A crash course on Galactic dynamics + Hands-on tutorial on Galpy orbit modeling

July 31st, 2024

Gustavo Medina Toledo
University of Toronto

Outline

- **Theoretical background**
  - Gravity and potentials
  - Lagrangian and Hamiltonian formalisms
  - Conserved quantities (e.g., energy, ang momentum)
  - Orbits in spherical and disk potentials
- **Observational background**
  - The Milky Way
  - Surveys
  - Streams
  - The accretion history of the Milky Way
  - The effects of satellite accretion
- **Galpy tutorial**
  - The basics: installation and getting to know the package
  - Generating orbits
  - The effect of the Large Magellanic Cloud
  - Comparing and modifying potentials

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What is a star?

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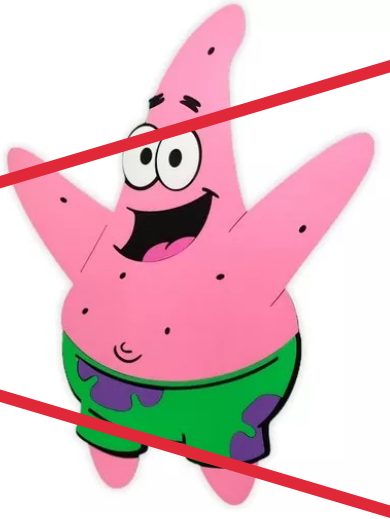
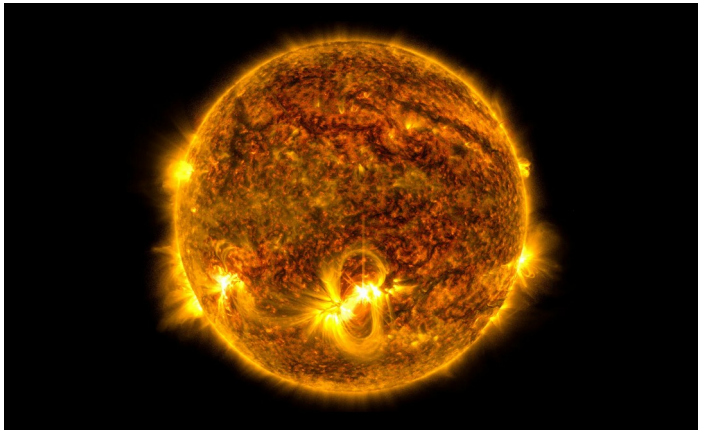


- In Galactic dynamics, a star is just a point mass with additional properties!

What is a star?

- A star can be characterized by its:
  - Position $\vec{x}$ and velocity $\vec{v}$
  - Mass m
  - Radius $R = 0$ and surface gravity $\log g$
  - Effective temperature T_{eff}
  - Luminosity $L \rightarrow$ magnitude and colors
  - Chemical composition $Z \Leftrightarrow [Fe/H] = \log_{10}\left(\frac{N_{Fe}}{N_H}\right)_{star} - \log_{10}\left(\frac{N_{Fe}}{N_H}\right)_{Sun}$
  - Age



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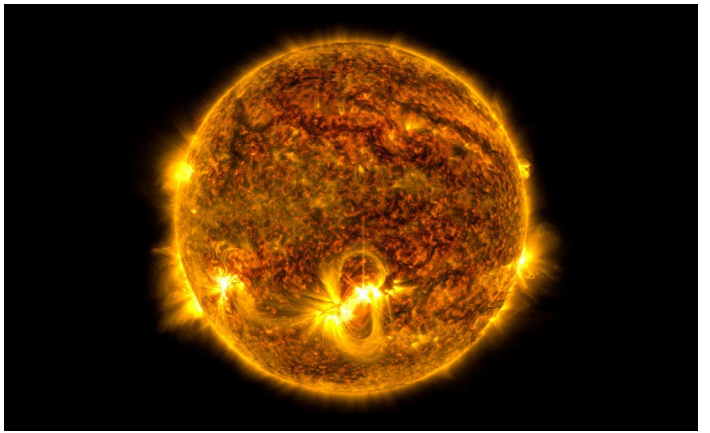
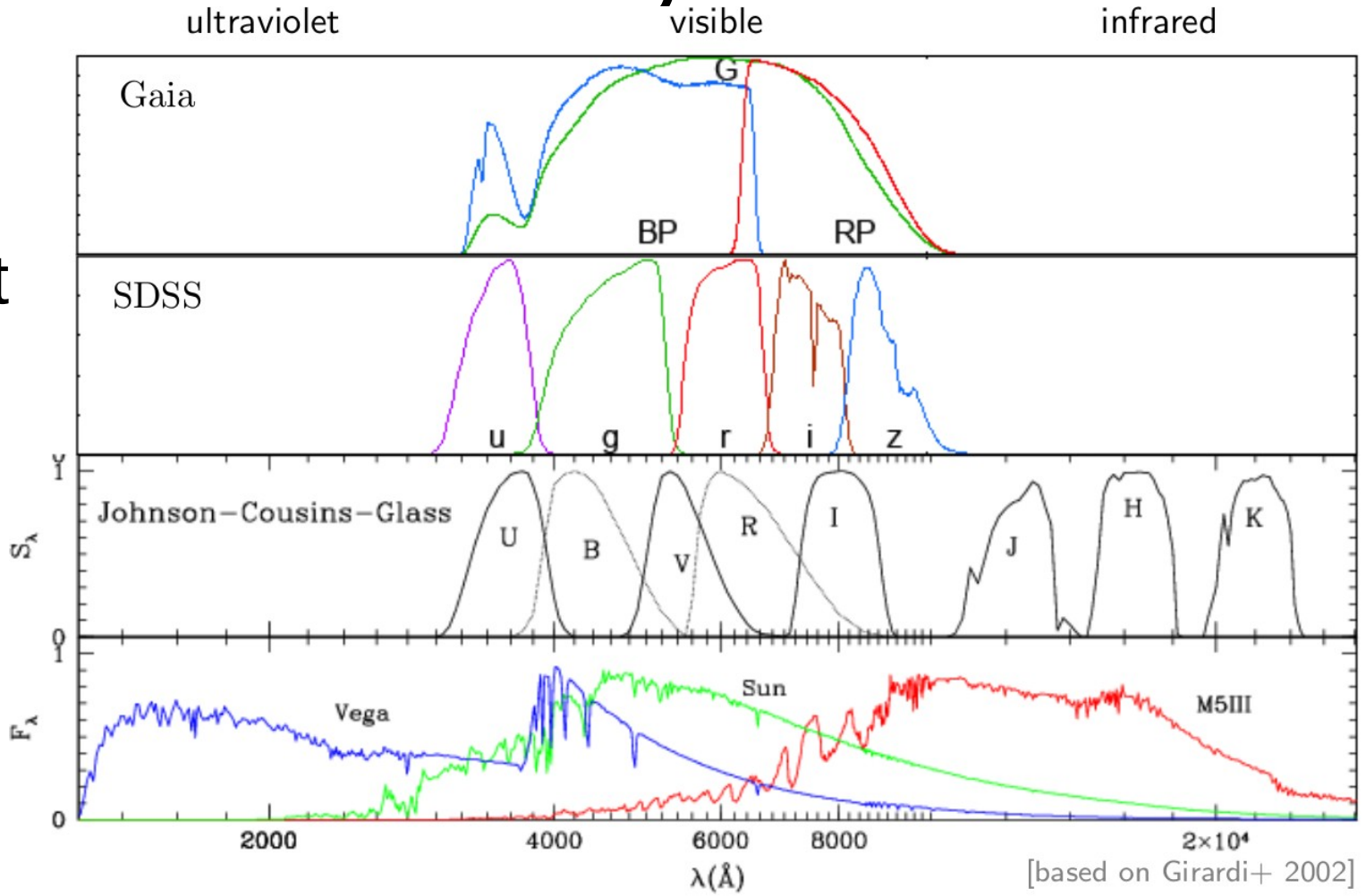


Astrometry

Photometry Spectroscopy

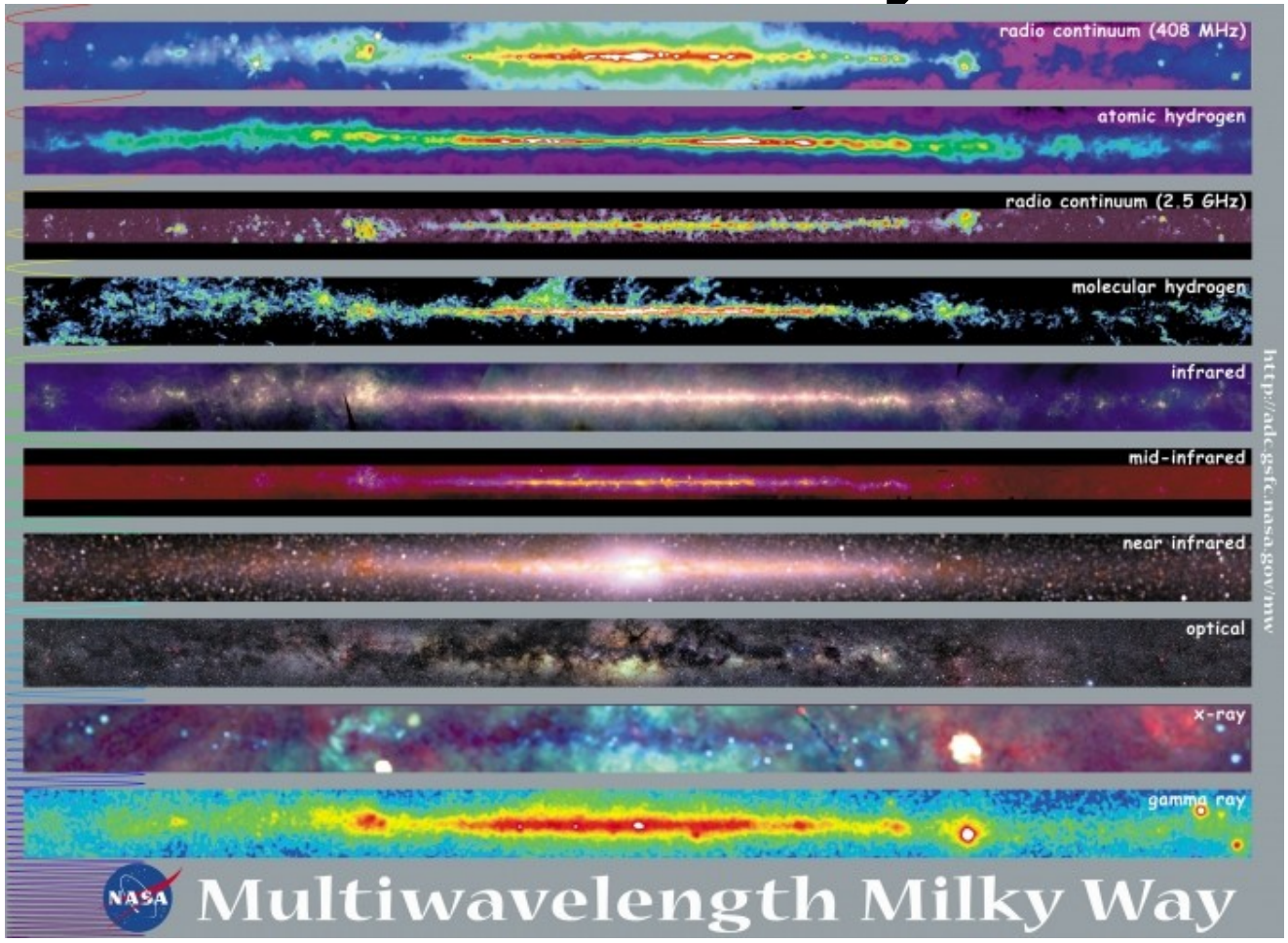
Photometry

Study of the intensity of light emitted by a source as a function of time



[based on Girardi+ 2002]

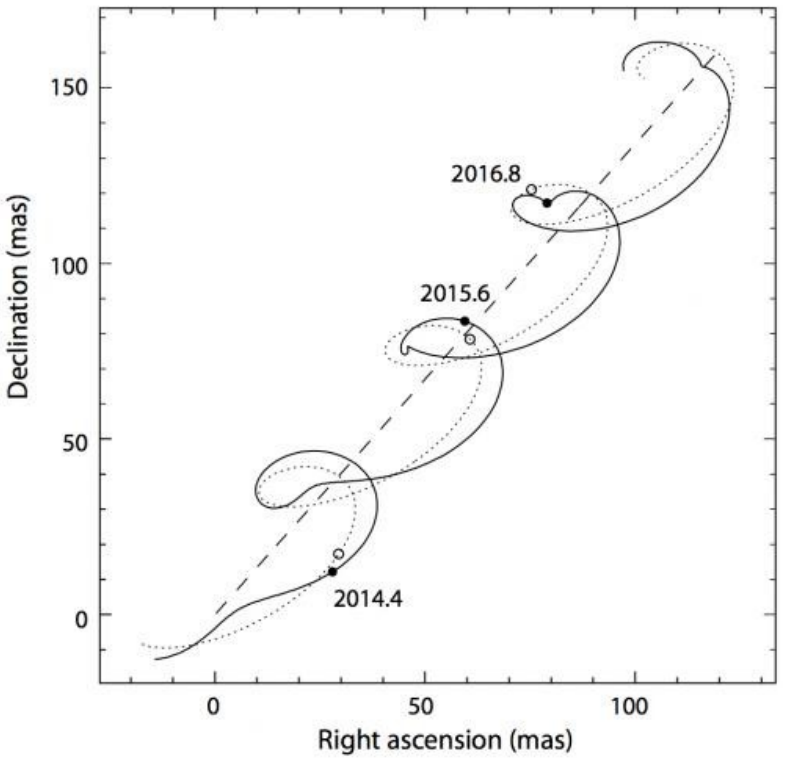
Photometry


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

Astrometry

Astrometry studies the **positions** and **movements** of objects in the sky

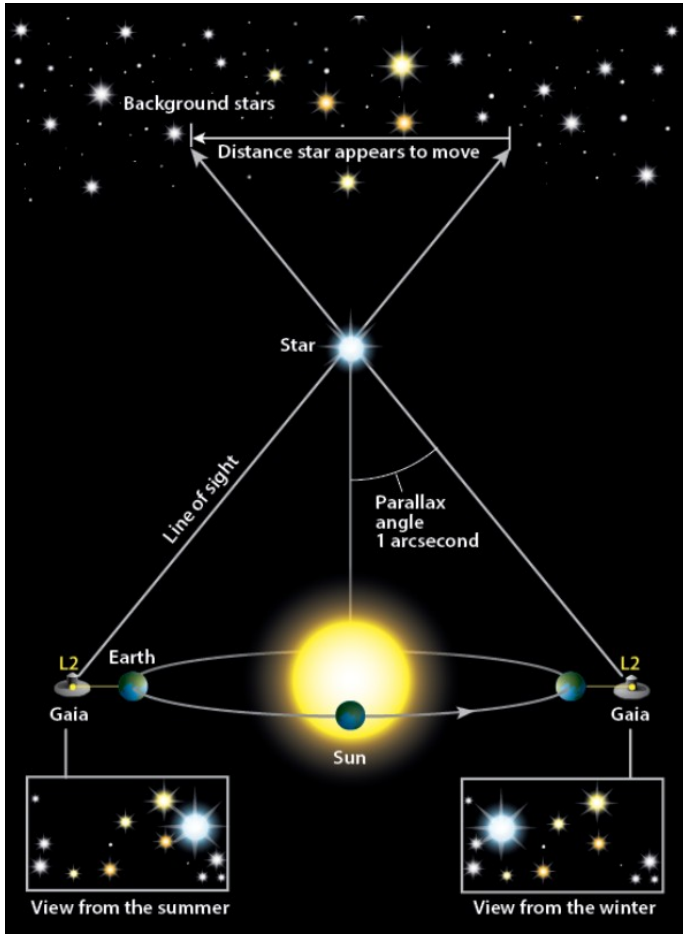
(from the measurement of positions over time)



