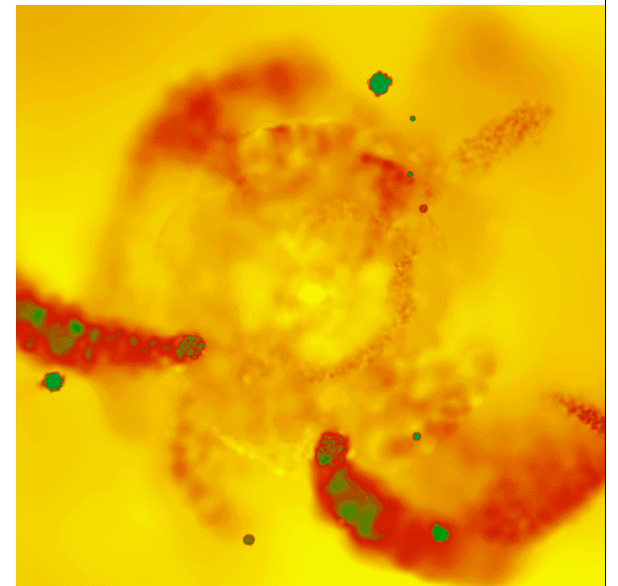
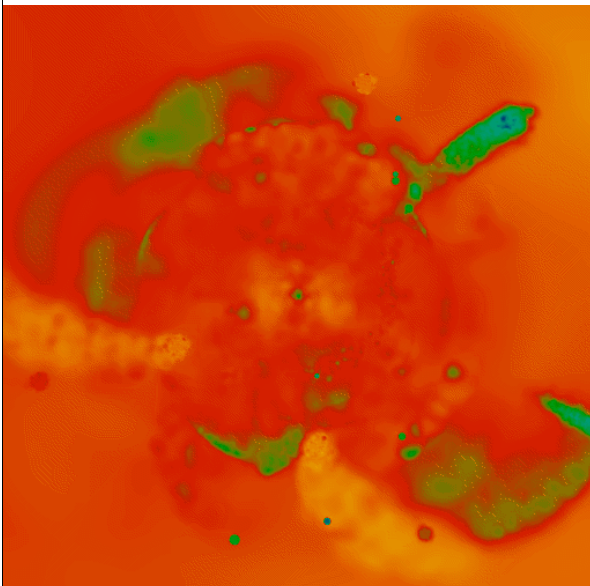


The Merger History of the Milky Way

Kathryn V. Johnston
(Columbia University)

Image credit: Sanjib Sharma



The last decade:

- Hierarchical formation => substructure
- We see substructure
 - ➔ confirm hierarchy: streams
 - ➔ limits of galaxy formation: satellites
- Hurray!

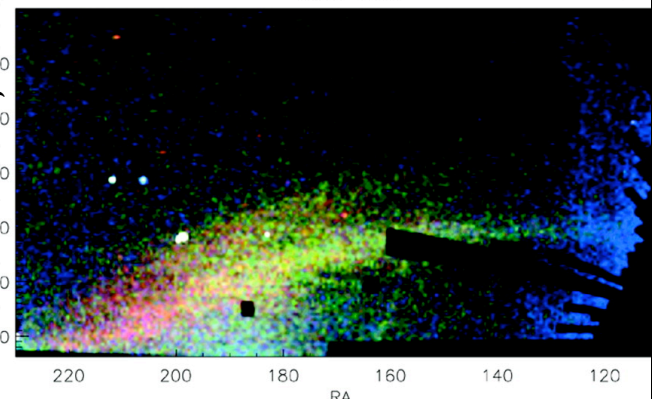
The next decade - photometric, astrometric, spectroscopic surveys:

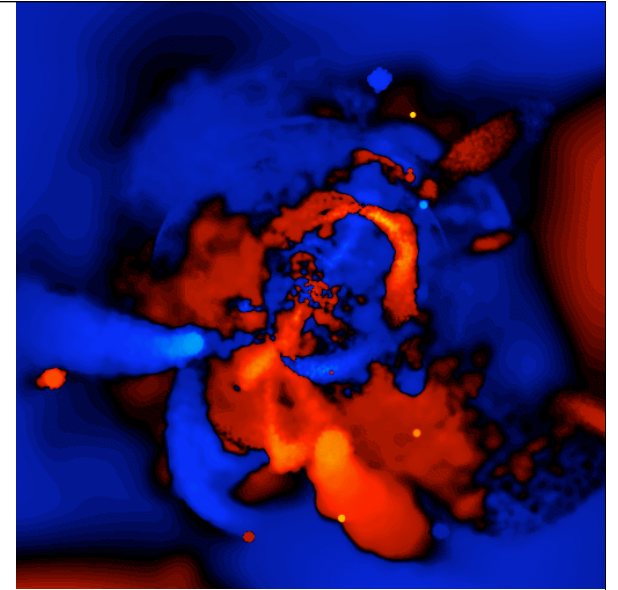
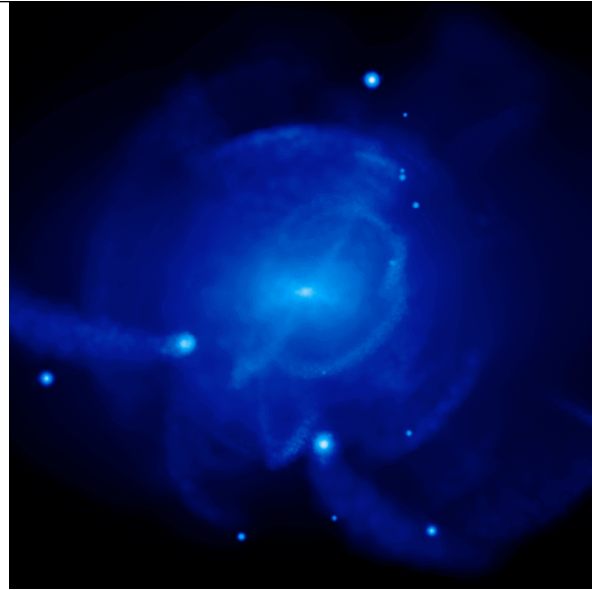
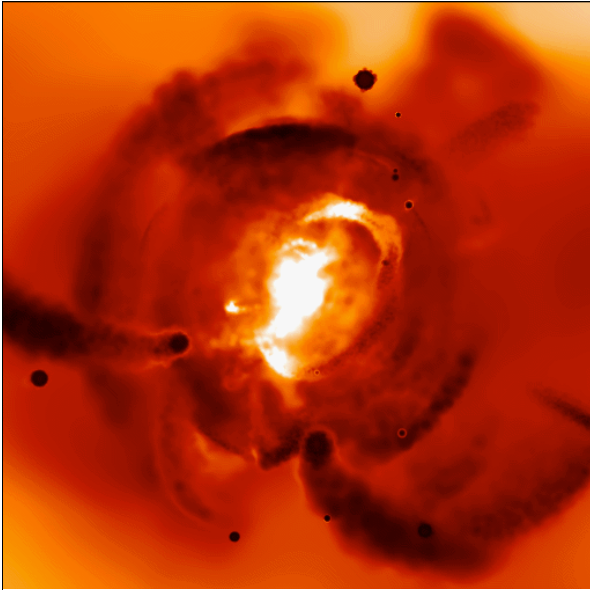
- larger volume, higher accuracy, larger numbers, more dimensions

Moore, Madau



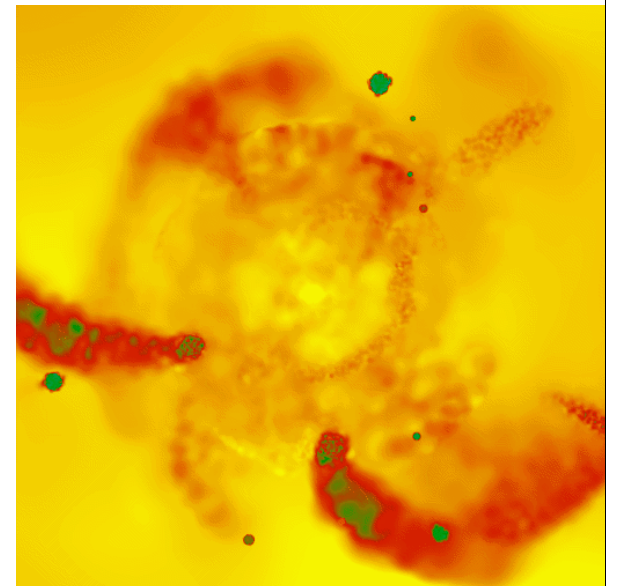
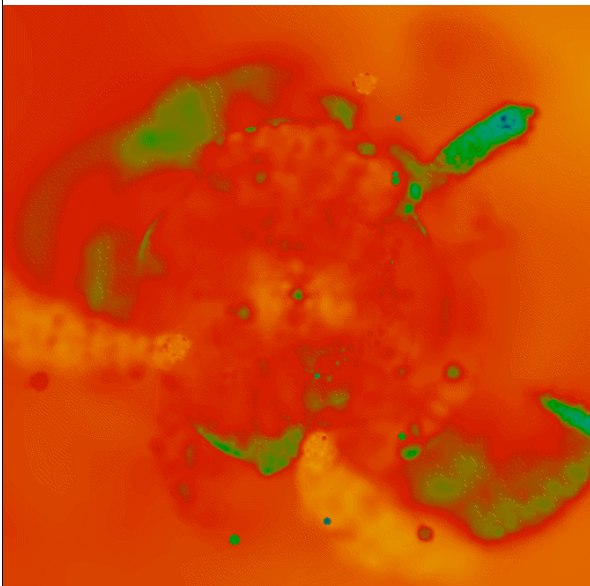
Belokurov et al, 2005

