Uncover galaxies' merger history combining stellar kinematics and populations

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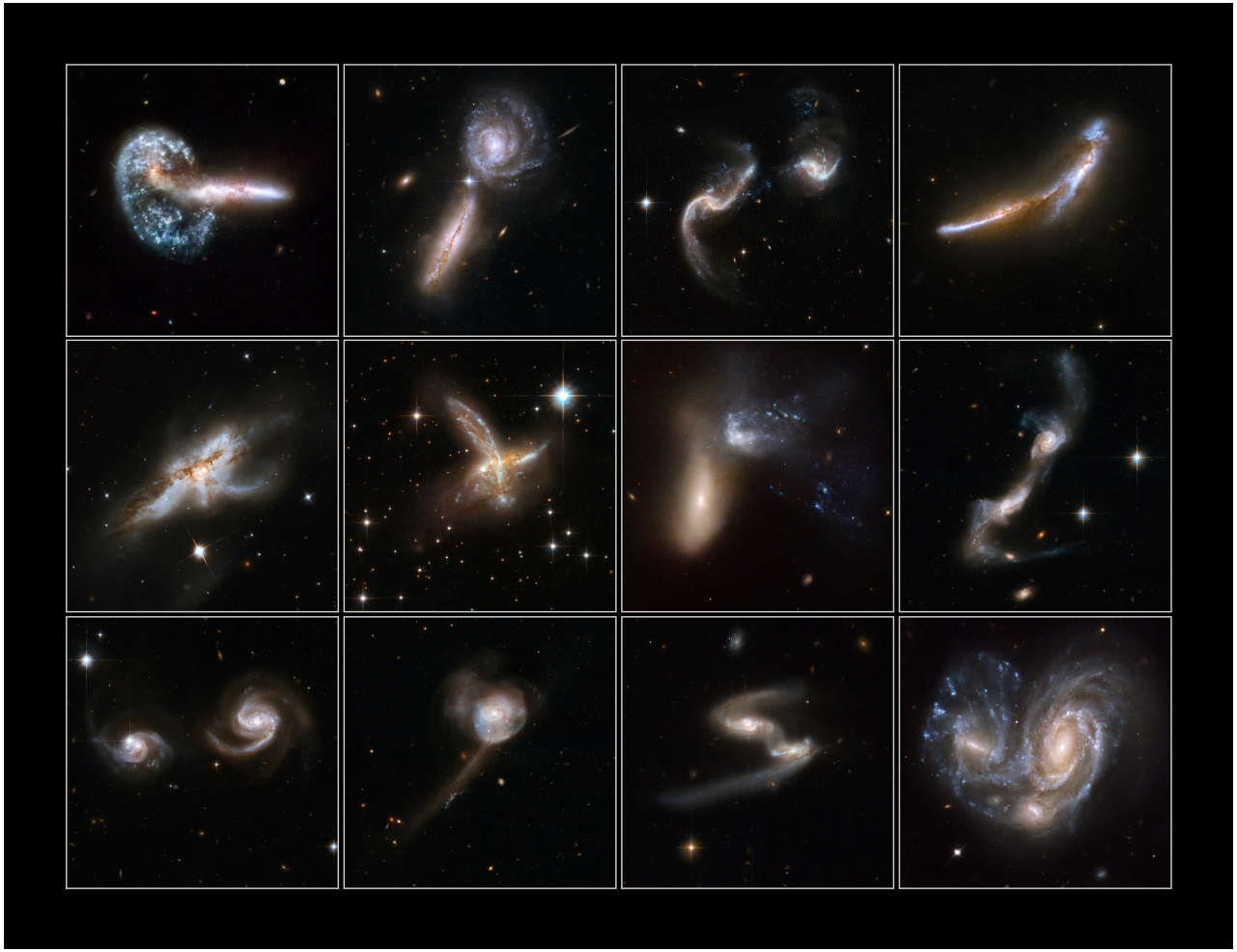
Dimitri Gadotti (Durham), the Fornax 3D team, the TIMER team.

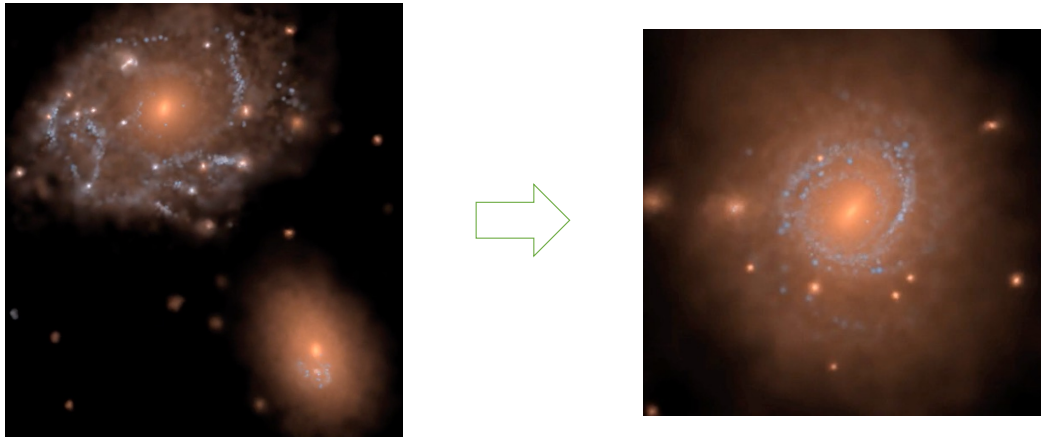
Annalisa Pillepich (MPIA): MPG Partner Group

Galaxies grow through mergers



Can we quantify the ancient mergers ?

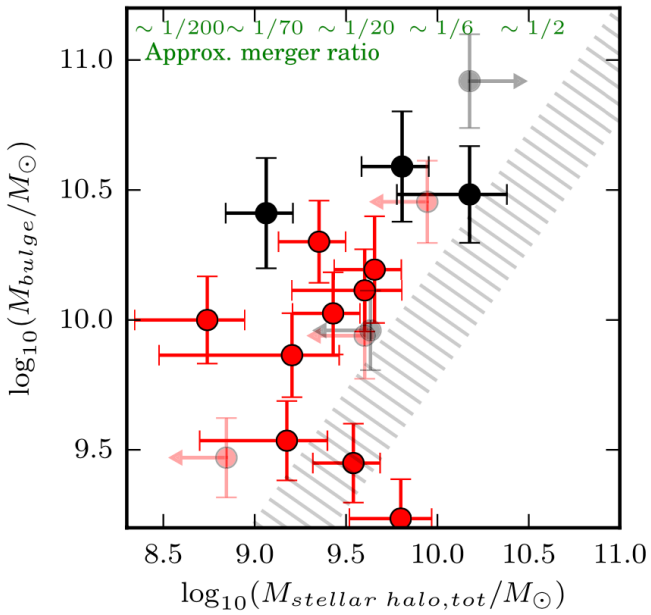
- Most mergers happen in the past.
- When did they happen?
- How massive the accreted satellite galaxies were?



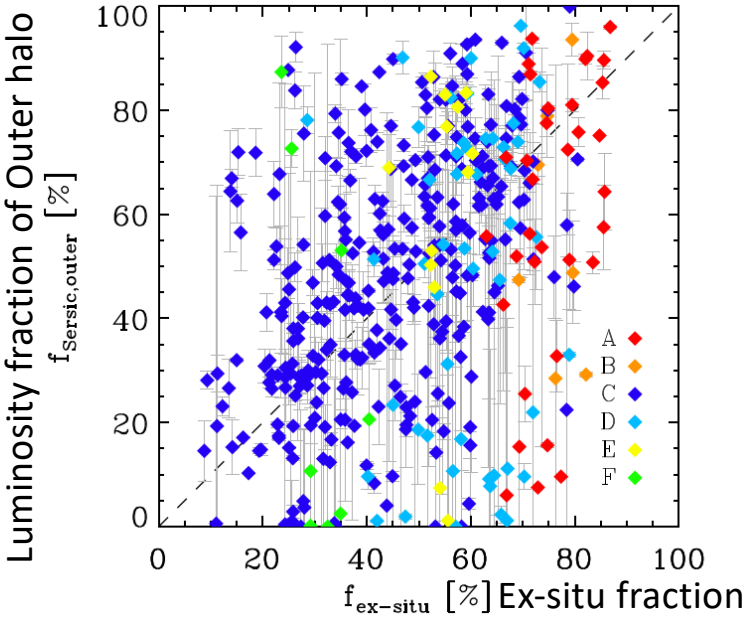
It is hard: merger event may last only < 1Gyr,
the stars from two progenitors are totally mixed

Galaxy structures as fossil records of the assembly history

Neither classic bulge nor outer halo from photometric decomposition is a good indicator of ex-situ mass



