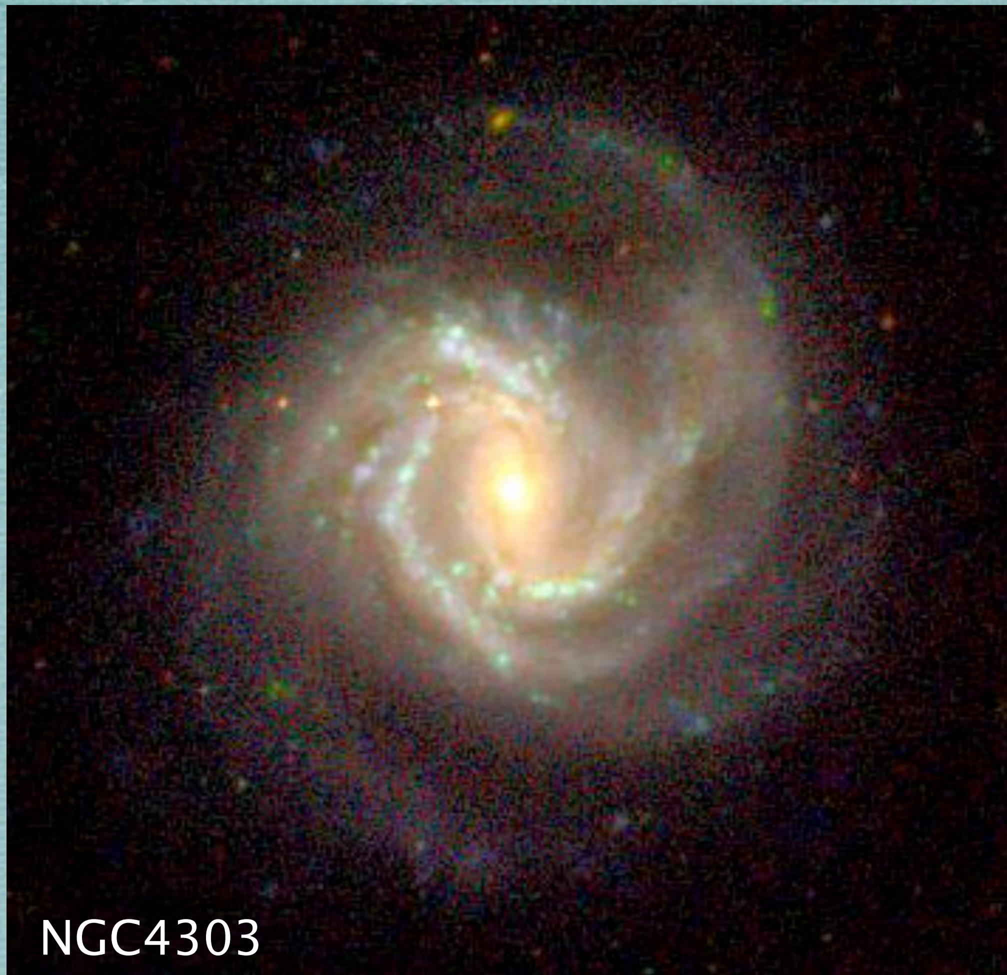
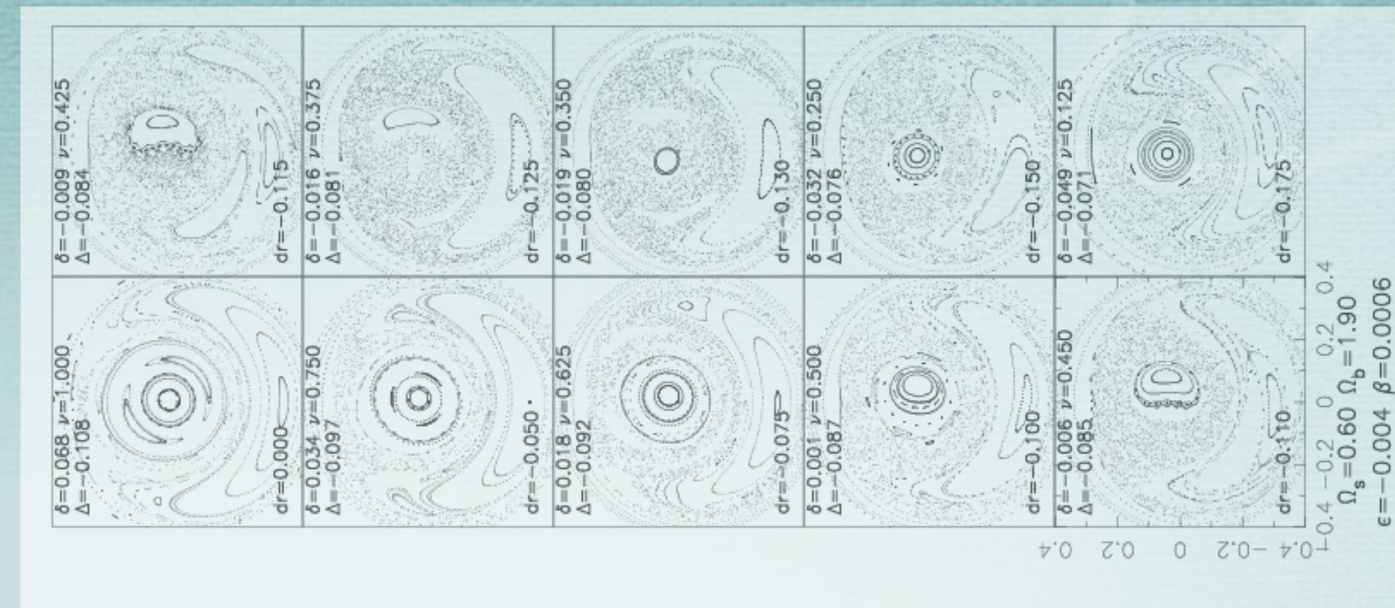




$$H \approx I_1^2 + I_1\delta - \varepsilon I_1^{1/2}\cos\phi - \beta I_1^{1/2}\cos[\phi + \nu t + \gamma]$$

A New Mechanism for Galactic Disk Mixing: Implications to the Milky Way

Ivan Minchev
Strasbourg Observatory

Observatoire astronomique de Strasbourg

Radial mixing of galactic discs
Current mechanisms

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

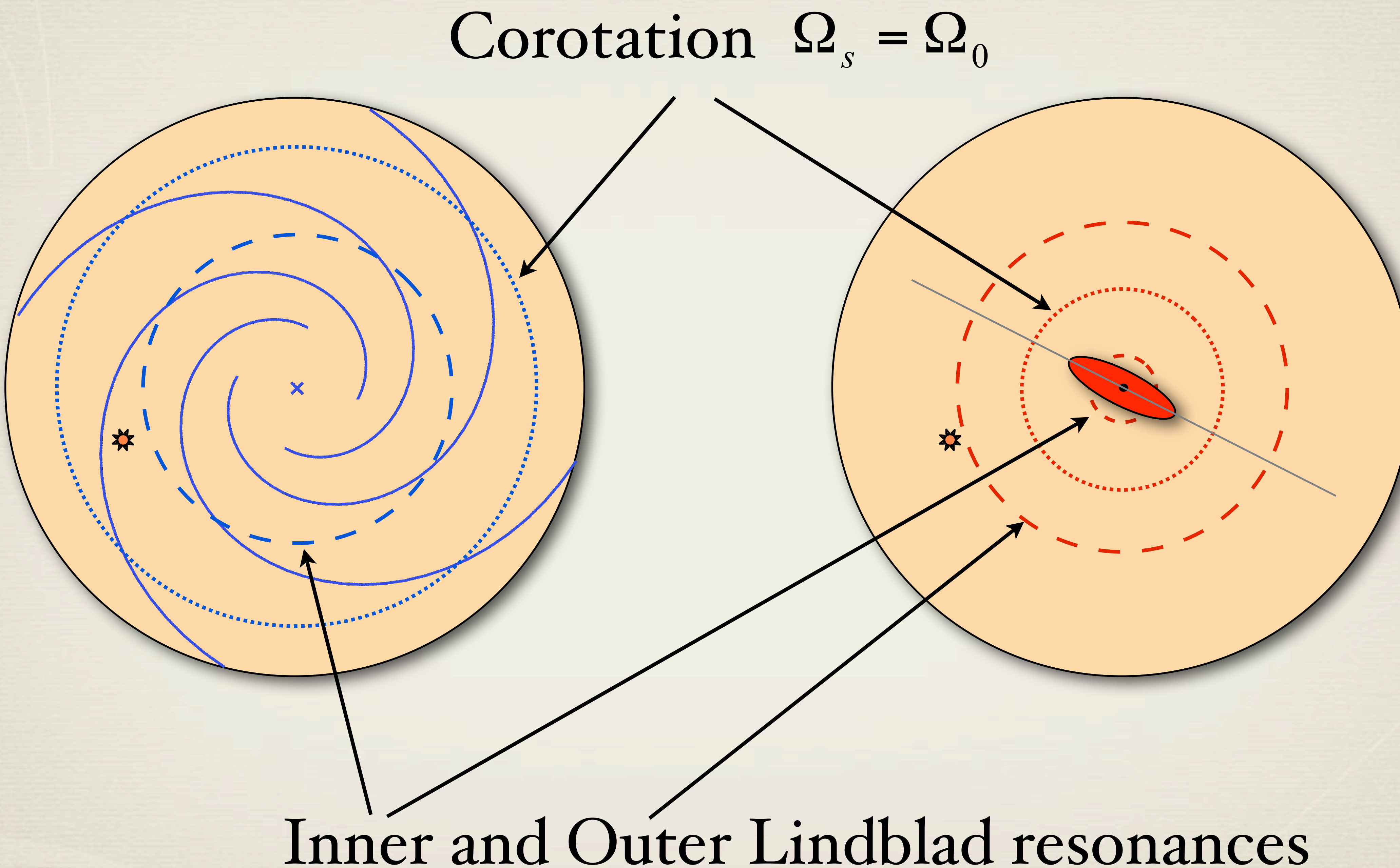
- Explained by stellar radial migration in the disc:

  - Transient Spirals (Sellwood & Binney 2002)

  - Small satellites can mix the outer disc (Quillen, Minchev, Bland-Hawthorn & Haywood 2009)

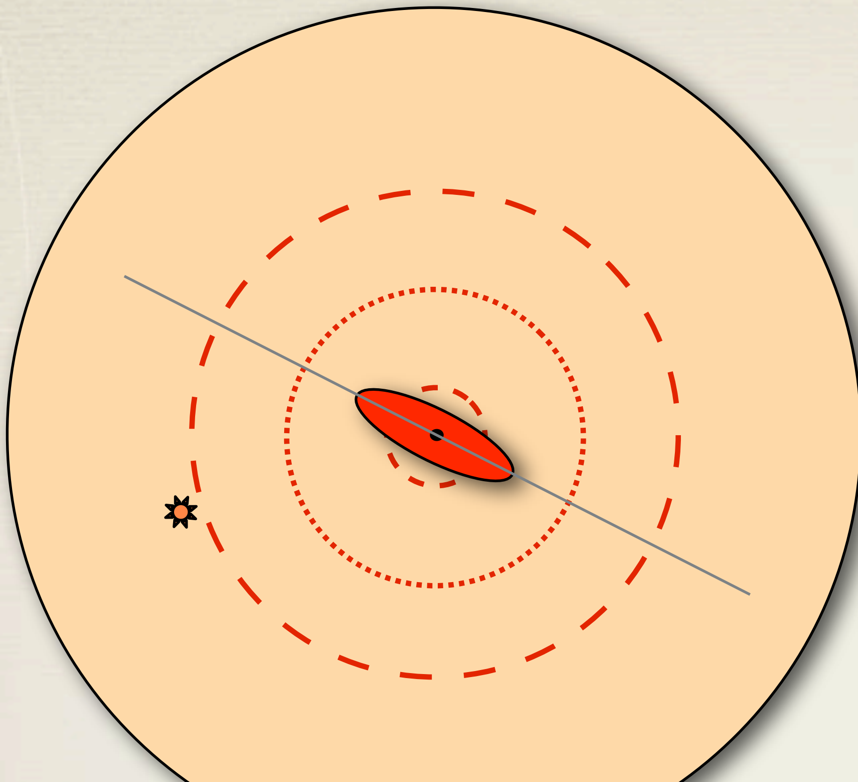
- **Are galactic Bars important for Radial Migration?**

