Astrofisica Generale II — 7

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The Galactic Center

What is the Galactic Center?

- It’s the center of the halo.
- We can define the center by averaging the position in 3D space of Globular Clusters (GC)
- It is located ~8 kpc away from us.

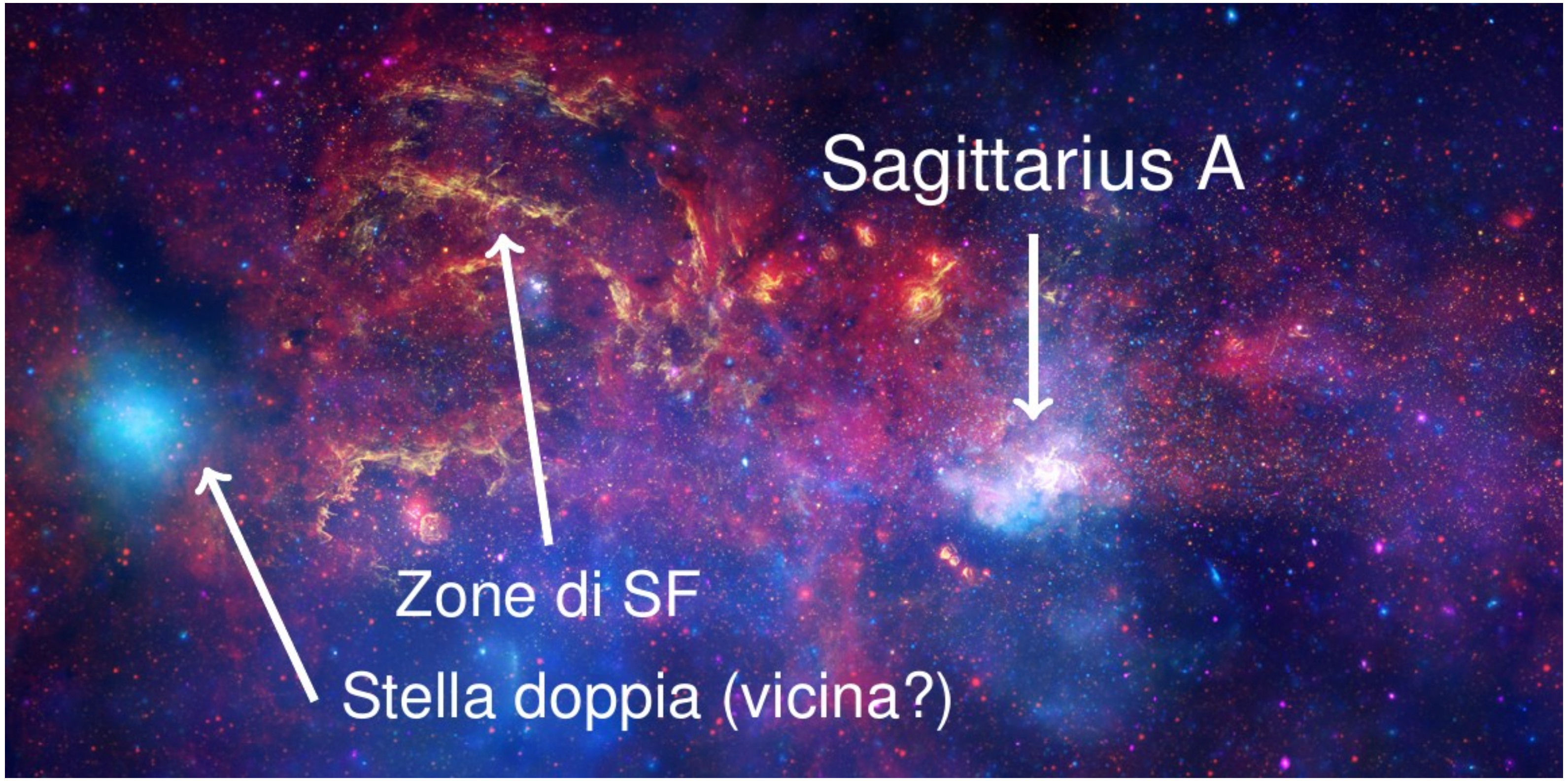
Study of the Galactic Center

- It is impossible to observe the GC ($R < 500\,\mathrm{pc}$) in the visible, due to dust extinction. The most used bands are:

  1. The *radio* band: we see the continuous emission of gas (HII) and the line emission from molecular clouds and interstellar molecules;
  2. The *infrared* band: we see dust (continuum) and neutral and ionized gas (lines).

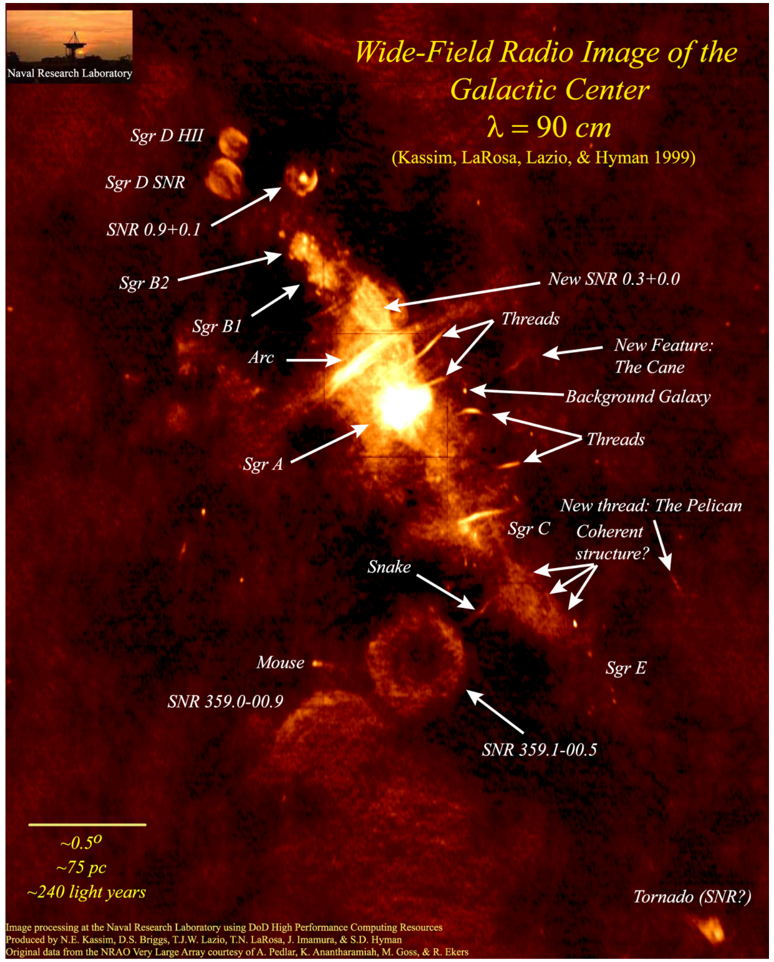
- Due to the distance (8 kpc), observations are generally of limited resolution: e.g., Spitzer only resolves structures larger than 0.1 pc.

