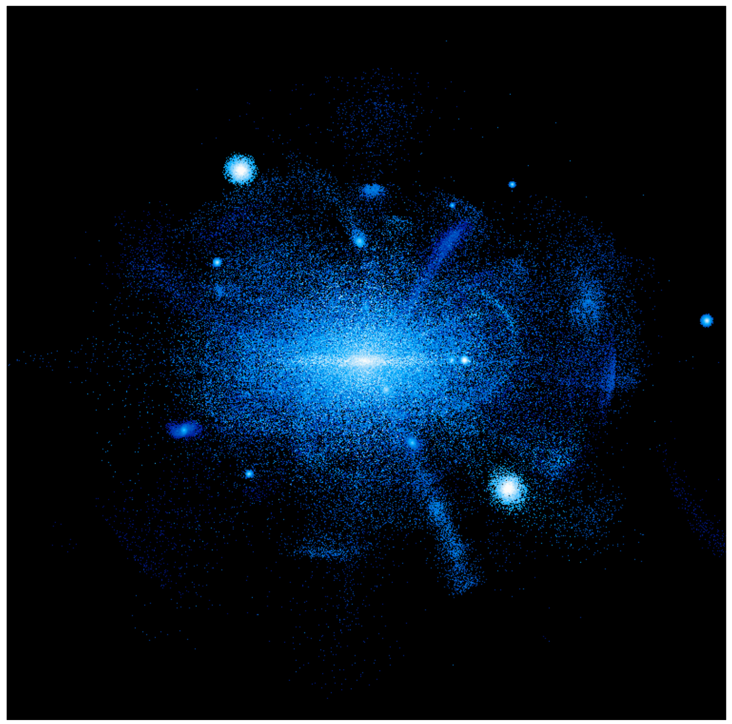
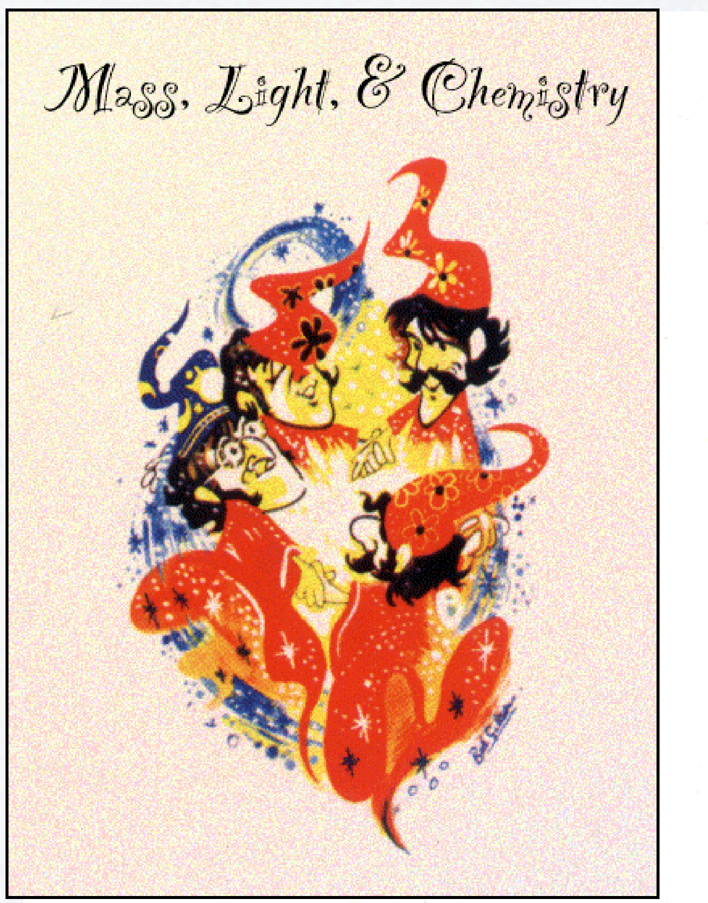


Stellar Halos in a Cosmological Context

James Bullock

CENTER FOR COSMOLOGY

UNIVERSITY OF CALIFORNIA, IRVINE



Probing Early Structure Formation with
Mass, Light & Chemistry
October 9, 2005

WILLIAM I. FINE
THEORETICAL PHYSICS INSTITUTE

Collaborators:

- **Kathryn Johnston** (Wesleyan)
- Andreea Font (Wesleyan)
- Brant Robertson (Harvard)
- Chris Purcell (UC Irvine)

JSB & Johnston 05 (astro-ph/0506467)
Robertson et al. 05; Font et al. 05

LCDM and stellar halos

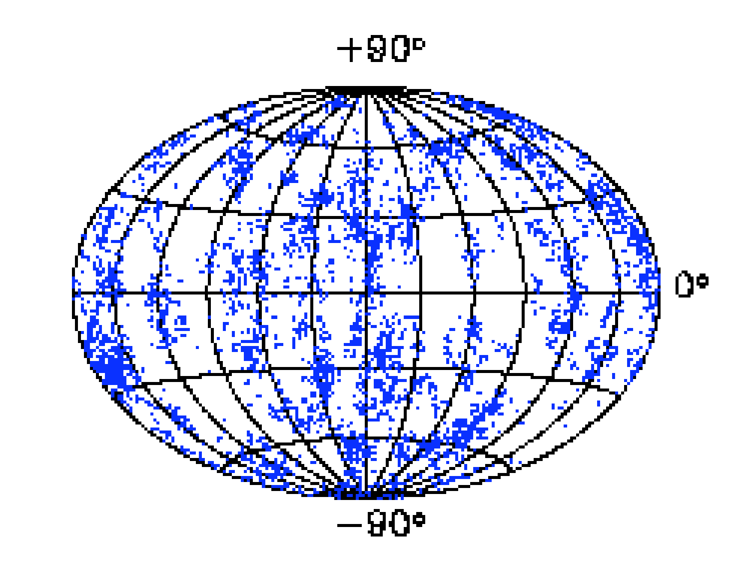
Hierarchical structure formation leads to idea that stellar halos formed from accreted, disrupted galaxies (~Searle & Zinn).
Stellar halo studies provide means to:

- Measure accretion rates: Stellar streams around galaxies
- Probe Early Star formation: Chemical abundance patterns.
- Test small-scale manifestations of CDM: Substructure counts

JSB, Kravtsov & Weinberg 01

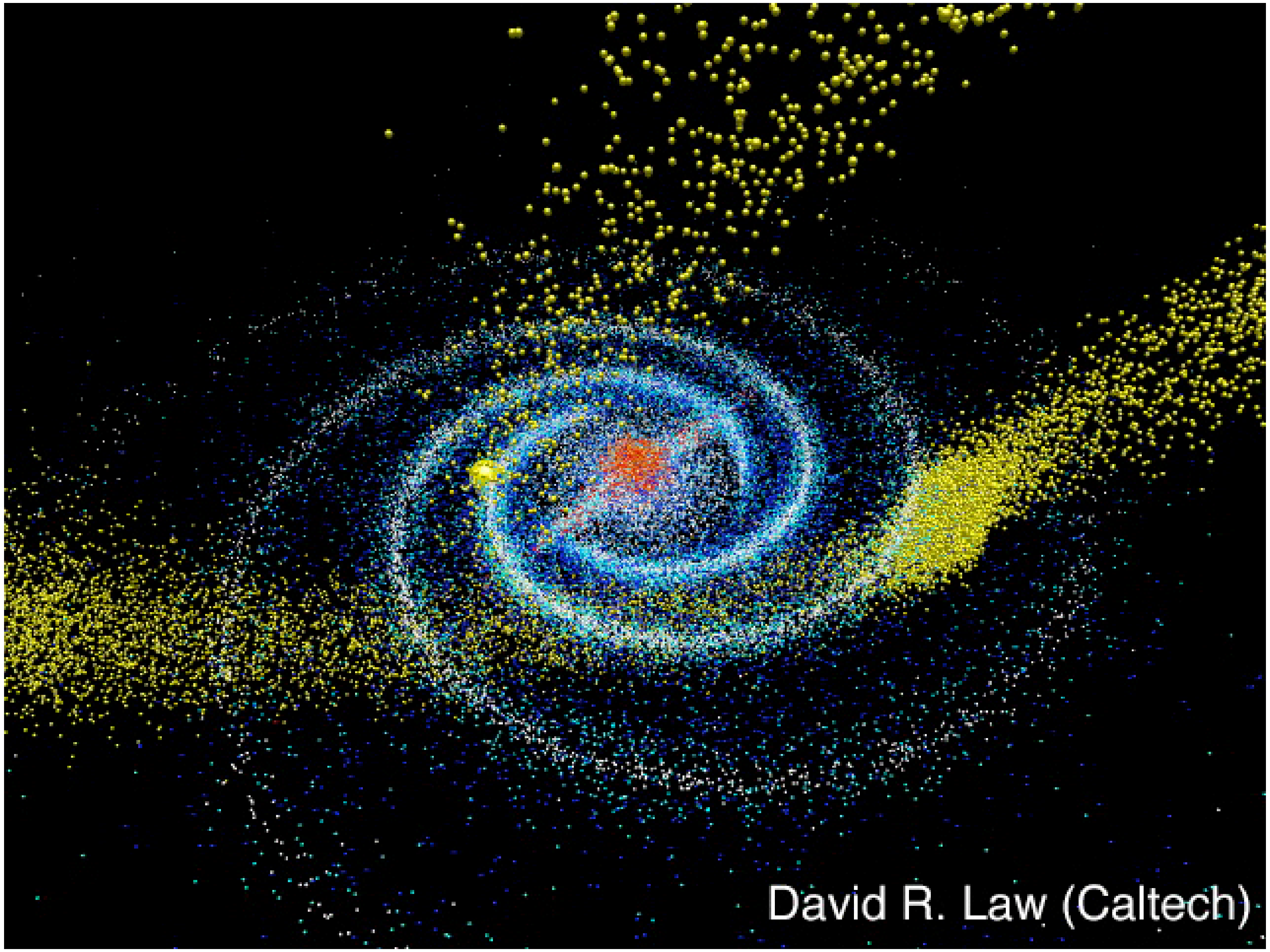
Johnston et al. 96, Helmi et al. 99

Talks byTumlinson, Mayer



Uncovering structures in the Milky Way halo...

Movie from Majewski's group:



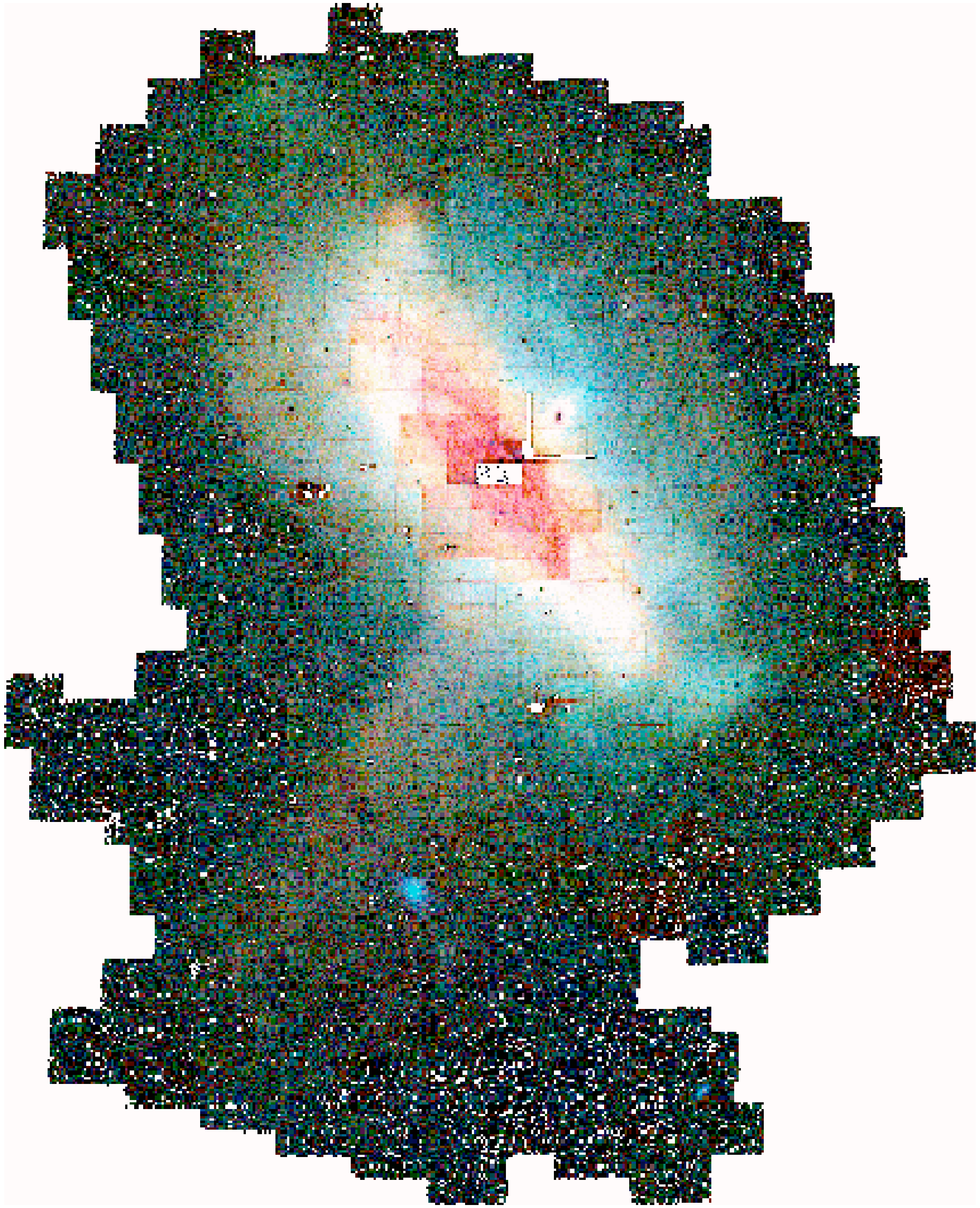
Majewski et al.

Yanny et al. 01
Newberg et al. 02
Majewski et al. 03
Ivezic et al. 01
Crane et al. 03
Frinchaboy et al. 04

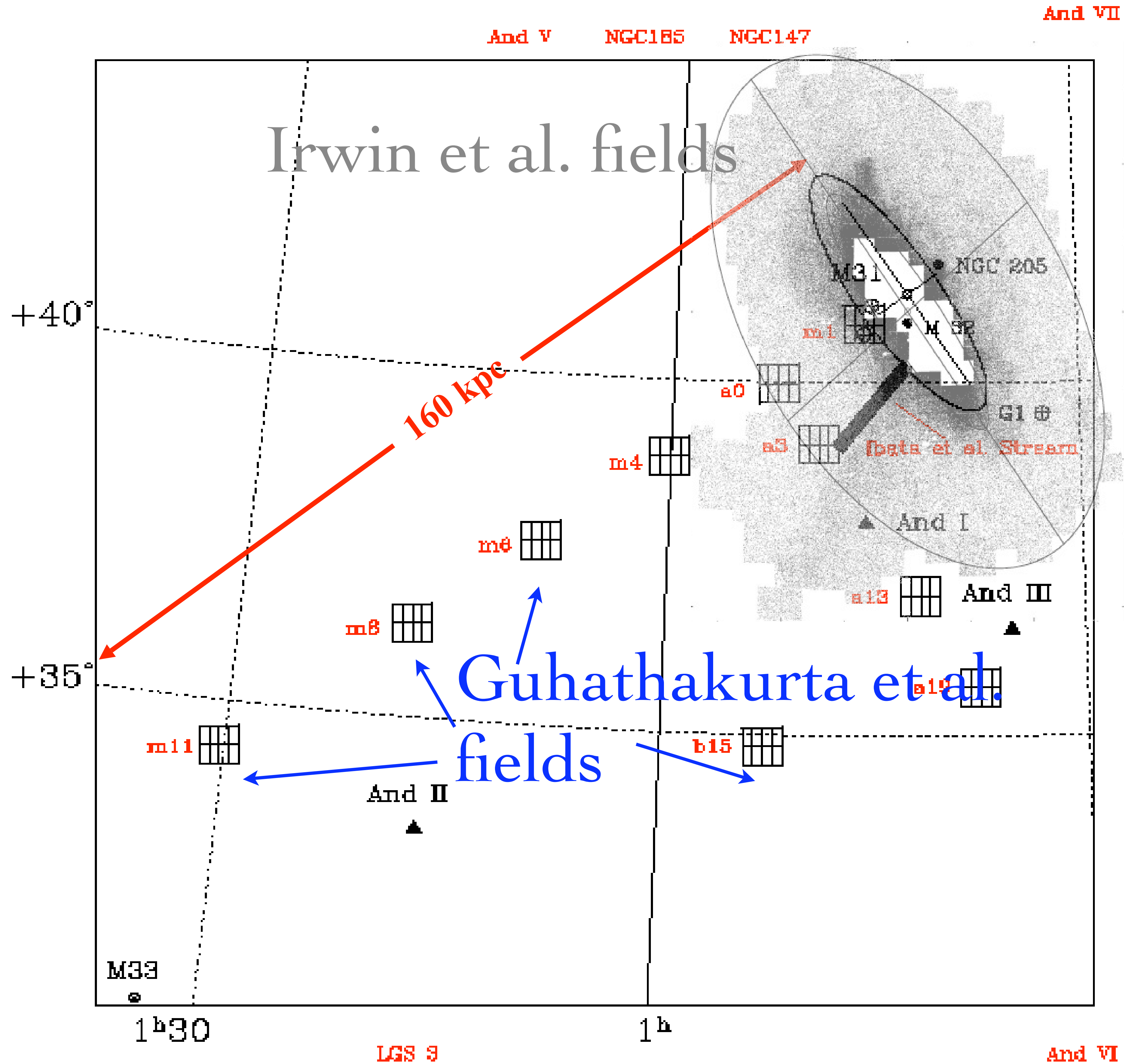
<u>Future is Bright</u>:
SEGUE
WFMOS
GAIA, SIM ...

Other Galaxies
Andromeda: spatial & metallicity structure

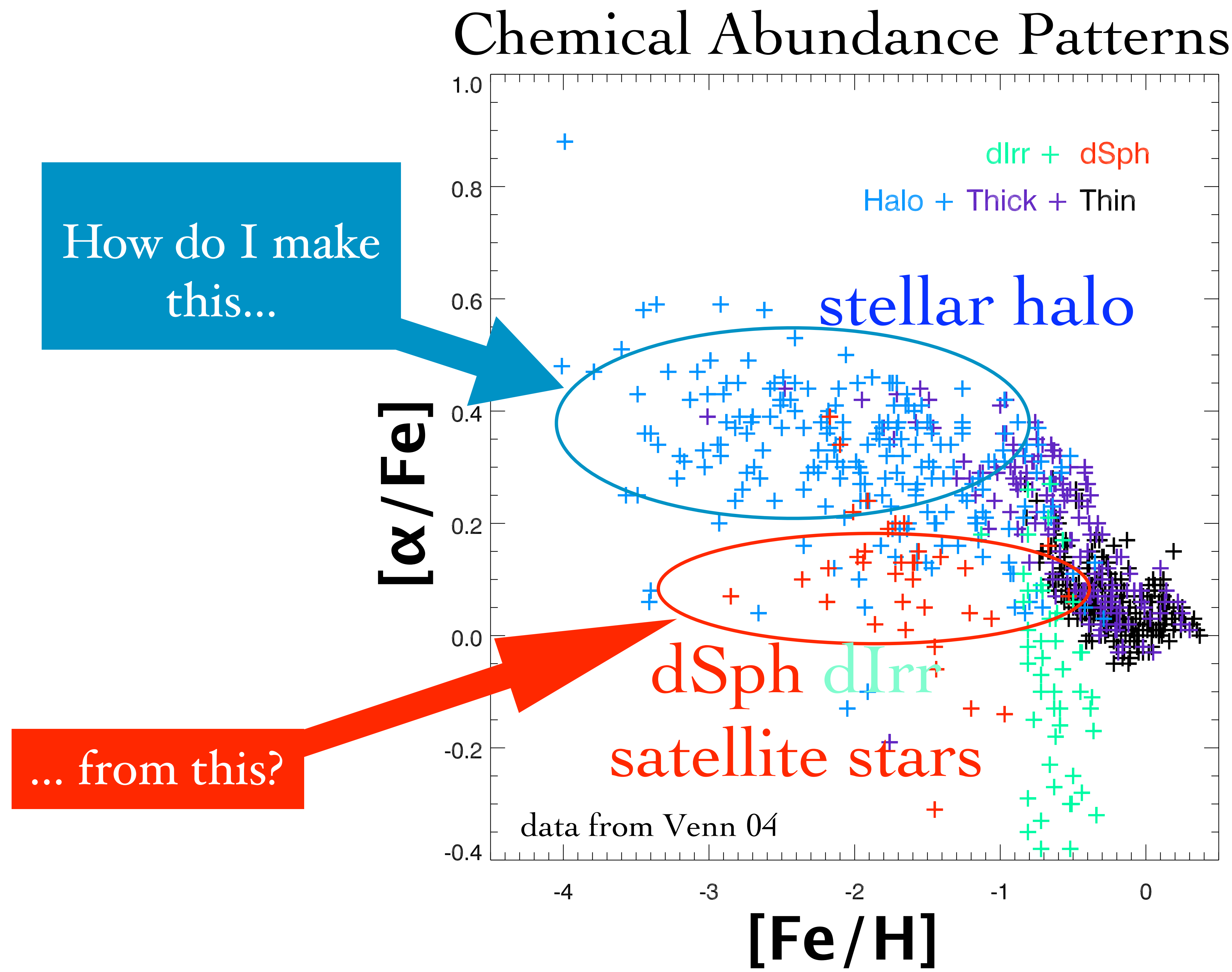
Irwin et al. 05



Ibata et al. 01
Ferguson et al. 02
Merret et al. 03
Zucker et al. 04
Reitzel et al. 04
Chapman et al. 05


And VII
And V
NGC185
NGC147
Irwin et al. fields
+40°
+35°
160 kpc
M31
NGC 205
M 32
G1
Ibata et al. Stream
m1
a0
a3
m4
m6
m8
m11
a13
b15
And I
And III
And II
M33
Guhathakurta et al. fields
1h30
1h
LGS 3
And VI

Often discussed: problem with the hierarchical picture…



Lots of discussion in the literature:
Unavane et al (1996)
Nissen & Schuster (1997)
Gilmore & Wyse (1998)
Shetrone et al. (2001)
Fulbright (2002)
Shetrone et al. (2003)
Tolstoy et al. (2003)
Venn et a. (2004)

Allgood et al. 05

Hierarchical Structure Formation

LCDM simulation:

uses ART code
Kravtsov et al. 97

$20h^{-1}$Mpc Sphere within 120 h^{-1}Mpc box.

