The Milky Way Galactic Center: A Laboratory for Extreme Astrophysics Revealed with Adaptive Optics

Devin S. Chu, PhD

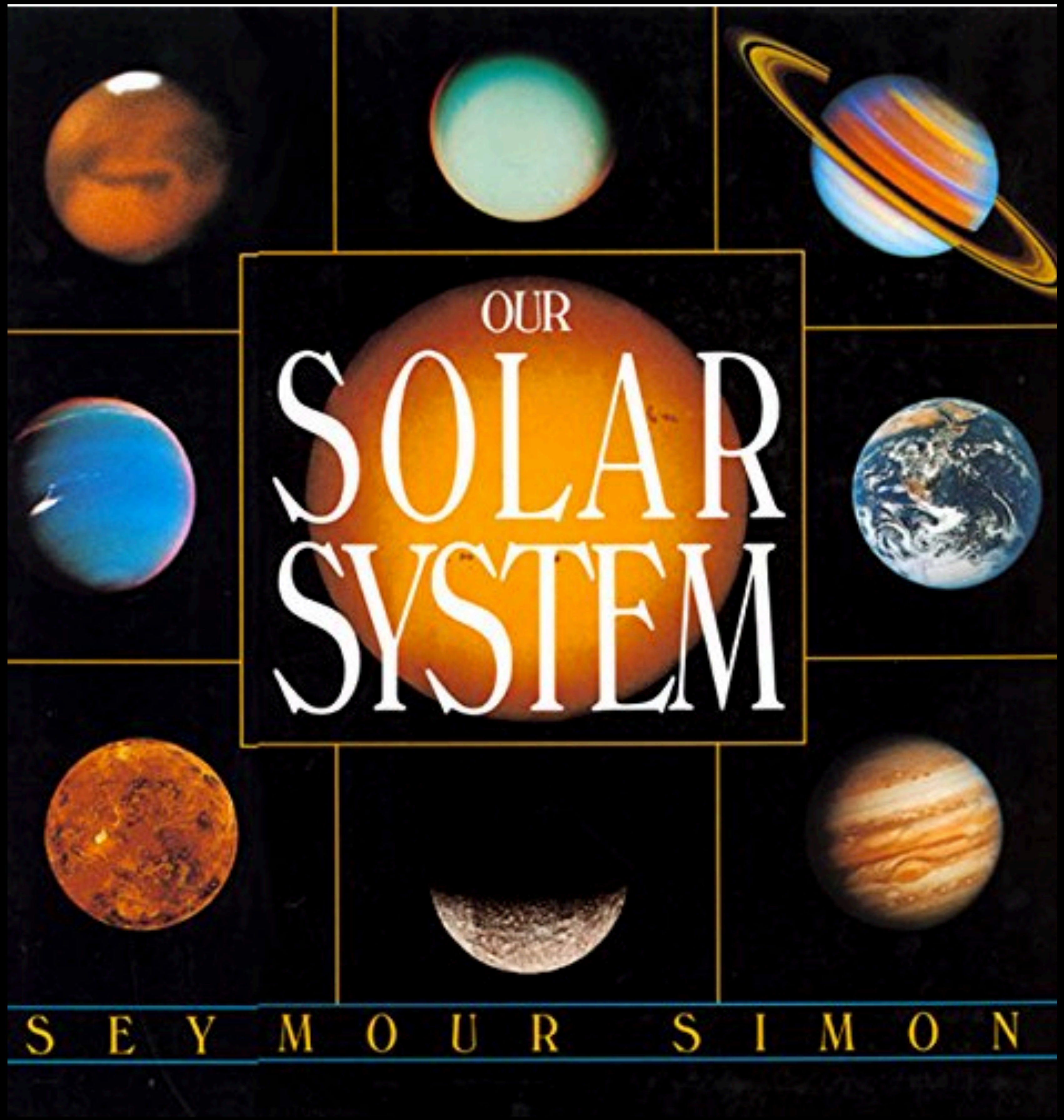
Postdoctoral Researcher - UCLA Galactic Center Group

UCLA
GALACTIC CENTER
GROUP

Gemini Observatory - November 2, 2023

Ethan Tweedie Photography


HILO
PUBLIC
LIBRARY


OUR
SOLAR
SYSTEM
SEYMOUR SIMON

Mahalo to Gemini to nurturing my scientific interest as a kid growing up in Hilo

Middle school science fair project with Peter Michaud

High school science fair project with Scot Kleinman

Akamai Internship with Atsuko Nitta and Scot Kleinman


Gemini's Laser!


UCLA
GALACTIC CENTER
GROUP

When you hear the term “Galactic Center”, what scale do you think of?

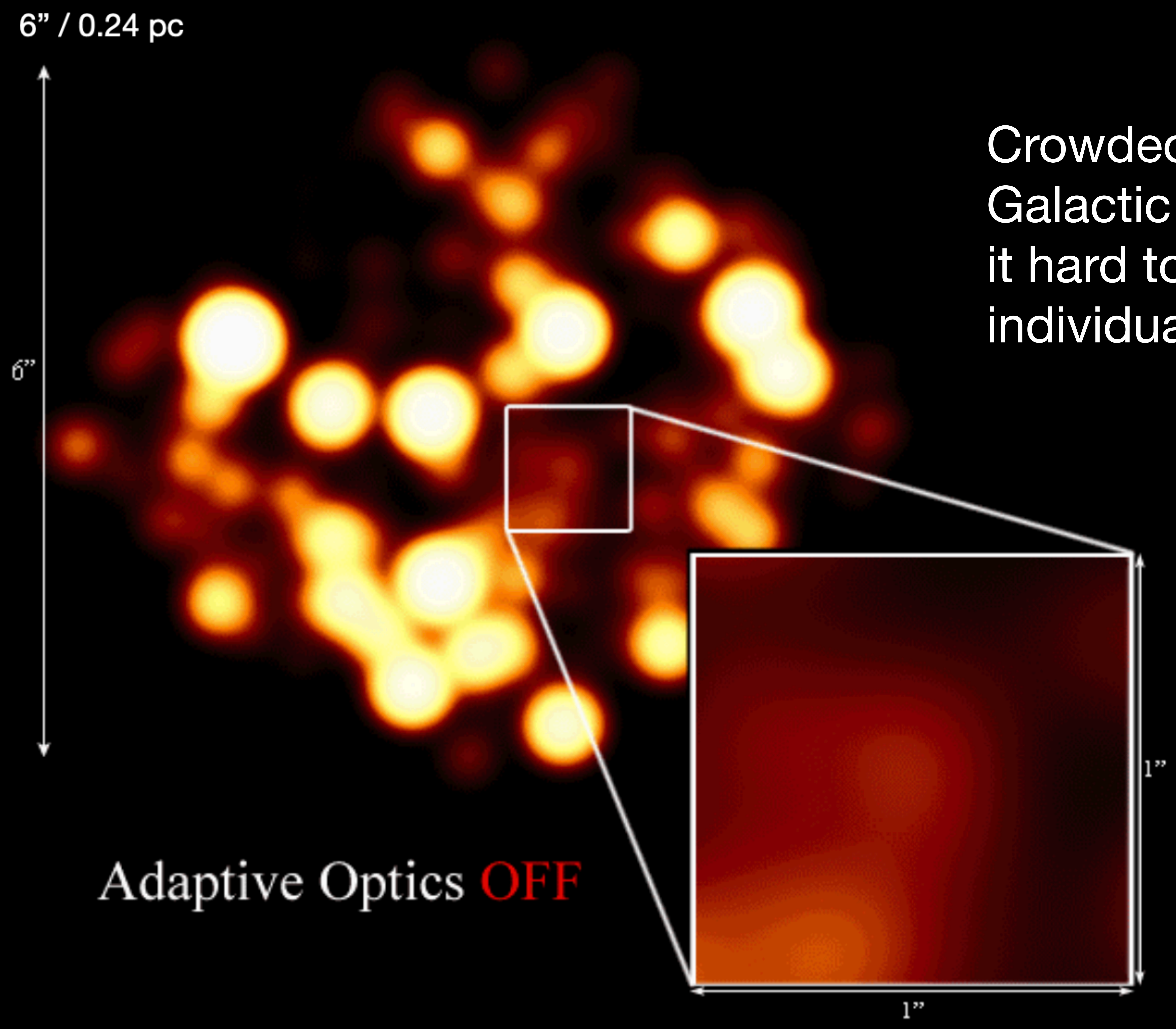
1. Central 10 kiloparsecs
2. Central kiloparsec
3. Central parsec
4. Central 0.1 parsec

This is what I think of. My talk will focus mostly within central 0.04 parsecs

The Galactic Center in infrared light

NASA/JPL-Caltech/S. Stolovy (Spitzer Science Center/Caltech)

The Galactic Center at 2.2 microns



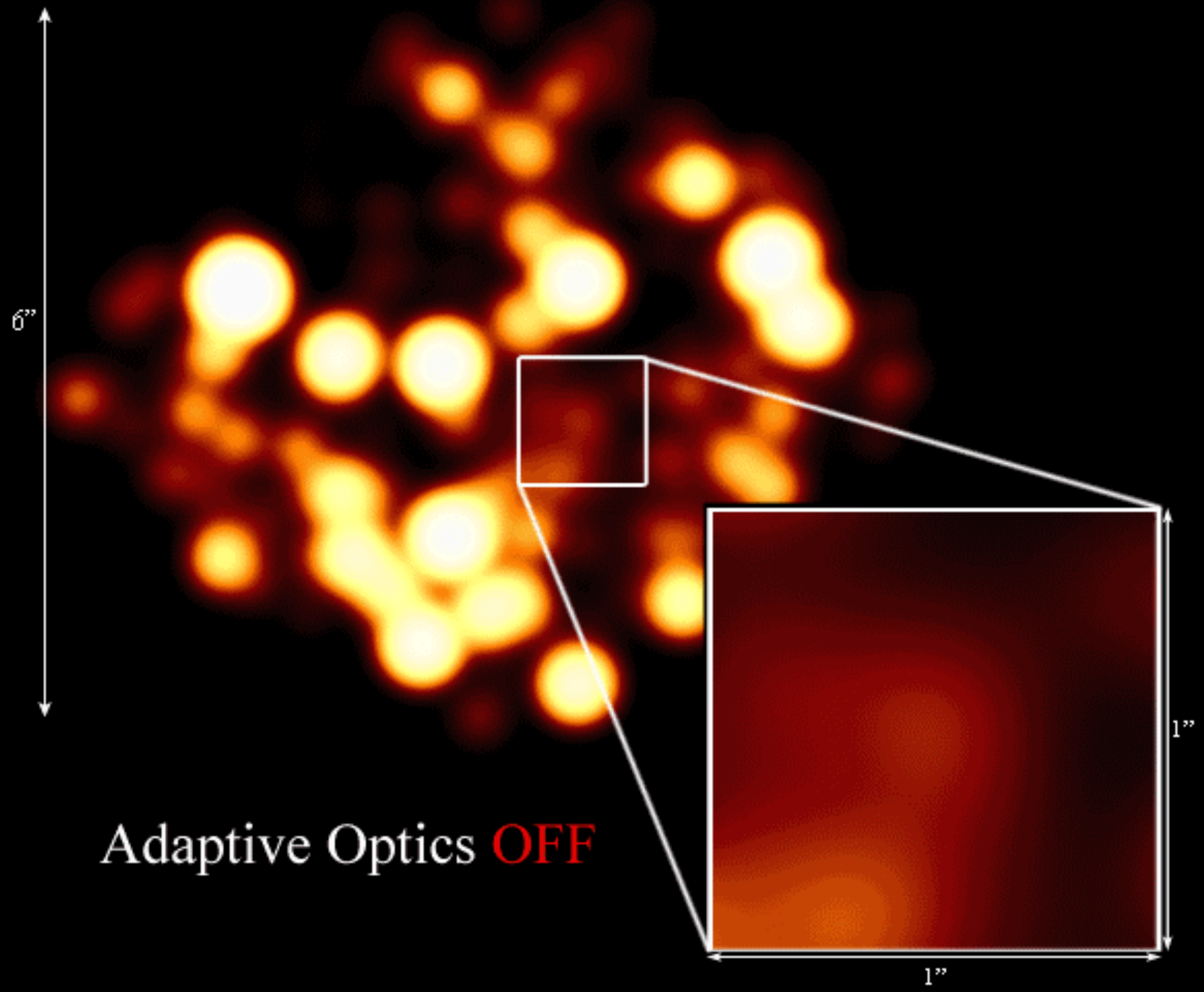
Crowded nature of Galactic Center makes it hard to resolve individual stars