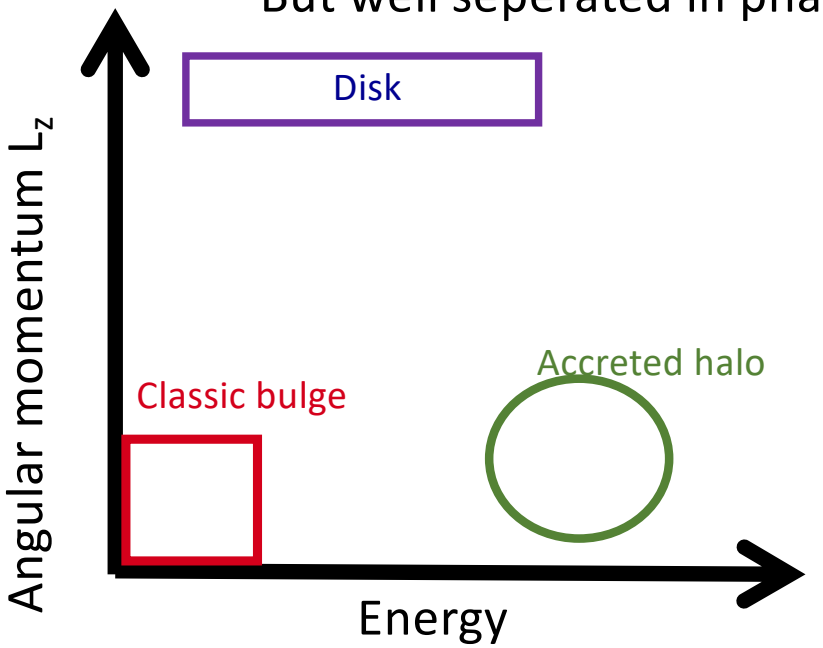
Bell+ 2017

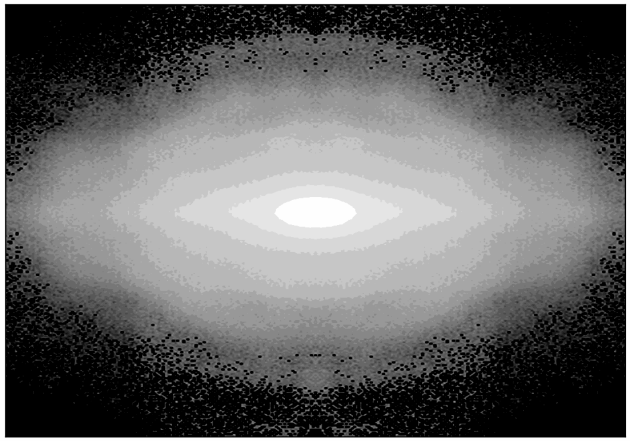


Remus+2022

Galaxy structures as fossil records of the assembly history

Stars in different structures overlap in spatial distributions
But well seperated in phase-space of E vs. Lz.

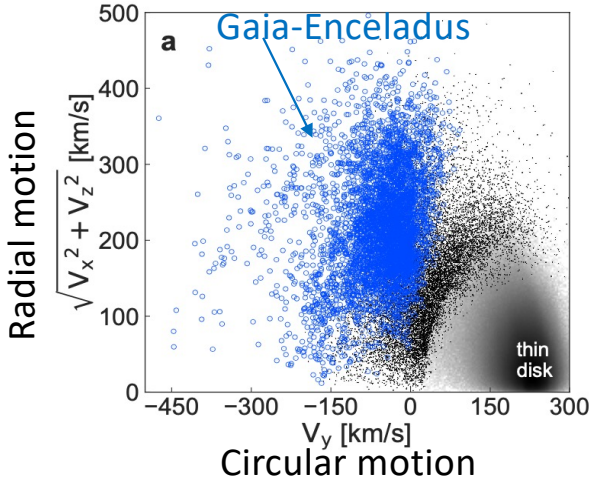


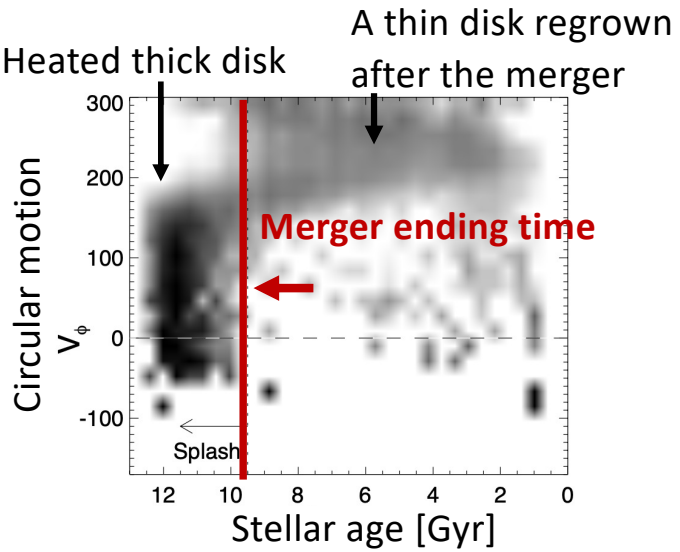


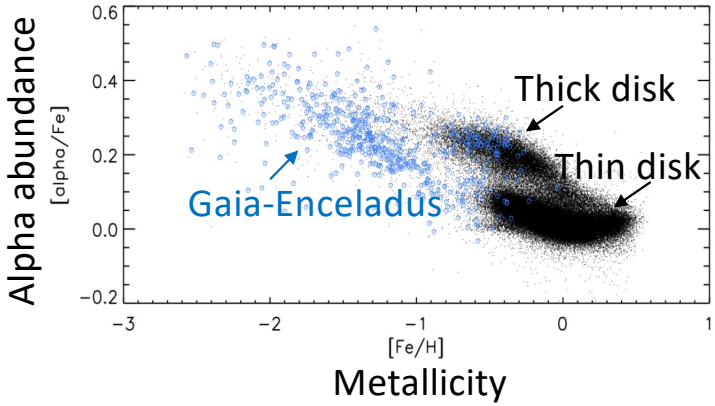
Kinematic structure decomposition:

- Physically motivated definition of structures.
- Widely used for simulations (e.g.,Abadi+2003, Obreja+2016, Du+2020).
- Expensive for real galaxies from observations.

Ancient massive mergers uncovered in MW





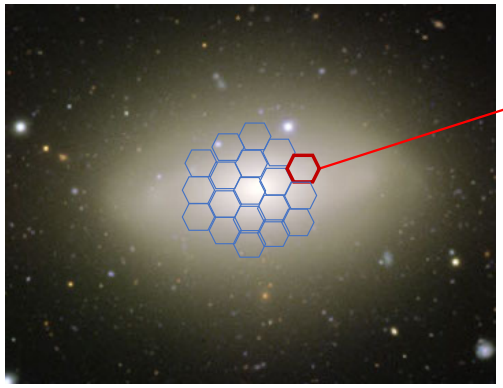


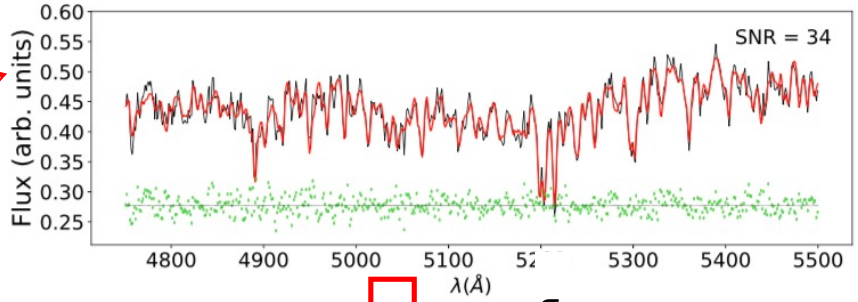
- Ancient massive merger events uncovered in MW, e.g., the Gaia-Enceladus-sausage.
- Combing stellar kinematics and chemistry.

Helmi+2018, Belokurov+2018,2019, Naidu+2020

Chemo-dynamical decomposition of nearby galaxies by applying a population-orbit superposition method to IFU data

Observations : Integral Field Spectroscopy





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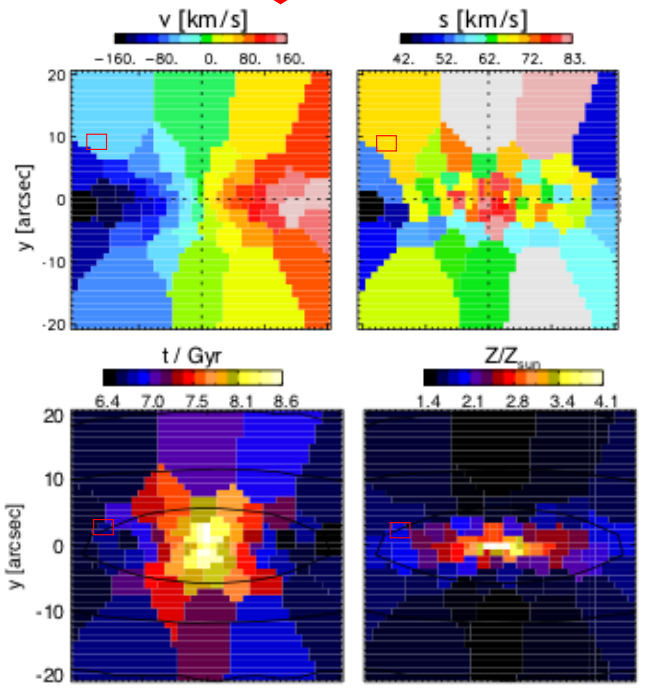


