Radial Migration

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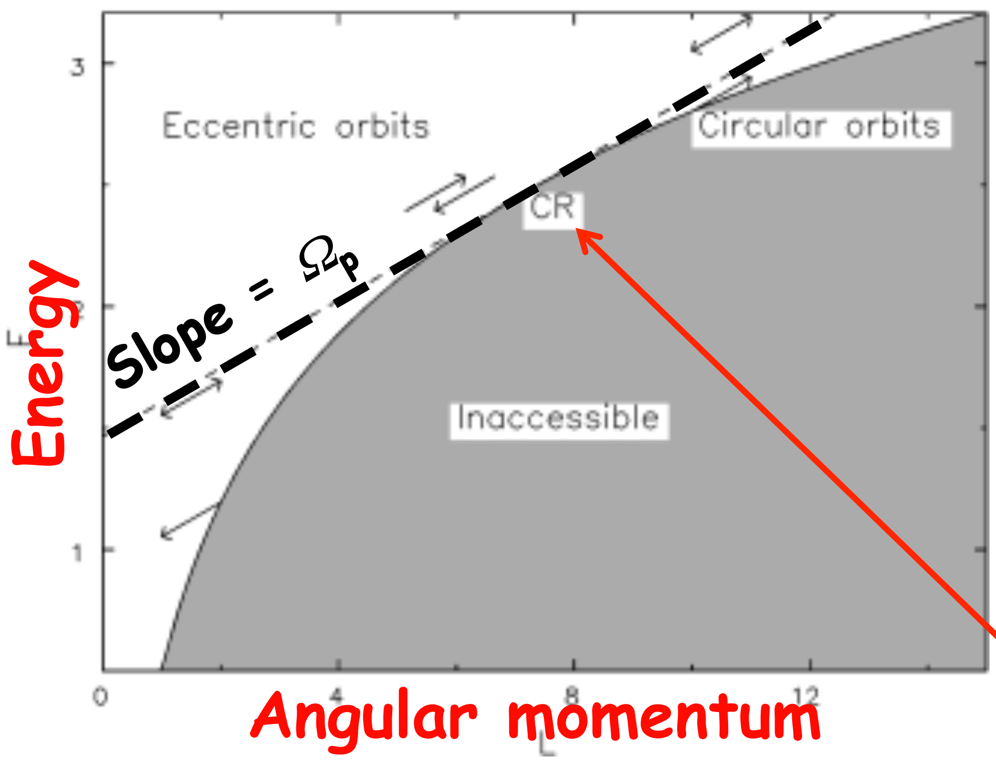
Migration WITHOUT Heating

For a steadily rotating perturbation with angular frequency Ω_p the energy in the co-rotating frame is conserved



$E_J = E - \Omega_p L$

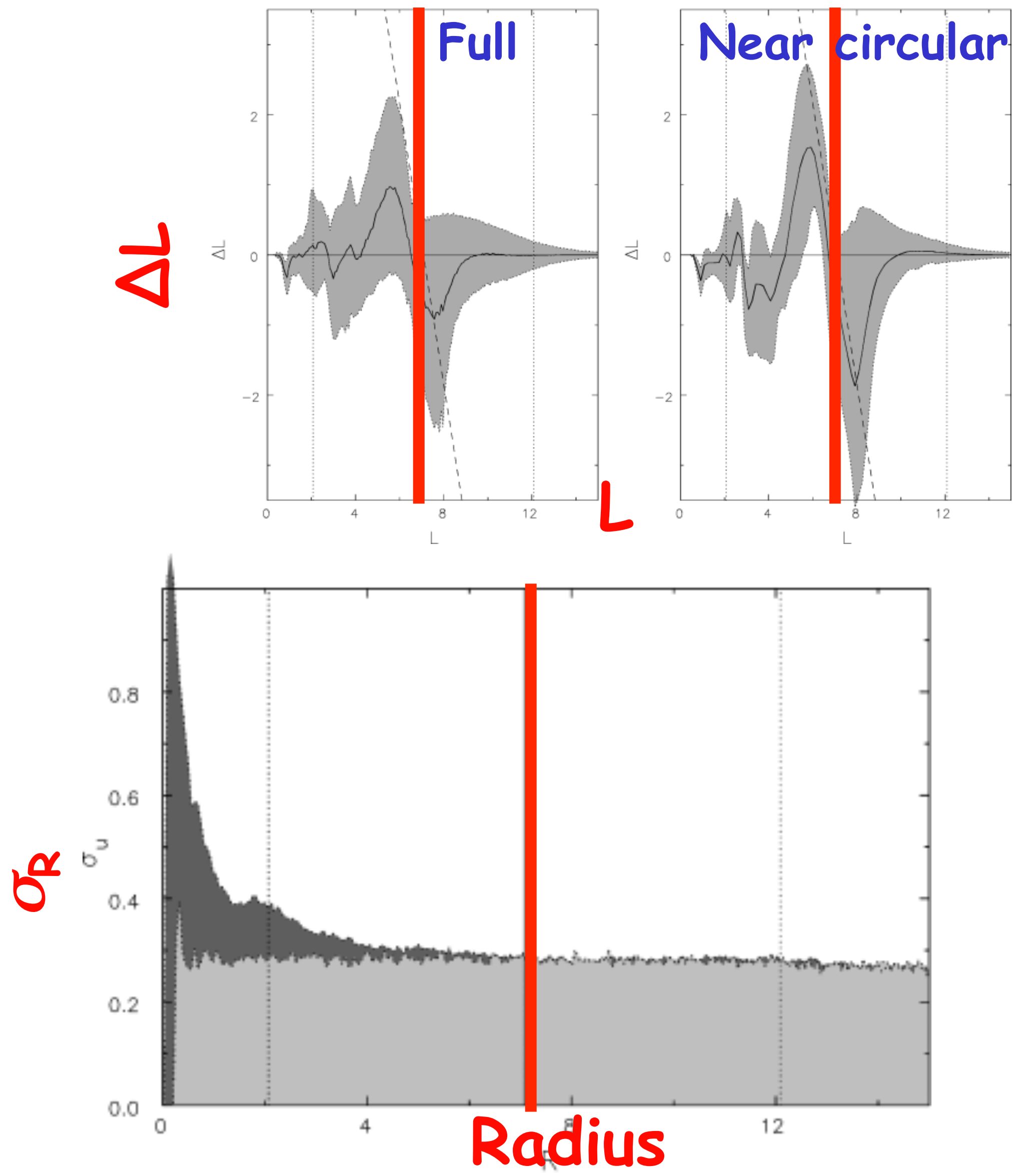
$\Delta E = \Omega_p \Delta L$

$\Delta J_R = (\Omega_p - \Omega) / \kappa \, \Delta L$

To first order, angular momentum changes do not cause heating at the corotation resonance

Sellwood & Binney 2002

Shuffling With Little Heating

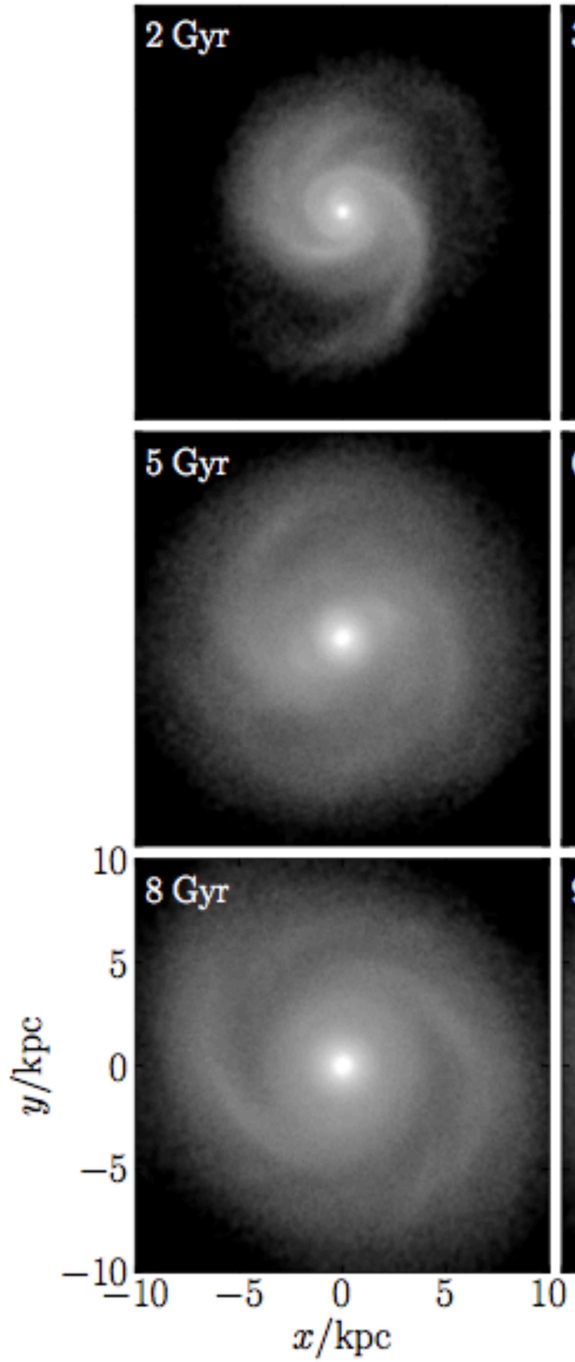


Strong exchanges at CR resonance; even larger for more circular orbits

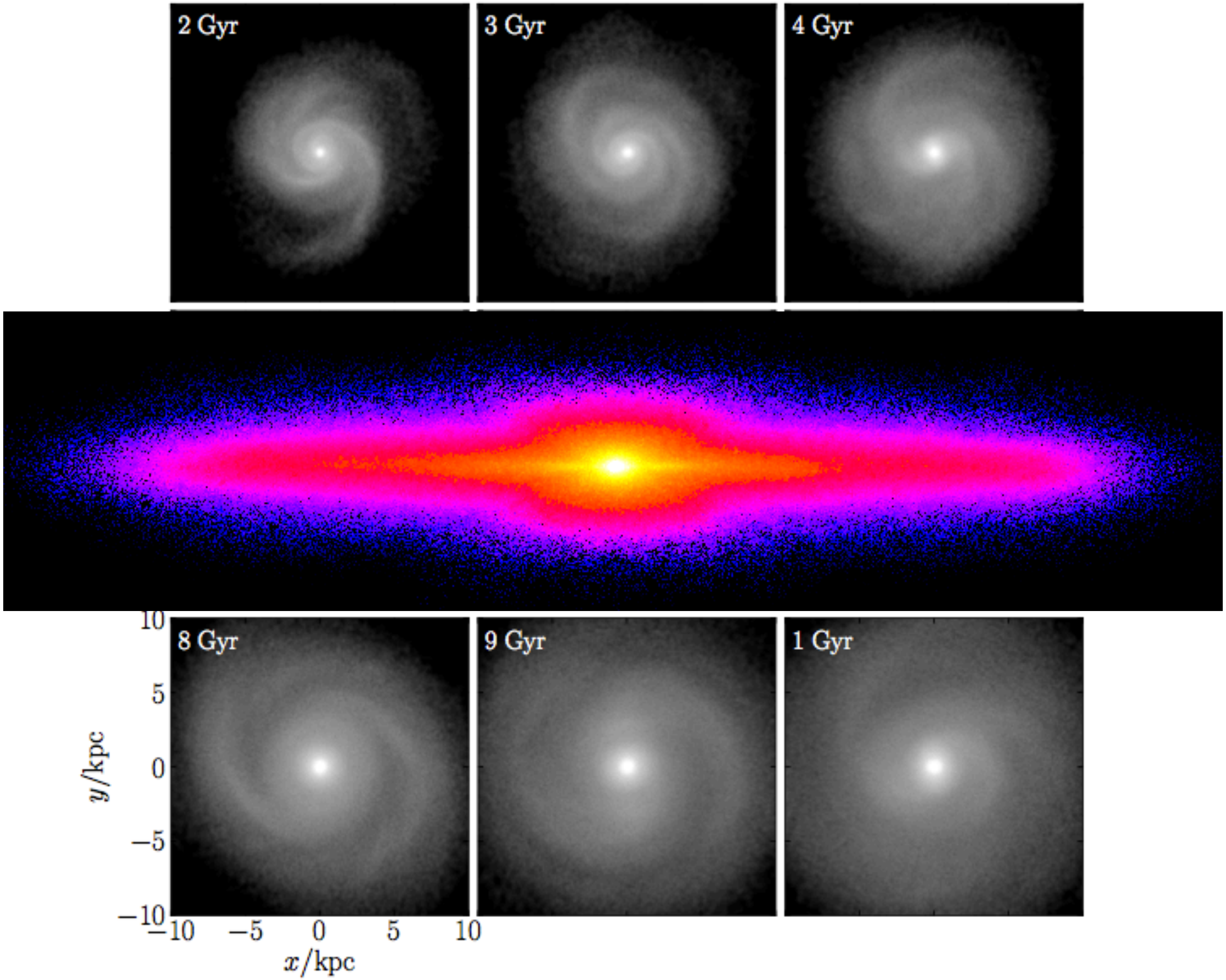
$\Delta J_R = (\Omega_p - \Omega)\, \Delta L/\kappa$

