Satellites galaxies in the Auriga simulations: a challenge to LCDM?

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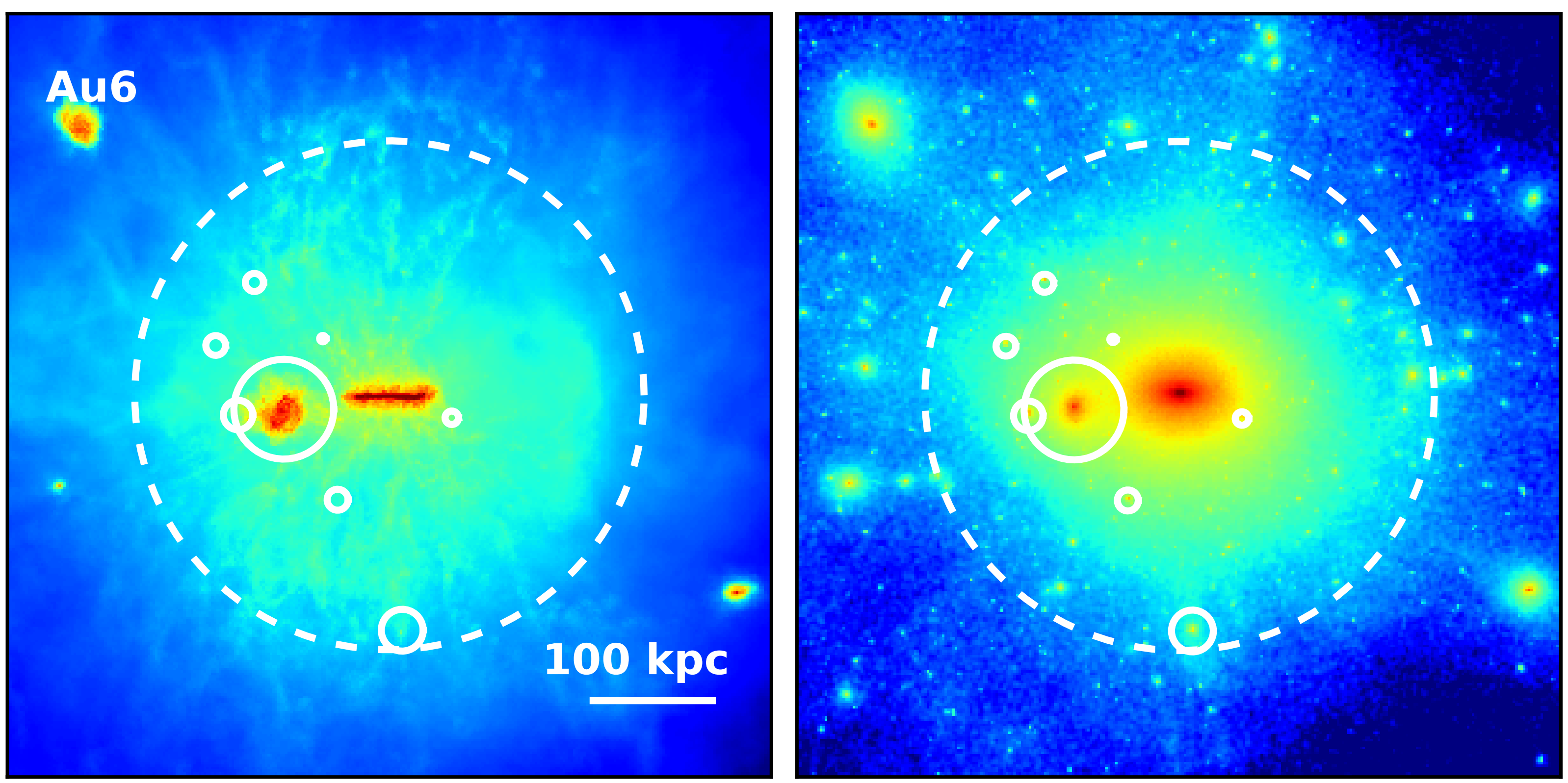
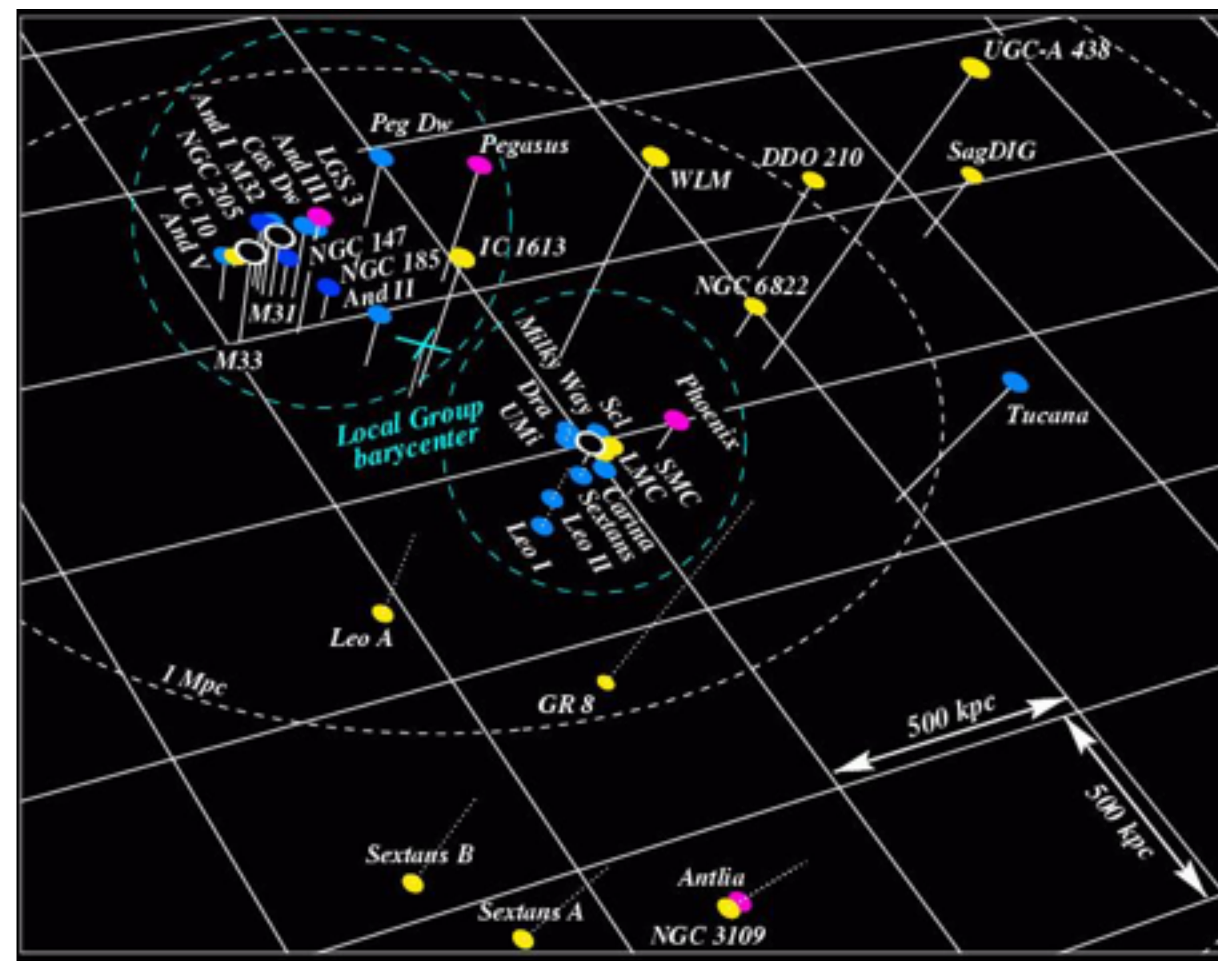


Collaborators:
The Auriga Project
and
The Virgo Consortium
Rob Grand (HITS)
Facundo Gómez (MPA)
Federico Marinacci (MIT)
Rüdiger Pakmor (HITS)
Volker Springel (HITS)
Dave Campbell (Durham)
Carlos Frenk (Durham)
And many others!

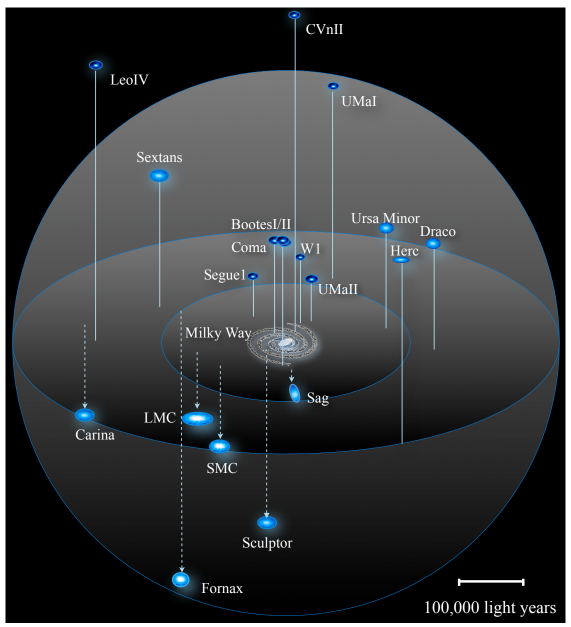
Outline

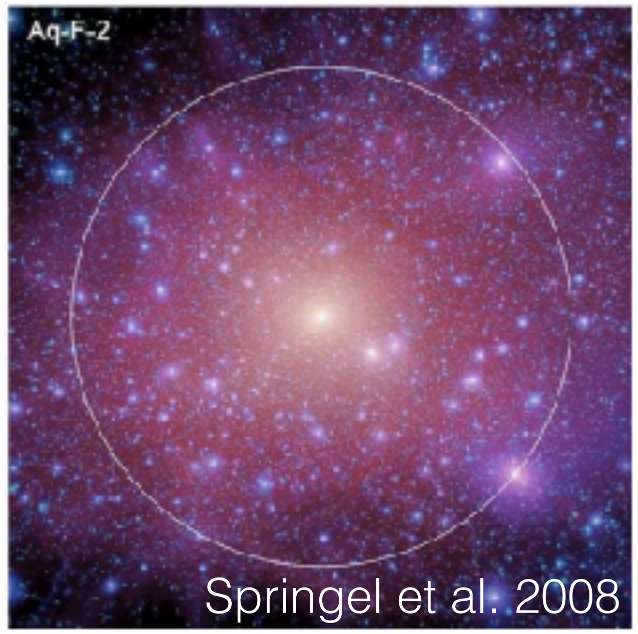
- LCDM small scale structure 'tensions' (more than 2σ)
- Cosmological simulations
- Satellites systems in Auriga
- Satellite debris in Auriga and *Aurigaia*



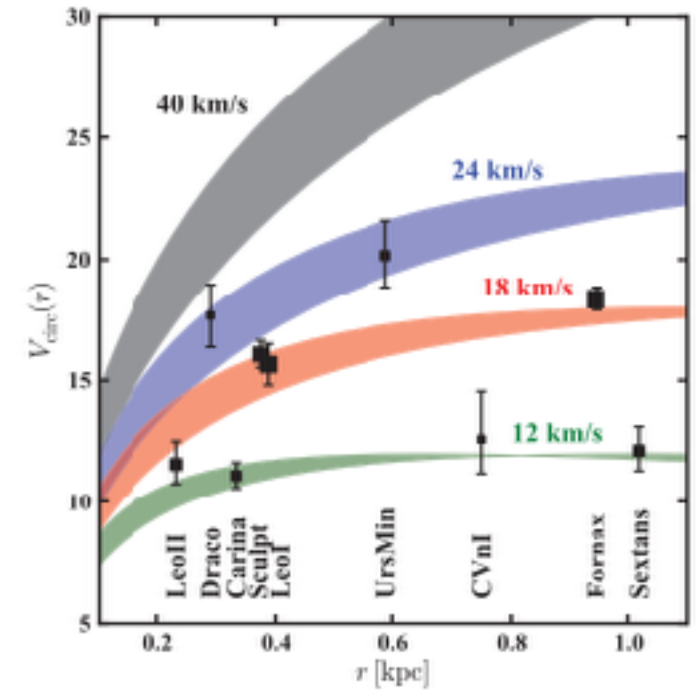
Inconsistencies between pure CDM predictions & observations especially acute at low masses

'Missing' Satellites
(e.g. Moore et al. 1999)

