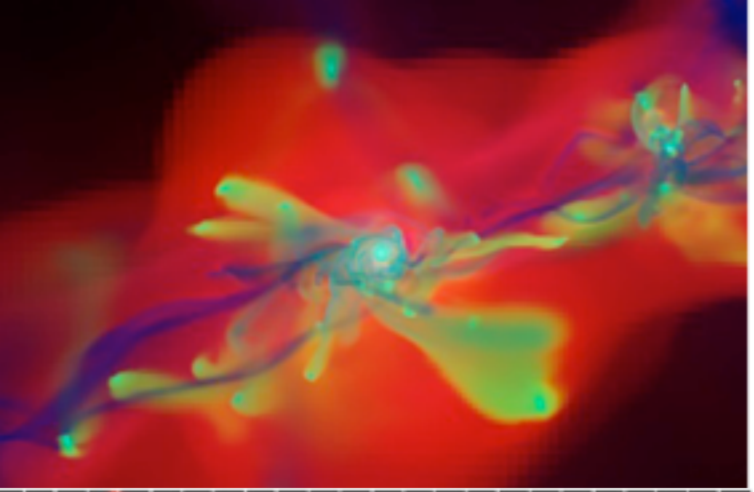
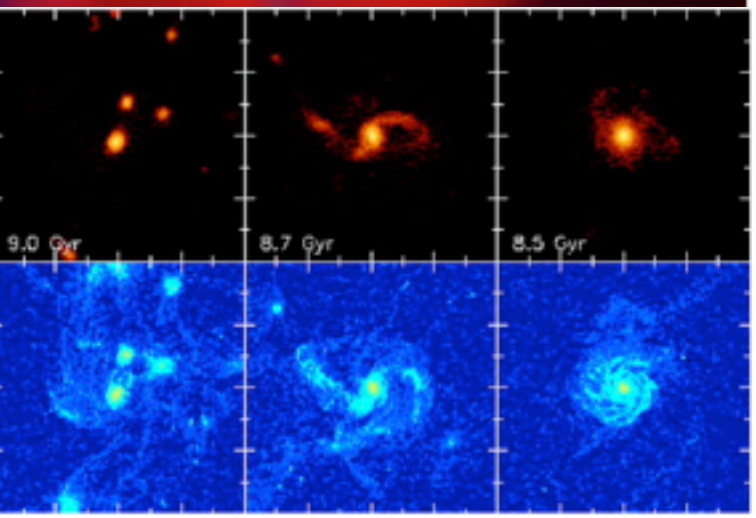
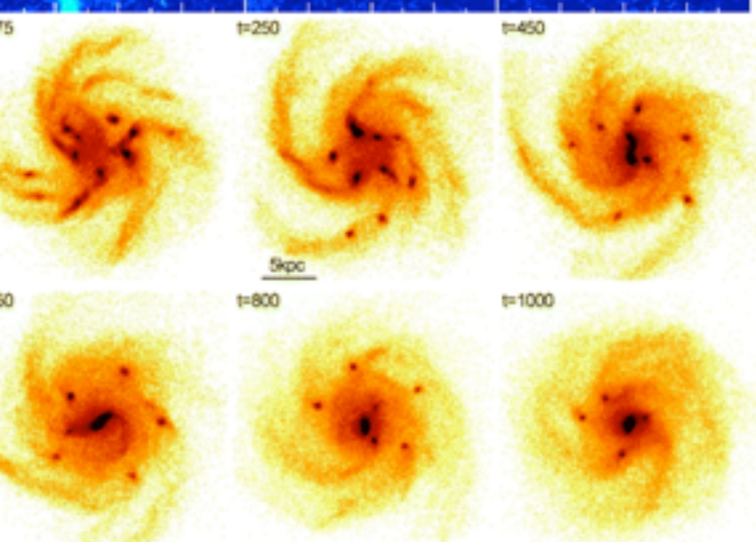
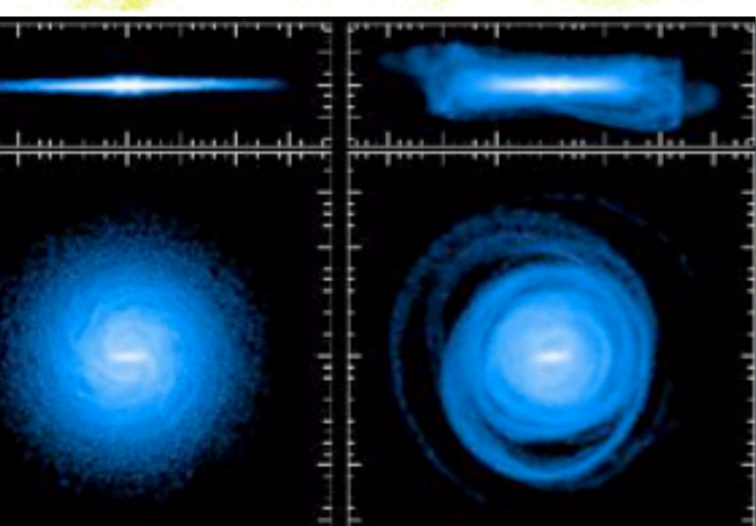








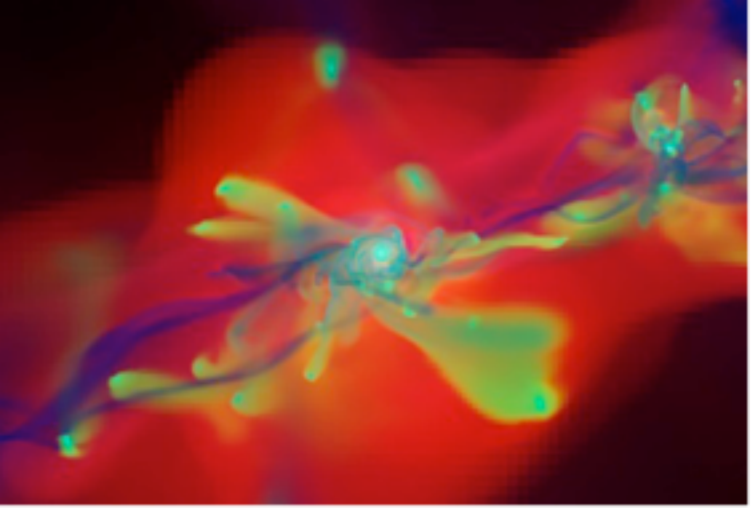
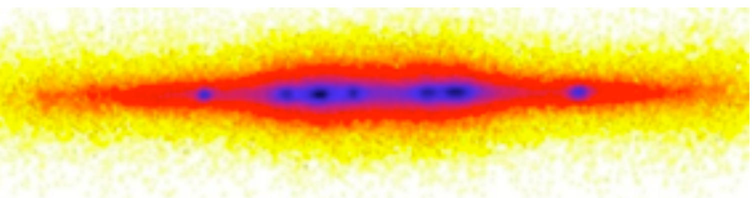
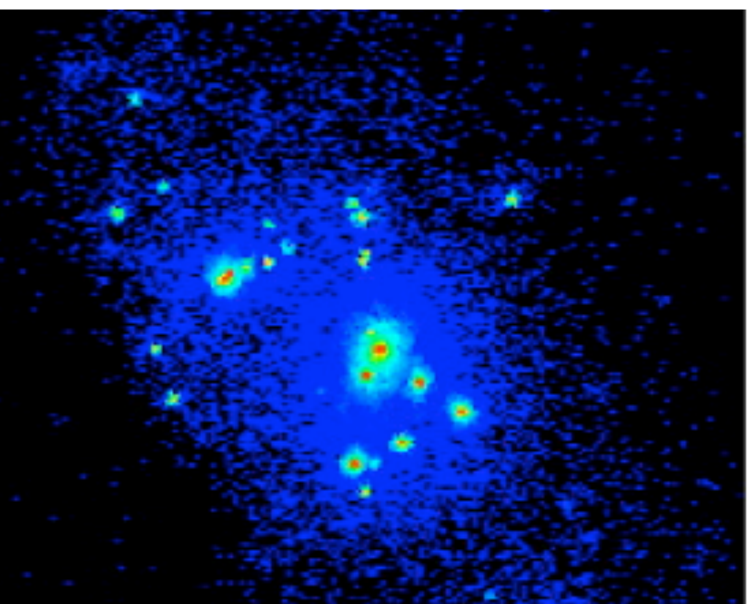
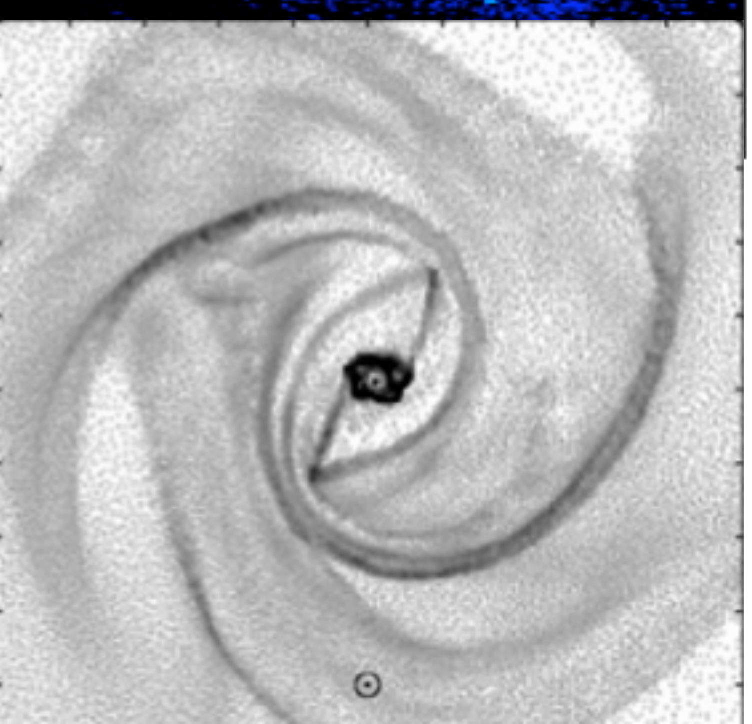
CHEMODYNAMICAL MODELLING OF THE GALAXY

Paola Di Matteo (GEPI, Obs de Paris)

MODELLING THE GALAXY(IES)

The Milky Way, as the other galaxies,
is a continuously evolving system,
due to internal and environmental processes as well.

There is not a unique process which determined the formation of the different Galactic components,
but very likely several processes, which played a role (maybe ?) at different times.

MODELLING THE GALAXY

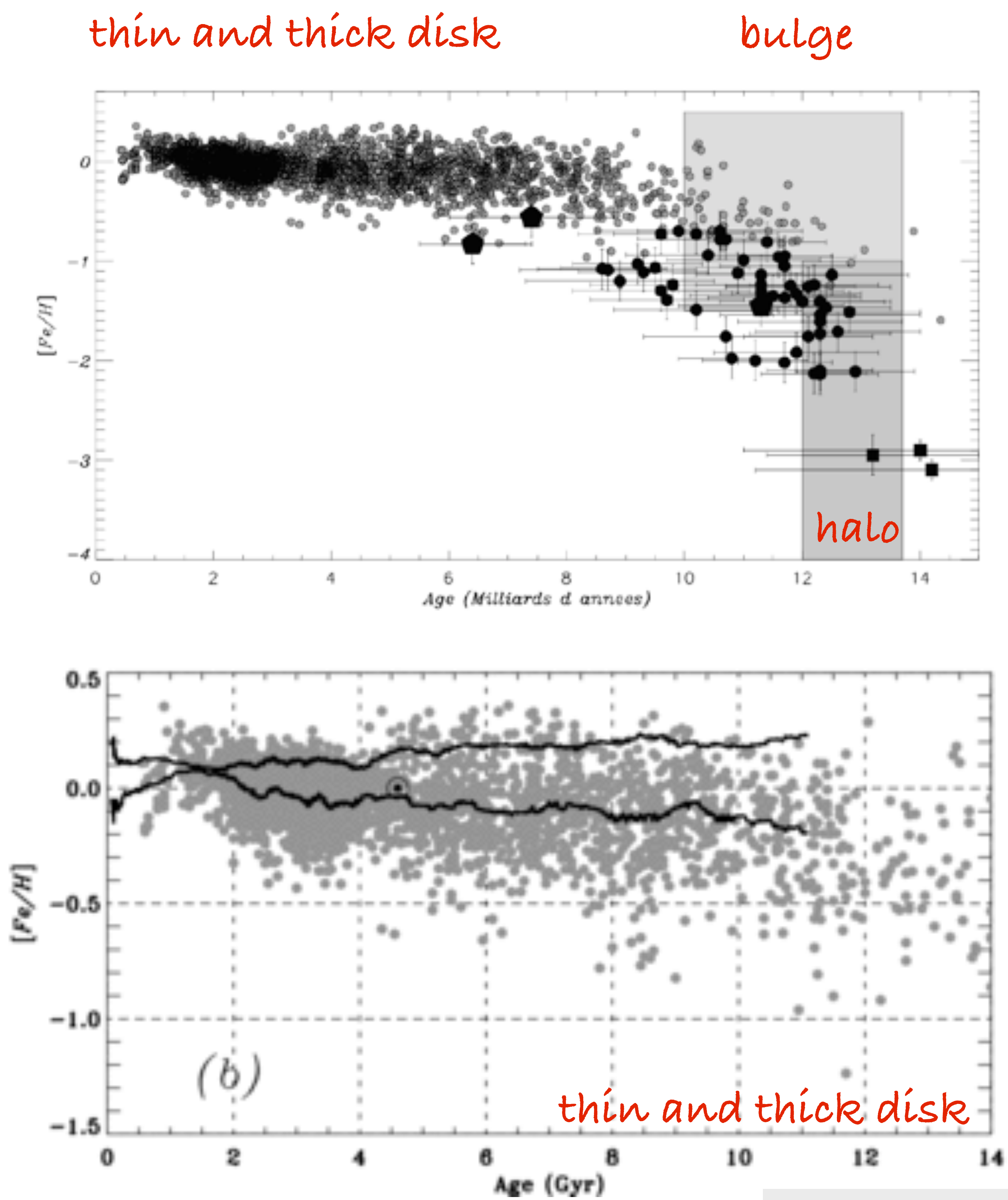
How did the Milky Way galaxy appear 10-13 Gyr ago, when the oldest stars found in the thick disk and in the bulge formed ?

Did it look like the clumpy disks observed at high redshift ? If so, to what extent these instabilities contributed to determine the properties we observe today ?

Did the Milky Way pass through a phase of satellites bombardment ? Multiple and repeated minor mergers ? If so, where are the signatures of these processes in our Galaxy, today ?

From a "violent" evolution at high redshift to a phase dominated by secular processes ? If so, is it possible to quantify the role of the bar(s) and spiral structure in the evolution of the MW components ?

AGE-METALLICITY RELATION



Haywood 2008

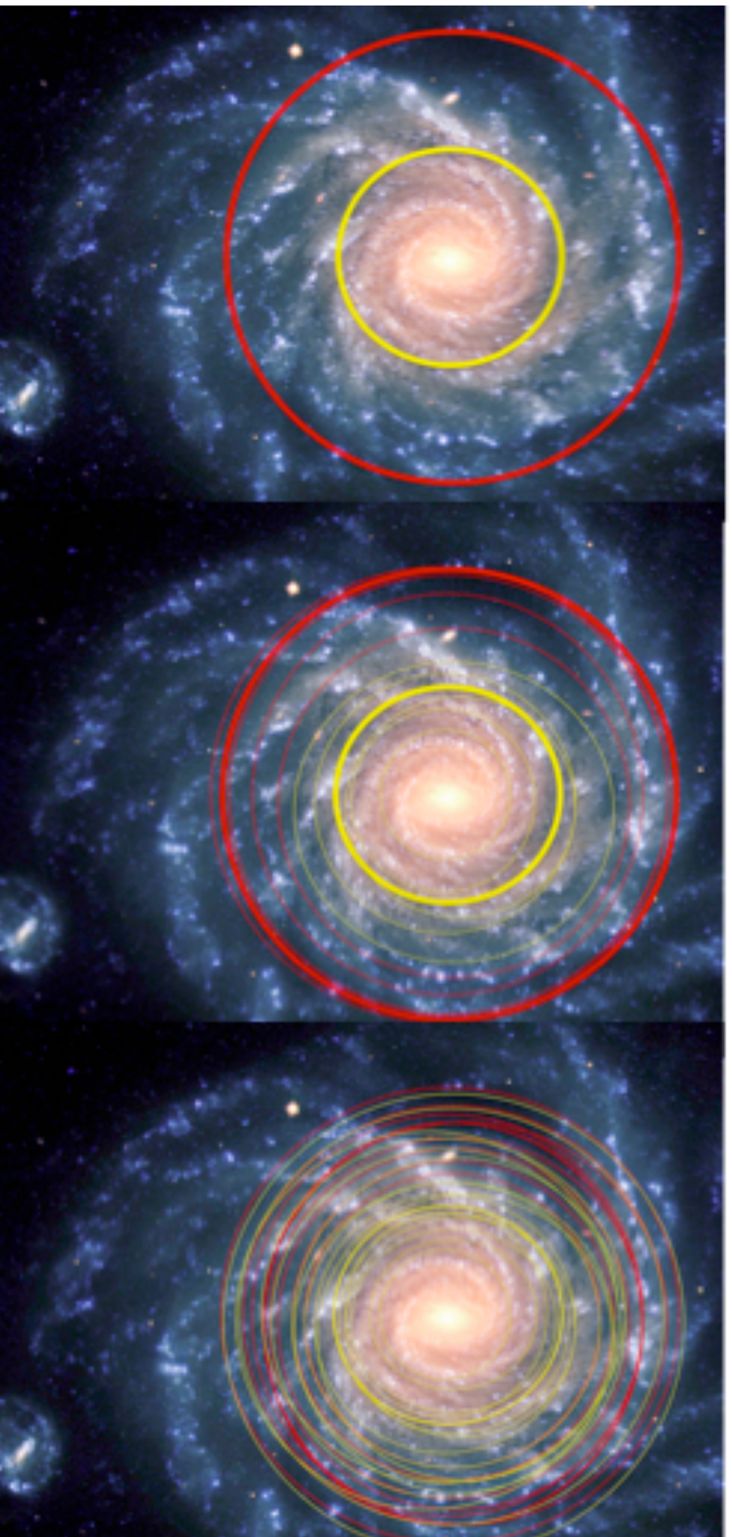
Global enhancement of the metallicity with age

But in the disk high dispersion in the metallicity at every age

How is this compatible with an homogeneous ISM (at spatial scales of several 100 pc) ?

