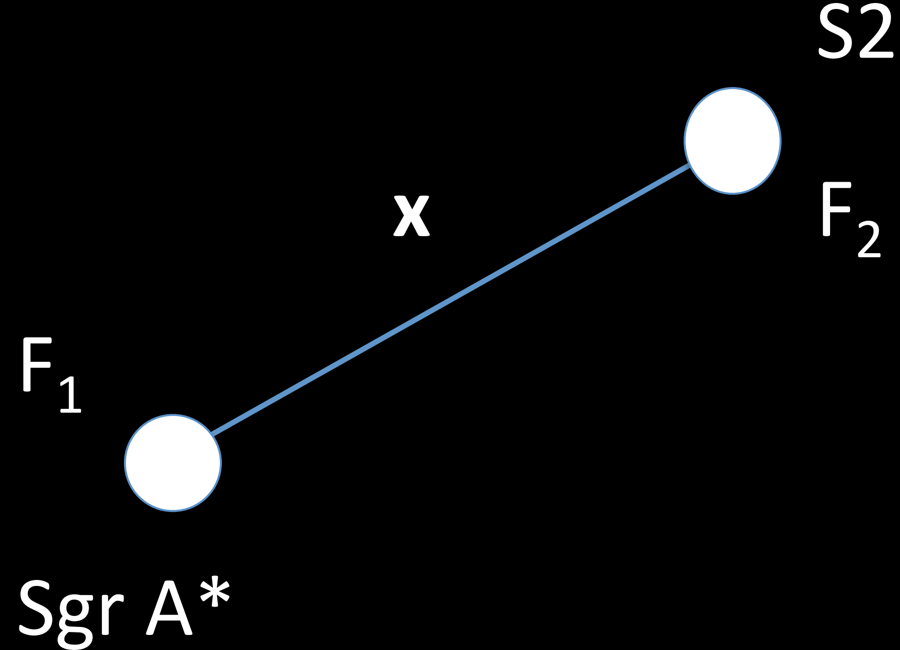
GRAVITY Collaboration+2017

Diffraction limited image



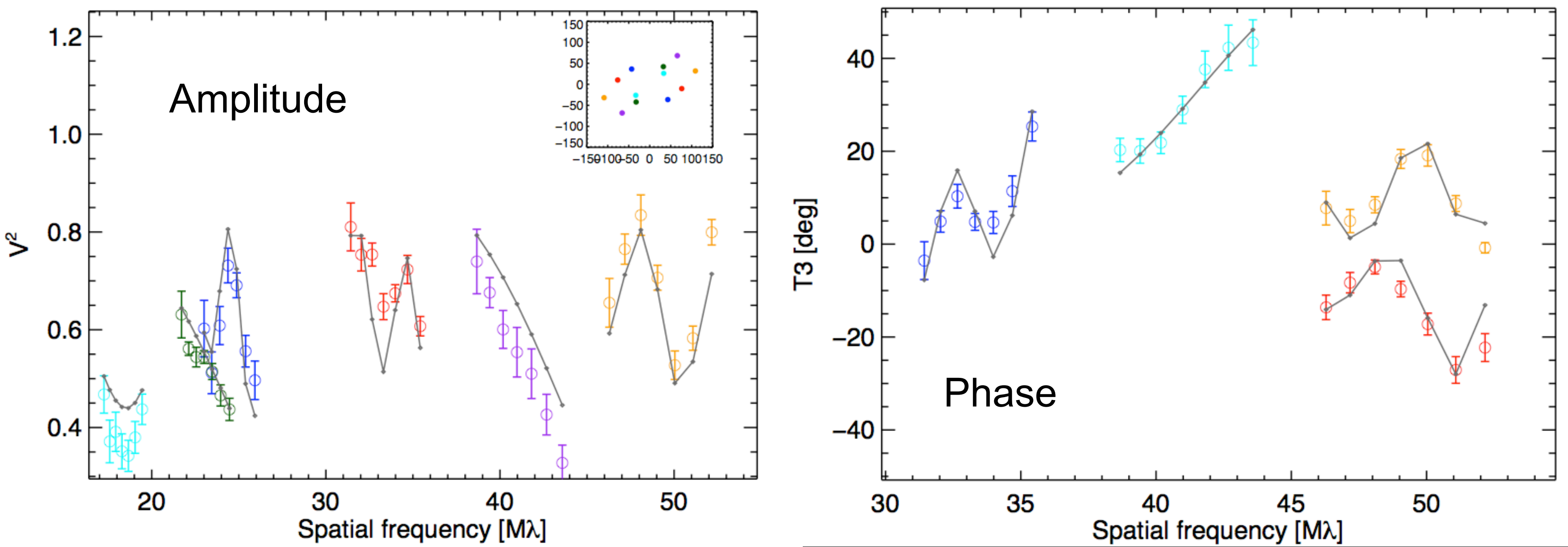
The Sgr A* - S2 binary

- Binary: $$\mathbf{I(u)} = \frac{\mathbf{1 + fe^{-2\pi i u \cdot x}}}{\mathbf{1 + f}}$$
- Separation **x**, flux ratio f = F_2/F_1



The Sgr A* - S2 binary

- Binary: $$\mathbf{I(u)} = \frac{\mathbf{1 + fe^{-2\pi iu \cdot x}}}{\mathbf{1 + f}}$$
- Separation ~ 50 mas, oscillation frequency ~ 5 Mλ, amplitude → f

