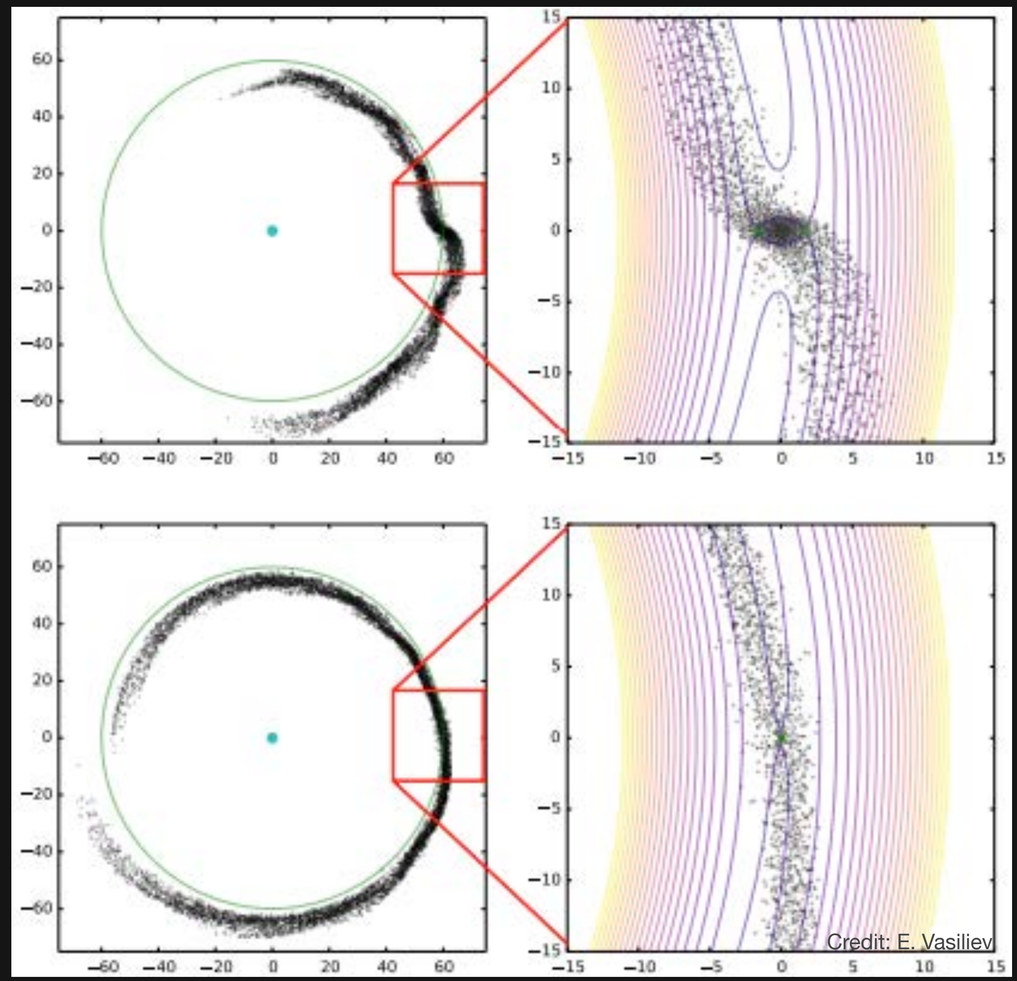
Galactic Archaeology

in the era of large surveys

GyuChul Myeong

Previously…

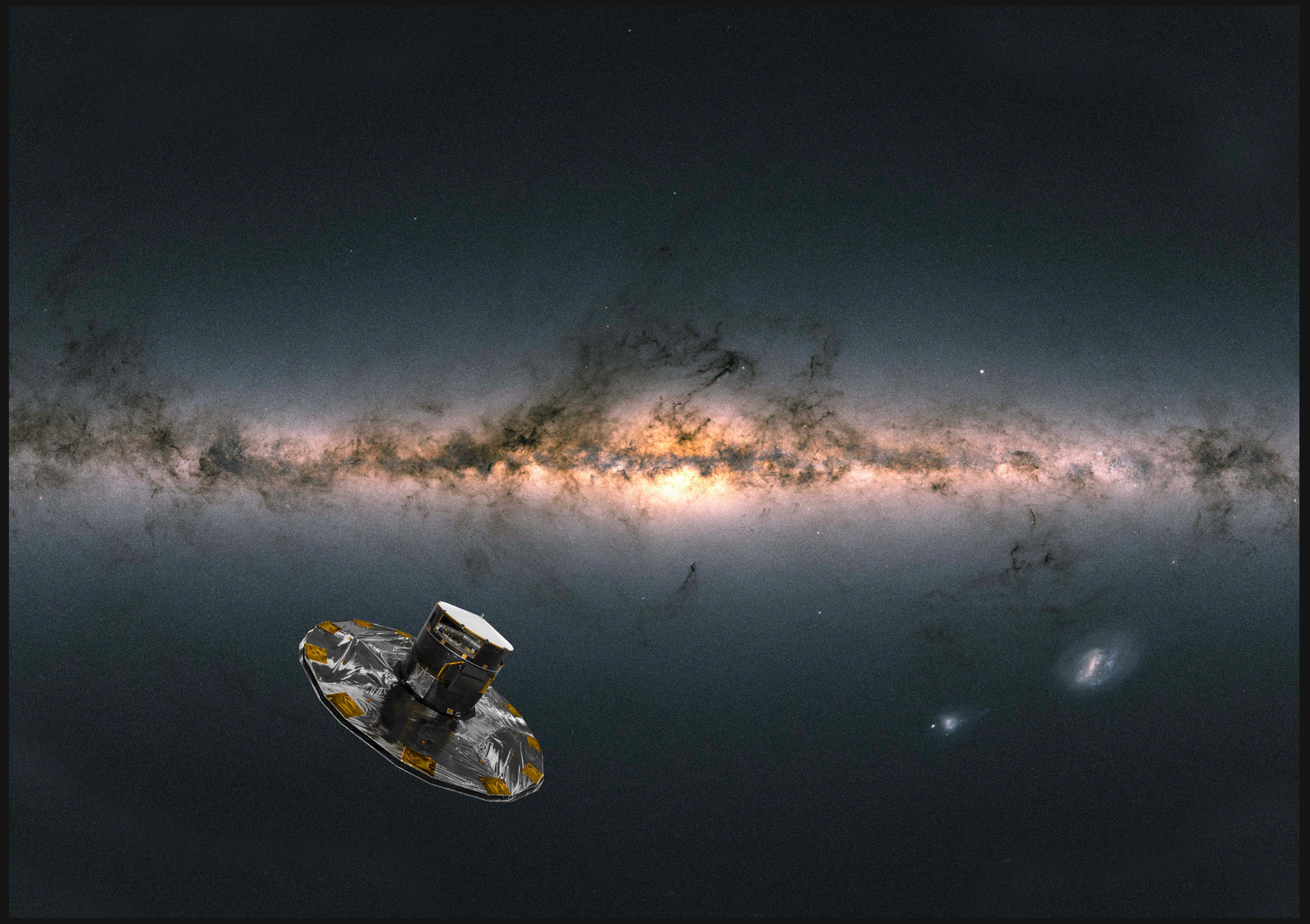
- **Various dynamical features**
  - Stellar Orbit
    - A trajectory of a star in motion through space as a function of time
    - Follows Hamiltonian mechanics!
    - Various useful orbital parameters
  - Action-angle variables (integrals-of-motion)
    - A set of canonical coordinates on phase space
    - For a closed (& periodic) orbit, action, J, is constant
    - Actions → what the star's orbit is like
    - Angles → where on the orbit the star is
  - Stellar Stream
    - Product of tidal disruption of a stellar system
    - An example of phase mixing
    - Lagrangian points as main escaping points
    - A family of orbits reflecting the properties of the progenitor system
    - Useful for studying the Galaxy's mass and components



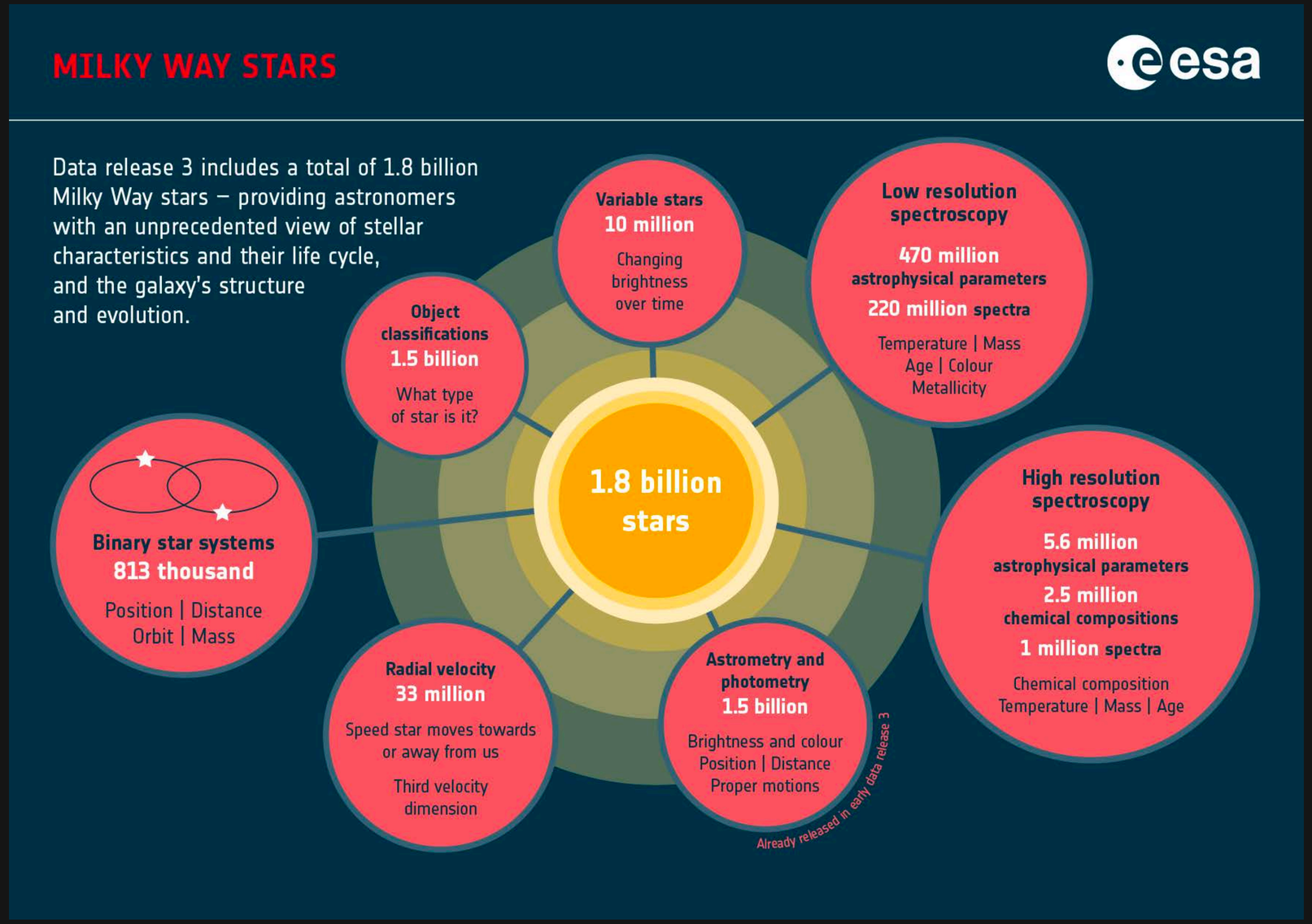
Lecture 9

- ***Gaia* mission**
  - Brief overview
  - Astrometry
- **Chemo-dynamical analysis**
  - Halo Structure & Substructure
  - in situ & ex situ populations
  - Chemo-dynamical view of Galactic components
- **Hands-on**
  - (mock) Stellar stream generation

