

- Prior to 1990, observed stellar velocities suggested the presence of a compact (enclosed) mass of $3 - 5 \times 10^6 M_\odot$ within the central 0.1pc. **Sgr A*** is believed to be a central **supermassive black hole** (SMBH). Velocities of *ionized gas* on the inner edge of the circumnebular ring at 0.1pc are of the order of $v \approx 700$ km/sec. Ionization is seeded by the intense X-ray flux. This provides the most stringent constraint on the central mass via Kepler's Third Law:

$$M_{\text{BH}} \lesssim \frac{v^2 r}{G} \approx 4.7 \times 10^6 M_\odot \quad . \quad (23)$$

The collective status in 1990 provided upper bounds to the mass of any central black hole on this order.

- Improved technology enabled more refined angular resolution on the 0.1 arcsec scales, principally via the Hubble and Keck Telescopes.

- * These permitted observations at the GC distance ~ 8.5 kpc on scales corresponding to Kepler periods of the order of 10-100 years.

- \Rightarrow a refined estimate of the BH mass of $M_{\text{BH}} = 4 \pm 0.3 \times 10^6 M_{\odot}$, corresponding to $R_s = 2GM/c^2 \approx 0.08 \text{ AU} = 16R_{\odot}$. There is still debate about the value between the two leading groups in Germany and the US.

Plot: Mass Determination of Central Supermassive Black Hole

- The activity of the SMBH of $L \sim 10^7 L_{\odot}$ is likely powered by accretion, leading to the estimate (using a 25% efficiency for radiation)

$$E \sim \frac{GM_{\text{BH}}M}{2R_s} = \frac{1}{4} Mc^2 \quad \Rightarrow \quad L = \frac{dE}{dt} \equiv \frac{1}{4} \dot{M}c^2 \quad . \quad (24)$$

This leads to an accretion rate estimate of

$$\dot{M} = \frac{4L}{c^2} \approx 1.9 \times 10^{20} \text{ g sec}^{-1} = 3 \times 10^{-6} M_{\odot} \text{ yr}^{-1} \quad , \quad (25)$$

being much less than the $\sim 10^{-3} - 10^{-2} M_{\odot} / \text{year}$ estimate from the observed stellar profile at small r . This latter estimate is obtained from accretion models from a peaked density profile.

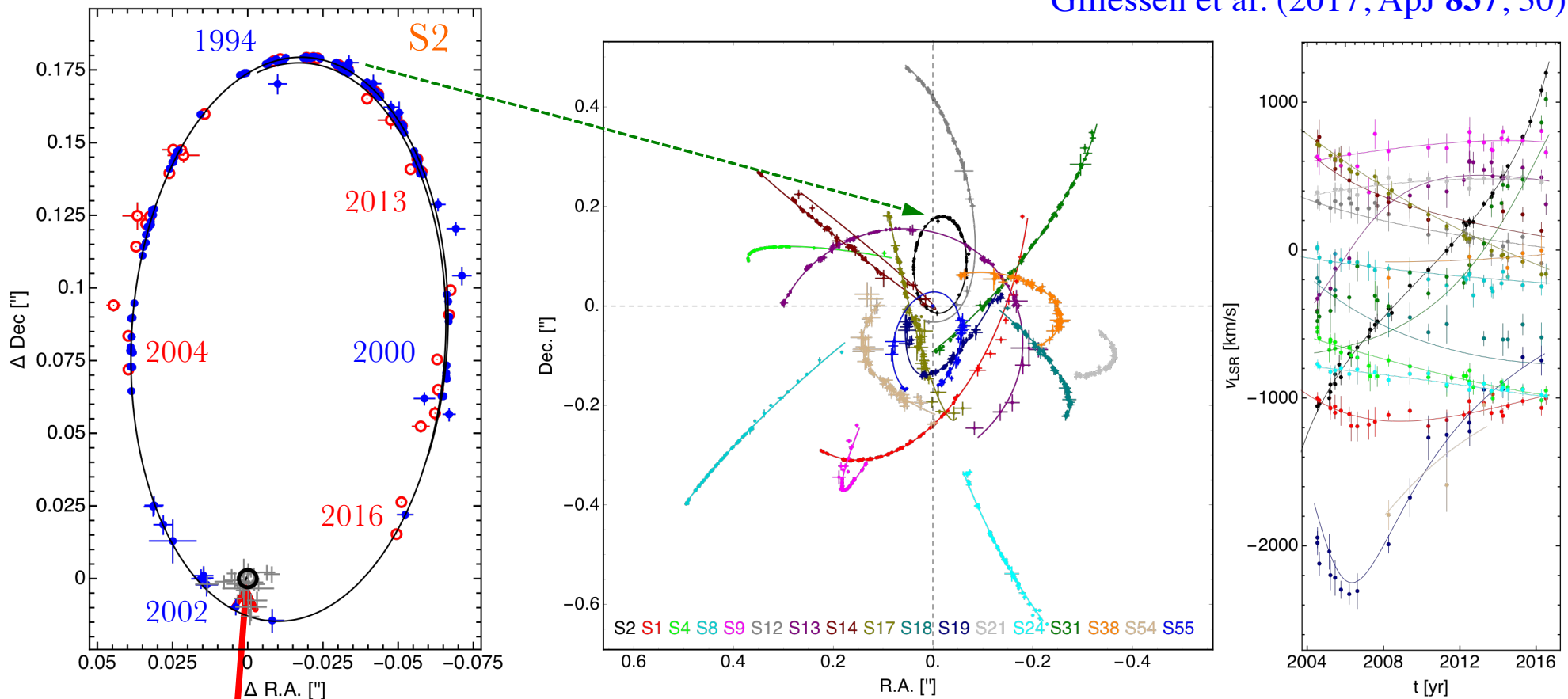
- * The estimate from Eq. (25) is not consistent with acquiring the observed SMBH mass over a Hubble time, implying that the *radiative efficiency* is much less than unity, typical 1–10%. A central density concentration enhances accretion rates. These two influences ameliorate the discrepancy.

