The Galaxy, its stellar halo and its satellites

(in a cosmological setting)

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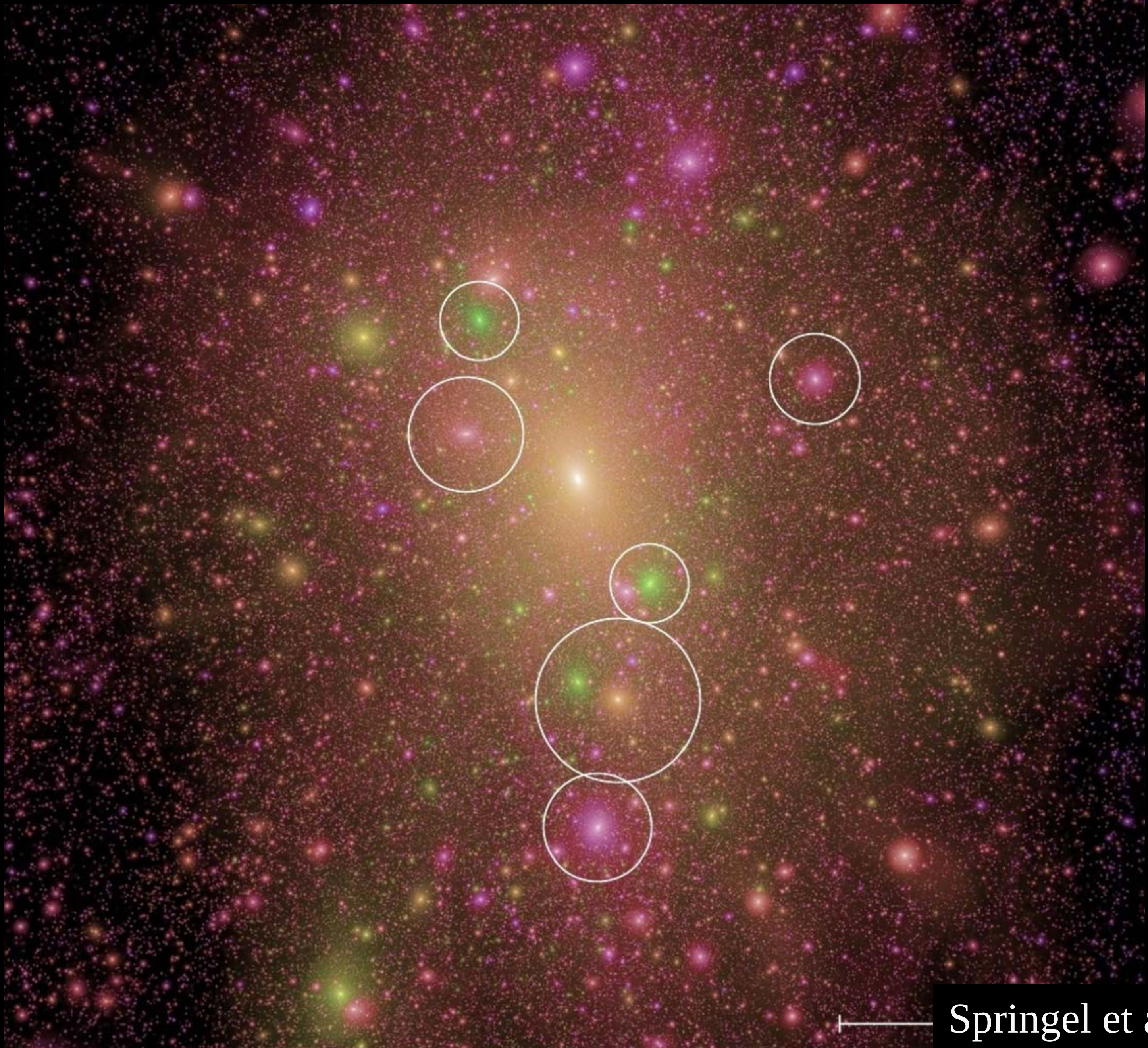
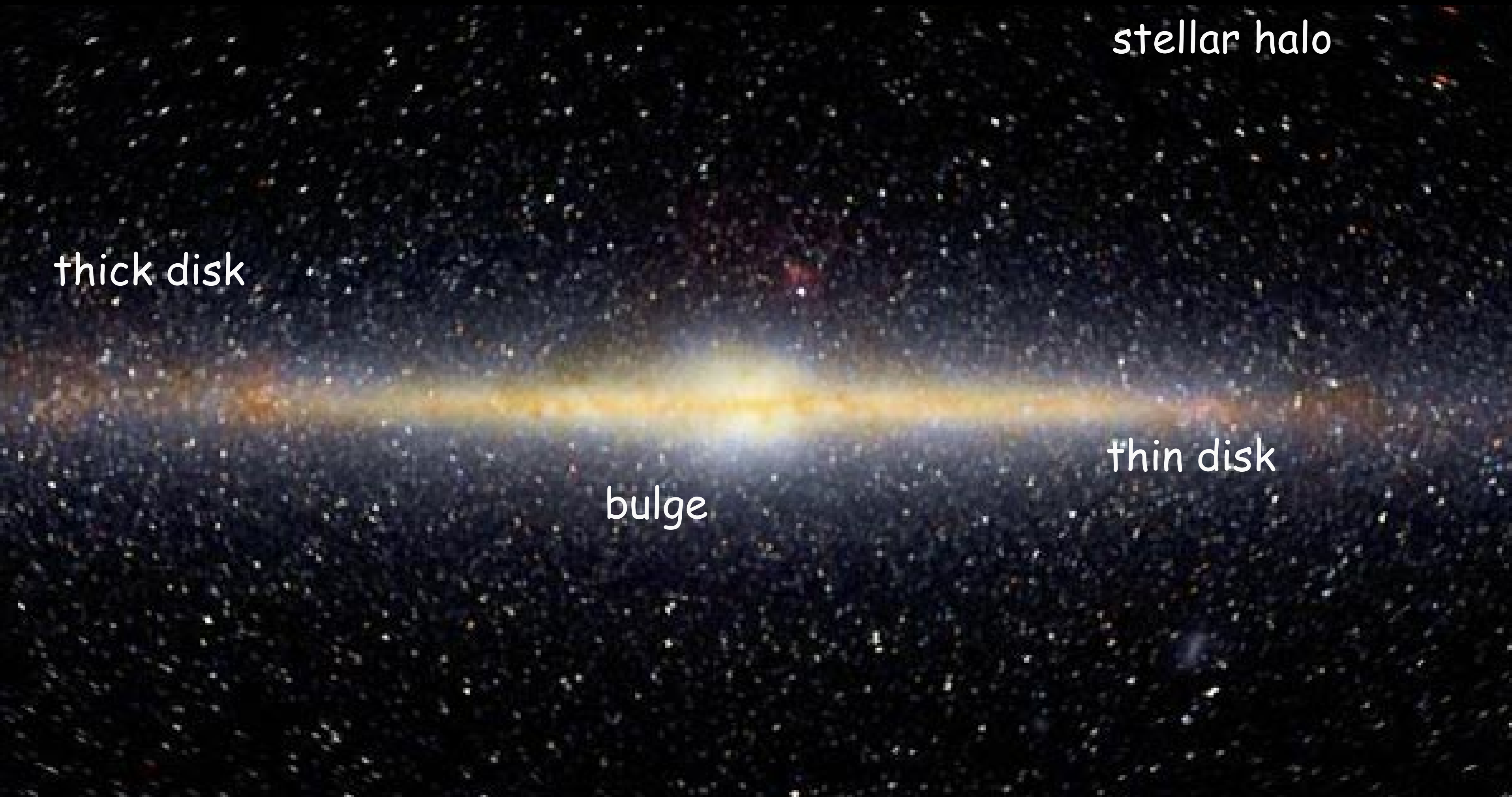
The Aquarius halo: the dark Galaxy...



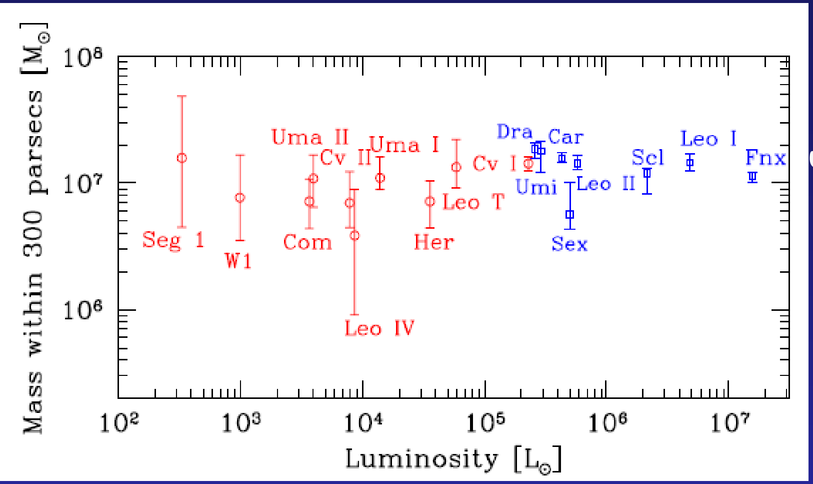
Springel et al. 2008

The luminous Galaxy



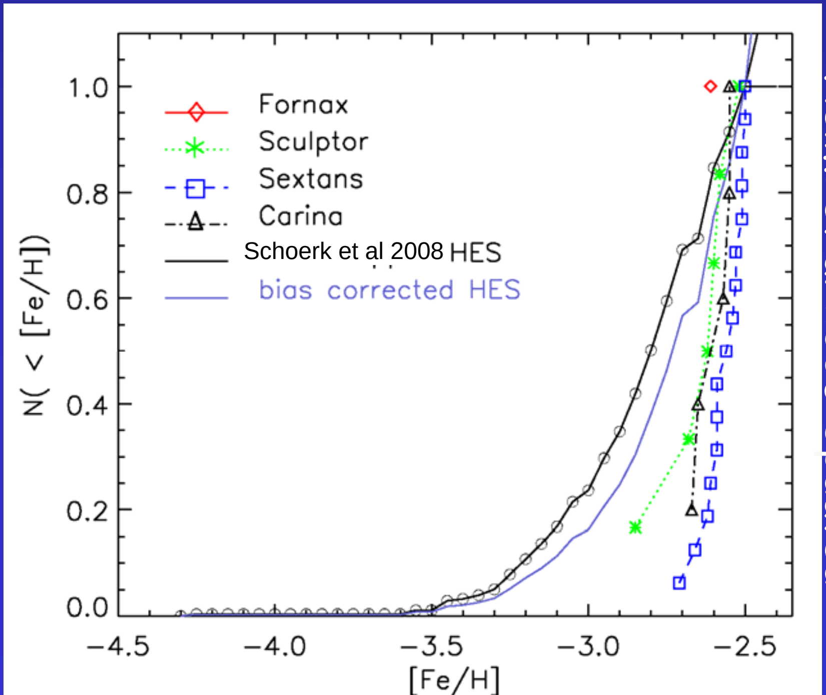
Satellite's Puzzles

- Common-mass scale of 10^7 Msun?
  Mateo 1998, Gilmore et al. 2007, Strigari et al 2007, 2008



Strigari et al 2008

- Chemical properties of stars in dSph different from halo stars in the Milky Way (Venn et al. 2004; Helmi et al. 2006)
  - Probability to find no stars more metal-poor than -2.9 dex if drawn from the halo is < 10^{-5}
  - Was the Milky Way stellar halo really built from systems like the progenitors of dSph?



