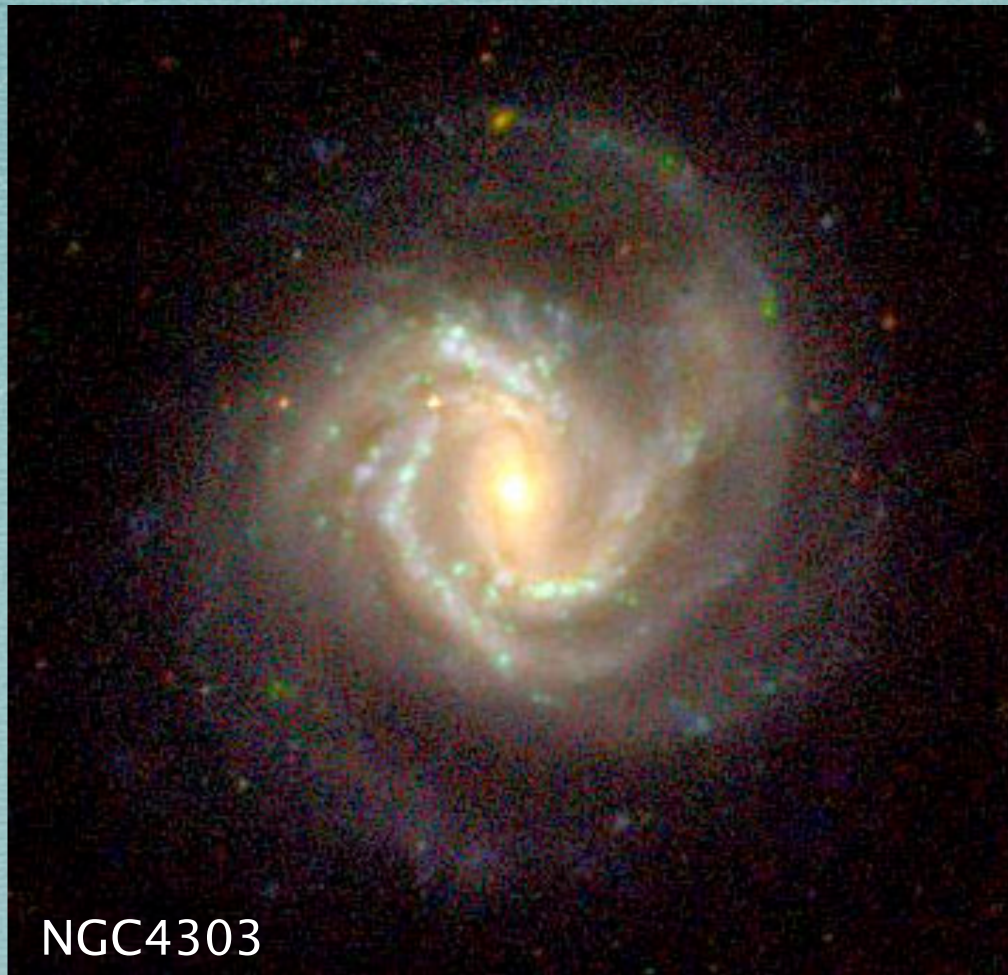

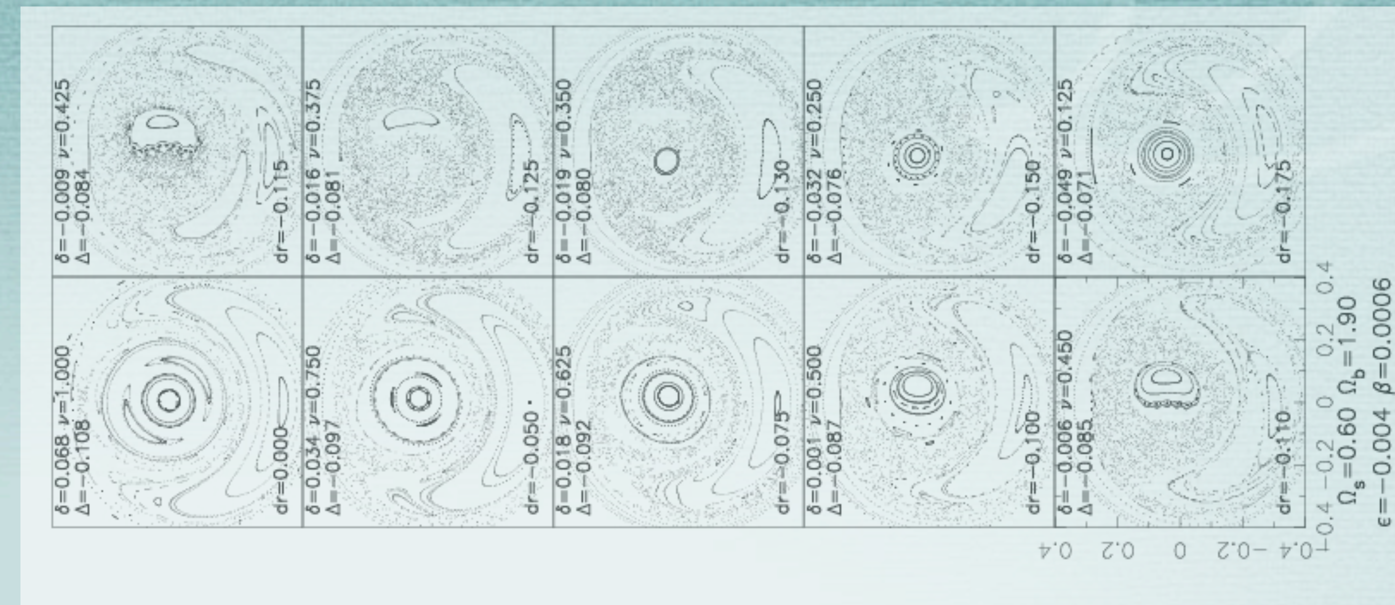

$$H \approx I_1^2 + I_1\delta - \varepsilon I_1^{1/2}\cos\phi \ - \beta I_1^{1/2}\cos[\phi + \nu t + \gamma]$$

A New Mechanism for Galactic Disk Mixing:
Implications to Galactic Disk Evolution

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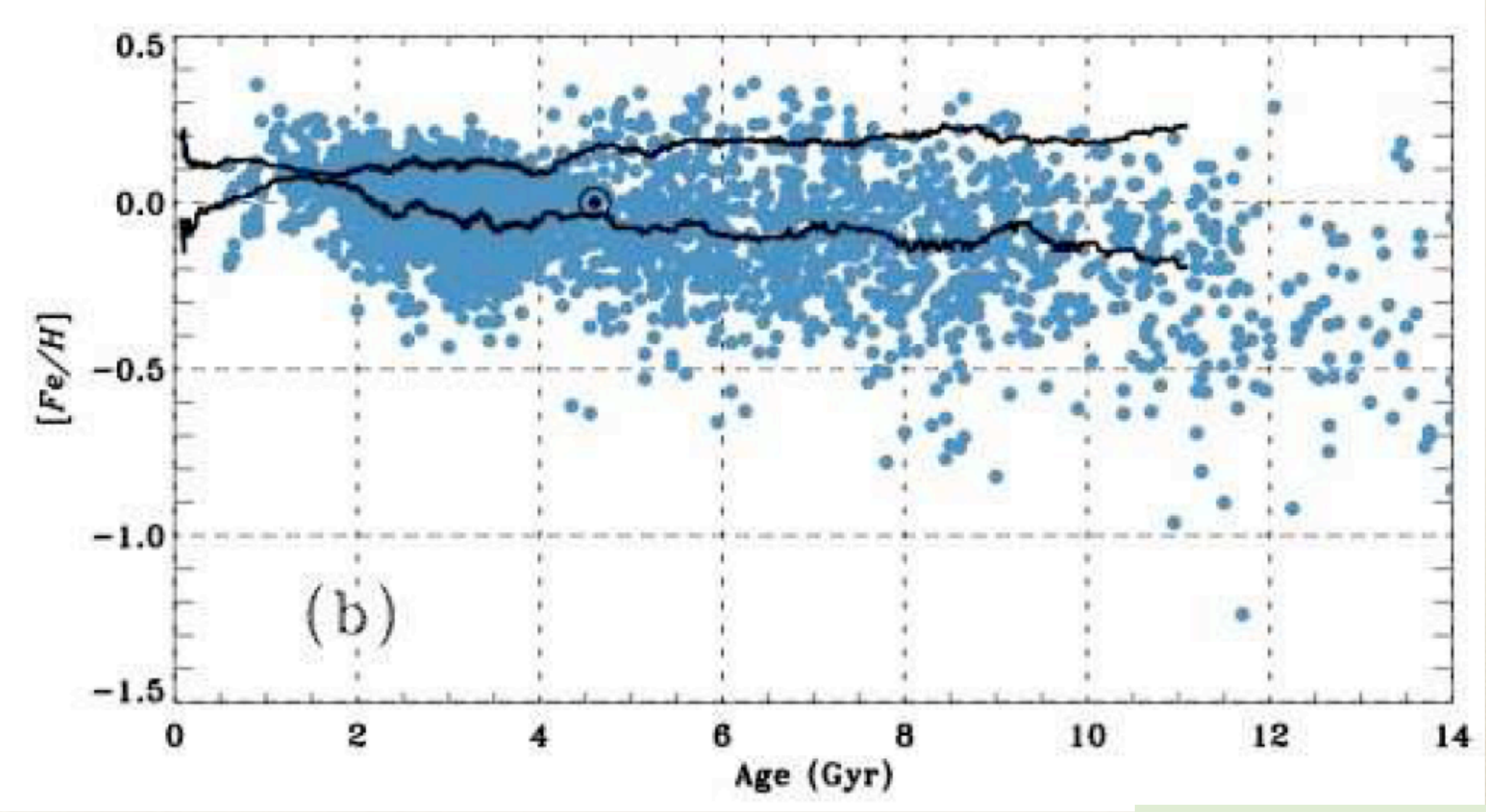
Strasbourg Observatory

Observatoire astronomique
de Strasbourg

The age-metallicity relation (AMR)

- The metallicities of stars in the solar neighborhood lack the expected correlation with age (e.g., Edvardsson et al. 1993; Haywood 2008).



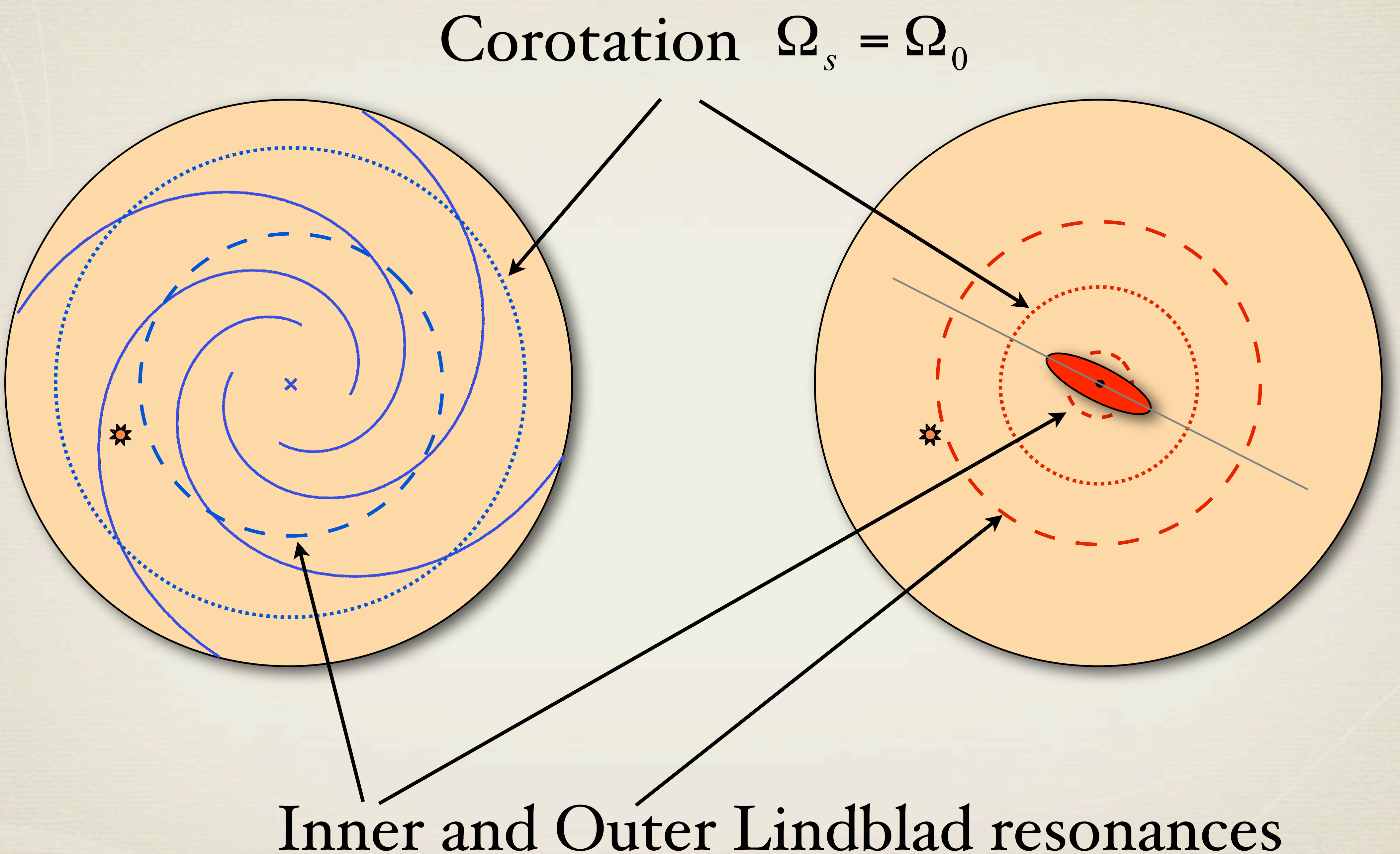
Haywood (2008)

Disk mixing mechanisms

- Scatter in AMR explained by stellar radial migration in the disk:
  - Transient Spirals (Sellwood & Binney 2002, Roskar et al. 2008, Schonrich & Binney 2009a, 2009b)
  - Small satellites can mix the outer disc (Quillen, Minchev, Bland-Hawthorn & Haywood 2009)

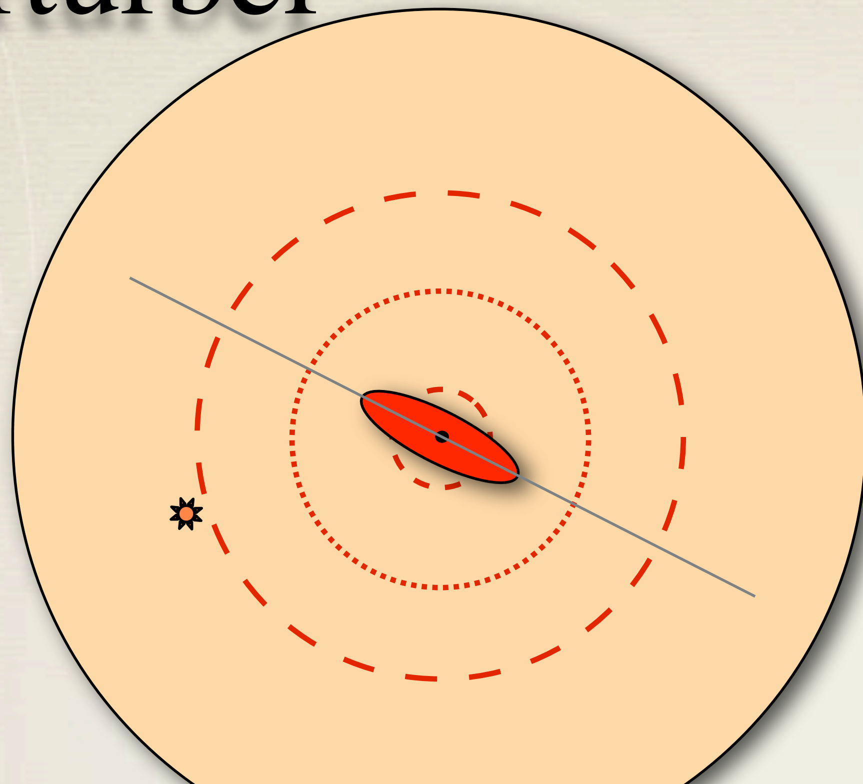
- **Are galactic Bars important for Radial Migration?**