IFU surveys
for thousands of galaxies

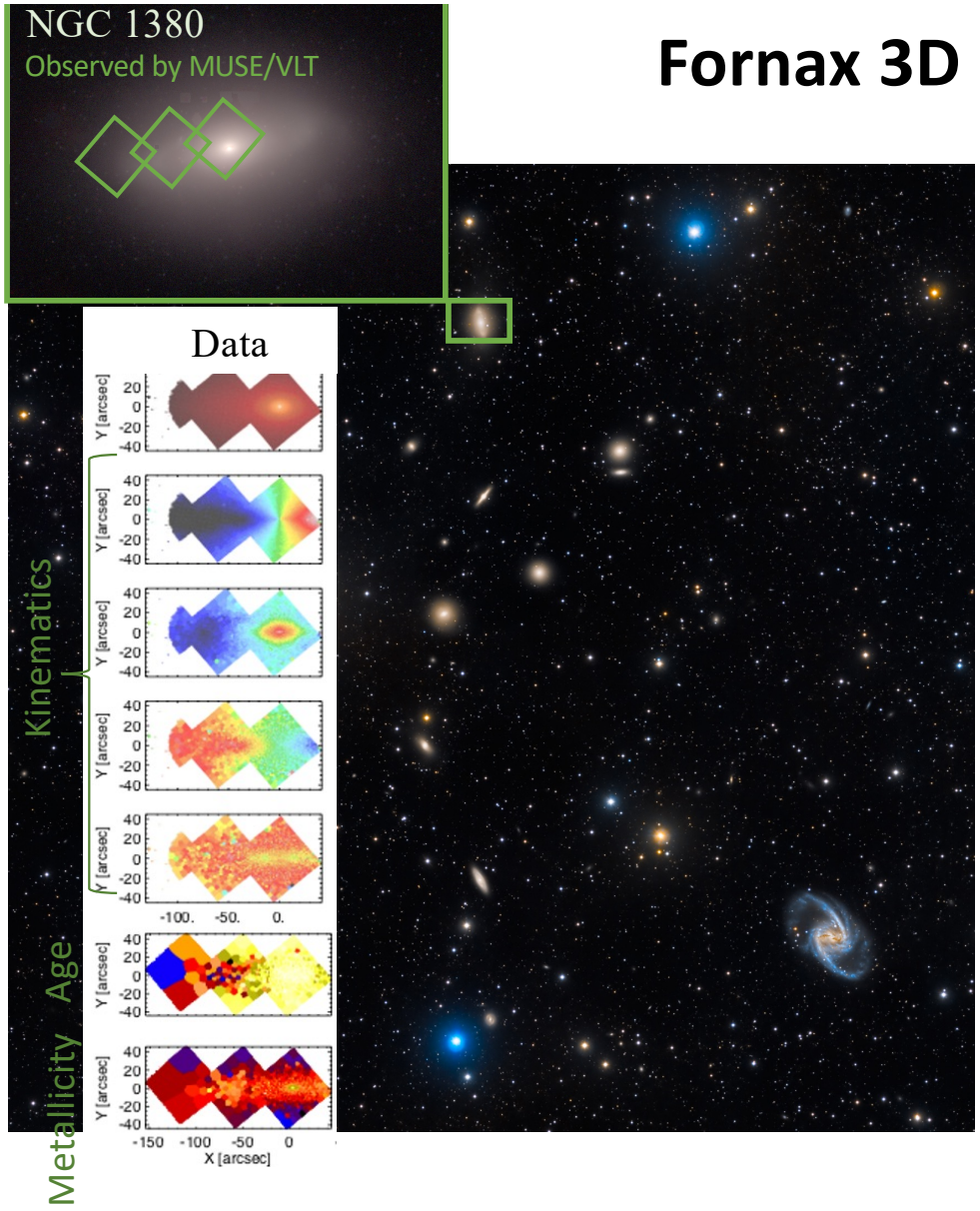
ATLAS 3D

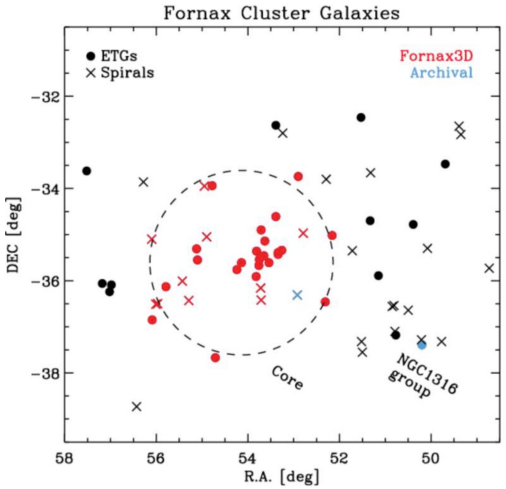
CALIFA Survey

sami galaxy survey

MaNGA

Fornax 3D survey

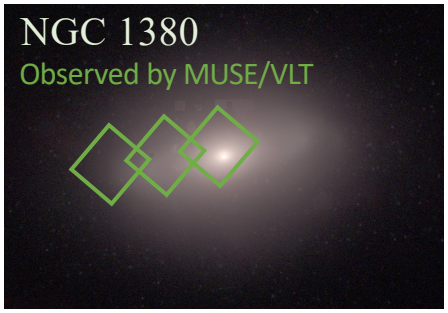




- Deep IFU using MUSE/VLT, FOV:1'x1', pixelsize:0.2''x0.2''
- 23 ETGs, 10 LTGs within R_v of the Fornax cluster.
- Cover the outer faint regions

Sarzi+2018

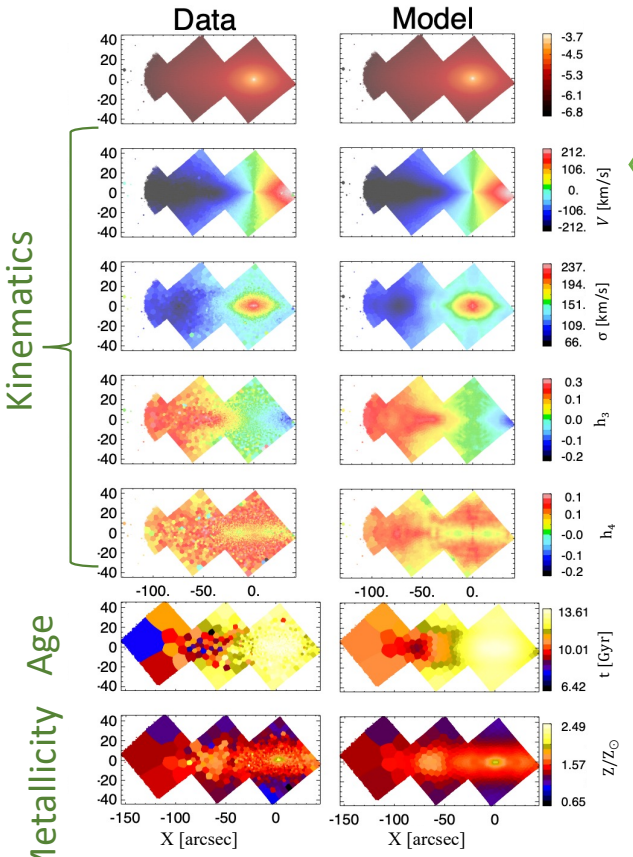
Data release: Sarzi, Iodice+ 2022

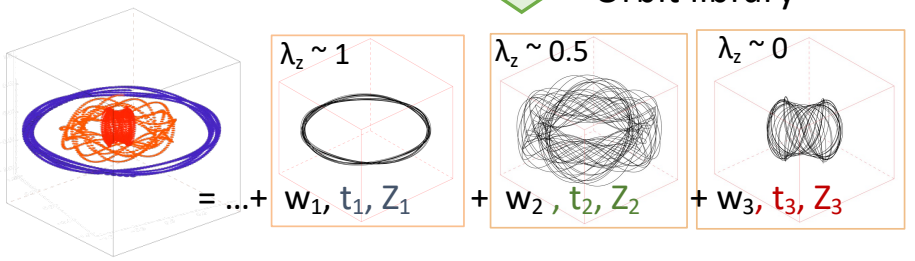


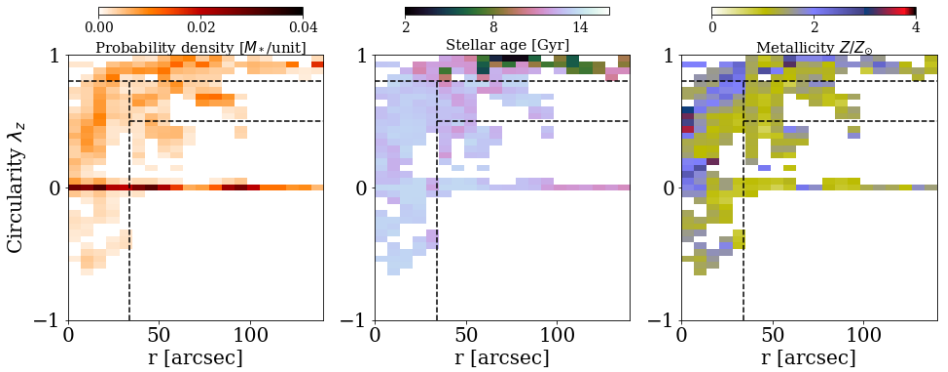
Population-orbital superposition model

Gravitational potential=
$M_*/L \times$ MGE + DM + ...

