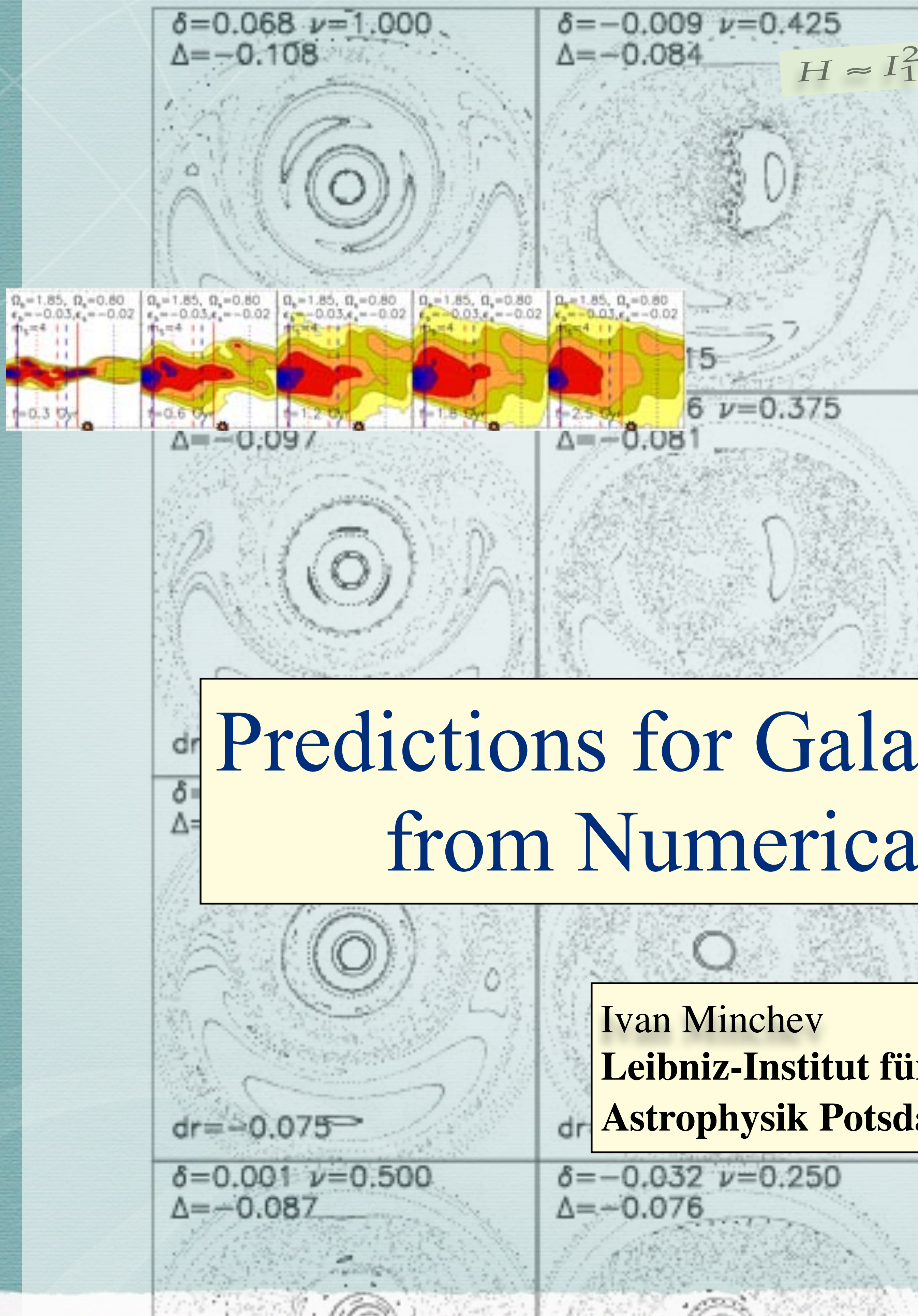
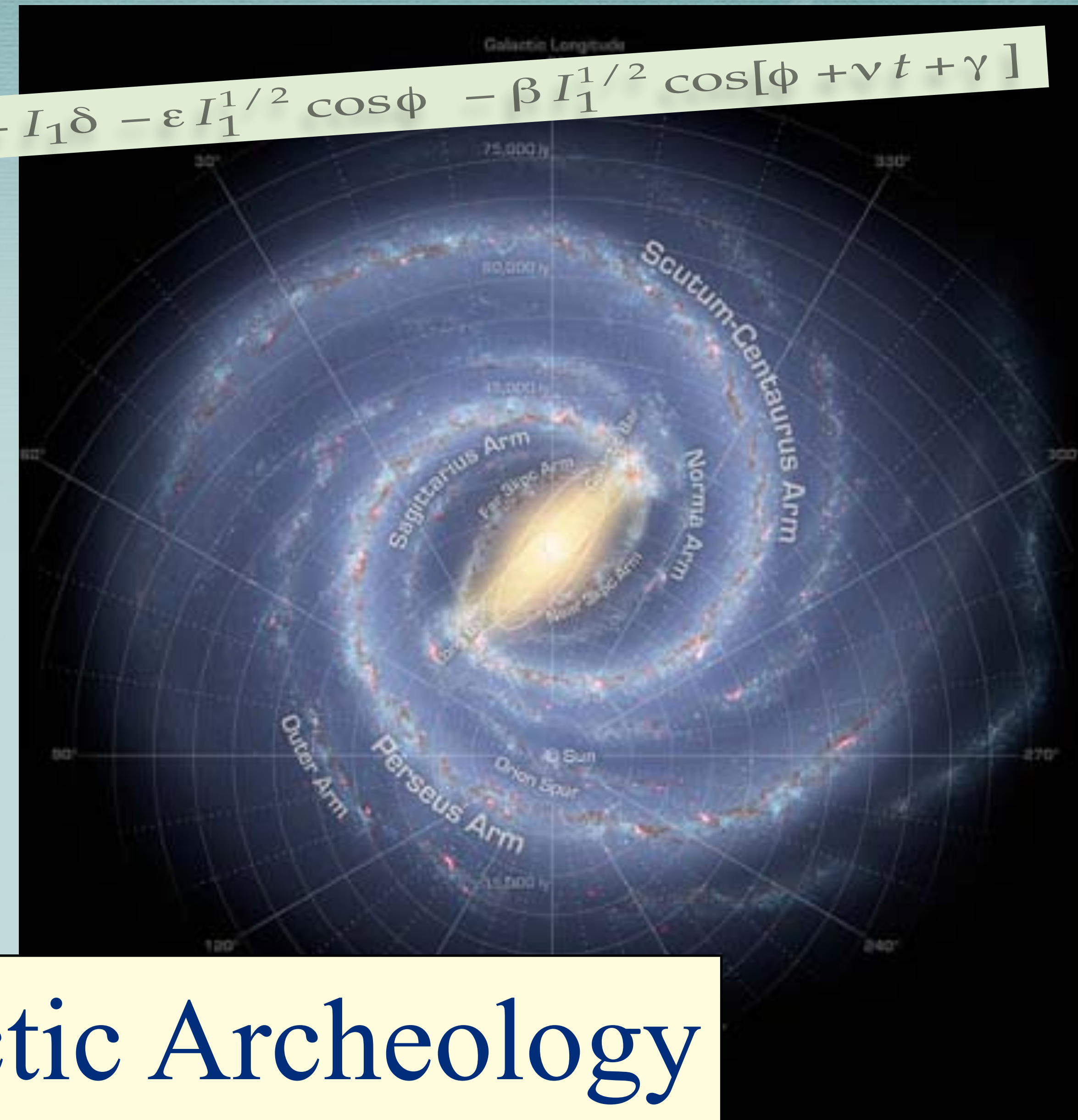




$$H \approx I_1^2 + I_1\delta - \varepsilon I_1^{1/2}\cos\phi - \beta I_1^{1/2}\cos[\phi + \nu t + \gamma]$$

