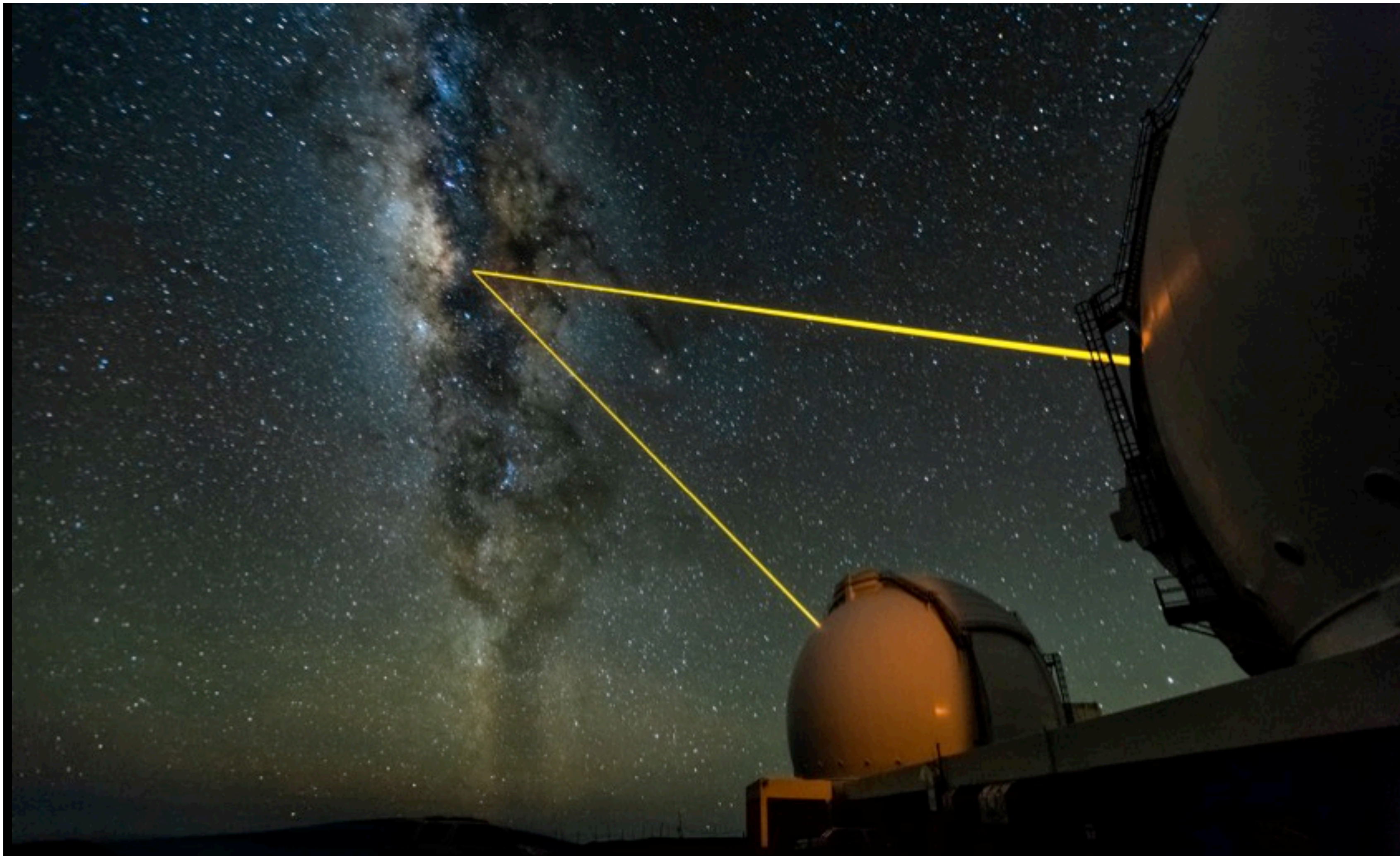
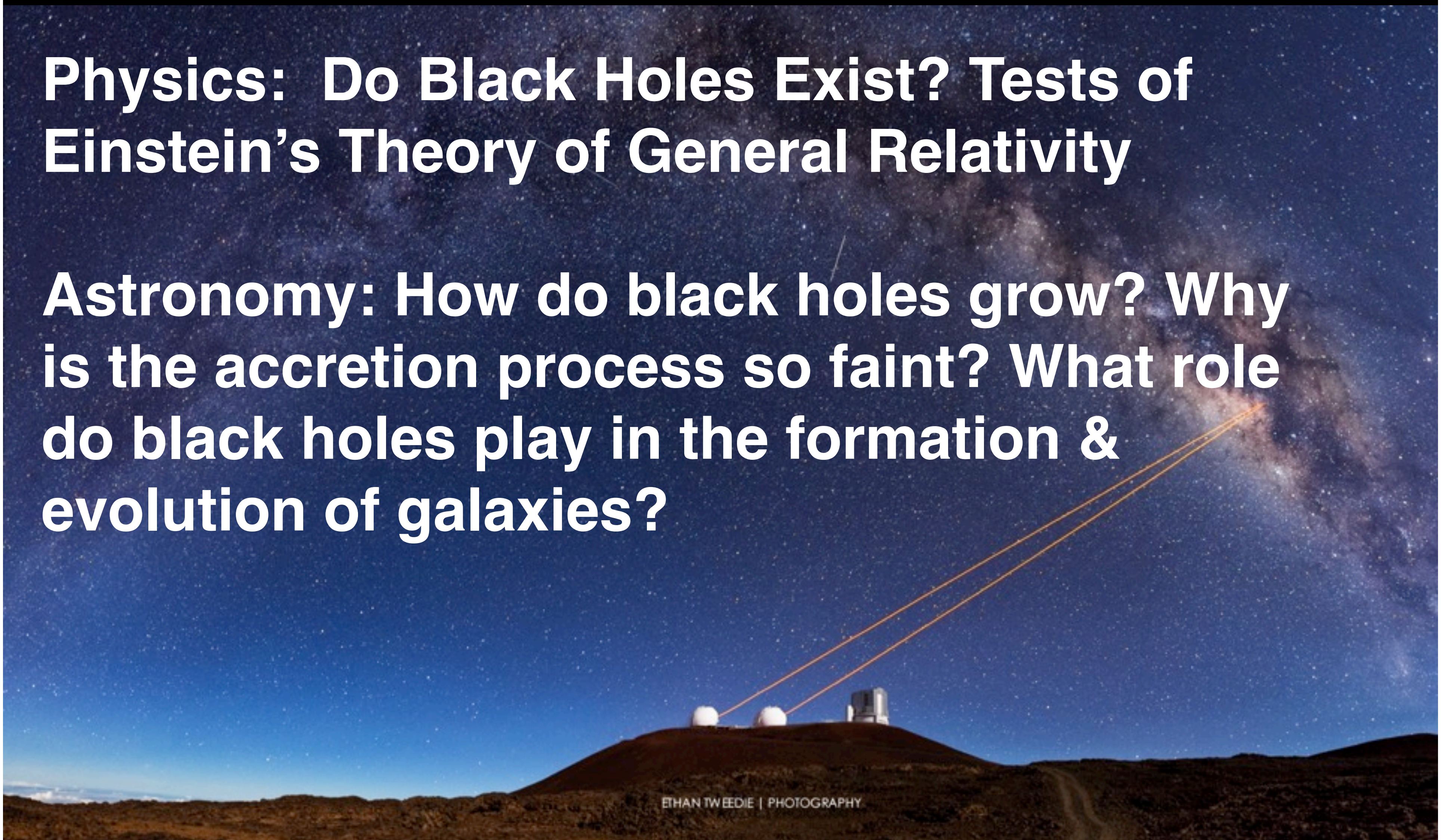
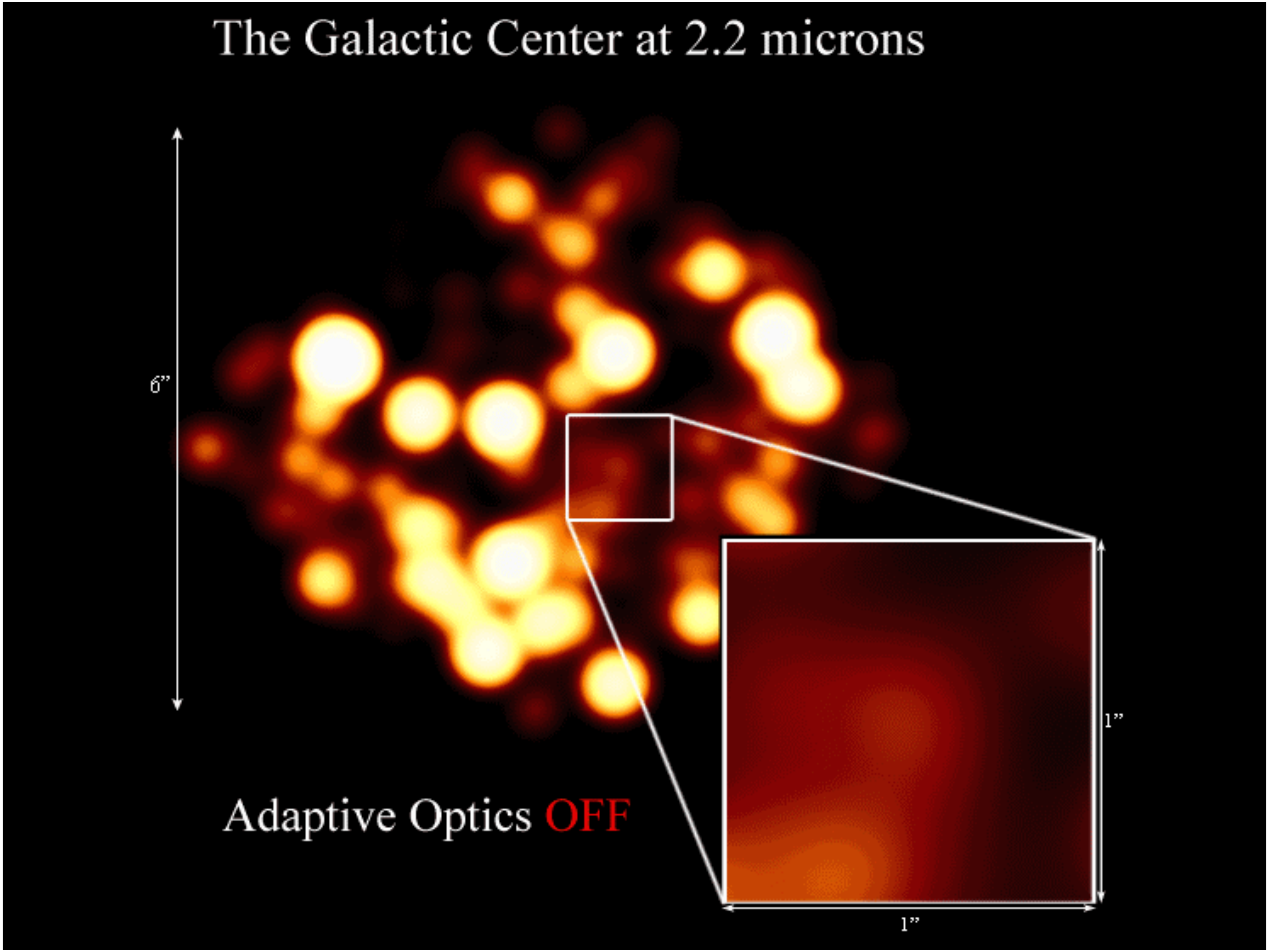


