Gaia anisotropic structure in the simulations

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Institute for Computational Cosmology
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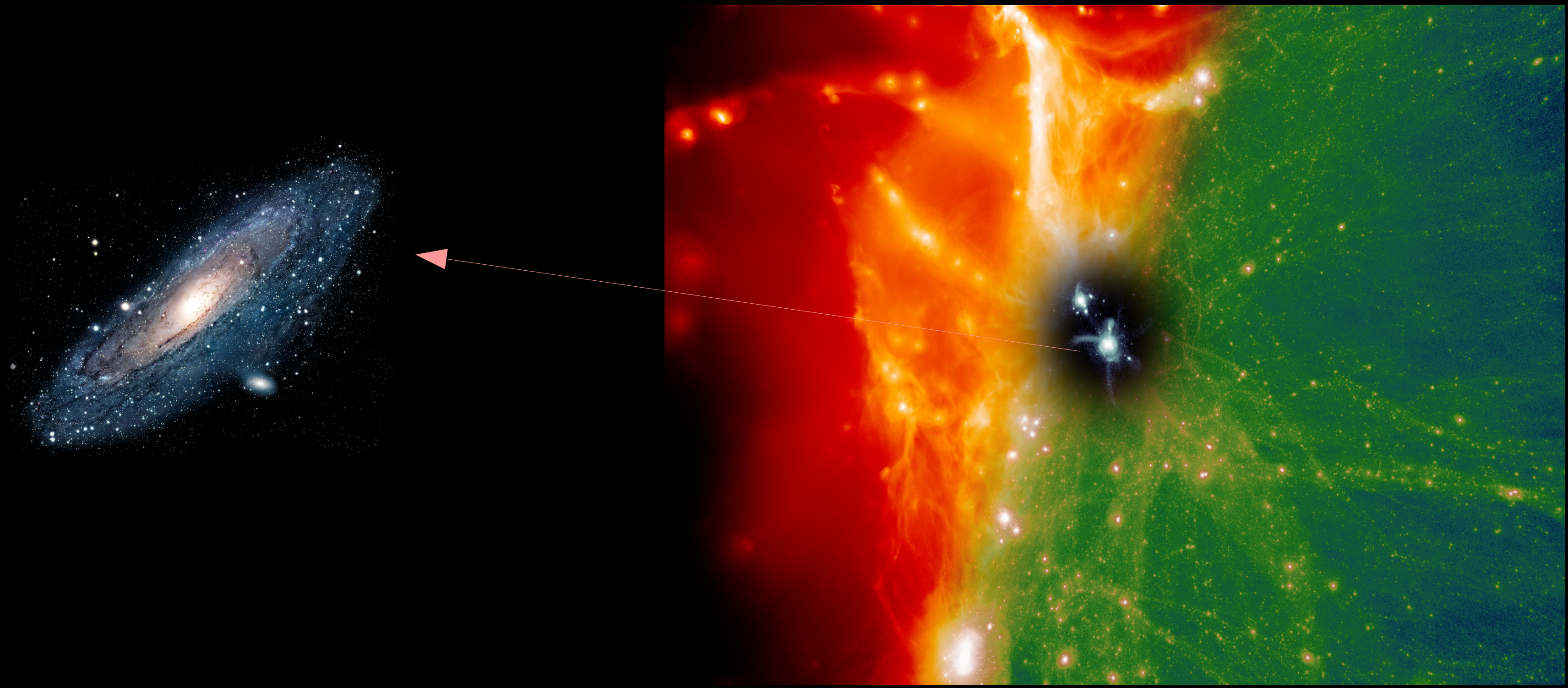
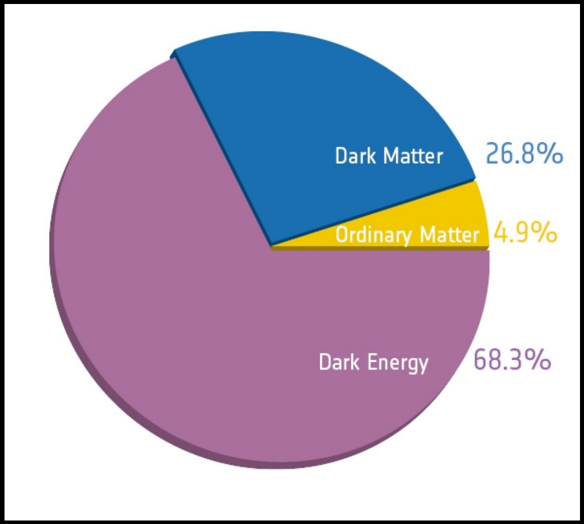
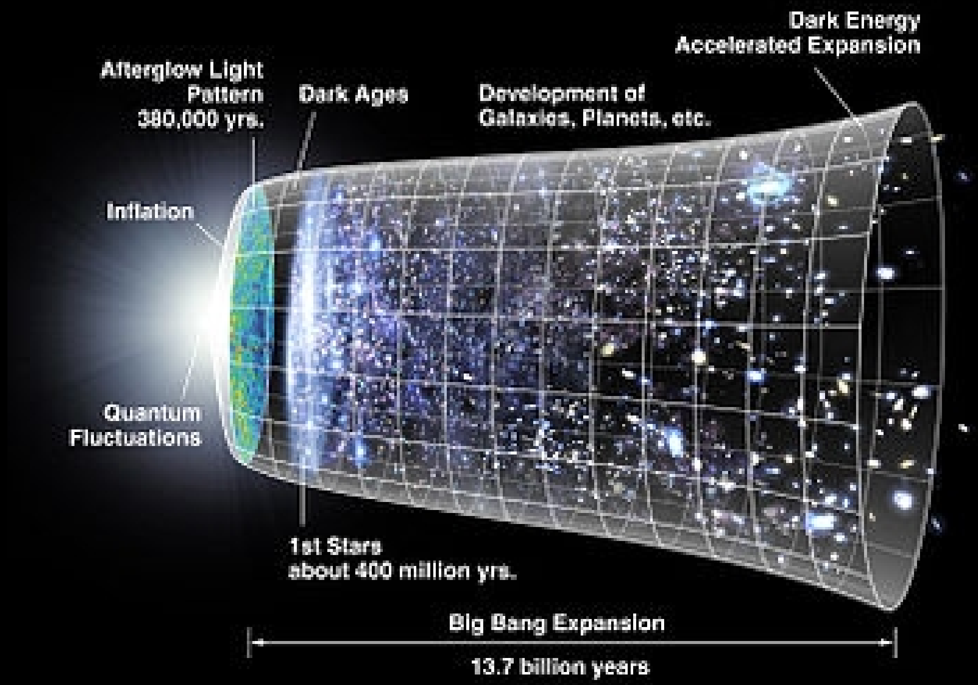


APOSTLE project
Gas, DM, and stars in a simuated Local Group

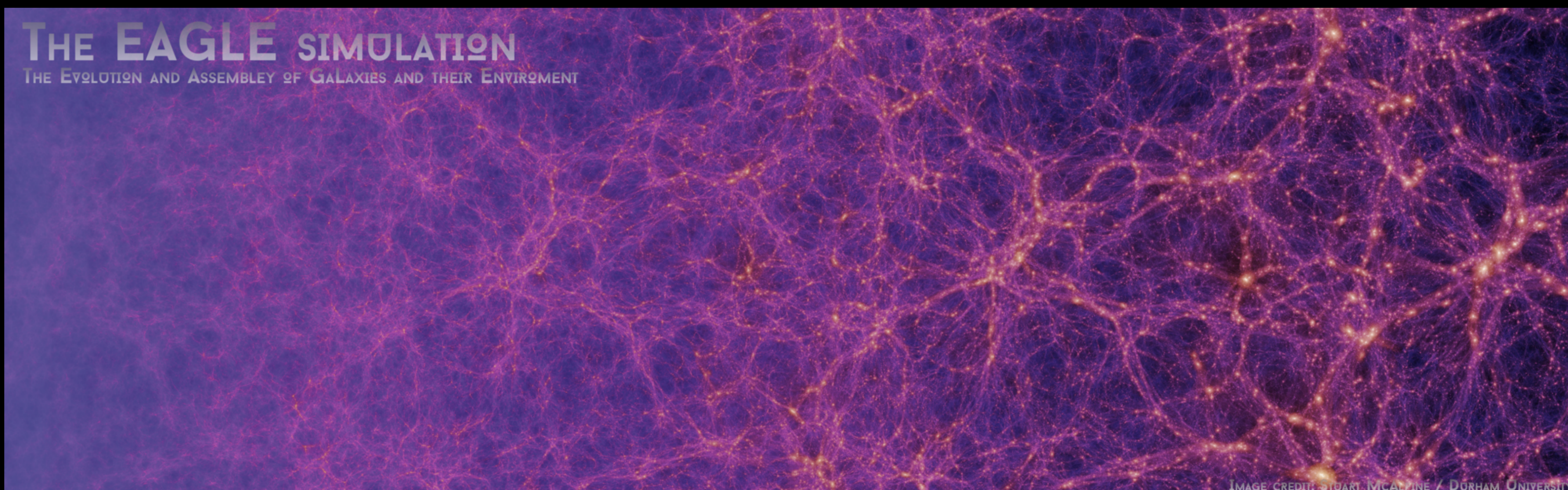
Standard model of cosmology:
Lambda-Cold Dark Matter (LCDM)



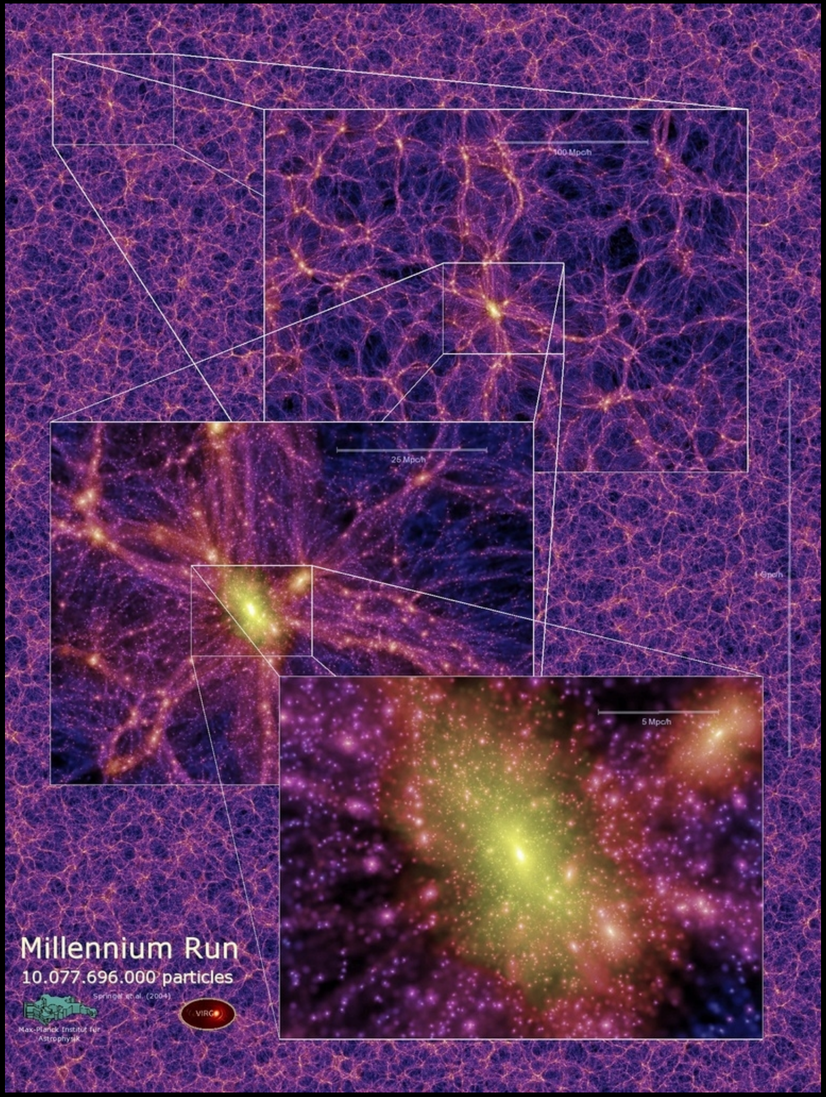
Planck collaboration



Dark matter evolution through cosmic time



Big Bang → Time → today

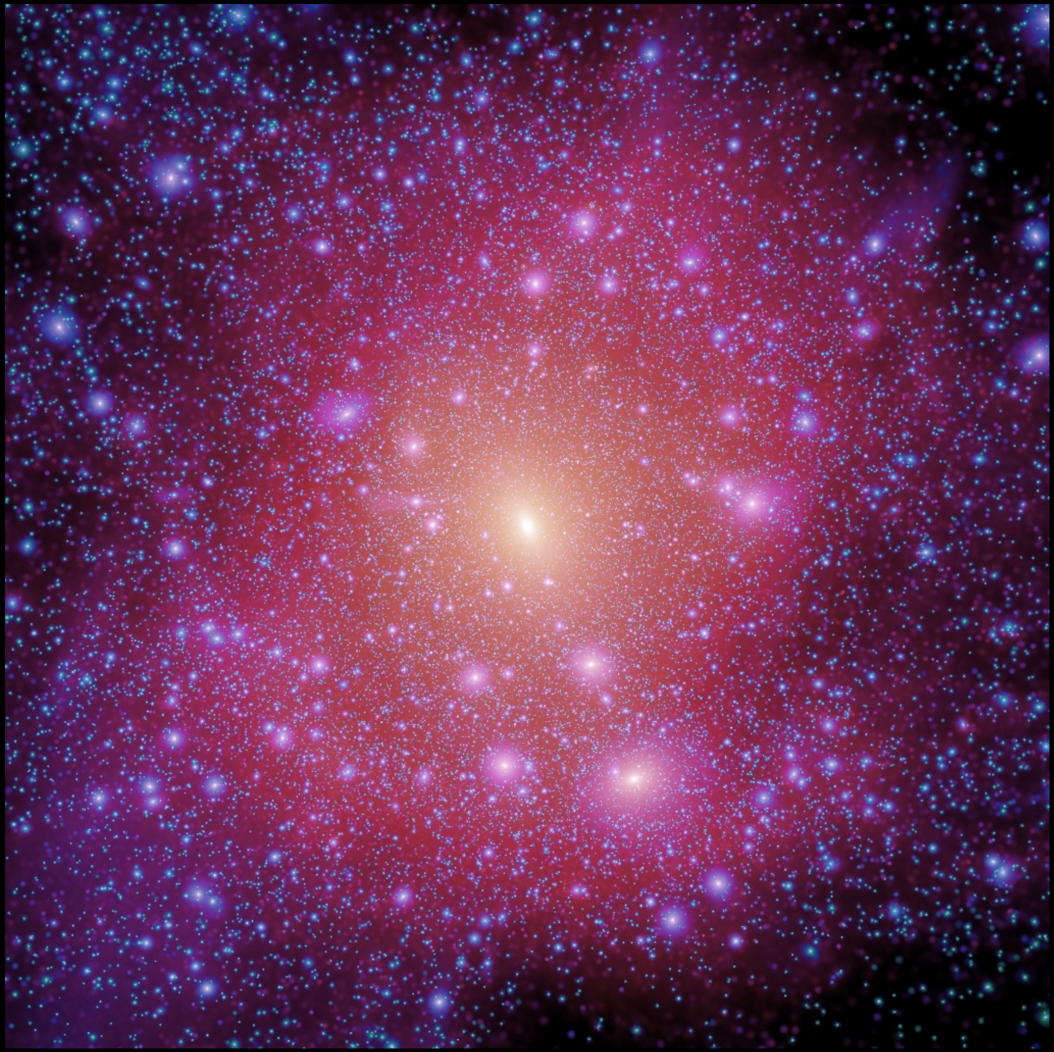


Millennium Simulation (Springel+2005)