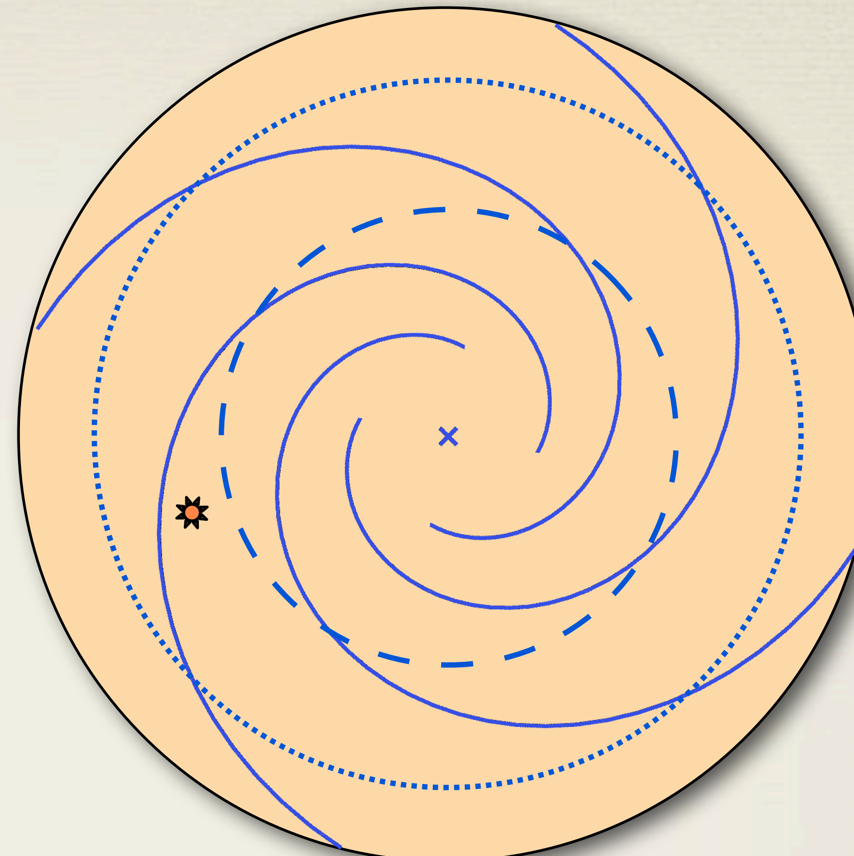
Resonances in galactic disks



- For a flat rotation curve $\Omega_s = \Omega_0 \pm \kappa / m$

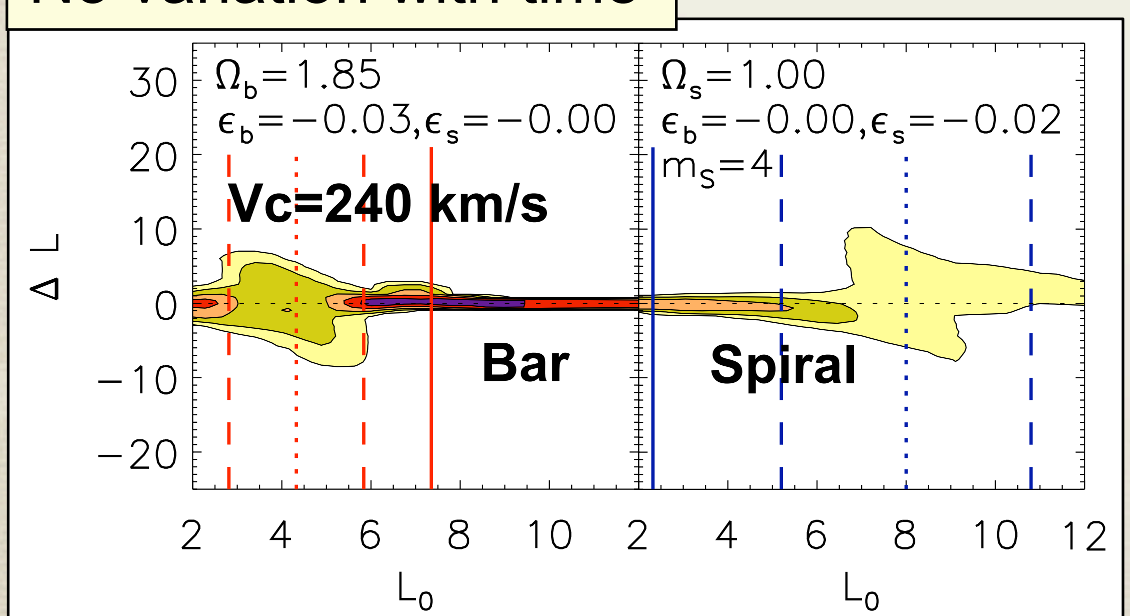
Radial migration (mixing) due to a single perturber





Change in angular momentum

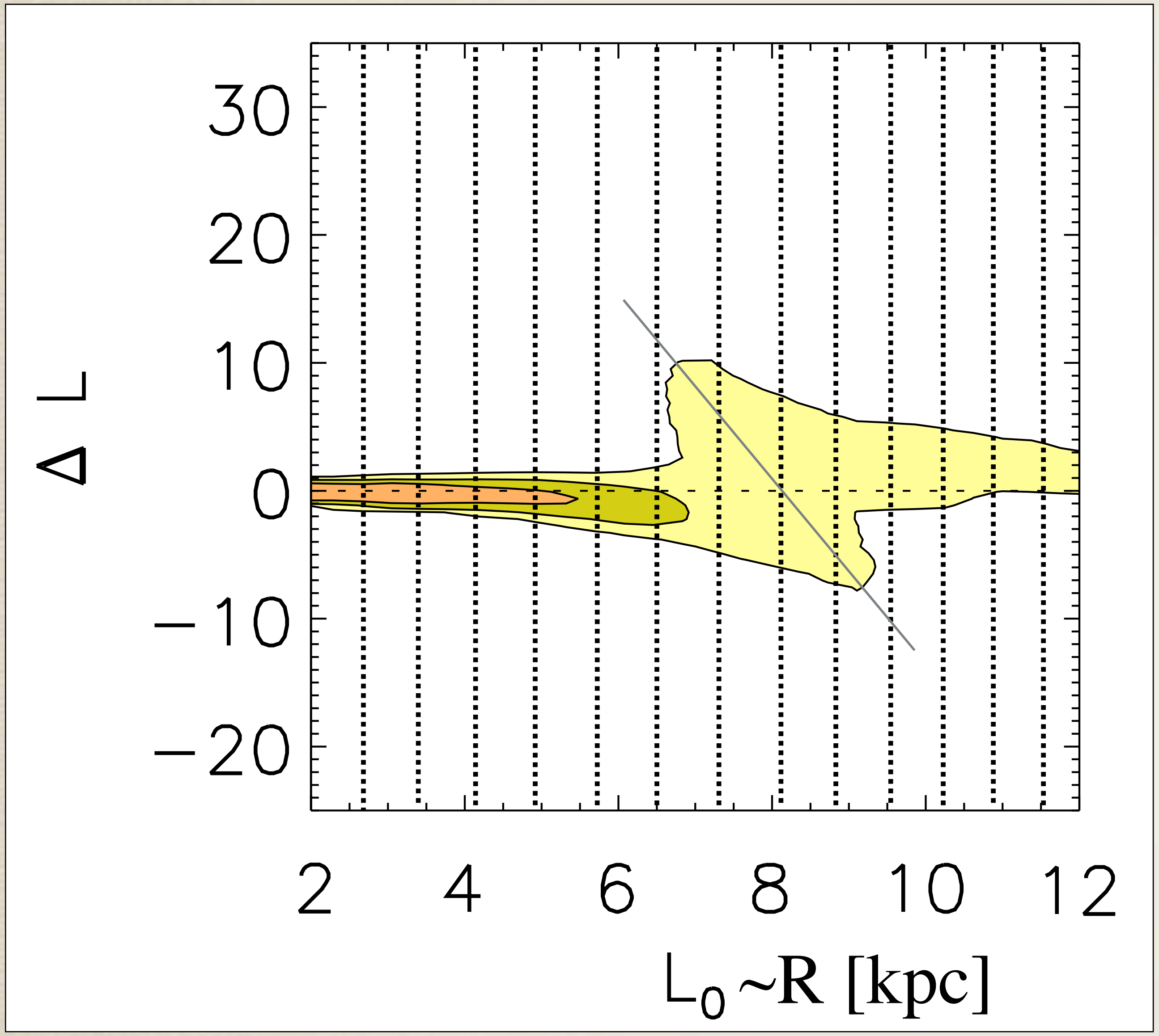
No variation with time

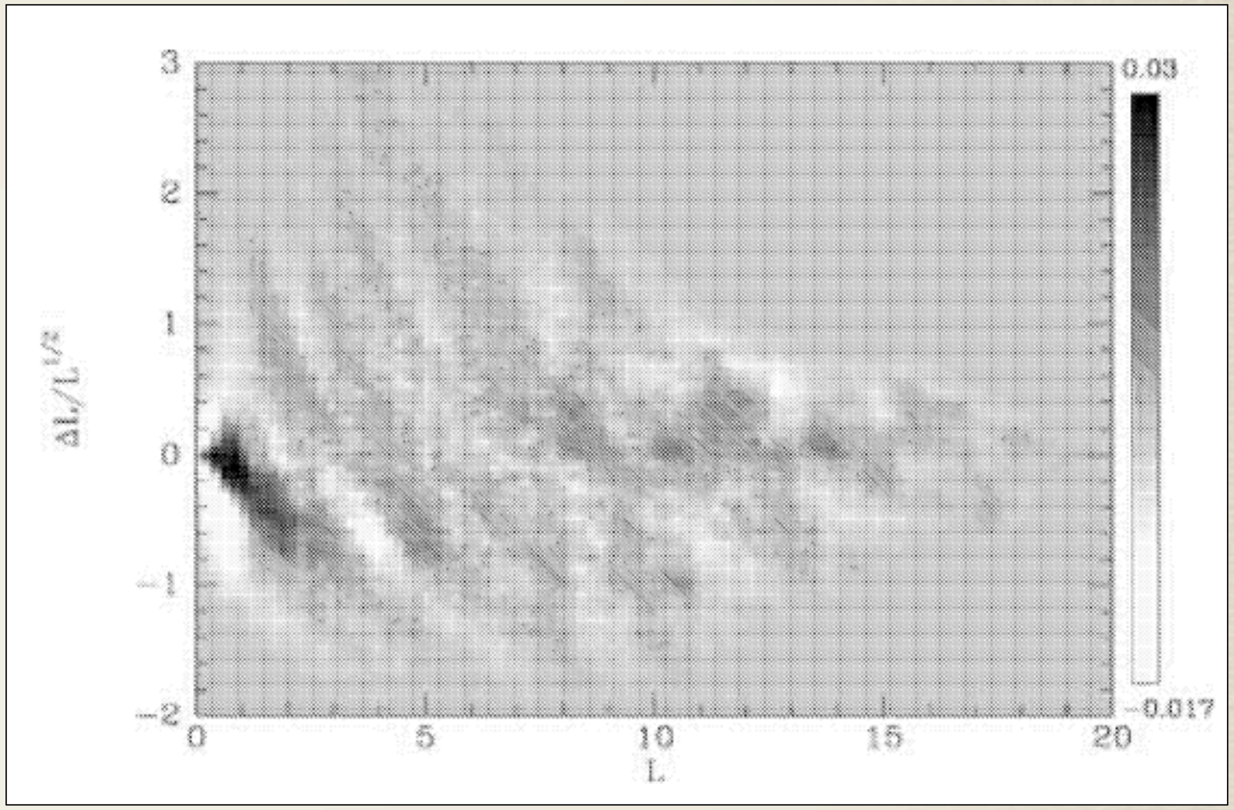


- Stars mix only near the corotation resonance of the Bar or Spirals (dotted lines).
- Not nearly enough to explain observations.

Mixing from Transient Spirals

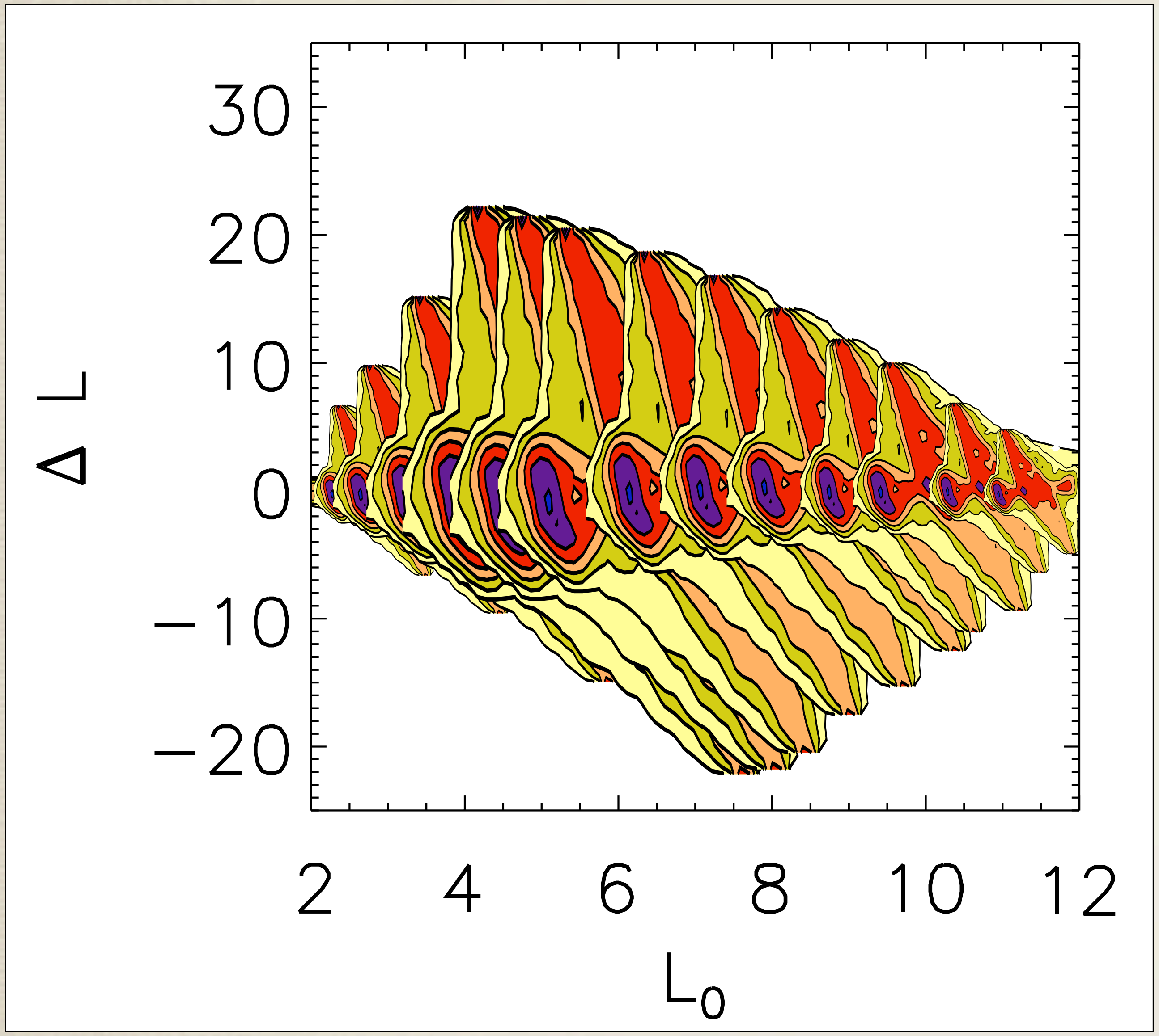
Corotation radii occurring at random ....

