



Stellar halos, intracluster light and accreted versus in situ stars (theory)

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Theory of stellar halos

Stellar halo: stars outside the main galaxy: $\left\{ \begin{array}{l} > 10 \text{ kpc (MW)} \\ > 100 \text{ kpc (Cluster)} \end{array} \right.$

Stellar halos include:

- Satellite galaxies
- Streams
- Diffuse stars

Together they make up $\leq 5\%$ of stars in **isolated galaxies**, but $\sim 90\%$ in brightest **cluster galaxies**

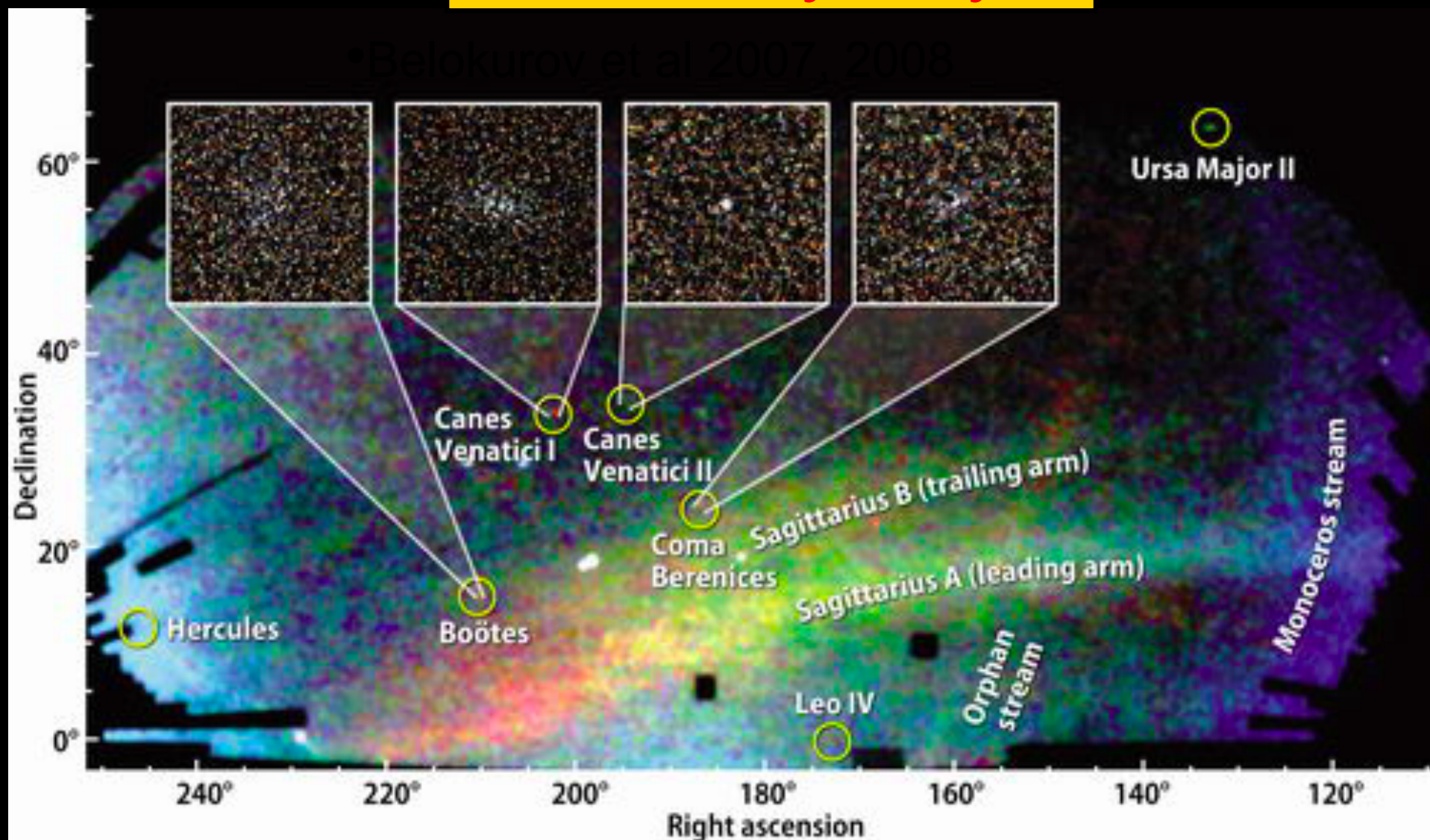
“In situ” – stars formed in the main progenitor of the final galaxy

“Accreted” – stars formed in satellites and later stripped

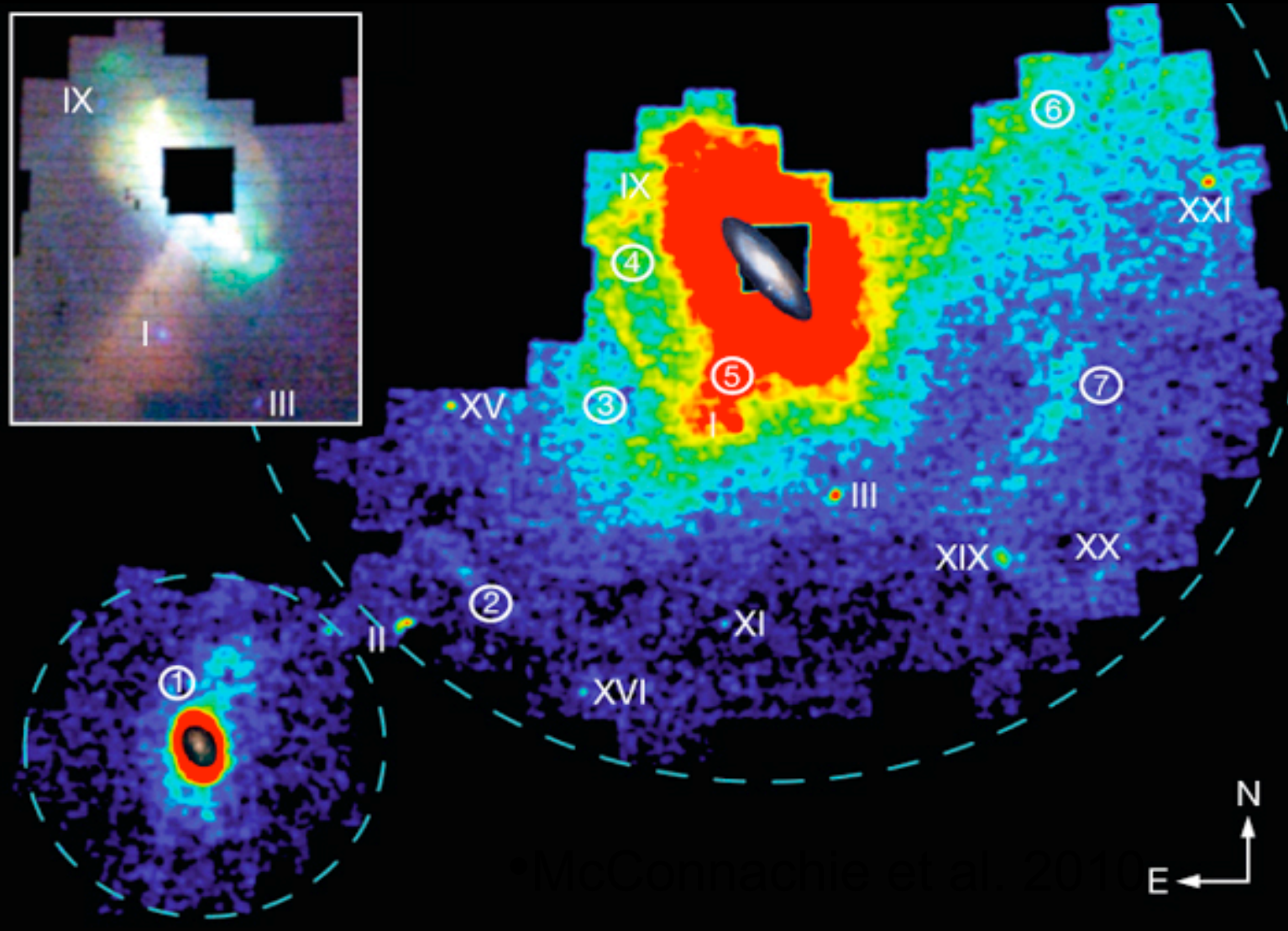
Stars formed from gas brought in by sats & subsequently tidally stripped $\rightarrow$ **“Endo-debris”** (Tissera)

The Milky Way

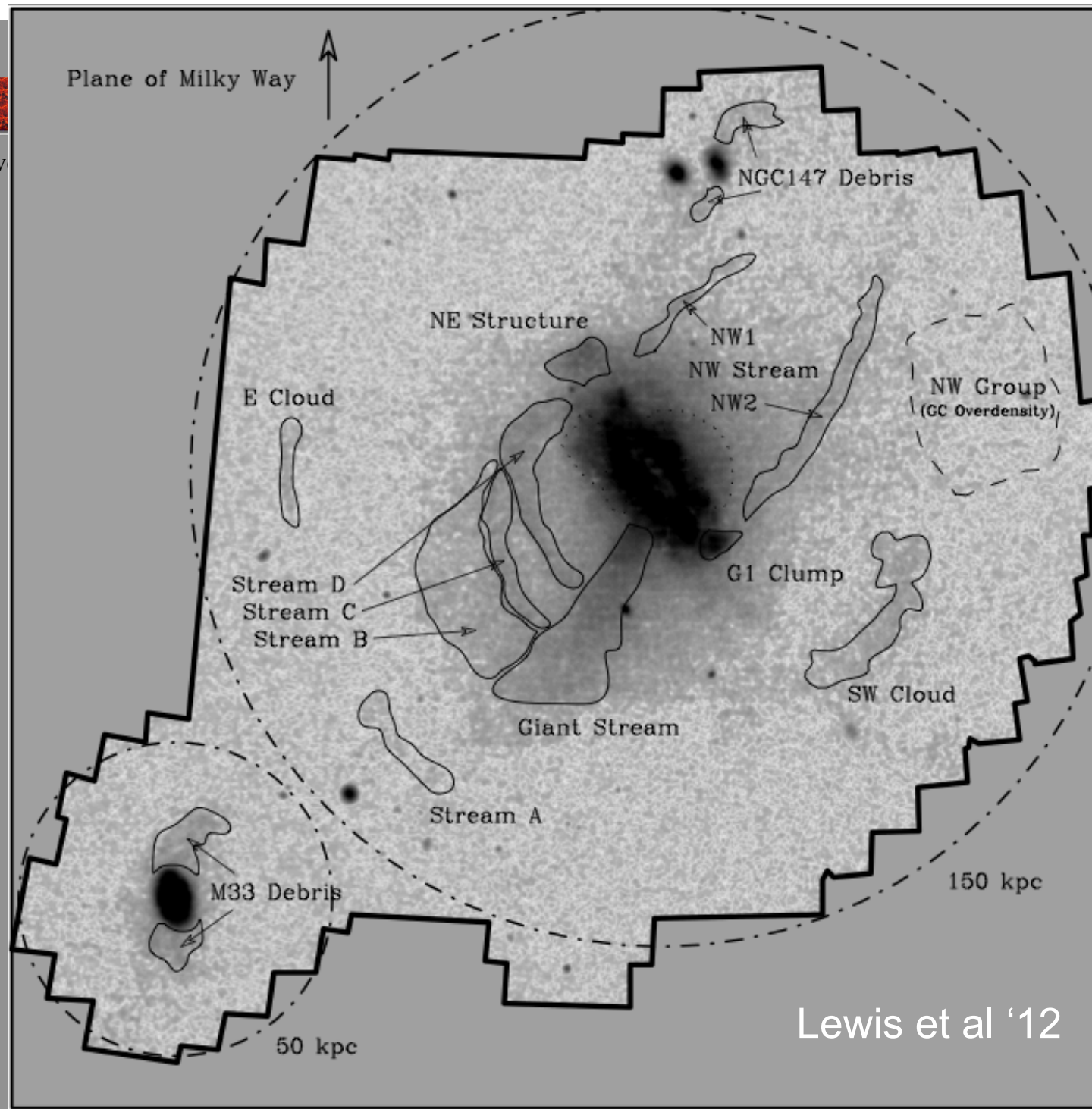
•Belokurov et al 2007, 2008



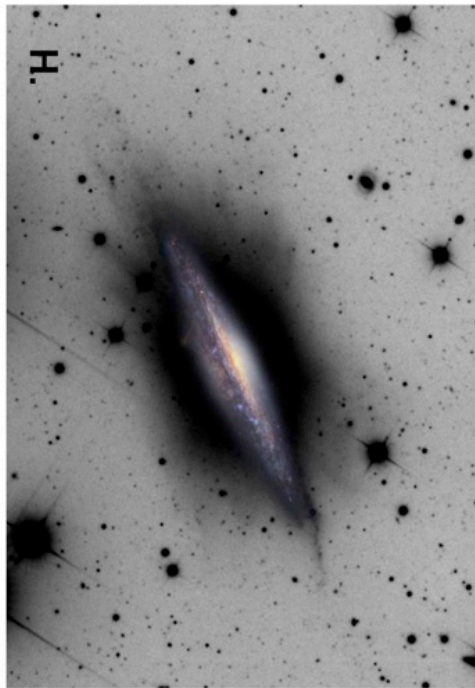
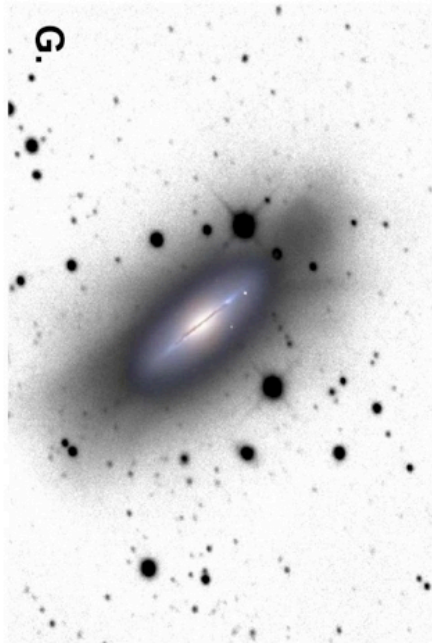
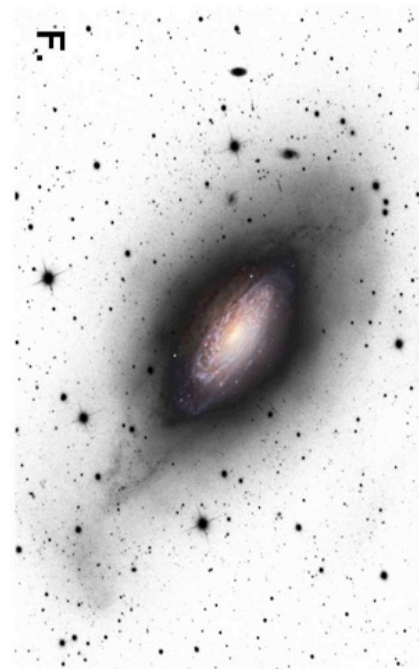
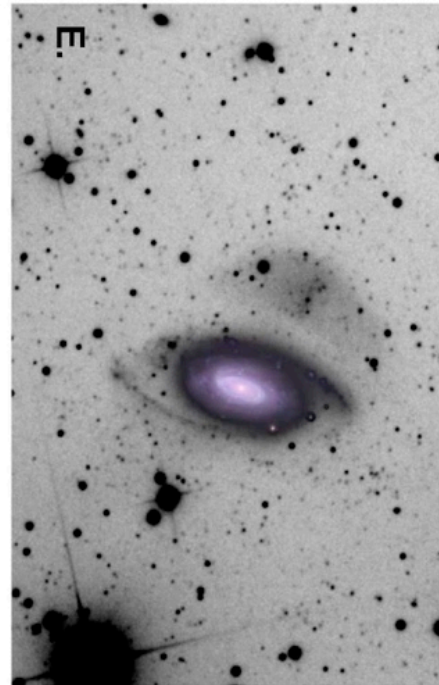
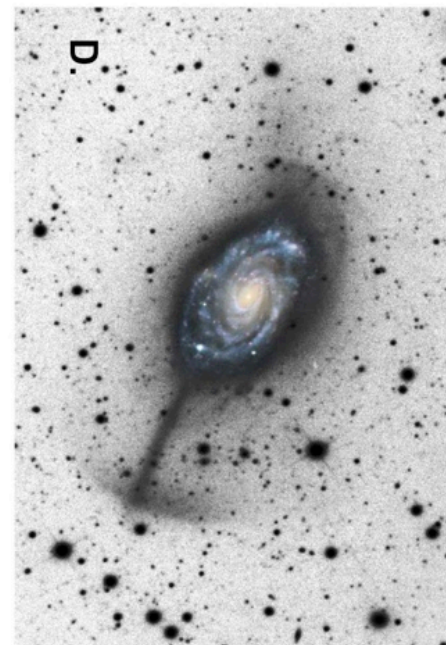
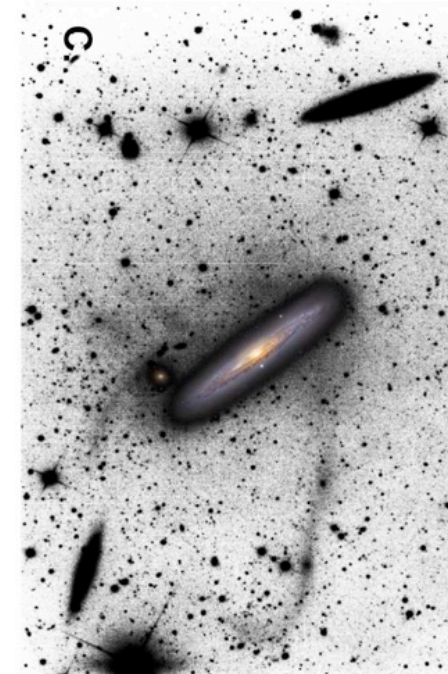
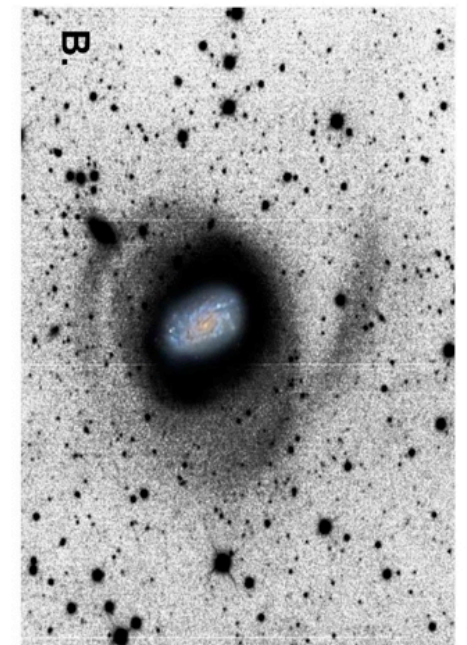
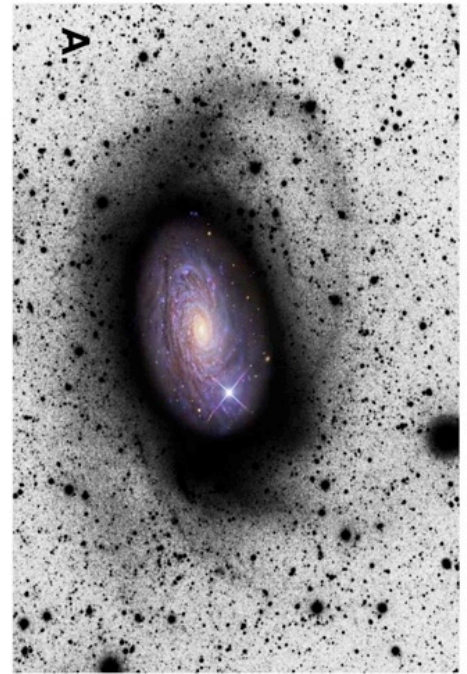
Andromeda



McConnachie et al. '10

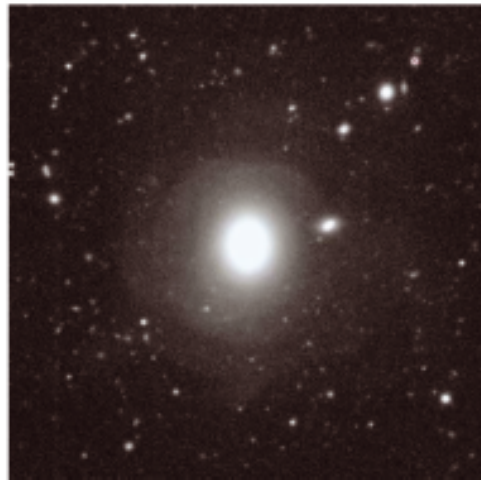
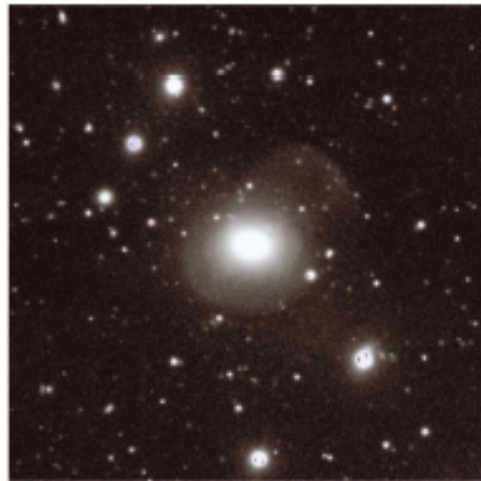
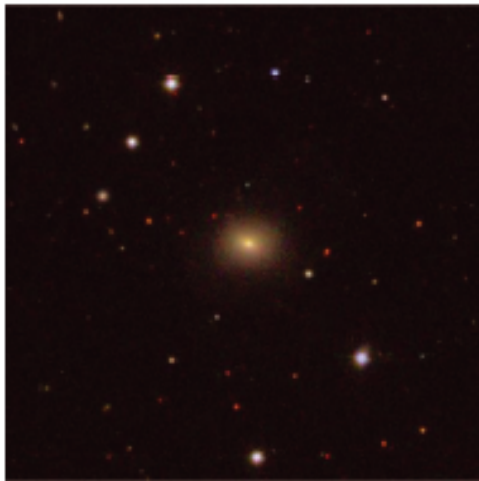
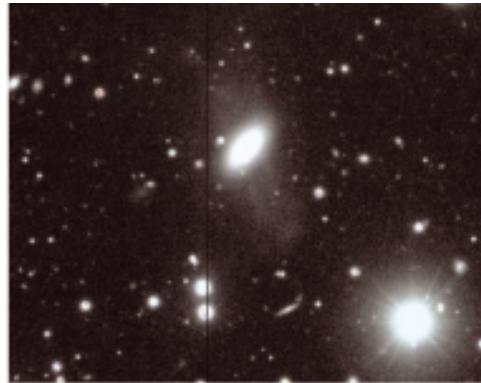


Lewis et al '12

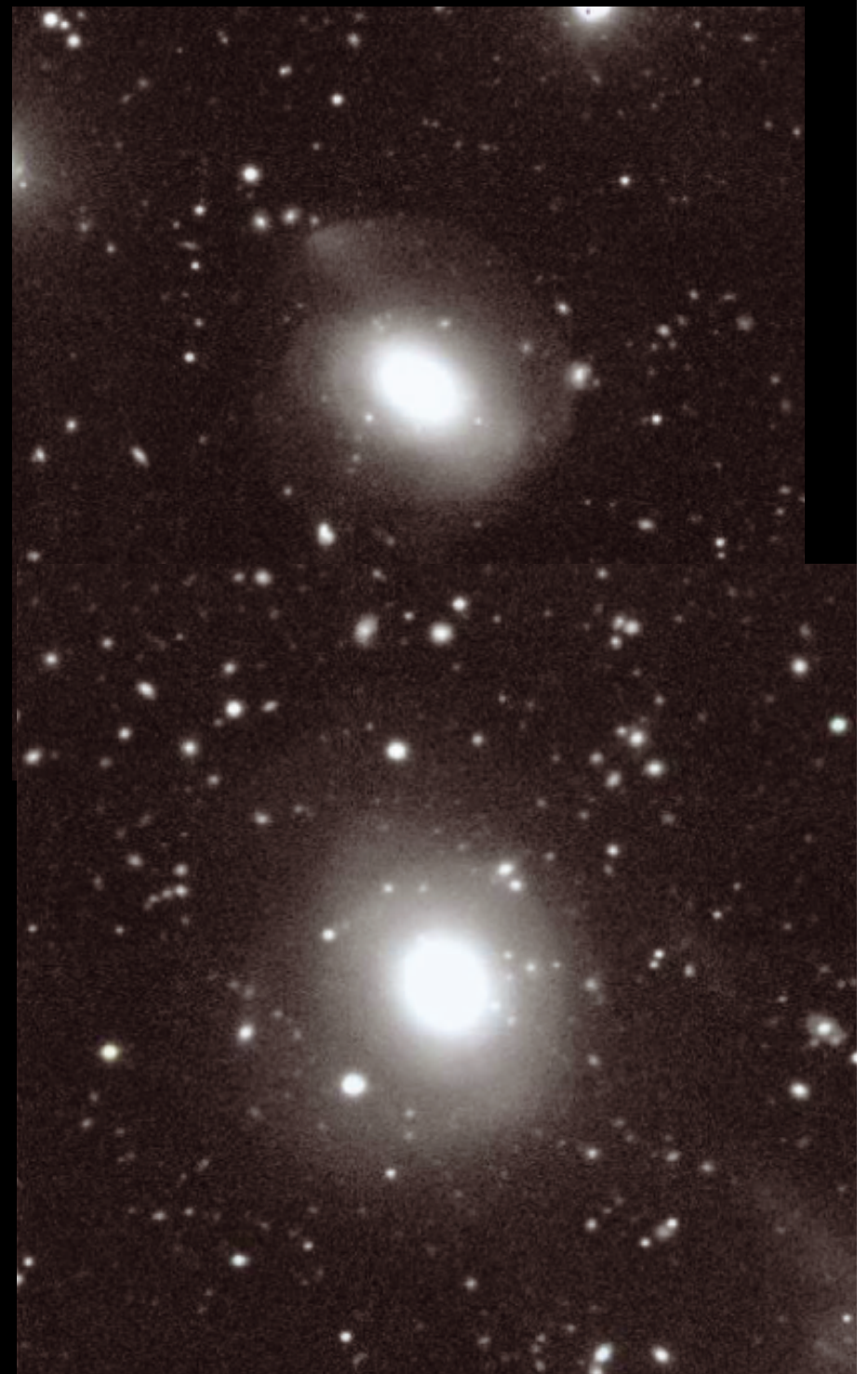


Martinez-Delgado et al. 2010

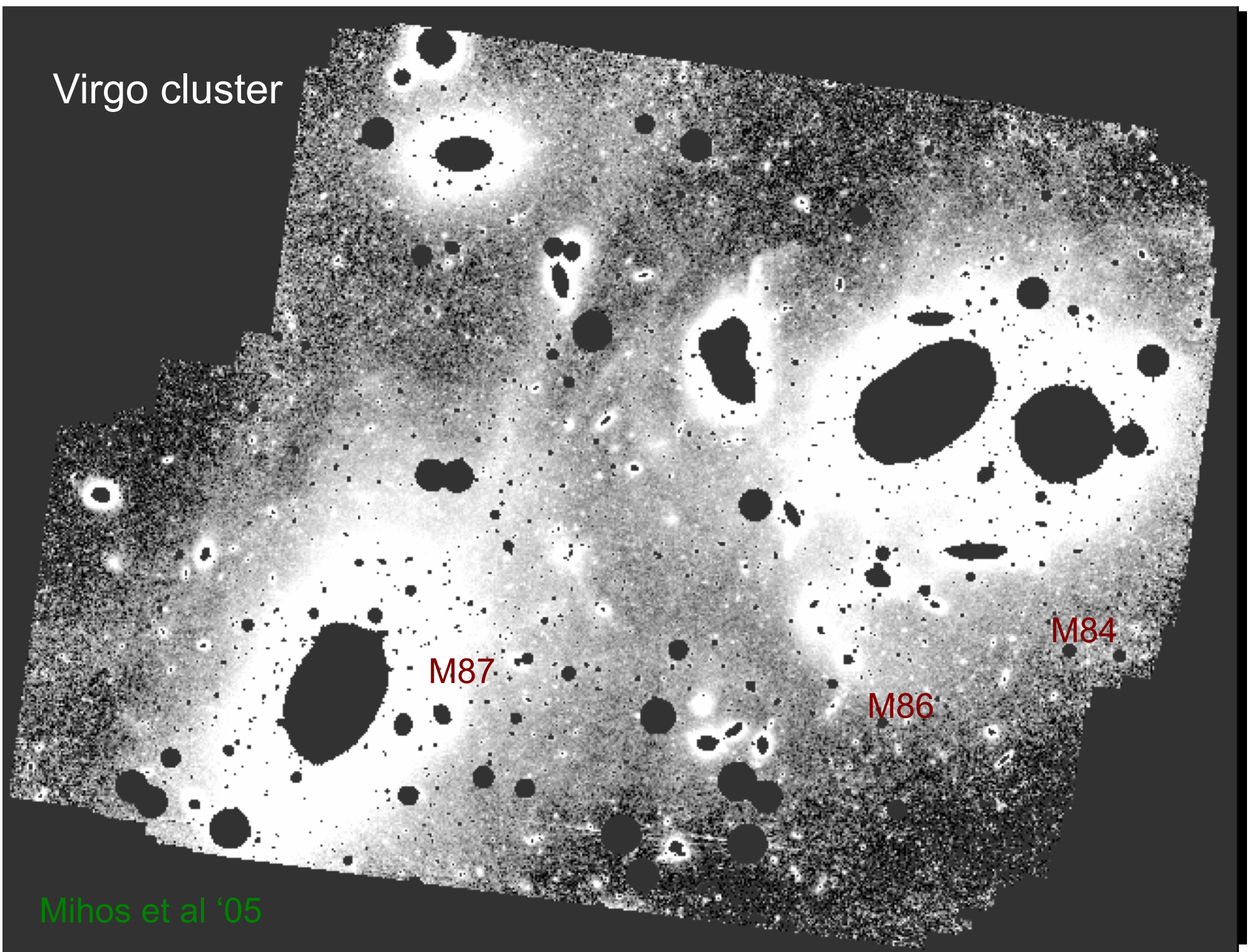
SDSS Stripe82



Kaviraj et al '10



Virgo cluster



Mihos et al '05

Theory of stellar halos

Why are stellar halos interesting?