Predictions of the standard model of cosmology:

- cosmic web structure
- Hierarchical growth
- “Clumpiness”
- Self-similarity of dark matter halos
- Distribution of dark matter inside halos

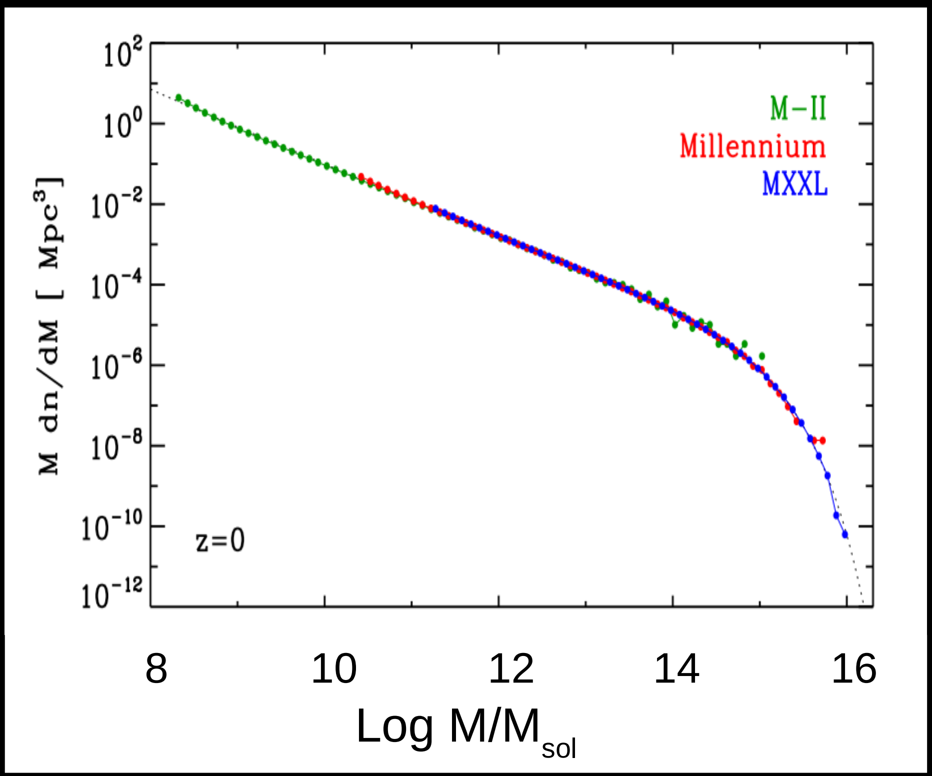
Dark matter halo of a MW size halo



Aquarius Simulations – Springel+2008

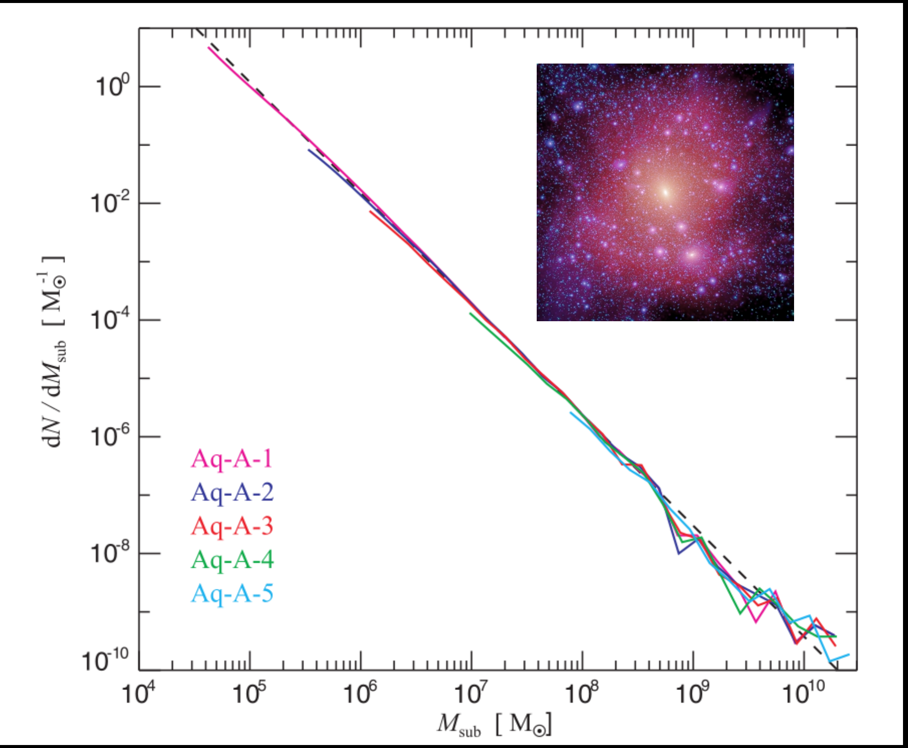
CDM predictions: Halo mass function

Halo mass function



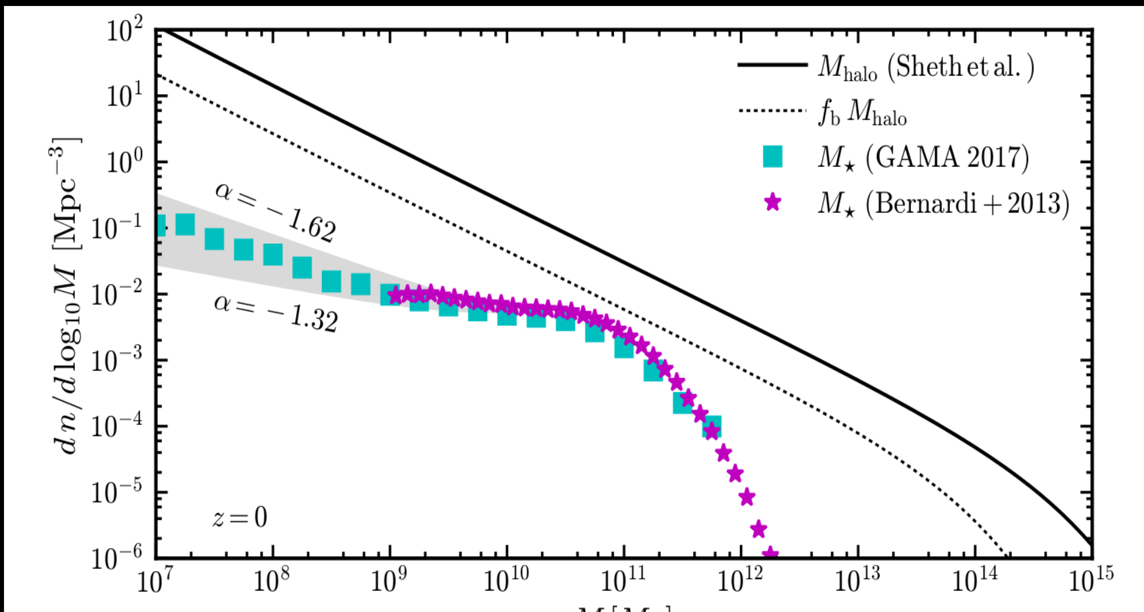
Jenkins+2010, Angulo+2012

Subhalo mass function

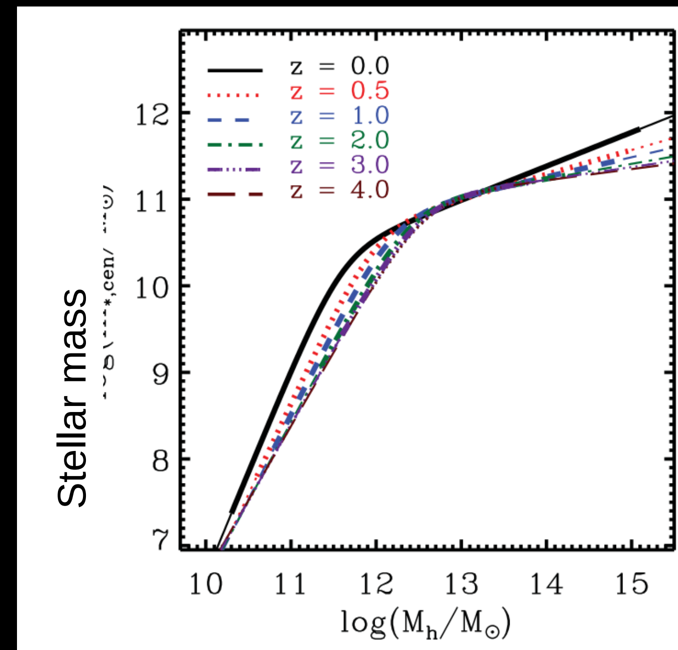


Aquarius Project-Springel+2008

CDM predictions: Halo mass function and galaxy formation



Bullock & Boylan-Kolchin 2017



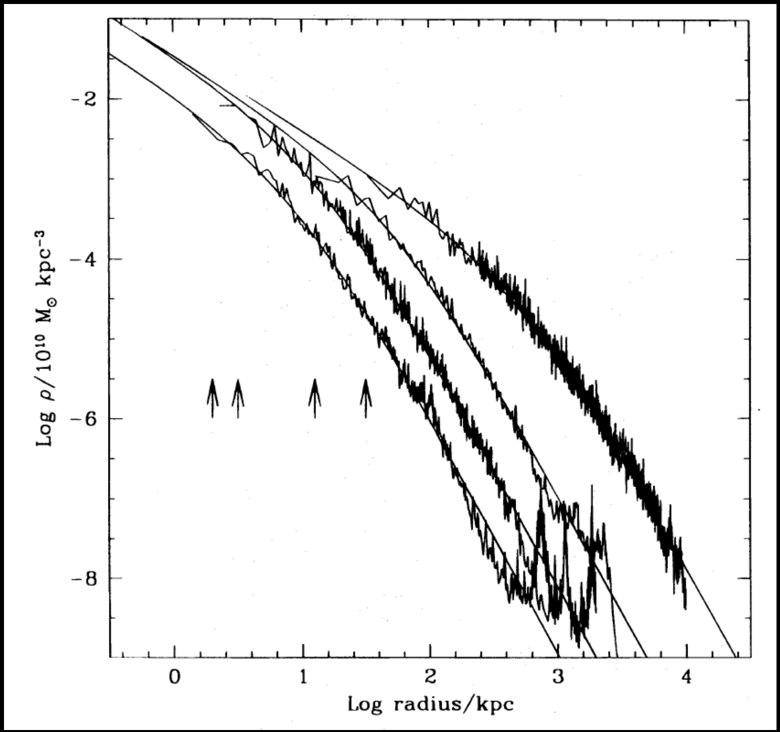
Moster+2013

“Abundance Matching” : assuming there is a one-to-one and monotonic relation between stellar mass and halo mass

(Frenk+1988, Kravtsov+2004, Guo+2010, Behroozi+2013, Moster+2013, etc)

CDM prediction: Internal structure of dark matter halos

Triaxial halos with a universal profile



Navarro, Frenk & White (1996,97)

NFW profile

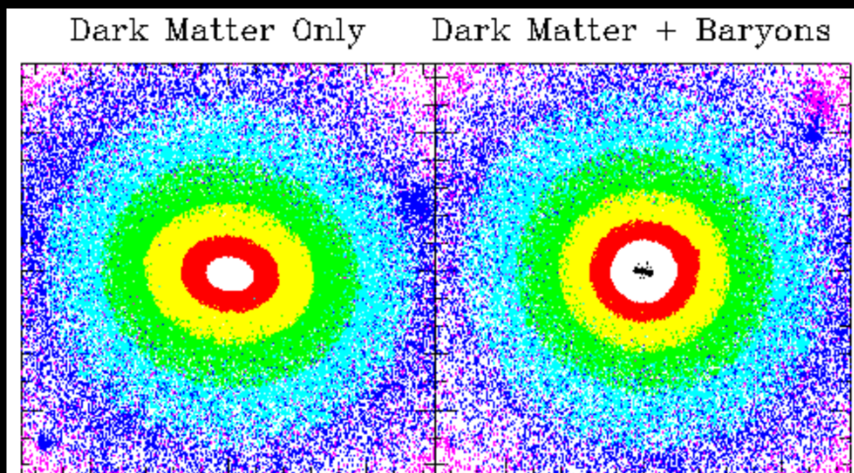
$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