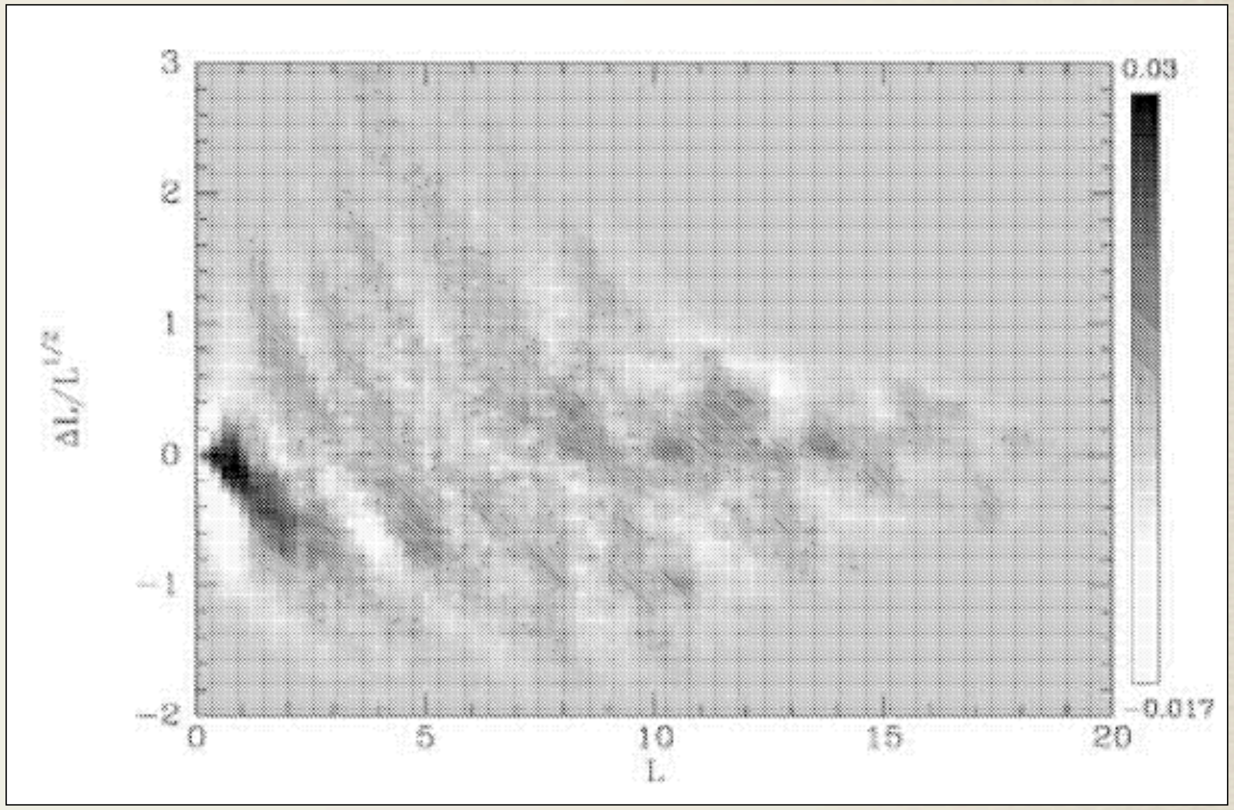




Sellwood & Binney (2002)

Mixing from Transient Spirals





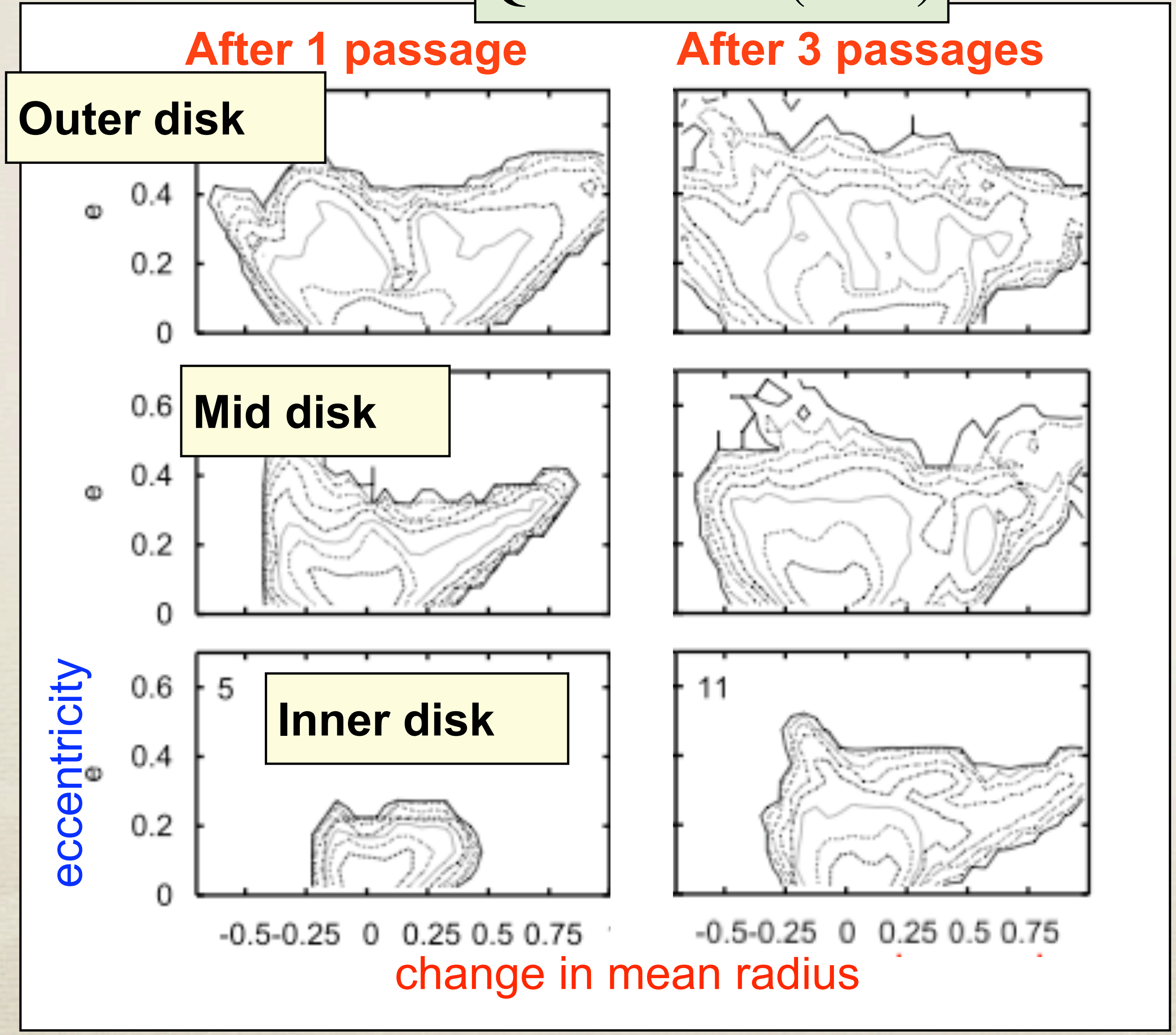
Sellwood & Binney (2002)

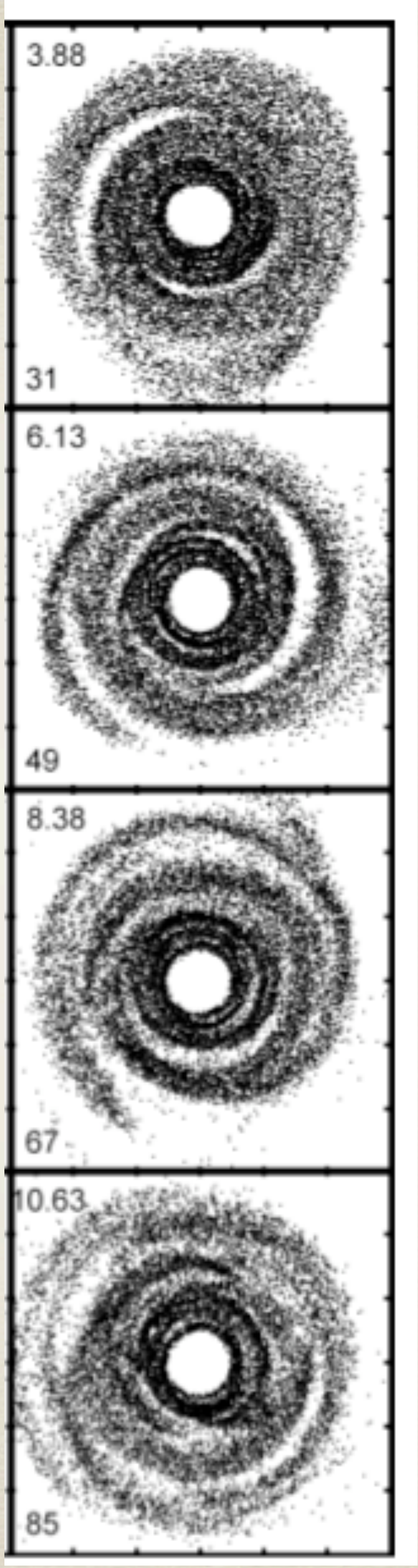
Requires ~9 Gyr for sufficient mixing

Mixing from small satellites

- **Mixing** in the outer disk caused by multiple perturbations from a low mass satellite galaxy

Quillen et al. (2009)





Why should we expect that resonance overlap can produce mixing

Hamiltonian including two perturbations

Third-order, post-epicyclic approximation

$$H_0(I_1, \theta_1; I_2, \theta_2) = aI_1^2 + 2bI_1I_2 + cI_2^2 + \kappa I_1 + \Omega I_2 + ...$$

Contopoulos (1975, 1988)

$$H(I_1, \theta_1; I_2, \theta_2) \approx H_0 +$$

$$\epsilon_b I_1^{1/2} \cos[\theta_1 + 2(\theta_2 - \Omega_b t)] +$$

Perturbation from Bar

$$\epsilon_s I_1^{1/2} \cos[\theta_1 - m(\theta_2 - \Omega_s t) - \gamma]$$

Perturbation from Spiral

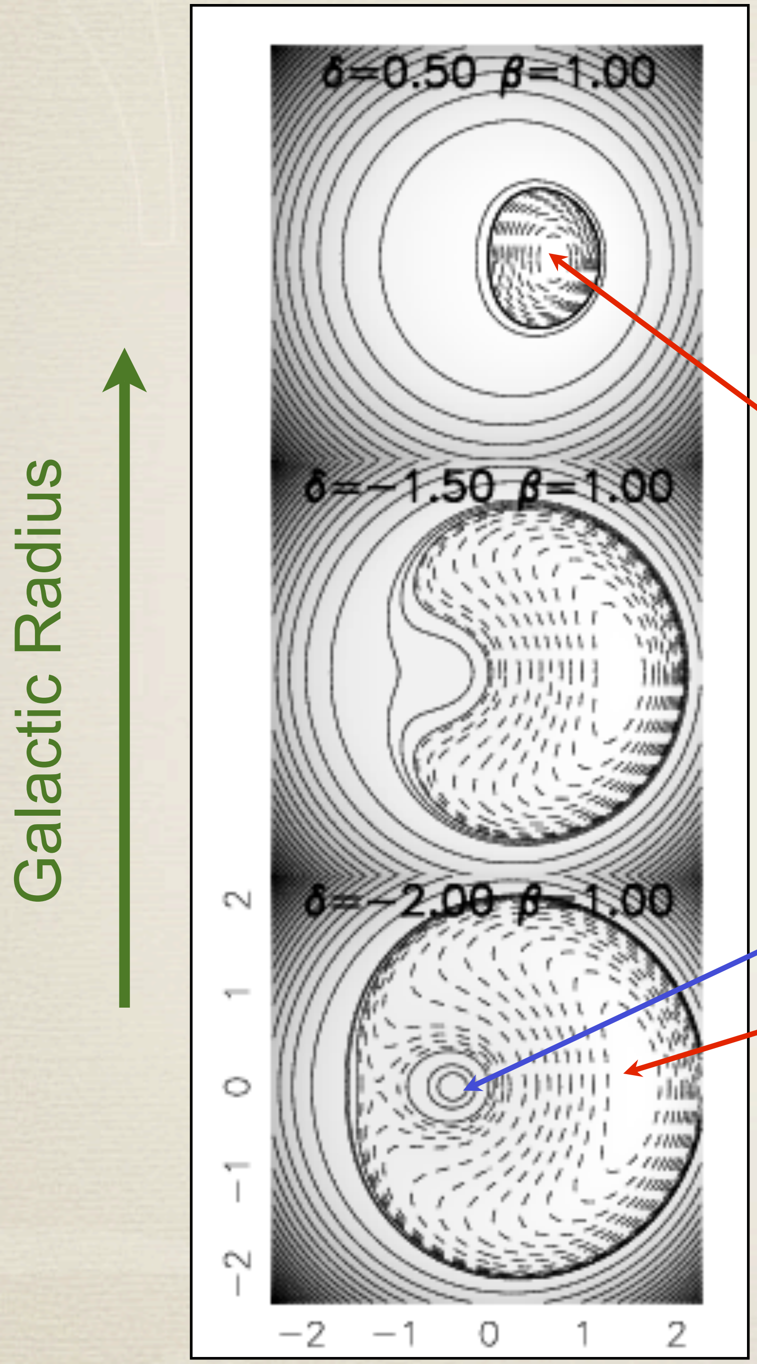
After a canonical transformation with a resonant angle $\phi = \theta_1 \pm m(\theta_2 - \Omega_p t)$

$$H(J_1, \phi) \approx aJ_1^2 + \delta J_1 + \beta J_1^{1/2} \cos(\phi) + \epsilon J_1^{1/2} \cos(\phi + \nu t - \gamma)$$

This is time independent and J_2 is conserved

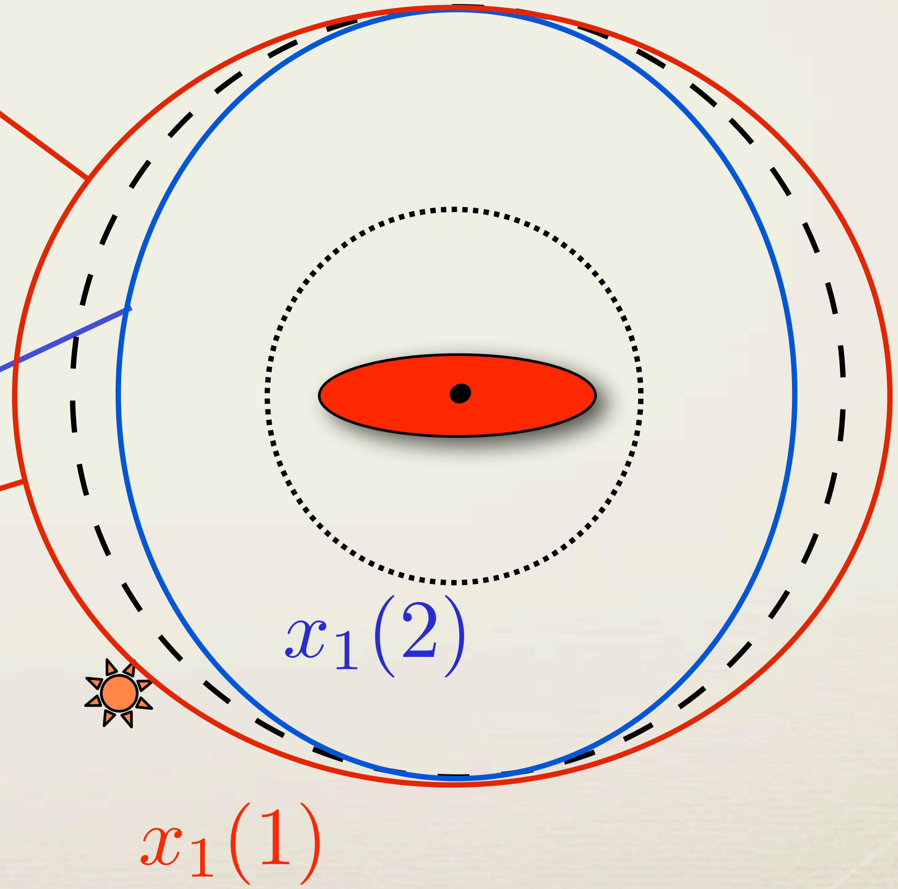
First order Lindblad Resonances with the Bar

Hamiltonian description



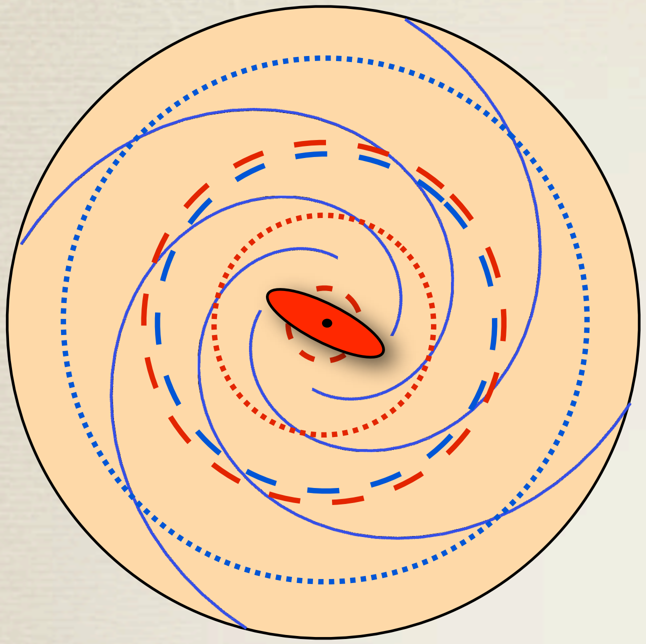
$$H(J_1, \phi) \approx aJ_1^2 + \delta J_1 + \beta J_1^{1/2}\cos(\phi)$$