Galaxy formation:

- Record of assembly of galaxies and clusters (“archeology”)
- History of outflows (feedback), metal enrichment, SFR, IMF ...

Cosmology:

- Test of hierarchical clustering characteristic of CDM
- Nature of dark matter: CDM or WDM or SIDM?

$z=5.7$

31.25 Mpc/h

$z=0$

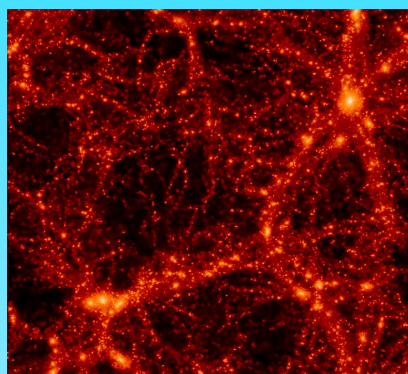
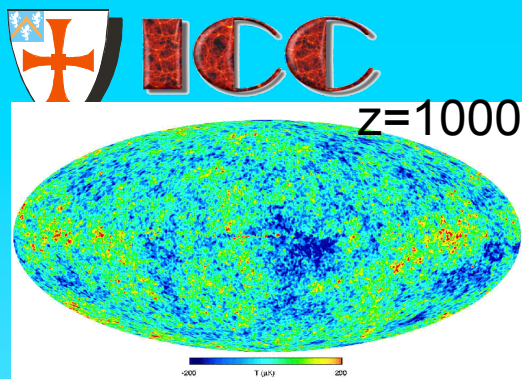
31.25 Mpc/h

15.6 Mpc/h

Theory of stellar halos

Formation of stellar halos

Must be part of a galaxy formation theory, in a cosmological context, i.e a physics-based model for the formation and evolution of galaxies



Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$; dark matter

Primordial fluctuations

$$\delta\rho/\rho(M, t)$$

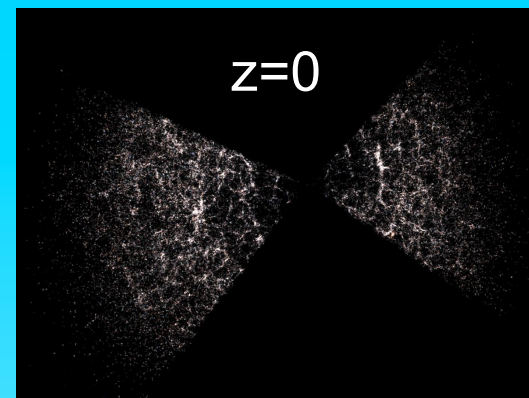
Dark matter halos
(N-body simulations)

Gas processes
(cooling, star formation, feedback)

Gasdynamic simulations

Semi-analytics

Formation and evolution of galaxies



Well understood

Modelling galaxy formation

Gas dynamical processes

Flows - shocks - radiative cooling - heating

Hydrodynamical simulation



Solve hydro equations
numerically

Semi-analytic model



Assume spherical symmetry
& solve analytically

Astrophysical processes

- Star formation and SN feedback
- Production & mixing of metals
- Dust obscuration
- Galaxy mergers
- Reionization
- Evolution of stellar pops
- AGN feedback

Lighting up Aquarius

Semi-analytic model

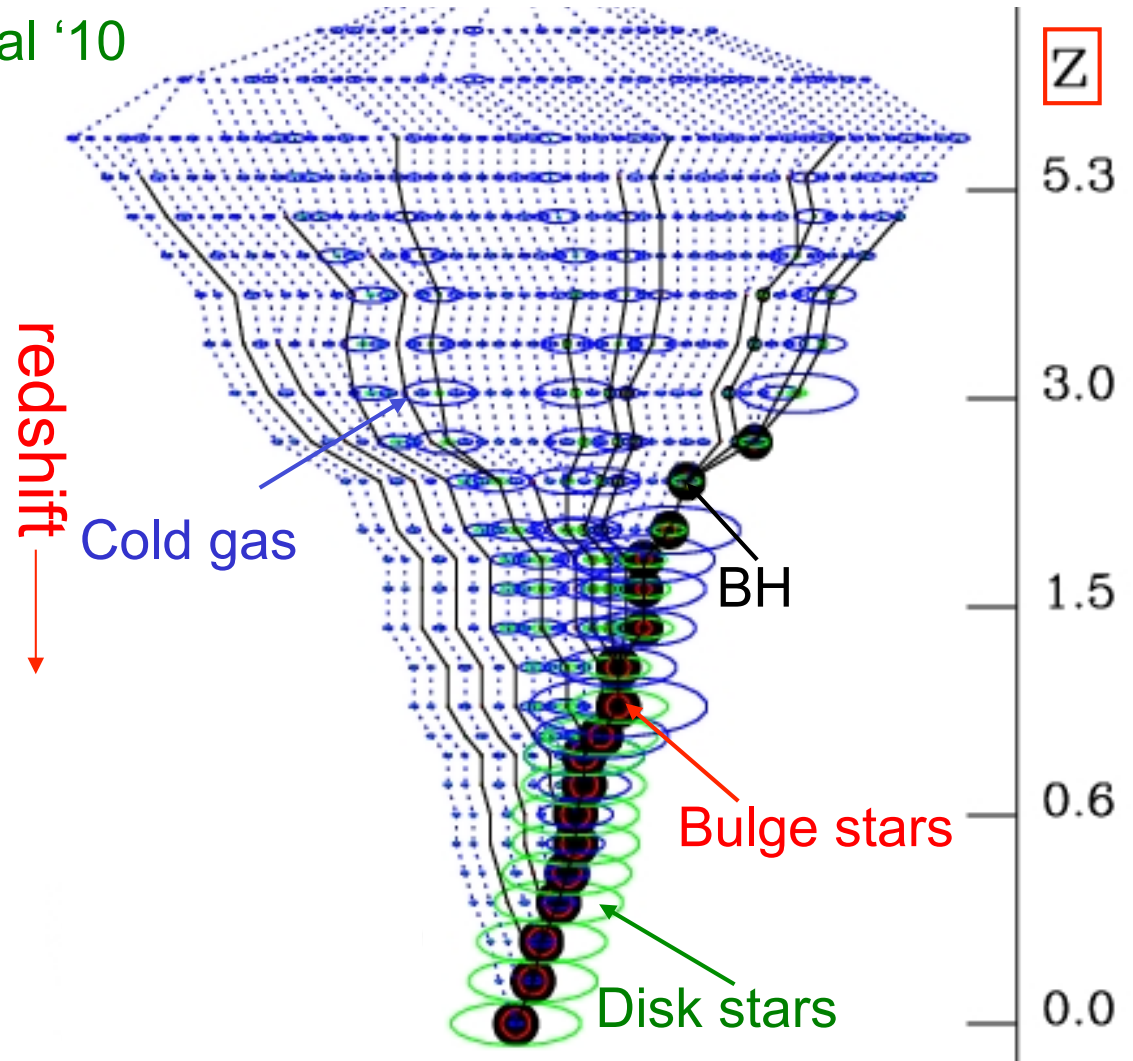
Cooper et al '10

1. At each simulation output GALFORM new mass of stars in each progenitor
 2. Assign stars mass, age, Fe/H to subset of DM particles
- Using 1% most bound DM particles gives good satellite sizes

"Tagging"

Can follow stellar halo, satellites, not the disk

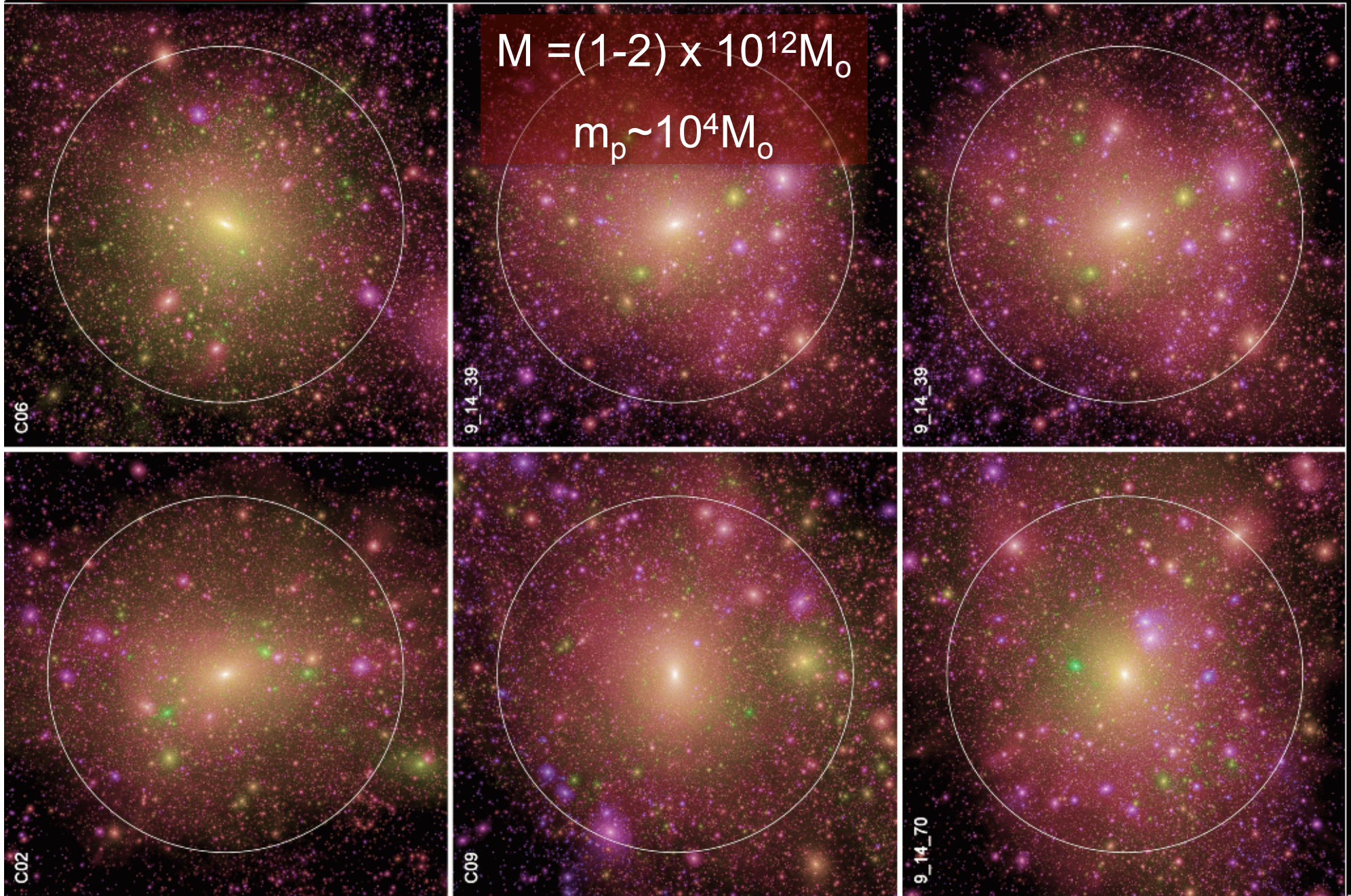
Halo merger tree for Aquarius halo



Malbon, Baugh, Frenk & Lacey '06

VIRG

Images of Aquarius galactic halos

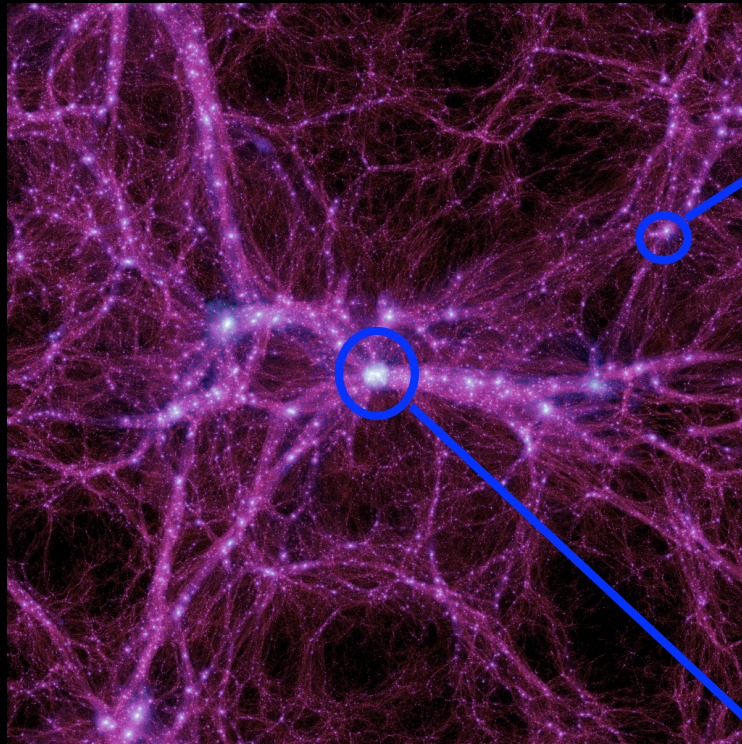




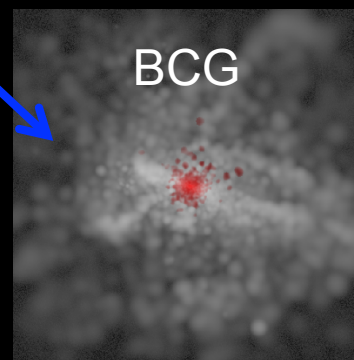
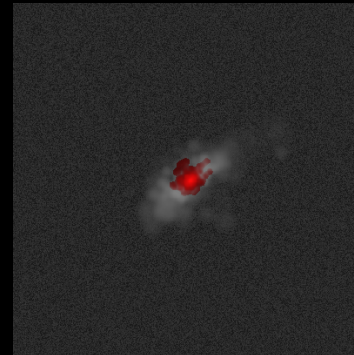
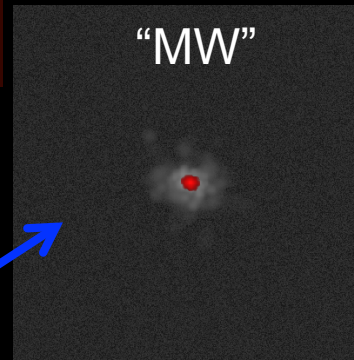
Lighting up Millennium-II

$$M = (0.5 \times 10^{11} - 10^{15}) M_{\odot}$$

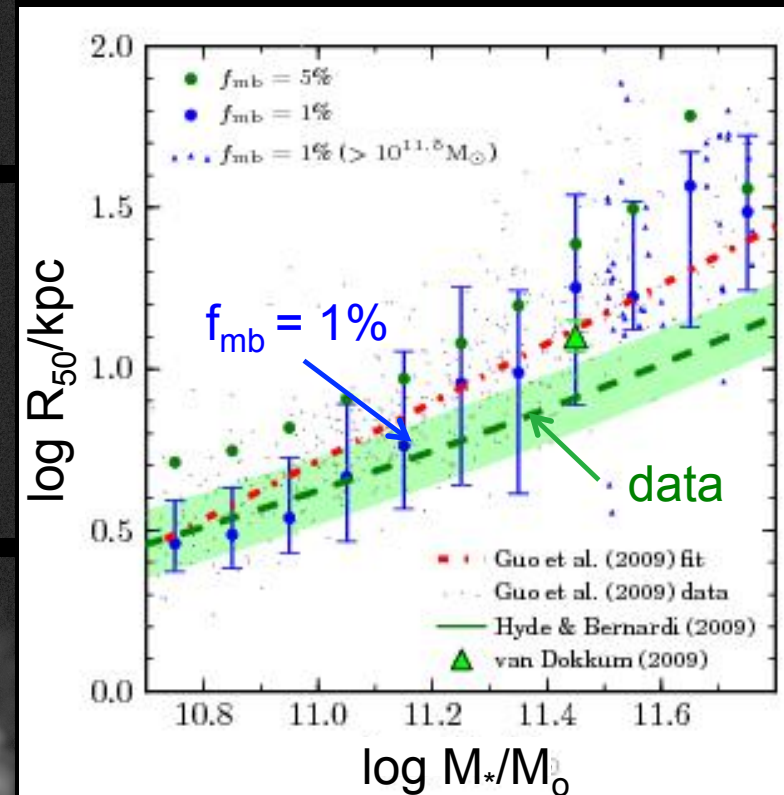
$$m_p \sim 10^7 M_{\odot}$$



Boylan-Kolchin et al. (2009)

