Course: *Galaxies and Extragalactic Astronomy*

Topic: *The Milky Way and the Local Group*

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The Milky Way

Introduction

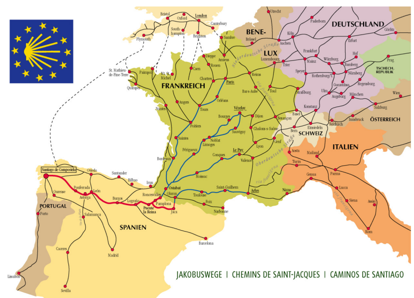
The Milky Way

View from Earth

Credit: U.S. Forest Service Coconino National Forest

- The ‘Galaxy’ (not ‘the galaxy’) ≡ the Milky Way galaxy ≡ ΓΑΛΑΞΙΑΣ ≡ axis of milk
- Ancient greek philosophers described/charted the Milky Way.
- **St. James Path**: guiding the pilgrims in the path of *Saint Jacques de Compostelle* ≡ Santiago de Compostella (legend of Sanctus Iacobus and Campus Stellæ)
- Galileo Galilei (17th century): the Milky Way is a cluster of many stars!
- W. Herschel (18th century): proper motions, star counts etc. Stellar distance and kinematic studies are on!

“Jupiter bringing the Hercules child to the sleeping Juno” (Ca. 1700). **Artist:** Jan Claudius de Cock.



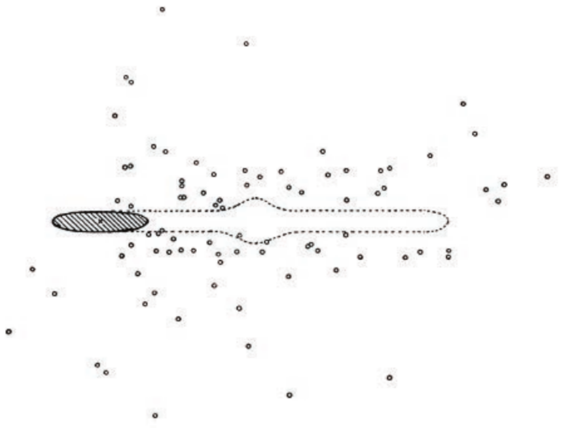
Credit: Manfred Zentgraf

THE MILKY WAY

HISTORY: LET'S DO SCIENCE!

Early 20th century:

- Jacobus Cornelius Kapteyn: observational campaigns – the Milky Way is a flattened ellipsoid
- Robert J. Trumpler: study of open clusters, extinction, and globular clusters.
- Harlow Shapley: distribution of globular clusters and Galactic center at 20 kpc.
- R. J. Trumpler revised the distance: 8 kpc (1936).
- ... there are other galaxies (Hubble, 1924)!

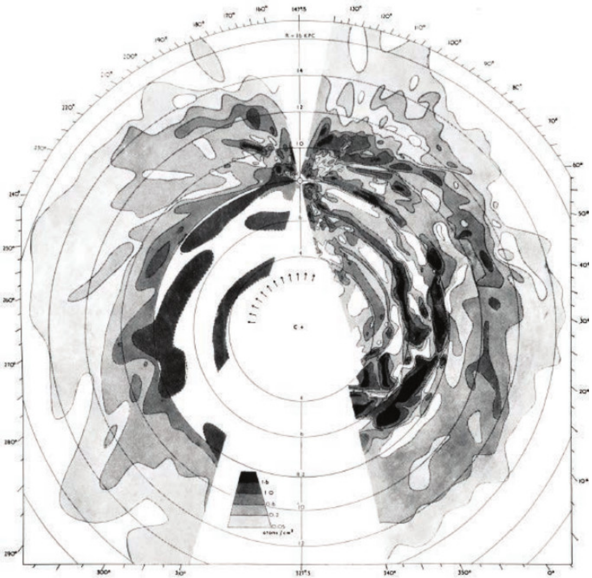


Credit: Trumpler et al. 1941 (PASP, 52, 155–165)

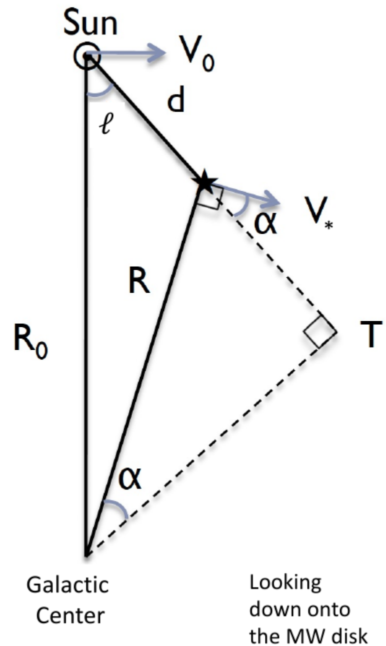
The Milky Way

History: rotation, and map of the Milky Way

- J. C. Kapteyn: two stellar streams of opposing directions
- Jan Oort (1927): differential rotation, Oort constants
- 21-cm line (50s): mapping the HI in the Milky Way!



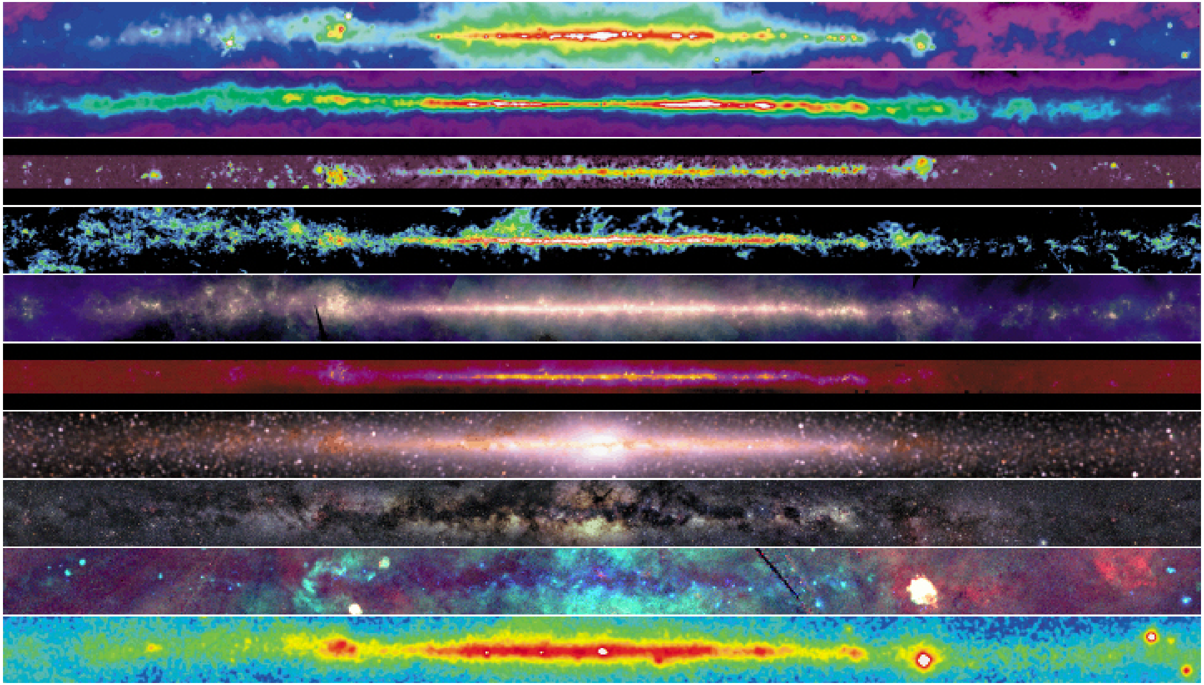
Credit: Oort et al. 1958



Credit: C. Mihos

The Milky Way

A multi-wavelength view

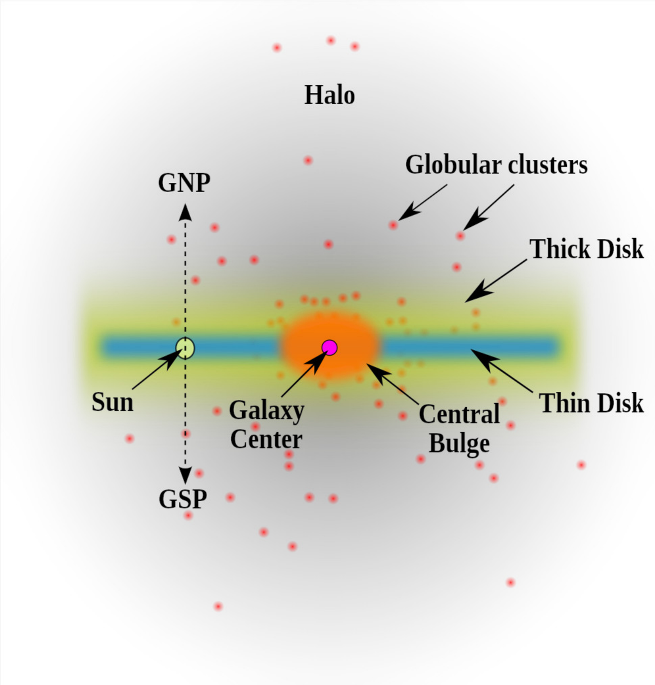


Credit: NASA Goddard Space Flight Center. (i) 408 MHz: e^{-1} synchrotron (B-field); (ii) 21 cm emission: HI; (iii) 2.5 GHz: ionized ISM; (iv) 115 GHz: molecules; (v) FIR: dust; (vi) MIR: PAHs; (vii) NIR: stars; (viii) Optical; (ix) X-ray: hot ISM, XRBs; (x) γ-ray: cosmic rays