$R = 2J_1$ Radius related to eccentricity



Closed orbits correspond to fixed points

Hamiltonian including two perturbations:
Analogy to the forced pendulum



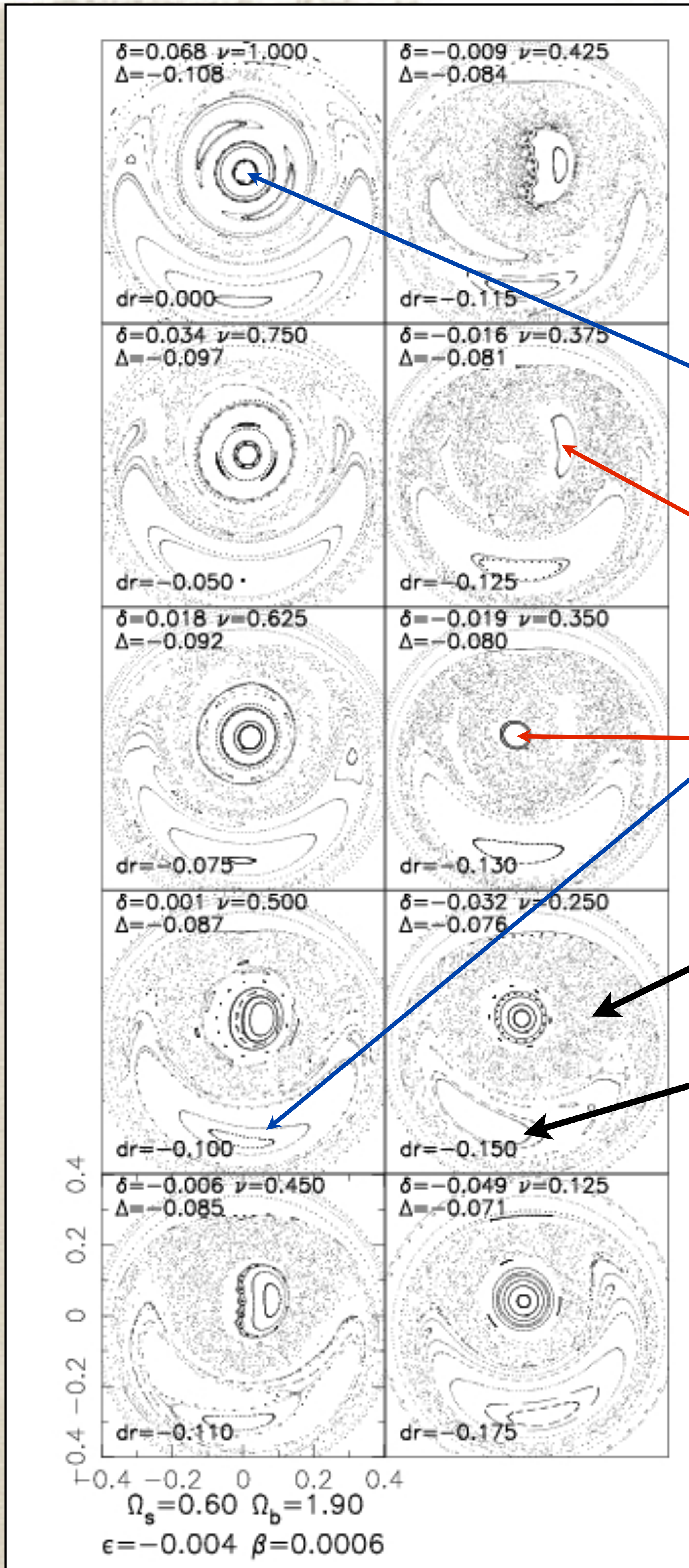
Strength of first perturbation

Strength of second perturbation

$$H(J_1, \phi) \approx aJ_1^2 + \delta J_1 + \beta J_1^{1/2} \cos(\phi) + \epsilon J_1^{1/2} \cos(\phi + \nu t - \gamma)$$

Controls center of first resonance and depends on radius

Controls spacing between resonances and also depends on radius

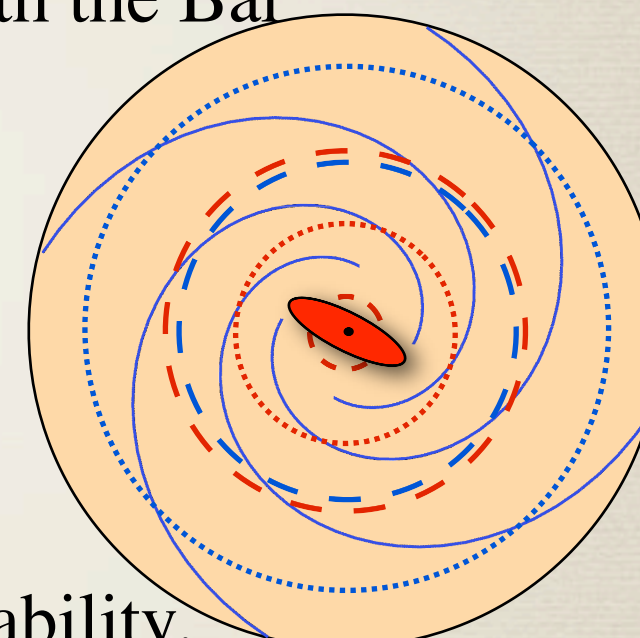


Spiral structure at the Bar's Outer Lindblad Resonance

- Oscillating primarily with spiral structure
- Perpendicular to Spiral Structure
- Oscillating primarily with the Bar
- Perpendicular to the bar

Area-filling orbits

Quasi-periodic orbits

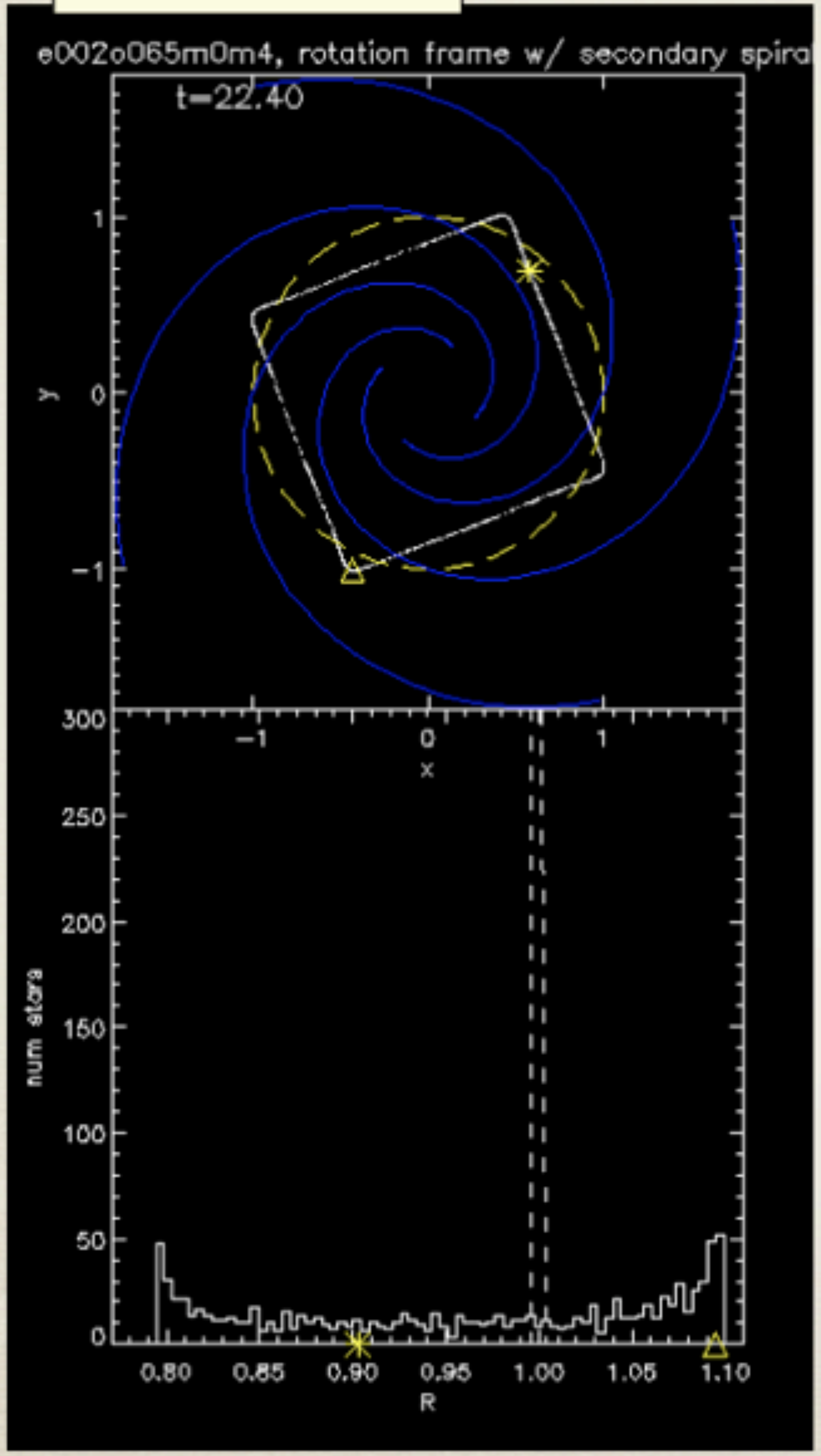


Poincare maps used to look at stability.
Plot every $\Delta t = \frac{2\pi}{\nu}$

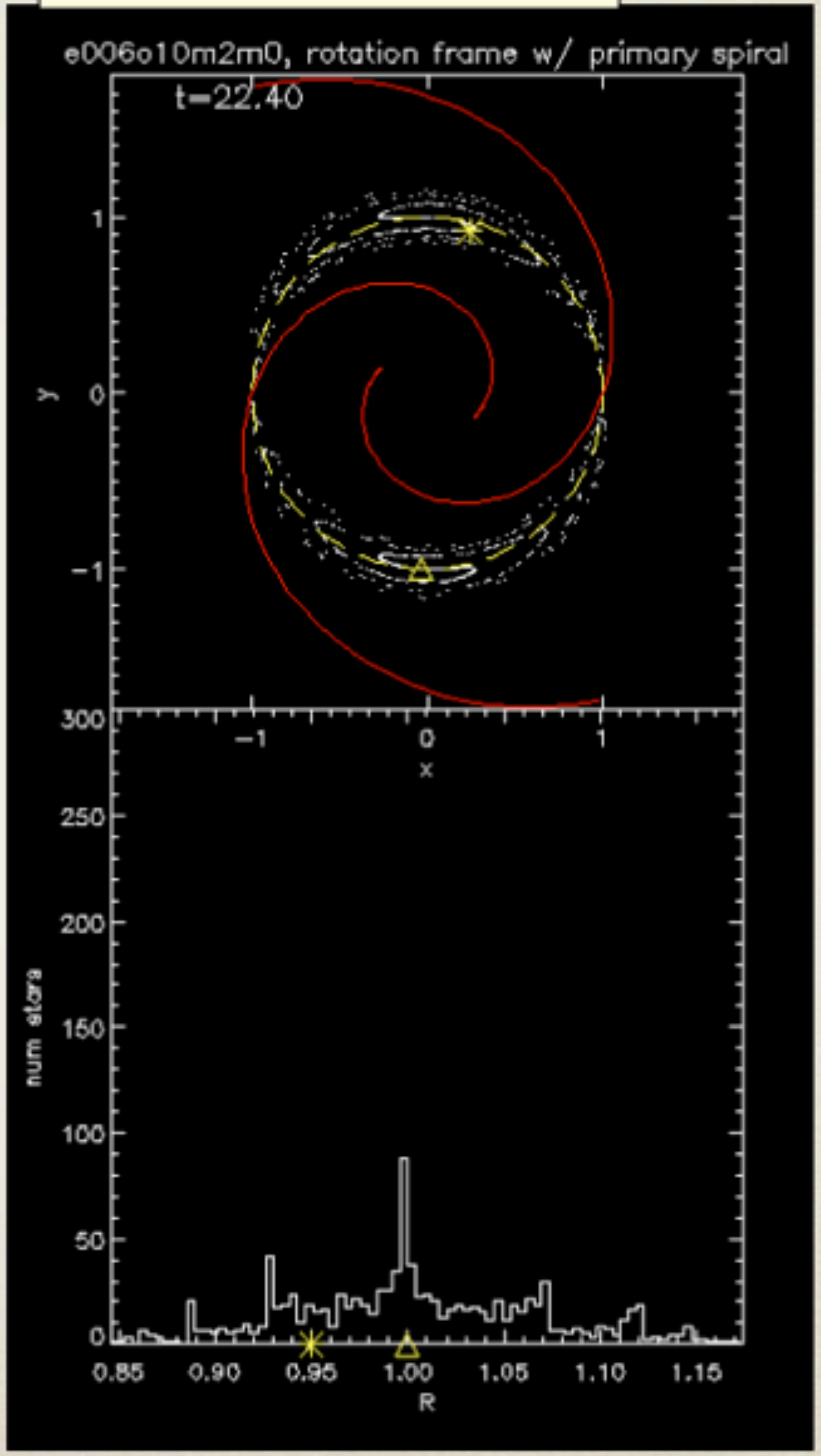
Orbits are either oscillating with both perturbations or are **Chaotic**: Induces **Heating** and **Migration** (Quillen 2003)