Multiband Image of the GC



Size: 32’×16’. Yellow: near-IR (Hubble), red: IR (Spitzer), blue: X (Chandra).

The Galactic Center in Radio



The Central Black Hole

- In 2022, observations by the *Event Horizon Telescope* (EHT) demonstrated that at the center of our Galaxy lies a black hole of $\sim 10^6 M_\odot$, Sgr A* (sometimes called CBH, *Central Black Hole*).
- The existence of supermassive black holes was observed before being predicted, unlike stellar black holes. (But the first image of a CBH was only obtained in 2019, when EHT published the observations of the CBH of the galaxy M87, of $\sim 10^9 M_\odot$).
- The characteristics of the CBH of our Galaxy had, however, already been deduced from the orbit of stars near Sgr A*.

Measuring the Mass of the CBH

- According to Kepler's third law, the closer a star with mass m is to Sgr A* (mass M), the shorter its orbital period P, assuming that $m \ll M$:

$$\frac{P^2}{a^3} = \frac{4\pi}{MG},$$

  with a being the semi-major axis of the orbit and M the mass of Sgr A*.
- It is therefore sufficient to observe a nearby star until it completes an orbit around Sgr A*: from the measurement of P and a, M is obtained.

Measuring the mass of the CBH

- Solving the equation from the previous slide for a, we obtain

$$a = \sqrt[3]{\frac{GMP^2}{4\pi}}.$$

- Assuming we can observe the surroundings of Sgr A* for ~20 years, and that $M \approx 10^6 M_\odot$, then stars for which

$$a < \sqrt[3]{\frac{6.67 \times 10^{-11}\,\frac{\mathrm{m}^3}{\mathrm{kg}\cdot\mathrm{s}^2} \cdot 4 \times 10^{36}\,\mathrm{kg} \cdot \left(6.3 \times 10^8\,\mathrm{s}\right)^2}{4\pi}} \approx 2 \times 10^{14}\,\mathrm{m}.$$

will complete at least one full period

Measuring the mass of the CBH

- The diffraction limit of a telescope is θ ~ λ/D, where λ is the wavelength and D is the size of the mirror.
- To resolve a motion $a = 10^{14}\,\mathrm{m}$ at a distance $R_0 = 8\,\mathrm{kpc}$ and assuming λ ~ 2 µm (K filter), we therefore need

$$\frac{\lambda}{D} = \frac{a}{R_0} \quad \Rightarrow \quad D = \frac{R_0\,\lambda}{a} \approx \frac{8\,\mathrm{kpc}\cdot 2\,\mu\mathrm{m}}{10^{14}\,\mathrm{m}} \approx 500\,\mathrm{cm},$$

(The largest mirror in Merate is the Ruths, at 134 cm!)

Studying the central black hole

- Having a 5 m mirror is not enough, because the atmosphere introduces a lot of disturbance and needs to be corrected.
- The first measurements of the orbits of the galactic center were therefore not **astrometric** but **spectroscopic**: they measured radial velocities.
- Important information can still be obtained from the velocity distribution by comparing it with simulations of orbits around a massive body.
- You can see an example in Eckart, Genzel (1996): *Observations of stellar proper motions near the Galactic Centre* (unfortunately it is behind a *paywall*) # First measurements
- Thanks to the use of adaptive optics and large telescopes, such as the Keck in Hawaii (10 m!), in the years 2008–2009 it was possible to measure the first



MEASURING DISTANCE AND PROPERTIES OF THE MILKY WAY'S CENTRAL SUPERMASSIVE BLACK HOLE WITH STELLAR ORBITS

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ABSTRACT

We report new precision measurements of the properties of our Galaxy's supermassive black hole. Based on astrometric (1995–2007) and radial velocity (RV; 2000–2007) measurements from the W. M. Keck 10 m telescopes, a fully unconstrained Keplerian orbit for the short-period star S0-2 provides values for the distance (R_0) of 8.0 ± 0.6 kpc, the enclosed mass ($M_{\rm bh}$) of $4.1 \pm 0.6 \times 10^6\ M_\odot$, and the black hole's RV, which is consistent with zero with 30 km $\rm s^{-1}$ uncertainty. If the black hole is assumed to be at rest with respect to the Galaxy (e.g., has no massive companion to induce motion), we can further constrain the fit, obtaining $R_0 = 8.4 \pm 0.4$ kpc and $M_{\rm bh} = 4.5 \pm 0.4 \times 10^6\ M_\odot$. More complex models constrain the extended dark mass distribution to be less than $3\text{–}4 \times 10^5\ M_\odot$ within 0.01 pc, ~100 times higher than predictions from stellar and stellar remnant models. For all models, we identify transient astrometric shifts from source confusion (up to 5 times the astrometric error) and the assumptions regarding the black hole's radial motion as previously unrecognized limitations on orbital accuracy and the usefulness of fainter stars. Future astrometric and RV observations will remedy these effects. Our estimates of R_0 and the Galaxy's local rotation speed, which it is derived from combining R_0 with the apparent proper motion of Sgr A*, ($\theta_0 = 229 \pm 18$ km $\rm s^{-1}$), are compatible with measurements made using other methods. The increased black hole mass found in this study, compared to that determined using projected mass estimators, implies a longer period for the innermost stable orbit, longer resonant relaxation timescales for stars in the vicinity of the black hole and a better agreement with the $M_{\rm bh}$-σ relation.