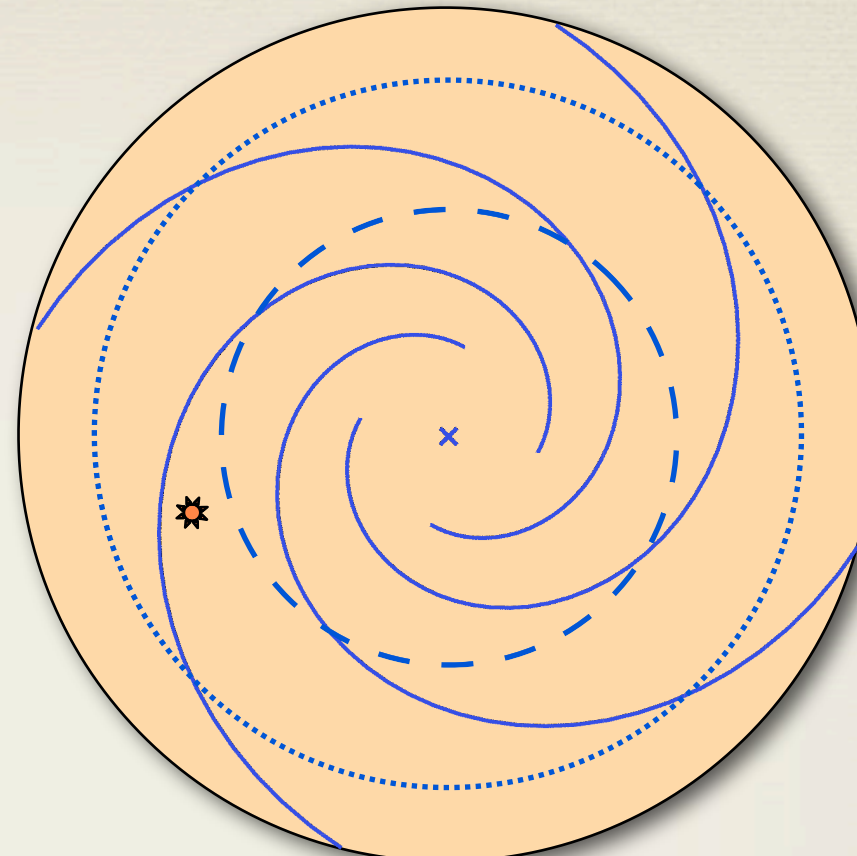
Resonances in galactic disks



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

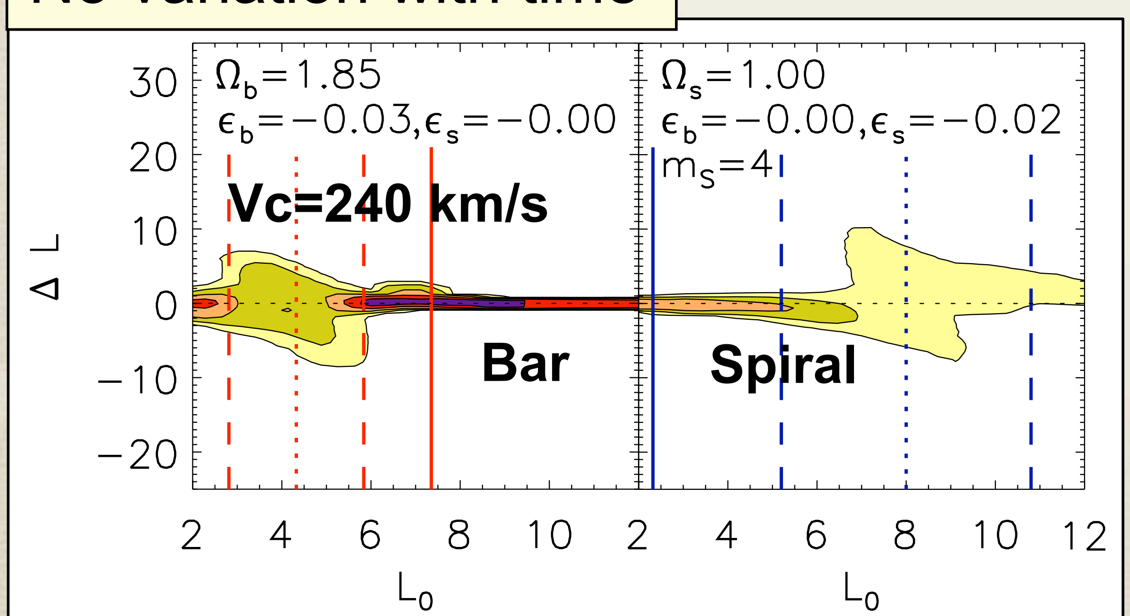
Radial migration due to a single perturber





