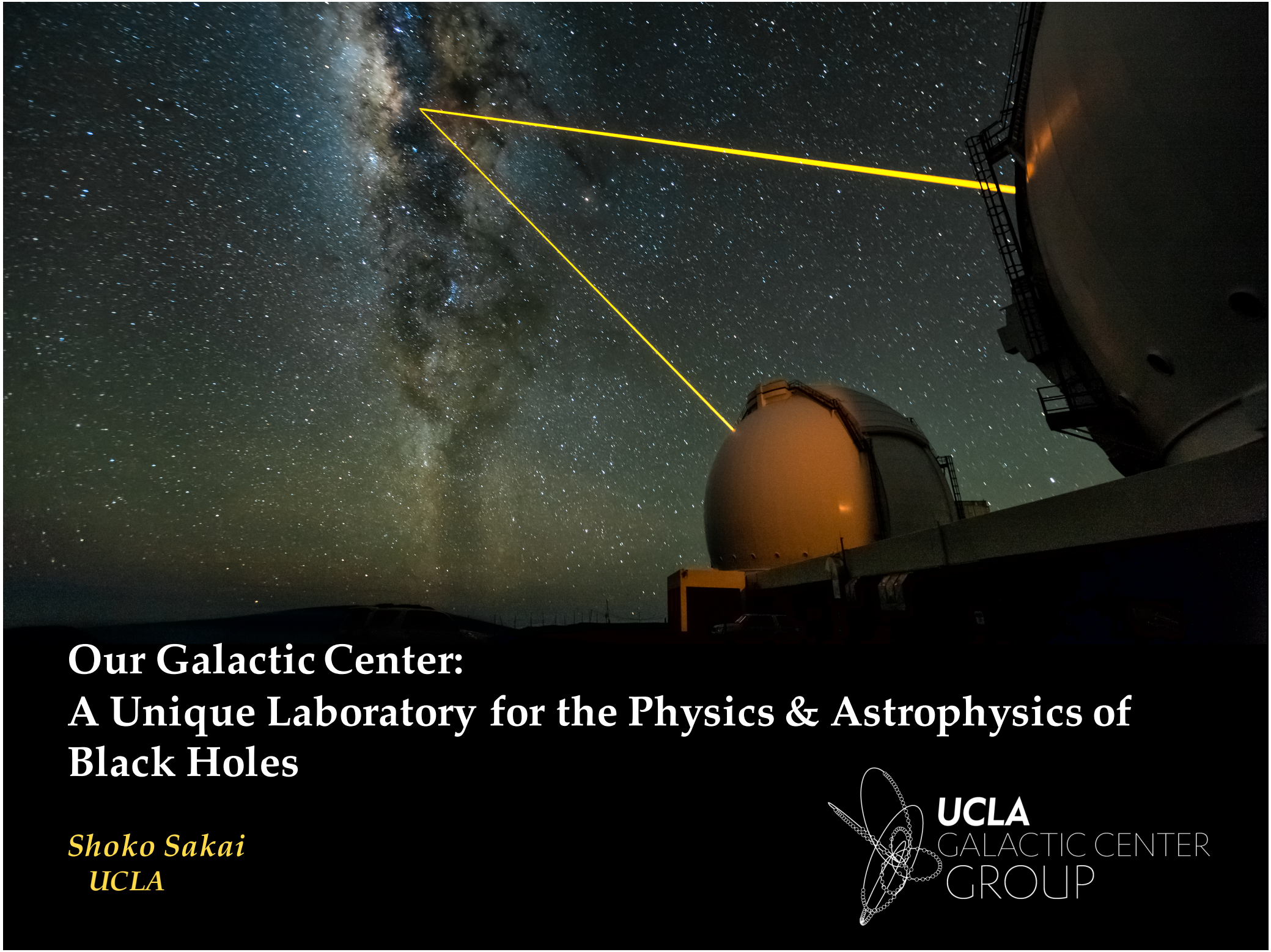
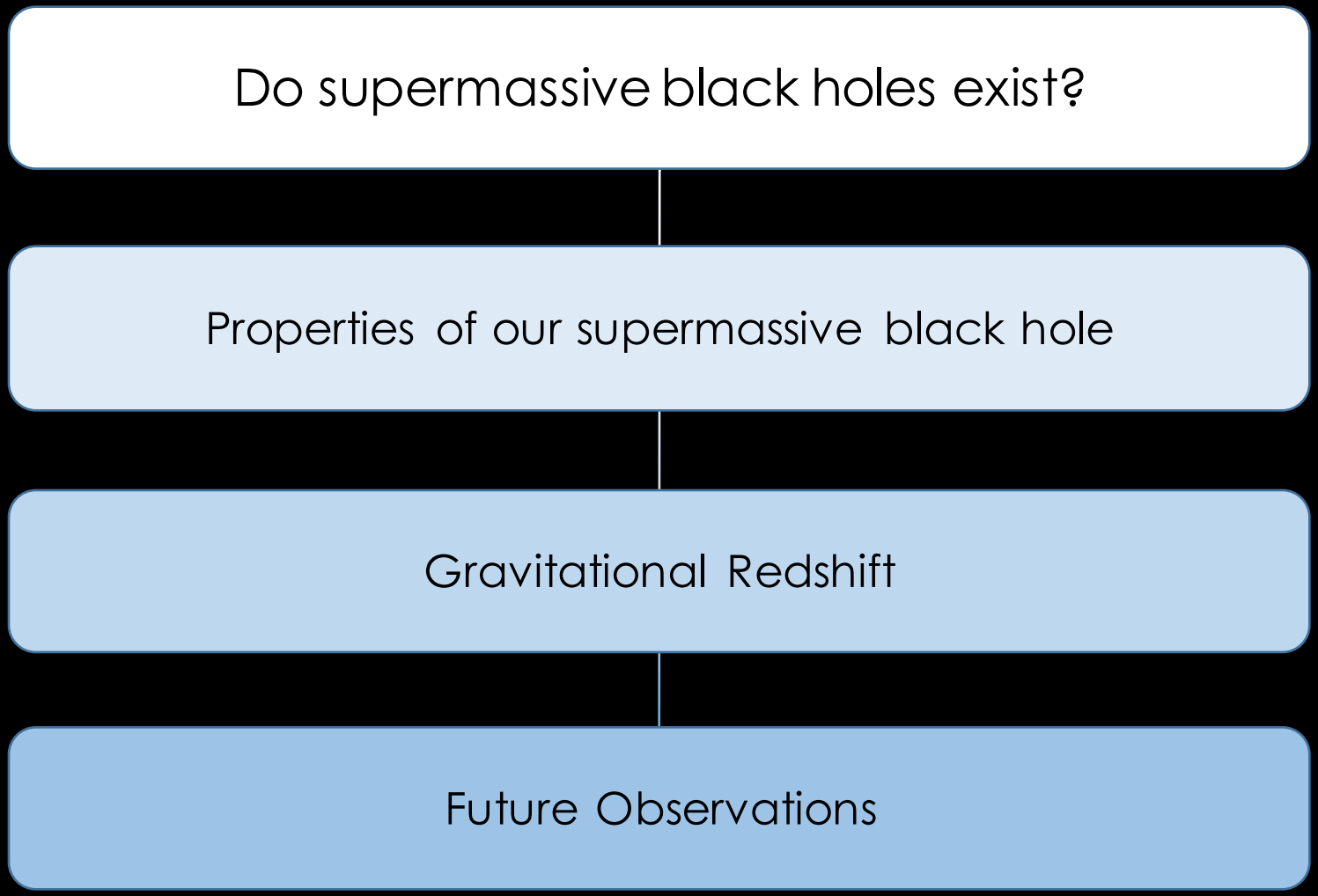


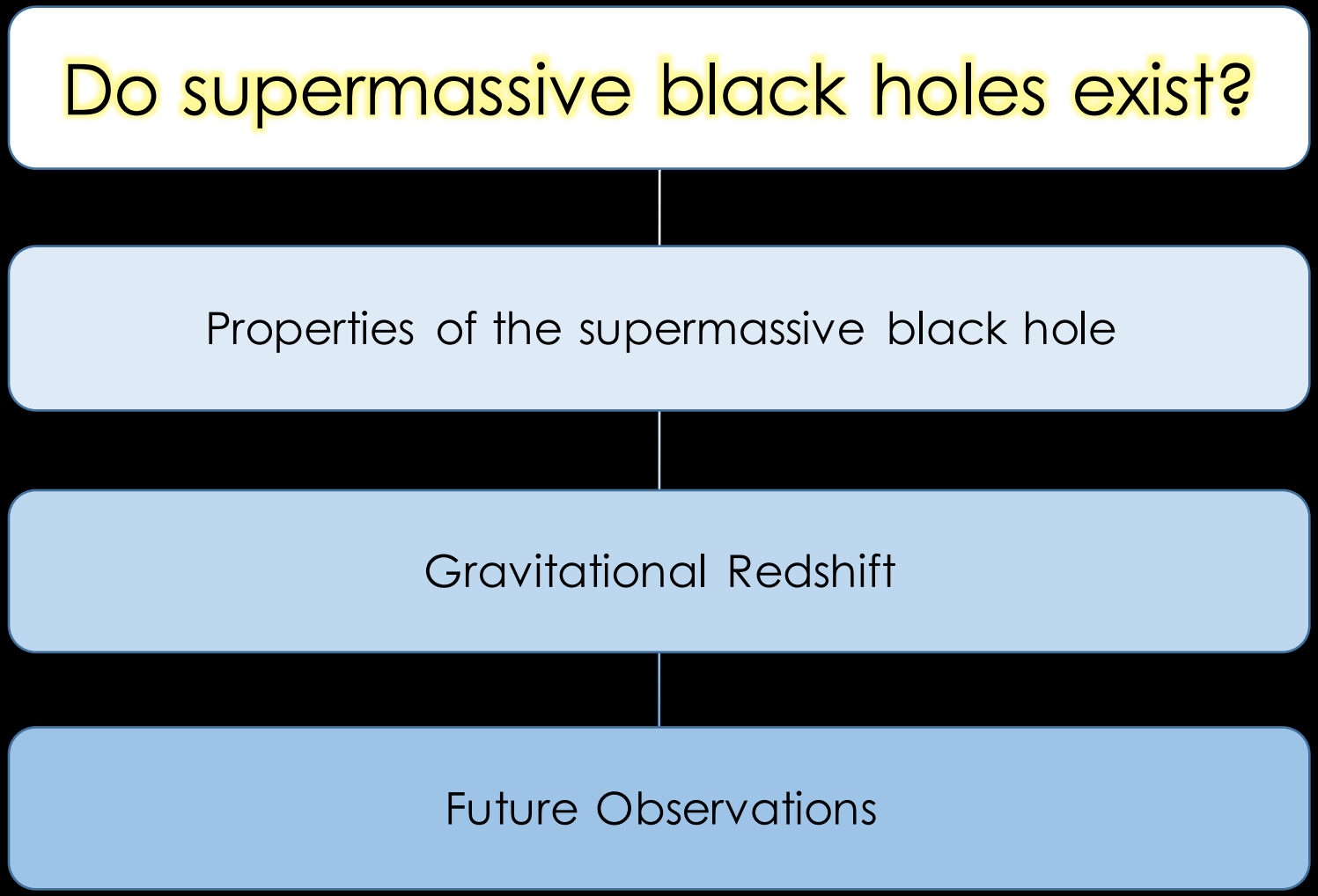
Our Galactic Center:
A Unique Laboratory for the Physics & Astrophysics of Black Holes

Shoko Sakai
UCLA

UCLA GALACTIC CENTER GROUP

UCLA Galactic Center Group


Do supermassive black holes exist?
Properties of our supermassive black hole
Gravitational Redshift
Future Observations


Do supermassive black holes exist?
Properties of the supermassive black hole
Gravitational Redshift
Future Observations

Do supermassive black holes exist?

Their dramatic gravitational effects are only measurable in a small region, very far away: e.g. the orbits of stars close to a black hole.

First, technological advances were needed to enable highly precise measurements at unprecedented spatial resolution.

Do supermassive black holes exist?

Two observational goals:

1. Probing as many stars as possible: going fainter
2. Higher resolution

Several Advances Made Measurements of Stellar Orbits Possible

1. Improved Infrared Detector Sensitivities with larger formats


A. Fujii
Visible
Spitzer Space Telescope
Infrared

Several Advances Made Measurements of Stellar Orbits Possible

2. Telescope Mirror Size Sharpens Images:

$\Theta_{\text{Diffraction-Limit}} = 1.2\,\lambda/D$

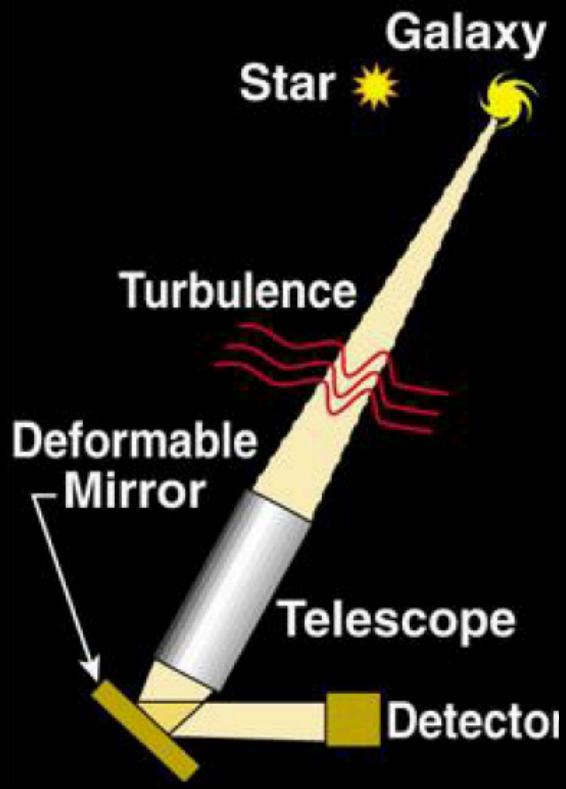
For a 10m-telescope & λ = 2.2 micron:

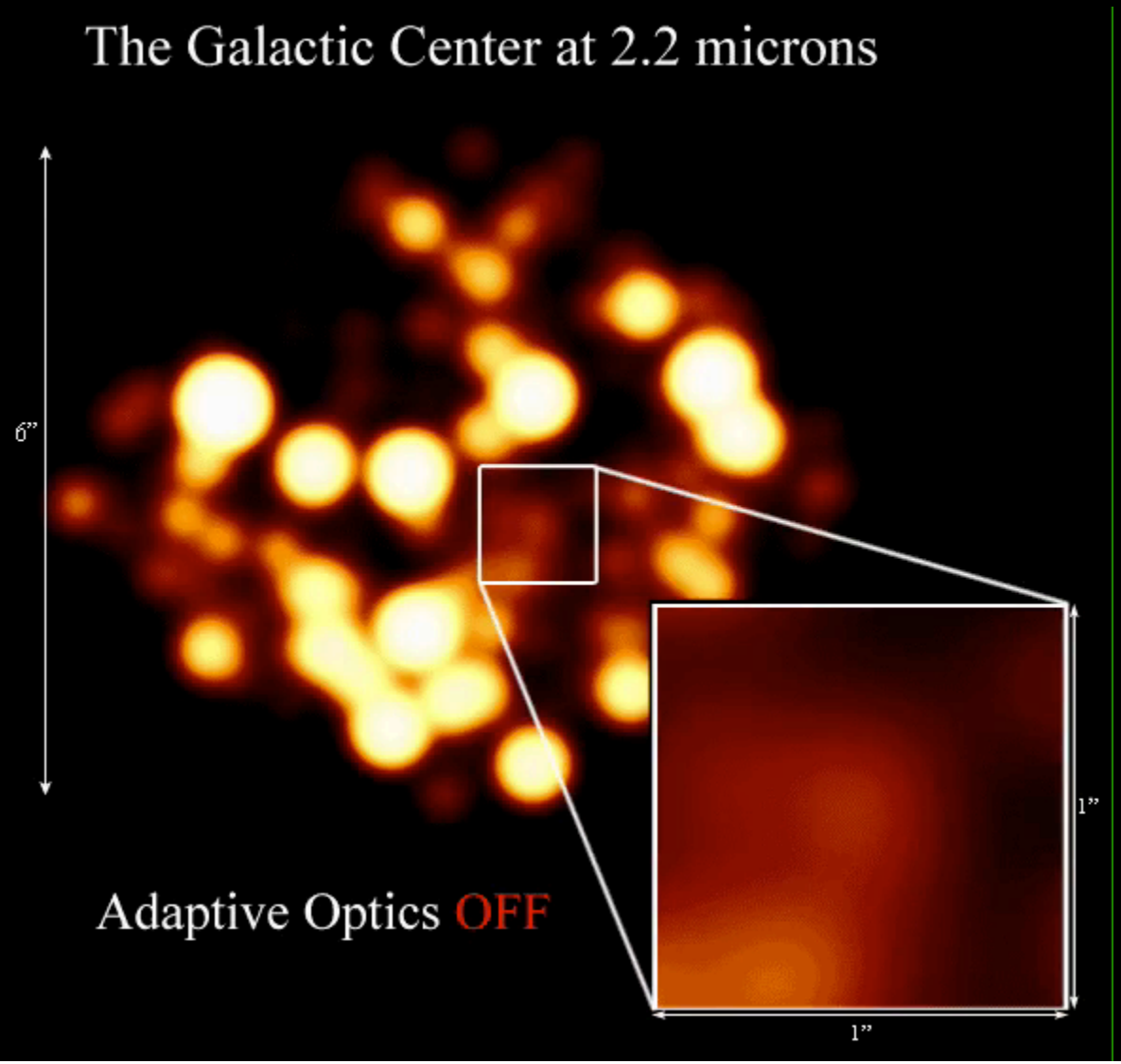
$\theta_{\text{diffraction-limit}}$ ~ 40 milli-arcsec

At distance of 8 kilo-parsecs: 40 milli-arcsec corresponds to ~400 AU

Several Advances Made Measurements of Stellar Orbits Possible

3. "Freezing" the Atmospheric Distortion





Two Independent High Resolution Studies

Keck (10-meter)

1995 - present

45 milli-arcsec

Ghez et al.

NTT (3.6-meter)

1992 - 2001

150 milli-arcsec

VLT (8-meter)

2002 - present

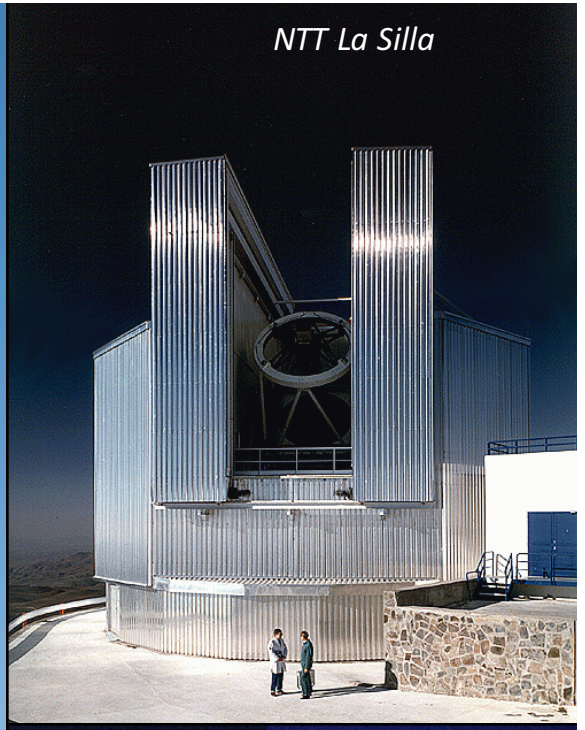
60 milli-arcsec

GRAVITY (4x8-m)

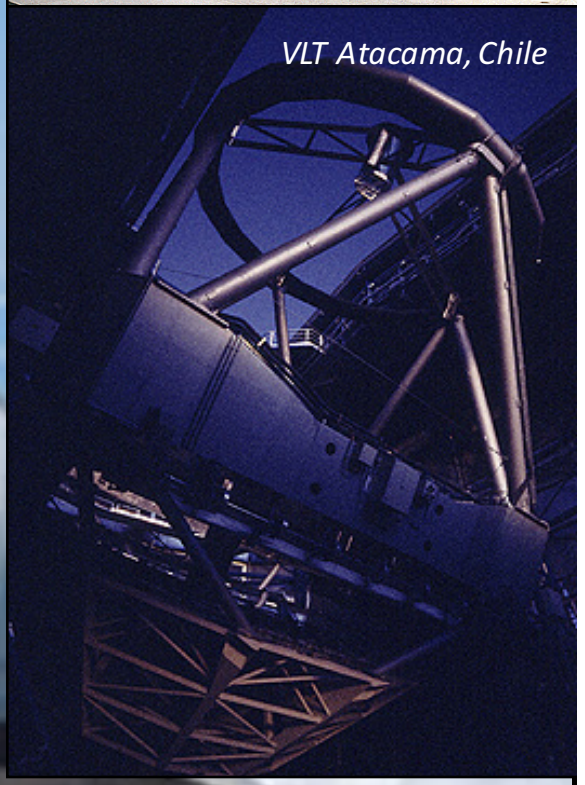
2018 - present

4 milli-arcsec

Genzel et al.



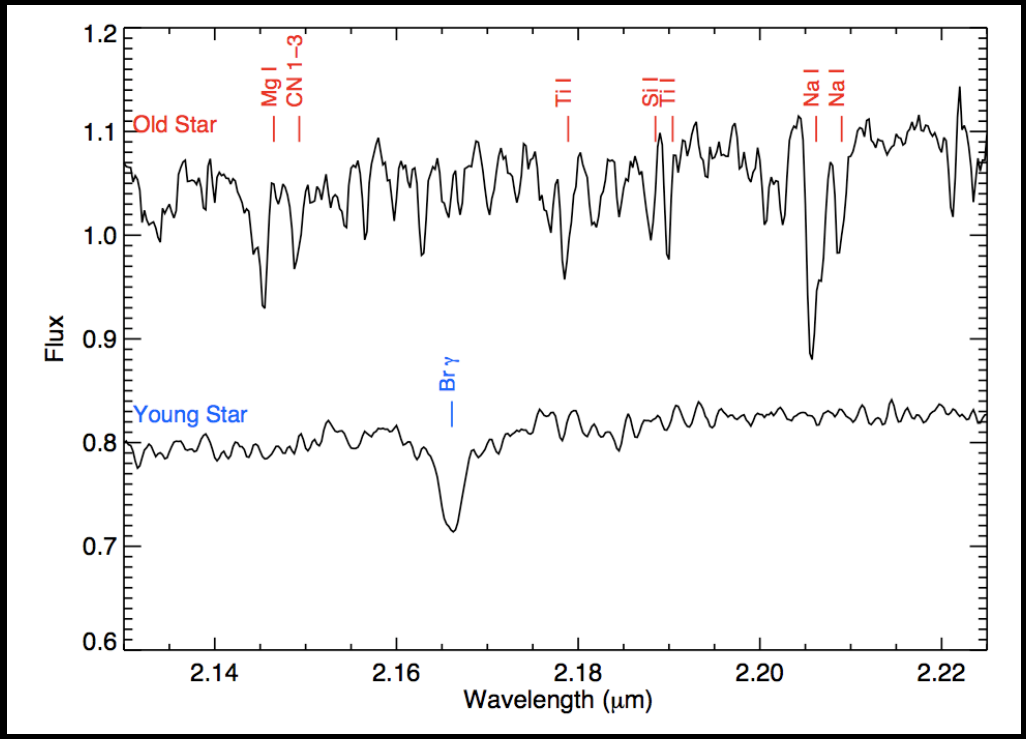
NTT La Silla



VLT Atacama, Chile

Keck Telescopes on Mauna Kea Hawaii

Adaptive Optics Added Spectroscopy Data



Physics

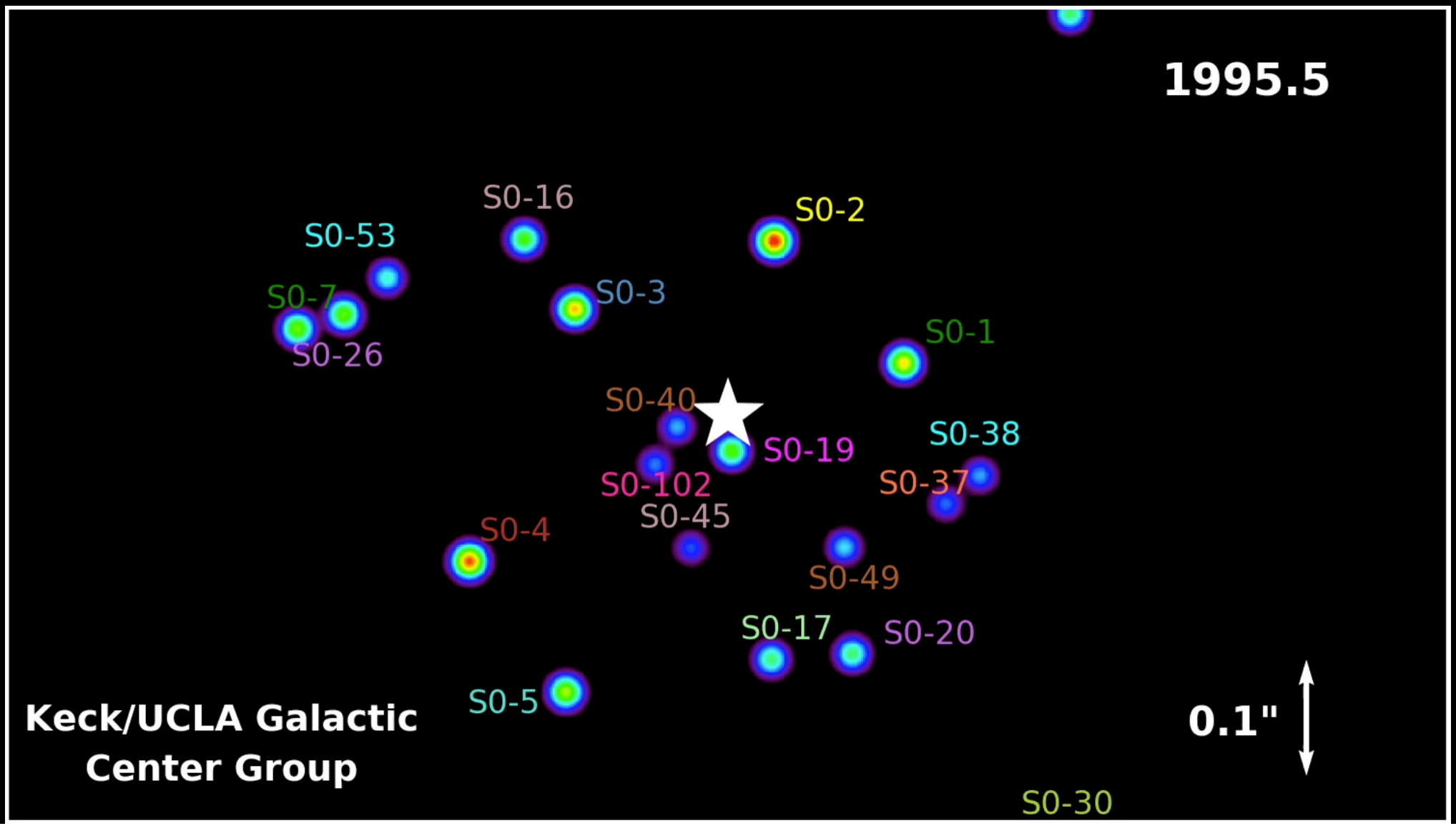
– Measures missing third dimension of motion

Astronomy

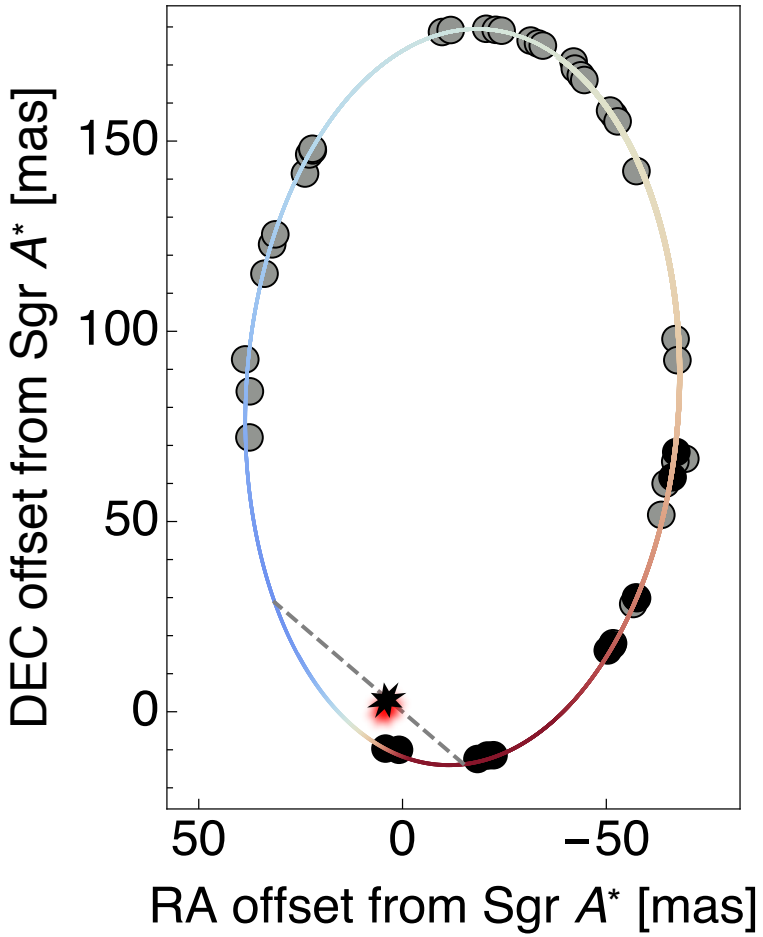
– Astrophysical nature of sources

– Reveals many surprises!!