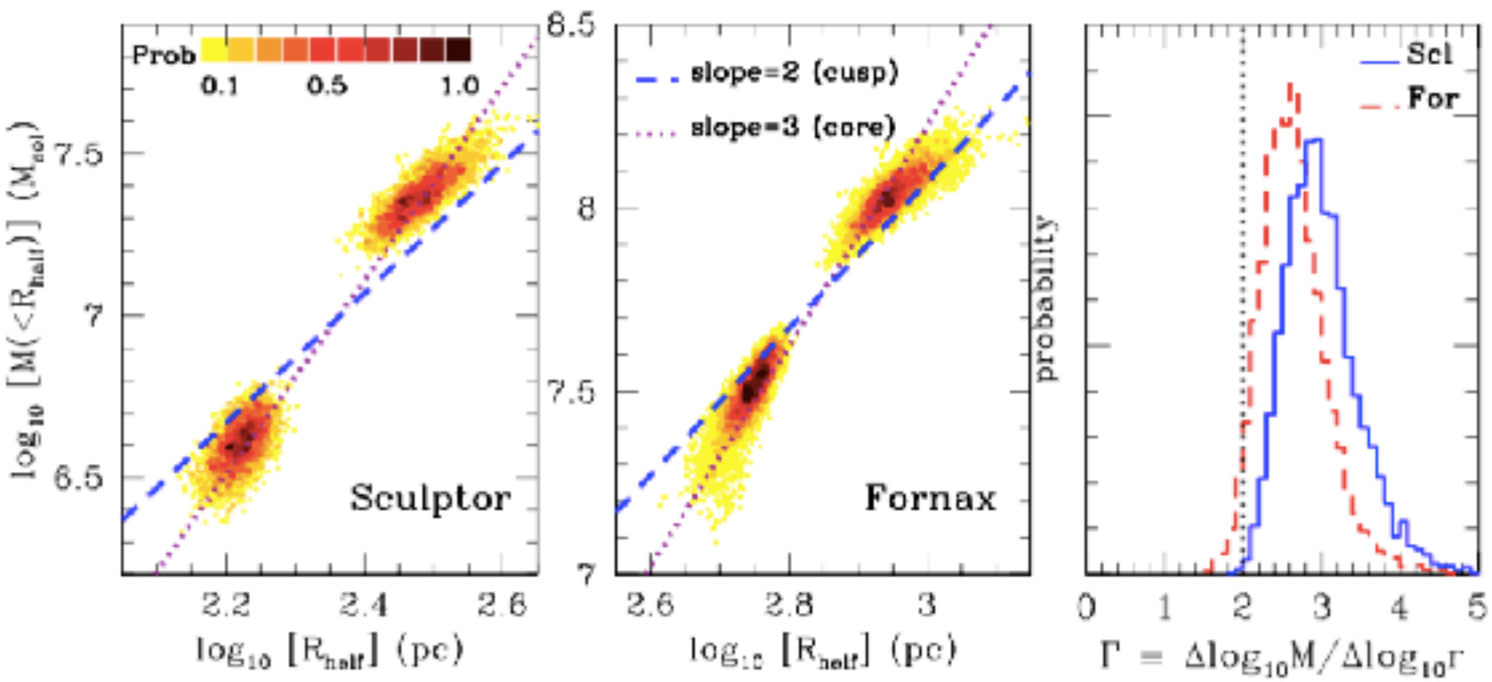




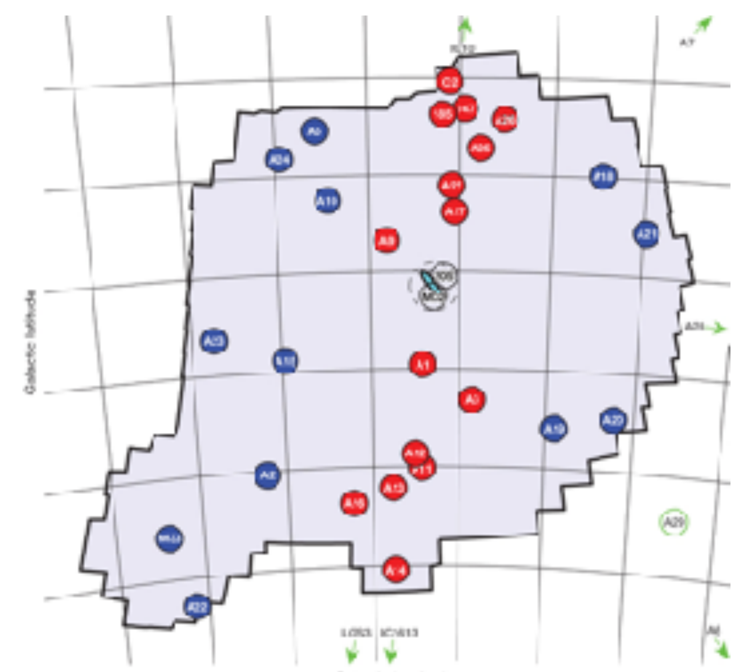
'Too big to fail'
(Boylan-Kolchin et al. 2012)



Dark matter profiles may be cored
(Walker & Penarrubia 2011)



Planes of satellites?
(Ibata et al. 2013)



Possible solutions: **Baryons?**

'Missing Satellites'

- **Reionization** and/or **stellar feedback** can suppress stellar masses

Too-big to fail

- can **stellar feedback** shuffle the the suppression of stellar masses between mass scales?

Core/cusp

- could **winds from star bursts** be dynamically important in the centers galaxies and impact the dark matter?

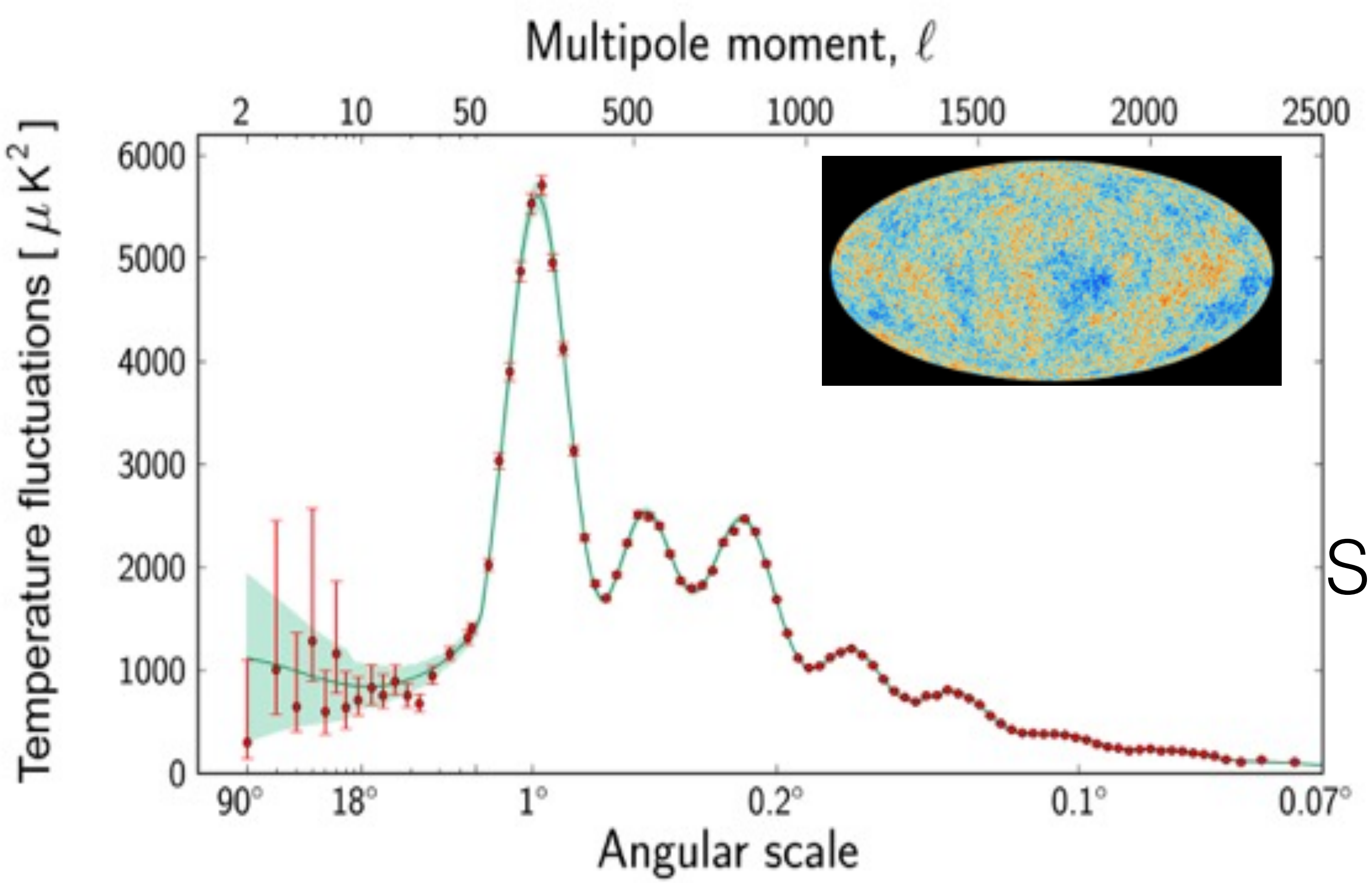
Planes of satellites

- ?
- (although, they are polar to the baryon disk, so a baryon connection is something to think about)

Amazing observational progress has specified the initial conditions

CMB CONSTRAINTS TODAY AS SEEN BY PLANCK (BUT ALSO WMAP & COBE)

Minimal, 6-parameter ΛCDM model is a great fit

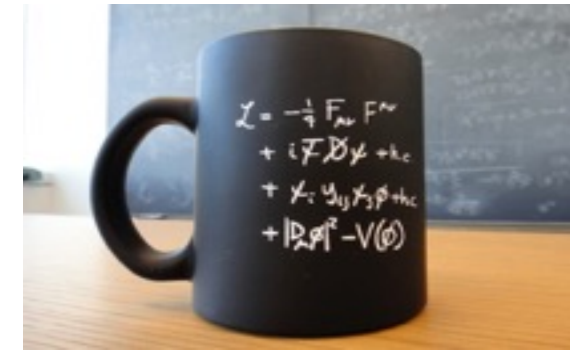


Planck Collaboration (2013)

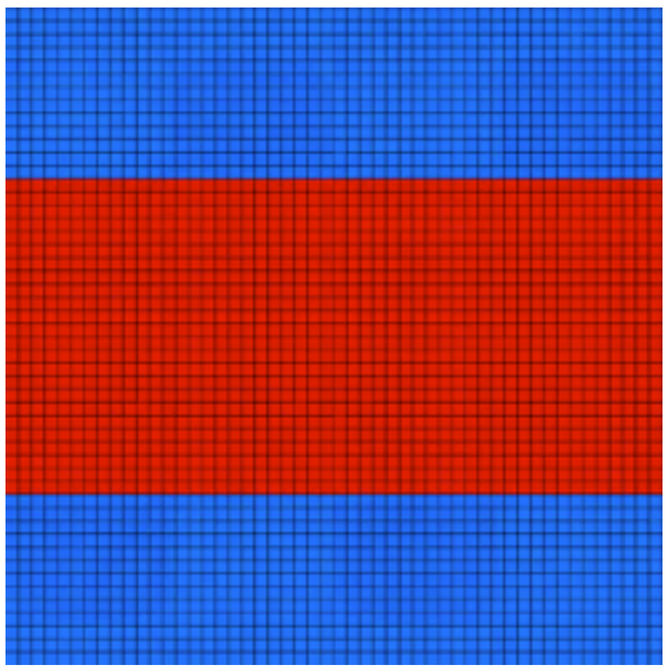
Simulations

Much of astrophysics is described through systems of **Partial Differential Equations (PDEs)**

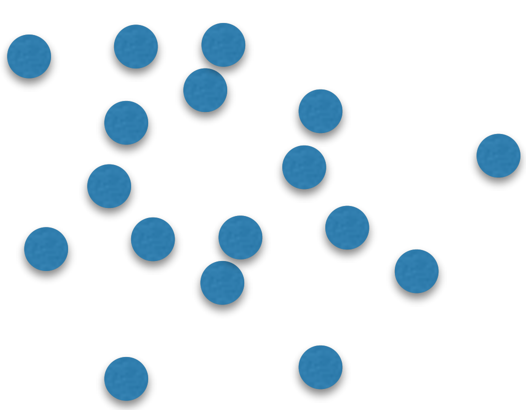
WE ALSO NEED TO DISCRETIZE THE PROBLEM



Discretize Gas on a Mesh



Discretize
Dark Matter & Stars
with Particles



Euler's Equations (Navier-Stokes, etc.)