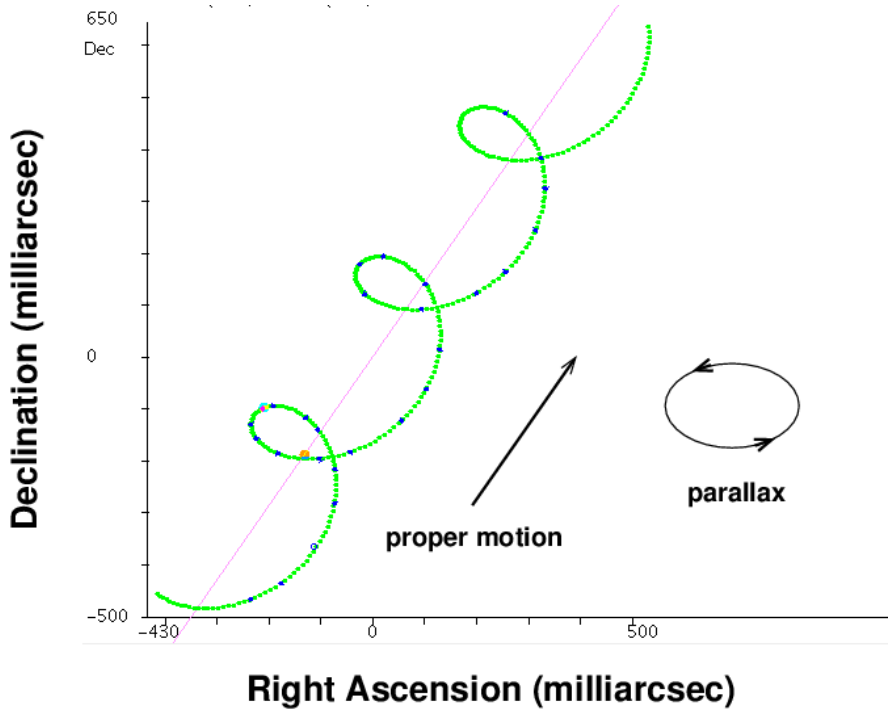
Credit: ESA

Astrometry

Parallax



Proper motion

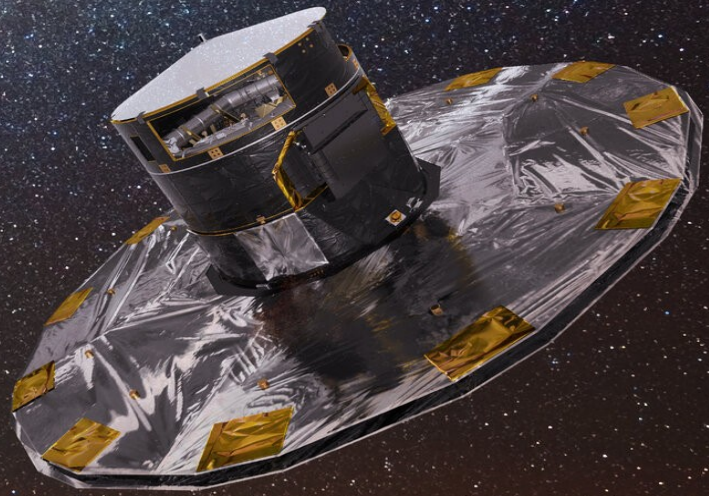


Credit: ESA, Hipparcos

Astrometry and the Gaia revolution

Launched Dec 2013

Orbits the Earth-Sun system
from the second Lagrange point



Credit: ESA

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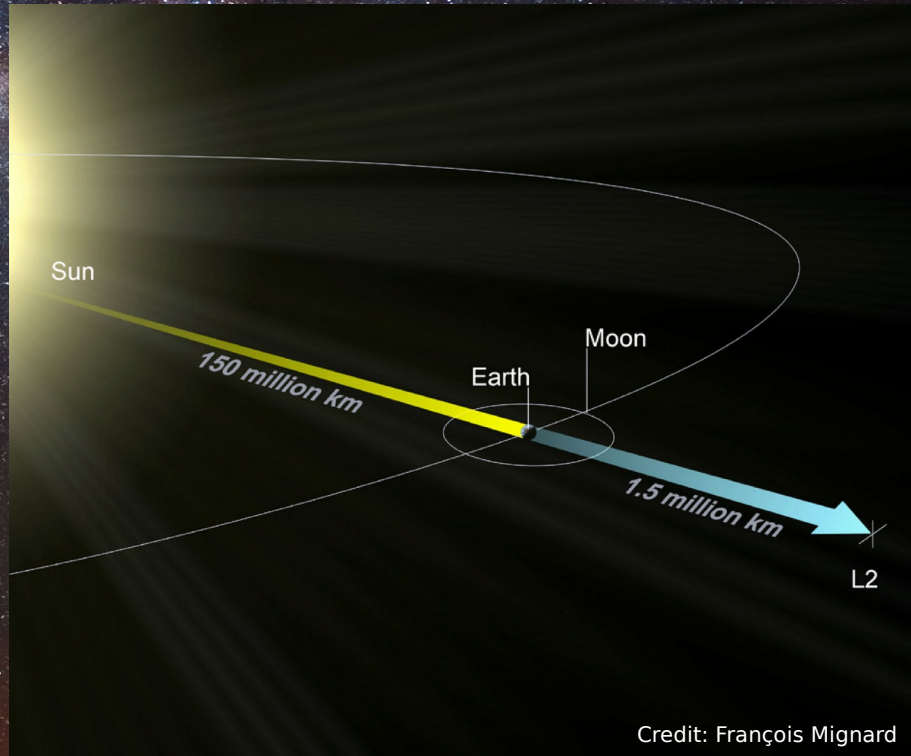
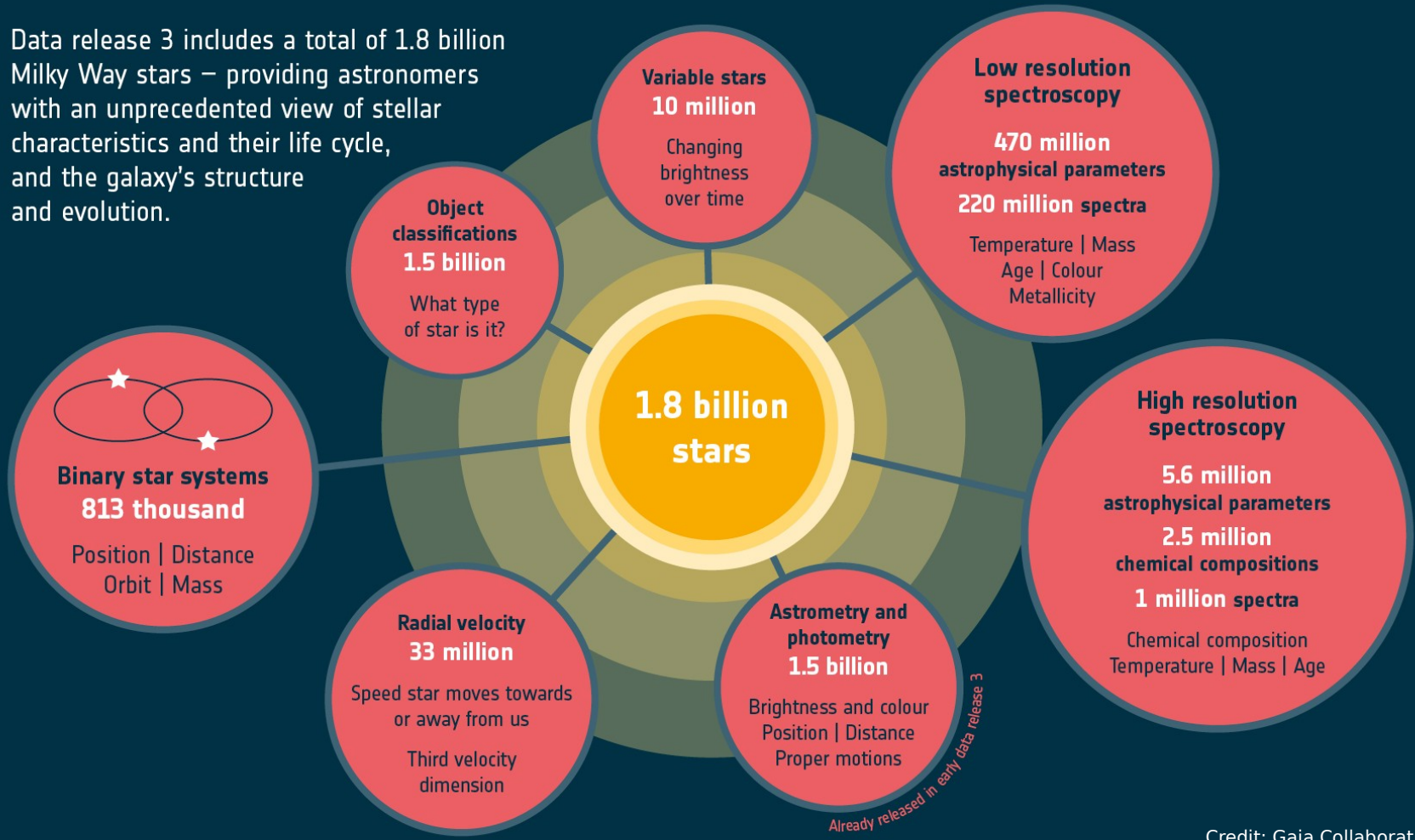


MILKY WAY STARS

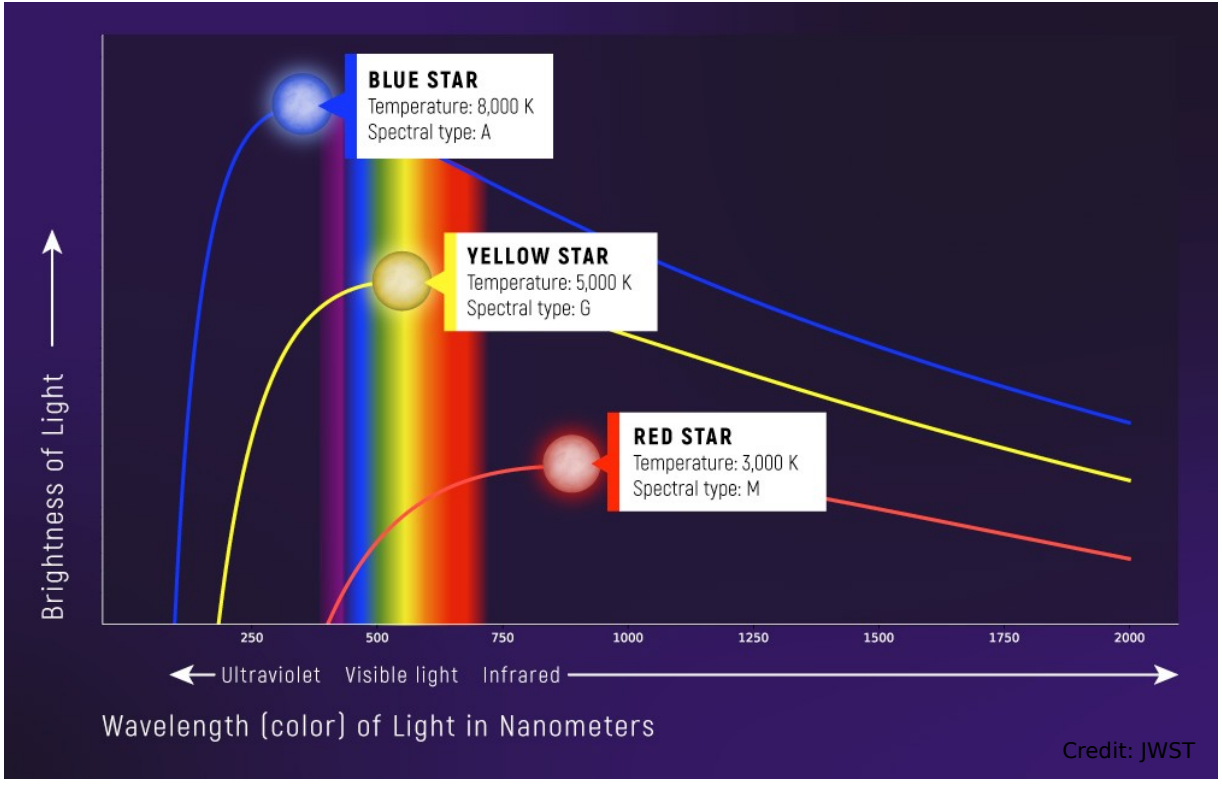
Data release 3 includes a total of 1.8 billion Milky Way stars – providing astronomers with an unprecedented view of stellar characteristics and their life cycle, and the galaxy's structure and evolution.



Credit: Gaia Collaboration

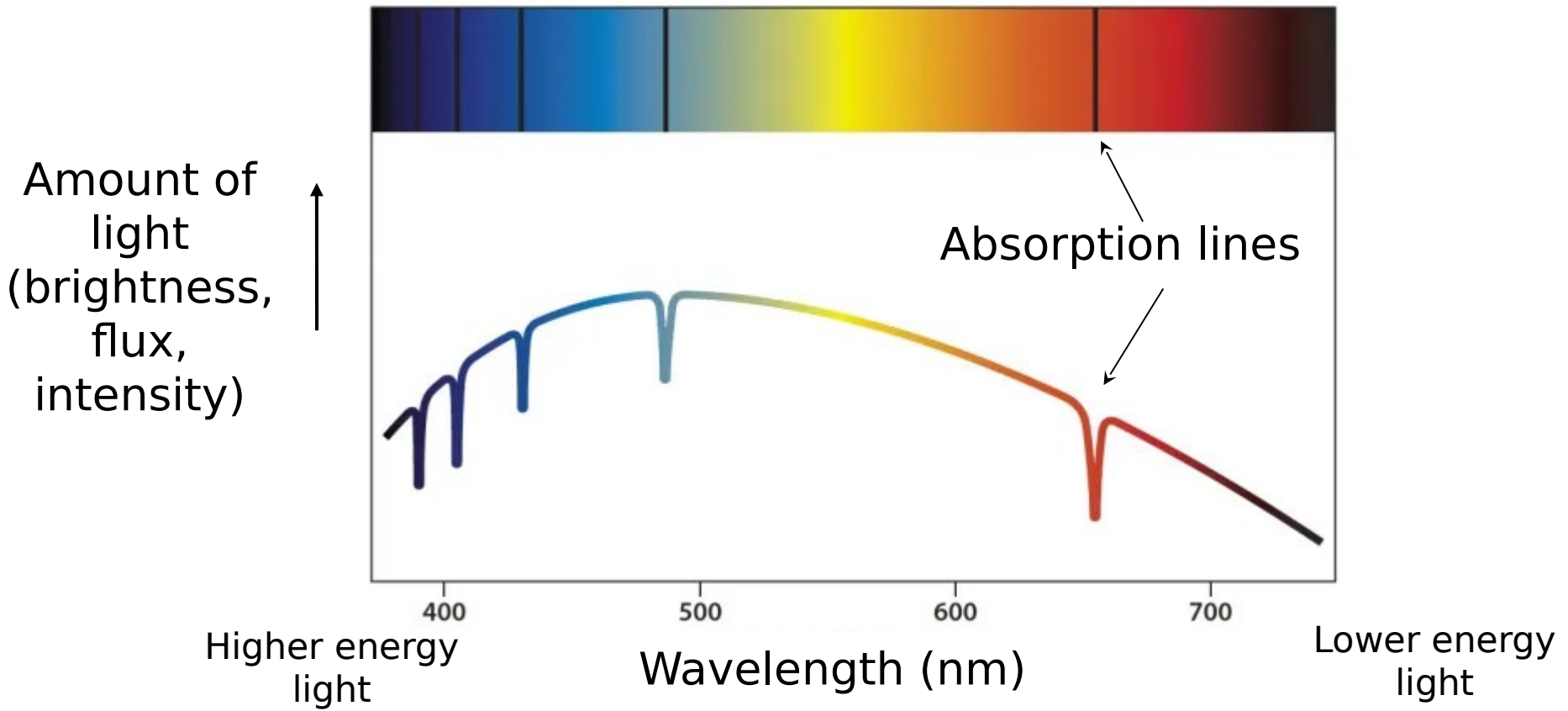
Spectroscopy

Study of electromagnetic radiation as a function of wavelength



A nice intro from JWST collaboration:
https://webbtelescope.org/contents/articles/spectroscopy-101--introduction

Stellar spectra



Credit: Rick Johnson, Mairead Heiger

What affects an observed spectrum?

- Chemical composition
- Surface temperature
- Surface gravity
- Velocity
- Instrument resolution, observing conditions, etc...

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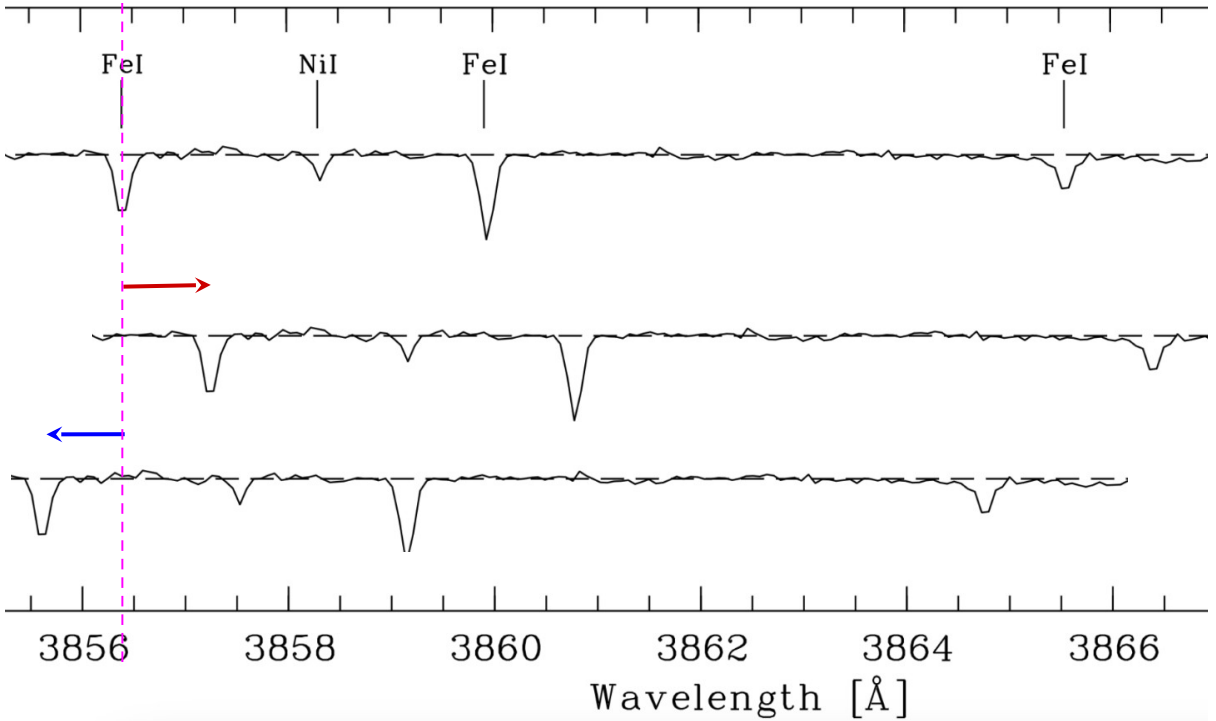
Velocity



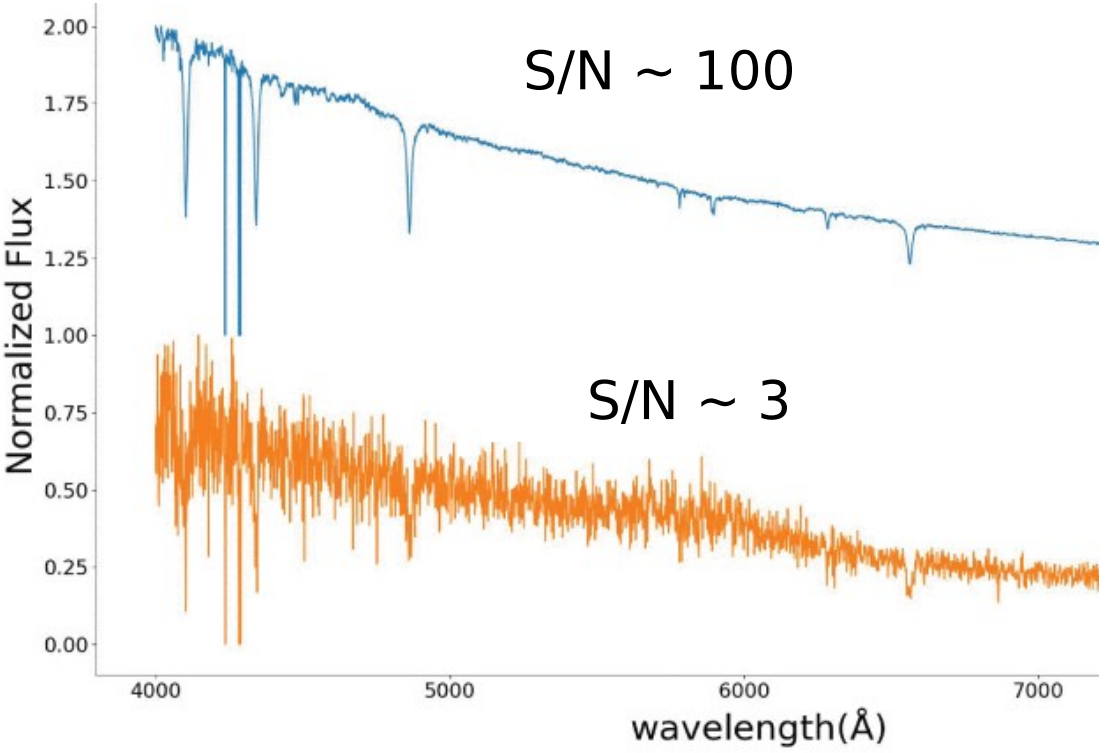
Laboratory (true)