Subject headings: black hole physics — Galaxy: center — Galaxy: kinematics and dynamics — infrared: stars — techniques: high angular resolution

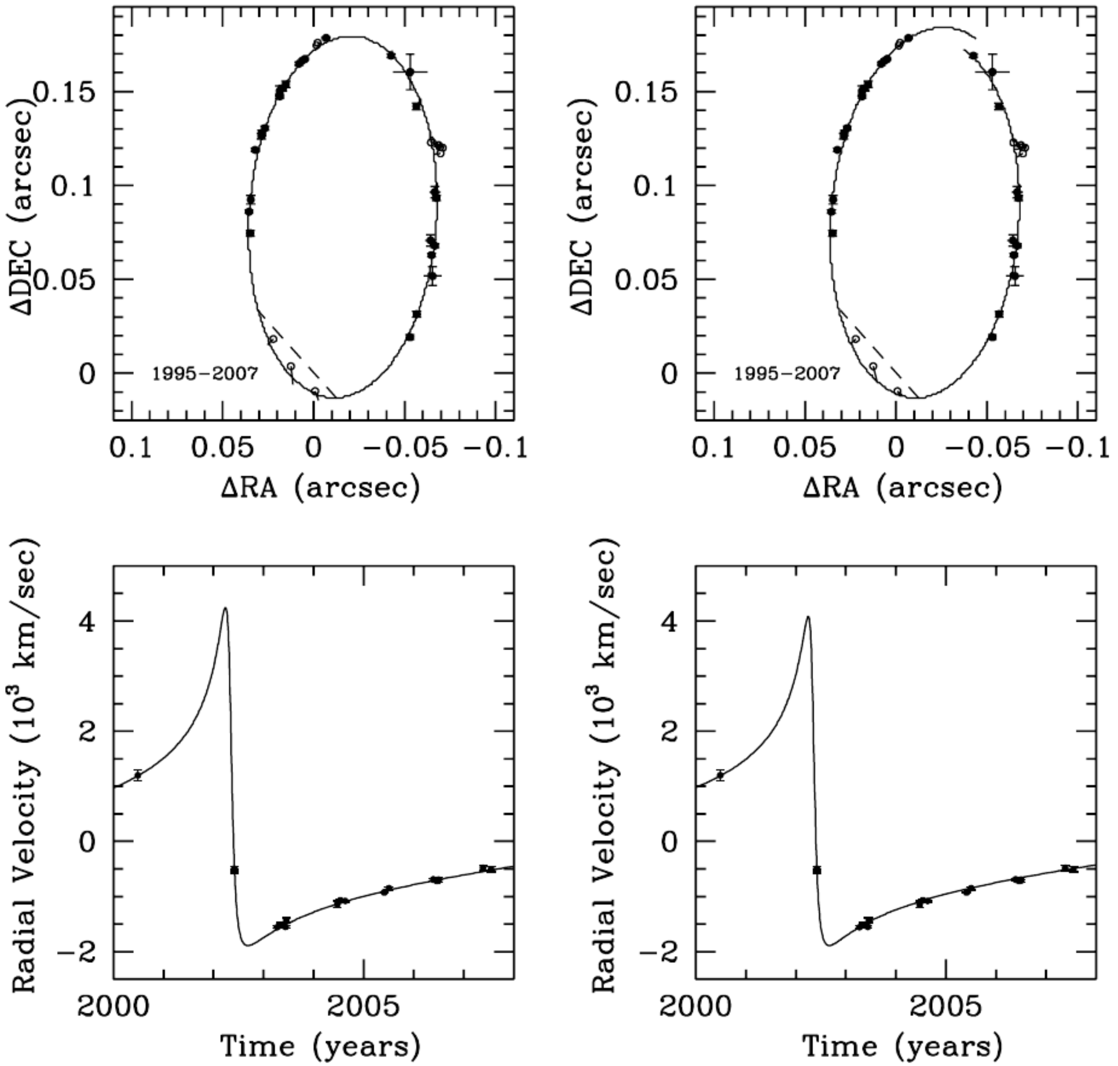


FIG. 9.— Best fit to the astrometric and RV data, assuming a Keplerian orbital model. The filled points were included in the formal fit, while the open points are measurements that are excluded due to source confusion. Uncertainties are plotted on all points, except the open/excluded points (here the uncertainties are comparable to the size of the points) for clarity. *Left*: To compare with what has been done in the past to estimate R_0, we show the fit to the data with a 10-parameter model, which includes the black hole's mass (M_{bh}), distance (R_0), and location in the plane of the sky (X_0, Y_0) as free parameters and which fixes the black hole's three-dimensional velocity (V_x, V_y, V_z) to zero. This results in a χ^2/dof ~ 1.4. *Right*: The data are better reproduced by a 13-parameter model, which includes the black hole's mass (M_{bh}), distance (R_0), location in the plane of the sky (X_0, Y_0), and three-dimensional velocity (V_x, V_y, V_z) as free parameters, and results in a χ^2/dof ~ 0.97. Adding these extra free parameters, and in particular V_z, increases the uncertainties in the black hole's properties by a factor of 2.