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

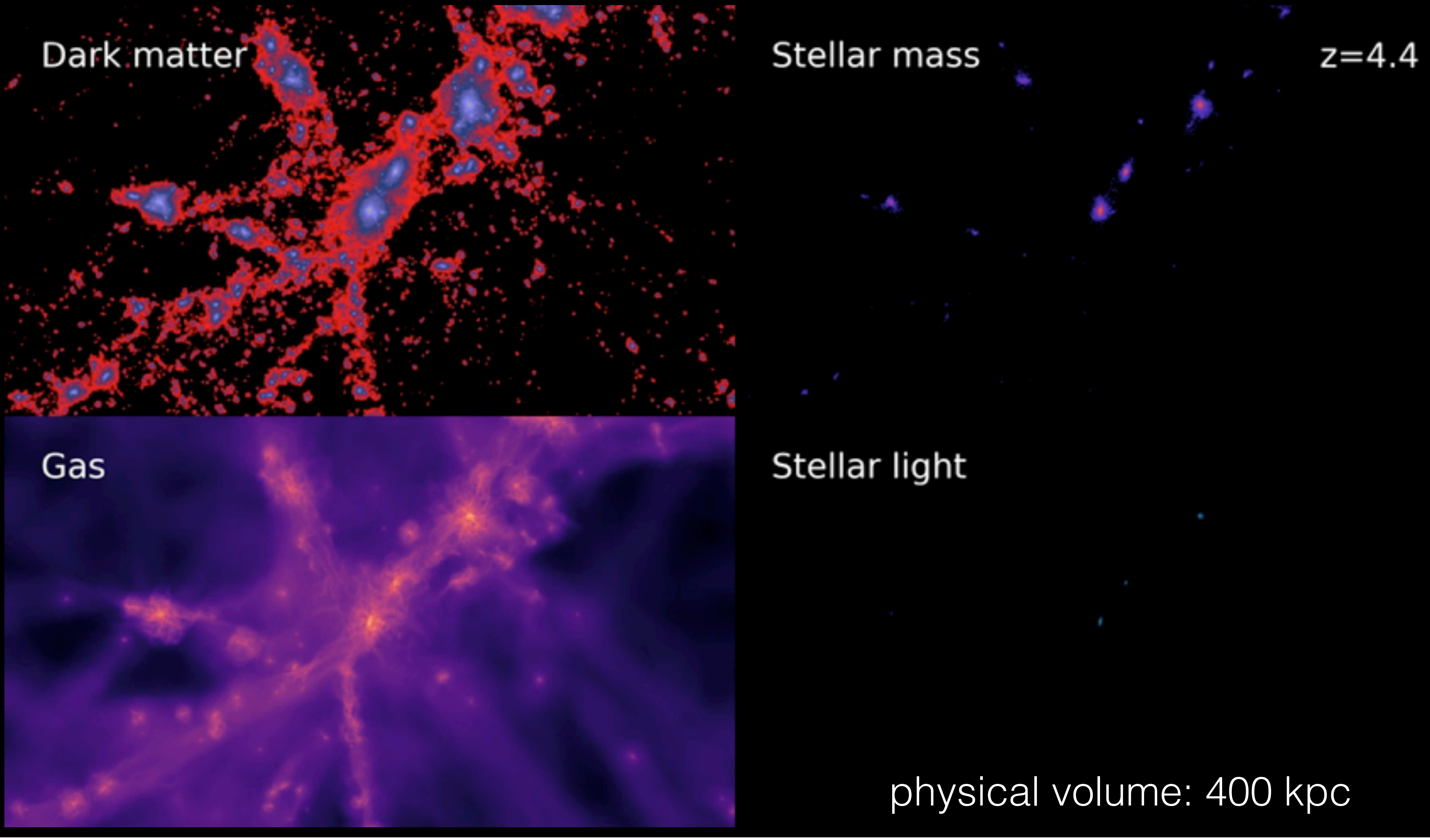
$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla(\rho \mathbf{v}\mathbf{v}^T + P) = \nabla \mathbf{\Pi}$$

$$\frac{\partial}{\partial t}(\rho e) + \nabla[(\rho e + P)\mathbf{v}] = \nabla(\mathbf{\Pi}\mathbf{v})$$

- Additional equations describe
  - collisionless dynamics
  - magnetic fields
  - sources of energy sinks, i.e. radiative cooling
  - **energy sources: stellar feedback, galactic winds, AGN feedback, metagalactic UV background**

The Auriga Project

Grand et al. 2017

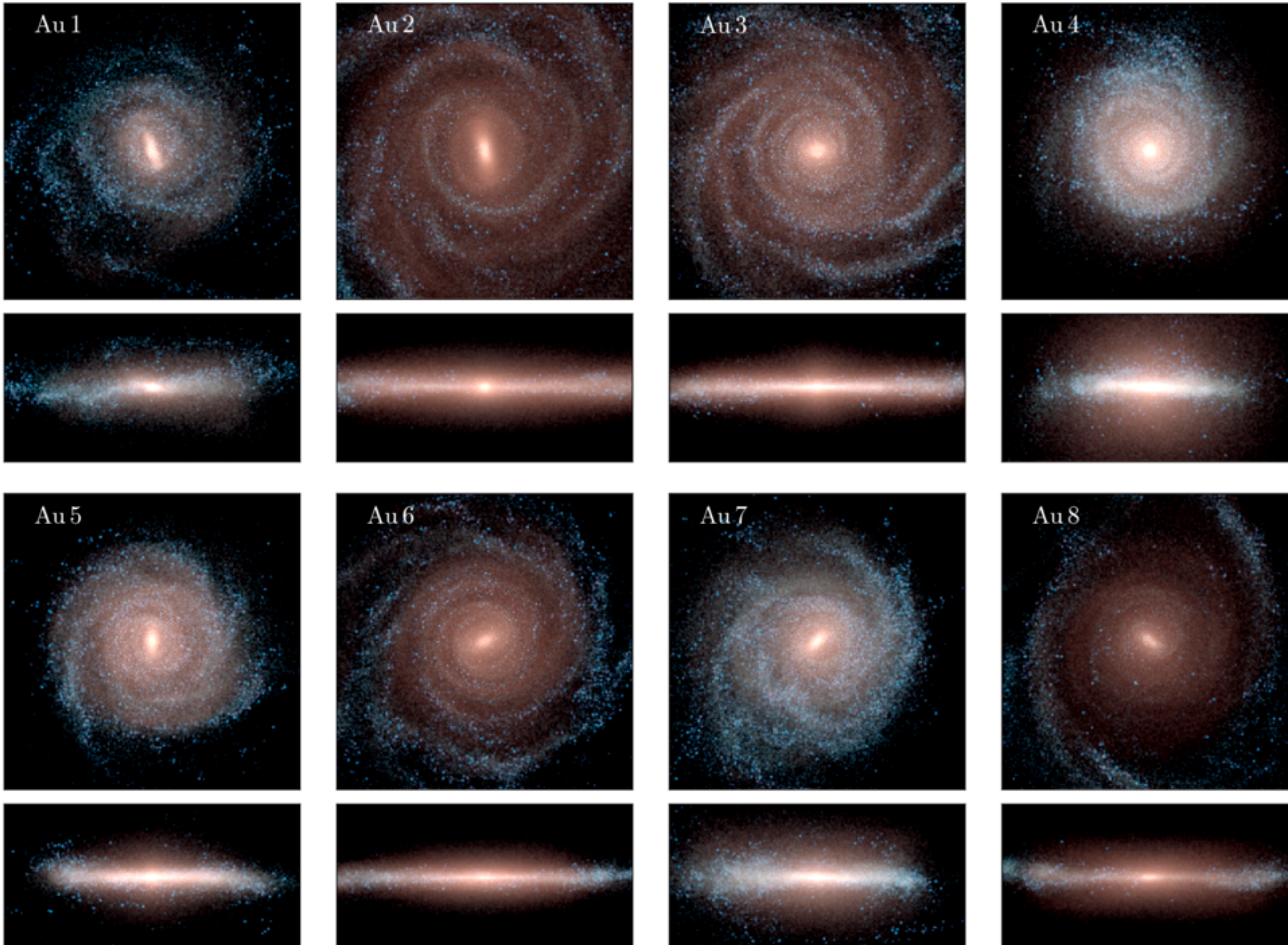


The Set-up & Physics

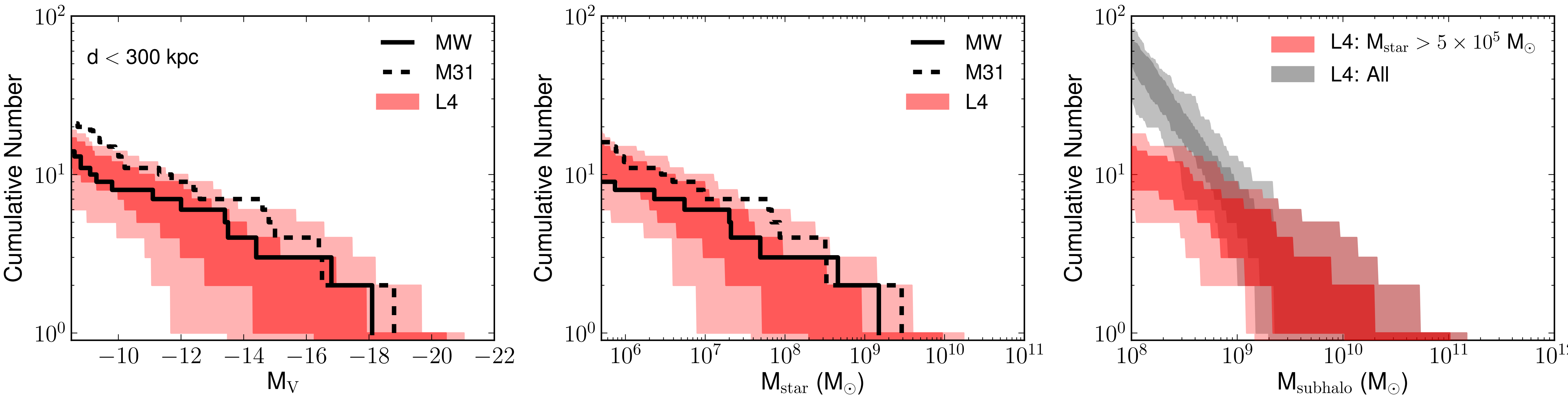
- Thirty cosmological zoom simulations of 10^{12} $M_{\odot}$ halos
- DM particle mass ~ 3 x 10^5 $M_{\odot}$; baryon cell/particle mass ~ 5 x 10^4 $M_{\odot}$
- Second-order hydrodynamics on a moving mesh (AREPO)
- MHD, SF & stellar feedback, AGN feedback, UV background, atomic & metal line cooling