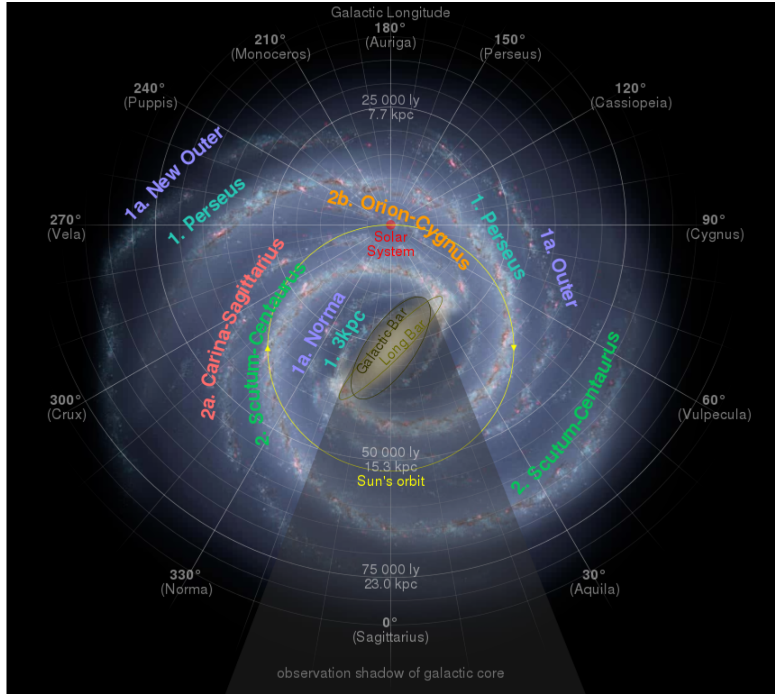
The Milky Way
The components of Milky Way

The Milky Way

The structure of Milky Way and Galactic coordinates



Credit: R. J. Hall



Credit: NASA/JPL-Caltech/ESO/R. Hurt

Mass breakdown

$$M \sim 10^{12}\,\mathrm{M}_\odot$$

$$M_{\mathrm{DM}} \sim 9 \times 10^{11}\,\mathrm{M}_\odot$$

$$M_\star \sim 10^{11}\,\mathrm{M}_\odot$$

$$M_{\mathrm{gas}} \sim 10^{10}\,\mathrm{M}_\odot$$

$$M_{\mathrm{dust}} \sim 10^{8}\,\mathrm{M}_\odot$$

$$M_{\mathrm{SMBH}} \sim 4 \times 10^{6}\,\mathrm{M}_\odot$$

Other characteristics

- SBbc galaxy:
  barred, grand-design spiral galaxy
- Luminosity:
  $L_{\mathrm{MW}} \sim (1-5) \times 10^{10}\,\mathrm{L}_\odot$
- Metallicity:
  $\log \frac{Z_{\mathrm{MW}}}{Z_\odot} \sim -0.25$

Component	Approximate mass	Comments
Bulge	$M_{\mathrm{bulge}} = 2.0 \pm 0.3 \times 10^{10}\,\mathrm{M}_\odot$	r~$2.5\,\mathrm{kpc}$
Disk	$M_{\mathrm{disk}} = 8 \times 10^{10}\,\mathrm{M}_\odot$	thin and thick disks
(thin disk)	~90% of M_{disk}	h~$350\,\mathrm{pc}$, λ~$3\,\mathrm{kpc}$
(thick disk)	~10% of M_{disk}	h~$1.4\,\mathrm{kpc}$, λ~$4.8\,\mathrm{kpc}$

- Assumption of Keplerian disk - what is the speed at a given radius?

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$$u^2 = \frac{GM}{r}$$

- What is M referring to?

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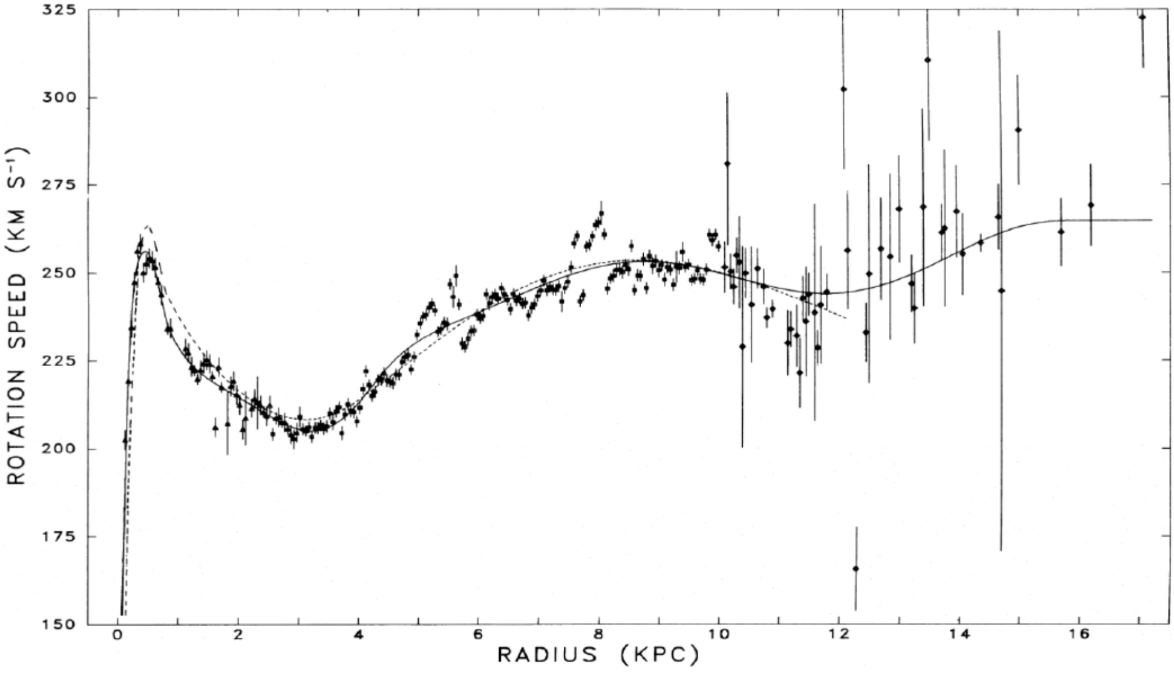
- What is M referring to?

$$u(r)^2 = \frac{GM(<r)}{r}$$

- Calculate M if $u_\odot = 230\,\mathrm{km\,s^{-1}}$ and $r_\odot = 8.2\,\mathrm{kpc}$.

THE MILKY WAY

THE STELLAR DISK: ROTATION CURVE (OLD)



Credit: Clemens et al. 1985

- Keplerian assumption:

$$u(r)^2 = \frac{GM(< r)}{r}$$

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- What is the mass profile if $u(r)$ is constant?

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$$u(r)^2 = \frac{GM(< r)}{r}$$

- What is the mass profile if $u(r)$ is constant?
- What is the density profile under the same assumptions?

- The density decreases far from disk plane and center. E.g.:

$$\rho(r,z) = \rho_0 \exp\left(-\frac{r}{h_r} - \frac{|z|}{h_z}\right)$$

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- What should be the velocity curve then?
- What if we add a bulge of mass M_{bulge}?

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- What should be the velocity curve then?
- What if we add a bulge of mass M_{bulge}?
- What if we add a bulge following the Plummer model?

$$\rho(r) = \frac{3M_0}{4\pi a^3}\left(1 + \frac{r^2}{a^2}\right)^{-\frac{5}{2}}$$

The Milky Way

The stellar disk: Realistic profile

- The density decreases far from disk plane and center. E.g.:

$$\rho(r,z) = \rho_0 \exp\left(-\frac{r}{h_r} - \frac{|z|}{h_z}\right)$$

- What should be the velocity curve then?
- What if we add a bulge of mass $M_{\rm bulge}$?
- What if we add a bulge following the Plummer model?

$$\rho(r) = \frac{3M_0}{4\pi a^3}\left(1 + \frac{r^2}{a^2}\right)^{-\frac{5}{2}}$$

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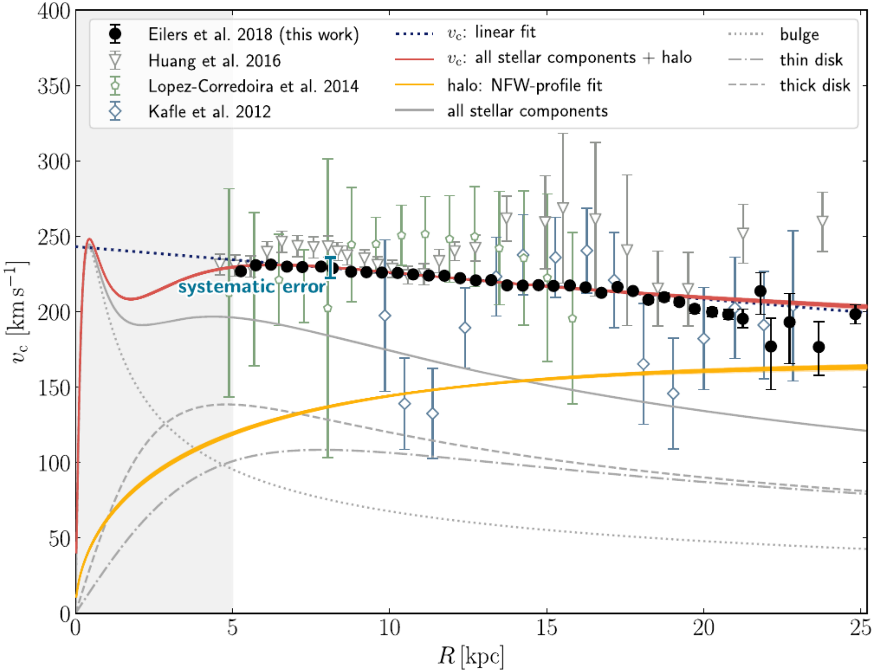
- What if we add a supermassive black hole?
- Adding Navarro–Frenk–White (NFW) profile:

$$\rho(r) = \frac{r_0}{\frac{r}{R}\left(1 + \frac{r}{R}\right)^2}$$

The Milky Way

The stellar disk: Rotation curve (new)

