Galactic archaeology

Eugene Vasiliev

Farnham Astronomical Society, September 2025

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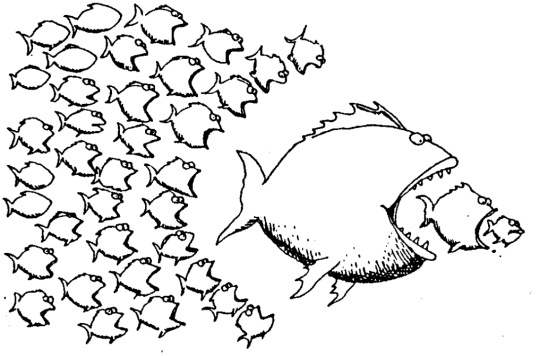
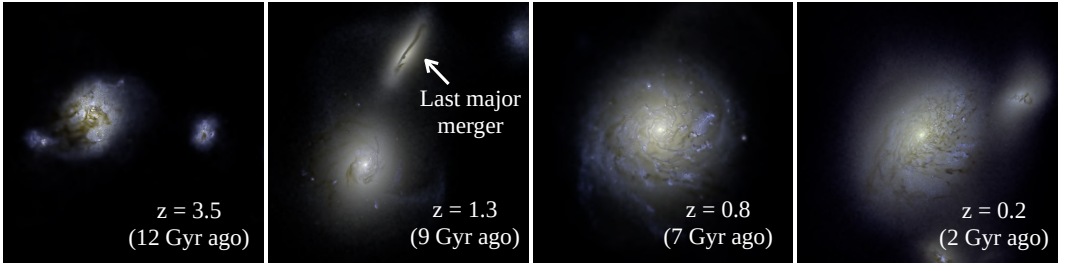
Galaxy formation

. . . is a violent story of mergers, hostile takeovers and destruction





Vintergatan simulation of Milky Way formation

Big Bang

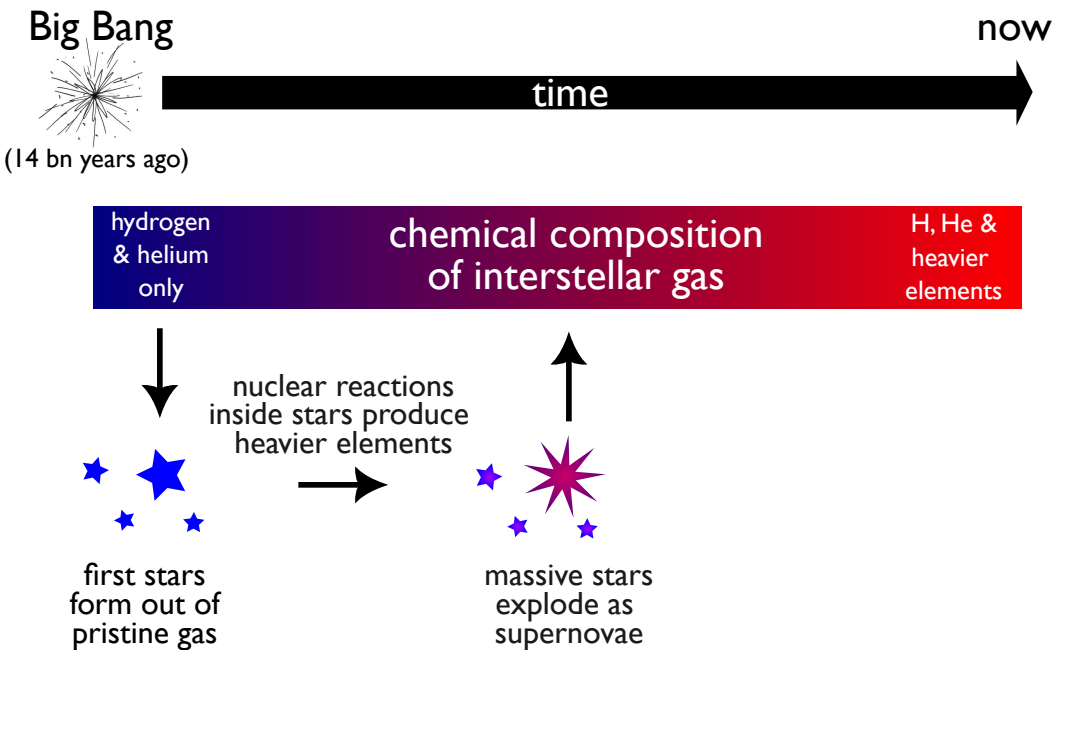
(14 bn years ago)