Orbit library



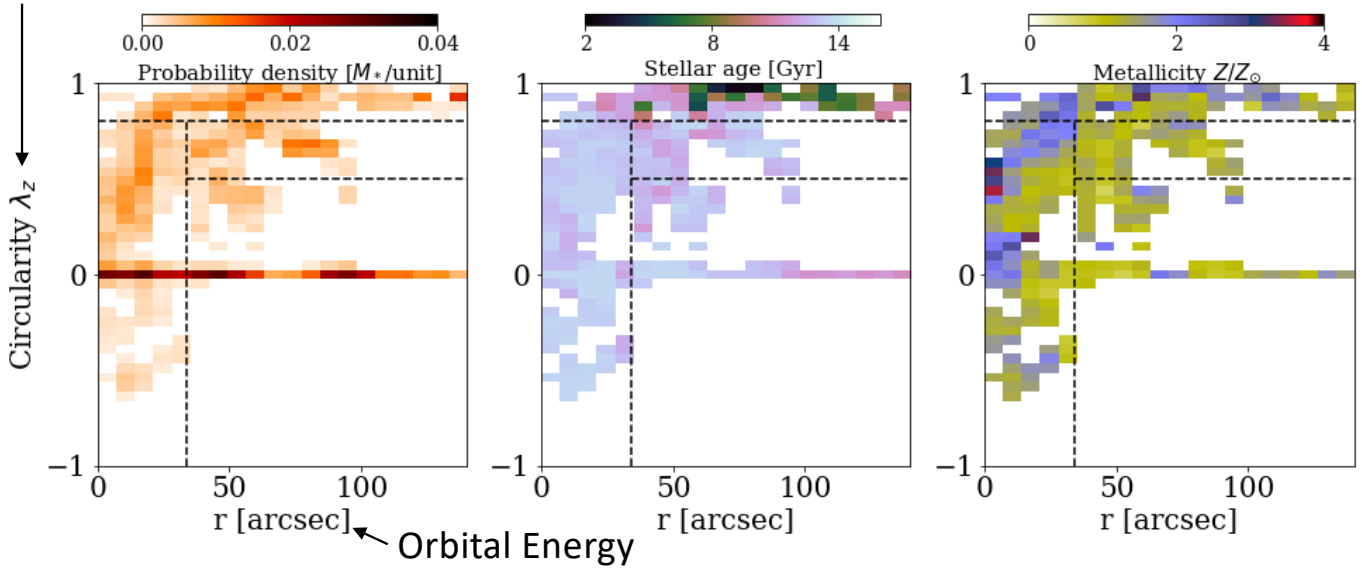




Zhu+2020, method validation

Orbital structure decomposition

$\lambda_z = L_z/J_c$



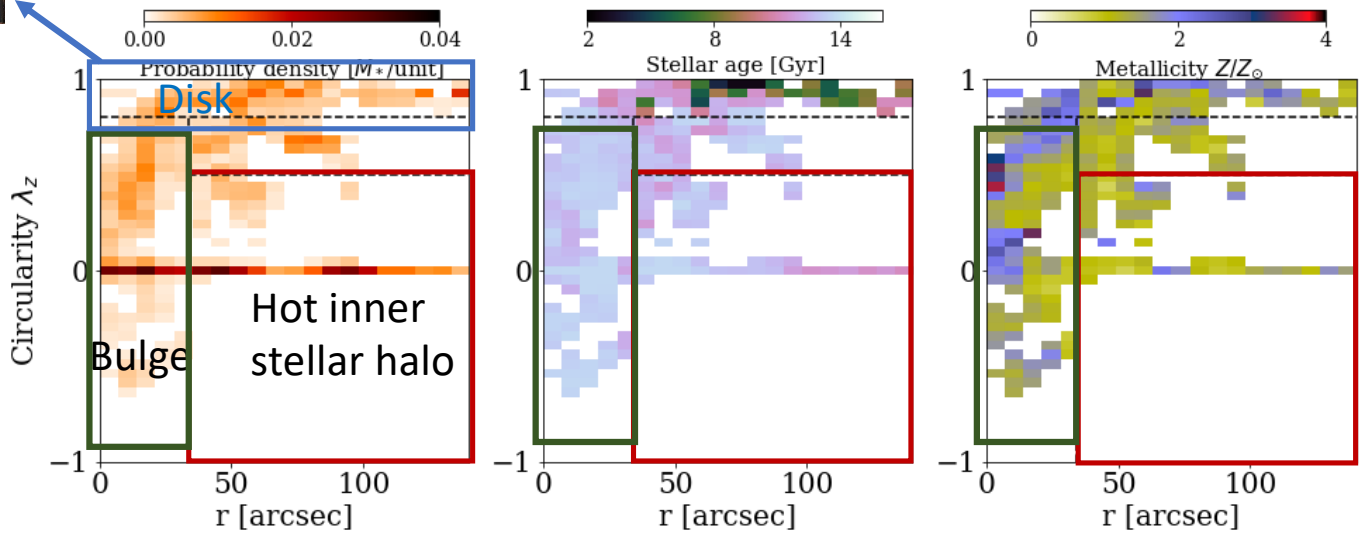
- Decompose a galaxy into multiple components in a flexible, physical-motivated way.
- Direct comparison of observed galaxy structures to simulations

Understand the origins of galaxy structures from TNG50

-Hot inner stellar halo as relics of ancient massive mergers

Yuchen Ding

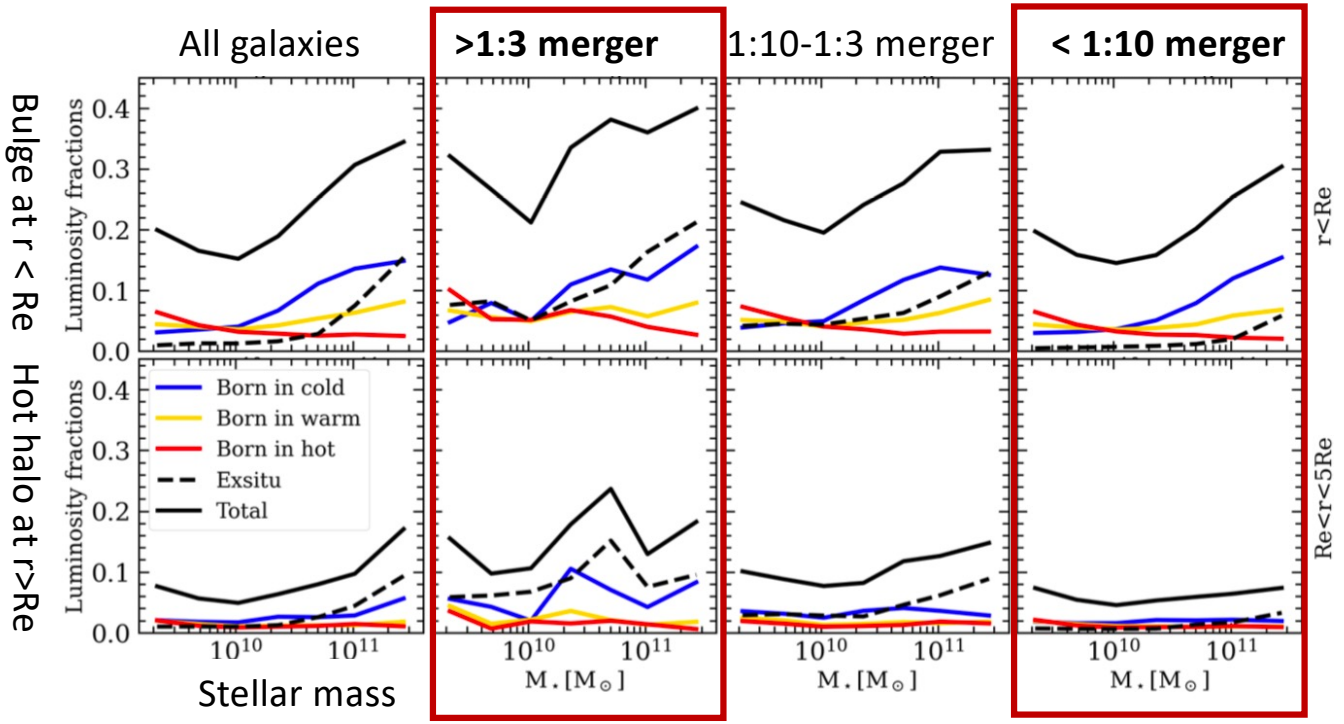
Orbital structure decomposition



- Disk: dynamically cold, relatively young and metal-rich
- Bulge: dynamically hot, old and metal-rich
- Hot inner stellar halo: dynamically hot, old and metal-poor

Diverse origins of the dynamically-hot bulge

Galaxies in Illustris TNG50



- Three major orgins of bulge: born hot, born cold but heated by secular process, heated or accerated by mergers.
- Galaxies with different merger histories have similar hot bulge fractions.
- Hot halo at r>Re is mainly produced by mergers.

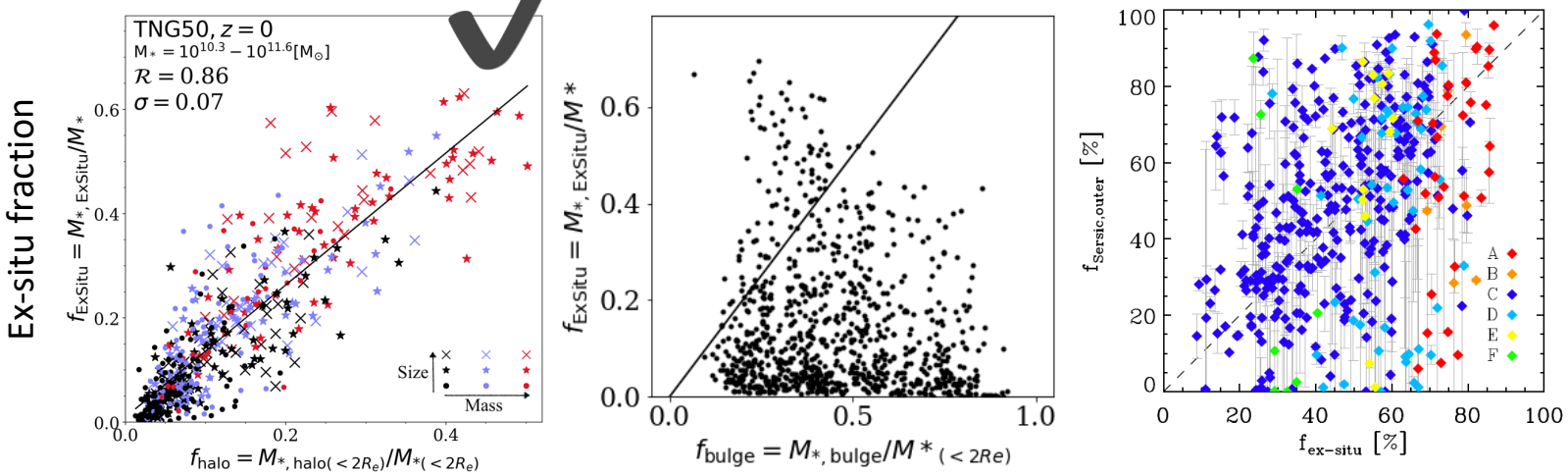
Zhang & Zhu+ in prepare

Hot inner stellar halo as relics of ancient massive mergers

Hot inner stellar halo

Hot bulge

Outer halo



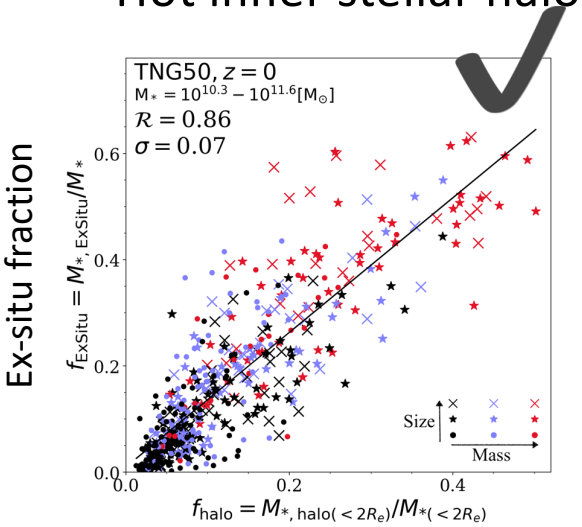
Zhu, Pillepich+2022

Remus+2022

- Tight correlation between the luminosity fraction of hot inner stellar halo and galaxies' ex-situ mass.
- Weak correlation between bulge fraction and ex-situ mass.