AURIGA disks

30 HIGH-RESOLUTION MILKY WAY-SIZED HALOS (Grand et al. 2017)

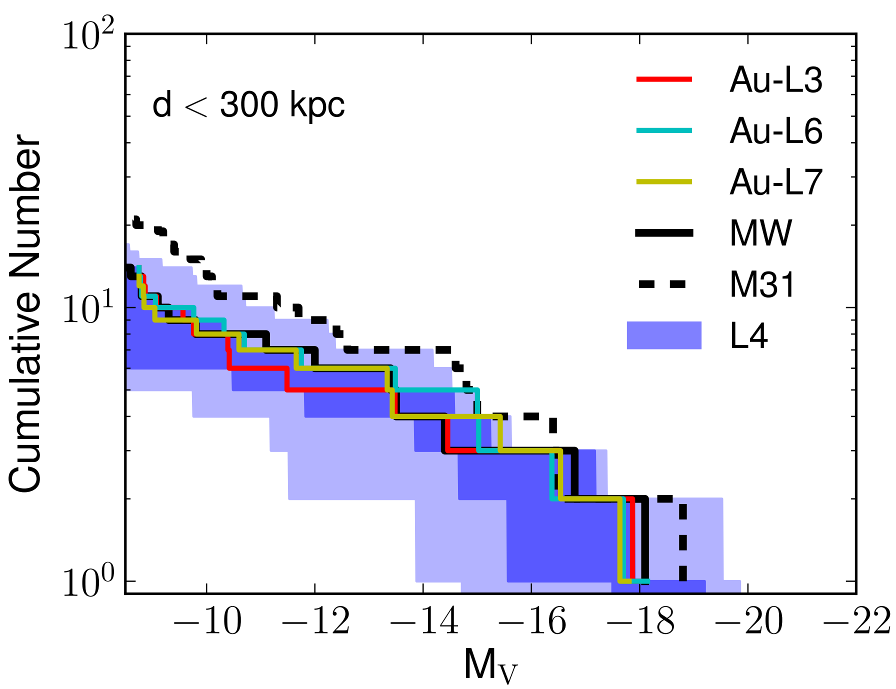


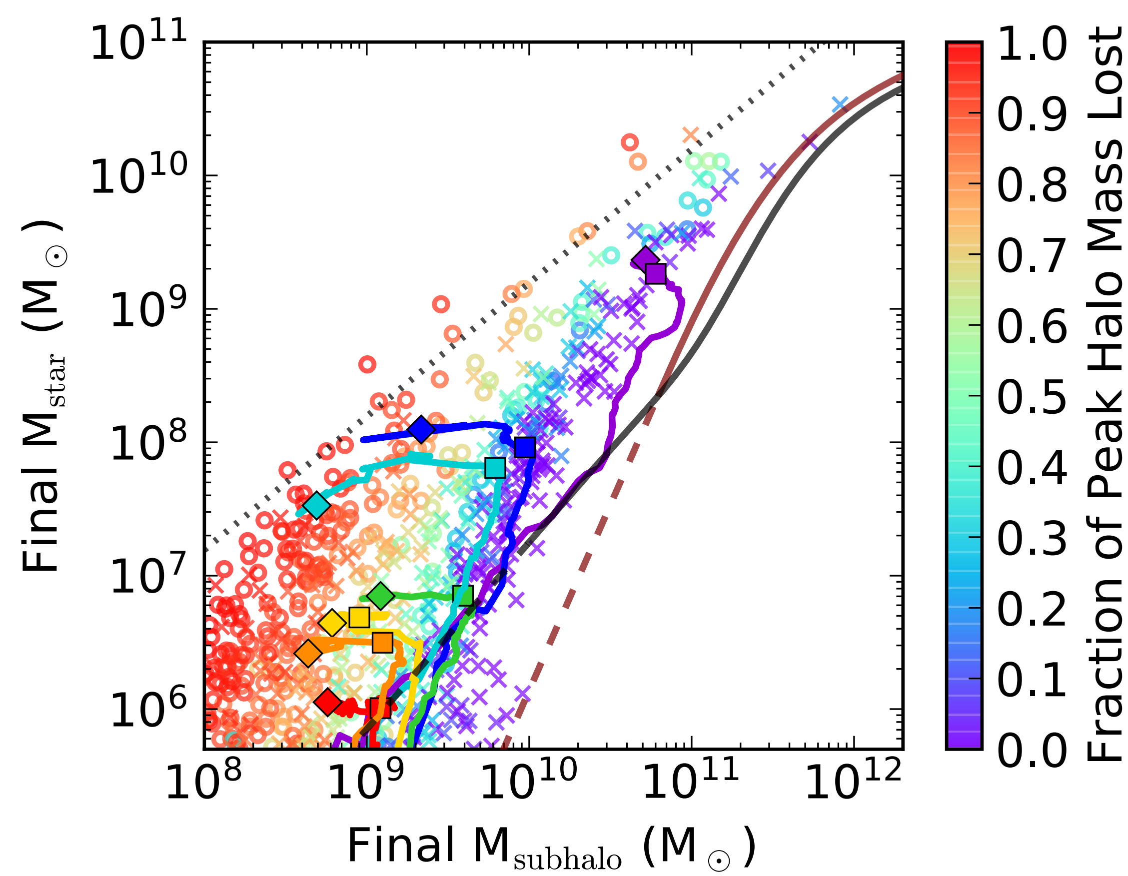
Numbers of Satellites



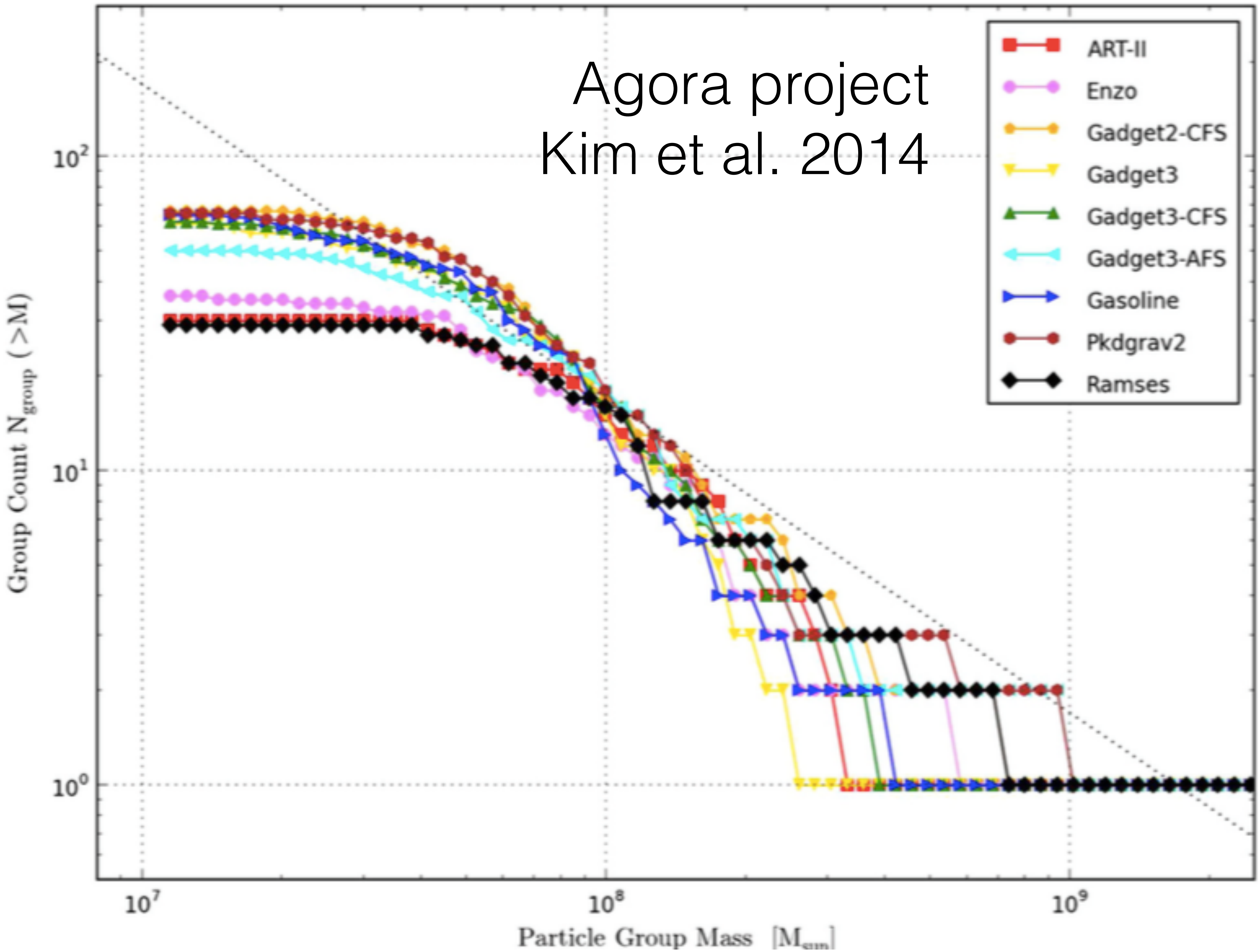
10 Low mass halos

($0.5 - 1 \times 10^{12}$ M☉)



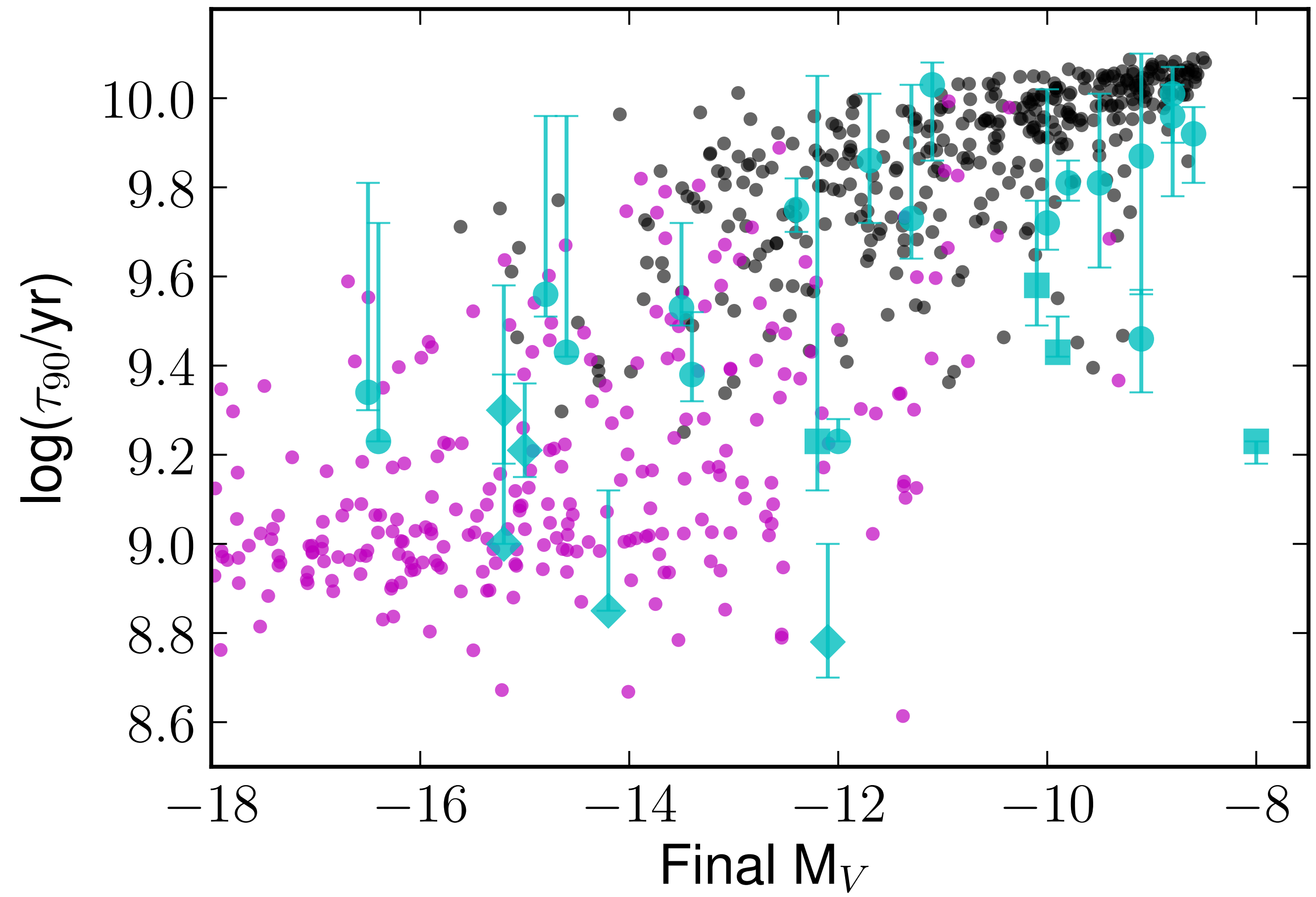


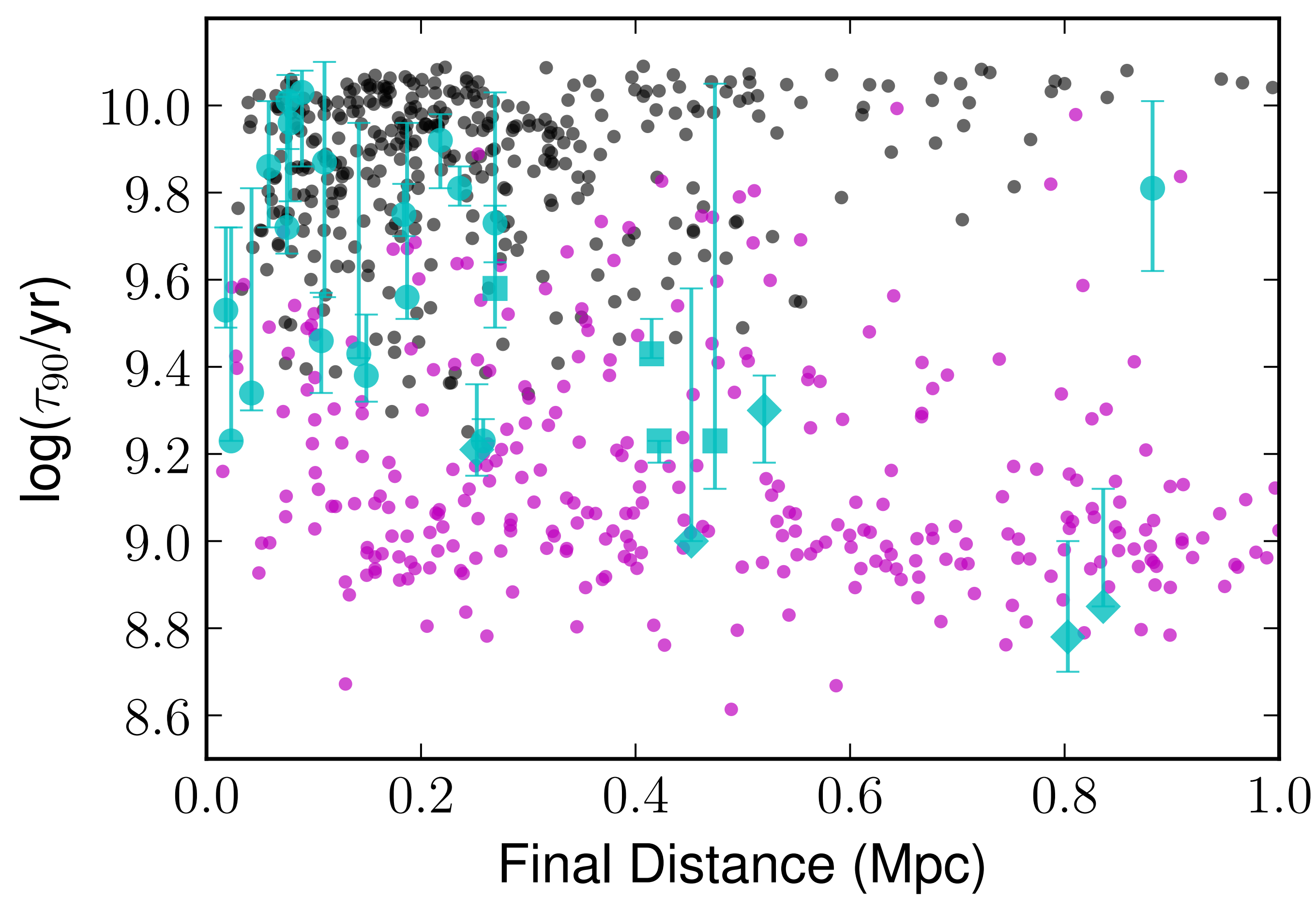
Code comparisons (dark matter only) can disagree too