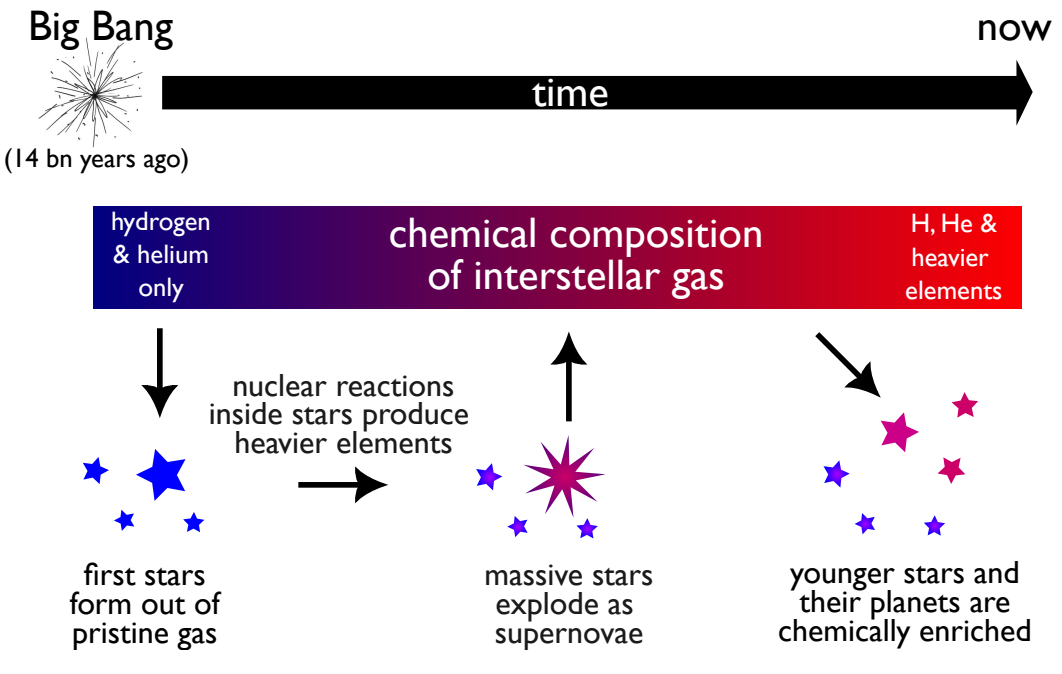
time

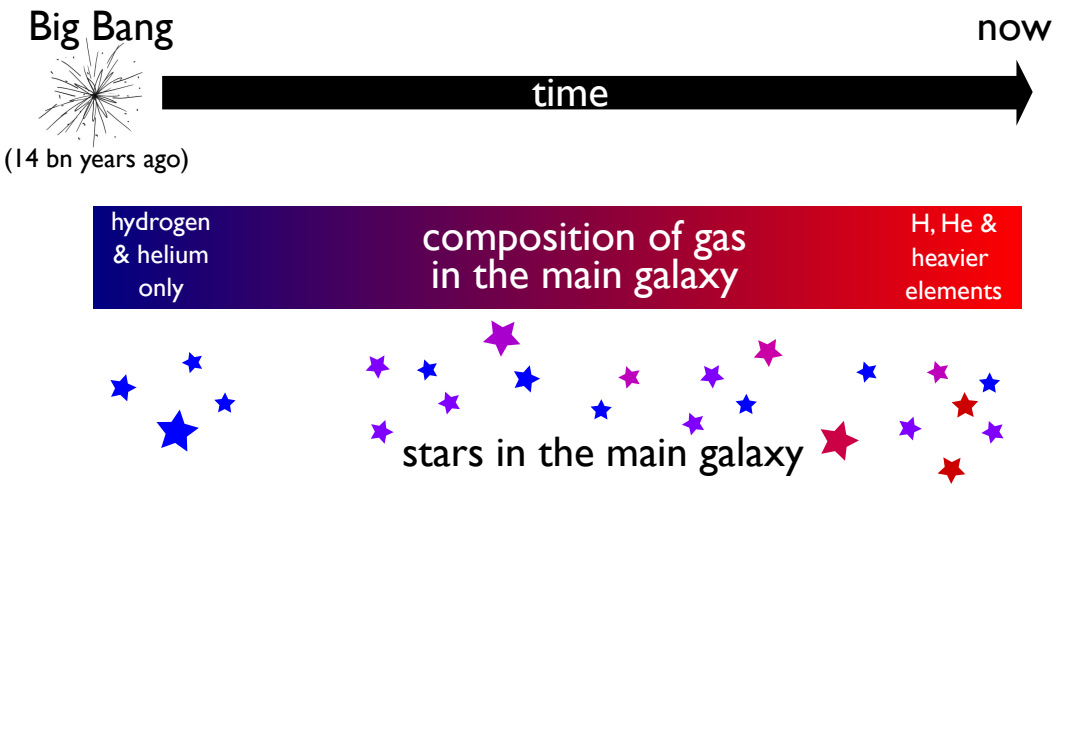
now

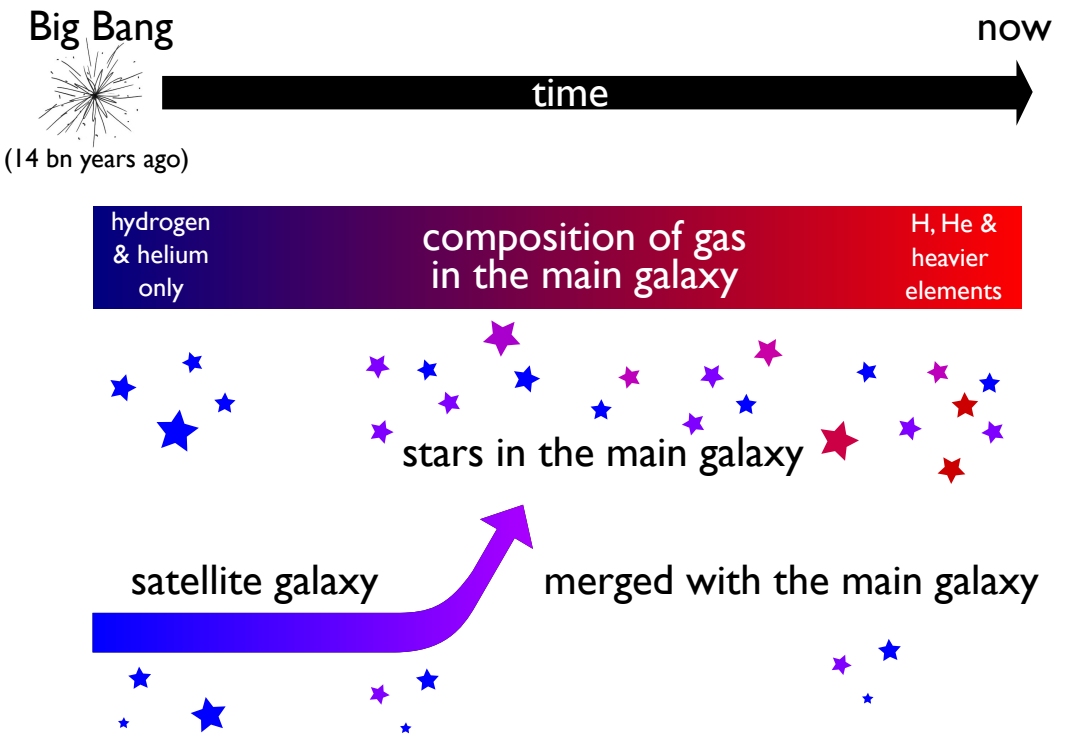
hydrogen & helium only

first stars form out of pristine gas

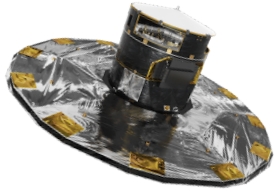

Big Bang
(14 bn years ago)
time
now
hydrogen & helium only
chemical composition of interstellar gas
H, He & heavier elements
nuclear reactions inside stars produce heavier elements
first stars form out of pristine gas
massive stars explode as supernovae


Big Bang
now
time
(14 bn years ago)
hydrogen & helium only
chemical composition of interstellar gas
H, He & heavier elements
nuclear reactions inside stars produce heavier elements
first stars form out of pristine gas
massive stars explode as supernovae
younger stars and their planets are chemically enriched


Big Bang
(14 bn years ago)
time
now
hydrogen & helium only
composition of gas in the main galaxy
H, He & heavier elements