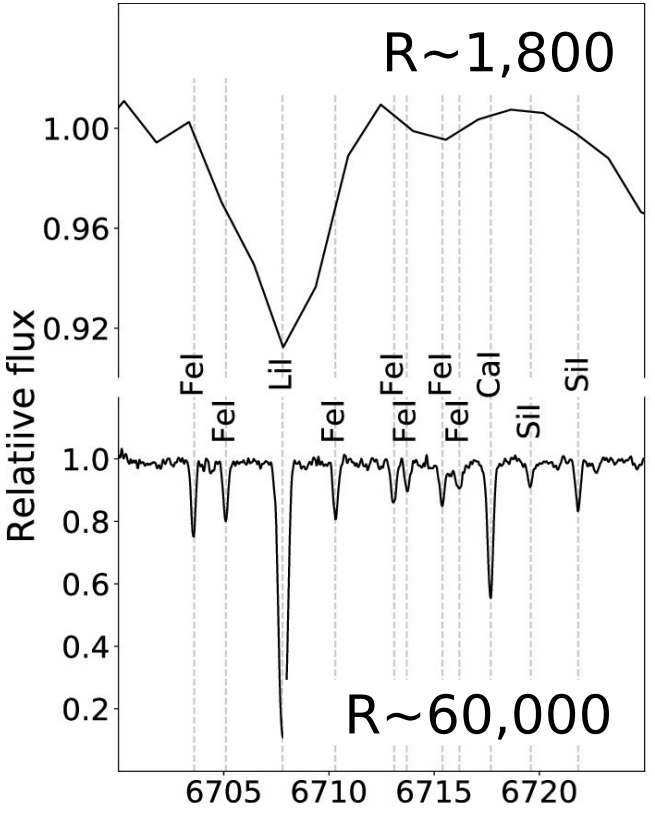
Moving away

Moving towards

Credit: M. Pettini, Mairead Heiger

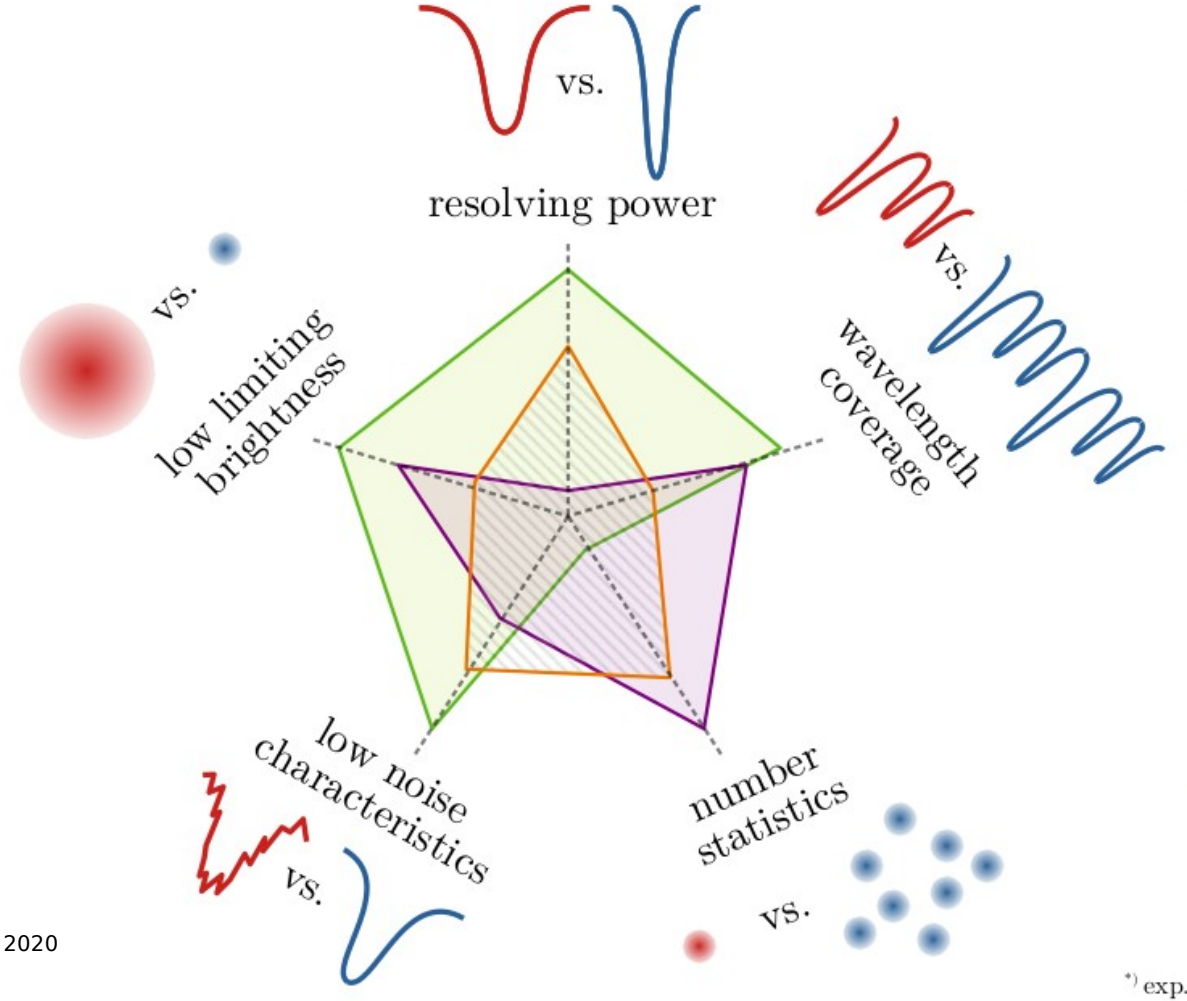
Resolution and S/N





Credit: Singh+2019, Wu+2020, Mairead Heiger

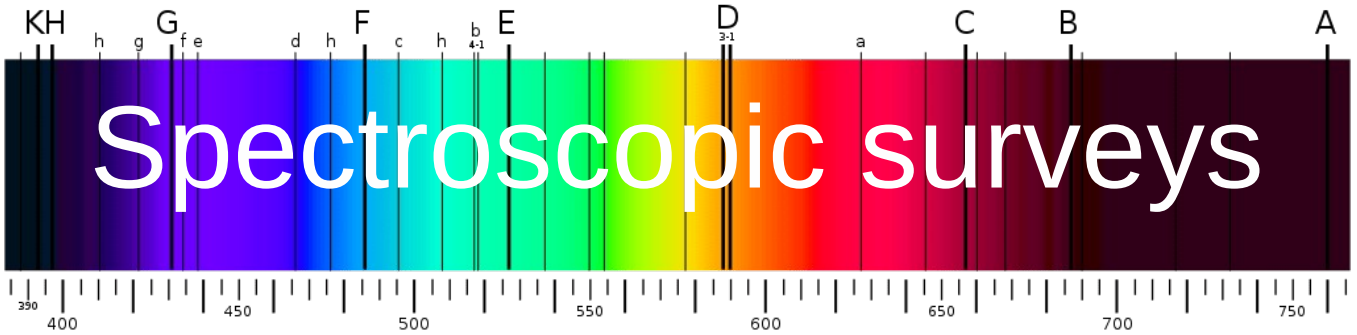
Spectroscopic surveys

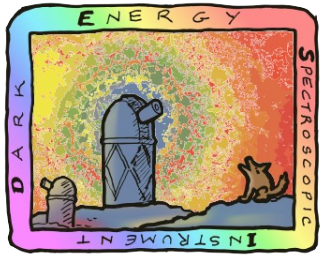


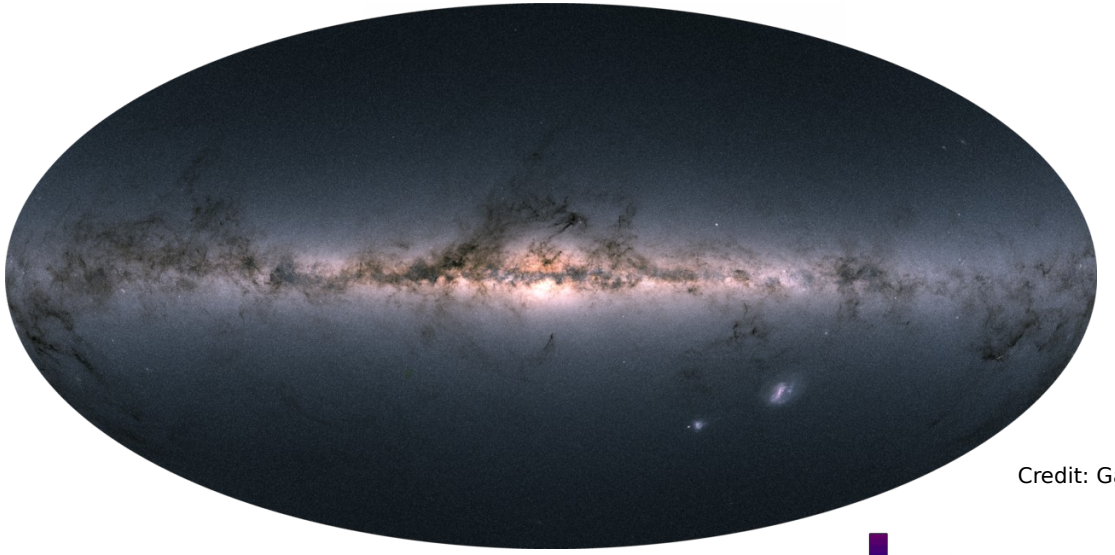
Credit: M. Hanke 2020

*) exp. time × telescope size (/# of fibers)

Spectroscopic surveys





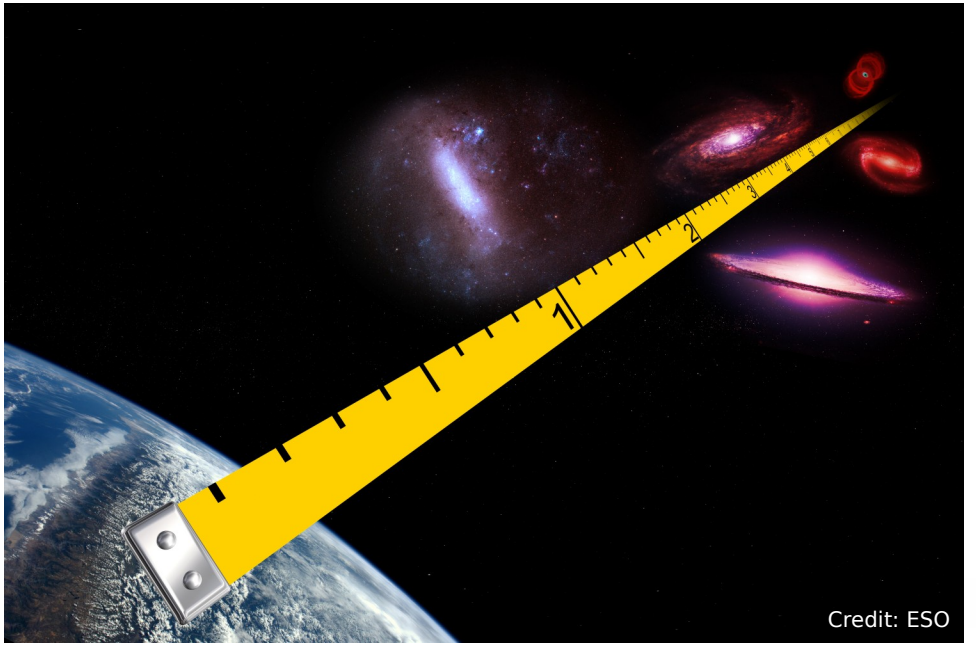


Credit: Gaia, ESA

etc…

Distance determination

- **Individual stars**
  - From parallax $d \approx 1/\varpi$
  - From photometry (standard candles; e.g., Cepheids, RR Lyrae, blue horizontal-branch stars, tip of the red giant branch, etc…)
  - From spectro-photometric and photo-astrometric modelling based on stellar evolution models
- **Stellar clusters, galaxies, etc…**
  - Standard candles
  - CMD fitting
  - Tully-Fisher
  - ...



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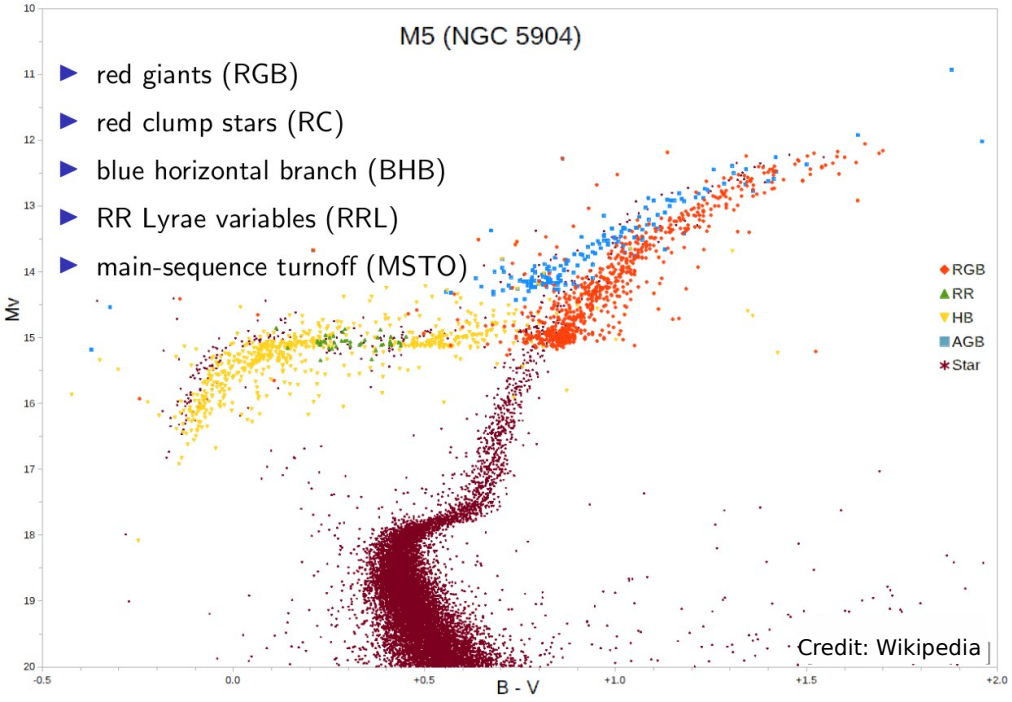
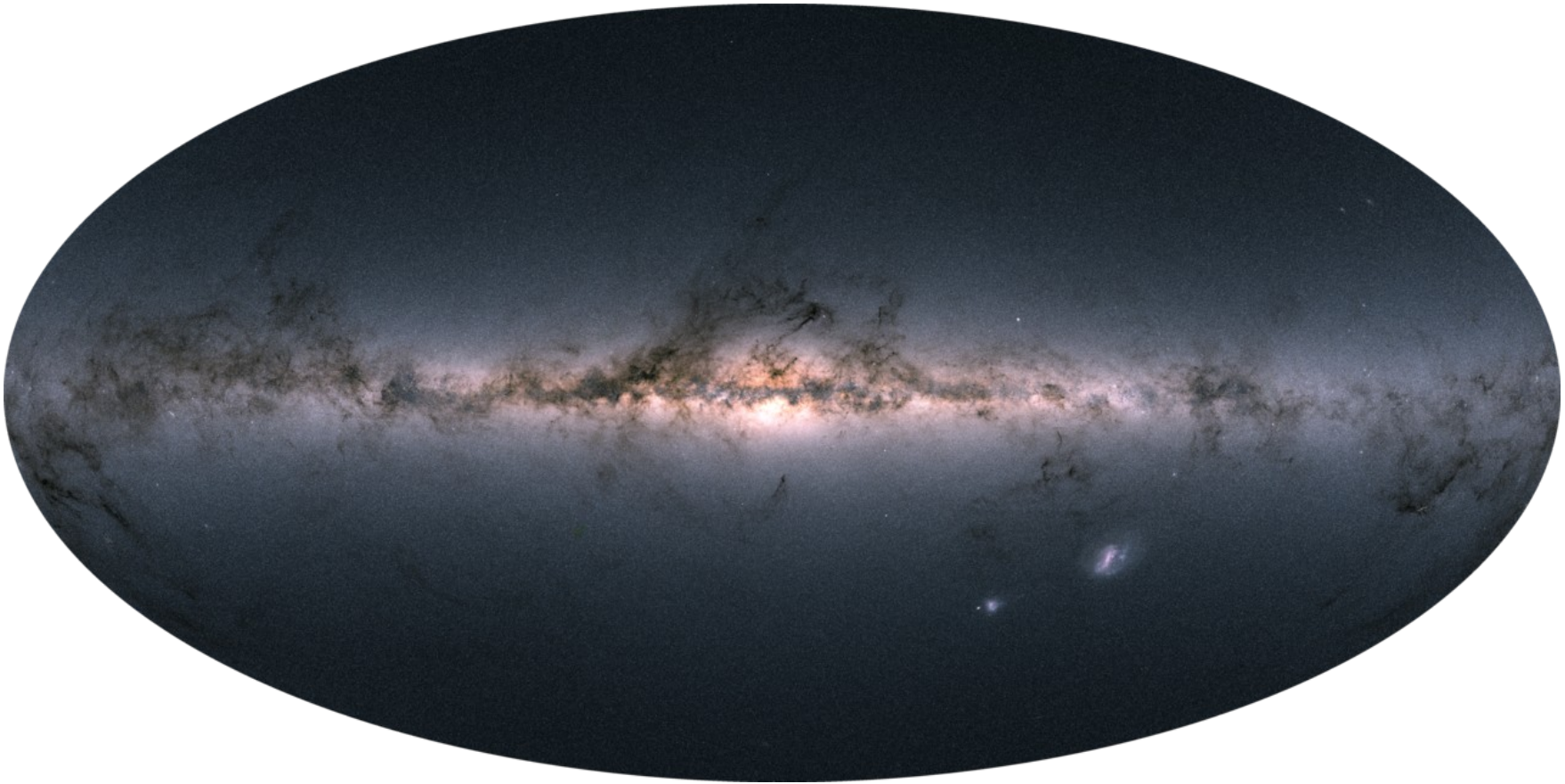


The structure of the Milky Way



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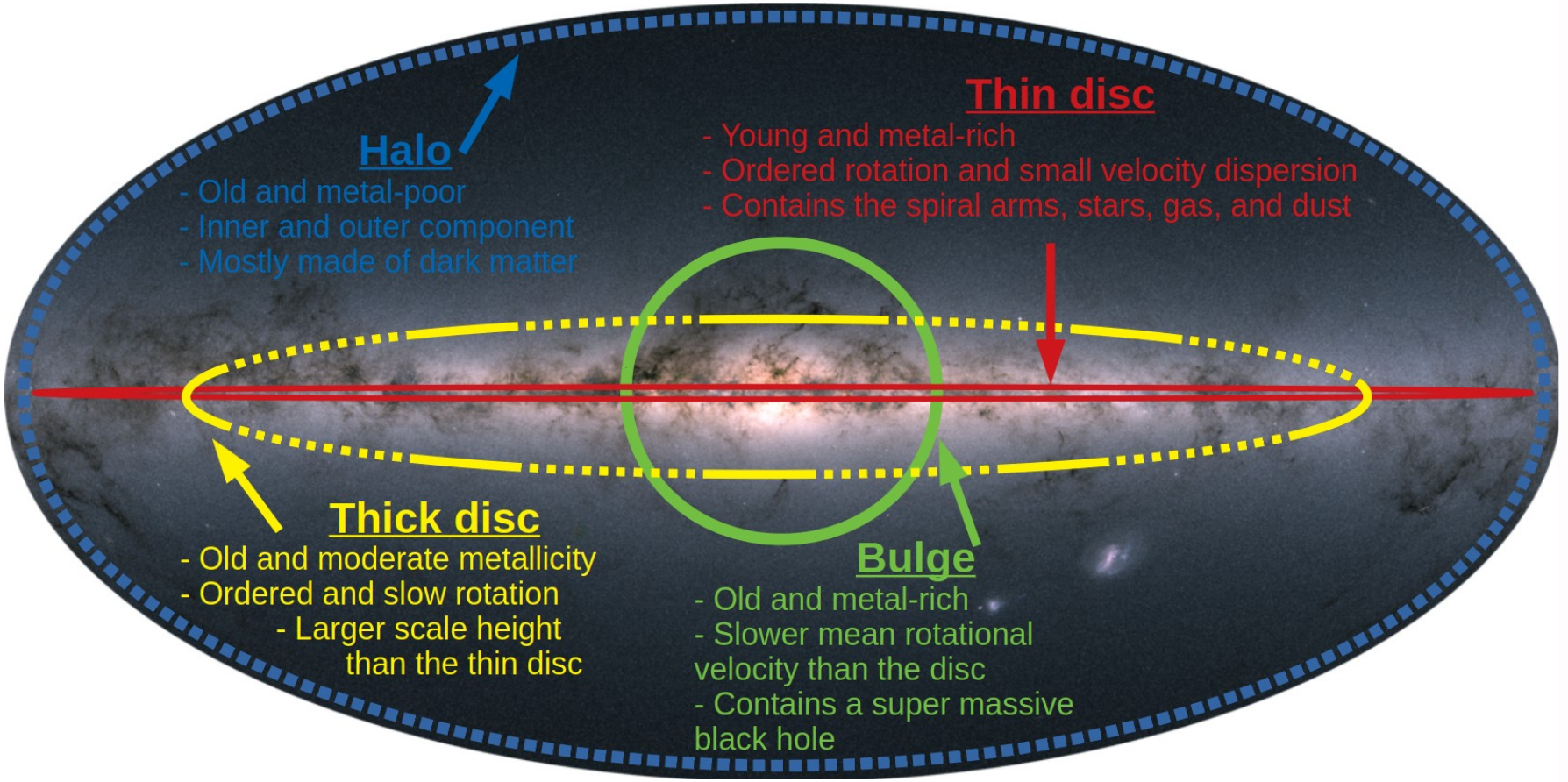
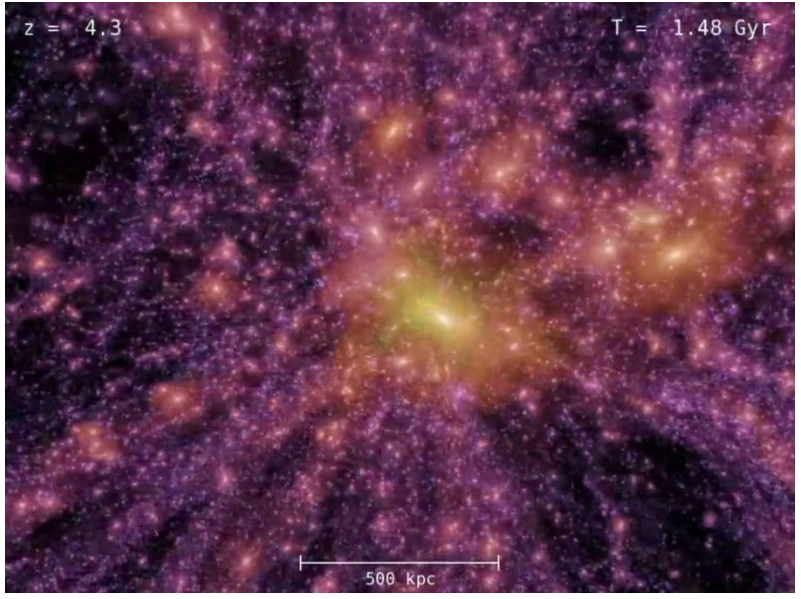


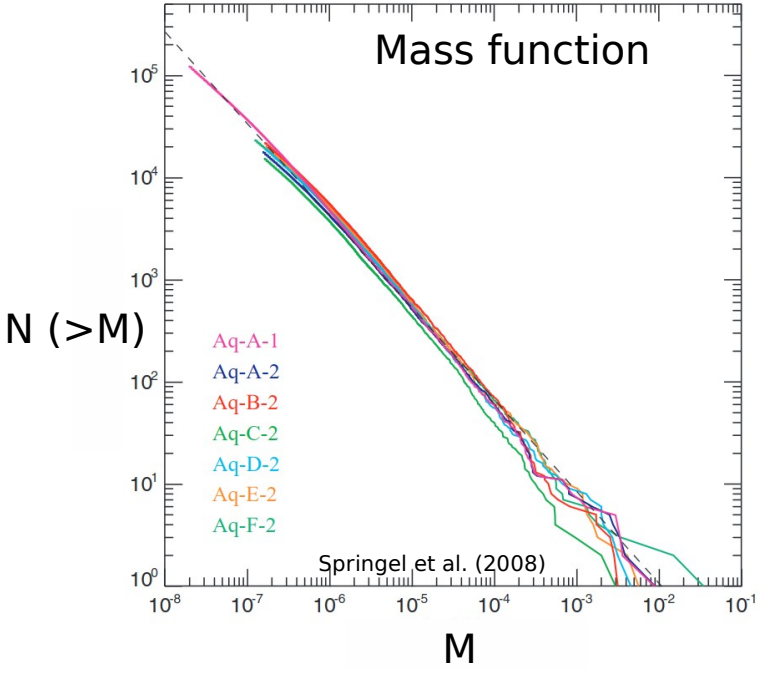
Credit: Gaia, ESA

Galaxy formation in LCDM

- Preferred cosmological paradigm: Lambda Cold Dark Matter (LCDM)
- Key prediction: Hierarchical structure formation
- The MW neighborhood is full of baryons and dark matter substructure

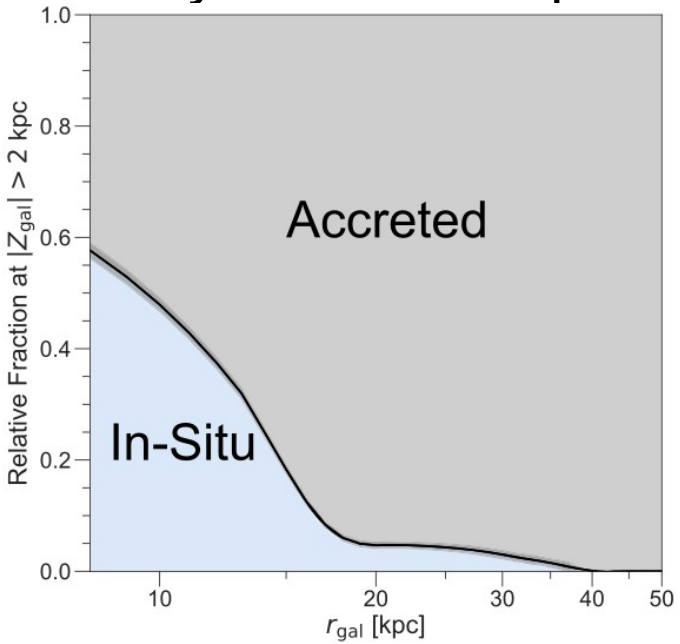


Credit: Aquarius simulation

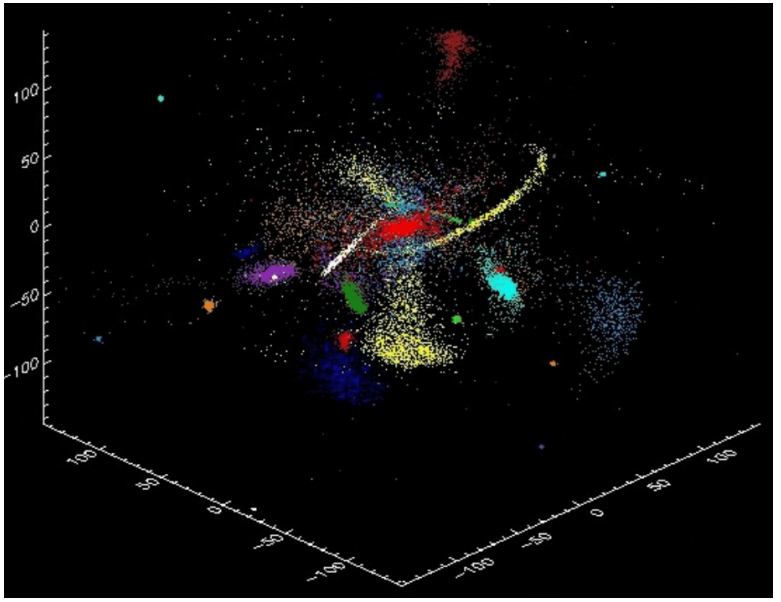


Galaxy formation in LCDM

The Milky Way is thought to have accreted and tidally destroyed hundreds of low mass systems in the past ~12 Gyr



