WELCOME !

Astrophysics IV :

Stellar & Galactic Dynamics

Spring 2024

Dr. Yves Revaz
Laboratoire d’astrophysique
Observatoire de Sauverny
CH – 1290 Versoix

EPFL

Mailing List

- Use Moodle : moodle.epfl.ch

Anyone missing ?

About me

- MER at the Laboratory of Astrophysics
- Native from le Valais
- Former EPFL student
- Thesis in galactic dynamics (Prof. Pfenniger)
- Postdoc in Geneva, Paris and EPFL

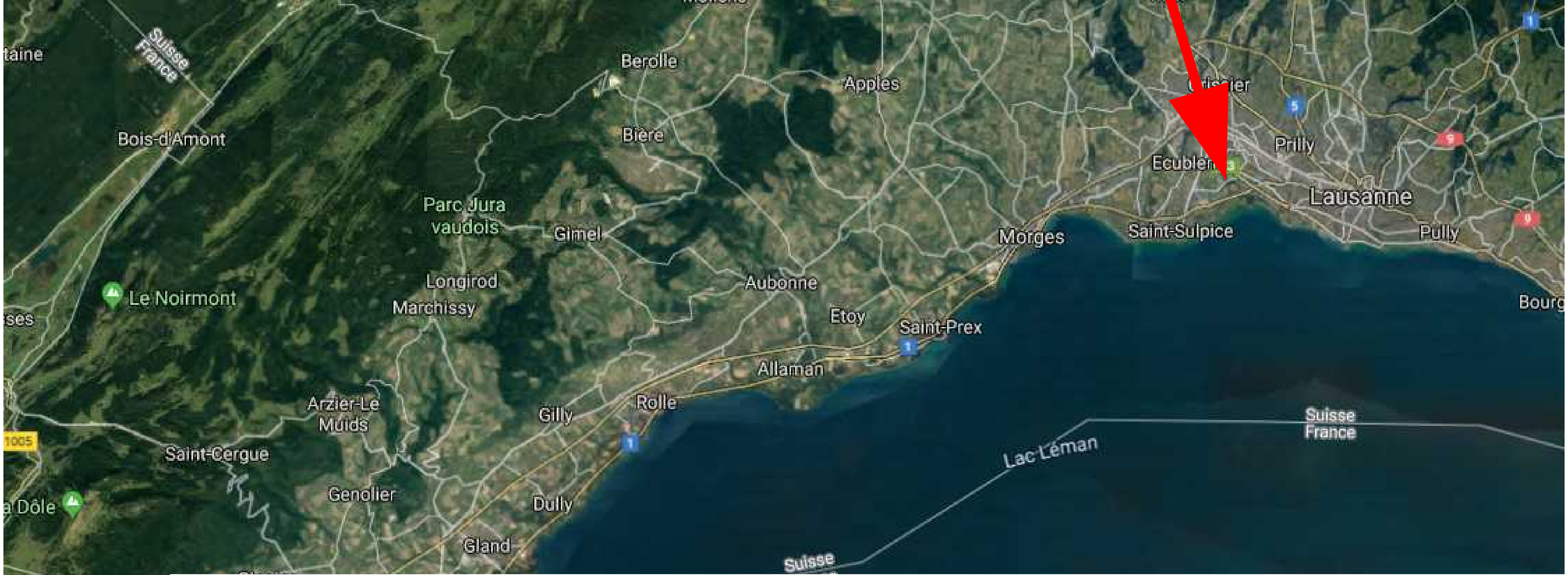
Research

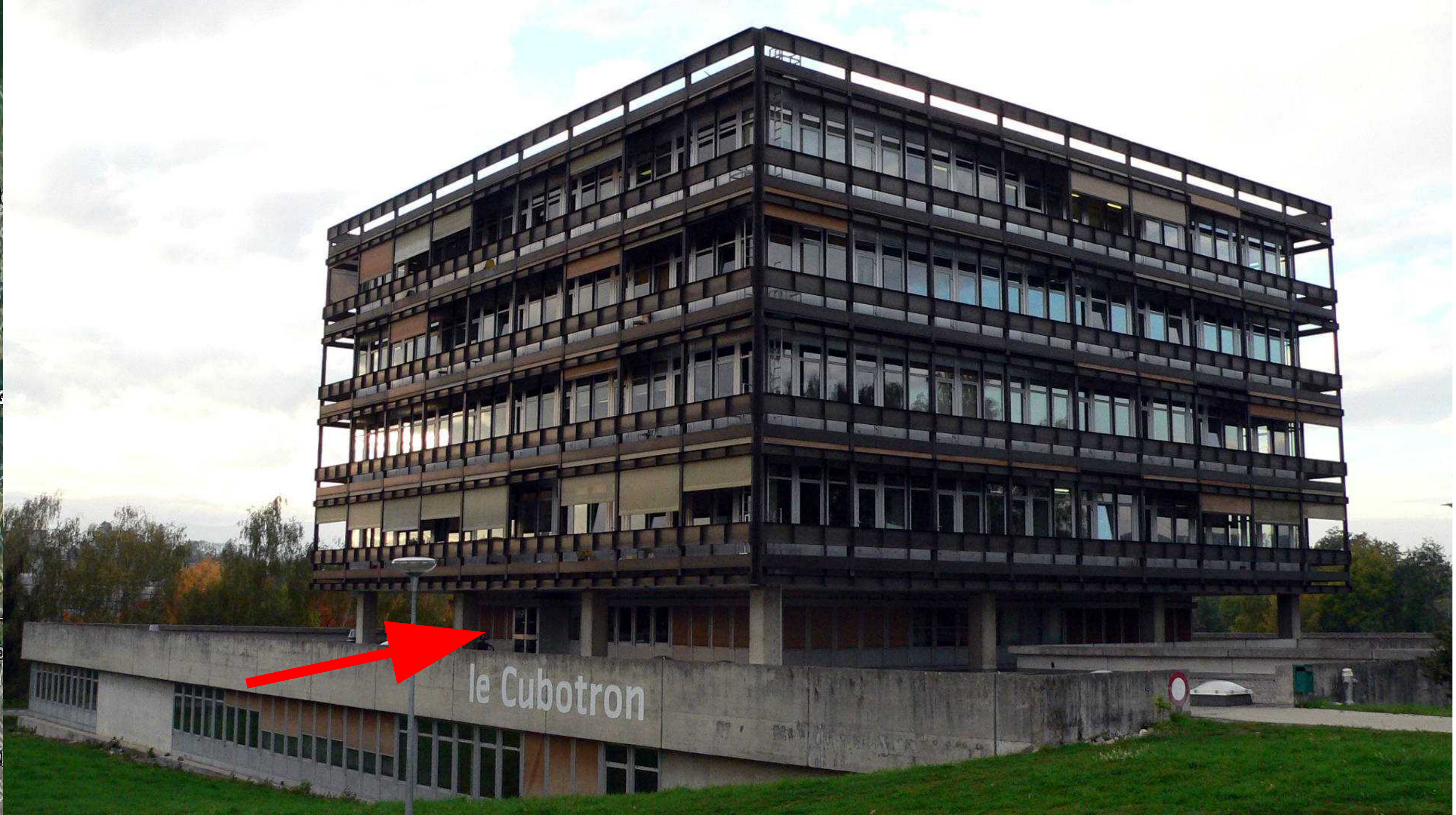
- Formation and evolution of galaxies
- Galactic dynamics, galaxy clusters, dwarf galaxies
- Development of numerical tools (Gear, pNbody, Swift)
- Core Team Member of the Arrakihs Space mission
- Virtual reality
  - VIRUP: The Virtual Reality Universe Project
  - https://go.epfl.ch/virup

Contacts

- Email : yves.revaz@epfl.ch
- Cubotron (BSP) 323
- Observatoire de Sauverny, 351


taine
Suisse
France
Berolle
Apples
Crissier
Bois-d'Amont
Bière
Prilly
Ecublens
Lausanne
Parc Jura vaudois
Gimel
Saint-Sulpice
Morges
Pully
Longirod
Marchissy
Le Noirmont
Aubonne
ses
Etoy
Saint-Prex
Bourg
Allaman
Arzier-Le Muids
Rolle
Gilly
Suisse
France
Saint-Cergue
Lac Léman
1005
Genolier
a Dôle
Dully
Gland
Suisse
France
Gingins
Mei
Évian-les-Bains
Lugrin
D1005
Grens
Prangins
Publier
Thollon-les-Mé
Nyon
Saint-Paul-en-Chablais
E62
Thonon-les-Bains
Yvoire
Champanges
D1005
Bernex
Divonne-les-Bains
Excenevex
Anthy-sur-Léman
Suisse
France
D902
Margencel
Sciez
Chens-sur-Léman
D1005
La Forclaz
Vacheresse
ssy
Coppet
Orcier
VAUD
GENÈVE
Douvaine
Perrignier
Bonnevaux
Loisin
D1005
D1005
Lullin
D902
La Baume
Abo
Veigy-Foncenex
Brenthonne
Bons-en-Chablais
Corsier
Le Biot
Ferney-Voltaire
Bellevaux
Collonge-Bellerive
Machilly
Habère-Poche
Seytroux
Pregny-Chambésy
D1206
Saint-Cergues
Habère-Lullin
Saint-Jean-d'Aulps
Le Grand-Saconnex
E62
Villard
D902
Boëge
Genève
Ville-la-Grand
Montriond
Annemasse
D903
Bogève


taine
Suisse
France
Berolle
Apples
Crissier
Bois-d'Amont
Bière
Prilly
Ecublens
Lausanne
Parc Jura
vaudois
Gimel
Morges
Saint-Sulpice
Pully
Longirod
Marchissy
Aubonne
Le Noirmont
ses
Etoy
Saint-Prex
Bourg
Allaman
Arzier-Le
Muids
Rolle
Gilly
1005
Saint-Cergue
Suisse
France
Lac Léman
a Dôle
Genolier
Dully
Gland
Suisse
Divonne-l
ssy
D1005
Ferney-Voltaire
Pregny-
Le Grand-Sac
E62
Ge


le Cubotron


Suisse
France
Berolle
Apples
Crissier
Bois-d'Amont
Bière
Prilly
Ecublens
Lausanne
Parc Jura vaudois
Gimel
Saint-Sulpice
Pully
Morges
Le Noirmont
Longirod
Marchissy
Aubonne
Etoy
Saint-Prex
Allaman
Arzier-Le Muids
Rolle
Gilly
Saint-Cergue
Suisse
France
Lac Léman
Genolier
Dully
Gland
Suisse
France
Gingins
Évian-les-Bains
Lugrin
Grens
Prangins
Publier
Nyon
Saint-Paul-en-Chablais
Thonon-les-Bains
Champanges
Yvoire
Bernex
Excenevex
Anthy-sur-Léman
Suisse
France
Margencel
Sciez
Chens-sur-Léman
La Forclaz
Vacheresse
Coppet
Orcier
VAUD
GENÈVE
Douvaine
Perrignier
Bonnevaux
Loisin
Lullin
La Baume
Veigy-Foncenex
Brenthonne
Corsier
Bons-en-Chablais
Le Biot
Ferney-Voltaire
Bellevaux
Collonge-Bellerive
Machilly
Habère-Poche
Seytroux
Pregny-Chambésy
Saint-Cergues
Habère-Lullin
Saint-Jean-d'Aulps
Le Grand-Saconnex
Villard
Boëge
Genève
Ville-la-Grand
Annemasse
Bogève
Montriond
D1005
D902
D1206
D903
E62
1
5
9


Suisse
France
Bois-d'Amont
Berolle
Apples
Crissier
Prilly
Ecublens
Lausanne
Pully
Bière
Parc Jura vaudois
Gimel
Morges
Saint-Sulpice
Le Noirmont
Longirod
Marchissy
Aubonne
Etoy
Saint-Prex
Allaman
Rolle
Bourg
Saint-Cergue
La Dôle
Gingins
Grens
Divonne-les-Bains
VAUD
GENÈVE
Loisin
Bonnevaux
Lullin
La Baume
Veigy-Foncenex
Brenthonne
Bons-en-Chablais
Le Biot
Corsier
Bellevaux
Ferney-Voltaire
Collonge-Bellerive
Machilly
Habère-Poche
Seytroux
Pregny-Chambésy
Saint-Cergues
Habère-Lullin
Saint-Jean-d'Aulps
Le Grand-Saconnex
Villard
Boëge
Genève
Ville-la-Grand
Annemasse
Bogève
Montriond
D1005
D1206
D902
D903
E62

Astrophysics @ EPFL Teaching

- **Astro I:** Introduction à l'astrophysique (Bachelor)
  - ~~Frédéric Courbin~~
- **Astro II:** Bases physiques de l'astrophysique (Master)
  - Pascale Jablonka
- **Astro III:** Galaxy Formation and Evolution
  - Michaela Hirschmann
- **Astro IV:** Stellar and Galactic Dynamics (Master)
  - Yves Revaz
- **Astro V:** Observational Cosmology (Master)
  - Jean-Paul Kneib
- The Variable Universe (EDPY)
  - Richard Anderson
- **MOOC:**
  - The radio-sky I : Science and Observations
    Frédéric Courbin, Jean-Paul Kneib
  - Introduction à l'astrophysique
    Frédéric Courbin

Astrophysics @ EPFL
Teaching

- **Astro I:** Introduction à l'astrophysique (Bachelor)
    - ~~Frédéric Courbin~~
- **Astro II:** Bases physiques de l'astrophysique (Master)
    - Pascale Jablonka
- **Astro III:** Galaxy Formation and Evolution
    - Michaela Hirschmann
- **Astro IV:** Stellar and Galactic Dynamics (Master)
    - Yves Revaz
- **Astro V:** Observational Cosmology (Master)
    - Jean-Paul Kneib
- The Variable Universe (EDPY)
    - Richard Anderson
- **MOOC:**
    - The radio-sky I : Science and Observations
      Frédéric Courbin, Jean-Paul Kneib
    - Introduction à l'astrophysique
      Frédéric Courbin

In addition:

- TP4a
- TP4b
- Specialisation semester
- Master's project

Astrophysics @ EPFL
Research

Research group leaders :

- Jean-Paul Kneib
- Michaela Hirschman
- Pascale Jabonka
- Yves Revaz
- Richard Anderson
- Jennifer Schober

Research fields:

Galaxy Formation & Evolution

Cosmological parameters

Astrophysical plasmas

Dark energy

Dark matter

Astrophysics @ EPFL
Research

Research group leaders :	Jean-Paul Kneib Michaela Hirschman Pascale Jabonka Yves Revaz Richard Anderson Jennifer Schober

Research Methods:

Observations

Machine learning

Numerical simulations

Introduction

Outlines of the 14th lectures

Introduction

Goal of the course

Teach you how a system (stellar or galactic) evolves under gravity forces that are generated by itself

$$\equiv$$

Evolution of a self-gravitating system

Introduction

Outlines

Week 1:

Introduction

- The standard model in cosmology
- Which physics
- Our galaxy the Milky Way
- Galaxies in general

Week 2:

The gravity : a long distance force

- collision-less systems : the relaxation time

Newton Mechanics (quick reminder)

The Potential Theory I

- General results
  - Newton law, gravitational field force and potential

Week 3:

The Potential Theory I

- Spherical systems
  - Newton's theorems
  - Circular speed, circular velocity, circular frequency, escape speed, potential energy
  - Useful relations for spherical systems

Week 4:

The Potential Theory II

- Examples of spherical models:
  - "Potential based" models
  - "Density based" models
- Axisymmetric models for disk galaxies
  - "Potential based" models
  - Potential of flattened systems
  - The potential of infinite thin (razor) disks (potential of a ring)
  - Potential of ellipsoidal systems
  - Potential of infinite thin disks and slabs

Week 5:

Stellar Orbits I

- Generalities : why studying stellar orbits ?

- Lagrangian and Hamiltonian mechanics (quick reminder)
  - Euler-Lagrange equations
  - Hamilton’s equations

- Orbits in spherical potentials
  - angular momentum conservation
  - equations of motion
  - radial orbits
  - non radial orbits

- Examples
  - Keplerian orbits
  - Orbits in an homogeneous sphere
  - Orbits in isochrone potentials

Week 6:

Stellar Orbits II

- Orbits in axisymmetric potentials
  - orbits in the equatorial plane
  - orbits outside the equatorial plane
  - equations of motion
  - orbits in the meridian plane
  - examples

Week 7:

Stellar Orbits III

- Nearly circular orbits
  - Epicycle frequences
  - The Oort constants
  - Probing the mass in the stellar disk

- Surface of section
  - Integral of motions
  - Poincaré maps

Week 8:

Stellar Orbits IV

- Orbits in planar non-axisymmetric potential
  - surface of sections

- Orbits in non-axisymmetric rotating potential
  - the Jacobi integral
  - Lagrange points
  - stability of orbits around Lagrange points
  - orbits not confined to Lagrange points

- Weak bars
  - the Lindblad resonances
  - orbit families in realistic bars

Week 9:

Equilibria of collisionless systems I

- The collisonless Boltzmann equation
  - The distribution function (DF) of stellar systems
  - The Collisionless Boltzmann equation
  - Limitations
- Relations between DFs and observables
  - Density, velocity distribution function, mean velocity, velocity dispersion
- The Jeans theorems
  - Solutions of the Collisionless Boltzmann equation
  - Symmetry and integrals of motion

Week 10:

Equilibria of collisionless systems II

- Self-consitent spherical models with Ergodic DF
  - DFs from mass distribution
    - The Eddington formula
    - Examples
  - Models defined from DFs
    - Polytropes and Plummer models
    - Parallel with hydrostatics polytropes
    - Isothermal models
    - Parallel with hydrostatics isothermal models

Week 11:

Equilibria of collisionless systems III

- Anisotropic distribution function in spherical systems
  - Motivations
  - General concepts
  - Example of an anisotropic DF
  - Application to the Hernquist model

- The Jeans Equations (moments equation)
  - Motivations
  - The Jeans Equations and conservation laws
  - The Jeans Equations in Spherical and Cylindrical coordinates

Week 12:

Equilibria of collisionless systems IV

- The Virial Equation and Virial Theorem
  - Theory
  - Applications

Stability of collisionless systems I

- Nbody- experiments
  - Are systems defined from a DF that solve the CB stable ?

Week 13:

Stability of collisionless systems II

- Linear response theory
  - in fluid systems
  - in stellar systems

- The Jeans instability
- The stability of uniformly rotating systems

Week 14:

Stability of collisionless systems III

- The stability of rotating disks : spiral stuctures
  - Spirals properties
  - The dispersion relation for a razor thin fluid disk
  - The WKB approximation

- The origin of spiral structures: another view

- Vertical instabilities
  - Nature is always more tricky...

Polycop... ? No.

- PDF manuscript notes ?
  - yes, on moodle.epfl.ch

- Recordings ?
  - No (except when I will be absent...)

- Additional material ?
  - yes, on moodle.epfl.ch

Is it a difficult course ?

