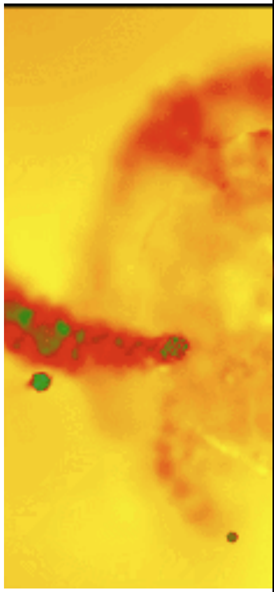
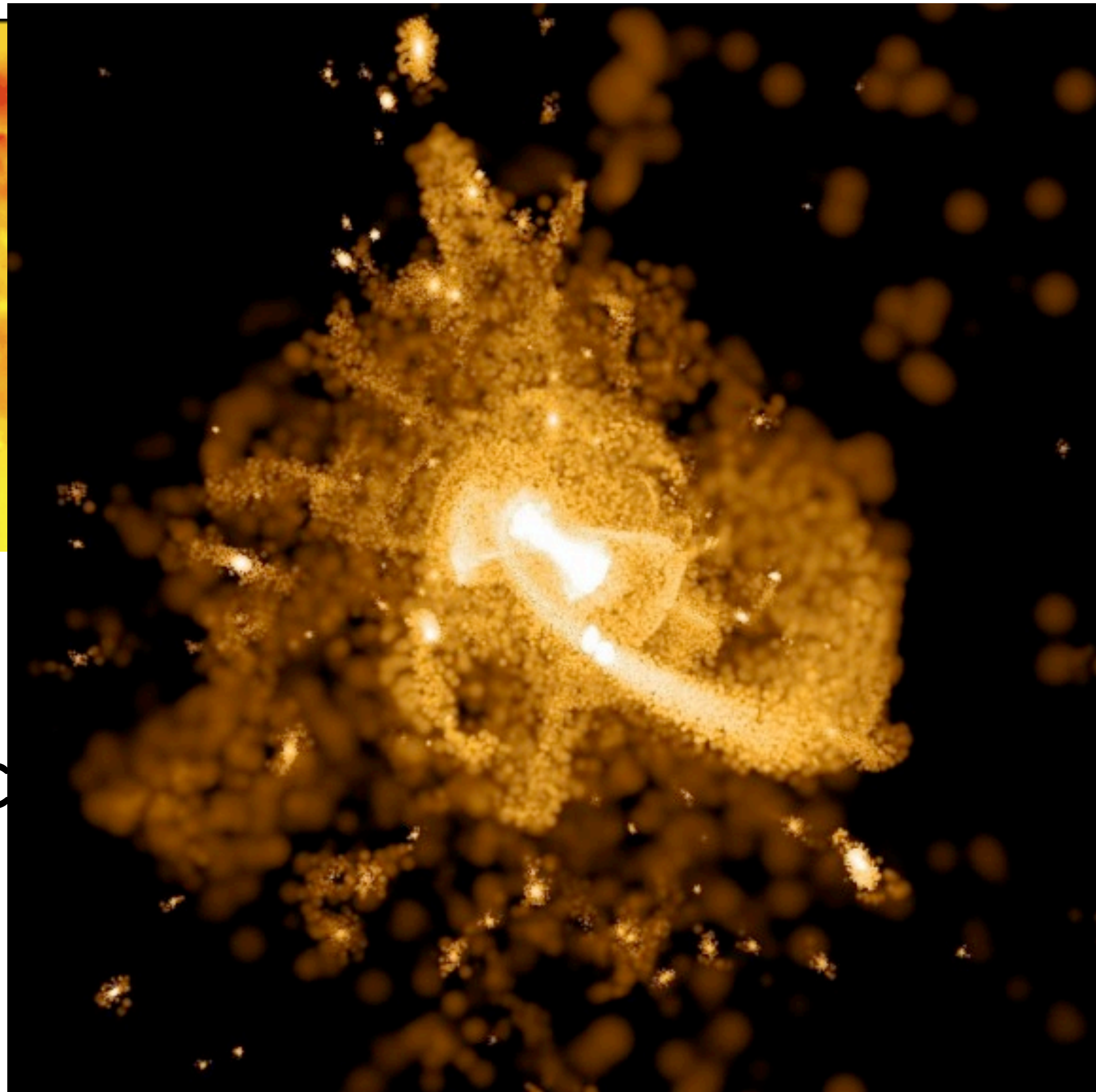
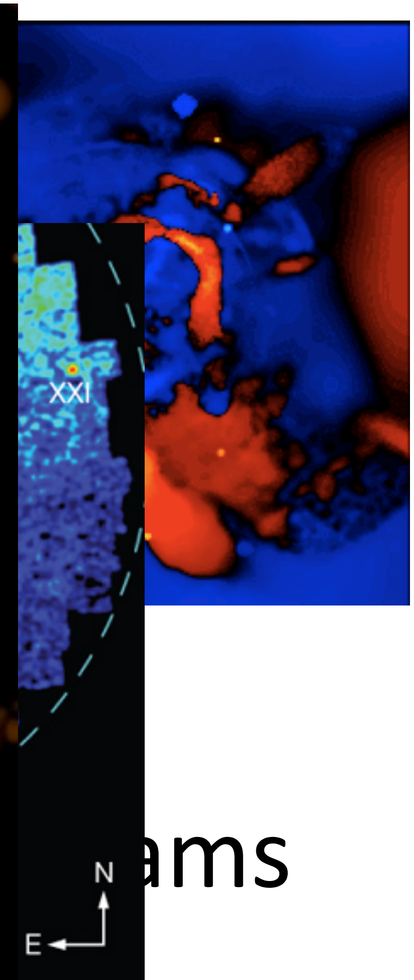
Images by Sanjib Sharma from Johnston/Bullock/Font/Robertson collaboration.

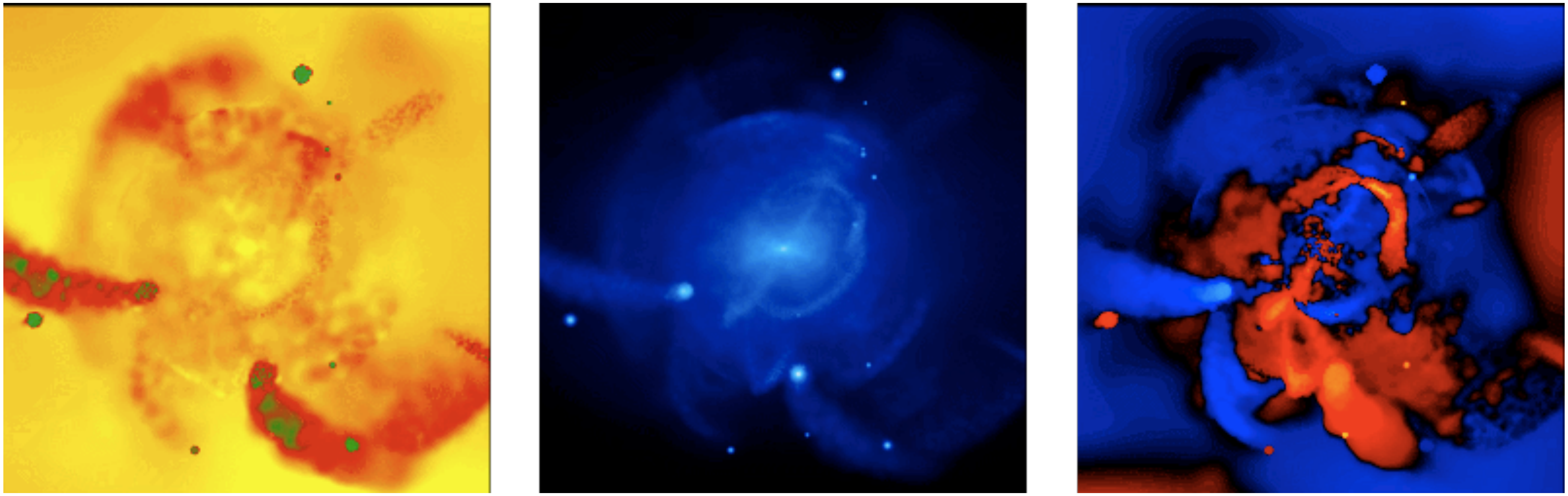






Acc … ams

Images by Sanjib Sharma from Johnston/Bullock/Font/Robertson collaboration.

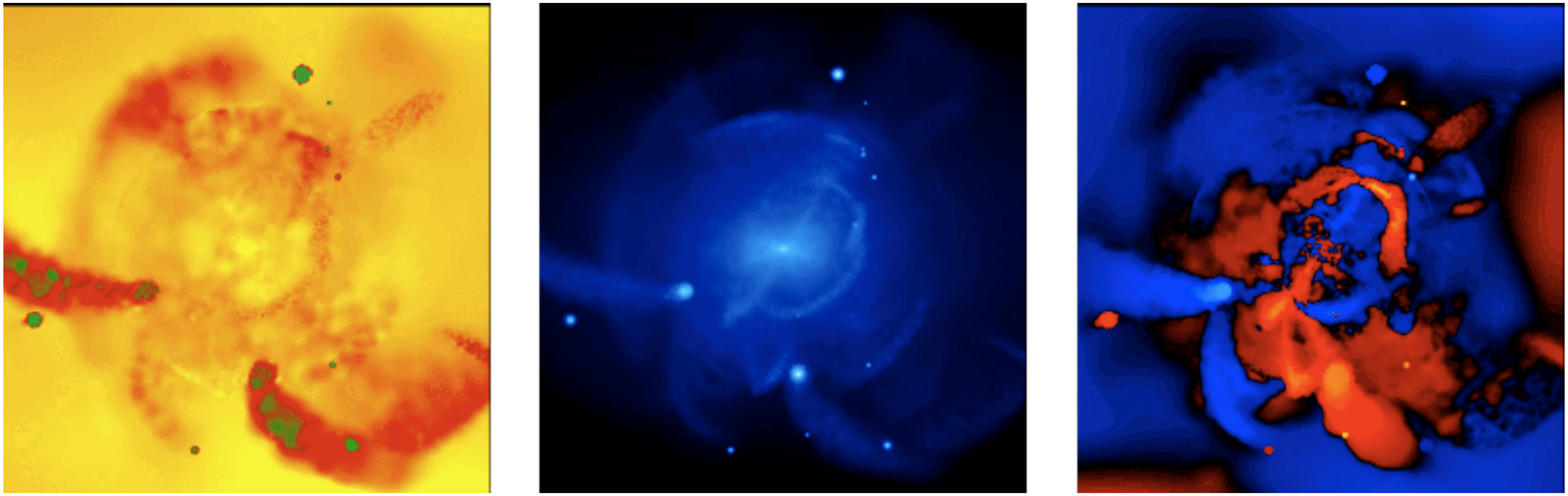


Accretion as Traced by Populations in Stellar Streams

Kathryn V. Johnston
(Columbia University)

Gas in Galaxies, 2011

Images by Sanjib Sharma from Johnston/Bullock/Font/Robertson collaboration.



hierarchical structure formation

+

gas processes?

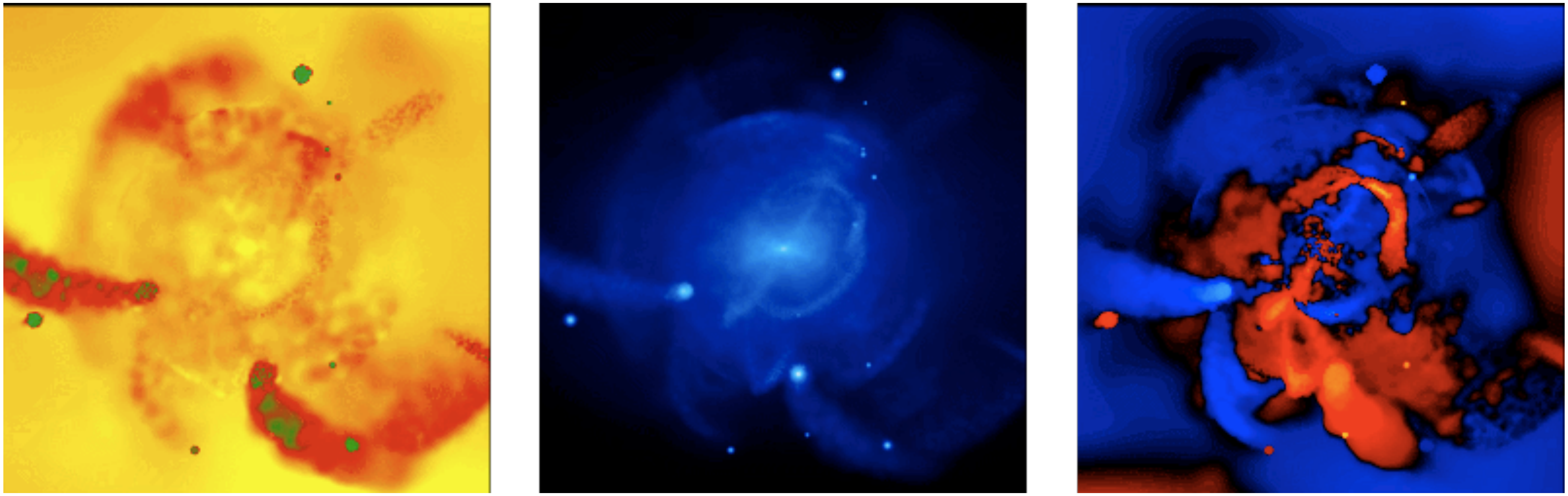
↓

chemical abundance distributions

solved

more data coming

Images by Sanjib Sharma from Johnston/Bullock/Font/Robertson collaboration.



