Introduction II

Outlines

Introduction II

- Our galaxy, the Milky Way
- The Local Group and beyond
- Luminosity Distribution Function

- The Hubble-De Vaucouleurs Sequence
  - Elliptical galaxies
  - Spiral Galaxies
  - Lenticular Galaxies
  - Irregular galaxies

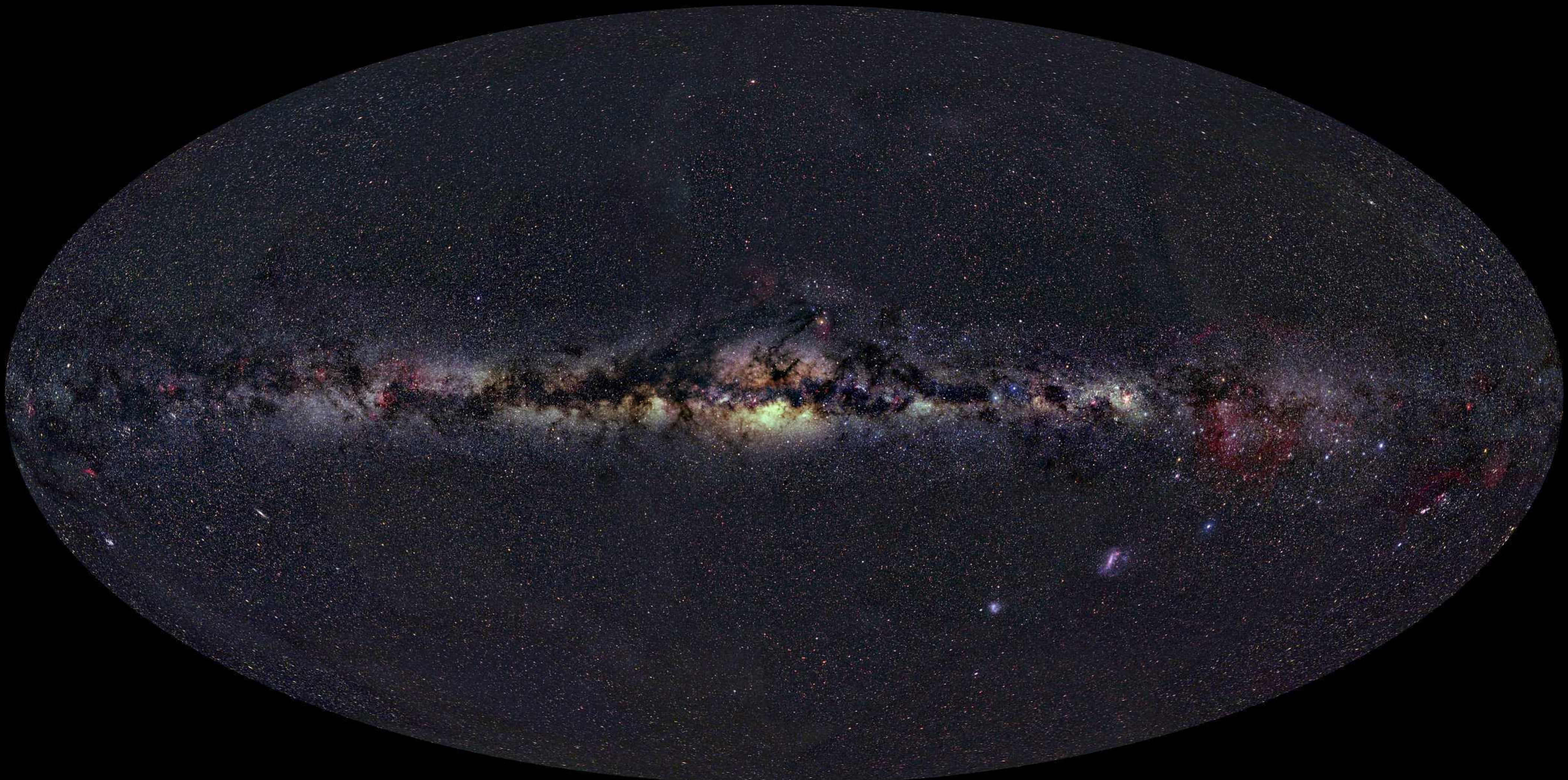
- The Hubble-Lemaître Law
- The Cosmic star formation history

The gravity : a long distance force

- collision-less systems
- the relaxation time

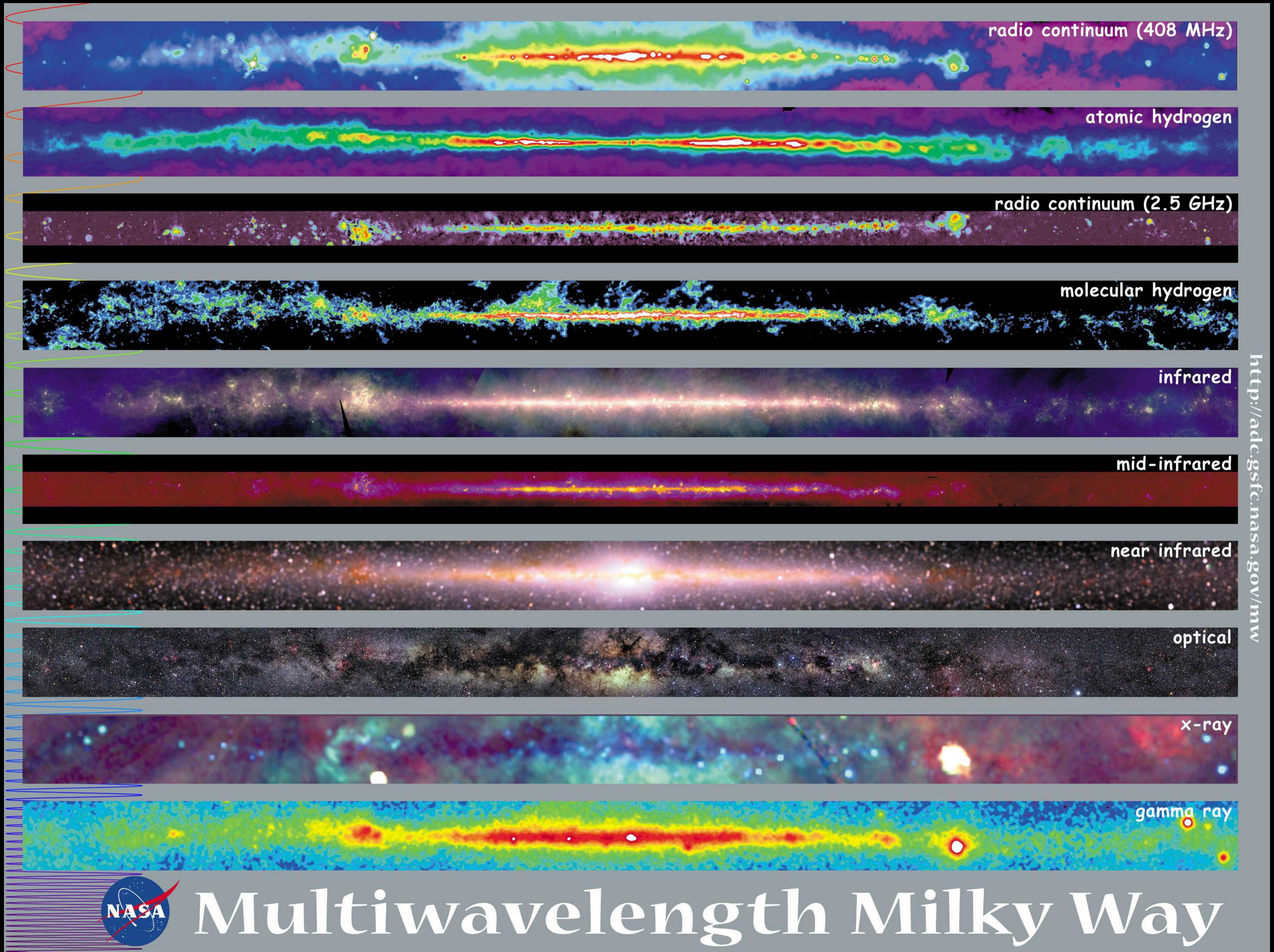
Introduction

Our galaxy
The Milky Way

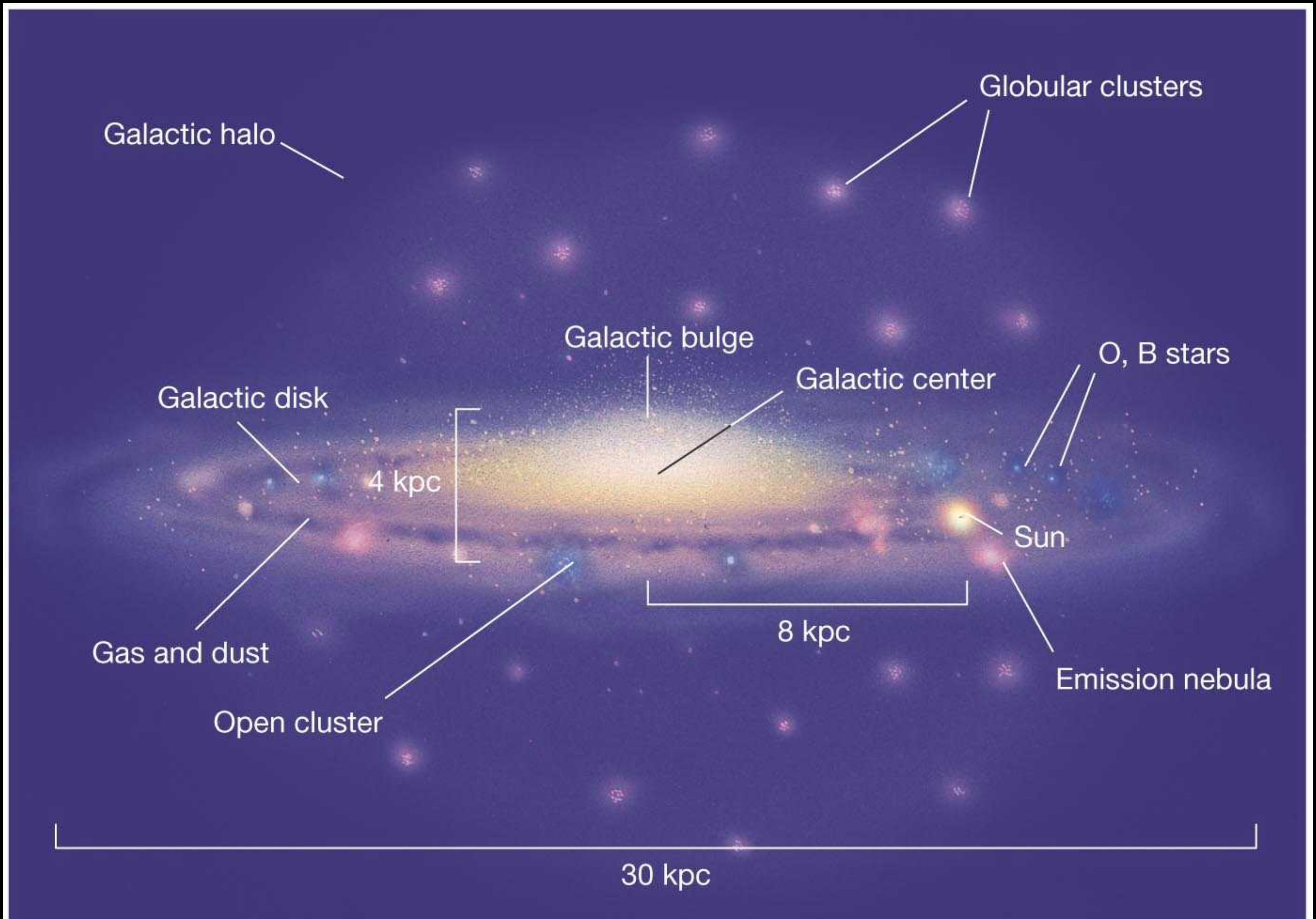


The Milky Way in different wavelength

The Milky Way in different wavelength

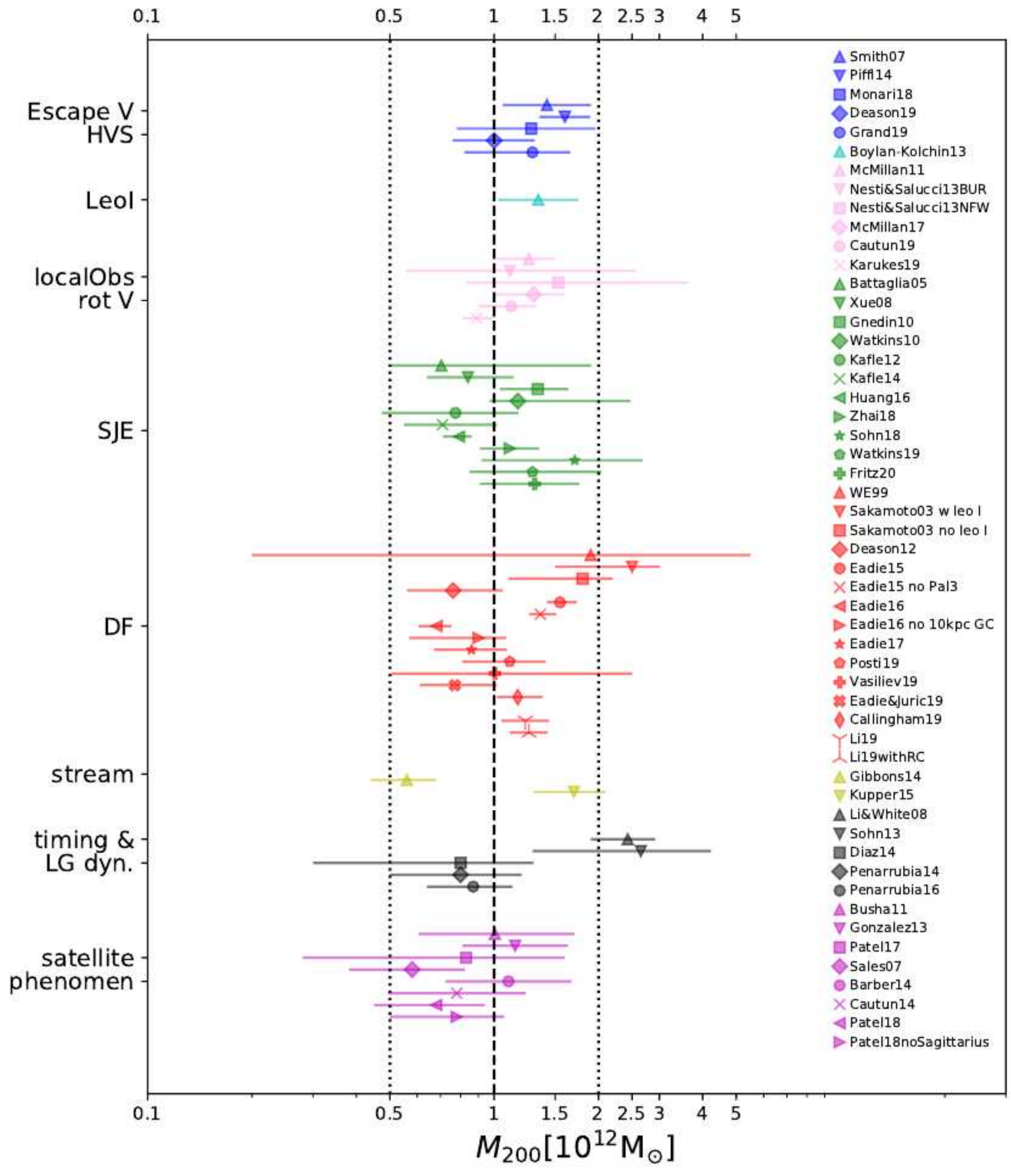

radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

Components of the WM



The Milky Way total (gravitational) mass

(Wang 2019, https://arxiv.org/abs/1912.02599)



Components of the WM

Diameter :

30 kpc

Total mass:

10^{12} $M_{\odot}$

Rotation :

200 Myr (sun)

500 Myr (ext.)

Stellar component : bulge/bar

$0.5 \times 10^{10}\, M_\odot$

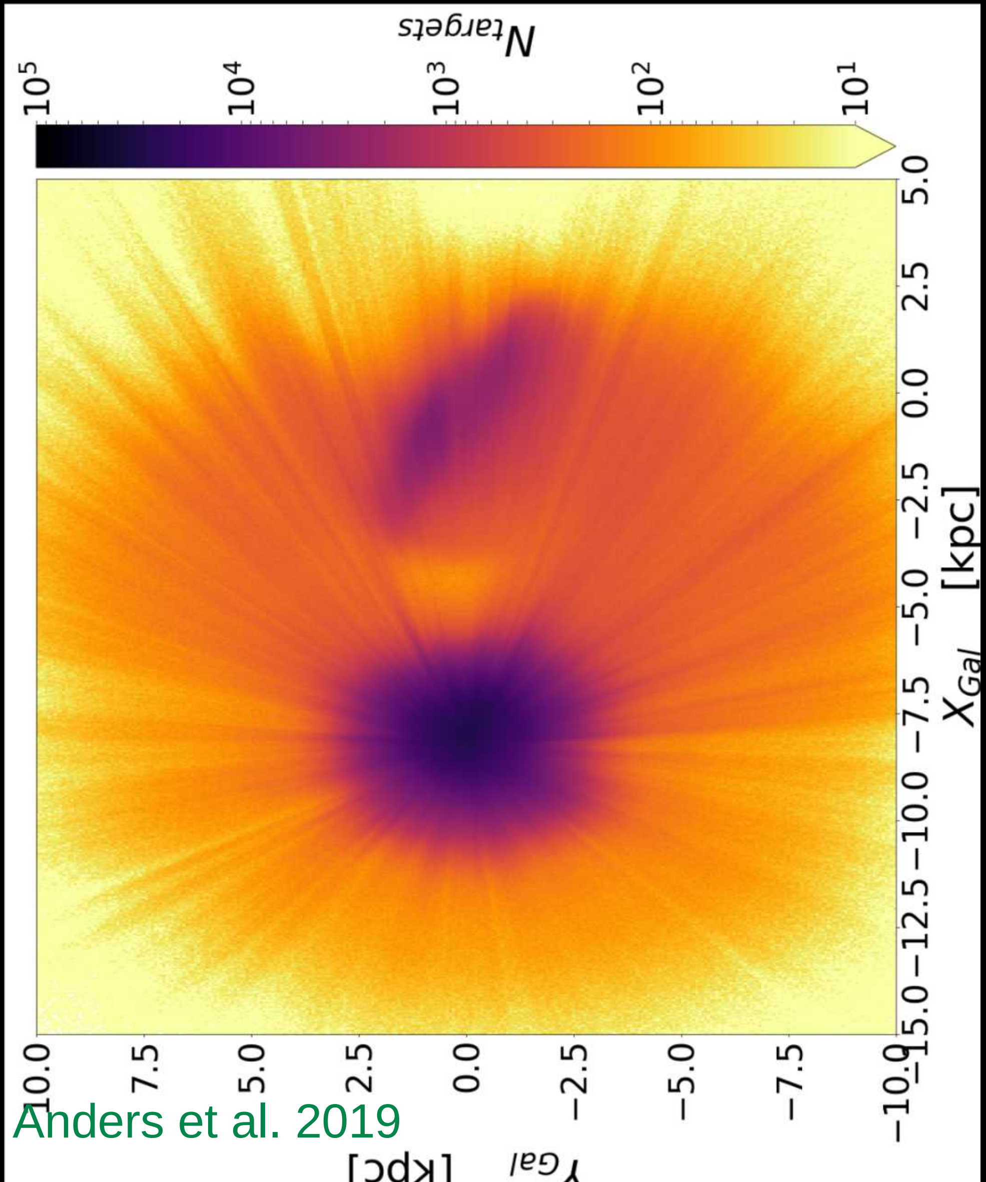
- old stars
- RMS vel ~150 km/s

Stellar component : bulge/bar

$0.5 \times 10^{10}\ M_{\odot}$

265 millions of stars !

https://sci.esa.int/j/61461



Anders et al. 2019

Stellar component : bulge/bar

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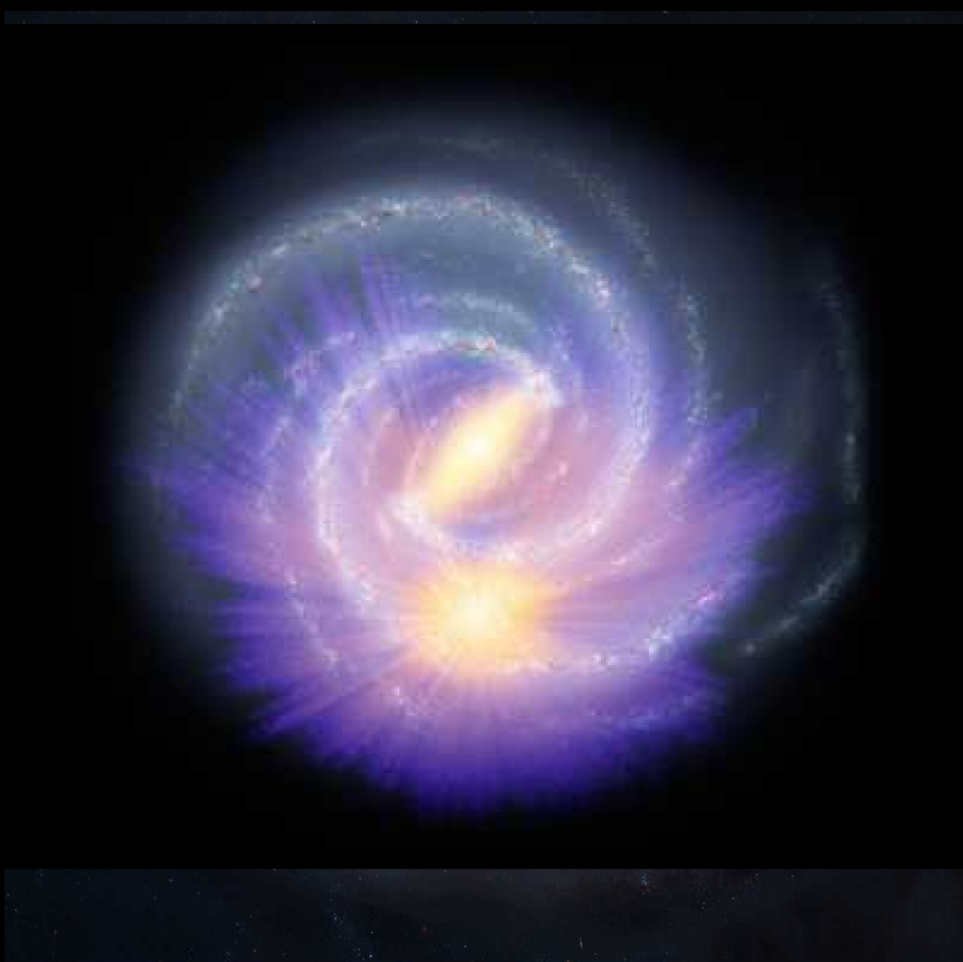
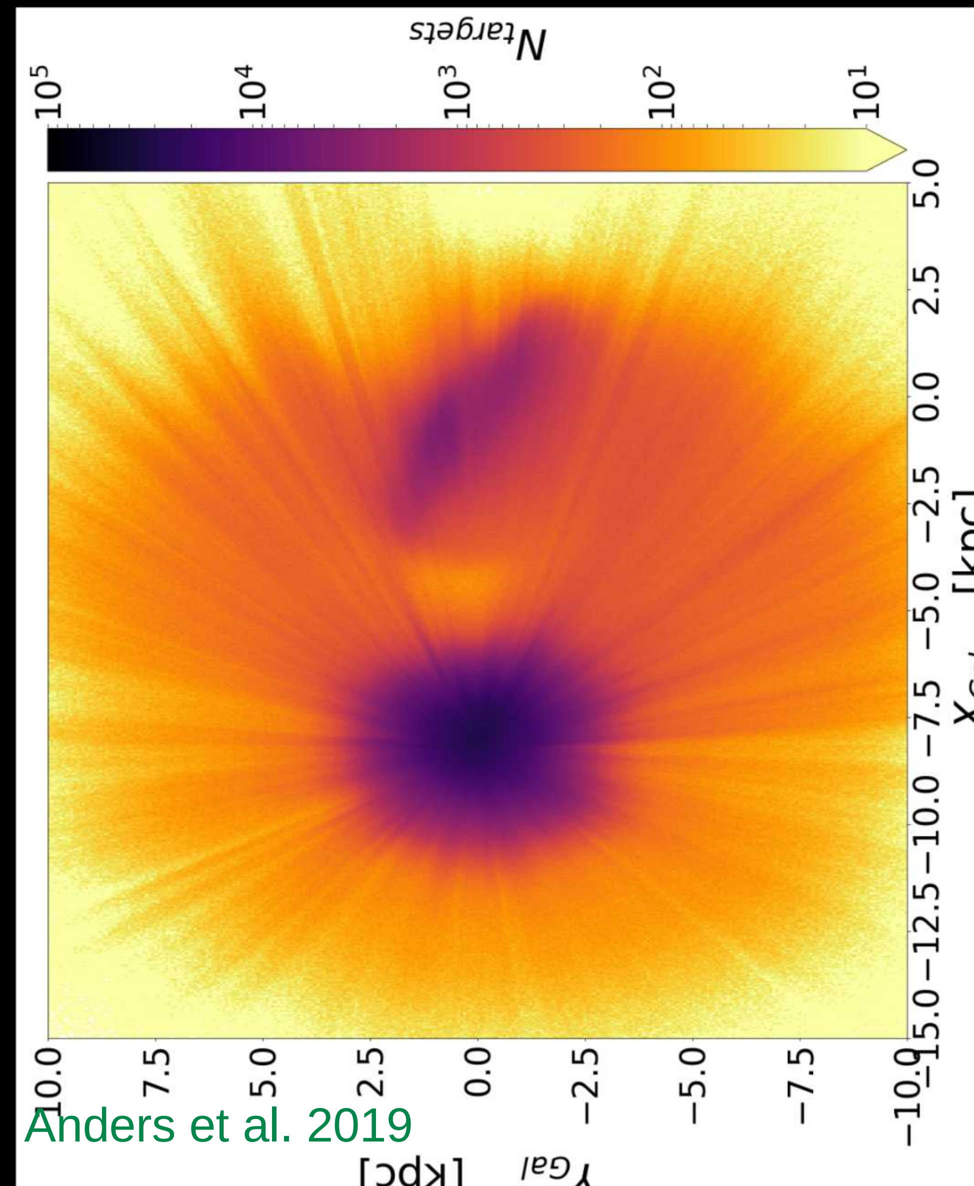
265 millions of stars !