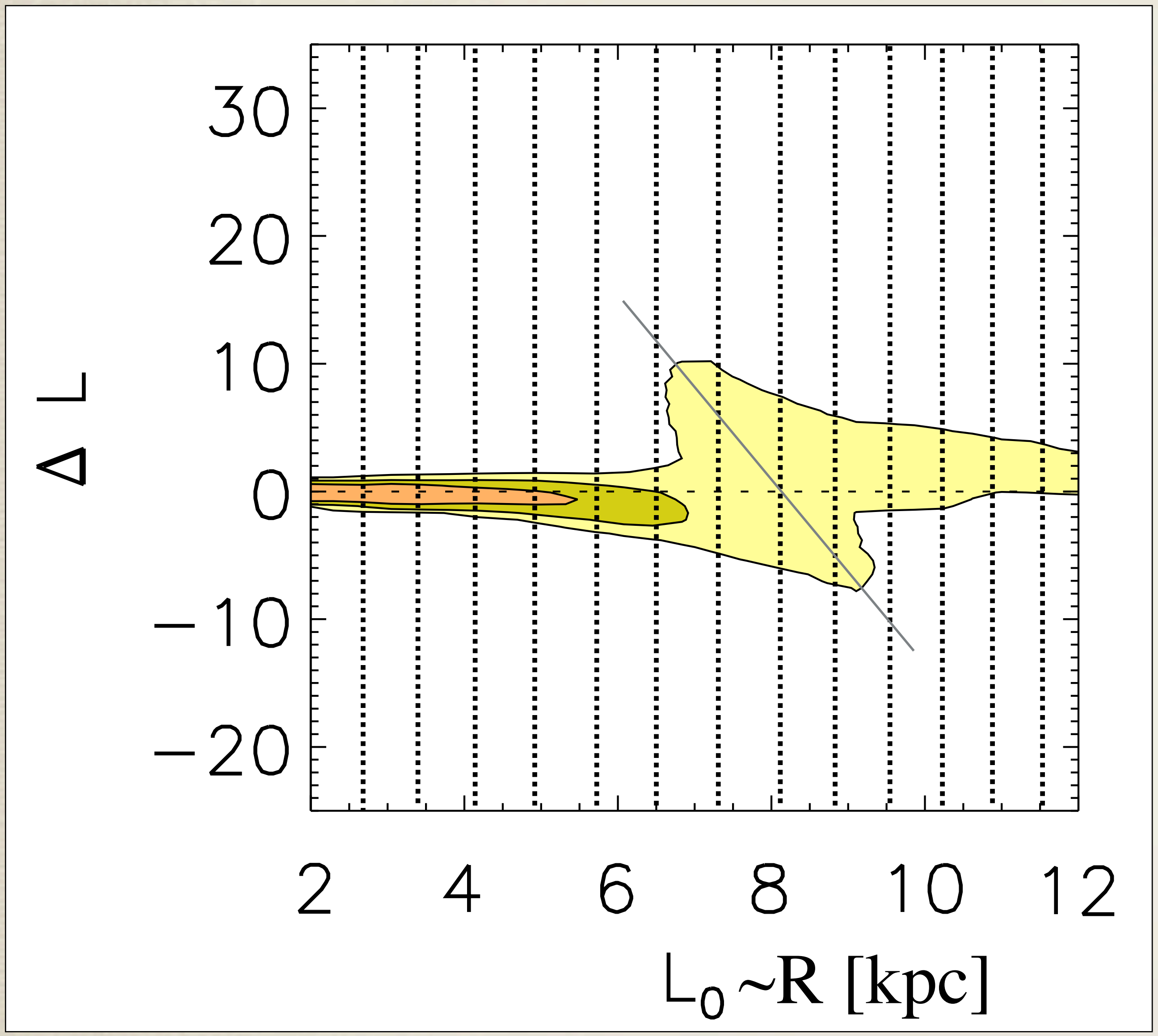
Change in angular momentum

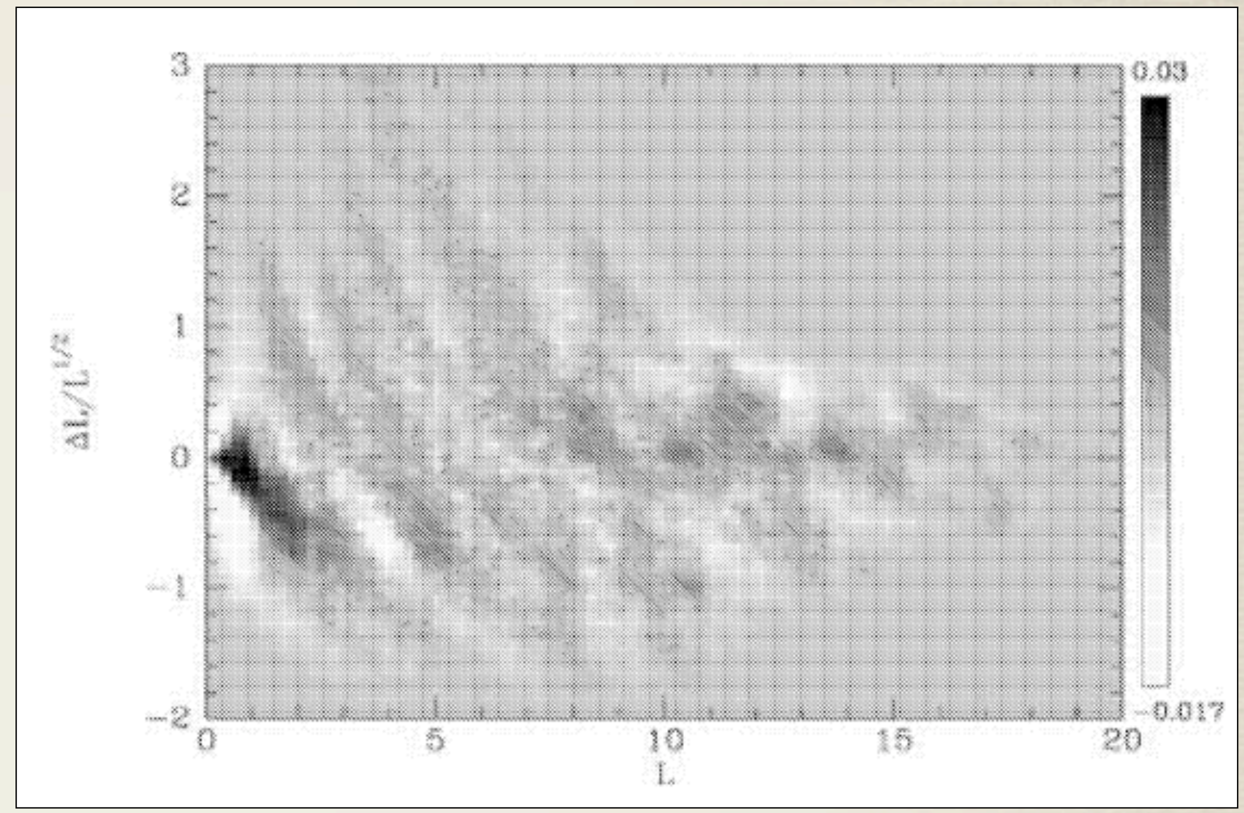
No variation with time



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

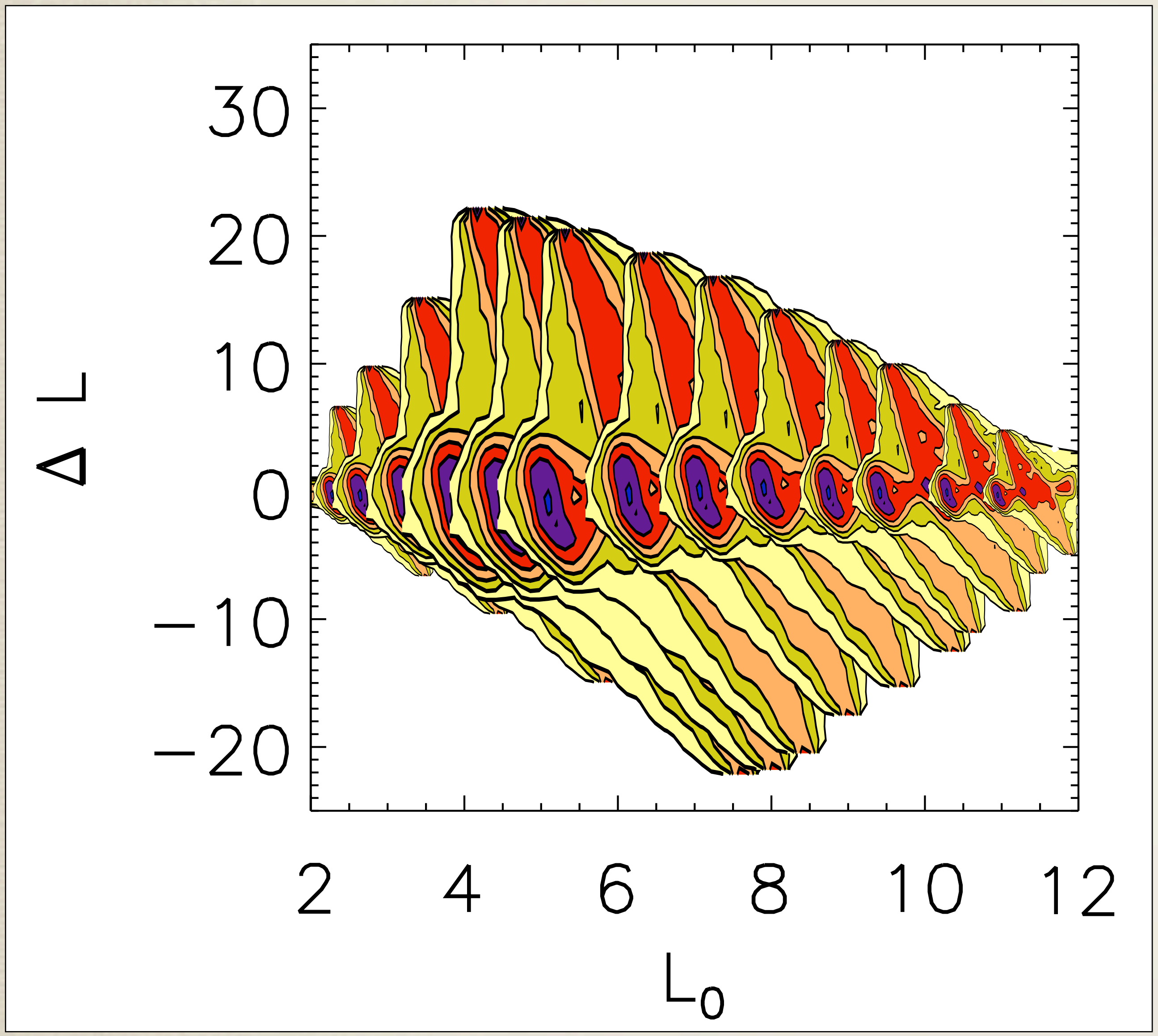
Radial migration from Transient Spirals

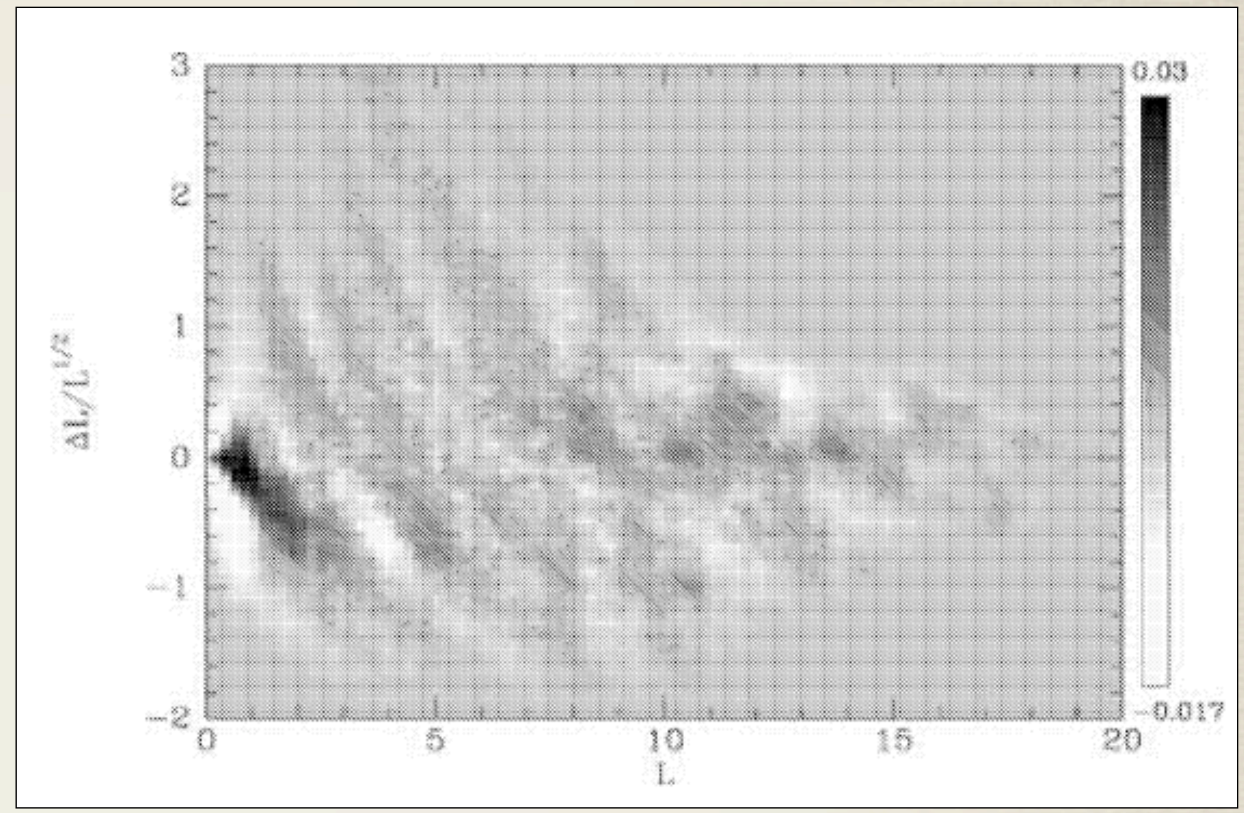




Sellwood & Binney (2002)

Radial migration from Transient Spirals





Sellwood & Binney (2002)

Requires ~9 Gyr for sufficient 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 $\phi = \theta_1 \pm m(\theta_2 - \Omega_p t)$

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

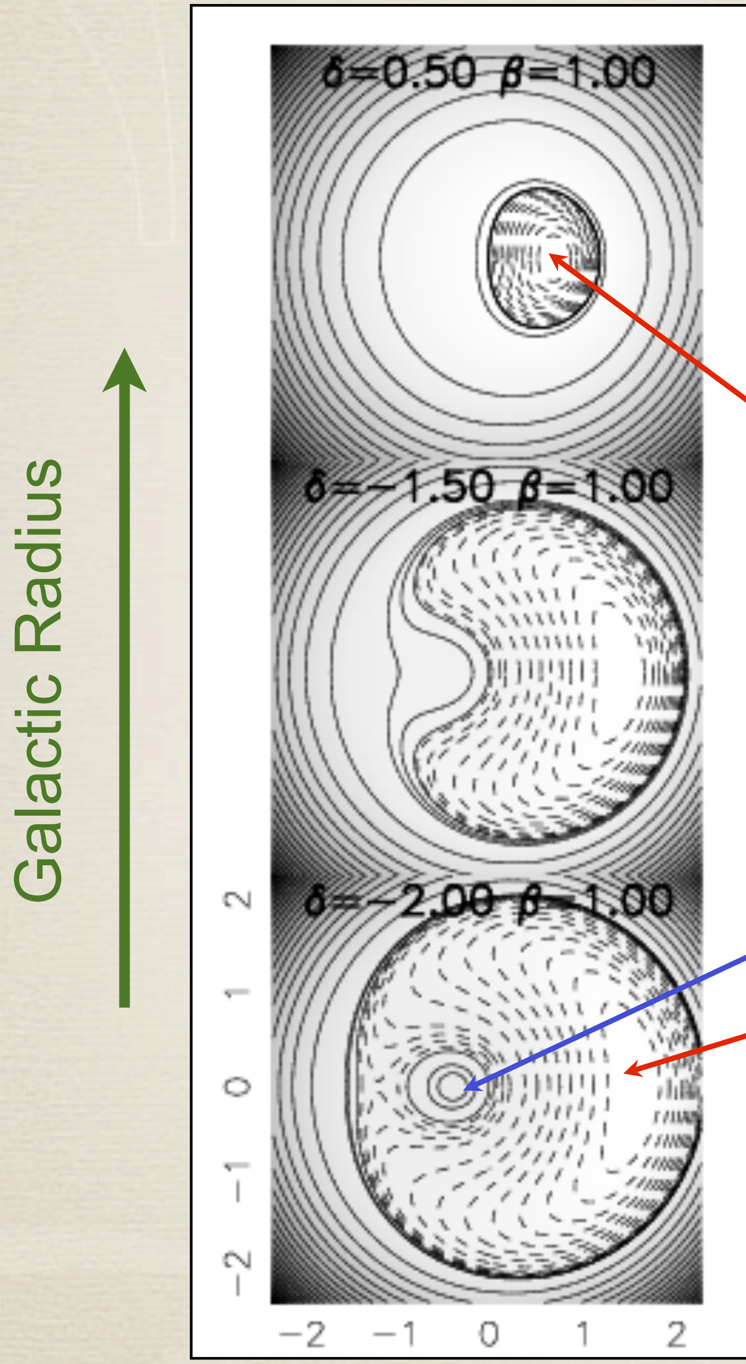
This is time independent and J_2 is conserved

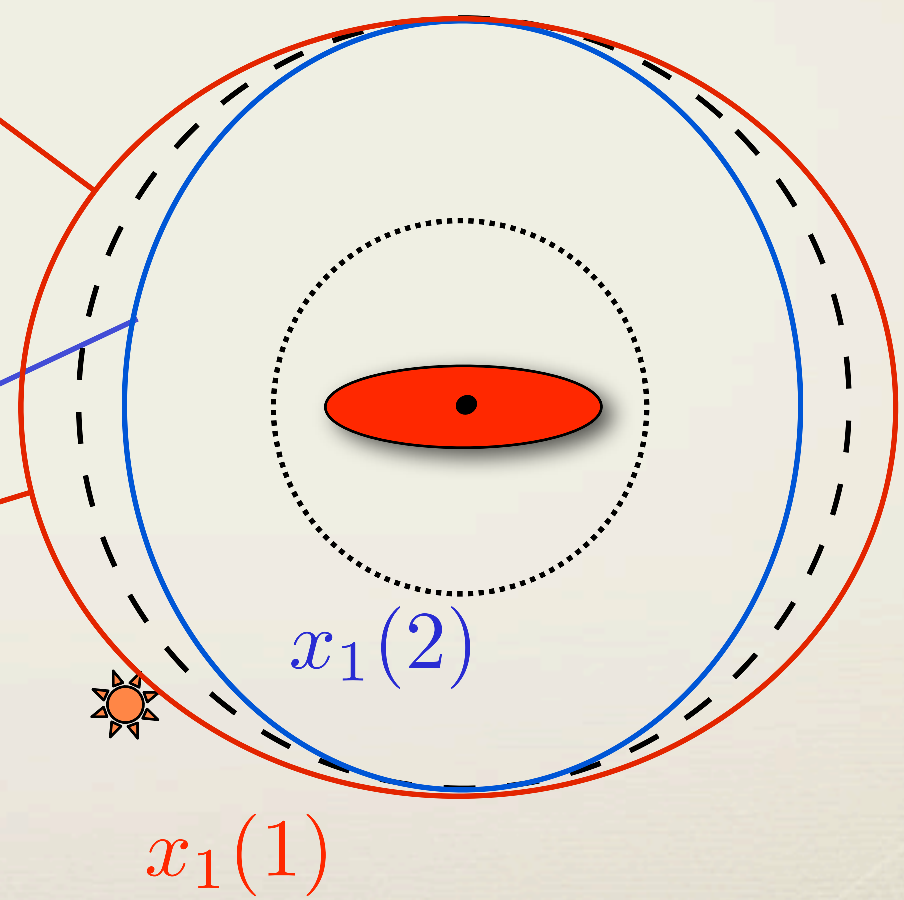
First order Lindblad Resonances with the Bar

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

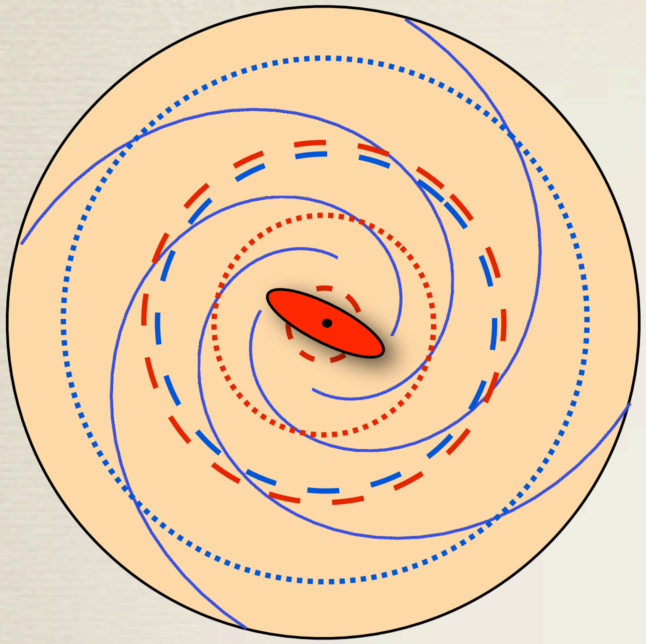




Closed orbits correspond to fixed points

Hamiltonian including two perturbations:

Analogy to the forced pendulum



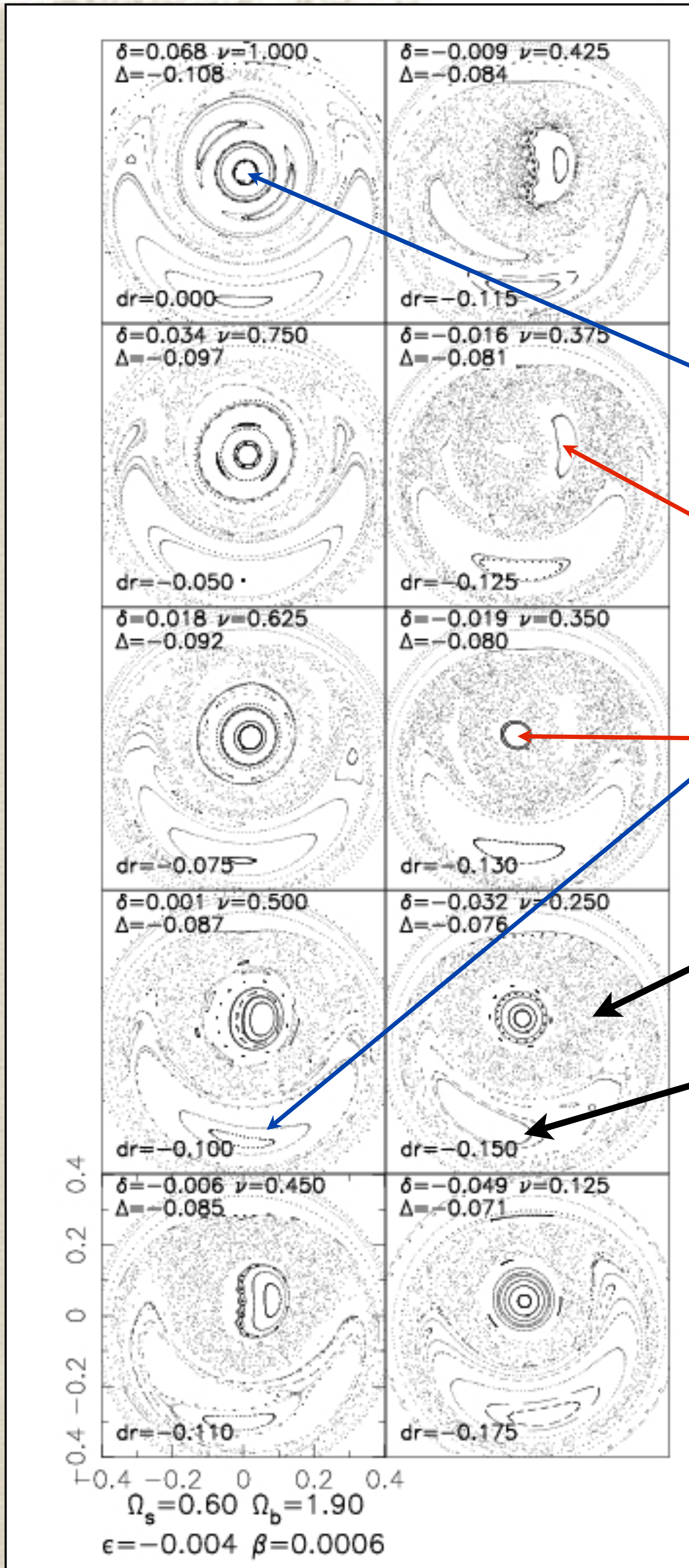
Strength of first perturbation

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

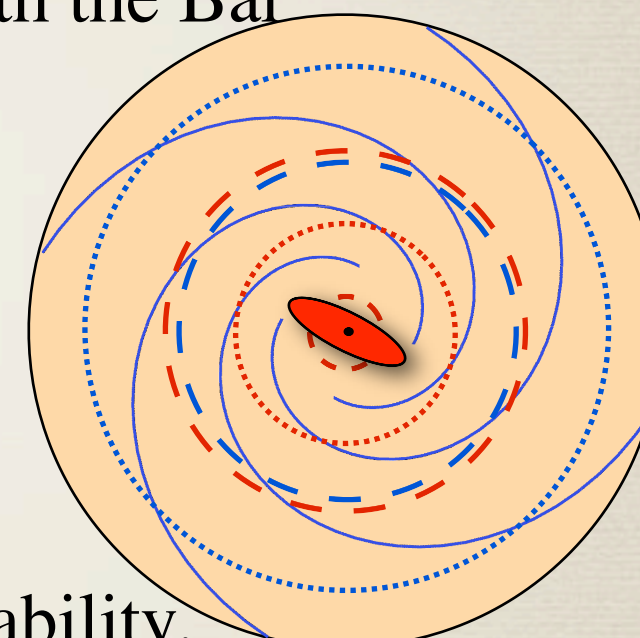


Spiral structure at the Bar's Outer Lindblad Resonance

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

Area-filling orbits

Quasi-periodic orbits

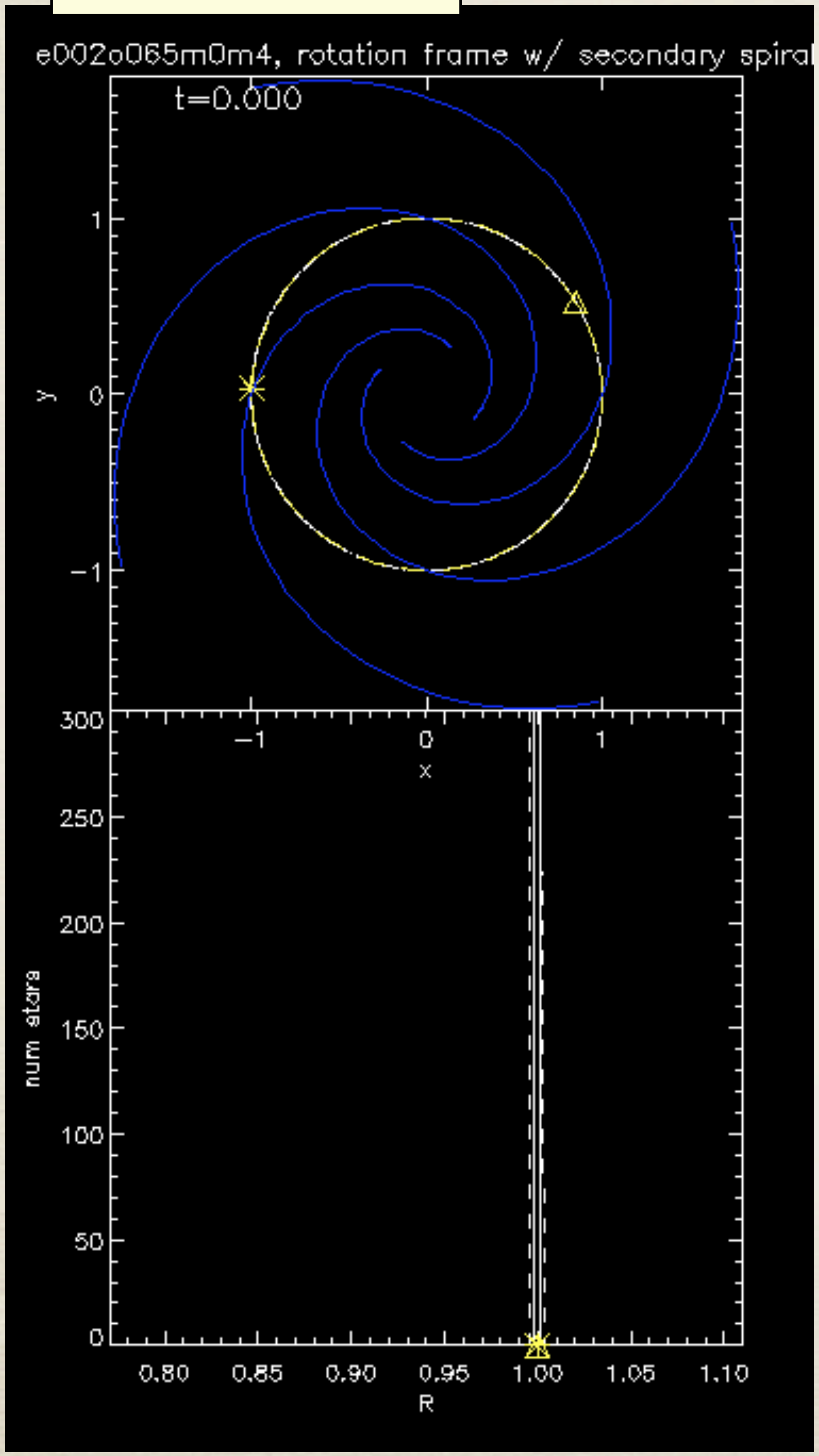


Poincare maps used to look at stability.
Plot every $\Delta t = \frac{2\pi}{\nu}$

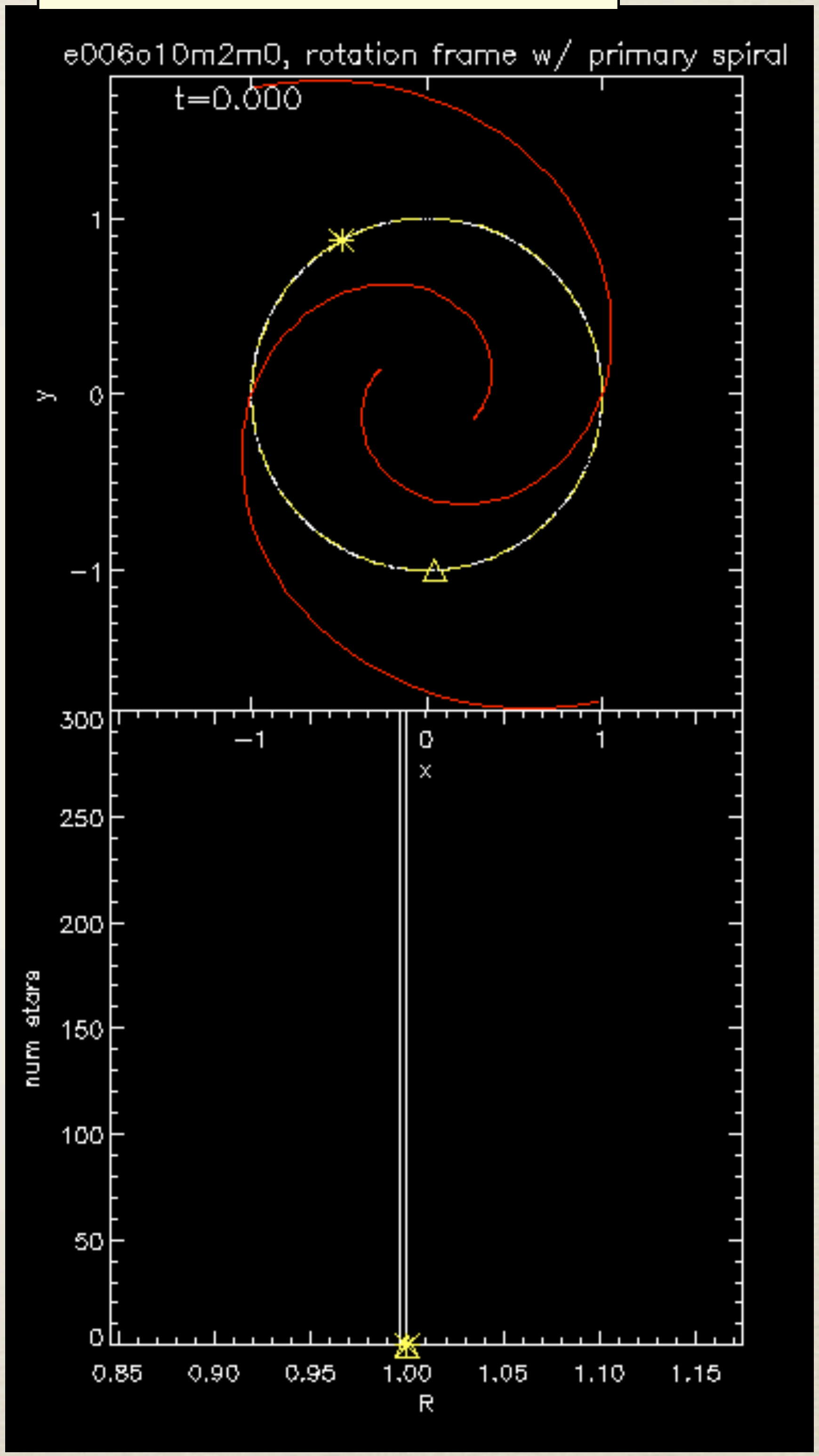
Orbits are either oscillating with both perturbations or are **Chaotic**: Induces **Heating** and **Migration** (Quillen 2003)