Radial migration at Corotation with Spiral

m=4 at OLR



m=2 at Corotation

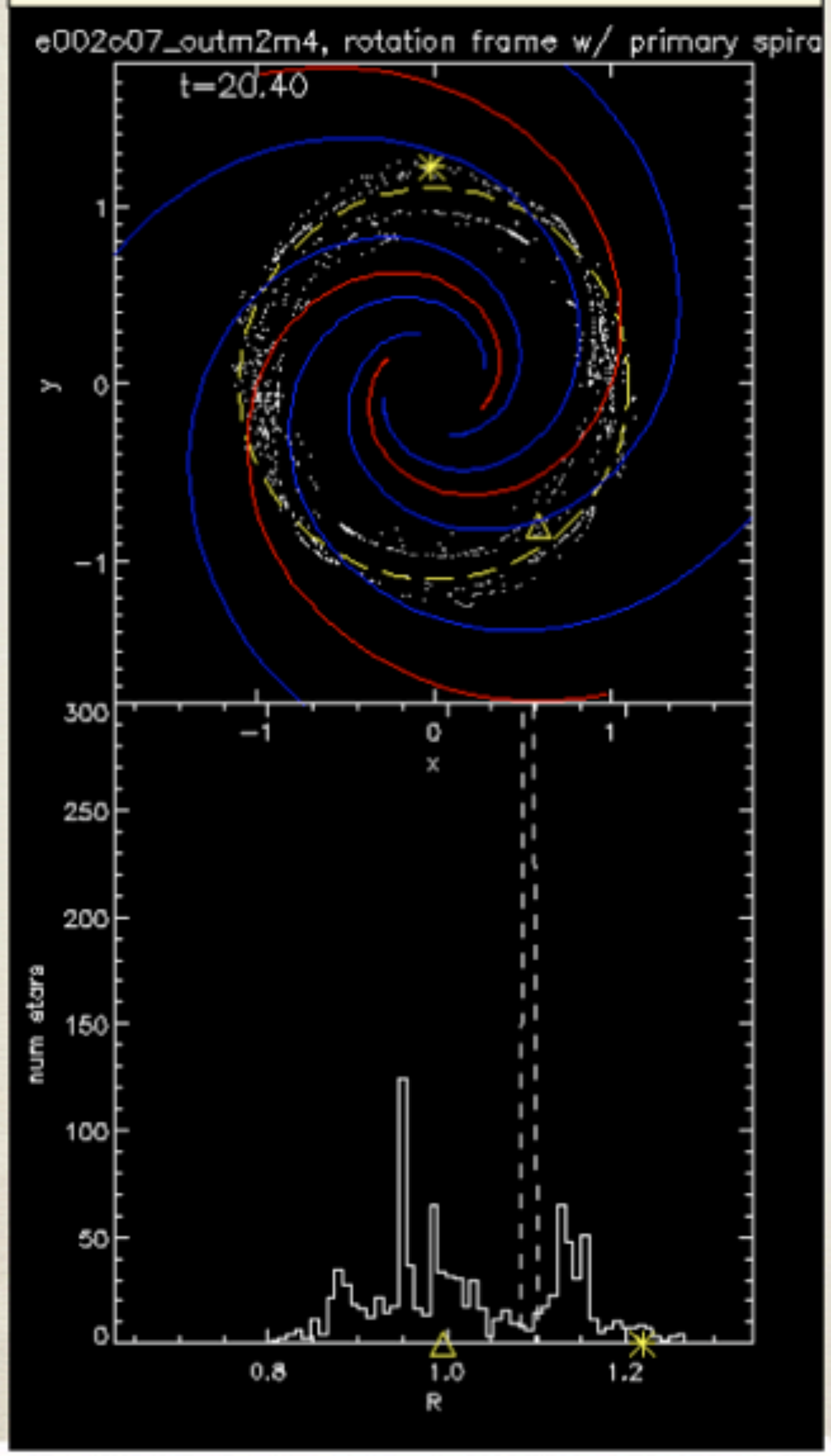


Two perturbers create stochastic regions

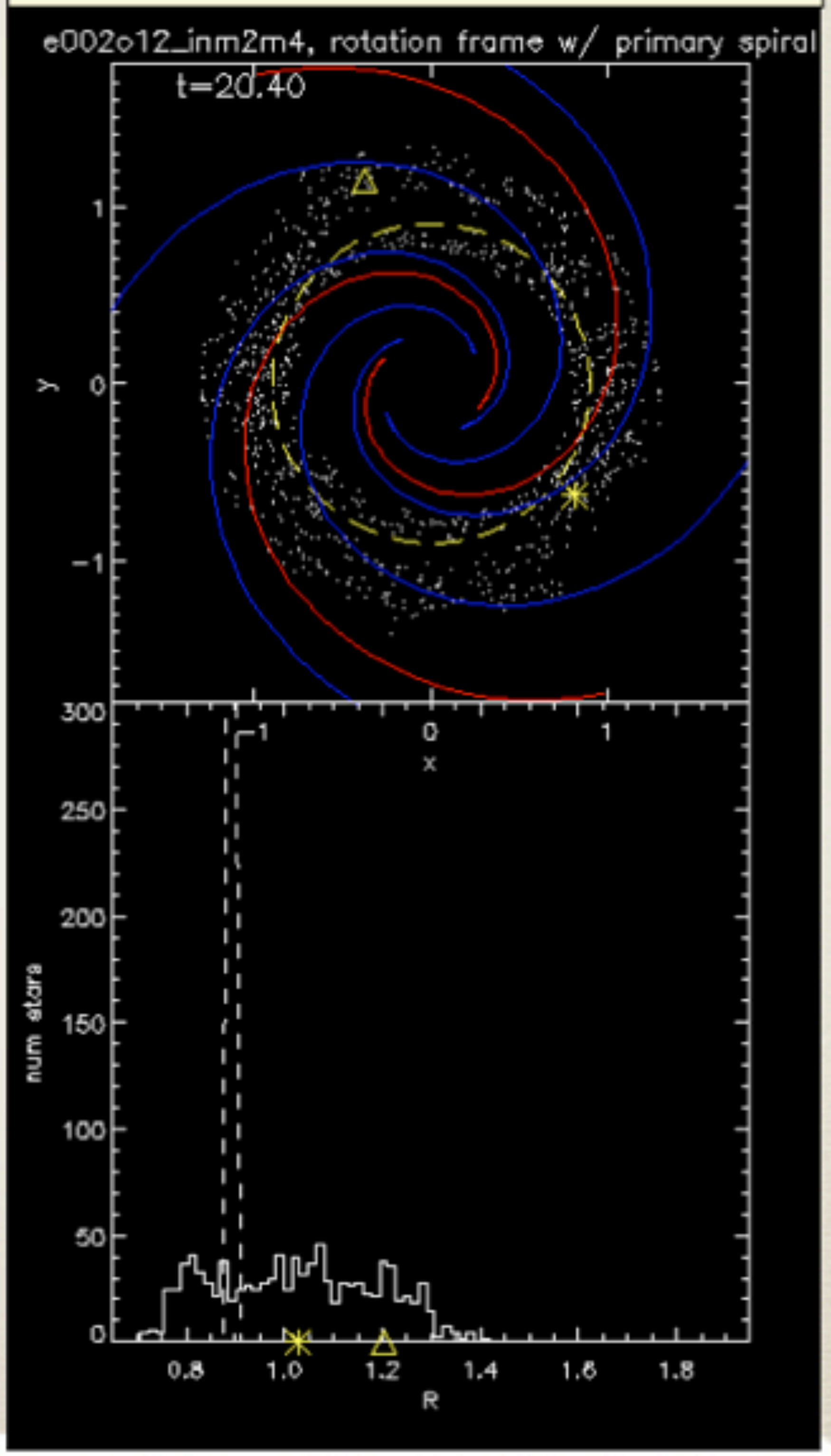
Multiple Spirals

Minchev & Quillen (2006)

m=4 just outside the ILR

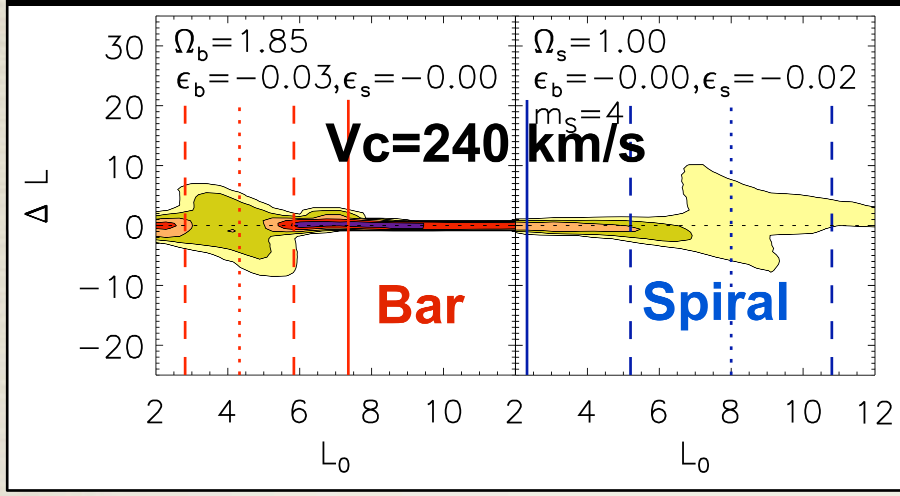


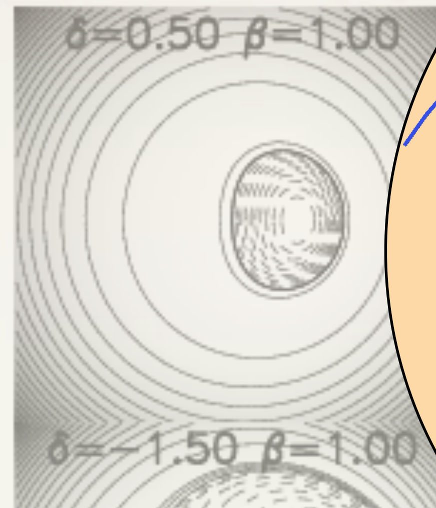
m=4 just inside the OLR

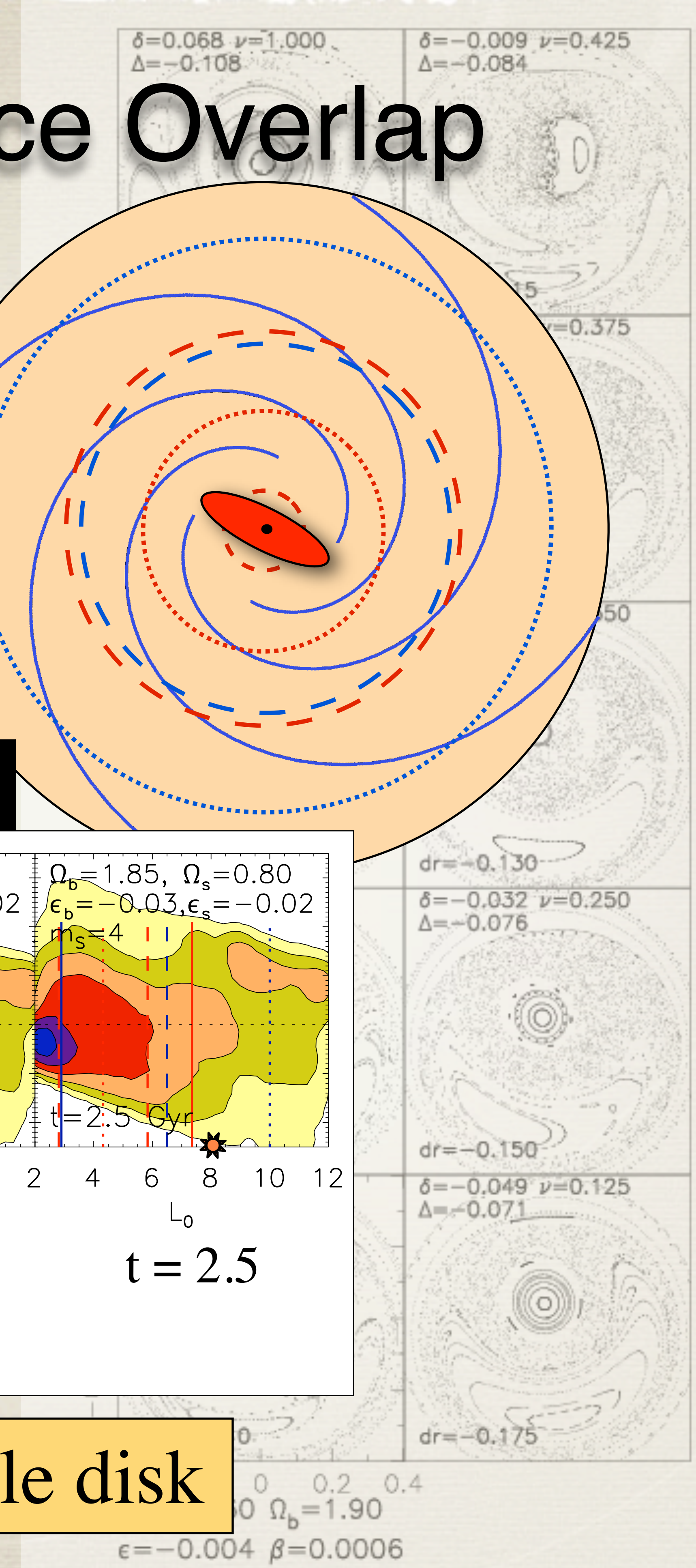


Migration due to Resonance Overlap

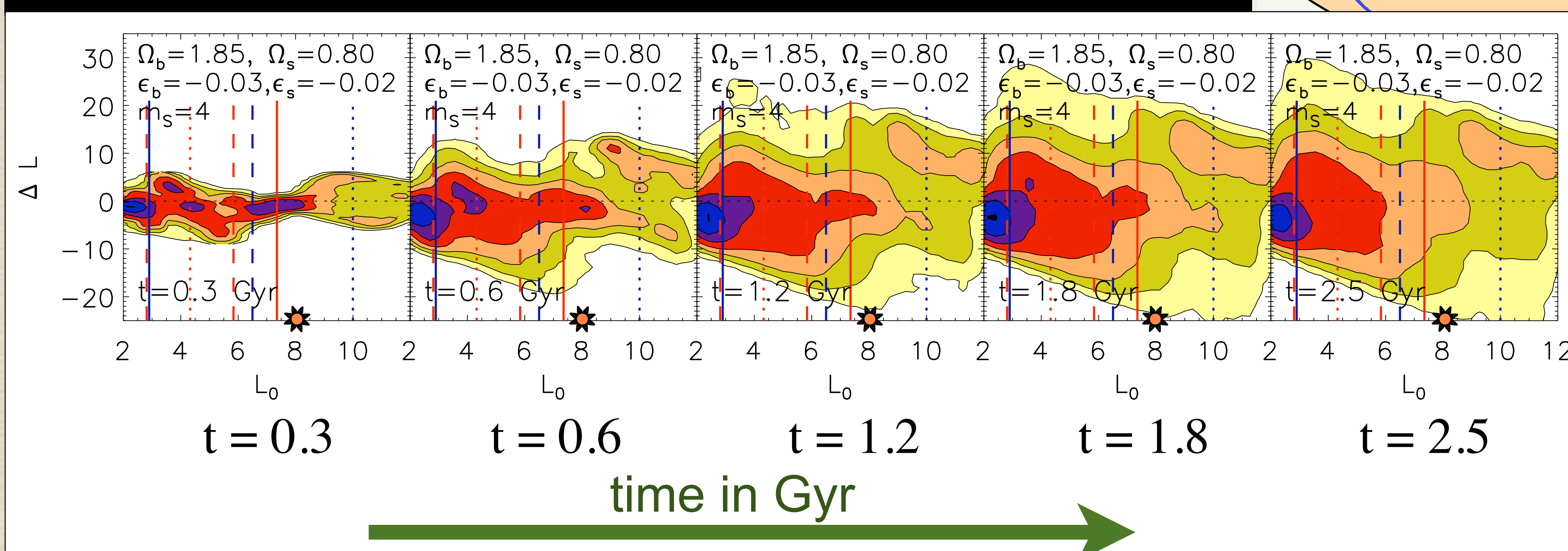
Single Perturber: No variation with time