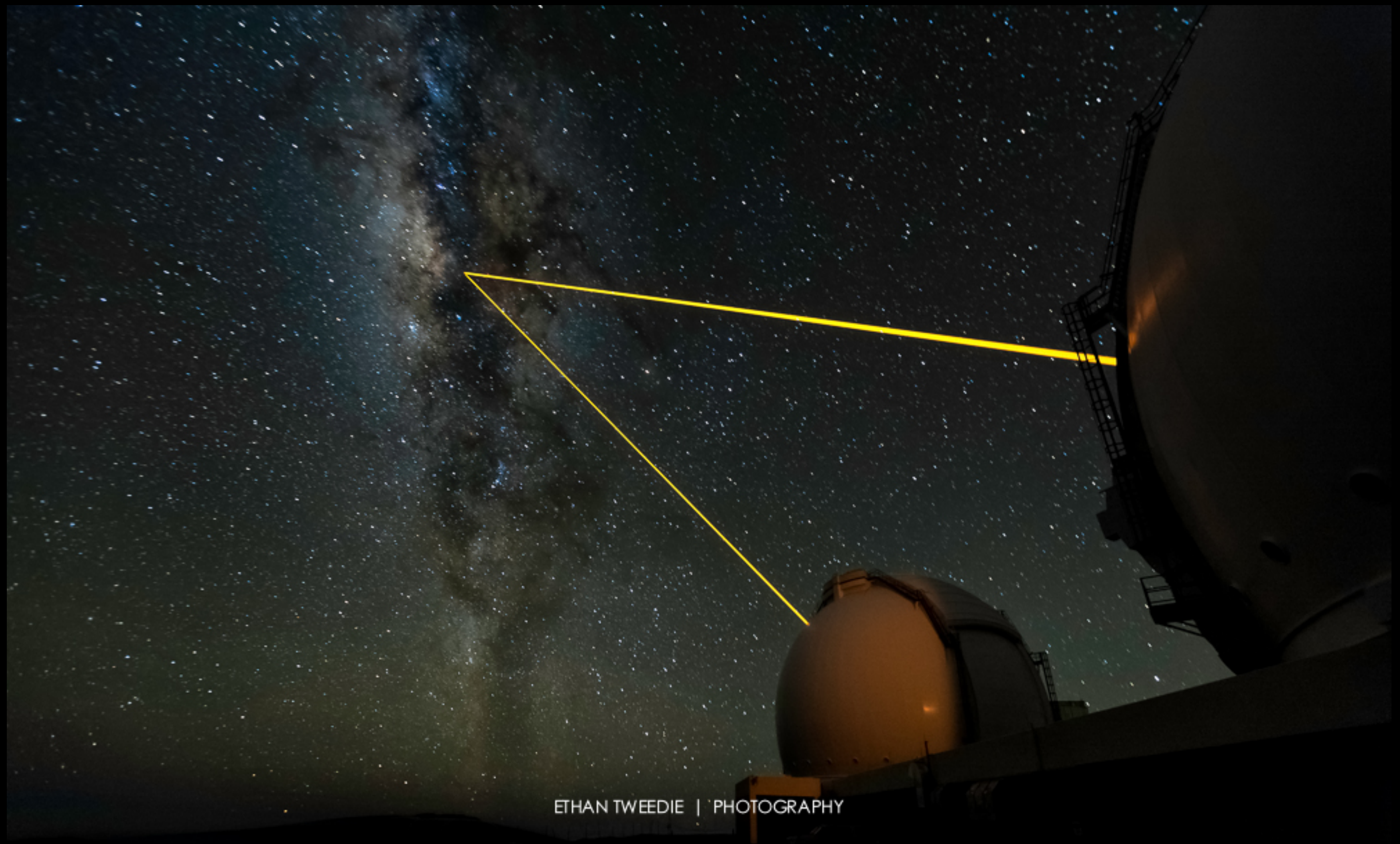
Devin S. Chu

UCLA GALACTIC CENTER GROUP

The Galactic Center at 2.2 microns

6” / 0.24 pc

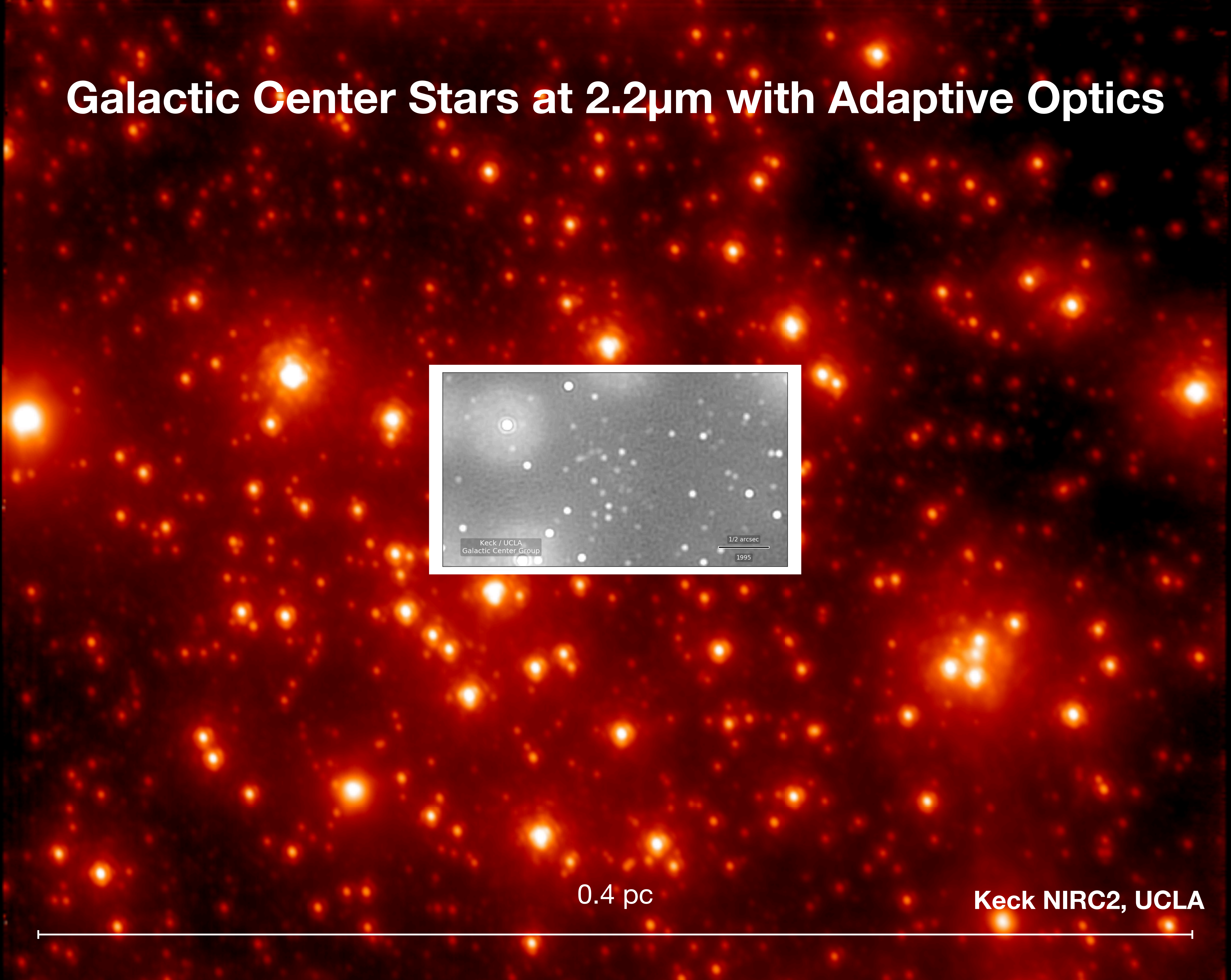




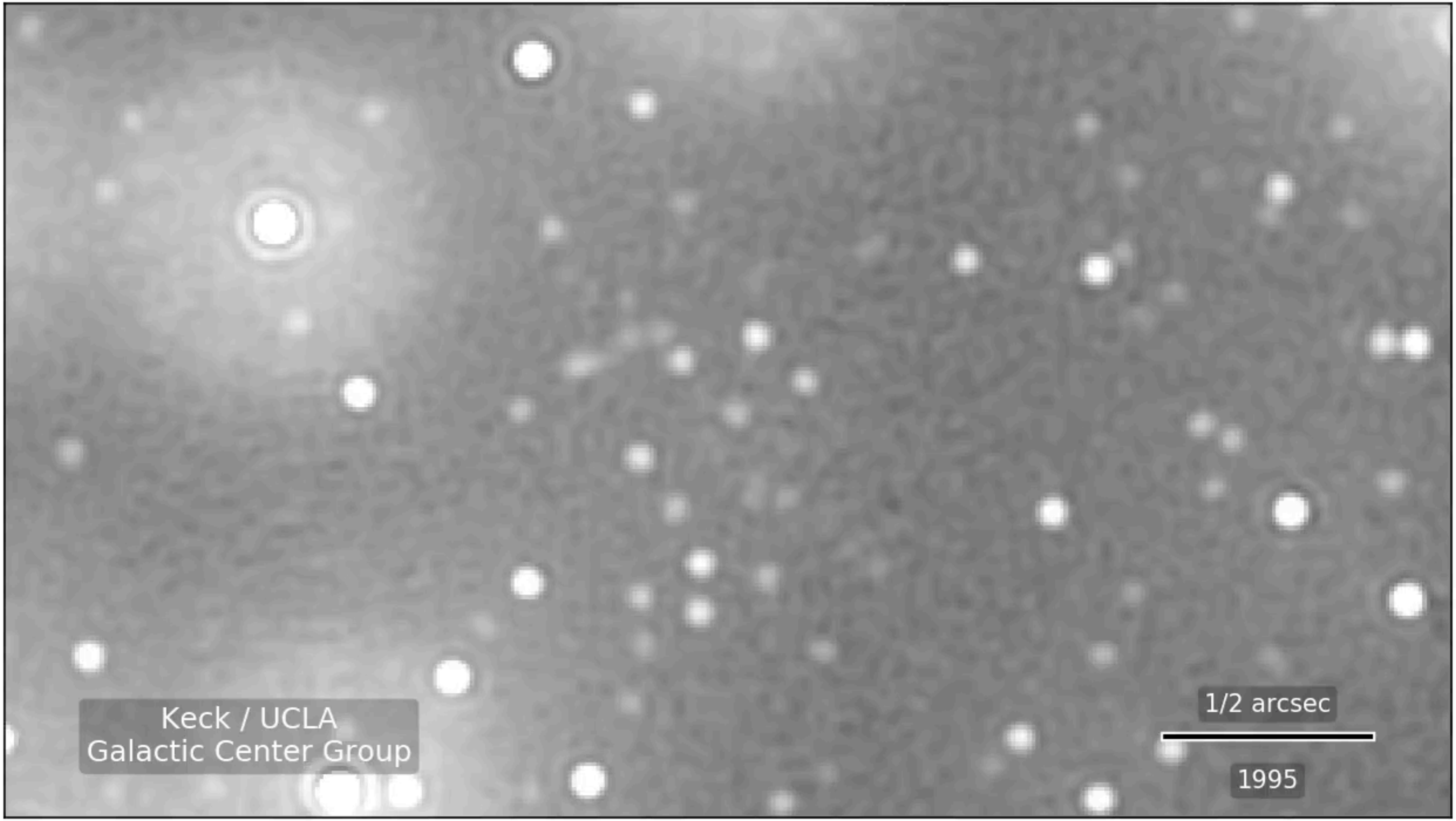
UCLA GALACTIC CENTER GROUP

- **Near-infrared wavelength coverage** is needed to peer through the dust at the Galactic Center
- **Adaptive optics** is needed to resolve individual sources in the crowded region

Galactic Center Stars at 2.2μm with Adaptive Optics



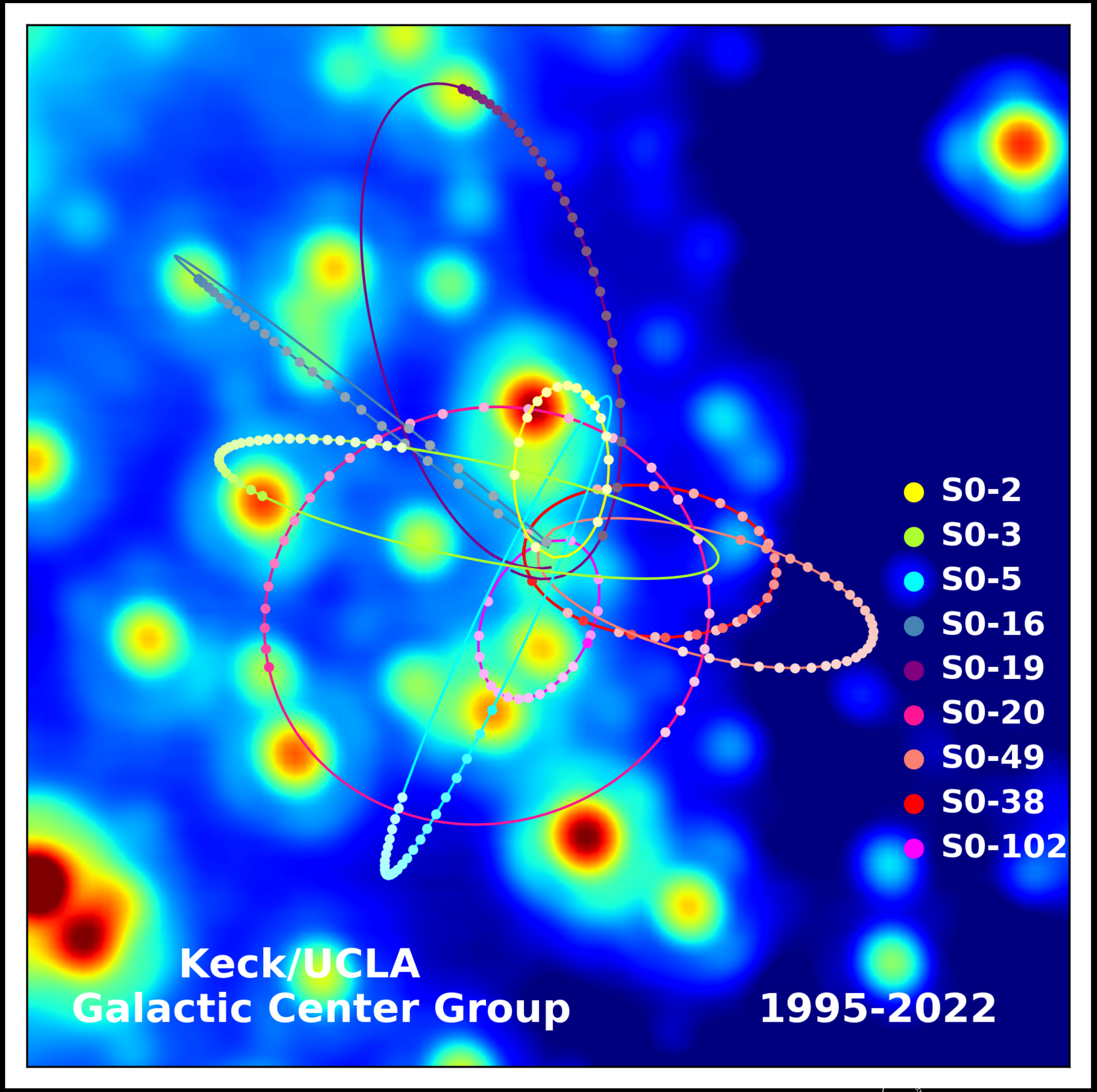
Devin S. Chu


Keck / UCLA
Galactic Center Group
1/2 arcsec
1995


Galactic Center S-stars
1995.5
S0-16
S0-2
S0-7
S0-3
S0-26
S0-1
S0-38
S0-19
S0-102
S0-4
Keck/UCLA Galactic Center Group
S0-17
S0-20
S0-5
0.1"
0.004 pc

The orbits of these S-stars have confirmed the existence of a supermassive black hole at the center of the galaxy

- Mass ~ 4 x 10^6 Solar Masses
- Distance ~ 8 kpc
- Do+ (2019, Science), GRAVITY collaboration (2018), references therein



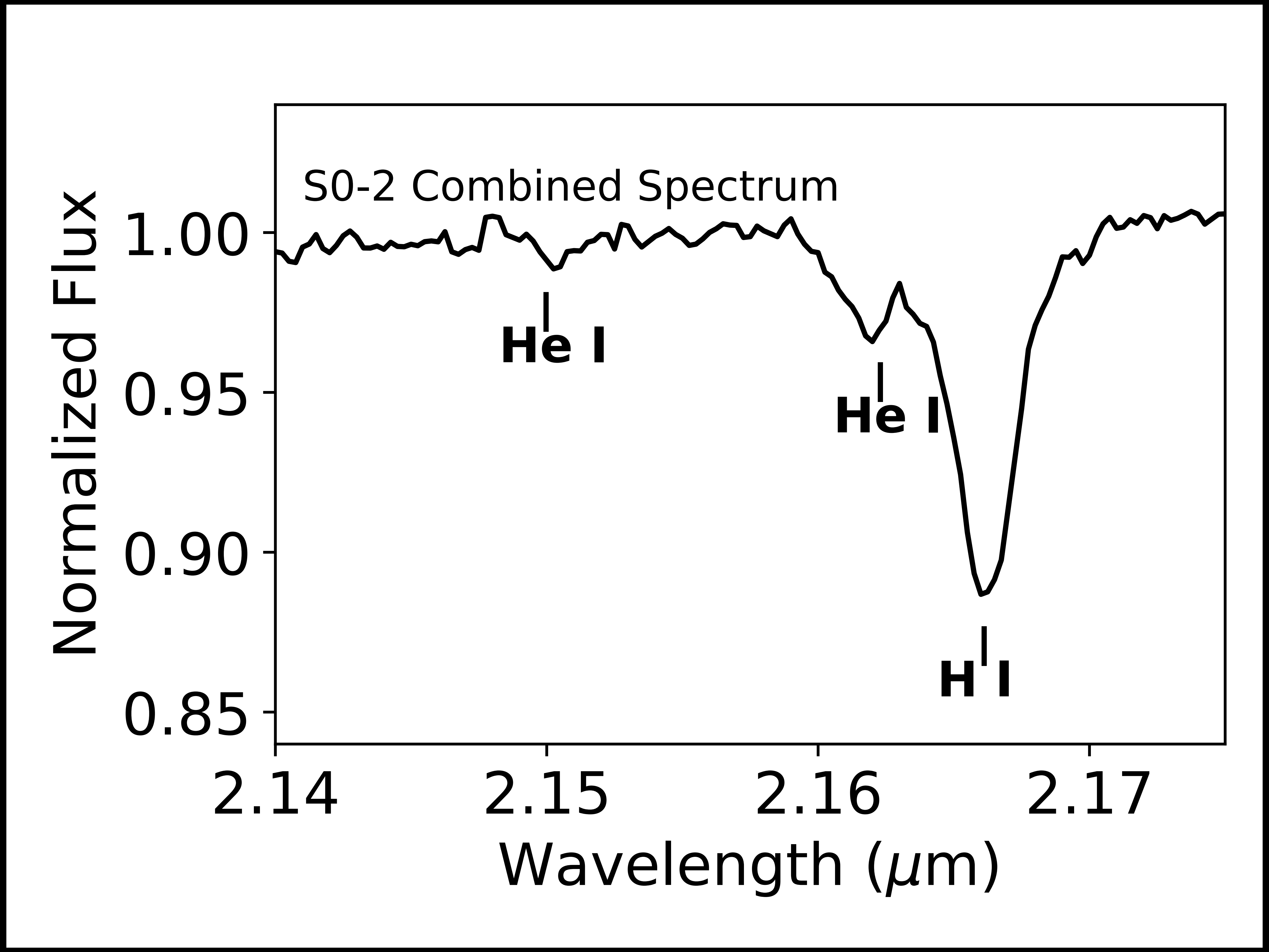
UCLA GALACTIC CENTER GROUP

Devin S. Chu

Adaptive optics-fed spectroscopy of Galactic Center stars led to next big leap in scientific progress