Stellar halo models created with semi-numeric approach

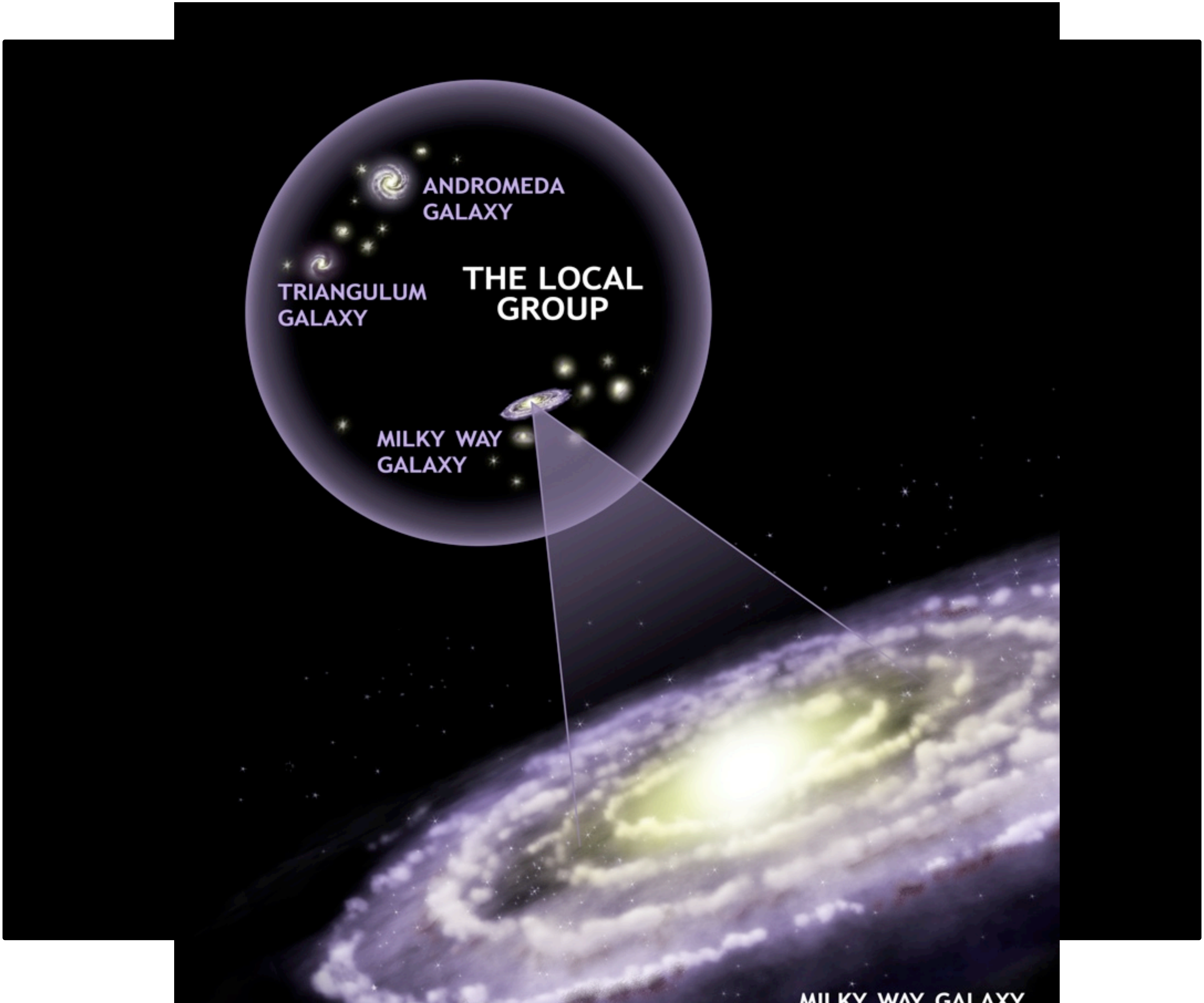
(Bullock & Johnston, 2005; Robertson et al 2005; Font et al 2006)

- N-body simulations of accreting dark matter halos from cosmological history
- painted with stars
- associated SF history and leaky-accreting chemical enrichment model

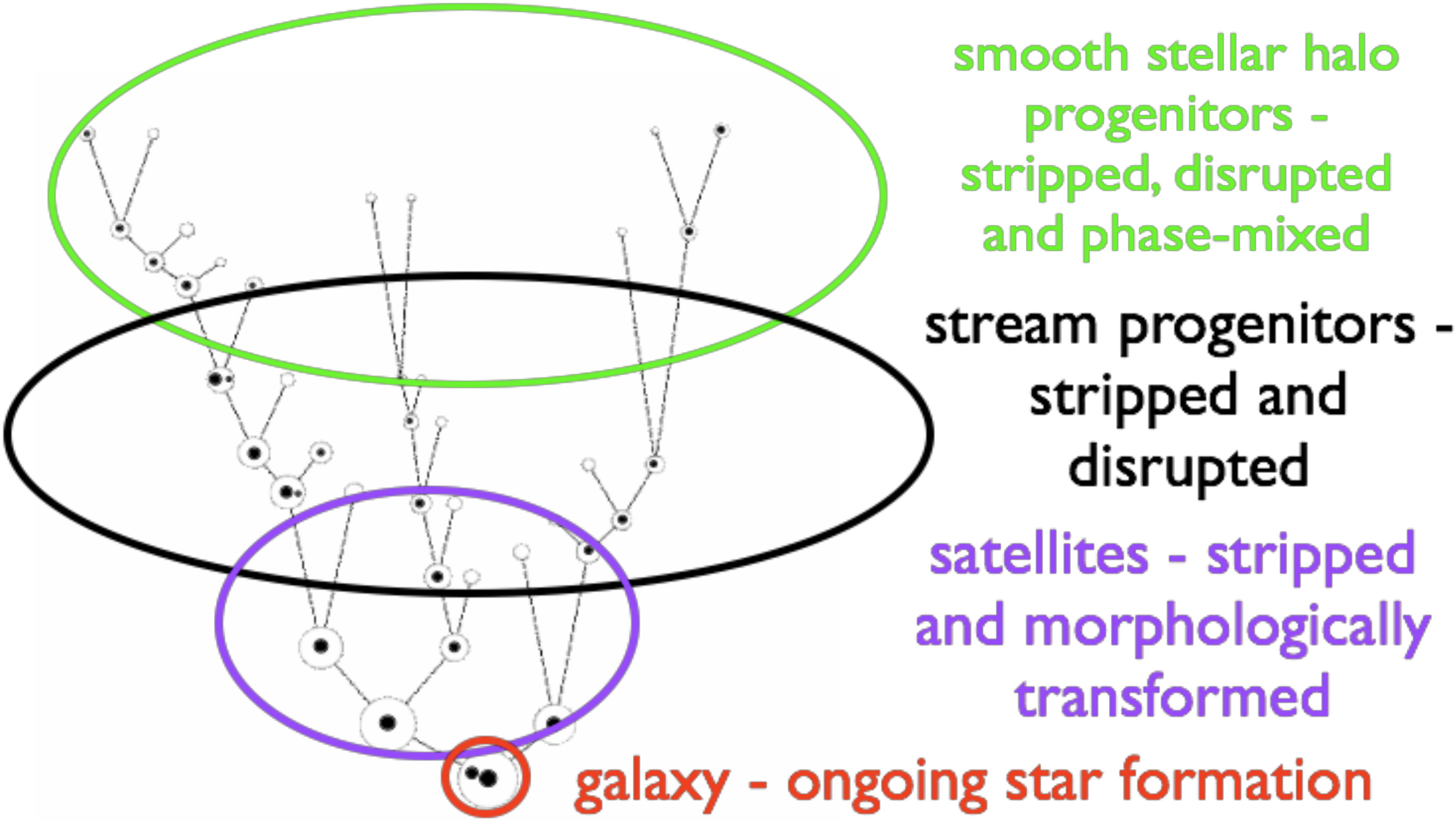
Overview of the overview

- Context
  - galaxy formation from nearby objects
  - following gas history star-by-star
- Application: stellar populations as tracers of
  - gas processes
  - accretion
- Future prospects

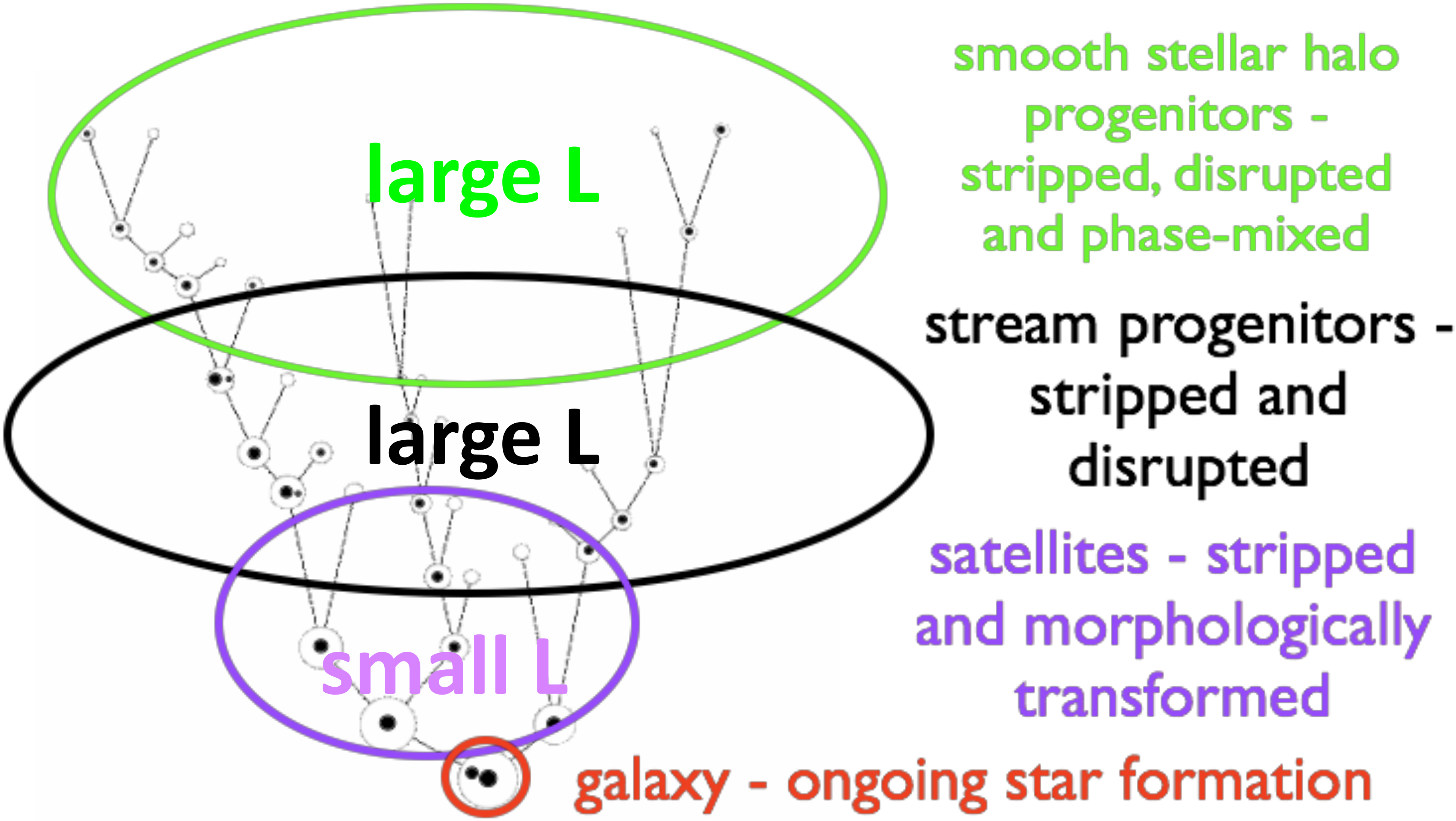
Context I:
Galaxy formation from nearby galaxies


ANDROMEDA
GALAXY
TRIANGULUM
GALAXY
THE LOCAL
GROUP
MILKY WAY
GALAXY

Timescales ⇔ When?