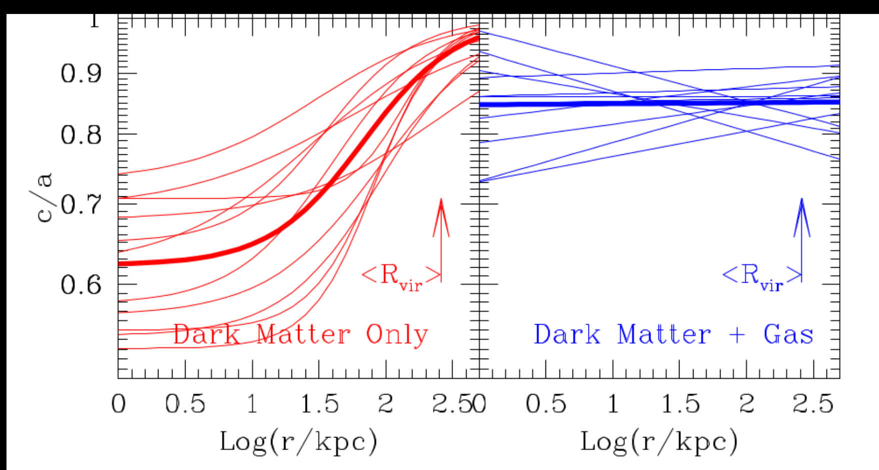
Two-parmeters profile:

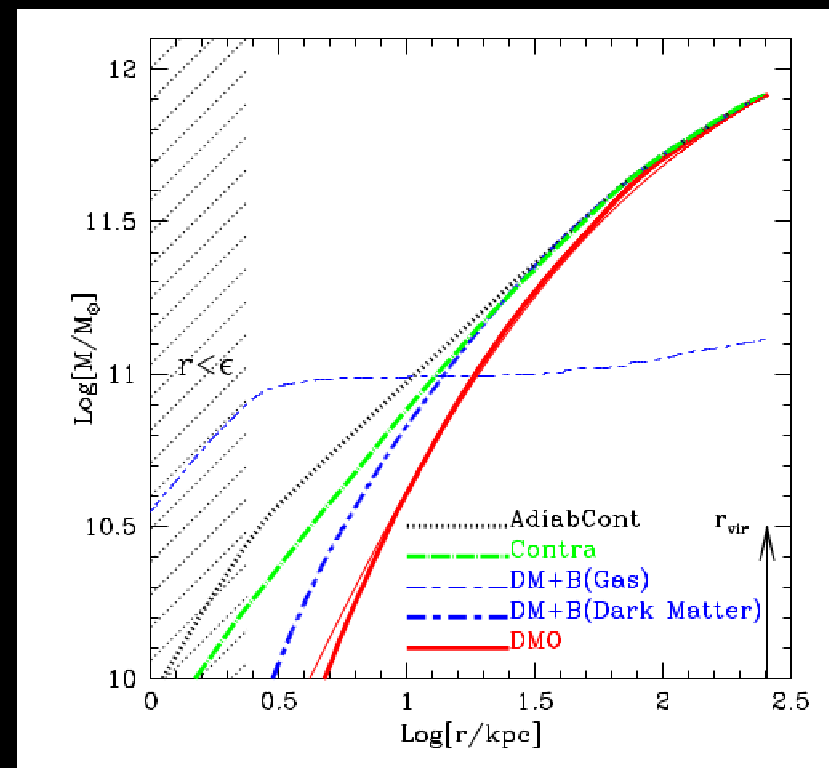
- r_s, ρ_s
- M_{200}, c

CDM prediction: Internal structure of dark matter halos

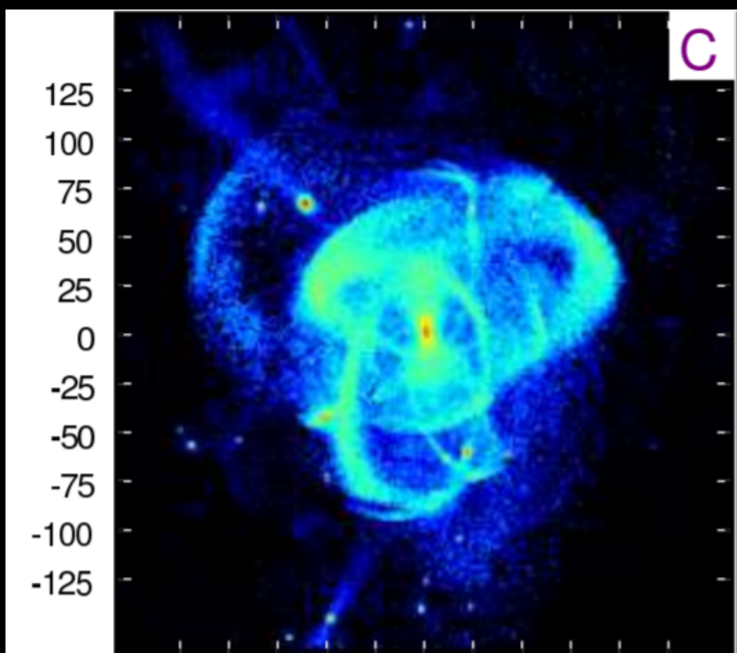
Effect of baryons



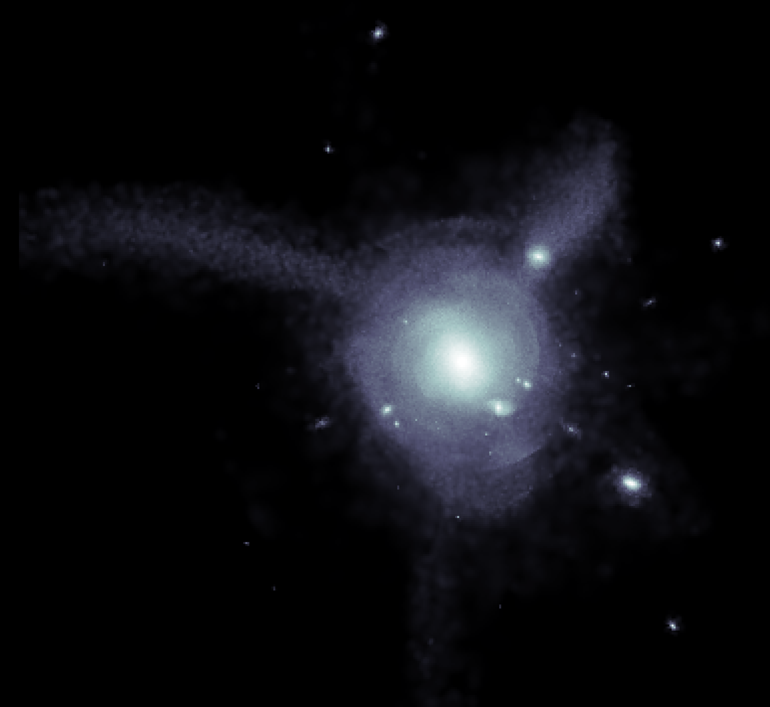




CDM predictions: Hierarchical Growth
disruption of dwarf galaxies and the formation of stellar halo

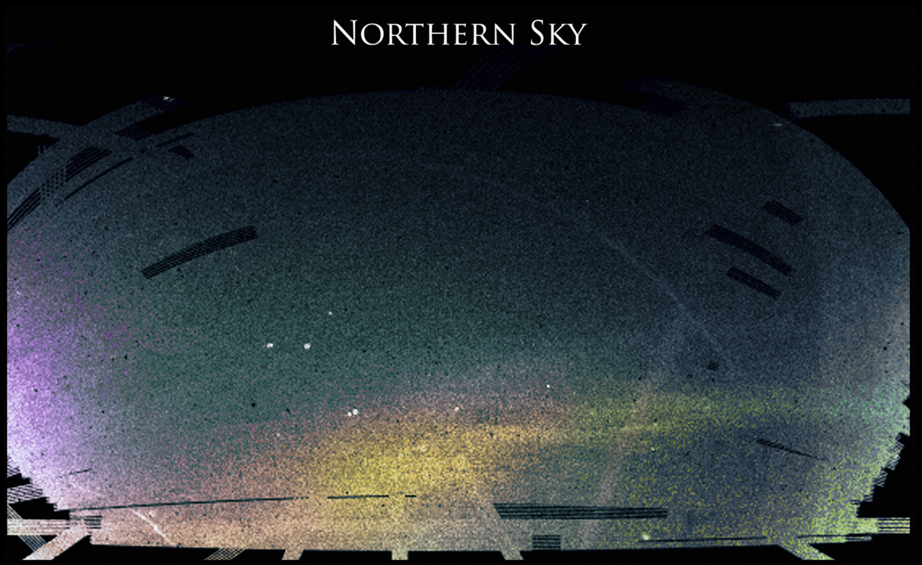


Aquarius simulations (DMO)
Cooper+2010

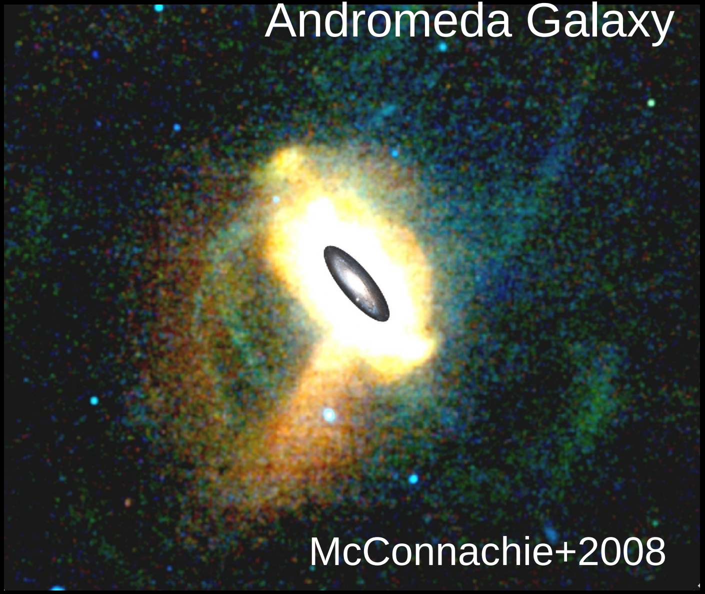


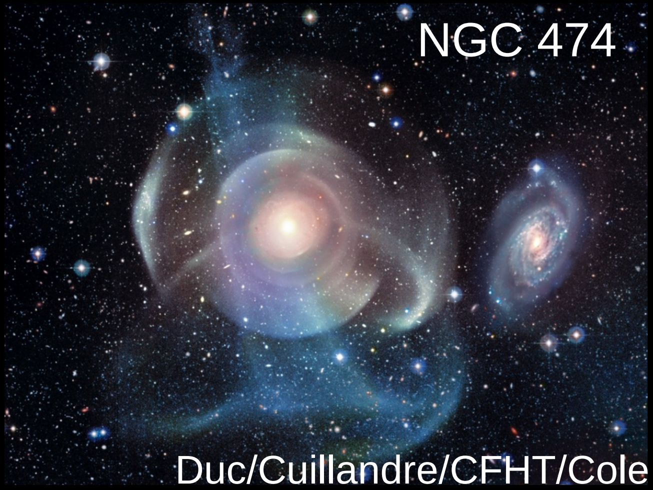
APOSTLE simulations (hydrodynamical)
Fattahi+2016, Sawala+2016