Gaia mission

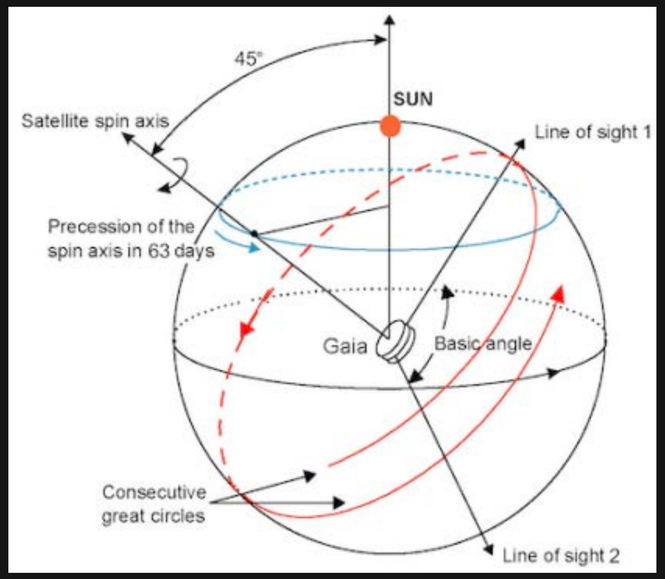


Gaia mission

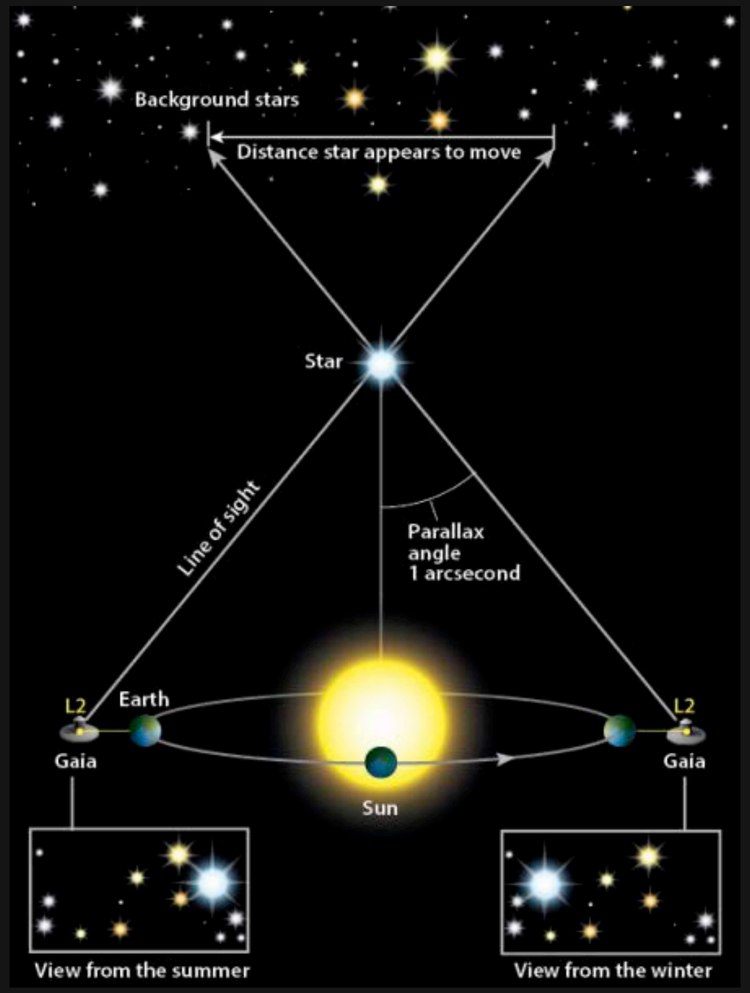


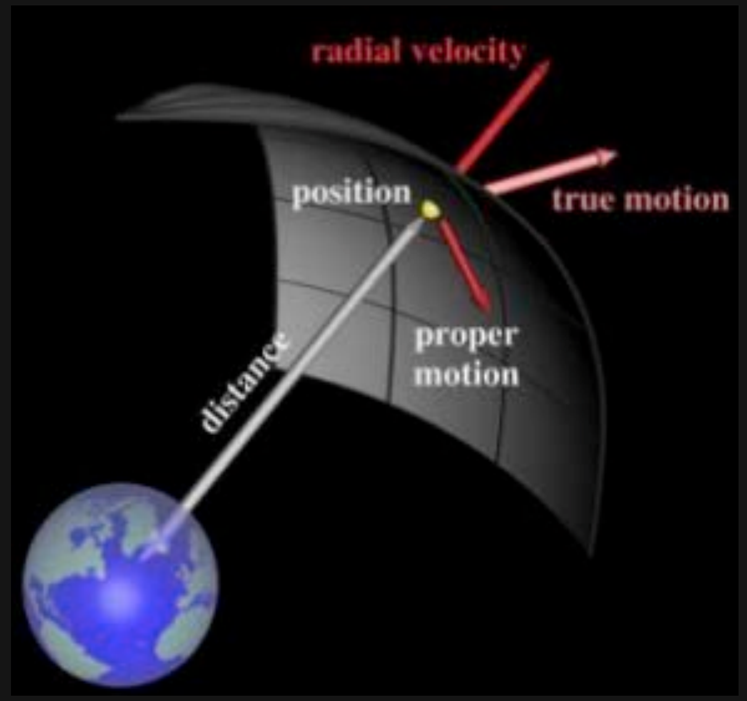
Gaia satellite

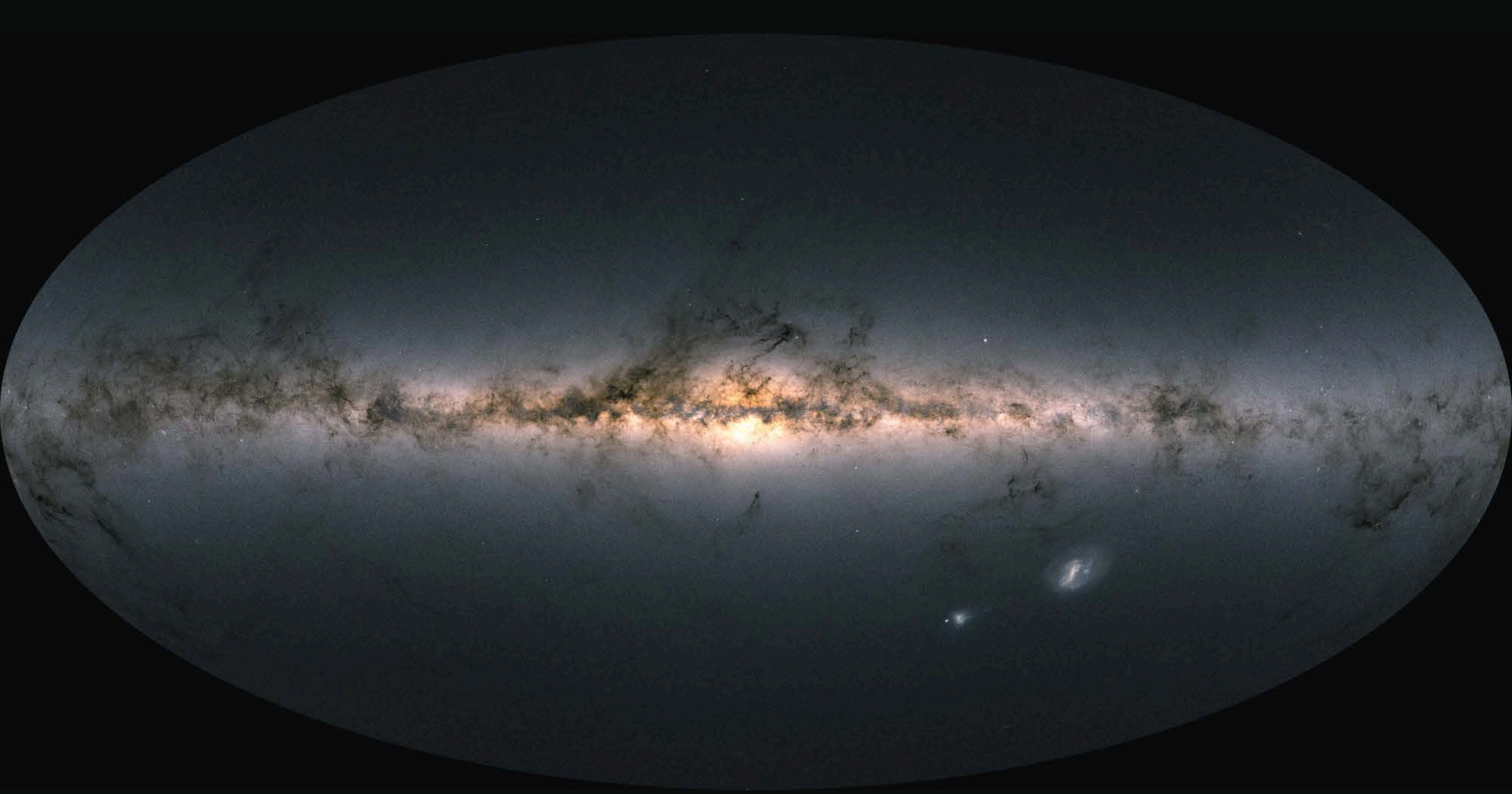
Gaia satellite



Gaia's astrometry







DIS Galactic Archaeology

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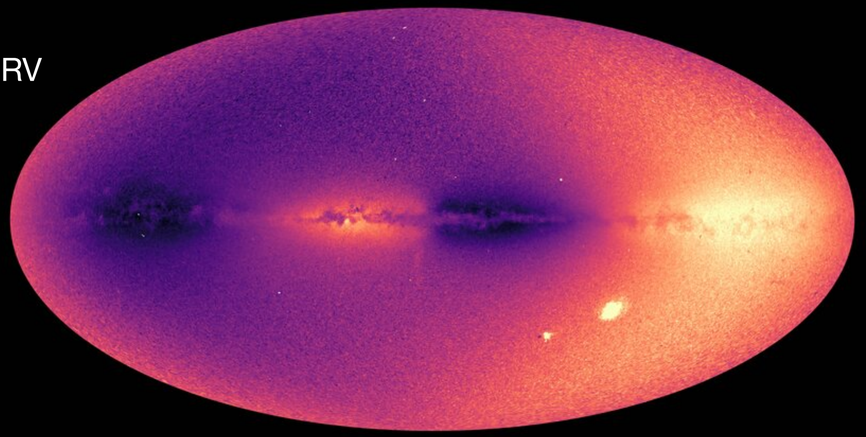
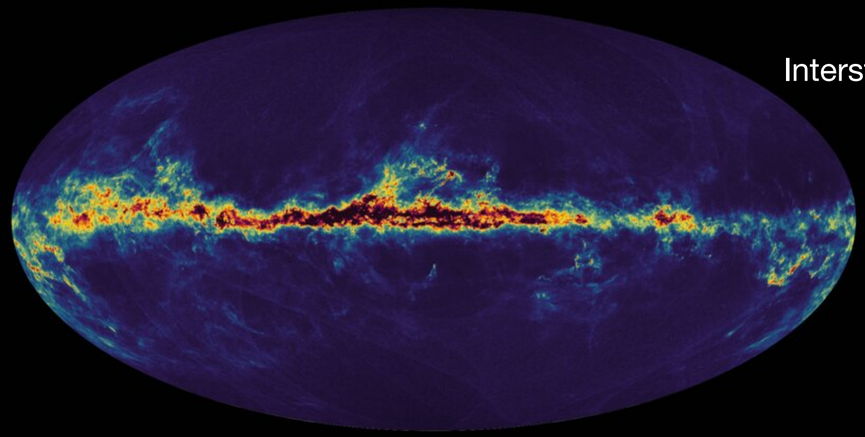
GAIA: EXPLORING THE MULTI-DIMENSIONAL MILKY WAY

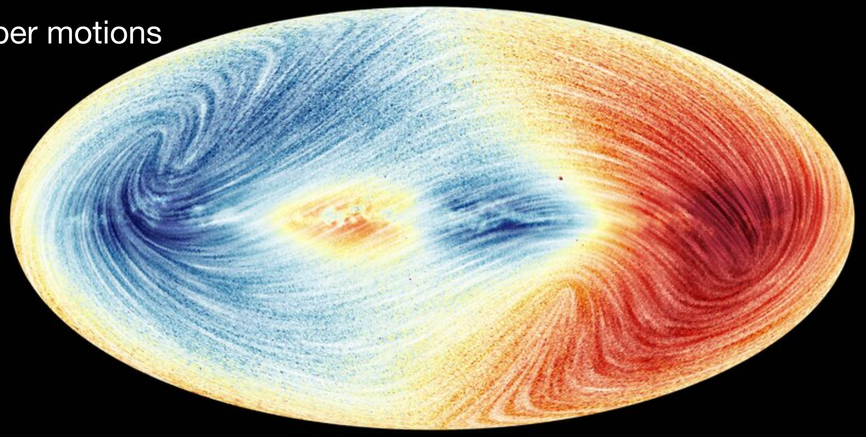
RV



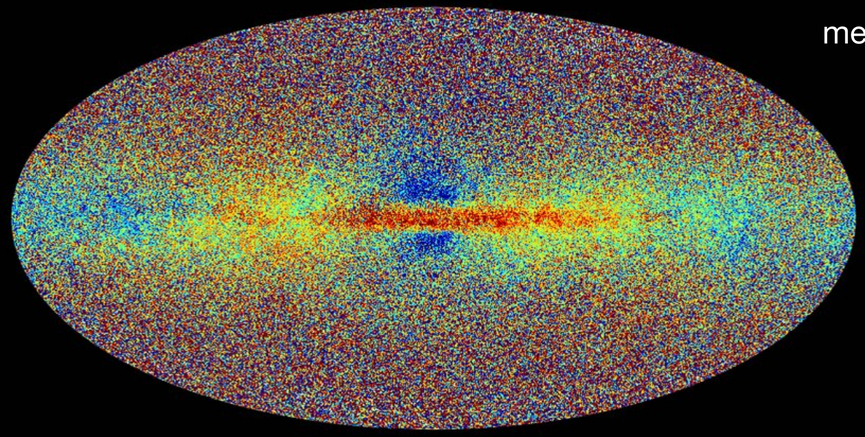
Interstellar dust



RV + proper motions



metallicity



www.esa.int

Credit: ESA/Gaia/DPAC

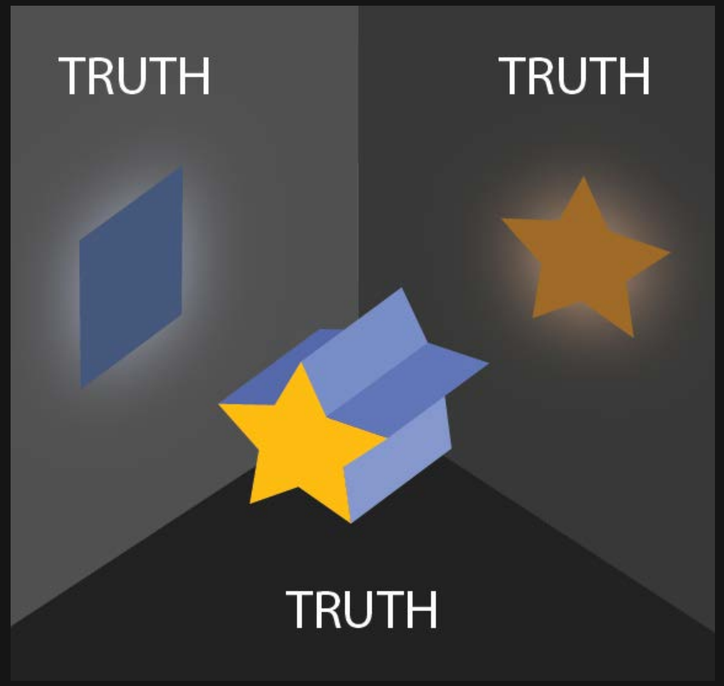
Before & After *Gaia*

Halo sample in *Gaia* era

- **Pre-*Gaia* time**
  - ~100 halo stars, within 1 kpc with 6-dimensional info (position & velocity)
  - or Incomplete phase space information (2~3D)
- ***Gaia* DR2, 3, …**
  - Astrometry for ~1.5 billion stars across the whole sky
  - Quality 5-dimensional phase space information to ~10 kpc from the Sun
  - Radial velocity for a subset → 6D!
  - (limited) Chemical abundances for a subset
- ***Gaia* x (APOGEE, LAMOST, GALAH, RAVE, Gaia-ESO)**
  - Full 6D phase space information + Spectroscopic chemical abundances

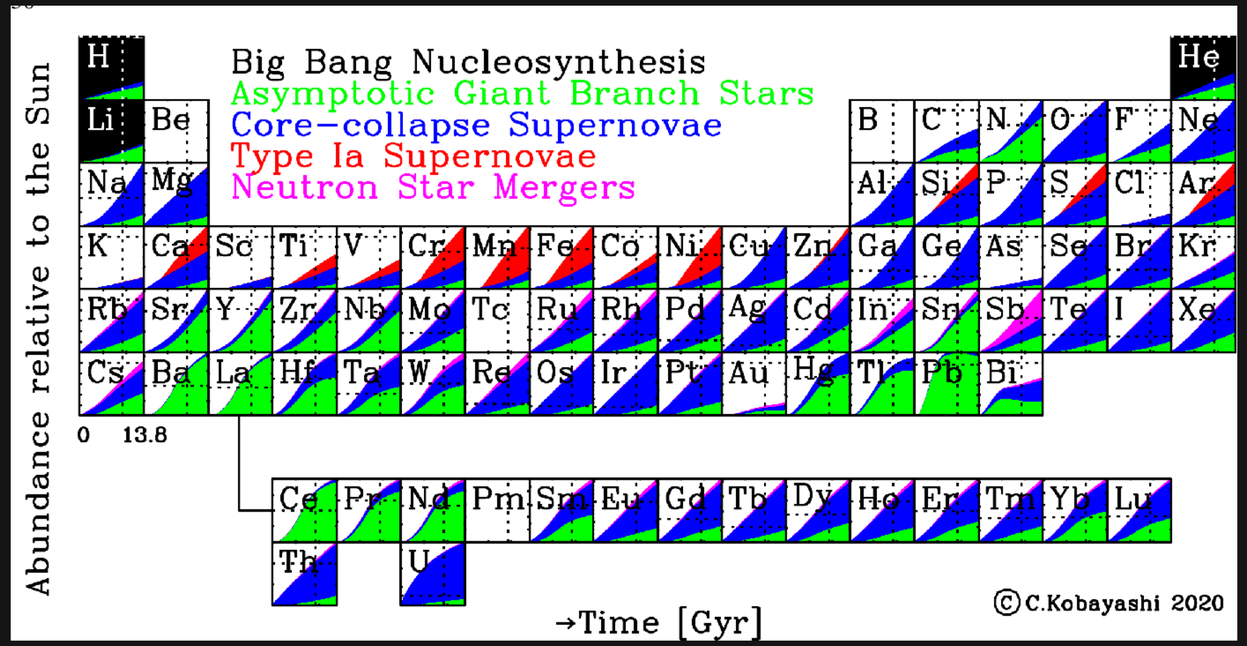
Combined approaches

- Full 6D kinematics + chemical information
  → *Gaia* x (APOGEE, LAMOST, GALAH, RAVE, H3, other literatures)
  for Stars, Globular clusters, Dwarf satellite galaxies
- Integrals-of-motions: **Action variables**
  → Characterisation of the orbit
  → Adiabatic invariant (like a living fossil!)
- **Chemo-Dynamical analysis!**
  - **Exploration in progress**
    - with dataset large in size and scale
    - with various parameters (e.g., Action-angle, age, chemical abundances)



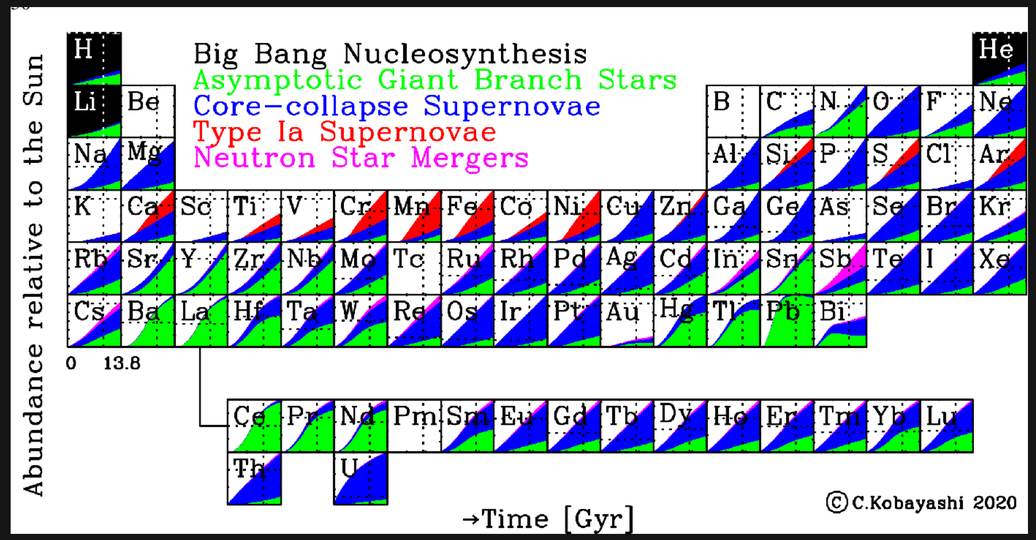
Chemical view

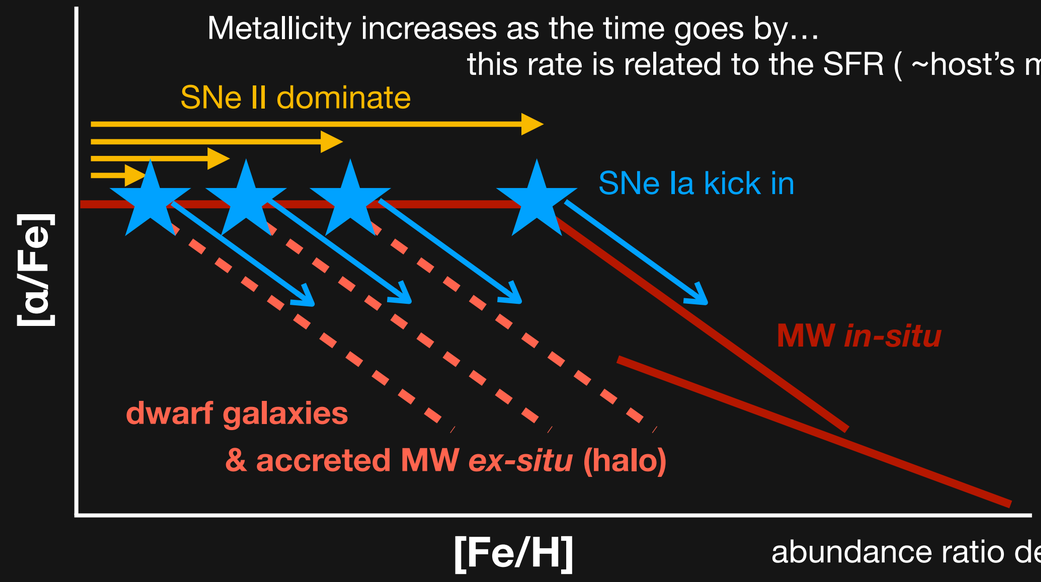
- **Viewing the Milky Way as a "collection of populations"**
  - Stellar population: stars with common (or similar) origin
    → comparable age & chemical composition
    → chemical abundances of a star reflect its formation environment
  - Different elements tracing different nucleosynthesis
  - Various attempts on chemical tagging/mapping with large spectroscopic data (e.g., GALAH)

