Sgr A*: How massive is it really?

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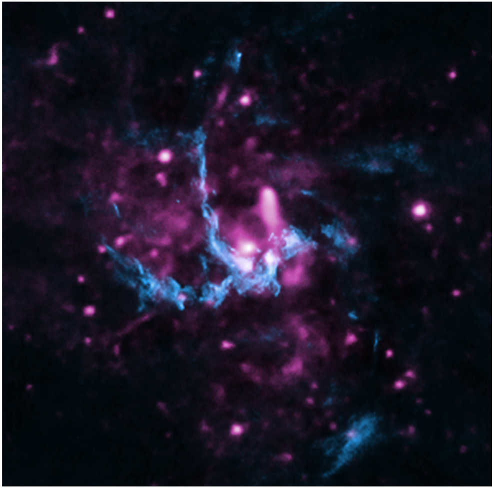
Content

1. Why do we think Sgr A* is a supermassive black hole (SMBH)?
2. How do we measure the mass of Sgr A*?
3. Suppose the black hole is cloaked in dark matter (stellar remnants, stars yet to be discovered, dust, DM...)

The radio and X-ray sky

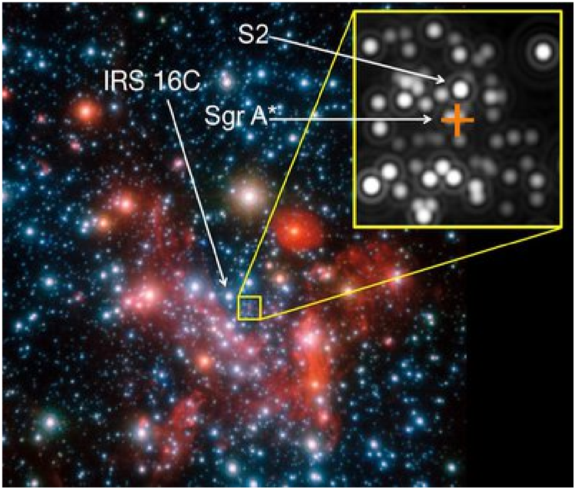
(X-ray: NASA/CXC/UCLA/Z.Li et al; Radio: NRAO/VLA)



- ⋆ image is 1.2 arcmin accross
- ⋆ radio emission from the inner 10 arcsec ($\approx$ 0.3pc $\approx 10^4$ AU) show a compact source
- ⋆ here also visible: a jet and three arms
- ⋆ Sgr A* is X-ray bright at the compact source, shock fronts in the eastern arm

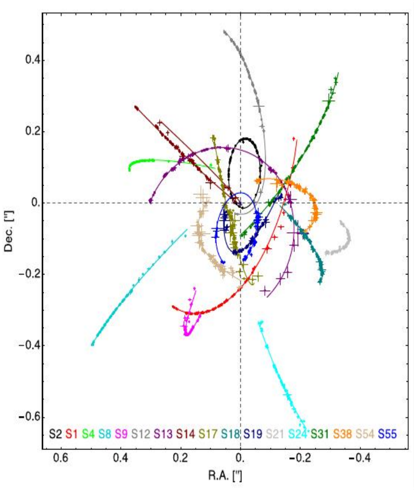
1. Proper motion of stars

(GC in HKL-bands, NACO/VLT, Gillessen et al)



1. Proper motion of stars

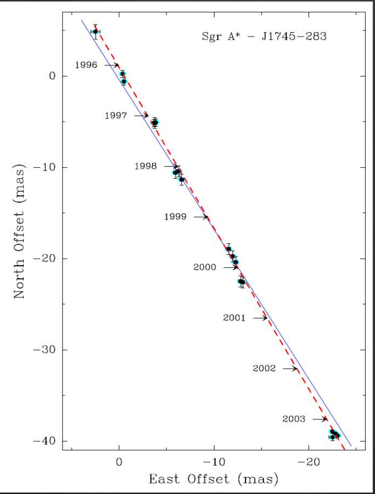
(Gillessen et al, 2016)



- ⋆ The proper motion of stars within 1" of Sgr A* show: they move extremely fast, some > 1000 km/s
- ⋆ We know one complete orbit (S2 star, see Marion's talk) that indicates a dark mass of $4 \times 10^6 M_\odot$
- ⋆ so far: consistent with Keplerian orbit
- ⋆ This mass is contained within 100 AU (pericenter of S2)

2. Sgr A* proper motion

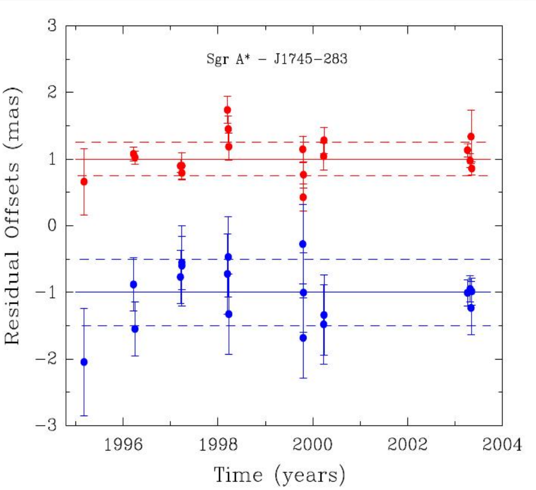
(Reid et al 2004)



- The proper motion of Sgr A* measured against an extra galactic quasar over 8 years showed: Sgr A* moves with 6 mas/yr
- The sun moves with 220 km/s at 8kpc around Sgr A* - this accounts for the 6 mas/yr
- subtracting the sun's orbital motion: Sgr A* is stationary within 1 km/s
- low speed $\Rightarrow$ high mass, at least 10% of $4 \times 10^6 M_\odot$ within 100 AU

2. Sgr A* proper motion

(Reid et al 2004)



- ⋆ Residual offsets of Sgr A* relative to a distant quasar in east (red) and north (blue) direction
- ⋆ Sgr A* shows short-period position excursions, larger in northern direction
- ⋆ what causes this wobbling?