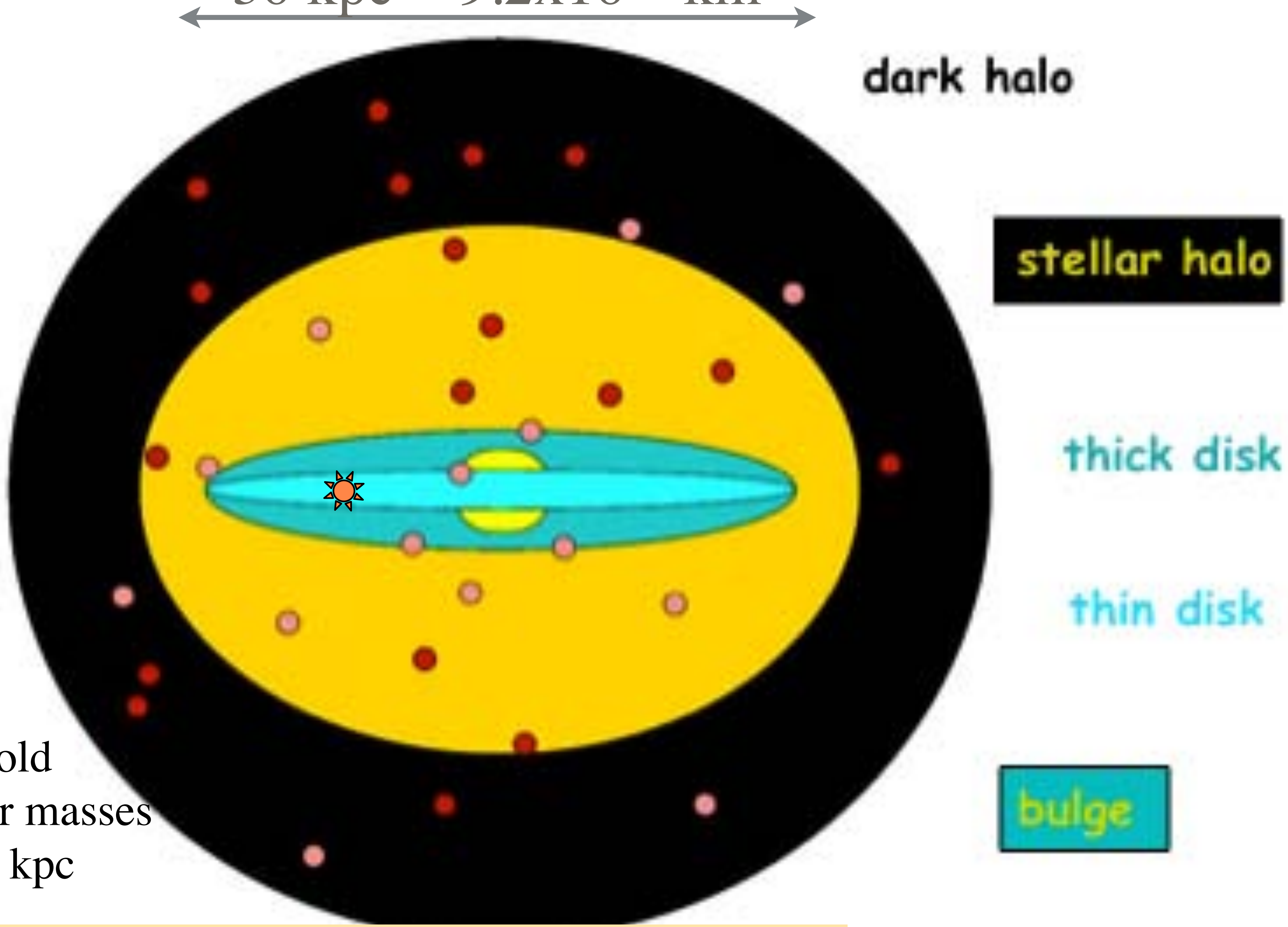
Predictions for Galactic Archeology from Numerical Modeling

Ivan Minchev
Leibniz-Institut für Astrophysik Potsdam (AIP)

