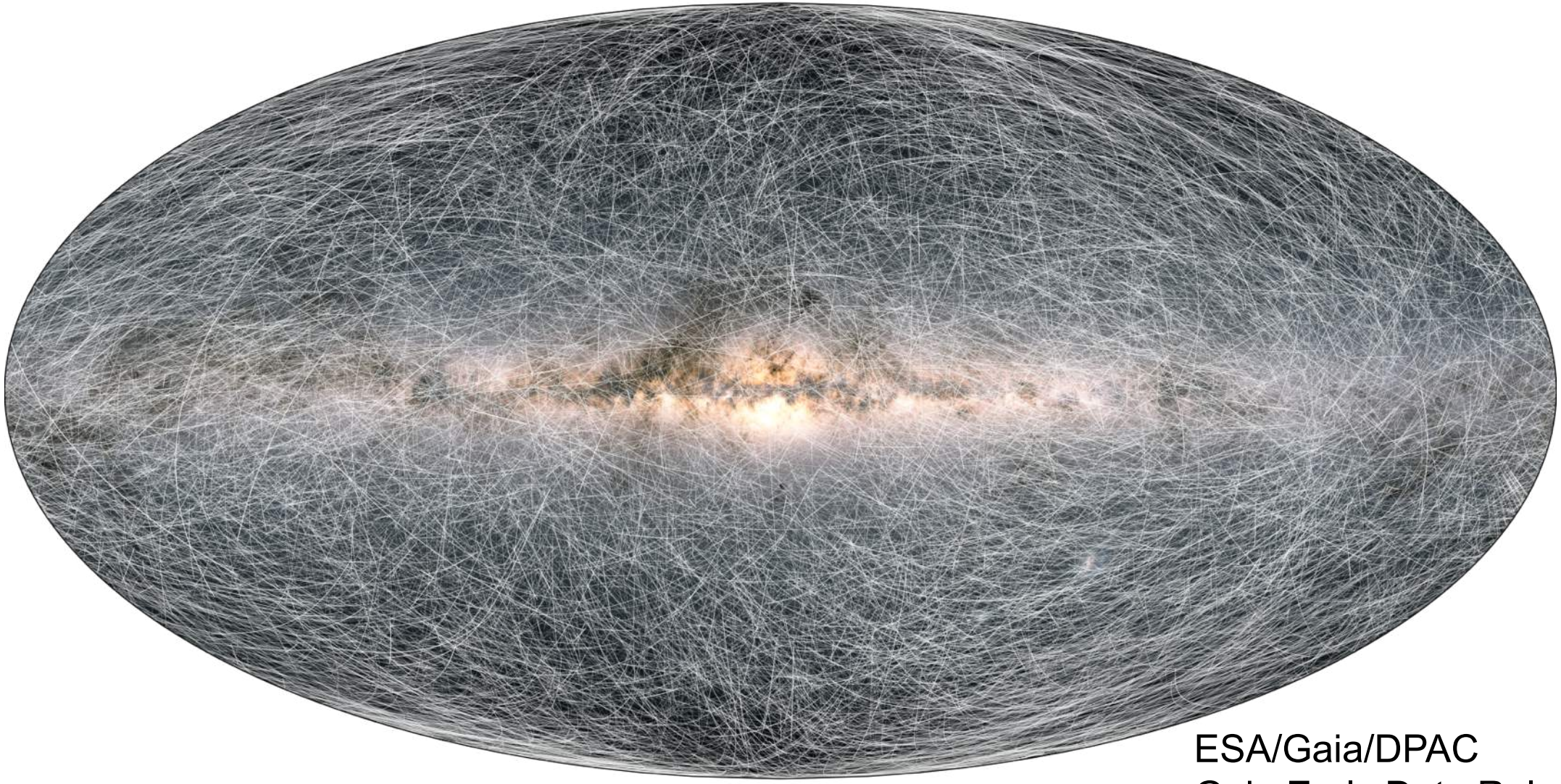
Mullard Space Science Laboratory

Gaia/JASMINE 時代の銀河系考古学のための数値シミュレーション

Daisuke Kawata
(Mullard Space Science Laboratory (MSSL), University College London (UCL))
Junichi Baba (NAOJ), Rob Grand (MPA fellow), Jason Hunt (Flatiron/CCA)
Jo (Ioana) Ciucă (MSSL, UCL→Astro3D fellow @ ANU)

Gaia Revolution!

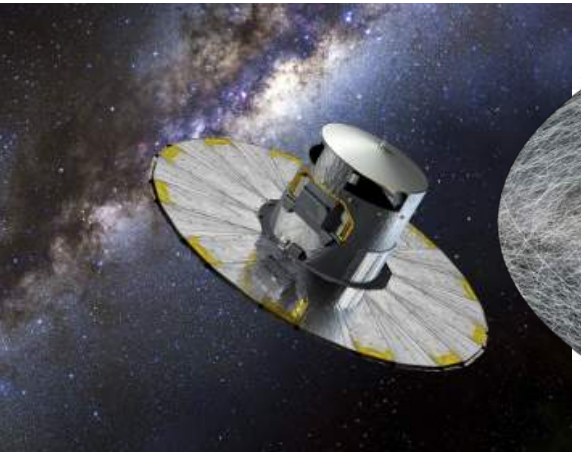
Gaia: precise position/distance and motion of about 1 billion stars in the Milky Way!

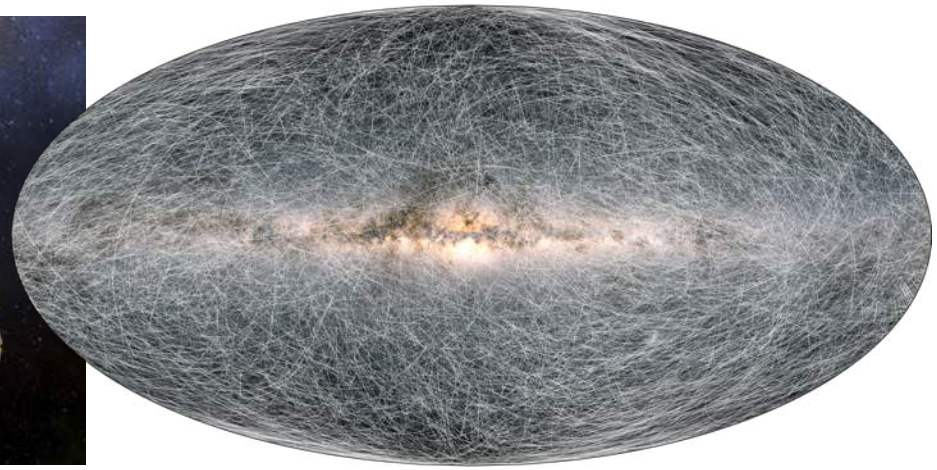


ESA/Gaia/DPAC
Gaia Early Data Release 3

Galactic archaeology

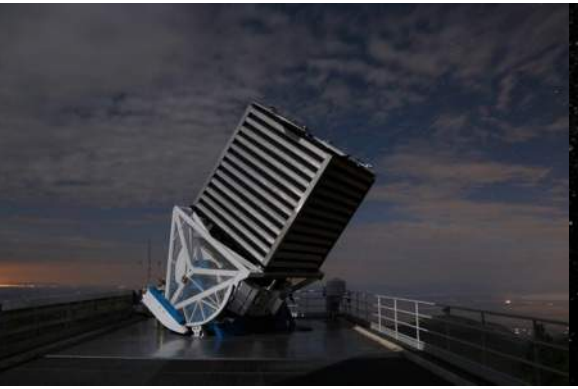
Motion and stellar populations (mass, temperature, metallicities and age) of stars in the Milky Way

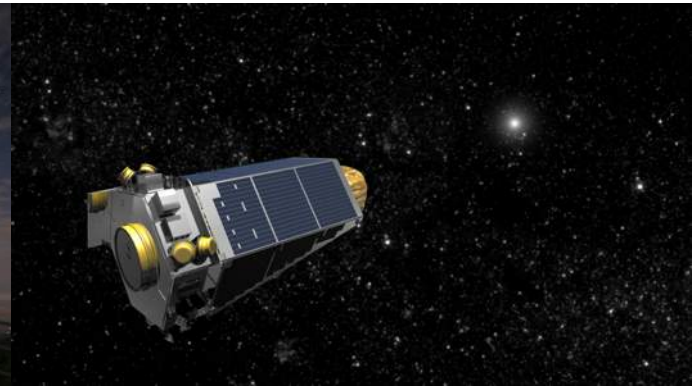




Theoretical models
Numerical simulations

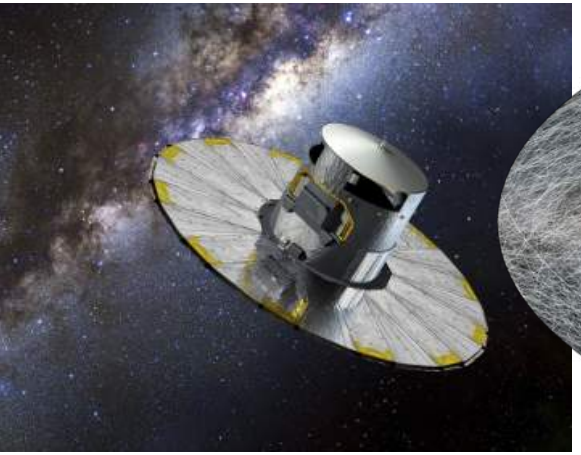
+ Ground-based photometric spectroscopic surveys
+ Asteroseismology from Kepler, K2, TESS, PLATO

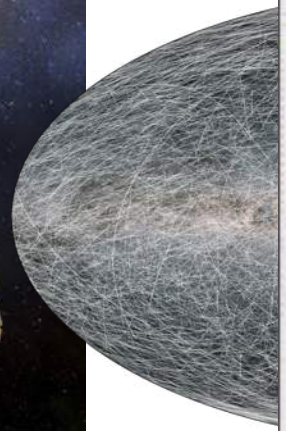




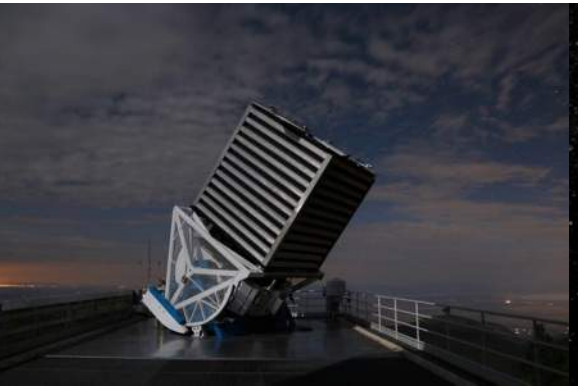
Where are we from? How did our Milky Way form?

