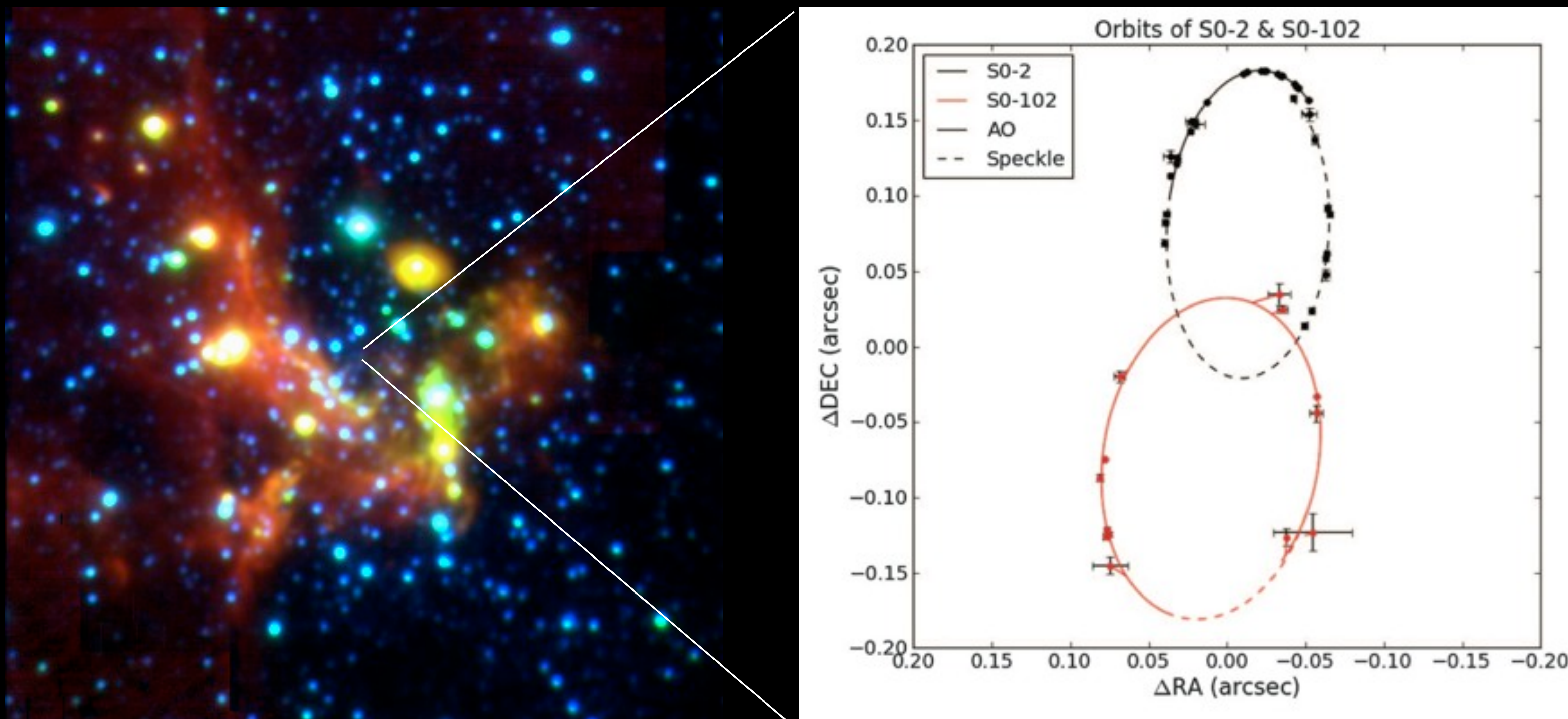
Short-Period Stars Near Our Galaxy's Supermassive Black Hole



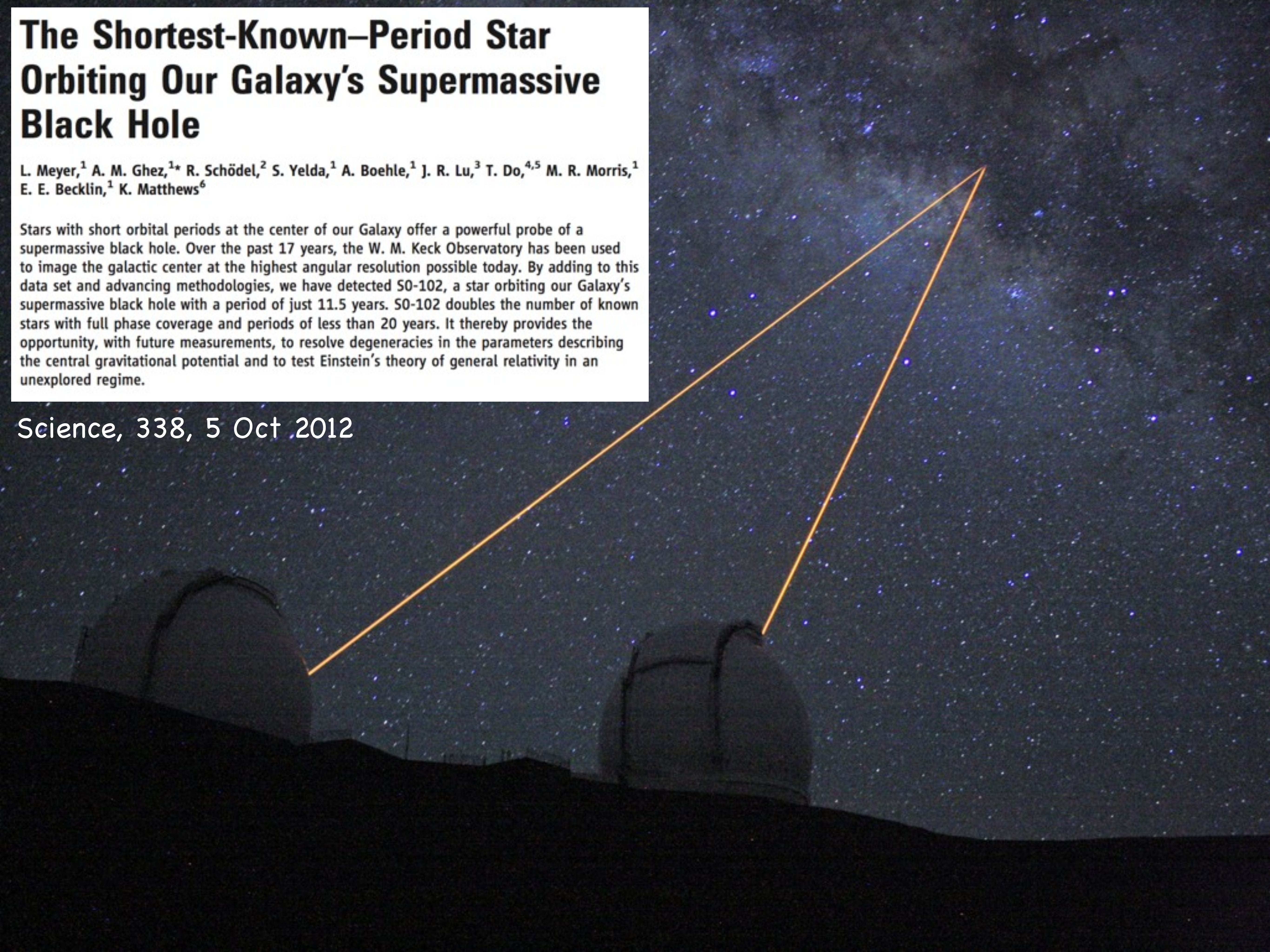
Rainer Schödel
Stellar Systems Group, IAA-CSIC
Institut für Astronomie, Universität Wien, 13 May 2013

The Shortest-Known–Period Star Orbiting Our Galaxy's Supermassive Black Hole

L. Meyer,[1] A. M. Ghez,[1*] R. Schödel,[2] S. Yelda,[1] A. Boehle,[1] J. R. Lu,[3] T. Do,[4,5] M. R. Morris,[1] E. E. Becklin,[1] K. Matthews[6]

Stars with short orbital periods at the center of our Galaxy offer a powerful probe of a supermassive black hole. Over the past 17 years, the W. M. Keck Observatory has been used to image the galactic center at the highest angular resolution possible today. By adding to this data set and advancing methodologies, we have detected S0-102, a star orbiting our Galaxy's supermassive black hole with a period of just 11.5 years. S0-102 doubles the number of known stars with full phase coverage and periods of less than 20 years. It thereby provides the opportunity, with future measurements, to resolve degeneracies in the parameters describing the central gravitational potential and to test Einstein's theory of general relativity in an unexplored regime.

Science, 338, 5 Oct 2012



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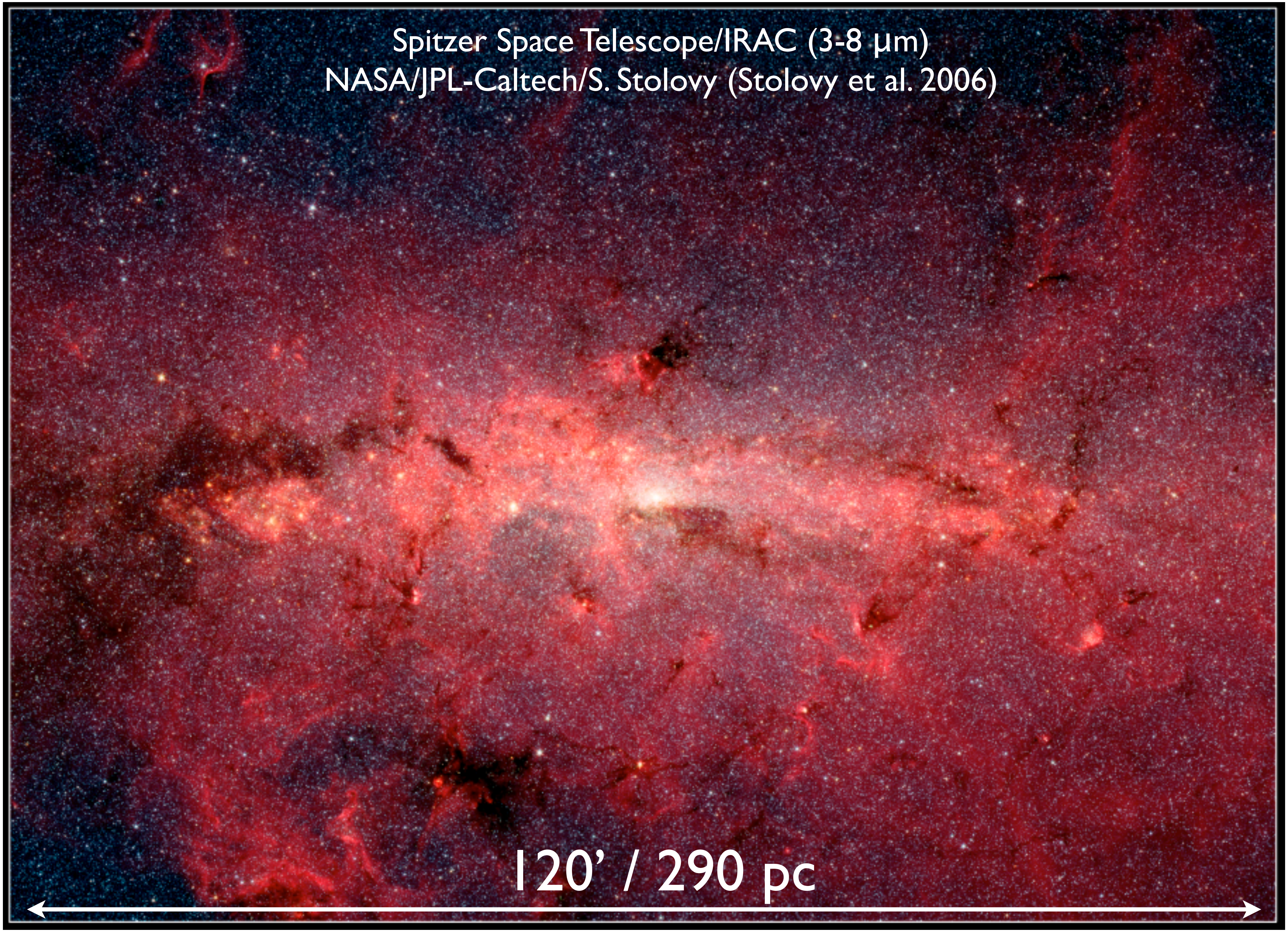
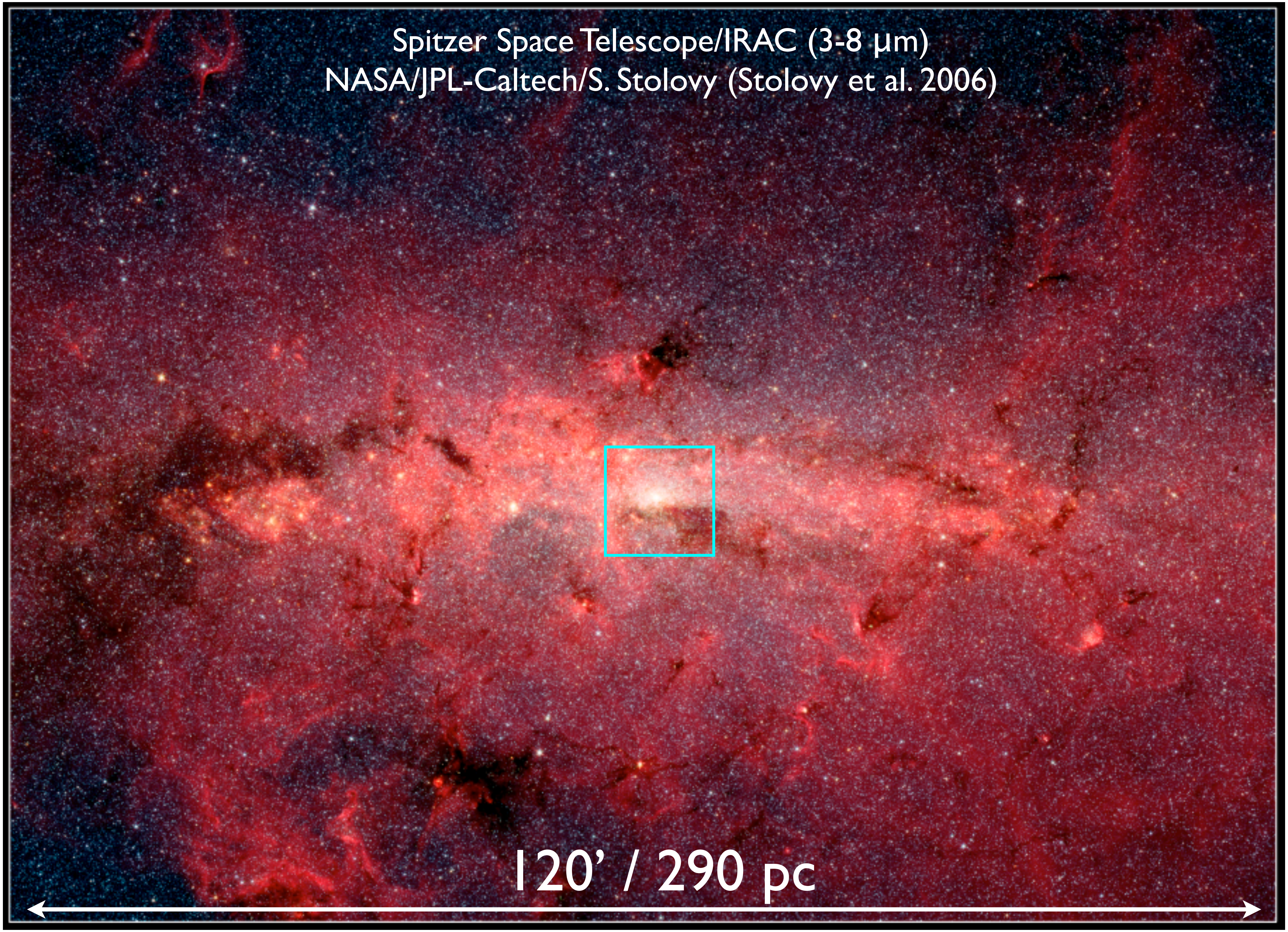
The Galactic Center: a Unique Laboratory


Spitzer Space Telescope/IRAC (3-8 µm)
NASA/JPL-Caltech/S. Stolovy (Stolovy et al. 2006)
120' / 290 pc



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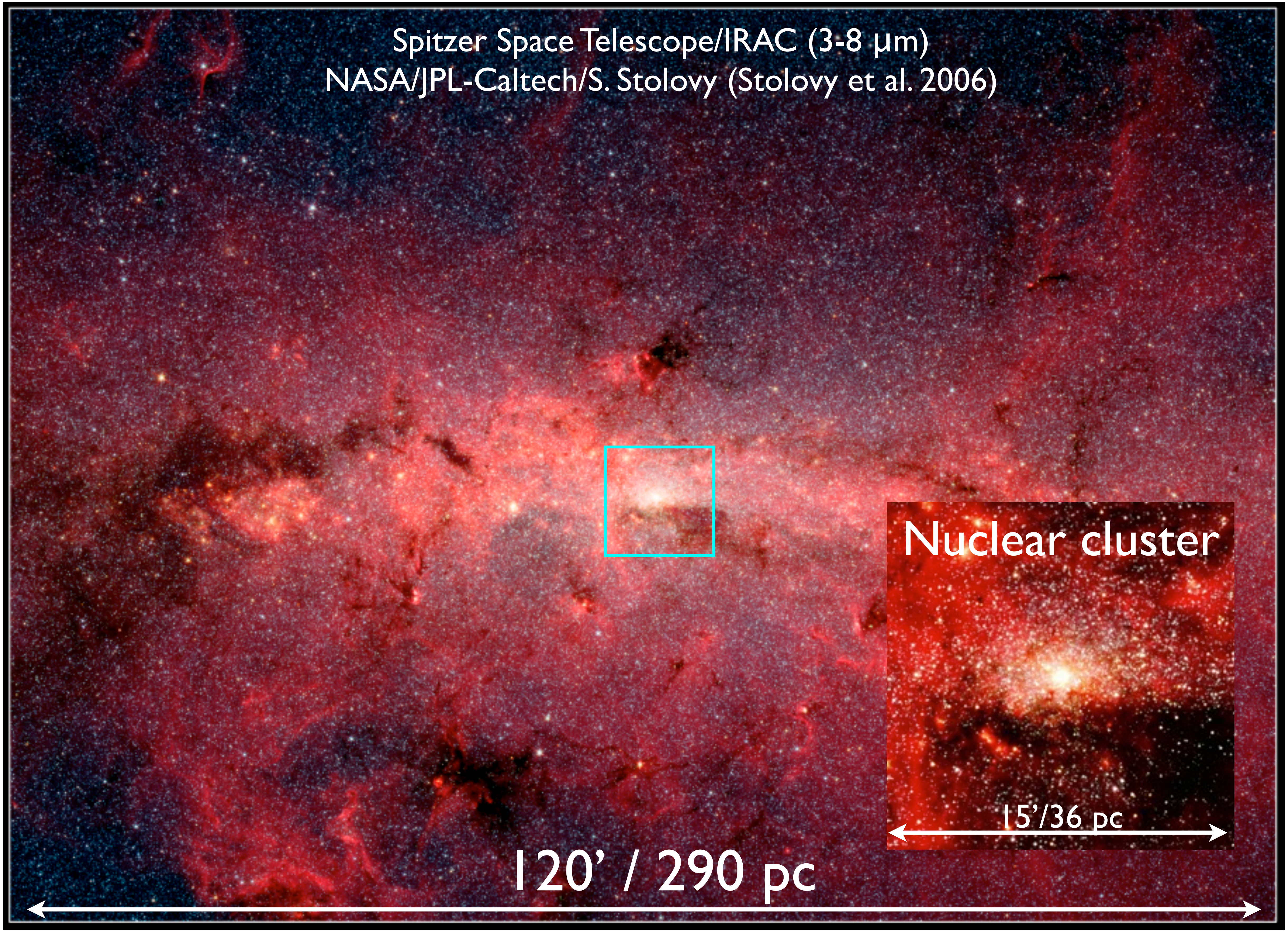
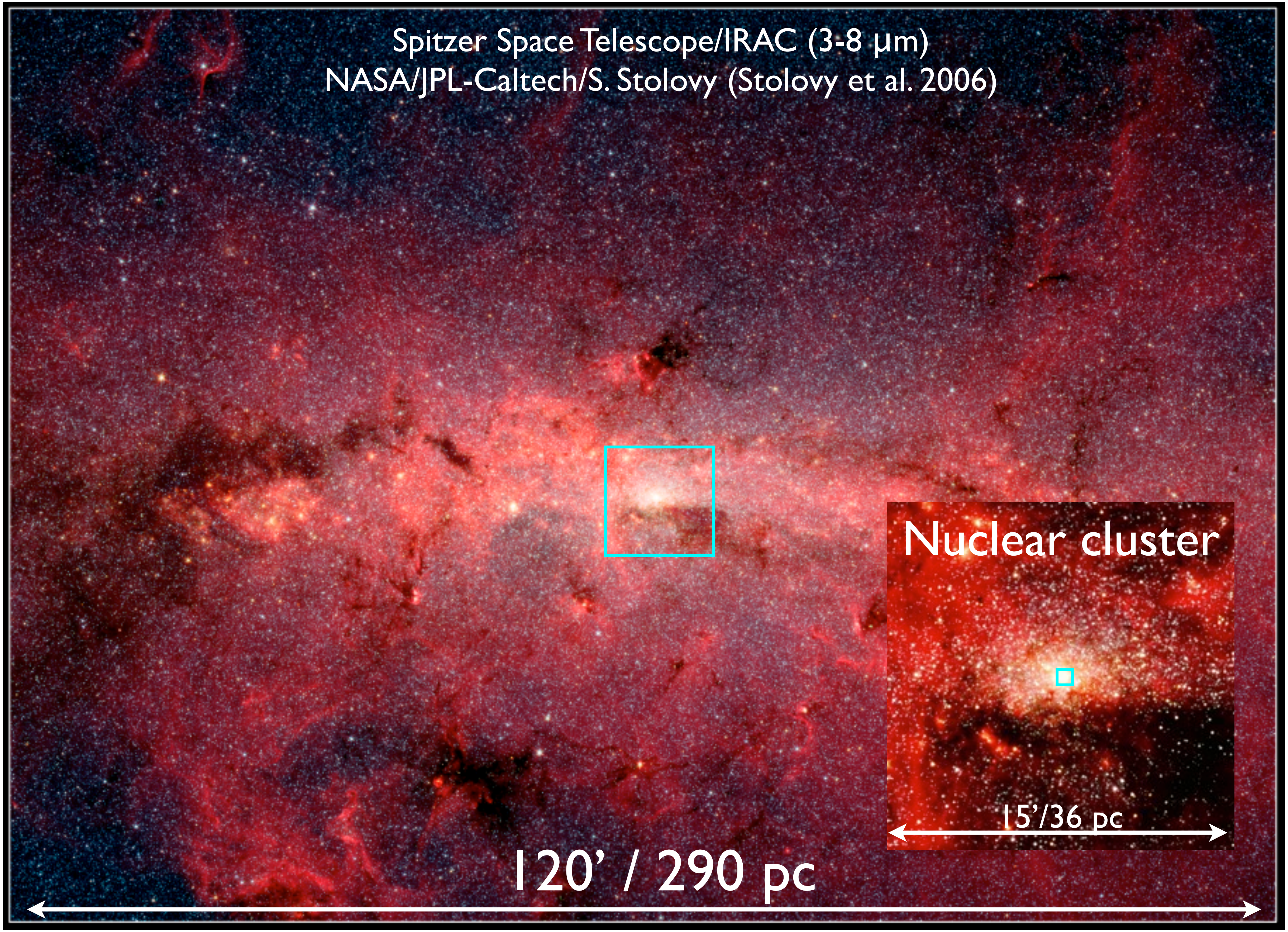

Spitzer Space Telescope/IRAC (3-8 µm)
NASA/JPL-Caltech/S. Stolovy (Stolovy et al. 2006)
Nuclear cluster
15'/36 pc
120' / 290 pc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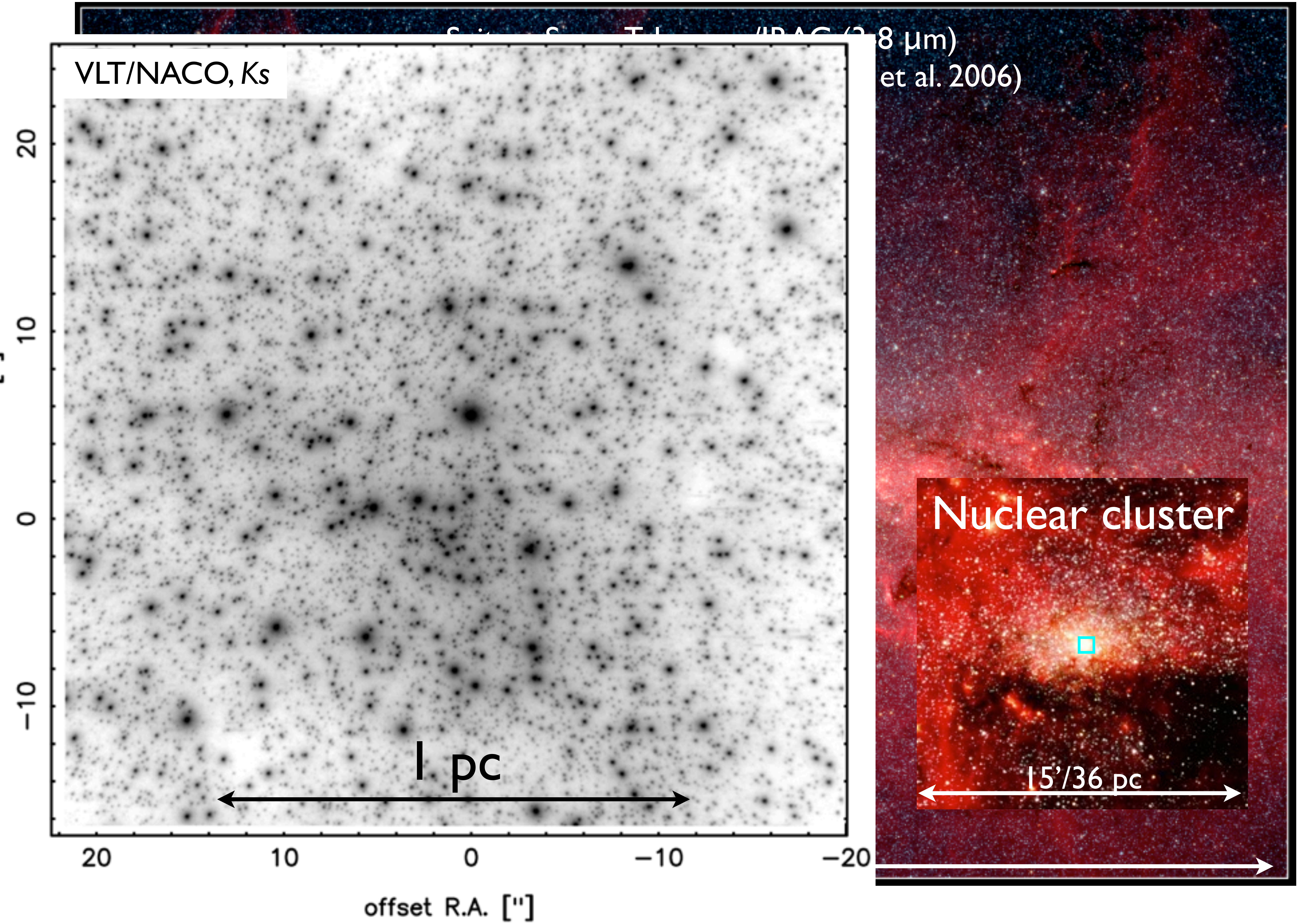