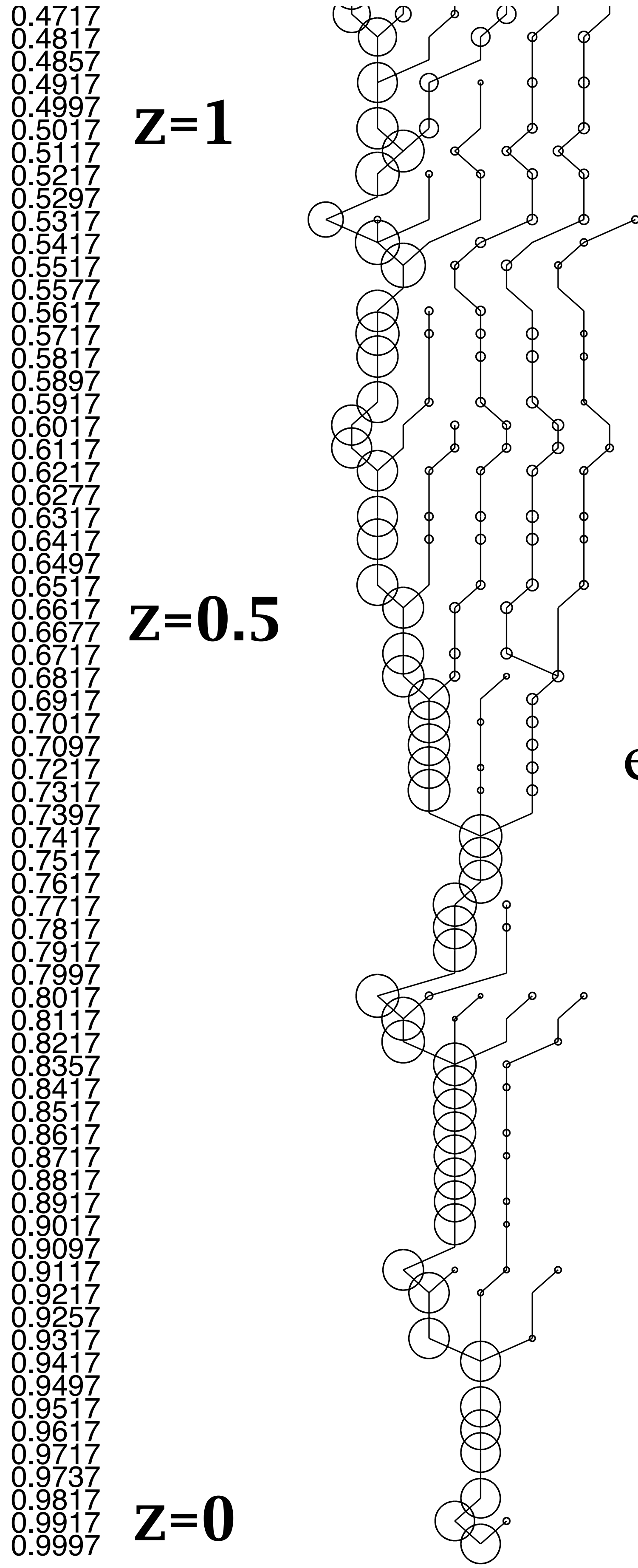
m_p = 10^8 Msun

$T_{lookback}$(Gyr)=13.3960

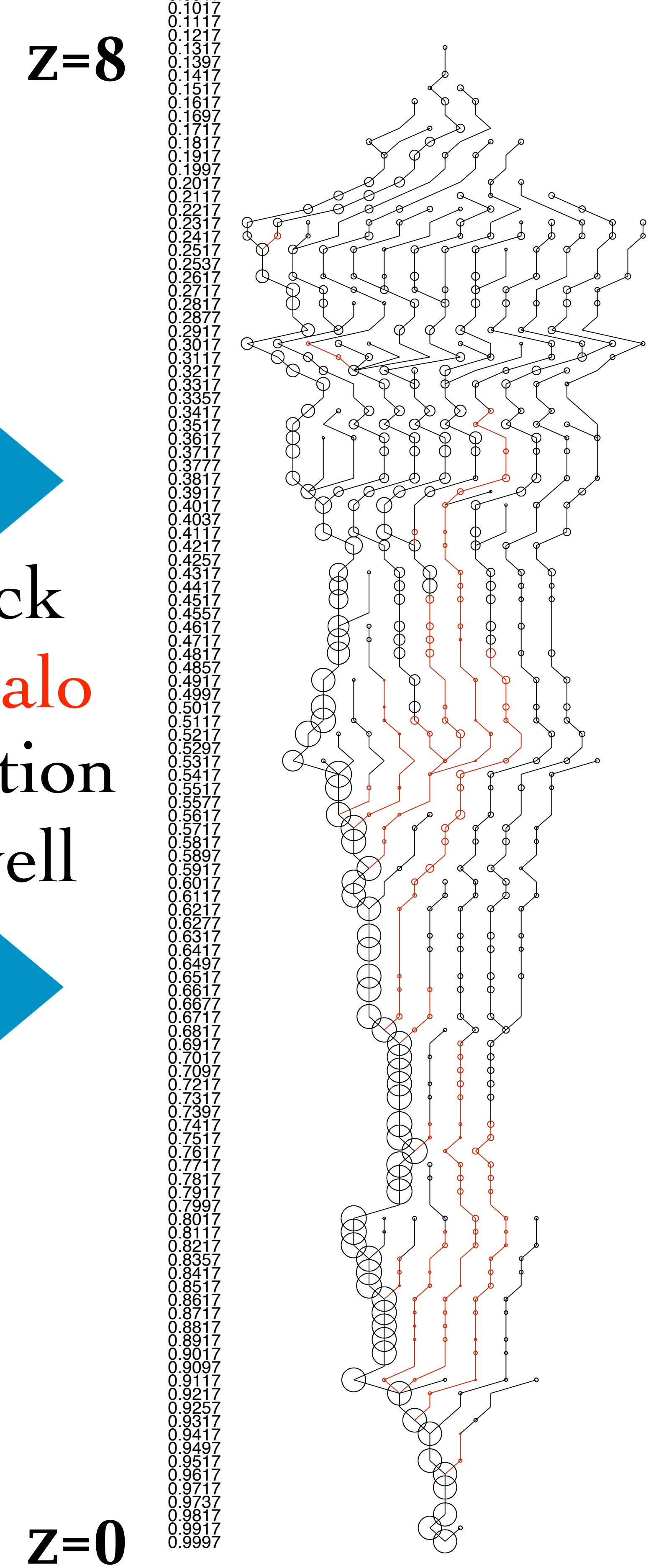
Mass accretion histories for N-body dark matter halos are now robustly predicted and well characterized

Allgood et al. in prep.

expansion factor →



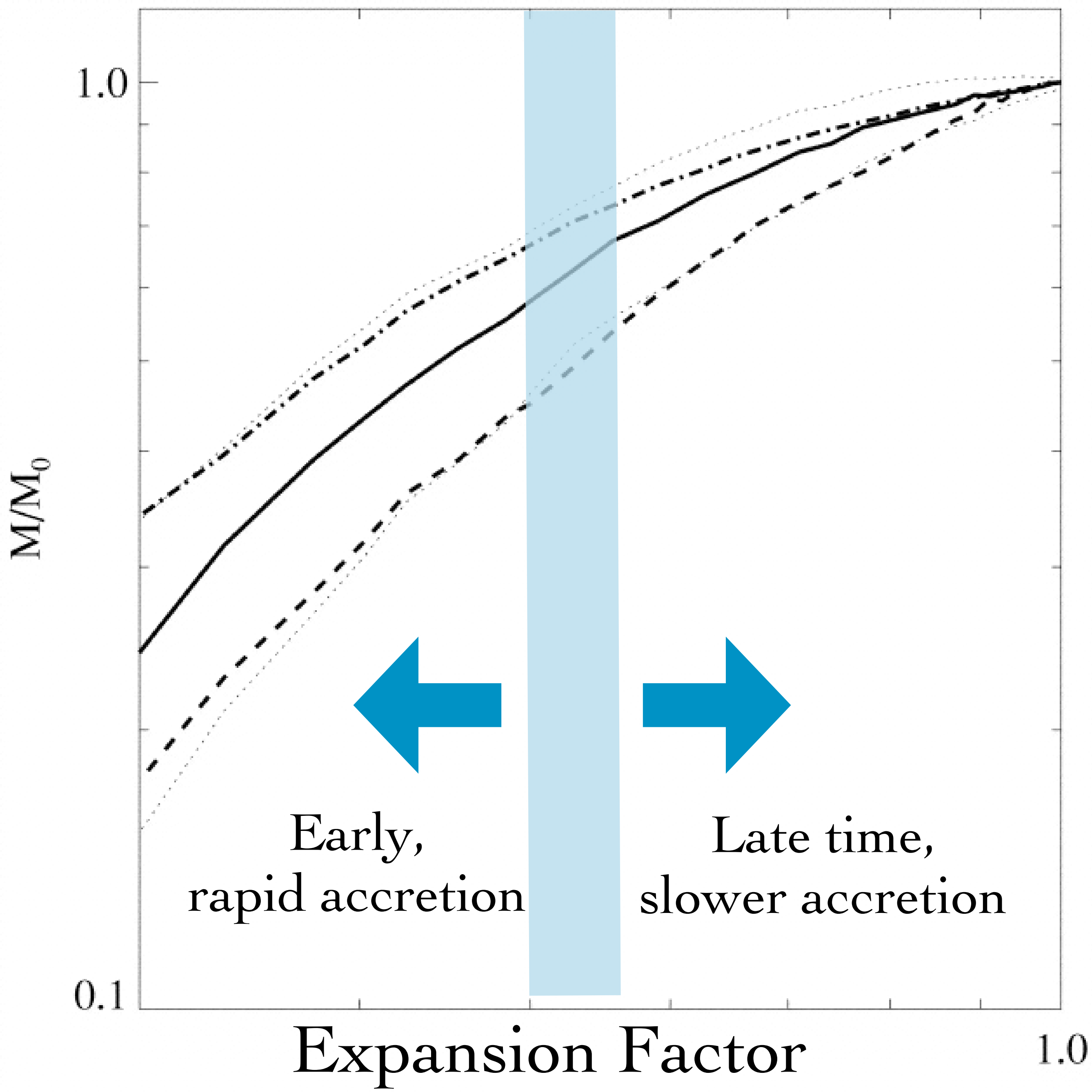
Track subhalo evolution as well



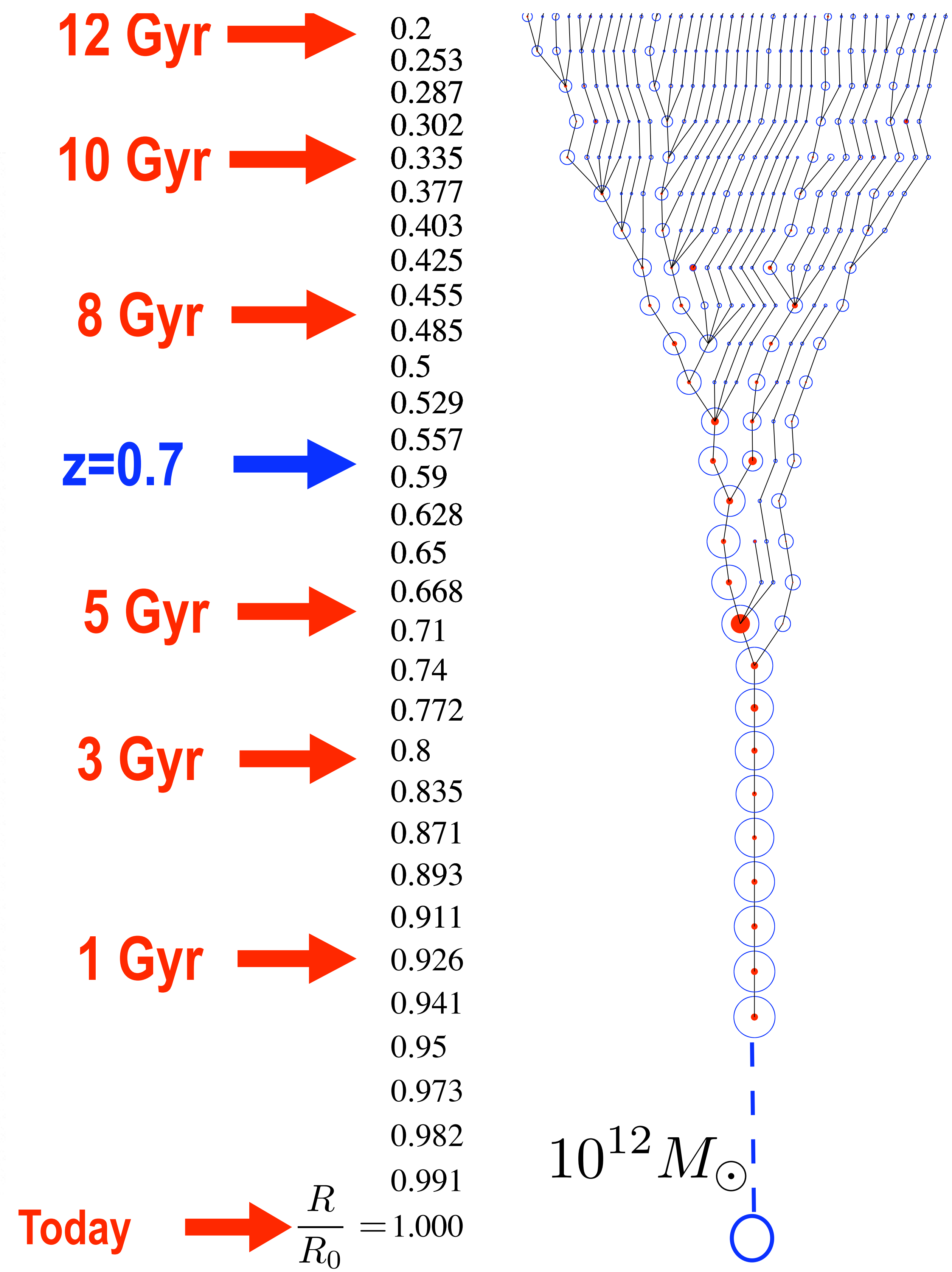
Universal Mass Accretion History for DM Halos

$$M_{\rm DM} = M_0 e^{-\alpha z}$$

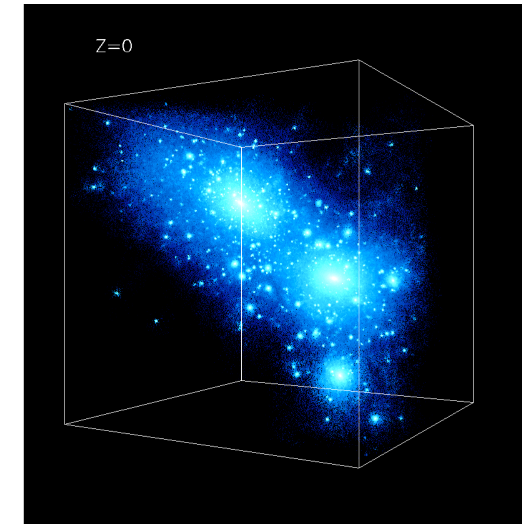
Wechsler, JSB, Primack, Kravtsov, & Dekel 02



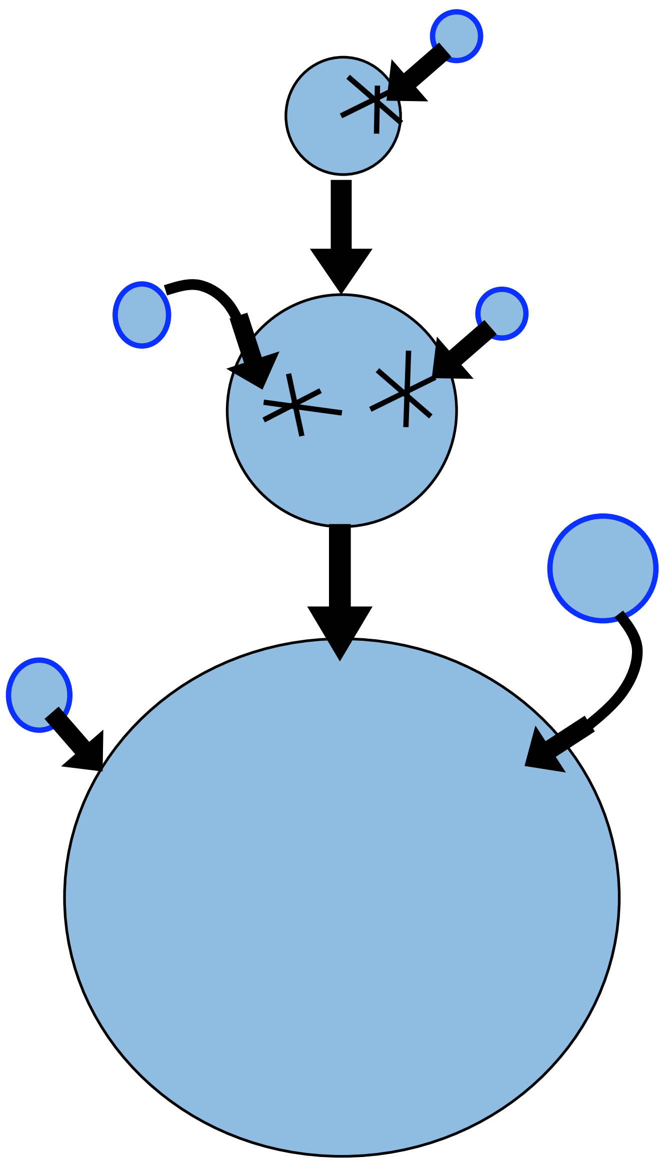
N-body merger tree



How do dark matter halos grow?



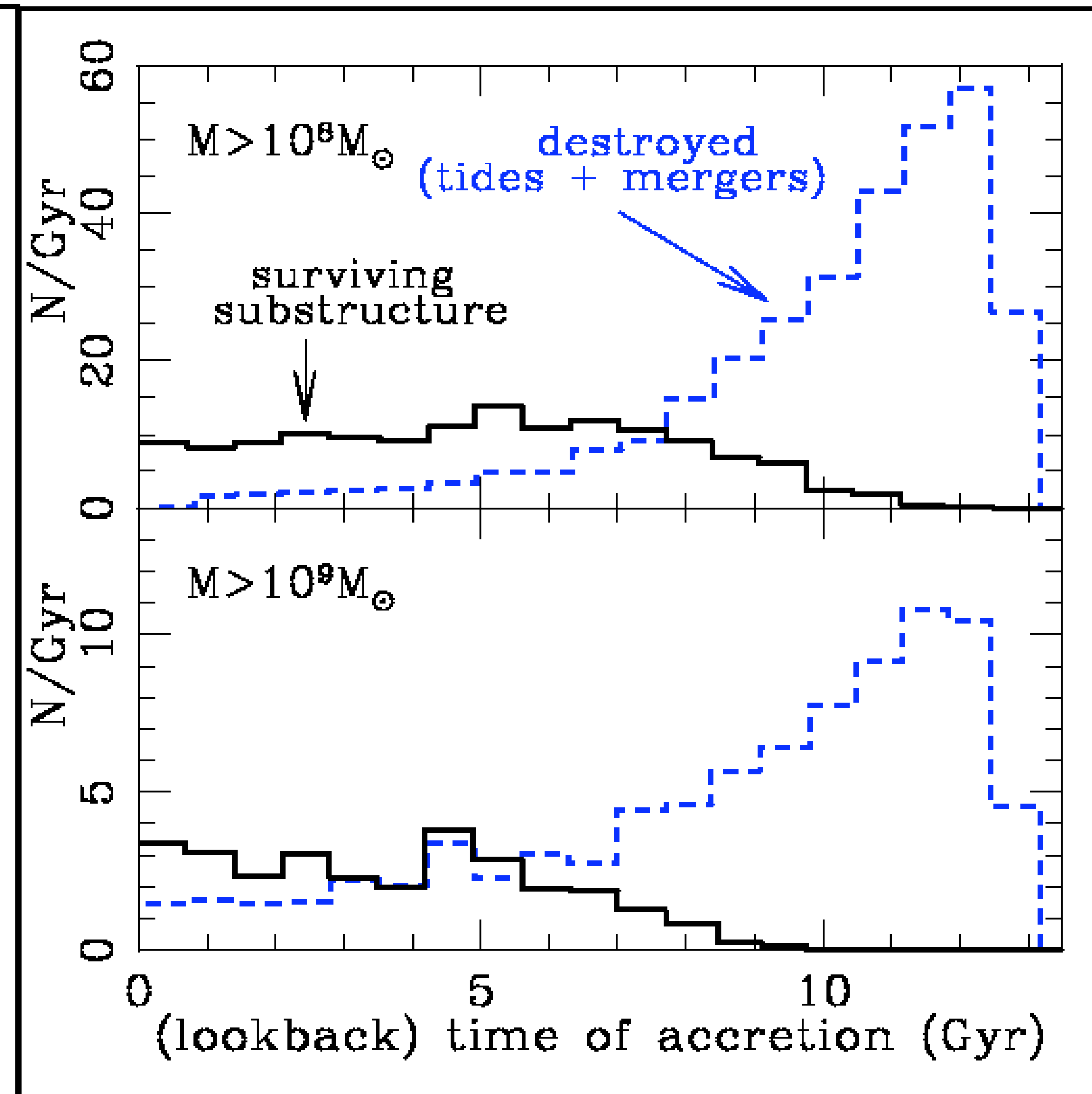
1. Accrete Smaller Systems
2. Destroy them via tides and mergers
3. Repeat



ZENTNER & JSB 03:

Most accreted subhalos are destroyed.

Destruction is quicker at early times because halos have higher average densities.



Also Zentner et al. 05

Dark Halo Assembly → Stellar Halo Assembly

Galaxy-size Dark Matter Halos: Robust Predictions

1. Most of the mass is accreted in ~10^{11}Msun subhalos (~LMC).
2. Majority of accreted systems are destroyed before z=0.
3. Surviving substructure is biased to be late-accreting objects.

→

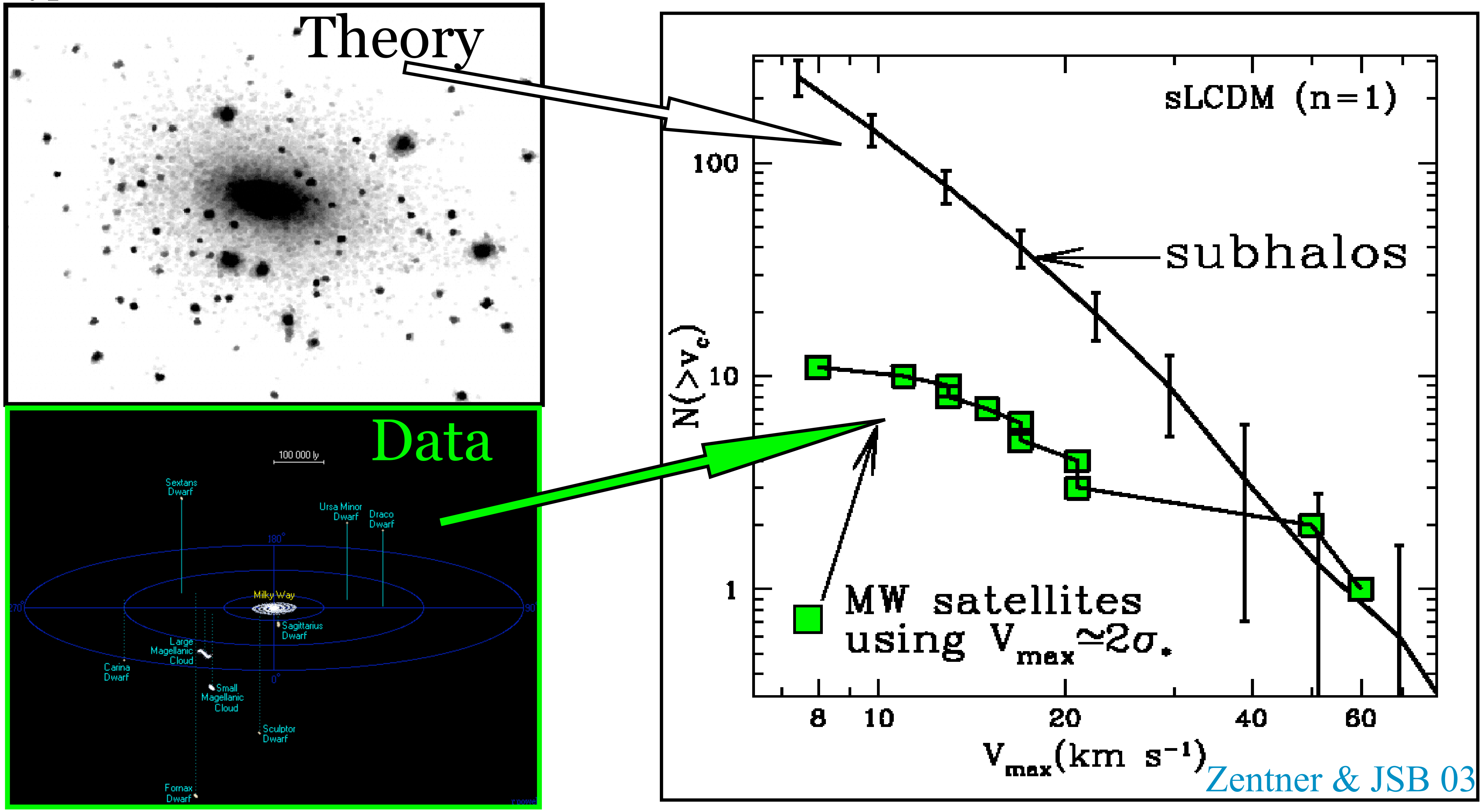
Stellar Halo Formation: Model Requirements

1. Must reproduce counts and characteristics for local group dwarfs.
2. Must reproduce observed stellar halo mass and density $\rho(r)$
3. Chemical abundance trends

The Dwarf Satellite Problem

LCDM predicts rising subhalo velocity function. Not observed for satellites of the Milky Way and Local Group:

Klypin et al. 99; Moore et al. 99



Zentner & JSB 03

What is the Dwarf Problem telling us?

Something about cosmology

-DARK MATTER NOT COLD?
(gravitino = DM?)