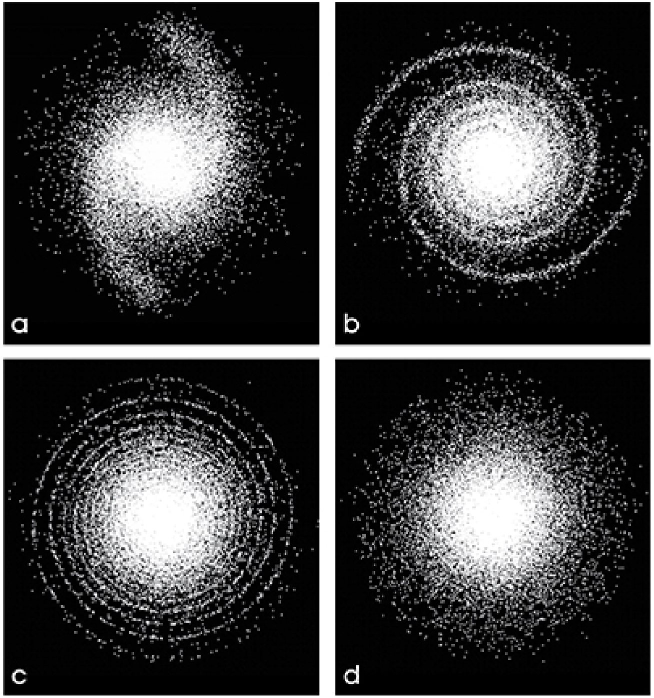


Credit: Eilers et al. 2018

The Milky Way

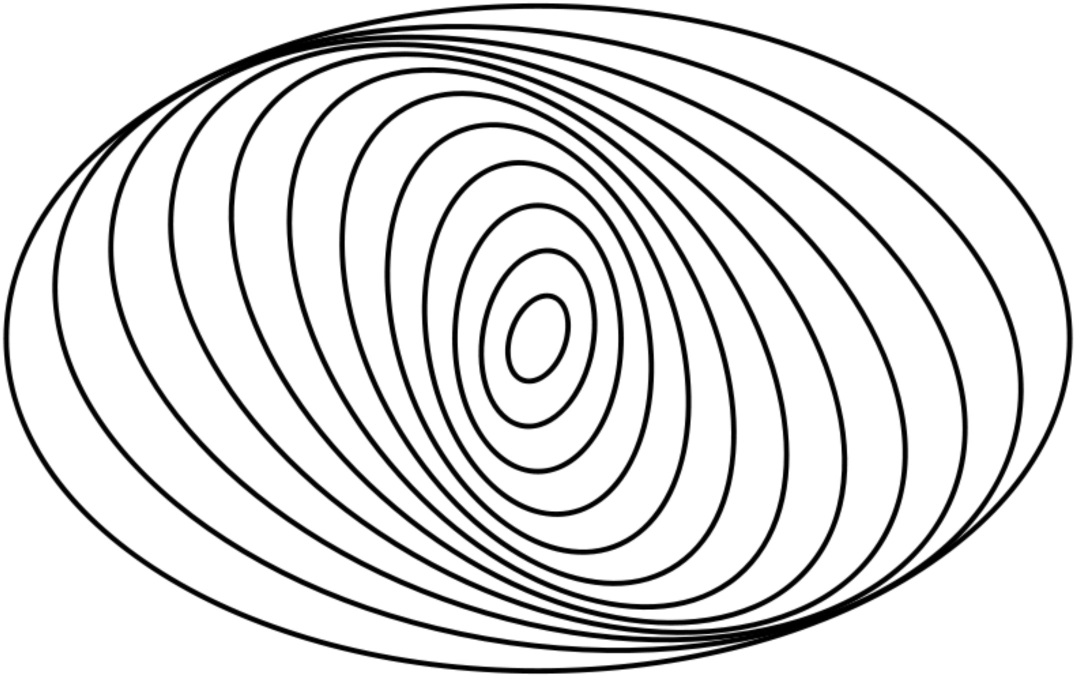
Spiral structure: The Winding Problem

- Age of Universe: $13.8\,\mathrm{Gyr}$
- Age of most galaxies: $\sim 10-12\,\mathrm{Gyr}$
- Sun's revolution: $\sim 230\,\mathrm{Myr}$
- Ten of revolutions of the Milky Way
- 70% of big galaxies are spirals
- ...something is not right!



Credit: Jake Hebert

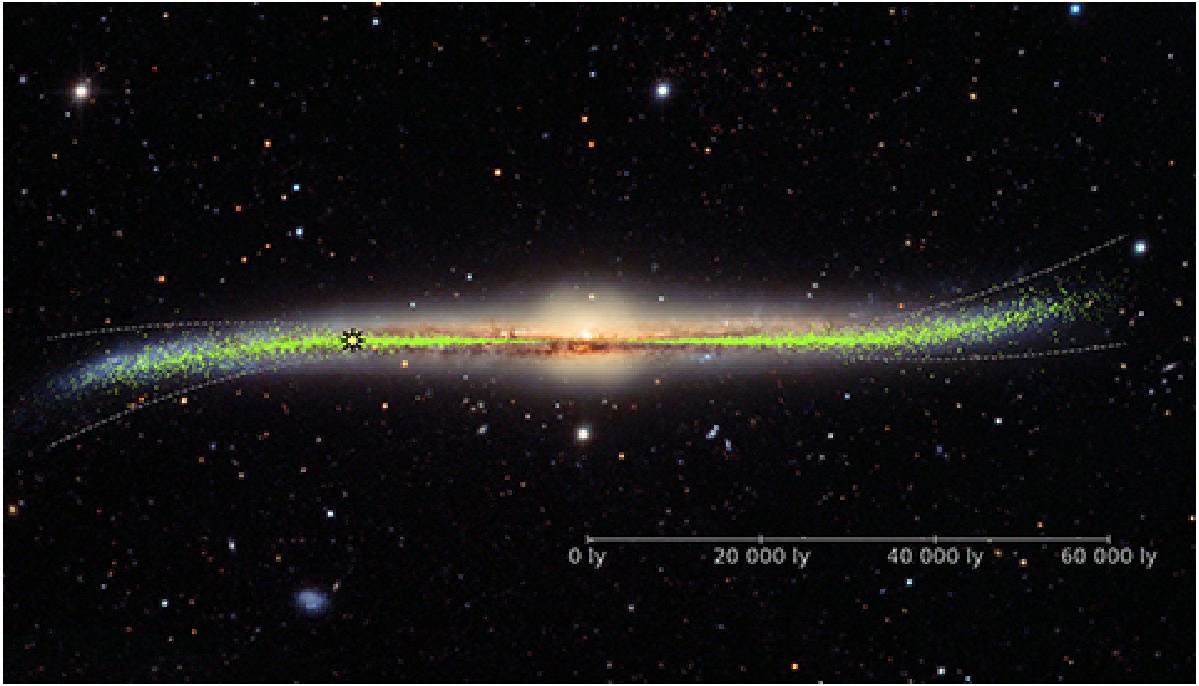
SPIRAL STRUCTURE: DENSITY WAVE THEORY



Credit: Wikipedia. **Density wave theory** (Lin & Shu), also explaining star-formation distribution.

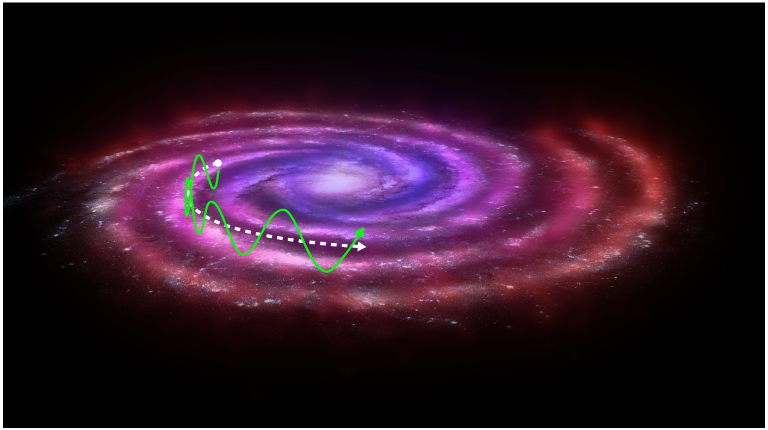
The Milky Way

The stellar disk: The warp

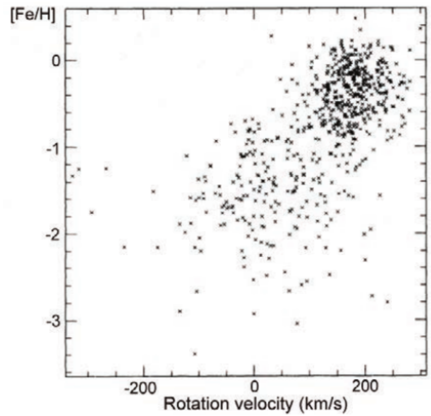


Credit: J. Skowron / OGLE / Astronomical Observatory, University of Warsaw

- Stars and gas follow the disk structure **on average**.
- All stars have their own orbits – some are retrograde! **Local Standard of Rest** (LSR)
- $\rho_0 \sim 0.08\,\mathrm{M_\odot\,pc^{-3}}$ from stars, gas, white dwarfs, etc.
- $\sigma \sim 5 - 20\,\mathrm{km\,s^{-1}}$ depending on stellar spectral type
- Scale height of ~80 pc for young stars, and ~300 pc for old stars.