- Theoretical lecture (a lots of equations)

<u>Physics</u>:

- Newtonwian gravity 👍
- Lagrangian/Hamiltonian formalism
- Distribution function
- A lots of paralell between different fields in physics:

  e.g. thermodynamics/statistical physics, hydrodynamics

<u>Mathematics</u>:

- Differencial equations, Fourrier transform, Abel integral, Eliptical coordinates

Exam

- **Oral Exam:**
  - Classical form : general questions on the lectures

Bibliography

- James Binney & Scott Tremaine
  - Galactic Dynamics, 2nd edition, Princeton Series in Astrophysics, Princeton University Press, 2008
- Landau & Lifshitz
  - Mechanics, 3nd edition Volume 1, Butterworth Heinemann, 1976
- Landau & Lifshitz
  - Fluid Mechanics, 2nd edition Volume 6, Butterworth Heinemann, 1987
- Landau & Lifshitz
  - Statistical Physics, 3rd edition Part 1, Volume 5, Butterworth Heinemann, 1980
- N. Deruelle & J.-P. Uzan
  - Théories de la Relativité, Belin, 2015
- S. Chandrasekhar
  - An Introduction to the Study of Stellar Structure, Dover Publications, 1939
- S. Chandrasekhar
  - Principles of Stellar Dynamics, Dover Publications, 1942
- K. F. Ogorodnikov
  - Dynamics of Stellar Systems, Pergamon Press, 1965
- D. Mihalas, B. Weibel Mihalas
  - Fundation of Radiation Hydrodynamics, Oxford University Press, 1984
- J. Binney, J. Kormendy & S.D.M. White
  - Morphology and Dynamics of Galaxies, Saas-Fee Advanced Course #3

Acknowledgements

- Daniel Pfenniger
- Pierre North
- George Meylan
- Jean-Paul Kneib

Introduction

The standard model in cosmology, a quick overview

The standard model in cosmology

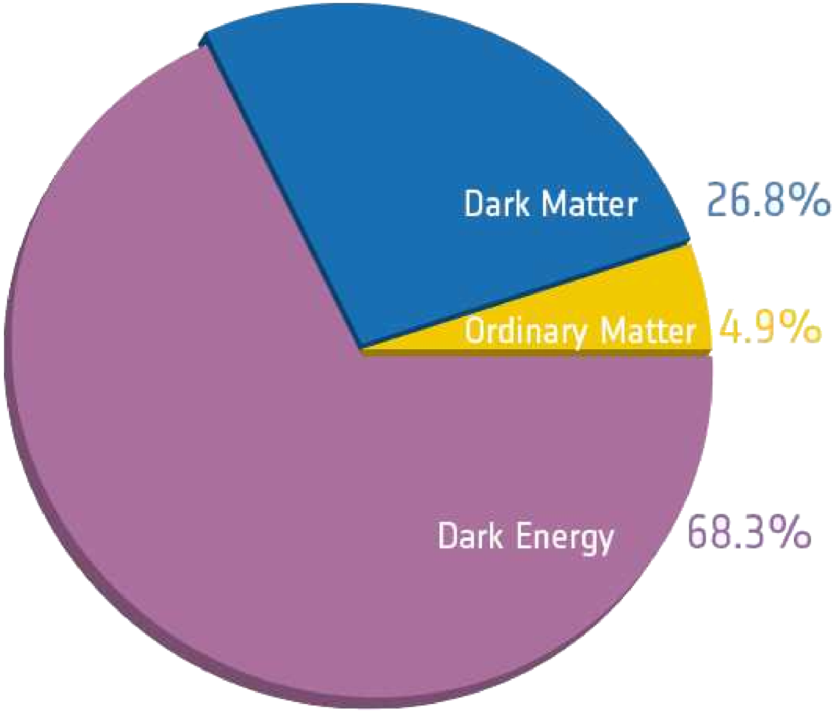
The cosmological principle:

The spatial distribution of matter in the universe is homogeneous and isotropic when viewed on a large enough scale.

The standard model in cosmology

ΛCDM model

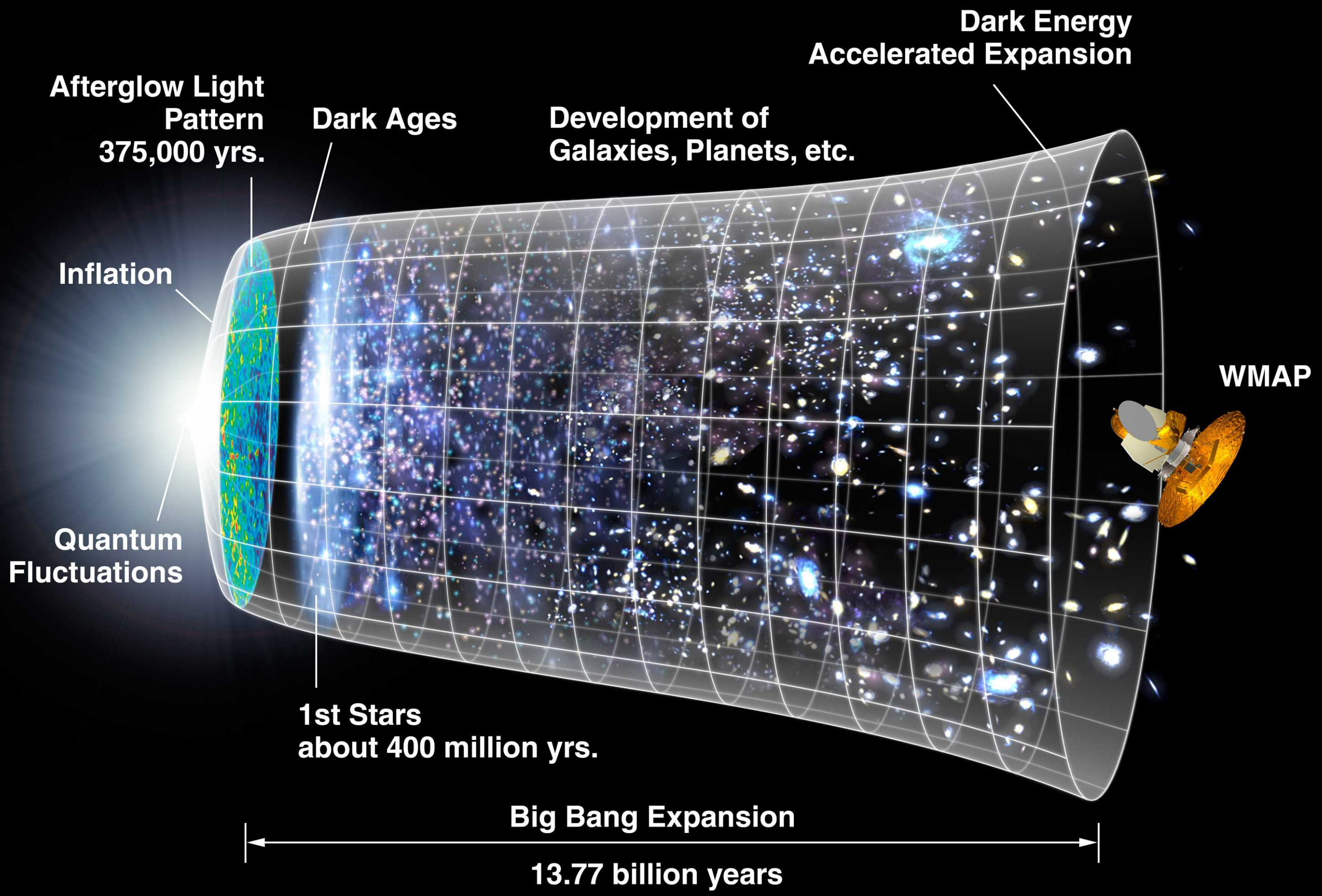
$$\Omega_M + \Omega_K + \Omega_\Lambda = 1$$



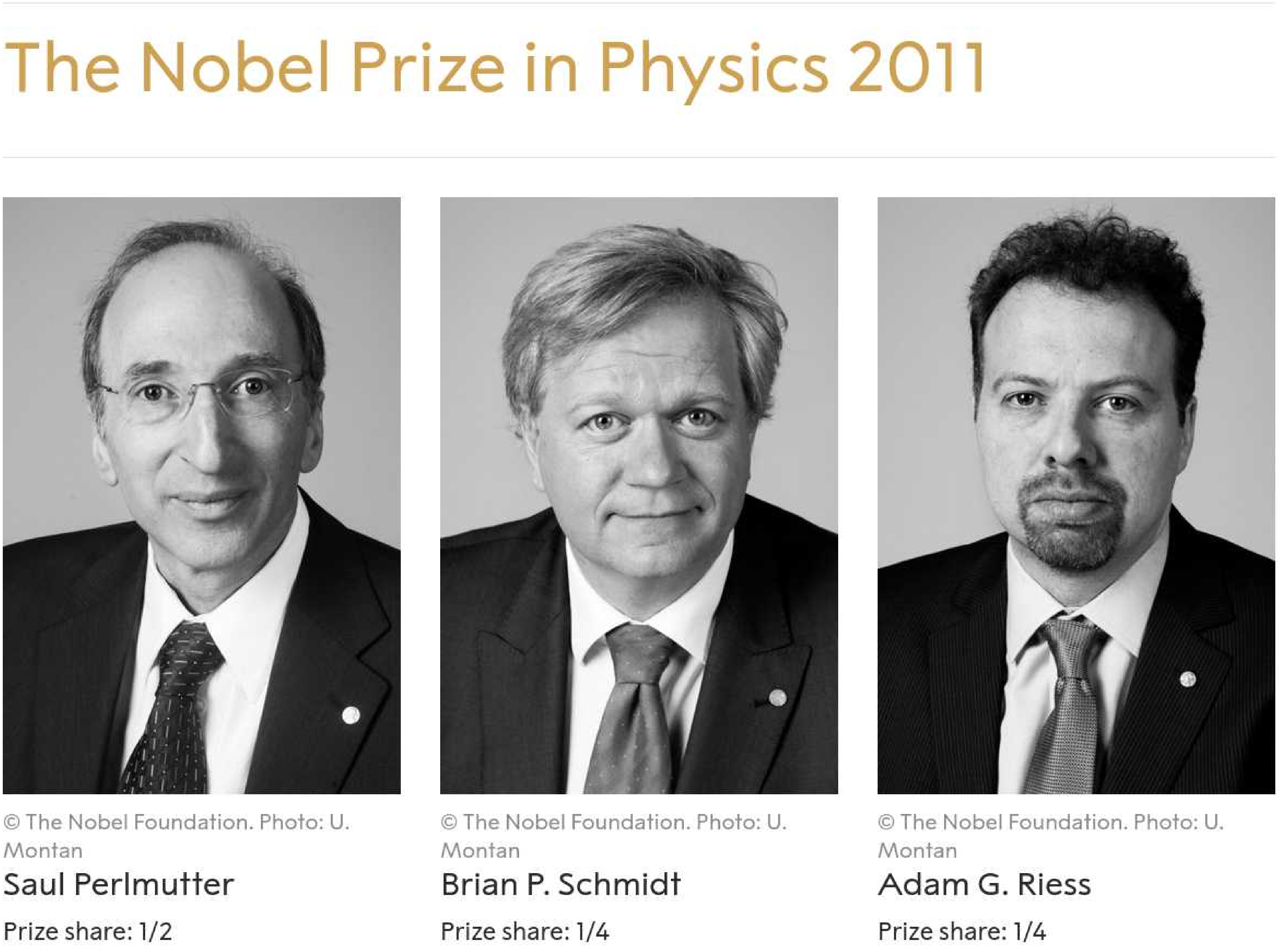
(baryons)

Credit : the Planck collaboration

$$a(t)=a(t,\Omega_M,\Omega_K,\Omega_\Lambda)$$



NASA/WMAP Science Team



The Nobel Prize in Physics 2011

© The Nobel Foundation. Photo: U. Montan

Saul Perlmutter

Prize share: 1/2

© The Nobel Foundation. Photo: U. Montan

Brian P. Schmidt

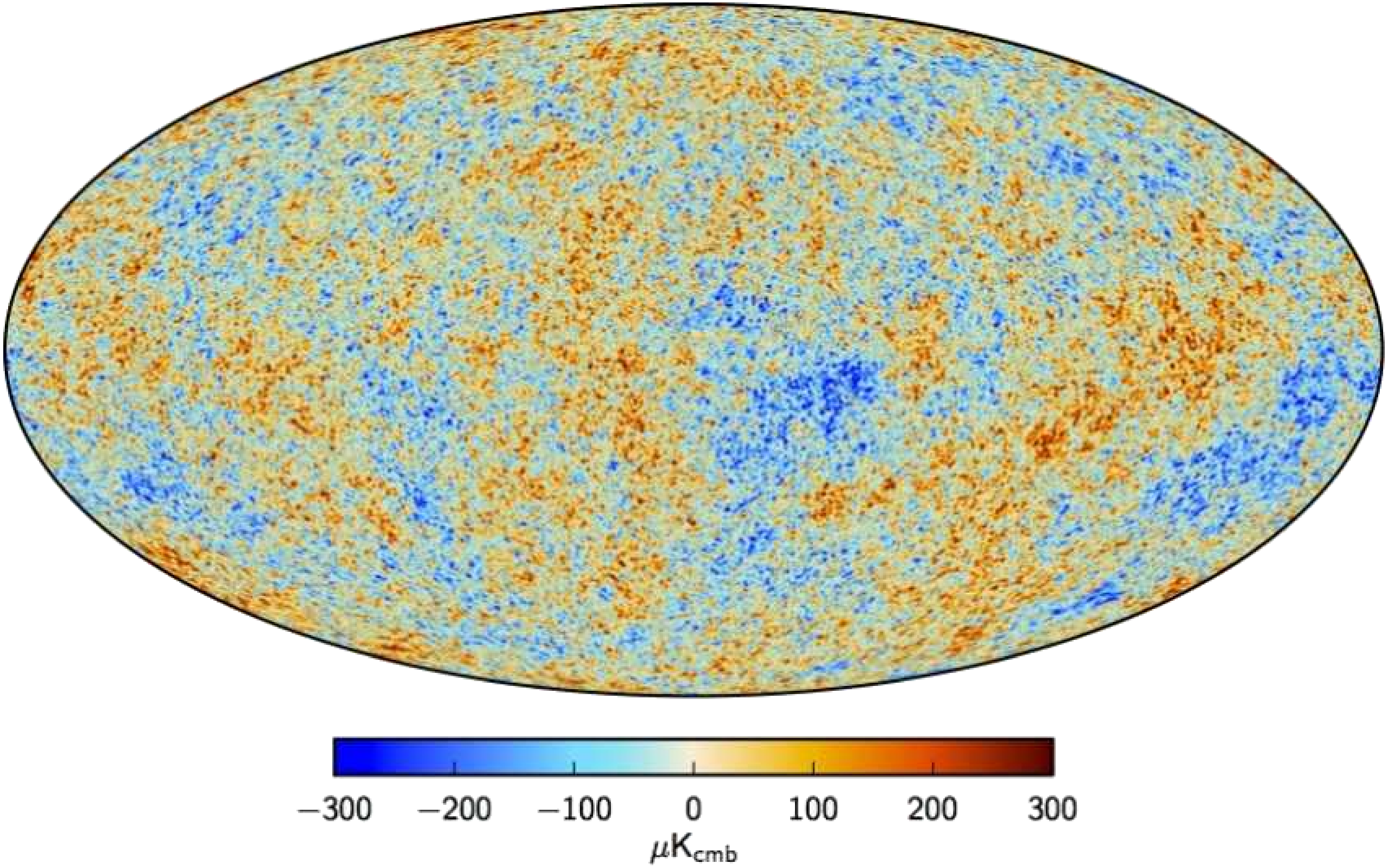
Prize share: 1/4

© The Nobel Foundation. Photo: U. Montan

Adam G. Riess

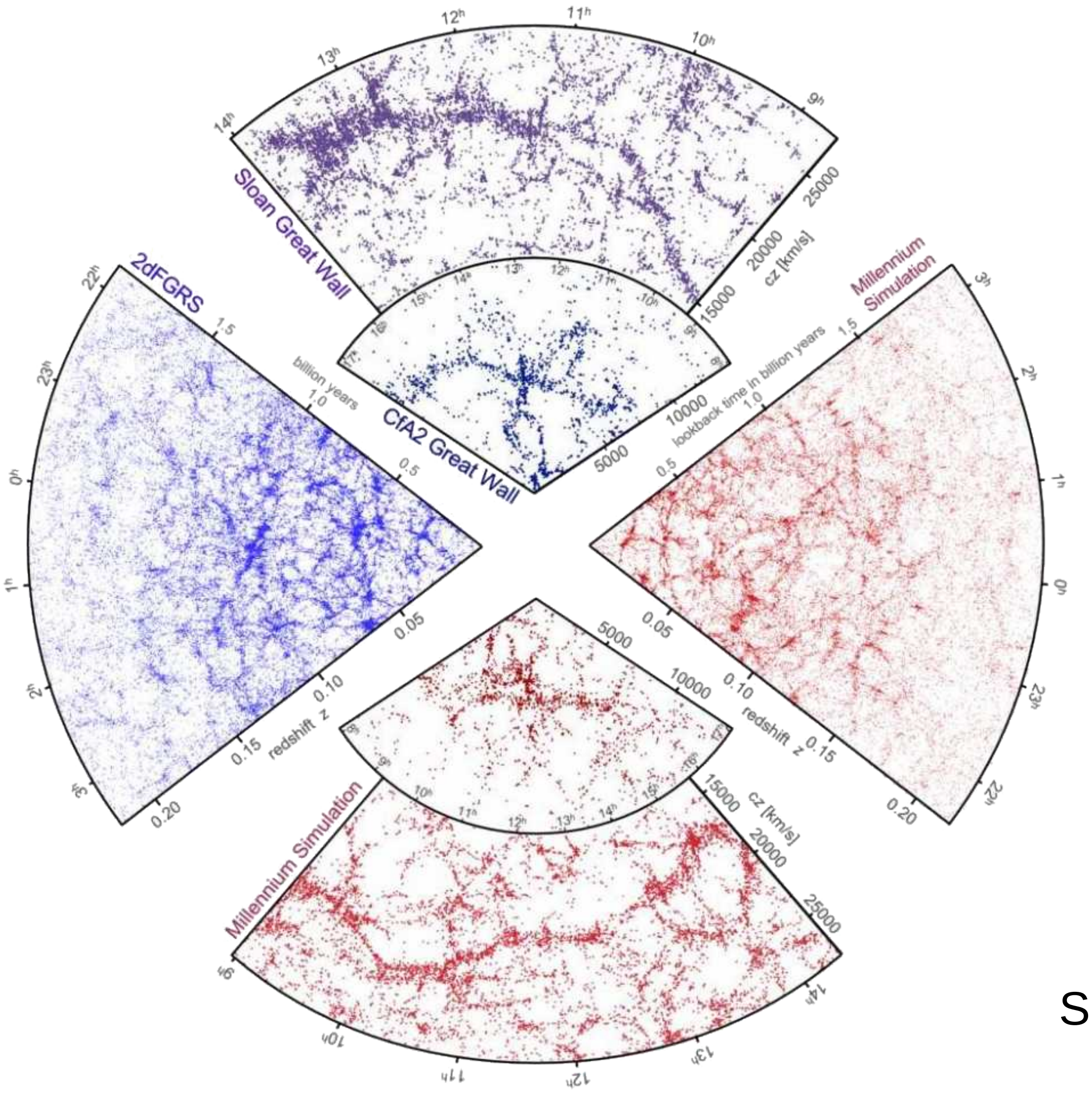
Prize share: 1/4

Temperature/Density fluctuations of the universe (CMB) at the recombination epoch, when it was only 380'000 years old

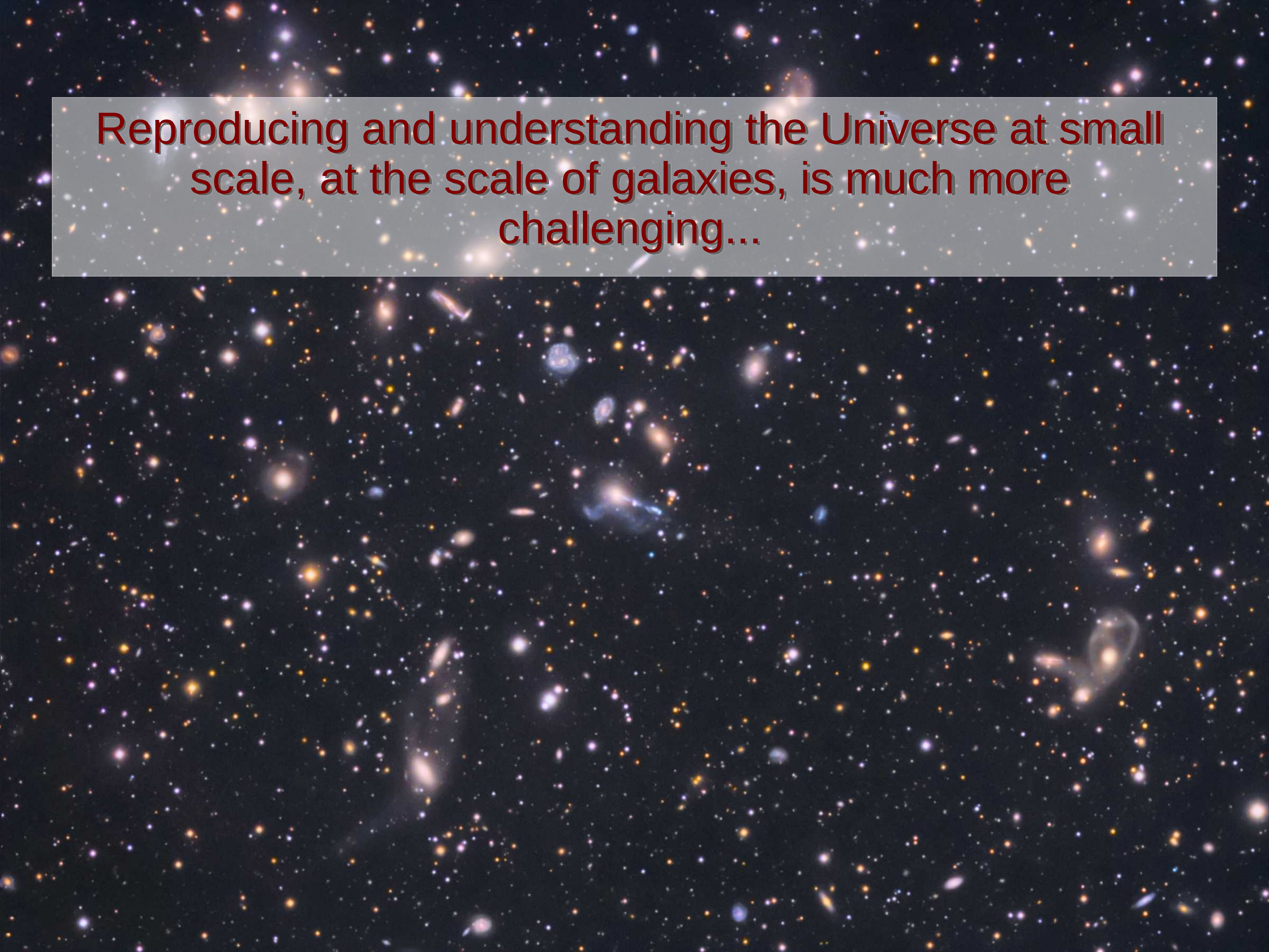


Credit : the Planck collaboration

ΛCDM is successful at reproducing the large scale structure of our Universe



Springel et al. 2006



Reproducing and understanding the Universe at small scale, at the scale of galaxies, is much more challenging...