- The next watershed development concerning the SMBH at the Galactic Center has been ushered in by the Event Horizon Telescope (EHT). This is a dedicated world-wide array of mm radio telescopes with coordinated interferometry that can probe angular scales $R_s/8.3 \text{ kpc} = 4.6 \times 10^{-11}$, which is $\sim 10 \mu \text{ arcsec}$. The GC and M87 are the EHT's prime science targets.

Plot: Event Horizon Telescope: Image of the Galactic Center

Stellar Passages Near the Galactic Centre

Gillessen et al. (2017, ApJ 837, 30)



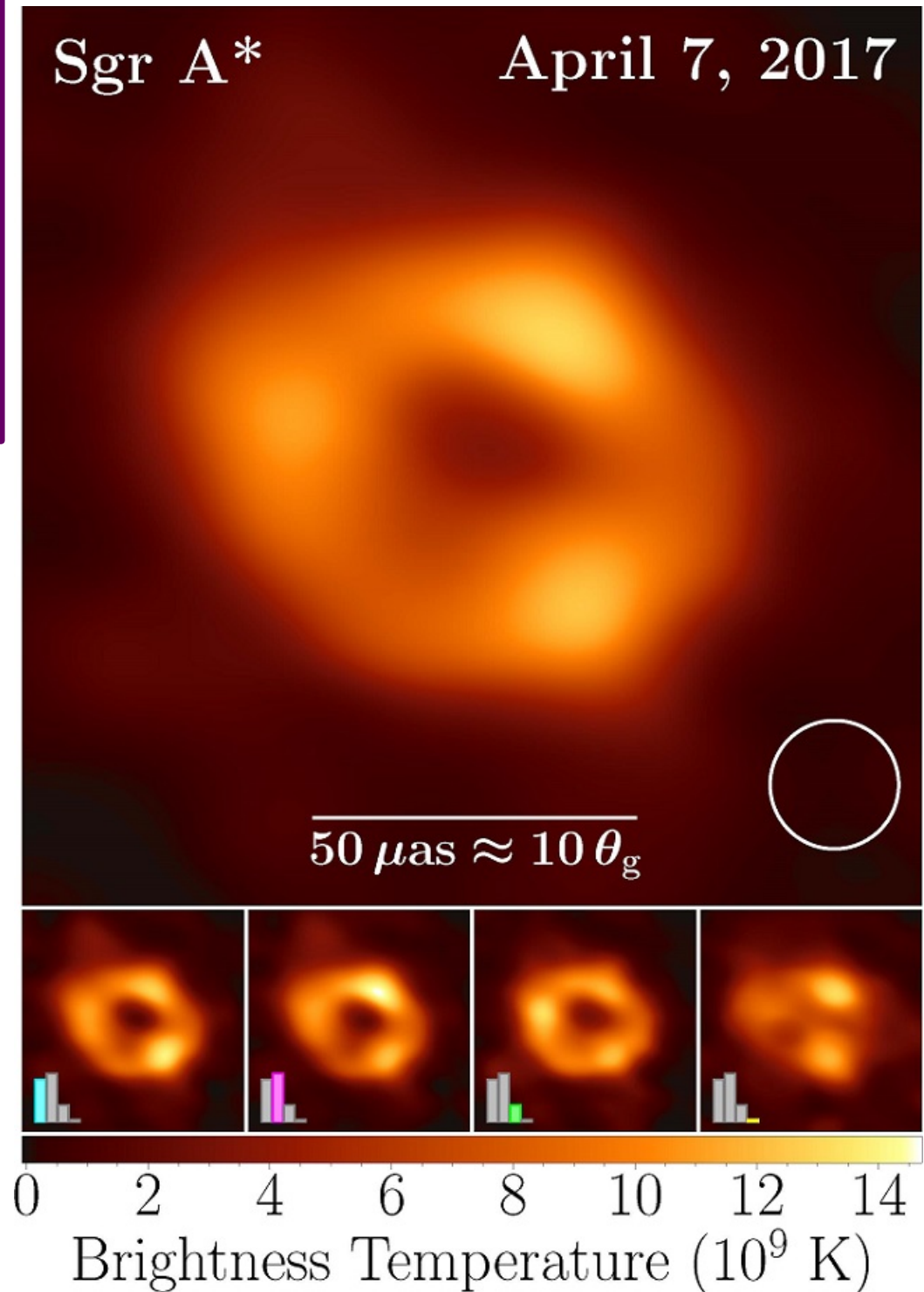
- *Left Panel:* passage of the star S2 in the epoch 1992-2017 (blue is before 2002, red after), which has a period of 15 years, imaged in IR using ESO's VLT in Chile, capturing **peribothron** in 2002 cleanly.
- S2 Pericentre is offset of 17.2 light hours (124 AU) promotes the existence of a central supermassive black hole (SMBH) of mass $4.0 \times 10^6 M_{\odot}$. GR with orbital **peribothron precession** improves fit.
- *Right Panels:* orbits during 2004-2017 and radial velocities for several stars around the SMBH.

Event Horizon Telescope (EHT): the Galactic Center

mm/sub-mm wavelengths: a
synchrotron emission signal

EHT Collaboration (ApJL, 930; 2022)

<https://eventhorizontelescope.org>



3. NORMAL GALAXIES

Matthew Baring – Lecture Notes for ASTR 360, Spring 2025

1 The Discovery of Galaxies

At the time of Kapteyn and Shapley's work on star counts, the universe was limited in scope to the Milky Way. Yet there were well-established observations of **spiral nebulae**. Whether these were Galactic in location or separate entities was a subject of contentious debate.