Over two decades of monitoring the stellar orbits in the Galactic Center region, we have excellent *knowledge of the Gravitational Potential , particularly from the stars which pass closest to the center*



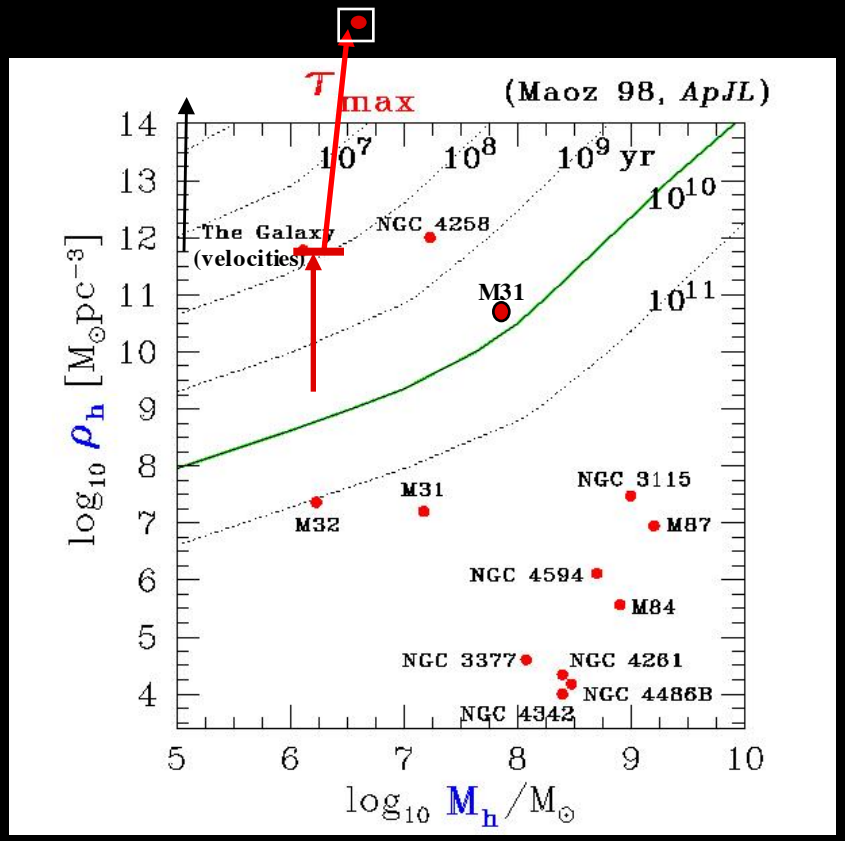
The well-observed orbit of Star S0-2, passing very close to the center, provides Strongest Case for Existence of a Supermassive Black Hole



Do et al. 2019

$M_{BH} = 4 \times 10^6$ solar mass

S0-2 orbit Provides Strongest Case for Existence of a Supermassive Black Hole

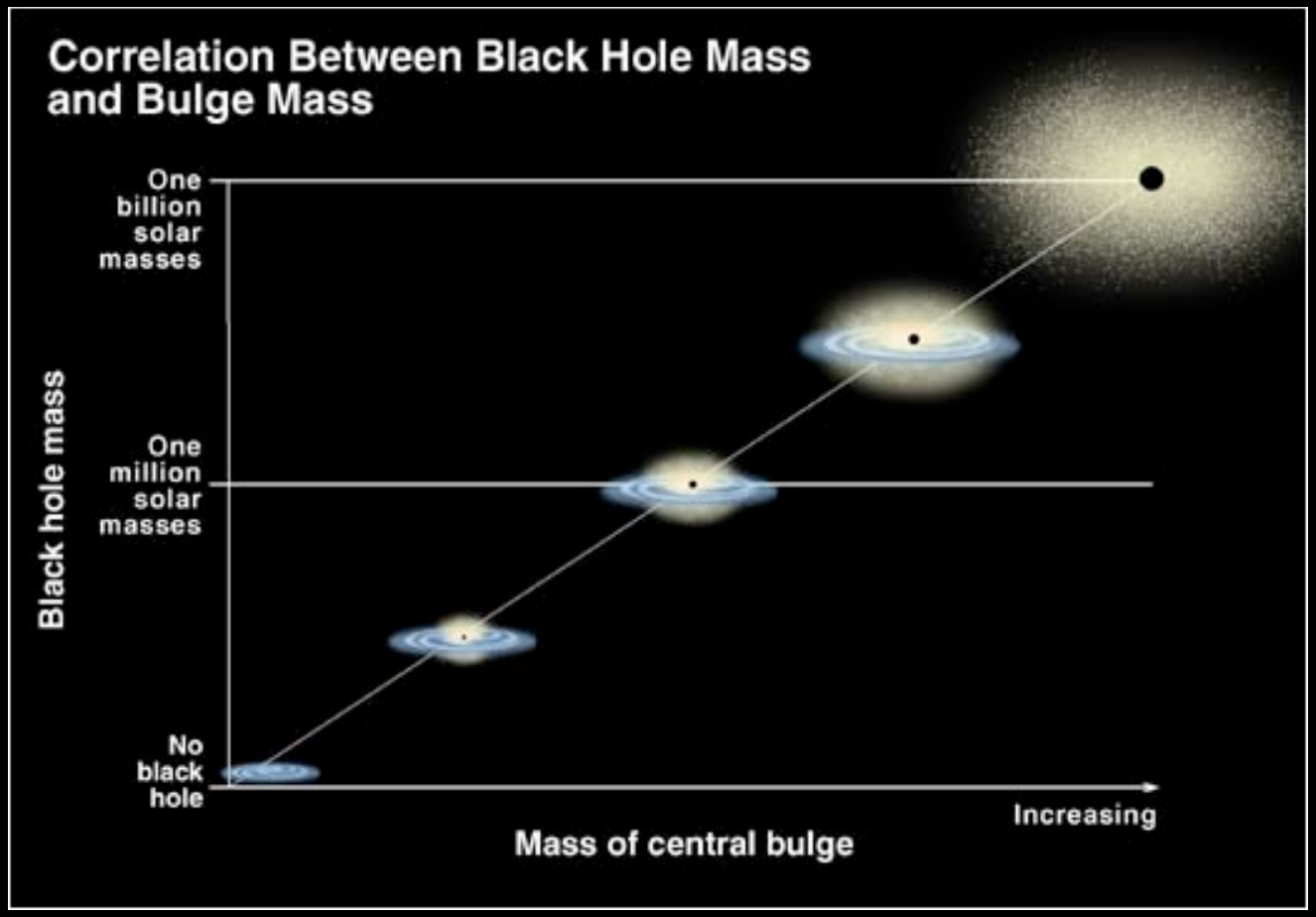


$\rho > 6 \times 10^{15}\ M_{Sun}/parsec^3$

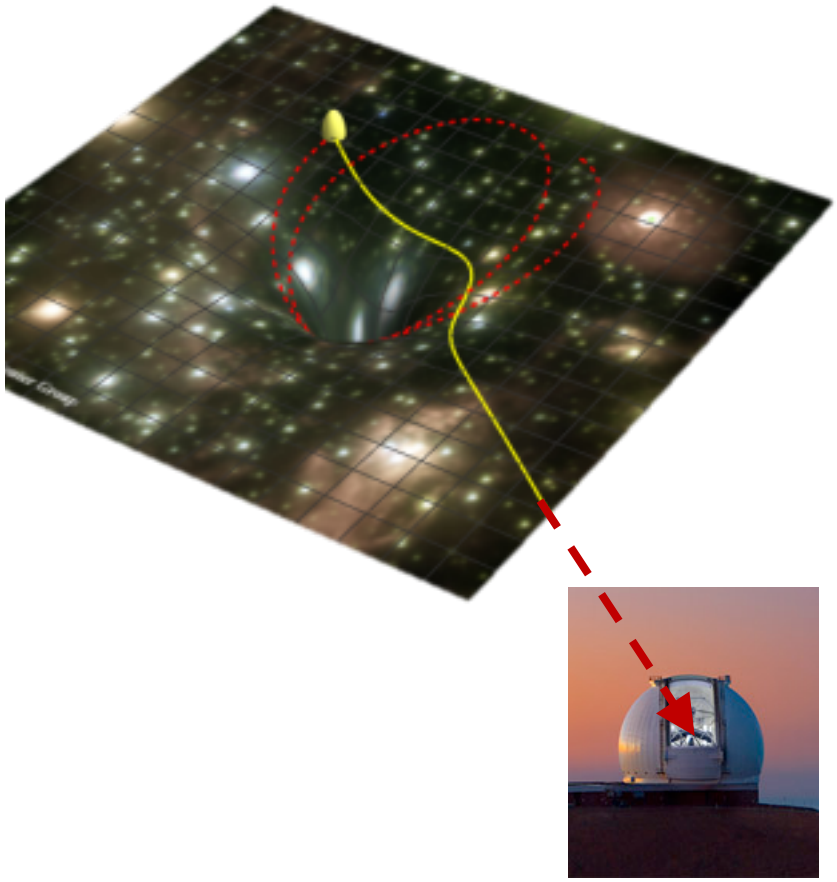
Inferred dark matter density in the center of our Galaxy is a factor of 10^7 higher than any estimates in any other galaxies (using other methods)

At least ONE supermassive black holes definitely exists!
…and that's why we believe the others do, too

What role do black holes play in the formation & evolution of galaxies,
ie., where do they come from and what do they do?



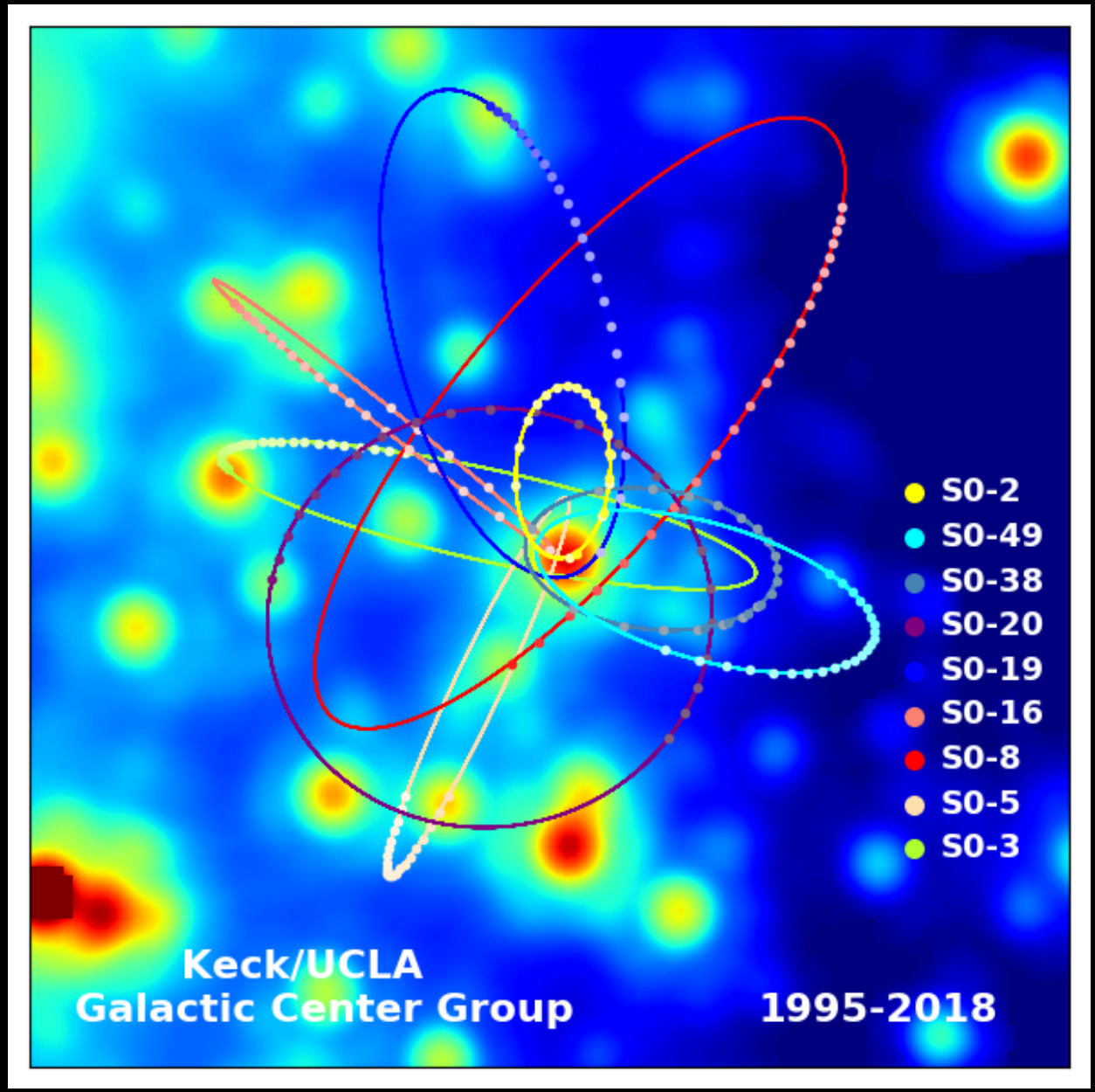
What Else Can be Probed with Stellar Orbits in the Galactic Center?



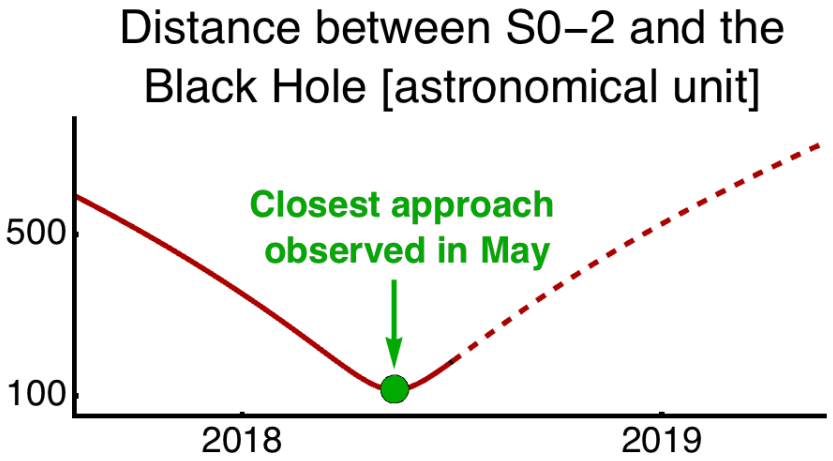
General Relativity &
alternative theories of Gravity

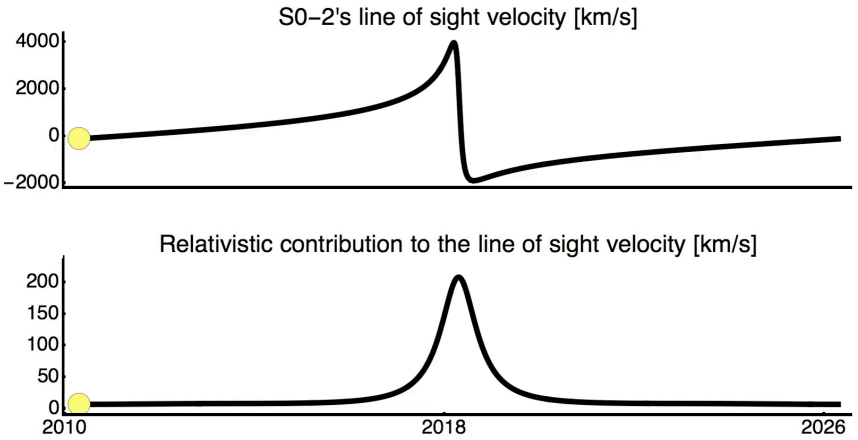
- Gravitational Redshift (GR Test #1)
- Precession of Periapse (GR Test #2)
- Spin of black hole (GR Test #3)