Galactic Center

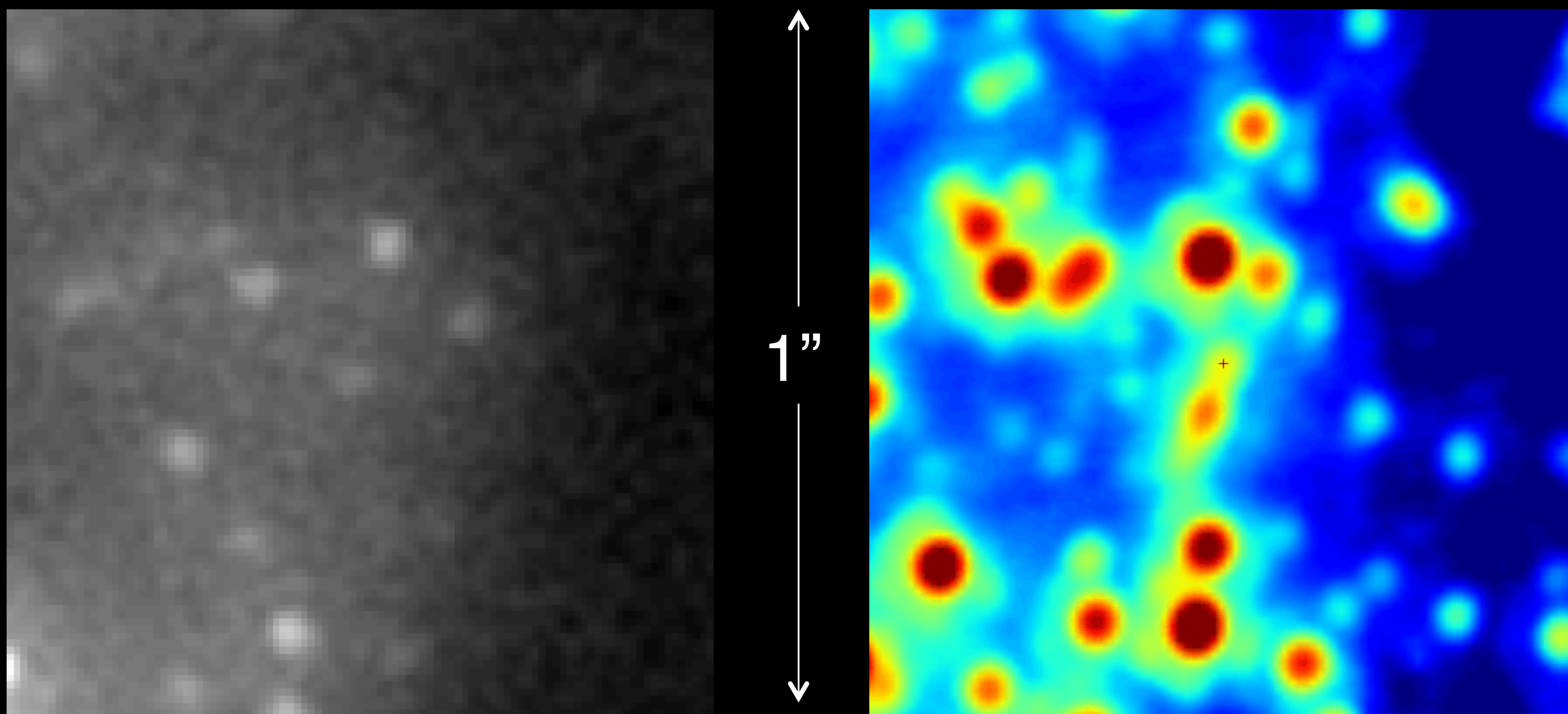
Andrea Ghez (UCLA/Keck Galactic Center Group)
Mark Morris, Eric Becklin, Tuan Do, Jessica Lu, Mike Fitzgerald, James Larkin, Keith Matthews, Peter Wizinowich, Anna Boehle, Randy Campbell, Sam Chappell, Devin Chu, Leo Meyer, Smadar Naoz, Breann Sitarski, Gunther Witzel, Sylvana Yelda,

Photo credit: Ethan Tweedie


Physics: Do Black Holes Exist? Tests of Einstein's Theory of General Relativity
Astronomy: How do black holes grow? Why is the accretion process so faint? What role do black holes play in the formation & evolution of galaxies?
ETHAN TWEEDIE | PHOTOGRAPHY


The Galactic Center at 2.2 microns
6”
Adaptive Optics OFF
1”
1”

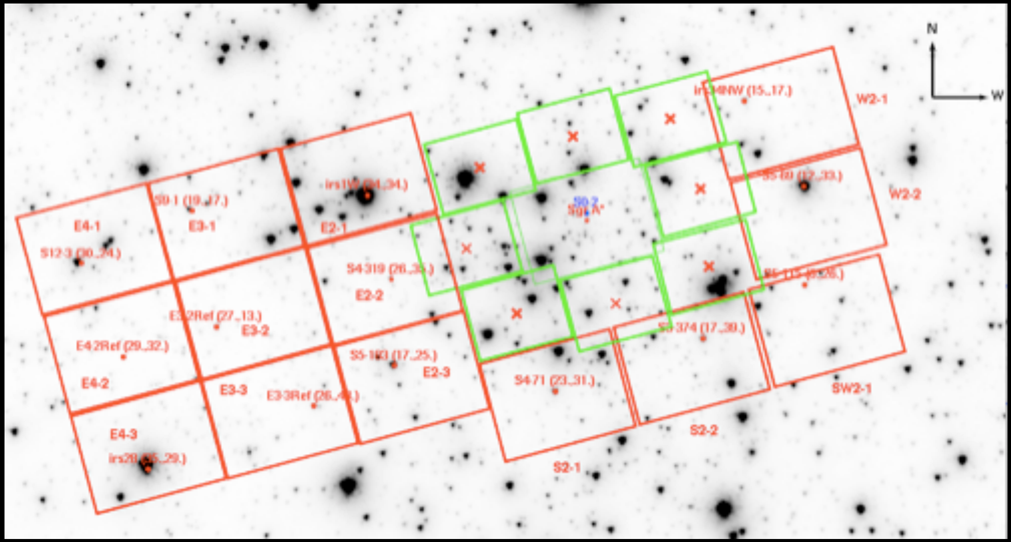
Improved Technology Increased the Quality of Images