Naidu et al. (2020)



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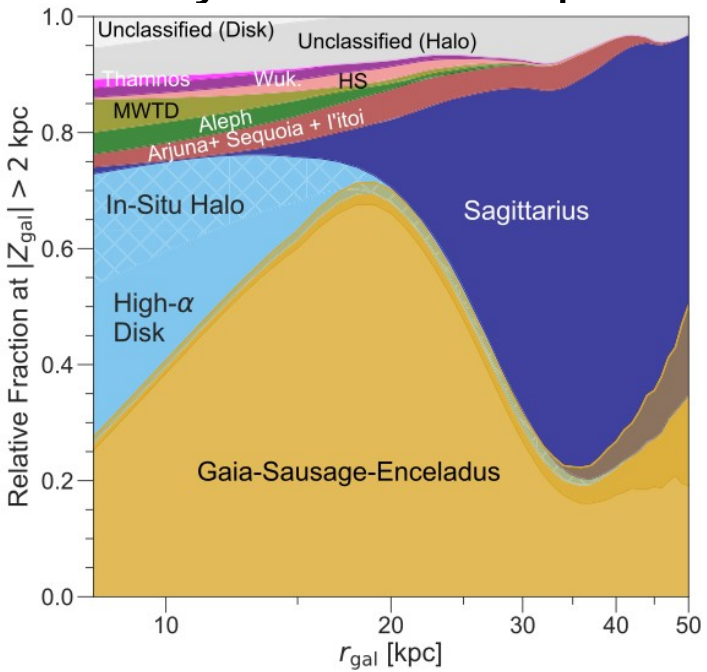

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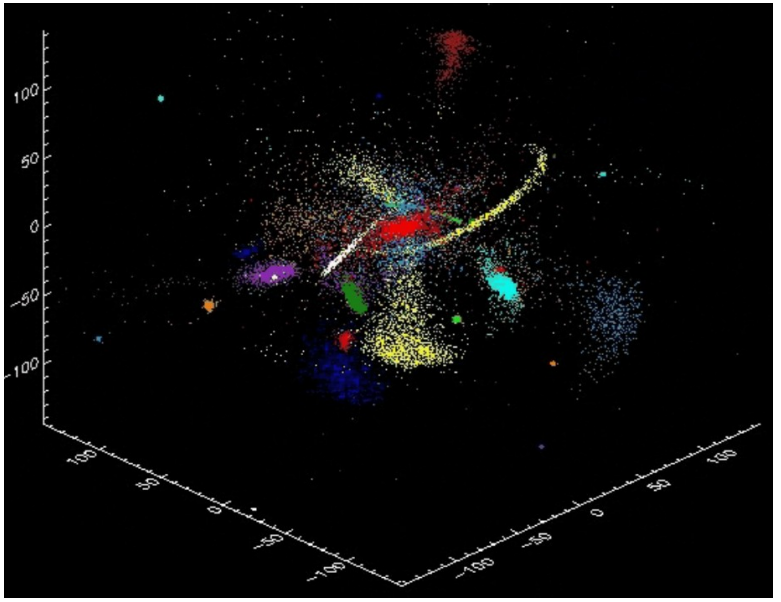

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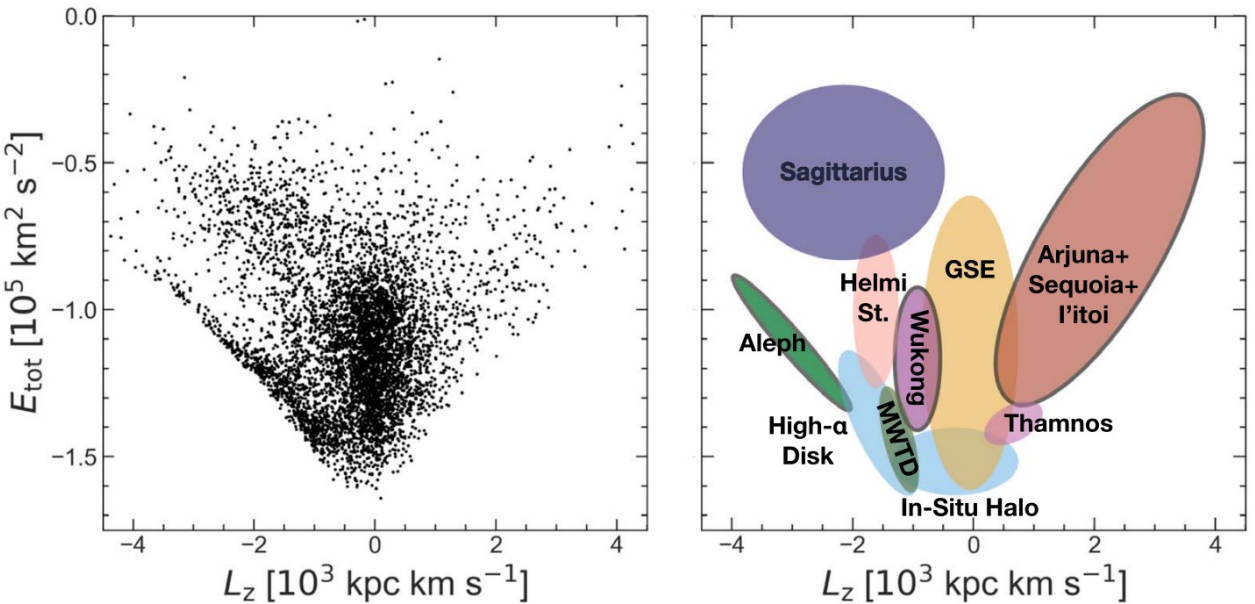

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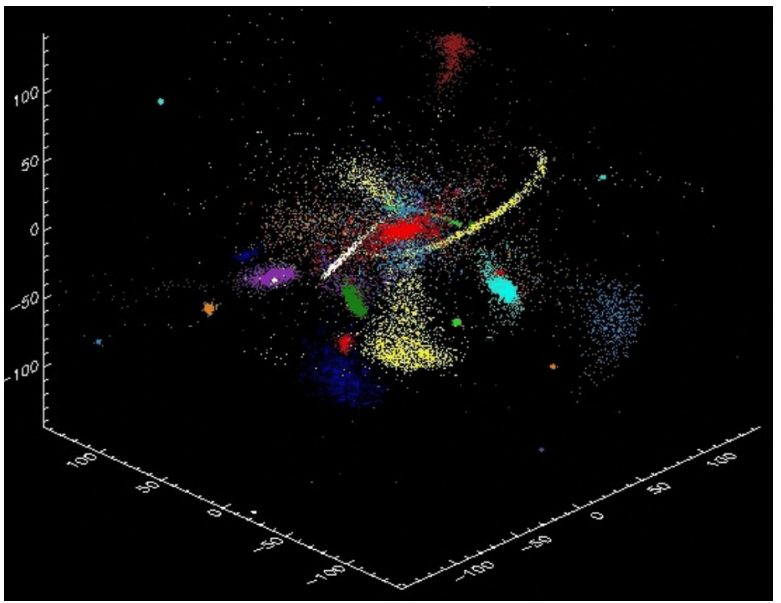
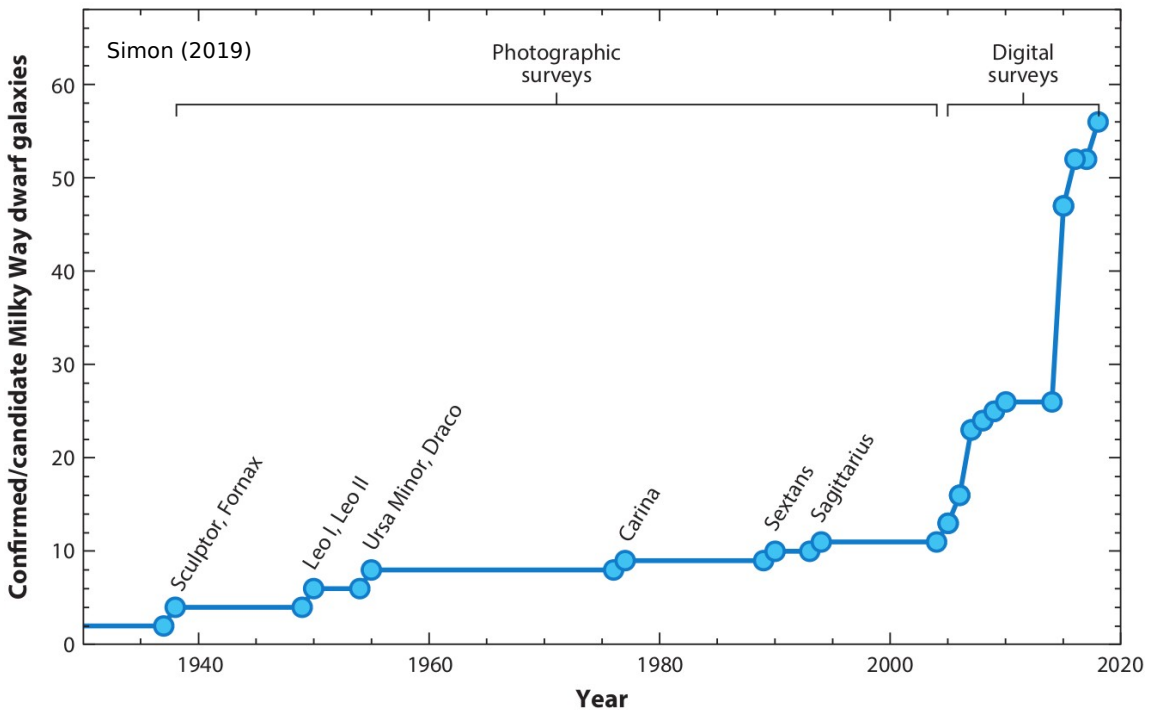
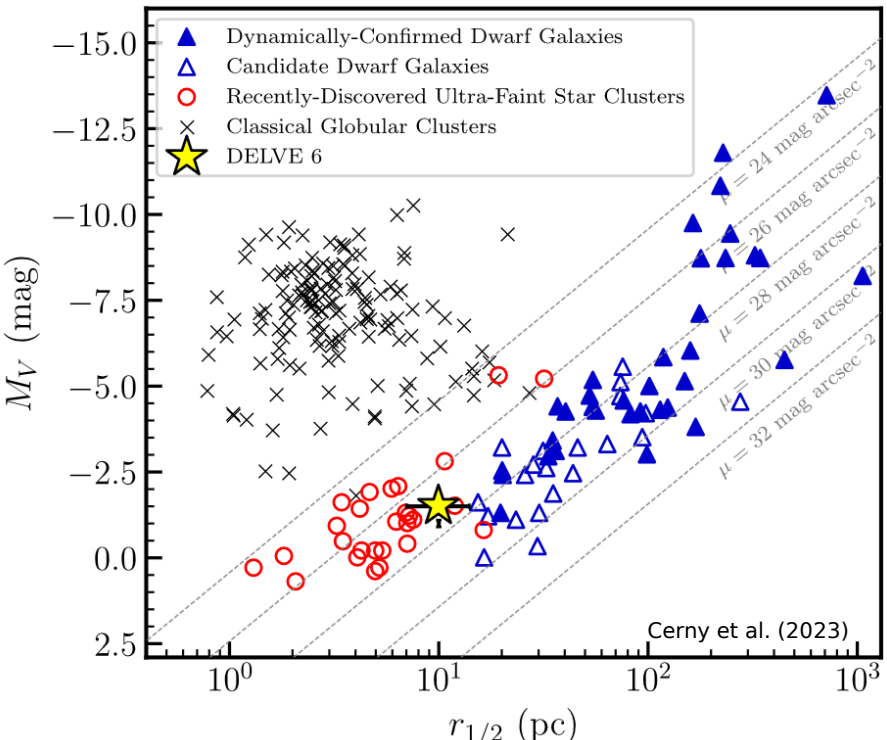


Bullock & Jhonston (2005)

Galaxy formation in LCDM

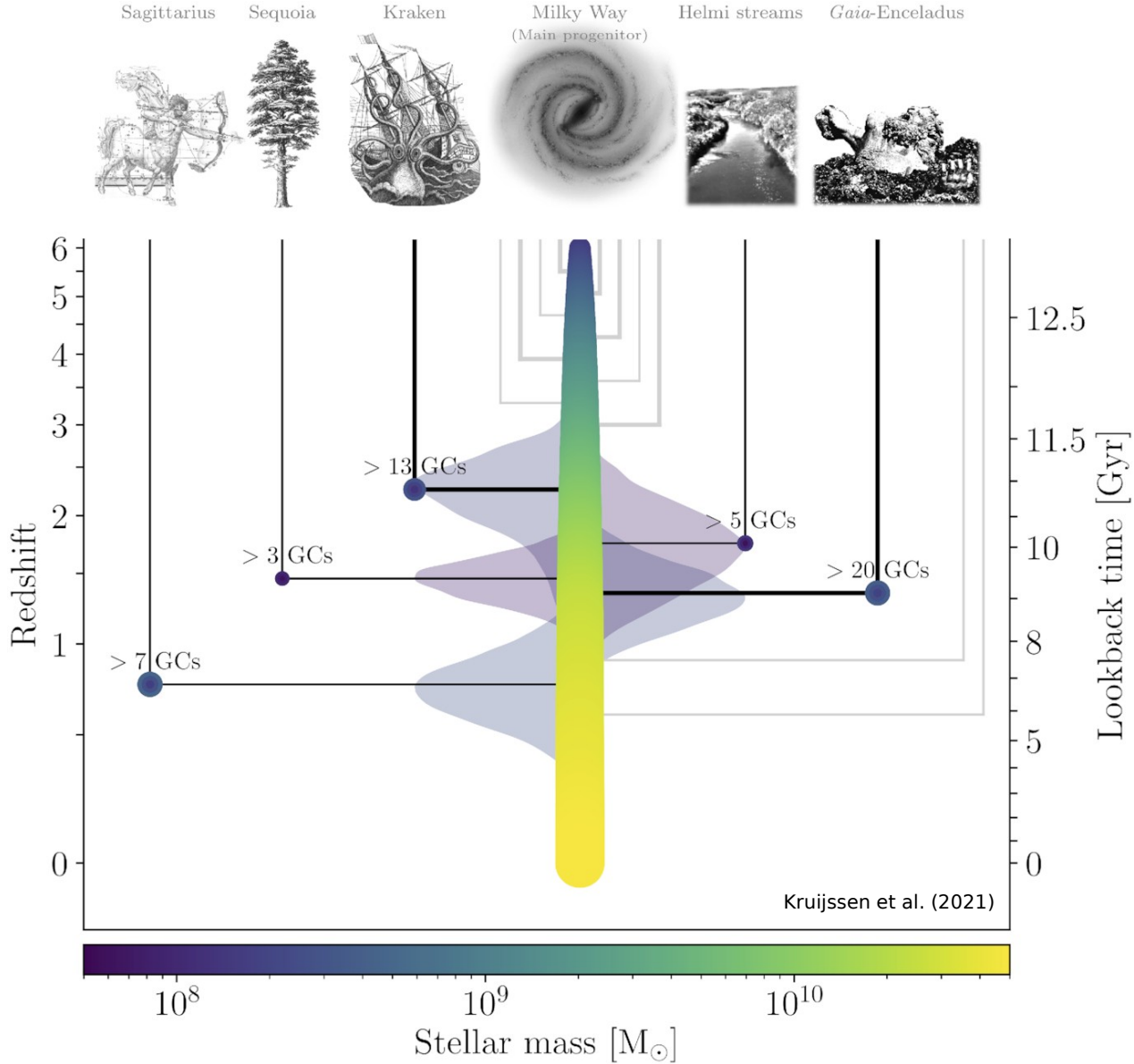
- New stellar systems, dwarf galaxies, and clusters discovered up to this day (~50 in the last 20 years)





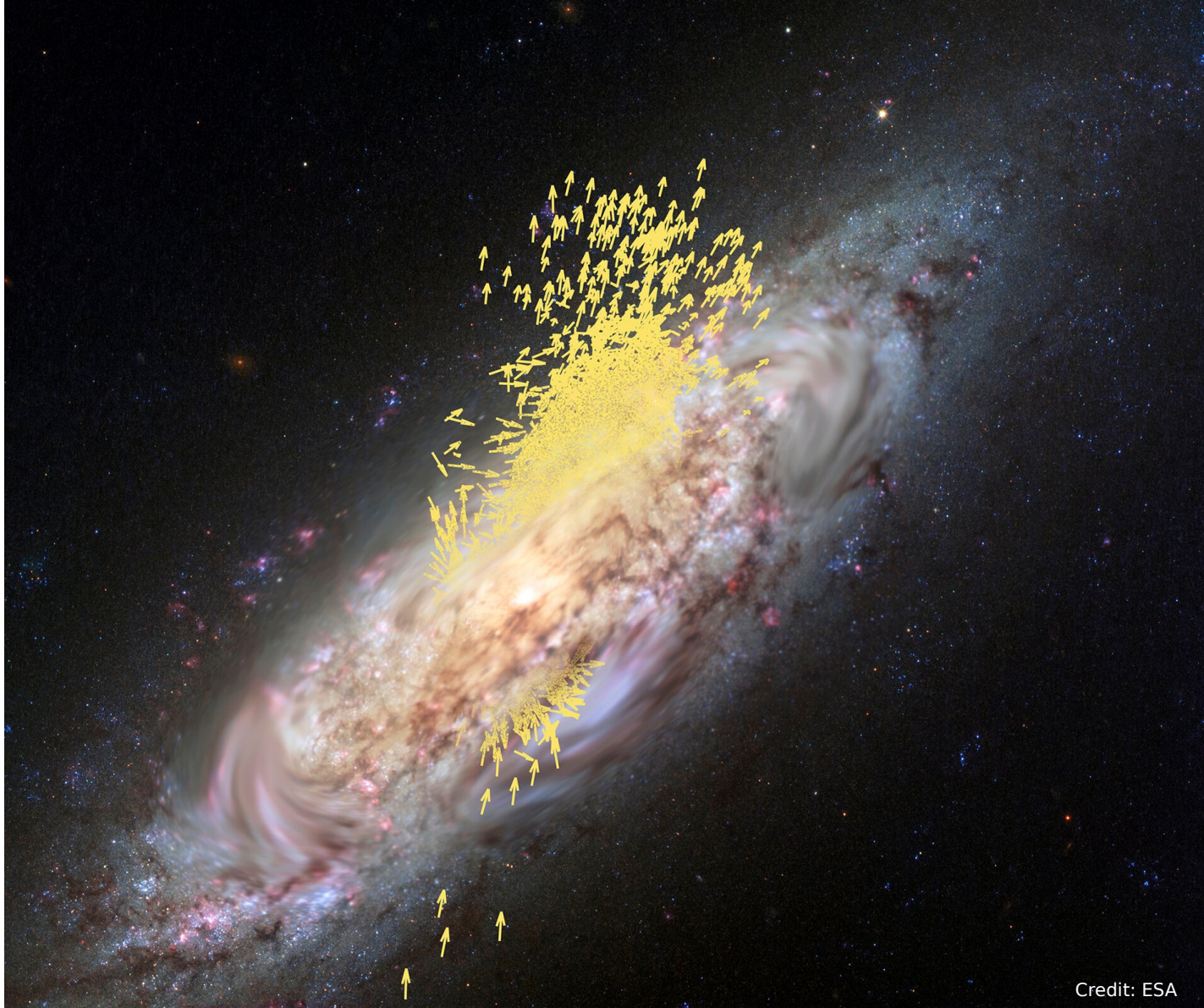
The Milky Way's merger tree

Not only intact satellites are being discovered



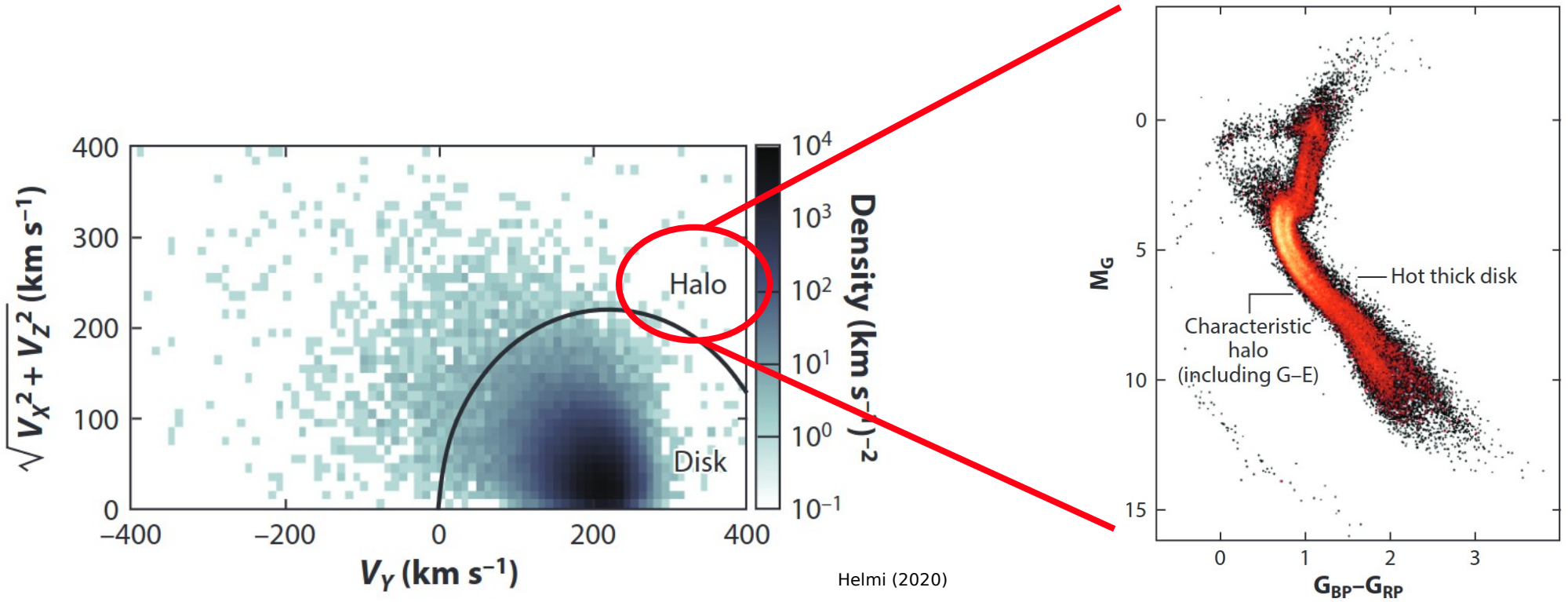
Discovery of an ‘odd collection’ of stars that move along elongated trajectories in the opposite direction to the majority of MW stars (also with lower metallicities)

Only possible with Gaia!