stars in the main galaxy


Big Bang
now
time
(14 bn years ago)
hydrogen & helium only
composition of gas in the main galaxy
H, He & heavier elements
stars in the main galaxy
satellite galaxy
merged with the main galaxy

Instruments

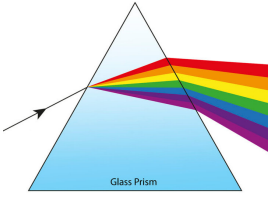


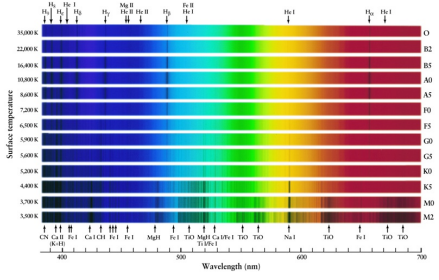
Gaia spacecraft

photometry, parallax and proper motions

Telescopes and spectrographs: line-of-sight velocity and chemical composition

William Herschel telescope

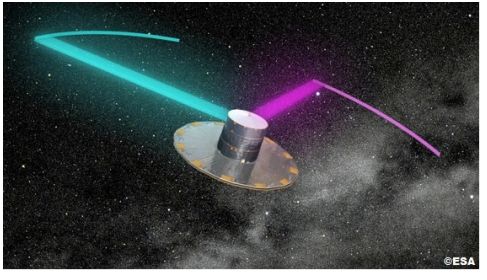


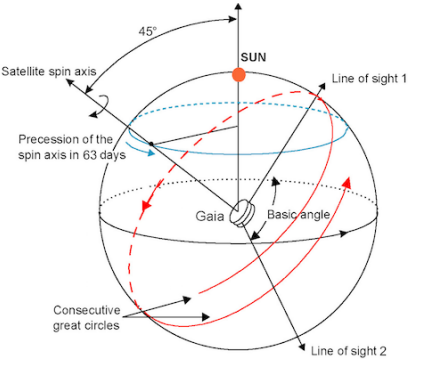


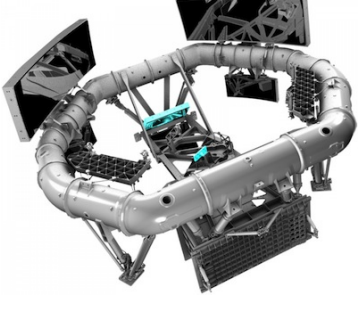
Gaia space telescope

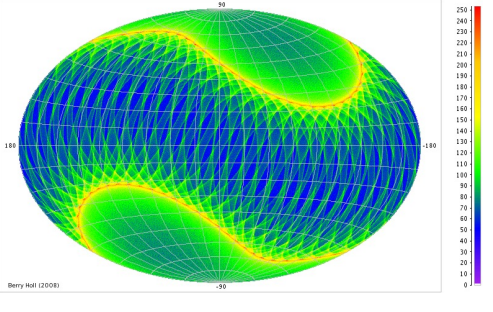
launched in December 2013 into the L2 point;
continued observations for over 10 years (twice the nominal mission duration) until January 2025;
publicly releases all data every few years (most recently in 2023; final data release expected around 2030)