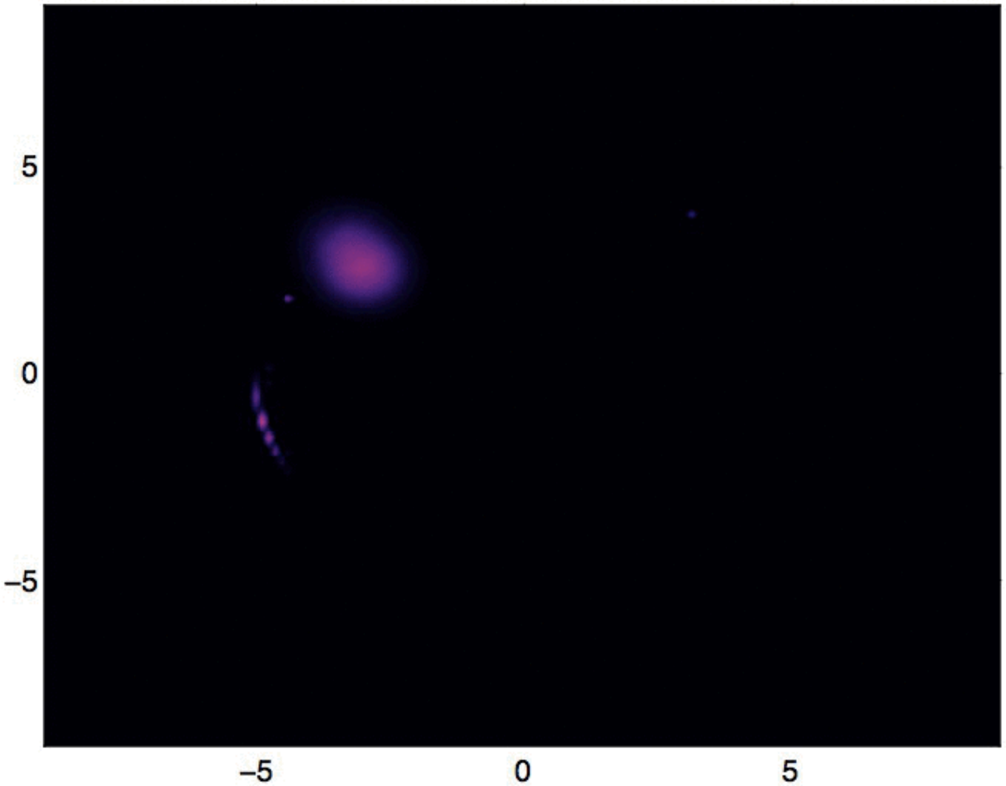


GRAVITY GC science

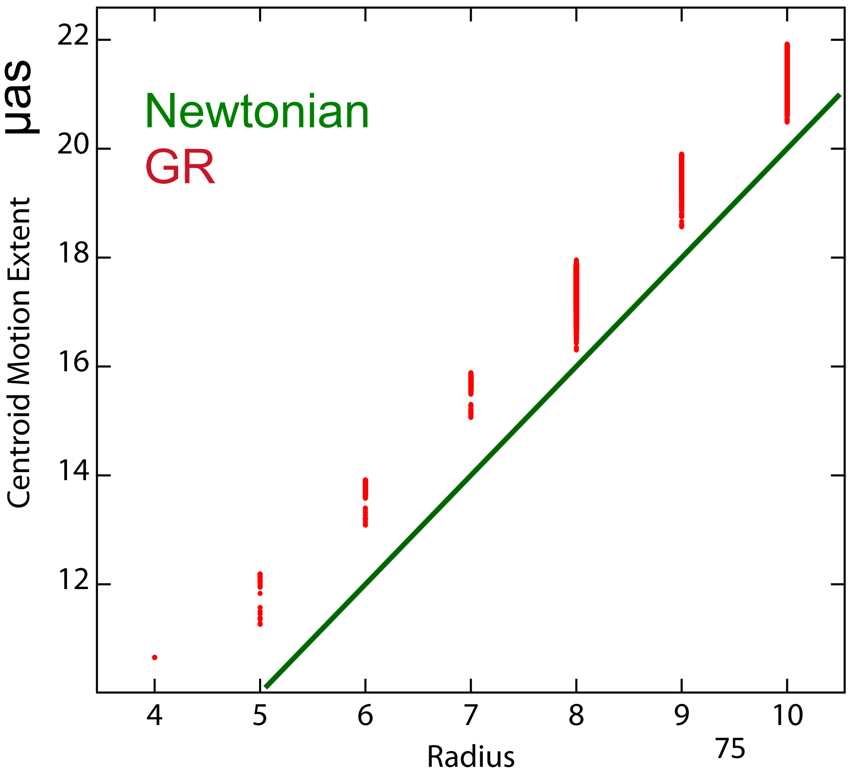
- S2 pericenter in 2018: gravitational redshift, orbital precession
- Discovering new S stars?
- Tracking flare motions