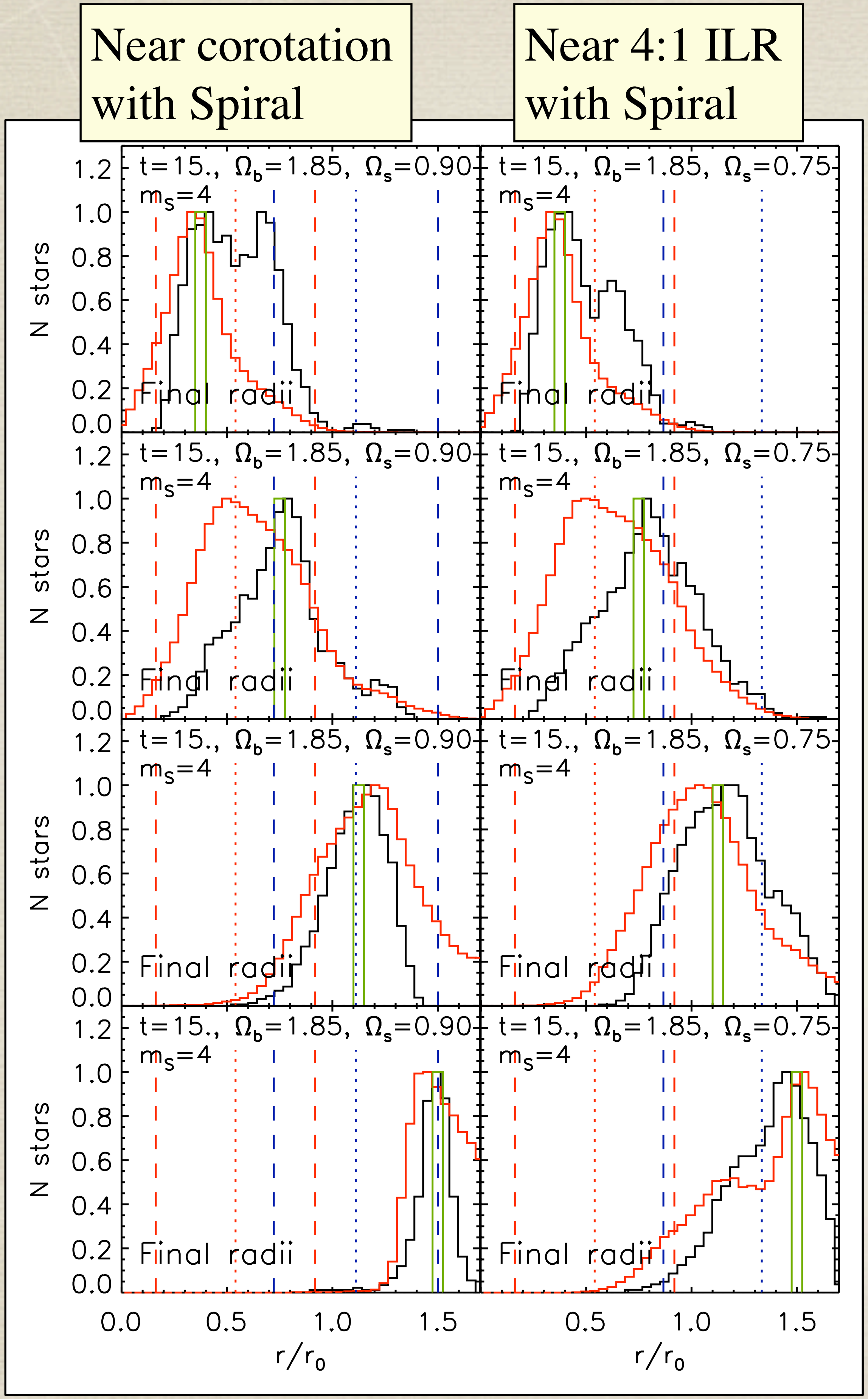


Bar + **Spiral Structure** propagating simultaneously



Stars migrate throughout the the whole disk

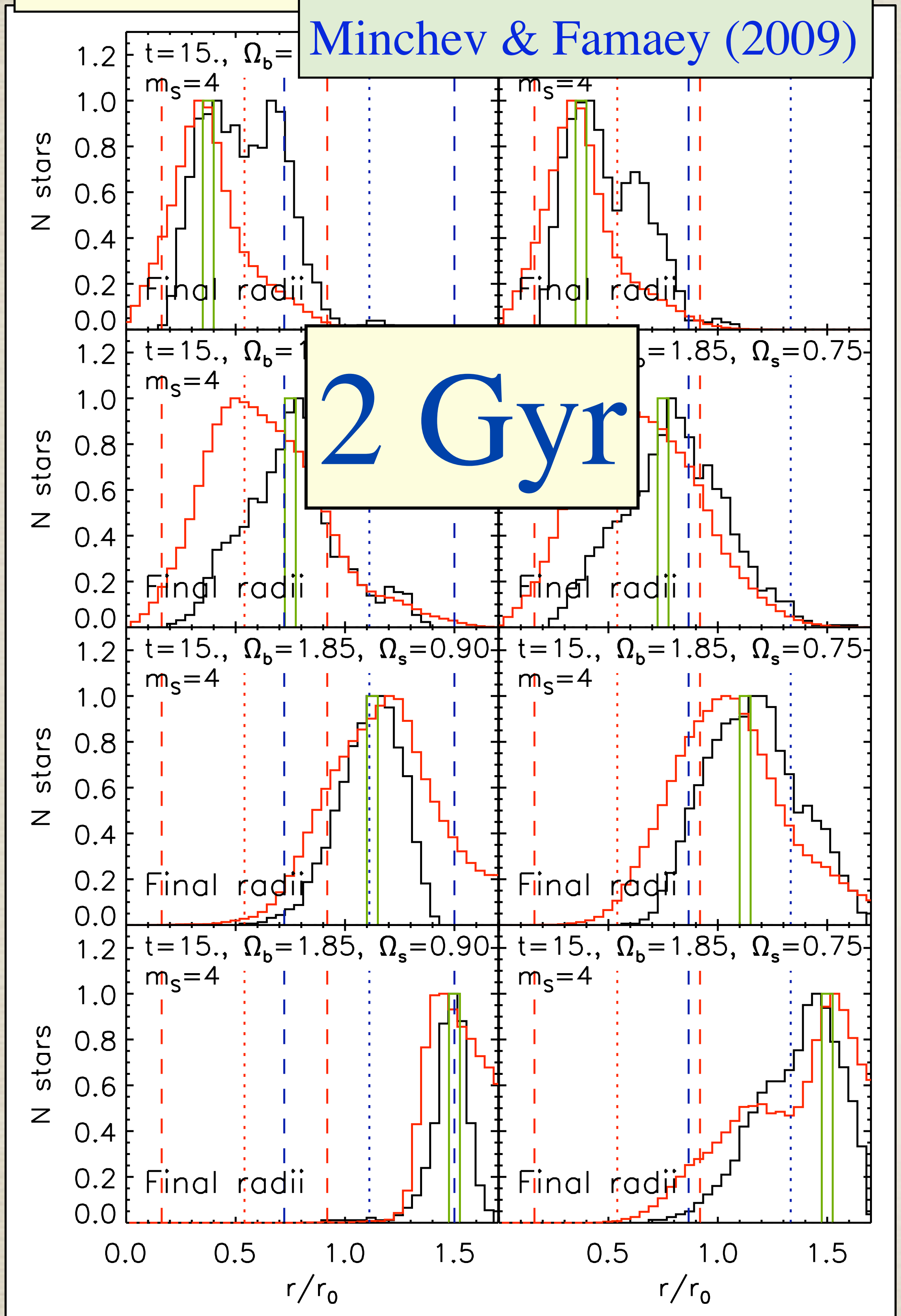
Mixing at different galactic radii



- Distribution of home radii at t ~ 2 Gyr of particles starting in the range indicated by the green lines (200 pc width).

Resonance Overlap

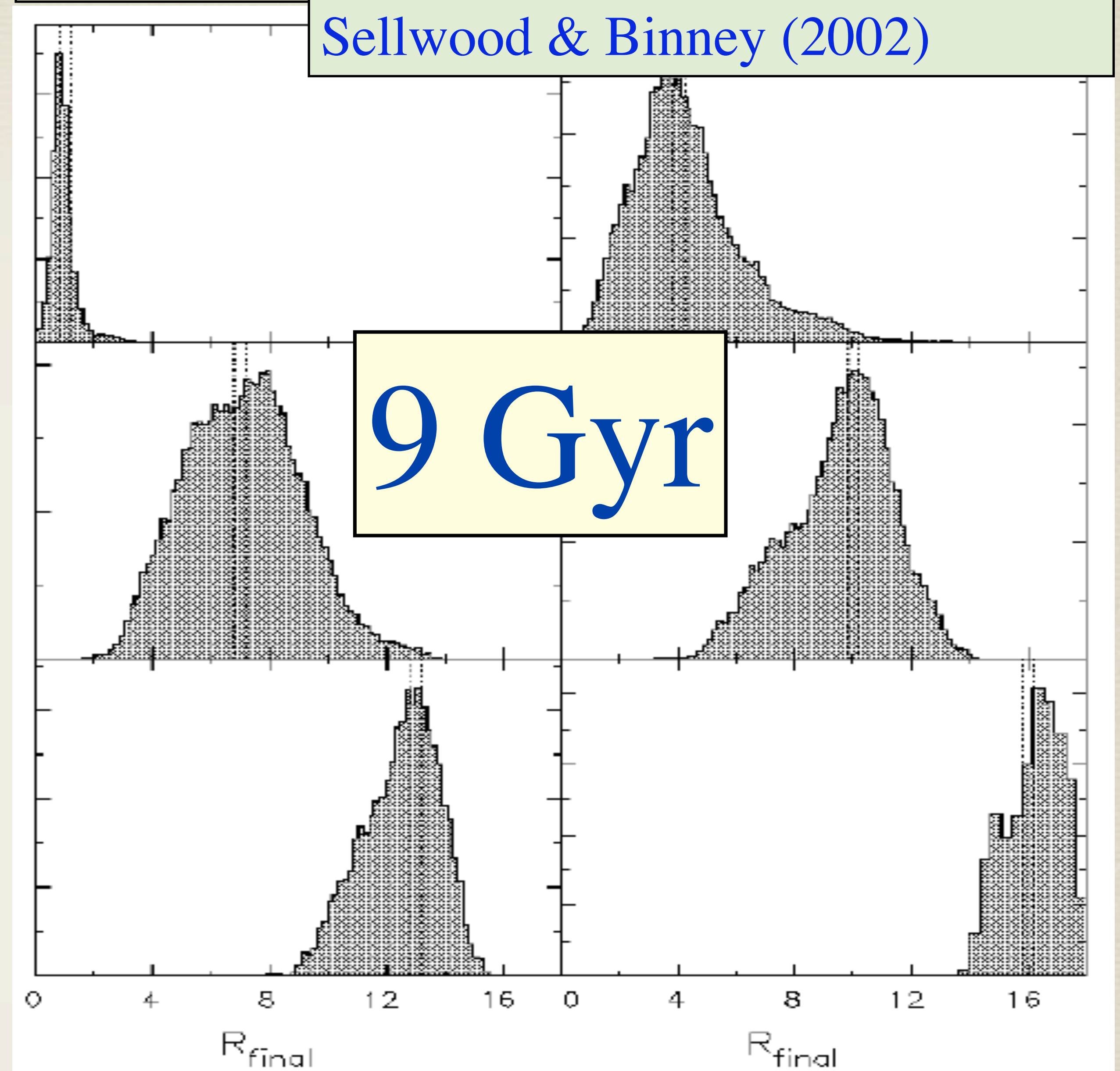
Minchev & Famaey (2009)



2 Gyr

Transient Spirals

Sellwood & Binney (2002)



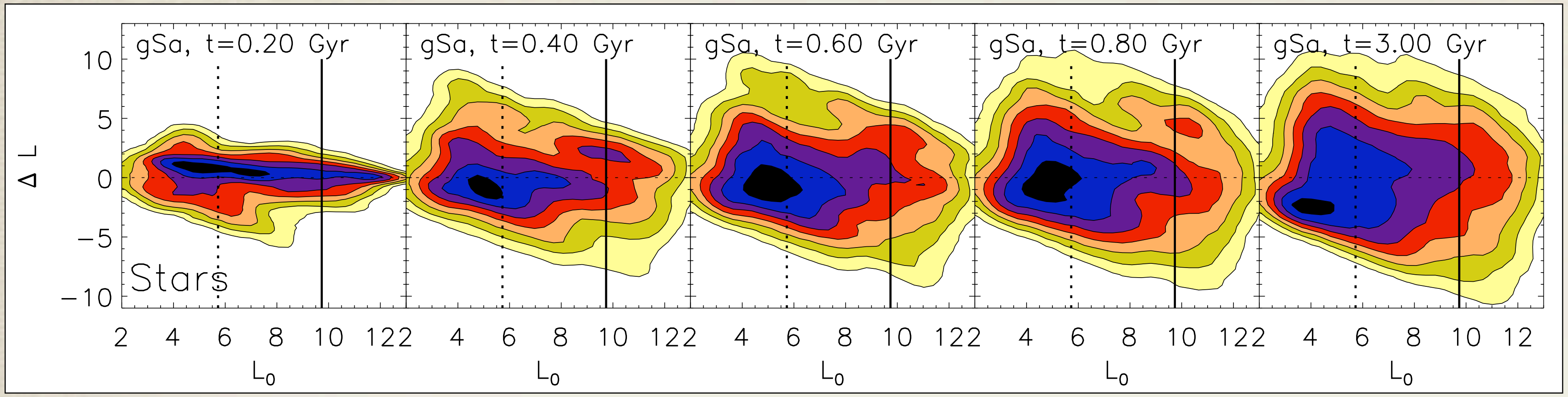
9 Gyr

Mixing by Resonance Overlap can be an order of magnitude more efficient than mixing by Transient Spirals.

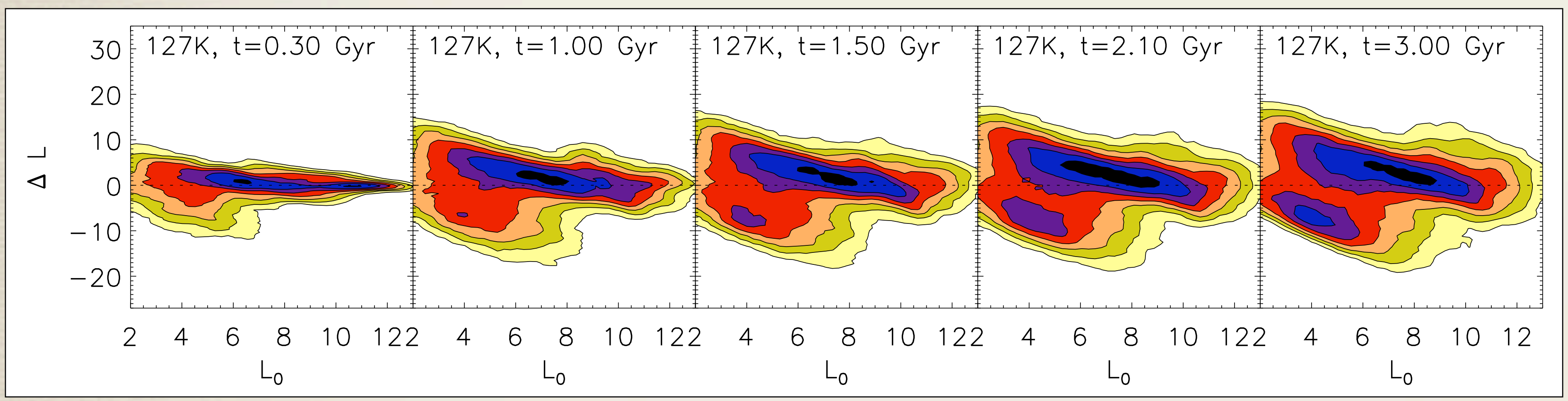
Migration from Resonance Overlap of Multiple Patterns

Confirmed in 3 independent simulation set-ups

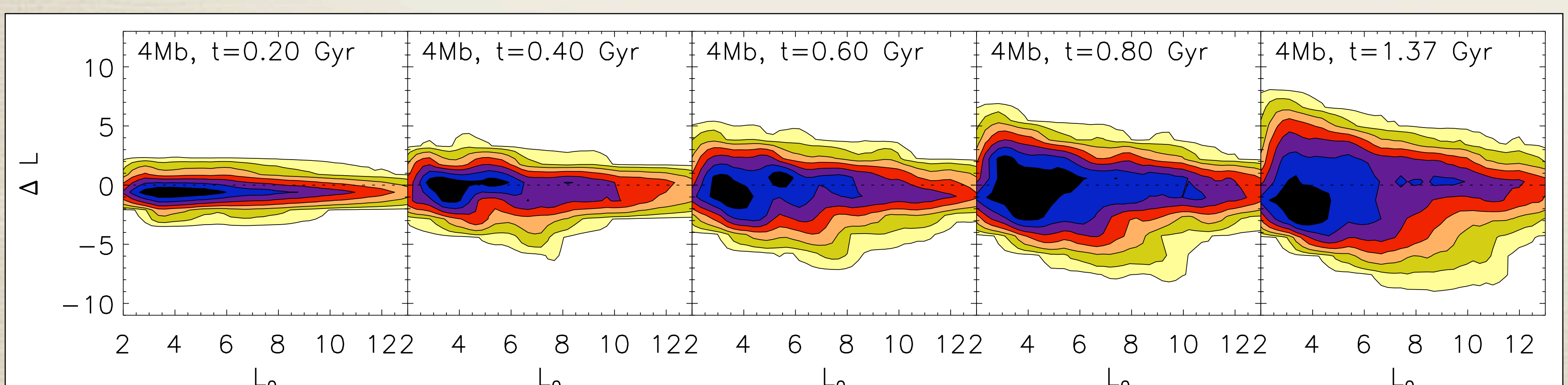
Minchev et al. (2010), arXiv:1006.0484



Tree-SPH, GalMer, Di Matteo et al. (2007)



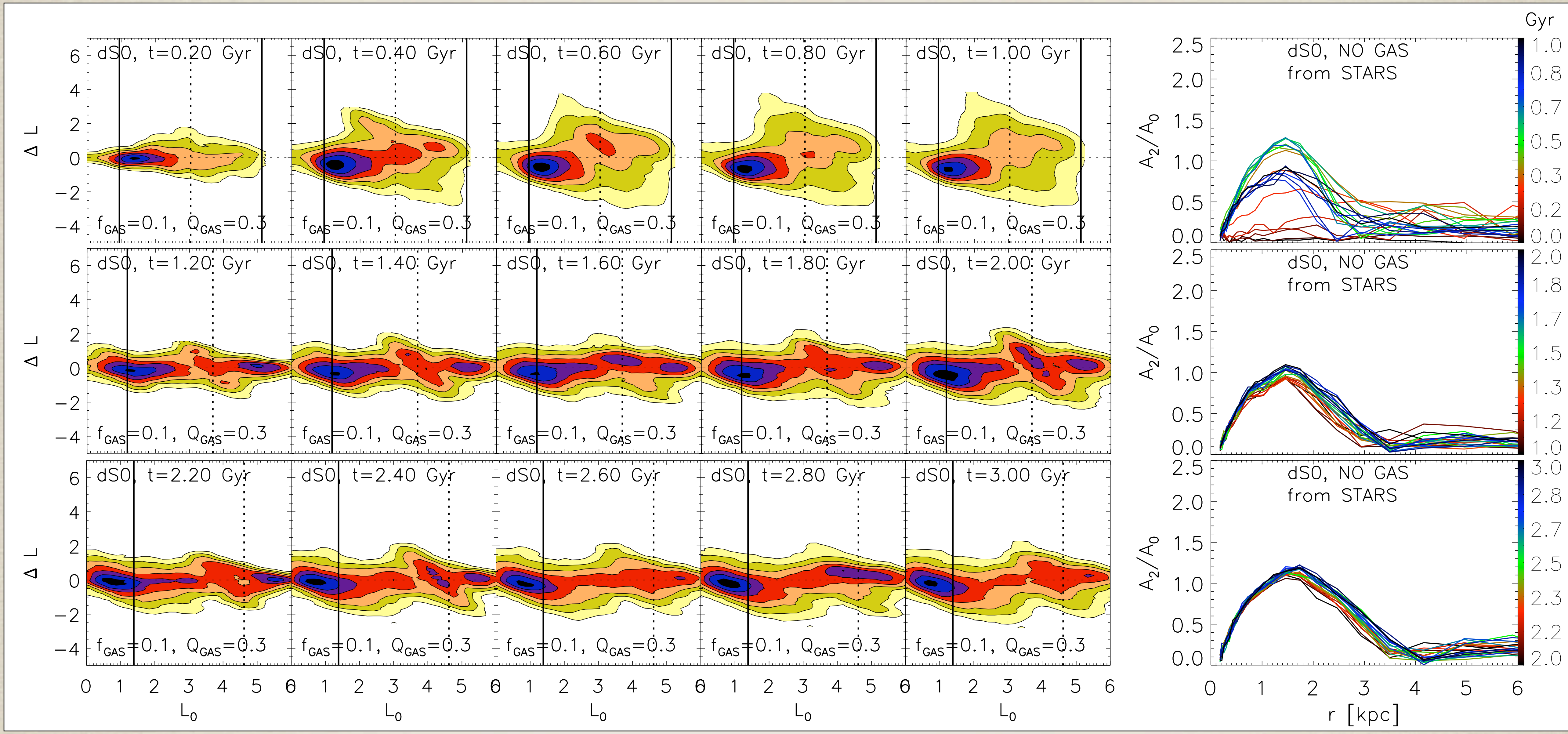
Particle-Mesh, Geneva Group code, Wozniak & Michel-Dansac (2009)