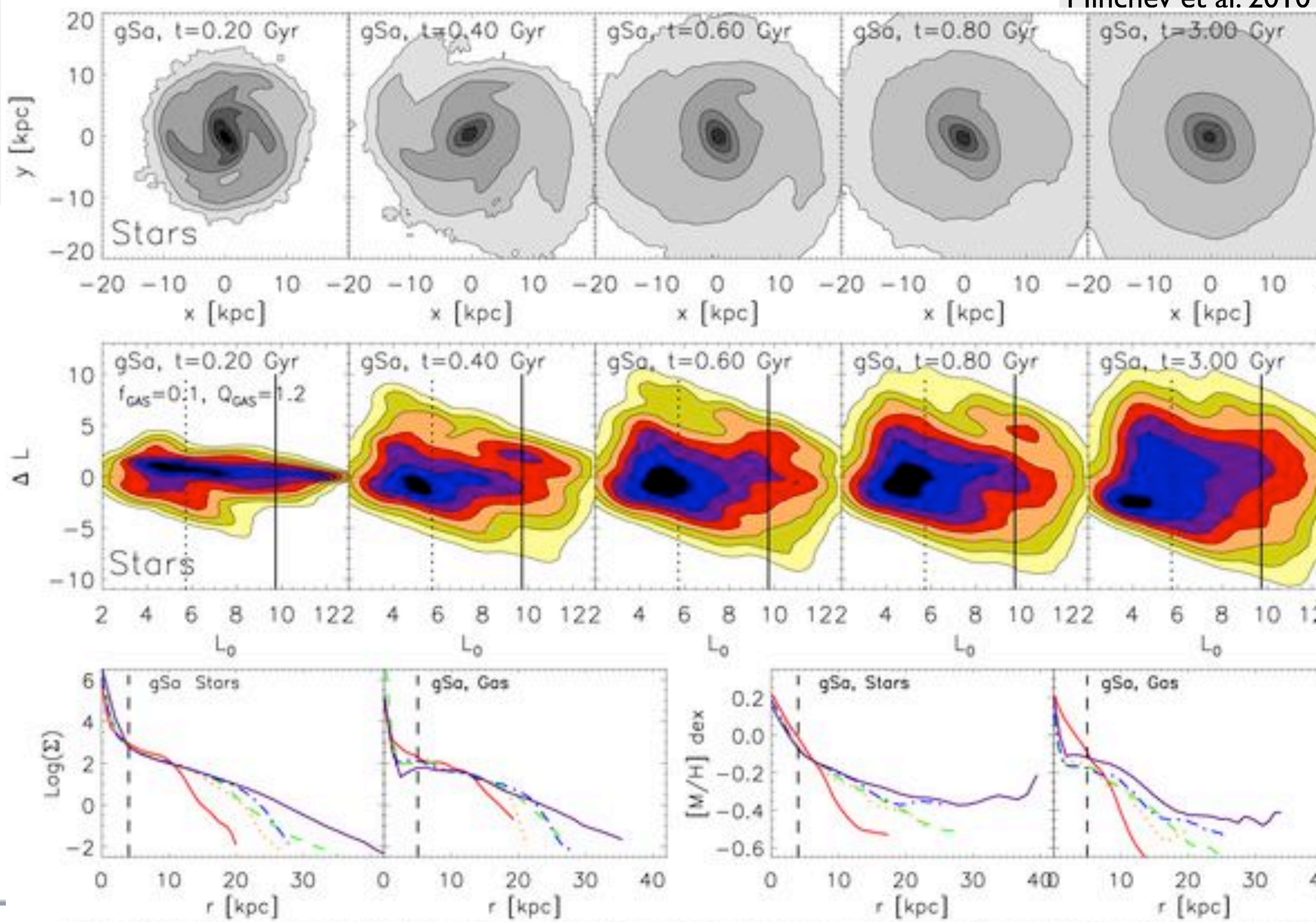
STELLAR MIGRATION IN THE DISK

Redistribution of angular momentum by the effect of resonances associated with a central bar and/or spiral structure

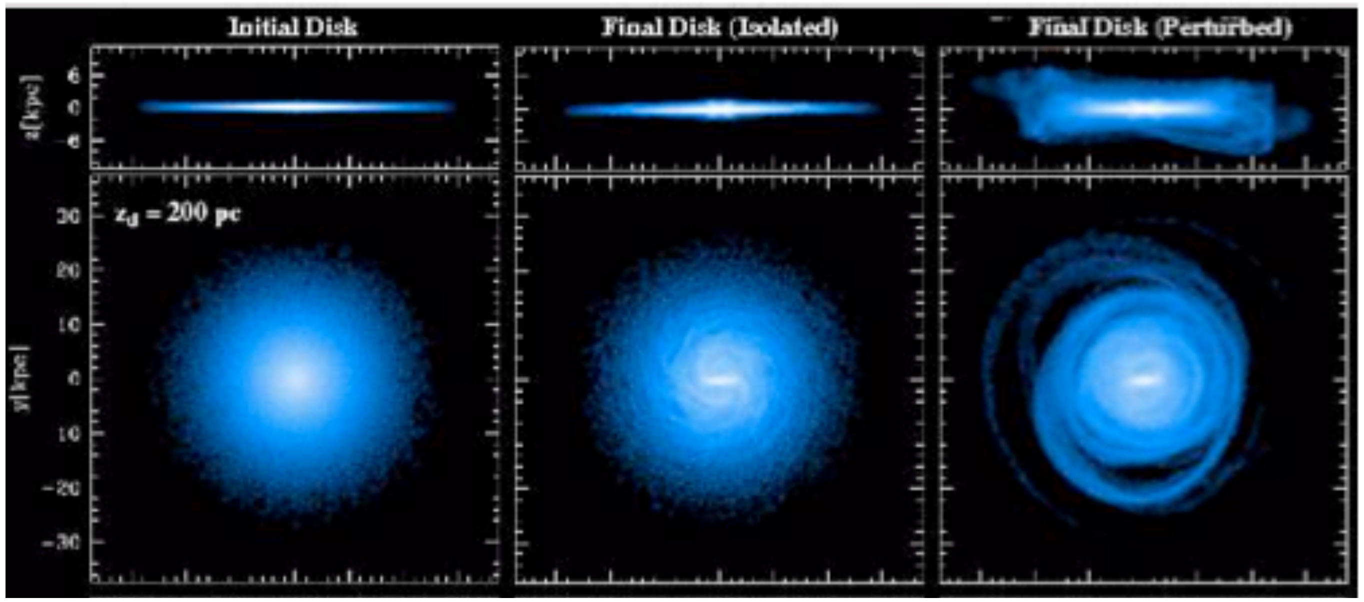


Credits : M. Haywood

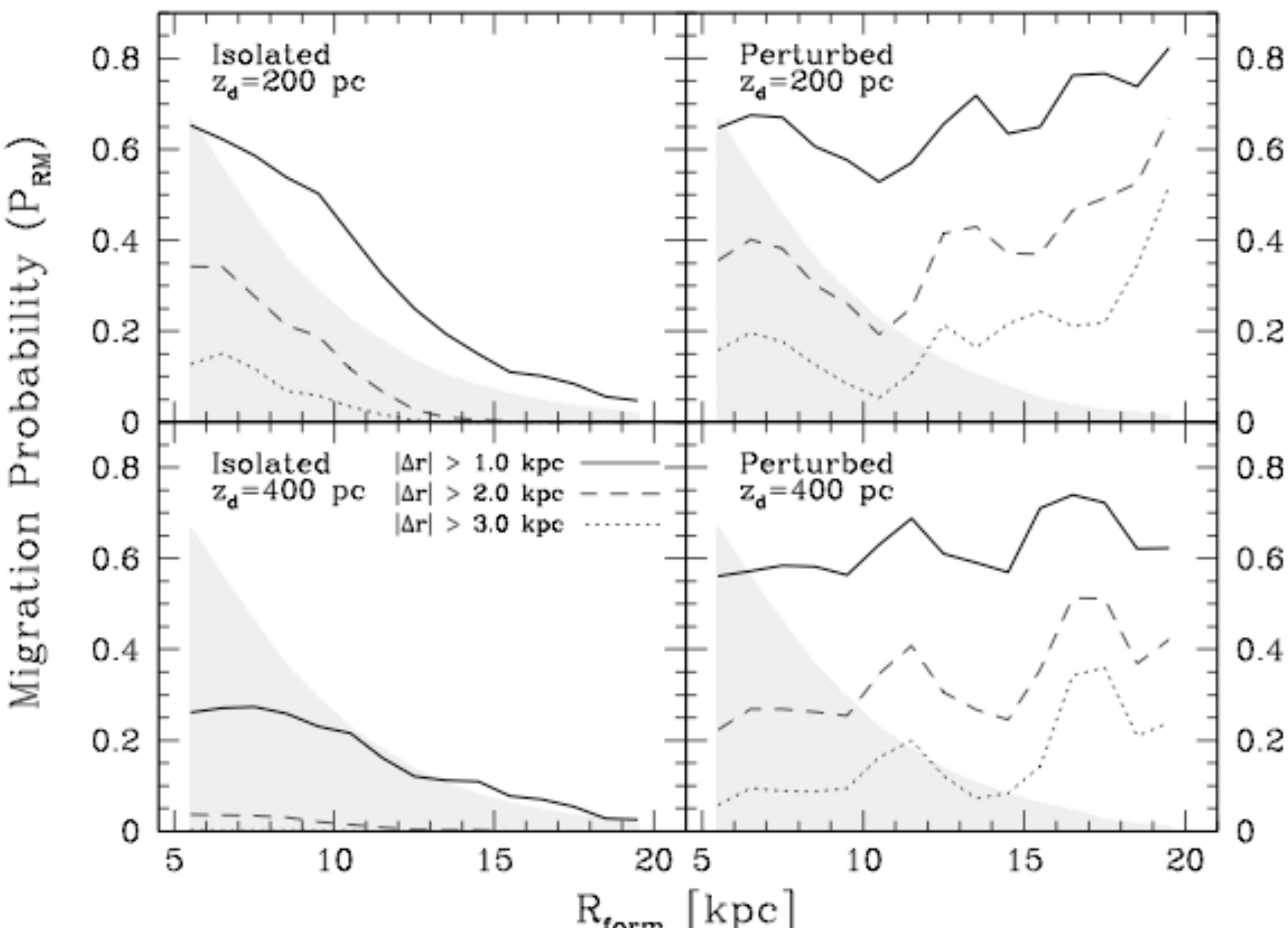
Minchev et al. 2010



STELLAR MIGRATION IN THE DISK



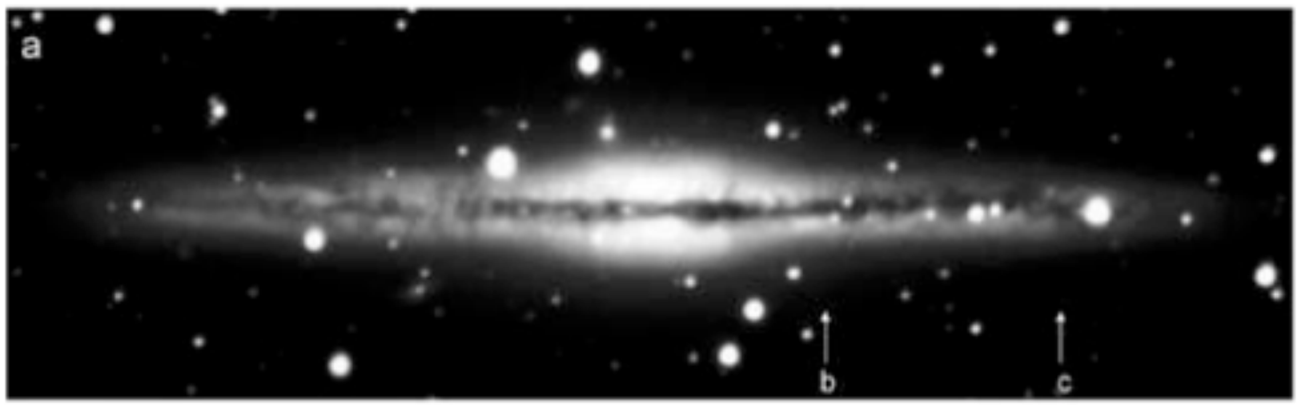
Radial mixing can also be induced by external processes, like satellites accretion



The migration probability follows the mass distribution in the isolated disks but is anti-correlated with mass in the perturbed disks.

Bird et al. 2011

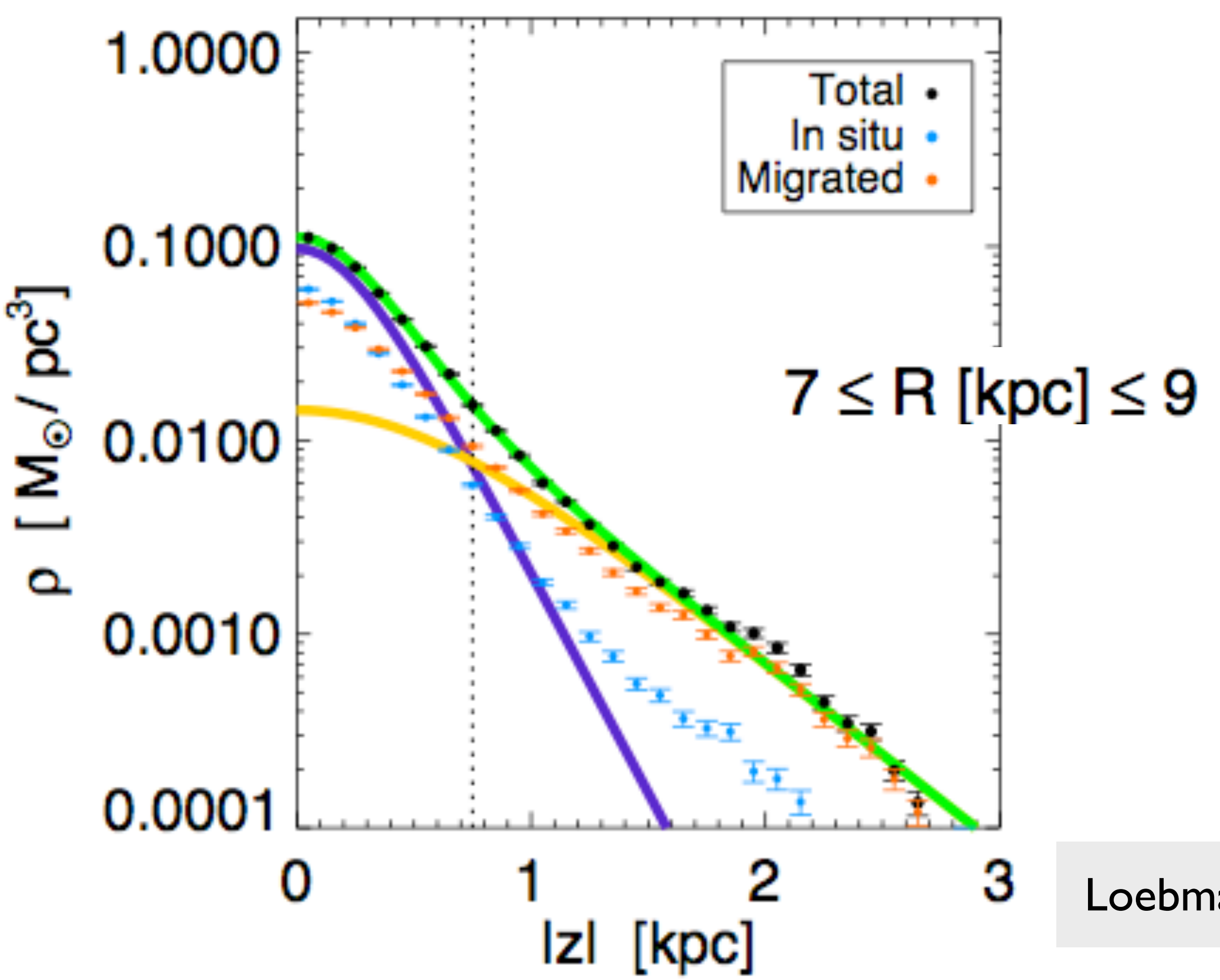
STELLAR MIGRATION AND VERTICAL STRUCTURE



(sigma z)$_b$ > (sigma z)$_c$

Stars migrate from the inner regions to the outer disk, where the gravitational force exerted by the disk is weaker.

Vertical velocity dispersions higher than those expected in the outer disk, they tend to redistribute in a thick component.