Disrupted dwarf galaxies and formation of stellar halo



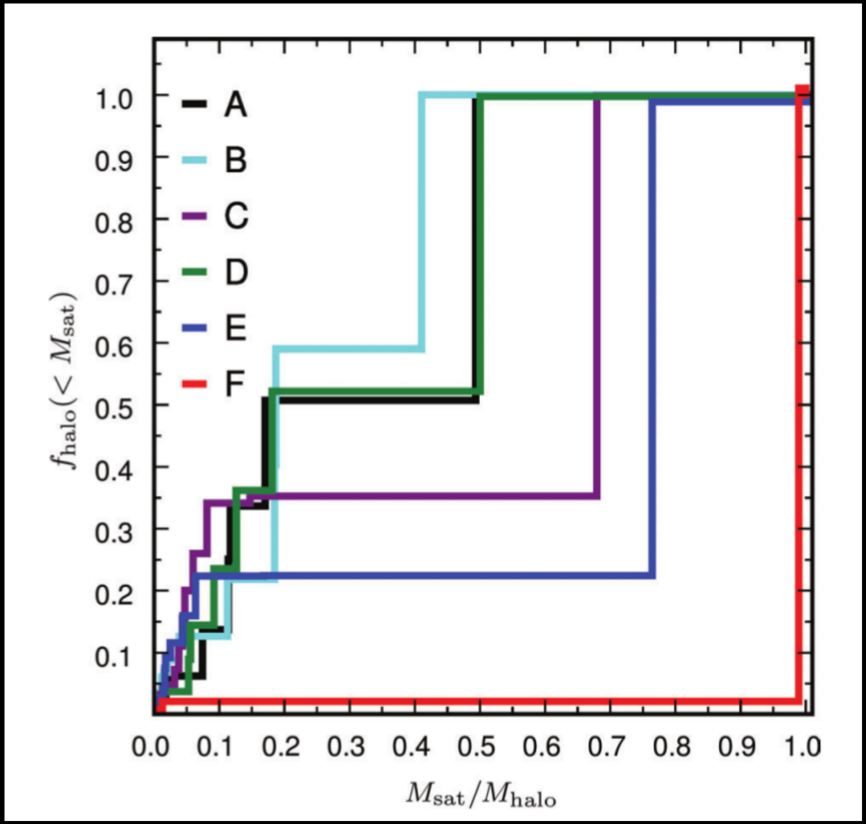
Bonaca+2012



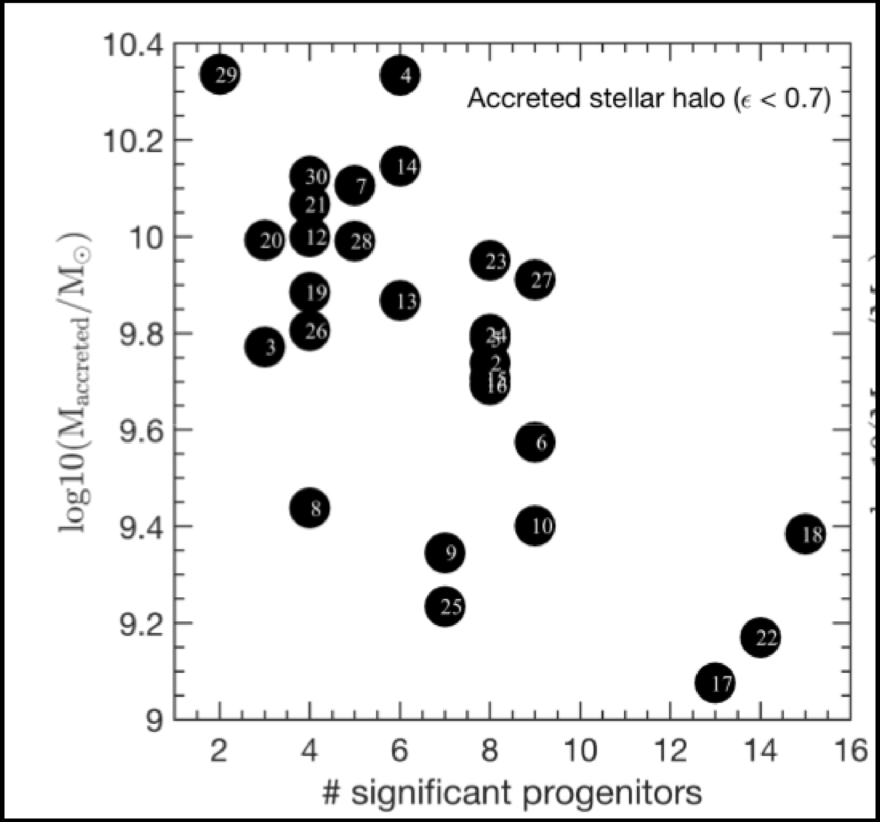


Progenitors of the stellar halo

Stellar halo is dominant in mass by a few more massive dwarfs



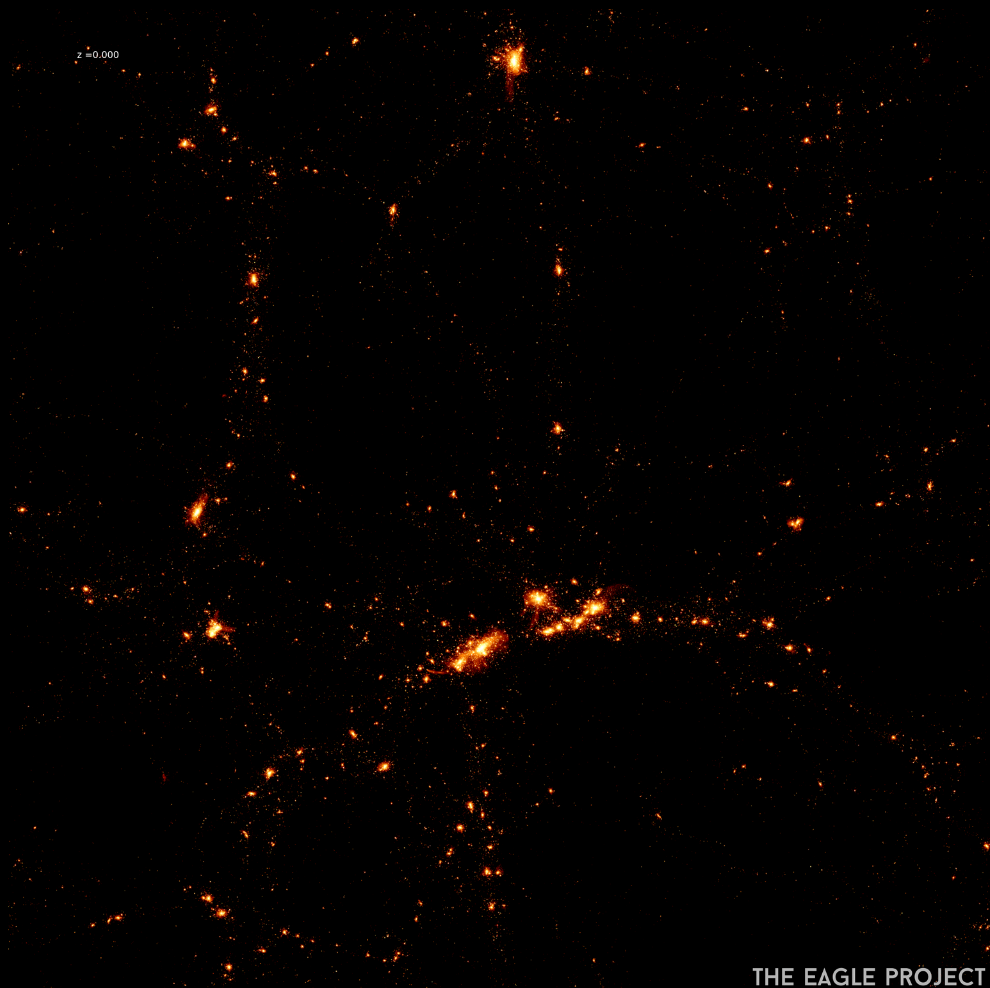
Cooper+2011



Monachesi+2017

Hydrodynamical simulations

100 Mpc

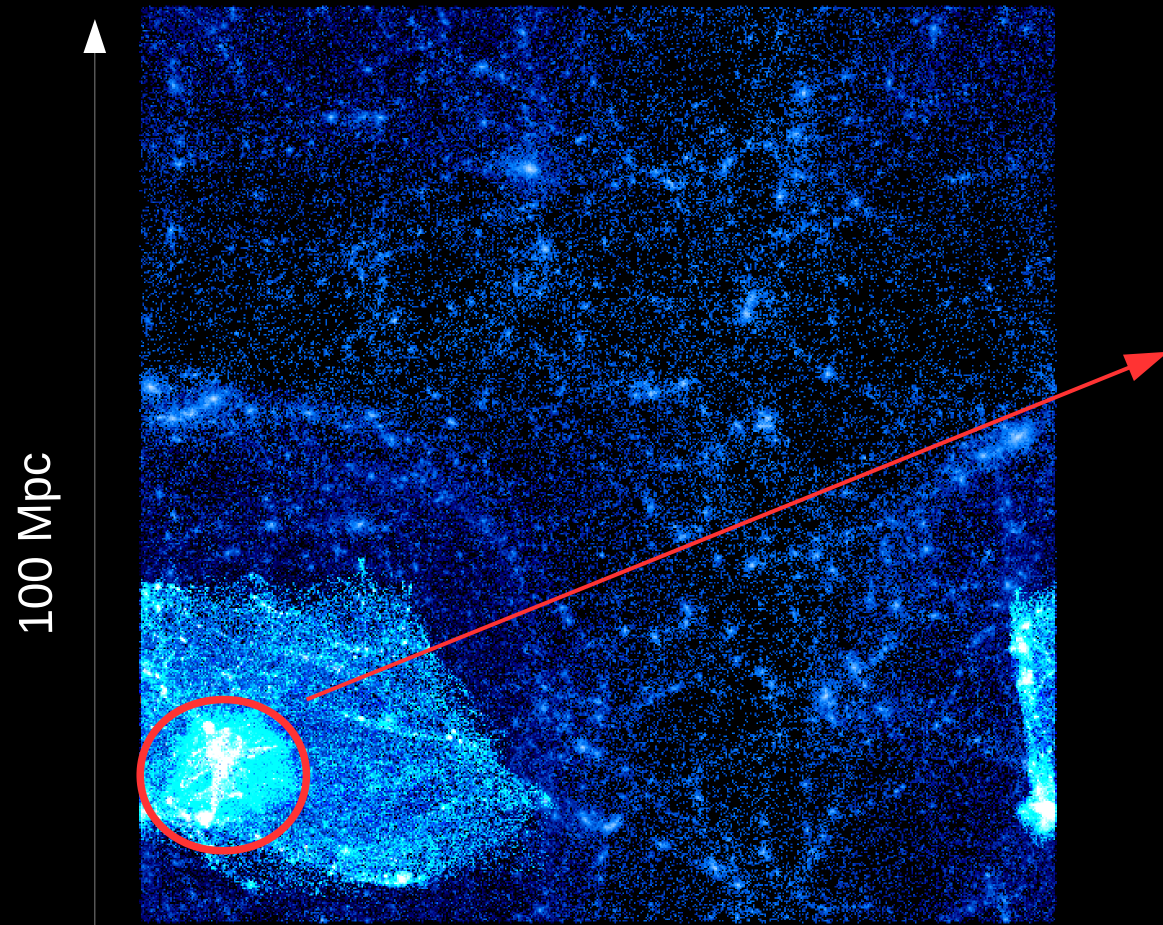


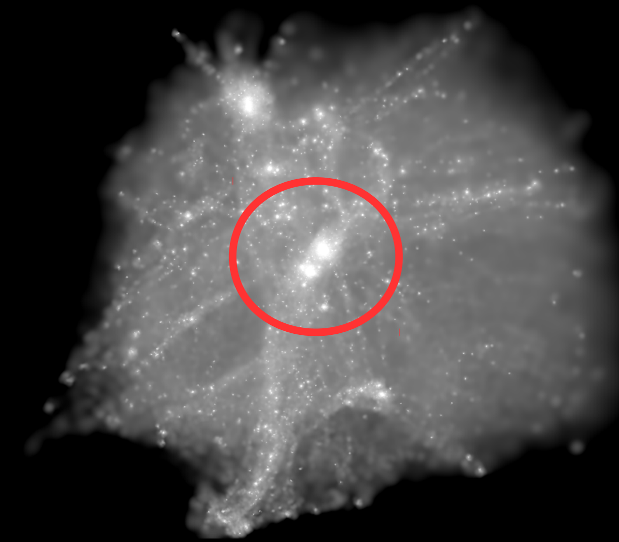
Physics included:

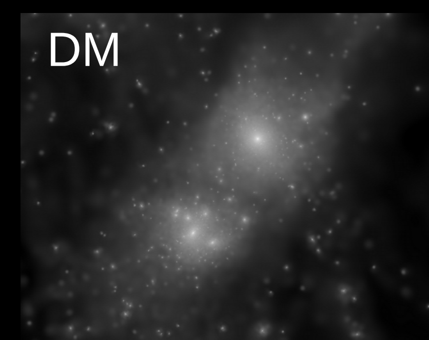
- Star formation
- cooling
- Stellar evolution
- Stellar and supernovae feedback
- UV radiation background
- AGN feedback
- ...

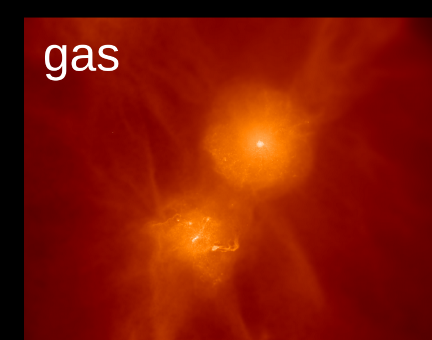
EAGLE (Schaye+2015)
Illustris (Vogelsberger+2014)
Illustris-TNG (Springel+2019)
Magneticum (Dalog+2015)
Horizon-AGN, ...

Zoom-in hydrodynamical simulations







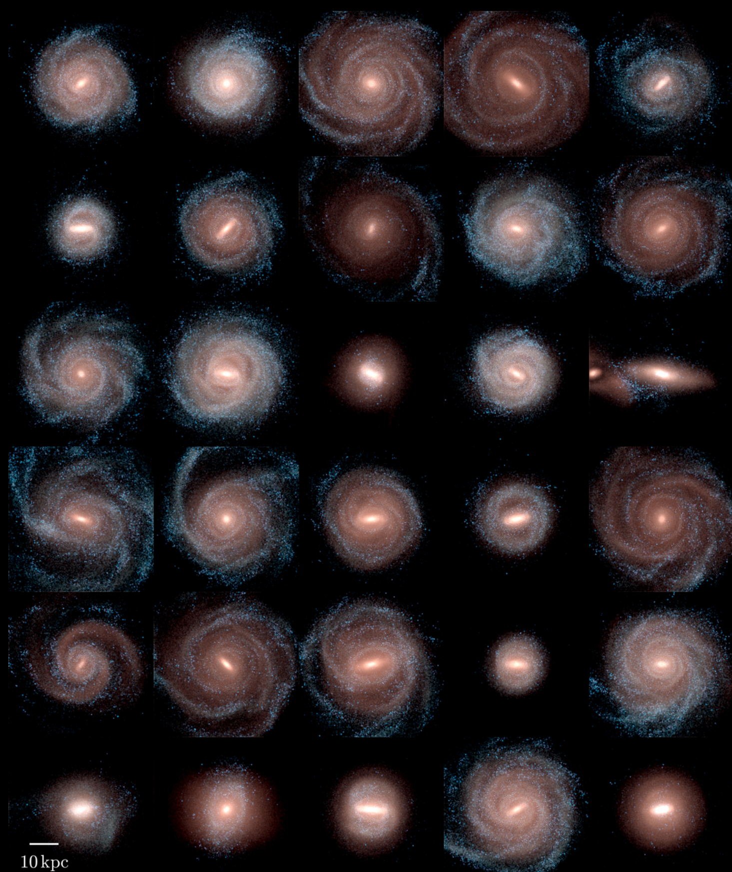


APOSTLE Local Group-like volumes
(Fattahi+2016, Sawala+2016)

DM particle mass ~ $5*10^4$ M_{sun}

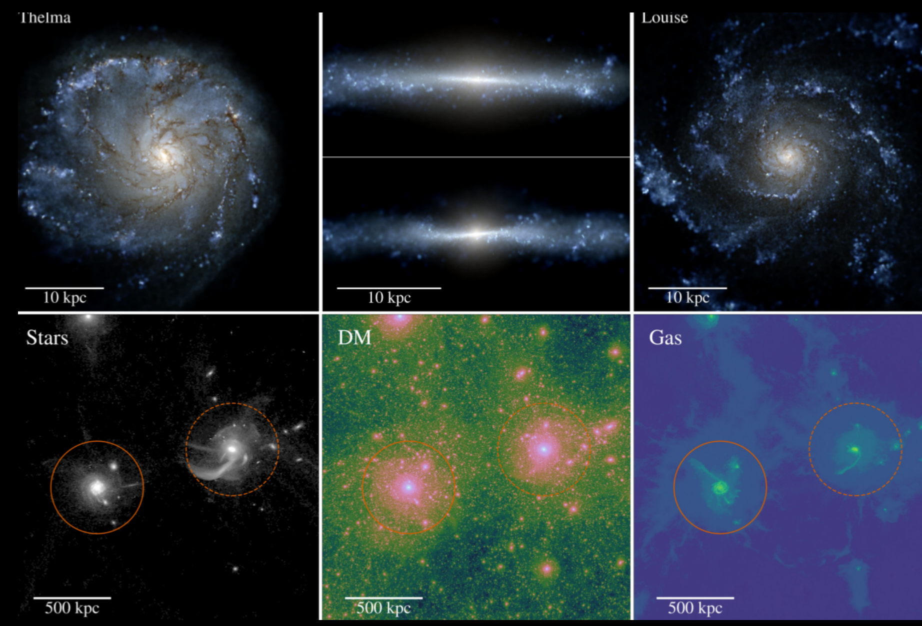
Zoom-in hydrodynamical simulations

Auriga simulations
Milky Way like halos
$m_{DM} \sim 5*10^4\ M_{sun}$



Grand+2017

FIRE simulalations
ELVIS: Local Group volumes
Latte: Milky Way halos
$m_{DM} \sim (1\text{-}2) * 10^4\ M_{sun}$