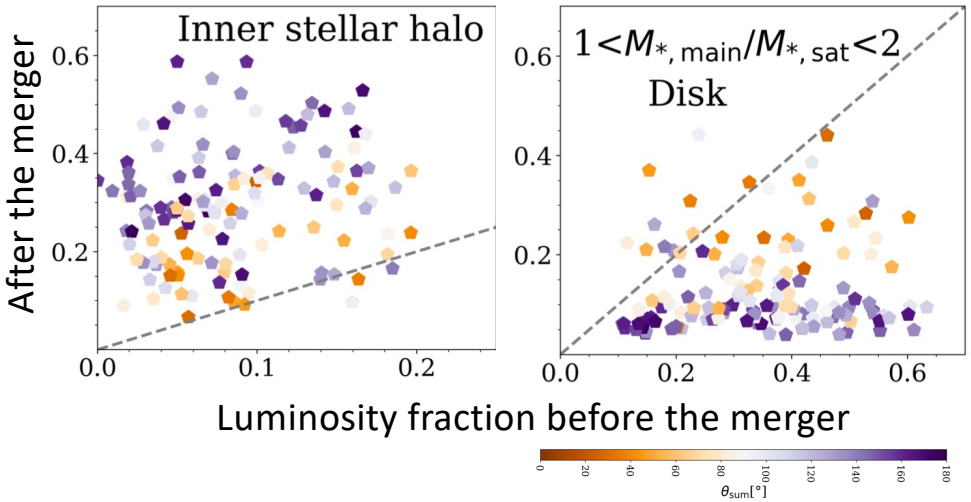
Hot inner stellar halo as relics of ancient massive mergers

Hot inner stellar halo



Zhu, Pillepich+2022

Scatter caused by merging orbits



(Wu & Zhu in prepare)

- Tight correlation between the luminosity fraction of hot inner stellar halo and galaxies' ex-situ mass.
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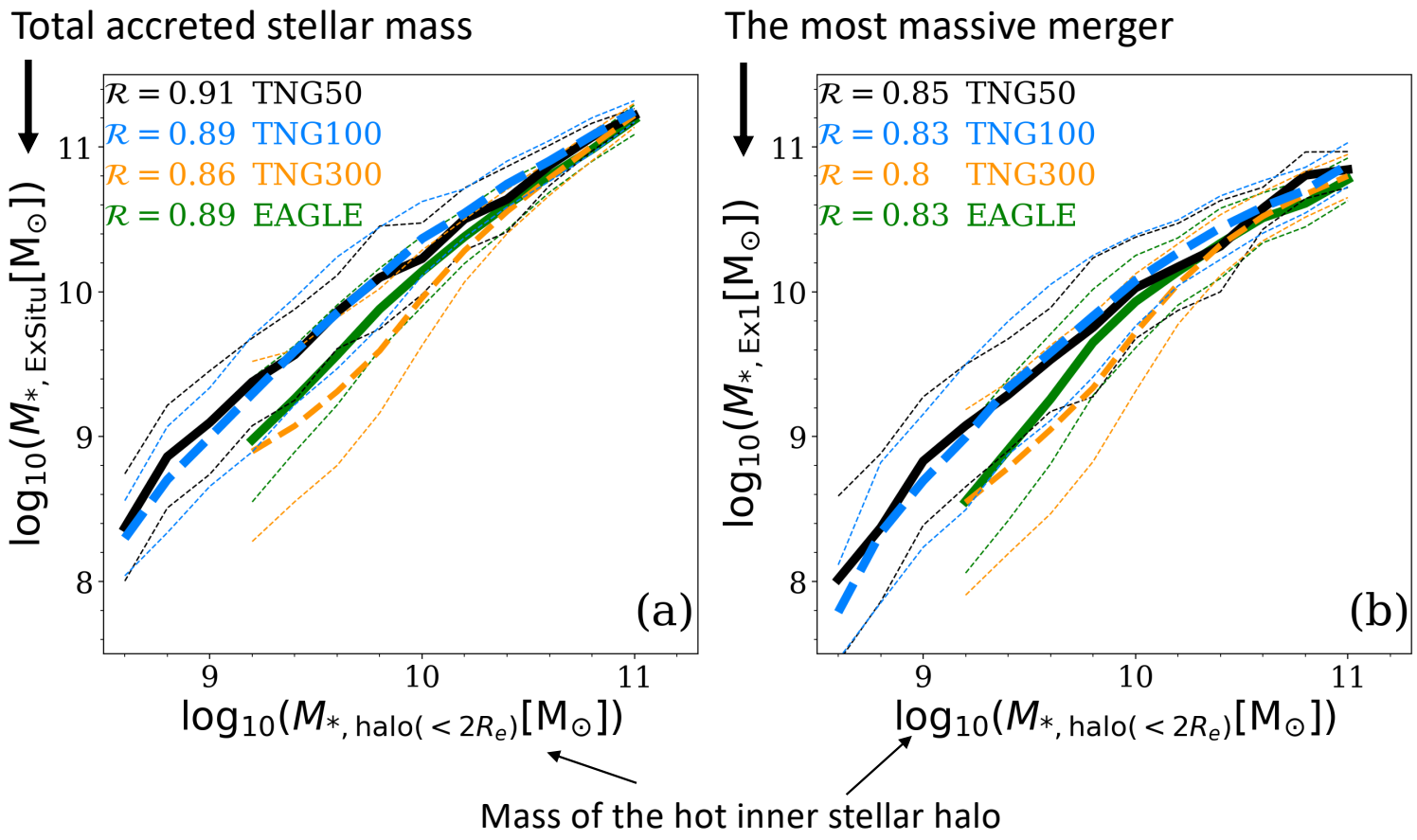
Hot inner stellar halo as relics of ancient massive mergers

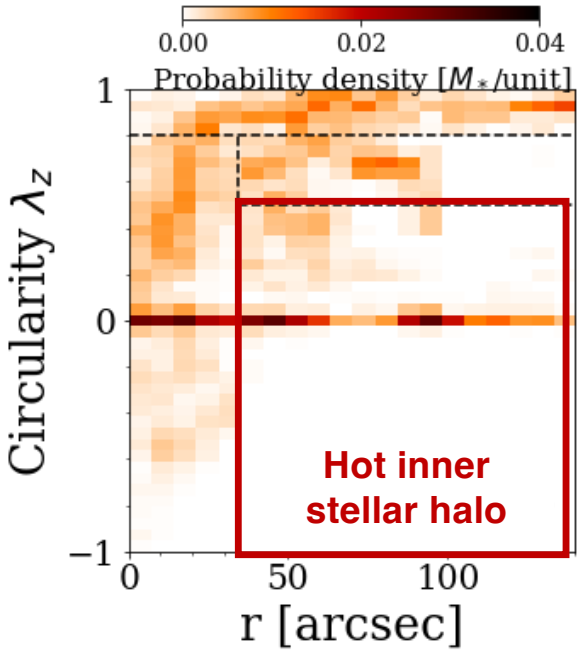


Zhu, Pillepich+2022

Weighing and timing ancient massive mergers in NGC 1380 and NGC1427

Hot inner stellar halo as relics of ancient massive mergers

NGC 1380:
from IFU + dynamical model



Hot inner stellar halo: stars on highly radial orbits, spatially more extended than the bulge; like the Gaia-Enceladus-Sausage in the MW.