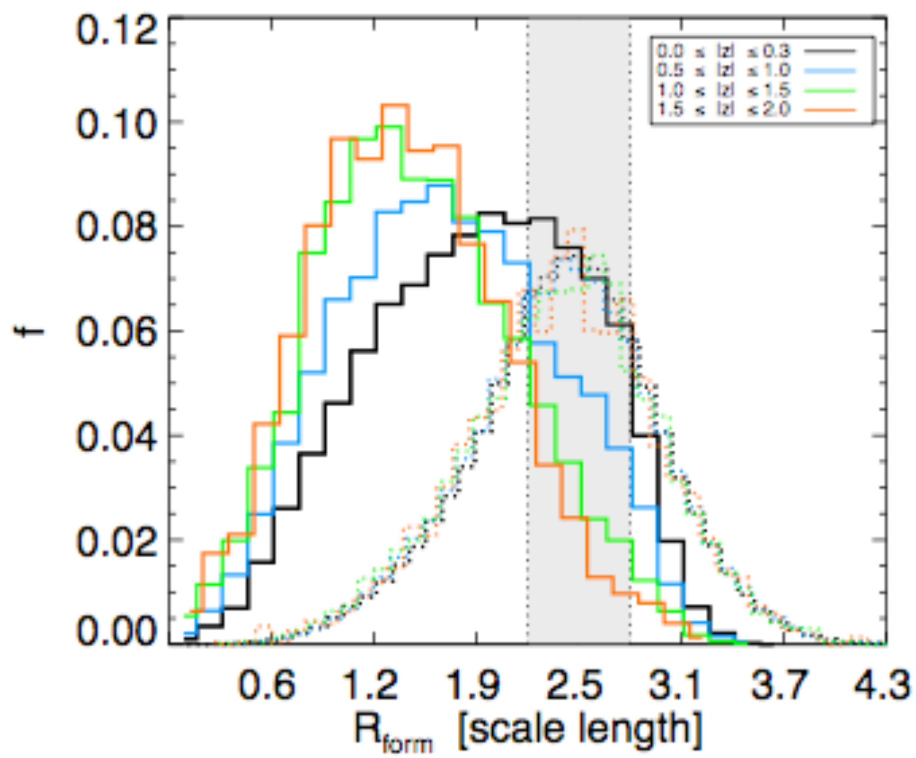


Loebman et al. 2010 : Idealized galaxy forming from dissipational collapse of gas embedded in a spherical dark matter halo

Most of the stars forming the thick disk have migrated from the inner regions

Loebman et al. 2010

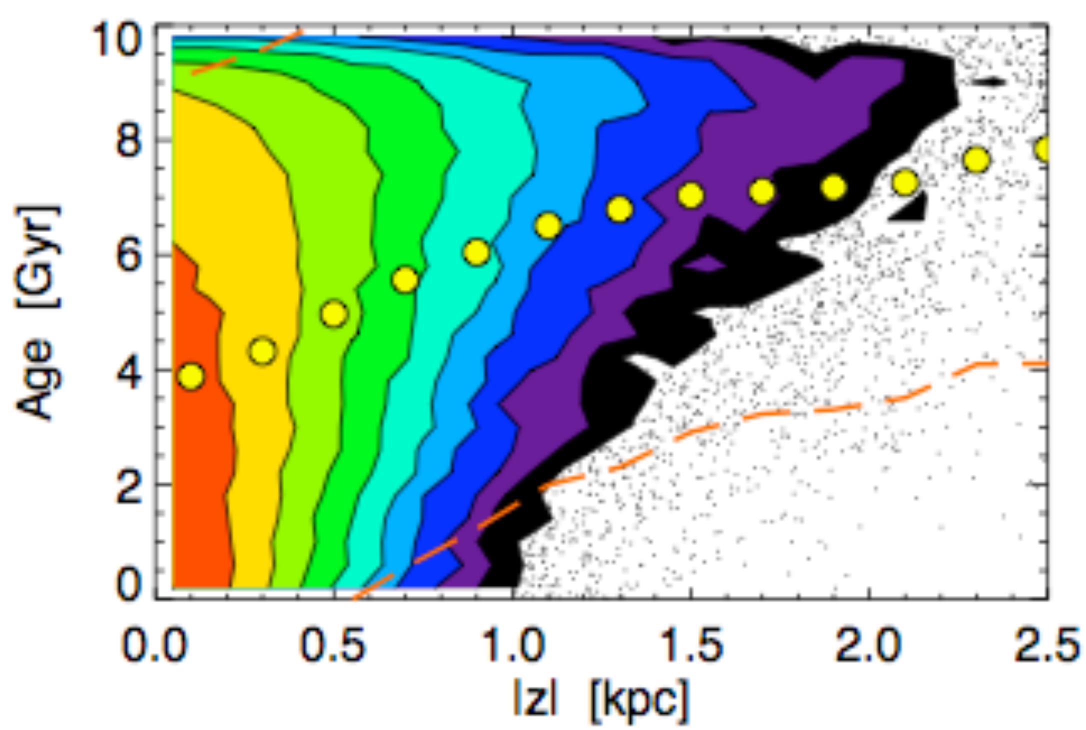
STELLAR MIGRATION AND VERTICAL STRUCTURE

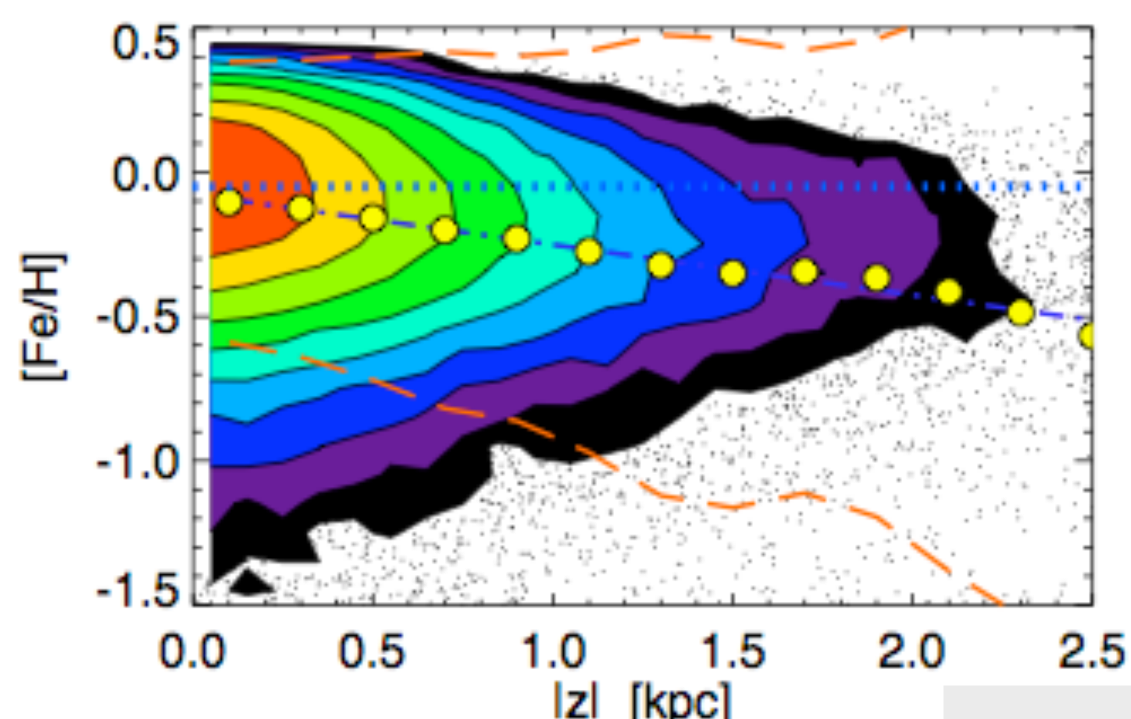


Formation radius of stars in the solar neighborhood :
most of the stars at high vertical distances from the mid-plane comes from the inner disk

↓

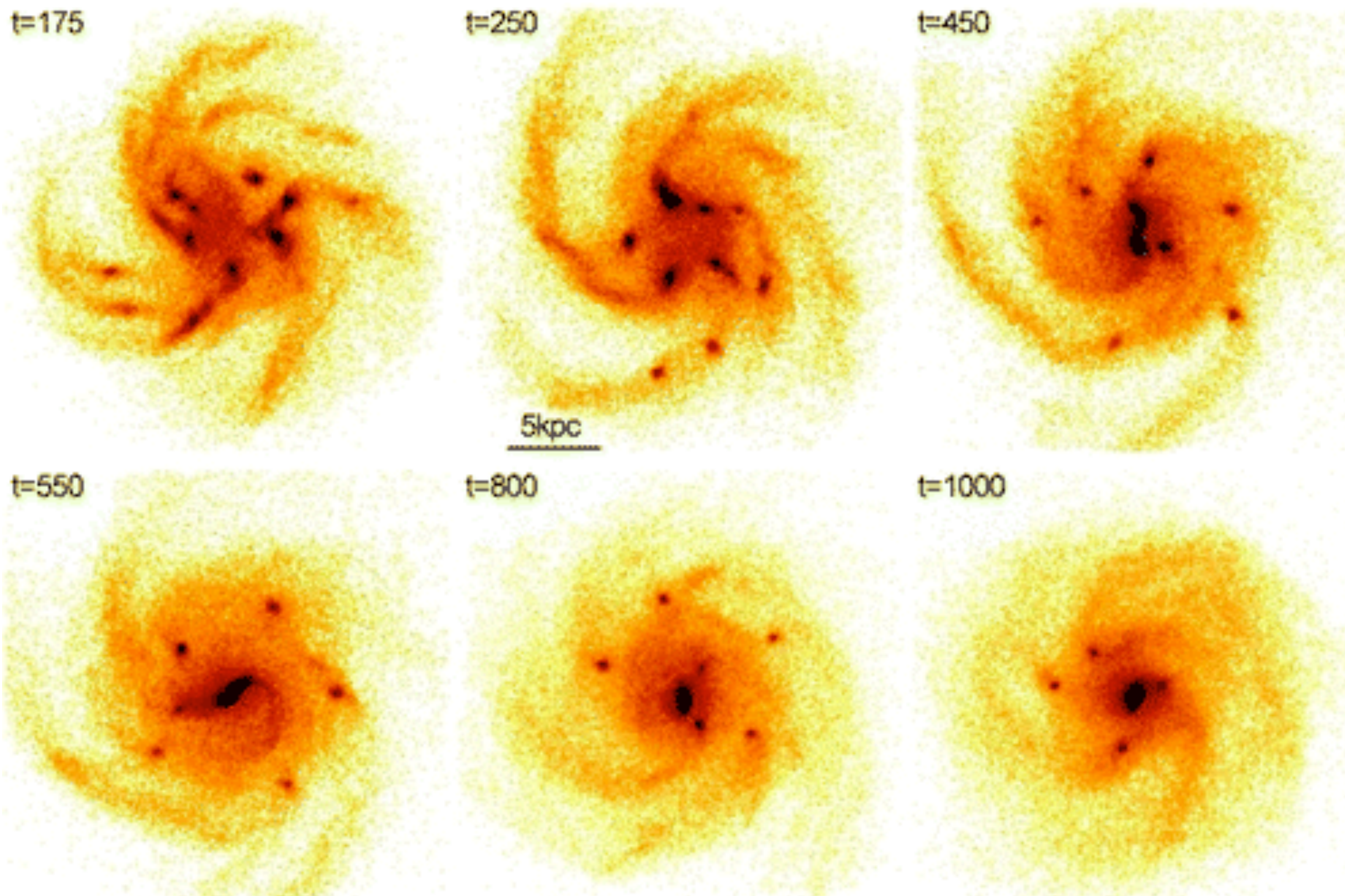
Vertical gradients in age and metallicity,
BUT this requires the process to be slow



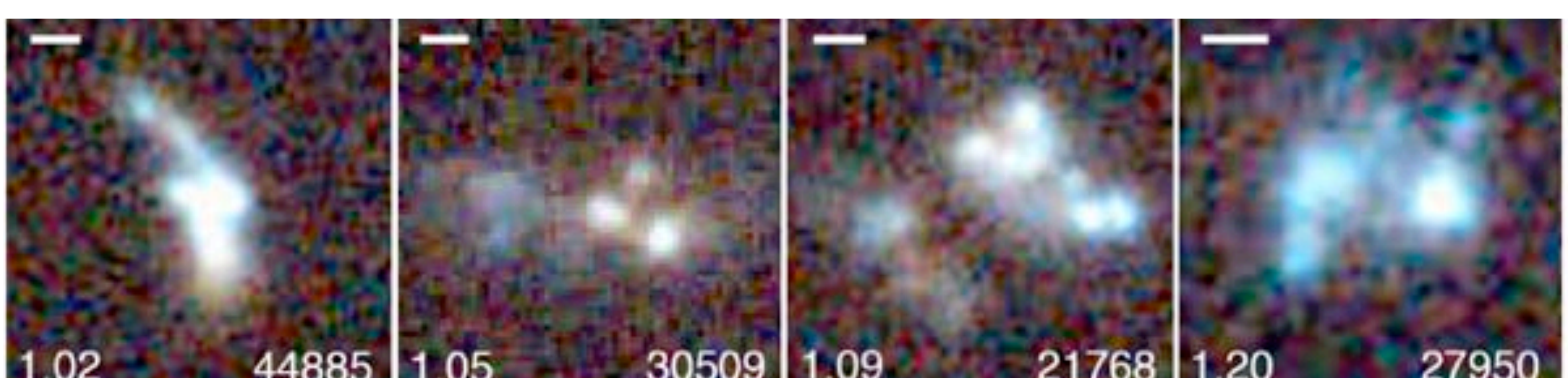


Loebman et al. 2010

CLUMPY GALAXIES



Bournaud et al. 2008

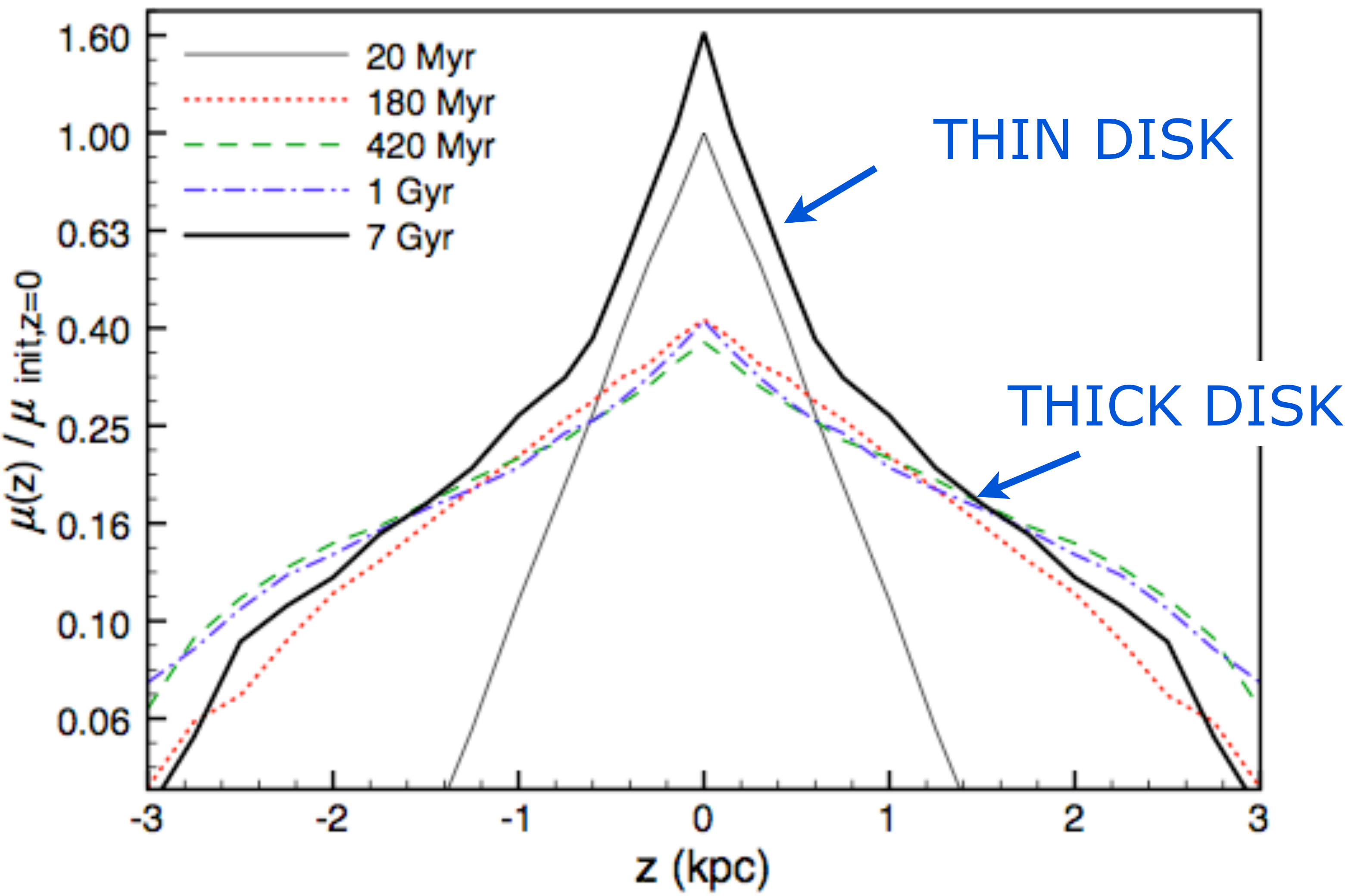


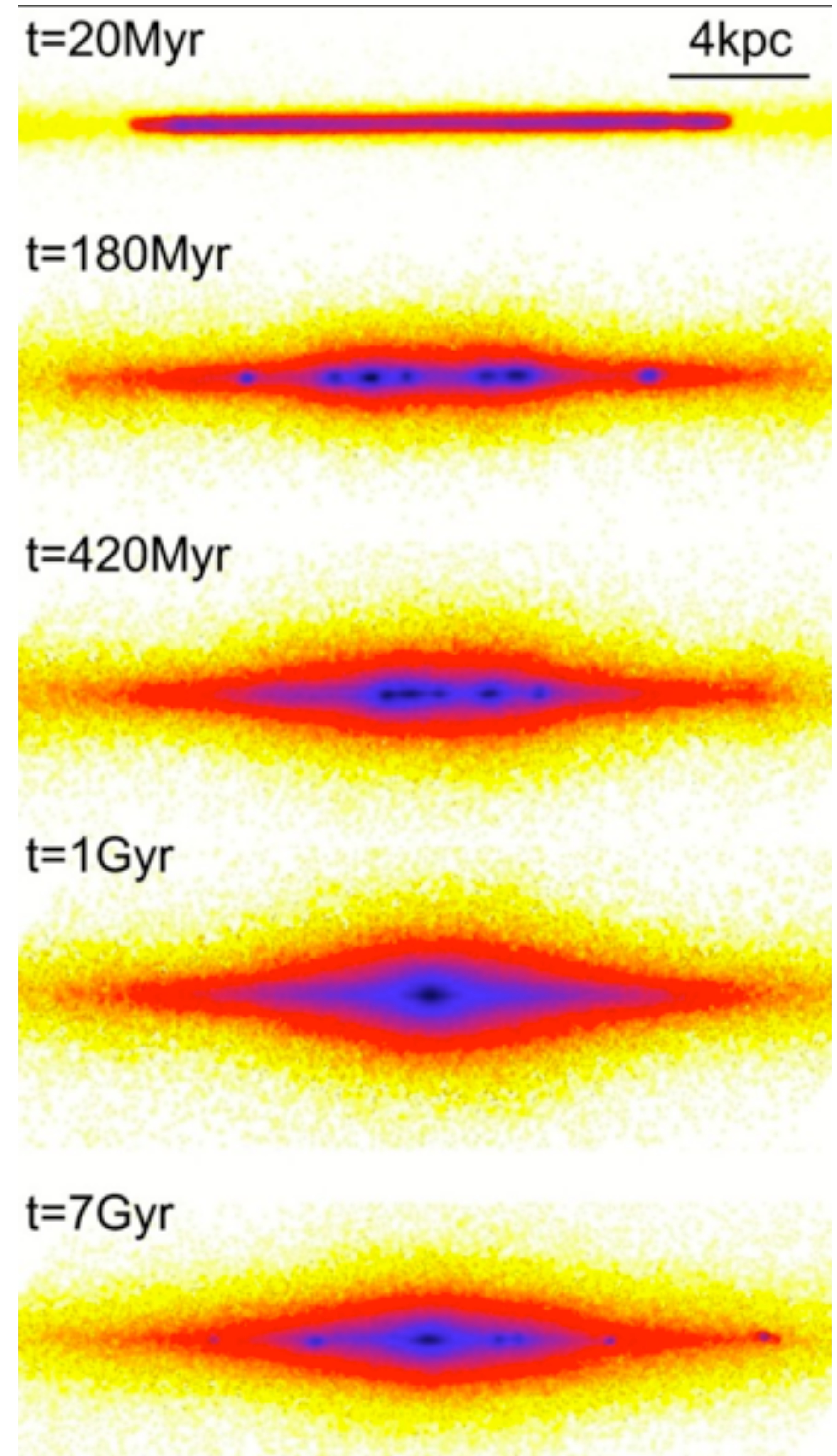
Elmegreen et al. 2009

Dense fragments resulting from Jeans instabilities in gas-rich and bulgeless disks (Noguchi 1999, Bournaud et al. 2007)

