WELCOME !

Astrophysics III :

Stellar & Galactic Dynamics

FALL 2022

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

EPFL

Face Mask

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)
- Virtual reality
  - VIRUP: The Virtual Reality Universe Project
  - https://go.epfl.ch/virup

Contacts

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- Cubotron (BSP) 323
- Observatoire de Sauverny, 351


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Divonne-les-Bains
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Bonnevaux
Montriond

Astrophysics @ EPFL Teaching

- **Astro I:** Introduction à l'astrophysique (Bachelor 2nd)
  - Frédéric Courbin
- **Astro II:** Bases physiques de l'astrophysique (Bachelor 3rd)
  - Pascale Jablonka
- **Astro III:** Stellar and Galactic Dynamics (Master)
  - Yves Revaz
- **Astro IV:** Observational Cosmology (Master)
  - Jean-Paul Kneib
- The Variable Universe (EDPY)
  - Richard Anderson
- Dynamics of astrophysical fluids and plasmas (EDPY)
  - Jennifer Schober
- **MOOC:**
  - The radio-sky I : Science and Observations
    Frédéric Courbin, Jean-Paul Kneib
  - Introduction à l'astrophysique
    Frédéric Courbin

Astrophysics @ EPFL
Research

Research group leaders :
- Jean-Paul Kneib
- Michaela Hirschman
- Frédéric Courbin
- 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 Frédéric Courbin 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

≡

Evolution of a self-gravitating system

Introduction

Outlines

Week 1:

Introduction I

- The standard model in cosmology
- Which physics
- Our galaxy the Milky Way
- The Local Group
- Luminosity Distribution Function
- The Hubble Lemaître Law

Week 2:

Introduction II

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

The gravity : a long distance force

- collision-less systems : the relaxation time

Week 3:

Newton Mechanics (quick reminder)

The Potential Theory I

- General results
  - Newton law, gravitational field force and potential
  - The Poisson Equation
  - Gauss Theorem
  - Total potential energy
- 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 ?
  - yes, but not of this year
- Additional material ?
  - yes, on moodle.epfl.ch

Exam

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

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- N. Deruelle & J.-P. Uzan
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  - An Introduction to the Study of Stellar Structure, Dover Publications, 1939
- S. Chandrasekhar
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- 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

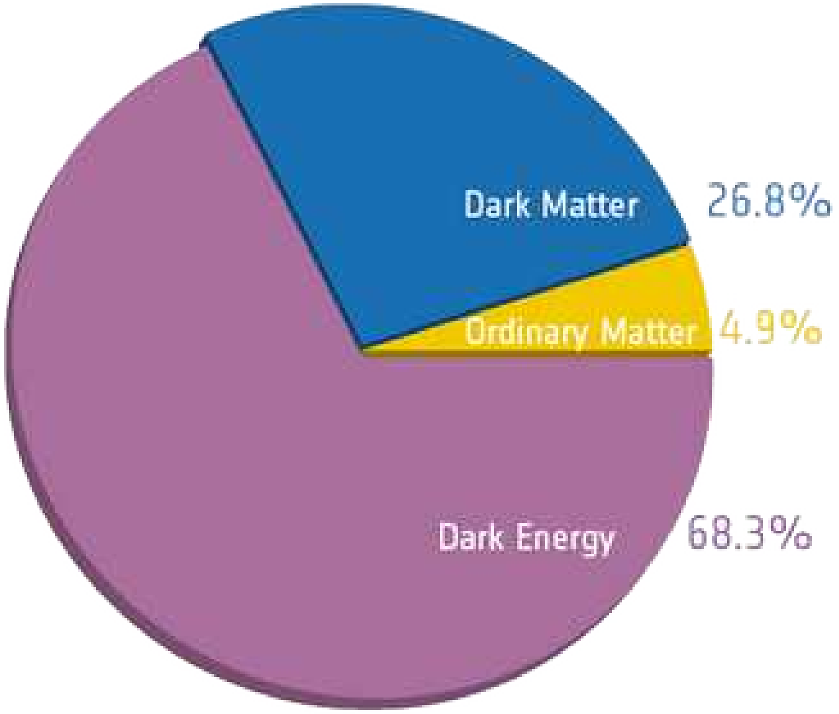
The cosmological principle:

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

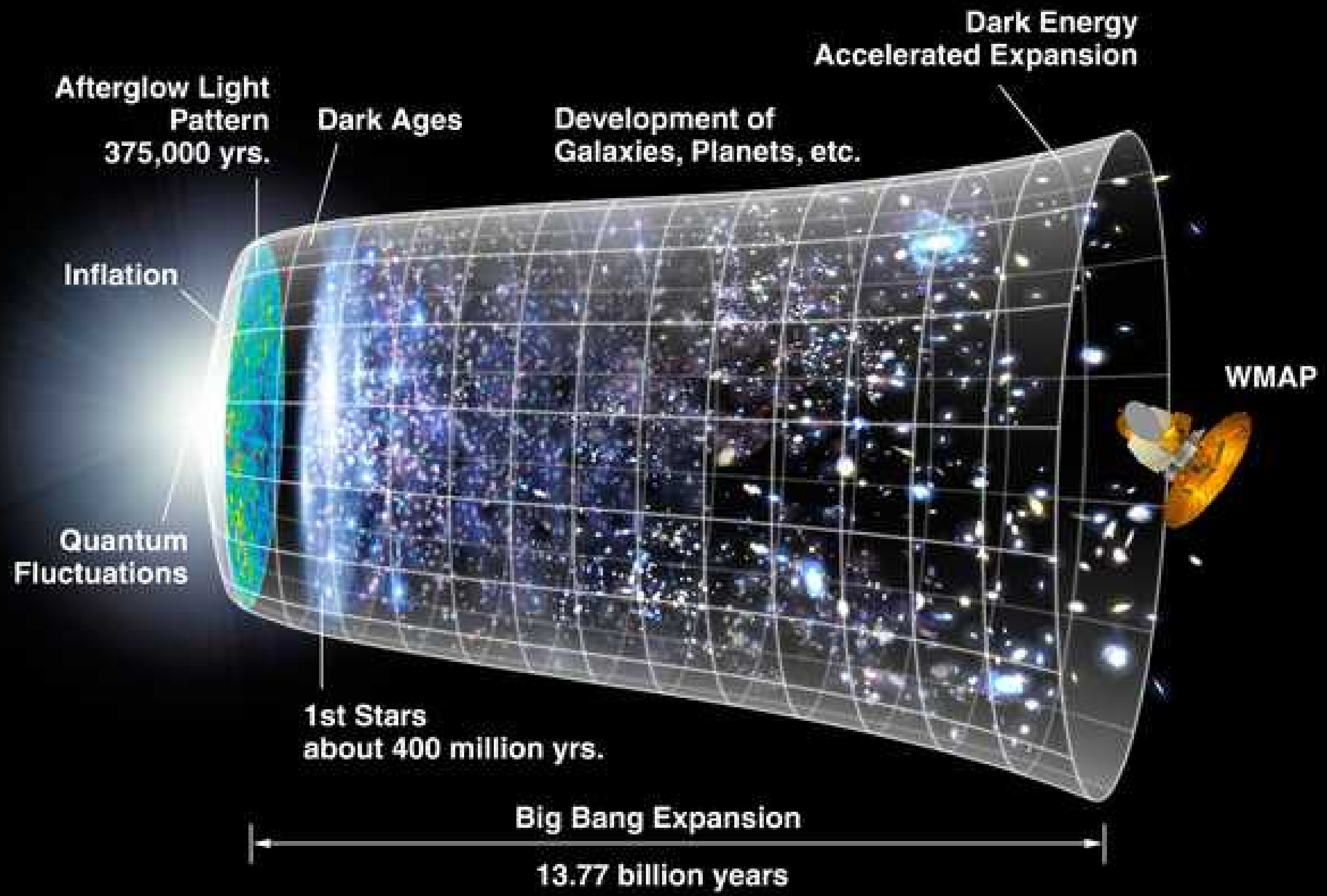
$$\Omega_M + \Omega_K + \Omega_\Lambda = 1$$



(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

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Brian P. Schmidt

Prize share: 1/4

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Adam G. Riess

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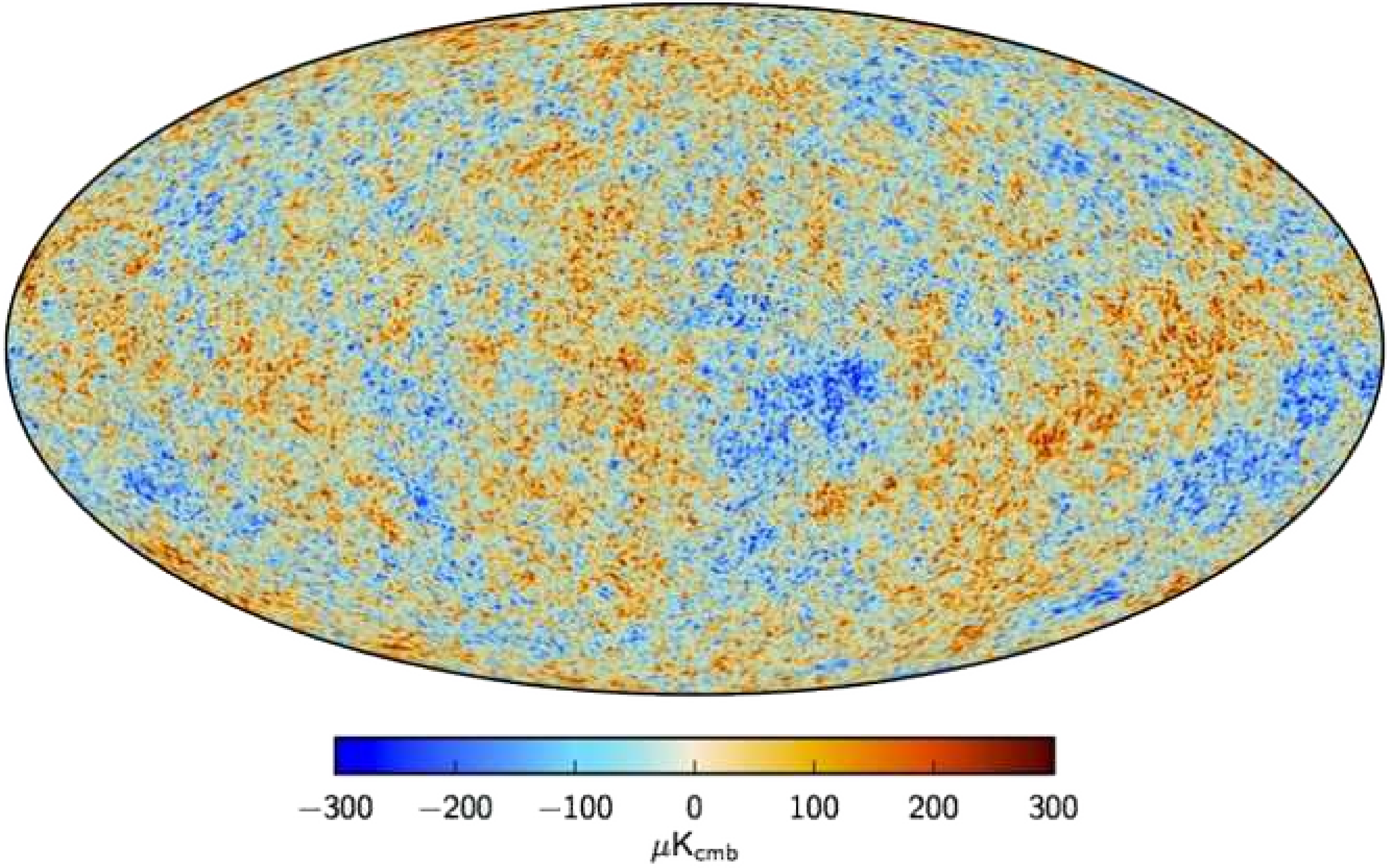
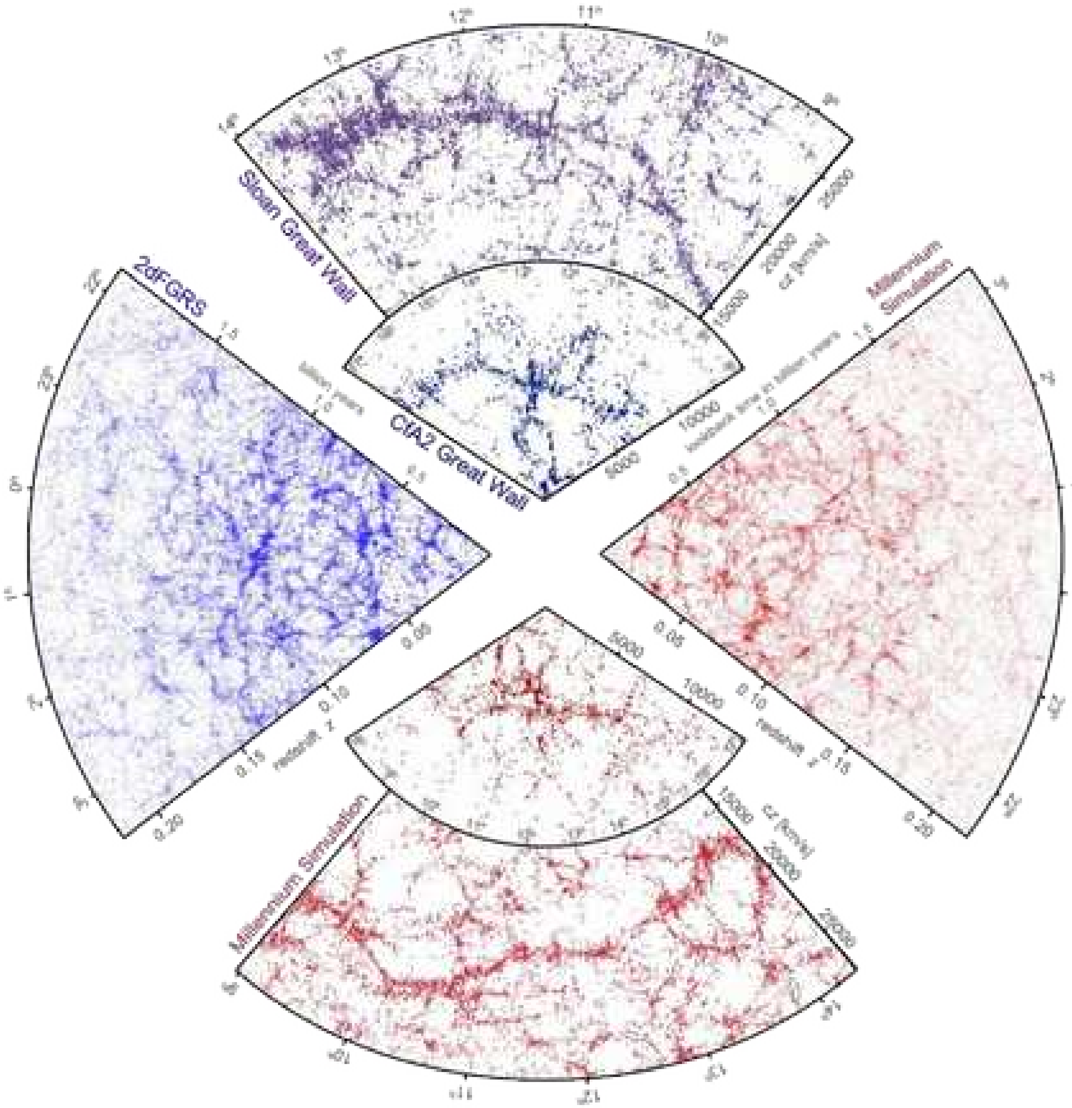
Temperature/Density fluctuations of the universe (CMB) at the recombination epoch, when it was only 380'000 years old

