Sgr A*

Mark Reid Harvard-Smithsonian CfA

Where is it?

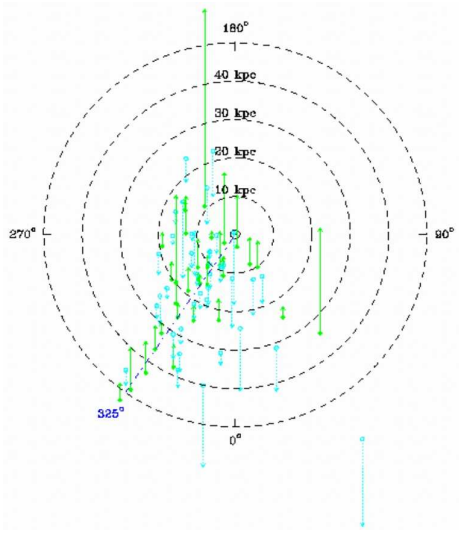
Does it move?

Karl Menten
Reinhard Genzel
Thomas Ott
Rainer Schoedel
Andreas Eckart

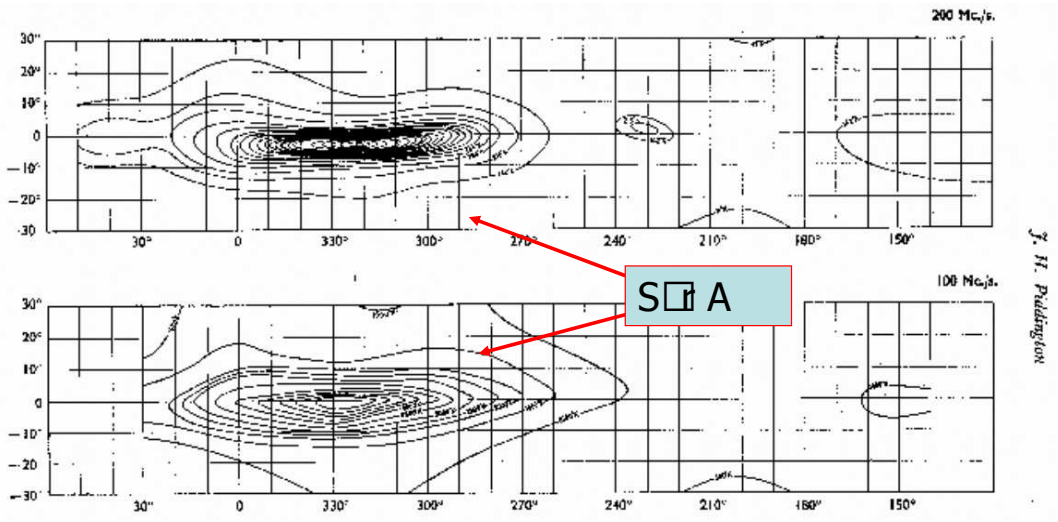
Andreas Brunthaler

Discovery of Galactic Center

- Sha□le□□□□□□□□
  Glo□ular □lusters □□oint□to
  Galactic □enter
- R_o □ □□k□t



Early Radio Observations



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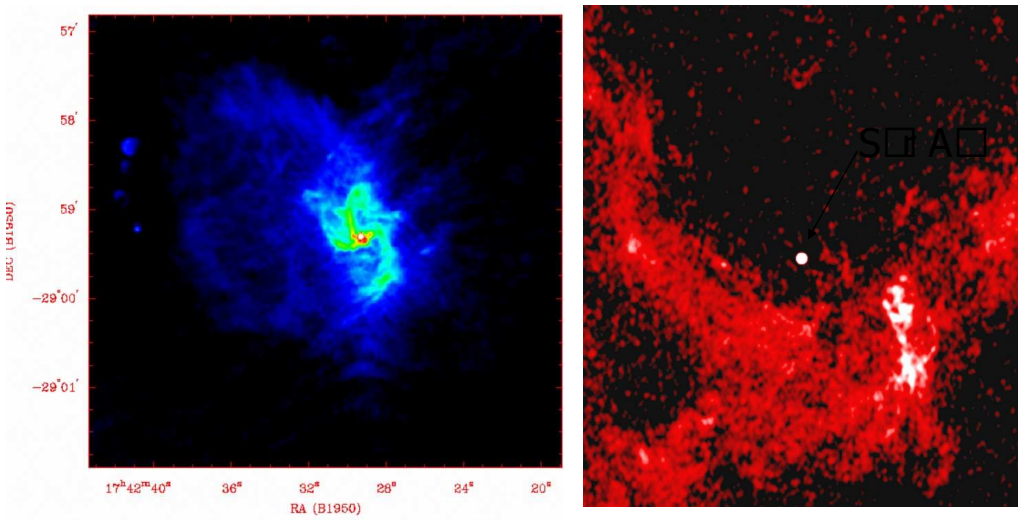
Brief History of Sgr A*

- Balick & Brown (1974) Discover Sgr A*:
  "Intense Sub-Arcsecond Structure"

- Lo et al (1985) Sgr A* < 20 AU
- Backer et al (1993) < 3 AU

- Rogers et al (1994)
  Krichbaum et al (1998) < 1 AU
  Doeleman et al (2001)
  Bower et al (2004)