``Clump-cluster'' galaxies have the appearance of highly clumpy disks. Some are bulgeless, while others have small red central concentrations that resemble primordial bulges

CLUMPY GALAXIES AND THICK DISKS



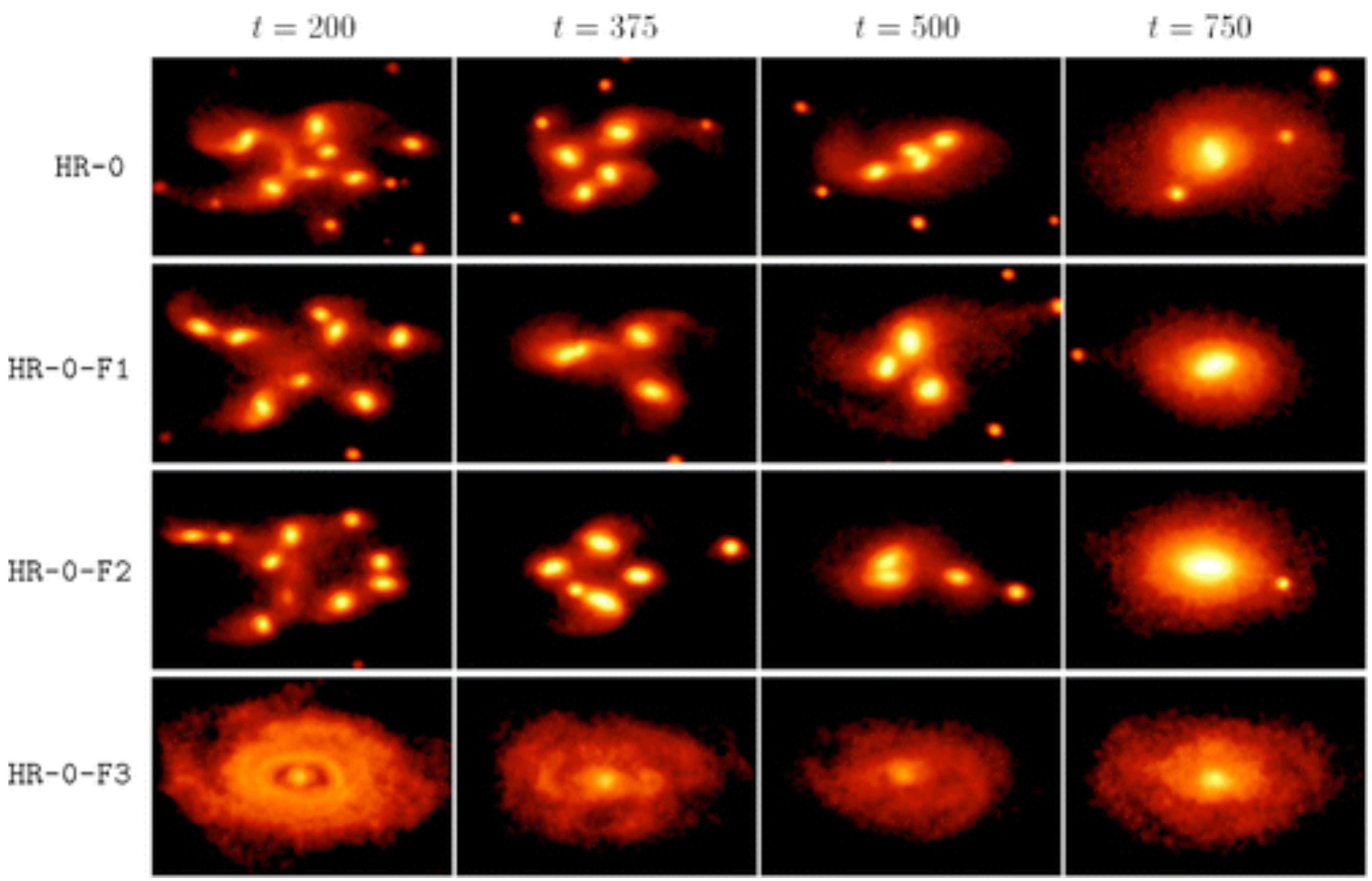


Bournaud et al. 2009

Thick disk formed in ~ 1 Gyr since the beginning of the clumpy phase.

Later gas accretion to reform a thin disk

CLUMPY GALAXIES AND CLASSICAL BULGES



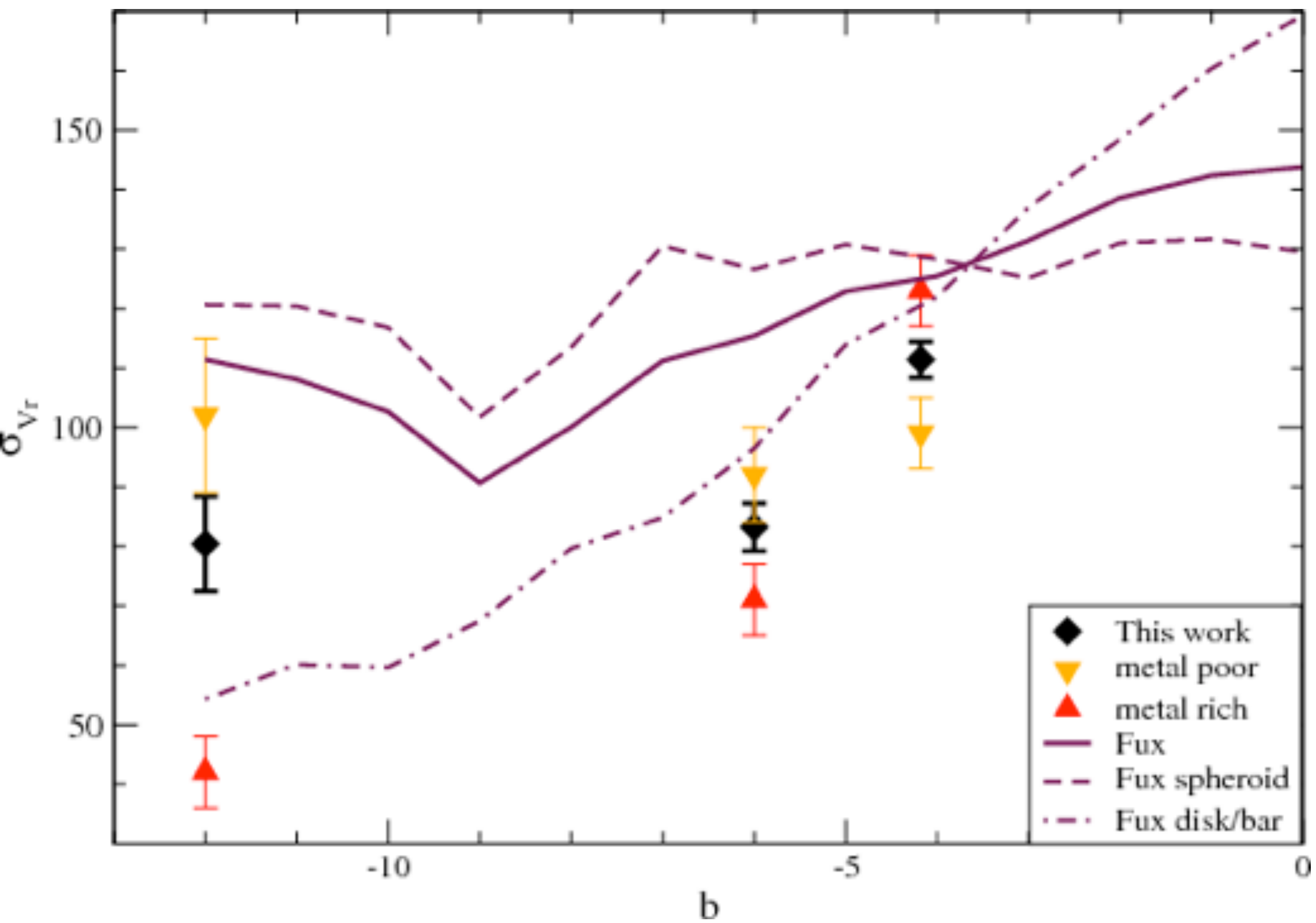
Thick, slowly rotating, and with high Sersic index, like classical bulges

Their rapid formation should also give them relatively high α-element abundances.

Elmegreen et al. 2008

Clumps survival affected by the strength of SNe feedback (Genel et al. 2010)

THE COMPLEXITY OF THE MILKY WAY BULGE



Babusiaux et al. 2010

Two distinct populations :

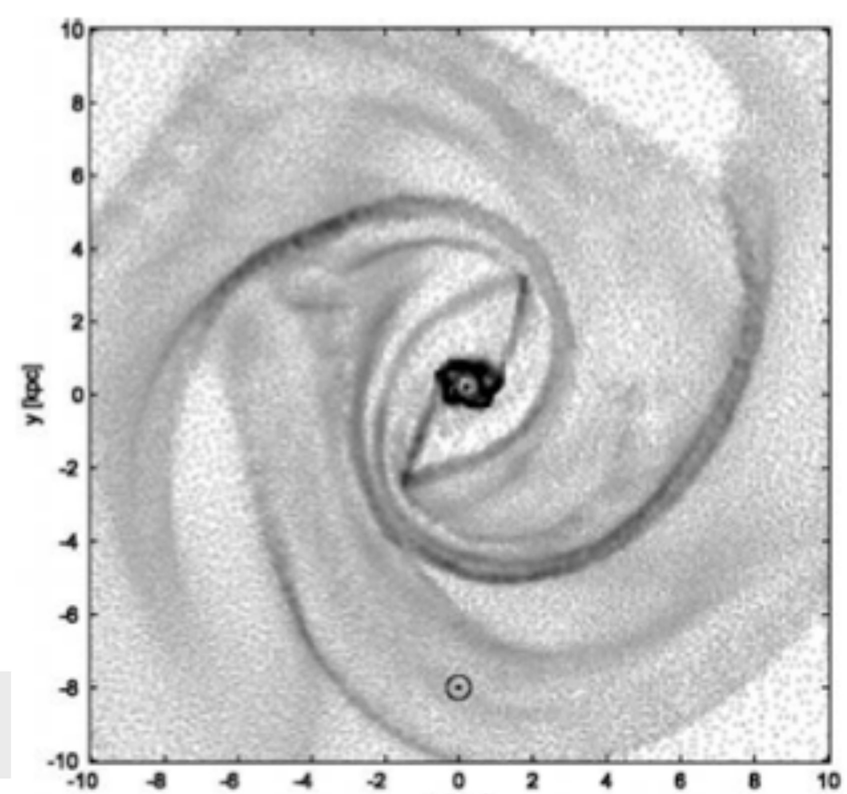
1. a metal-poor component that it is consistent with an isotropic rotating population and that is enriched in [Mg/Fe]

2. a metal-rich component consistent with that expected from a population with orbits supporting a bar and with [Mg/Fe] near solar.

Old spheroid with a rapid time-scale formation

+

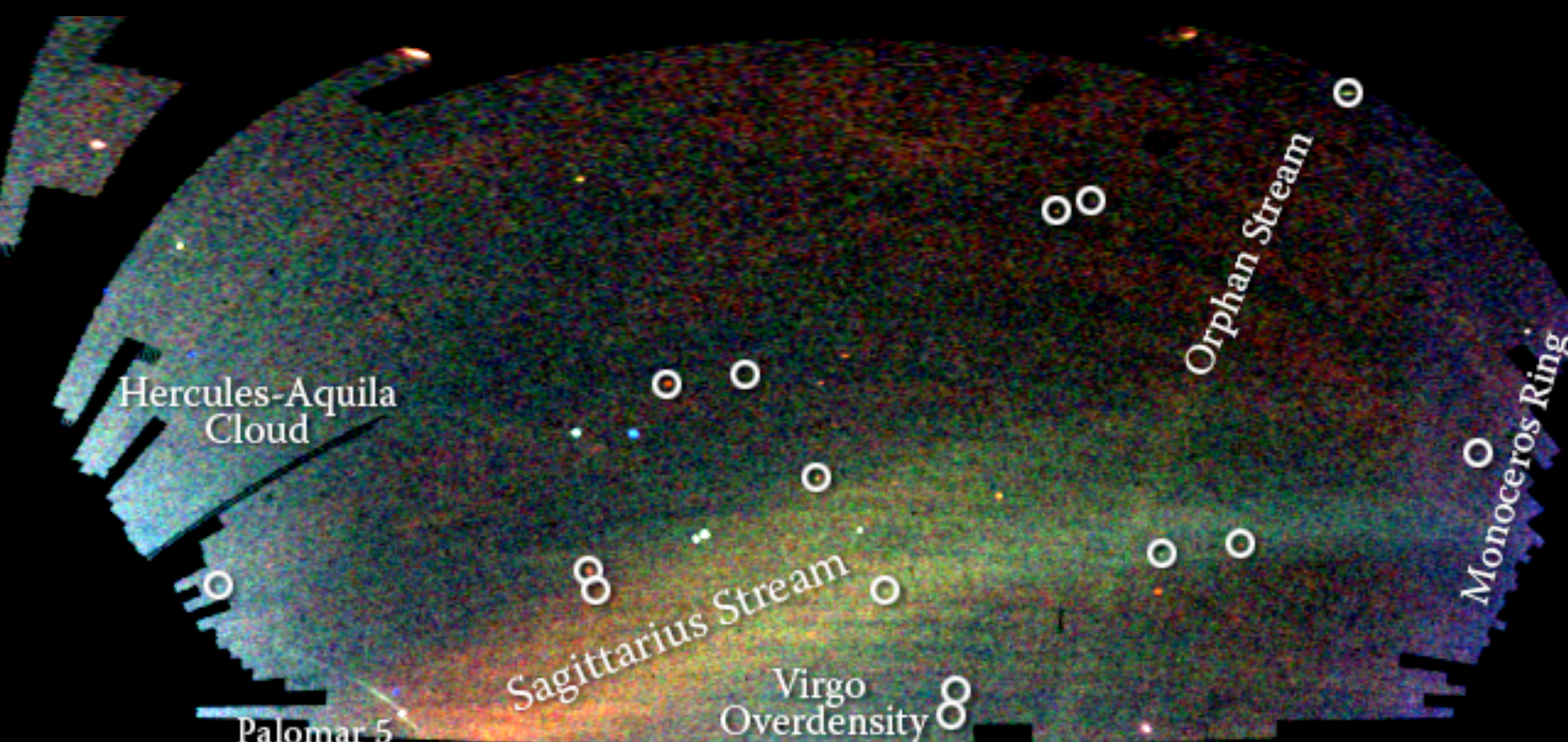
pseudo-bulge formed over a long time-scale through disc secular evolution under the action of a bar