Helmi et al 2006 Updated

Outline

- Models of the Galaxy in a cosmological context
  - Dark-matter simulations and semi-analytic models
  - Structure and properties of the stellar halo
    - density profile, chemistry…

- Satellites in LCDM
  - Luminosity function and metallicity distribution
  - Star formation histories
  - Common-mass scale at M(<0.6kpc)?

- Summary

Thanks to: Yang-Shyang Li (Kapteyn), Gabriella De Lucia (MPA), Mark Vogelsberger (MPA), Volker Springel (MPA) and the VIRGO consortium

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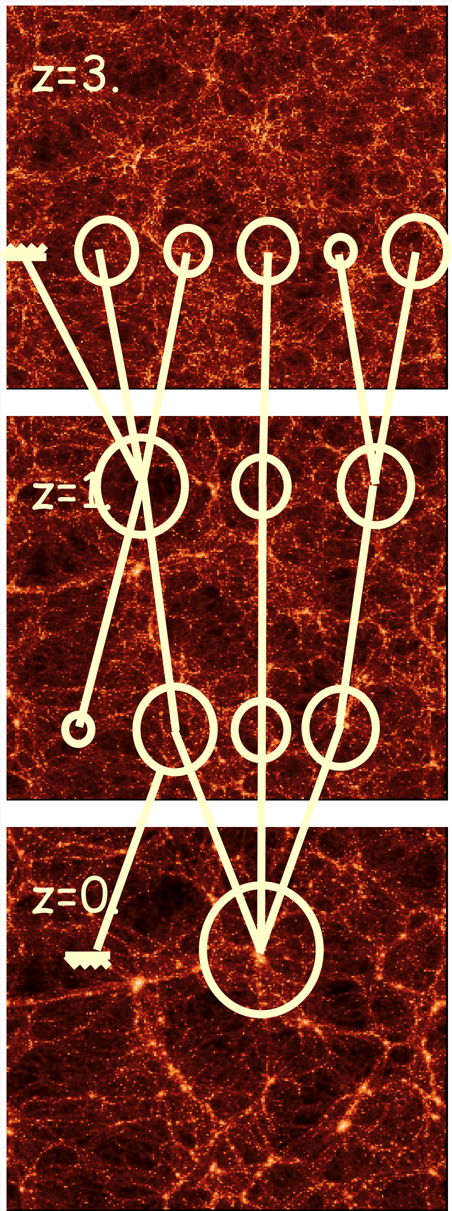
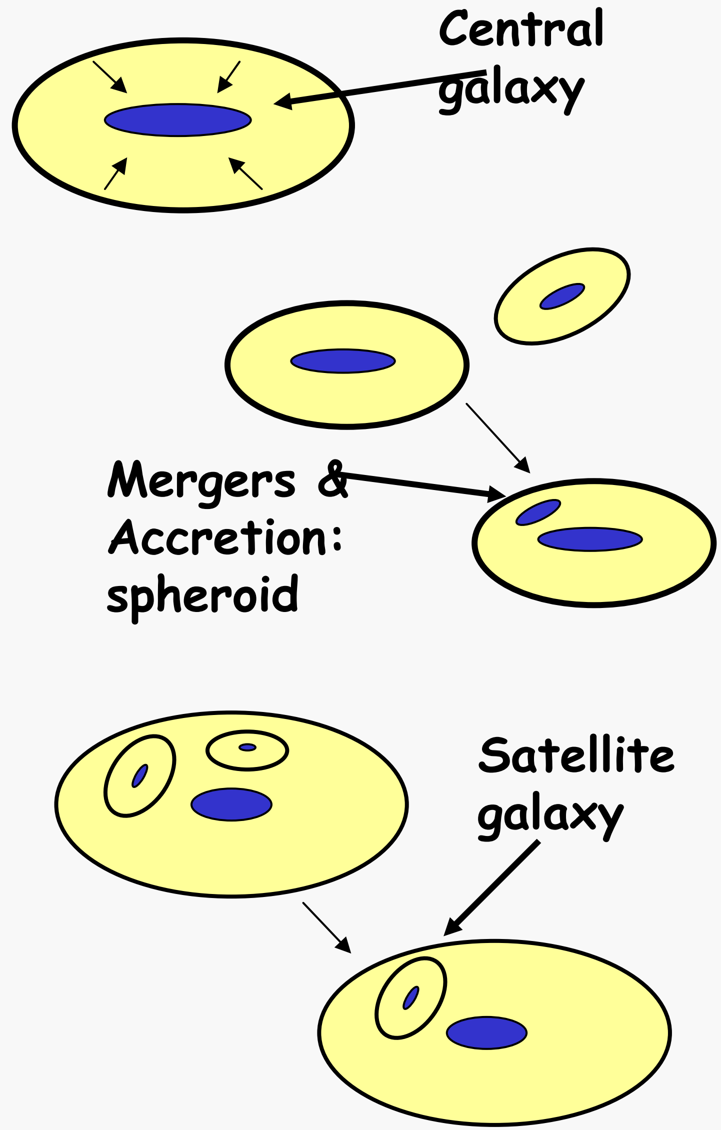
Hybrid modeling of the Galaxy in ΛCDM: simulations



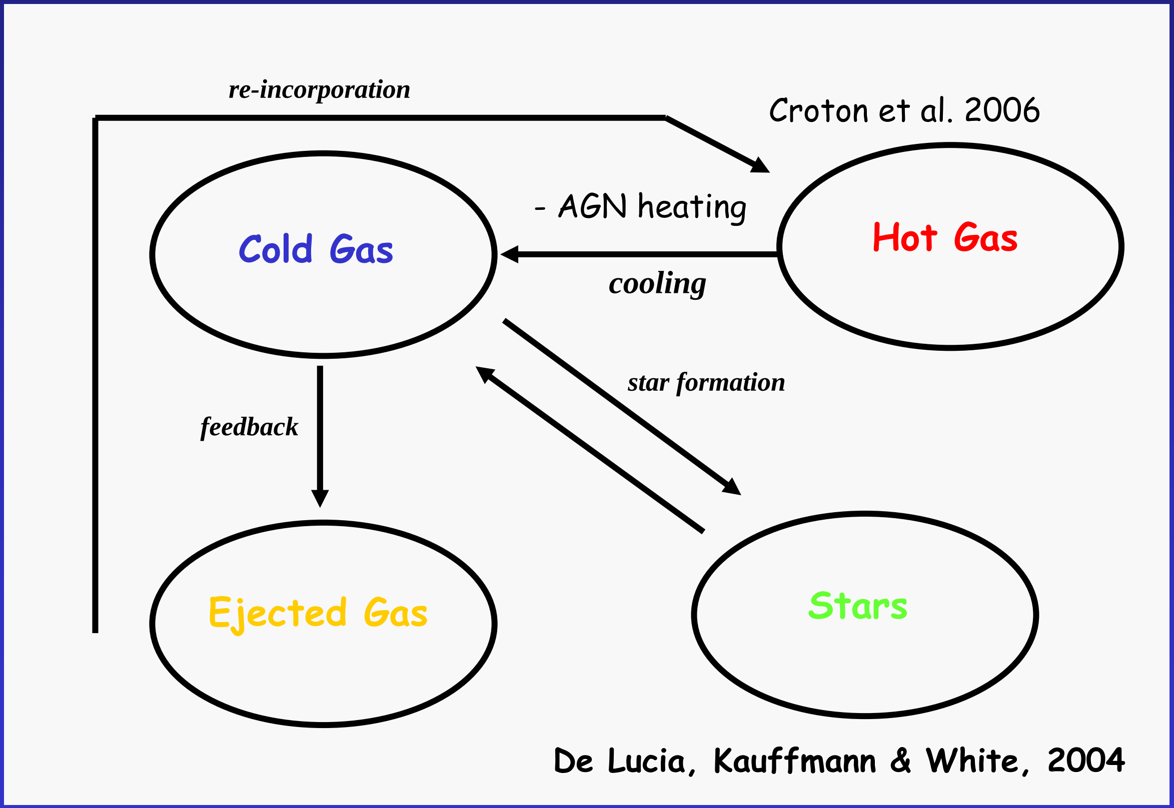
Kauffmann et al., 1999



De Lucia et al., 2004

Hybrid modeling of the Galaxy in ΛCDM: baryons

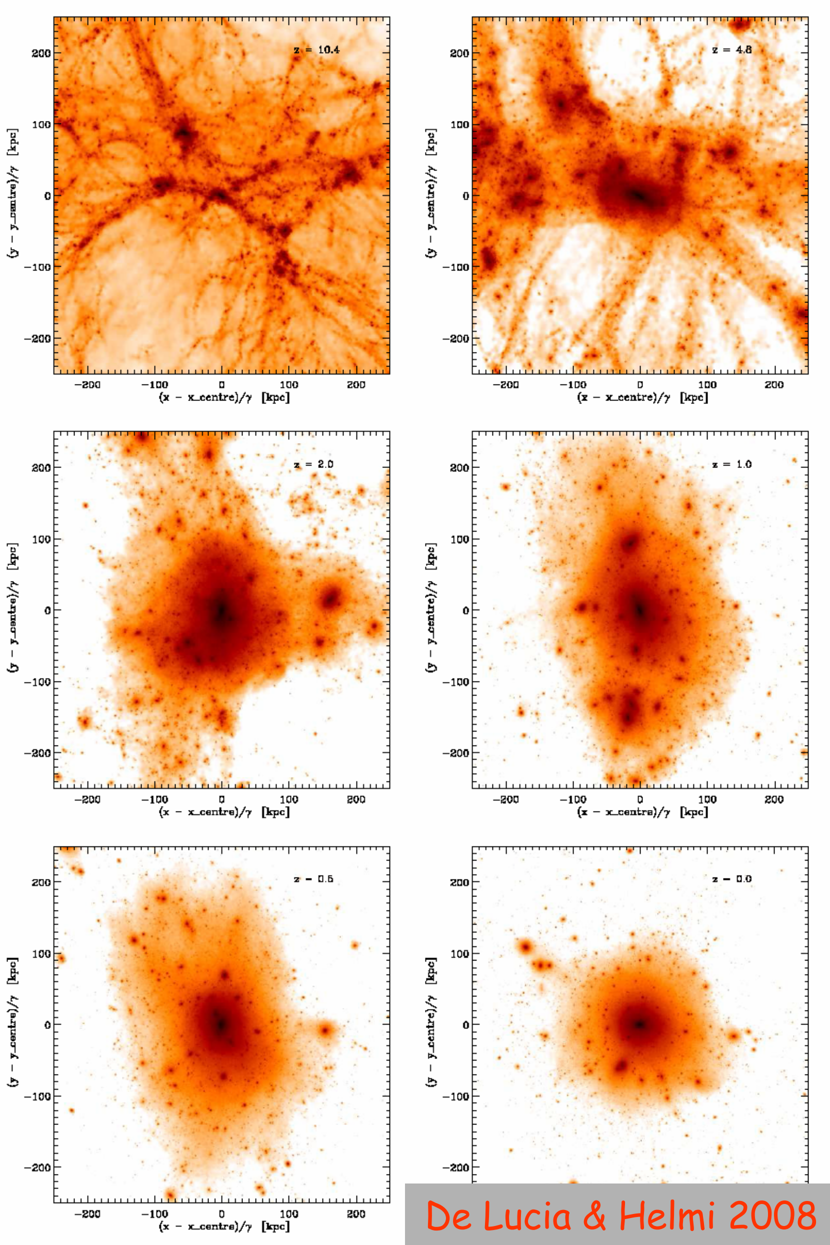
semi-analytic model to follow physics of baryons
(simple, physically/observationally motivated prescriptions)



Also White & Frenk 1991, Somerville et al, Benson et al …. Gnedin et al, Bullock & Johnston.