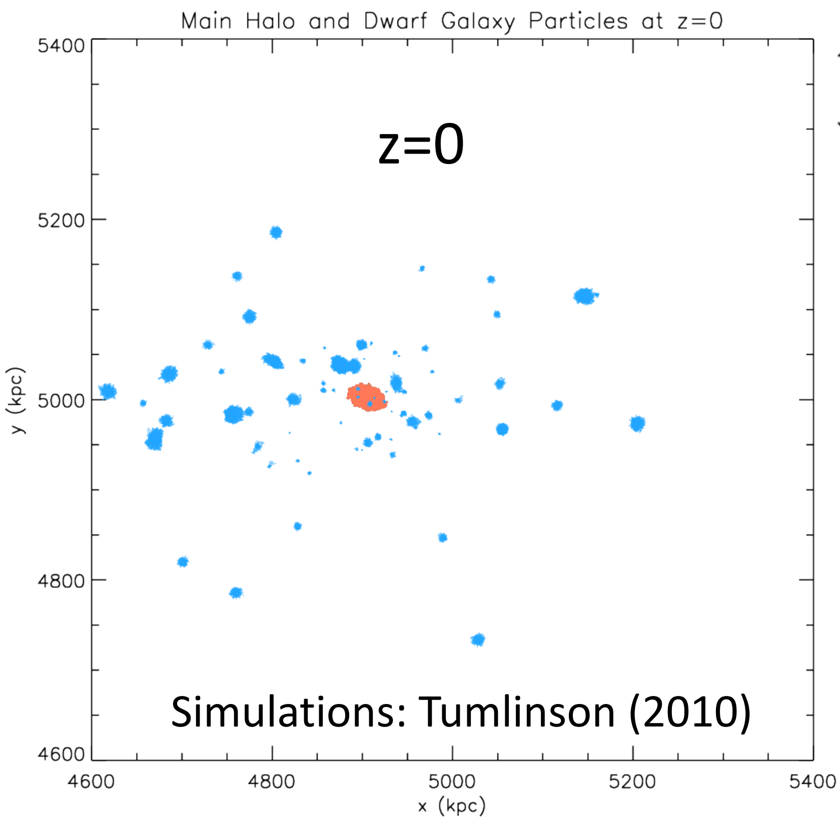


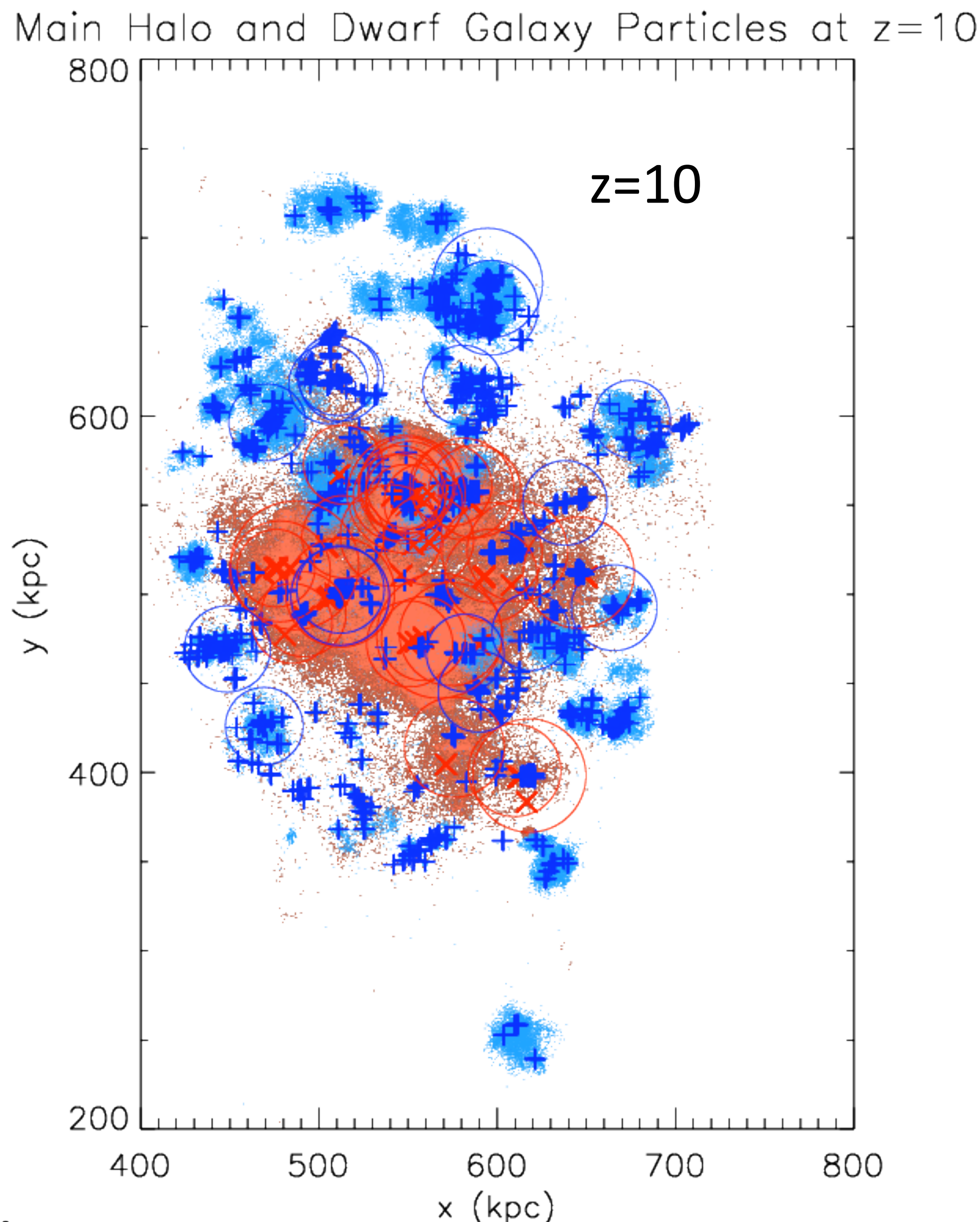
DM Halos ⇔ What?



Environment⇔Where?

- E.g "where do high-sig peaks end up" Moore, Madau & Diemand, 2005
- or "where do satellites come from?" Lauren Corlies, Johnston, Tumlinson & Bryan, 2011, *in prep*





Context I:
Galaxy formation from nearby galaxies

- Variety in histories imposed by hierarchy:

	Timescale	DM halo	Environment
Stellar halo	short	large	more dense
Streams	longer	large	less dense
Satellites	longest	small	less dense

laboratory for gas processes that make galaxies

Context II: Gas history star-by-star

Accreted gas

- in halos and along filaments
- forms *in situ* stellar population
- dominate the disk

Accreted stars

- in halos
- forms accreted stellar population
- dominate the stellar halo

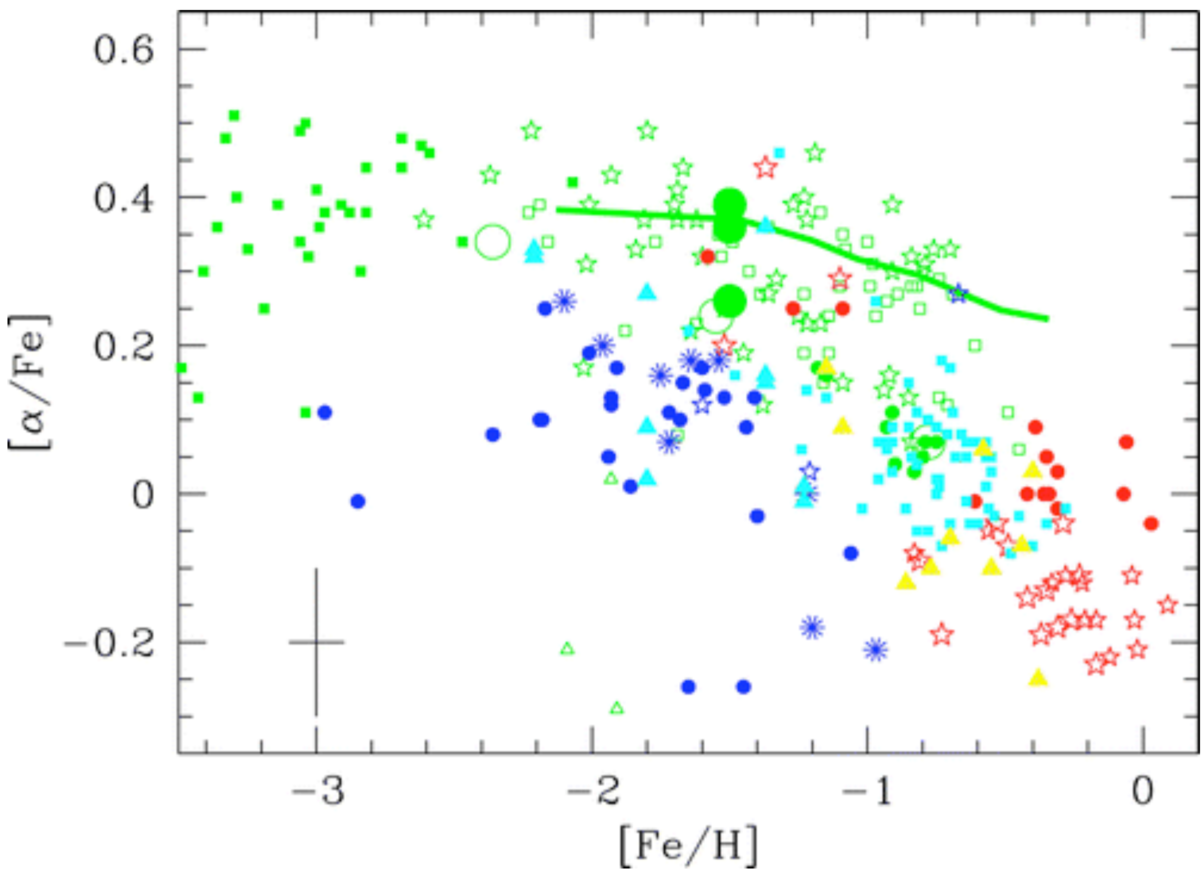
Gas forgets but stars remember!

phase-space structure ⇔ halo in which born

chemical abundances ⇔ birth-cloud and prior processing

Stellar Populations I: Gas History

- chemical abundances ⇔ birth-cloud + prior processing
- local objects ⇔ variety of histories



green - halo
blue - low mass dSph
yellow - dIrr
red - Sgr
cyan - LMC

(data compilation from Geisler et al, 2007)

Stellar Populations I: Gas History

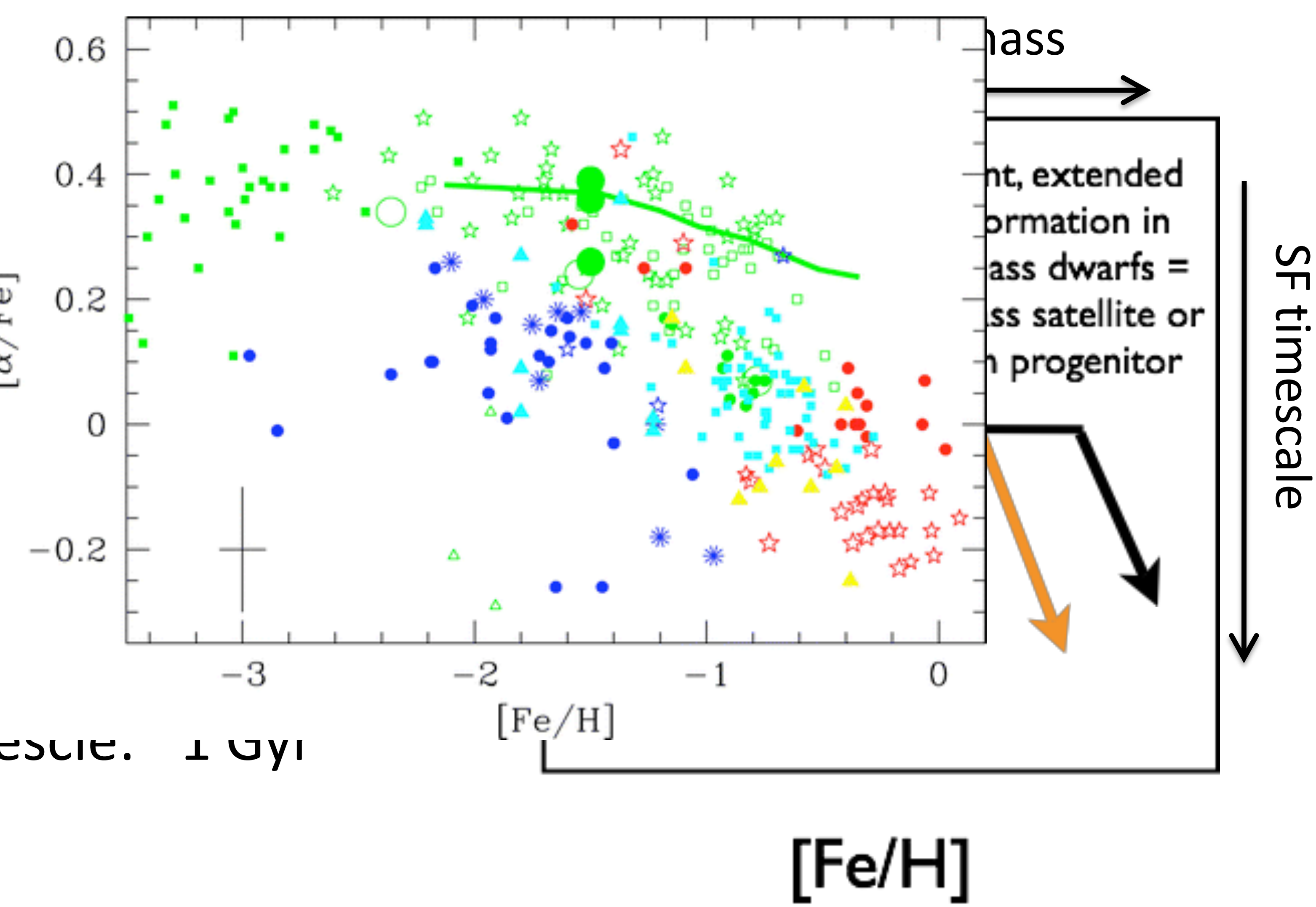
- abundances ⇔ birth-cloud + prior processing
- local objects ⇔ variety of histories

	Timescale	DM halo	Environment
Stellar halo	short	large	more dense
Streams	longer	large	less dense
Satellites	longest	small	less dense

Chemical abundance patterns from hierarchical structure formation + gas processing

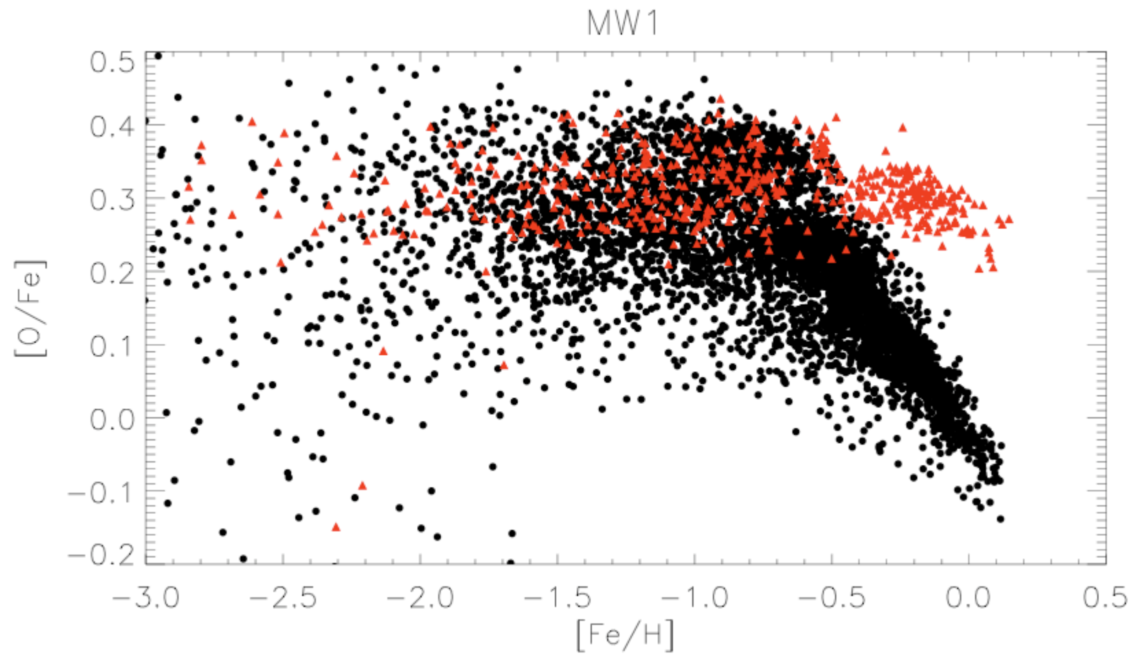
Gas pro

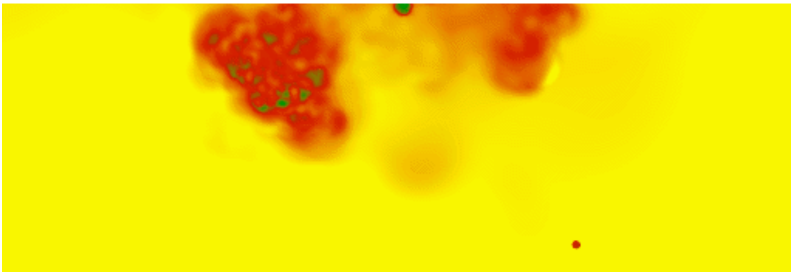
- Alpha
  - Sou
  - Tim
    10-
- Fe
  - Sou
  - Timescale: 1 Gyr