But negligible heating associated with the migration

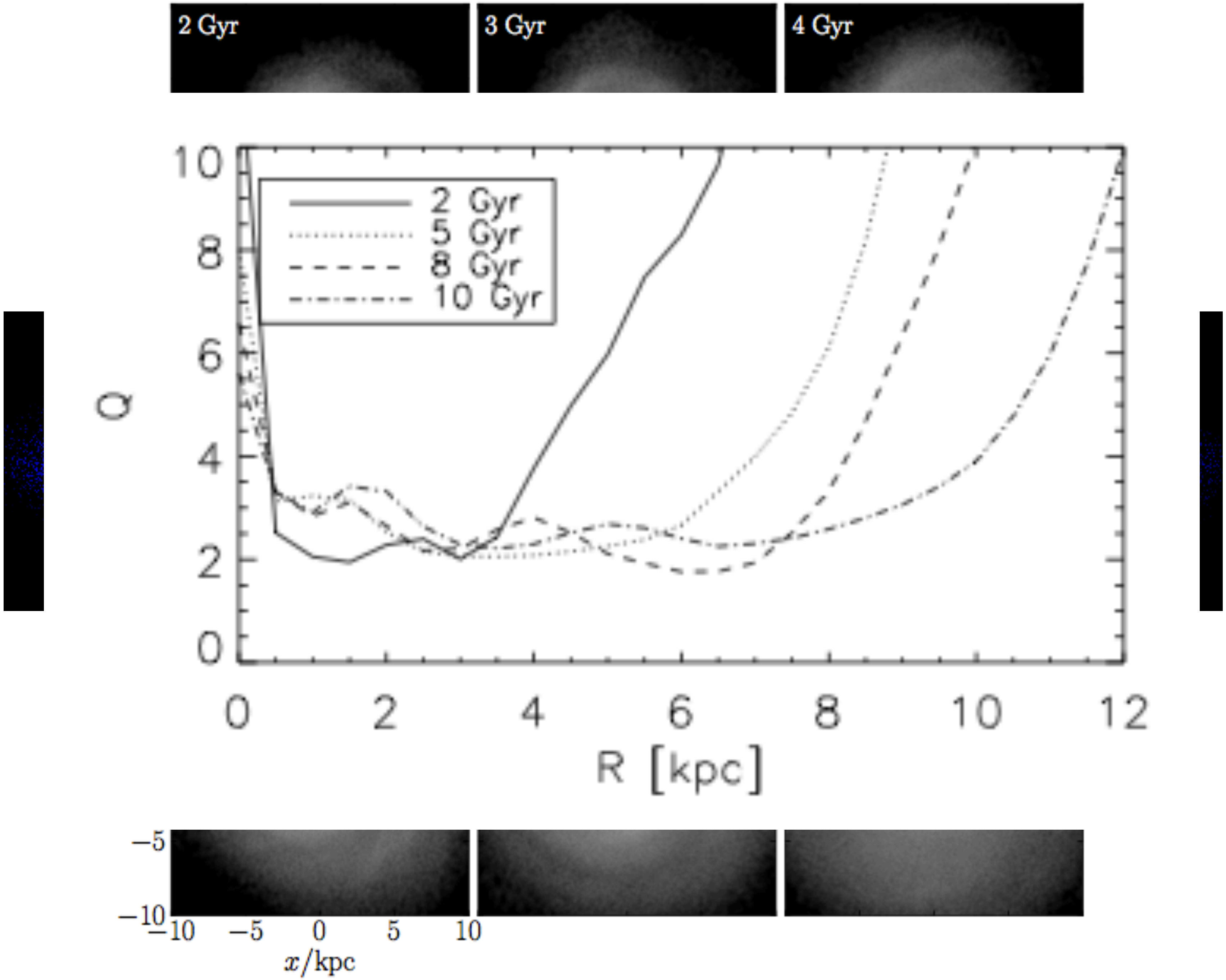
Sellwood & Binney 2002



2 Gyr
3 Gyr
4 Gyr
5 Gyr
6 Gyr
7 Gyr
8 Gyr
9 Gyr
1 Gyr
10
5
0
−5
−10
y/kpc
−10
−5
0
5
10
x/kpc



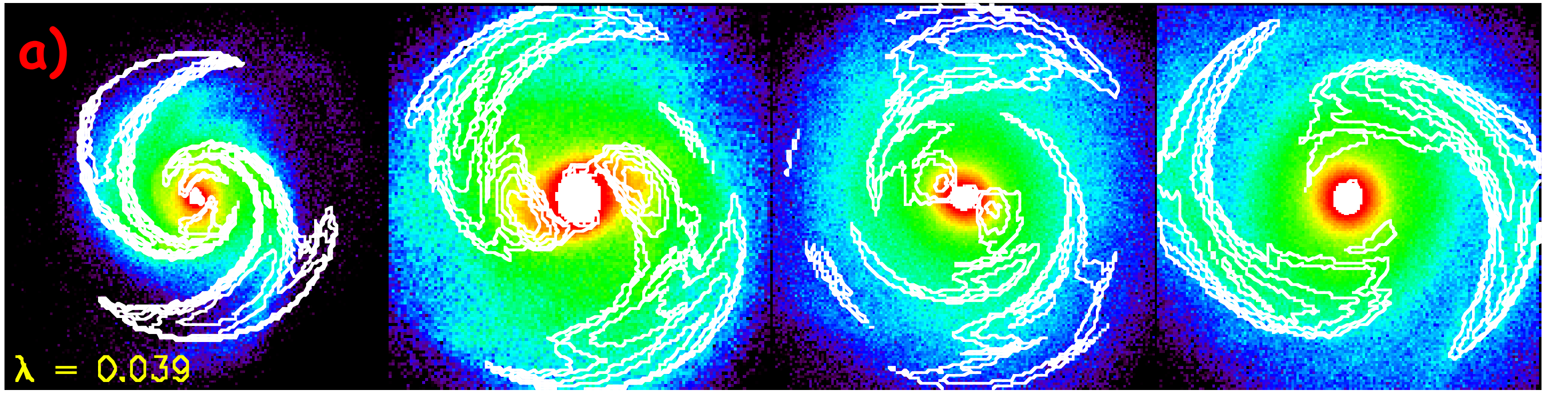
2 Gyr
3 Gyr
4 Gyr
8 Gyr
9 Gyr
1 Gyr
10
5
0
−5
−10
y/kpc
−10
−5
0
5
10
x/kpc

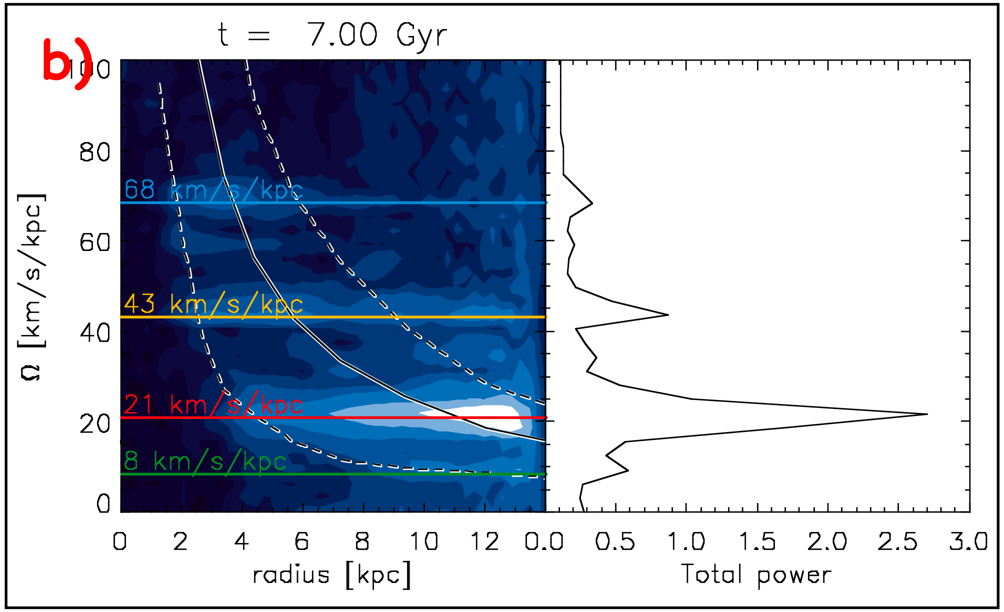


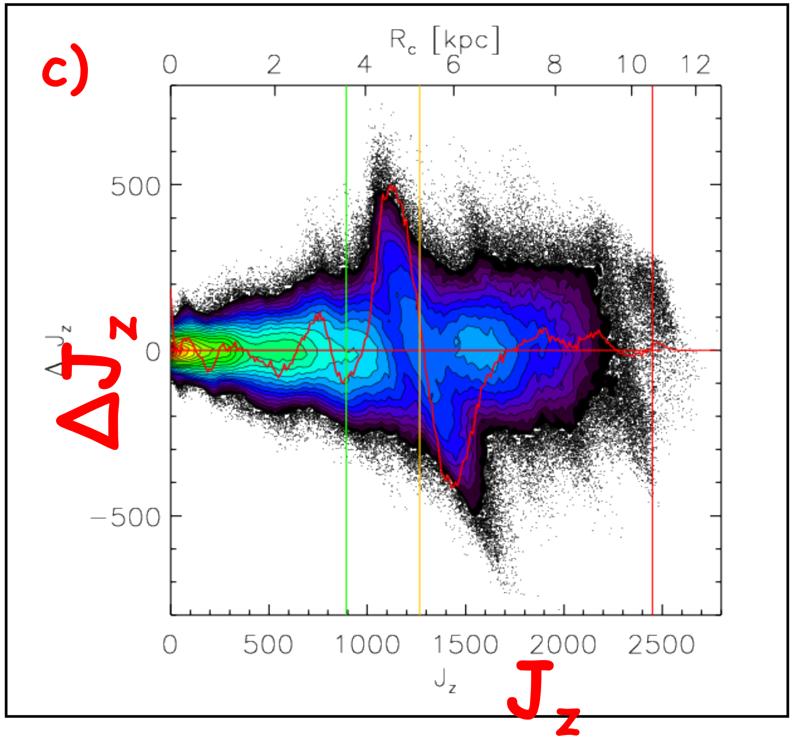
2 Gyr
3 Gyr
4 Gyr
2 Gyr
5 Gyr
8 Gyr
10 Gyr
Q
R [kpc]
0
2
4
6
8
10
12
−5
−10
−10
−5
0
5
10
x/kpc