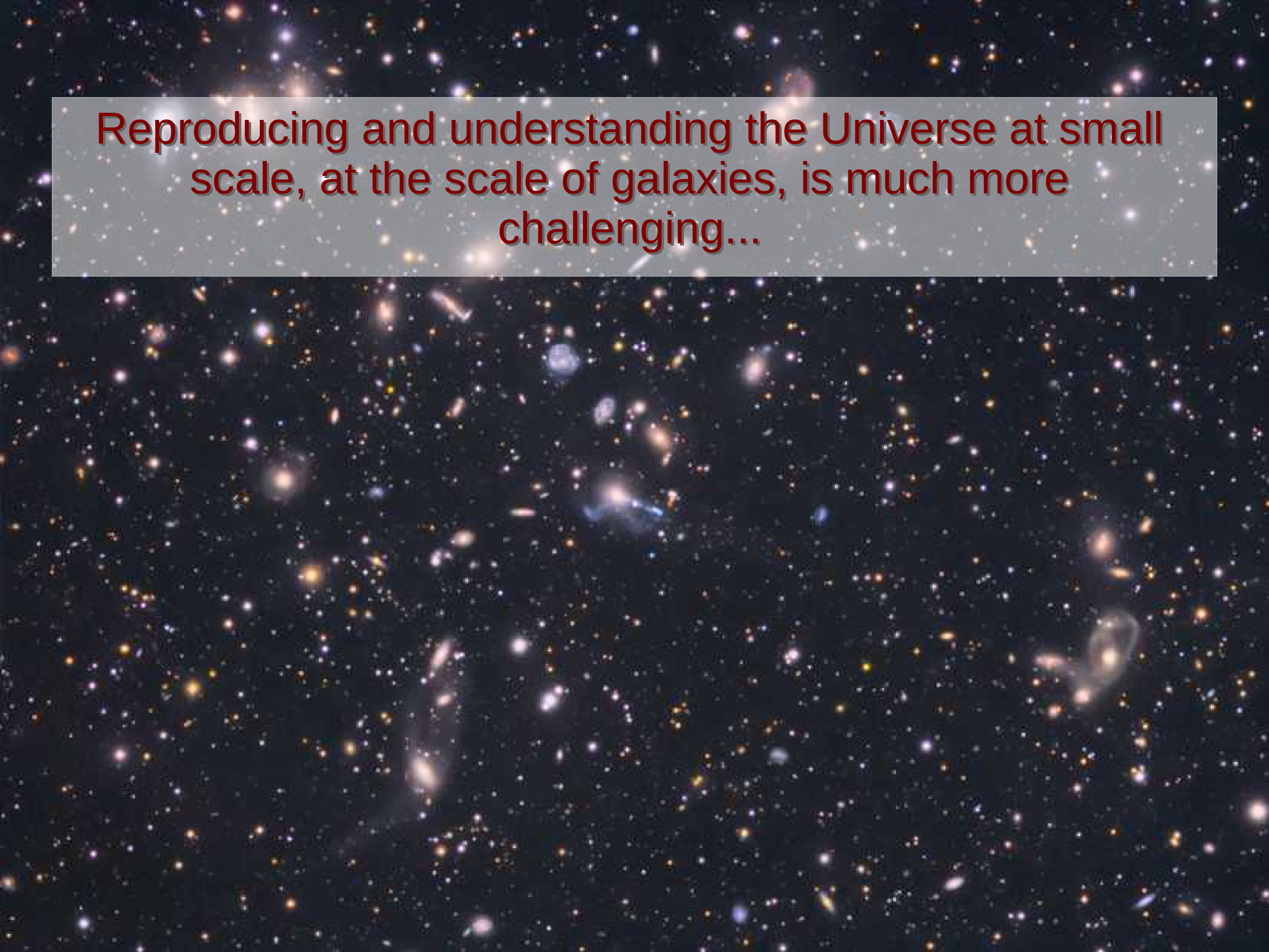


Credit : the Planck collaboration

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 ?

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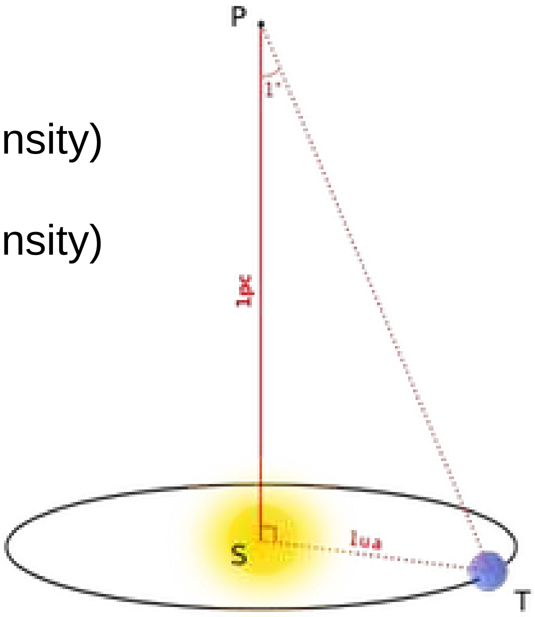
- Magnetic fields
- Thermal conductivity
- Dust
- ...

Units

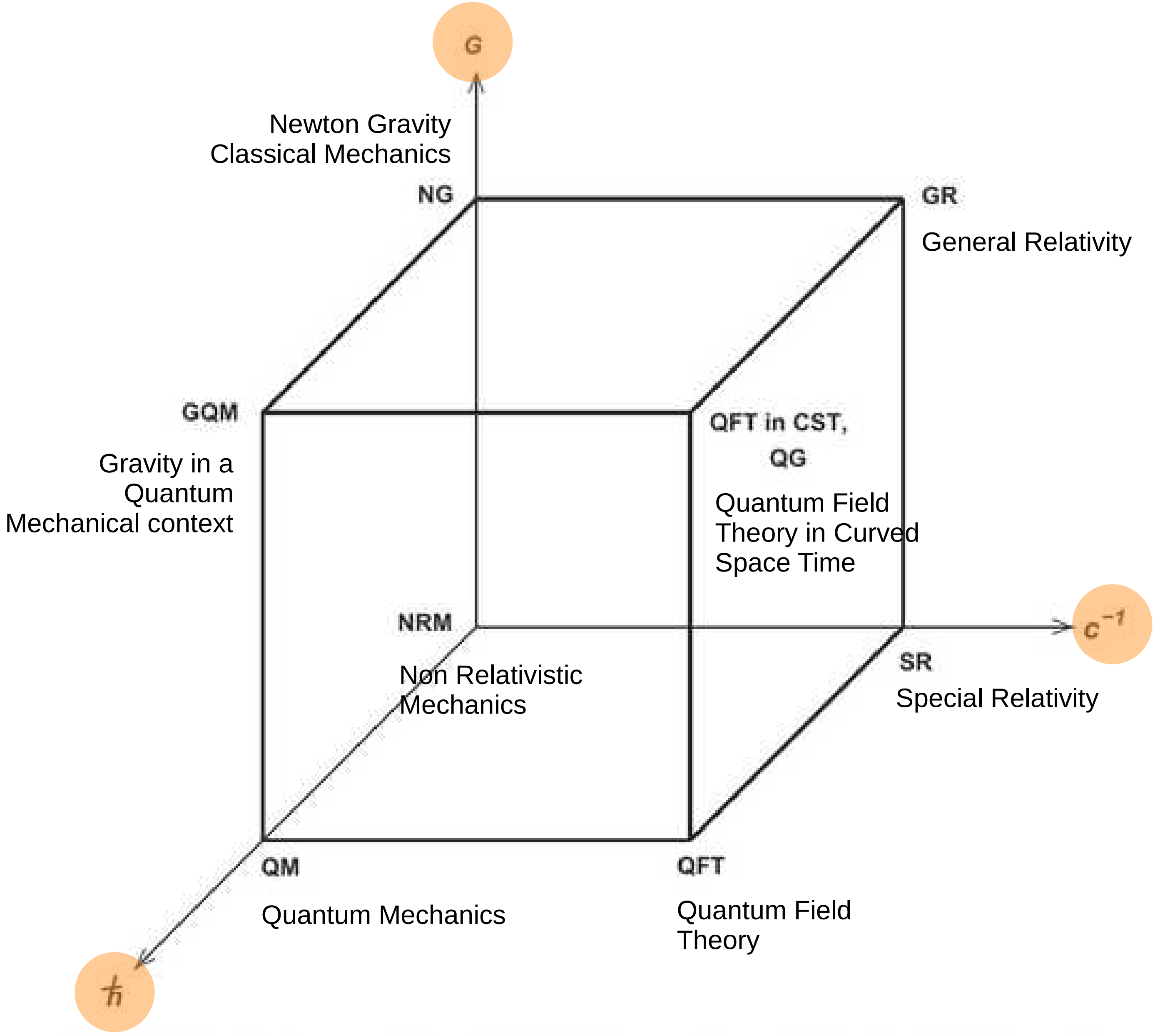
Distances:	Parsec (pc)	= 3.2616 light year = 3.085x10^{16} meter
Masses:	Solar Mass ($M_\odot$)	= 2x10^{30} kg
Luminosities:	Solar Luminosity ($L_\odot$)	= 3x10^{26} Watt
Time:	Giga Year (Gyr)	= 10^{9} yr
	Mega Year (Myr)	= 10^{6} yr
Speed:	km/s	= km/s
Densities	atom/cm^3	= 1.7x10^{-21} kg/m^3 (air density)
	$M_\odot$ / pc^3	= 6.7x10^{-20} kg/m^3 (air density)



Credit : wikipedia

The cube of theoretical physics

Sleeping Beauties in Theoretical Physics (T. Padmanabhan)



Newton Gravity
Classical Mechanics

General Relativity

Gravity in a
Quantum
Mechanical context

Quantum Field
Theory in Curved
Space Time

Non Relativistic
Mechanics

Special Relativity

Quantum Mechanics

Quantum Field
Theory

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.