Radial migration at Corotation with Spiral

m=4 at OLR



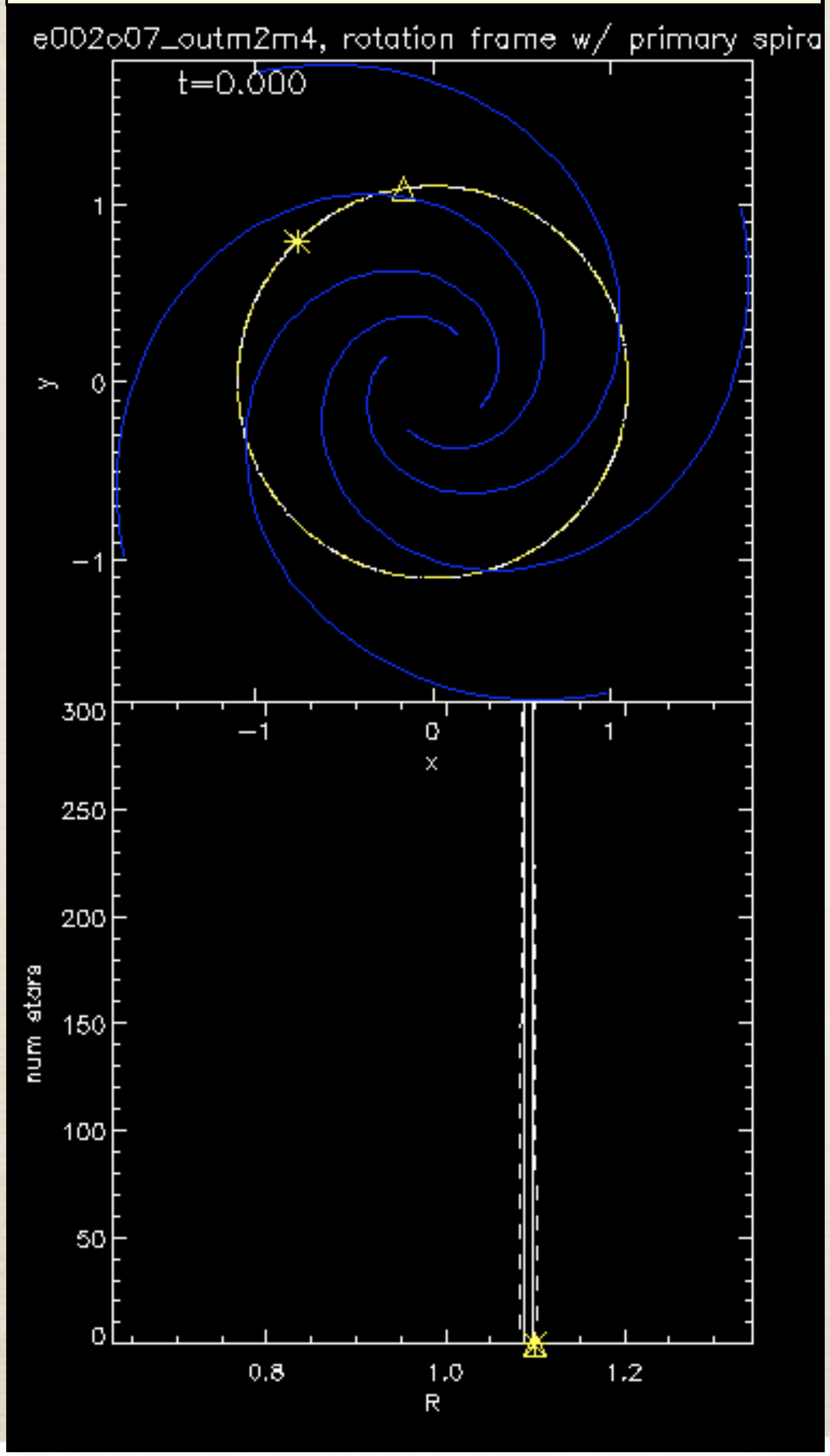
m=2 at Corotation



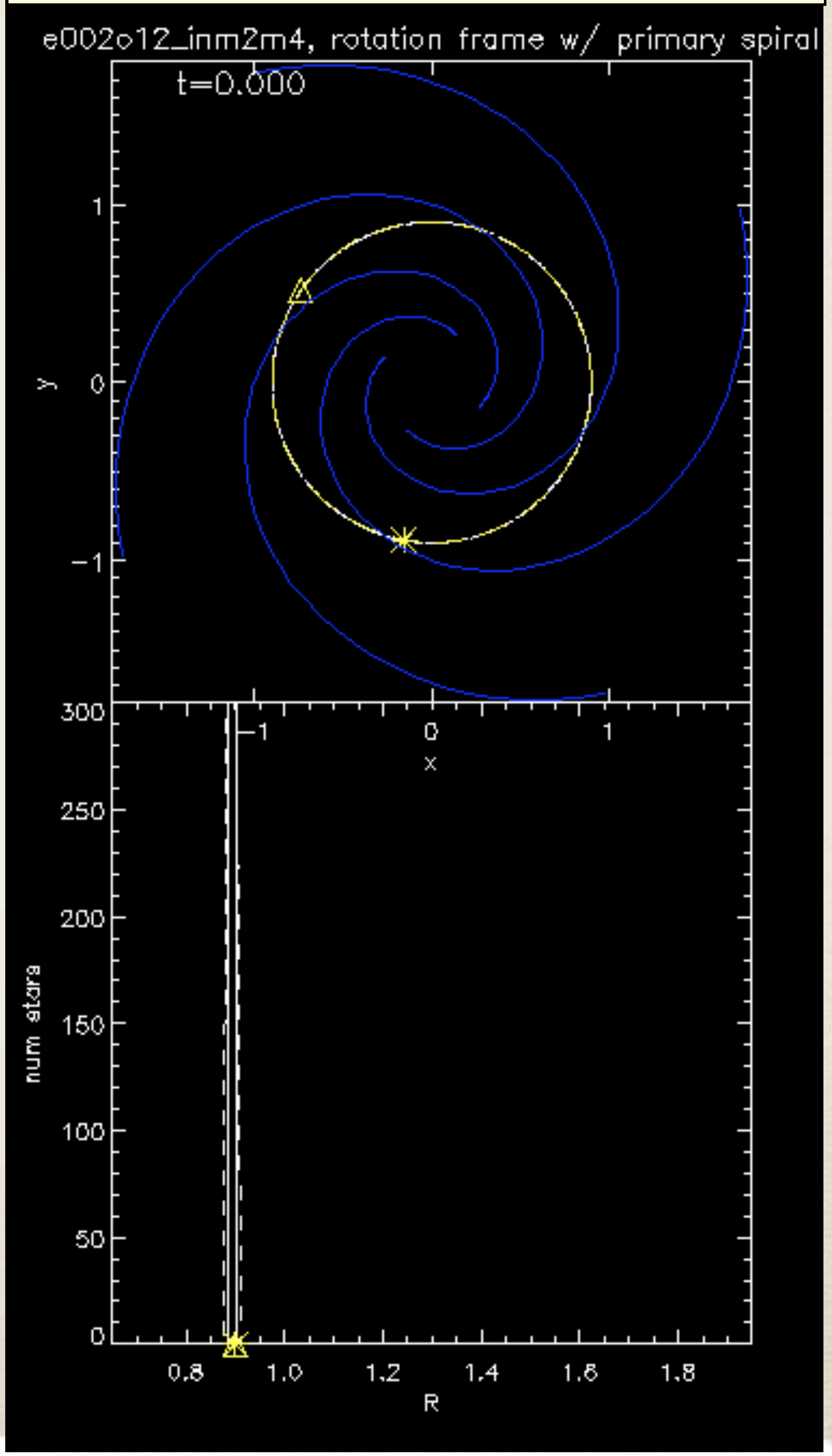
Two perturbers create stochastic regions