Leibniz-Institut für Astrophysik Potsdam
AIP

Overview of our Galaxy

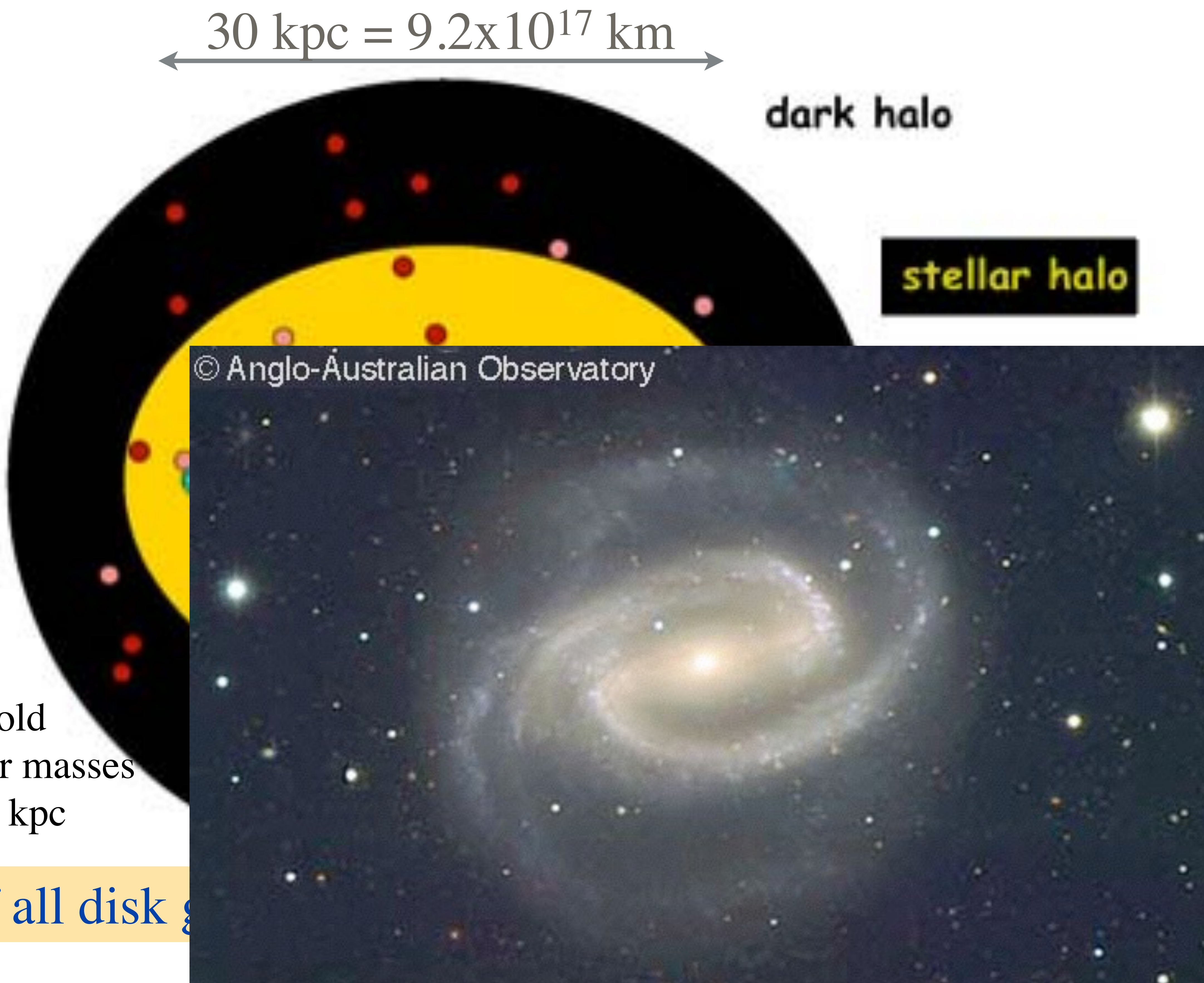
$30\ kpc = 9.2 \times 10^{17}\ km$



Age ~13.5 Gyr old
Mass ~10^{12} solar masses
Solar radius ~ 8 kpc

2/3 of all disk galaxies have central bars

Overview of our Galaxy



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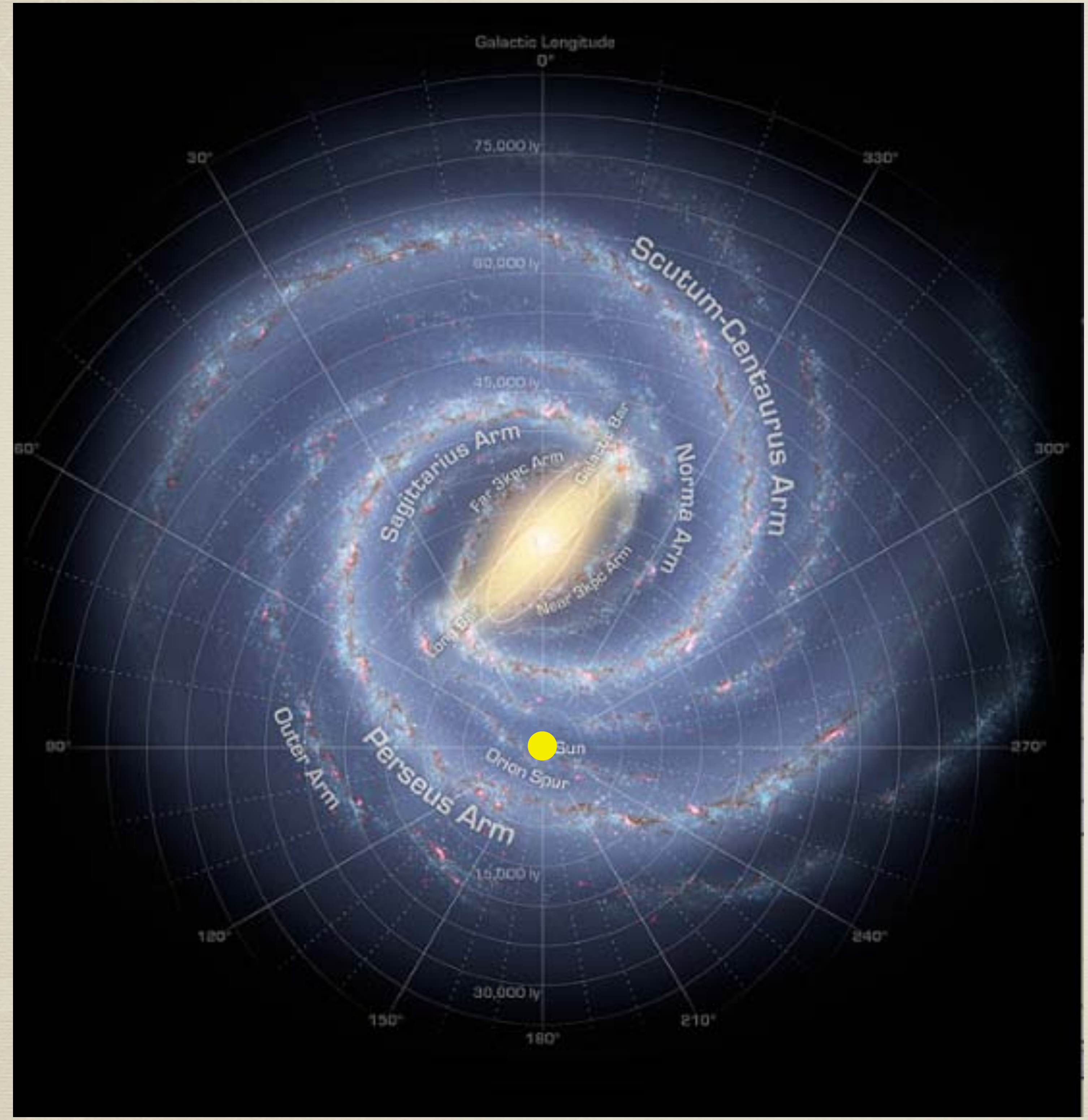
2/3 of all disk g

