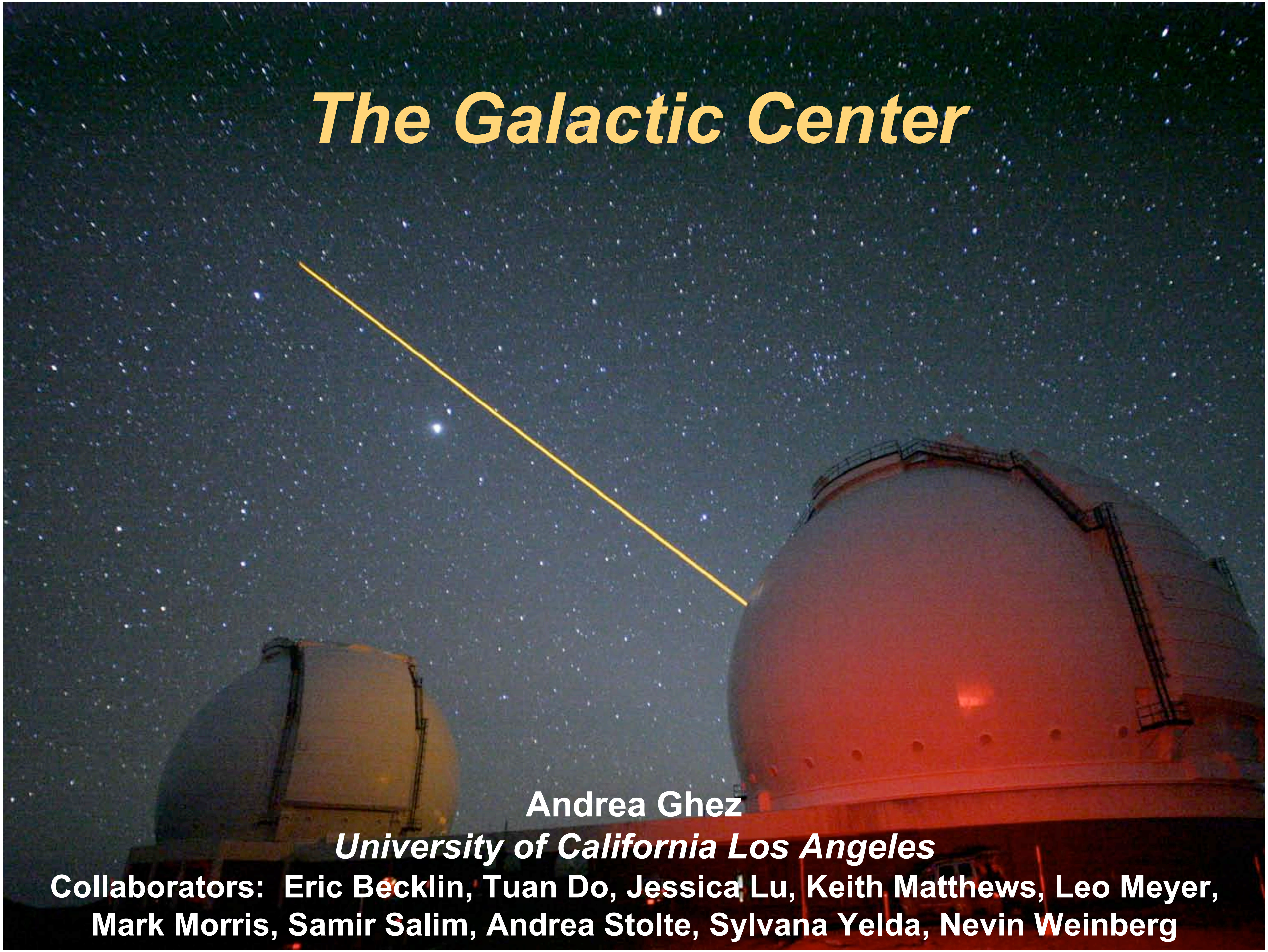
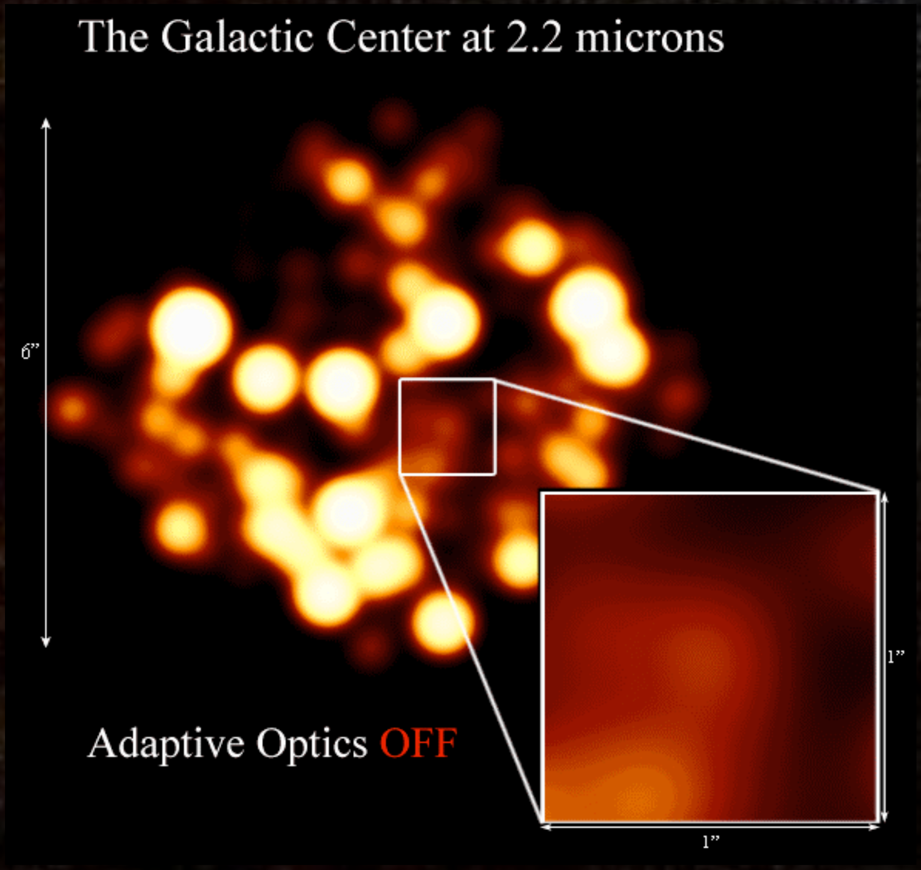


The Galactic Center

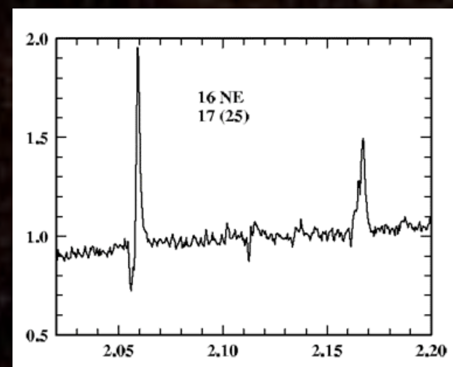
Andrea Ghez
University of California Los Angeles
Collaborators: Eric Becklin, Tuan Do, Jessica Lu, Keith Matthews, Leo Meyer, Mark Morris, Samir Salim, Andrea Stolte, Sylvana Yelda, Nevin Weinberg

Diffraction-Limited Data on the Galactic Center Offer Insight into a Number of Key Questions

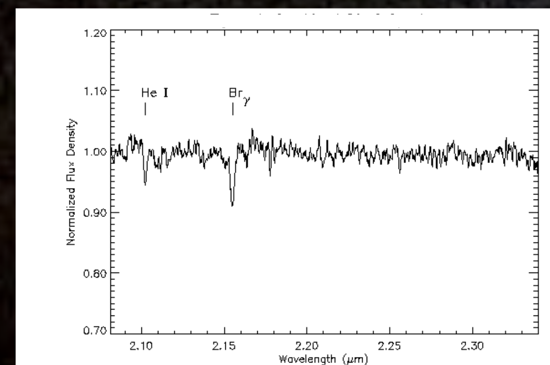
- **Is there a supermassive black hole at the center of our Galaxy?**
- **If so,**
  - **What are its properties?**
    - *Position (association with SgrA*)*
    - *Mass (M_{bh} vs σ)*
    - *Distance (Galactic Structure)*
    - *Future (M_{ext}, GR, spin?)*
  - **What are the properties of the accretion flow and why is it so under-luminous (10^{-9} L_{Ed})?**
  - **How do young stars come to reside in its vicinity?**



Presence of Young Stars Close to Center of our Galaxy Presented an Argument Against a Central Supermassive Black Hole



R. Genzel et al. (2000)



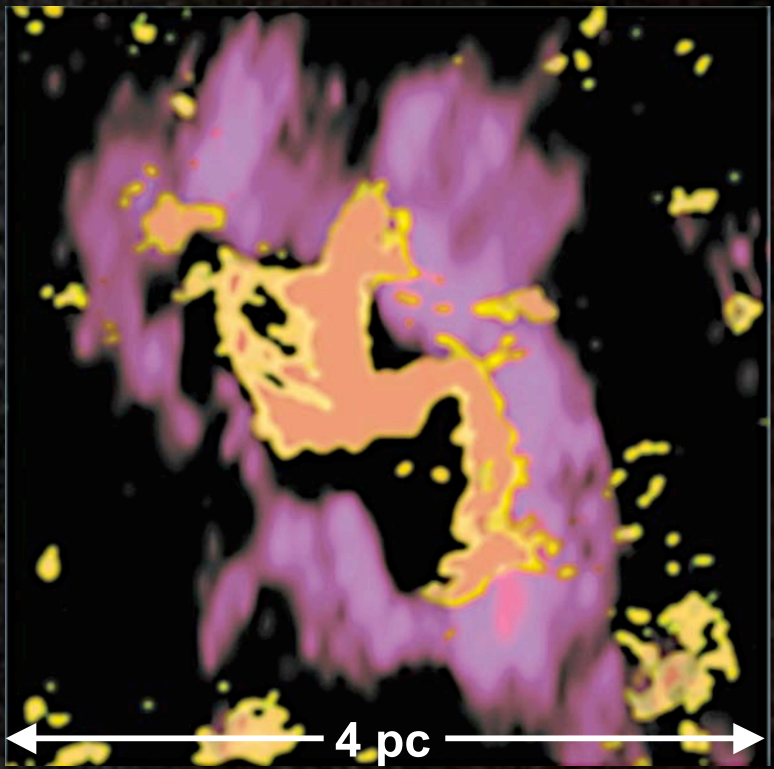
Ghez et al.

- Wolf-Rayet stars
- Progenitors were > 20 M_o
- Ages of 5-7 Myr
- Between 0.04 - 0.4 pc (1-10")

- OB Main-Sequence stars
- Masses < 15 M_o
- Ages < 20 Myr
- Between 0.004 - 0.4 pc (0.1 - 10")

Forrest et al. 1987; Allen et al. 1990; Krabbe et al. 1991, 1995; Blum et al. 1995; Tamblyn et al. 1996; Paumard et al. 2001, 2006; Ghez et al. 2003, Eisenhauer et al. 2005, Martins et al. 2008

Observed Gas Densities are Insufficient for Self-Gravity to Overcome Tidal Forces



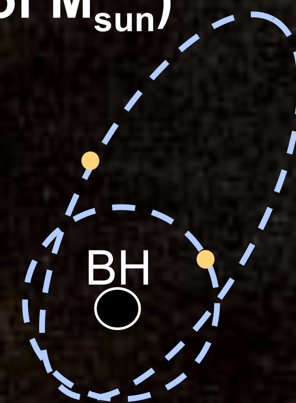
Yusef-Zadeh, Melia, & Wandle (2000; orange)
Wright et al. (1993; purple)

- Required Densities
  - $\rho > 1\text{x}10^{11}\ (M_{bh}/\ 10^{6}\ M_{o})\ (1''/R)^{3}\ \text{cm}^{-3}$
- Observed
  - Circum-Nuclear Disk (CND)
    r ~ 1 pc (25”)
    $\rho \sim 10^{3}$ - $10^{7}\ \text{cm}^{-3}$
  - Ionized Mini-Spiral
    r<1 pc
    $\rho < 10^{3}\ \text{cm}^{-3}$