Introduction

Galaxy formation:
Which physics ?

Galaxy formation
Which physics ?

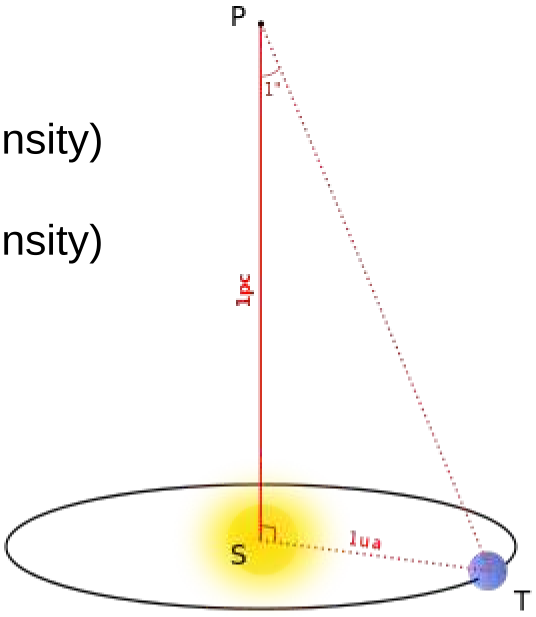
- Gravity
- Gas hydrodynamics
- Gas radiative cooling, gas heating
- Star formation
- Stellar feedback (Supernovae Ia/II, AGB, etc.)
- Chemical evolution, gas mixing, diffusion
- Active Galactic Nuclei (AGN) feedback
- Cosmic rays
- Magnetic fields
- Thermal conductivity
- Dust
- ...

Galaxy formation
Which physics ?

- Gravity
- Gas hydrodynamics
- Gas radiative cooling, gas heating
- Star formation
- Stellar feedback (Supernovae Ia/II, AGB, etc.)
- Chemical evolution, gas mixing, diffusion
- Active Galactic Nuclei (AGN) feedback
- Cosmic rays
- Magnetic fields
- Thermal conductivity
- Dust
- ...

Units

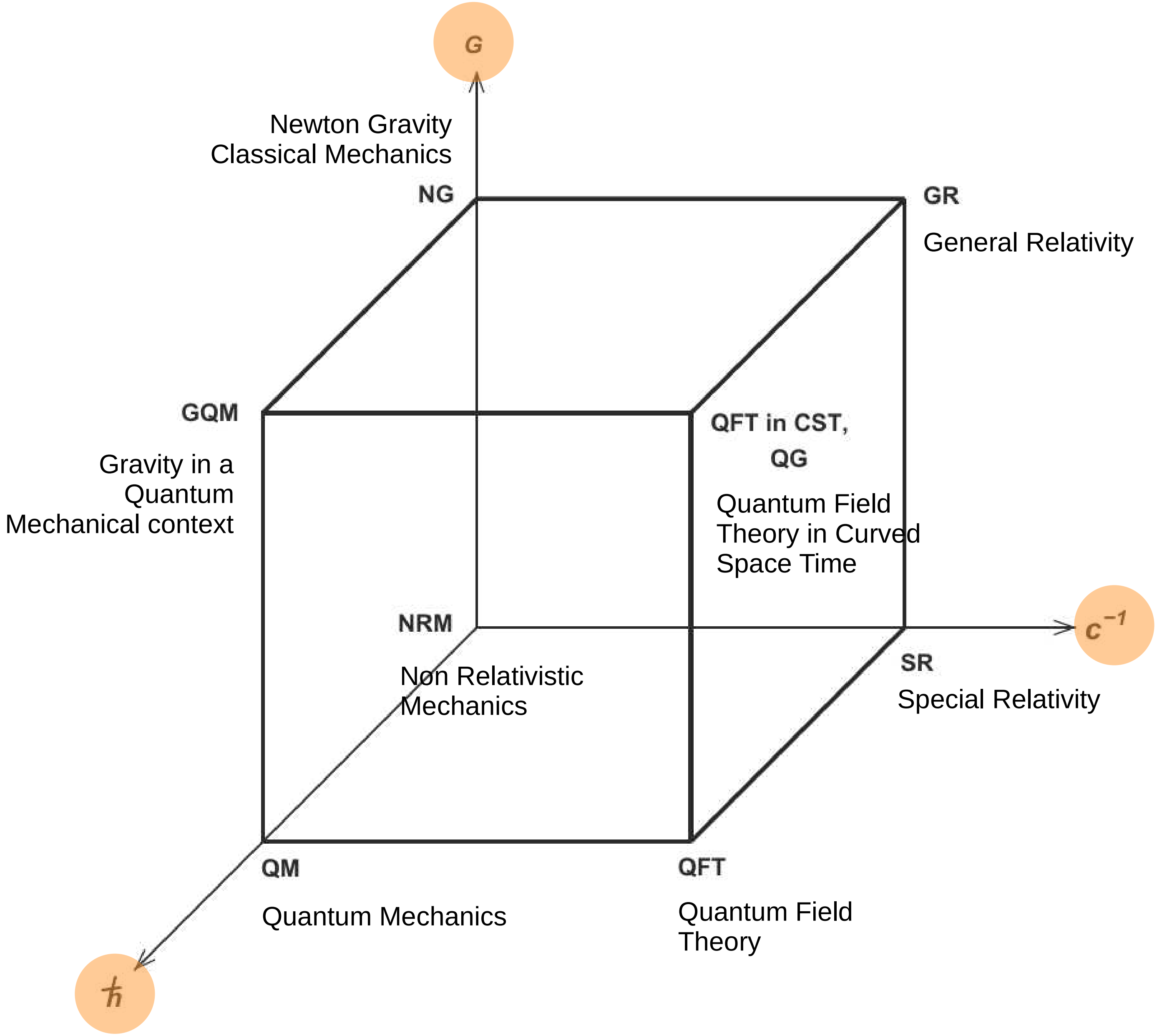
Distances:	Parsec (pc)	= 3.2616 light year = 3.085×10^{16} meter
Masses:	Solar Mass ($M_\odot$)	= 2×10^{30} kg
Luminosities:	Solar Luminosity ($L_\odot$)	= 3×10^{26} Watt
Time:	Giga Year (Gyr) Mega Year (Myr)	= 10^9 yr = 10^6 yr
Speed:	km/s	= km/s
Densities	atom/cm^3	= 1.7×10^{-21} kg/m^3 (air density)
	$M_\odot$ / pc^3	= 6.7×10^{-20} kg/m^3 (air density)



Credit : wikipedia

The cube of theoretical physics

Sleeping Beauties in Theoretical Physics (T. Padmanabhan)



G

Newton Gravity
Classical Mechanics

NG

GR

General Relativity

GQM

Gravity in a
Quantum
Mechanical context

QFT in CST,
QG

Quantum Field
Theory in Curved
Space Time

NRM

Non Relativistic
Mechanics

c^{-1}

SR

Special Relativity

QM

Quantum Mechanics

QFT

Quantum Field
Theory

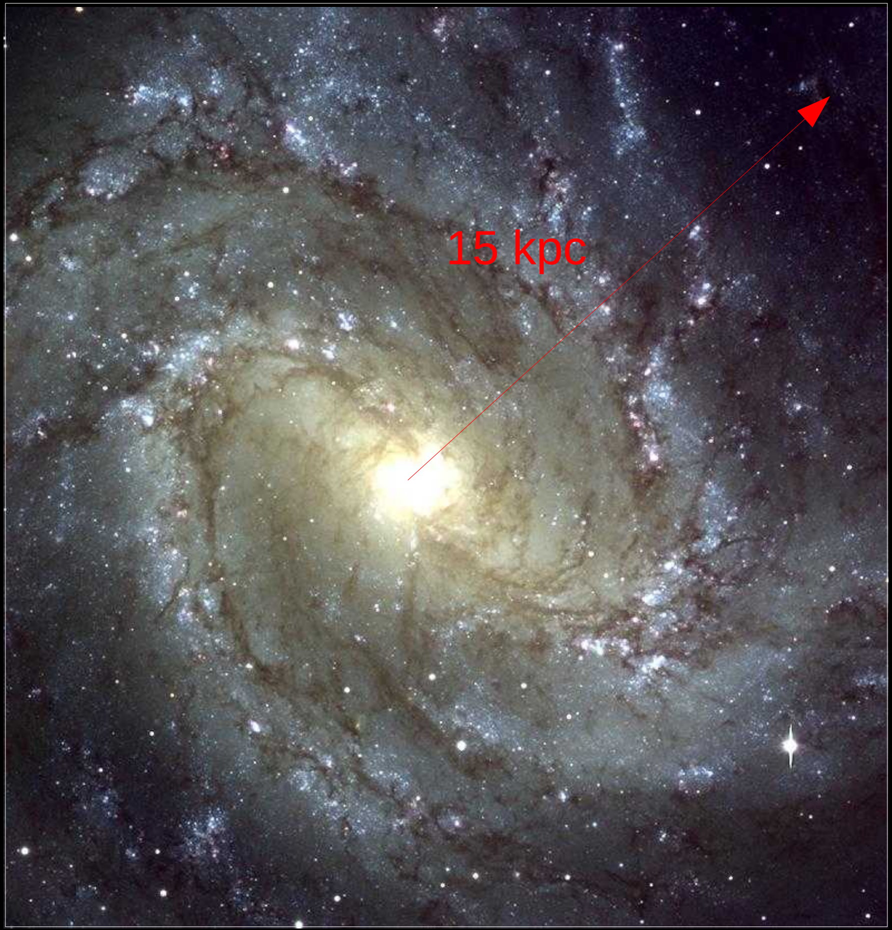
$\hbar$

Fig. 1.1: The landscape of theoretical physics can be concisely described by a cube — The Cube of Theoretical Physics — whose axes represents the three fundamental constants $G, \hbar$ and c^{-1}. The vertices and linkages describe different structural properties of the physical theories. See text for detailed description.

