Vincent van Gogh Starry Night Painting

Hvězdná noc, 1889

Struktura a kinematika galaxií

Bruno Jungwiert

Astronomical Institute of the Czech Academy of Sciences

Přednášky č. 1 a 2 (22. 10. 2020)

1. Mléčná dráha – morfologie, složení, rozměry, hmotnosti

2. Gravitační pole galaxií, rotační křivka, dráhy hvězd

Přírodovědecká fakulta MU - F7567 - 2020

The Milky Way, our Galaxy,
as seen from the European Southern Observatory, Chile

http://www.eso.org/gallery/v/ESOPIA/Paranal/phot-33a-07.tif.html

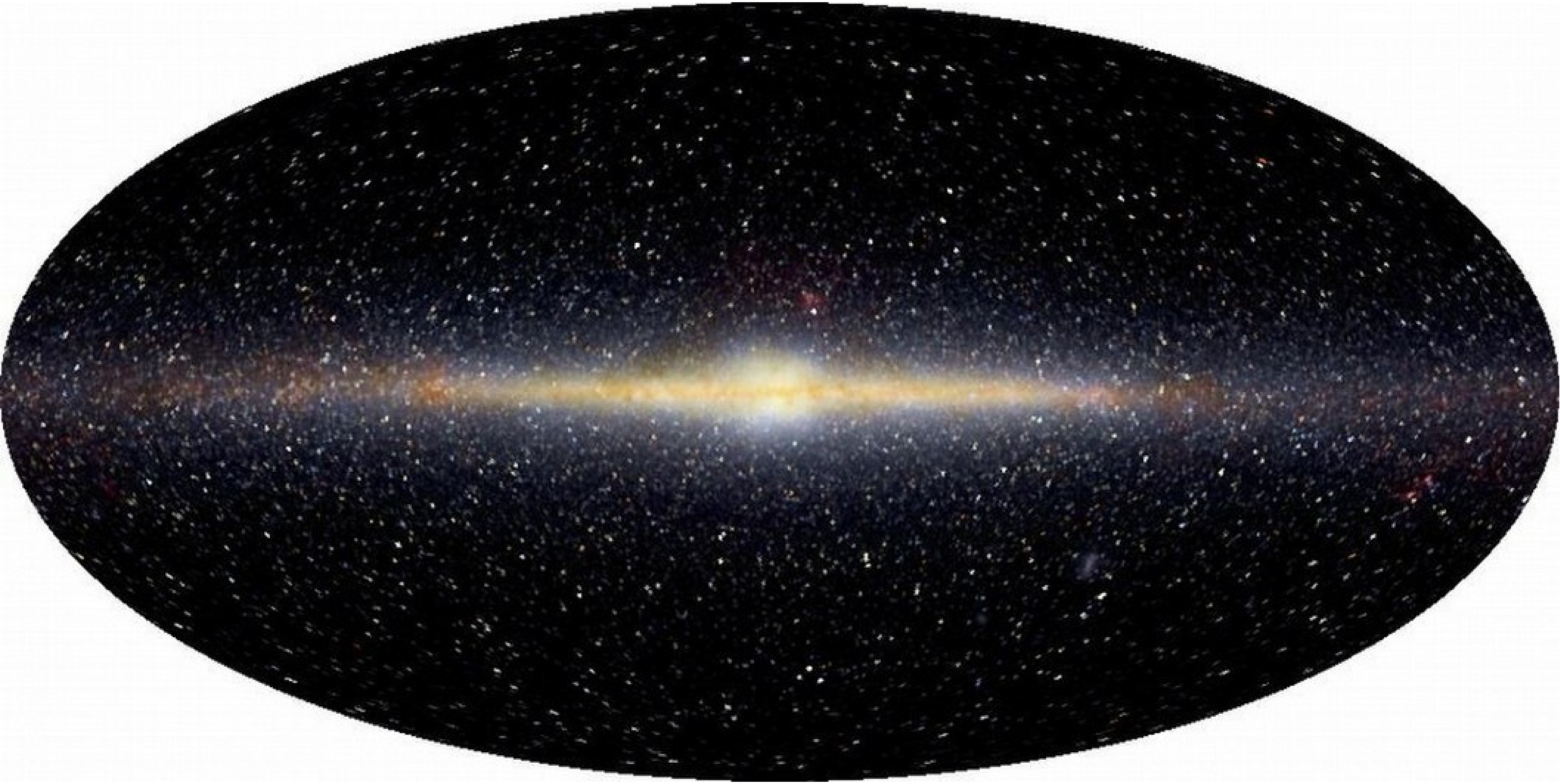
The Milky Way Sets
Image Credit & Copyright: Juan Carlos Casado (TWAN, Earth and Stars)

Explanation: Under dark skies the setting of the Milky Way can be a dramatic sight. Stretching nearly parallel to the horizon, this rich, edge-on vista of our galaxy above the dusty Namibian desert stretches from bright, southern Centaurus (left) to Cepheus in the north (right). From early August, the digitally stitched, panoramic night skyscape captures the Milky Way's congeries of stars and rivers of cosmic dust, along with colors of nebulae not readily seen with the eye. Mars, Saturn, and Antares, visible even in more luminous night skies, form the the bright celestial triangle just touching the trees below the galaxy's central bulge. Of course, our own galaxy is not the only galaxy in the scene. Two other major members of our local group, the Andromeda Galaxy and the Triangulum Galaxy, lie near the right edge of the frame, beyond the arc of the setting Milky Way.

credit: http://apod.nasa.gov/apod/ap160826.html

The Milky Way, our Galaxy (optical image), seen “edge-on”