How Gaia astrometry works

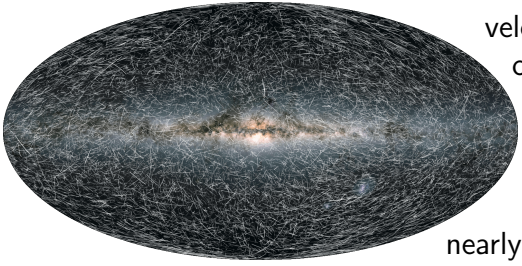




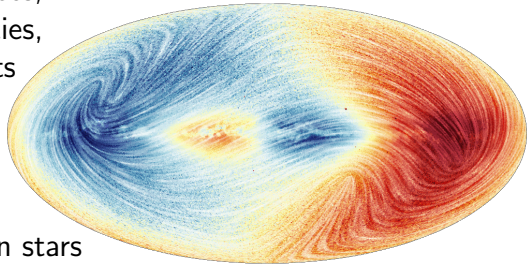




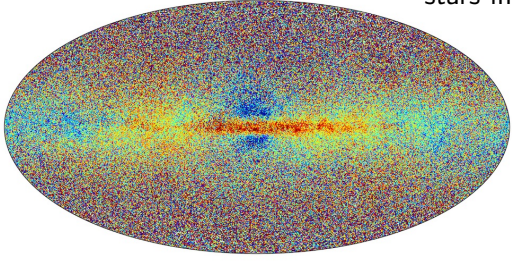
Gaia data products



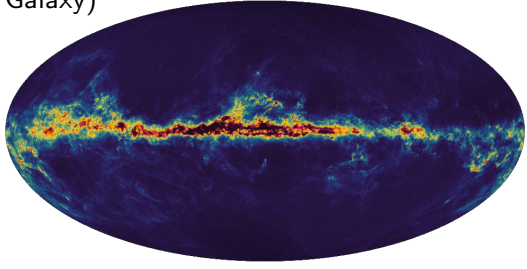
distances,
velocities,
orbits



nearly 2bn stars
(still only 1% of all
stars in our Galaxy)



chemical composition



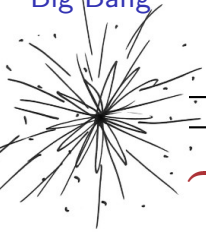
interstellar dust

A brief history of the Milky Way

Gaia–Enceladus

Sagittarius

Big Bang

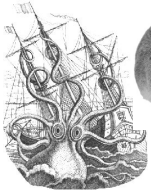


now

10 Gyr

3 Gyr

0.5 Gyr

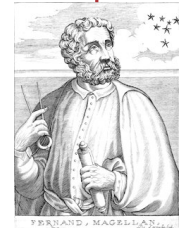


Kraken

Koala

Arjuna

Sequoia



Magellanic clouds

A brief history of the Milky Way

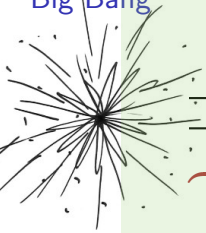
discovered since 2018

Gaia–Enceladus

discovered in 1994

Sagittarius

Big Bang



now

10 Gyr

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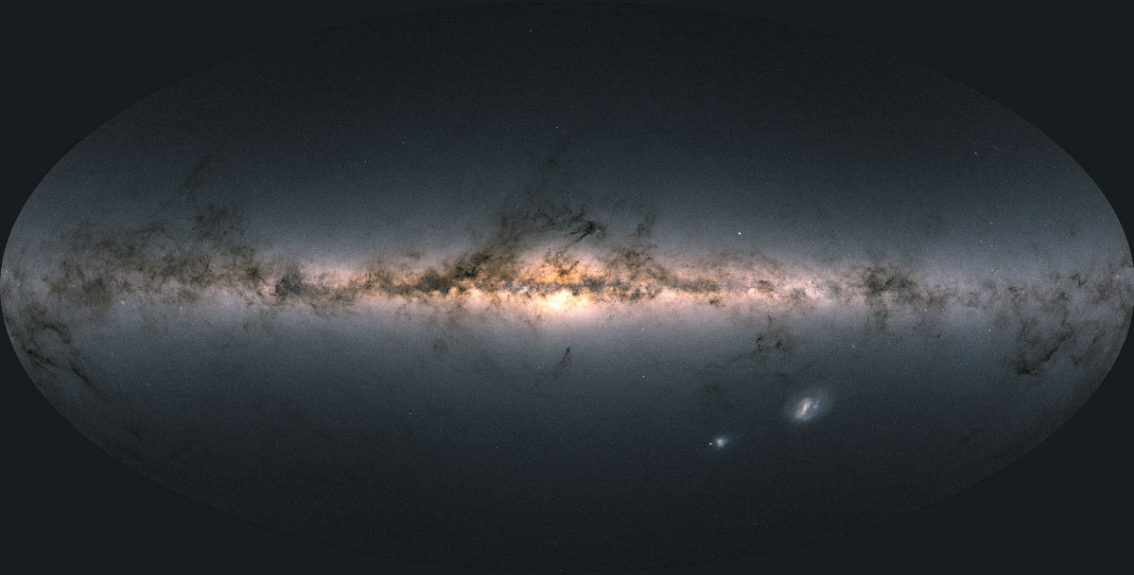
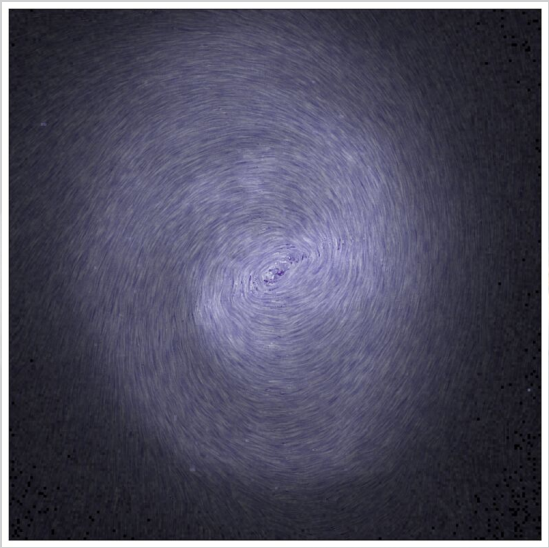
Magellanic clouds