TABLE 5

ORBITAL ELEMENTS FOR S0-2 AND THE IMPLIED BLACK HOLE PROPERTIES

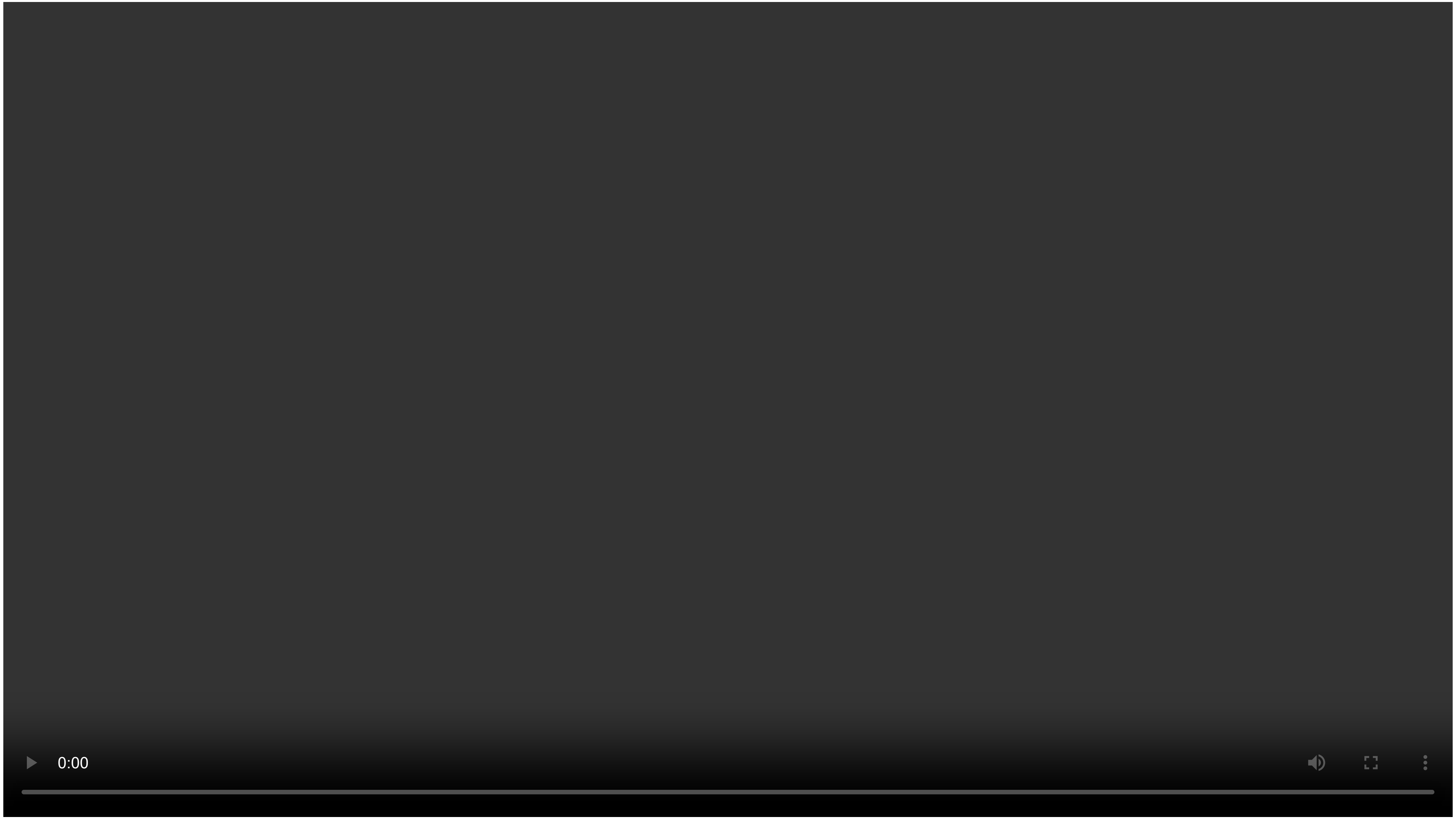
Parameter	V_z = 0 Case[a]	V_z Unconstrained Case
Distance (R_0) (kpc)[b]	$8.36\pm^{0.30}_{0.44}$	$7.96\pm^{0.57}_{0.70}$
Period (P) (yr)	15.78 ± 0.35	$15.86\pm^{0.10}_{0.45}$
Semimajor axis (a) (mas)	$124.4\pm^{2.4}_{3.3}$	$126.5\pm^{1.8}_{5.0}$
Eccentricity (e)	0.8866 ± 0.0059	$0.8904\pm^{0.0051}_{0.0075}$
Time of closest approach (T_0) (yr)	$2002.3358\pm^{0.0065}_{0.0093}$	2002.342 ± 0.010
Inclination (I) (deg)	135.3 ± 1.3	134.6 ± 1.3
Position angle of the ascending node (Ω) (deg)	225.9 ± 1.3	$226.44\pm^{0.71}_{1.4}$
Angle to periapse (ω) (deg)	65.18 ± 1.2	$66.0\pm^{1.1}_{1.7}$
X dynamical center (X_0-$X_{\mathrm{Sgr\ A^*\text{-}radio}}$) (mas)[b, c]	$0.95\pm^{0.46}_{1.4}$	$1.49\pm^{1.1}_{0.87}$
Y dynamical center (Y_0-$Y_{\mathrm{Sgr\ A^*\text{-}radio}}$) (mas)[b, c]	$-4.8\pm^{2.2}_{1.6}$	-5.4 ± 2.0
X velocity (V_x) (mas yr^{-1})	-0.40 ± 0.25	$-0.47\pm^{0.12}_{0.33}$
Y velocity (V_y) (mas yr^{-1})	$0.39\pm^{0.09}_{0.18}$	0.36 ± 0.12
Z velocity (V_z) (km s^{-1})	...	$-20\pm^{29}_{37}$
Mass (M_{bh}) ($10^6\ M_\odot$)	$4.53\pm^{0.34}_{0.55}$	$4.07\pm^{0.52}_{0.78}$
Density (ρ) ($10^{15}\ M_\odot\ \mathrm{pc}^{-3}$)	$5.83\pm^{0.28}_{0.97}$	$6.3\pm^{0.56}_{1.4}$
Periapse distance (R_{min}) (mpc)	0.570 ± 0.037	$0.535\pm^{0.049}_{0.071}$

NOTE.—Parameters below the horizontal line are derived from those above the line and are provided for convenience.

[a] Allowing for the uncertainty in the LSR in V_z (± 2 km s^{-1}; Gould 2004) produces results that are not distinguishable from those reported above for the $V_z = 0$ case.

[b] The reference time for the position of the black hole, when the velocity is a free parameter, is J2000.0.

[c] Uncertainties in the position of Sgr A*–radio are not incorporated into the uncertainties of X_0 and Y_0.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Observation of the BH

- The observations of Genzel and Ghez led to an estimated mass $M_{\mathrm{BH}} \approx 4 \times 10^6\ M_\odot$.
- This corresponds to a Schwarzschild radius equal to

$$r_s = \frac{2GM_{\mathrm{BH}}}{c^2} \approx \frac{2 \cdot 6.67 \times 10^{-11}\ \frac{\mathrm{m}^3}{\mathrm{kg}\cdot\mathrm{s}^2} \cdot 1.6 \times 10^{37}\,\mathrm{kg}}{9.0 \times 10^{16}\,\mathrm{m/s}} = $$
$$\approx 2.4 \times 10^{10}\,\mathrm{m} = 0.16\,\mathrm{AU}.$$

- The BH is obviously not visible, but it is expected that the hot gas envelope will be visible for $r \gtrsim 3r_s$

Event Horizon Telescope

- We again use the relation $\lambda/D \sim 3r_s/R_0$ to estimate the size of the telescope needed to see the hot gas disk:

$$D = \frac{R_0\,\lambda}{3r_s} \approx \frac{8\,\mathrm{kpc}\cdot 2\,\mu\mathrm{m}}{0.5\,\mathrm{AU}} \approx 6600\,\mathrm{m}.$$

  This is absolutely impossible!