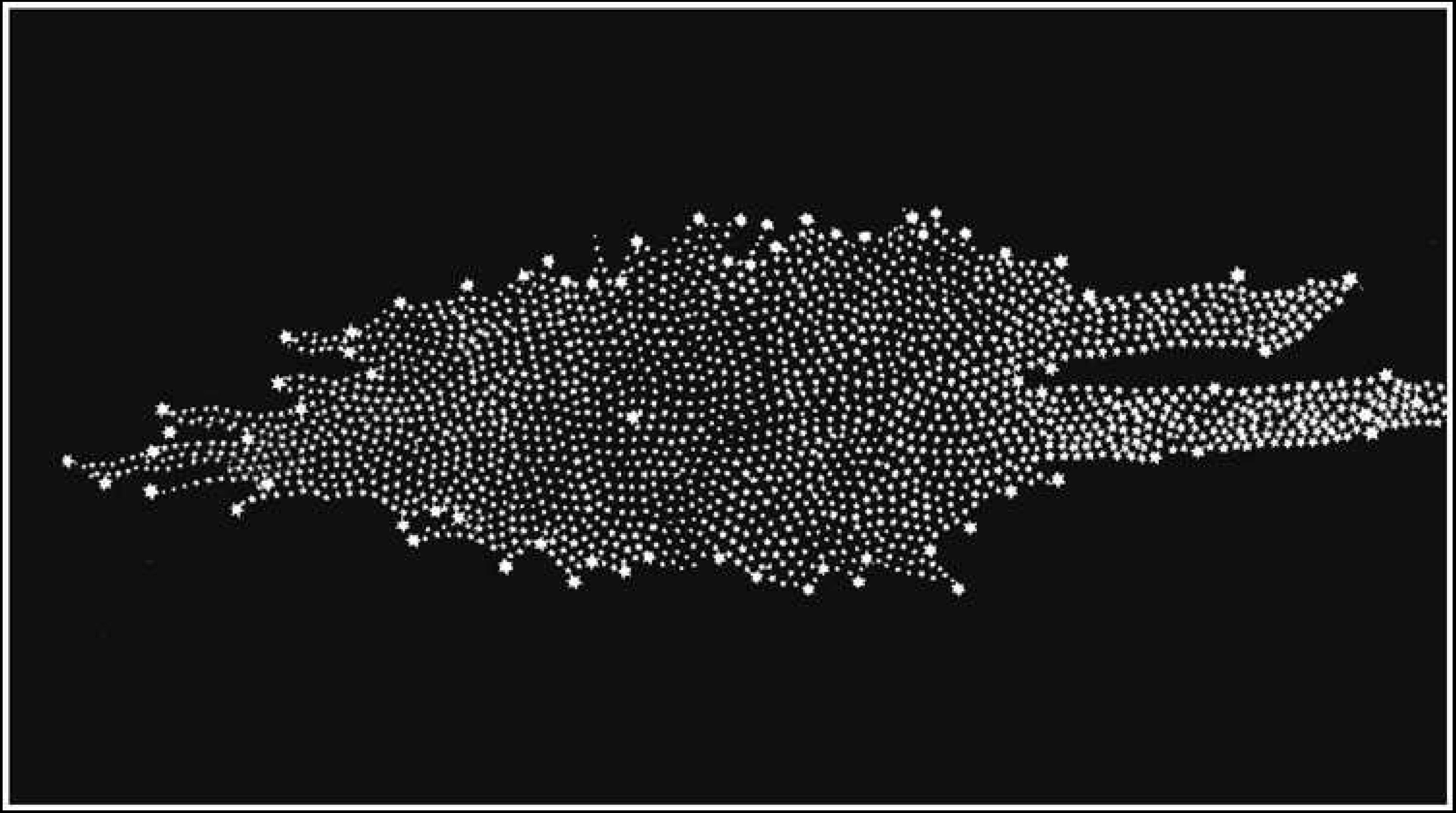
Introduction

Our galaxy
The Milky Way

William Herschel

1738 – 1822

First stellar counts to map the structure of the Galaxy (1783)