VLA Images of Sgr A

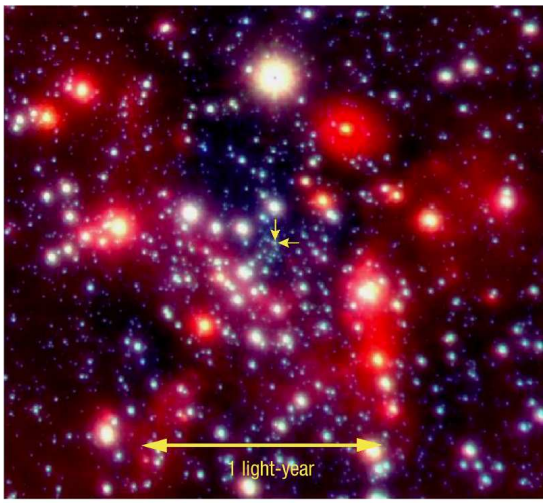


□□□ □hao

IR Image of GC

□□□□um ima□e

□□here is S□r A□□



The Centre of the Milky Way
(VLT YEPUN + NACO)
ESO PR Photo 23a/02 (9 October 2002) ©European Southern Observatory

7 Questions:

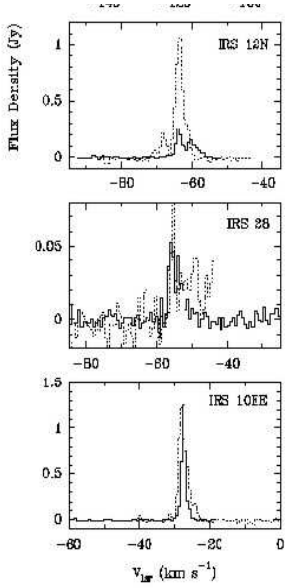
- Is Sgr A* at the center of the stellar cluster?
- Is the stellar cluster tied to Sgr A*?
- Is Sgr A* at the dynamical center of the Galaxy?
- Does Sgr A* have a peculiar motion?
- Does Sgr A* have all the mass sensed by stars?
- Could exotic dark matter dominate the G. C. mass?
- Can intermediate mass black holes be in the G. C.?

Radio/IR frame alignment

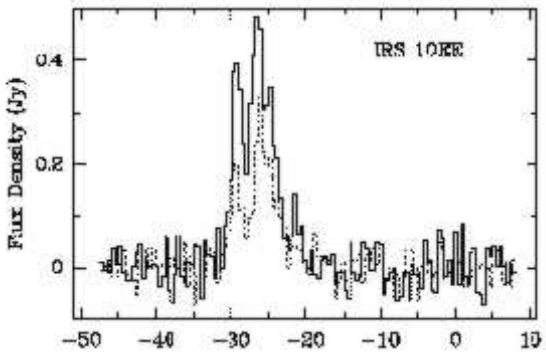
- Use stars visible in both Radio and IR:
  Red Giants with masers
- Compare Radio and IR positions:
  Solve for IR plate scale & rotation;
  Align IR with Radio to find Sgr A*