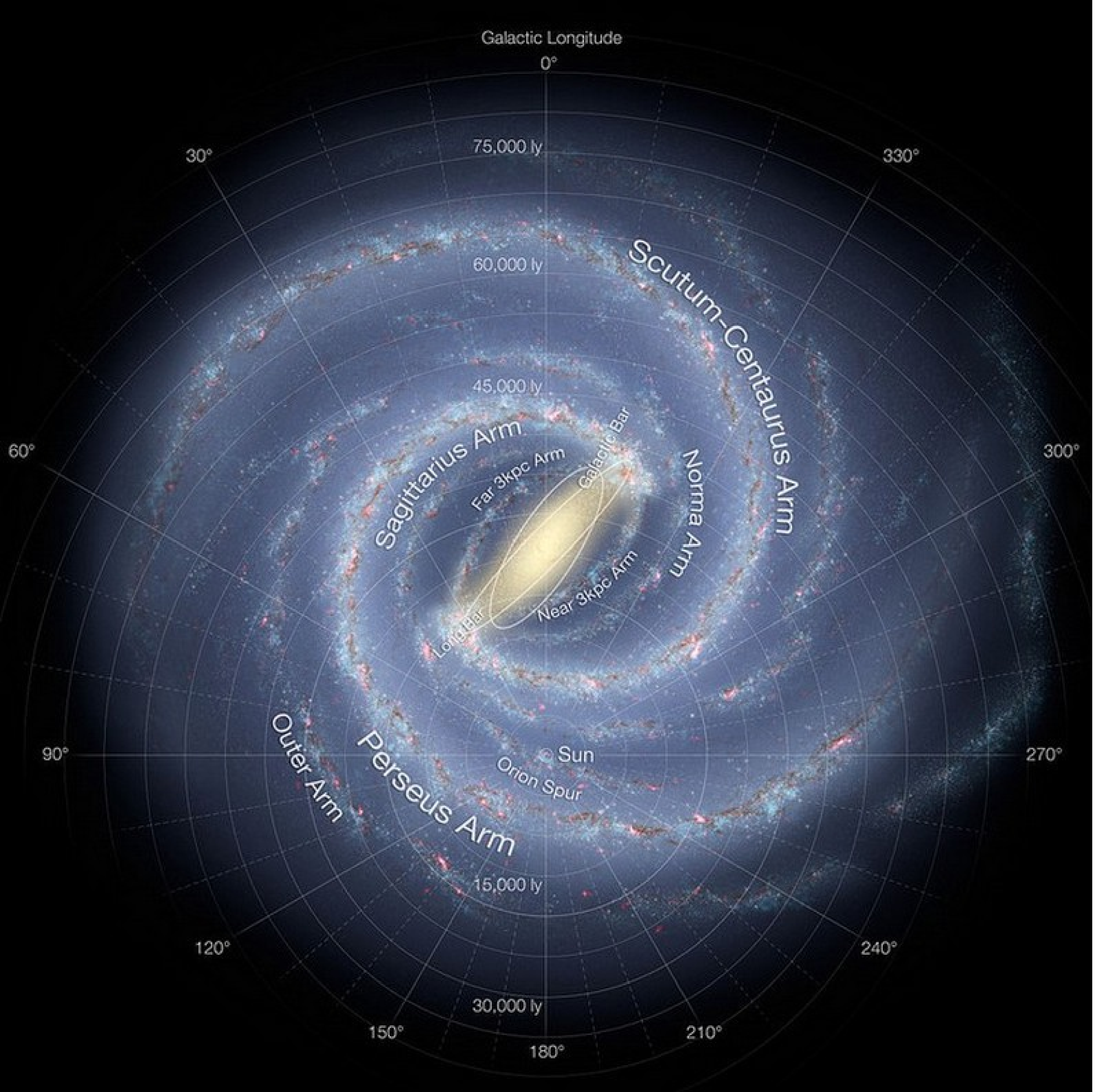
(credit: ESO)



The Milky Way Galaxy seen in the near infrared

COBE/DIRBE JKL image credit: NASA

The image shows a composite all-sky photo of the Milky Way Galaxy as taken by the NASA spacecraft COBE in 1993. The photo clearly shows the disky nature of our Galaxy as well as the fact that we live close to the mid-plane of the disk. The central puffy region is the Milky Way's bar. Note that the dark patches – due to starlight absorption by interstellar dust – appearing on optical images of the Milky Way (see previous slides) are considerably reduced (the IR radiation is absorbed by dust much less than visible light).



The Milky Way's structure
as seen from "face"
in the starlight
(= visible light)

(artist's picture)

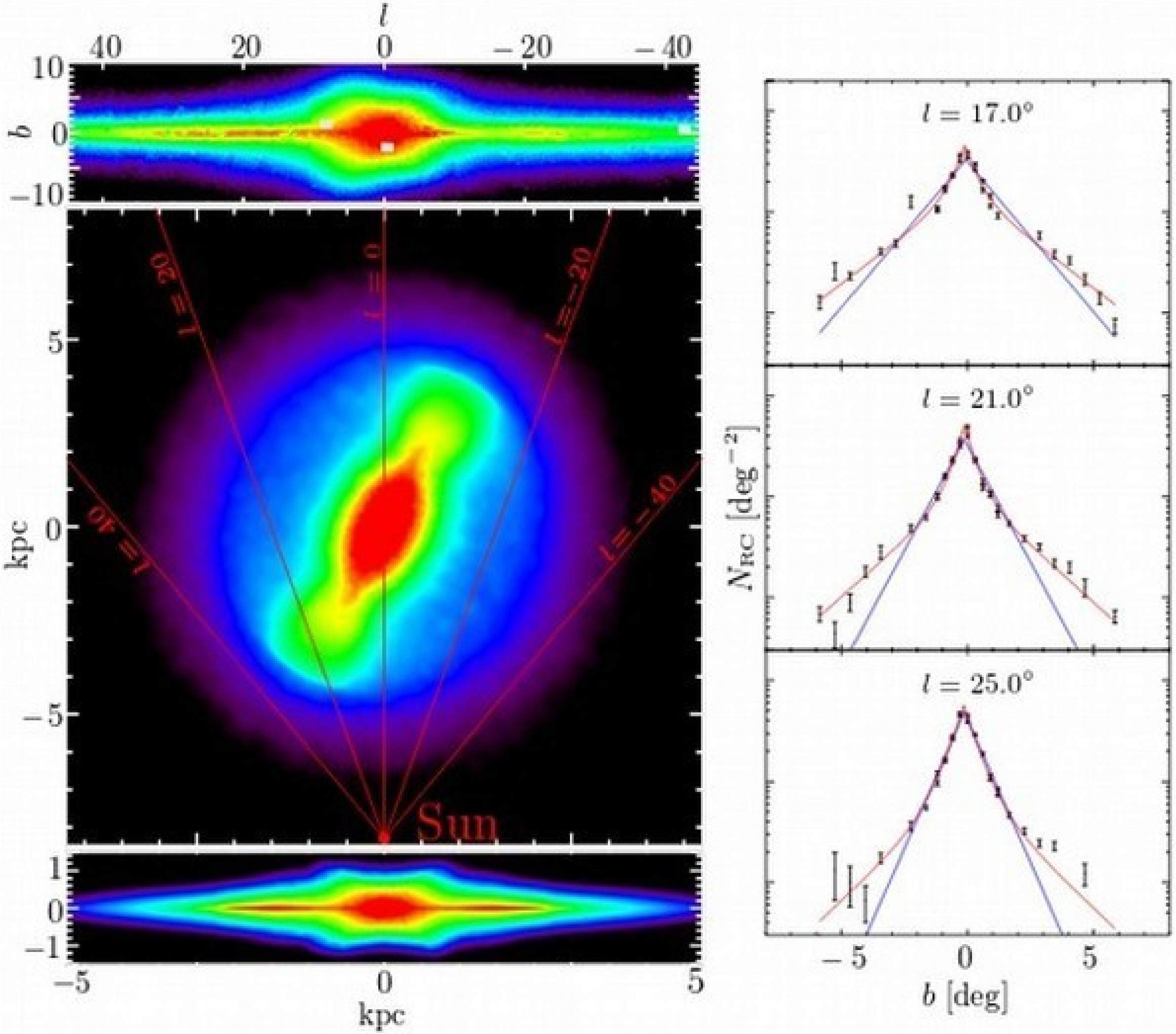
main structural components seen in this figure (all made of stars):