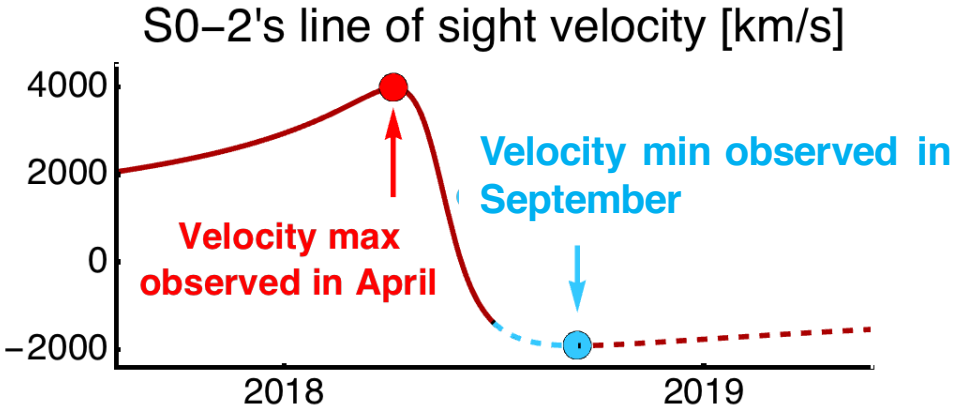
Over 2 decades of monitoring the orbit of S0-2 was required for GR Test #1

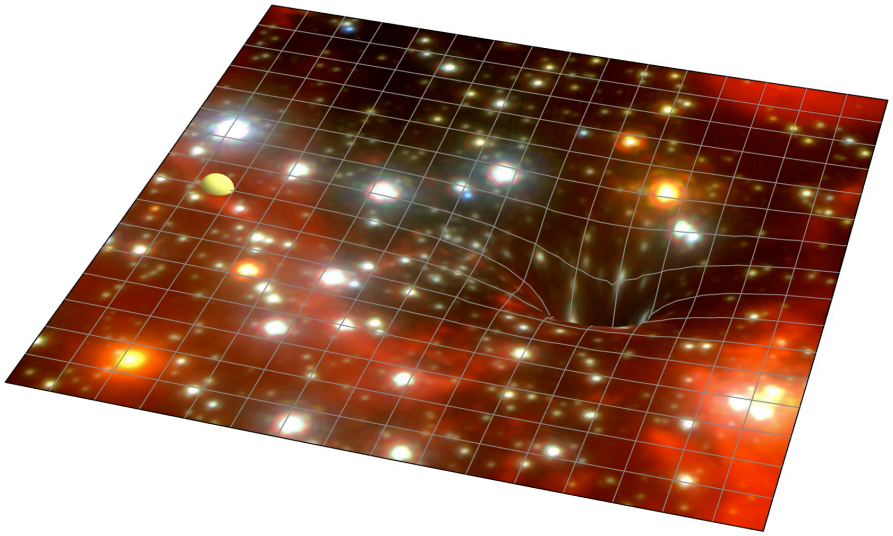


Three important events to measure in S0-2's orbit this year



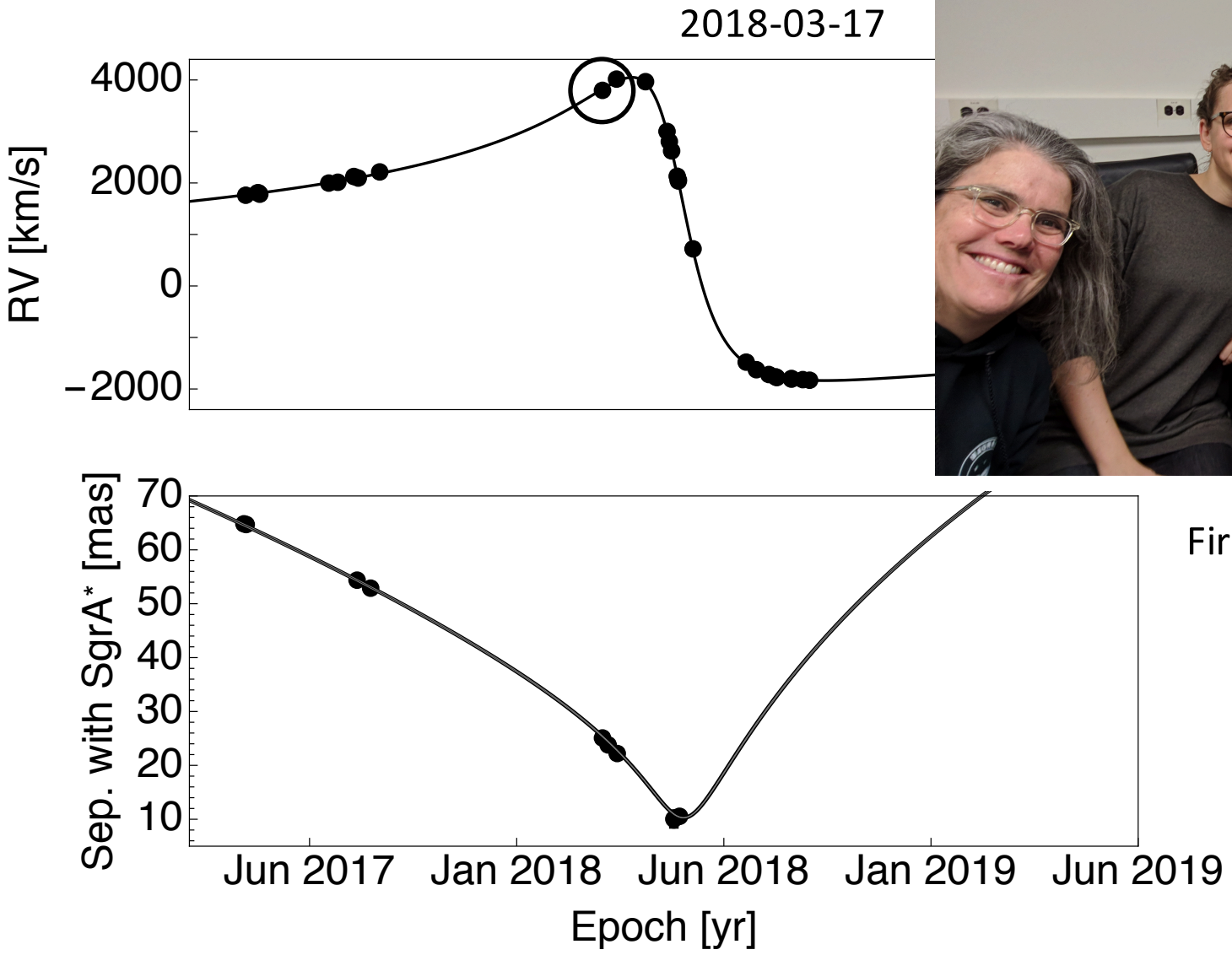






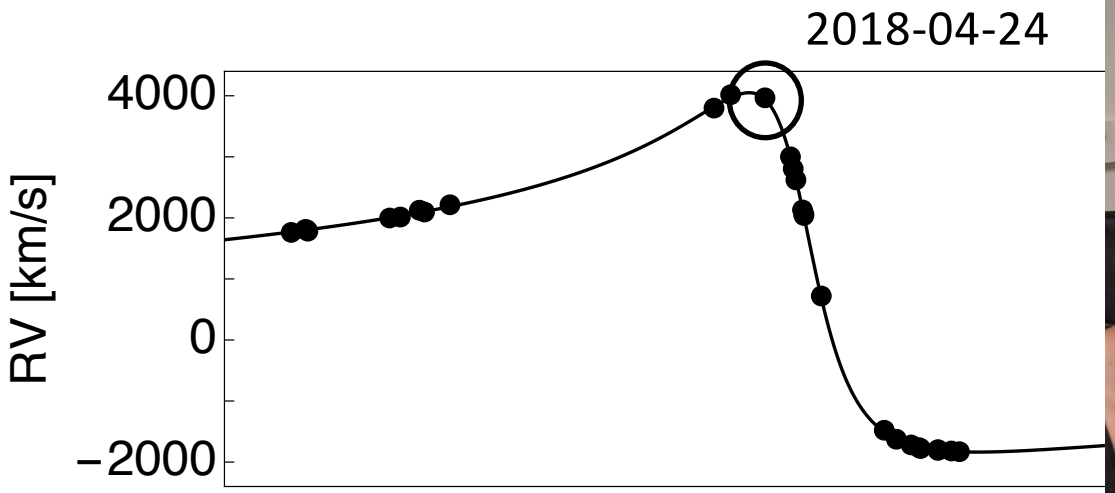
A. Hees / UCLA Galactic Center Group

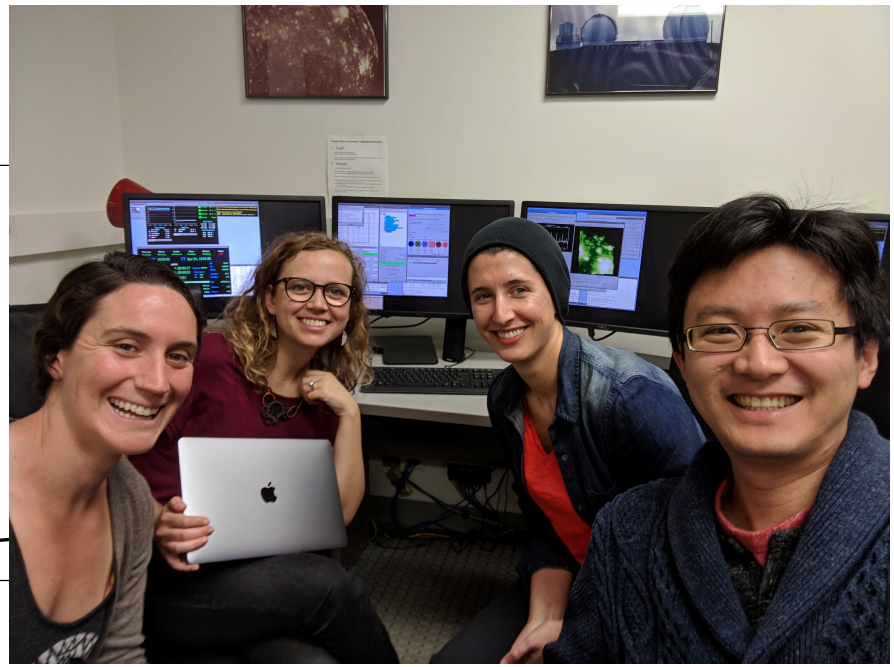
Observations in 2018!

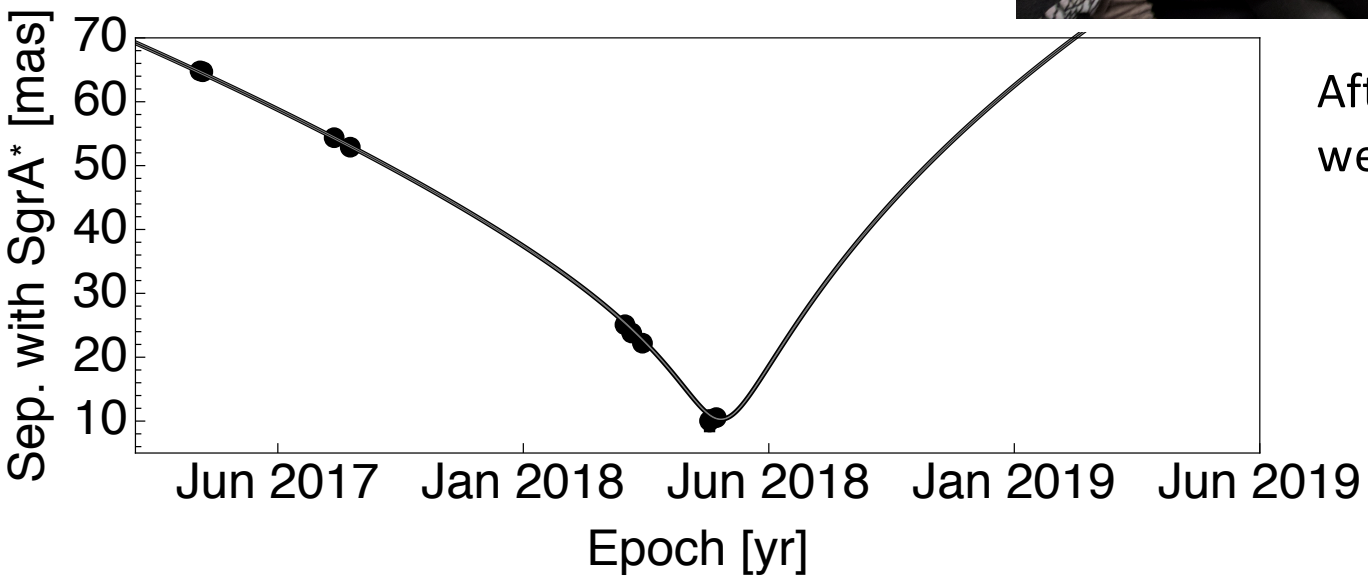


First observations in 2018!

Observations in 2018!