Multiple Spirals

m=4 just outside the ILR

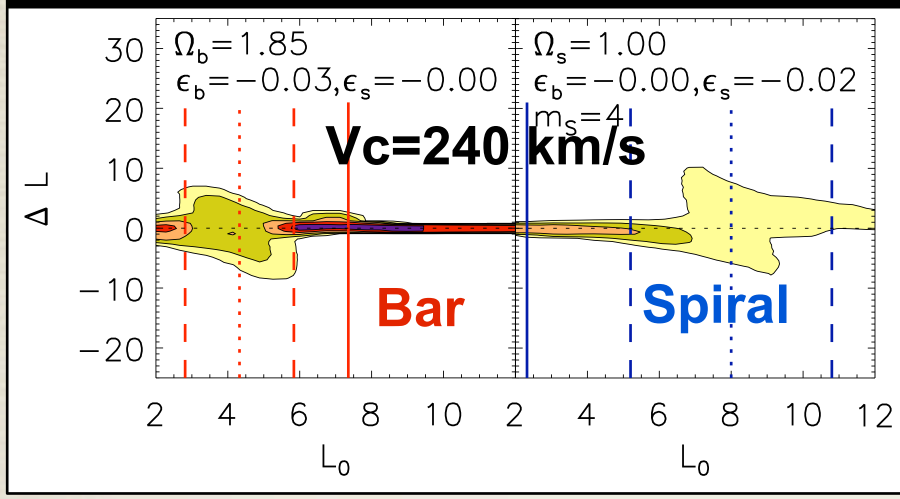


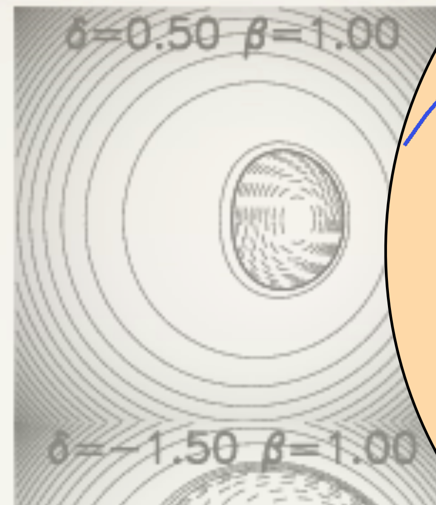
m=4 just inside the OLR

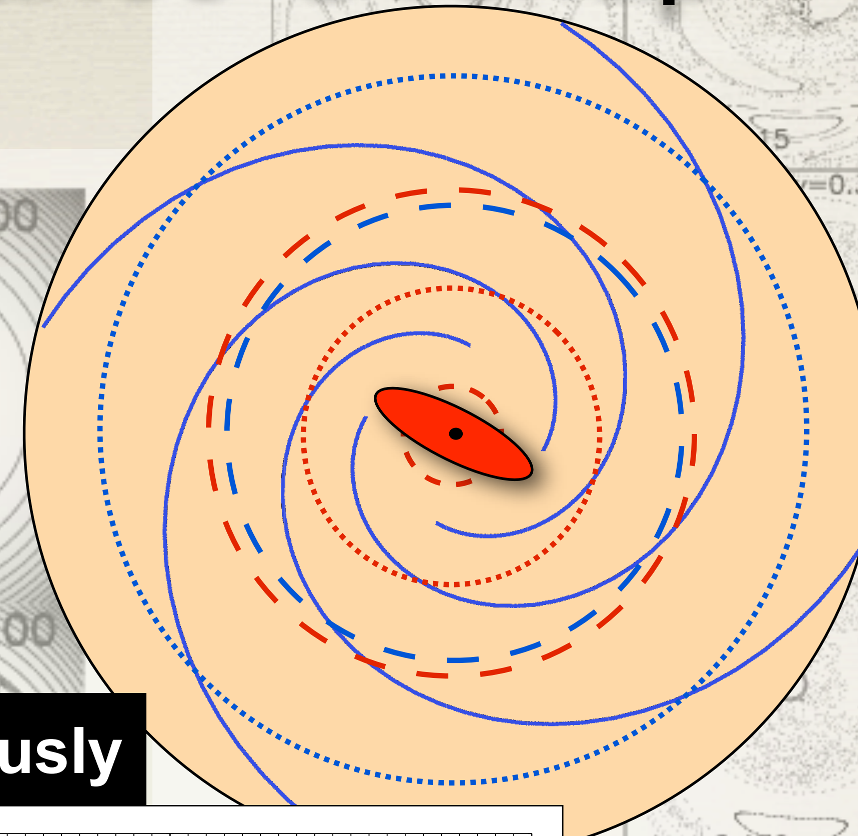


Migration due to Resonance Overlap

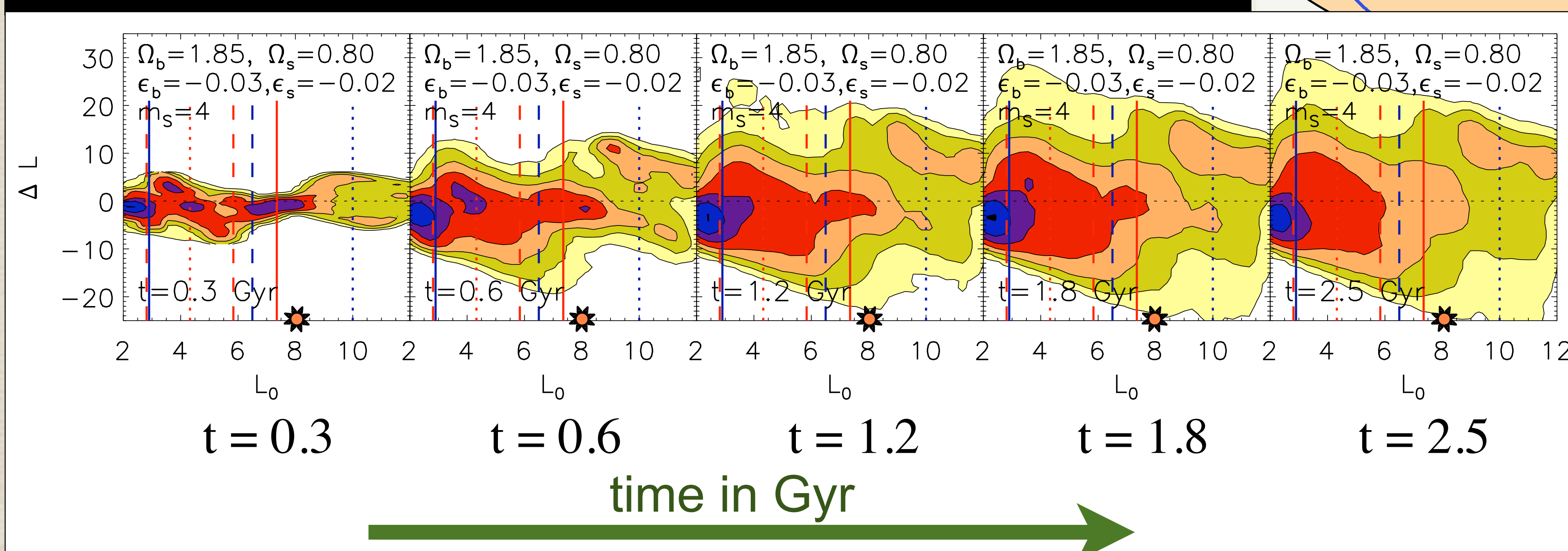
Single Perturber: No variation with time



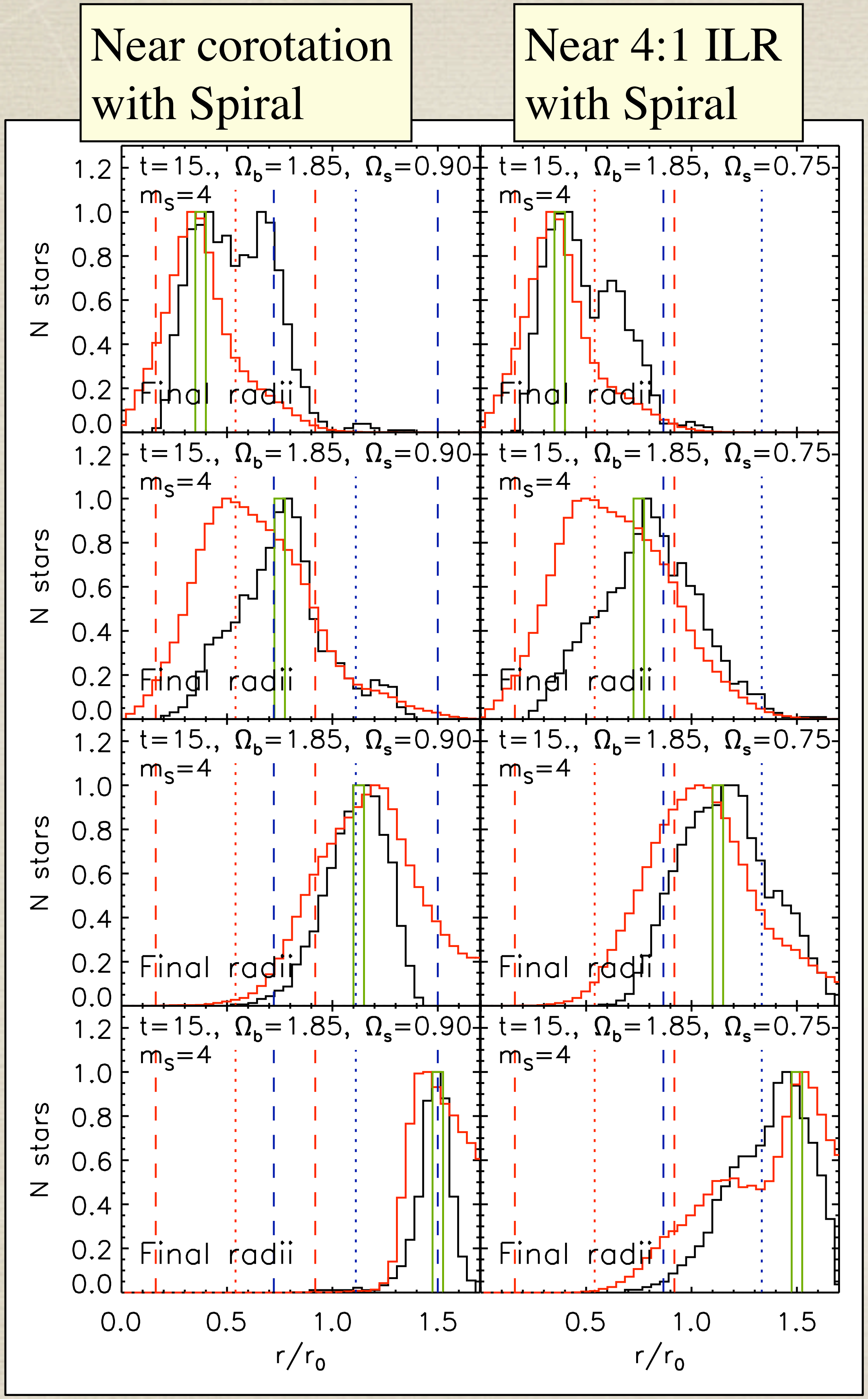




Bar + Spiral Structure propagating simultaneously



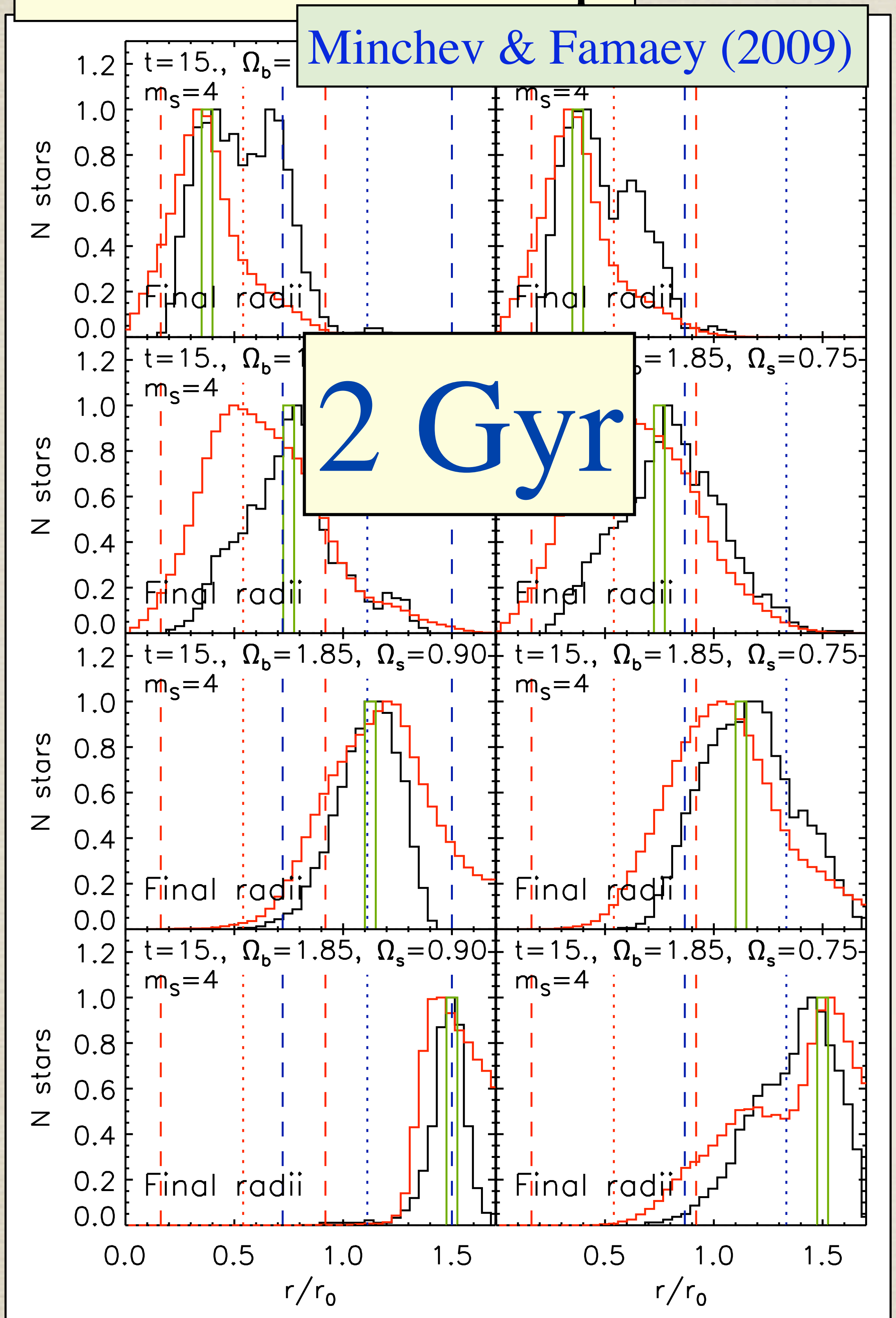
Stars migrate throughout the the whole disk