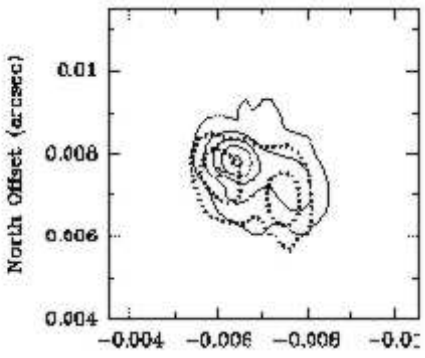
VLA positions for stars

- SiO masers
- positions to mas
- mas/yr motions in years



VLBA proper motions



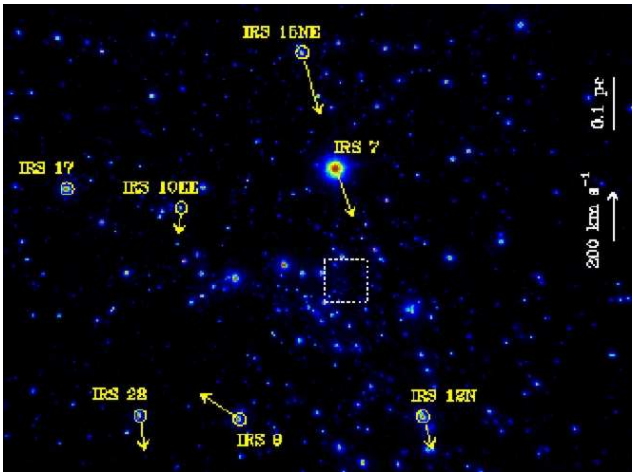


Reid et al

- Su mas positions
- mas/yr motions in months

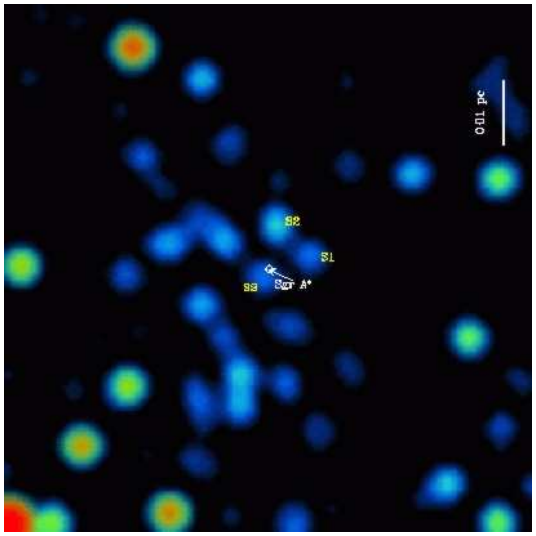
Stellar positions & motions

- SiO maser stars
- positions mas
- motions km/s



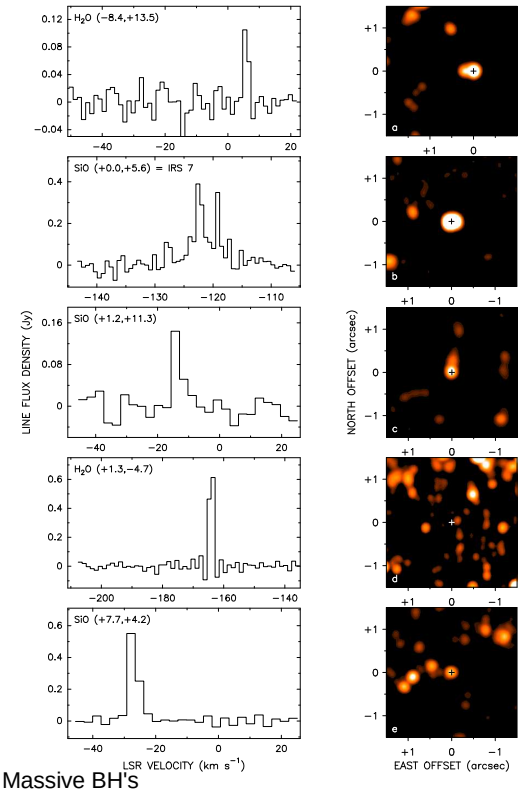
Where was Sgr A* in 1995

- mas accurac
- Bet een stars
  - S S S
- Sgr A m



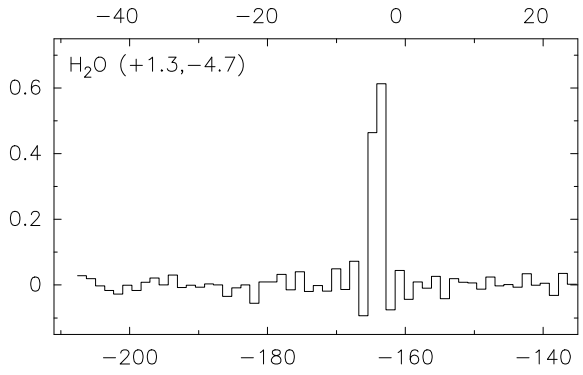
Stellar or Star Forming Masers?

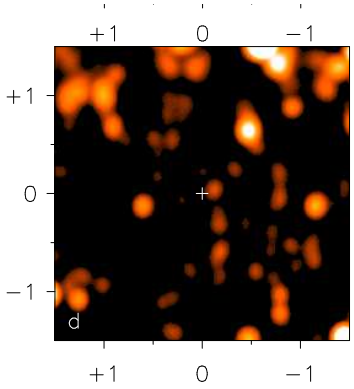
- SiO masers => Red Giant stars
- H_2O masers either RG stars or star forming regions



Menten, Reid, Eckart & Genzel (1997)

Star Forming Region H_2O Maser





- No IR source
- Projected only 5” (0.2 pc) from Sgr A*
- V(LSR) = -165 km/s

VLT with Adaptive Optics

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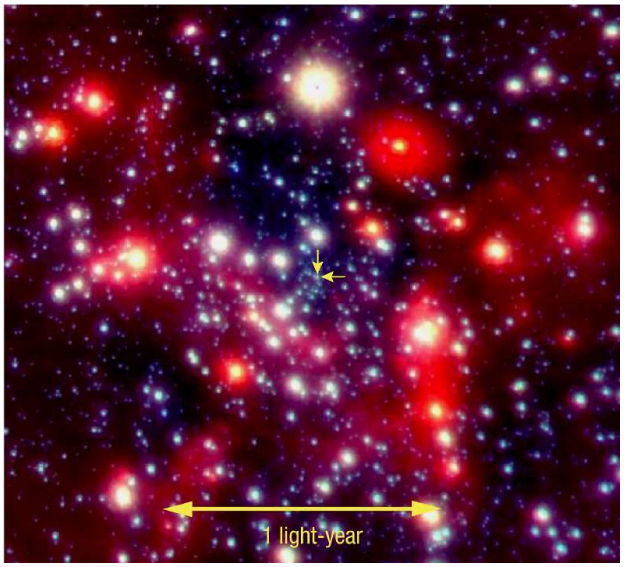