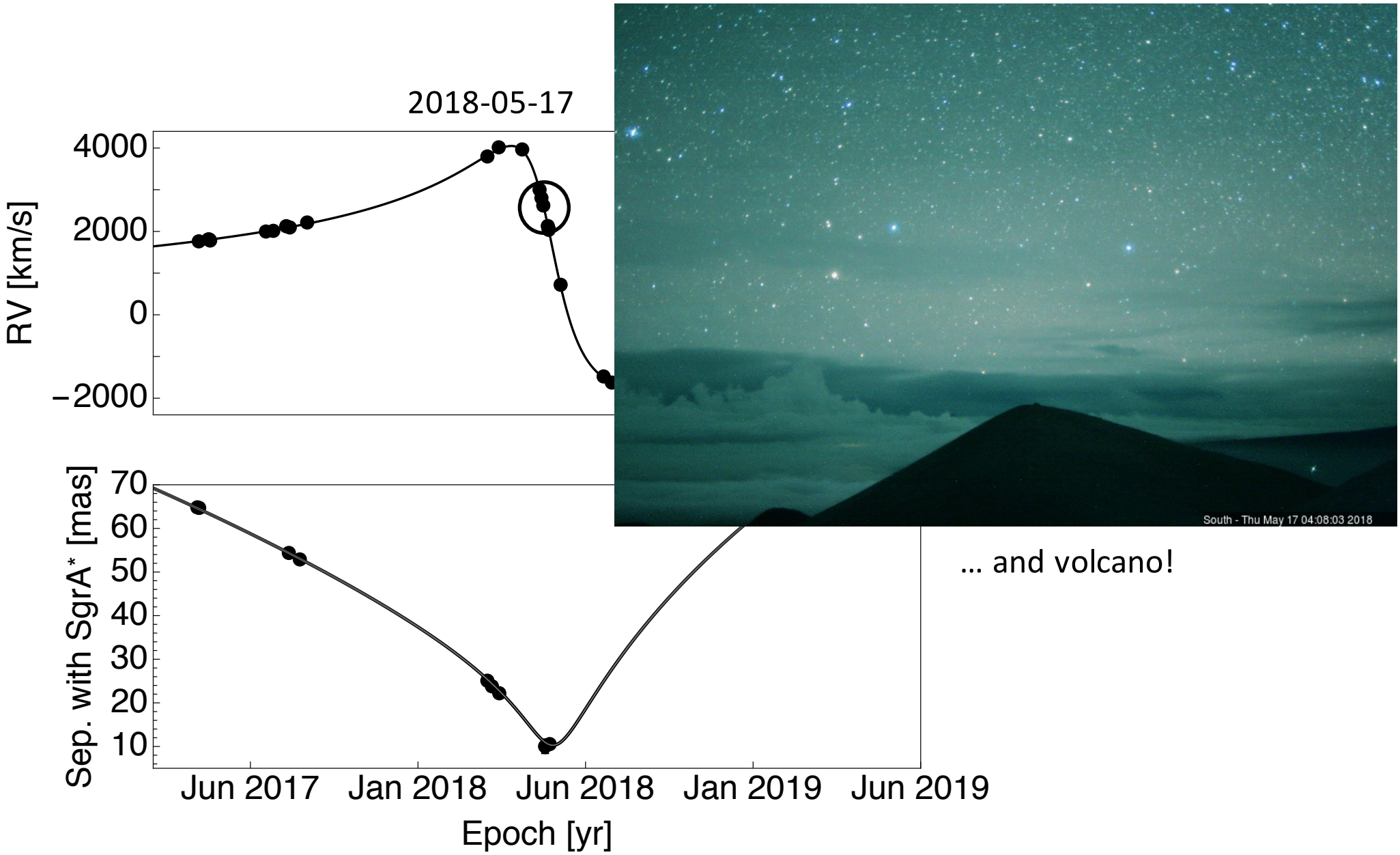






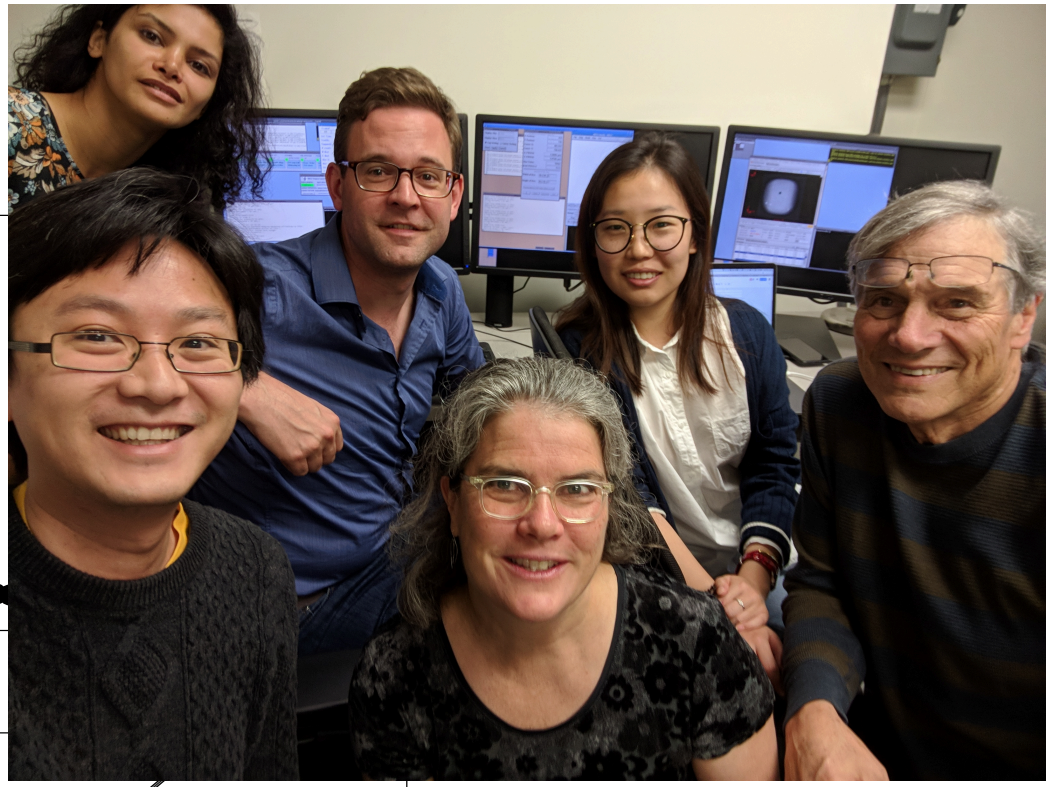
After A LOT of bad weather… Data again!

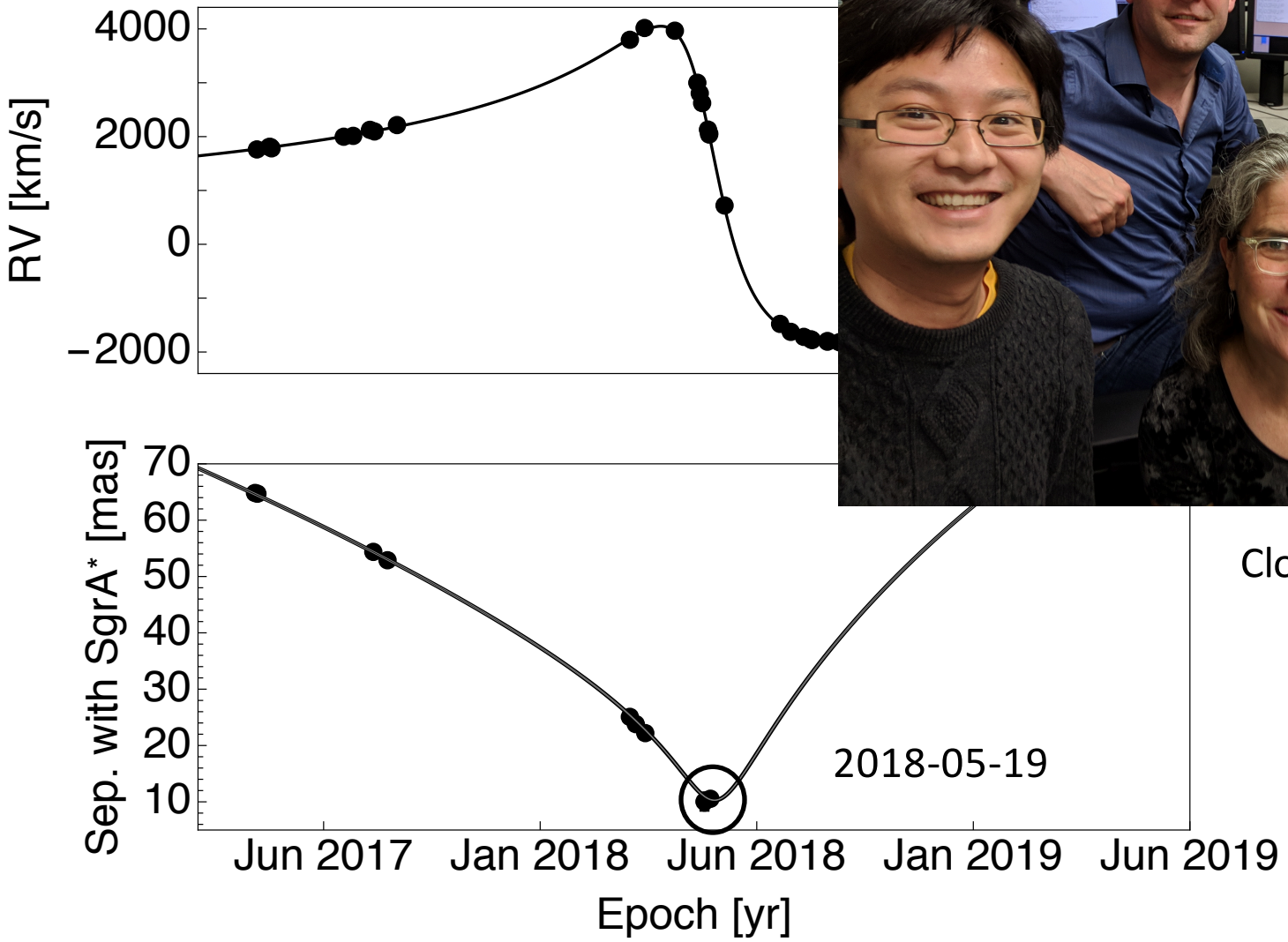
Observations in 2018!



… and volcano!

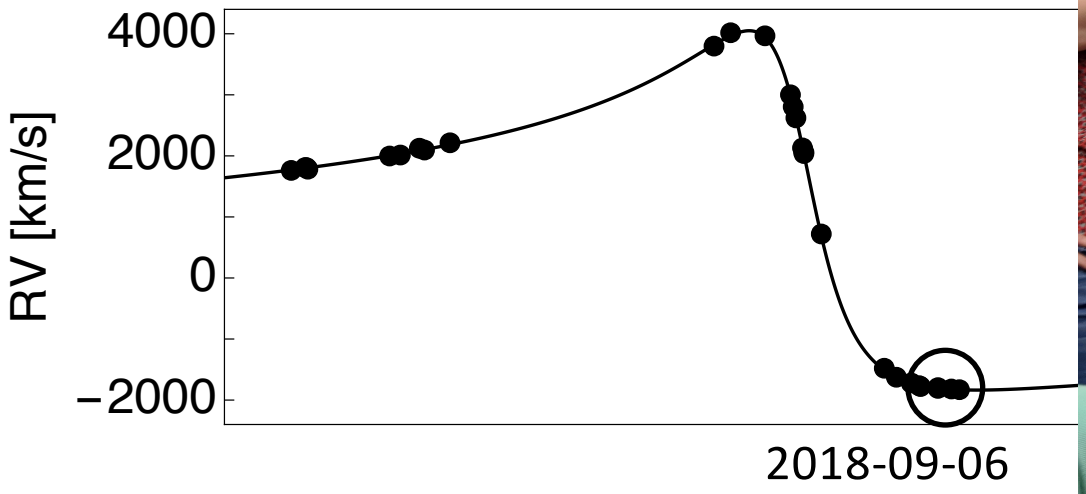
Observations in 2018!

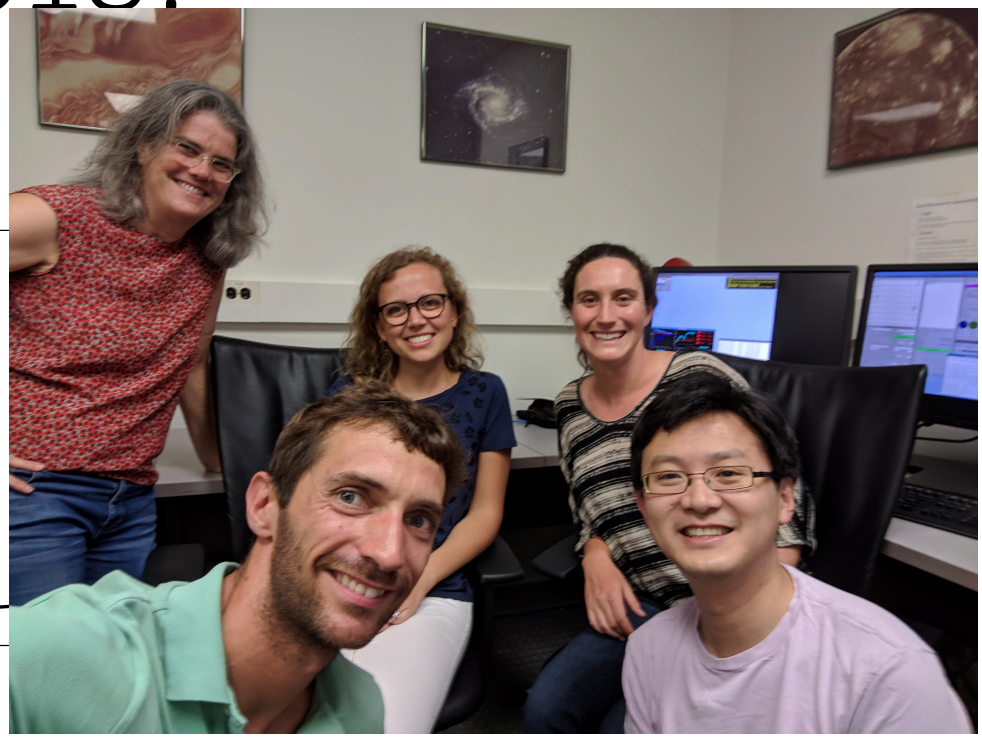


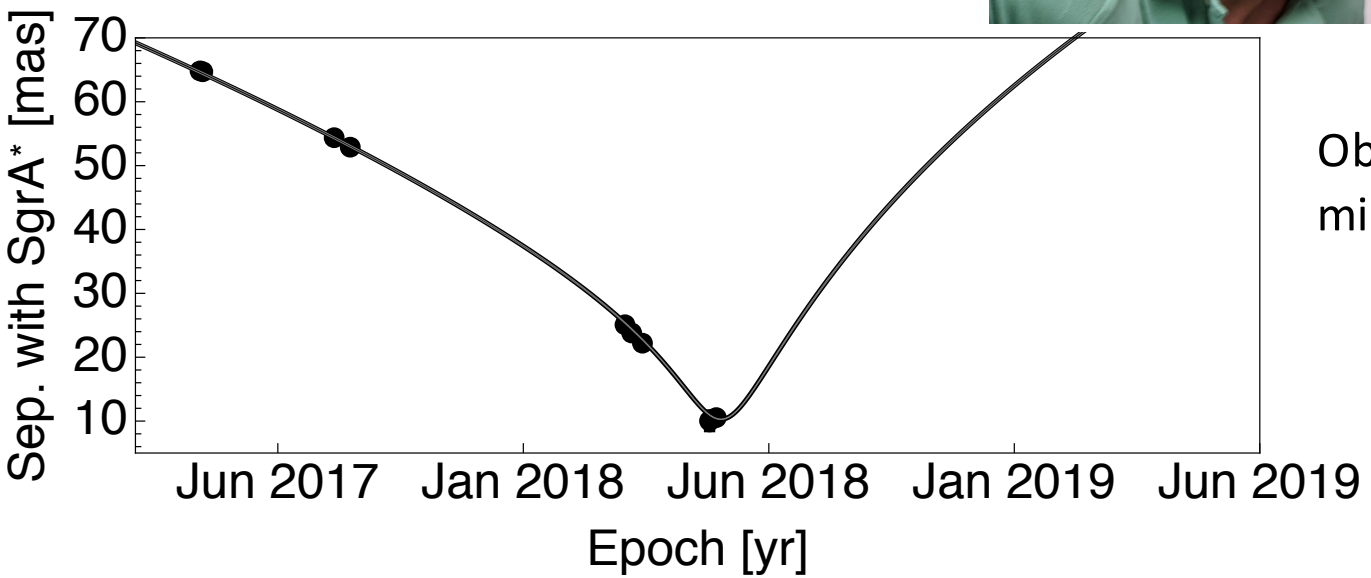


Closest approach!

Observations in 2018!