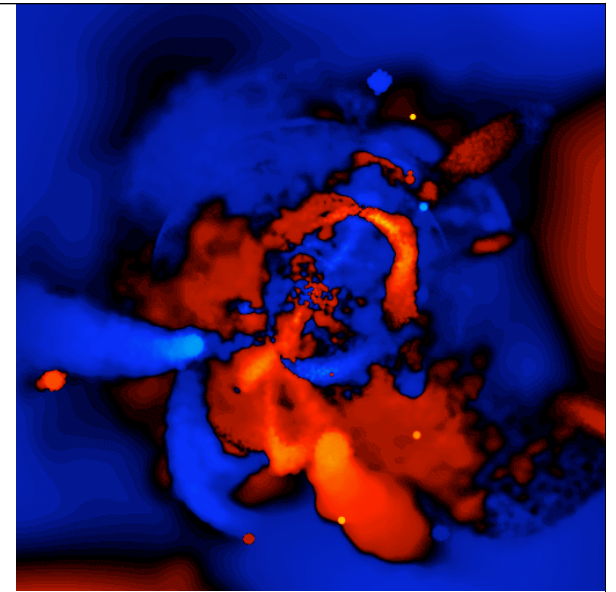
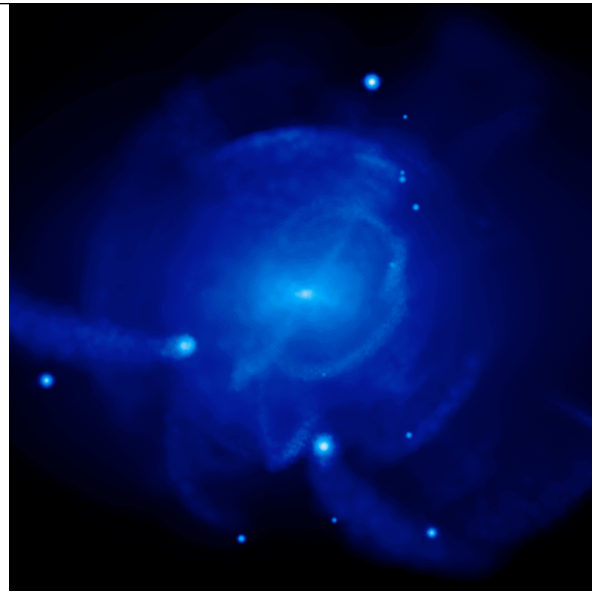
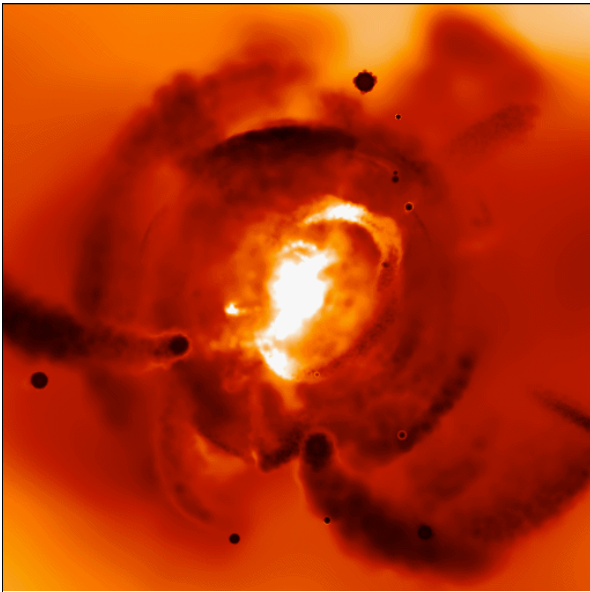




WHY?

1. Reconstructing merger history
2. The Milky Way as 1000 galaxies
3. Merger history to galaxy formation



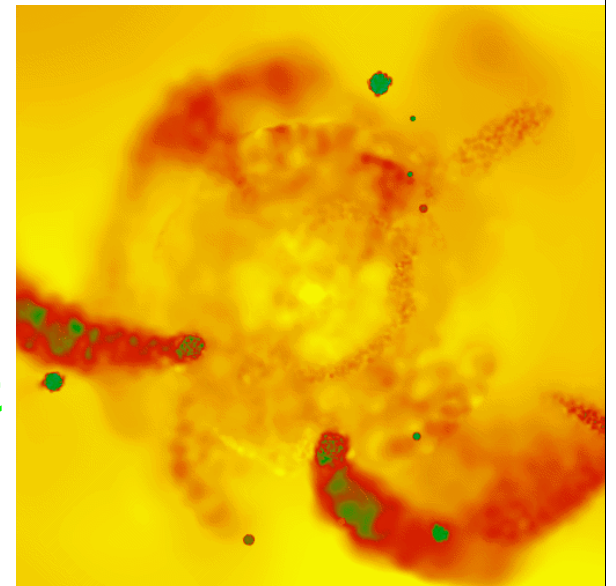
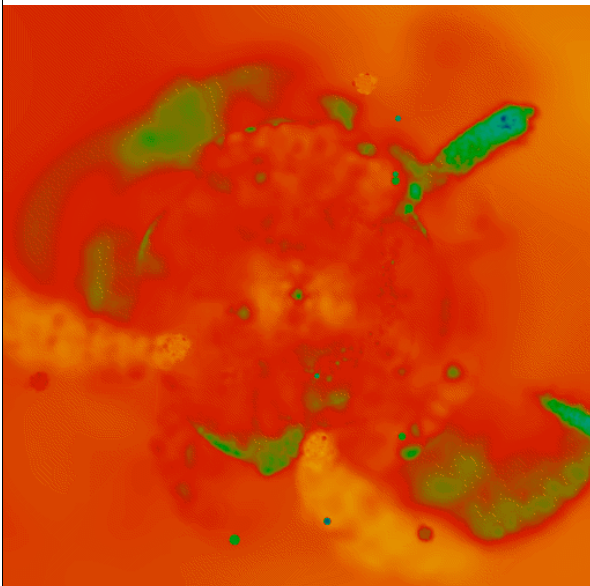


The Models

II stellar halos:

- dark matter
 - ➔ N-body satellites
 - ➔ analytic parents
- stars
 - ➔ structure from LG dwarfs
 - ➔ SFH from gas content
 - ➔ leaky/accreting box
 - ➔ chemical evolution

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



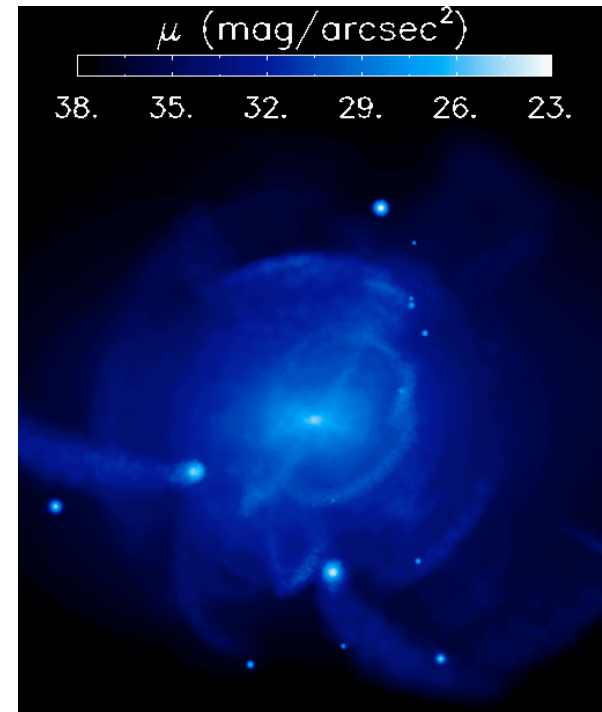
I. Reconstructing the merger history

- Aim - for accreted objects:

- ➔ luminosities
- ➔ orbits
- ➔ accretion times

? New things we can do with increases in:

- ➔ number
- ➔ volume
- ➔ accuracy
- ➔ dimensions



A. Wandering stars

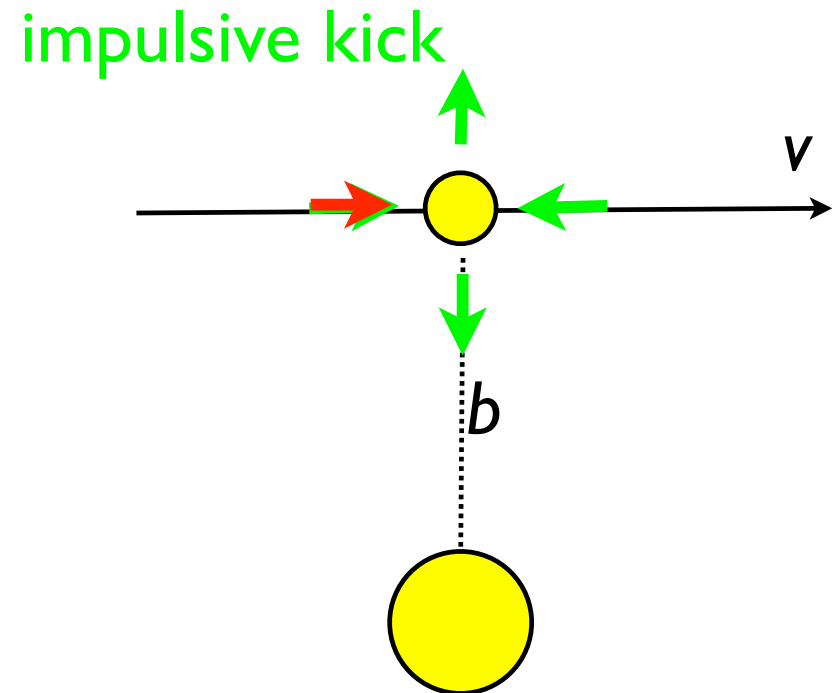
B. Photometric Surveys

~~C. Chemical tagging~~

I. Reconstructing the merger history

A. wandering stars

- LSST: Classical Novae:
N~10-100, R~20Mpc
(Shara, 2006)
- What might “wandering stars” tell us? (Teyssier et al, 2009 - *in prep*)



$$\Delta E = \mathbf{v} \cdot \Delta \mathbf{v} + \frac{1}{2} \Delta v^2$$

$$\Delta v \sim \frac{GM r_*}{b^2 v}$$

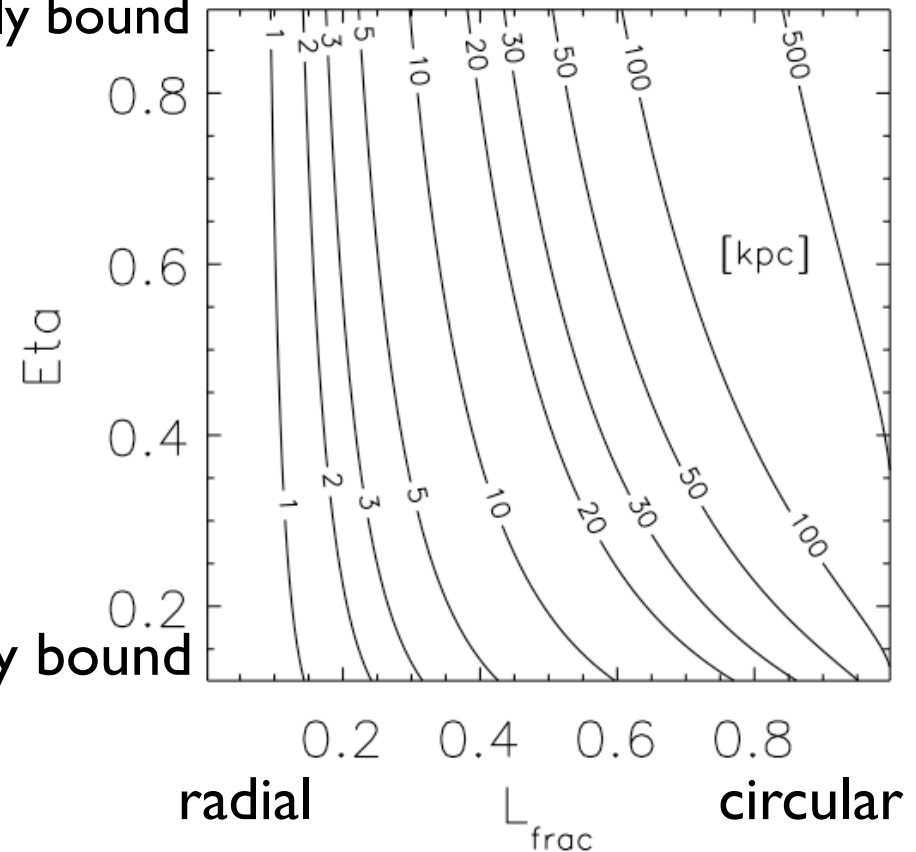
A. Wandering stars

- For escape:

$$\Delta E = v \cdot \Delta v > |E| \quad \text{loosely bound}$$

$$\Rightarrow \Delta v \sim \frac{GM r_*}{b^2 v} > \frac{|E|}{|v|}$$

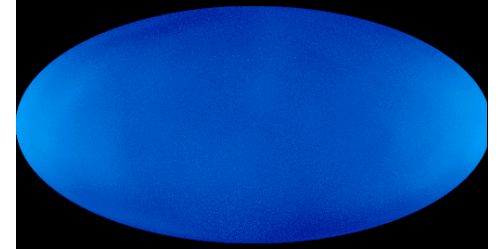
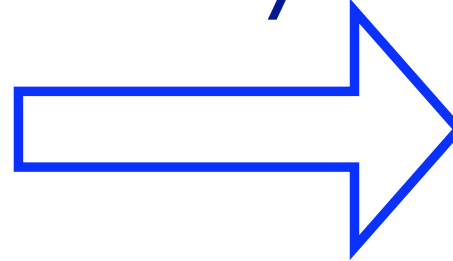
$$\Rightarrow r_* > \frac{|E| b^2}{GM}$$



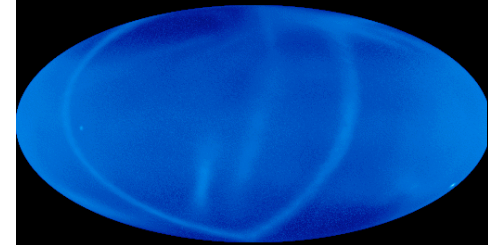
Implications: wandering stars
and....

- galaxy formation?
- IGM enrichment?
- old high velocity stars? (see also Abadi, Navarro & Steinmetz, 2008)

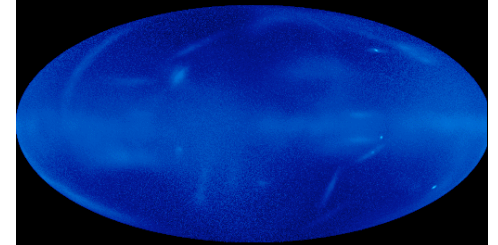
I.
Reconstructing
merger history:
B. Photometric
surveys



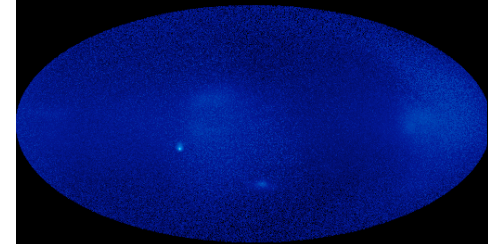
$15 < d_{\text{mod}} < 17$



$17 < d_{\text{mod}} < 19$



$19 < d_{\text{mod}} < 21$

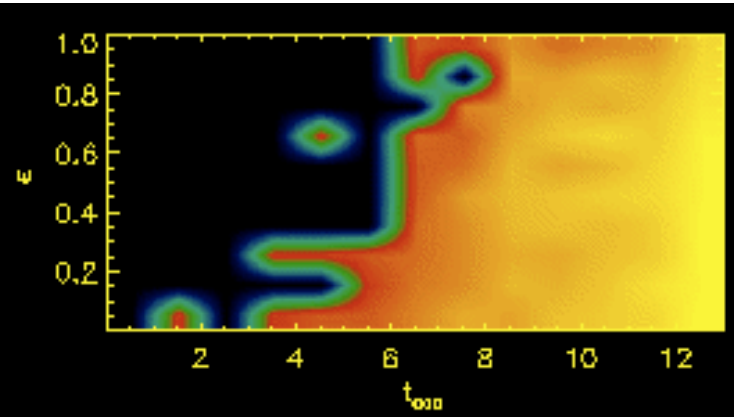
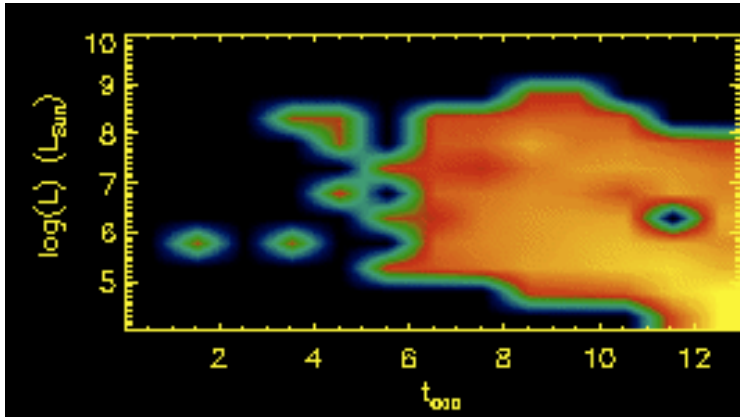


Sharma et al (2009), *in prep*

- generate samples
- simulate surveys
- run group finder in 3D (Sharma & Johnston, 2009)
- groups correspond to which accretion events?