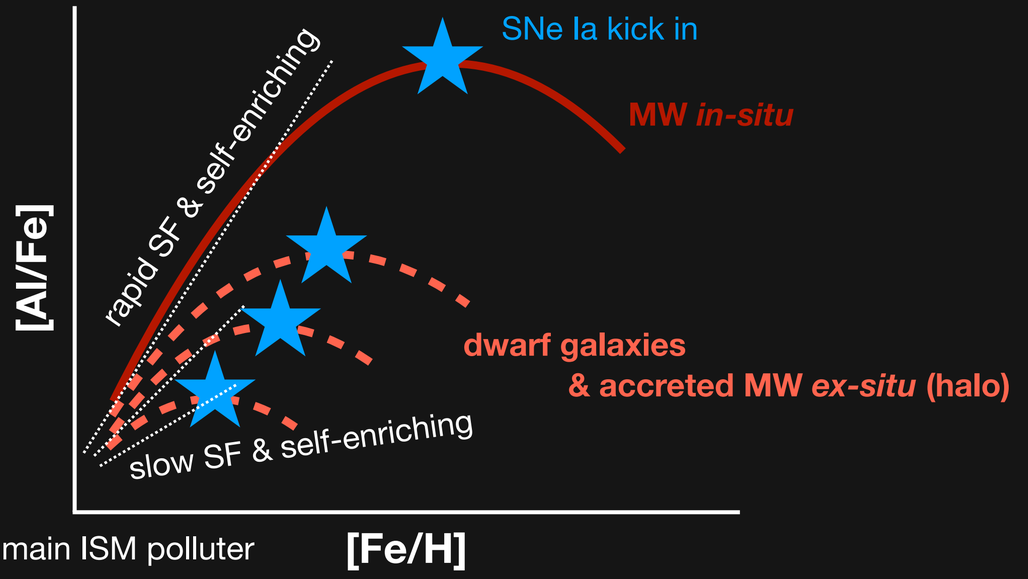


Chemical view

- Chemical abundances depend on:
  - the main ISM polluter (e.g., SNe II vs SNe Ia)
    - → different nucleosynthesis yields
    - → different delay time from the star formation
    - → transition causes change in abundance ratios
  - the star formation and self-enriching rate
    - → usually proportional to the host galaxy's mass (and IMF)



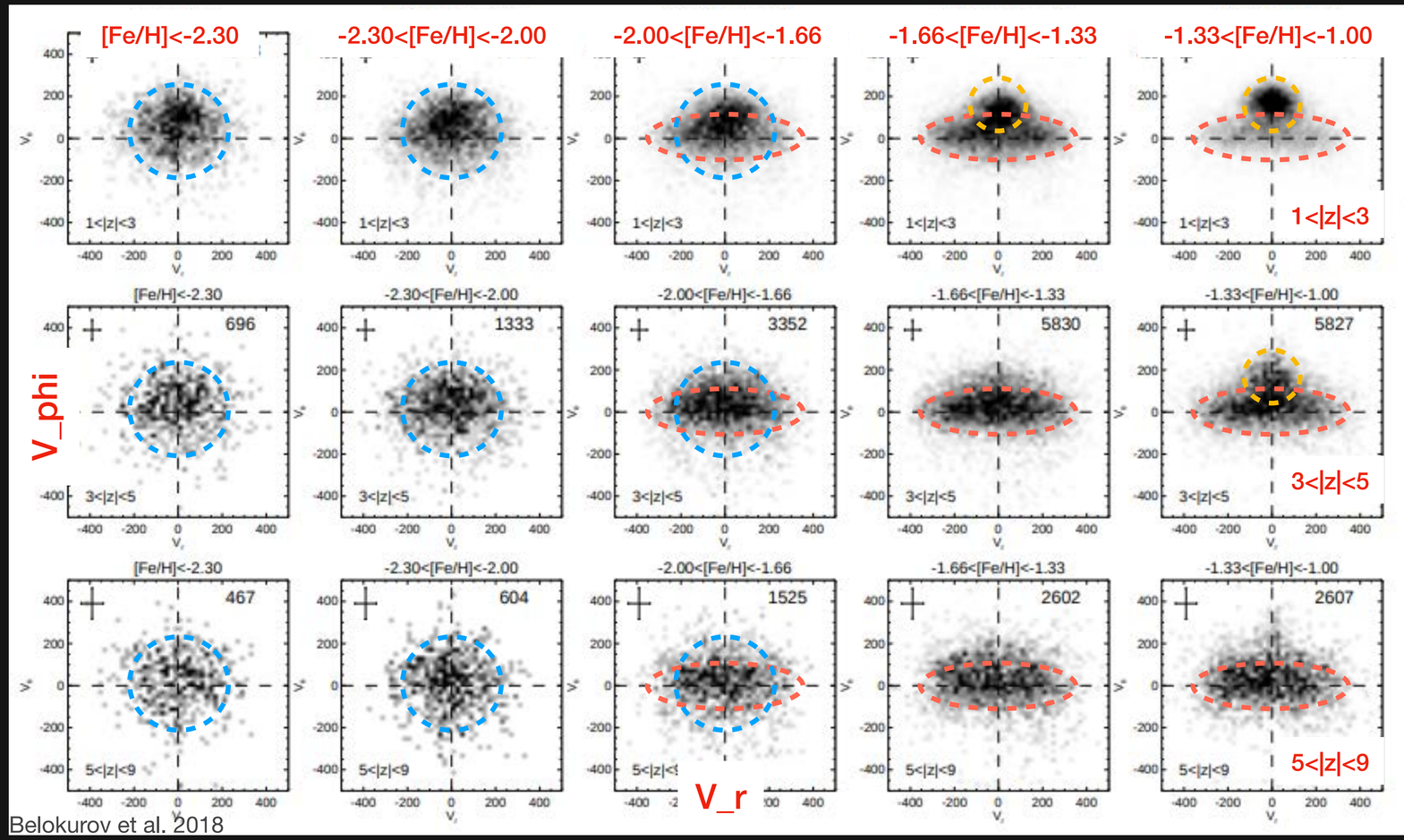




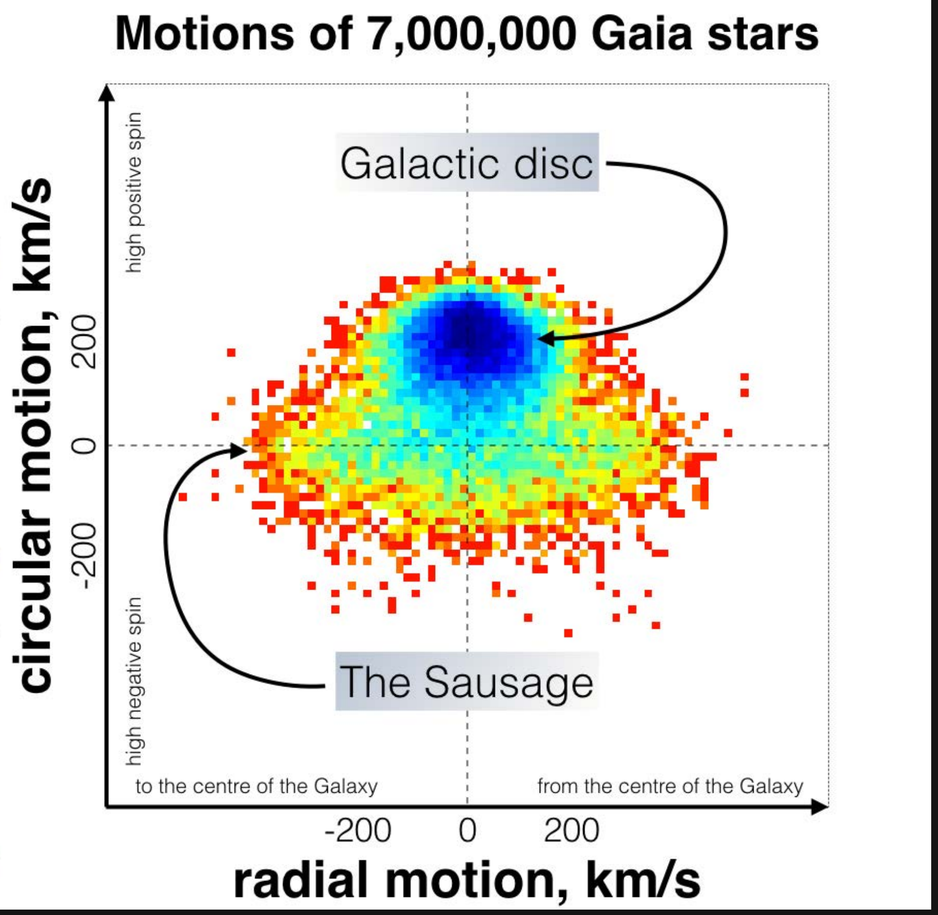
abundance ratio depends on the main ISM polluter

A massive merger! (GS/E)

- Halo as a composite of multiple velocity ellipsoids
  - Clear dichotomy between the metal-rich & radial population and the metal-poor & isotropic population

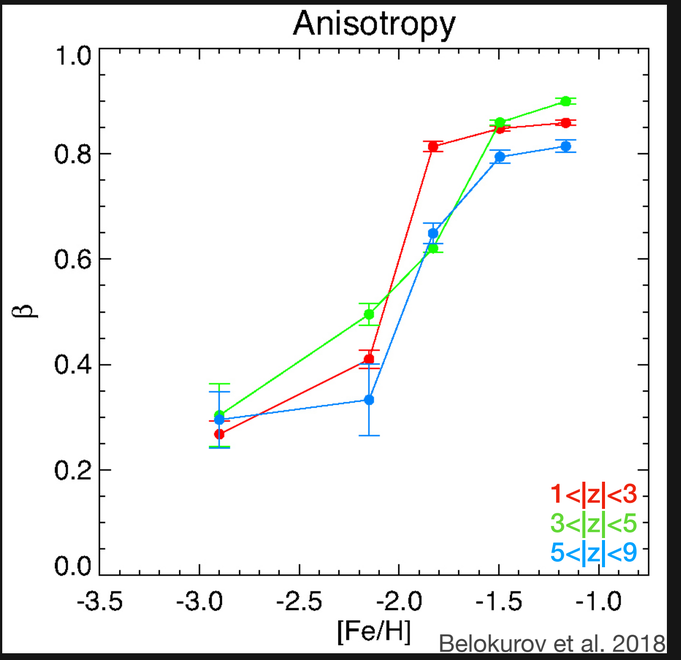


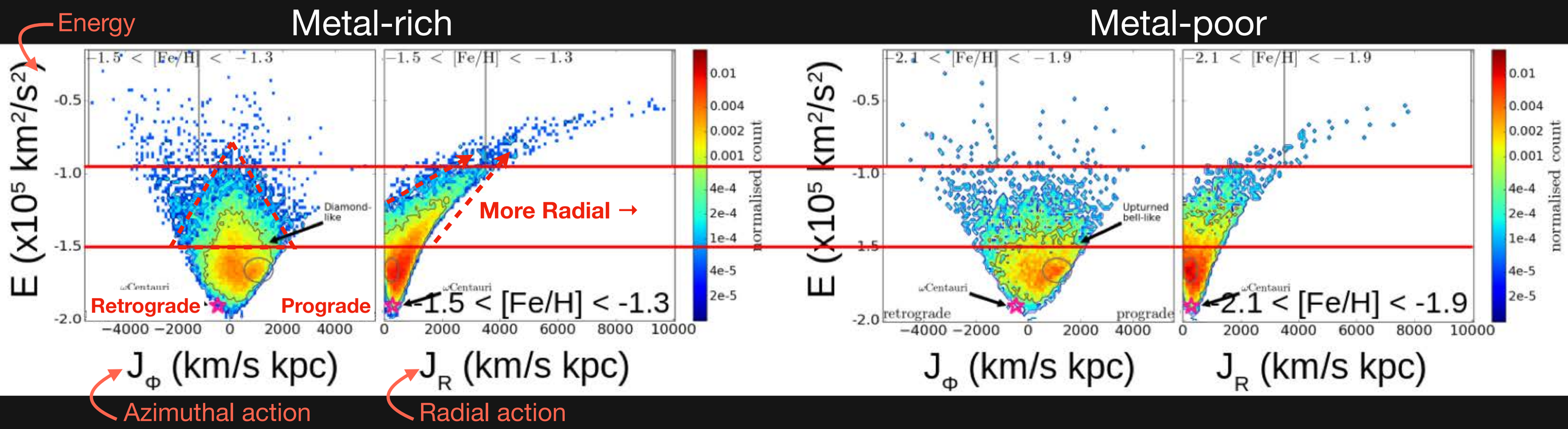
Belokurov et al. 2018



A massive merger! (GS/E)

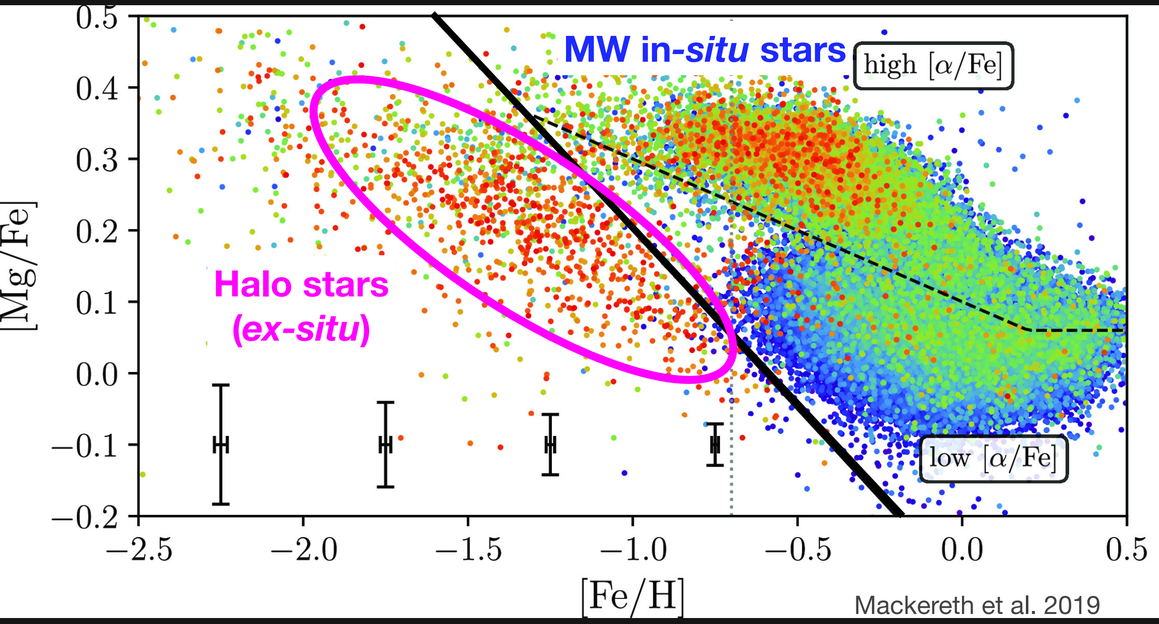
- **Chemo-dynamical dichotomy**
  - Metal-rich halo population with extended J_R, narrower J_ϕ
    - radial anisotropy → originated from the **radial infall of a massive satellite! (GS/E)**
  - Metal-poor halo population appears more isotropic → sum of earlier smaller accretions
  - Velocity anisotropy, β, of the stellar halo
    - sharp transition from nearly isotropic at low metallicity to extremely radial at higher metallicity



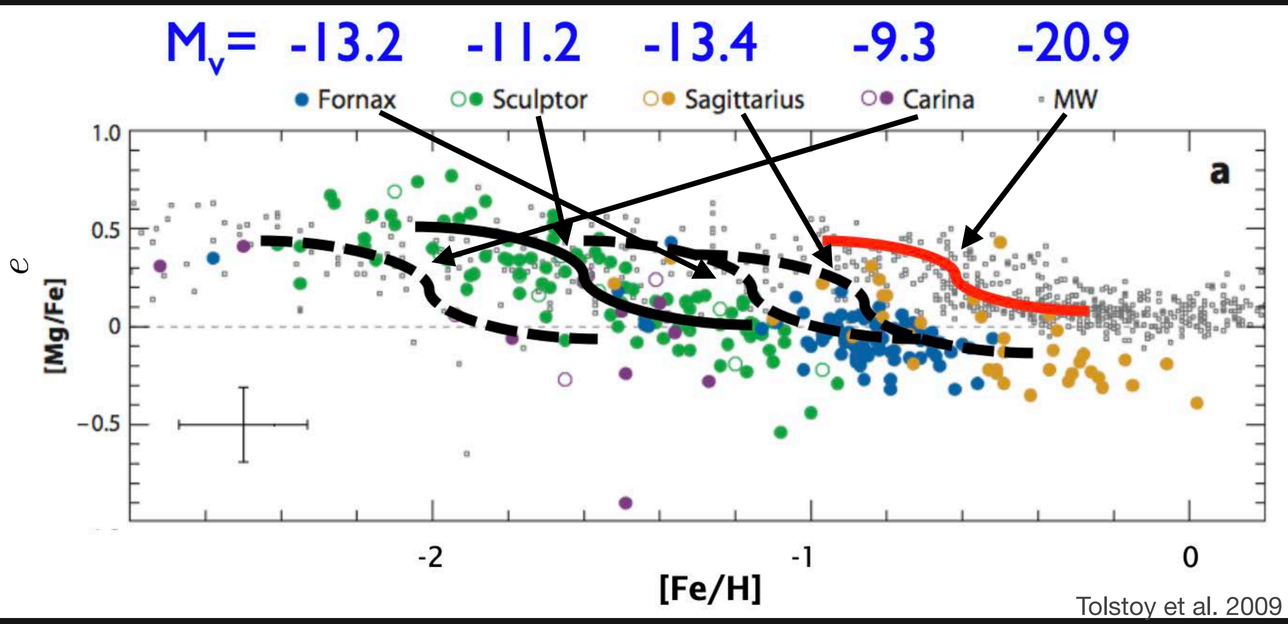


A massive merger! (GS/E)

- Location of the “α-knee” transition: a race between the metallicity evolution and SNe Ia domination time
  - rate of metallicity growth proportional to the SFR (~ the galaxy mass)
  - [α/Fe] abundance ratio changes drastically when SNe Ia become the dominating polluter
- MW halo stars showing distinct alpha-abundance trend from other MW components at similar metallicity range
  - halo’s α-knee resembles the case of dwarf galaxies (lower mass, lower SFR)
  - low stellar density makes the *in-situ* SF unlikely at the current halo location (so a different mechanism!)