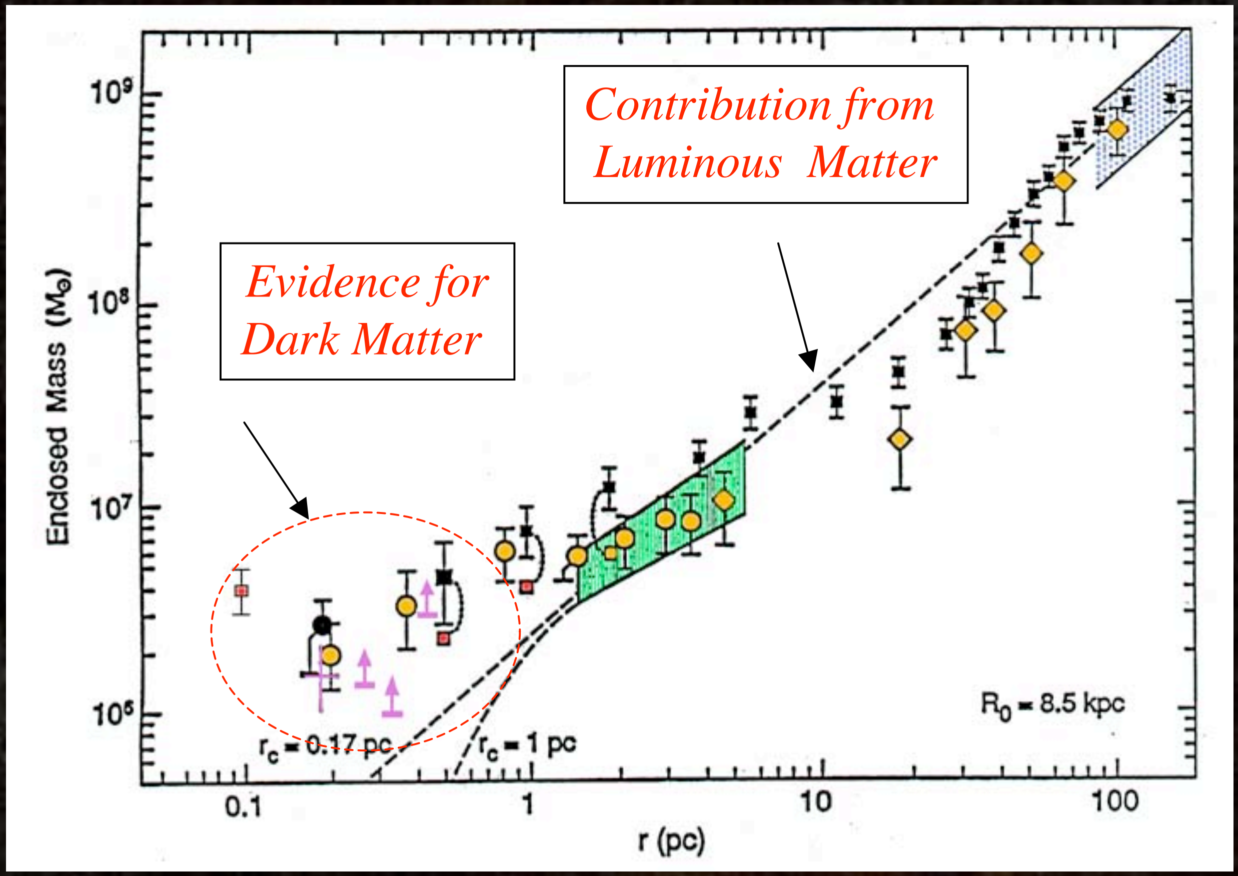
Dynamics Provide Best Proof of a Black Hole

- **Need to show mass confined to a small volume**
  - **R_{sh} = $2GM_{bh} / c^2$ = 3 x M_{BH} km (M_{BH} in units of M_{sun})**

- **Use stars as test particles**
  - **Φ = -G M_{encl} m / R**
    - ***Impatient:* velocity dispersions (ensemble)**
    - ***Patient:* full 3-d orbits (individual)**



Seeing Limited Measurements Gave First Hint of Central Dark Mass



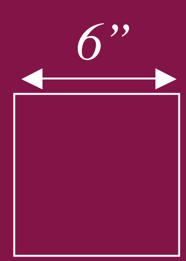
Line of Sight Velocity Dispersion Measurements

Gas *(e.g., Rougoor & Oort 1960; Ooort 1977; Sinha 1978; Gatley et al. 1986; Guesten et al. 1987; Serabyn & Lacy 1985; Serabyn et al. 1987)*

Stars *(e.g., McGinn et al. 1989; Sellgren et al. 1990; Linquist et al. 1992; Genzel et al. 1996)*

However, Inferred Dark Matter Density was too Small to Definitively Claim a Black Hole

- Black Hole Alternatives
  - Clusters of dark objects permitted with the inferred density of $\sim 10^9 M_o/pc^3$
  - Fermion Ball



- High spatial resolution techniques needed to make further progress.

Speckle Imaging Allowed First Measurements of Stellar Kinematics Inside r ~ 0.1 pc

Resolution_K = 0.”05

Strehl Ratio = 0.05

K_{lim} = 16 mag

Imaging Only

Animation: 1995-2004 raw speckle images from Keck

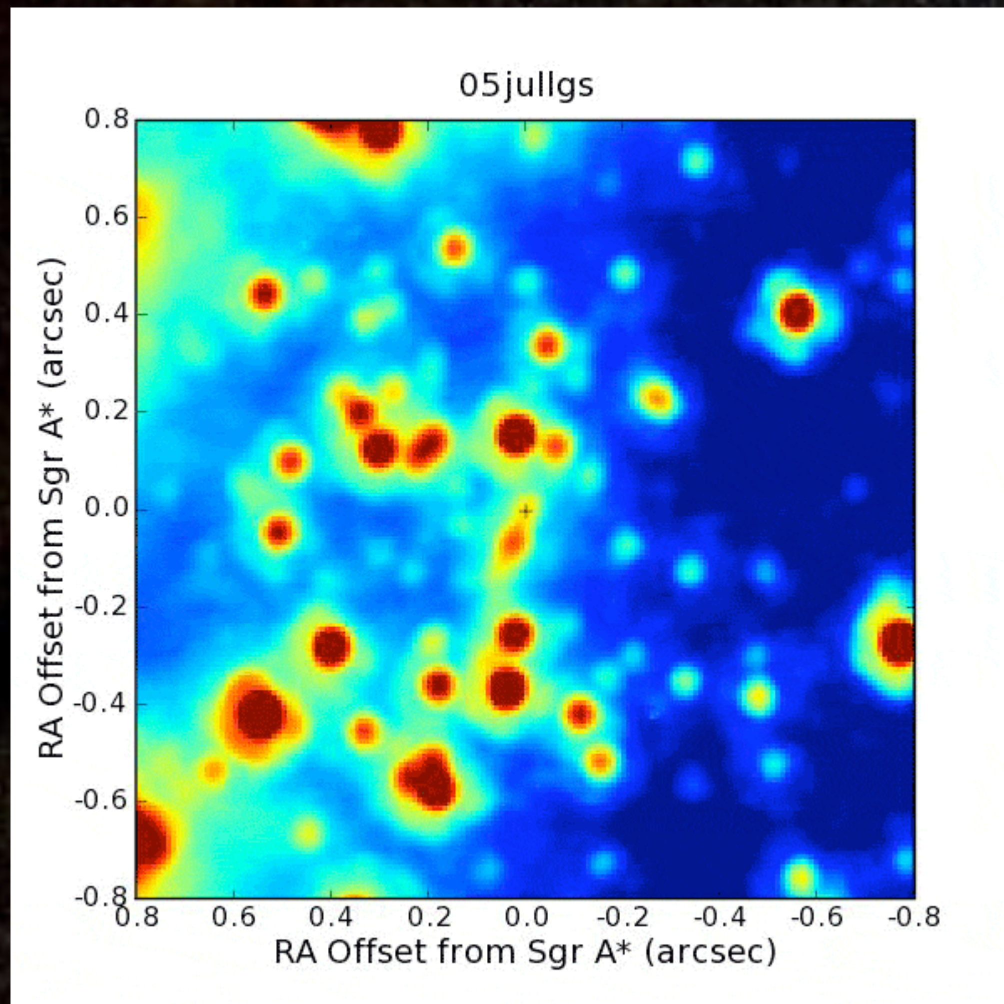
Eckart & Genzel 1997; Genzel et al. 1997; Genzel et al. 2000; Ghez et al. 1998, 2000, 2005

Adaptive Optics Has Dramatically Improved our Ability to Measure Stellar Kinematics

Strehl Ratio = 0.3 - 0.4

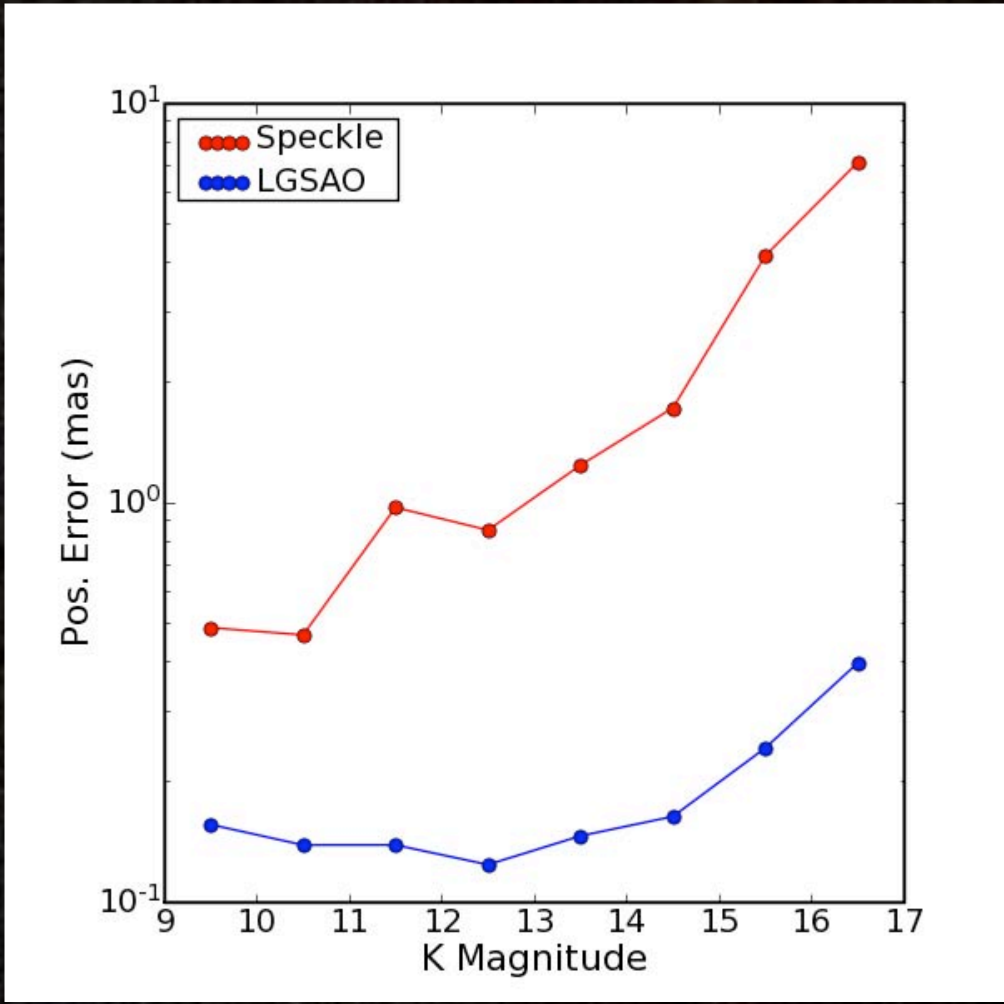
K_{lim} = 19 mag

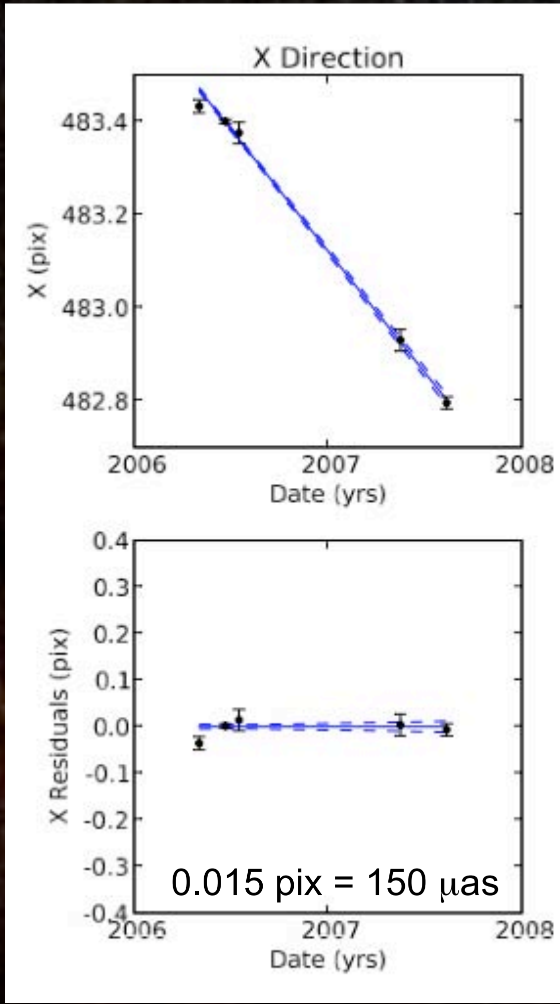
Better astrometry & spectra!!!