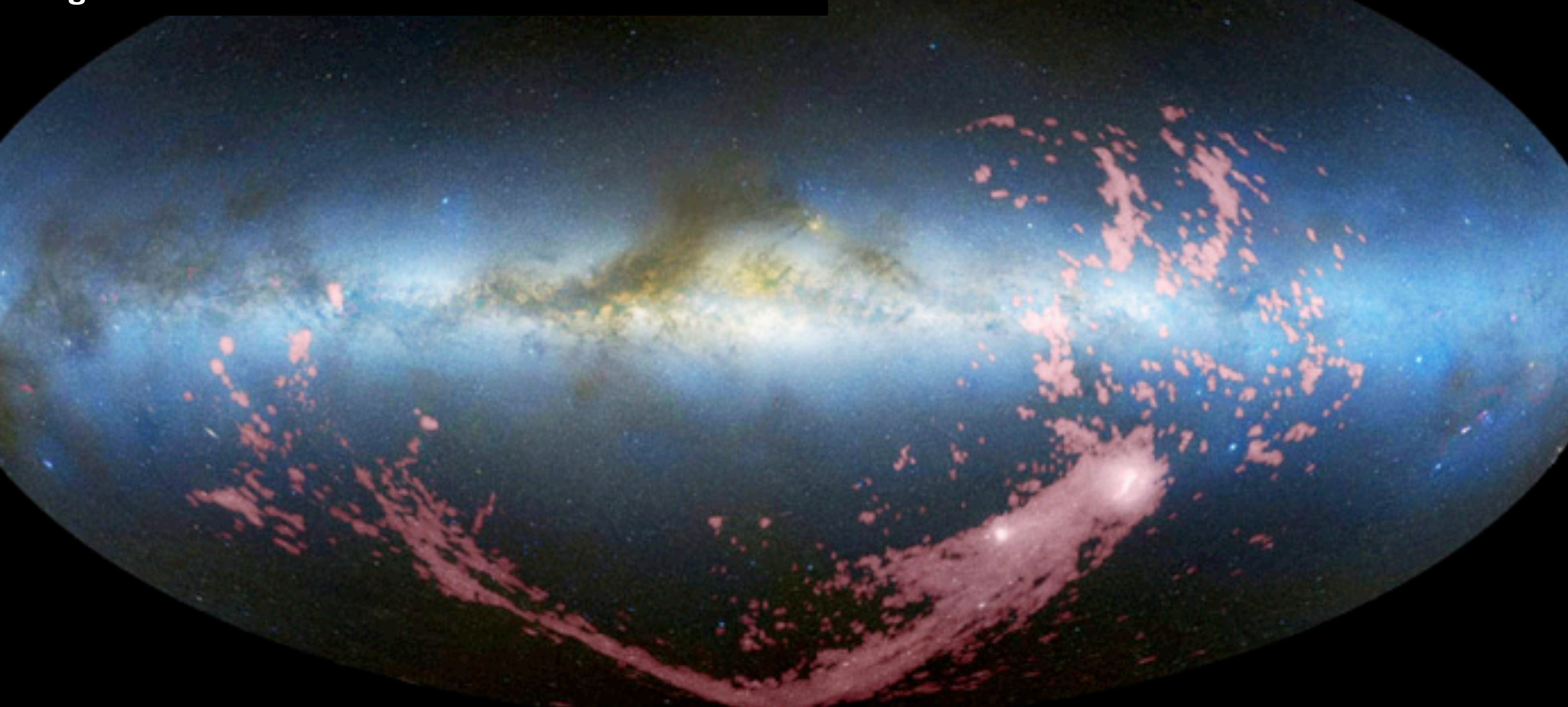
Fux et al. 1997

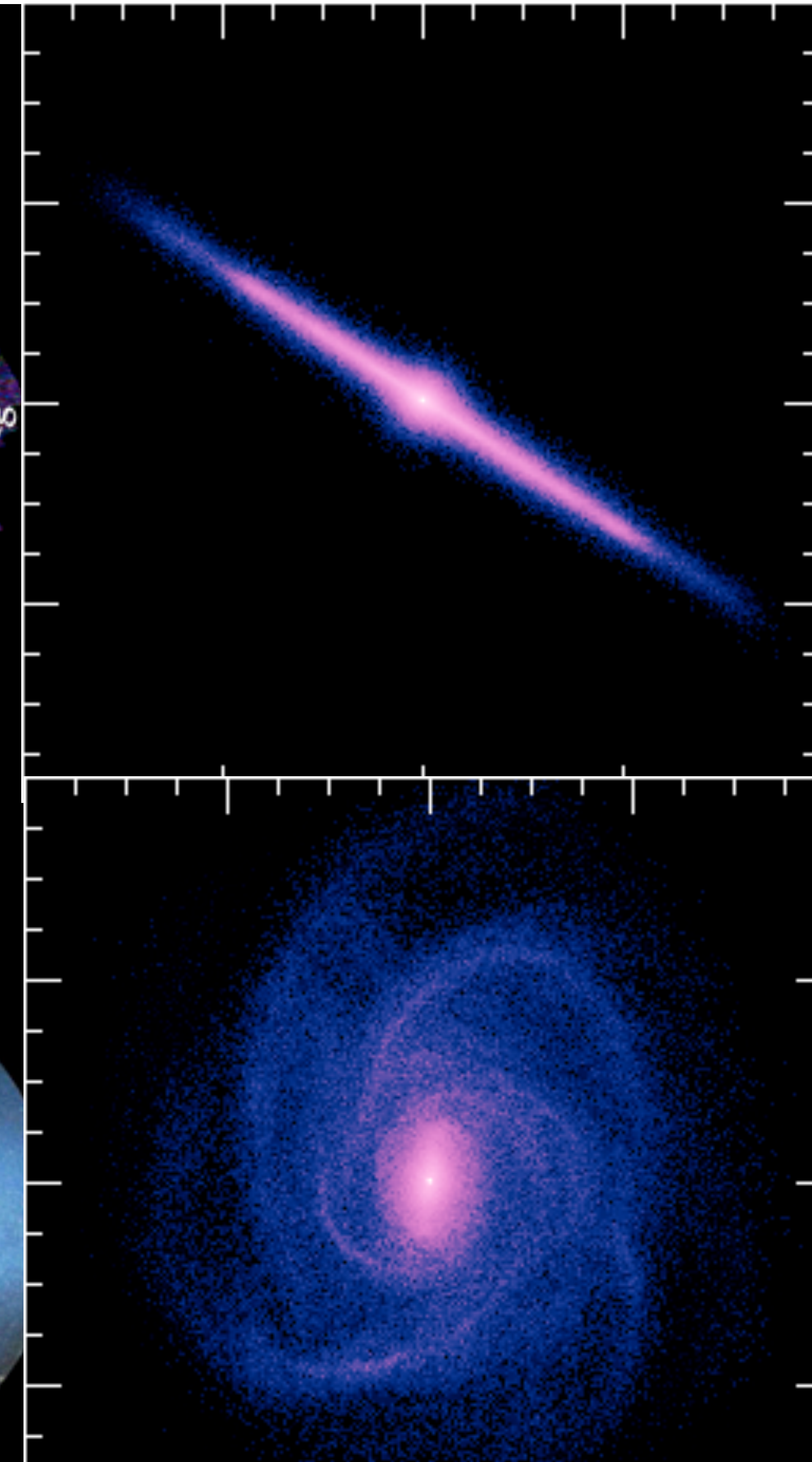
MINOR MERGERS

Stellar streams in the MW halo - Belokurov et al. 2006



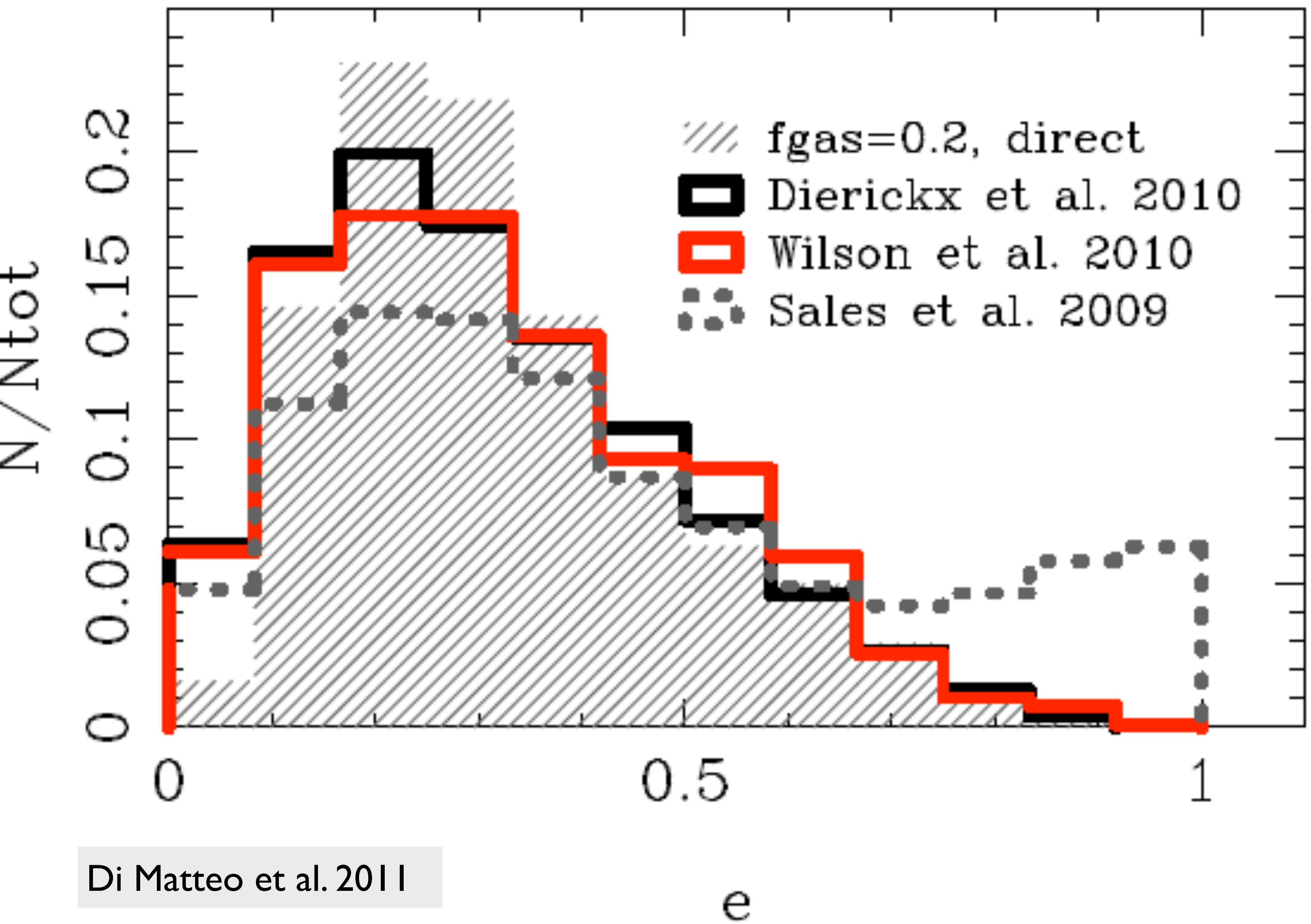
Magellanic clouds and stream - Nidever et al. 2005





Disk galaxy undergoing a 1:10 minor merger – from the GalMer Project, http://galmer.obspm.fr

CAN MINOR MERGERS EXPLAIN THE PROPERTIES OF THE MW THICK DISK ?



Di Matteo et al. 2011

Apocenter of the orbit

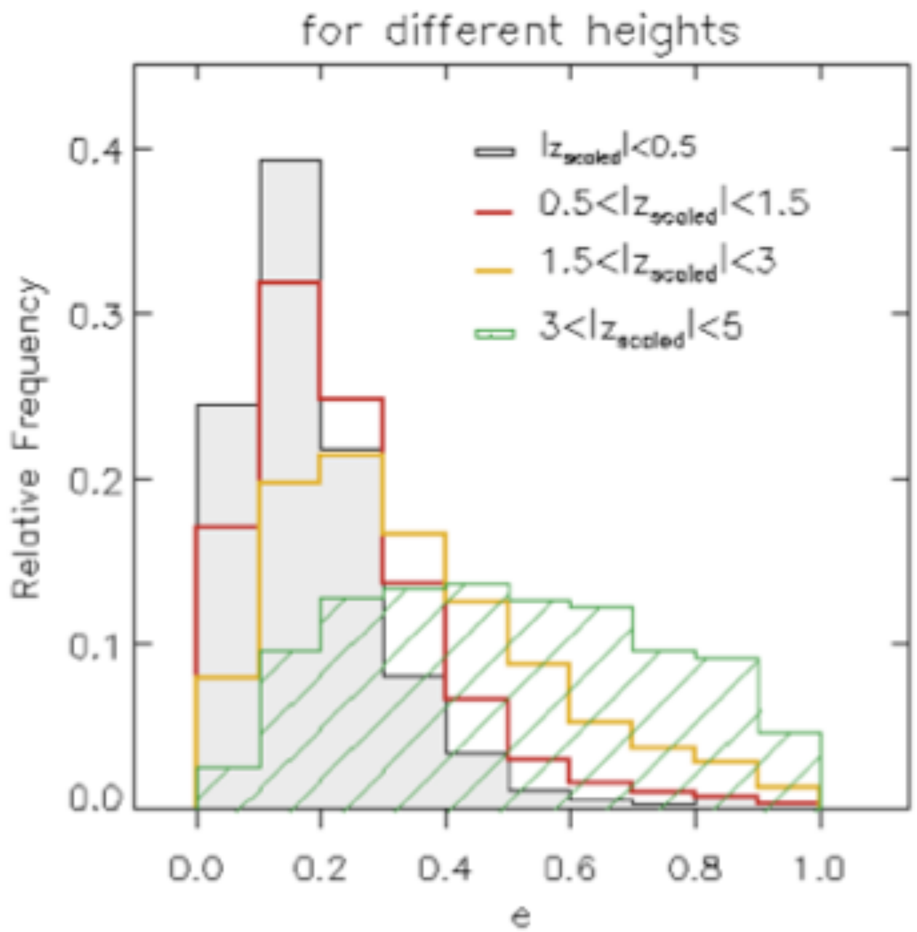
$$e = \frac{R_a - R_p}{R_a + R_p}$$

Pericenter of the orbit

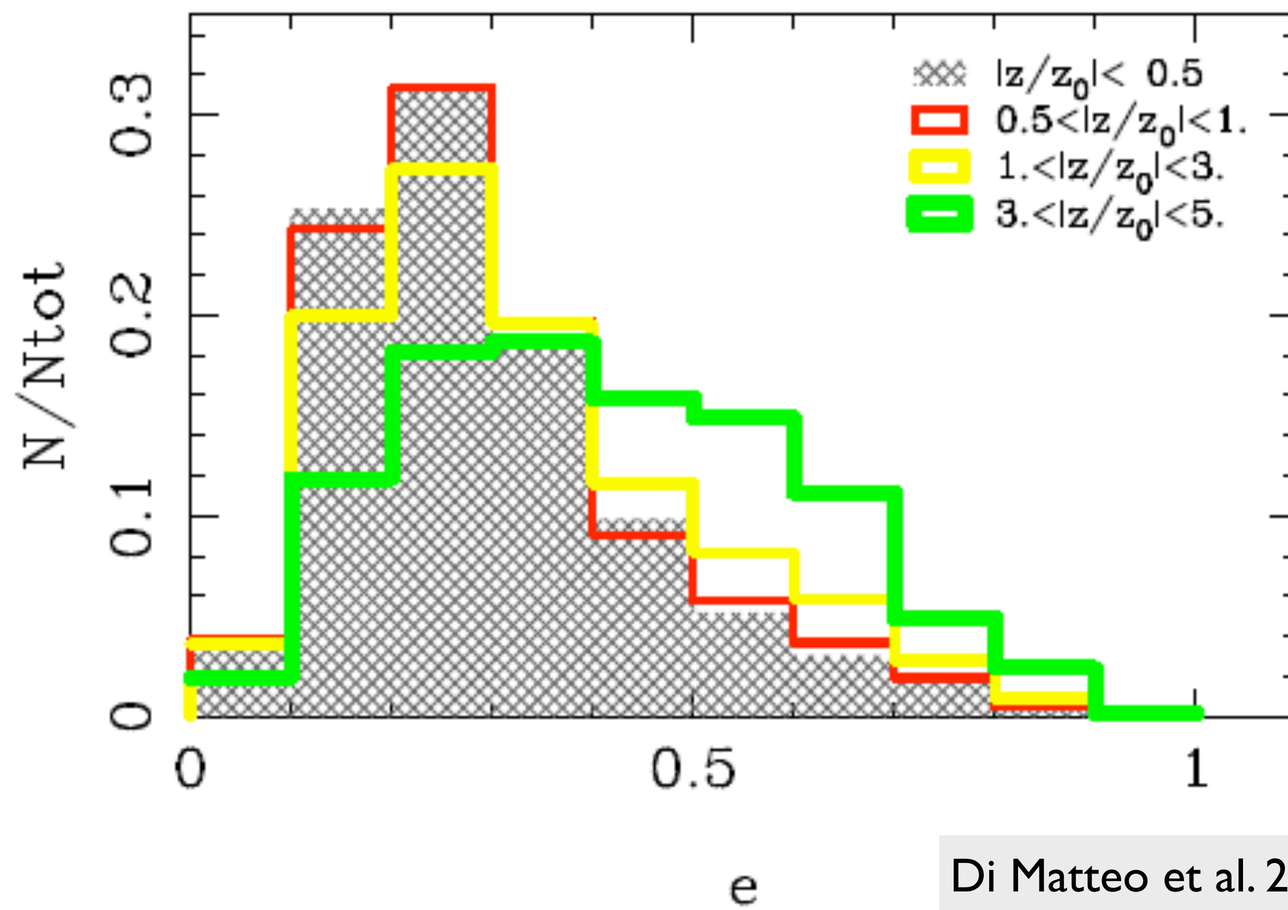
The eccentricity distribution of stars in thick disks formed through minor mergers are remarkably similar to those observed :

a peak at low eccentricities and a smooth decline at higher values

CAN MINOR MERGERS EXPLAIN THE PROPERTIES OF THE MILKY WAY THICK DISK ?



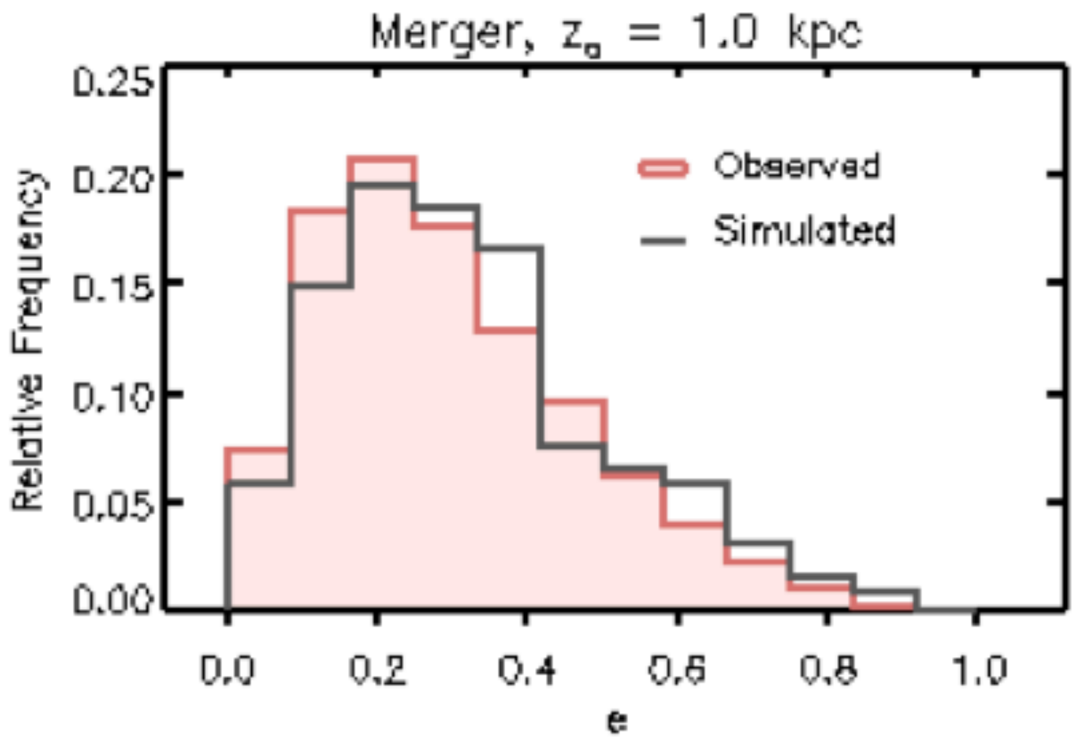
Dierickx et al. 2010



Di Matteo et al. 2011

If minor mergers have been the dominant mechanism for the formation of the Milky way thick disk, the major contribution should come from the merger of satellite(s) on direct orbits.

CAN MINOR MERGERS EXPLAIN THE PROPERTIES OF THE MW THICK DISK ?