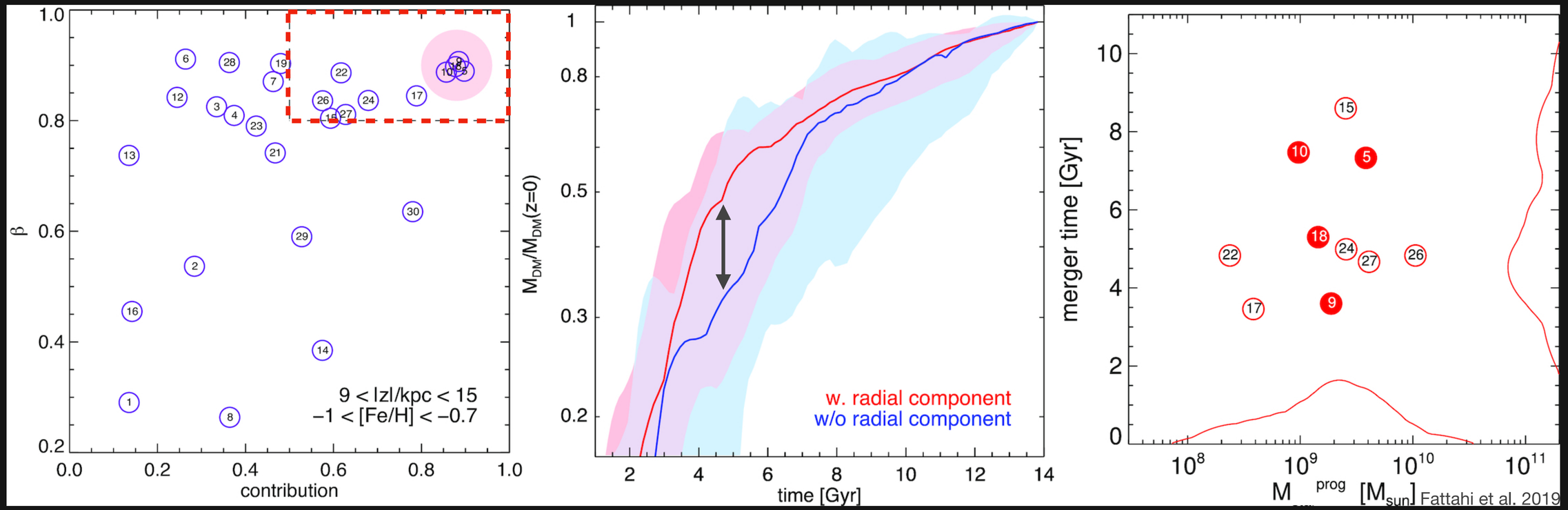
Mackereth et al. 2019



Tolstoy et al. 2009

A massive merger! (GS/E)

- **More clues from simulations**
  - Galaxy analogues in the Auriga cosmological hydrodynamics zoom-in simulation
    - velocity anisotropy, β, and mass contribution comparable to our Galactic halo's case isn't too rare (~36%)
    - more rapid (DM) mass accumulation at earlier time
    - progenitor mass, merger time also in agreement with other estimates (e.g., stellar population study)



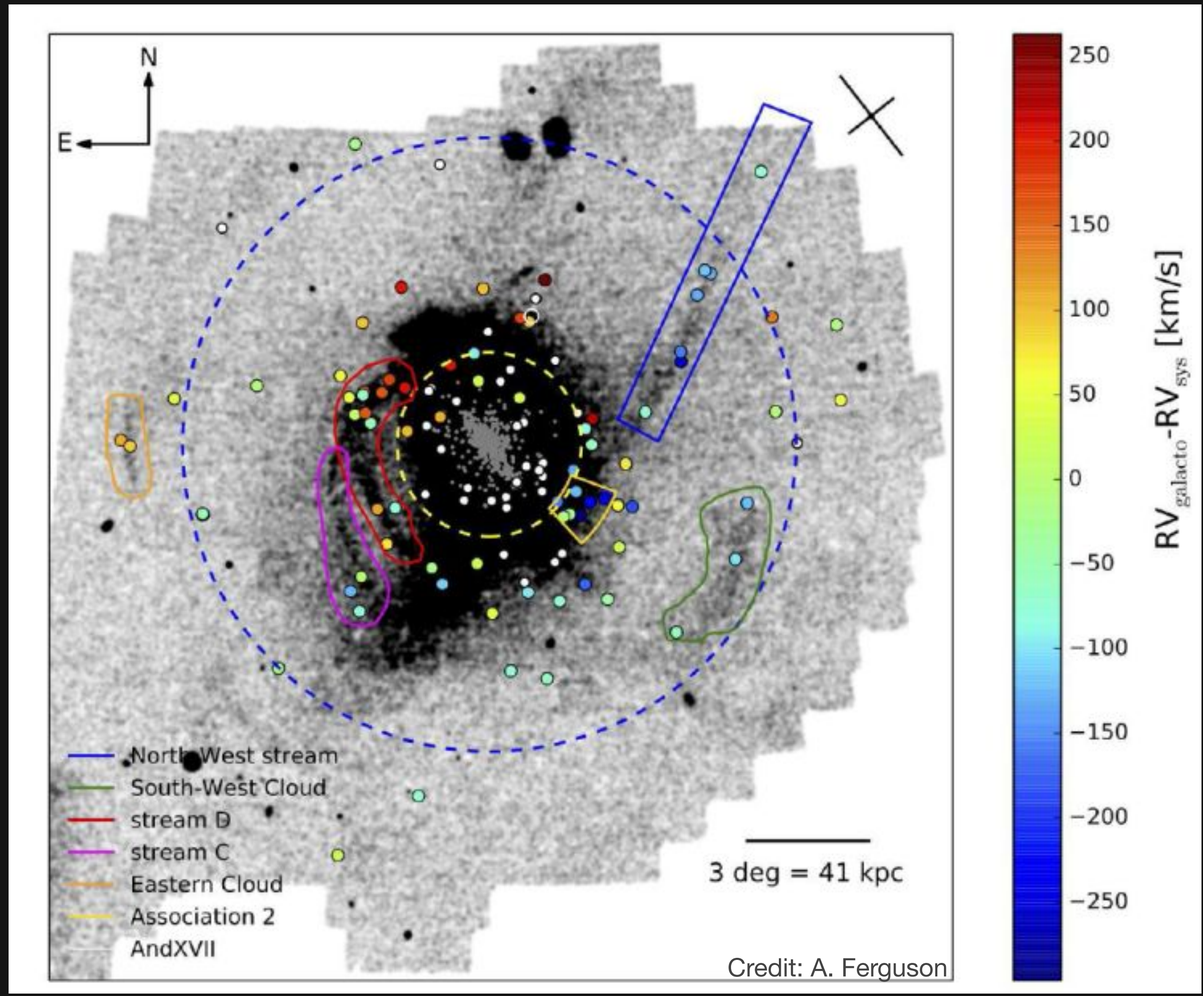
They have ‘minions’

- Massive dwarf galaxy as a progenitor of the metal-rich halo stellar population

  → might have brought with it a **population of globular clusters**

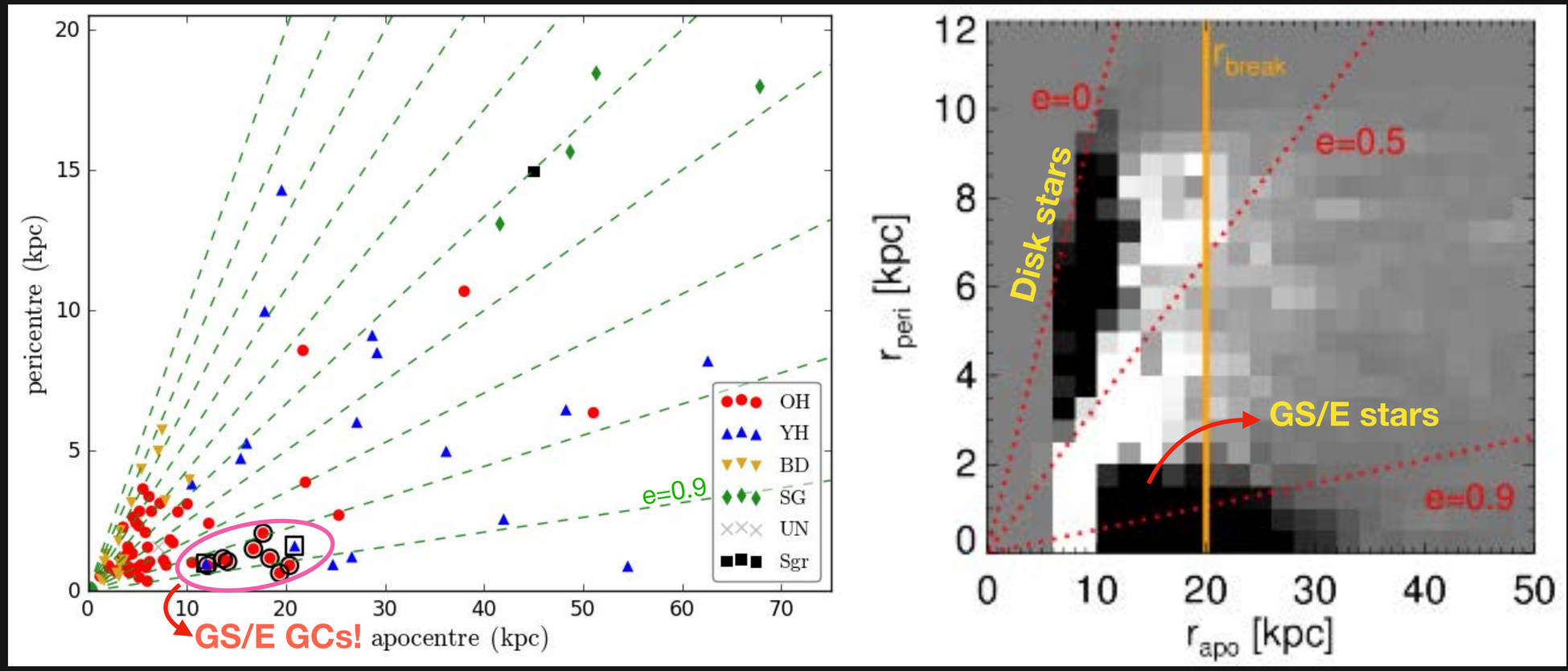
  - e.g., M31 with its globular clusters, Sagittarius dwarf with 'Sgr clusters'
  - ~15 – 17% of Old halo (OH) clusters might have been accreted (see e.g., Mackey & Gilmore 2004, Mackey & van den Bergh 2005)

  → likely for them to have similar orbital characteristics & age-metallicity trend

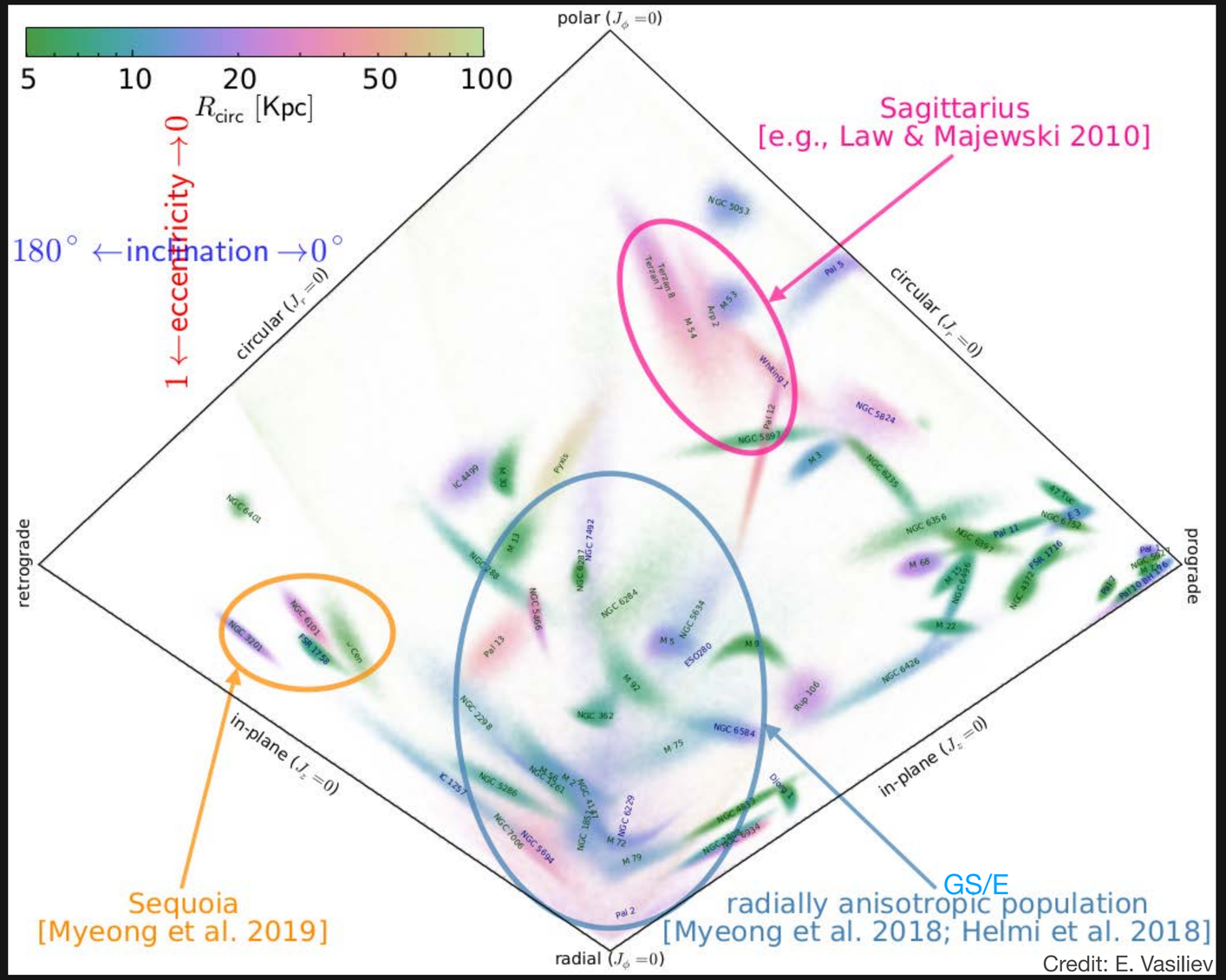


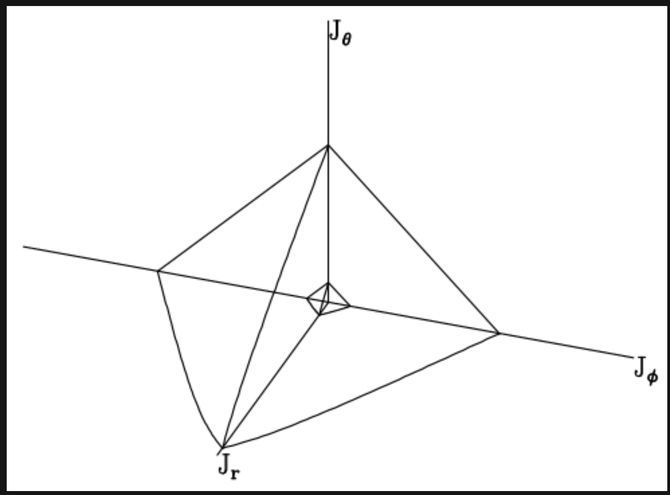
‘*ex-situ*’ globular clusters

- **A group of globular clusters with orbits comparable to the GS/E stars** (merger remnant → metal-rich halo)
  - comparable eccentricity ($e \geq 0.85$)
  - within a comparable apocentre range
  - not only YH globular clusters but also OH globular clusters