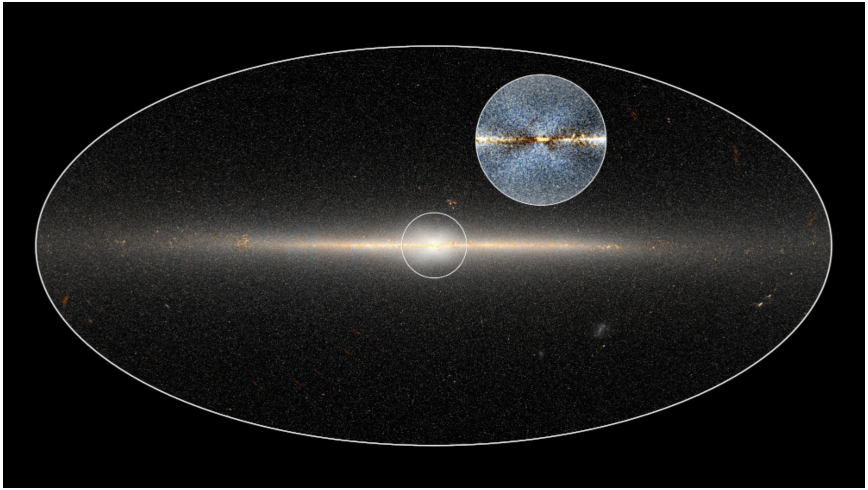
Credit: C. Carreau (ESA)



Credit: Nissen et al. 1991

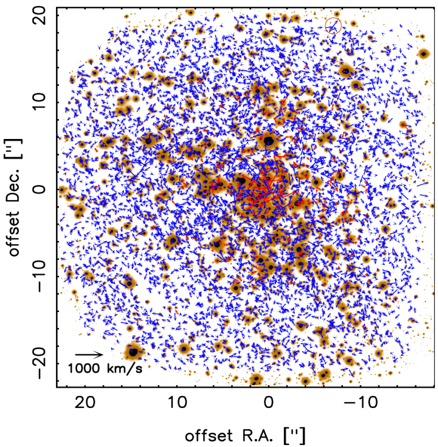
The Milky Way
The bulge

- Typically we consider galactic bulges as flattened ellipsoids.
- Some galaxies have ‘boxy’ bulges.
- Infrared observations (e.g., Ness et al. 2016) show an X-shaped Galactic bulge.
- Dense region of stars (mostly old), gas and dust. Formed by early mergers?

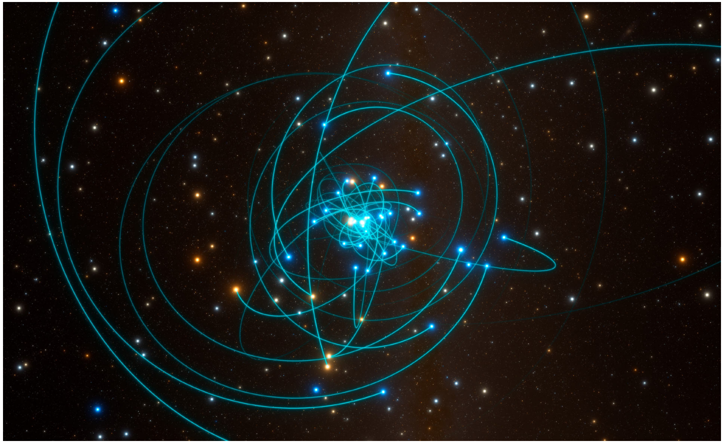


Credit: NASA/JPL, Caltech

- At the direction of Sagittarius, inside the bulge the barycenter of the Milky Way.
- Dense region of old stars (but also some new).
- Contains the supermassive black hole **Sgr A***, with a *Nuclear Stellar Cluster* around it ($r \lesssim 10\,\mathrm{pc}$)



Credit: Schödel et al. 2009

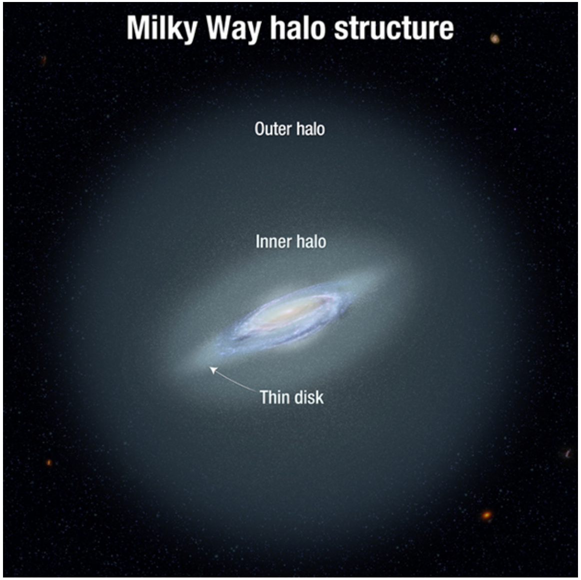


Credit: ESO / L. Calçada

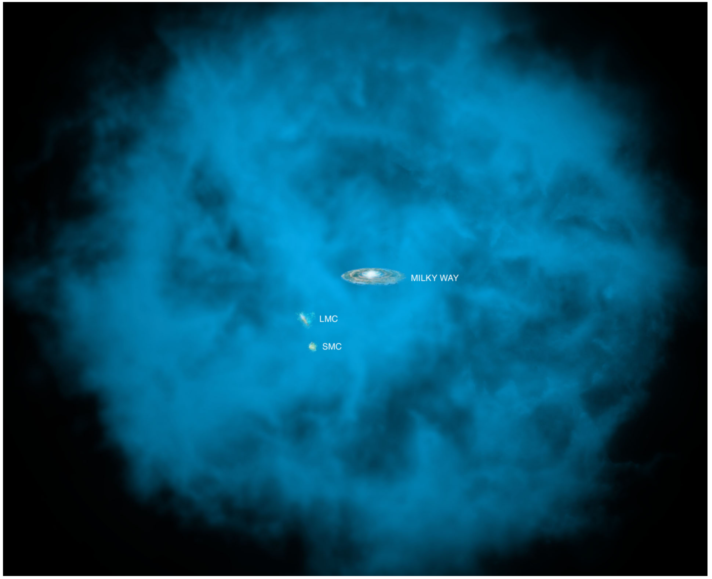
The Milky Way

The Galactic halo

- Diffuse, extended region ($R \sim 200\mathrm{kpc}$) of the MW, containing mostly **dark matter** (as in dark matter haloes)
- More than 150 **globular clusters** (GC; $10^3 - 10^6\,\mathrm{M_\odot}$) and a population of old **halo field stars**
- X-ray emitting **hot gas** ($T \gg 10^6\ \mathrm{K}$) and **tidal streams** from disruptions of satellite galaxies and GCs



Credit: NASA, ESA, and A. Feild



Credit: NASA/CXC. A. Gupta et al. 2012

THE MILKY WAY
TIDAL STREAMS

Credit: James Josephides and Southern Stellar Stream Spectroscopic Survey

The Milky Way
Models and current developments

Ingredients:

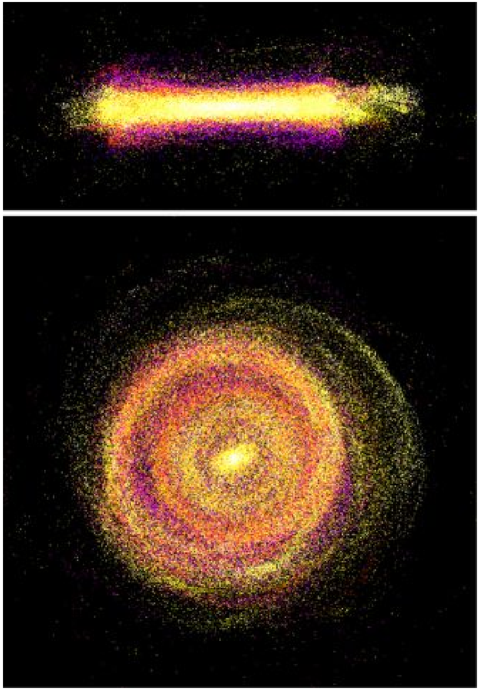
- Mass models: for the different components
- Star counts models: luminosity functions of different components
- Kinematic models: velocity distribution at each location

Formation models:

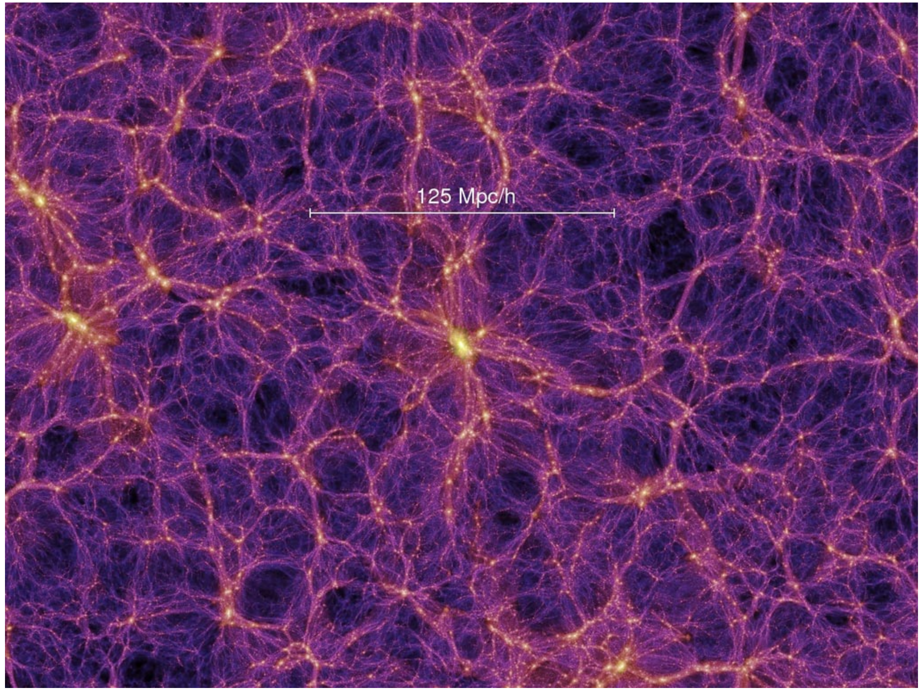
- Eggen et al. 1962: free-falling metal-free spherical cloud → disk-shaped, eccentric GCs
- Searle et al. 1977: merging of independently-evolved fragments: complex metallicity distribution
- We now have simulations!
    - collapse of primordial dark matter and gas: gravitational wells and first stars
    - accretion of more gas and dark matter: structure formation
    - globular cluster system, and galaxy satellite system form
    - angular momentum and dynamical friction → disk forms
    - galaxy mergers and tidal interactions