Measuring orbits from flares

- GRAVITY could constrain orbital radii

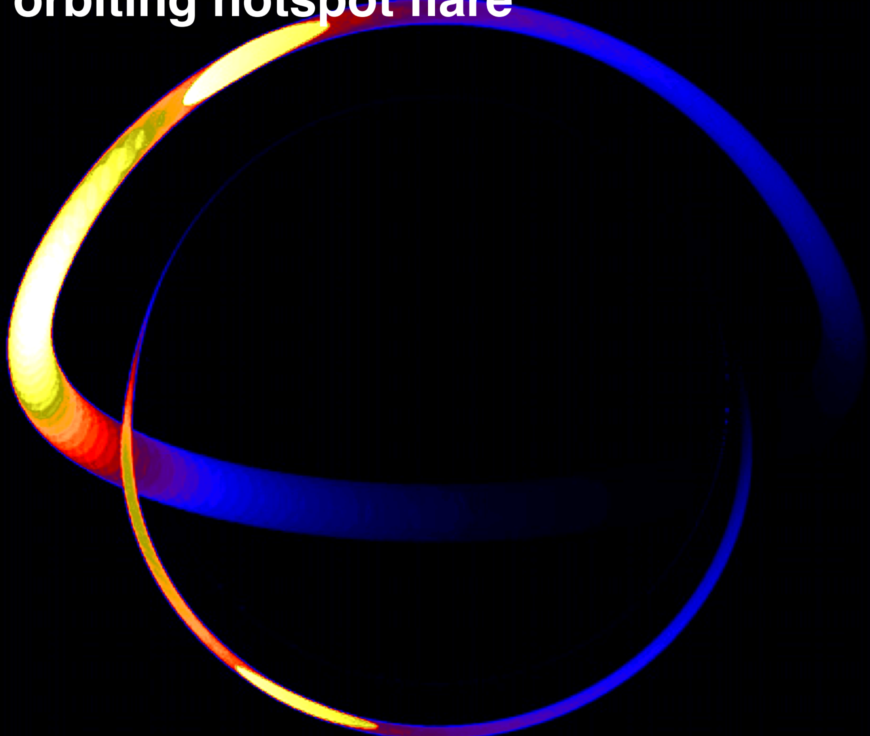


M. Bauböck