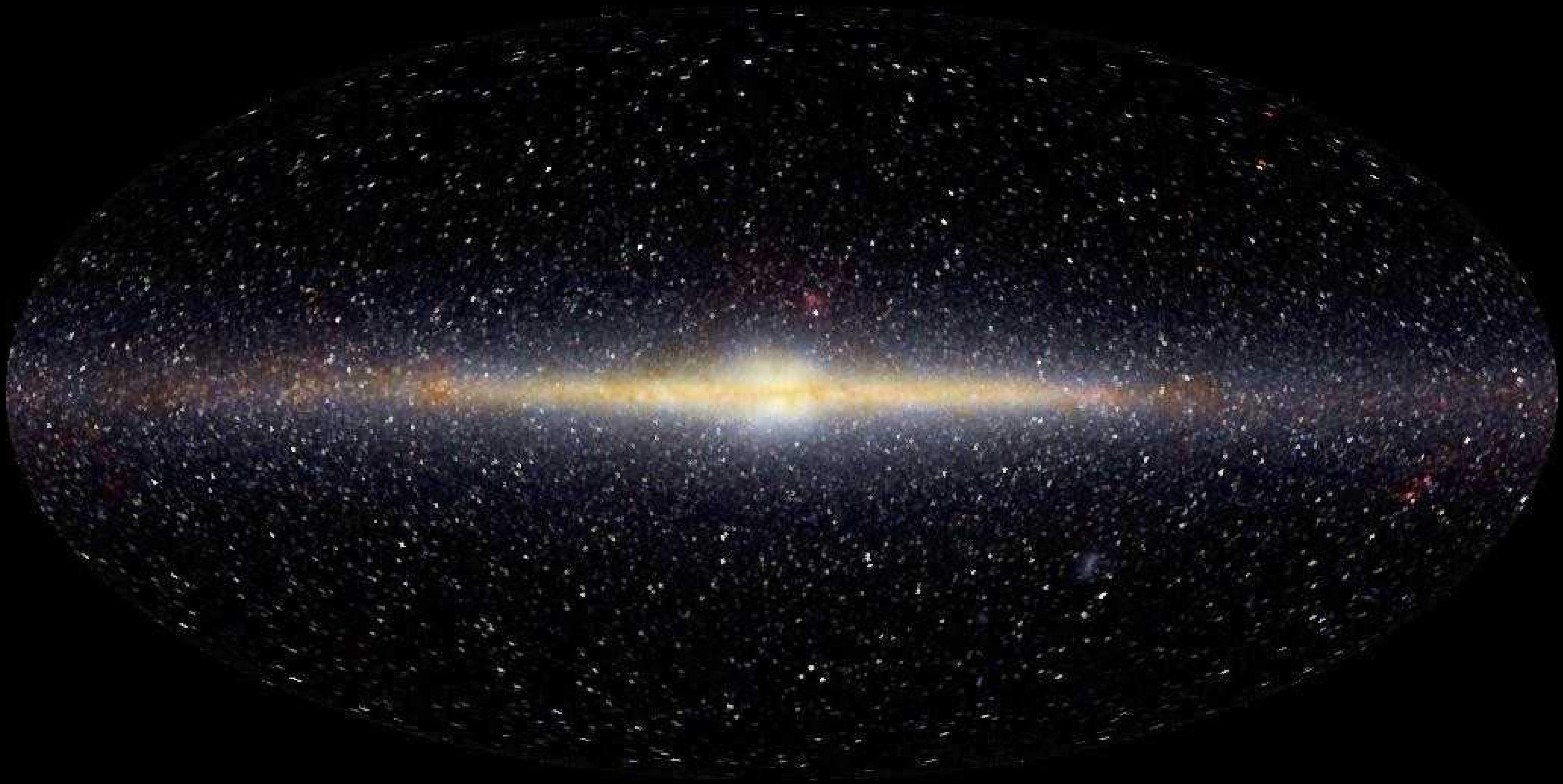




https://sci.esa.int/j/61461

Anders et al. 2019

COBE satellite view of the MW in infrared light



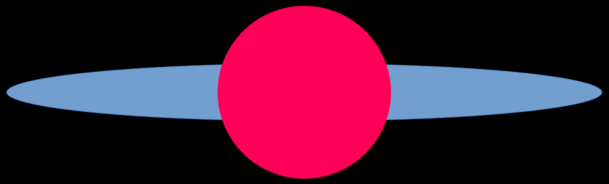
Robert Nemiroff (MTU) & Jerry Bonnell (USRA)

Stellar component : disk

$5\times10^{10}\,M_\odot$ (10 % of total)

thin disk:

- 90% of the stellar disk
- scale height : ~300 pc
- RMS vel ~50 km/s

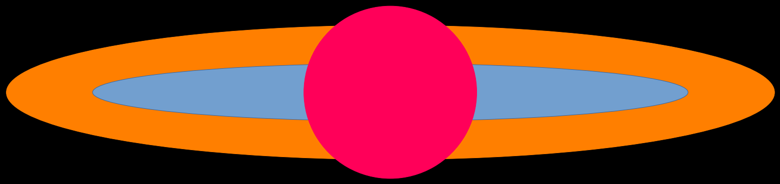


Stellar component : disk

$5 \times 10^{10}\ M_\odot$ (10 % of total)

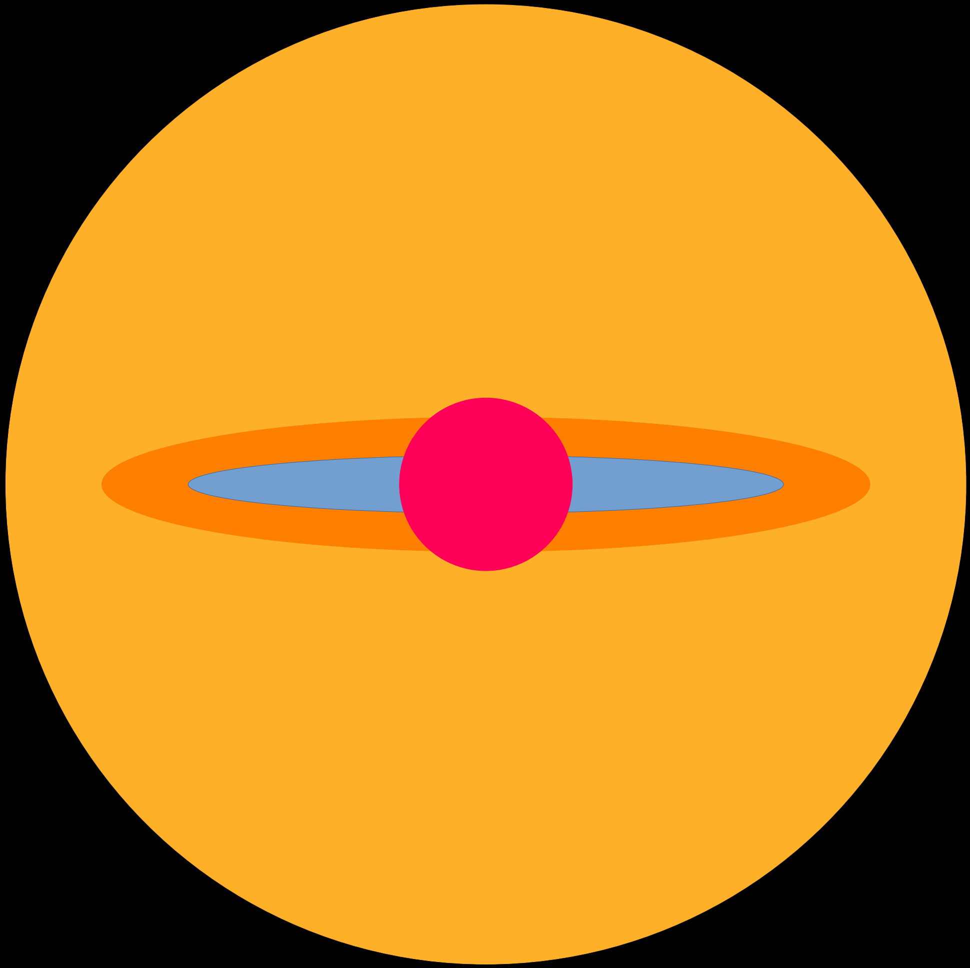
thick disk:

- 10% of the stellar disk
- scale height : ~1 kpc
- RMS vel >~50 km/s



Stellar component : halo

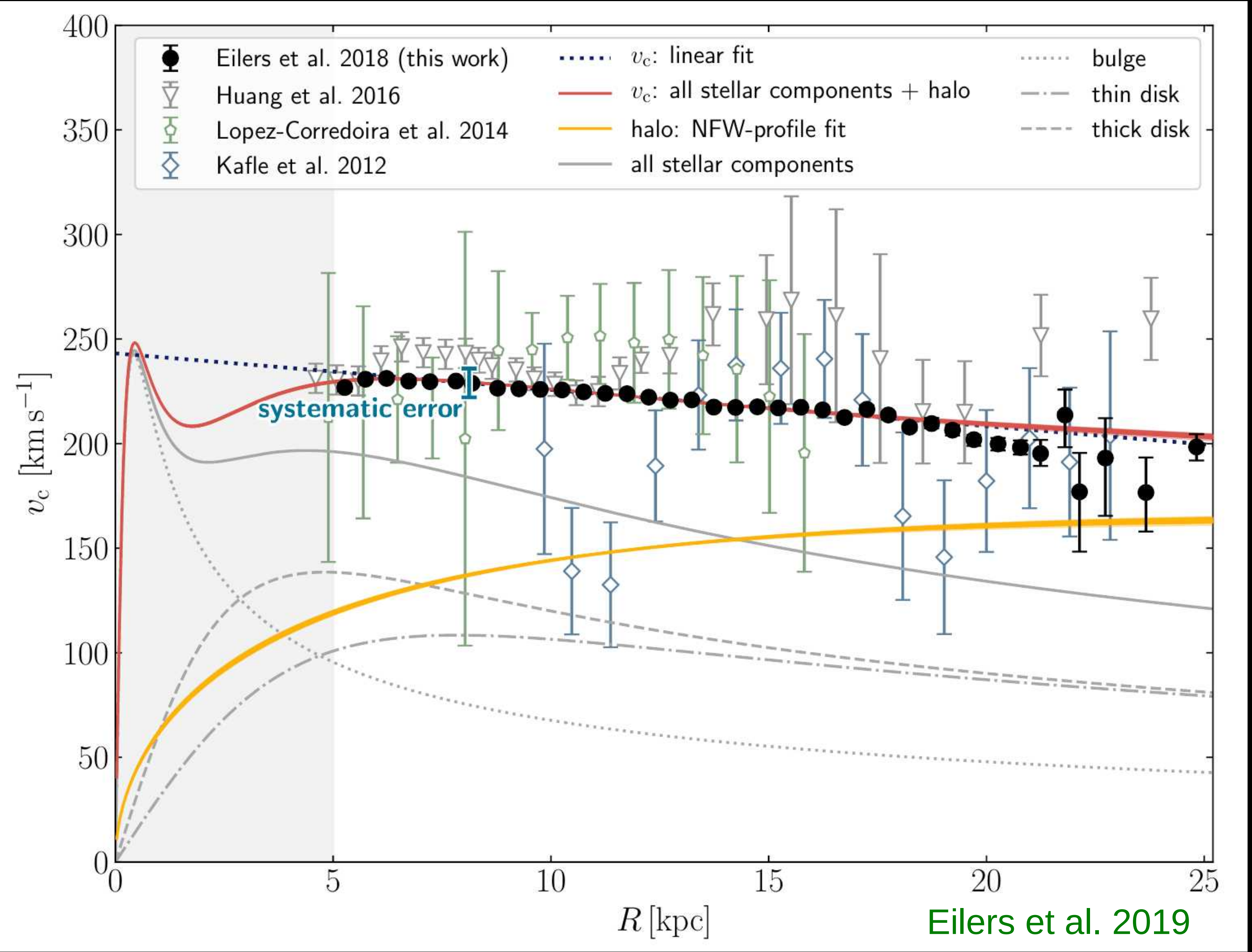
$5x10^{8}\ M_{\odot}$ (1 % of stars)
- old stars
- no mean rotation



Gaseous component : disk, HVC

$10^9\ M_\odot$ (0.1 %)

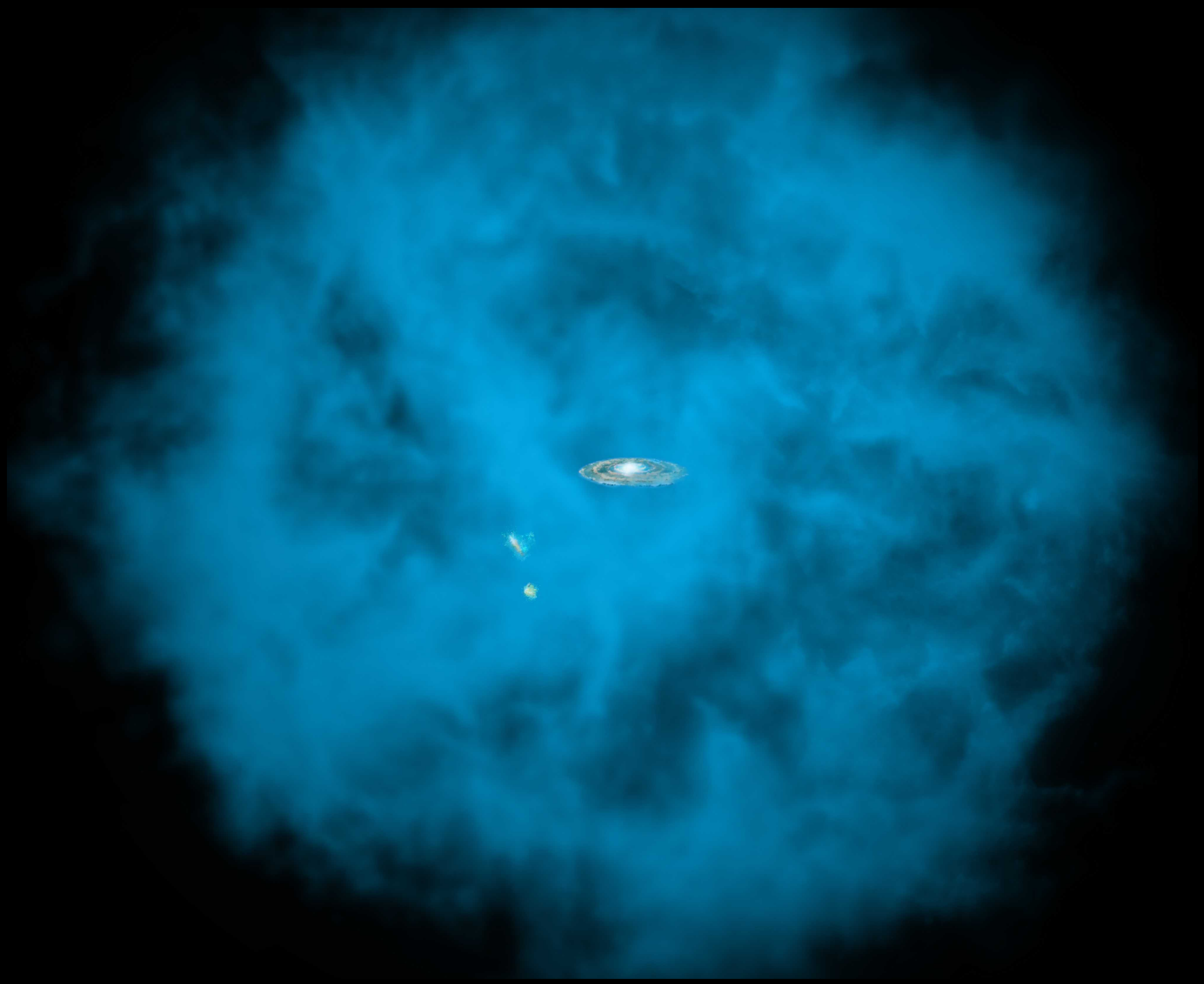
The circular rotation curve of the MW



Eilers et al. 2019

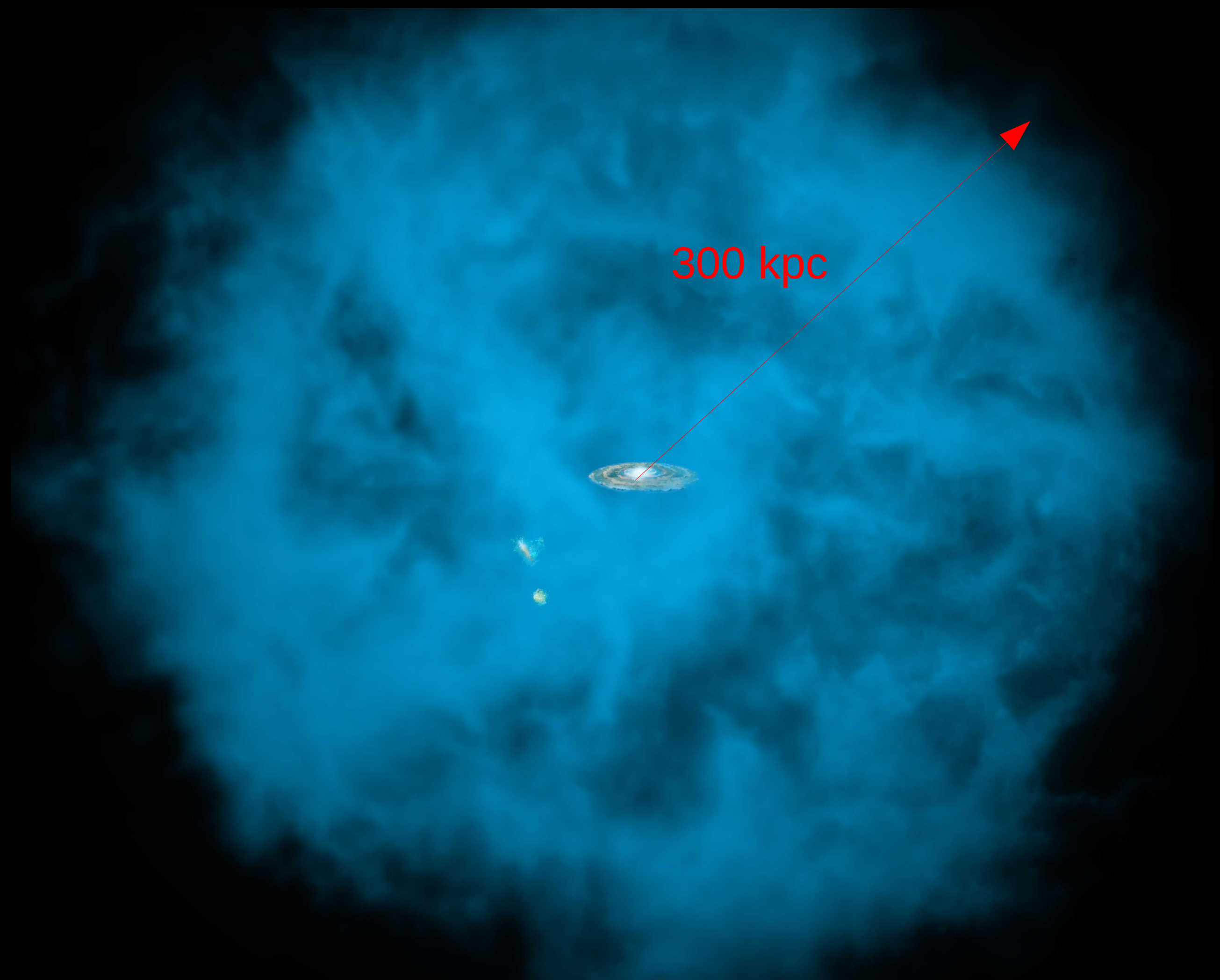
dark component : dark matter halo

about 90% of the total mass, $10^{12}\ M_{\odot}$



dark component : dark matter halo

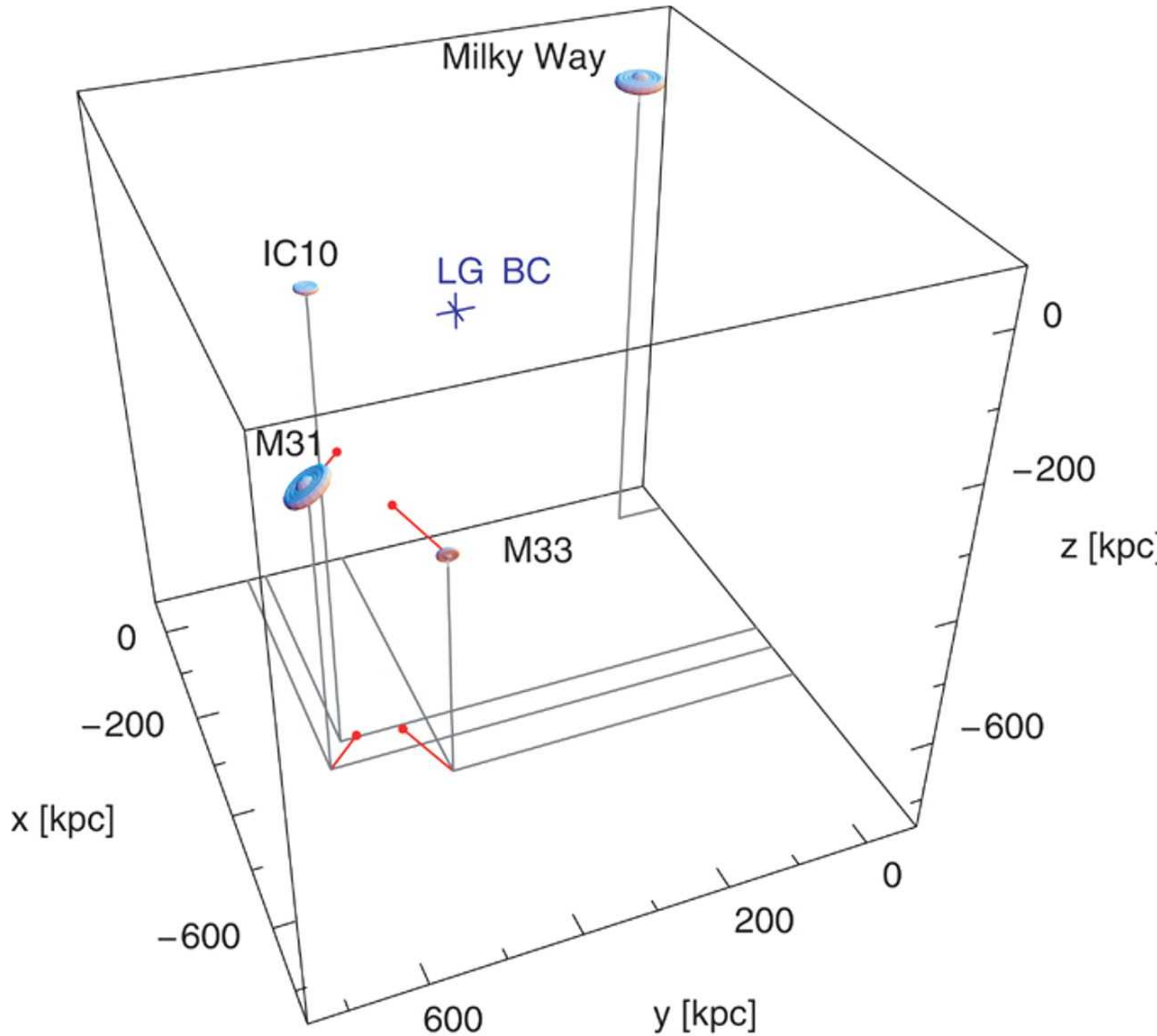
about 90% of the total mass, 10^{12} $M_\odot$



Observation of Galaxies

The Local Group

~ 3 Mpc



Milky Way
IC10
LG BC
M31
M33
0
−200
−600
z [kpc]
0
−200
−600
x [kpc]
0
200
600
y [kpc]

M31 : The Andromeda Galaxy

distance 770 kpc, total mass ~10^{12} $M_\odot$

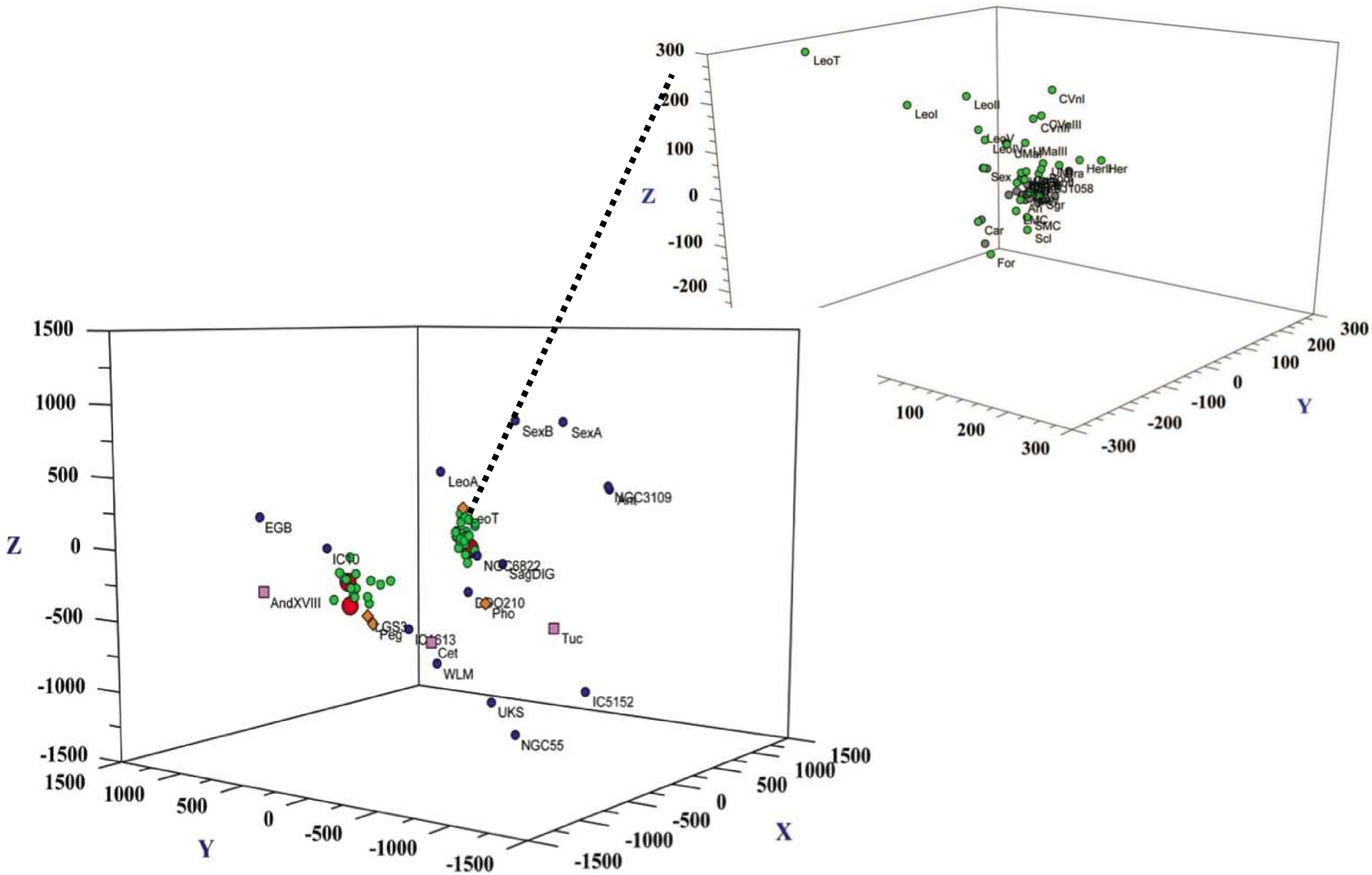
M33 : The Triangulum Galaxy

distance 847 kpc, total mass $6 \times 10^{10}\ M_{\odot}$

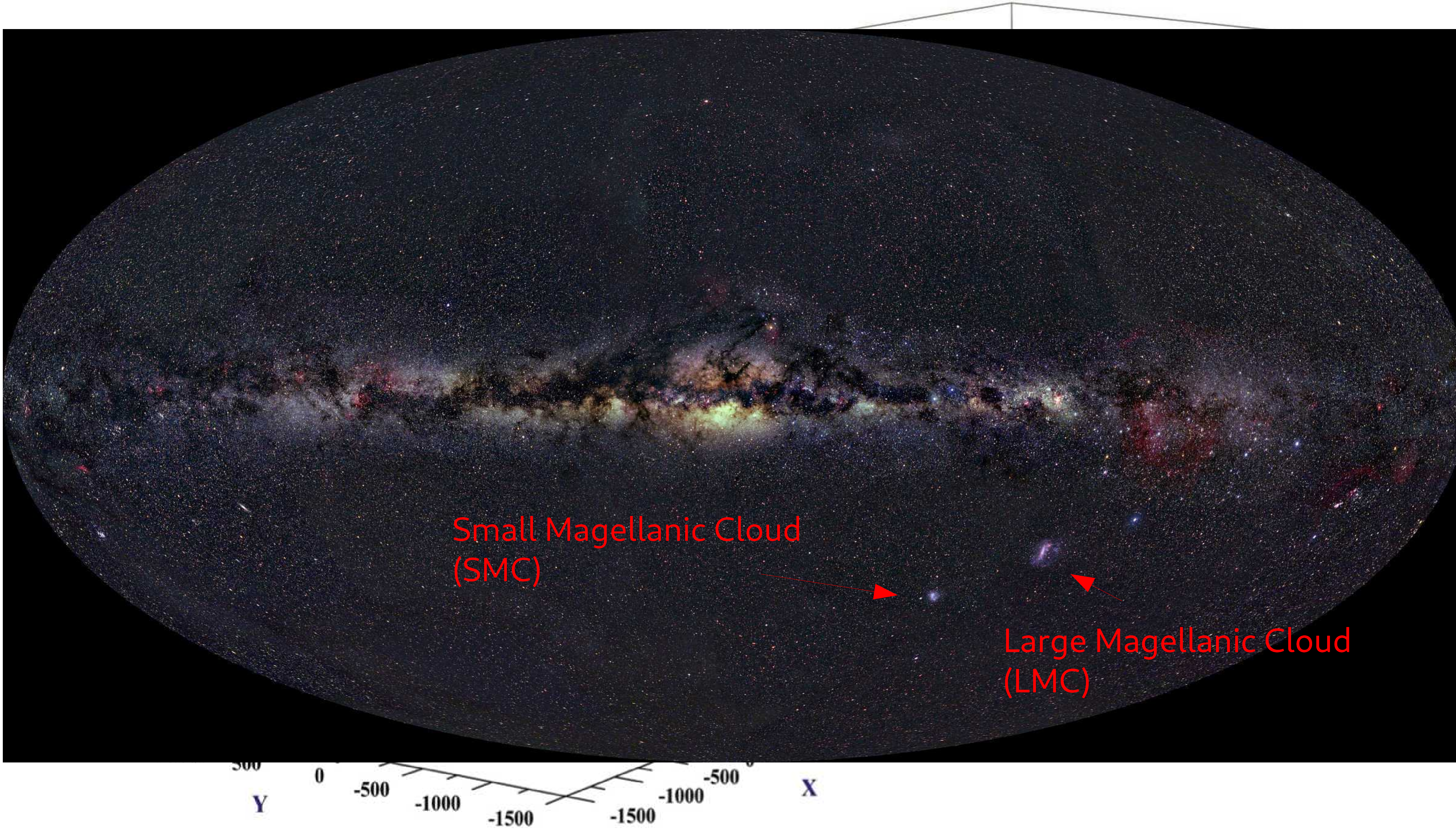
IC 10 : an irregular galaxy

distance 660 kpc, total mass ~$2 \times 10^9\ M_\odot$

+ about 130 satellite dwarfs...



+ about 130 satellite dwarfs...



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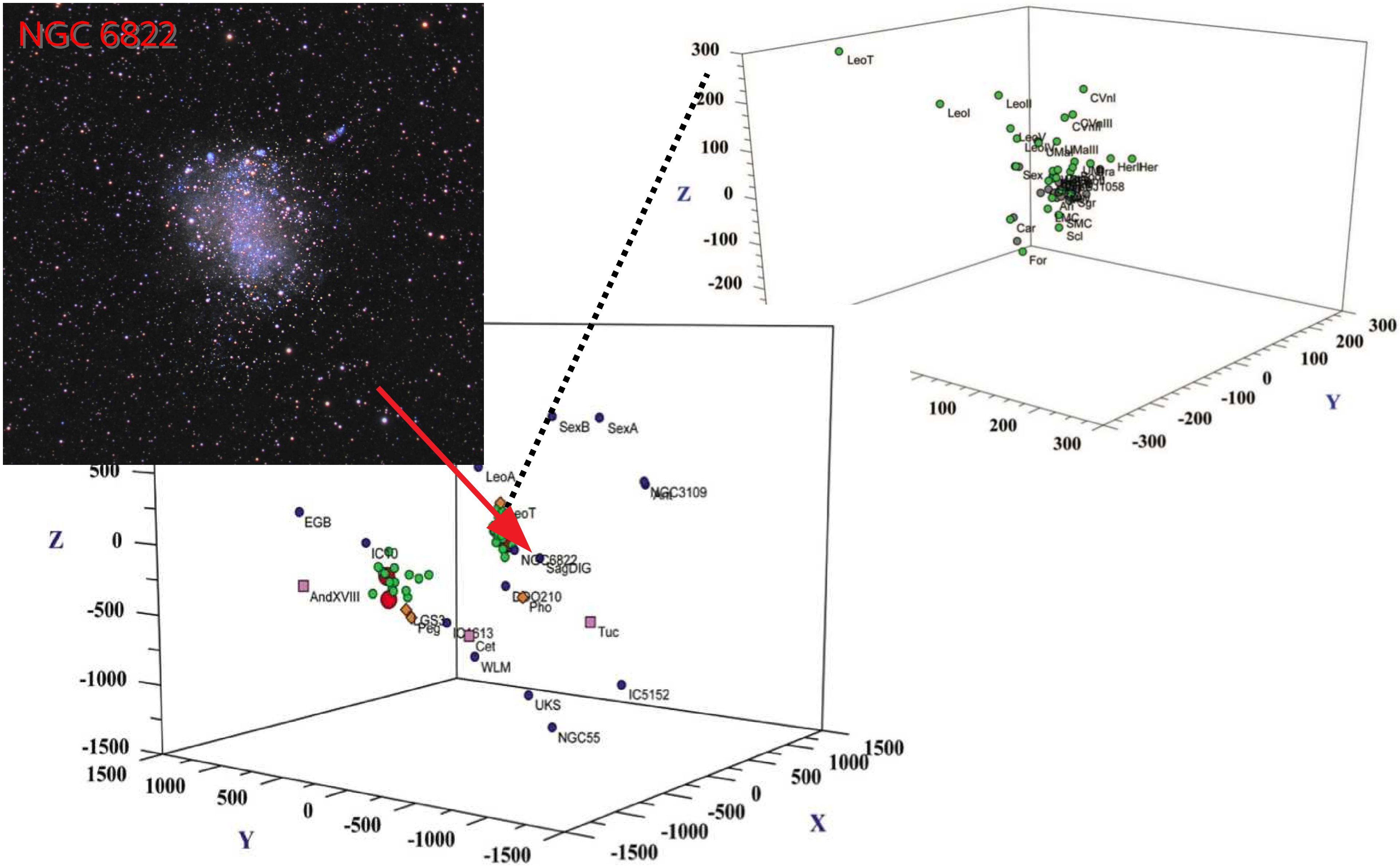
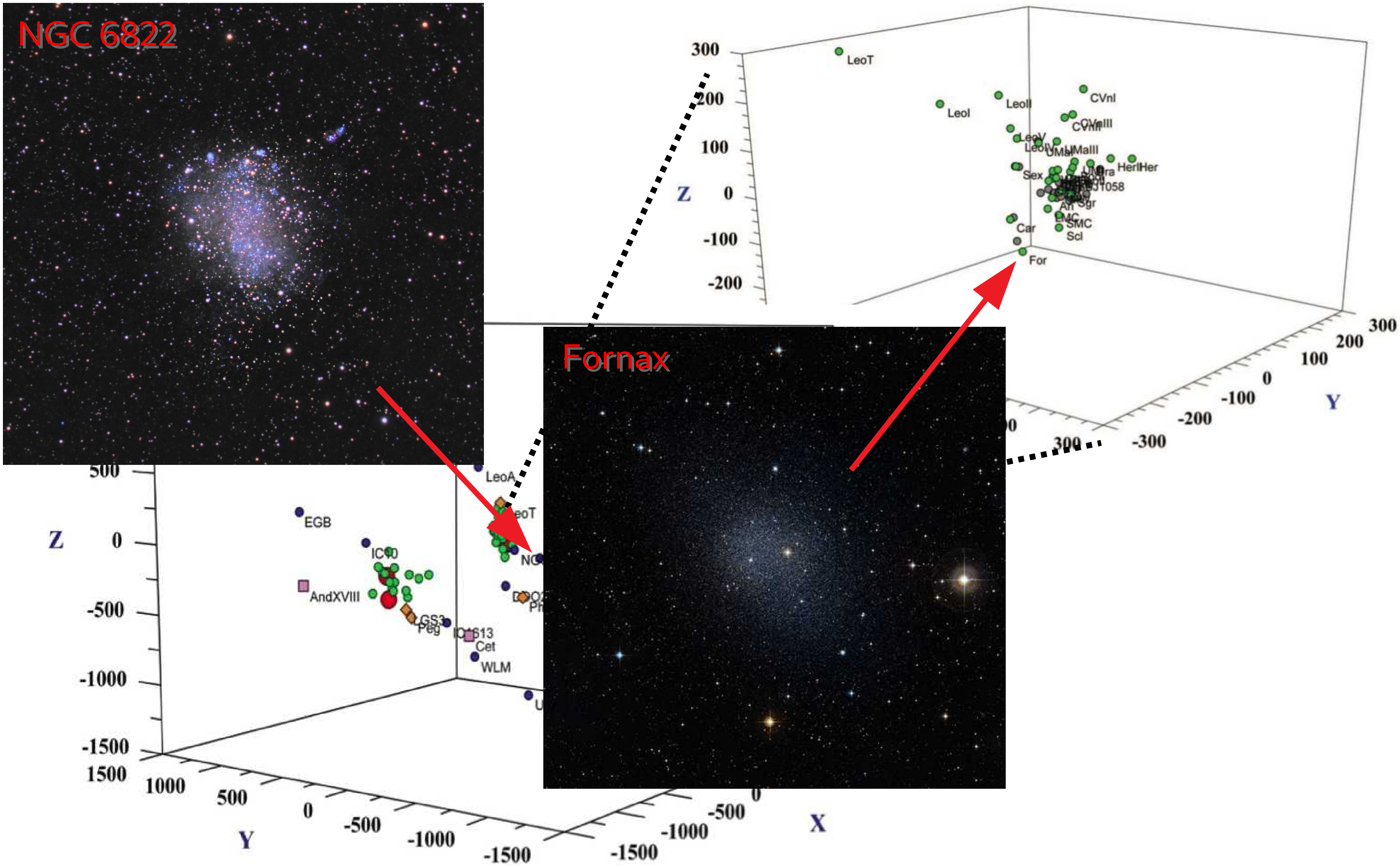


+ about 130 satellite dwarfs...