Where was Sgr A* in 2002

□S□r A□□osition□□□mas
Reid et al □□□□□□□
□Star □S□□
seen at □e□icenter □assa□e
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Or□it determined
Schoedel et al □□□□□□□

S2's orbit

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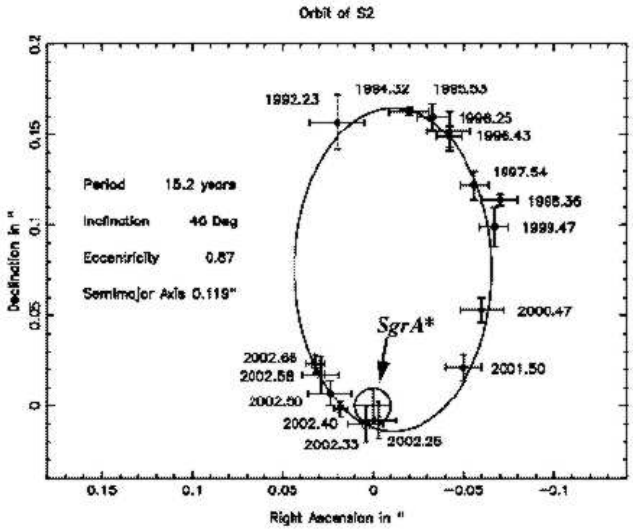


□Schoedel et al □□□□□□

Stellar Orbits

□□stars □th or□its

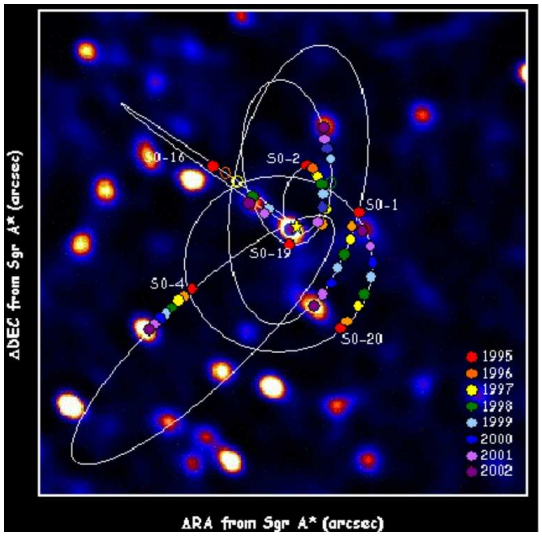
□Enclosed mass□

□□□□□M_{sun}

□thin □□□□A□radius

□S□r A□□thin □□□□A□

Ghez et al



Question 1:

- Is Sgr A* at the center of the stellar cluster?
  Yes… to better than 10 mas (80 AU)

Radio/IR frame alignment

- Compare Radio(SiO) and IR positions:

- Compare Radio(SiO) and IR motions:
  SiO maser motions relative to Sgr A*
  Tie IR motions to Sgr A*

Velocity Alignment

East,North proper motions in mas/yr

Star	Radio	Infrared	Difference
IRS 9	+3.6,+2.4	+2.0,+0.5	+1.6 (0.7),+1.9 (1.2)
IRS 7	-1.6,-4.5	-0.8,-3.6	-0.8 (1.0),-0.9 (3.5)
IRS 12	-0.8,-2.8	-3.3,-0.8	+2.4 (0.5),-2.0 (0.8)
IRS 10	+0.2,-2.1	+0.1,-2.2	+0.1 (0.4),+0.1 (1.0)
Unweighted mean (sem)			+0.8 (0.8),-0.25(1.0)

□mas□□r □ □□km□s

□□entral star cluster mo□es □th S□r A□to □□□km□s

Question 2:

- Is the stellar cluster tied to Sgr A*?