Introduction

Our galaxy
The Milky Way

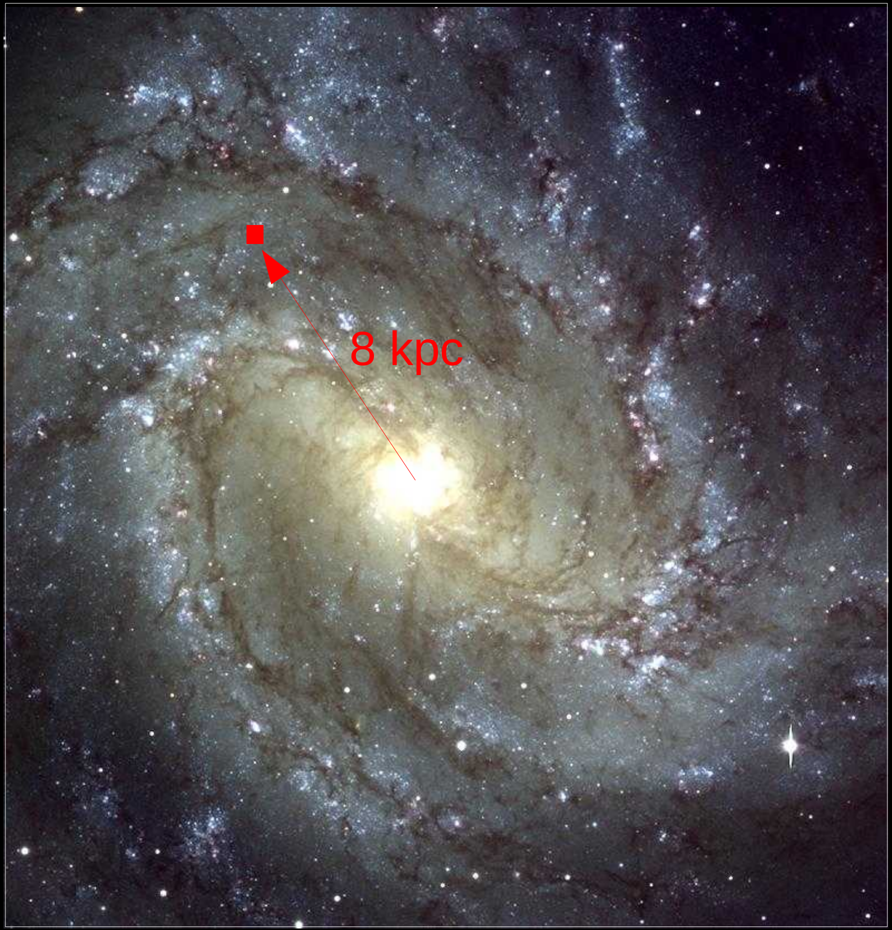
The Milky Way : a disky galaxy



M83

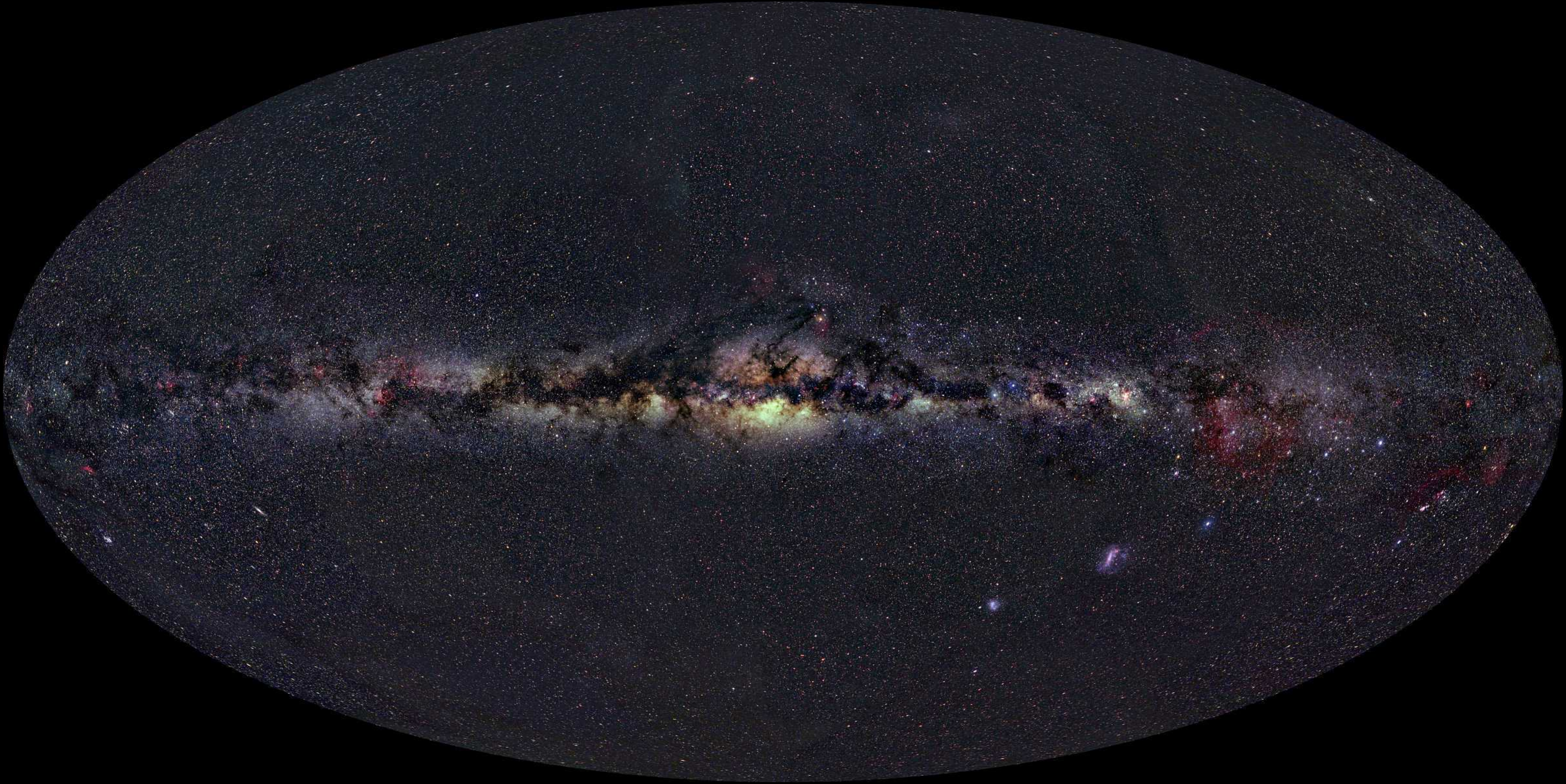
NGC4945

Position of the Sun

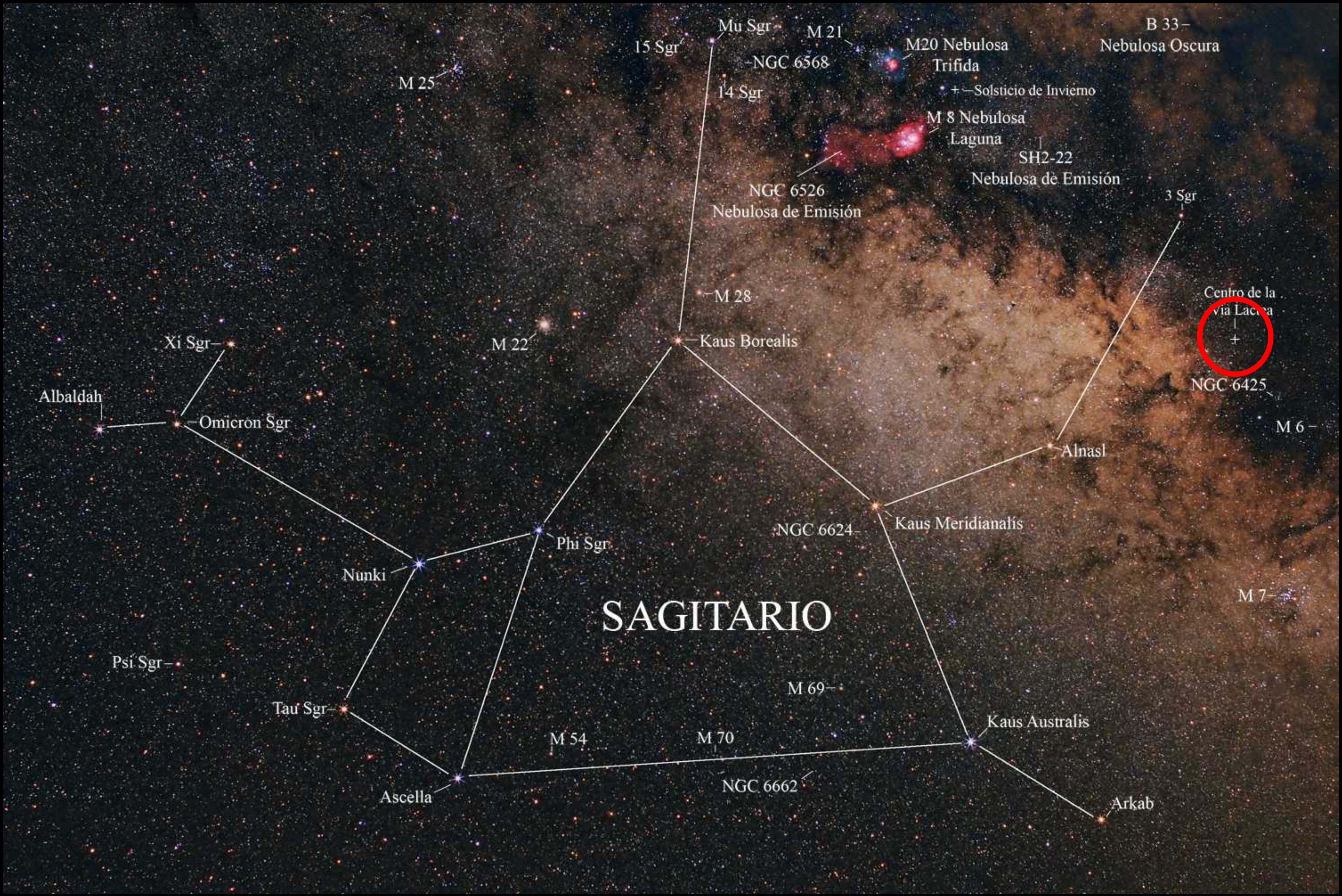


M83

NGC4945



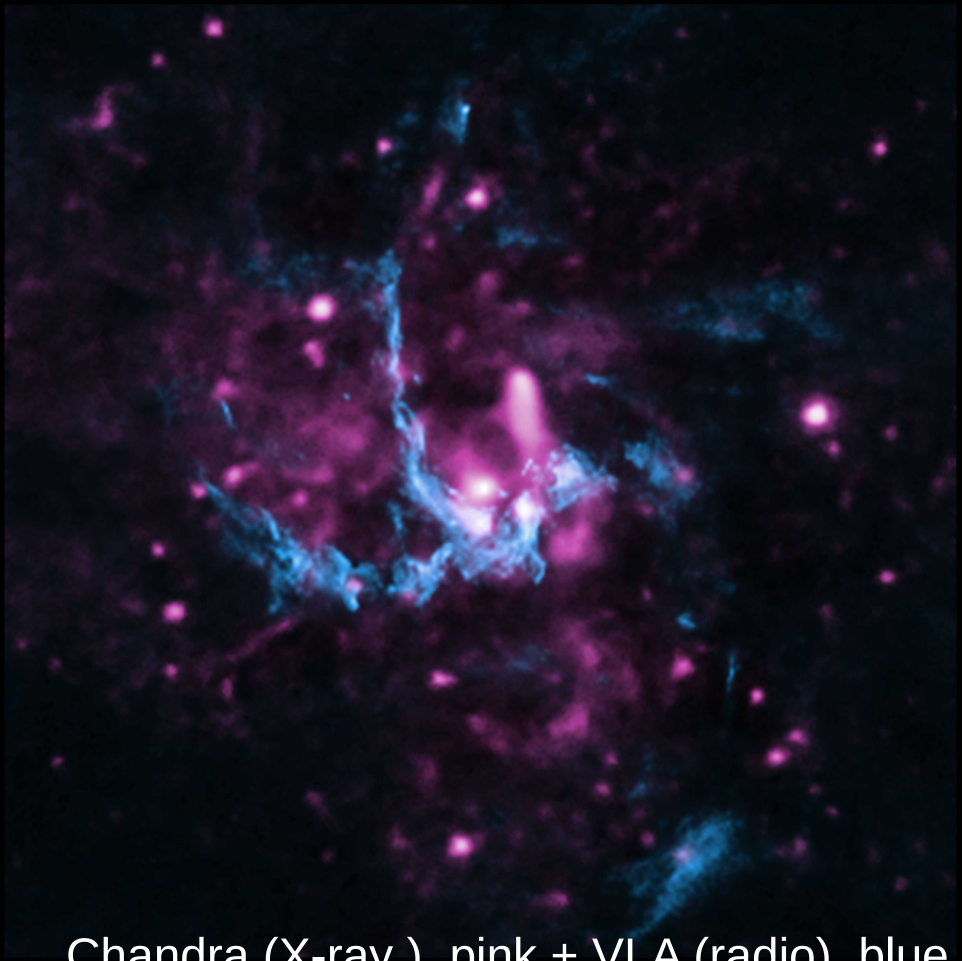
The Galactic Centre



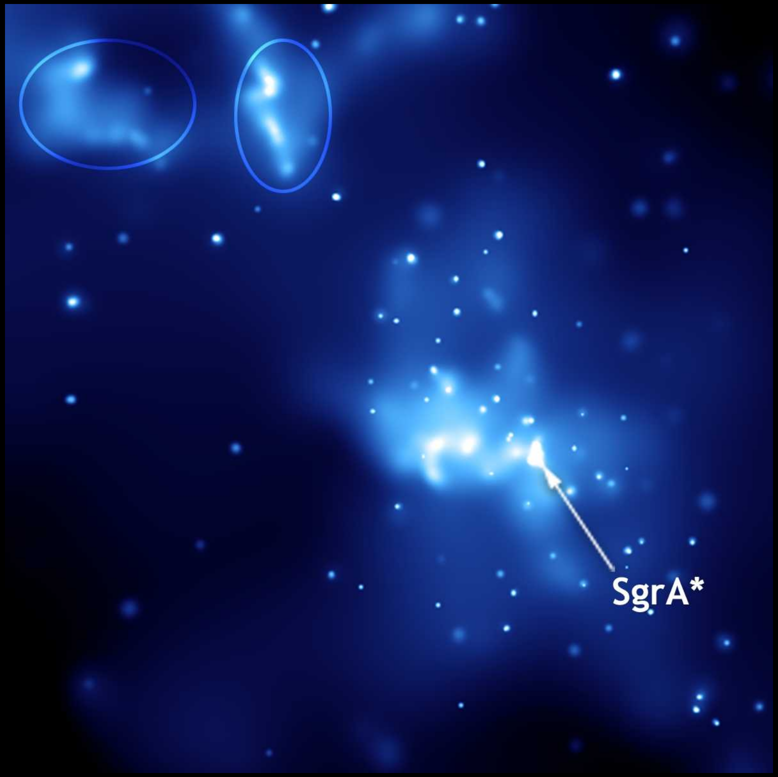
The Galactic Centre

Very well determined via radio observations of the radio-source Sagittarius A* (Galactic Black Hole)

Location : 17h45m 40.0409s (RA), -29º0’28.118’’ (DEC)
Distance: 25.900±1.400 light years (7.940±420 pc)
Mass: 4.31±0.38 10^6 $M_\odot$

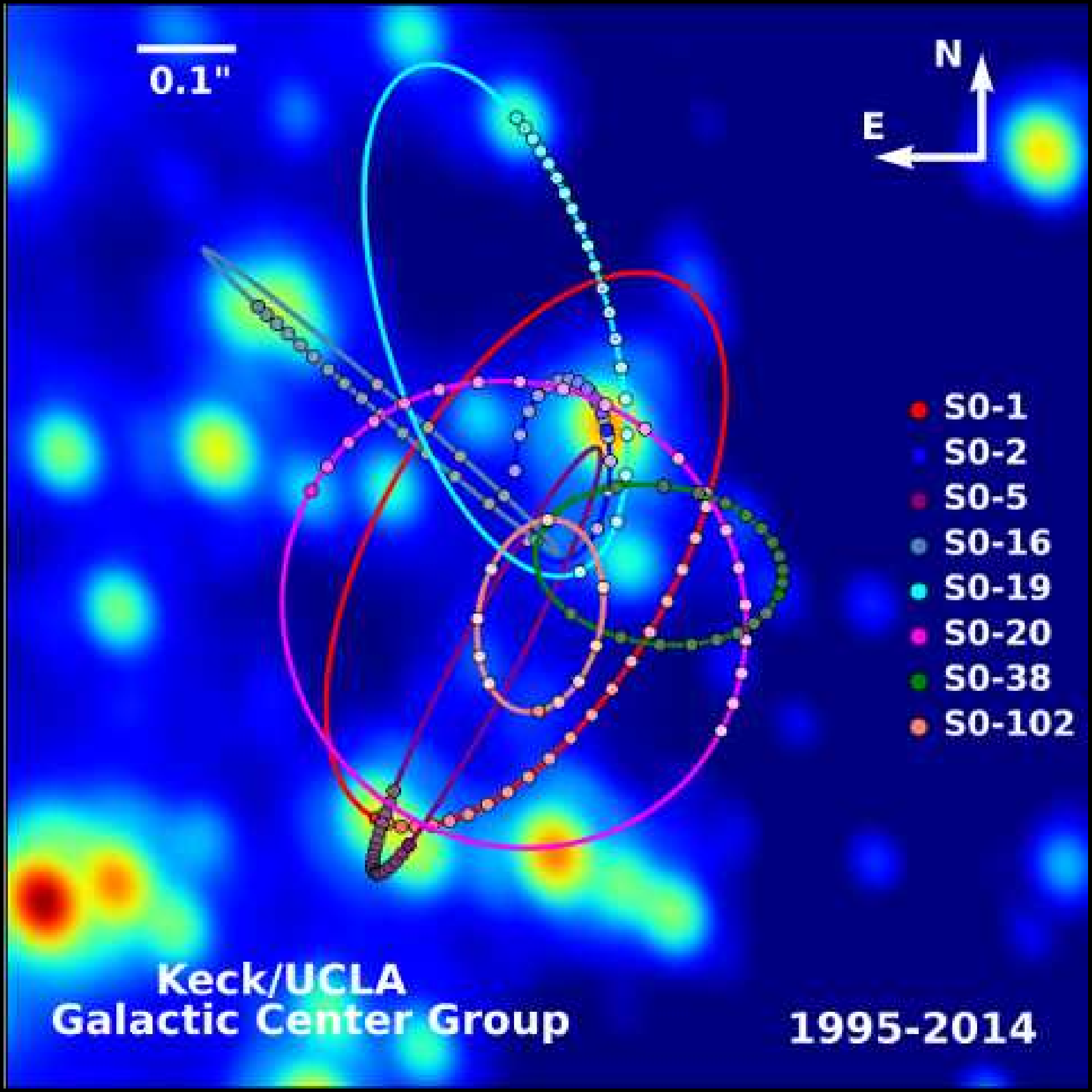


Chandra (X-ray), pink + VLA (radio), blue



Chandra (X-ray)

The Galactic Centre BH

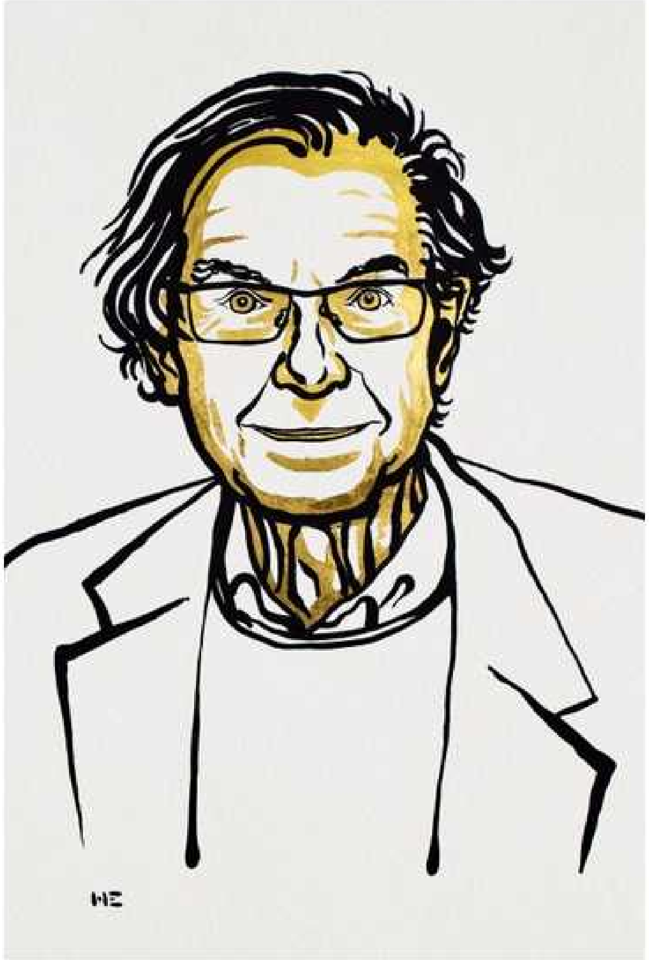


http://www.astro.ucla.edu/~ghezgroup/gc/blackhole.html

https://youtu.be/xHMZOaQttqw

https://youtu.be/if2opecmev8

The Nobel Prize in Physics 2020



Ill. Niklas Elmehed. © Nobel Media.

Roger Penrose

Prize share: 1/2

Ill. Niklas Elmehed. © Nobel Media.

Reinhard Genzel

Prize share: 1/4

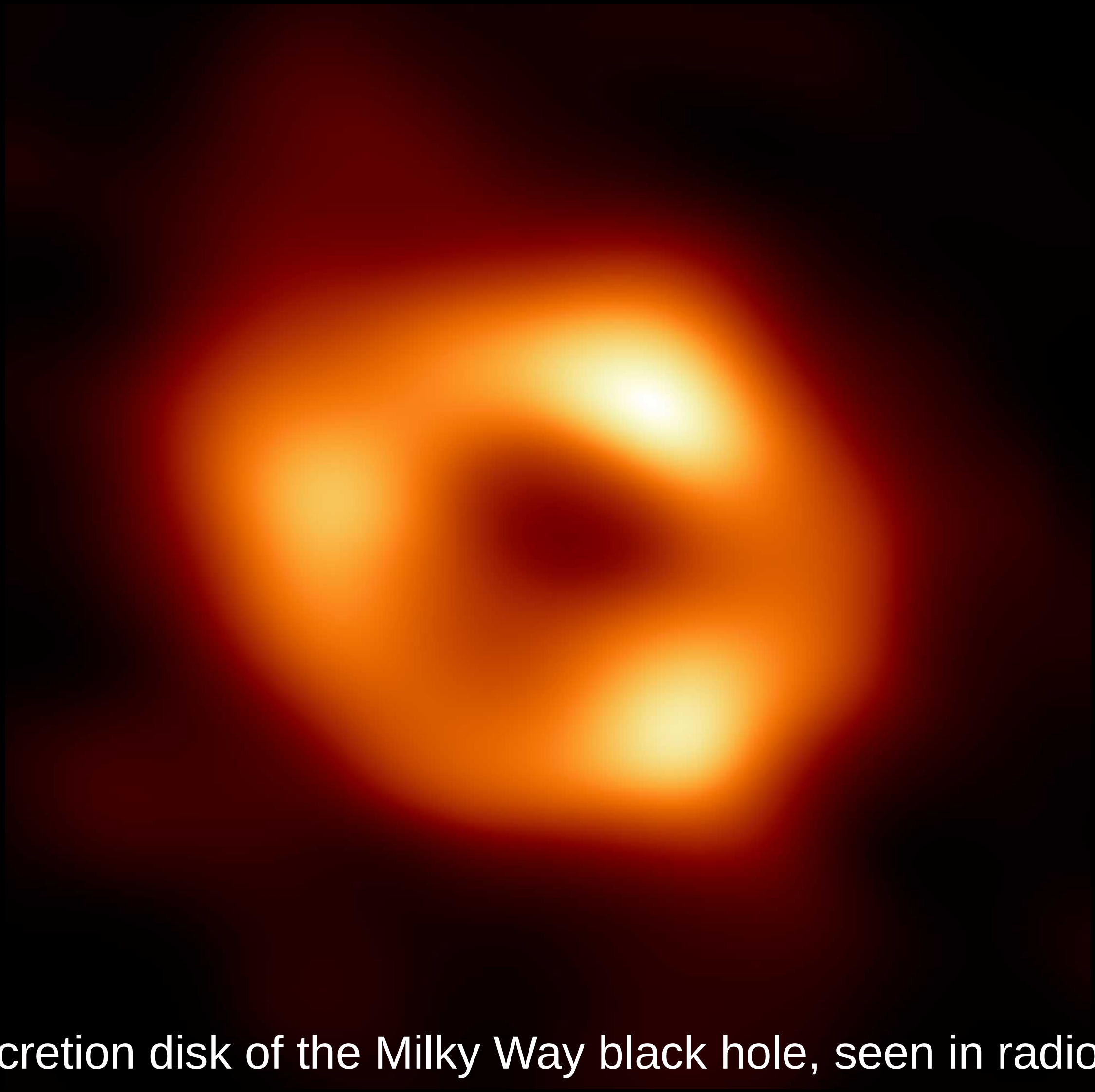
Ill. Niklas Elmehed. © Nobel Media.