The Milky Way

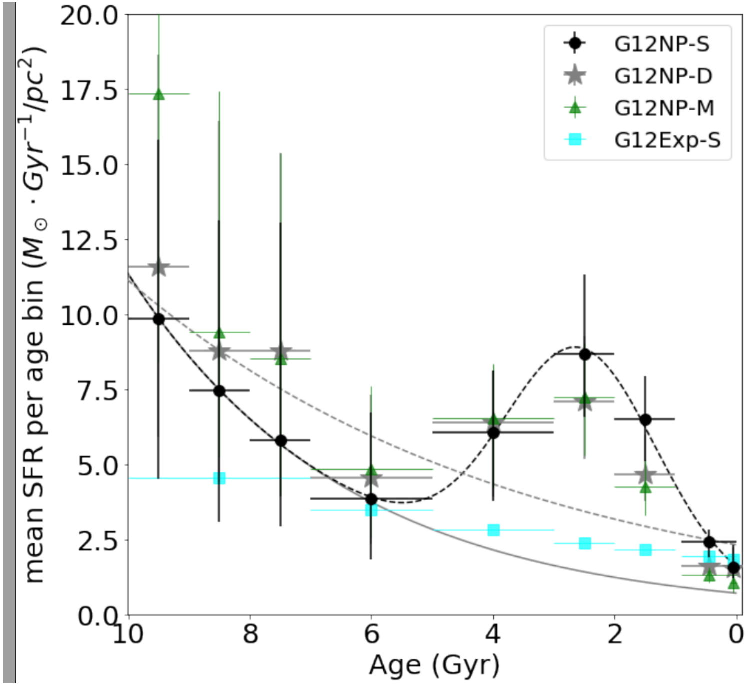
Galaxy simulations



Credit: GUAIX



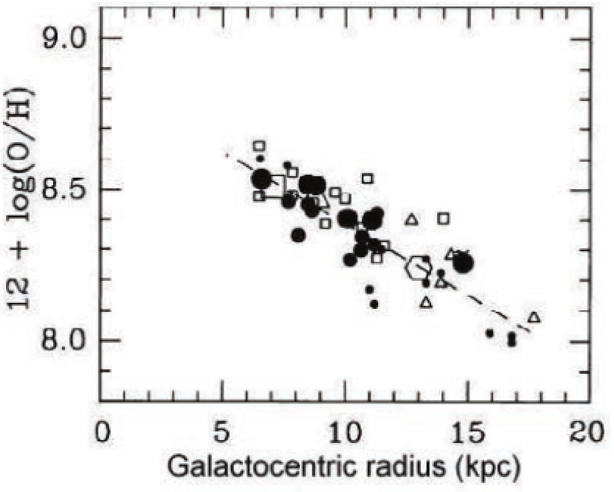
Credit: Illustris-TNG



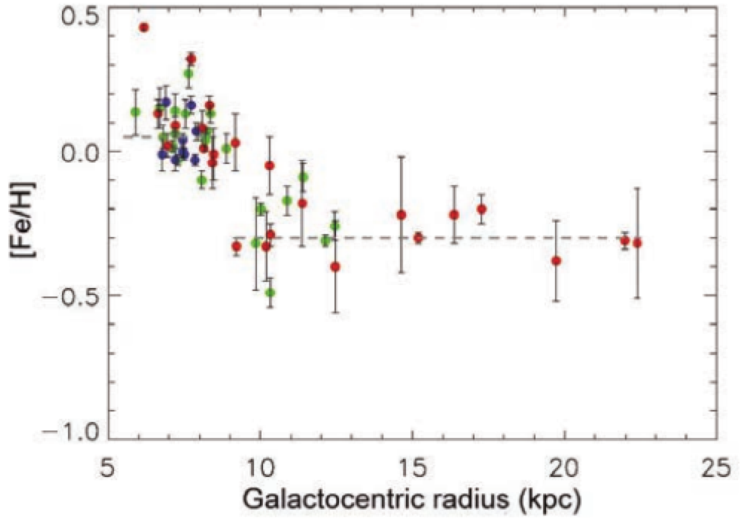
Credit: Mor et al. 2019. Recent burst: Sagittarius dwarf galaxy?

The Milky Way

Star formation: Metallicity



Credit: Deharveng et al. 2000

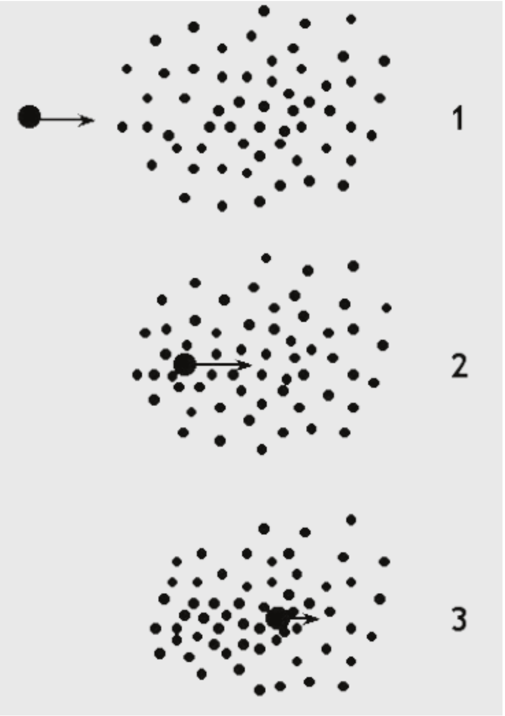


Credit: Lépine et al. 2011

The Milky Way

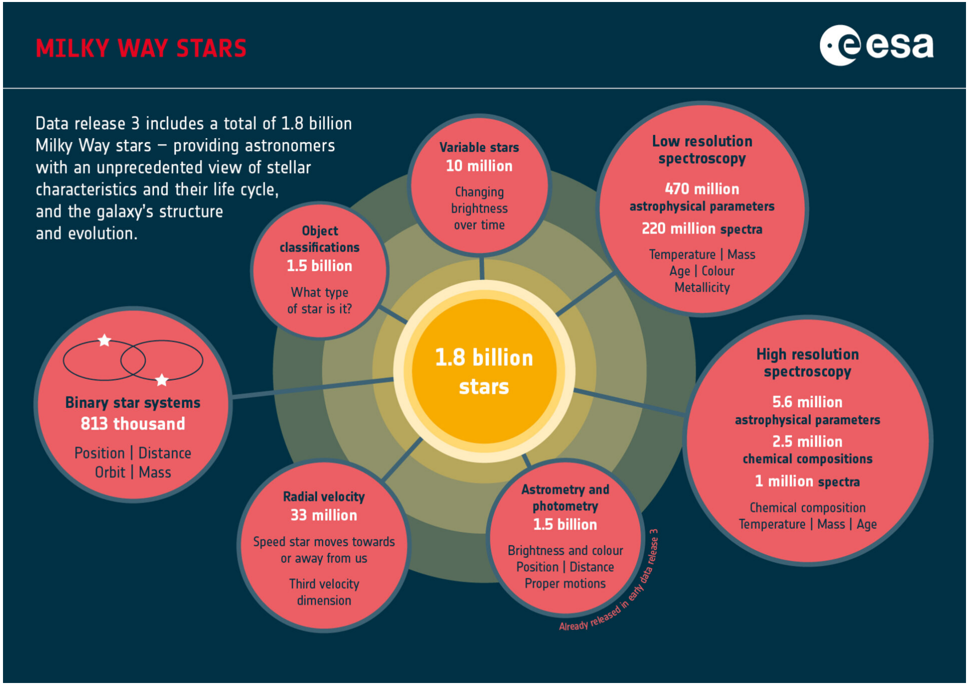
A complicated picture...

- Galaxies are the results of mergers
- Massive black holes form, sink, merge...
- Dynamical friction
- Stars do not follow Keplerian orbits
- Open clusters dissolve, globular clusters penetrate
- Flybys affect the distribution/velocity of stars
- Hypervelocity stars are escaping the Galaxy
- ...