8 µm)
et al. 2006)
VLT/NACO, *Ks*
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−10
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offset R.A. ["]
1 pc
Nuclear cluster
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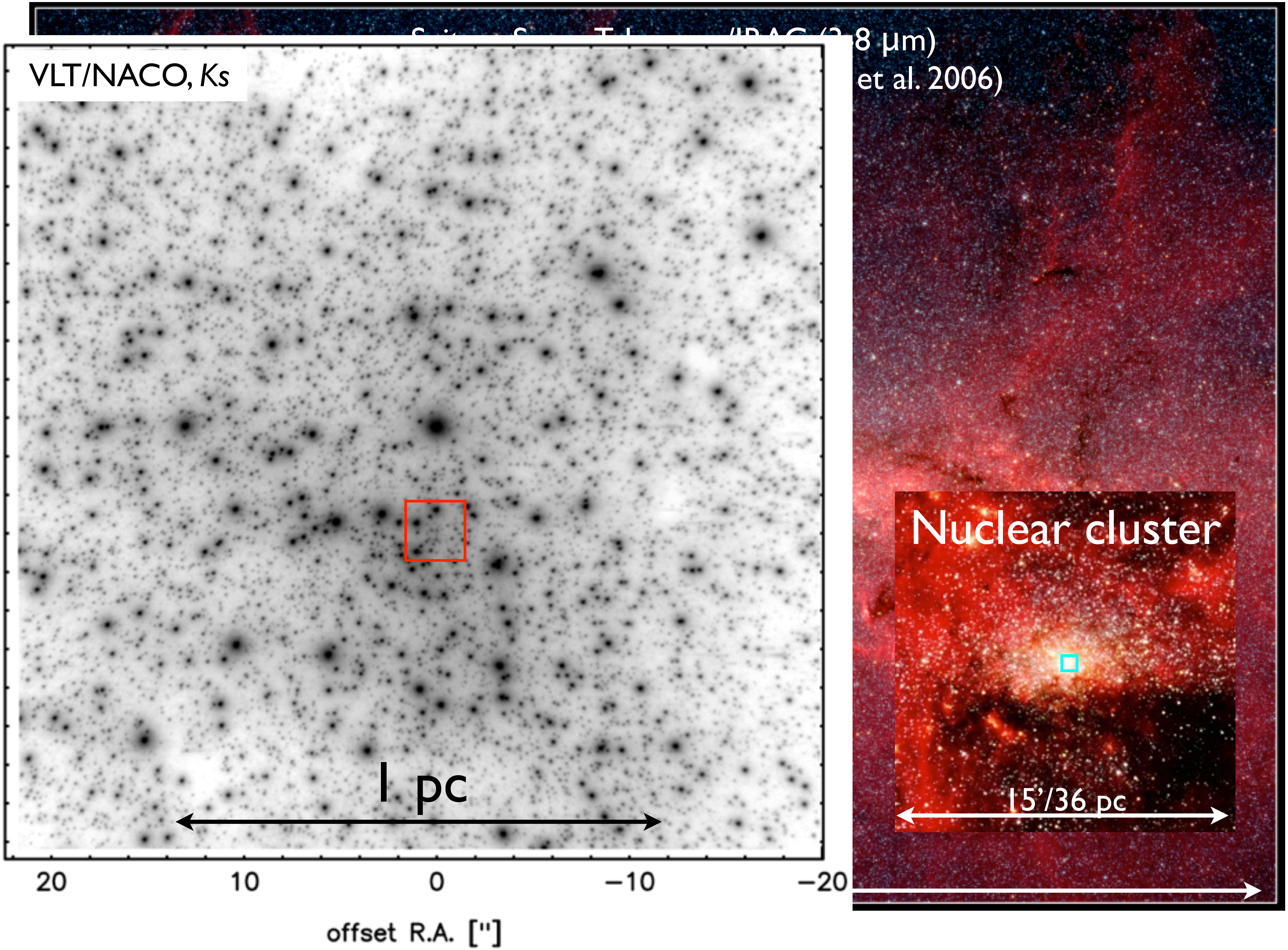

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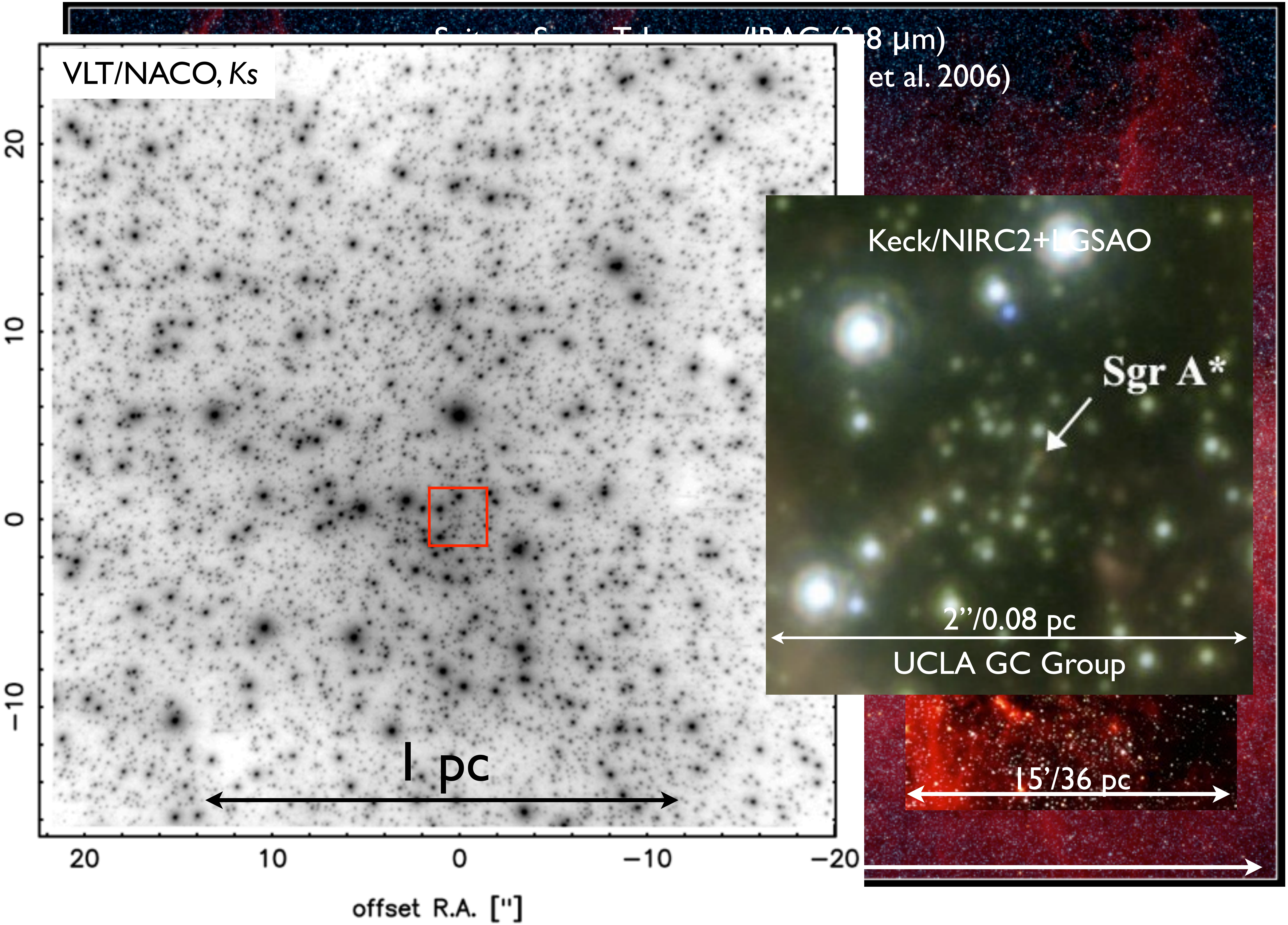

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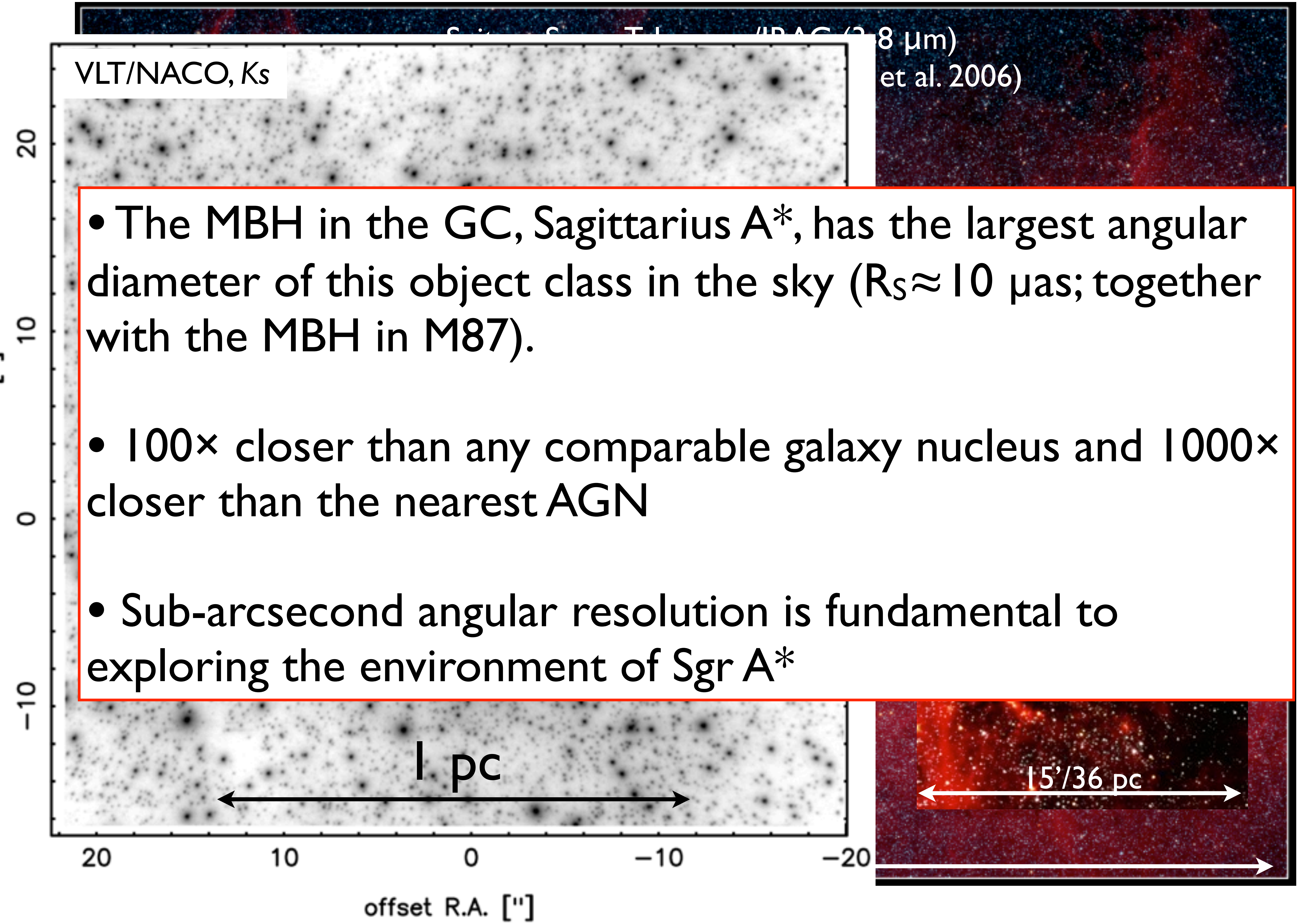
1 pc
Keck/NIRC2+LGSAO
Sgr A*
2"/0.08 pc
UCLA GC Group
15'/36 pc



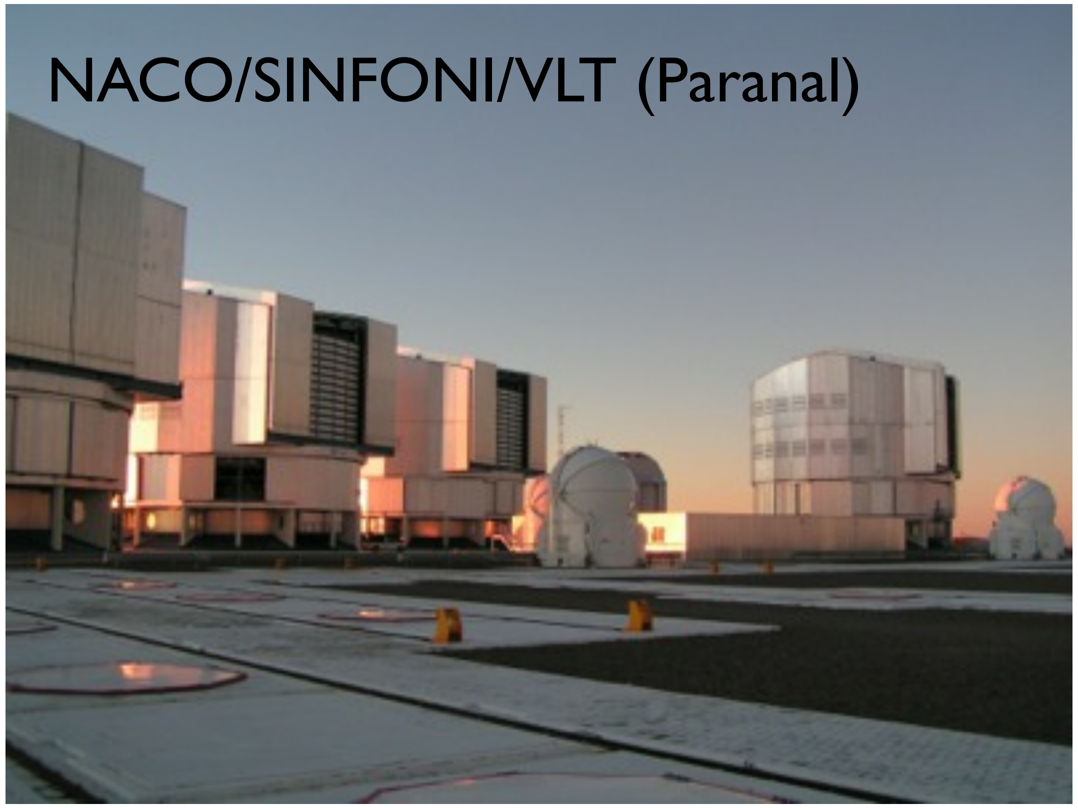
- The MBH in the GC, Sagittarius A*, has the largest angular diameter of this object class in the sky ($R_S \approx 10$ μas; together with the MBH in M87).

- 100× closer than any comparable galaxy nucleus and 1000× closer than the nearest AGN

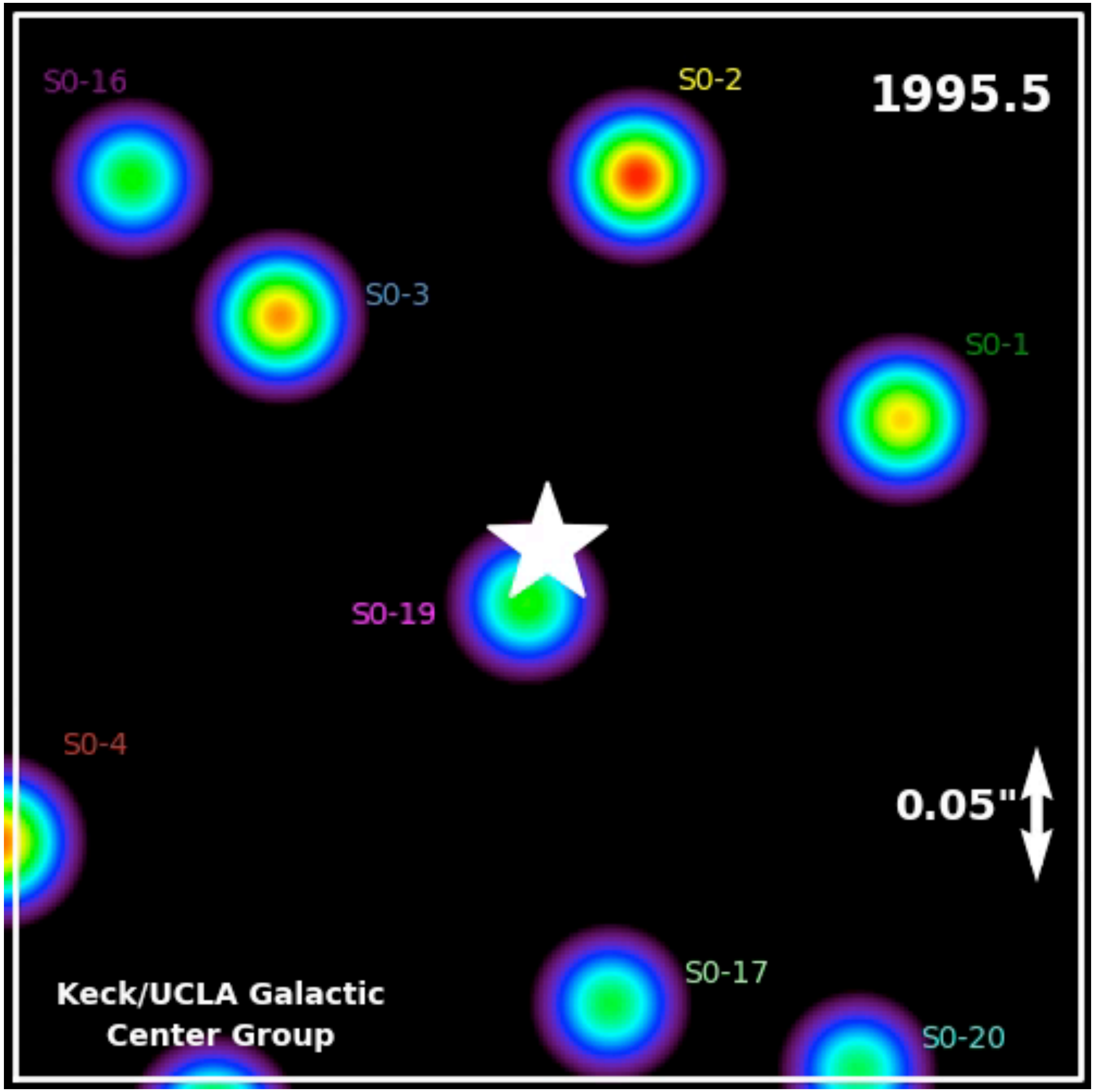
- Sub-arcsecond angular resolution is fundamental to exploring the environment of Sgr A*

Stars are ideal test bodies to measure the gravitational potential.

Ongoing experiment since 1992 (*R. Genzel, A. Eckart et al.*) and1995 (*A. Ghez et al.*), respectively.



Stellar orbits establish the existence of a massive black hole and allow us to measure its properties.



e.g., Eckart et al. (1997, 2002), Genzel et al. (1997), Ghez et al. (1998, 2000, 2008), Schoedel et al. (2002, 2003), Gillessen et al. (2009)

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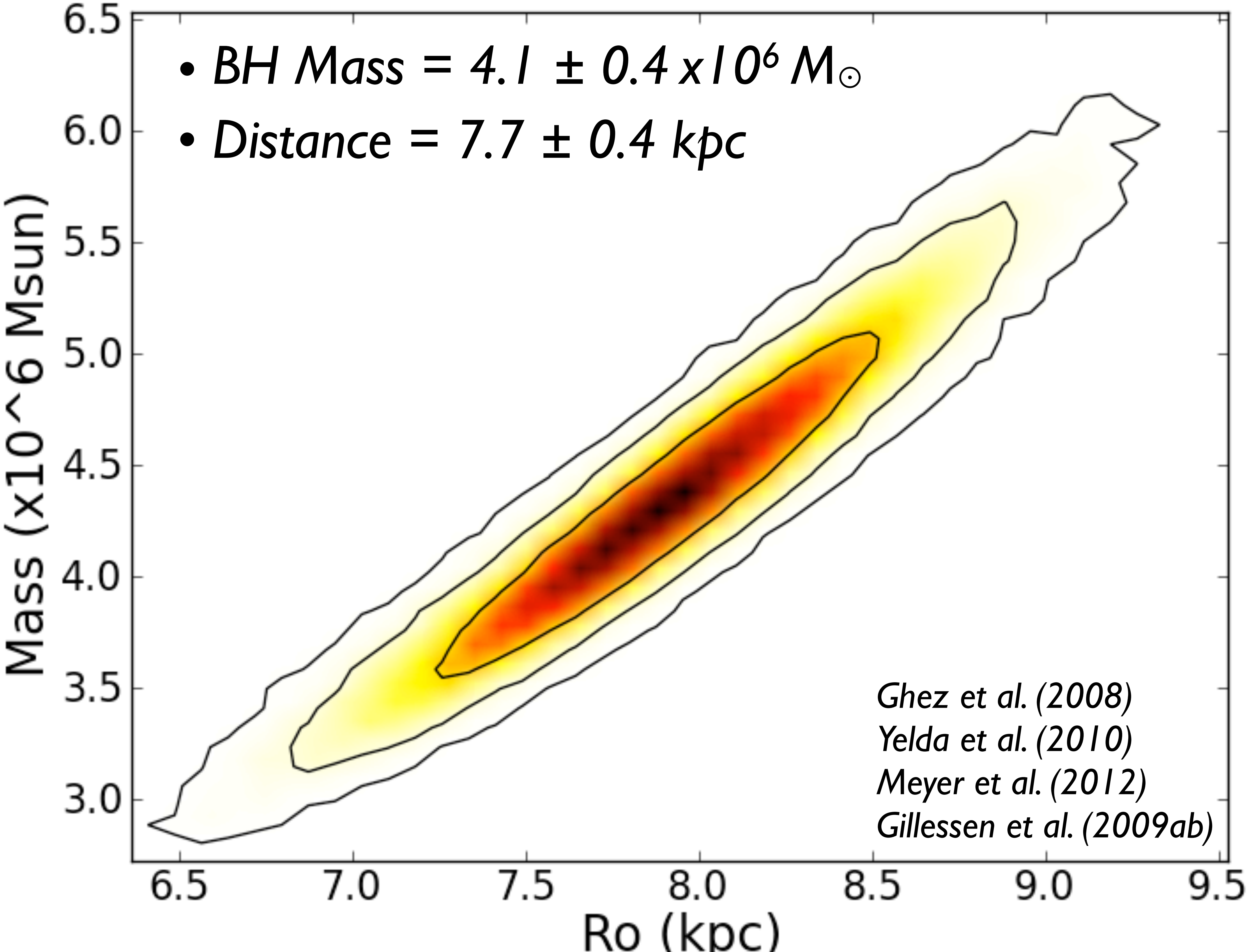
S0-2 dominates our knowledge about the central potential



Testing General Relativity with short period stars at the GC

General Relativity

The Principle of Equivalence:

All local, freely falling, non-rotating laboratories are fully equivalent for the performance of all physical experiments.

Curvature of space

Time dilation/gravitational redshift

Einstein's *field equations*

Gravitational redshift/Time dilation

Gravitational redshift

$$\frac{\Delta\nu}{\nu_0} = -\frac{v}{c} = -\frac{gh}{c^2}$$

(for small h)

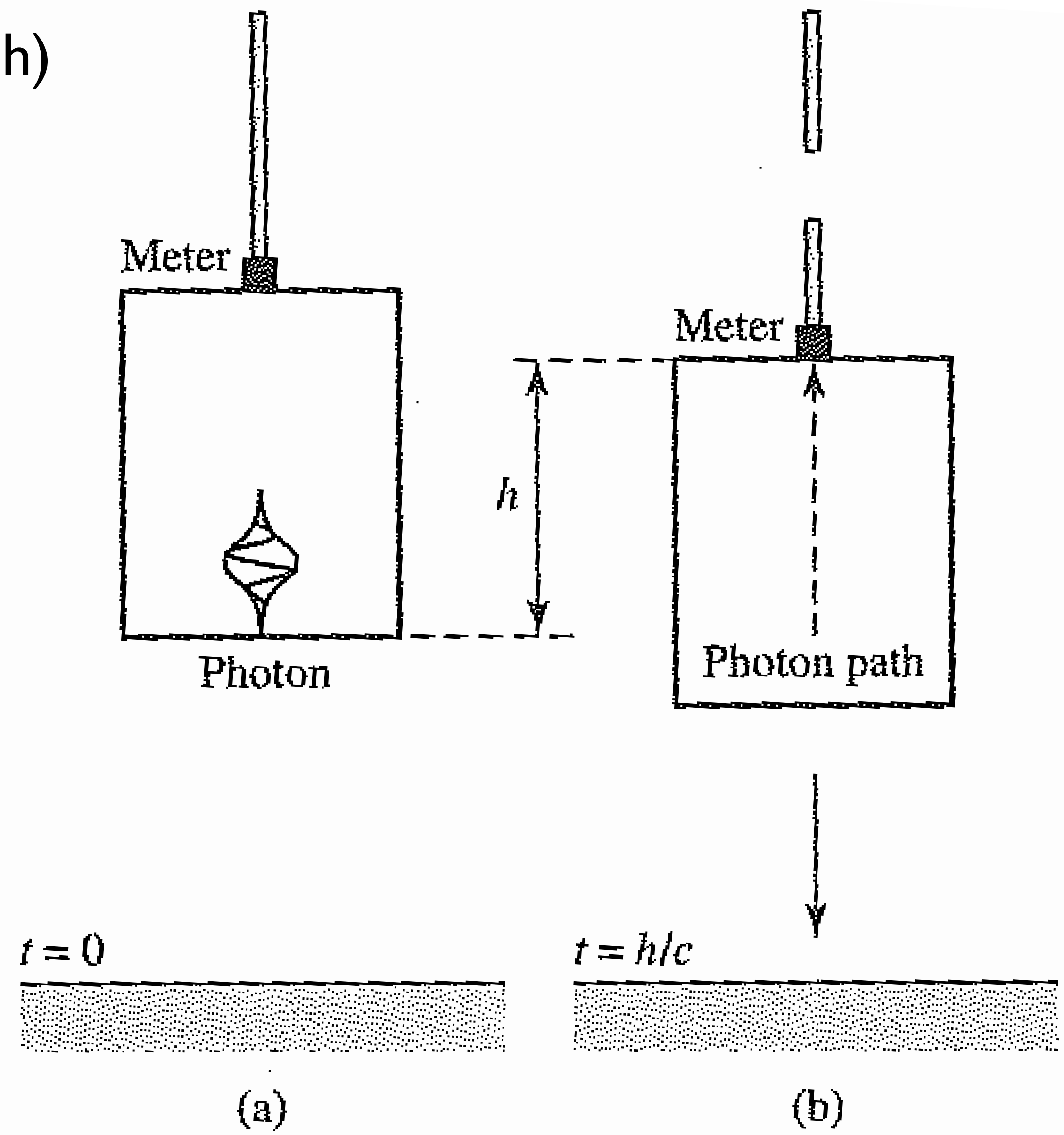


FIGURE 17.11 Equivalence principle for a vertically traveling light. The photon (a) leaves the floor at $t = 0$, and (b) arrives at the ceiling at $t = h/c$.

Credit: Carroll & Ostlie: An Introduction to Modern Astrophysics

Gravitational redshift/Time dilation

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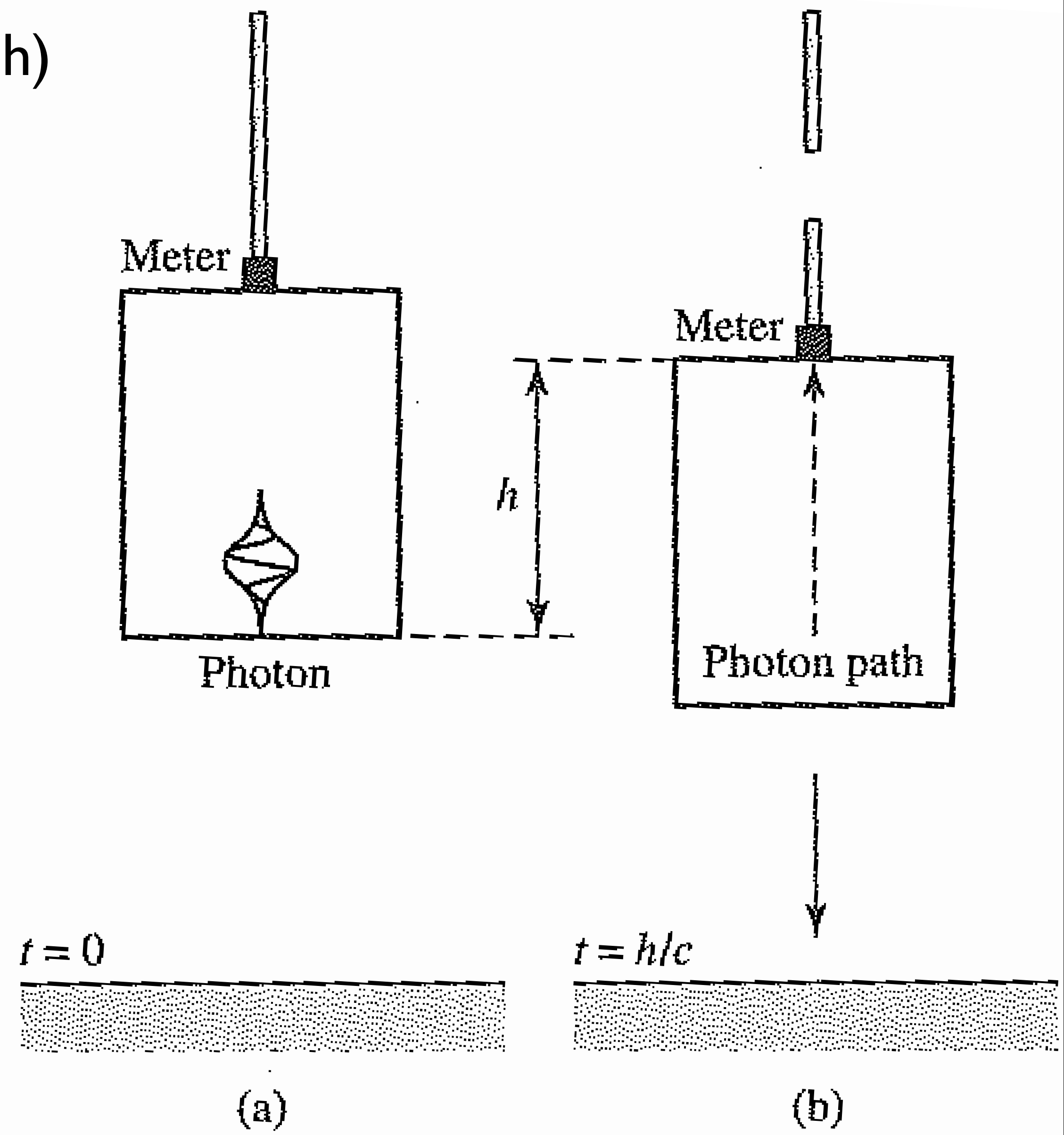

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Time passes slower near a massive object

$$\frac{\nu_\infty}{\nu_0} = \left(1 - \frac{2GM}{r_0 c^2}\right)^{1/2}$$

$$\Delta t_0 = \Delta t_\infty \left(1 - \frac{2GM}{r_0 c^2}\right)^{1/2}$$

Observer located at ∞

S0-2 is truly remarkable!