- The Event Horizon Telescope is a collaboration that has used interferometry to obtain an image of the BH. How did they do it?

Interferometry

- Interferometry is a technique that consists of collecting the signal from different telescopes and combining it in phase.
- The achievable resolution is always $\theta \sim \lambda/D$, but in this case *D* is the distance between telescopes!
- Unfortunately, phase coherence requires that any defects in the optical guides be much smaller than the wavelength, which makes it suitable only for observations in the microwave and radio bands.
- However, this is a problem!

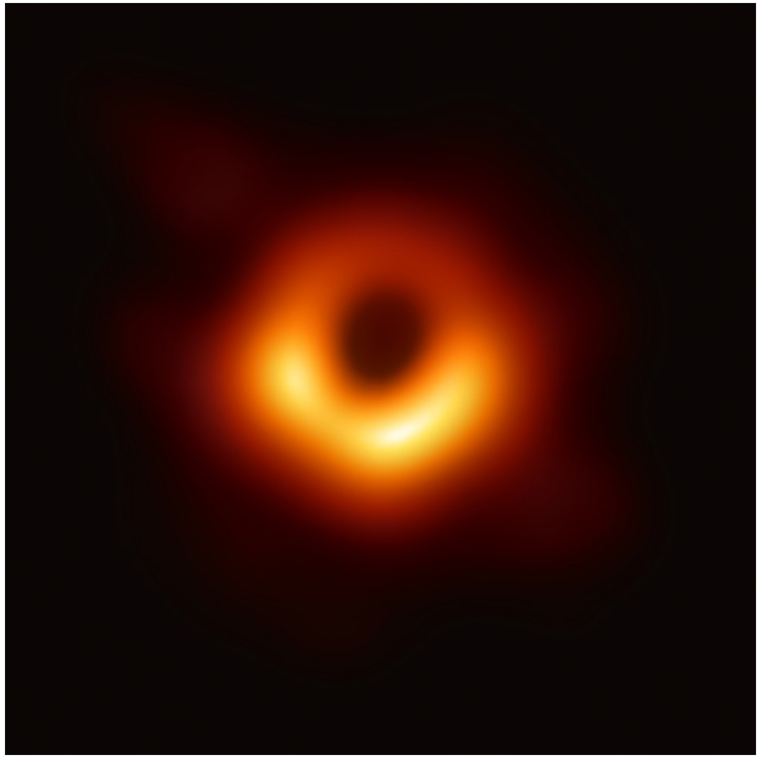
Interferometry for the BH

- If we increase λ, the size *D* needed to obtain the desired resolution also increases! EHT made the measurements with λ = 1.3 mm, so

$$D = \frac{R_0\,\lambda}{3r_s} \approx \frac{8\,\mathrm{kpc}\cdot 1.3\,\mathrm{mm}}{5\,\mathrm{AU}} \approx 4\times 10^5\,\mathrm{m} = 430\,\mathrm{km}.$$

- For EHT it was therefore necessary to operate telescopes that covered a good portion of the Earth's surface!

BH of M87 (April 10, 2019)



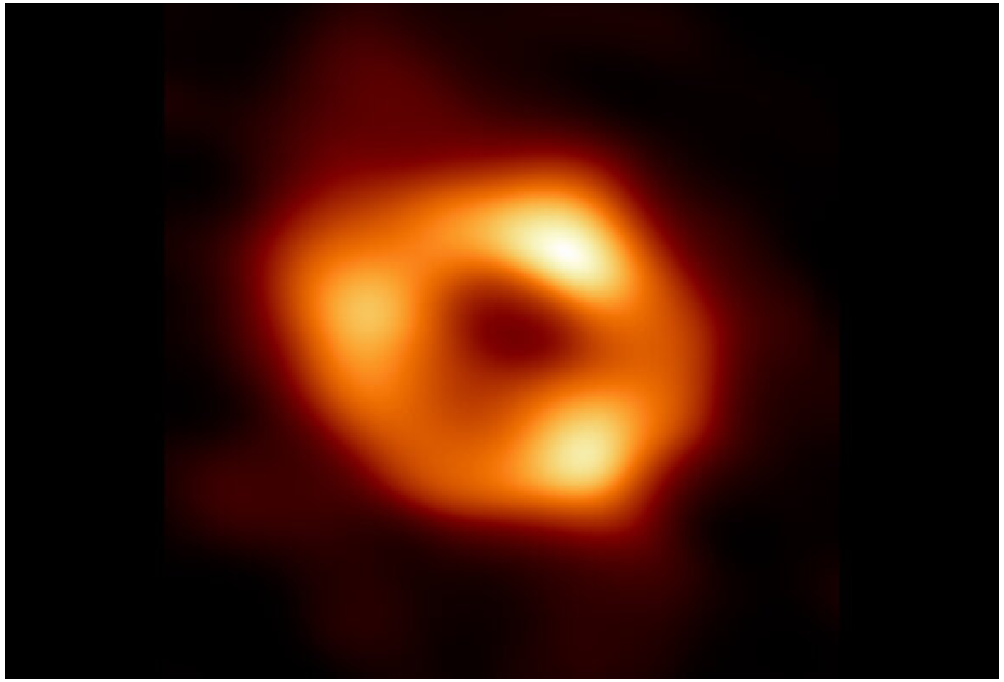
Why was M87's black hole measured first?

Comparing BHs

- M87's BH is 1000 times farther away than Sagittarius A* (16 Mpc vs. 8 kpc).
- However, it is not located on the galactic plane, so the dust obscuration is lower (also because it is an elliptical galaxy).
- Furthermore, the black hole is 1000 times more massive, which means that r_s is 1000 times larger:

  1. The apparent diameter is the same;
  2. The orbital period of the gas is $P \propto r_s^{3/2}/M^{1/2}$, so $P' = 10^3 P$: the gas takes several days instead of tens of minutes to orbit, and the image is less blurred.