Zhu, vdVen, Leaman, et al. (2022)

Helmi+2018, Belokurov+2018

Hot inner stellar halo as relics of ancient massive mergers

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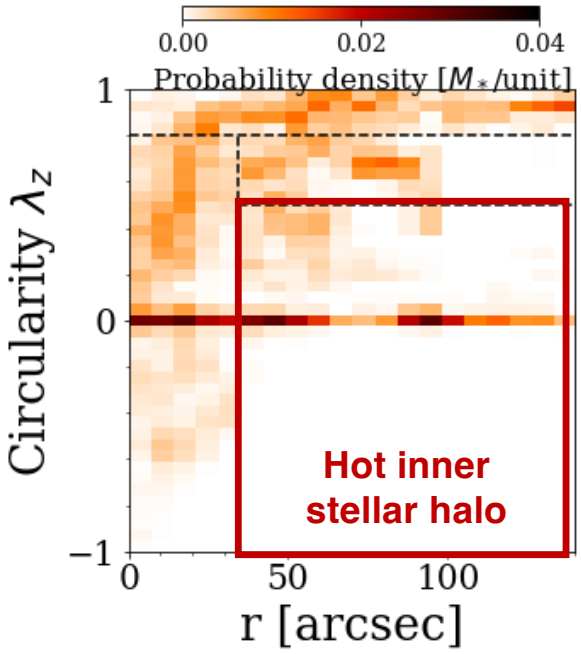
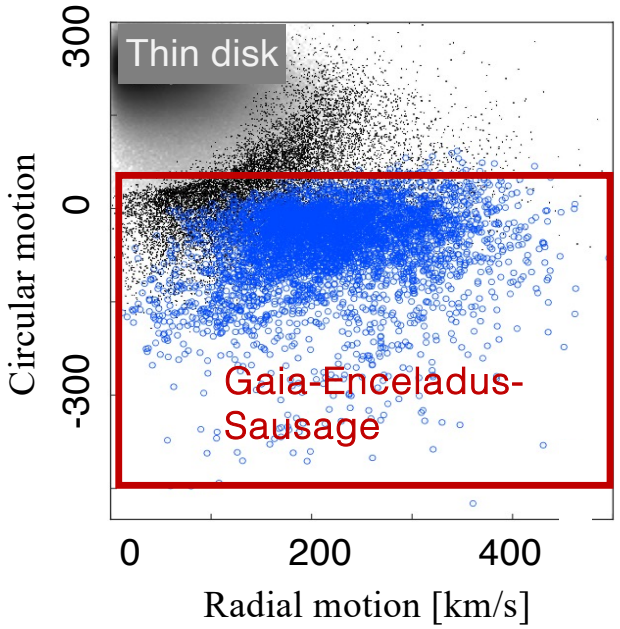


Milky Way:
from resolved stars



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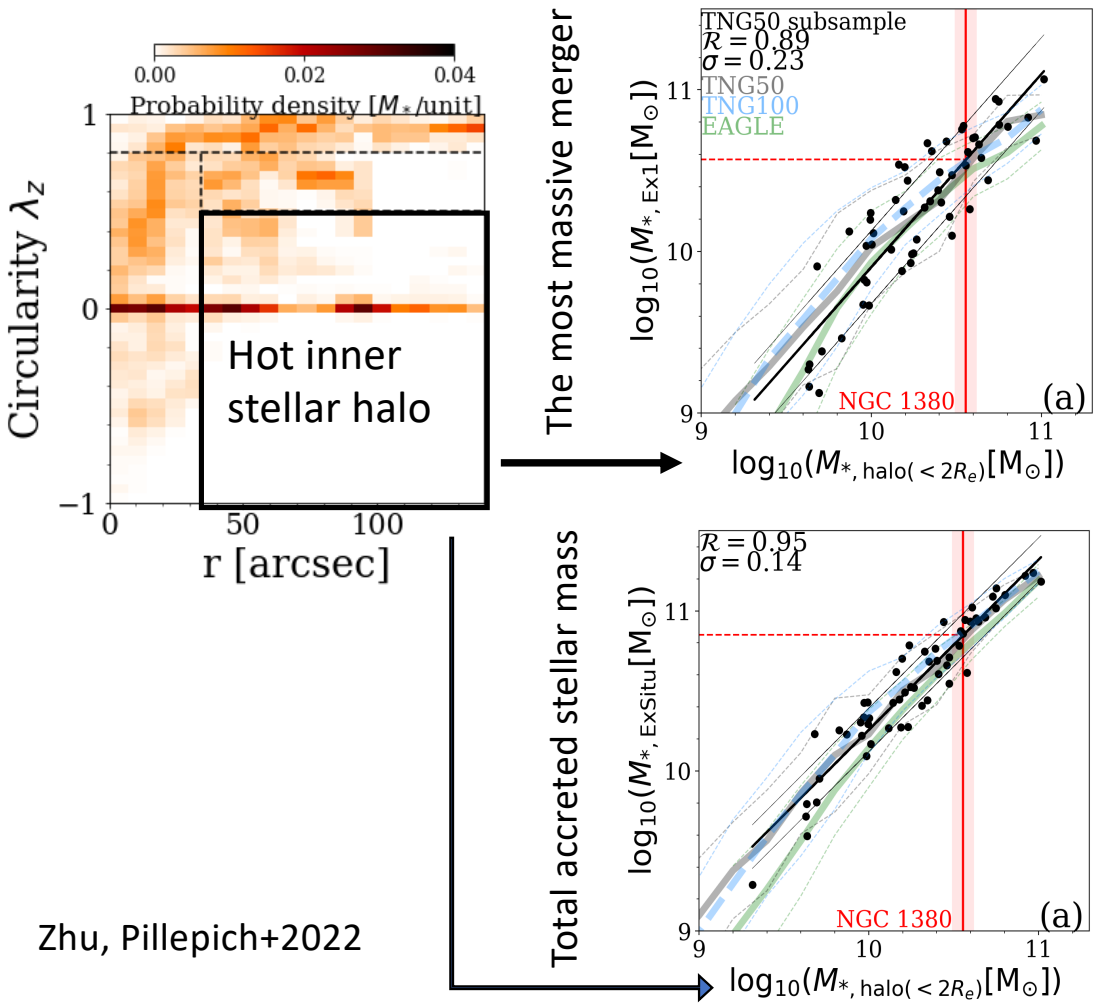
Zhu, vdVen, Leaman, et al. (2022)

Helmi+2018, Belokurov+2018

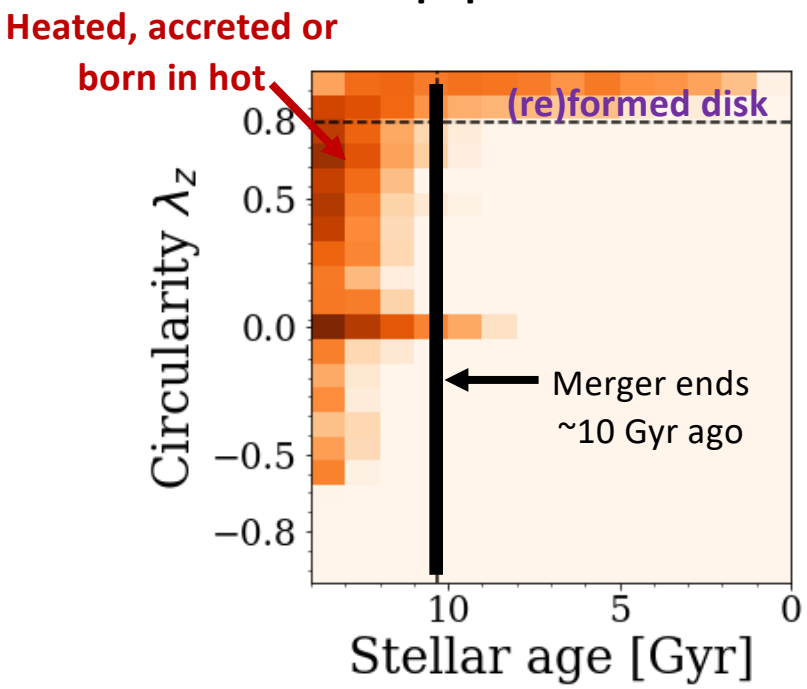
Merger Mass of Fornax galaxies NGC 1380 and NGC 1427



Zhu, Pillepich+2022

Population-dynamics: merger timing

NGC 1380:
from IFU + population-orbit model

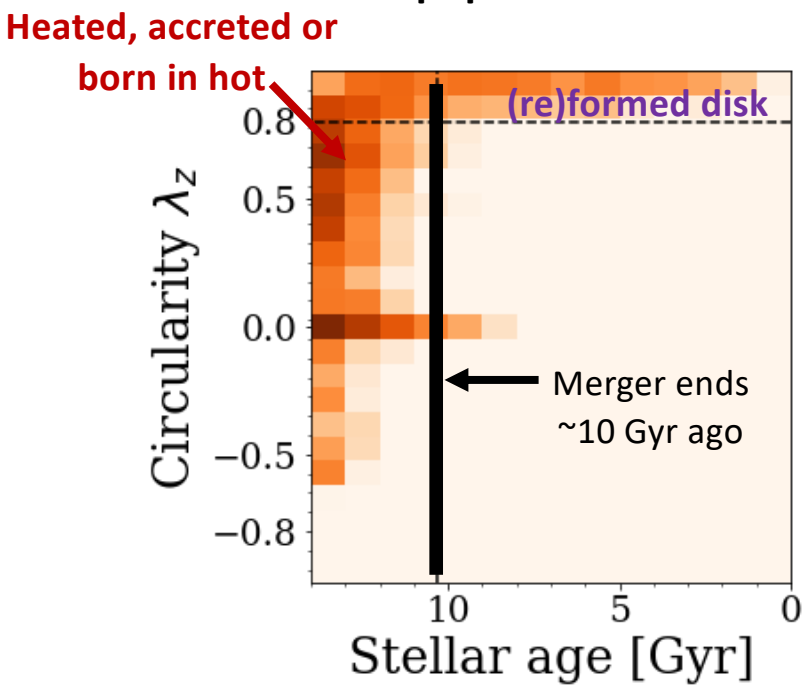


Only after the last major merger, a cold stellar disk could reform and survive until today