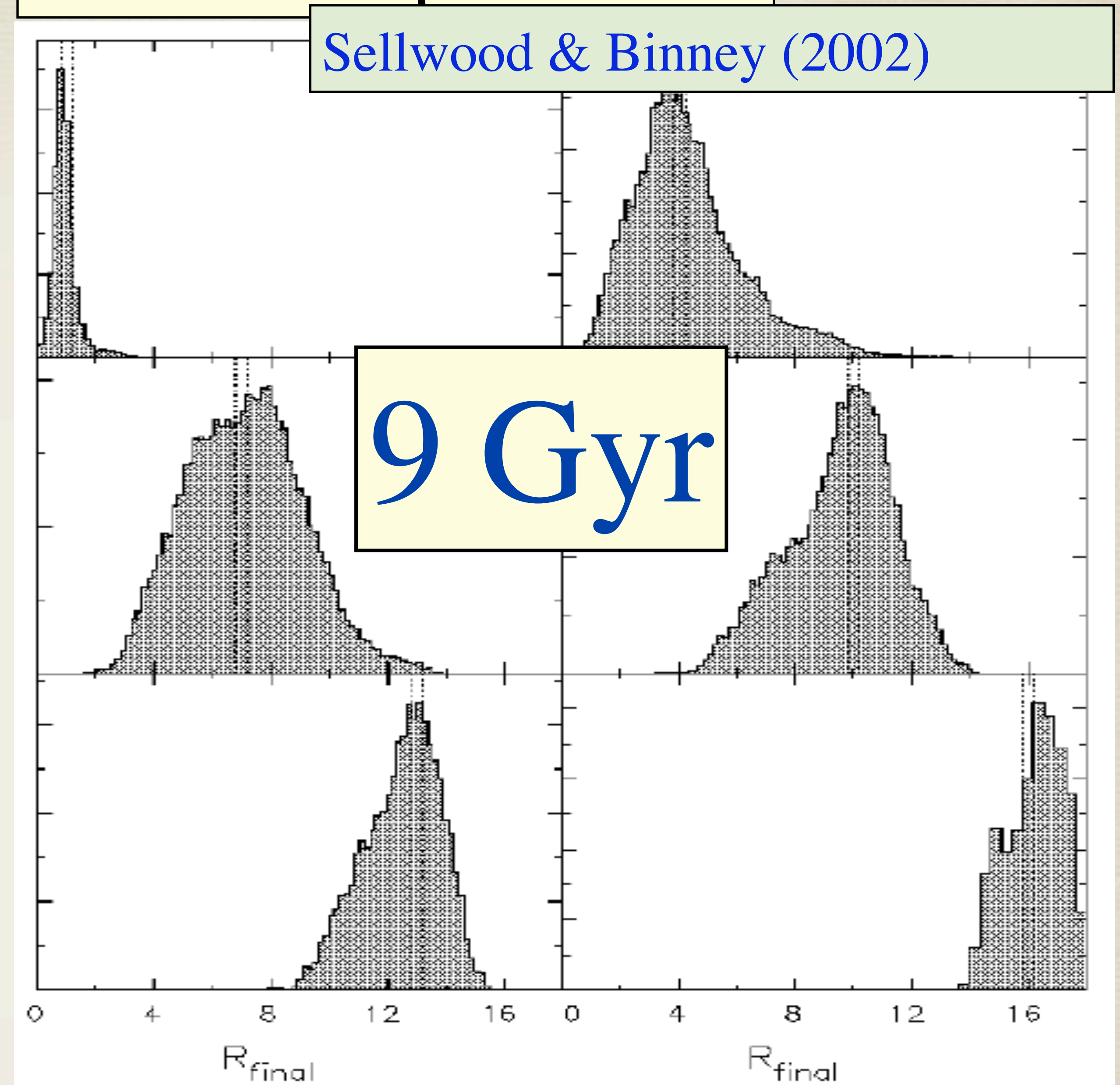
Mixing throughout the entire disk

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

Resonance Overlap



Transient Spirals

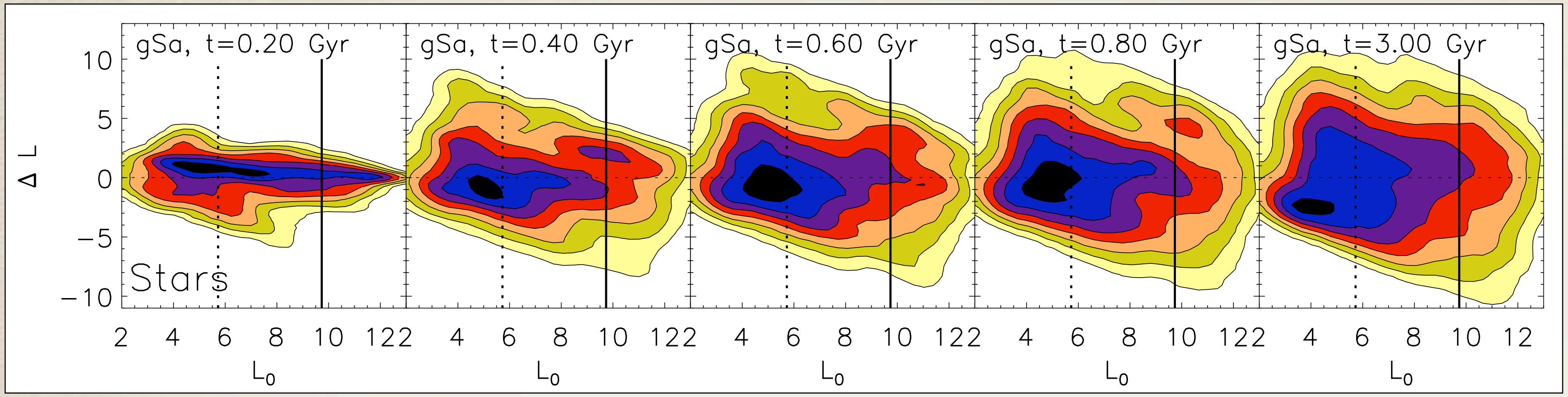


- Mixing by Resonance Overlap can be an order of magnitude more efficient than mixing by Transient Spirals.

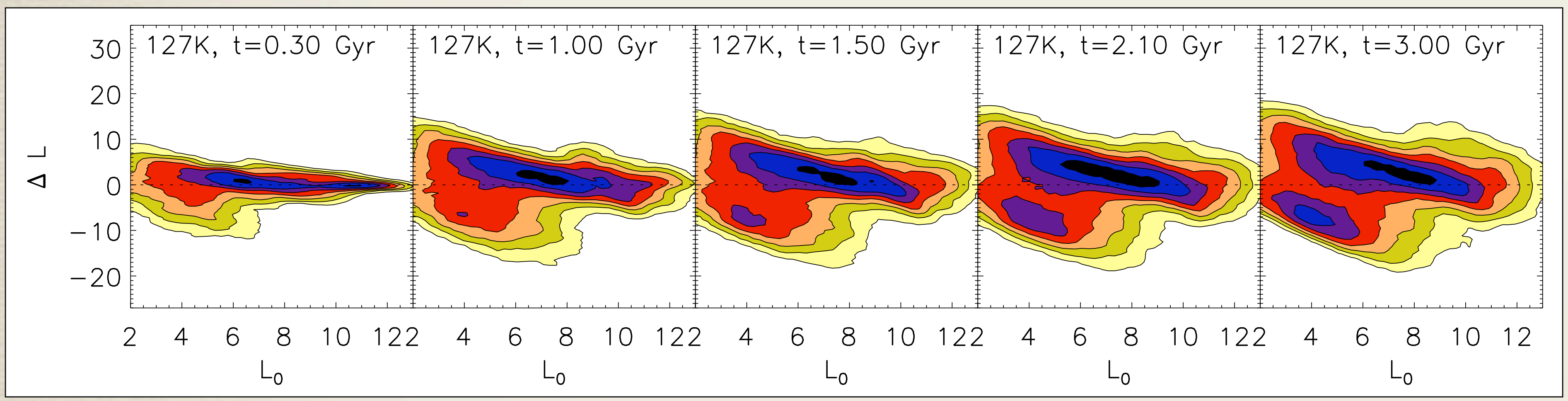
Migration from Resonance Overlap of Multiple Patterns

Confirmed in 3 independent simulation set-ups

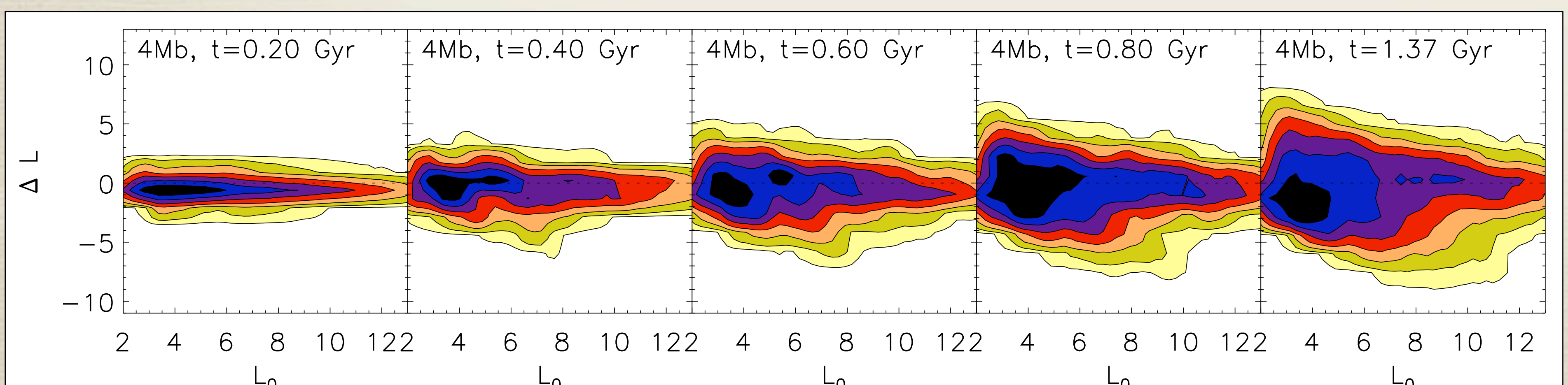
Minchev, Famaey, Combes, Di Matteo & Wozniak (2010), arXiv:1006.0484



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

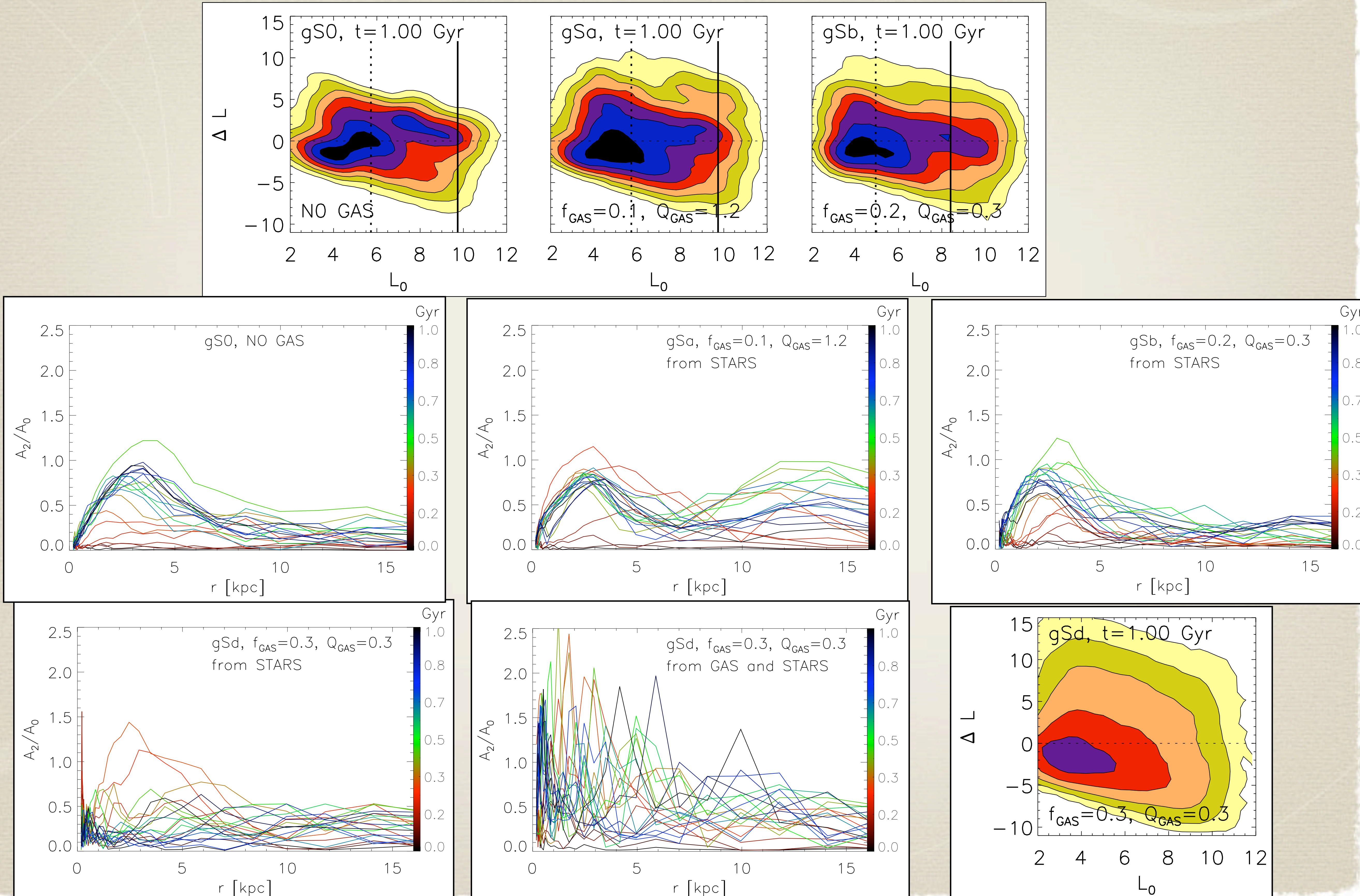


Particle-Mesh, Geneva Group code, Wozniak & Michel-Dansac (2009)