Reproduce quenching times

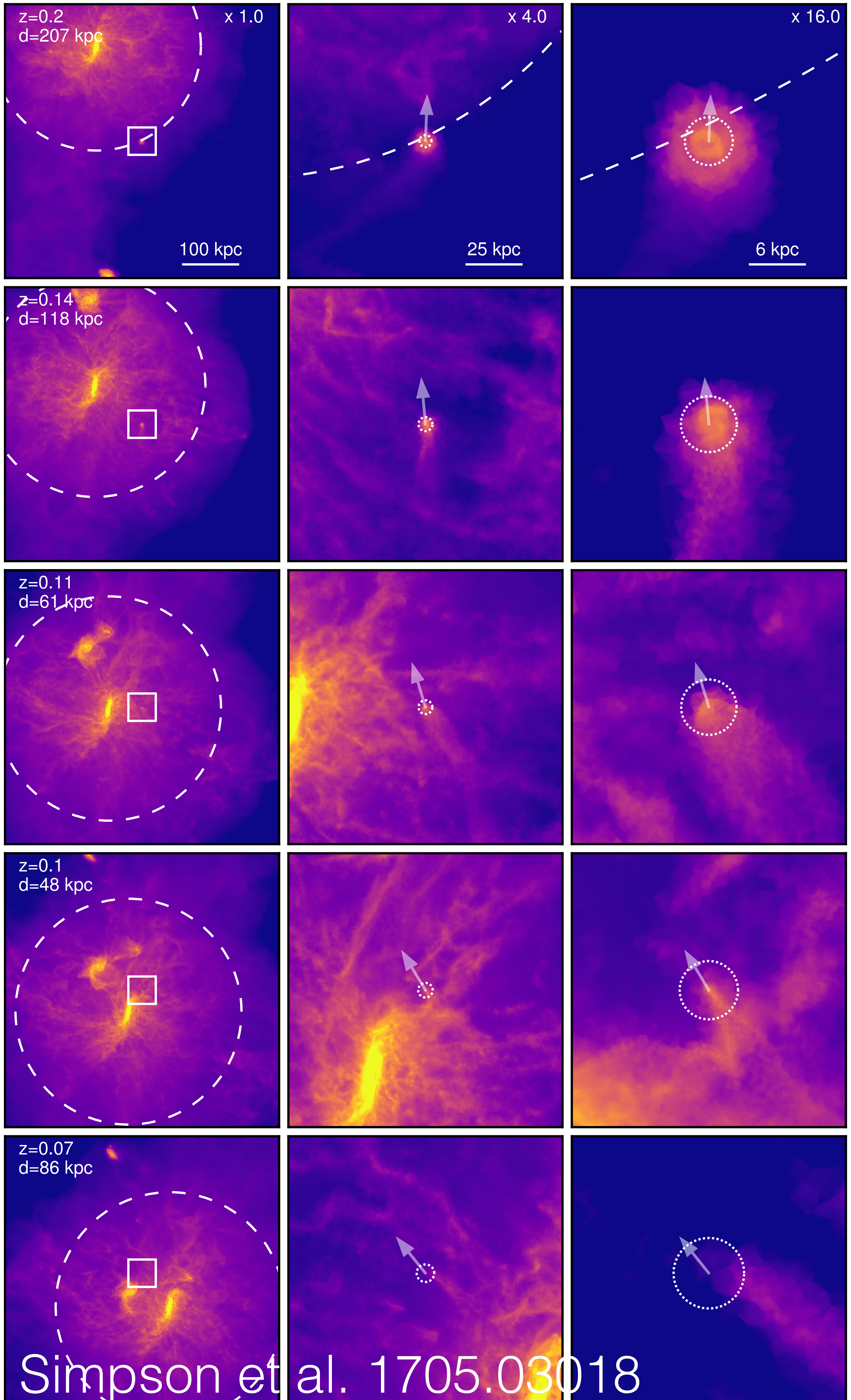
τ_{90} is the time by which 90% of a system's stellar mass formed
(data: Weisz et al. 2015)