- **disk** with **spiral arms**

- **bulge/bar** region

The Sun is located within one of fainter spiral arms, so- called Orion arm (or Orion spur)

http://www.eso.org/public/images/eso1339e



Bland-Hawthorn & Gerhard, 2016

Figure 9

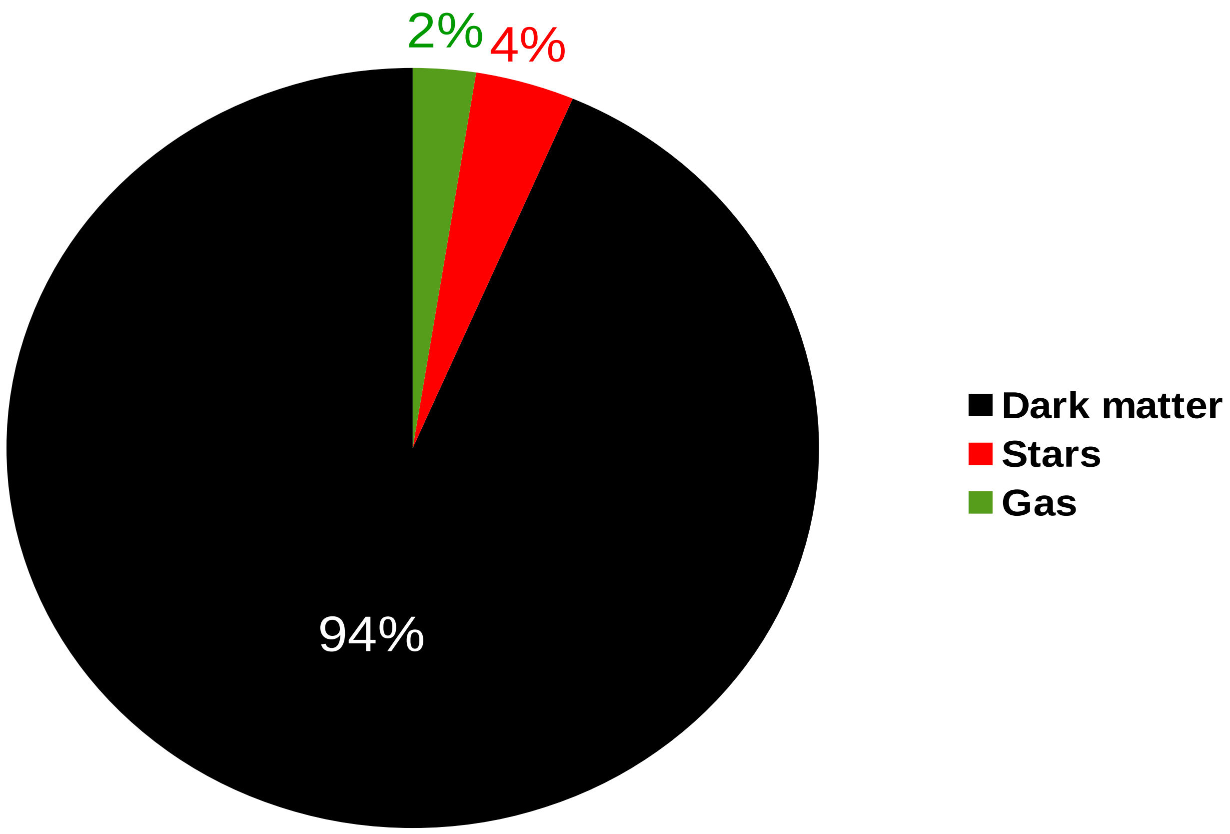
Left: projections of the Galactic b/p-bulge and long bar reconstructed from NIR star counts. Top: inner Galaxy as seen from the Sun, in bright star counts complete across several NIR surveys. Middle: Projection of best-fitting RCG star count model as seen from the North Galactic Pole. Viewing directions from the Sun are indicated for longitudes $|l| = 0°, 20°, 40°$. Bottom left: side-on view showing the transition from the b/p bulge to the long bar and disk. Right: Vertical surface density profiles of RCG stars for several longitude slices in the long bar region. Blue lines show single exponential fits. Red lines show the preferred double exponential model consisting of a superthin ($h_z = 45$ pc) and a thin bar component ($h_z = 180$ pc). The fraction of stars in the superthin component increases with longitude (adapted from Wegg, Gerhard & Portail 2015).

The Milky Way's bar

The Milky Way is a *barred spiral galaxy*. The presence of its bar can be deduced by counting stars along different lines-of-sight on its infrared image (previous slide). For a bar tilted with respect to the line joining our position and the center of the Galaxy, as is the case, the lines-of-sight taken symmetrically on the left and on the right side of the Galaxy will result in different star counts.

The Milky Way in a nutshell:

- a large barred spiral galaxy containing some **200 billion stars**
- the total mass is estimated to be around **1.5 trillion (1.5 x 10^{12}) solar masses**
- most of the mass, more than **90%**, is believed to be in the form of ***dark matter***
- only **3-4%** of the mass are made of **stars**
- remaining **2-3%** are **gaseous**

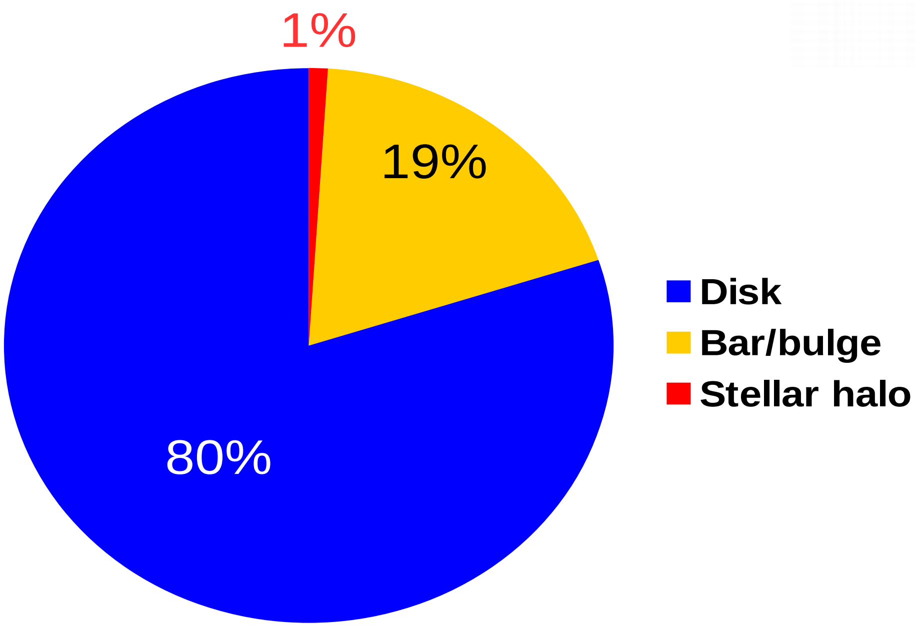


The Milky Way’s disk extends to roughly 100,000 l.y. (30 kpc) in radius.
Our Sun is at 27,000 l.y. (8.2 kpc) from the center of the Galaxy.
This is less than 1/3 of the disk radius, however more than 90% of all Milky Way’s stars are located within the Sun’s nearly circular orbit.
The dark matter halo (see next slides) extends to 0.5 - 1 million light years (150 – 300 kpc).

Stars are distributed in several structural components:

- stellar **disk** with **spiral arms**
- stellar **bar** (or **bulge-bar**)
- stellar **halo** (see next slide)

The **total stellar mass** is roughly $6 \cdot 10^{10}$ solar masses.