Something about astrophysics

-REIONIZATION?
-SUPERNOVA FEEDBACK?
(See Gnedin's Talk)

Stellar Halo Models: Our Method

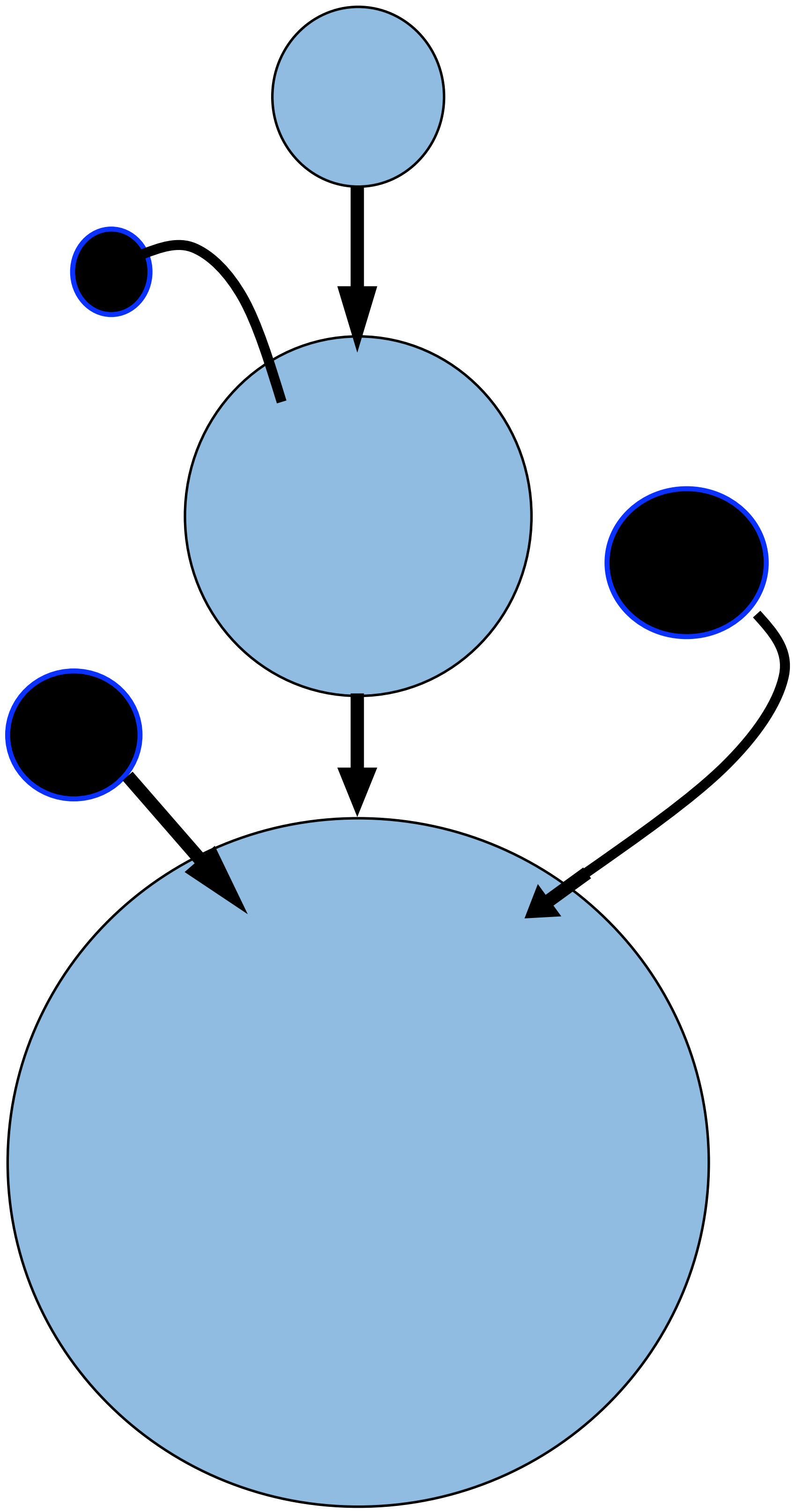
Fully self-consistent cosmological simulations with the dynamic range needed are effectively impossible.

In order to overcome this difficulty, we adopt a hybrid approach:

1. Use a semi-analytic monte-carlo approach to set star formation histories and dynamic initial conditions.

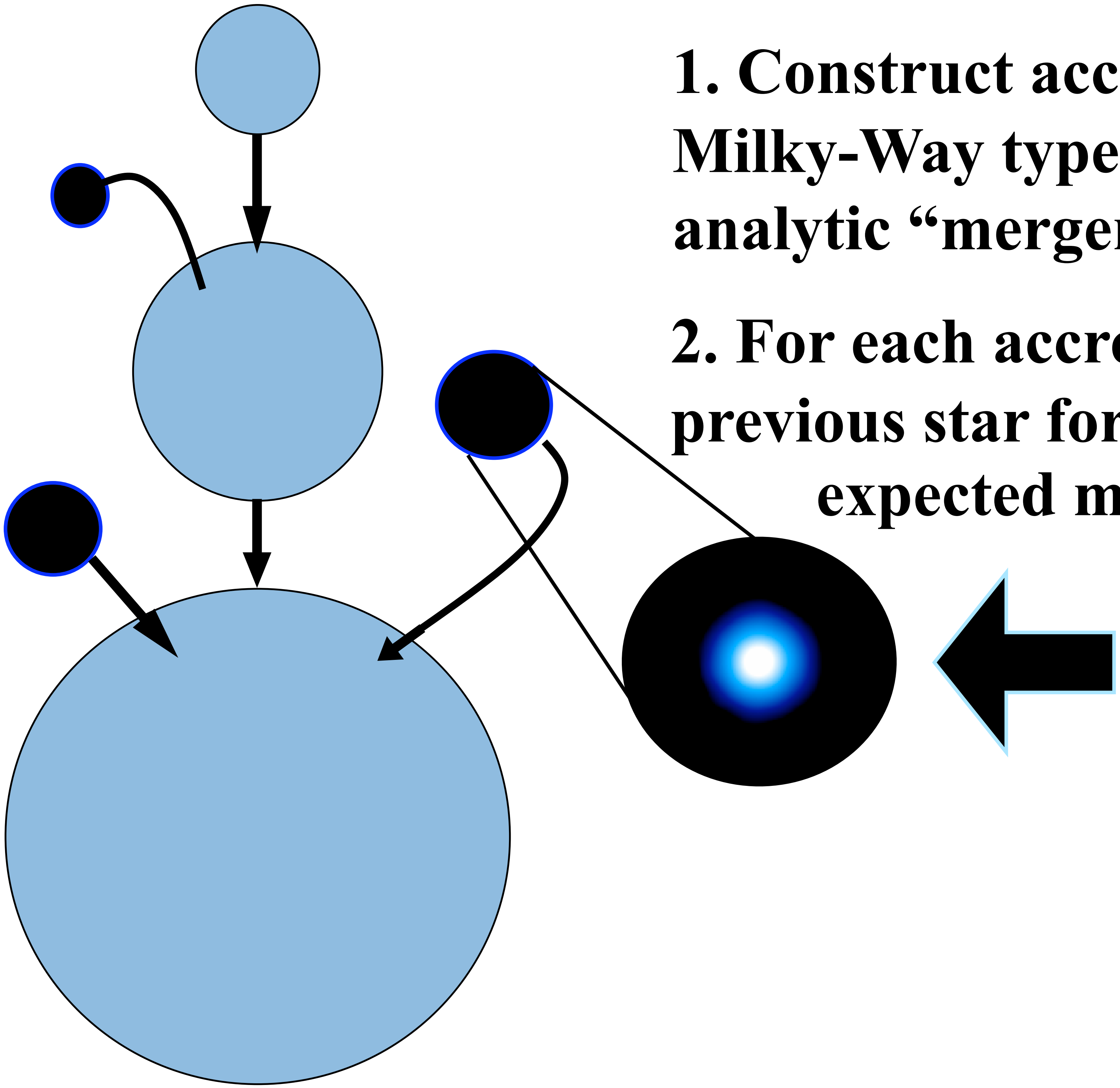
2. Follow dynamics of merging satellites using a fast expansion-based code with 100,000 particles per accretion event.

Our Model/Approach:



1. Construct accretion histories for Milky-Way type halos using semi-analytic “merger tree”.

Our Model/Approach:

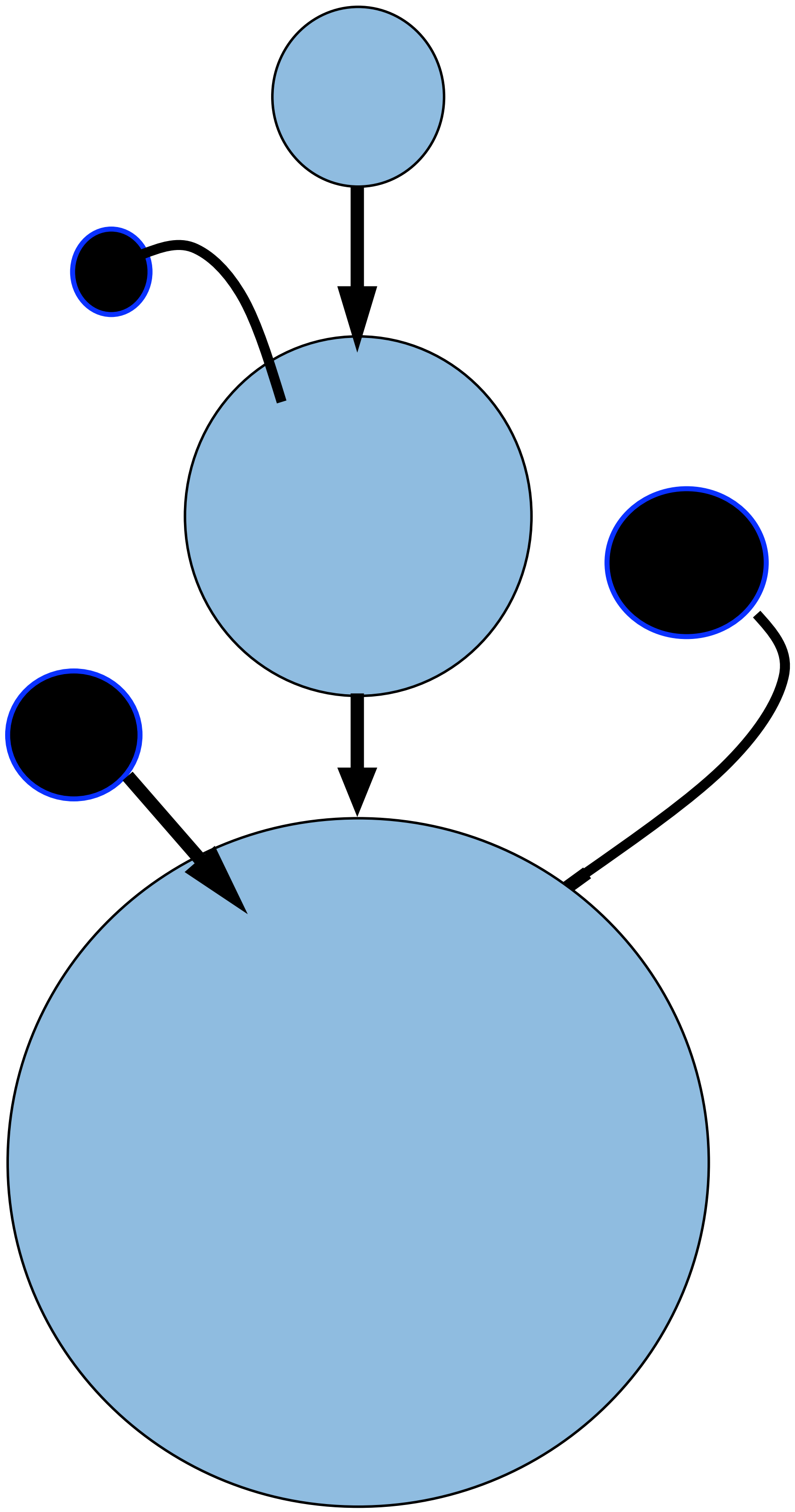


1. Construct accretion histories for Milky-Way type halos using semi-analytic "merger tree".

2. For each accreted system, model its previous star formation history based on expected mass growth history:

$$\dot{M}_* = \frac{M_{\rm gas}}{t_*}$$

Our Model/Approach:



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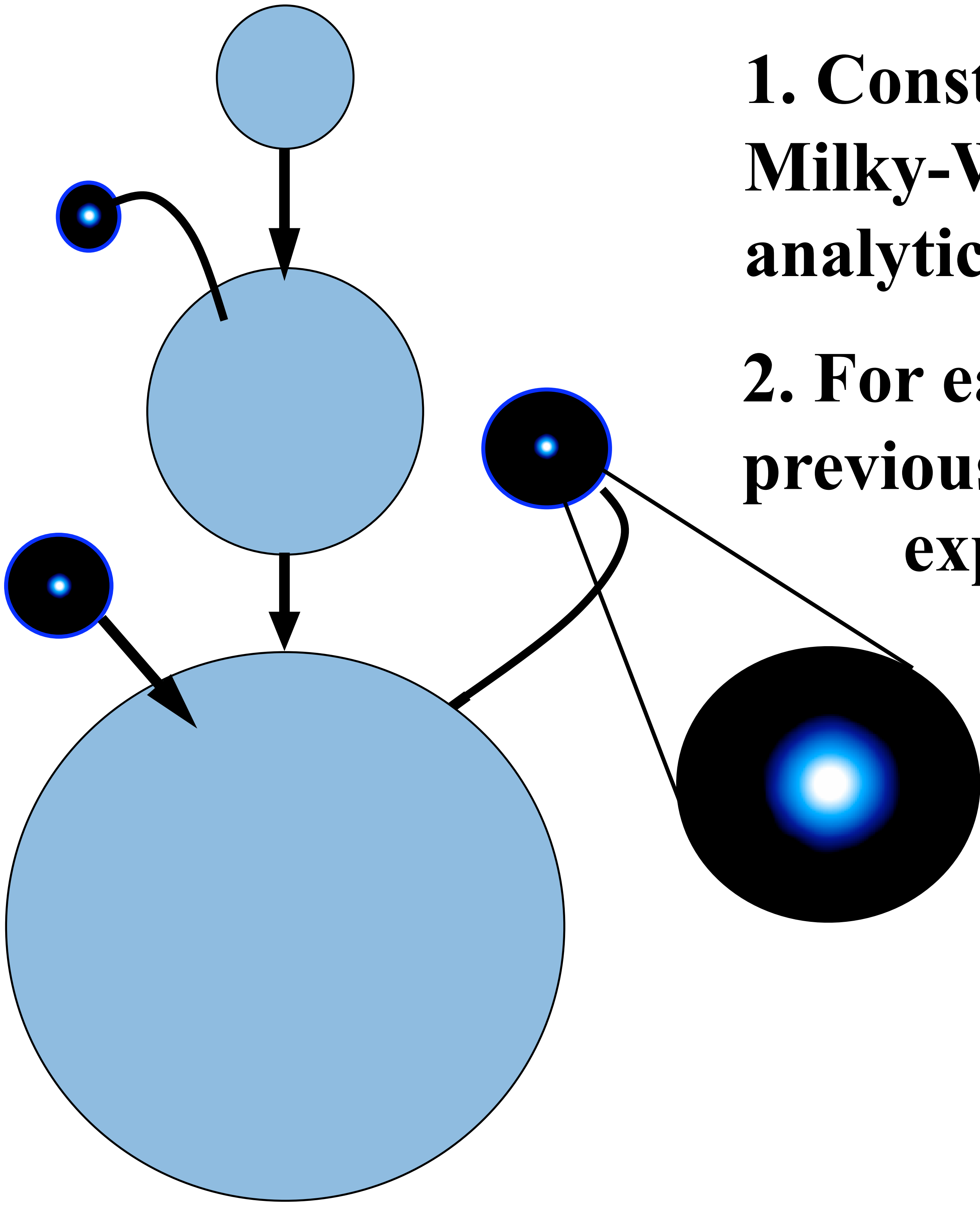
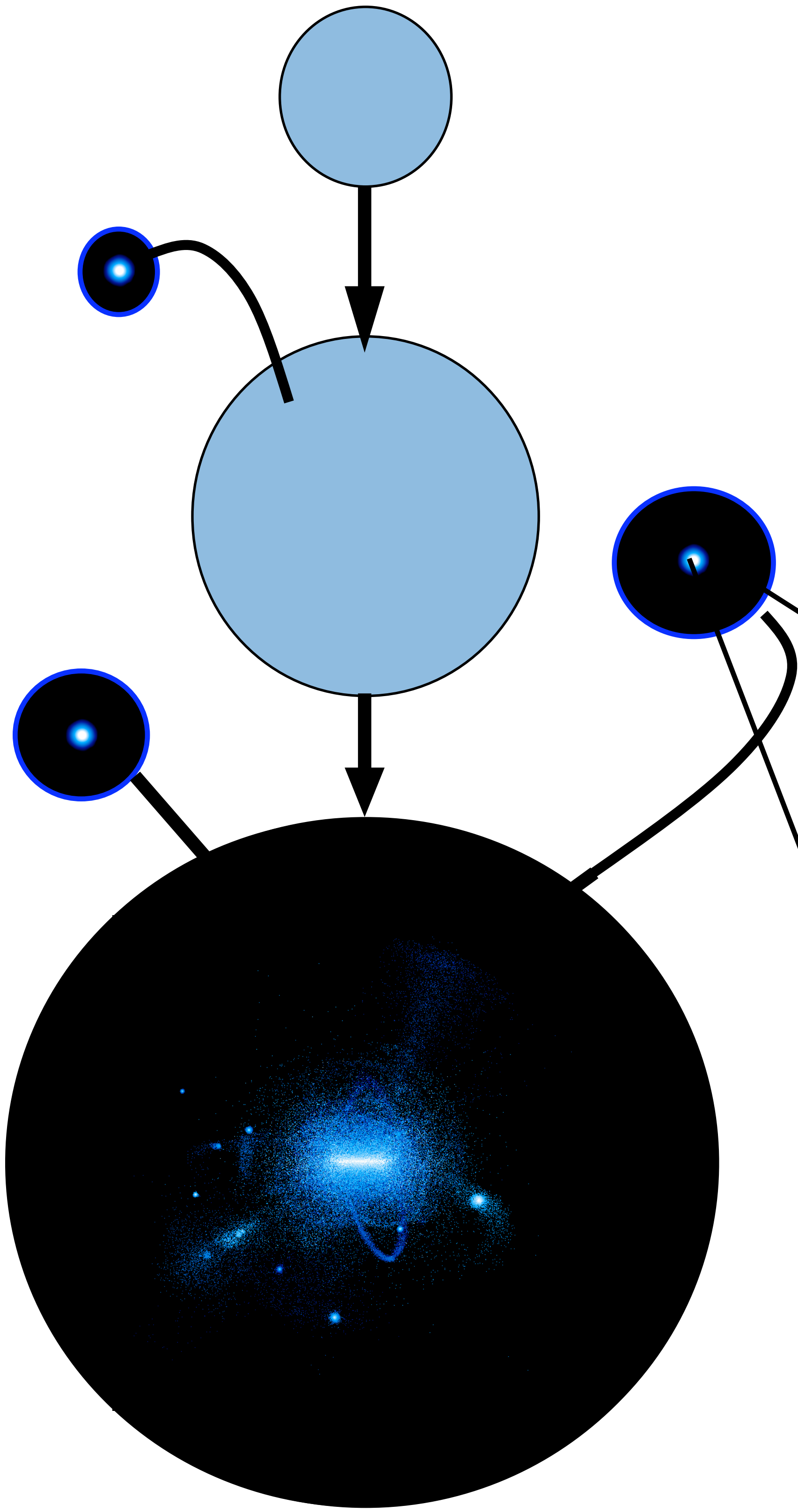


1. Construct accretion histories for Milky-Way type halos using semi-analytic “merger tree”.

2. For each accreted system, model its previous star formation history based on expected mass growth history:

3. Initialize simulations, embed stellar content into the center of accreted dark matter halo to match a realistic galaxy light profile.

Our Model/Approach:



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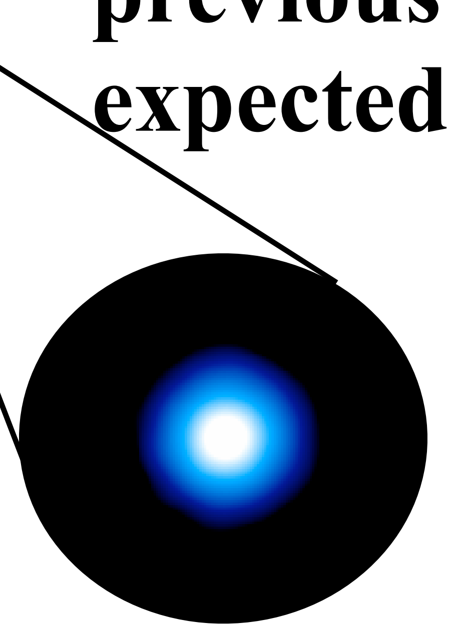


3. Embed stellars in the center of accreted dark matter halo.

4. Follow evolution within the (growing) host halo using basis function expansion code. 100,000 particles per event.

Star formation and feedback in satellites:

Gas / DM mass accretion history: $M_{\rm DM} = M_0 e^{-\alpha z}$

N-body simulations
(Wechsler et. al. 2002)

Star formation law: $\dot{M}_\star \approx \frac{f_{\rm gas} M_{\rm DM}}{t_\star}$

t* = 8Gyr:
Set to match velocity-luminosity relationship for surviving satellites

JSB, Kravtsov, & Weinberg (00)

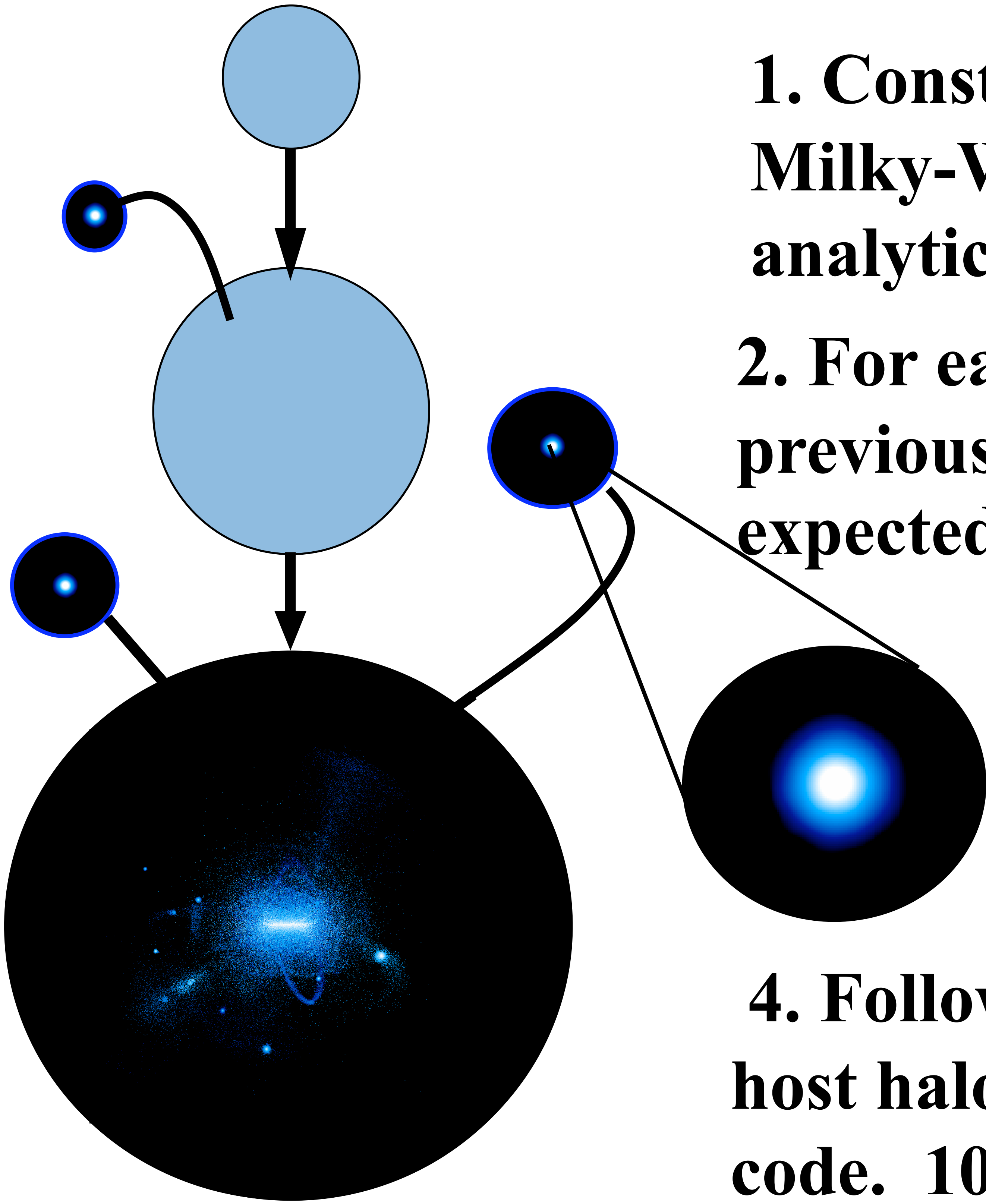
Dwarf halos that formed before reionization retain gas. The rest are dark

Blow-out Feedback Law:

$w \propto V_{\rm max}^{-2}$

Set to match metallicity vs. luminosity relation for local group dwarfs

Our Model/Approach:



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Example Realization:

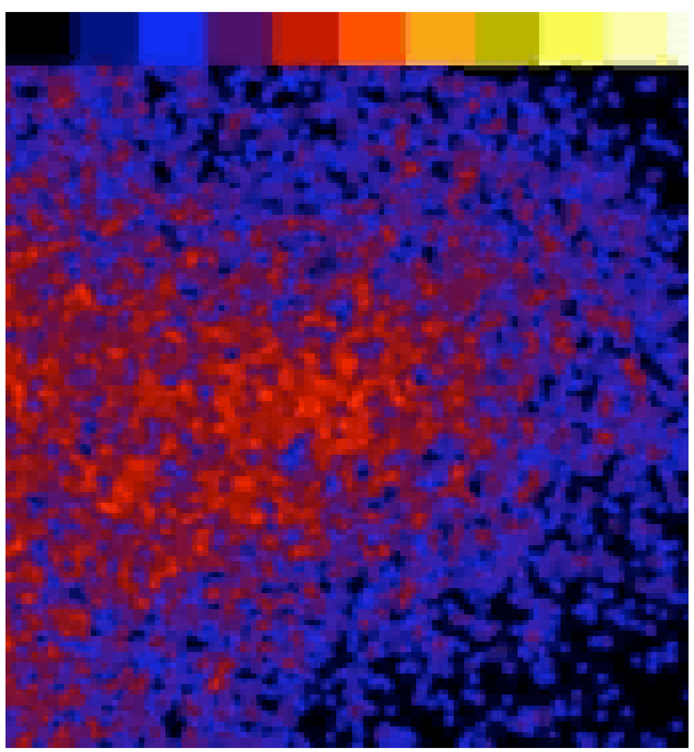
The difference between light and dark matter