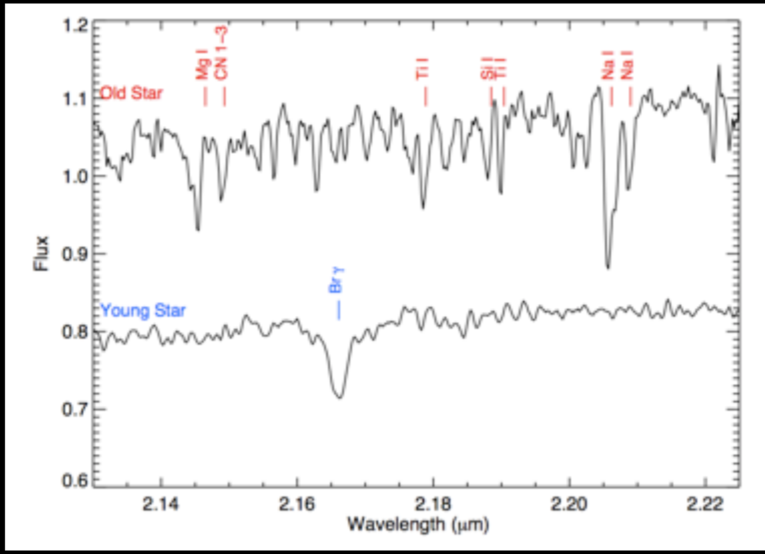


Speckle Imaging
1995 – 2004

Adaptive Optics
2005 – today

Improved Technology Introduced Spectroscopy





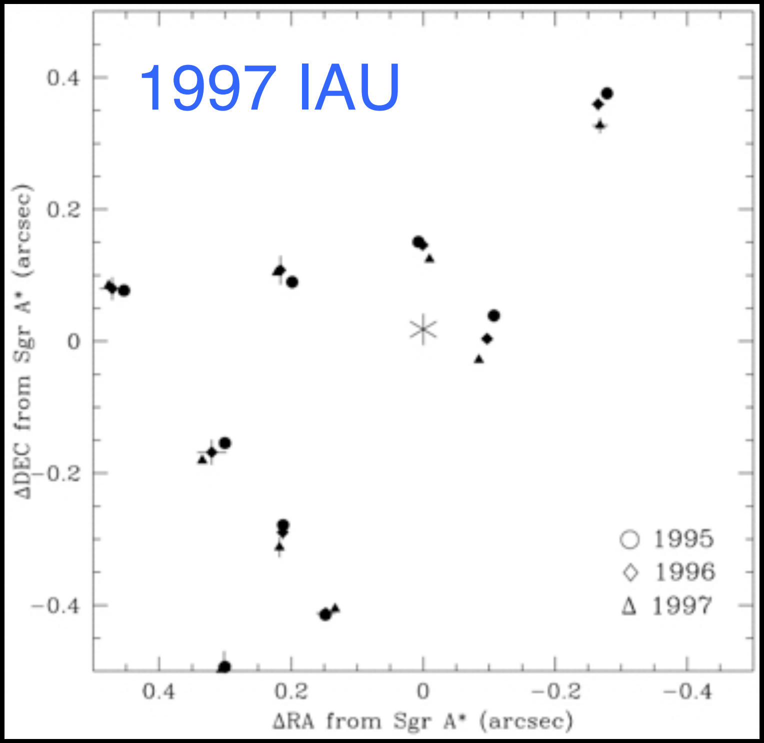
Physics

– Measures missing third dimension of motion

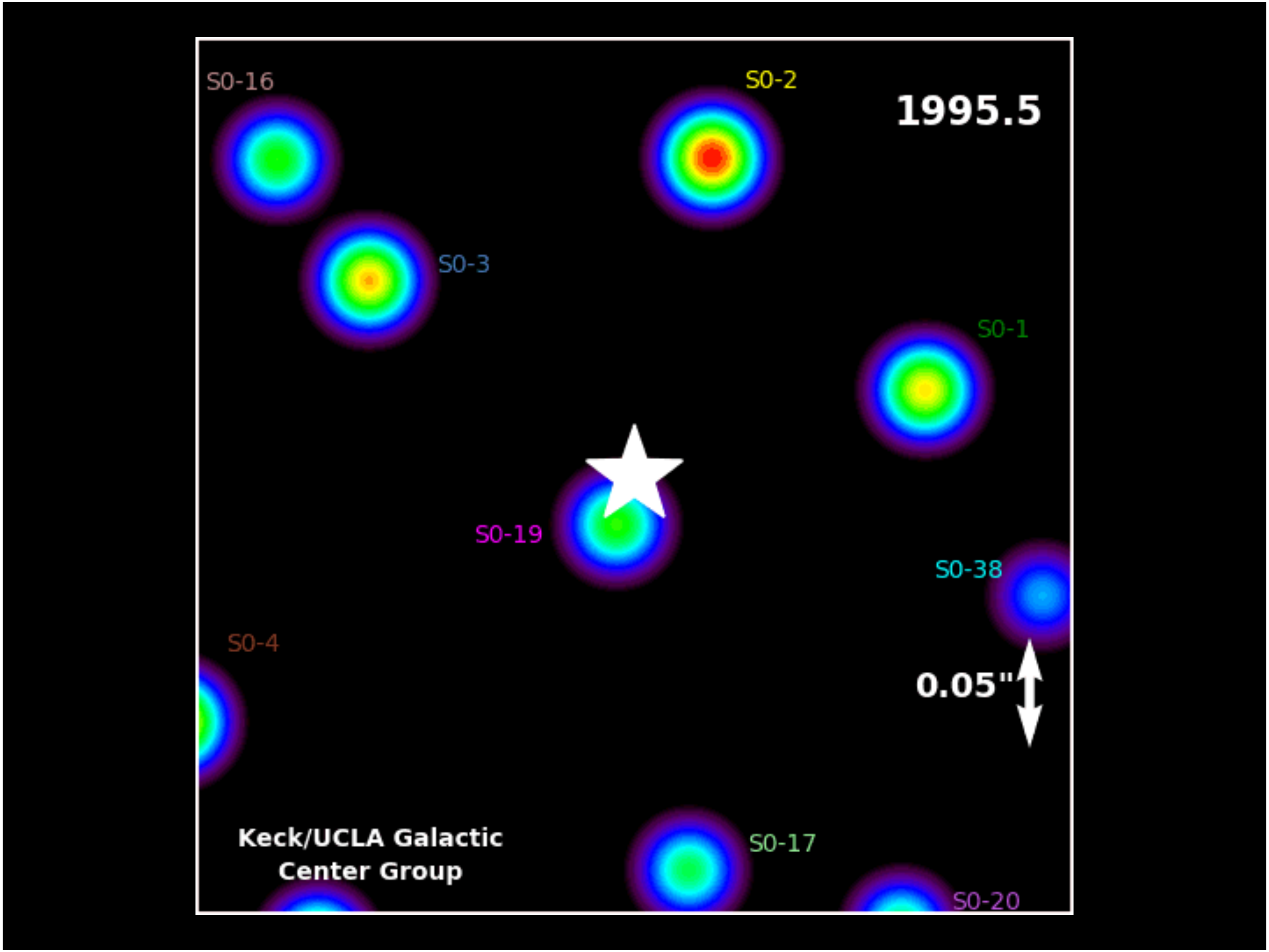
Astronomy

– Astrophysical nature of sources

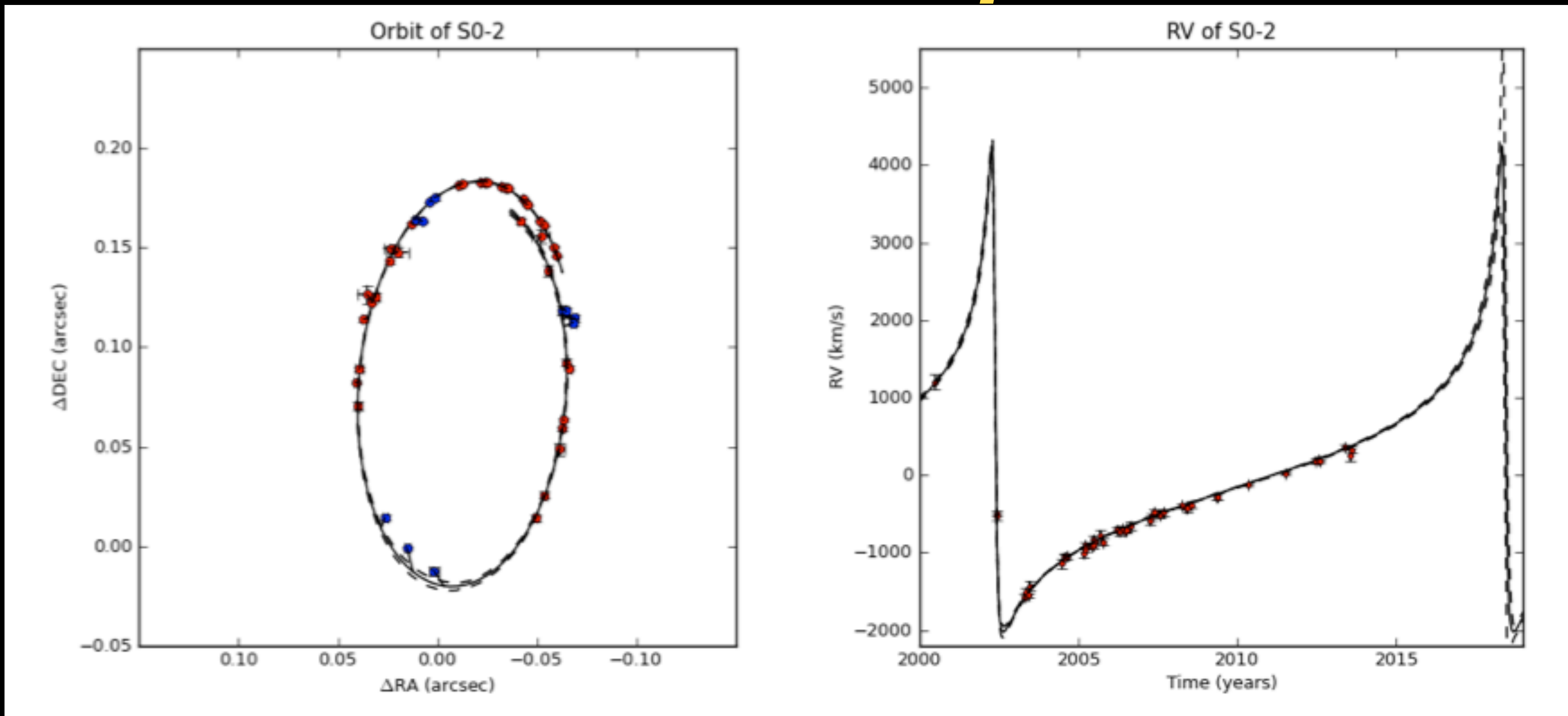
– Reveals many surprises!!



PROBING THE CENTRAL POTENTIAL WITH STELLAR ORBITS


S0-16
S0-2
1995.5
S0-3
S0-1
S0-19
S0-38
S0-4
0.05"
Keck/UCLA Galactic
Center Group
S0-17
S0-20

Today S0-2 Offers Strongest Case for Existence of Black holes & MW Black Hole Properties



$\rho = 6.3 \pm 0.8 \times 10^{15}\ M_o/pc^3$

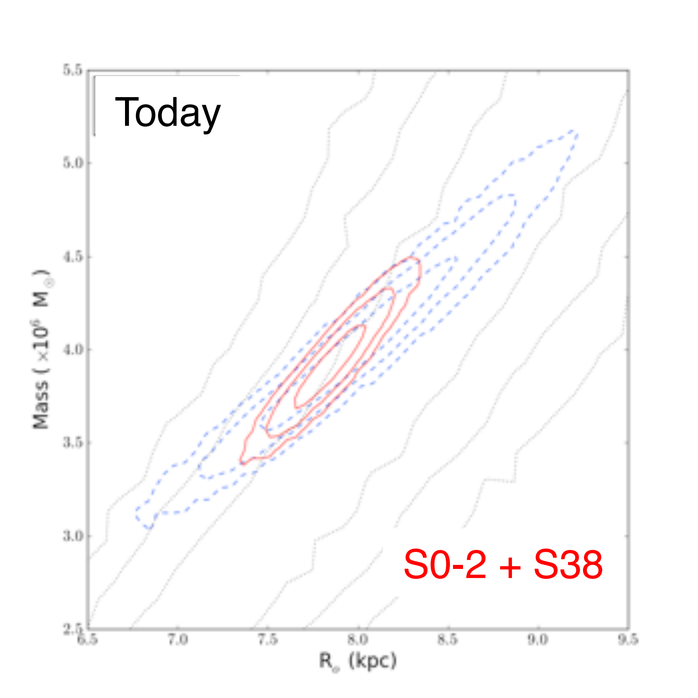
10,000,000x greater than previously known at GC

10,000x larger than in any other galaxy today

Black Holes Exist!

Eisenhauer et al. 2003, 2005; Ghez et al. 2003, 2005, 2008; Gillessen et al. 2009a,b; Yelda 2012; Meyer et al. 20012; Boehle et al. 2015

More Precision in Black Hole Properties from Stellar Orbits is Possible & Necessary