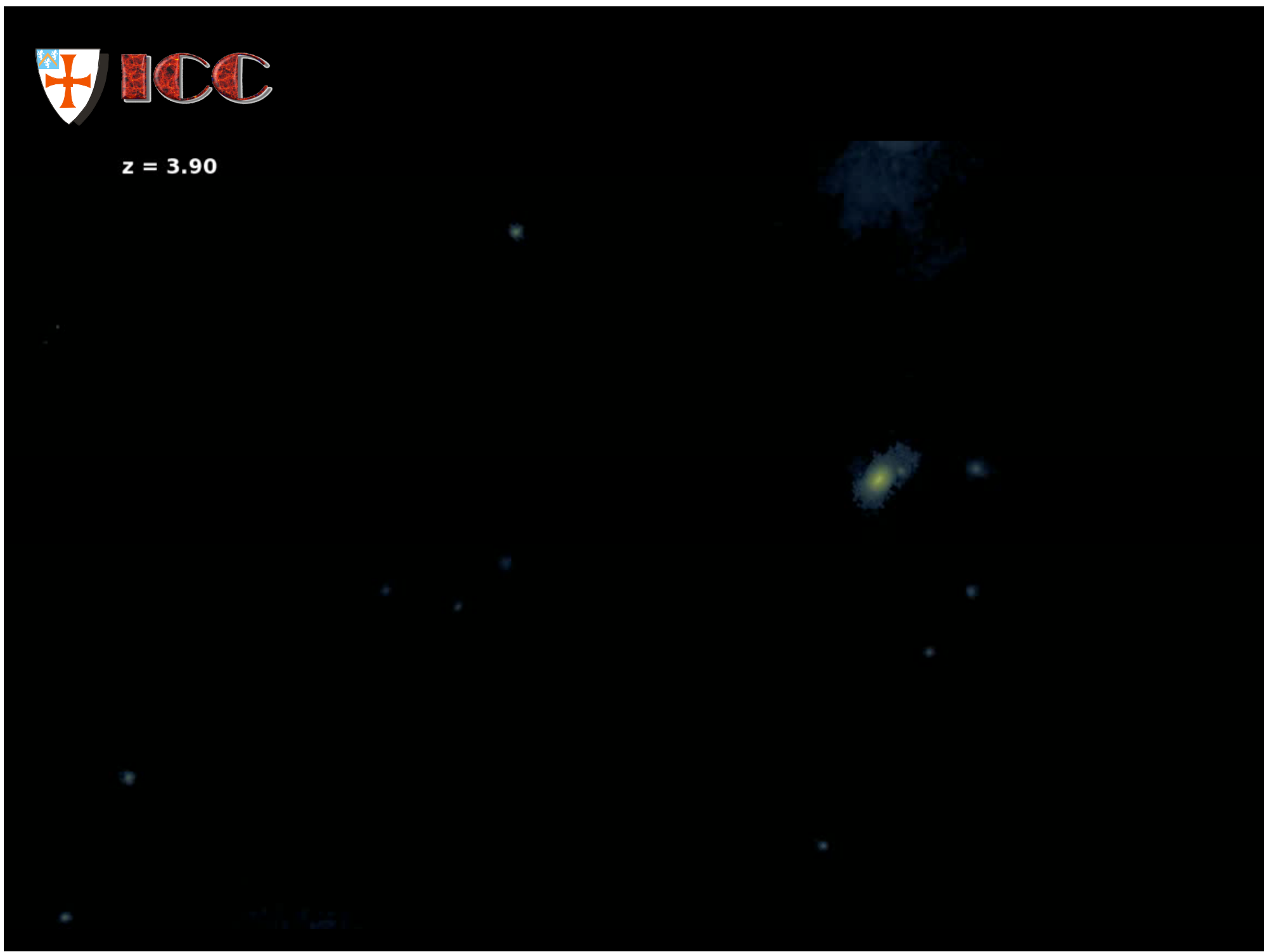


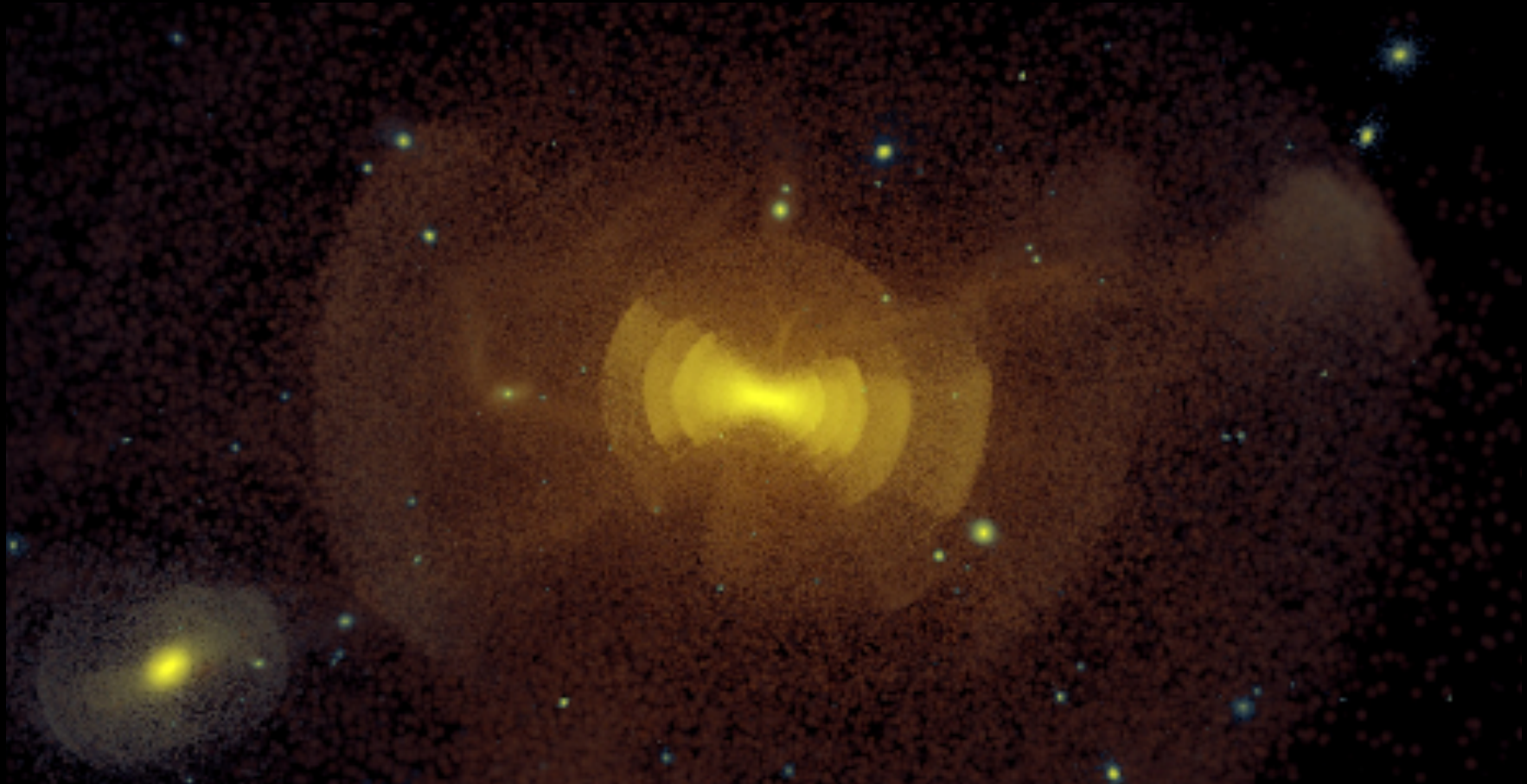
Cooper et al '13





$z = 3.90$





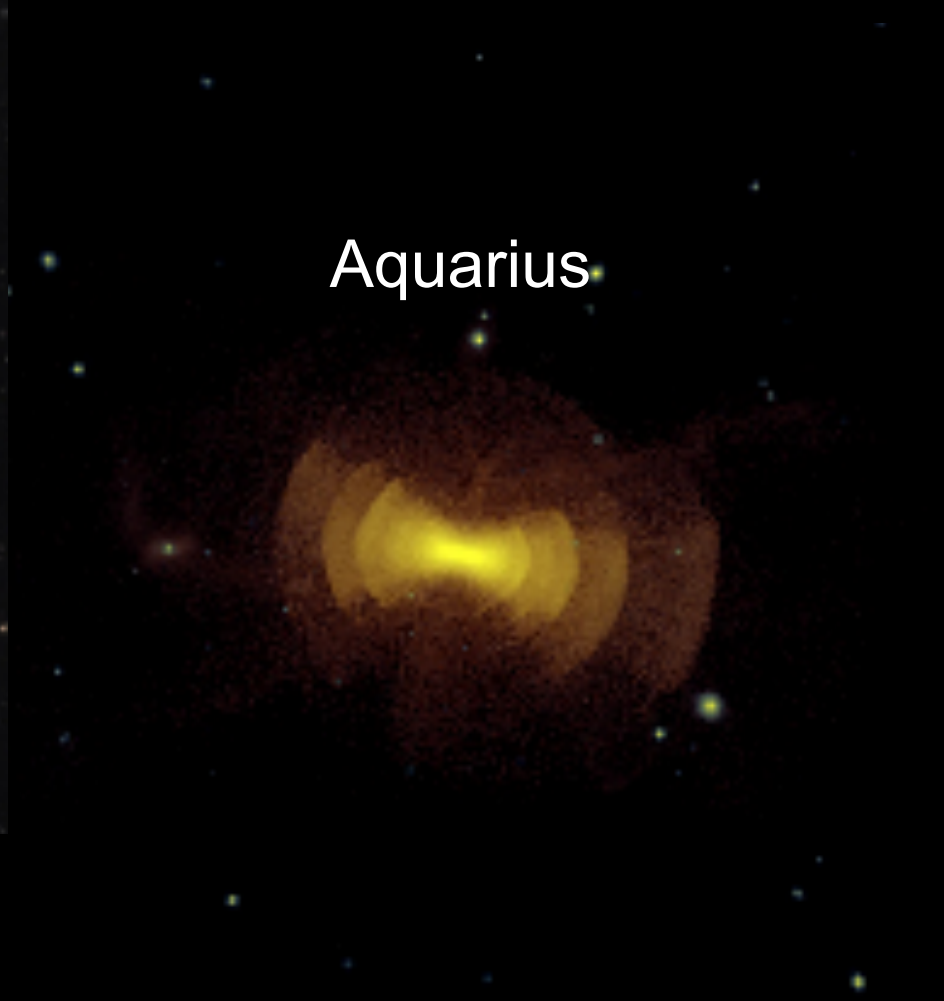
NGC 7600





NGC 7600

Aquarius



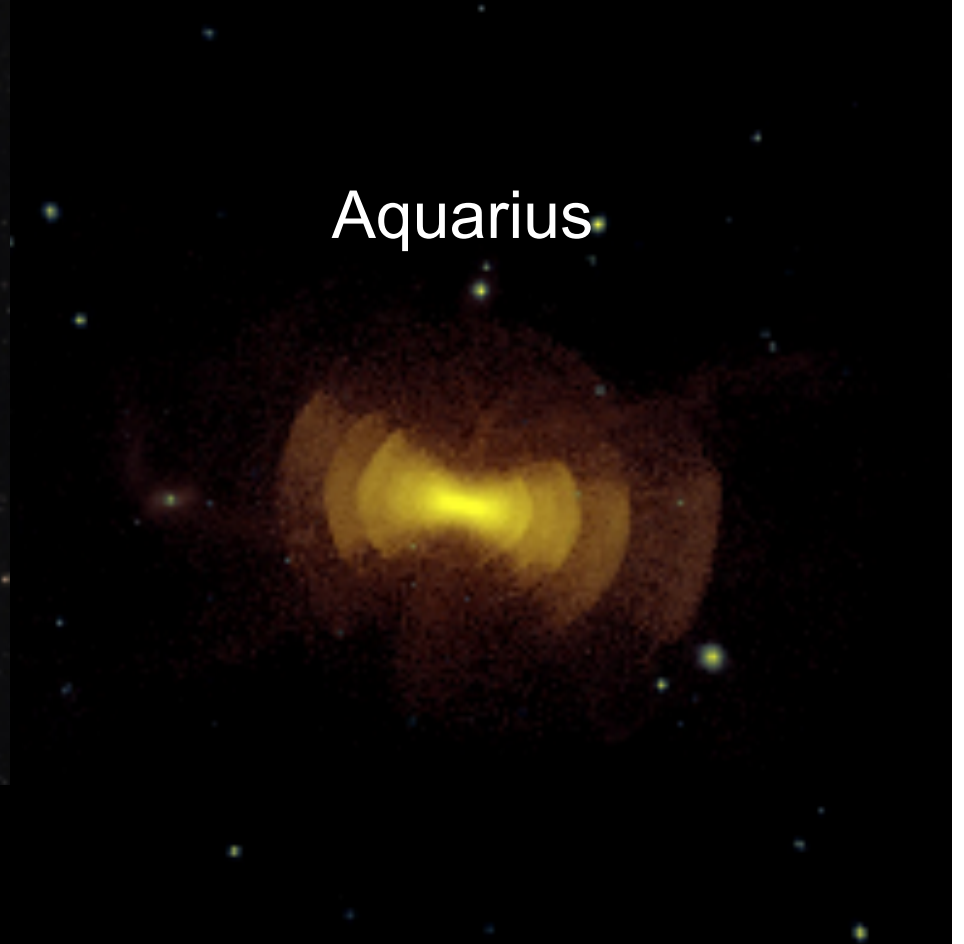


Cooper et al arxiv1111.2864



NGC 7600

Aquarius



(<http://www.virgo.dur.ac.uk/shell-galaxies>)

Theory of stellar halos

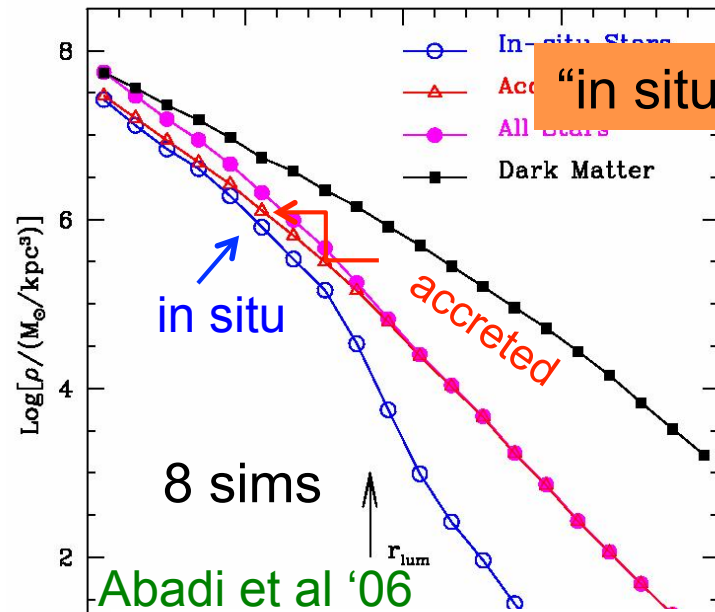
Galaxy formation & the stellar halo: seven questions:

1. How is the halo **built up**: accreted **vs** *in-situ* stars?
2. What is the **relative importance** of accreted, in-situ and satellite stars as a function of radius?
3. How do these properties **depend** on halo **mass**?
4. If there are halo stars formed **in-situ**, how did they get there?

For “Milky Way” halos:

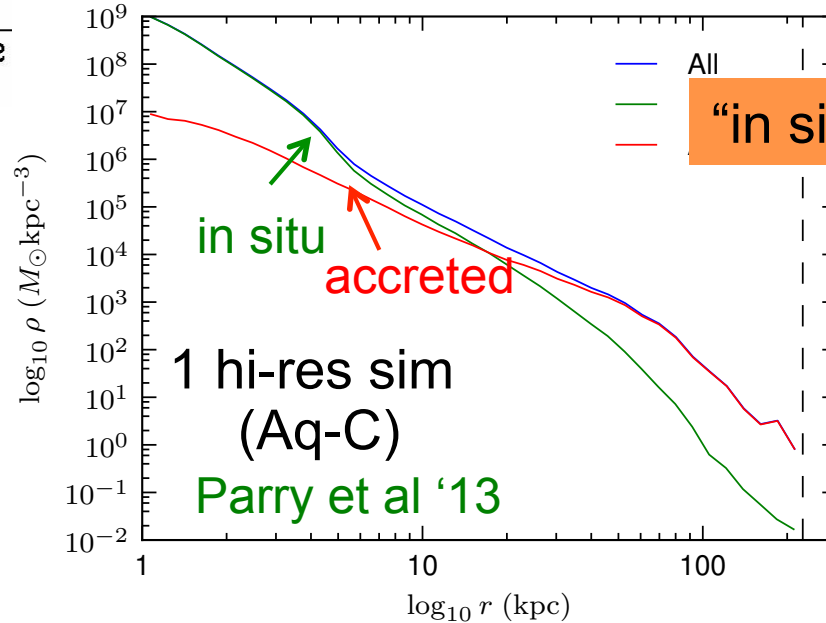
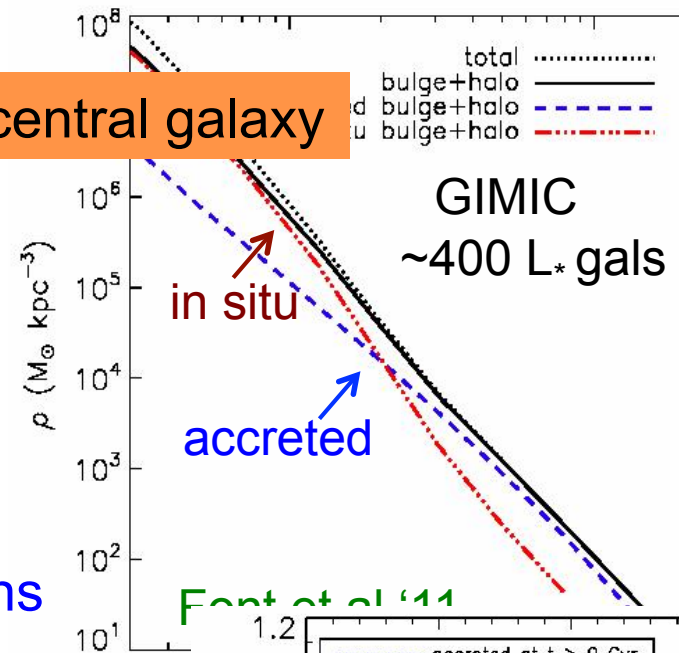
5. How many **satellites** contribute to the **accreted** stellar halo mass, when are they accreted and are they still around?
6. Are there **differences** between **satellites** that give stars to the halo and those that survive intact?
7. How **lumpy** is the stellar halo? Does it make sense to talk of a **mean** stellar density profile or a mean metallicity profile?

1. Stellar halos: accreted vs *in-situ*?

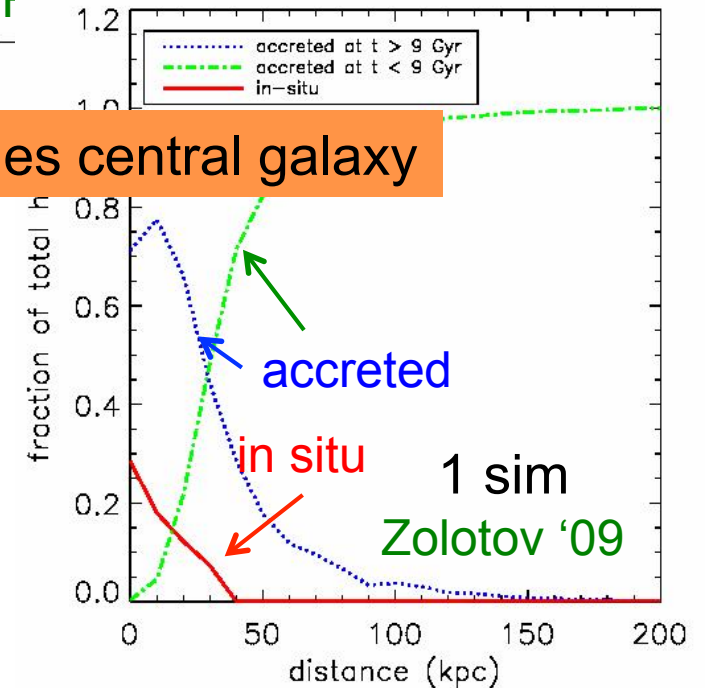


"in situ" includes central galaxy

SPH simulations



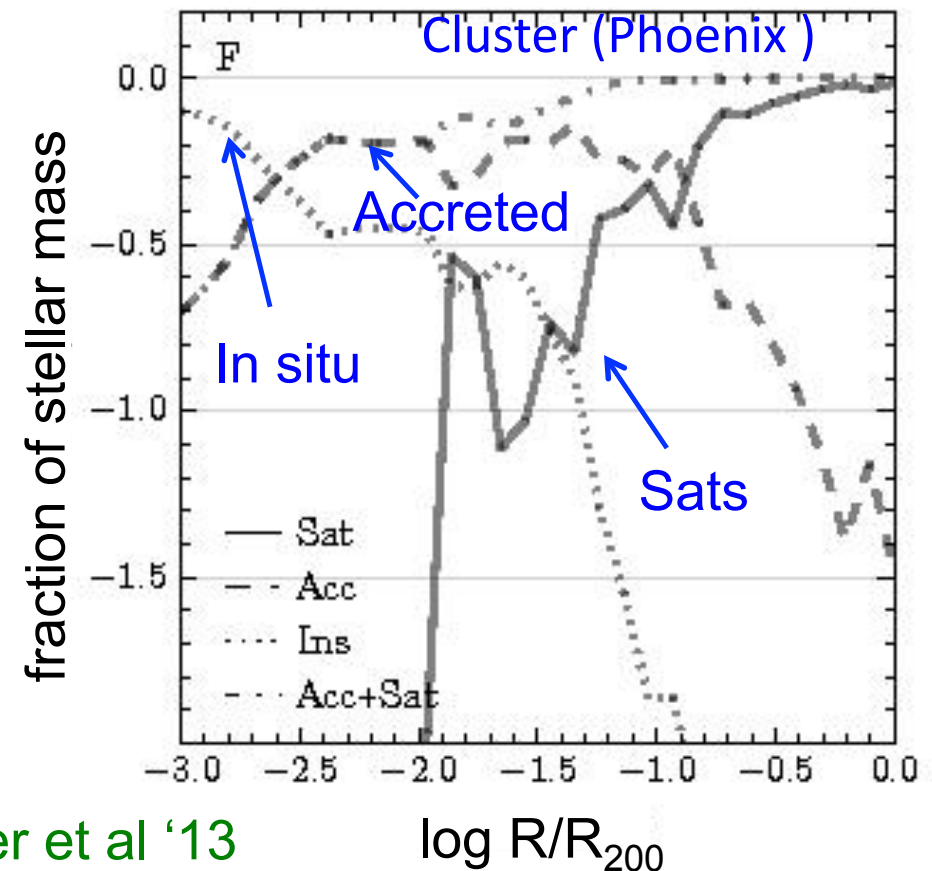
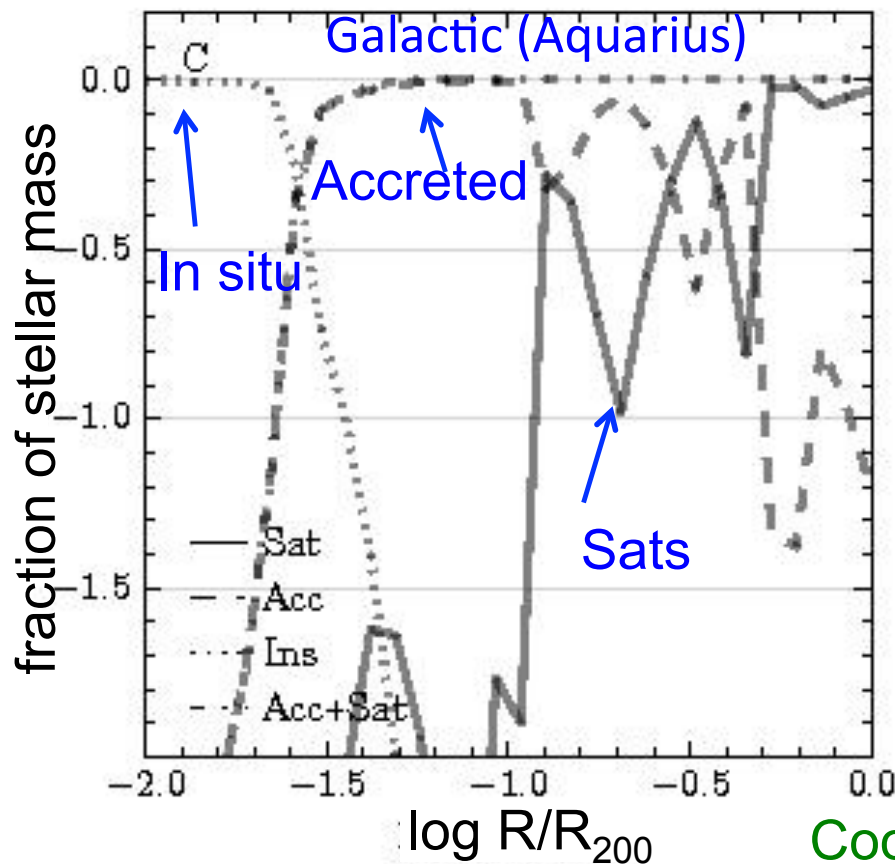
"in situ" excludes central galaxy



Stellar halos: components

2. What is the relative importance of accreted, in-situ and satellite stars as a function of radius?

fraction of stellar mass in each component at each radius
(in-situ includes central galaxy)



Cooper et al '13

1. Stellar halos: accreted vs *in-situ*?

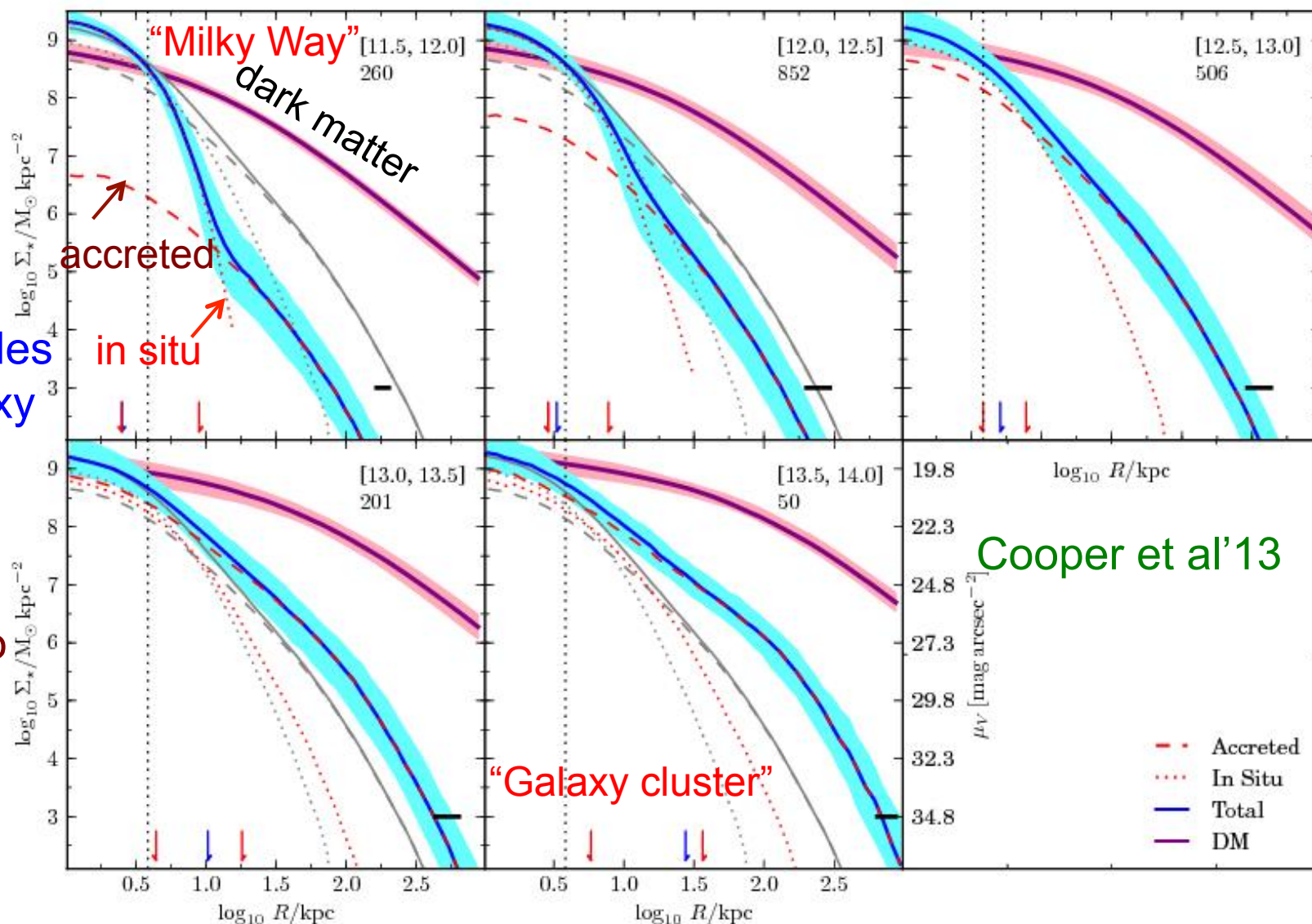
3. How do these properties depend on halo mass

Millennium-2
part. tagging

“in situ” includes
central galaxy

Systematic
variation of
profile w. halo
mass

Large scatter



1. Stellar halos: accreted vs *in-situ*?

1. How is the halo built up: accreted vs *in-situ* stars?

2. What is the relative importance of accreted, *in-situ* and satellite stars as a function of radius?

In galactic halos ($\sim 10^{12} M_{\odot}$) simulations agree that:

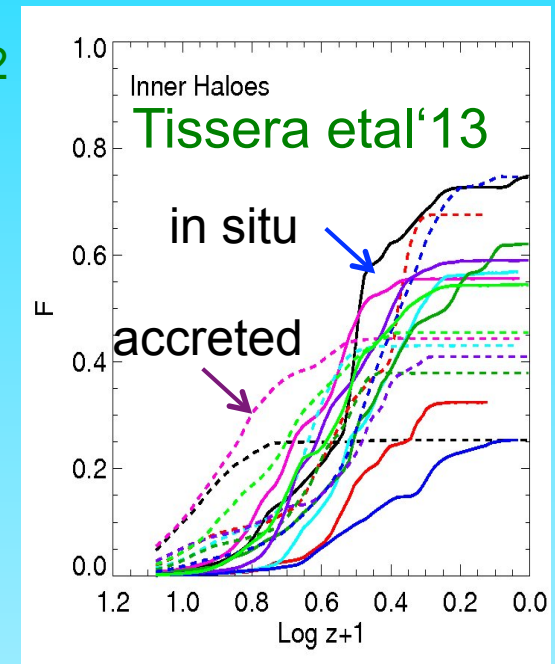
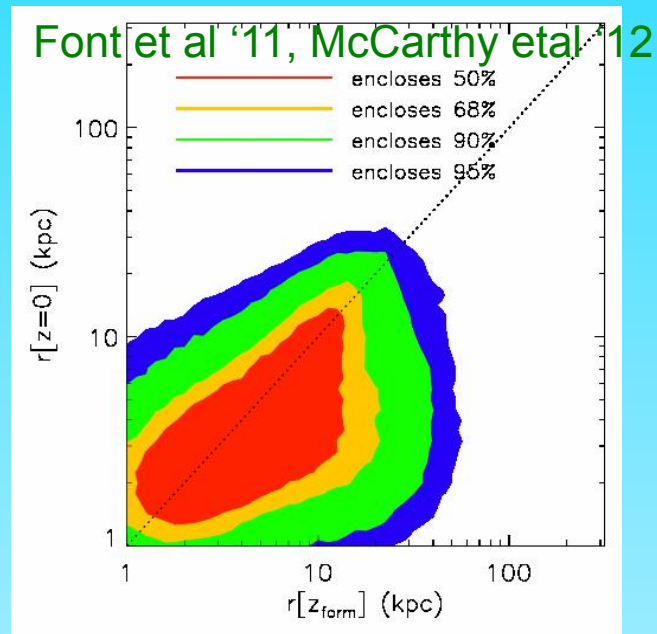
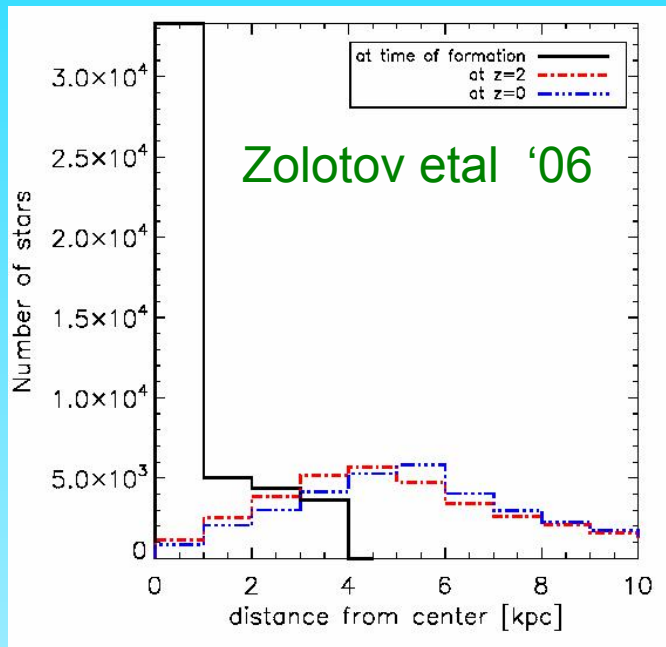
- **Outer** halo dominated by **accreted** stars
- **Significant** (dominant?) comp. of ***in-situ* halo** stars in inner parts
- $\rightarrow$ stellar density profile **flatter** in **outer** parts
- Large halo-to-halo scatter (Font et al '11; Cooper et al '13)

3. How do these properties depend on halo mass

- Importance of accreted comp. increases with $M_{\text{halo}} \rightarrow$ systematic variation of density profile for $M = (5 \times 10^{11} - 10^{14}) M_{\odot}$ (Cooper et al '13)

Stellar halos: accreted vs *in-situ*?