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- *It follows a geodesic with velocities unmatched by any other observable free-falling object in the universe!*

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compare with:

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compare with:
Geosynchronous Earth satellite: ~0.00005 c

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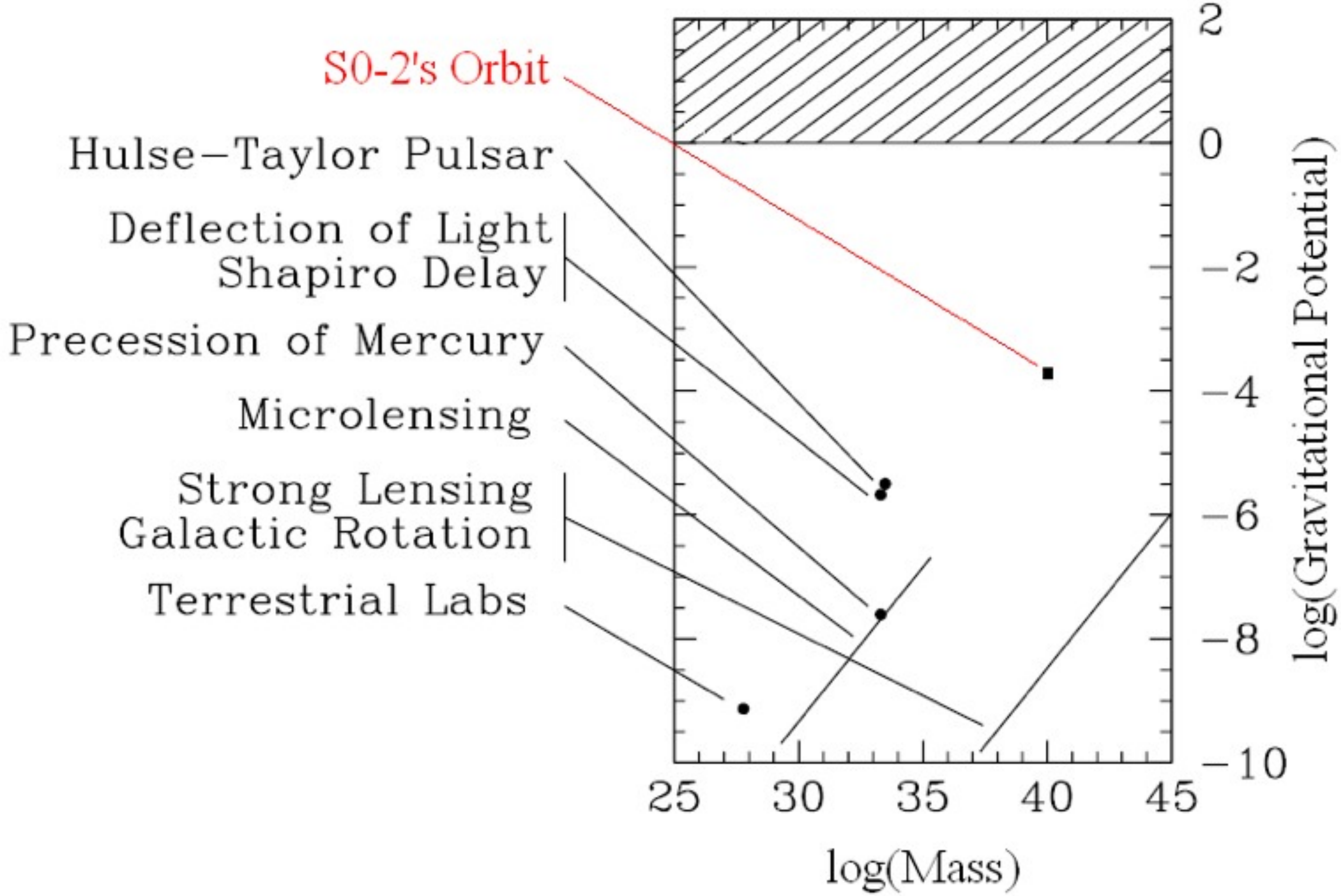
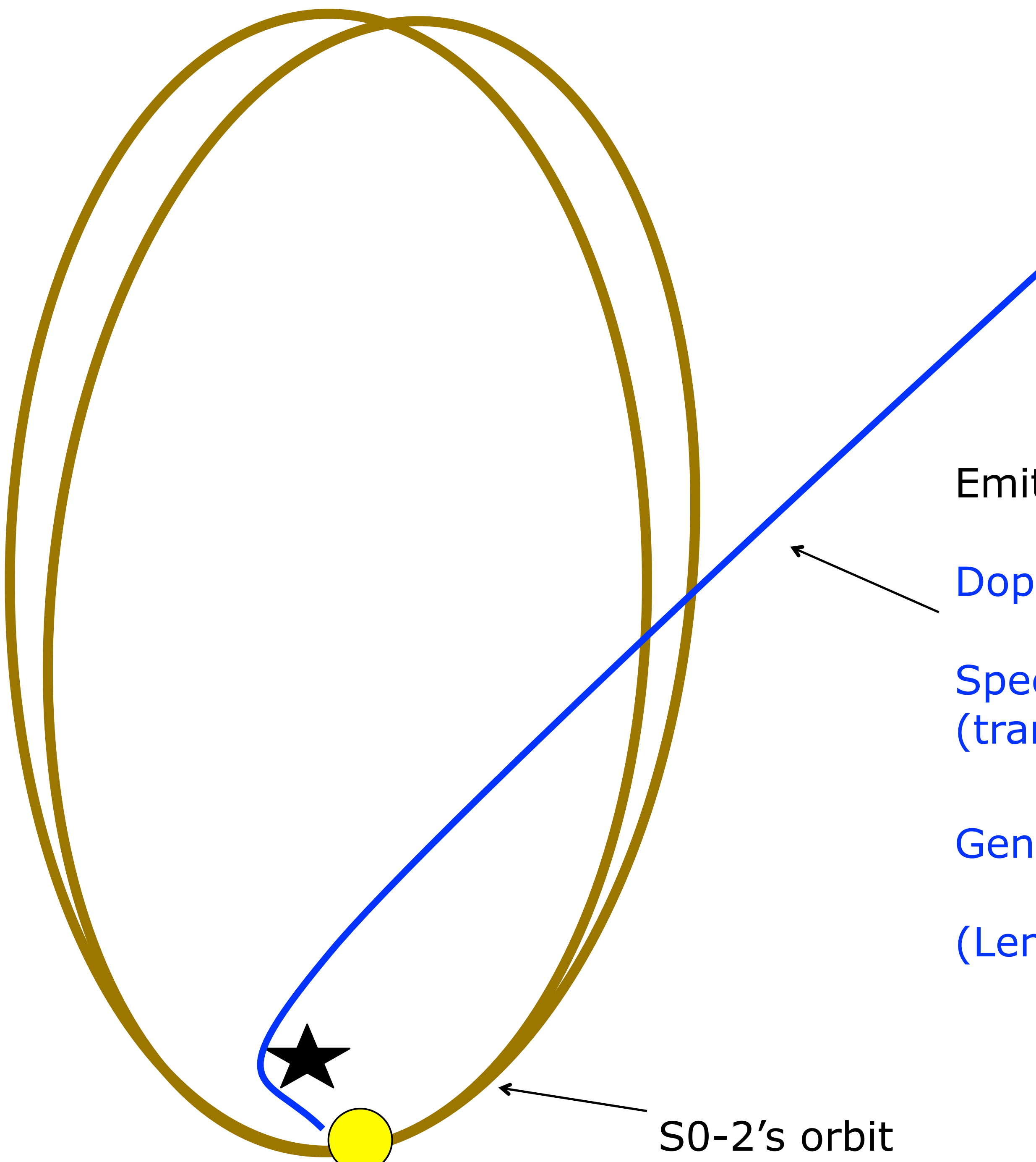
compare with:
Geosynchronous Earth satellite: ~0.00005 c
Mercury: ~0.00016 c
Binary pulsars ~0.003 c

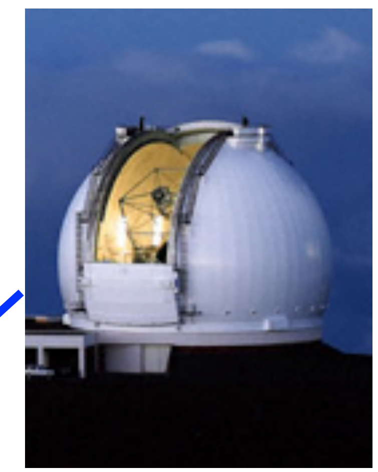
S0-2 measurements can test General Relativity in an unexplored regime



Adapted from Psaltis (2004)

Effect of curved spacetime on stellar orbits near Sgr A*





Emitted light ray is redshifted by

Doppler effect

Special Relativistic Redshift
(transverse Doppler effect)

General Relativistic Redshift

(Lensing, Shapiro time delay, ...)

S0-2's orbit
Precession of the Periapse

Post-Newtonian treatment of orbits

GR effects typically expressed in terms of $\beta = v/c$.
with $v^2 \sim GM/r \rightarrow \beta \sim r^{-1/2}$

Spectroscopy	
Doppler effect	$\mathcal{O}(\beta^1)$
Transverse Doppler effect	$\mathcal{O}(\beta^2)$
Gravitational redshift	$\mathcal{O}(\beta^2)$
Astrometry	
Prograde precession of periapse	$\mathcal{O}(\beta^2)$
Frame dragging (for spinning BH)	$\mathcal{O}(\beta^3)$
Higher order effects...	

Time delay from classical *Rømer effect* must also be accounted for:
spectroscopy - $O(\beta^2)$, astrometry - $O(\beta^1)$

e.g. Rubilar & Eckart (2001), Zucker+ (2006), Will (1993, 2008), Weinberg+ (2005), Angelil+ (2010)

Rømer Effect

Ole Rømer (1644-1710) measured the finite speed of light by using Jupiter's moons as a clock on the sky.

Using the measured period between eclipses of Io for a given relative position between Earth and Jupiter one can predict the time of future eclipses correctly **only if one takes into account the relative motion between Earth and Jupiter and the finite speed of light**.

The Rømer effect describes the different apparent time delay for different phases of an observed orbit, taking into account the geometry of the target-observer system. It can also be used to measure the speed of light.

In case of the GC, the relevant time delay happens at the GC (stellar orbits >> Earth orbit).

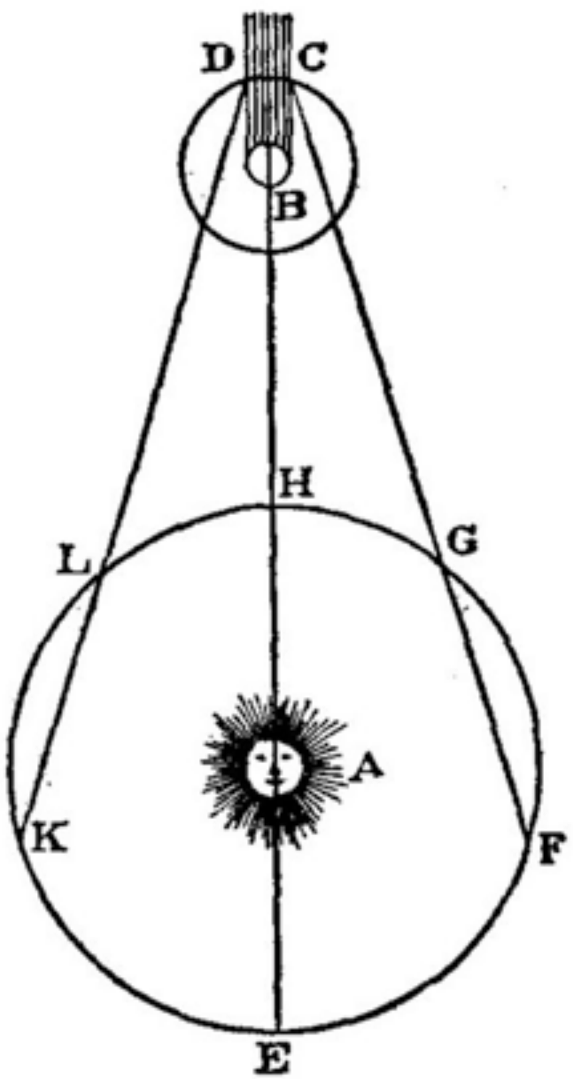
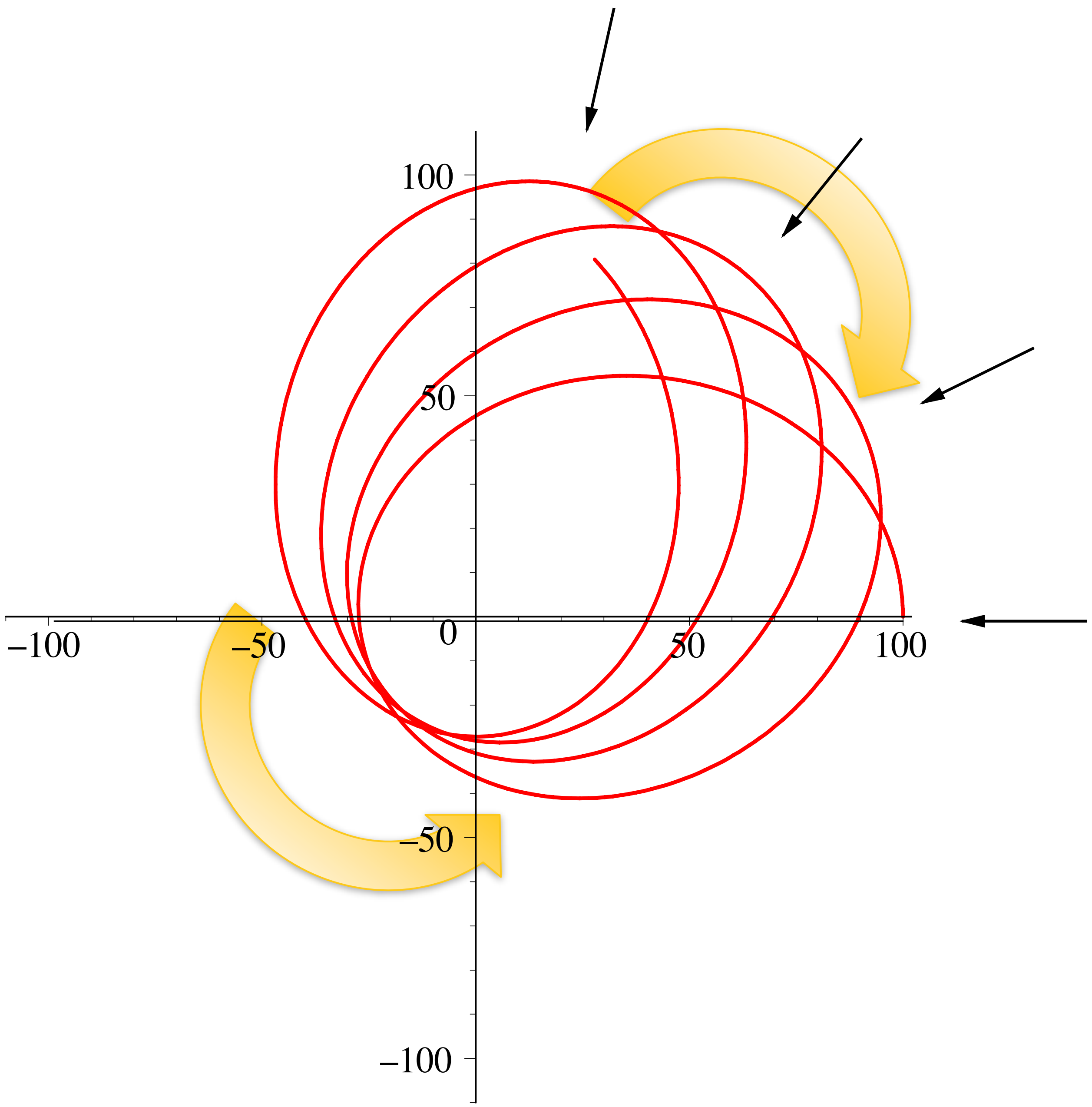


FIG. 70.

Periapse precession tests Einstein's Equations

$$\nabla\Phi = \frac{GM(r)}{r^3}\mathbf{r}, \quad M(r) = 4\pi \int_0^r r^2 \rho(r) dr$$

Point mass + spherically symmetric extended mass



Rubilar & Eckart (2001)

- GR: prograde precession, best visible at apoapse

  Δs = 0.8 mas for S0-2

- Extended mass leads to a retrograde precession

- ***More than one star is needed to break degeneracy between extended mass and GR***

Redshift tests Equivalence Principle

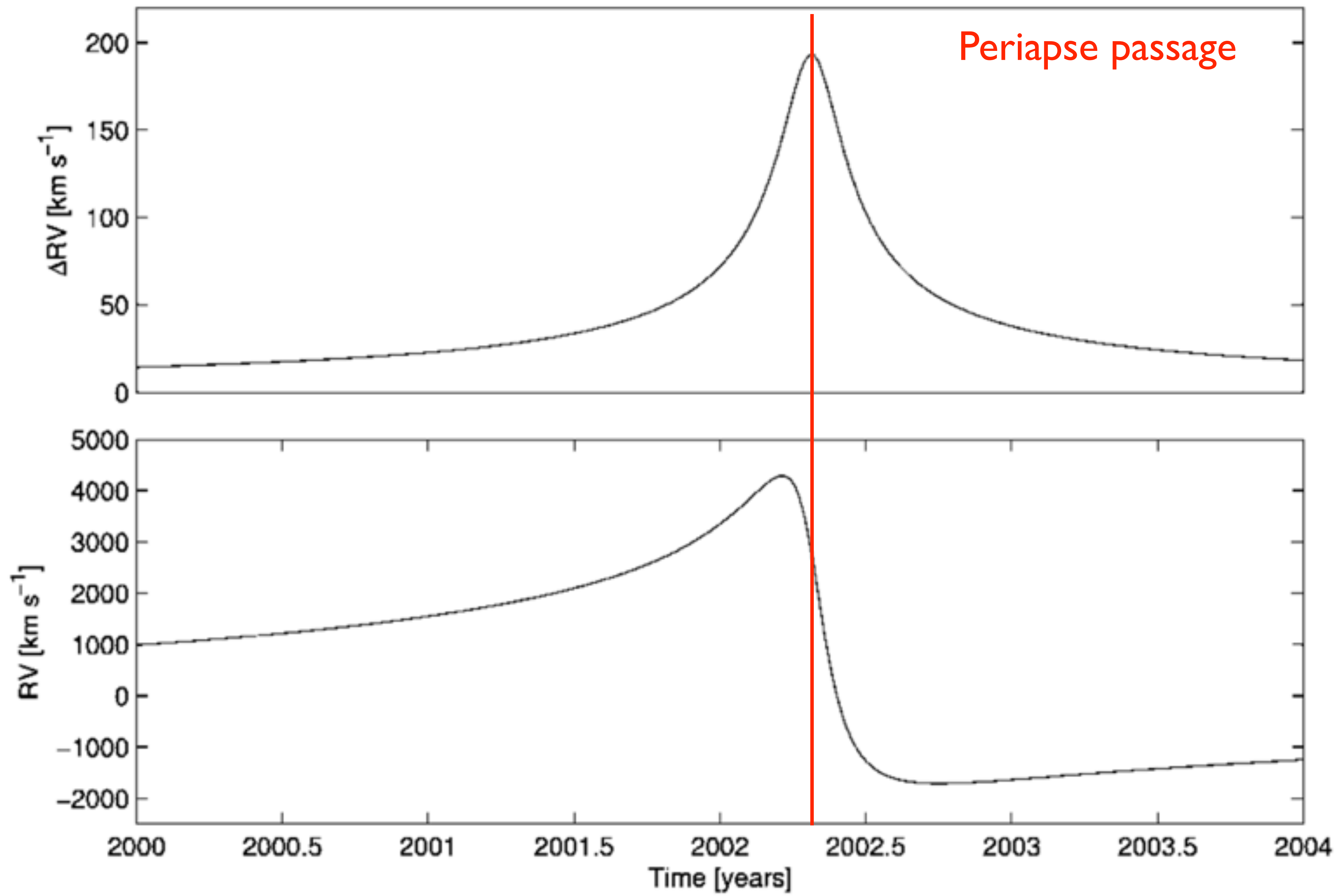
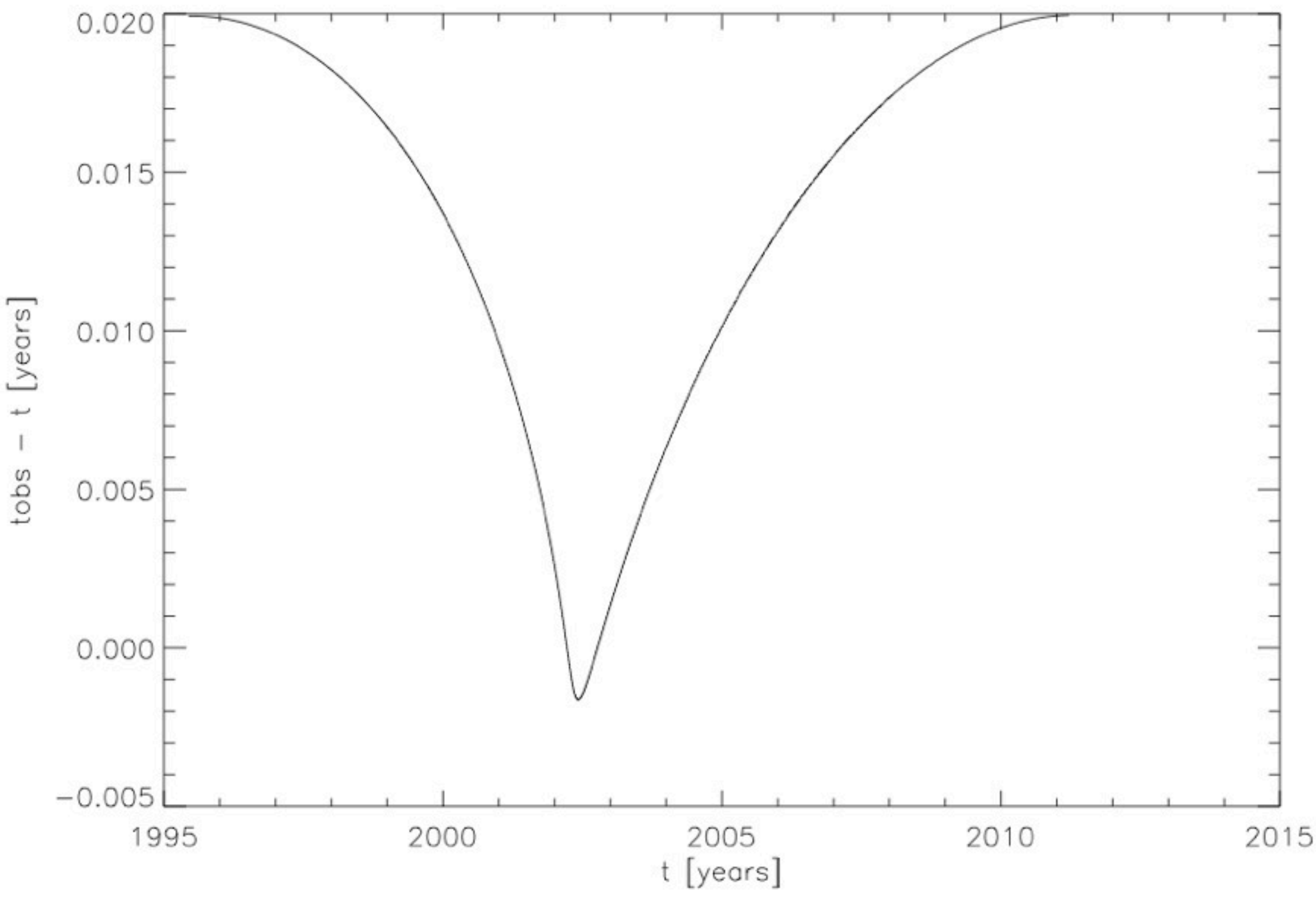


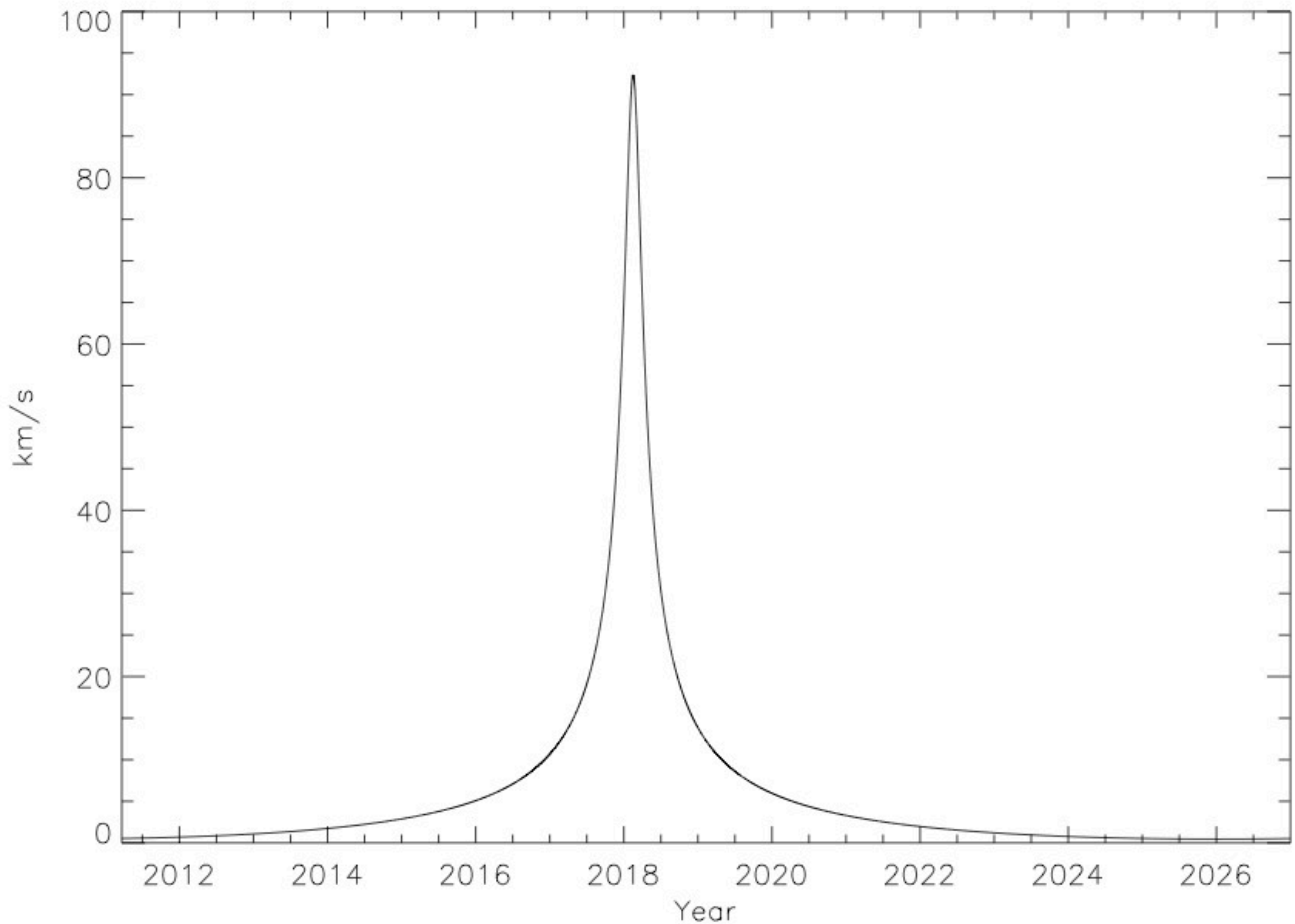
FIG. 1.—*Bottom*: Full relativistic radial velocity curve of S2 near periapse. *Top*: Contribution of the PN β^2 effects of the gravitational redshift and transverse Doppler shift to the total.