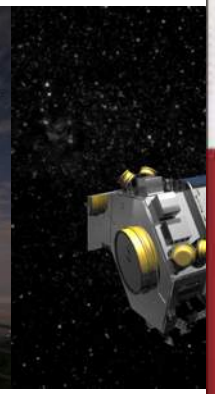
Motion and stellar populations (
metallicities and age) of stars

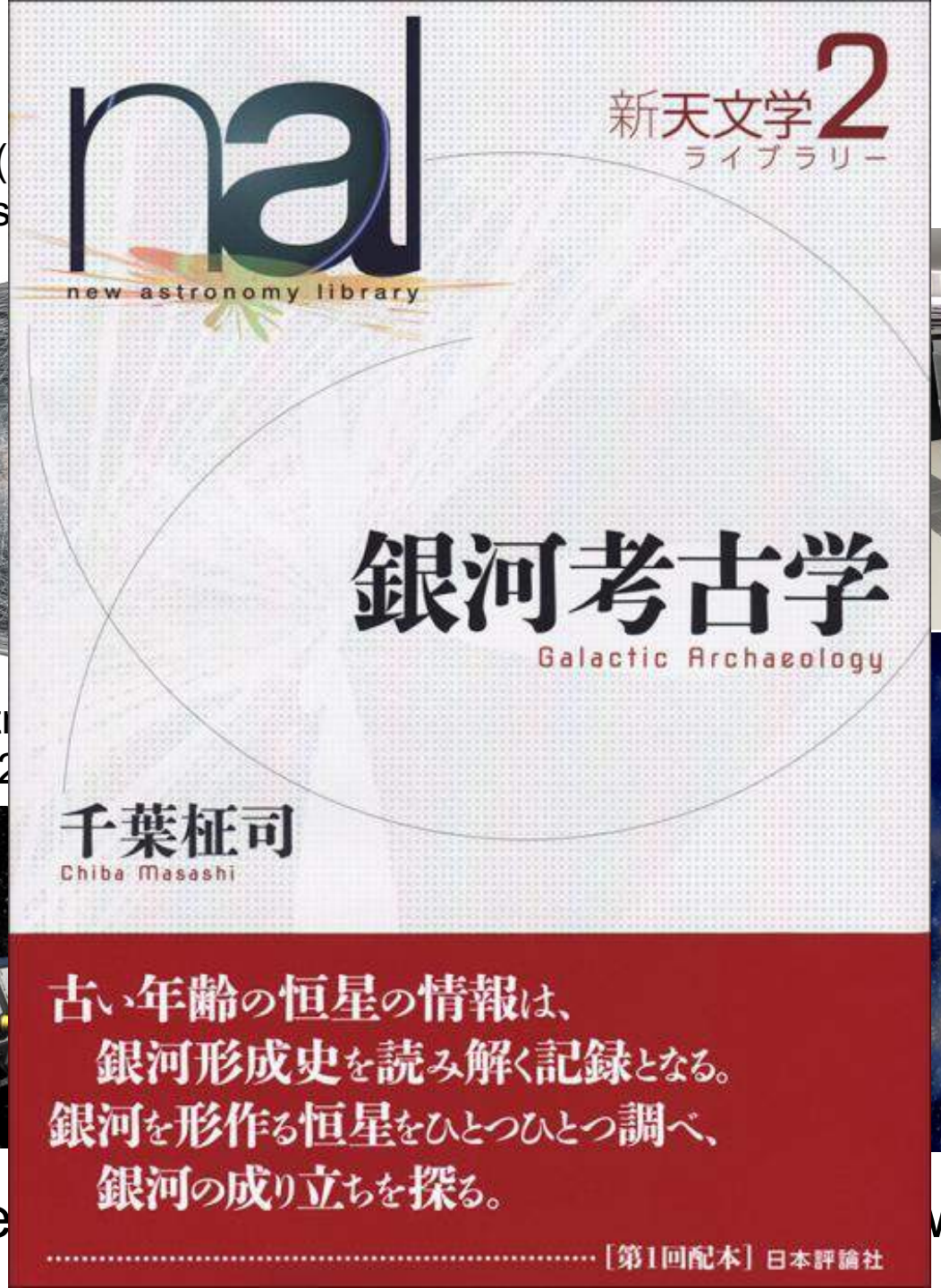




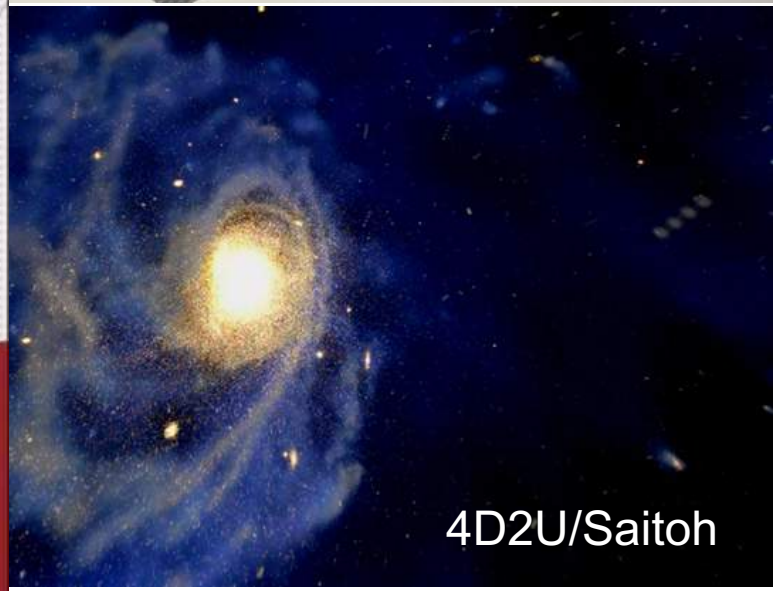
+ Ground-based photometric spectr
+ Asteroseismology from Kepler, K2







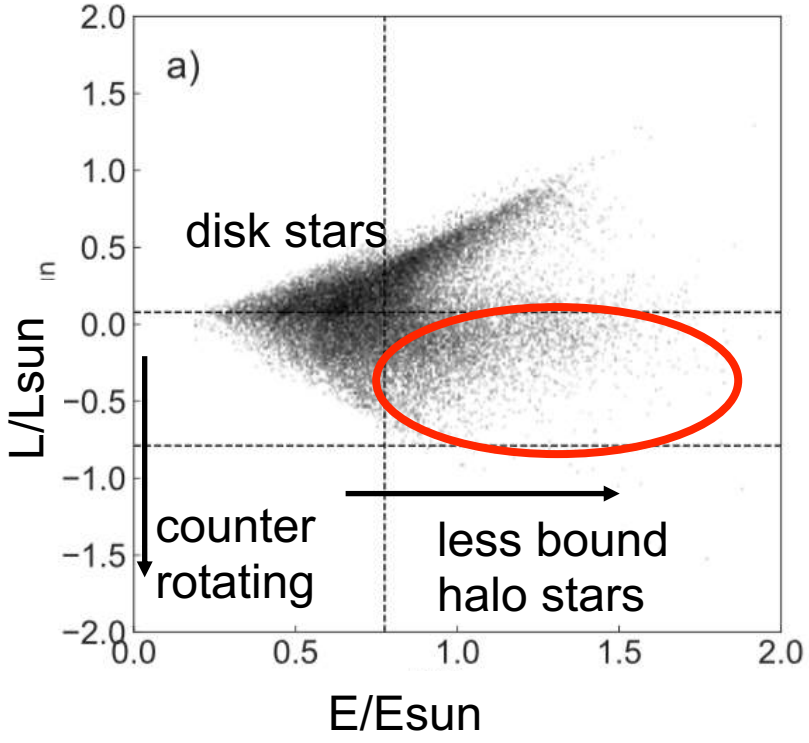
Theoretical models
Numerical simulations



Whe

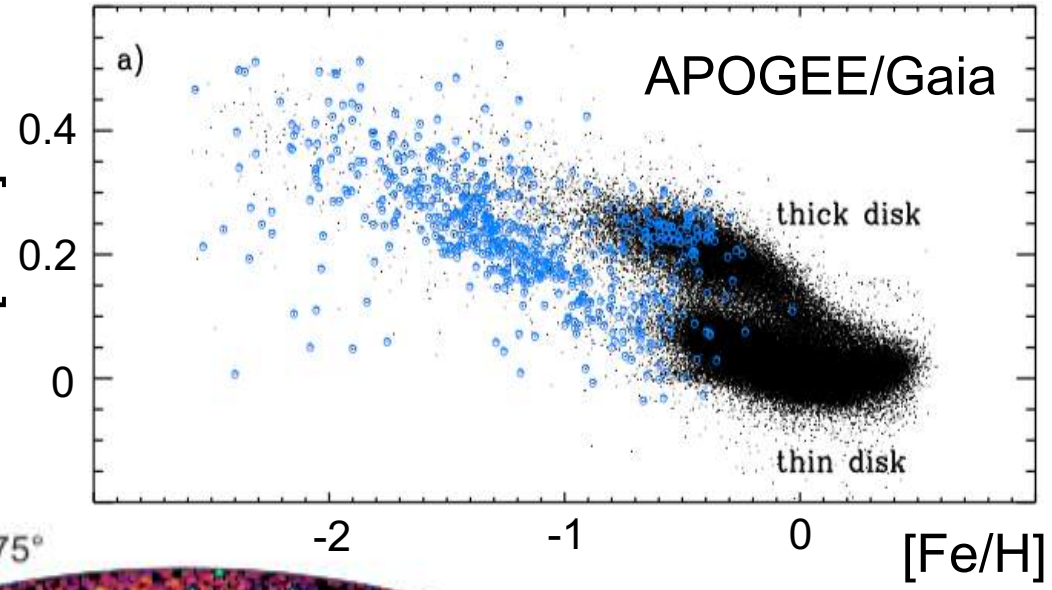
Way form?