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- In April 1920, Shapley and Heber Curtis conducted a public debate, a defining point in astronomical history. The **Shapley-Curtis Great Debate** did not resolve the issue.

- * Shapley advocated a galactic origin for the nebulae; Curtis argued that they were extragalactic. Both had flawed arguments as well as correct ones.

- * For example, Curtis argued that the dark lanes seen in edge-on spiral nebulae, if due to obscuration, if they were present in the Milky Way, would explain the zone of avoidance for globular clusters.

- Resolution of the issue did not come until Hubble (1923) first observed Cepheids in Andromeda (M31), and obtained a distance estimate of 285 kpc, far more distant than either Kapteyn's universe or Shapley's Galactic scale.

- * While the debate was then settled, leading to a profound change in the paradigm of the cosmos, Hubble's distance determination was flawed due to the miscalibration of the Cepheid period-luminosity relation. Now, $d_{M31} = 772 \pm 44$ kpc (see Ribas et al. 2005, ApJL 635, L37).

2 Hubble's Classification of Galaxies

• Hubble propelled the field of galaxy studies by classifying the types of galaxies according to the apparent geometrical morphology. He identified them as:

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pp. 942–7

- elliptical (15%), designated **En**, where higher numbers **n** denote greater elongation;
- lenticular (20%), designated S0, that are like flattened pancakes, i.e. and extreme case of ellipticals;
- normal and barred spirals (60%) Sa, Sb, Sc; SBa, SBb, SBc. The second letters denote progressively smaller central bulges.

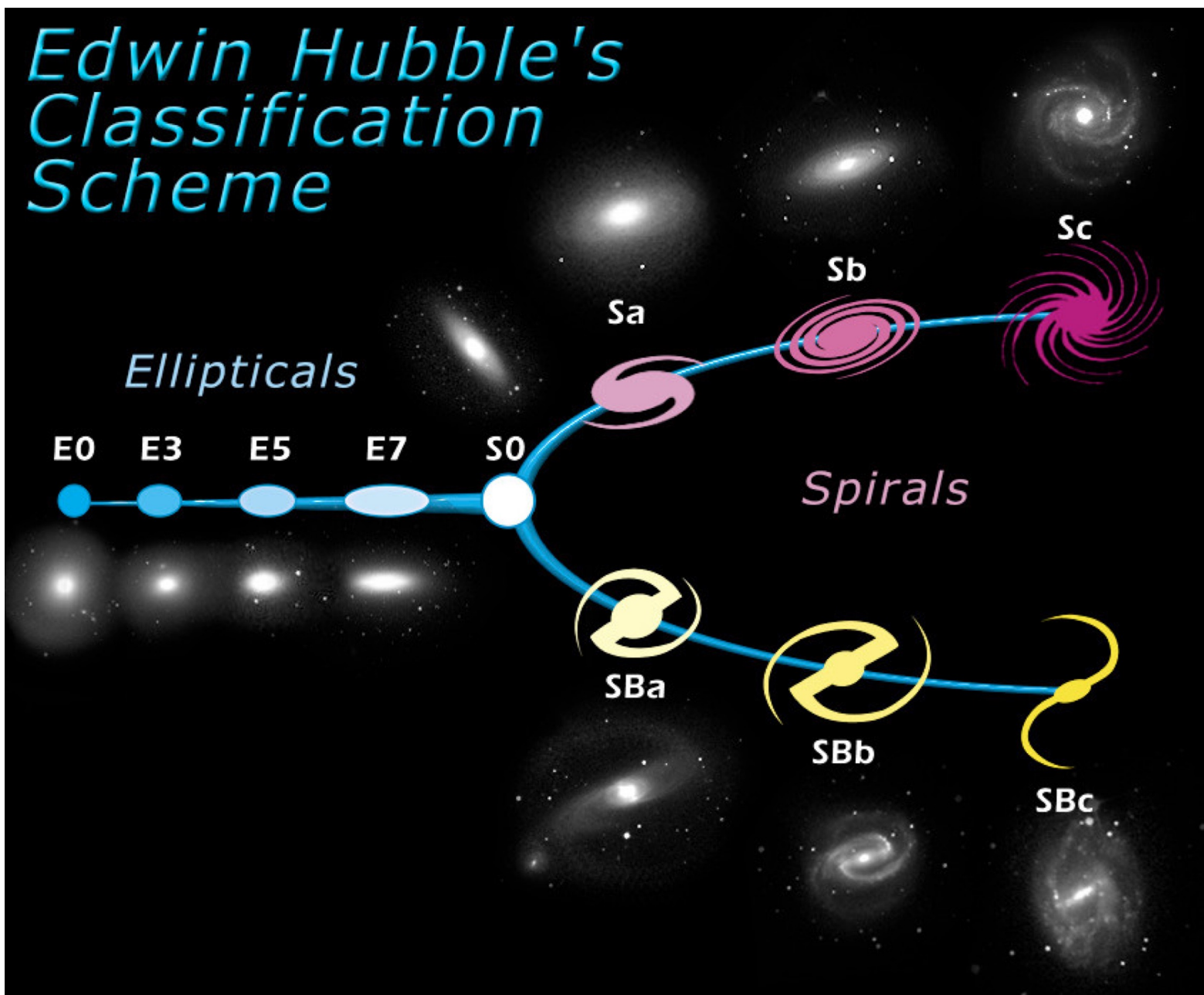
Percentages correspond to bright (nearby) galaxy sampling. These morphologies can be summarized in Hubble's famous **tuning fork diagram**.