4. If there are halo stars formed in-situ, how did they get there?



stars form in “cold flows” in central parts & scattered to large radii during mergers

some stars form at large radii from cooling of hot gas; others were in disk

“endo-debris” (from sat gas; <35%) + disc heated stars (~20%)

→ different predictions for ages and metallicities of in situ stars

Stellar halos: accreted component

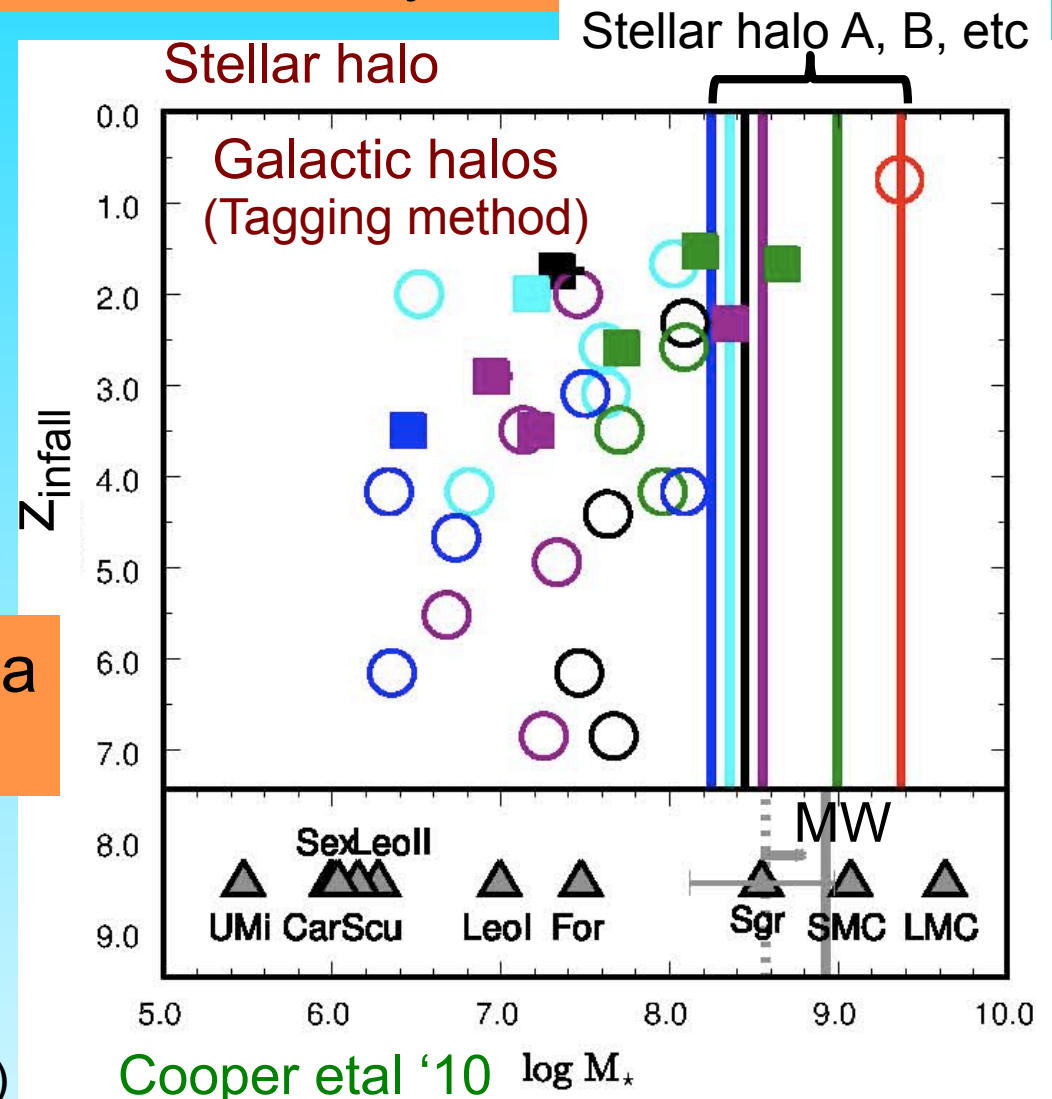
5. How many satellites contribute to accreted stellar halo mass, when are they accreted and are they still around?

- Contribution from defunct satellite
- Contribution from surviving satellite

Most halo stars stripped from a few sats, some still present

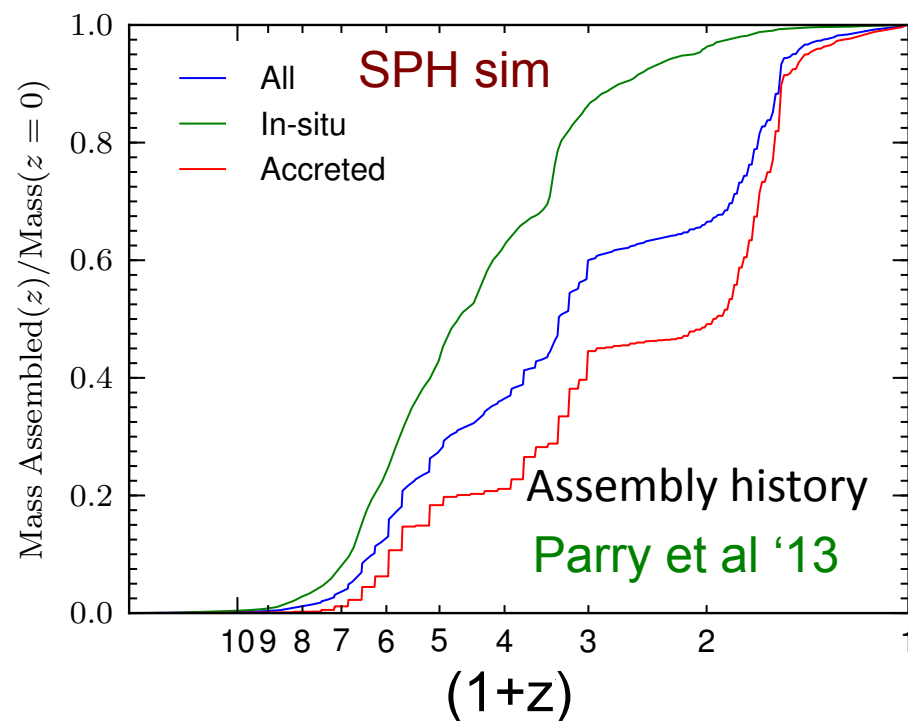
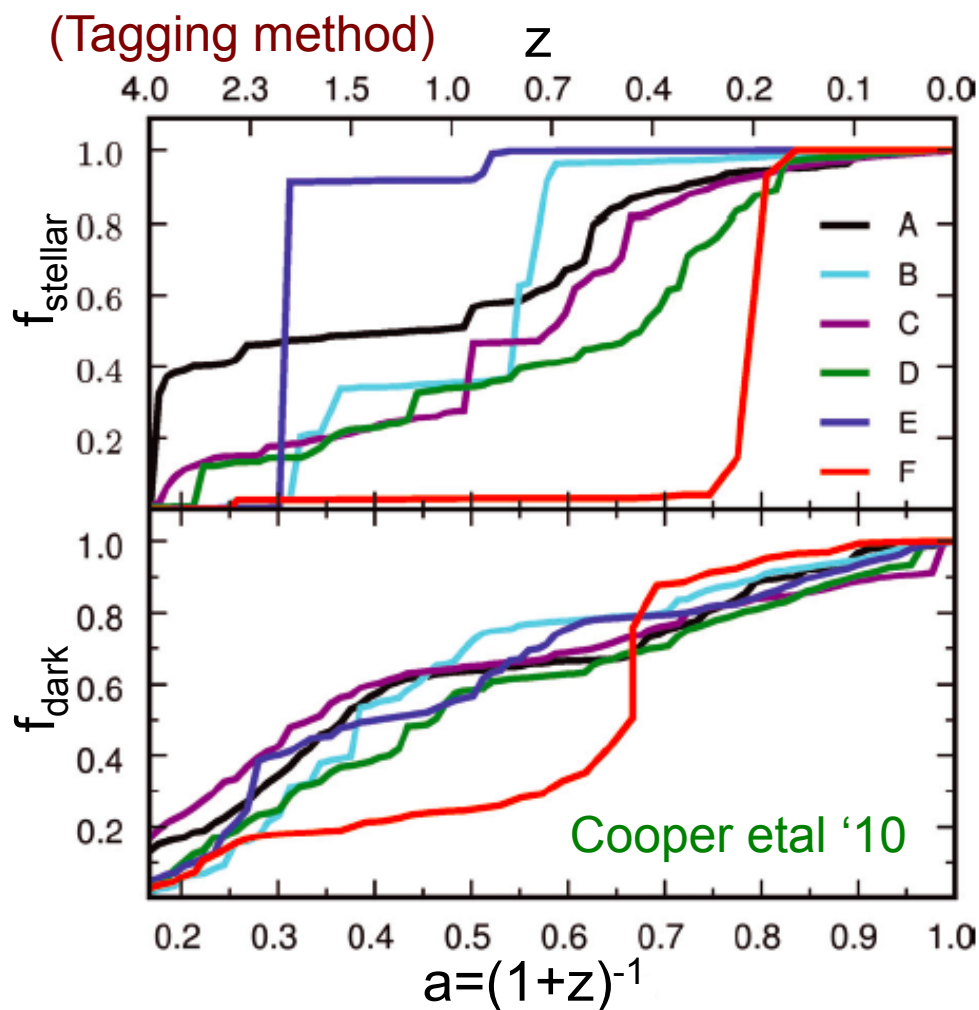
Large variety of formation histories

(Points plotted account for 95% of mass)



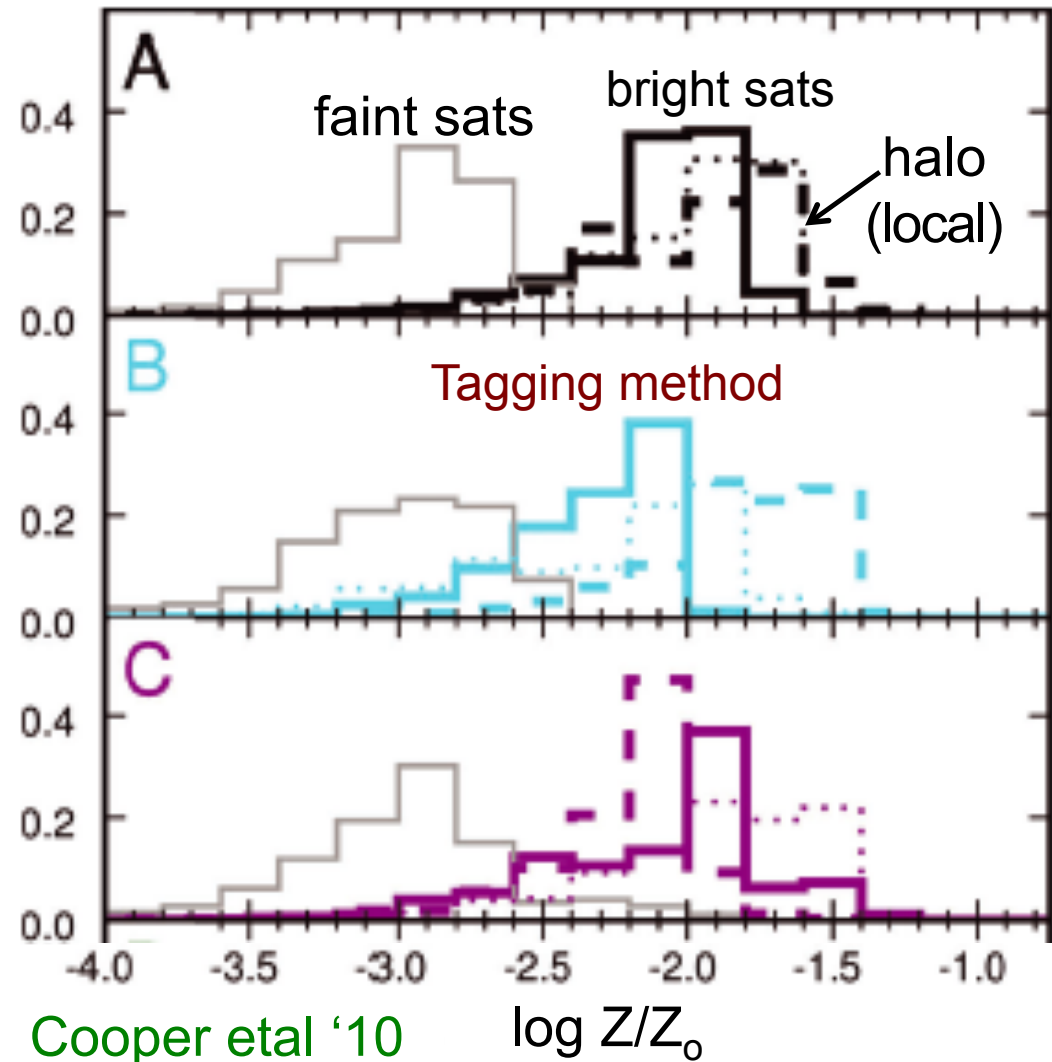
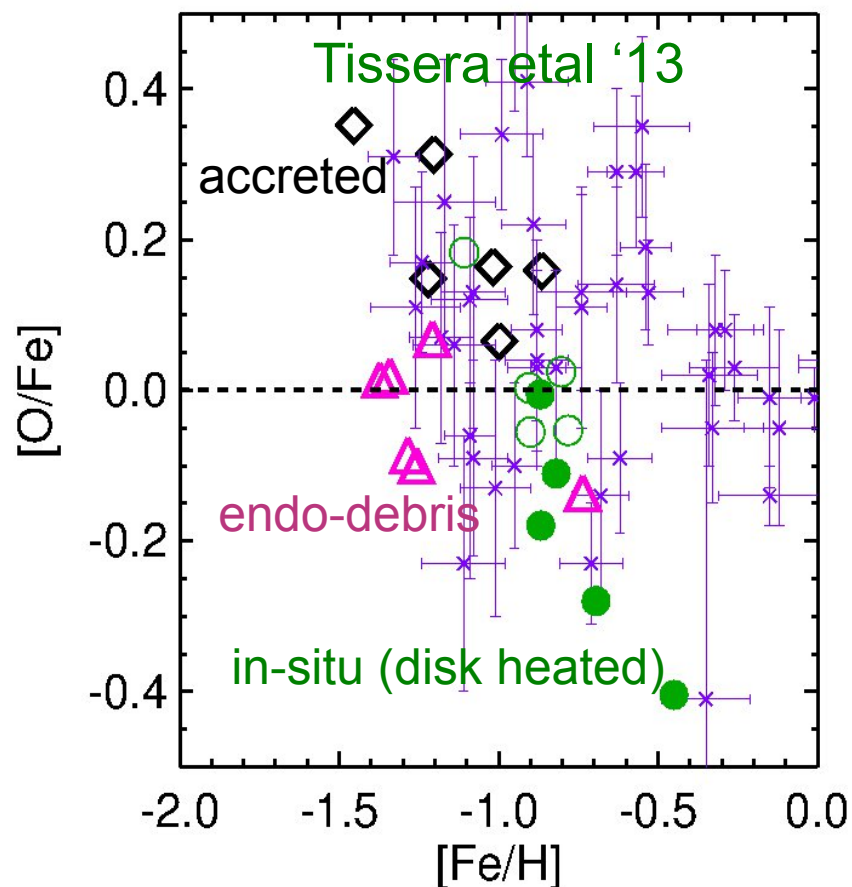
Stellar halos: accreted component

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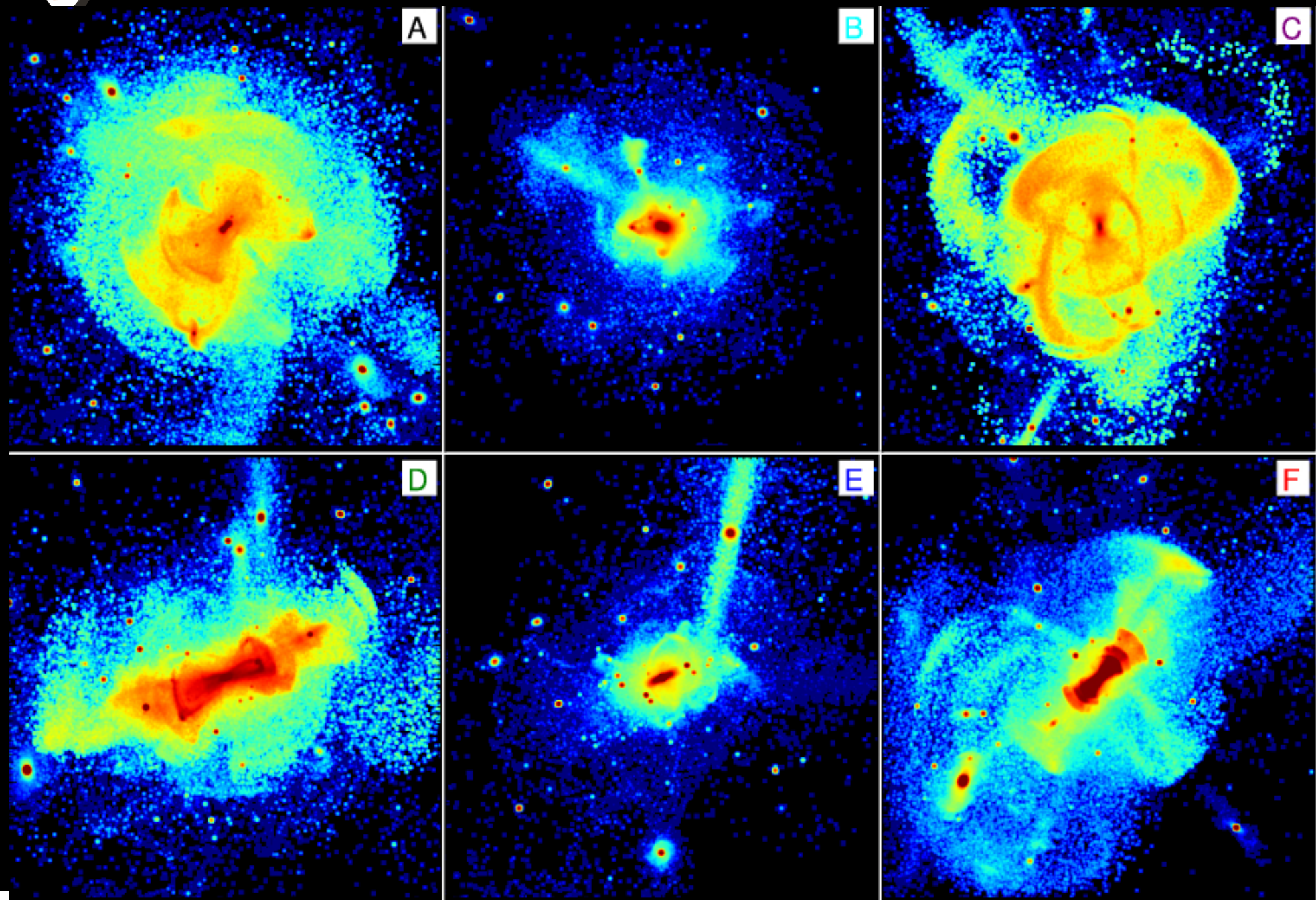
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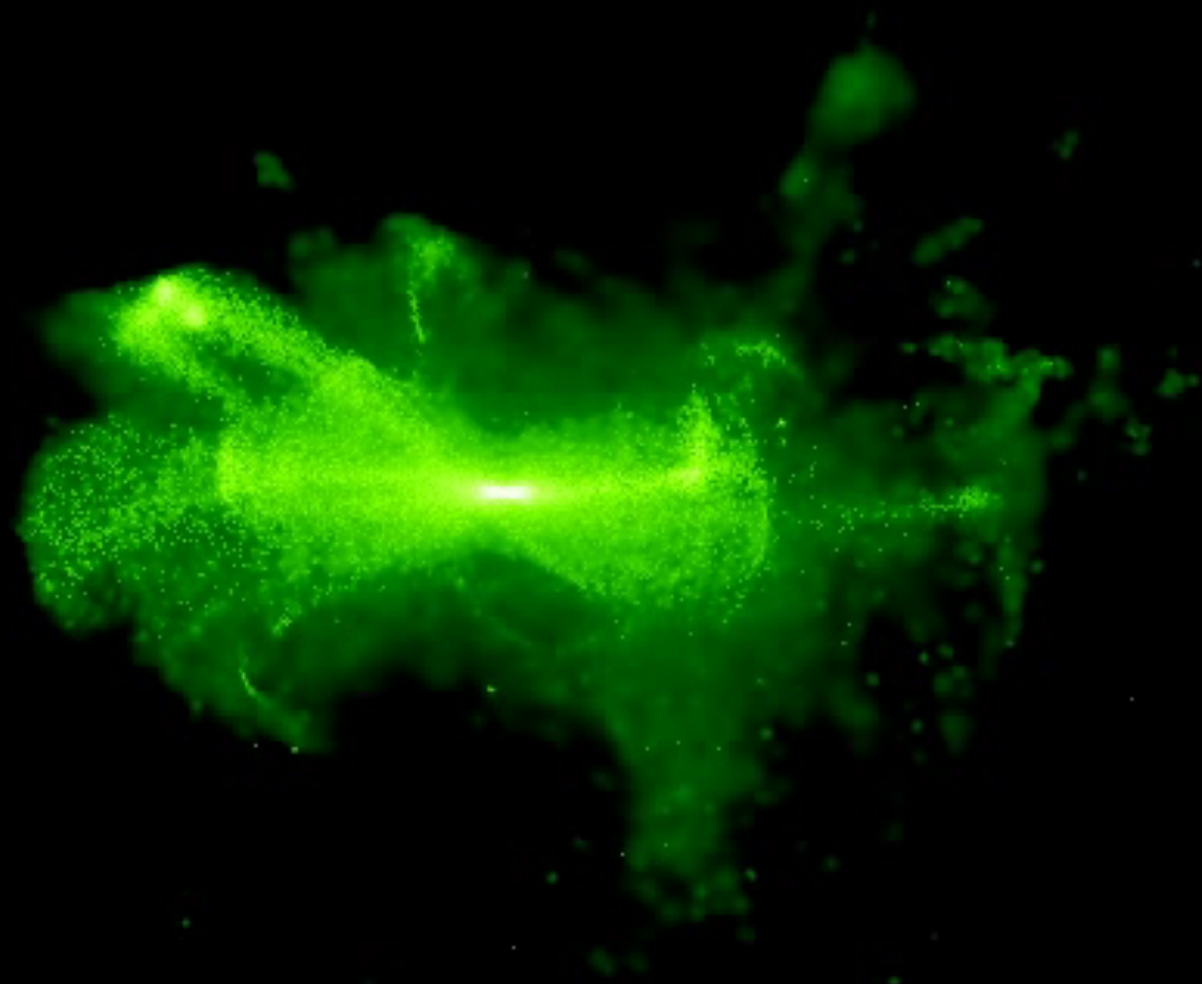
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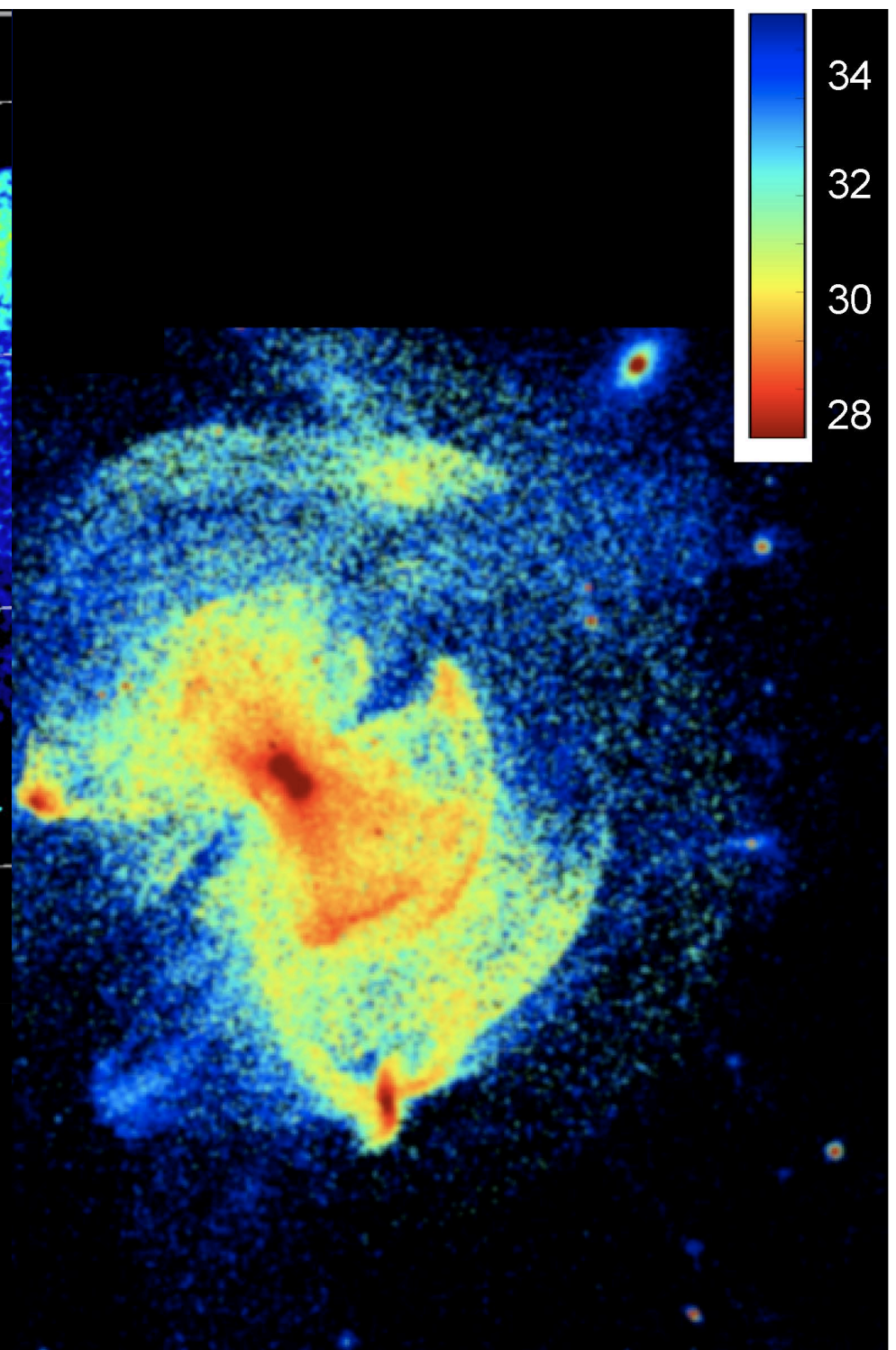
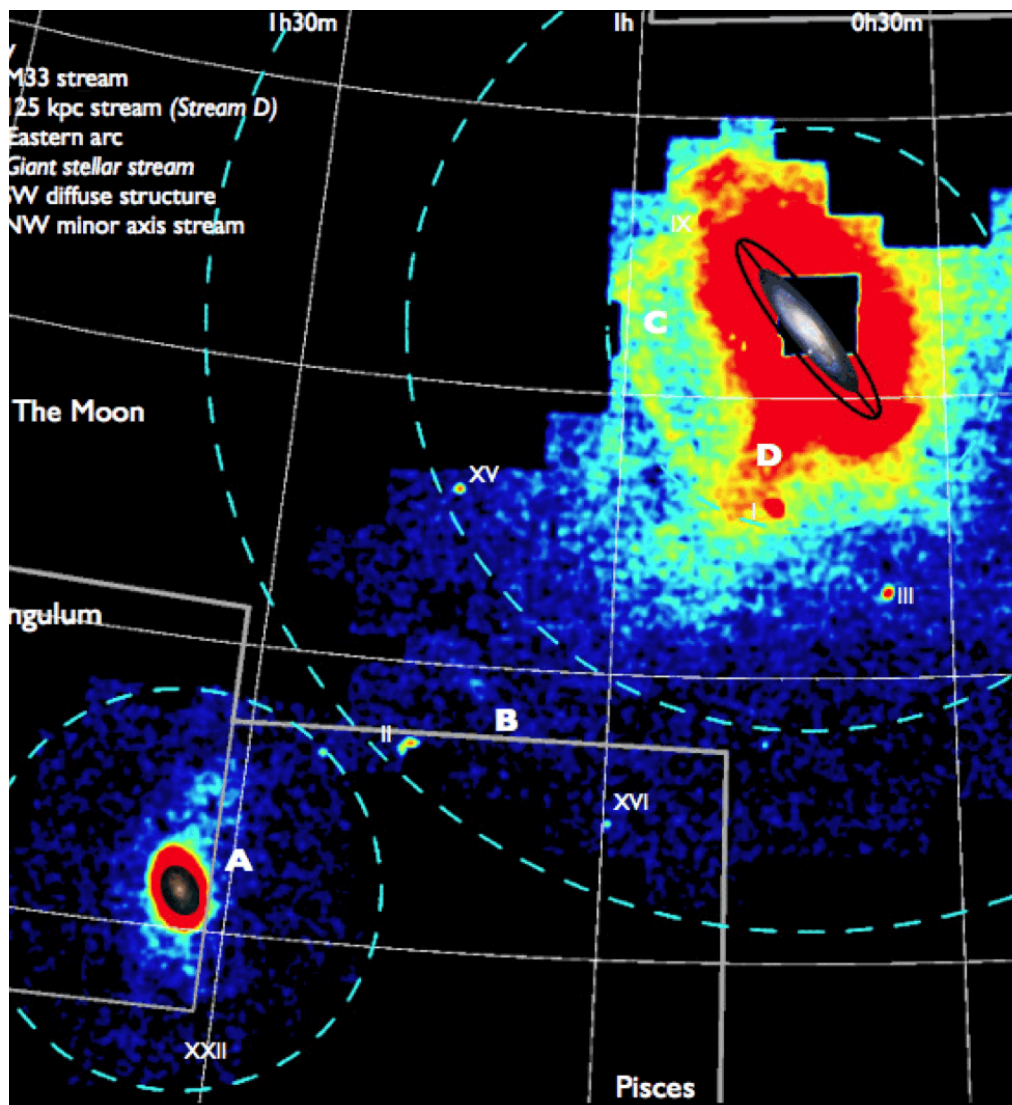
7. How lumpy is the stellar halo? Does it make sense to talk about a mean stellar density profile or a mean metallicity profile?