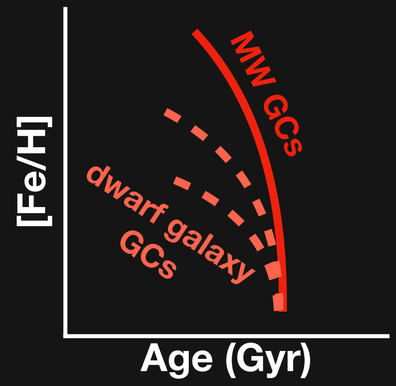


‘*ex-situ*’ globular clusters

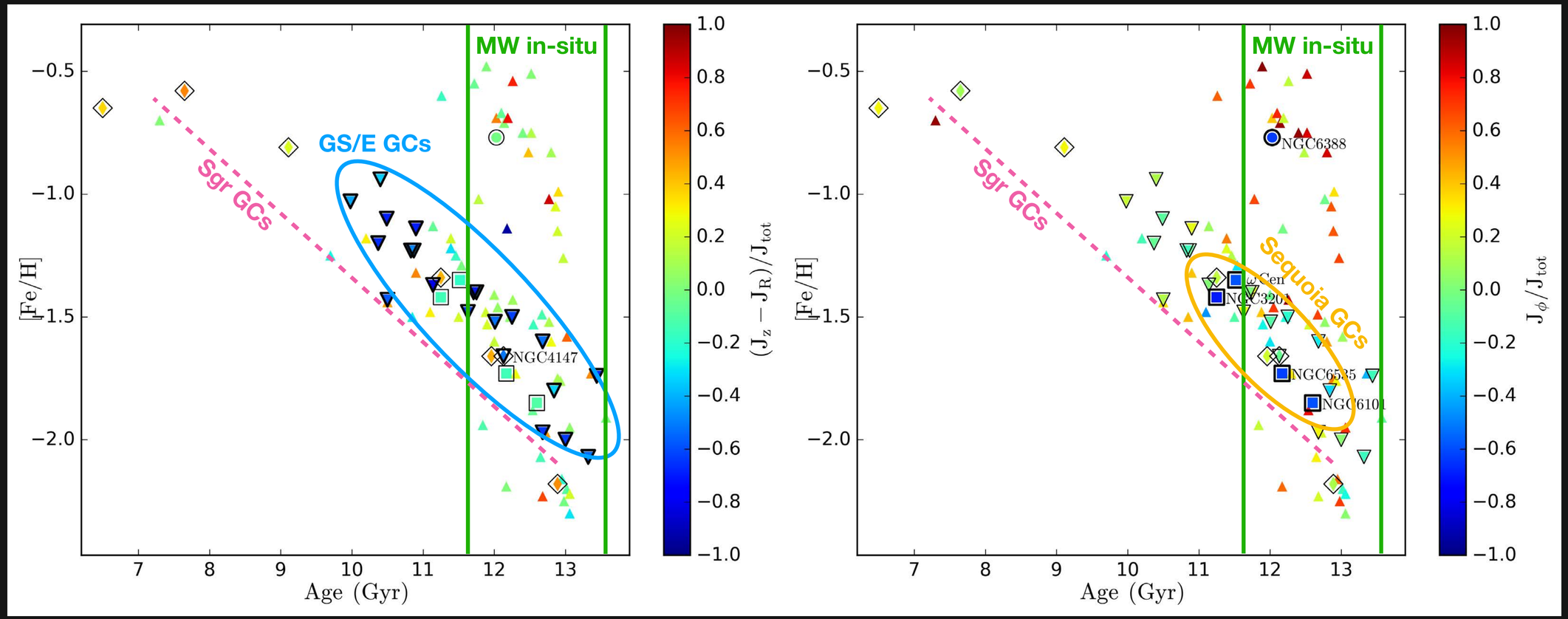




'*ex-situ*' globular clusters



- A group identified based on dynamics also shows a unique chrono-chemical properties
  - distinct track on the age-metallicity relation! → another evidence of *ex-situ* population
  - number of potential members, age range → in accord with other mass estimates (e.g., Belokurov et al. 2018; Kruijssen et al. 2018; Fattahi 2019)

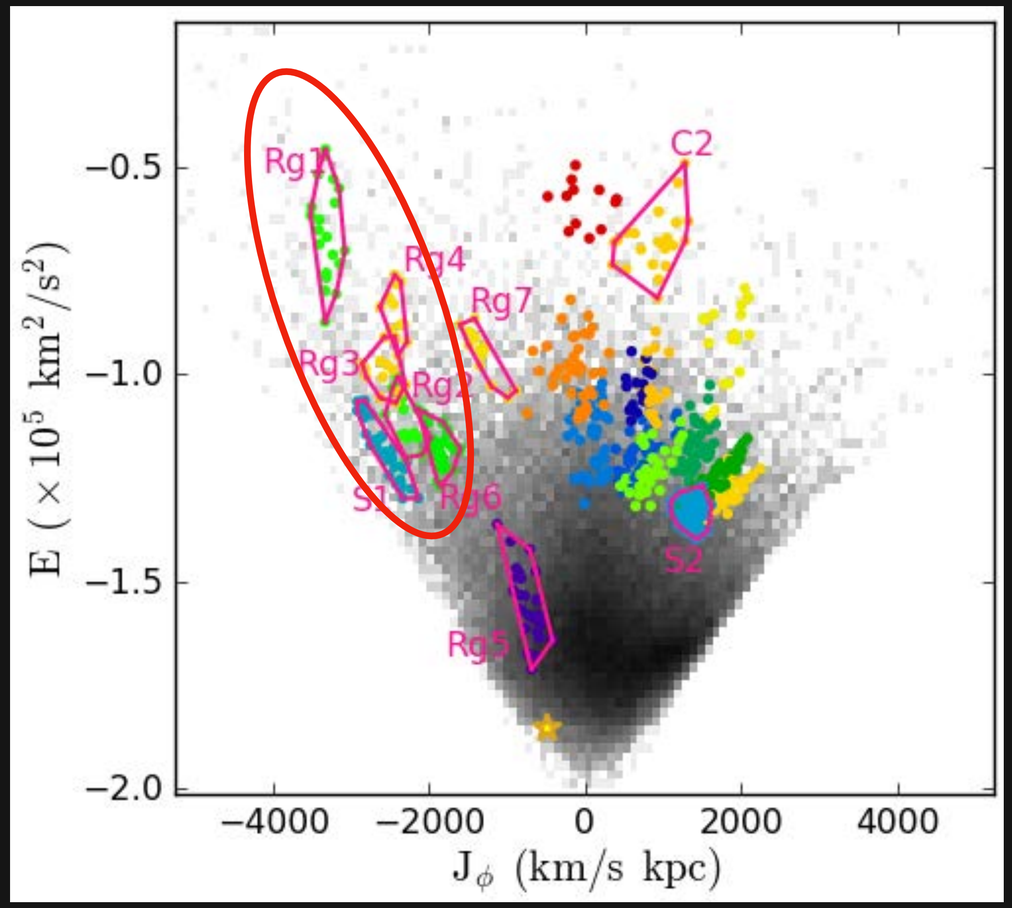


A brief summary for GS/E…

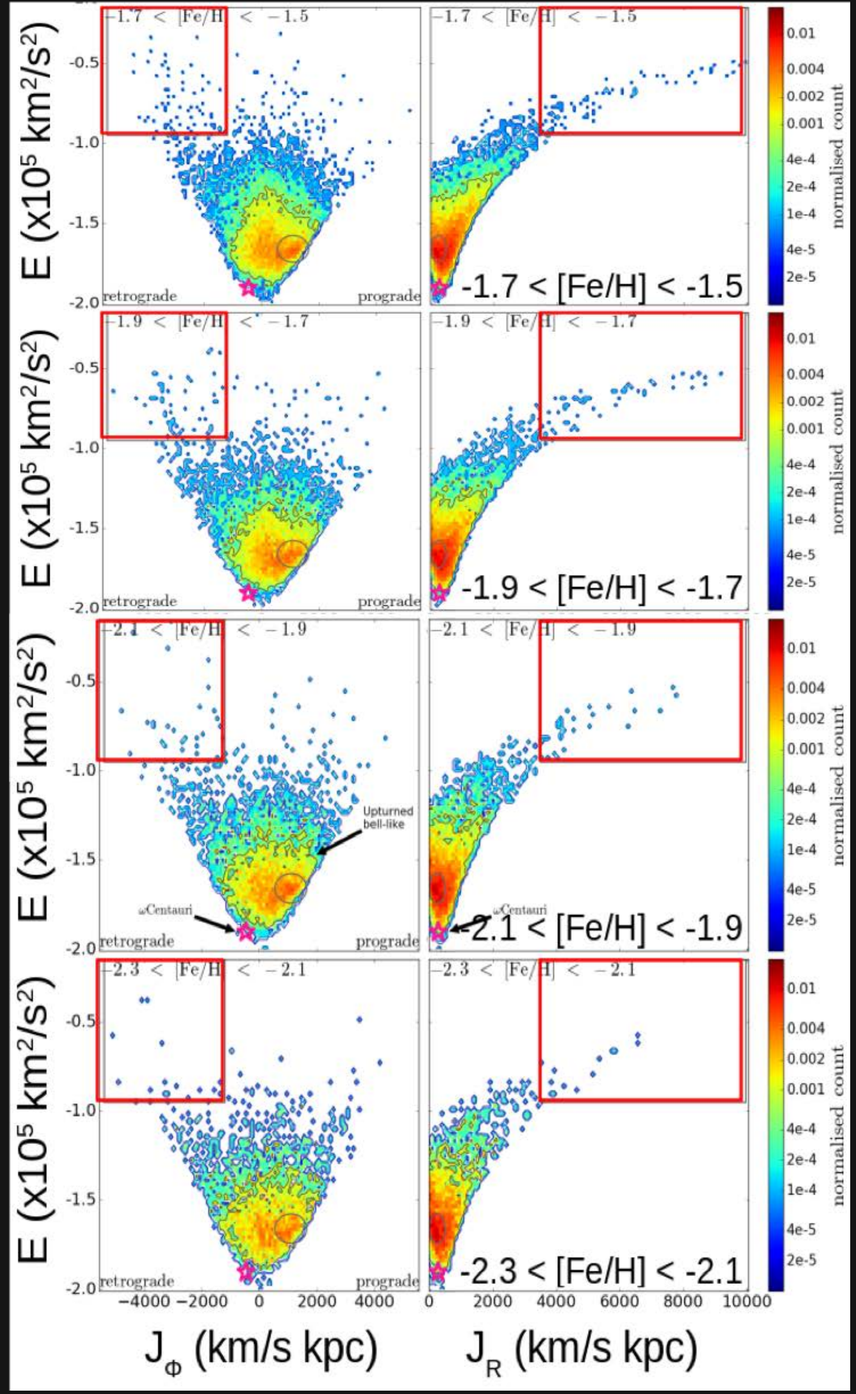
- **Milky Way experienced a major galactic merger!**
  - This merger, **GS/E**, happened $\sim 10\,\mathrm{Gyr}$ ago, with progenitor mass $\sim 10^{10}\,\mathrm{M}_{\odot}$
  - GS/E is now disrupted and merged to the Milky Way
  - **GS/E remnants** are now seen as the **Milky Way's metal-rich halo!**
  - There are **GS/E originated (*ex-situ*) globular clusters** now residing **in the Milky Way!**

* **Of course there were other accretions other than GS/E!**

Retrograde accretion



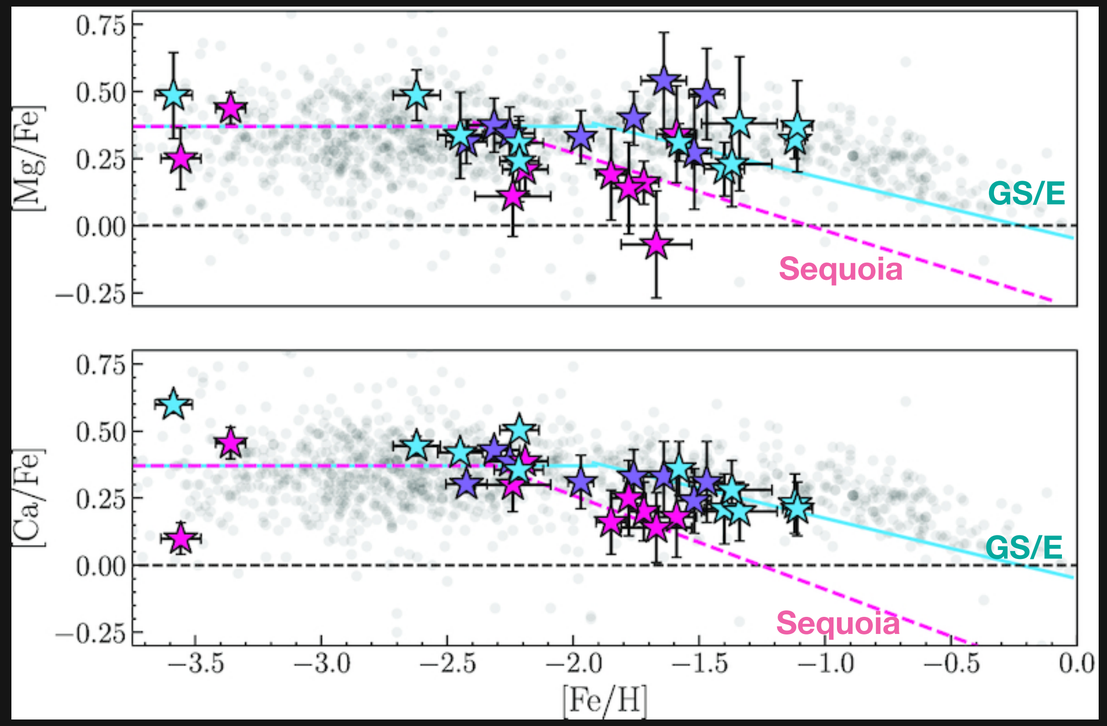
- Tail of high significance region in action space → trace of orbital decay of a past accreted progenitor (dwarf galaxy)

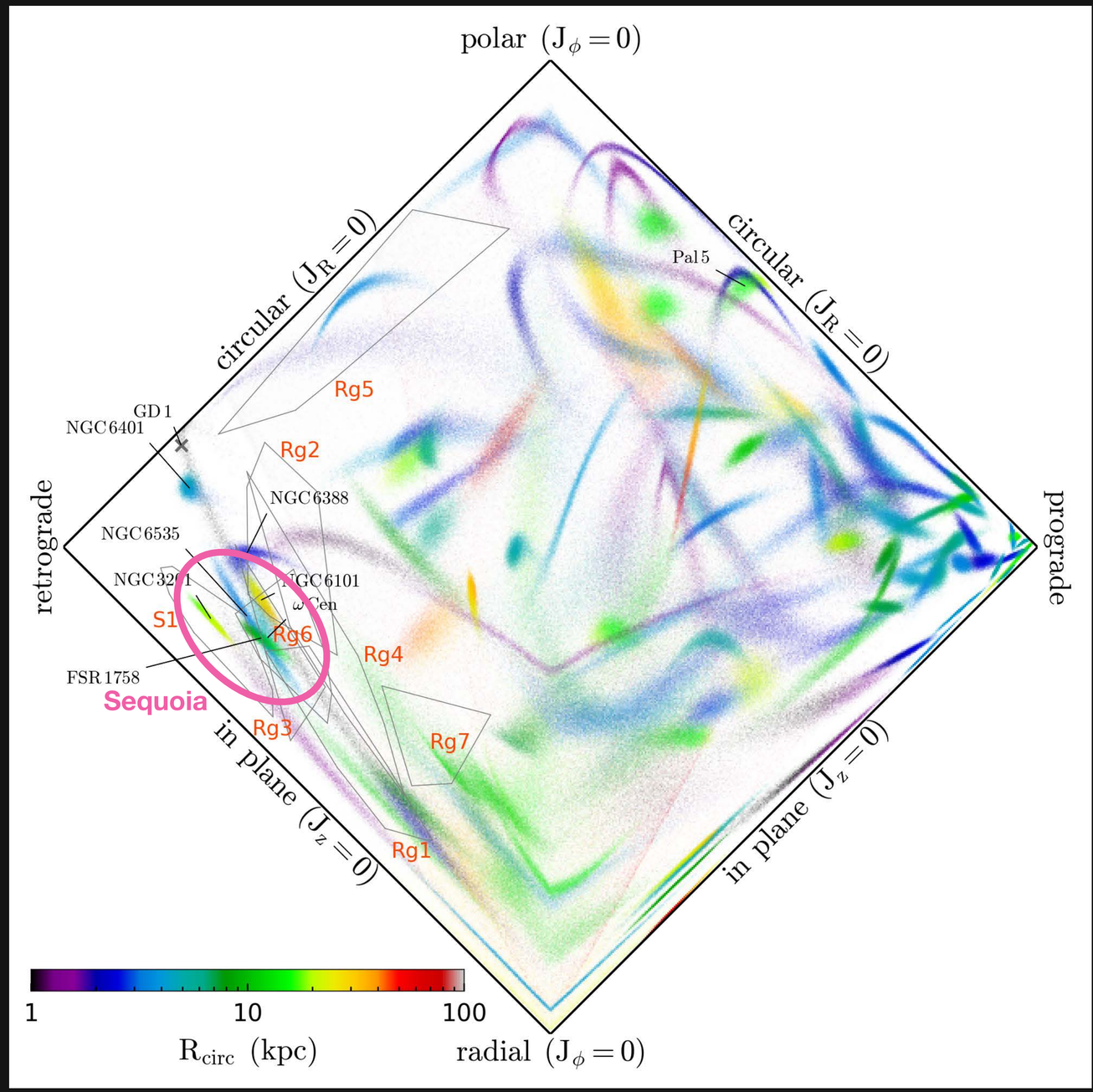


Retrograde Sequoia 🌲

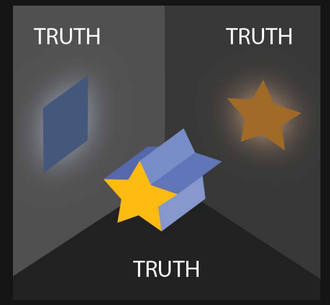
- **Multiple evidences of another past accretion (Sequoia)**
  - Abundance of halo substructures (stellar streams, GCs) with specific orbital properties ($e \sim 0.6$, incl. $\sim 150°$)
  - Stars show a distinct chemical trend from MW or GS/E + GCs also show a distinct age-metallicity track

    → lower mass progenitor!





