Quantifying stellar radial migration: blurring, churning, and the outer regions of galaxy discs

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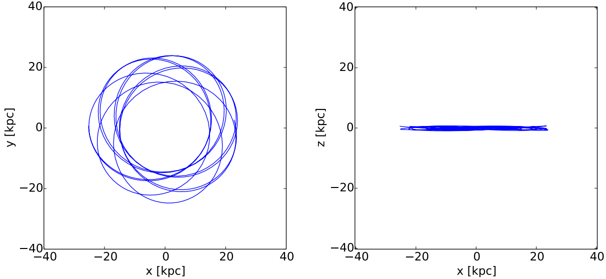
Observations difficult to explain by inside-out growth of discs and stars remaining on almost circular orbits of fixed radius:

- age-metallicity scatter in solar neighbourhood (e.g. Haywood et al 2013)
- U-shaped age profiles in nearby spirals: old outskirts of discs?

Theoretical/numerical works include:
Sellwood & Binney 2002
Schoenrich and Binney 2009
Minchev et al 2009, 2011, etc
Roskar et al (2008, 2013), Kubryk et al 2013, 2015, Vera-Ciro et al 2014, Di Matteo et al 2013, 2014, etc.

Most stars in galactic discs on "rosette" orbits with angular frequency $\Omega \neq$ radial frequency κ:



Radial (epicyclic) excursions between minimum and maximum radii around a guiding radius: **blurring**

Non-axisymmetric potential perturbations (bars and spiral arms) can change guiding radii of some stars by angular momentum exchange: **churning**
Exchange of angular momentum at resonances.

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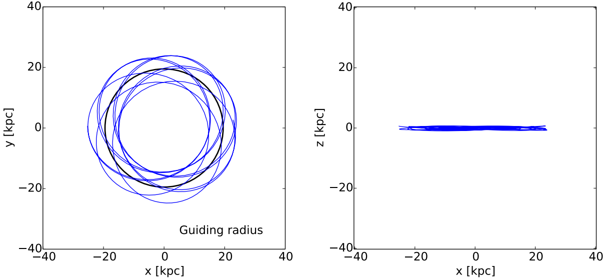

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If pattern (bar, spiral arms) of angular frequency Ω_P, stars resonate with the pattern when $n(\Omega - \Omega_P) = l\kappa$.

Main resonances:

- Corotation CR for $\Omega = \Omega_P$
- Inner Lindblad resonance ILR (of π-periodic pattern) for $\Omega - \Omega_P = \frac{\kappa}{2}$
- Outer Lindblad resonance OLR (of π-periodic pattern) for $\Omega - \Omega_P = -\frac{\kappa}{2}$

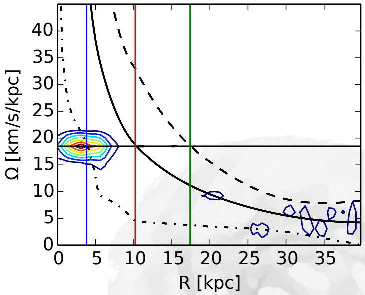


Figure : Black solid: $\Omega(R)$, -.: $\Omega(R) - \dfrac{\kappa(R)}{2}$, - -: $\Omega(R) + \dfrac{\kappa(R)}{2}$. Red: CR radius, Blue: ILR, Green: OLR.

Possible exchange of angular momentum at resonances $\Rightarrow$ churning.

Sellwood & Binney 2002: large angular momentum permanent changes induced by corotation ($\Omega = \Omega_P$) of transient spirals

Minchev et al 2009, 2011, etc: non-linearity of angular momentum exchanges when bar + spiral arms

Radial migration by churning used to explain mixing of discs, but:

- Difficult to quantify
- Intriguing observation in Milky Way: different stellar populations in central disc and outskirts, metallicity step at solar radius (Haywood et al 2013, Anders et al 2014 e.g.).

$\Rightarrow$ In this work, quantification of radial migration in a Sb-type galaxy simulation with respect to location of main resonances in the disc.

Gadget-2 (V. Springel) N-body+SPH simulation.