Episode 1: Magellanic clouds and the Milky Way



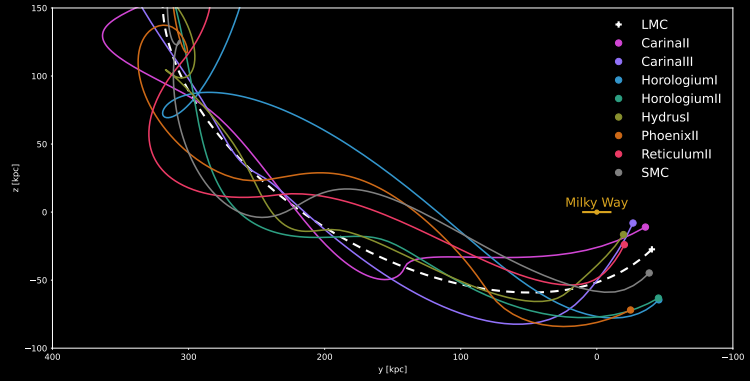
Episode 1: Magellanic clouds and the Milky Way



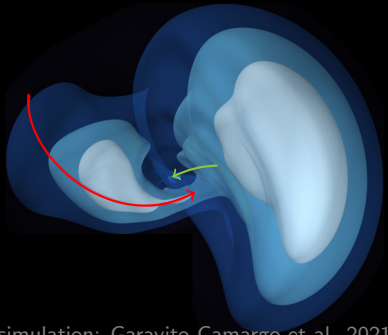
LMC rotation as seen by Gaia [Luri et al. 2021]

Magellanic clouds and other satellite galaxies

- LMC is the most massive satellite of our Galaxy
  ($\sim$5–10 times smaller than the Milky Way itself)
- It is currently just flying past its pericentre at $\sim$50 kpc
  (6$\times$ further away from the Galactic centre than the Sun)
- It comes with a retinue of $\sim$10 satellites, including the SMC

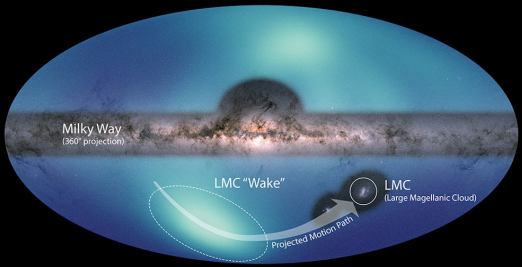


LMC-induced perturbations in the Milky Way



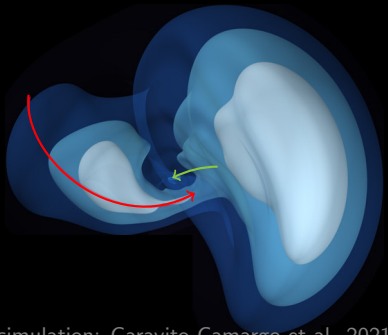
simulation: Garavito-Camargo et al. 2021

LMC creates a "density wake" along its past orbit and displaces the Milky Way halo as a whole, changing the velocities of stars in the outer halo by tens of km/s.



observations: Conroy et al. 2021

LMC-induced perturbations in the Milky Way



simulation: Garavito-Camargo et al. 2021

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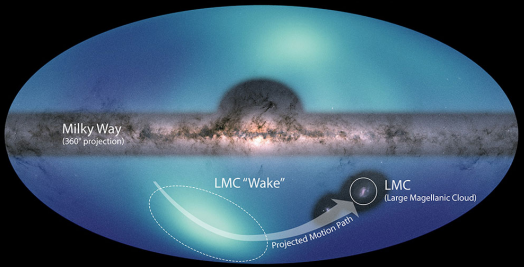
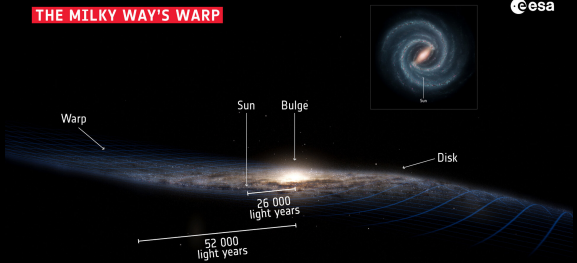
LMC also likely bends the outer Galactic disc (although there are other contenders).