Zucker et al. (2006)

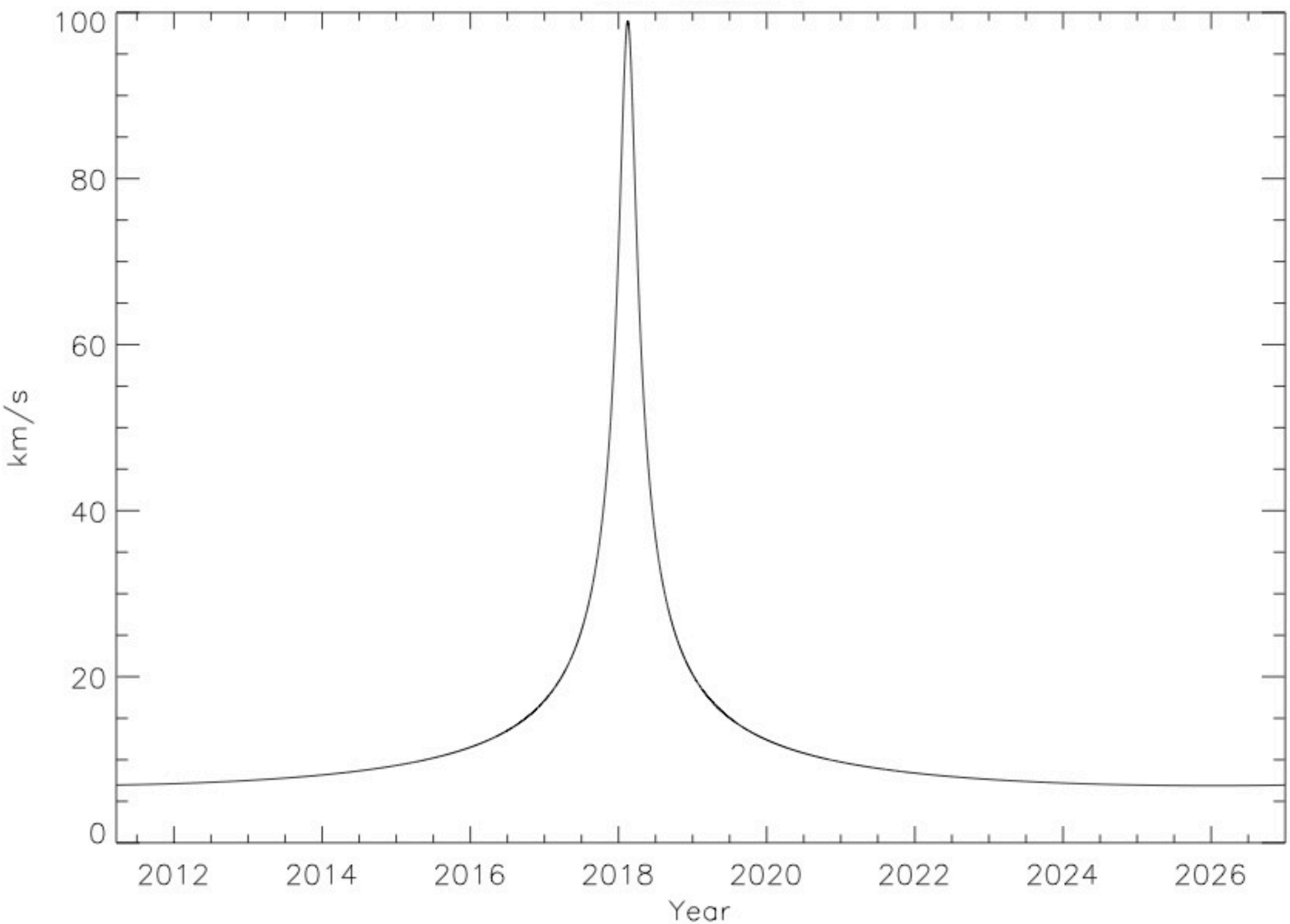
Rømer effect



Transverse Doppler shift



Gravitational redshift



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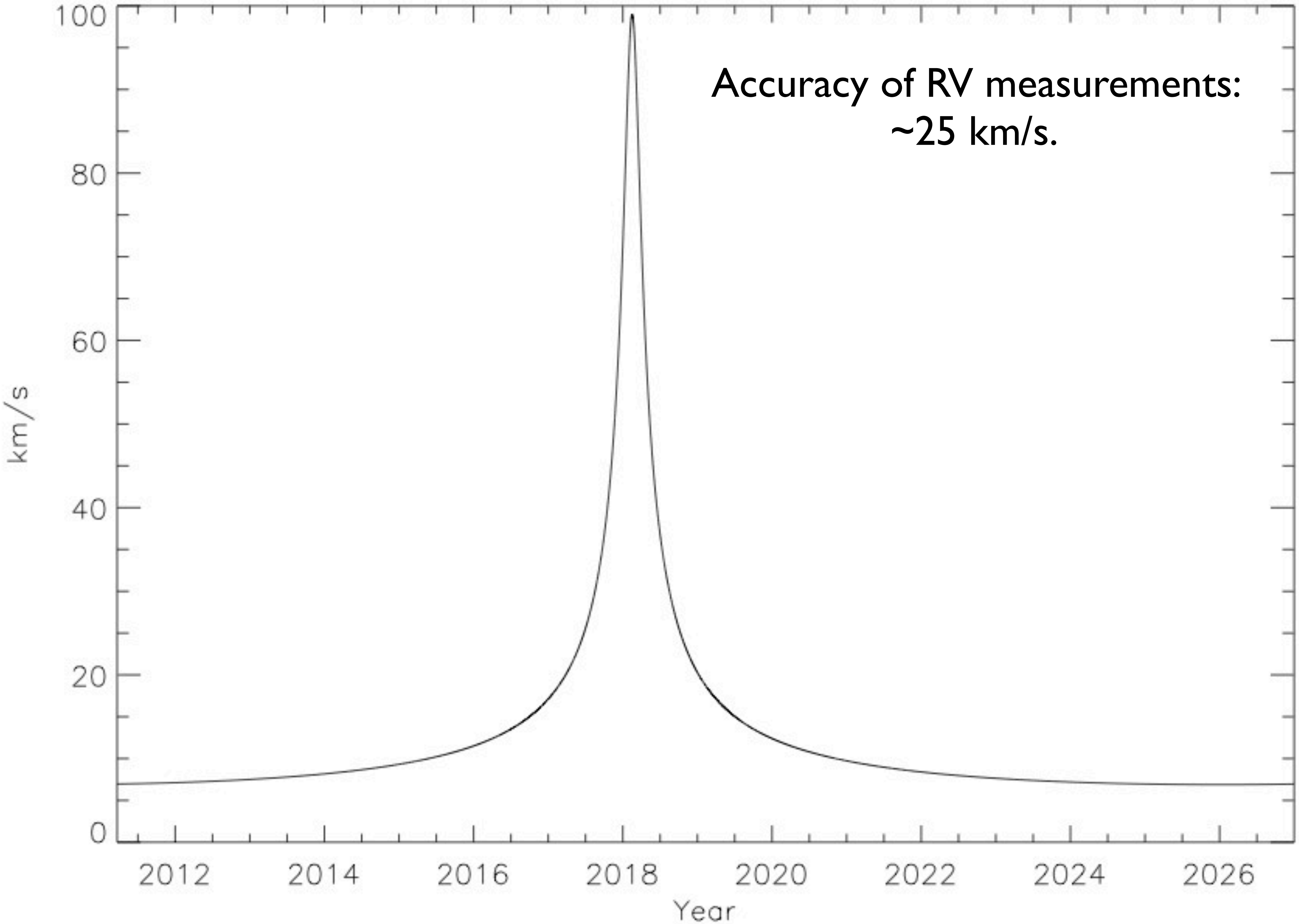
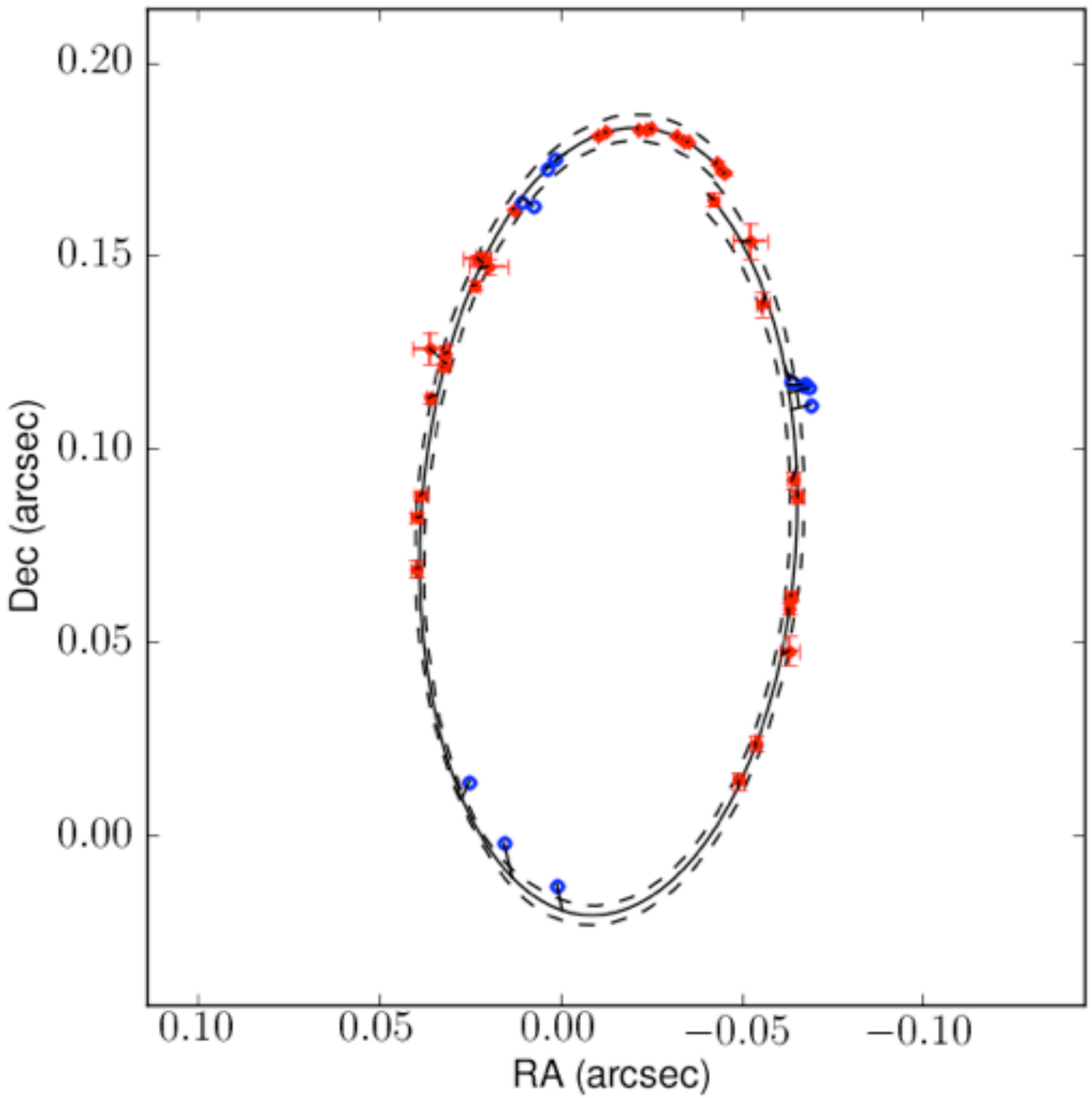


Detecting the relativistic redshift is within reach at the next closest approach of S0-2 in 2018

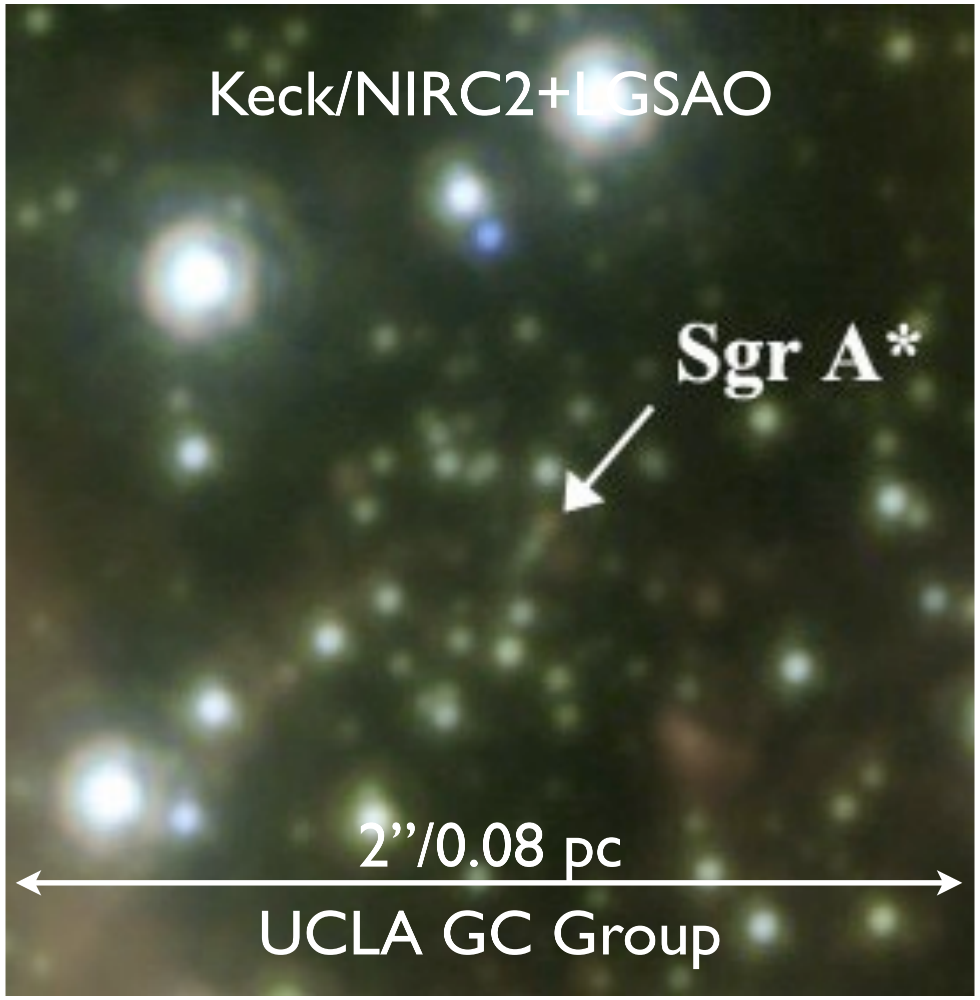


With the current approach of S0-2 alone and simple sampling we should be able to determine the redshift parameter to a relative precision of ~75% (3 σ).

A signal on the order of 100 km/s is HUGE, so: Where's the catch?

Observations: Challenges and Solutions

1) Confusion and stellar types limit the accuracy of spectroscopy



AO-assisted integral-field spectroscopy is indispensable to overcome source confusion!

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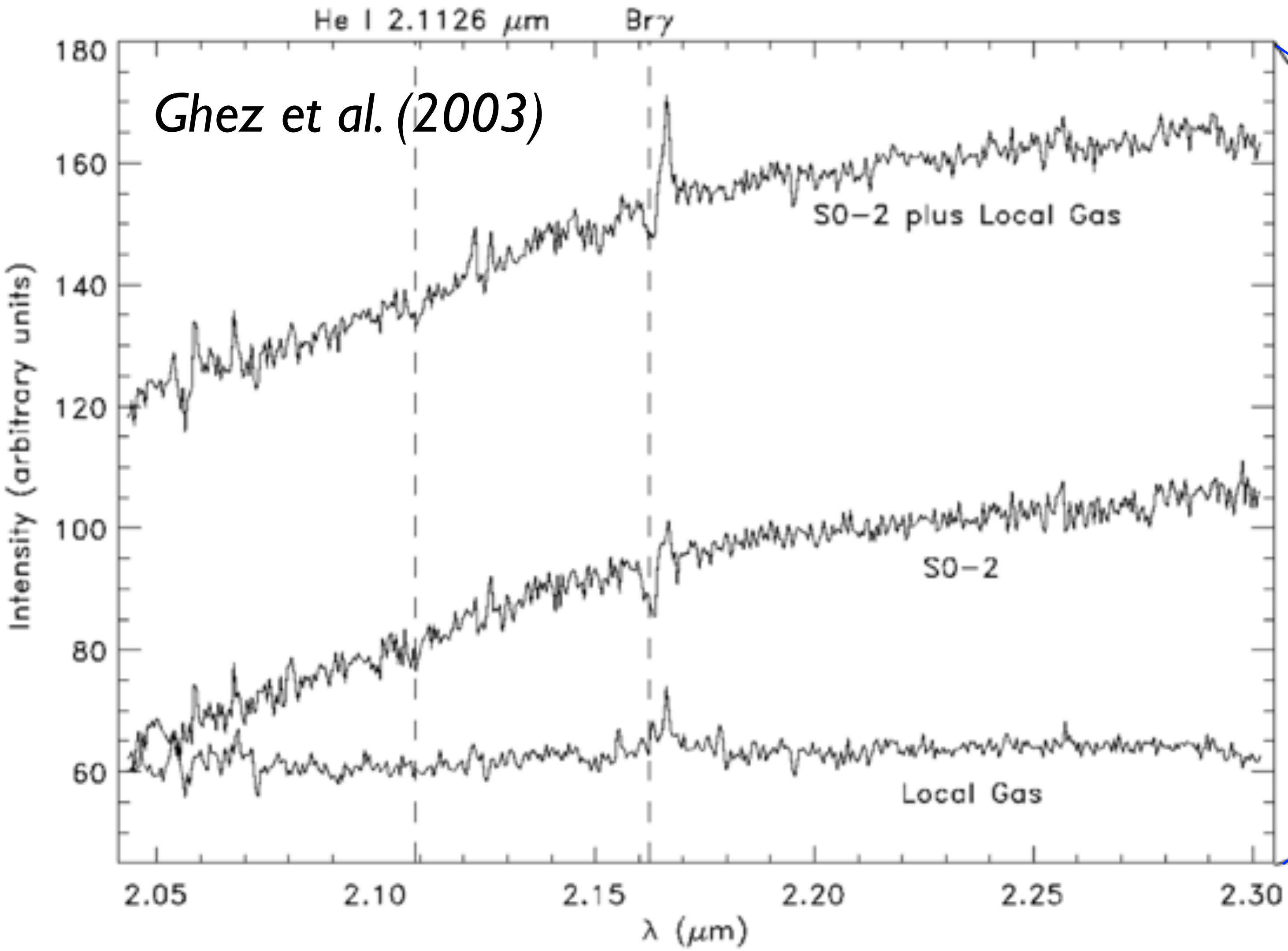

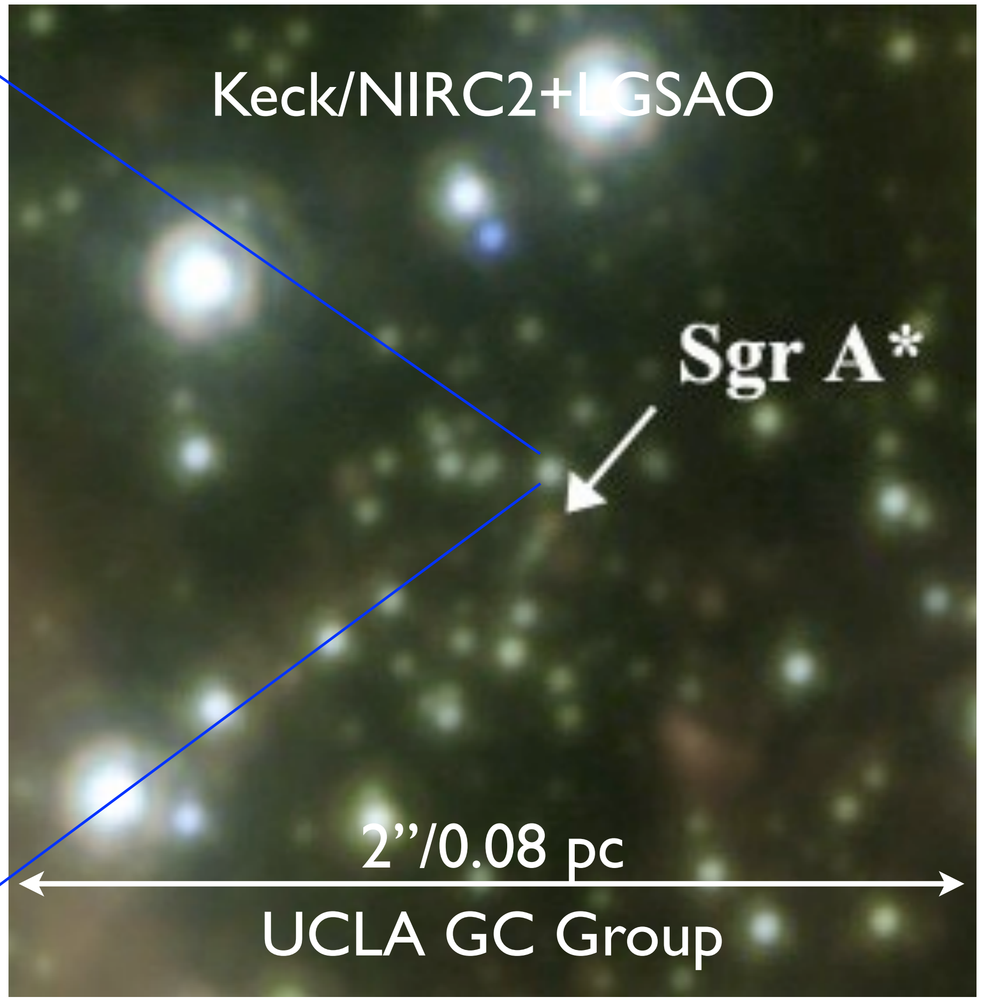

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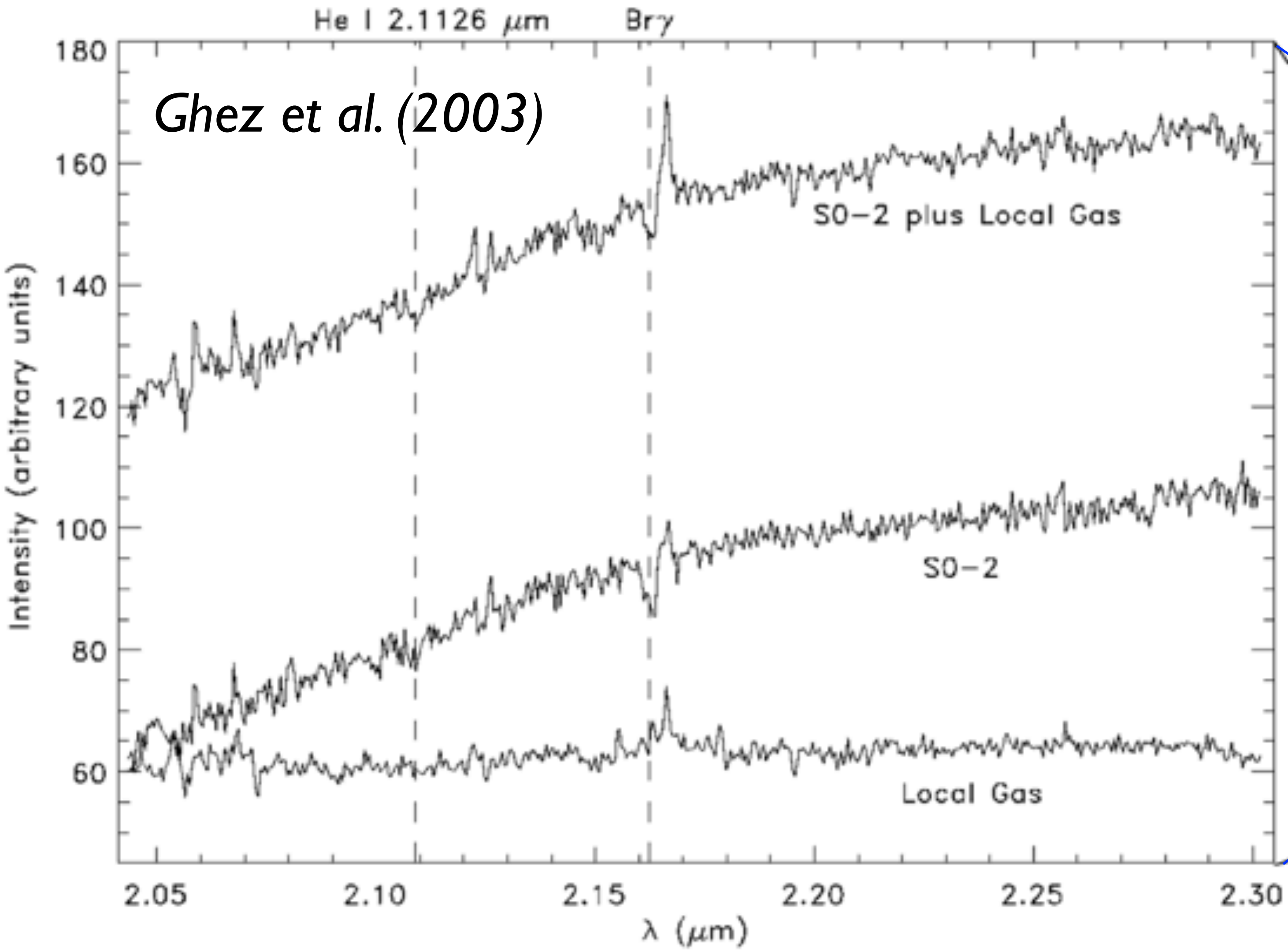

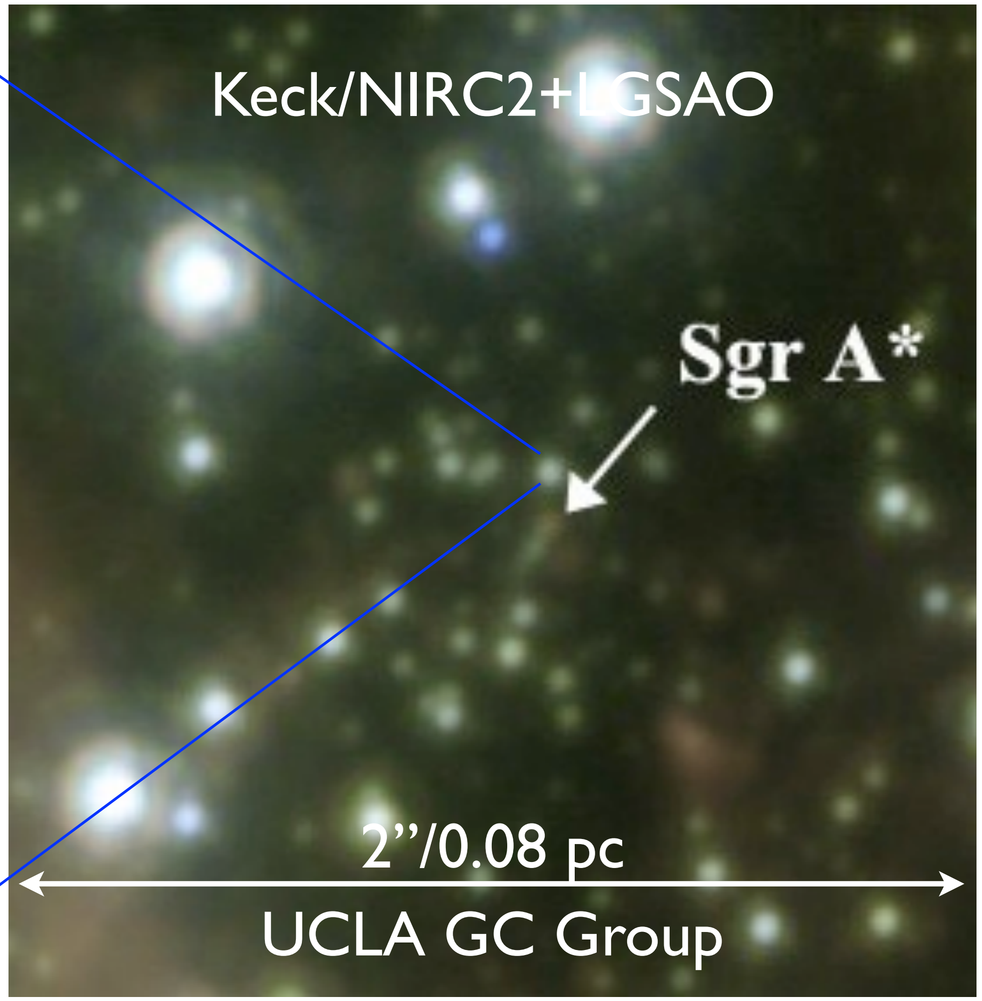

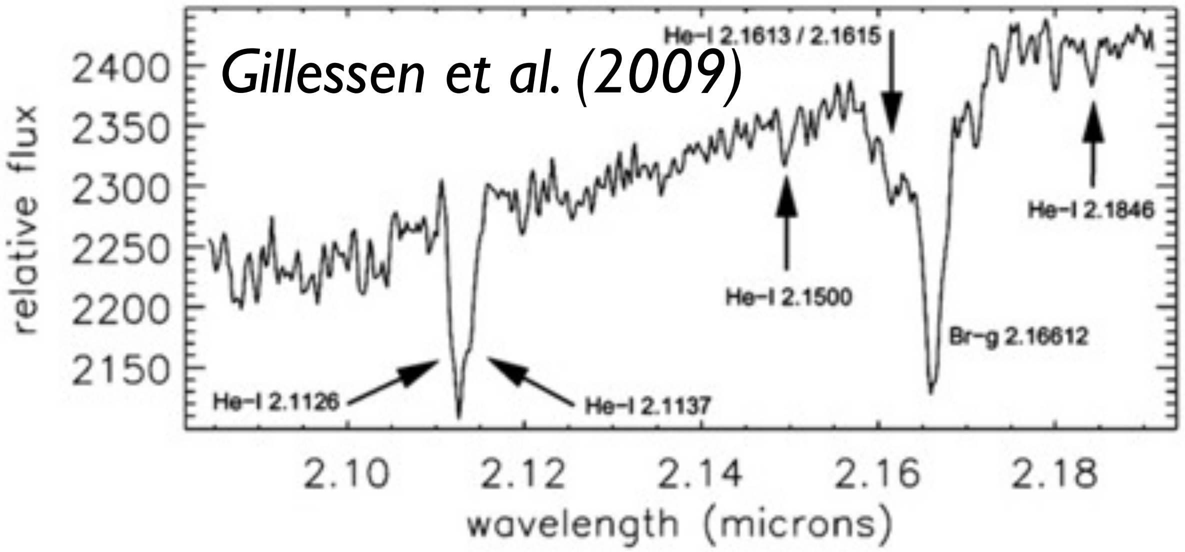

Figure 11. Combined S2 spectrum from the 2004–2006 SINFONI data, used as velocity template.