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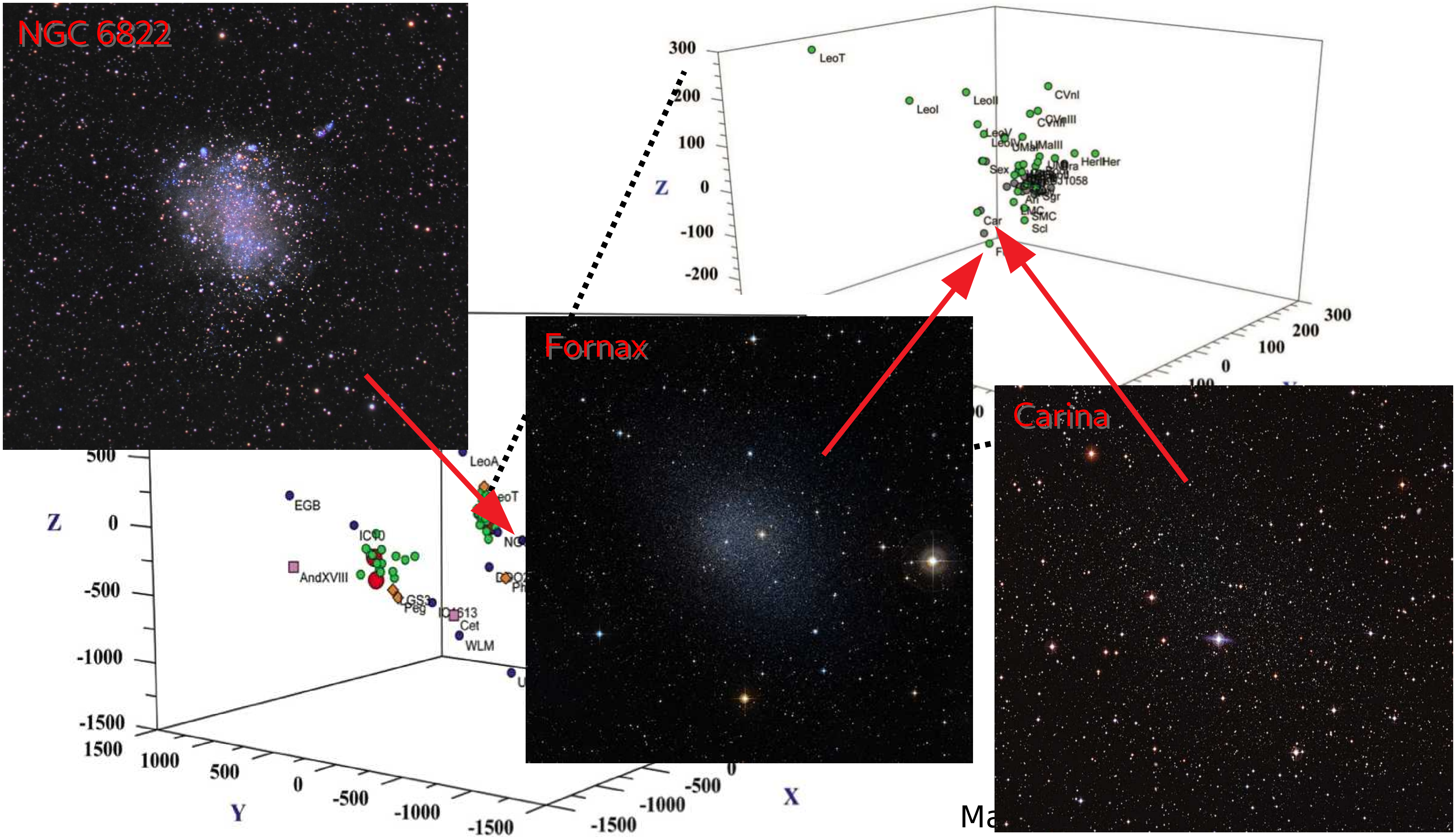
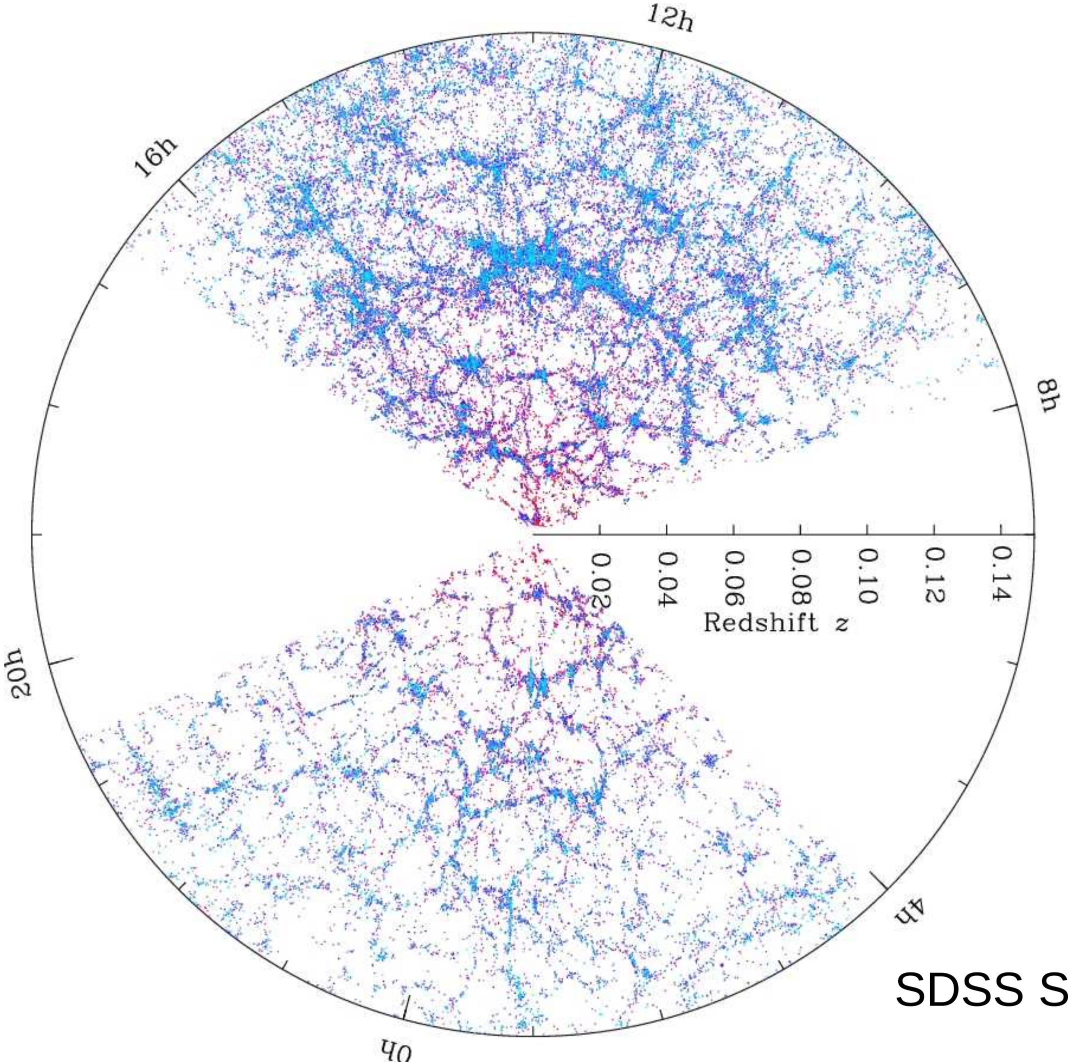


MW – Andromeda collision

https://youtu.be/6aqsvkMp4ns

Observation of Galaxies

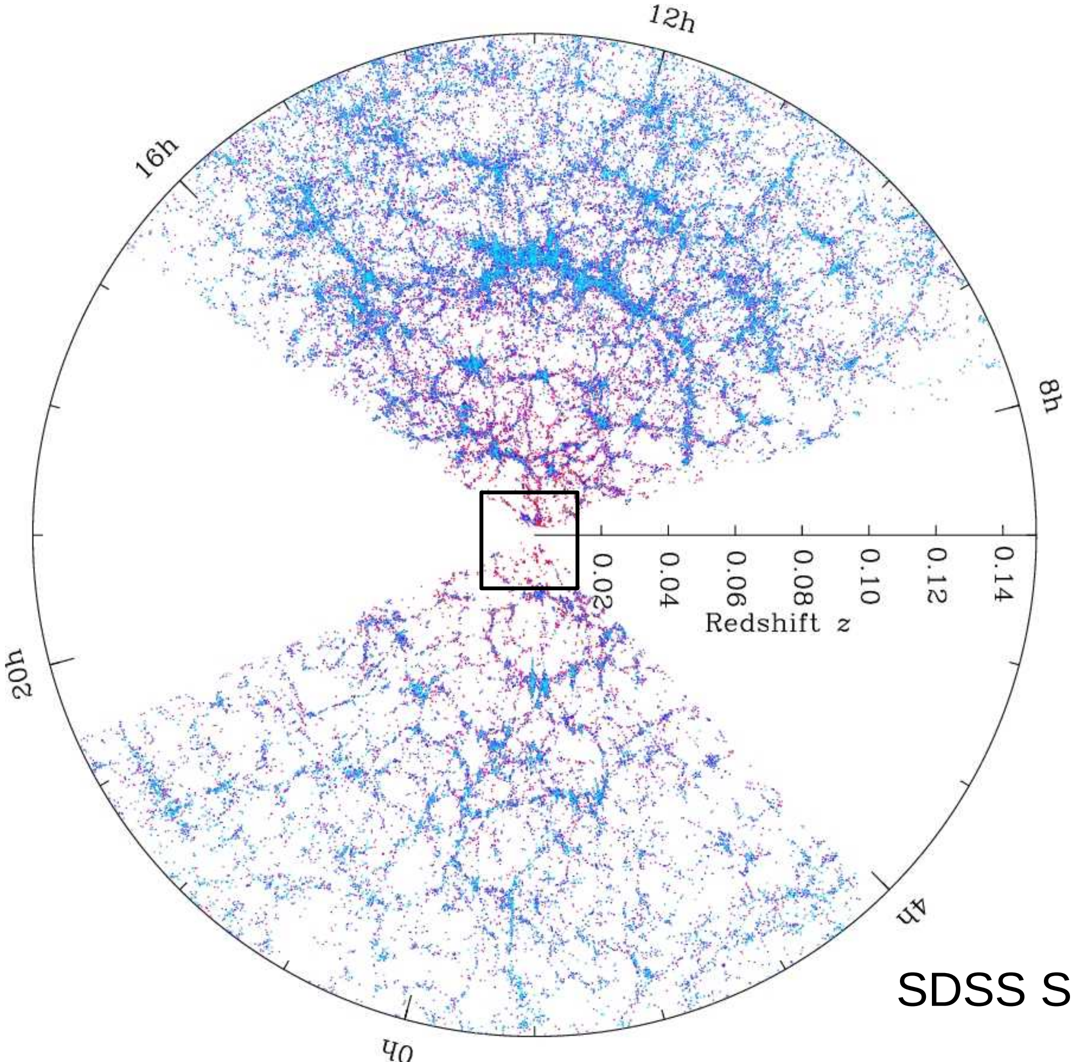
Beyond the LG… the LV



SDSS Sloan Digital Sky Survey

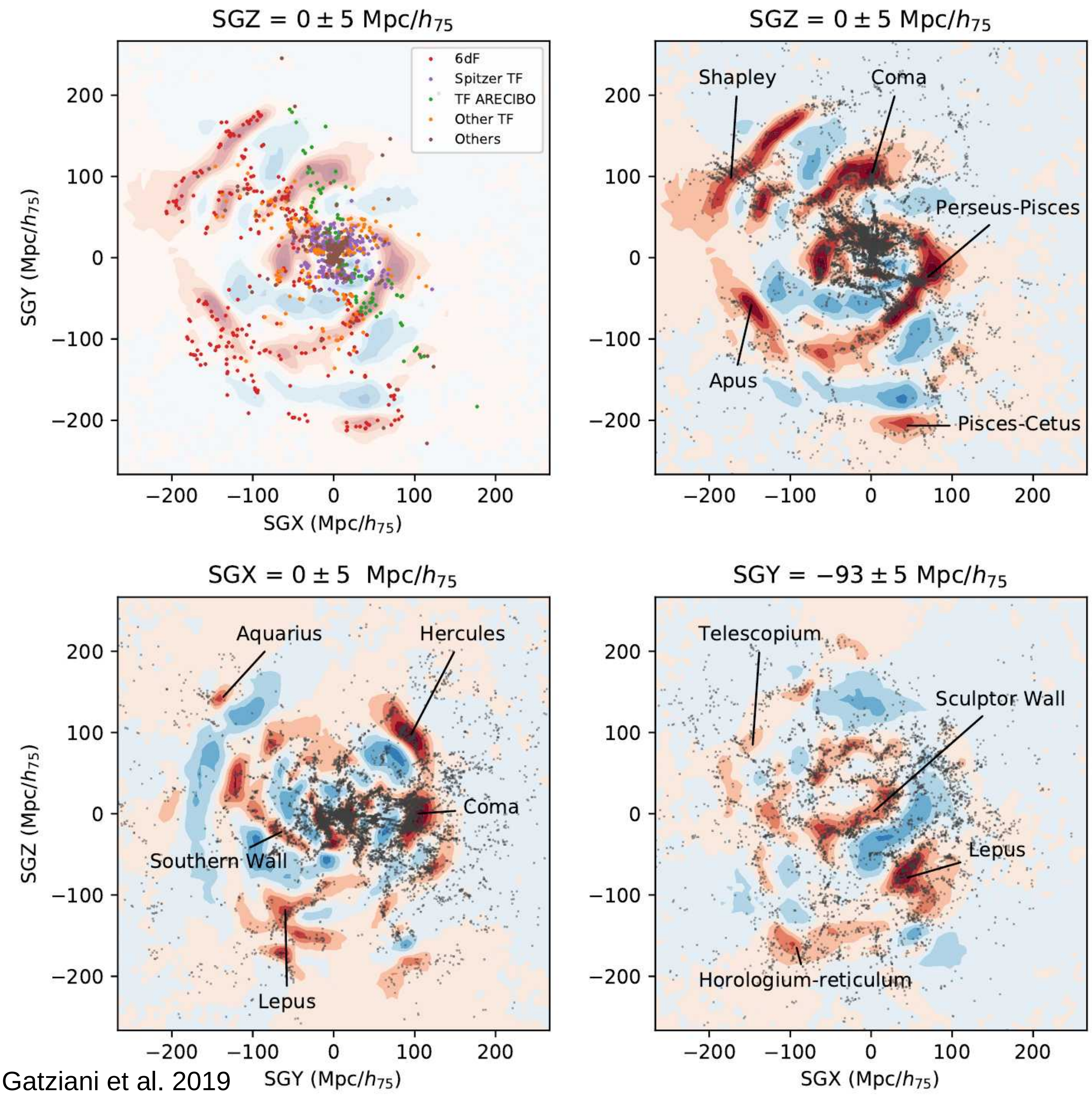
Observation of Galaxies

Beyond the LG… the LV



~500 galaxies
with D < 10 Mpc

SDSS Sloan Digital Sky Survey



CosmicFlow : Gatziani et al. 2019

The most detailed 3D view of the Universe
SDSS/eBOSS

https://youtu.be/KJJXbcf8kxA

Observation of Galaxies

Luminosity Distribution Function

Luminosity distribution function

Luminosity Function: Schechter law (1976)

number of galaxies in the luminosity range [L, L+dL]

$$\Phi(L)\,dL = \Phi_\star \left(\frac{L}{L_\star}^{\alpha}\right) \exp(-L/L_\star)\frac{dL}{L_\star}$$

with α ~= -1.1

L_* ~= 2.9×10^{10} $L_\odot$

$L_* = 2.9\times10^{10}\ L_\odot$

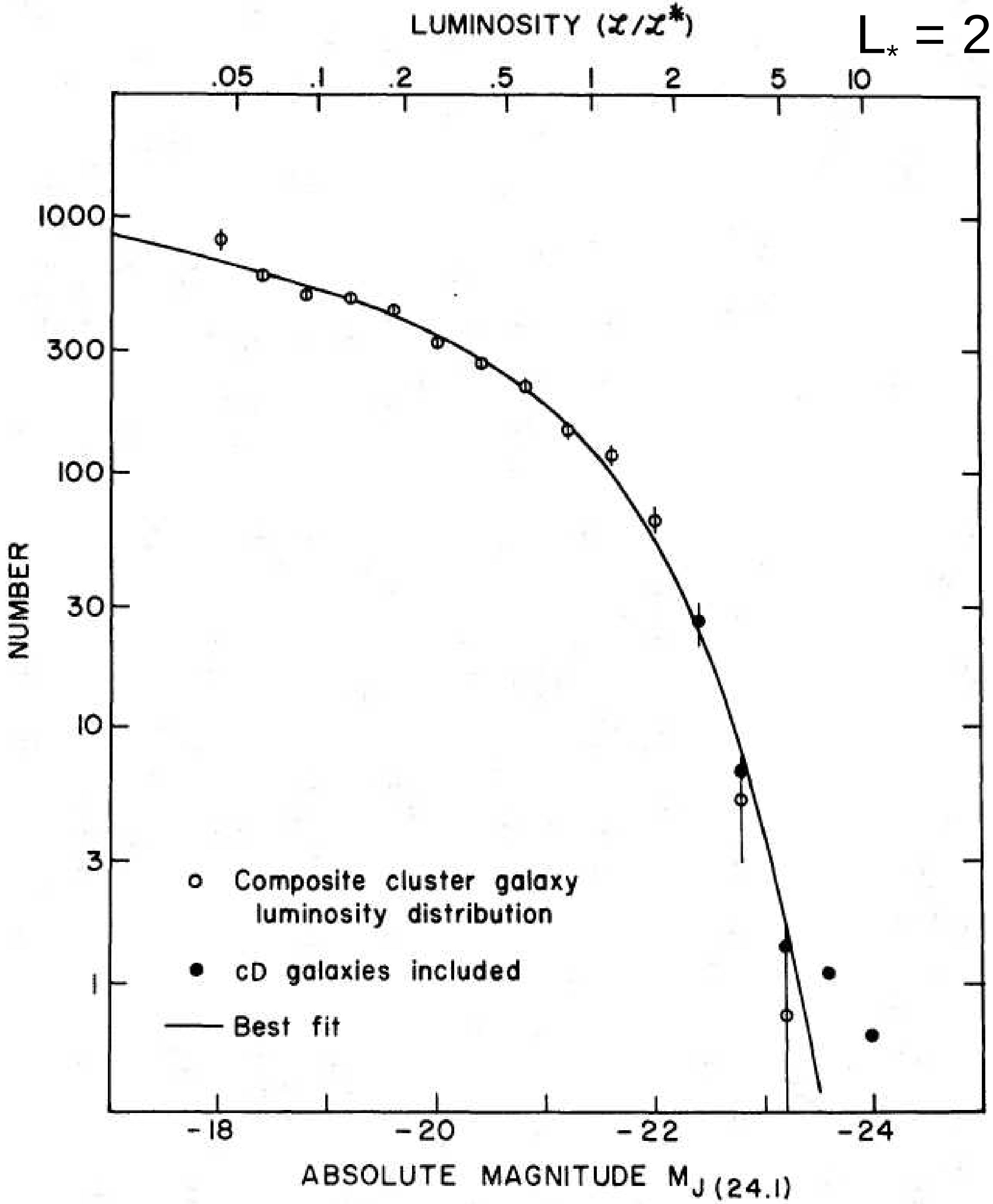
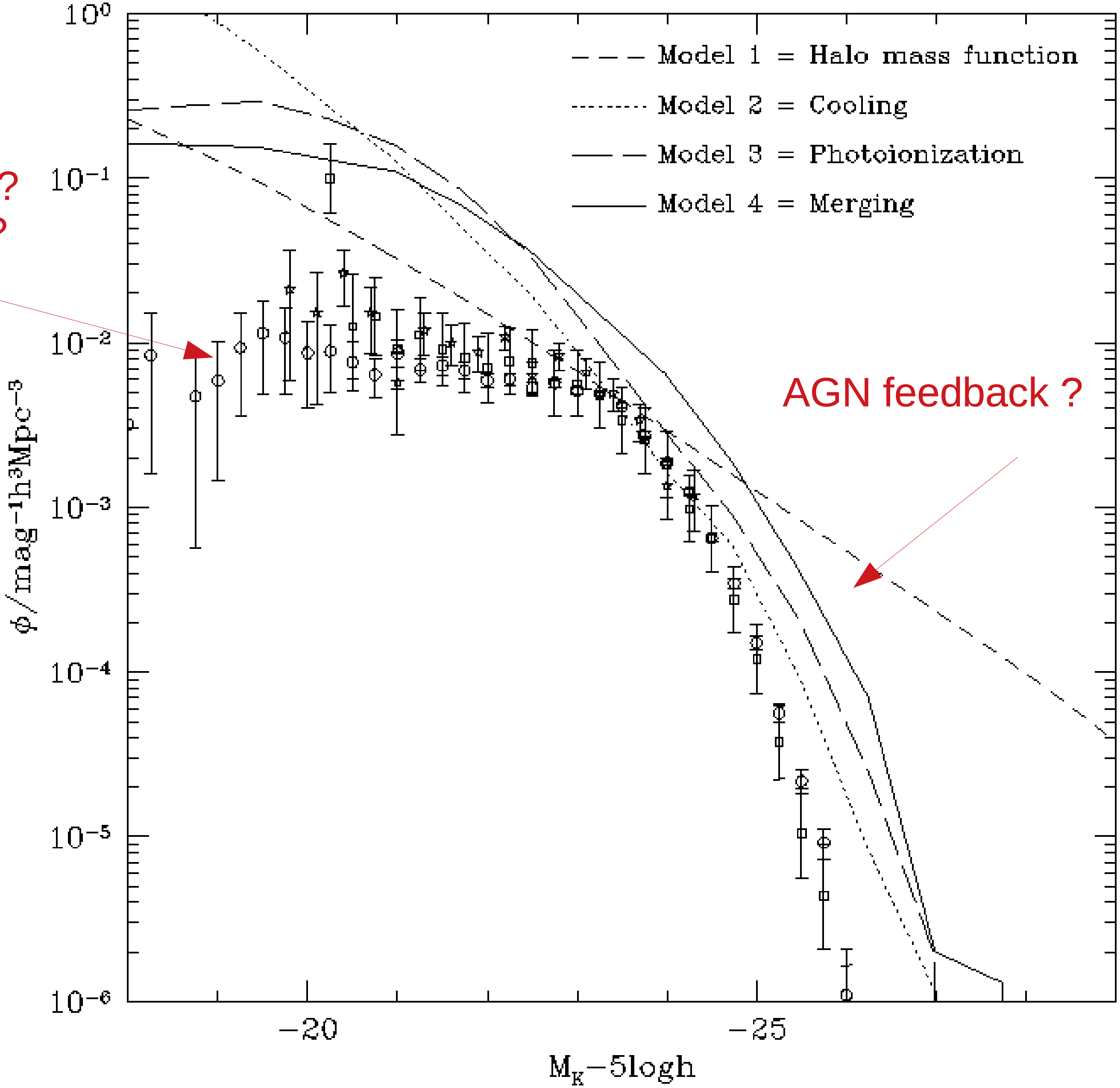


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

Schechter 1976

Stellar feedback ?
UV-background ?

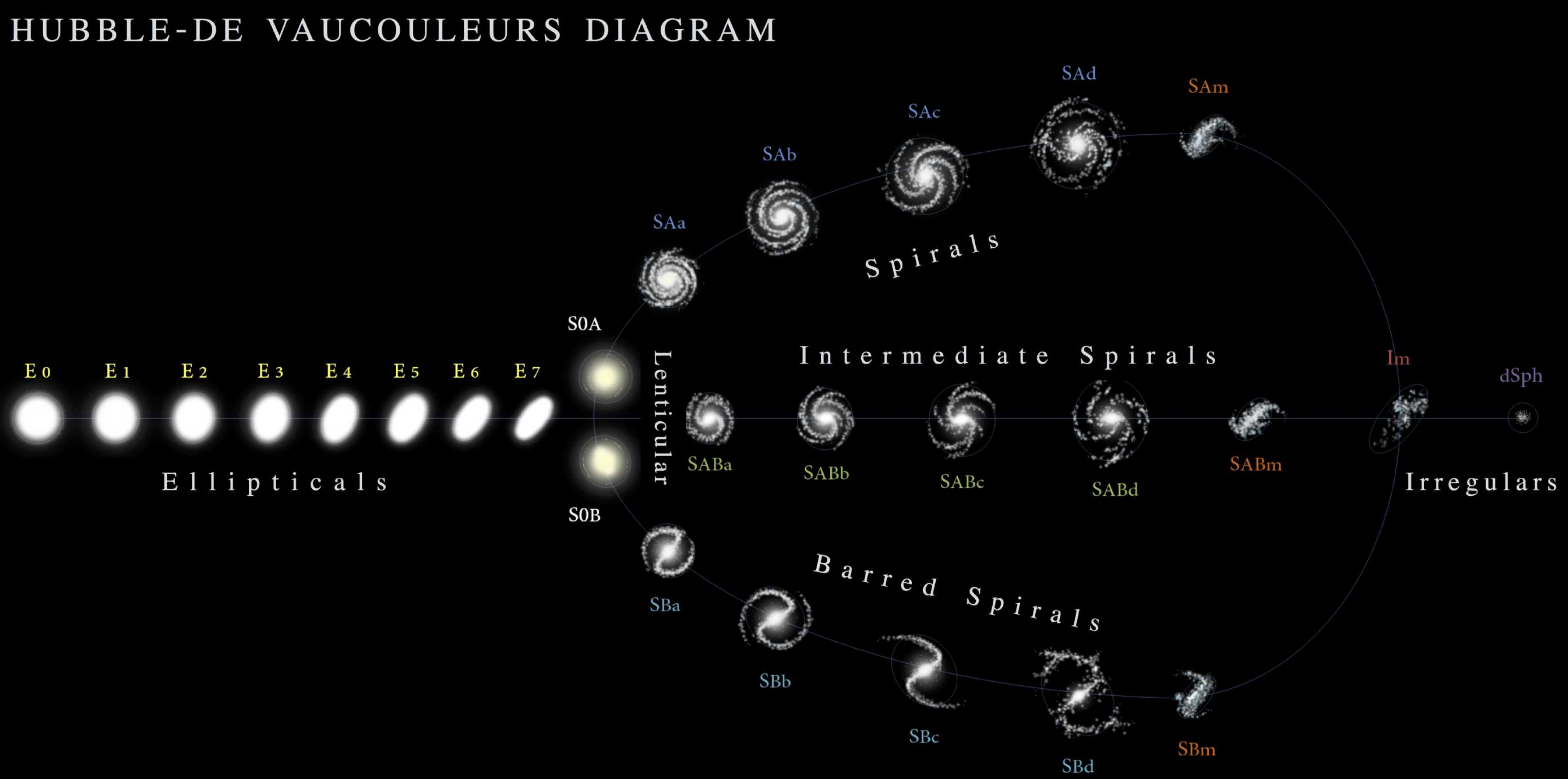


AGN feedback ?