Confirming Role of Spirals

a) Fourier expansion -> b) power spectrum -> c) identify patterns/resonances

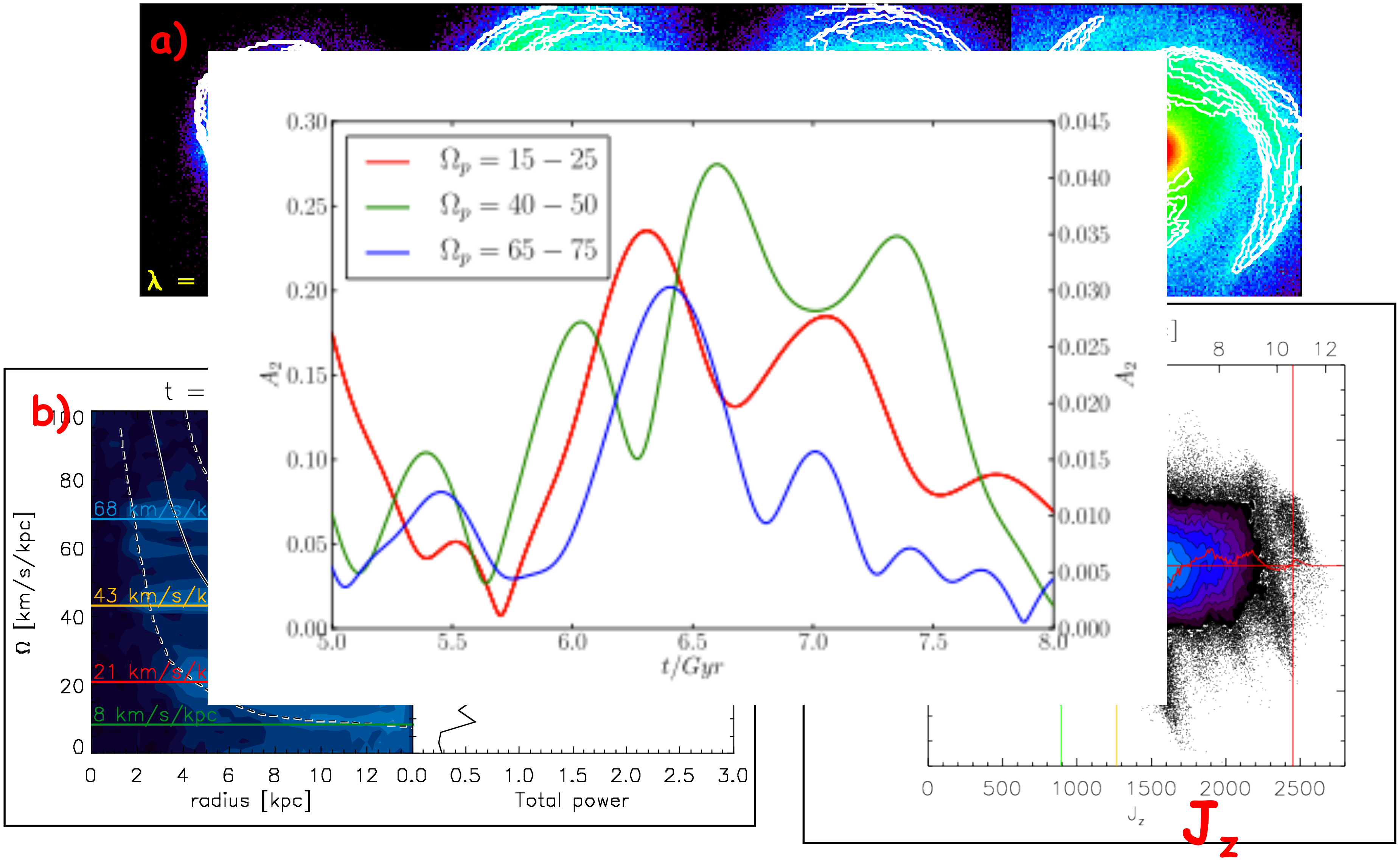




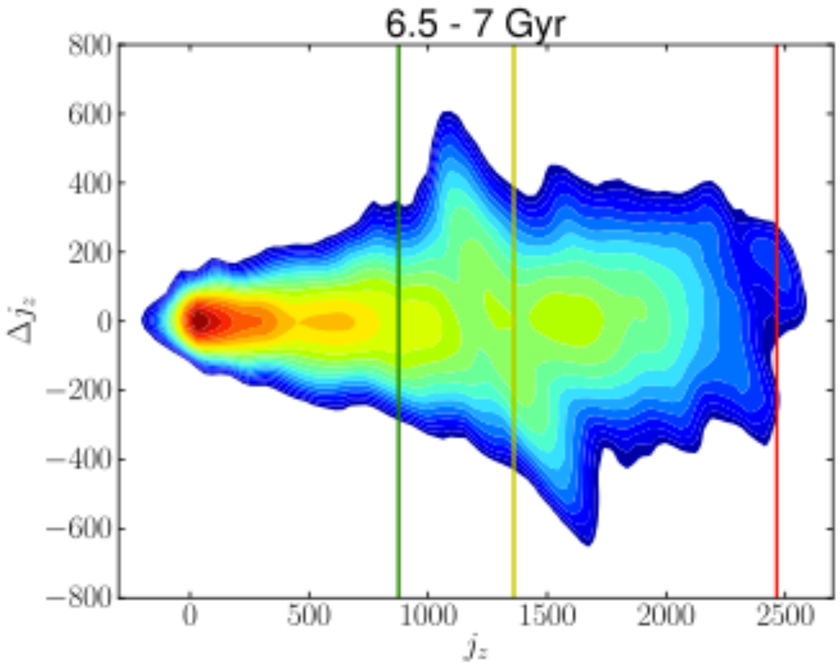


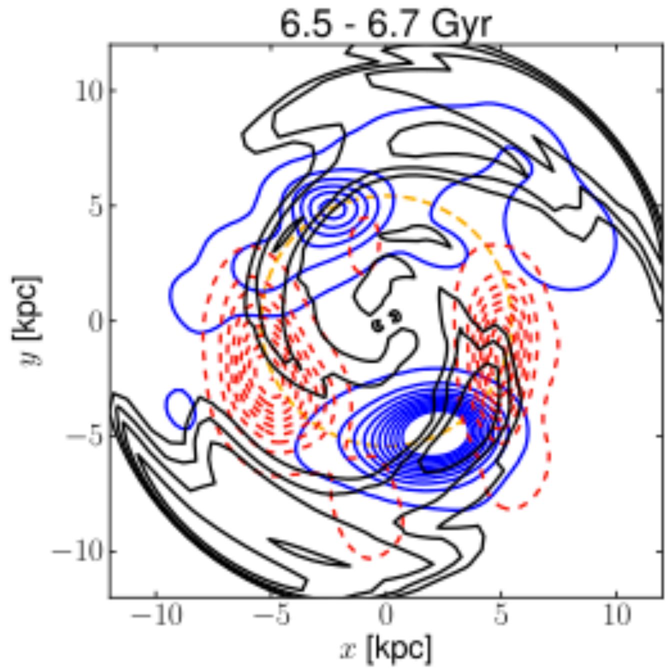
Confirming Role of Spirals

a) Fourier expansion -> b) power spectrum -> c) identify patterns/resonances



Where are the migrators?

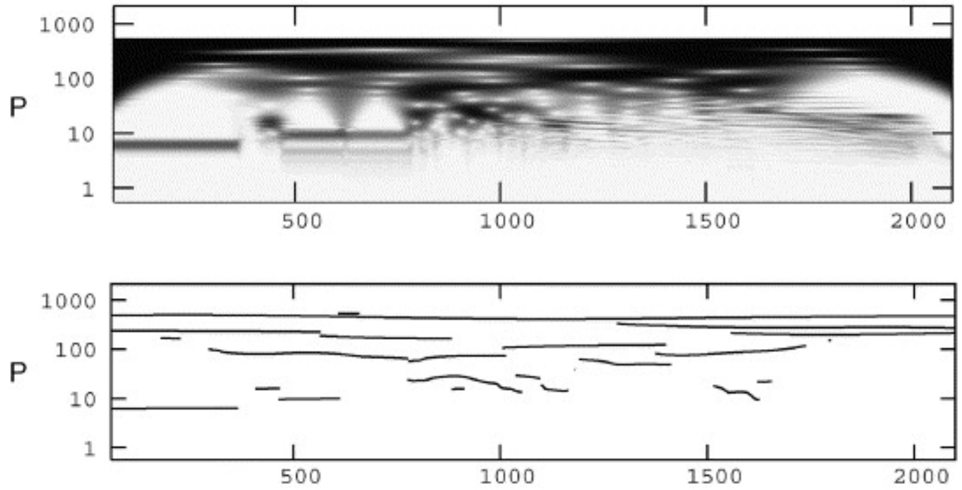




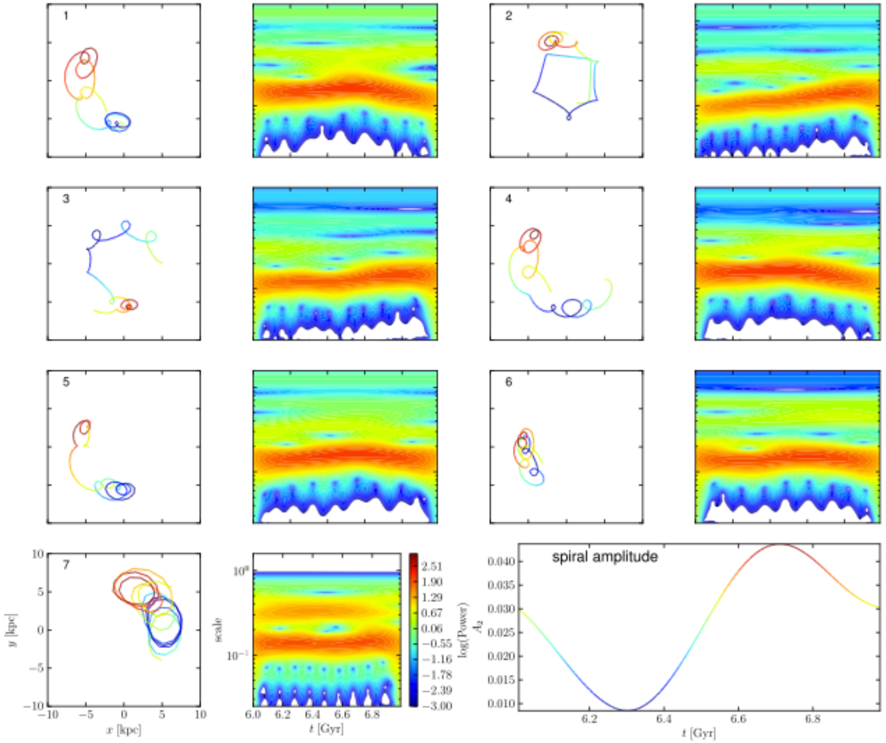
Migrating particles are overwhelmingly found at the CR of spirals: inward migrators ahead of the spiral while outward migrators are behind it

Roskar+ 2012

Chaos?



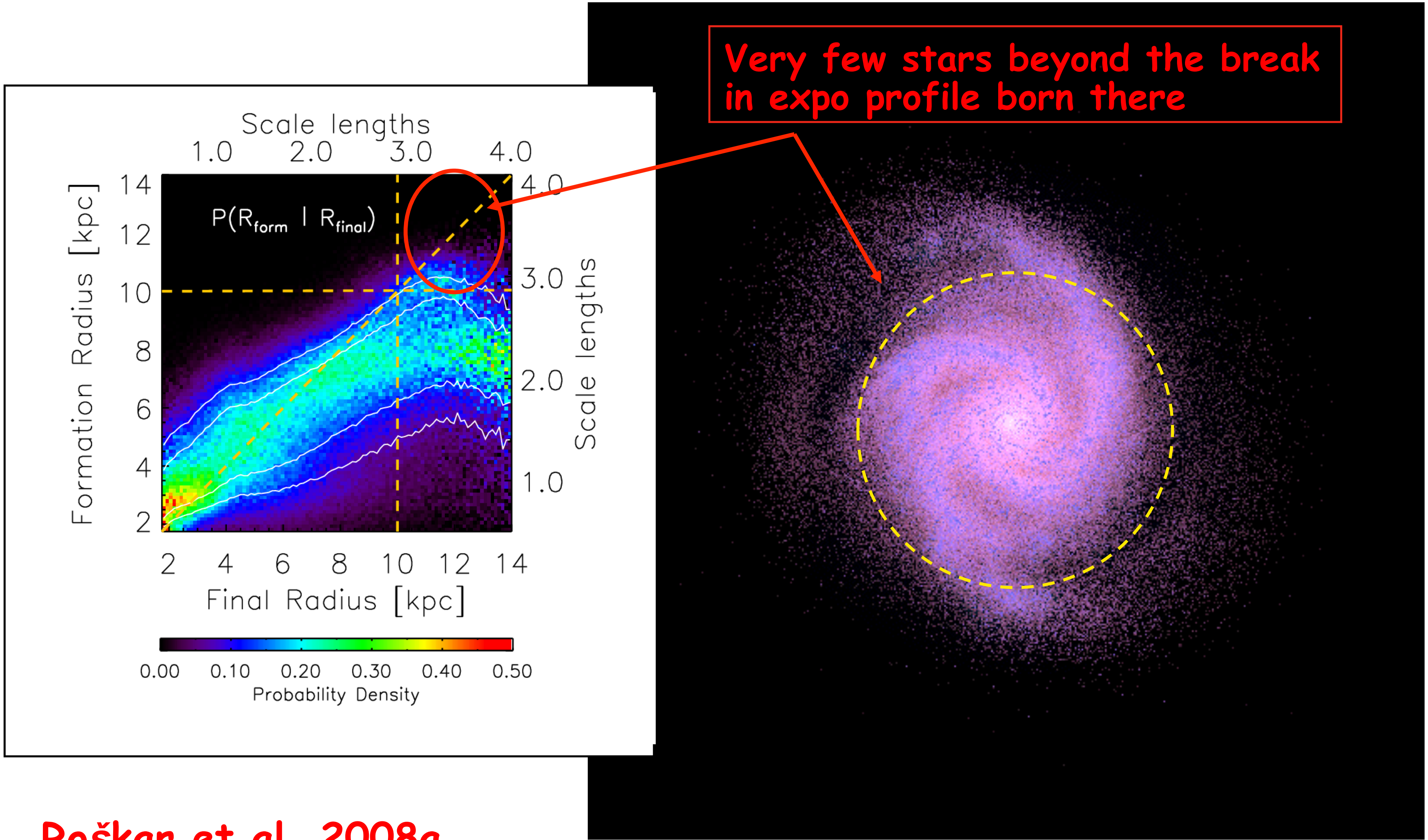
Gemmeke+ 2008



Roskar+ 2012

Scalograms: a density plot of the power(frequency) in a wavelet transform

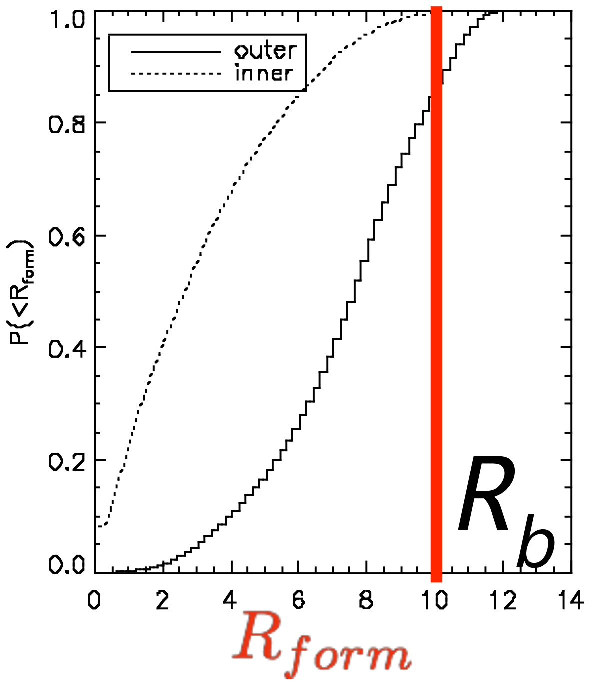
More chaos = more bends and more discontinuities