Andrea Ghez

Prize share: 1/4

Event Horizon Telescope (EHT)

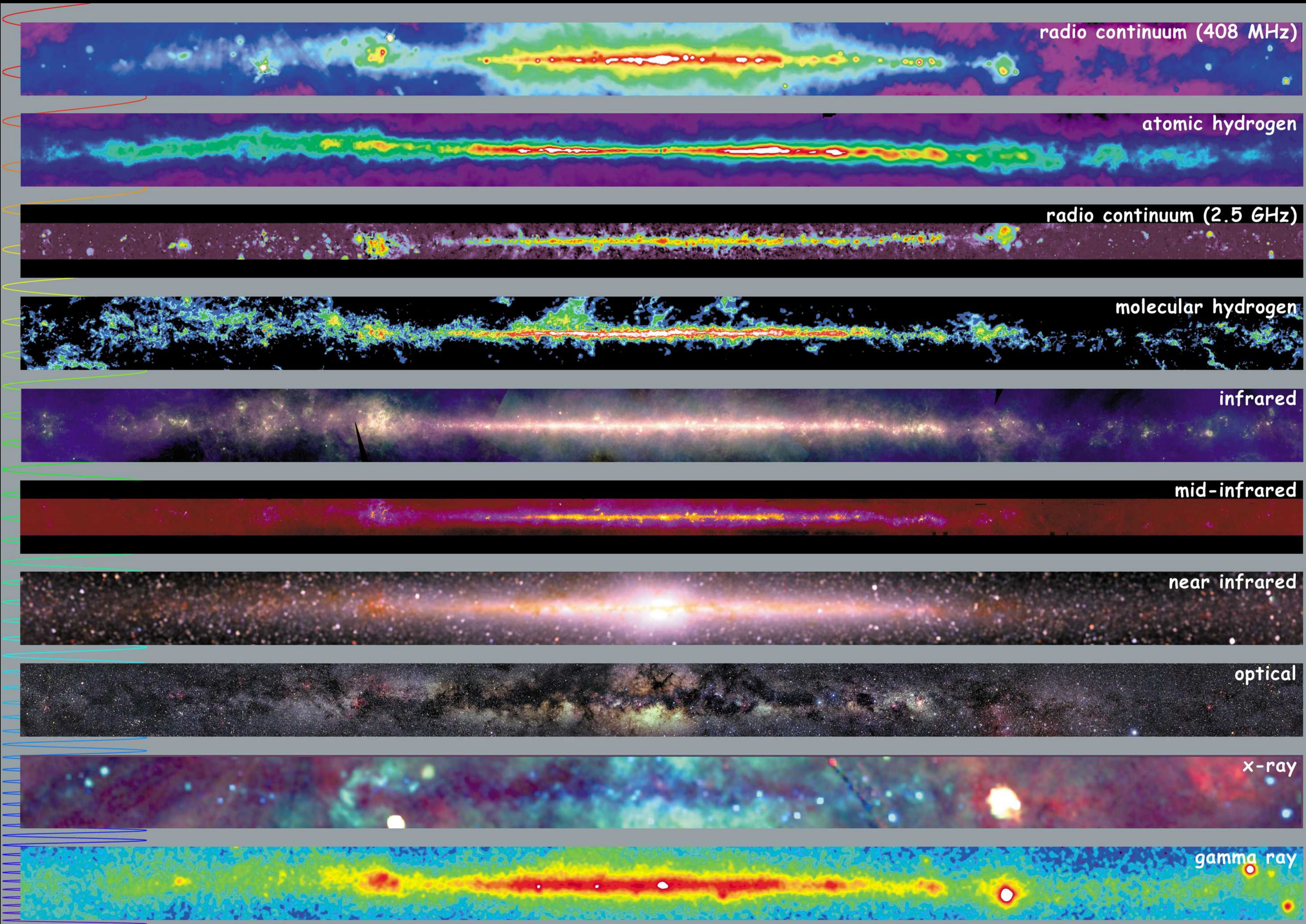
2019



The accretion disk of the Milky Way black hole, seen in radio

The Milky Way in different wavelength

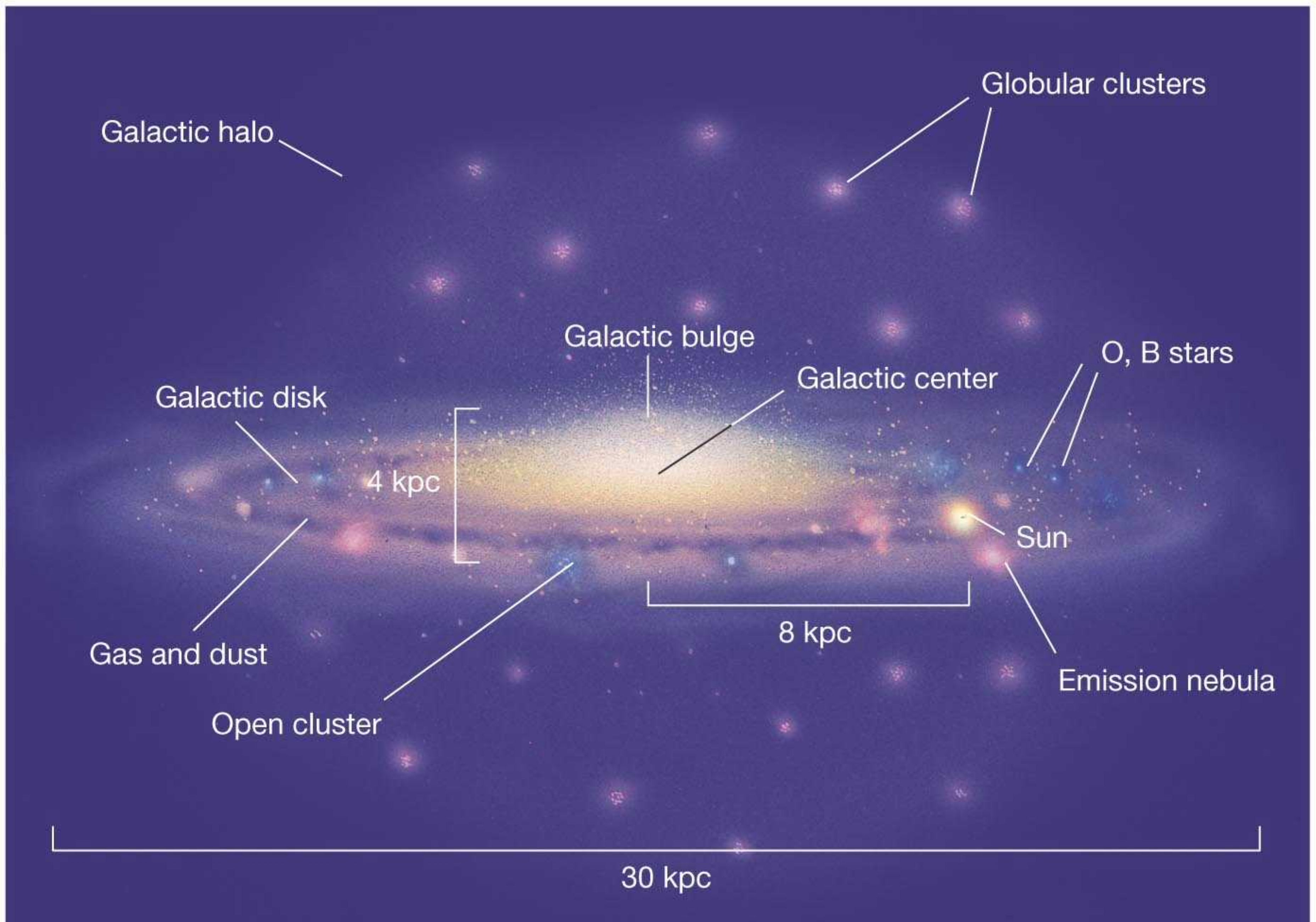
The Milky Way in different wavelength



http://adc.gsfc.nasa.gov/mw

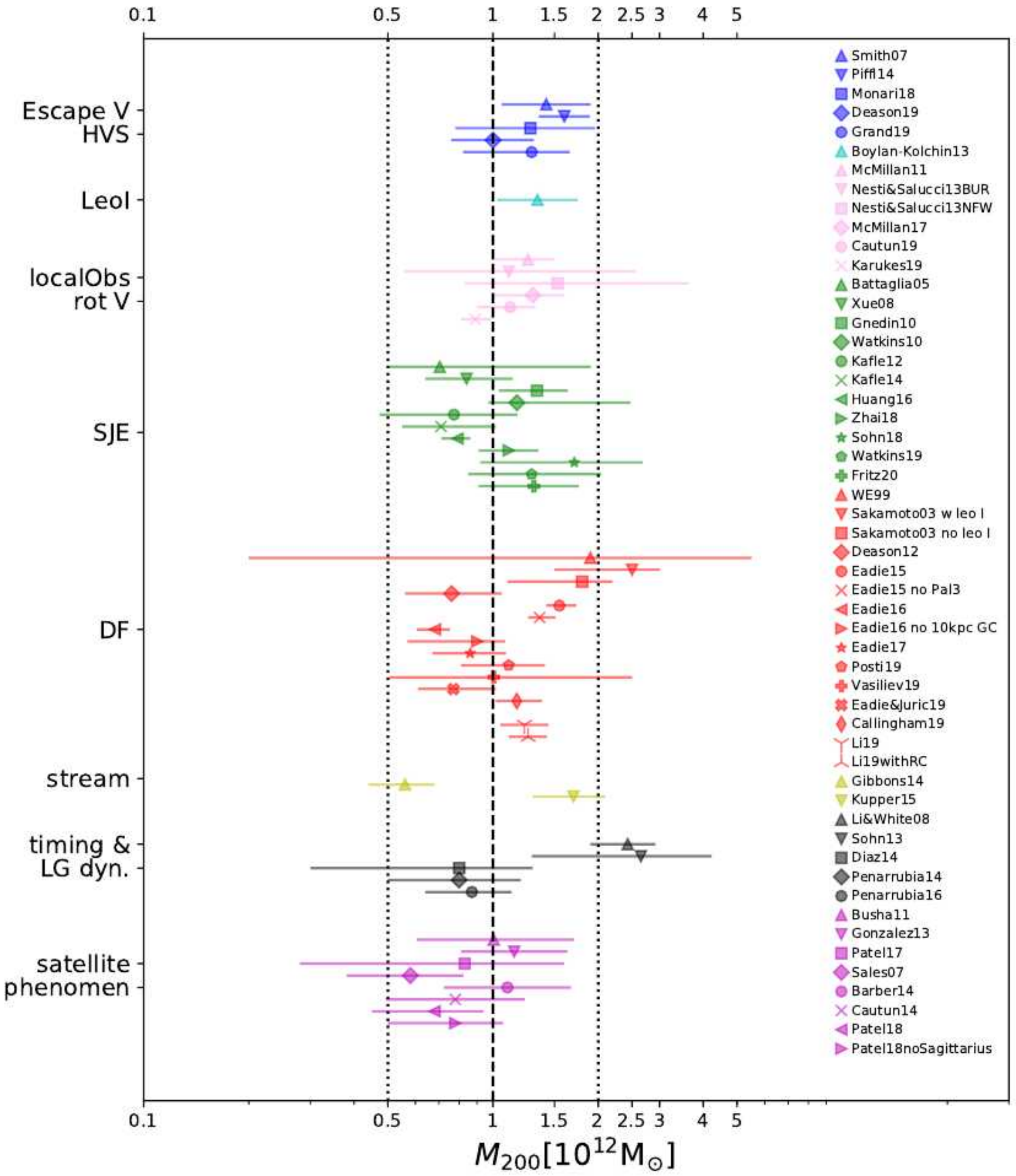
Multiwavelength Milky Way

Components of the WM

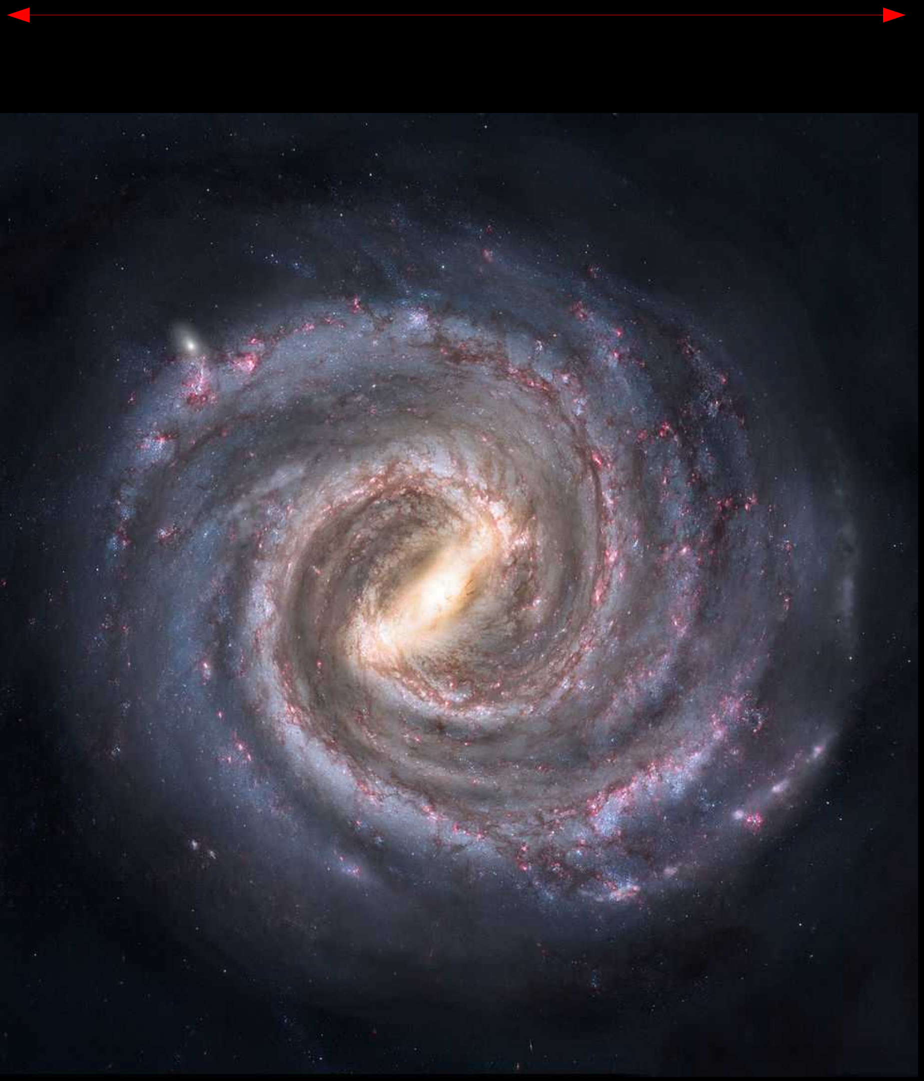


The Milky Way total (gravitational) mass

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



Components of the WM



Diameter :

30 kpc

Total mass:

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

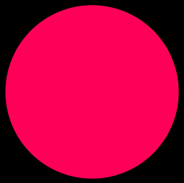
Rotation :

200 Myr (sun)
500 Myr (ext.)

Stellar component : bulge/bar

$0.5\text{x}10^{10}\,M_\odot$

- old stars
- RMS vel ~150 km/s

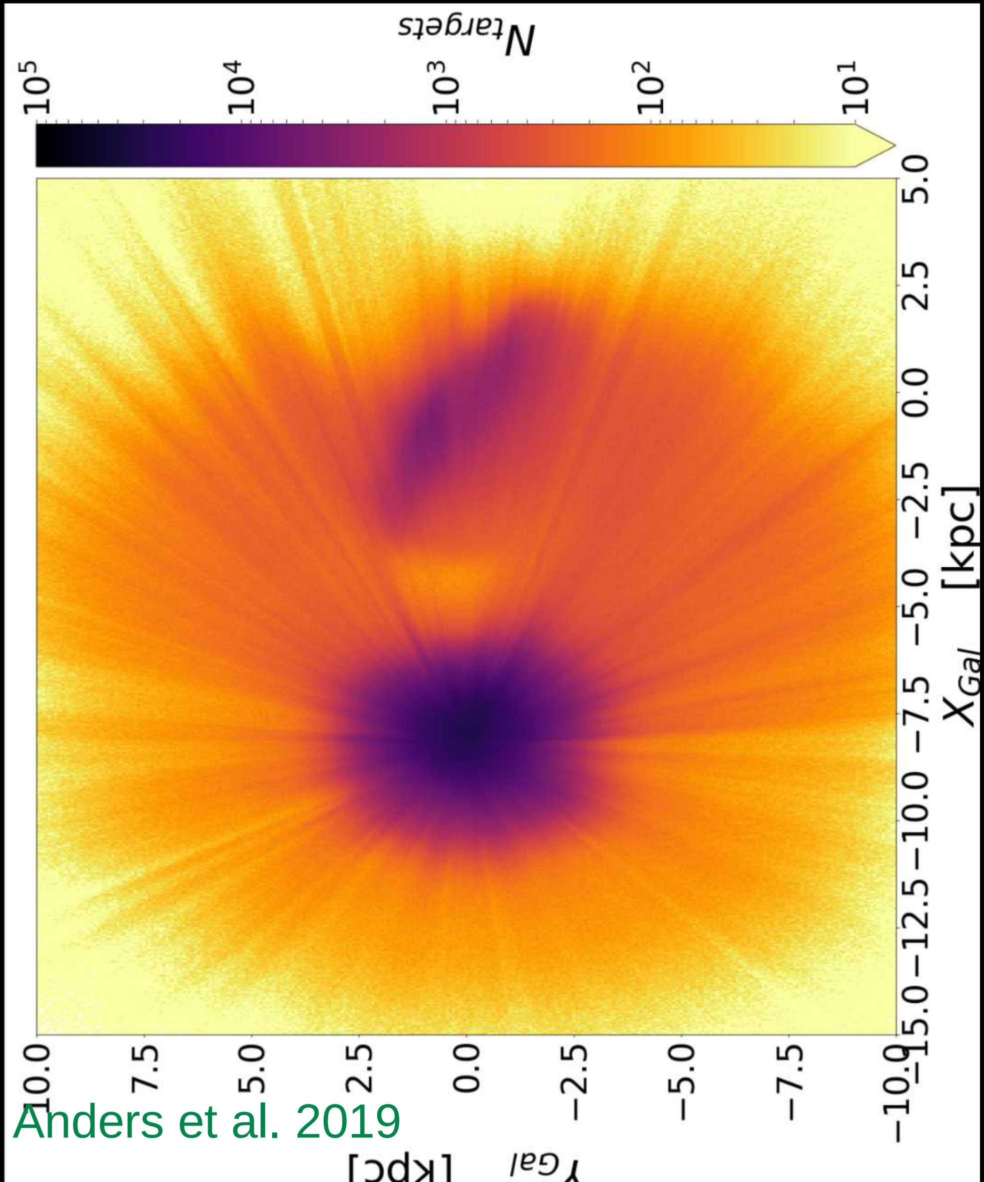


Stellar component : bulge/bar

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

265 millions of stars !