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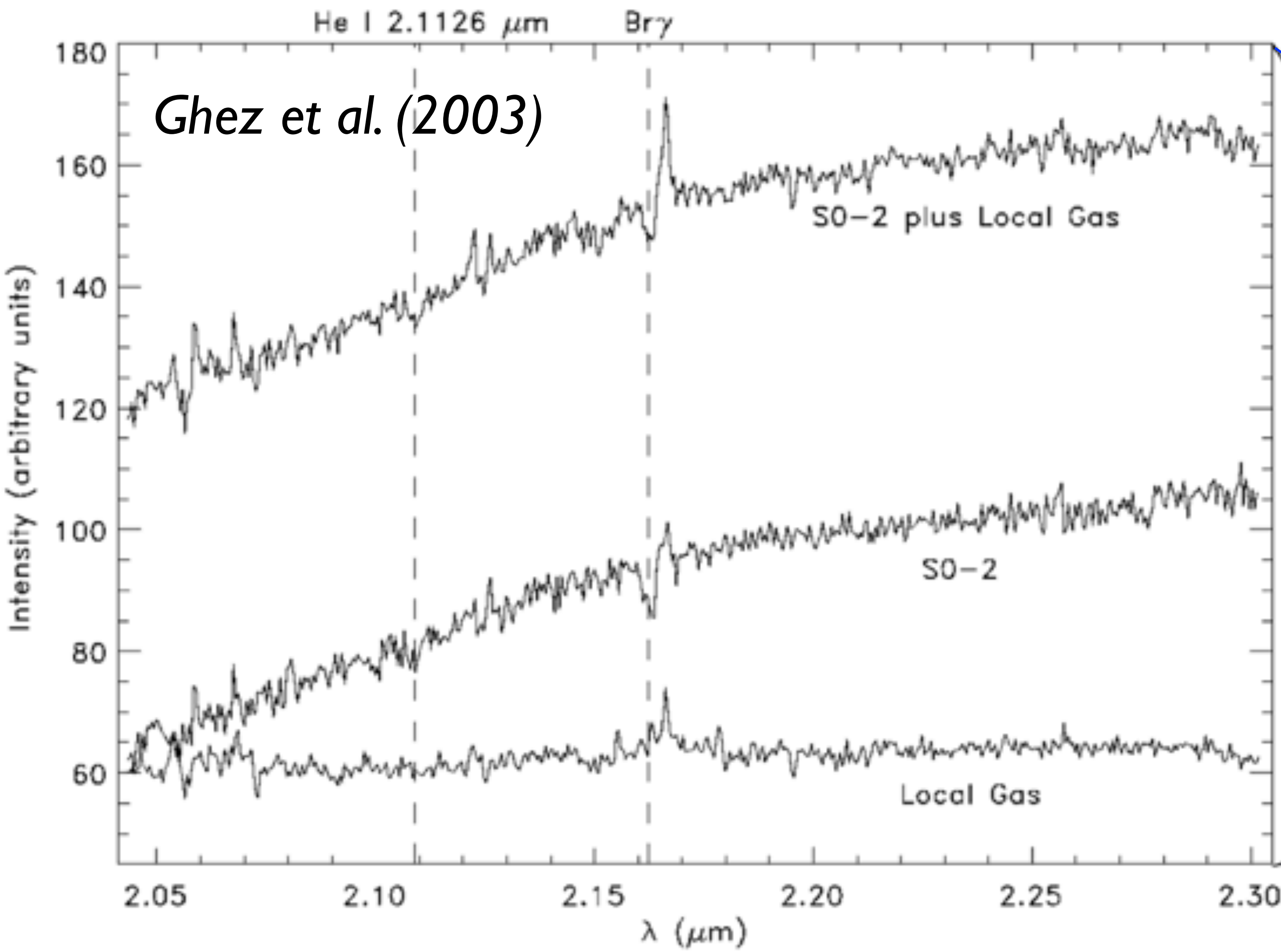
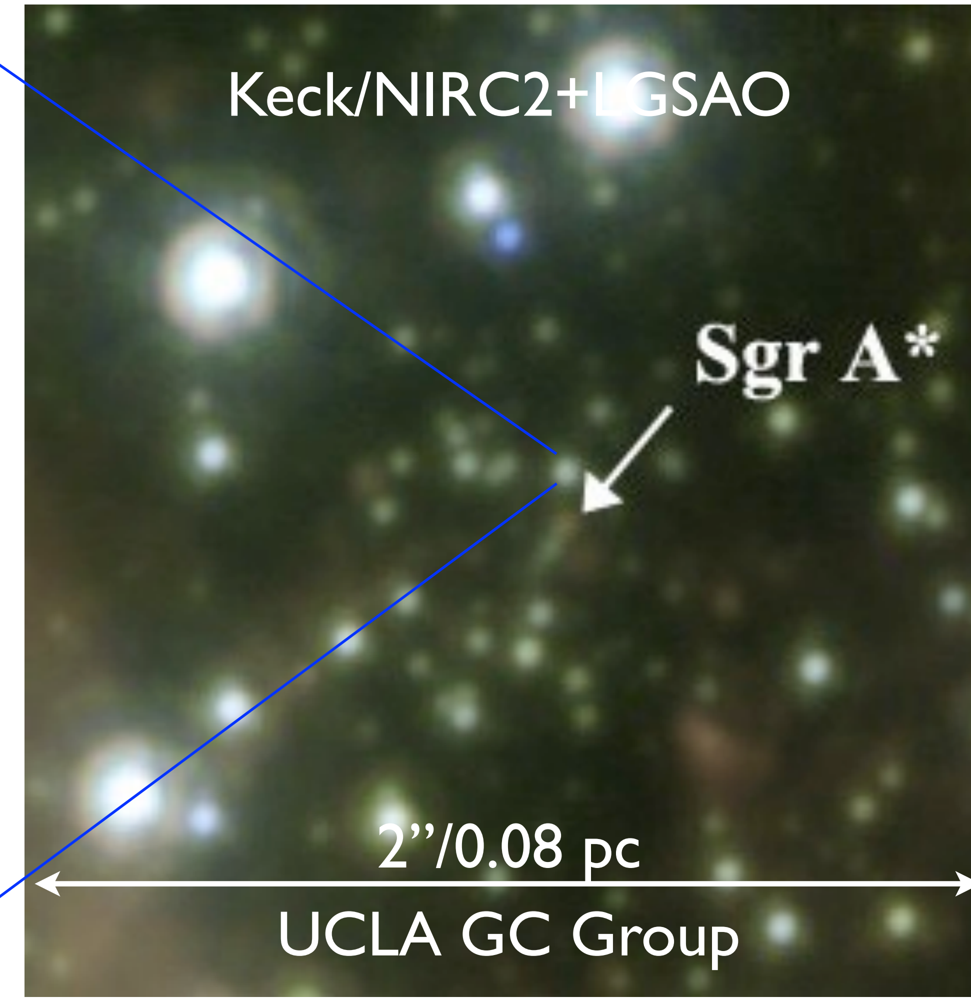
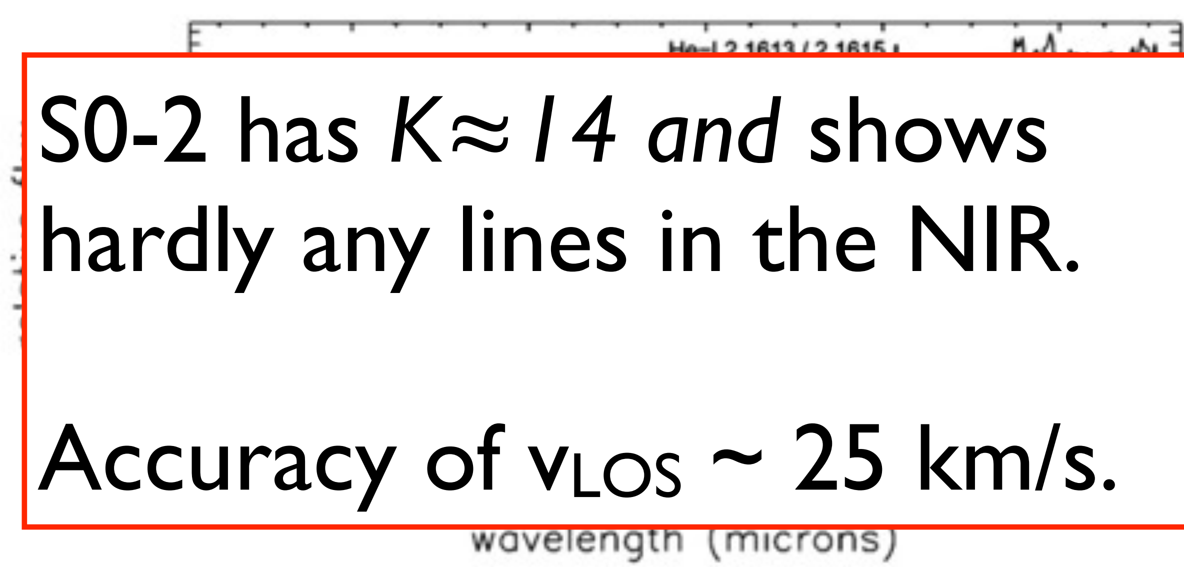




S0-2 has *K≈14 and* shows hardly any lines in the NIR.

Accuracy of v_{LOS} ~ 25 km/s.



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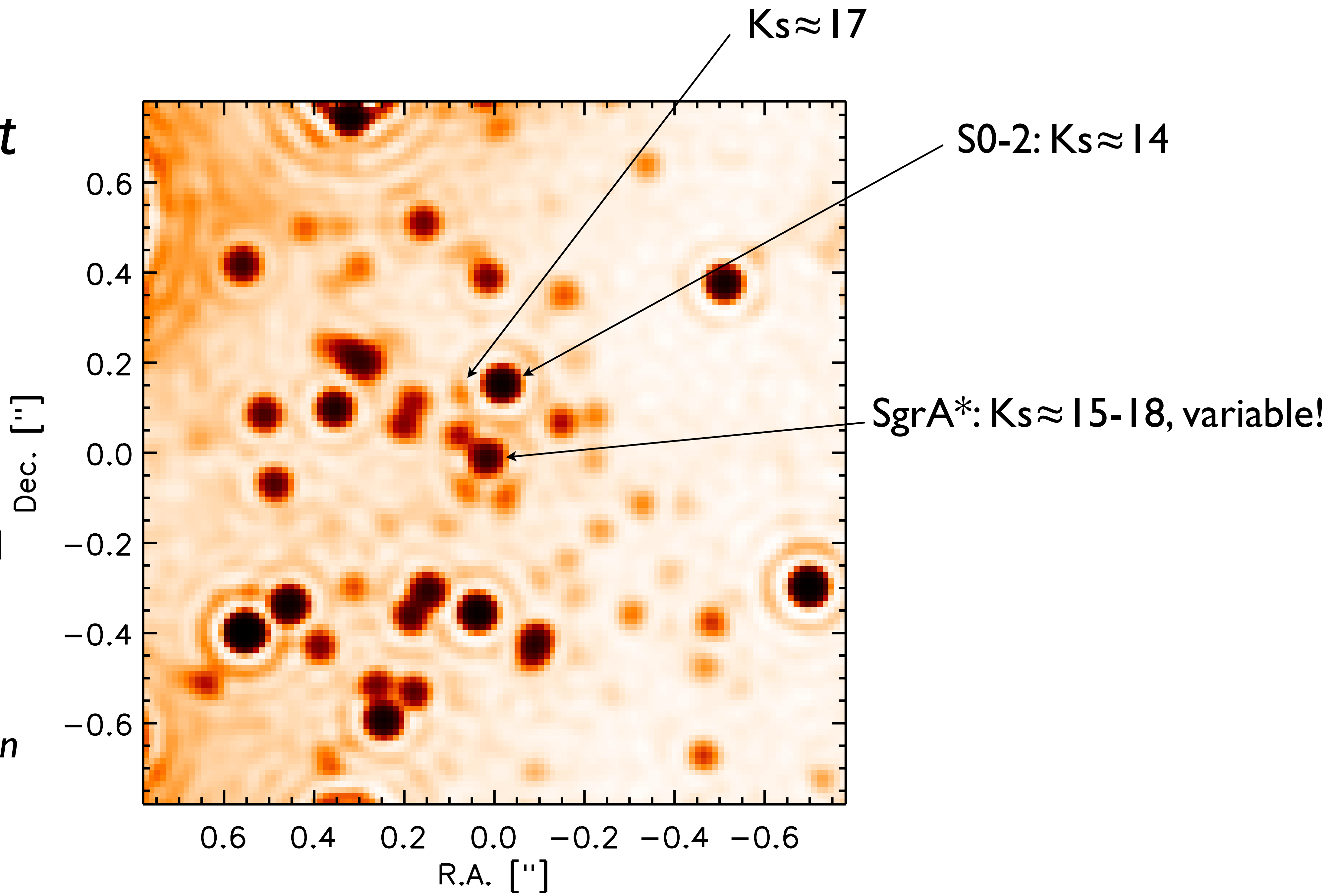
AO-assisted integral-field spectroscopy is indispensable to overcome source confusion!

2) Confusion limits the accuracy of astrometry

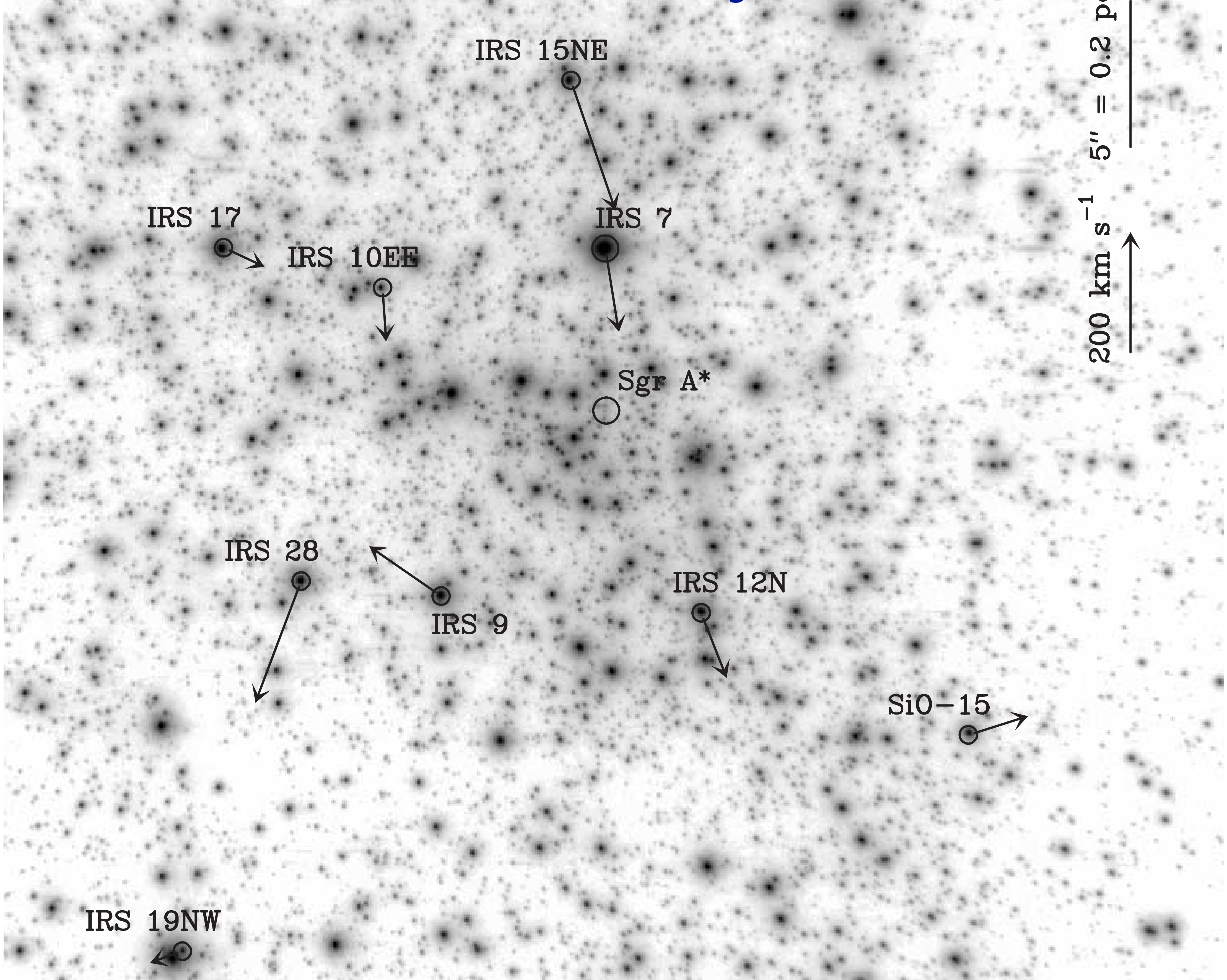
Completeness limit near SgrA* is *Ks≲17*

Overlap with unresolved sources can easily introduce astrometric errors of a few mas. *(Ghez et al., 2008; Gillessen et al., 2009)*



NACO/VLT, *Ks*, Sept 2010
State-of-the-art: AO + holography
60 mas FWHM

2) Stability of Reference Frame limits the accuracy of astrometry

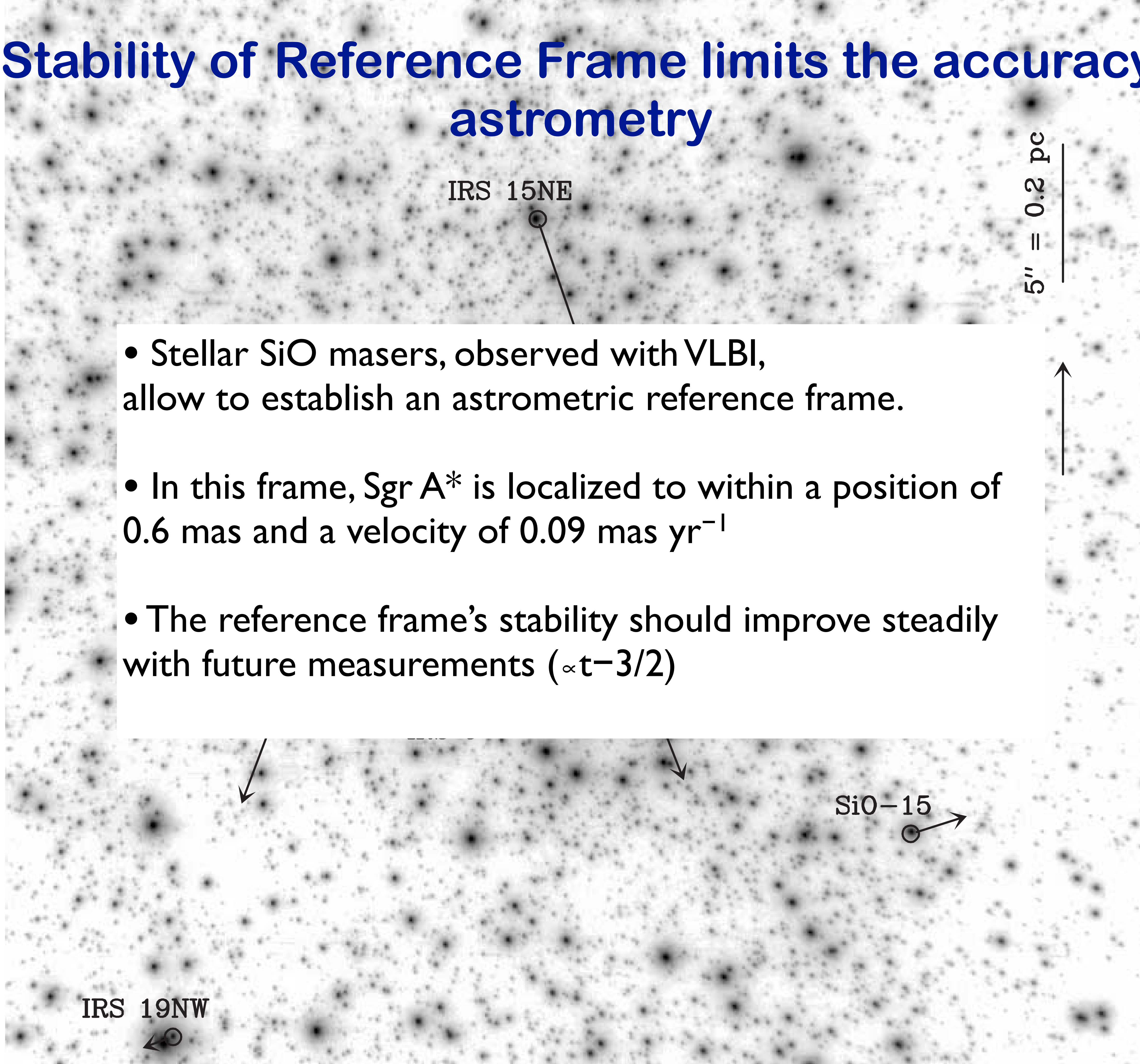


2) Stability of Reference Frame limits the accuracy of astrometry

- Stellar SiO masers, observed with VLBI, allow to establish an astrometric reference frame.

- In this frame, Sgr A* is localized to within a position of 0.6 mas and a velocity of 0.09 mas yr^{-1}

- The reference frame's stability should improve steadily with future measurements ($\propto t^{-3/2}$)



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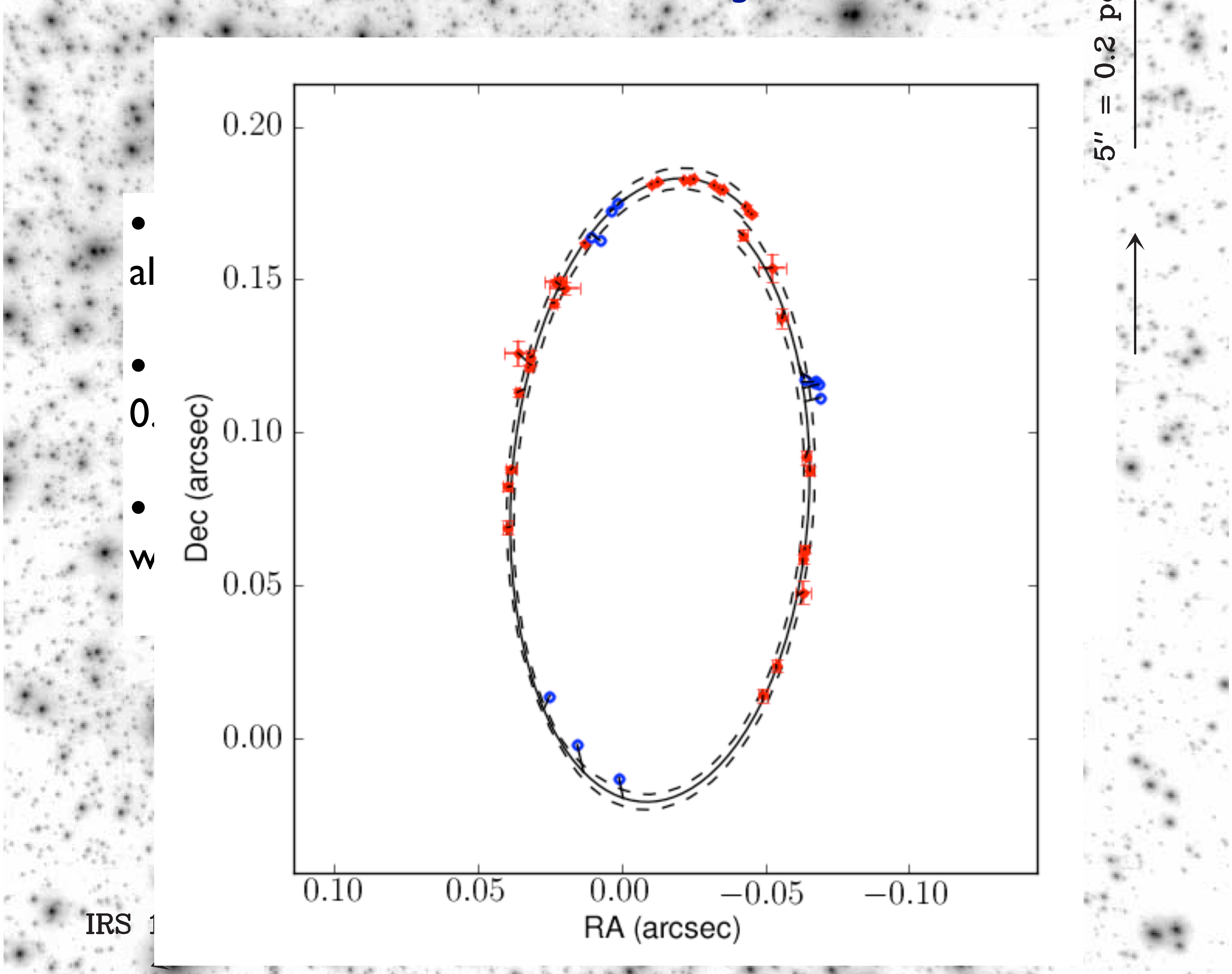

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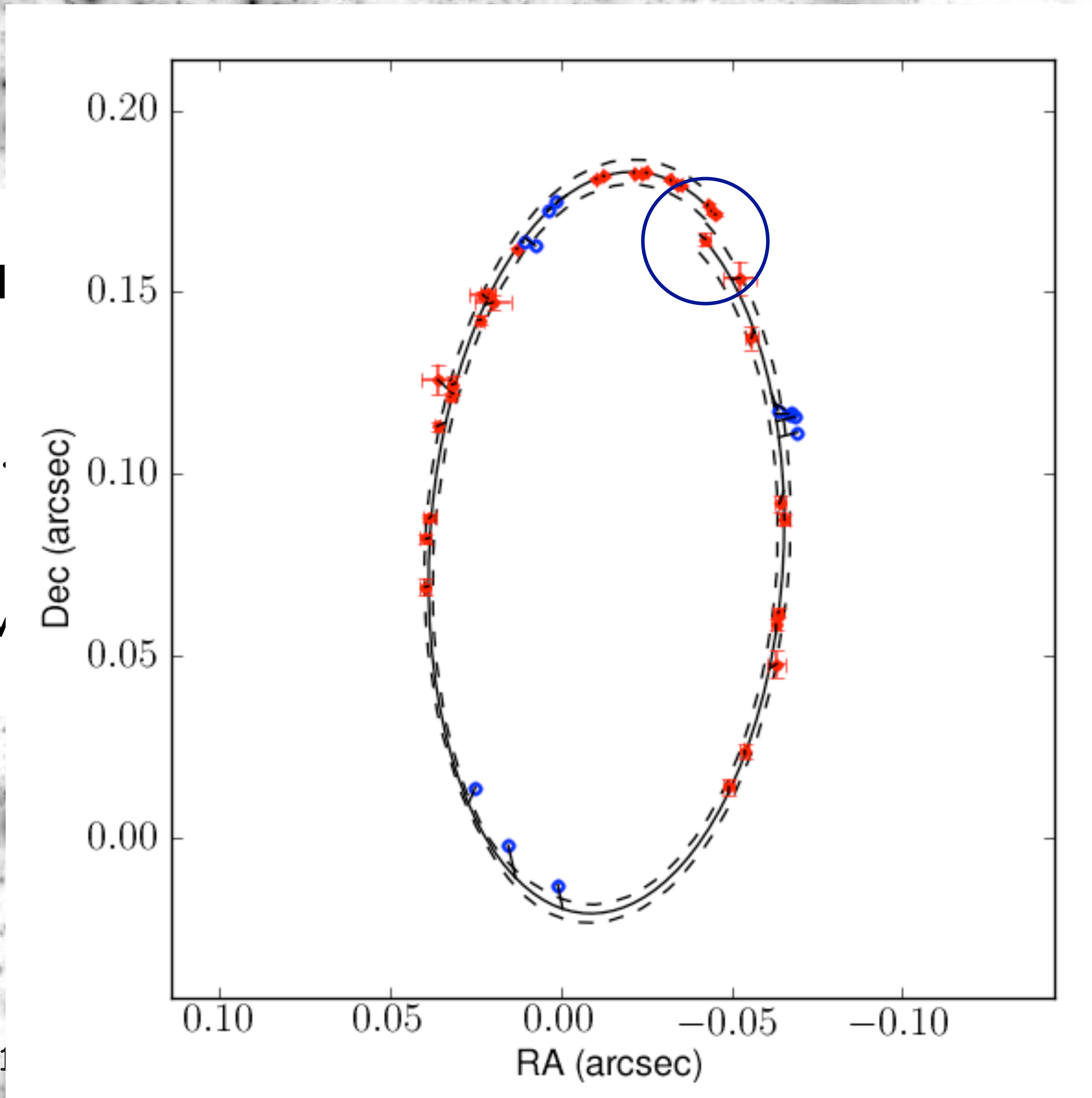

5″ = 0.2 pc

3) Degeneracies require the use of multiple stars

Redshift: Inclination must be known.