1 200 000 particles in:

- Stellar disc $M_* = 4.5\,10^{10}\mathrm{M}_\odot$
- Gas disc $M_g = 0.9\,10^{10}\mathrm{M}_\odot$
  Toomre parameters
  $Q = \frac{\sigma_r \kappa}{3.36 G \Sigma} = 1.$
- Stellar bulge $M_B = 1.1\,10^{10}\mathrm{M}_\odot$
- Dark Matter halo $M_H = 1.7\,10^{11}\mathrm{M}_\odot$

Baryonic physics:

- Detailed metal-lines cooling at low T.
- Stochastic star-formation.
- Feedback from SNII.

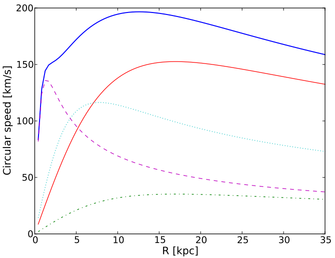
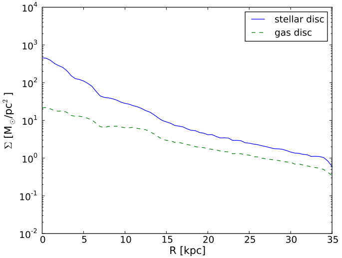
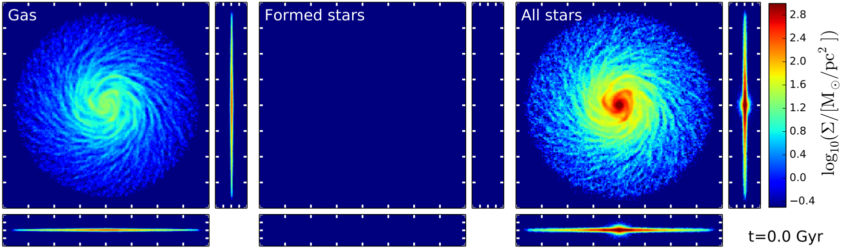


Figure : Dotted: stellar disc, Dash-dotted: gas disc, Dashed: stellar bulge, Solid red: DM Halo

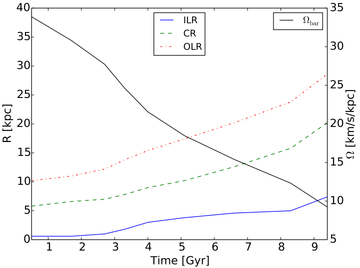


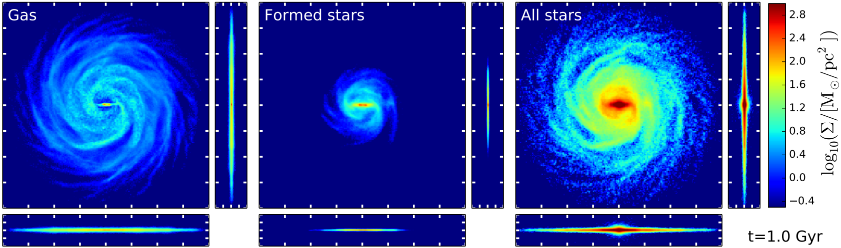


Strong bar weakens when buckling instability and strengthens again.

Bar grows and slows down (angular momentum transfer with disc, bulge and dark halo).

⇒ shift of resonances locii with time.





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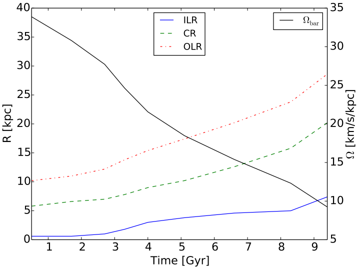