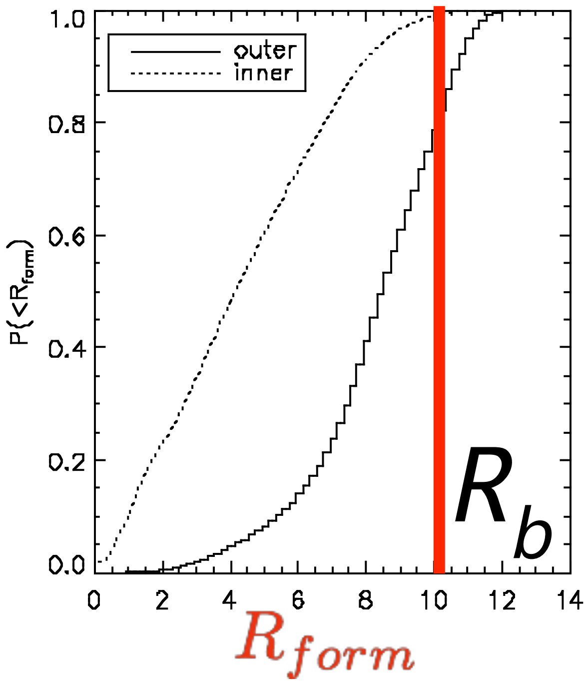
Roškar et al. 2008a

Outer Disk Kinematics

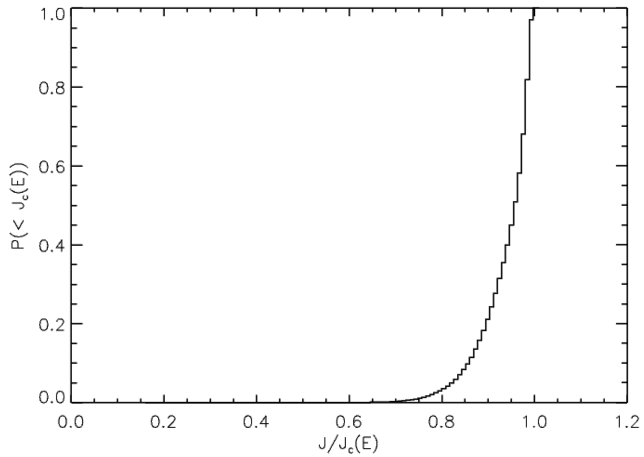
All



Circular



Outer disk only

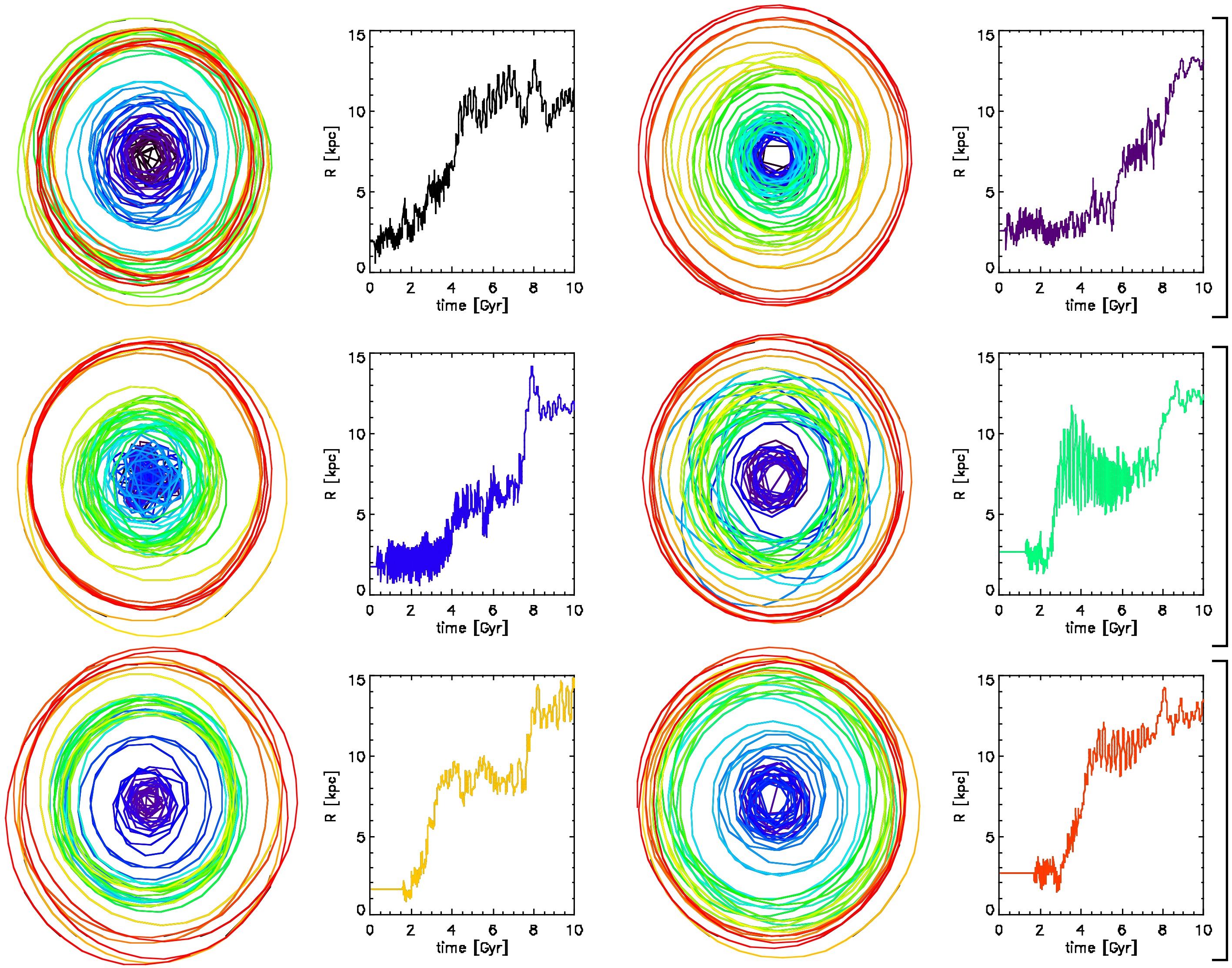


J/Jc(E)

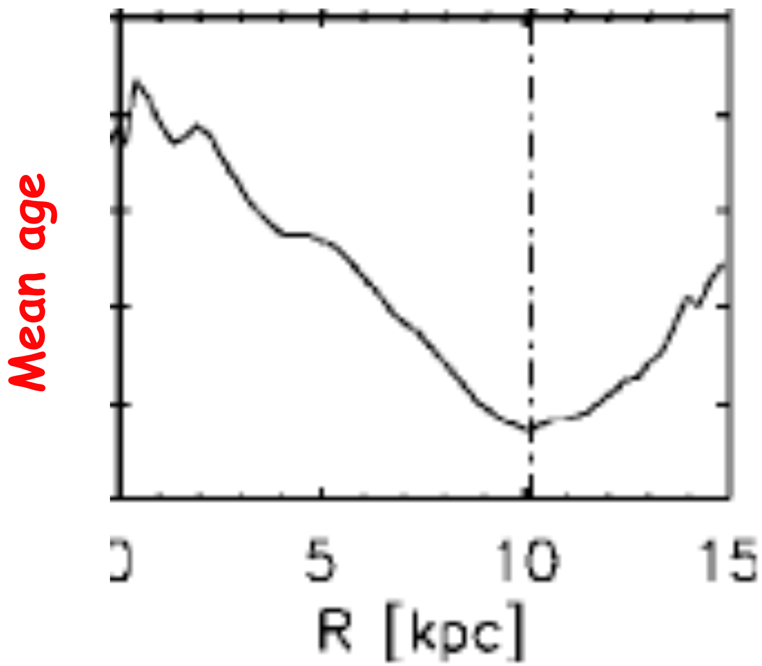
Most particles in the outer disk still retain nearly circular orbits

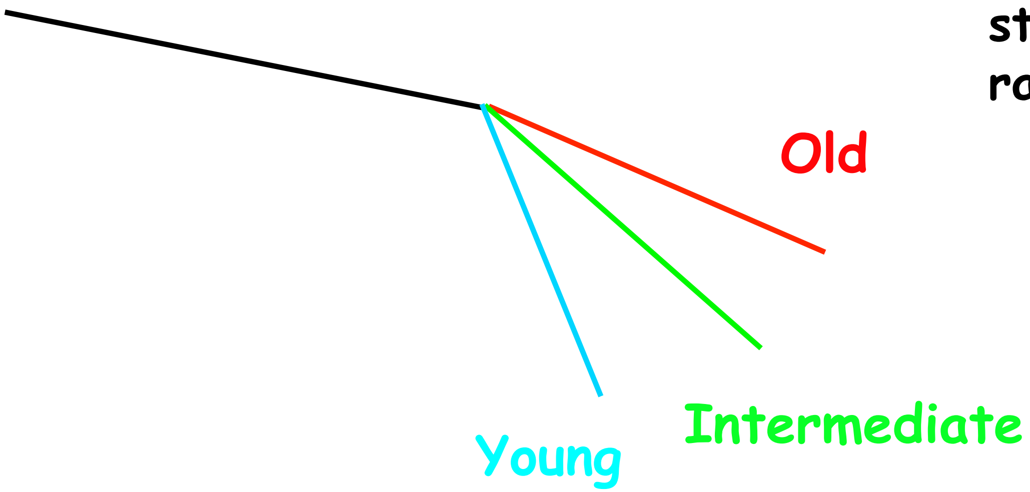
Sample of Orbits Ending in Outer Disk

Typical velocities are $\Delta R/\Delta t \leq$ 5kpc/ 200Myr = 25 km/s



Outer Disk Stellar Pops



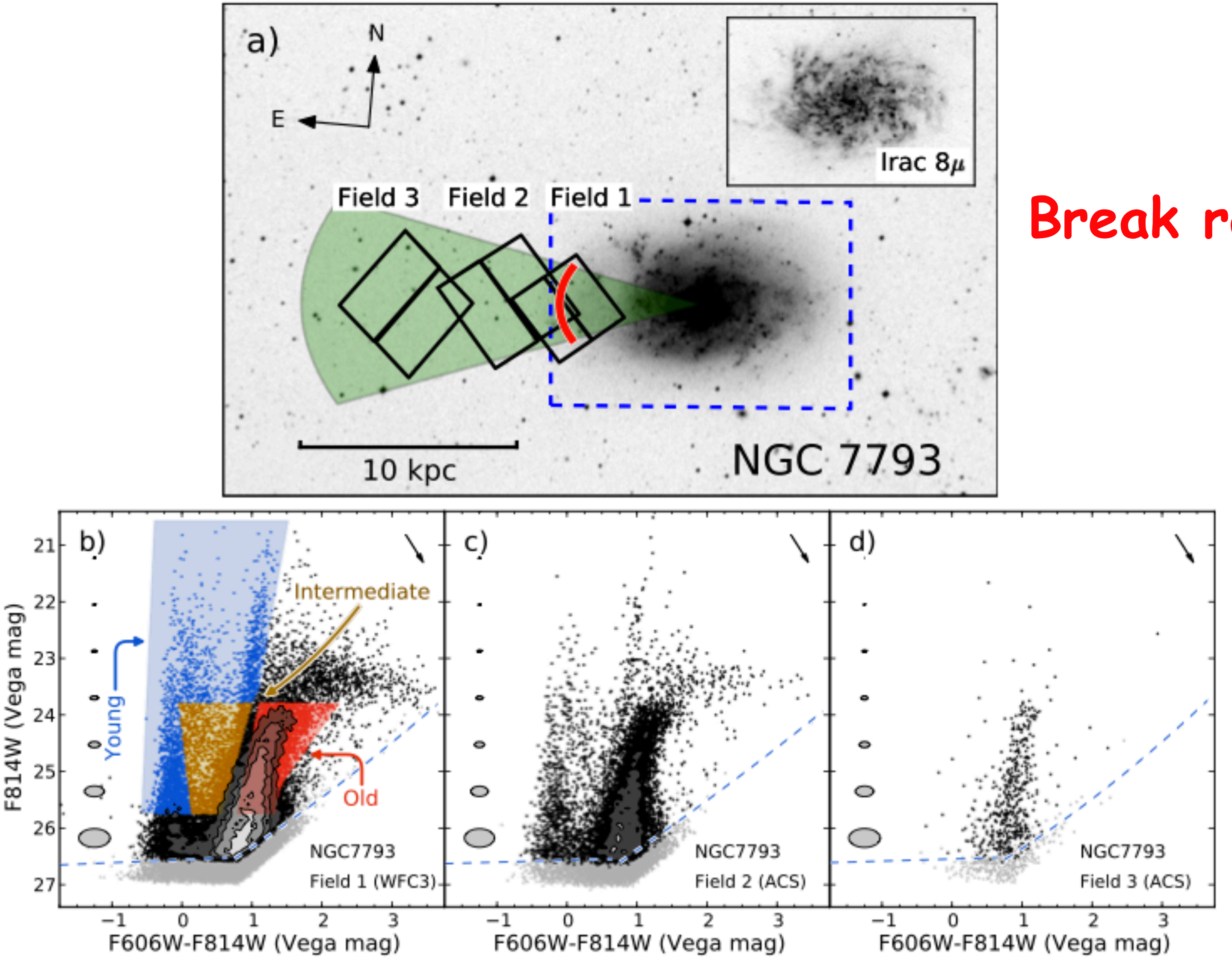


Migration is basically a random walk, so older stars get to larger distance from formation

Expect the mean age of disk stars to increase beyond the break

The variation of outer disk scale-length for different age stellar bins constrain migration rates