The Milky Way : a disky galaxy

M83

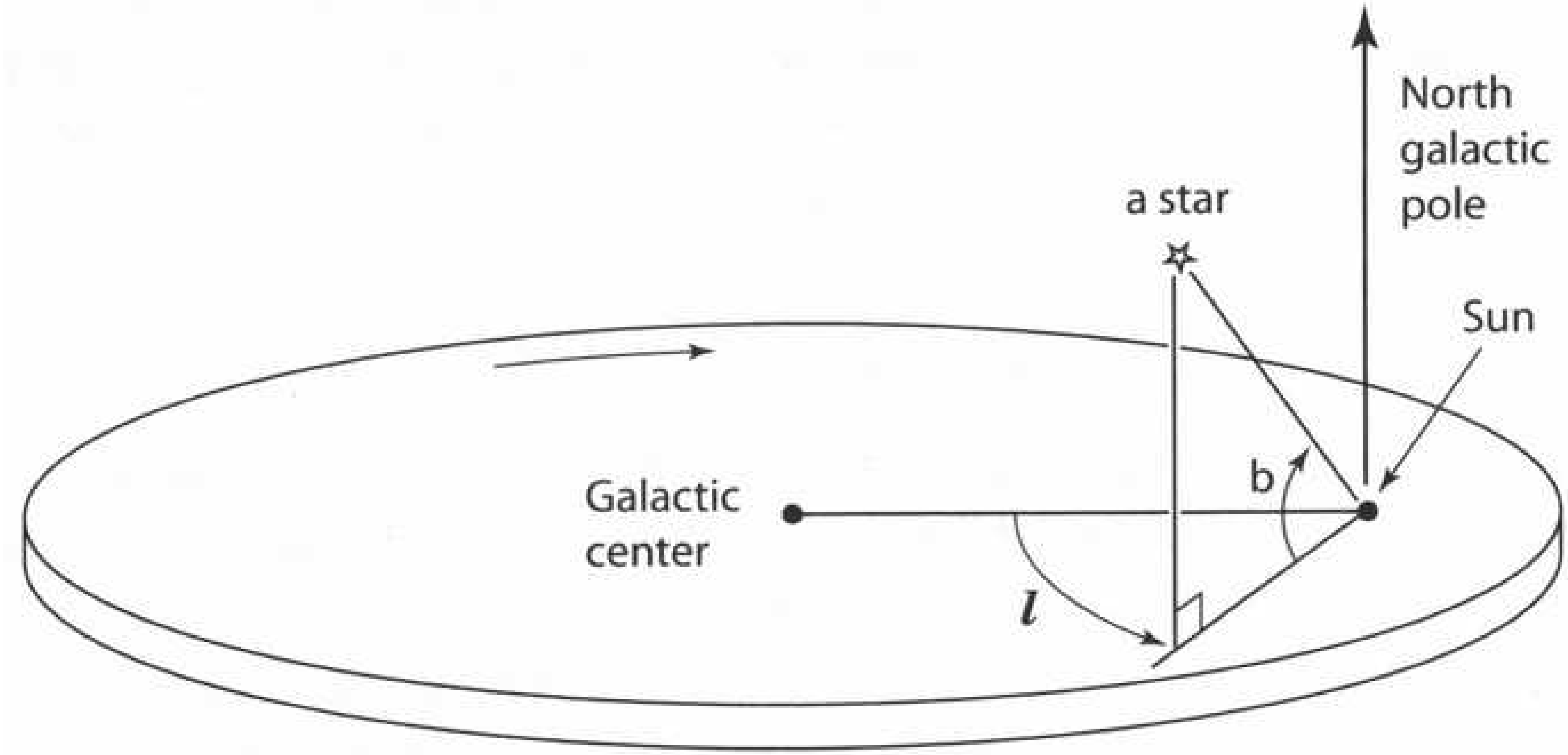
NGC4945

Position of the Sun

M83

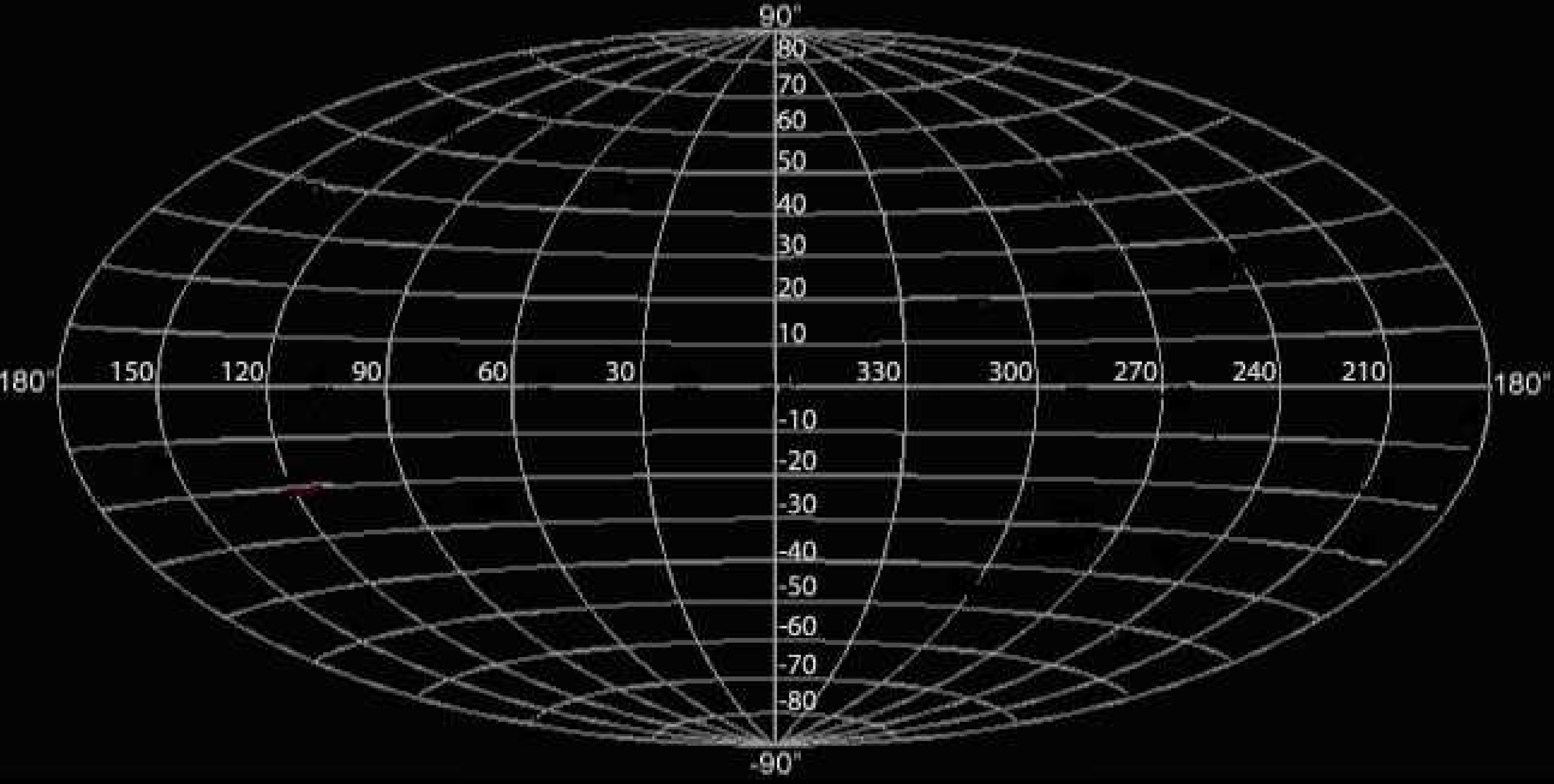
NGC4945

The galactic heliocentric coordinate system



the galactic plane

l : galactic longitude [0º,-360º]
b : galactic latitude [-90º,+90º]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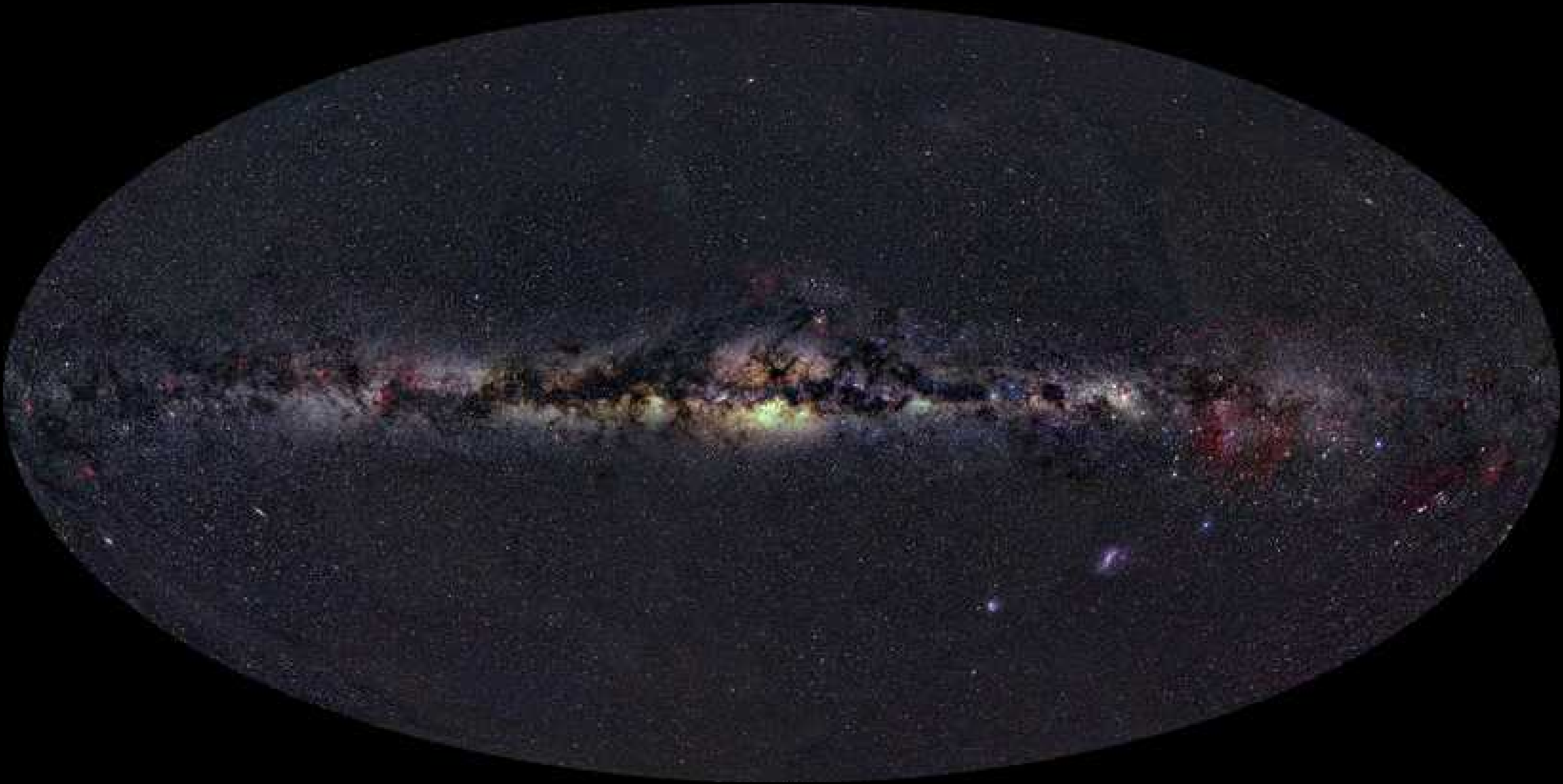
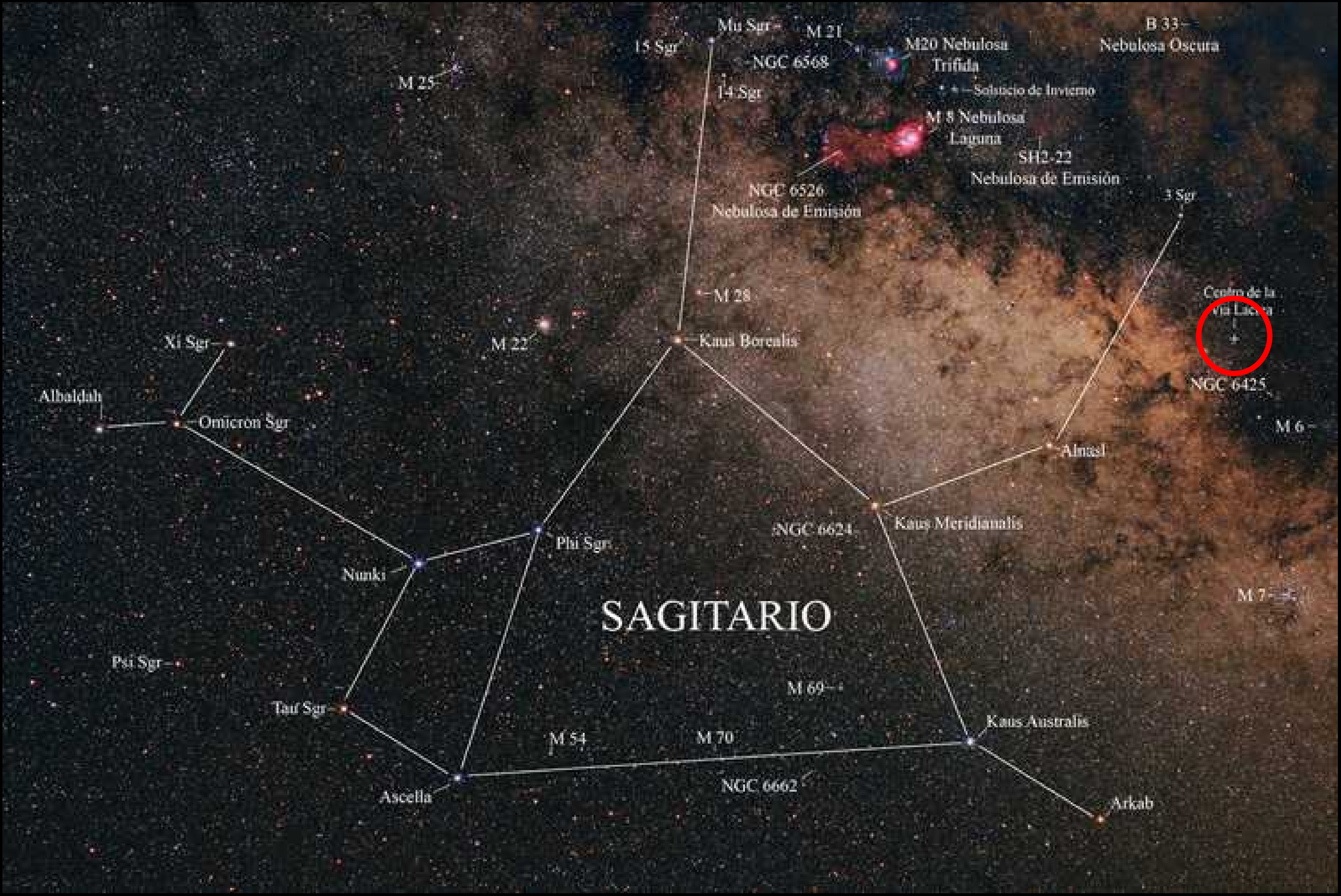


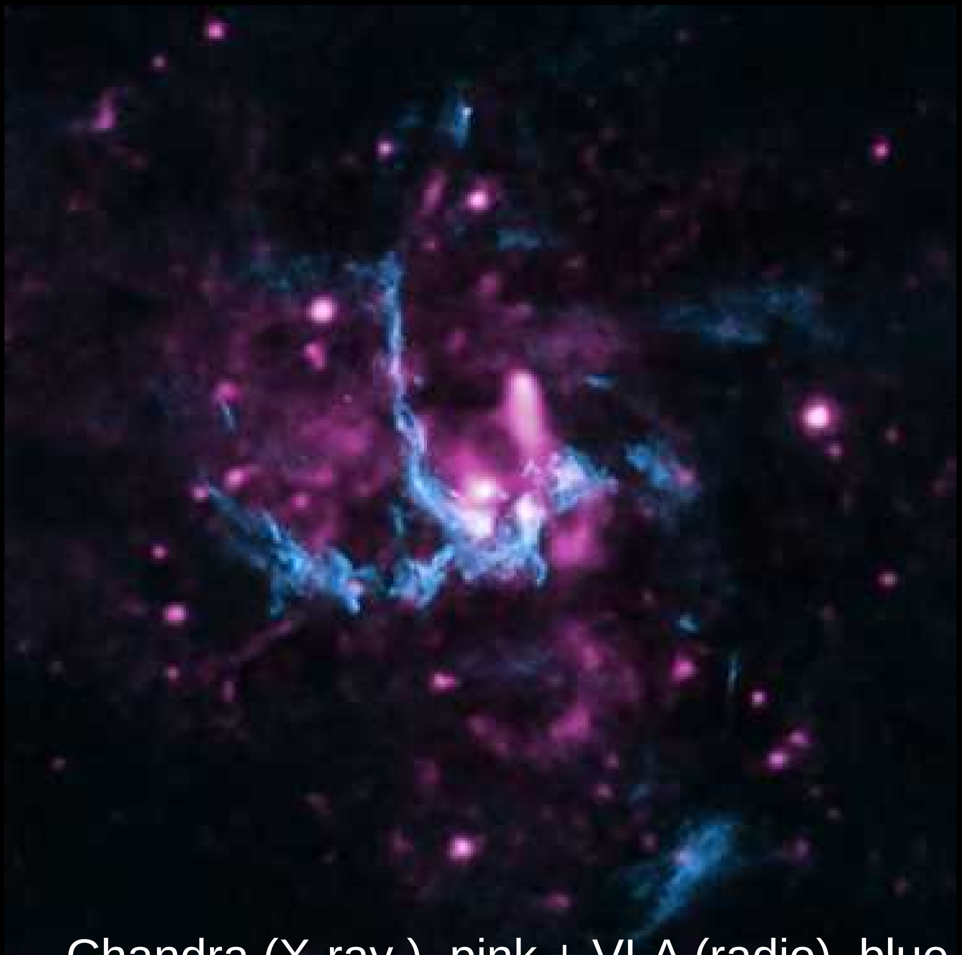
The Galactic Centre



The Galactic Centre

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

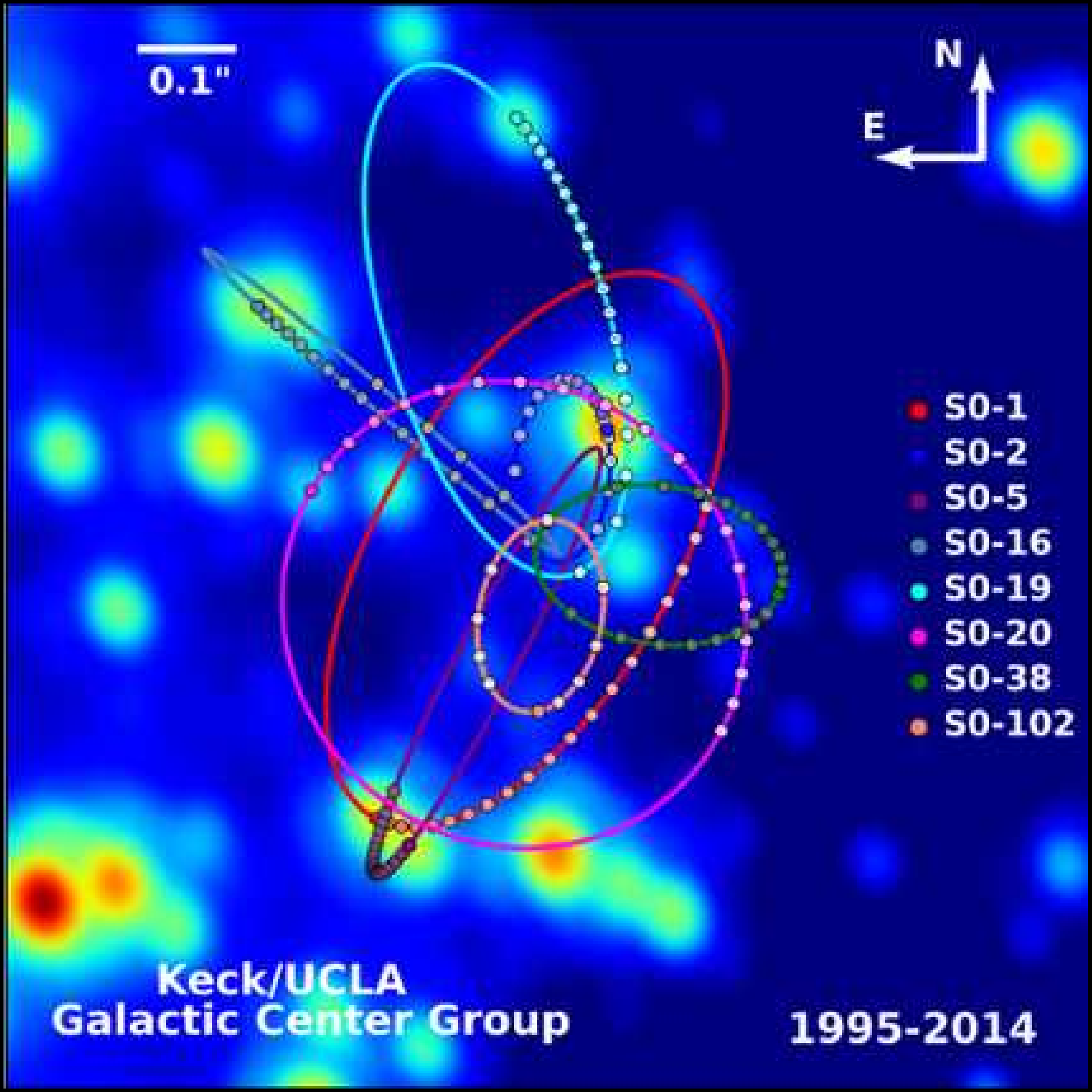
Location : 17h45m 40.0409s (RA), -29º0’28.118’’ (DEC)
Distance: 25.900±1.400 light years (7.940±420 pc)
Mass: 4.31±0.38 10^6 $M_\odot$