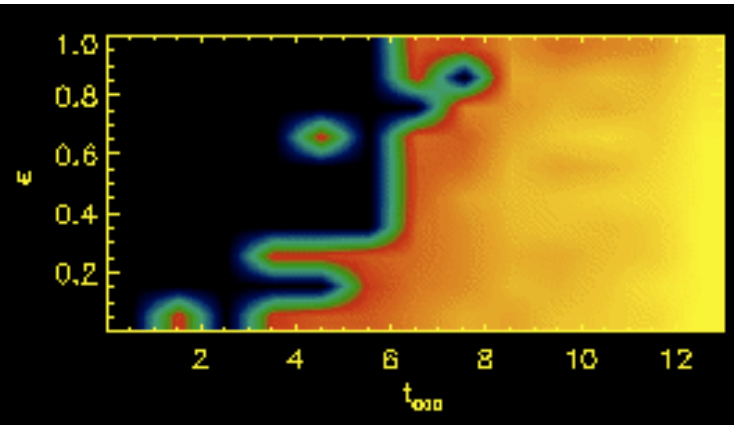
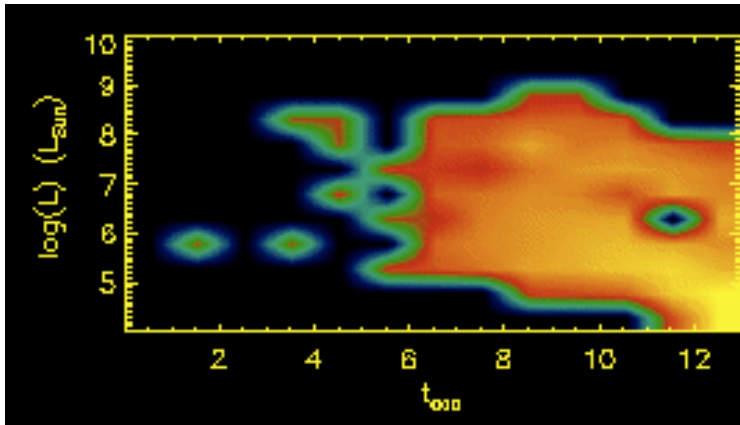
- Average history in models

log(luminosity)



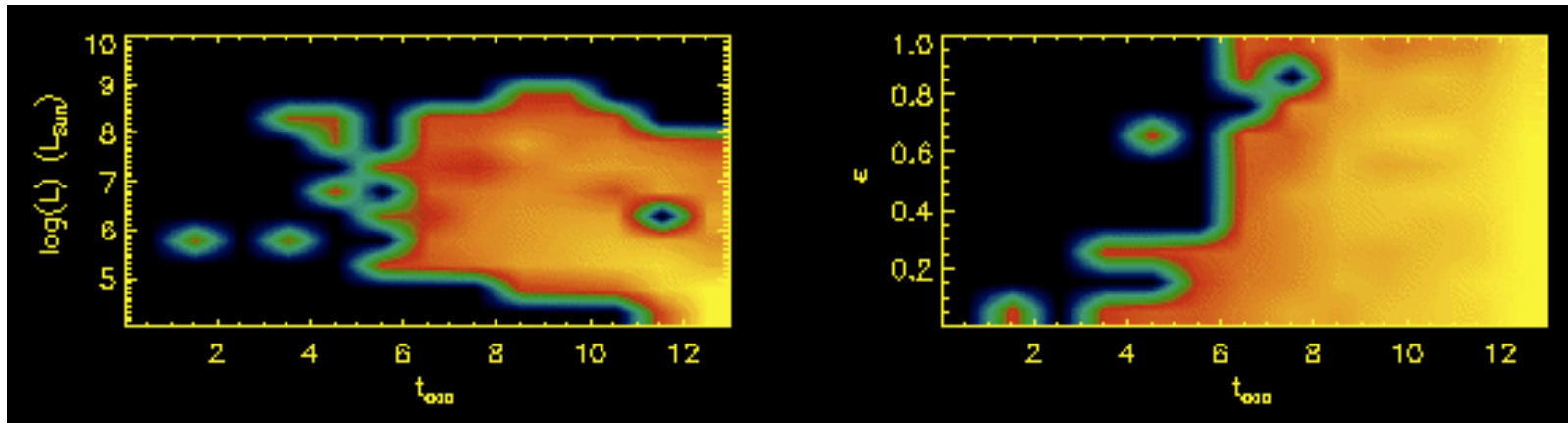
accretion time

radial orbit circular



- Average history in models

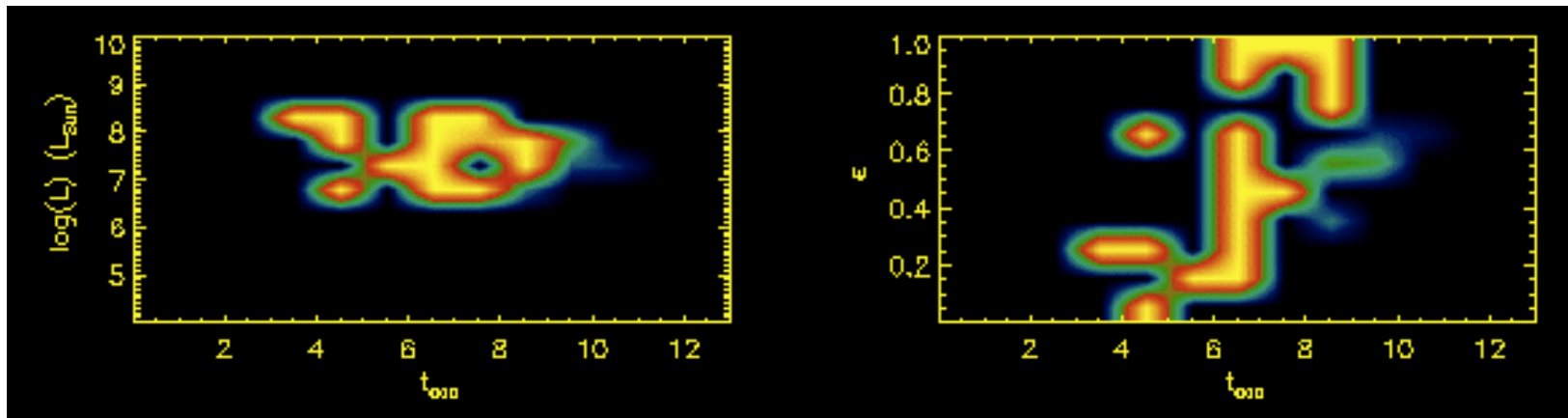
log(luminosity)



accretion time

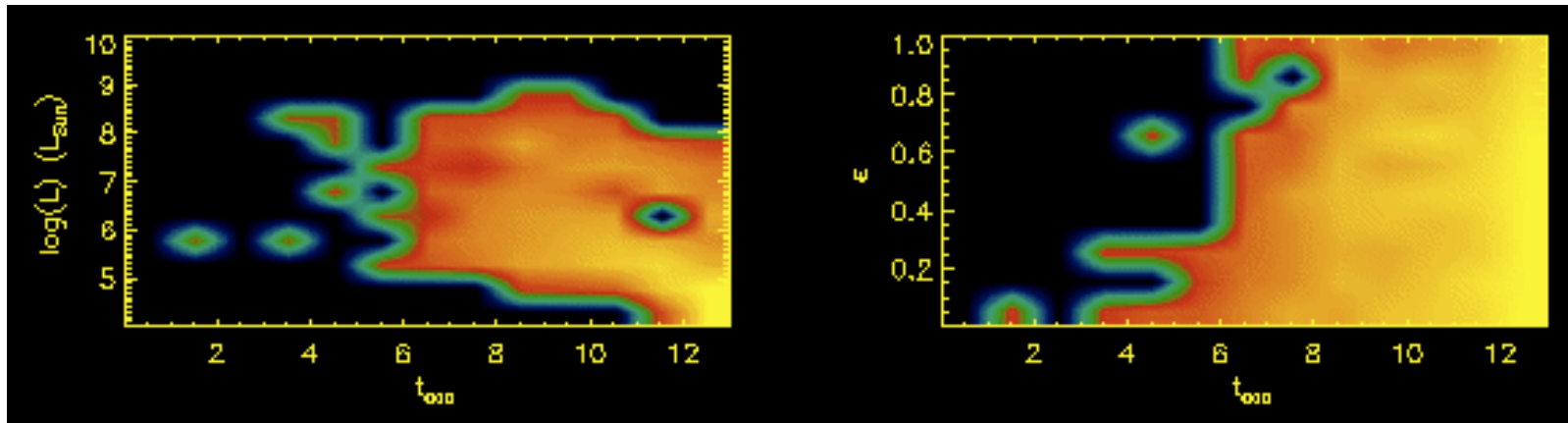
radial orbit circular

- 2MASS M-giant survey: $N \sim 100,000$, $R \sim 100$ kpc, magnitude spread $\sim 20\%$ distances