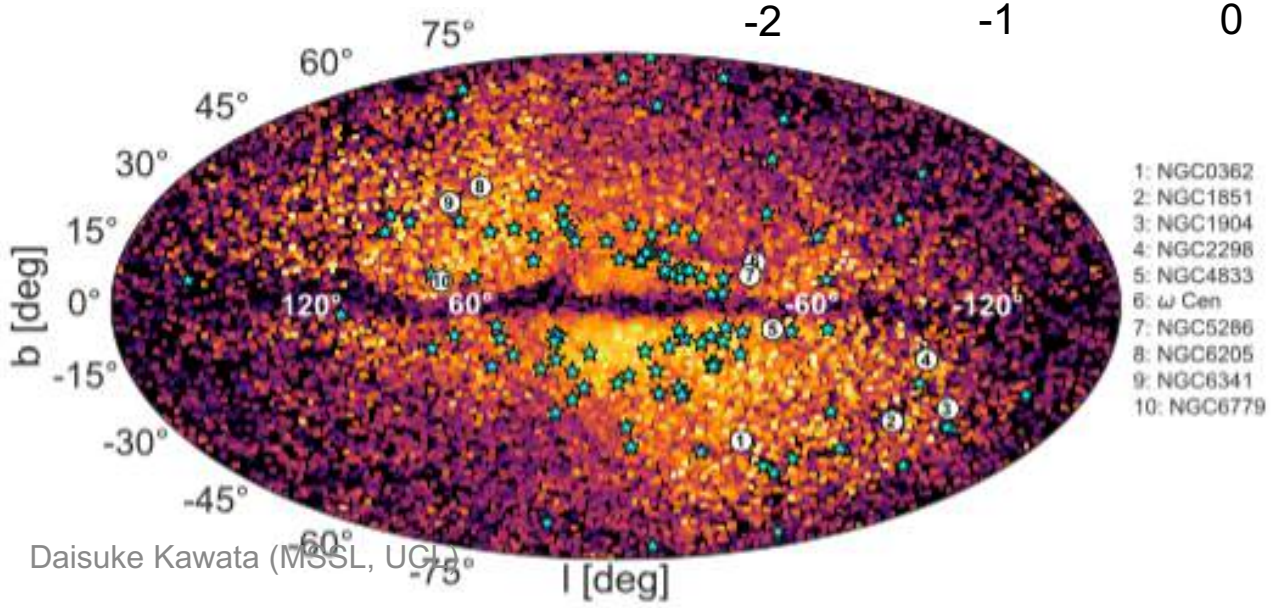
Counter-rotating (?) low [α/Fe] halo stars from a SMC-size galaxy last major merger at ~10 Gyr ago? Gaia Enceladus! (Helmi et al. 2018)



Mainly from SNe Ia (~Gyr)

O, Mg… SNeII (~Myr)



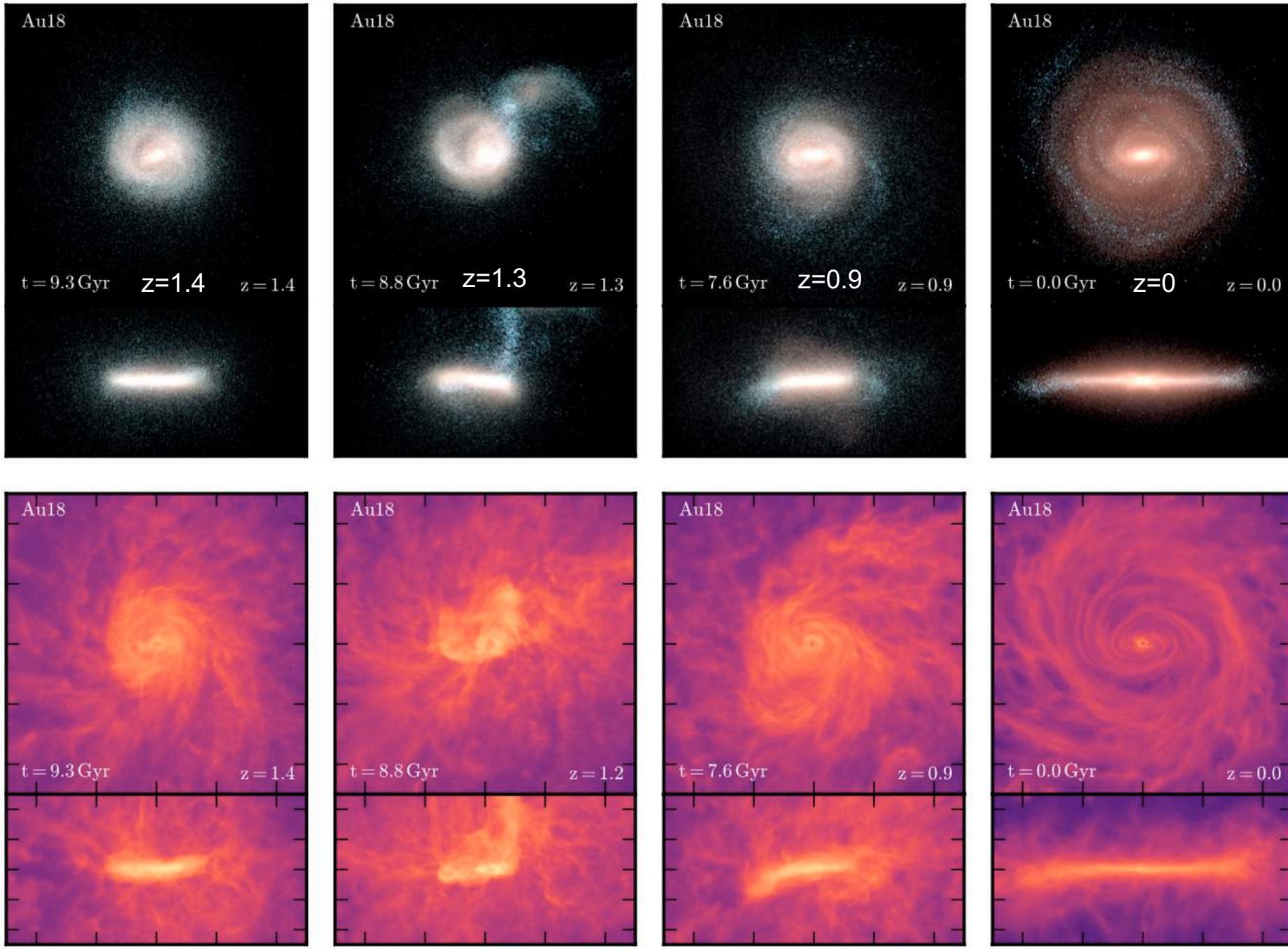


Helmi et al. (2018, Nature)
See also
Belokurov et al. (2018) for a DR1 feature known as Gaia Sausage,
Brook, Kawata et al. (2003) with Hipparcos data.

Credit: ESA, NASA, Koppelman, Villalobos and Helmi,

Sausage & Mash!
Grand, Kawata et al. (2020)

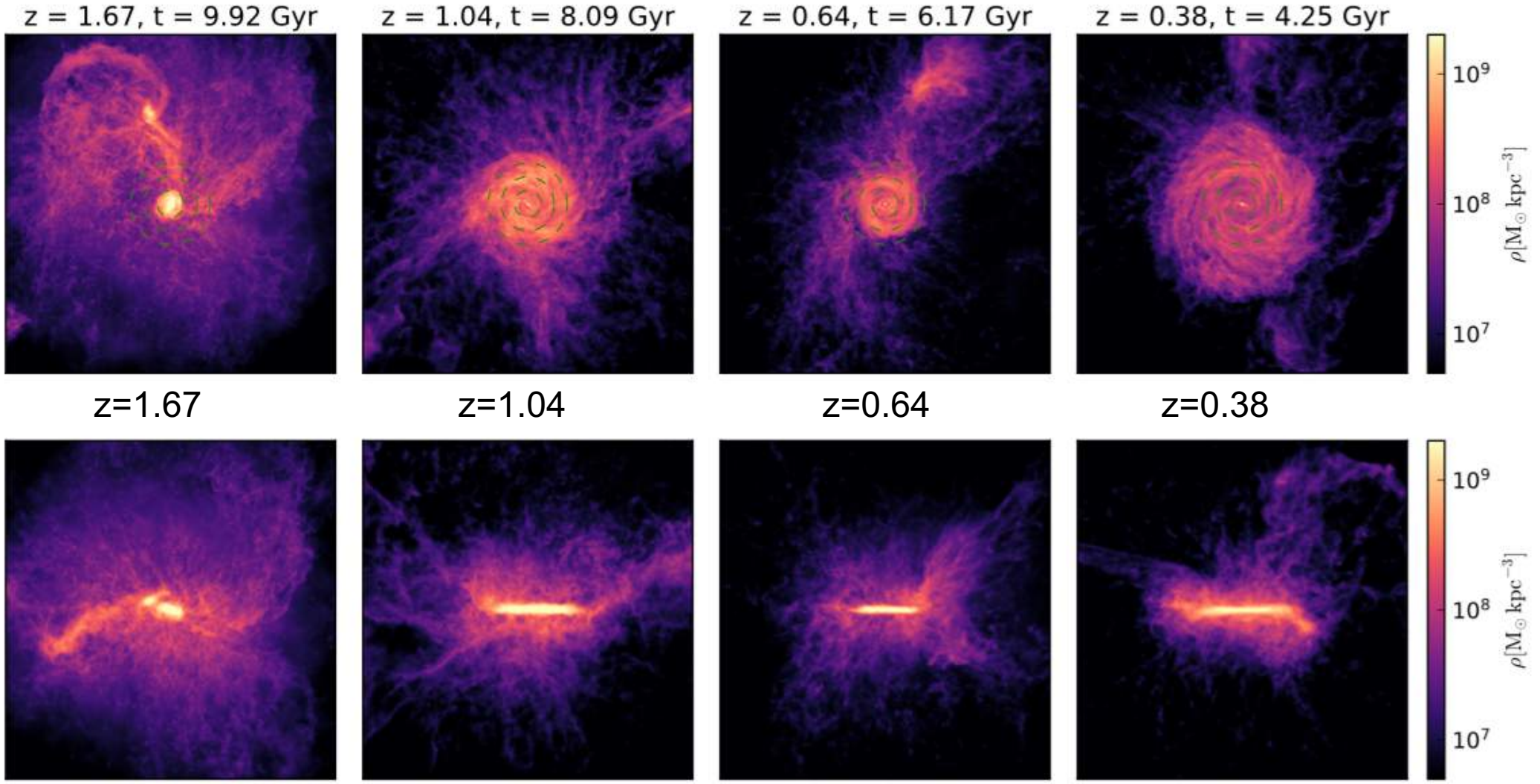
Gaia Enceladus (aka Sausage) was likely to be a gas-rich merger and make mash, i.e. halo and thick disk!