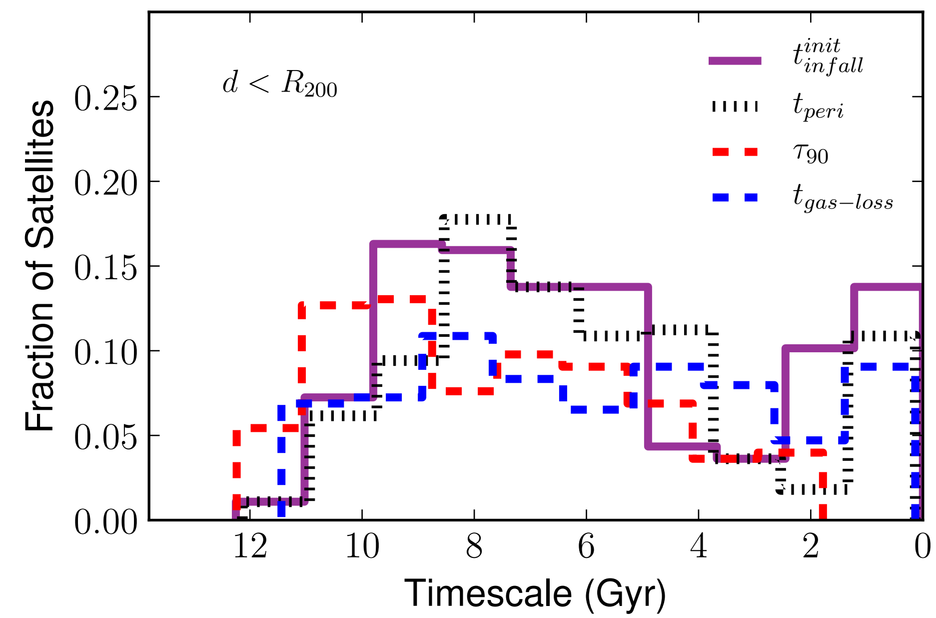


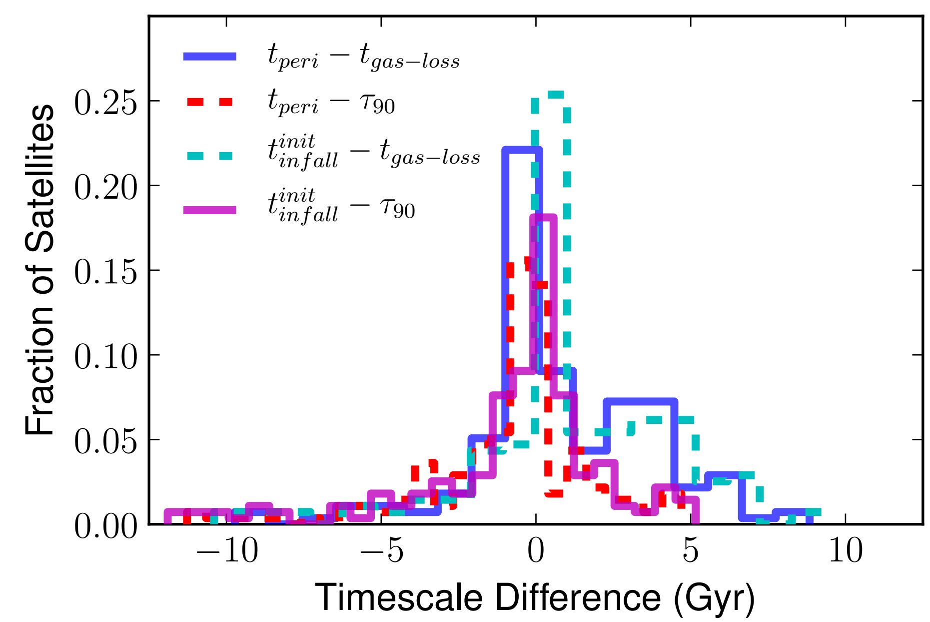
Simpson et al. 1705.03018

Quenching mechanisms: Ram pressure



Simpson et al. 1705.03018



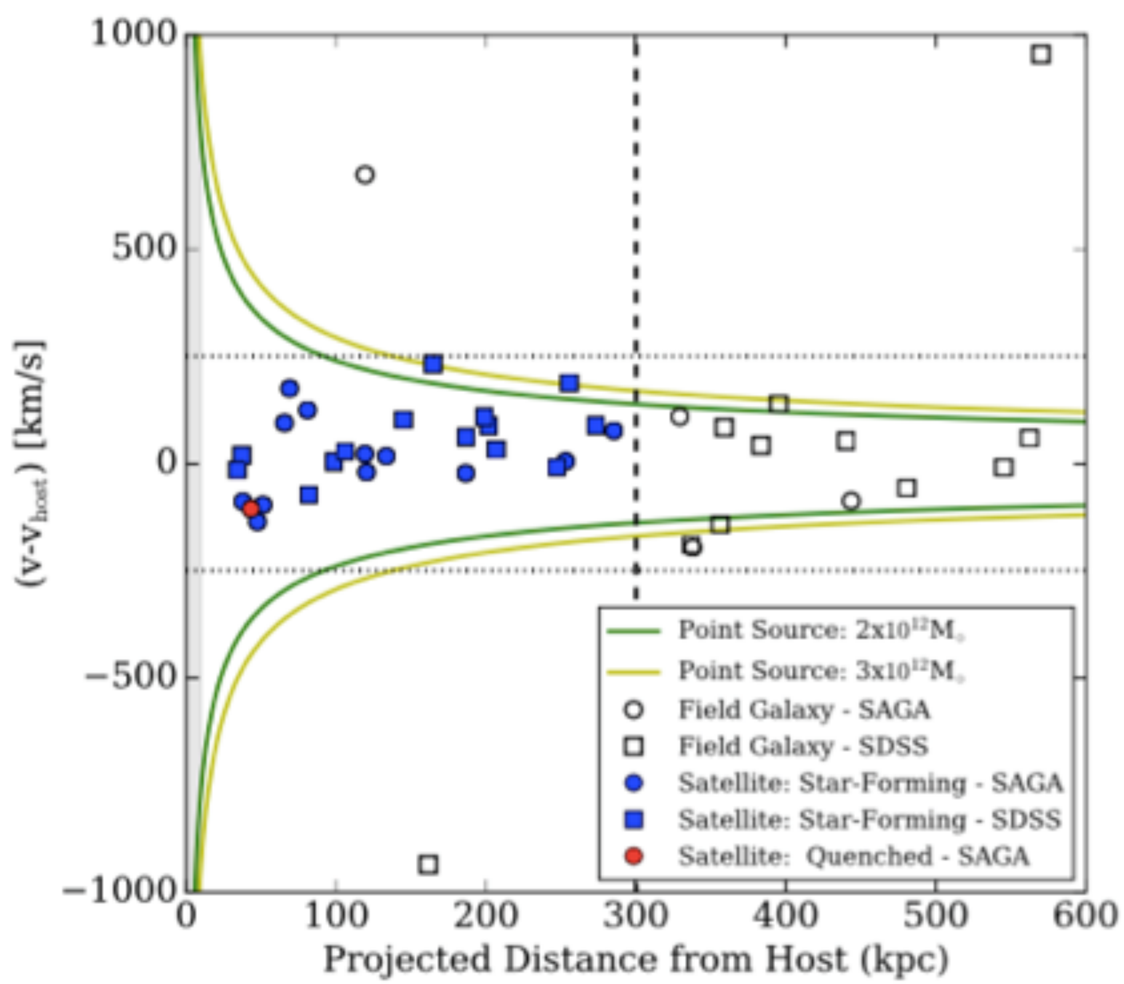


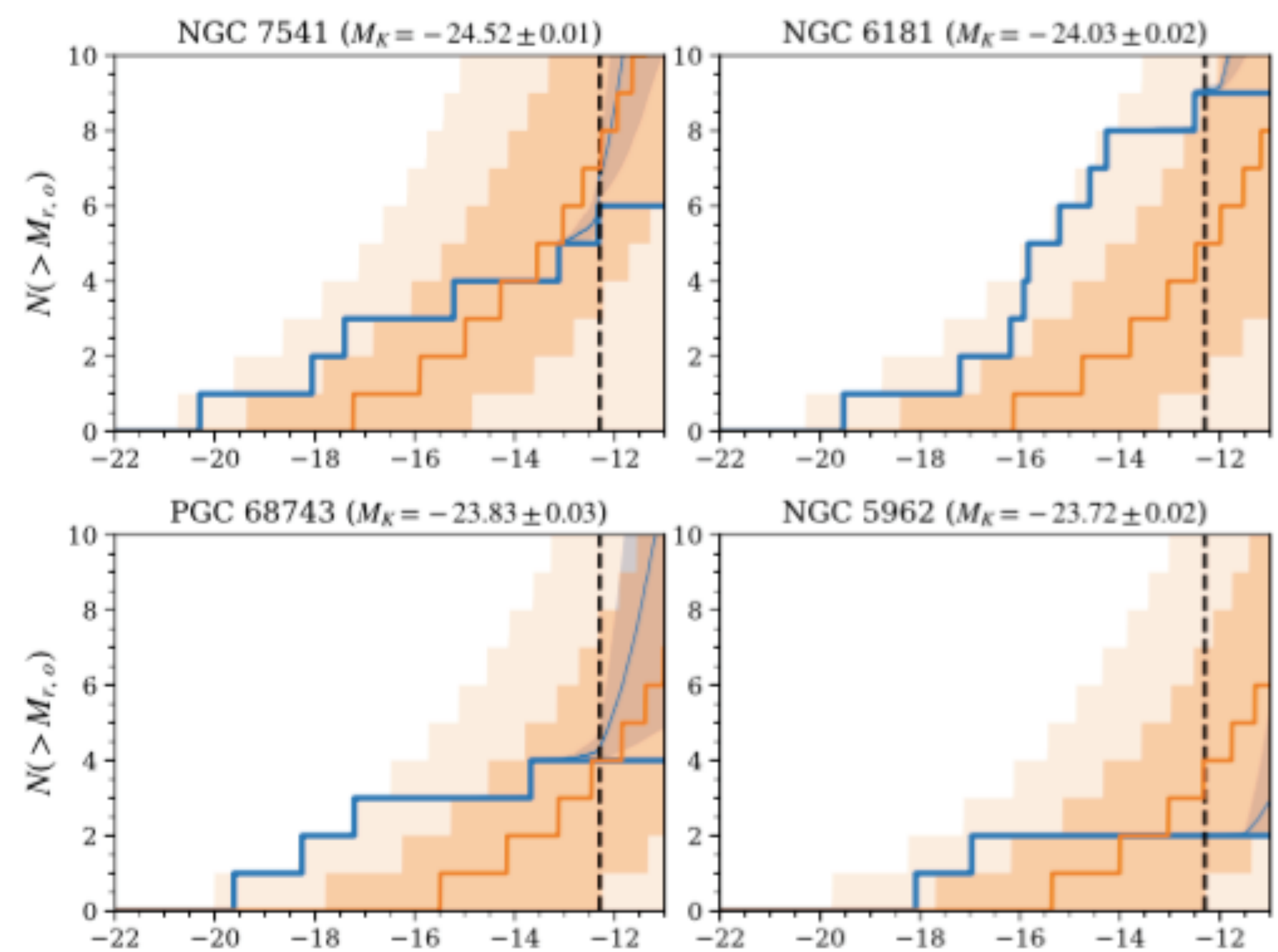
- This system is ~ 6.3 x 10^6 $M_\odot$ in stellar mass

How typical are the satellites of MW & M31?

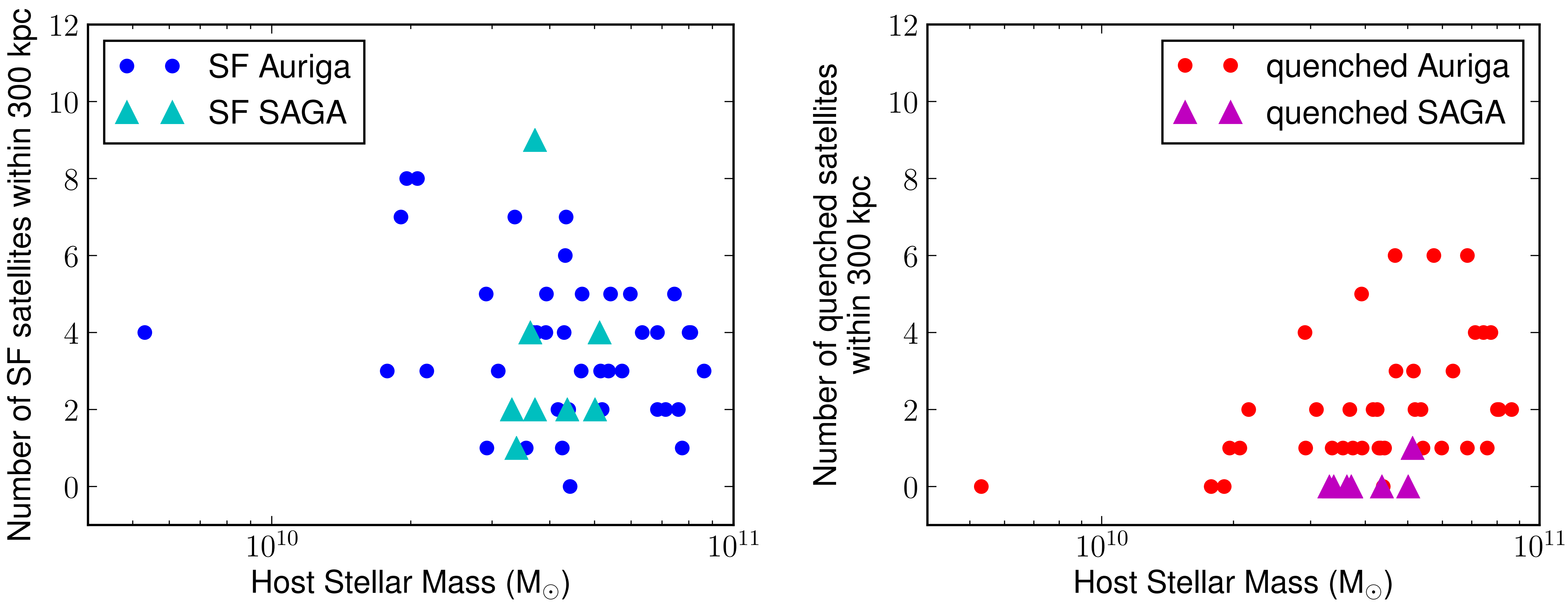
THE SAGA SURVEY:
I. SATELLITE GALAXY POPULATIONS AROUND EIGHT MILKY WAY ANALOGS

MARLA GEHA[1], RISA H. WECHSLER[2,3], YAO-YUAN MAO[4], ERIK J. TOLLERUD[5], BENJAMIN WEINER[6], REBECCA BERNSTEIN[7], BEN HOYLE[8,9], SEBASTIAN MARCHI[10], PHIL J. MARSHALL[3], RICARDO MUÑOZ[10], AND YU LU[7]

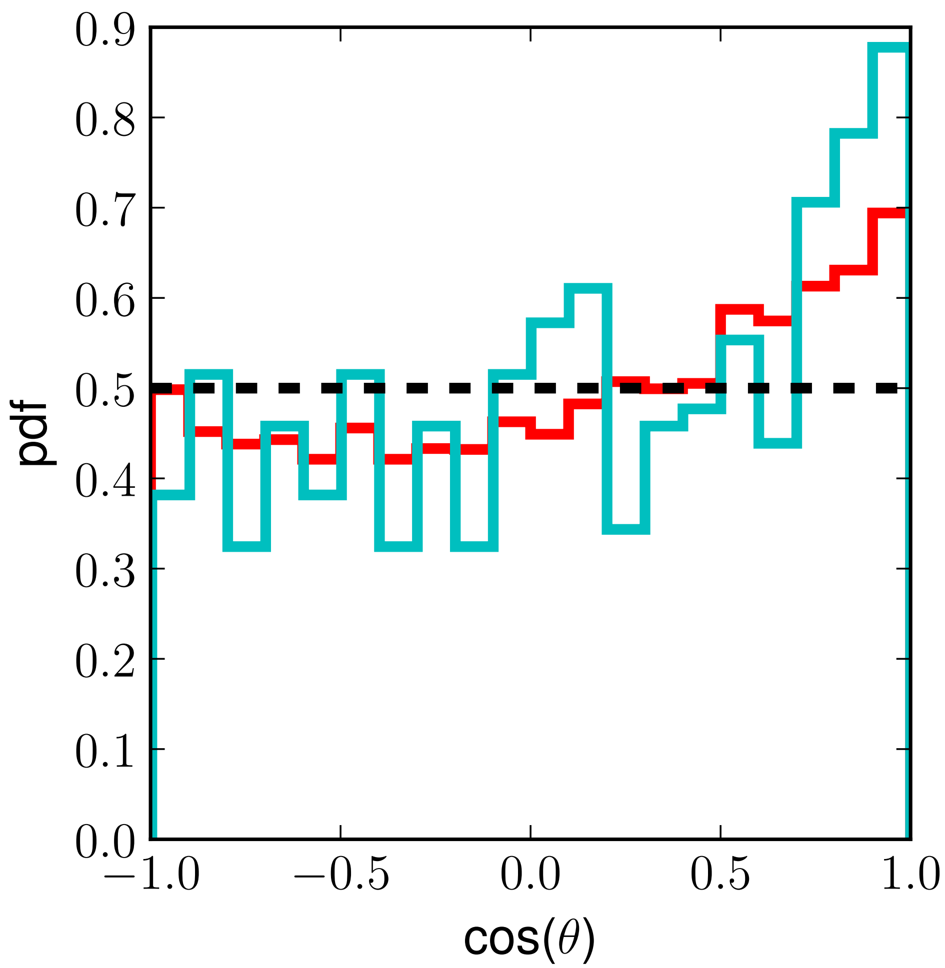




How many star forming satellites does Auriga have?