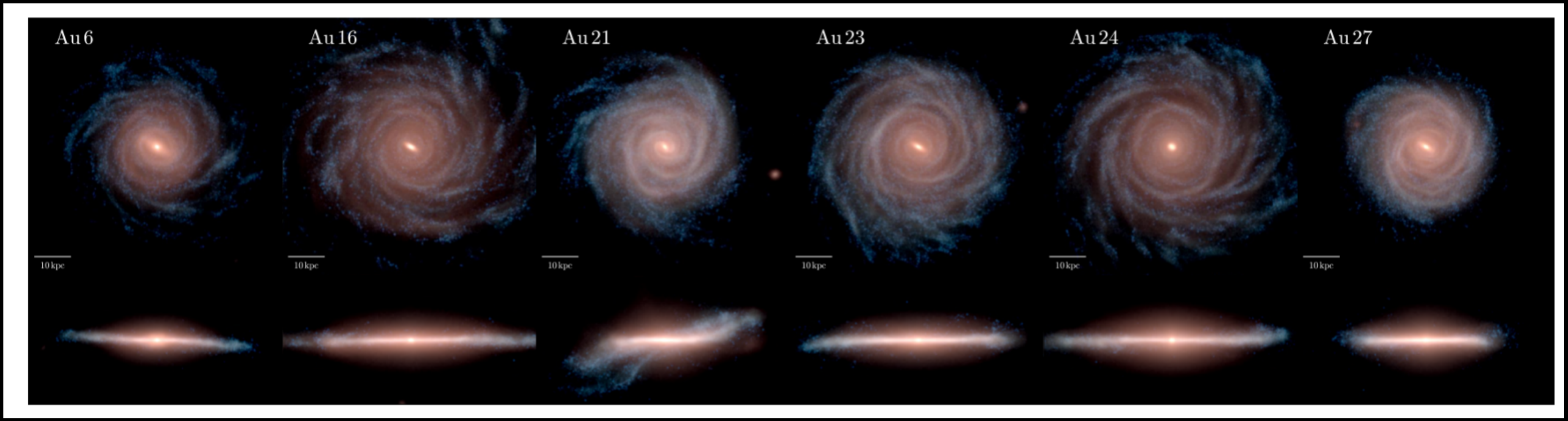
Garrsion-Kimmel+2018
Wetzel+2016

The origin of the highly radial stars in the Galactic halo

Fattahi et al. 2018 (arXiv: 1810.07779)

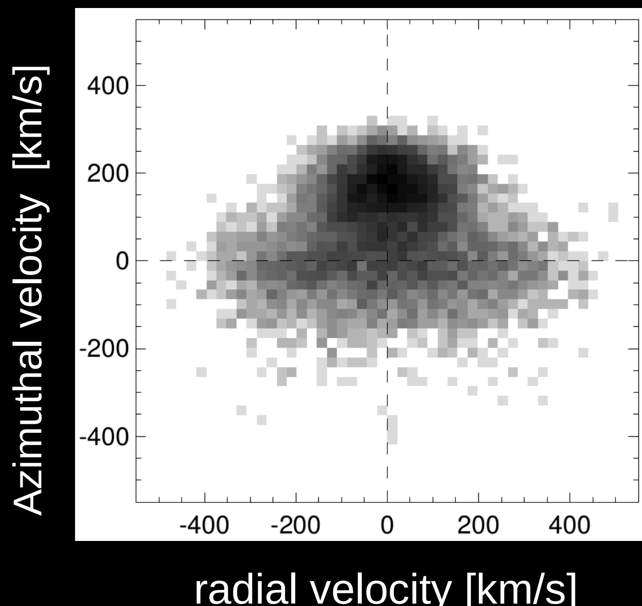
with

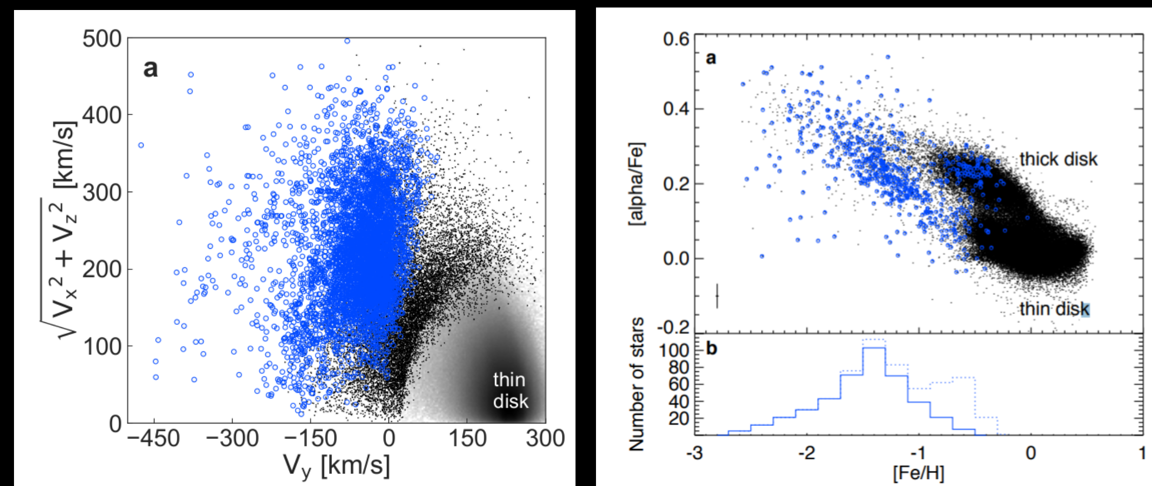
Vasily Belokurov, Alis Deason, Carlos Frenk and the Auriga team



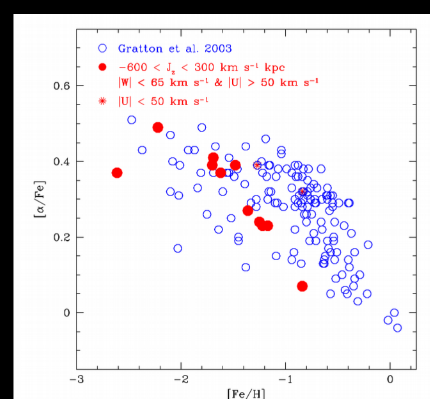
Kinematic features of the inner stellar halo (Gaia-Sausage, Enceladus, GRASP)

Belokurov+2018

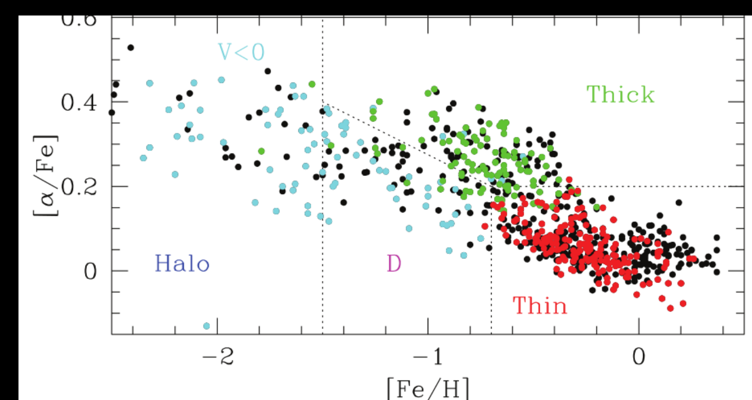




Helmi+2018



Meza+2005



Navarro+2011

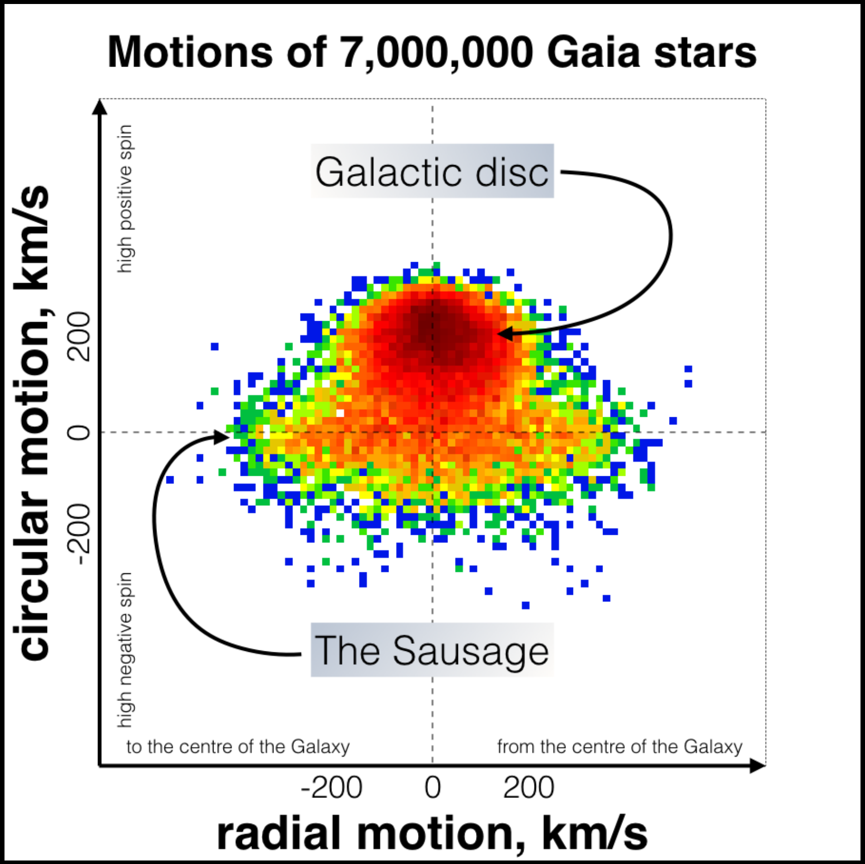
Kinematics of the inner stellar halo

Gaia-Sausage (Belokurov et al. 2018)

Gaia DR1 + SDSS

Velocity space of stars
([Fe/H] < -1 , b > 25 deg)
shows two prominent features

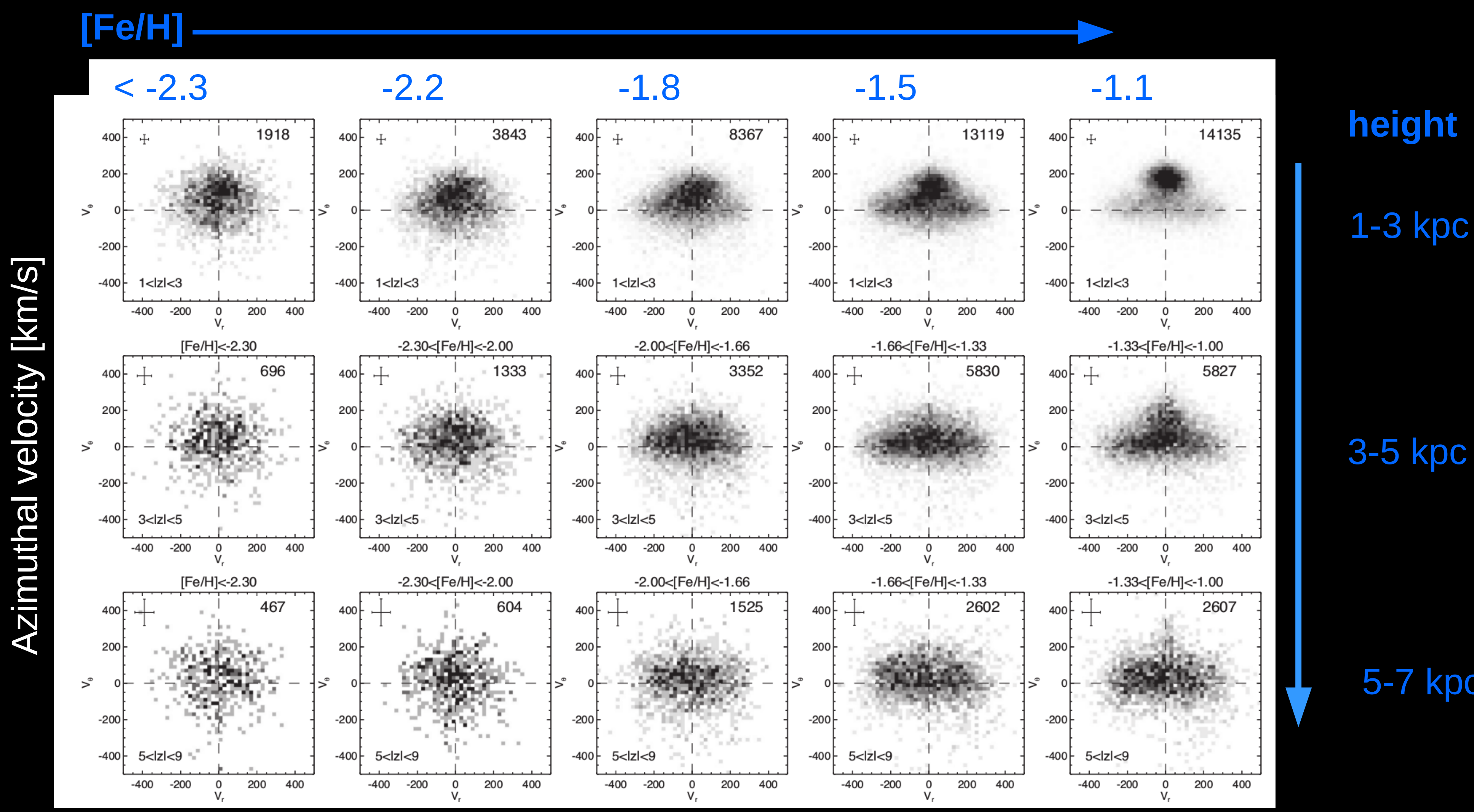
- Galacic disk rotating with ~ 200 km/s
- halo component with highly orbital anisotropy, beta β ~ 0.85



Belokurov et al. 2018

Kinematics of the inner stellar halo

Gaia-Sausage (Belokurov et al. 2018)