e.g. satellites *vs* streams *vs* stellar halo

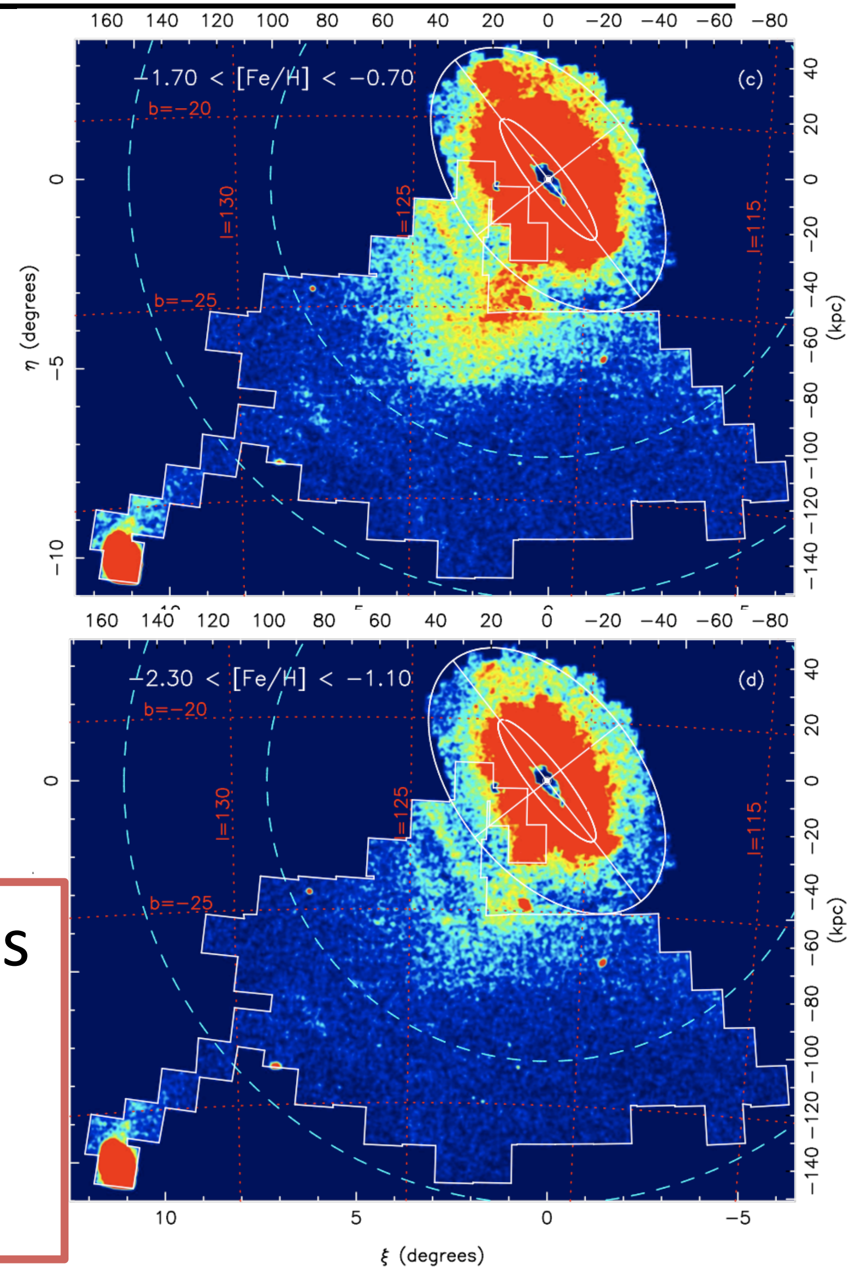
- Mass ⇔ brightest streams – metal-rich (Gilbert et al 2009)
- Timescale ⇔ streams/satellites – alpha-poor (Font et al 2008)
- Mass/timescale ⇔ *in situ* halo stars – metal-rich and alpha-rich (Zolotov et al 2010, see also Font et al 2010)





Observations: stream-stream variations

- M31
  - Photometry (PANDAs)
  - Spectroscopy (SPLASH)
- Milky Way (SDSS)
  - Photometry: ratio of BHB/ MSTO stars (Bell et al 2010)
  - Spectroscopy: ECHO's (Schlaufman et al, 2010)

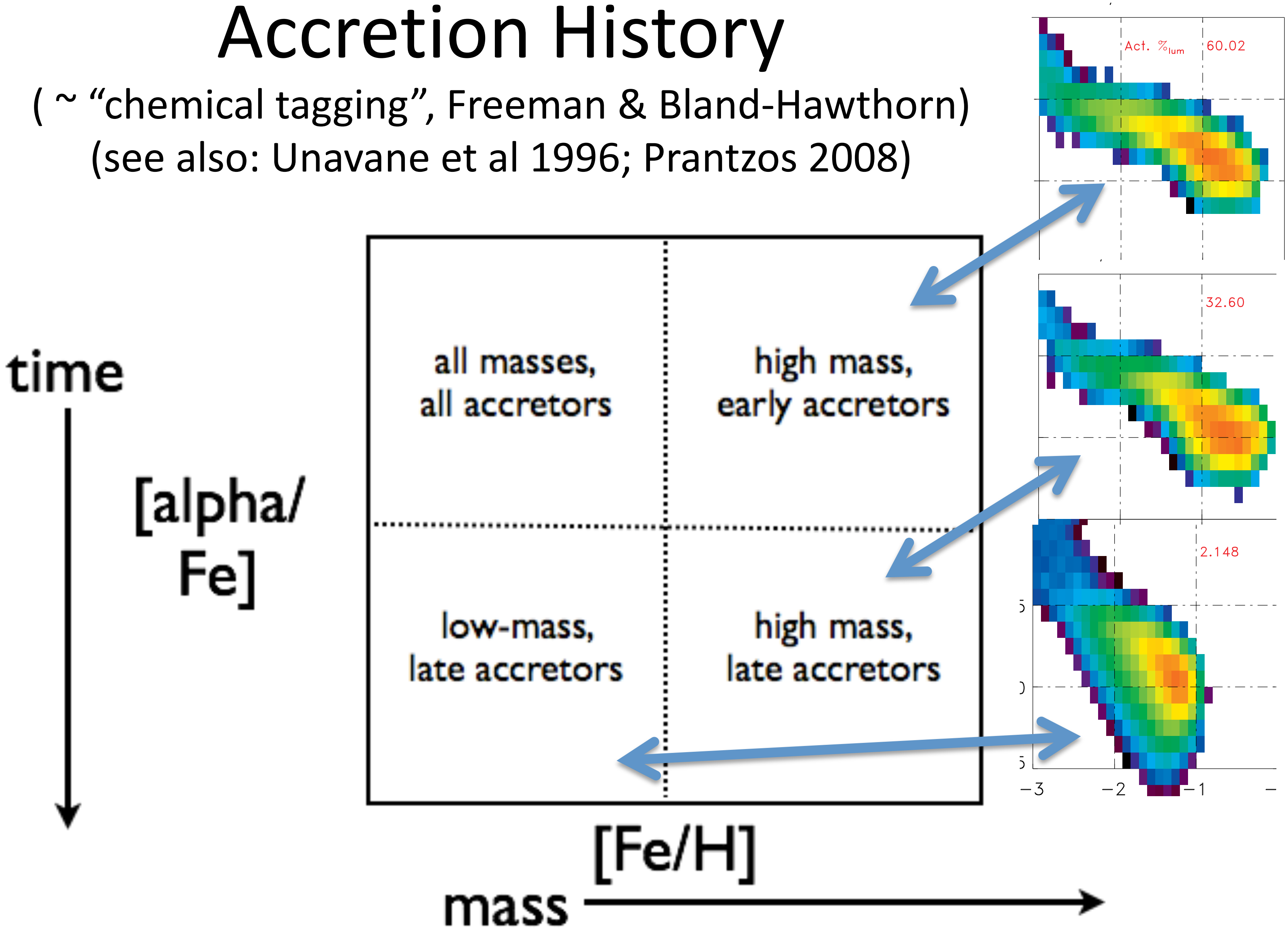


Variations in history ⇔ differences

- stream ~ stream
- satellite ~ stream ~ halo
- accreted ~ *in situ* stars

Stellar Populations II: Accretion History

(~ “chemical tagging”, Freeman & Bland-Hawthorn)
(see also: Unavane et al 1996; Prantzos 2008)

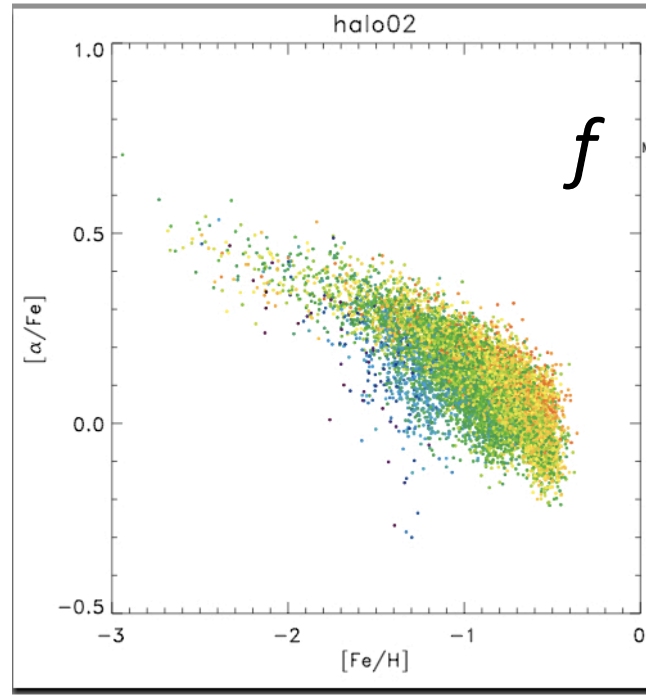


The idea..

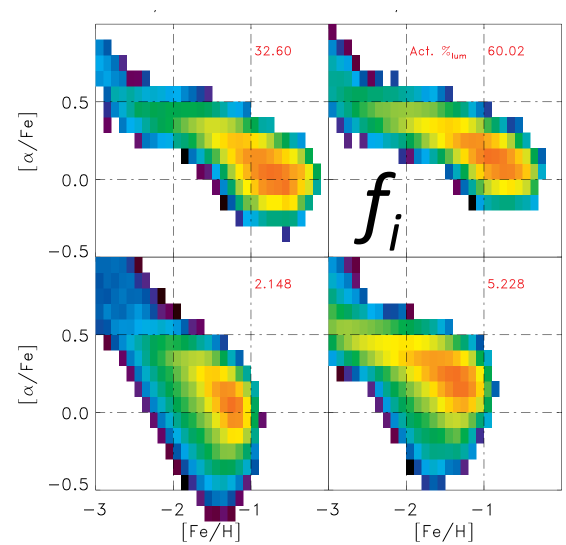
1. *f*= observed distribution
2. f_i= template distributions for different (M_*, t_{acc}) bins
3. find A_i such that

$$f = \Sigma_i A_i f_i$$

A_i =fraction of stars accreted in each (M_*, t_{acc}) bin = accretion history!



M_*=



10^7-10^9 Msun

10^4-10^7 Msun

t_{acc}= 0-8 Gyrs 8-14 Gyrs

Testing the idea…

<u>Duane Lee,</u> Johnston, Jessop, Sen, 2011, *in prep*

$$f = \Sigma_i A_i f_i$$

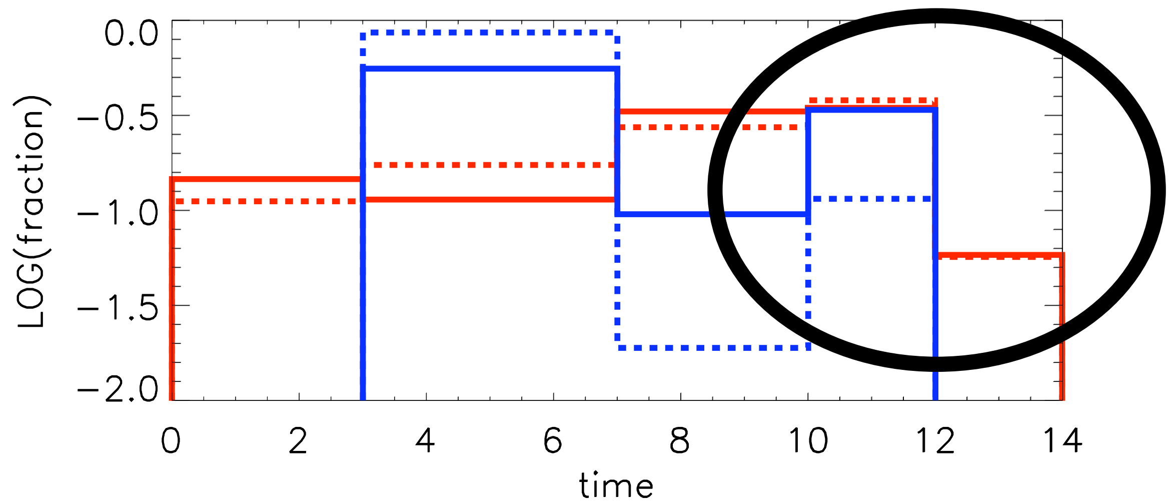
- f = "observations" of 11 model stellar halos
- f_i = 5x5 grid of (M_*, t_{acc}) bins of all satellites
- Statistical approach
  - Define likelihood:

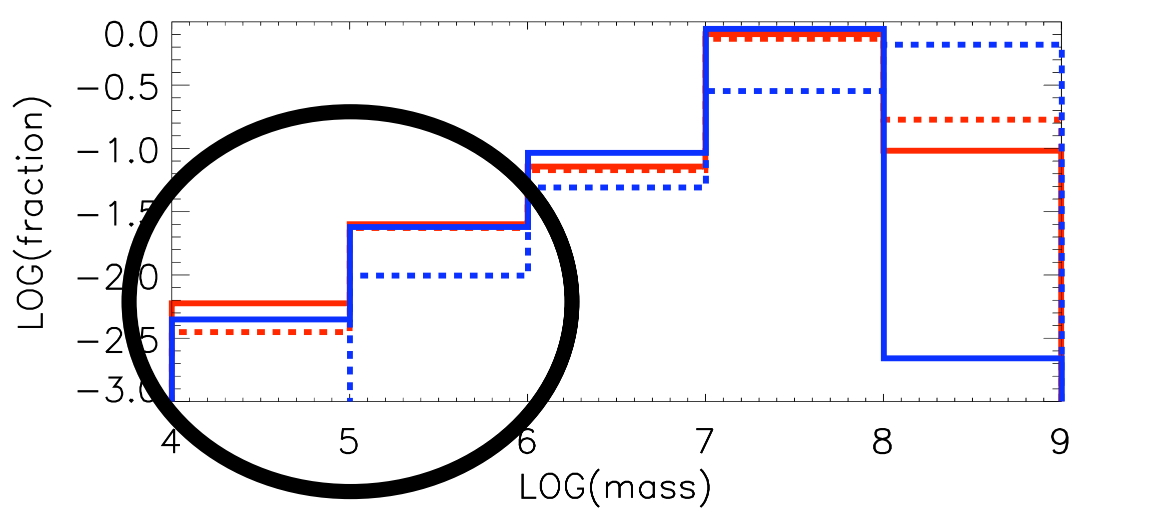
$$L(\mathbf{A}) = \Pi_{j=1}^{n} f(x_j, y_j) = \Pi_{j=1}^{n} \Sigma_{i=1}^{m} A_i f_i(x_j, y_j)$$