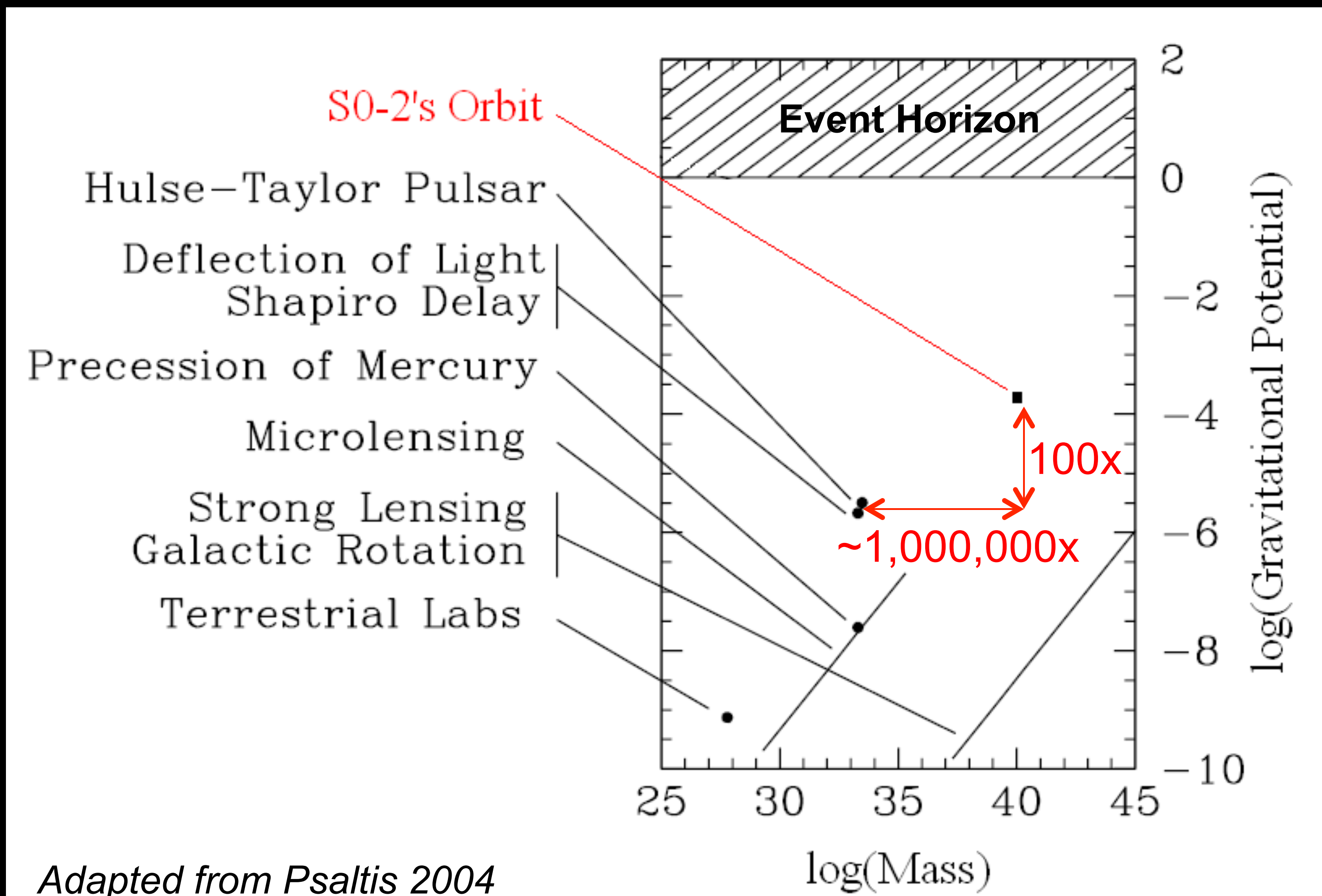


- Today's Values
  - M_{bh} = 3.9 ± 0.1 x10^6 M_o
  - R_o = 7.8 ± 0.1 kpc

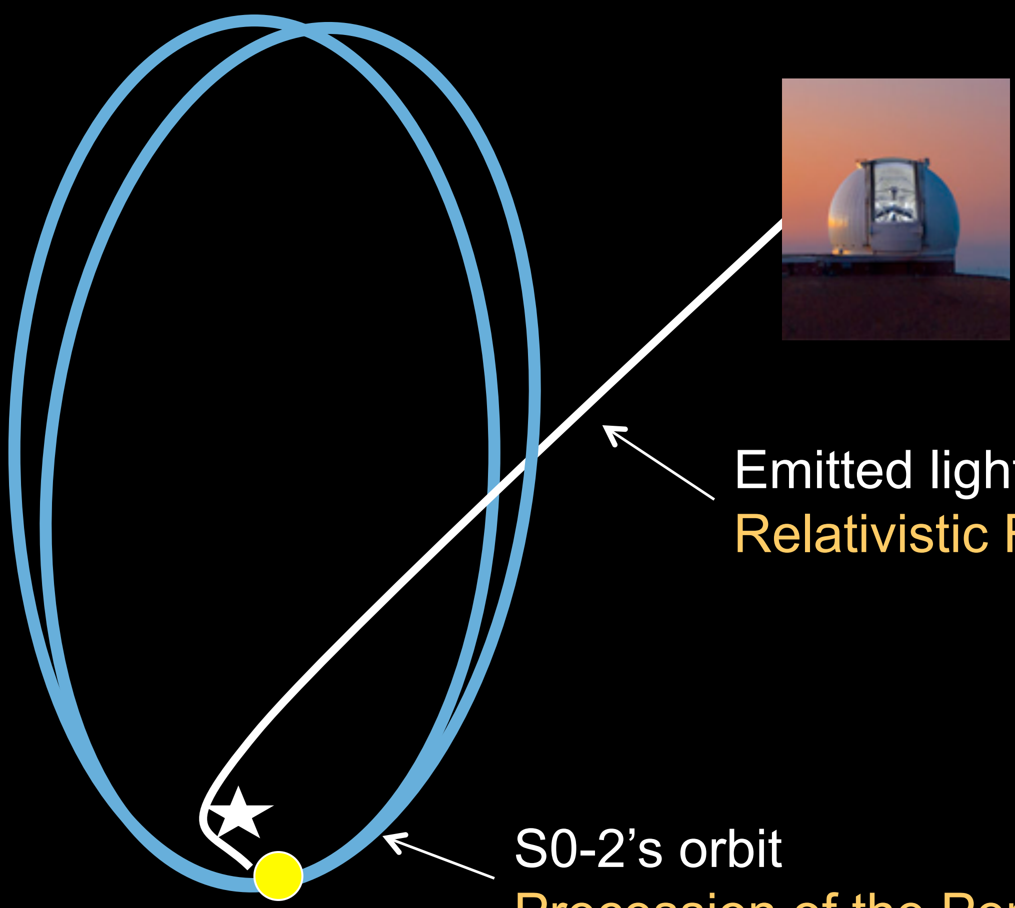
- Event Horizon Telescope depends on M/R_o from stellar orbits to be measured the <4%

- R_o is key parameter for structure of dark matter within our Galaxy

Orbits Offer an Opportunity to Test General Relativity in an Unexplored Regime

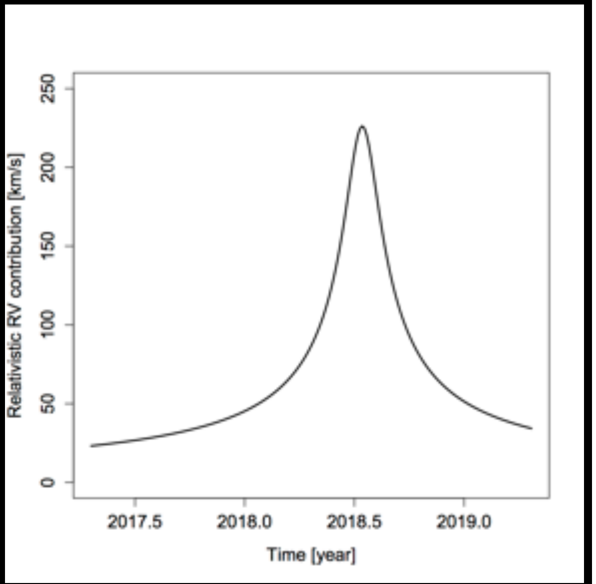


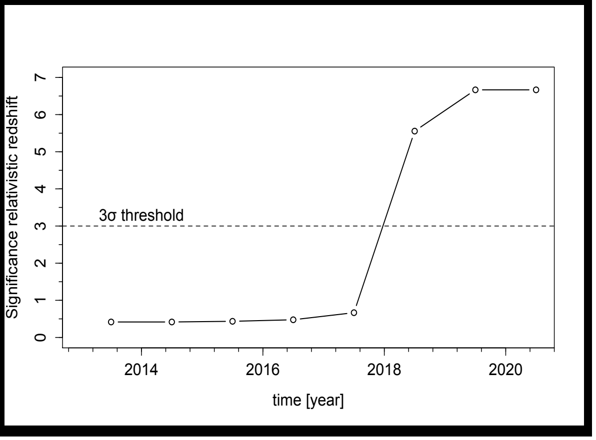
First of Many Tests of GR Possible in 2018