Gaia-Enceladus

- Merger with the Milky Way: ~10 Gyr ago



Helmi (2020)

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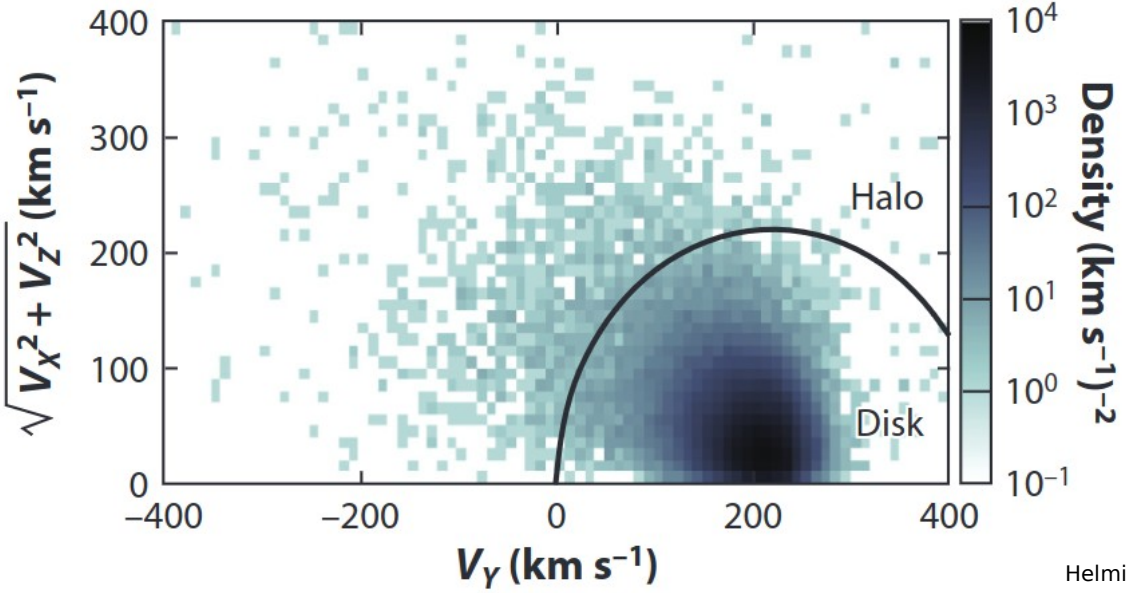

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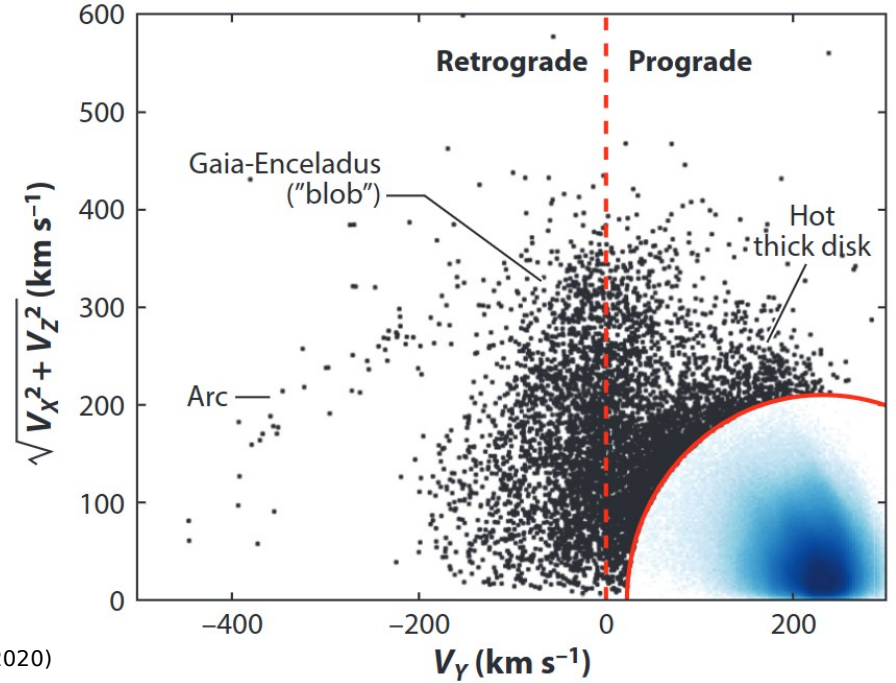
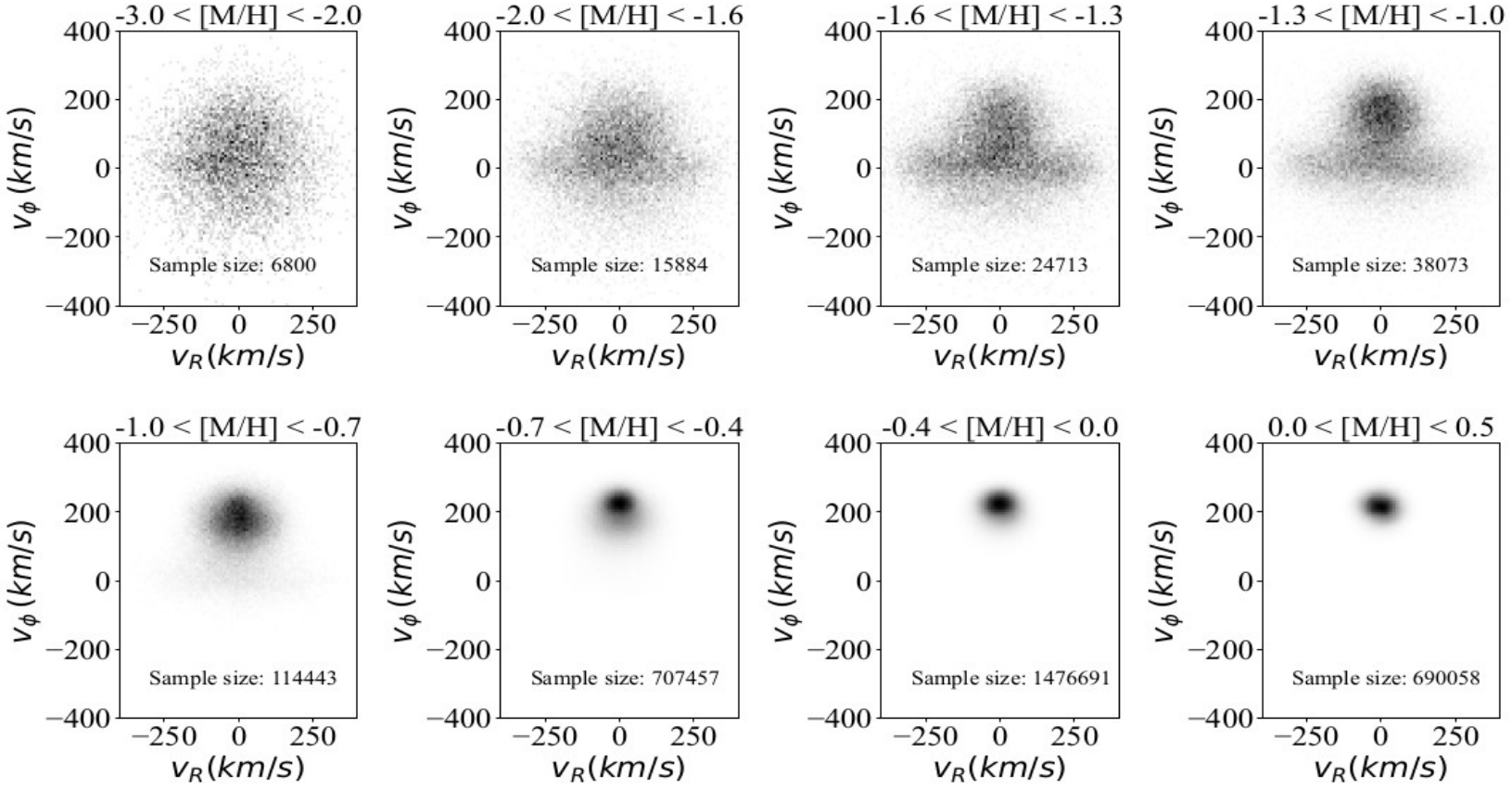


Gaia-Enceladus: Chemo-dynamical decomposition

Zhang et al. (2023)



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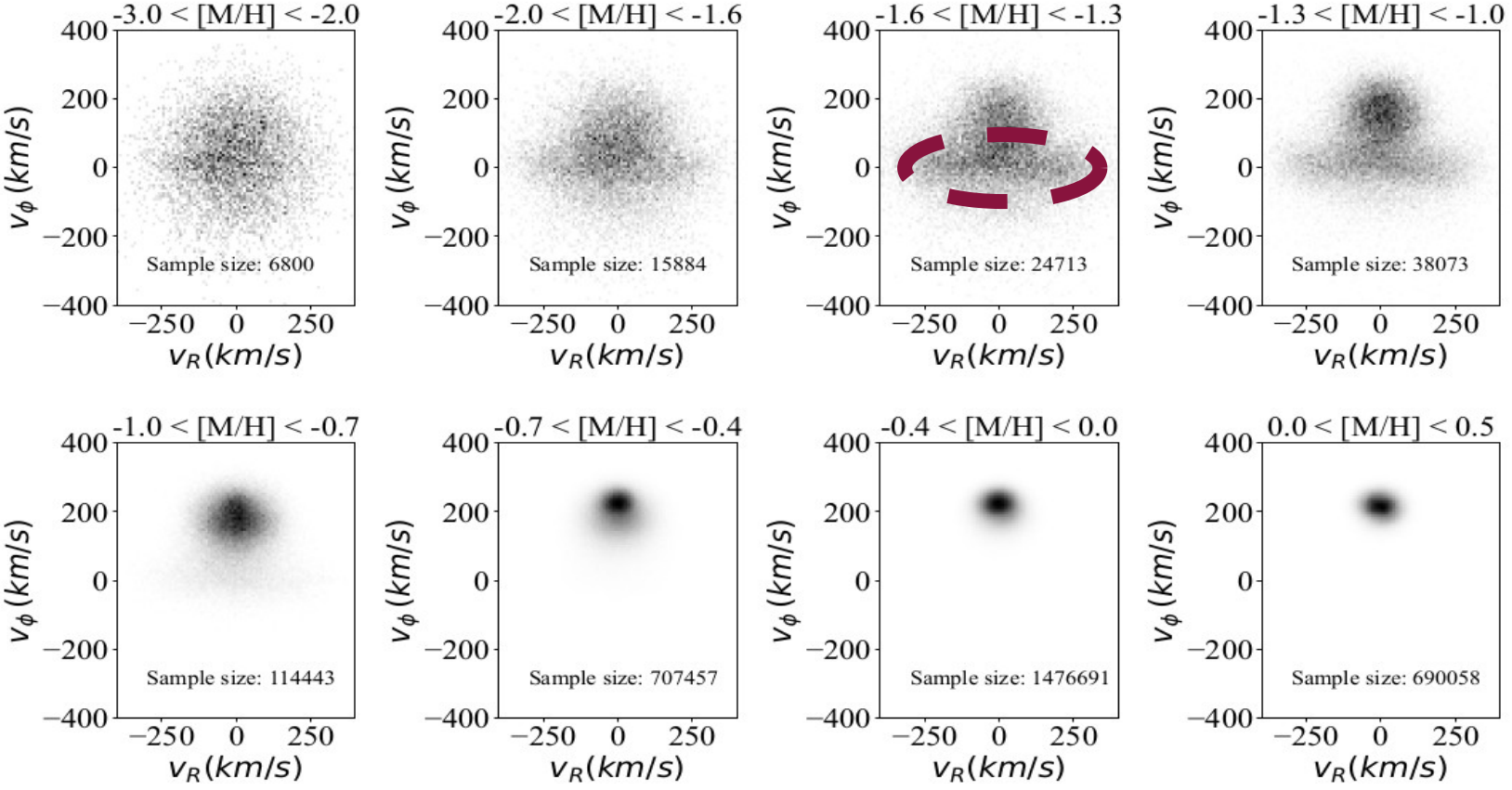
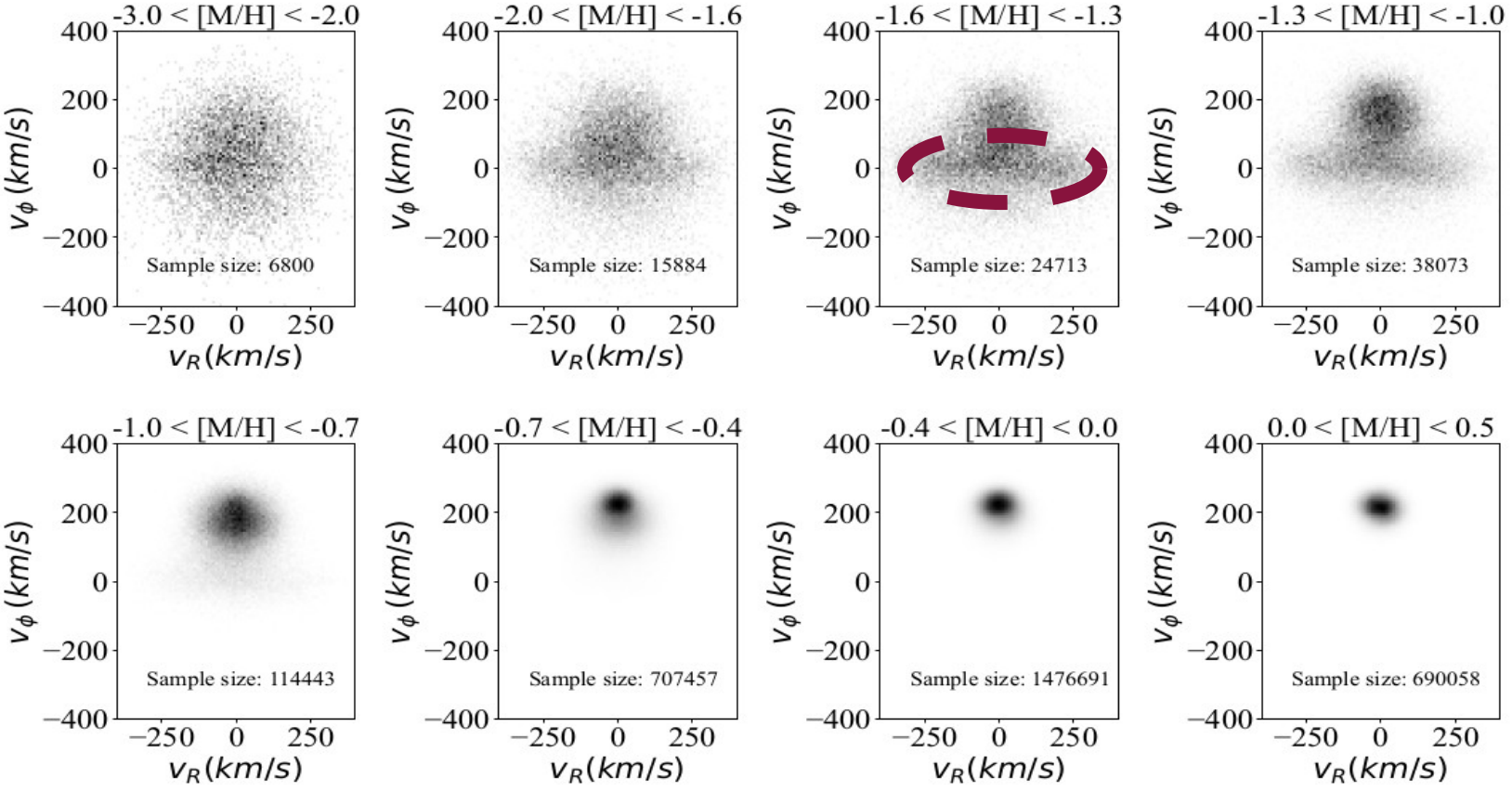


Gaia-**Sausage**-Enceladus: Chemo-dynamical decomposition

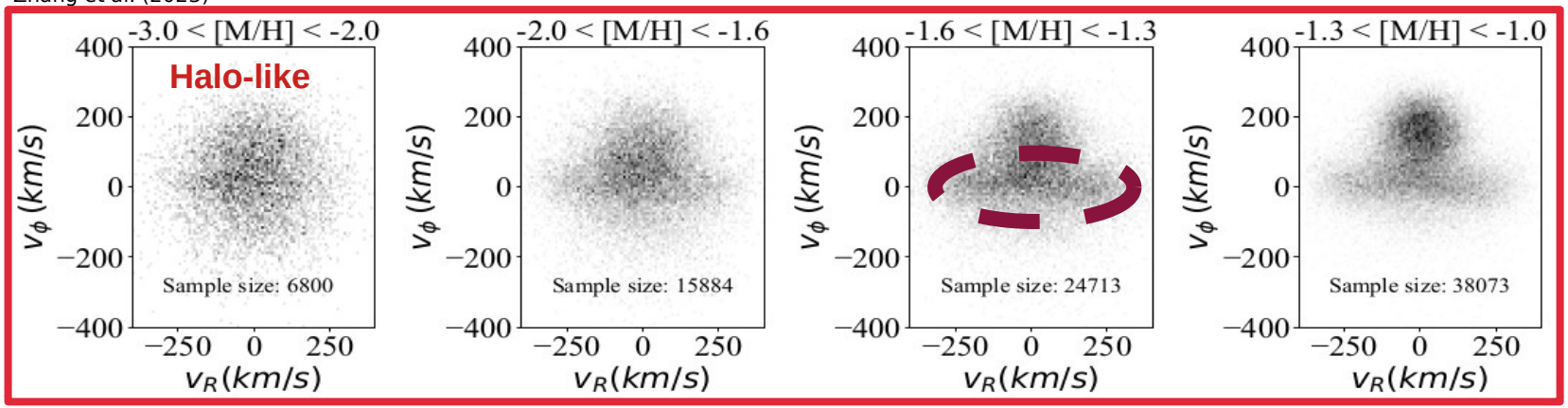
Zhang et al. (2023)



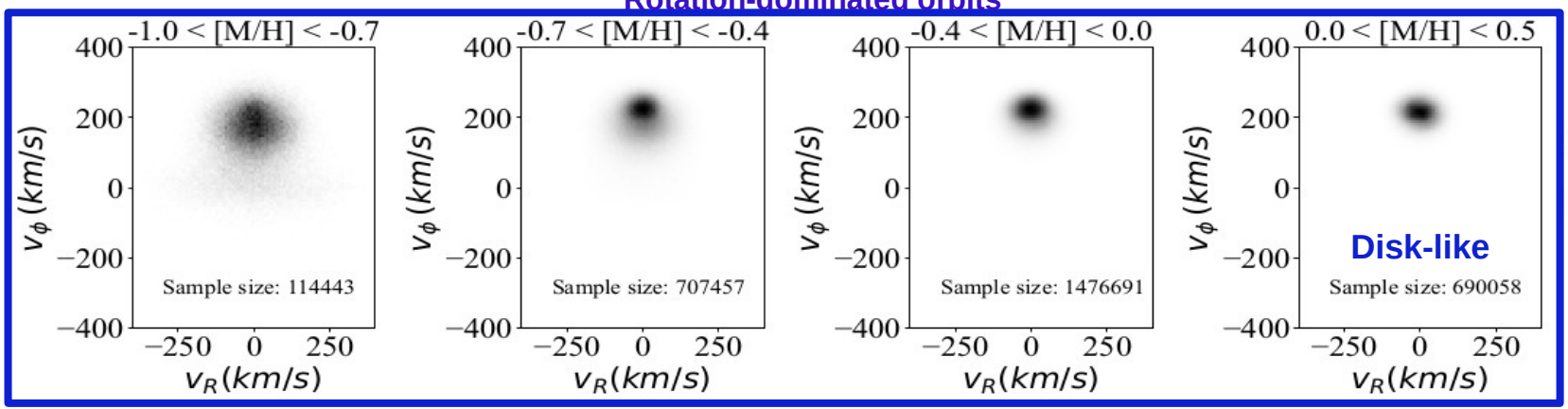
Gaia-Sausage-Enceladus: Chemo-dynamical decomposition