The Galaxy in ΛCDM

- high resolution dark-matter simulation of a galaxy size halo
  - $N_{vir} \sim 10^7$; $m_p \sim 10^5\ M_\odot$
  - no major merger z < 1.5
- semi-analytic models: (Munich version)
  - fiducial model based on Millenium Run
  - Set of parameters: FIXED
- star formation occurs in disks (quiescent + minor mergers) + starbursts (major mergers)
- spheroid grows from minor mergers + disk instability
  - spheroid = stellar halo + bulge



De Lucia & Helmi 2008

General properties

- Questions:
  - Mass growth of various components; metallicity, age distribution...
  - When and where stars in stellar halo formed
  - Correlations between spatial distribution, metallicity, age...

- Results:
  - mass in disk & spheroid ✓
  - cold gas content ✓
  - metallicity of cold gas & stars ✓

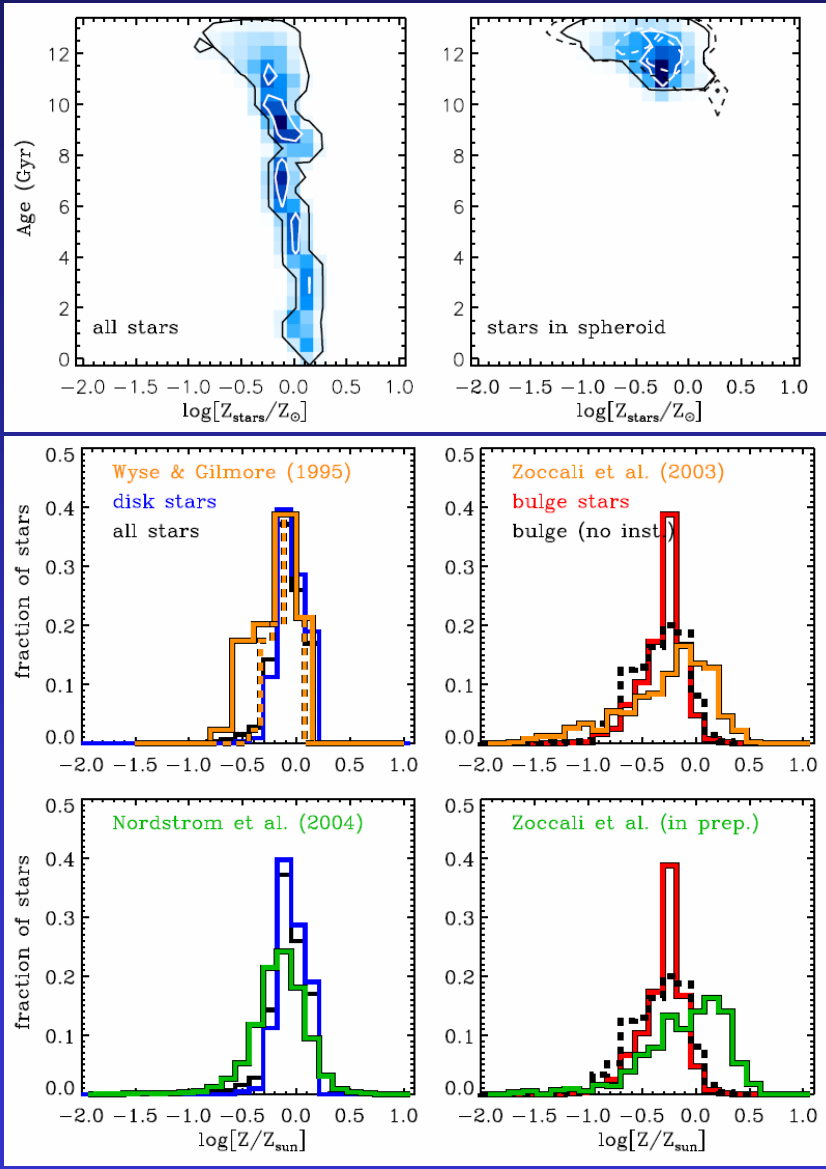
} standard model values & parameters

(Croton et al. 2006; De Lucia & Blaizot 2007)

Age & metallicity

- <u>Age distribution</u>
  - Disk: very weak age-metallicity relation (Nordstrom et al. 2004)
  - Spheroid: old

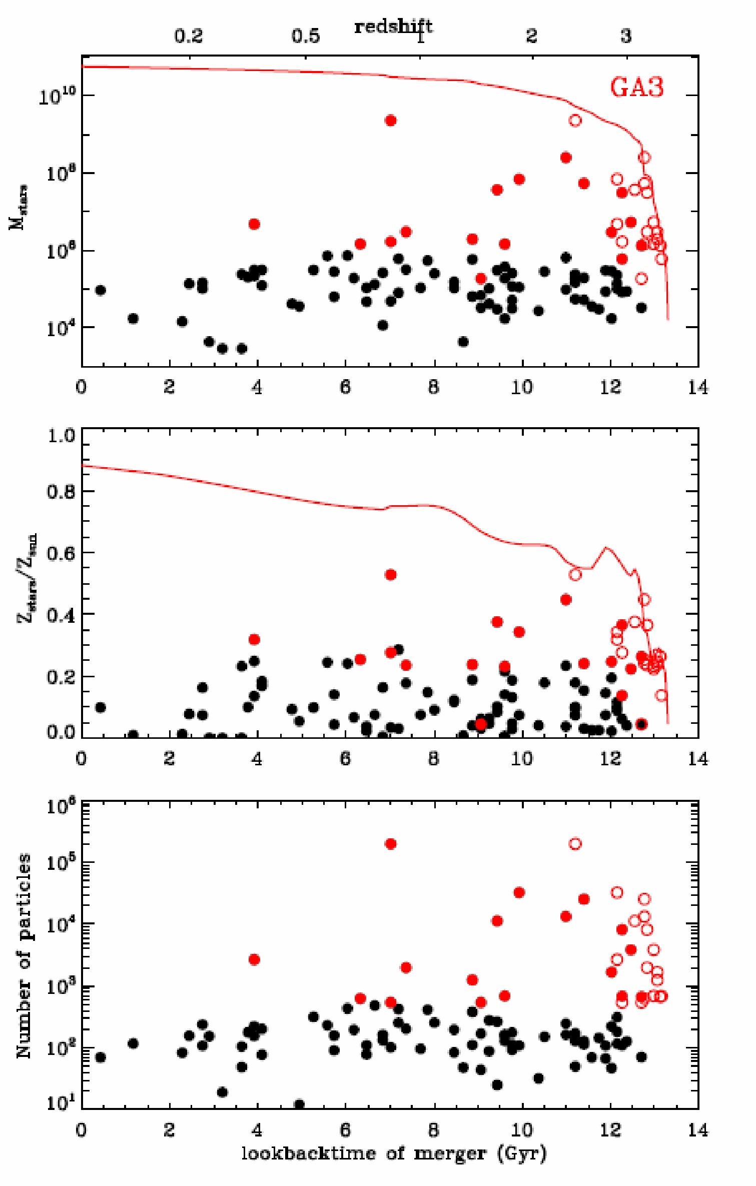
- <u>Metallicity distribution</u>
  - Disk
    - peak value OK
    - careful comparison between Z and [Fe/H]... better to [O/H]
  - Spheroid:
    - peak metallicity log $Z/Z_{\odot}$ ~ -0.25
    - extended tail towards low metallicities



De Lucia & Helmi 2008

Stellar halo progenitors

- Assume stellar halo built by accreted galaxies
  - Many small objects accreted
  - Few (largest) contribute most stars
    - Inner halo: 65% from one object, the rest by three objects of comparable size
  - Dark-matter halos accreted relatively early (> 11 Gyr ago)
    - Stars: on dynamical friction timescale (> 9 Gyr ago)
  - Most massive objects highest metallicity
  - no strong dependence on accretion time