  Yes… to better than 70 (35) km/s

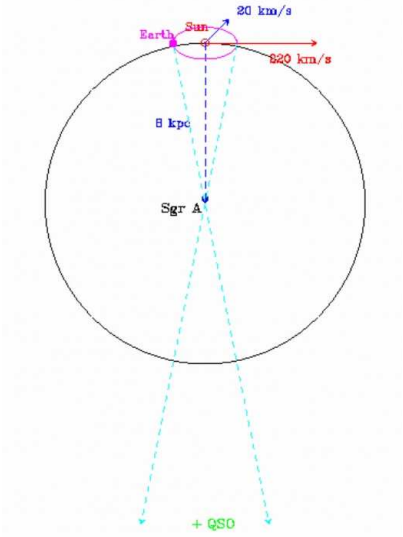
Proper Motion of Sgr A*

Sun's Galactic Orbit

Mass Period

km/s / kpc

mas/yr

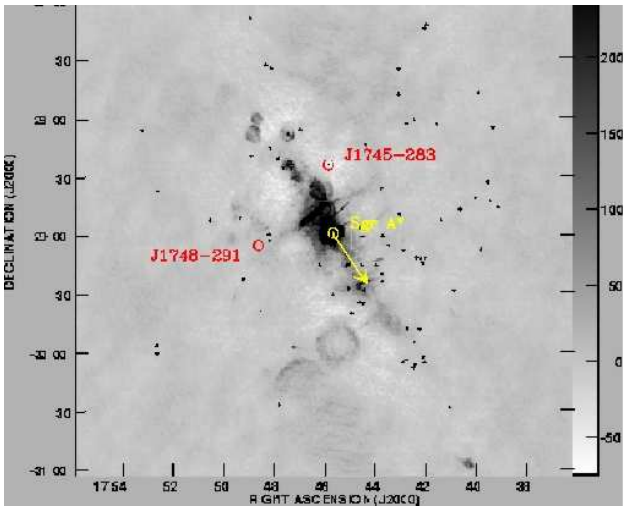


Project History

- 1979: Proposal to US VLBI Network
  - "To Study Feasibility of Detecting Proper Motion of the Galactic Center"
  - 15 GHz; OVRO, HRAS, GB, Haystack
  - Failed:
    - Scatter broadened Sgr A*
    - Limited sensitivity
- Needed VLBA !

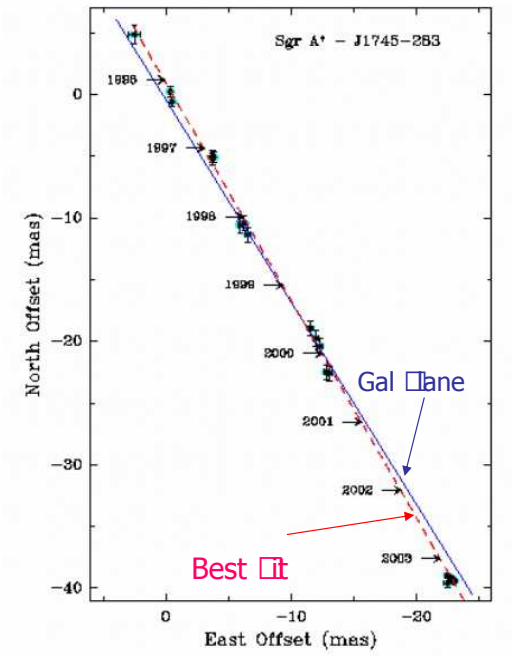
Sgr A*'s apparent motion

- Relative to Quasars
- Sun's Galactic Orbit
  - 220 km/s at 8.0 kpc
  - 6 mas/yr in Gal Plane



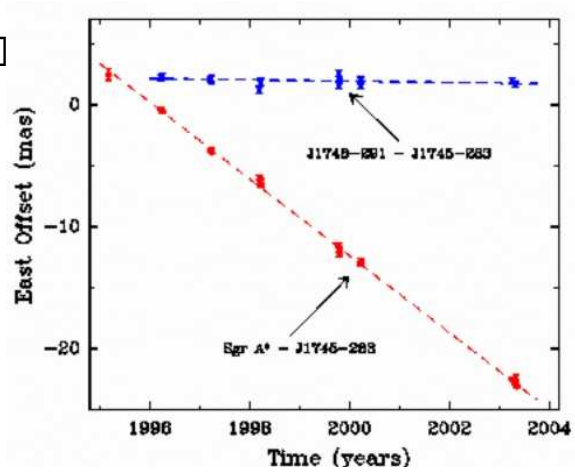
Sgr A*'s Apparent Motion

- Moves mostly along Galactic Plane
- Slight deviation from Sun's



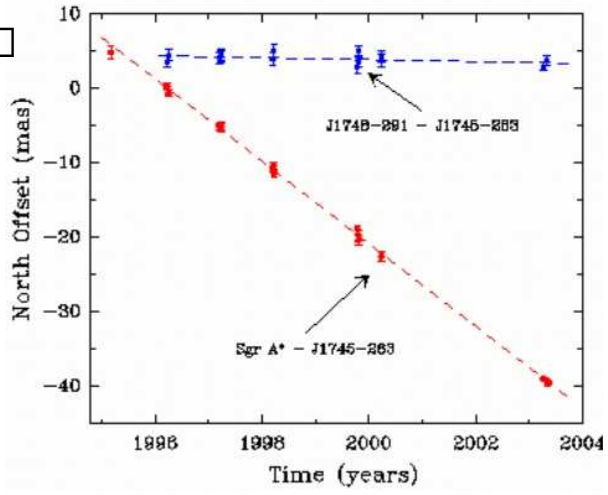
Eastward Motion

- Sgr A drifts smoothly
- QSOs don't move



Northward Motion

- Sgr A drifts smoothly
- QSO don't move
- But error bars larger than eastward positions



Sgr A* motion Galactic Coords:

□Motion in Galactic □lane□

Θ_o/R_o □ □□□□□□□□□□km□s□k□c

□om□are to

□A□B□R_o□ □□□□□□□□□□km□s□k□c

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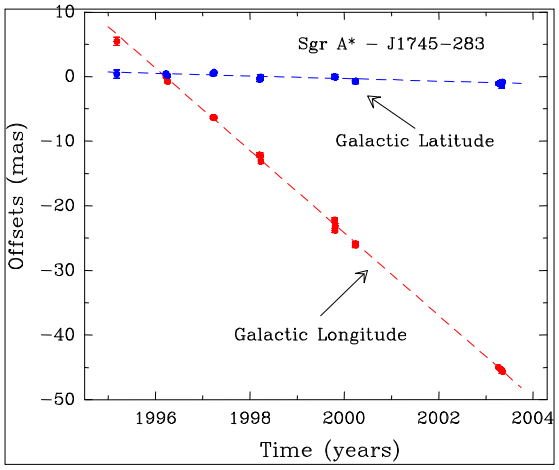
□Motion out o□Galactic □lane□