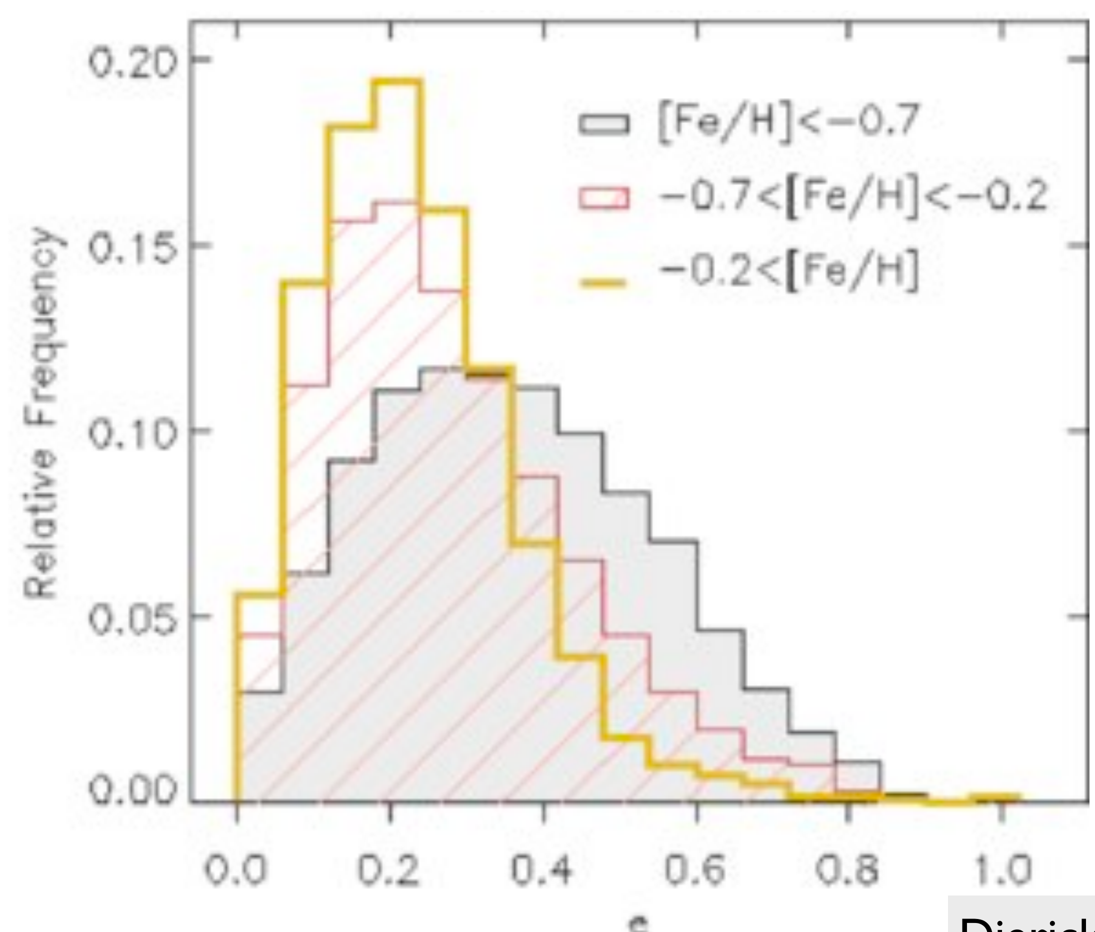
Sales et al. 2009

Other scenarios

- like the formation of a thick disk by gas-rich mergers at high redshift - can reproduce the distribution of the eccentricities of stars in the MW thick disk.

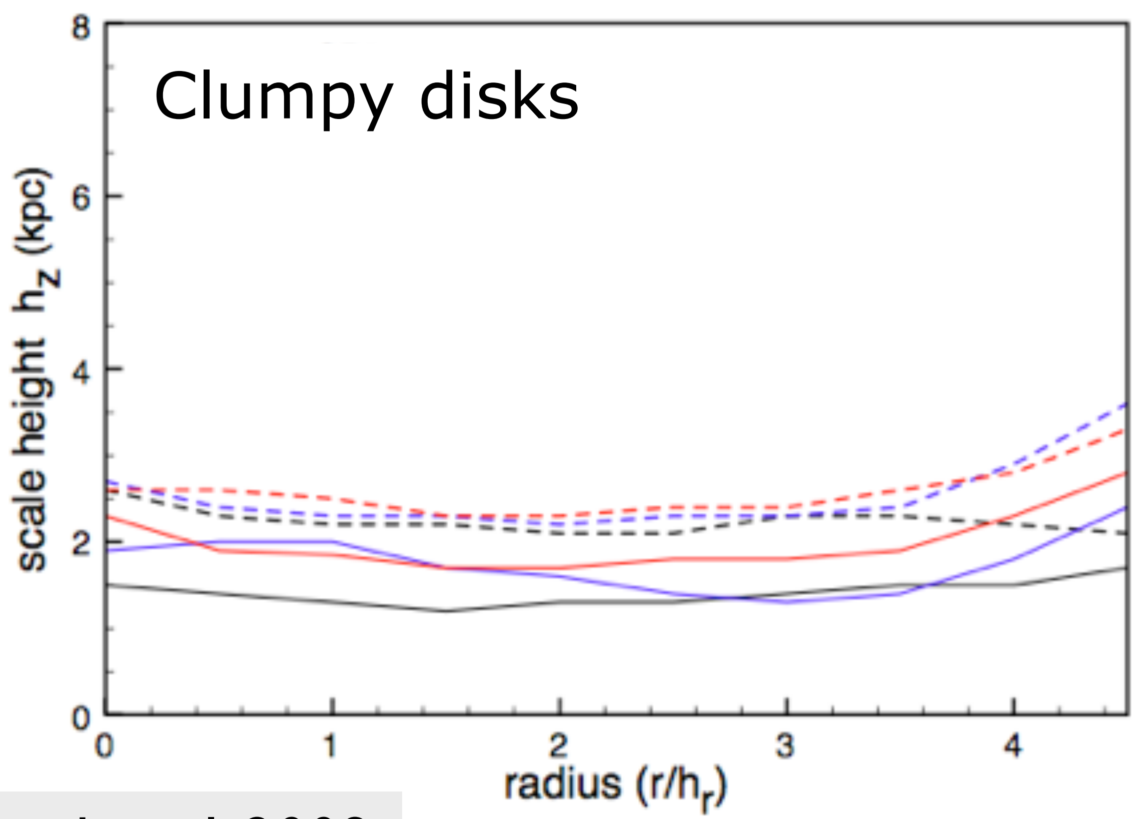
Problem of degeneracy ?

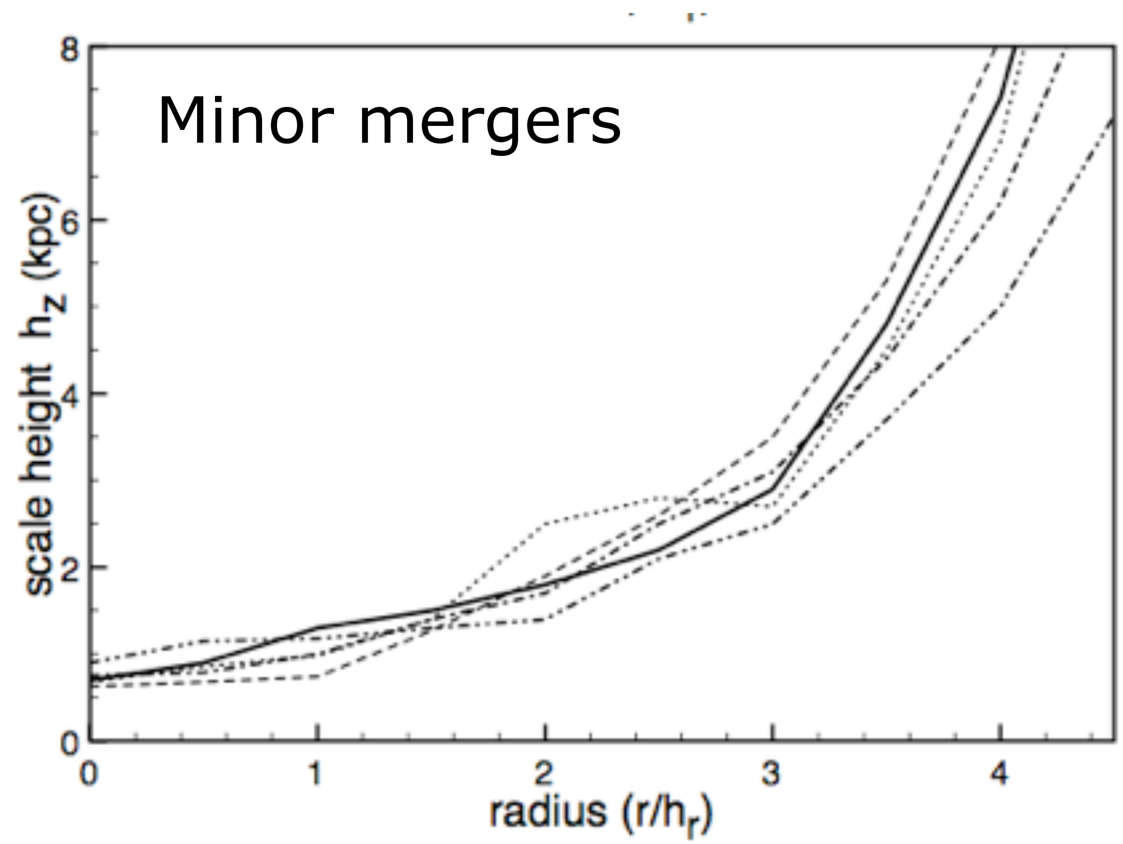
A way to solve it may be to test other correlations, for ex eccentricity vs metallicity. Can the different scenarios all reproduce the observed trend ?



Dierickx et al. 2010

MINOR MERGERS vs CLUMPY DISKS : VERTICAL STRUCTURE OF THE THICK DISKS





Bournaud et al. 2009

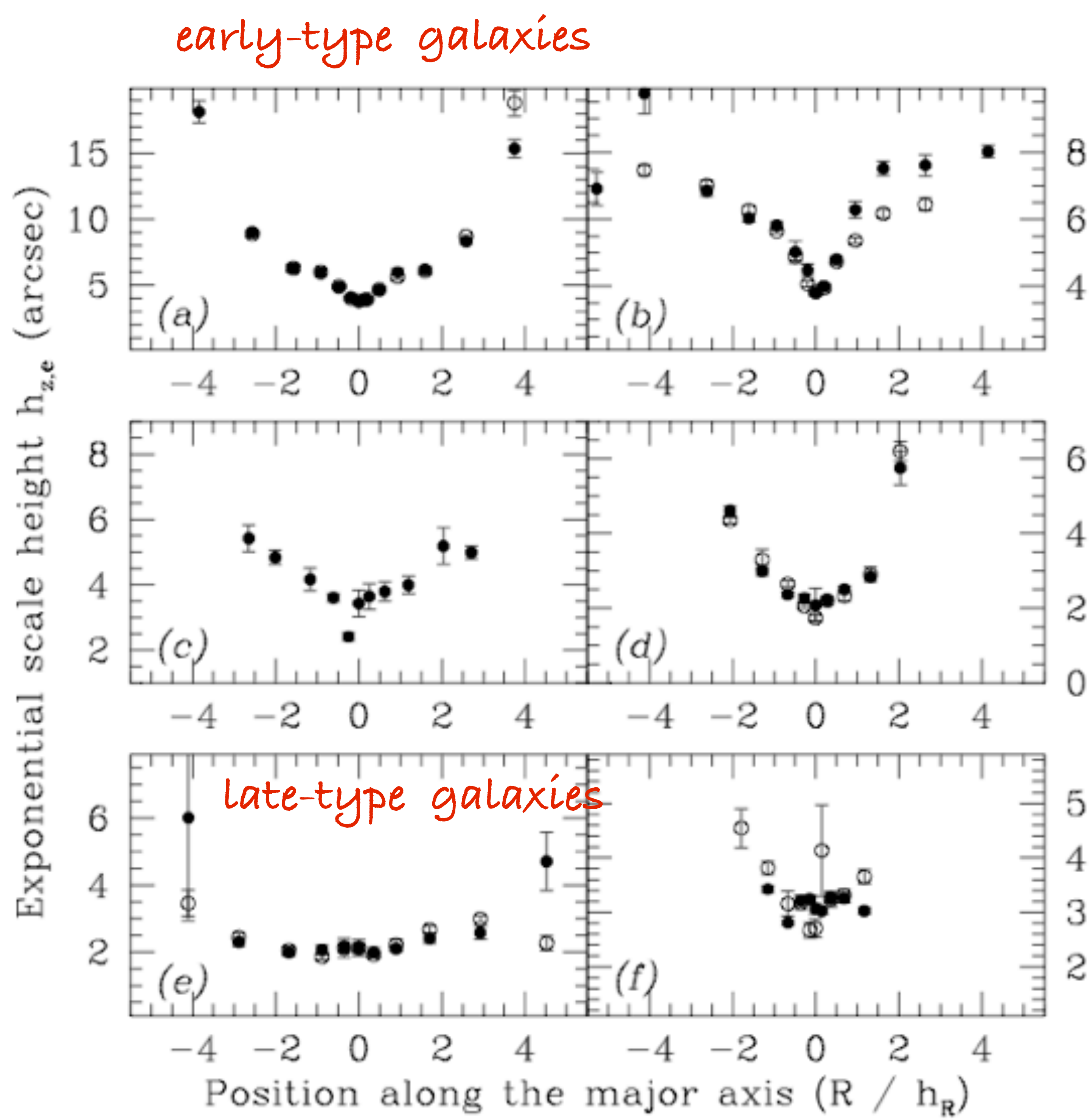
Internal processes generally predict a constant scale height as a function of radius

External processes predict an increasing scale height with radius

MINOR MERGERS vs CLUMPY DISKS : VERTICAL STRUCTURE OF THE THICK DISKS

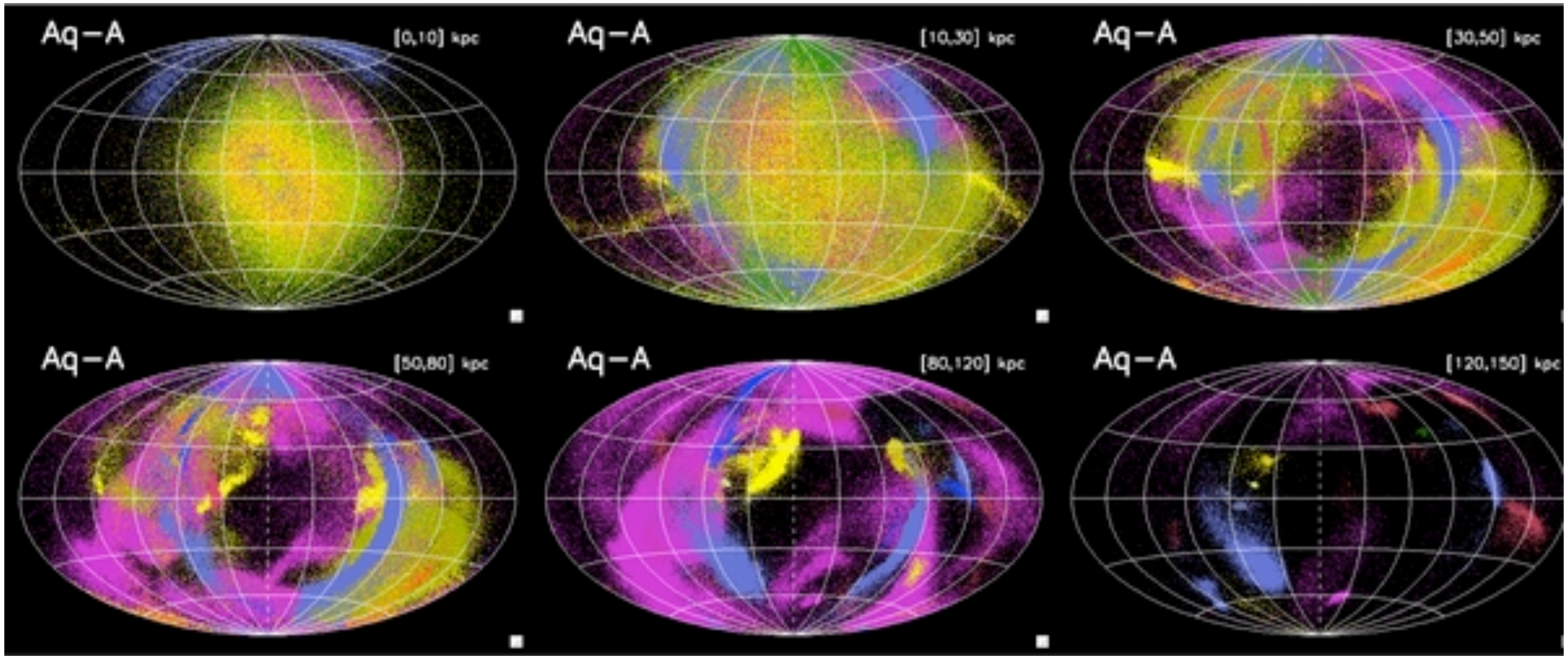
The knowledge of the MW thick disk scale height as a function of the galactocentric distance would help to constraint the process

In external galaxies a variety of possibilities, from stellar disks whose scale height is constant with *r*, to moderate or strongly flaring disks.