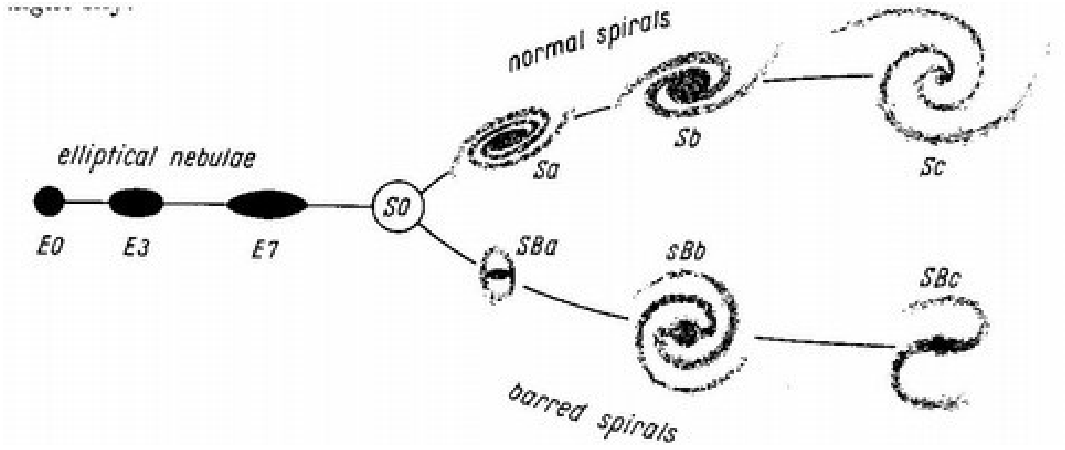
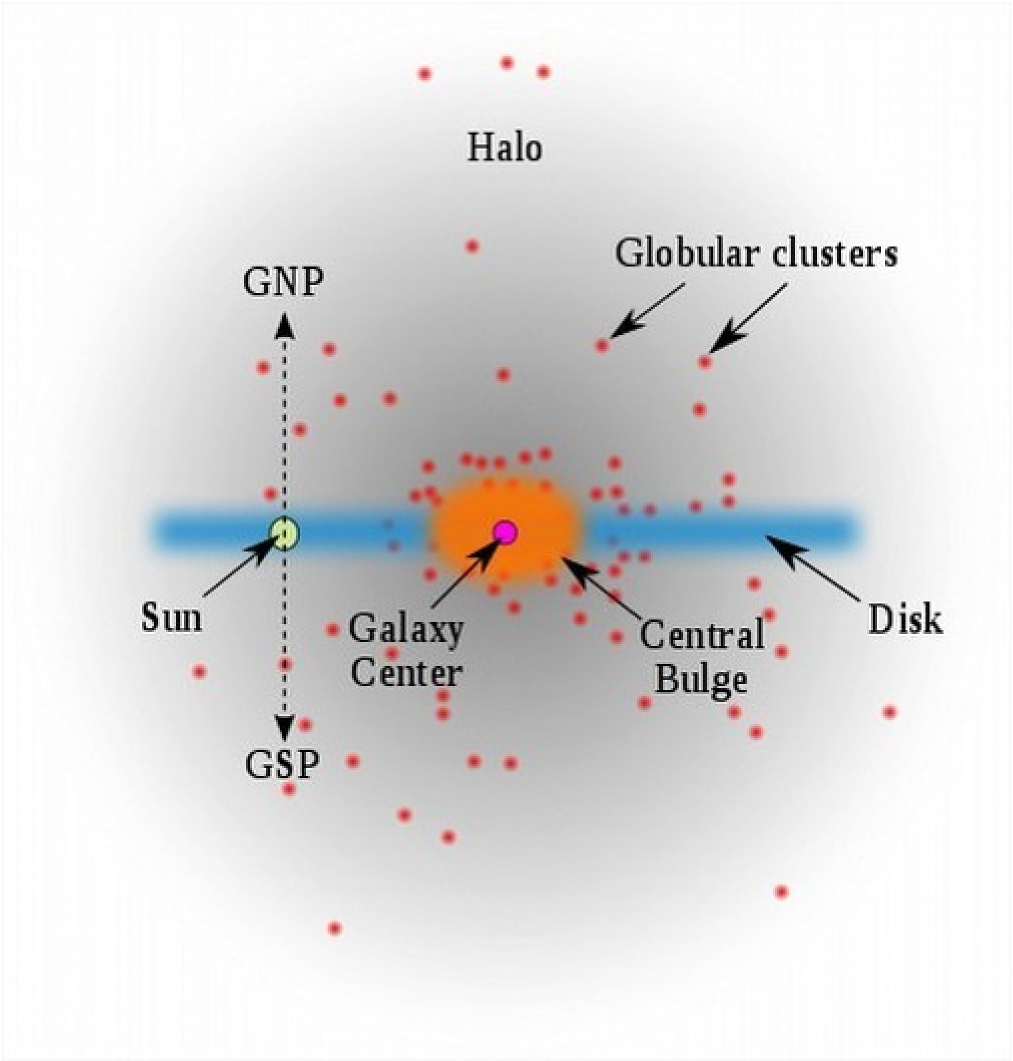


Image credit: E. Hubble, *The Realm of the Nebulae*

The Milky Way Galaxy is a **barred spiral galaxy**, probably of the Hubble type **SBbc**

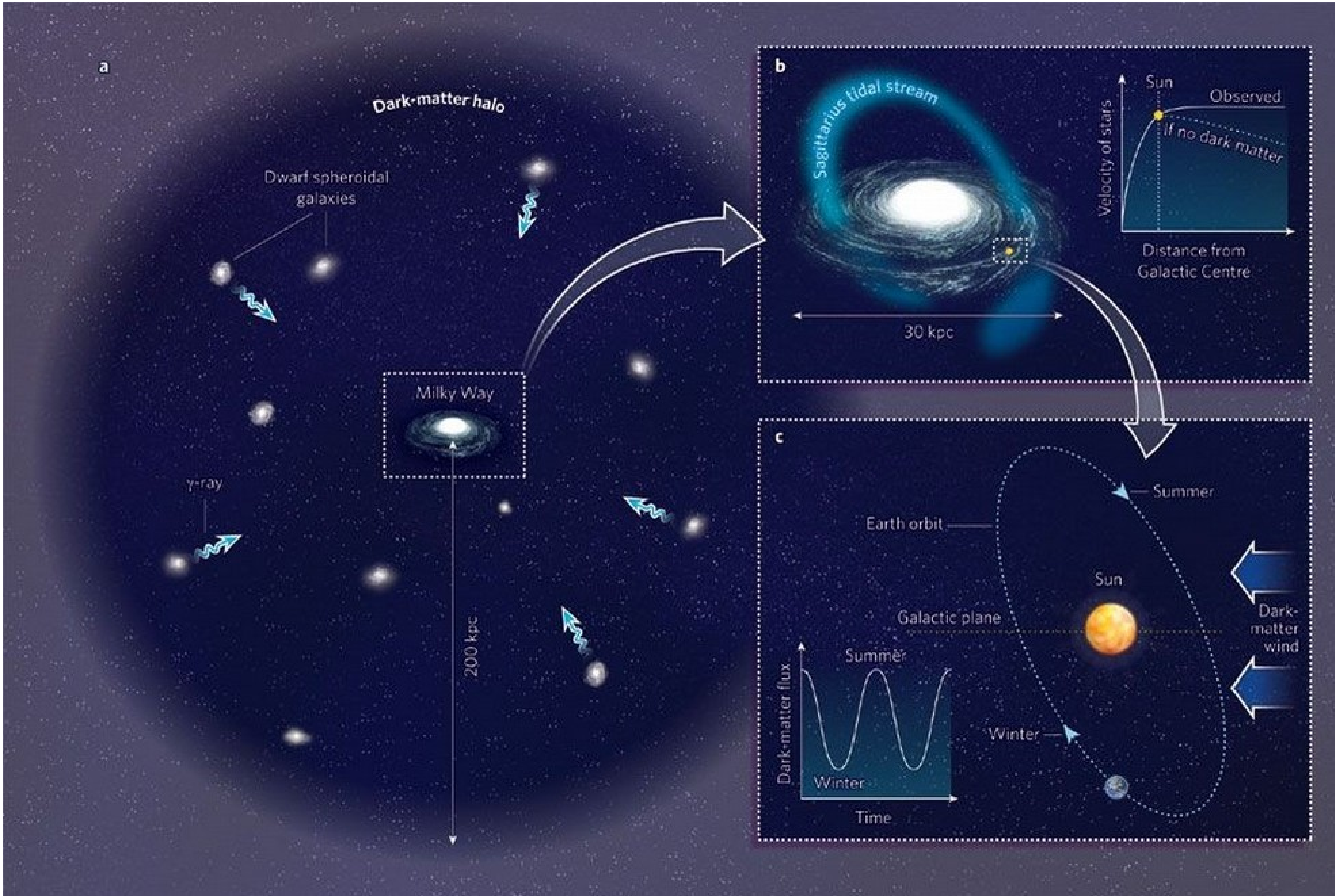
The *stellar halo* and *globular clusters*