Age ~13.5 Gyr old
Mass ~10^{12} solar masses
Solar radius ~ 8 kpc

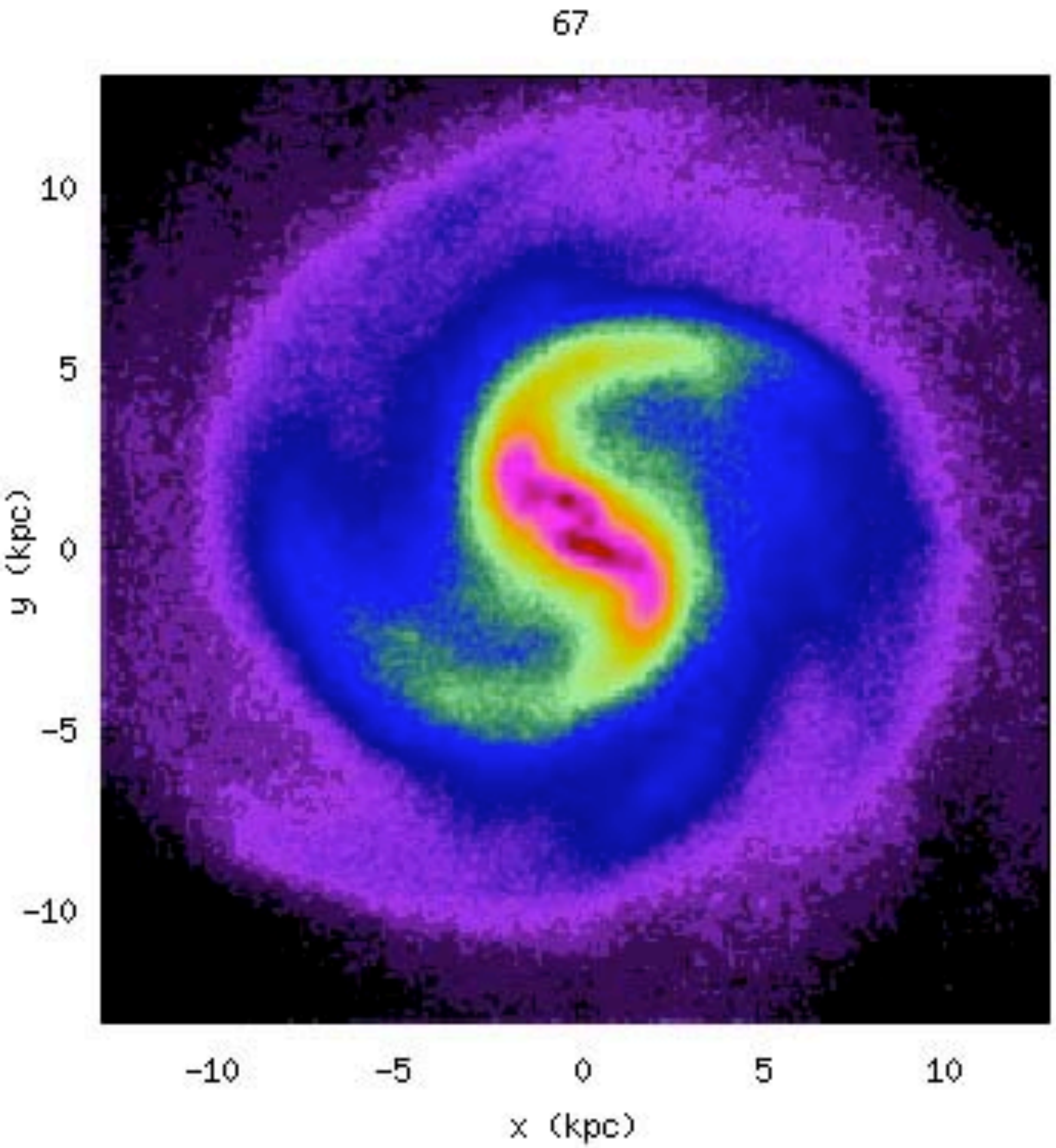
2/3 of all disk g

What we think our Galaxy looks like



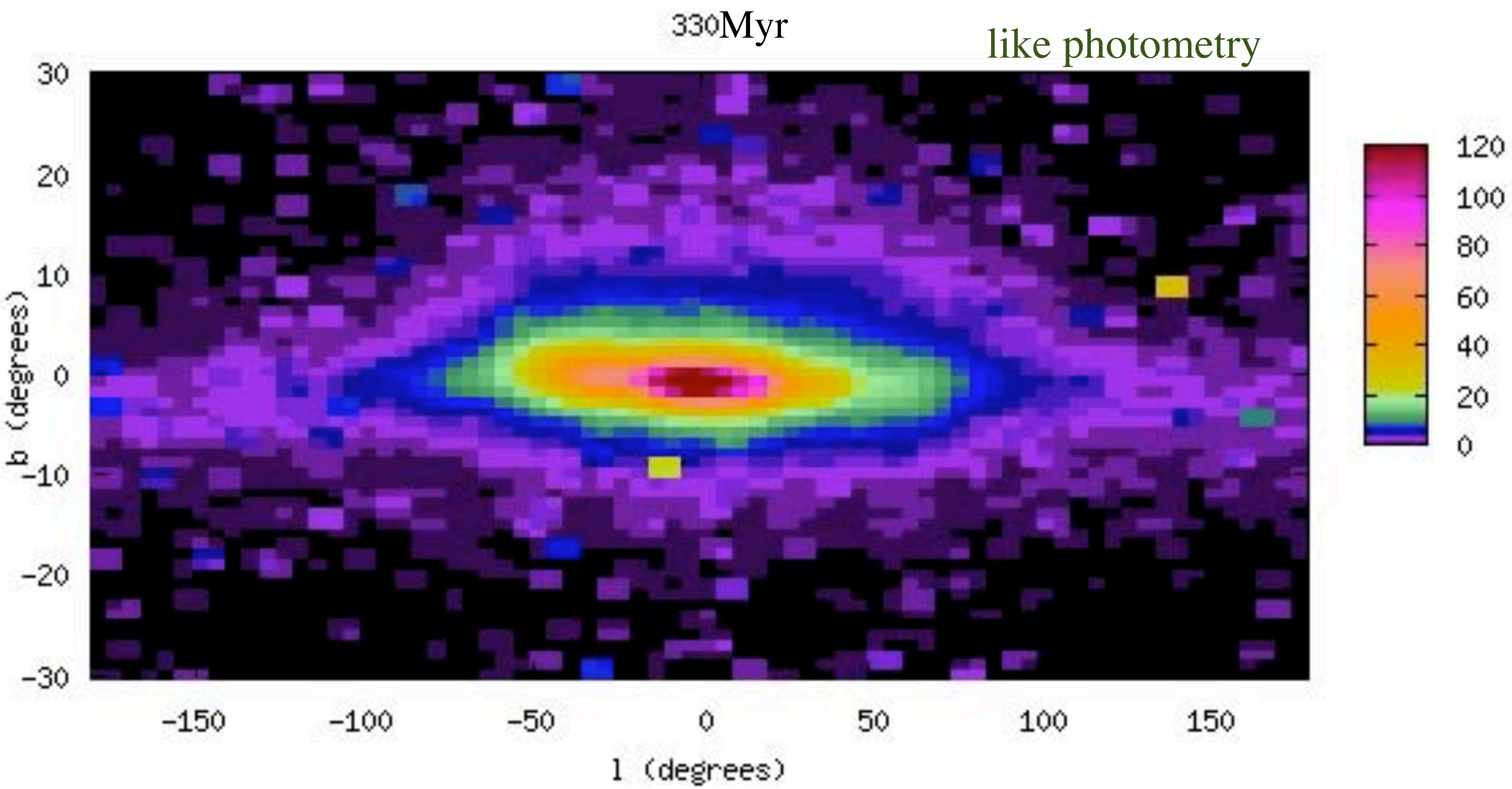
Due to our position in the disk, the disk morphology is still largely unknown

N-body simulation of a galactic disk



Spiral arms and a bar develop, similar to what we think we have in our Galaxy

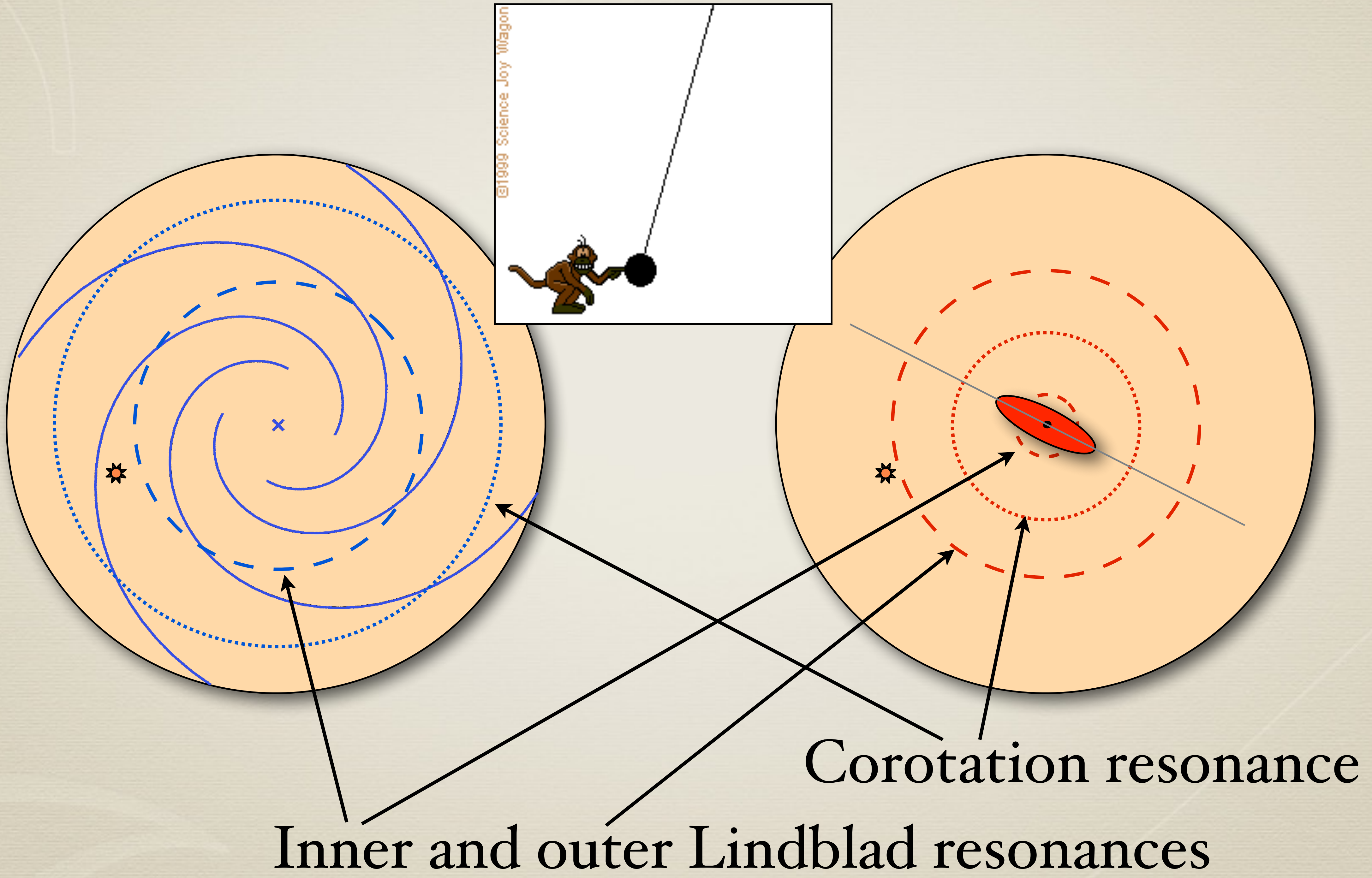
Hard to infer the Milky Way morphology from our position in the disk