- Average history in models

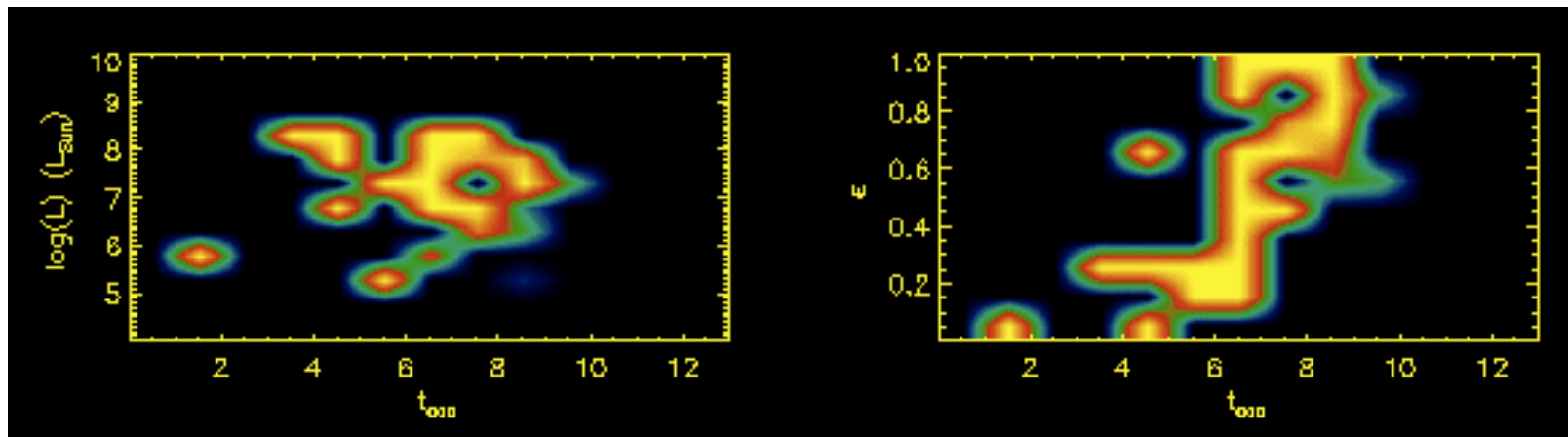
log(luminosity)



accretion time

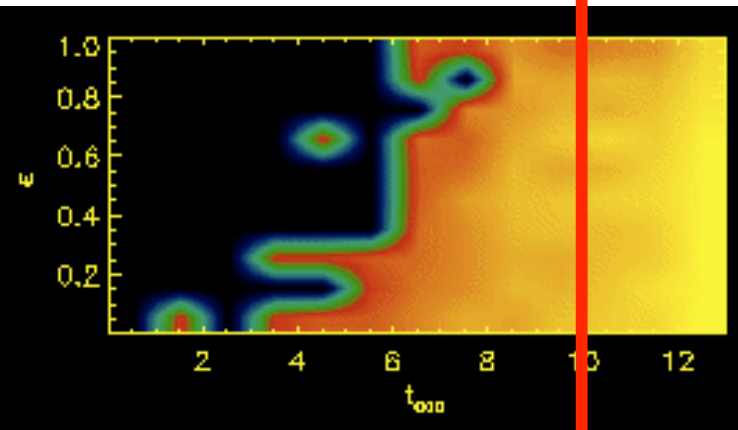
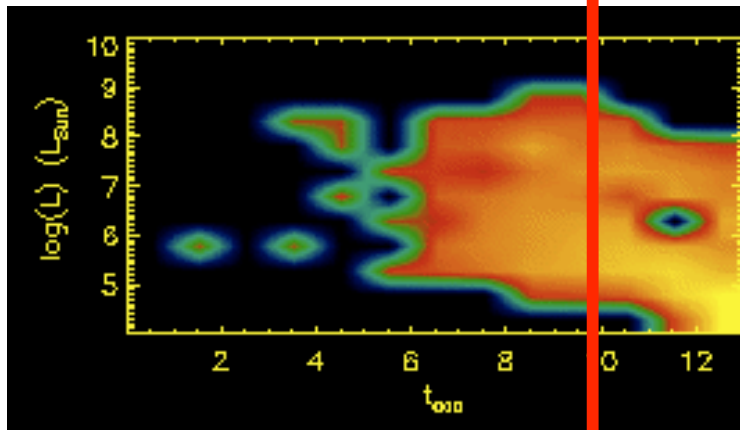
radial orbit circular

- LSST main-sequence-turnoff survey: $N \sim 4$ million, $R \sim 100$ kpc, magnitude spread $\sim 25\%$ distances



- Average history in models

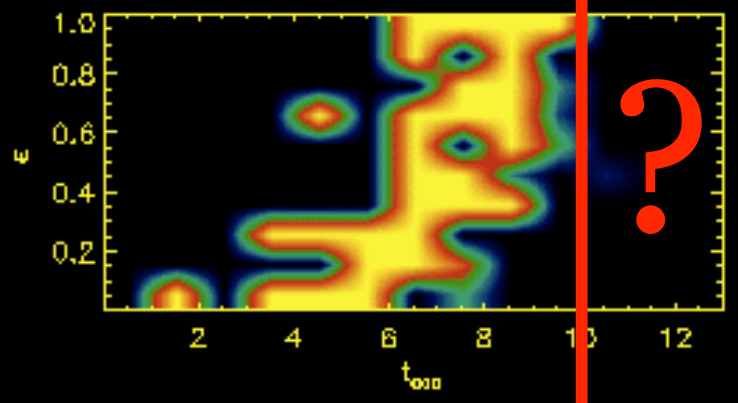
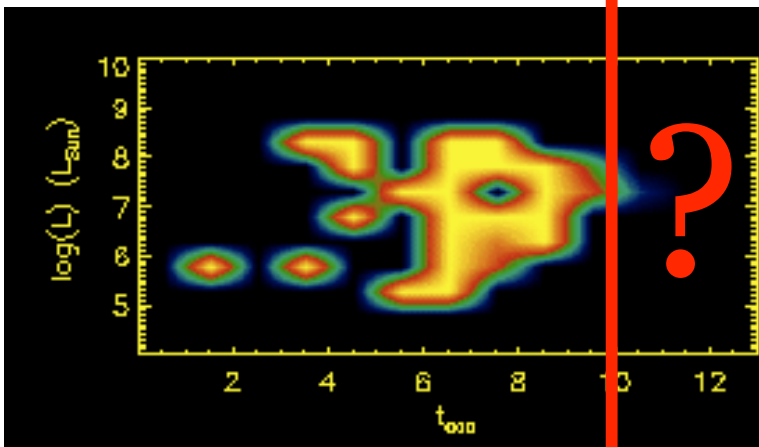
log(luminosity)



accretion time

radial orbit circular

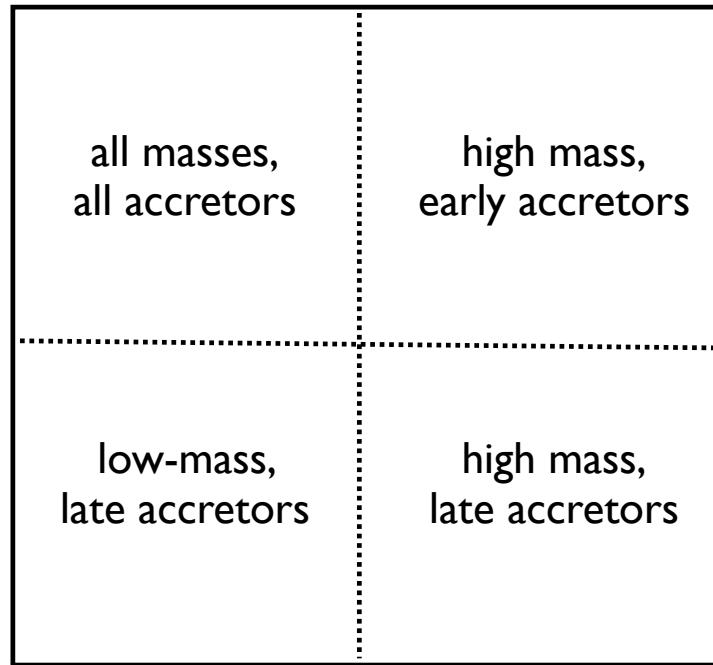
- LSST RR Lyraes : $N \sim 100,000$, $R \sim 350$ kpc, 5% distances



time



[alpha/
Fe]