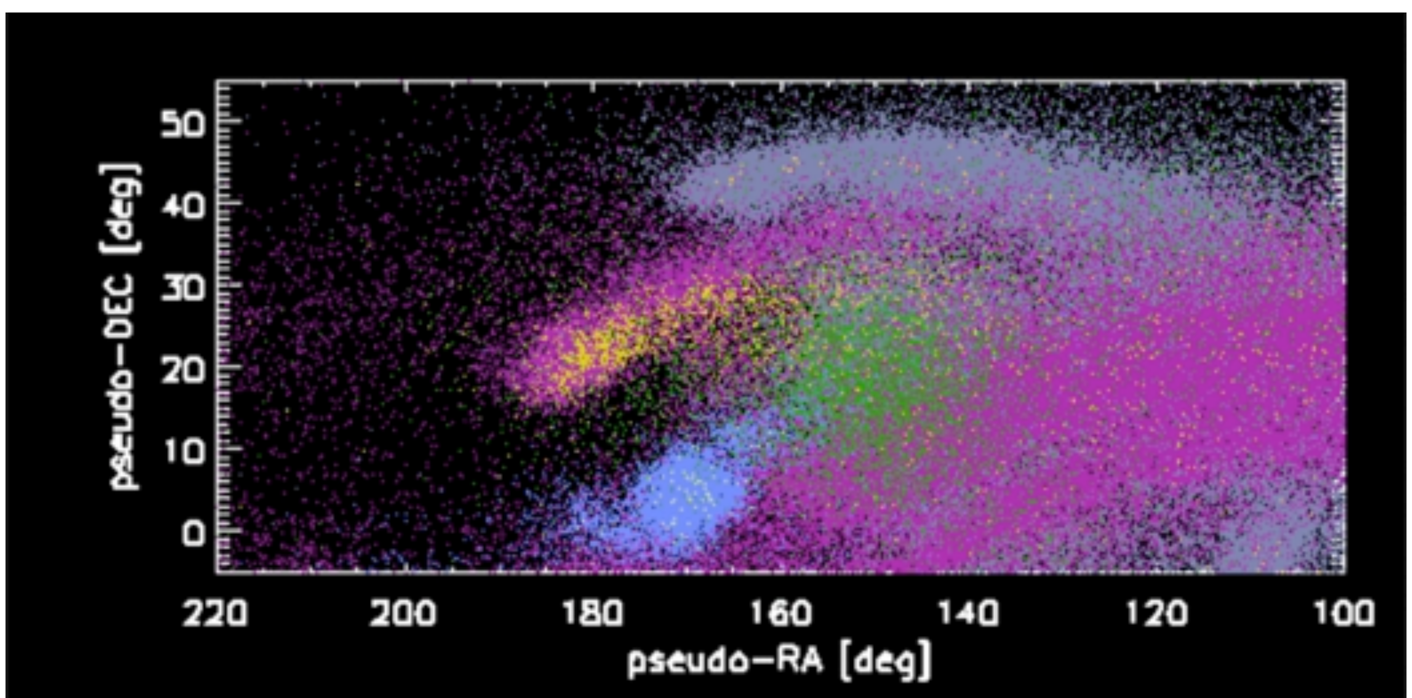


de Grijs & Peletier 1997

IMPACT ON THE STELLAR HALO : STREAMS



Substructures in the simulated stellar halos, formed by the disruption of satellite galaxies

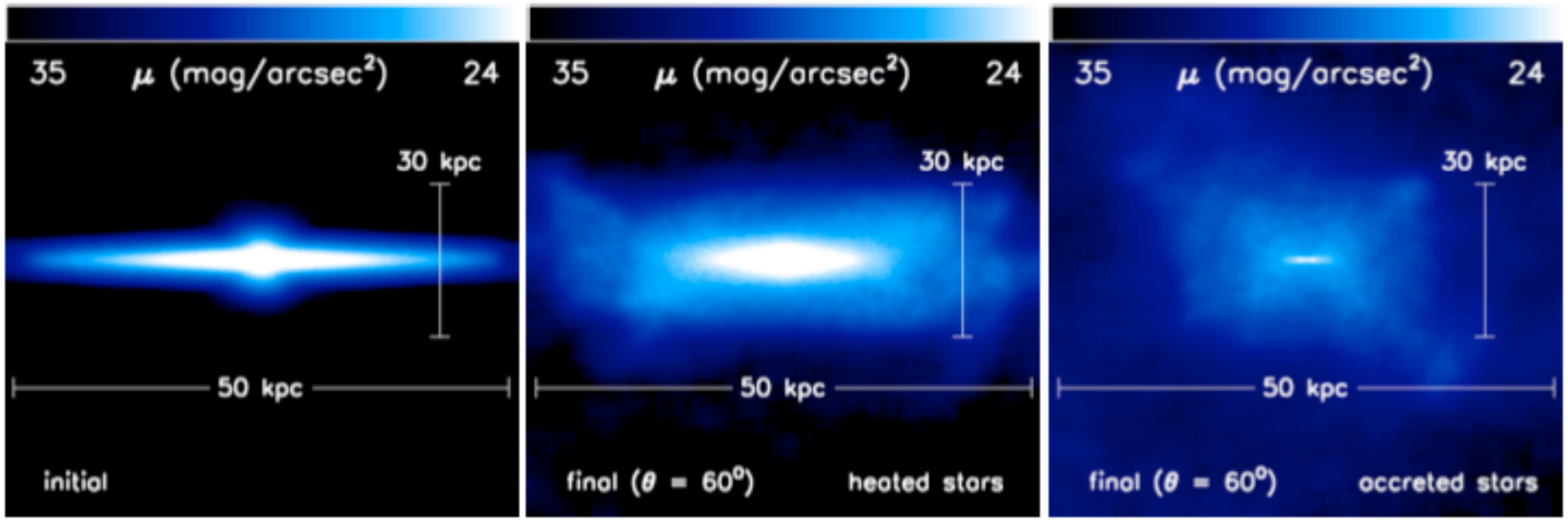


Helmi et al. 2011

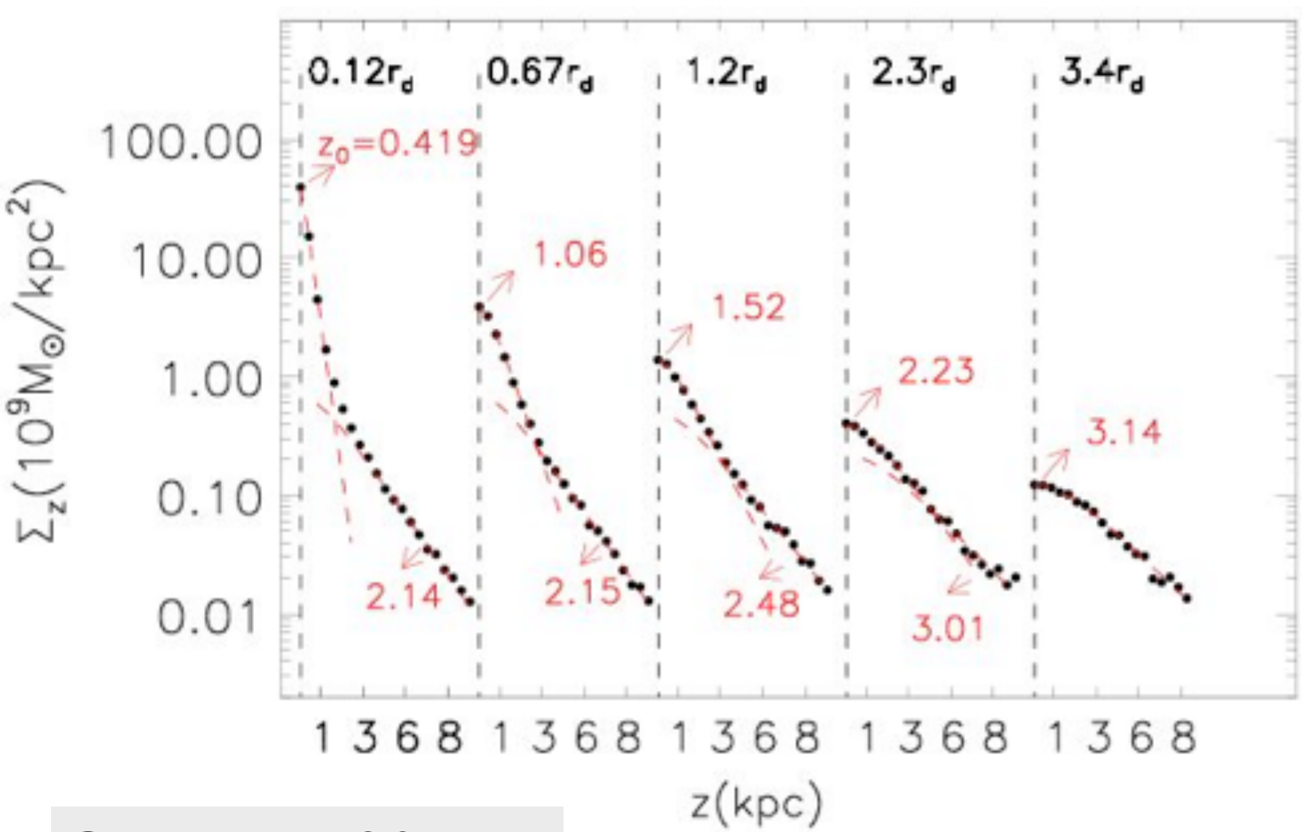
Broad overdensities and very narrow faint streams akin to those observed around the Milky Way

The substructures are distributed anisotropically on the sky, because of the correlated infall directions and also due to group infall.

IMPACT ON THE STELLAR HALO : STELLAR EXCESS



Purcell et al. 2010

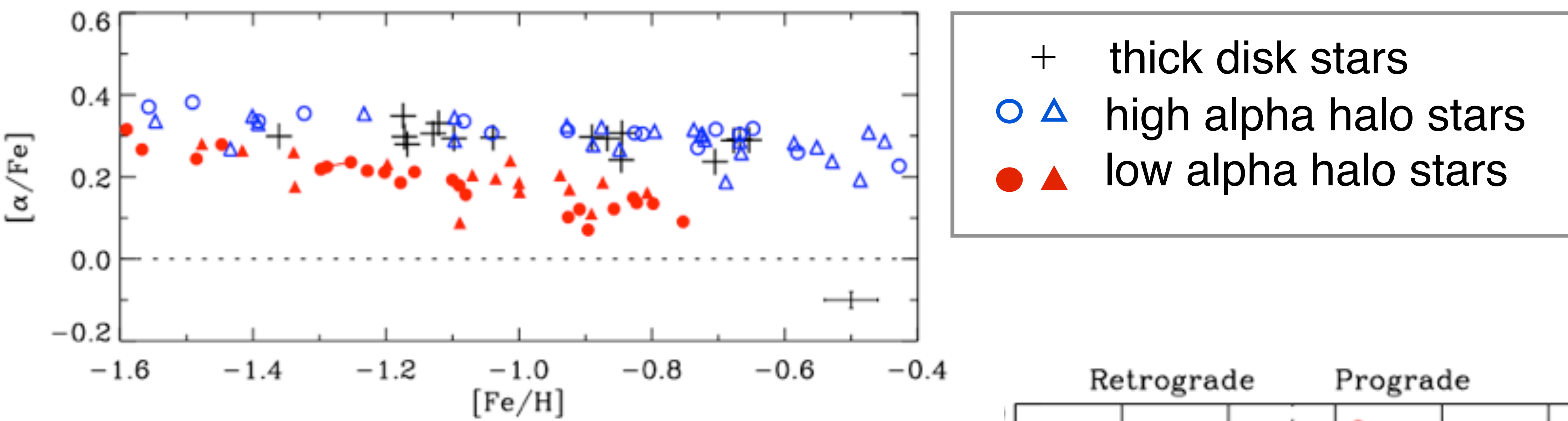


Qu, Y. et al. 2011

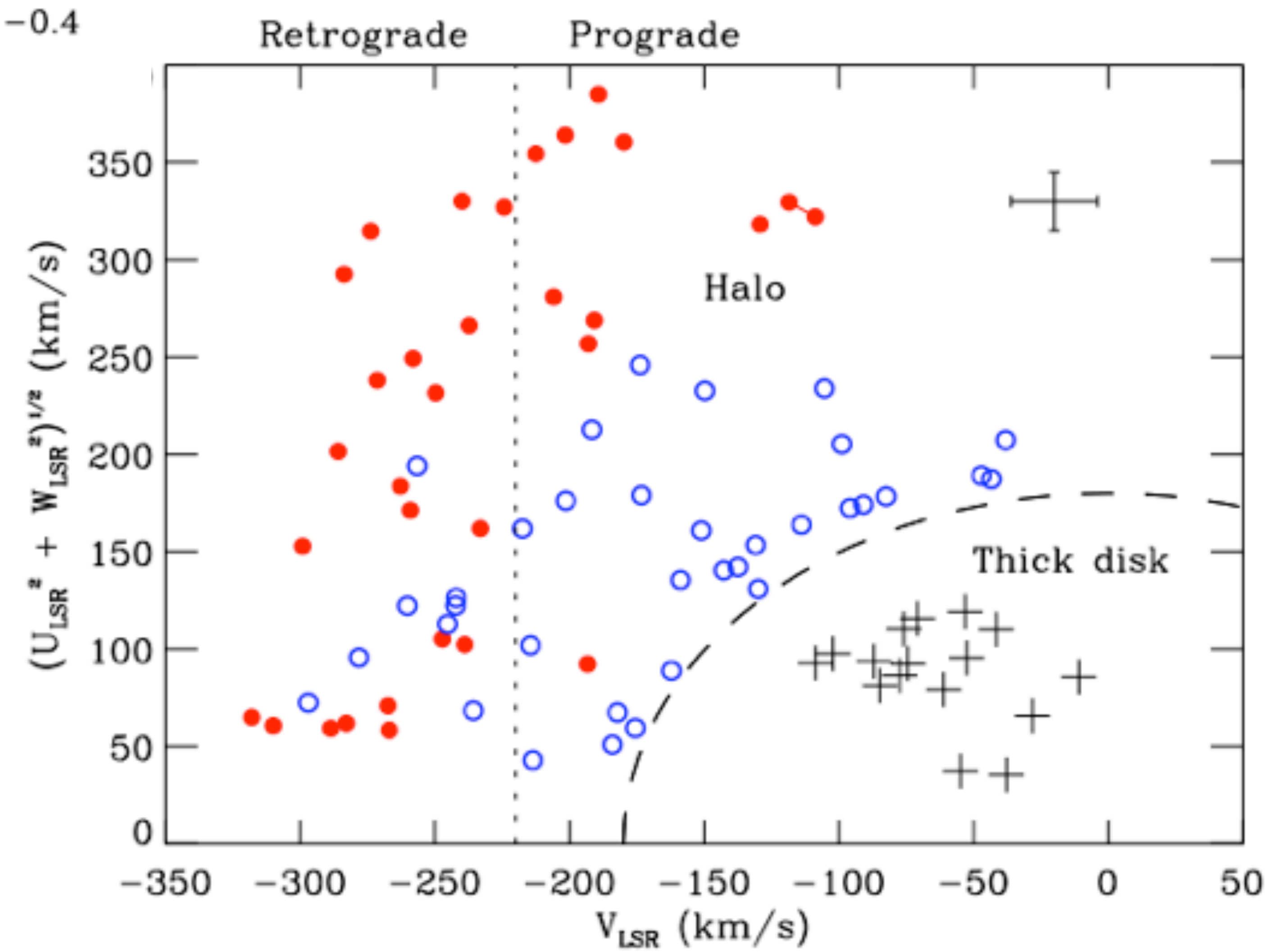
➡ Minor mergers can eject disc stars into a diffuse light component that resembles a stellar halo both spatially and kinematically

➡ ~ 1% of the initial disc stars in the solar neighbourhood would be classified kinematically as halo stars.

IS THERE ANY EVIDENCE OF THESE STARS IN THE STELLAR HALO OF THE MW ?



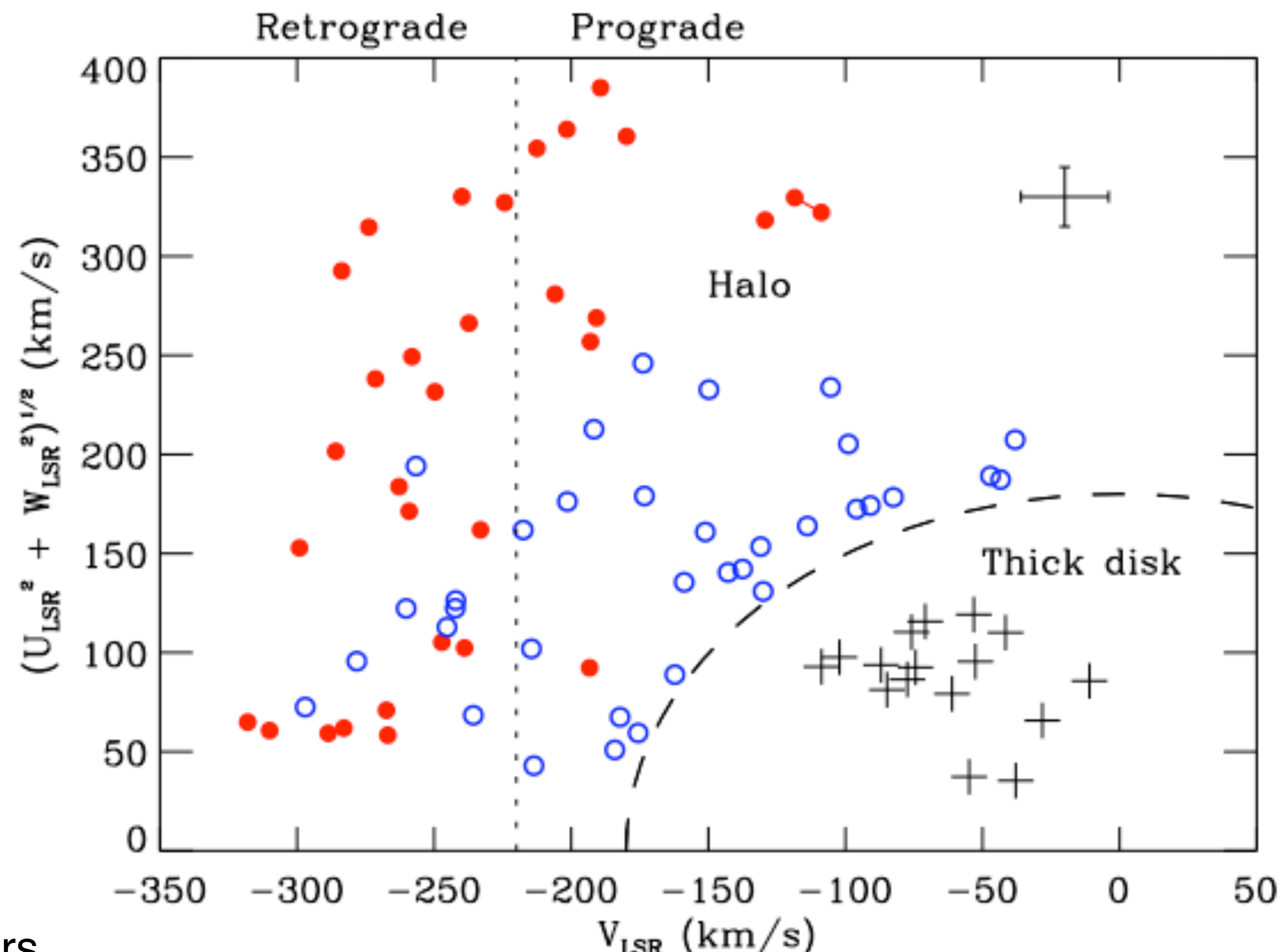
Abundance ratios for ~ 100 dwarf stars with –1.6 < [Fe/H]< –0.4, and distances D ~< 330 pc



The halo stars fall into two populations, separated in [α/Fe], where α refers to the average abundance of Mg, Si, Ca, and Ti.