de Lucia & Helmi 2008

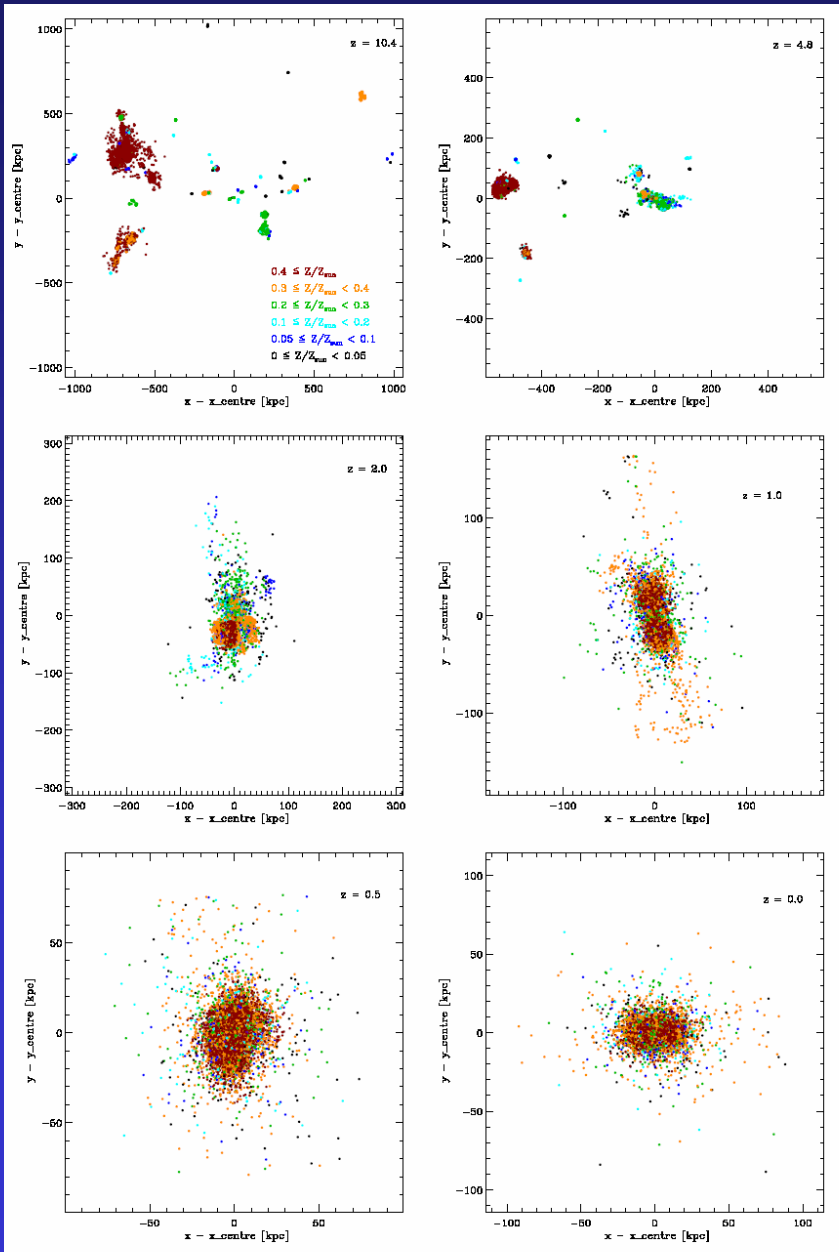
Where did the stars form?

- Select 10% most bound particles from dark matter halos
  - accreted onto main branch
  - assign stellar pops properties at time of accretion

- Pockets of stars with similar chemical properties

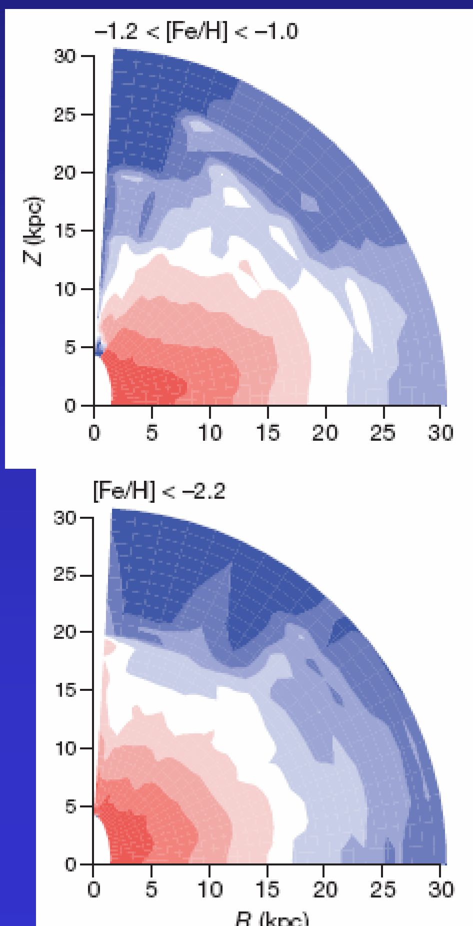
- Rather well-mixed by present-time

- No very clear gradient



Chemistry and structure: observations

- [Fe/H] - Rotational velocity - shape: Dichotomy (SDSS/SEGUE data)
  - inner halo peaks at -1.6 dex, flattened, no mean rotation
  - outer halo (d ~ 5 - 10 kpc) peaks at -2.2 dex, rounder, retrograde

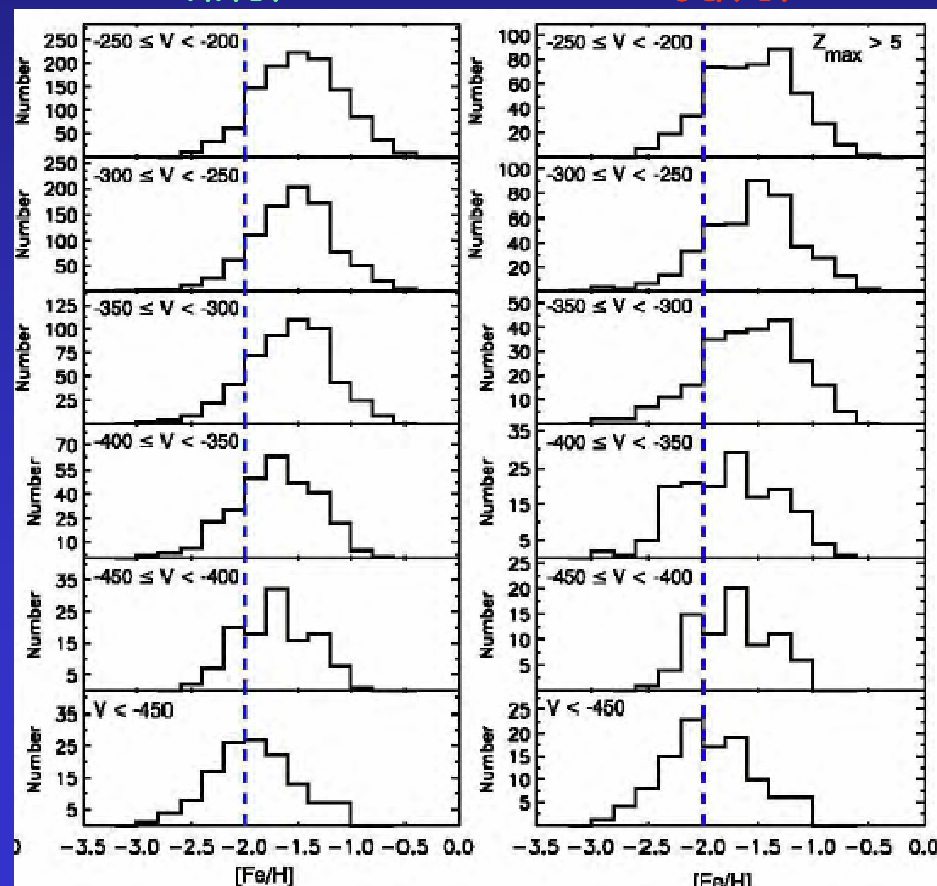


"metal-rich"

metal-poor

inner

outer



Carollo et al. 2007

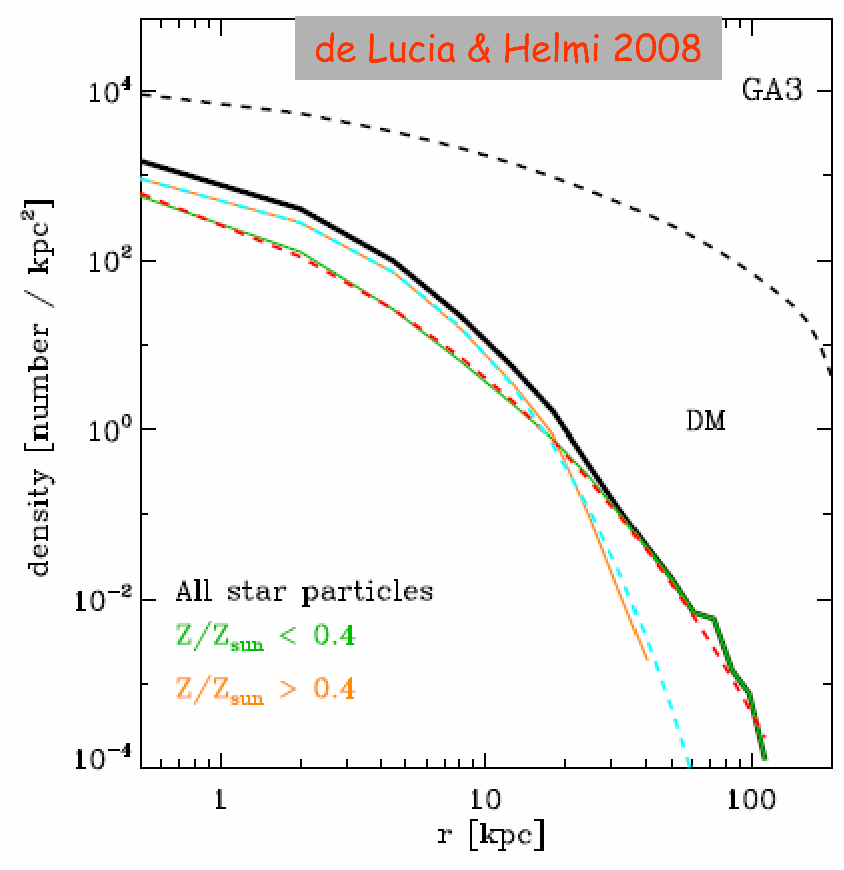
Dichotomy of stellar halo: models

- "Metal-rich" stars:
  - centrally concentrated, density log slope ~ -3.3 near the Sun
- "Metal-poor" stars:
  - more extended, density log slope ~ -3.1 near the Sun

- Half-light radius ~ 4 kpc (like MW)

- Origin of dichotomy:
  mass-metallicity relation

- Implications:
  - more chances of finding metal-poor stars in outskirts (r > 15 kpc)
  - different types of progenitors (?)