Sagittarius A* (May 12, 2022)



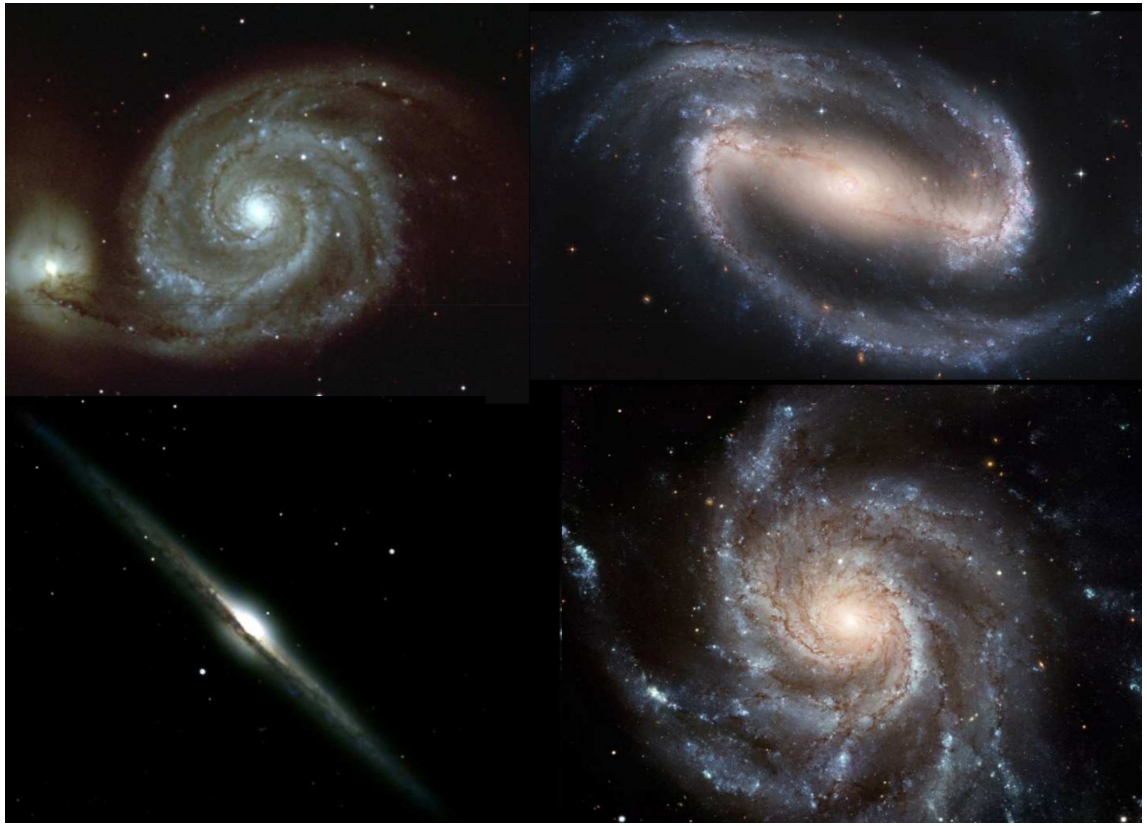
Genzel's *Easter lecture*

Reinhard Genzel: A 40 year Journey

Testing the Massive Black Hole Paradigm in the Galactic Centre (Bologna, 2022)

Observing the Milky Way

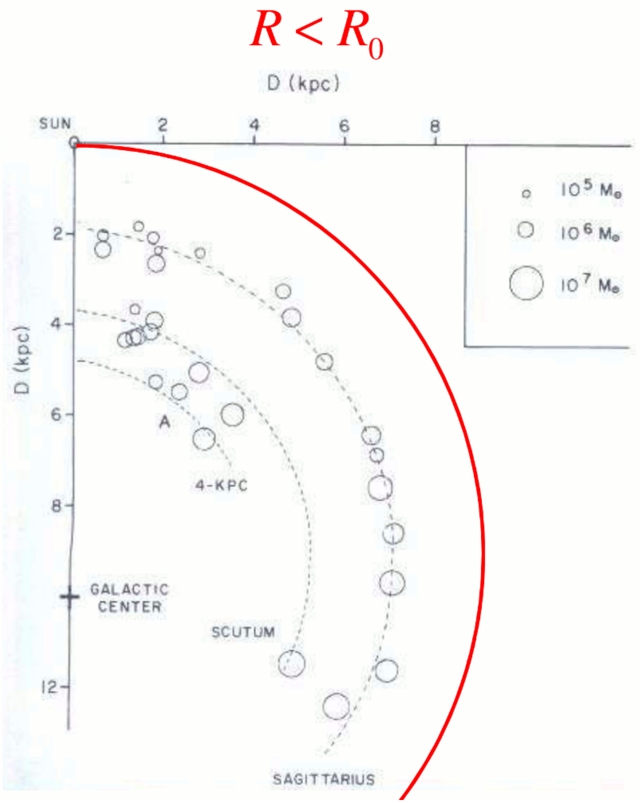
Shape of the Milky Way



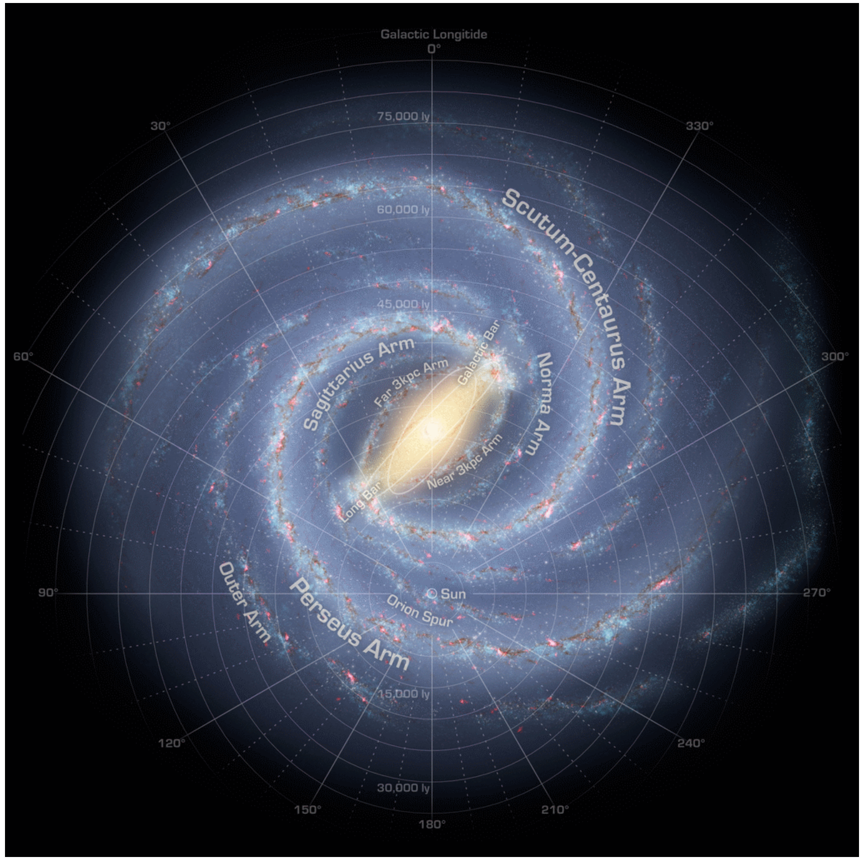
We have evidence that galaxies with spiral arms exist. Is this also true for the Milky Way?