3. Is Sgr A* home alone?

Sgr A* has a size of about 1 AU but it wobbles - bound within about 4 AU - and has at least a mass of 10% of $4 \times 10^6 M_\odot$

- $\star$ Could Sgr A* have a SMBH binary companion?
  - NO, they would coalesce due to GW in $<< 10^6$ yr
- $\star$ ANY binary companion HAS to be significantly smaller
- $\star$ Could Sgr A* have a IMBH binary companion?
  - MAYBE, the wobbling allows for a $10^3 - 10^4 M_\odot$ IMBH at a distance $10^3 < r < 10^5 AU$ (Hansen et al, 2003)
- $\star$ Brownian motion due to stars in cluster?
  - NO, rapid equilibrium with surrounding sea of stars
- $\star$ Dark matter cluster (NS, BH)
  - MAYBE: a dark mass of $\propto 10^4 M_\odot$ compatible with measured motion of Sgr A*.

4. Sgr A* cloaked in dark matter

The strong gravity regime of a BH is modified if it is embedded in dark matter. We consider a static and spherically symmetric metric

$$ds^2 = B(r)dt^2 - A(r)dr^2 - r^2 d\theta^2 + \sin^2\theta d\varphi^2, \qquad (1)$$

where A and B are determined from solving the Einstein equations. The dark matter halo is assumed to be collisionless and at rest. The enclosed dark mass is given by

$$m(r) = \int_0^r 4\pi R^2 \rho(R) dR, \qquad (2)$$

where the density profile for the system comprising the BH of mass M_{BH} (point mass) and the dark matter spike of mass M_{DM} and radius R_{DM} is (α from normalisation)

$$\rho(r) = M_{BH}\frac{\delta(r)}{4\pi r^2} + \alpha r^{-\gamma} \qquad \text{using} \qquad \gamma = 7/3 \qquad (3)$$

4. Sgr A* cloaked in dark matter

For

$$ds^2 = B(r)dt^2 - A(r)dr^2 - r^2 d\theta^2 + \sin^2\theta d\varphi^2, \qquad (4)$$

one then gets Lacroix & Silk (2013) the following metric coefficients

$$\begin{aligned} A(r) &= \left(1 - \frac{2m(r)}{r}\right)^{-1} = \left(1 - \frac{r_S}{r}\left[1 + \frac{M_{DM}}{M_{BH}}\left(\frac{r}{R_{DM}}\right)^{3-\gamma}\right]\right)^{-1} \\ B(r) &\approx A(r)^{-1} \end{aligned} \qquad (5)$$

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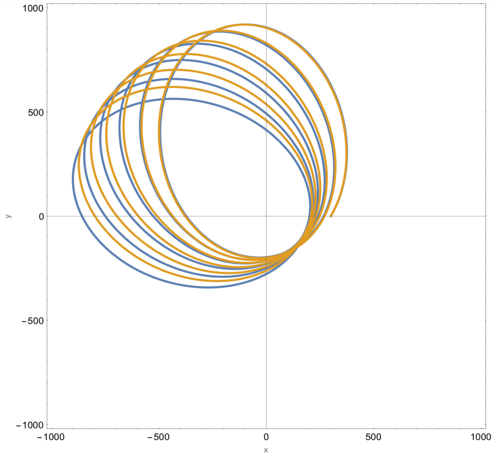
To implement this metric into the GYOTO ray-tracing library, we compute the co- and contravariant metric coefficients, the Christoffel symbols and the equations of motion via the Hamiltonian quantities $(\dot{t}, \dot{r}, \dot{\theta}, \dot{\varphi}, \dot{p}_t, \dot{p}_r, \dot{p}_\theta, \dot{p}_\varphi)$.

- ✓ GYOTO code compiles
- X bug with setting the initial condition $\dot{t}_0$

4. Sgr A* cloaked in dark matter

(Straub et al in prep)



- S2 orbit in extended/standard Schwarzschild metric
- Schwarzschild BH → prograde orbits (blue)
- Schwarzschild BH with extended mass distribution (1% of M_{BH} is dark mass) → retrograde orbits (orange)
- orbits calculated with Mathematica

Summary/Answers

- ⋆ Why do we think Sgr A* is a supermassive black hole?
  - Proper motion of stars within 1” indicates a dark gravitational mass of $4 \times 10^6 M_\odot$ contained within 100 AU (centered on the position of Sgr A*)
  - In radio, the radius of Sgr A* is smaller than 1 AU (BTW we know stars with $R_\star > 7AU$)
- ⋆ How can we estimate the mass of Sgr A*?
  - From the proper motion of stars in orbit around Sgr A* and from the proper motion of Sgr A* itself
- ⋆ Is Sgr A* home alone?
  - We don’t know. Not a binary. But it may cloaked by dark matter (e.g. stellar remnants) that make up $\propto 1\%$ of the estimated BH mass

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References

- ⋆ Lynden-Bell and Rees (1971), hypothesize SMBH in Milky Way
- ⋆ Balick and Brown (1974), discovery with NRAO
- ⋆ Reid et al (1999, 2004), Sgr A* mass, excursions
- ⋆ Schoedel et al (2002)
- ⋆ Ghez et al (2005)
- ⋆ Gillessen et al (2008, 2016), stellar orbits monitoring
- ⋆ Genzel et al (2010), GC review
- ⋆ Lacroix and Silk (2013), dark matter in the GC
- ⋆ Boehle et al (2016), mass and distance

The end