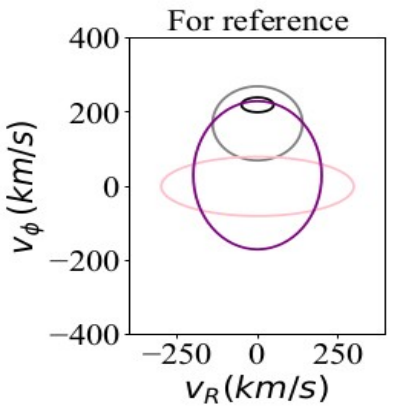
Zhang et al. (2023)

Pressure-dominated orbits

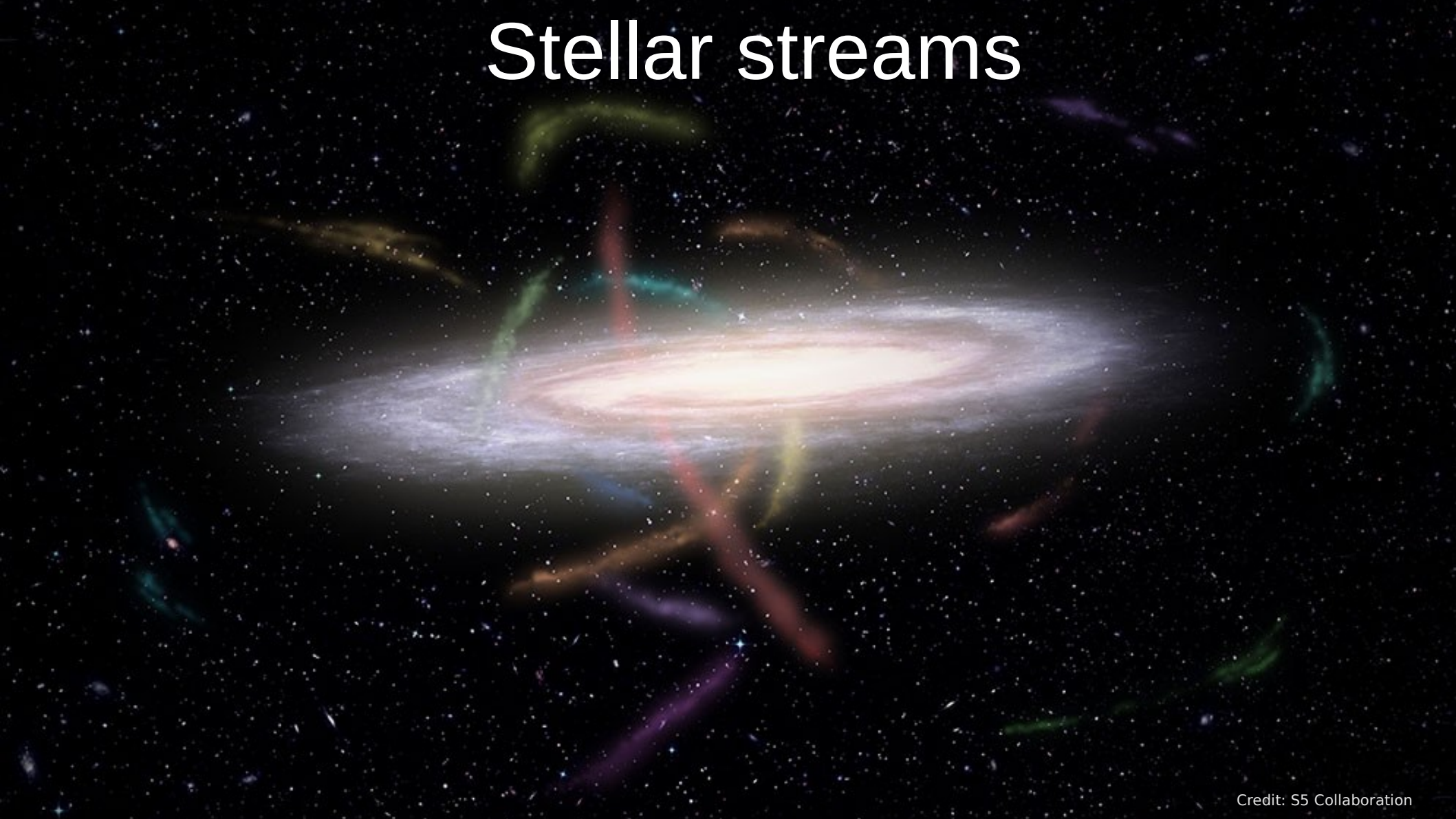


Rotation-dominated orbits





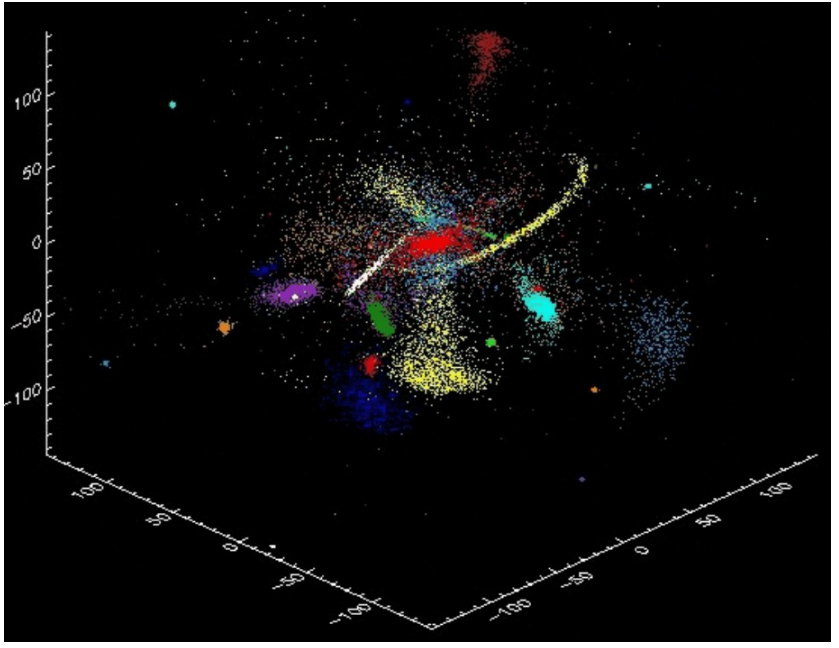
Stellar streams



Credit: S5 Collaboration

Stellar streams

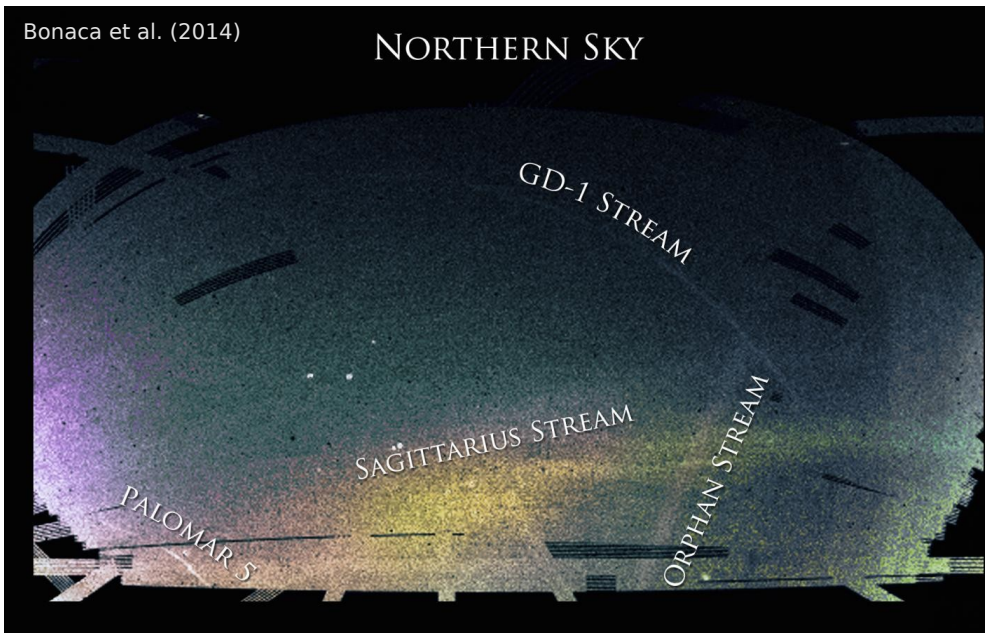
- Products of the accretion of small stellar systems
- Tens-hundreds expected around the MW
- They trace the Galactic accretion history and its potential
- Roughly follow orbits

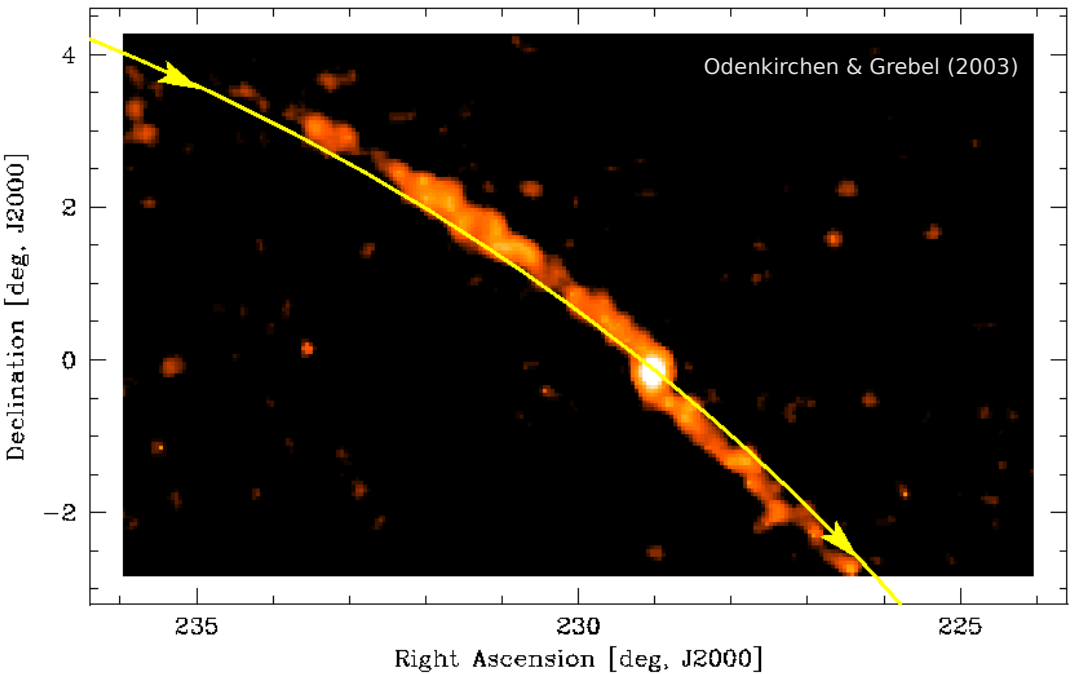


Bullock & Jhonston (2005)

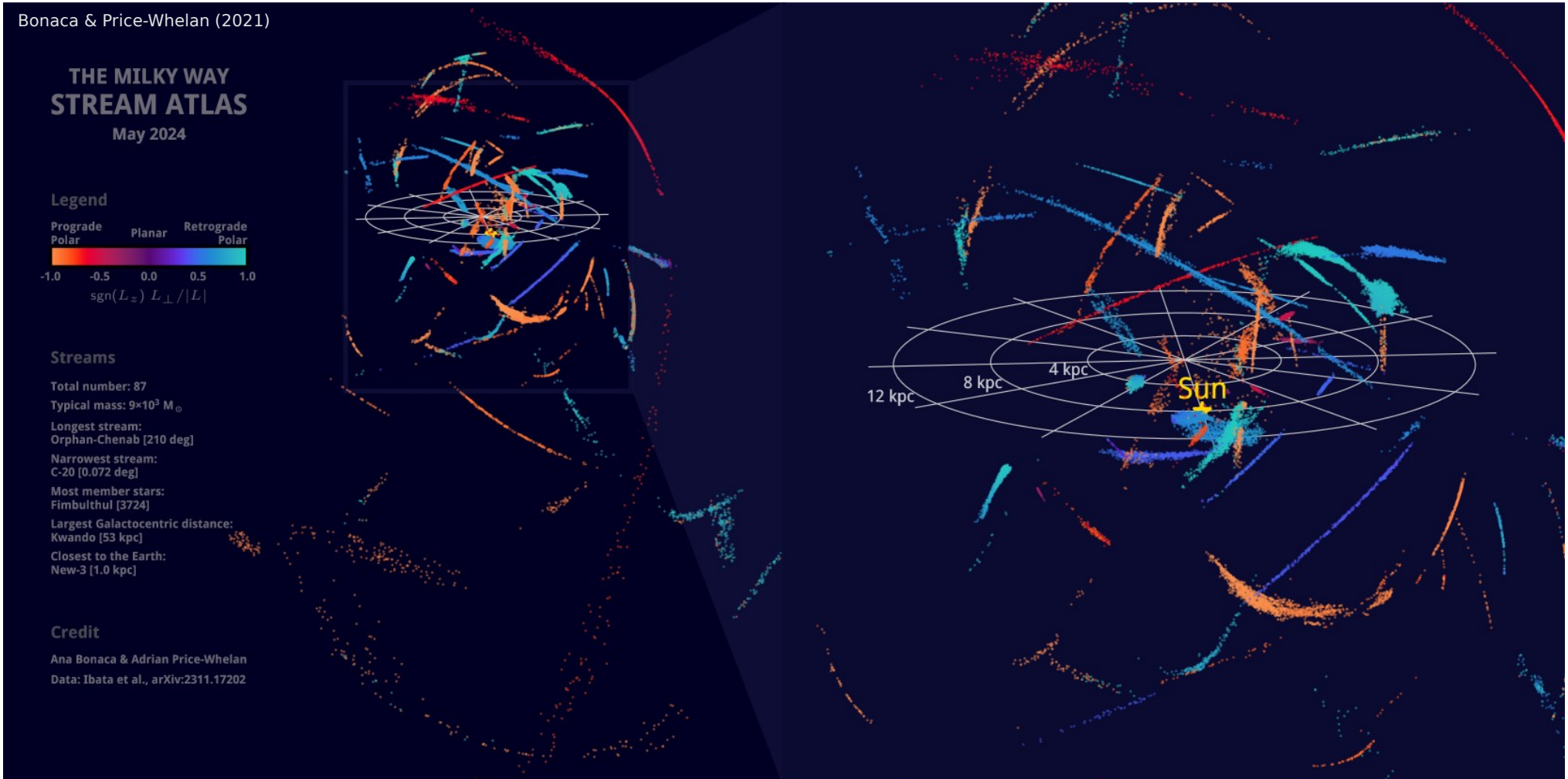
Discovery of streams

Early discoveries mostly in photometric surveys





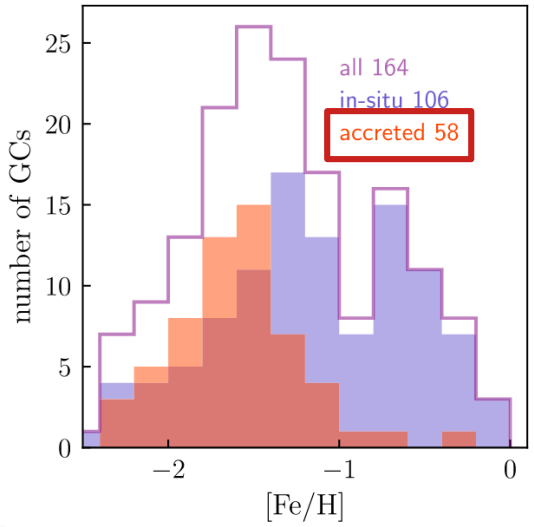
Discovery of streams: The Gaia revolution



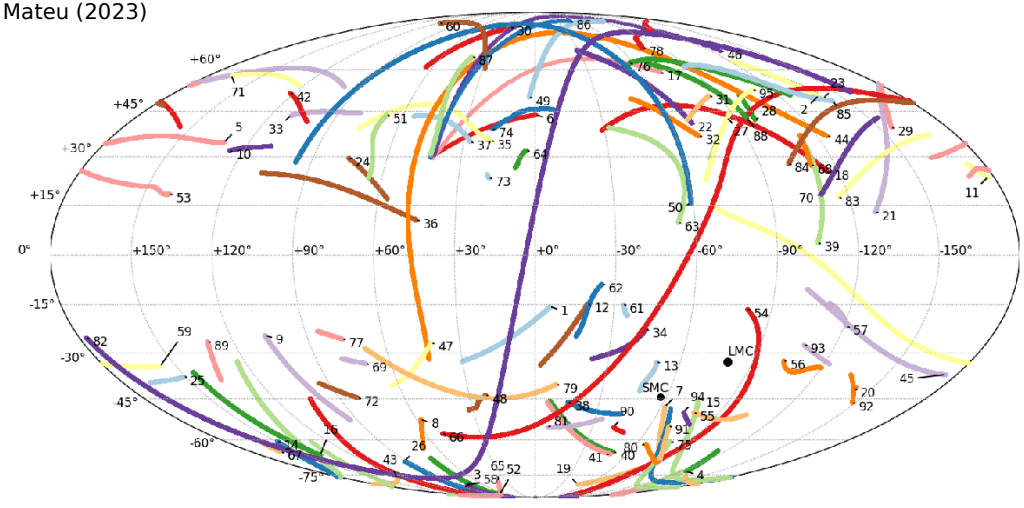
Streams as probes of the MW accretion history

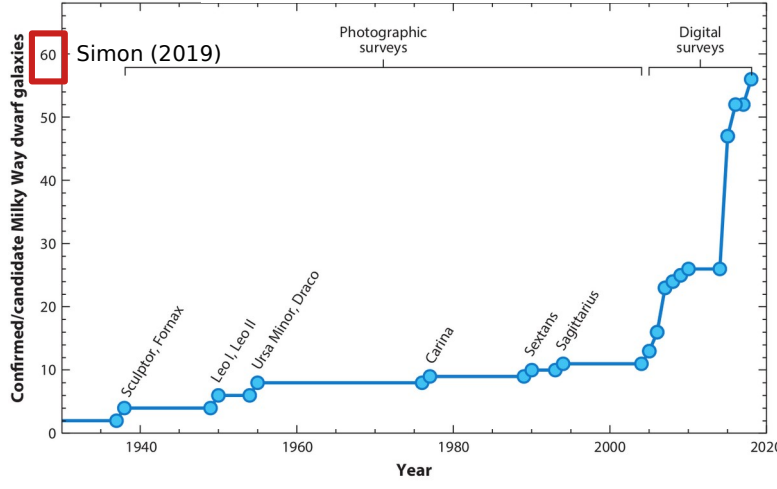
The number of streams is comparable to the number of surviving dwarf galaxies and accreted MW globular clusters

Belokurov & Kravtsov (2024)



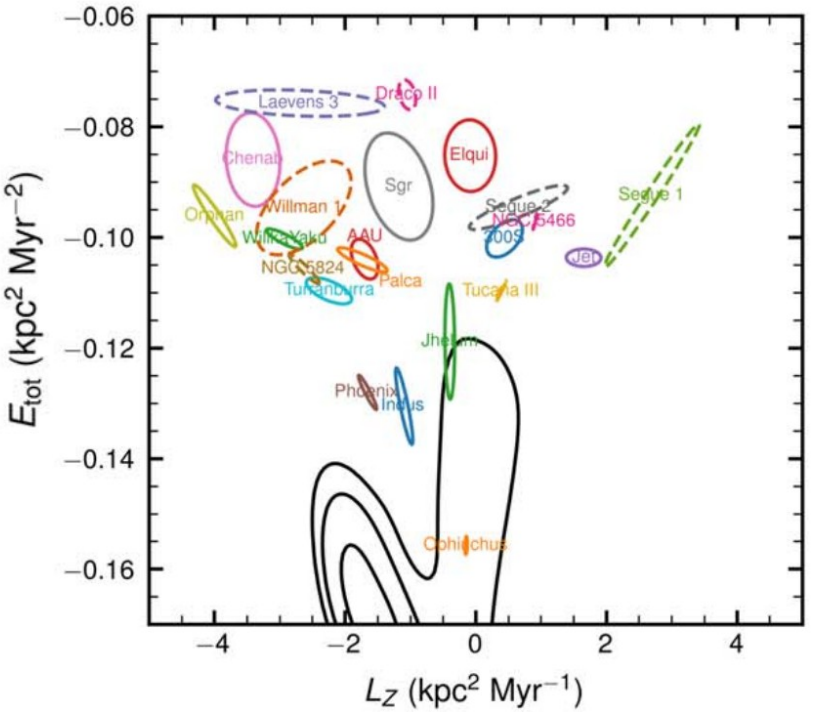
Mateu (2023)