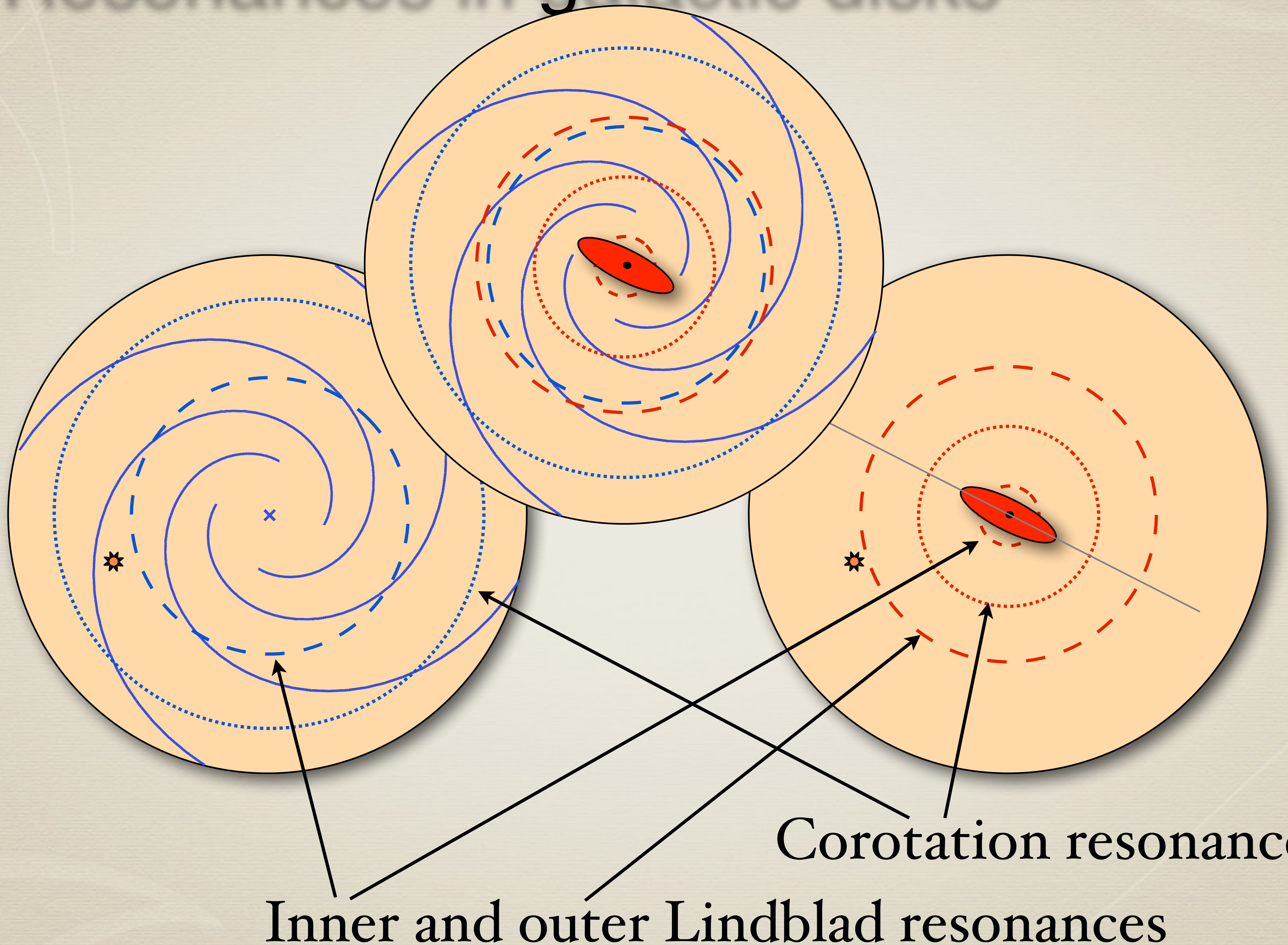
Like our view in the Milky Way disk

N-body simulation (phi grape GPU, Quillen et al. 2011)

Resonances in galactic disks



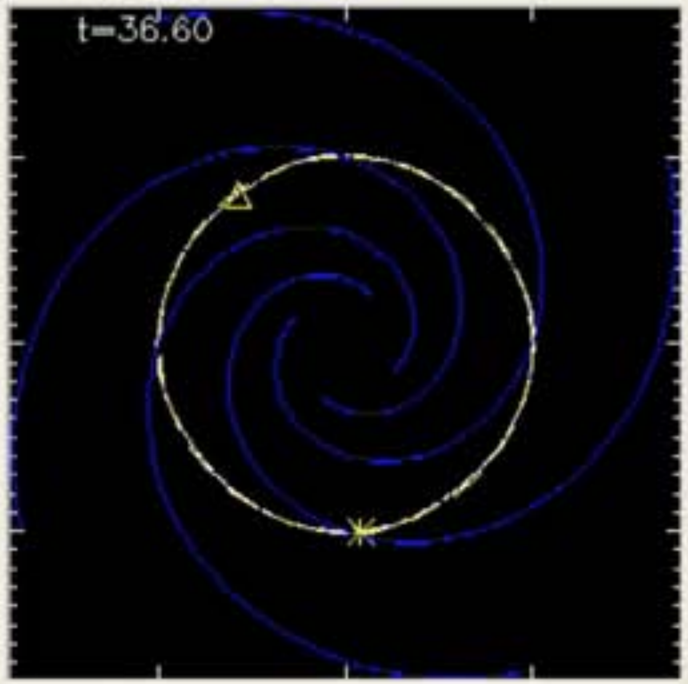
Resonances in galactic disks



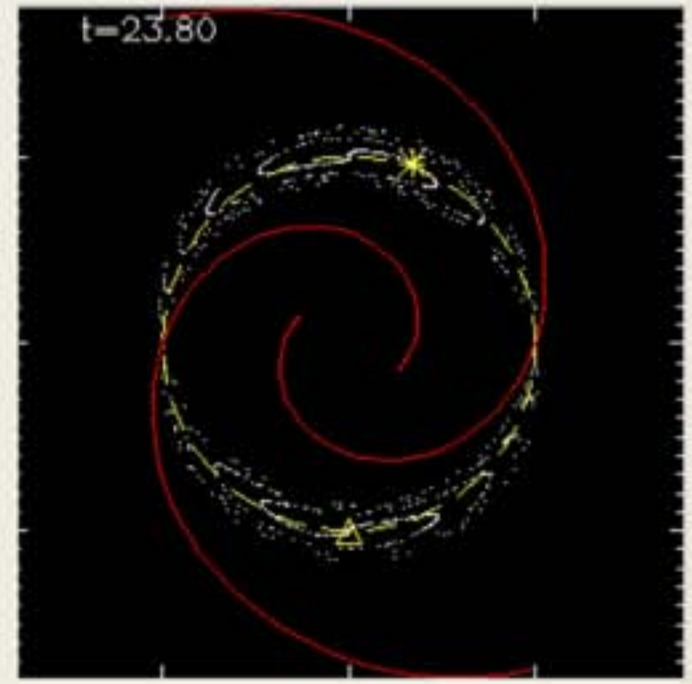
Stellar orbits near resonances

Single spiral wave

Near OLR

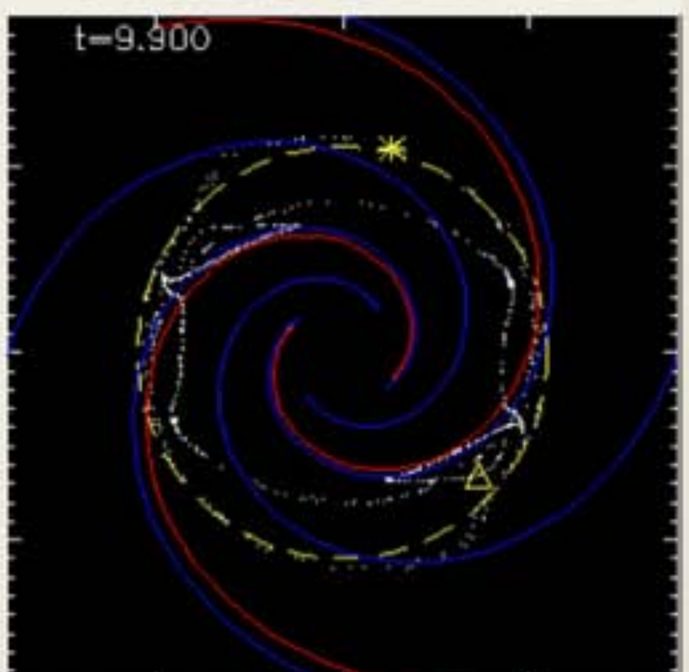


Near Corotation (CR)