[Fe/H]

mass



e.g. Unavane, Wyse & Gilmore, 1996;
Prantzos 2008

2. The Milky Way as 1000 galaxies

Galaxy formation - star formation within merging dark matter halos

- “parameters”:

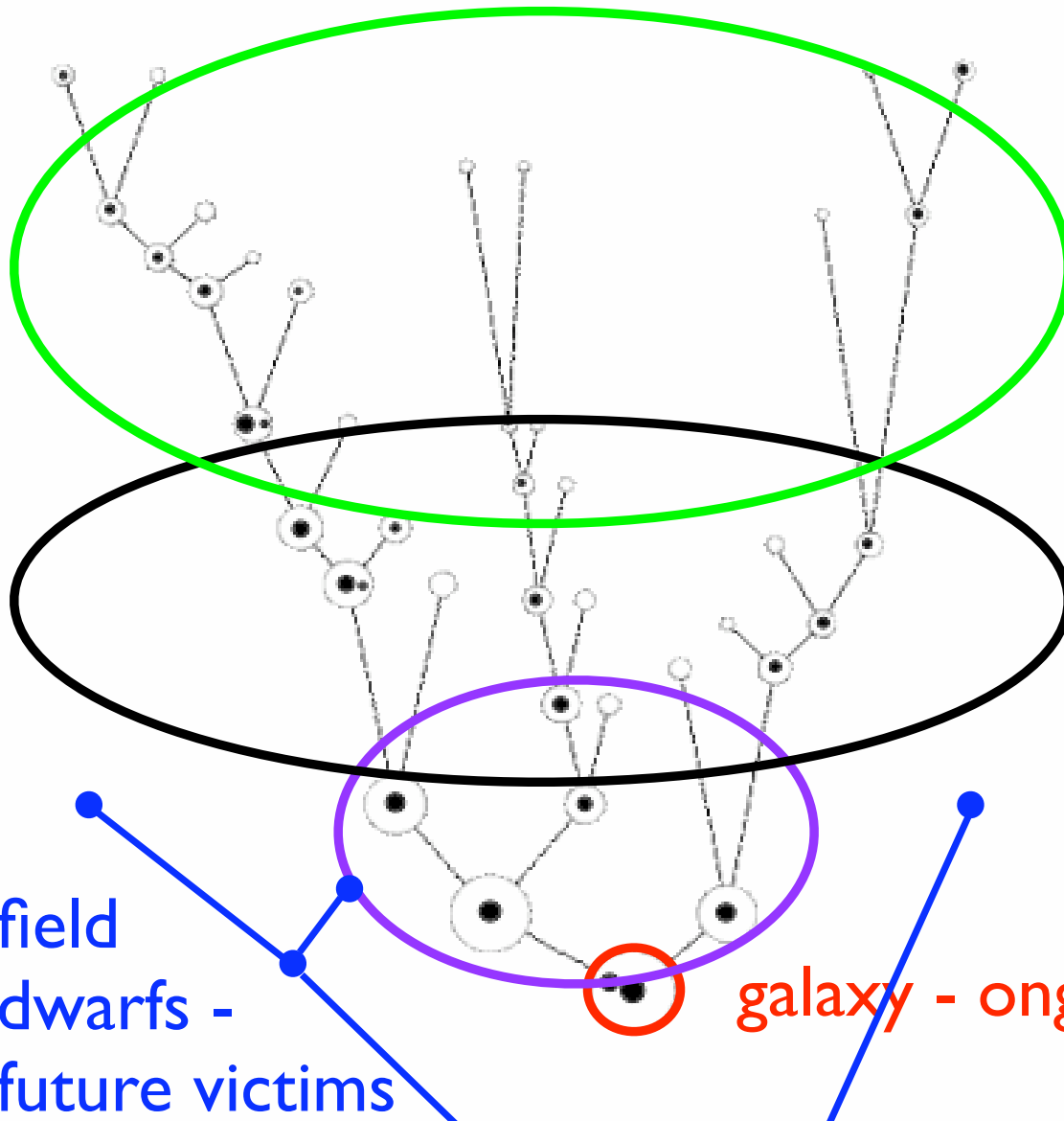
- ➔ size of dark matter halo what?

- ➔ duration of star formation when?

- ➔ external influences where?

- ➔ hierarchical structure formation => 1000's Galaxy progenitors => 1000 different experiments

When?



smooth stellar halo
progenitors -
stripped, disrupted
and phase-mixed

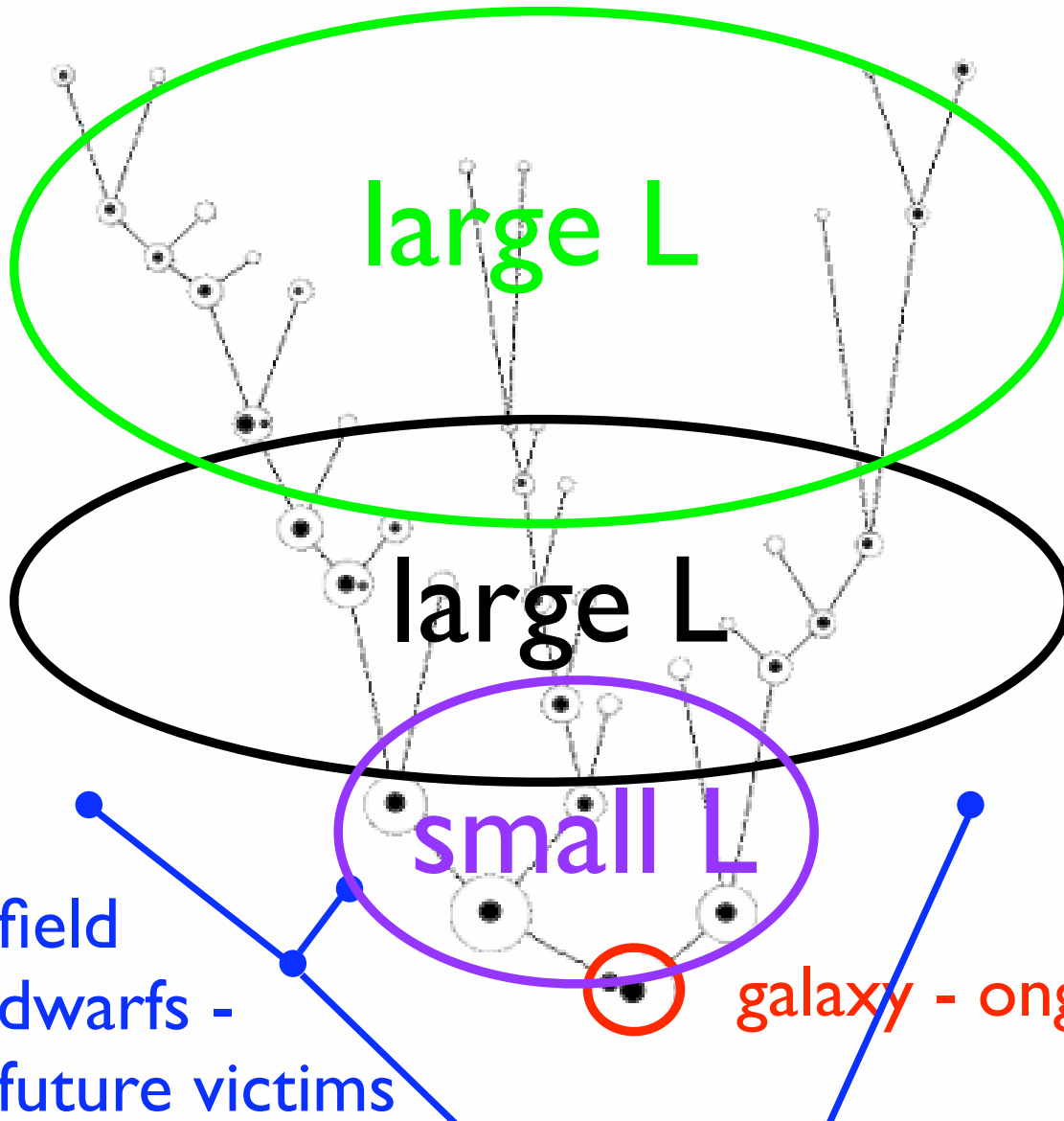
stream progenitors -
stripped and
disrupted

satellites - stripped
and morphologically
transformed

field
dwarfs -
future victims

galaxy - ongoing star formation

What?