Apart from the disk and the central bar-bulge region, the Milky Way (as well as other spiral galaxies) possesses a large spherical stellar component, a *stellar halo.* Stars in the halo appear either as dispersed individuals (so-called halo *field stars*, or group in the so-called *globular clusters*.



The dark matter halo:

The stellar and gaseous disk of the Milky Way is believed to be embedded in a much larger ***dark matter halo*** having a diameter of more than 1 million light years. The dark matter halo dominates the mass of the Galaxy.



Spiral galaxies thought to resemble the Milky Way Galaxy

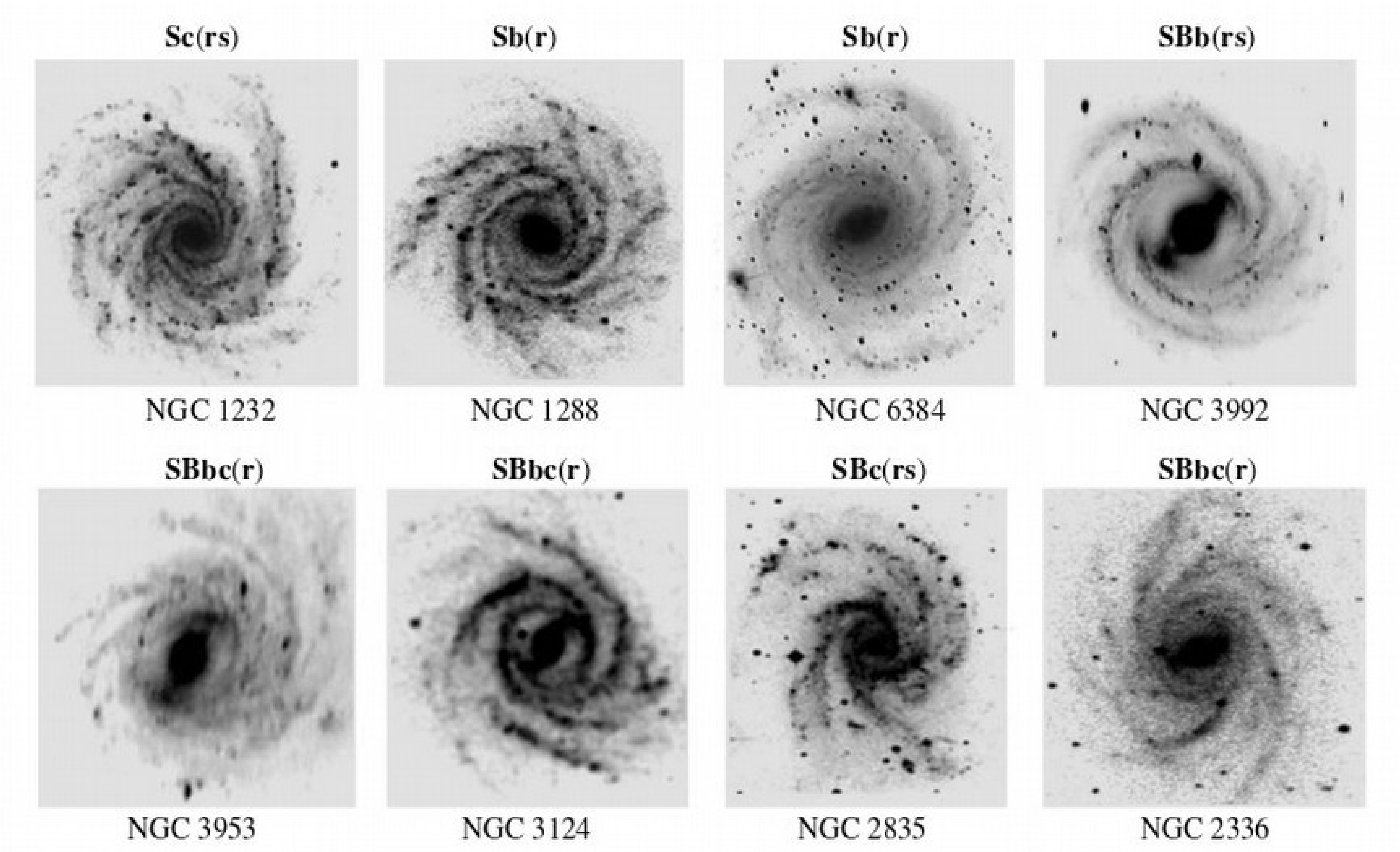
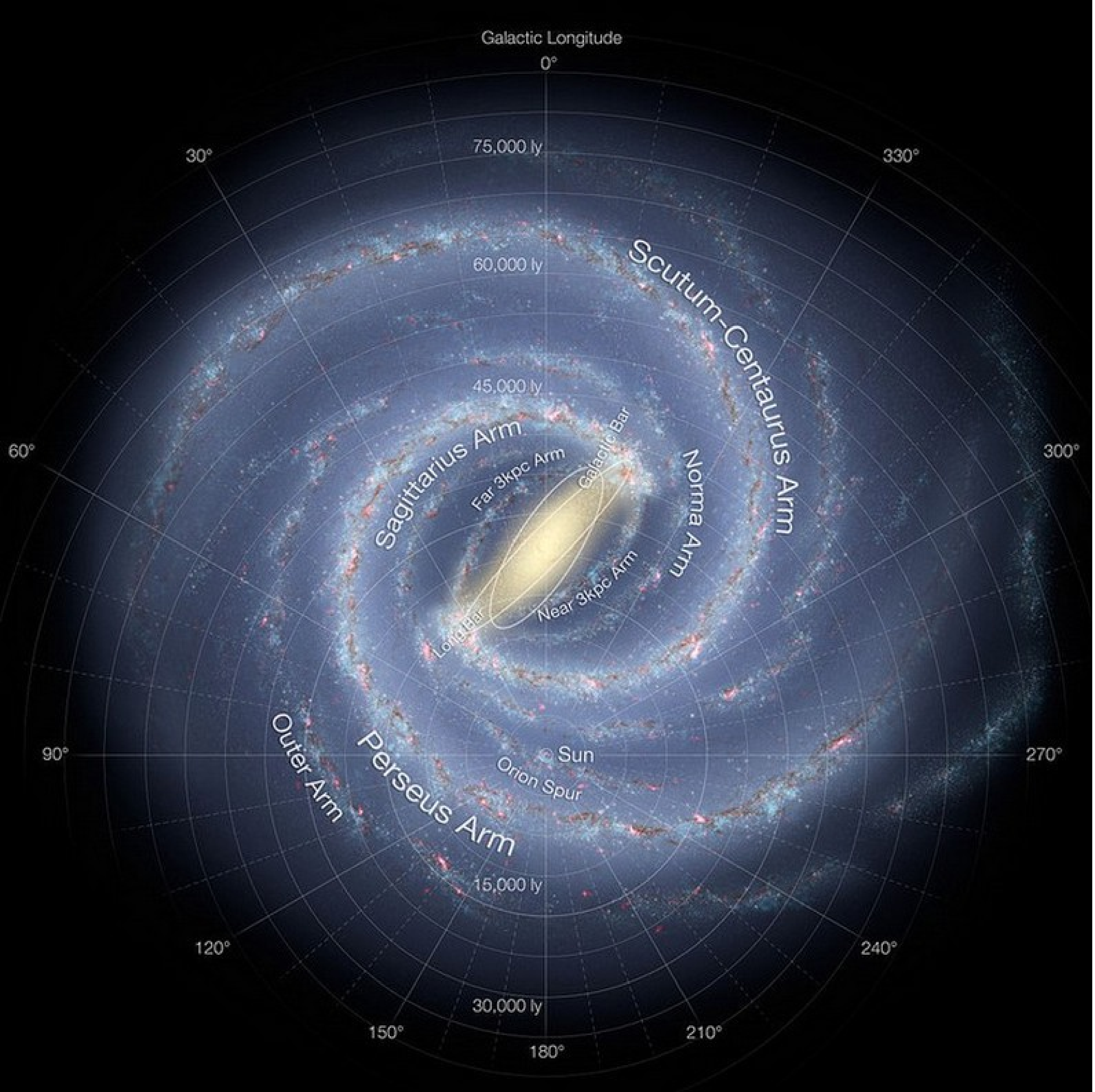