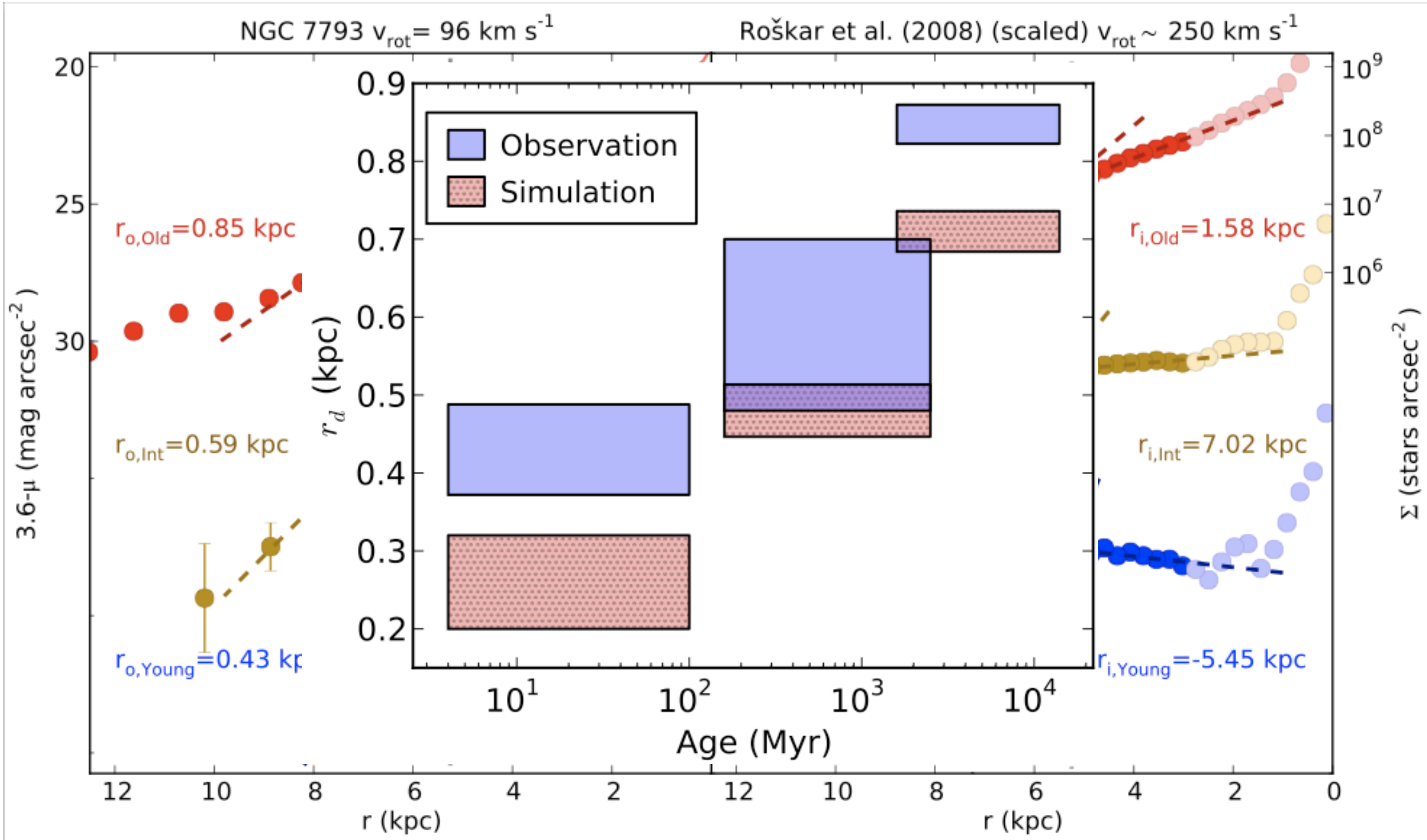
NGC 7793



Break radius

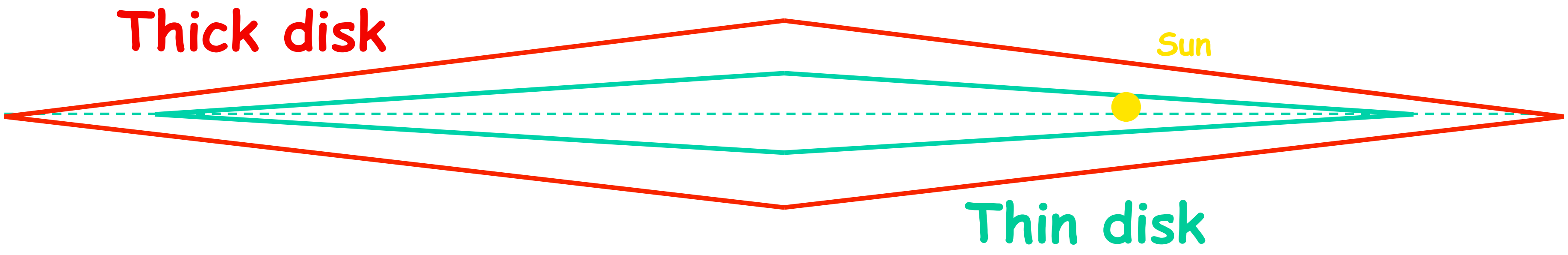
Radburn-Smith+ submitted

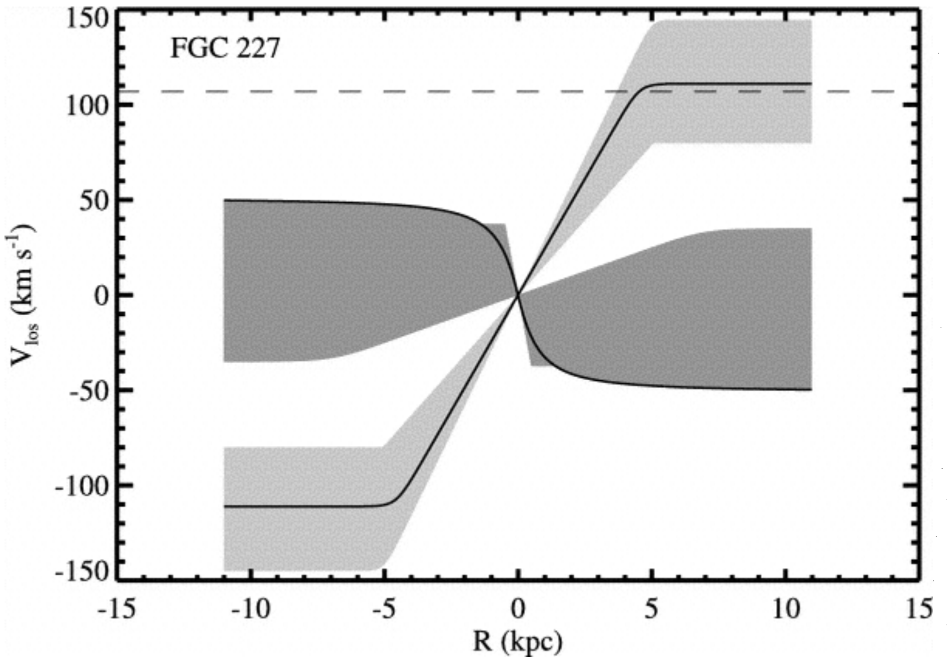
NGC 7793



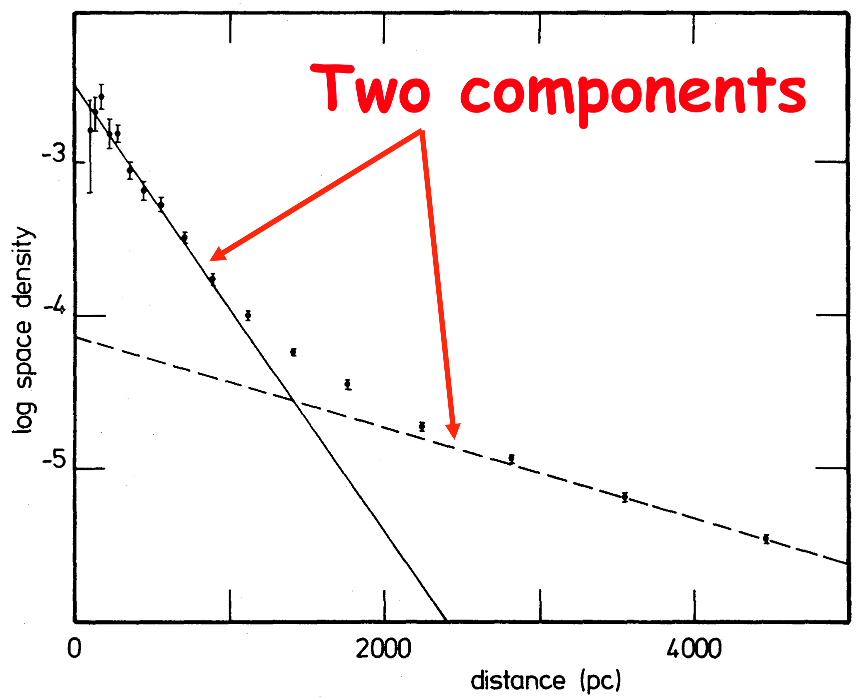
Radburn-Smith+ submitted

Thick Disk Formation





Yoachim & Dalcanton 2005



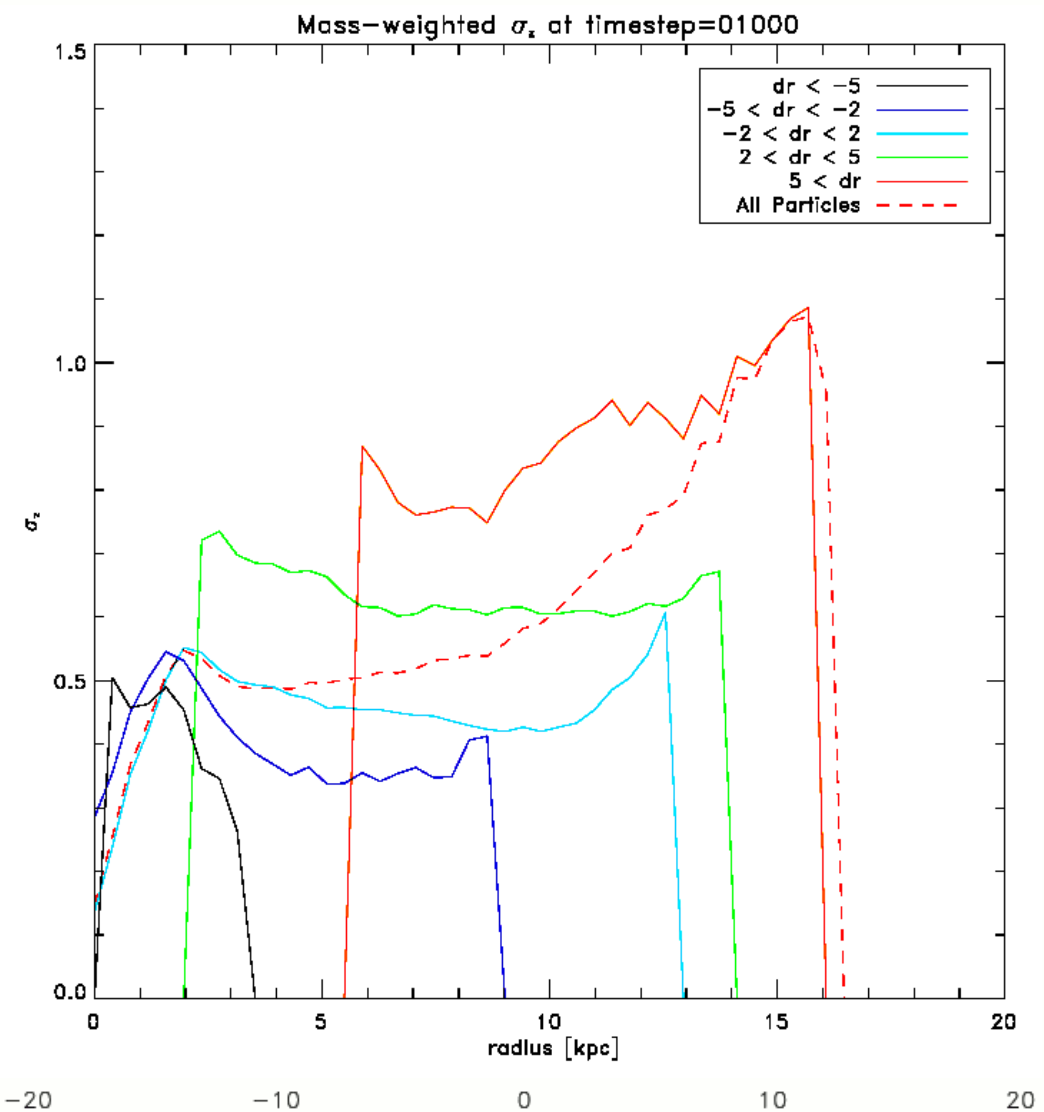
Gilmore & Reid 1983

Effect on Vertical Direction

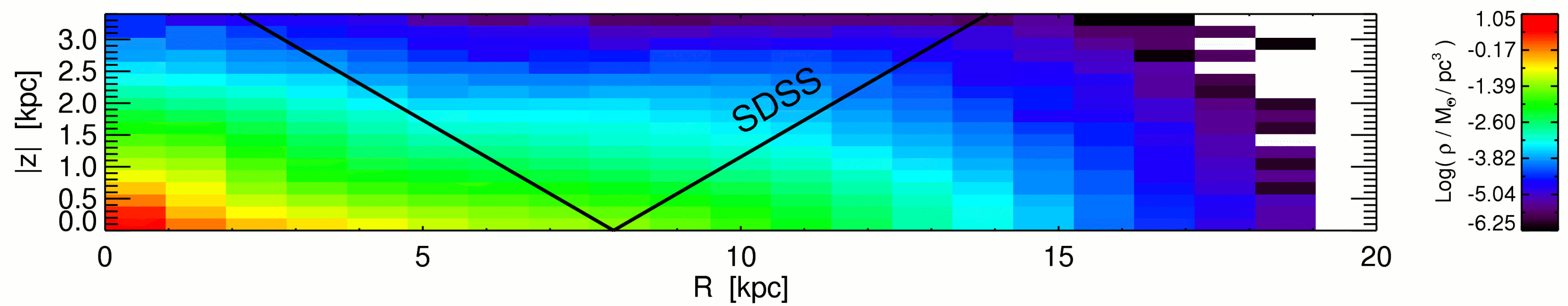
If vertical action is conserved by migration then stars moving outwards puff up and vice-versa

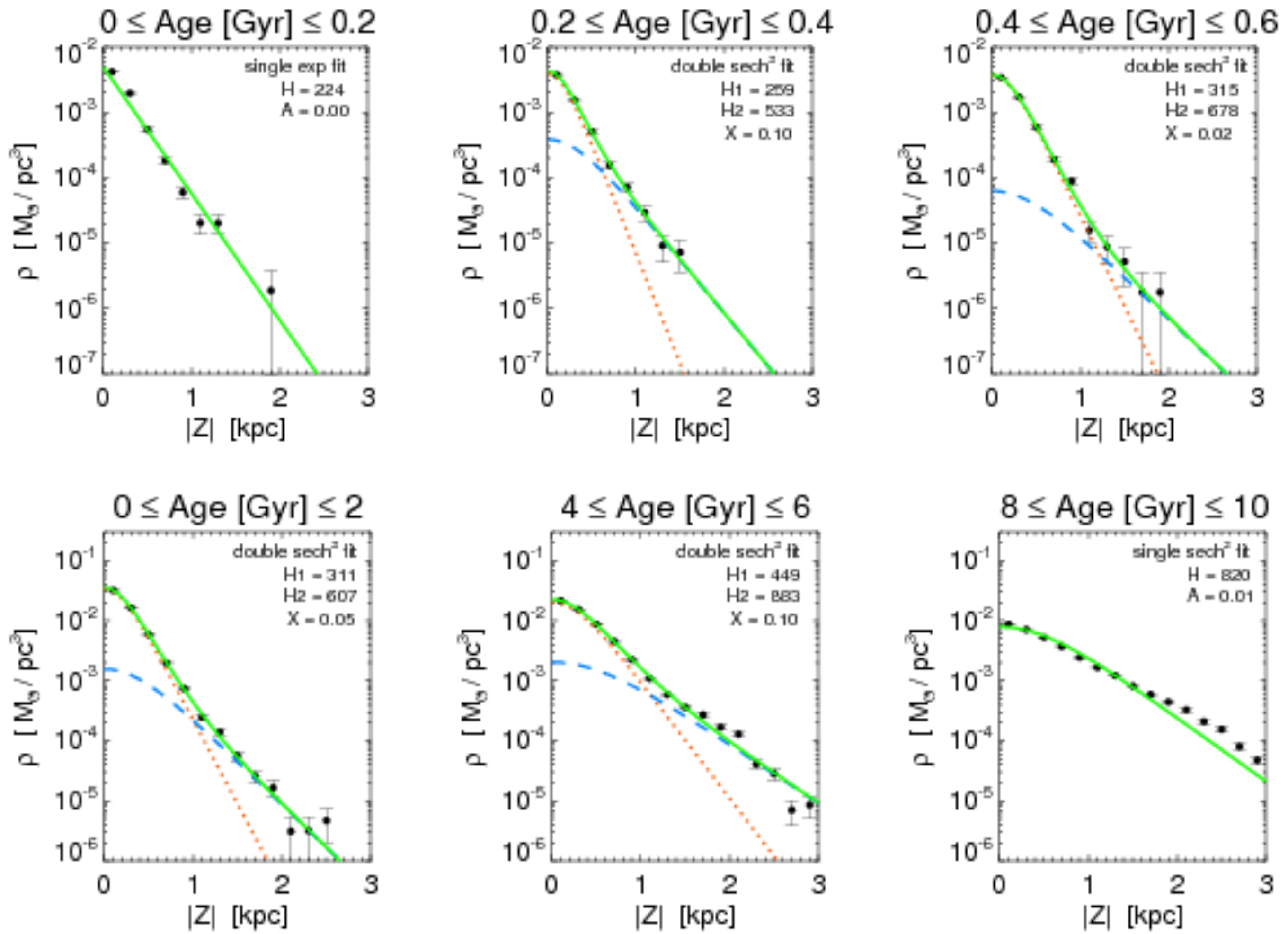
Is there such a thing as a dynamically distinct thick disk?