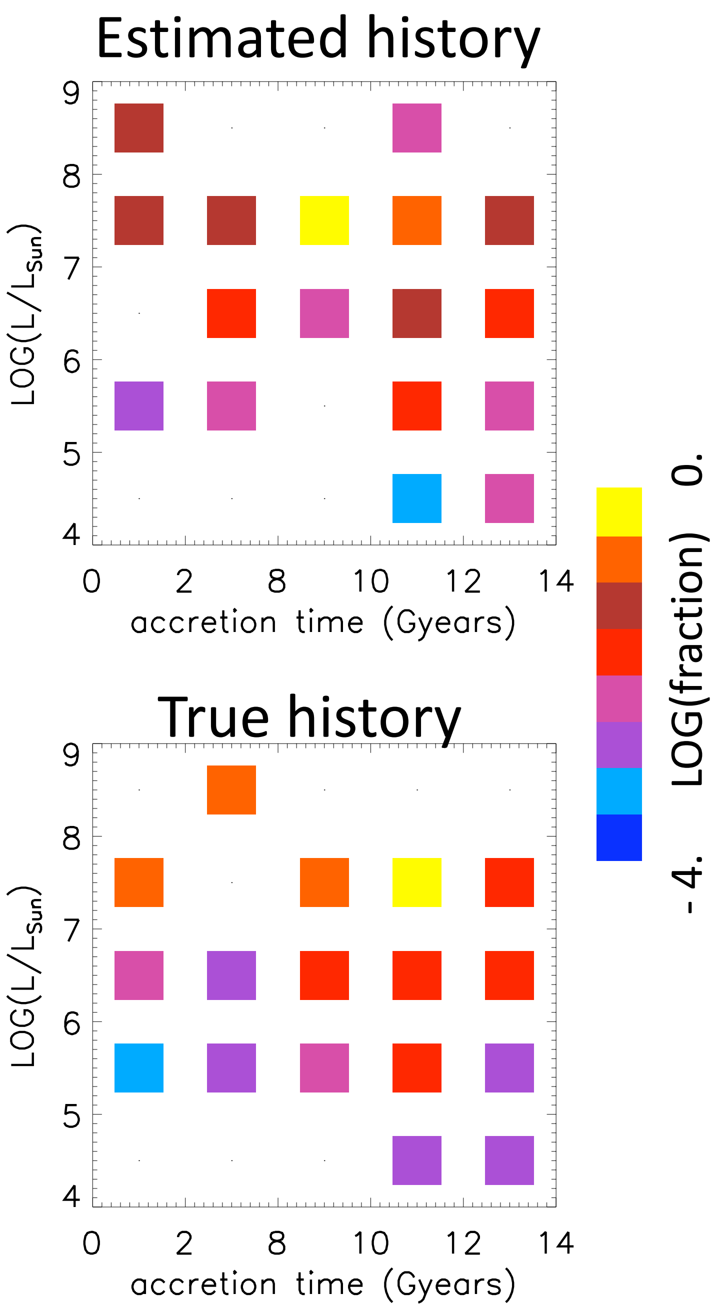
$$x_j = [\mathrm{Fe/H}], \quad y_j = [\alpha/\mathrm{Fe}]$$

  - Use expectation-maximization technique to find A_i

Results I: projected accretion histories







Results II:
Full 2-D Accretion History

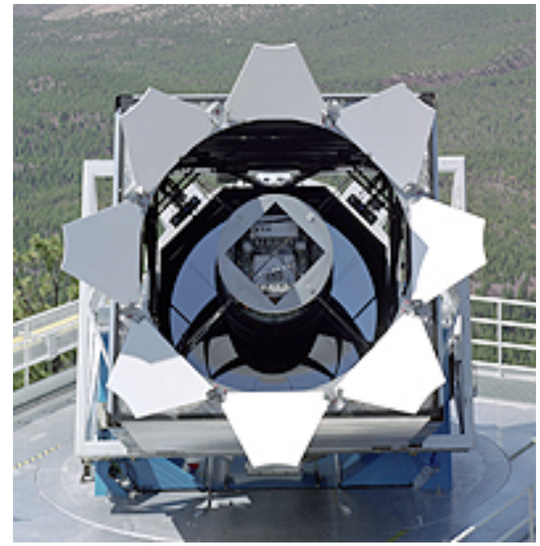
Abundances indicate:

- low mass end of luminosity function
- early accretion epoch

Future Prospects for Populations: more data in more dimensions

- High-resolution, multi-fiber spectroscopy:
  - APOGEE (SDSS), 2011 , IR, 15 elements for 10^5 stars (R~20,000 to H=12.5)
  - Hermes (AAT), 2012, optical, Fe alpha, r-, s-process, 10^6 stars

Source	elements	Timescale	Energy-scale
SN Ia	Fe, alpha	~0.1-3 Gyr	explosive
SN II	alpha, Fe, r-process	~10-30 Myr	explosive
AGB	s-process	~0.1-3 Gyr	winds

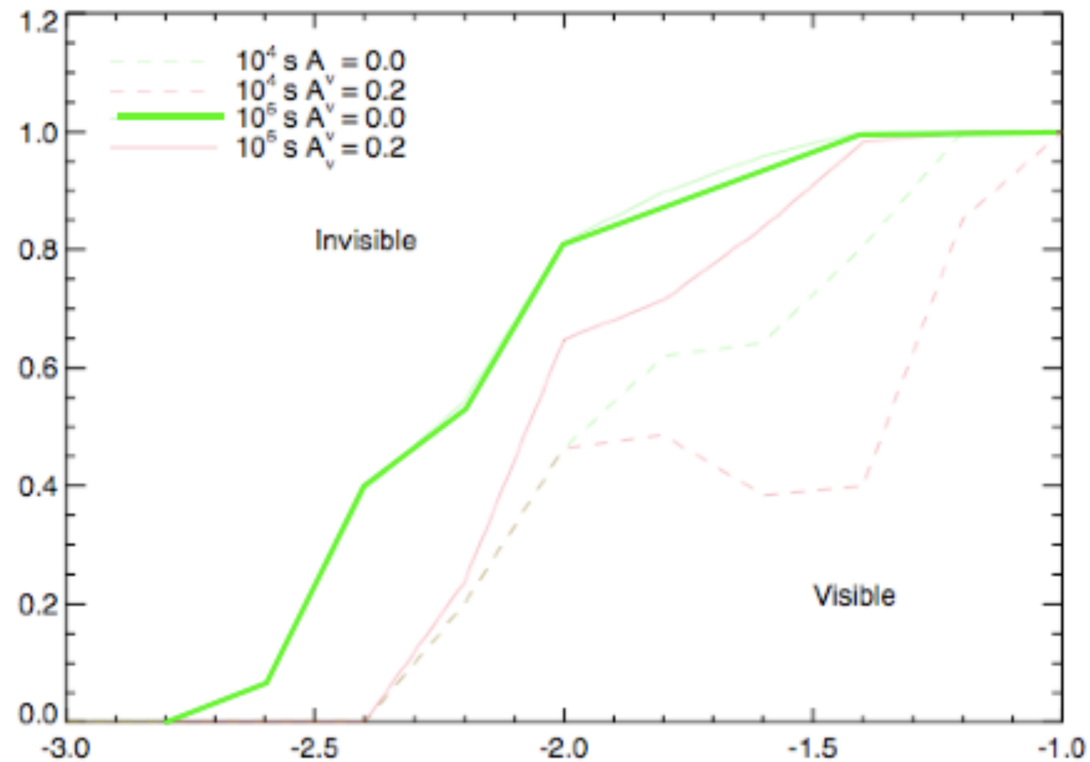


+ observed abundance *distributions*
+ hierarchical structure formation
➢ gas processing

Future Prospects for Populations: low-Fe stars and MW progenitors

Okrochkov & Tumlinson 2010 – "observing" a cosmological simulation with JWST.....

fraction of MW progenitor galaxies visible with JWST

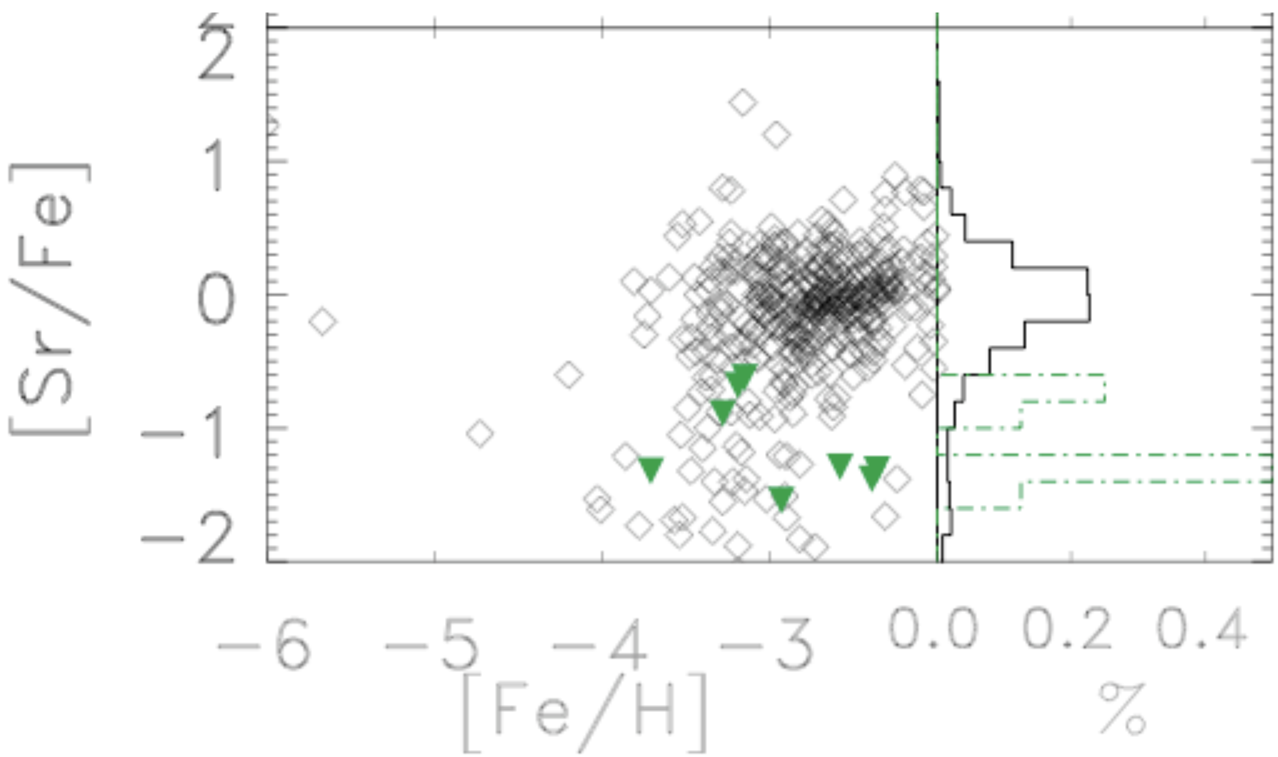


metallicity of stars in those progenitors

Low metal stars = effective way to observe the first stages of formation of L_* galaxies

Future Prospects for Populations: low-Fe stars and MW progenitors

- e.g. neutron-capture elements at low metallicity - compilation by Frebel (2010): black = halo stars; green = stars in ultra-faint dwarfs



Interpretation: Frebel & Bromm (2010); Lee, Johnston, Simon & Sen (2011), *in prep*

Summary

- Chemical abundance distributions of stars in our own and nearby galaxies tell us something about:
  - gas processing
  - accretion
  - today and in early Universe.

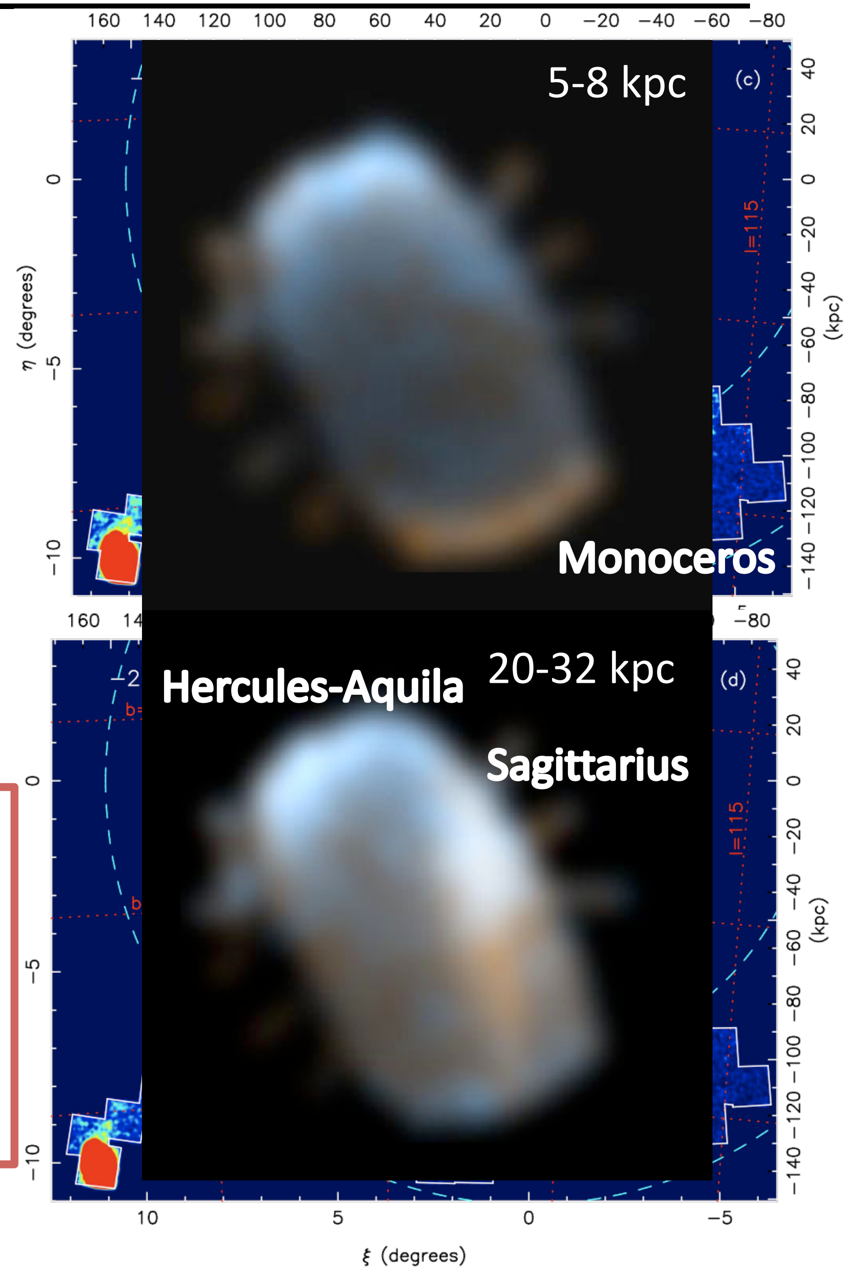
WHAT?