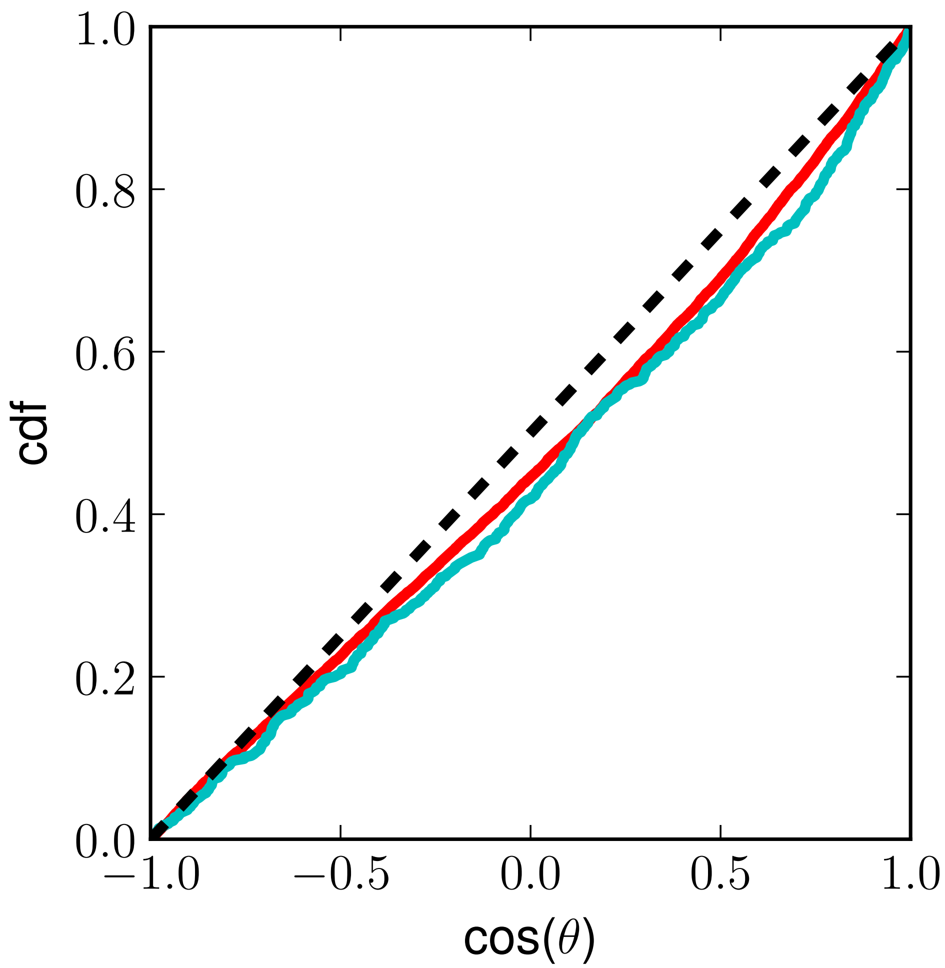
Magnitude Limit: $M_r < -12.3$

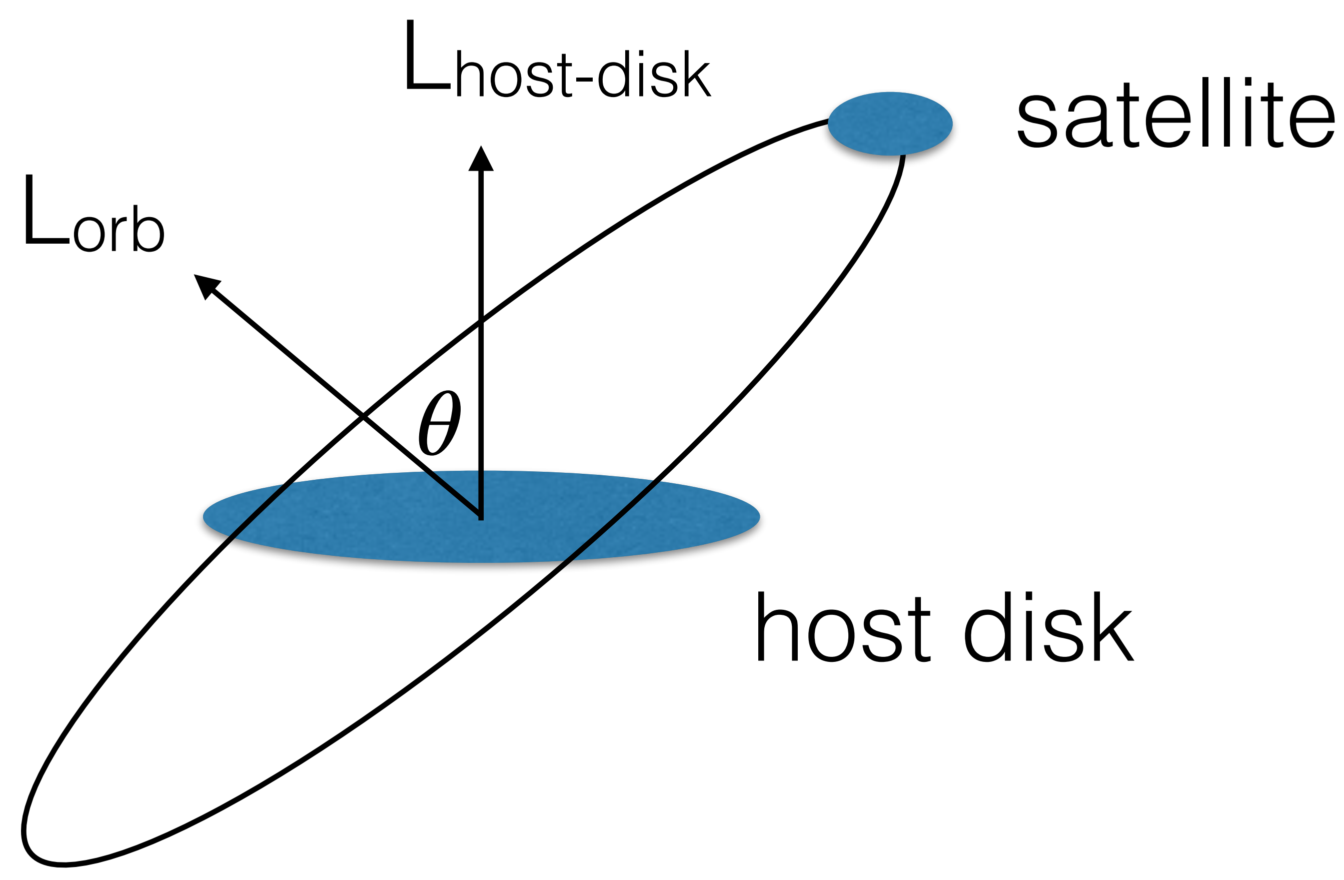


Satellite-Host Disk connection

Angle between L_{orb} and $L_{host\text{-}disk}$

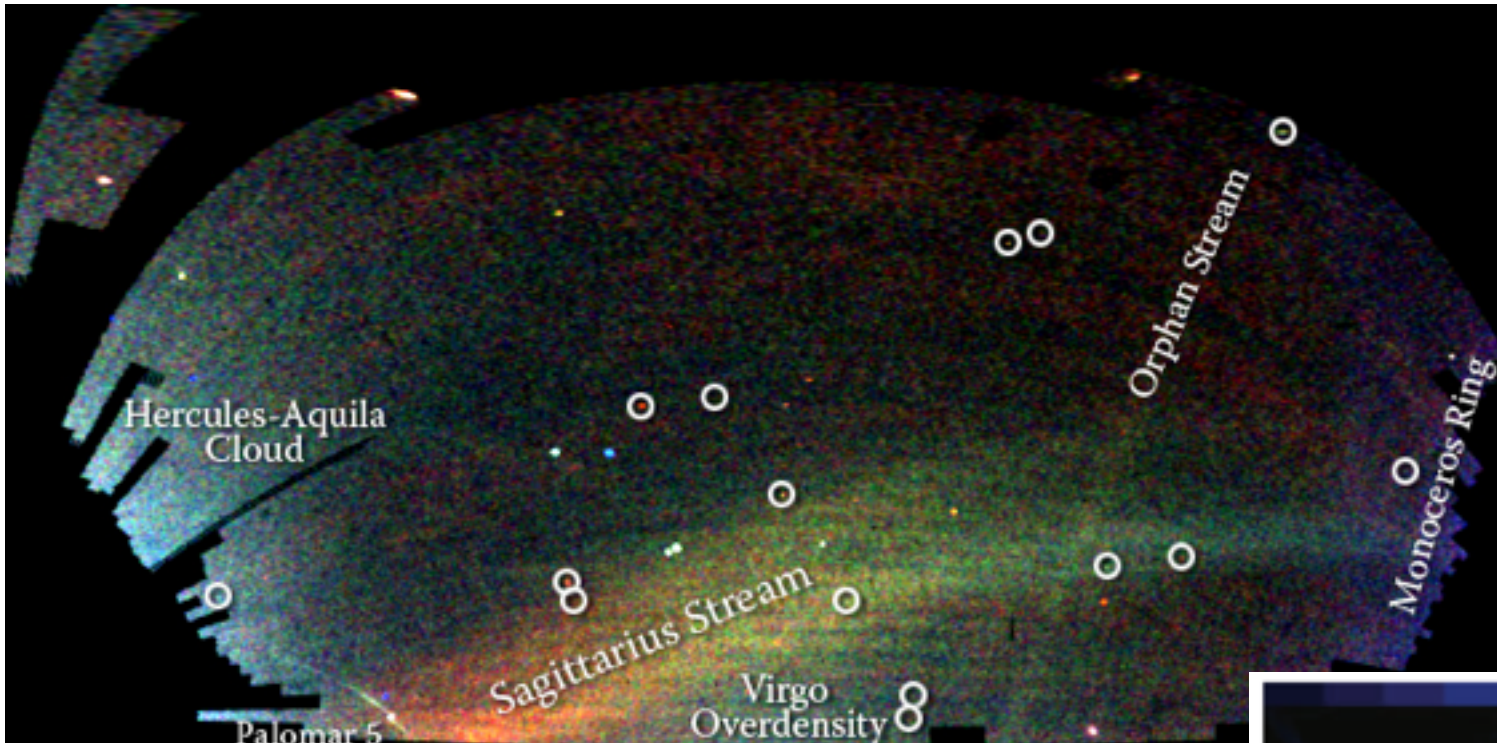
Red: Dark Satellites
Cyan: Luminous satellites



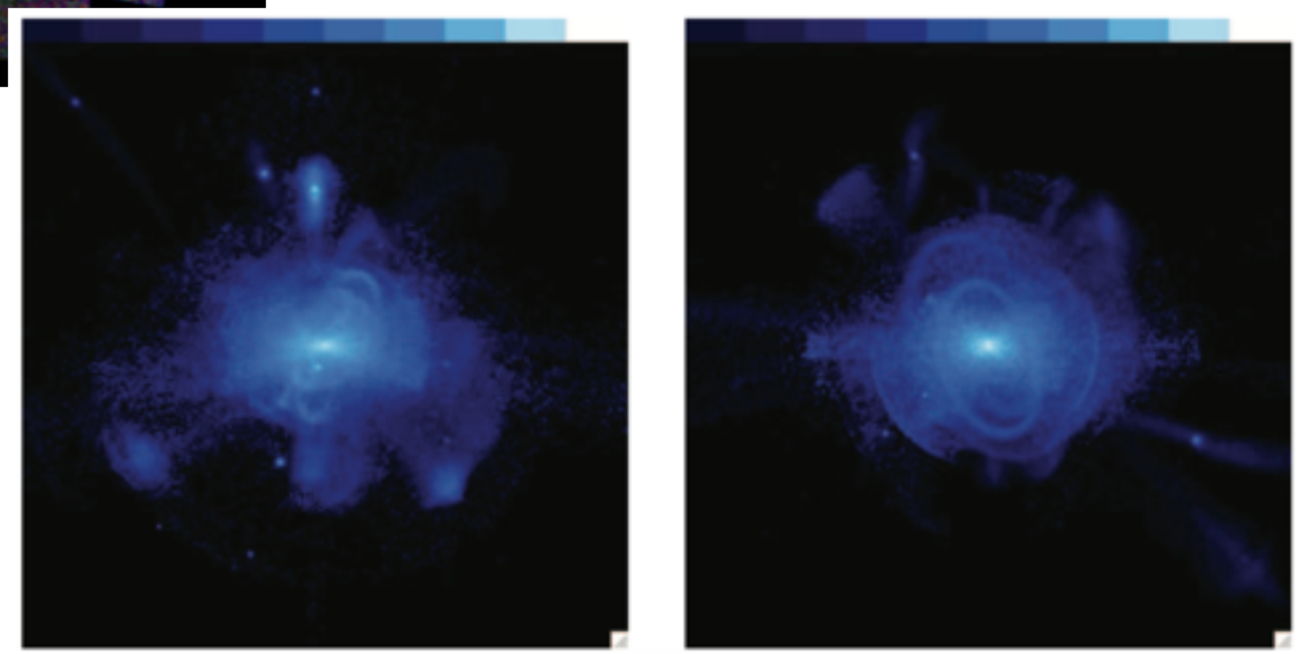


Satellite Debris

Satellite debris in the Milky Was has the potential to tell us about the assembly history of the galaxy