... or are any of the (spherically averaged) model predictions testable?

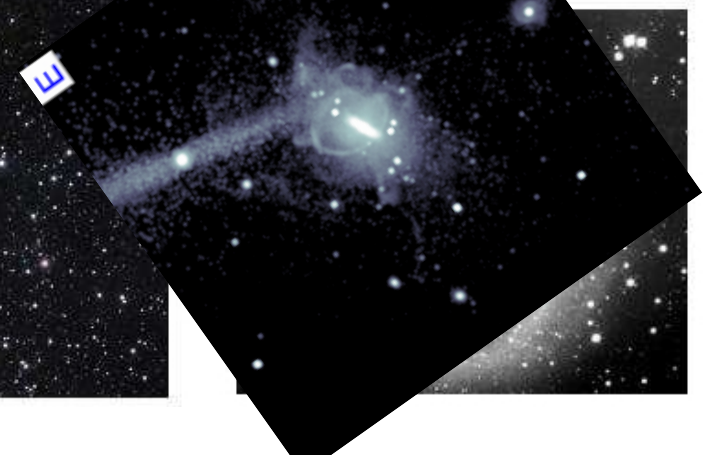
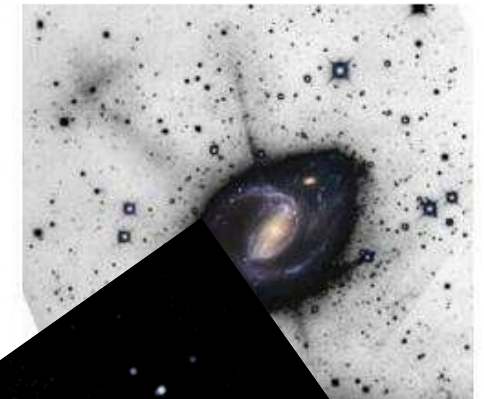
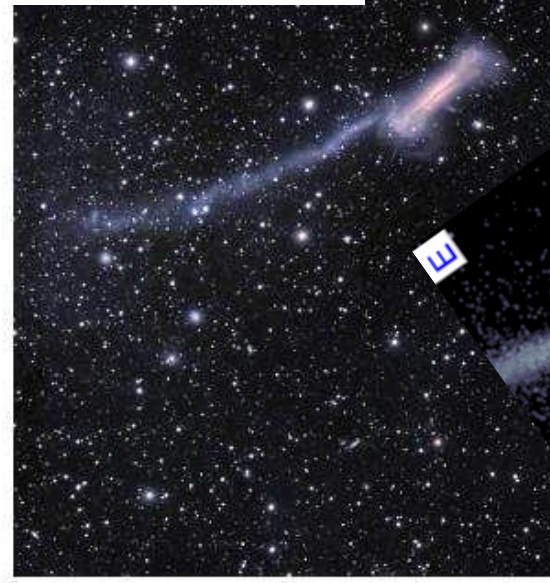
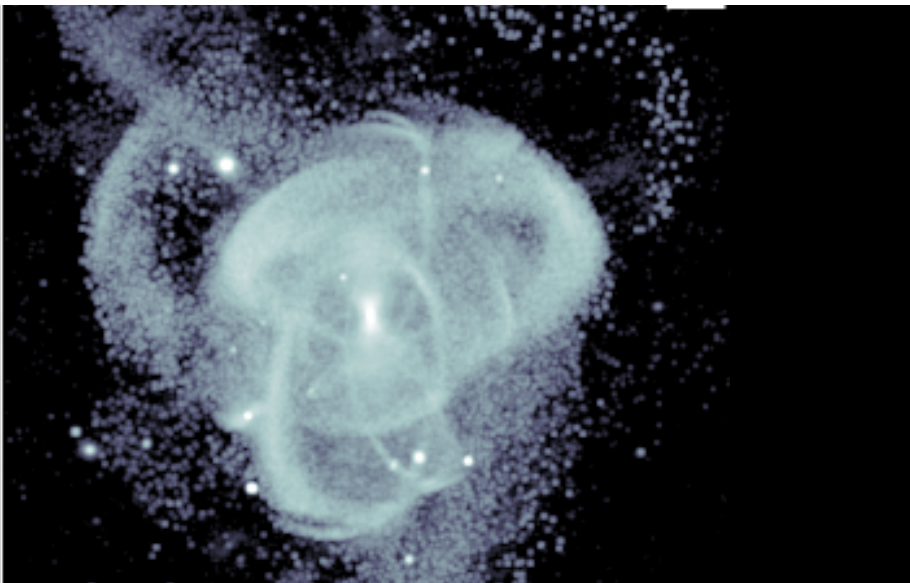
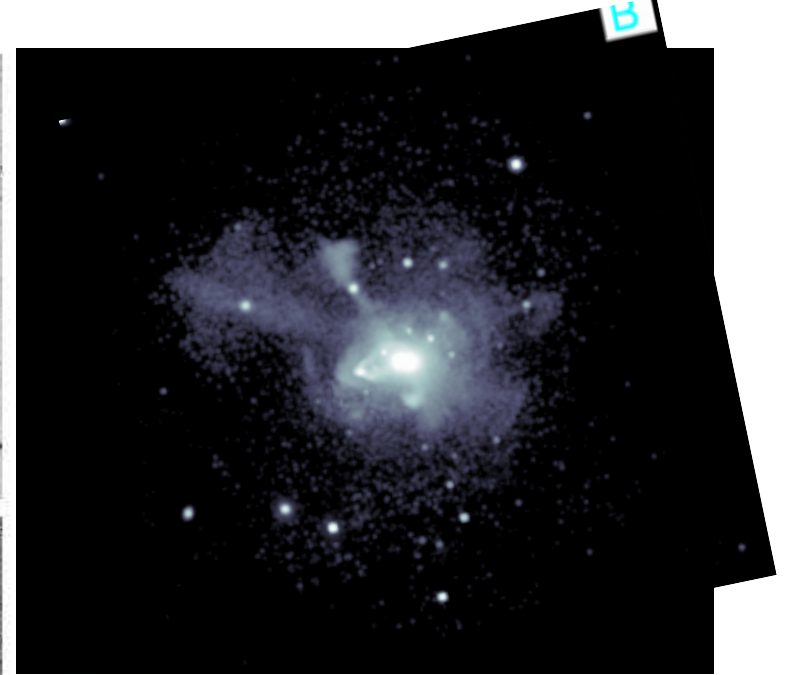
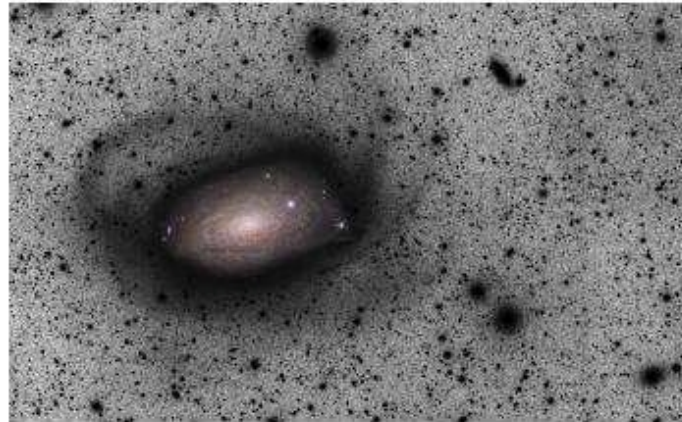
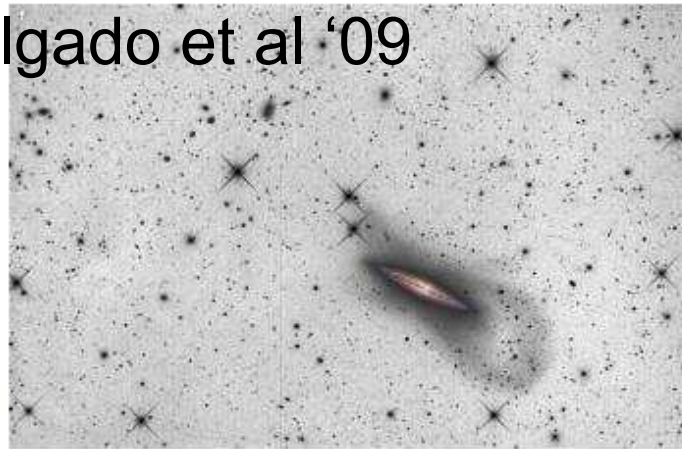




Ben Lowing



Martinez-Delgado et al '09



Stellar halos: mock catalogues

Based on tagging technique

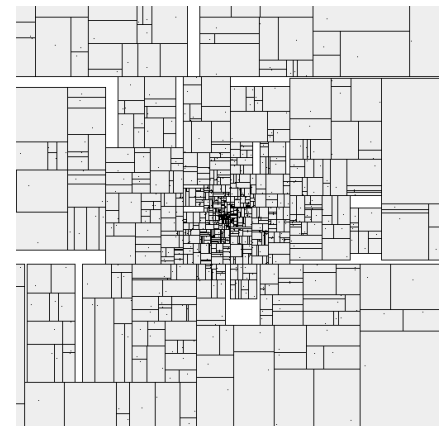
Lowing, Cole, Cooper & Frenk '13

1. Stellar population synthesis

- Convert massive particles into individual stars
- Consider each particle as single stellar population
- Theoretical PARSEC isochrones (Bressan et al. 2012) determine the abundances of each type of star for a population of that age & metallicity

2. Phase space sampling:

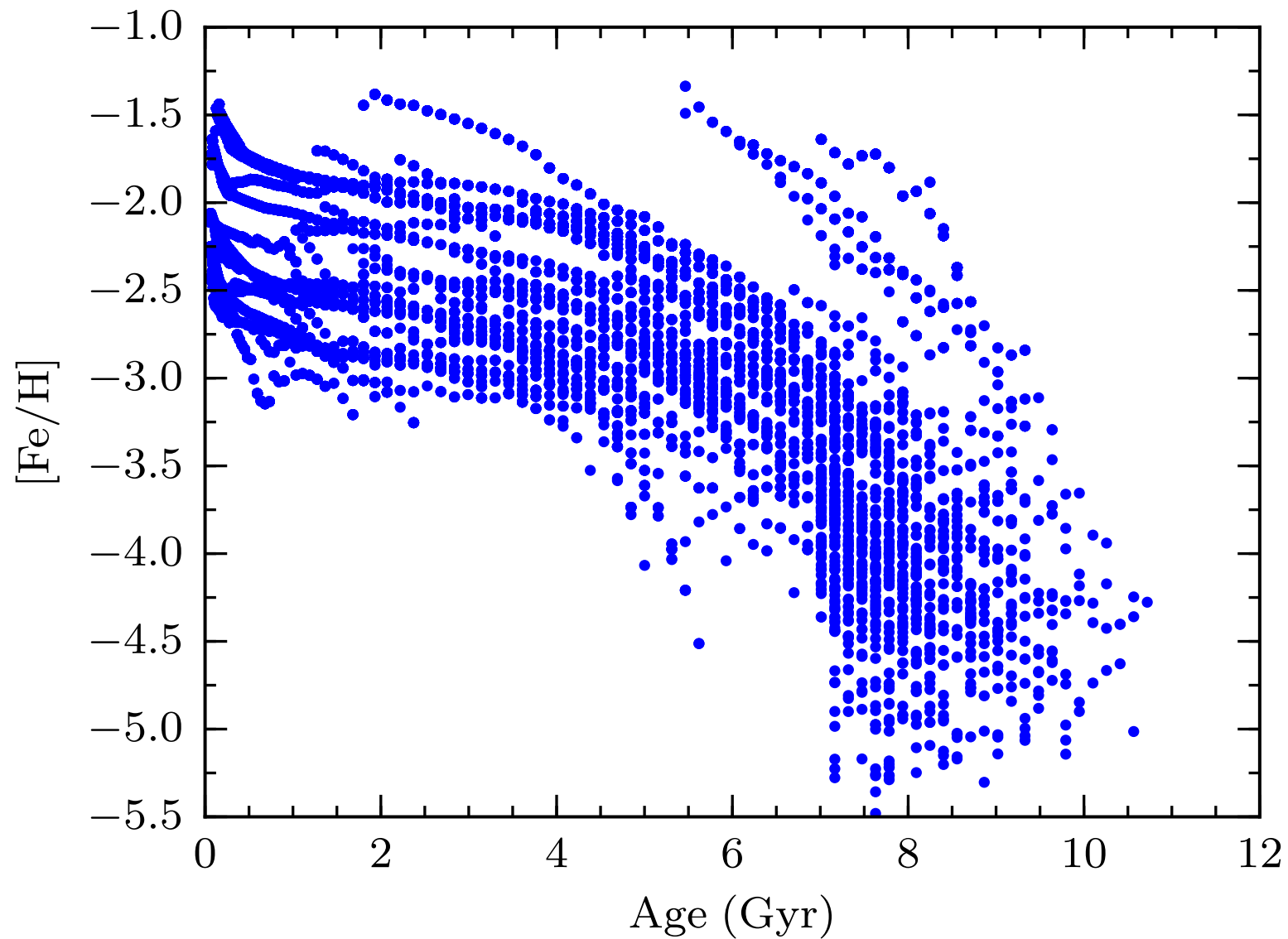
- Use Entropy-based binary decomposition (EnBiD) code (Sharma and Steinmetz, 2006) to calculate the phase-space volume each tagged particle occupies
- Create N stars randomly distributed over phase space volume of the tagged particles
- Assign position and velocity to each star



Example EnBiD 2d space decomposition

Age-Metallicity:

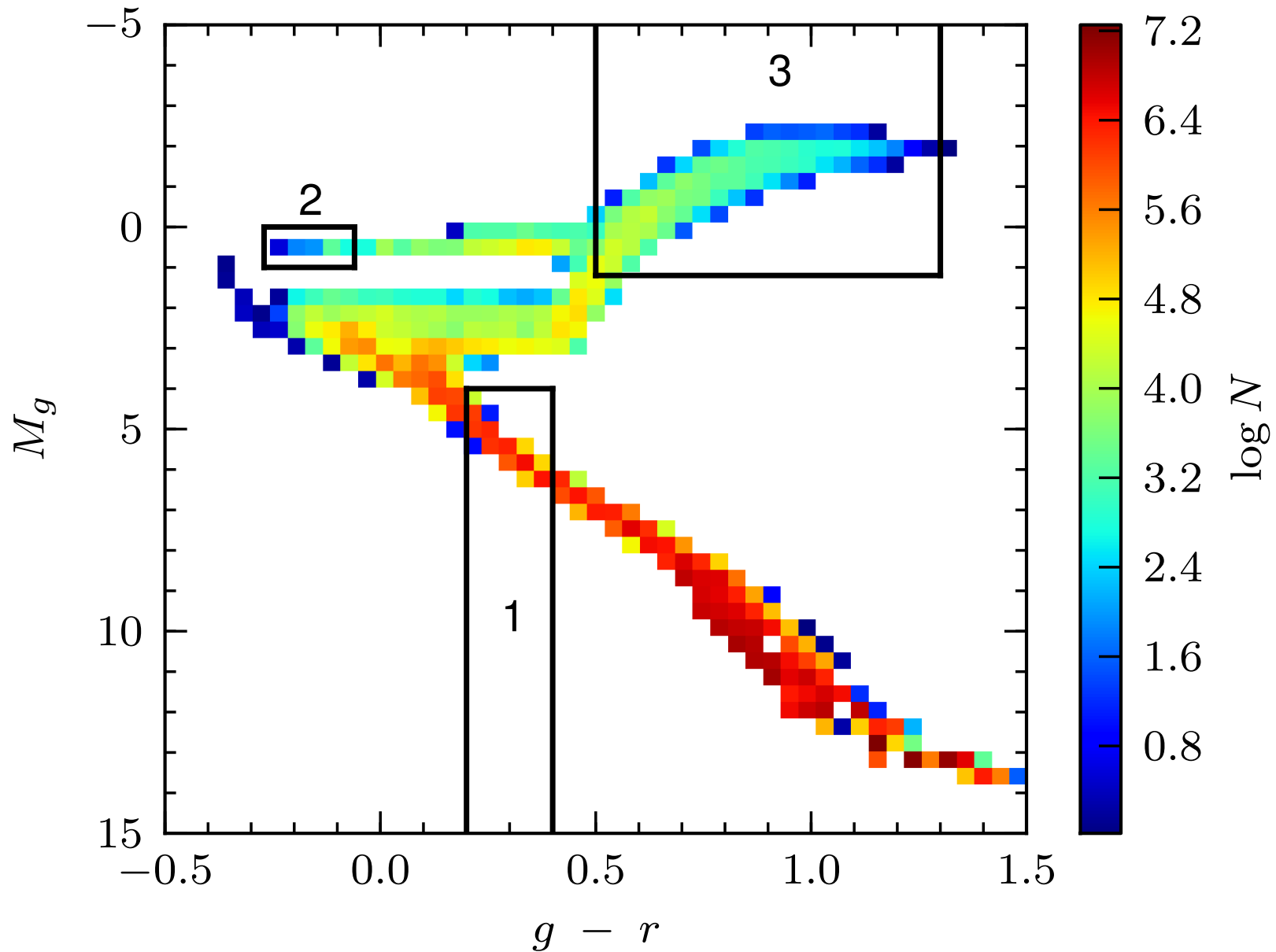
Lowing et al '13



The age-metallicity of the tags in the stellar halo of Aq-A (including satellites)

Colour magnitude diagram:

Lowing et al '13



Constructed from tags and theoretical isochrones

Stellar halos: mock catalogues

Based on tagging technique

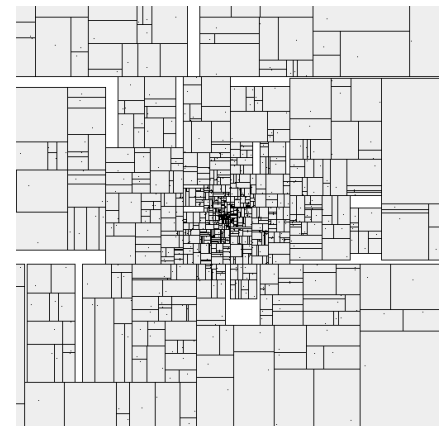
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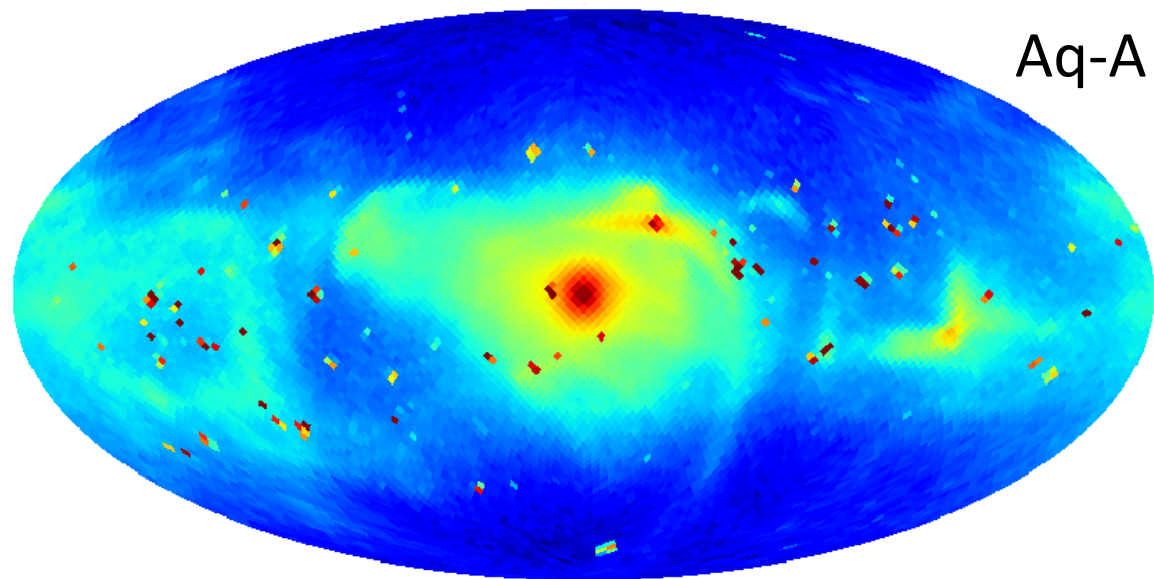
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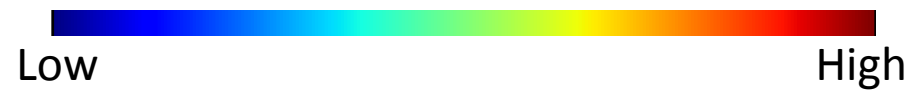
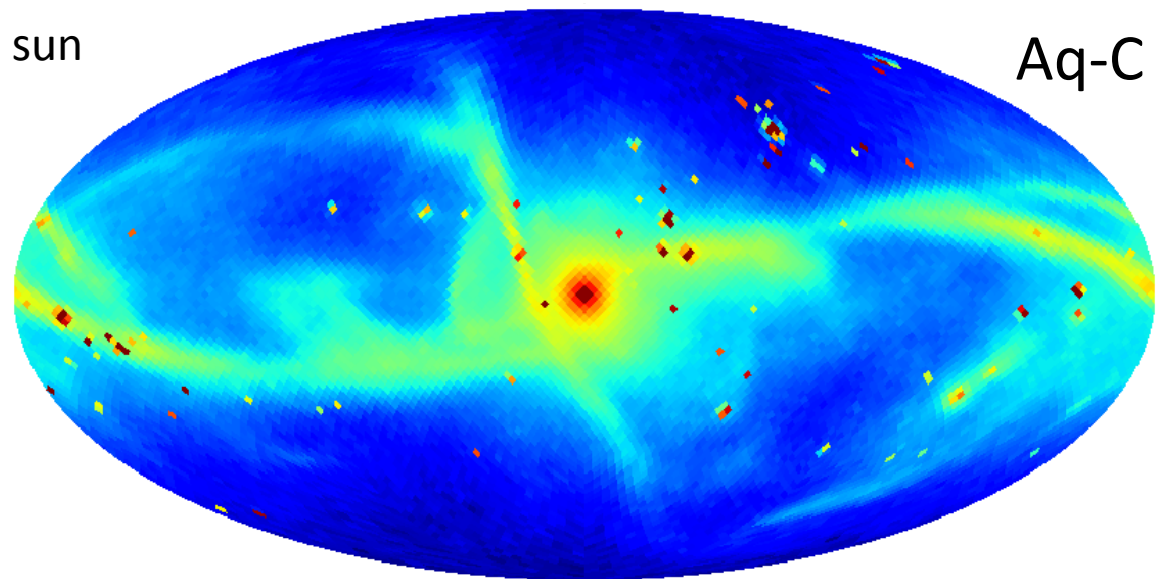
Example EnBiD 2d space decomposition