NGS-AO: Gezari et al. 2002, Genzel et al. 2003, Ghez et al. 2003; Eckart et al. 2004
LGS -AO: Ghez et al. 2005, 2008, Hornstein et al. 2007, Do et al. 2008, Lu et al. 2008

Adaptive Optics (AO) Has Improved Relative Astrometry by an Order of Magnitude

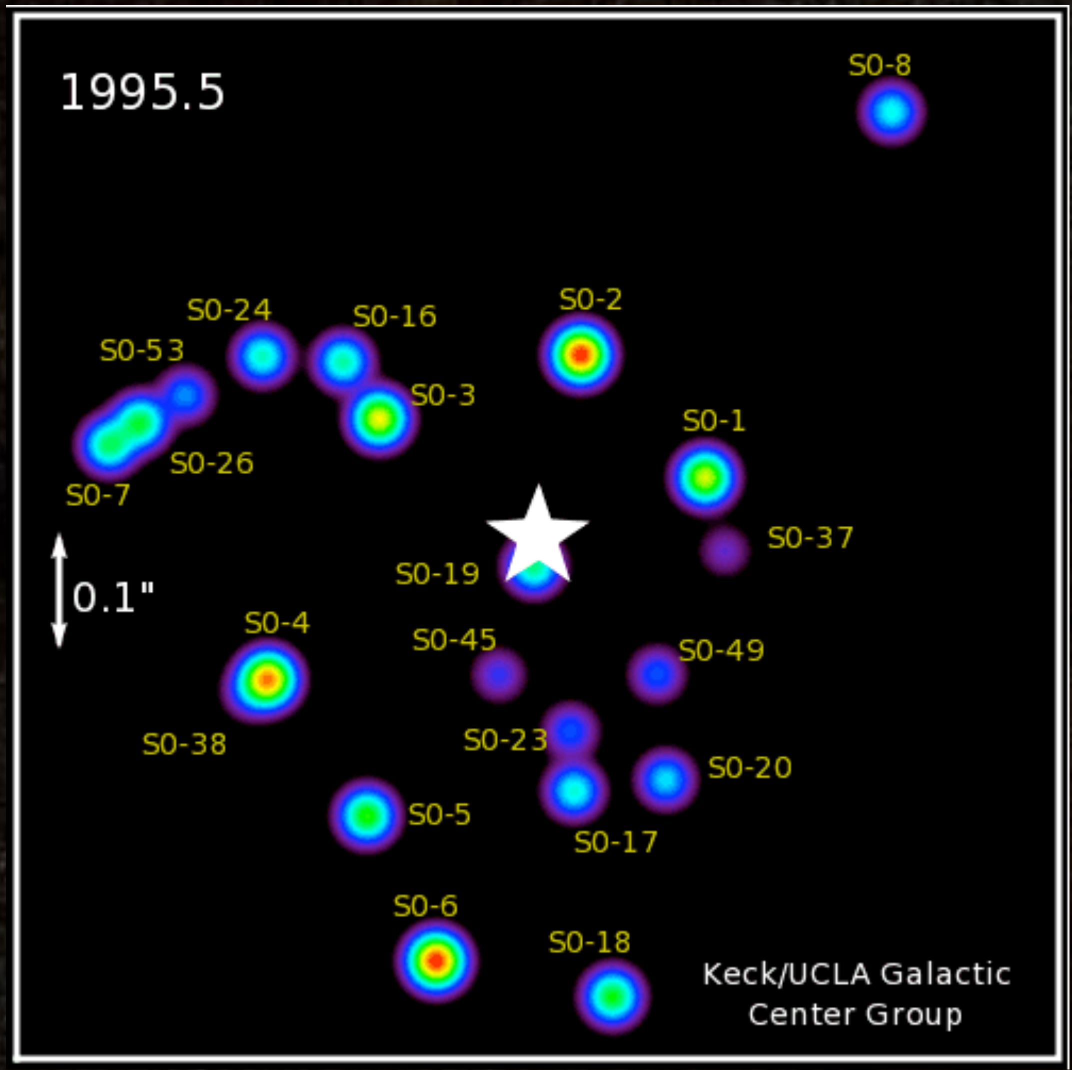




$<\sigma_{pos}> = 150\ \mu$–arcsec

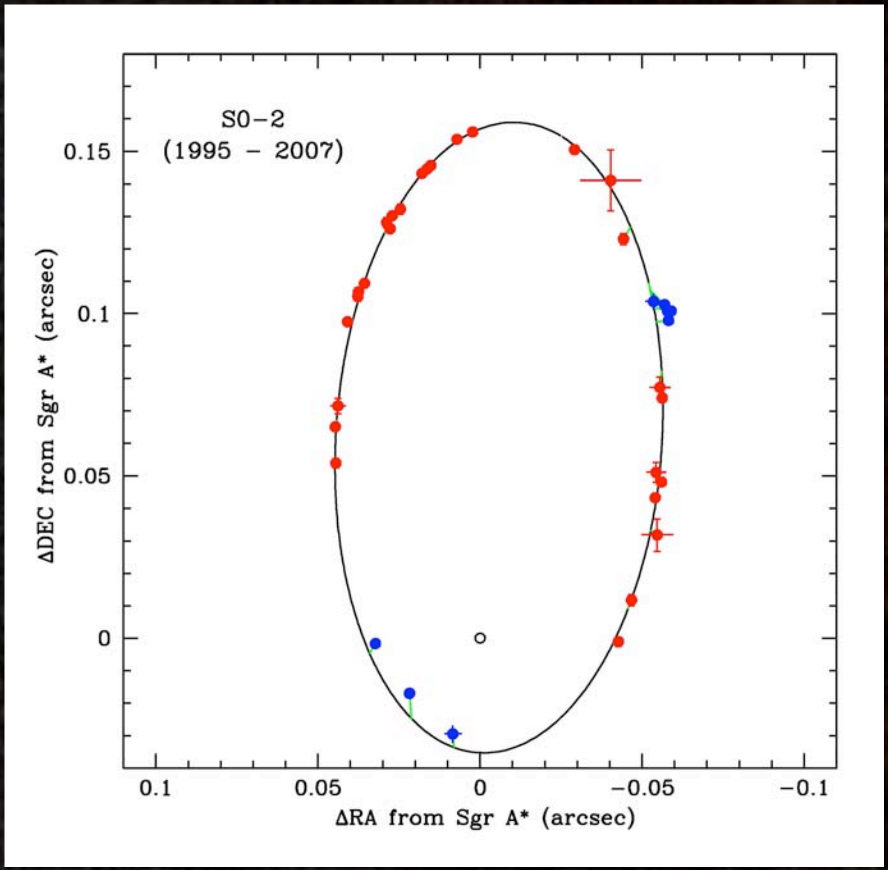
Ghez et al. 2008

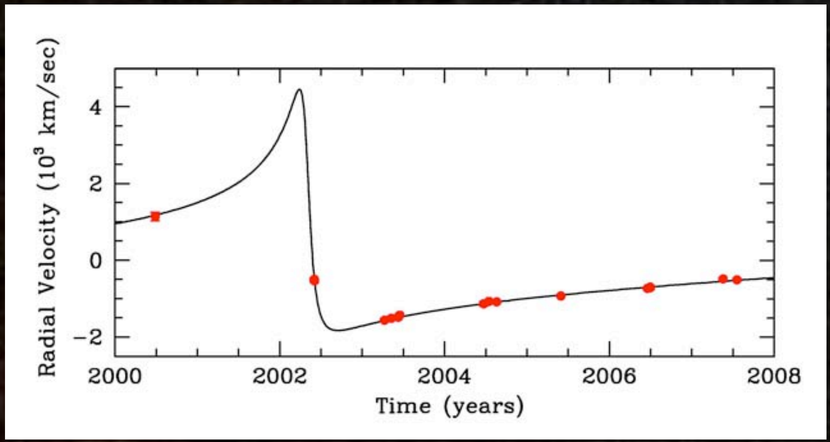
With More than a Decade of Measurements, Complete Keplerian Orbital Solutions Possible



Shoedel et al. 2002, 2003; Ghez et al. 2003, 2005, 2008; Gillissen et al. 2009

Orbit of S0-2 Dominates Knowledge of Central Potential





Mass = 4.1 ± 0.4 (± 0.5)* x10^6 M_o

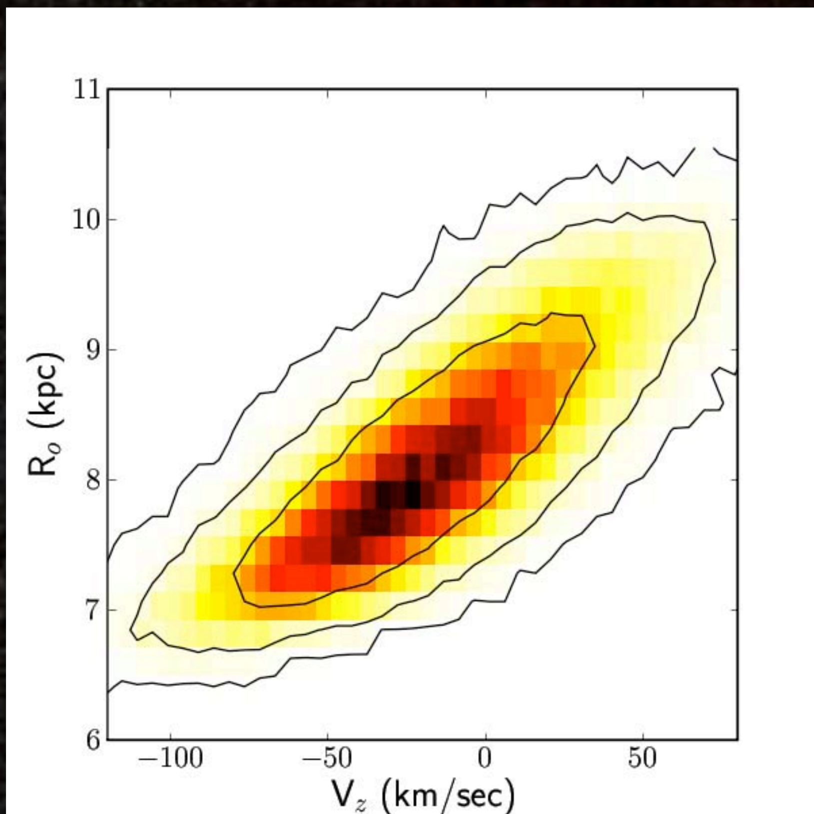
R_0 = 8.0 ± 0.4 (± 0.5)* kpc

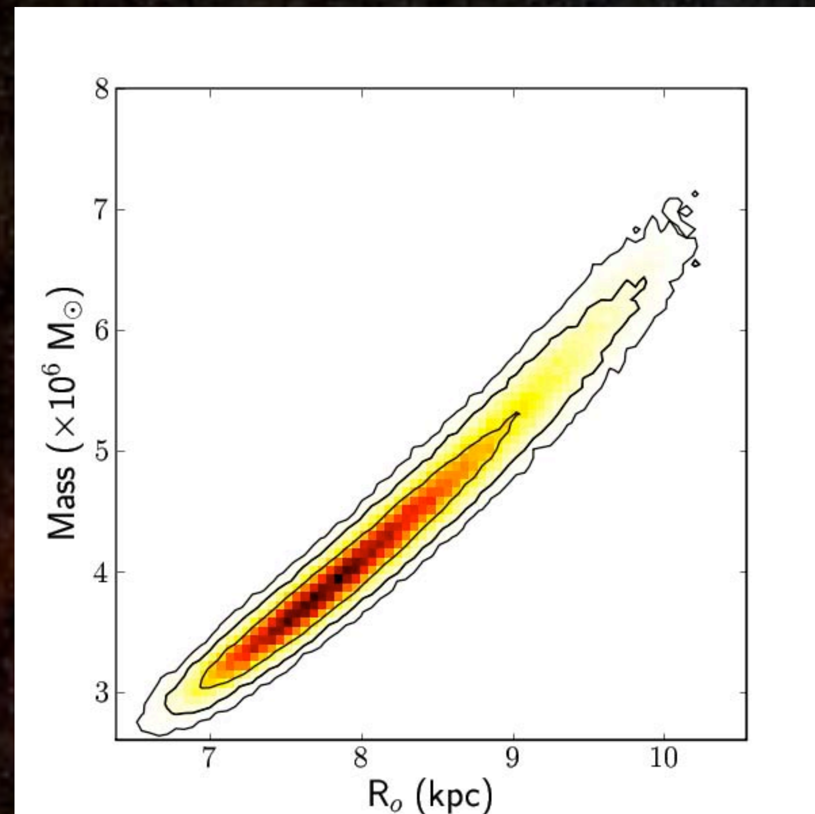
* don't fix $V_{z,bh}$

- Known source confused with S0-2
- No known source of confusion

Shoedel et al. 2002, 2003; Ghez et al. 2003, 2005, 2008 (shown)

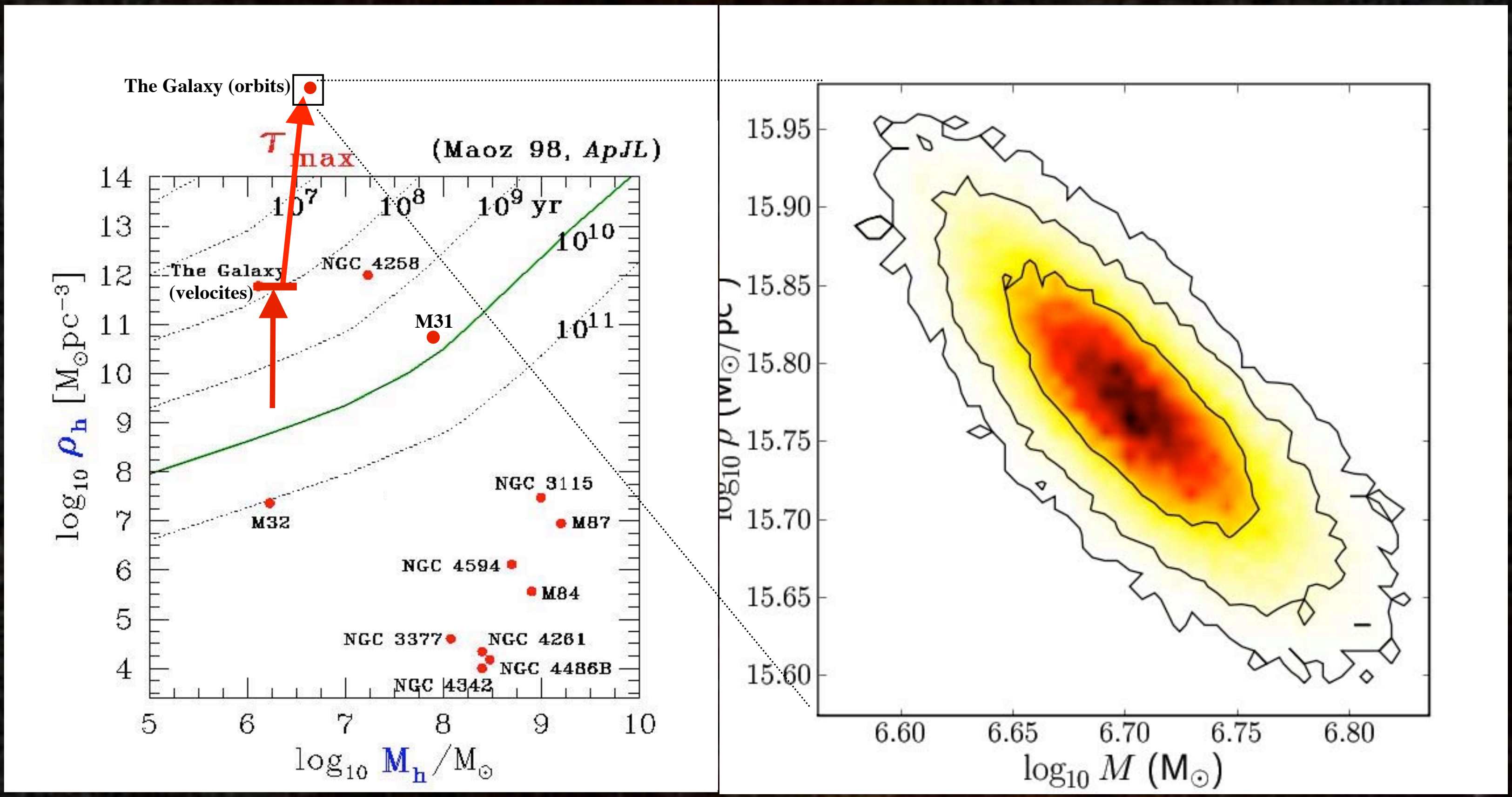
Dominant Source of Uncertainty is $V_{z,\ bh}$