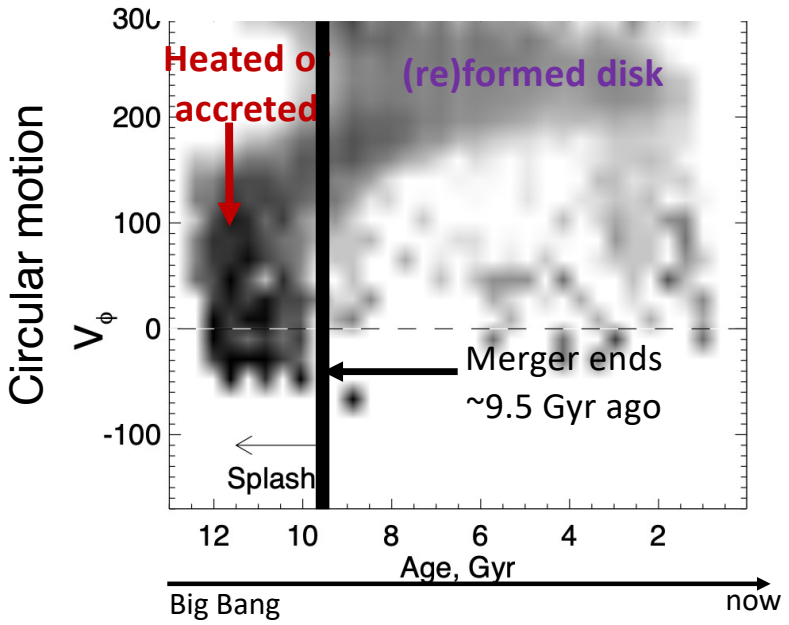
Zhu, vdVen, Leaman, et al. (2022)

Population-dynamics: merger timing

NGC 1380:
from IFU + population-orbit model



Milky Way:
from resolved stars



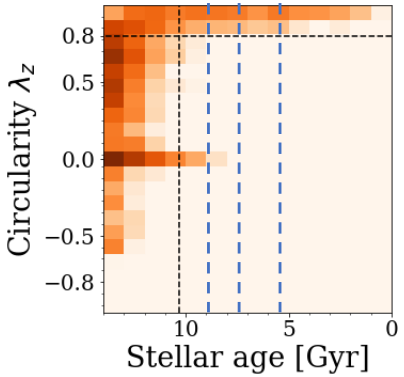
Only after the last major merger, a cold stellar disk could reform and survive until today

Zhu, vdVen, Leaman, et al. (2022)

Belokurov et al. (2020)

NGC 1380 in the past

- Progenitor of the galaxy at different redshifts
- Build by stars with different stellar age



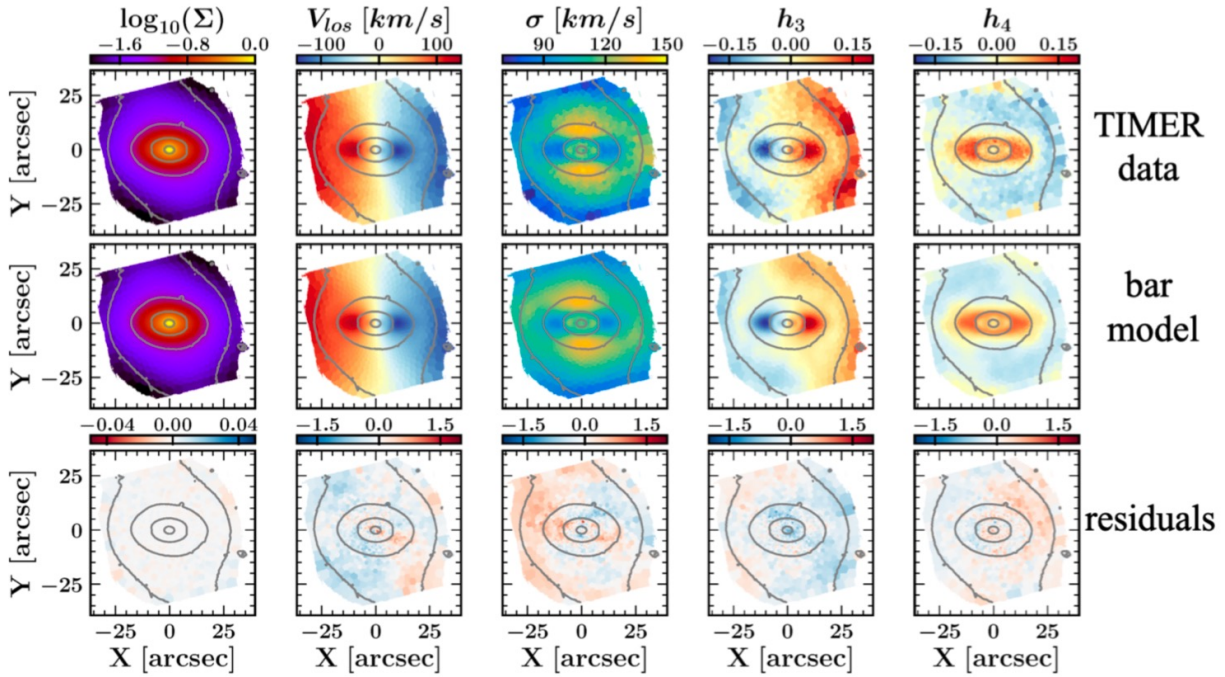
A major merger at z>1.8,
with M_{*sat}~4x$10^{10}M_{sun}$

Orbit-superposition model of Barred galaxies

Behzad Tahmasebzadeh

Modelling of barred galaxies

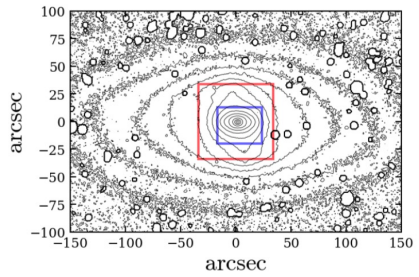
NGC 4371 observed by MUSE and ATLAS3D

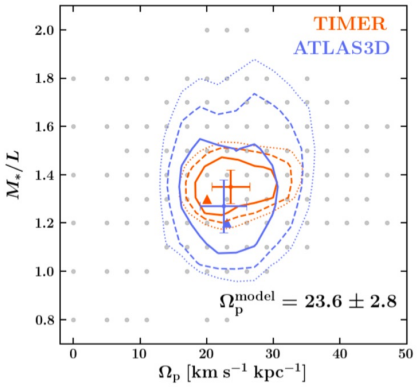


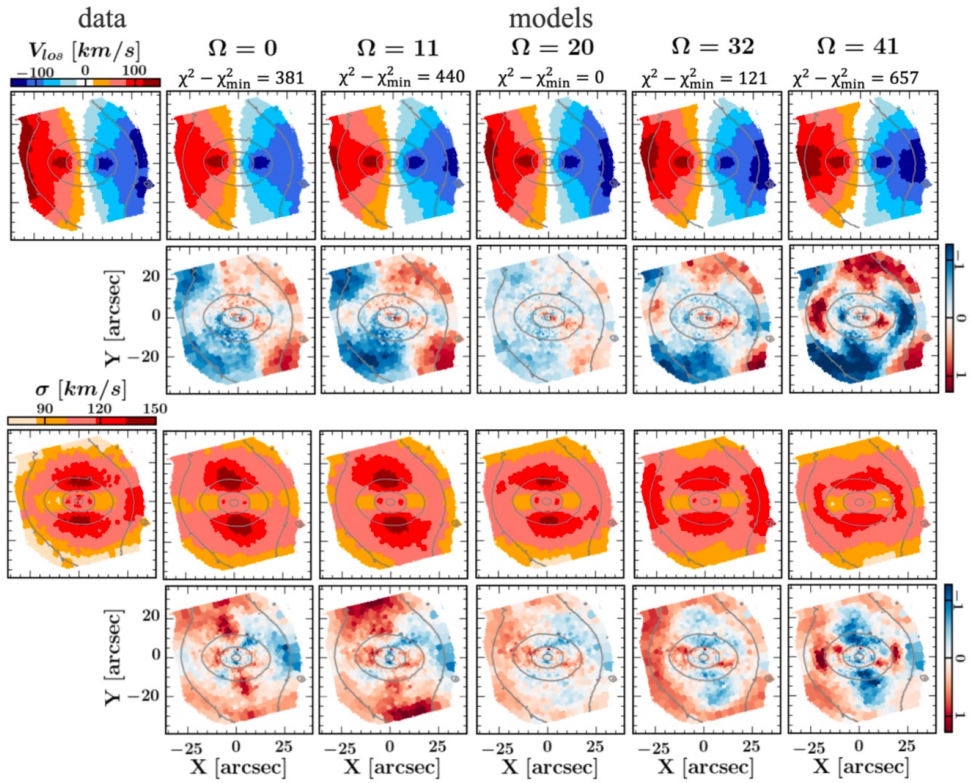
Good fit to bar features in photometry and kinematic data

Tahmasebzadeh, Zhu, Shen et al. 2022 method validation
Tahmasebzadeh, Zhu, Shen et al. 2023 submitted for NGC4371