Summary

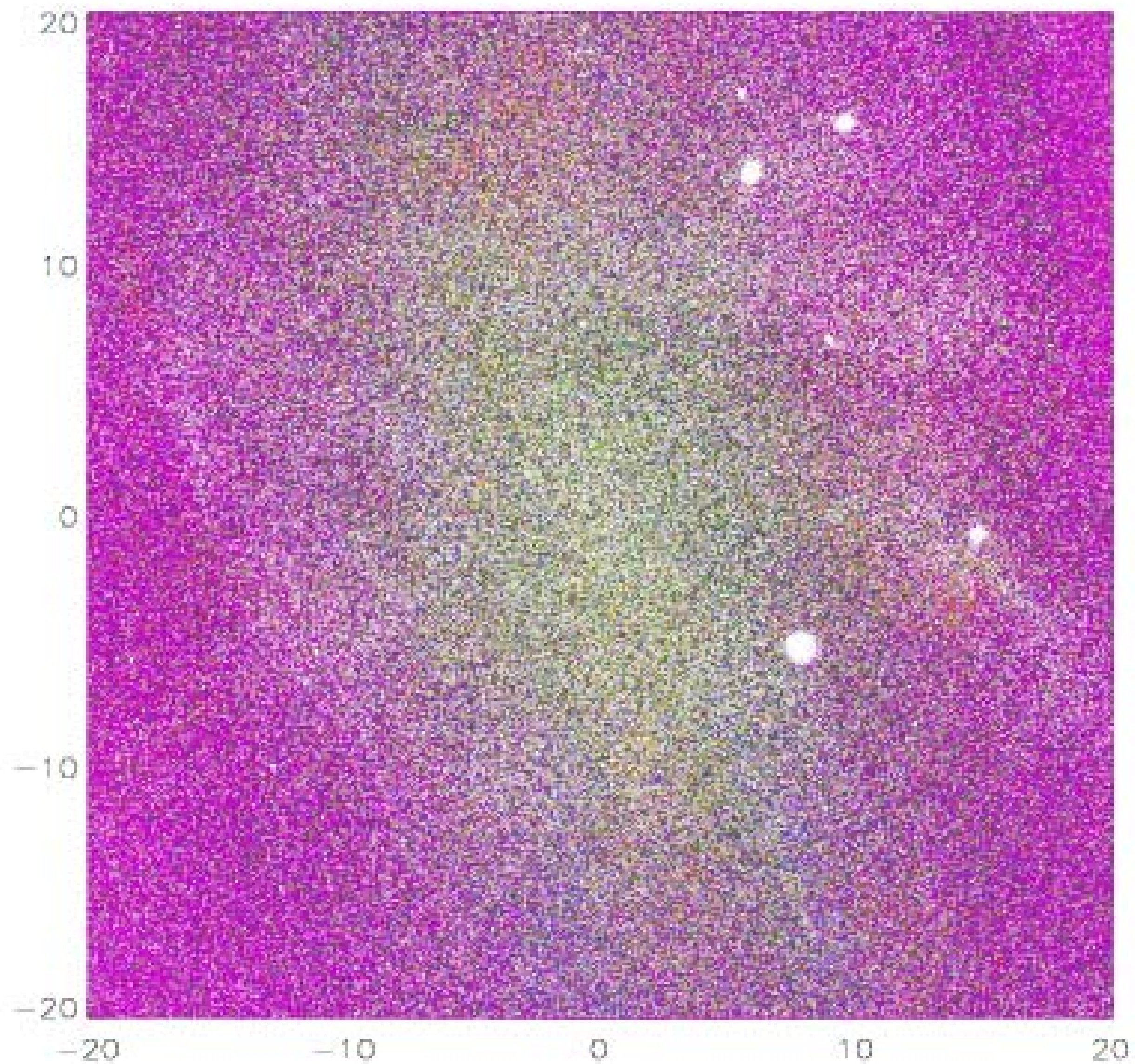
- Main properties of the Galaxy: reproduced well without fine-tuning
  - Although:
    - stellar halo: too metal-rich
    - star formation rate: too high

- Stellar halo:
  - metallicity and correlations: dichotomy result of dynamics and mass-metallicity relation of the progenitors
  - progenitors: many by number, but a few most massive dominate budget
  - fully built by accretion

- Substructure: need even higher resolution (> 10^7 particles!)

Aquarius: dark matter in the inner halo

Some streams visible but most of the material is smoothly distributed



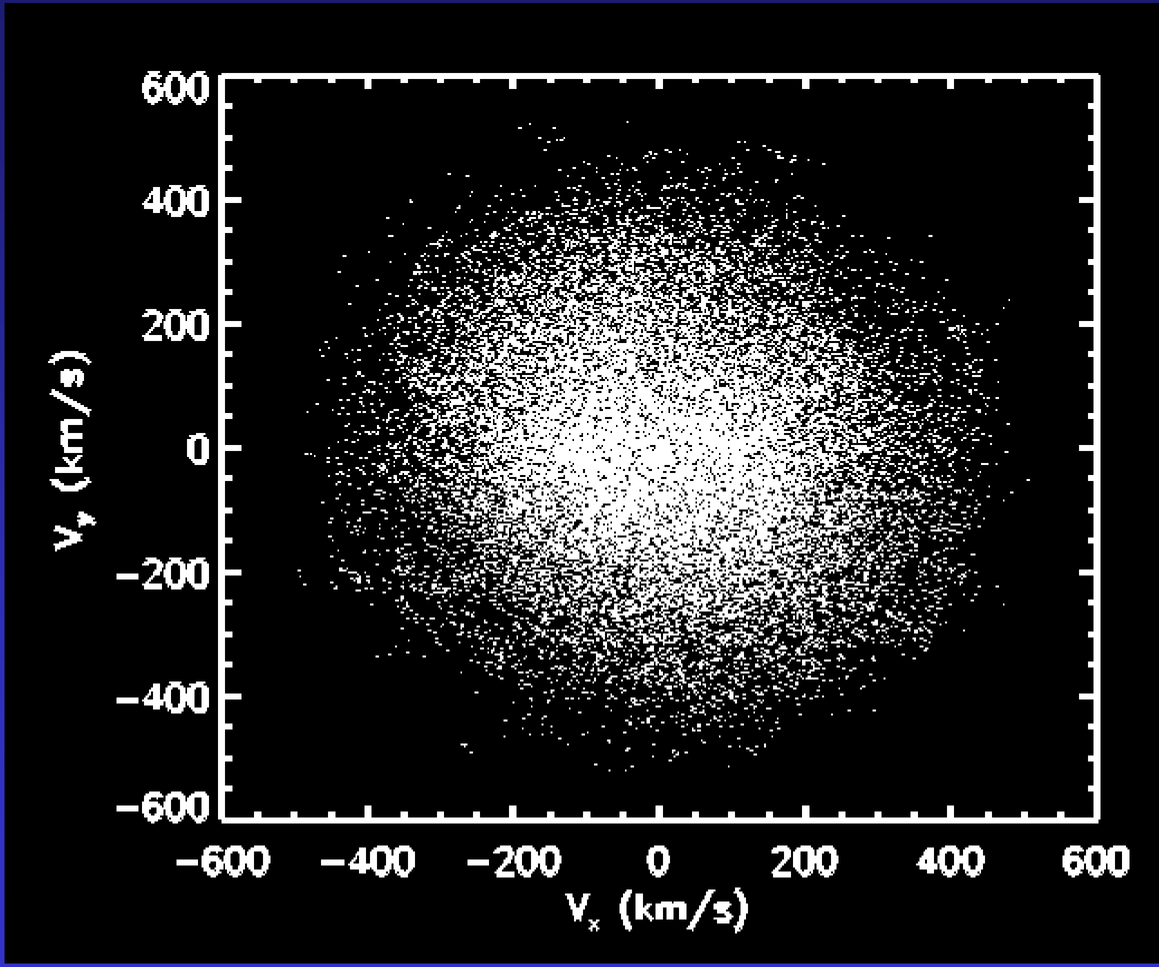
Aquarius: dark matter in the inner halo

Some streams visible but most of the material is smoothly distributed

- Streams they are not that narrow
- And there are a lot of these

Aquarius: dark matter near the Sun

Where are the streams?

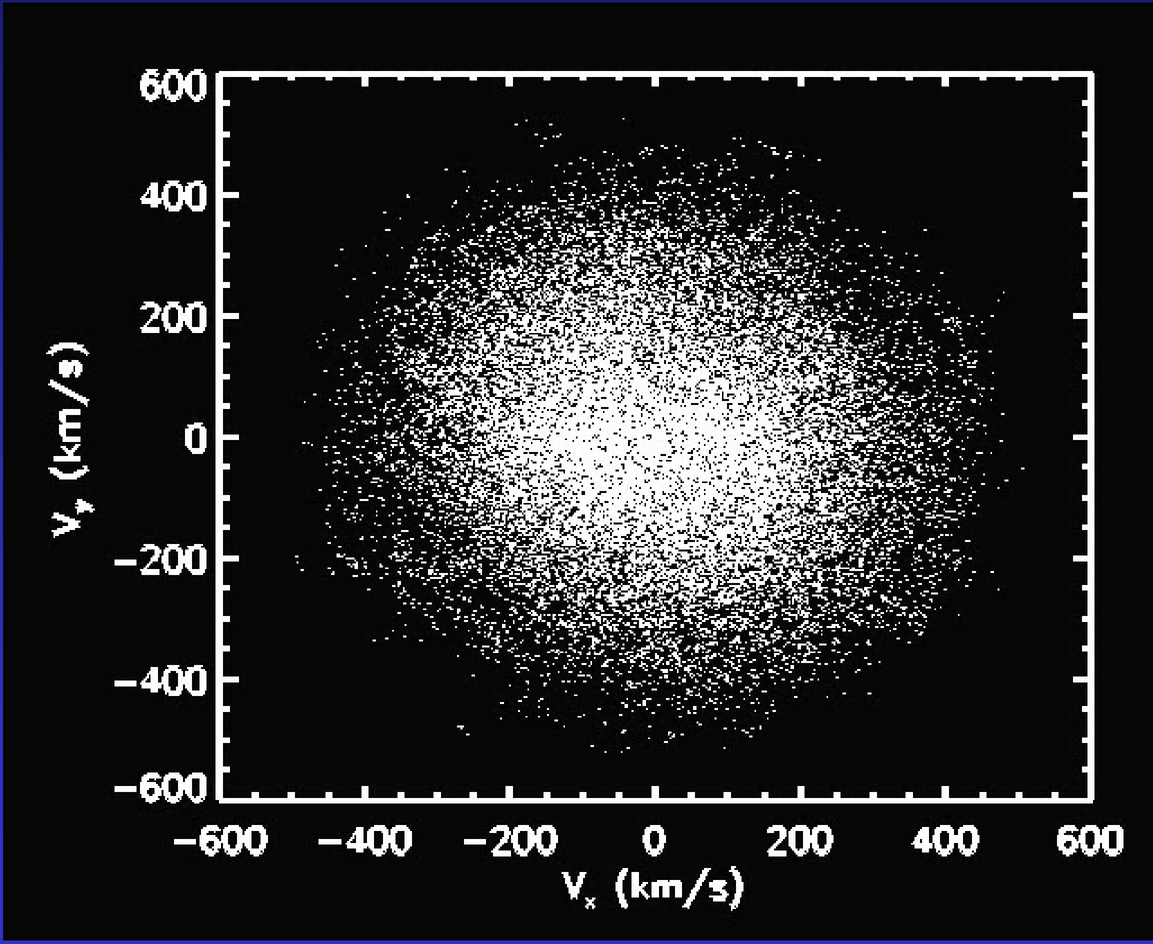


Vogelsberger, Helmi et al. 2008

Aquarius: dark matter near the Sun

Where are the streams?