Direct N-body, phiGRAPE (Harfst, S. et al., 2006), Alice Quillen on GPU

Migration in Low-Mass galaxies

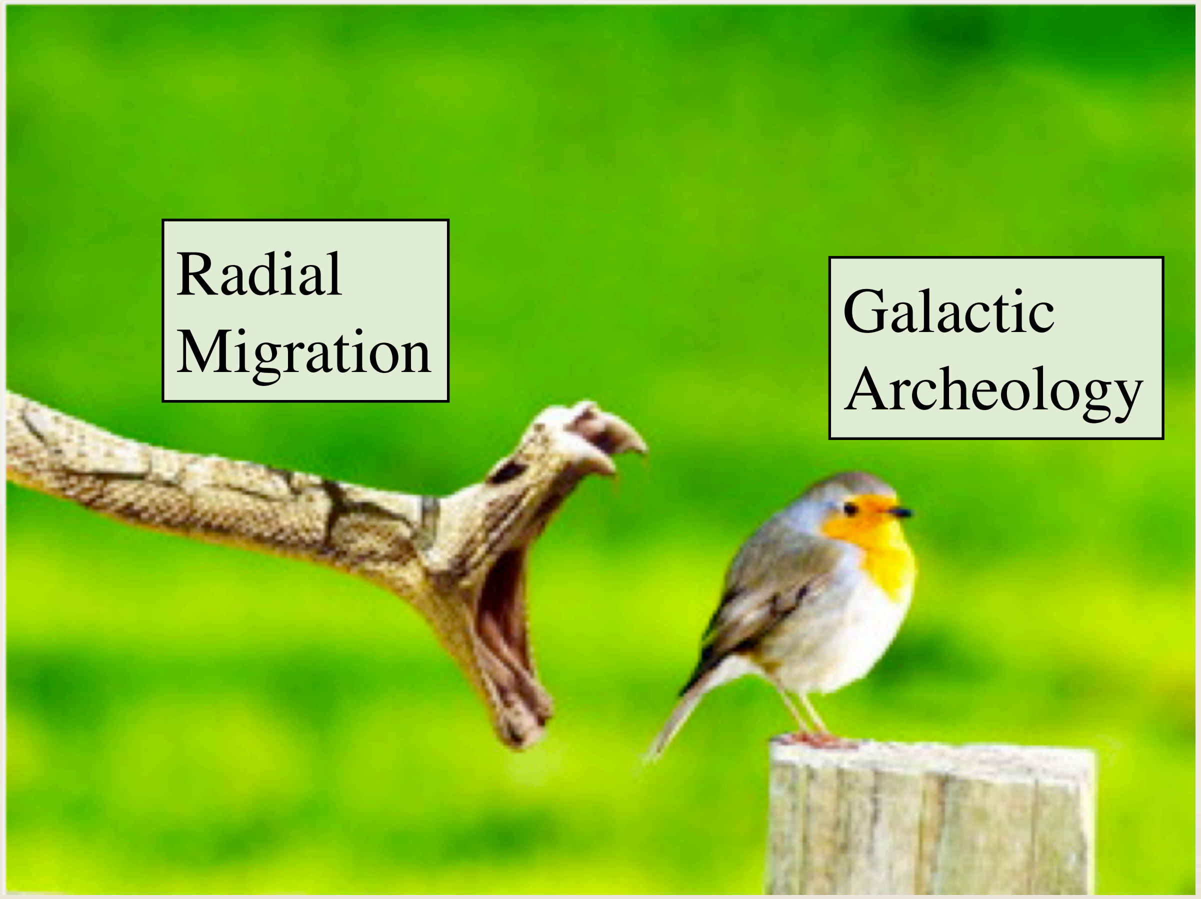
GalMer dwarf Sa model, Vc~100 km/s



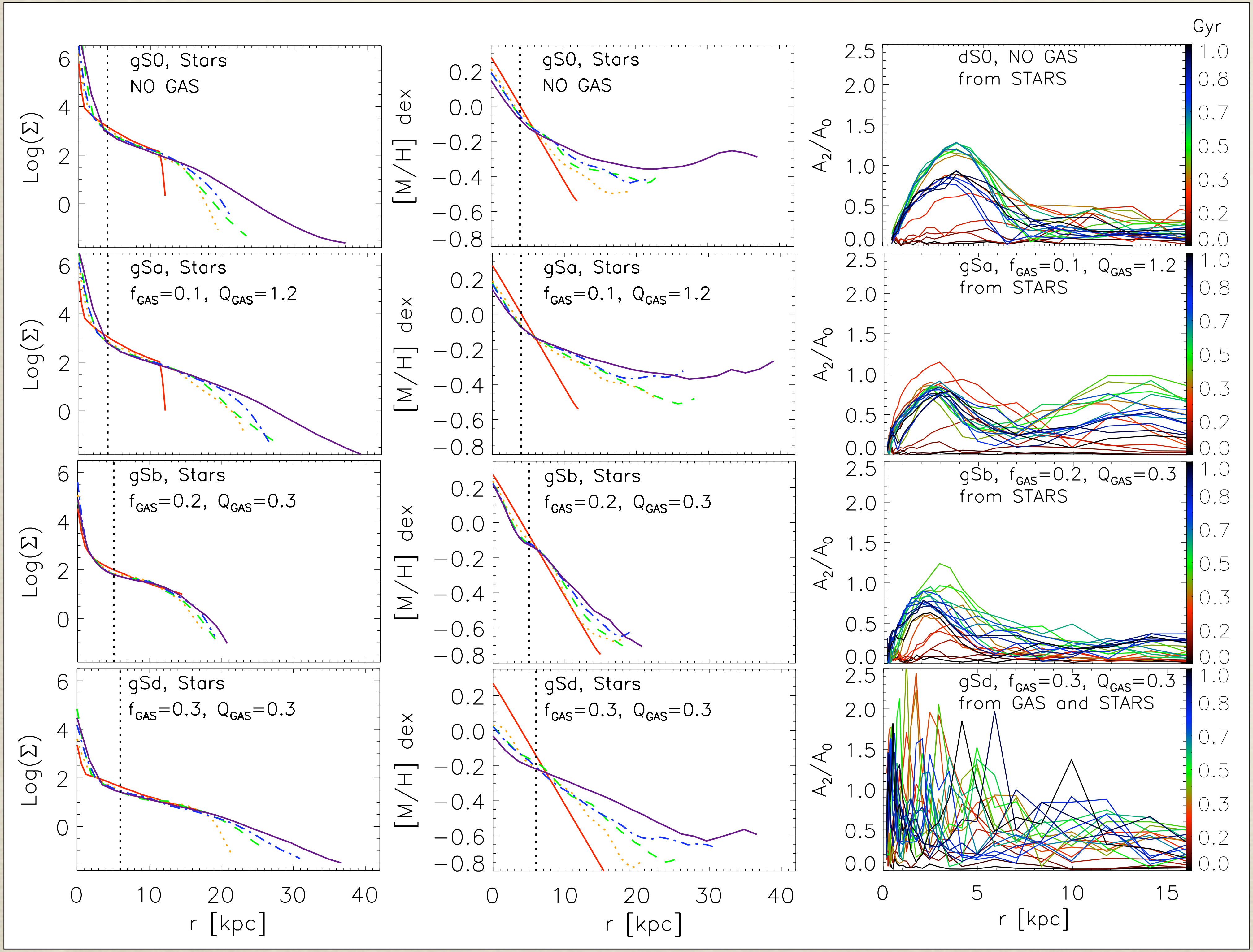
Dynamics in Low-mass galaxies

dominated by the Bar's Corotation?