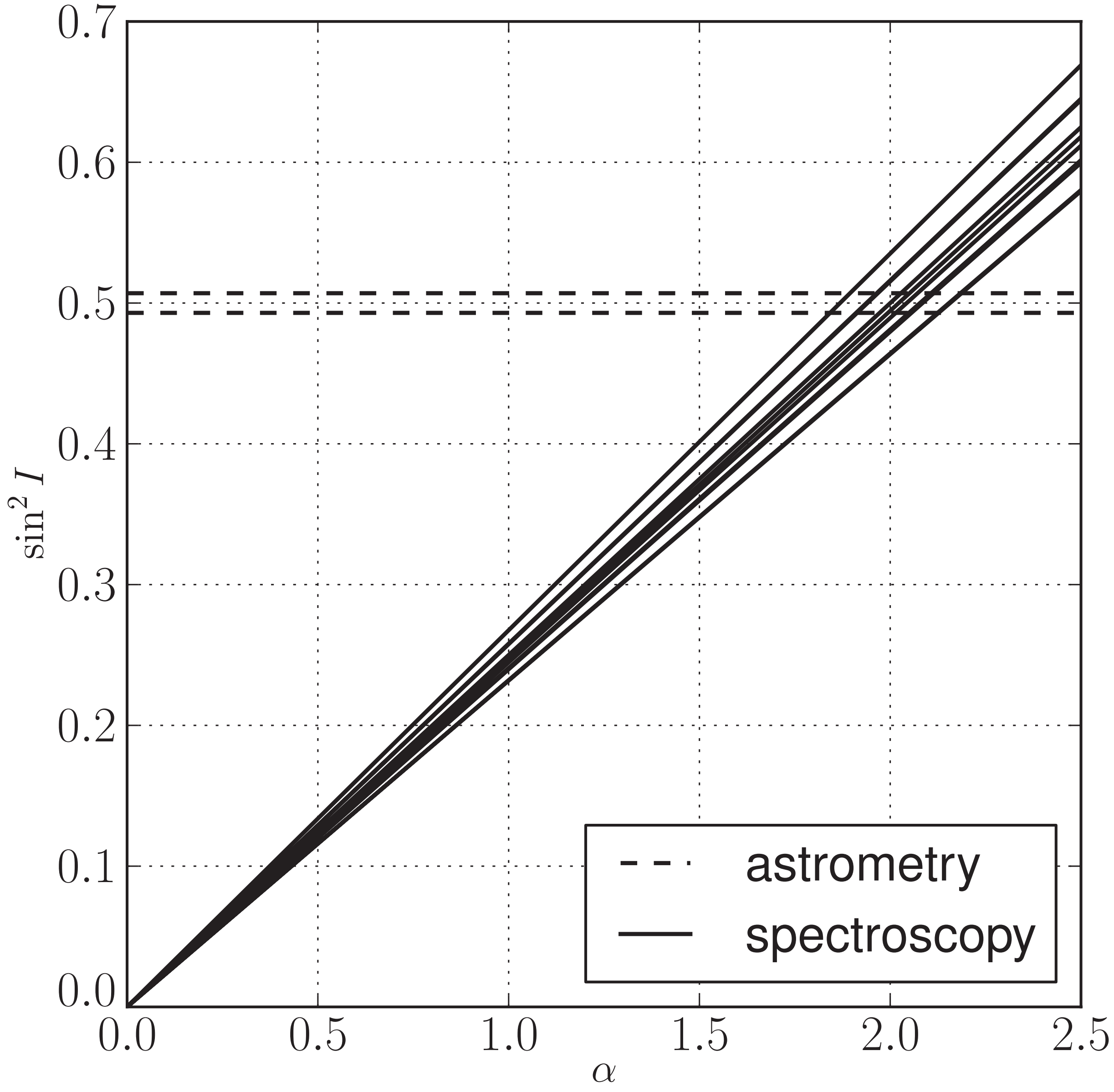

Figure 1. Recovery of α for 10 mock data sets. The ratio A_C^2/A_R is the slope of the lines in the above plot and is recovered from mock spectroscopic data of 14 data points with accuracy 10 km s^{-1}, concentrated around pericenter. The horizontal lines are the upper and lower confidence levels for the recovered inclination from astrometry, taken from Gillessen et al. (2009b). The intersection point corresponds to the value of α for which both data types agree on the inclination.

Angelil & Saha (2011)

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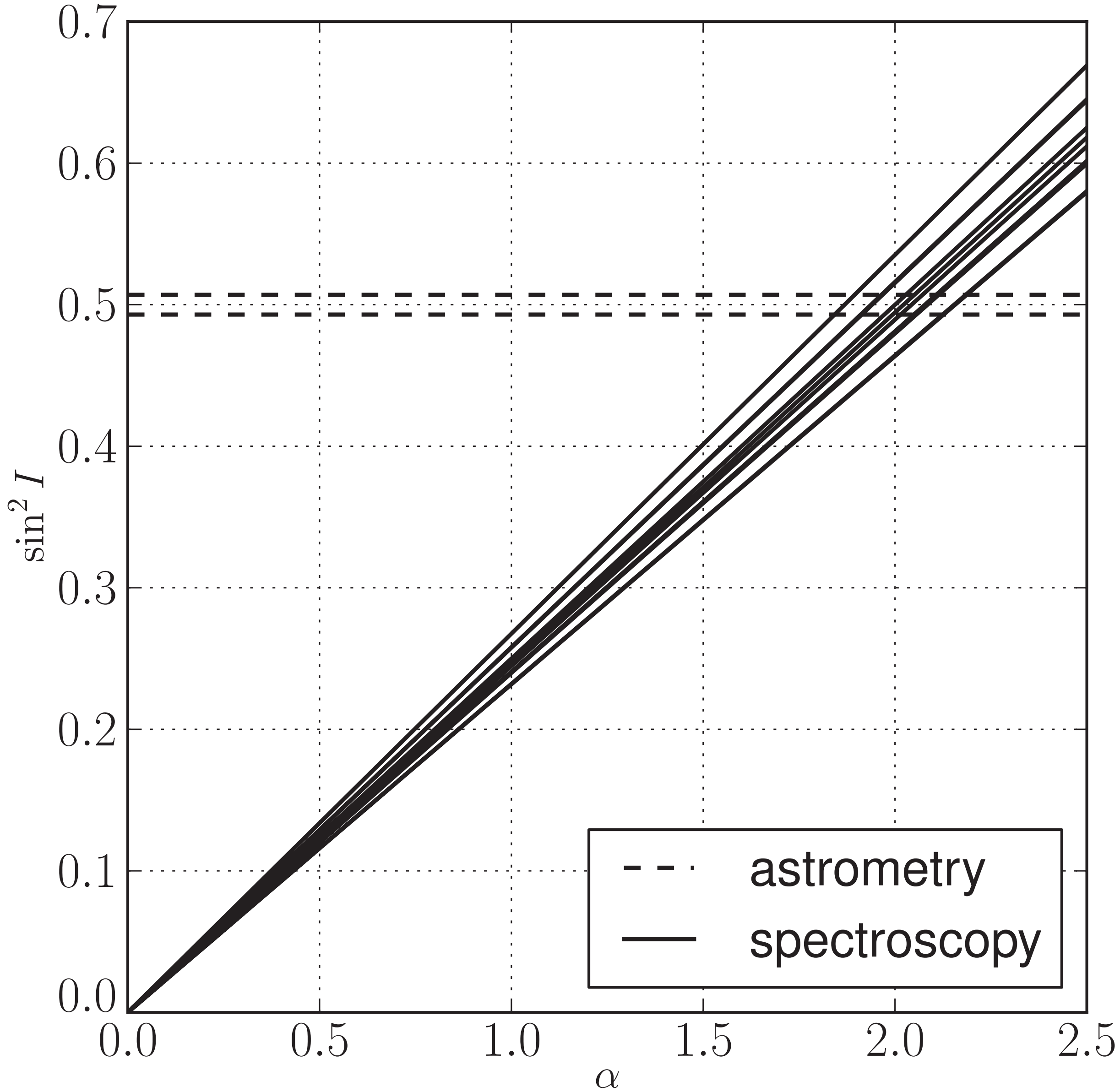

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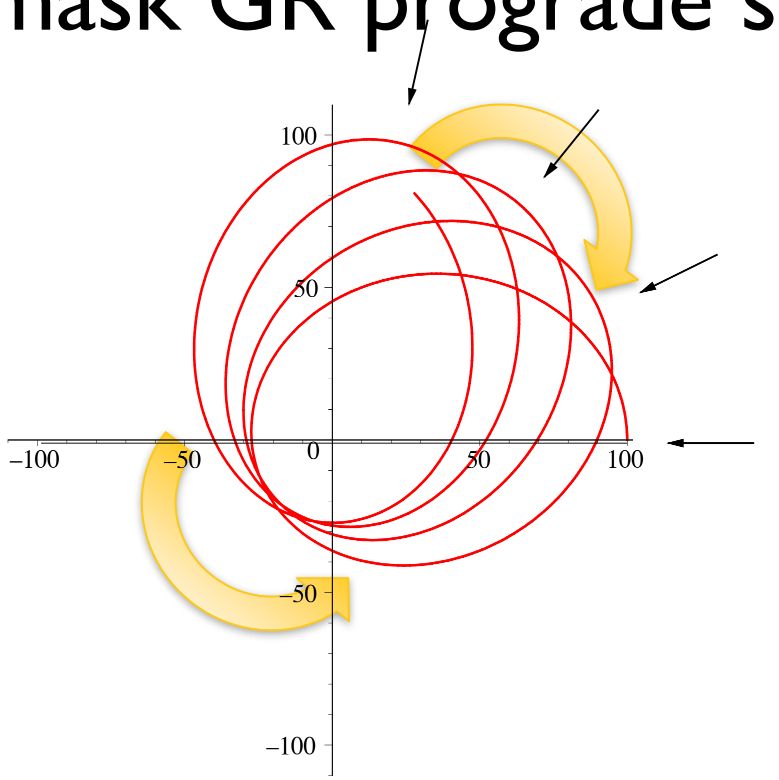
Angelil & Saha (2011)

Periapse precession:
Newtonian retrograde shift can mask GR prograde shift.



Rubilar & Eckart (2001)

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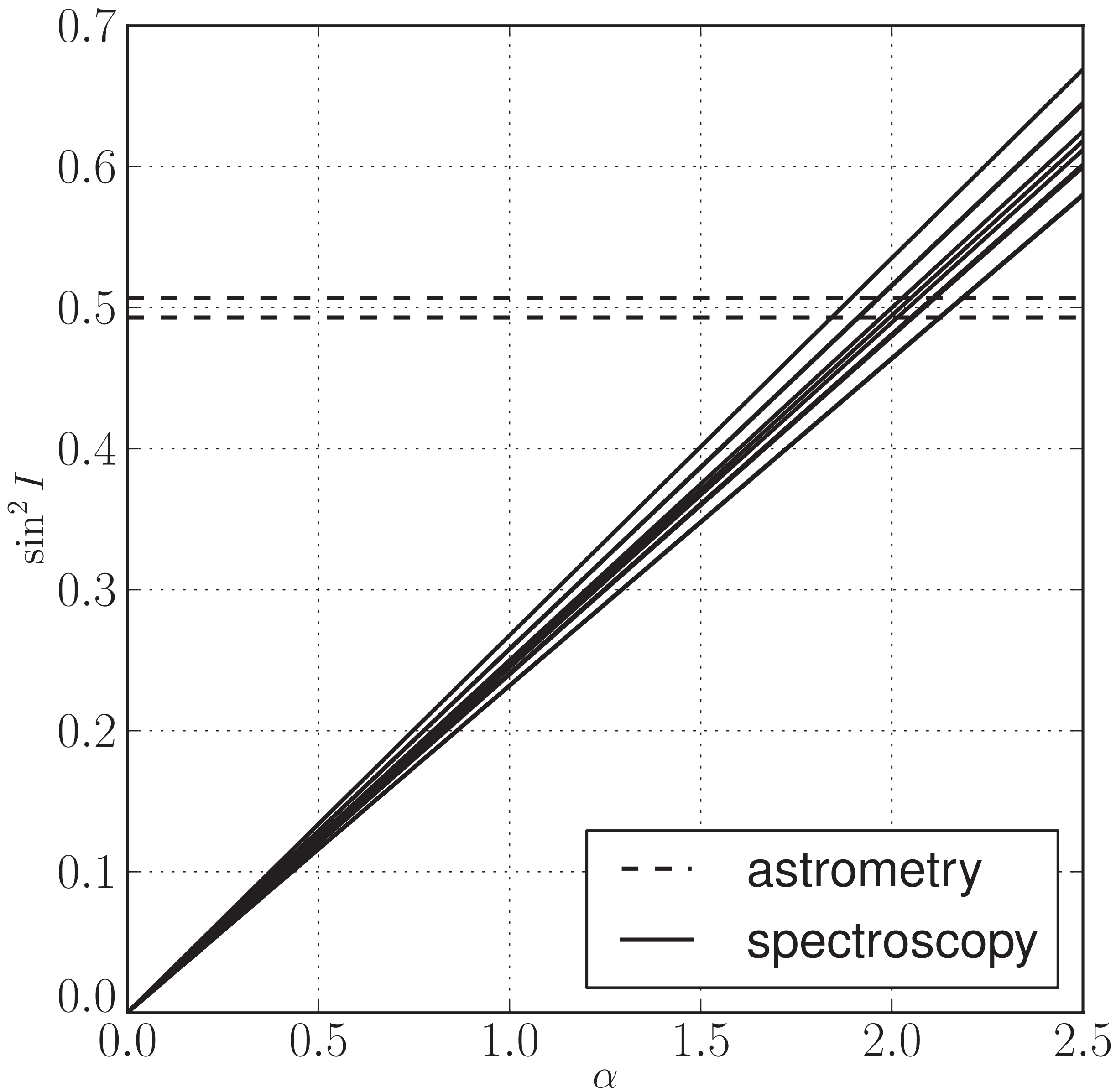

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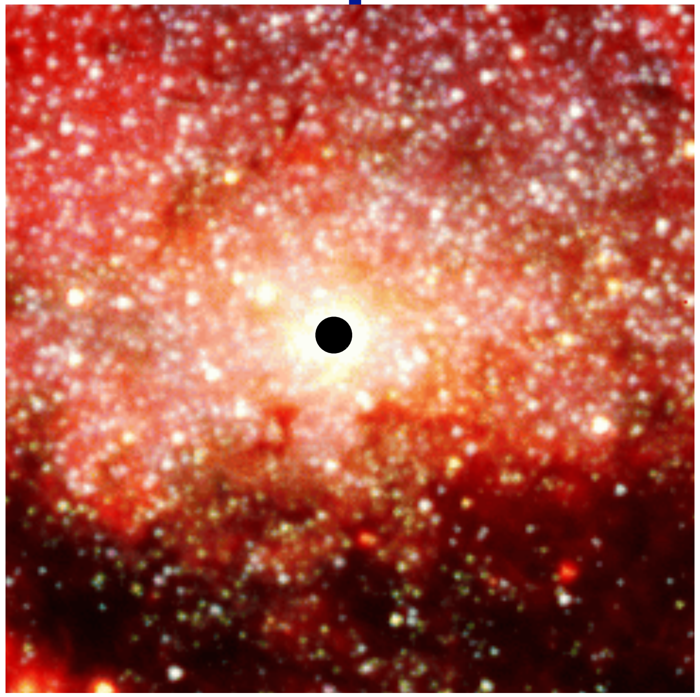

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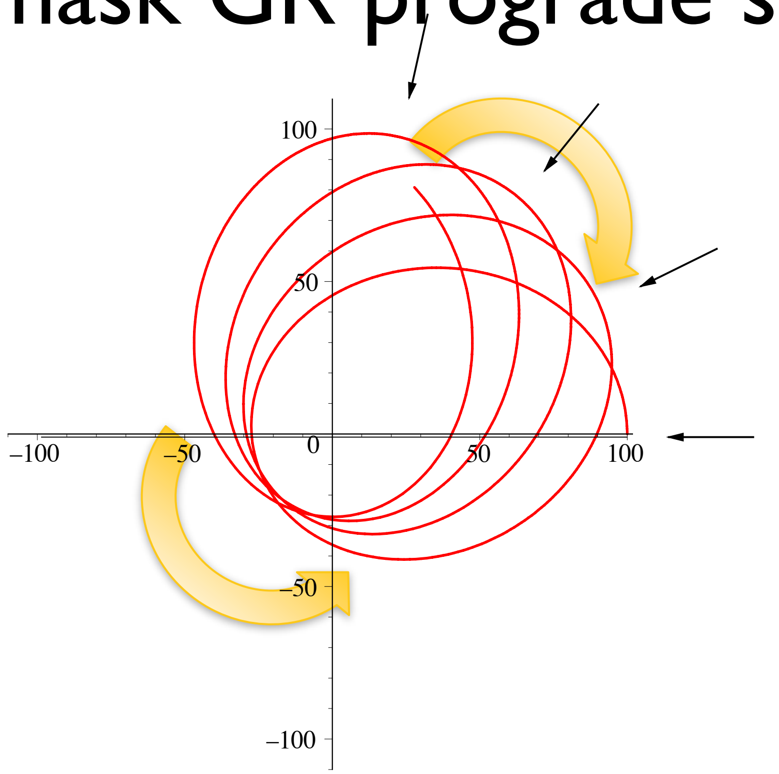

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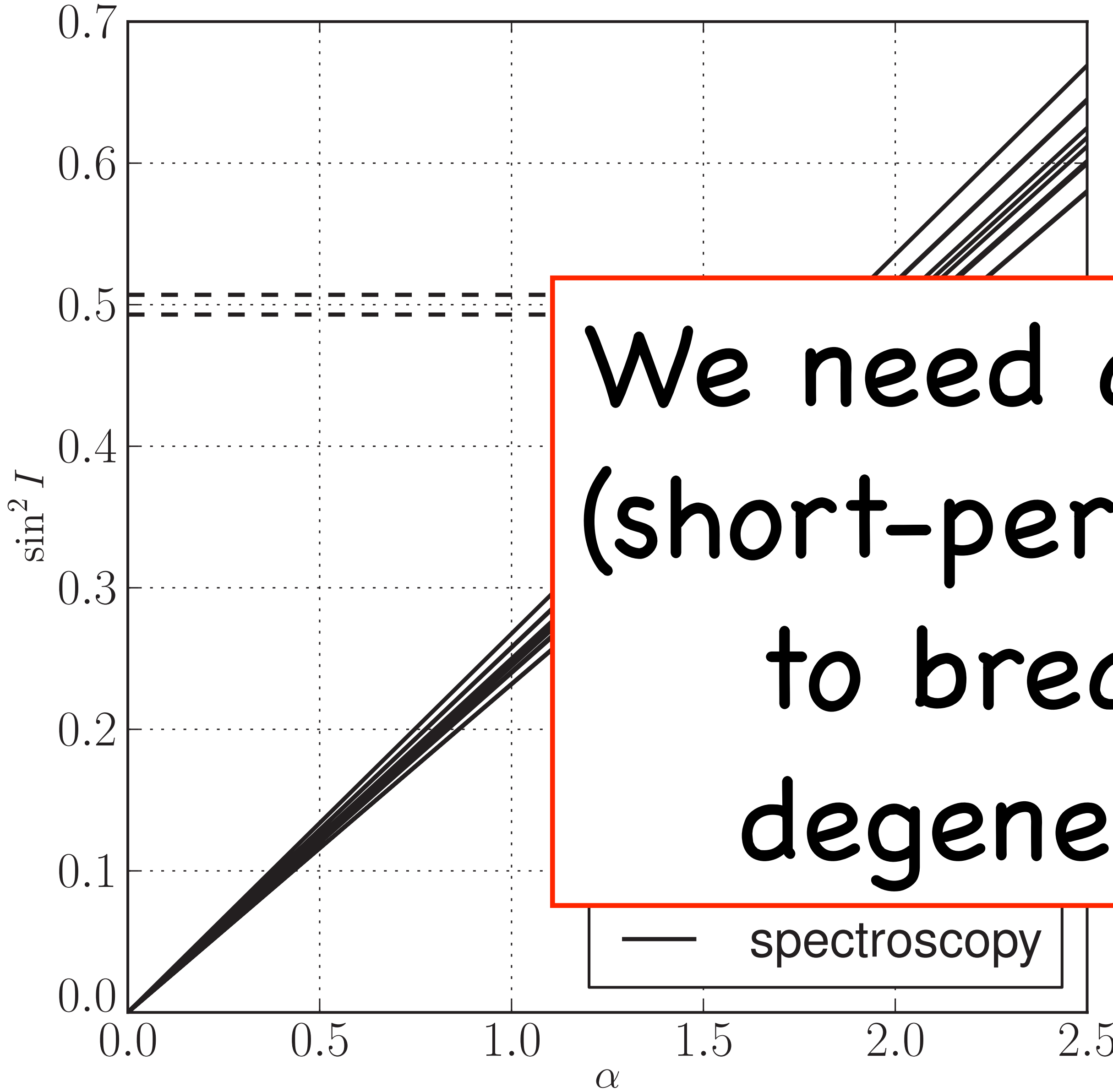

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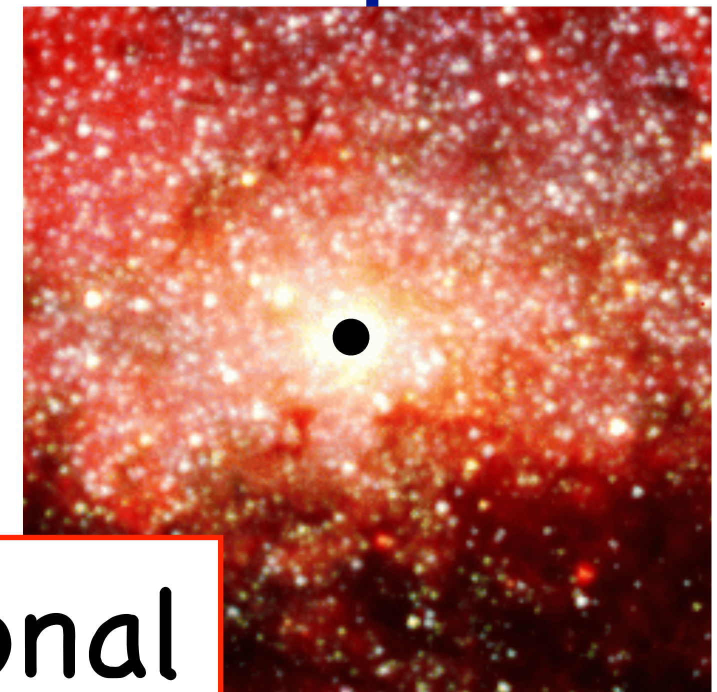
Angelil & Saha (2011)

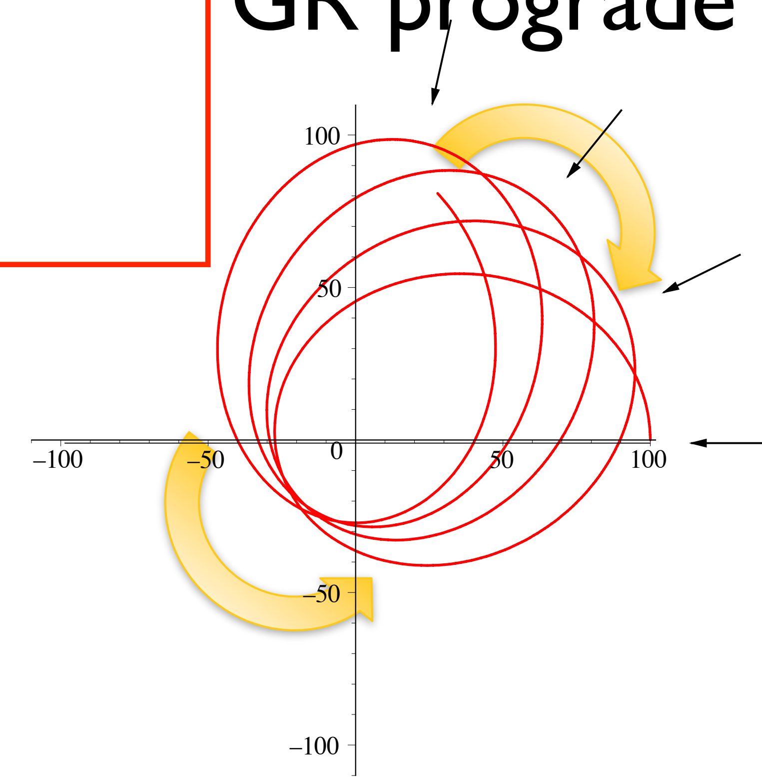
We need additional (short-period) stars to break the degeneracies.



...pse precession:

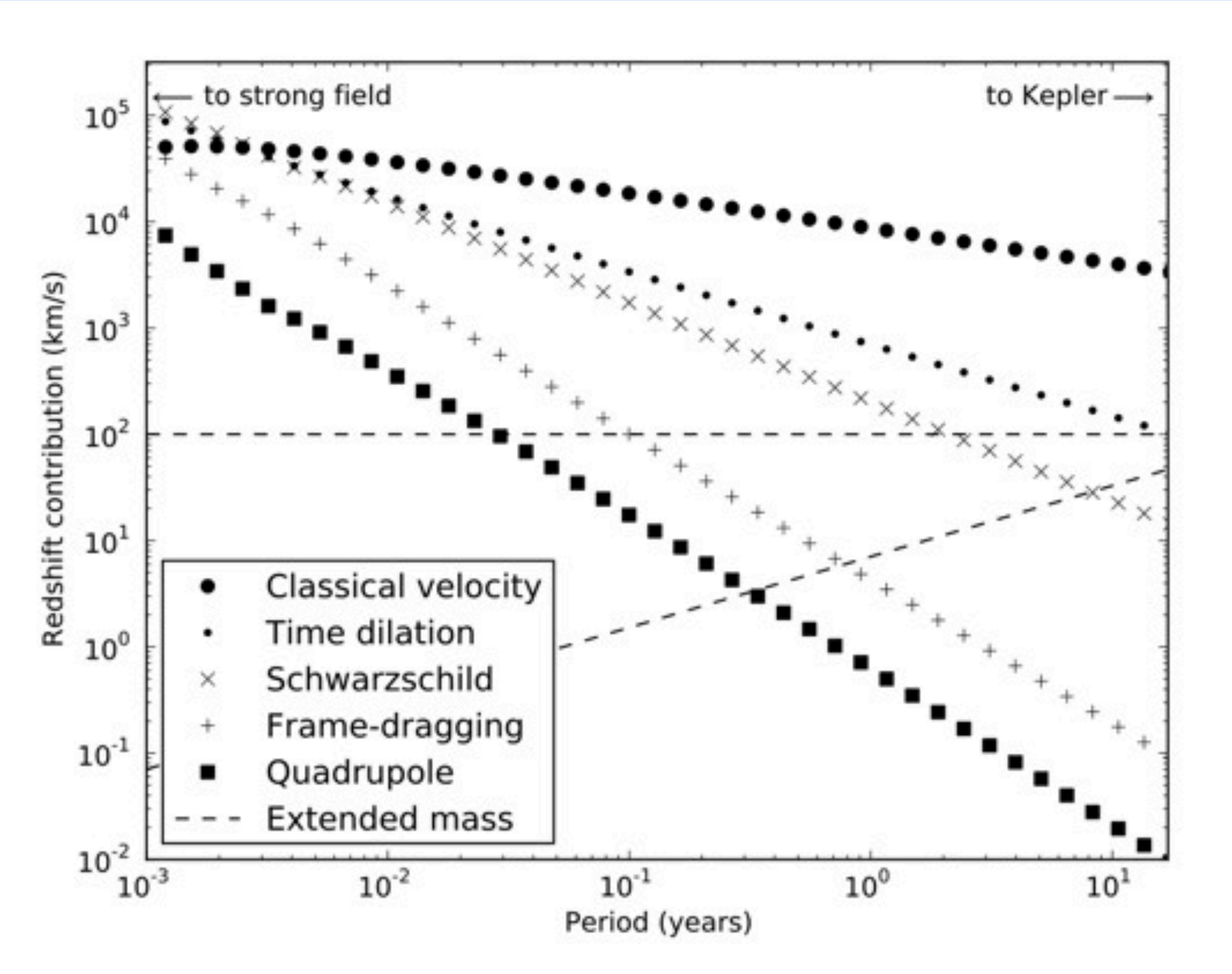
...an retrograde shift

... GR prograde shift.