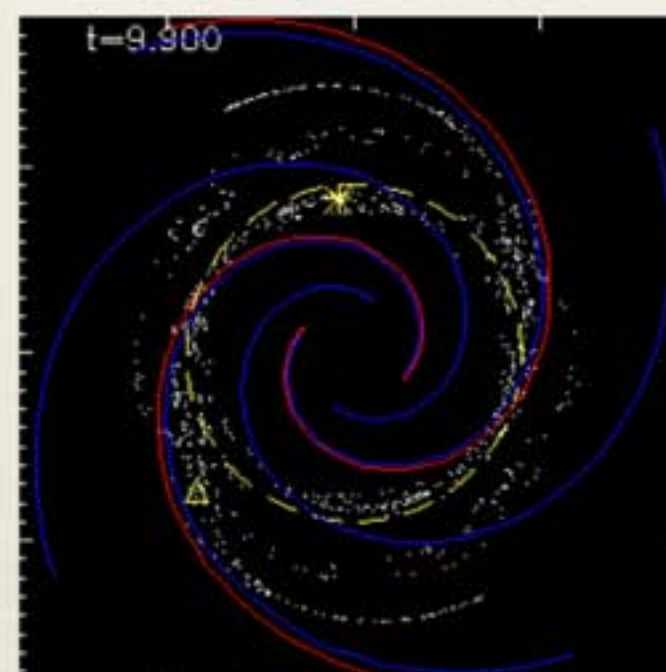


2 spiral waves

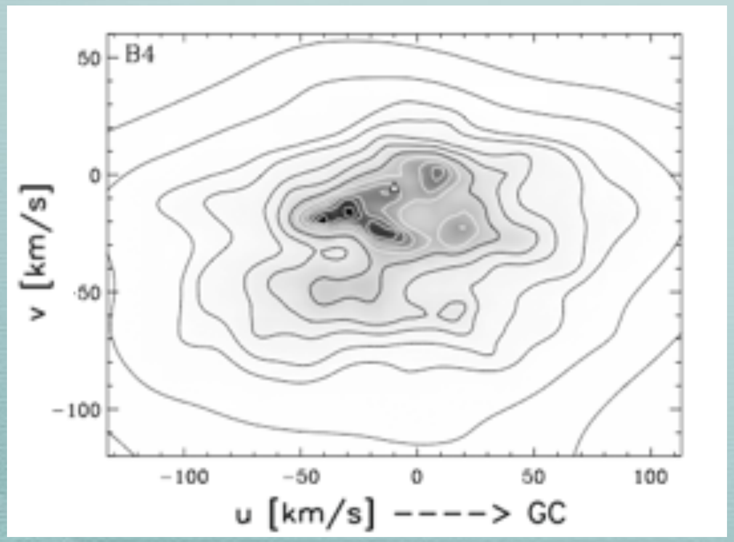
Outside OLR+CR

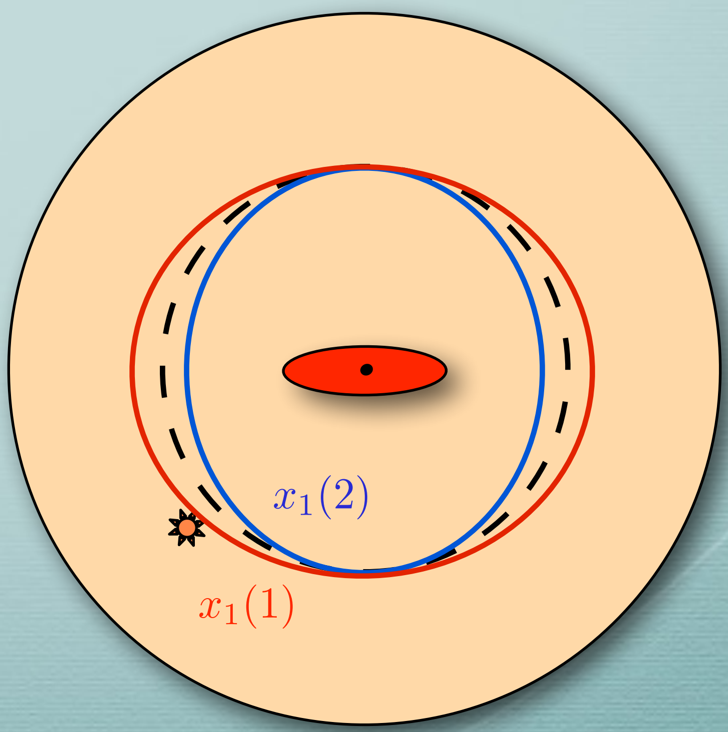


Inside OLR+CR



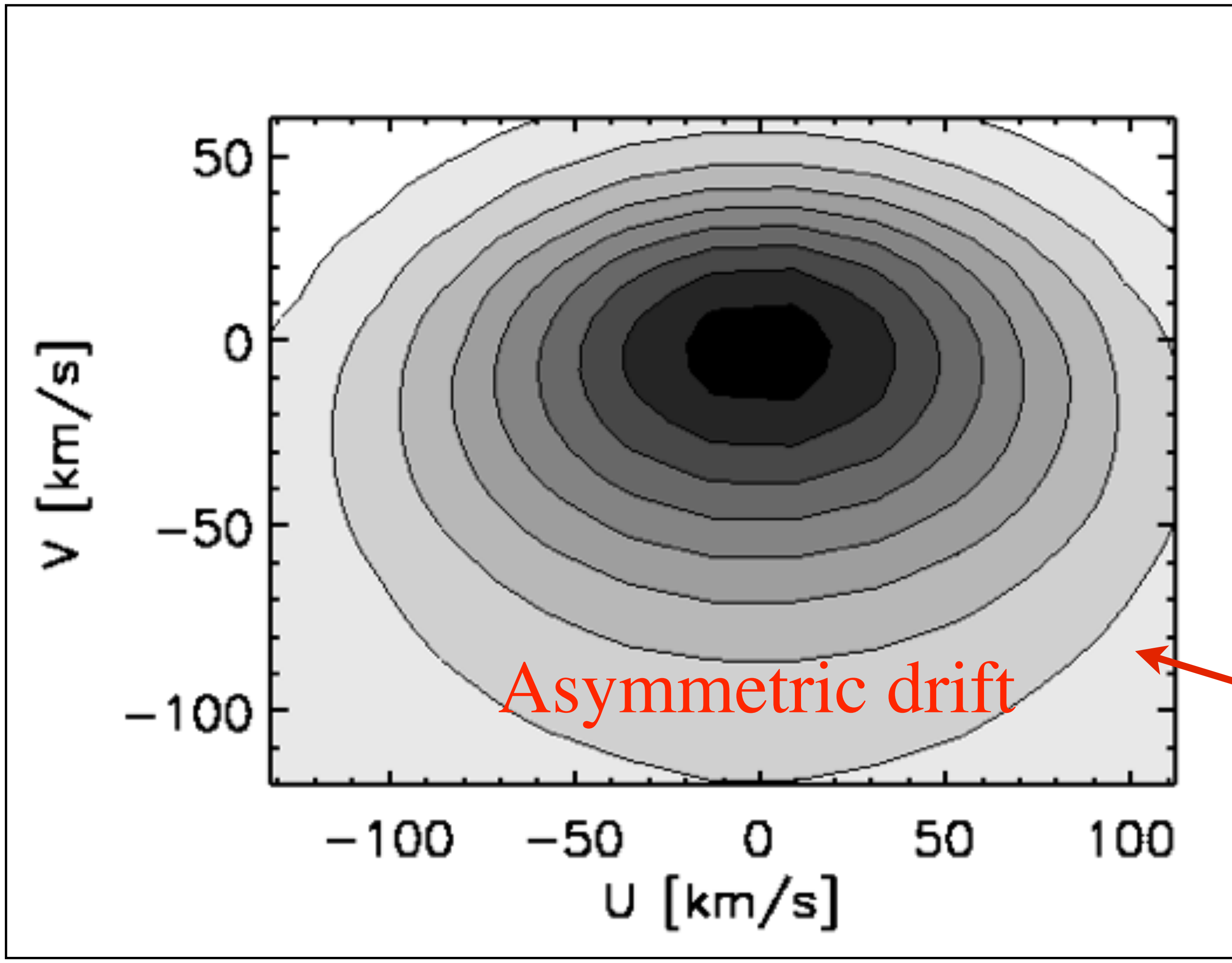
Resonant moving groups (or streams) in the solar neighborhood