Benson et al. 2003

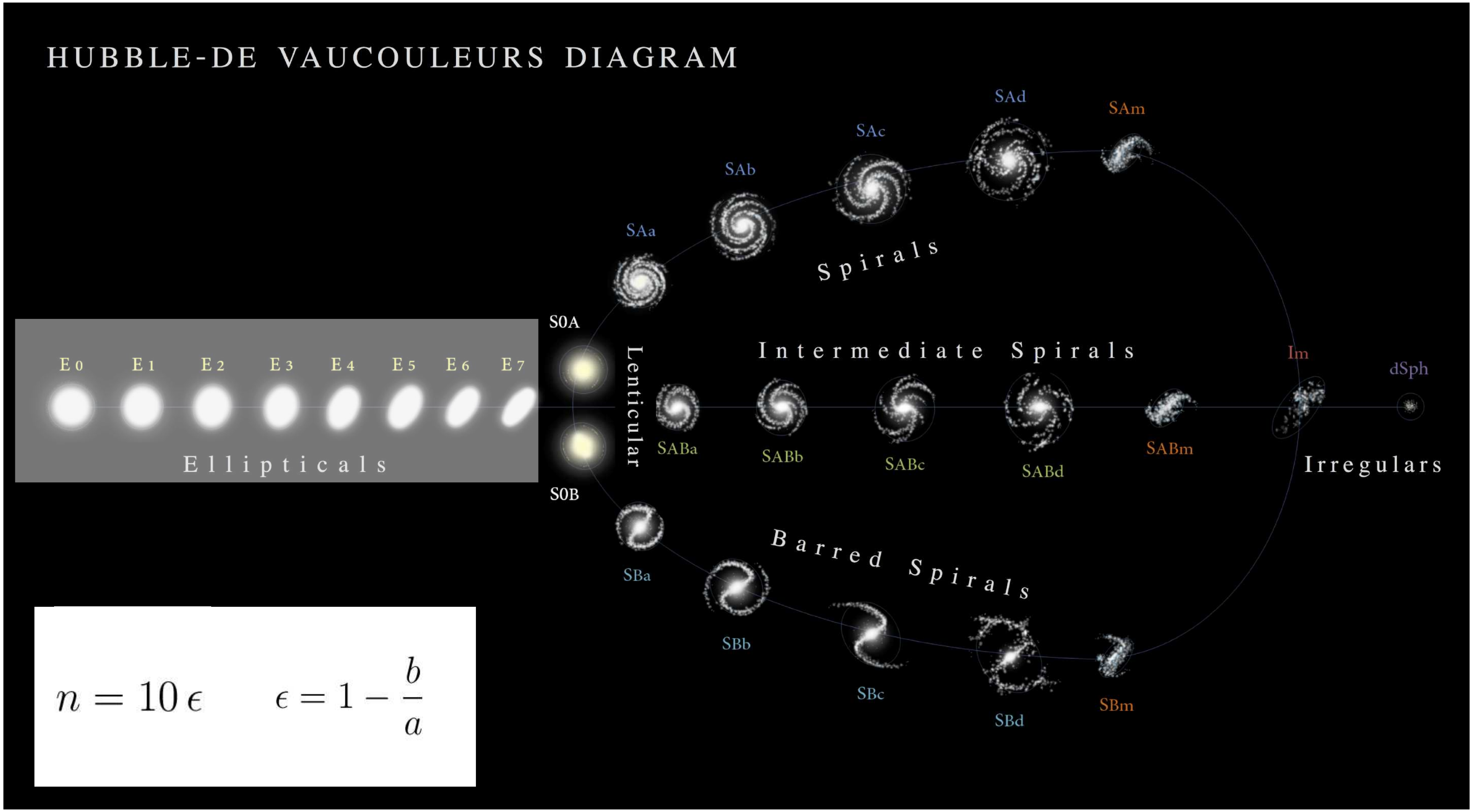
The Hubble-De Vaucouleurs Sequence

The Hubble-De Vaucouleurs Sequence



Observation of Galaxies

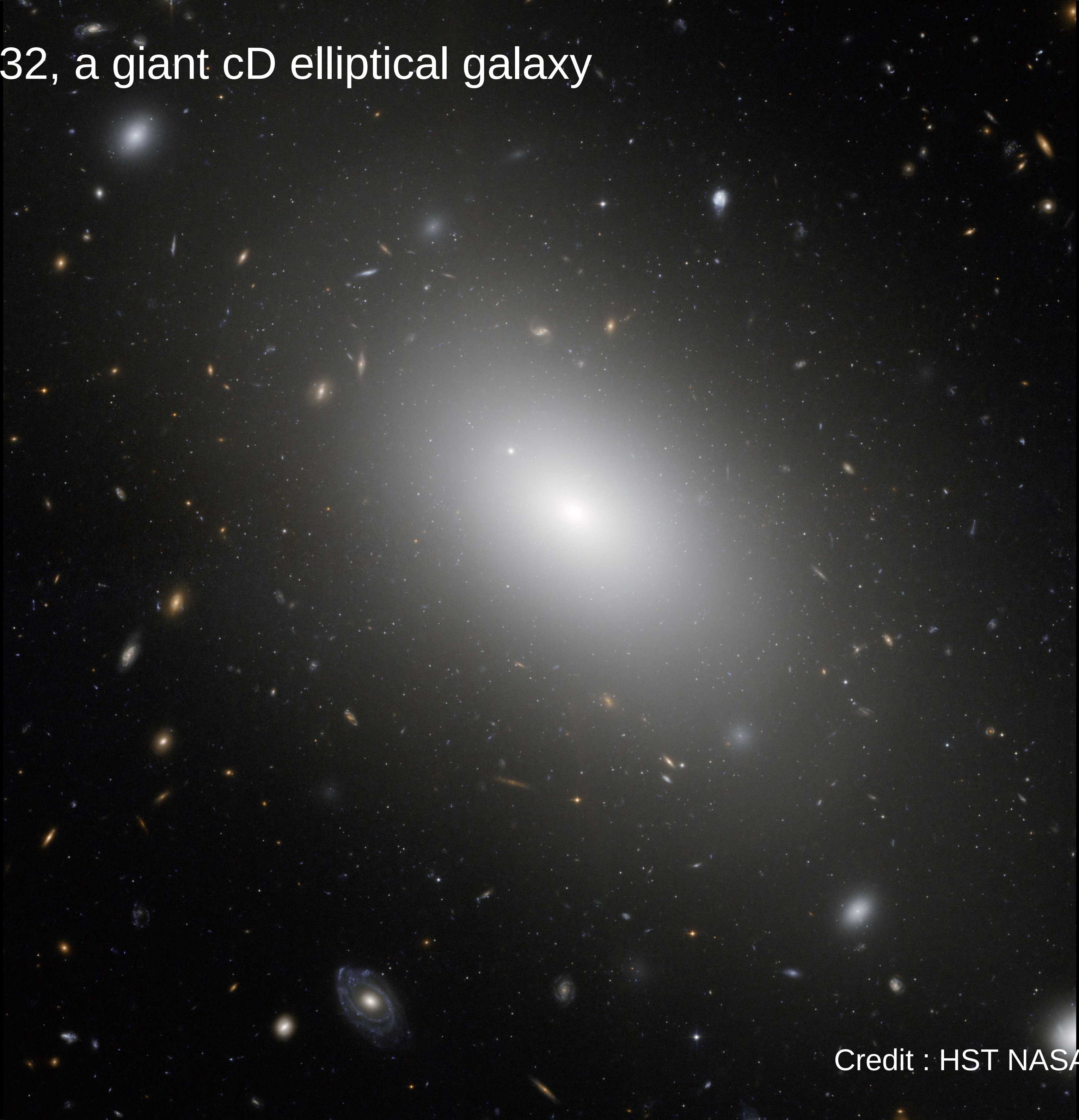
Elliptical Galaxies



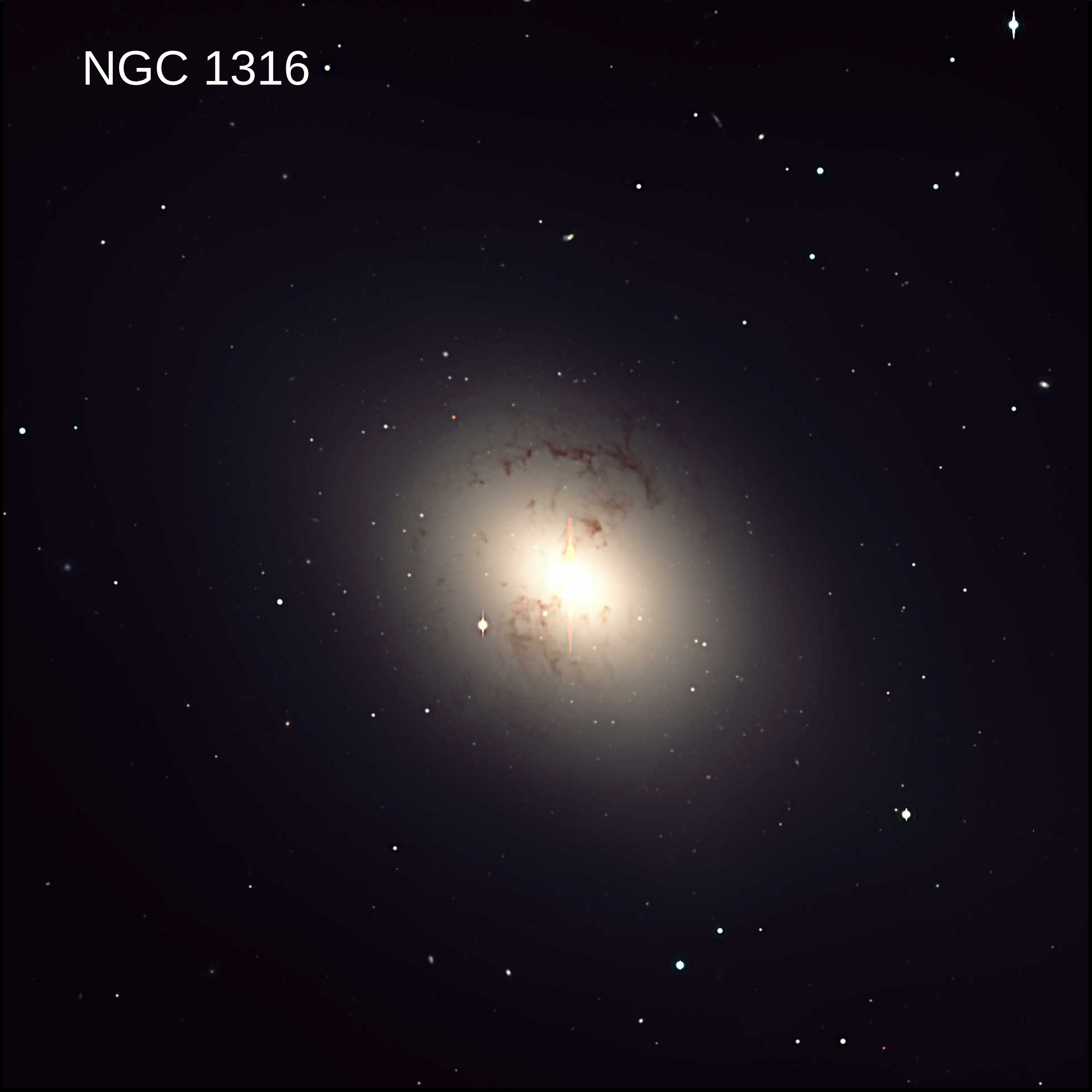
$$n = 10\,\epsilon \qquad \epsilon = 1 - \frac{b}{a}$$

M87 (cD or BCG, bright cluster galaxy) and several other ellipticals

NGC 1132, a giant cD elliptical galaxy



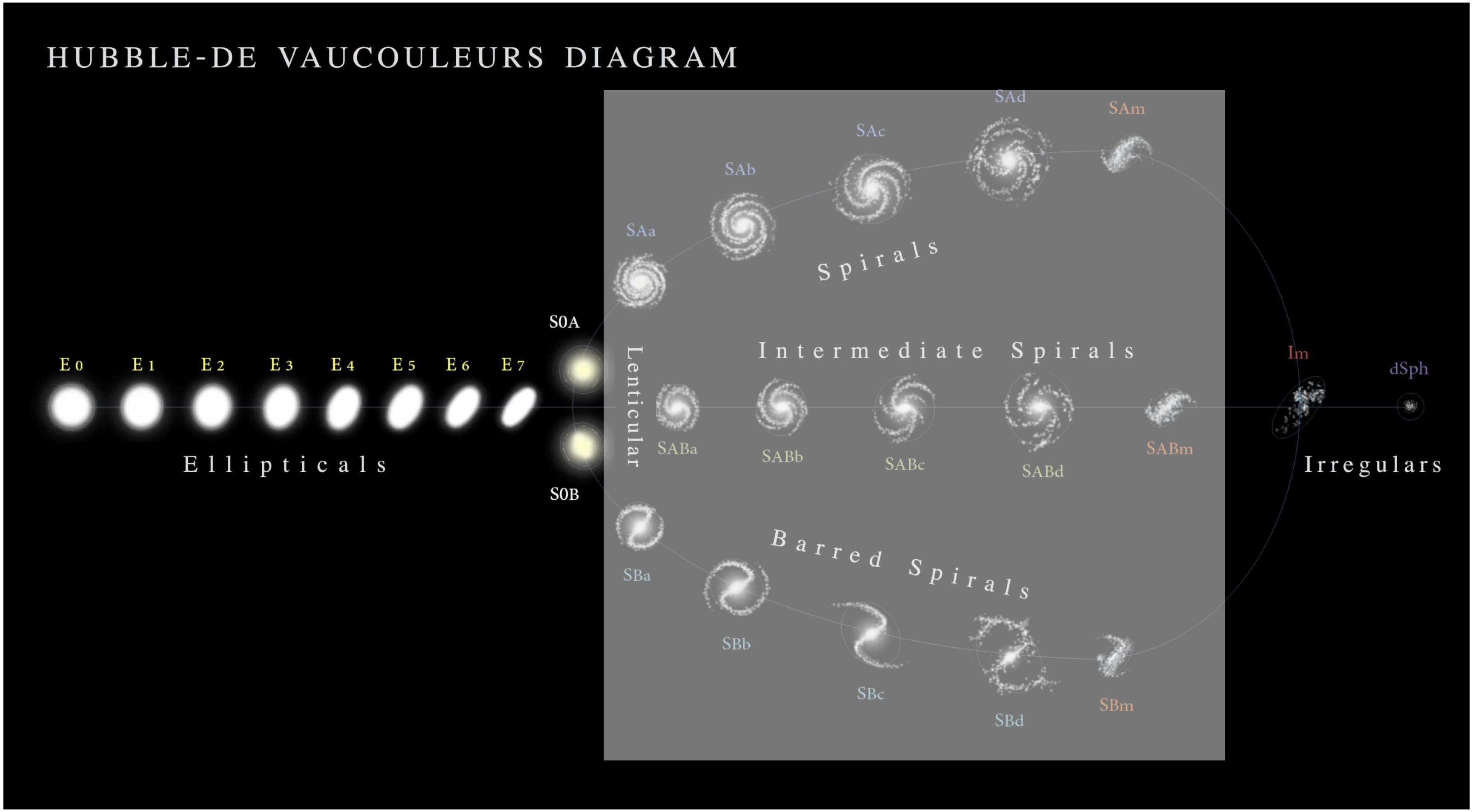
Credit : HST NASA/ESA



Credit : ESO VLT

Observation of Galaxies

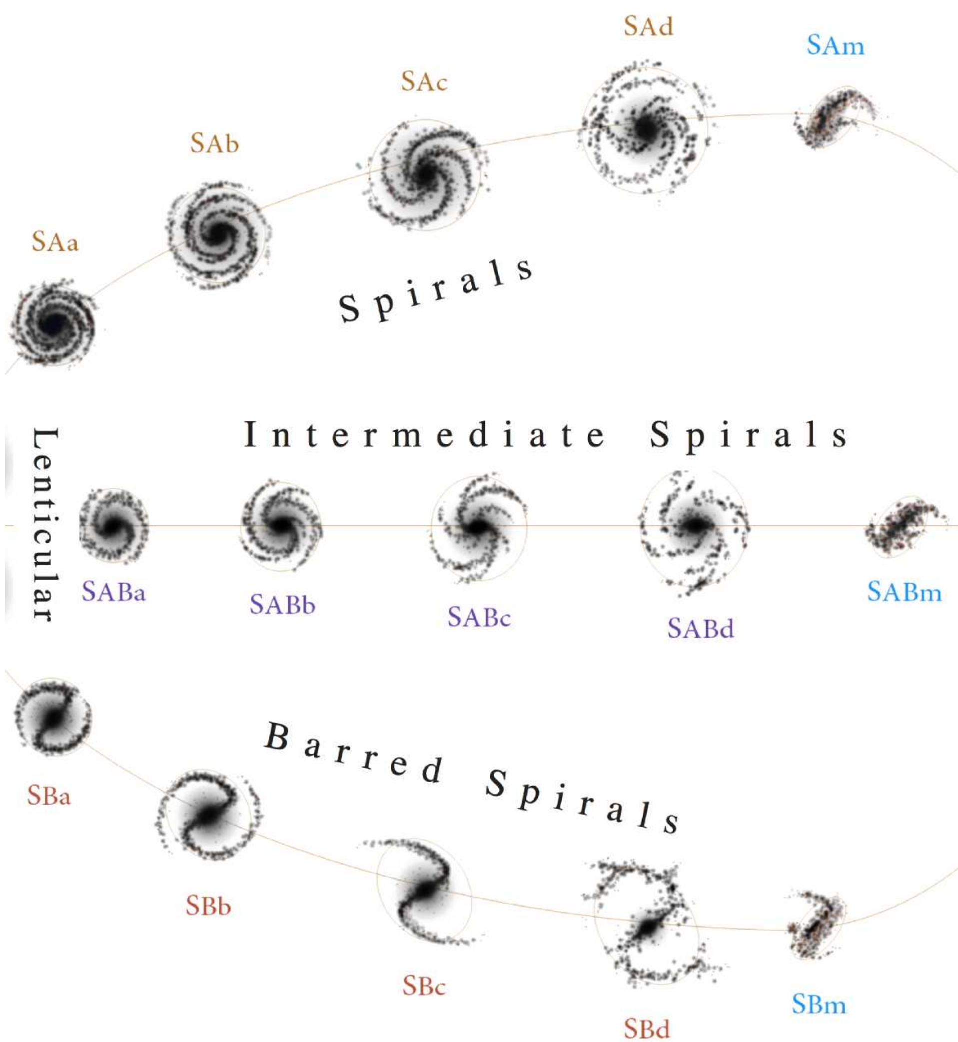
Spiral Galaxies



Spiral Galaxies

The relative importance of bulges with respect to disks is a classification criteria of spiral galaxies.

presence/importance of a bar

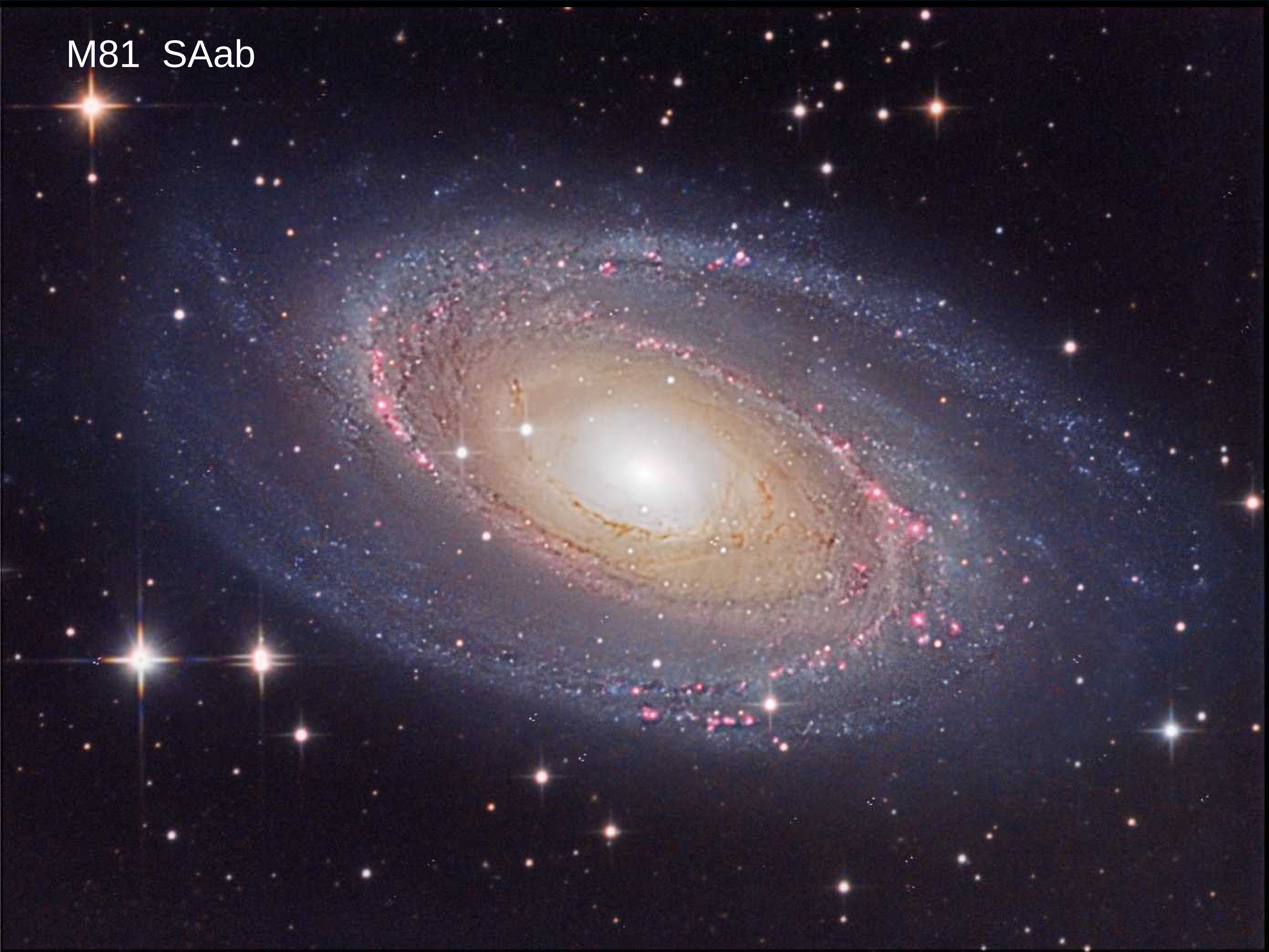


- fainter bulge
- spiral arms loosely wound
- more gas
- more clumps, more star forming regions