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



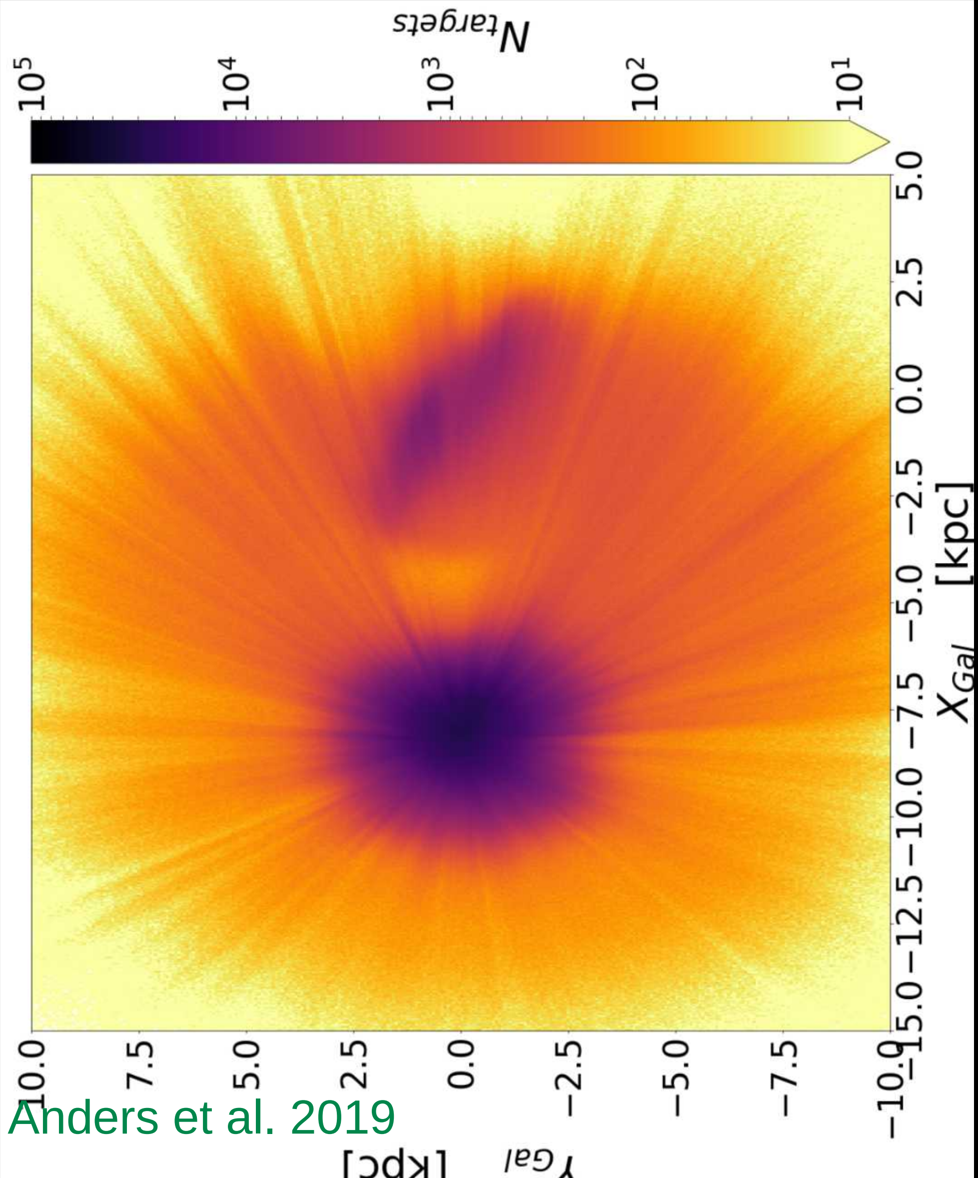
Anders et al. 2019

Stellar component : bulge/bar

$0.5\times10^{10}\ M_{\odot}$

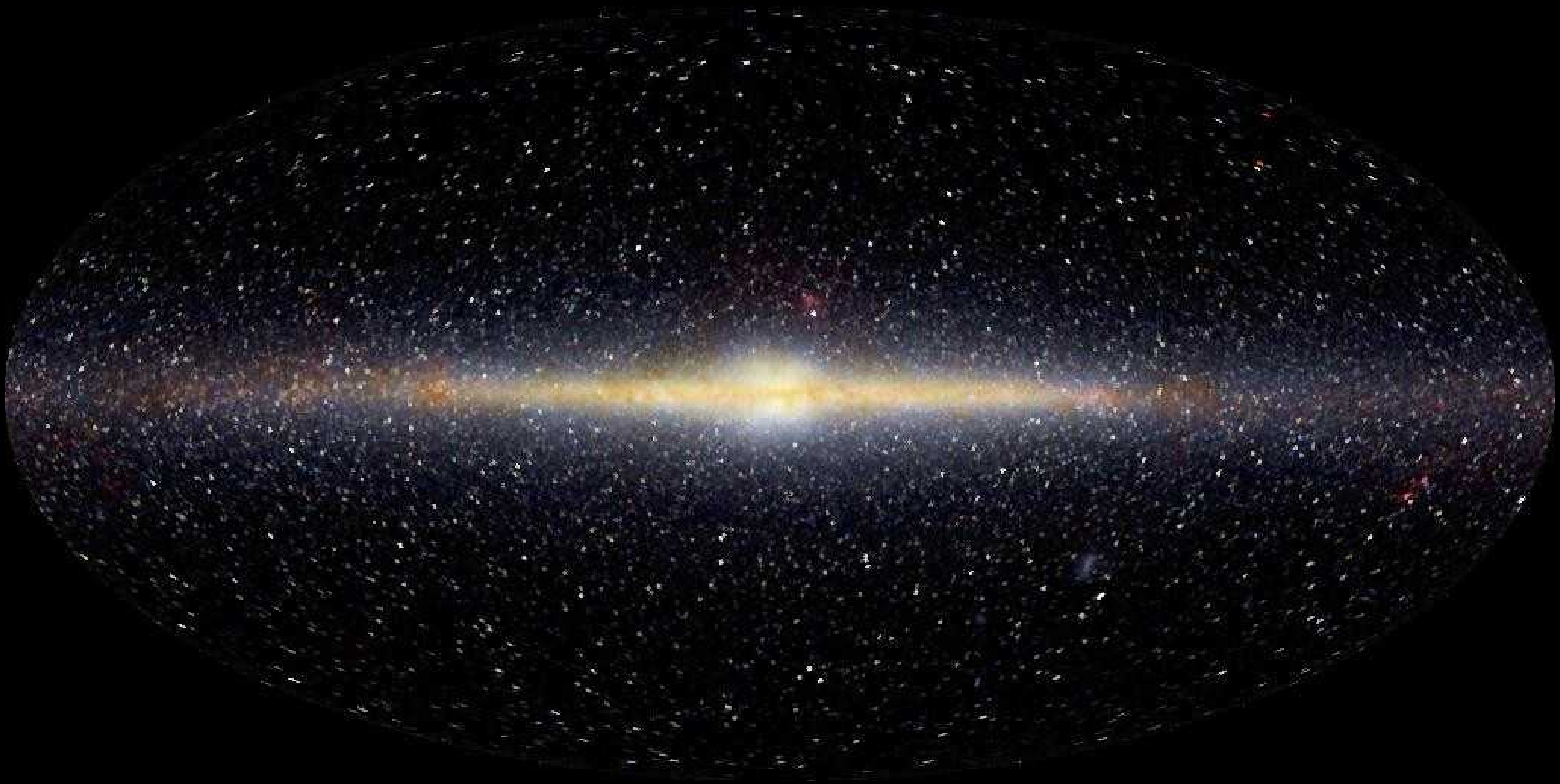
265 millions of stars !

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



Anders et al. 2019

COBE satellite view of the MW in infrared light



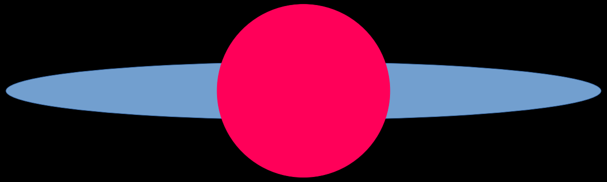
Robert Nemiroff (MTU) & Jerry Bonnell (USRA)

Stellar component : disk

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

thin disk:

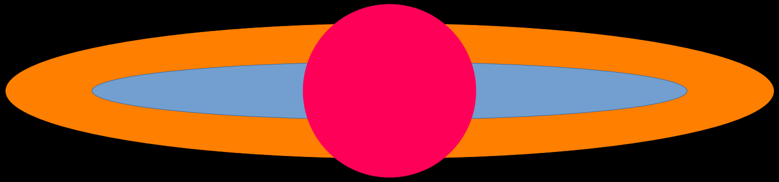
- 90% of the stellar disk
- scale height : ~300 pc
- RMS vel ~50 km/s



Stellar component : disk

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

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



Toomre Diagram

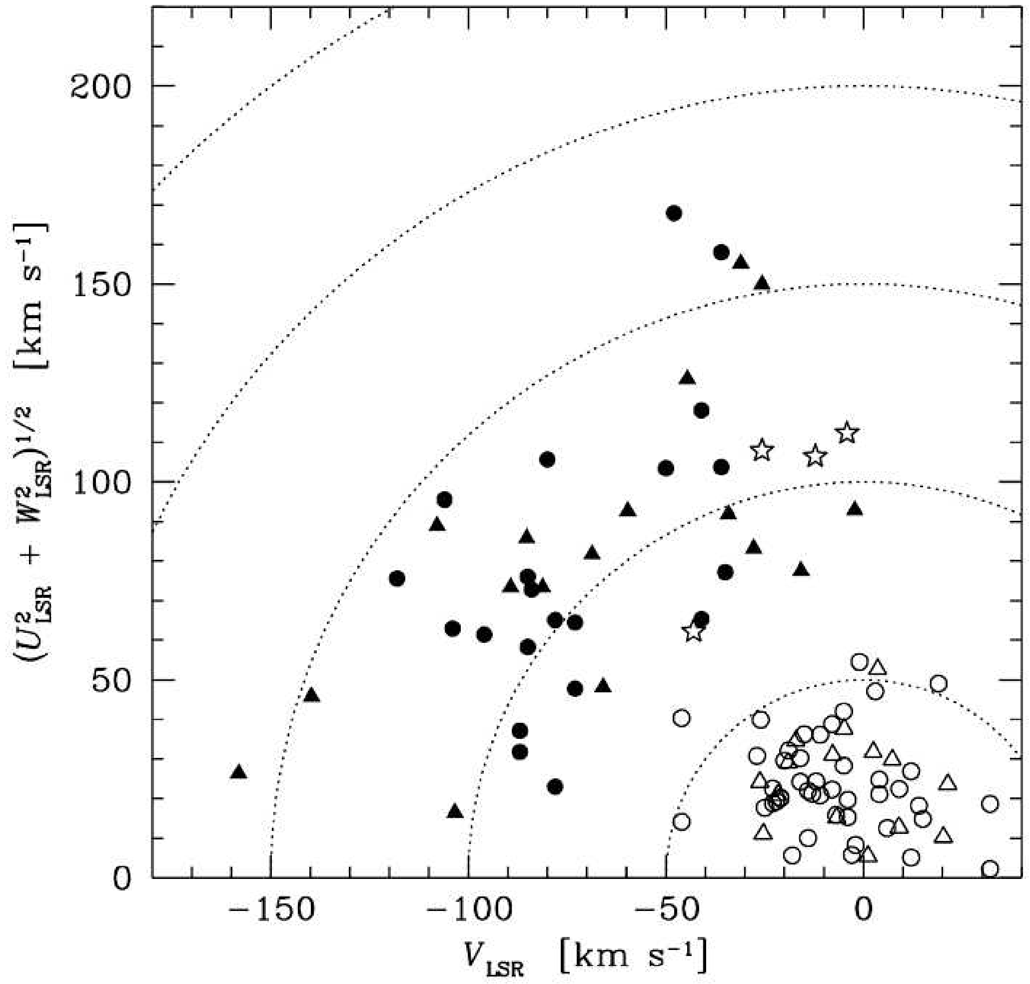


Fig. 1. Toomre diagram for the full stellar sample (102 stars). Thick and thin disk stars are marked by filled and open symbols, respectively. Stars that have been observed with SOFIN or UVES are marked by triangles and those from Bensby et al. (2003) are marked by circles. "Transition objects" are marked by "open stars".

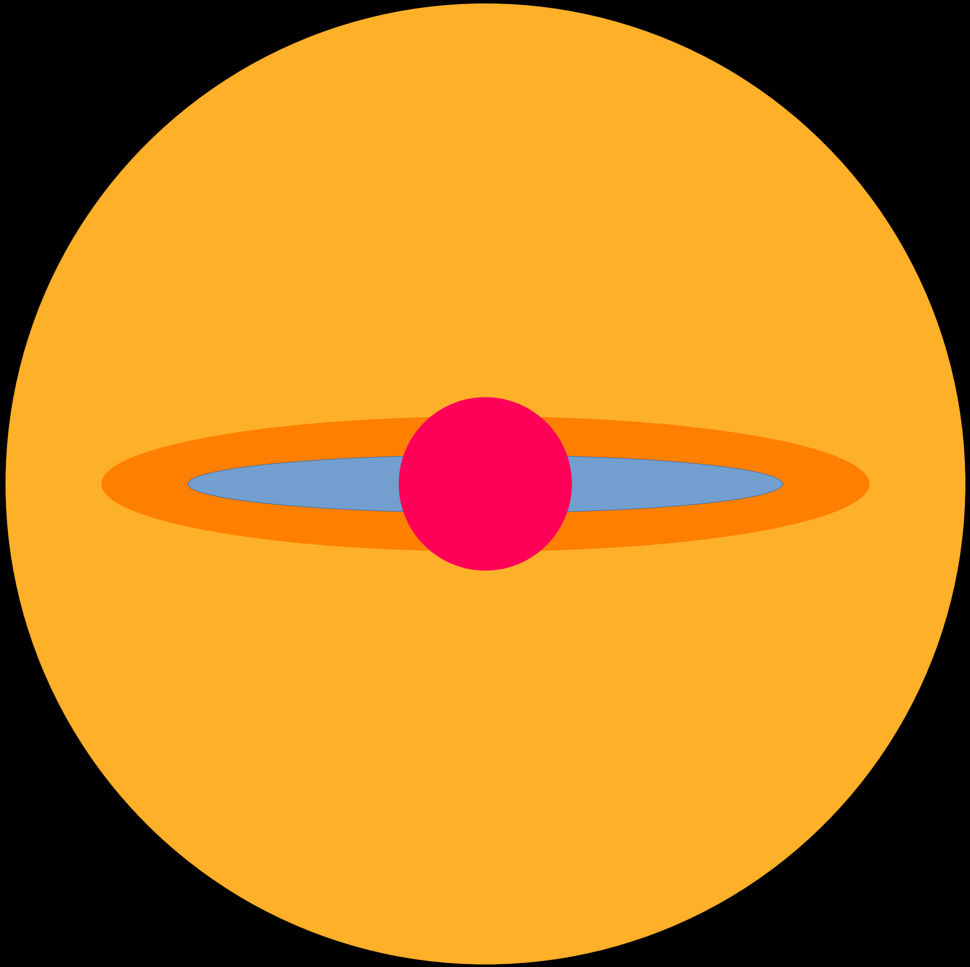
Disentangling
thin disk from thick disk stars
based on their kinematics

Bensby et al. 2005

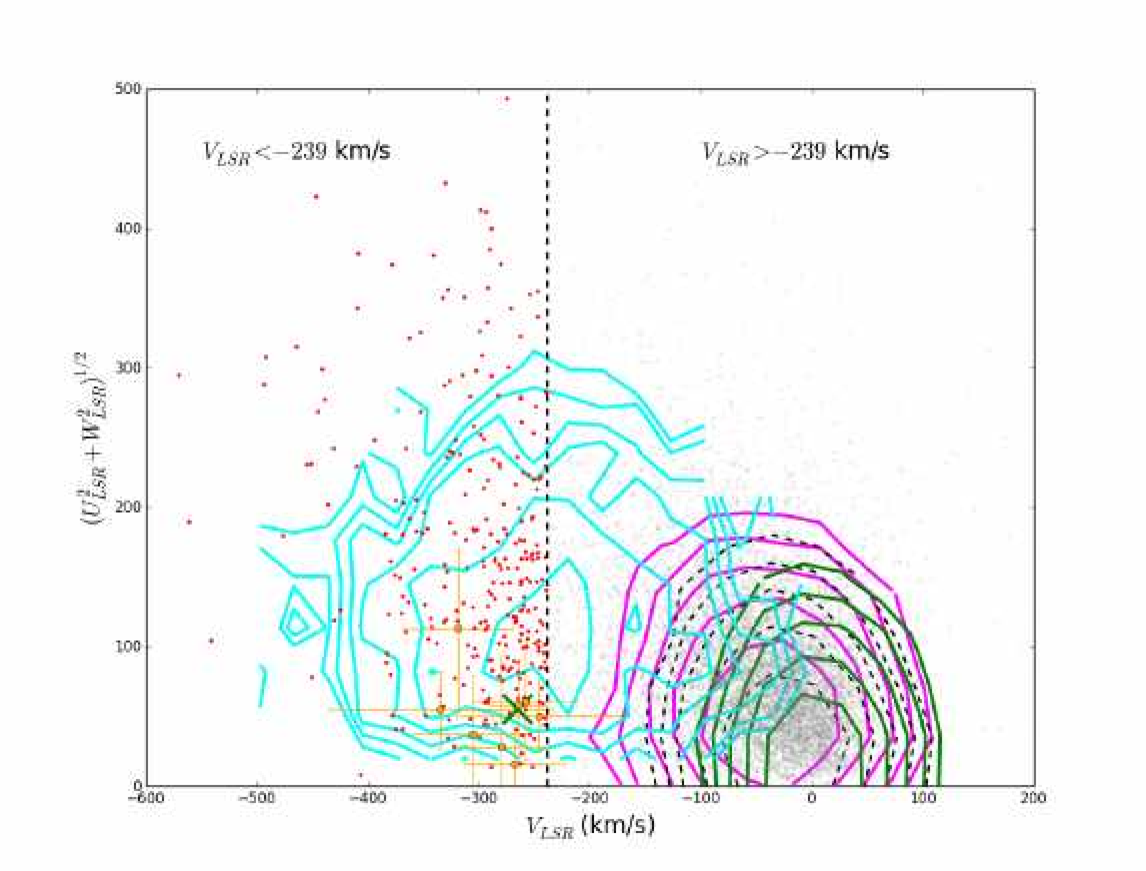
Stellar component : halo

$5 \times 10^8 M_\odot$ (1 % of stars)

- old stars
- no mean rotation



Toomre Diagram



Disentangling
halo stars from disk stars
based on their kinematics
(RAVE)

Fernandez-Trincado et al. 2015

Key Numbers for the Milky Way stellar disk

Surface Brightness:

$I(R) = I_d \exp(-R/R_d)$ with $R_d \sim 2\text{-}3$ kpc

Circular velocity of the Sun:

$v_0 \equiv v_c(R_0) = 220 \pm 20$ km/s with $R_0 = 8.0 \pm 0.5$ kpc

$v_0 = 236 \pm 15$ km/s from proper motion of GC (Sag. A*)

Velocity dispersion of stars :

20-50 km/s (« cool stars»)

Density ⊥ to the disk:

Thin disk

$\rho(R,z) = \rho(R,0) \exp(-|z|/z_d(R))$ with

$z_d \sim 100$ pc for massive stars

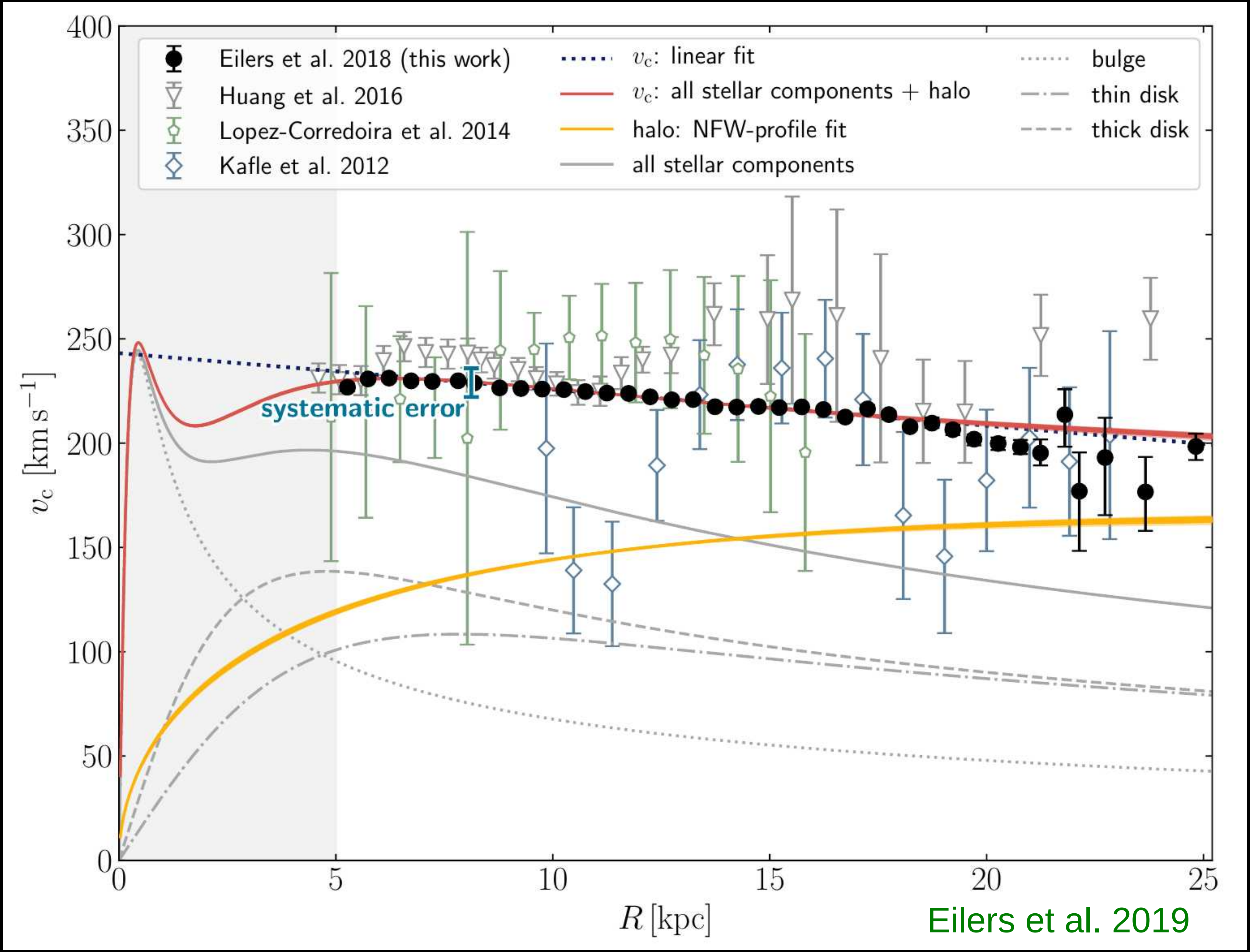
$z_d \sim 300$ pc for low-mass stars

Thick disk:

$z_d \sim 1$ kpc

Surface density in the solar neighbourhood: $\rho \sim 50\ M_\odot/\text{pc}^2$

The circular rotation curve of the MW

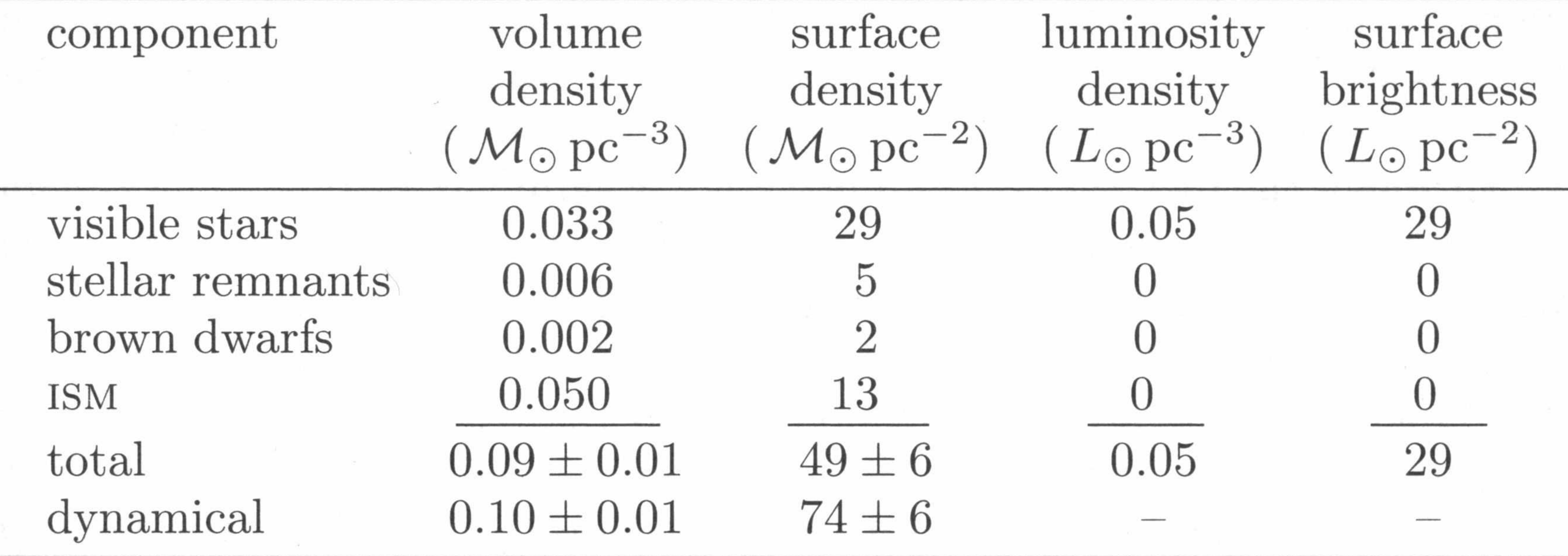


Eilers et al. 2019

Gaseous component : disk, HVC

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

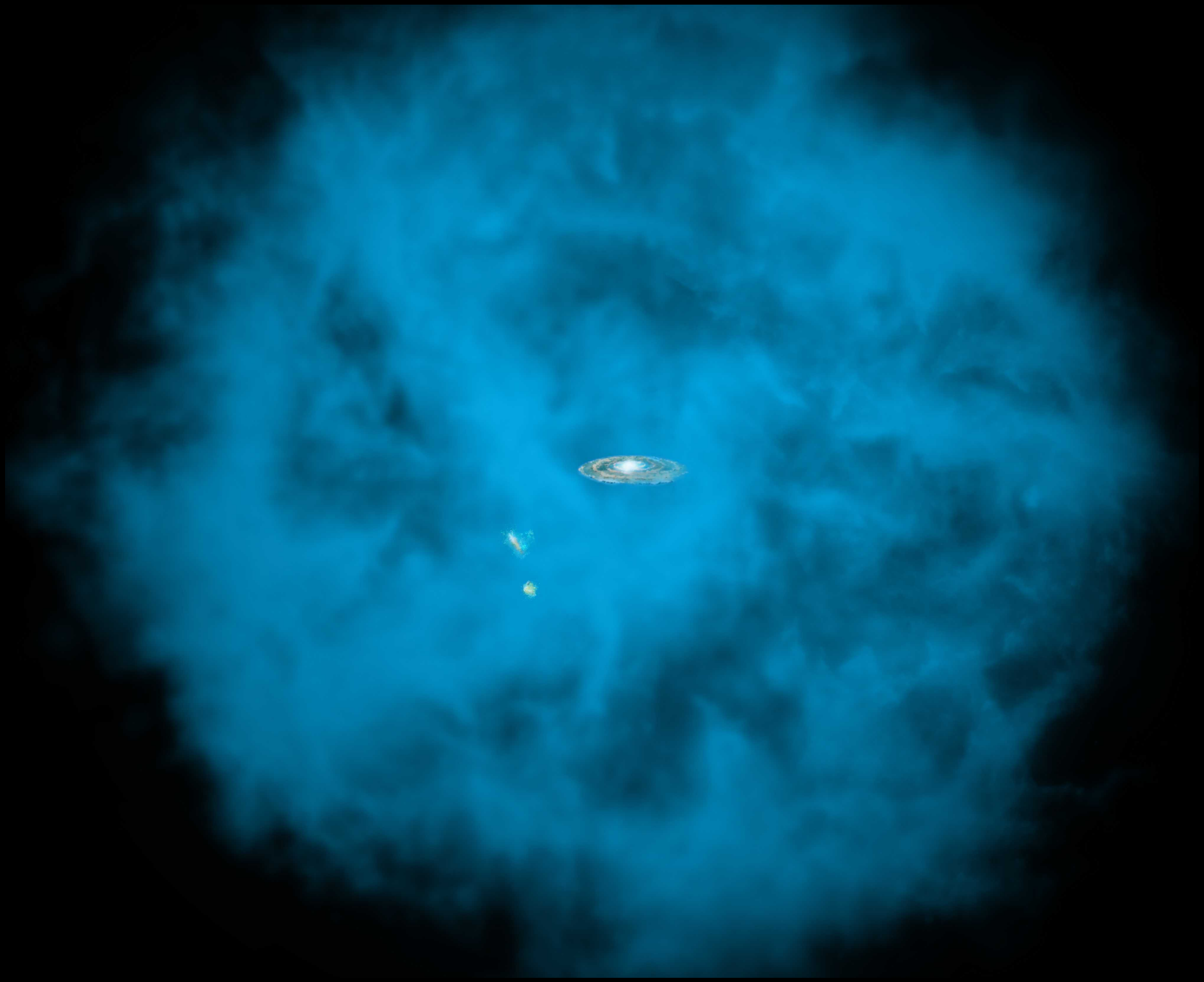
Inventory at the solar vincinity



component	volume density ($\mathcal{M}_\odot\,\mathrm{pc}^{-3}$)	surface density ($\mathcal{M}_\odot\,\mathrm{pc}^{-2}$)	luminosity density ($L_\odot\,\mathrm{pc}^{-3}$)	surface brightness ($L_\odot\,\mathrm{pc}^{-2}$)
visible stars	0.033	29	0.05	29
stellar remnants	0.006	5	0	0
brown dwarfs	0.002	2	0	0
ISM	0.050	13	0	0
total	0.09 ± 0.01	49 ± 6	0.05	29
dynamical	0.10 ± 0.01	74 ± 6	–	–

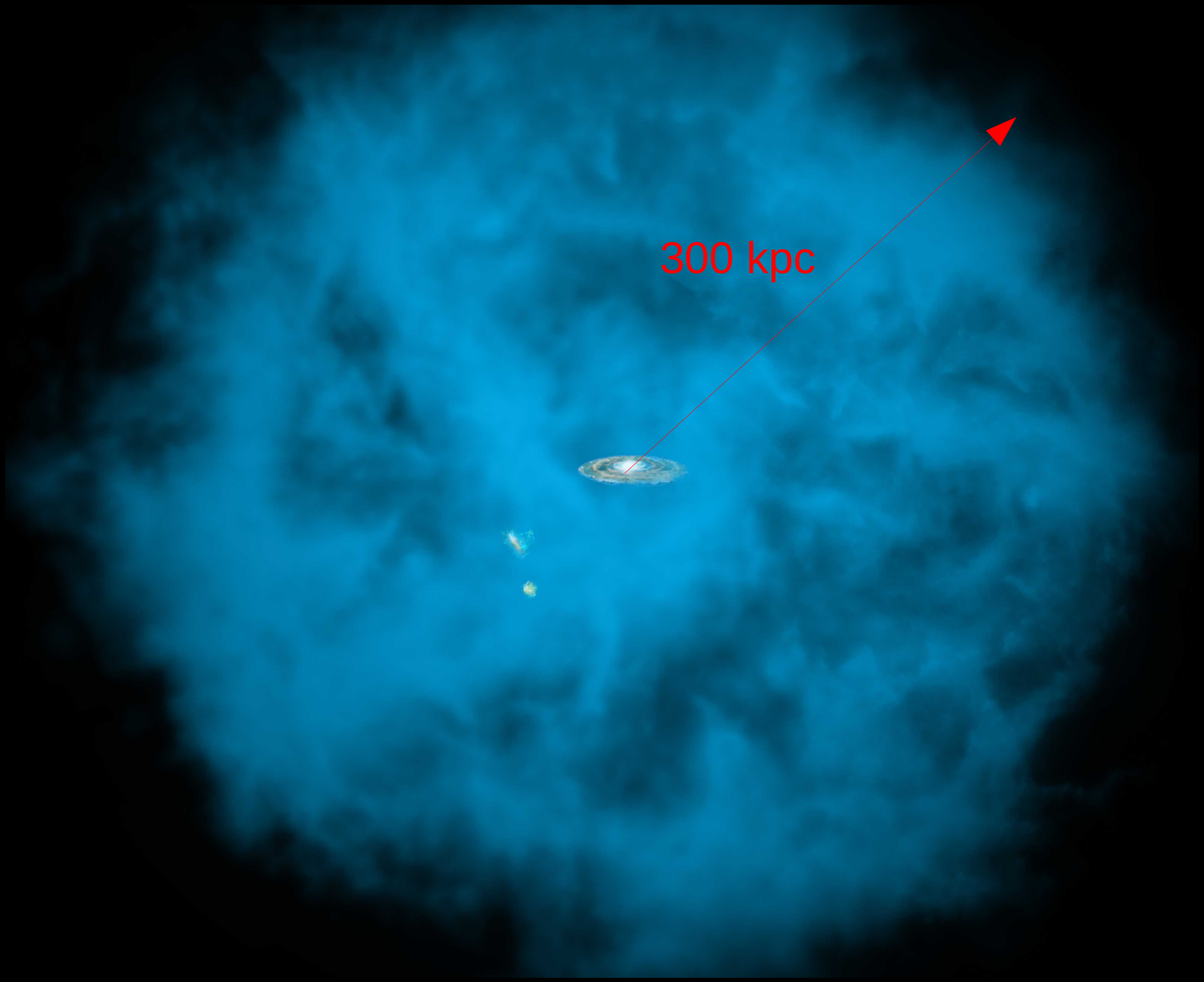
dark component : dark matter halo

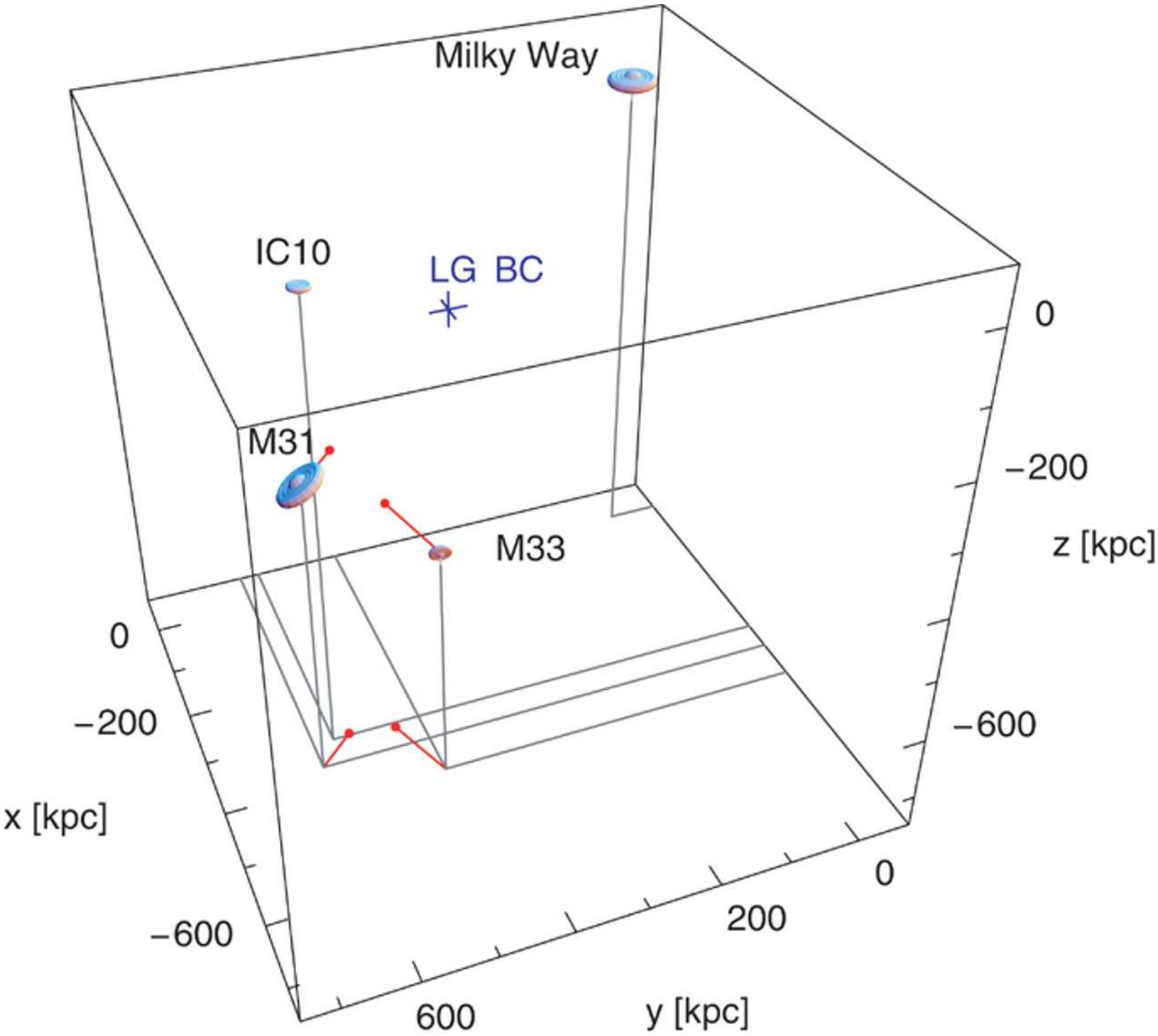
about 90% of the total mass, 10^{12} $M_\odot$