Auriga cosmological simulation (Grand et al. 2017, ~30 Milky Way-sized galaxy simulations with AREPO)

Early gas-rich mergers, turbulent small thick disk ⇒ Later inside-out thin disk formation (Brook, Kawata et al. 2004, Grand, …, Kawata et al. 2018)

Grand et al. (2018) Auriga simulation

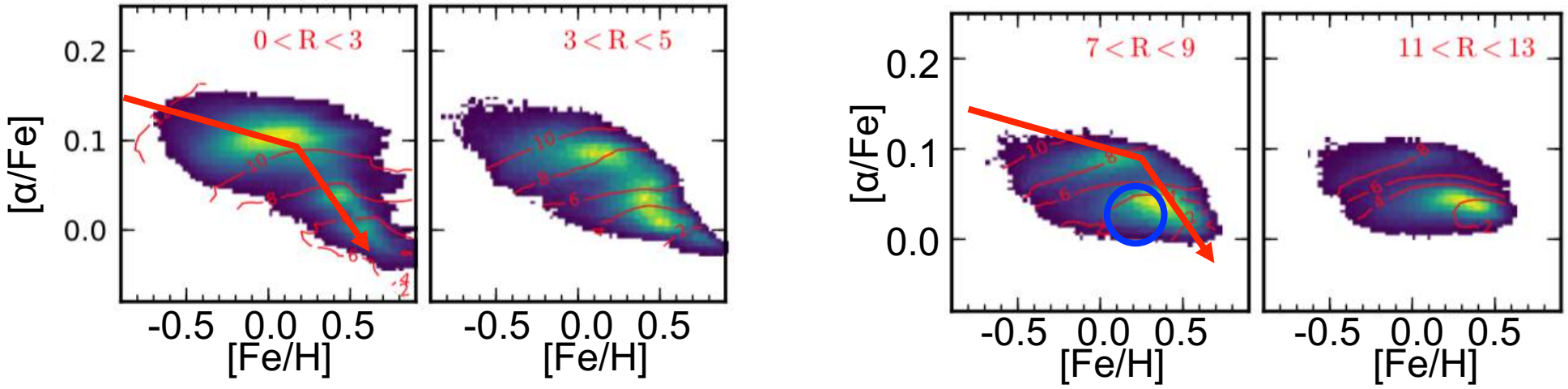


Early violent star formation with mergers.

Later inside-out growth of the thin disk at the later epoch.

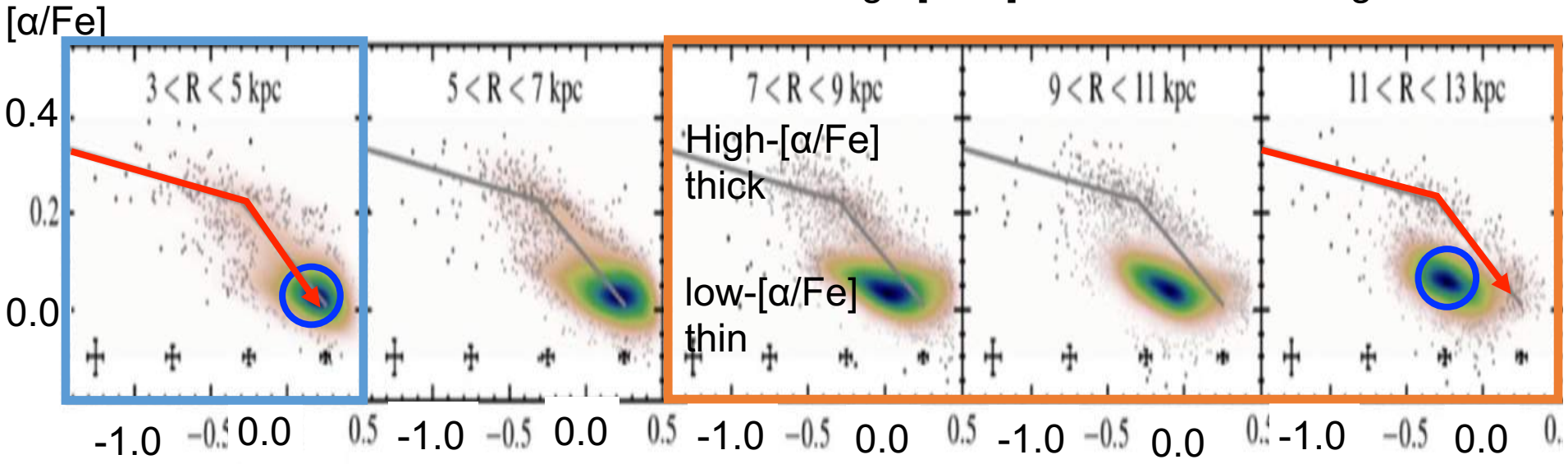
Two pathways of thick/thin disk formation (Grand et al. 2018, see also Noguchi 2018)

Auriga simulation: Grand et al. (2018)



Inner disk
compact thick disk → metal rich thin disk

outer disk
later metal poor disk from the accreted gas
+ high [α/Fe] thick disk radial migration from inner disk

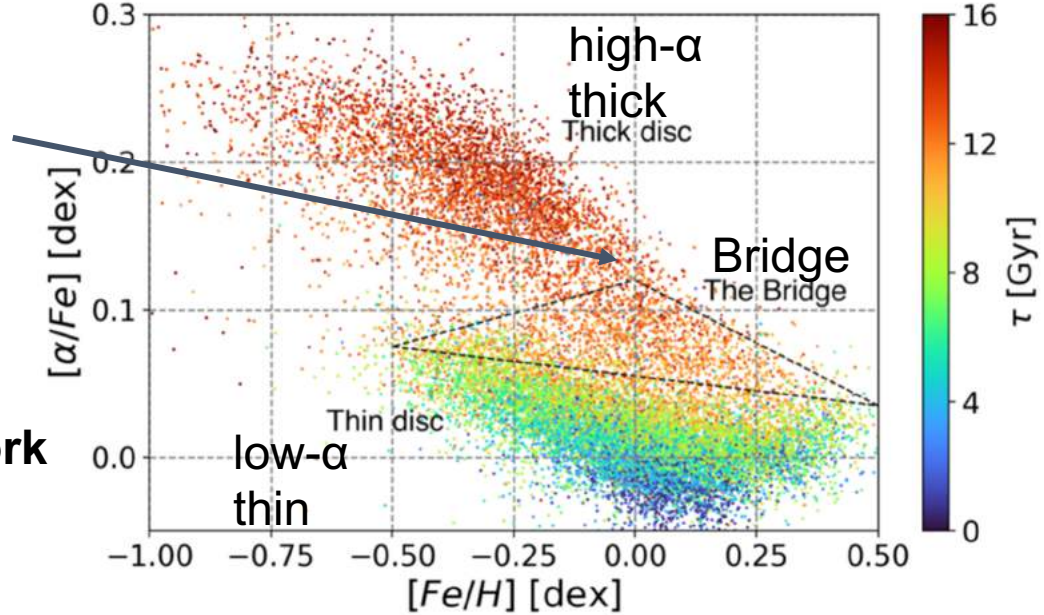


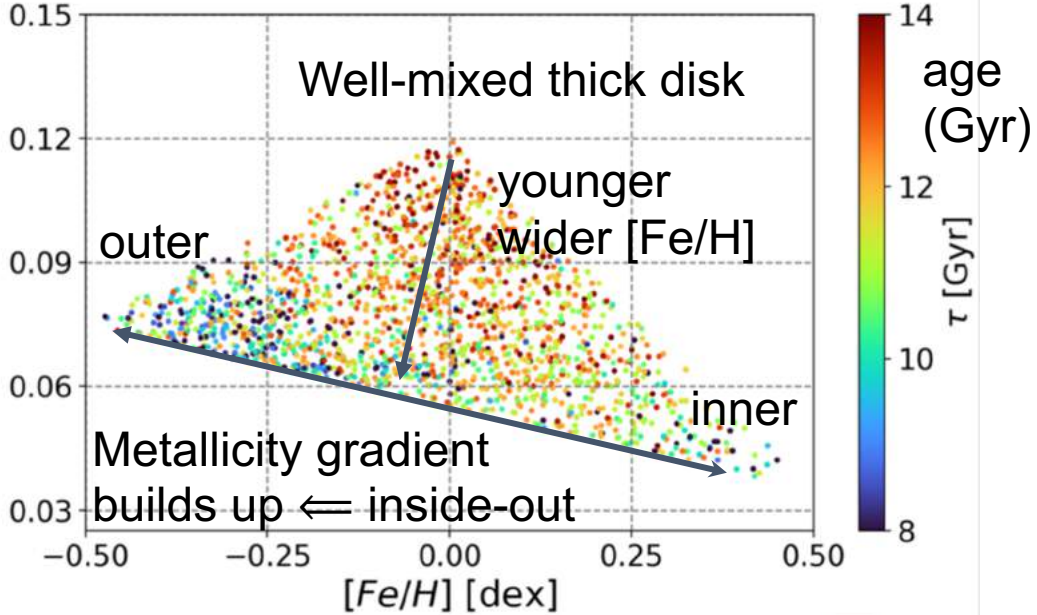
Observation: Hayden et al. (2015)