SAa

Sombrero Galaxy • M104

Hubble Heritage


M81 SAab

M33 SAcd


M100 SABbc

M101 SABc

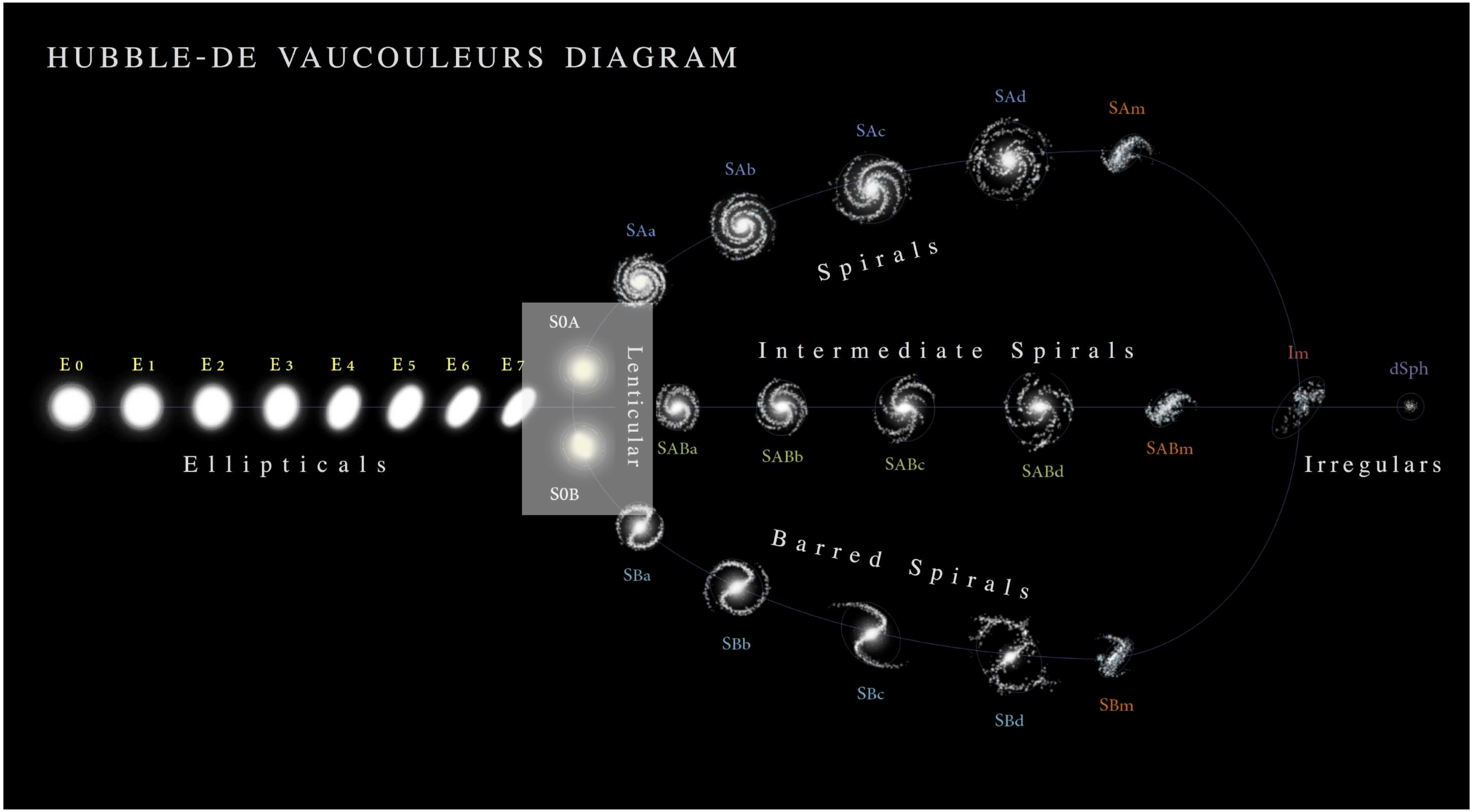
NGC 1365 SBb

NGC 1300 SBb

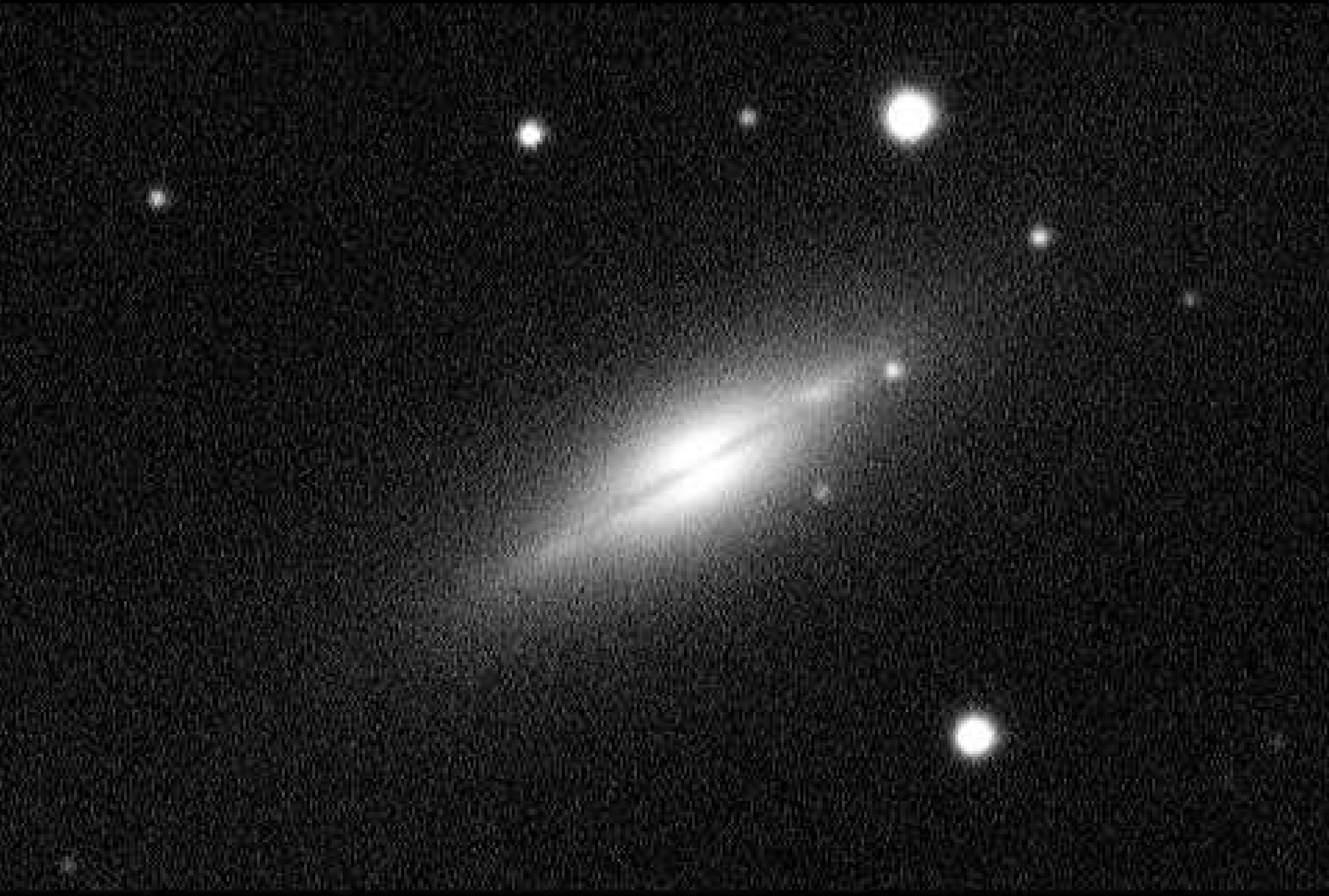
M109 SBc

Observation of Galaxies

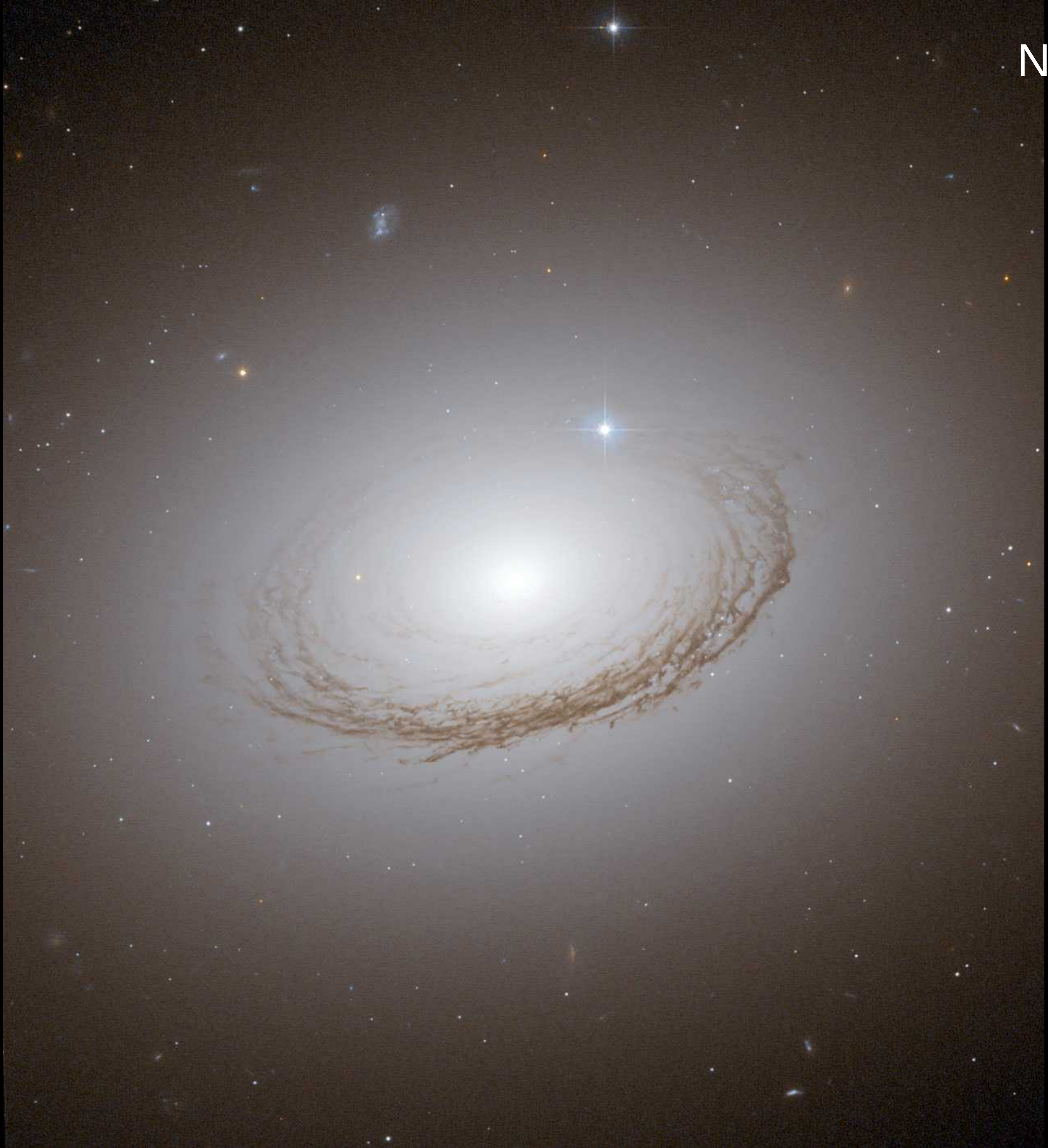
Lenticular Galaxies

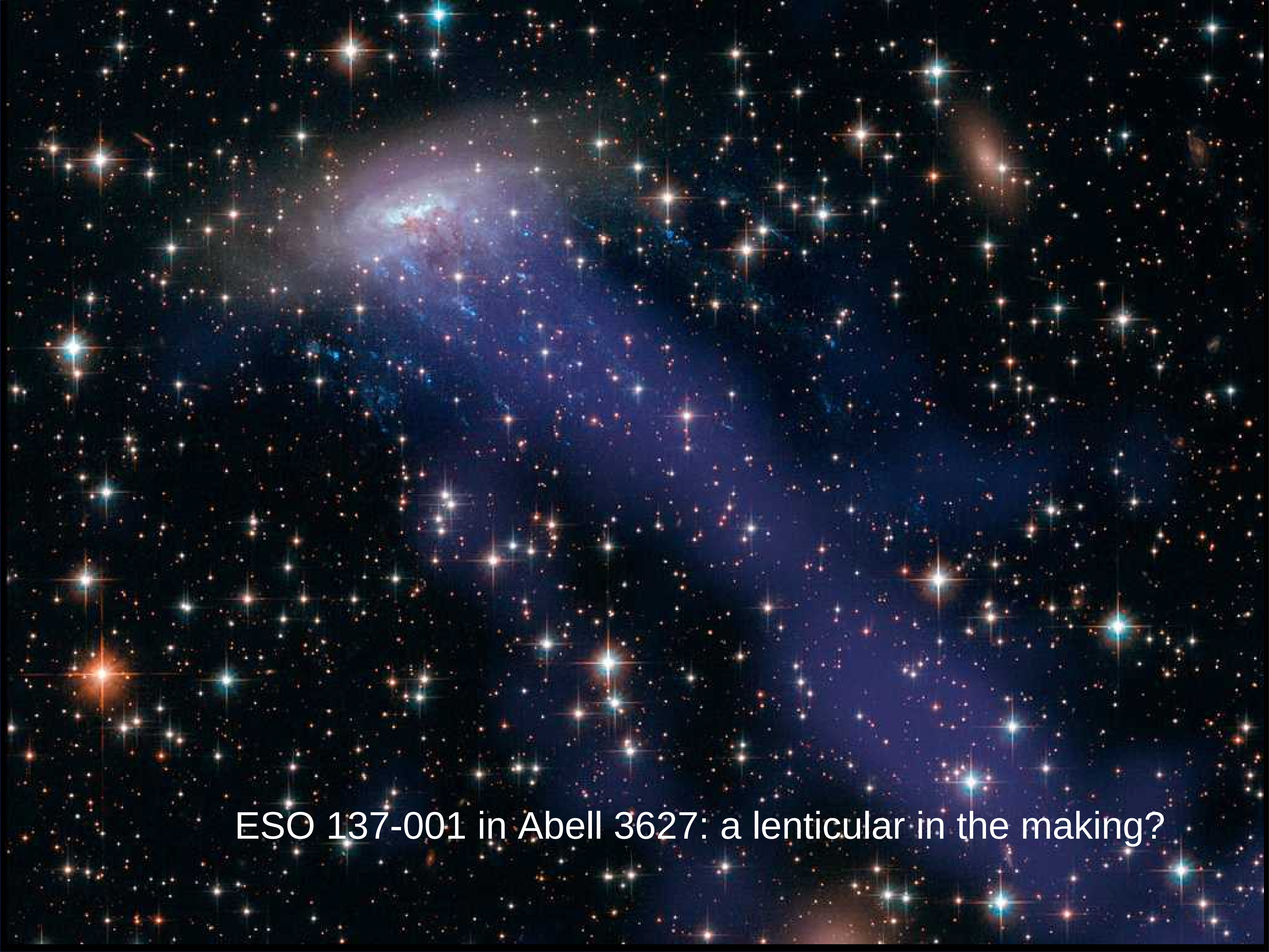


The lenticular galaxy NGC 5866



The lenticular galaxy NGC 1381

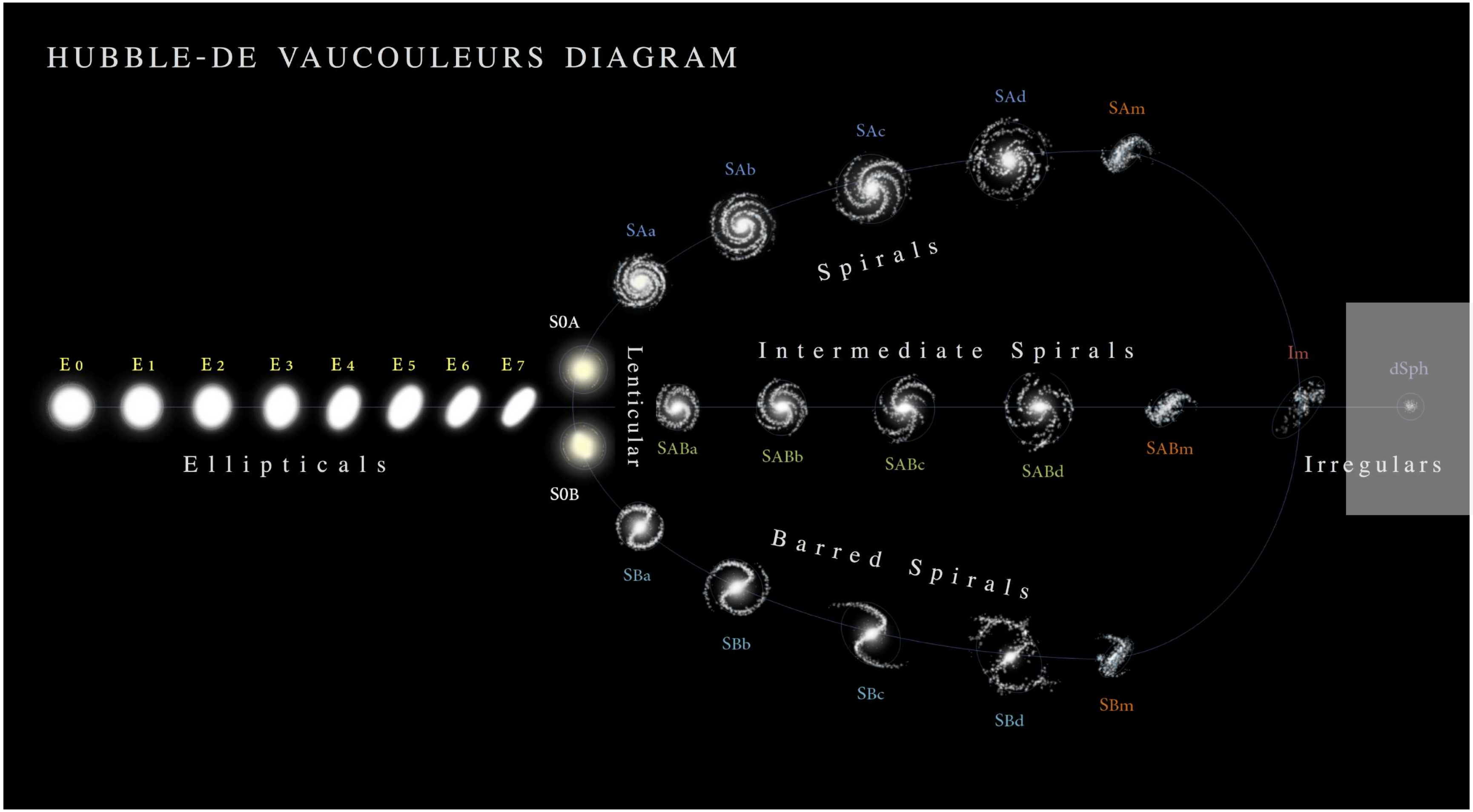

NGC 7049



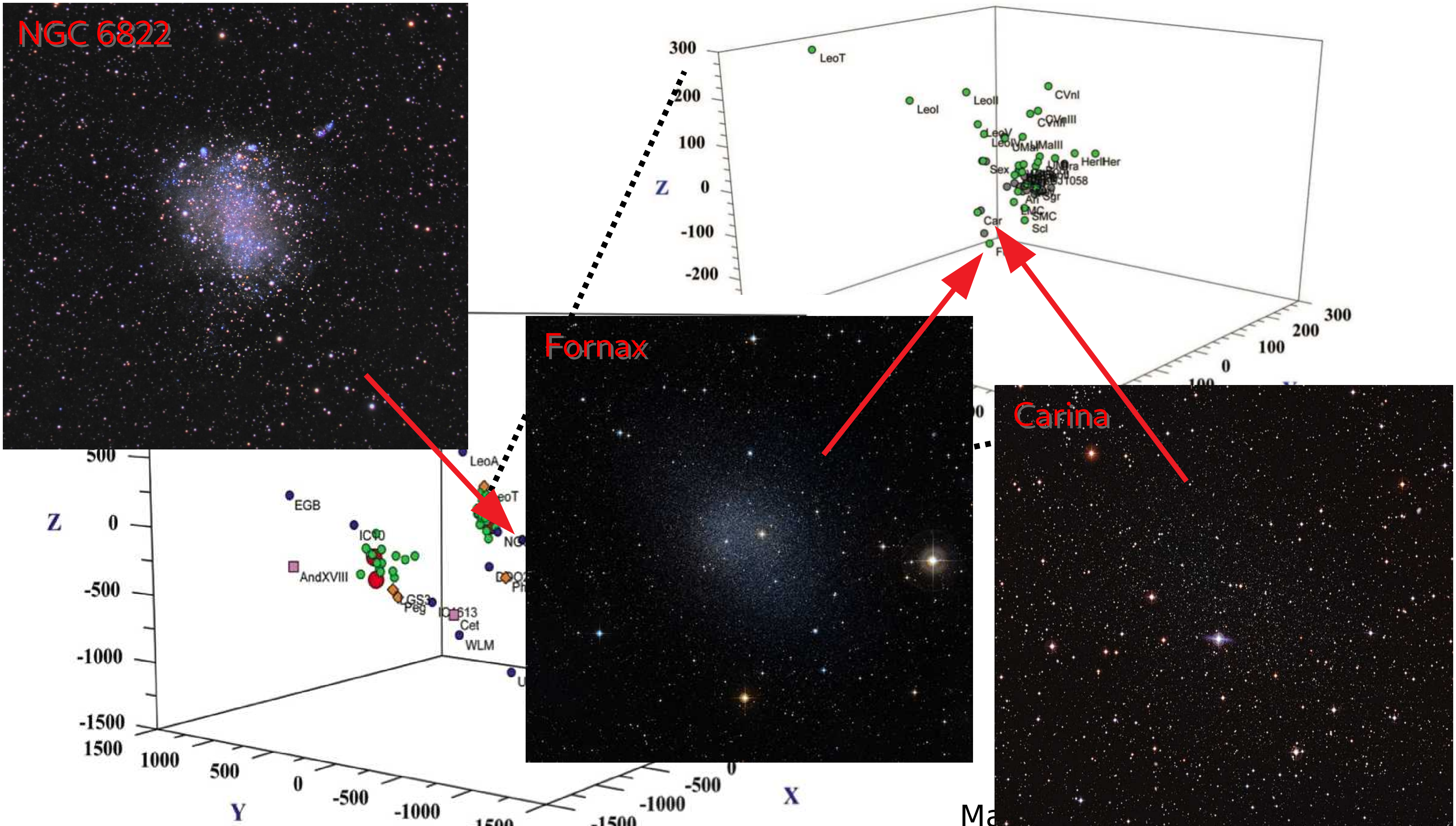
ESO 137-001 in Abell 3627: a lenticular in the making?

Observation of Galaxies

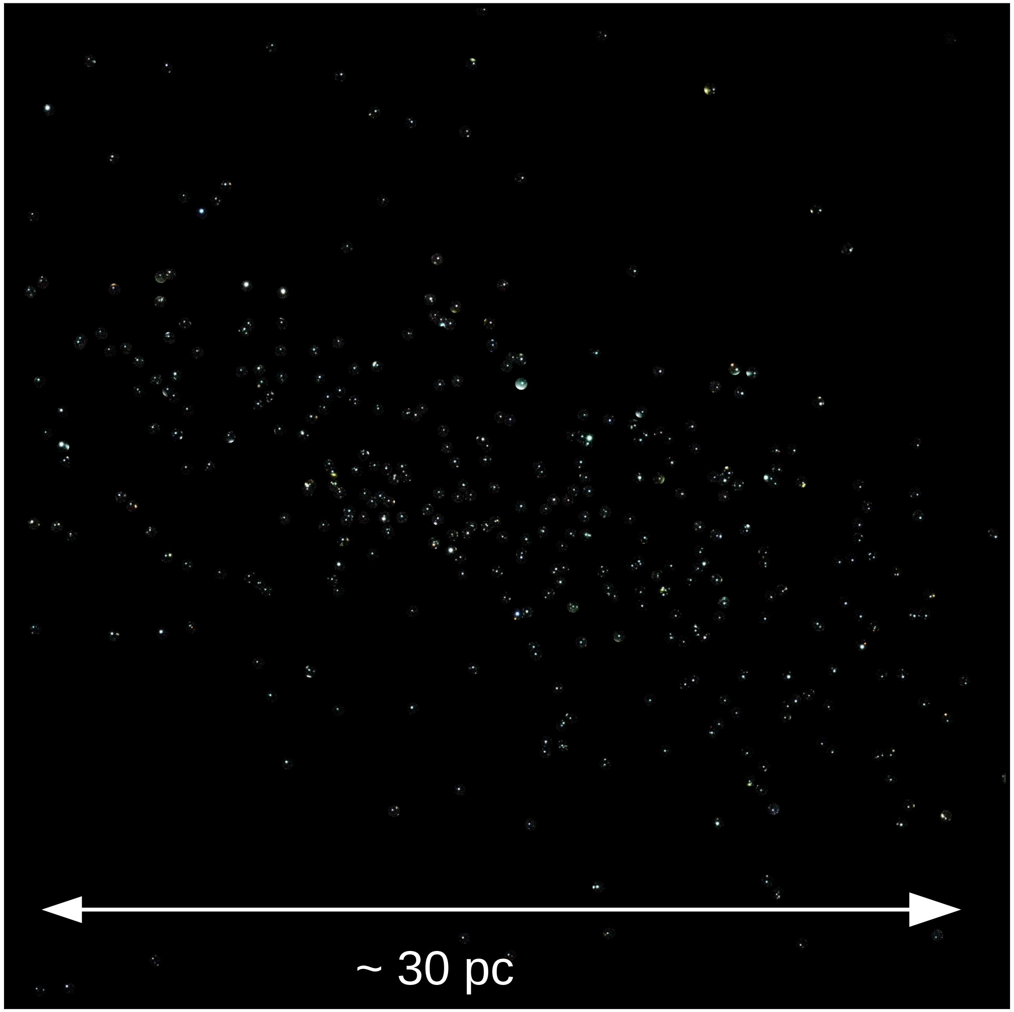
Dwarf spheroidal (dSph) + ultra-faint dwarfs (UFDs)




Leo I dwarf galaxy (dSph)


NGC 6822
Fornax
Carina
LeoT
LeoI
LeoII
CVnI
Sex
Car
SMC
Scl
Z
300
200
100
0
-100
-200
EGB
AndXVIII
LeoA
Cet
WLM
500
0
-500
-1000
-1500
Y
X
Ma

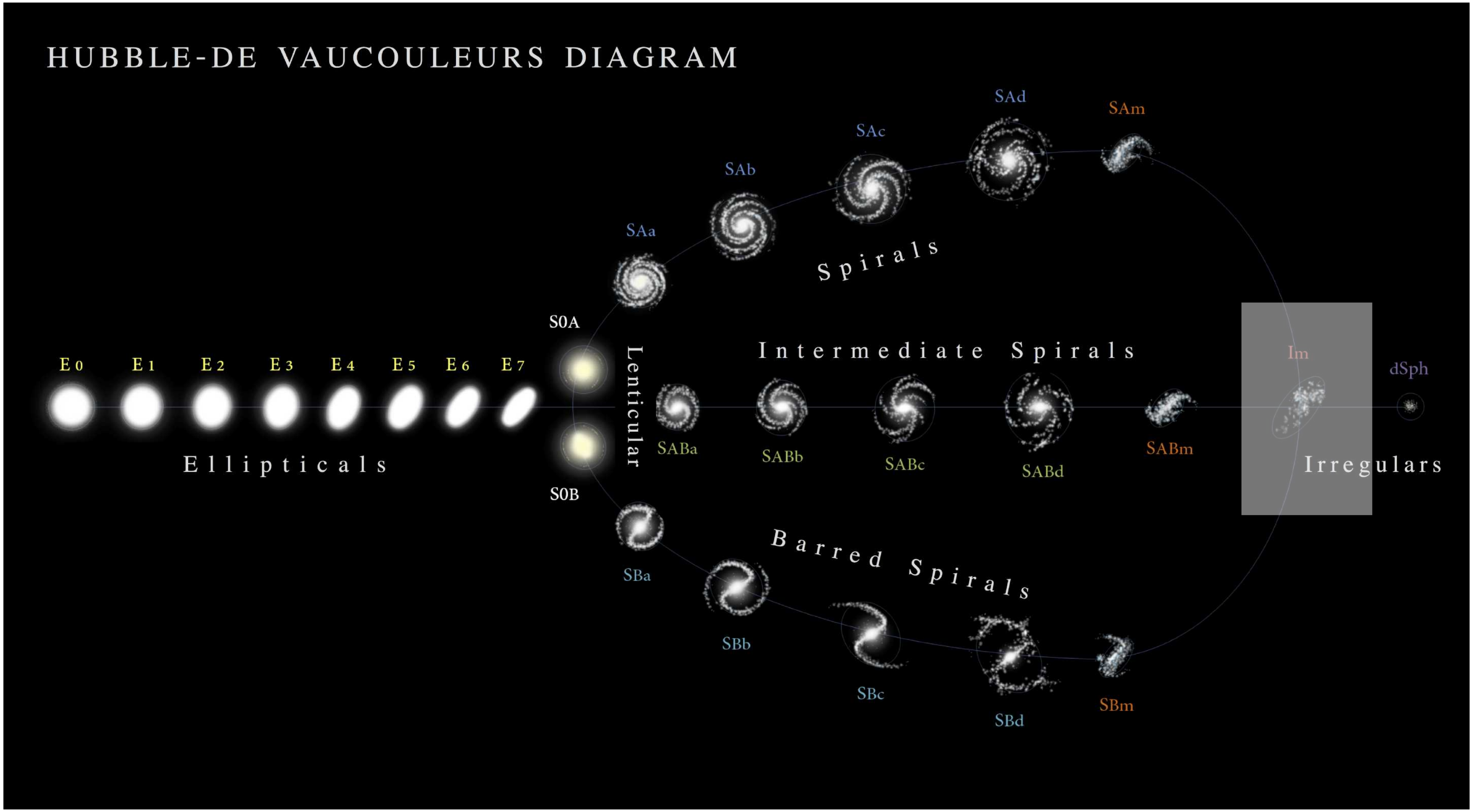
Reticulum II (UFD) $L_{\mathrm{V}} \cong 1000 L_{\odot}$



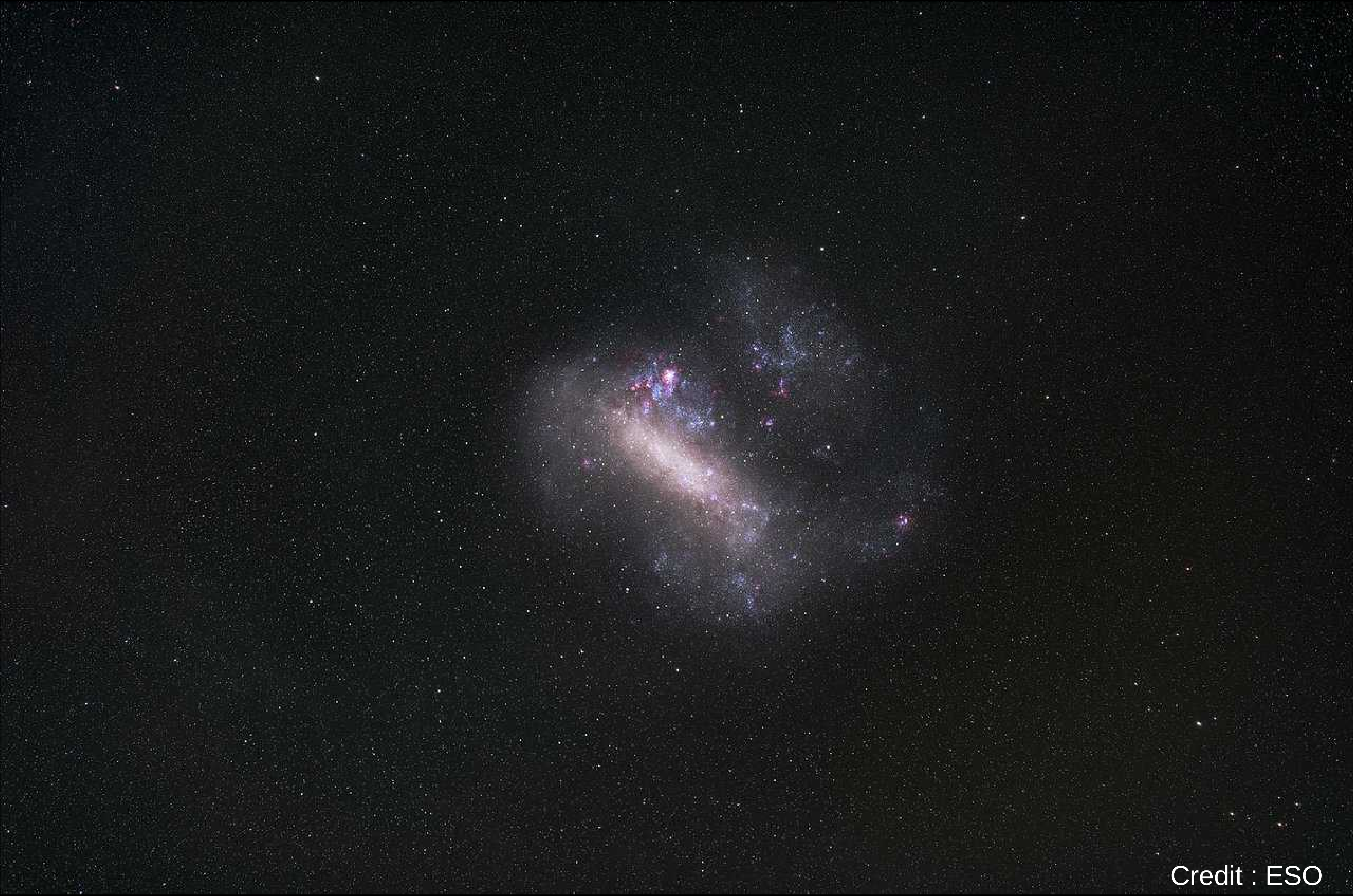
Dark Energy Survey

Observation of Galaxies

Irregular Galaxies



The Large Magellanic Cloud (LMC)



Credit : ESO

The Small Magellanic Cloud (SMC)