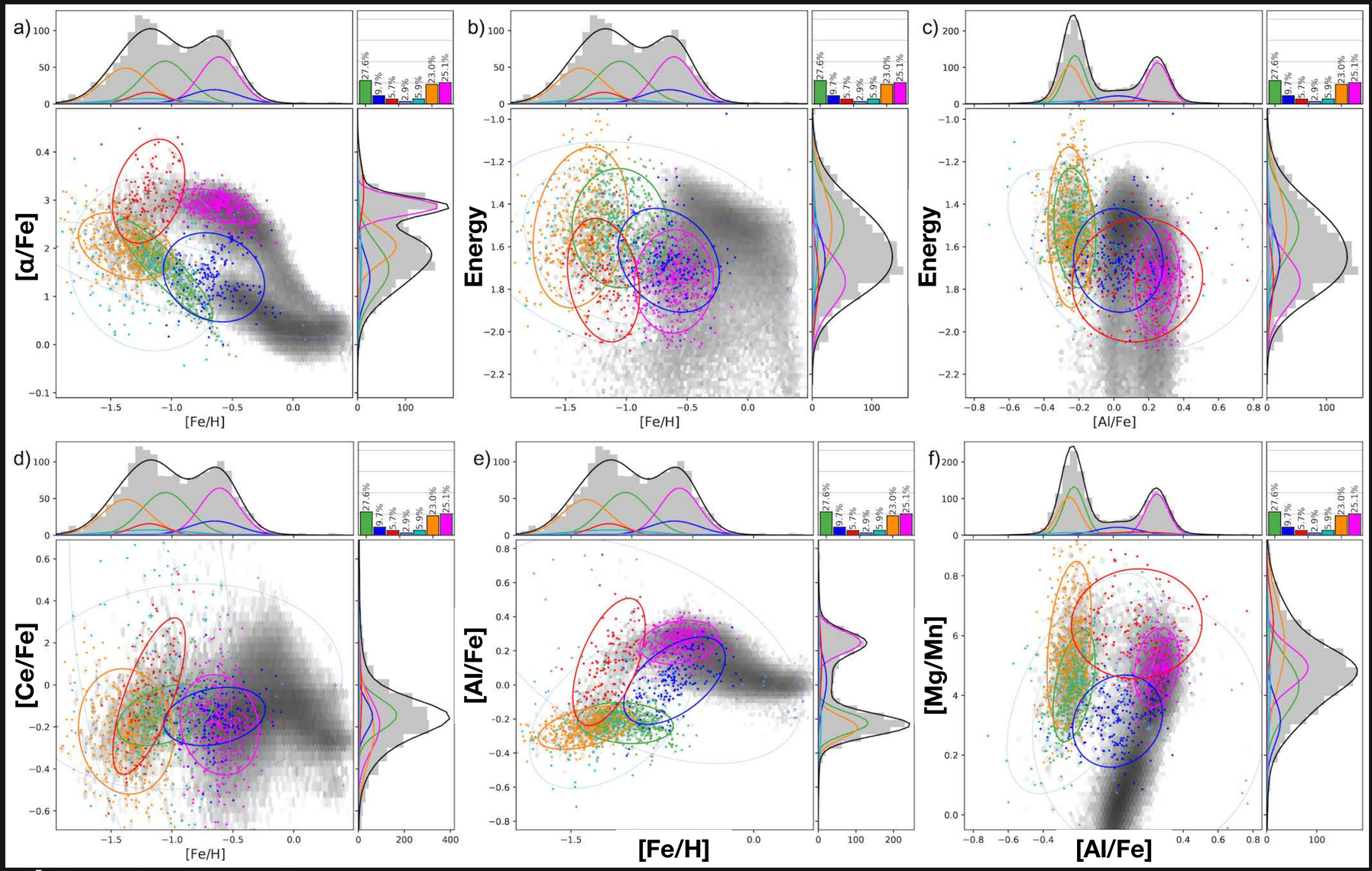
Combined analysis



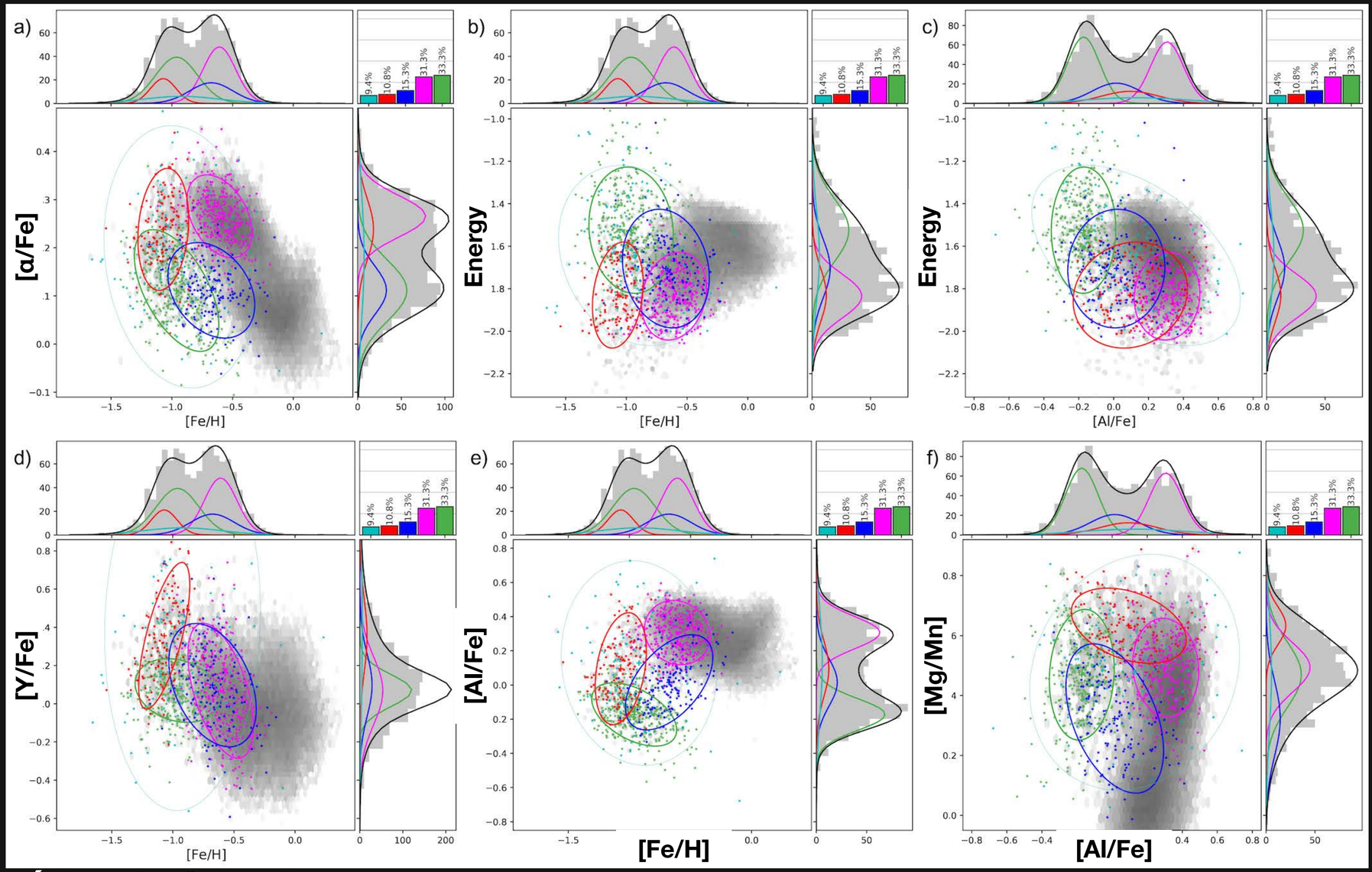
- **Tracing chemo-dynamical trend of Galactic components**
  - Various tracers for dynamics (e.g., actions, energy) and chemistry (e.g., α-, odd-Z, r-process, s-process elements) considered **simultaneously**

  → Hyper-dimensional clustering algorithm (e.g., mixture modelling)
    - unsupervised probabilistic modelling for unlabelled data
    - e.g., assumes the overall data distribution as a sum of a finite no. of model distributions (e.g., Gaussians) with unknown parameters
    - the optimal (maximum likelihood) model parameters can be searched using Expectation—Maximization (EM) iterations