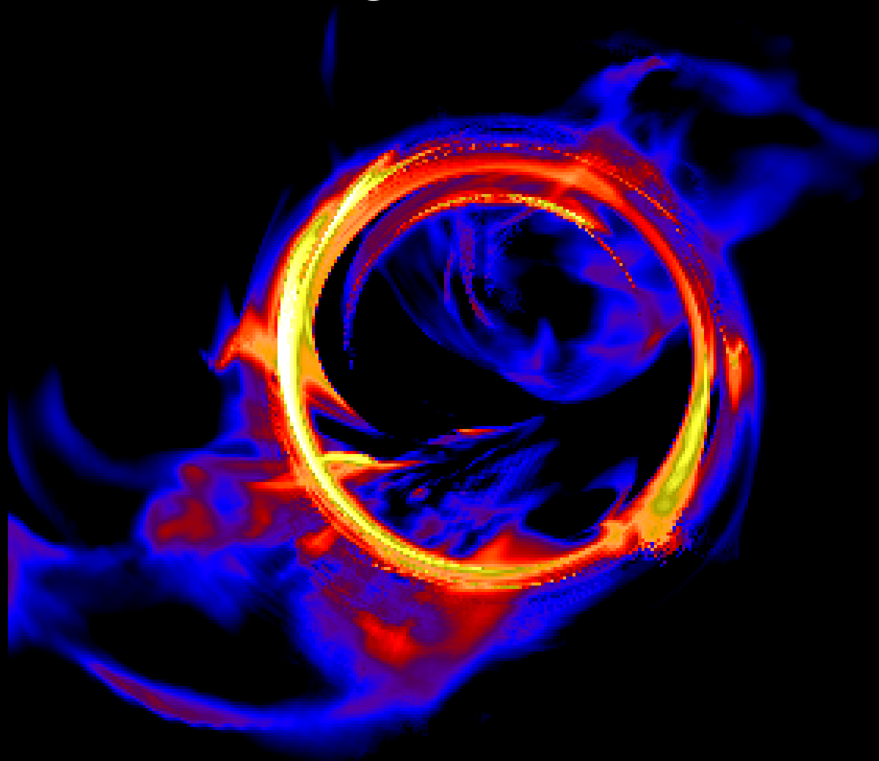


GRAVITY: tracking flare motions

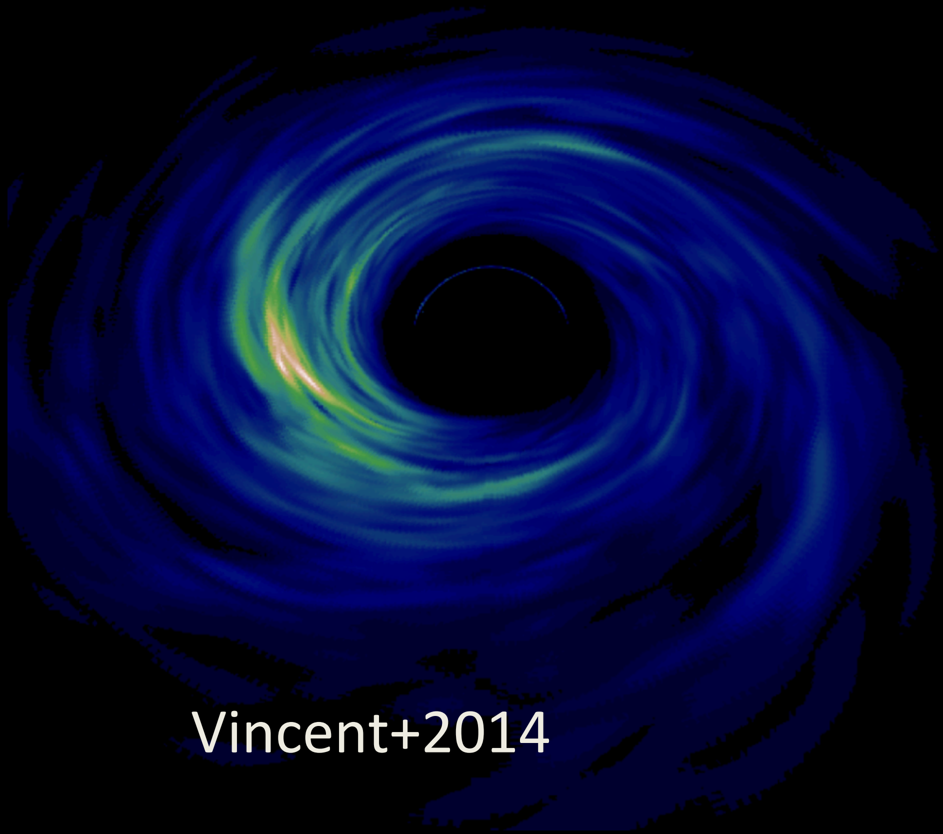
Hotspot (Hamaus+2009)