Shape of the Milky Way

By studying giant molecular clouds, we get a sense that the Milky Way also has similar structures.



Spitzer 2008



How did we come to discover that the Milky Way would actually appear this way to an external observer?

Thomas Wright (1711–1786)

- Mathematician, astronomer, architect, and garden designer
- In his book *An Original Theory or New Hypothesis of the Universe* (1750) he expounds an original cosmo-theological theory:
  - Many solar systems;
  - Invisible stars;
  - Spherically symmetric distribution.

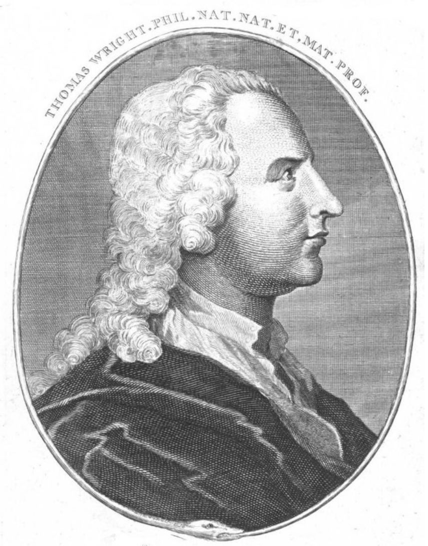
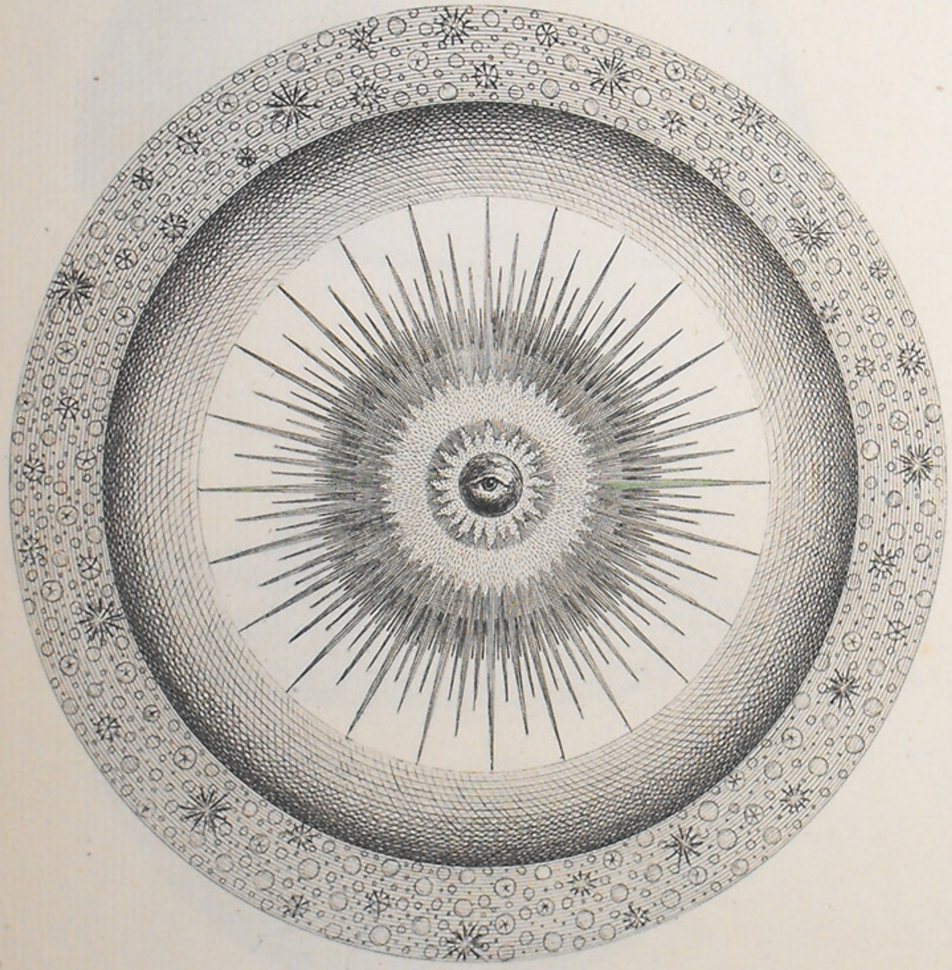
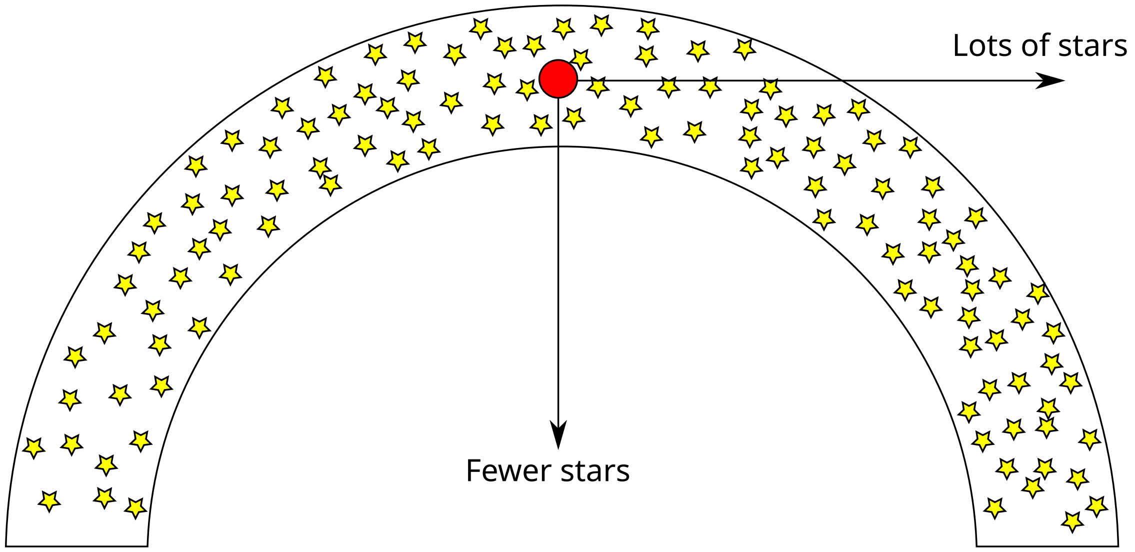