Schöenrich & Binney 2009



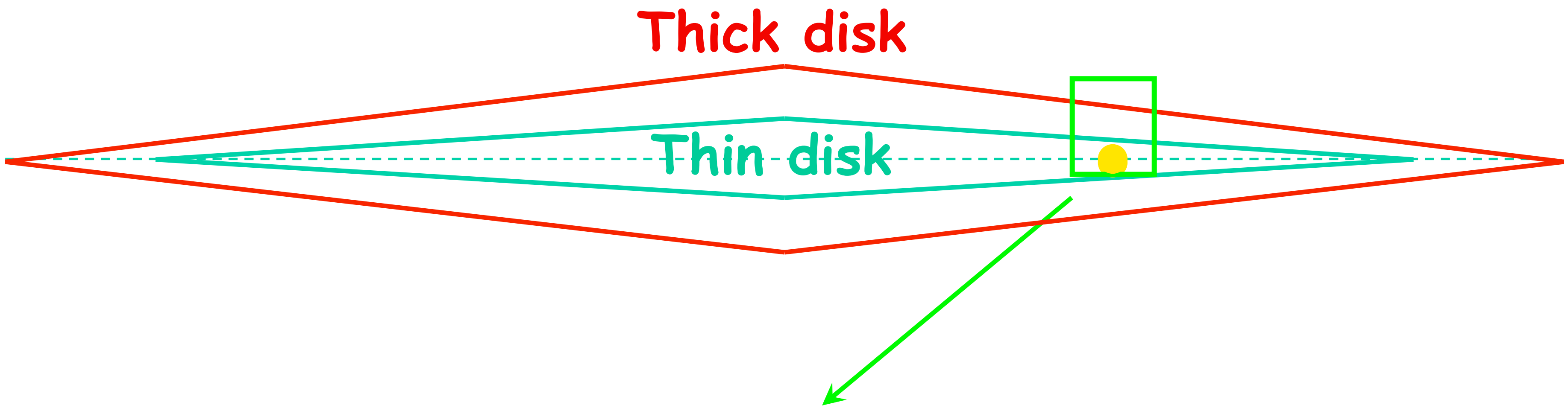
Caruana 2009





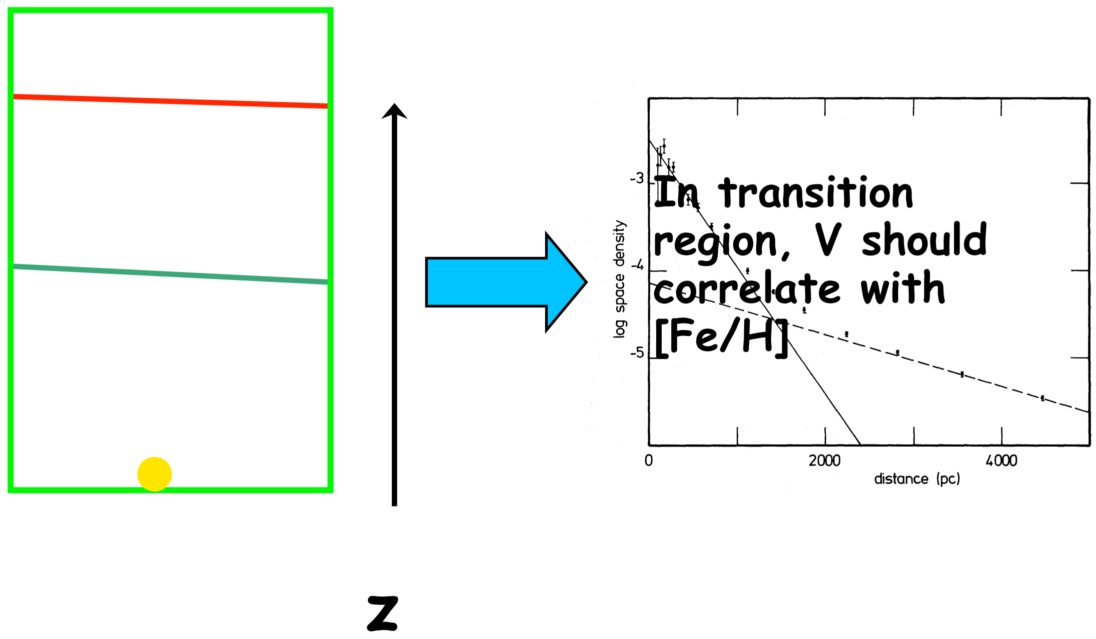
Stars form with a single expo profile but quickly develop a second component

Testing Thick Disk Formation



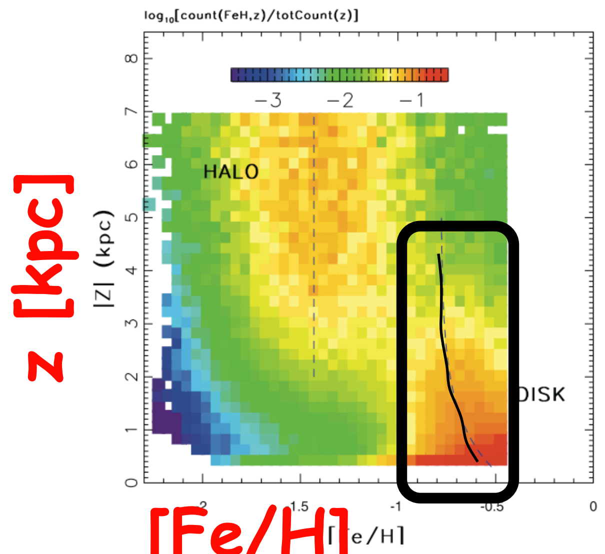
Metal poor + slow rotation

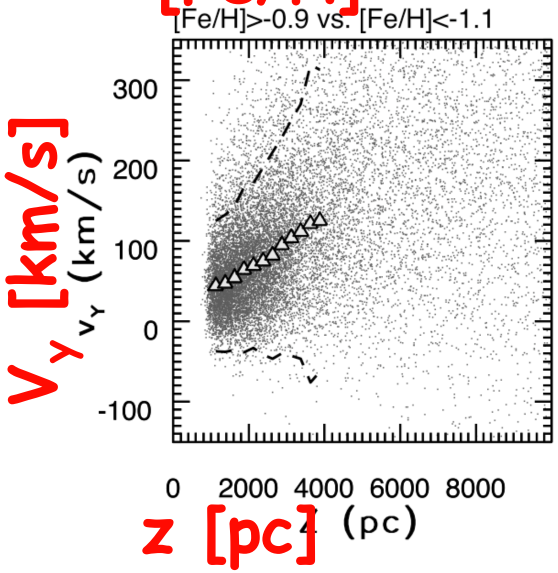
Metal rich + fast rotation

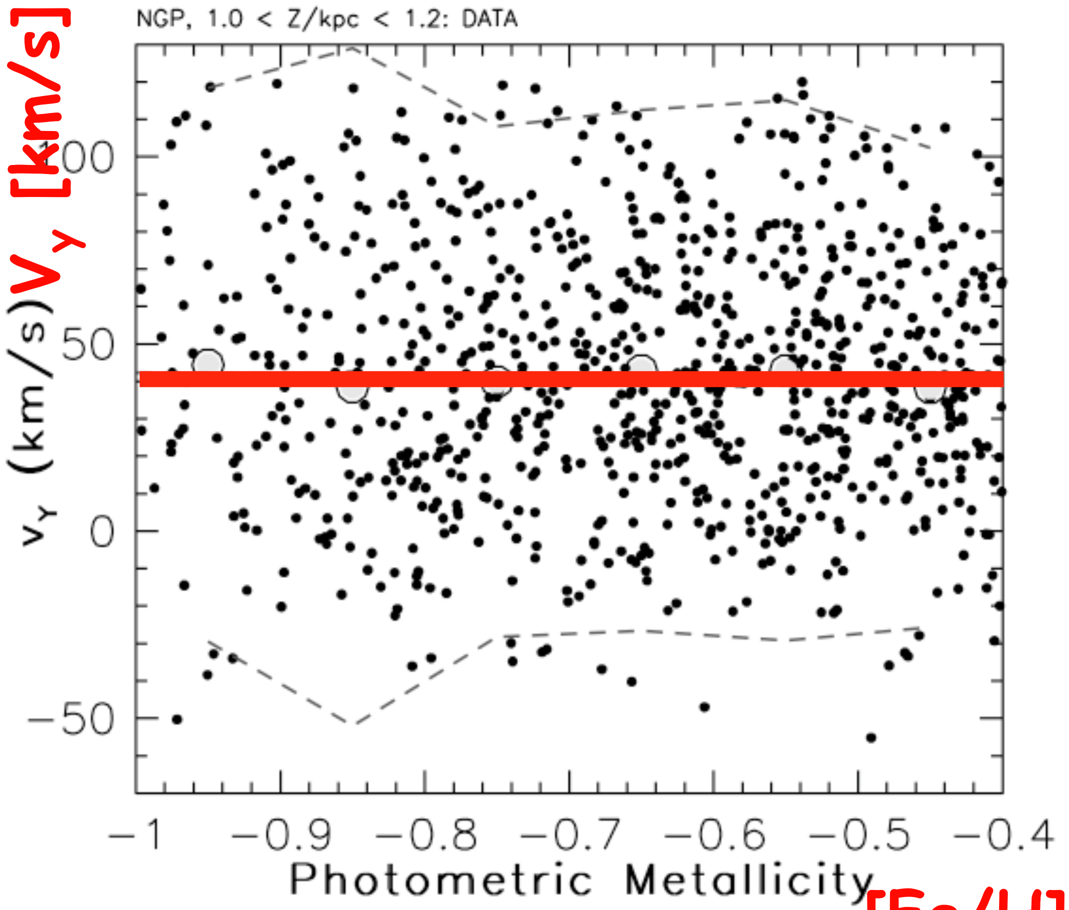


SDSS View

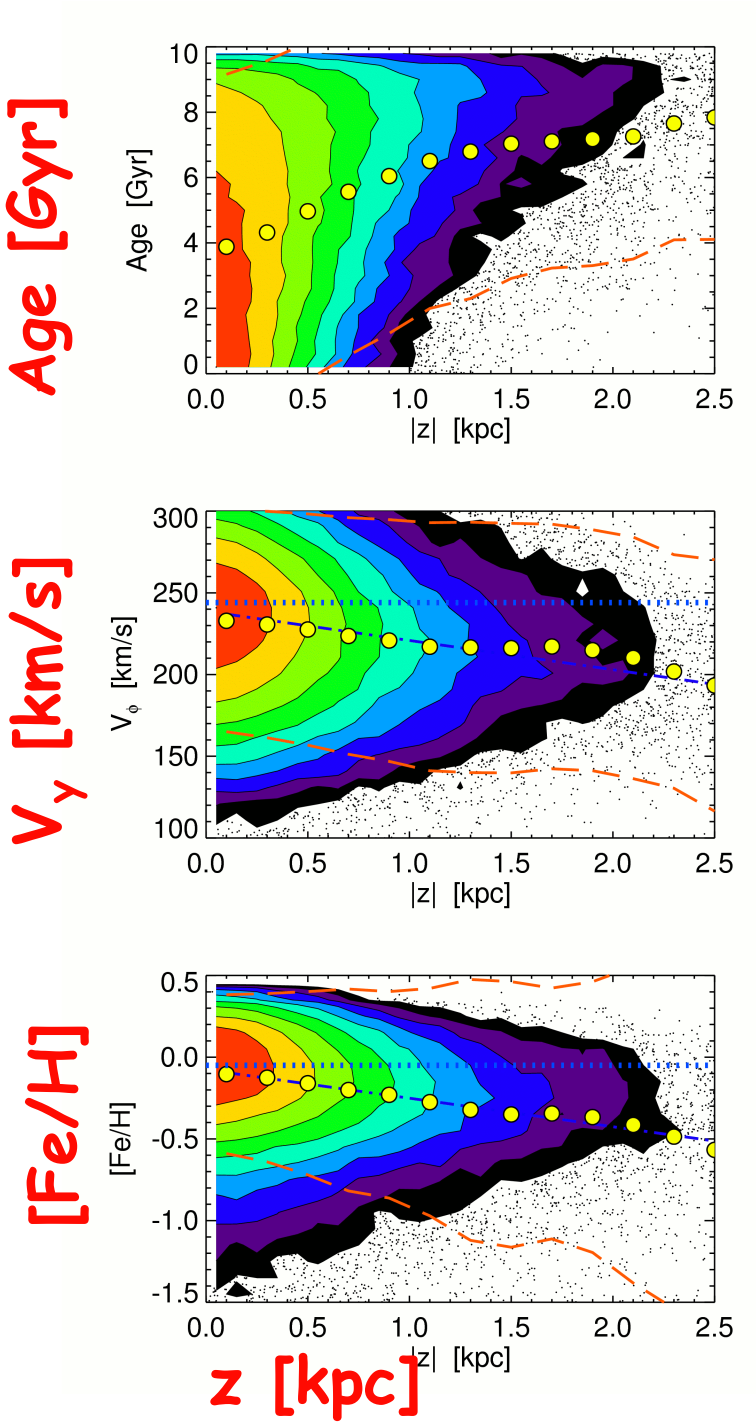
Decreasing metallicity and v_{rot} with height