Rubilar & Eckart (2001)

The meaning of a short period



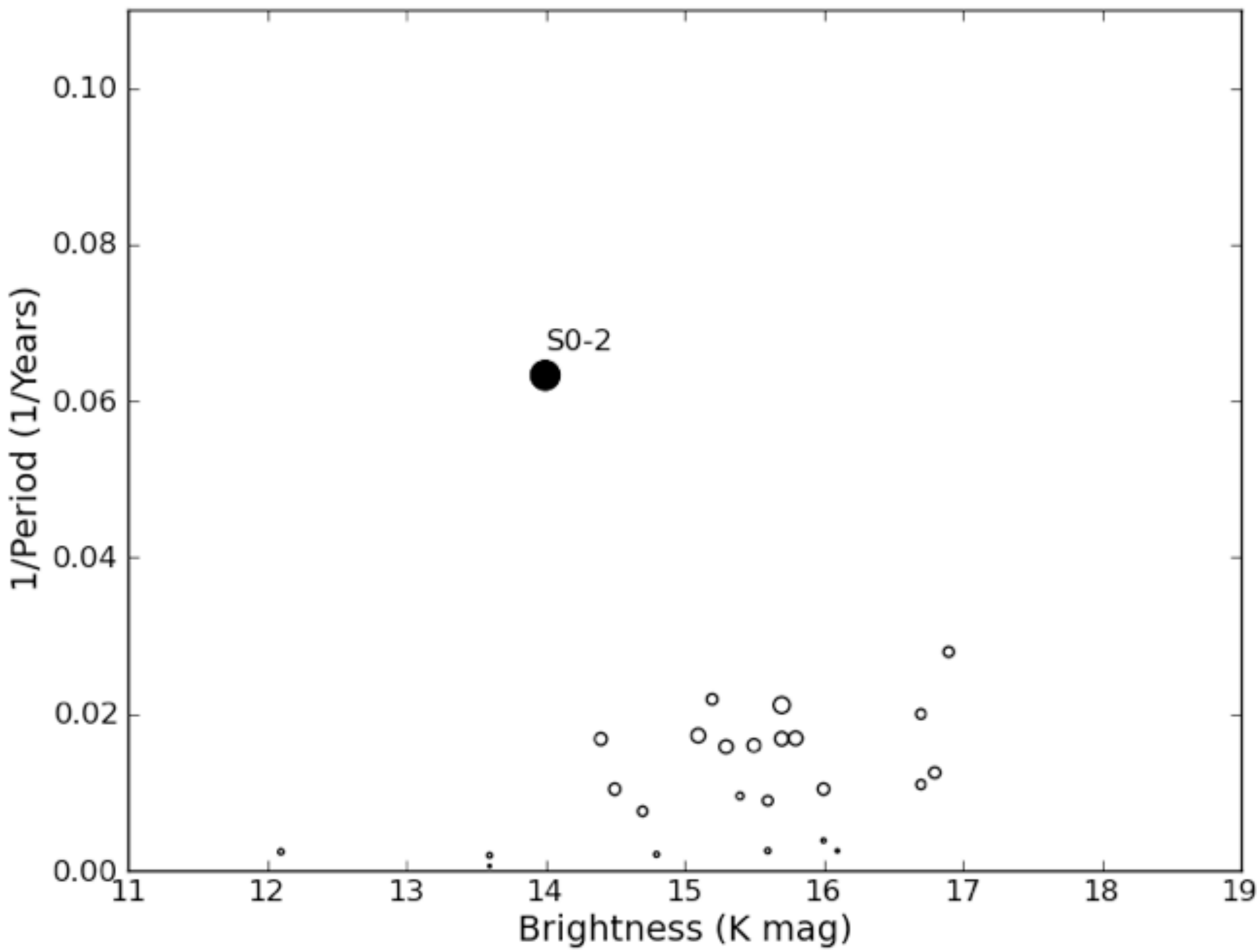
The various relativistic effects scale with period (from Angelil et al. 2010)

- Only stars with short periods can have a significant fraction of their orbits covered. This is key in determining a reliable orbit, especially in the Galactic center since confusion events can mimic orbital curvature!

UCLA

The Shortest-Known Period Star

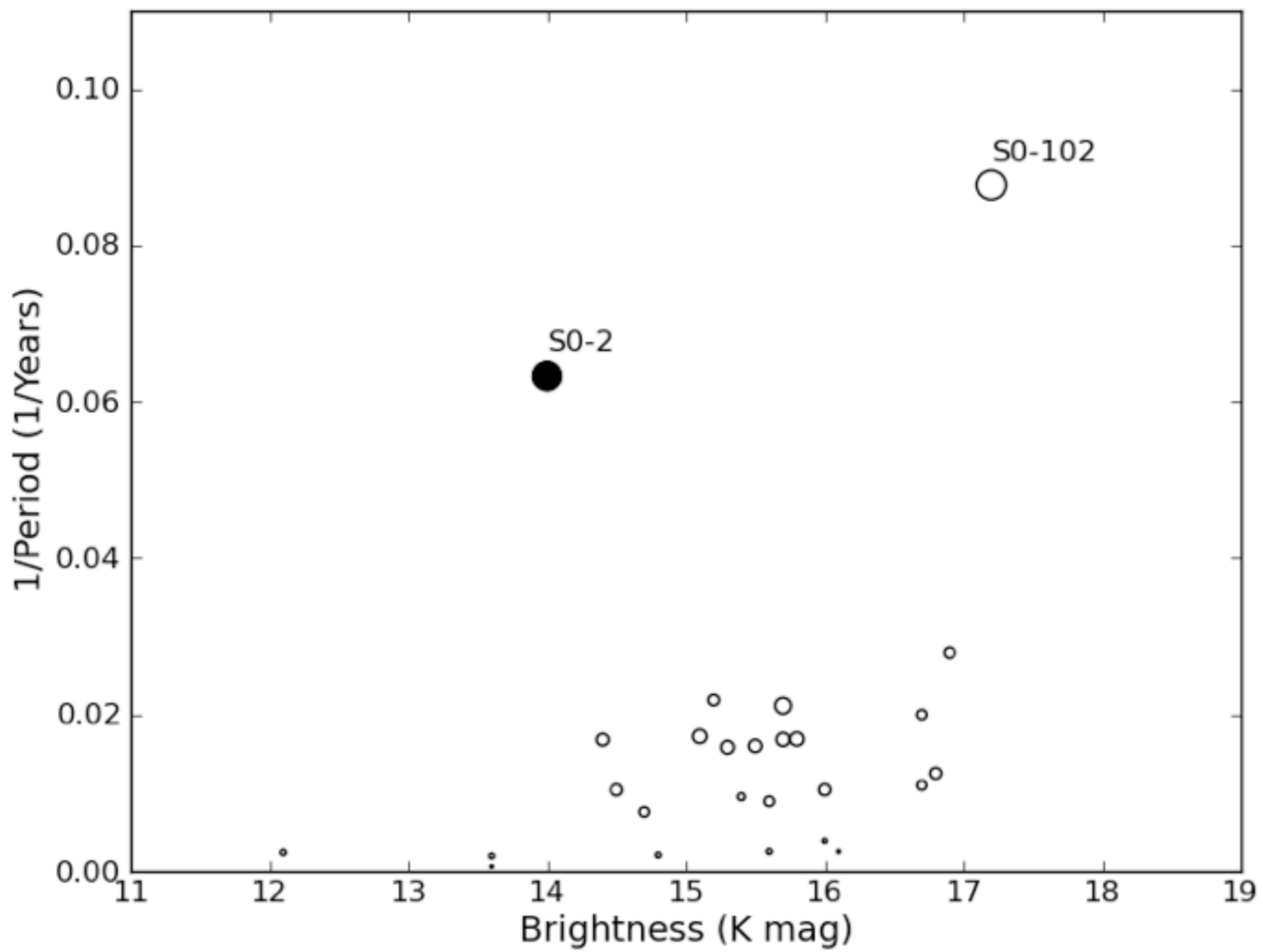
We need more stars with short orbital periods…



Ghez et al. (2005, 2008)
Gillessen et al. (2009)

UCLA

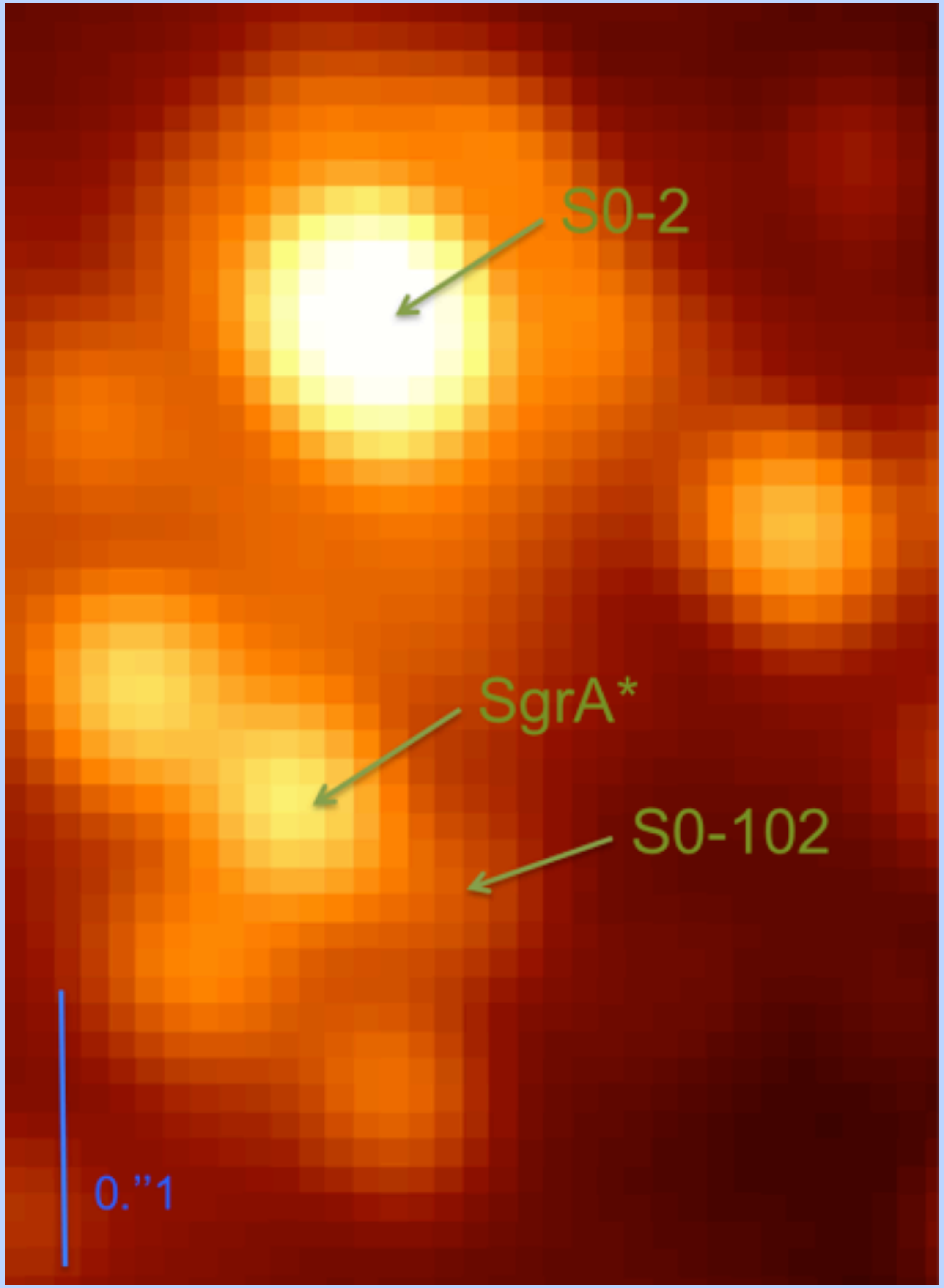
..and we found one!!



Meyer, Ghez, Schoedel et al. 2012, *Science*

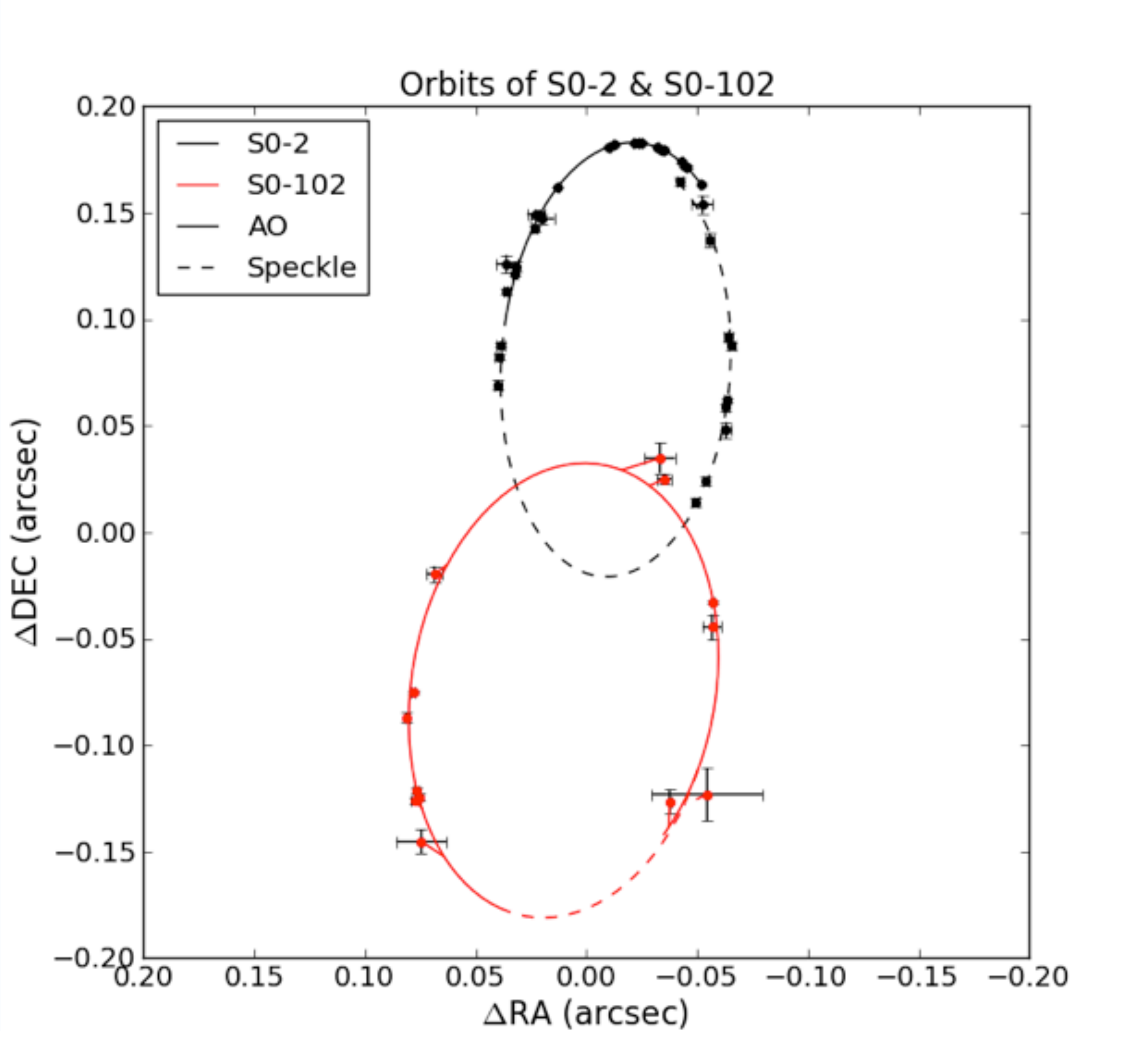
UCLA

S0-102's magnitude (K=17.3) makes it prone to source confusion



UCLA

S0-102 has an orbital period of 11.5 yrs



Kmag = 17.3

P = 11.5 ± 0.3

e = 0.68 ± 0.02

i = 151 ± 3 deg

Periapse dist = 1.3 ± 0.1 mpc

Future AO measurements will allow us to obtain a more accurate orbital solution for S0-102.

UCLA

Digging for Gold in Old Data

Speckle imaging

1) take short exposures with $t_{exp} \sim \tau_0$
2) reconstruct images off-line

<u>Simple Shift-and-Add (SAA) algorithm:</u>

1. choose a reference star and reference pixel
2. shift each image in stack so that brightest speckle of reference star comes to rest on reference pixel
3. average stack

(see, e.g., Christou, 1991; Eckart & Genzel 1996; Ghez et al., 1998)

Selection of best frames
⇒ Strehl ratios 10%-30% in K-band

(4-10m telescopes, Ks-band, e.g. Schoedel et al., 2003; Ghez et al. 2005)

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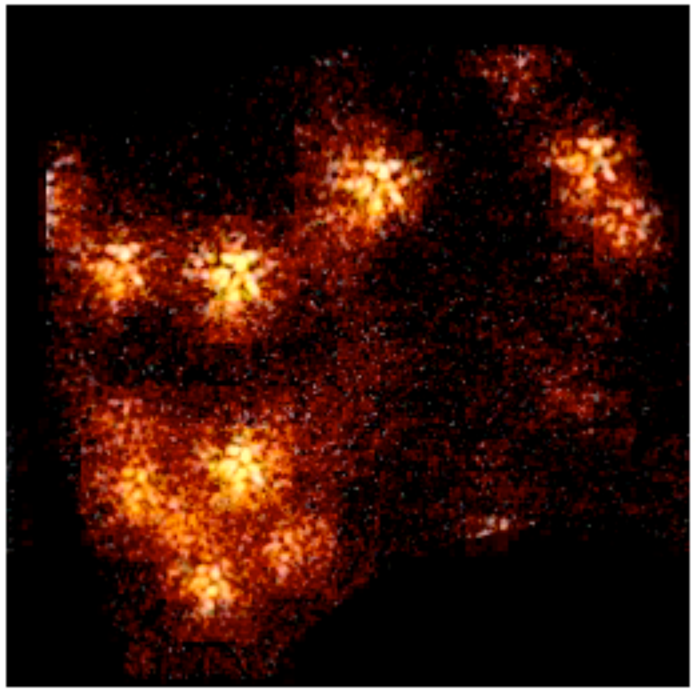

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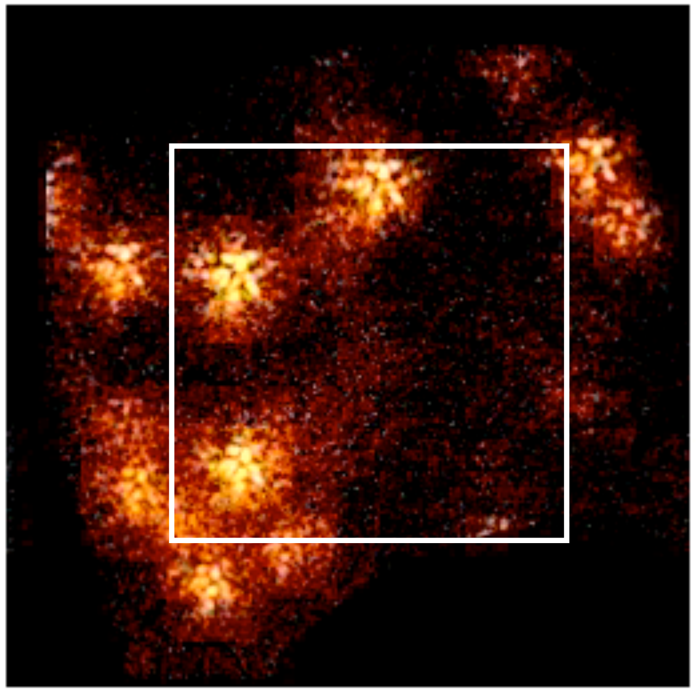

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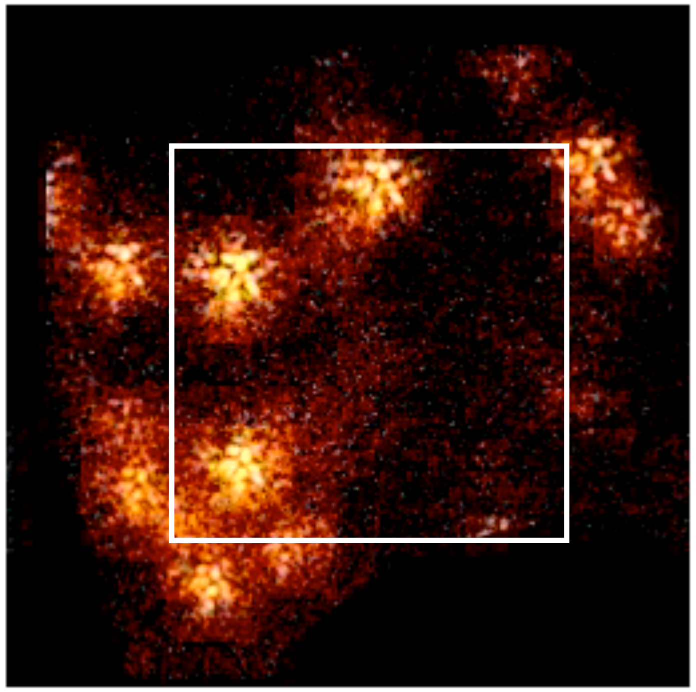
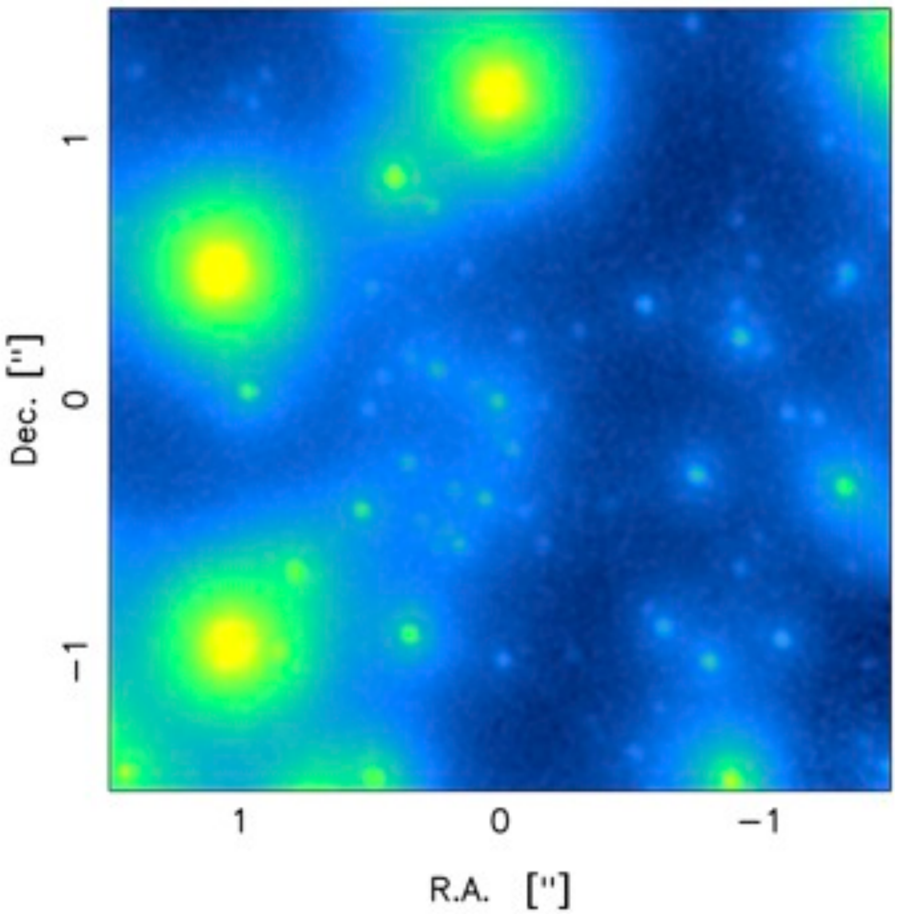