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

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Andrea Ghez

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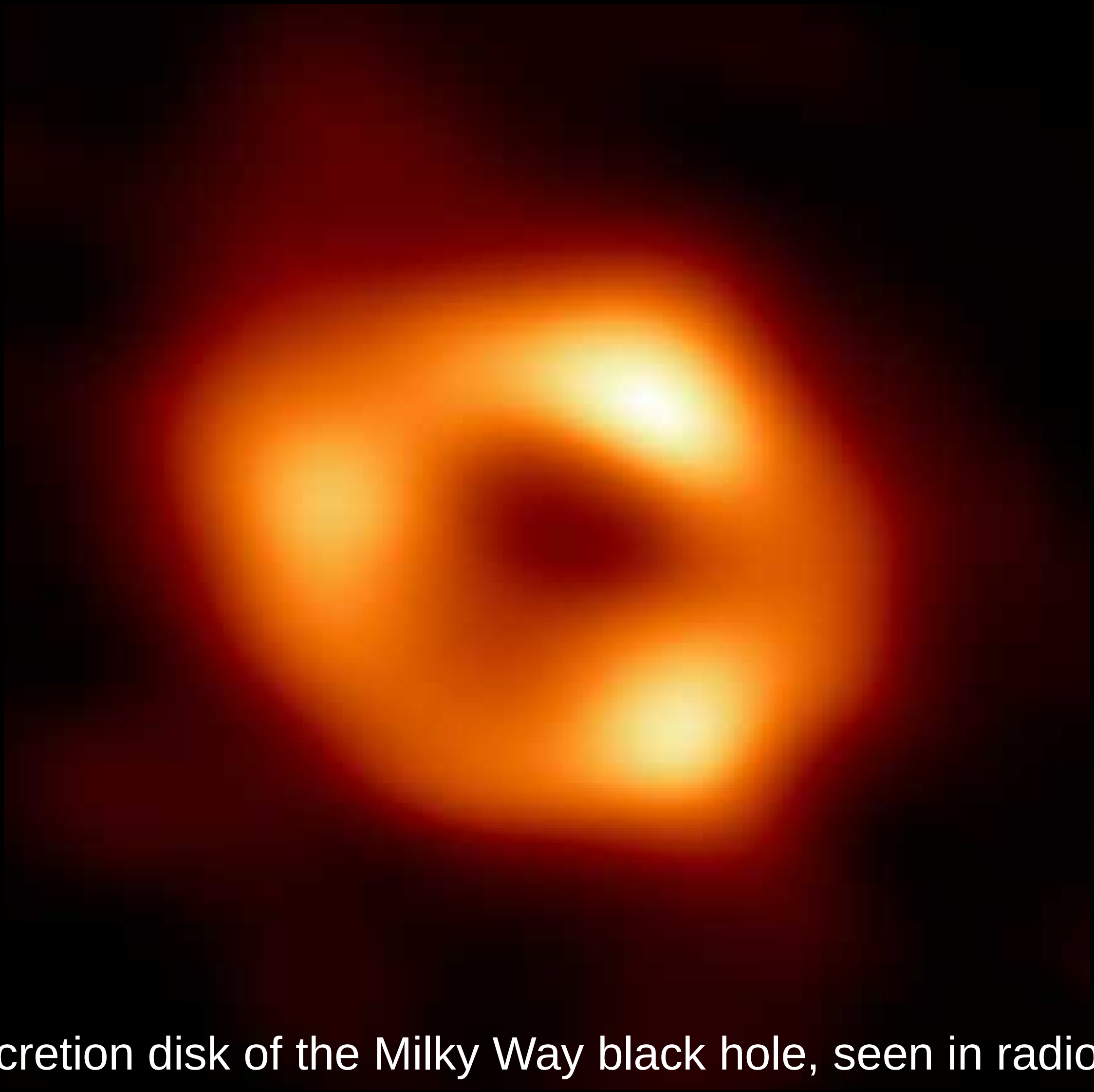
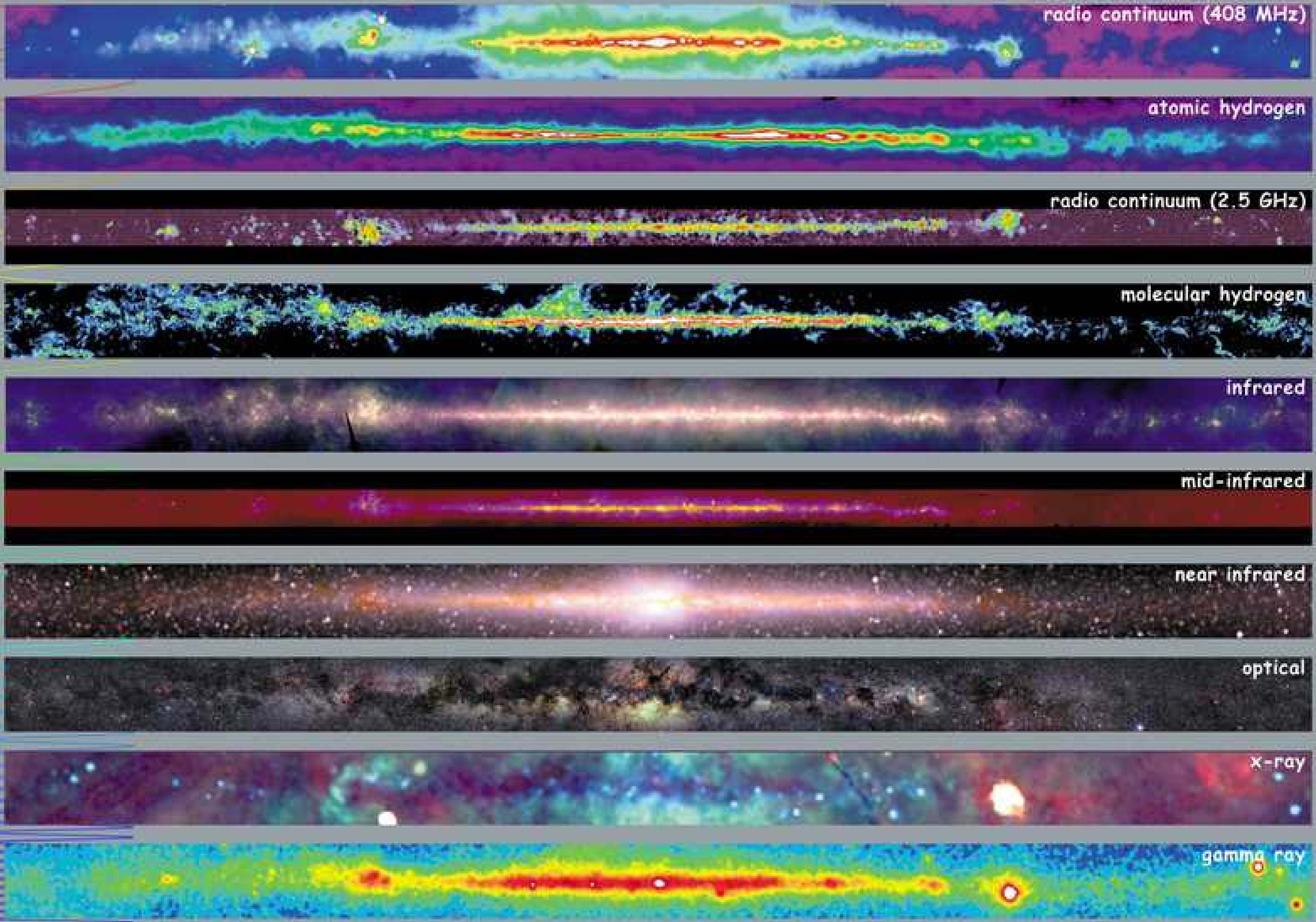
Event Horizon Telescope (EHT)



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

The Milky Way in different wavelength

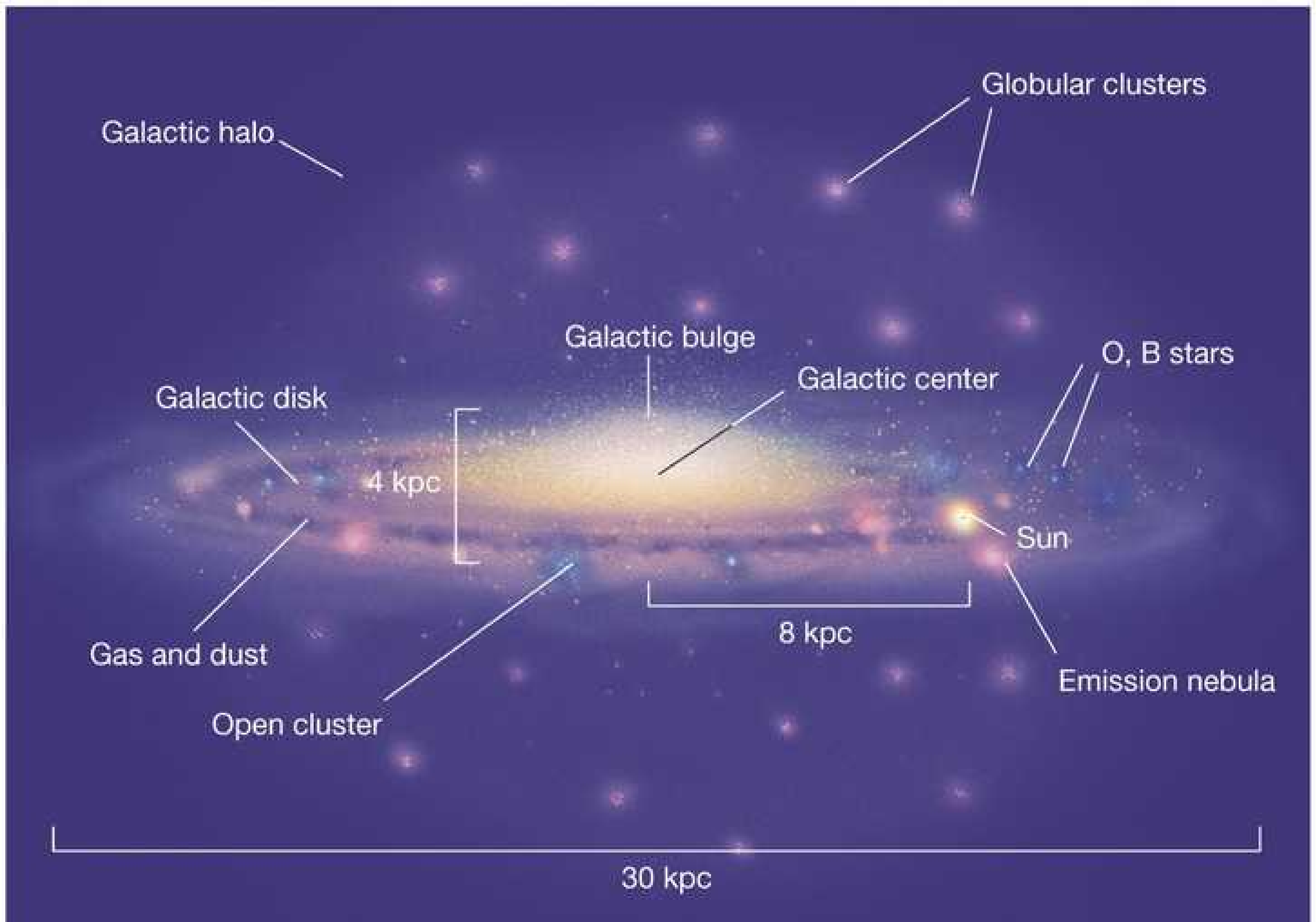
The Milky Way in different wavelength



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

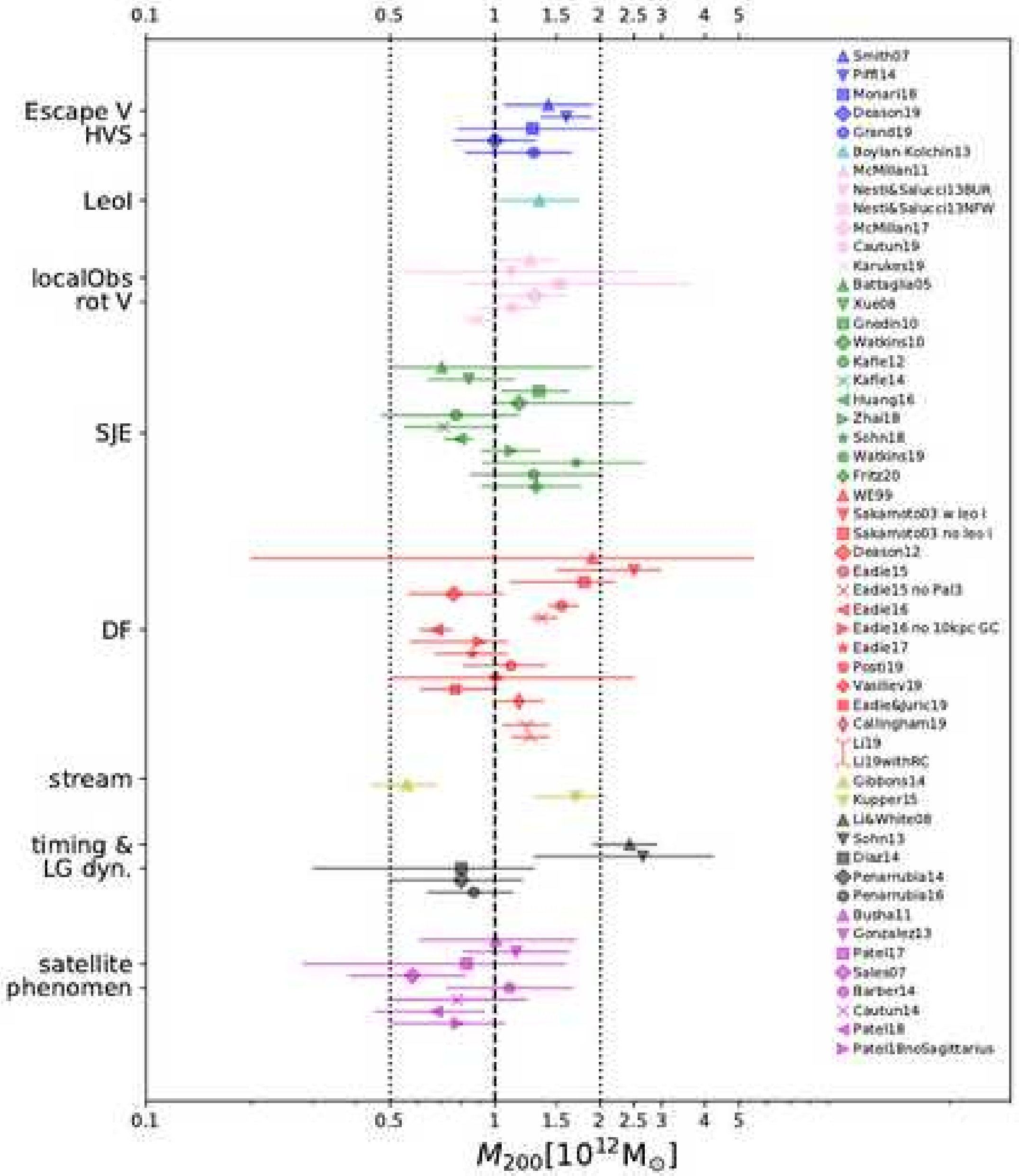
Multiwavelength Milky Way

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:

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

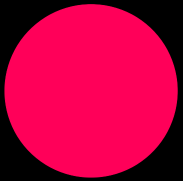
Rotation :