Credit : ESO

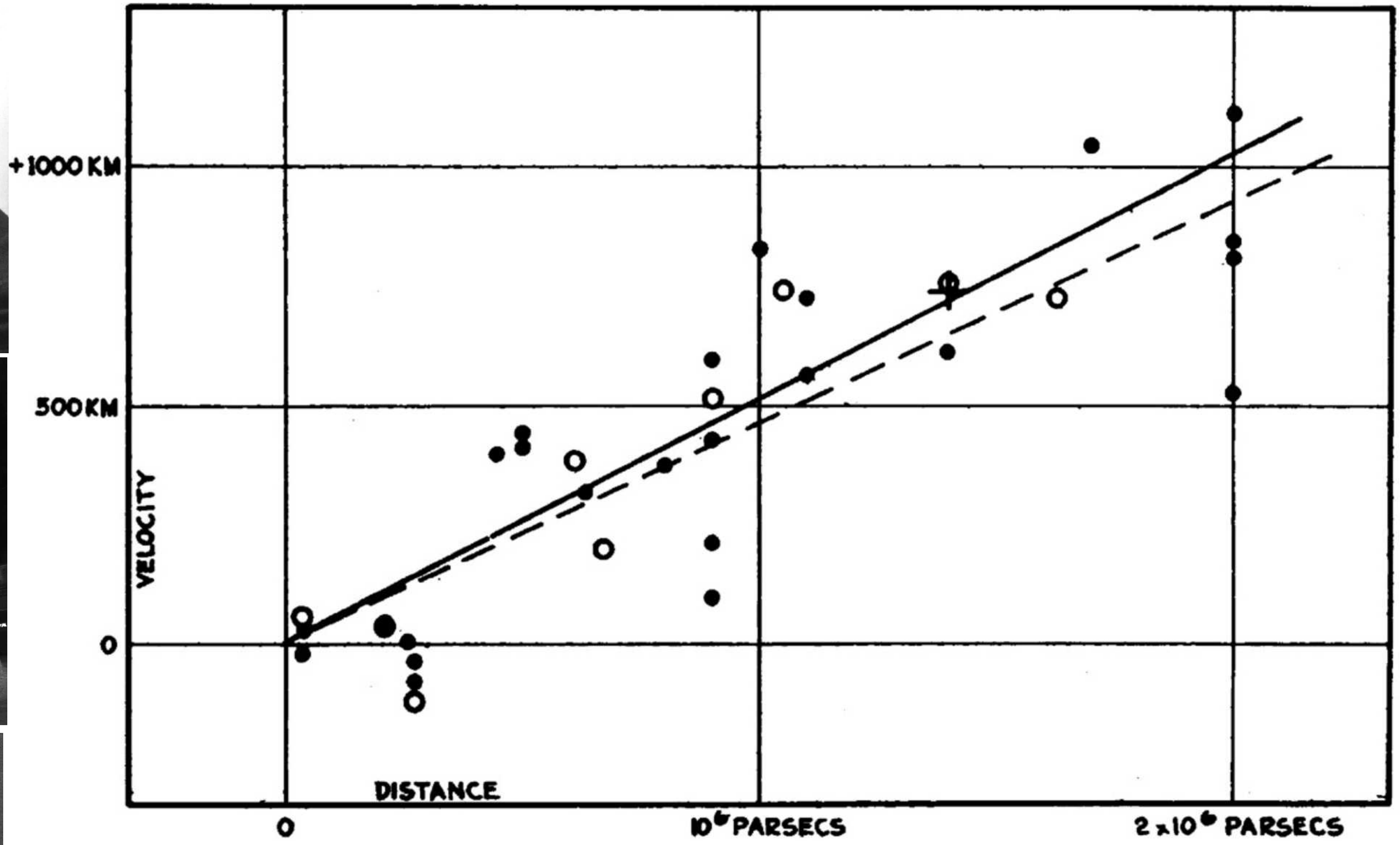
NGC 6745

Credit : Hubble

Observation of Galaxies

Hubble Lemaître Law

A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae

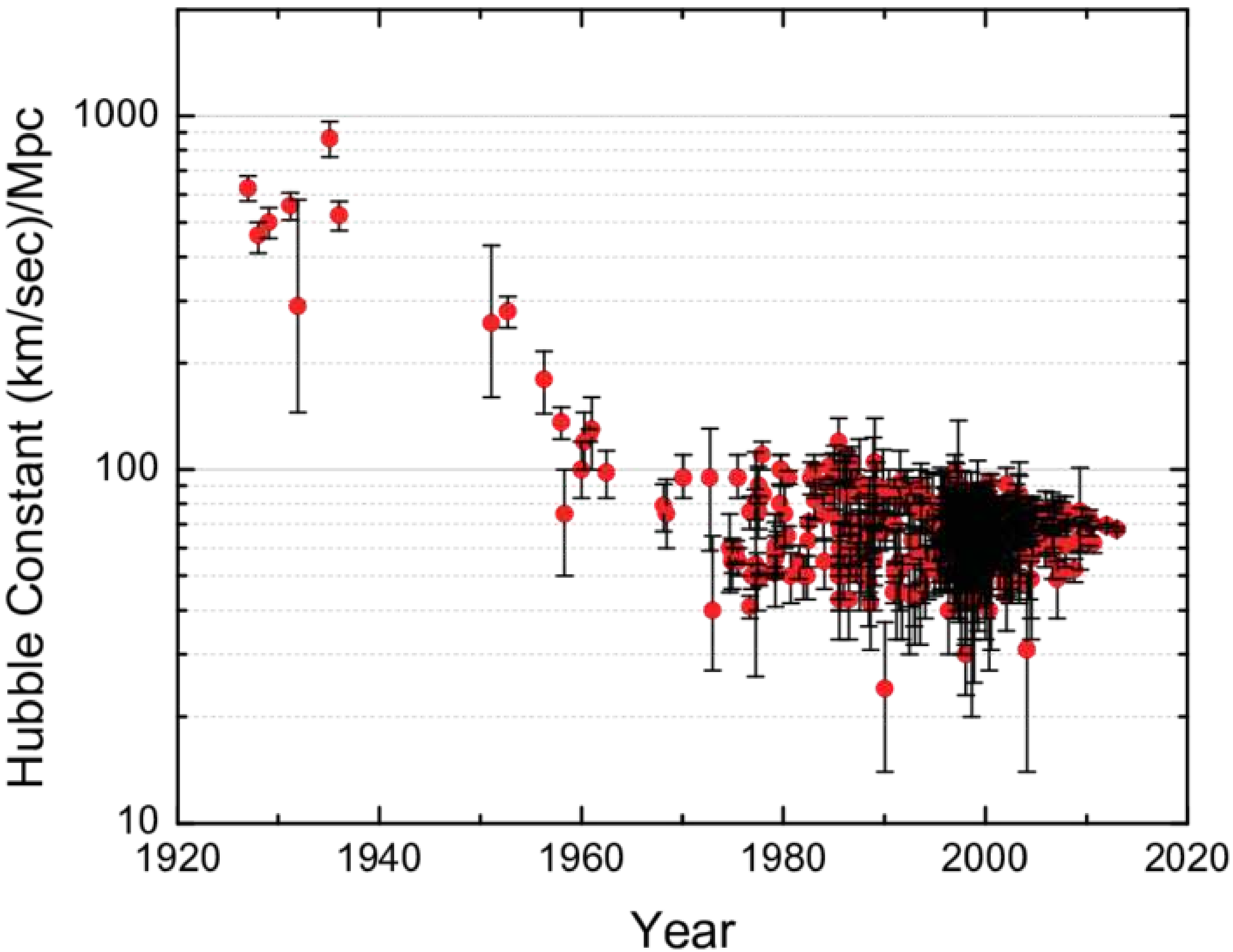


Hubble 1929

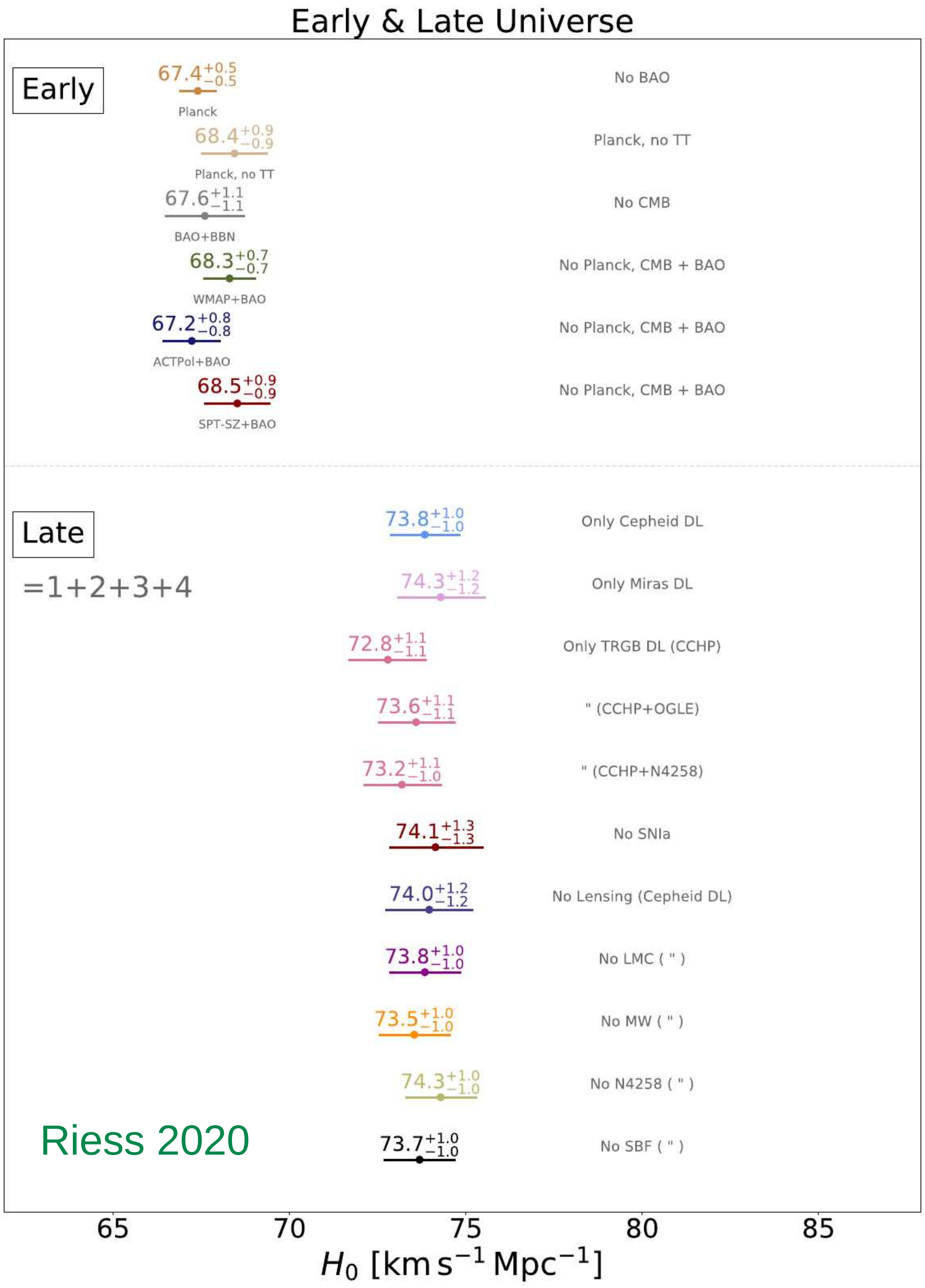
$$\boxed{v = H_0\, d}$$

$$H_0 = 100\, h \,\mathrm{km\, s^{-1}\, Mpc^{-1}} \cong 70 \,\mathrm{km\, s^{-1}\, Mpc^{-1}}$$

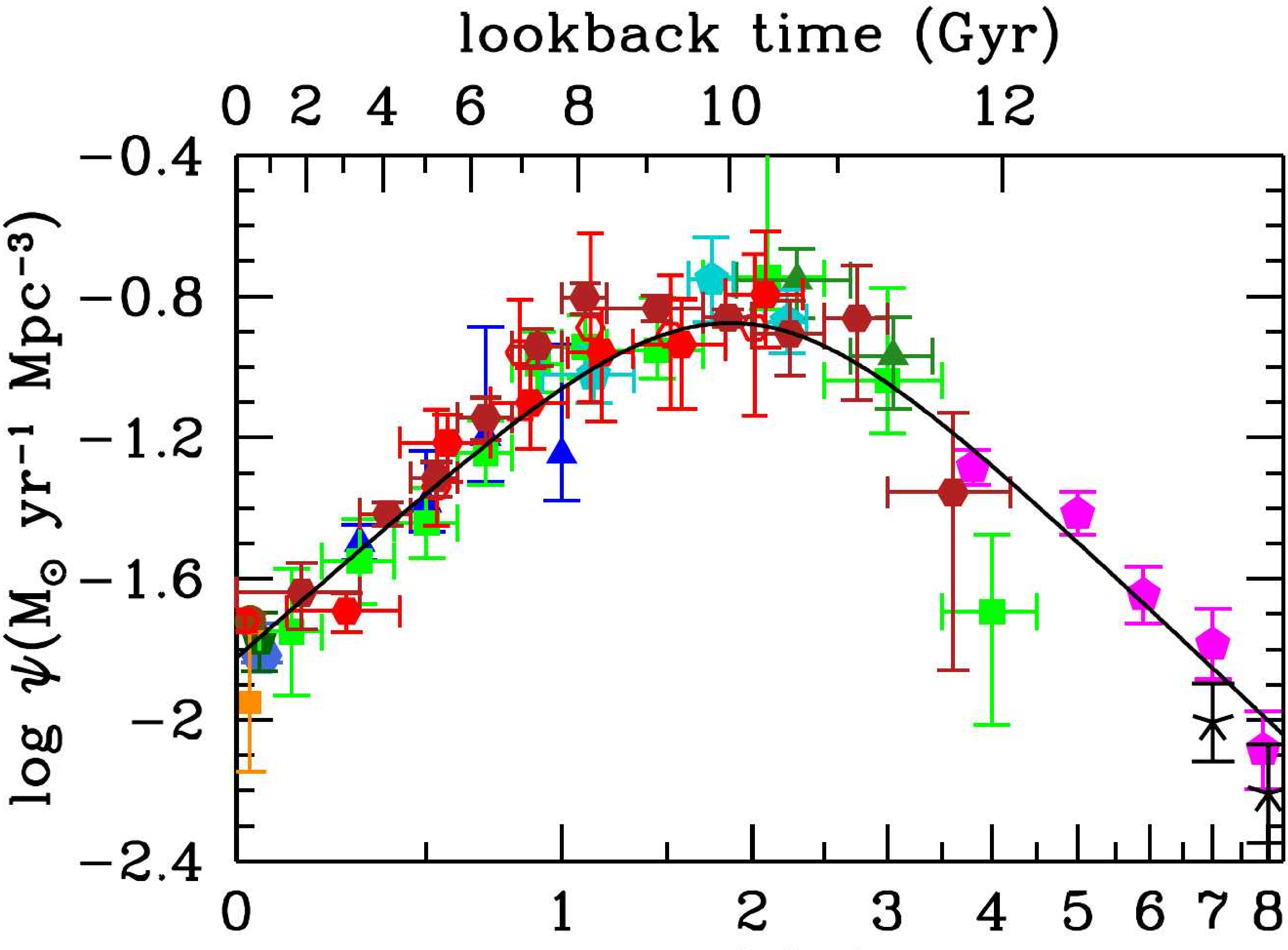
Historical evolution of the Hubble constant



The Hubble Tension



The cosmic star formation history



Madau & Dickinson 2014

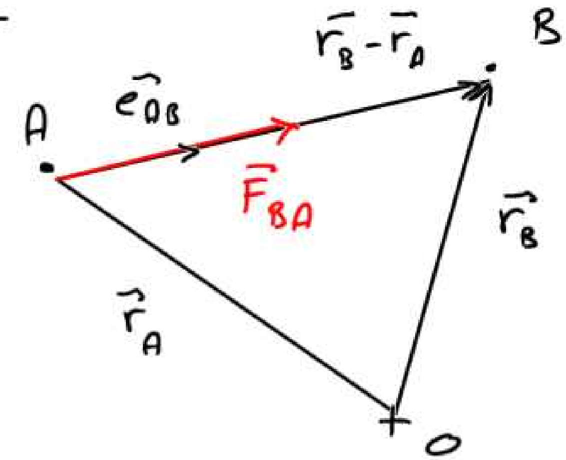
The Gravity :
a long distance force

The gravity : a long range force

$$\boxed{\vec{F}_{BA} = \frac{G\, m_A\, m_B}{|\vec{r}_B - \vec{r}_A|^2}\, \vec{e}_{AB}}$$

$$\boxed{\vec{F}_{BA} = \frac{G\, m_A\, m_B}{|\vec{r}_B - \vec{r}_A|^3}\, \vec{r}_B - \vec{r}_A}$$

$$\boxed{|\vec{F}_{BA}| = \frac{G\, m_A\, m_B}{r_{AB}^2}}$$



$$\vec{e}_{AB} = \frac{\vec{r}_B - \vec{r}_A}{|\vec{r}_B - \vec{r}_A|}$$

$$r_{AB} = |\vec{r}_B - \vec{r}_A|$$

$$[G] = \frac{cm^3}{g\, s} \equiv \frac{erg\ cm}{g^2}$$

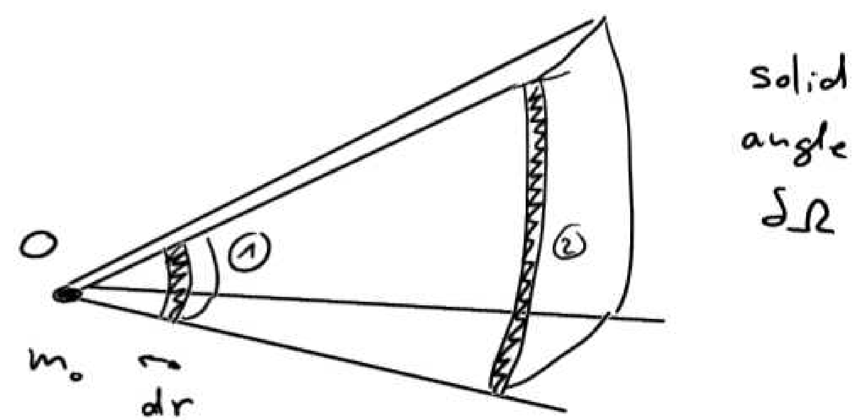
$$[erg] = \frac{cm^2}{s^2}\, g$$

Contrary to, for example, molecular forces, gravity is a long range force, i.e: we cannot neglect distant regions

Illustration: an homogeneous medium ($\rho(\vec{x}) = \text{cte}$)

Force on point O due to a thin shell of mass δm at distance r

$$\delta F = \frac{G\, m_0\, \delta m}{r^2}$$

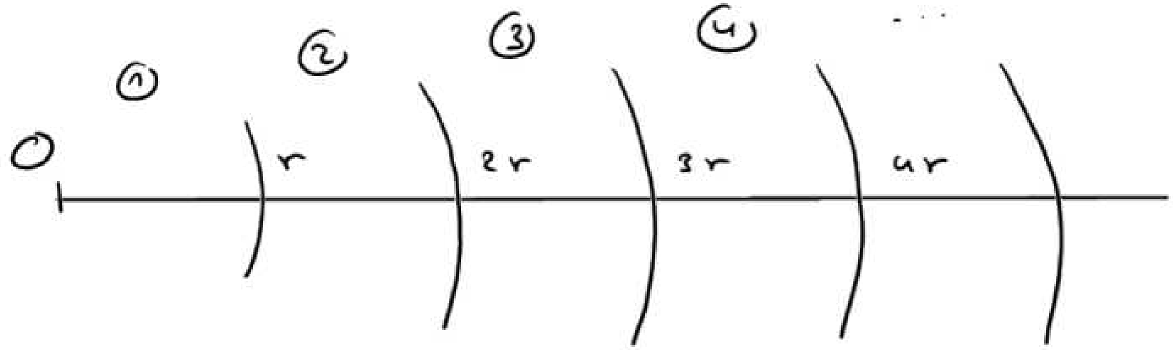


but $\delta m = \rho\, r^2\, \delta\Omega\, dr$

thus

$$\boxed{\delta F = \underbrace{G\, m_0\, \rho\, \delta\Omega}_{\text{cte indep. of } r}\, dr}$$

Split the space in shells of thikeness r



$$\delta F_1 = \int_0^r \delta F = \int_0^r dr \; G m_0 \rho \, \delta\Omega = G m_0 \rho \, d\Omega \, r$$

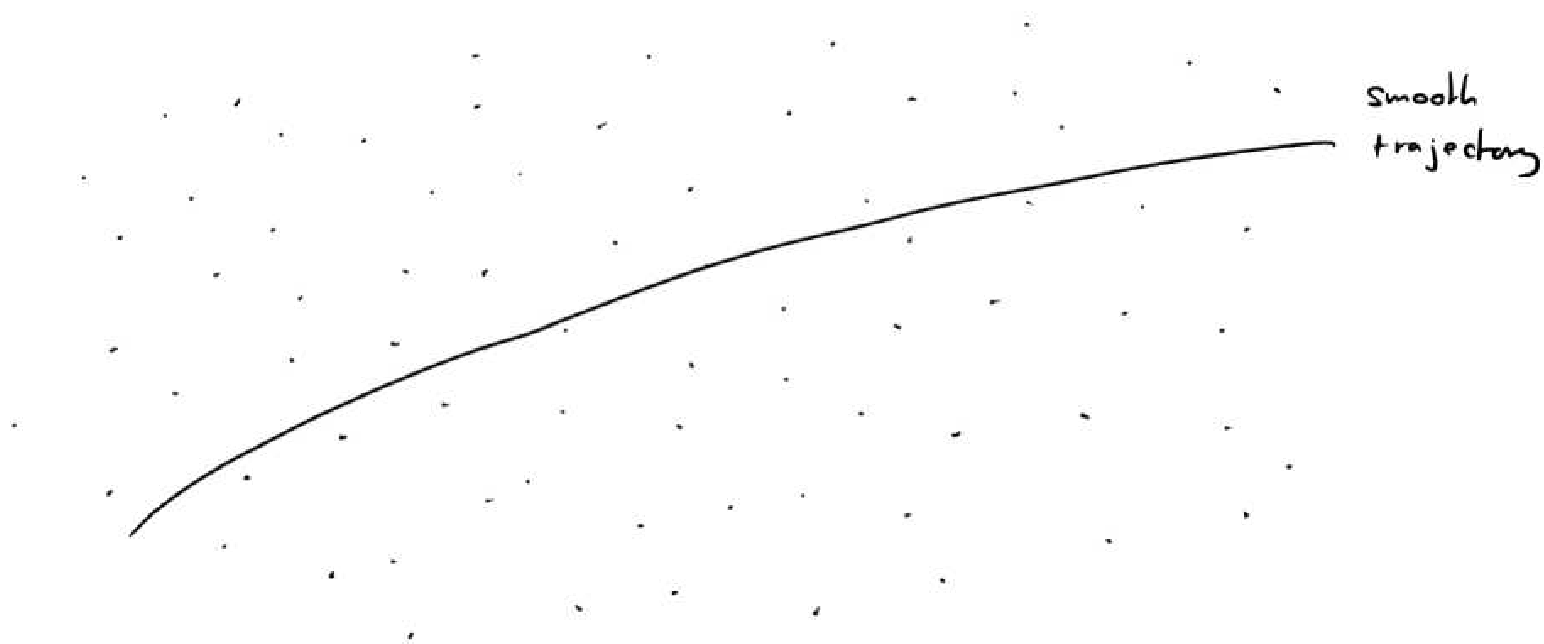
$$\delta F_2 = \int_r^{2r} \delta F = \quad \dots \quad = G m_0 \rho \, d\Omega \, r$$

$$\boxed{\text{As the contribution of all shell is the same, the contribution of the stars with } r' > r \text{ will dominate over the ones with } r' < r}$$

$$\boxed{\text{We cannot neglect regions at large distances !}}$$

Corollary : As the force is dominated by the mass at large scale, the force varies smoothly along the trajectory of a particle (star).

Stellar systems can be modeled by smooth mass distributions



Notes

1. **2D case**

$$\delta F = -\frac{G m_0}{r^2}\,\delta m = -\frac{G m_0}{r^2}\,\Sigma\, \delta\theta\, r\, dr = -G m_0 \rho\, \delta\theta\, dr\, \frac{1}{r}$$

$$\boxed{F_r = -G m_0 \Sigma\, \delta\theta}$$

Σ : surface density

1D case

$$\delta F = -\frac{G m_0}{r^2}\,\delta m = -\frac{G m_0}{r^2}\,\lambda\, dr$$

$$\boxed{F_r = -G m_0 \lambda \frac{1}{r}}$$

λ : linear density

2. **Molecular dynamics**

"long distence" attraction force between two molecules,

Van der Waals Force $\sim r^{-7}$

$\boxed{\Rightarrow \text{local molecules dominates}}$

Relaxation Time

Question :

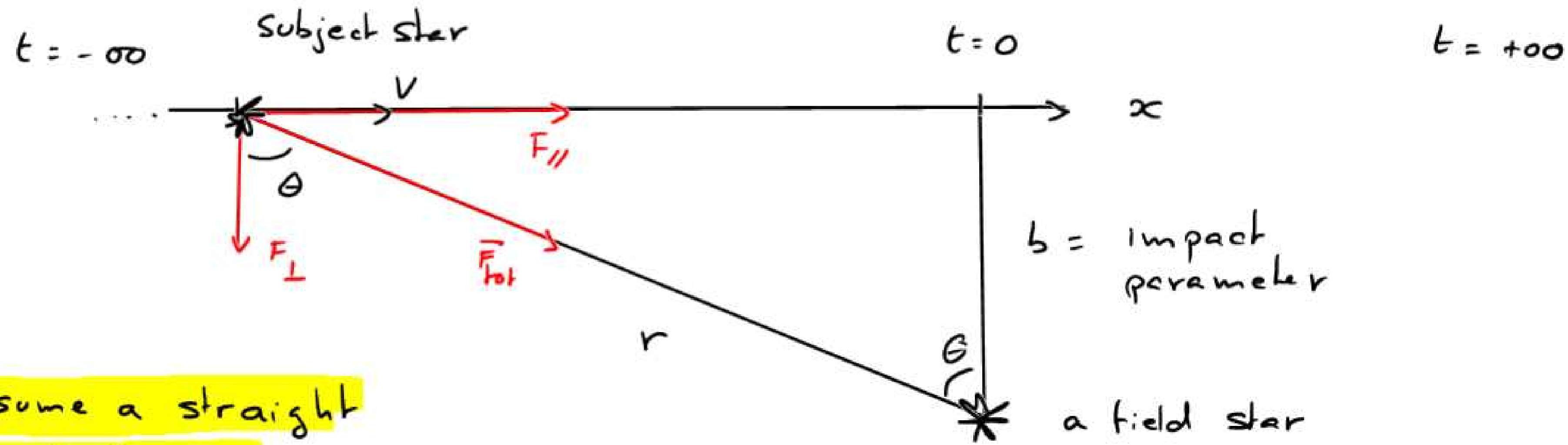
How accurate is the assumption that a galaxy may be modelled as a smooth distribution ?

1) Effect of one star on the orbit of a peculiar star.

2) Effect of all stars of a stellar system on a peculiar star.

3) Under which conditions the orbit of a peculiar star is strongly influenced by the discrete nature of the stellar system (importance of “collision” with other stars).

1. Estimate the effect of one star on the trajectrory of a peculiar star



We assume a straight line trajectory

1) acceleration along x ($F_{//}$) does not matter, as it is symetric (the star decelerate after passing the field star

2) acceleration perpendicular to x ($F_\perp$)

$$|F_\perp| = |F_{tot}| \cos\theta = \frac{Gmm}{r^2} \cos\theta \qquad \text{but } \cos\theta = \frac{b}{r}$$

$$= \frac{Gmm}{x^2+b^2} \frac{b}{\sqrt{x^2+b^2}} = \frac{Gmm}{(x^2+b^2)^{3/2}} b$$

$$= \frac{Gmm}{\left(1+\frac{x^2}{b^2}\right)^{3/2}} \frac{1}{b^2} = \frac{Gmm}{b^2} \left(1+\frac{x^2}{b^2}\right)^{-\frac{3}{2}}$$

<u>with $x = vt$</u>

$$\boxed{F_\perp = |F_\perp| = \frac{Gmm}{b^2} \left(1+\left(\frac{vt}{b}\right)^2\right)^{-\frac{3}{2}}}$$

<u>Newton 2nd law</u>

$$F_\perp = m a_\perp = m \frac{dV_\perp}{dt}$$

Integrating over time from $t = -\infty$ to $t = \infty$

$$\int_{-\infty}^{\infty} F_{\perp}\, dt = \int_{-\infty}^{\infty} m \frac{dV_{\perp}}{dt}\, dt = m\, \delta V_{\perp}$$

net velocity increase

$$= \int_{-\infty}^{\infty} \frac{Gm\,m}{b^2} \left(1 + \left(\frac{vt}{b}\right)^2\right)^{-3/2} dt$$

$$\delta V_{\perp} = \frac{Gm}{b^2} \int_{-\infty}^{\infty} \left(1 + \left(\frac{vt}{b}\right)^2\right)^{-3/2} dt$$

with $s = \dfrac{vt}{b}$ $\qquad ds = \dfrac{v}{b}\, dt$

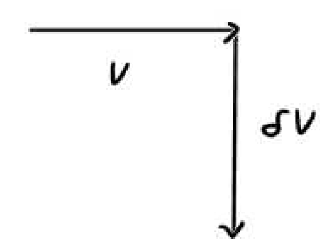
$$\delta v_\perp = \frac{Gm}{b^2}\int_{-\infty}^{\infty}\left(1+s^2\right)^{-3/2} dt = 2\,\frac{Gm}{bv}$$

$$\boxed{\delta v_\perp = \underbrace{\frac{Gm}{b^2}}_{\substack{\text{acceleration}\\ \text{at the closest}\\ \text{approach}}} \cdot \underbrace{\frac{2b}{v}}_{\substack{\text{"duration"}\\ \text{of the closest}\\ \text{approach}}}}$$

<u>Note</u> : our hypothesis of a straight line is ok if $\underline{\delta v \ll v}$

$$\Rightarrow \quad \boxed{b \gg \frac{2Gm}{v^2} \equiv b_{90}}$$

b_{90} define as $v = \delta v$



2 Effect of all stars of a stellar system on the trajectory of a peculiar star

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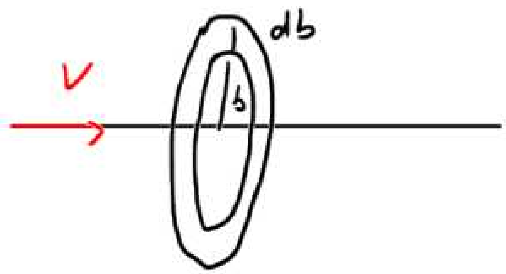
N : total number of stars $\qquad$ R typical size of the system

- number density of stars per unit of surface $n = \dfrac{N}{\pi R^2}$
- number of stars met by the star with $[b, b+db]$

which induces a $\delta v_\perp = \dfrac{2Gm}{bv}$ change of $v_\perp$

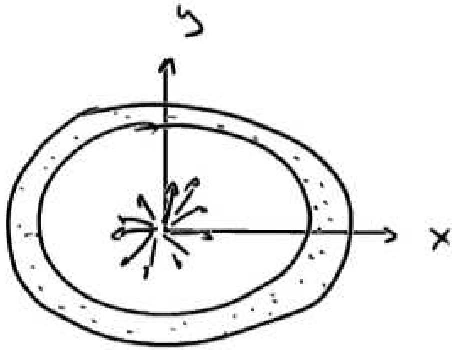
$$\delta N = 2\pi b \, db \cdot n$$

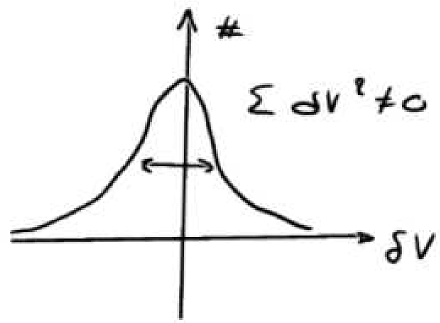
$$= 2\pi b \, db \, \frac{N}{\pi R^2}$$

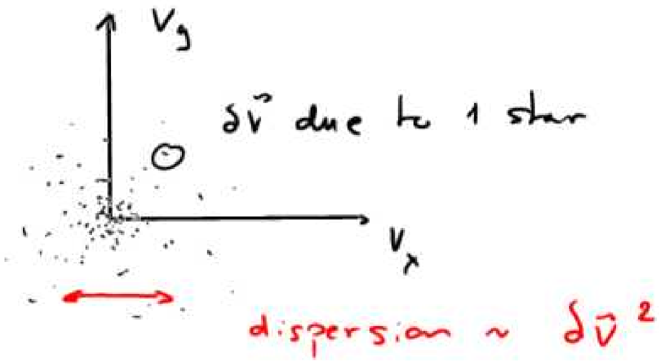


Each star in the ring induces a $\delta\vec{V}$ of the same amplitude, such that in average $\sum \delta\vec{V} \cong 0$

however $\sum \delta\vec{V}^2 \neq 0$







configuration space

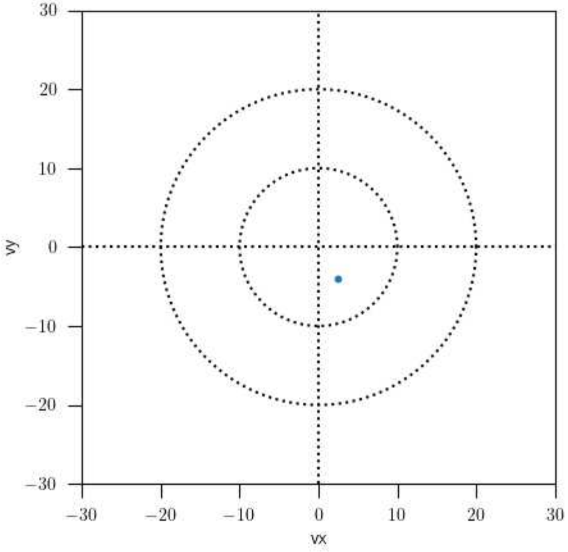
velocity space

Estimation of $\sum \delta\vec{V}^2$

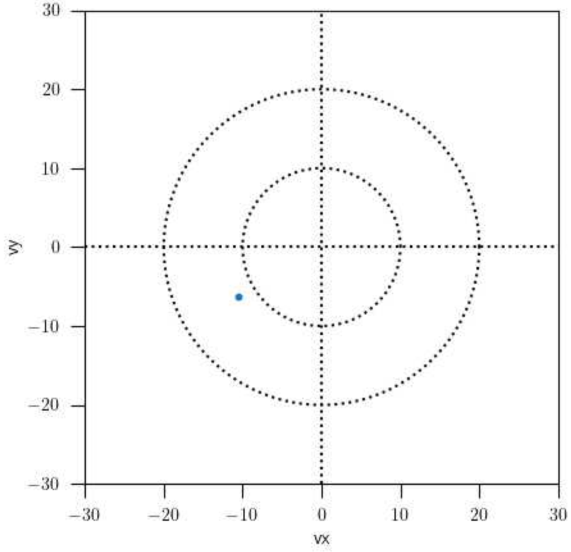
$$\sum \delta\vec{V}^2 = \delta N \cdot \delta\vec{V}^2 = \left(2\pi b\, db \, \frac{N}{\pi R^2}\right)\left(\frac{2Gm}{bv}\right)^2 = \frac{8NG^2m^2}{v^2R^2}\frac{db}{b}$$

Spread in the velocity space due to two-body encounters

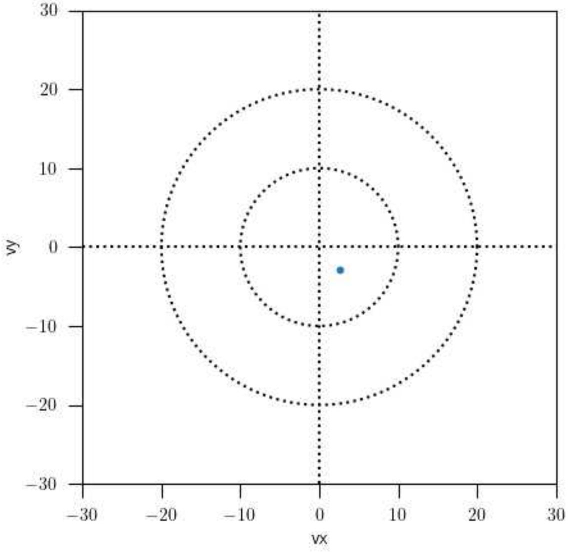
N=1



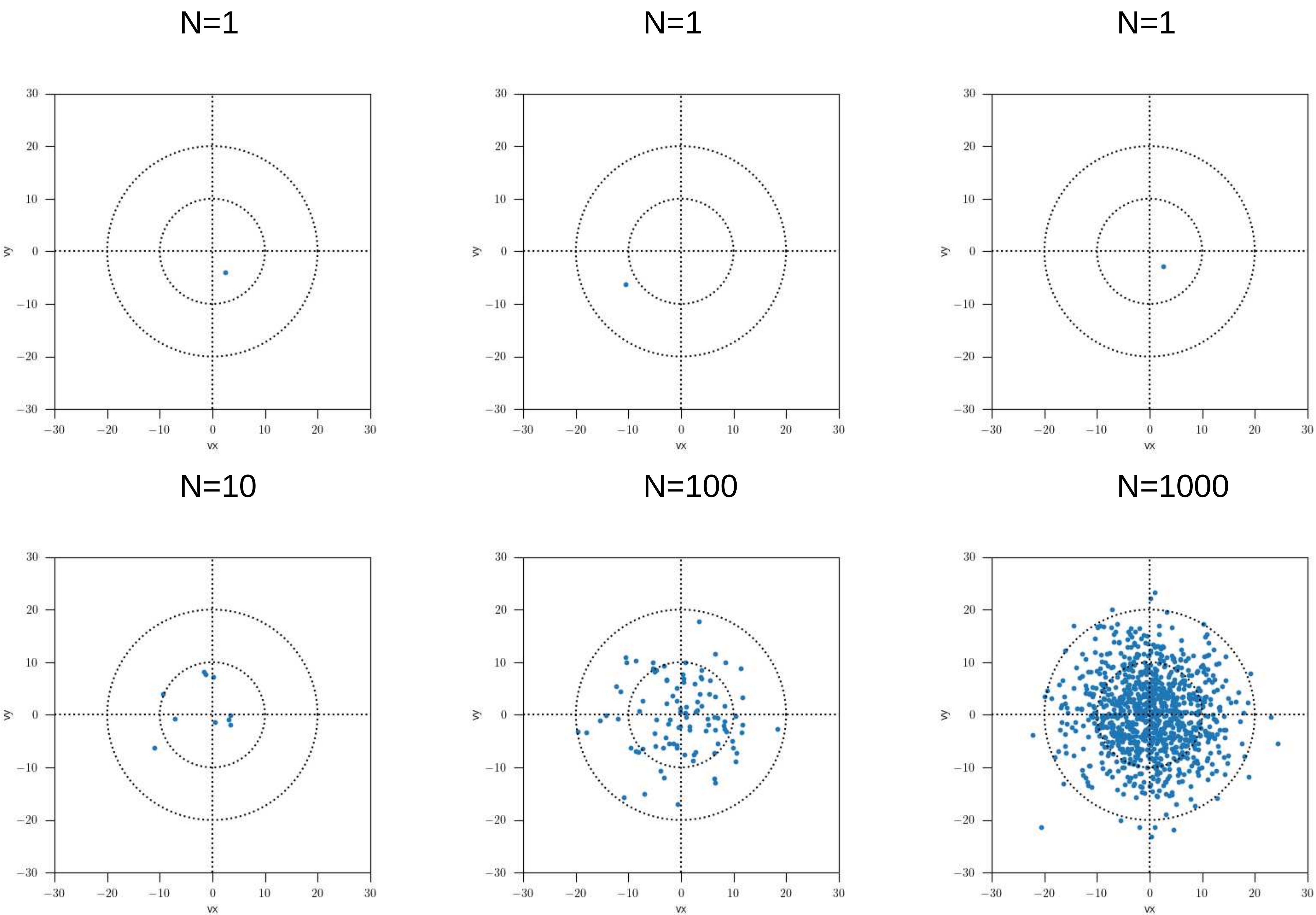
N=1



N=1



Spread in the velocity space due to two-body encounters



For all encounters, we integrate over b from b_{min} to b_{max}

$b_{min} := \delta_1 \, b_{90}$ if $b < b_{90}$ $\delta v \sim v$ $\delta_1 \approx 1$

$b_{max} := \delta_2 \, R$ if $b > R$ the density is no longer constant $\delta_2 \approx 1$

we get

$\ln \Lambda$: Coulomb logarithm

$$\Delta v^2 = 8N \left(\frac{Gm}{vR}\right)^2 \int_{b_{min}}^{b_{max}} \frac{db}{b} = 8N \left(\frac{Gm}{vR}\right)^2 \ln\left(\frac{b_{max}}{b_{min}}\right)$$

$$\boxed{\Delta v^2 = 8N \left(\frac{Gm}{vR}\right)^2 \left[\ln\left(\frac{R}{b_{90}}\right) + \underbrace{\ln\left(\frac{\delta_2}{\delta_1}\right)}_{\simeq 0} \right]}$$

- variation due to one crossing.