□er□small□



Question 3:

- Is Sgr A* at the dynamical center of the Galaxy?
  Yes… to within our knowledge of Θ_o/R_o

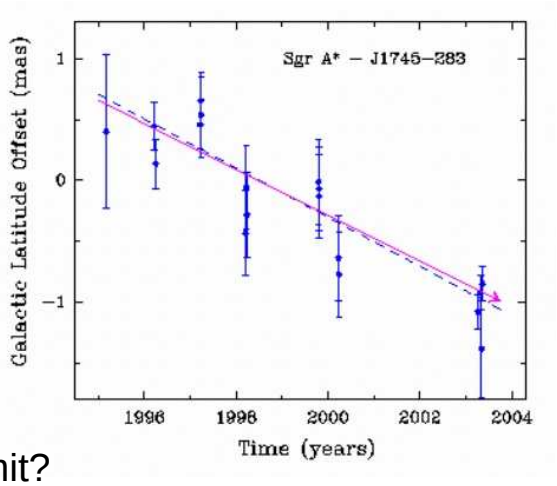
Sgr A* motion toward Galactic Pole

□Solar Motion □□□km□s

□S□r A□s □eculiar motion

□□□□□□□□□km□s

• Sgr A* must be massive!



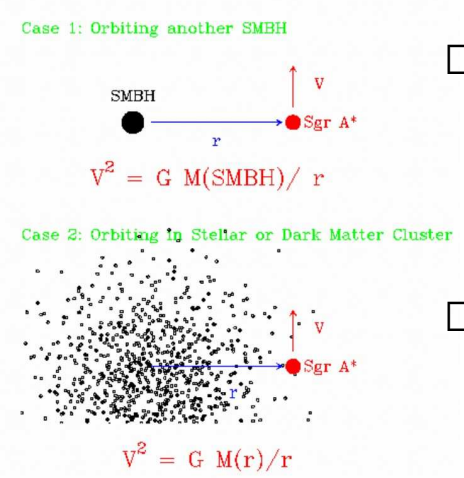
Can we quantify a mass limit?

Question 4:

- Does Sgr A* have a peculiar motion?

  No … less than 1.8 km/s (out of Plane)

If Sgr A* is not a SMBH…



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□eca□s □□Gra□Radiation
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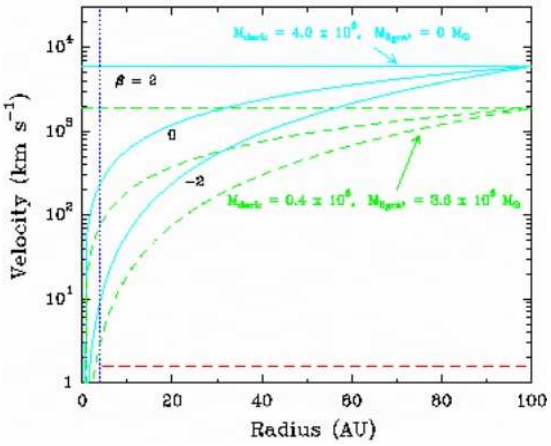
e□□□densit□□o□er la□□p ~ $1/r^{\beta}$

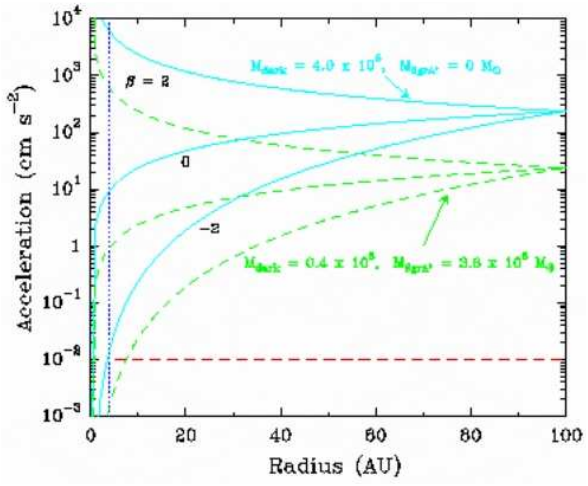
If Sgr A* is not a SMBH…

□□□□ □km□s □or an□
dark matter distri□ution□
unless M_{dark} □□



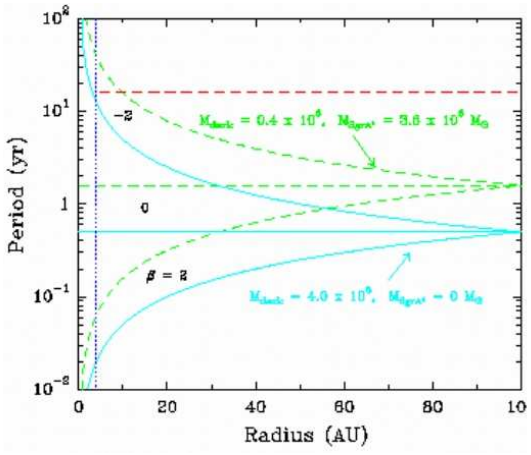
If Sgr A* is not a SMBH…

- Accel □□ □□ cm s□
- □□ould □e easil□ o□ser□ed □ □□ □



Sgr A* “orbital period”