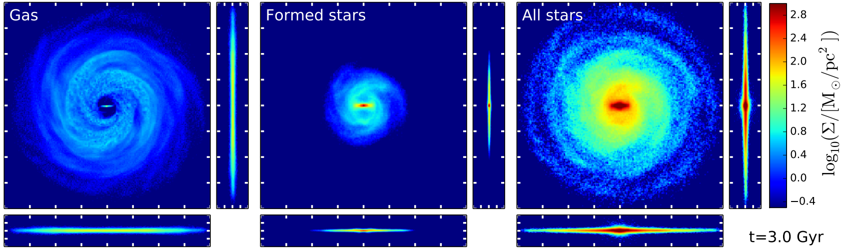

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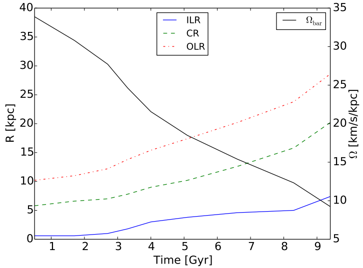

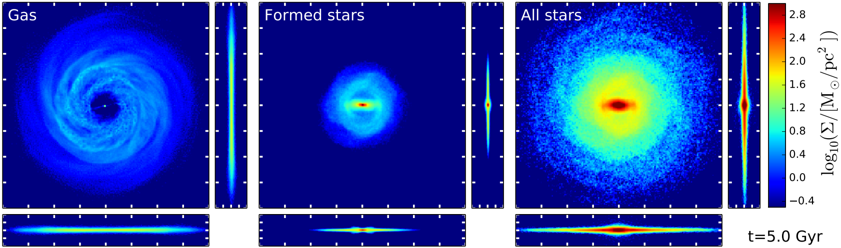

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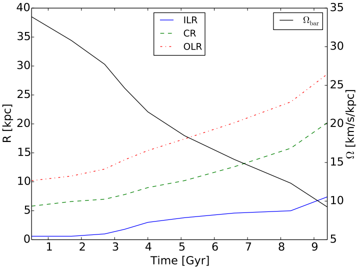

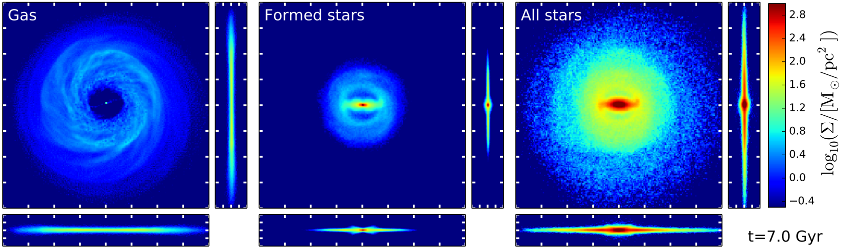

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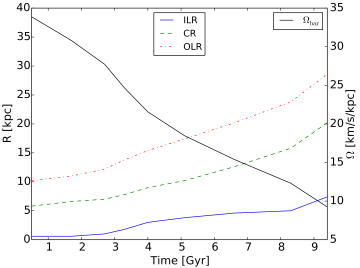

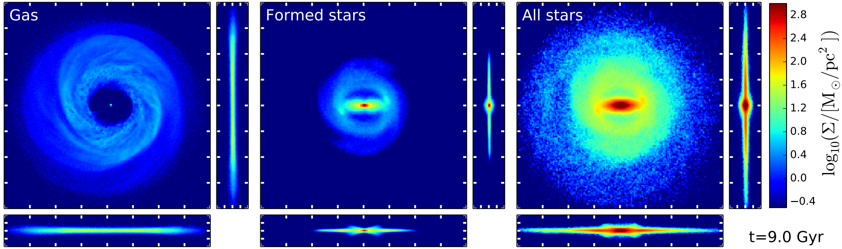

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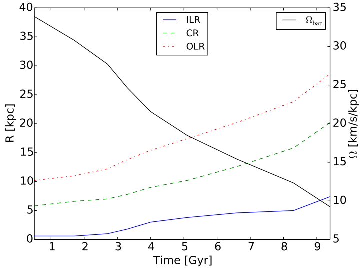