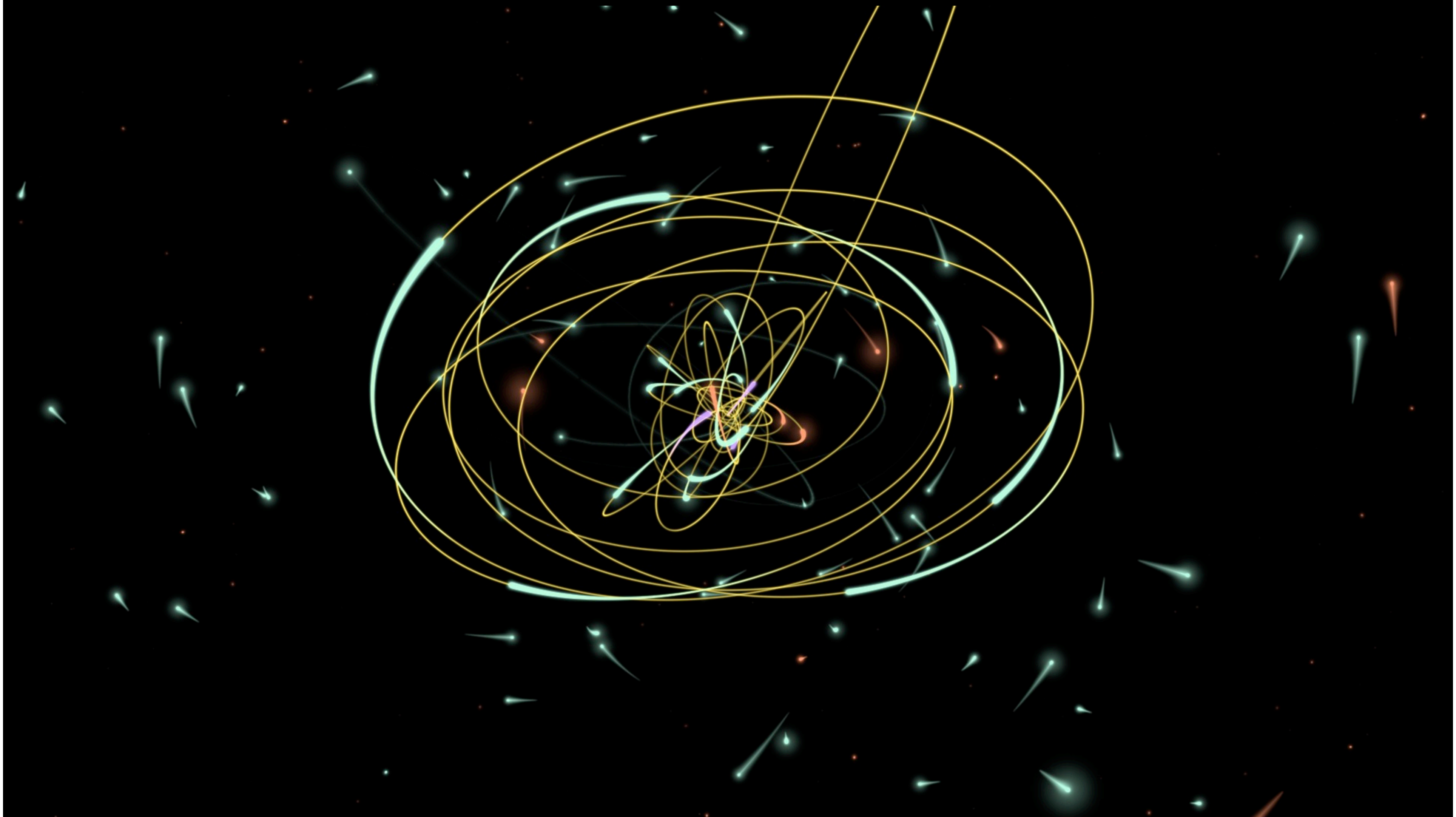
Emitted light ray
Relativistic Redshift

S0-2's orbit
Precession of the Periapse





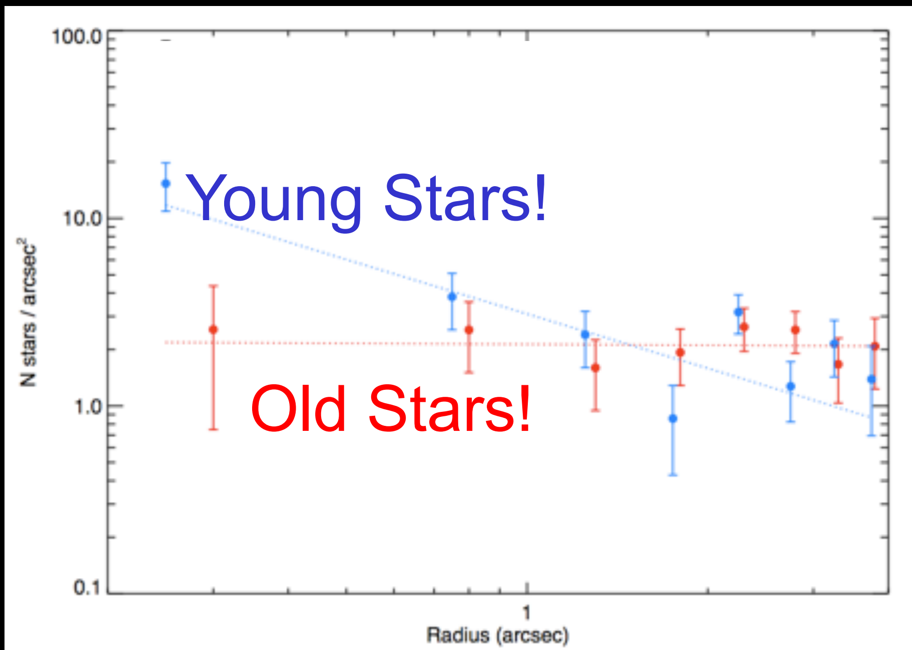
PROBING THE BLACK HOLE ENVIRONS



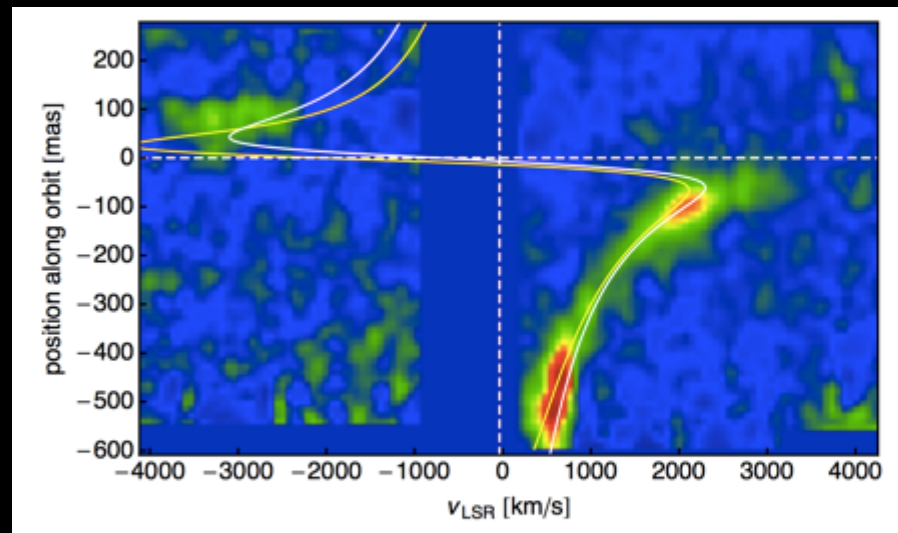
http://www.galacticcenter.astro.ucla.edu/animations.html

The Galactic Center host the only central black hole that can be studied with stellar orbits!

Many Unexpected Results



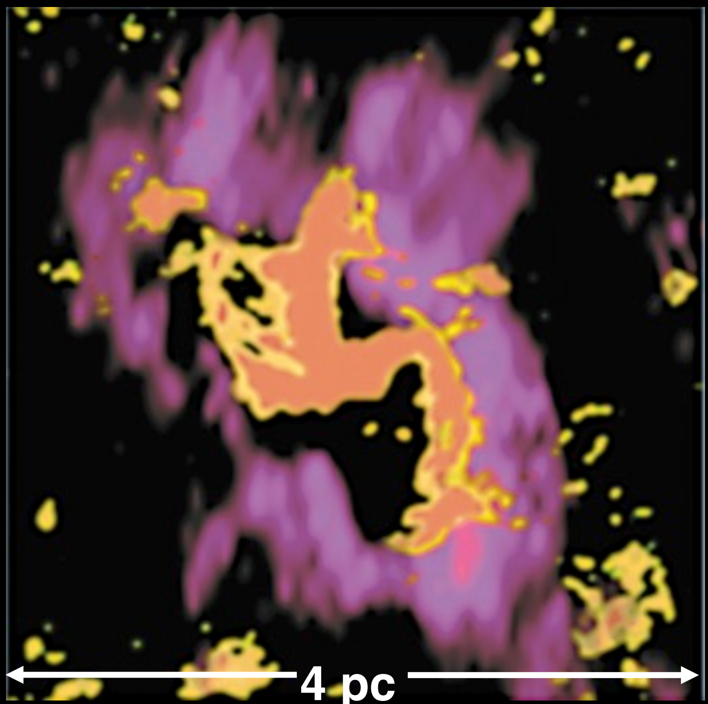
Do et al. 2009, 2013; Shoedel et al. (2009); Bartko et al. 2010; Gezari et al. 2002; Ghez et al. 2003; Eisenhauer et al. 2005



Gillessen et al. 2012, 2013ab; Phifer et al. 2013; Pfuhl et al. 2014; Witzel et al. 2014

- Lots of young stars where none expected
- A dearth of giant stars in lieu of a cusp
- G2! A tidally interacting object at ~2000 R_s

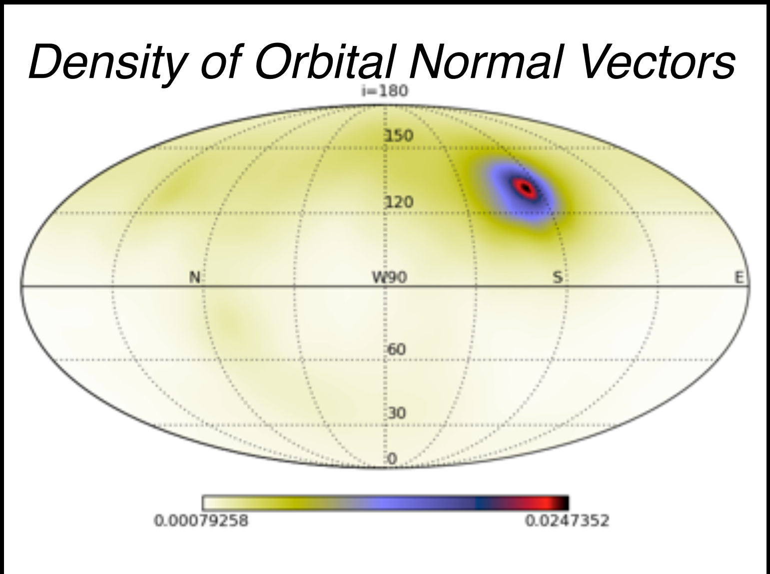
Unexpected Result #1: Young Stars Present a Paradox of Youth

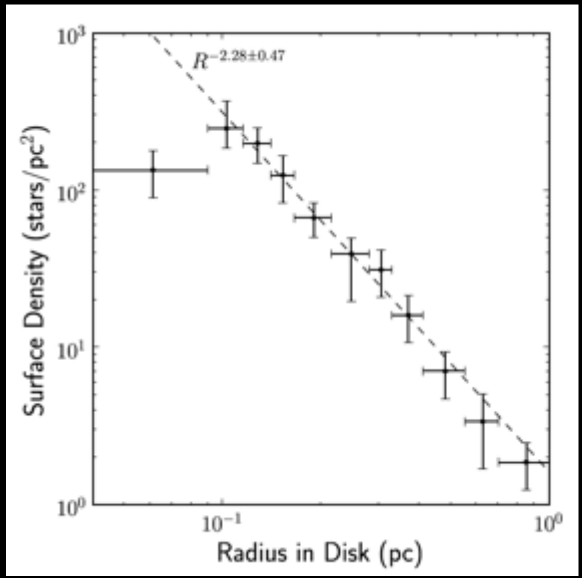


Yusef-Zadeh, Melia, & Wandle (2000; orange)
Wright et al. (1993; purple)

- **Observed local gas densities are insufficient for self-gravity to overcome tidal forces**
  - Required Densities
    - $\rho > 1\text{x}10^{11}\ (M_{bh}/\ 10^6\ M_o)\ (1''/R)^3\ \text{cm}^{-3}$
  - Observed Locally ($r < 10'' = 0.4$ pc)
    - $\rho < 10^3\ \text{cm}^{-3}$

Stellar Dynamics Point to in-situ Formation in a Pre-existing Disk r >1"



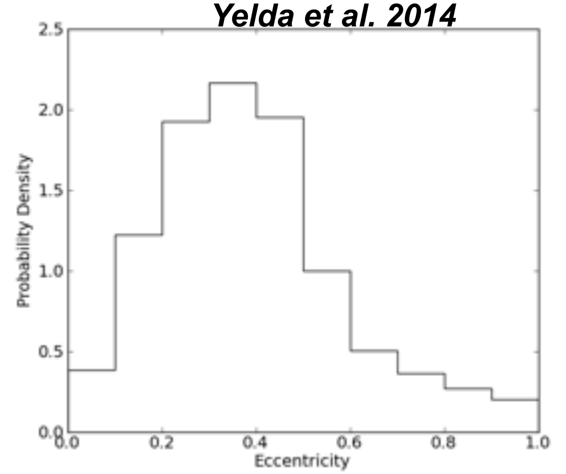


Individual stellar orbits provide direct evidence for a *single*, nearly edge-on stellar disk with

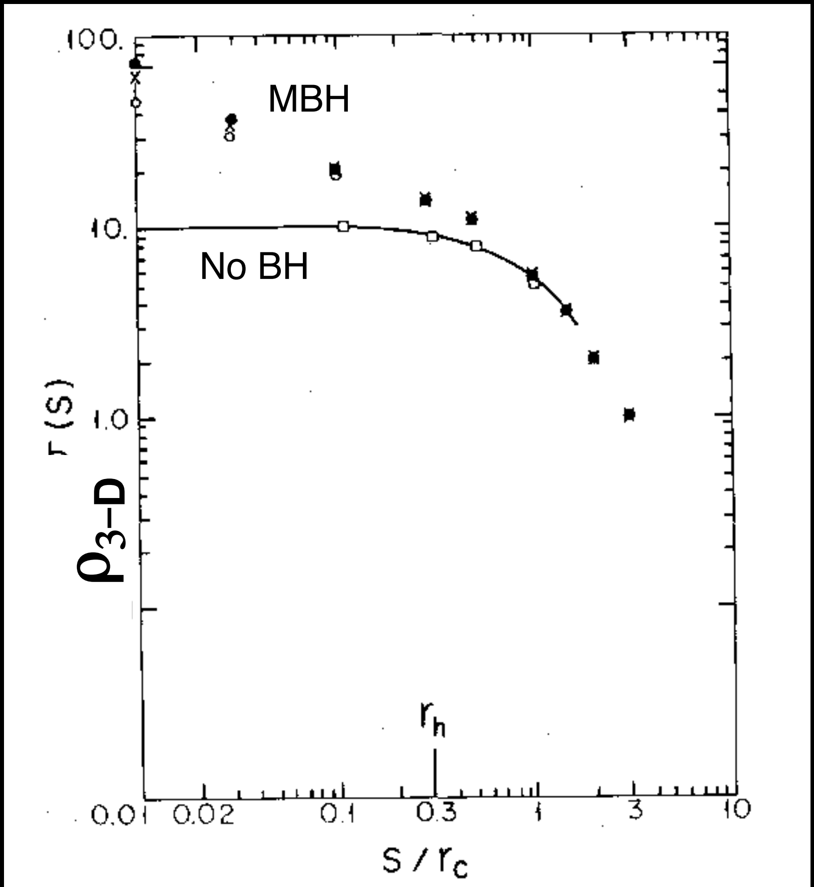
- r^{-2} surface density (inner cut-off at 1")
- 20% young star population (remnant disk!)
- Disk fraction appears independent of mass
- <e> = 0.3