Measurement Time Baseline
Astrometry = 14 years
RV = 8 years

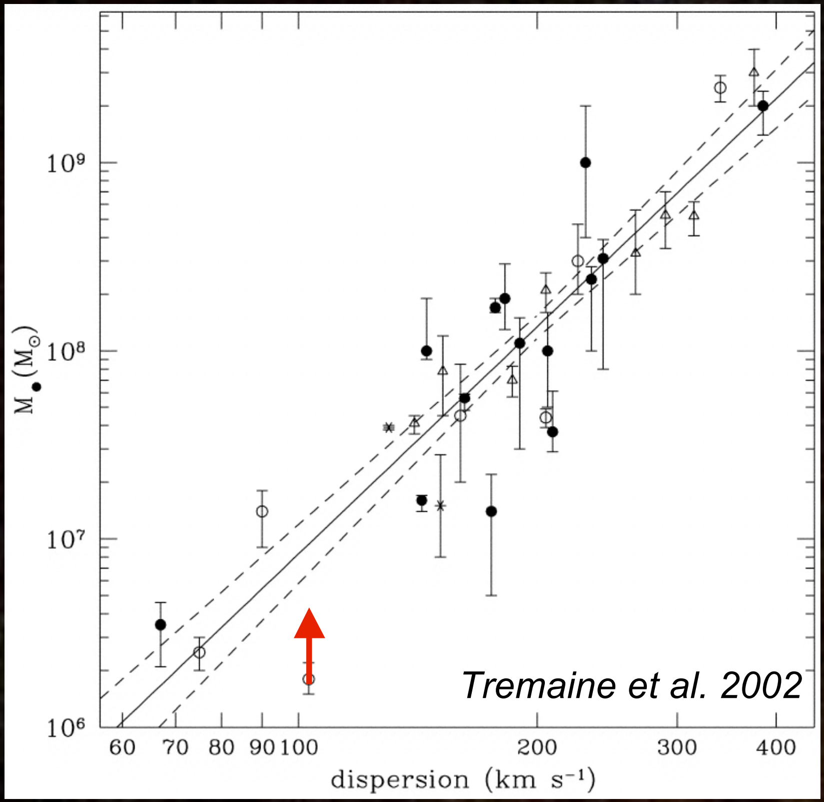
Case for a Supermassive Black Hole in the Milky Way Has Been Dramatically Improved



Inferred dark matter density increased by 10^7

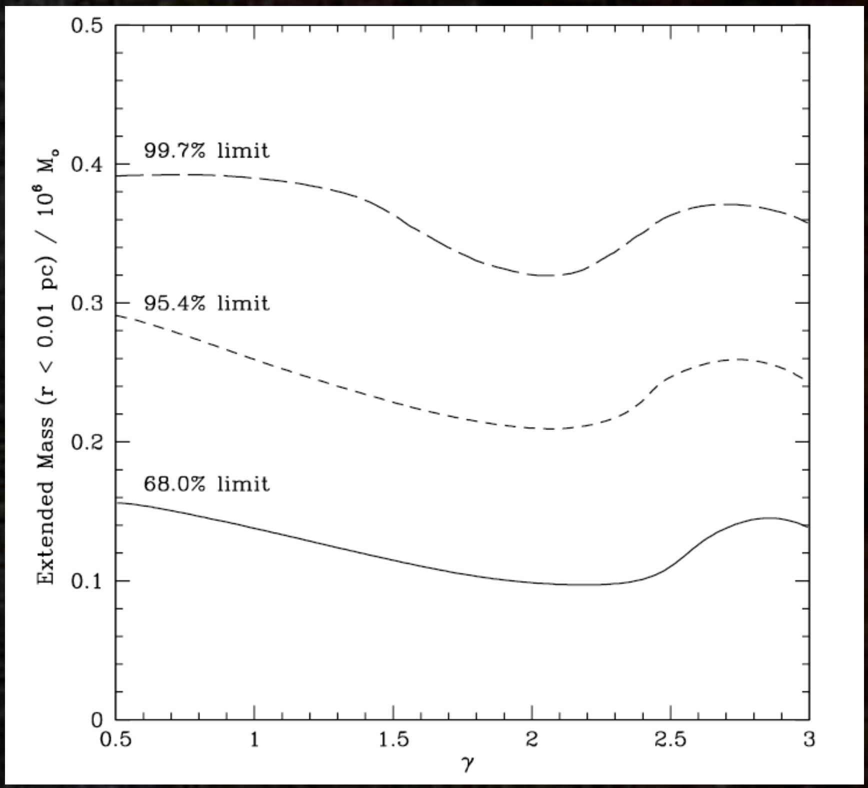
Velocity disperion (high res.): Eckart & Genzel 1997; Genzel et al. 1997,2000; Ghez et al. 1998
Accelarations: Ghez et al. 2000; Eckart et al. 2000
Orbits: Schoedel et al. 2002, 2003, Ghez et al. 2003, 2005, 2008, Gillisen et al. 2008

Mass from Orbital Analysis is ~2x Higher than from Velocity Dispersion



- **Velocity Dispersion Depends**
  - **Assumptions about orbits and number density distribution**
  - **Entire population being measured**

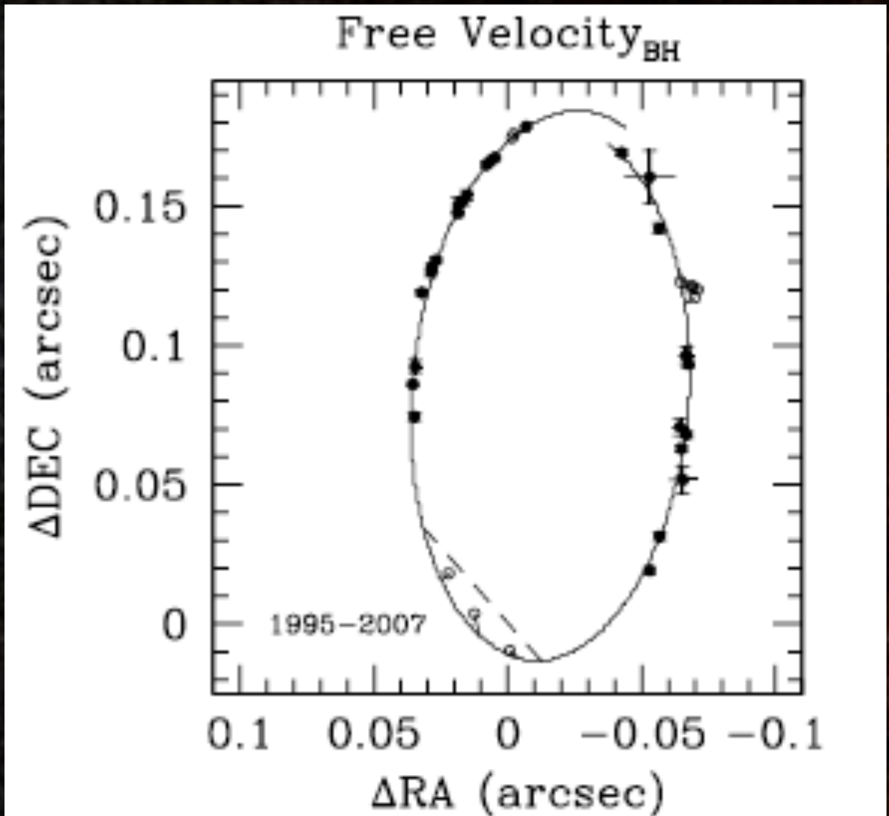
Extended Dark Mass Distribution is less than $1x10^5 M_o$ within 0.01 pc



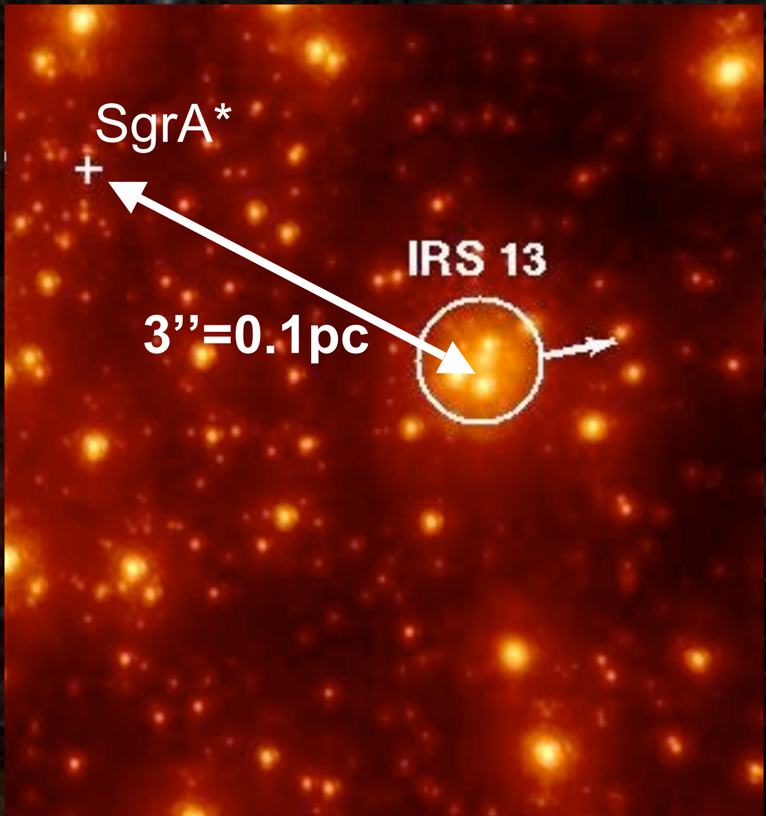
Ghez et al. (2008)

- **Model**
  - **Central Point Mass + density profile $\rho(r)=\rho_o(r/0.01pc)^{-\gamma}$**
  - **Probe 120 - 2000 AU**
- **Limit more than 100x larger than predictions**
  Dark Matter Halo Particles: *Gondolo & Silk 1999, Ullio et al. 2001, Merritt et al. 2002, Gnedin & Primack 2004*
  Stellar Remnants: *Morris 1993, Miralda-Escude & Gould 2000*

Companion Black Hole Mass Limited to Less than $2x10^5 M_o$ (R/0.1 pc)$^{1/2}$



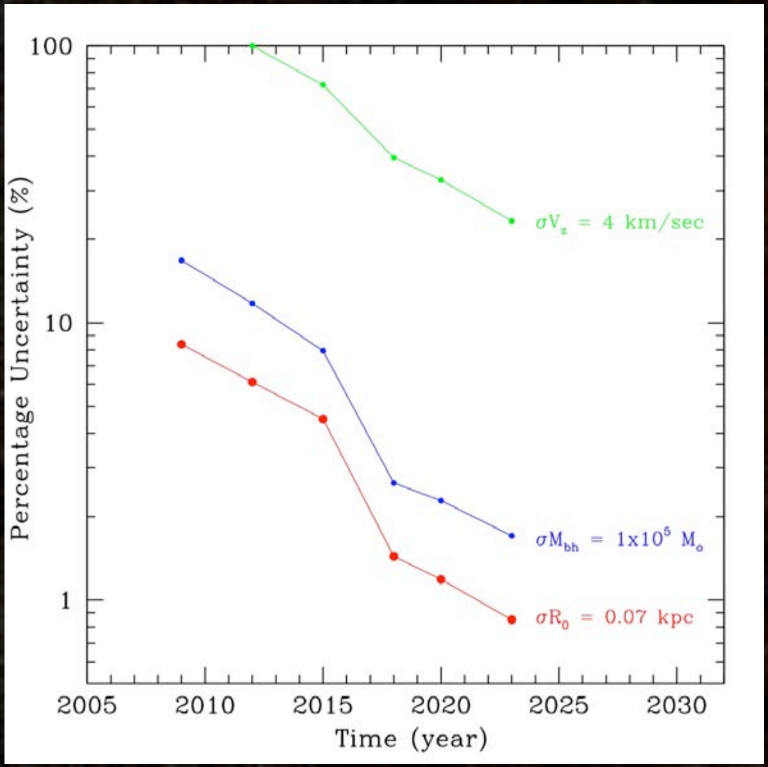
Ghez et al. (2008)