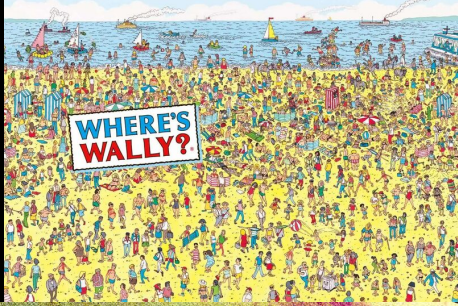


observations: Conroy et al. 2021

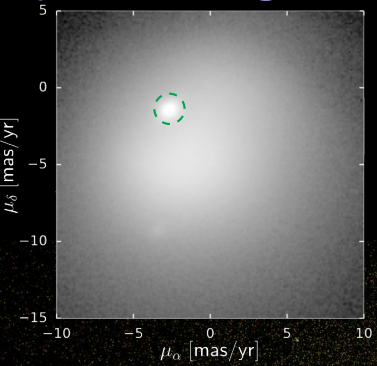


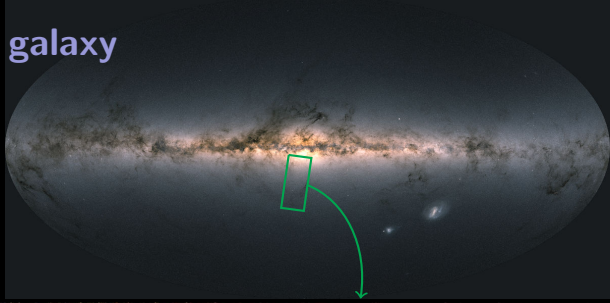
Poggio et al. 2020

Episode 2: Sagittarius dwarf galaxy



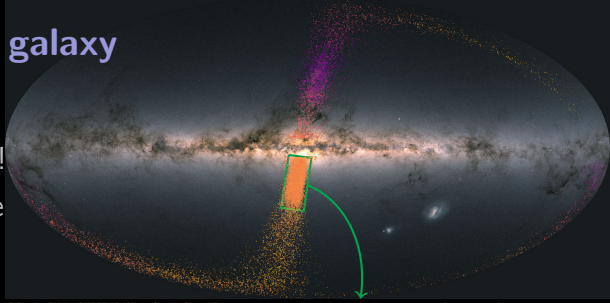
Episode 2: Sagittarius dwarf galaxy





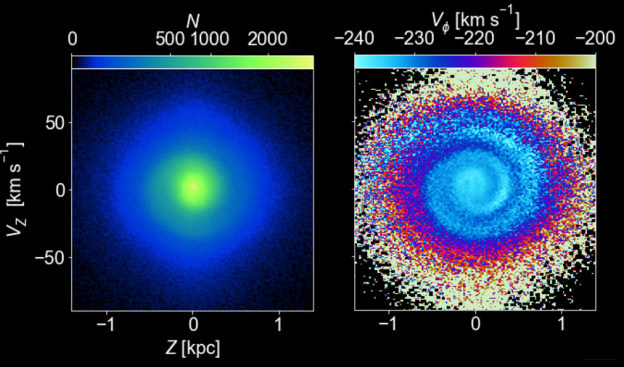
everywhere! (after filtering by proper motion)

Episode 2: Sagittarius dwarf galaxy

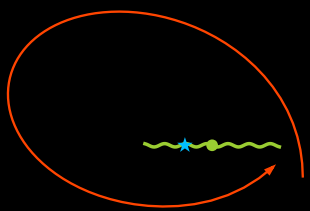


- third-largest MW satellite (after MCs)
- discovered only in 1994, accidentally!
- located at $\sim$18 kpc from MW centre
  (twice more distant than the Sun)
  on the opposite side of the Galaxy
- produces a prominent tidal stream spanning the entire sky

The *Gaia Snail* in the Milky Way disc

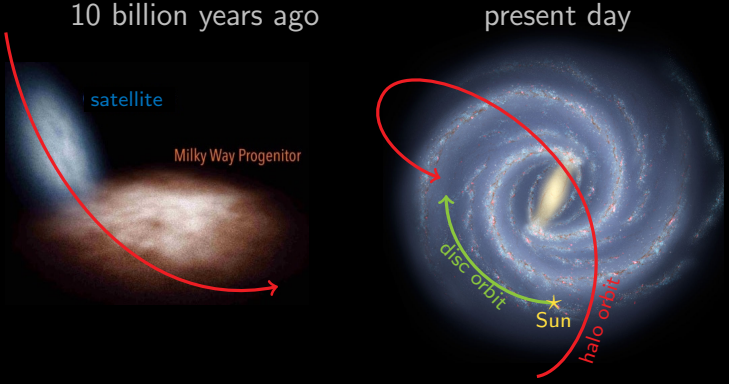


[Antoja et al. 2018, 2023]



perturbations in the vertical position and velocity of disc stars, most likely caused by the Sagittarius galaxy hitting the Milky Way disc about 1 Gyr ago