Levin & Beloborodov 2003, Genzel et al. 2003, Paumard et al. 2006, Lu et al. 2008; Bartko et al. 2009; Yelda 2012; Yelda et al. 2014

Yelda et al. 2014



Unexpected Result #2: Dearth of Old Stars



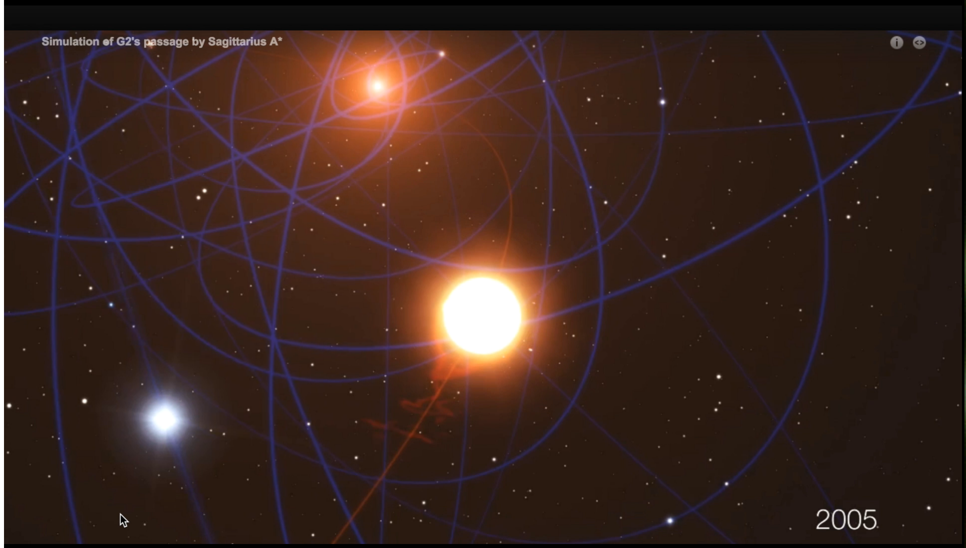
- Black holes predicted to alter stellar structure and generate a "cusp" of stars
- Key prediction for
  - understanding evolution of galactic nuclei (e.g., black hole merger rates
  - finding black holes in other galaxies

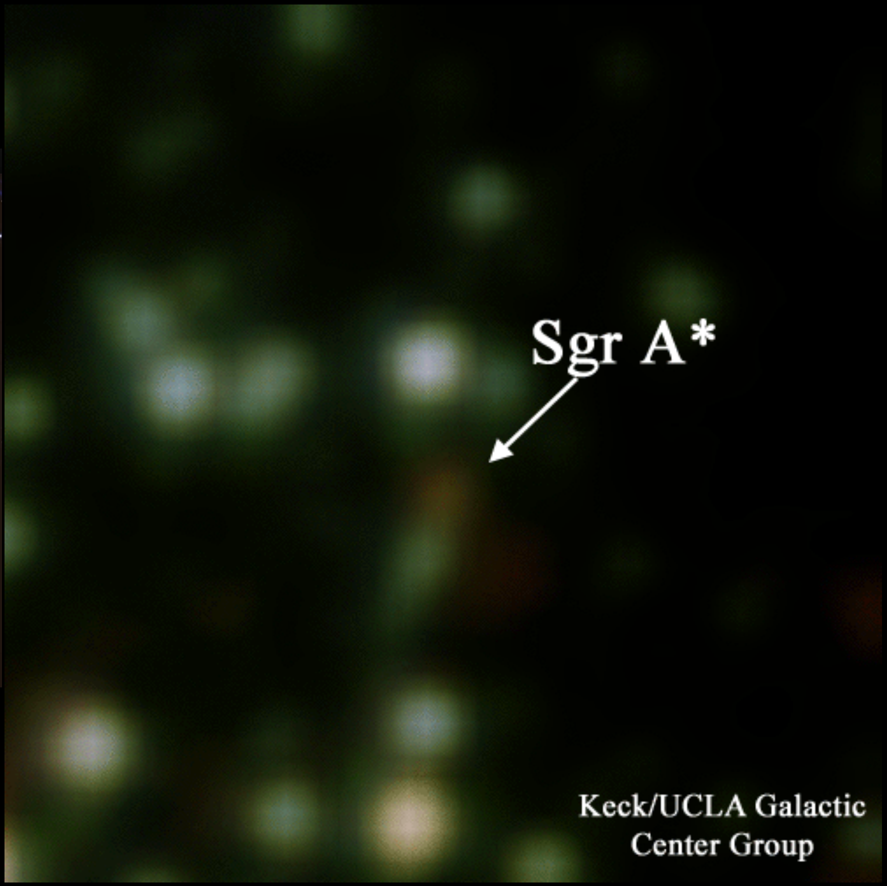
- Theory Prediction for stellar surface density profile: $3/2 < \gamma < 7/4$

  Bahcall & Wolf 1977 (shown), Young 1980, Lee & Goodman 1989, Quinlan et al. 1995
- Observed: $\gamma = 0.6 \pm 0.2$ (r<~6") …. Hole? Stripping?

  Do, Lu, Ghez et al. 2013, Do, Martinez, Yelda, Ghez et al. 2013 ; Chappel et al. in prep (accelerations)

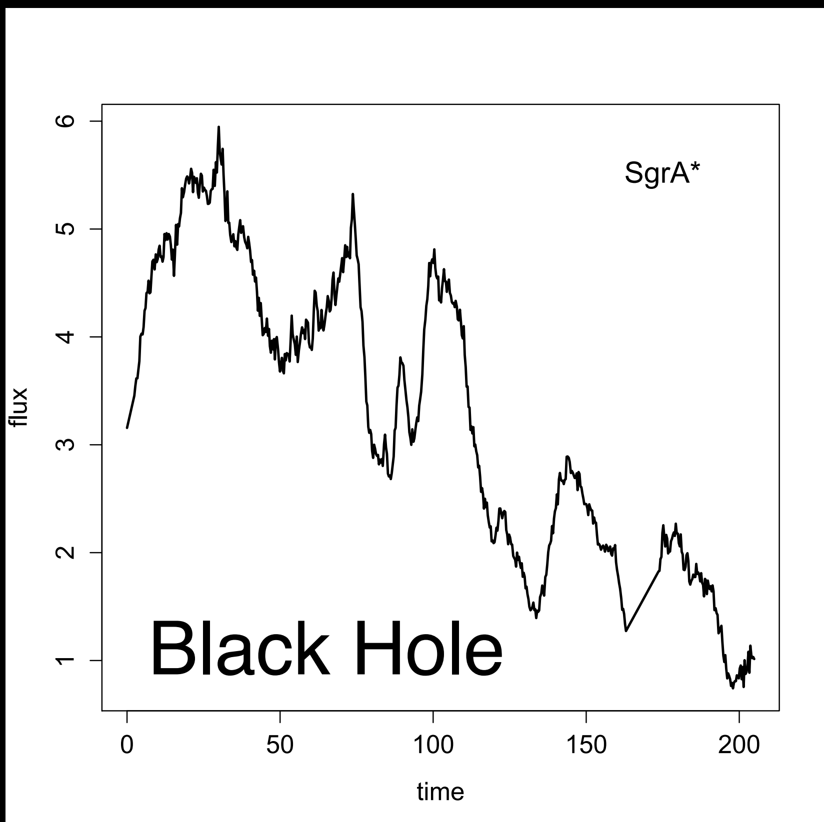
G2 - An Incoming 3 M_{Earth} Gas Cloud?

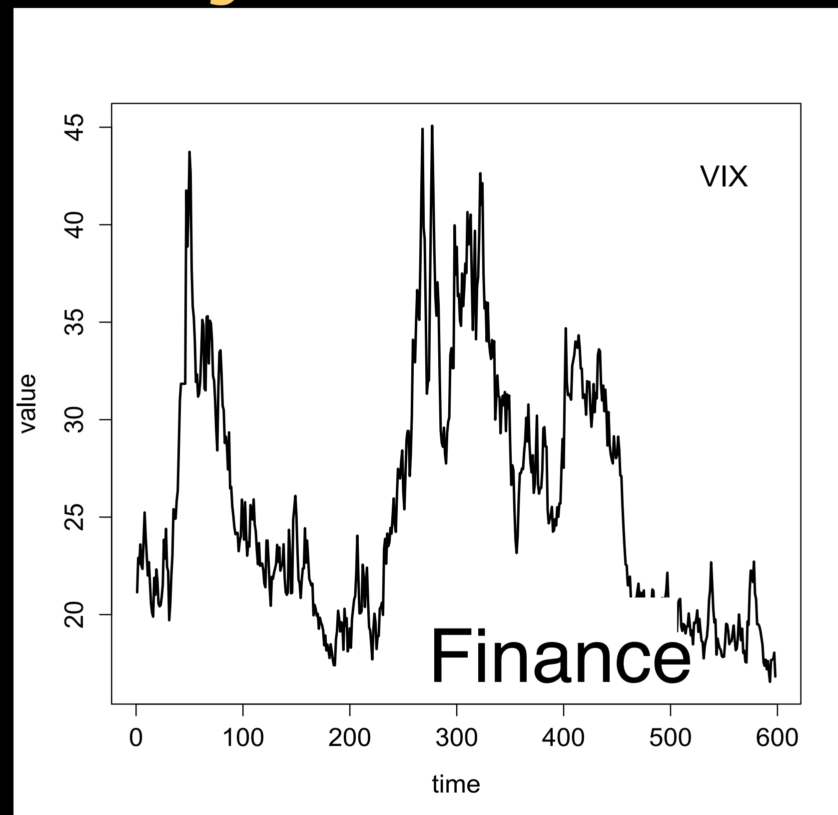




- Unique opportunity to observe a predicted accretion event?
- Closest approach Spring/Summer 2014