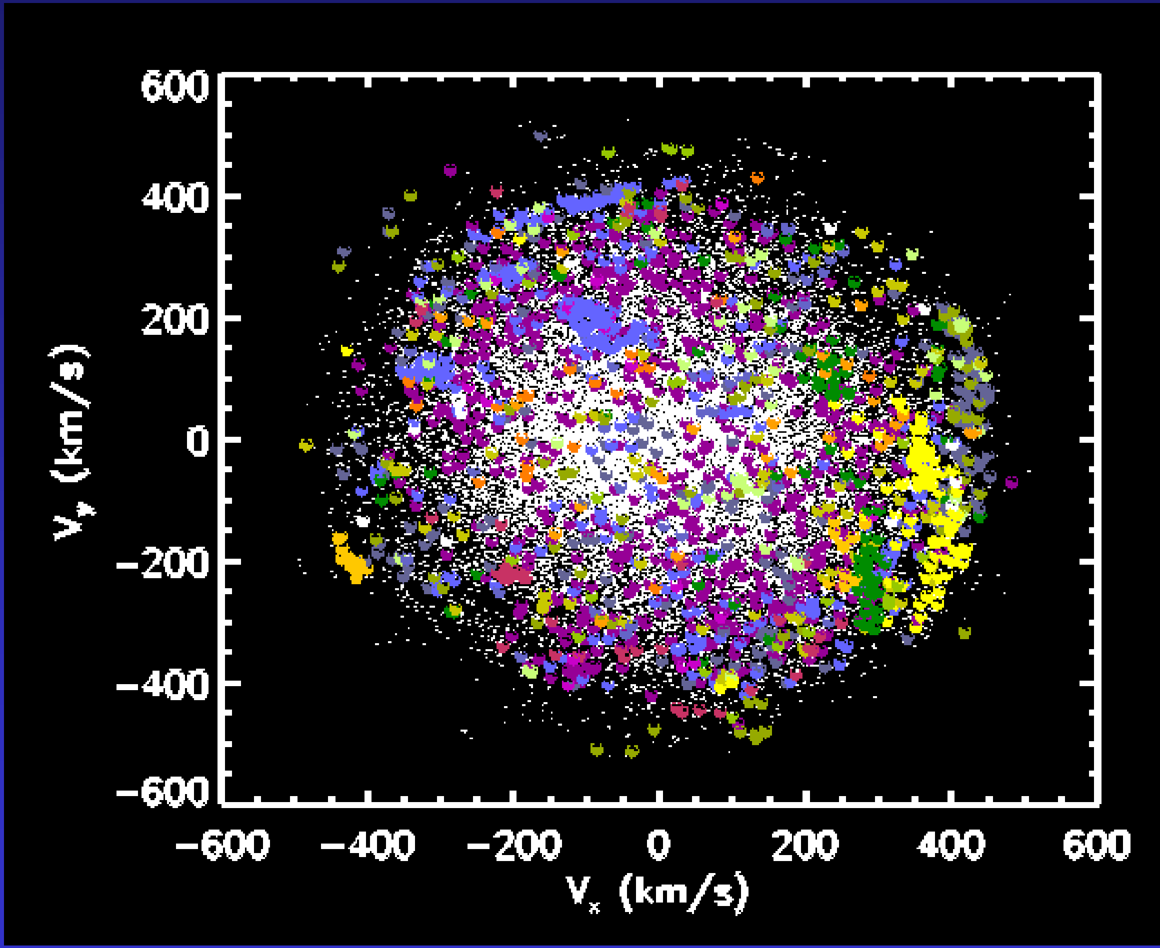
We can resolve the streams unequivocally for the first time!



Vogelsberger, Helmi et al. 2008

Aquarius: dark matter near the Sun

- We can resolve the streams unequivocally for the first time!
- 4×10^4 particles in volume
  - 27 halos contribute at least 10 particles (0.025% of the total)
  - Most prominent streams have ~ 100 particles (0.25% of the total)



Vogelsberger, Helmi et al. 2008

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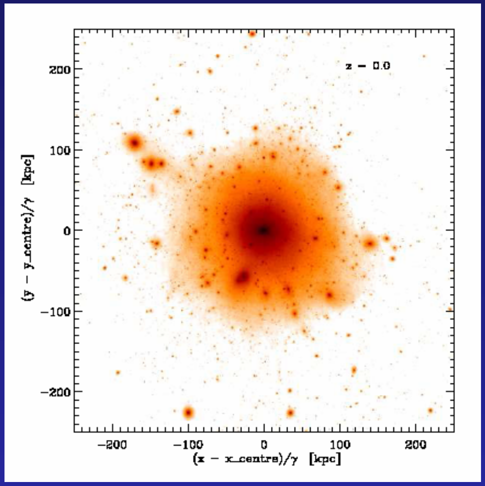
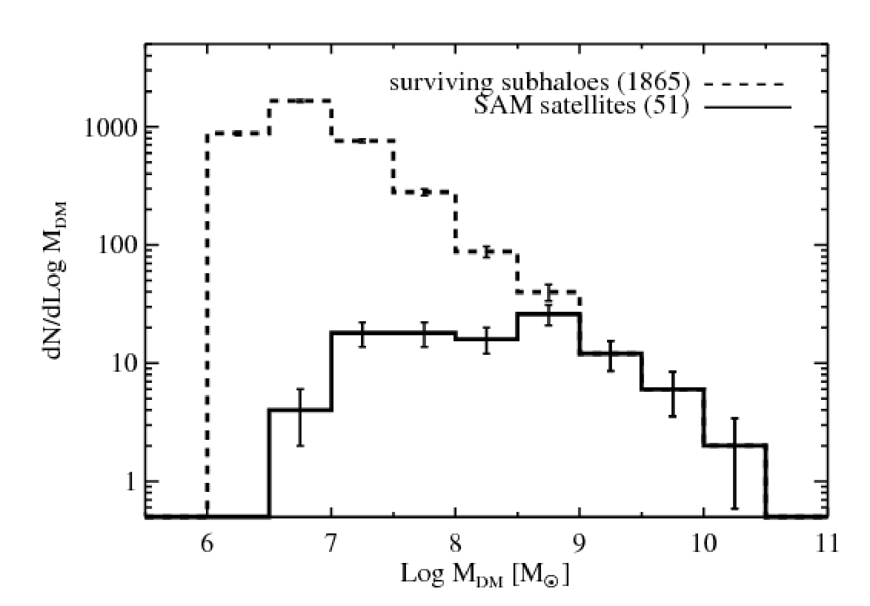
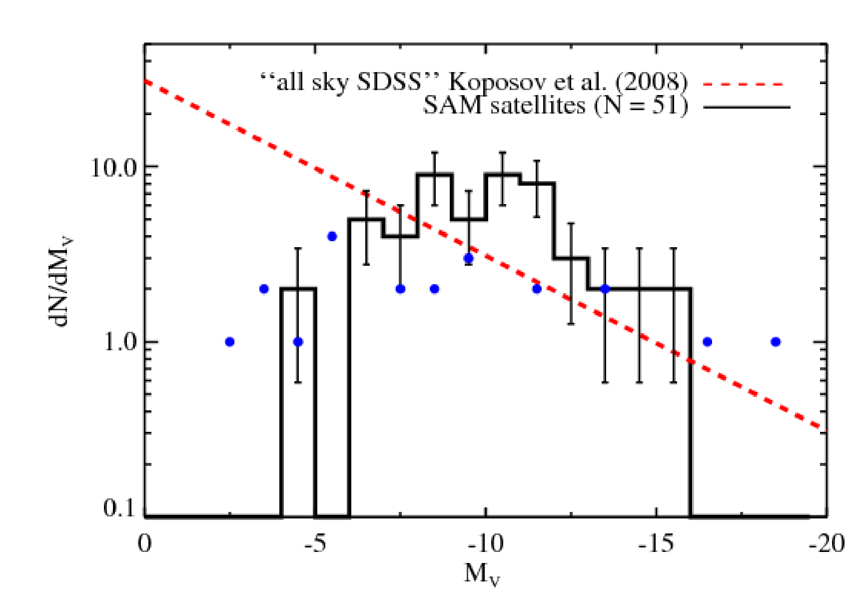
Modeling the satellites in ΛCDM

- Subhalos vs satellites:
  - many more subhalos than luminous satellites
  - processes included in SA models to account for this:
    - re-ionization: z_i = 15 to z_f = 11.5 (Gnedin 2000)
    - small halos (T < 10^4 K) cannot cool (lack/inefficient coolants)
  - no fine-tuning of parameters
    - improvement: metals are recycled through hot phase (Mac Low & Ferrara 1999)