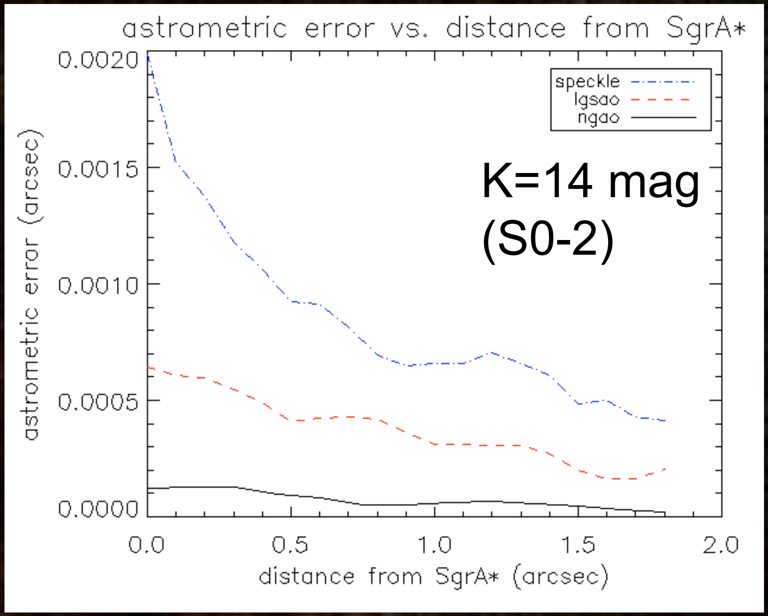


Maillard et al 2004, Schoedel et al. 2005

IRS 13
Co-moving group & X-ray source
Requires $M=10^4\ M_o$ to be bound

Determination of Orbital Parameters Will Improve with Time



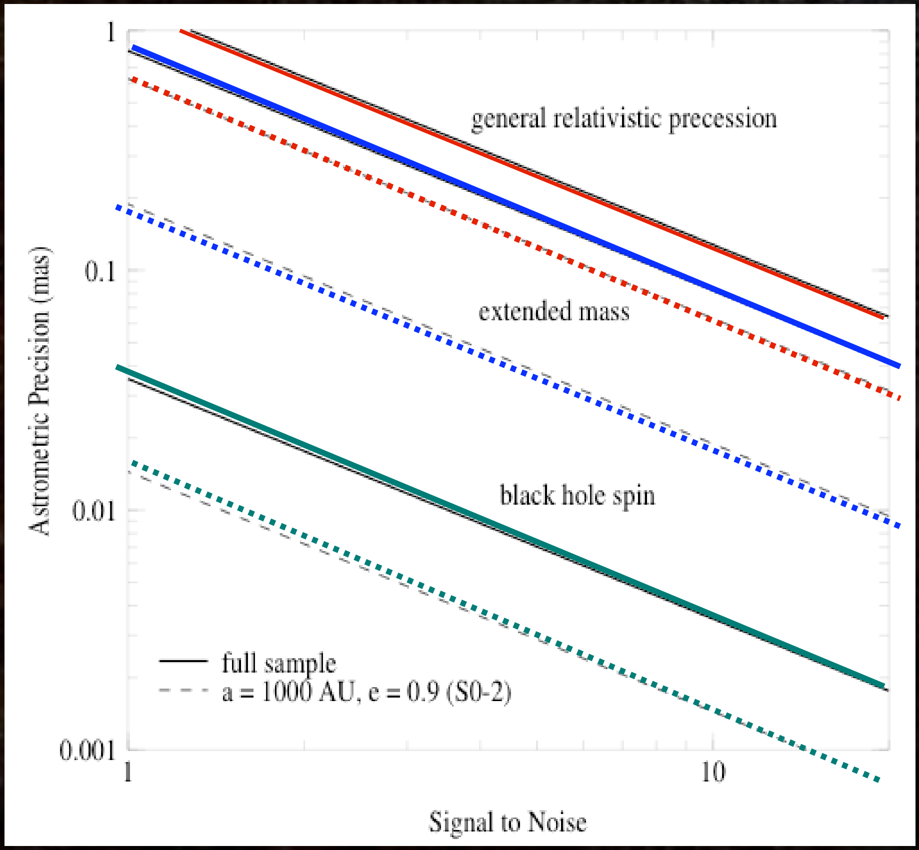


Astrometic measurements of S0-2 are limited by unknown sources to 500 μas

Better AO systems (and larger telescopes help!)

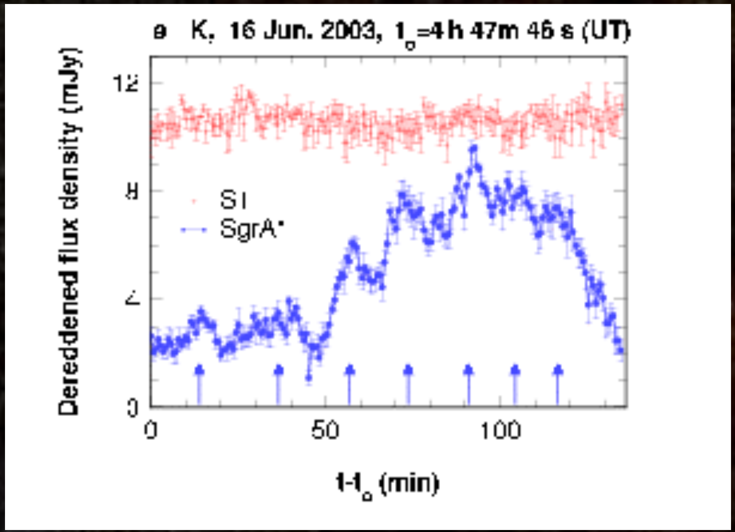
Need ELT to Overcome Stellar Confusion to Reach Long-Term Goals

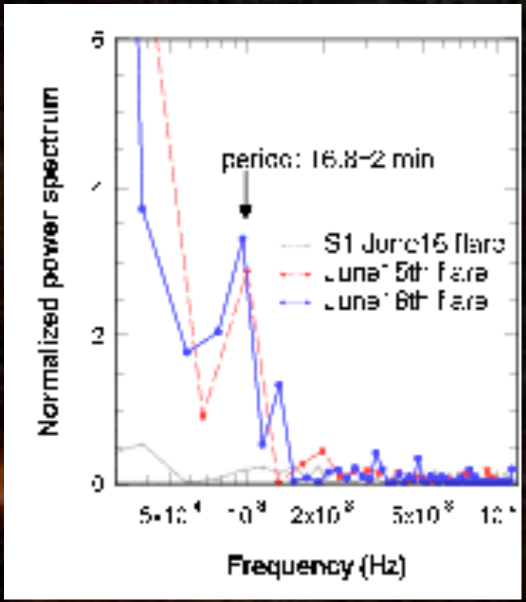
- **Keplerian model**
  - **R_o to <0.1 % (vs 9% today)**
- **Deviations from Keplerian model**
  - **Relativistic prograde precession**
  - **Extended mass distribution**
  - **Frame drag due to spin of black hole**



Weinberg, Milosavljevic, & Ghez (2005)

Early Experiments Found a Possible 20 minute Periodicity in Light Curve Suggesting Spinning Black Hole



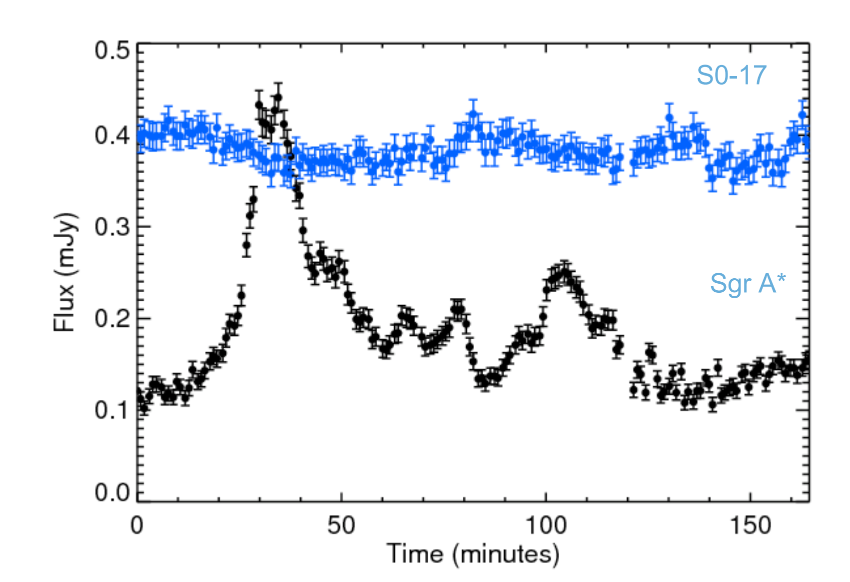


Genzel et al. 2003

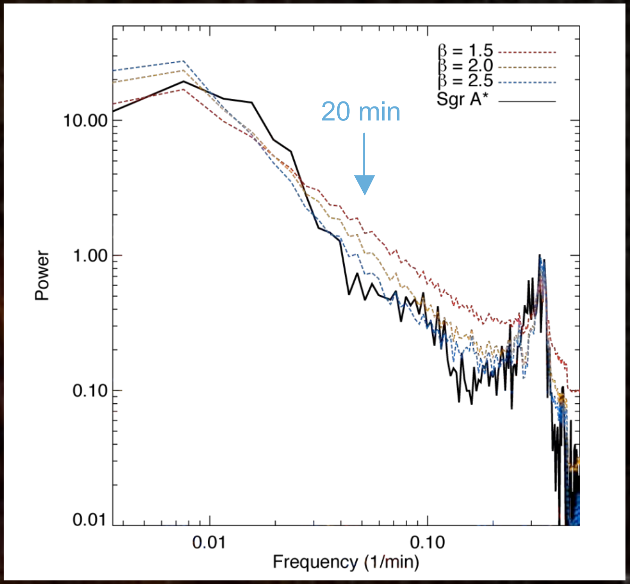
- **Orbital radius inferred from this period is inside the radius of the last stable orbit for a non-spinning black hole (inner most stable orbit for non-spinning black hole P=~30 min)**
- **A spinning black hole decreases the radius of the last stable orbit**

More Recent Work Suggests Intensity Variations Consistent With "Red-Noise"

K' (2 micron) light curve from 1 night



Combined 5 nights of K' periodograms



Do, Ghez, et al. 2008 (shown); Meyer, Ghez et al. 2008

Need to Explain Presence of Young Stars in Vicinity of Black Hole

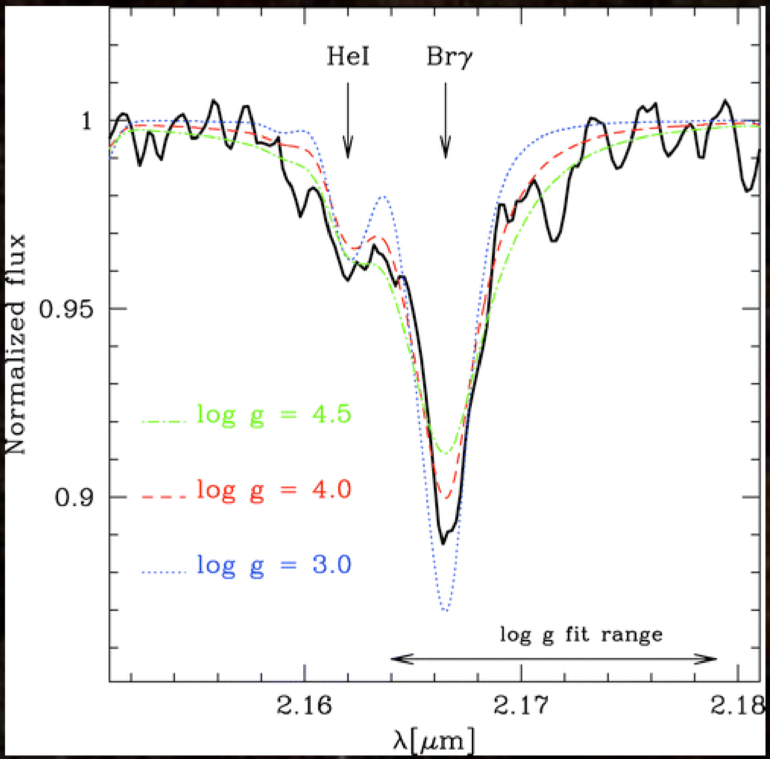
SgrA =*
Black Hole

- **Old Stars Masquerading as Youths** *(e.g., Morris 1993, Lee 1994, Davies et al. 1998, Genzel et al. 2003, Alexander & Morris 2003)*

- **Young Stars that Formed at Larger Radii (“cluster infall”)** *(e.g., Gerhard et al. 2000, Kim & Morris 2003, Portegies-Zwart et al 2003 Hansen & Milosavljevic 2003, Gould & Quillen 2003, Perets & Alexander 2007, Fujii [poster]*

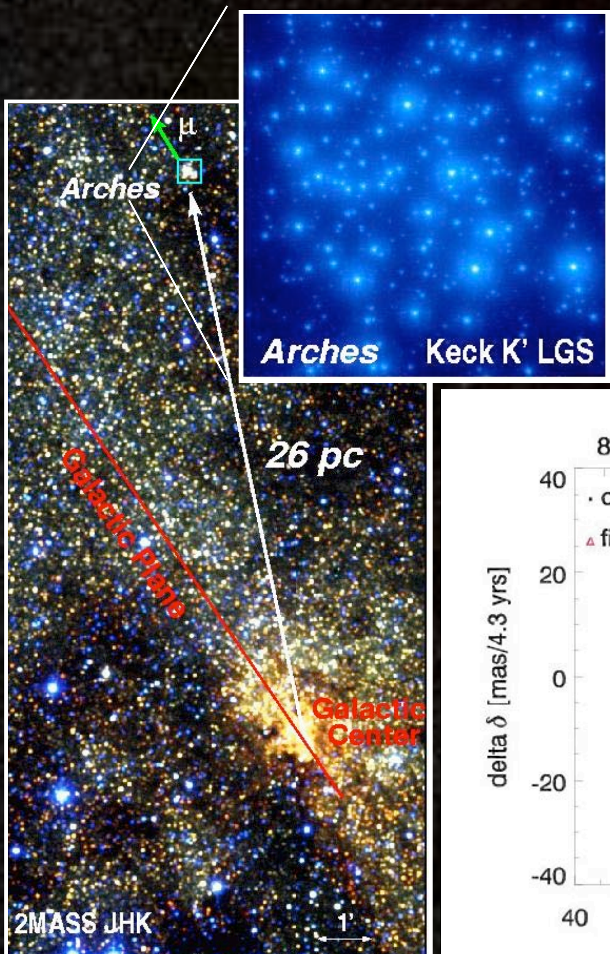
- **Young Stars that Formed In-Situ** (e.g., *Morris et al. 1993, Sanders 1998, Levin & Belobordov 2003; Nyakshin & Cuadra 2005; Nayakshin et al. 2007; Levin 2007, Bonnell & Rice 2008*

Line Shape Observations Show That These Really are Massive Stars….