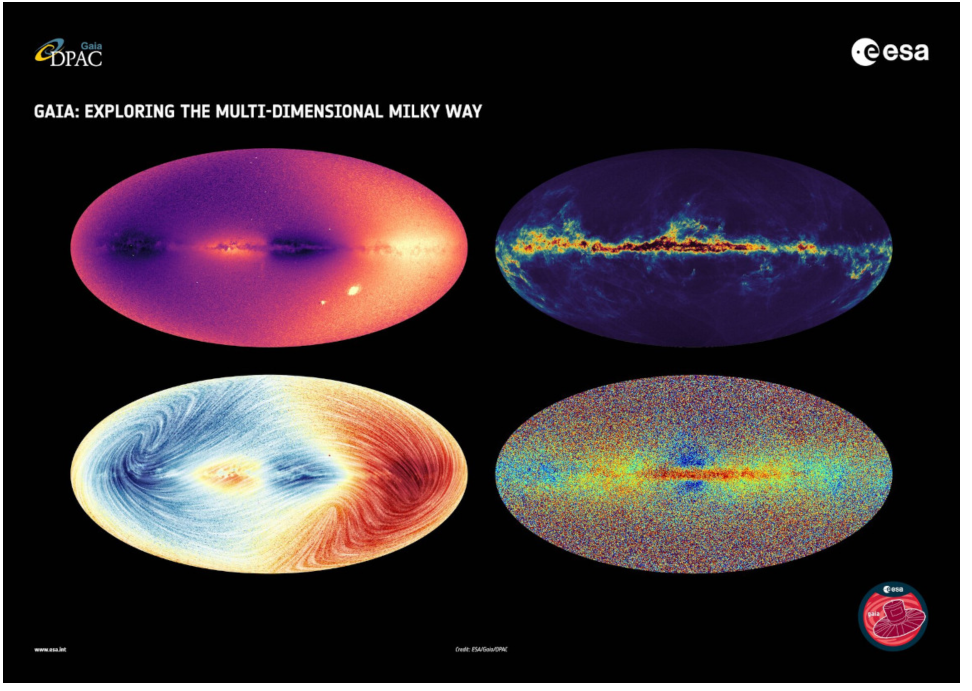
Credit: F. Combes and J. Lequeux (2016)

The Milky Way
GAIA observations

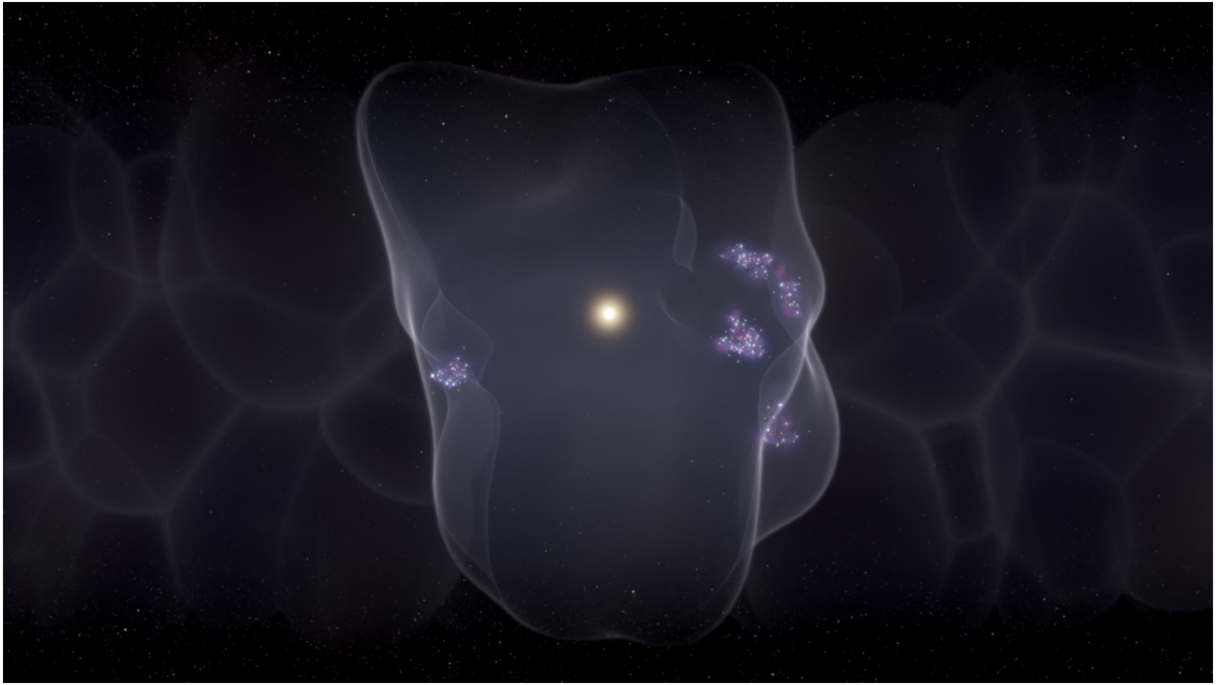


Credit: ESA

The Milky Way
GAIA Data Release 3



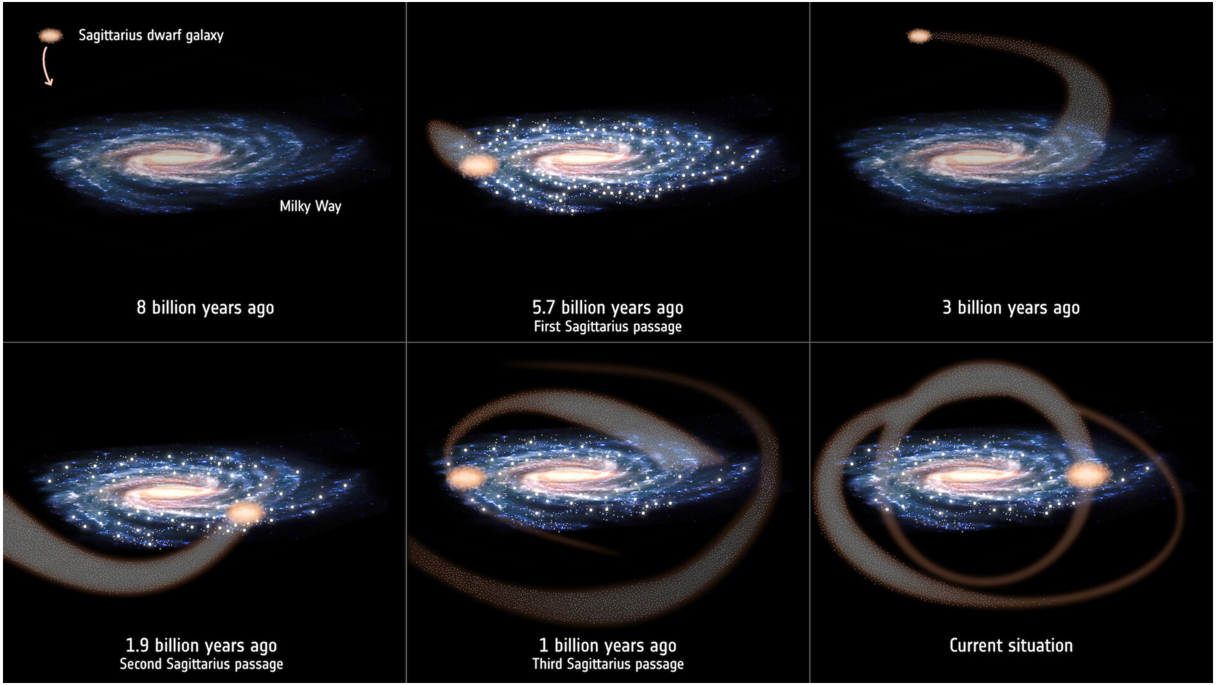
Credit: ESA. **Upper left**: Radial velocity; **Lower left**: Velocity field; **Upper right**: Dust; **Lower right**: Stellar metallicity.