Puzzling stellar population: Spectroscopy with adaptive optics revealed most of the S-stars to be main-sequence B stars

- **S0-2 Properties** (Habibi+ 2017)
  - ~ 28000 K
  - ~13 $M_\odot$
  - ~6 Myr
- These stars are **hot, massive, and young**
- Young stars are not expected to form so close to the black hole due to extreme tidal forces



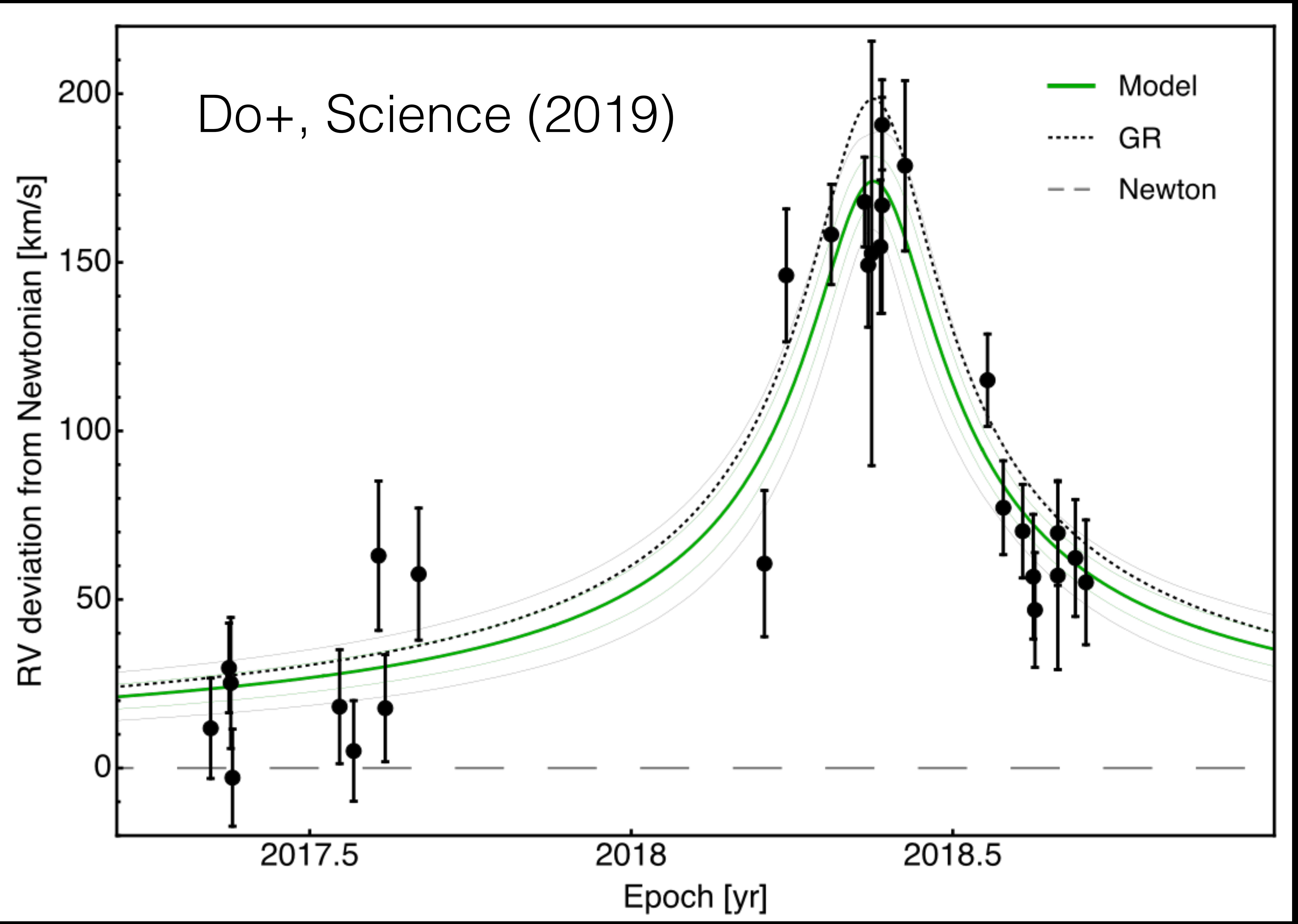
Do+ including Chu 2019 Science. See also Ghez+ (2003), Eisenhauer+ (2005), Martins+ (2008), Habibi+ (2017), etc

Devin S. Chu

CENTER

General Relativity: Gravitational redshift of the star S0-2 was measured at its closest approach to the black hole

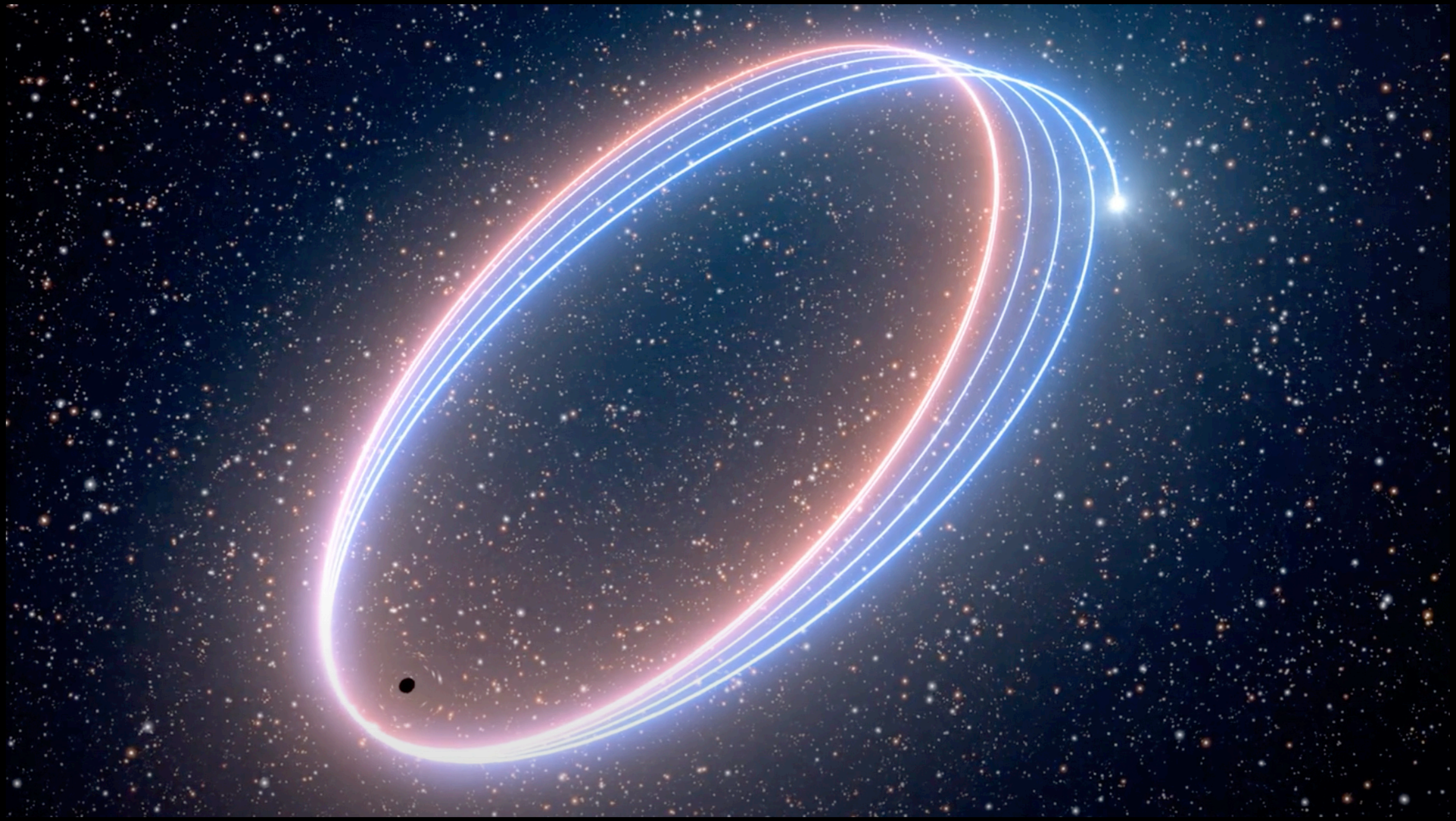
Result includes Gemini NIFS data



See also Chu+ 2018, GRAVITY Collaboration 2018

General Relativity: Periapses precession of the star S0-2

- Reported measurement in GRAVITY Collaboration 2020
- Stay tuned for our result!
- Our dataset includes Gemini NIFS data



GRAVITY Collaboration 2020

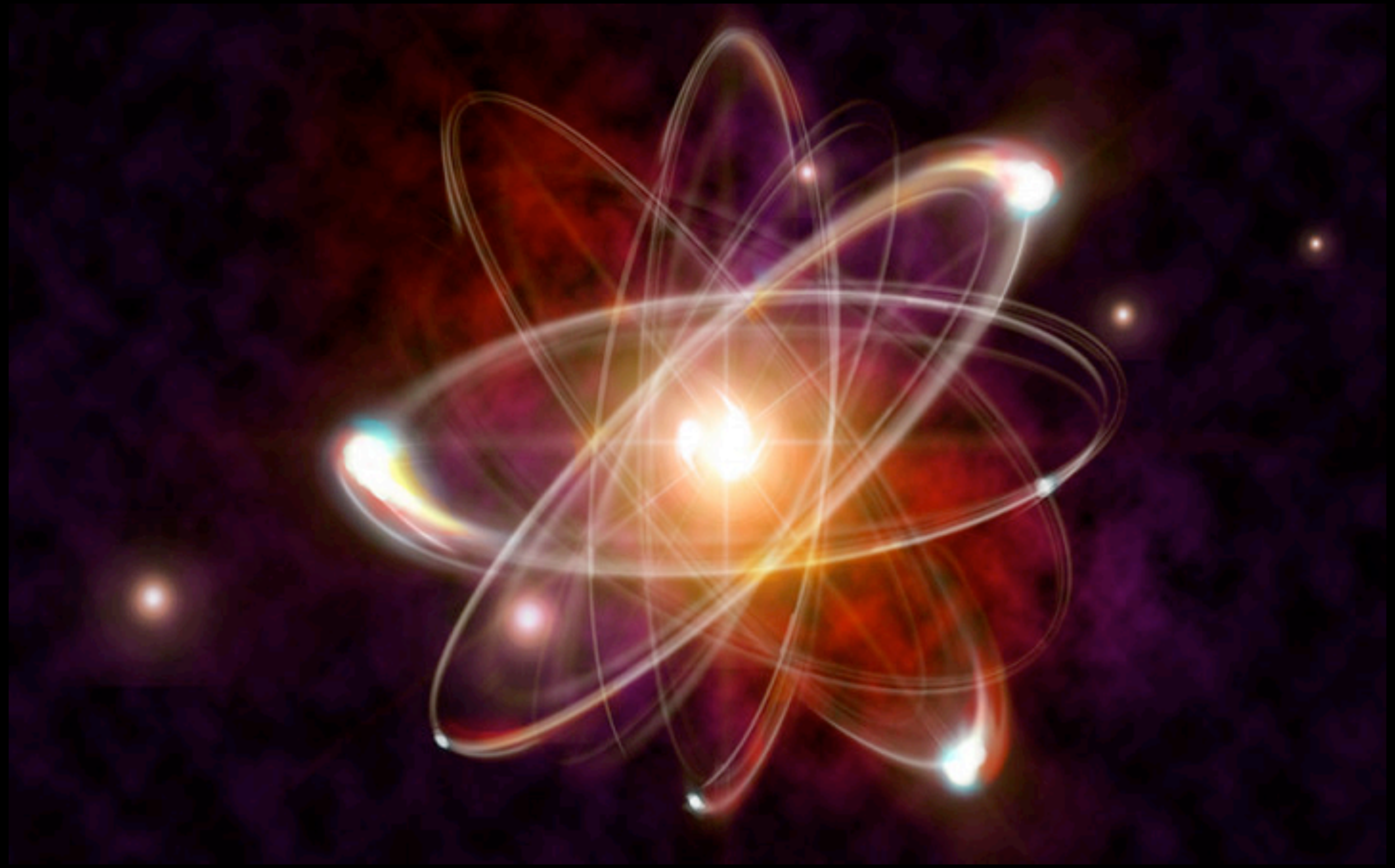
Fundamental physics: Fine-structure constant α variation tested in extreme gravitational environment near supermassive black hole

- Hees+ 2020 looked at spectral absorption lines variations in different stars

- Variation constraint of α to less than 10^{-6}

- Study is unique in the ***depth of gravitational potential*** and ***compactness of central source***

- Result included Gemini NIFS data



Let’s return to the puzzling young, massive S-stars around the black hole

Binary star systems are prevalent among massive stars in the solar neighborhood

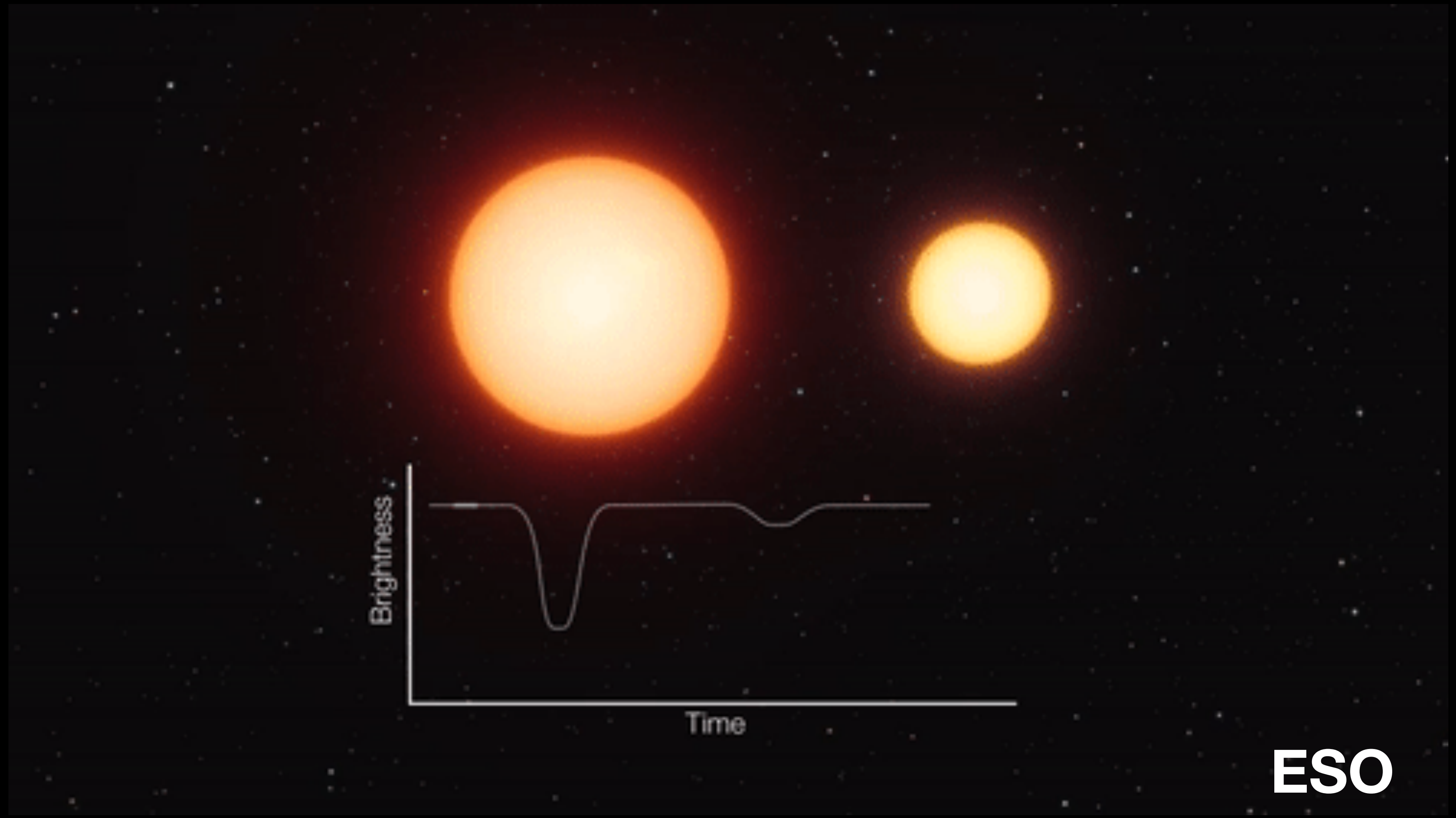
- Binary fractions of OB clusters can be as high as 70% (e.g. Sana+ 2012)
- **Is this also true for the S-stars at the Galactic center?**