Observing Radial Velocity minimum

Relativistic redshift as a scale parameter

RV Offset

RV from Keplerian orbit

Special Relativity

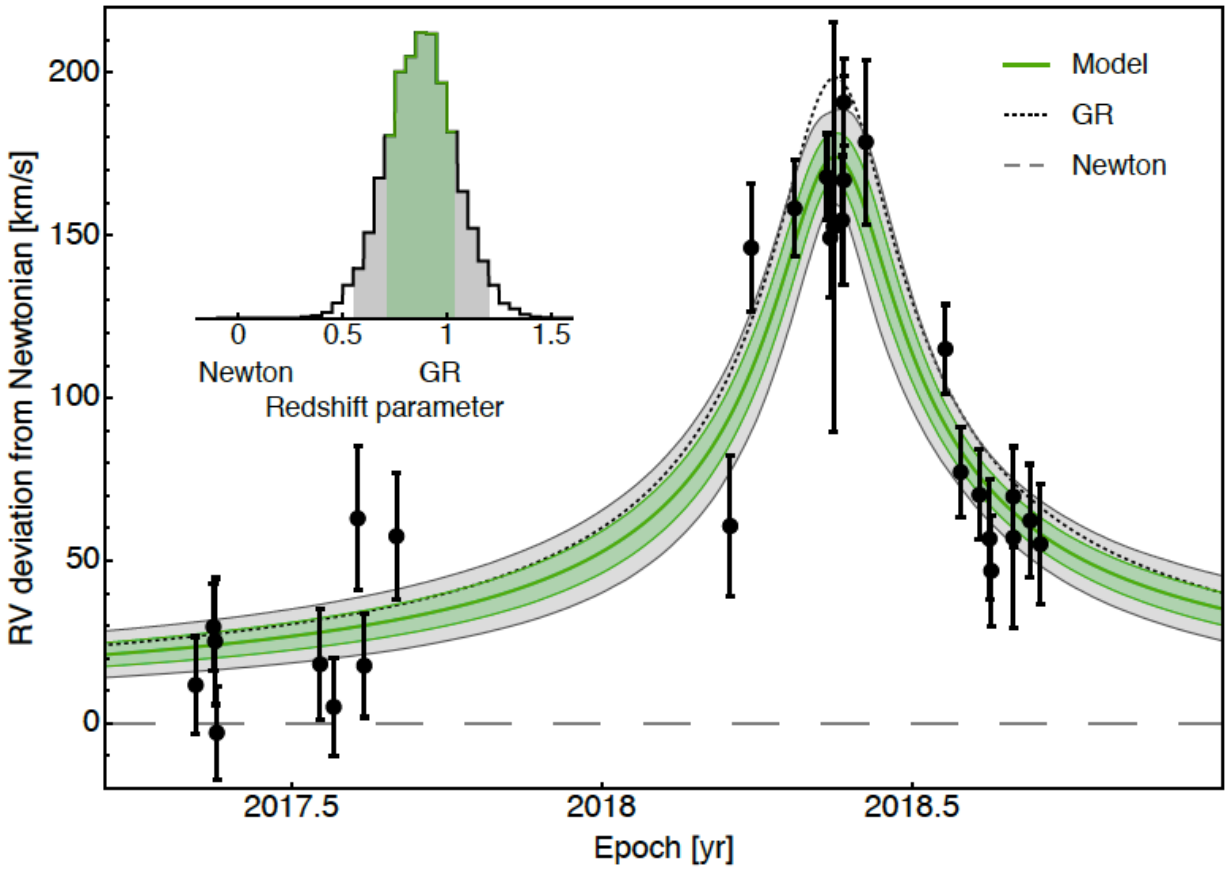
General Relativity

$$RV = v_{z_0} + V_{Z,\mathrm{S0-2}} + \Upsilon \left[\frac{V_{\mathrm{S0-2}}^2}{2c} + \frac{GM}{cR_{\mathrm{S0-2}}} \right]$$

Observed Radial Velocity

Redshift Parameter

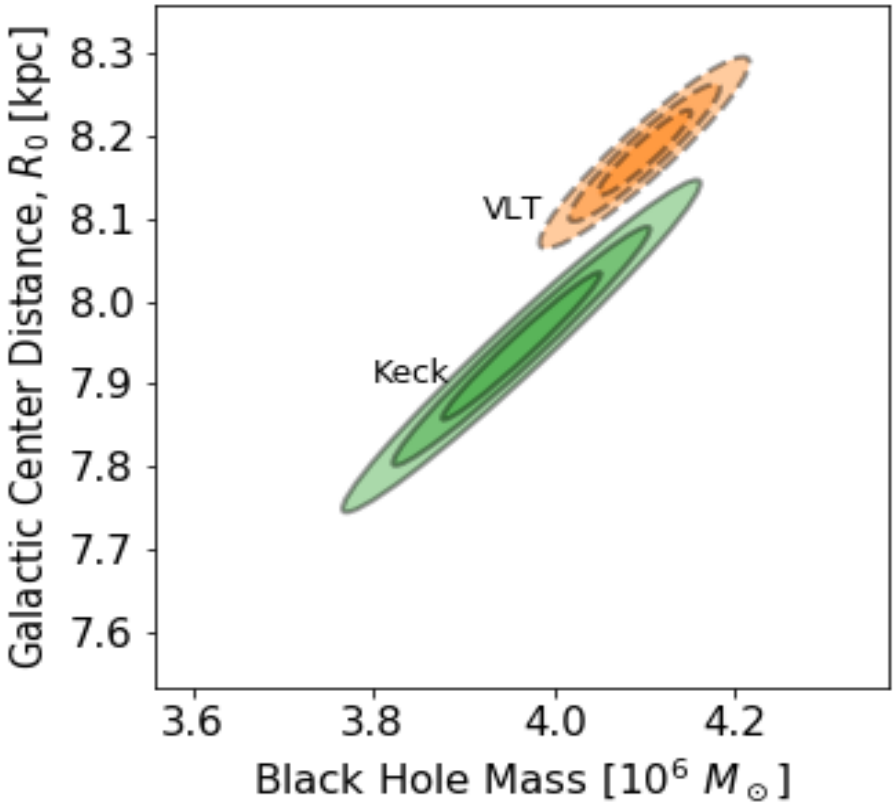
Einstein G.R. model is 43,000 times more likely than the Newtonian model to explain the data



$$RV = v_{z_0} + V_{Z,\mathrm{S0-2}} + \Upsilon \left[\frac{V^2_{\mathrm{S0-2}}}{2c} + \frac{GM}{cR_{\mathrm{S0-2}}} \right]$$

GRAVITY Collaboration 2018; Do, Hees, Ghez, + GCOI 2019

Understanding Systematics is Critical for this Precision Measurement

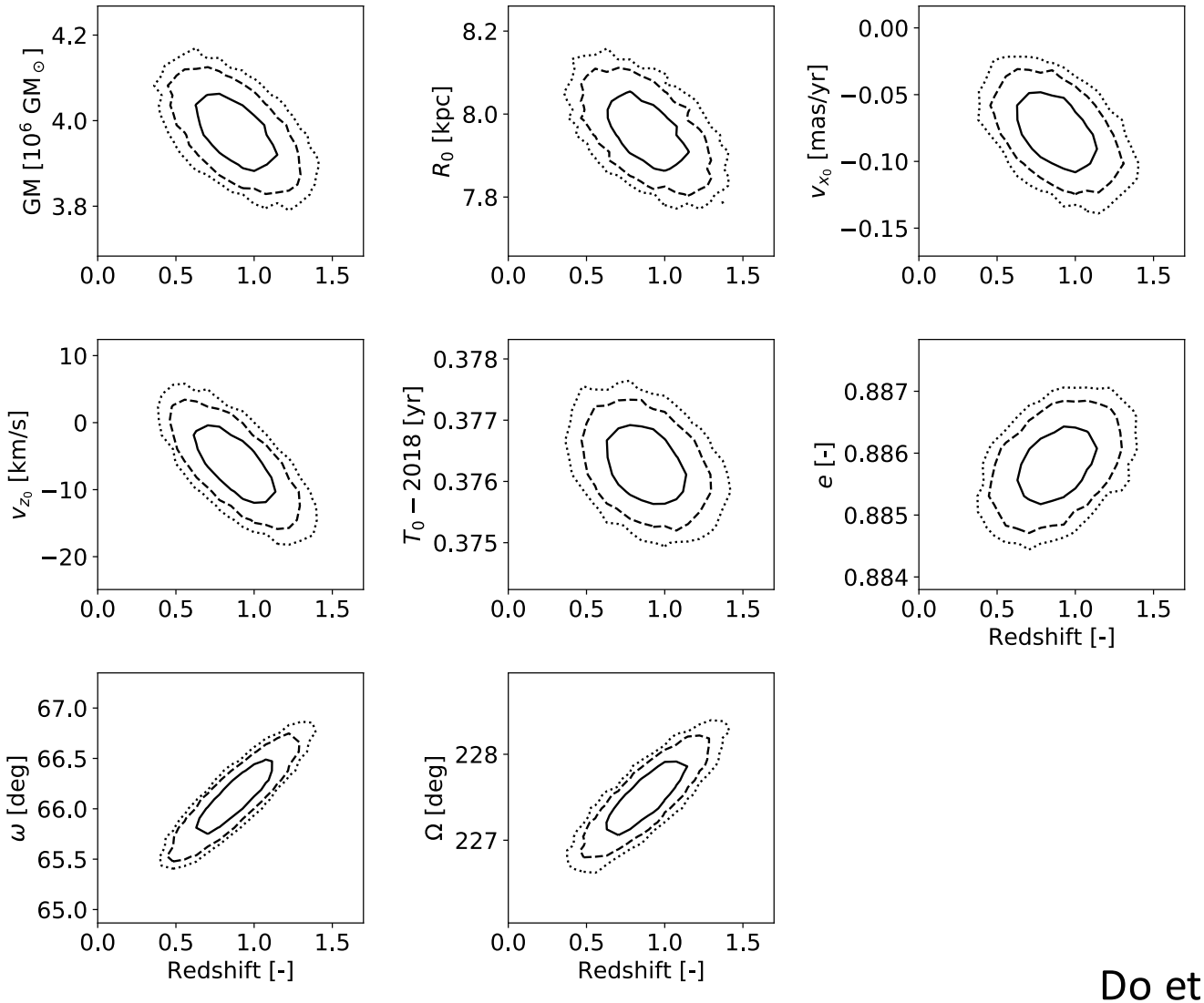


- Instrumental Upgrades
- Measurements Correlations
- Astrometric Reference Frame Construction

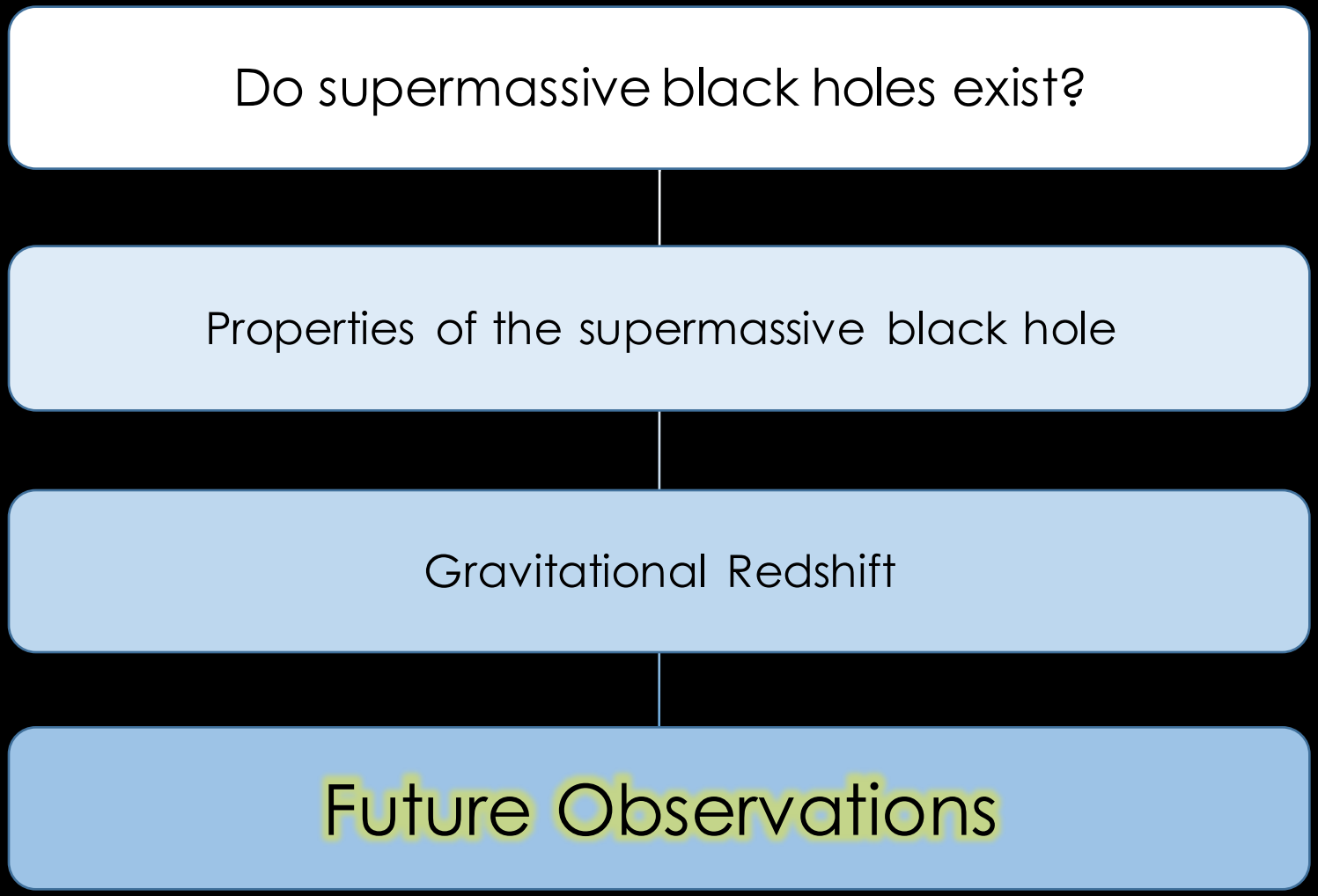
M_{bh} = 3.98 ± 0.06 x 10^6 $M_\odot$

R_0 = 7.97 ± 0.06 kpc

The redshift is correlated with BH & angular orbital parameters



Do et al. submitted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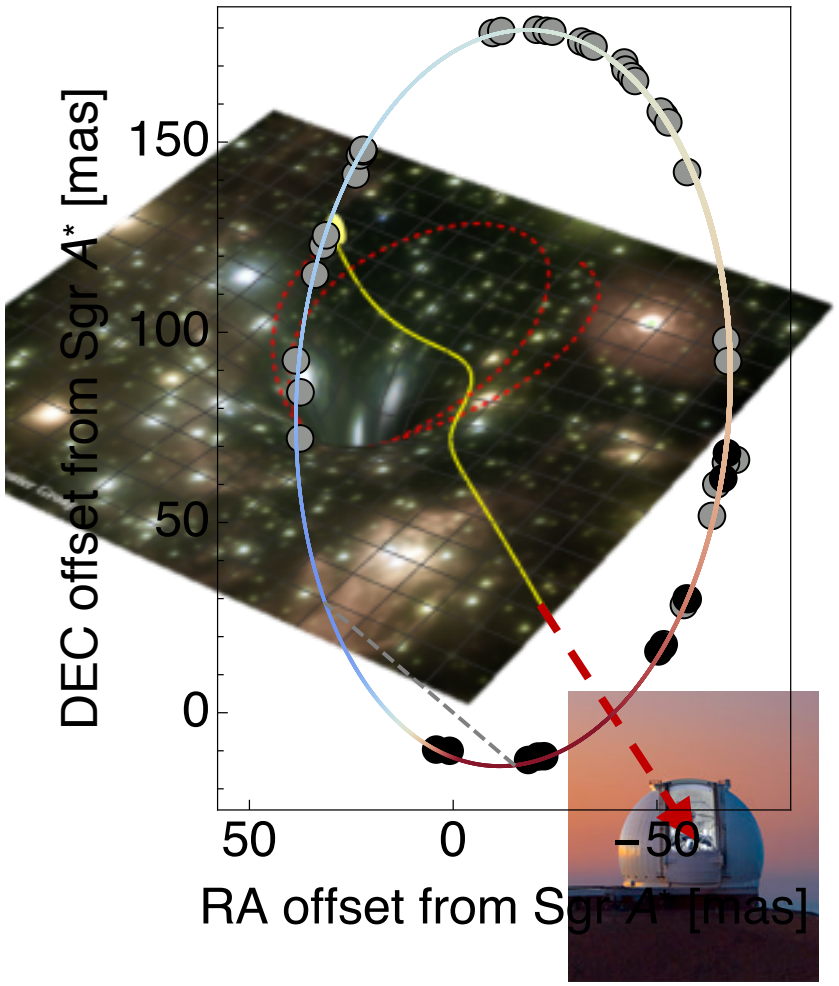
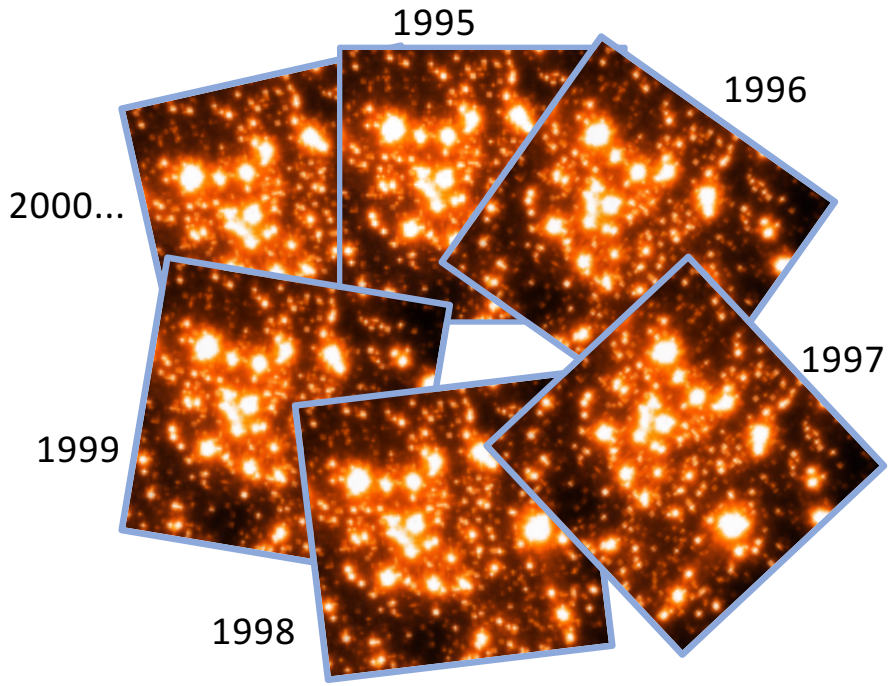