Credit: ESA

The Milky Way

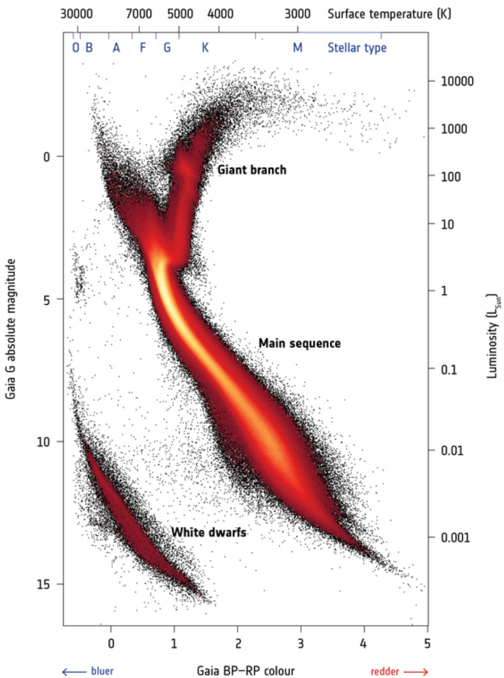
GAIA and Sagittarius Dwarf galaxy



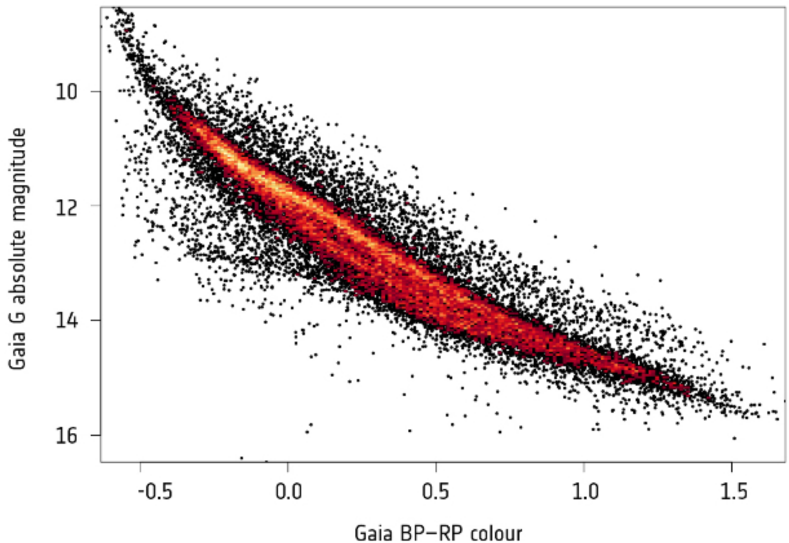
Credit: ESA

The Milky Way

GAIA Stellar Evolution



Credit: ESA/Gaia/DPAC



Credit: ESA/Gaia/DPAC

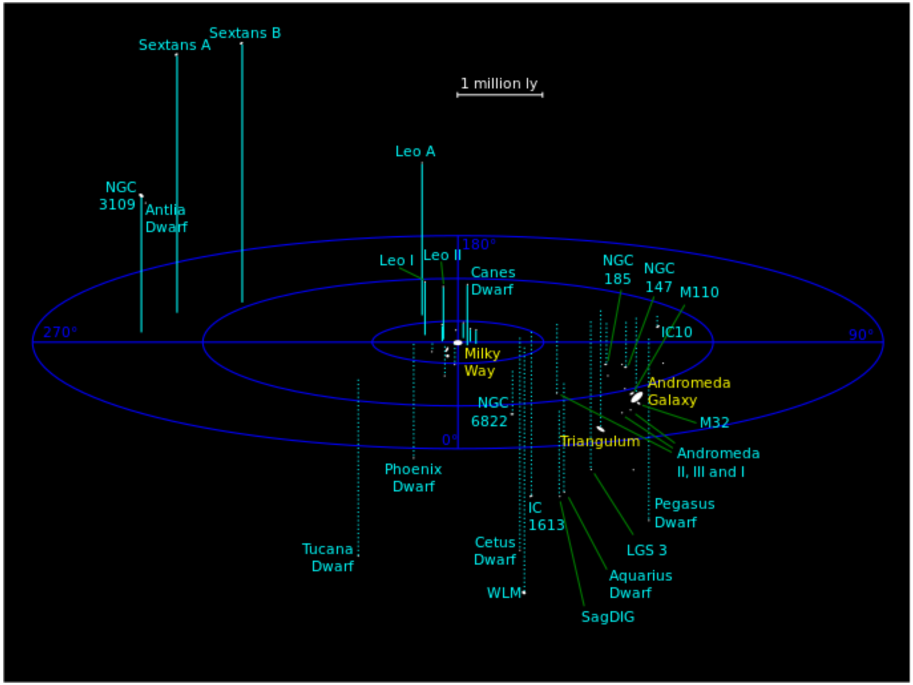
The Local Group

The Local Group

Introduction

The Local Group

3D View



Credit: Richard Powell

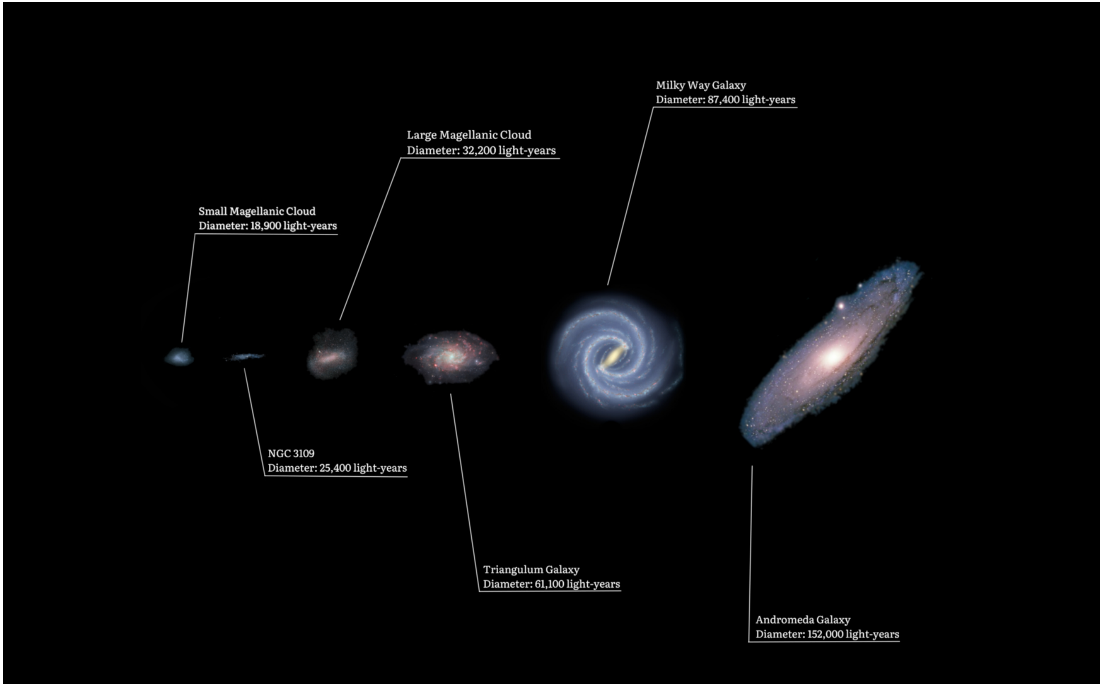
The Local Group

Composition

- $R \sim 1.5\,\mathrm{Mpc}$
- $M \sim 2.3 \times 10^{12}\,\mathrm{M}\odot$ (Peñarrubia et al. 2014)
- Two main subgroups separated by $\sim$0.8 Mpc: Milky Way and Andromeda subgroups
- Antlia-Sextans (sub)group?
- Three big spiral galaxies:
  1. Milky Way: SBbc.
  2. Andromeda galaxy (M31): SA(s)b but barred! A bit larger than MW.
  3. Triangulum galaxy (M33): SA(s)cd – about half as MW, satellite of M31?
- Three small spiral and elliptical galaxies
  1. Large Magellanic Cloud (LMC): Irr or SB(s)m ≡ Magellanic spiral (one arm) — satellite of MW.
  2. NGC 3109: SB(s)m — in Antlia-Sextans group, interacting with Antlia Dwarf.
  3. M32: cE/E2 — compact elliptical galaxy, warp of M31
- $\gtrsim$150 irregular, dwarf spheroidal, and dwarf elliptical galaxies
- Globular cluster systems, tidal streams, gas, rogue stars, etc.

The Local Group

Comparisons



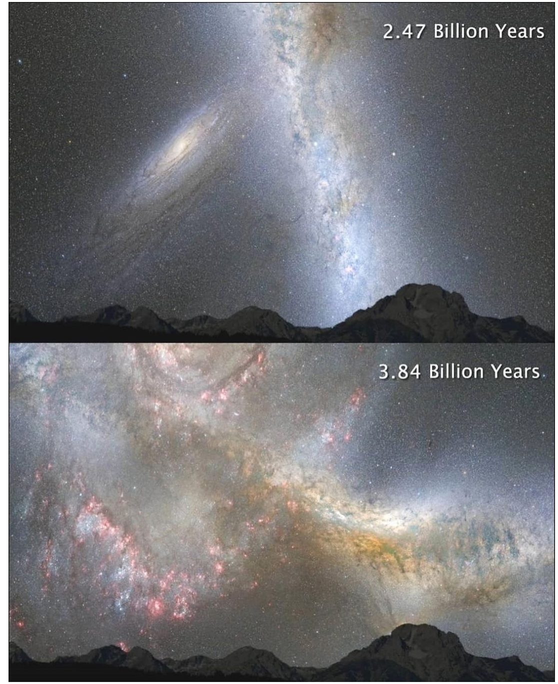
Credit: SkyFlubber, Wikipedia Commons

The Local Group
M31: The Andromeda galaxy

The Local Group

M31: The Andromeda galaxy

Credit: HST-Subaru-NOAO-RC-SS



Credit: NASA/ESA

The Local Group

M33: The Triangulum galaxy

The Local Group

M33: The Triangulum galaxy

Credit: Robert Grendler

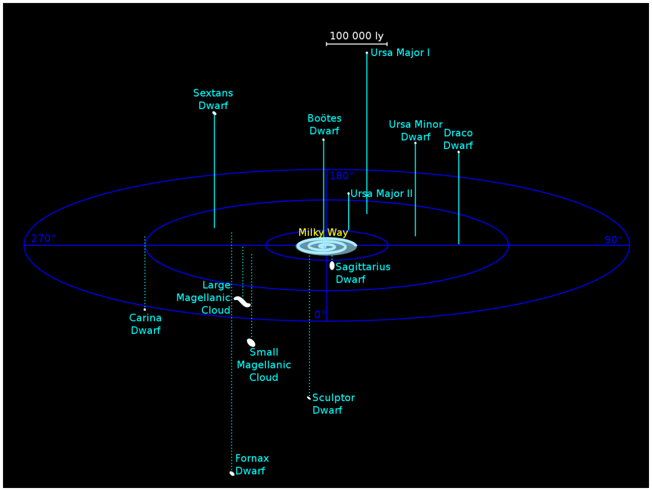
The Local Group

The Galaxy's satellites: Milky Way subgroup

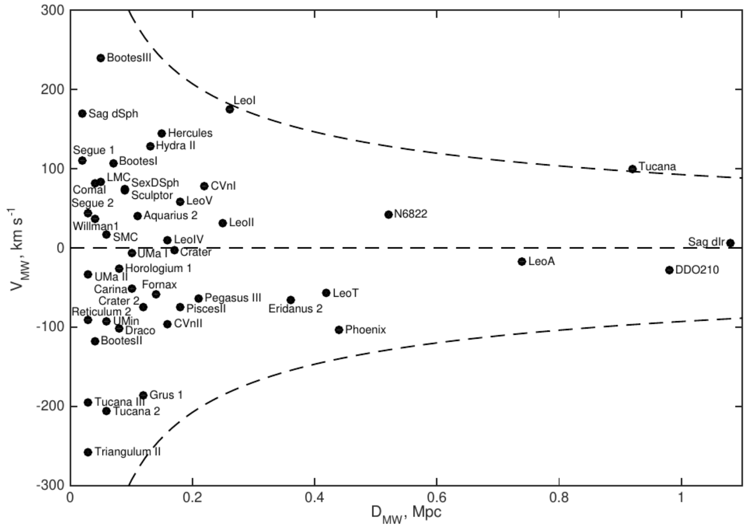
The Local Group

The Galaxy's satellites: Milky Way subgroup

- $\sim$60 dwarf galaxies in $D \lesssim 0.4\,\mathrm{Mpc}$, orbiting around MW or other dwarf galaxies
- Those closer, have less H: evidence of stripping



Credit: Richard Powell



Credit: Kashibadze et al. 2017

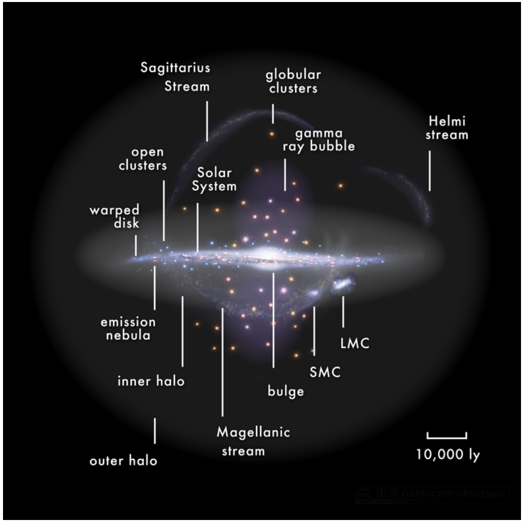
The Local Group

The Magellanic Clouds

THE MAGELLANIC CLOUDS: SKY VIEW

Credit: ESO/Yuri Beletsky.