Universe Today

UCLA GALACTIC CENTER GROUP

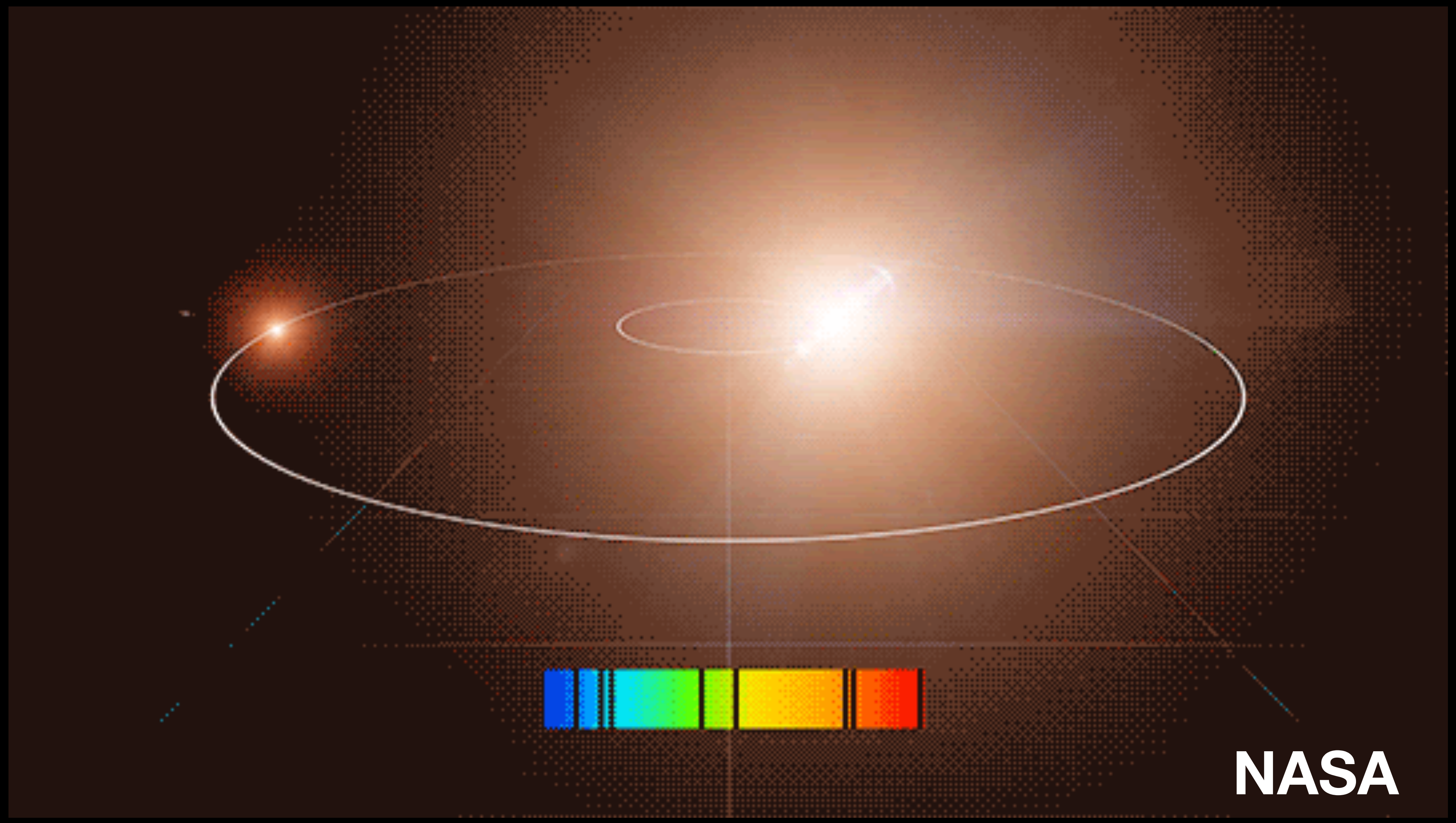
Devin S. Chu

Two main ways to look for binary stars at the Galactic center



Eclipsing method using imaging

Pros: Less expensive for telescope time
Cons: Less sensitive to binary orientation



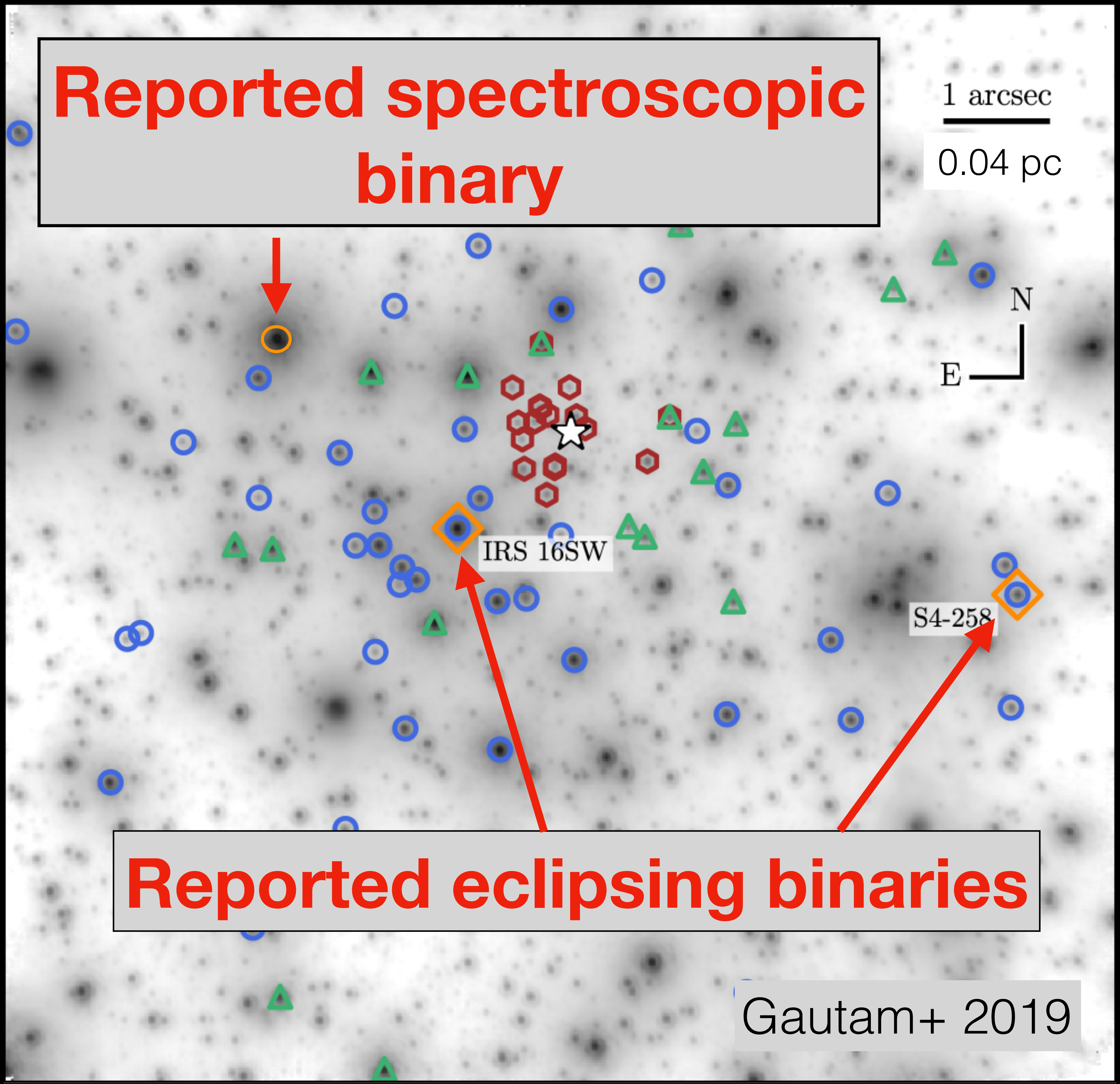
Radial velocity method using spectroscopy

Pros: Sensitive to more binary orientations compared to eclipsing, gives star masses
Cons: More expensive for telescope time

Devin S. Chu

UCLA GALACTIC CENTER GROUP

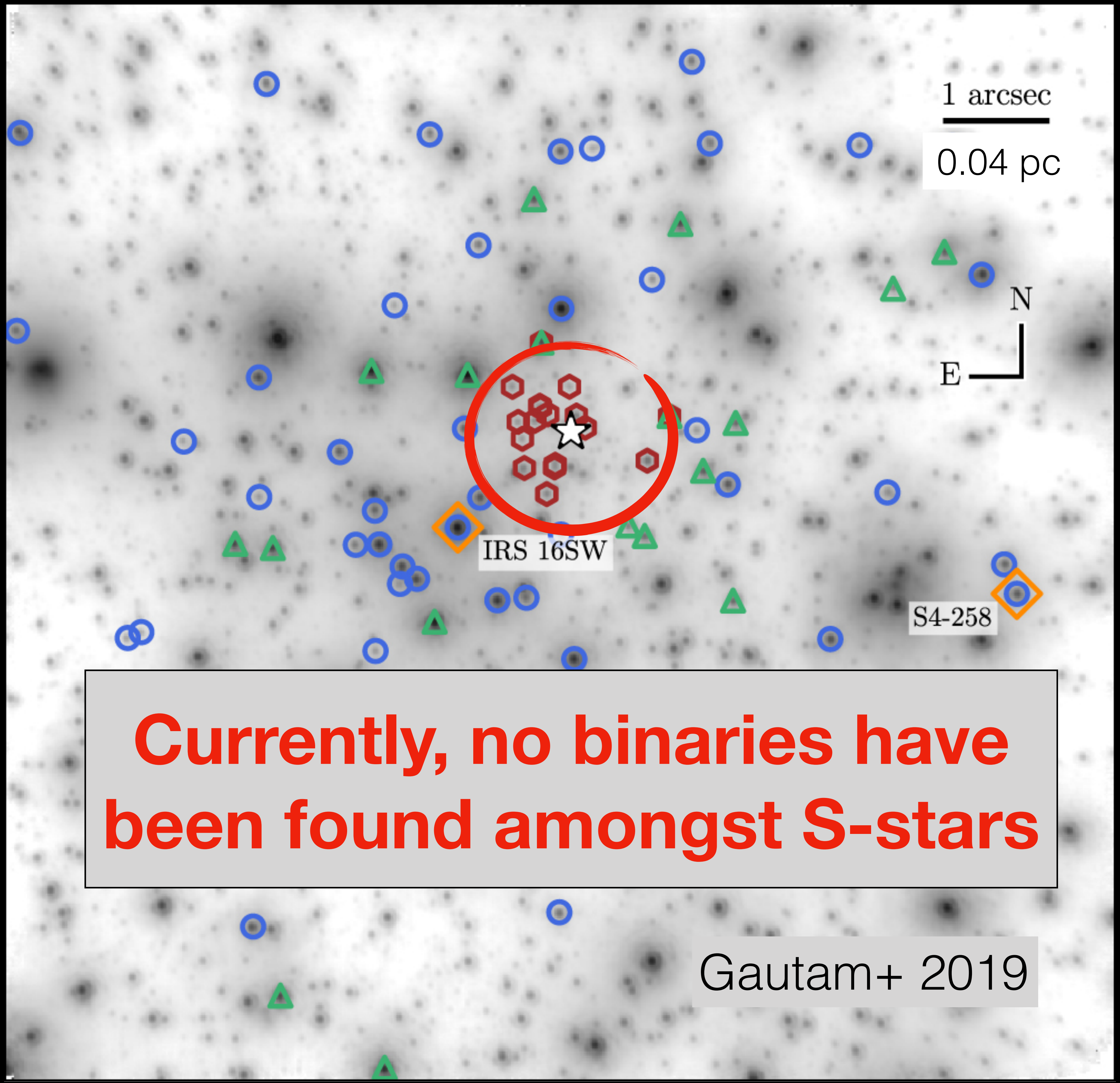
Binaries have been found at the Galactic center through photometry and spectroscopy



- Eclipsing binary fraction is consistent with solar neighborhood (e.g. Rafelski+ 2007, Pfuhl+ 2014, Gautam+ 2019, submitted)
- Previous spectroscopic binary search focused on brightest stars at Galactic center (Pfuhl+ 2014)

Devin S. Chu

There has not been a systemic search for spectroscopic binaries amongst S-stars

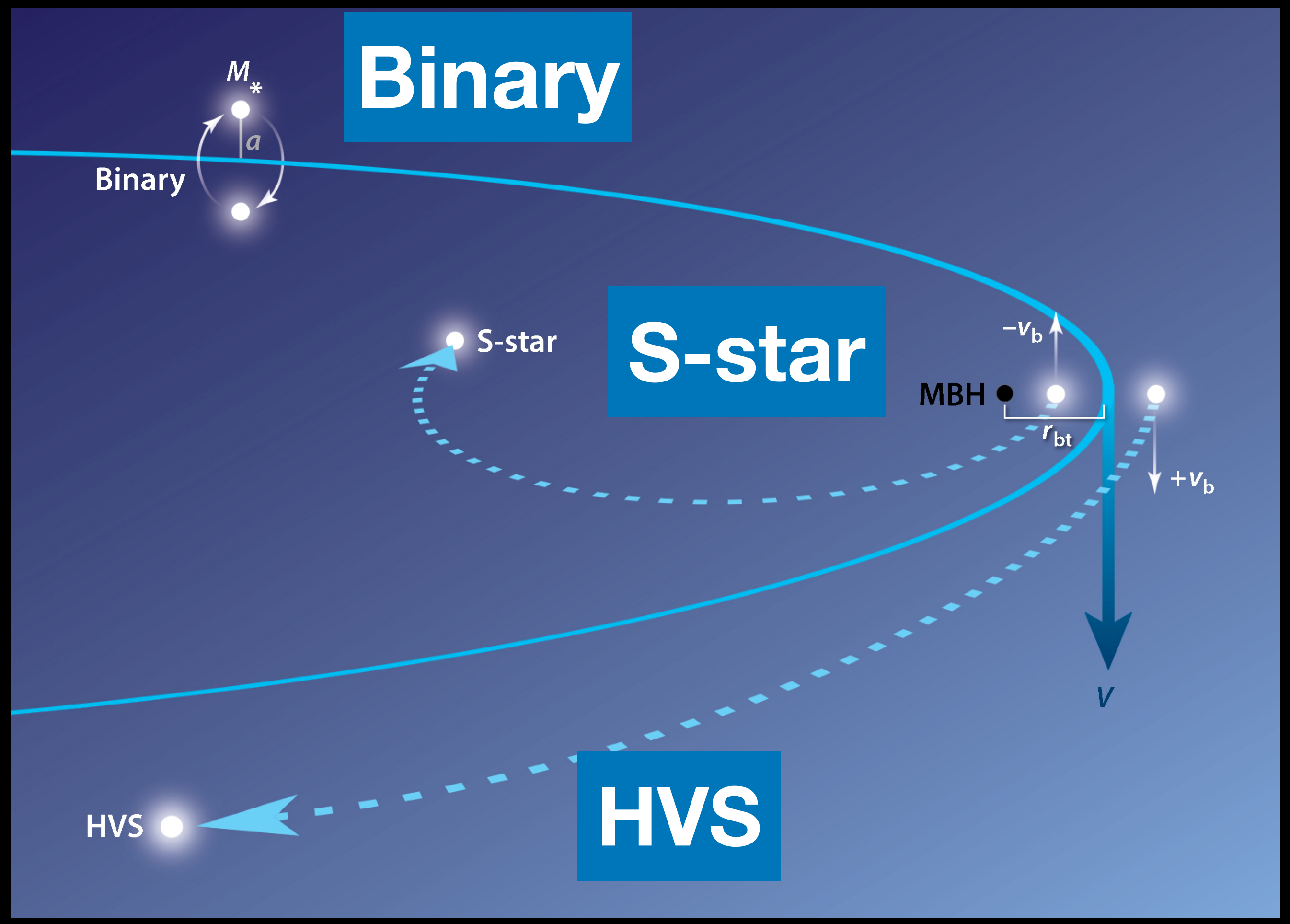


- No eclipsing binary candidates identified amongst S-stars (Gautam+ 2019)
- S-stars were excluded from previous spectroscopic searches (Pfuhl+ 2014)