Plot: Hubble's Tuning Fork Diagram

- Spirals possess major dust lanes and much gas in their disks, as well as high σ^2 , quasi-spherical, low rotation halos. Ellipticals possess very little gas and dust and are homogenous in their appearance.
- A small percentage of galaxies are irregular, and often these constitute strongly **interacting galaxies** that exhibit pronounced stellar trails, much like the Magellanic stream.
- De Vaucouleurs refined Hubble's classification in 1959.
- While spirals dominate the field galaxy census, particularly relatively nearby, *ellipticals are more frequently found in galaxies that are members of clusters*, and in fact constitute over 50% of cluster galaxies at significant redshift.

Plot: Population Census vs. Projected Galaxy Density

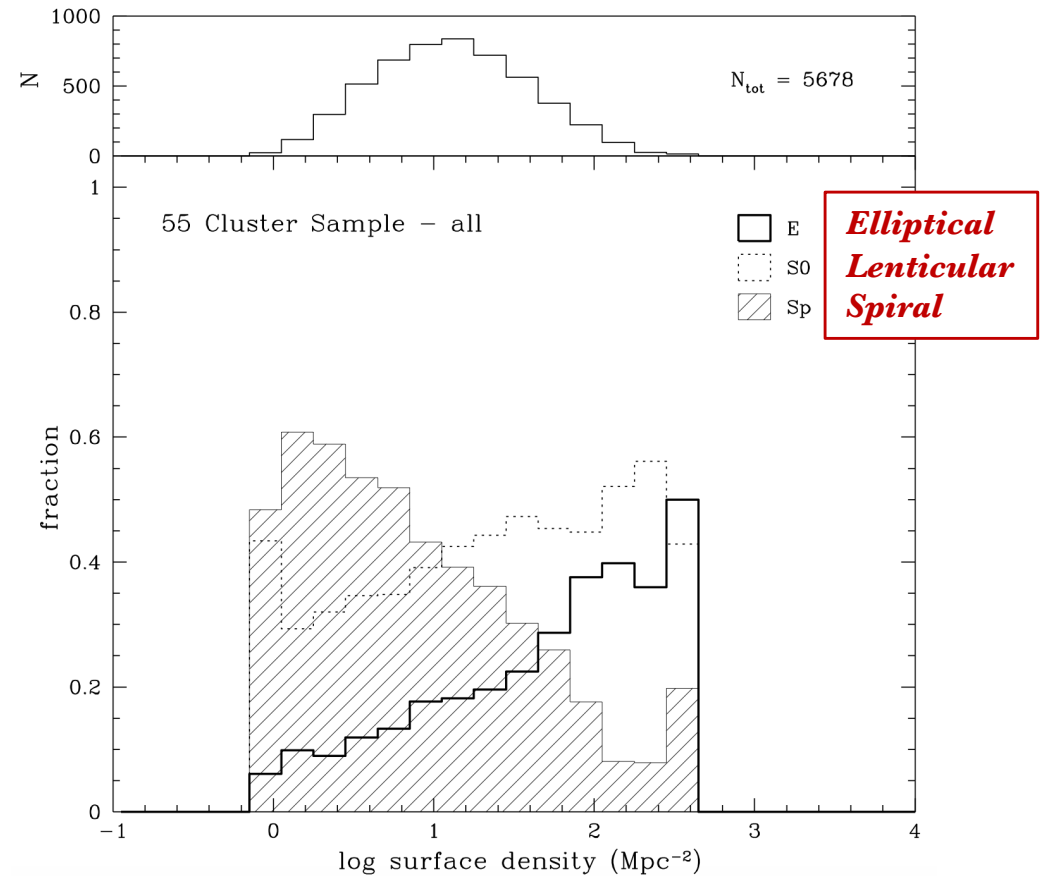
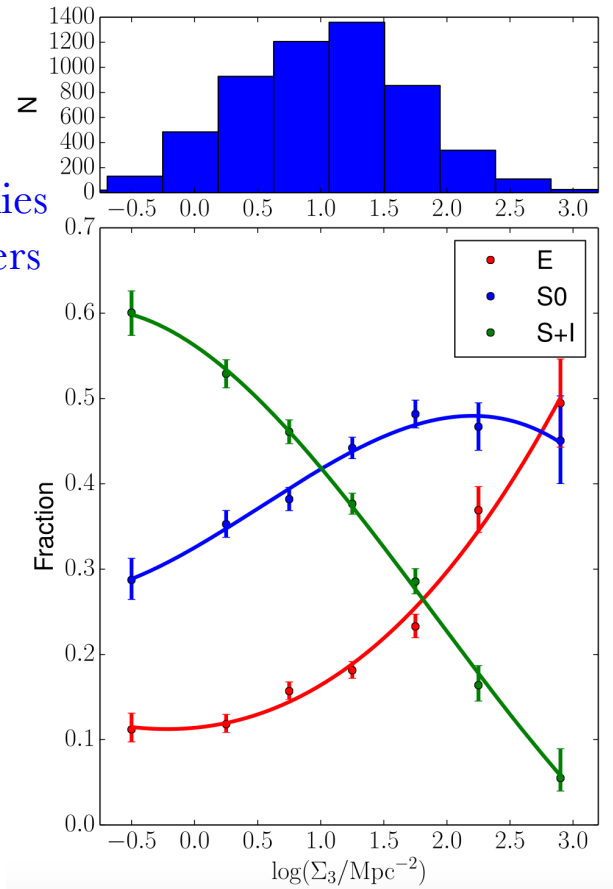
Tuning Fork Diagram



Credit: spacetelescope.org

Morphology-Density Relation for Galaxies

5450 galaxies
in 53 clusters



- *Left*: fraction of galaxies of different types as a function of sky density. Houghton update (MNRAS **451**, 3427; 2015) of original Dressler (ApJ, **236**, 351; 1980). sample that includes revisions of distance determinations and modern cosmology.
- *Right*: Dressler et al. (1997, ApJ, **490**, 577) update of Dressler (1980) cluster study. Larger surface density corresponds to larger clusters that possess mostly ellipticals.