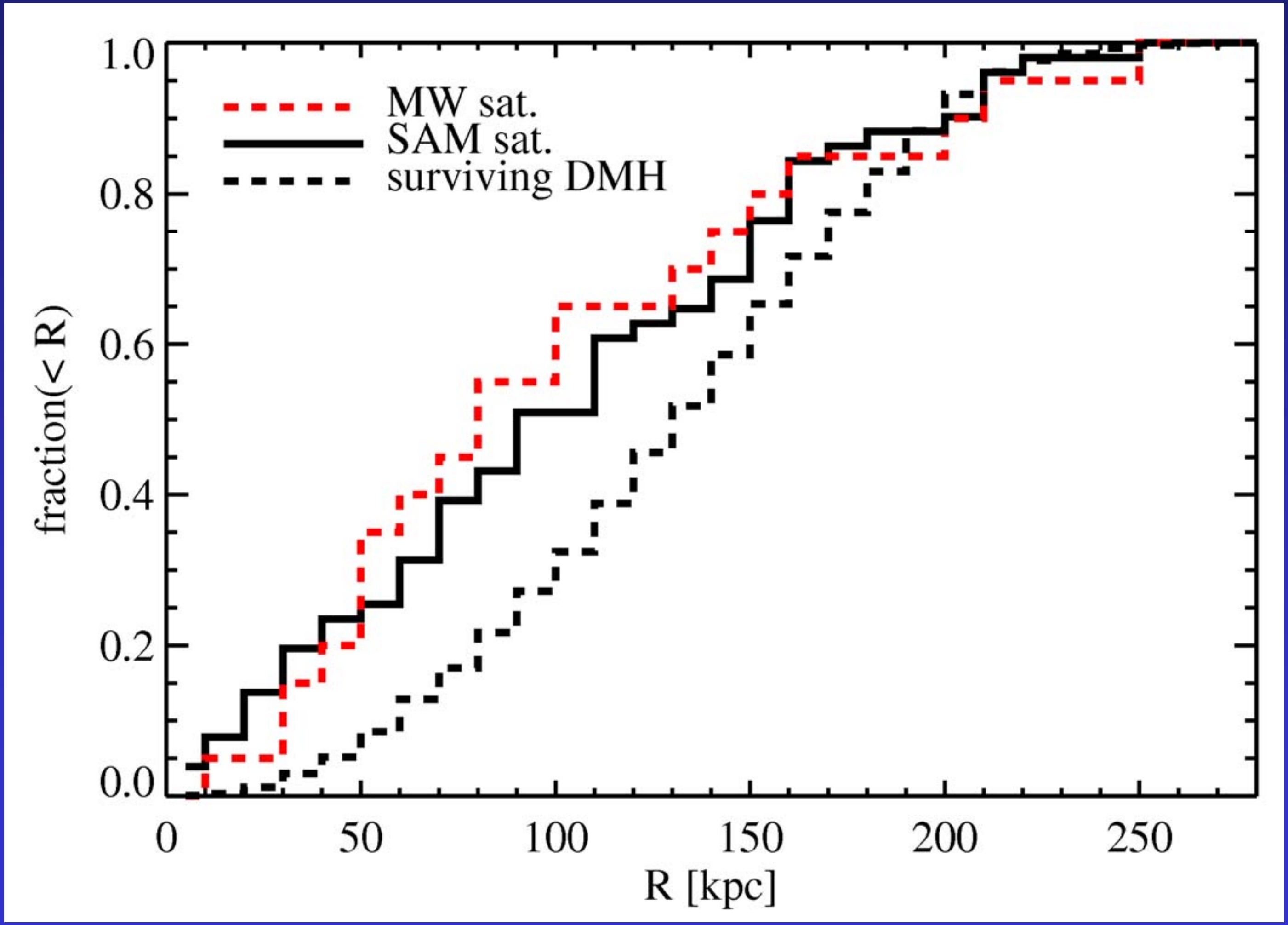
Li, Helmi & de Lucia in prep





Modeling the satellites in ΛCDM

- Bonus: predict the right distribution as function of radius

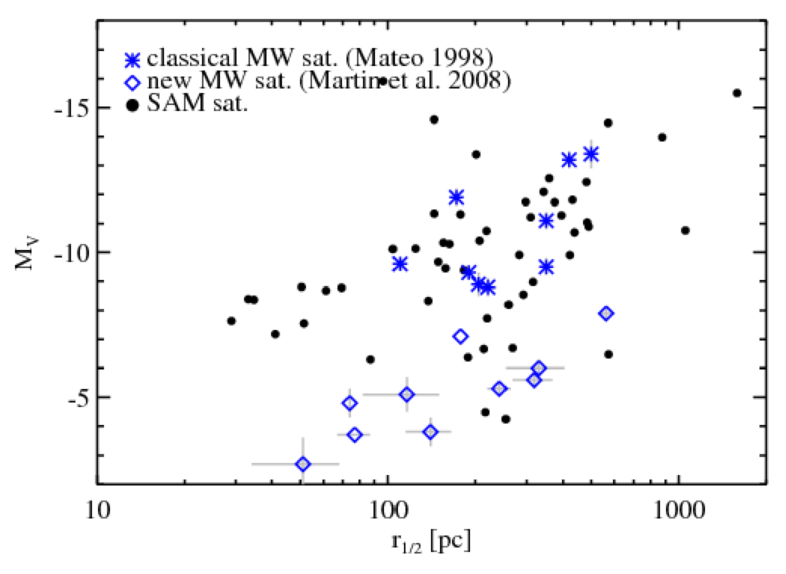


Li et al. in prep.

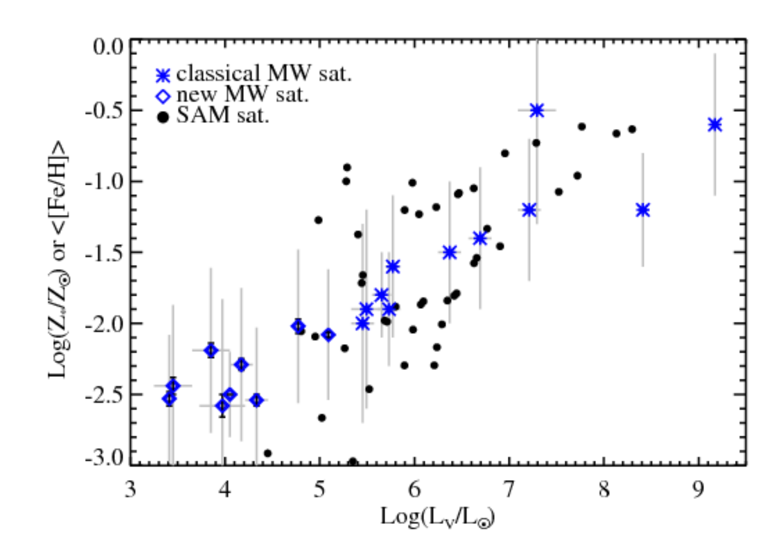
e.g Gao et al. 2004, Yang et al. 2005; Zentner et al 2005

Satellites in ΛCDM: scaling relations

- Luminosity - size relation:
  - similar for 11 brightest sats
  - too bright (or too small) at faint end



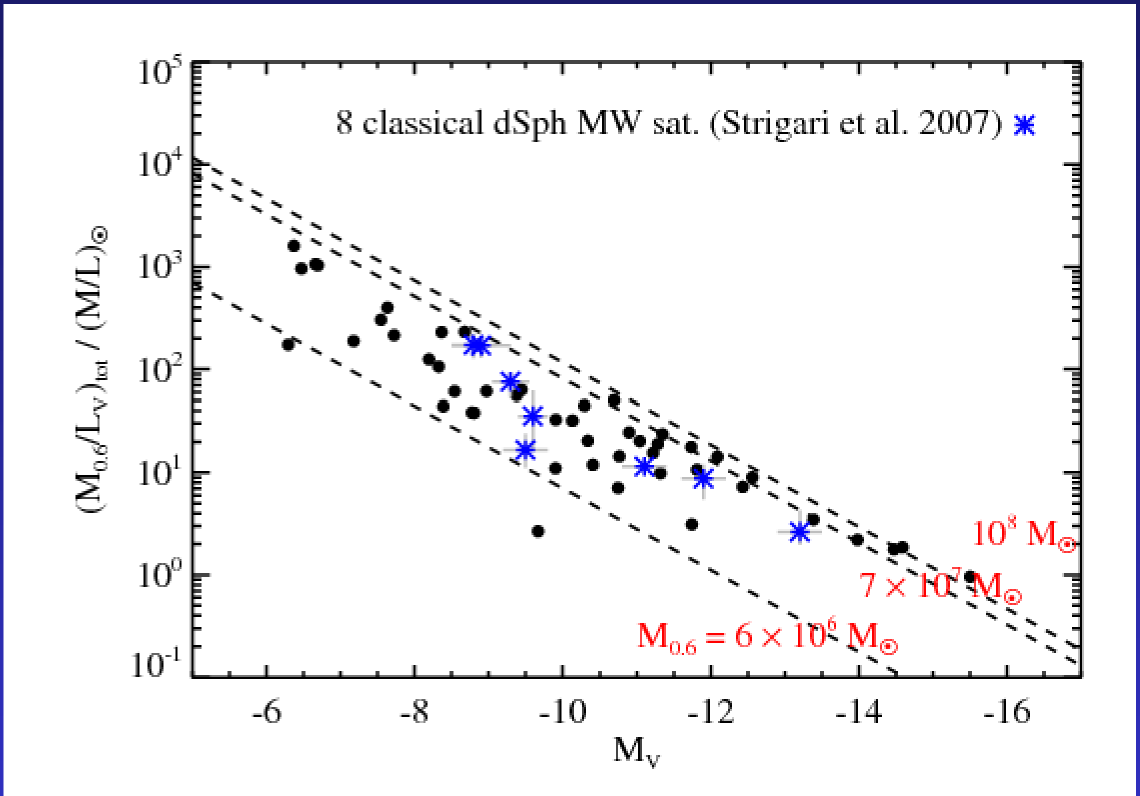
- Luminosity - metallicity relation close to observed
  - clear trend: the faintest satellites are the most metal-poor
    (Simon & Geha 2007, Kirby et al. 2008)



- Caveat: chemical-enrichment uses instantaneous recycling approx -> do not model [Fe/H]

Li et al in prep

Scaling relations: M/L vs L



Li et al in prep

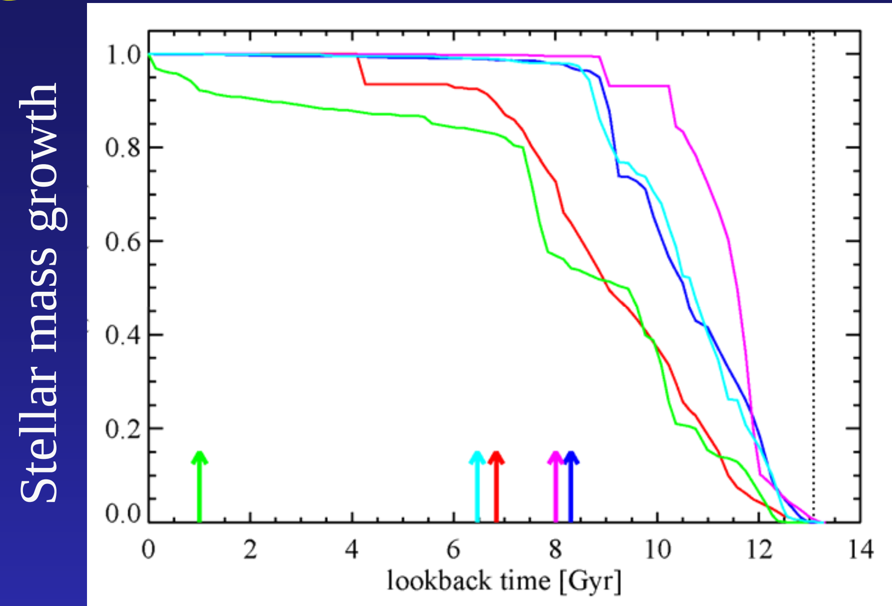
- M/L vs Luminosity: similar to observed
  - faintest galaxies are the most dark-matter dominated

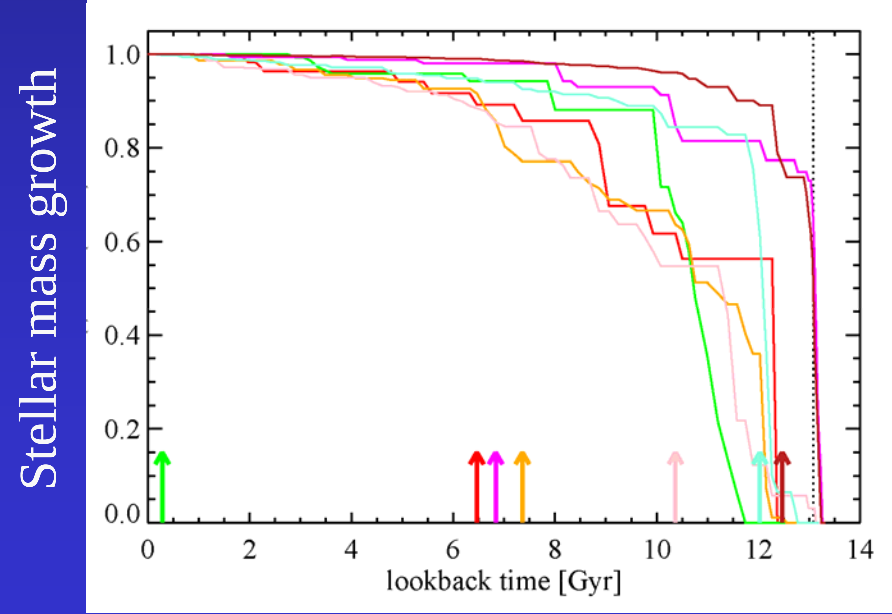
  - not a common mass halo... but a mass scale below which no stars form
  - results in a large scatter in the properties above this scale