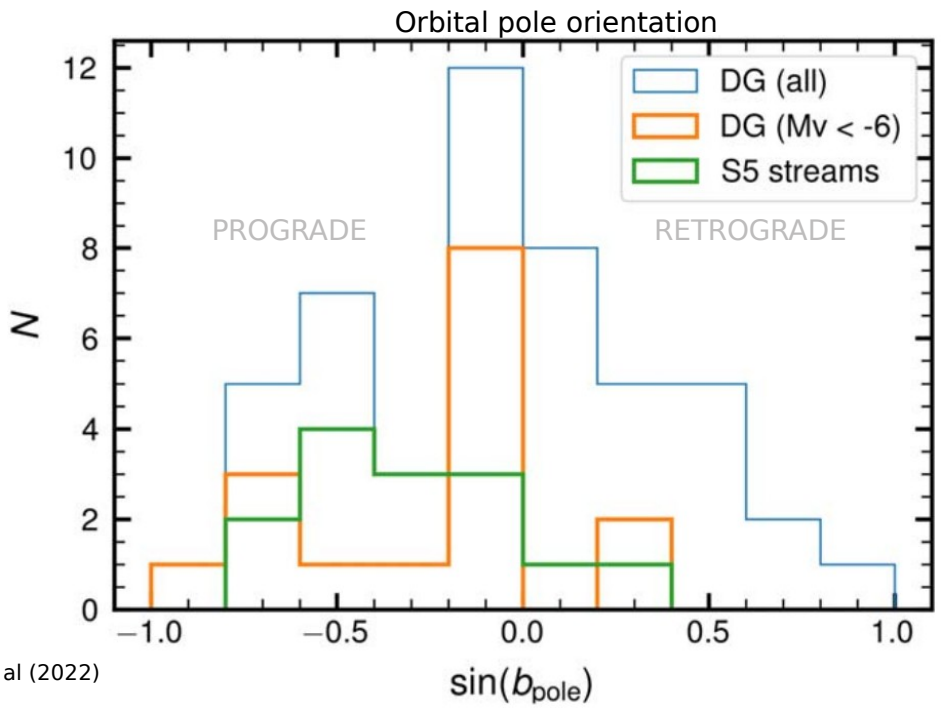




Orbital properties of streams

- Streams can be associated with specific accretion events
- Streams seem to be biased towards prograde rotation





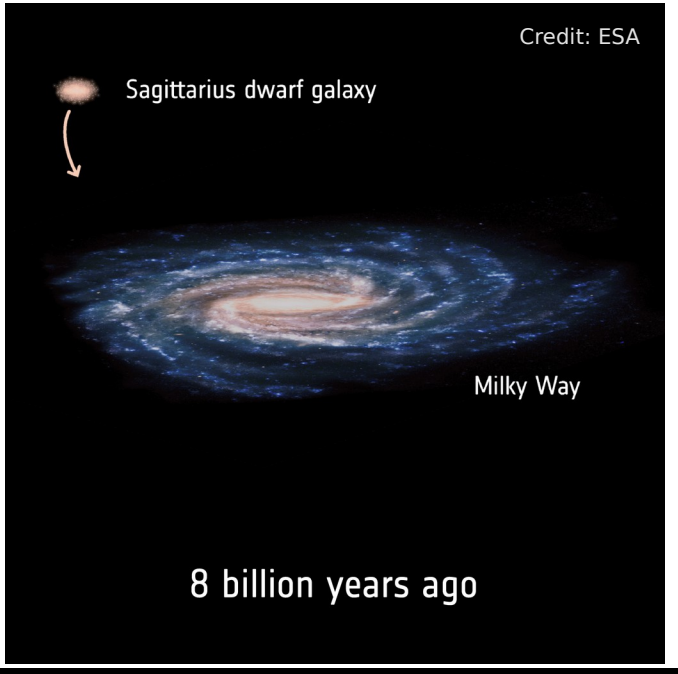
Li et al (2022)

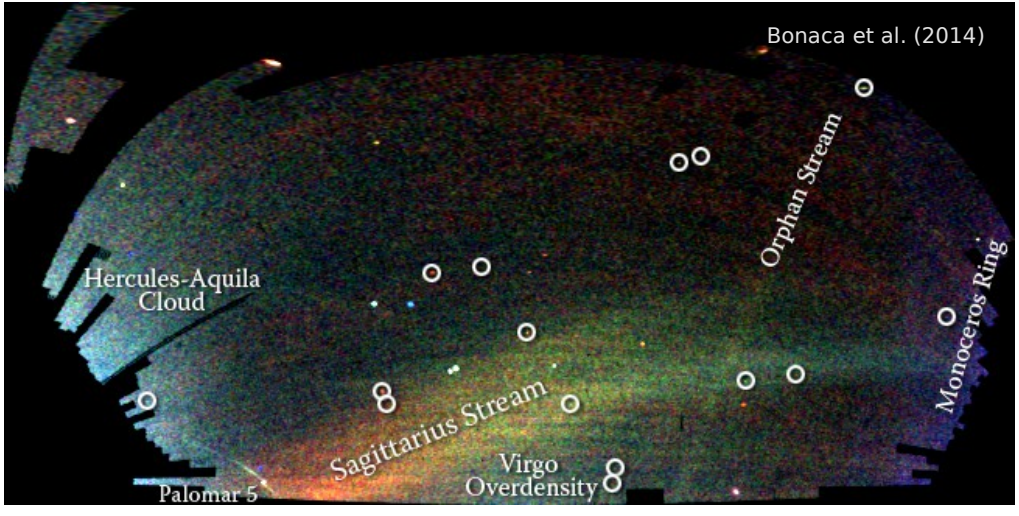
The impact of mergers on the Milky Way

Credit: Ron Miller

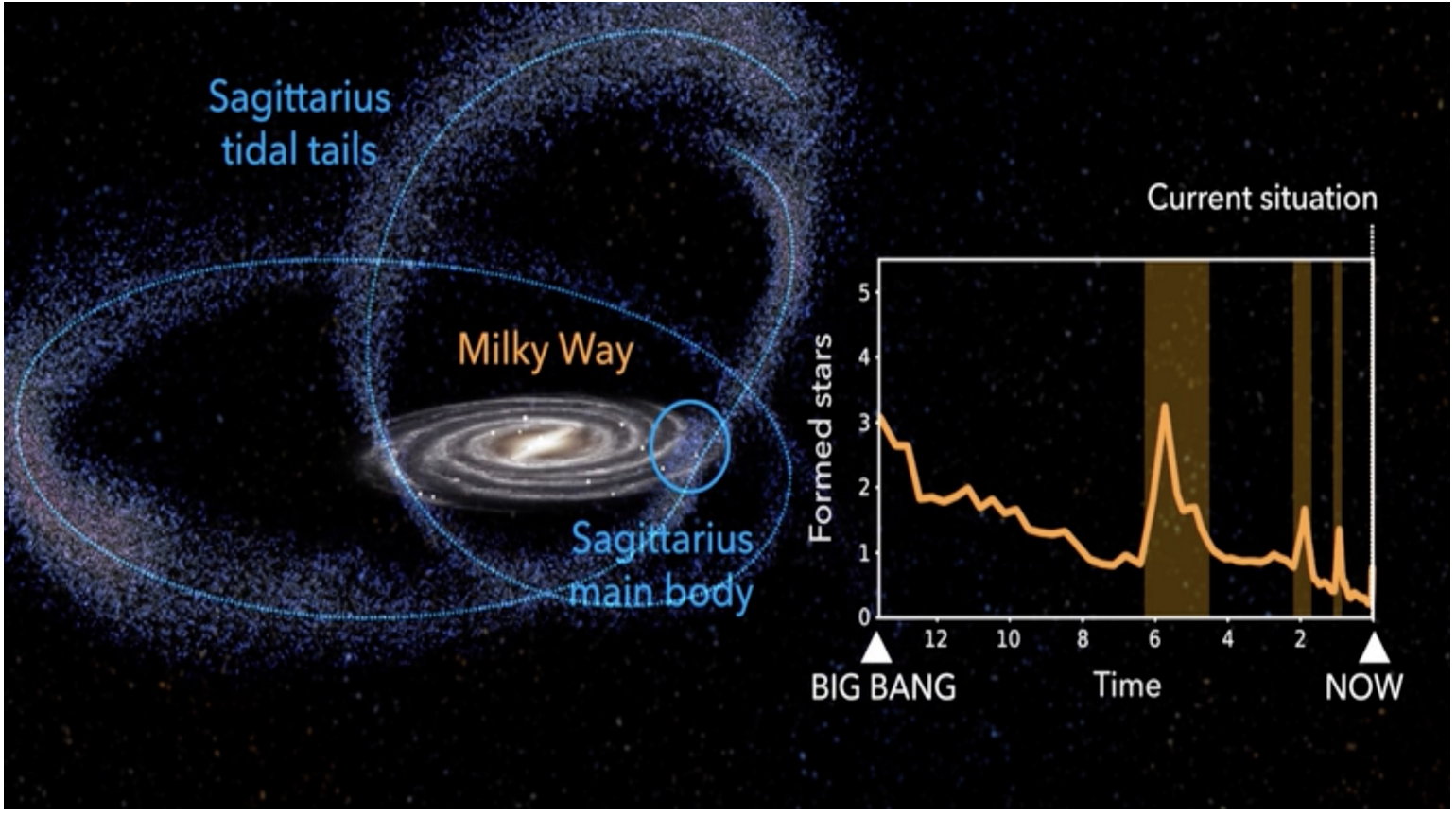
Sagittarius

- Sagitarius (Sgr), currently 18 kpc behind the bulge of our MW.
- It is one of the most prominent features in the MW halo
- Contributed several globular clusters
- And it is believed to had interacted with the MW disk since 6-8 Gyr in the past, with a first infall about 5.5. Gyr ago





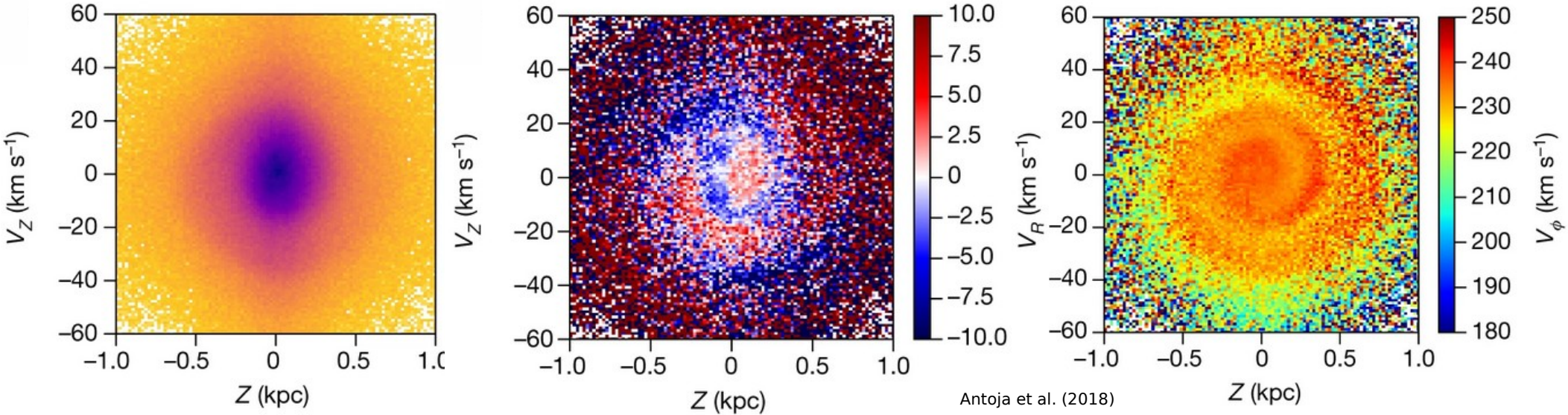
The effect of Sagittarius



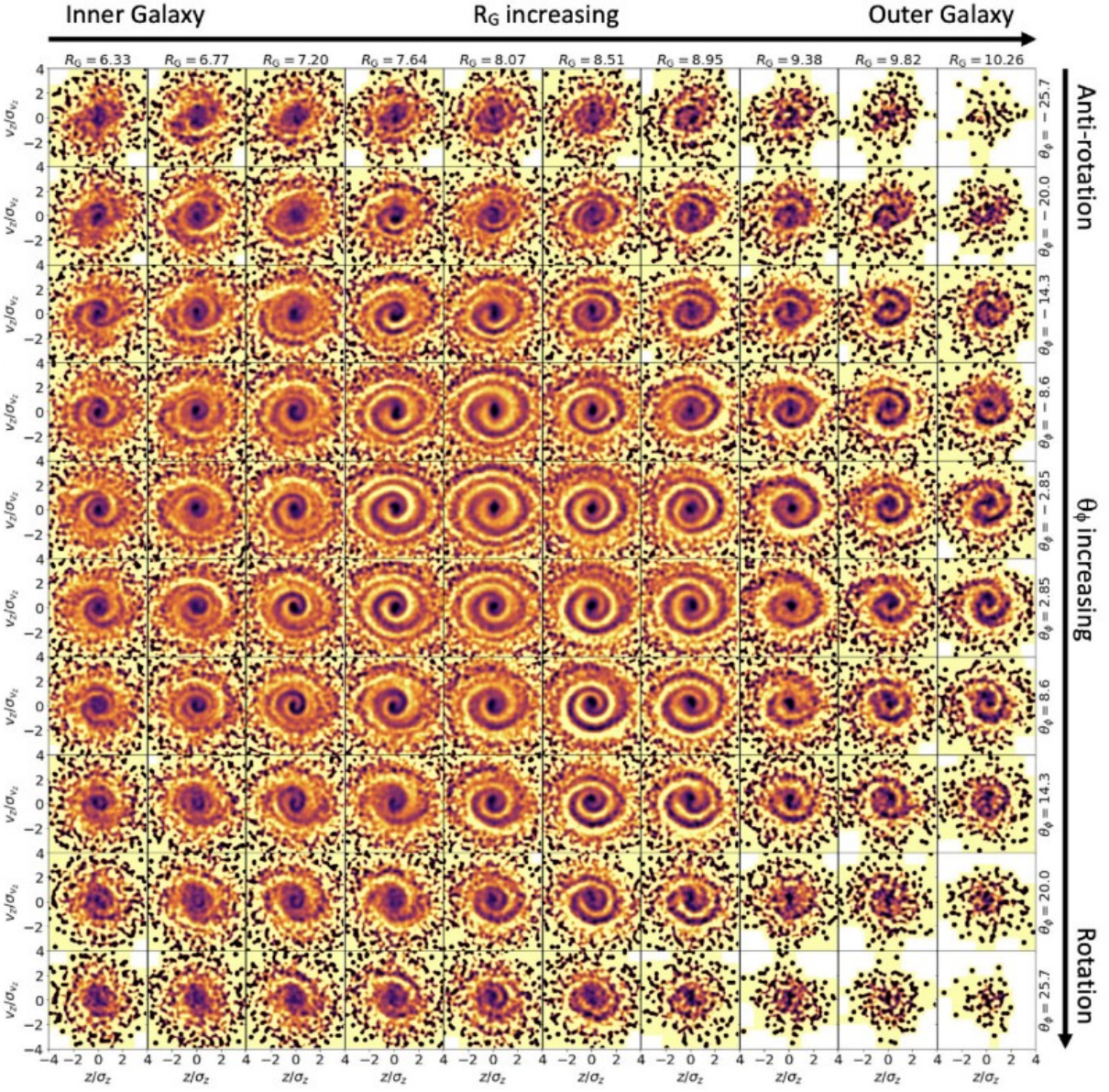
Credit: Gabriel Perez Diaz erez-Diaz

The effect of Sagittarius

- Oscillations in the disk: Stars follow a curled, spiral-shaped distribution (the phase-spiral)
- Sgr's present-day mass is not sufficient to drive the perturbation

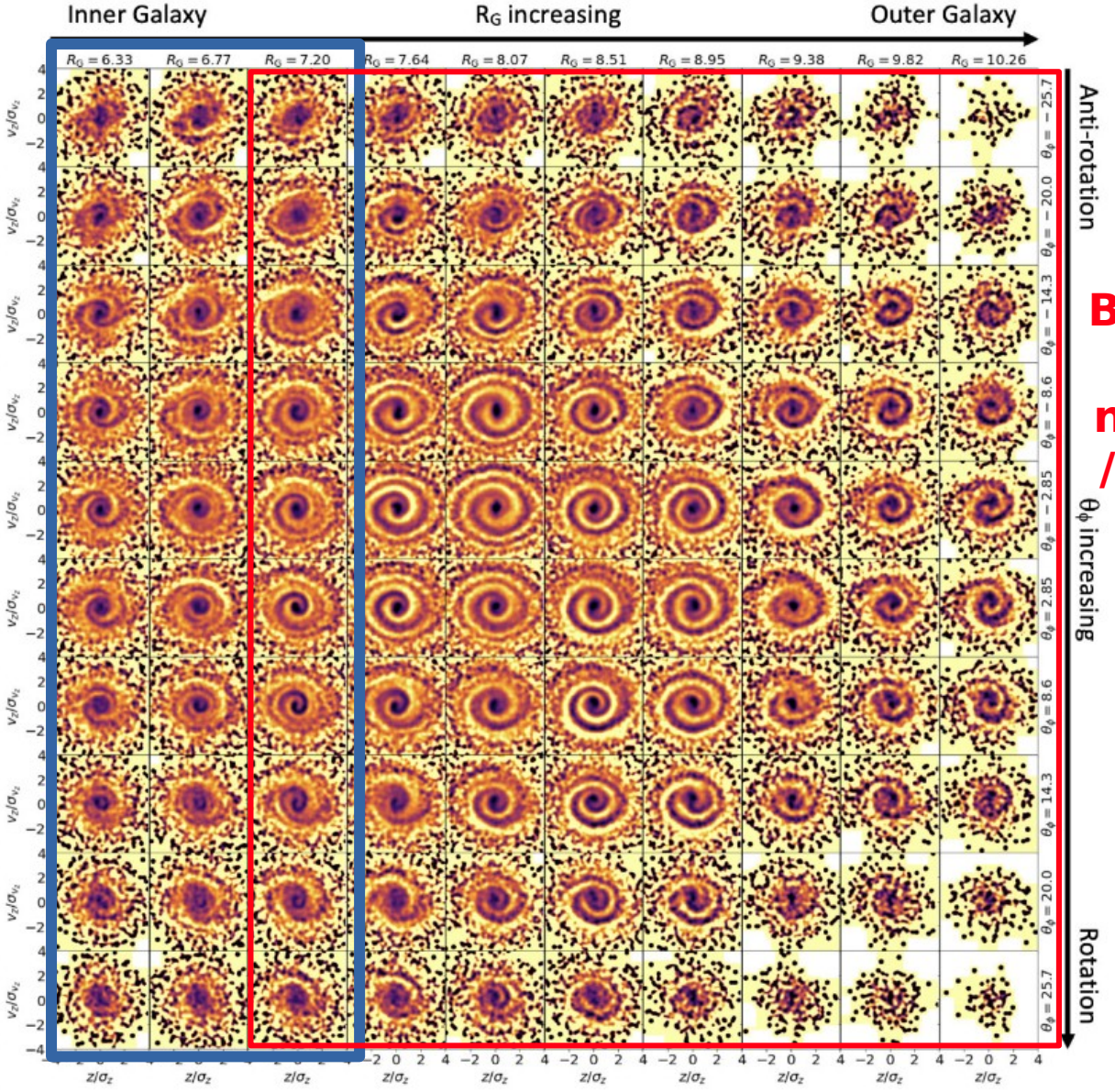


Antoja et al. (2018)



Hunt et al. (2022)

Breathing mode in the inner Galaxy



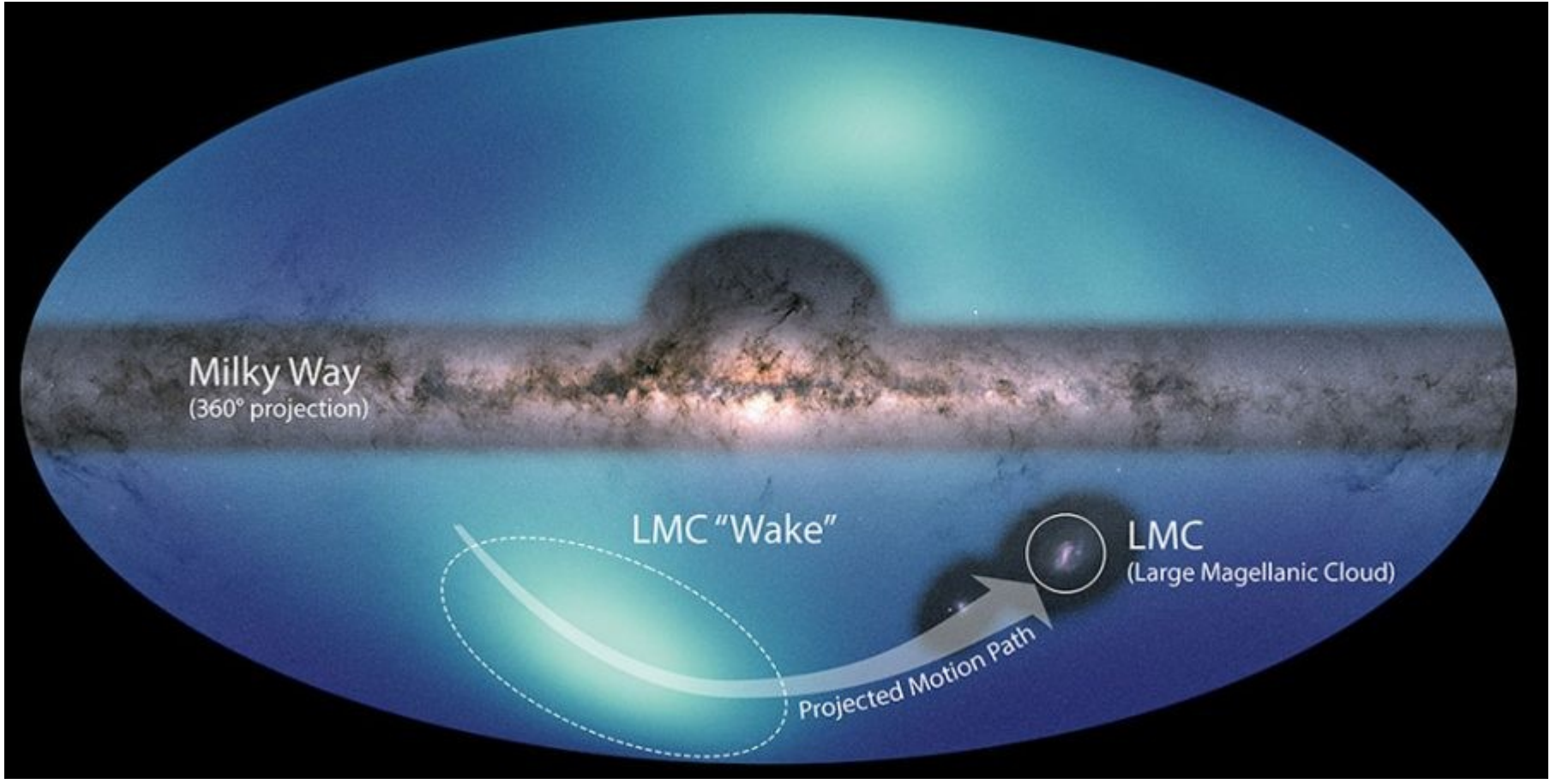
Bending mode in the Solar neighborhood /outer Galaxy