The brightness distribution of galaxies is given by their **luminosity function**. This is traditionally given by the *Schechter formalism*, after the work of Paul Schechter (1976). The differential luminosity distribution is broad, and is empirically given by the form

$$\boxed{\frac{dn}{dL} = \phi_* \left(\frac{L}{L_*}\right)^\alpha \exp\left(-\frac{L}{L_*}\right) .}$$
 (1)

Here the subscript $*$ denotes a constant, representative of the absolute magnitude of typical stars in these galaxies.

* The value $\alpha \sim -5/4$ is usually realized, and the Schechter function is more or less universal for **field galaxies** and distant cluster galaxies. Yet, some deviation from this form is observed in clusters, where galaxy interaction can drive dynamics and star formation.

• In magnitudes, $\log_{10}(L/L_*) = -0.4(M - M_*)$, so that the luminosity function becomes

$$\frac{dn}{dM} \propto 10^{0.4(\alpha+1)[M_*-M]} \exp\left\{-10^{0.4[M_*-M]}\right\}$$
 (2)

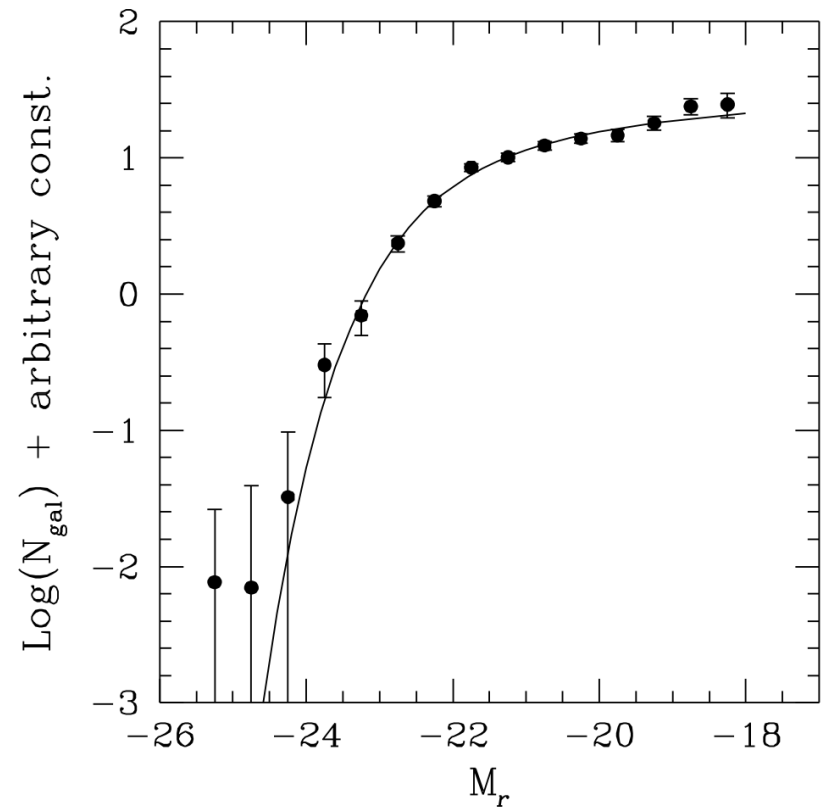
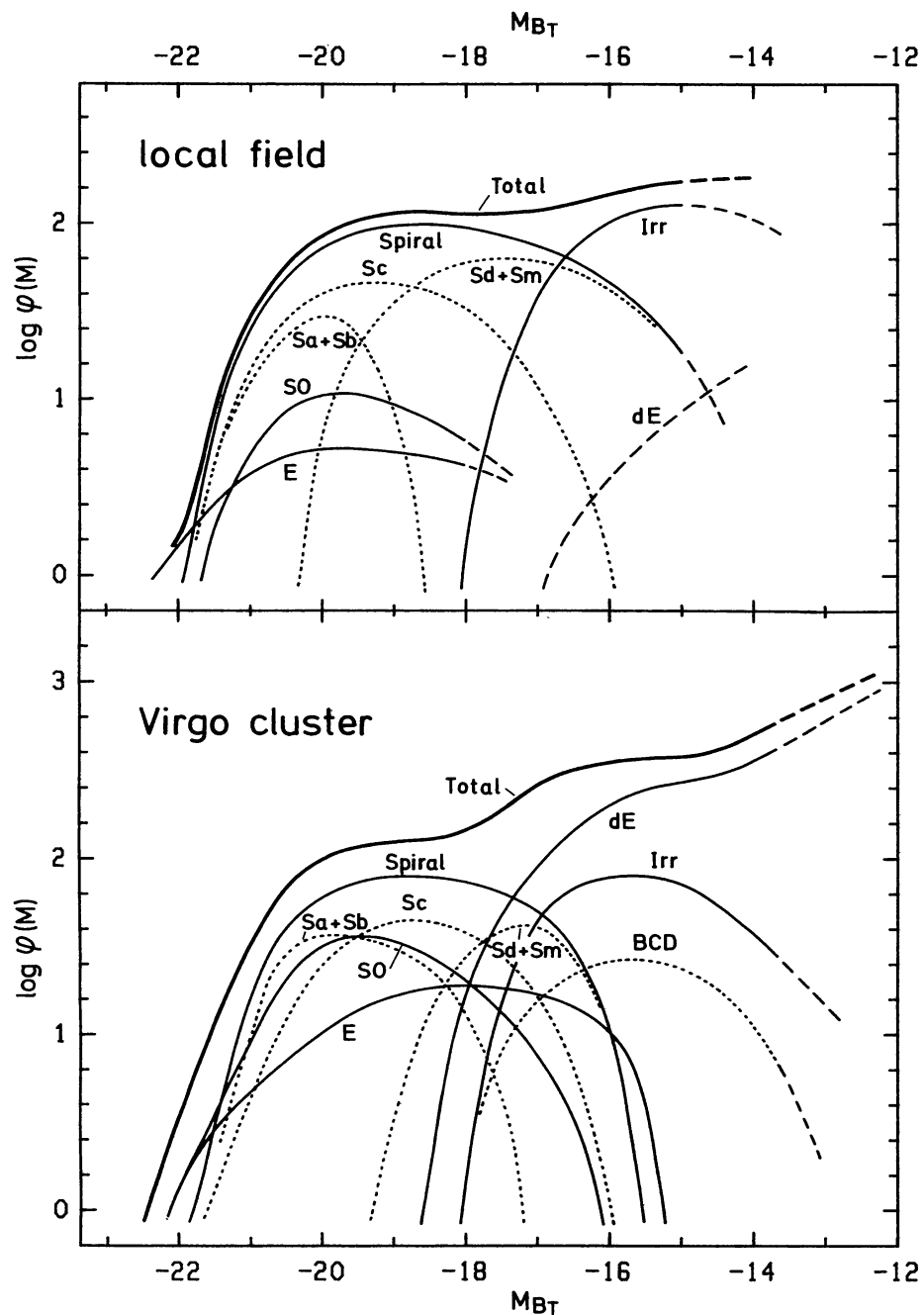
This is an increasing function of magnitude M , since $\alpha + 1 < 0$.