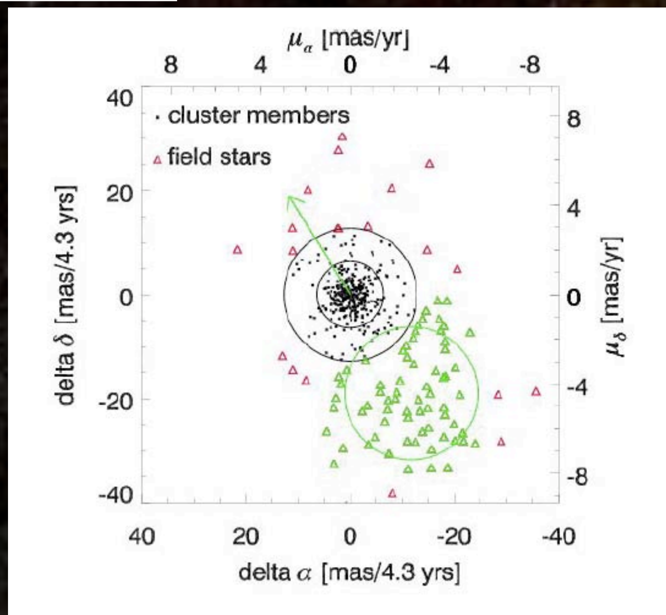
Martins et al. 2008

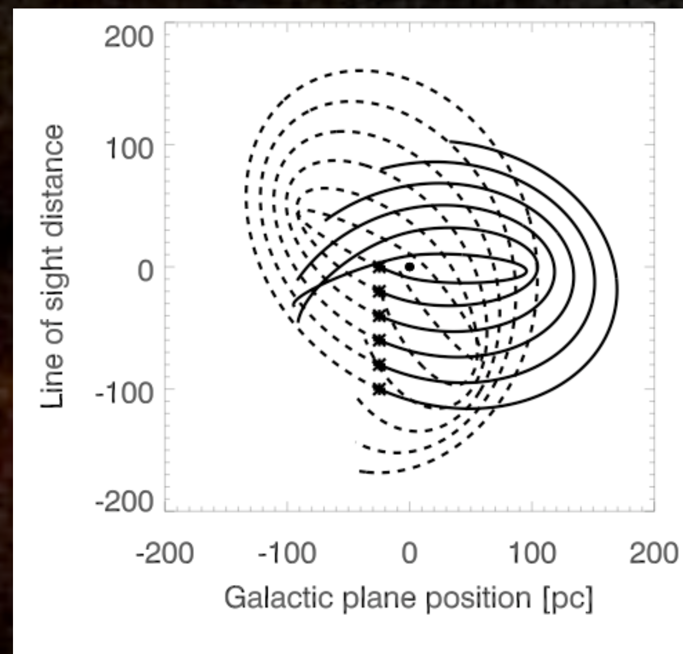
Orbits of Nearby Massive Young Clusters Unlikely to Deposit them at the Center



Also no trail of young stars…

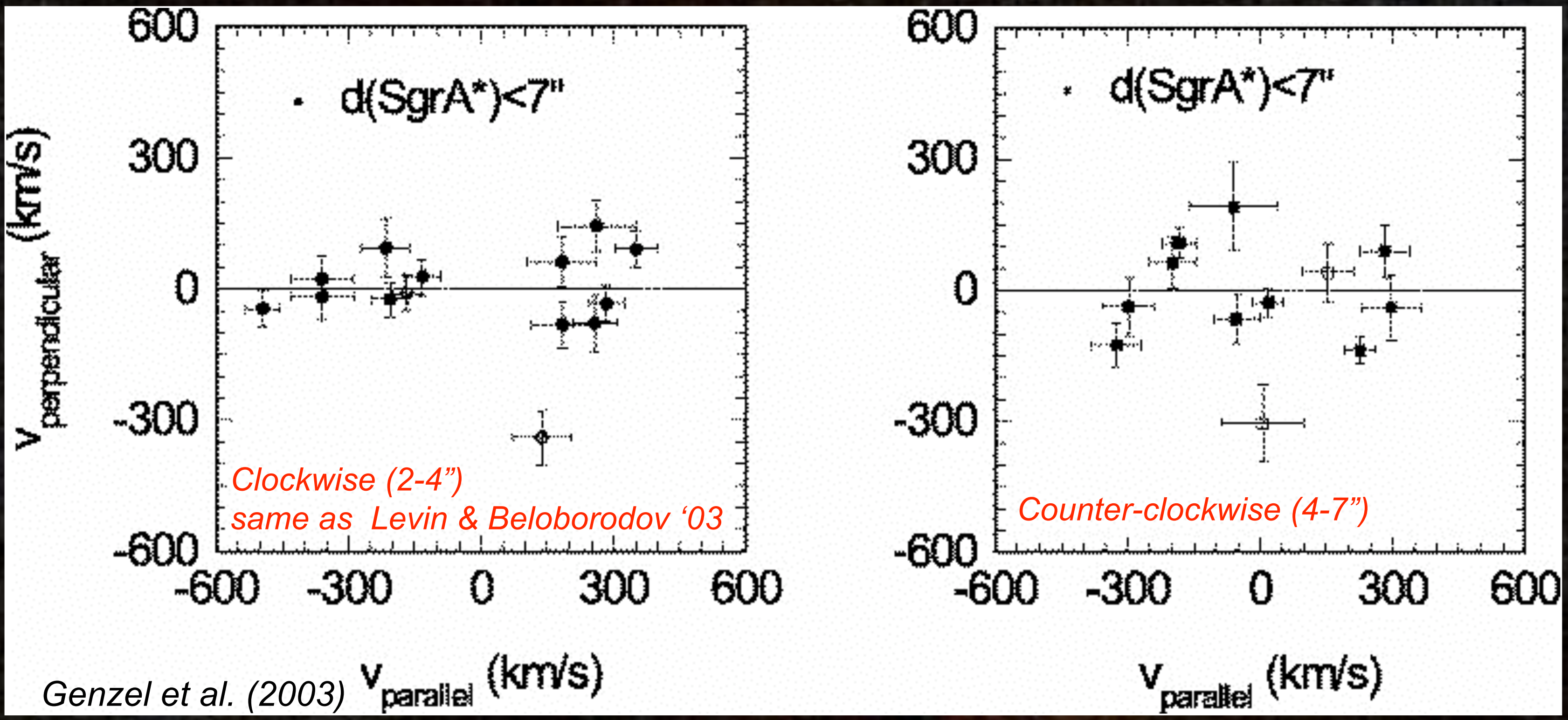
Limits on IMBH will soon be available





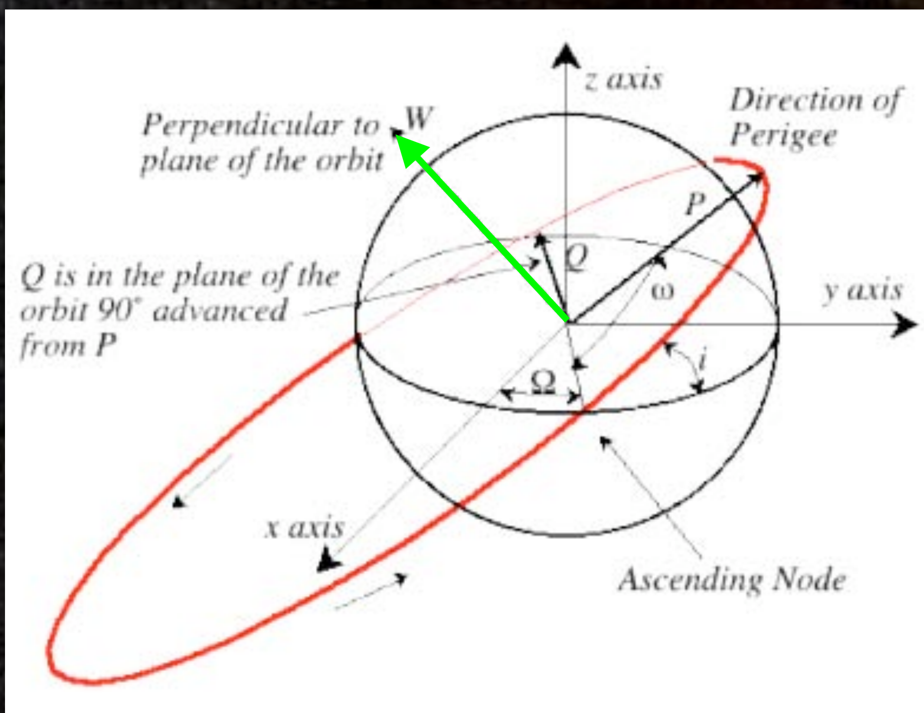
Arches: Stolte, Ghez et al. 2008
Quintuplet: Stolte, Ghez et al. in prep

Statistical Analysis of 3-D Velocities Suggested Presence of Disk(s)



- First (CW) disk is
  - Well-defined
  - Not aligned with any Galactic structure
- Second (CCW) disk is
  - Less well-defined
  - Orthogonal to first
  - Roughly face-on, which is easiest to generate from an isotropic distribution

Stellar Orbits Give a Direct Measure of Orbital Orientation on a Star-by-Star Basis

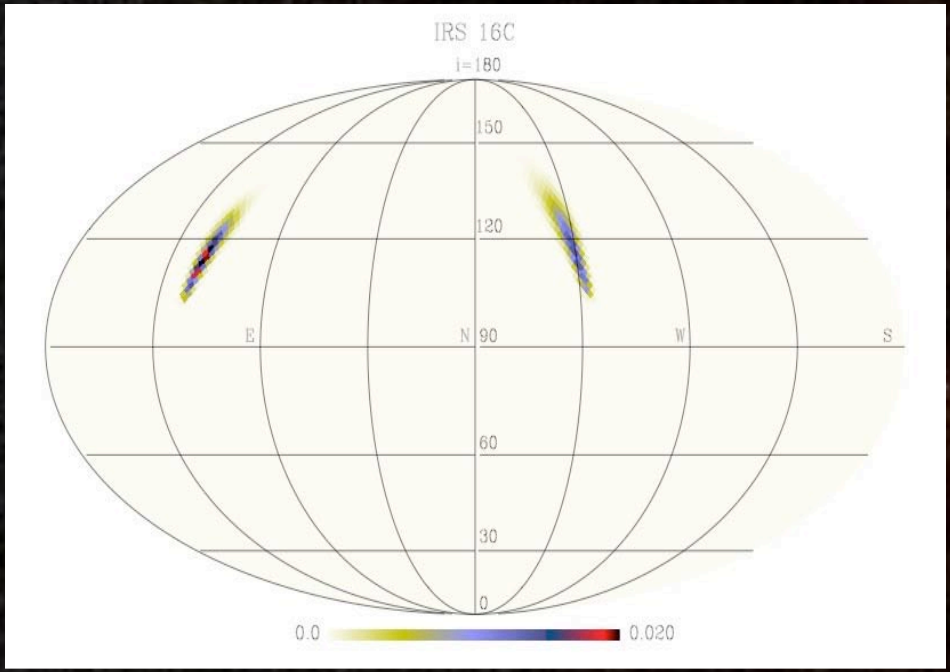


- With known black hole properties, addition of acceleration in the plane of the sky determines orbit
  - 6 unknowns (i, Ω, ω, e, P, To)
  - Need 6 kinematic variables
    - X, Y, V_x, V_y, V_z
    - Z from a_ρ