Fig. 14. Galaxies resembling our Galaxy.

Image credit: Efremov 2011



The Milky Way and our Sun:

- the Sun is located **27,000 light years**, or **1.7 billion AU, from the Galactic center**, close to the mid-plane of the Milky Way disk

- it orbits the Milky Way at a **speed of 240 km/s,** or 540,000 mph, (8 times faster than the orbital speed of the Earth around the Sun (30 km/s))

- one orbit takes **220 million years** to complete (this is sometimes referred to as the ***Galactic year***)

- since the age of the Sun is **4.6 billion years**, the Sun has accomplished just about **20 turns** around the Galactic center (assuming its orbit has not changed too much)

DRÁHY HVĚZD V GALAXIÍCH

$$\nabla^2 \Phi = 4\pi G \rho$$ (Poissonova rovnice) $\Rightarrow$

ρ … hustota hmoty

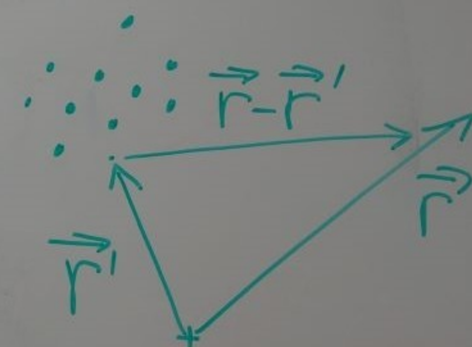
Φ … gravitační potenciál

FORMÁLNÍ ŘEŠENÍ:

$$\Phi(\vec{r}) = -G \int \frac{\rho(\vec{r}\,')\, d^3\vec{r}\,'}{|\vec{r} - \vec{r}\,'|}$$

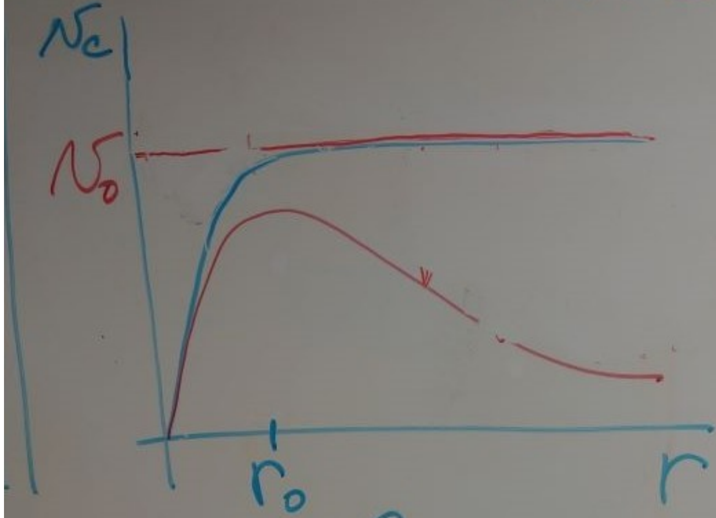
$$\vec{F} = -\nabla \Phi$$

$\vec{F}$ … gr. síla na jednotku hmoty (= intenzita gr. pole)

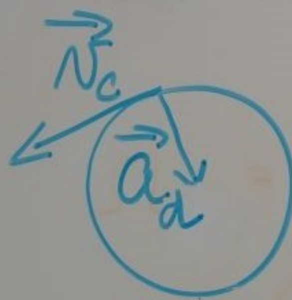


$$\ddot{\vec{r}} = -\nabla \Phi$$ (pohybová rovnice hvězdy v inerciální soustavě)

ROTAČNÍ KŘIVKA GALAXIÍ



v_c - KRUHOVÁ RYCHLOST



$$a_d = \frac{v_c^2}{r}, \quad a_d = |F_r|$$

RADIÁLNÍ SLOŽKA GR. SÍLY

$$\Rightarrow v_c^2 = r \cdot |F_r| = r \cdot \left|\frac{\partial \Phi}{\partial r}\right| = r \cdot \frac{\partial \Phi}{\partial r}$$

$$\Phi(r) = \int \frac{v_c^2(r)}{r} \, dr$$

APROXIMACE: $v_c = v_0 = \text{Const.}$

$$\Phi = v_0^2 \ln r + C \Rightarrow F_r = -\frac{d\Phi}{dr} = -\frac{v_0^2}{r}$$