Summary

- Local stars ⇔ tracers of galaxy formation
- Futures directions
  - More data and more dimensions
  - Abundance distributions tracing
    - Accretion back to earlier times and low luminosity objects
    - Gas processing in early Universe

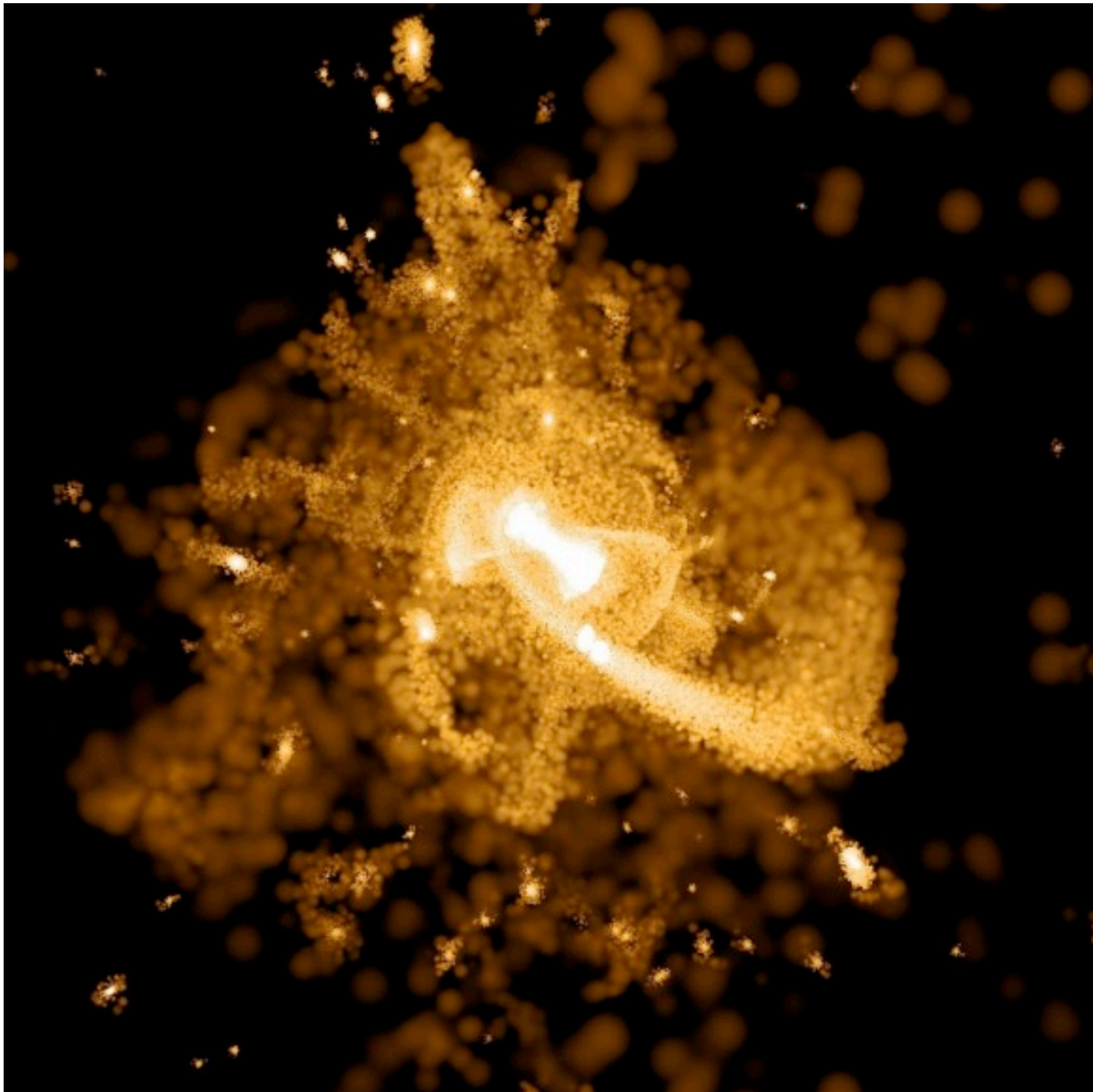
Observations: stream-stream variations

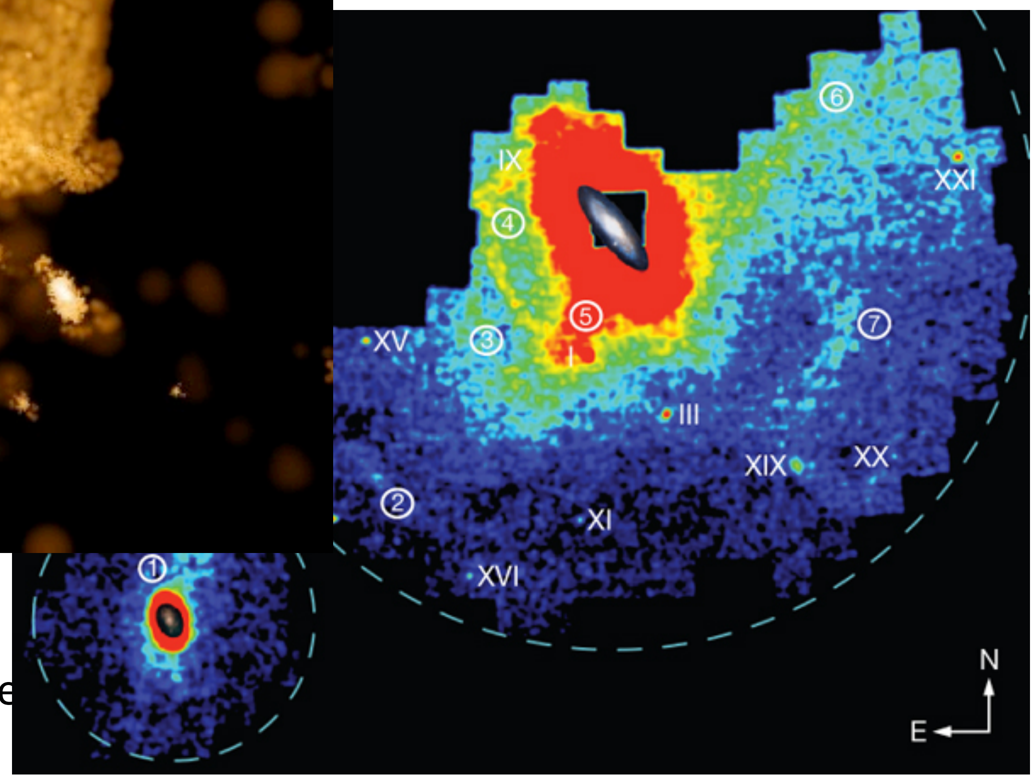
- M31 (PANDAs survey)
- Milky Way (SDSS)
  - Photometry: ratio of BHB/ MSTO stars (Bell et al 2010)
  - Spectroscopy: ECHO's (Schlaufman et al, 2010)



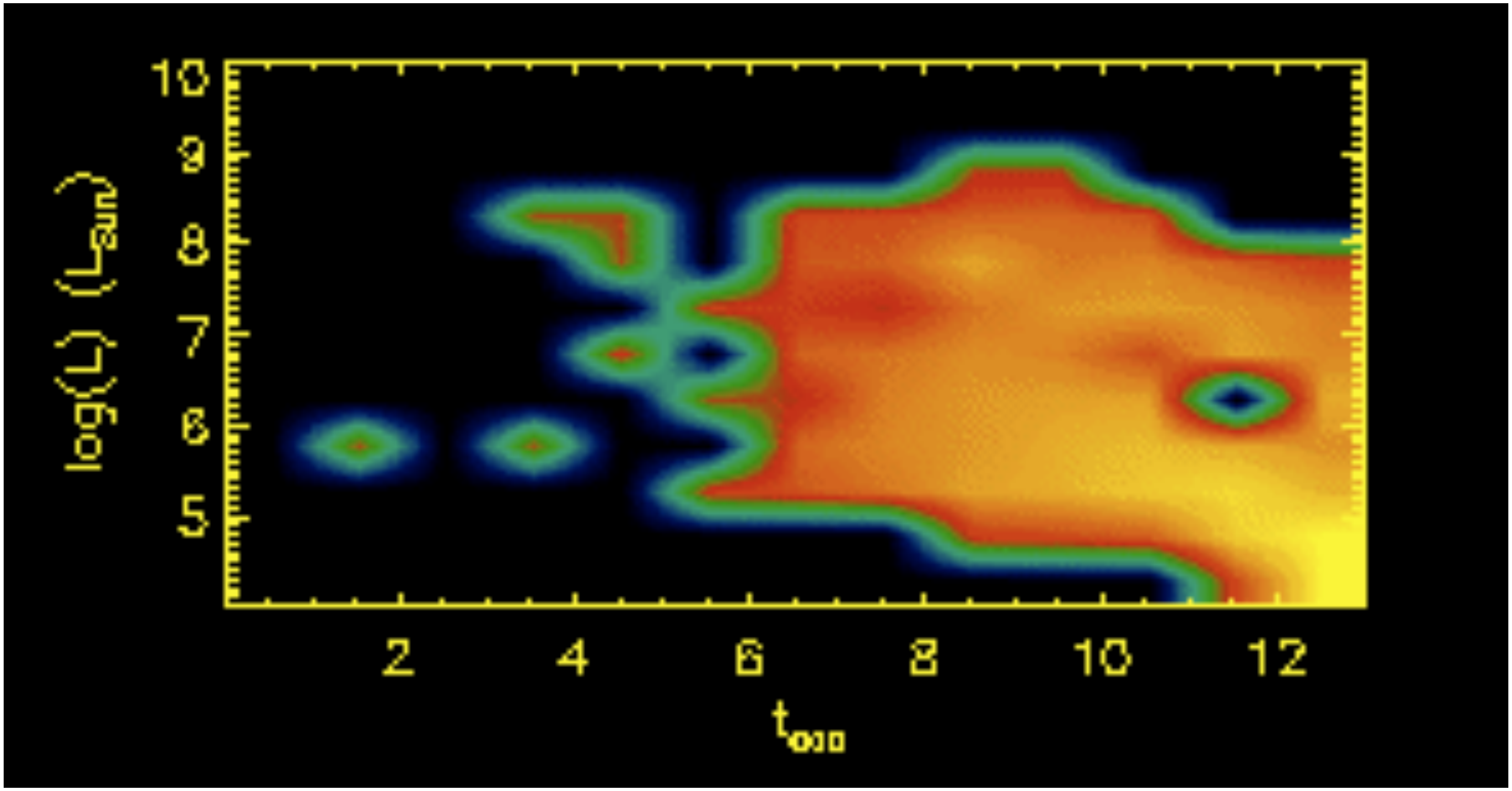
Variations in history
⇔stream-stream differences
⇔ satellite/stream/halo differences