Plot: Luminosity Functions for Samples of Galaxies

• In addition, determination of the luminosity function is influenced by the wavelength window of observations. More distant galaxies are more redshifted, so that K-band emission is enhanced relative to B-Band. This potential spectral bias must be accounted for in ensemble determinations of luminosity functions, and is called a **K-correction**.

* Bolometric luminosities of more distant galaxies can be underestimated without this correction.

Galaxy Luminosity Functions



- *Above:* for 39 Abell cluster galaxies (Paolillo et al. *A&A* **367**, 59; 2001); mostly spirals and irregulars.
- *Left:* Nearby field and Virgo cluster galaxies (Binggeli et al. *ARAA* **26**, 509; 1988); mostly ellipticals.

3 Spiral Galaxies

- The Milky Way is in many ways a typical spiral galaxy, so the structure of spirals is summarized by the considerations of the previous Chapter.

C & O,
Sec. 25.2

A key property of spirals is that earlier on in their evolution, the gaseous halo decouples from the old halo population and gravitationally collapses to form the disk, roughly conserving angular momentum. The disk is the site for current star formation; ellipticals possess only limited star formation.

- The luminosity of the central bulge obeys a **de Vaucouleurs profile**, which assumes a form for the surface brightness distribution $\mu(r)$ of

$$\mu(r) = \mu_e + 8.3268 \left\{ \left(\frac{r}{r_e} \right)^{1/4} - 1 \right\} . \quad (3)$$

Here r_e is the bulge's **effective radius**, and $\mu_e = \mu(r_e)$. The generalized de Vaucouleurs profile or **Sérsic profile** is of similar form, but with $4 \rightarrow n$.

- * The units of this surface profile are mag arcsec⁻², rather than $L_\odot \text{ pc}^{-2}$.
- * Contours of constant surface brightness are called **isophotes**.

The disk's surface light distribution assumes Freeman's exponential form

$$\mu(r) = \mu_0 + 1.09 \frac{r}{r_h} , \quad (4)$$

which is an $n = 1$ Sérsic profile.

- The vertical structure of spirals decouples from the radial profile, and is simply described via the physics of self-gravitating systems. The key property is that the velocity dispersion $\sigma_z^2 = \langle v_z^2 \rangle$ along z is independent of vertical height z (**isothermal assumption**). Energy densities are described by

$$P = \rho \sigma_z^2 , \quad \rho = \rho(z) . \quad (5)$$

Hydrostatic equilibrium (force balance) in the z direction then gives

$$\text{Force/Volume:} \quad \frac{\partial P}{\partial z} = -\rho \frac{\partial \Phi}{\partial z} , \quad (6)$$

where the gravitational potential function $\Phi(z)$ satisfies Poisson's equation

$$\nabla^2\Phi \equiv \frac{\partial^2\Phi}{\partial z^2} = 4\pi G\rho \quad . \quad (7)$$

This solves as

$$\rho(z) = \frac{\rho_0}{\cosh^2(z/H)} \quad , \quad H = \sqrt{\frac{\sigma_z^2}{2\pi G\rho_0}} \quad , \quad (8)$$

for $\rho_0 = \rho(z = 0, r)$. Here H is the hydrostatic scale height, analogous to the scale height of the Earth's atmosphere.

* Setting $\Sigma(r) = H\rho_0$ as the radial surface density along the disk, which can be estimated using the brightness profile, we can determine H via measurables:

$$H = \frac{\sigma_z^2}{2\pi G\Sigma(r)} \quad . \quad (9)$$

• Assuming that luminosity traces mass (a good but not perfect correlation), then the vertical luminosity profiles are $L \propto 1/\cosh^2(z/H)$.

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p. 885

Plot: Radial Brightness Profiles for Spirals NGC 4565 and NGC 5907

* The observed similar values of H for all radii in NGC 4565 and NGC 5907 implies that $\sigma_z^2(r)$ depends on r in the same way as $\rho_0(r)$.

* The high z excesses probably imply a thickening of the disk — principal evidence for the thick disk component!