LOGARITMICKÝ POTENCIÁL

MODIFIKACE:

$$\Phi = \frac{v_0^2}{2} \ln(r^2 + r_0^2) \Rightarrow$$

DOMÁCÍ ÚKOL:

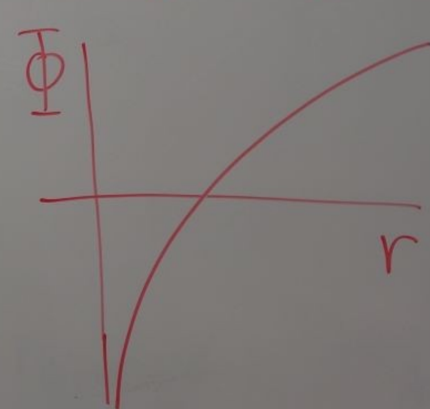
$F_r(r) = ?$, $v_c(r) = ?$, $\rho(r) = ?$

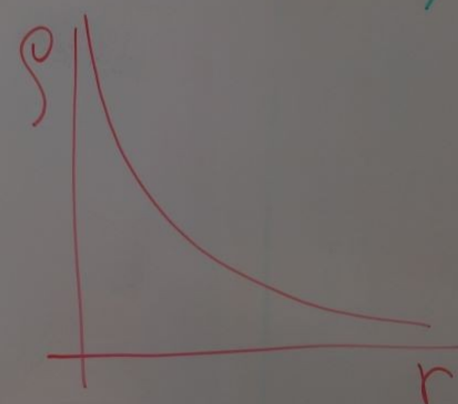
Výpočet hustoty pro $\Phi = v_0^2 \ln r$

$$\nabla^2 \Phi = 4\pi G \rho \,, \quad \frac{d\Phi}{dr} = \frac{v_0^2}{r}$$

pro sférickou symetrii (tj. $\rho(\vec{r}) = \rho(|\vec{r}|)$, $\Phi(\vec{r}) = \Phi(|\vec{r}|)$):

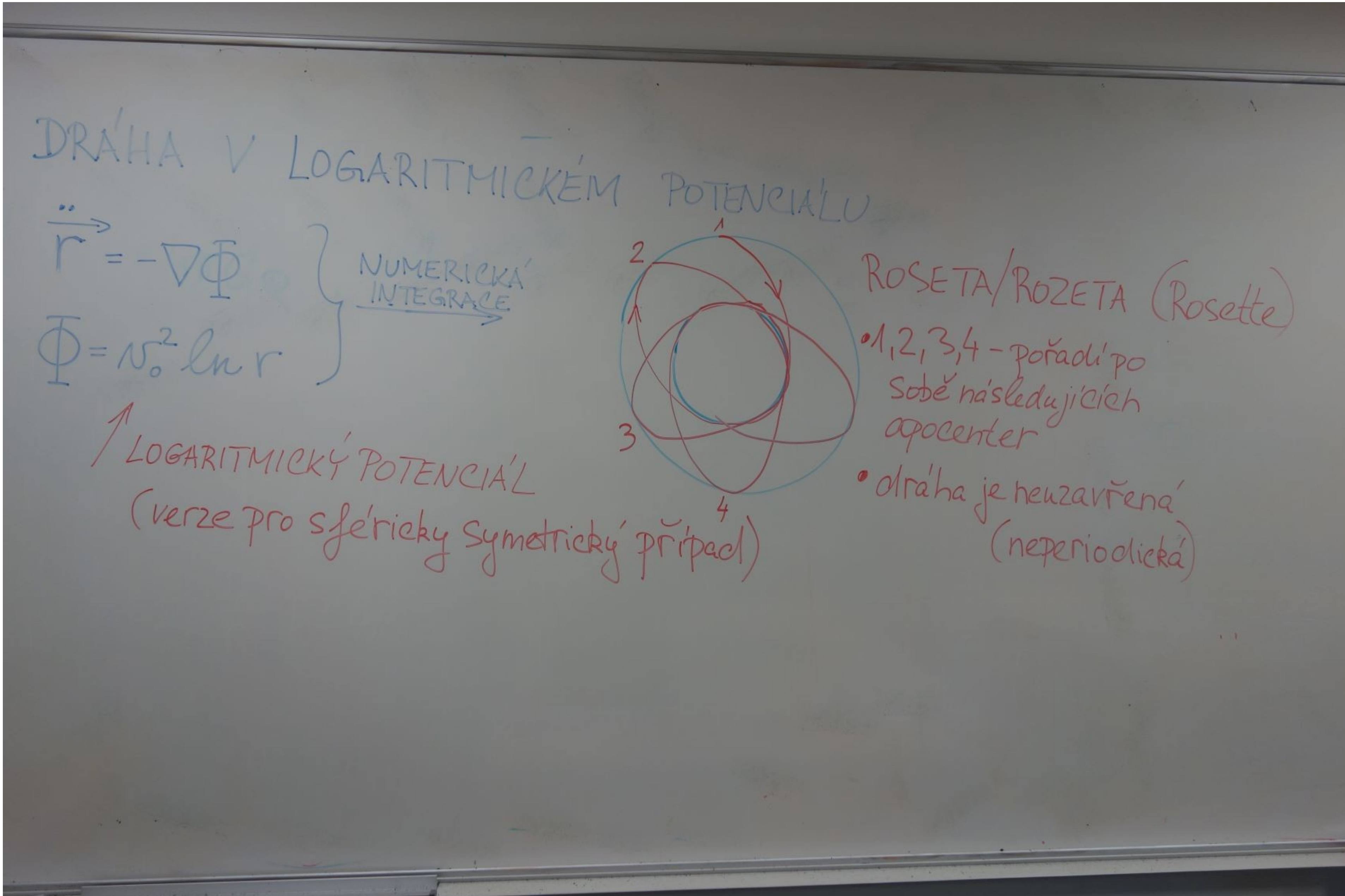
$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 \frac{d\Phi}{dr}\right) = 4\pi G \rho$$





$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 \frac{v_0^2}{r}\right) = 4\pi G \rho$$

$$\frac{v_0^2}{r^2} = 4\pi G \rho \Rightarrow \boxed{\rho(r) = \frac{v_0^2}{4\pi G r^2}}$$


DRÁHA V LOGARITMICKÉM POTENCIÁLU
$\ddot{\vec{r}} = -\nabla\Phi$
$\Phi = v_0^2 \ln r$
NUMERICKÁ INTEGRACE
LOGARITMICKÝ POTENCIÁL
(verze pro sféricky symetrický případ)
1
2
3
4
ROSETA/ROZETA (Rosette)
• 1,2,3,4 - pořadí po sobě následujících apocenter
• dráha je neuzavřená (neperiodická)