ew

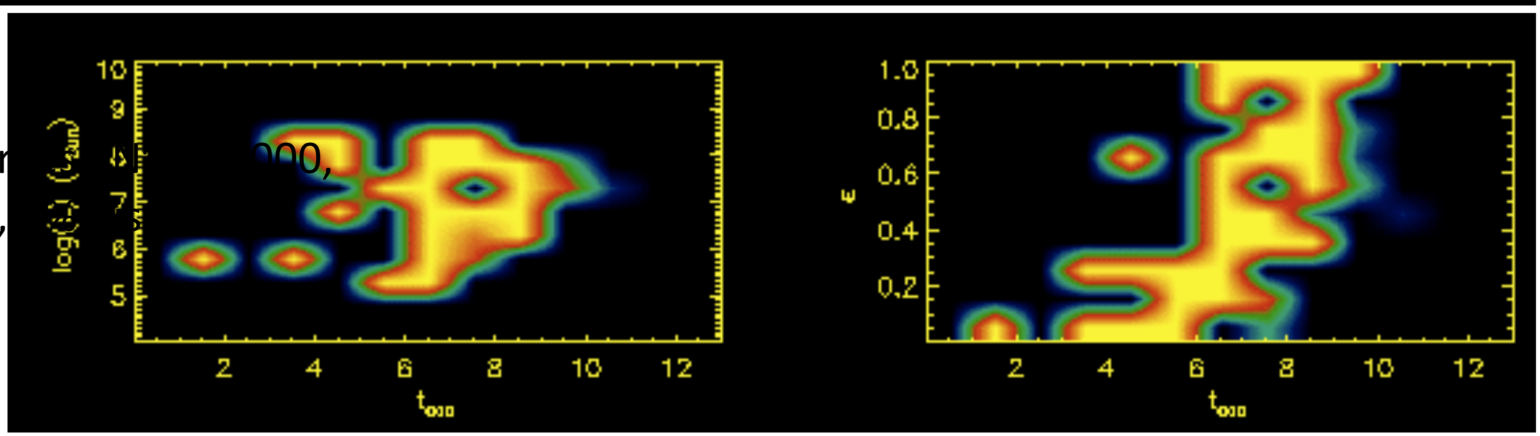




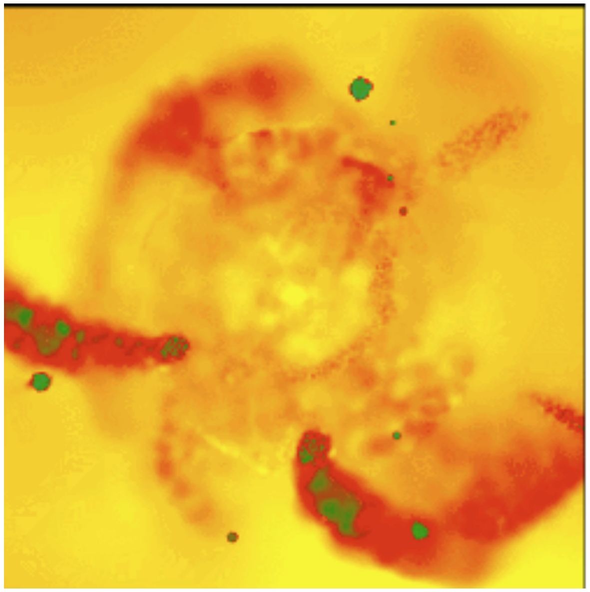
Accretion happens at rate ~ consiste

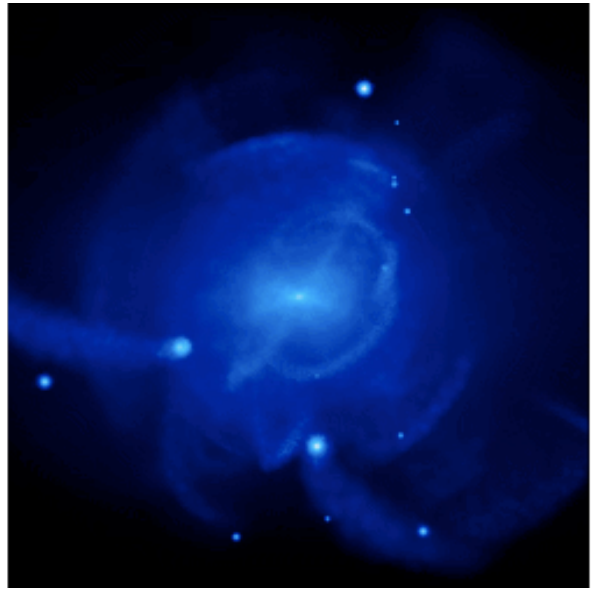


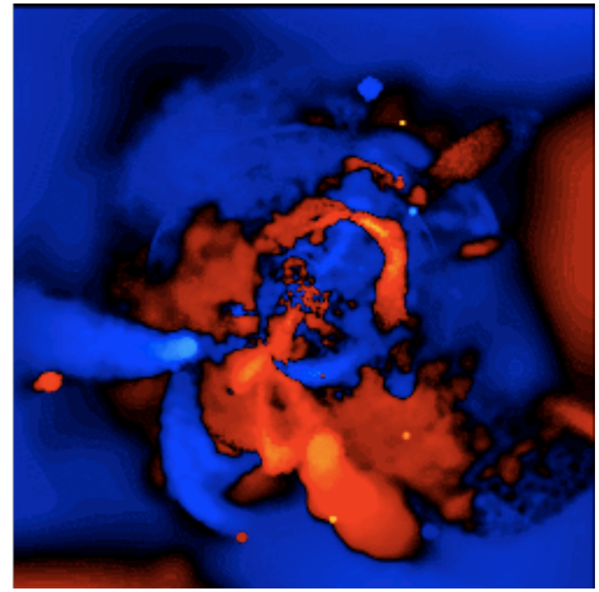
LSST RR Lyr 000,
R~350 kpc,



Images by Sanjib Sharma from Johnston/Bullock/Font/Robertson collaboration.







Tracing accretion with.....

...alpha-element abundances

• conserved indefinitely

... surface brightness

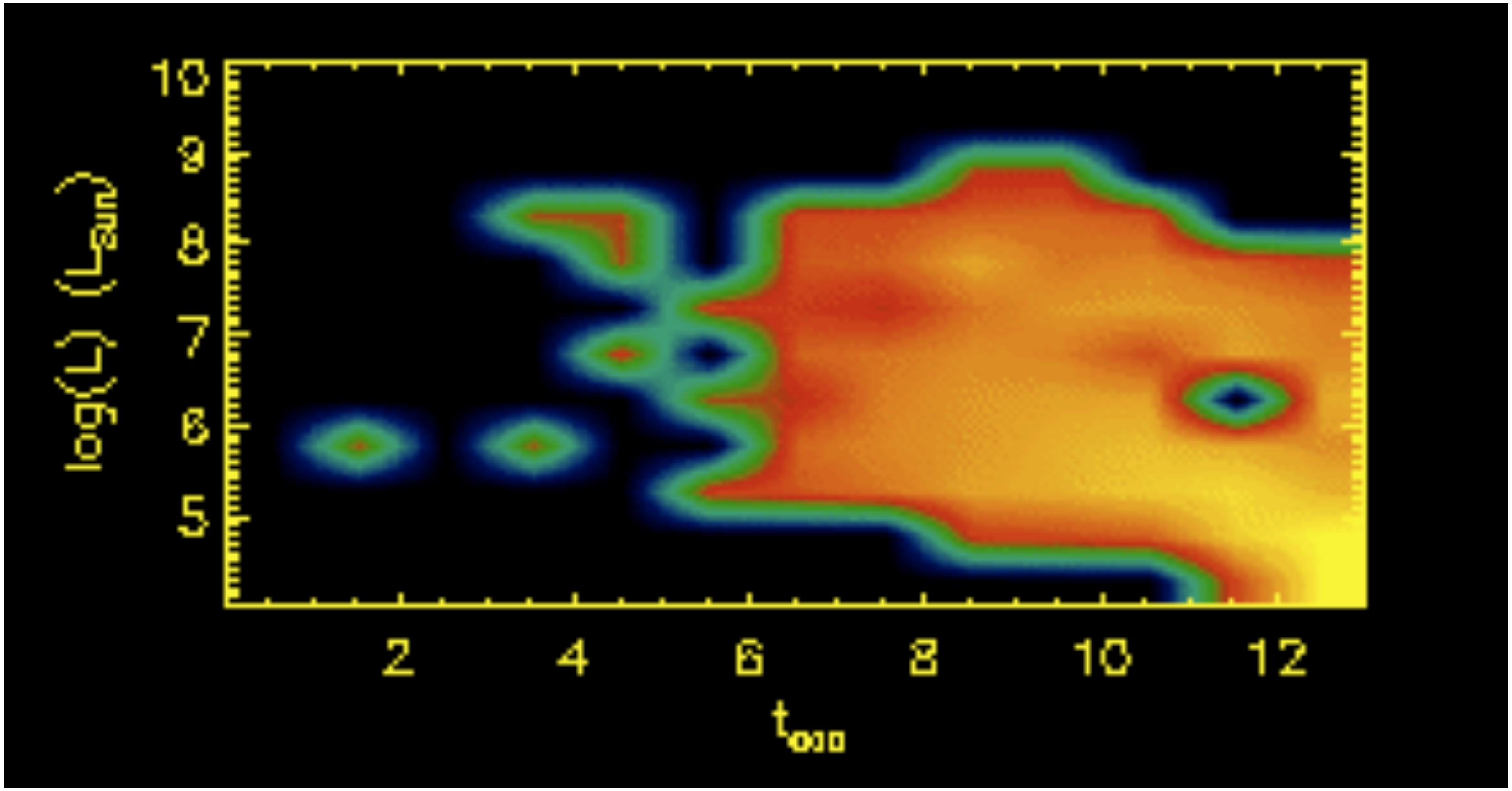
• fades due to phase-mixing

• see Sharma et al (2010)

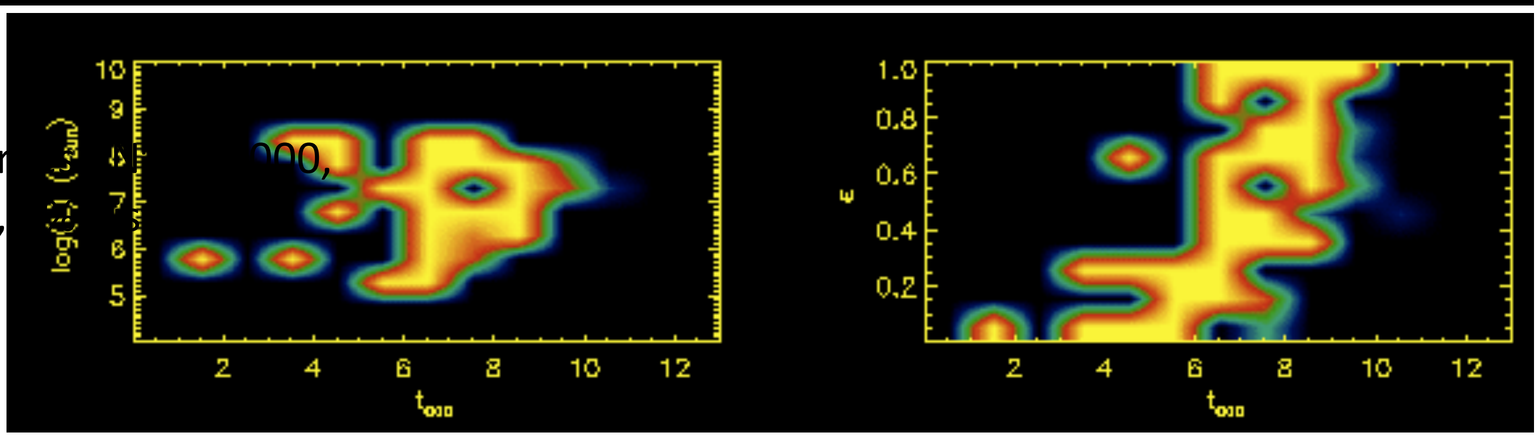
... phase-space structure

• conserved in the absence of dynamical evolution

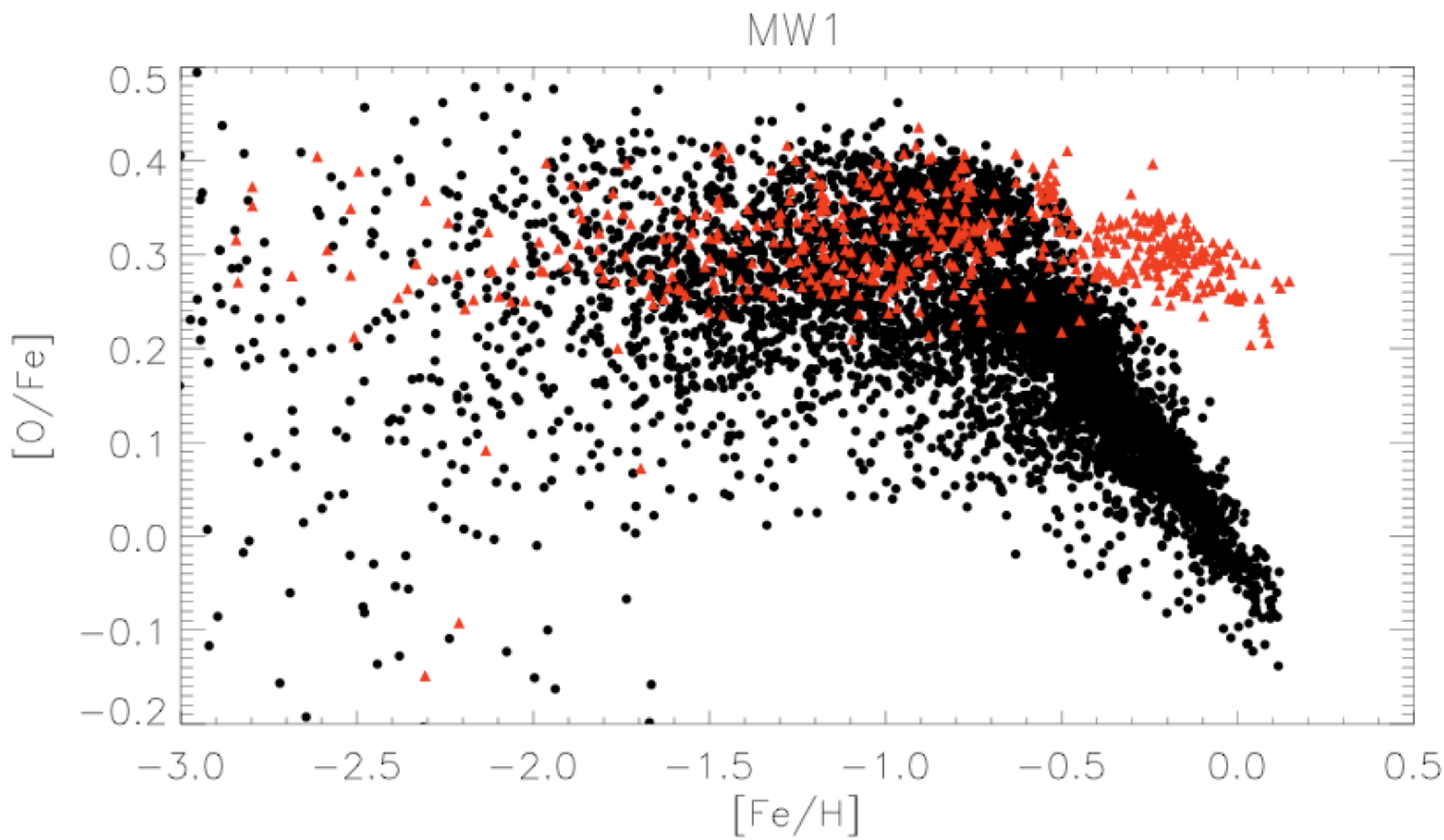
• see Helmi & White (1999), McMillan & Binney ??, Gomez et al???