Need a Discriminating Tool To Assess Possible Changes in SgrA*'s Variability

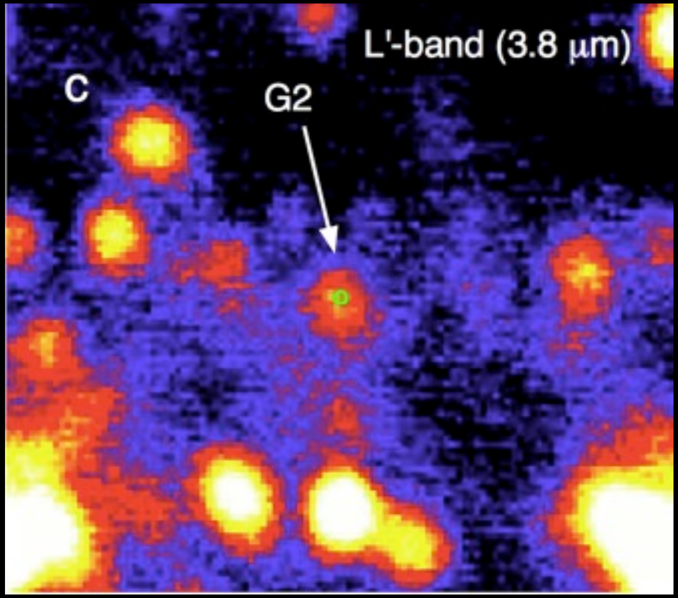


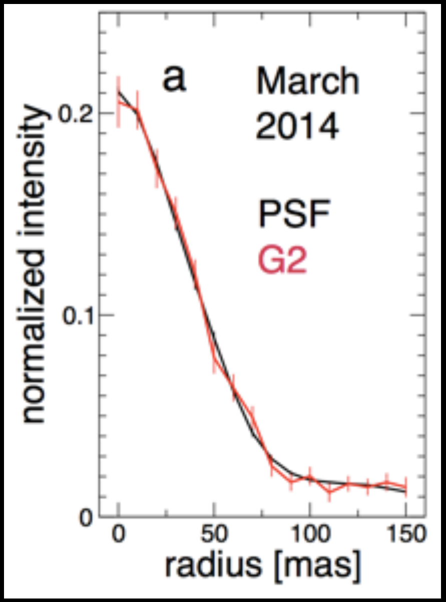


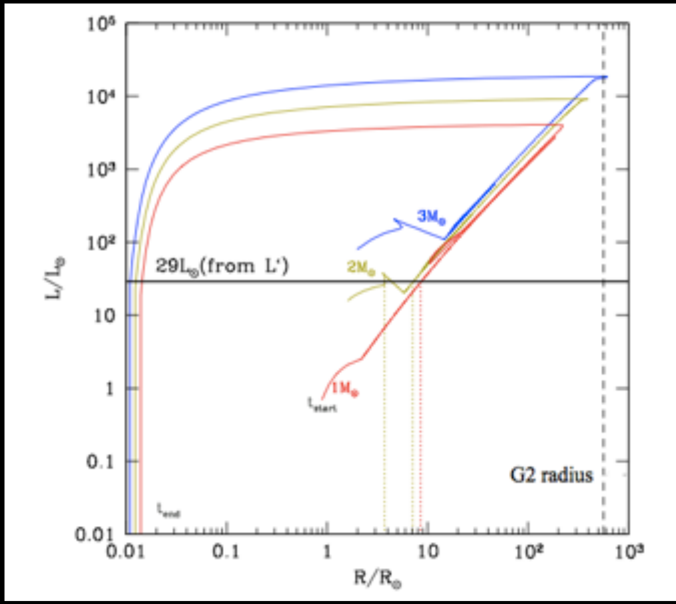
Developed a new method that fully incorporates timing information!
Hidden Markov Model (used for financial market analysis)…

Meyer, Longstaff, Witzel, Ghez 2014, ApJ, 791, 24 single state (red noise, no QPO)

But G2 Survived Periapse Intact as a Compact Constant Brightness L' source….



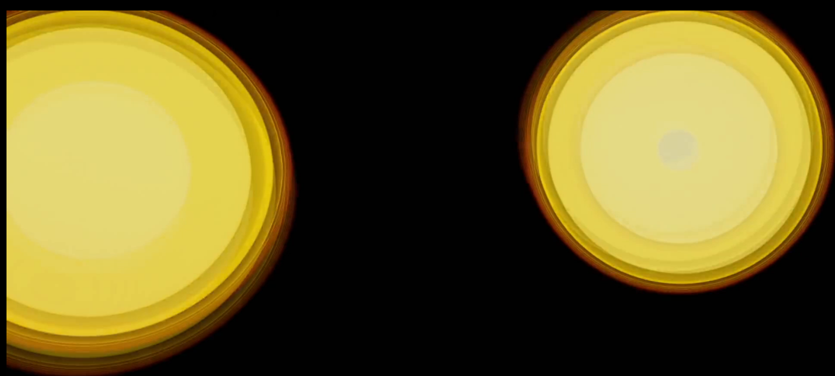




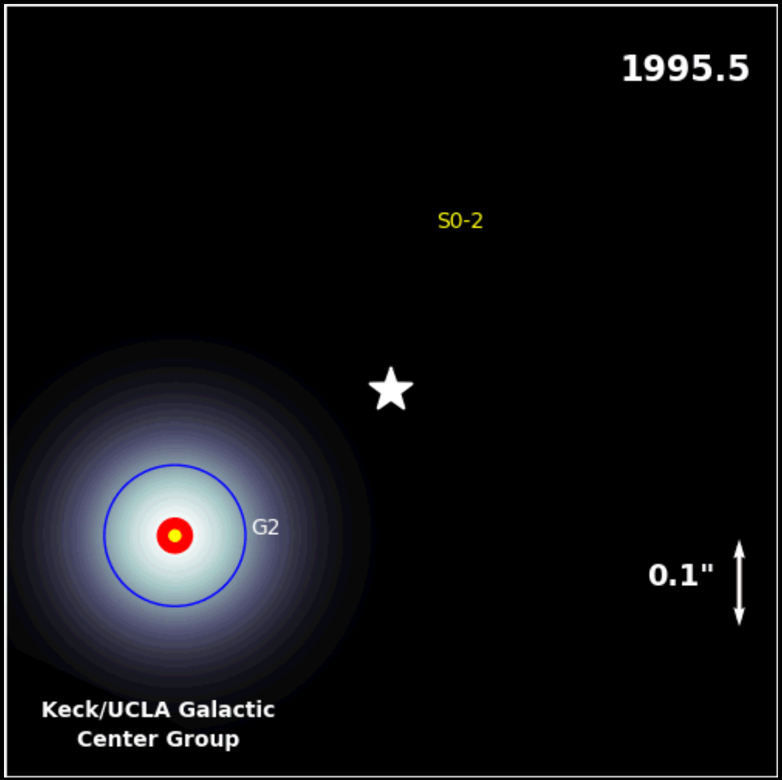
G2 is not a simple gas cloud….

Witzel, AMG, MM et al. (2014)

G2 May be a Black Hole Driven Binary Star Merger



Black hole can drive binary to merge via Kozai-Lidov effect

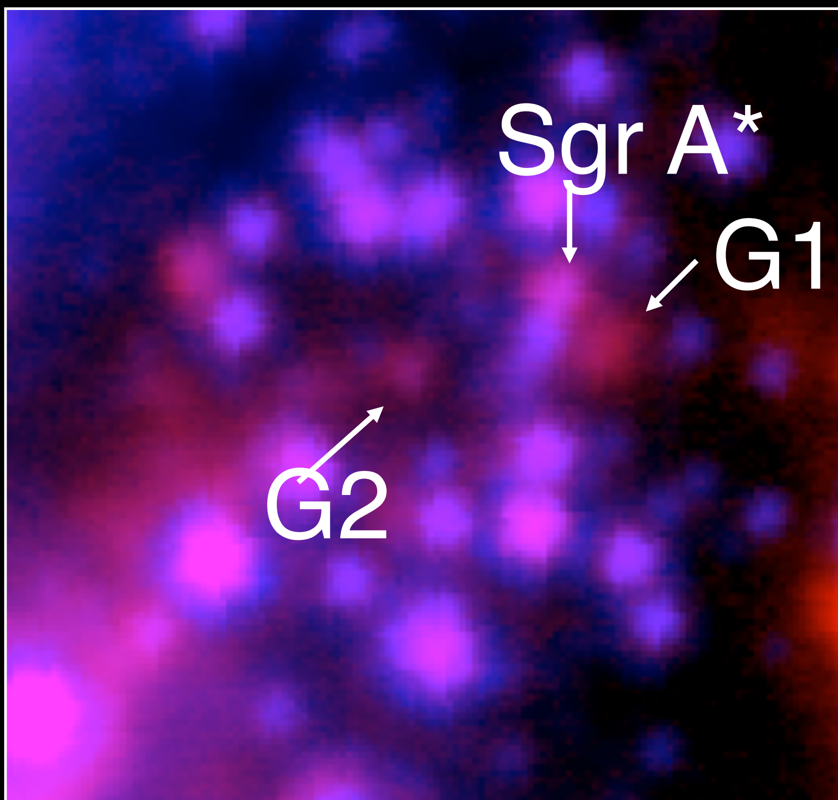


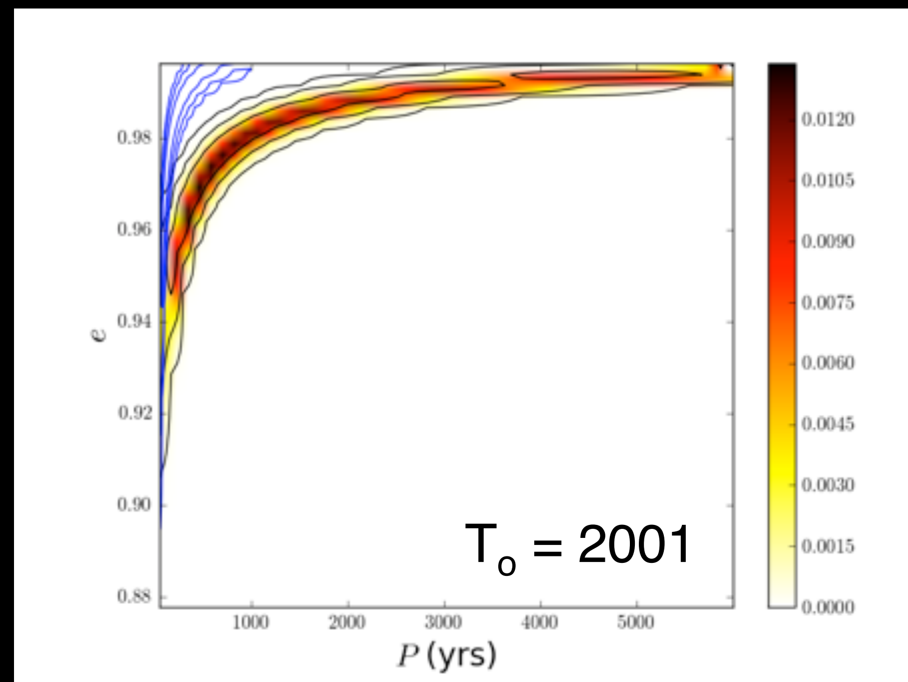
Red: optically thick 3 μm (internally heated)
White: optically thin Br-γ (externally heated)

Pfuhl et al. 2014; Witzel et al. 2014; Prodan et al. 2014; Zajacek et al. 2014

Lots of other models have been proposed: Burkert et al. 2012, Miralda-Escude 2012, Schartmann et al. 2012, Murray-Clay & Loeb 2012, Schoville & Burkert 2013

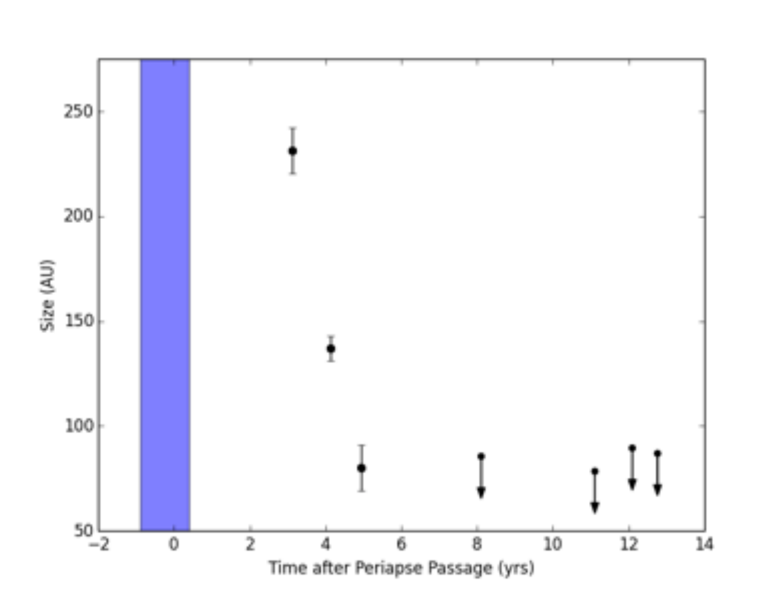
G2 is not Unique!