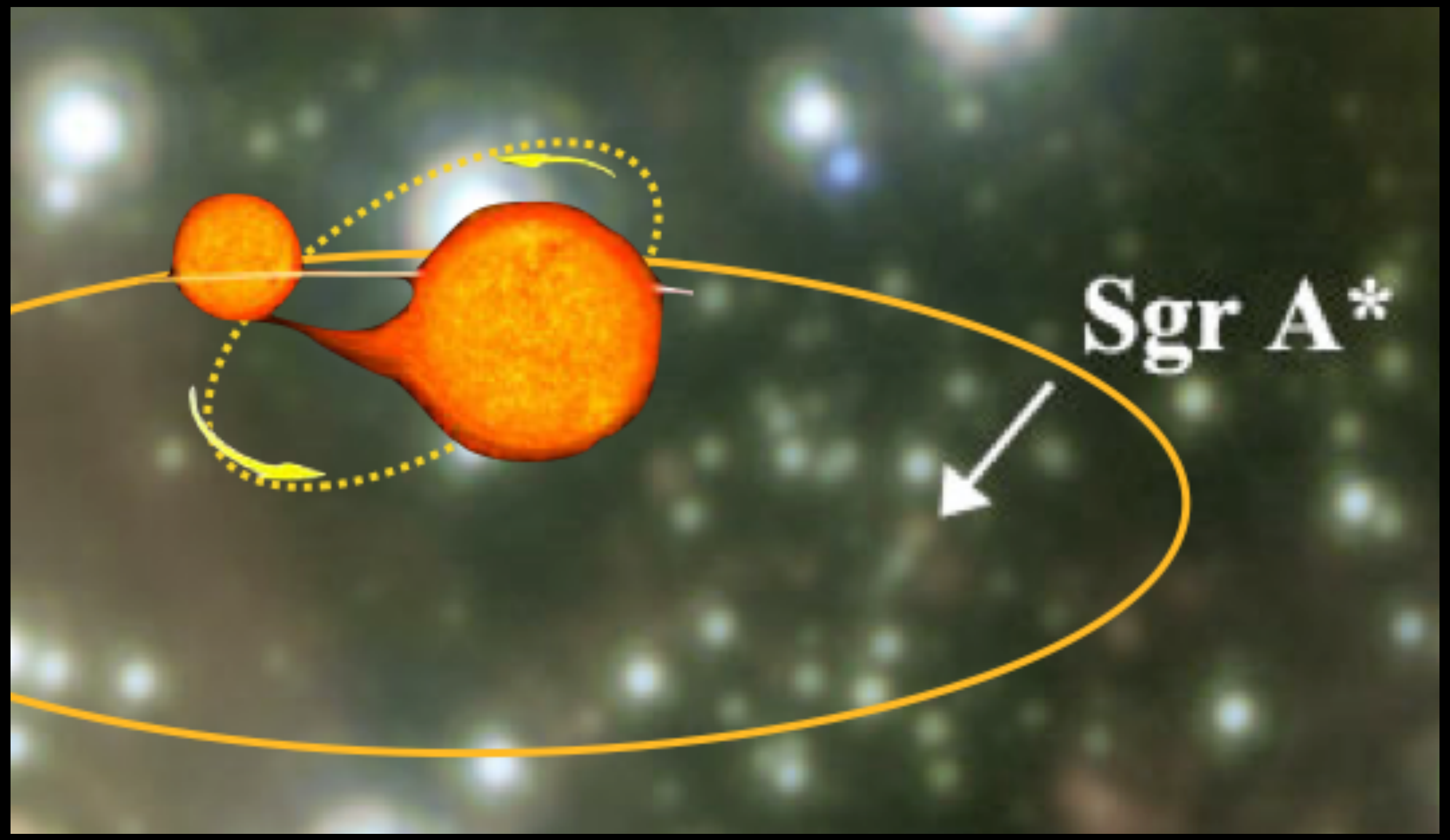
Devin S. Chu

UCLA GALACTIC CENTER GROUP

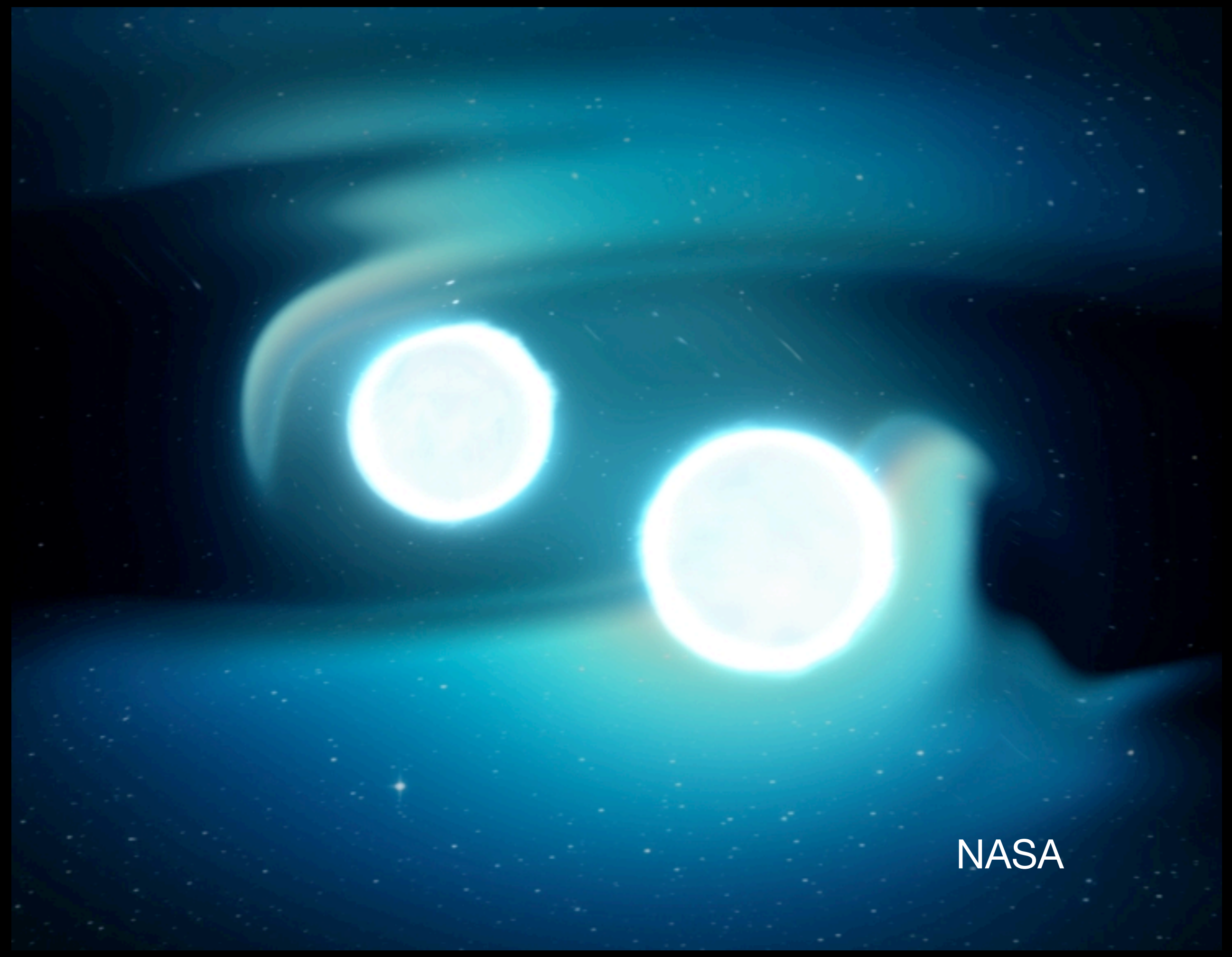
Binary stars systems may explain how the young S-stars exist around the supermassive black hole



Binary capture
and ejection
(e.g. Hills 1988)



Merged stars
(e.g. Stephan+ 2016, 2019, Ciurlo+ 2020, Nature)



Dynamical interactions
and scattering
(e.g. Levin 2007)

Devin S. Chu

UCLA GALACTIC CENTER GROUP

Binary stars systems may explain how the young S-stars exist around the supermassive black hole

How can we determine the evolution of the S-star cluster?

Binary capture and ejection (e.g. Hills 1998)

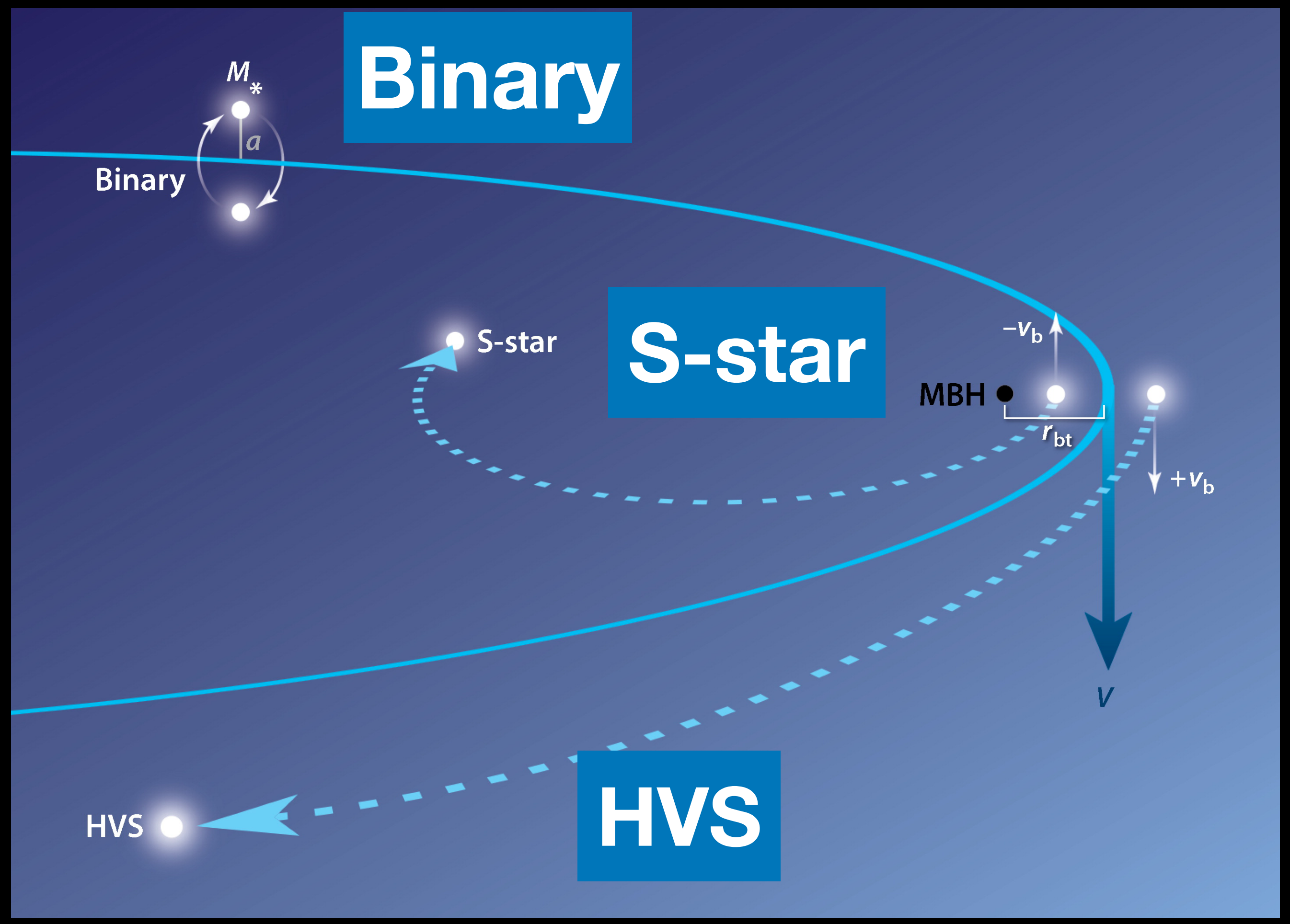
Merged stars (e.g. Stephan+ 2016, 2019, Ciurlo+ 2020, Nature)

Dynamical interactions and scattering (e.g. Levin 2007)