smooth stellar halo
progenitors -
stripped, disrupted
and phase-mixed

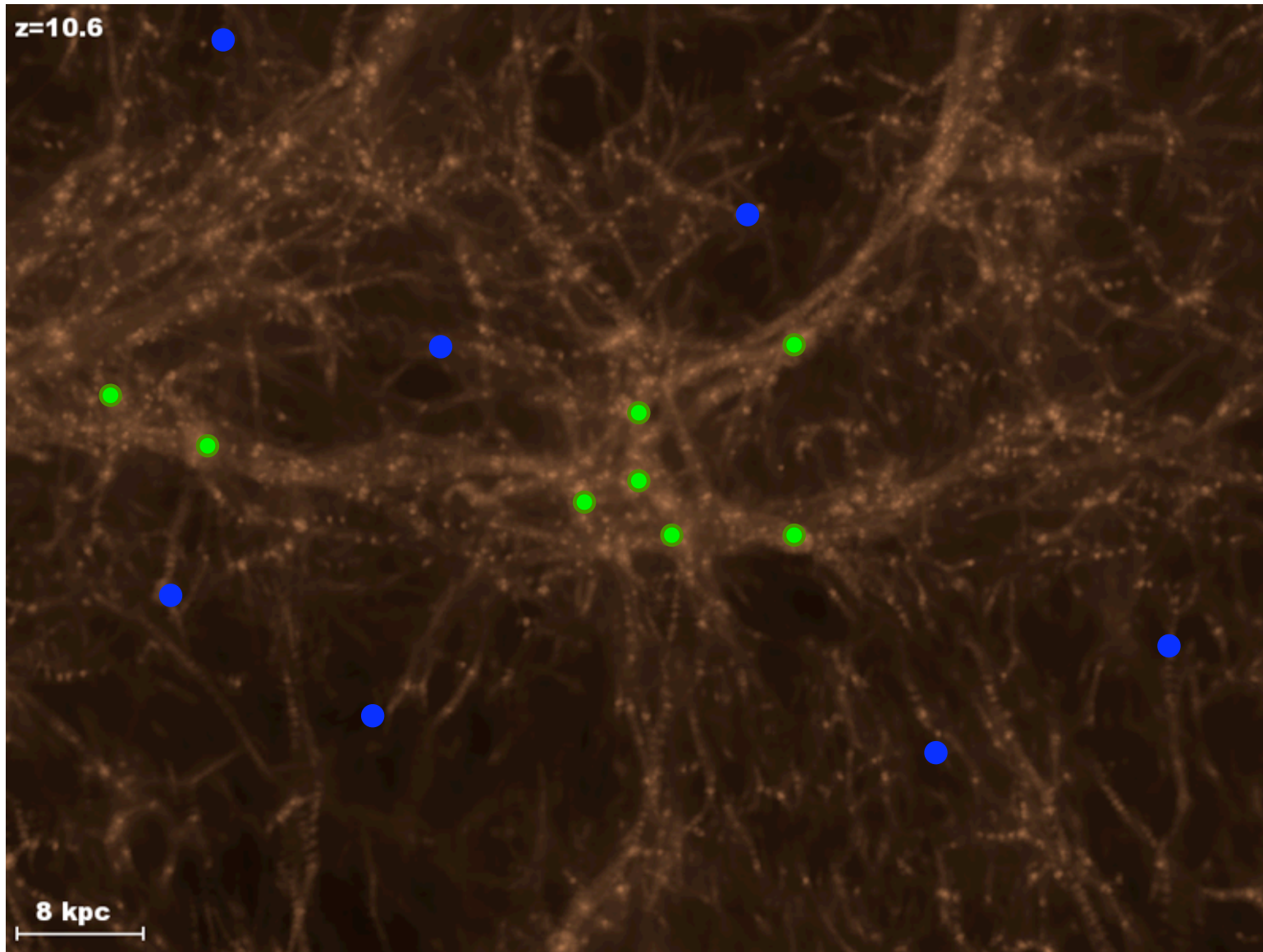
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stripped and
disrupted

satellites - stripped
and morphologically
transformed

galaxy - ongoing star formation

field
dwarfs -
future victims

Where?



Halo
progenitors
and sites of
first stars?

Field galaxy
progenitors

Image from
Via Lactea -
Diemand,
Kuhlen &
Madau

2. The Milky Way as 1000 galaxies

Implication: potential to study diverse influences

Properties of Dominant Contributors				
Component/ system	When? SFH: rate/duration	What? potential well	Where? 1) birth place	Where? 2) interaction history
disk	steady/ongoing	deep	dense	quiescent?
stellar halo (smooth)	steady/few Gyrs	medium	dense	destructive!
star streams	steady/6-13 Gyrs	medium	less dense?	destructive!
satellites (dSph)	slow/8-13 Gyrs	shallow	less dense?	moderate
field dwarfs (dIrr)	slow/ongoing	shallow/ medium	less dense?	quiescent?

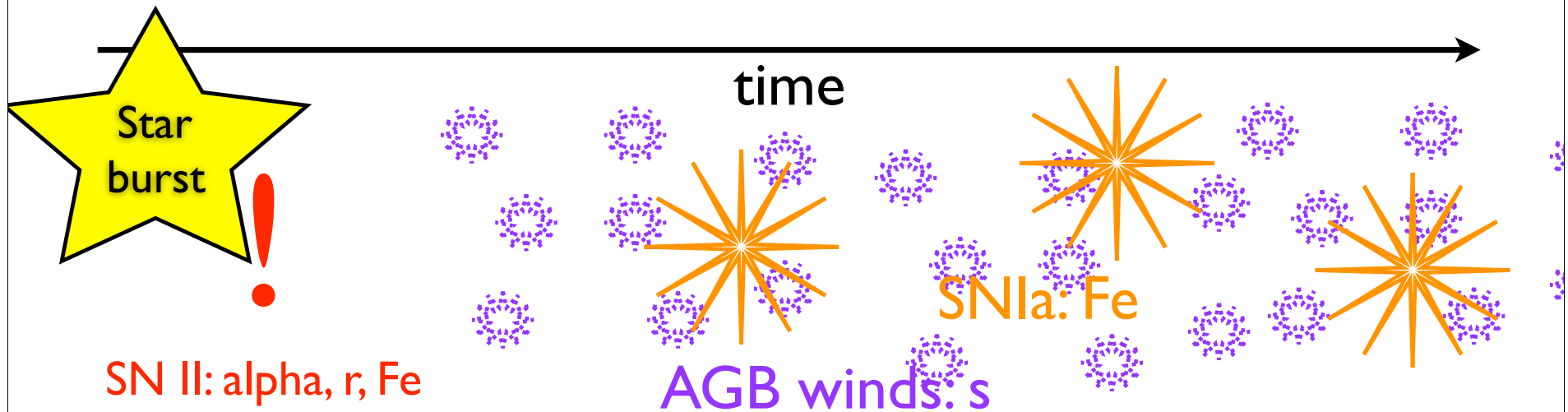
3. Merger history to galaxy formation

➡ hierarchical structure formation => 1000 Galaxy progenitors => 1000 different experiments

- Diagnostics: alpha-, r-, s-process and Fe-peak elements

- ➡ different time- and energy- scales

- ➡ SFH, feedback, mixing....