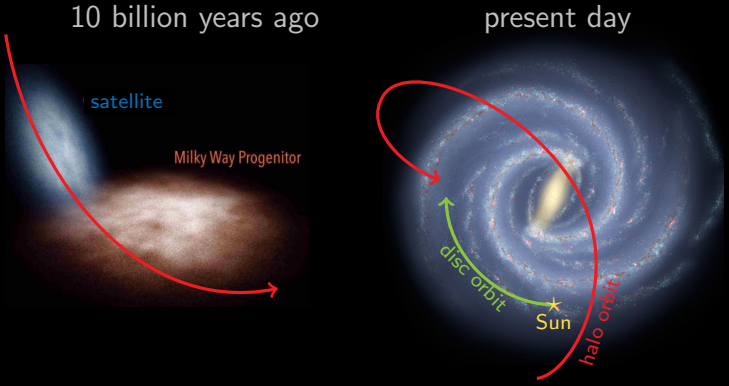
Episode 3: Gaia–Enceladus

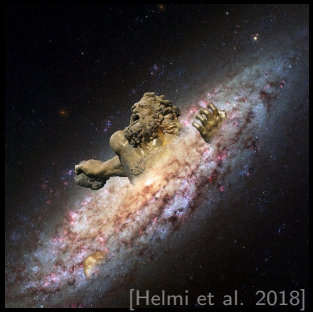


Stars in the Milky Way disc move on (close to) circular orbits, and orbits of stars in the halo are more eccentric.

The most eccentric and chemically distinct stars are accreted from a satellite galaxy that merged with the Milky Way early in its history.

Episode 3: Gaia–Enceladus




[Helmi et al. 2018]

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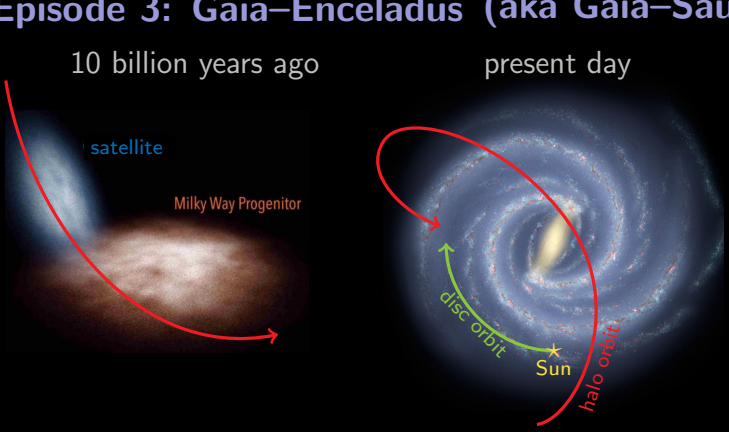
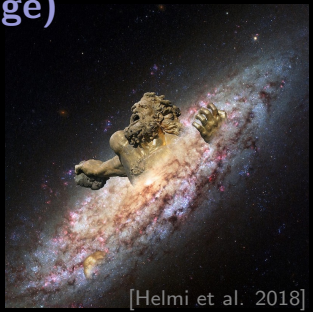
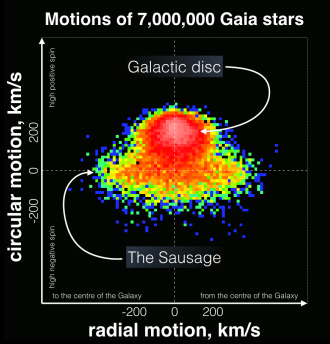
Episode 3: Gaia–Enceladus (aka Gaia–Sausage)





[Helmi et al. 2018]



[Belokurov et al. 2018]

Stars in the Milky Way disc move on (close to) circular orbits, and orbits of stars in the halo are more eccentric.

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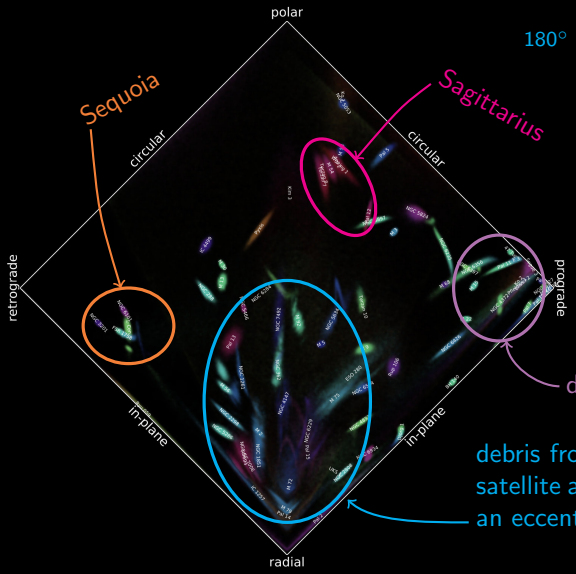
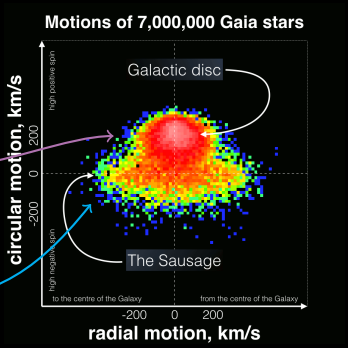
Structures in the space of orbits