Nissen & Schuster 2010

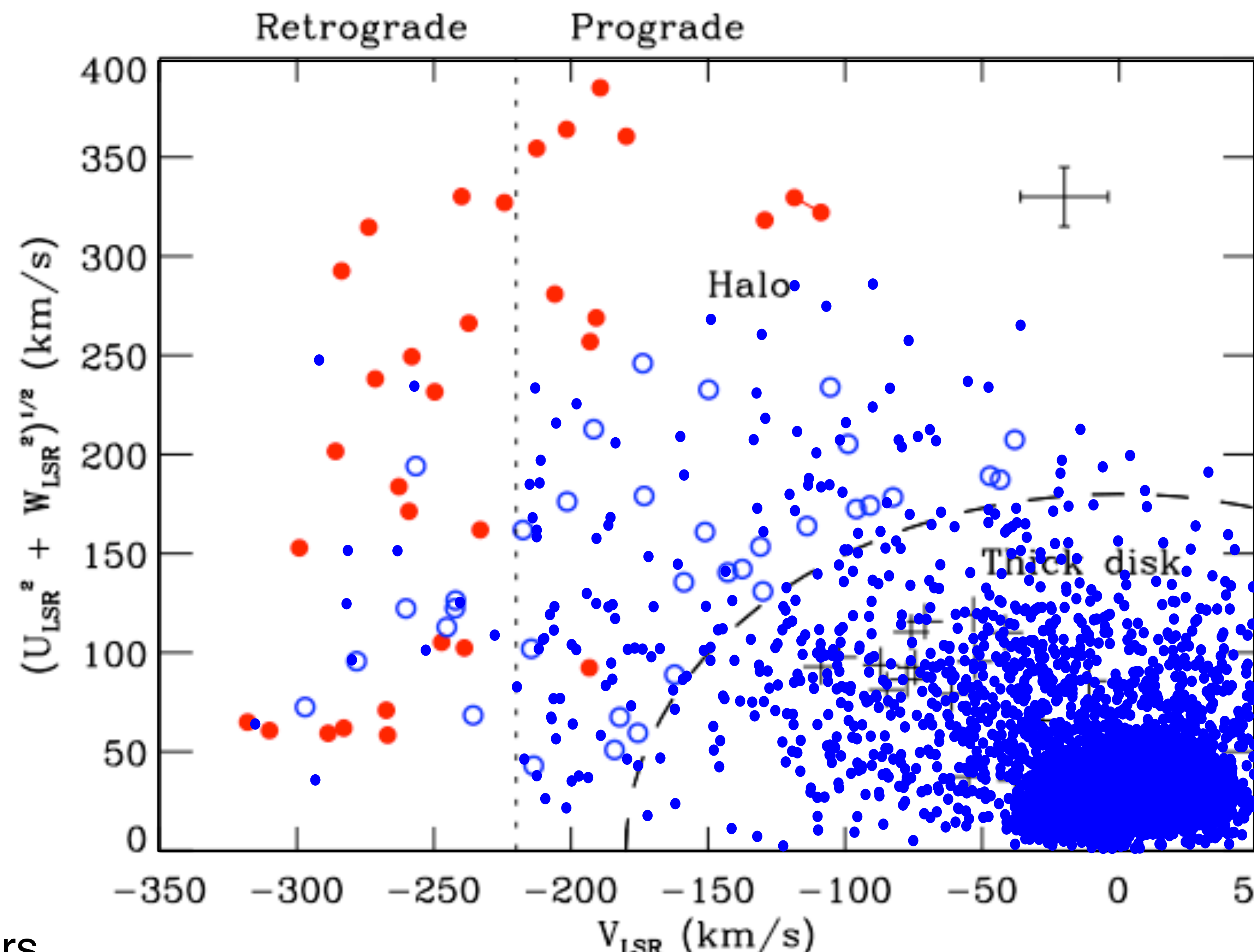
MINOR MERGERS and HIGH-α HALO STARS



+ thick disk stars
○ △ high alpha halo stars
● ▲ low alpha halo stars
• simulations : stars vertically heated during minor mergers

Nissen & Schuster 2010 + Qu et al. 2011

MINOR MERGERS and HIGH-α HALO STARS



+ thick disk stars

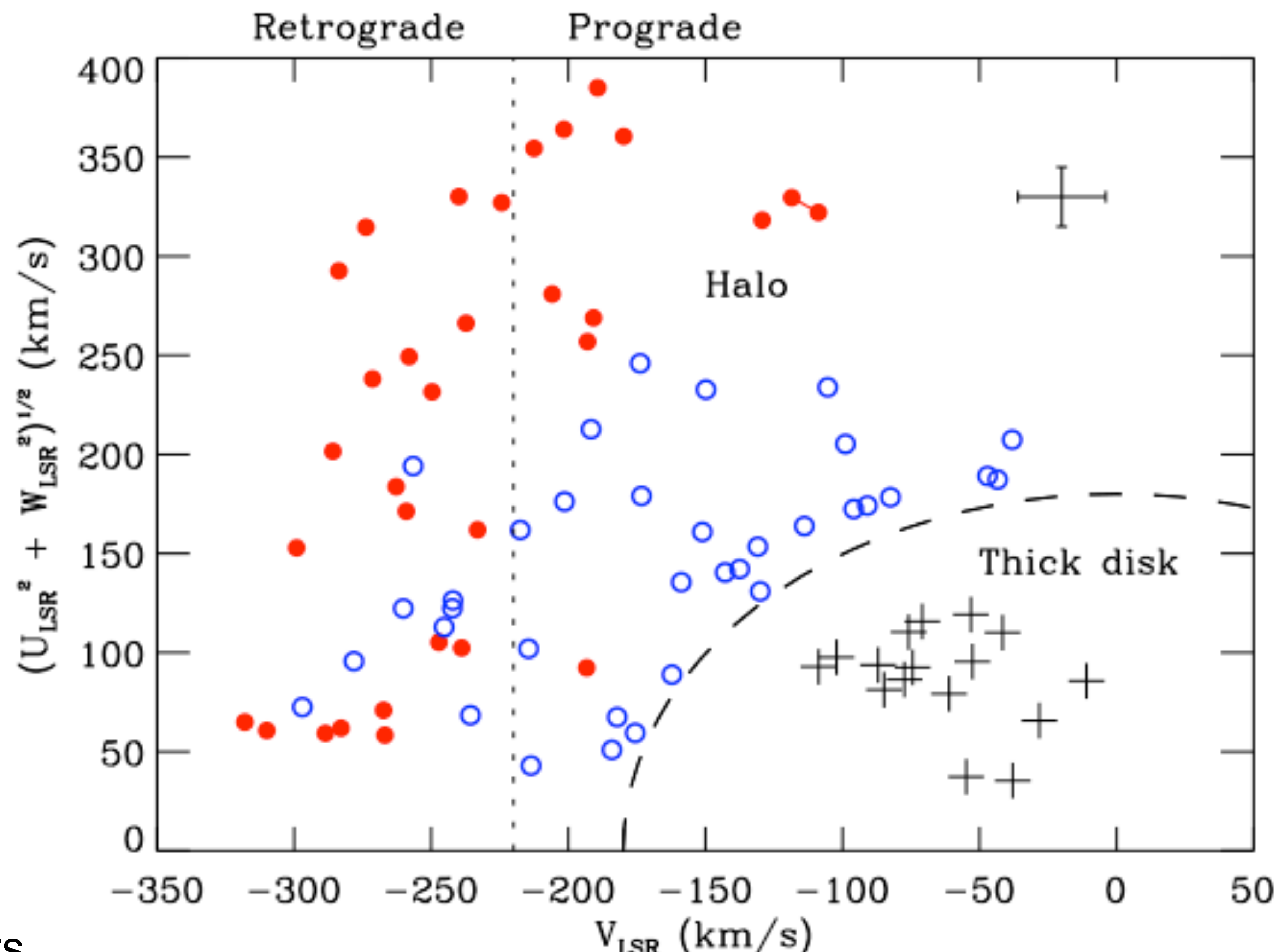
○ △ high alpha halo stars

● ▲ low alpha halo stars

• simulations : stars vertically heated during minor mergers

Nissen & Schuster 2010 + Qu et al. 2011

CLUMPY DISKS and HIGH-α HALO STARS



+ thick disk stars

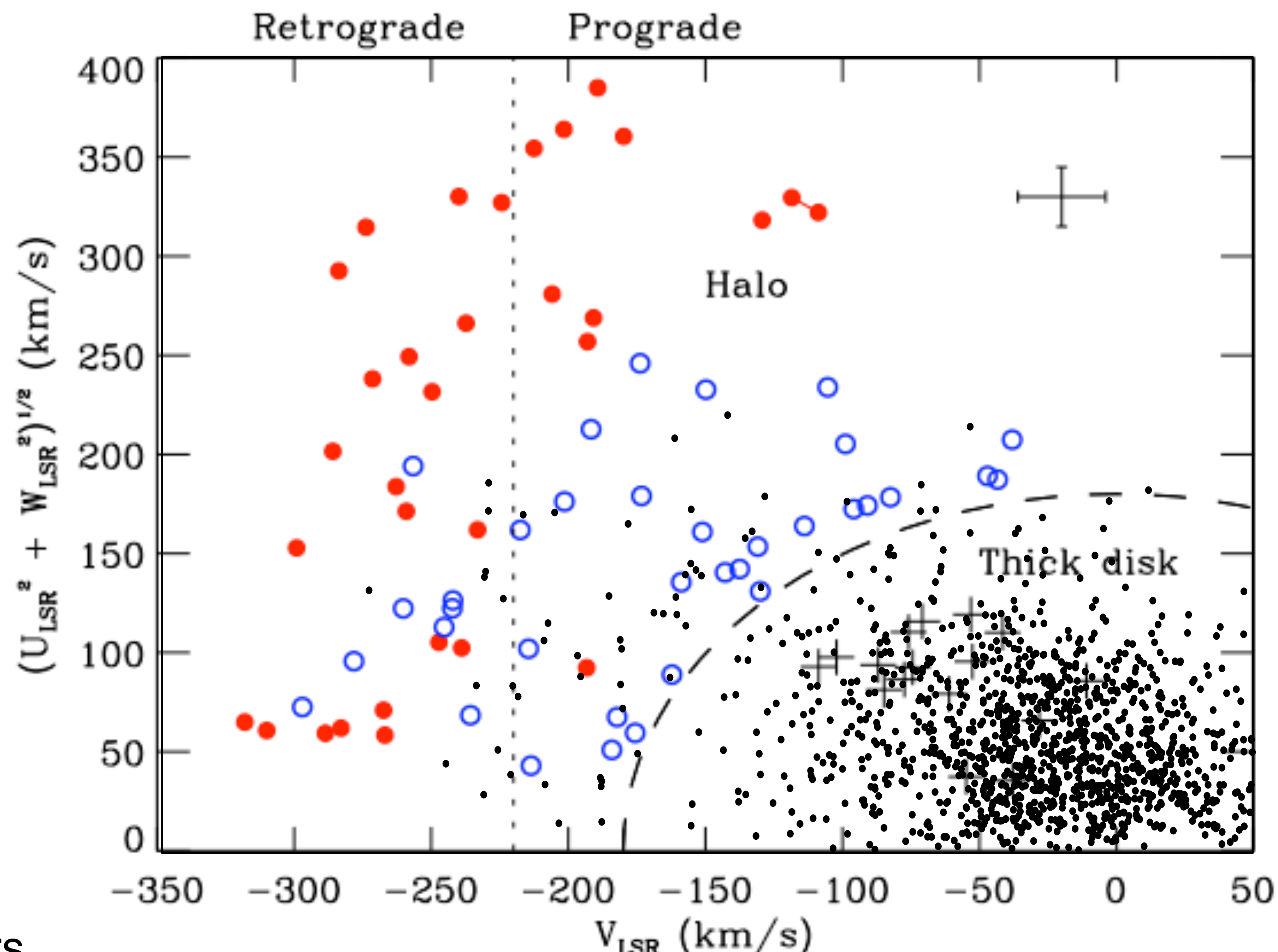
○ △ high alpha halo stars

● ▲ low alpha halo stars

• simulations : stars vertically heated by clumps in the disk

Nissen & Schuster 2010 + Qu et al. 2011

CLUMPY DISKS and HIGH-α HALO STARS



+ thick disk stars

○ △ high alpha halo stars

● ▲ low alpha halo stars

• simulations : stars vertically heated by clumps in the disk

Nissen & Schuster 2010 + Qu et al. 2011

CONCLUSIONS

Predictions need to be robust.

- Results often depend on an important number of parameters.

This dependence needs to be quantified. How probable a certain outcome is ?

➡ This requires a large number of realizations

- Need to explore the evolution of the thin disk, in particular of its vertical structure.

➡ This requires a high spatial resolution (~ 50 pc), at the limit of the current simulations.

Waiting for Gaia, need to :

keep characterizing the signatures of different formation scenarios on the Galactic components ;

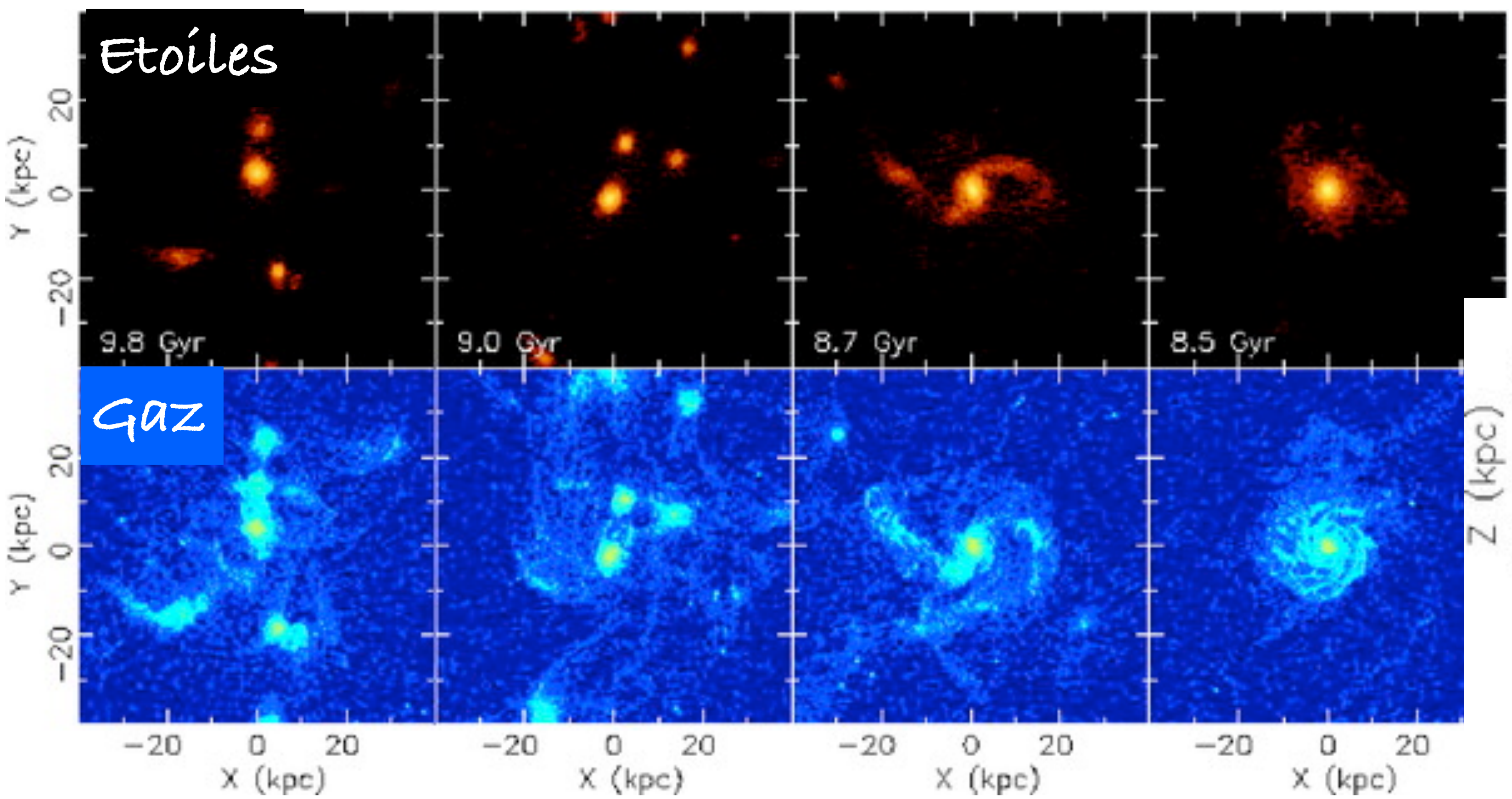
couple the dynamics and the chemical evolution, in order to trace the evolution of metal abundances.

Are the structural, kinematical and chemical signatures erased if other processes intervene ?

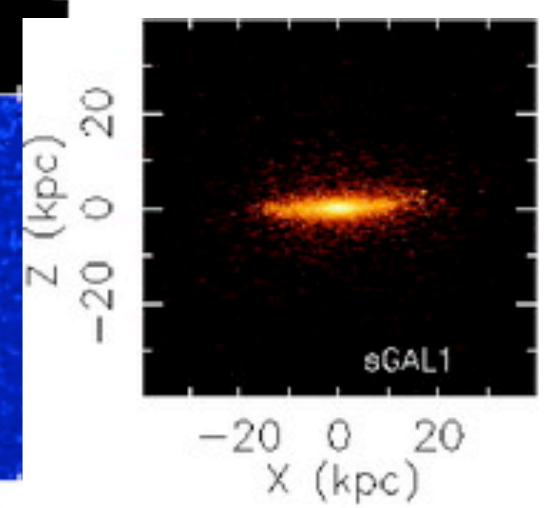
FORMATION DU DISQUE EPAIS par
FUSIONS RICHES EN GAZ

Formation du disque épais par fusion de sous-halos riches en gaz à haut redshift (t > 8 Gyr). Dans ce scenario, **les étoiles du disque épais se forment à partir du gaz accrété et distribué dans une configuration épaisse**.

Epoque de fusions riches en gaz



Distribution des étoiles du residu de fusions @ z=0



Formation d'une galaxie spirale avec un disque épais par fusions riches en gaz à haut redshift – Brook et al. 2004, 2005