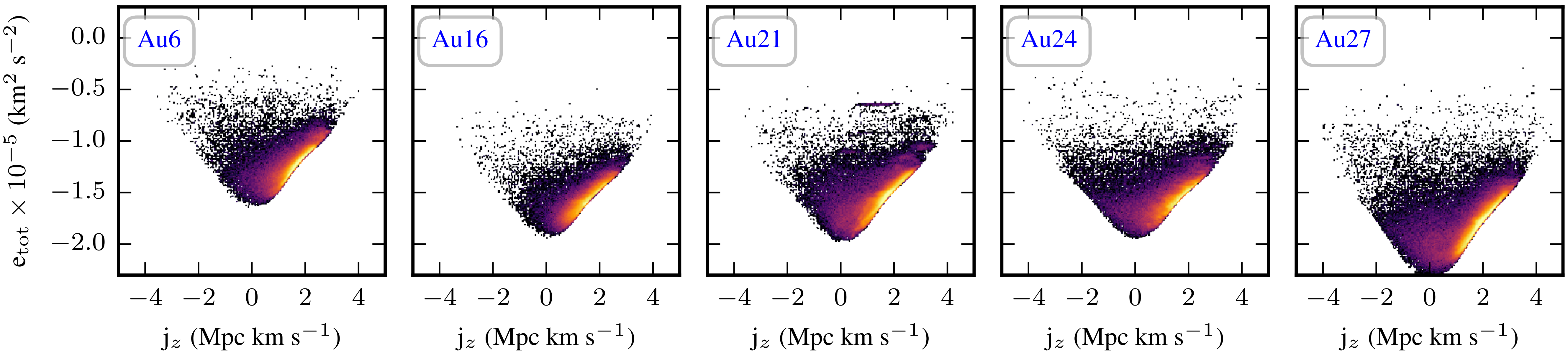
V. Belokurov & SDSS



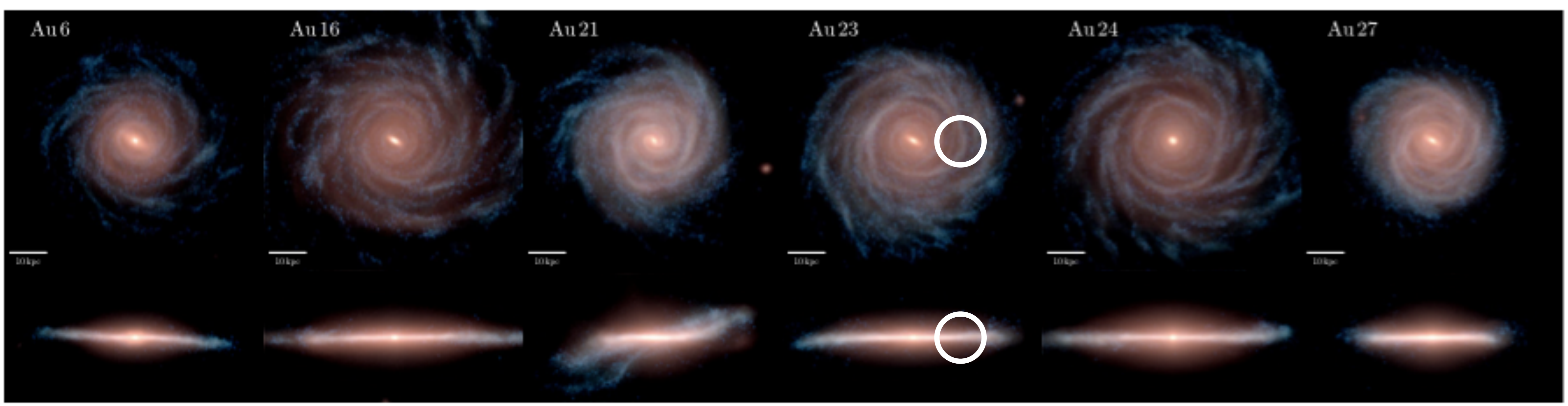
Bullock & Johnston 2005

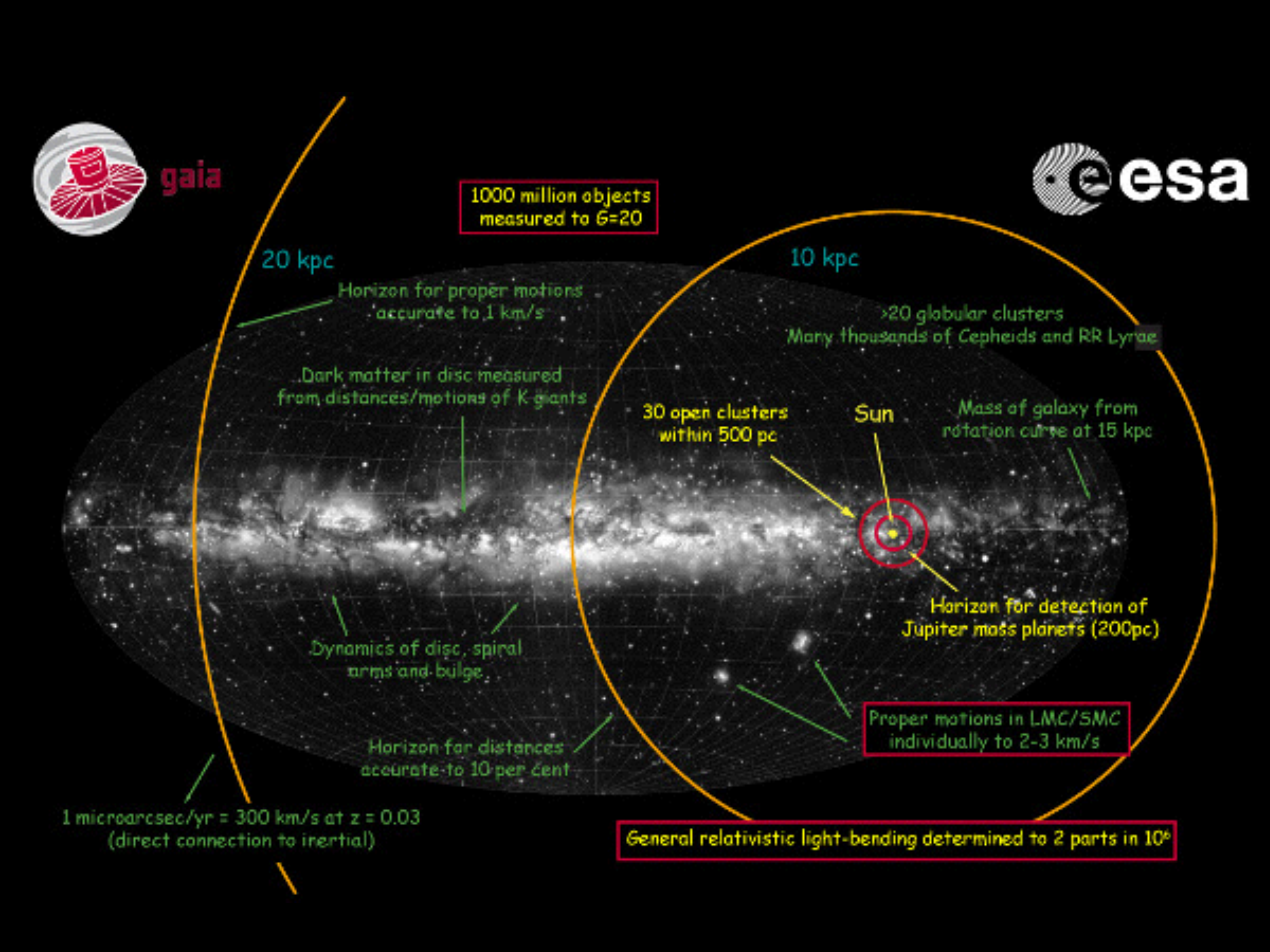
We should also expect debris in the disk

We can look for signatures in phase space, e vs. j_z:

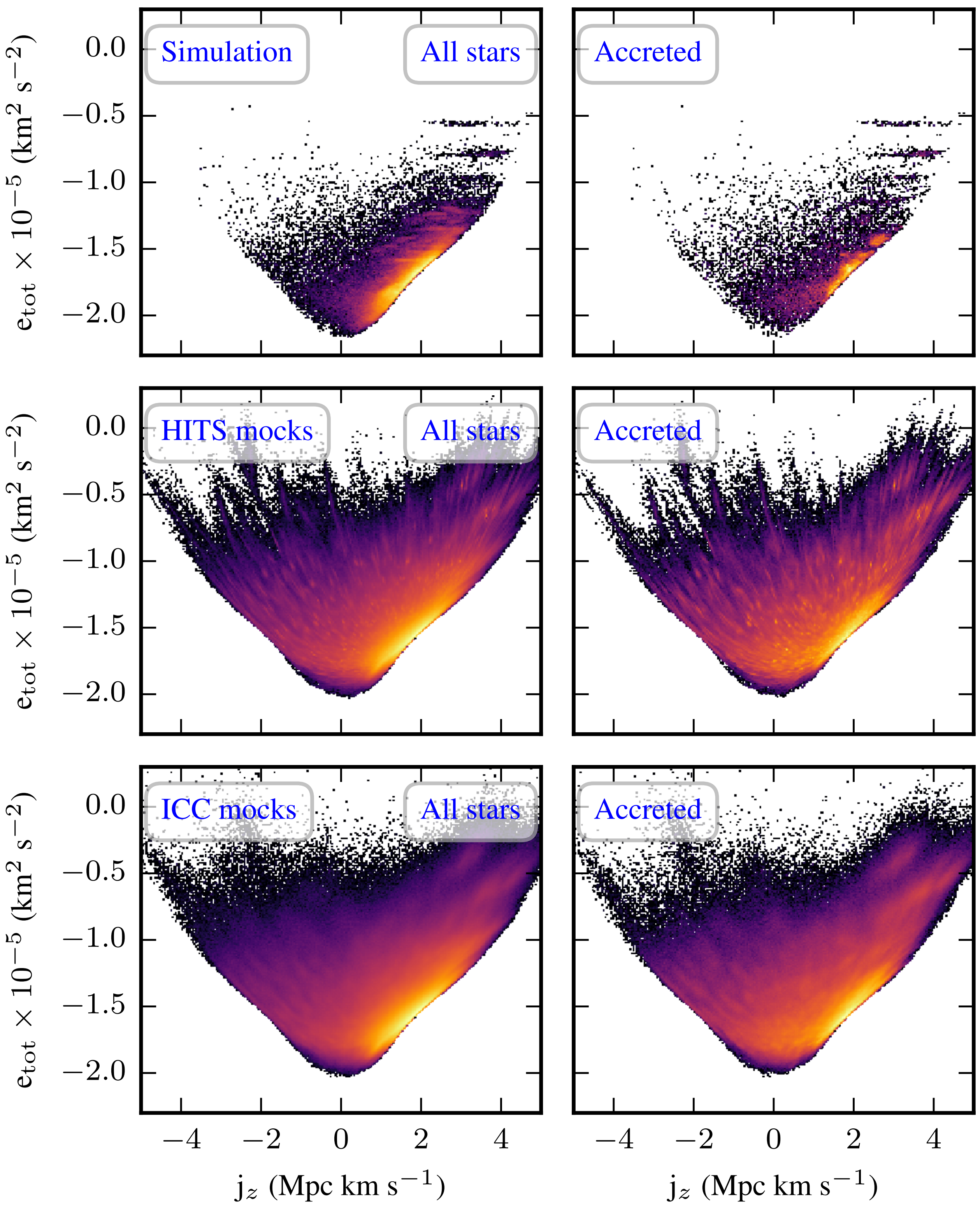


that may not be obvious in configuration space:



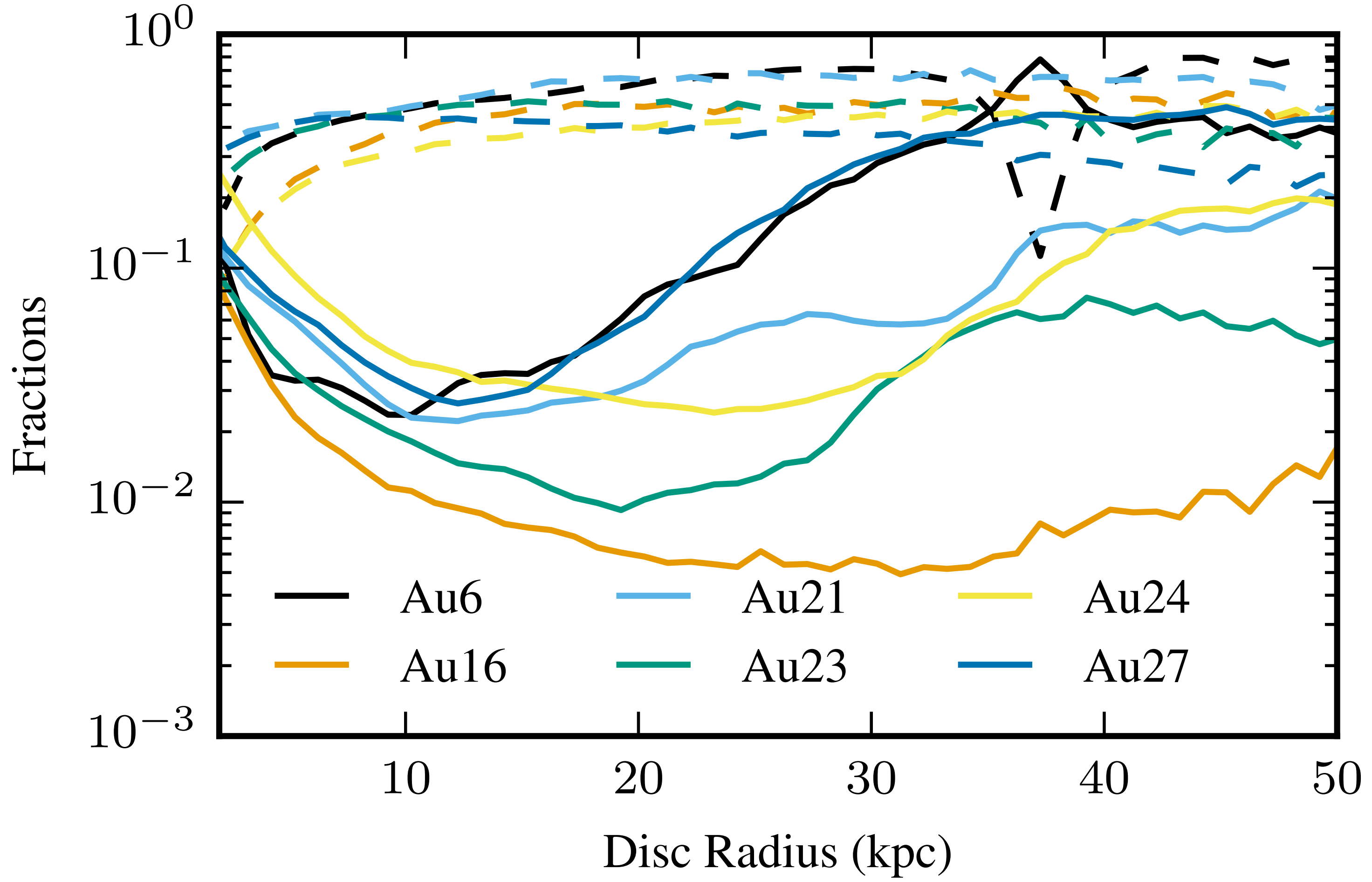

gaia
esa
1000 million objects measured to G=20
20 kpc
10 kpc
Horizon for proper motions accurate to 1 km/s
>20 globular clusters
Many thousands of Cepheids and RR Lyrae
Dark matter in disc measured from distances/motions of K giants
30 open clusters within 500 pc
Sun
Mass of galaxy from rotation curve at 15 kpc
Horizon for detection of Jupiter mass planets (200pc)
Dynamics of disc, spiral arms and bulge
Proper motions in LMC/SMC individually to 2-3 km/s
Horizon for distances accurate to 10 per cent
1 microarcsec/yr = 300 km/s at z = 0.03
(direct connection to inertial)
General relativistic light-bending determined to 2 parts in 10⁶

Mock Gaia data (*Aurigaia*)



- Work in progress!
- We need to get a better handle on how to make predictions for substructures from the mocks
- These predictions can then be compared to Gaia

Counter-rotating stars



solid: fraction of counter-rotating stars

dashed: fraction of counter-rotating stars that are accreted

Conclusions

- Are there tensions with LCDM and the Auriga model?
  - Potentially, yes, but there is still work needed to analyze the simulations
  - Some apparent tensions may be due to our understanding of baryon physics in galaxy formation

- What we can say:
  - Auriga produces the correct number of satellite systems
  - They have star formation properties consistent with observations
  - Orbits of satellites correlate with the disk (but not in a polar way)
  - Issues like core/cusp, TBTF require higher resolution studies
  - Debris from satellites may also be an important diagnostic & not just in the halo