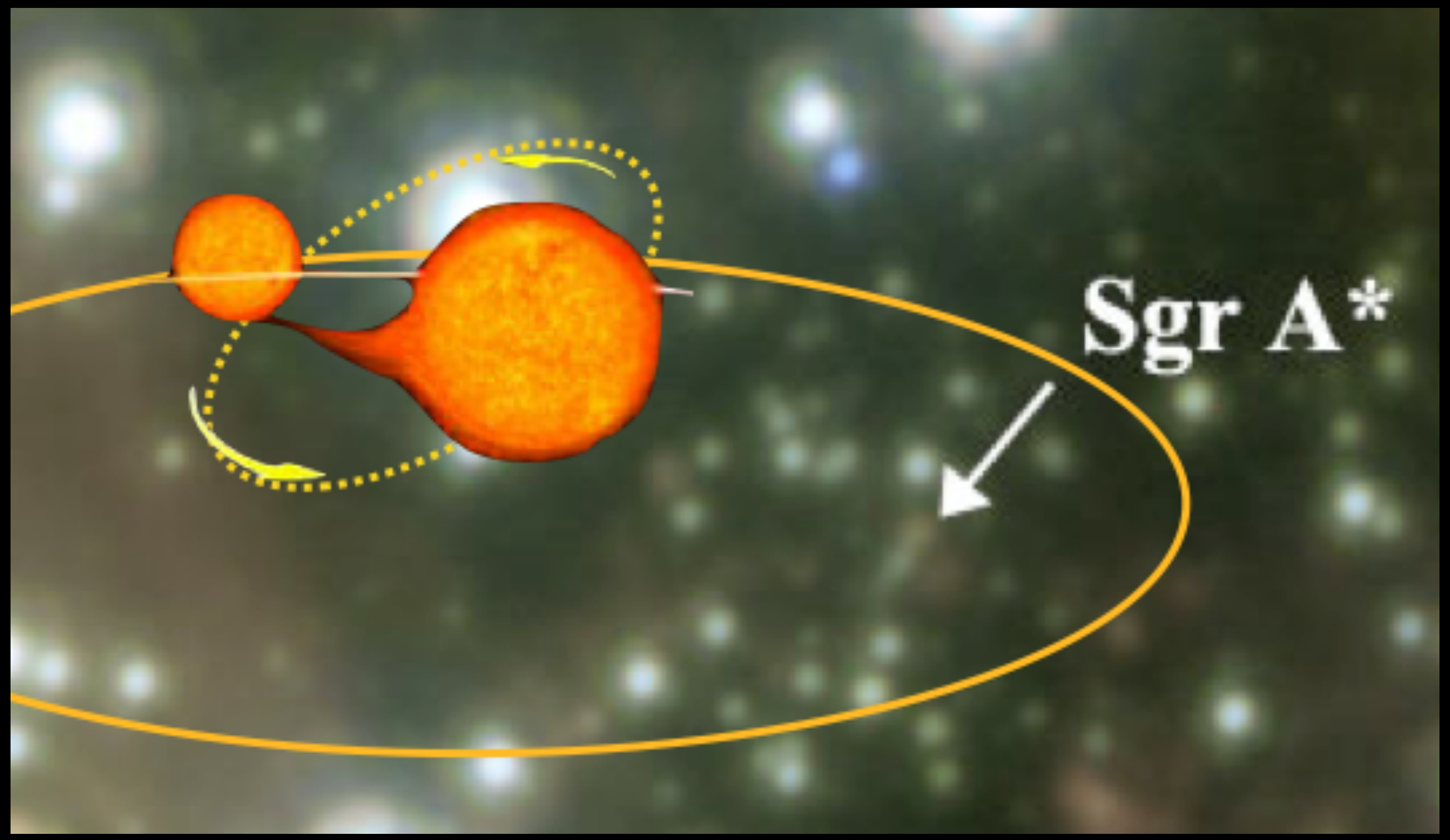
Devin S. Chu

UCLA GALACTIC CENTER GROUP

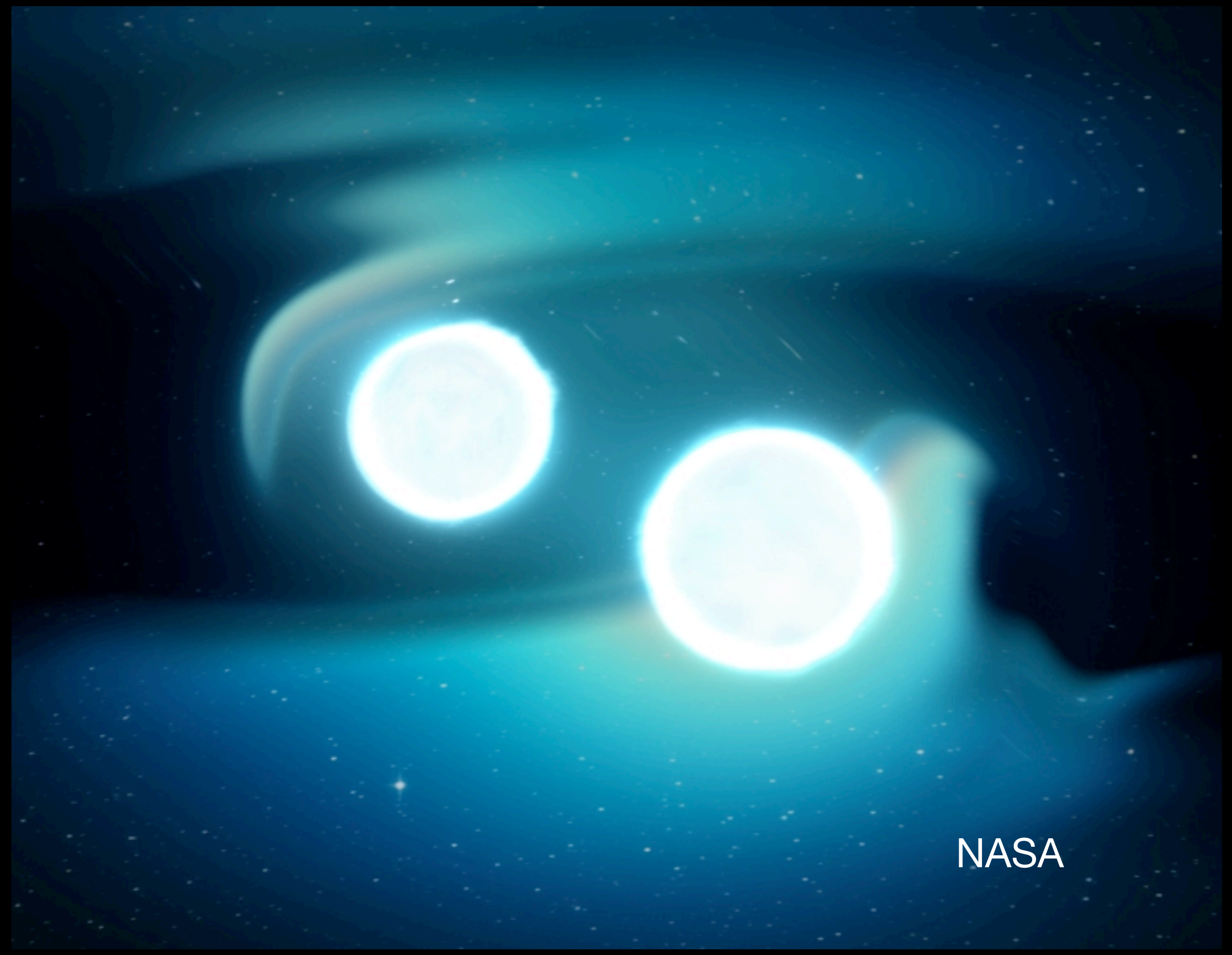
Observed binary fraction may attest to evolution mechanisms



Expected binary fraction: ~0%



Expected binary fraction: ~50% (Stephan+ 2016, using Sana+ 2012)



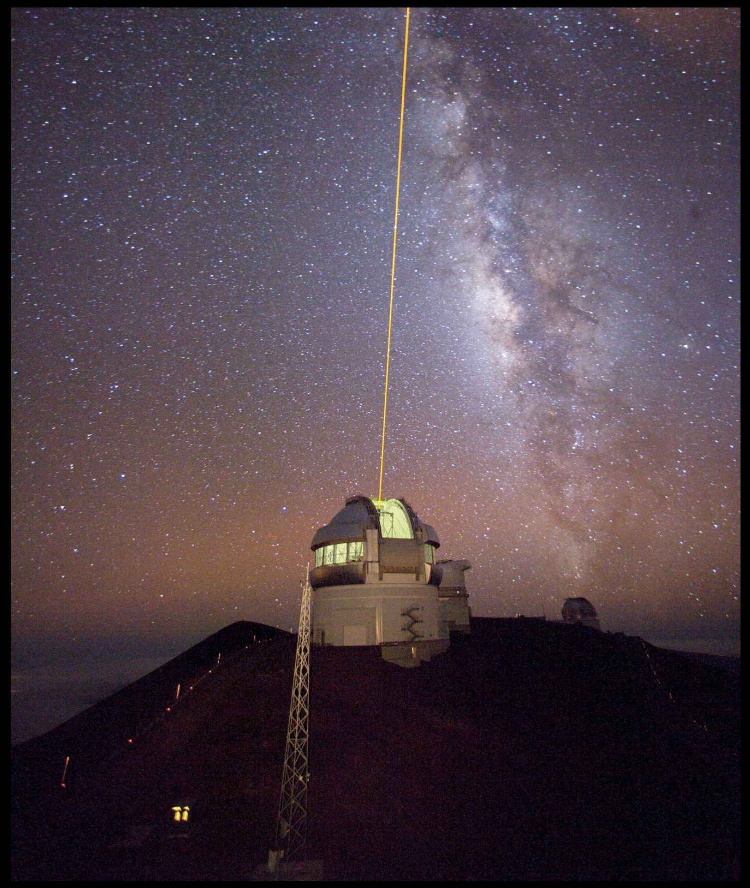
Expected binary fraction: ~70% (Sana+ 2012)

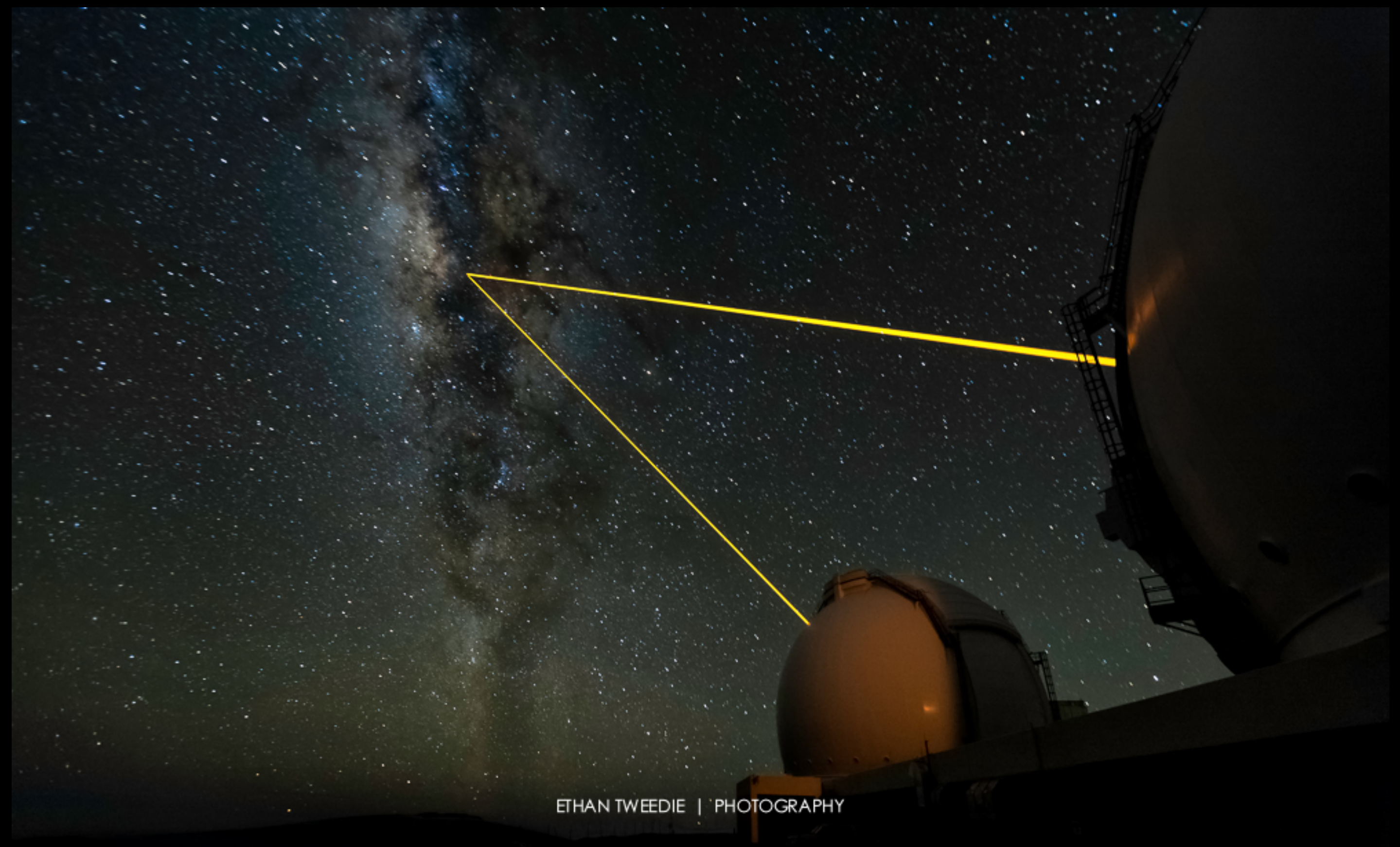
Devin S. Chu

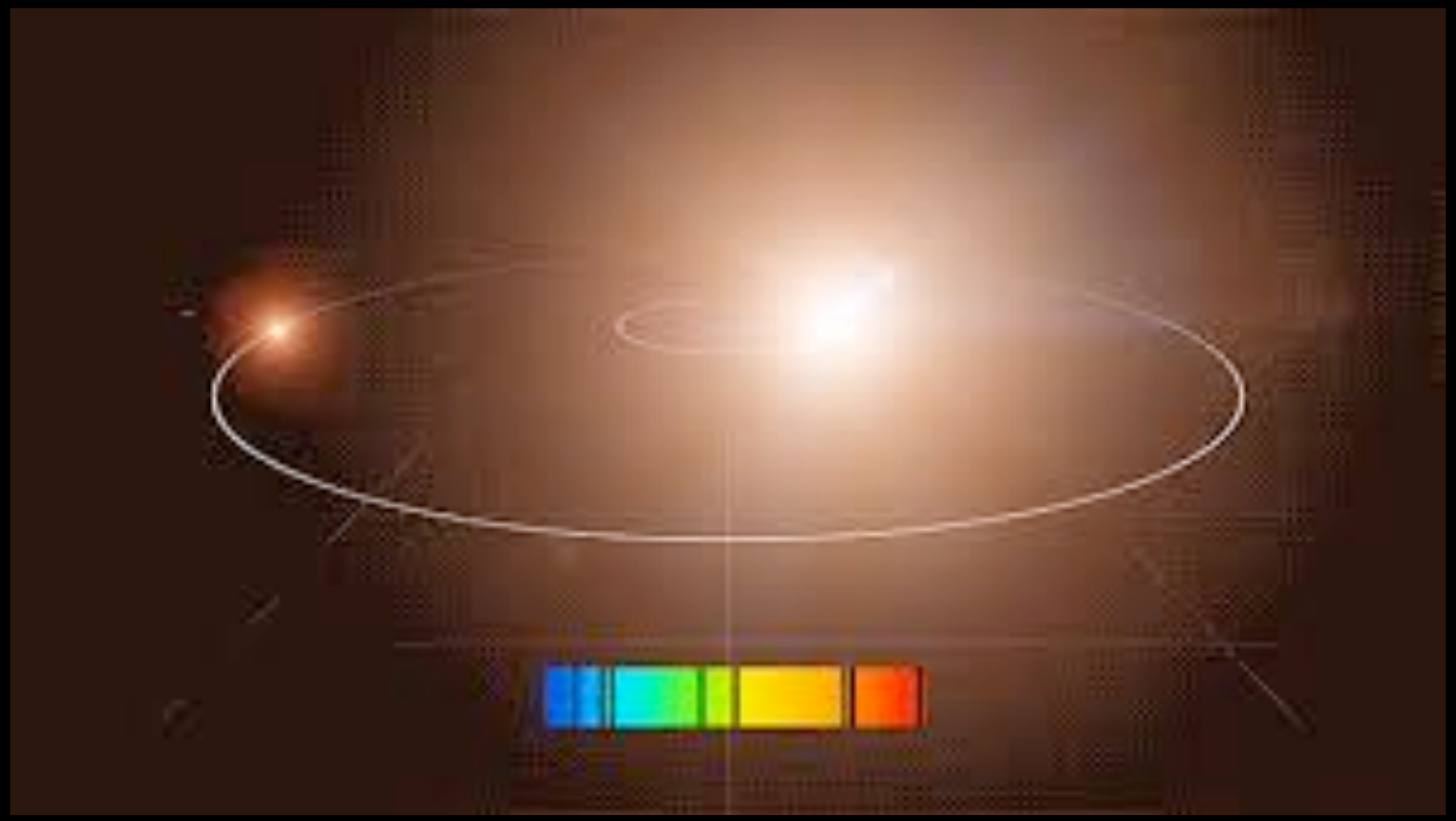
UCLA GALACTIC CENTER GROUP

Data is available to search for binaries using spectroscopy

- Over a decade (almost 50 full nights) of Keck OSIRIS and Gemini NIFS spectroscopy data are available to search for binaries
- Multiple epochs of data per year increase our sensitivity to spectroscopic binaries