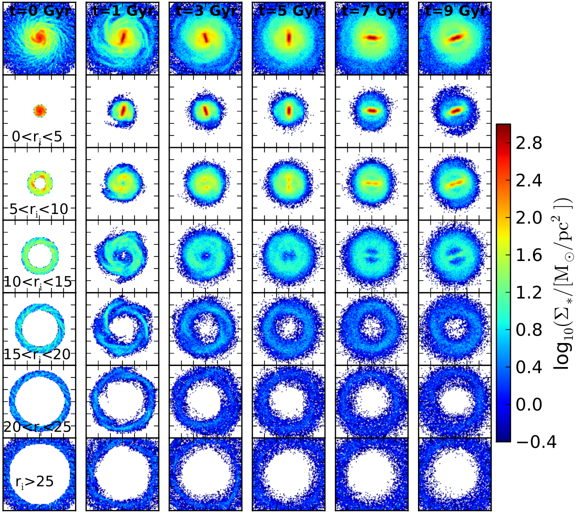


Figure : Migration of stars in initial rings. Di Matteo et al 2014

Comparison of migration in terms of:

- galactocentric radius (due to churning + blurring)
- guiding radius (pure churning)

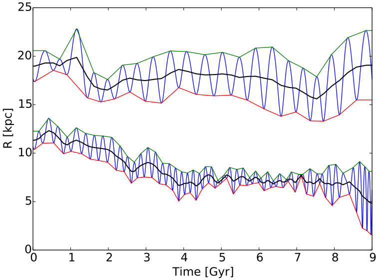
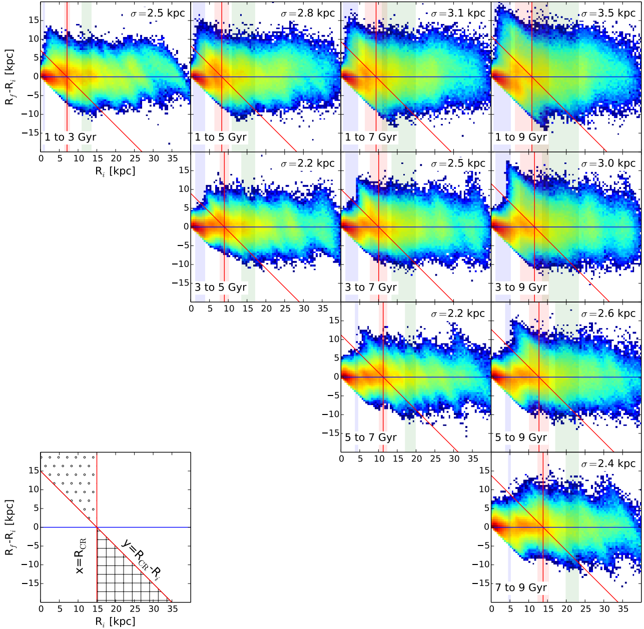
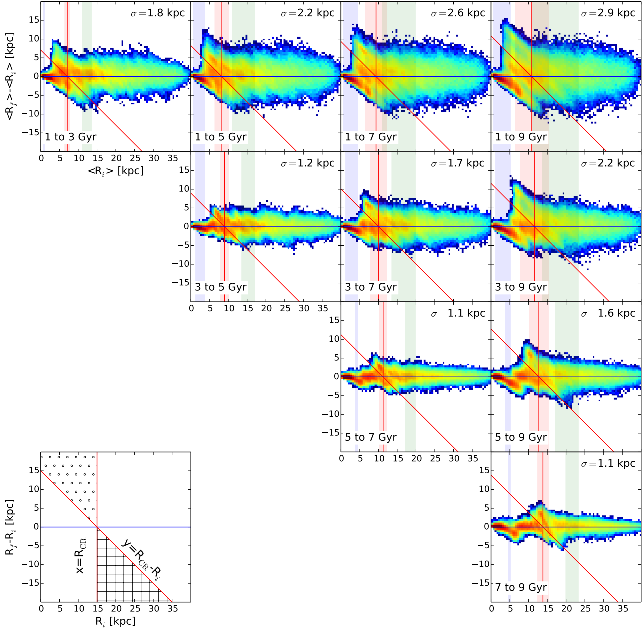


Figure : Galactocentric radii of two stars and determination of their guiding radii.