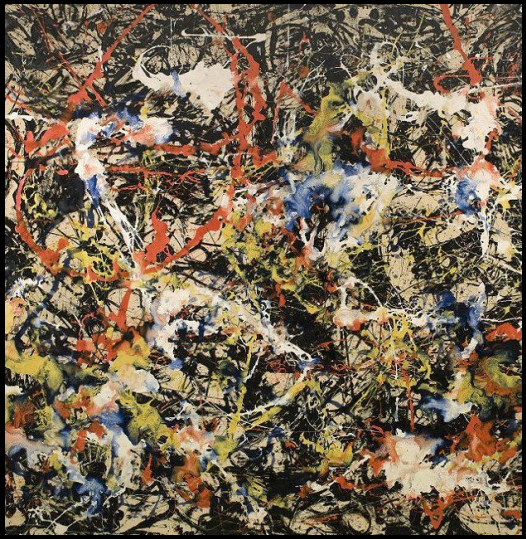
classification of globular clusters





Structures in the space of orbits

Kliment Redko, "Uprising"

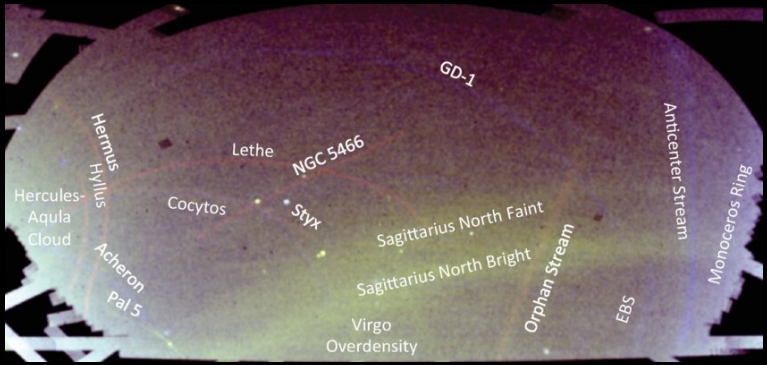


Jackson Pollock, "Convergence"

Stellar streams in the Milky Way

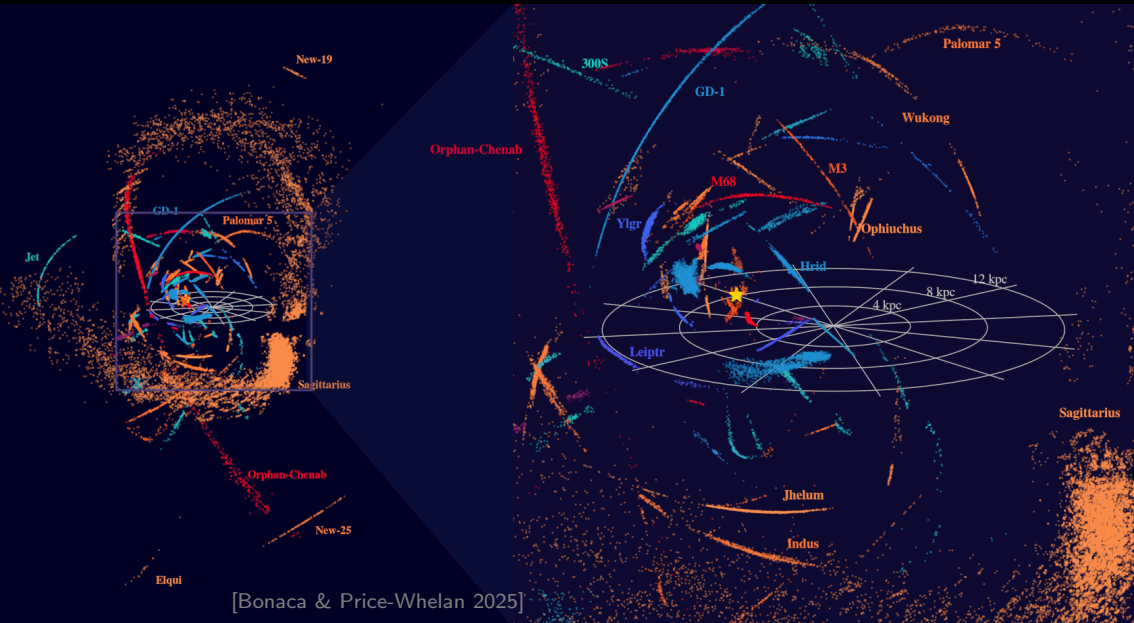
Tidal stripping of star clusters and satellite galaxies produces streams of stars, which trace the orbit of their progenitor even long after it has been fully disrupted.

First streams were discovered in early 2000s, and in the Gaia era more than 100 streams are catalogued.



Sloan Digital Sky Survey; Belokurov et al. 2006

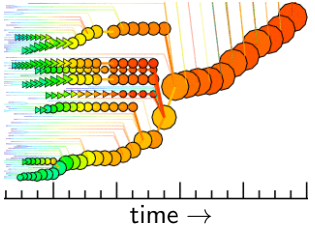
Stellar streams in the Milky Way



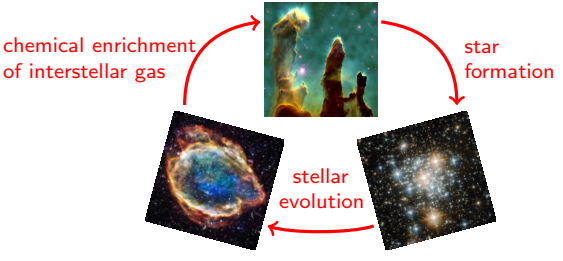
[Bonaca & Price-Whelan 2025]

What do we learn from galactic archaeology?

- discover the assembly history of our Galaxy



- understand the chemical evolution of the Universe



each accreted satellite has its own unique chemical signature and history of elements