Dark Matter Density → Stellar luminosity →

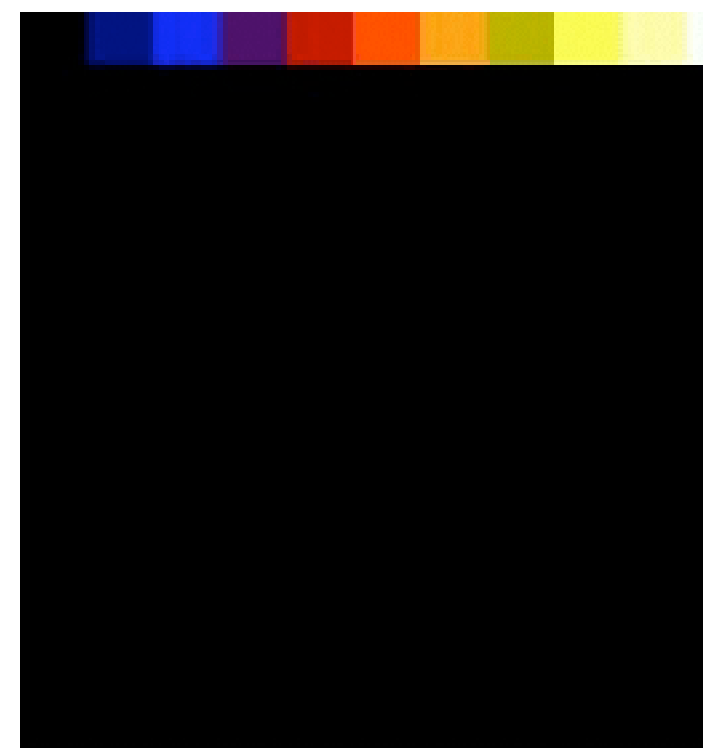
Example Realization:

The difference between light and dark matter

Dark Matter Density



Stellar luminosity



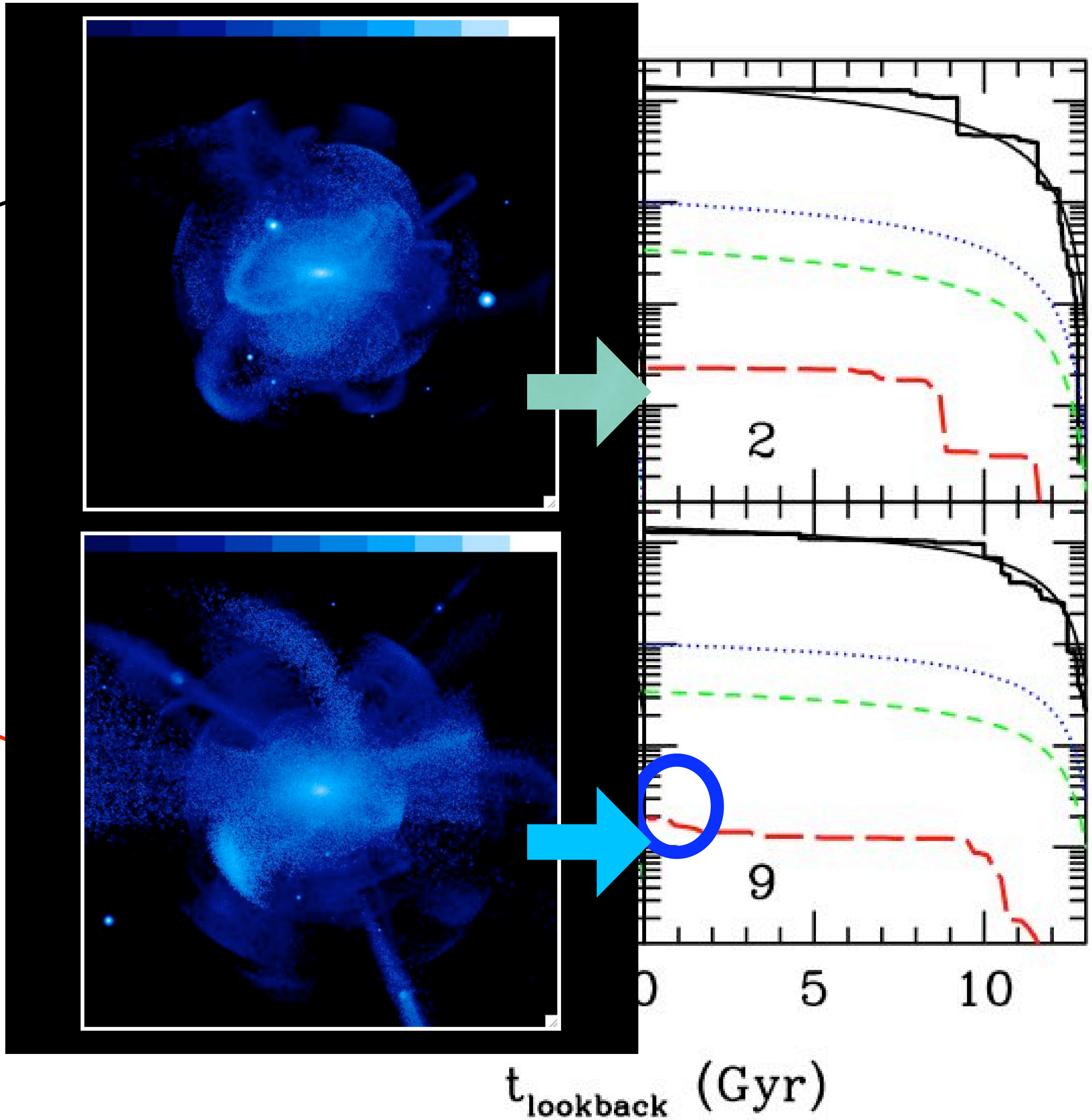
Stars are initially more tightly bound than majority of dark matter -> tight streamer structure...

Example Mass Accretion Histories

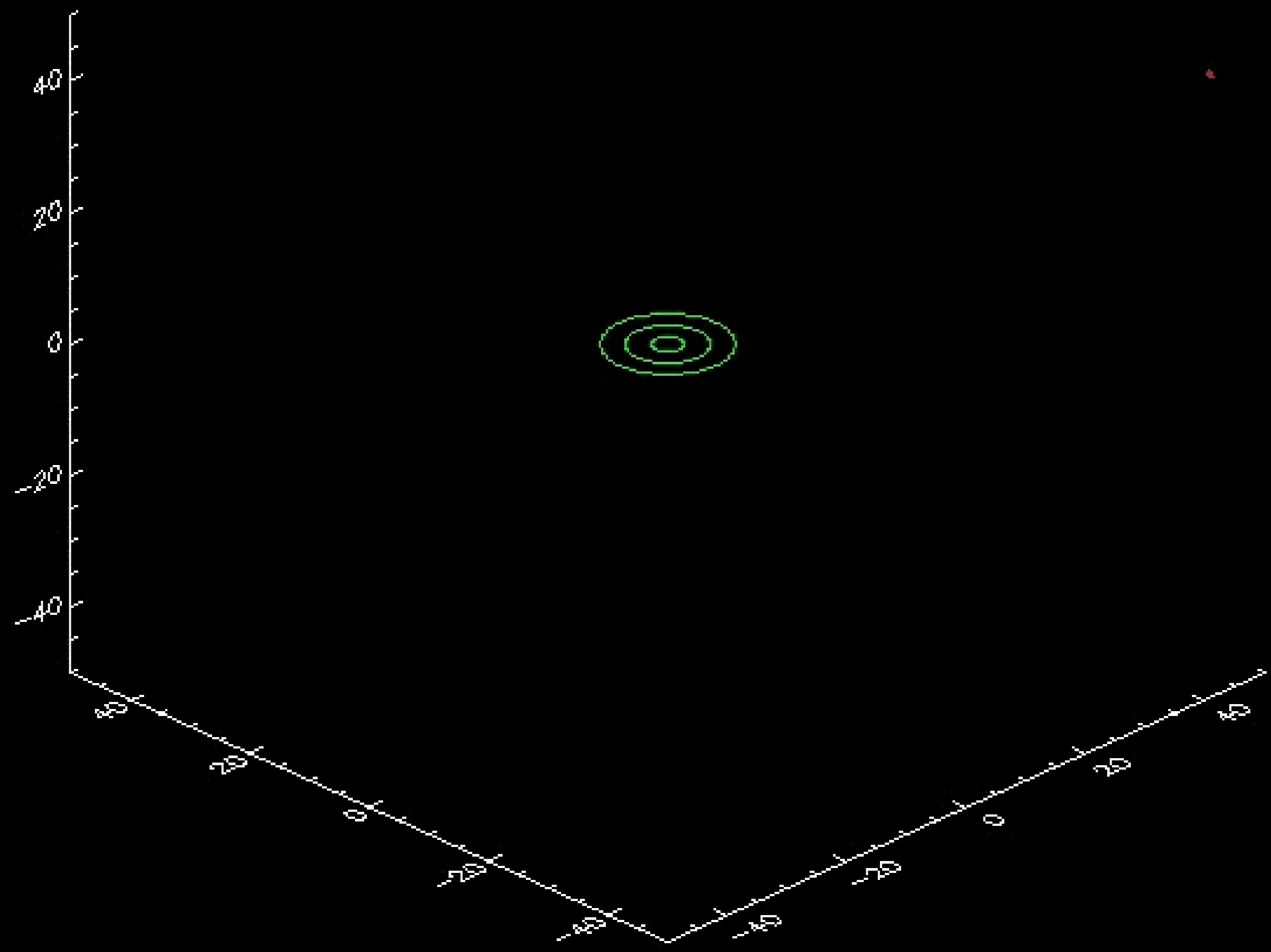
Dark Matter Halo

Disk
Bulge

Stellar Halo
(Accreted stellar material)



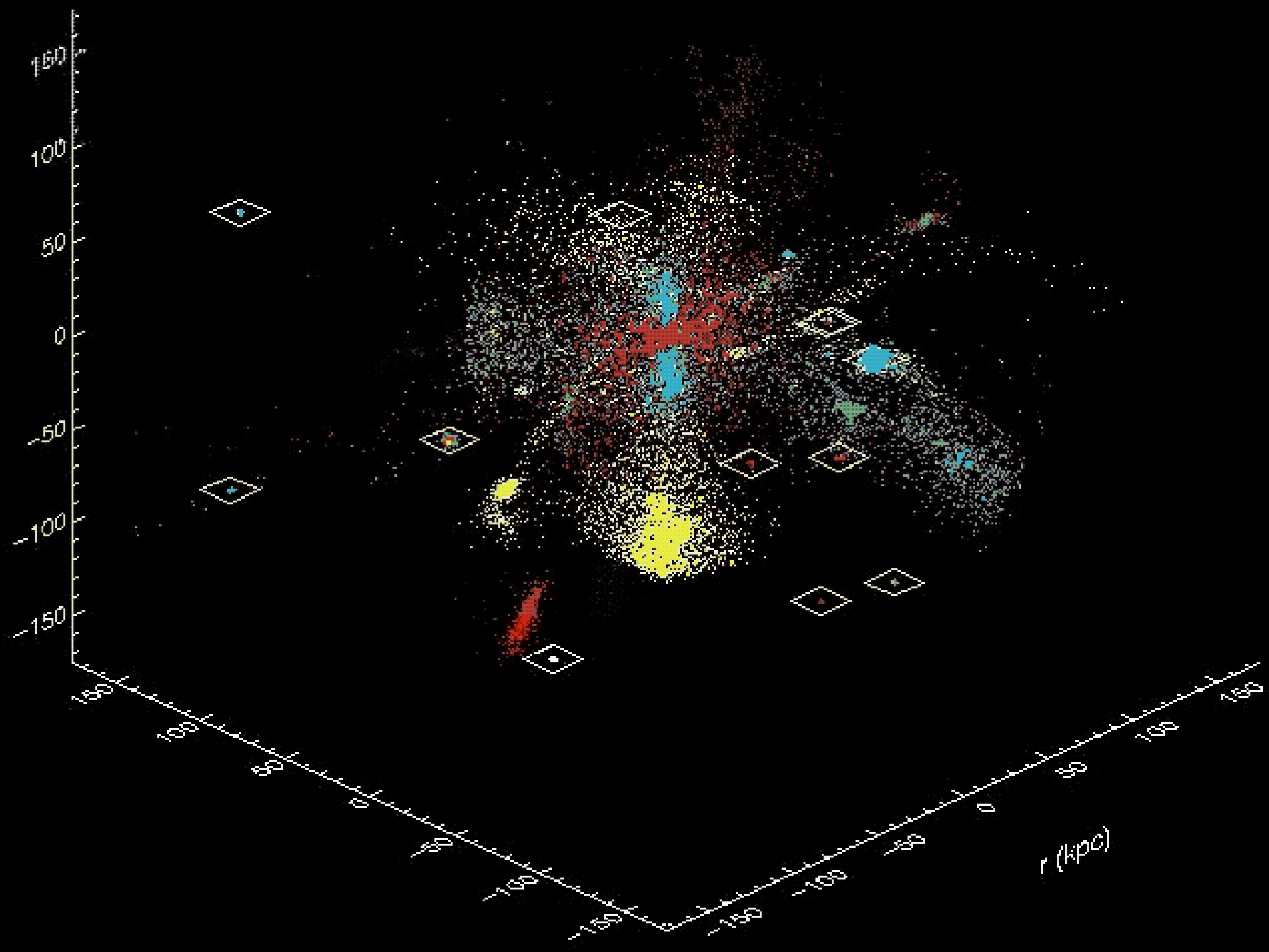
Each point = 1 Tracer Star



Start: t=8Gry Lookback time

End: t=0 (present time)

Each point = 1 Tracer Star



z=0 Flythrough

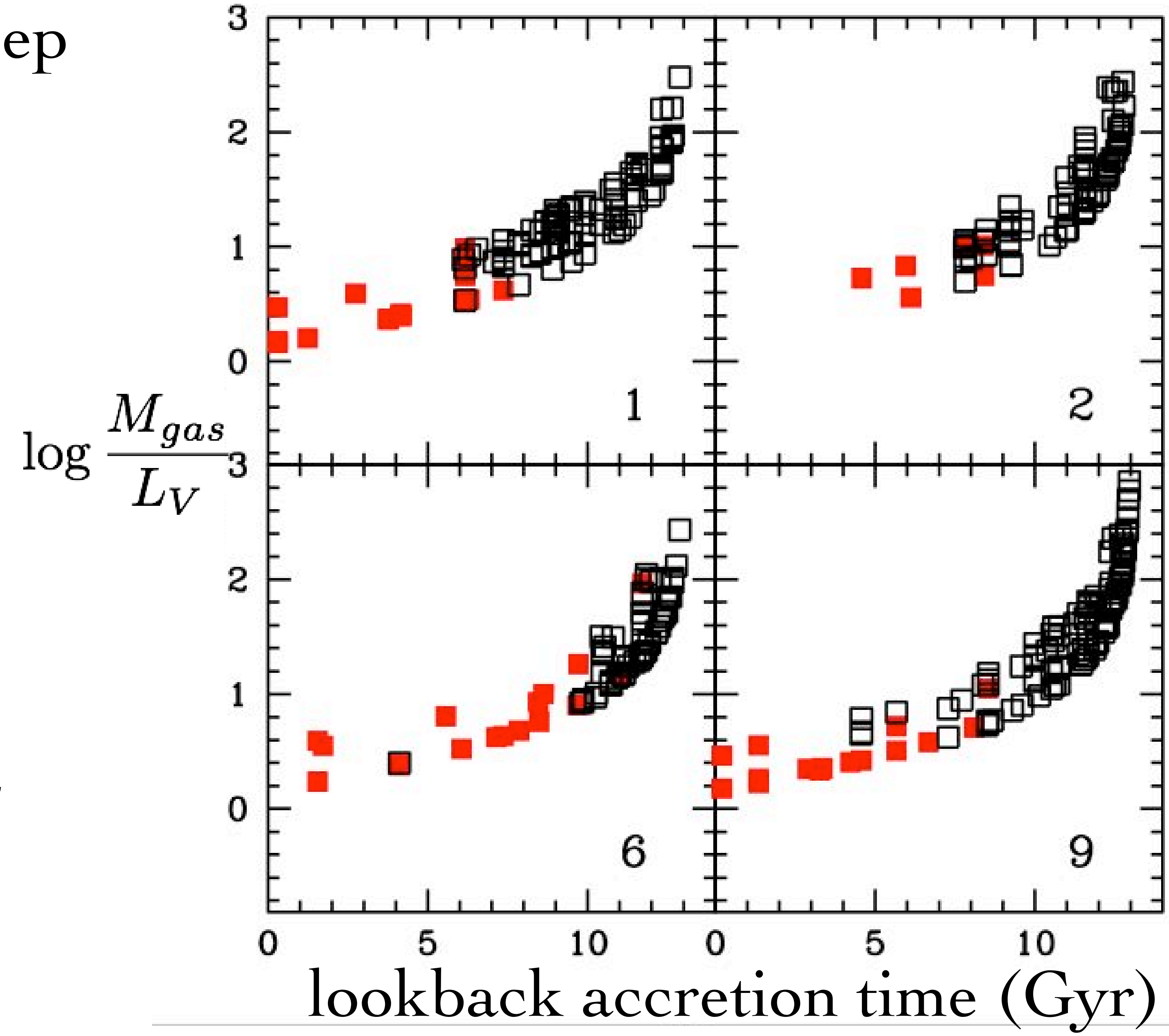
Gas fractions in accreting dwarfs:

- Accreted systems are very gas-rich at early times. This is needed in order keep stellar halo mass near observed level.

- Late-accreted dwarfs match typical gas mass fractions seen in *isolated* dwarfs.

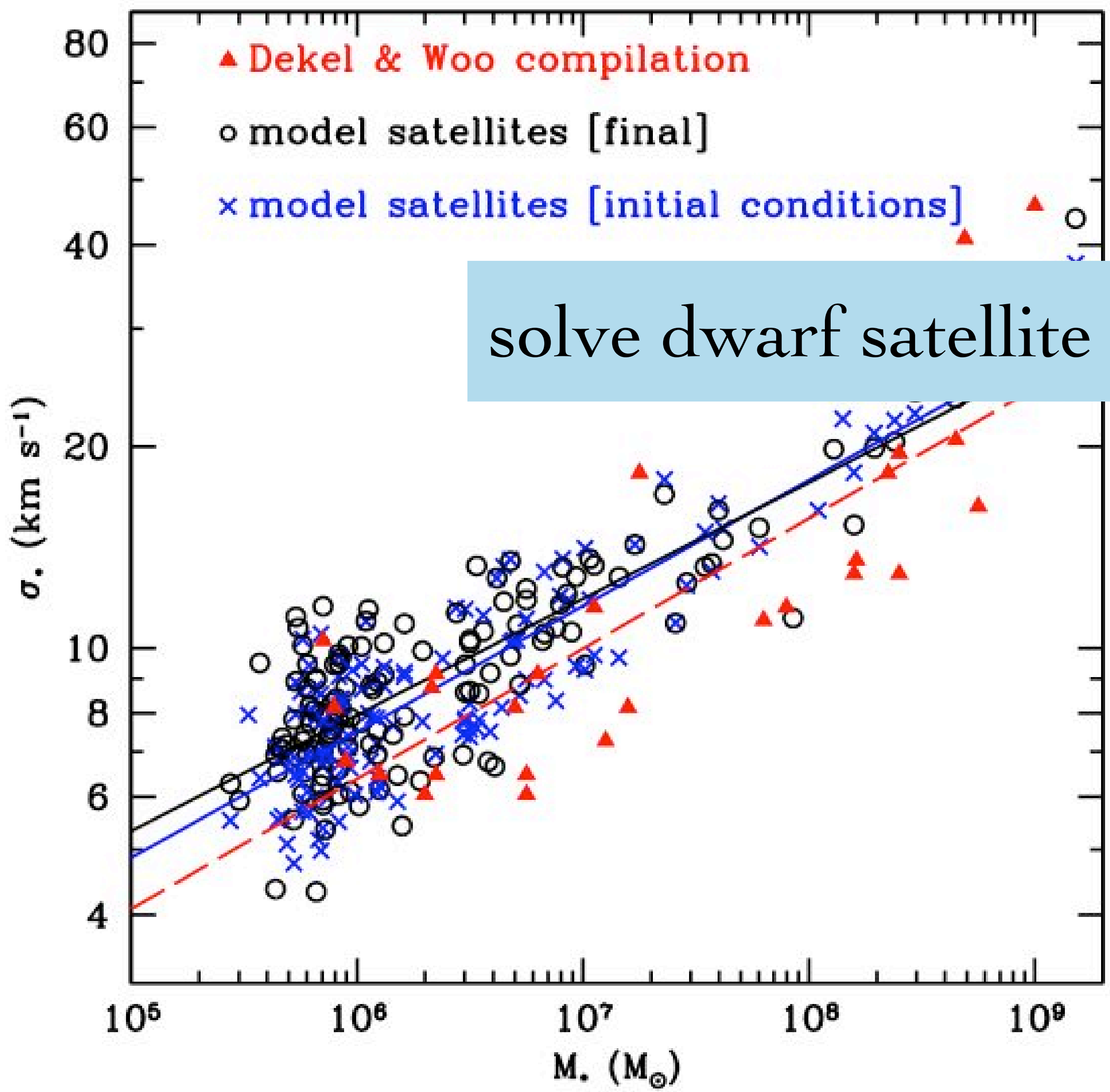
We appeal to ram pressure stripping to explain nearby gas-poor dwarfs:
-- Maller & JSB 04
-- Mayer et al. 05,
-- Mayer's Talk.

red: surviving satellites
black: destroyed satellites

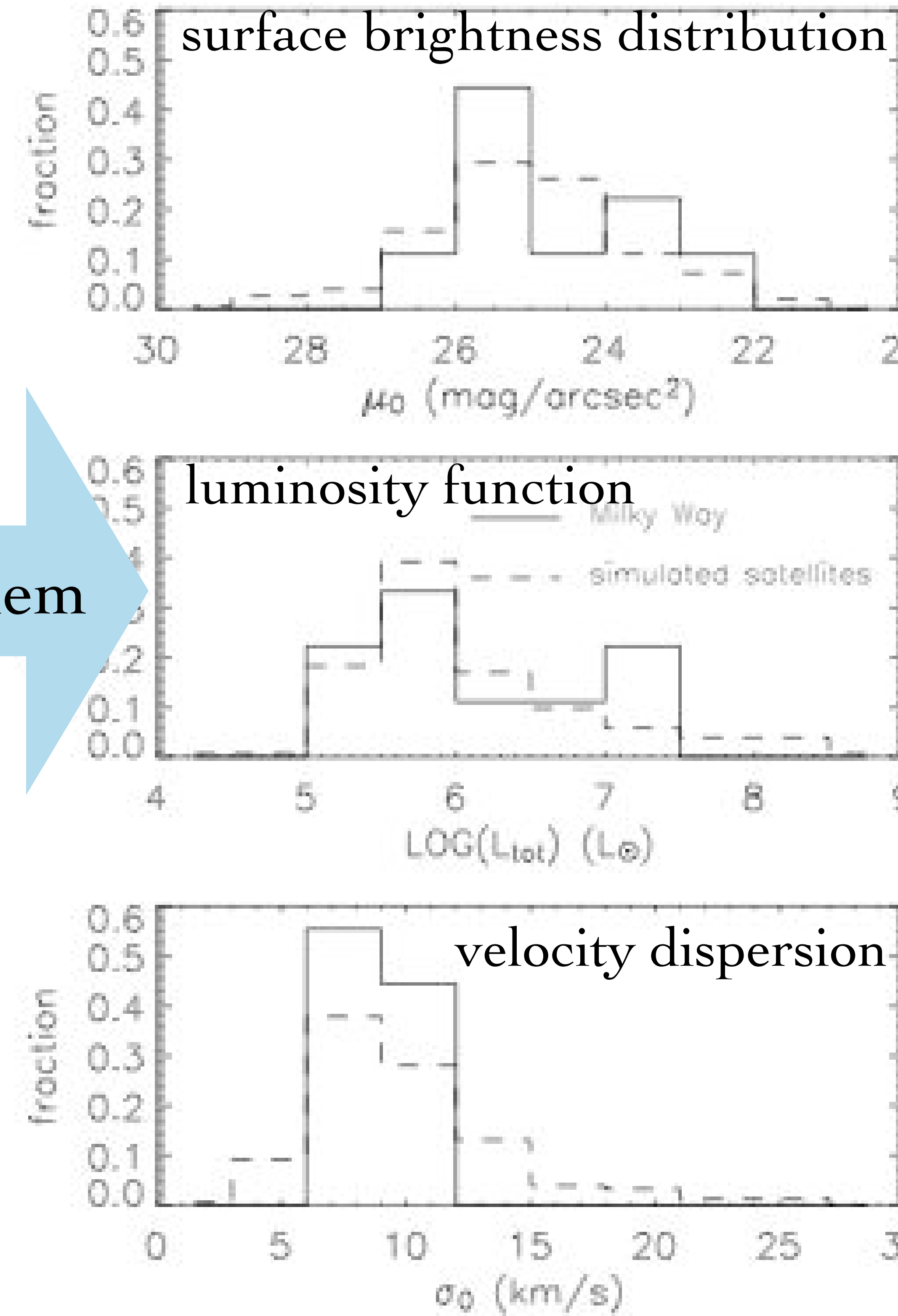


Match structural properties of MW satellites:

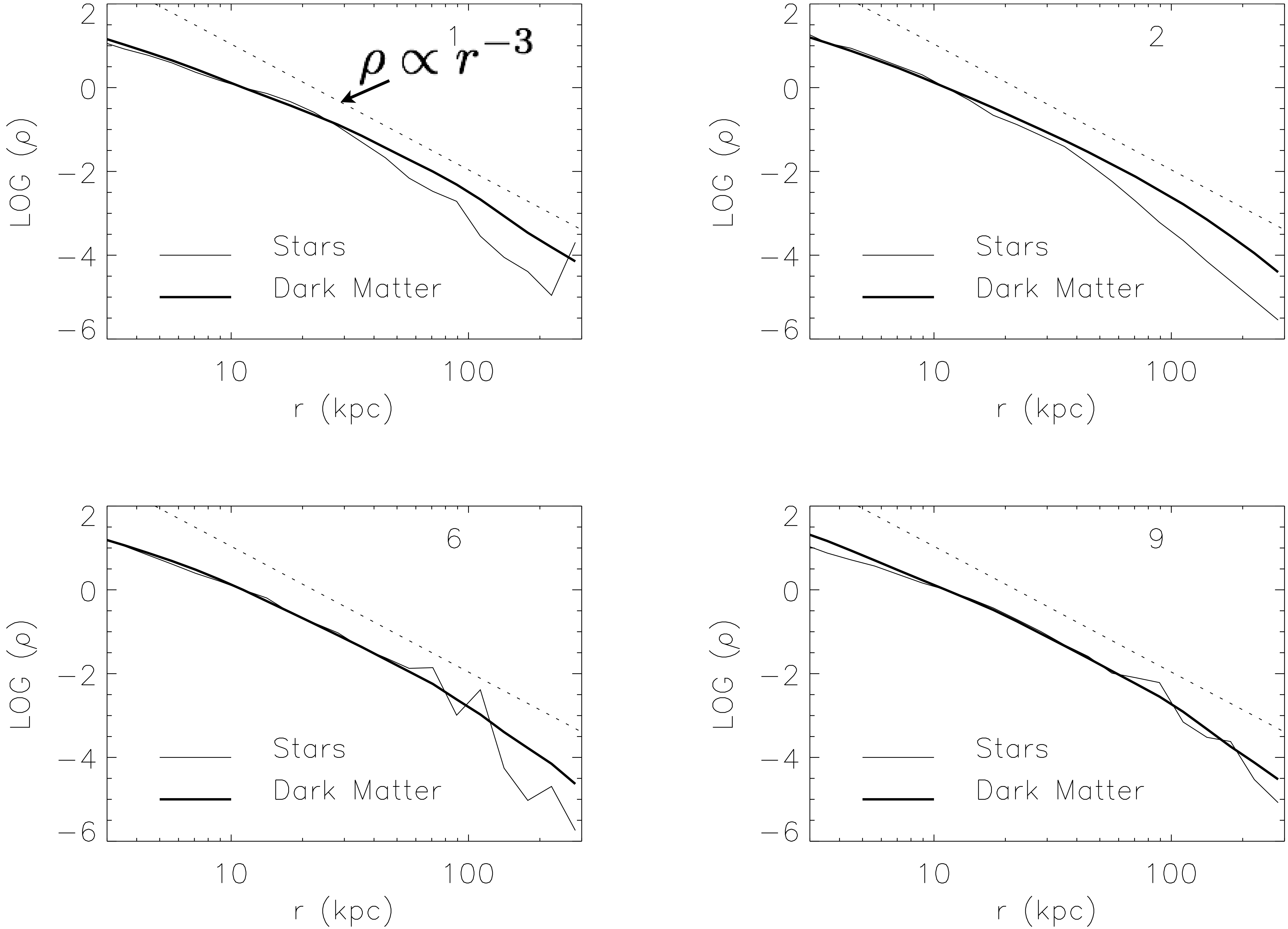
Stellar velocity dispersion vs.
Stellar Mass relation



solve dwarf satellite problem



Stellar halo density profiles: $\rho \propto r^{-2} \rightarrow r^{-4}$(r>50-100 kpc)

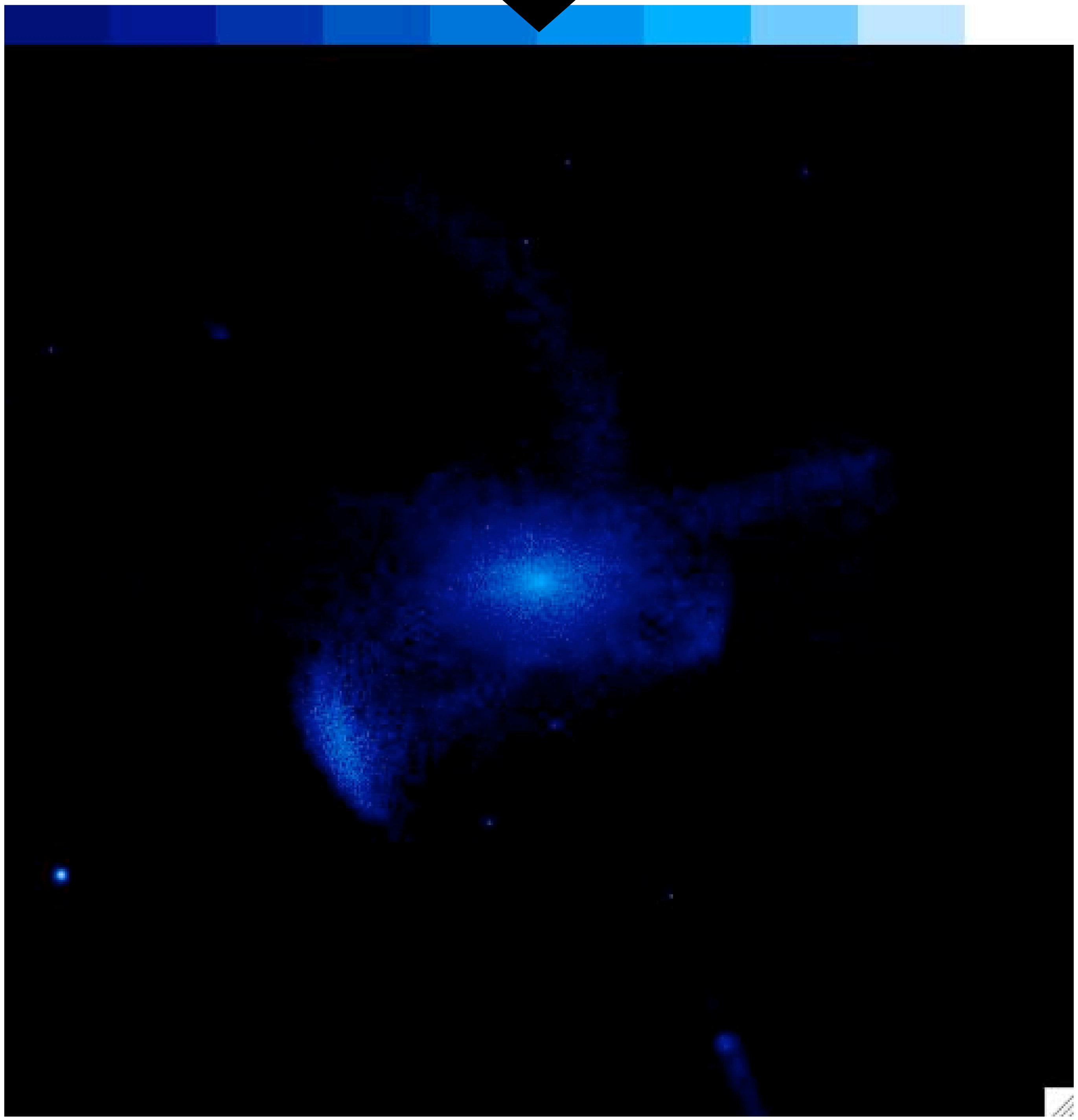


External Galaxy View

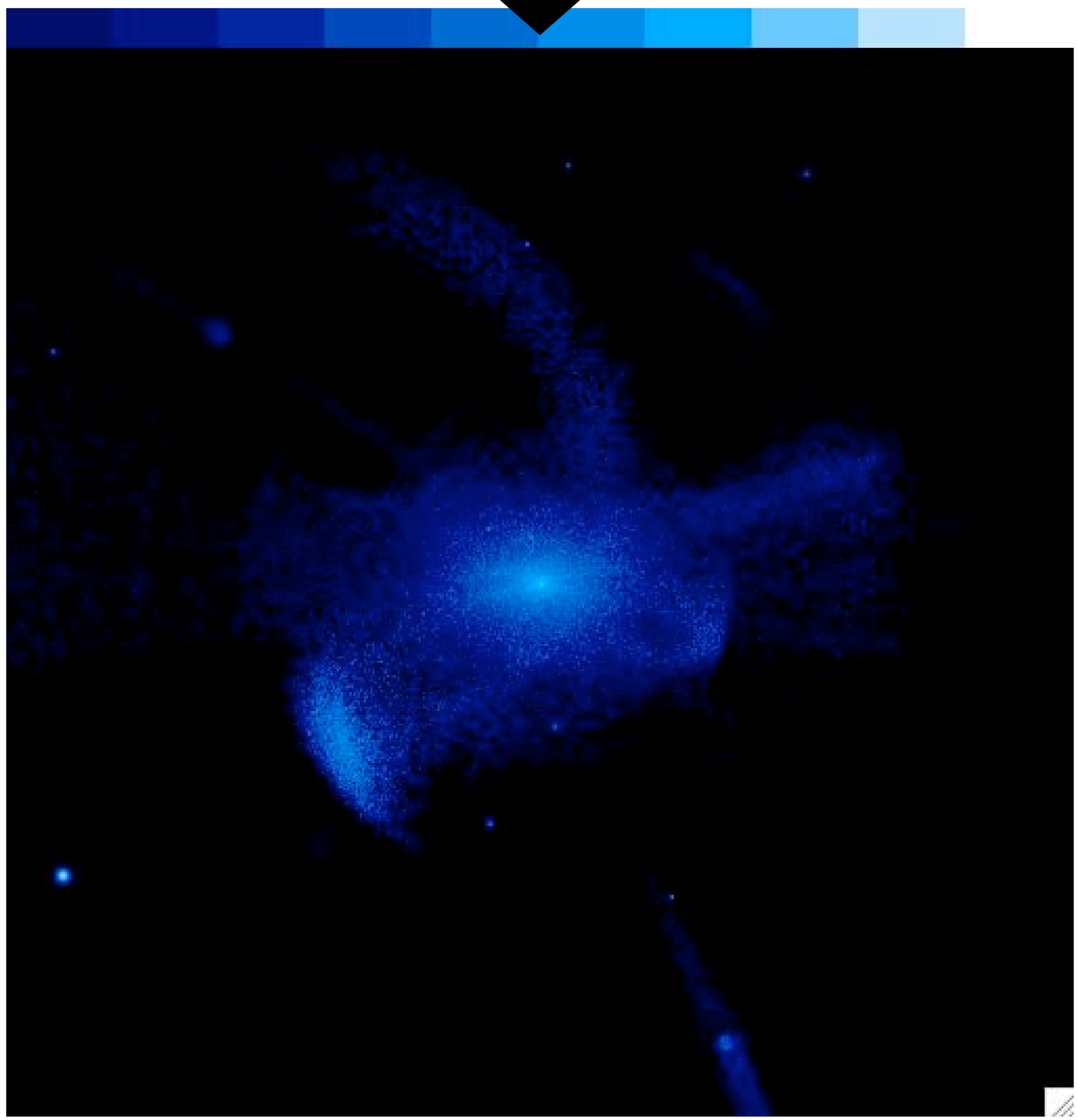
$\mu_0 = 30 \frac{\text{mag}}{\text{arcsec}^2}$

26.5

$23 \frac{\text{mag}}{\text{arcsec}^2}$



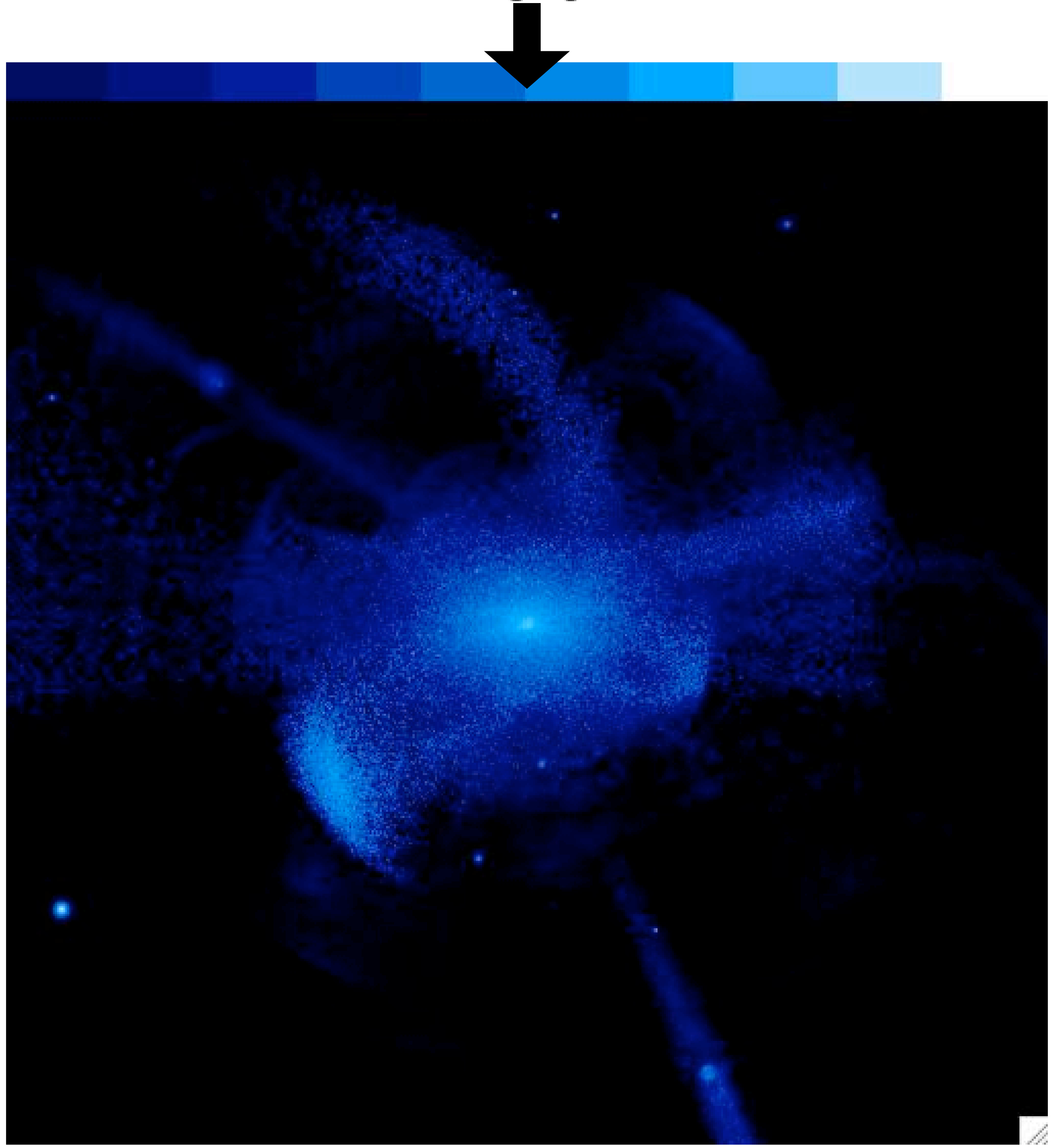
External Galaxy View



External Galaxy View

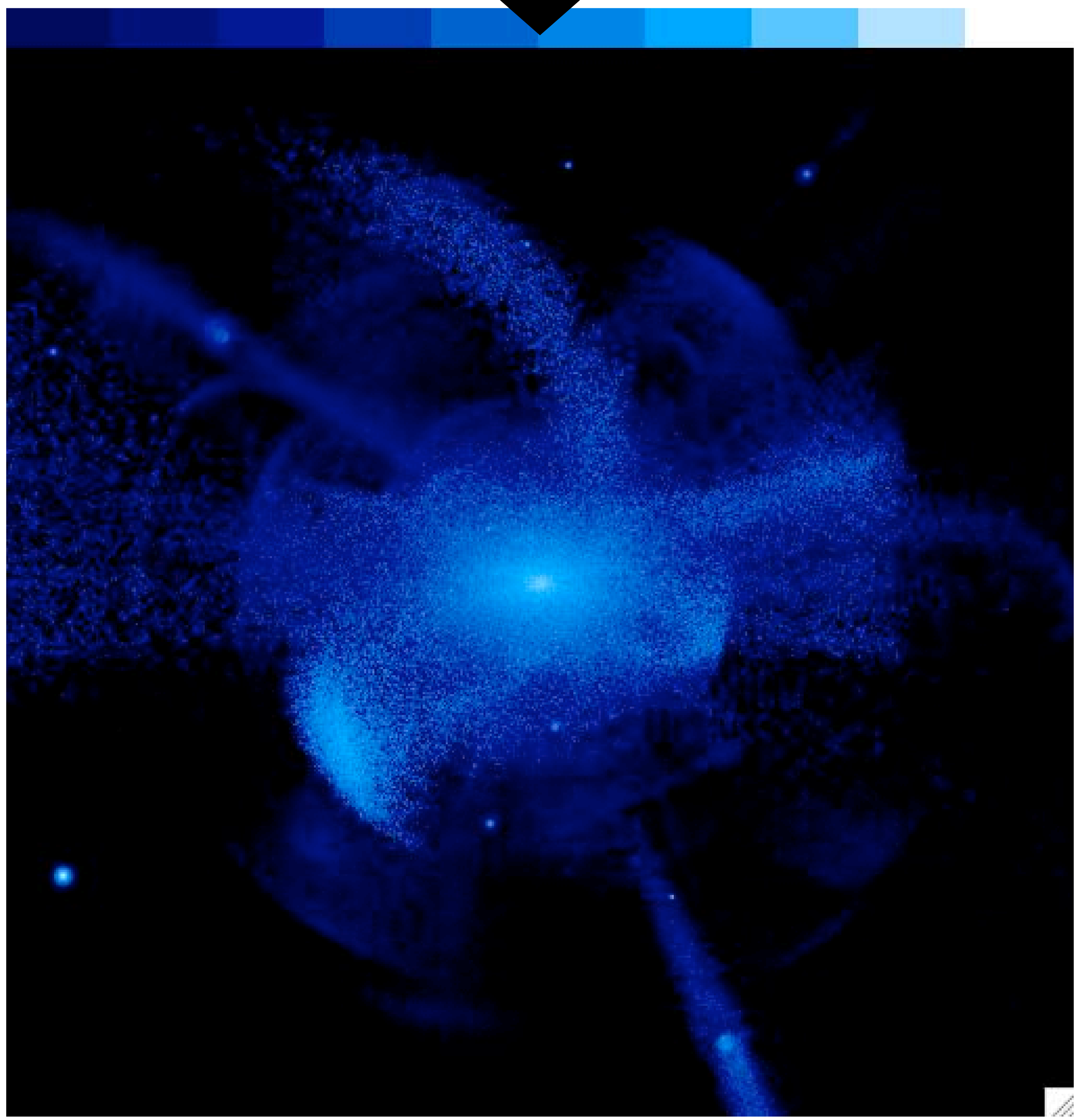
$\mu_0 = 34 \frac{\text{mag}}{\text{arcsec}^2}$