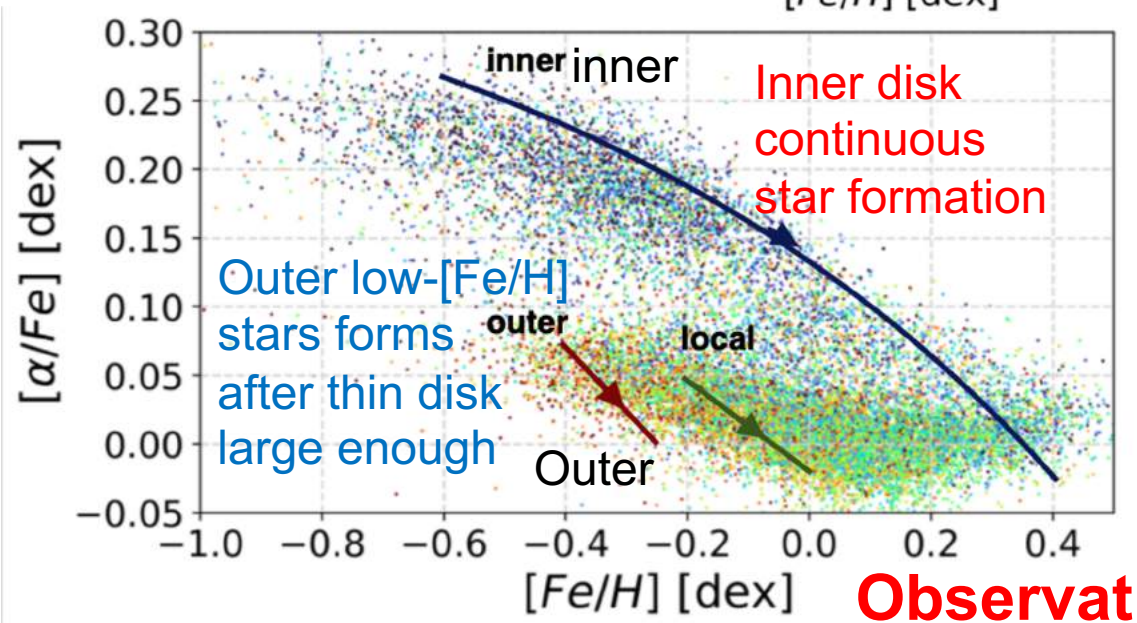
GES merger end of thick disc phase followed by inside-out thin disc formation?
Observational data: Gaia+APOGEE: Ciucă, Kawata et al. (2021)
consistent with simulations in Brook et al. (2004, 2012), Grand et al. (2018, 2020)!

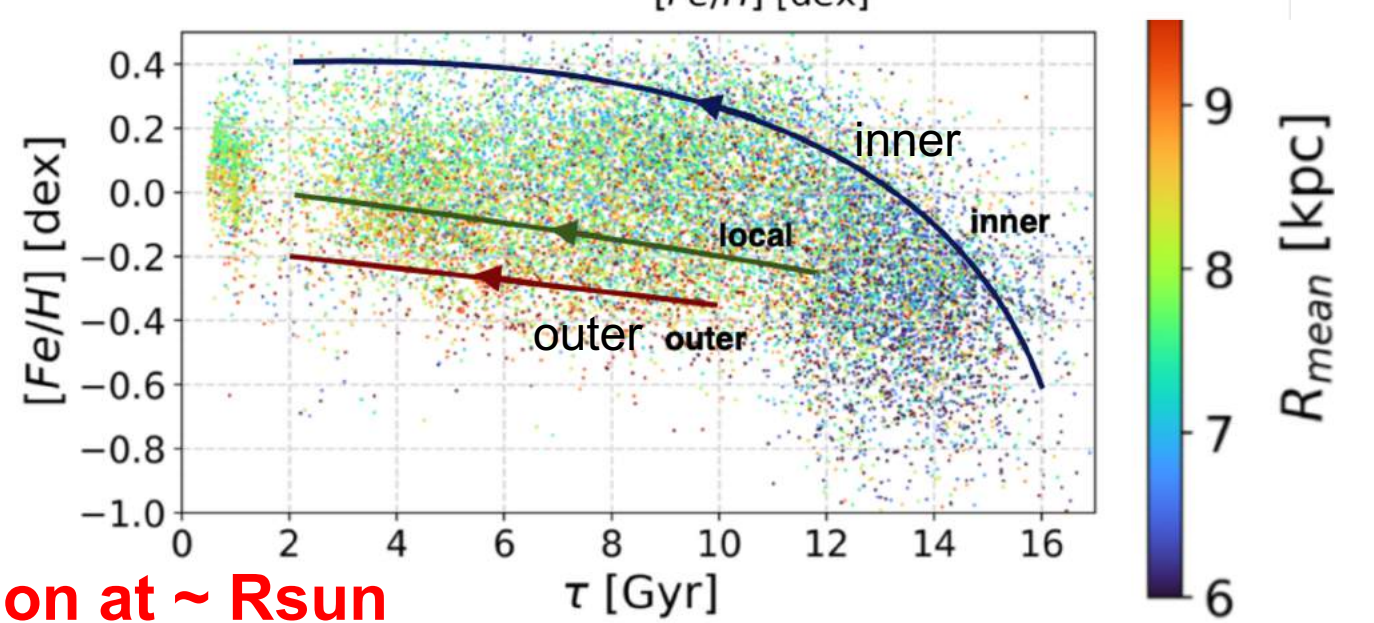
end of GES merger?

Gaia+ SDSS/APOGEE spec survey data with **neural network trained age**. Ciucă et al. (2021)





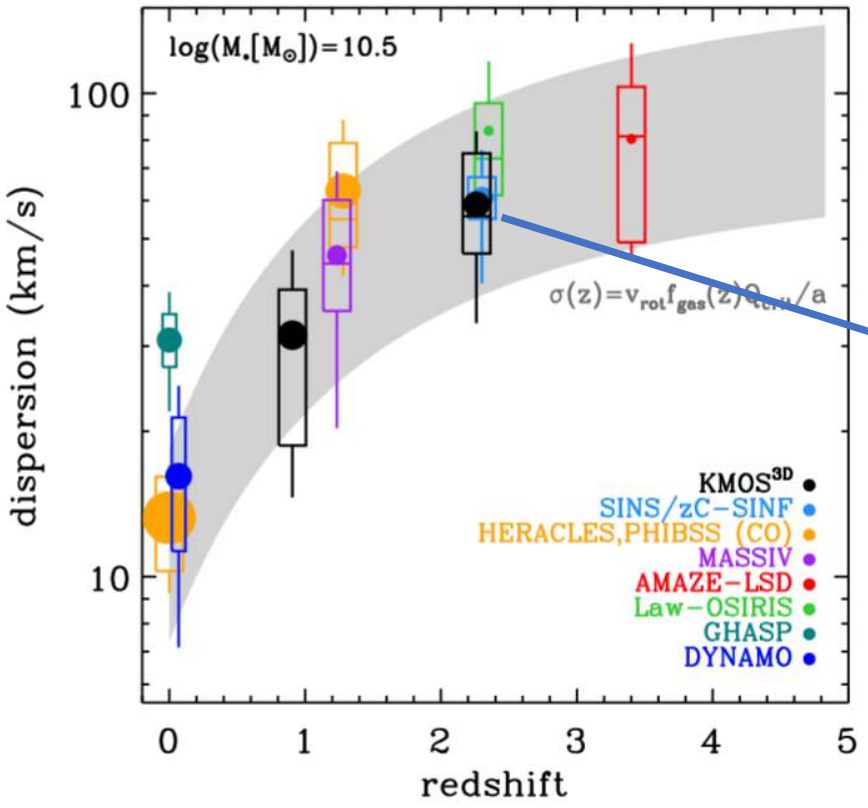




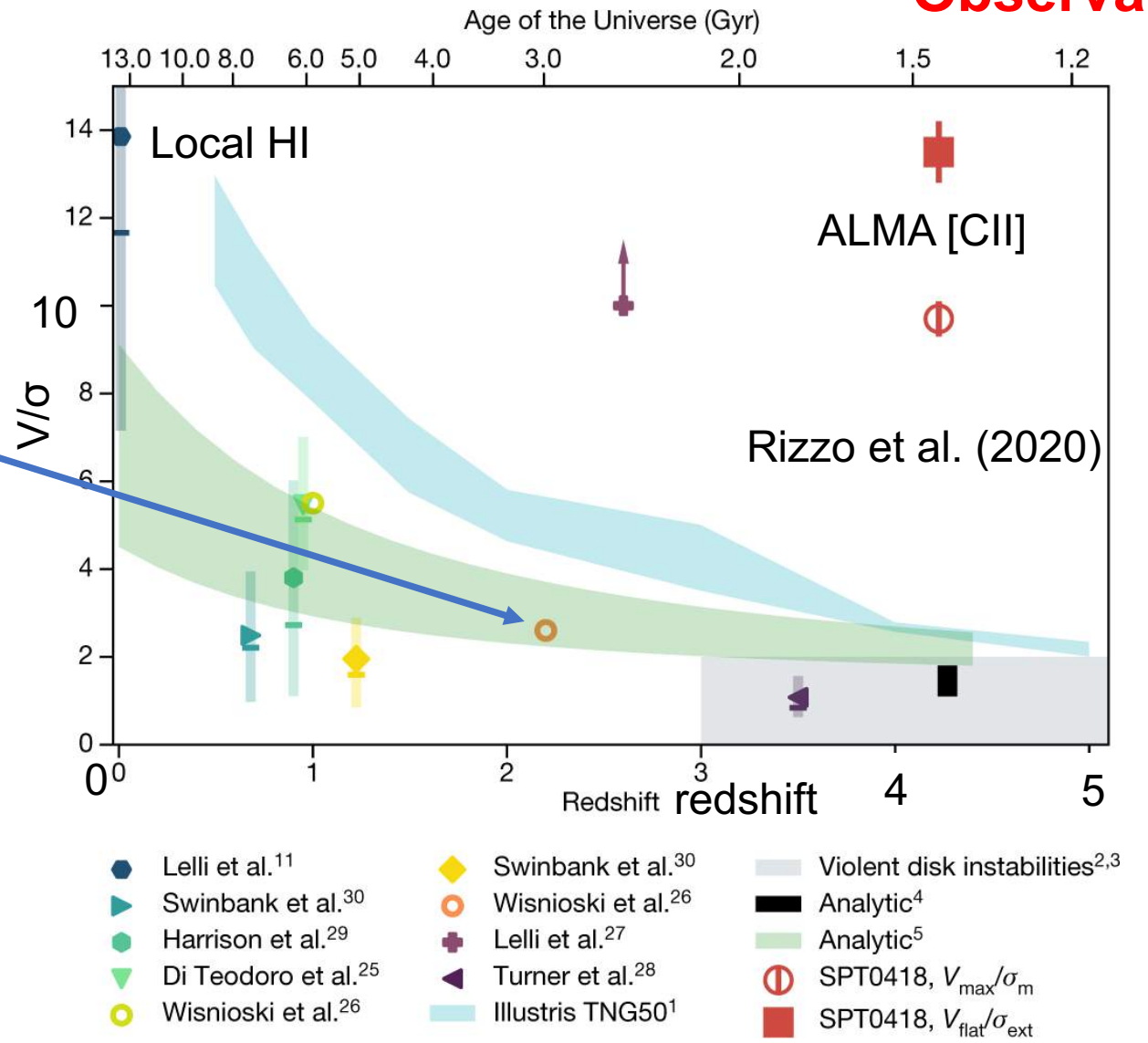
Observation at ~ Rsun

Thick disk formation in action? high-z (z>1) disk are kinematically hot?