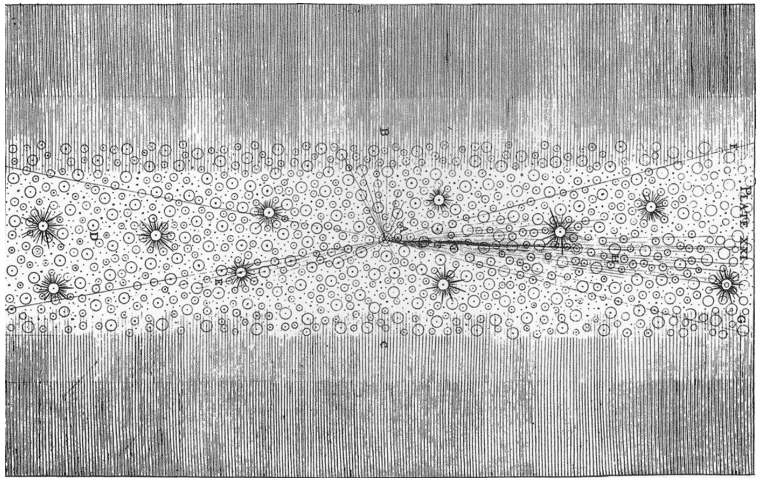
PLATE XXV.





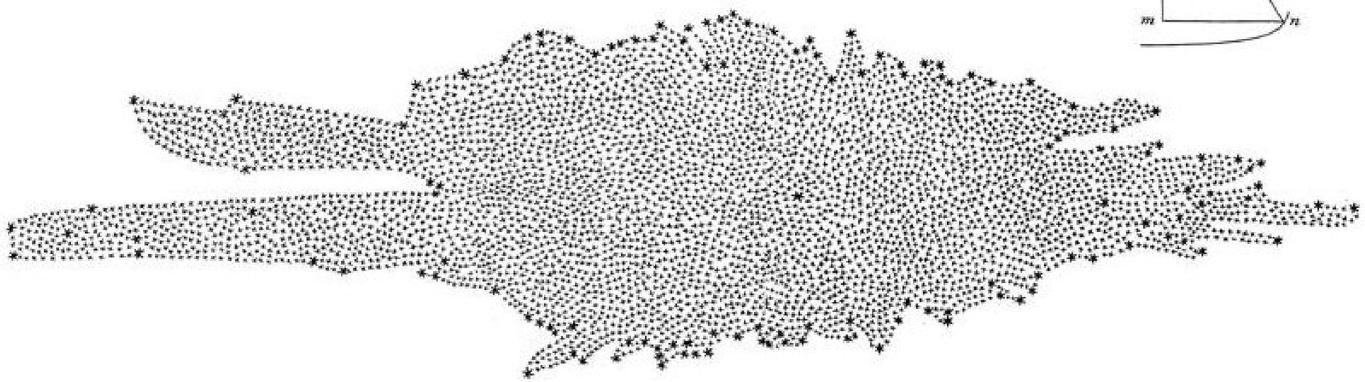
Wright’s model explains the apparent shape of the Milky Way. Moreover, he hypothesizes that all the stars share the same luminosity, so that the farthest ones are invisible.

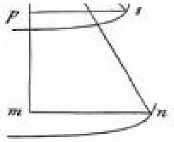
- In his work *Allgemeine Naturgeschichte und Theorie des Himmels* (1755), Immanuel Kant quotes Wright.
- Unfortunately, his interpretation was based on a review of Wright’s oeuvre that misunderstands the meaning of this image:



William Herschel (1738–1822)

- Musician with a strong passion for astronomy.
- He and his siblings Alexander and Caroline have been formidable telescope-makers, which they built for their own use and for aristocrats.
- Unlike Wright, Herschel's model is strictly linked to observations (done by himself).

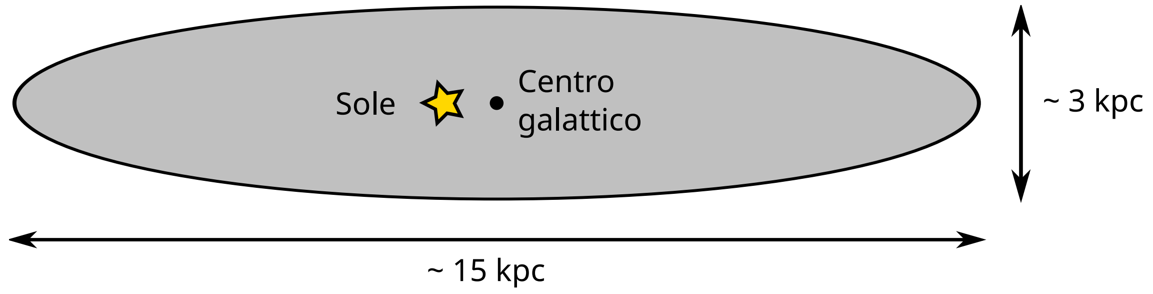




- He suggested a flat structure for the Milky Way (*On the construction of the Heavens*, 1802)
- He assumed that stars are distributed with constant numeric density n. By measuring their column density $n_{\rm col}$, he could derive the depth $l = n_{\rm col}/n$.
- Shape derived from stellar counts in 675 regions of the celestial sphere (some points are an average over multiple observations). The Sun is in the middle.

Jacobus Kapteyn (1851–1922)

- In *First attempt at a theory of the arrangement and motion of the sidereal system* (1922), he used parallaxes and statistics to estimate the shape of the Milky Way.
- He severely underestimated stellar reddening, so that his model is accurate only at high Galactic latitudes.


Sole
Centro
galattico
~ 3 kpc
~ 15 kpc

Harlow Shapley (1885–1972)

- He estimated the distance of GCs using RR Lyrae stars.
- He did not correct for interstellar absorption.
- He understood the structure of the Milky Way and the position of the Sun.