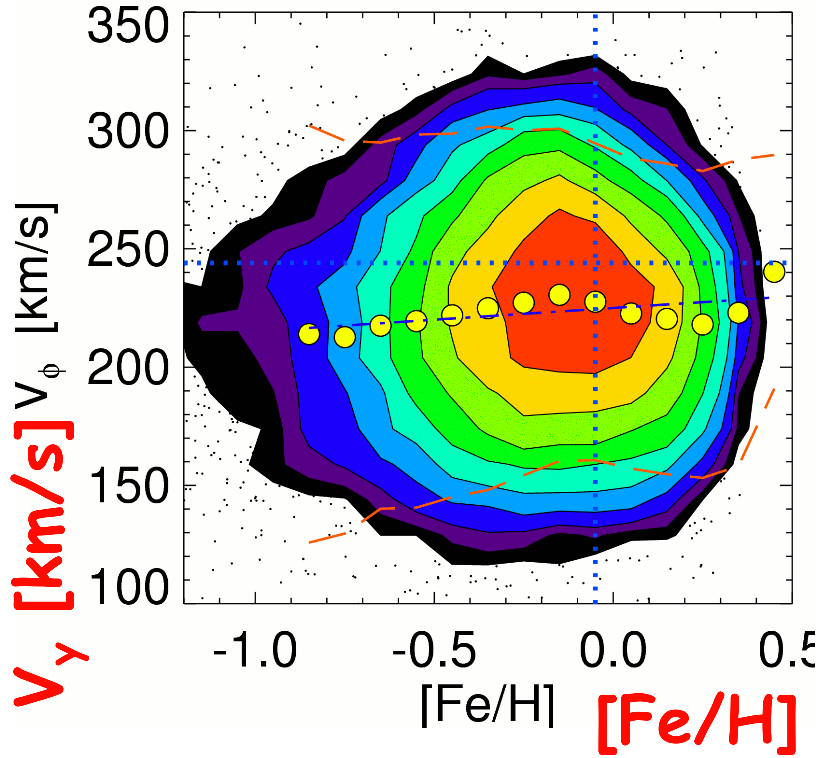


Ivezic+ 2008 (also Bond+ 2010)



Age, velocity and metallicity all correlate with height above the mid-plane.

But there is little correlation between velocity and metallicity, as found by SDSS

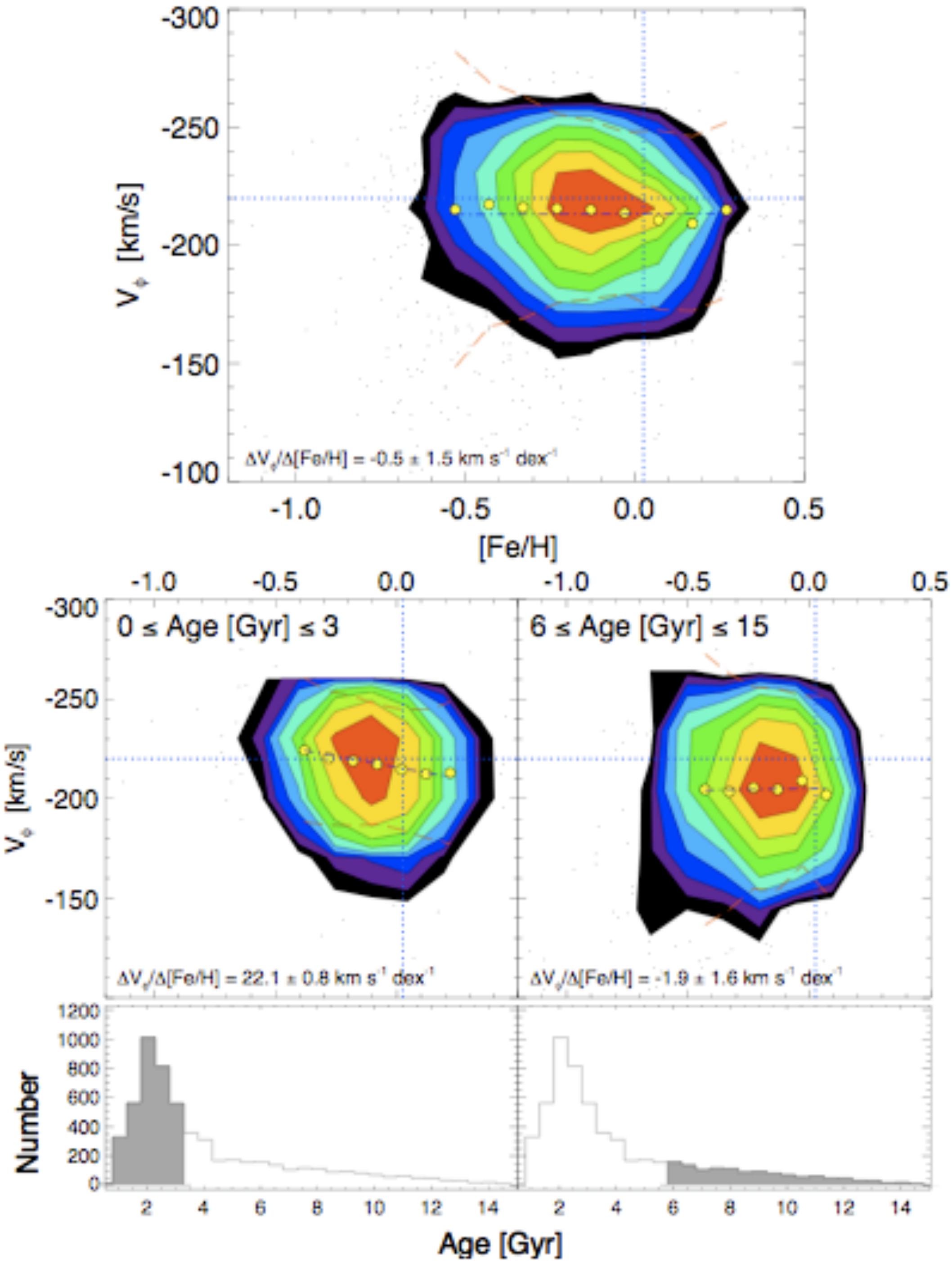


young

In the transition zone:
$0.5 < z < 1$ kpc

Geneva-Copenhagen Survey in mid-plane (after selecting non-binary stars)