Satellites in ΛCDM: histories

- Brightest satellites
  (-16 < M_V < -13):
  - cross virial radius at z < 1
  - 50% of stars younger than 10 Gyr

- Low to intermediate luminosity
  (-8 < M_V < -10)
  - infall biased to z > 1 (upto very high redshifts)
  - 50% of stars older than 12 Gyr
    - very few objects formed > 50% stars around reionization epoch
    - More "fossil-like" (Kravtsov et al)



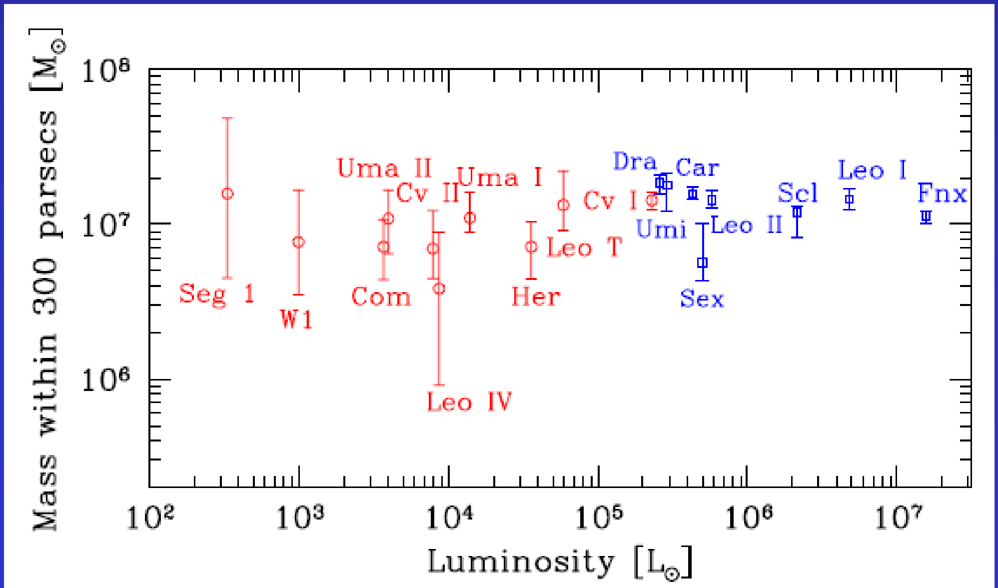


Li et al in prep

The common mass scale of the dSph

- dSph have similar masses in innermost region: M(r<300 pc) ~ 10^7 Msun
  - Also 600 pc if the classical dwarfs are considered
  - 5 orders of magnitude in luminosity vs 1 order of magnitude scatter in mass

- Possible explanations:
  - Dark matter does not cluster with M < 10^7 Msun (not cold?)
  - Astrophysical mechanism preventing the formation of stars in small objects



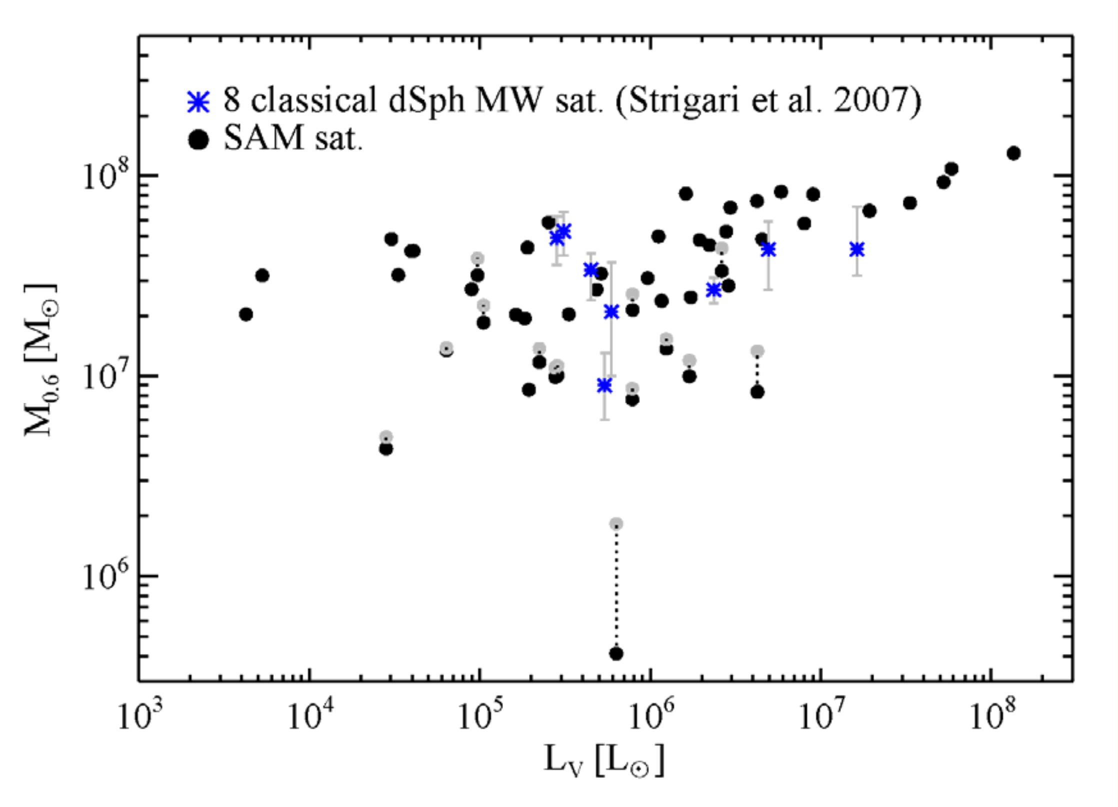
Strigari et al 2008

Does LCDM predict a common mass scale?

- We measure M(r<600pc) for our satellites
  - 600 pc ~ 4 * Softening
  - Typically > 400 particles in this region (so generally well-resolved)

- Most of the satellites have M(r < 600 pc) in the range observed

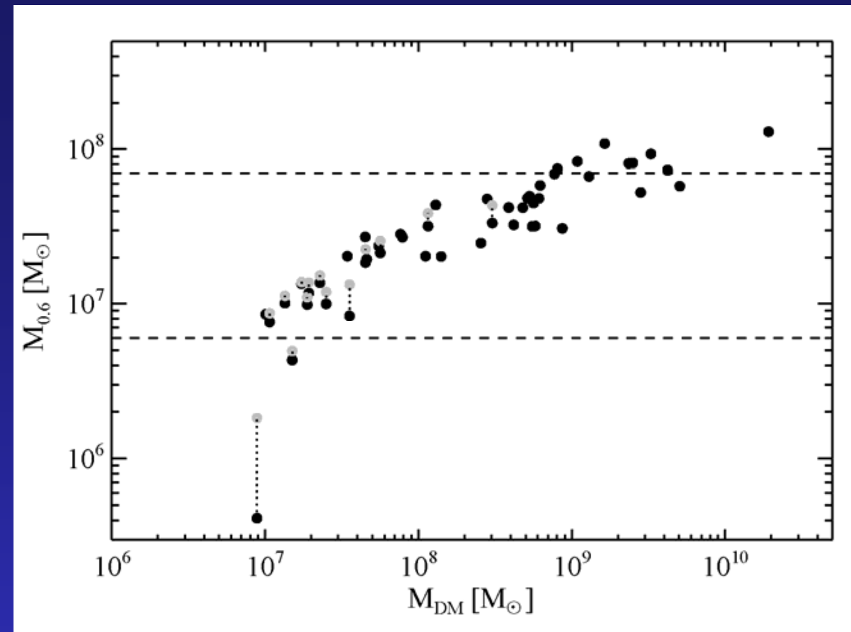
- Factor 10 spread in innermost mass, a factor 10^5 in luminosity!

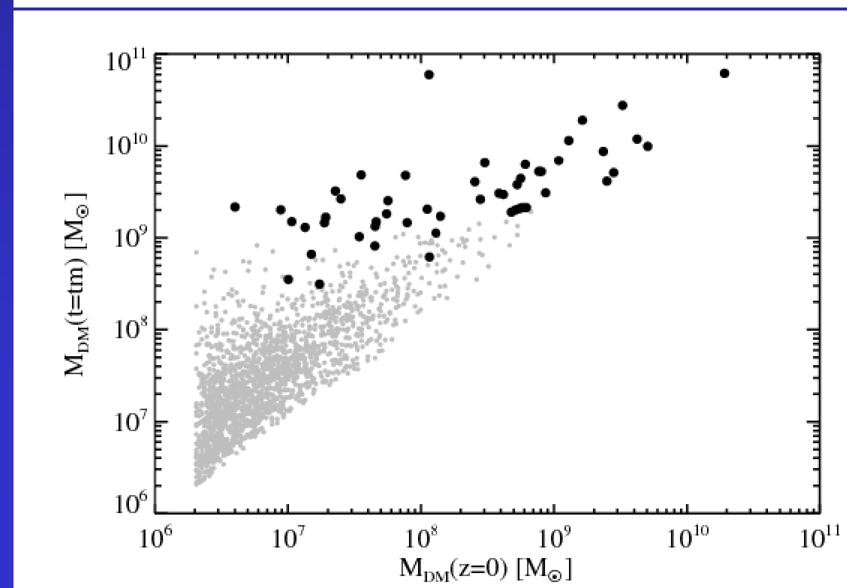


Li, Helmi & de Lucia 2008

Do satellites have the same total mass?

- Large range in present-day total dark matter mass
  - factor 5 x 10^3
- Weak correlation: lightest have also the smallest innermost mass
- There is a minimum mass scale at time of accretion
- Large range in maximum mass (or mass at the time of accretion)
  - factor 5 x 10^2
  - Objects do not all have the same characteristic mass of 10^9 Msun





Li, Helmi & de Lucia 2008

Summary: Satellites in LCDM

- SA model (without fine tuning) produces right luminosity and metallicity distributions
  - Coupling between dynamical history and star formation/chemical enrichment:
    - luminous satellites are typically accreted later and are on average younger and metal-rich
    - fainter satellites are accreted earlier ($z > 1$), are dominated by old populations and are more metal-poor

- We recover the common-mass scale found for dSph
  - But satellites do not live in a common mass-halo
    - stars only form in halos with $T > 10^4$ K (at $z = 10$ -> $M > 10^8\ M_\odot$)
    - threshold results large variety of properties around this scale

Summary and Outlook

- Hybrid approach rather successful in reproducing properties of the Milky Way and satellites
- Useful to gain insight into the physical processes at play, and the origin of correlations (halo dichotomy, bright vs faint satellites…)
- Future:
  - Implement chemical evolution in detail: follow enrichment histories
  - Detailed comparisons between progenitors of the stellar halo and satellites
  - Substructure: quantification/development of methods for identification/comparison to observations