$$a_\rho = \frac{-GM\rho}{r^3} = \frac{-GM\rho}{(\rho^2 + z^2)^{3/2}}$$

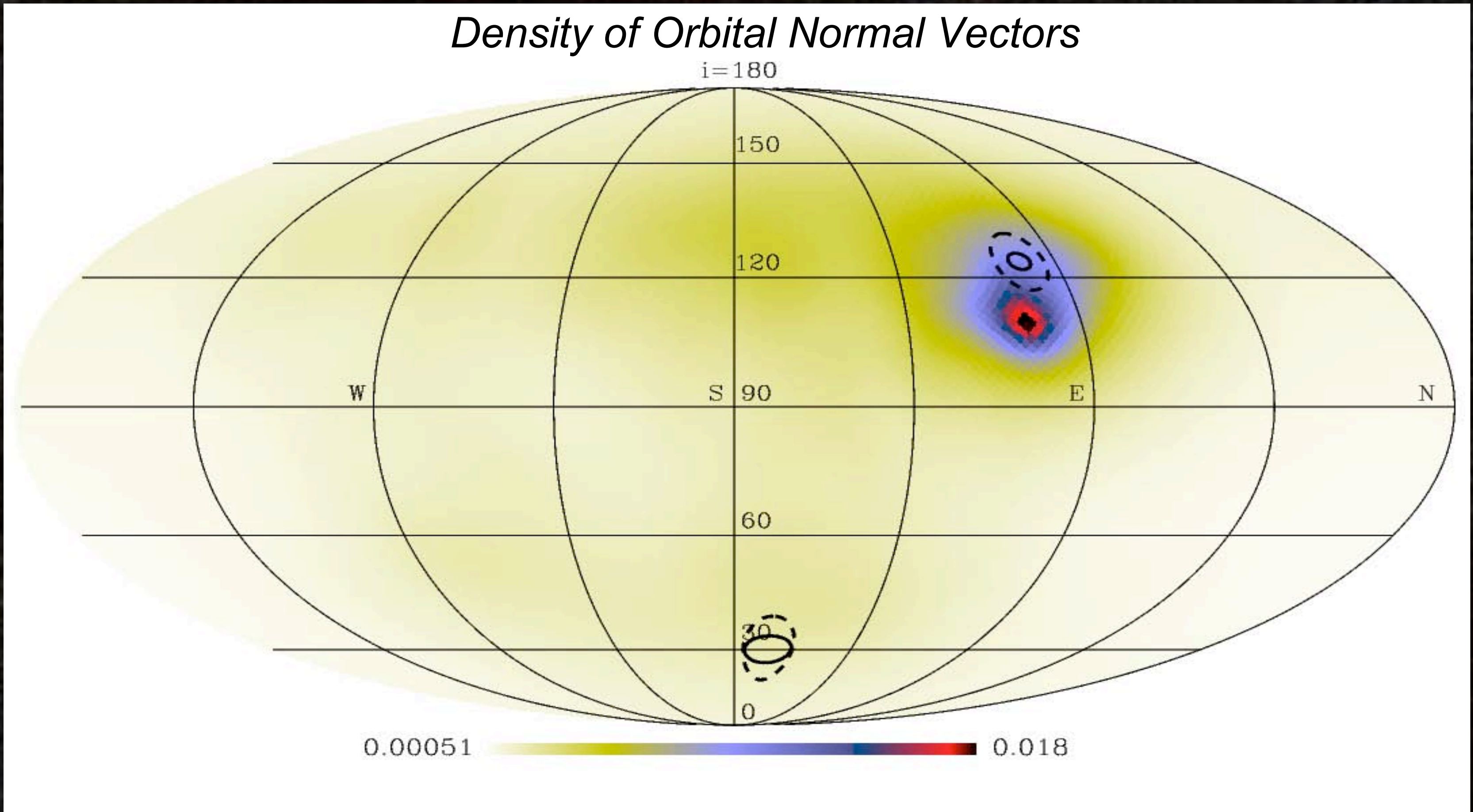
- Need to get beyond 1”!

Each Star Has a Well Constrained Orientation on the Sky



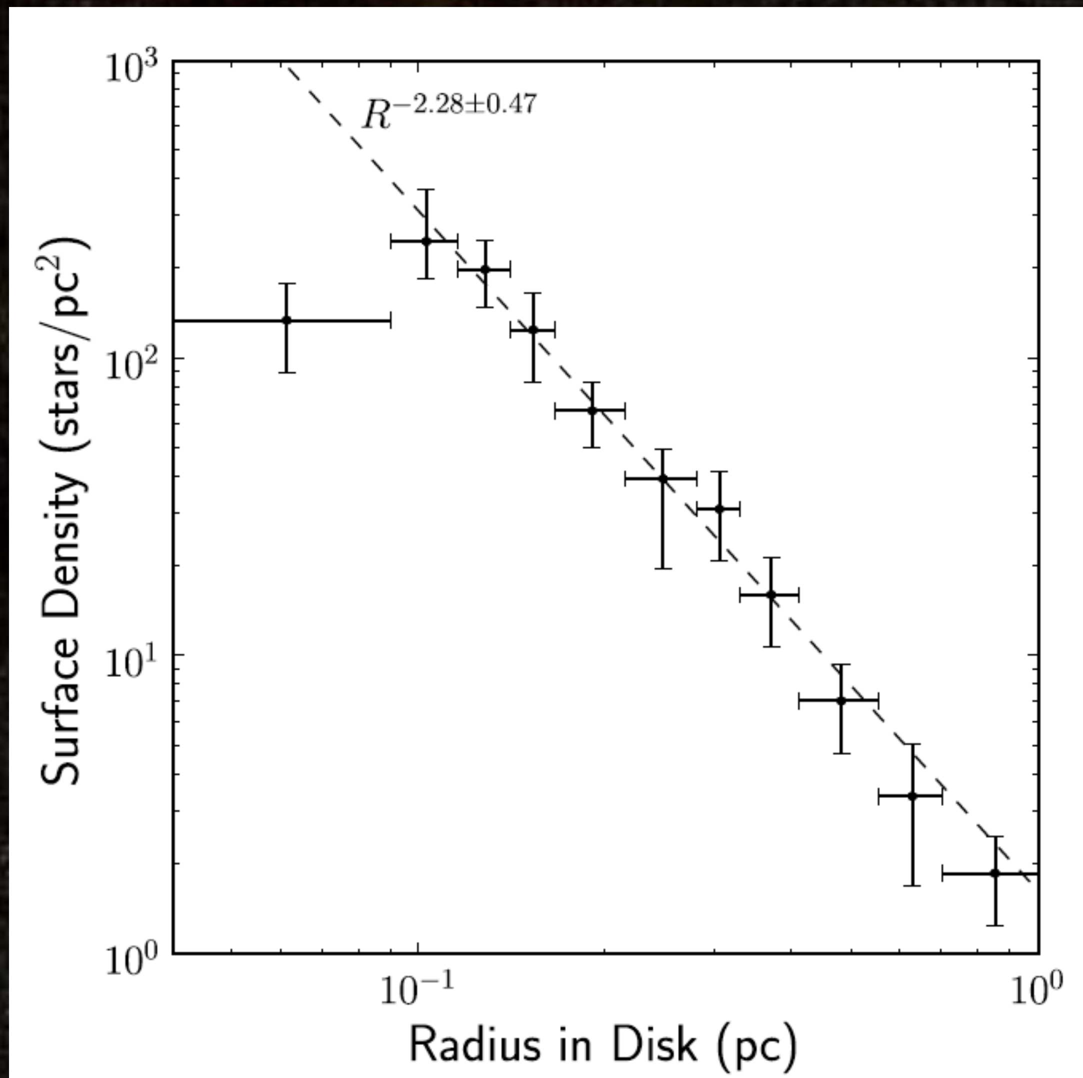
- Probability distribution for direction of normal vector plotted on celestial sphere as seen from Sgr A*.
- Combine results from all stars to test for existence of disks.
- Two solutions from ± z

Stellar Orbits Reveal ~50% of Young Stars in a Single Stellar Disk



Lu, Ghez et al. 2008

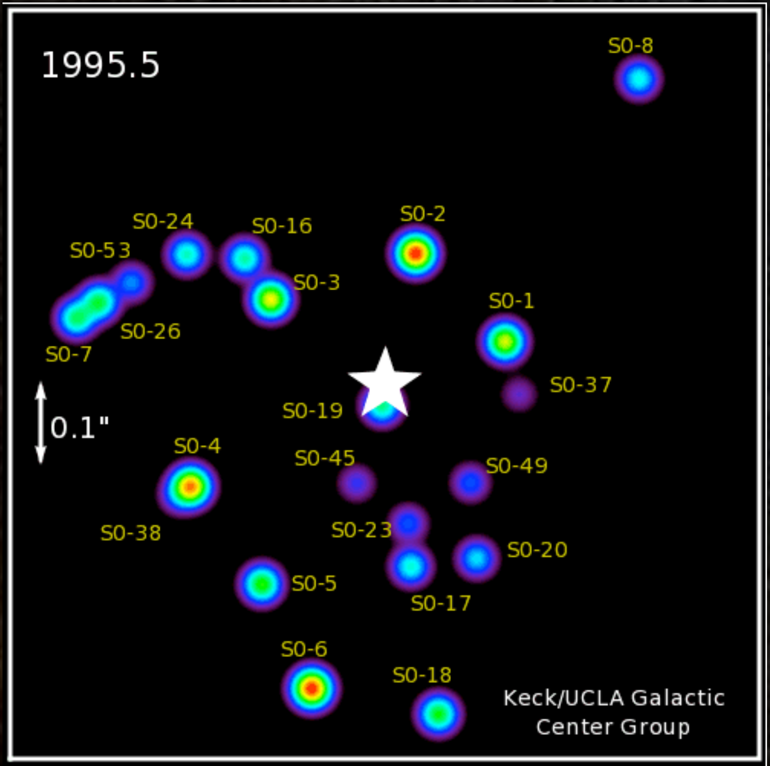
Stellar Surface Density in the Disk Falls Off as r^2

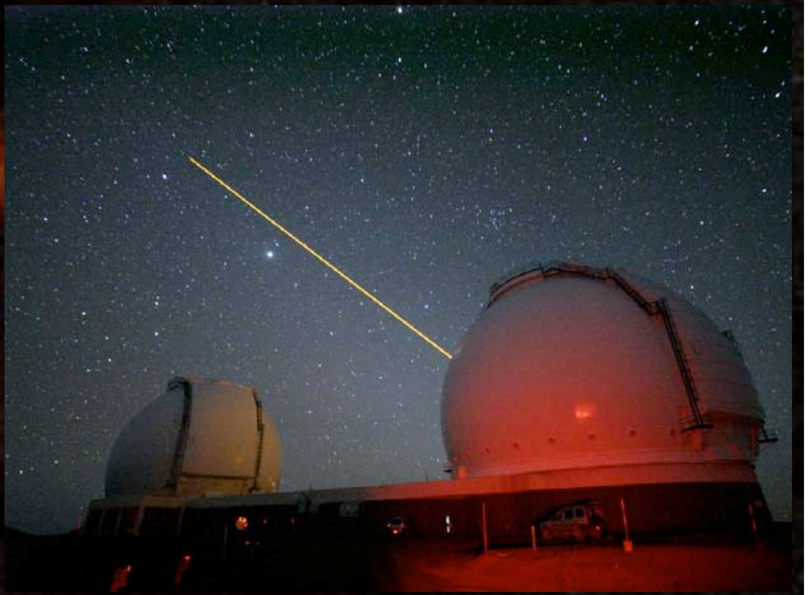


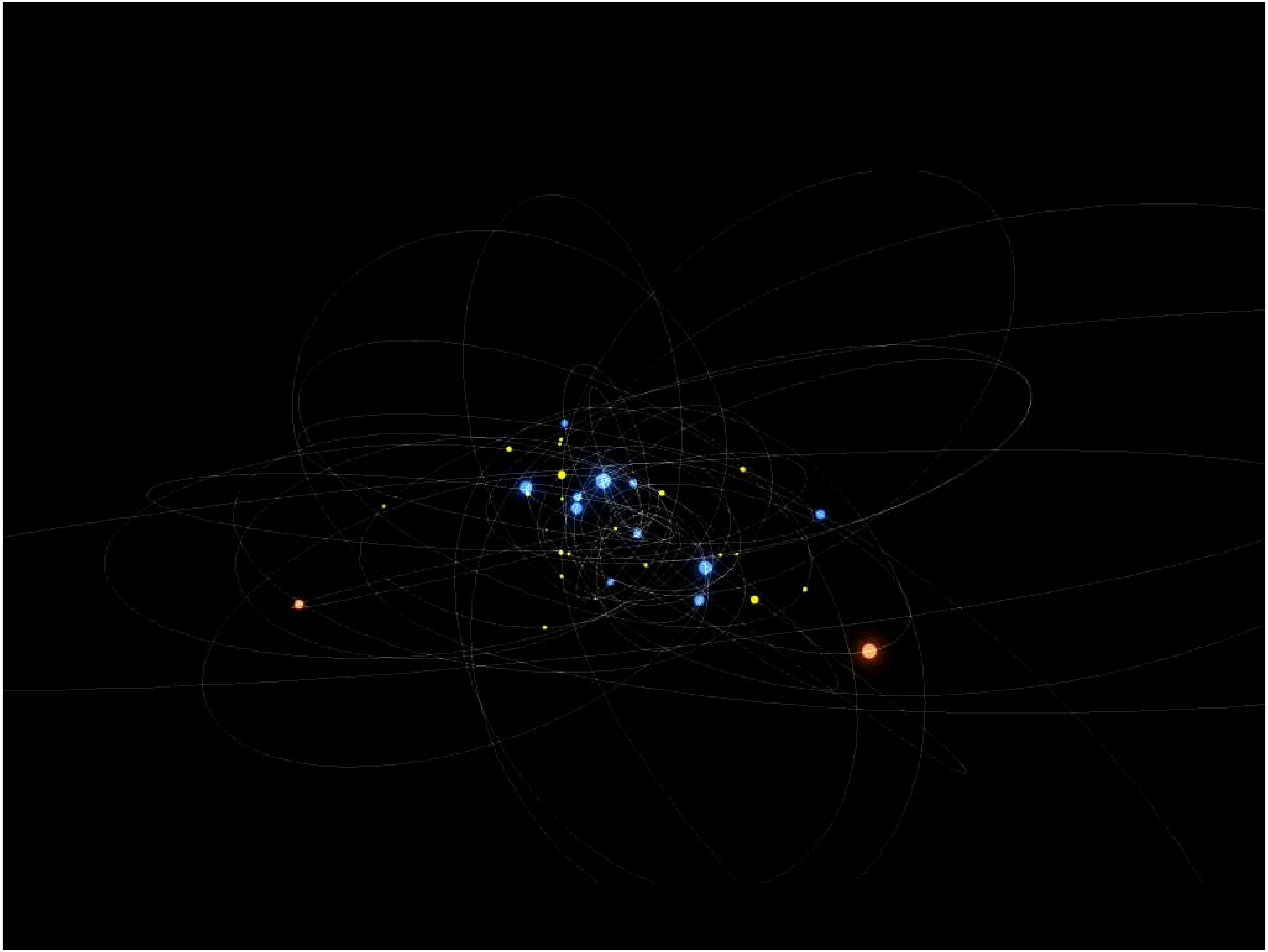
Consistent with fragmentation from disk hypothesis