• The HI (21cm line) rotational velocity profiles of spirals generally mimic the character of that of the Milky Way. Near the bulge, the rotation curves rise rapidly and then saturate at a plateau.

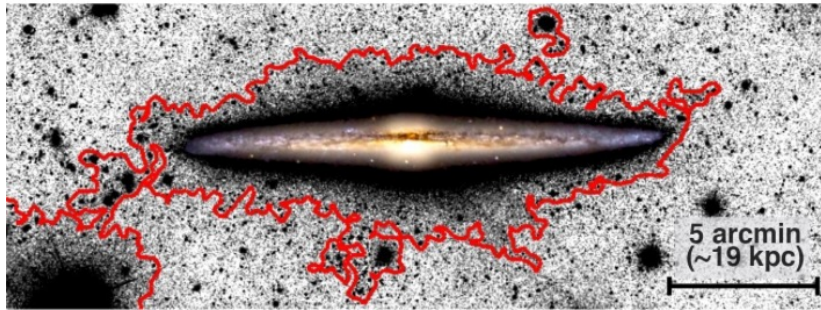
Plot: Rotation Curves for Various Spiral Galaxies

The plateau velocity v_c is referred to as a spiral's **mean circular velocity**.

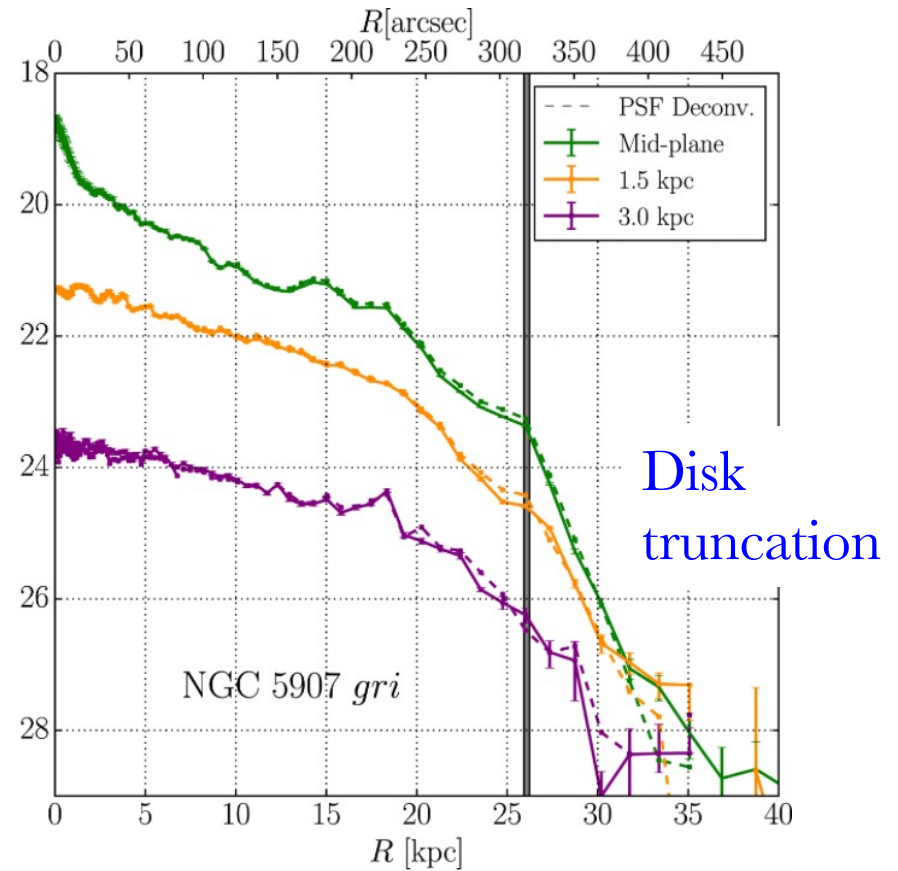
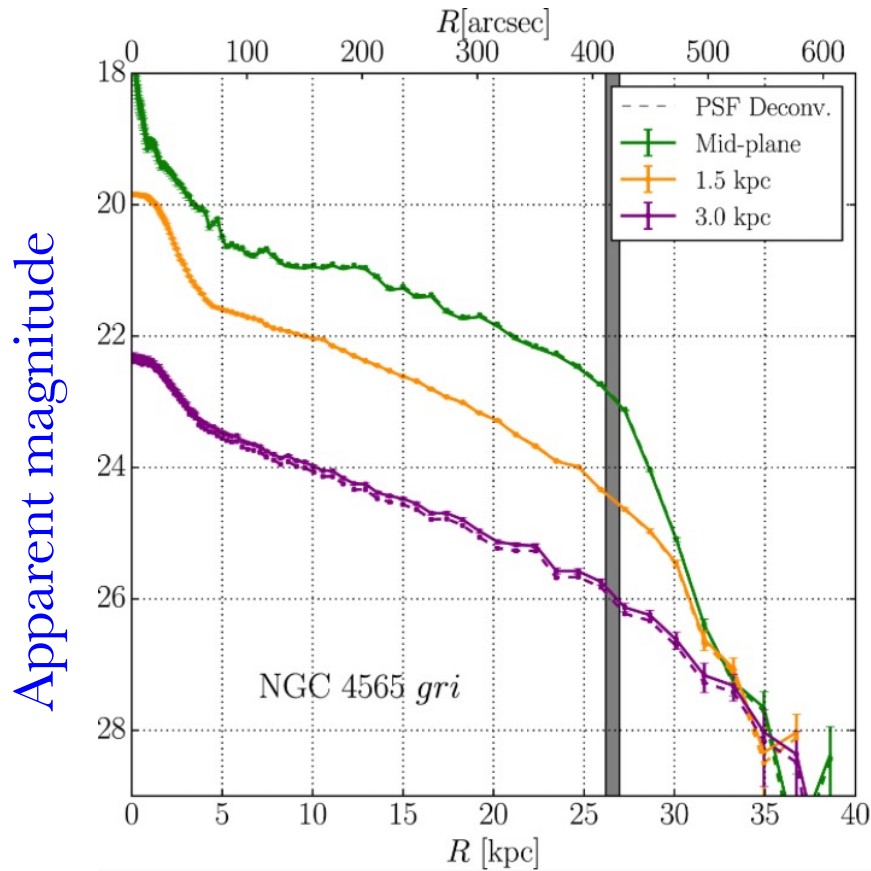
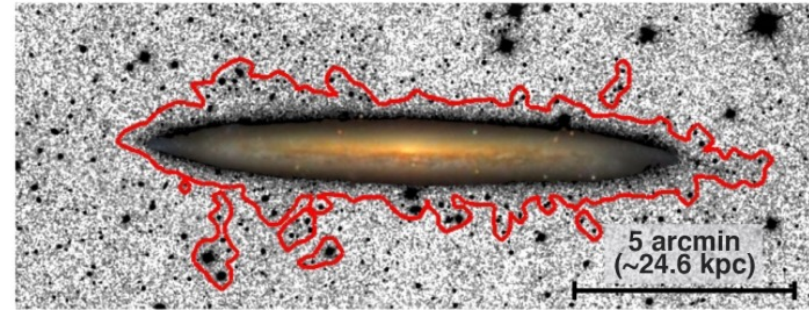
• The ubiquity of non-Keplerian rotation curves in spirals gives a global indication of the *pervasiveness of dark matter* in the Universe.