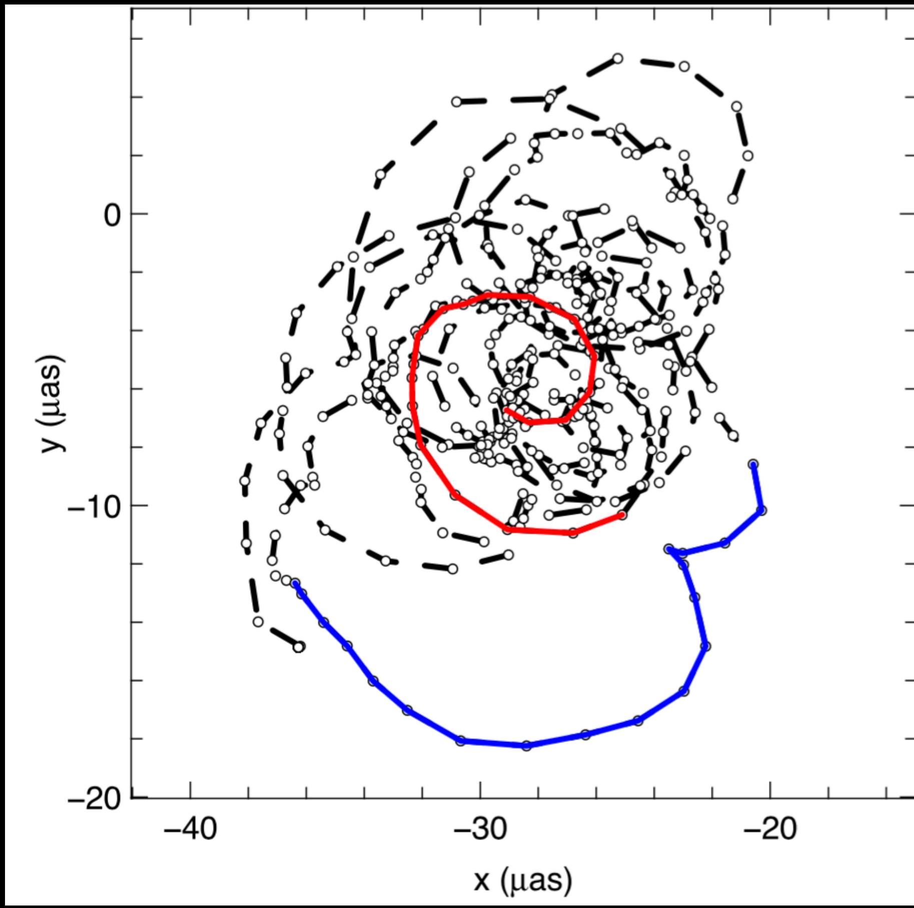


Shock (Dexter & Fragile 2013)



GRAVITY: tracking flare motions





What is the nature of flares?