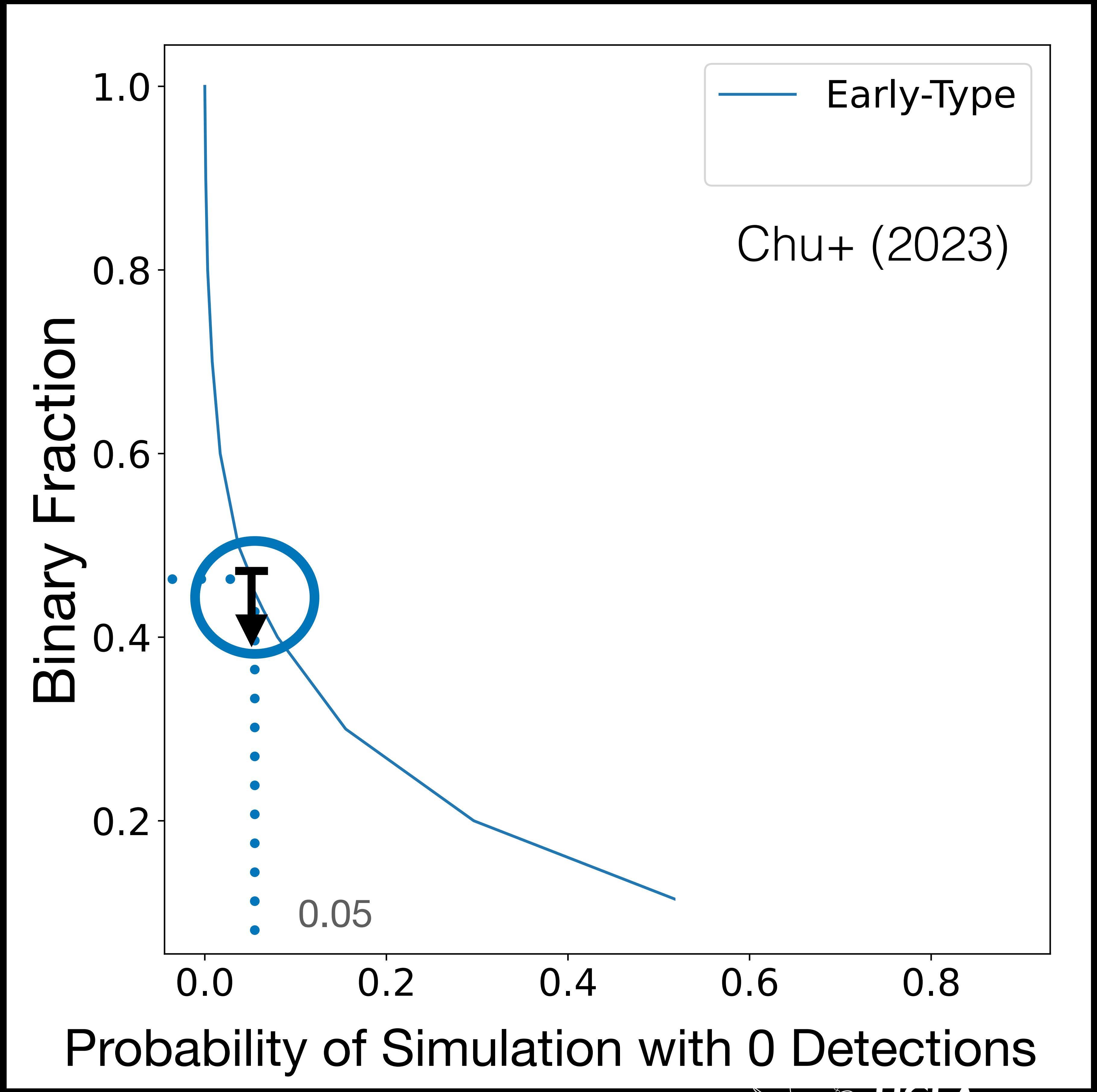


Devin S. Chu

UCLA GALACTIC CENTER GROUP

We detected no signs of binary stars in our sample and placed an upper limit on the S-star binary fraction

- 2σ (95% confidence) upper limit on binary fraction for young stars: 47%
- Full details published in Chu+ 2023

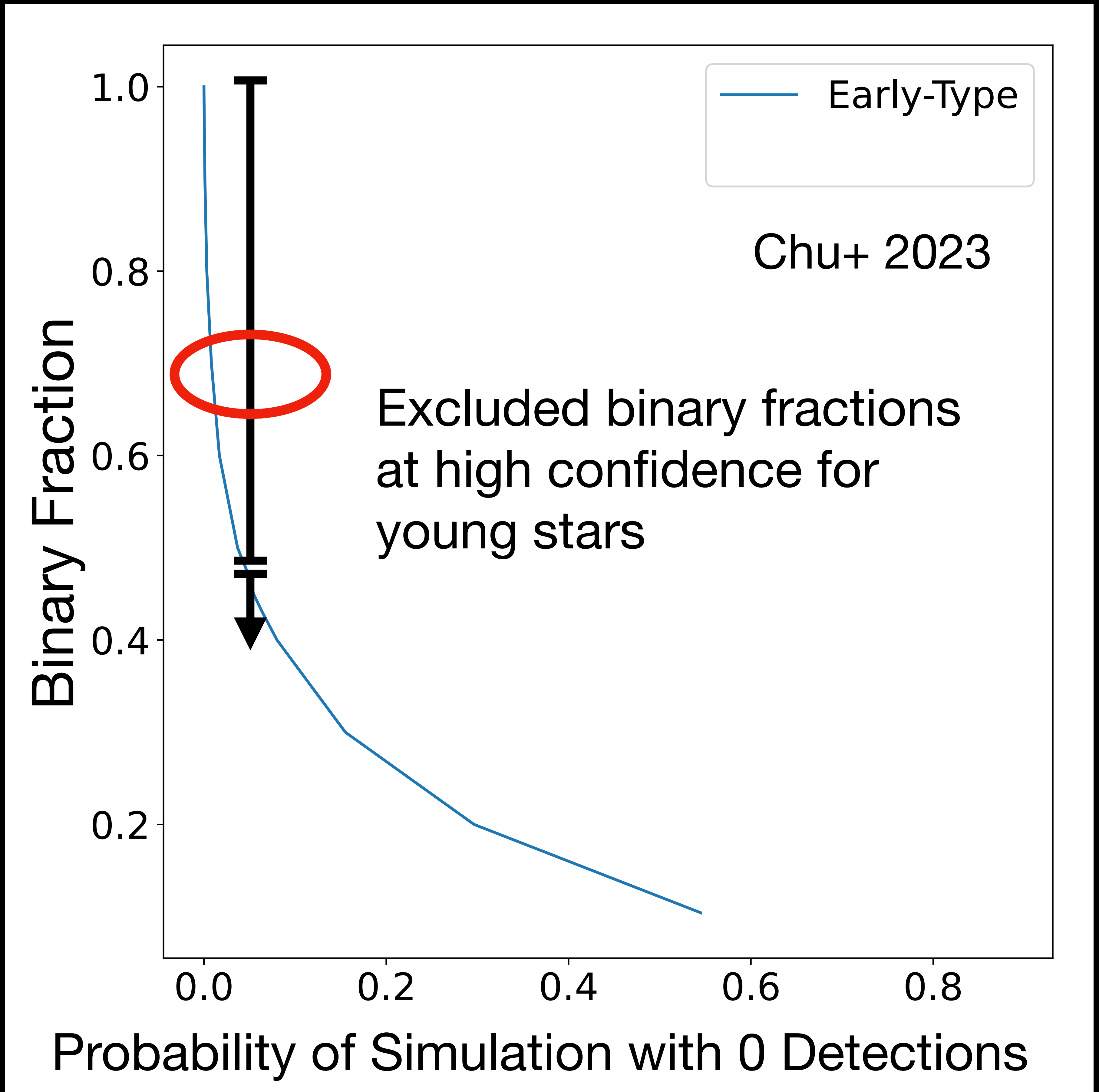


Devin S. Chu

UCLA GALACTIC CENTER GROUP

We can exclude solar neighborhood binary star binary fraction of 70% at high confidence

S-star binary fraction is ***inconsistent*** with massive stars binary fraction in solar neighborhood



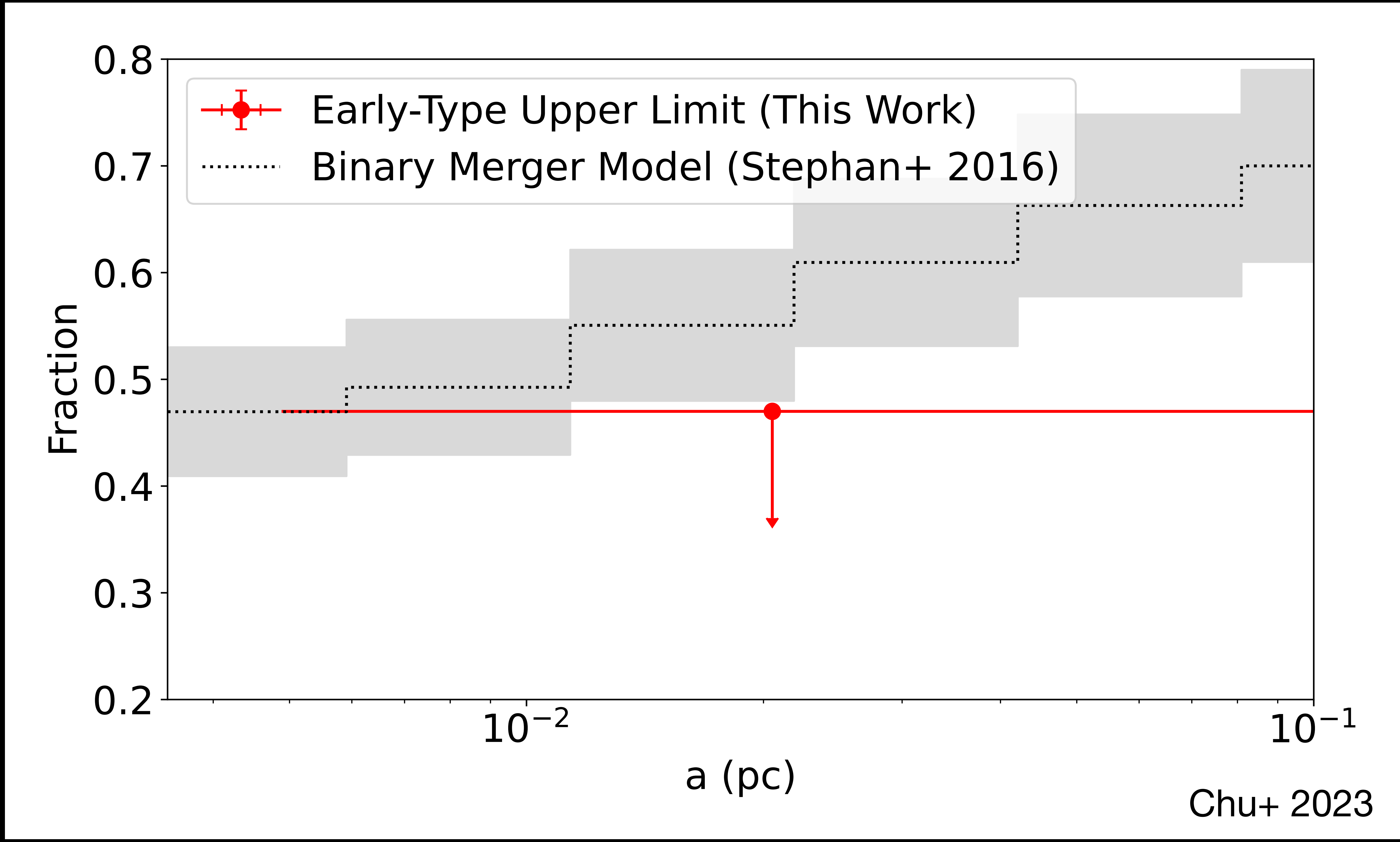
Devin S. Chu

UCLA GALACTIC CENTER GROUP

Binary fraction limit disfavors the dynamical interaction and scattering mechanism

- Expected binary fraction: ~70% (Sana+ 2012, Gautam+ submitted)
- We place an upper limit at 47%

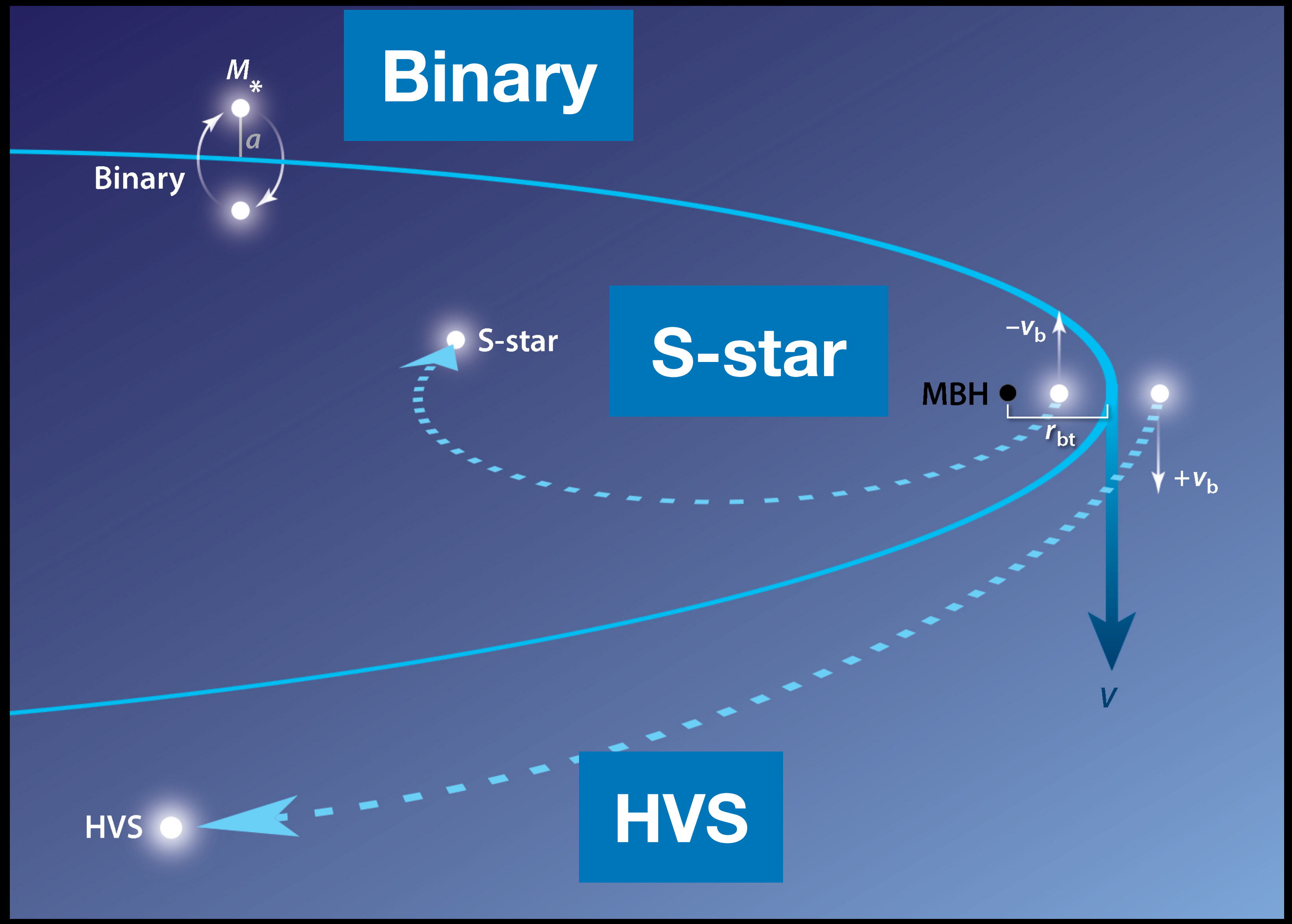
Binary fraction limit is consistent with binary merger model for stars closest to black hole