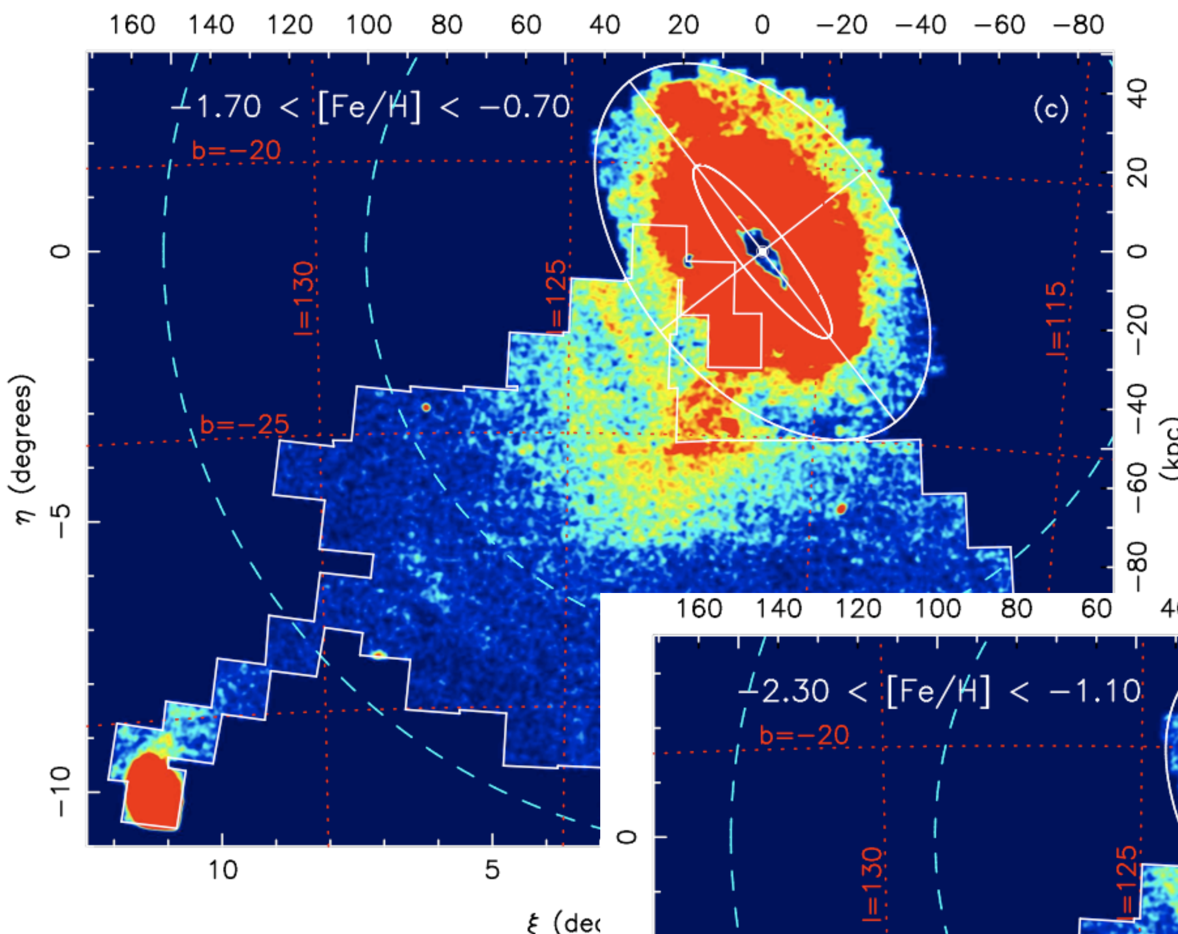
LSST RR Lyr ... 000,
R~350 kpc,

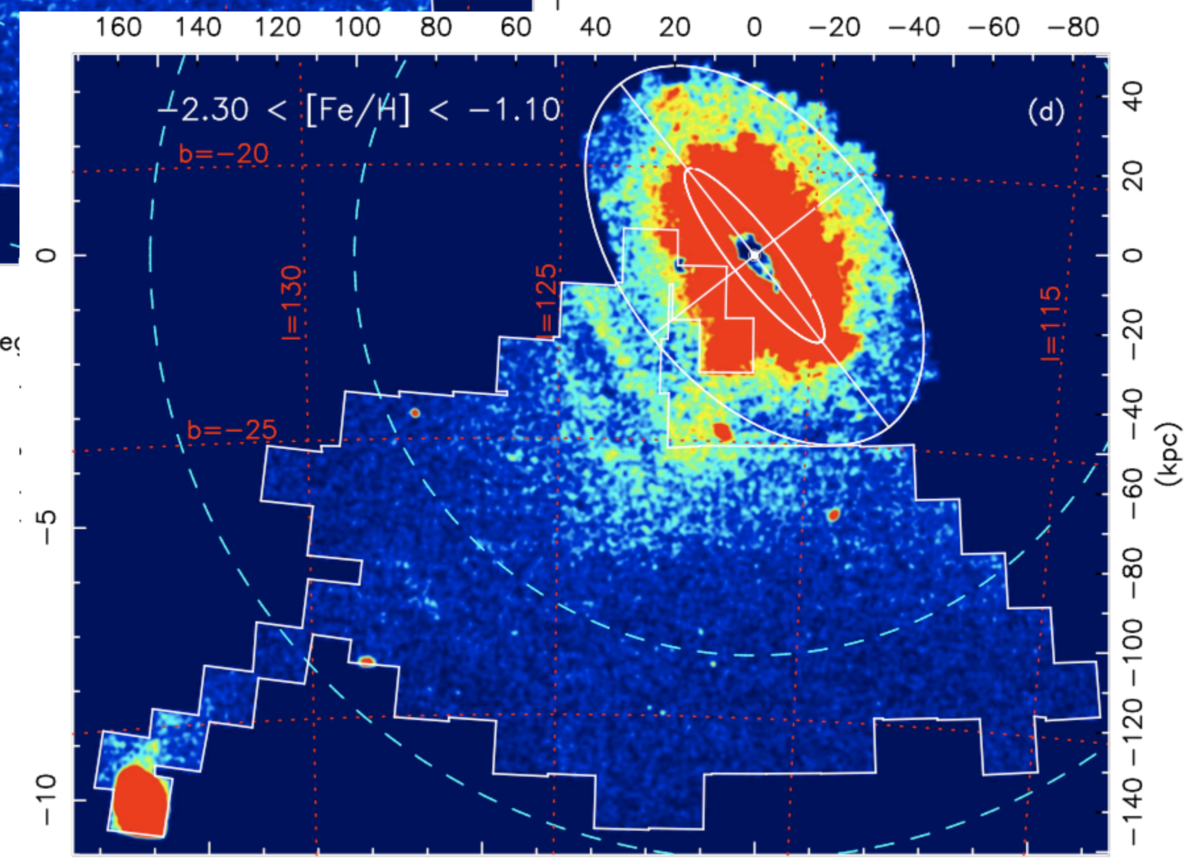


in situ stars: high [Fe/H] and [alpha/Fe] (Zolotov et al, 2010)



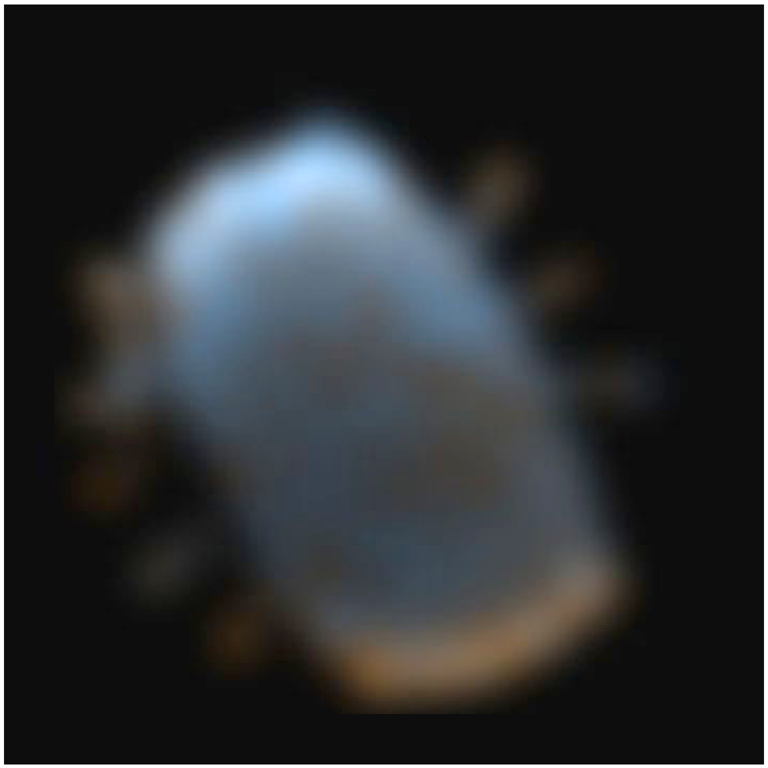
Observations: M31 (PANDAs team)





Observations: the Stellar Halo

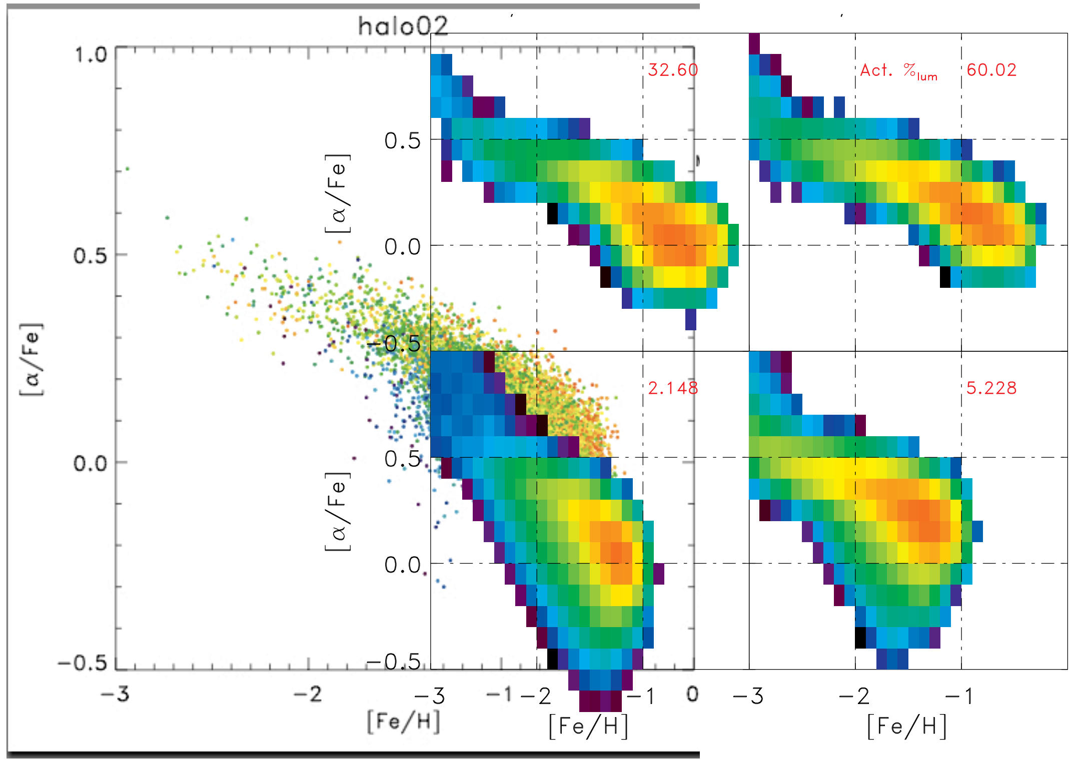
Bell et al (2010) [see also ECHOs – Schlauffman et al]



"f" = observed distribution

"f_i" = template distributions for different bins in (M_*, t_{acc})

M_*=



10^7-10^9 Msun

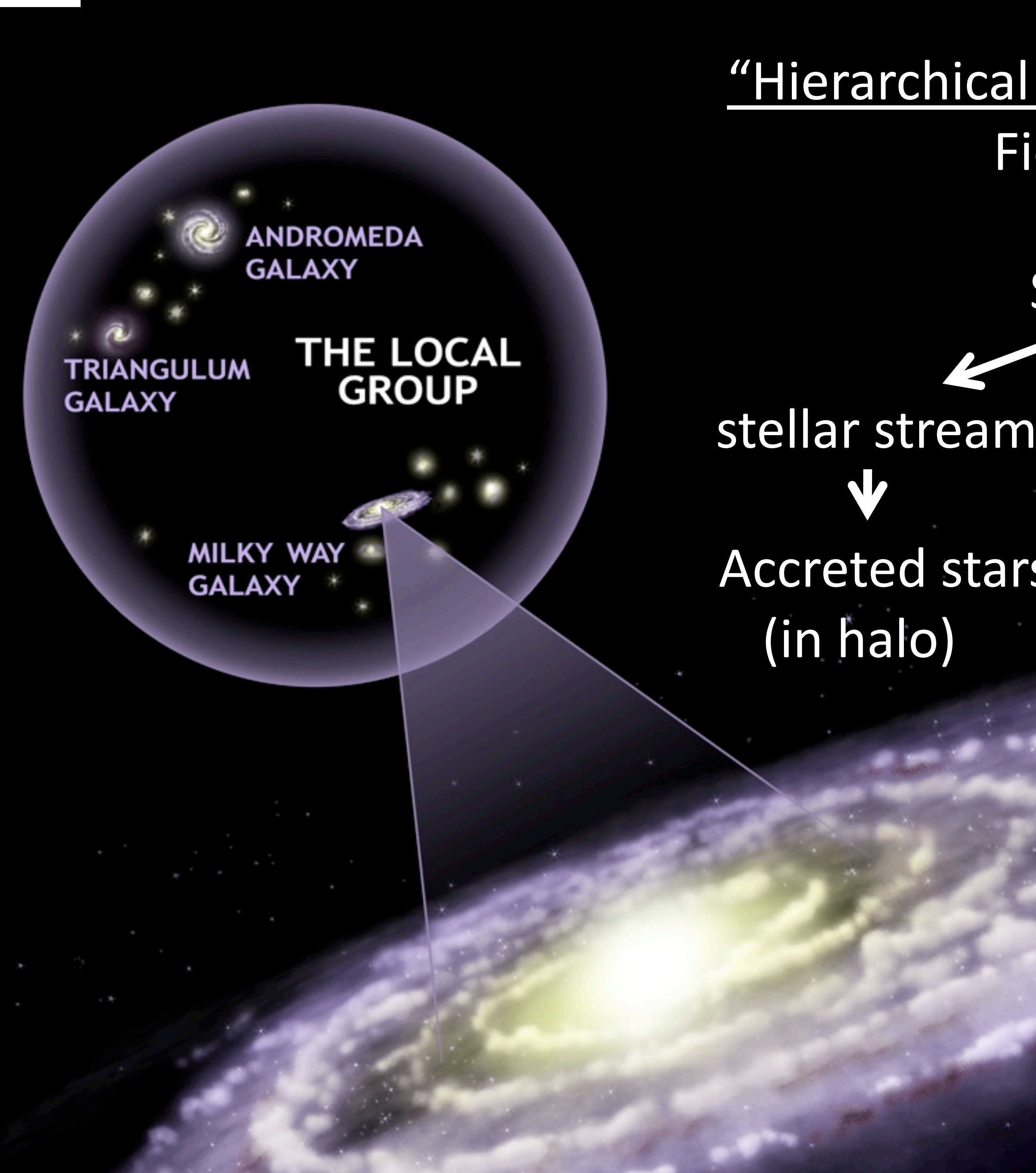
10^4-10^7 Msun

t_{acc}= 0-8 Gyrs 8-14 Gyrs

Find A_i such that

$$f = \Sigma_i A_i f_i$$

A_i =fraction of stars accreted in each mass/time bin = <u>accretion history!</u>



“Hierarchical Structure Formation”

Field dwarfs

↓

Satellites

↙ ↘

stellar streams → Accreted stars (in halo)

stripped gas → *in situ* stars (in disk)

Note: smooth infall dominates accreted gas component