Is this the end of Galactic Archeology

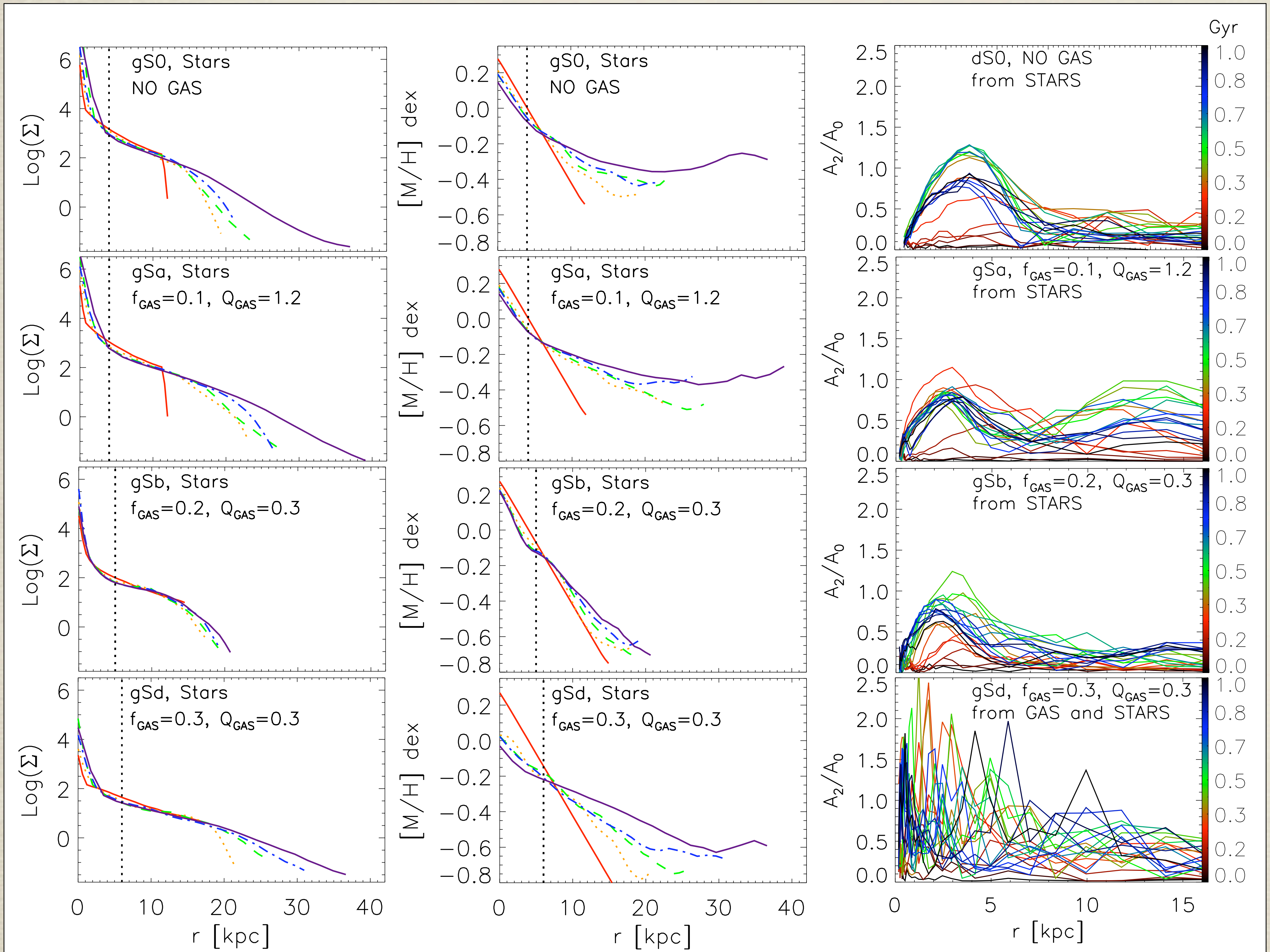


Extended disks in massive barred spirals, Vc~260 km/s



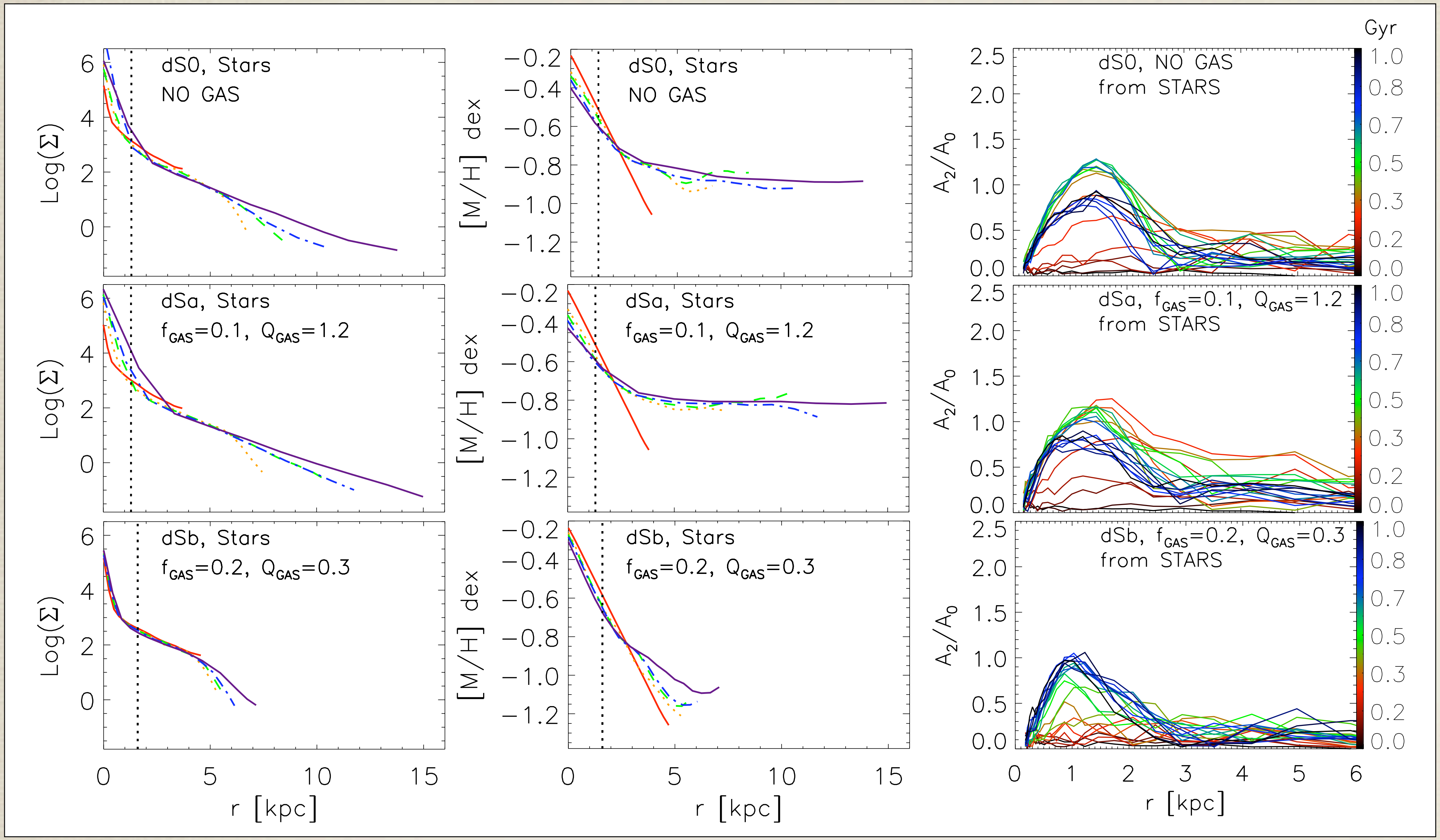
Multiple spirals

Extended disks in massive barred spirals, Vc~260 km/s



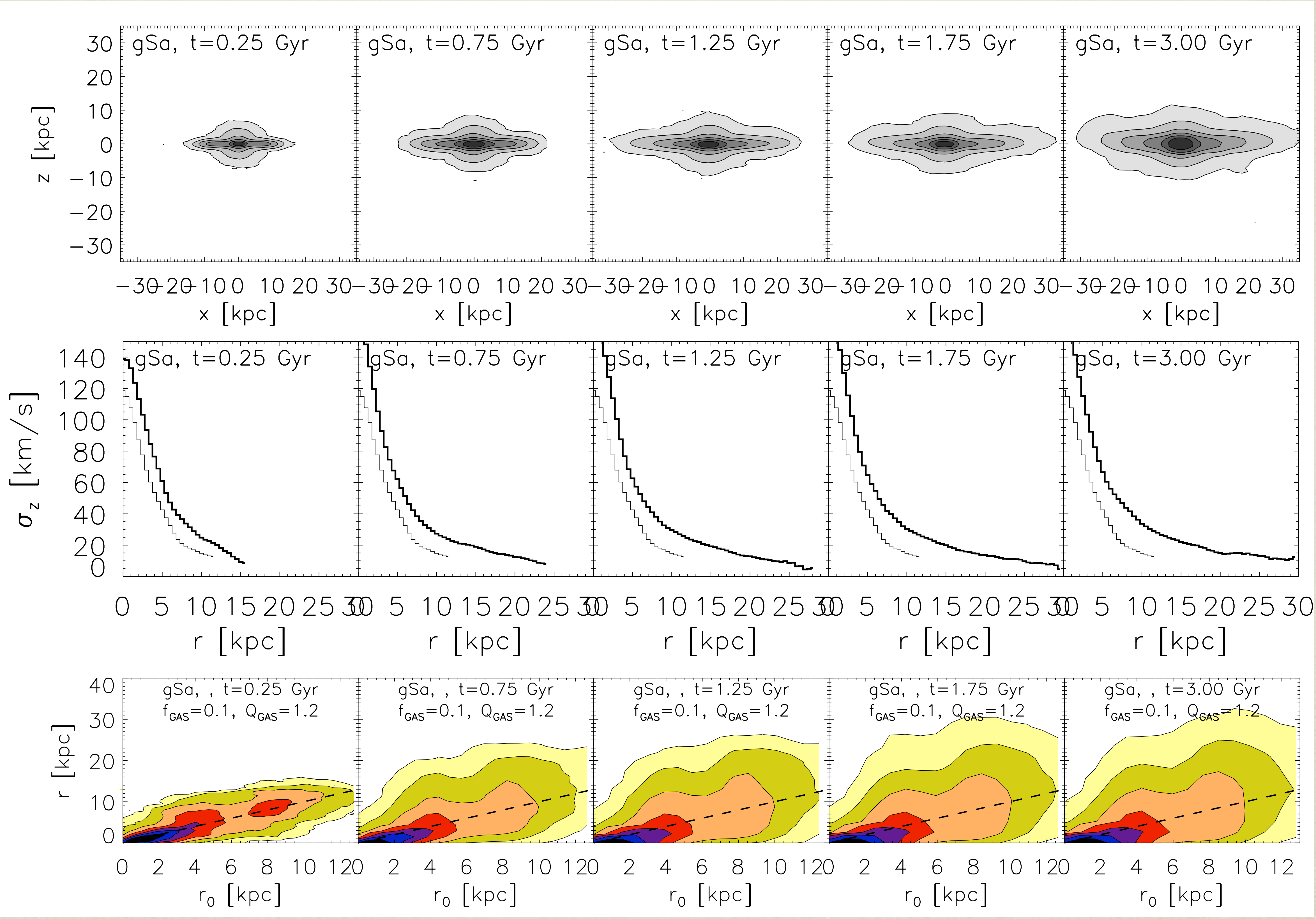
Multiple spirals

Extended disks in low-mass galaxies, Vc~100 km/s

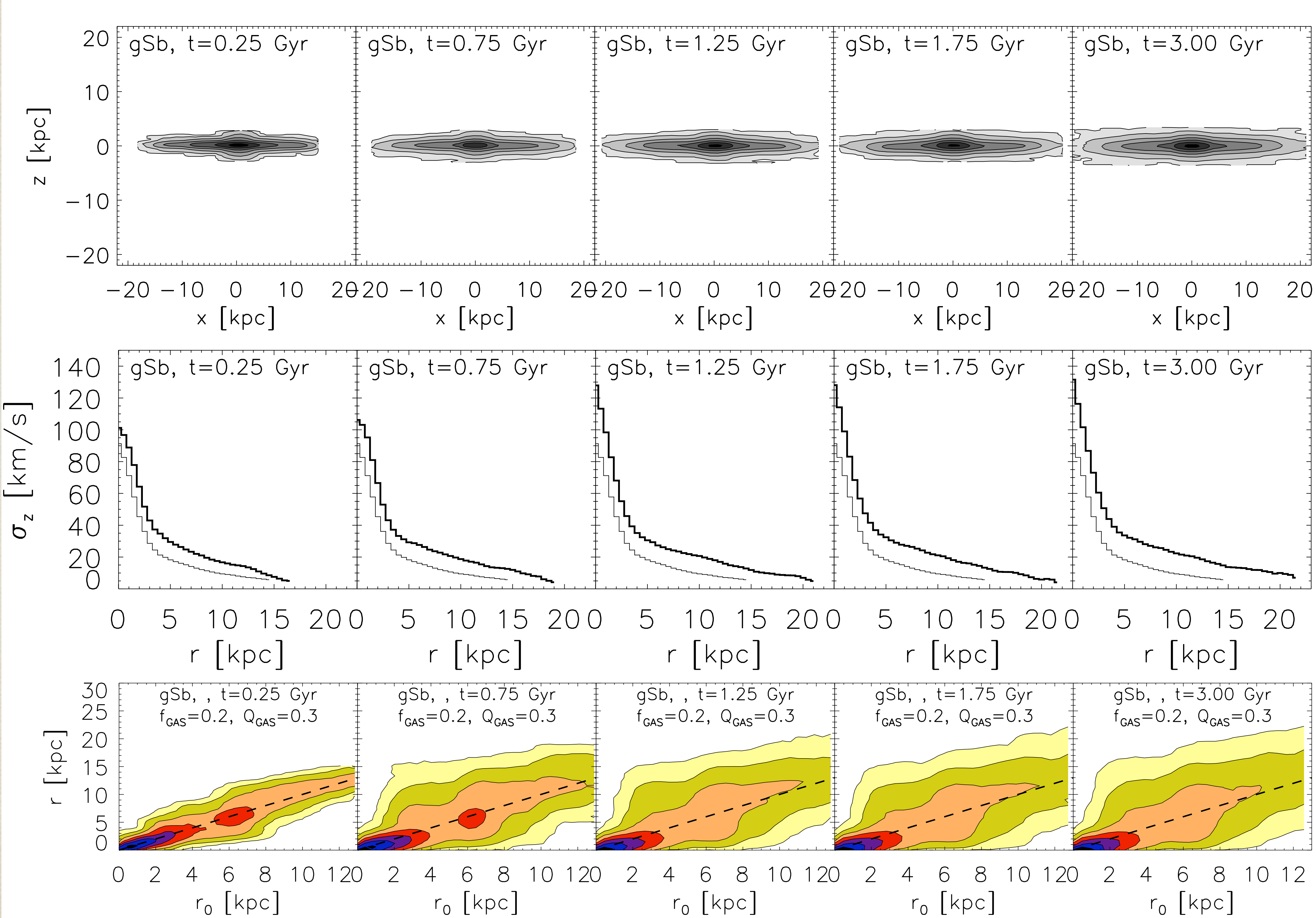


- NGC 300 and M33 had a central Bar?
- NGC 300 and M33 have/had multiple spirals?

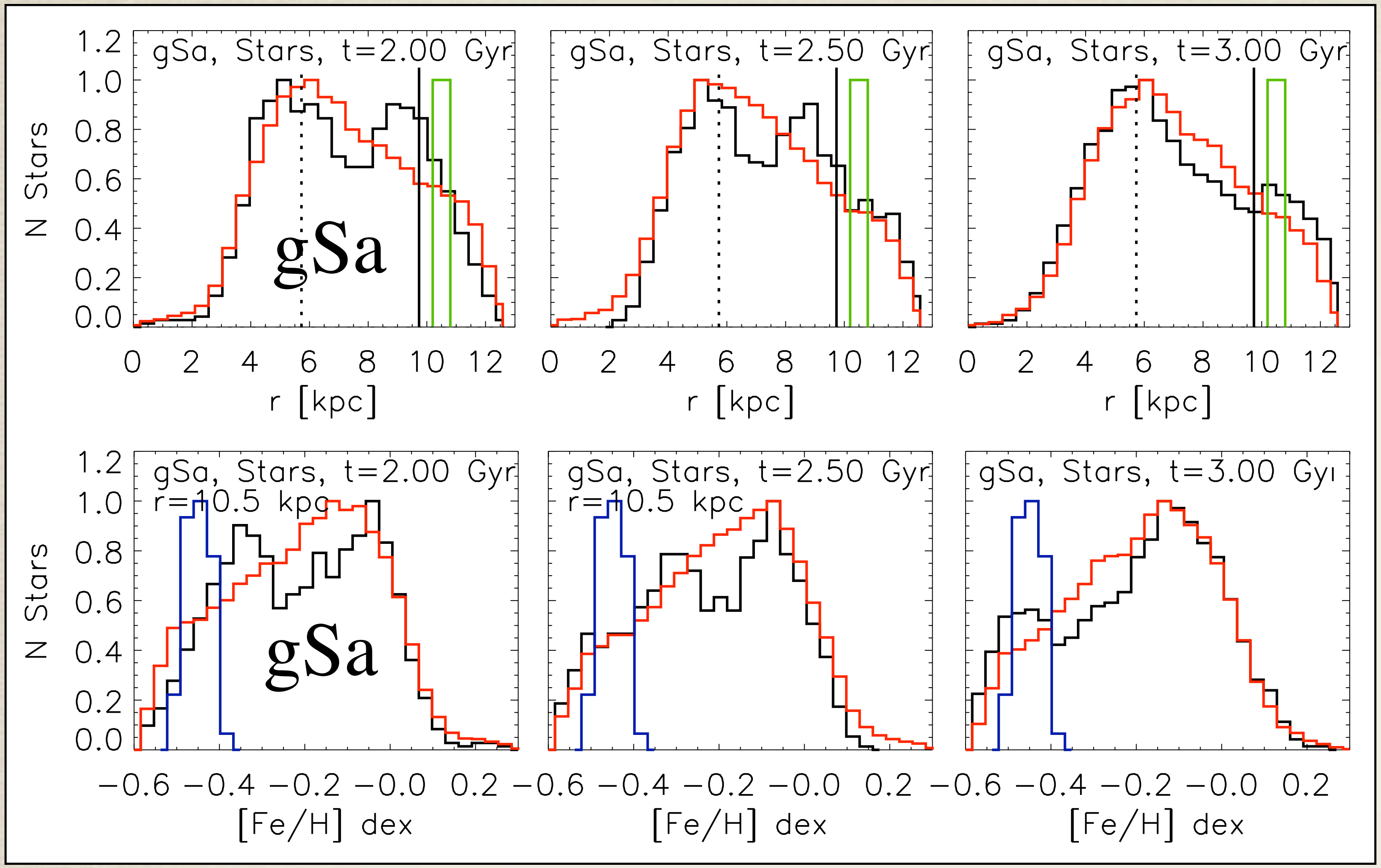
Formation of a thick disk, gSa



Formation of a thick disk, gSb



GalMer giant Sa model, Vc~260 km/s

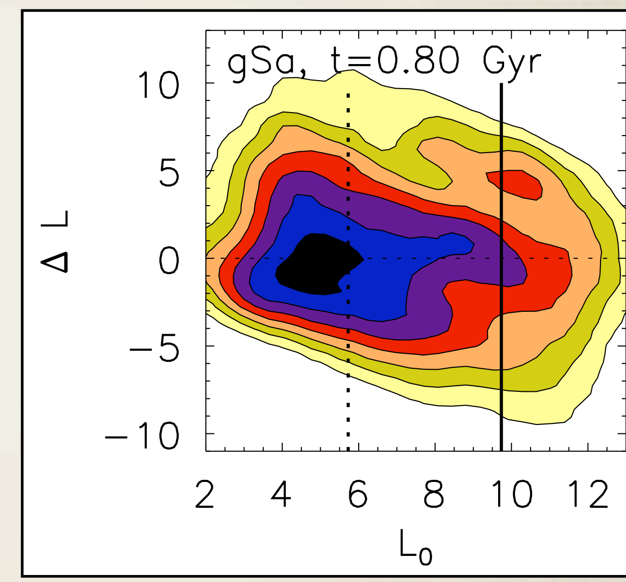


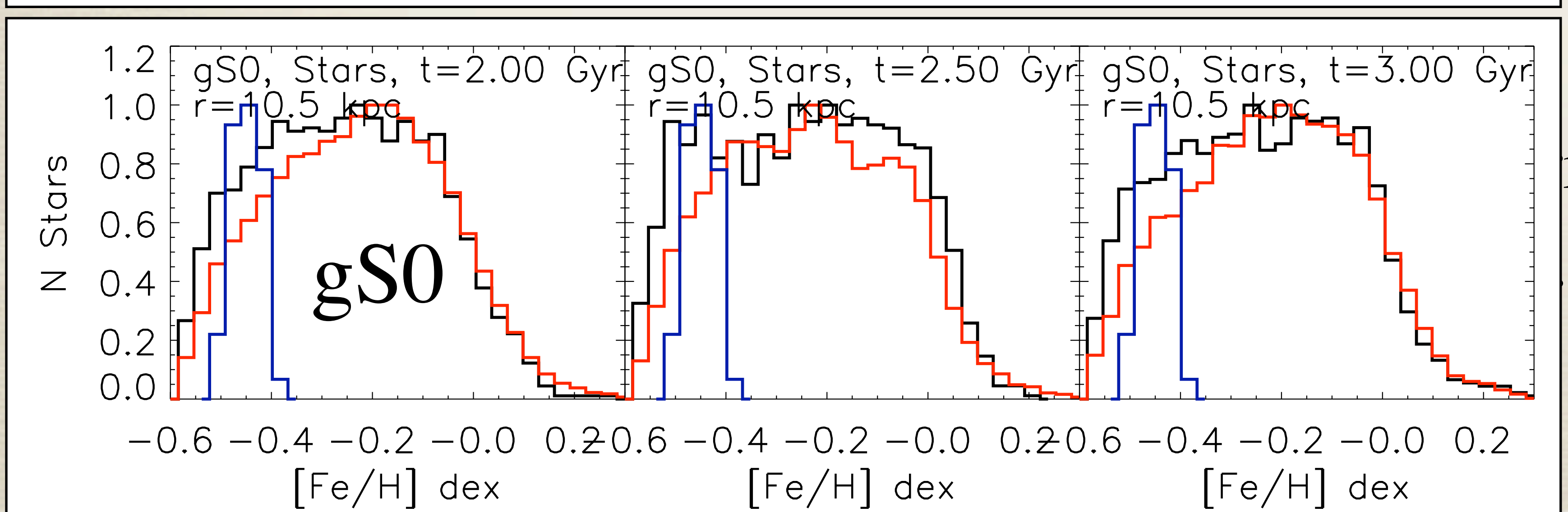
Radii Now

Cold orbits

Hot orbits

Initial metallicity





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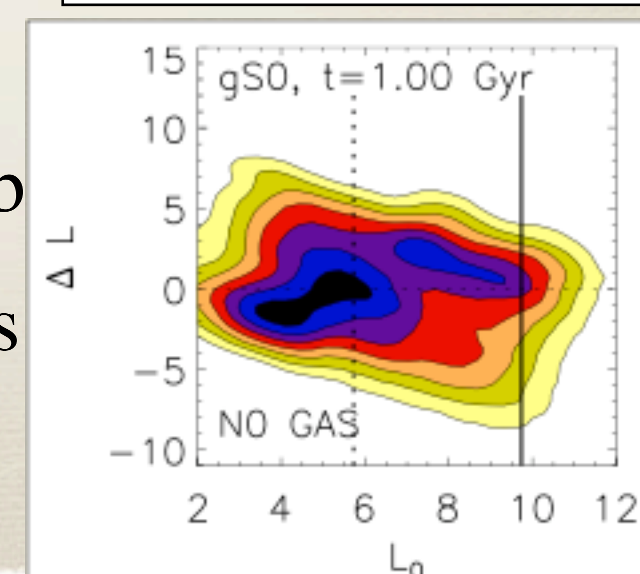

How do we expect to identify this mechanism in the Milky Way?

- History of Milky Way bar and spiral structure currently unknown.
- Look for different signatures in the density and metallicity distribution at different locations in the Galaxy (RAVE, GAIA, APOGEE).
- Most promising: Chemical tagging (Freeman & Bland-Hawthorn 2002) -- Up to 35 elements, 7 to 9 dimensional space. A dissolved star cluster will be a point in chemical space (HERMES, GYES).
- Extended Milky Way disk? Extensions to HERMES, GYES and LAMOST.

Conclusions

- Disk mixing by resonance overlap is very efficient, strongly dependent on the strength of the perturbers.
- Creation of extended disks in both MW-size and low-mass galaxies (e.g., NGC 300, M33).
- Creation of a thick disk component in only a couple of Gyr.
- Future work needed to examine different galactic evolution scenarios: e.g., long-lived vs short-lived non-axisymmetric structure.
- We need a new chemo-dynamical disk model incorporating the effect of the Galactic bar.