SSA reconstruction



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Adaptive Optics

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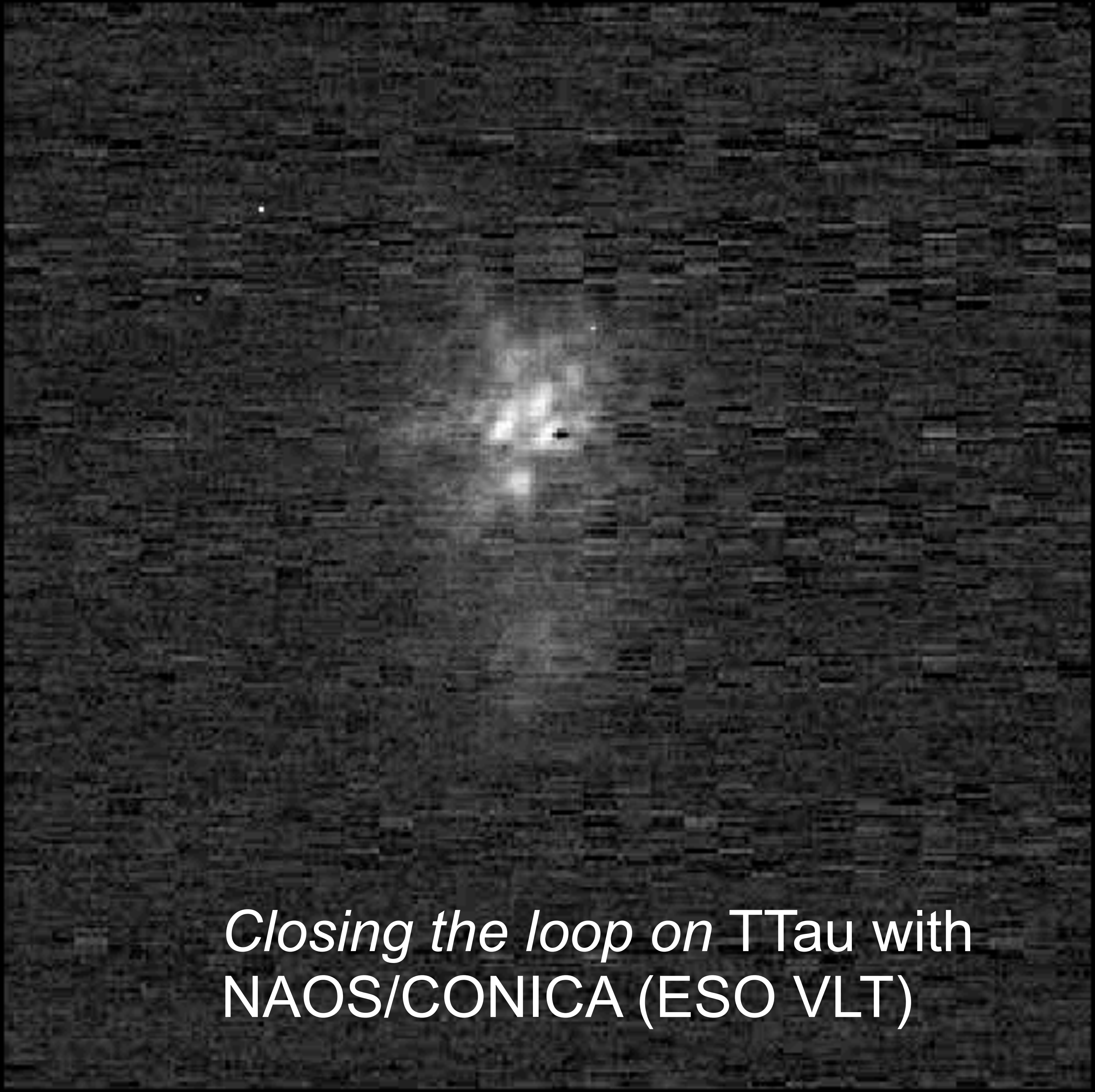
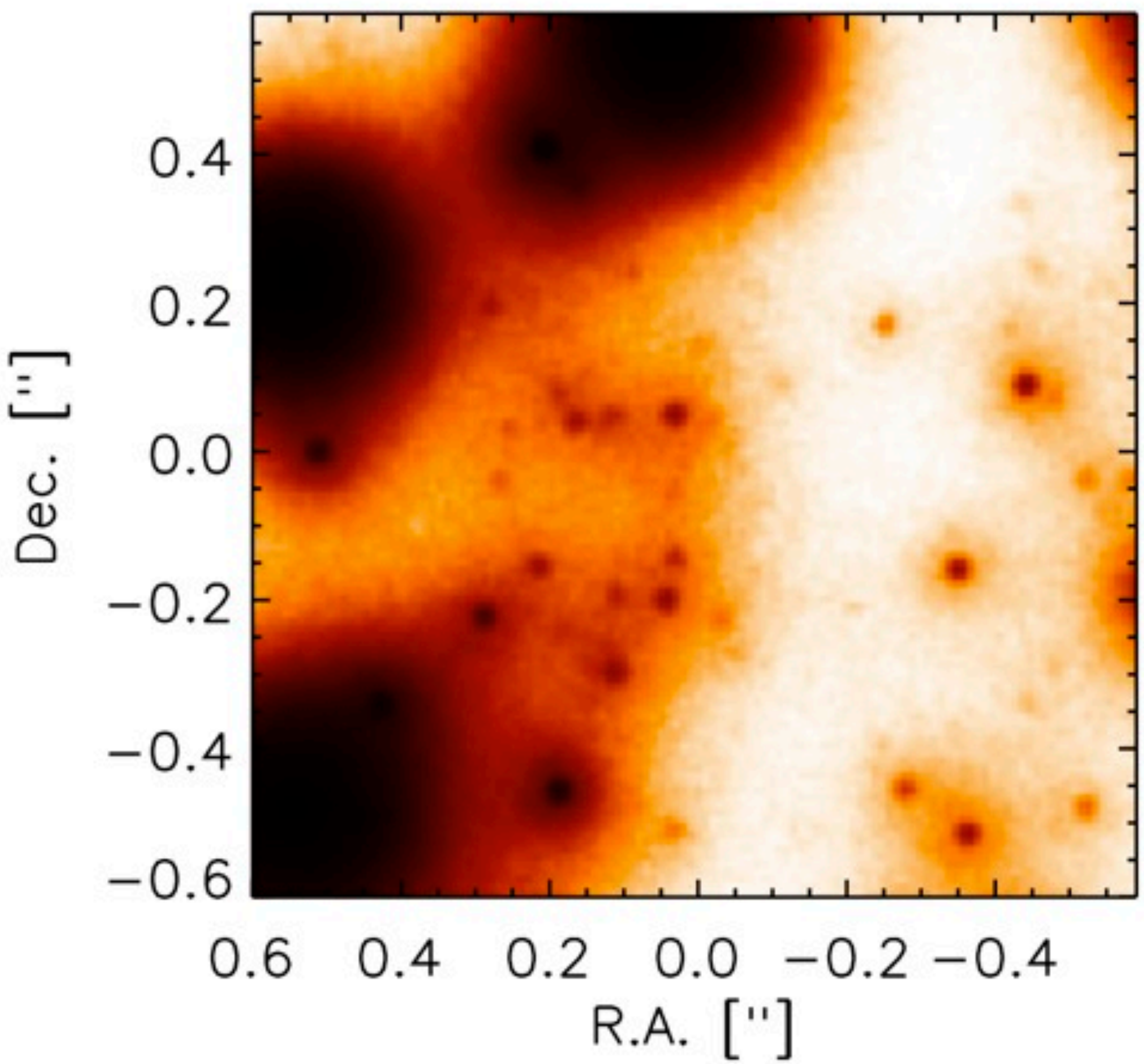
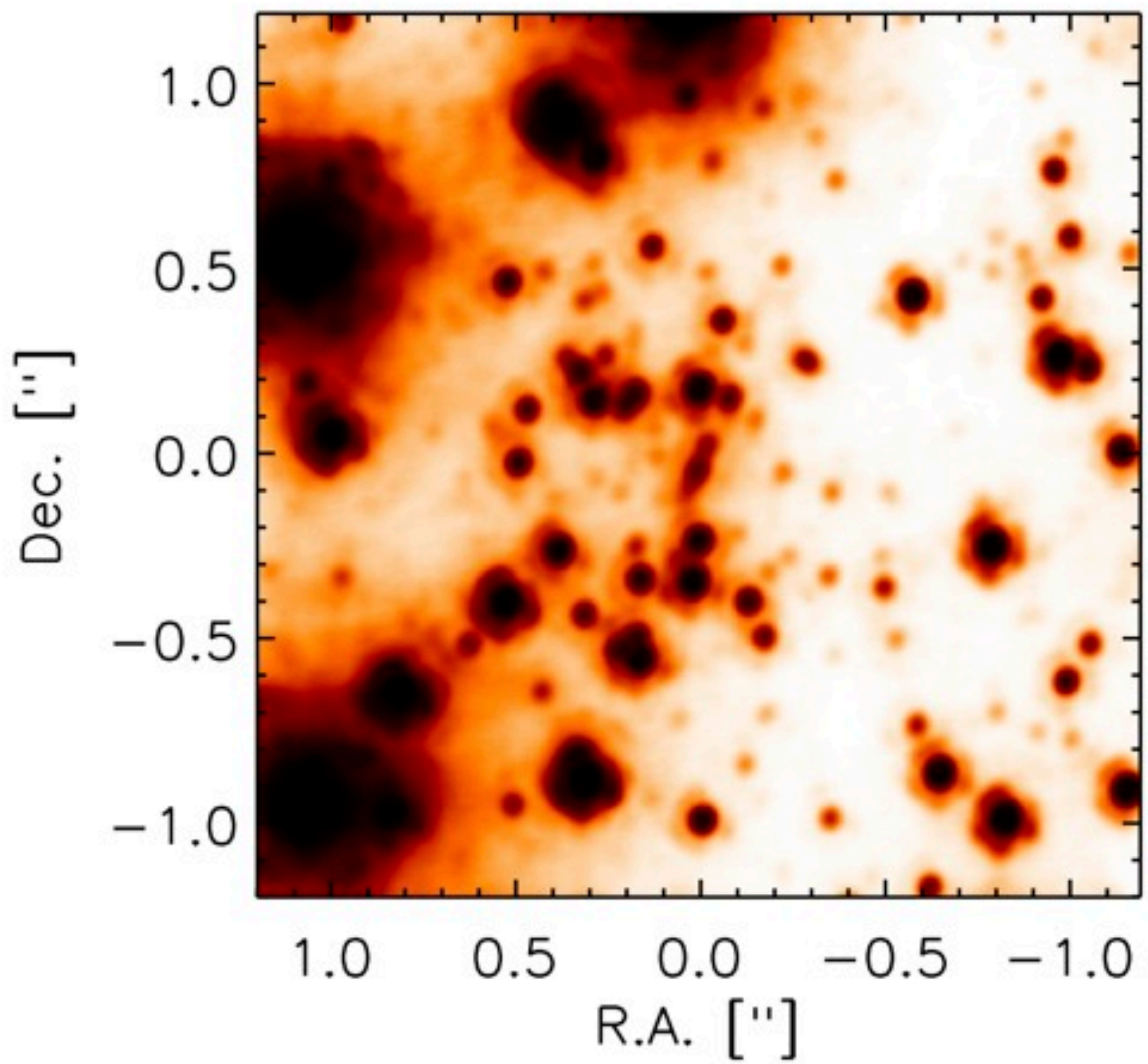


Closing the loop on TTau with NAOS/CONICA (ESO VLT)

Holographic image reconstruction maximizes the scientific return of historic speckle data.



Speckle imaging+SSA
Keck/NIRC, 1995-2005



AO + LGS
Keck/NIRC2, since 2005

Schödel et al. 2013, MNRAS

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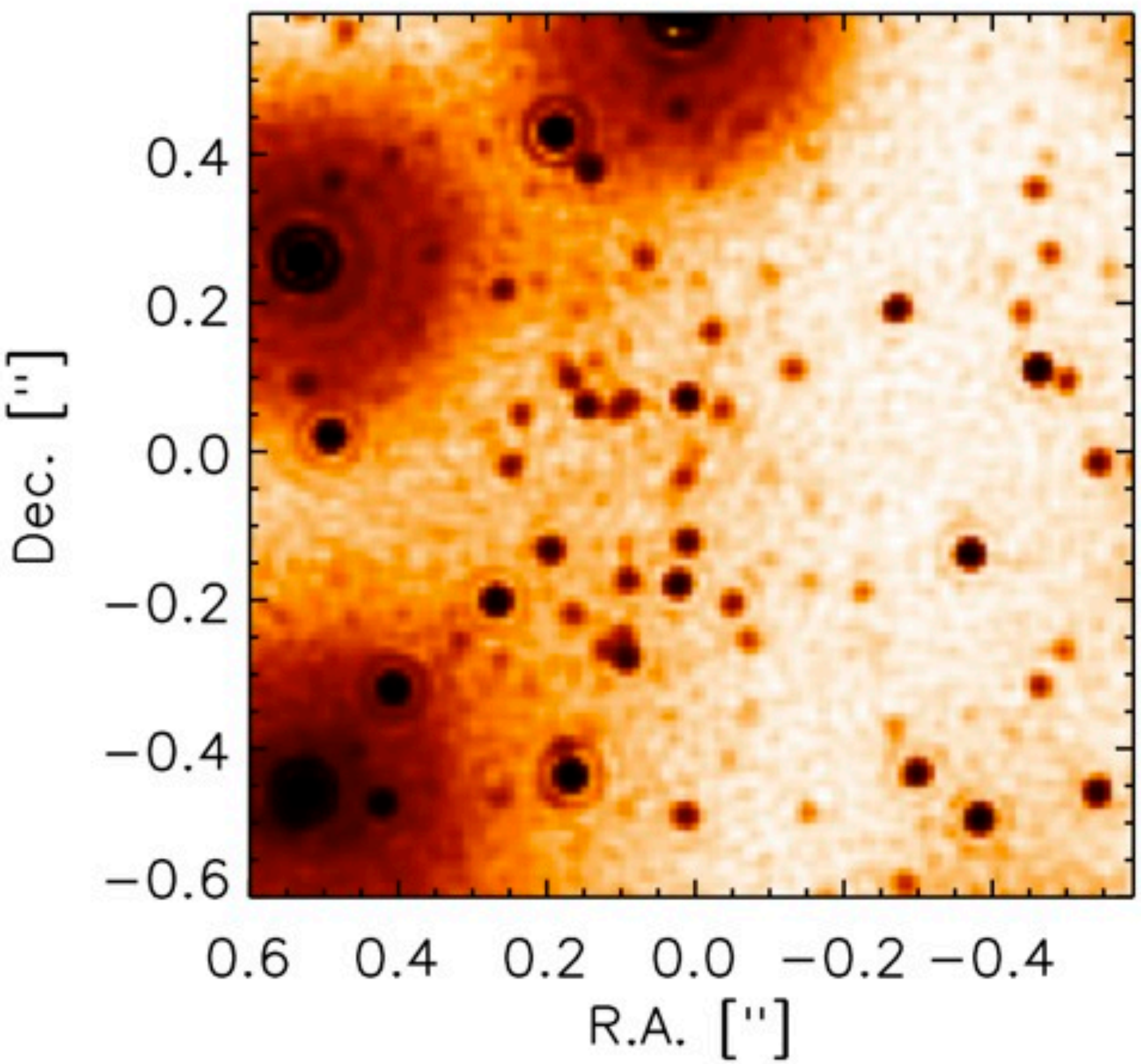
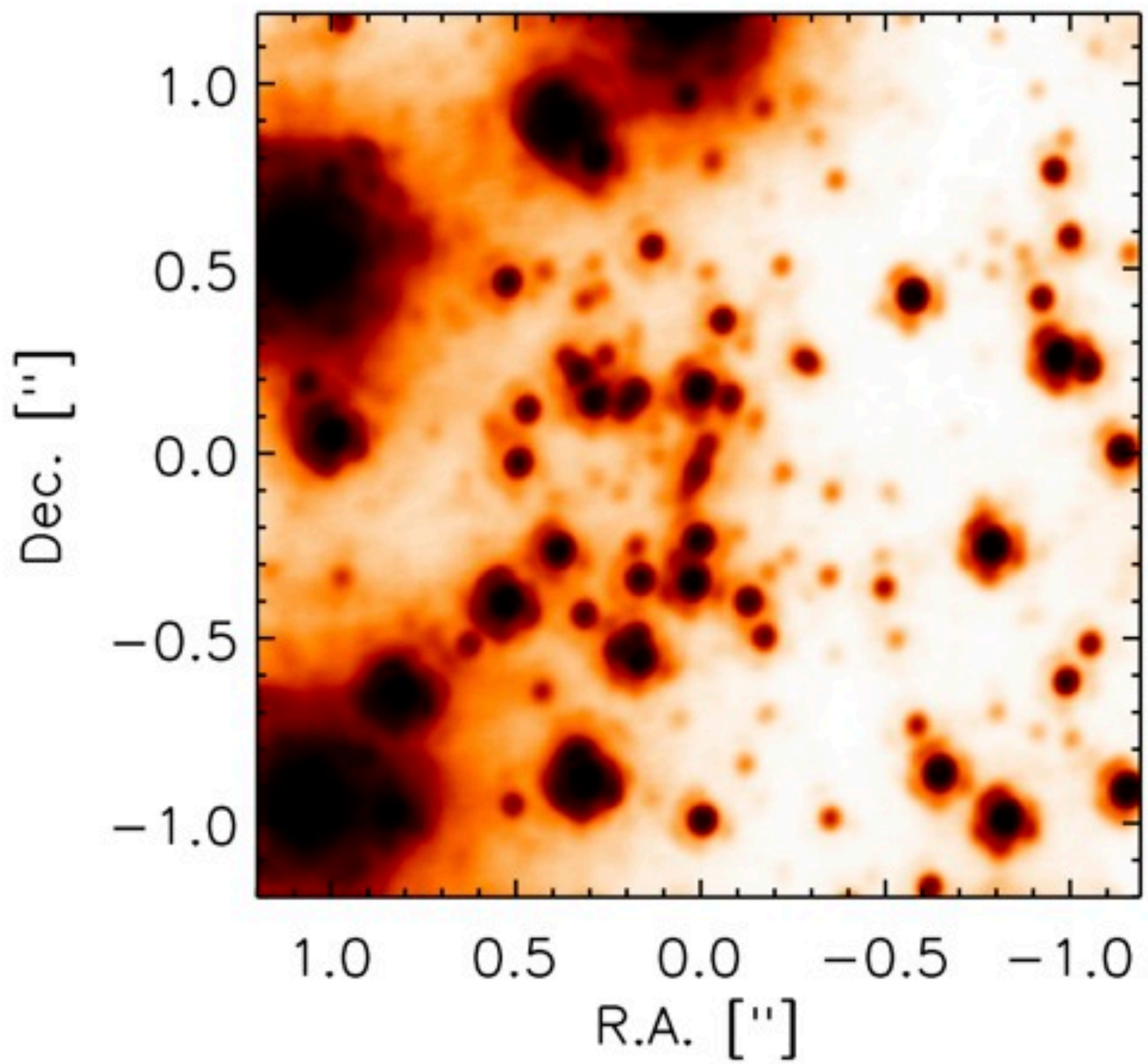


Speckle imaging+Holography
Keck/NIRC, 1995-2005



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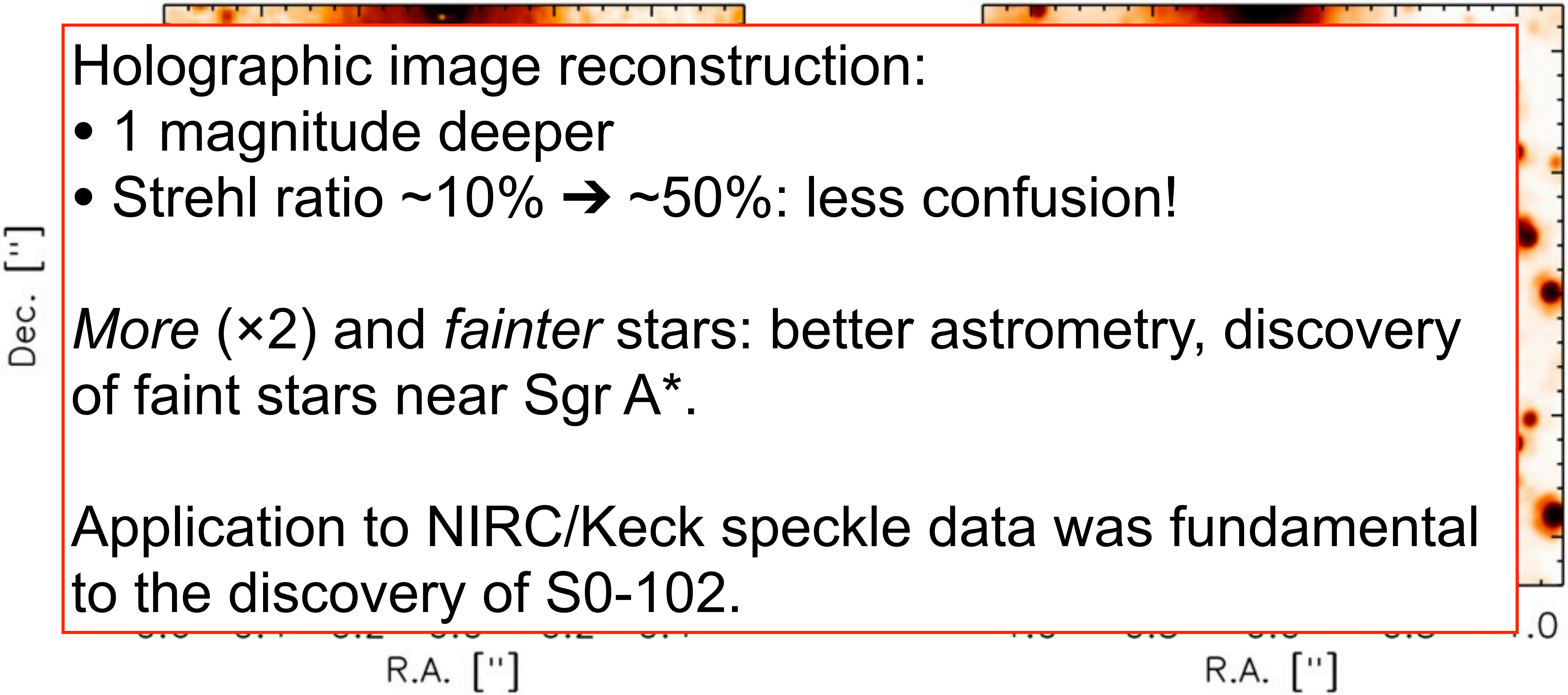


Holographic image reconstruction:

- 1 magnitude deeper
- Strehl ratio ~10% ➔ ~50%: less confusion!

More (×2) and *fainter* stars: better astrometry, discovery of faint stars near Sgr A*.

Application to NIRC/Keck speckle data was fundamental to the discovery of S0-102.

Speckle imaging+Holography
Keck/NIRC, 1995-2005

AO + LGS
Keck/NIRC2, since 2005

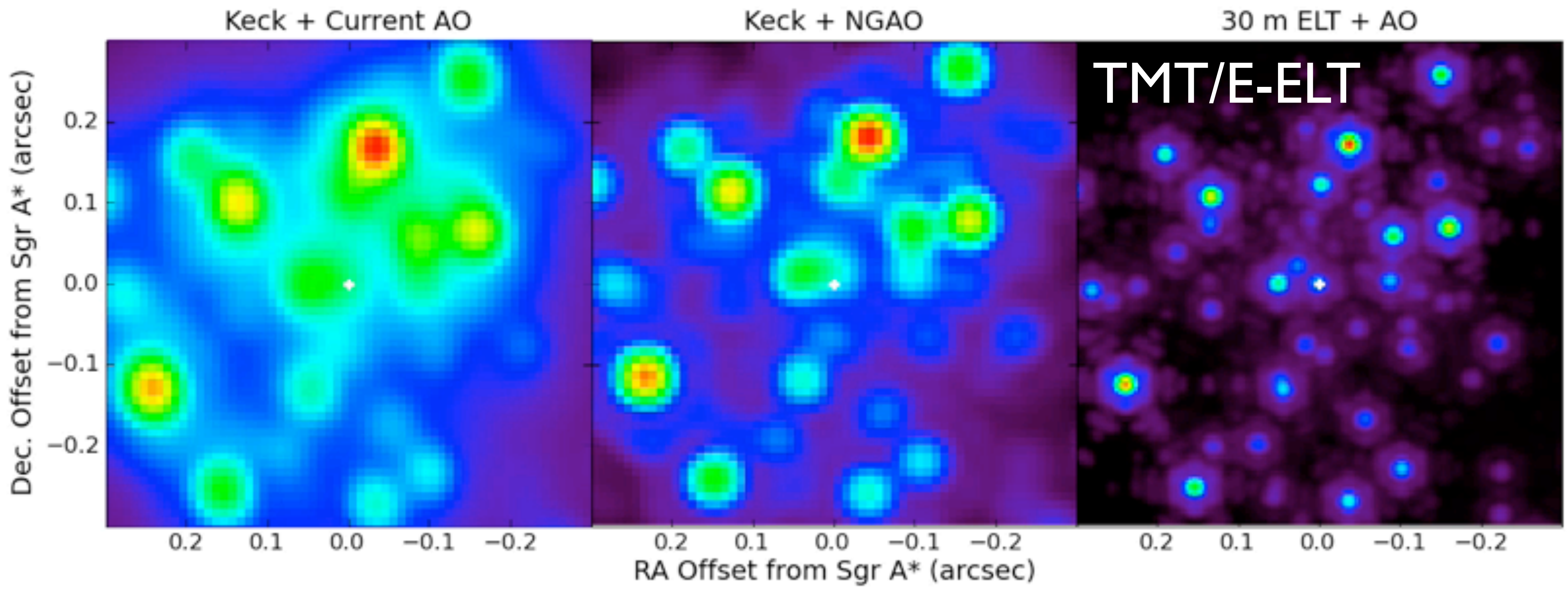
Schödel et al. 2013, MNRAS

Conclusions and Outlook

Conclusions

- Stars are ideal probes of the spacetime around a supermassive black hole
- We will be able to test Einstein's equivalence principle when S0-2 passes periapse in 2018 with Keck observations
- Detection of further short-period stars and increasing accuracy for orbits of known S-stars will allow us to break the degeneracy between orbital parameters and GR effects
- We have discovered a star with the shortest known orbital period to date (P=11.5 yrs)
- This star is necessary to break the degeneracy between GR and Newtonian periapse shifts
- With improved image processing and data analysis techniques as well as the continued acquisition of new data we will be able to identify more short-period stars in the near future

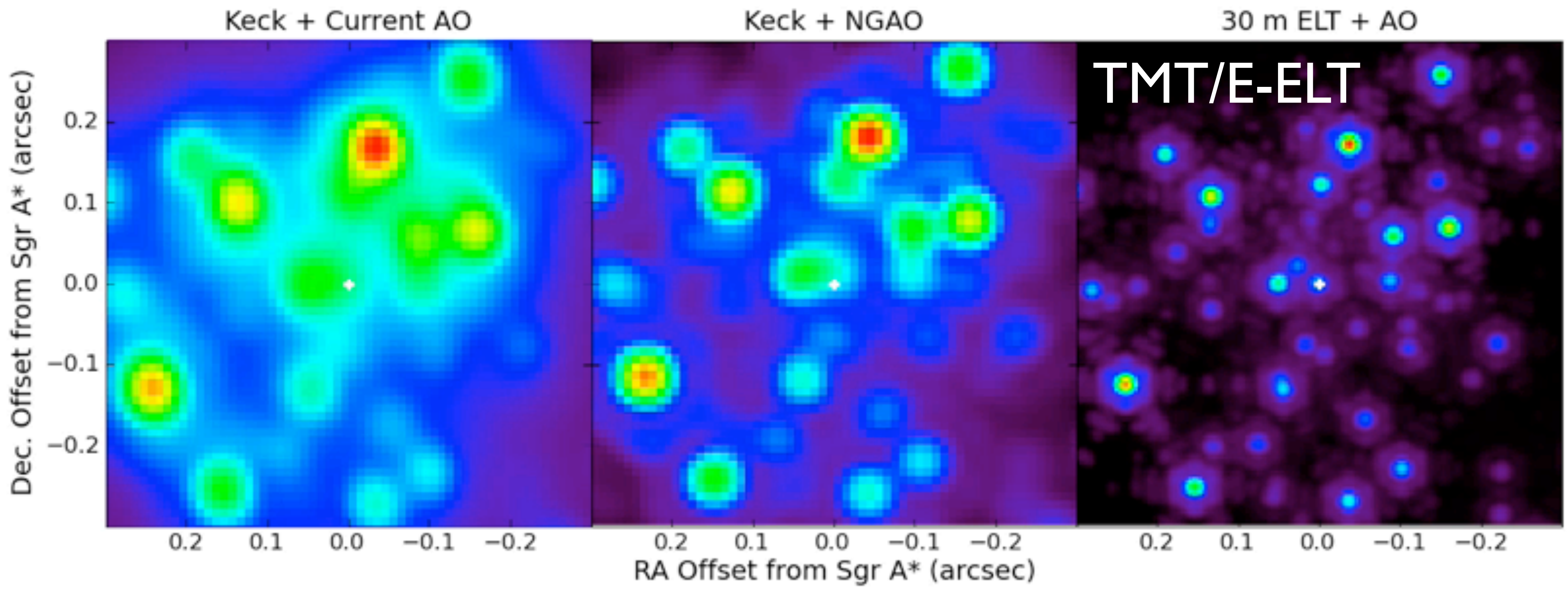
Outlook



credit: UCLA Galactic Center Group http://www.astro.ucla.edu/~ghezgroup/gc/pictures/Future_GCorbits.shtml

see Gillessen et al. (2010)

Outlook



credit: UCLA Galactic Center Group http://www.astro.ucla.edu/~ghezgroup/gc/pictures/Future_GCorbits.shtml

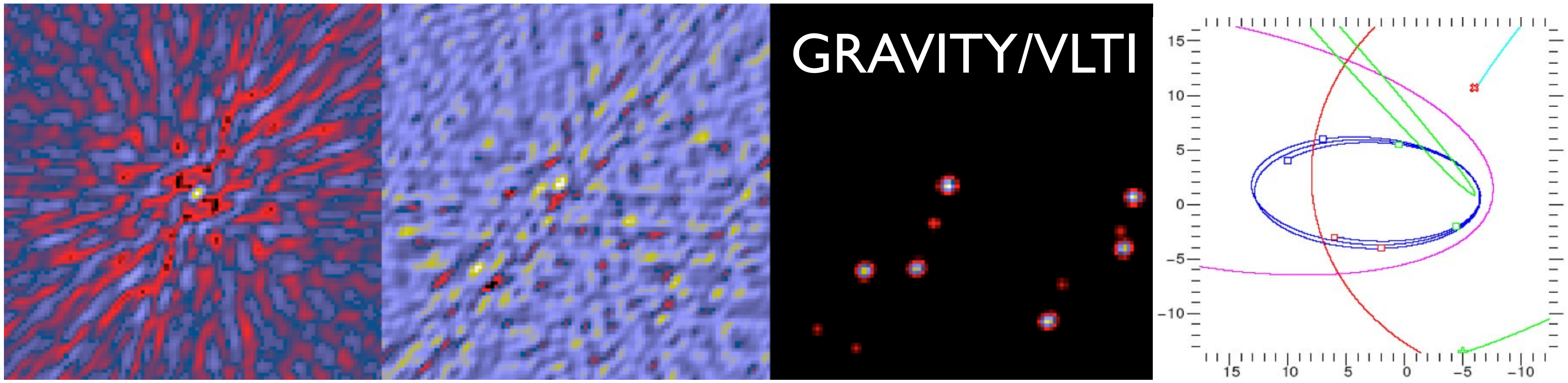


Figure 4: Simulated observation of a star field with 6 stars placed in orbit around Sgr A* in a 100 mas square field. Left: The PSF for one night of VLTI observations. Middle-left: The reconstructed image. Middle-right: The recovered image from the middle panel, using a simple CLEAN algorithm. Right: Simulated orbit figures (in mas) for the stars using images from several epochs. The strong precession due to the Schwarzschild metric is evident after even only two revolutions, each lasting no more than a year.

see Gillessen et al. (2010)

Thank you.

Research Interests

Science:

- The Galactic Center: Nuclear Star Cluster, star formation, properties of the massive black hole Sgr A*, ISM near Sgr A*
- Massive stars and massive clusters
- MBHs, IMBHs in general

Methodology:

- Near- and mid-infrared imaging
- High angular resolution imaging: Adaptive Optics, lucky imaging, speckle imaging, long baseline interferometry