Observation



KMOS3D (Hα)
Wisnioski et al. (2015)

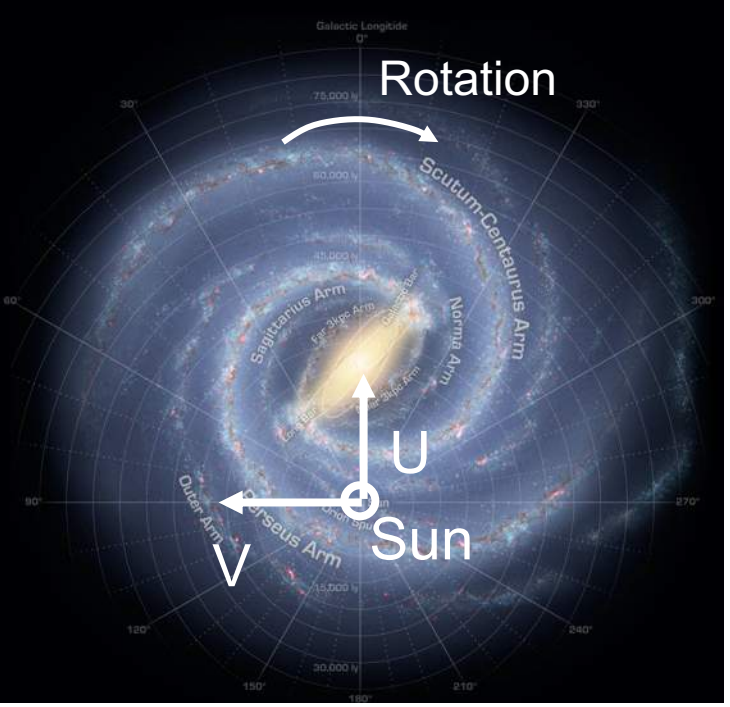


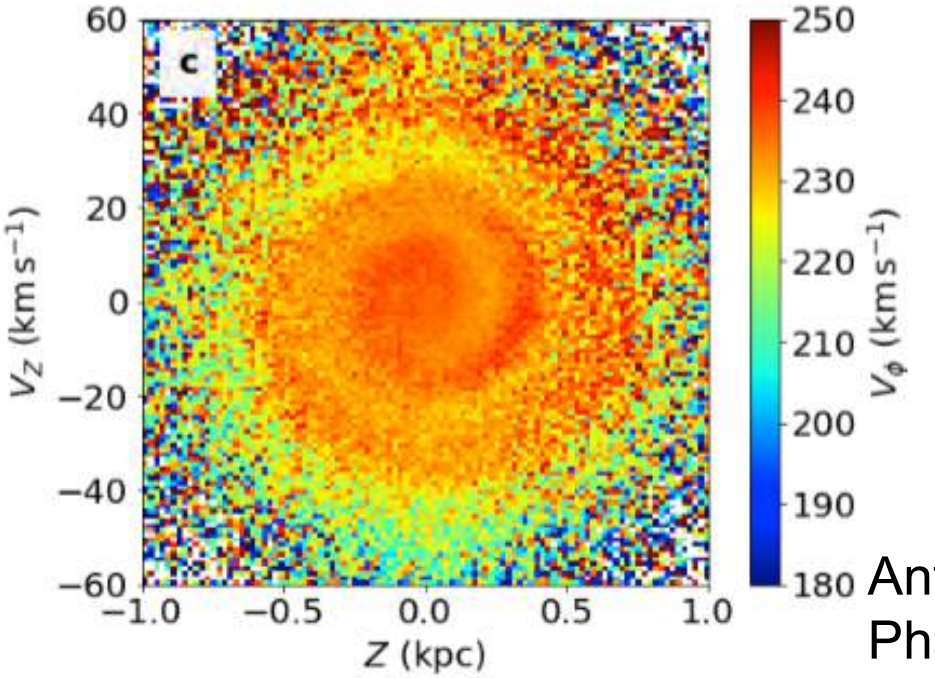
Need for self-consistent high-resolution simulations with gas and star formation
to resolve the gas-rich mergers at high-z and thick and thin disk chemo-dynamical structures at z=0.

Back to Solar neighbourhood kinematics revealed by Gaia…

Daisuke Kawata (MSSL, UCL)

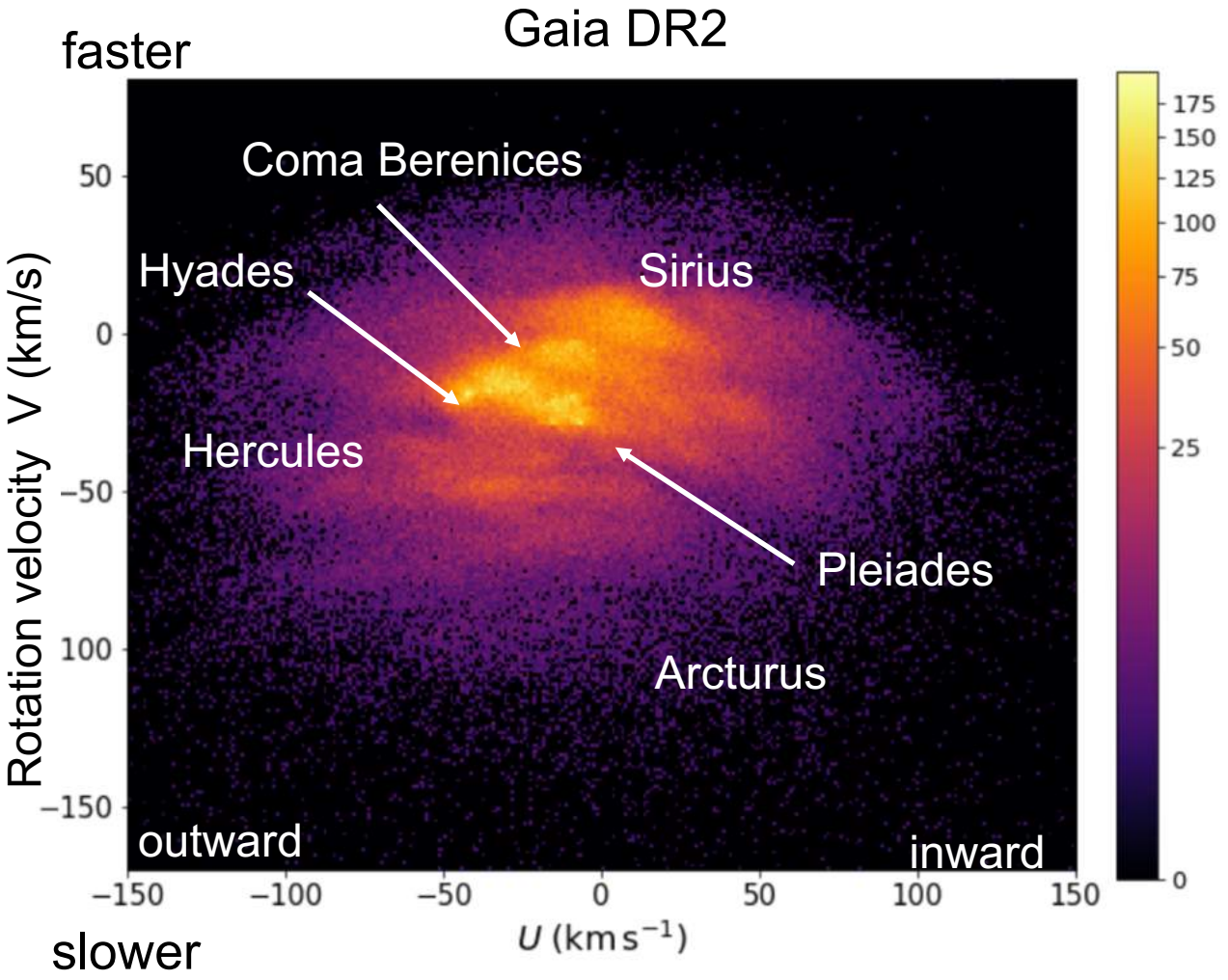
Stellar velocity distribution in the solar neighbourhood
Many velocity ~ km/s scale structures!





Antoja et al. (2018)
Phase spiral

Gaia DR2

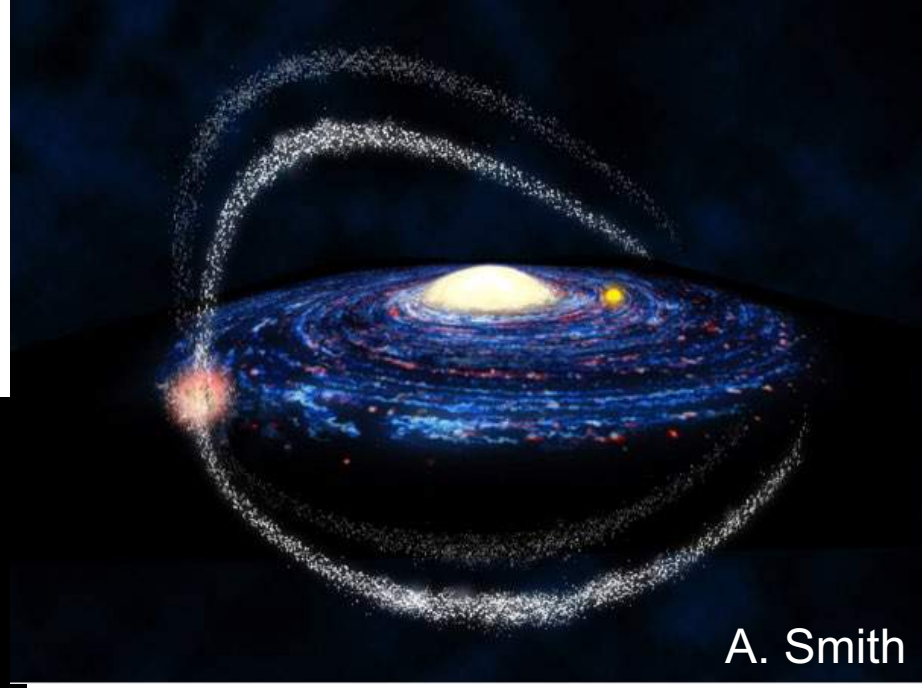


Galactocentric radial velocity U (km/s)

Gaia Collaboration, Katz et al. (2018)

Sagittarius dwarf impacting the Galactic disk?
e.g. Gómez et al. (2013), Laporte et al. (2017, 2018)
Disk response to the perturbation
⇒ Galactoseismology ⇒ disk and halo mass.