Hunt et al. (2022)

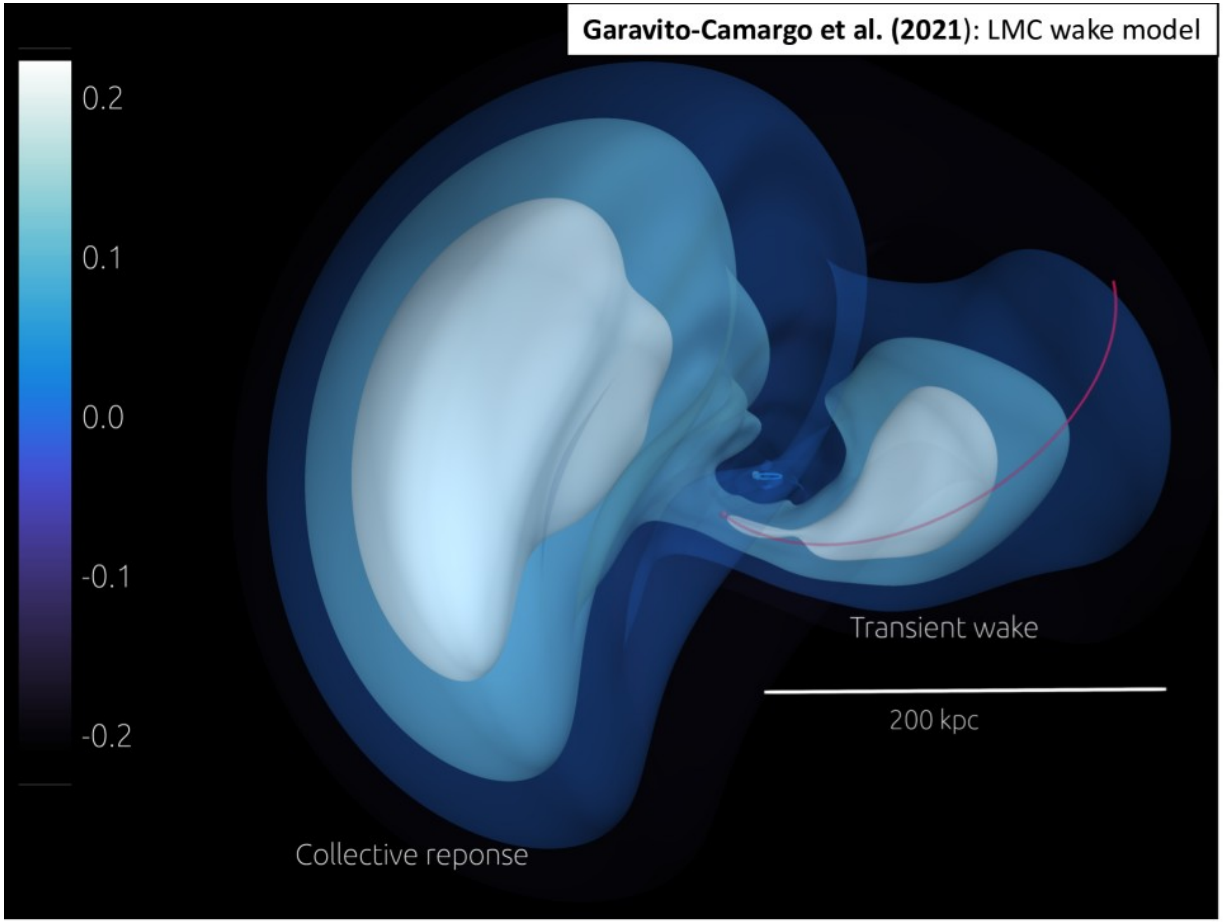
The Large Magellanic Cloud

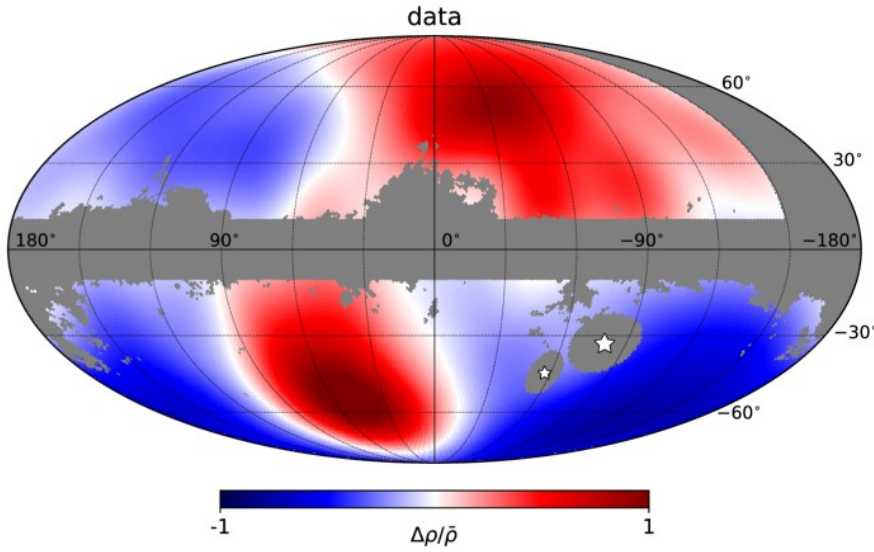
- The Large Magellanic Cloud (LMC) is the most luminous and massive MW satellite
- Mass of $1-2\times10^{11}\,Mo$
- The dark matter (collective) response to the MW/LMC interaction (“the wake”)

The effect of the LMC



The effect of the LMC

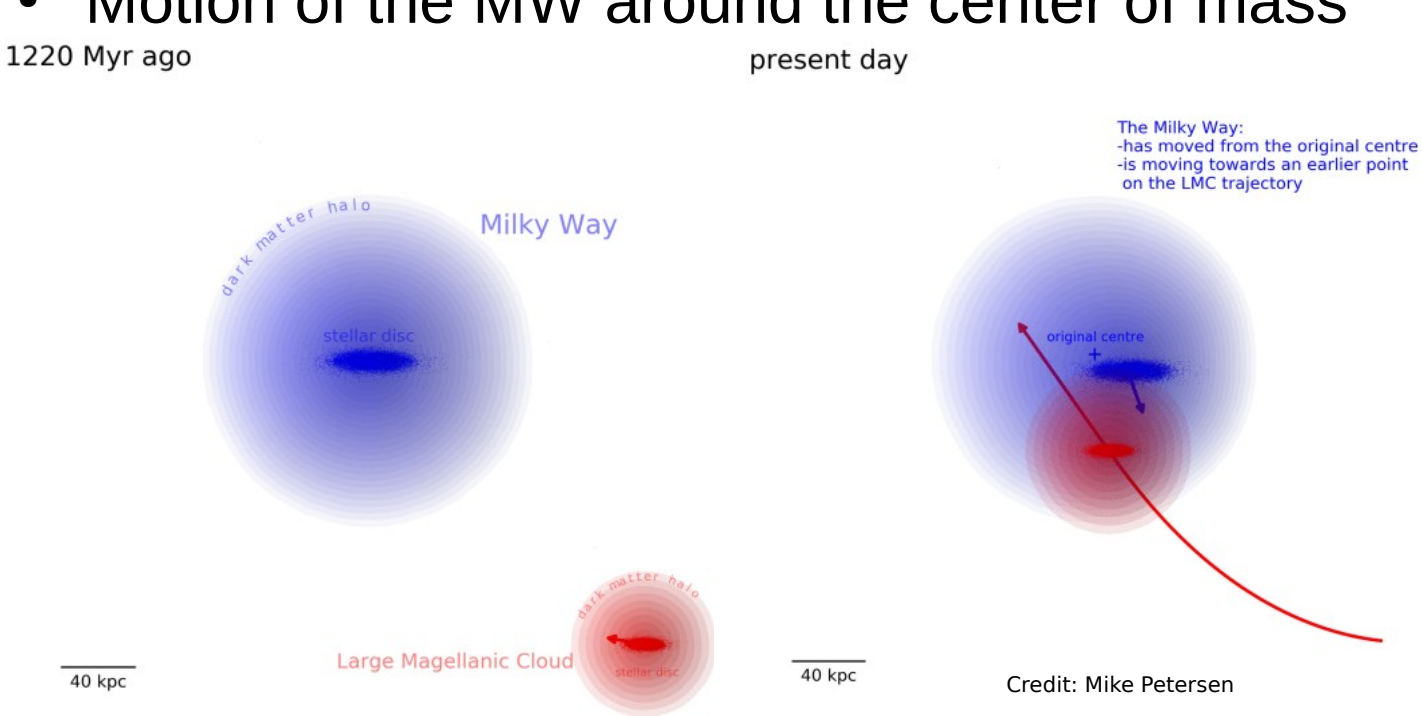




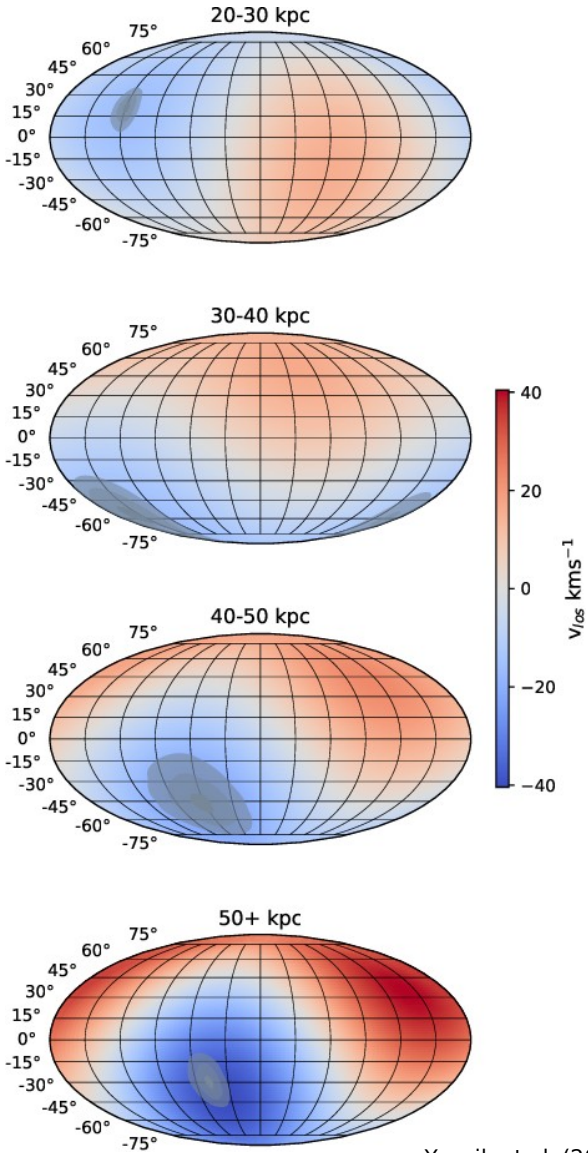
Conroy et al. (2021): EGDR3 + WISE halo giants

The effect of the LMC

- The LMC deforms the halo and pulls objects off their orbits (e.g., Orphan-Chenab and Sgr stream), and warps the MW disk
- Motion of the MW around the center of mass



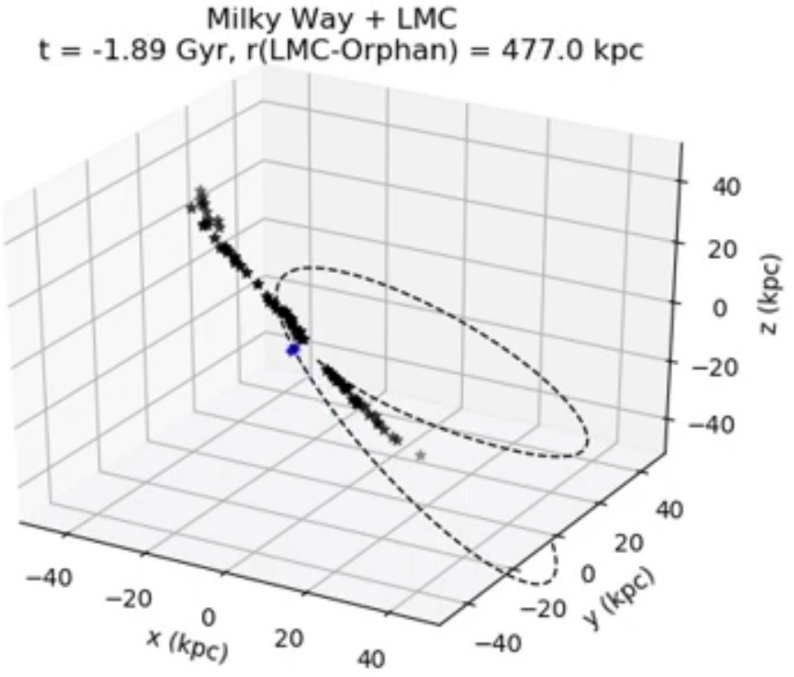
Credit: Mike Petersen



Yaaqib et al. (2024)

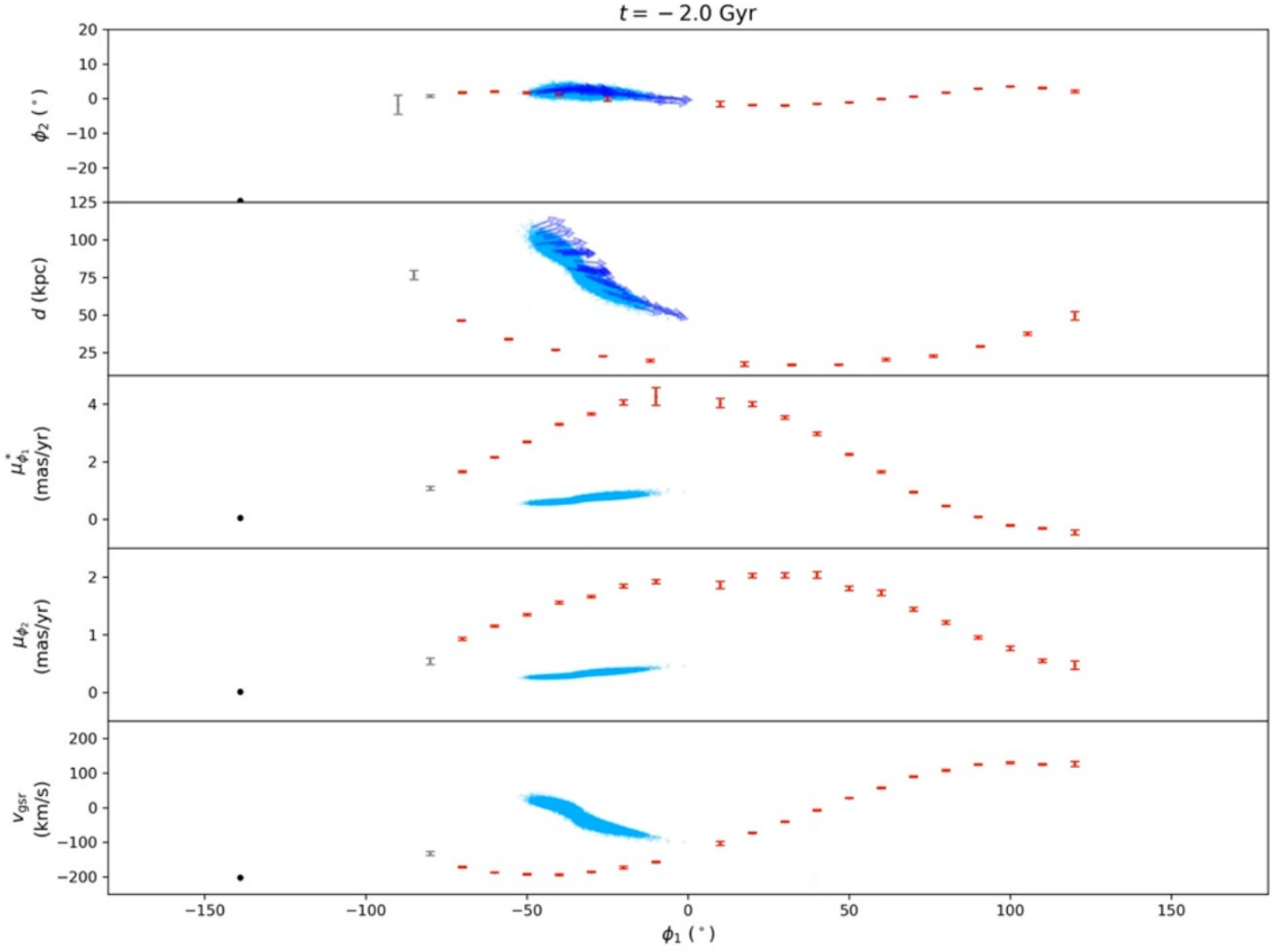
The effect of the LMC

Time-varying potential!



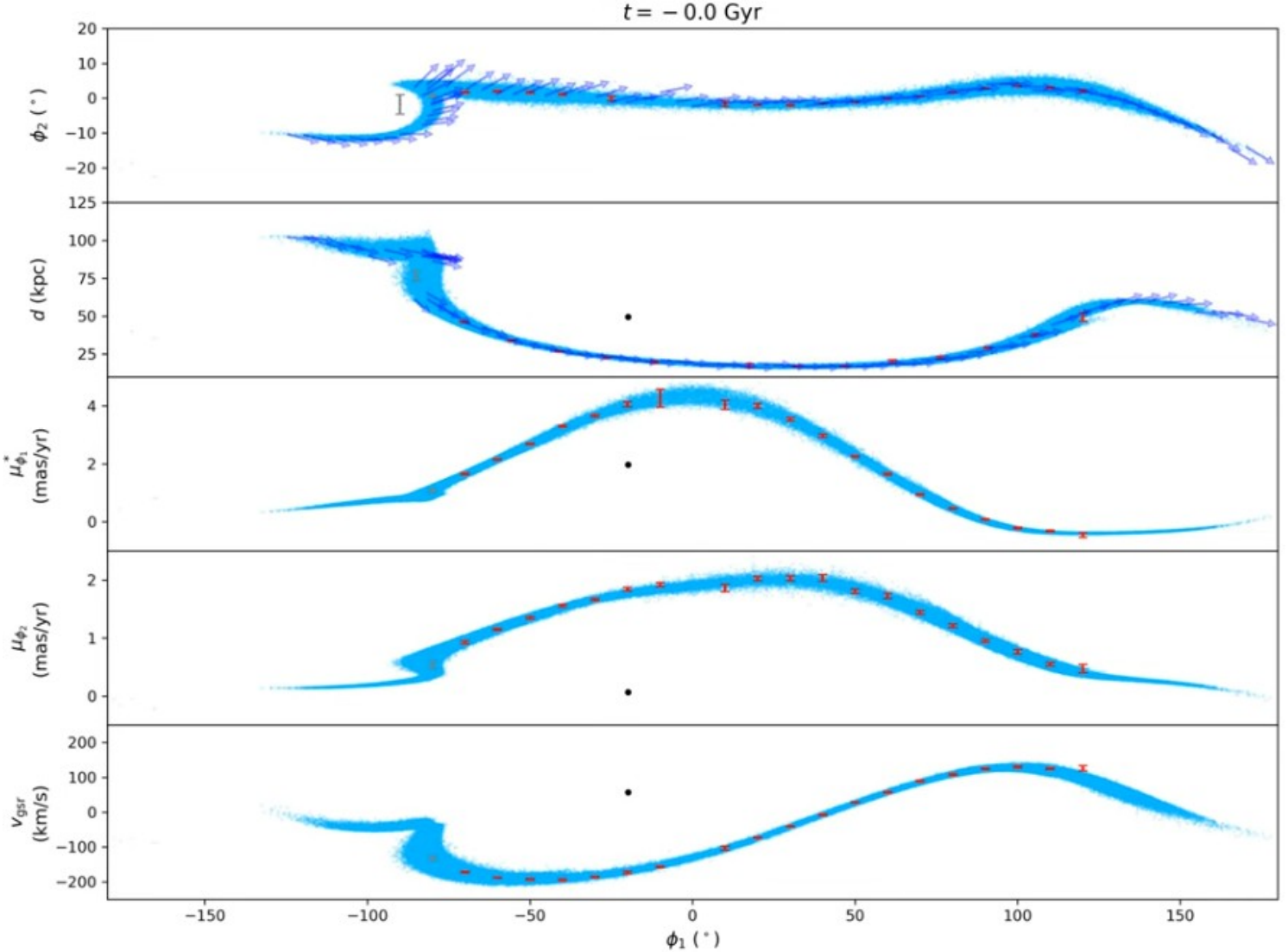
Credit: Denis Erkal

Orphan-Chenab stream



Credit: Denis Erkal

Orphan-Chenab stream



Credit: Denis Erkal