all

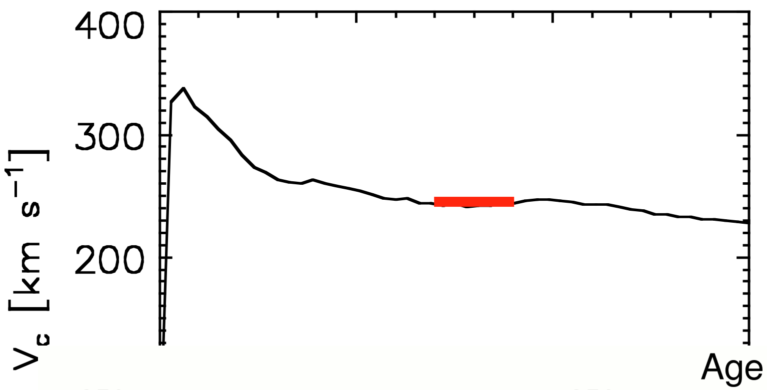


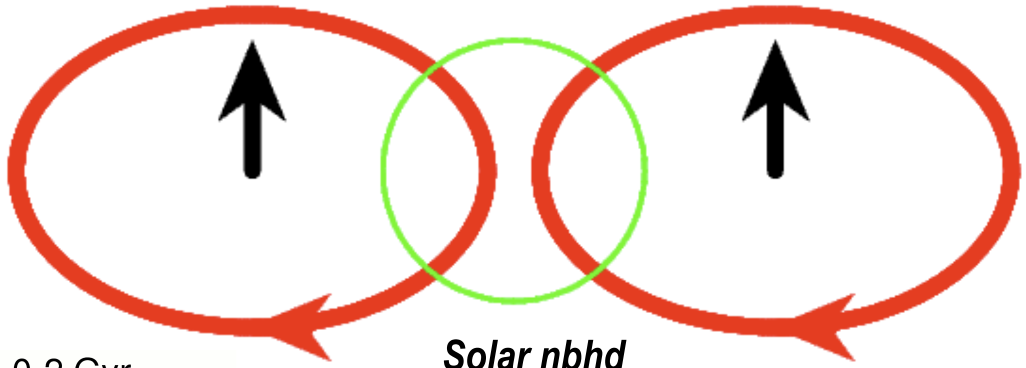
young

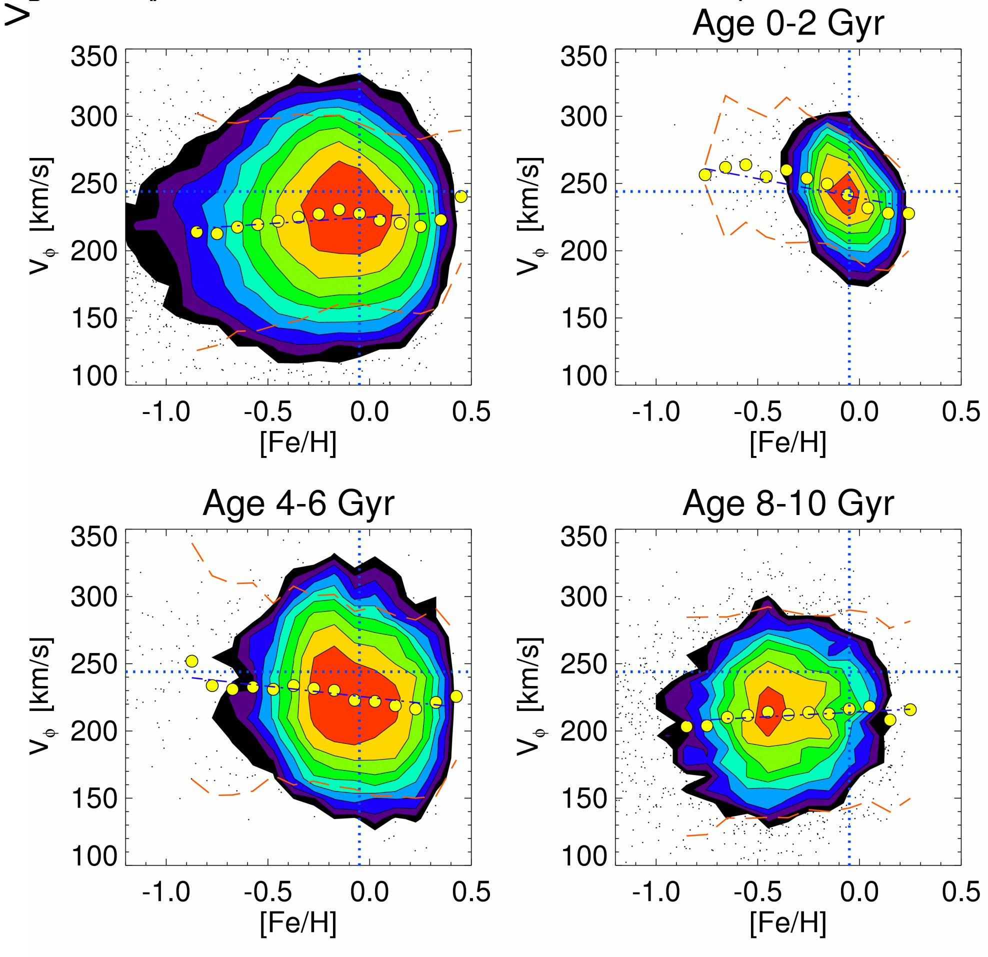
old

interi

old



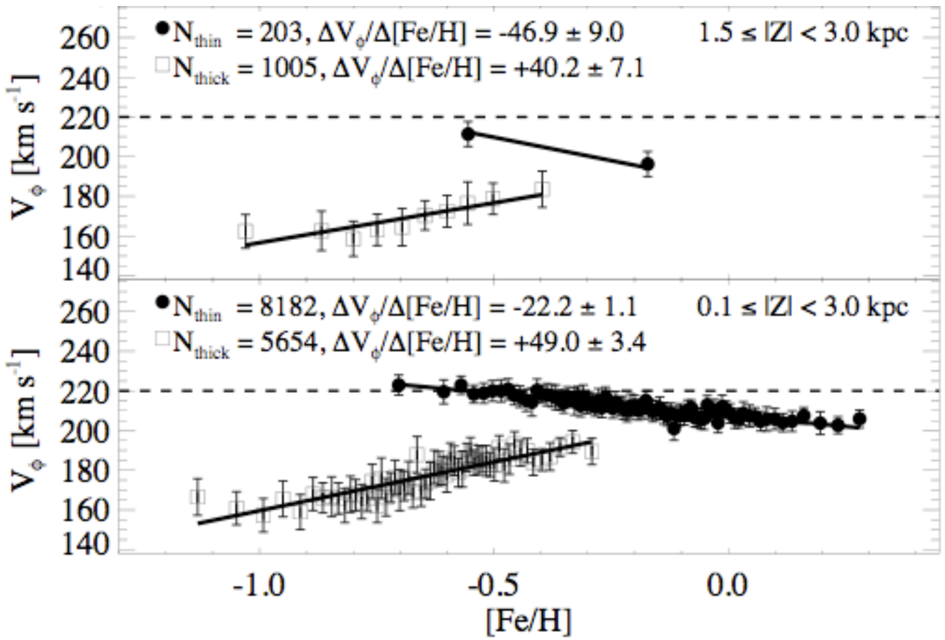


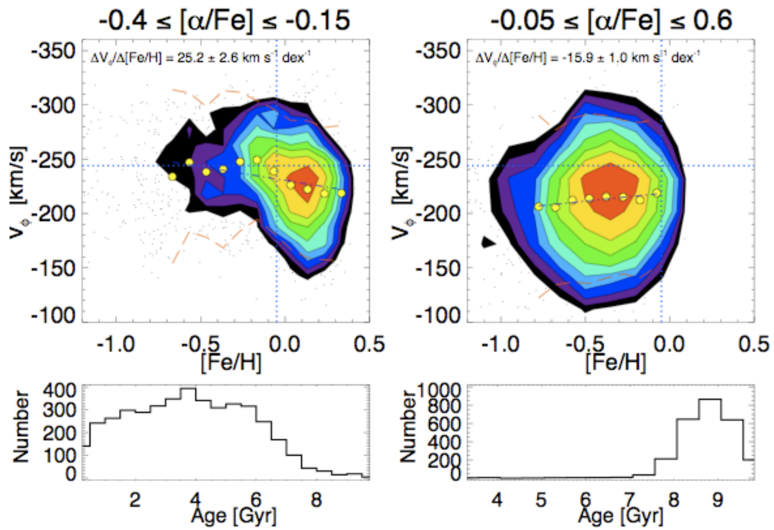


Stars are born on circular orbits and hence have no correlation between V and [Fe/H]. Heating brings stars into the local volume creating a correlation. Migration shuffles [Fe/H] and erases the correlation

Loebman+ 2011

Splitting by [α/Fe]



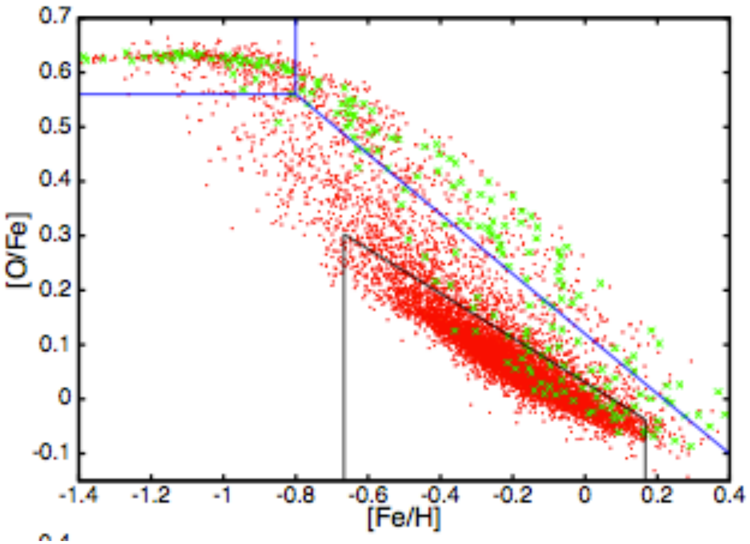


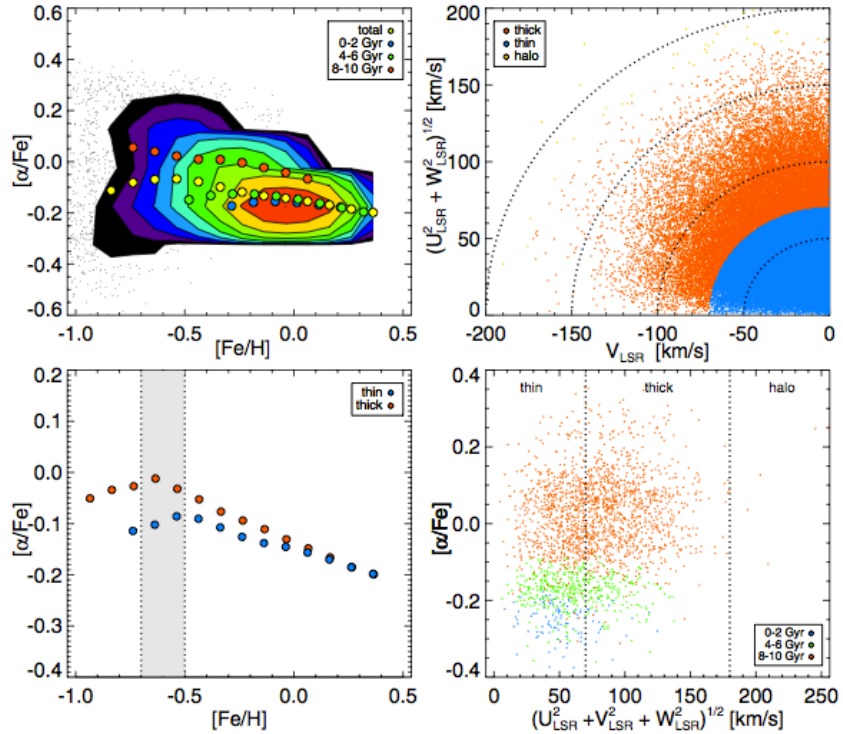
G-dwarf sample within
3 kpc of the sun

$\Delta V/\Delta$[Fe/H]
Thin disk: -22.2 ± 1.1
Thick disk: 49.0 ± 3.4

$\Delta V/\Delta$[Fe/H]
Thin disk: -25.2 ± 2.6
Thick disk: 15.9 ± 1.0

Lee+ 2011

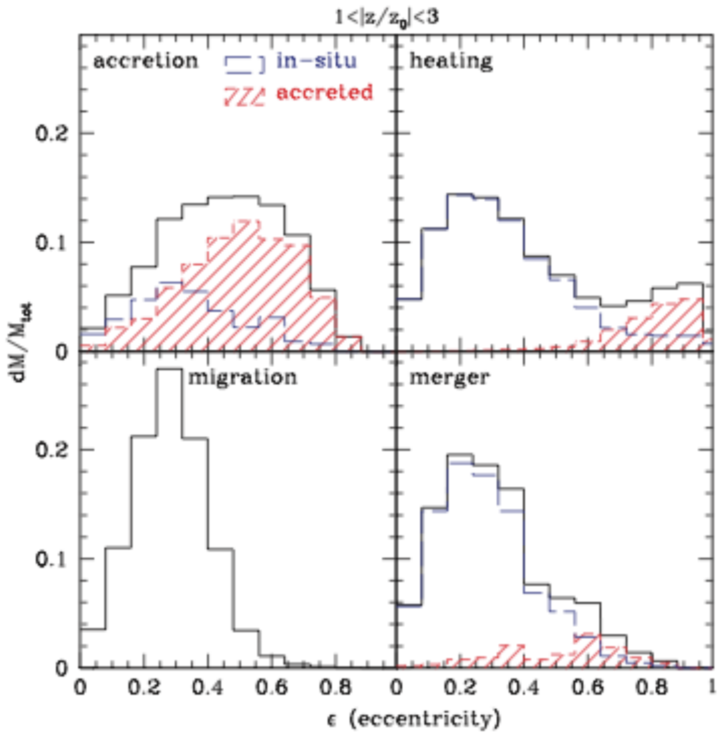




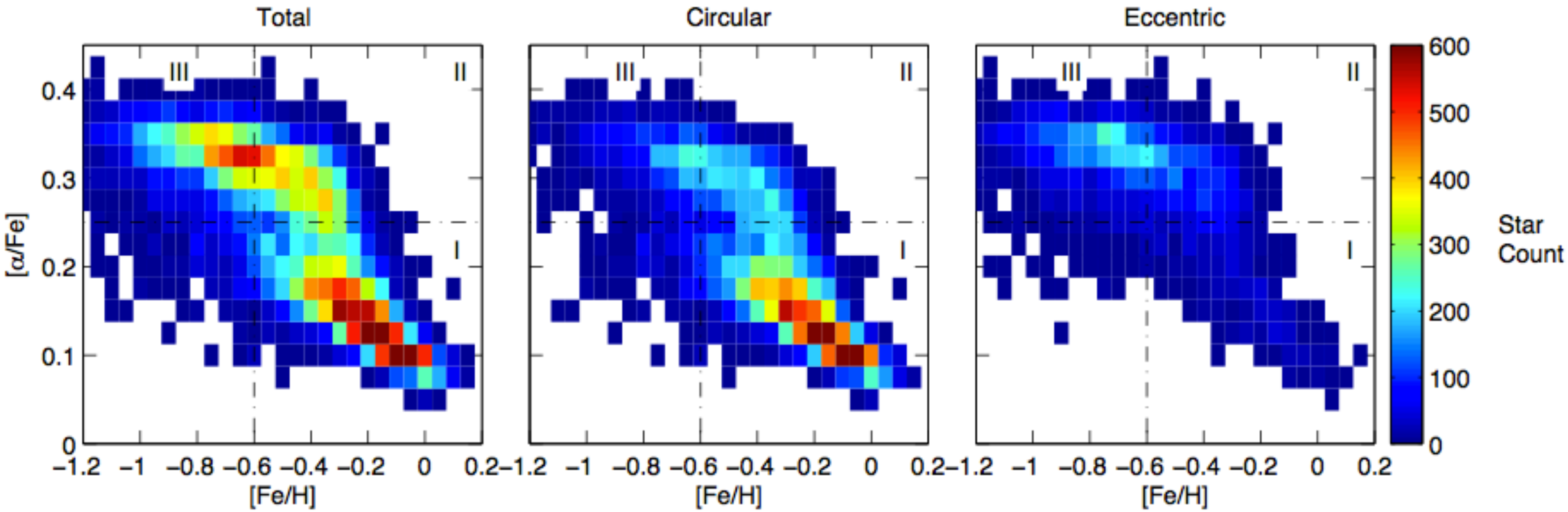
Analytic chemodynamical model of a GCS-like solar neighborhood including heating and migration

Schönrich & Binney 2009

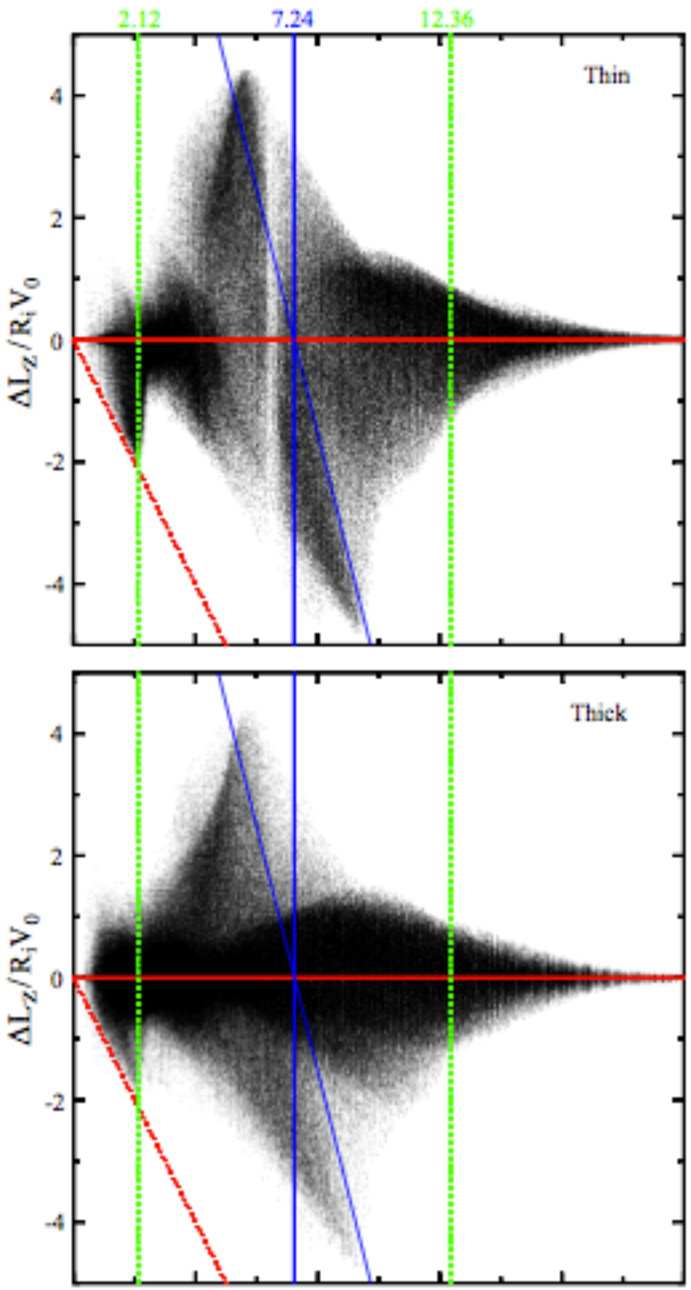
Loebman+ 2011



Sales+ 2009



Liu & van de Ven 2012



Thin disk

Spirals arising in the thin disk are able to drive migration also of stars in a dynamically distinct thick disk

Thick disk

Solway+ 2012

Conclusions

★ Contrary to decades of assumption, a mechanism for mixing stars radially without heating exists: scattering at corotation off transient spirals. This can substantially alter stellar populations in disks.

★ A large fraction of stars in outer disks probably formed at smaller radii and migrated outwards. There is a growing body of evidence that disks get increasingly old outwards of the break.

★ The galactic archaeologist must deal with jumbled strata.

★ Migration may also be the explanation for at least part of the thick disk. Many of the properties and trends of the thick disk can be qualitatively matched by migration