ESA
Antoja et al. (2018)

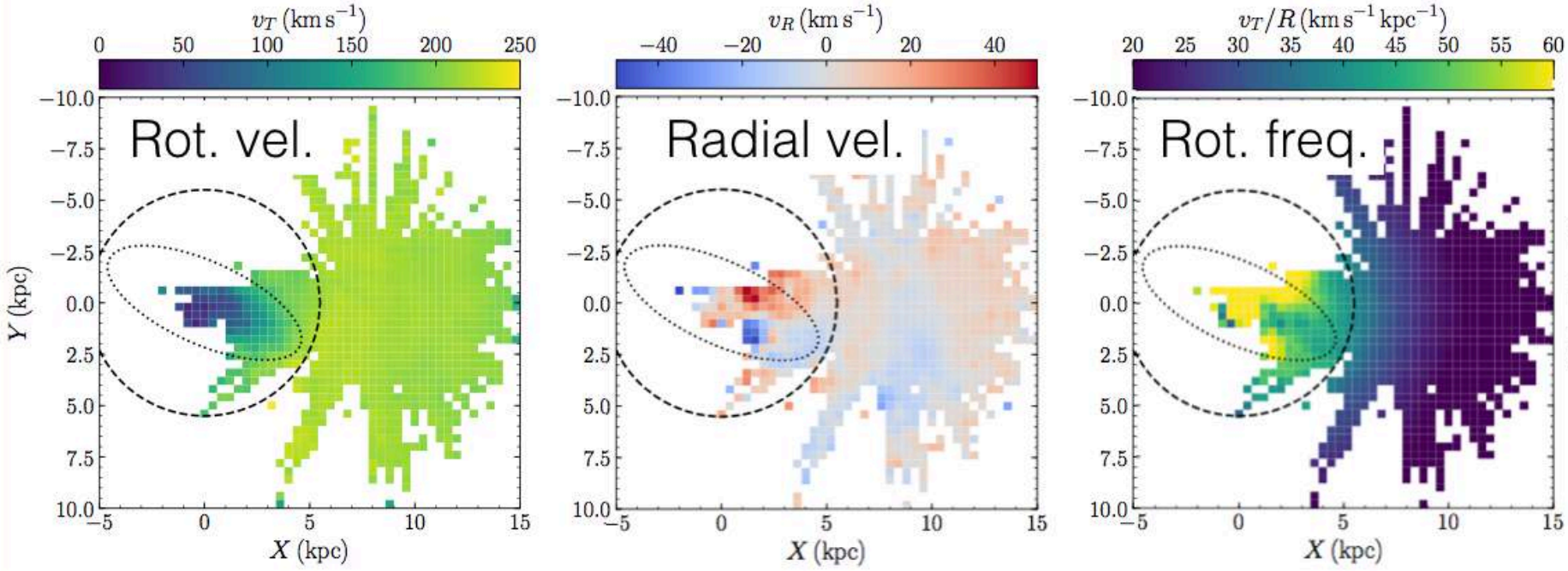


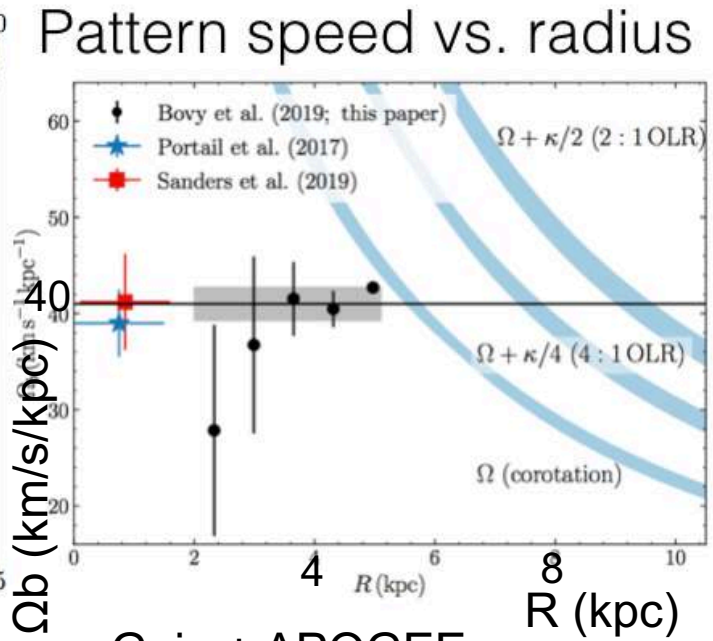
A. Smith

However, required mass of the perturbed (~5×10^{10} $M_\odot$), much heavier than Sgr. (~10^8 $M_\odot$) (Bland-Hawthorn, Tepper-García 2019,
Bennett & Bovy 2021).

Need a better model?

Bar pattern speed slower than pre-Gaia belief, and even slowing down?





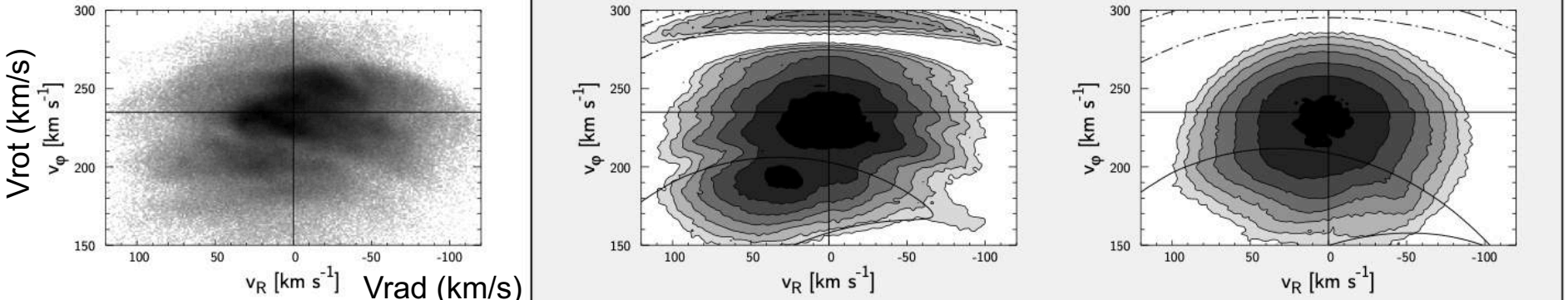
Gaia + APOGEE
Bovy et al. (2019)

Test particle simulation Ω_p = 35.0 km/s/kpc

Gaia DR2

Slowing bar

Constant bar

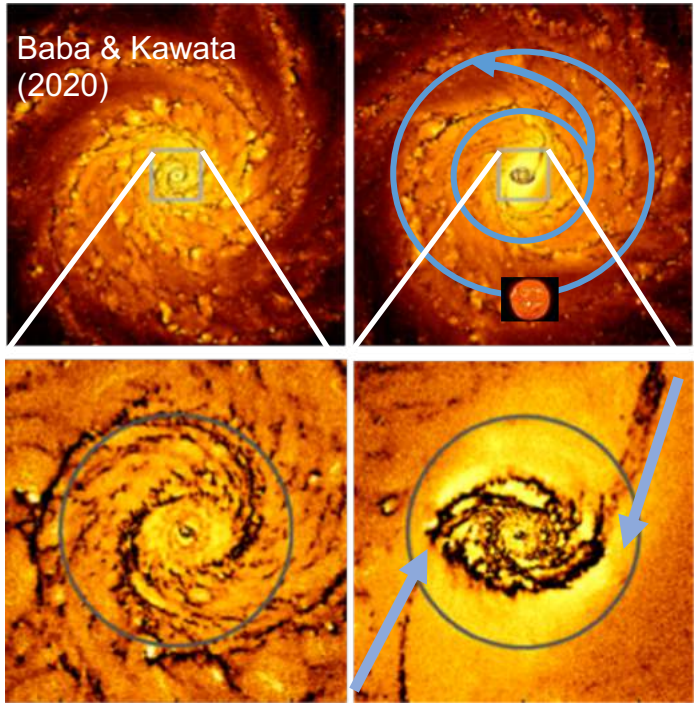


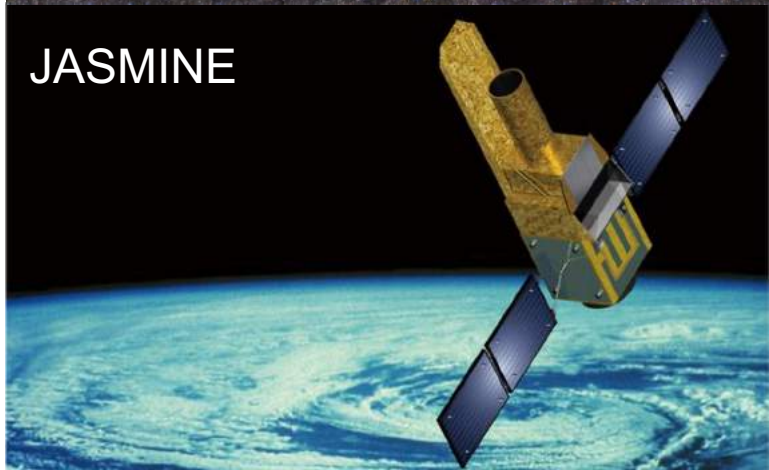
Chiba, Friske, Schönrich (2021a,b)

Slow-down bar due to dynamical friction?
⇒ Nature of dark matter.
CDM, ULDM, MOND, MOG

Remaining question: The epoch and impact of the bar formation?