Galactocentric radial velocity [km/s]

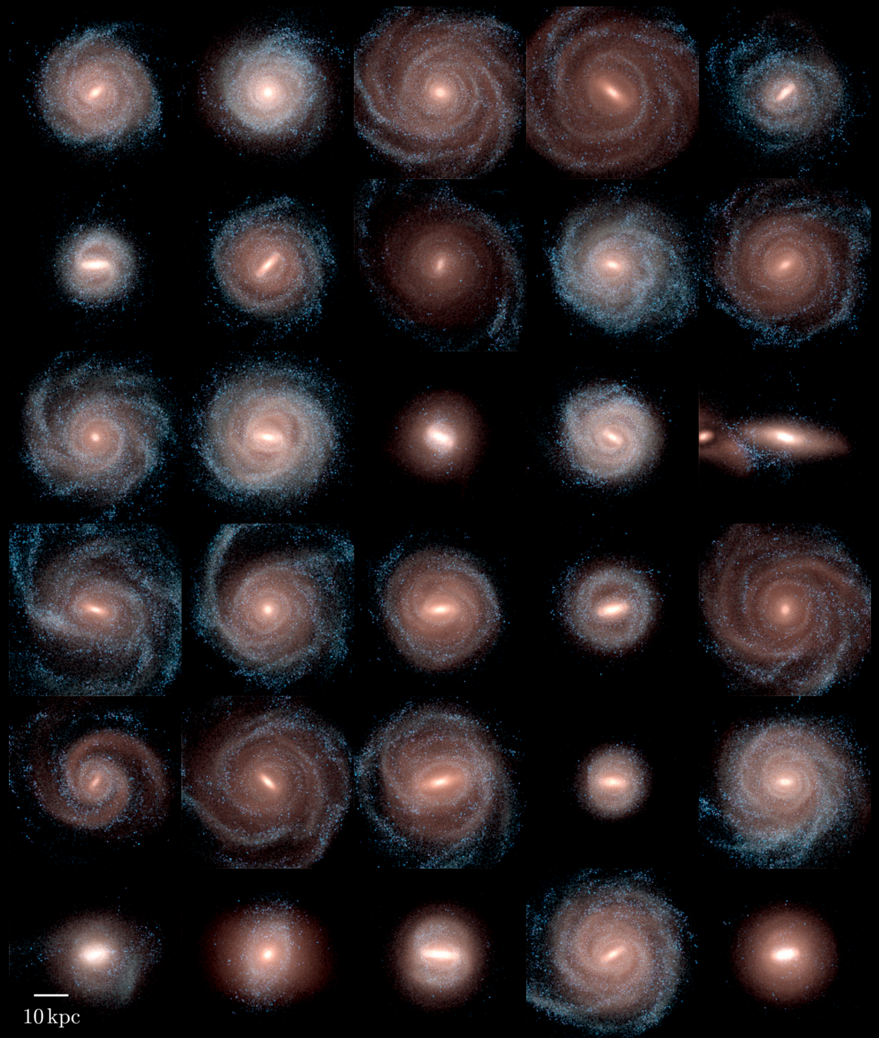
Auriga hydrodynamical simulations

(Grand+2017)

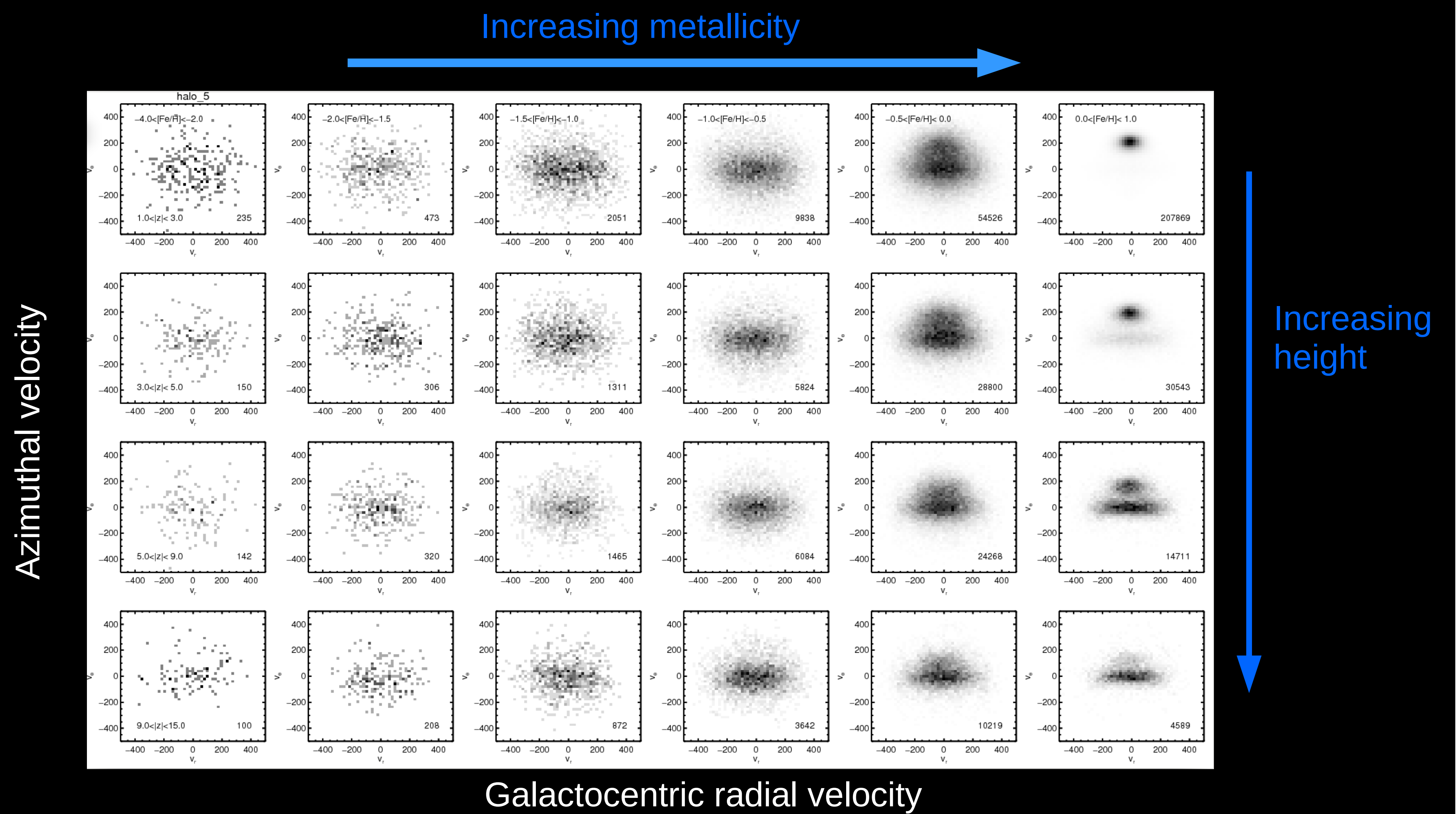
- Zoom-in hydrodynamical simulations of Milky Way-like halos

- Isolated halos with mass ~ 10^{12}
  - 30 halos at the fiducial resolution

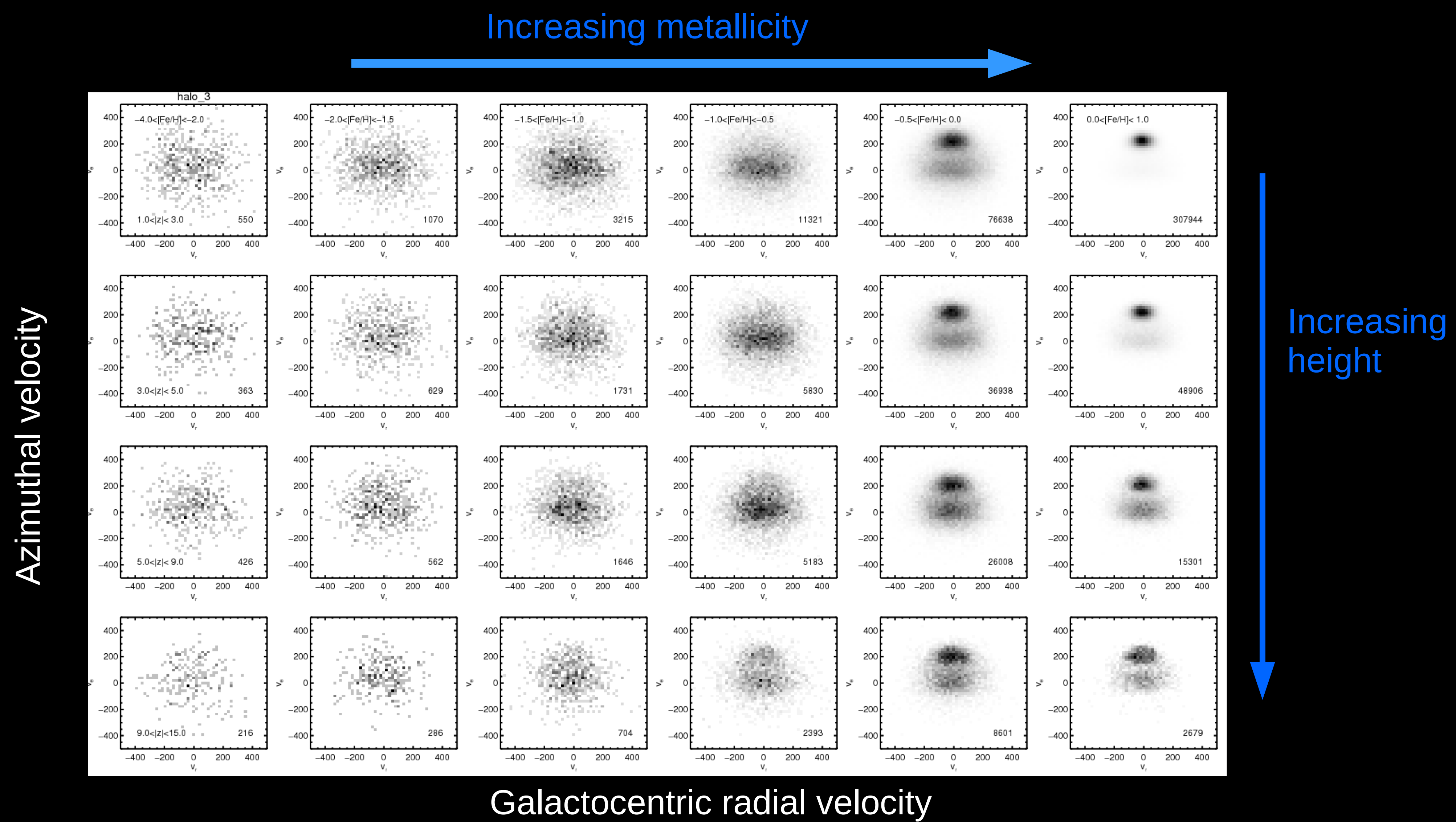
- Run with Arepo (Springel 2010) full hydrodynamics + MHD