dark component : dark matter halo

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




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} $M_\odot$

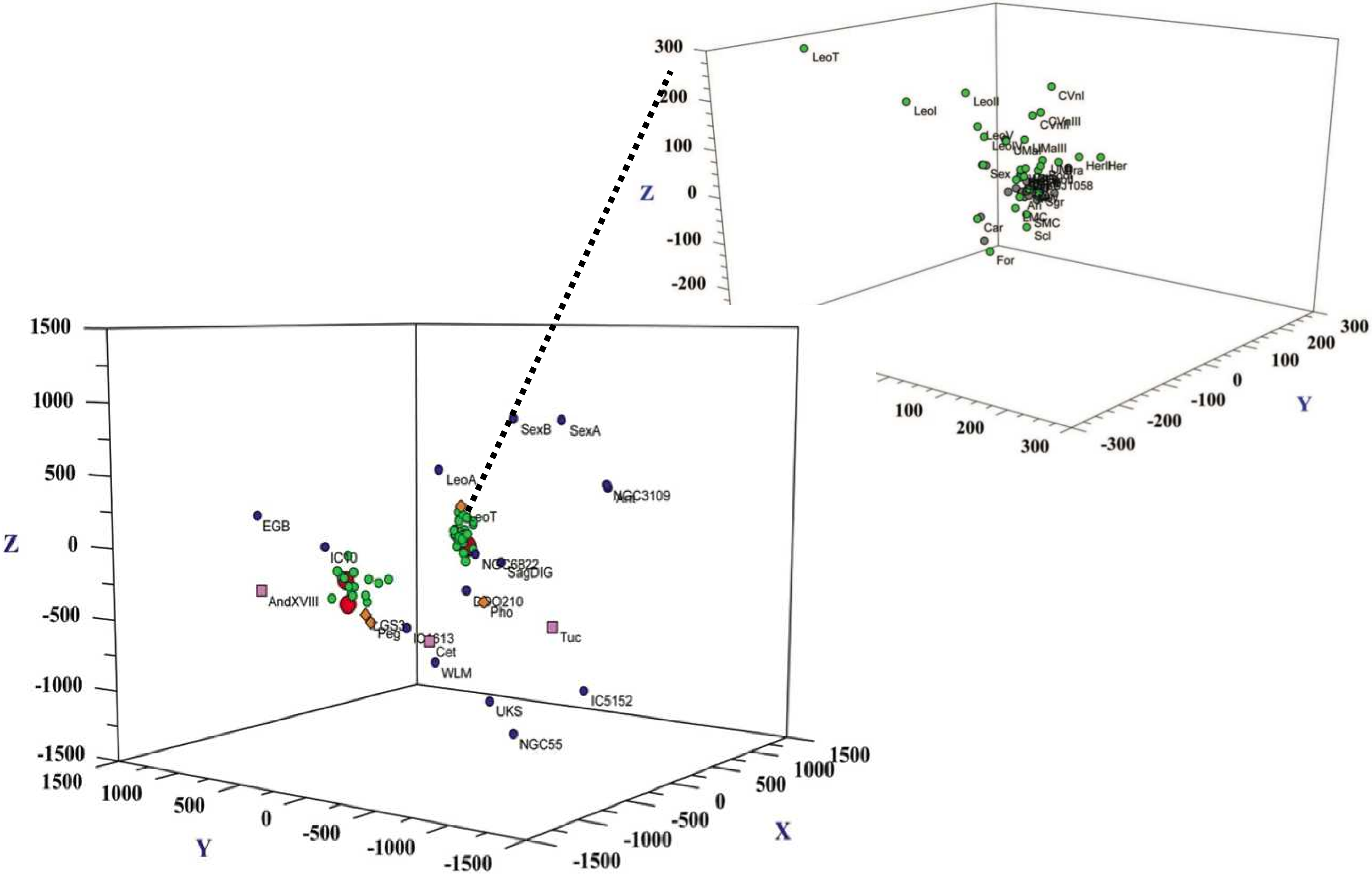
M33 : The Triangulum Galaxy

distance 847 kpc, total mass $6x10^{10}$ $M_{\odot}$

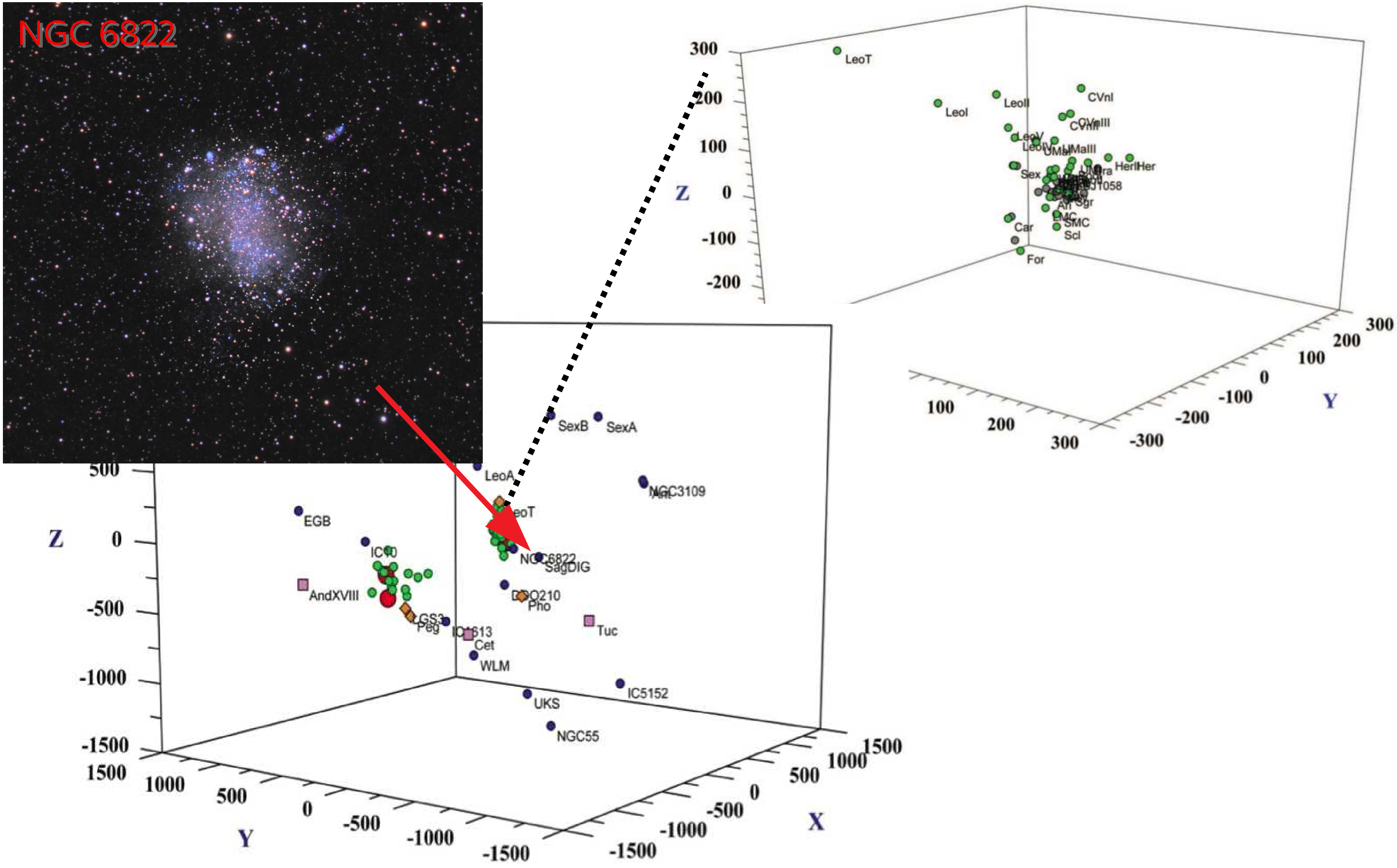
IC 10 : an irregular galaxy

distance 660 kpc, total mass ~$2\times10^9\,M_\odot$

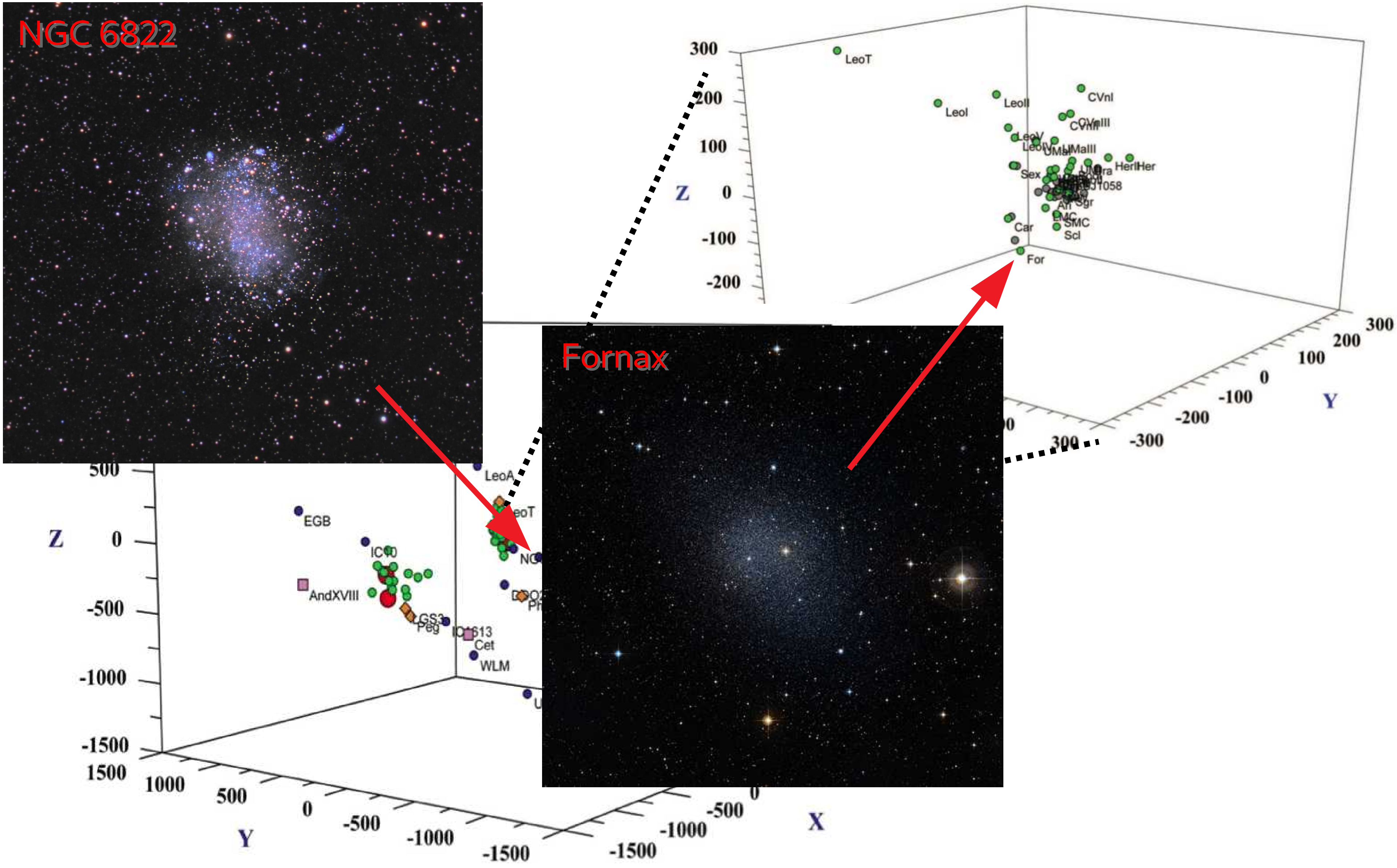
+ about 130 satellite dwarfs...



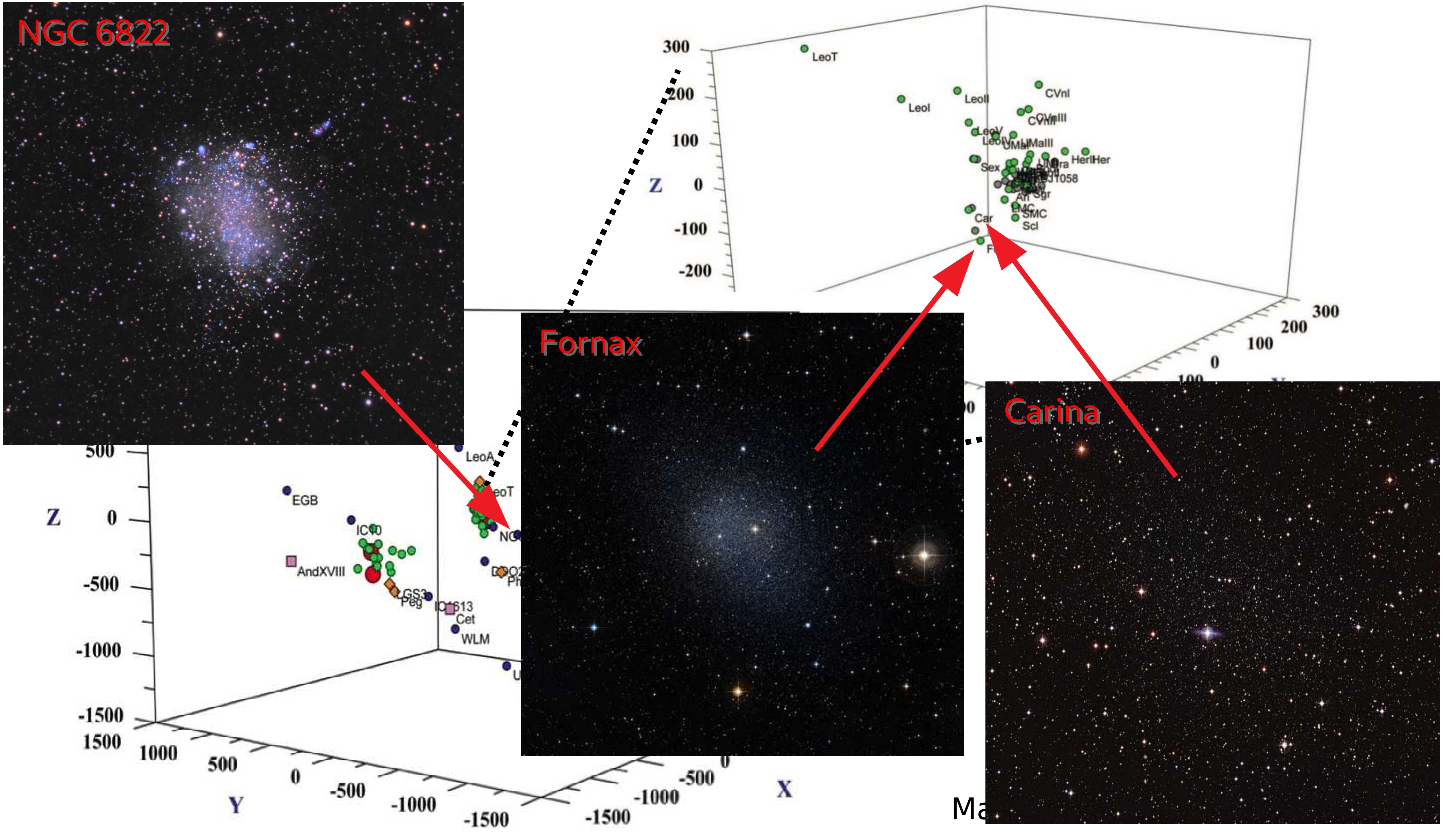
+ about 130 satellite dwarfs...



+ about 130 satellite dwarfs...

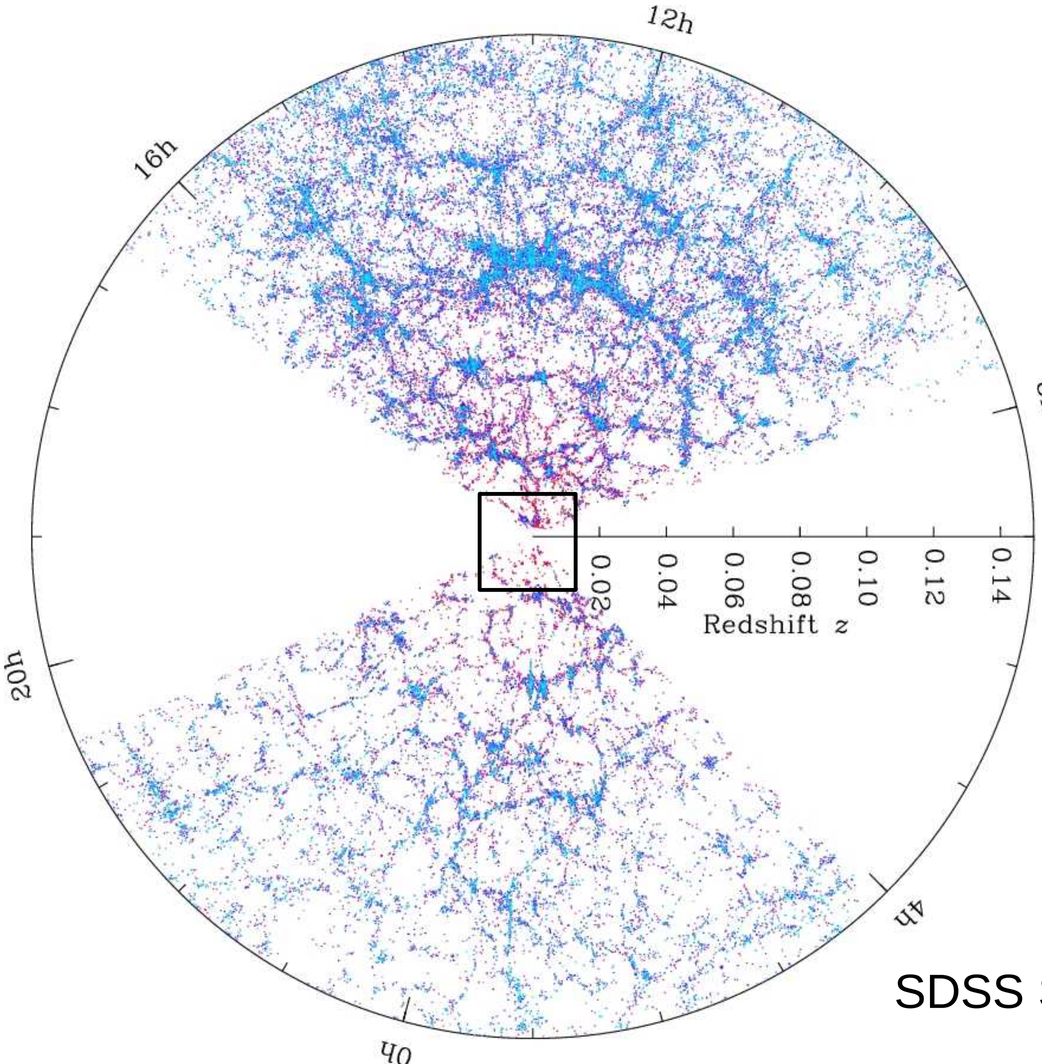


+ about 130 satellite dwarfs...



Observation of Galaxies

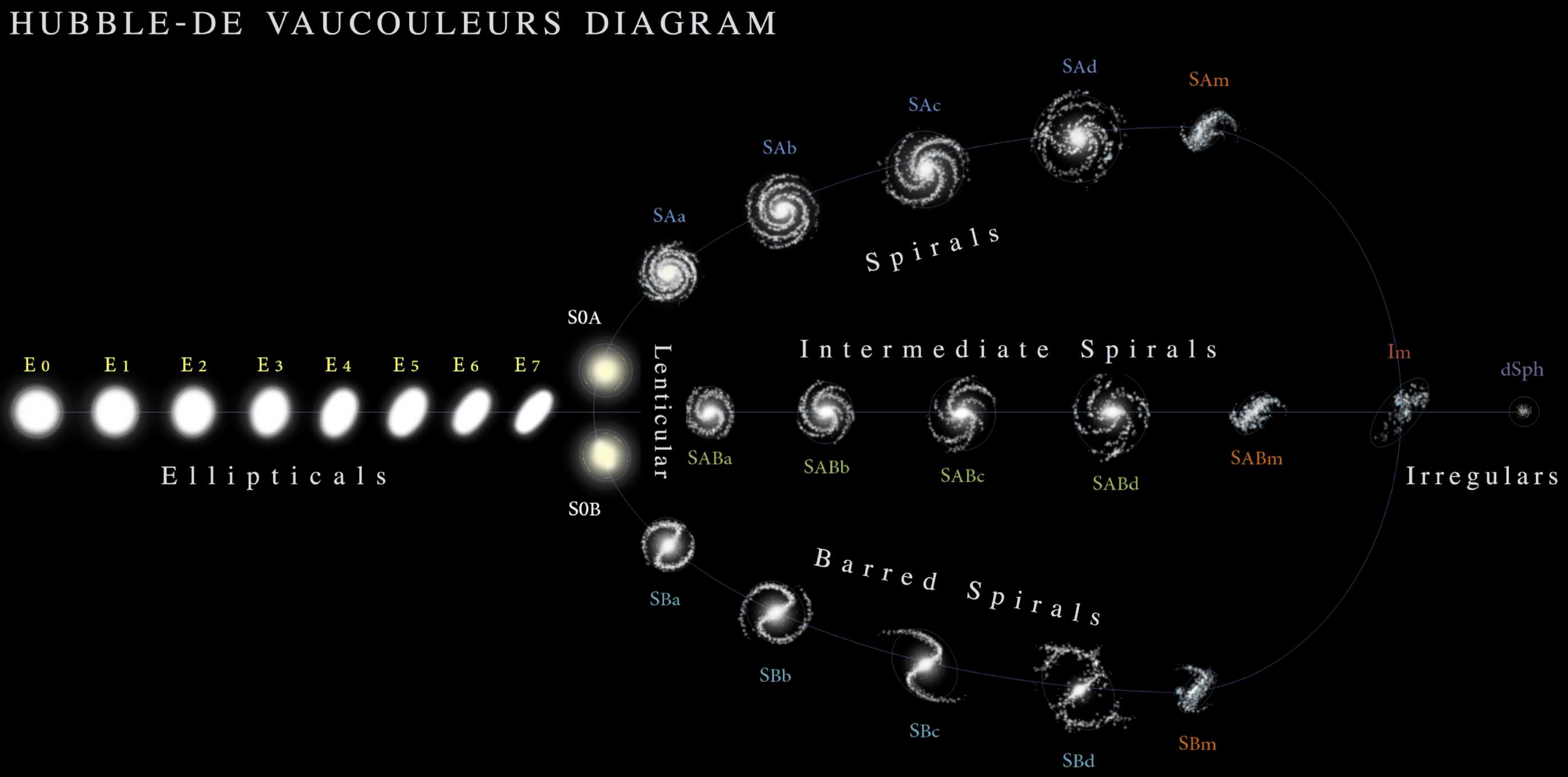
Beyond the LG



~500 galaxies
with D < 10 Mpc

SDSS Sloan Digital Sky Survey

The Hubble-De Vaucouleurs Sequence



The End