200 Myr (sun)
500 Myr (ext.)

Stellar component : bulge/bar

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

- old stars
- RMS vel ~150 km/s

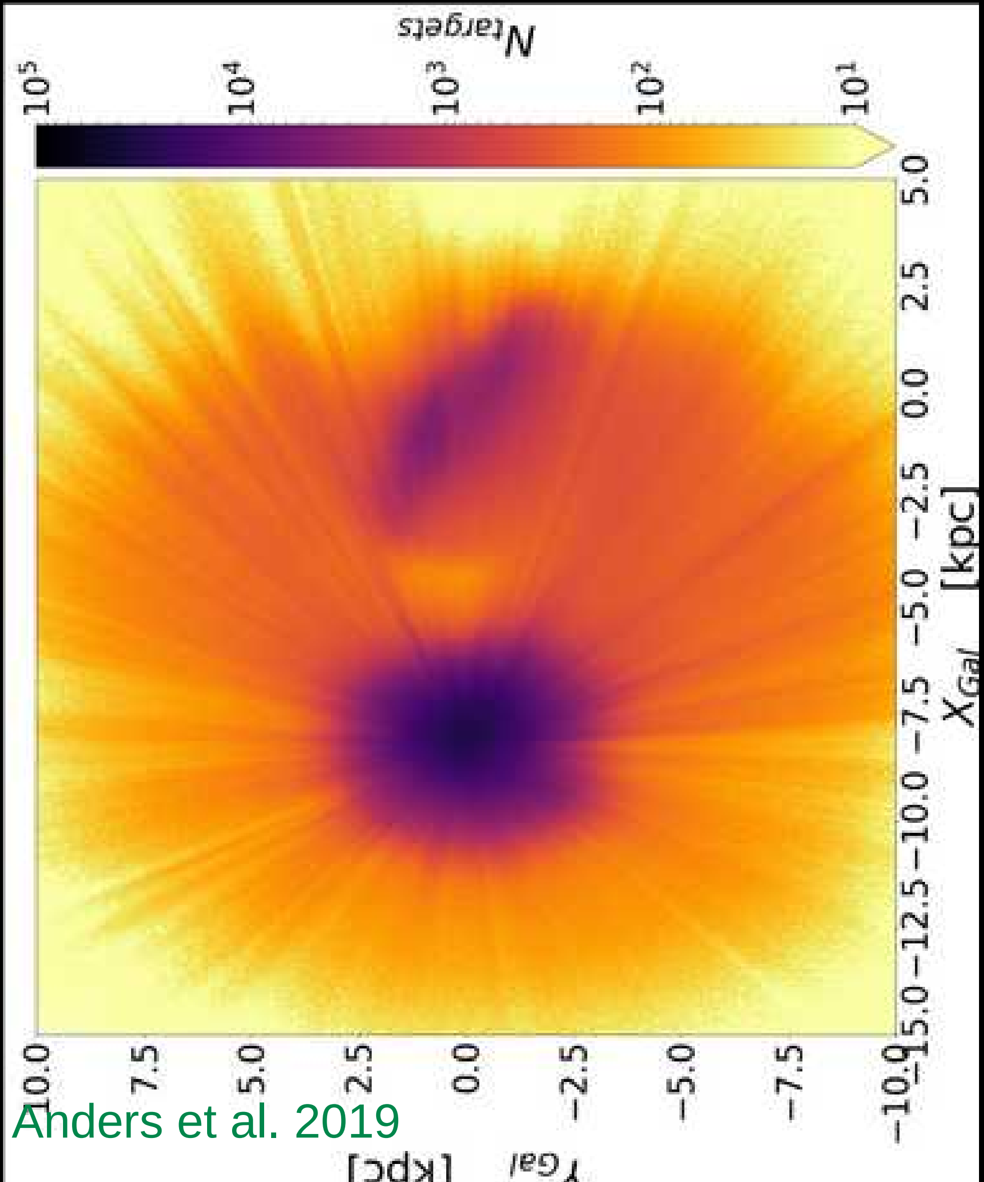


Stellar component : bulge/bar

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

265 millions of stars !

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



Anders et al. 2019

Stellar component : bulge/bar

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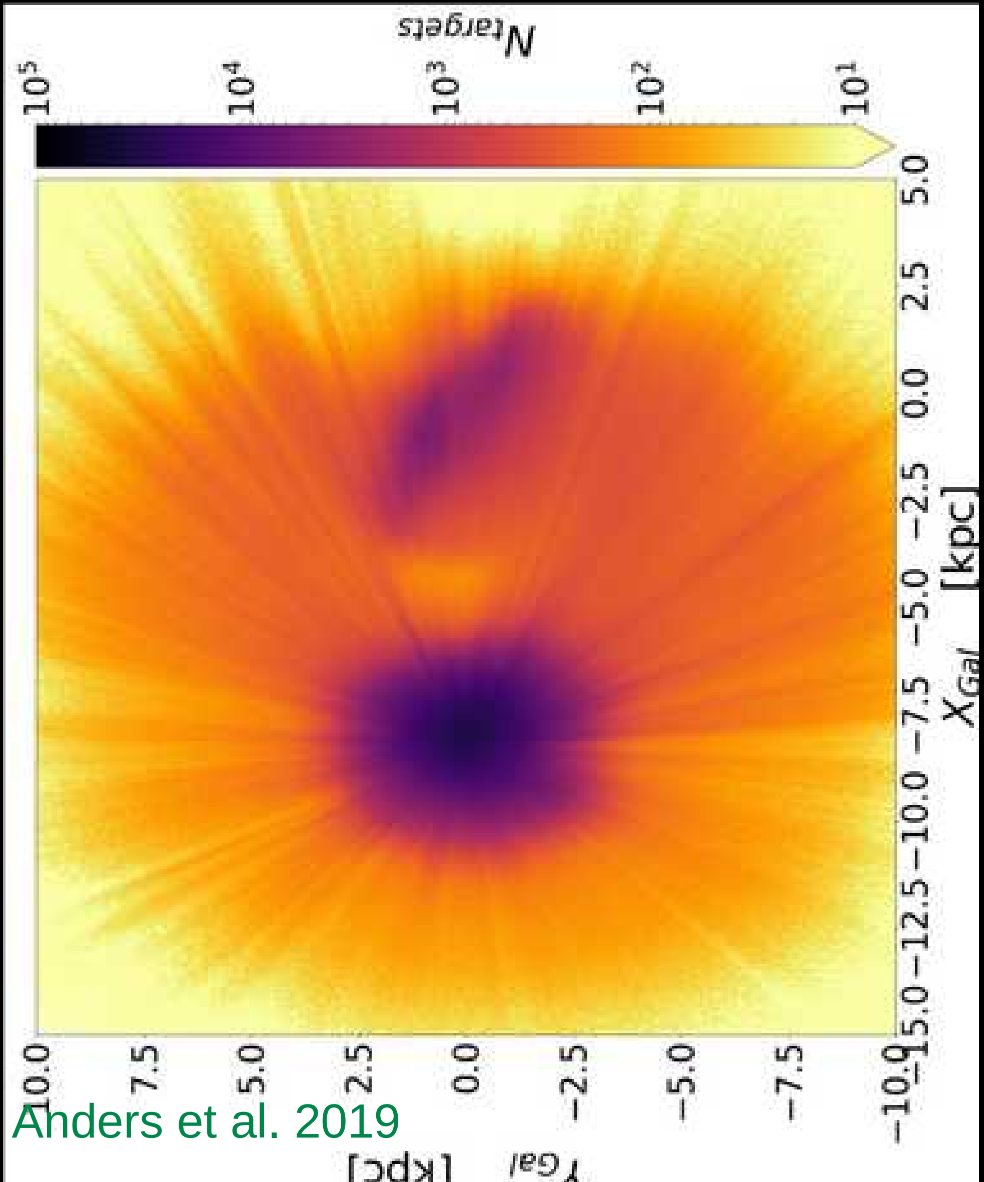
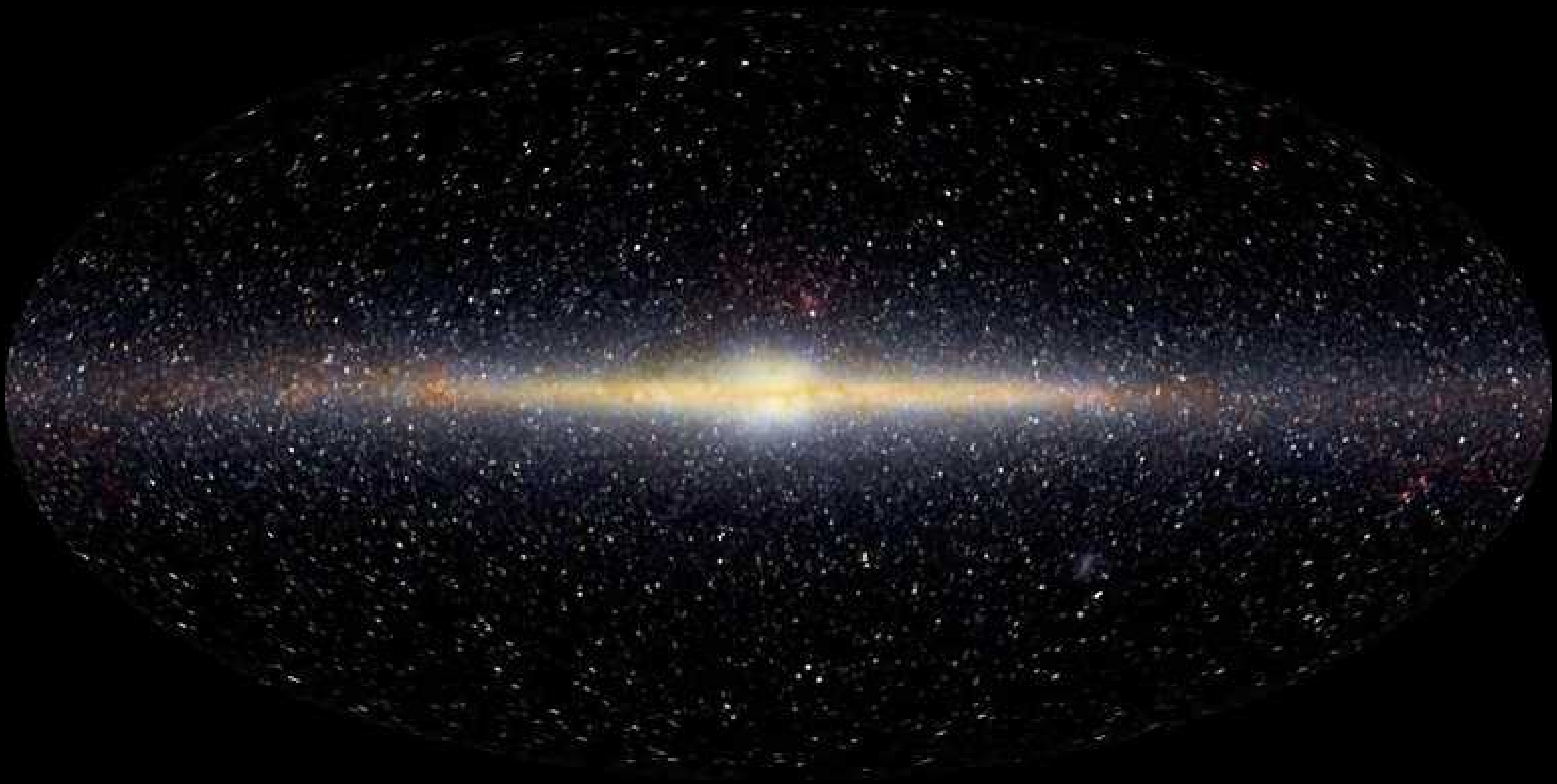
https://sci.esa.int/j/61461



Anders et al. 2019

COBE satellite view of the MW in infrared light

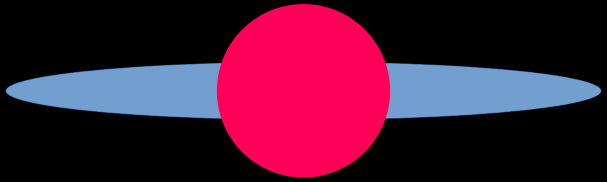


Robert Nemiroff (MTU) & Jerry Bonnell (USRA)

Stellar component : disk

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

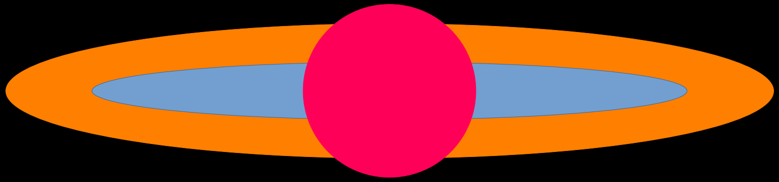
thin disk:
- 90% of the stellar disk
- scale height : ~300 pc
- RMS vel ~50 km/s