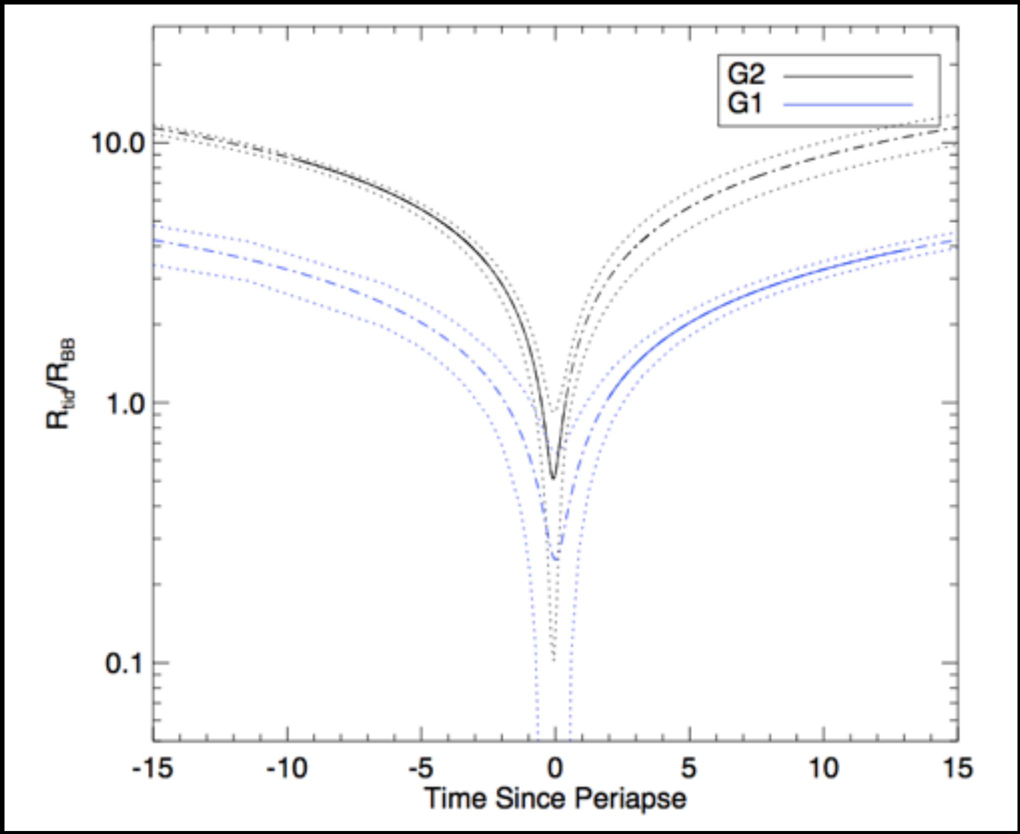




Sitarski, Witzel, Ghez et al. 2014

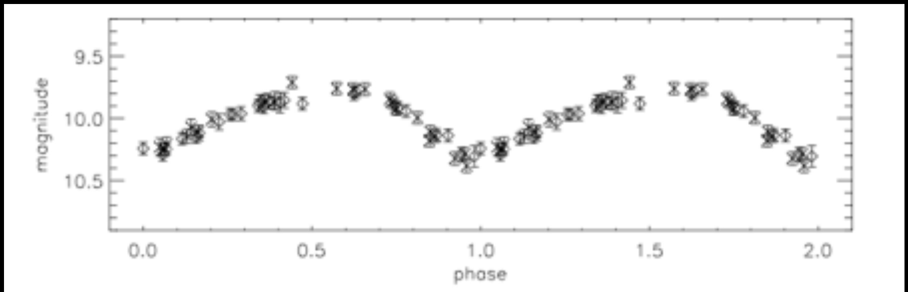
G1 Appears to Have Had a Similar Tidal Interaction 13 Years Ago





Binaries at the Galactic Center?

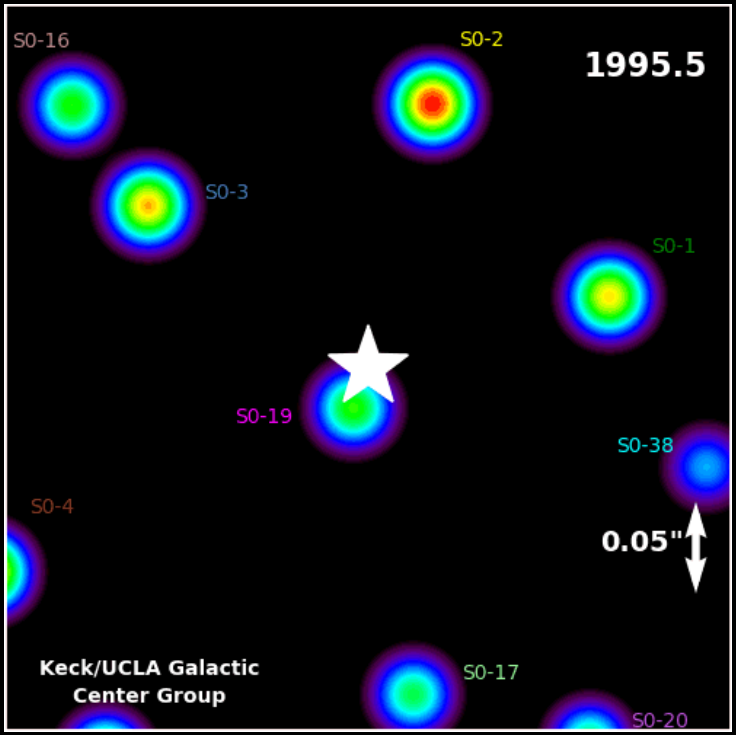
- Binaries exist at the Galactic Center
  Ott et al. 1999; Rafelski et al. 2007; Pfuhl et al. 2014

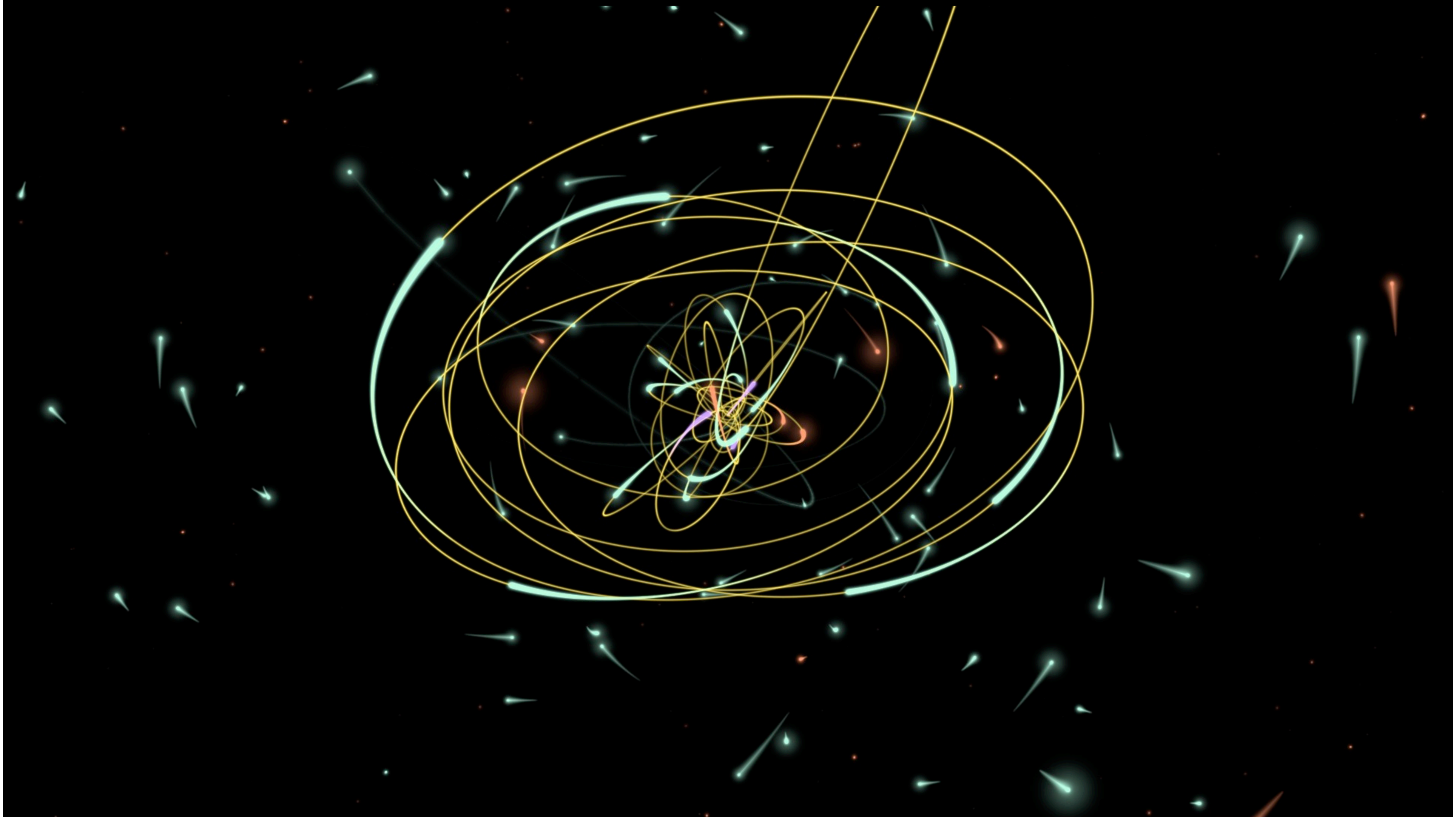


- Are we spatially resolving the region in which BH drives Kozai, which increases the rate of binary star interactions?
- Ideas
  - Will G2/G1 become part of S-star cluster?
  - Is the hole in the giant stars a stripping as binaries get driven to high eccentricities?
- Much more to be done in understanding characteristics and effects of binary stars at GC!

Conclusions

- **Adaptive Optics has transformed our understanding of the center of our Galaxy**
  - Our Galaxy harbors a 4 x 10^6 M_o supermassive black hole
    - SMBHs exist!
    - Most, if not all, galaxies must harbor a central SMBH
  - Great laboratory for understanding
    - Fundamental physics *(testing Einstein's theory of General Relativity in an important & unexplored regime)*
    - The role of central black holes *(binary star mergers, accretion physics, paradox of youth, dearth of old stars)*





http://www.galacticcenter.astro.ucla.edu/animations.html

Visualization by Stuart Levy & Robert Patterson, NCSA, University of Illinois