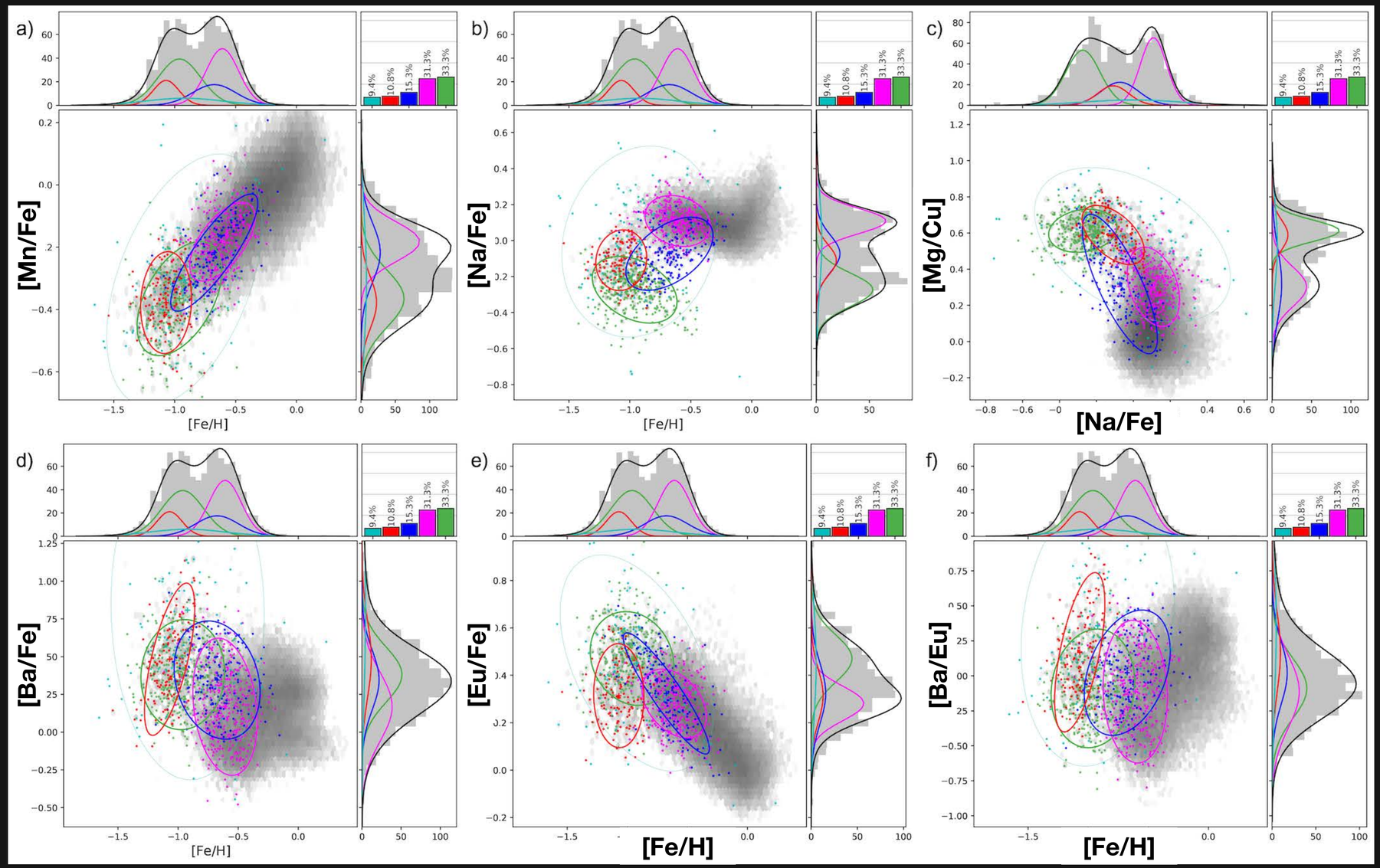
Galaxy's eccentric constituents



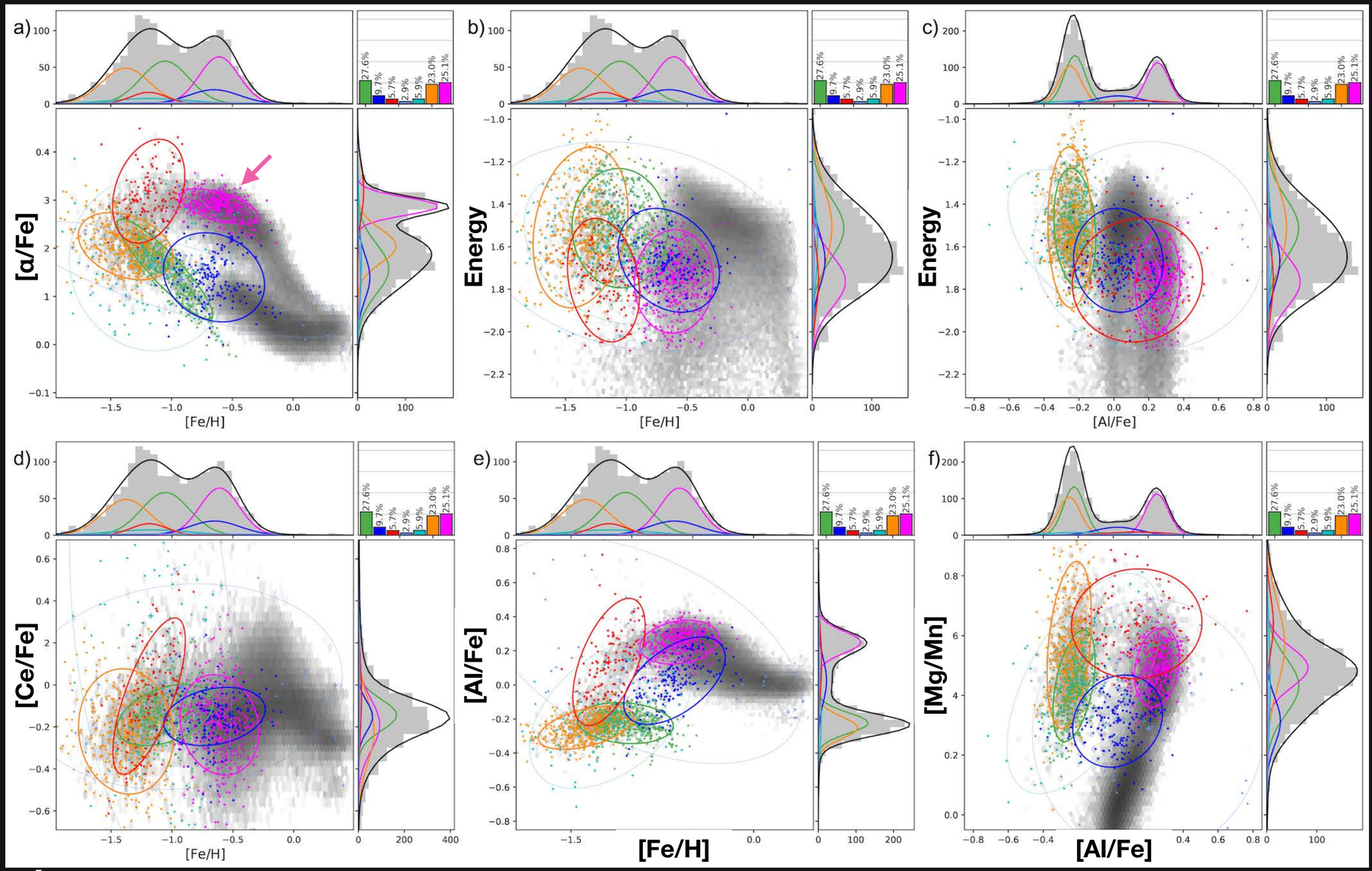
Galaxy's eccentric constituents



Galaxy's eccentric constituents

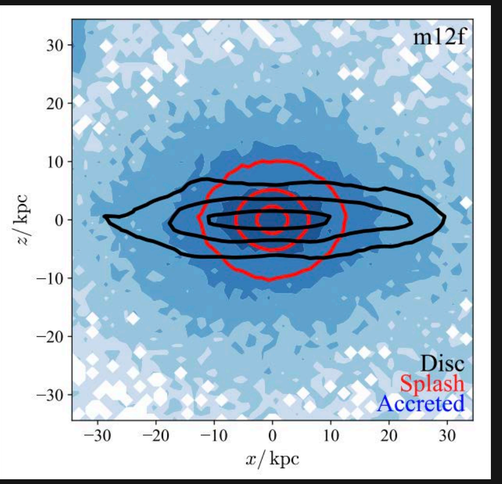


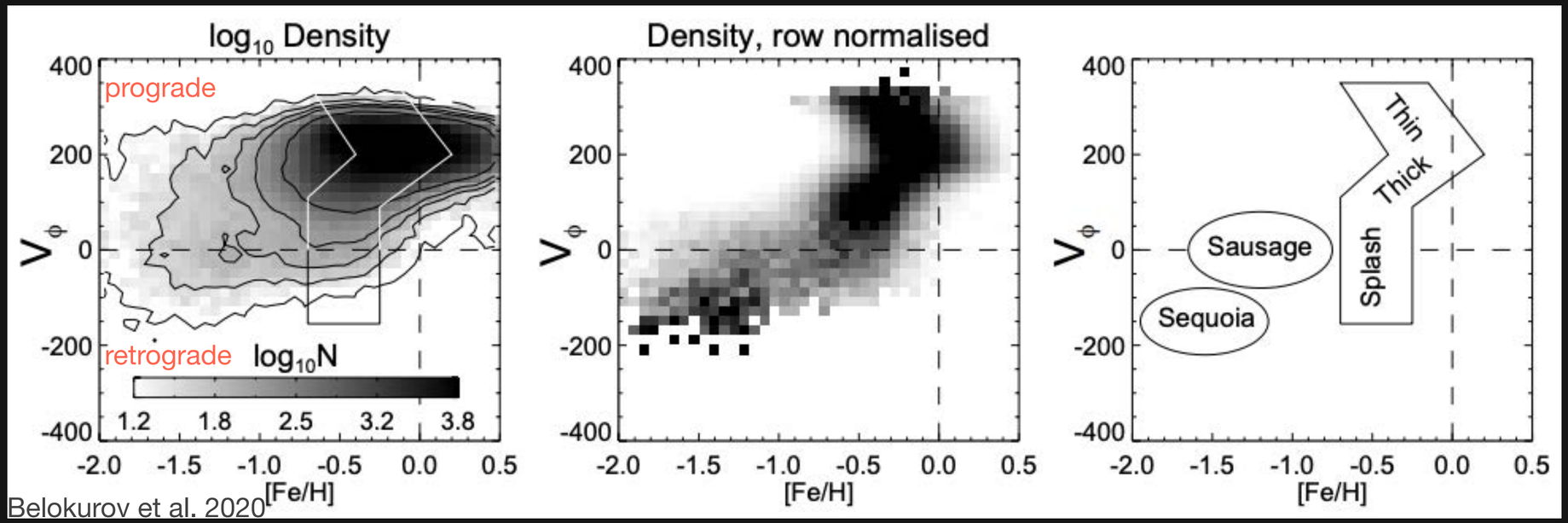
Galaxy's eccentric constituents



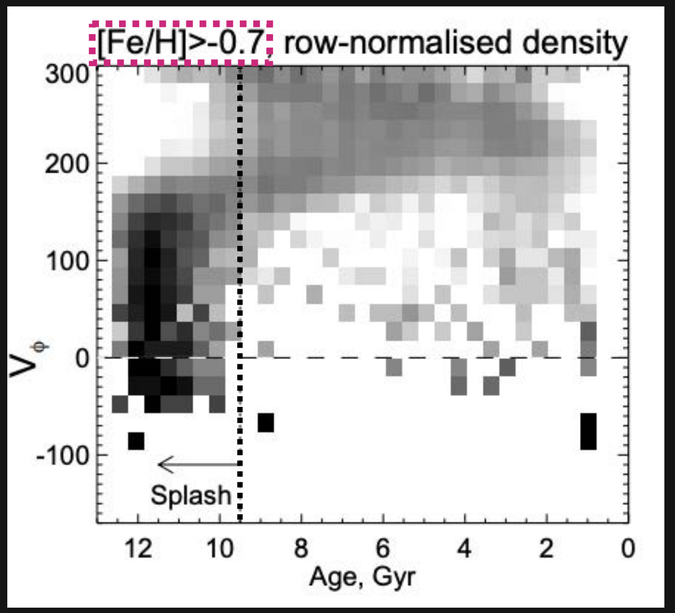
The biggest Splash

- **Splashed by the Galactic merger**
  - Milky Way's proto-disk **prior** to the massive ancient merger event (GS/E) which drastically altered their orbits
    - → Halo-like orbit (negligible net rotation; $V_\phi \sim 0$), but metal-rich ($[Fe/H] \approx -0.7$), thick disk-like chemistry
    - → lower orbital energy than accreted (e.g., GS/E) halo populations
    - → age **older** than the GS/E merger time, sharp transition in age-V_ϕ distribution!
    - → Splash adds more knowledge for constraining the details of the GS/E merger

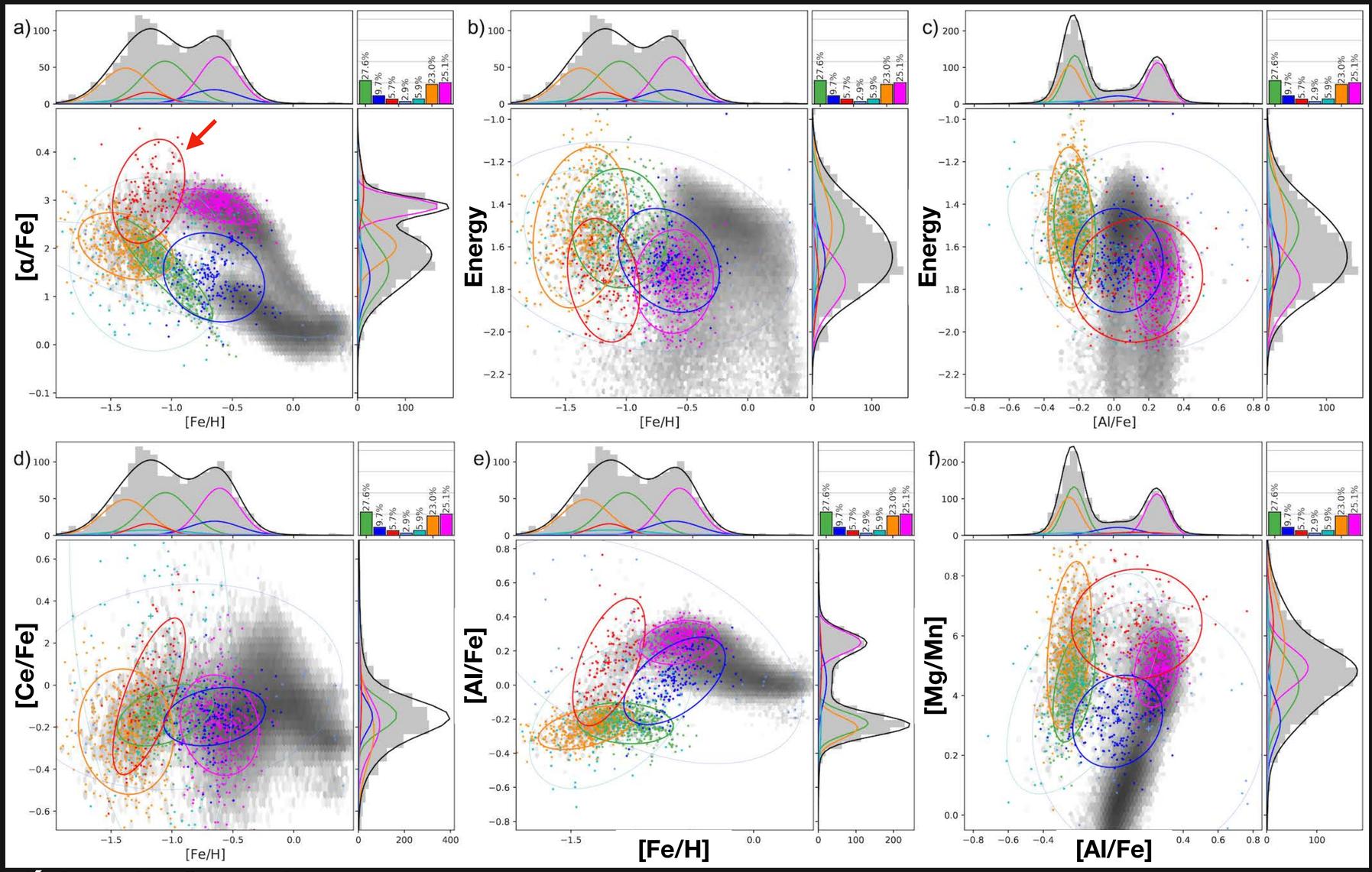




Belokurov et al. 2020

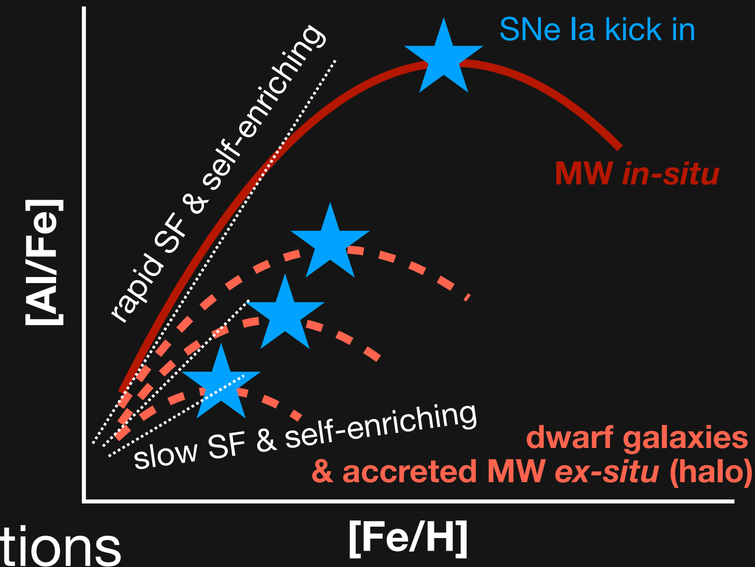


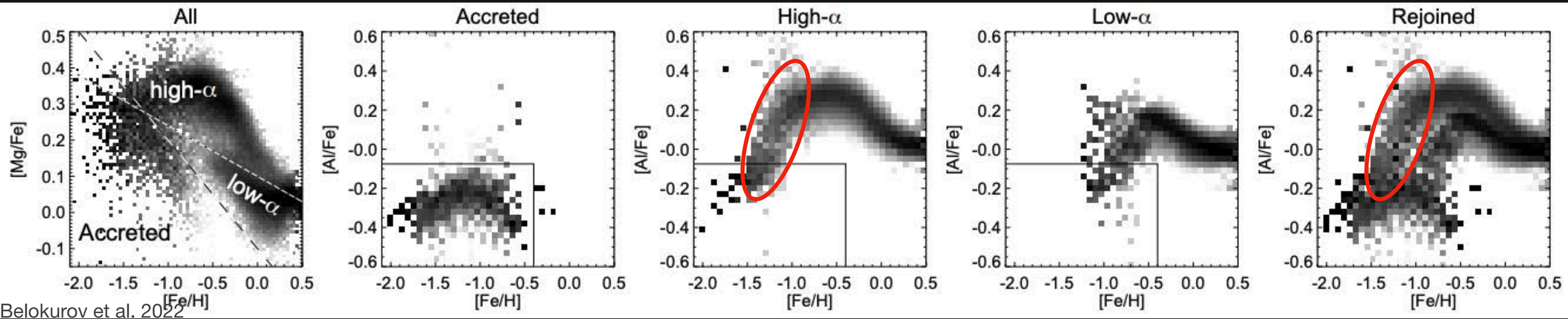
Galaxy's eccentric constituents



Aurora

- **An ancient *in-situ* population**
  - **Early evolution**: chaotic pre-disk evolution ~ spin-up phase
    - → rapid star formation & self-enriching period
    - → early evolution phase of progenitor of MW-size galaxy
    - → lower orbital energy than accreted (e.g., GS/E) halo populations
    - → near-isotropic velocity ellipsoid, modest net rotation

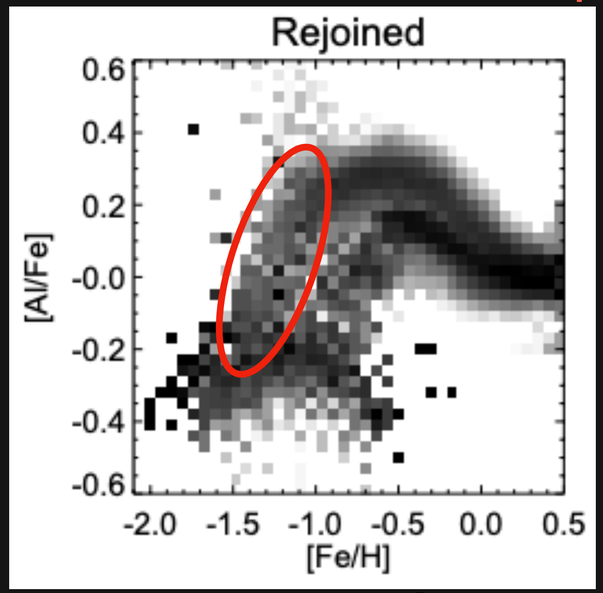


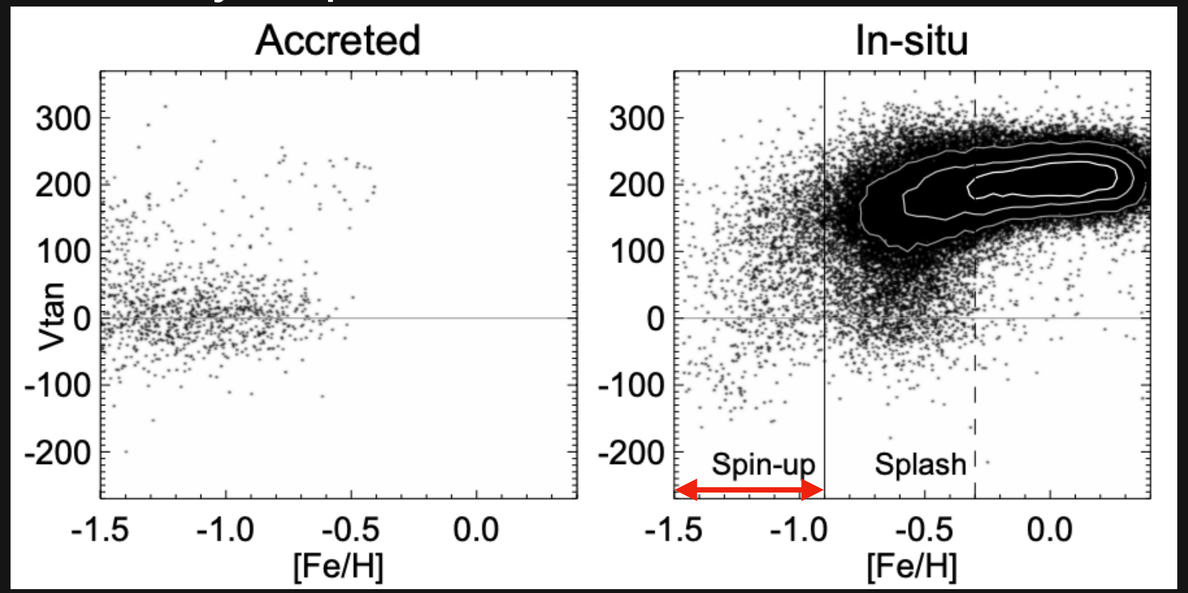


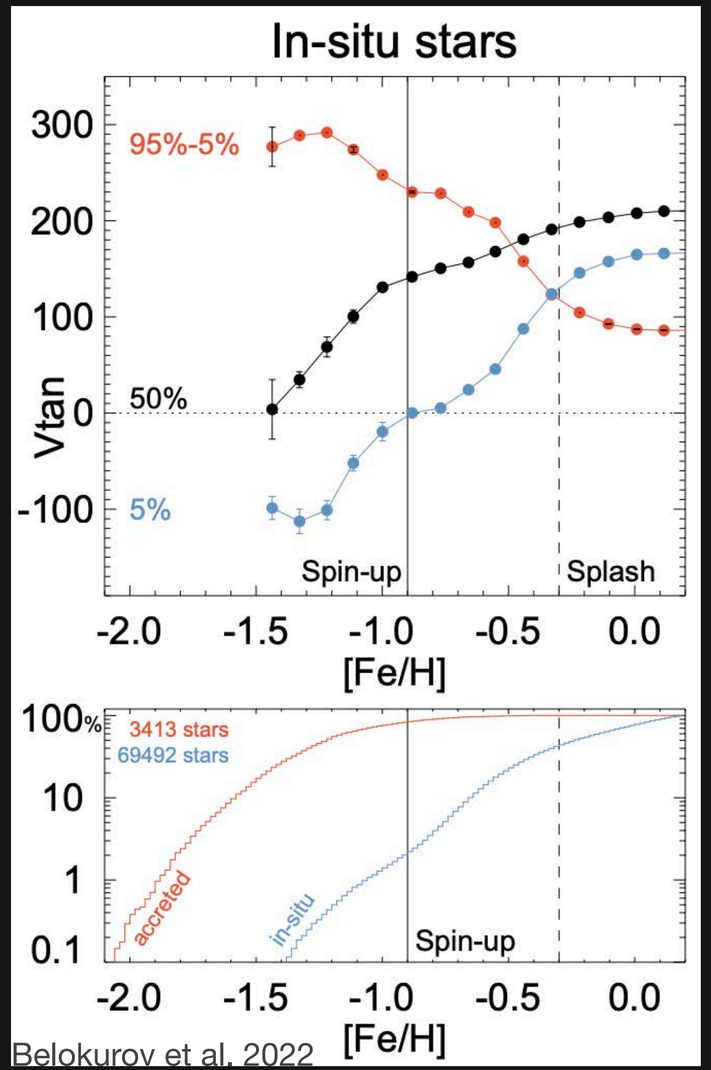
Belokurov et al. 2022

Aurora

- **An ancient *in-situ* population**
  - **Early evolution**: chaotic pre-disk evolution ~ spin-up phase
    - → rapid star formation & self-enriching period
    - → early evolution phase of progenitor of MW-size galaxy
    - → lower orbital energy than accreted (e.g., GS/E) populations
    - → near-isotropic velocity ellipsoid, modest net rotation