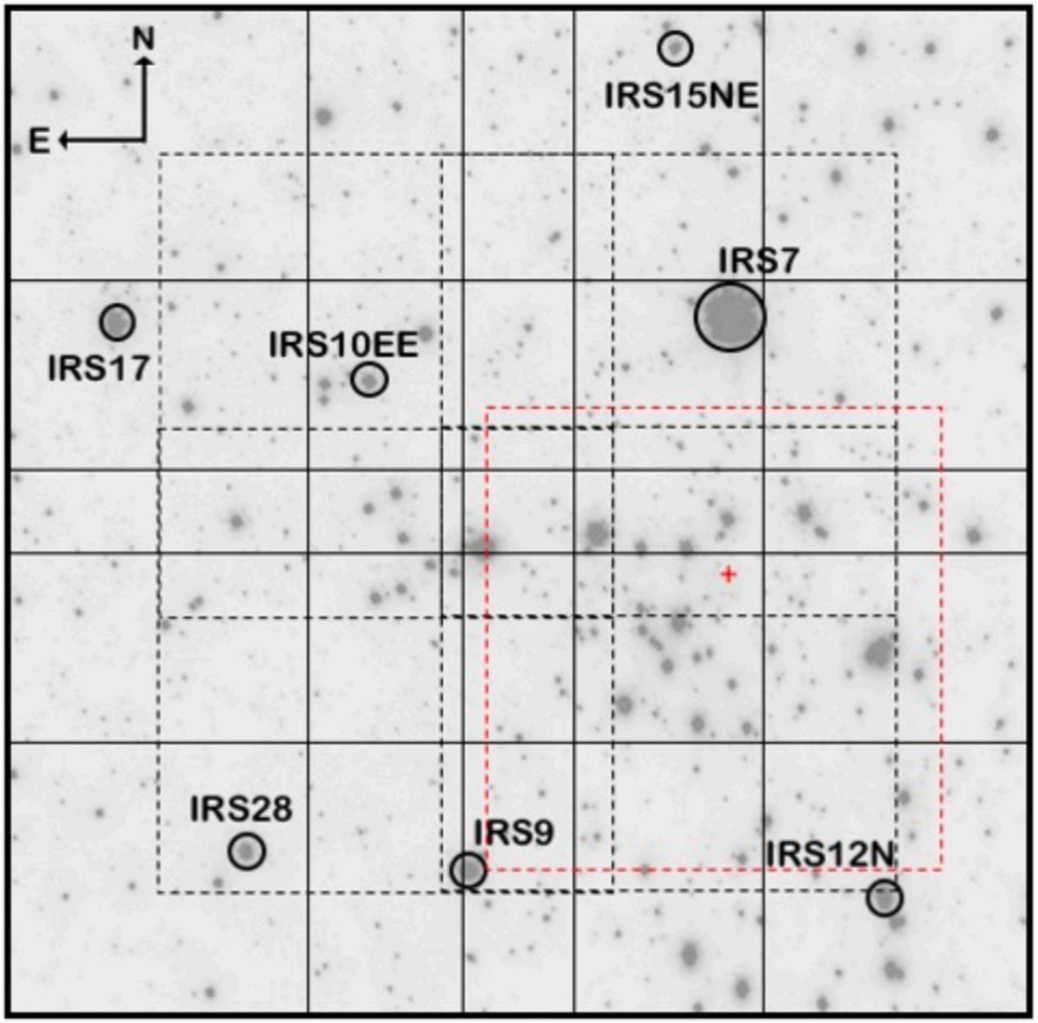
General Relativity & alternative theories of Gravity

- Gravitational Redshift (GR Test #1)
- Precession of Periapse (GR Test #2)
- Spin of black hole (GR Test #3)

If all the stars move, how do we put them in one correct coordinate system?



Reference frame is determined from seven maser stars

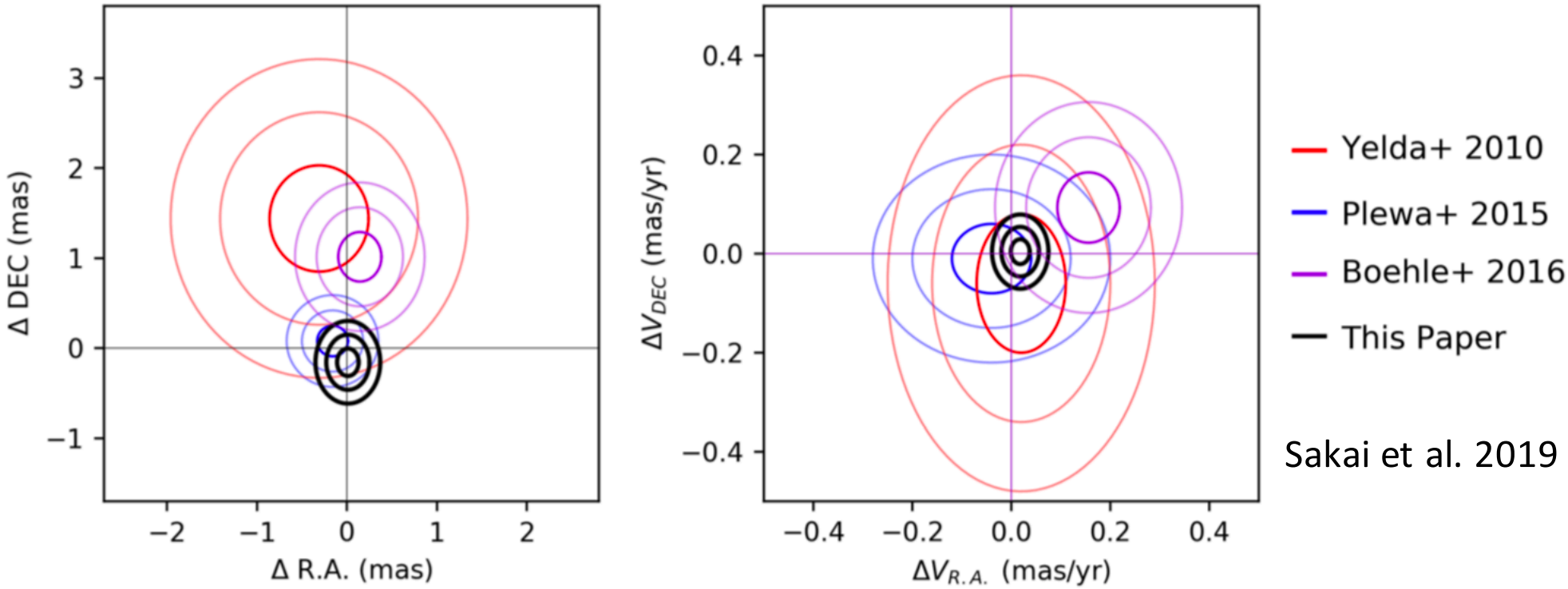


Sakai et al. 2019

See also Yelda et al. (2010), Plewa et al. (2015)

The reference frame stability is improved by a factor of 4

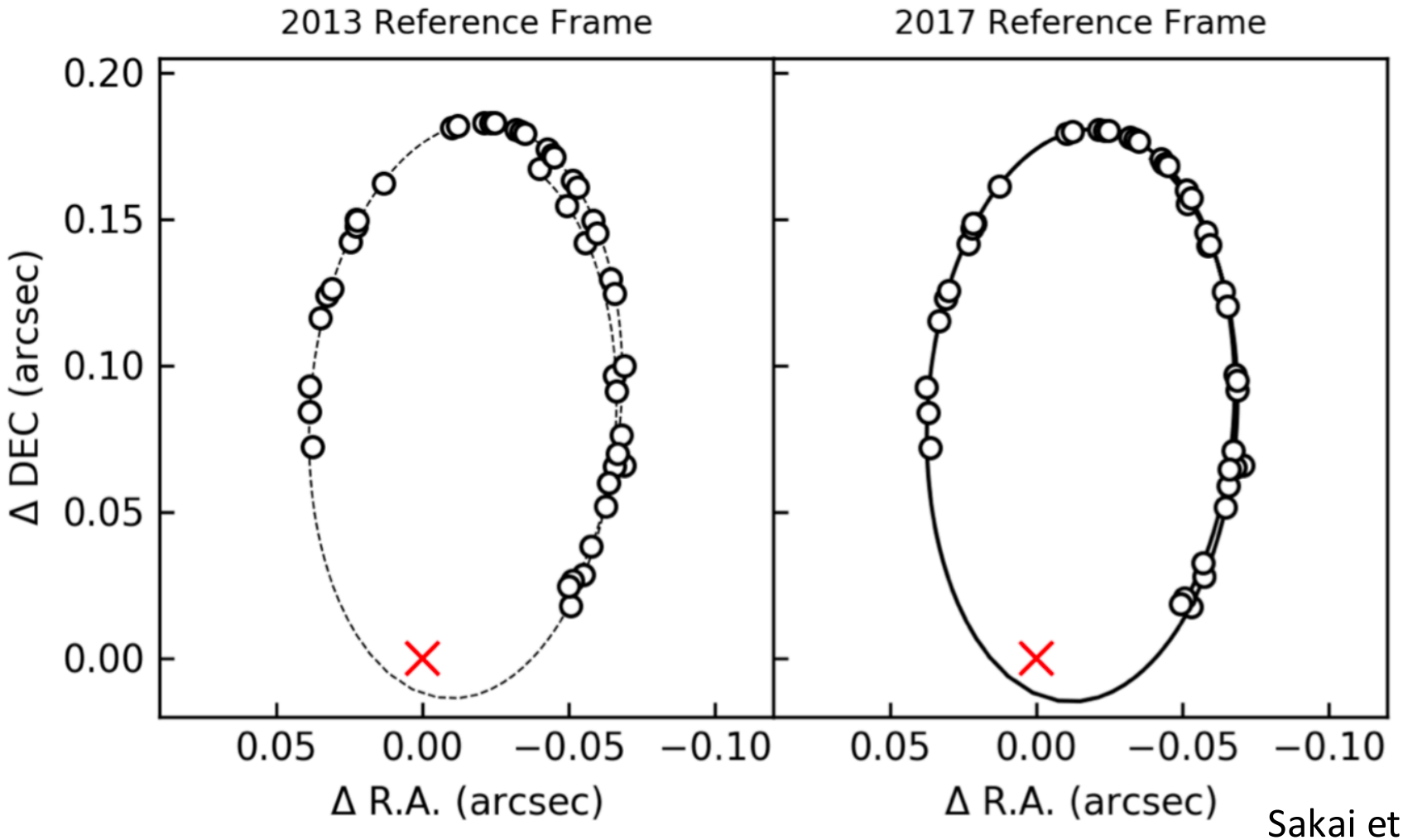
- New maser velocities (Reid et al. in prep)
- New point source detection method (AIROPA, Witzel et al. in prep)
- Higher order transformation and better source matching method



Sakai et al. 2019

See also Yelda et al. (2010), Plewa et al. (2015), Boehle et al. (2016)

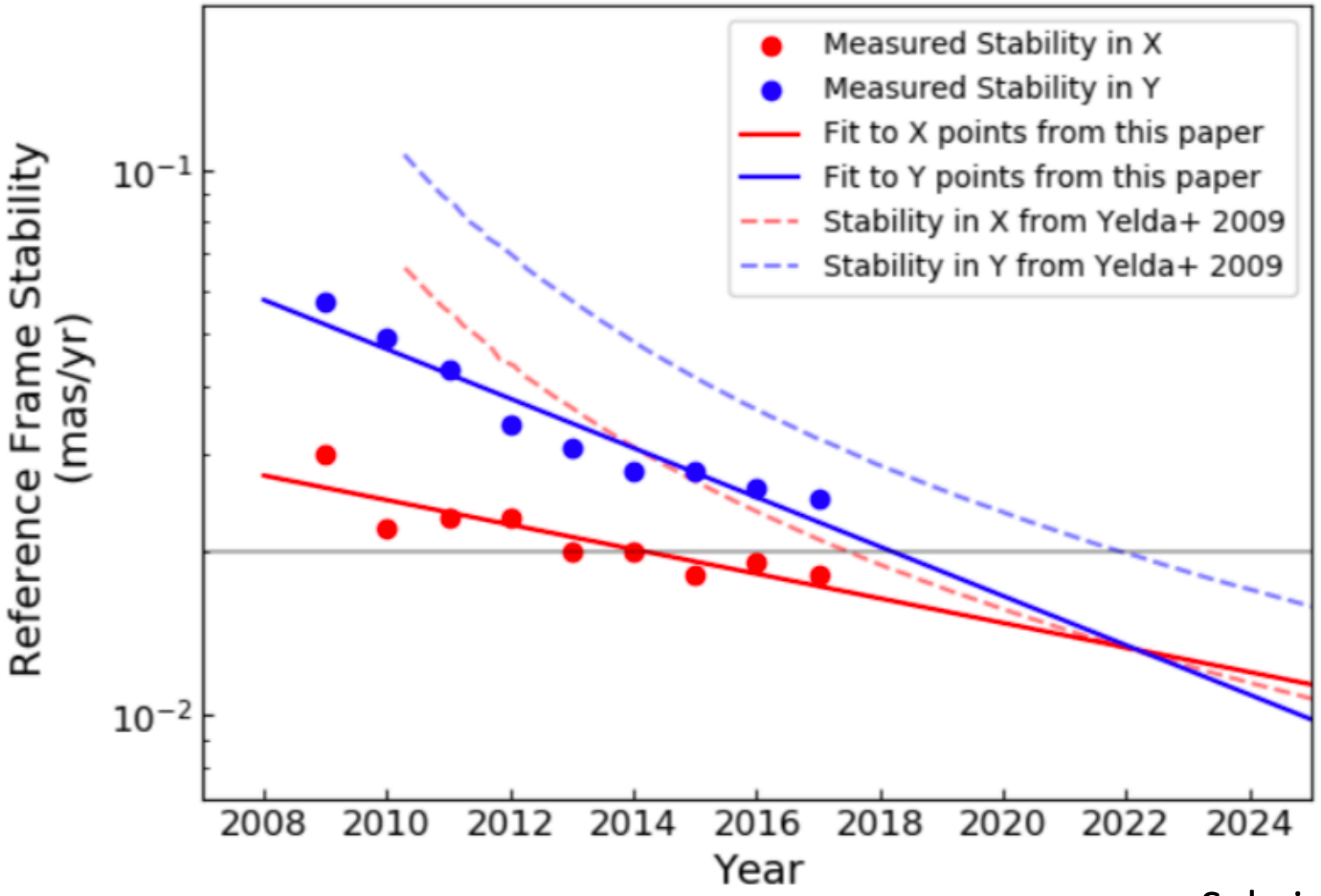
The reference frame stability is improved by a factor of 4