Constraint on bar pattern speed



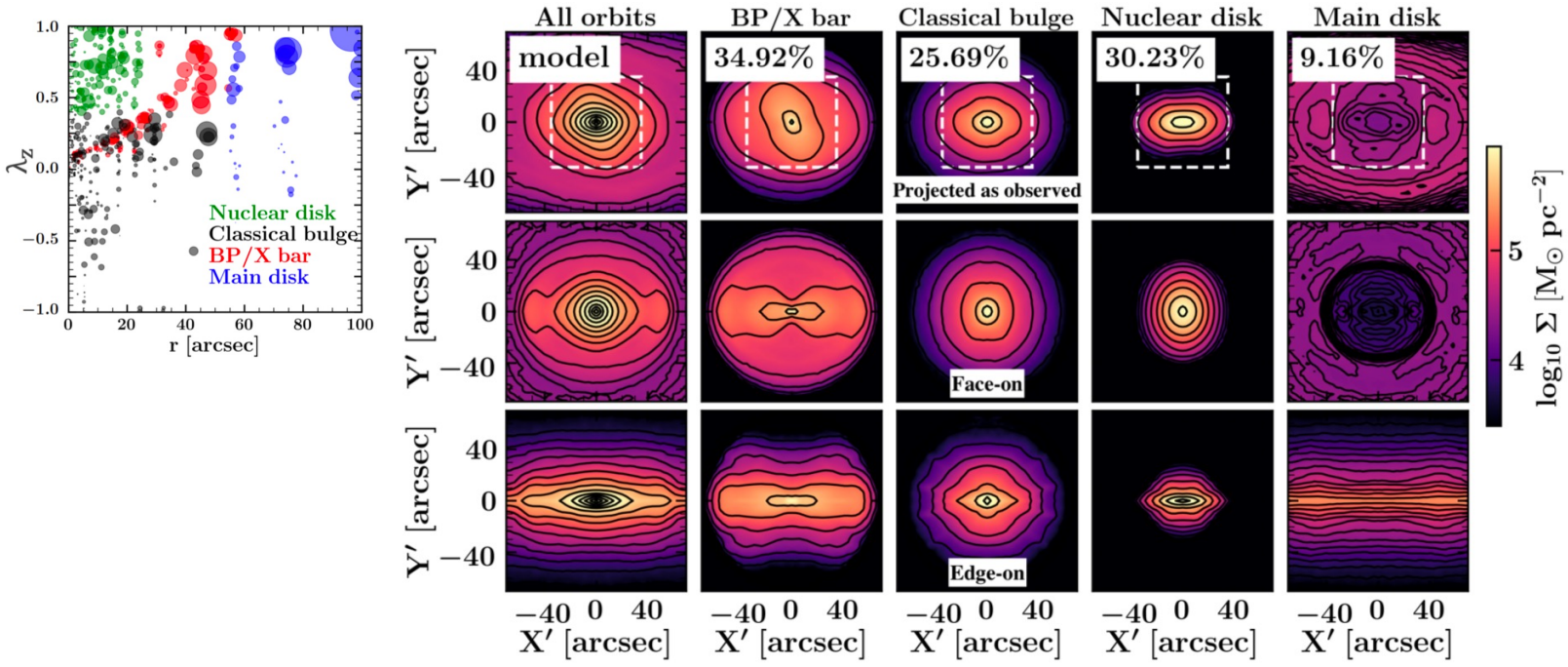




- Strongly constrain the bar pattern speed, even with limited data spatial coverage.
- Bar constrained by both the mean velocity and velocity dispersion maps
- A slow bar, with the dimensionless bar rotation parameter of R=2.2.

Tahmasebzadeh, Zhu, Shen et al. 2023 submitted

Dynamical structure decomposition for NGC 4371

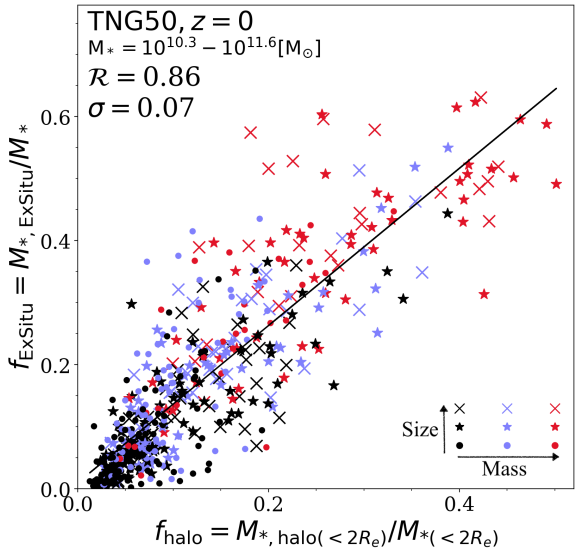


- BP/X bar identified from orbit frequency analysis (x1 dominates).
- Nuclear disk/classic bulge separated by circularity distribution.

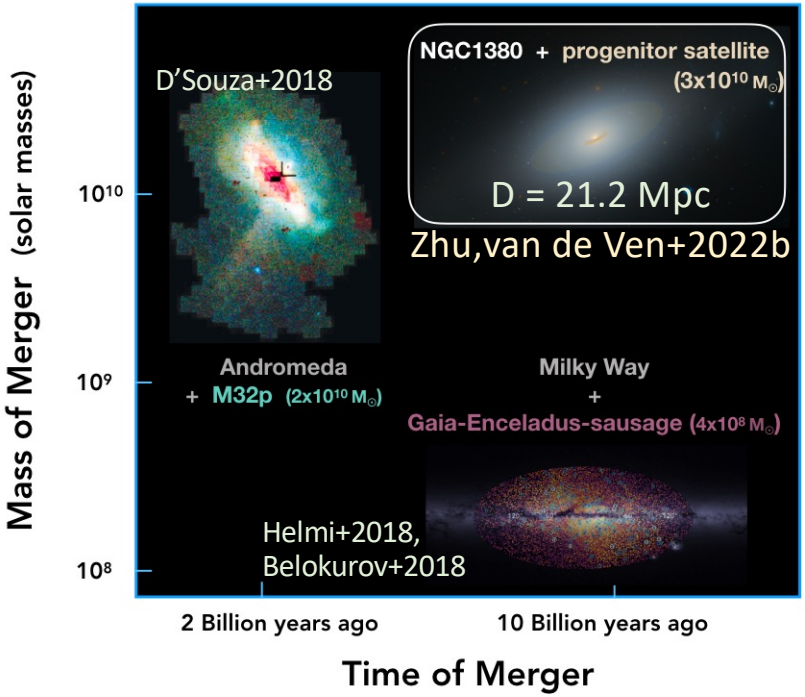
Tahmasebzadeh, Zhu, Shen et al. 2023 submitted

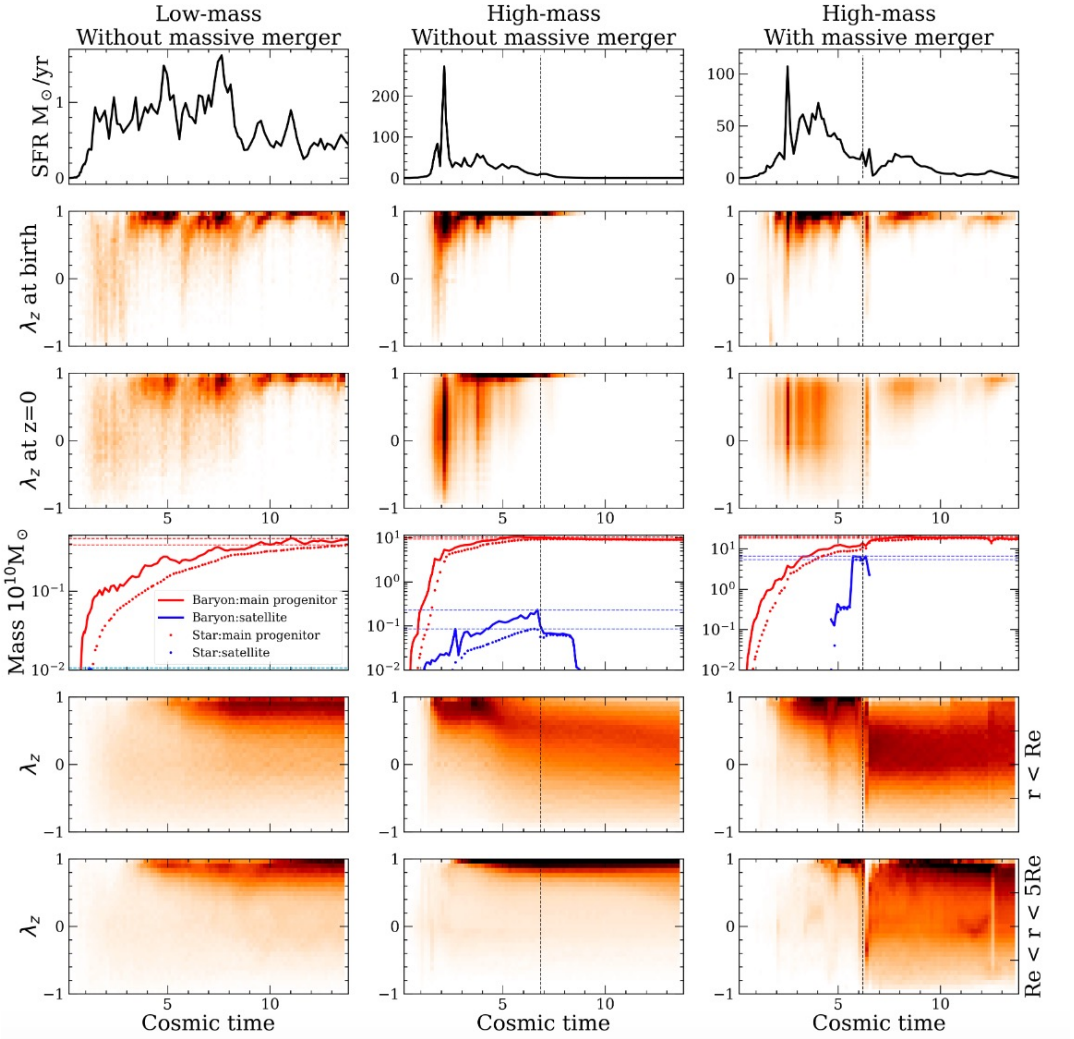
Summary

- We created a population-orbit superposition method (Zhu+2020), and modified it to barred galaxies (Tahmasebzadeh, Zhu, Shen+ 2022, 2023).
- Three major physical origins of dynamically hot bulge.
- Hot inner stellar halo is a good indicator of ancient massive mergers.
- Uncover the assembly history of NGC 1380 with high-quality MUSE data.



Zhu,Pillepich+2022a




Low-mass
Without massive merger
High-mass
Without massive merger
High-mass
With massive merger
SFR M⊙/yr
λz at birth
λz at z=0
Mass 10^10M⊙
Baryon:main progenitor
Baryon:satellite
Star:main progenitor
Star:satellite
λz
r < Re
Re < r < 5Re
Cosmic time