- Measured □□□ A□ not sensiti□e to □□□□□rs
- □Essentiall□ all dark mass distri□utions □i□e □□□□□rs



But □all is not lost□

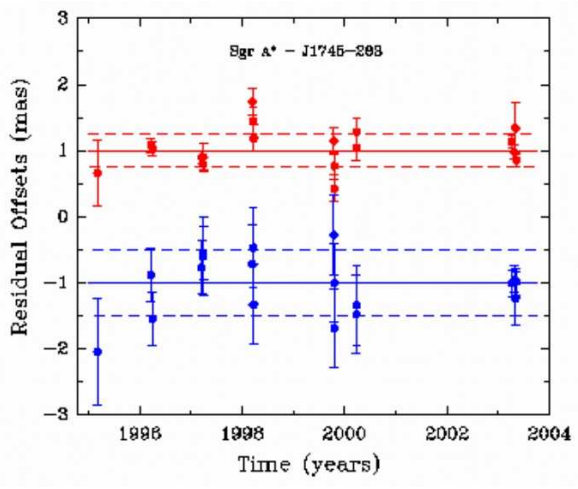
Sgr A* position excursions

□□ould easil□see
□osition e□cursions□
□□□□□mas □□A□□n RA□
□□□□mas □□A□□n □ec

□S□r A□must either

i□□□□□□□M$_{sun}$

ii□□□ound□□thin □A□



BH Brownian motion:

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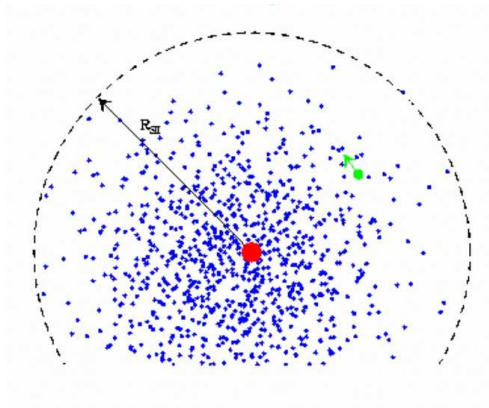


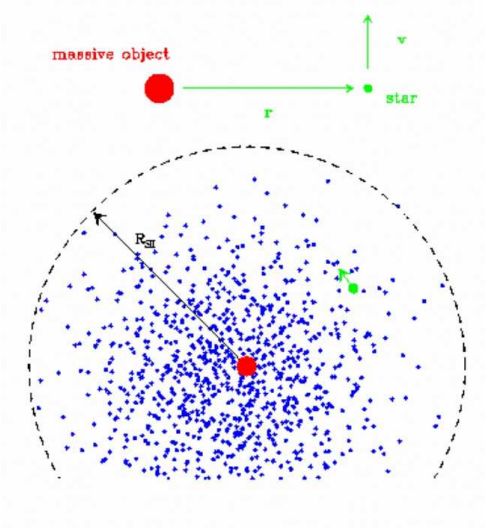
Stars orbiting Sgr A*

- Consider star orbiting a massive object

$$M \gg m$$

- Add in large number of stars → random fluctuations like

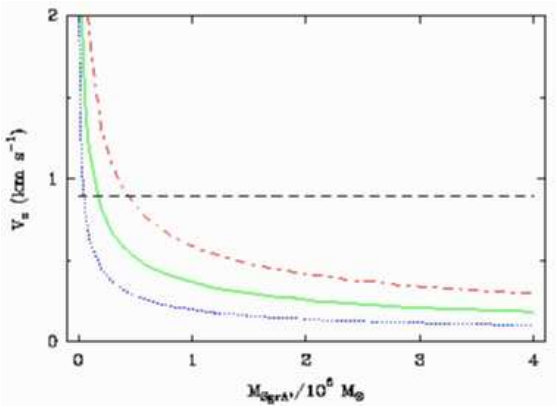
$$M \pm \sqrt{N}\, m \pm \sqrt{N}$$



Effect of Bound Stars on Sgr A*

Recipe

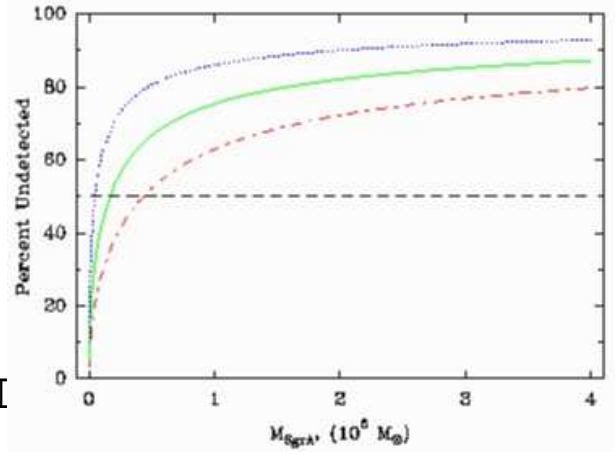
- Put 10^4 stars in computer
- Place SMBH at center of mass of system
- Solve Kepler's Eq for each star
- Calculate COM after 10^2 years
- Determine position then velocity of SMBH
- Repeat as needed to get σ_{rms}