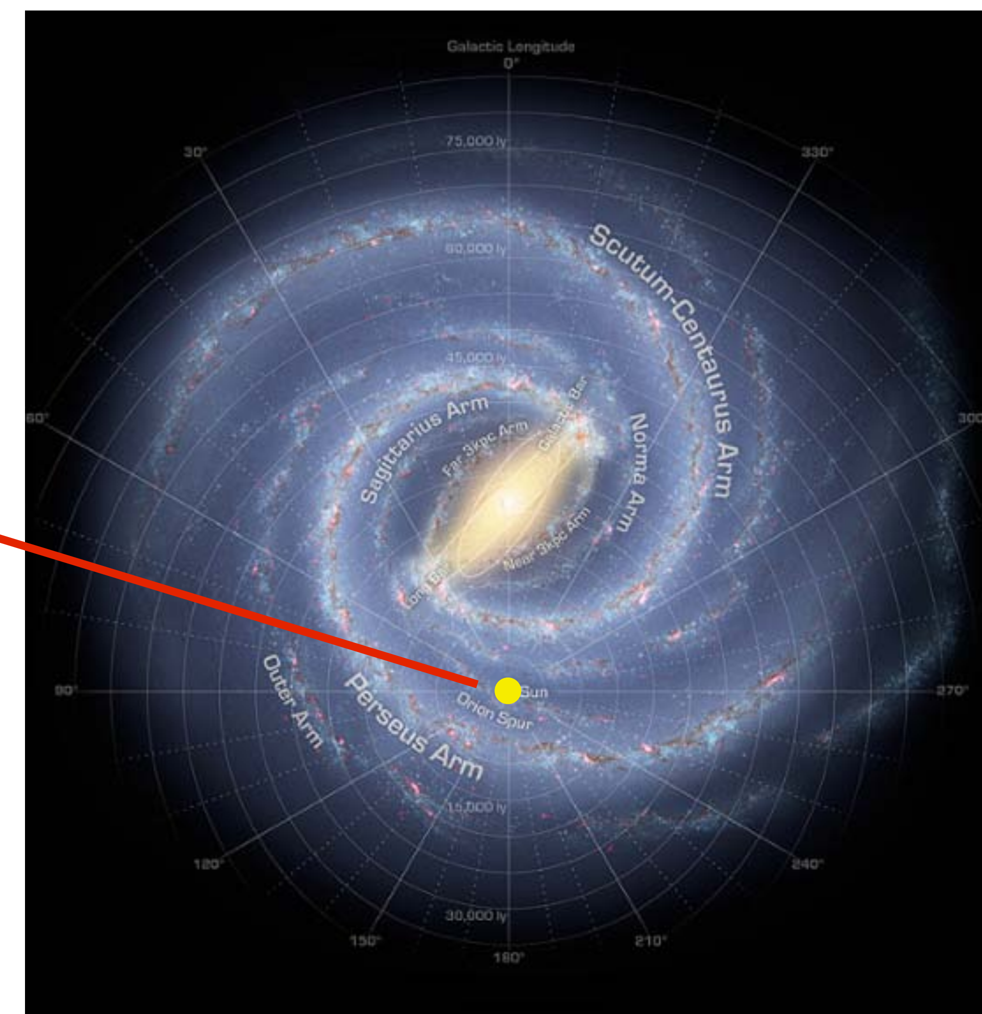


Velocity space in a small spatial region in the disk (the u-v plane)

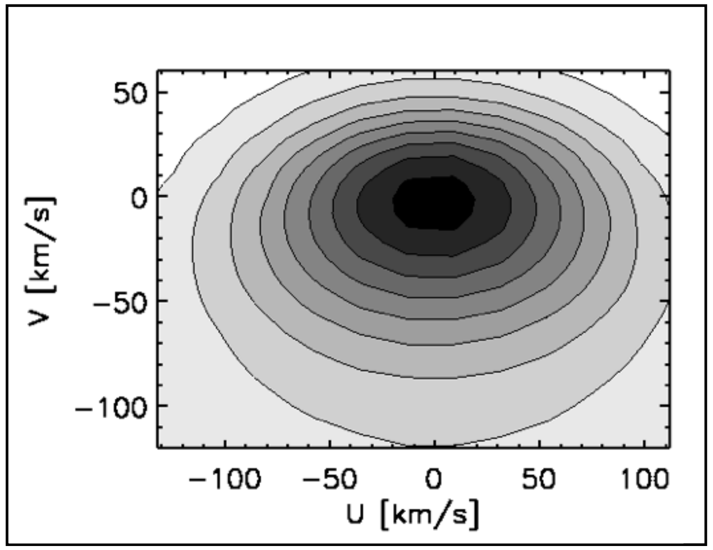
If the Milky Way disk were axisymmetric



V - tangential velocity
U - radial velocity



Hipparcos stellar velocity distribution

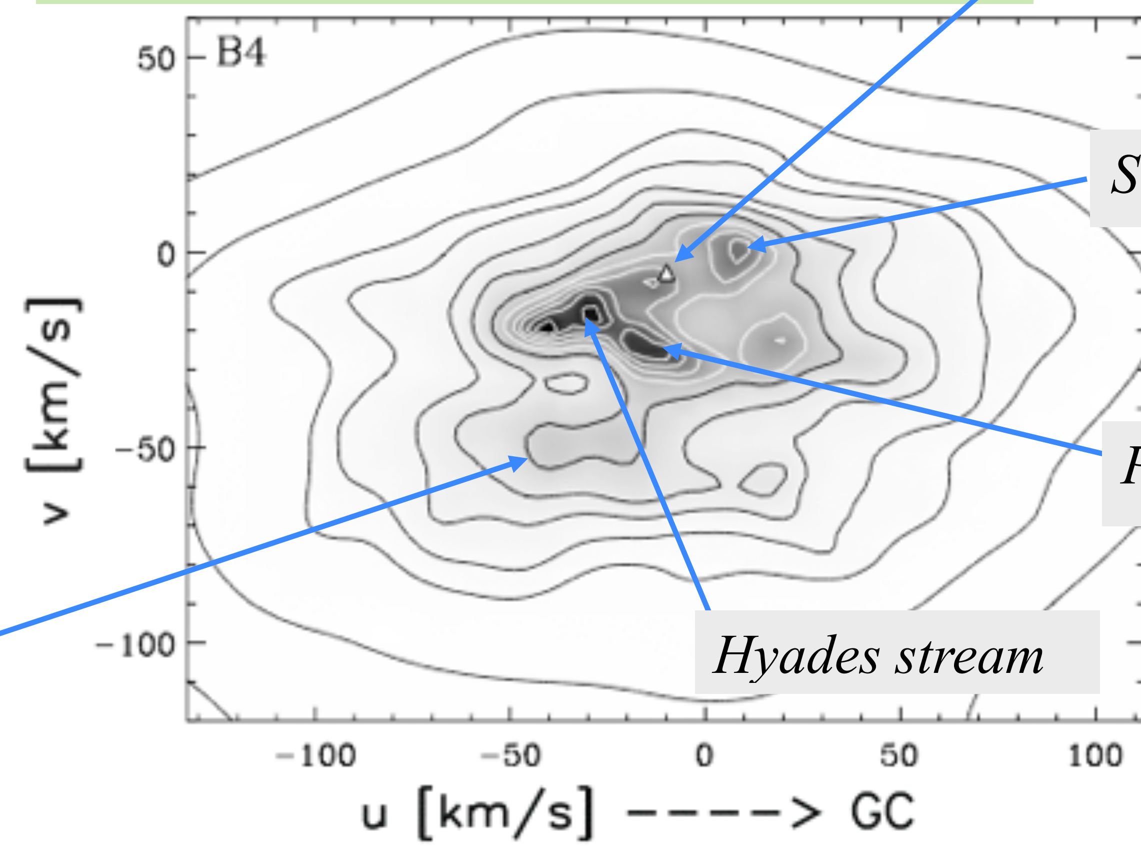


- Lots of structure is seen in the u-v plane.
- The most prominent low-velocity moving groups in the solar neighborhood favor a dynamical origin (e.g., Famaey et al. 2008).
- Created near resonances with bar or spiral structure

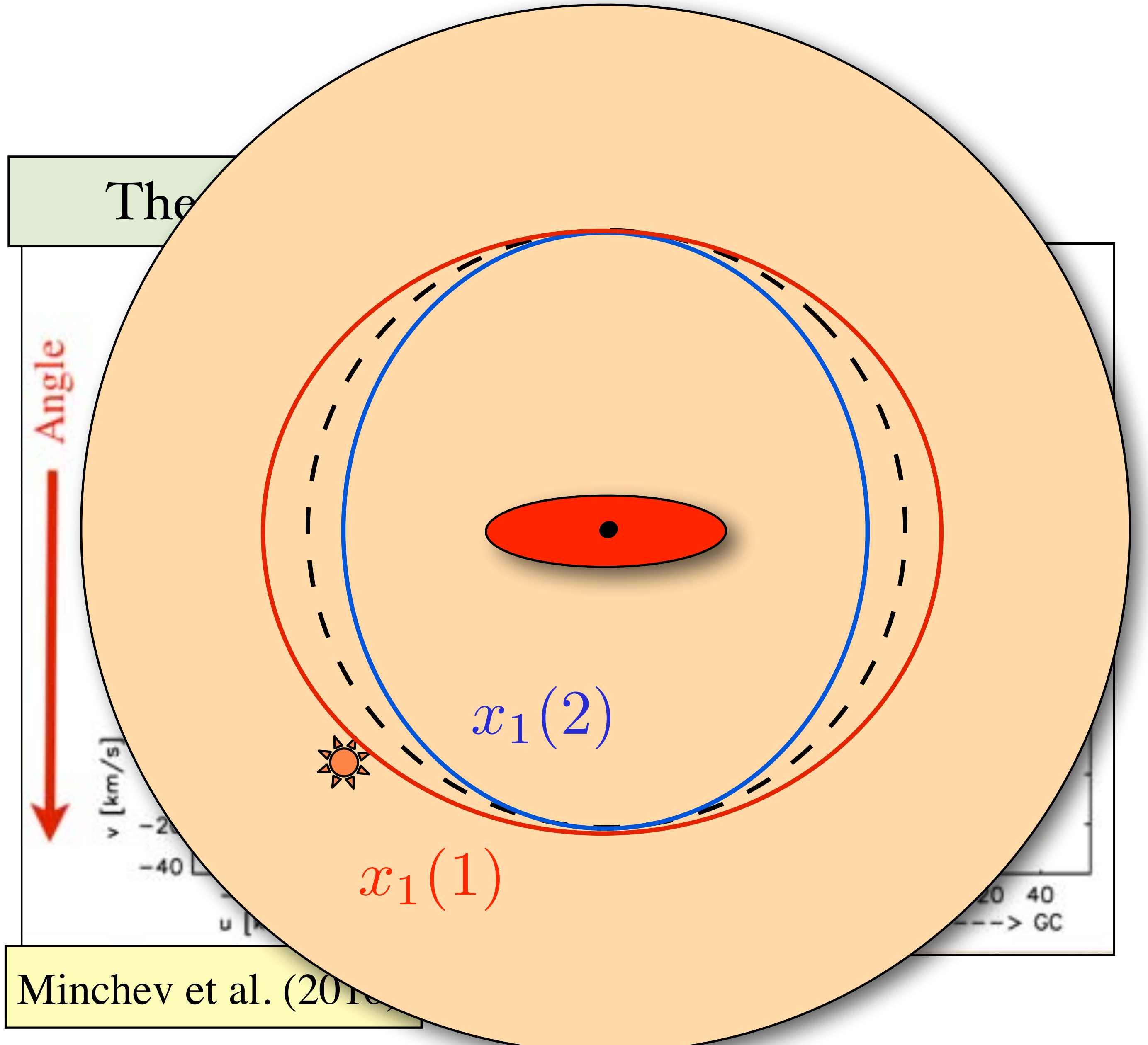
Can constrain both angular velocity and orientation