Crossing time / relaxation time

Typical velocity of one star (circular orbit)

$$v^2 \sim \frac{GNm}{R} \qquad R = \frac{GNm}{V^2}$$

$$\Delta v^2 = 8N\left(\frac{Gm}{vR}\right)^2 \ln\Lambda = 8N\left(\frac{V}{N}\right)^2 \ln\Lambda = 8\,\frac{V^2}{N}\ln\Lambda$$

$$\boxed{\Delta v^2 = 8\,\frac{V^2}{N}\ln\Lambda}$$

- Each time a star will cross the system, the square of its velocity will change by an amount Δv^2

$n_{cross} \Rightarrow$ $$\boxed{\Delta v^2_{n_{cross}} = n_{cross} \cdot v^2 \frac{8}{N} \ln \Lambda}$$

- n_{relax} : number of crossing time to have $\Delta v^2 \cong v^2$

$$n_{relax} \cdot v^2 \frac{8}{N} \ln \Lambda = v^2$$

$$\boxed{n_{relax} = \frac{N}{8 \ln \Lambda}}$$

Crossing time t_{cross}

Time for the star to cross the system

$$t_{cross} \cong \frac{R}{v} \qquad \left(v^2 \sim \frac{G N m}{R} \right)$$

Relaxation time t_{relax}

Time for n_{relax} crossing.

$$\boxed{t_{relax} = \frac{N}{8 \ln \Lambda} \cdot t_{cross}}$$

$\equiv$ Time after which a star change significantly its orbit with respect to a smooth density field

If $t < t_{relax}$: the perturbations of nearby stars does not matter $\Rightarrow$ collision less system

Estimations for stellar systems

N, m, R

using

$$b_{90} = \frac{2Gm}{v^2}$$

circular orbit: $a = \frac{v^2}{r} = \frac{GNm}{r^2} \Rightarrow v^2 = \frac{GNm}{r}$

we get

$$\boxed{b_{90} = \frac{2R}{N}}$$

$$\boxed{\frac{R}{b_{90}} = \frac{N}{2}}$$

$$\boxed{\ln \Lambda \simeq \ln N}$$

$$\boxed{t_{relax} = \frac{N}{8 \ln \Lambda} \cdot t_{cross}} \Rightarrow \boxed{t_{relax} \simeq \frac{0.1\, N}{\ln N}\, t_{cross}}$$

$\ln \Lambda \simeq \ln N$

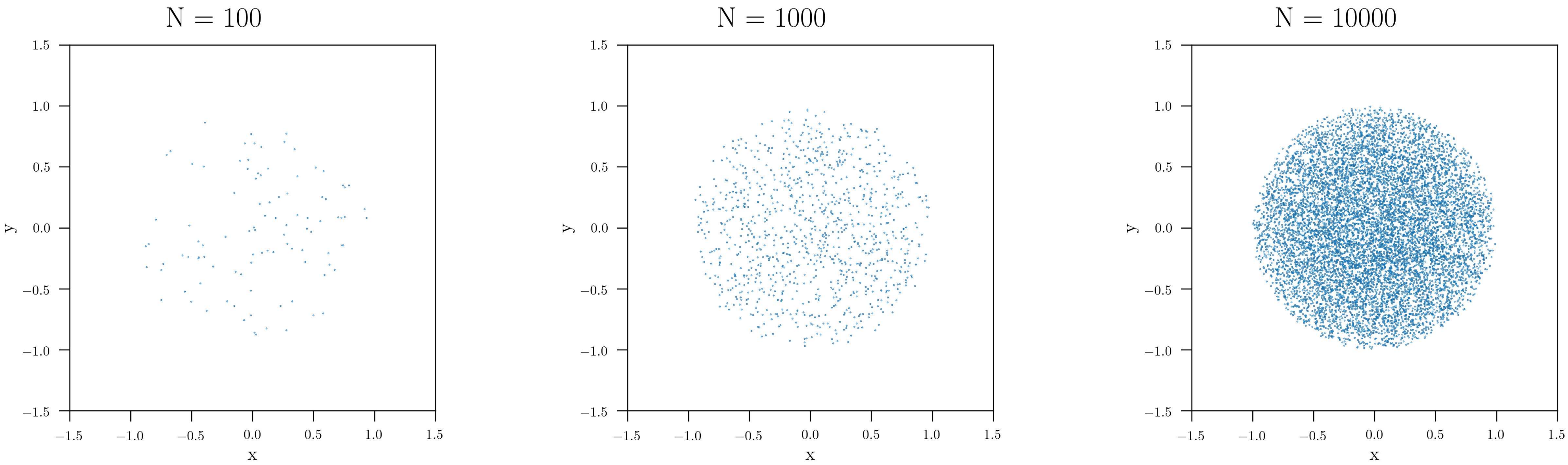
$\frac{1}{8} \simeq 0.1$

Numerical application / Relaxation Time

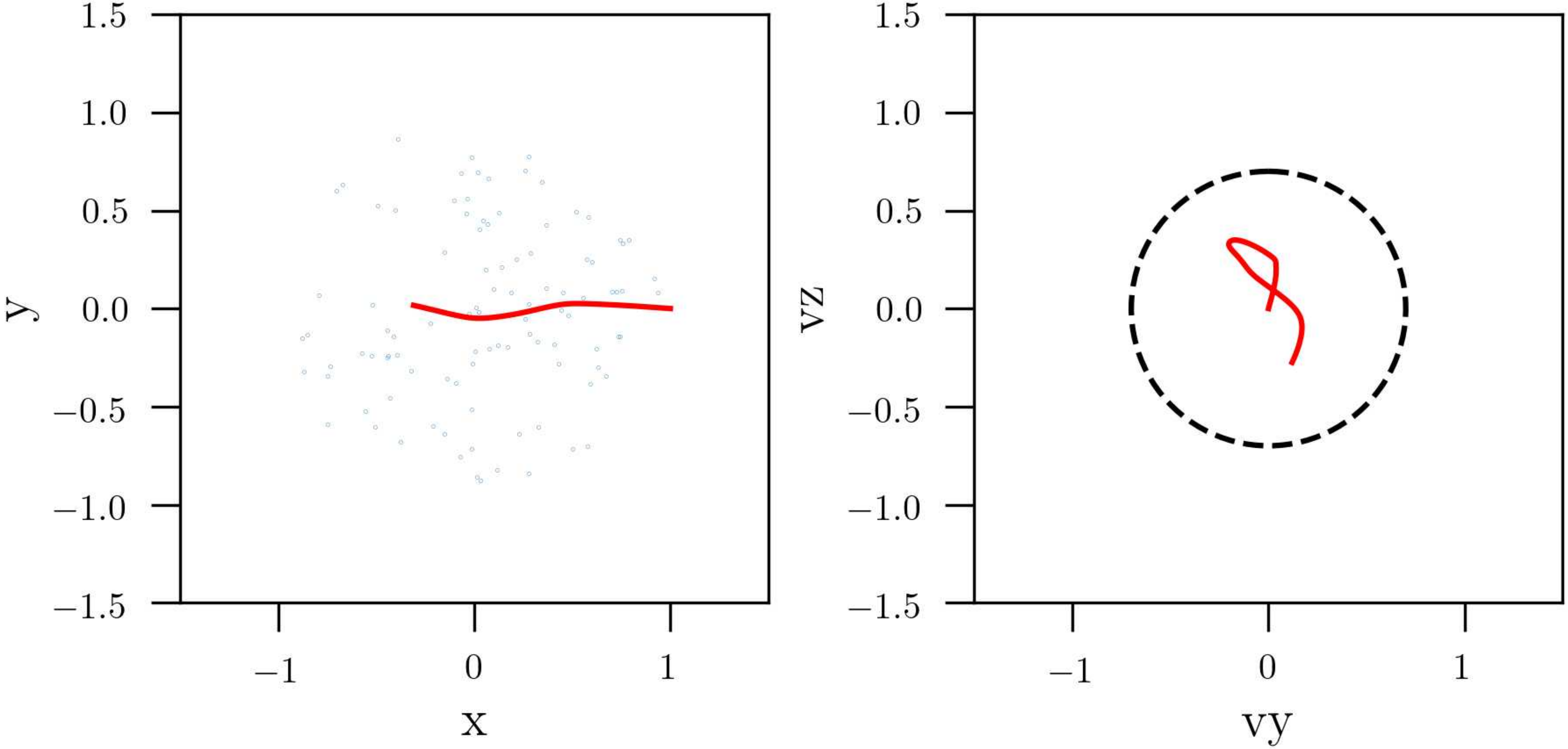
	N	R	b_{90}	$\ln(R/b_{90})$	t_{relax}
Globular Cluster	10^5	10 pc	2×10^{-4} pc	~10	~1 Gyr
Dwarf Galaxy	10^6	1 kpc	2×10^{-3} pc	~13	~4 Gyr
Spiral Galaxy	10^{10}	15 kpc	3×10^{-6} pc	~20	$\gg t_{Hubble}$
Galaxy Cluster	10^{13}	1 Mpc	2×10^{-7} pc	~30	$\gg t_{Hubble}$

Numerical illustration

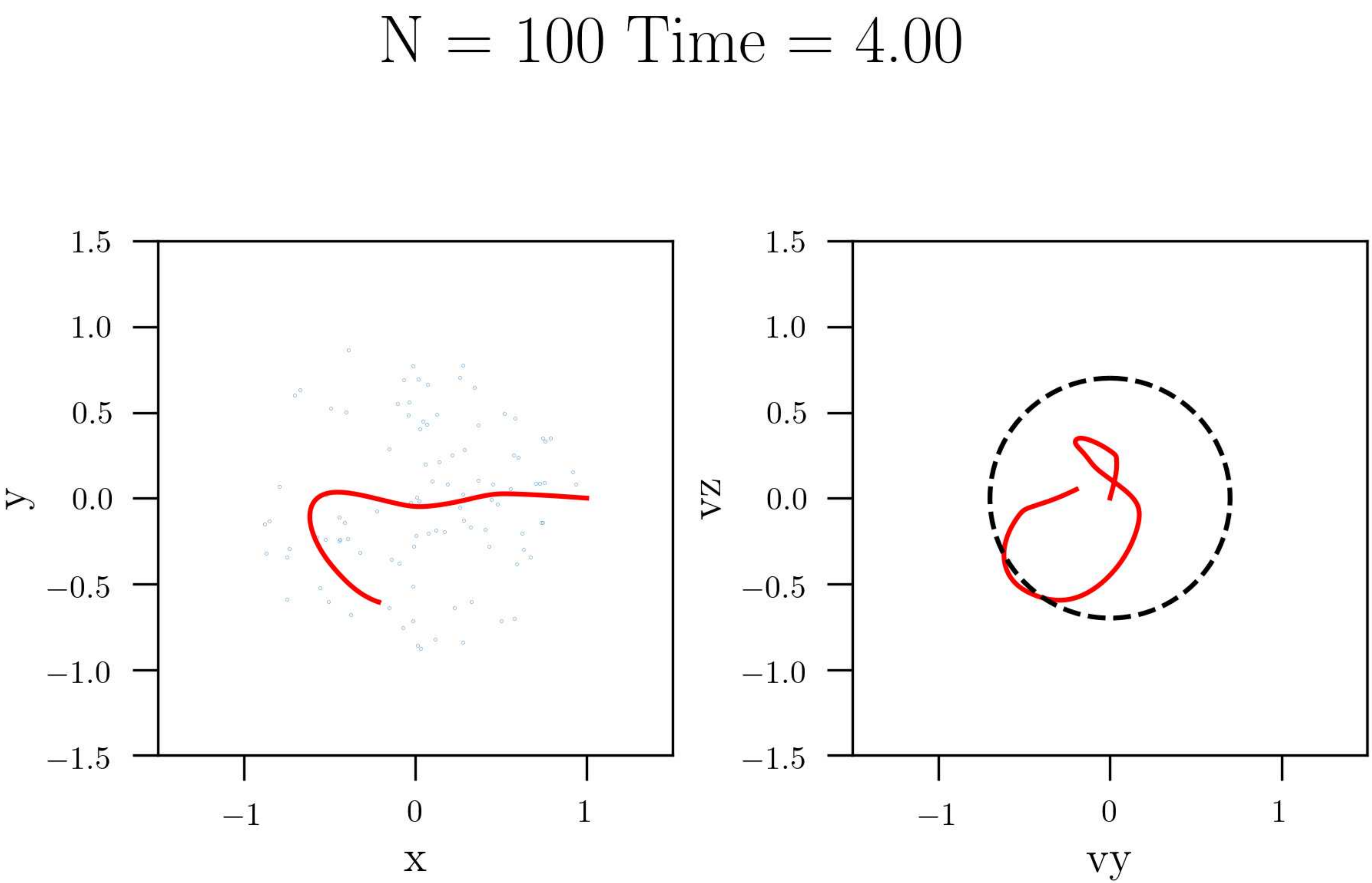
Orbit of a point mass in an homogeneous sphere sampled with a discrete number of stars.



$N = 100$ Time $= 2.00$



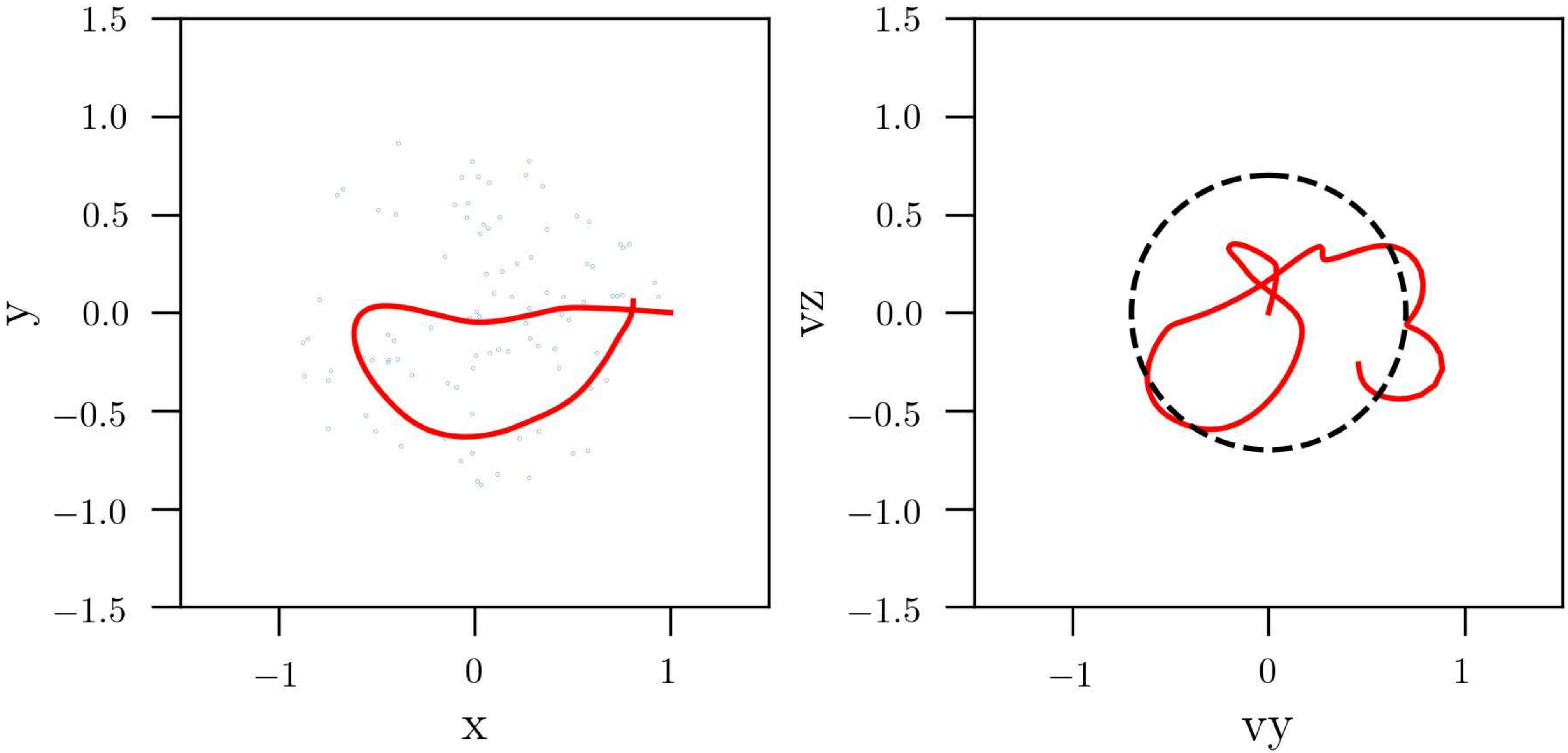
t_{relax}=3



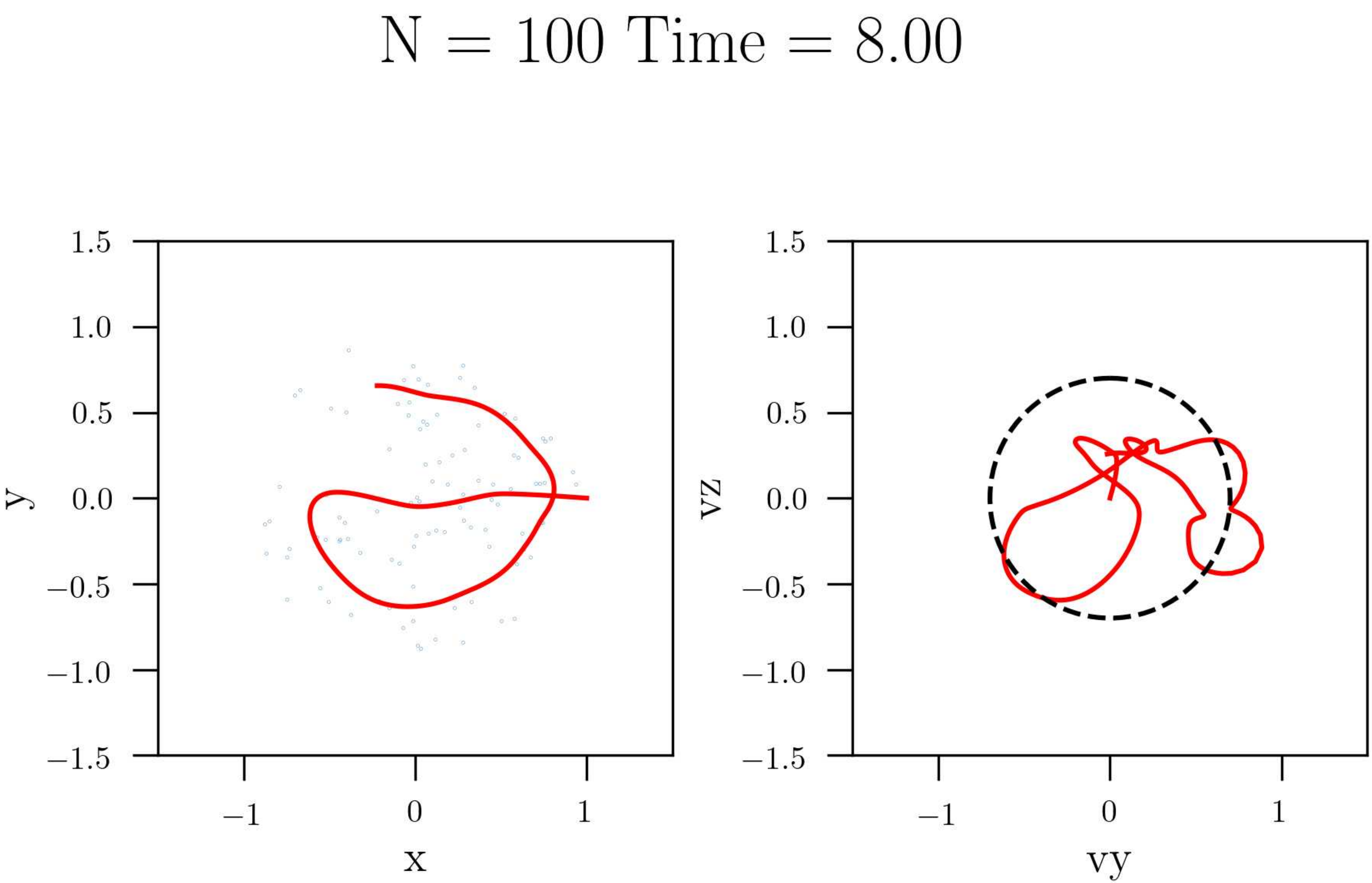
N = 100 Time = 4.00
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y
−1
0
1
x
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
vz
−1
0
1
vy