28.5



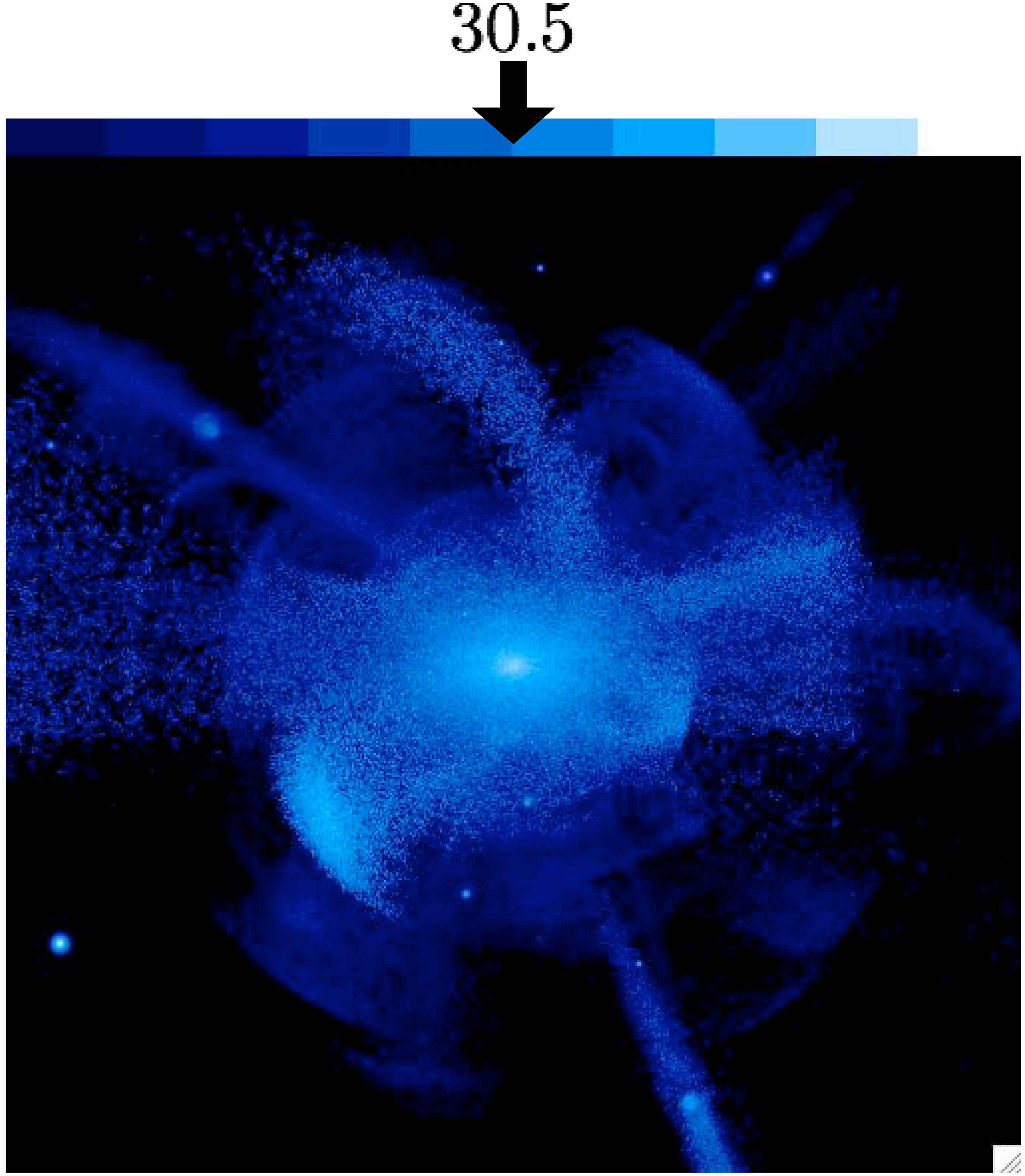
$23 \frac{\text{mag}}{\text{arcsec}^2}$

External Galaxy View

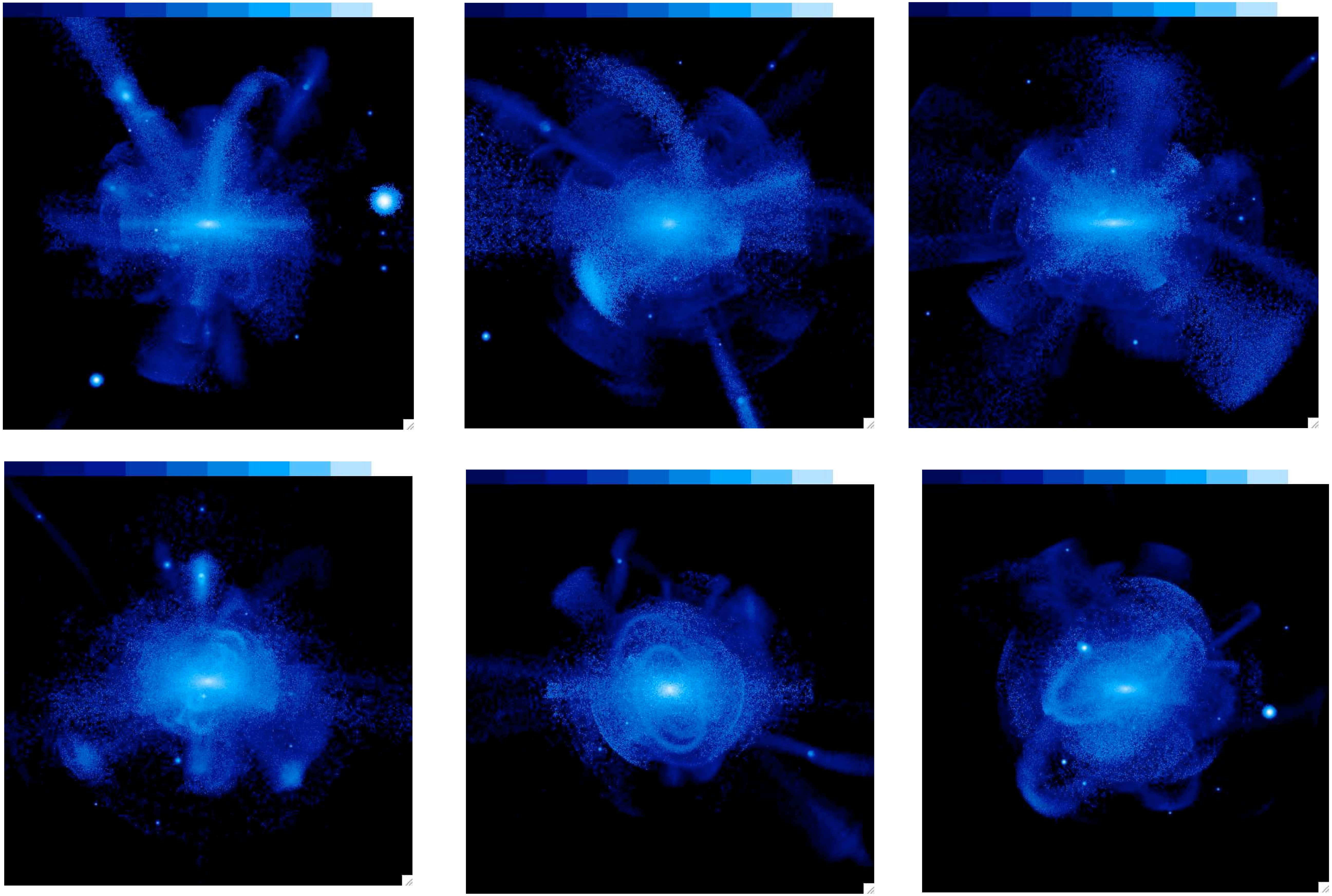


External Galaxy View

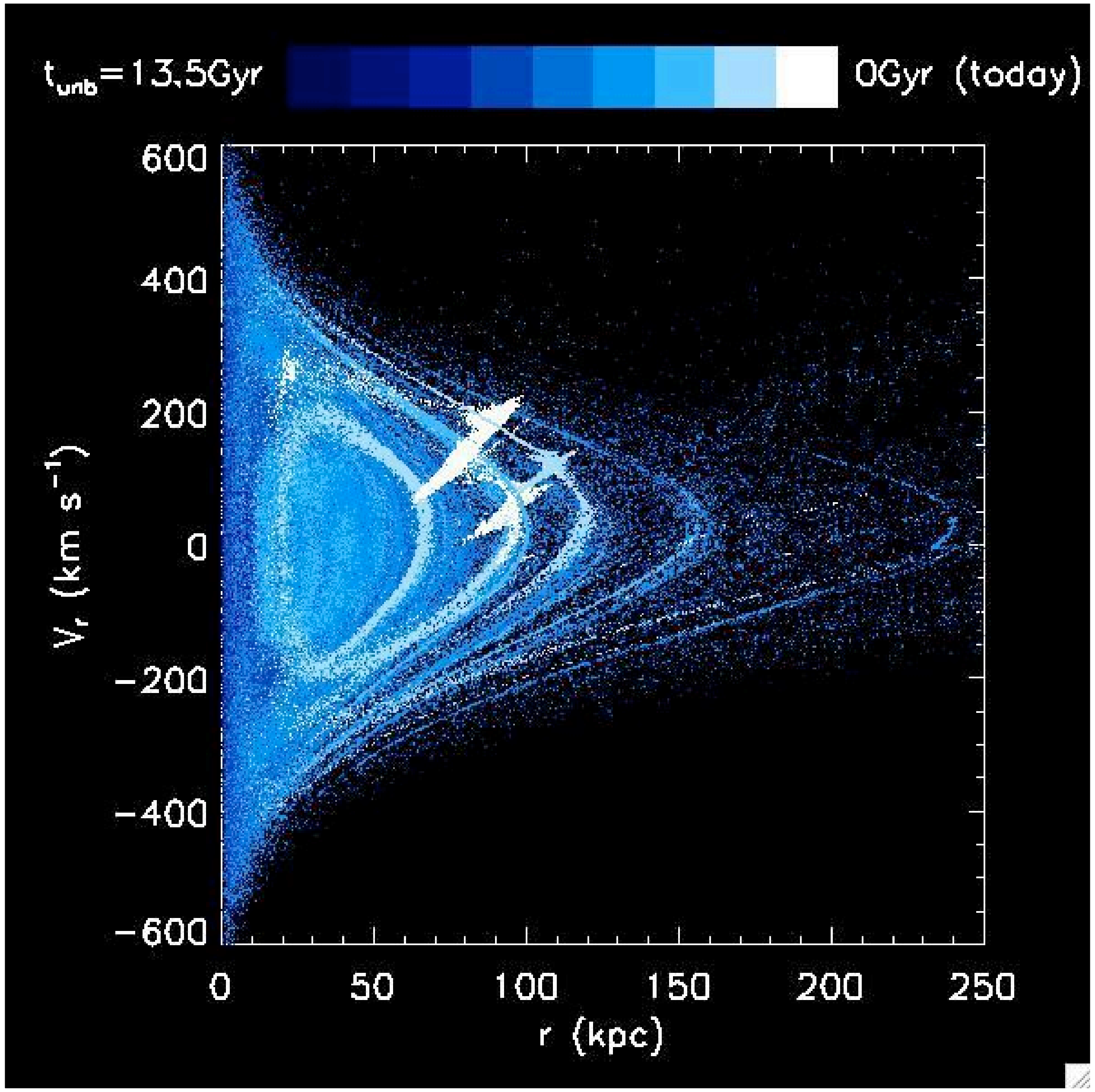
$\mu_0 = 38 \frac{\text{mag}}{\text{arcsec}^2}$

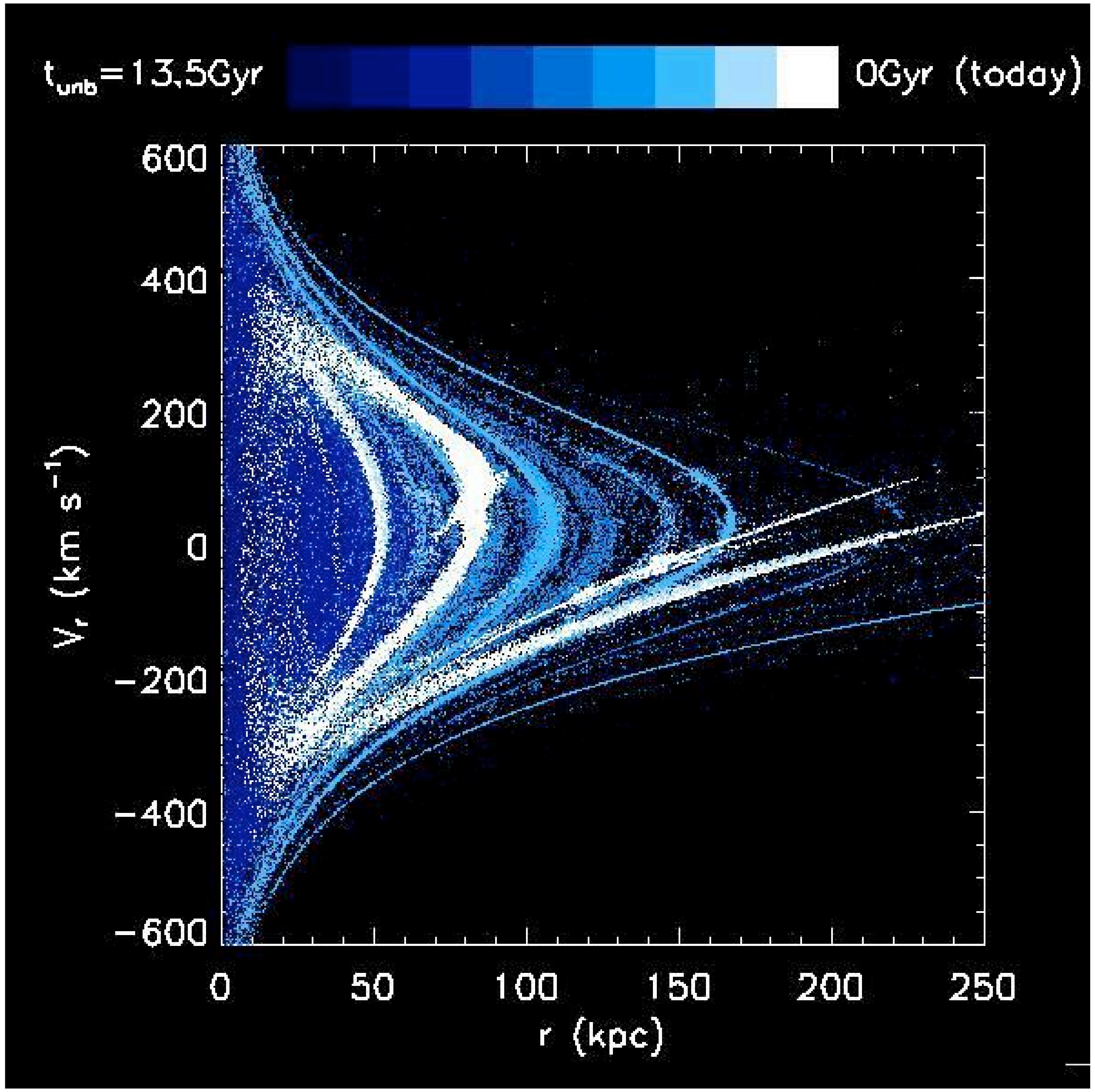


$23 \frac{\text{mag}}{\text{arcsec}^2}$



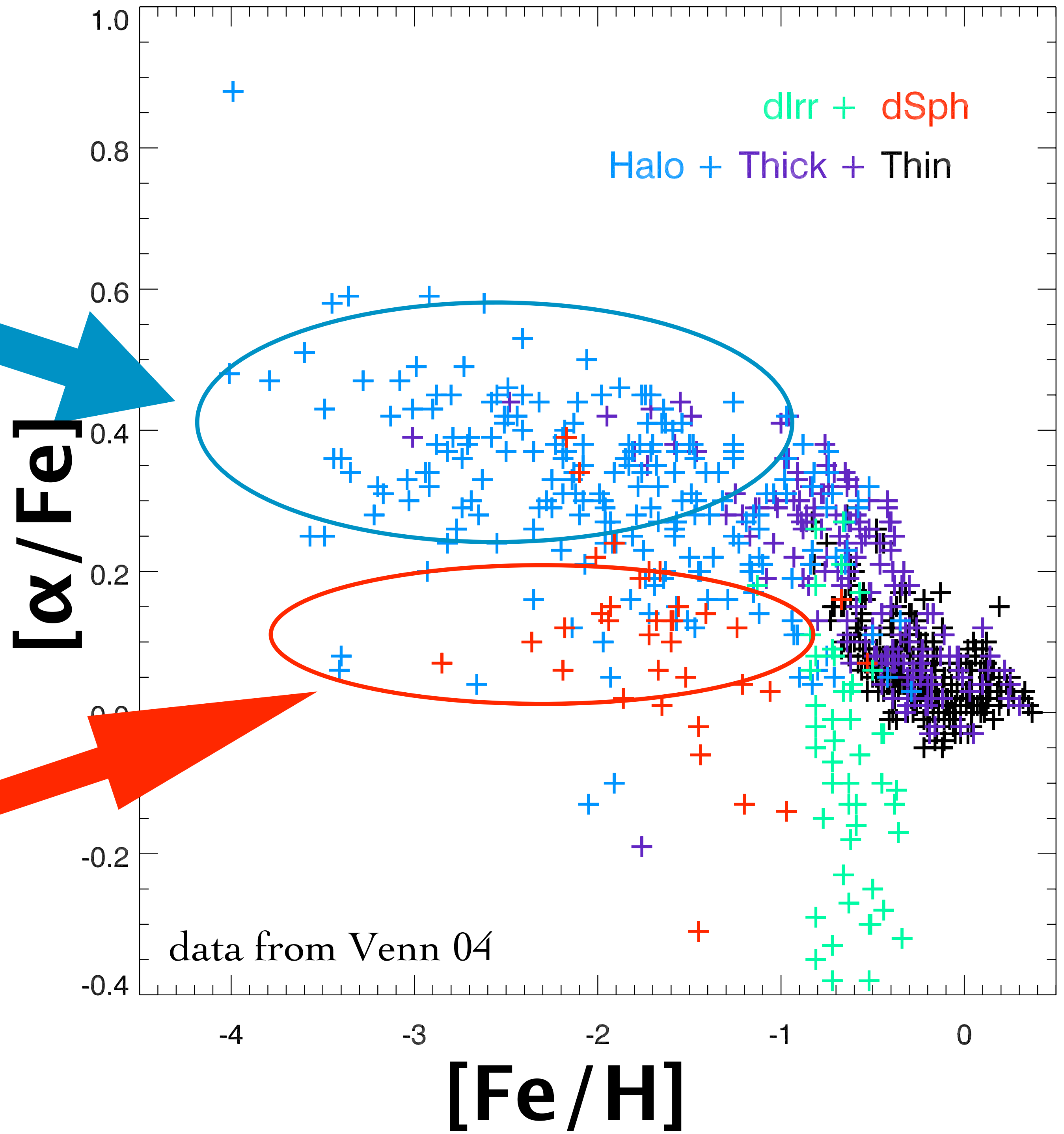
Phase Space Structure





Alpha abundances...

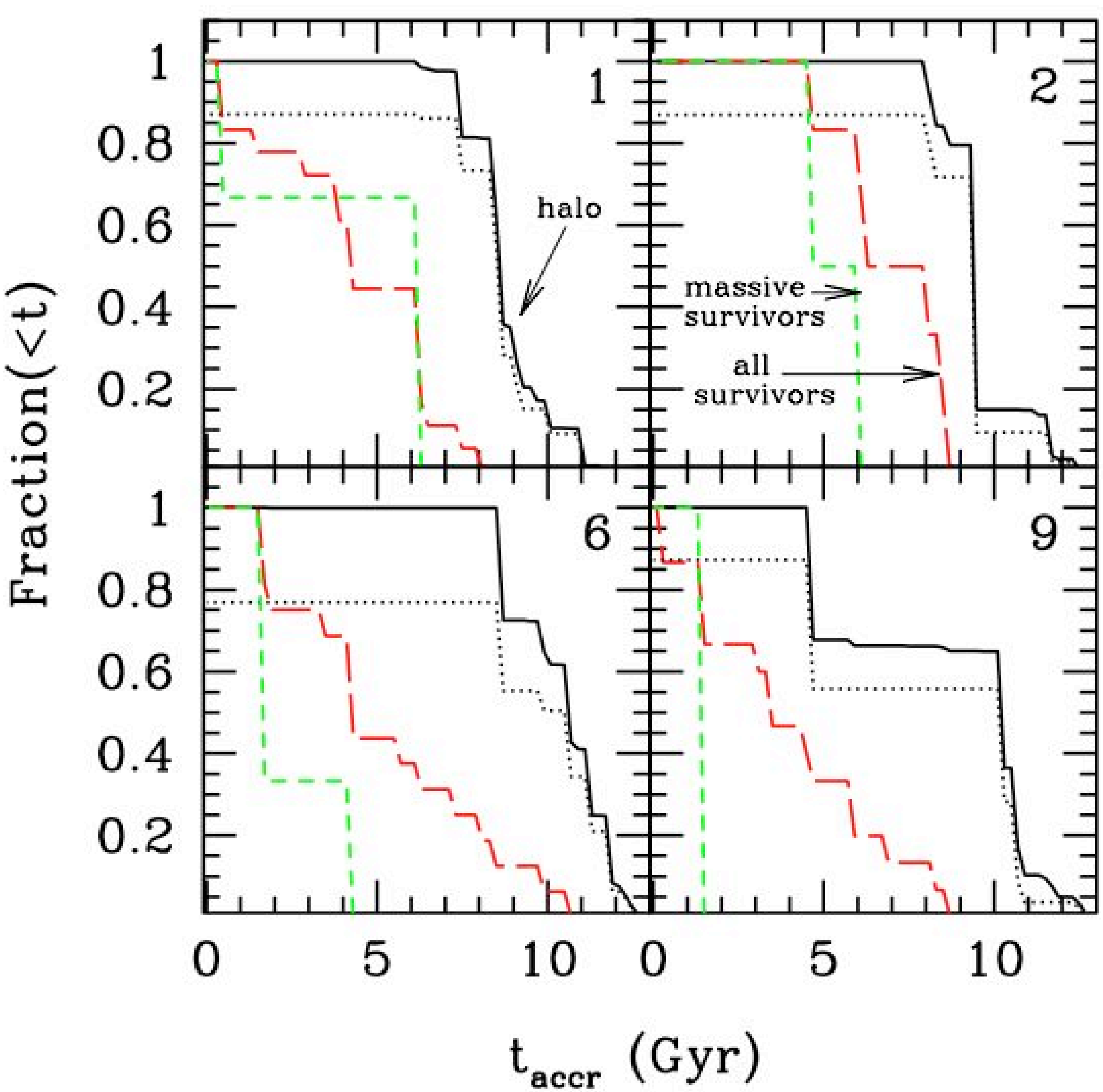
Halo:
Enhanced alpha abundances (rapid star formation)



Lots of discussion in the literature:
Unavane et al (1996)
Nissen & Schuster (1997)
Gilmore & Wyse (1998)
Shetrone et al. (2001)
Fulbright (2002)
Shetrone et al. (2003)
Tolstoy et al. (2003)
Venn et a. (2004)

Satellite galaxies: intermediate alpha abundances

Solution? Surviving dwarfs are biased.



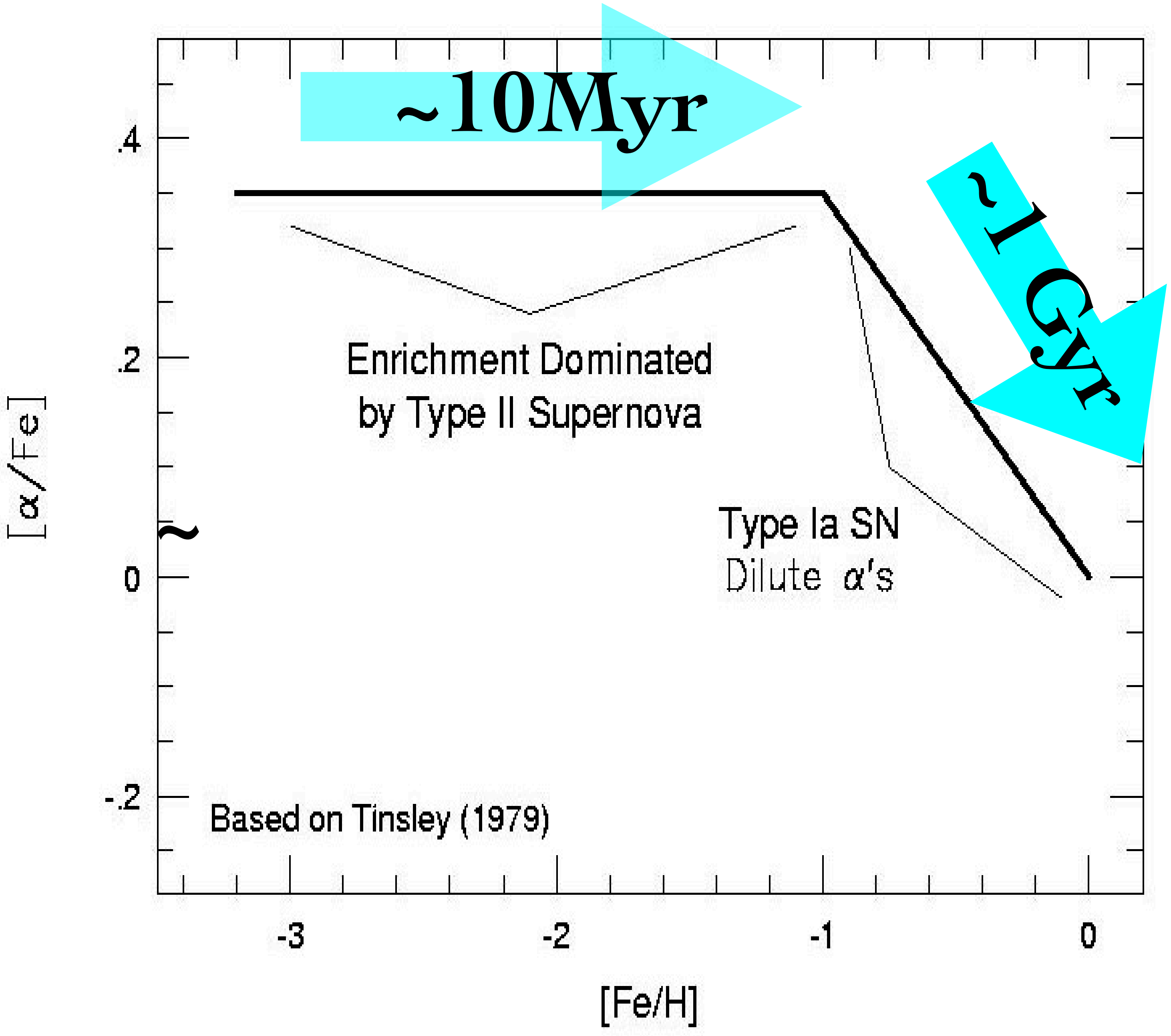
1. Early accretion events are destroyed.

2. Late accretion events survive.

3. Most of the *mass* is accreted in LMC-size systems.

Chemical abundance patterns

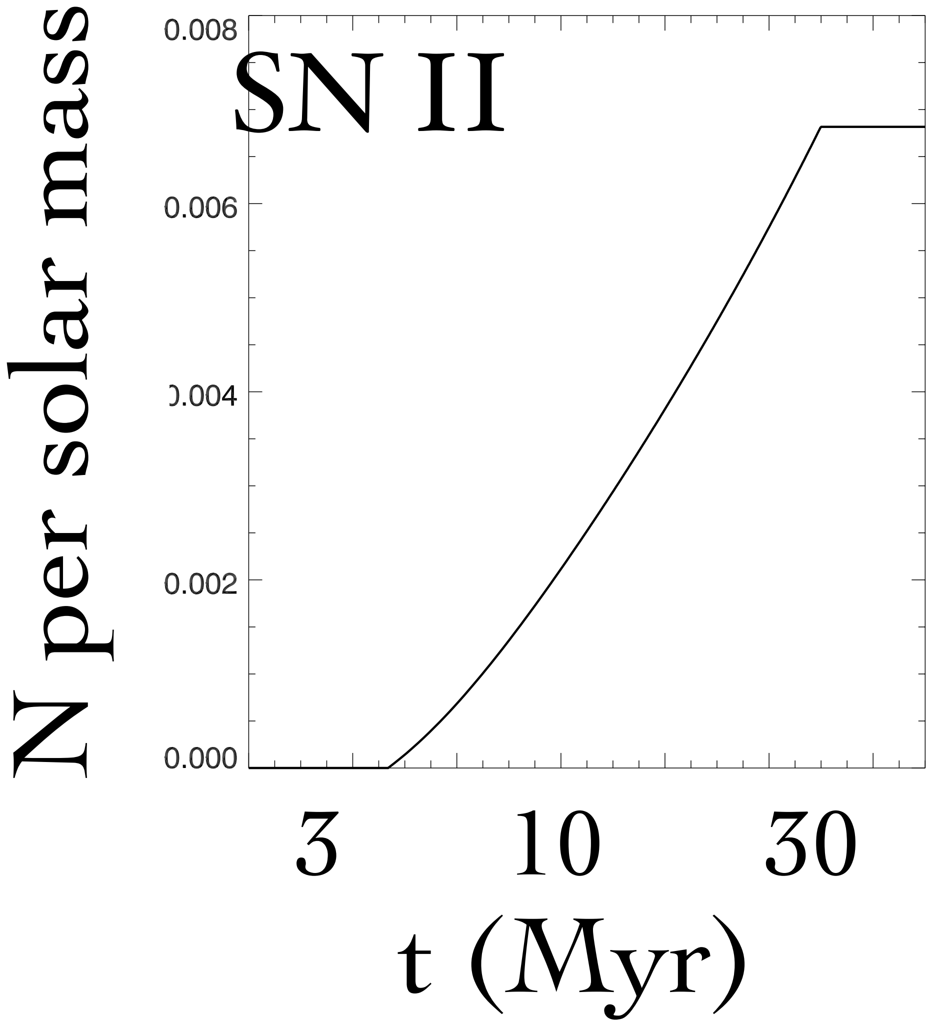
- **Stars with M > 10 M_{sun} explode as Type II supernova within ~10^7 yr. TypeII SN eject large amounts of "even-Z" α elements.**
- **About 1 Gyr later, Type Ia supernova begin to heavily contribute. Mostly eject Fe-group elements. This 'dilutes' the [α/Fe] value.**
- **A galaxy's (or star's) position on this diagram constrains the type of star formation history it had.**

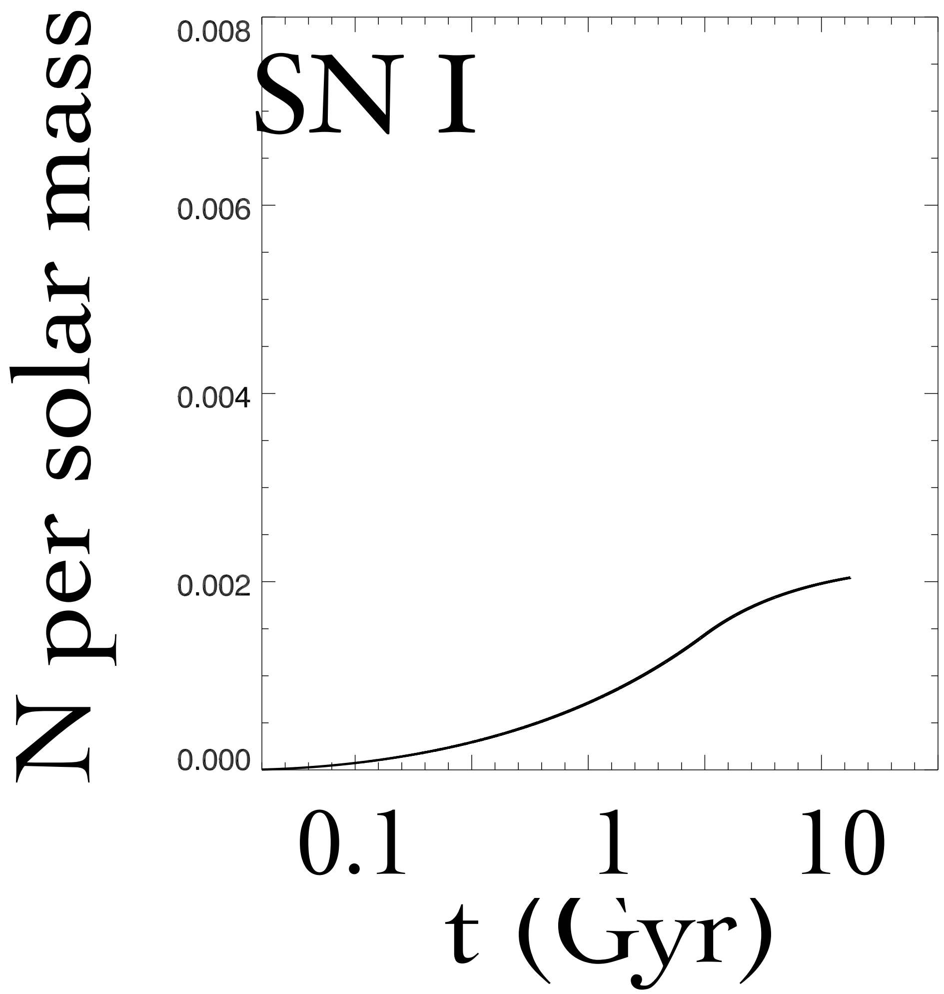


Fulbright

Chemical Evolution Model: Robertson et al. 05

Start calculation at "z_re=10" with [Fe/H]=-4, with a Kroupa "Pop II" IMF.