Projected Density on Sky

Lowing et al '13

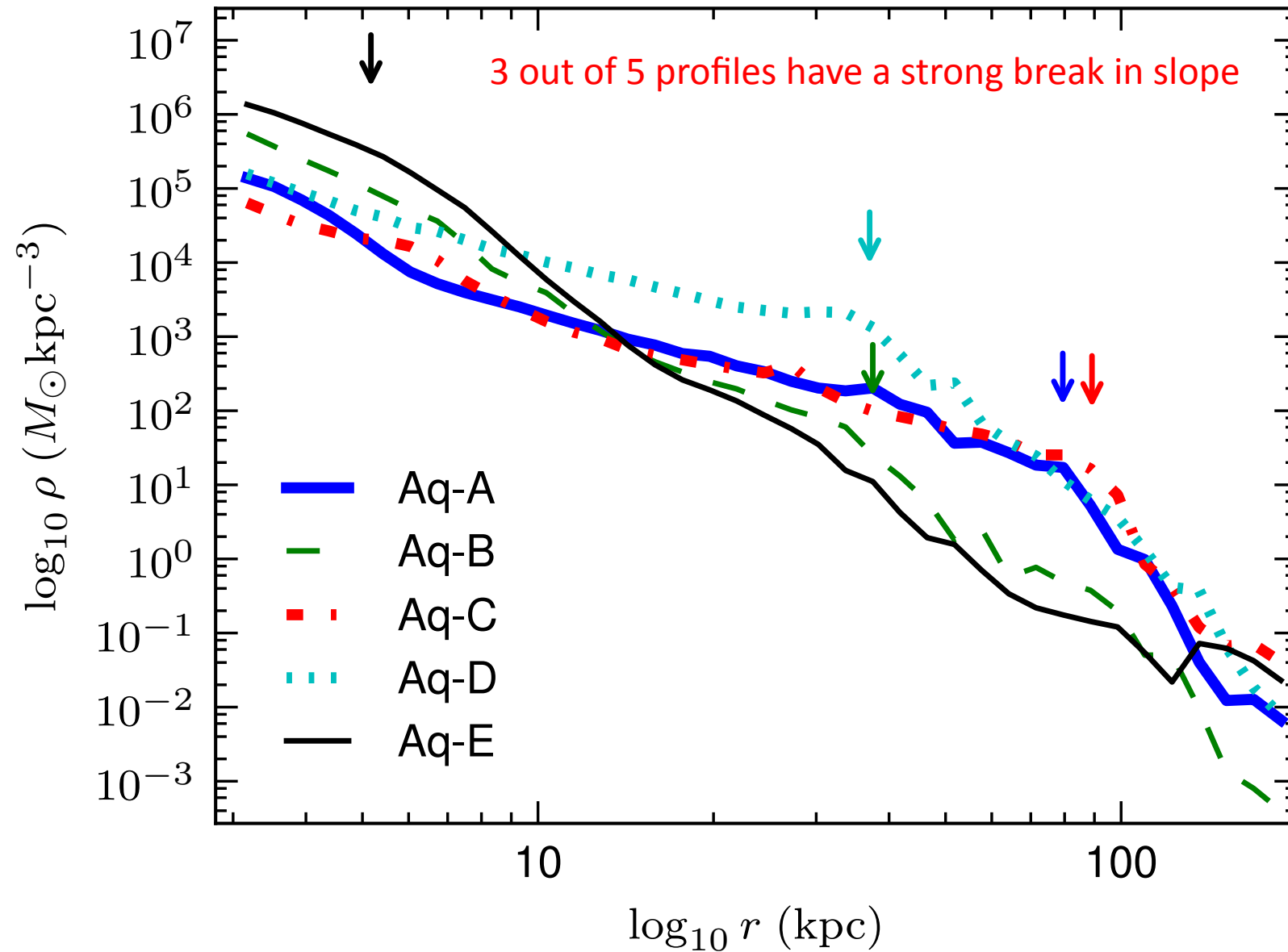


As observed from the sun

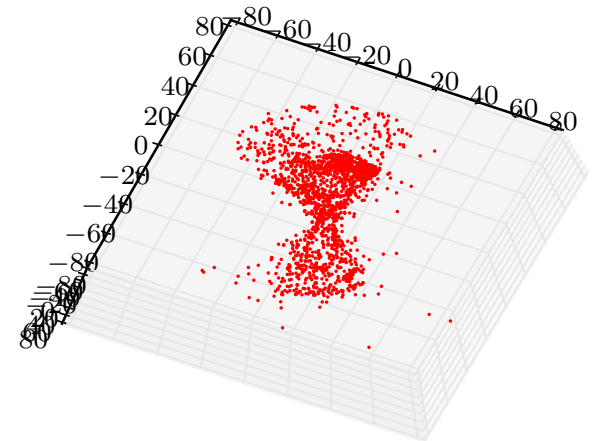
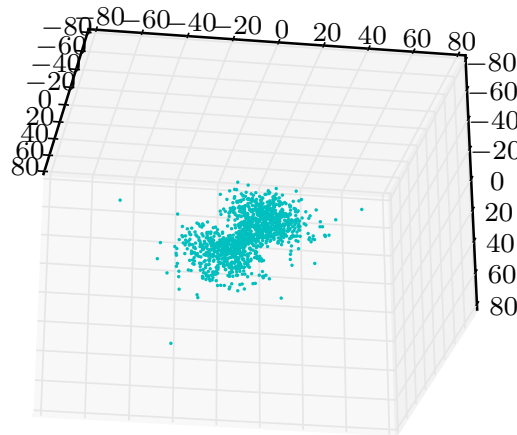
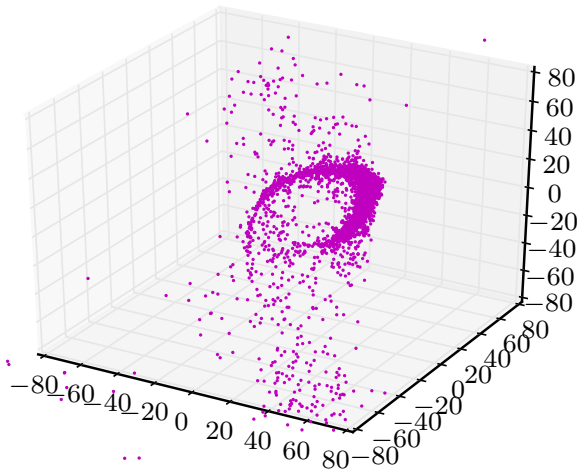
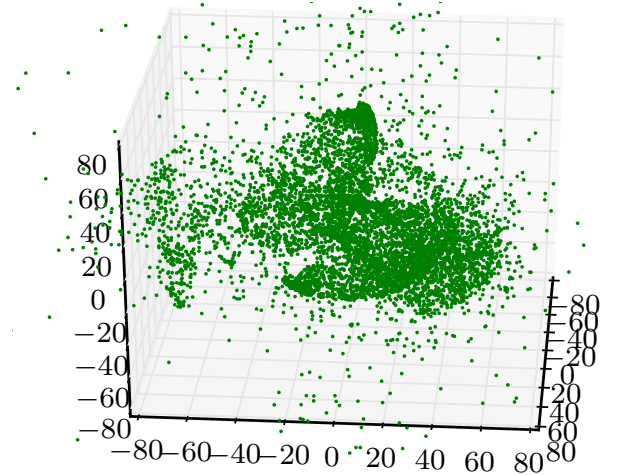
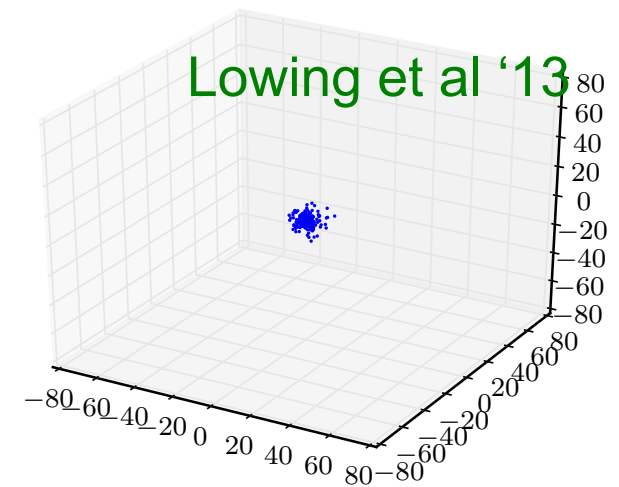
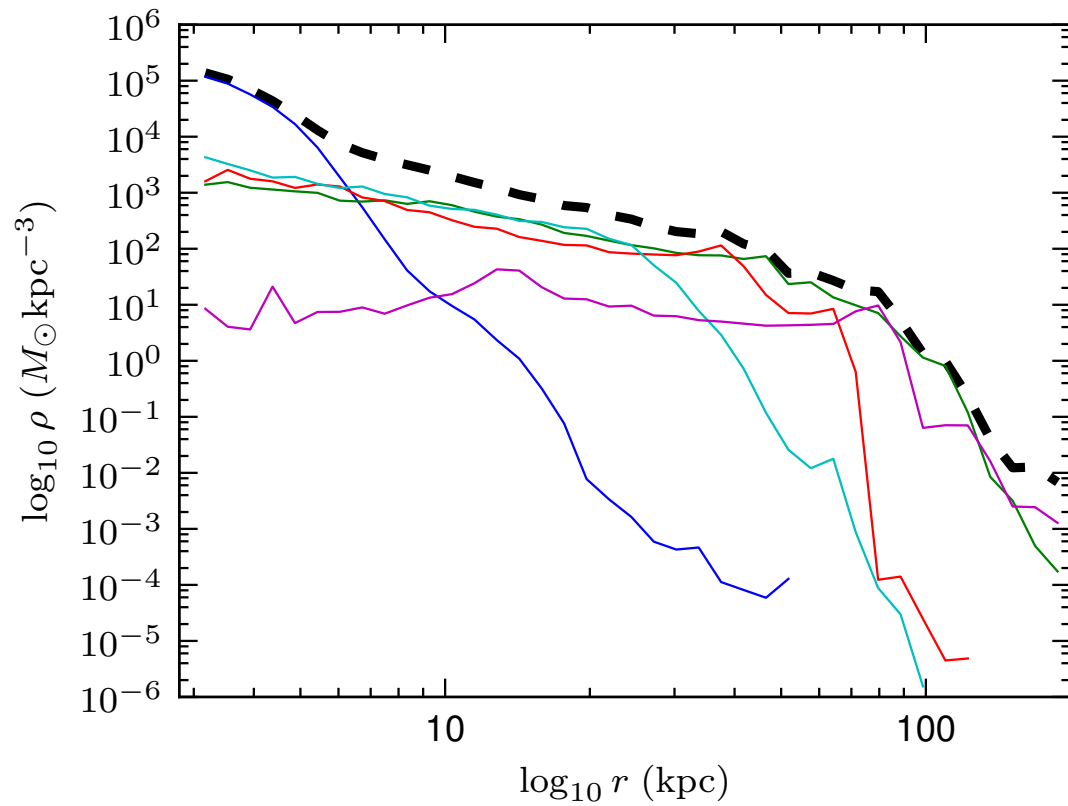


Density Profiles:

Lowling et al '13



5 Largest Contributors:



The Milky Way stellar halo

The density profile of the Milky Way stellar halo

Fit : $\rho(r) \propto r^n$ to star counts in halos

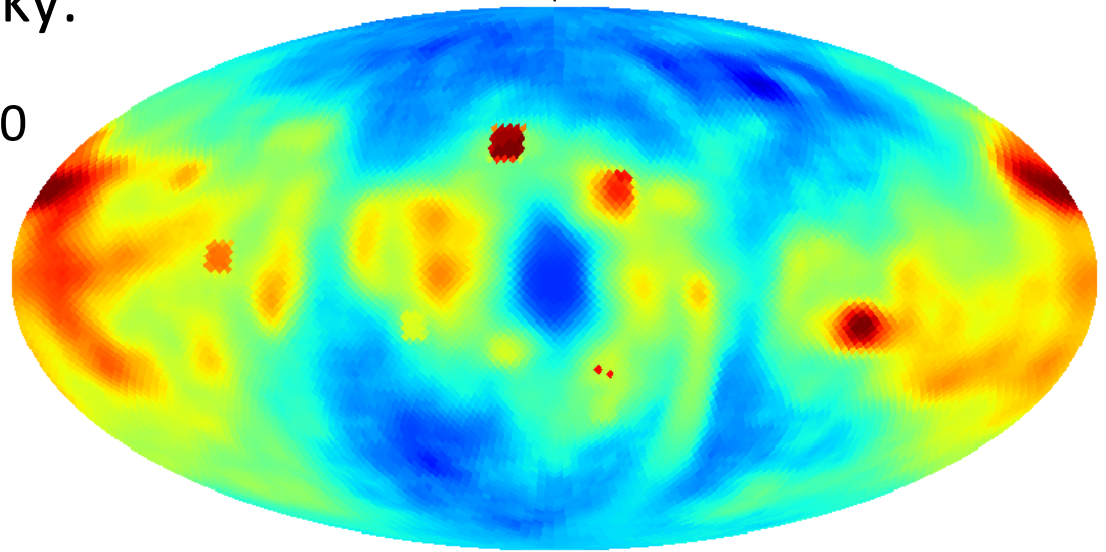
Siegel et al '02	2.75	
Newberg & Yanny '06	3.1	
Bilic et al '06	3.6 ± 0.1	
Juric et al '08	3.8 ± 0.03	
Watkins et al' 09	2.4 (R<25 kpc)	4.5 (R>25 kpc)
Sesar et al '11	2.62 ± 0.04 (R<25 kpc)	3.8 ± 0.1 (R>25 kpc)
Deason et al '11	2.3 (R<27 kpc)	4.6 (R>27 kpc)

Who is right?

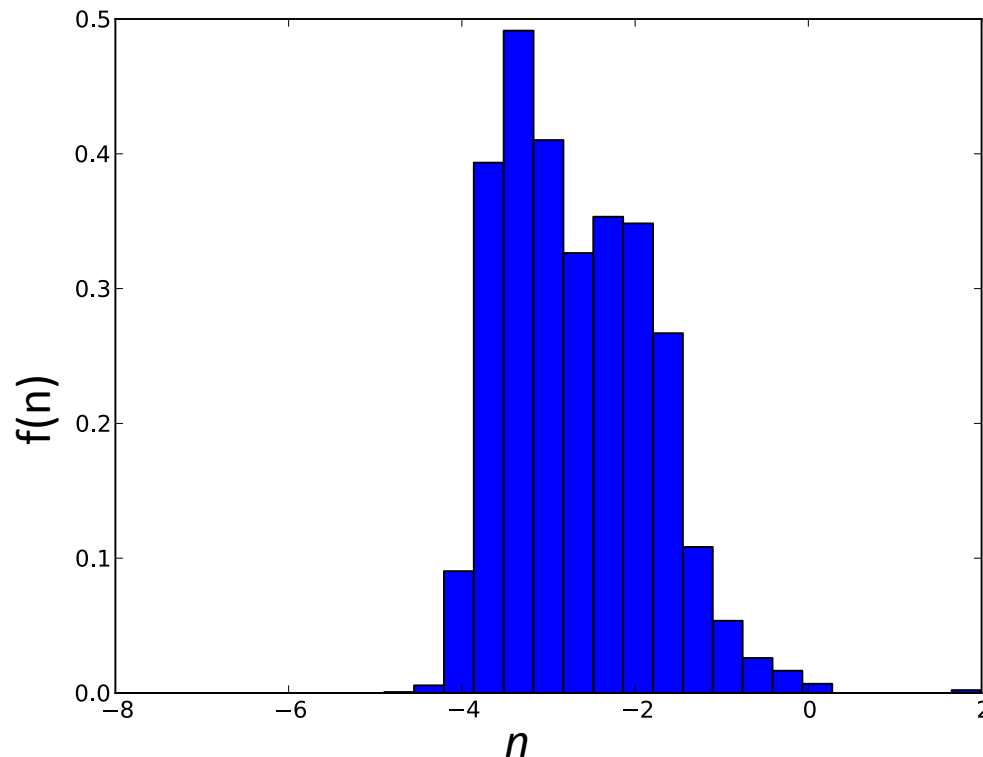
Variation in profile slope over sky:

- Measure density profile between 10 and 30 kpc using thin pencil beams
- Fit power-law and measure slope

$$\rho(r) \propto r^n$$



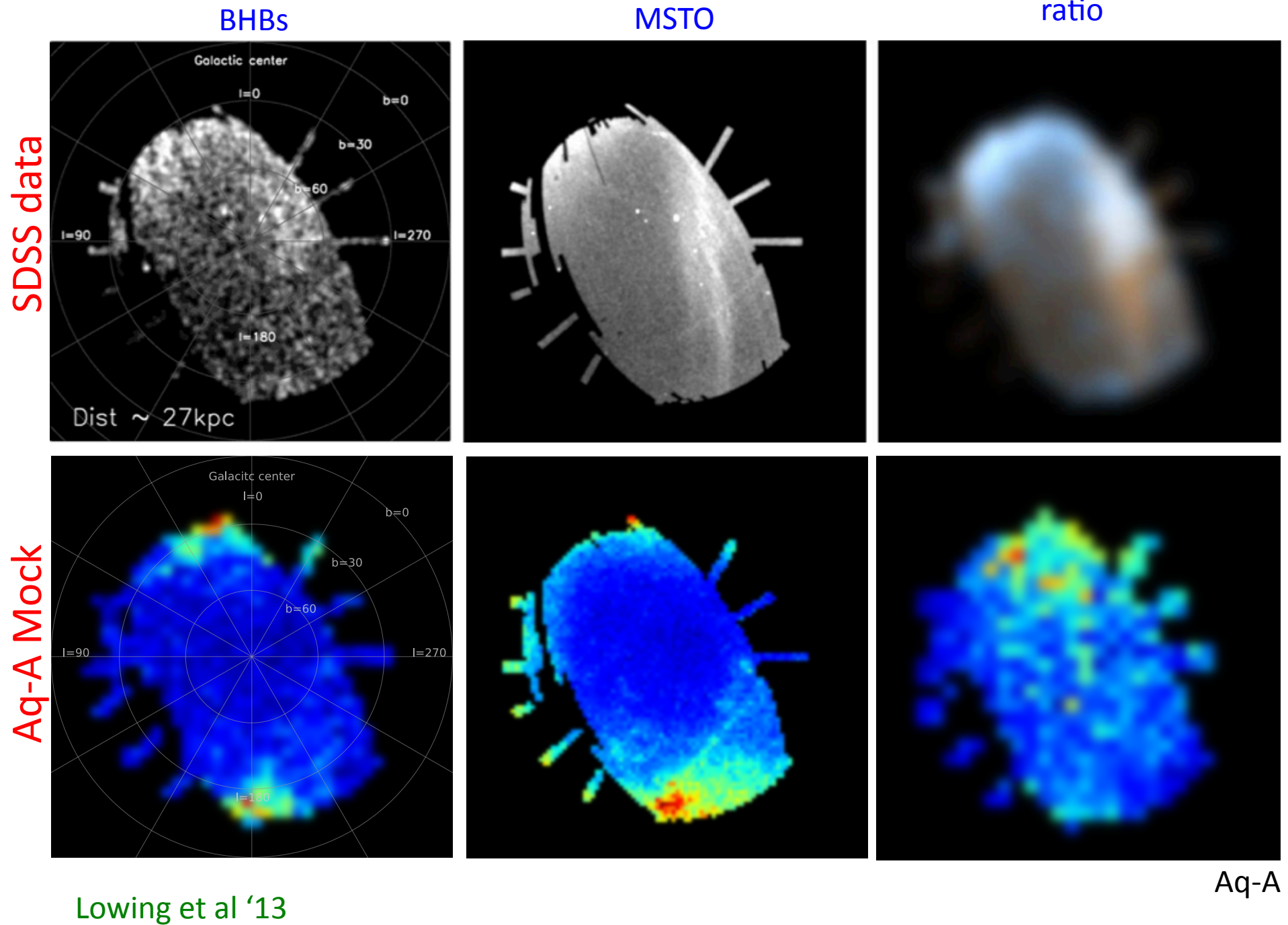
-5 slope n 0



Huge variation in slope
in different directions!

Lowing et al '13

Bell et al '10



Public Mock Catalogues:

Lowing et al '13

- Will be making available mock catalogues of accreted halo stars
- Individual stars – positions, velocities, metallicities, ages, magnitudes...
- Contains all stars with $M_g < 7$
- Simple web interface
- Coming soon...

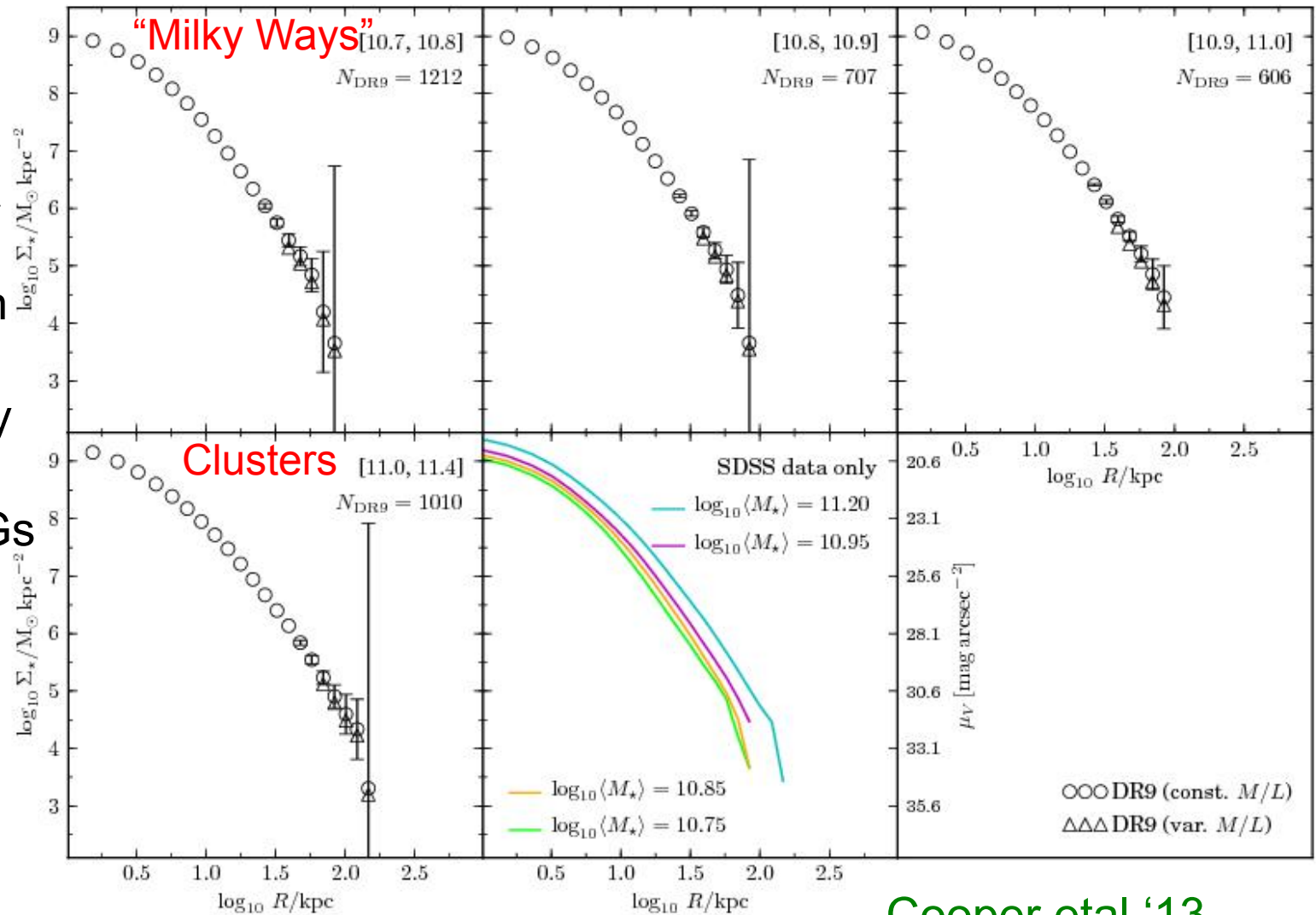
Stellar halo density profiles

Determining $\rho_*(r)$ for **individual** galaxies (e.g. MW) is tricky because halo is so **lumpy**

→ **average** stellar halos of a large **number** of nearby galaxies

Density profiles of stellar halos

Richard D'Souza
stacked 2500
SDSS galaxies in
mass bins and
measured density
profiles of halos,
from MWs to BCGs

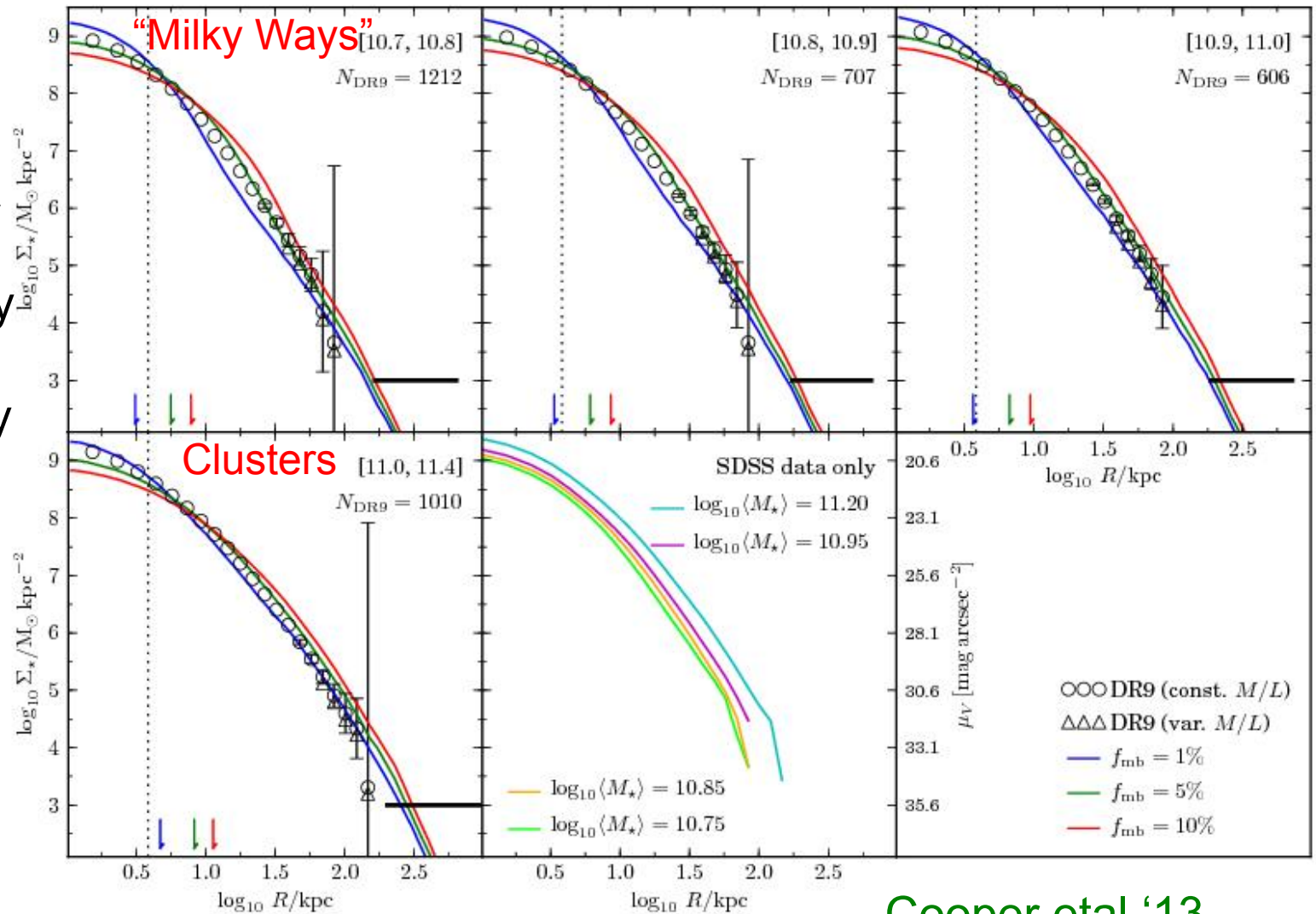


Cooper et al '13

Density profiles of stellar halos

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Impressive
agreement with
tagging in
Millennium-II



Cooper et al '13

Theory of stellar halos

Why are stellar halos interesting?