Conclusions

- **Dramatically improve the case for black hole.**
  - M_{bh} = 4.2 (± 0.4 ± 0.5) x 10^6 M_o
  - R_0 = 8.0 (± 0.4 ± 0.5) kpc
- **IR variations associated with black hole consistent with "red-noise" (no 20 min. QPO)**
- **Star formation does proceed in vicinity of black hole**
  - Roughly 1/2 of known young (~6 x 10^6 yrs old) stars reside in a single thin, nearly ede-on disk (0.04 - 0.4 pc) with $n(r) \alpha r^{-2}$
  - Remaining 1/2 consistent with isotropic distribution
  - Next talk (earlier epochs?)
- **Exciting Future: possibility of deviations from Keplerian orbits (GR test, extended mass, spin?)**





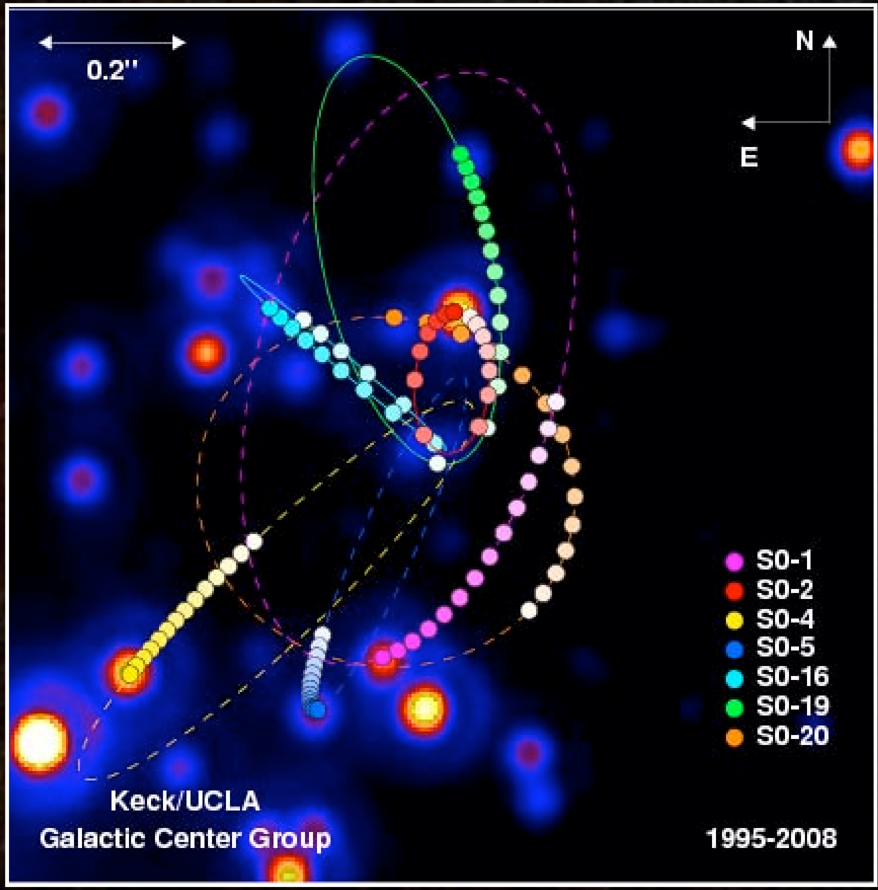


Thoughts

- BH companion
- Reid - theta0
- Doleman
- HVS?
- Why inner hole?

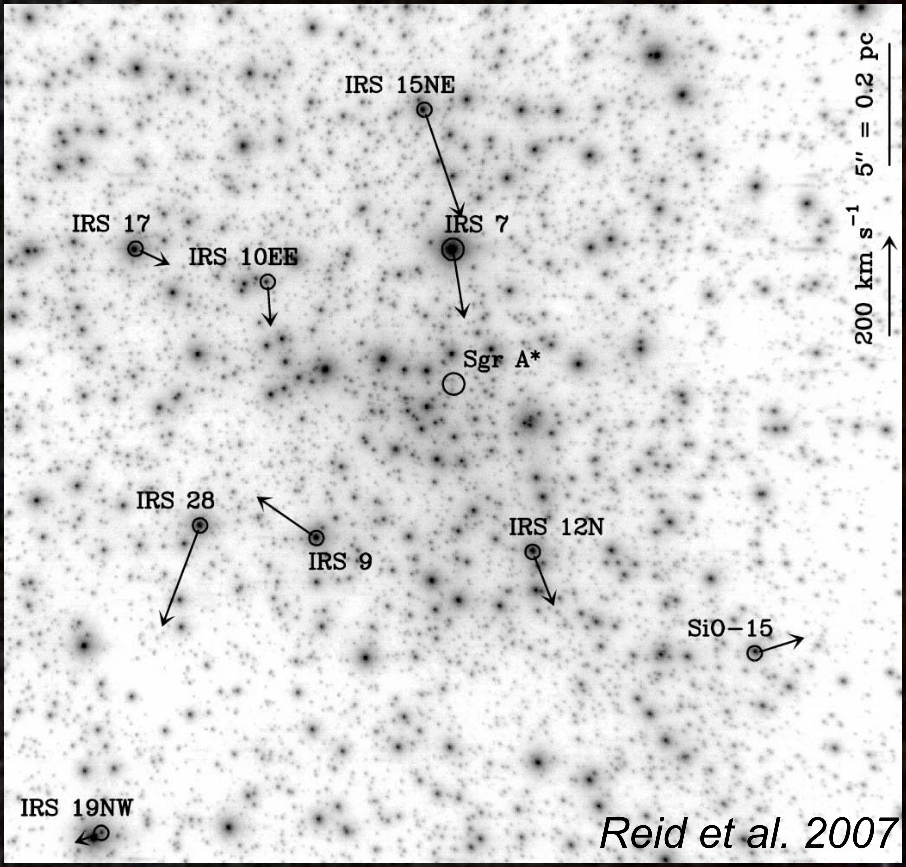
Stellar Orbits Offer Insight into a Number of Key Questions

- Is there a supermassive black hole at the center of our Galaxy?
- If so,
  - What is its mass?
  - How do young stars come to reside in its vicinity?



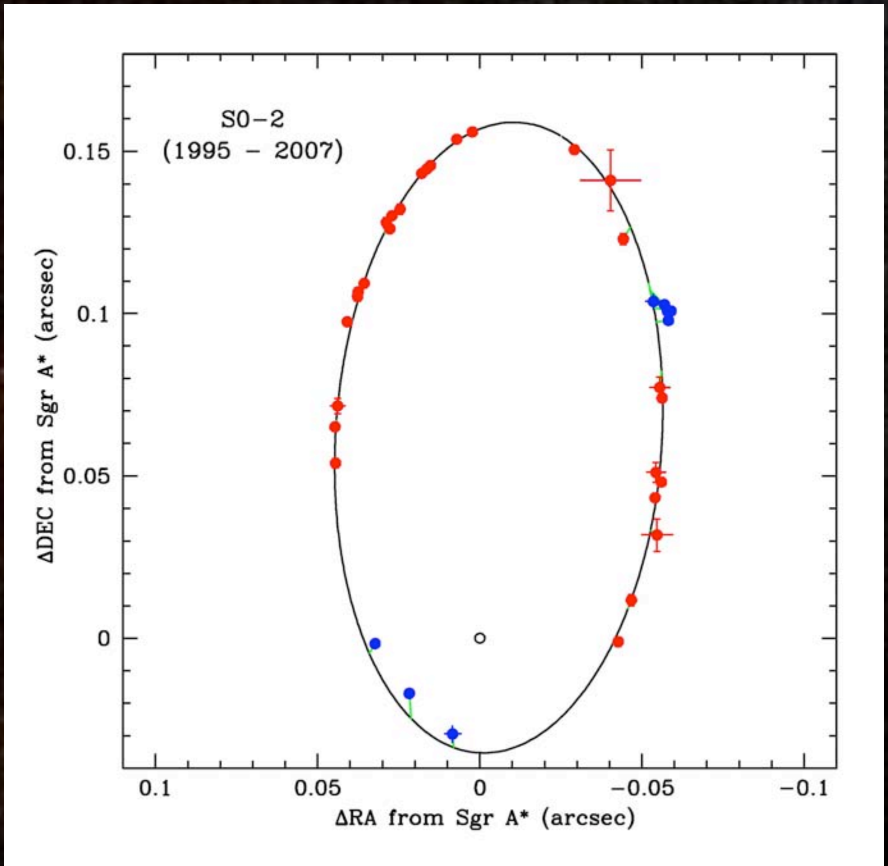
Critical to Account for Biases

Reference Frame Stability



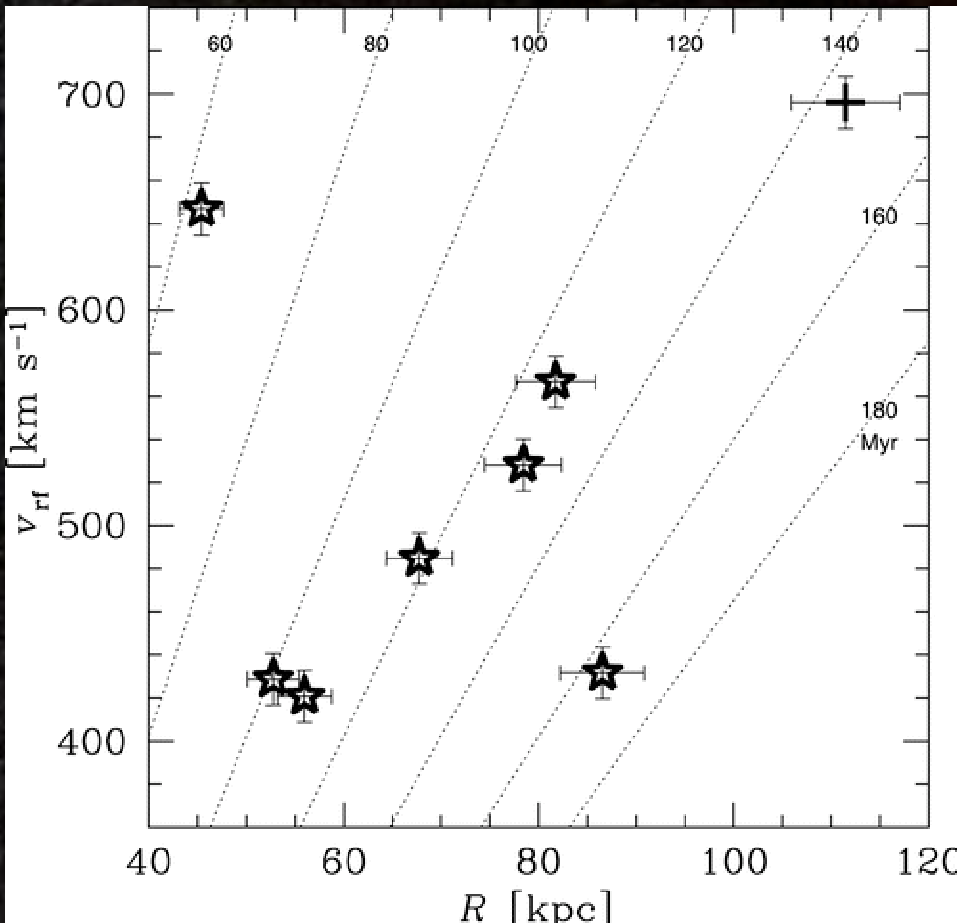
Need ~40"x40" FOV to tie-in to radio (quasar) reference frame via masers

Stellar Confusion



- Known source confused with S0-2
- No known source of confusion

Hyper-velocity B star in Halo Support Previous "Events"



- **B stars in halo targeted** *(Brown et al. 2005, 2007)*
  - **Several found to be moving at faster than escape speed**
  - **Origin consistent with Galactic center**
  - **Travel time > a few Myr (age of stellar disk population)**
- **Three body interactions with central black hole are likely explanation** *(e.g., Ginsberg & Loeb 2007)*
- **Relevant to mechanism to create more distributed nuclear star cluster?**