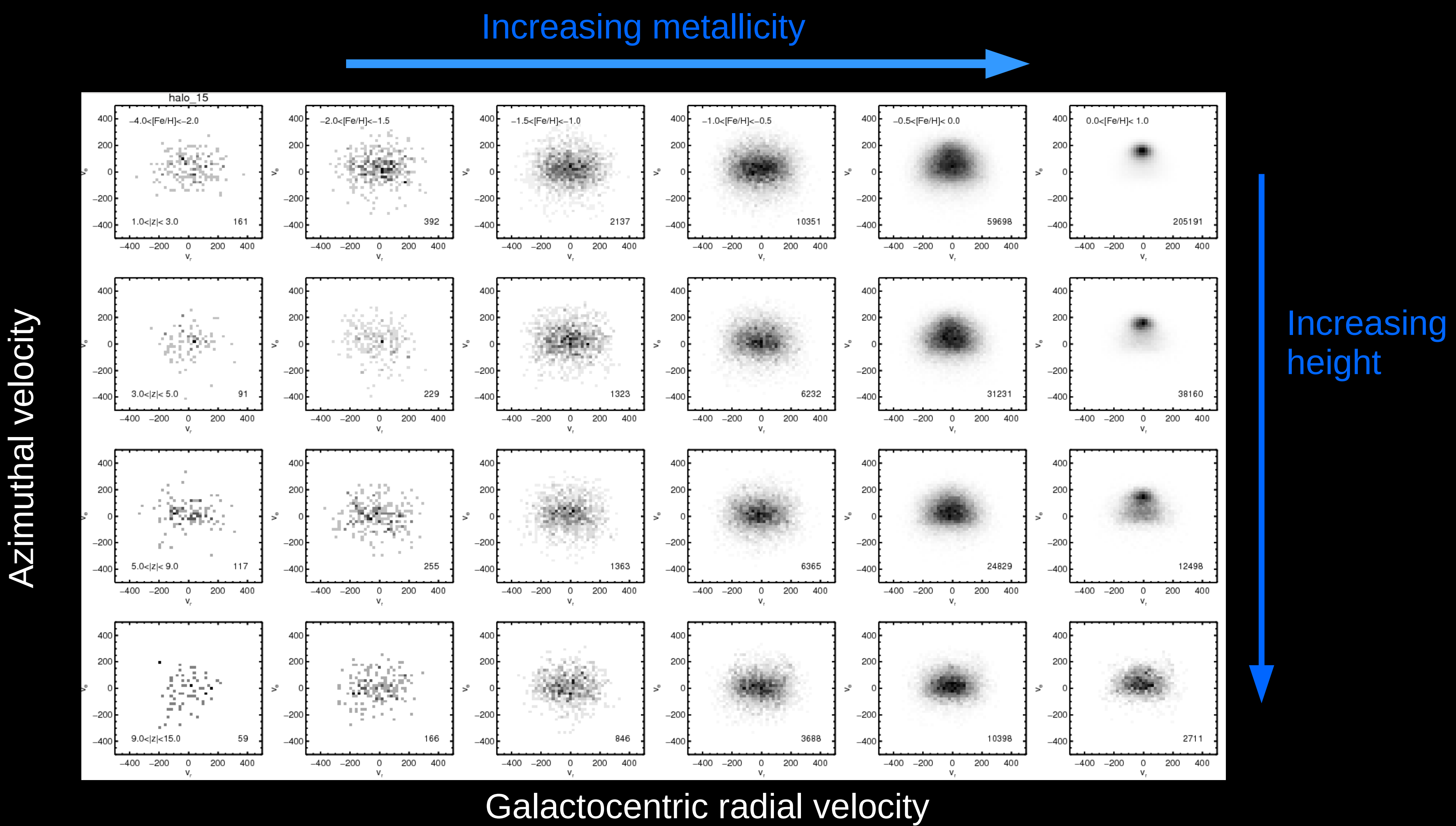
Inner stellar halo in Auriga: examples



Inner stellar halo in Auriga: examples



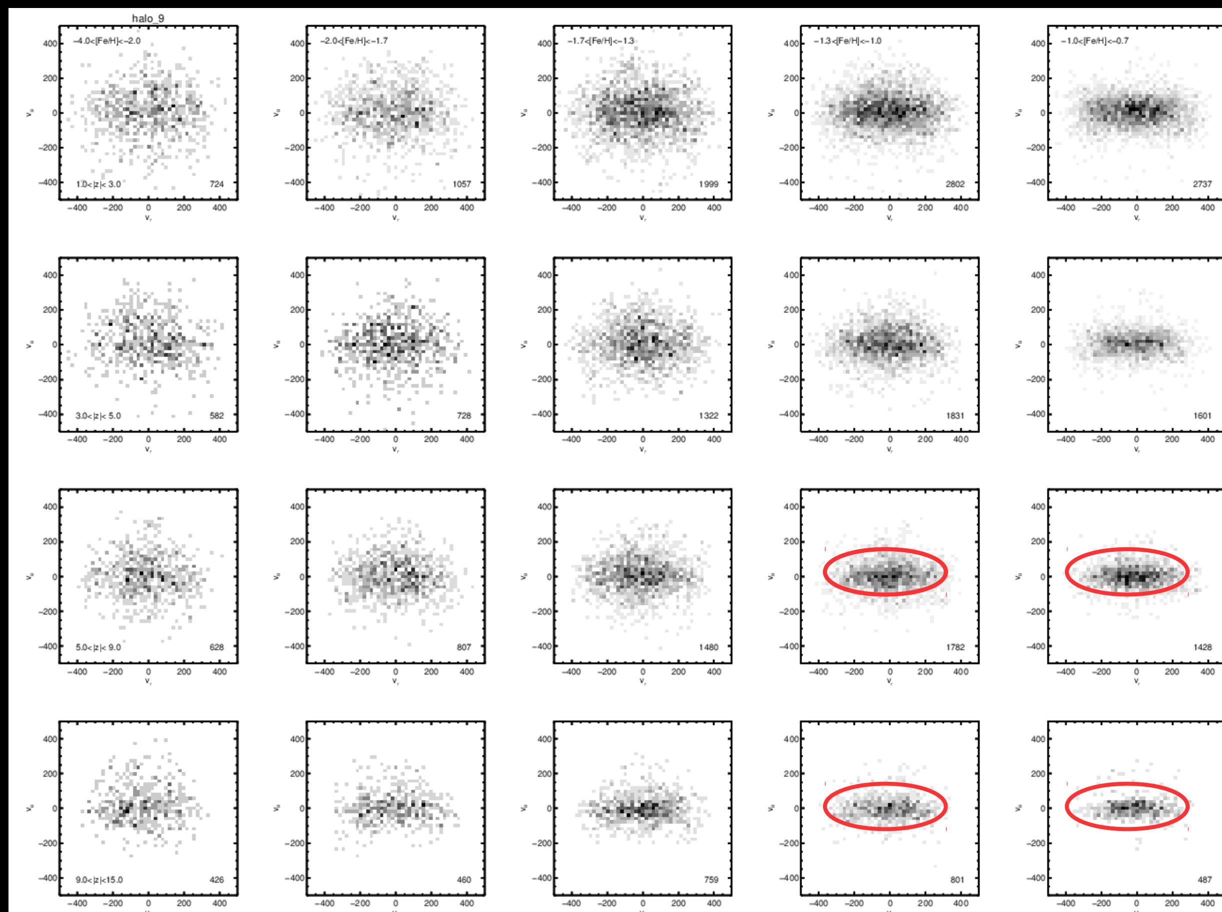
Inner stellar halo in Auriga: examples



Inner stellar halo in Auriga: examples

Increasing metallicity

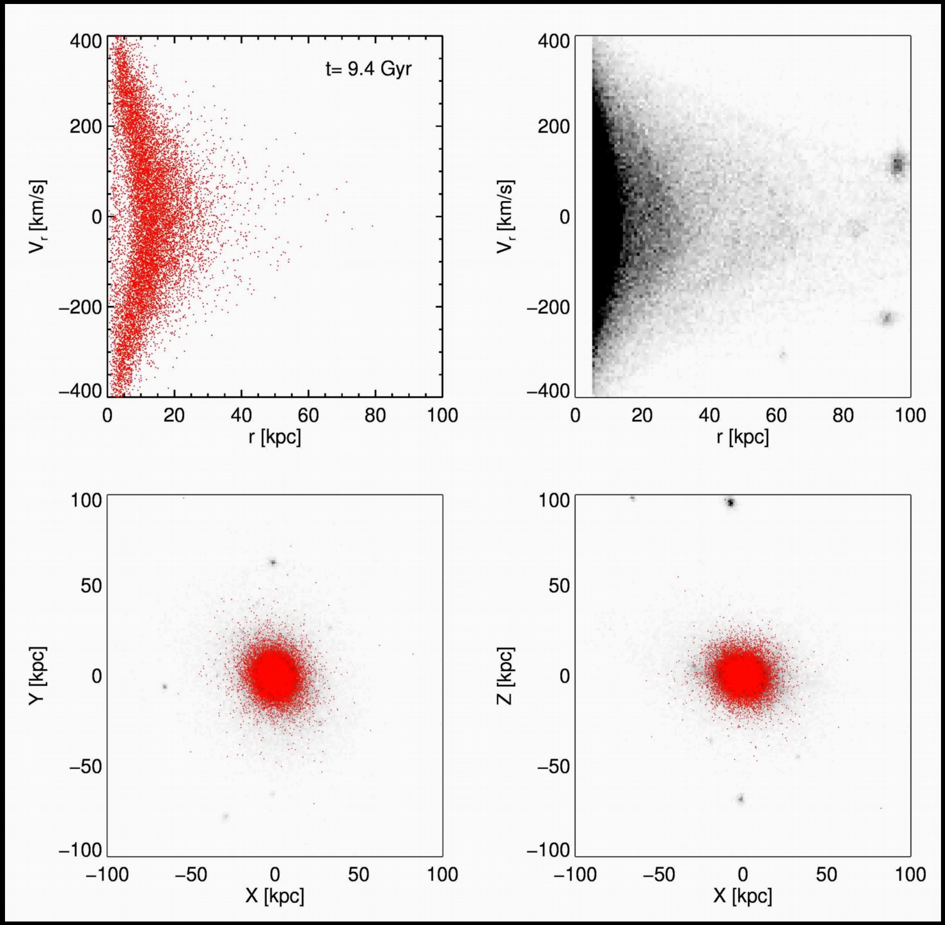
Azimuthal velocity



Increasing height

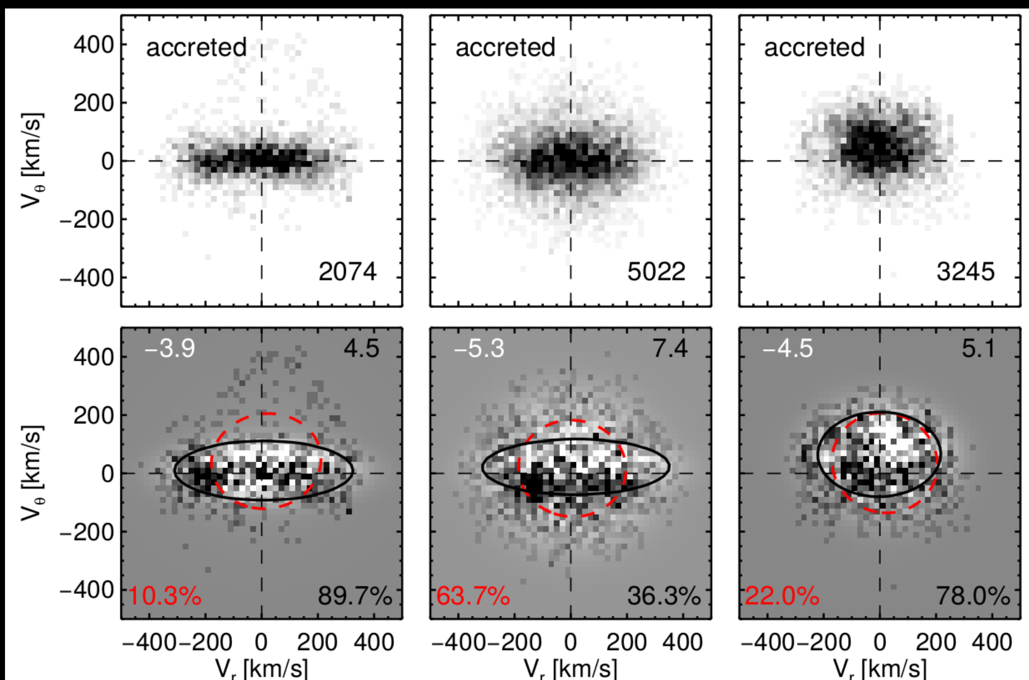
Galactocentric radial velocity

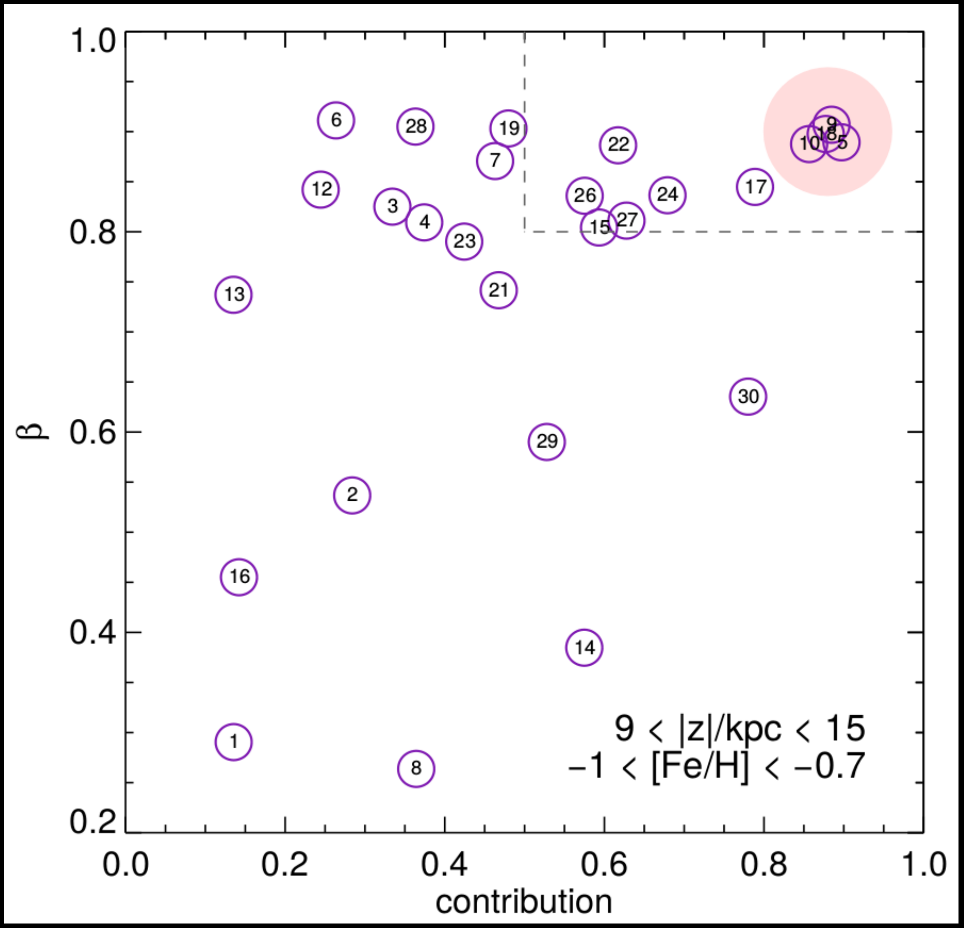
Lessons from Auriga: The origin of highly radial stars



Lessons from Auriga:
Galaxies with features similar to Gaia Sausage

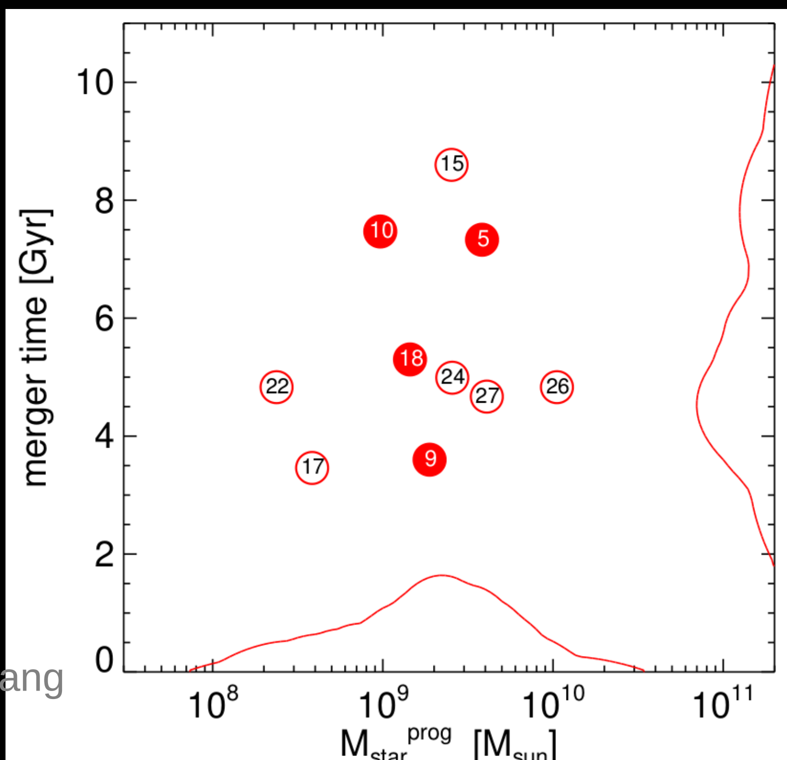
Fitting velocity ellipsoids to **acrreted** stars:





Lessons from Auriga: Progenitors of the highly radial stars

In most cases more than 50% of the "highly radial stars" are coming from one progenitor

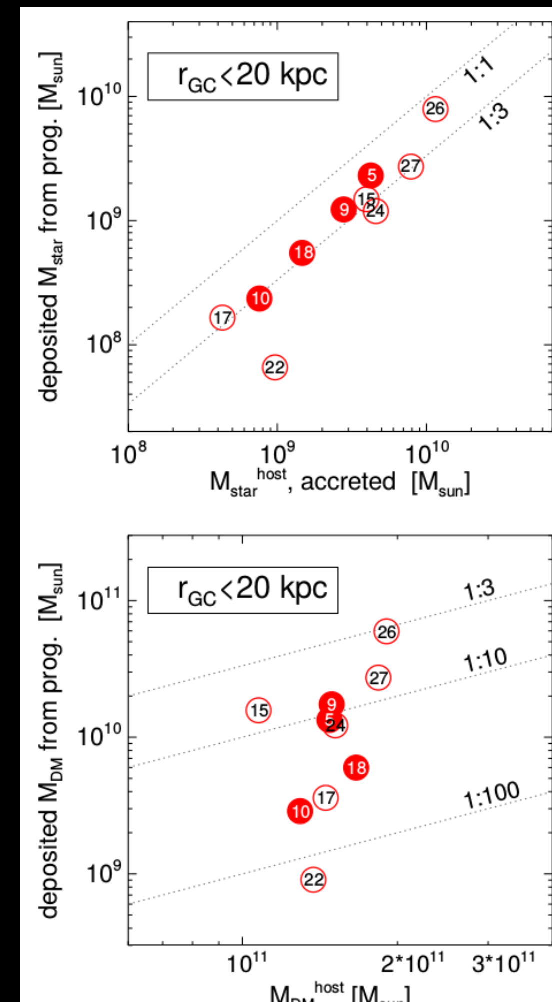


Big bang

Stars

How much did the progenitor contribute to the inner regions of MW?