ZACHOVÁNÍ MECHANICKÉ ENERGIE PODÉL DRÁHY

PODMÍNKA: konzervativní silové pole, tj. $\Phi(\vec r, \cancel{t}) = \Phi(\vec r)$

$$\ddot{\vec r} = -\nabla\Phi \quad / \cdot \dot{\vec r}$$

$$\ddot{\vec r}\cdot\dot{\vec r} = -\nabla\Phi\cdot\dot{\vec r}$$

$$\frac{1}{2}\frac{d}{dt}\left(\dot{\vec r}^2\right) = -\nabla\Phi\cdot\dot{\vec r} = -\frac{d\Phi}{dt}$$

$$\frac{d\Phi}{dt} = \underbrace{\frac{\partial\Phi}{\partial t}}_{=0} + \nabla\Phi\cdot\frac{d\vec r}{dt} = \underbrace{\nabla\Phi\cdot\frac{d\vec r}{dt}}_{\nabla\Phi\cdot\dot{\vec r} = \nabla\Phi\cdot\vec v}$$

$$\Rightarrow \frac{d}{dt}\left(\frac{\dot{\vec r}^2}{2} + \Phi\right) = 0 \Rightarrow \frac{\dot{\vec r}^2}{2} + \Phi = E = \text{konst.}$$

$\frac{\dot{\vec r}^2}{2}$: KIN. EN.; Φ: POT. EN; E: CELKOVÁ ENERGIE

(na jednotku hmoty)

ZACHOVÁNÍ MOMENTU HYBOSTI PODÉL DRÁHY

1) SFÉRICKÁ SYMETRIE, tj. $\Phi(\vec{r}) = \Phi(|\vec{r}|) = \Phi(r)$

$$\vec{L} \equiv \vec{r} \times \vec{v}$$

$$\Rightarrow F(\vec{r}) = f(|\vec{r}|) \cdot \vec{r}$$

(CENTRÁLNÍ SILOVÉ POLE)

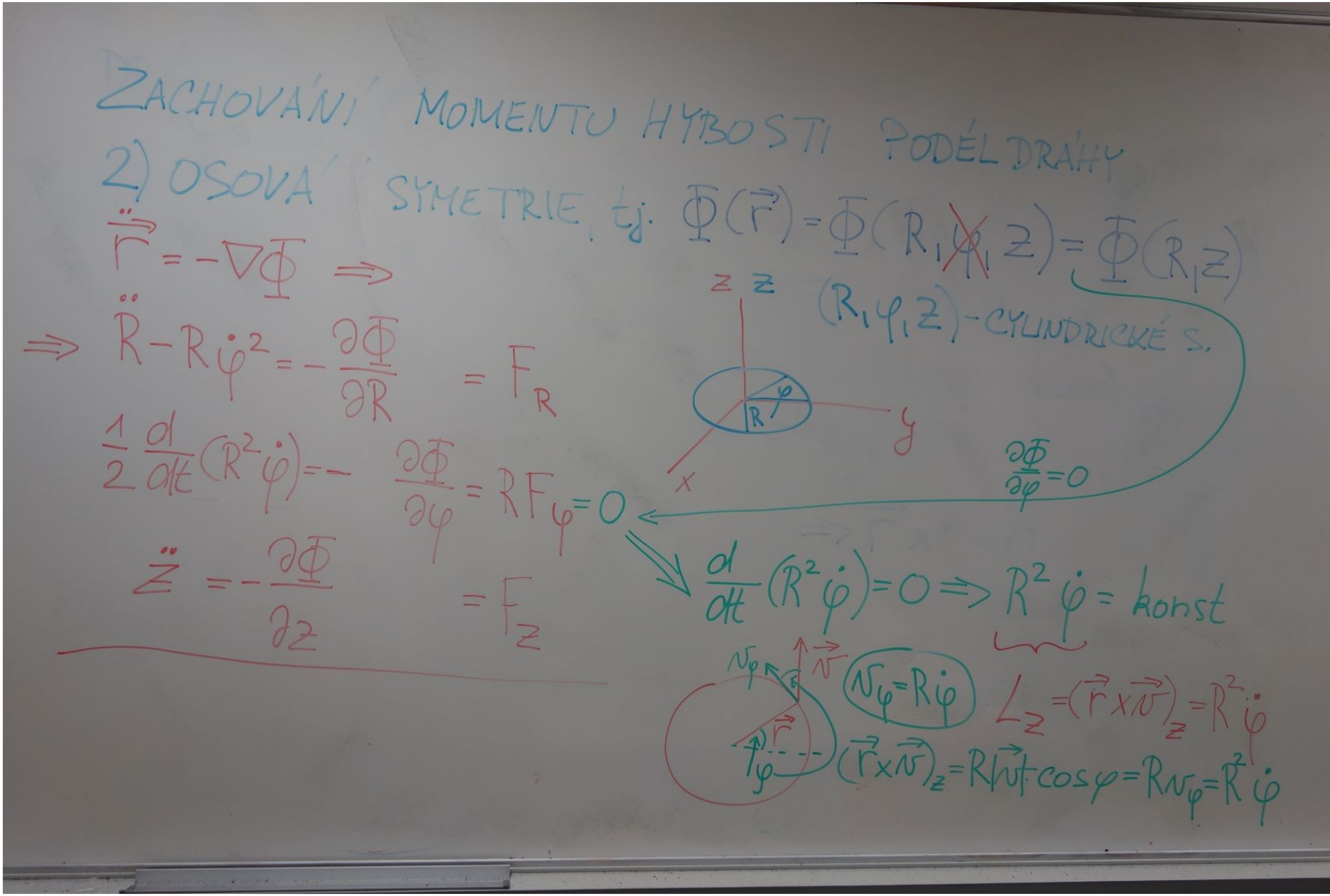
$$\frac{d\vec{L}}{dt} = \frac{d\vec{r}}{dt} \times \vec{v} + \vec{r} \times \frac{d\vec{v}}{dt} =$$

$$= \underbrace{\vec{v} \times \vec{v}}_{0} + \underbrace{\vec{r} \times \ddot{\vec{r}}}_{0} = 0$$

$$\Rightarrow \ddot{\vec{r}} = f(r) \cdot \vec{r} \Rightarrow \ddot{\vec{r}} \parallel \vec{r} \Rightarrow$$

$$\Rightarrow \ddot{\vec{r}} \times \vec{r} = 0$$

$$\Rightarrow \vec{L} = \text{konst.}$$


ZACHOVÁNÍ MOMENTU HYBOSTI PODÉL DRÁHY
2) OSOVÁ SYMETRIE, tj. $\Phi(\vec{r}) = \Phi(R, \varphi, z) = \Phi(R, z)$
(R, φ, z) - CYLINDRICKÉ S.
$\ddot{\vec{r}} = -\nabla\Phi \Rightarrow$
$\Rightarrow \ddot{R} - R\dot{\varphi}^2 = -\frac{\partial\Phi}{\partial R} = F_R$
$\frac{1}{2}\frac{d}{dt}(R^2\dot{\varphi}) = -\frac{\partial\Phi}{\partial\varphi} = RF_\varphi = 0$
$\ddot{z} = -\frac{\partial\Phi}{\partial z} = F_z$
$\frac{\partial\Phi}{\partial\varphi} = 0$
$\frac{d}{dt}(R^2\dot{\varphi}) = 0 \Rightarrow R^2\dot{\varphi} = konst$
z
y
x
R
φ
$v_\varphi = R\dot{\varphi}$
$L_z = (\vec{r} \times \vec{v})_z = R^2\dot{\varphi}$
$(\vec{r} \times \vec{v})_z = R|\vec{v}| \cdot \cos\varphi = Rv_\varphi = R^2\dot{\varphi}$