SNI & SNII rates and yields

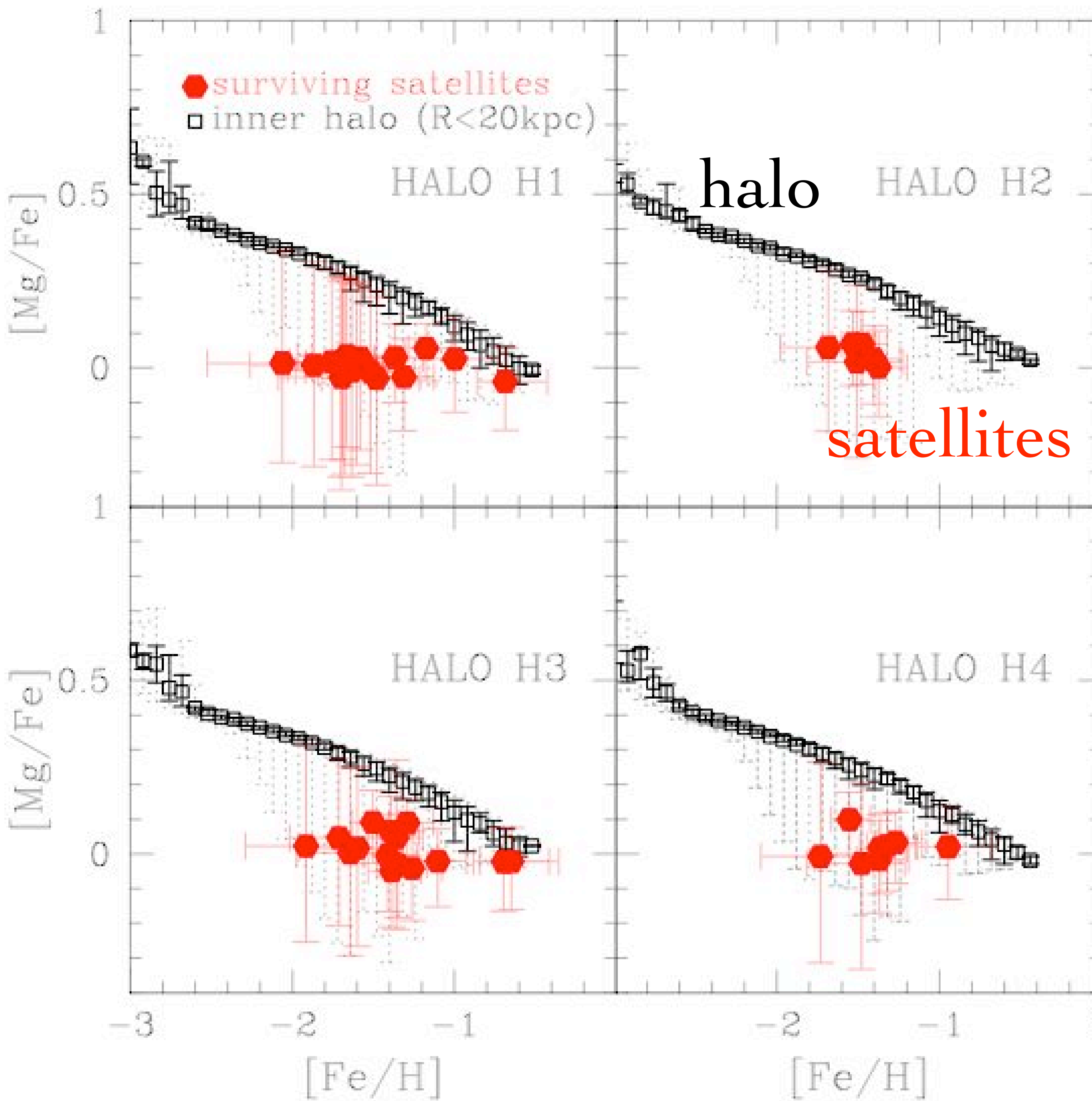
(Greggio & Renzini 1983, Thielemann et. al. 1996, Nomoto et. al. 1997)

Stellar wind enrichment

(van den Hoek & Groenewegen 1997)

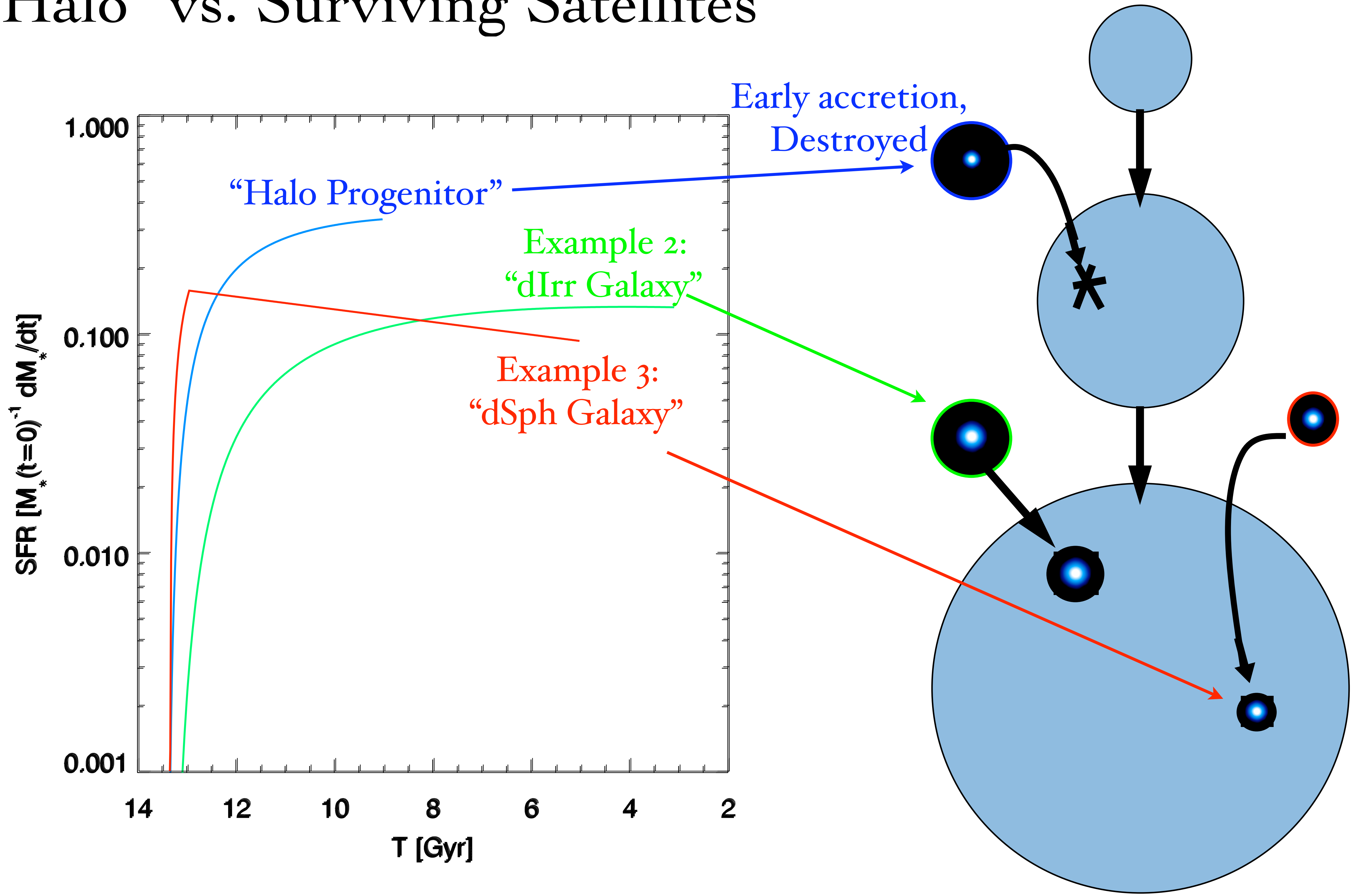
Font et al. 05

Chemical evolution models + N-body simulations

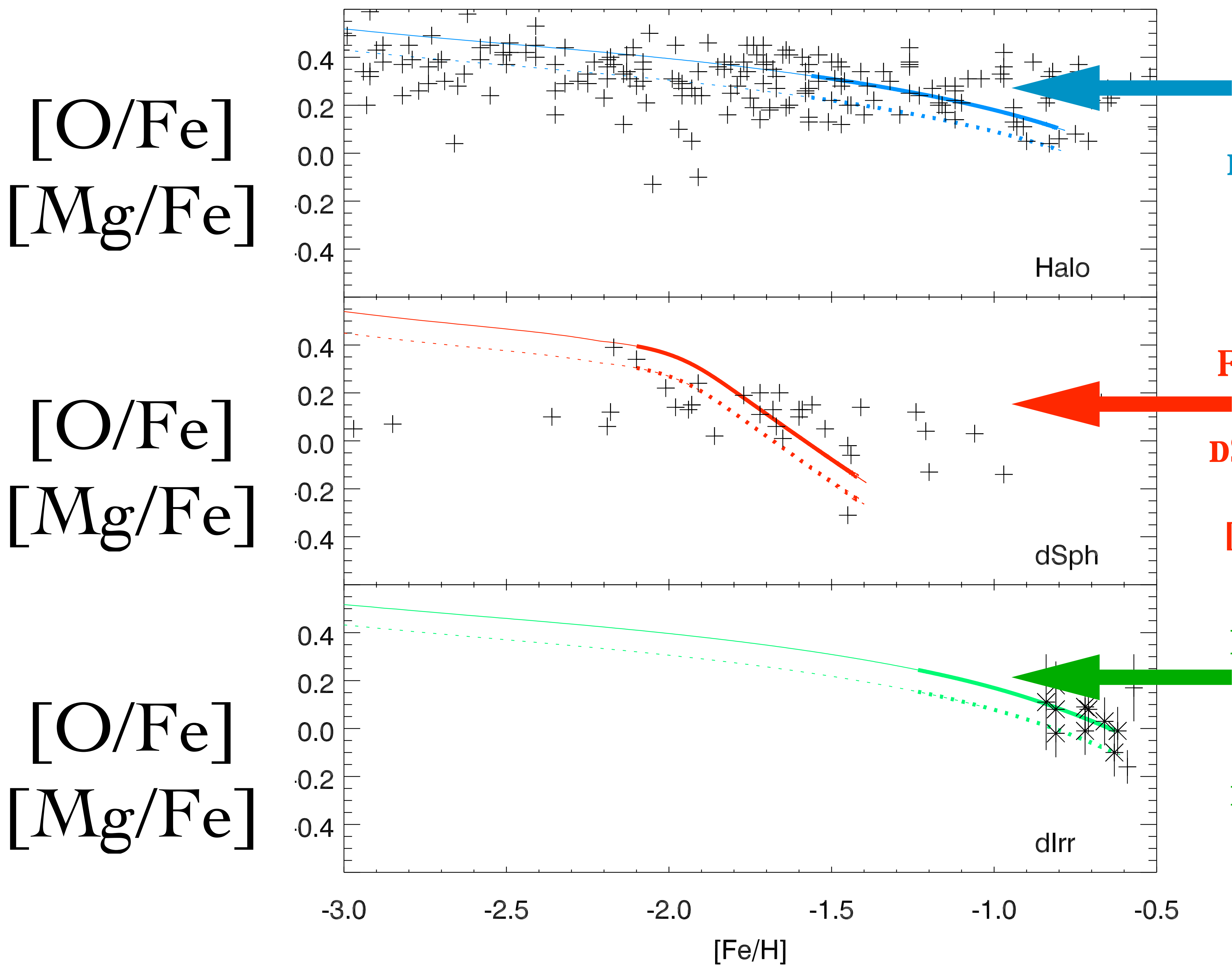


Halo is alpha-enhanced because it is formed from earlier accretion events. Surviving satellites were accreted later.

Characteristic star formation histories: "Halo" vs. Surviving Satellites



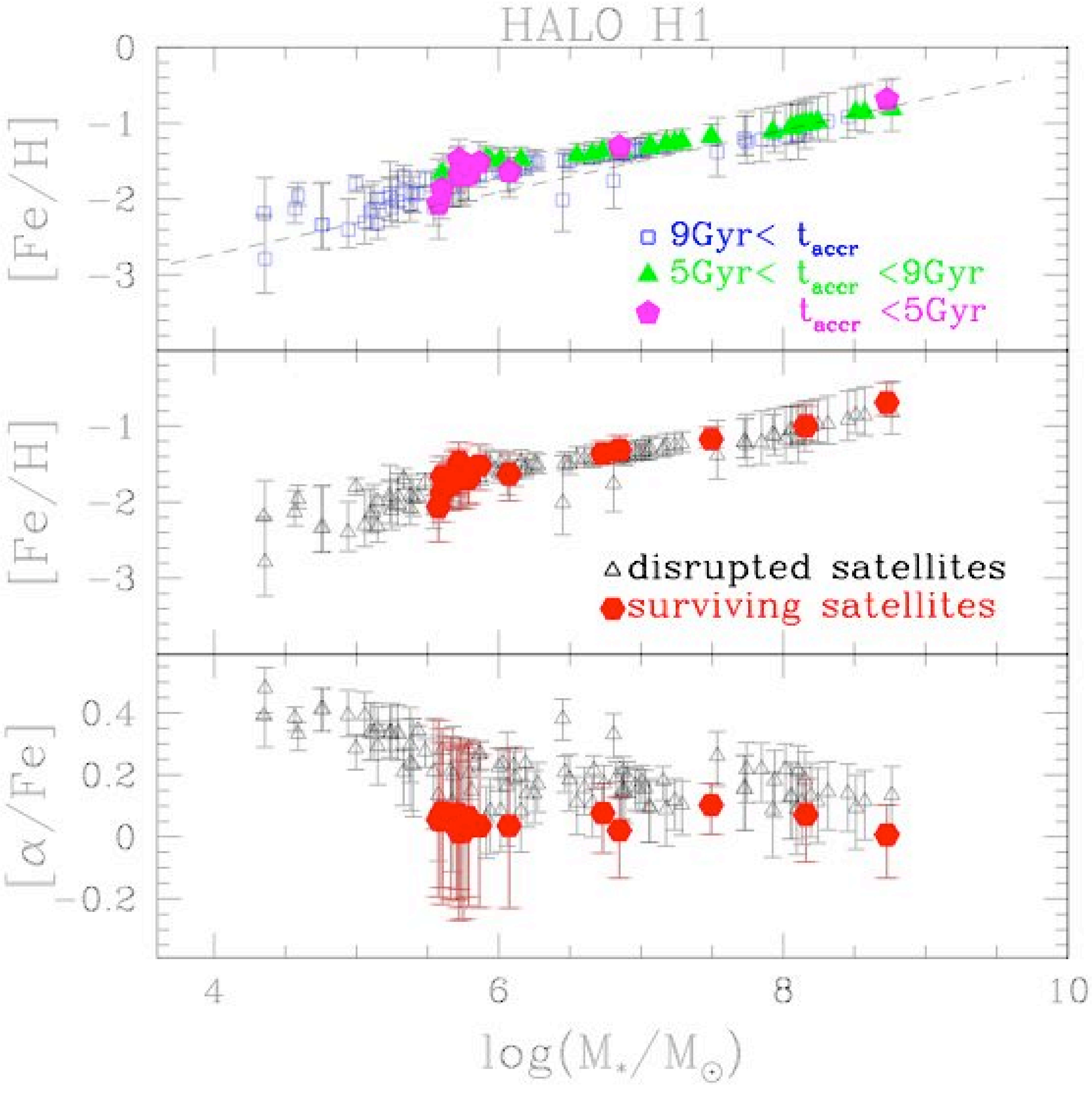
Robertson, JSB, Font, Johnston & Hernquist 05



HALO PROGENITOR FORMS QUICKLY, RETAINS HIGH [α/FE], LOW [FE/H]

FEEDBACK EFFICIENT IN LOW MASS DSPH GALAXIES, GAIN INTERMEDIATE [α/FE], LOW [FE/H]

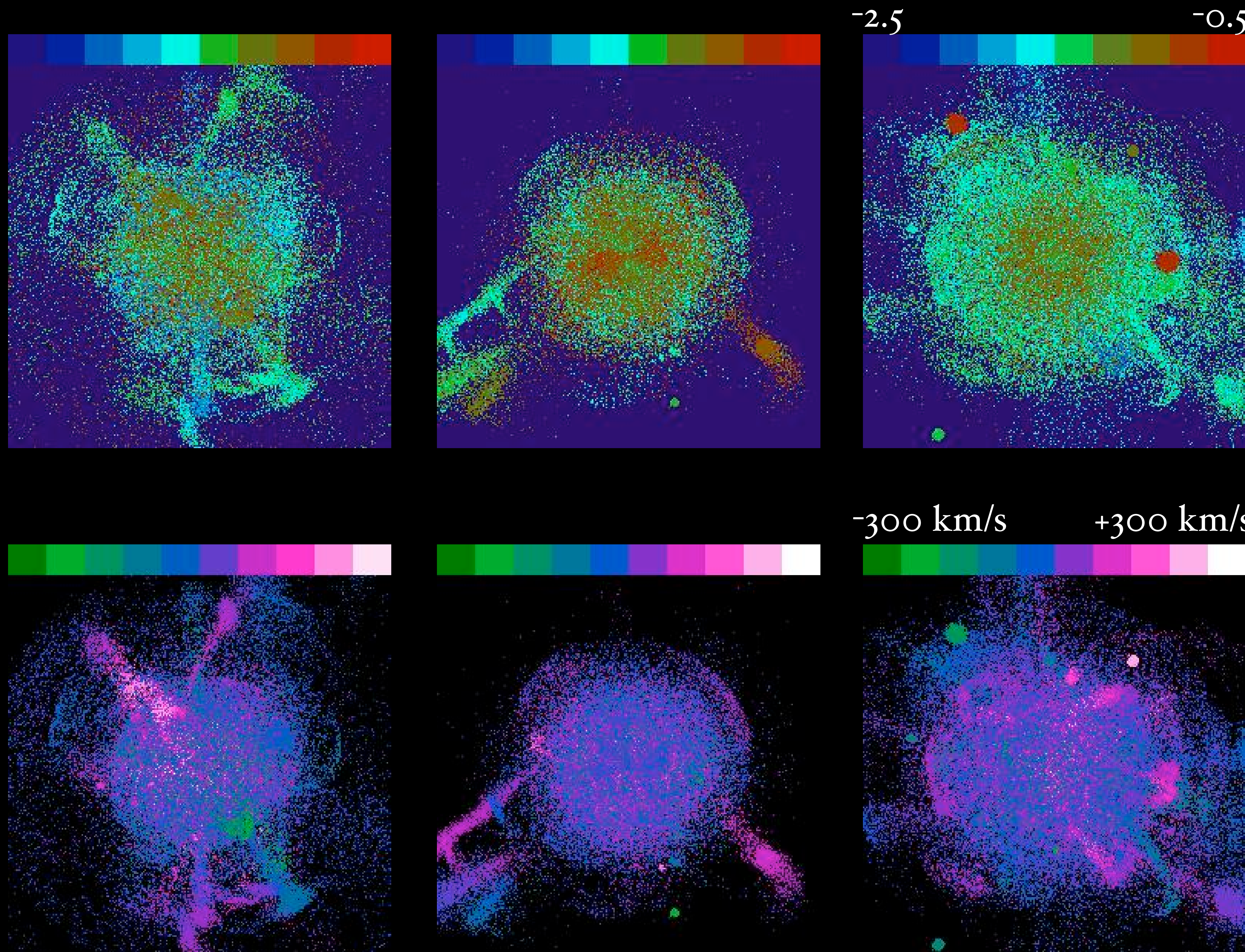
FEEDBACK INEFFICIENT IN HIGH MASS DIRR GALAXIES, GAIN ~SOLAR [α/FE], INTERMEDIATE [FE/H]


HALO H1
[Fe/H]
0
−1
−2
−3
9Gyr< t_{accr}
5Gyr< t_{accr} <9Gyr
t_{accr} <5Gyr
[Fe/H]
−1
−2
−3
disrupted satellites
surviving satellites
[α/Fe]
0.4
0.2
0
−0.2
4
6
8
10
log($M_*/M_\odot$)

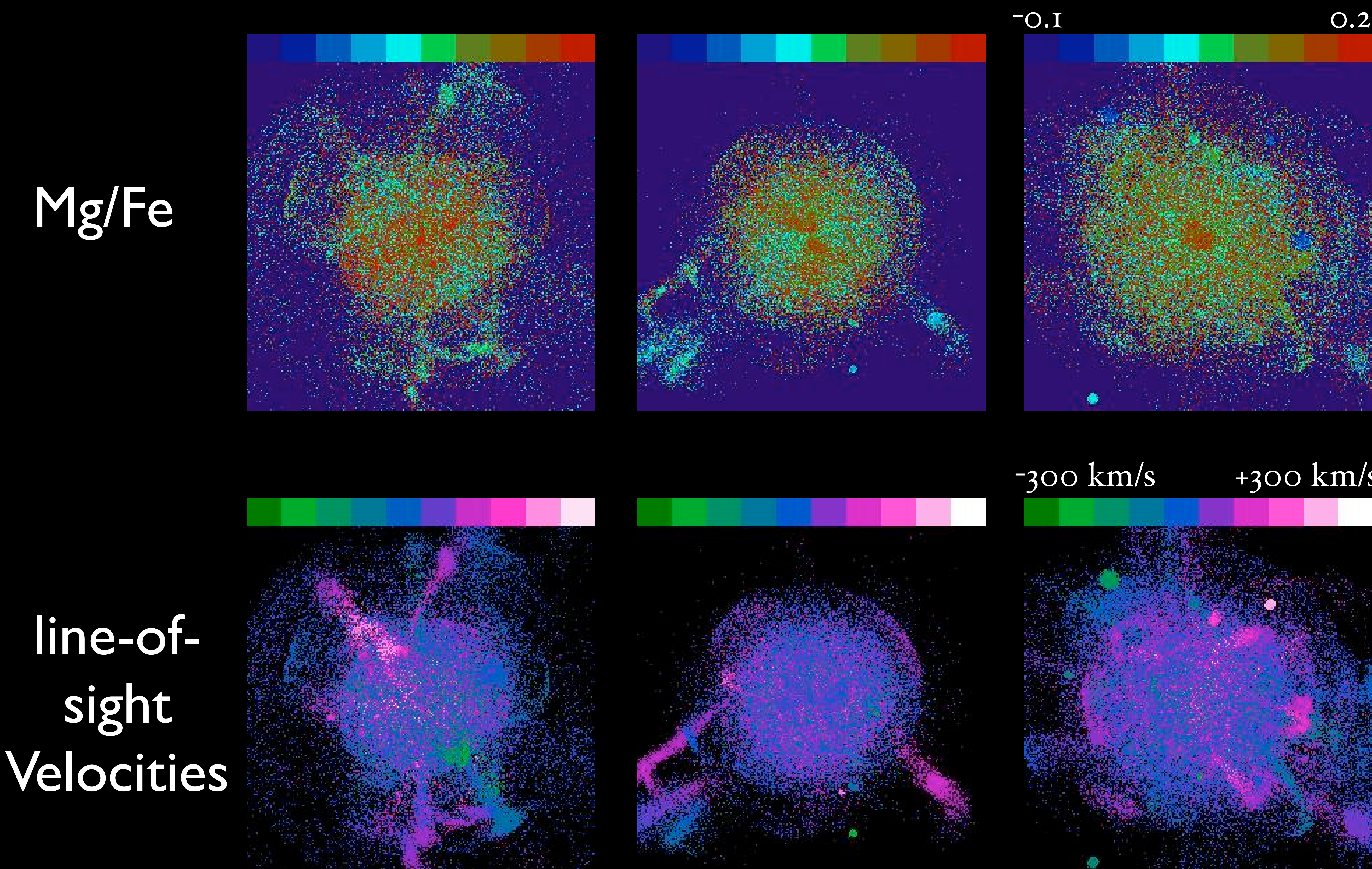
Full chemical evolution models + N-body simulations:

Fe/H

line-of-sight Velocities

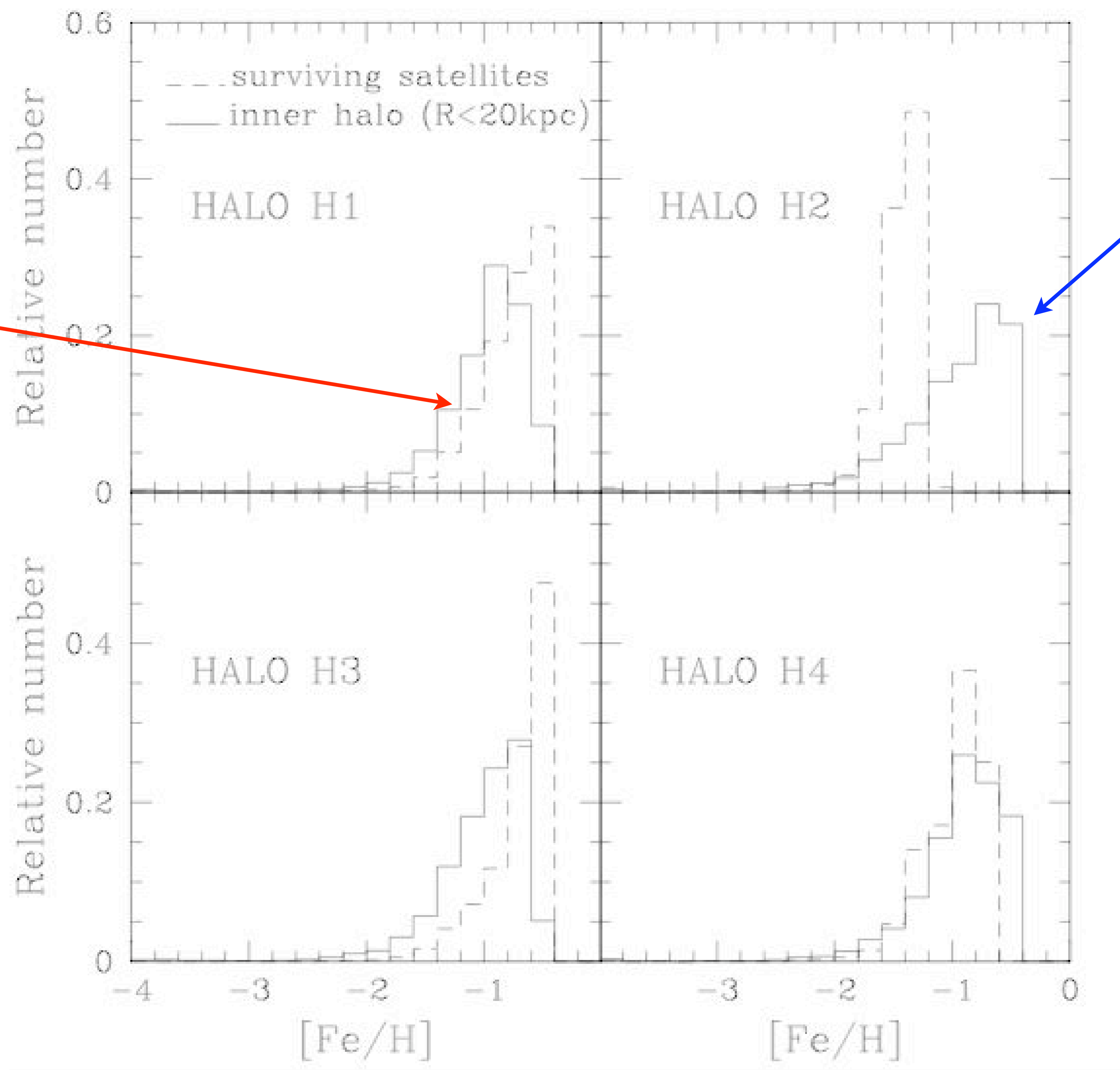


Full chemical evolution models + N-body simulations:



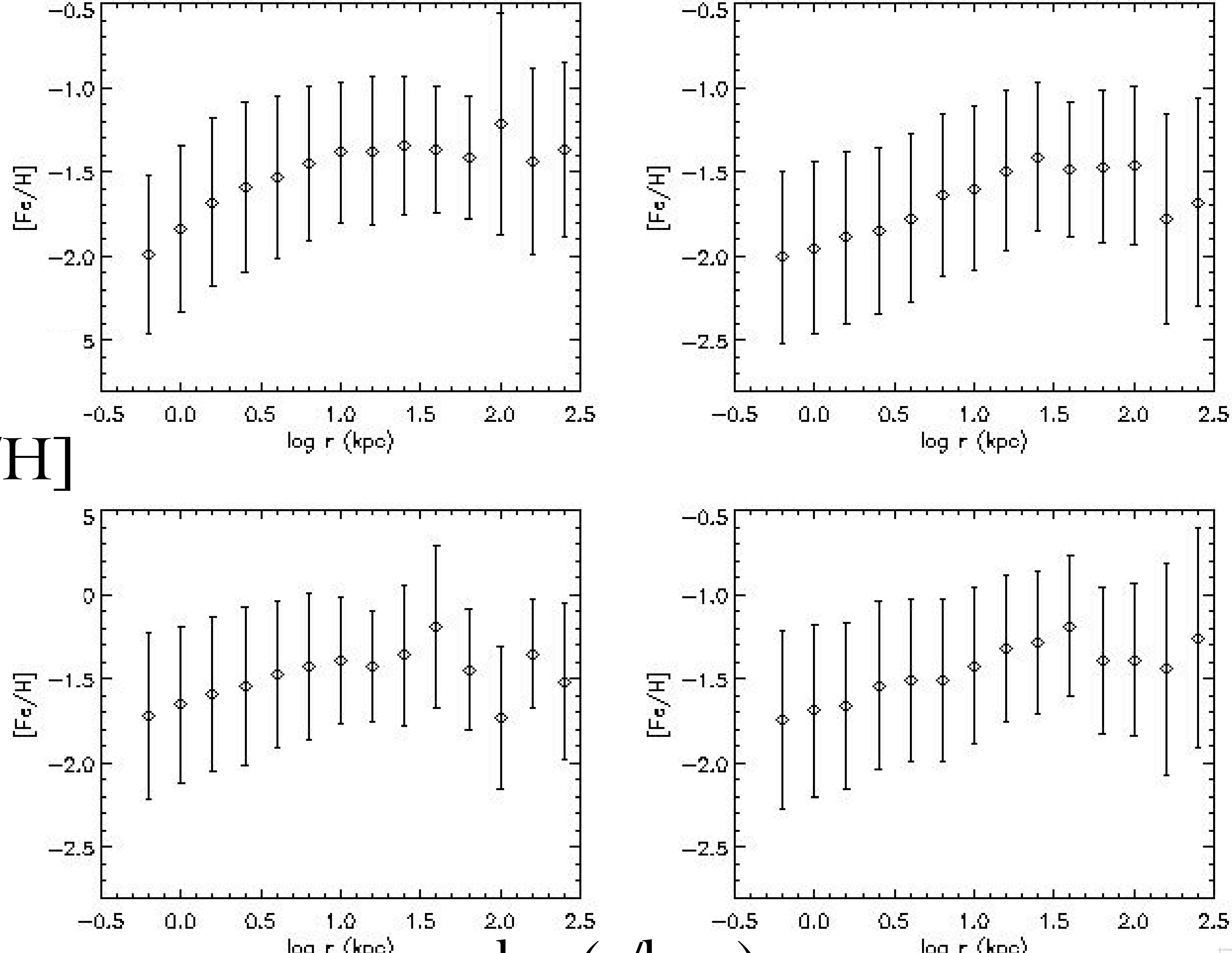
Metallicity Distribution Functions

Formed from large # of low-mass dwarfs.



metal rich: Formed from a few massive dwarfs.

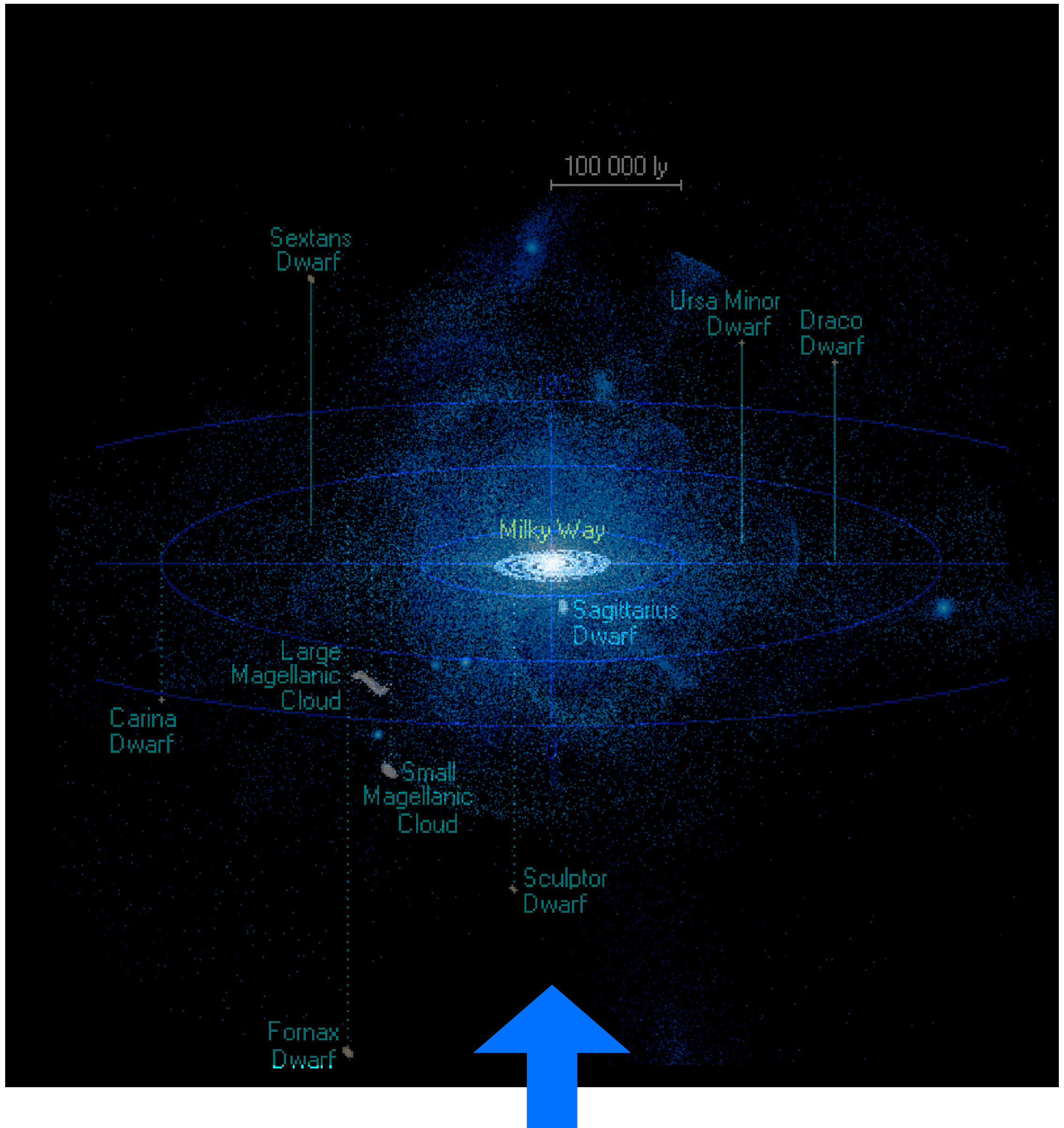
Metallicity Gradient: Outer Regions more metal rich



[Fe/H]

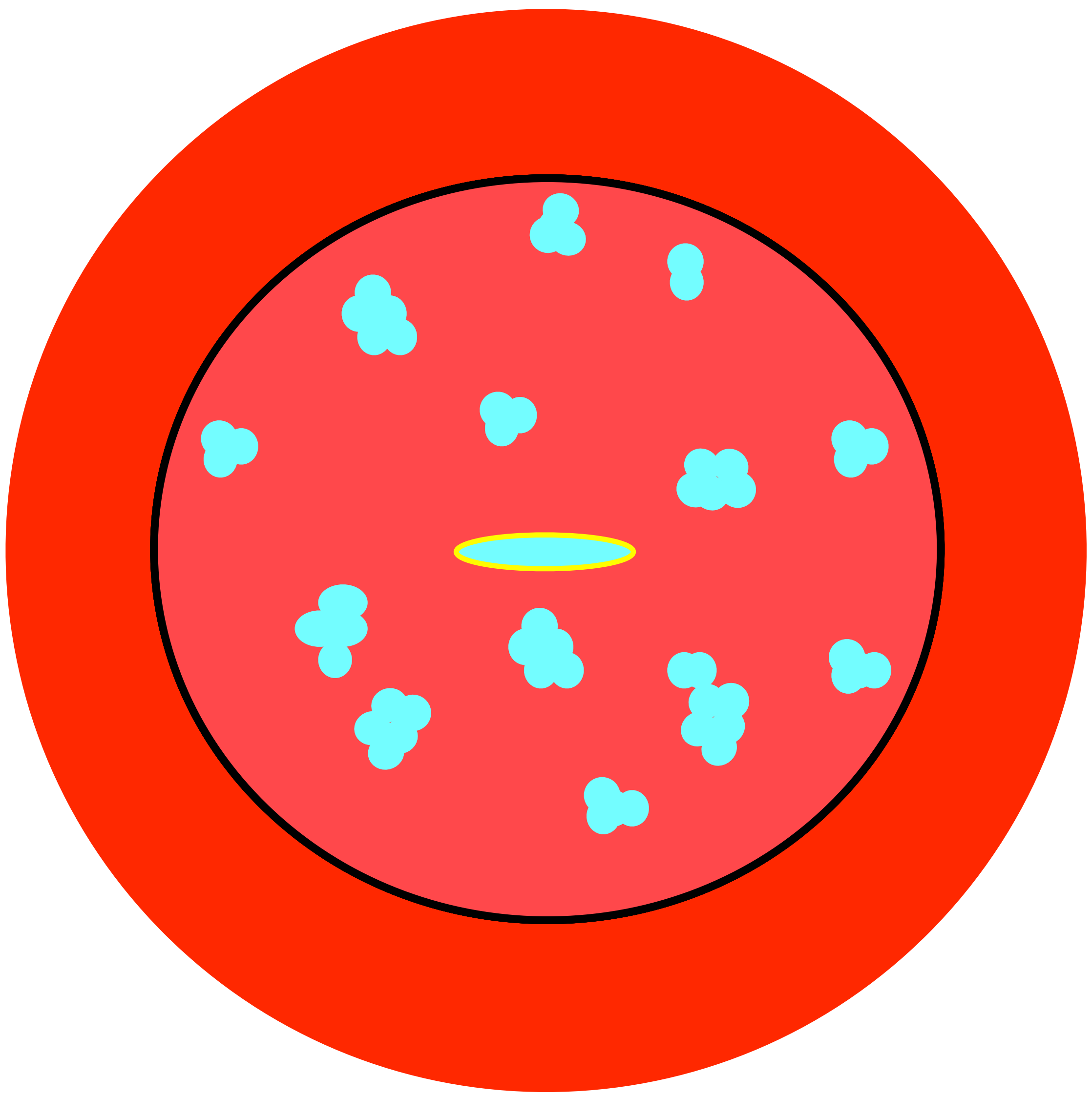
log(r/kpc)

Conclusions



- Models for the stellar halo based within the LCDM context can reproduce the gross characteristics of the stellar halo and local group satellites.
- Chemical Abundance Pattern seems to arise naturally in this context.
- Surveys are underway to test whether the stellar halos of the Milky Way and other nearby galaxies look like this... test whether structure formation is indeed hierarchical on small scales.

Maller & JSB 04

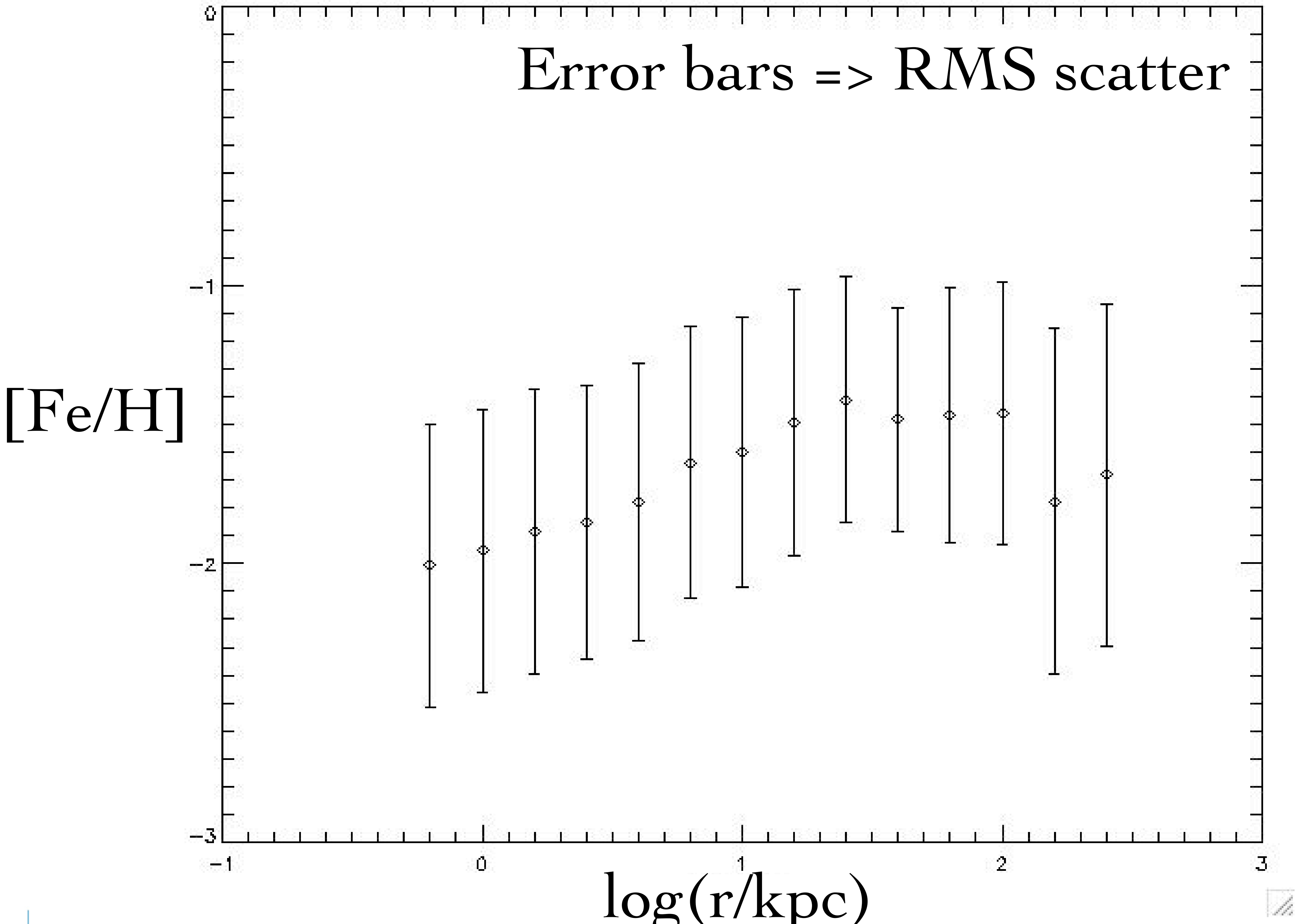


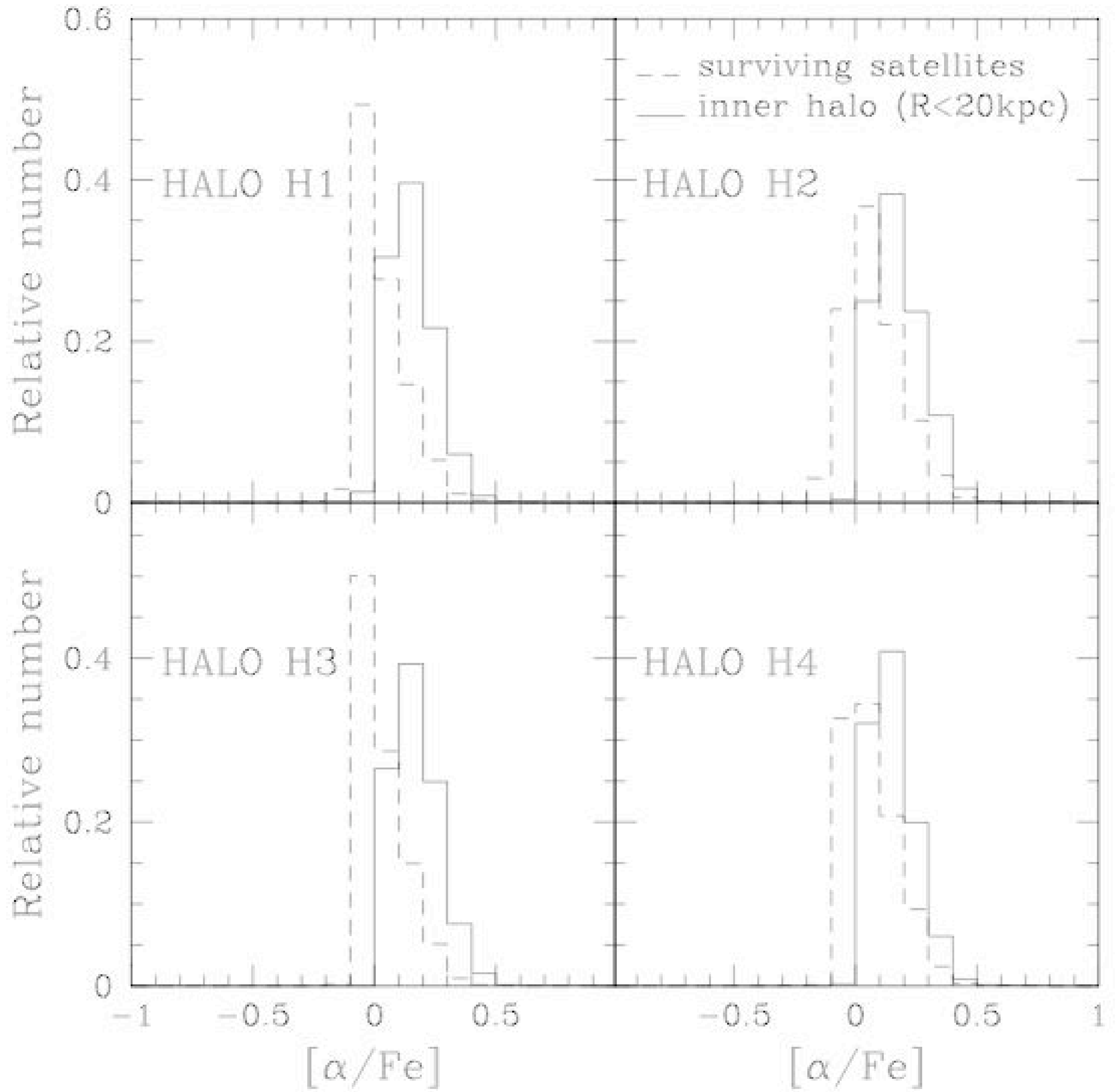
Thermal instability & fragmented Cooling

Helps “overcooling” in massive galaxies.

Residual, low density 10^6K galactic corona, important for ram pressure stripping.

Metallicity Gradient: Outer Regions more metal rich




surviving satellites
inner halo (R<20kpc)
HALO H1
HALO H2
HALO H3
HALO H4
Relative number
Relative number
0.6
0.4
0.2
0
0.4
0.2
0
-1
-0.5
0
0.5
-0.5
0
0.5
1
[α/Fe]
[α/Fe]