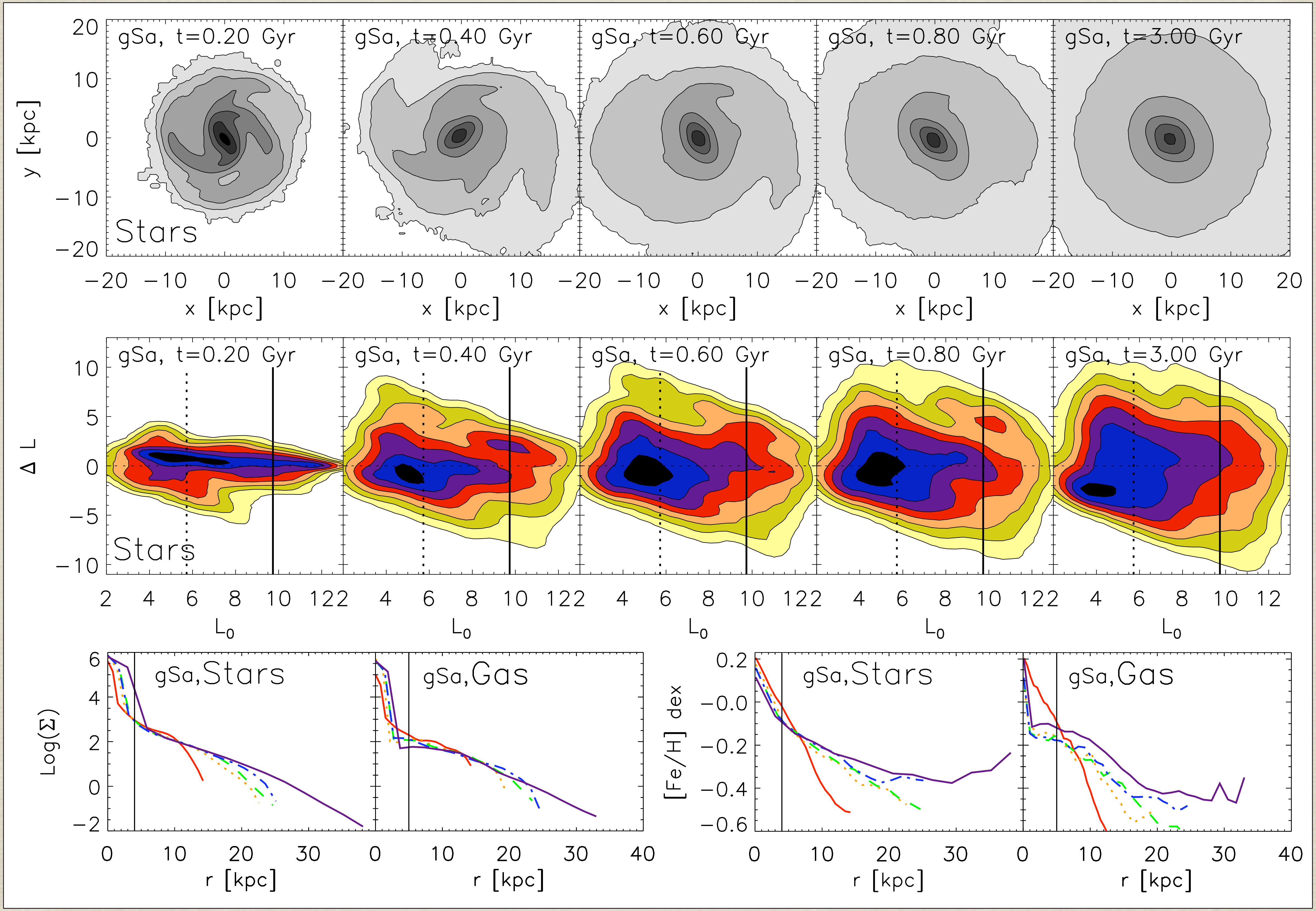


Direct N-body, phiGRAPE (Harfst, S. et al., 2006),
Alice Quillen on GPU

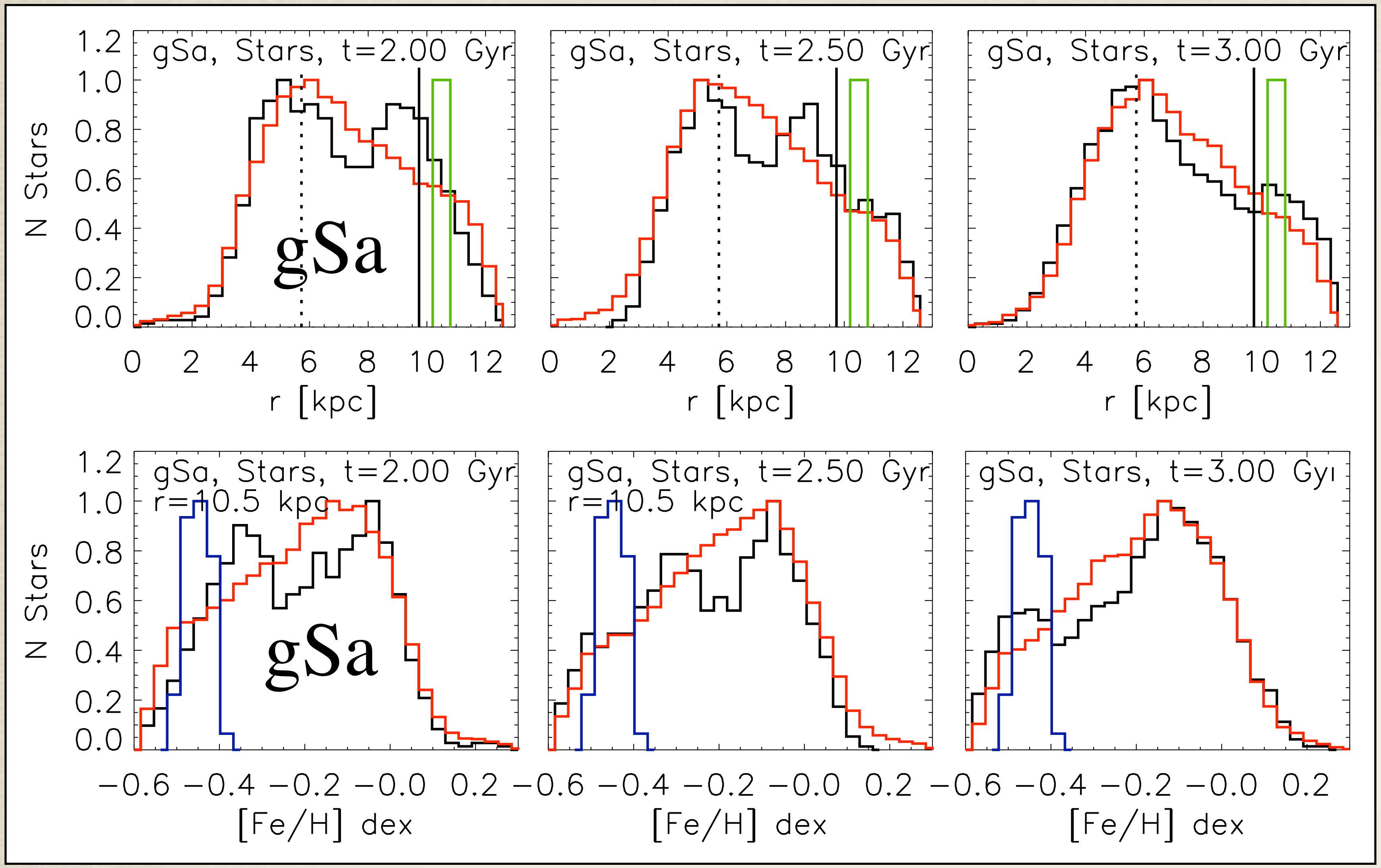
The importance of a gaseous component



GalMer giant Sa model, Vc~280 km/s



GalMer giant Sa model, Vc~280 km/s

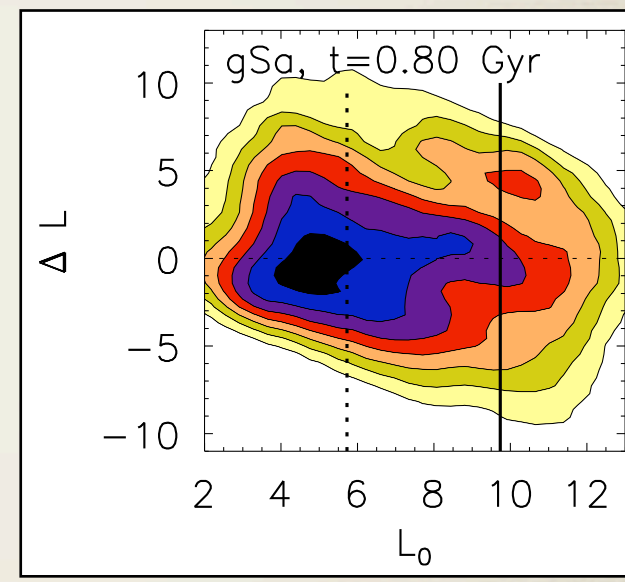


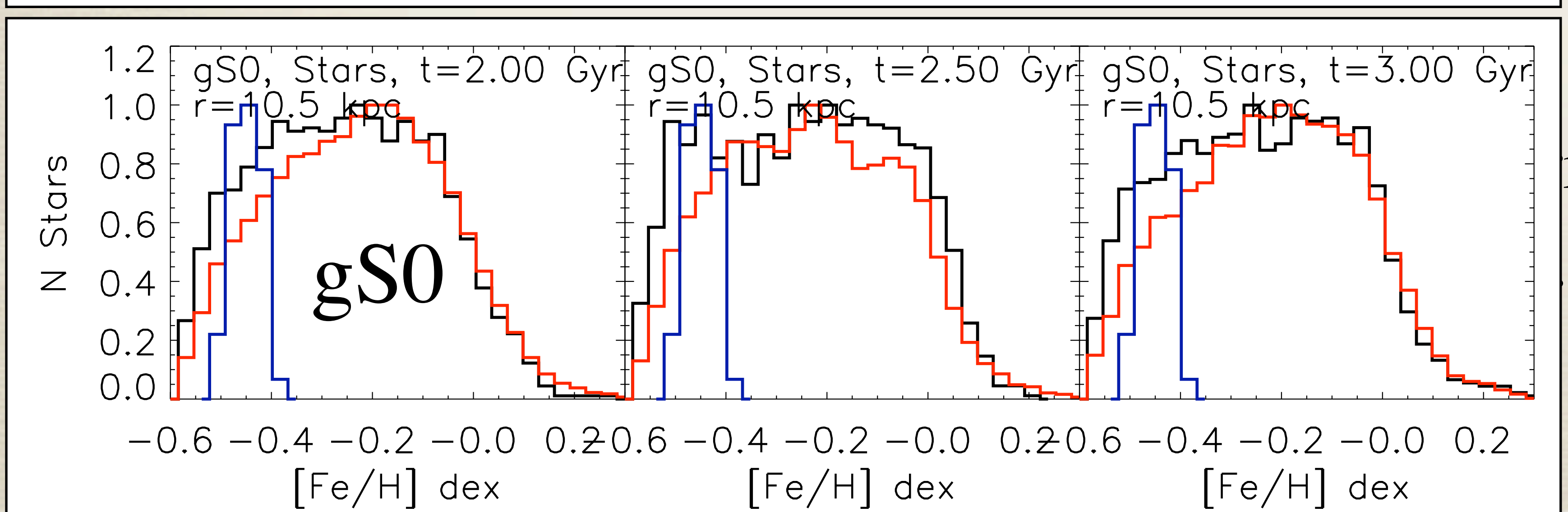
Radii Now

Cold orbits

Hot orbits

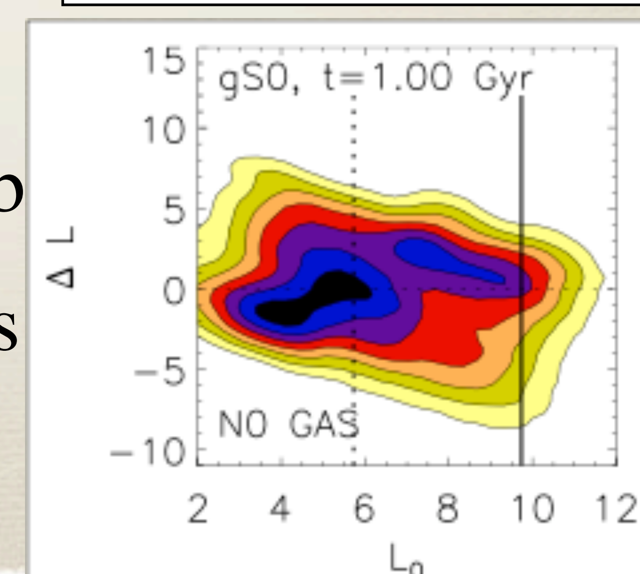
Initial metallicity





ib

’s



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

- History of Milky Way bar and spiral structure currently unknown.
- Are we currently in an episode of strong mixing?
- Chemical tagging, as suggested by Ken and Joss. Up to 35 elements, 7 to 9 dimensional space. A dissolved star cluster will be a point in chemical space (HERMES, GYES).
- Look for different signatures in the density and metallicity distribution at different locations in the Galaxy (RAVE, GAIA, APOGEE).
- Extended Milky Way disk? Extensions to HERMES and GYES.
- A chemo-dynamical disk model including the effect of the Galactic bar is currently being developed (D. Pfenniger's group in Geneva).