for different stellar IMFs

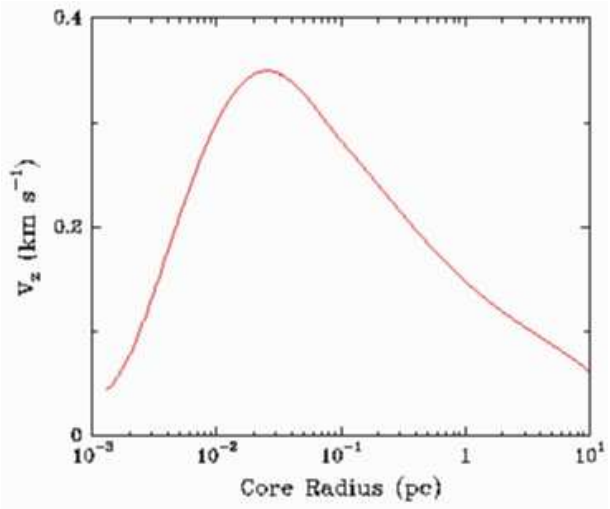
Sgra A* must be massive…

- Compare simulated systems with trial measurements
- Sgr A*'s mass (M_{sun})
  - Best estimate
  - 90% confidence
- Even conservative calculations favored effects of M_{sun} cluster in 1' stars



Cluster of Stellar Remnants

- Expect stellar remnants in GC
- Rich stellar orbits allow remnants
  - Moualad Eckart et al
- Calculate effect on orbits with star in core radii
- V_z 1 km/s possible
  - Comparable to observed stars



Question 5:

- Does Sgr A* have all the gravitational mass?
  Probably … current est. >10% of $4 \times 10^6 M_{sun}$

Bayesian Approach:
Laun & Merritt (2004)

- Expected Vz of 0.1 km/s
- Median value Vz < 0.9 km/s is $10^5 M_{sun}$

Dark Matter:

- Could exotic dark matter dominate the G.C. mass?
  Not likely… $>10^6$ M_{sun} within 4 AU hard to do
- Tied radiative source to the mass…
  "Fermion ball" probably can't give Sgr A*'s SED
- First time a large mass tied directly to an AGN

Intermediate Mass Black Holes:

- SMBH (Sgr A*) – IMBH "binary":

$$V_{SgrA} \sim (M_{IMBH}/M_{SgrA})\, V_{IMBH}$$

$$\sim 1.5 \text{ km/s } (M_{IMBH}/10^4\ M_{sun}) / (r/10^4 \text{ AU})$$

- Combining orbital excursions and velocity of Sgr A*, intermediate mass black holes constrained:
  $M<10^4\ M_{sun}$ for $10^3 < r < 10^5$ AU (~0.005-0.5pc)
  (Hansen & Milosavljevic 2003)
- Caveat: Only for motion out of Galactic plane.
  IRS 16 SW out of plane
  IRS 13 near plane, but motion not in plane

7 Questions: 7 Answers

- Is Sgr A* at the center of the stellar cluster?
  Yes … to within 10 milli-arcsec
- Is the stellar cluster tied to Sgr A*?
  Yes … to within 70 km/s
- Is Sgr A* at the dynamical center of the Galaxy?
  Yes … to within our knowledge of Θo/Ro
- Does Sgr A* have a peculiar motion?
  No … less than 1.8 km/s
- Does Sgr A* have all the mass sensed by stars?
  Probably … (>10% and "rising")
- Could exotic dark matter dominate the G. C. mass?
  Not likely … (density too extreme; can't give SED)
- Can intermediate mass black holes exist in G. C.?
  IMBHs > 10^4 Msun unlikely between 0.005 – 0.5 pc

Must Sgr A* be a SMBH?

Object	Density (M_{sun}/pc^3)	Method	Mass & Radius
M 87	2×10^6	HST:	3×10^9 M_{sun} in 7 pc
NGC 4258	7×10^9	VLBA : H_2O	3×10^7 M_{sun} in 0.1 pc
Sgr A*	2×10^{17}	S2's orbit	4×10^6 M_{sun} in 45 AU
Sgr A*	2×10^{19}	excursions	4×10^6 M_{sun} in 4 AU
Sgr A*	7×10^{21}	proper motion	4×10^5 M_{sun} in 0.5 AU
SMBH	2×10^{25}	R_{sch}	4×10^6 M_{sun} in 0.08 AU

(10μas @ 8kpc)

VLBI (eg, SMA-ALMA-LMT-CARMA…) @ 1 mm -> 20 uas

The Utimate Proof/Prize

- Image SMBH with resolution R_{Sch}
- Show all of the mass is contained within R_{Sch}
- See how accretion disk, black hole and jets work