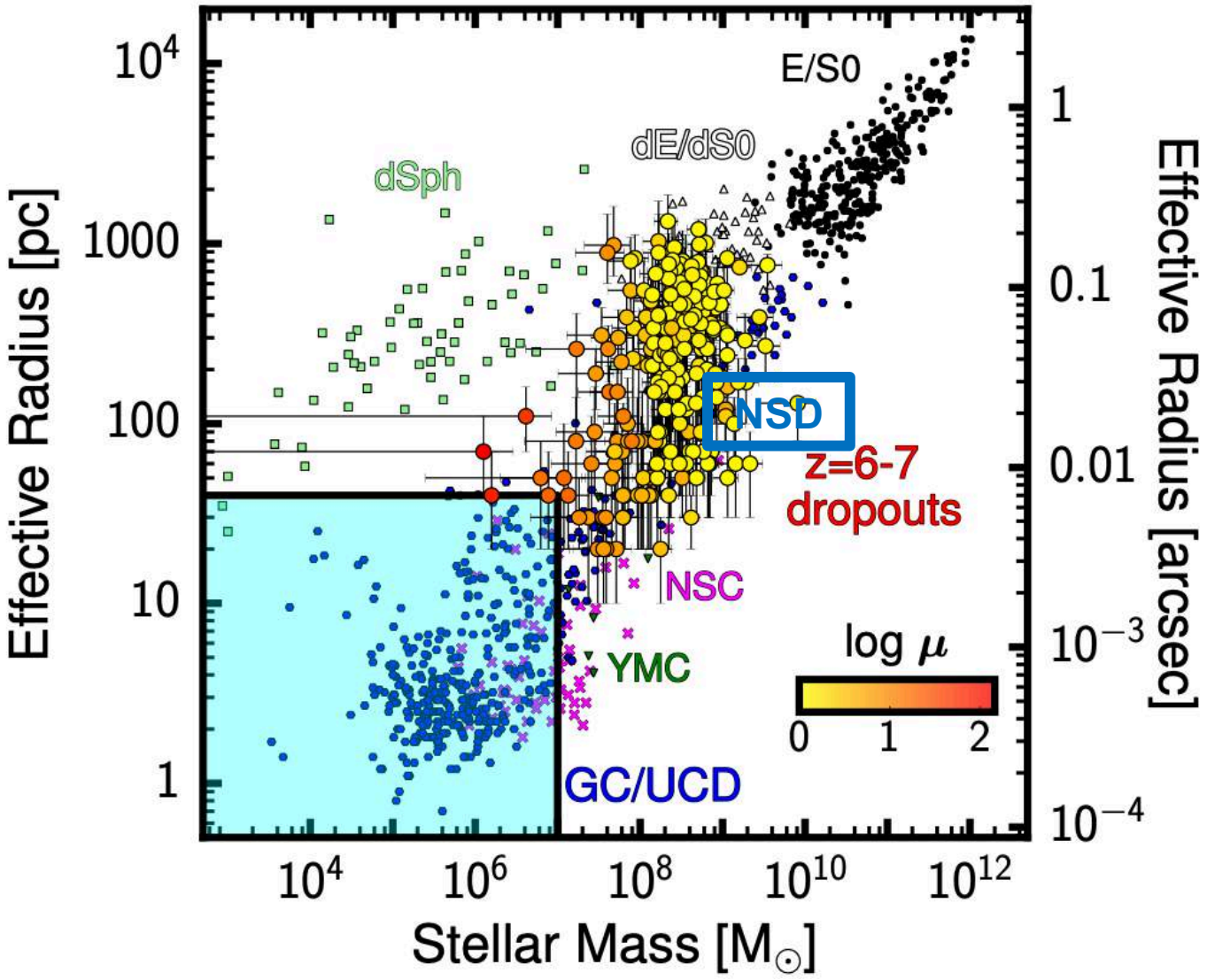
Hierarchical clustering at
the early Universe



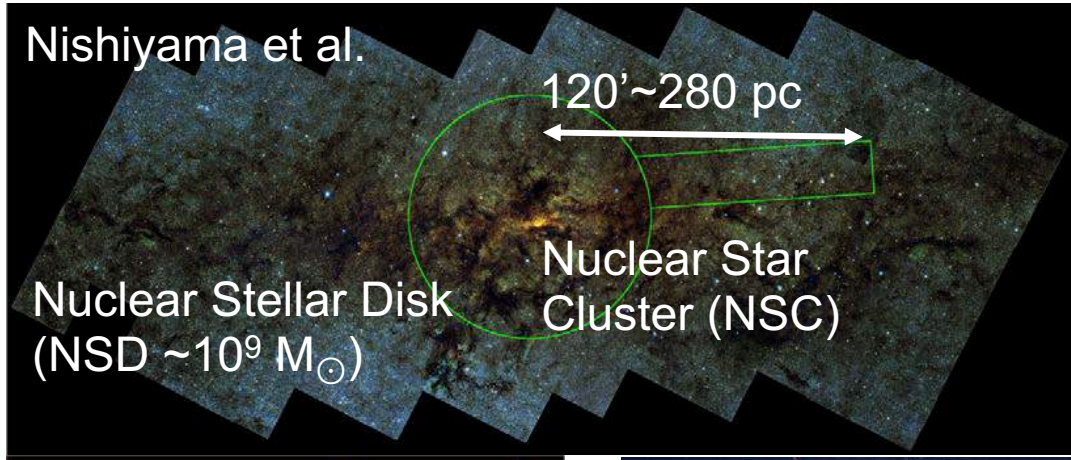


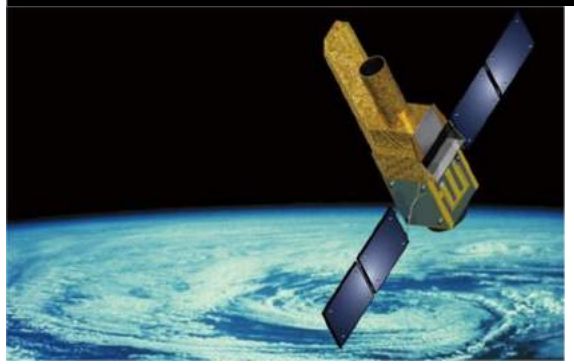
The burst of star formation in the cold nuclear disk (NSD)
= the formation epoch of the Galactic bar
Bar formation epoch ~ Age of NSD
Impact to radial migration of the Sun?
⇐ **JASMINE NIR astrometry mission** by ISAS/JAXA, NAOJ
the Gaia-level astrometry for the Galactic centre stars.

NSD: Link to first galaxies?



Kikuchihara et al. (2020)

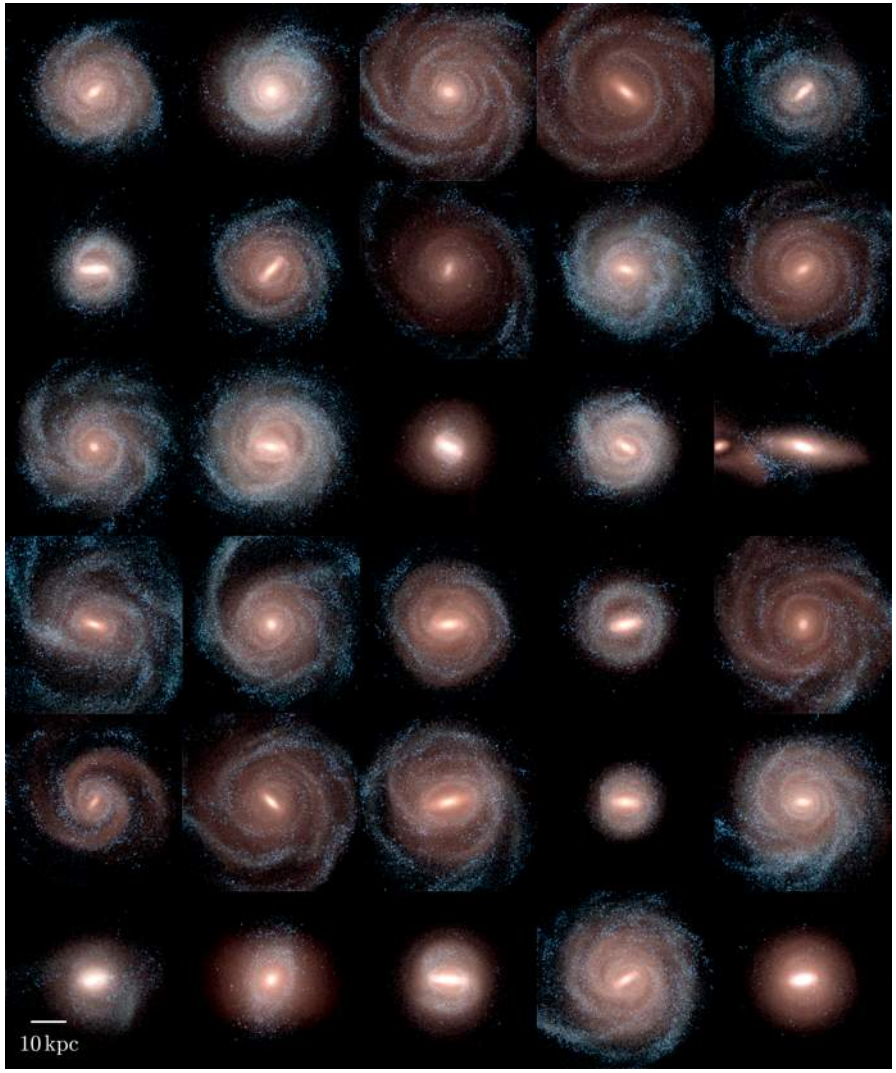




JASMINE (precise astrometry for bright stars) & **SUBARU ULTIMATE** (faint stars populations and motion with JASMINE reference frame) synergy.

Self-consistent high-resolution simulations of the Milky Way-like galaxies with different formation histories?

- Questions
  - Remnant of the first galaxy and ancient mergers?
  - Thick disk formation vs. high-z cold gas disk. Thick disk formed as thick or heated up?
  - Galactic bar formation: when and the impact.
  - Bar slow down? Disk corrugation? Galactoseismology, nature of dark matter
  - How the Sun migrated from the inner disk?
- Need for simulations to resolve
  - z>6 first galaxy formation
  - high-z gas-rich mergers, cold and ionized gas disk.
  - Chemodynamical-structure from NSD, thick and thin disk and the remnant of the ancient mergers.
  - a few km/s scale perturbation.
  - ~ a few 10 Myr outputs
  - Variety of formation and evolution histories



Auriga suit (Grand et al. 2017)