Stellar component : disk

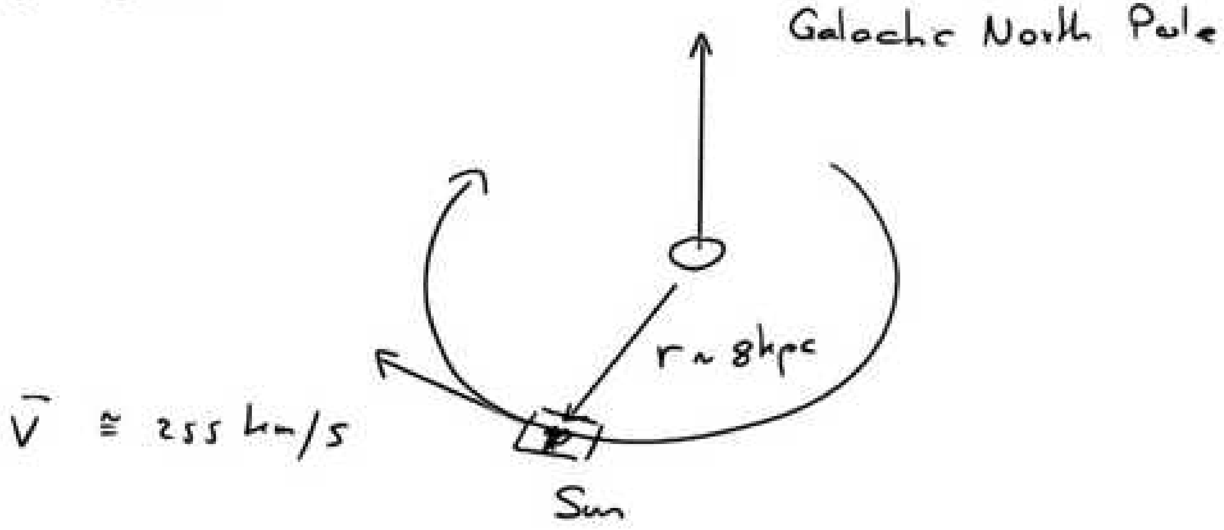
$5\times10^{10}\ M_\odot$ (10 % of total)

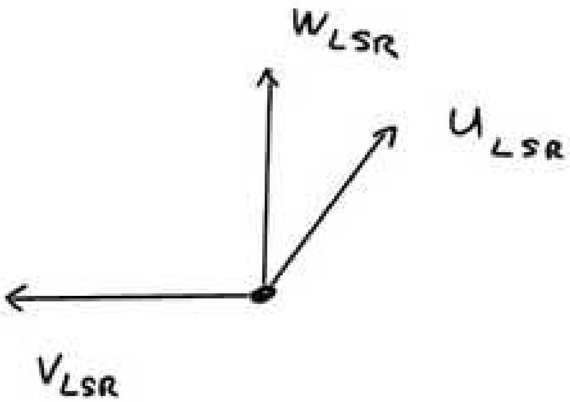
thick disk:
- 10% of the stellar disk
- scale height : ~1 kpc
- RMS vel >~50 km/s



Local Standard of Rest (LSR)

Rest frame that follows the mean motions in the neighborhood of the Sun





- $V_{LSR}, U_{LSR}, W_{LSR} = 0, 0, 0$

  nearly circular orbit

- $V_{LSR} < -255$

  counter-rotating orbit

Toomre Diagram

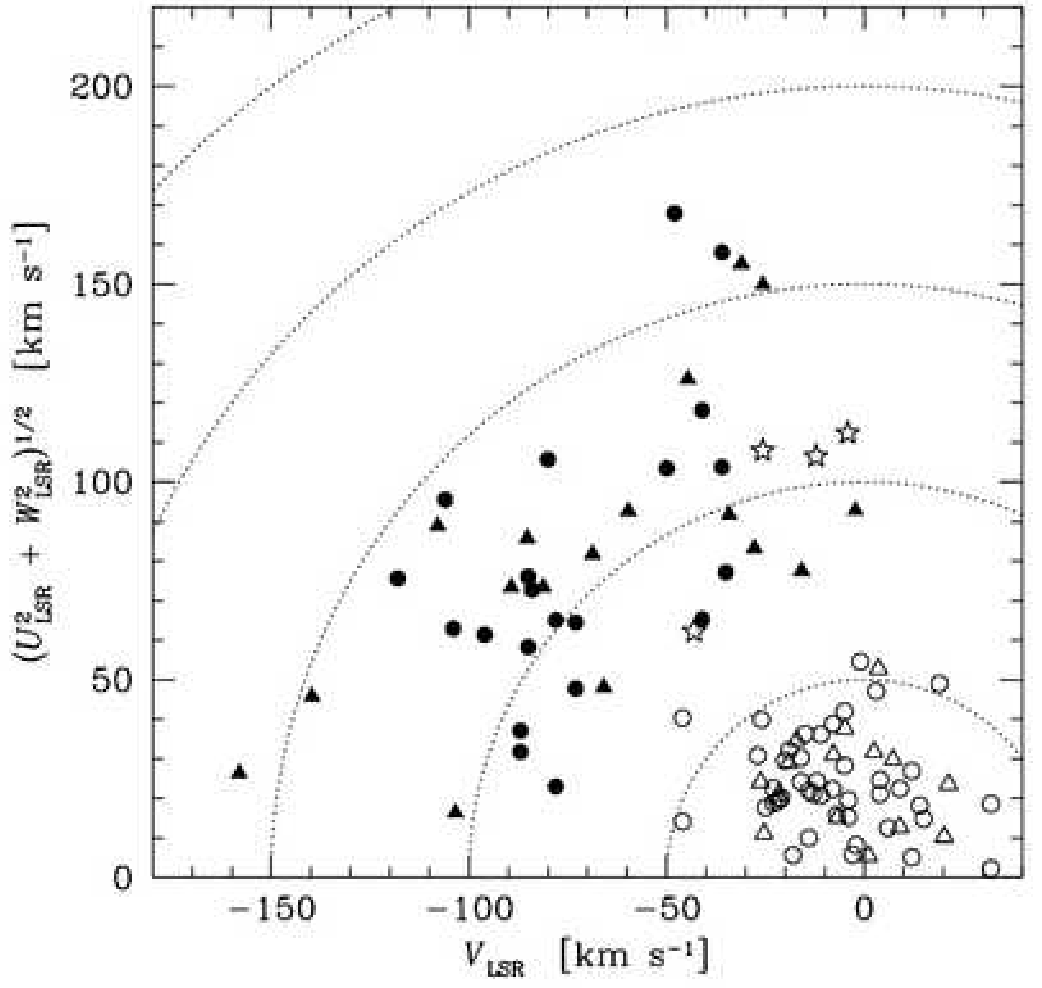


Fig. 1. Toomre diagram for the full stellar sample (102 stars). Thick and thin disk stars are marked by filled and open symbols, respectively. Stars that have been observed with SOFIN or UVES are marked by triangles and those from Bensby et al. (2003) are marked by circles. "Transition objects" are marked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

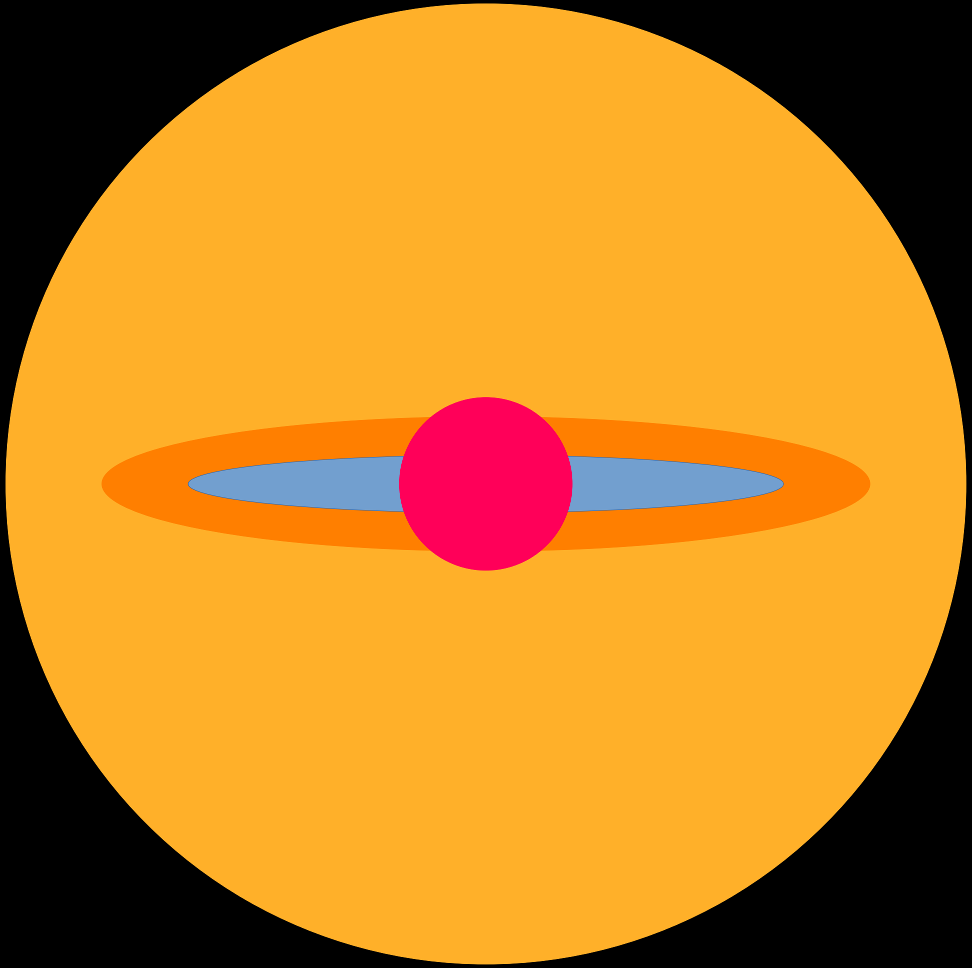
Disentangling
thin disk from thick disk stars
based on their kinematics

Bensby et al. 2005

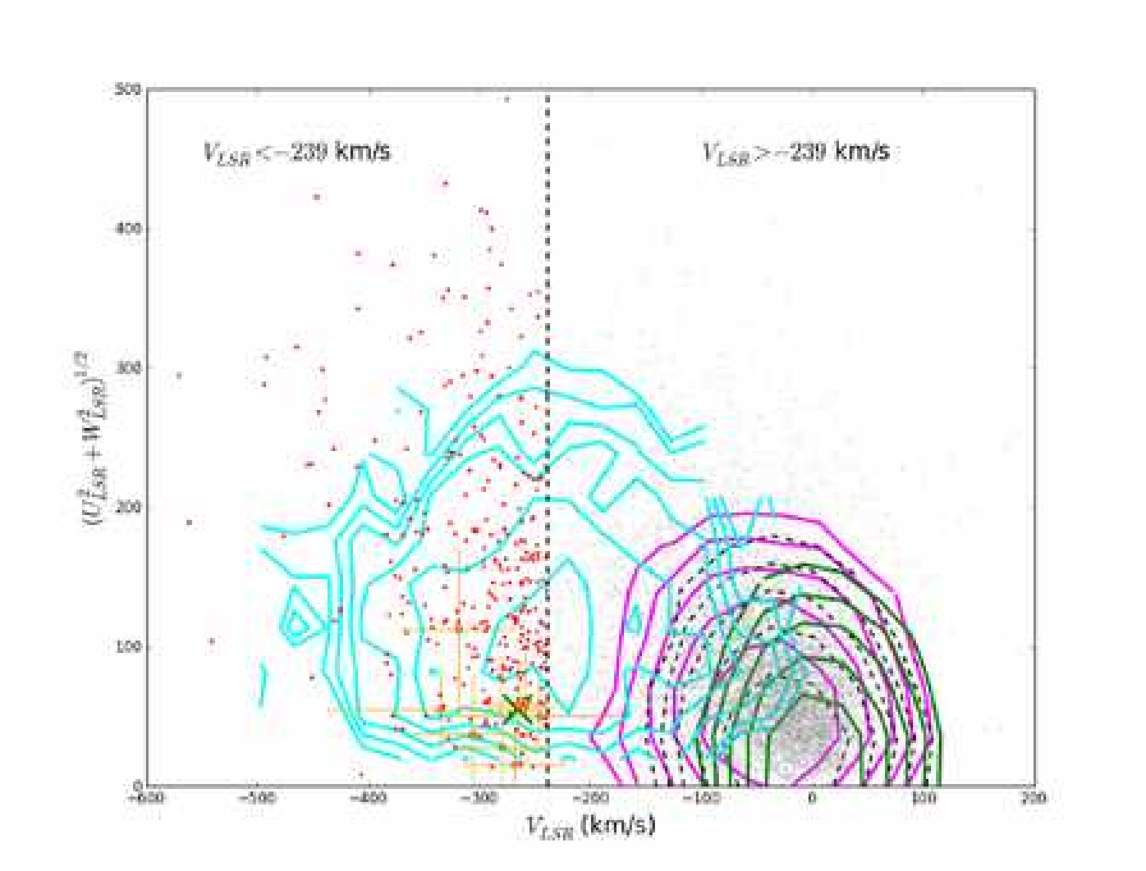
Stellar component : halo

$5 \times 10^8\ M_\odot$ (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 $R_d \sim$ 2-3 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