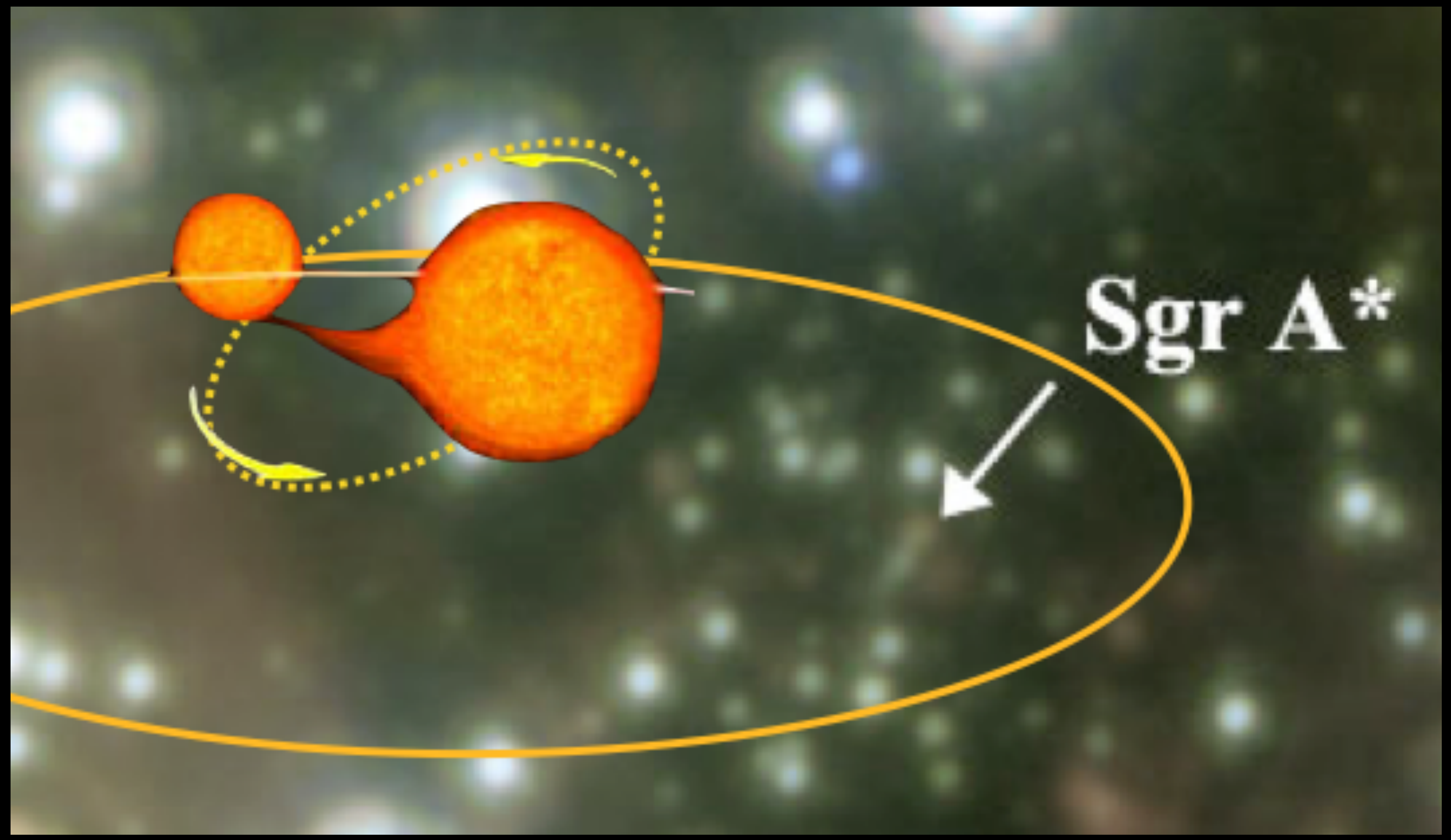
Devin S. Chu

UCLA GALACTIC CENTER GROUP

Binary fraction limits are consistent with binary capture & ejection, merger mechanisms



Expected binary fraction: ~0%

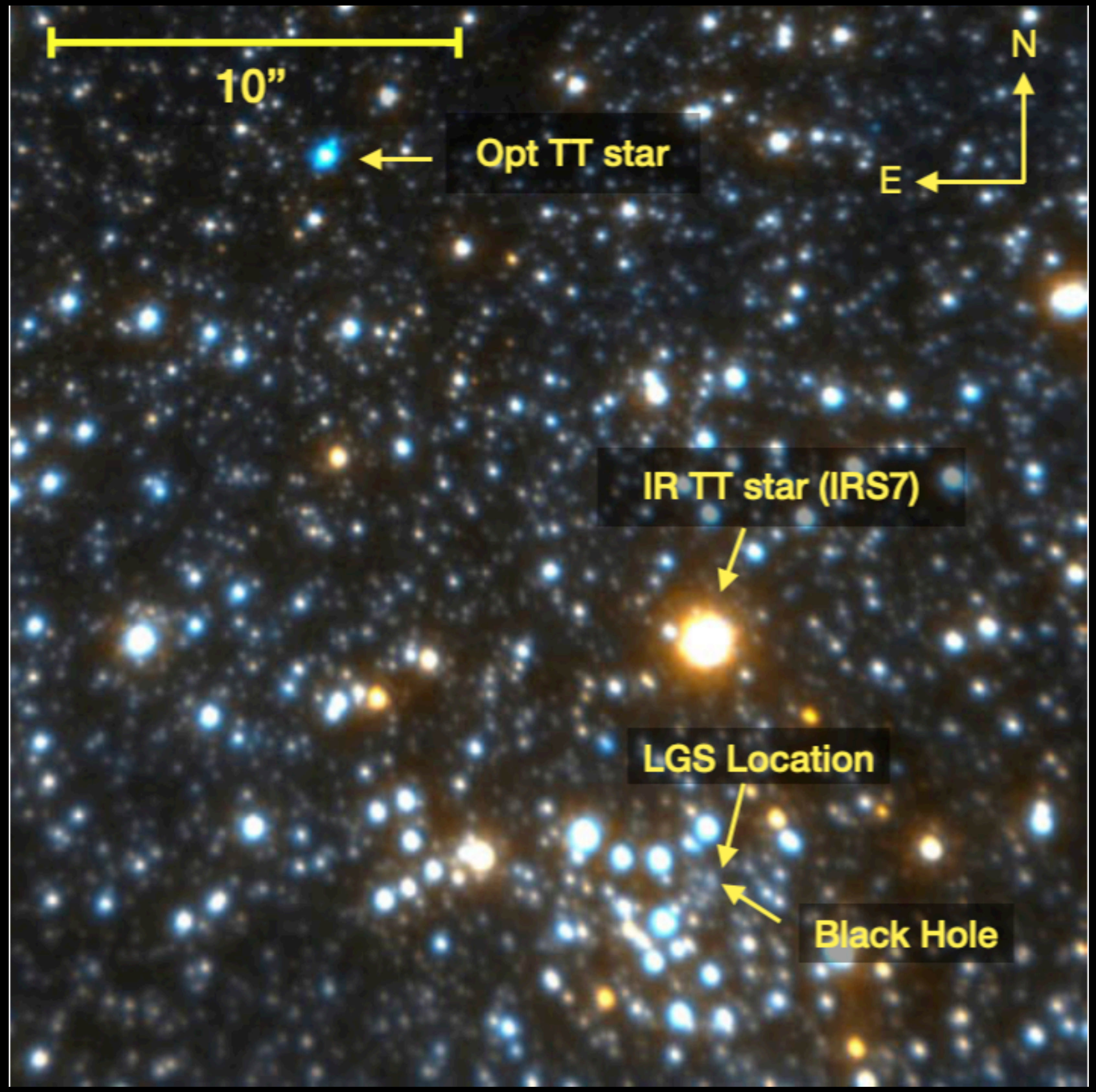


Expected binary fraction: ~50% (Stephan+ 2016, using Sana+ 2012)

Upgrades in adaptive optics will lead to further progress in Galactic Center science

Galactic Center is an ideal location for using an infrared-bright star for tip-tilt corrections

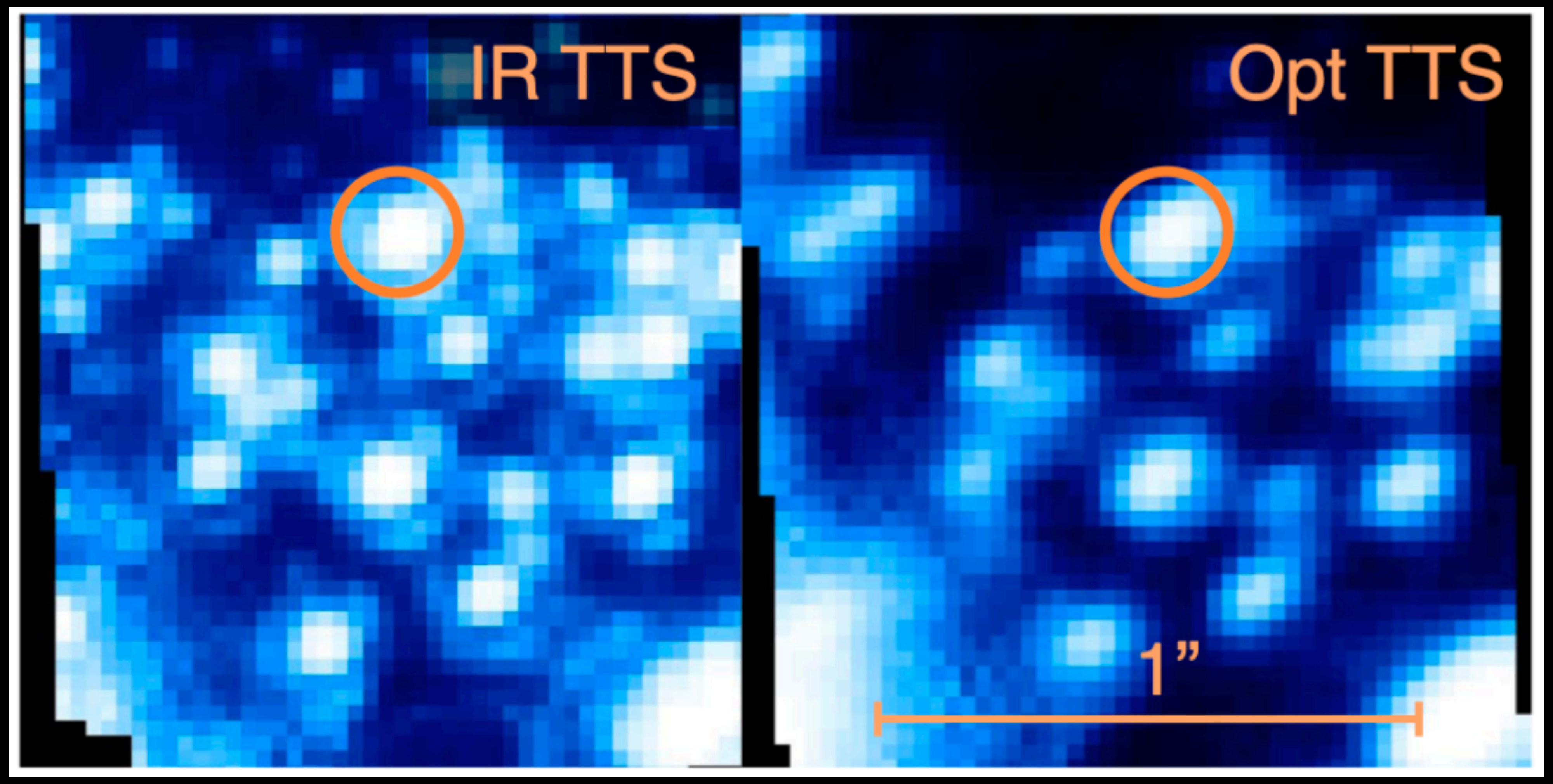
- Infrared-bright star is 8 arcseconds from black hole
- Optical tip-tilt star is 20 arcseconds away from black hole
- Closer star reduces tip-tilt error



Gemini Hokupa‘a/QUIRC AO. Chu+ 2022, SPIE

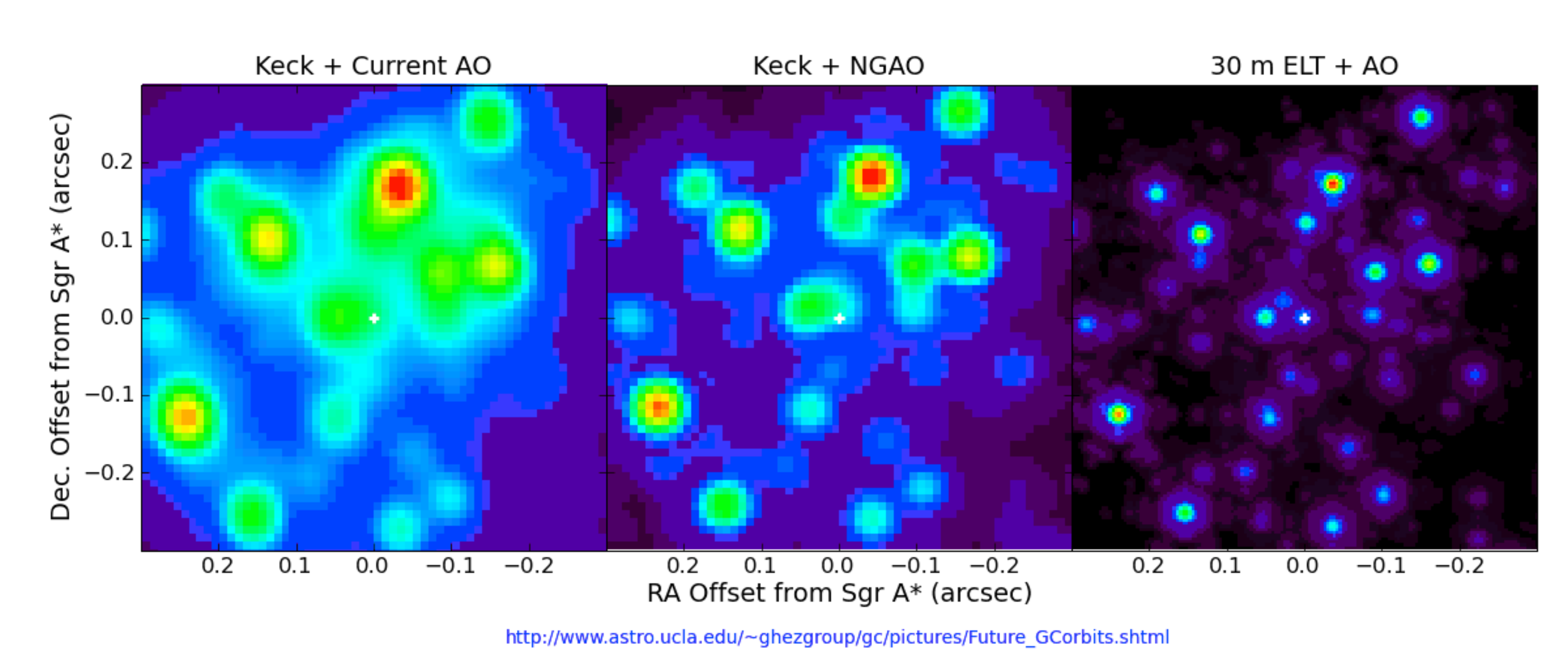
Infrared tip-tilt star and sensor improves AO correction and Galactic center data quality

- Imaging benefits: improved Strehl and FWHM
- Spectroscopy benefits: improved spectral signal and FWHM
- Science benefits include more precise data for stellar orbits, radial velocity variation, etc.
- Infrared tip-tilt sensing will be crucial for AO for ELTs
- See Chu+ 2022 SPIE proceeding, Ning+ in prep (including Chu)



Keck OSIRIS data cube. Chu+ 2022, SPIE

Instrumentation utilizing improved AO will improve sensitivity to fainter stars



Simulation by Tuan Do

Conclusions

- Milky Way Galactic Center is an ideal laboratory to test fundamental physics and astrophysics in an extreme dynamical environment near a supermassive black hole
- Infrared wavelengths and adaptive optics are crucial for studying Galactic Center due to dust extinction and crowding
- Chu+ 2023 reports upper limit binary fraction of young stars closest to supermassive black hole is inconsistent with field star binary fraction
- Upgrades to adaptive optics will lead to further improvements in Galactic Center science

Mahalo nui loa!
Thank you very much!

Devin S. Chu, PhD
dchu@astro.ucla.edu

Jason Chu Photography