DM



Lessons from Auriga:
Progenitors of the highly radial stars

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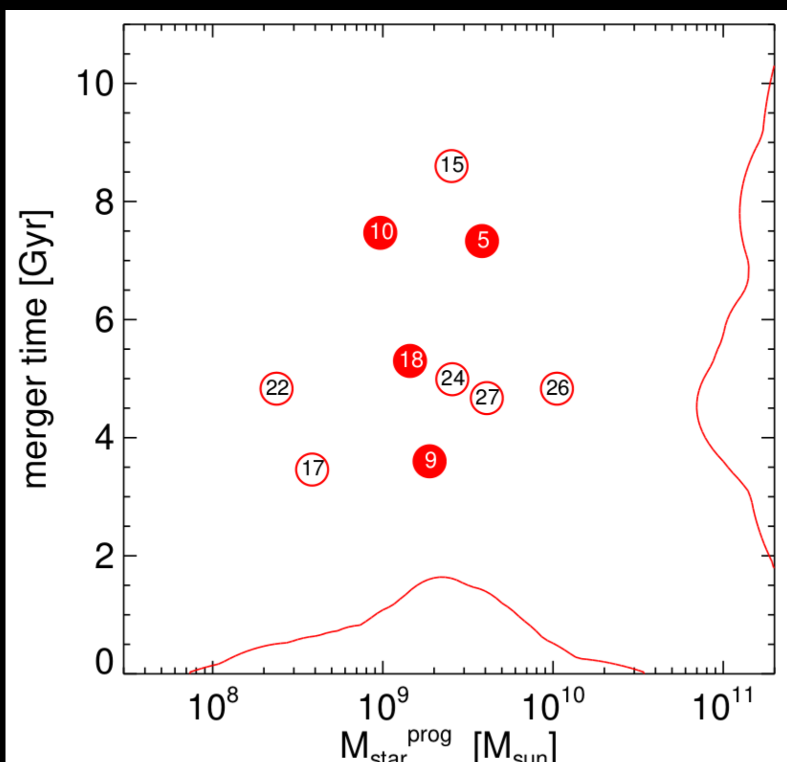

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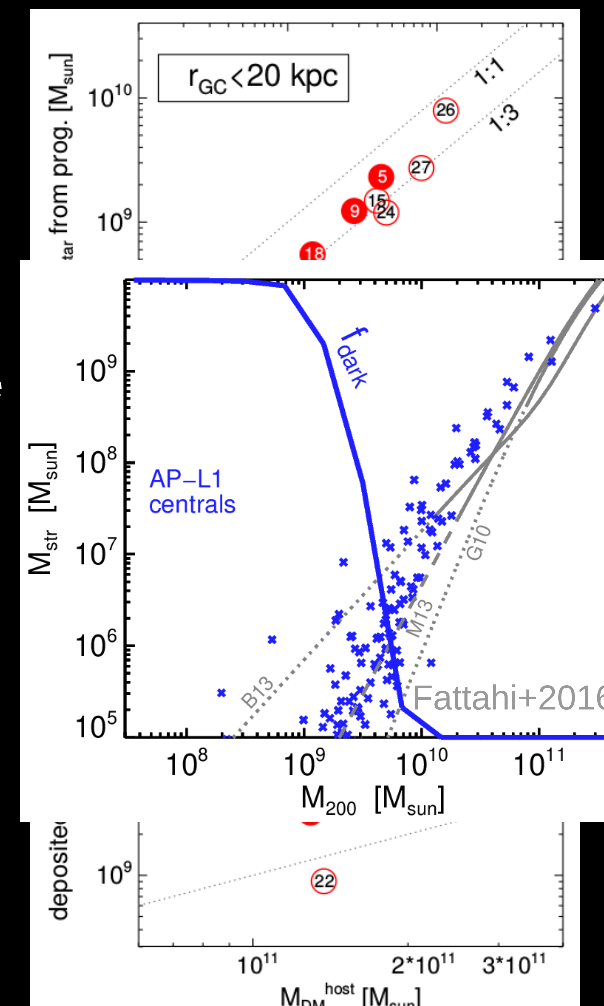

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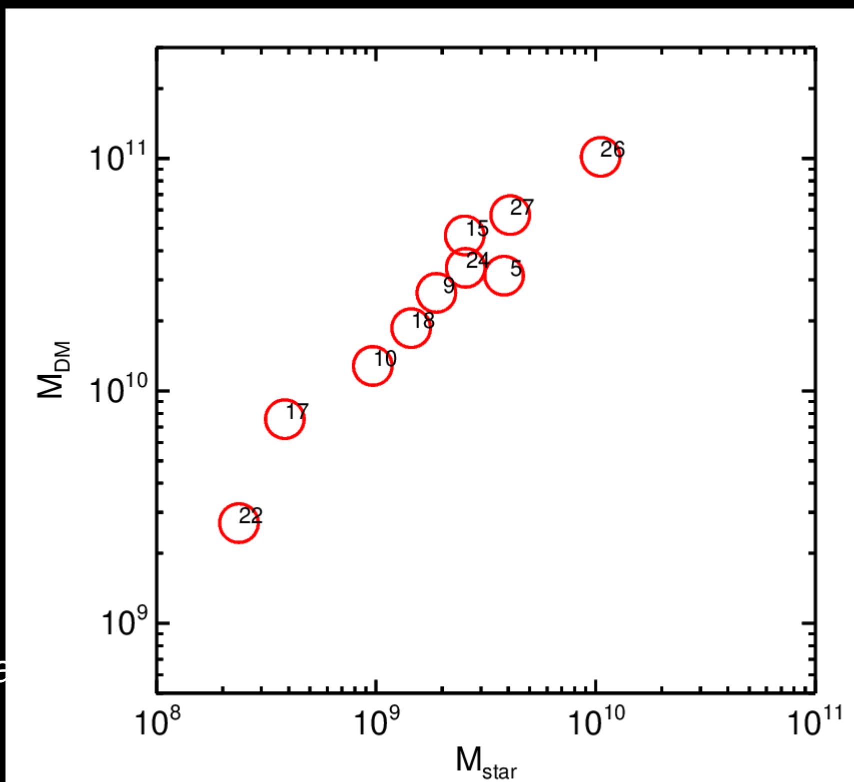

Big ba

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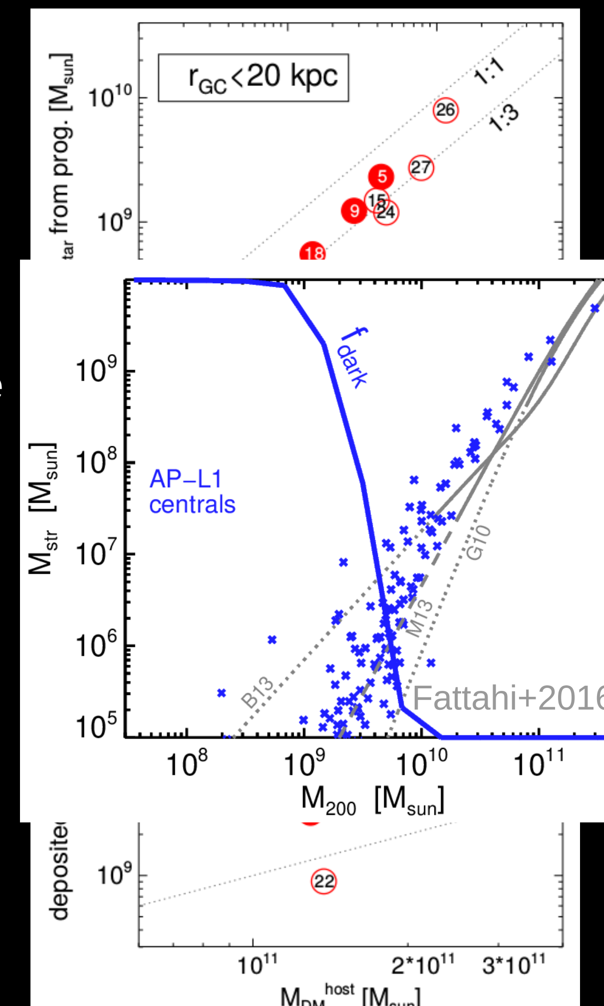
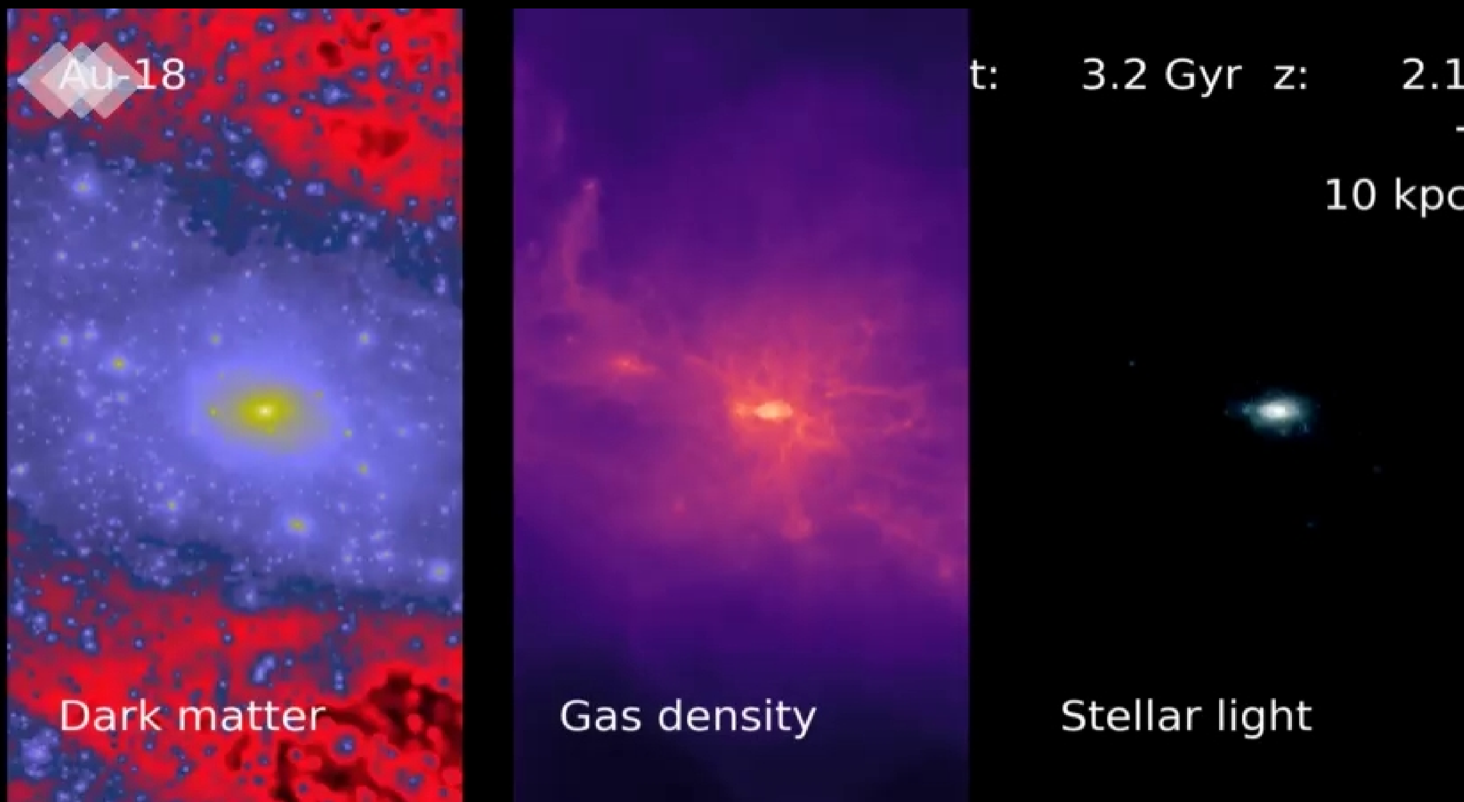


Take home messages

- Galactic inner stellar halo is dominated by a highly radial component.
- This kinematic property is common amongst Auriga halos; 1/3 of them have a prominent highly radial component
- The origin of this component is a merger with a relatively massive dwarf galaxy ~6-10 Gyr ago.
- The debris from this merger formed most of the inner stellar halo, but NOT the DM content in the inner regions


Au-18
t: 3.2 Gyr z: 2.1
10 kpc
Dark matter
Gas density
Stellar light