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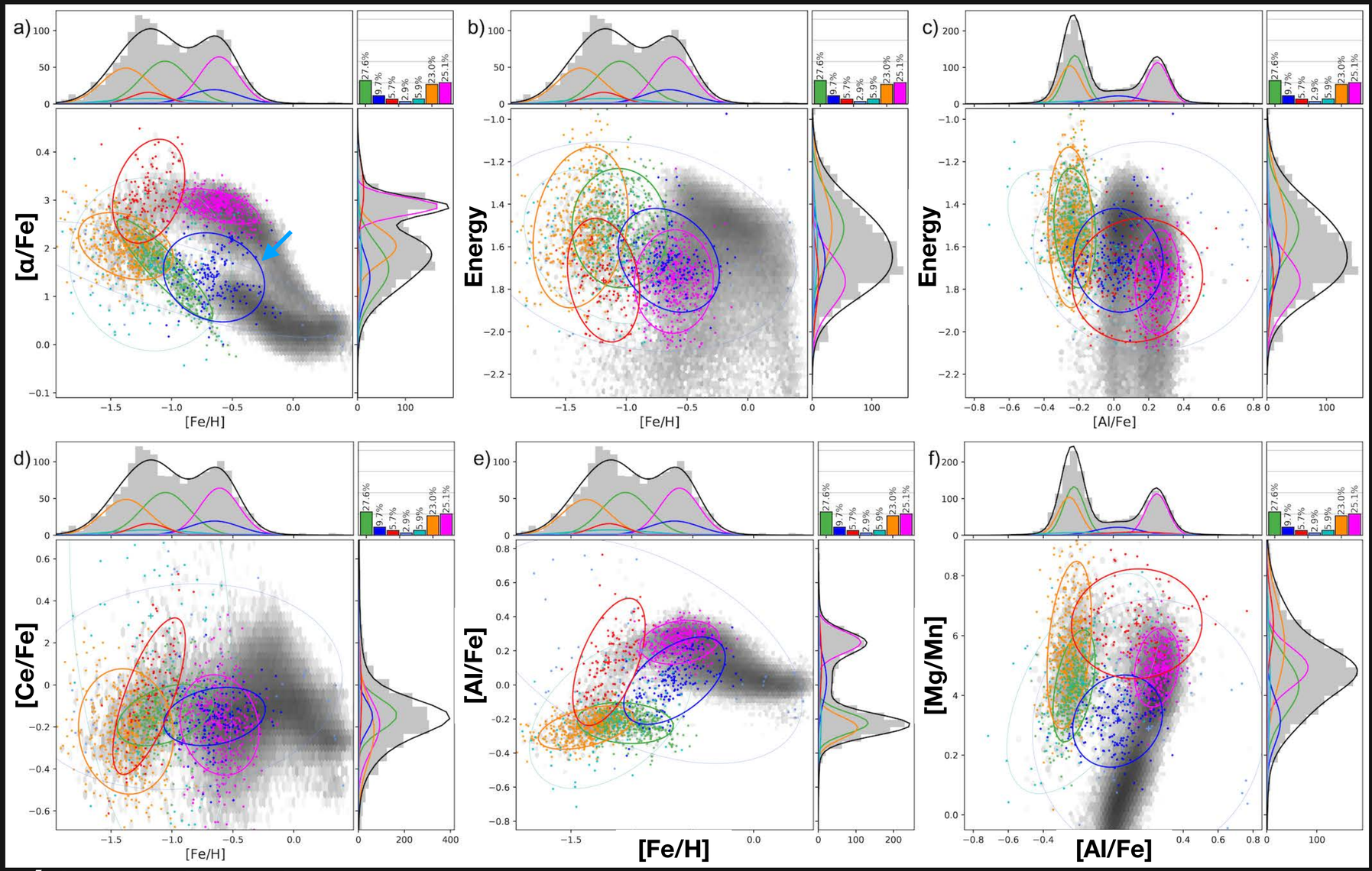
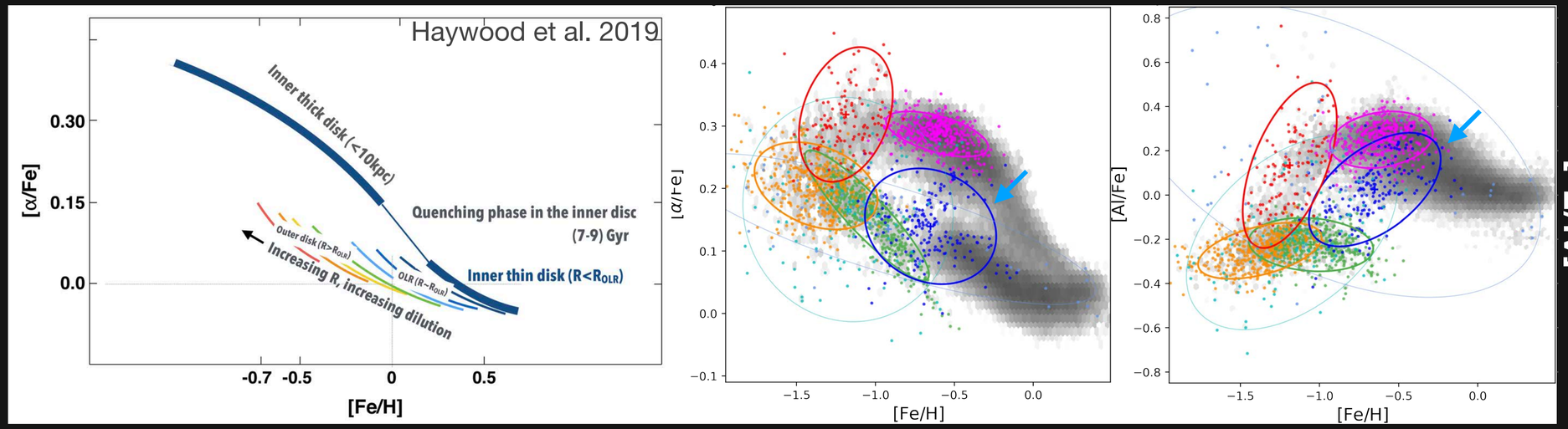
Galaxy's eccentric constituents

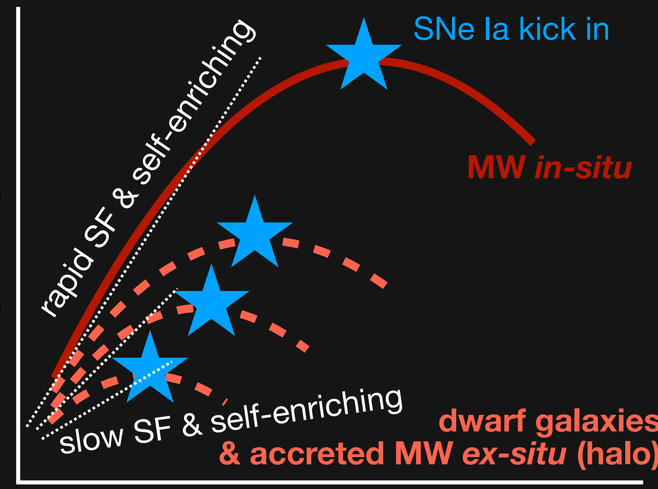


GS/E (mr, mp)
Splash
Aurora
Eos

Eos

- **Early stage of *in-situ*, metal-poor outer disk… and an hybrid**
  - Milky Way's outer "disk" originated from the gas polluted by the GS/E
    - → fast star formation triggered by the merger's tidal compression
    - → gas after the thick disk formation + gas from the GS/E
    - → lower orbital energy than accreted (GS/E) population, higher than Splash or Aurora
    - → not a disky orbit (misaligned, eccentric), but evolves to the outer thin disk population





Eos

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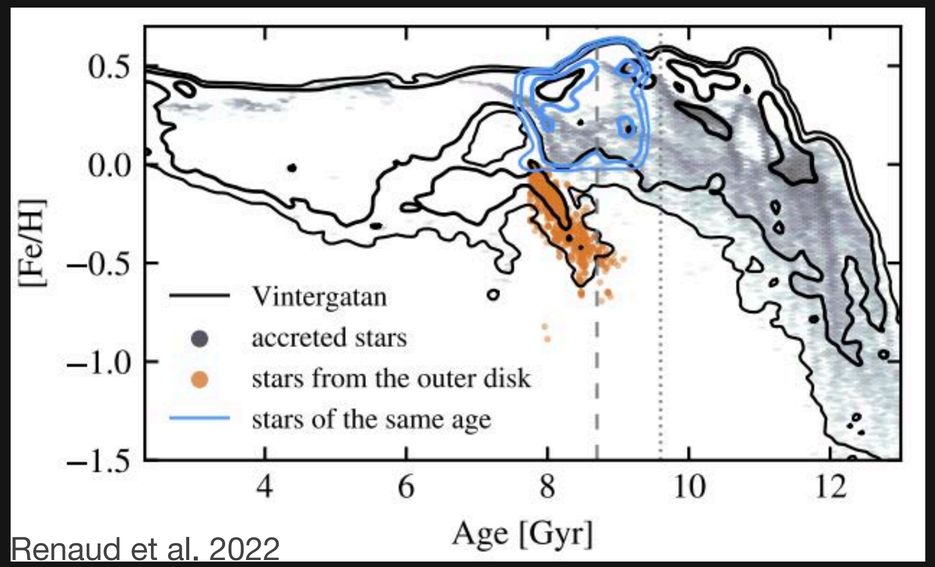
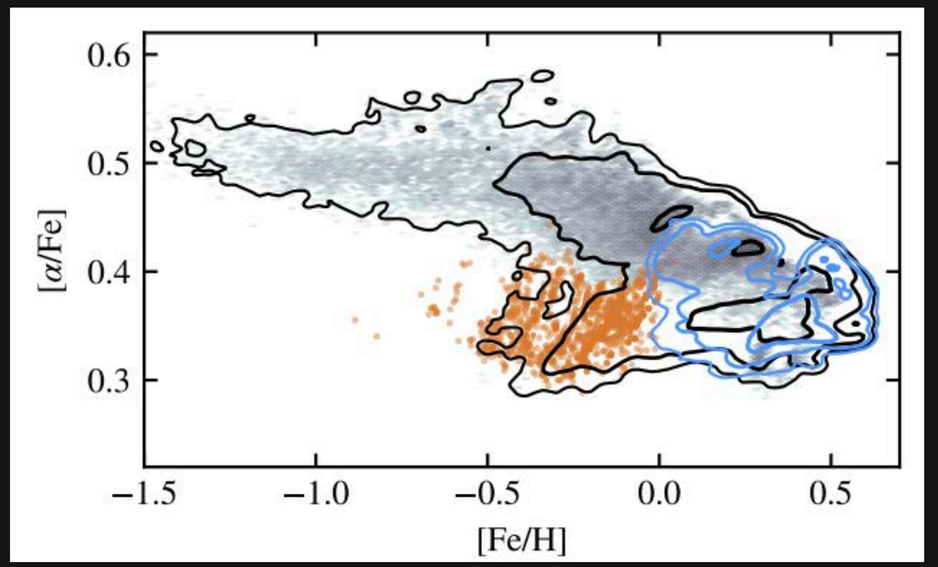
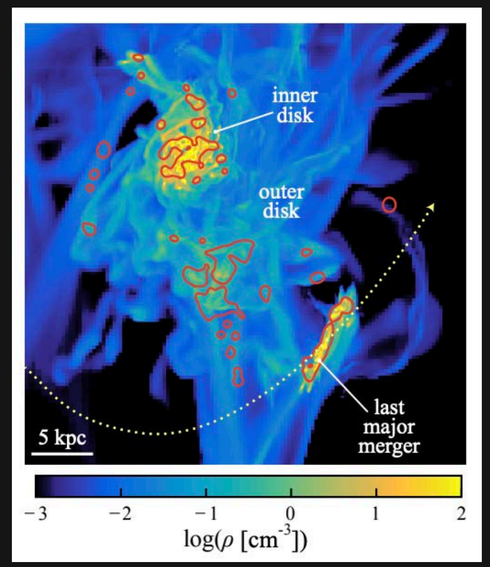


Renaud et al. 2022





Eos

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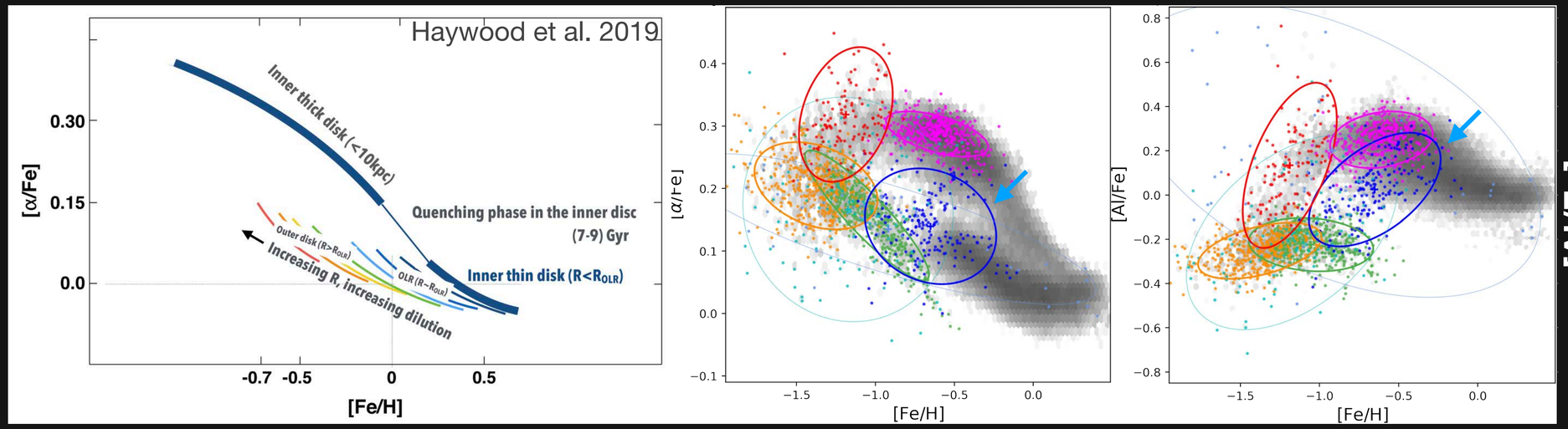
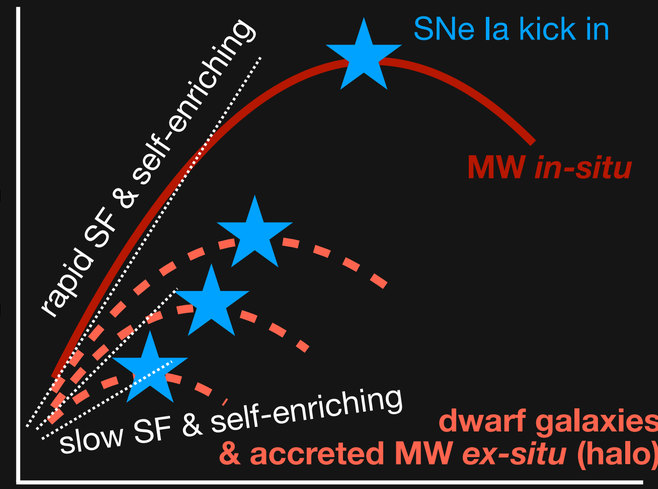


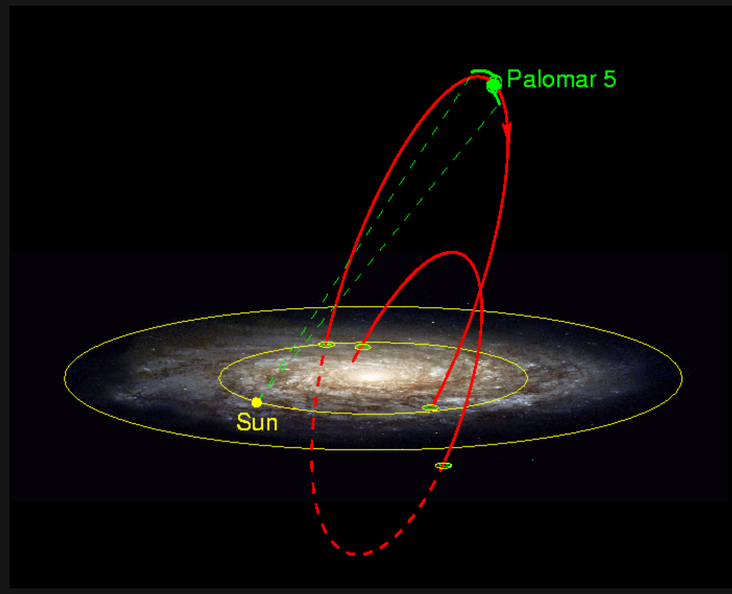


A Recap

- **Milky Way experienced a major galactic merger!**
  - This merger called **GS/E** happened $\sim 10\,\mathrm{Gyr}$ ago, with progenitor mass $\sim 10^{10}\,\mathrm{M}_{\odot}$
  - GS/E is now disrupted and merged to the Milky Way
  - GS/E remnants are now seen as the **Milky Way's metal-rich halo!**
  - There are GS/E originated (*ex situ*) globular clusters now residing **in the Milky Way!**
  * There are other *ex situ* populations now living in the Milky Way too!
- **Many of Milky Way components created/modified by the GS/E merger**
  - GS/E merger dynamically splashed Milky Way's proto-disk → **Splash**
  - Galaxy's low metallicity, outer disk originated from the gas polluted by GS/E → **Eos**
  - There is also a pre-disk *in-situ* population during the rapid SF period → **Aurora**

Hands-on

- **(mock) Stellar stream generation**
  - `mock_stream_generation_demo_hands-on.ipynb` on Moodle
  - Gala: Python package for various galactic dynamics analysis
  - Based on the current day observables of a globular cluster, Palomar 5 (Pal 5)
    - Code first integrates the orbit of Pal 5 back in time (for a given period) from the given current position
    - Creates a model for Pal 5
    - Integrates the orbit forward to the current position of Pal 5, while spraying particles (stars)
  - Try different Galaxy potential models & see how the stream changes!




Thank you!
about 9~10 Gyrs ago…
Sausage Galaxy
Milky Way
First Approach
Smash!
Turn-around