t_{relax}=3

N = 100 Time = 6.00

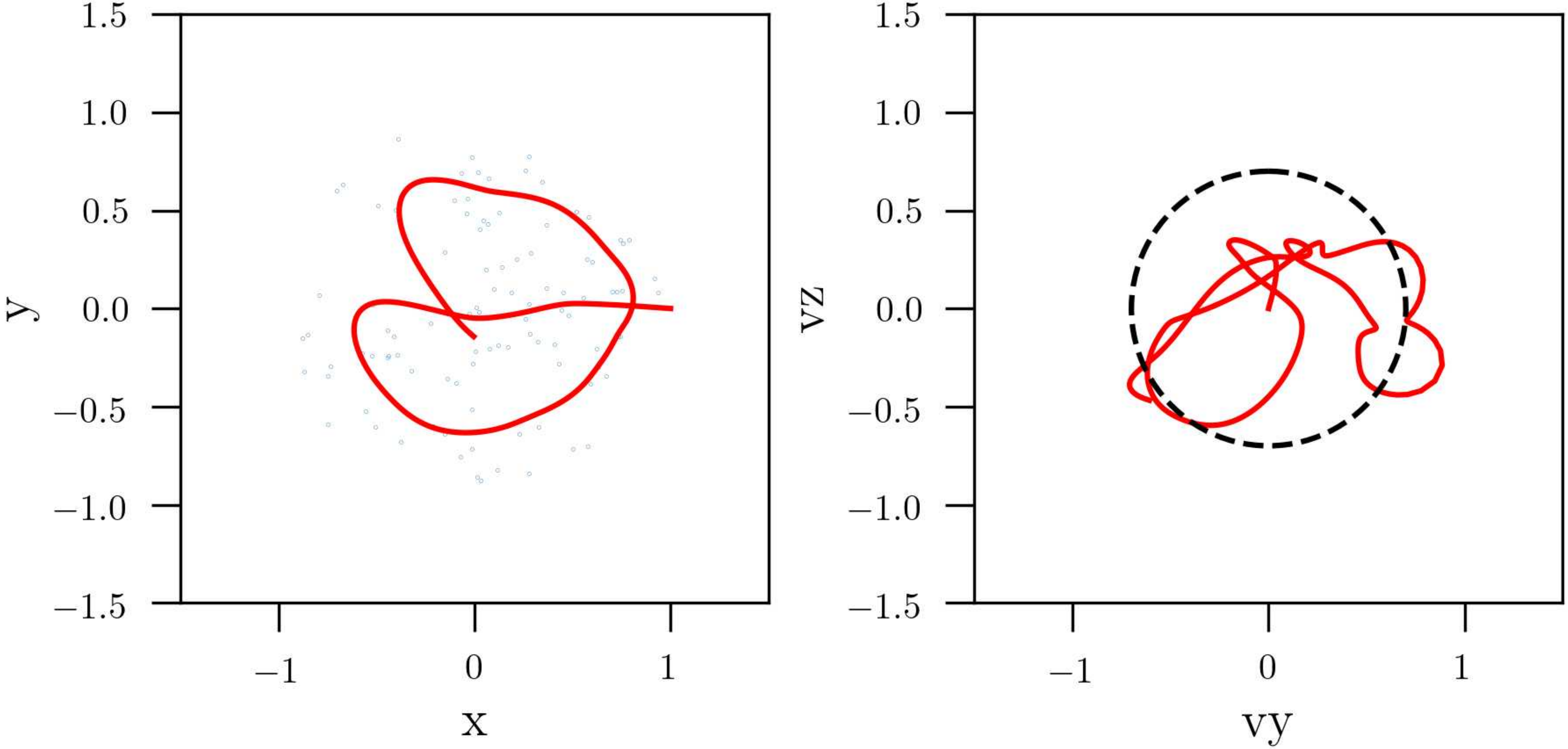


t_{relax}=3

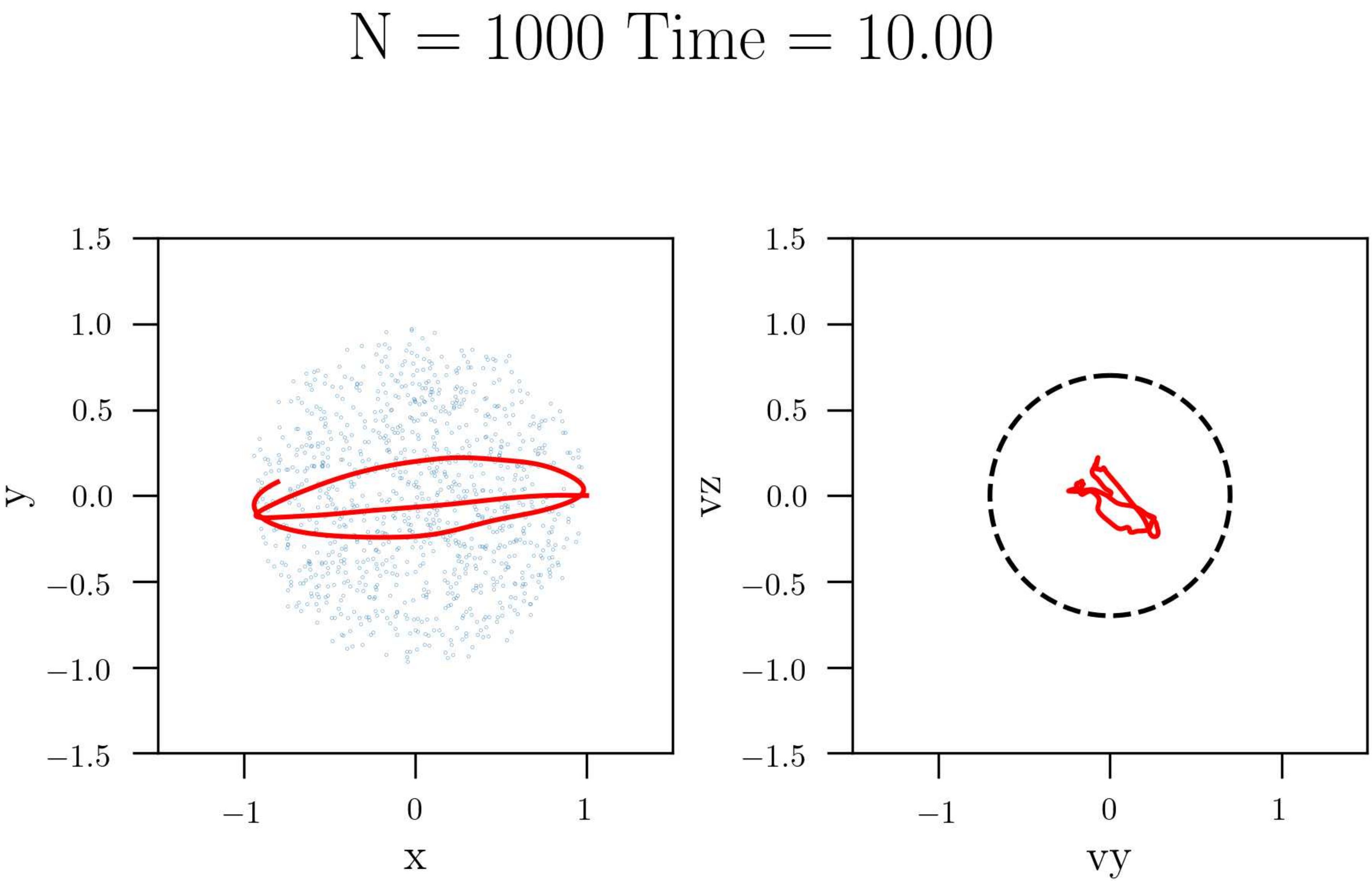


t_{relax}=3

$N = 100$ Time $= 10.00$

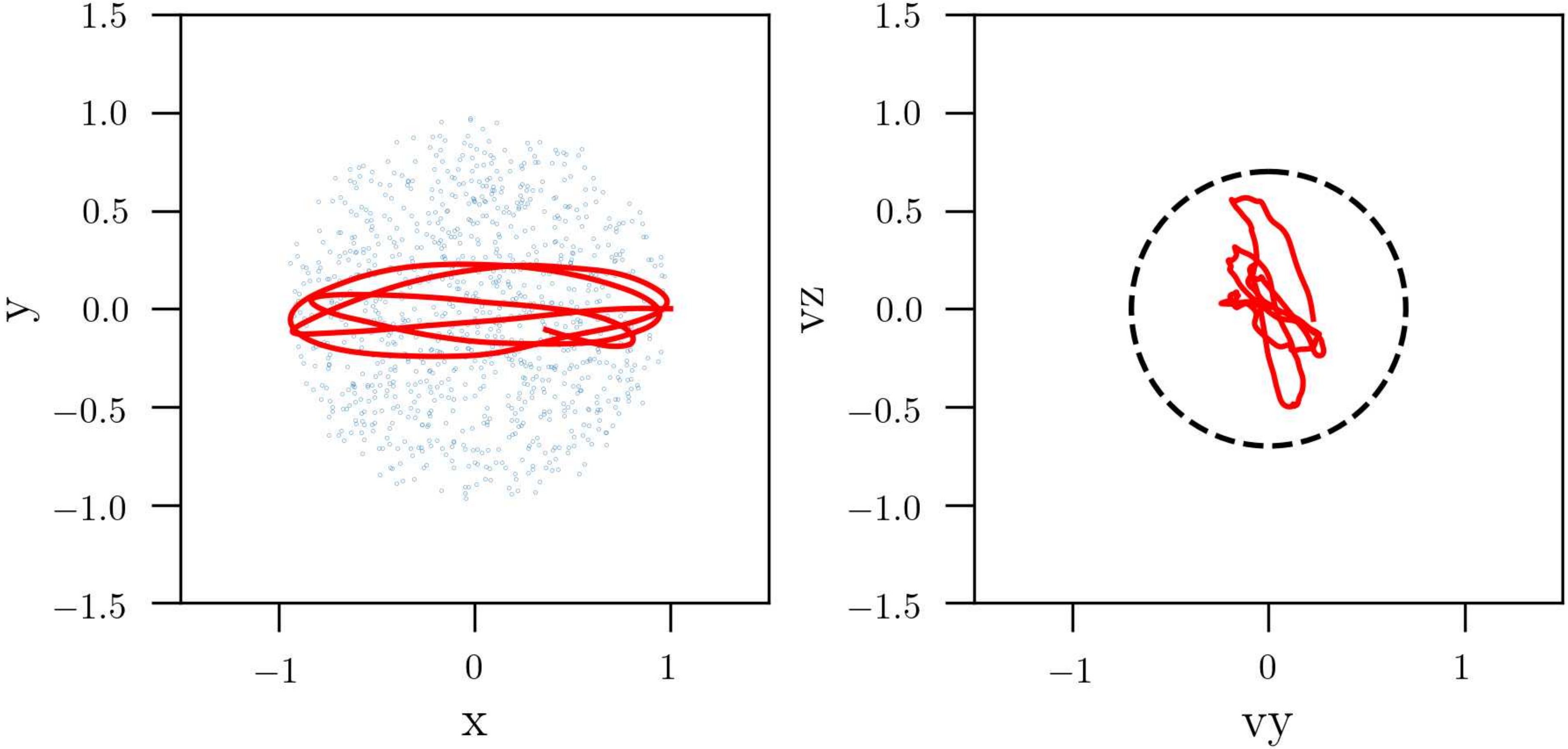


t_{relax}=3



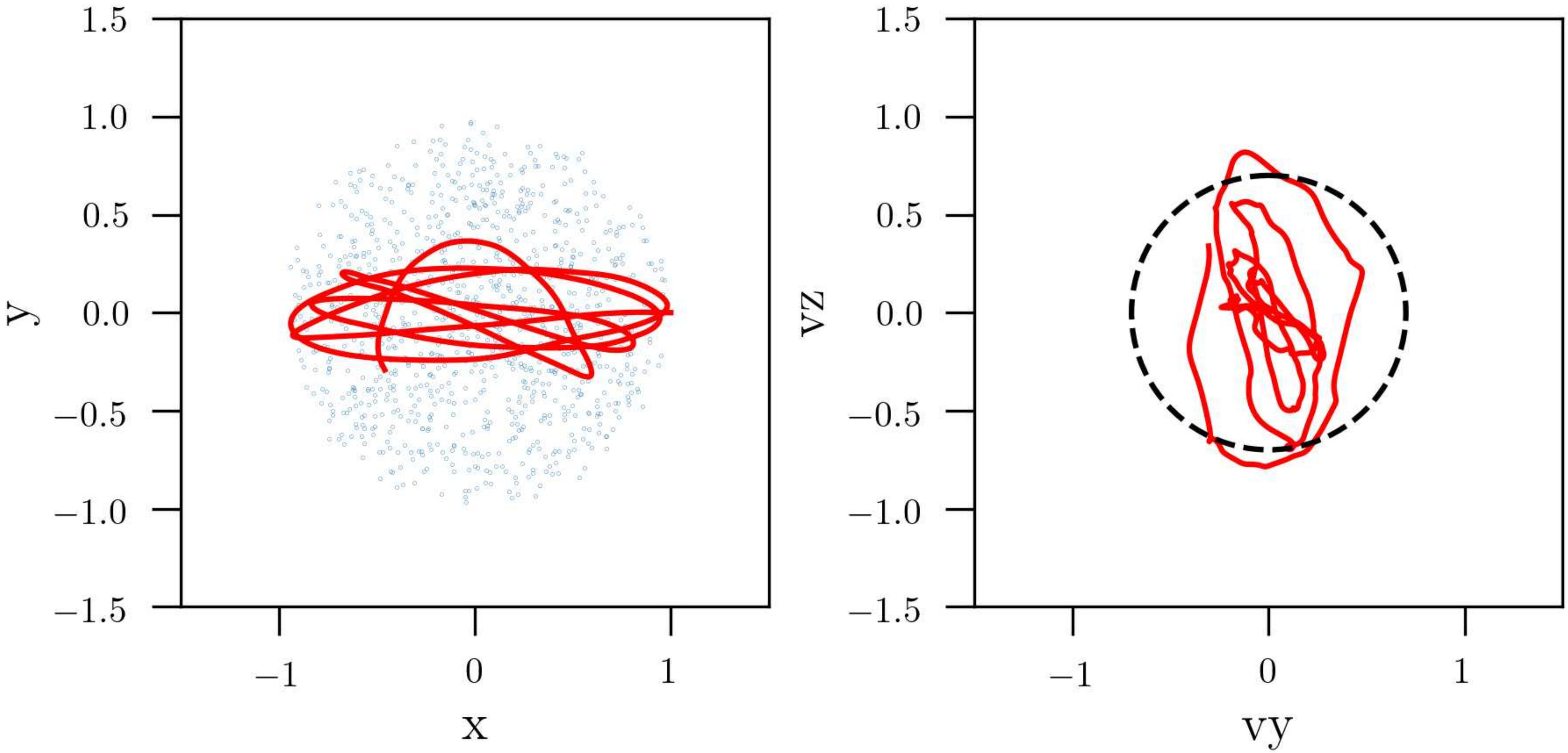
t_{relax}=20

$N = 1000$ Time $= 20.00$

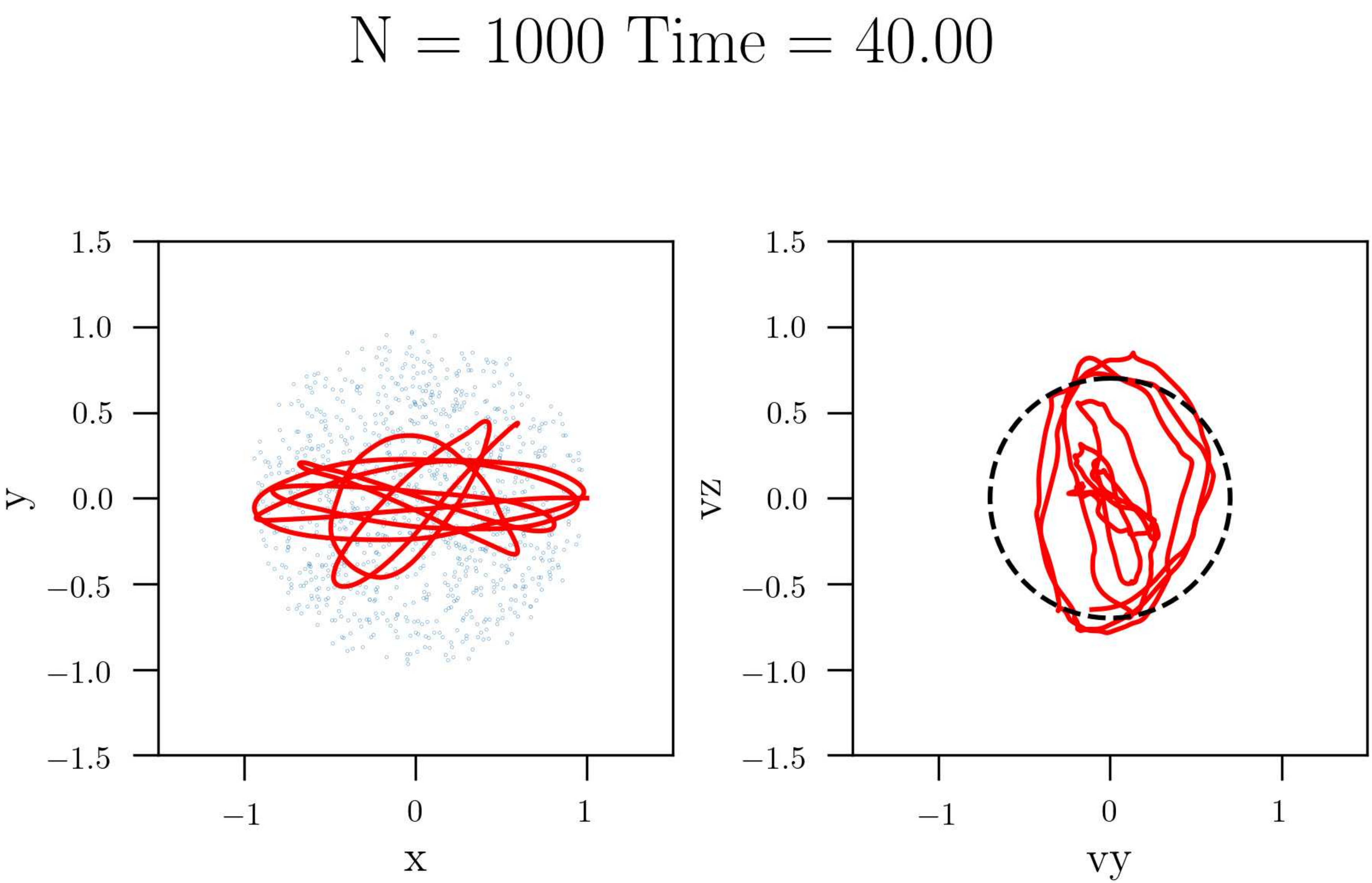


t_{relax}=20

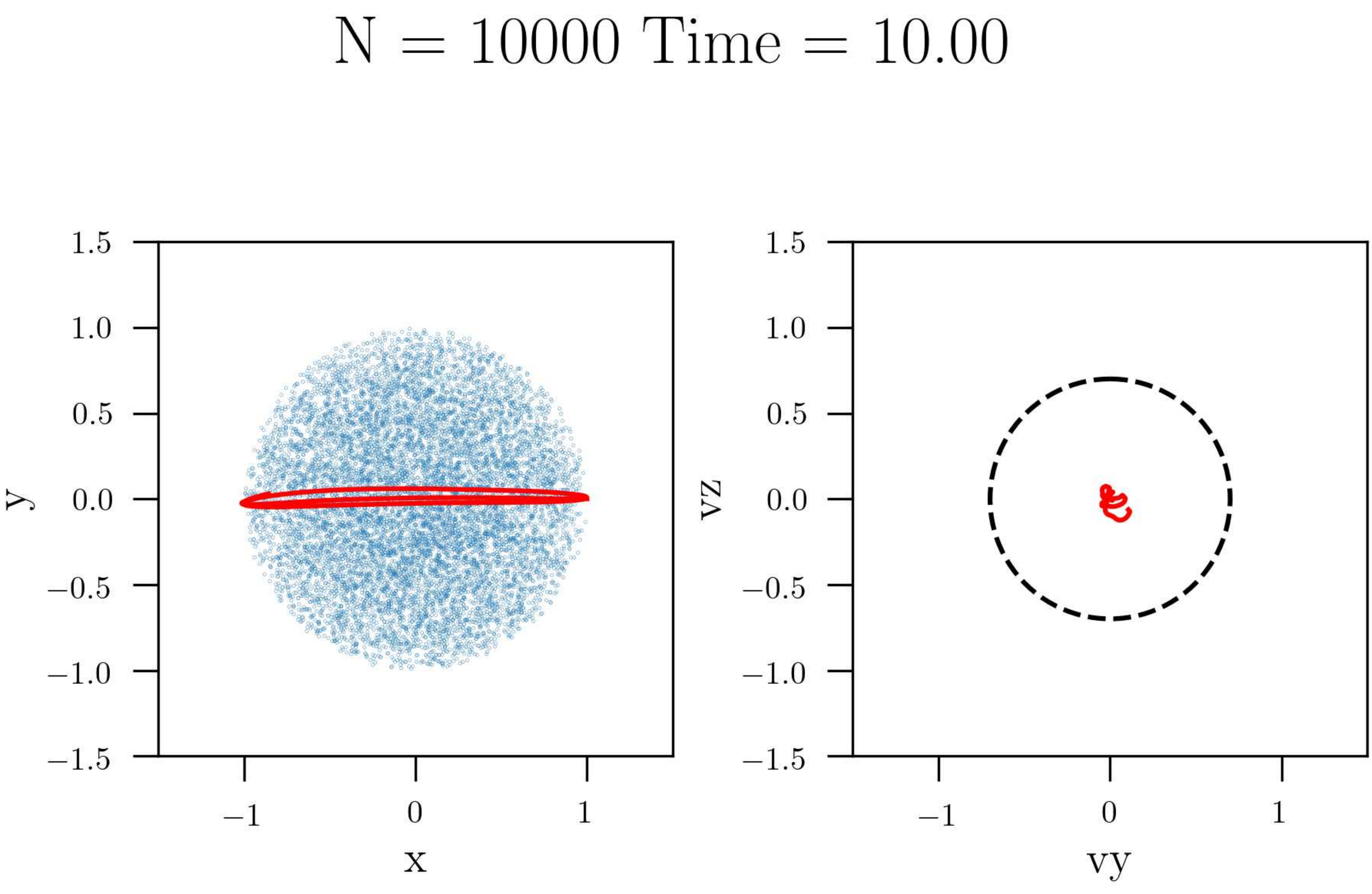
$N = 1000$ Time $= 30.00$



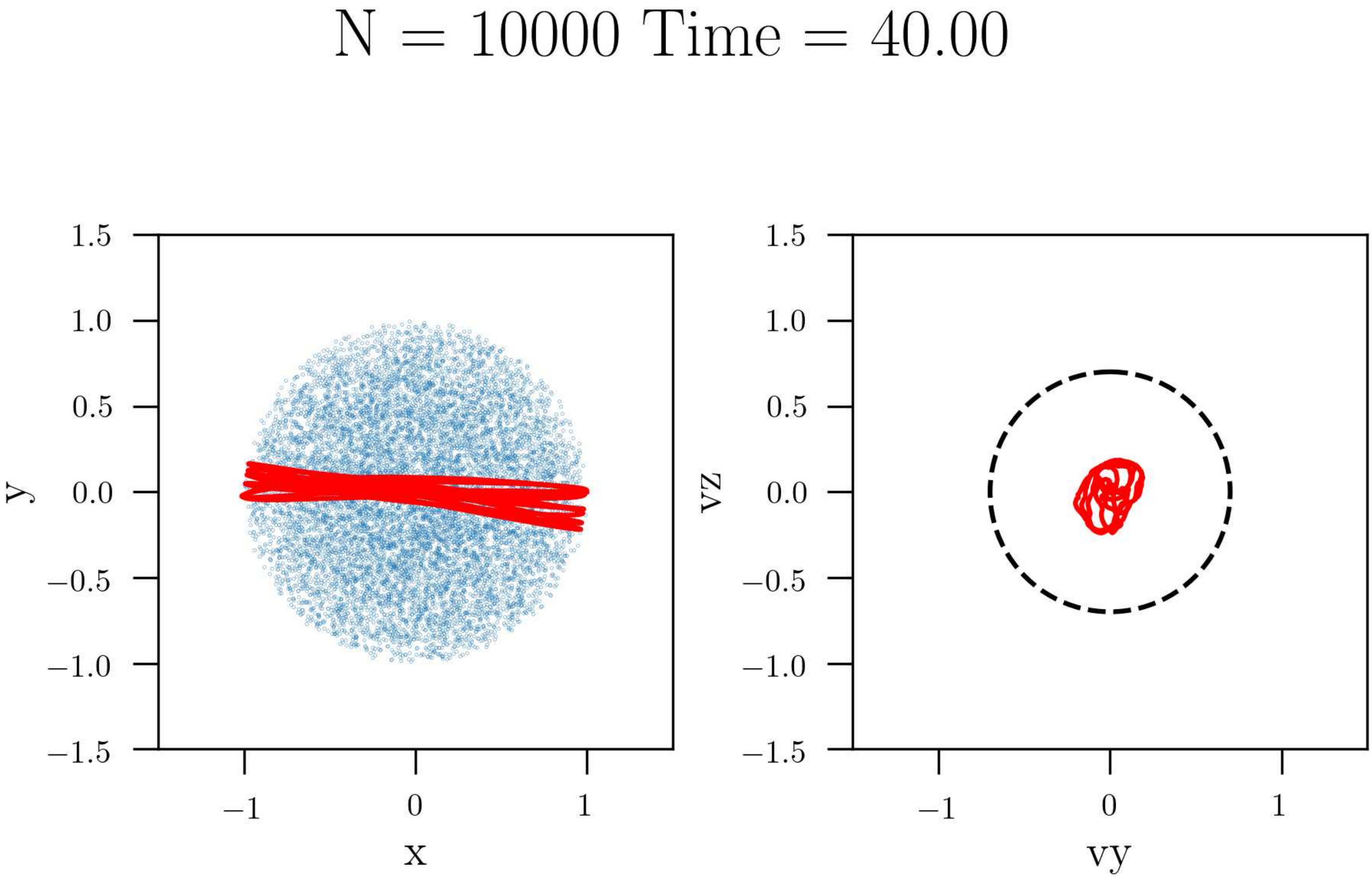
t_{relax}=20


N = 1000 Time = 40.00
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y
−1
0
1
x
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
vz
−1
0
1
vy

t_{relax}=20

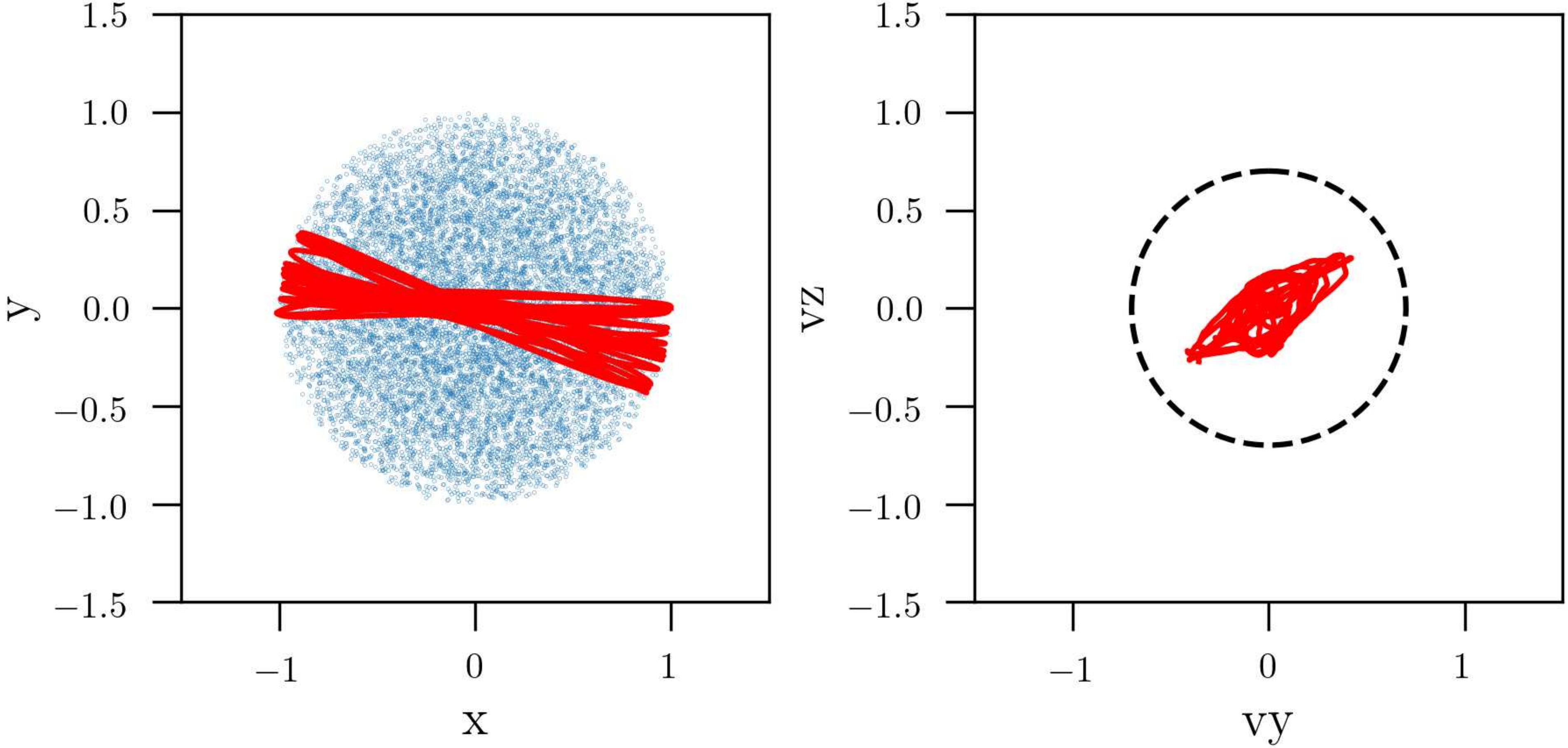

N = 10000 Time = 10.00
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y
−1
0
1
x
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
vz
−1
0
1
vy

t_{relax}=150

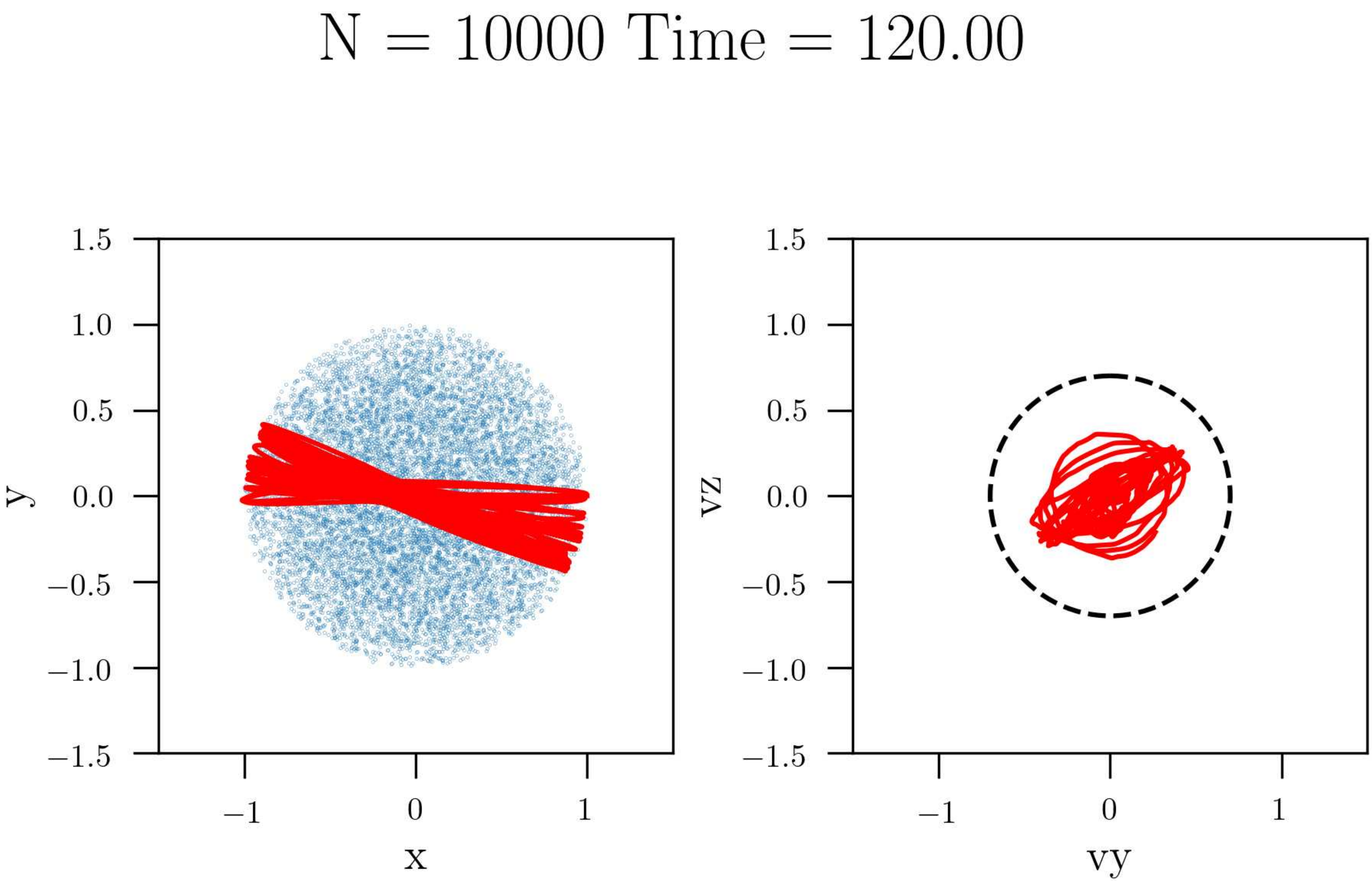


t_{relax}=150

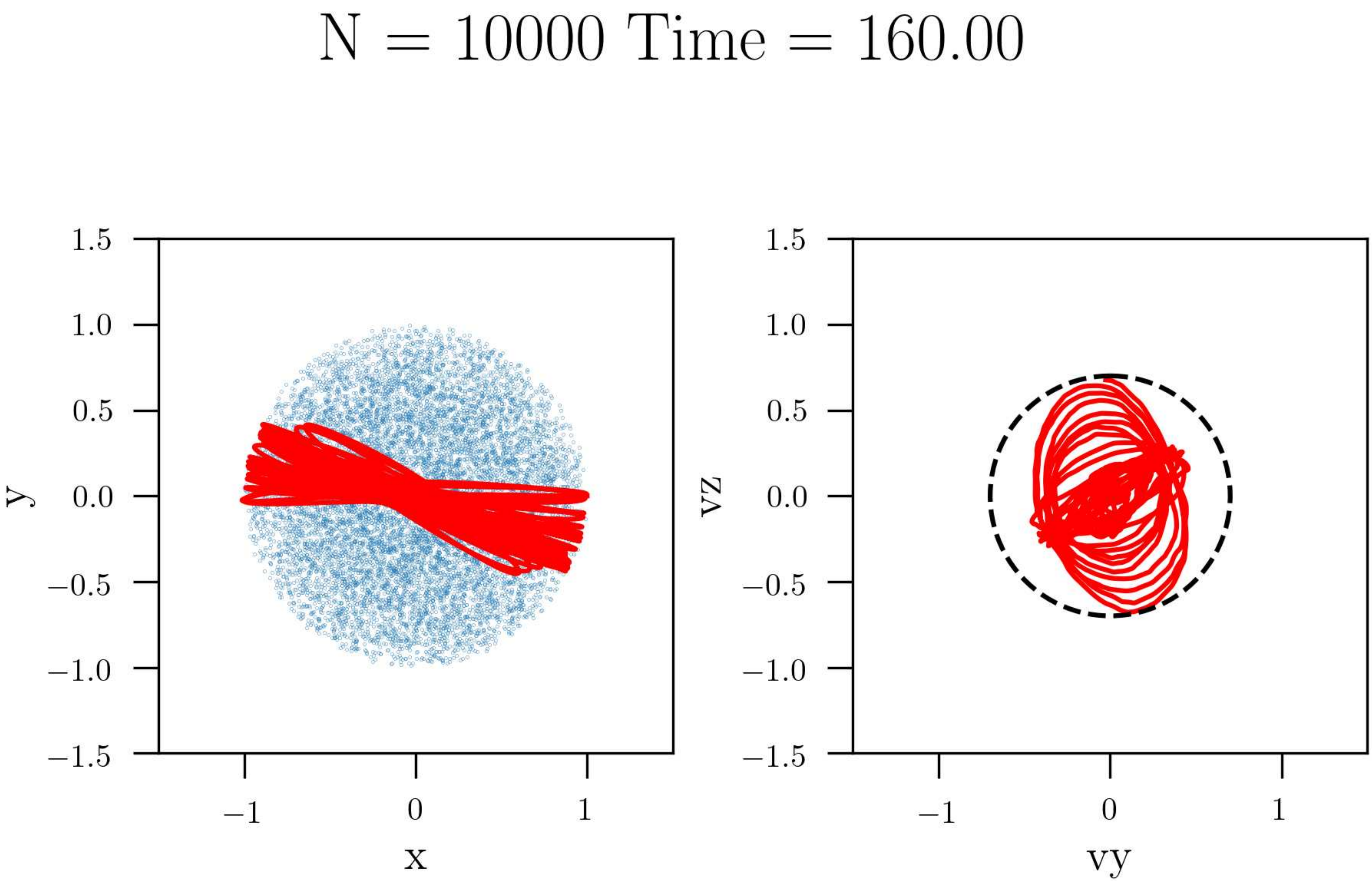
$N = 10000$ Time $= 80.00$



t_{relax}=150



t_{relax}=150



t_{relax}=150

The End