Galaxy formation:

- Record of assembly of galaxies and clusters (“archeology”)
- History of outflows (feedback), metal enrichment, SFR, IMF ...

Cosmology:

- Test of hierarchical clustering characteristic of CDM
- Nature of dark matter: CDM or WDM or SIDM?

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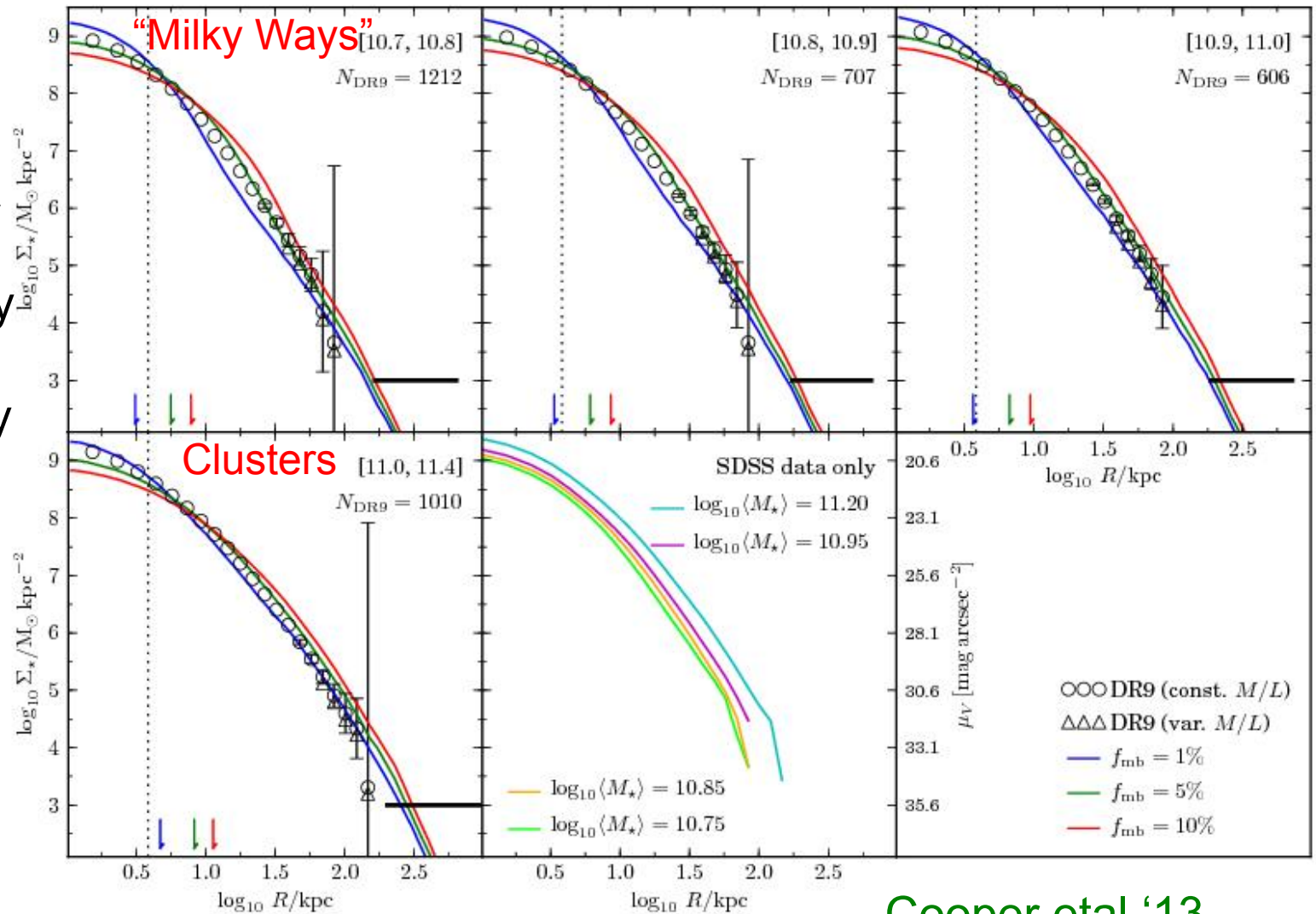
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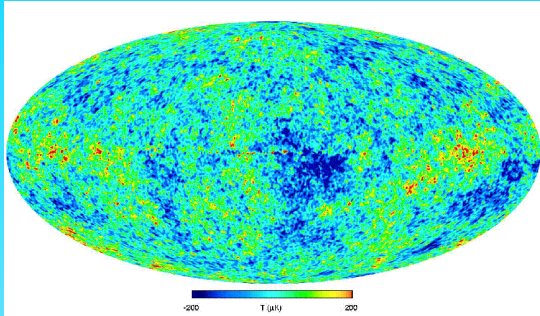
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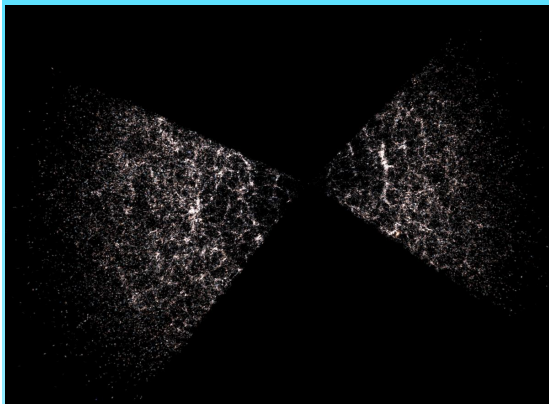
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The cosmic power spectrum: from the CMB to the 2dFGRS



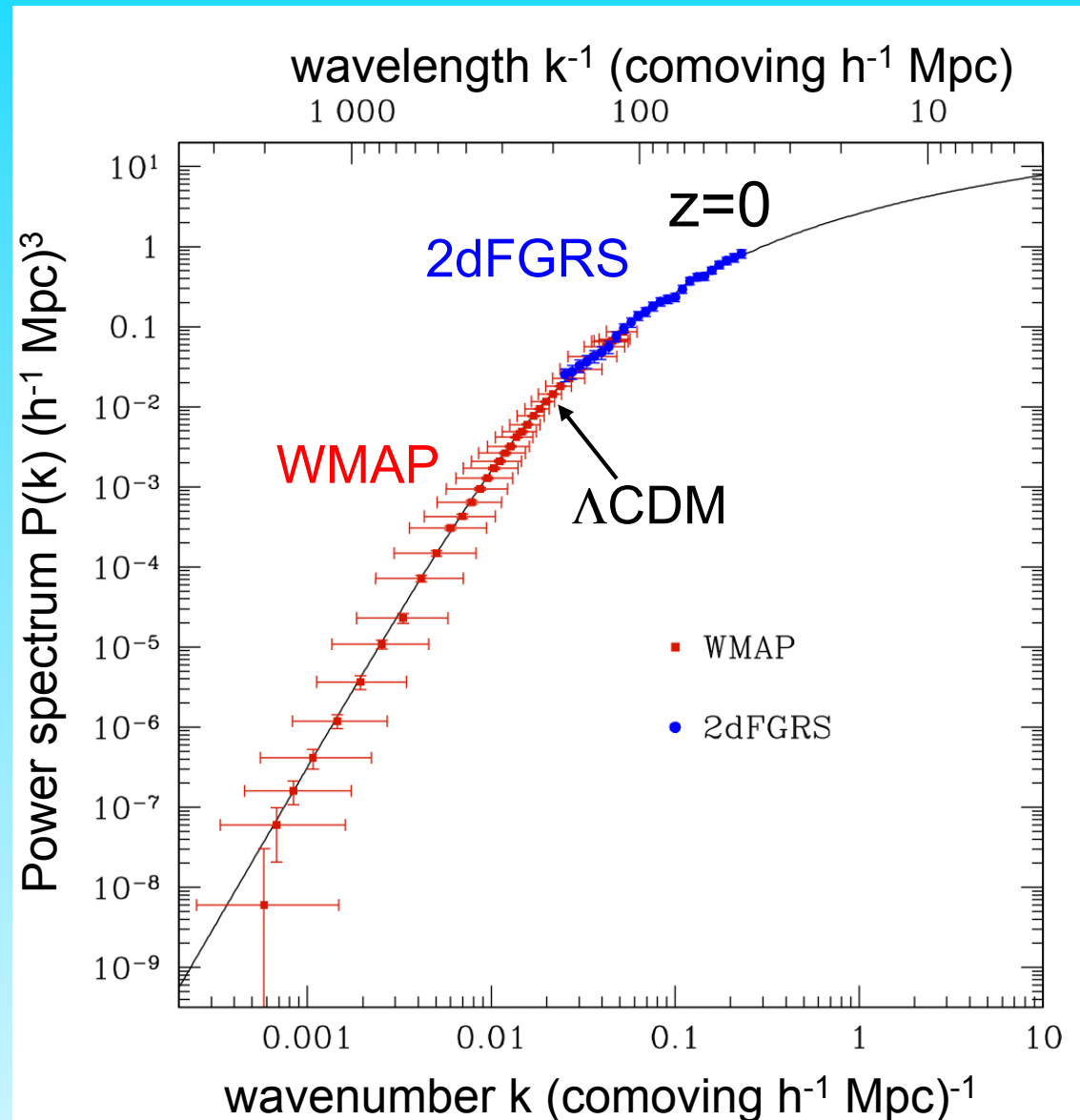
$z \sim 1000$



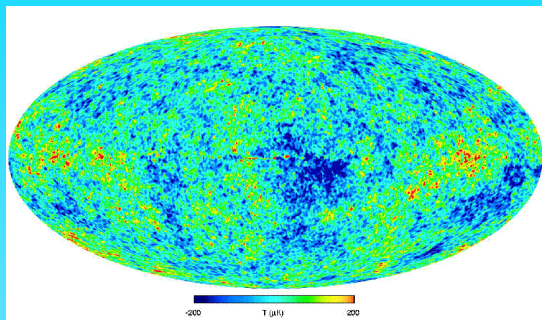
$z \sim 0$

⇒ Λ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

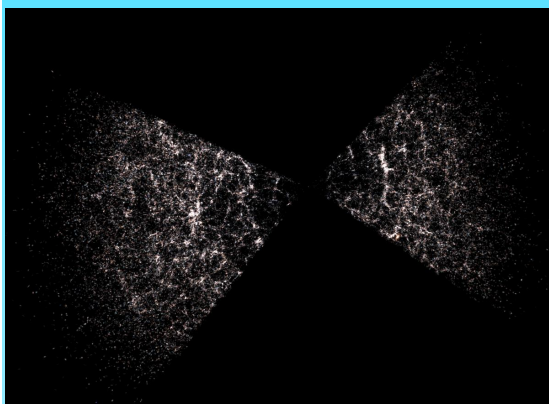
Sanchez et al 06



The cosmic power spectrum: from the CMB to the 2dFGRS



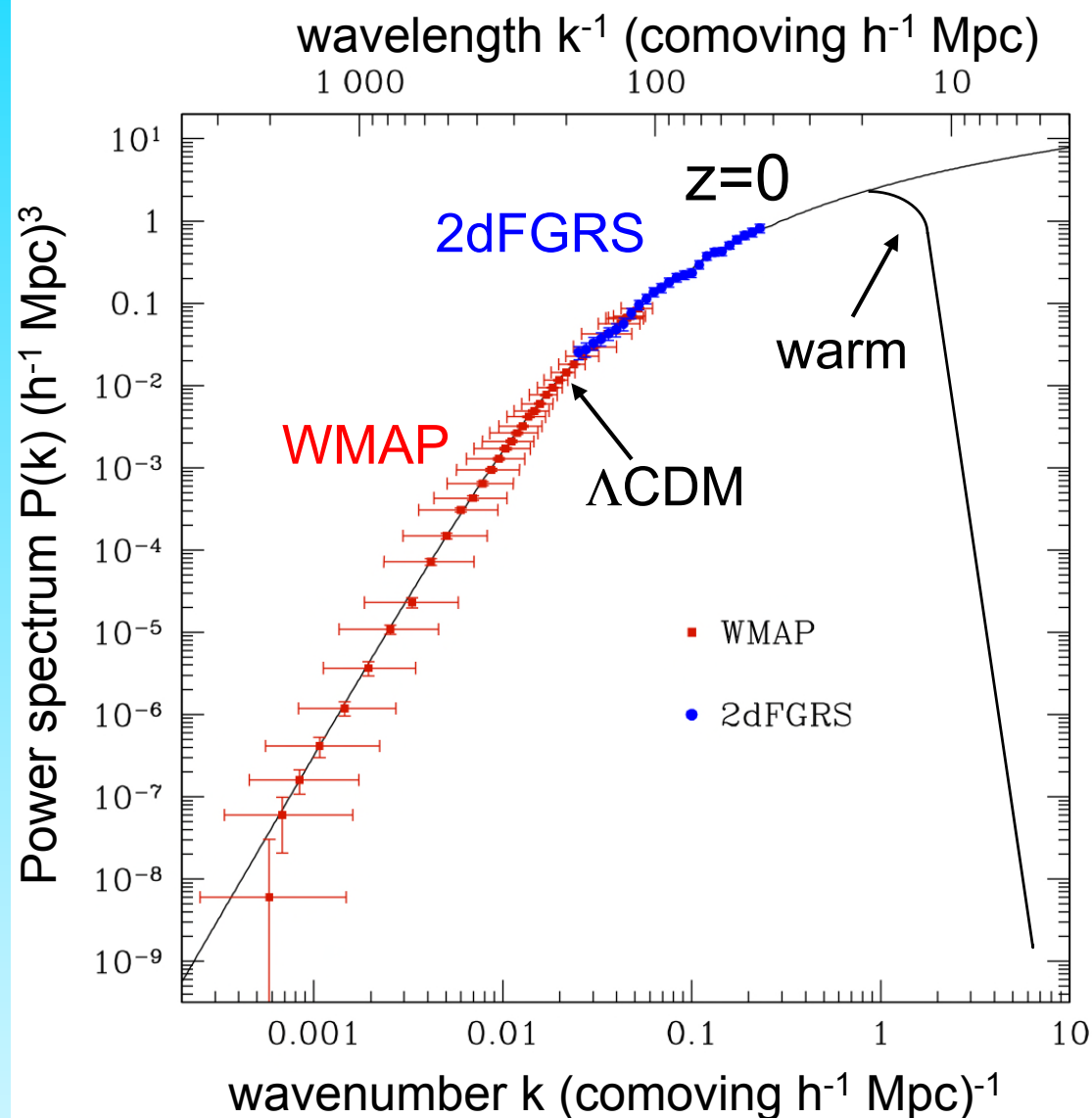
$z \sim 1000$



$z \sim 0$

$\Rightarrow \Lambda$ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06





Cold Dark Matter

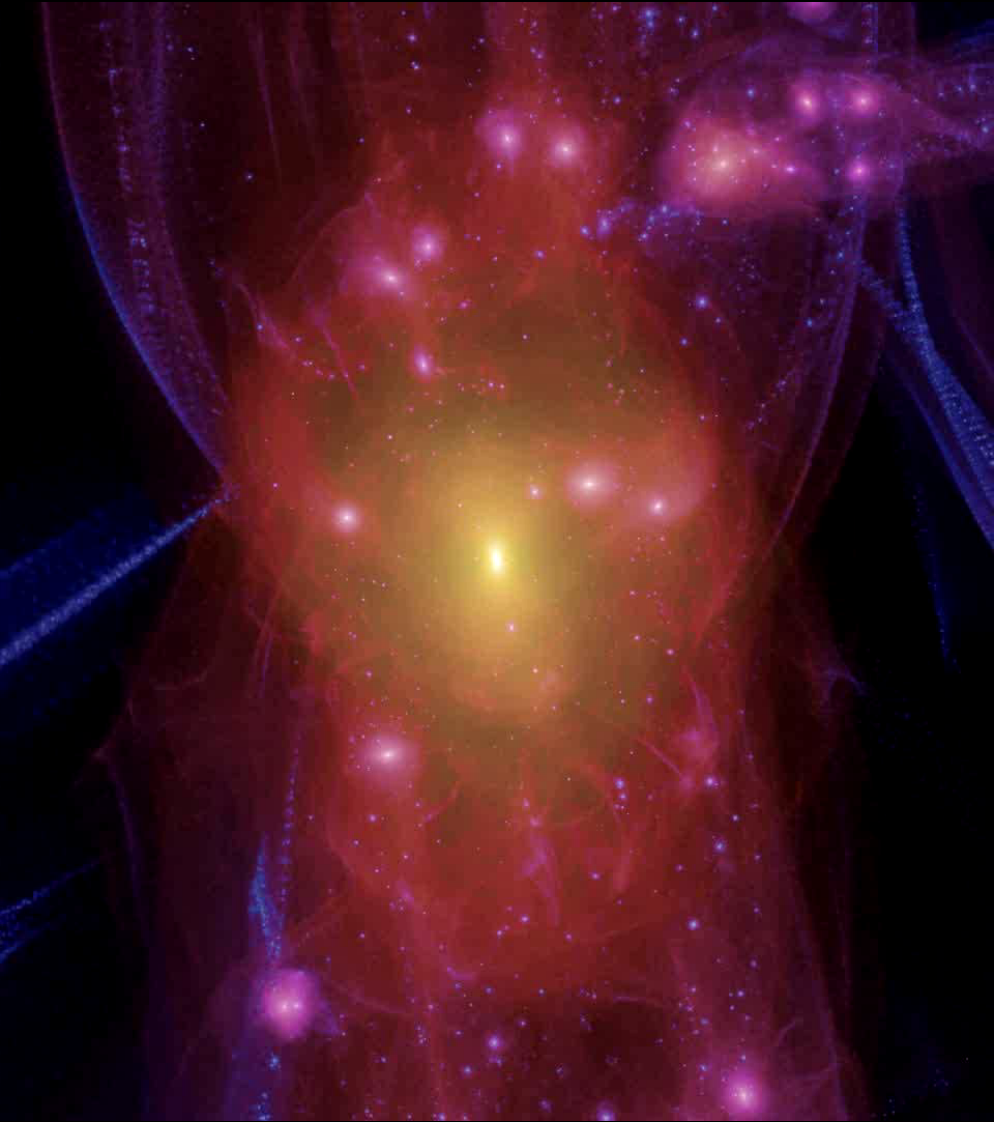
Warm Dark Matter

13.4 billion years ago

cold dark matter



warm dark matter



Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
BoyarSKI & Ruchayskiy '12



Warm DM: different ν mass

$z=3$

CDM

WDM

1.4keV

2.3keV

2.0keV

1.6keV

WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV

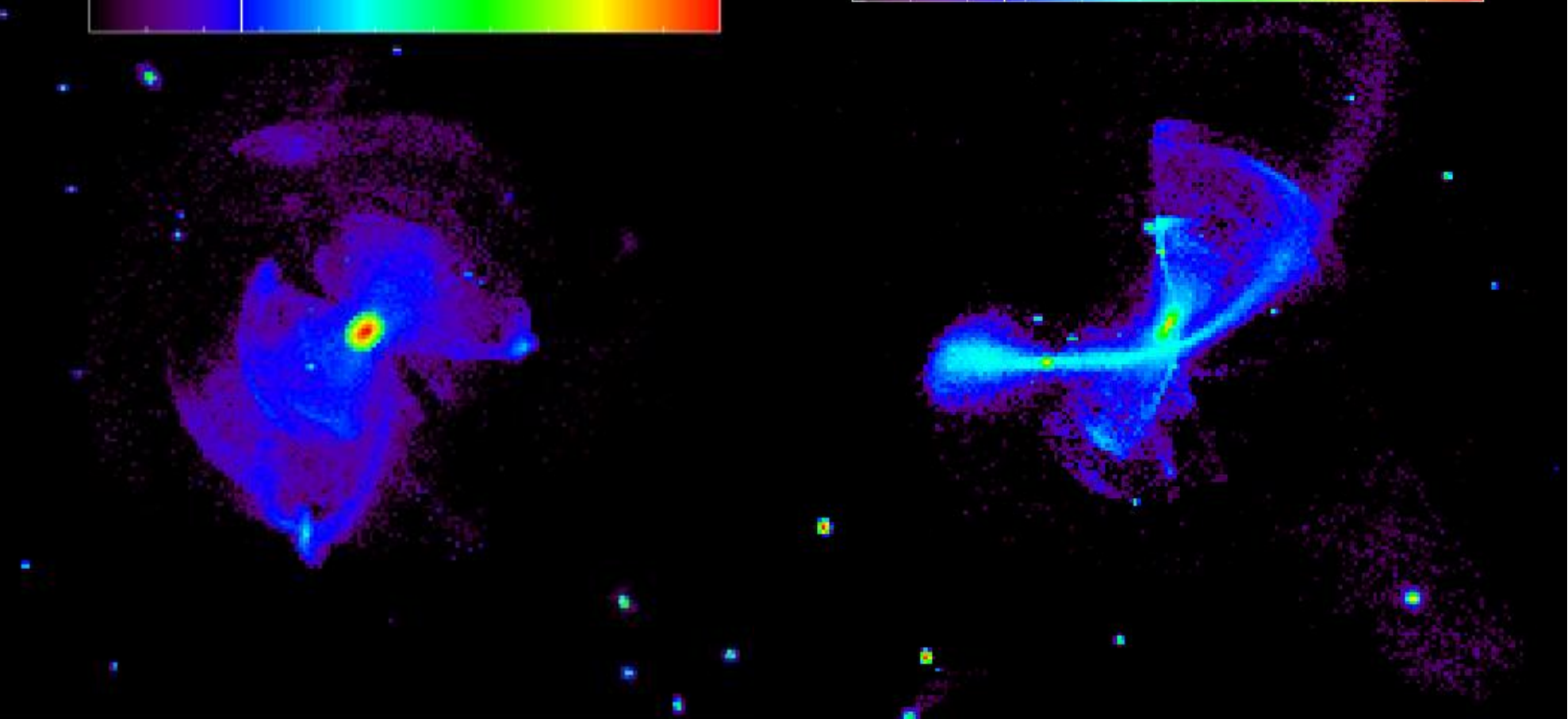
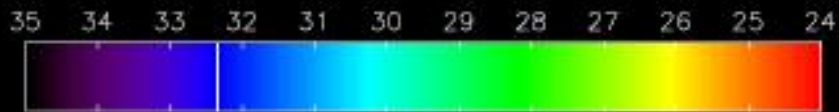


Cold vs Warm dark matter

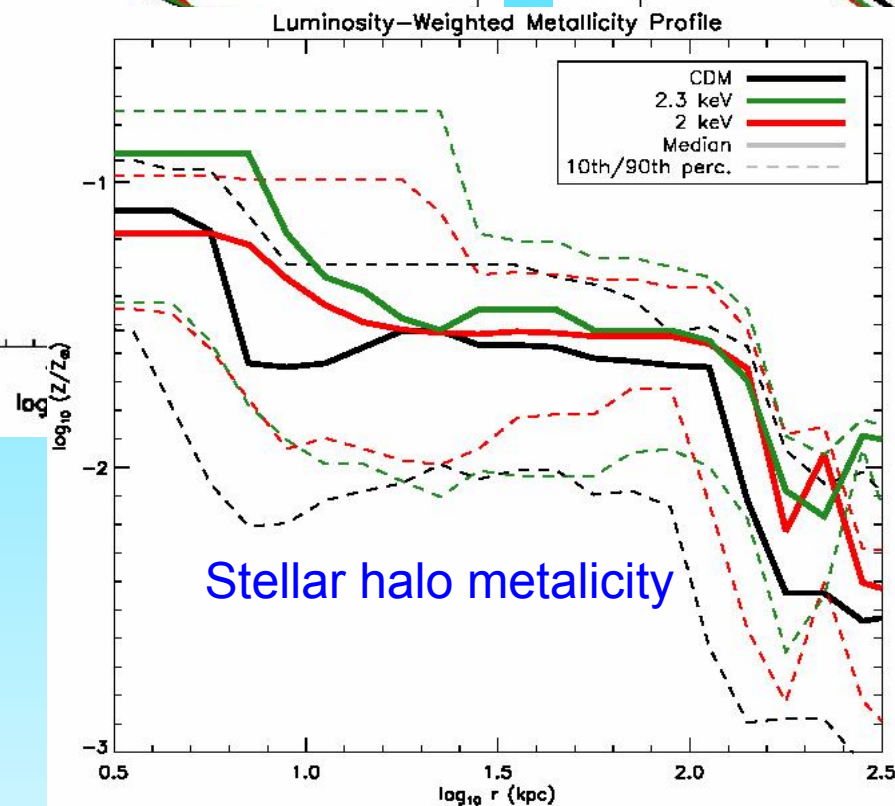
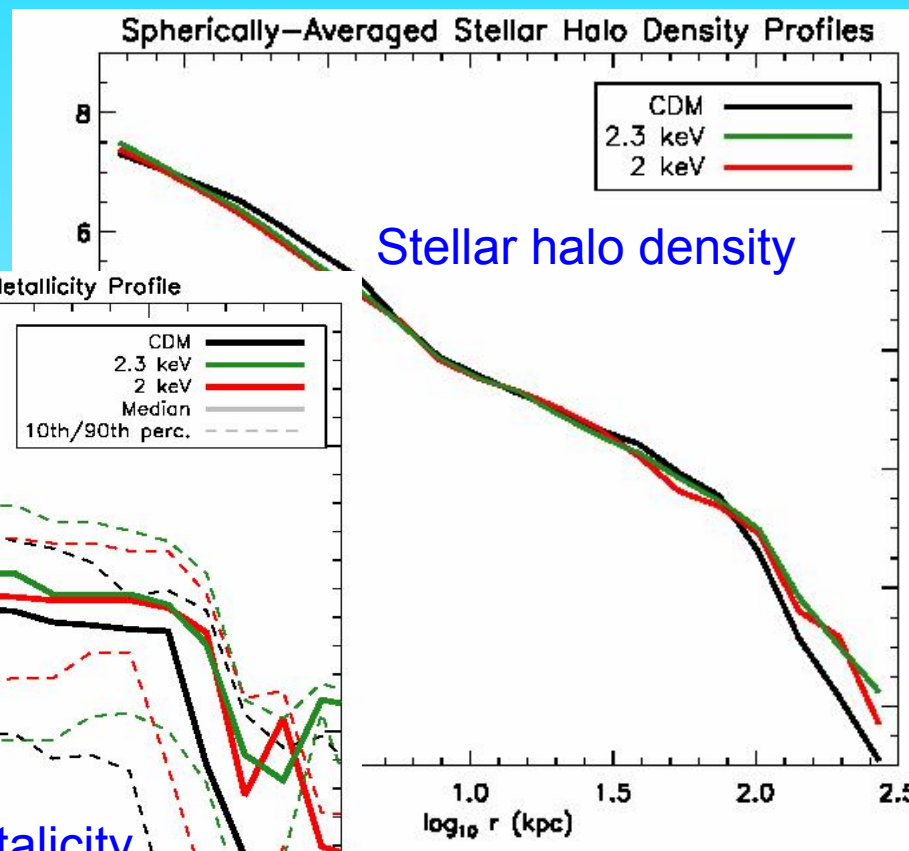
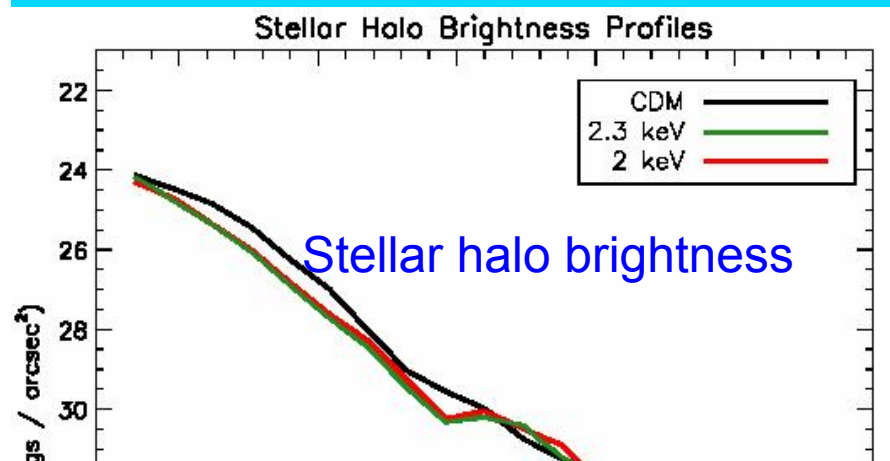
Tagging technique