Change in radius



Change in guiding radius



Epicyclic excursions + heating (increase of radial oscillations amplitude with time) ⇒ migration by churning of lower rms and extent than total migration.

Main churning region at corotation of the bar. Largest angular momentum exchanges.

Blurring progressively takes over churning due to weaker bar and heating of the disc.

Other quantifications of churning vs blurring in Halle, Di Matteo, Haywood, Combes 2015 (2015A&A...578A..58H).

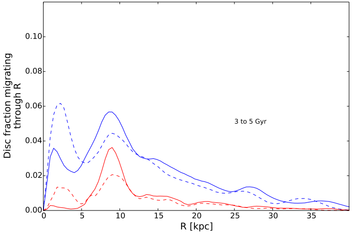
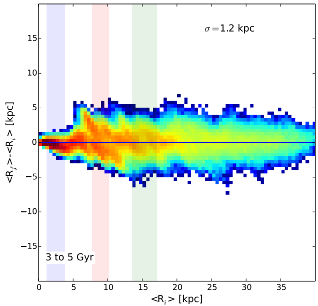


Figure : Migrating mass. Red: Radius and guiding radius cross R. Blue: Radius crosses R. Solid: outward flux. Blue: inward flux.

Few migrators cross the Outer Lindblad Resonance (OLR) from the inner or outer disc.



Vertical line: OLR radius (increases with bar growth).

Dot-filled: Outward-migrators through the OLR.

Grid-filled: Inward-migrators through the OLR.

Consistent with the large distance from CR and the absence of stars resonating with the bar after the OLR.

Sun is about at the OLR of the Milky Way (Dehnen 2000) ⇒ could be linked to the apparent difference in metallicity and chemistry between the inner and outer MW discs.

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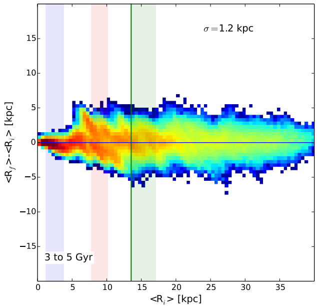

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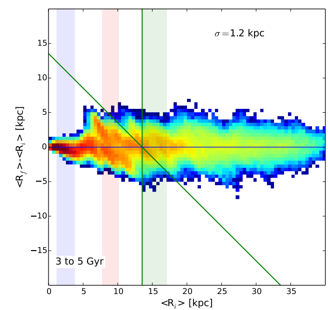

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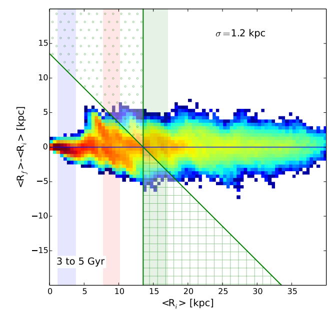

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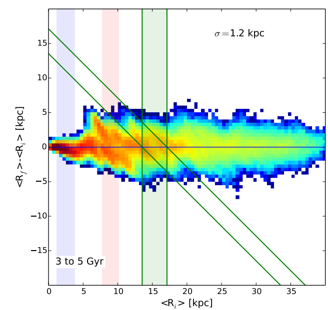

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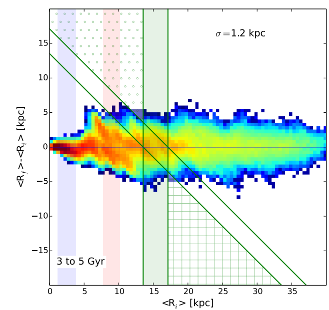

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Conclusions

Confirms that corotation of the main pattern (bar) is the main "churning" region.

Large part of stellar disc affected by churning as bar CR radius evolves.

Reduced mixing between central disc and disc outskirts: challenges the current view of the effect of radial migration (when only a main asymmetric pattern is present).

May affect the understanding of stellar populations in bar-dominated galaxies.

Will be investigated further with various methods (including a 4D Vlasov-Poisson solver).