Radial Brightness Profiles

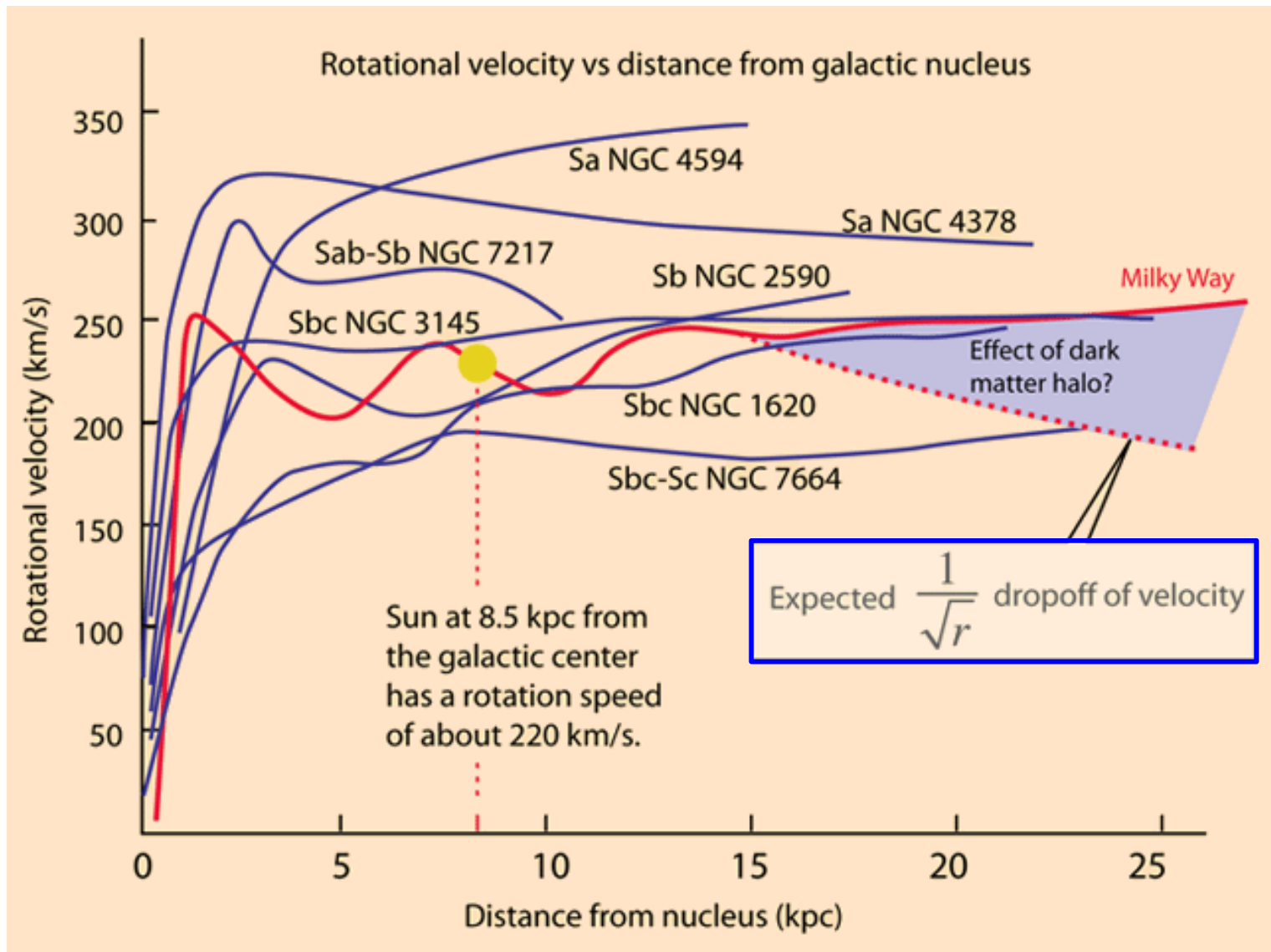
NGC 4565



NGC 5907



Rotation Curves for Spiral Galaxies



Credit: GSU adaptation of data from Rubin et al. *ApJL* **225**, L107 (1978)