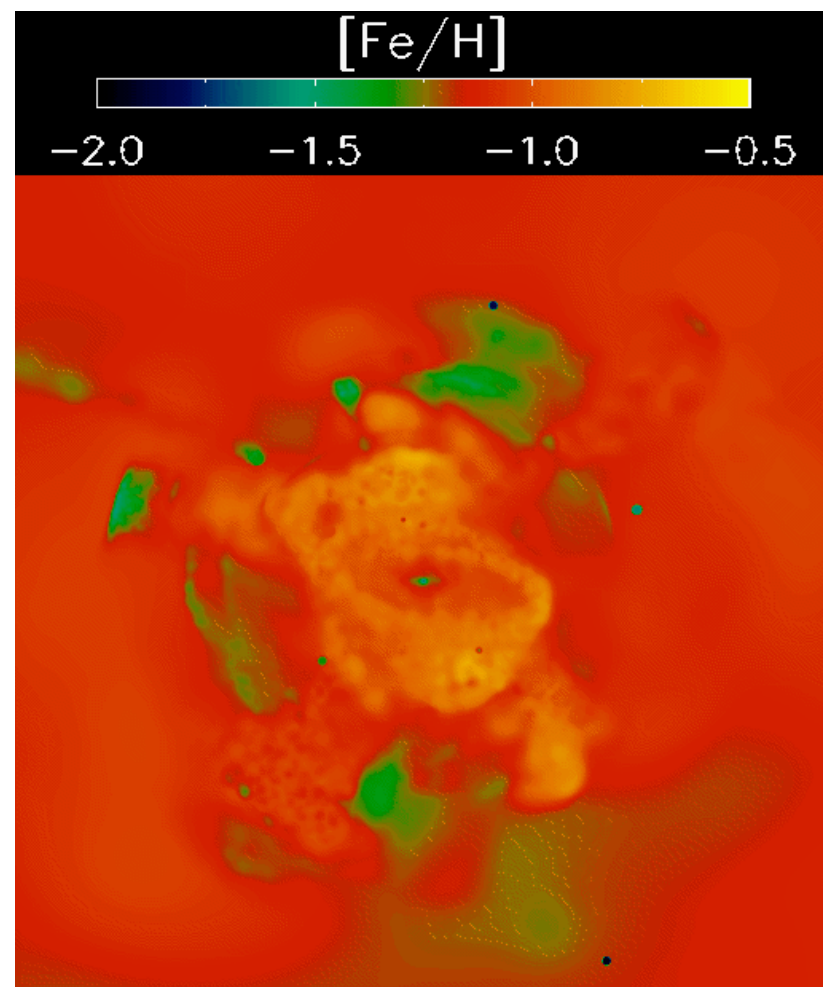
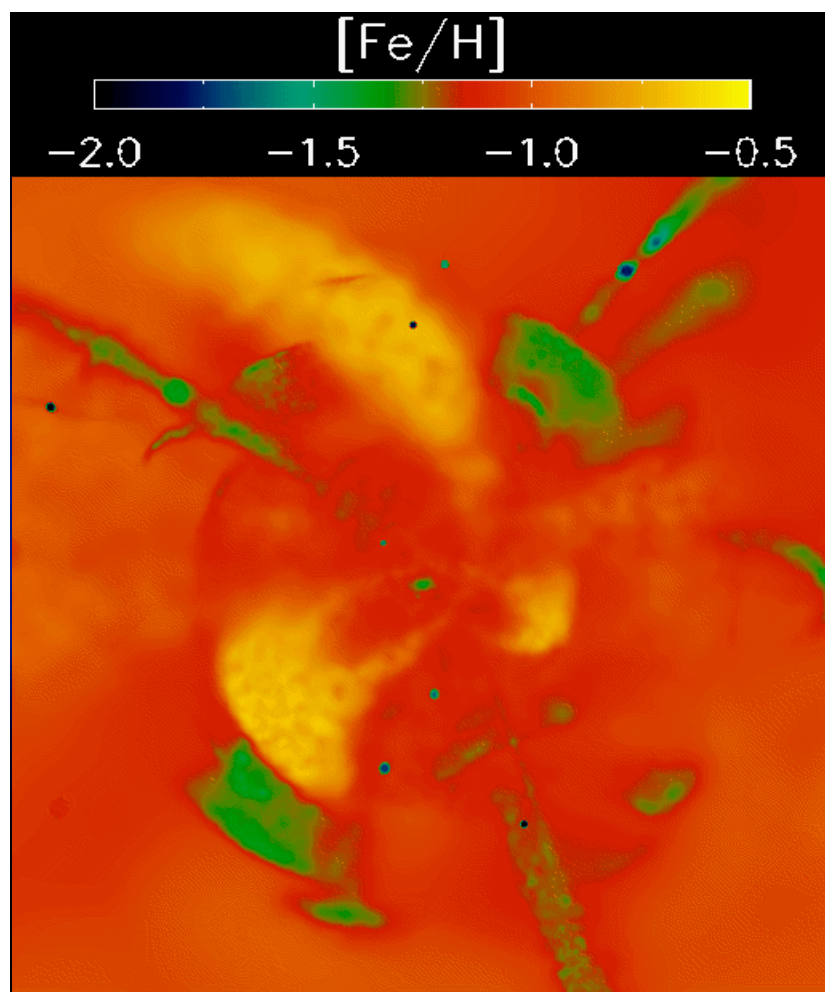
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e.g. 3 experiments....

dominant streams are metal rich....

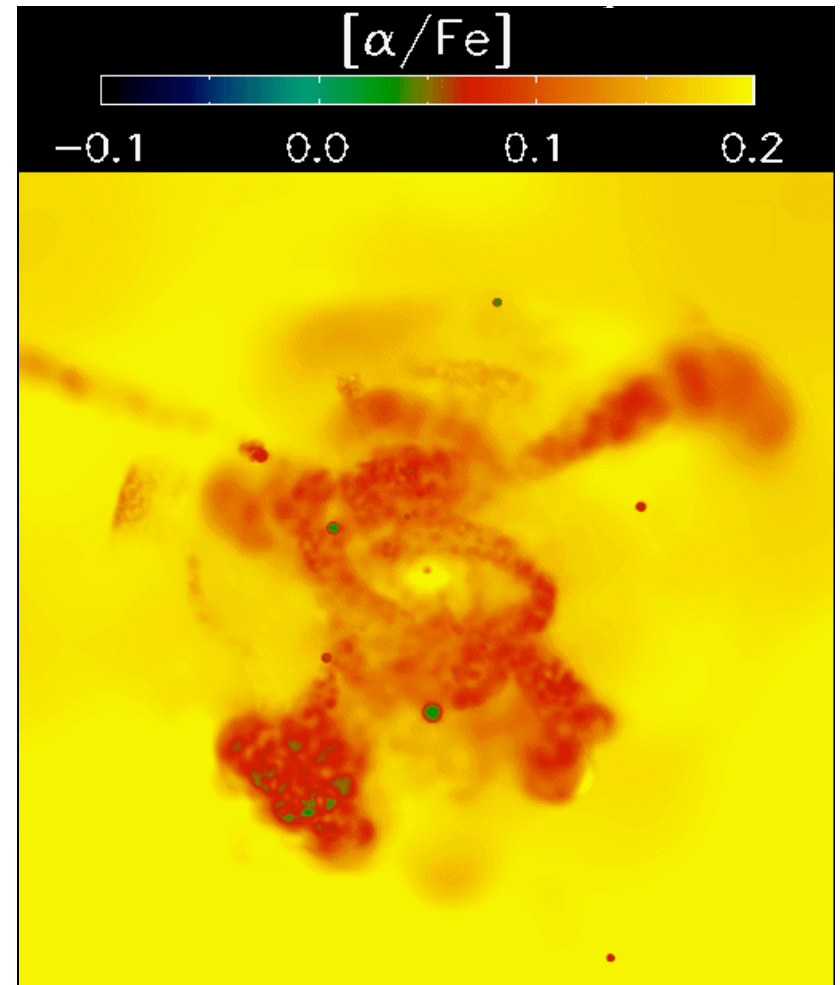
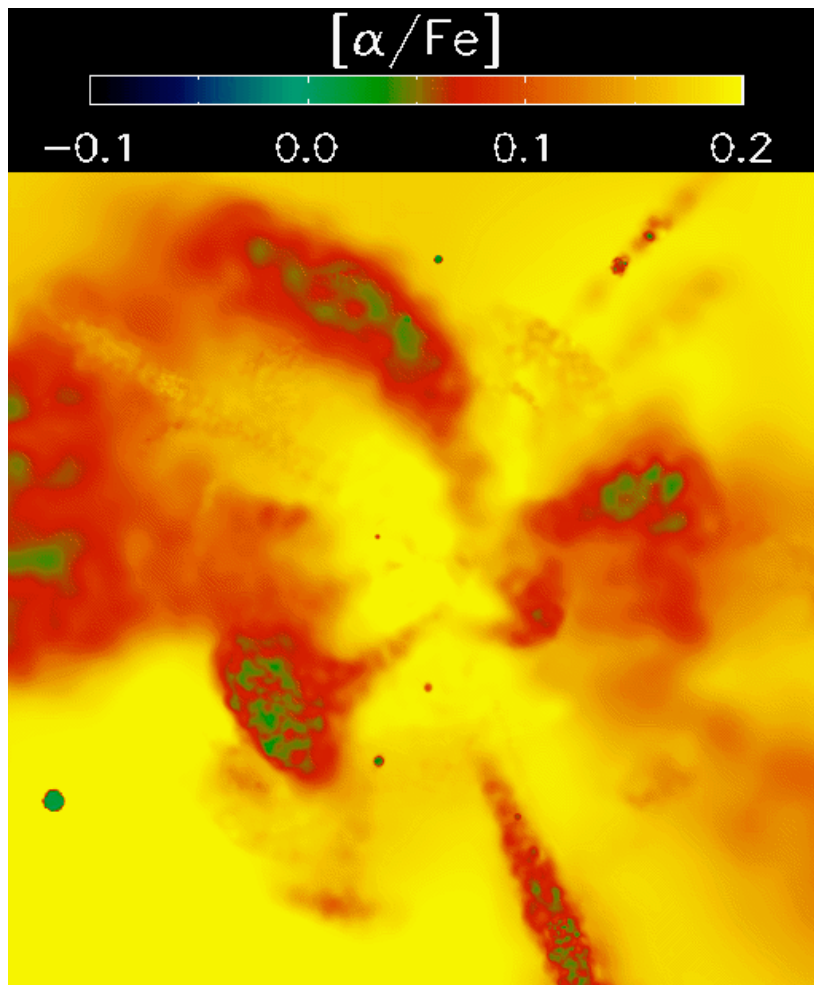
Font et al 2008, Gilbert et al 2009



e.g. 3 experiments....

- satellites and substructure are alpha-poor...

Robertson et 2005, Font et al 2006a, 2006b, 2007



Properties of Dominant Contributors

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The Local Group Manifesto

- All dimensions are created equal
 - ➔ photometric surveys: volume and low-contrast features
 - ➔ astrometric surveys: fully mixed regions
 - ➔ spectroscopic surveys: further back in time; galaxy formation diagnostics
- Celebrate diversity
 - ➔ the Milky Way as 1000 galaxy formation experiments
- Don't forget the little people
 - ➔ streams; classical and ultra-faint dwarfs; tails of velocity and abundance distributions
 - ➔ limits of galaxy formation; model most confidently