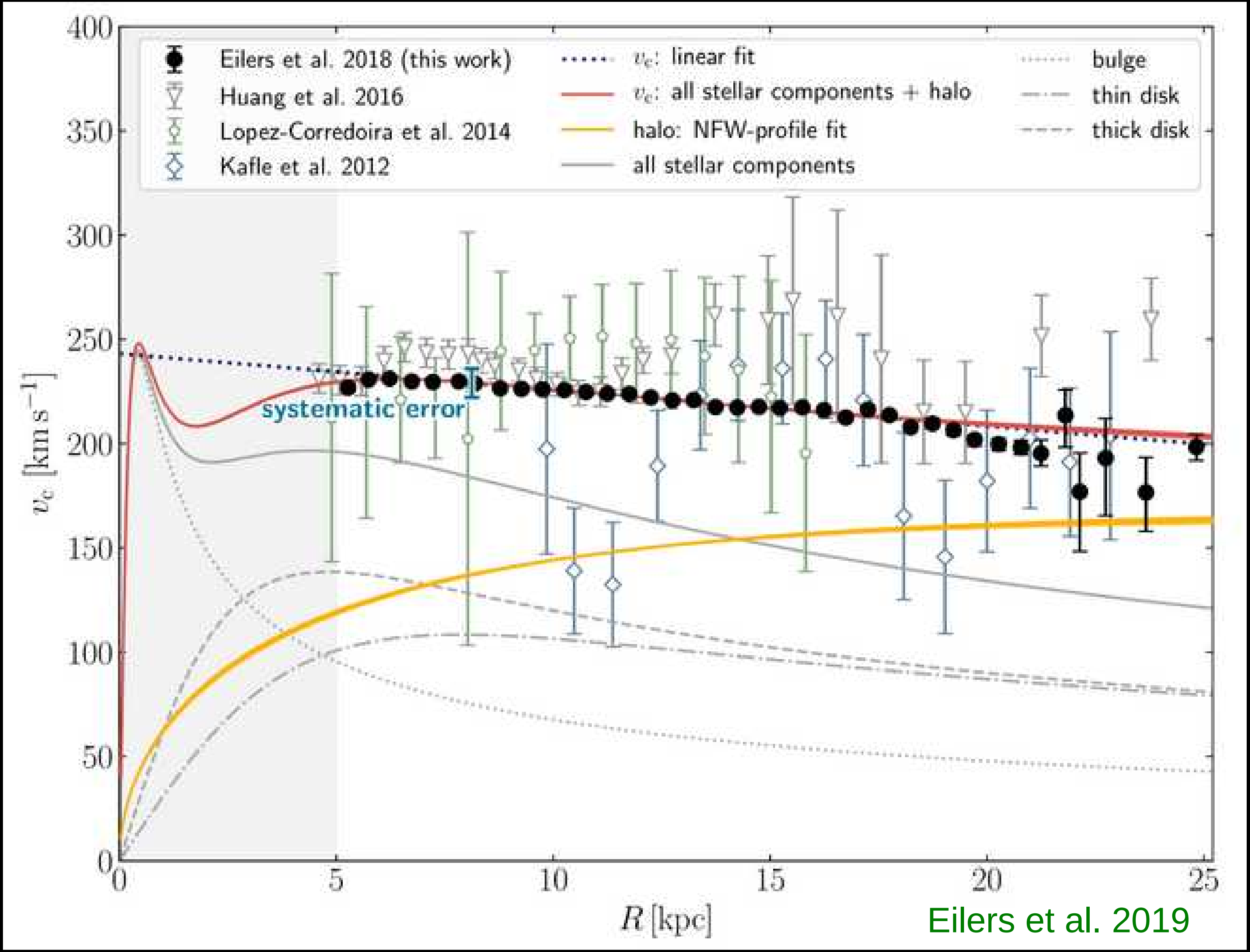
$z_d \sim 300$ pc for low-mass stars

Thick disk:

$z_d \sim 1$ kpc

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

The circular rotation curve of the MW

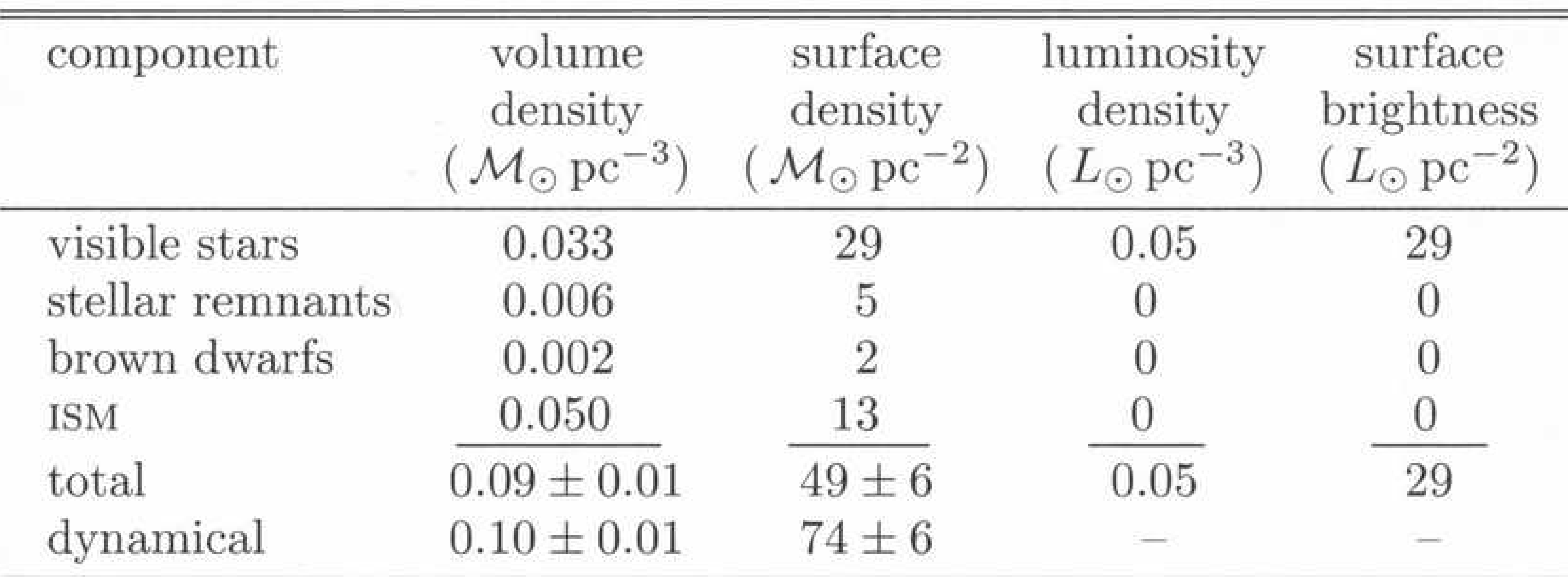


Eilers et al. 2019

Gaseous component : disk, HVC

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

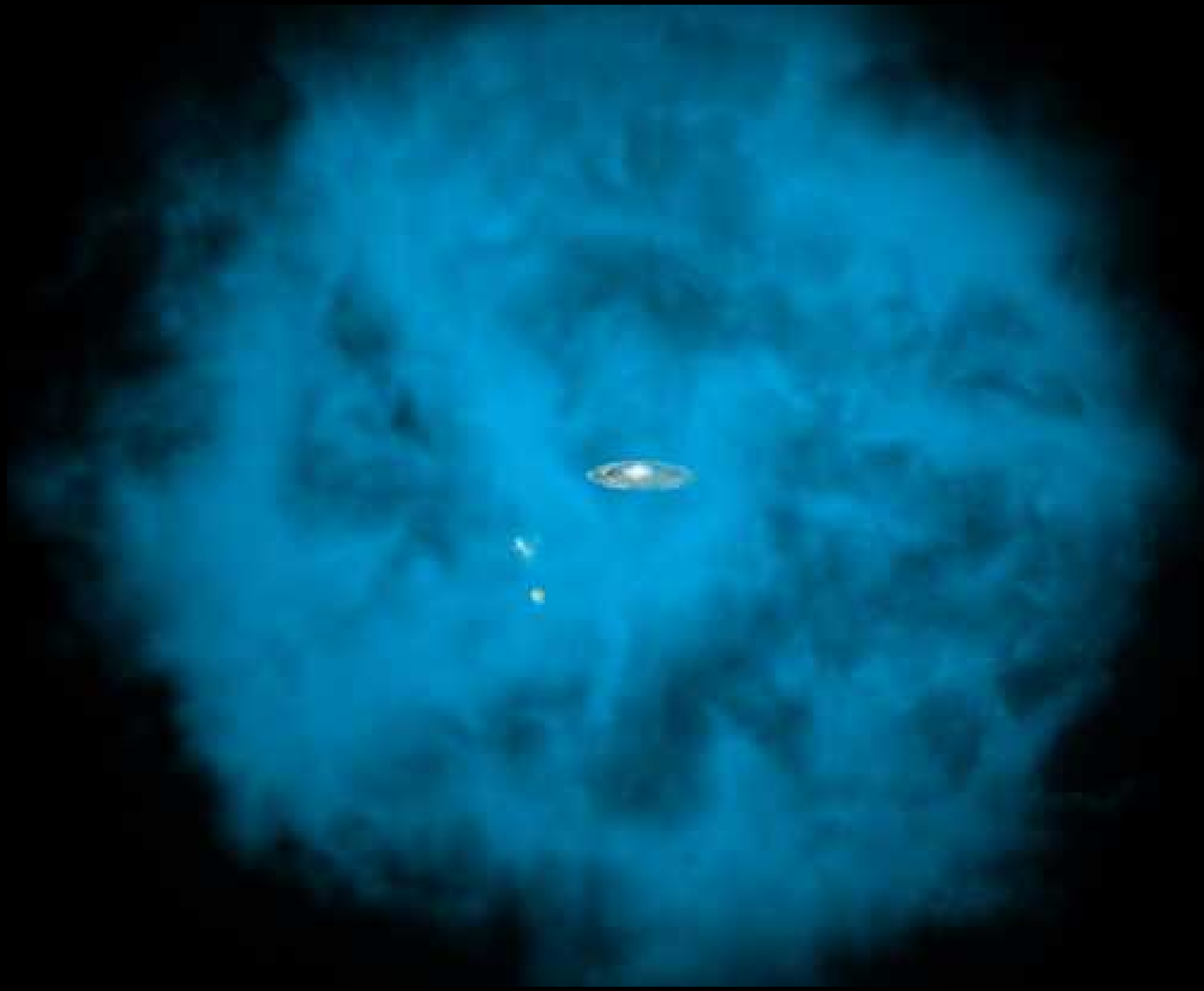
Inventory at the solar vincinity



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	–	–

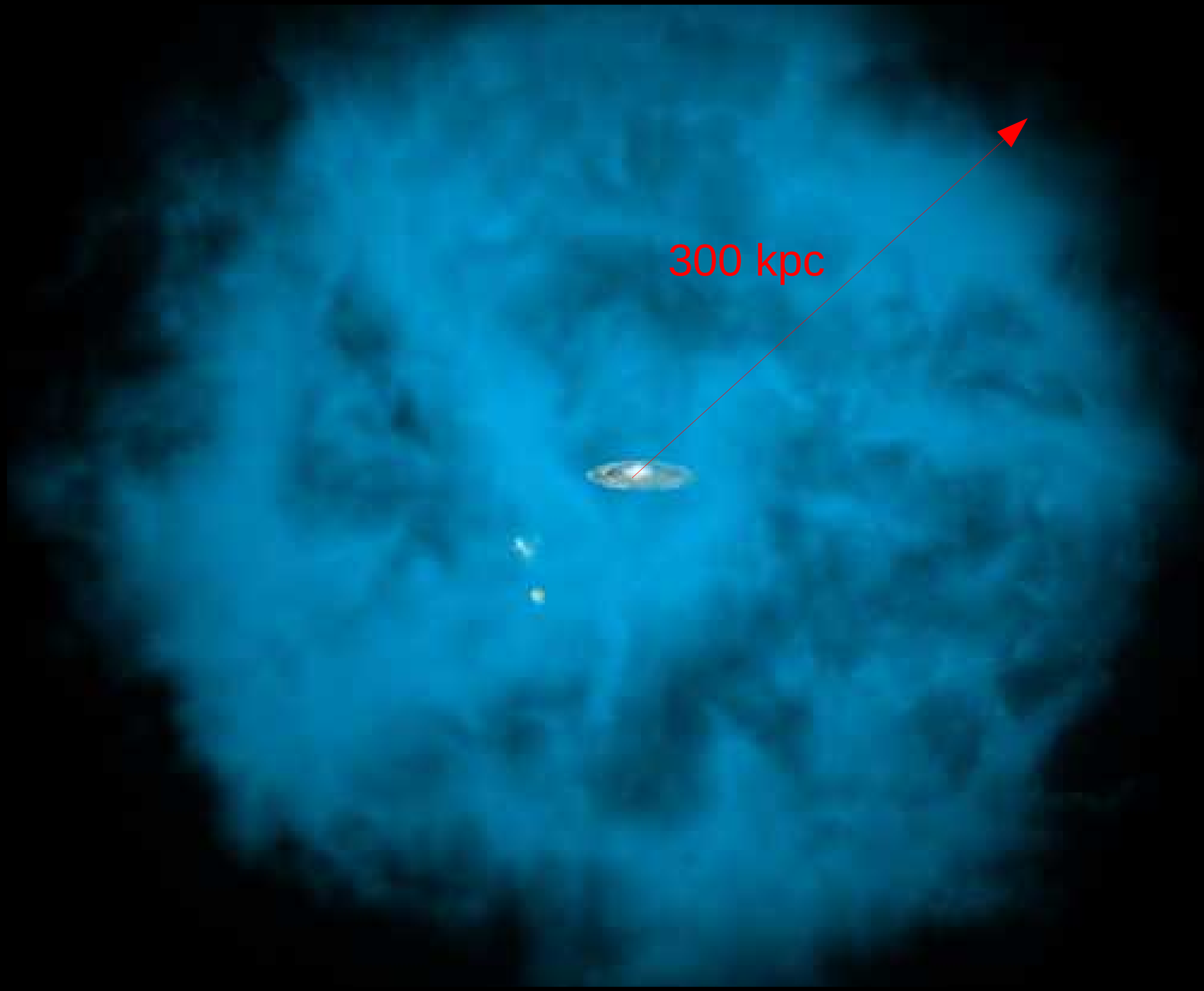
dark component : dark matter halo

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



dark component : dark matter halo

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



The End