- Relatively big for the MW?
- LMC: 50 kpc away. Has its own GCs and satellite galaxies!
- SMC: 62 kpc away. Used to be a satellite of LMC?



Credit: Pablo Carlos Budassi

Credit: John Rowe Animations

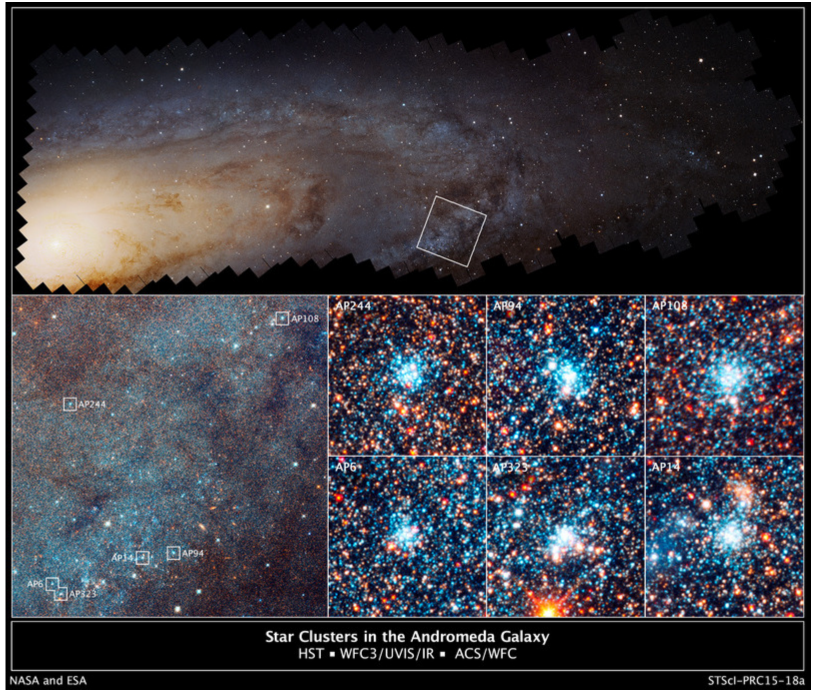
The Local Group

What we learn studying the local group

The Local Group

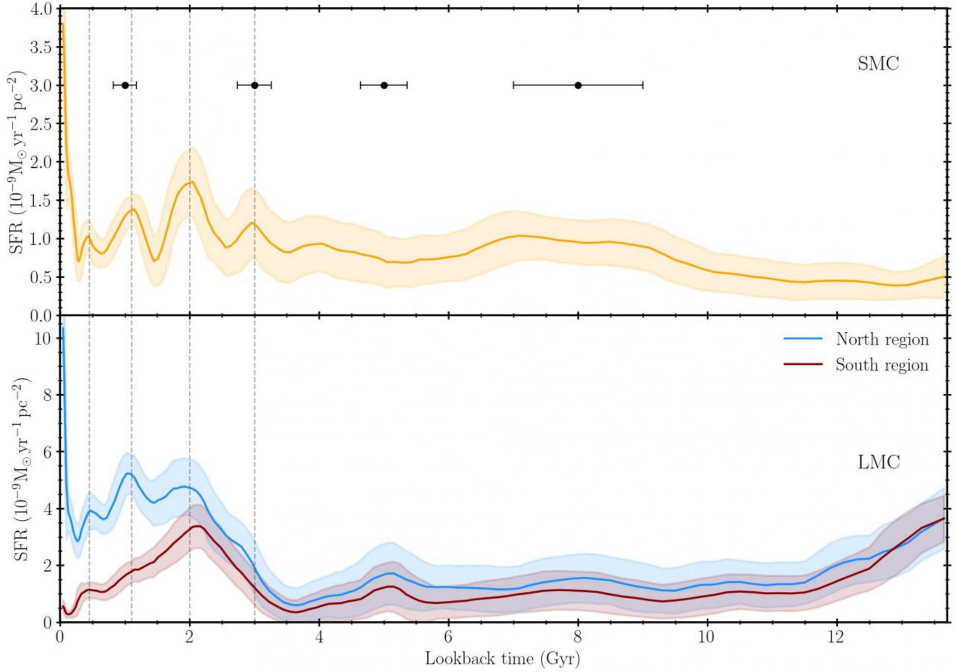
So close no matter how far...

- Individual stars in LG: how stars evolve in **different environments**?
- Studying the effect of age and metallicity by spotting star clusters: **star-formation processes**
- Stellar feedback: stellar winds and supernovæ explosions
- Small-scale gas, dust and metal distribution



The Local Group

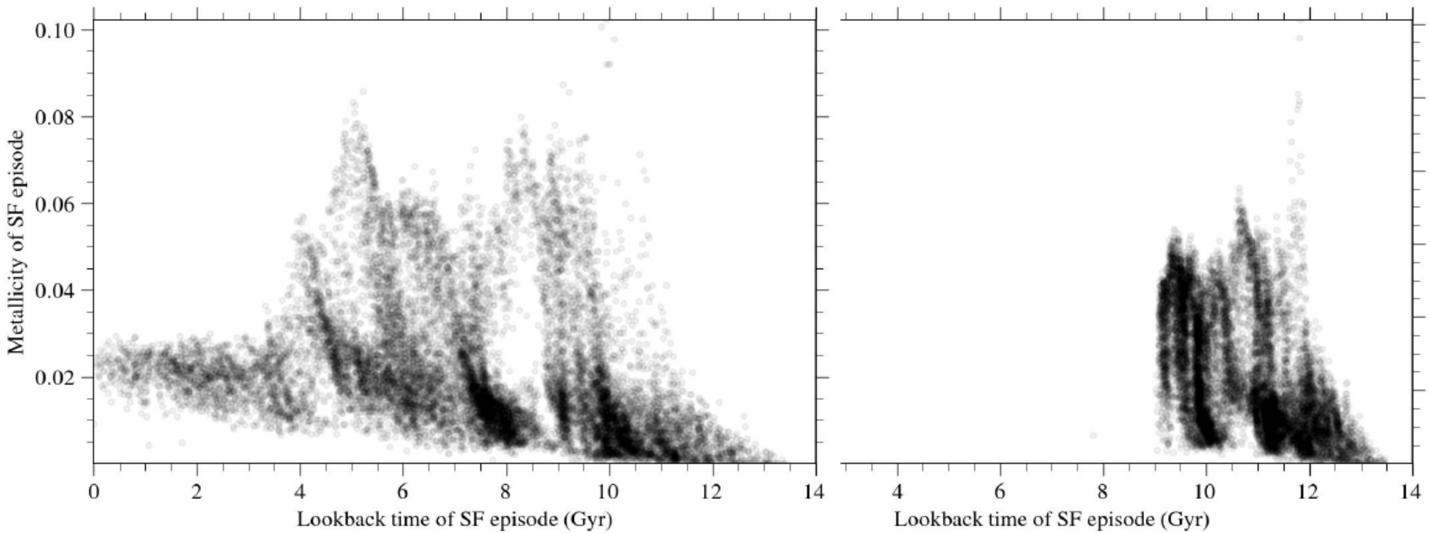
Star-formation histories



Credit: Massana et al. 2022

The Local Group

Star-formation histories: models



Credit: Kovlakas et al. in prep.

- Dwarf galaxies have lower metallicities
- Dwarf galaxies have more dark matter
- Irregular galaxies have *bursty* star-formation histories
- More dwarf galaxies in earlier times
- Comparisons with simulations: galaxy evolution
- Missing satellites: reionization & feedback?

References and Literature

Relevant YouTube videos

Milky Way formation: `https://www.youtube.com/watch?v=VQBzdcFkB7w`

Formation of a galaxy: `https://www.youtube.com/watch?v=O674AZ_UKZk`

Four interacting galaxies: `https://www.youtube.com/watch?v=YCbIjZEtmcY`

Collision of Milky Way and Andromeda galaxies: `https://www.youtube.com/watch?v=4disyKG7XtU`

Illustris-TNG zoom: `https://www.youtube.com/watch?v=Rdd9KAUcvgQ`

Waltzing around: `https://www.youtube.com/watch?v=R5t5nYioIgo`

Differences of cosmological simulations: `https://www.youtube.com/watch?v=XVvarp6bJHU`

References and Literature

Relevant books

- Françoise Combes & James Lequeux (2016).
  The Milky Way: Structure, Dynamics and Evolution.
  EDPS Sciences / CNRS Éditions. ISBN: 978-2-7598-1915-7.
- James Binney & Scott Tremaine. (2008).
  Galactic Dynamics.
  Princeton University Press. 2nd Edition. ISBN: 9780691130279.
- James Binney & Michael Merrifield (1998).
  Galactic Astronomy.
  Princeton University Press. 1st Edition. ISBN: 9780691025650.
- Sidney van den Bergh (2000).
  The Galaxies of the Local Group
  Cambridge University Press. ISBN: 9780511546051.
- Paul W. Hodge, Brooke P. Skelton & Joy Ashizawa (2002).
  An Atlas of Local Group Galaxies.
  Springer Dordrecht. ISBN: 978-1-4020-0673-9.