Sakai et al 2019

See also Yelda et al. (2010), Plewa et al. (2015), Boehle et al. (2016)

The reference frame stability is crucial for precession measurements



Sakai et al. 2019

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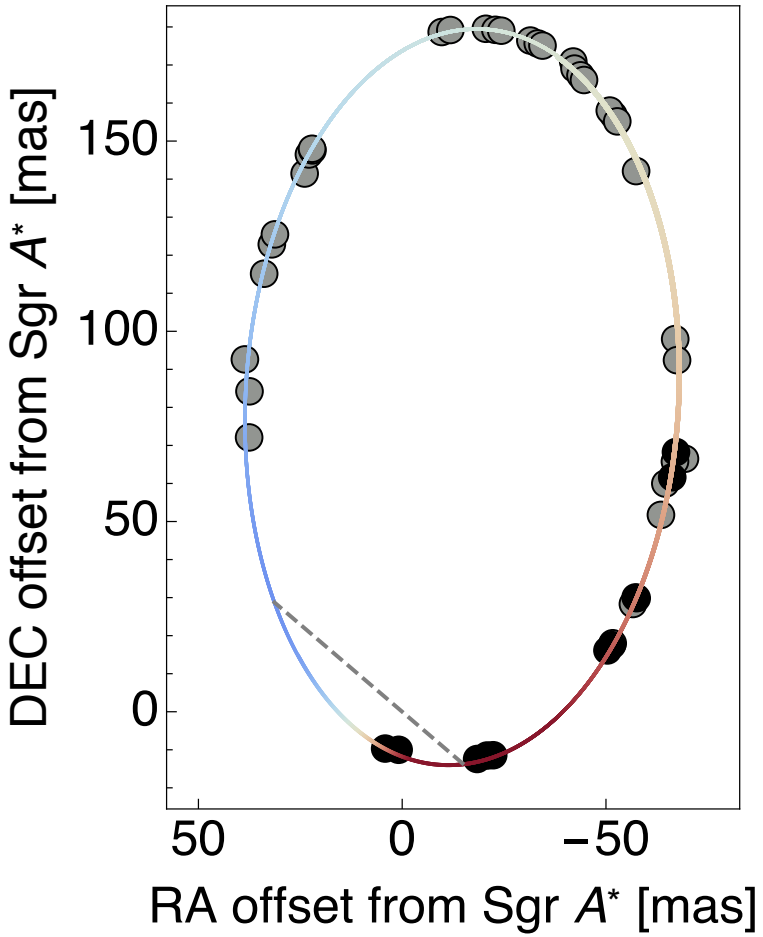
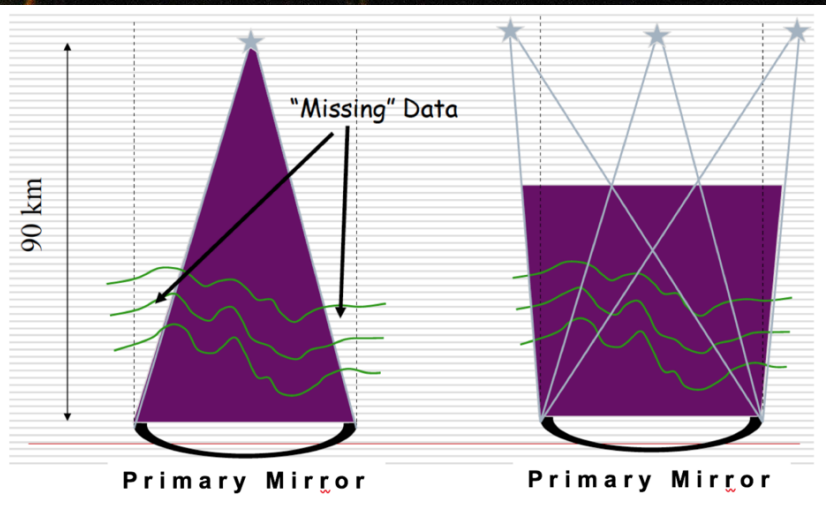
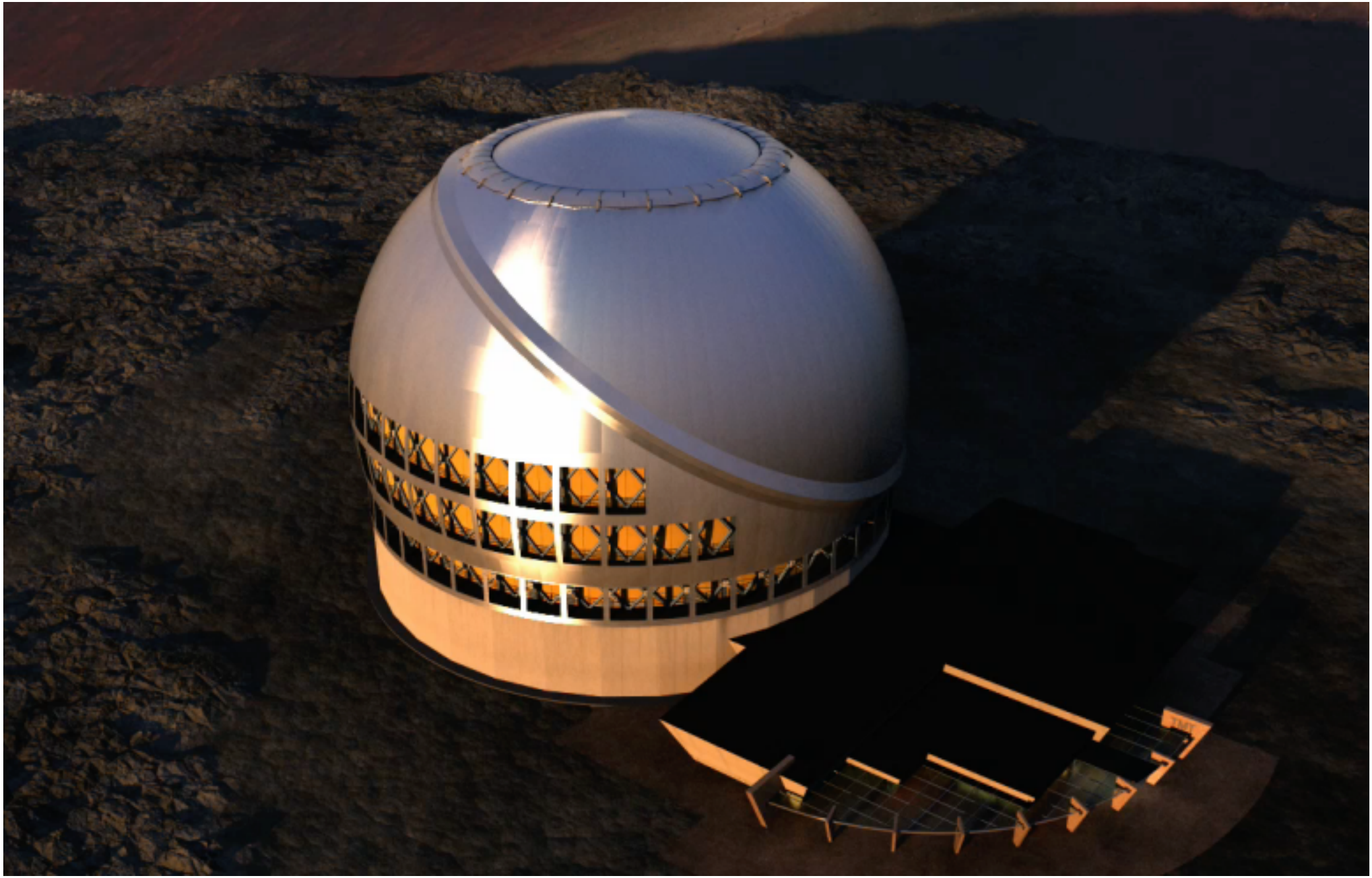
What Can be Probed with Stellar Orbits at Galactic Center?



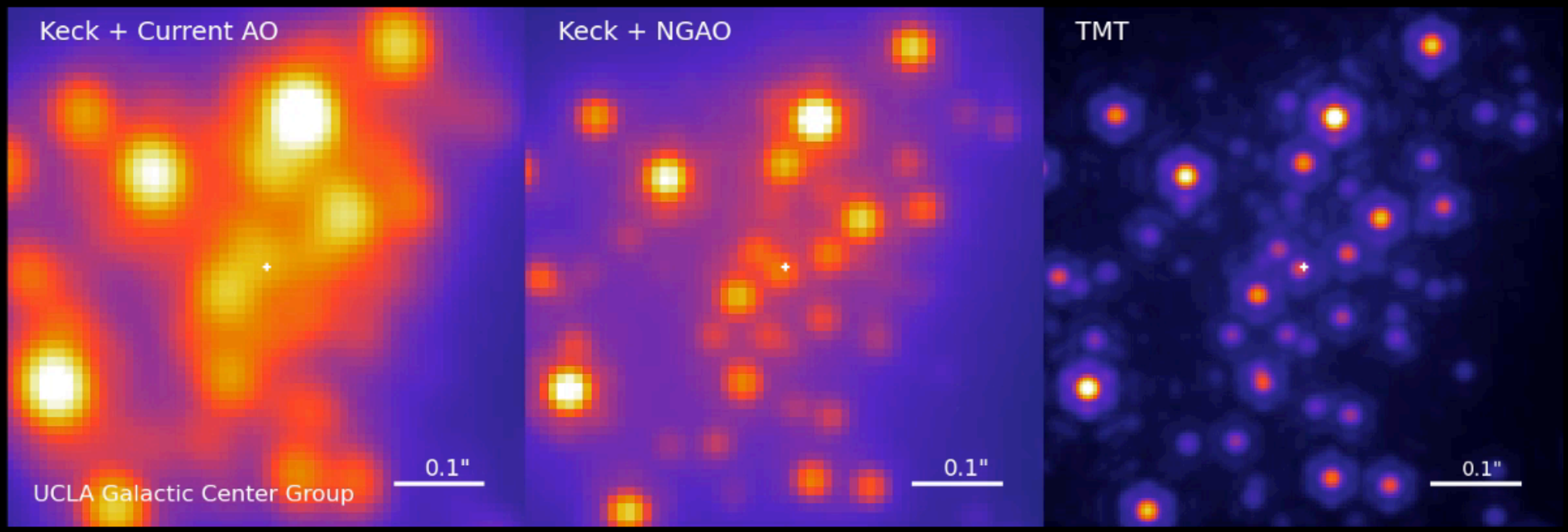
- General Relativity & alternative theories of Gravity
  - Gravitational Redshift (GR Test #1)
  - Precession of Periapse (GR Test #2)
  - Spin of black hole (GR Test #3)

Coming soon to Keck: Next Generation Adaptive Optics Using Multiple Laser "Stars"

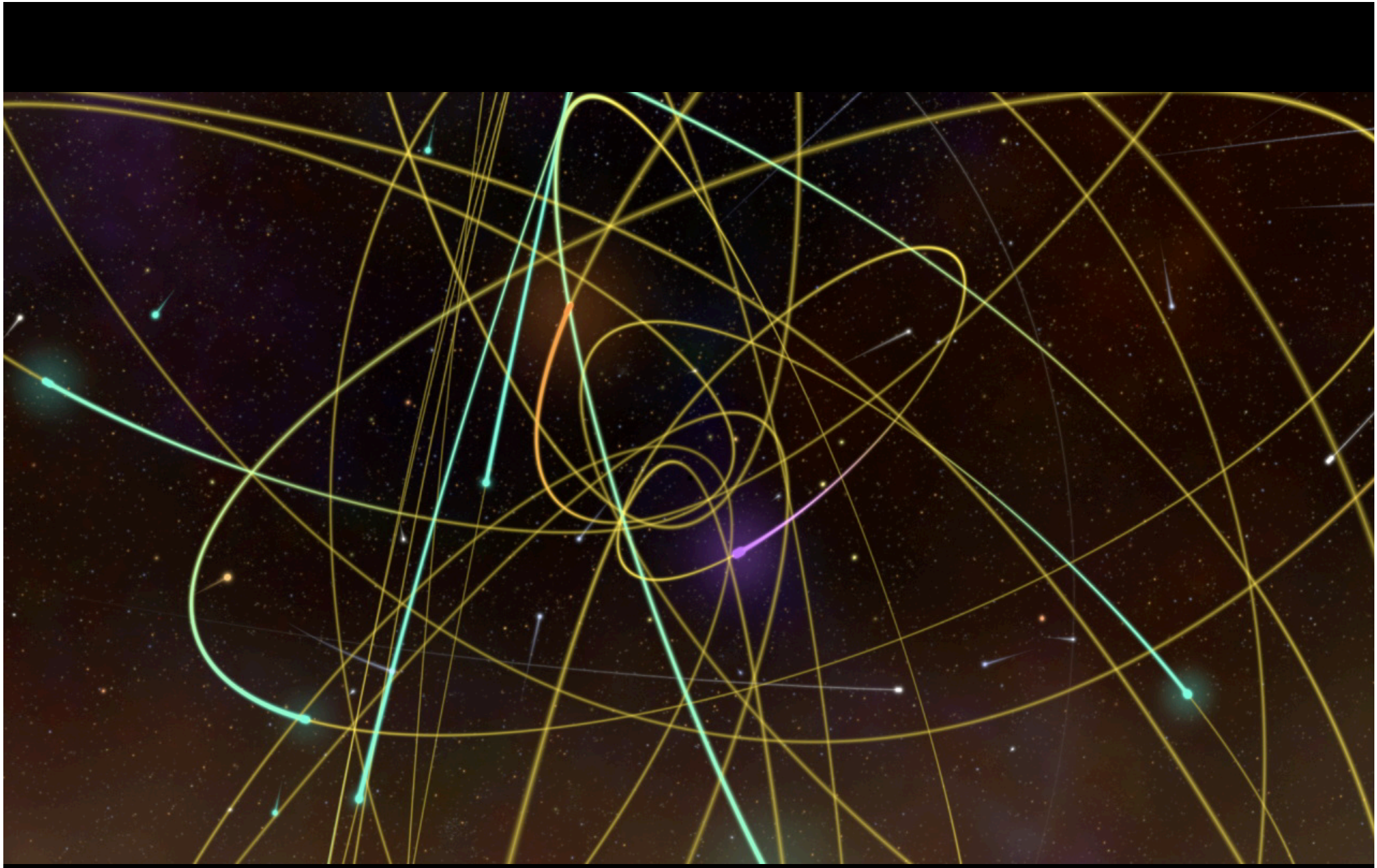




Three International 30-meter class Projects:
ELT, GMT & TMT



http://www.astro.ucla.edu/~ghezgroup/gc/animations.html



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