Stellar halo: CDM

Stellar halo: WDM



Cold vs Warm dark matter

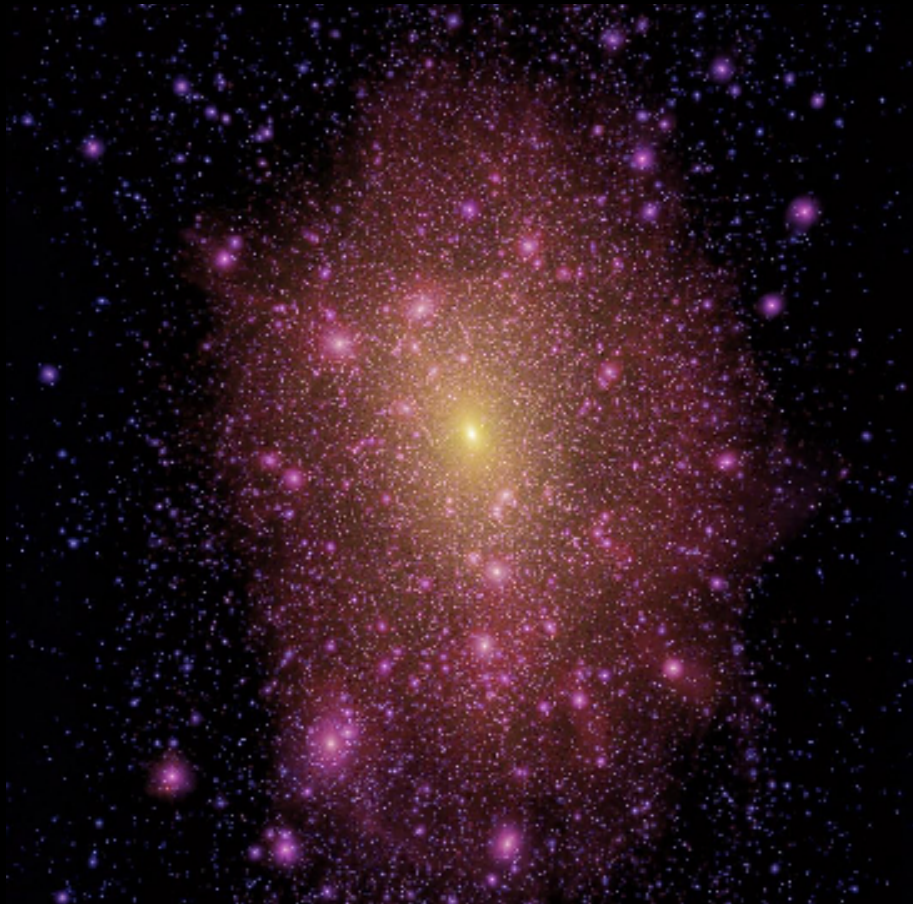


Kennedy et al '03



Tests of the nature of the DM

cold dark matter



warm dark matter

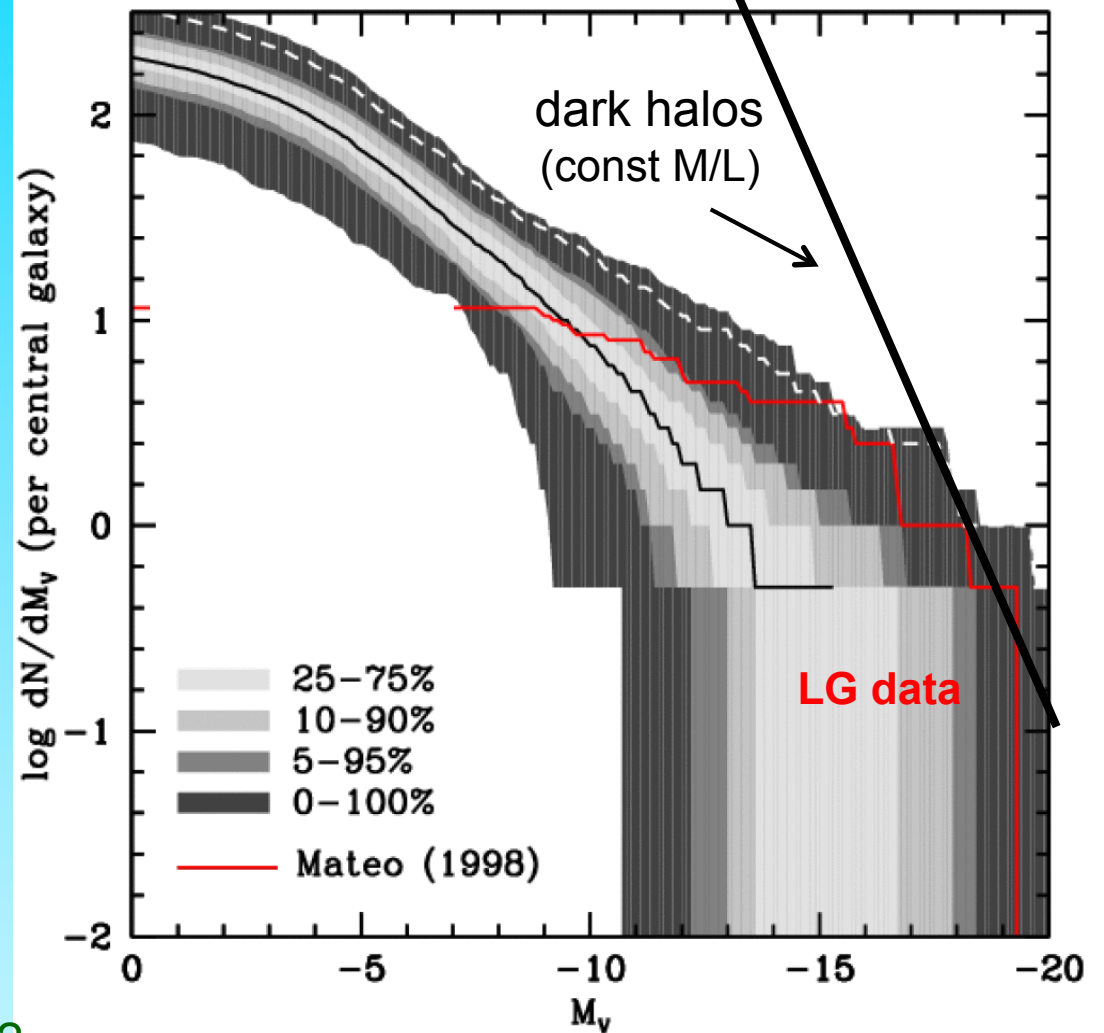


Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '12

Institute for Computational Cosmology

Luminosity Function of Local Group Satellites

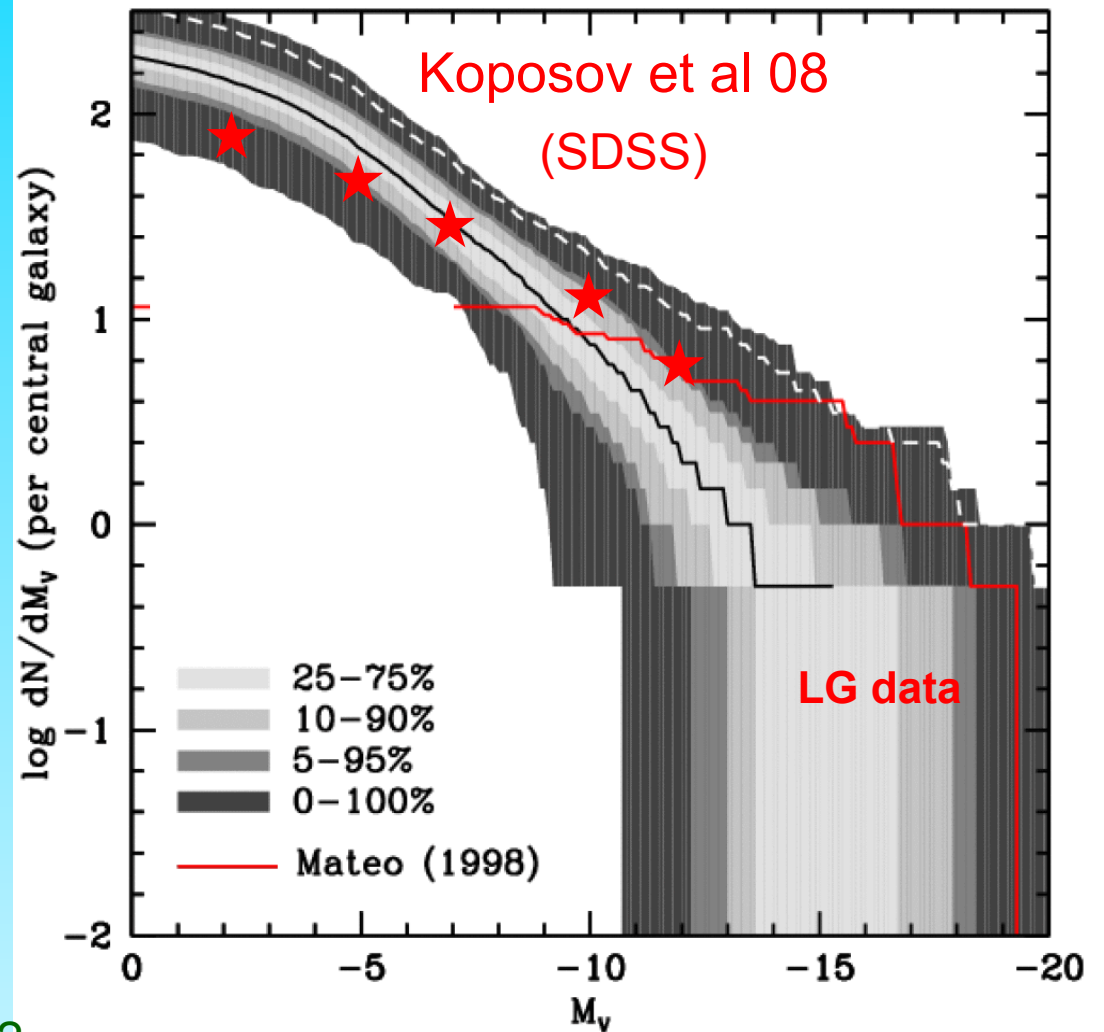
- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)

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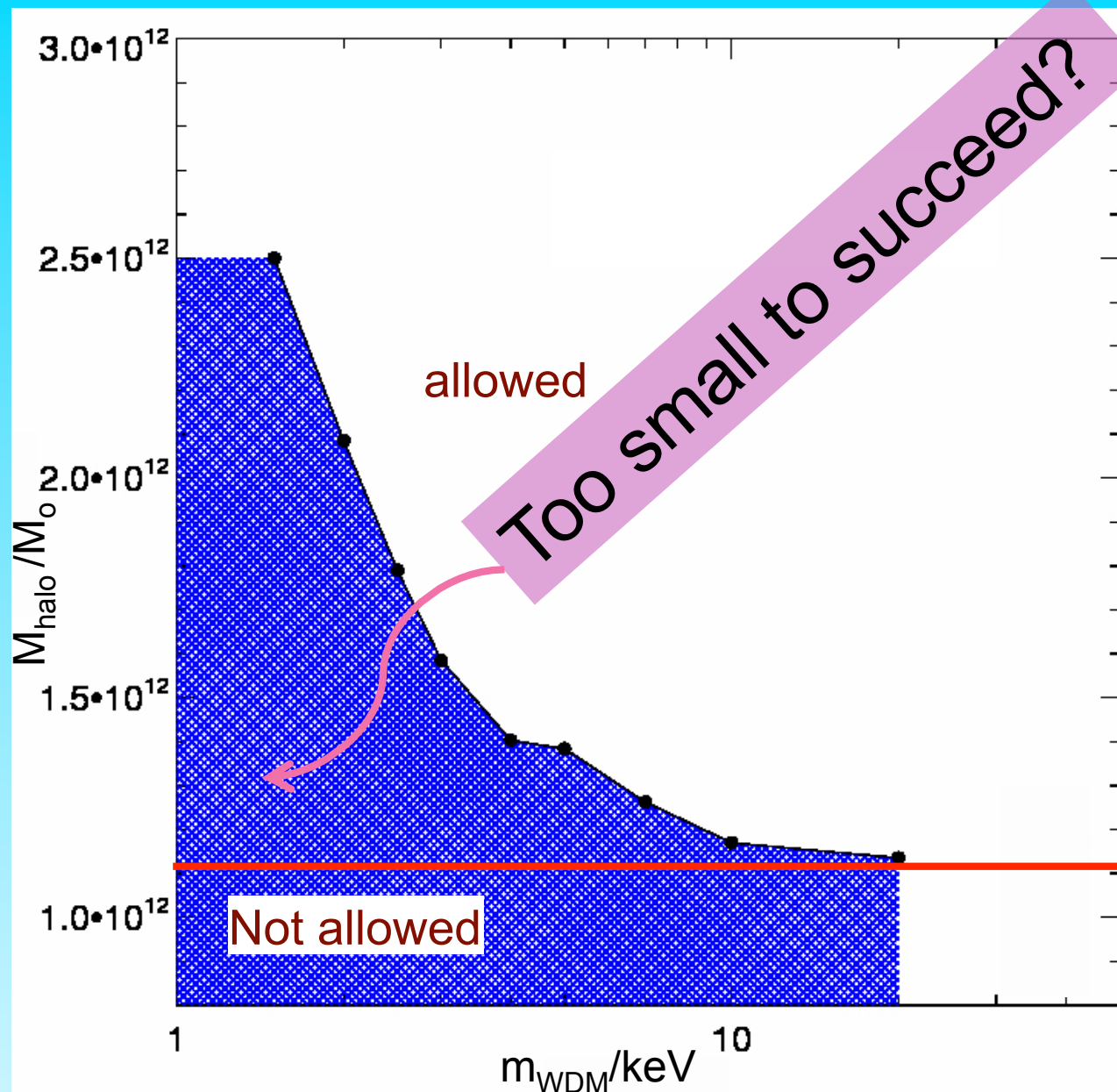
Limits on WDM particle mass

For given m_{wdm} model
must predict **at least**
observed no of sats

→ lower limit on m_{wdm}

For standard galaxy
formation model,
WDM ruled out if
 $M_{\text{halo}} < 1.1 \times 10^{12} M_{\odot}$

Kennedy, Cole & Frenk '13



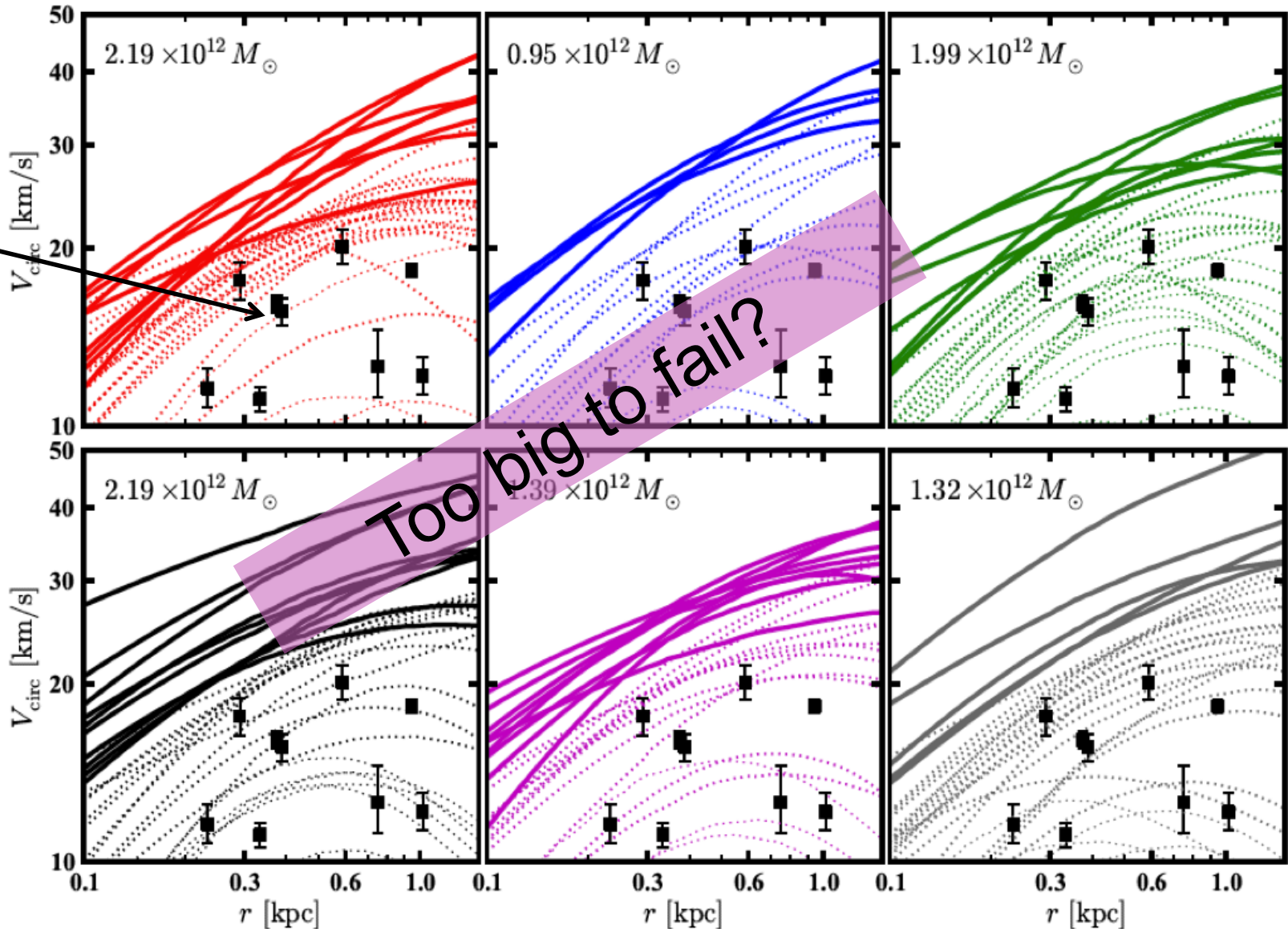
Rotation curves of Aquarius subhalos

Boylan-Kolchin et al. '11

$$V_c = \sqrt{\frac{GM}{r}}$$

9 dwarf
satellites of
Milky Way:
Mass within
half-light
radius

Excludes
LMC, SMC,
Sagittarius



Probability of massive subhalos

Probability of having no more than 3 subhalos with $V_{\max} > 30$ km/s

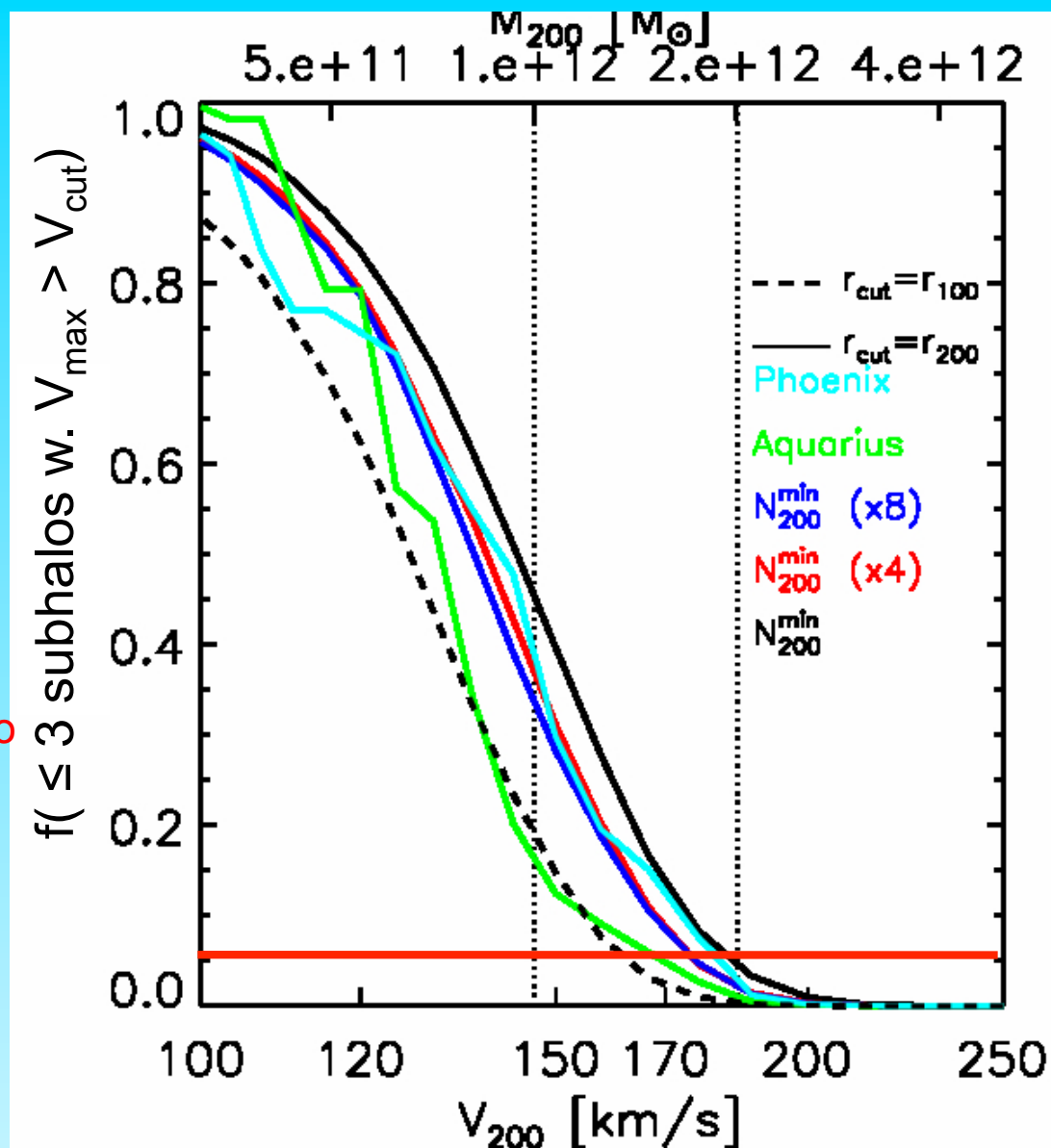
Depends strongly on M_{200} (and V_{cut})

If mass of MW halo $> 2 \times 10^{12} M_{\odot}$
pure CDM is ruled out

CDM requires

$M_{\text{halo}} < 1.5 \times 10^{12} M_{\odot}$ (95% confidence)

Wang, Frenk, Navarro, Gao '12



Constraints on CDM & WDM from the Milky Way satellites

With our standard assumptions: at 95% confidence

Cold dark matter :

Ruled out unless $M_{\text{halo}} < 1.5 \times 10^{12} M_{\odot}$

(from abundance of massive satellites)

Unless baryon effects
are important

Warm dark matter :

Ruled out unless $M_{\text{halo}} > 1.2 \times 10^{12} M_{\odot}$

(from abundance of satellites)

Theory of stellar halos

Galaxy formation & the stellar halo: seven questions:

1. How is the halo **built up**: accreted **vs** *in-situ* stars?
2. What is the **relative importance** of accreted, in-situ and satellite stars as a function of radius?
3. How do these properties **depend** on halo **mass**?
4. If there are halo stars formed **in-situ**, how did they get there?

For “Milky Way” halos:

5. How many **satellites** contribute to the **accreted** stellar halo mass, when are they accreted and are they still around?
6. Are there **differences** between **satellites** that give stars to the halo and those that survive intact?
7. How **lumpy** is the stellar halo? Does it make sense to talk of a **mean** stellar density profile or a mean metallicity profile?

Conclusions

Galaxy formation & the stellar halo: seven questions:

1. In MW gals, halo makes up $<5\%$ of stars; in clusters $>90\%$. In SPH sims, some halo stars formed **in-situ**; most are **accreted**
2. **In-situ** dominates near **centre**, **accreted** in the **middle** and **satellite** stars in the **outer** parts
3. Systematic **variation** in halo profile w. **mass** reflecting **increasing** importance of **accreted** component in **larger** halos
4. In sims: most **in-situ** stars **scattered** from disk by heating?

For “Milky Way” galaxies

5. Accreted stars brought in **a few sats** ($4 < z < 1$), **some surviving**
6. Halo more **metal rich** than brightest sats.
7. Outer halo **dominated** by a **few** streams or sats – **not smooth**