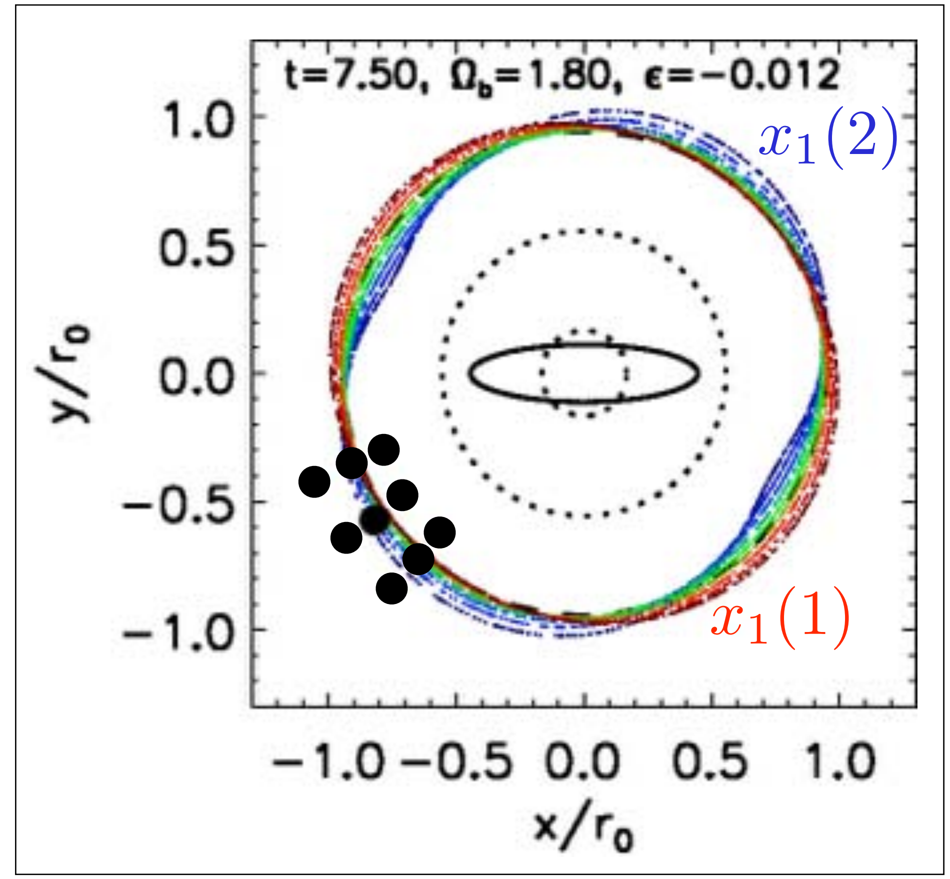
Dehnen (2000)
Quillen & Minchev (2005)
Minchev et al. (2010)

Stellar velocity distribution, Dehnen (1998)



Modeling the u-v plane



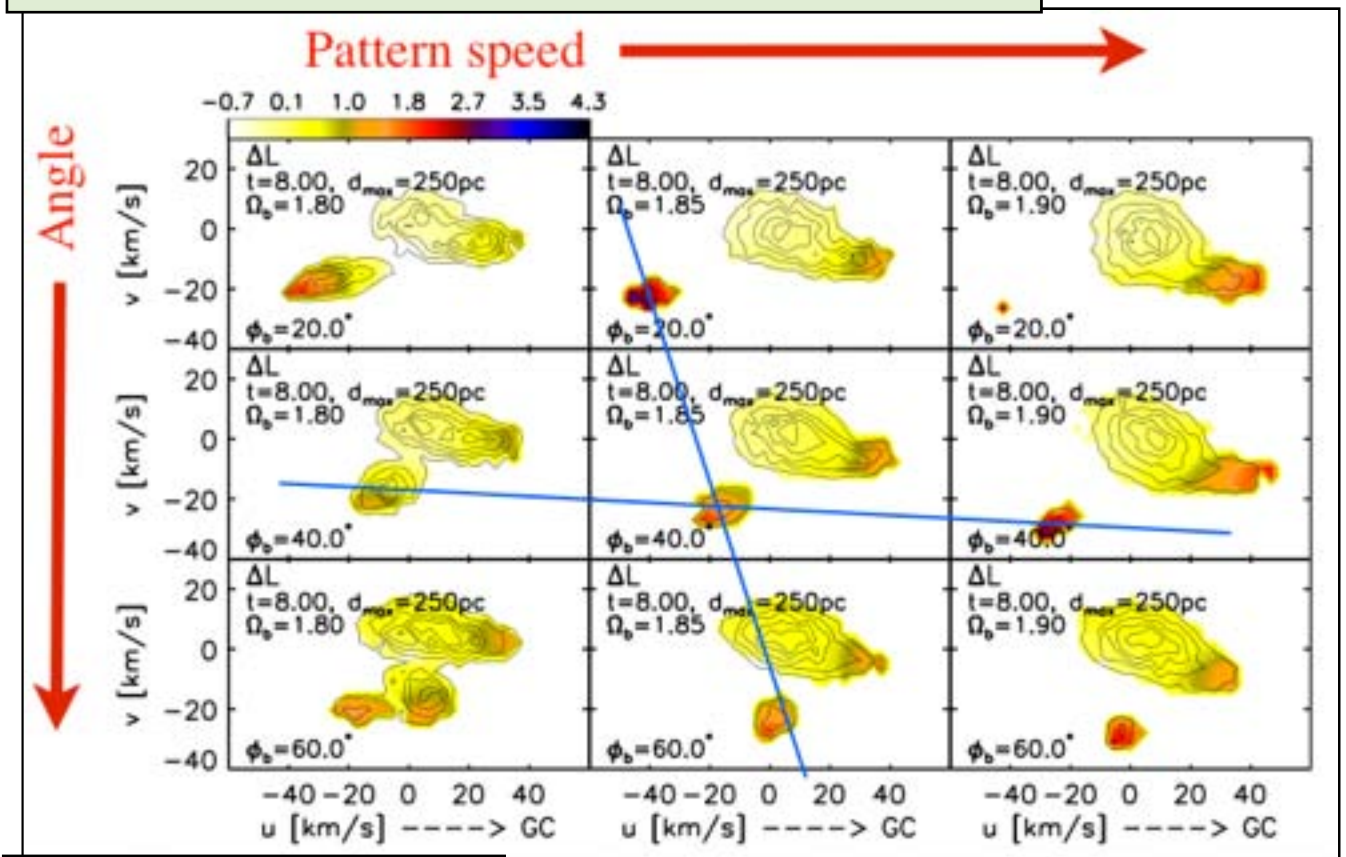


Clumps shift with galactic radius and azimuth

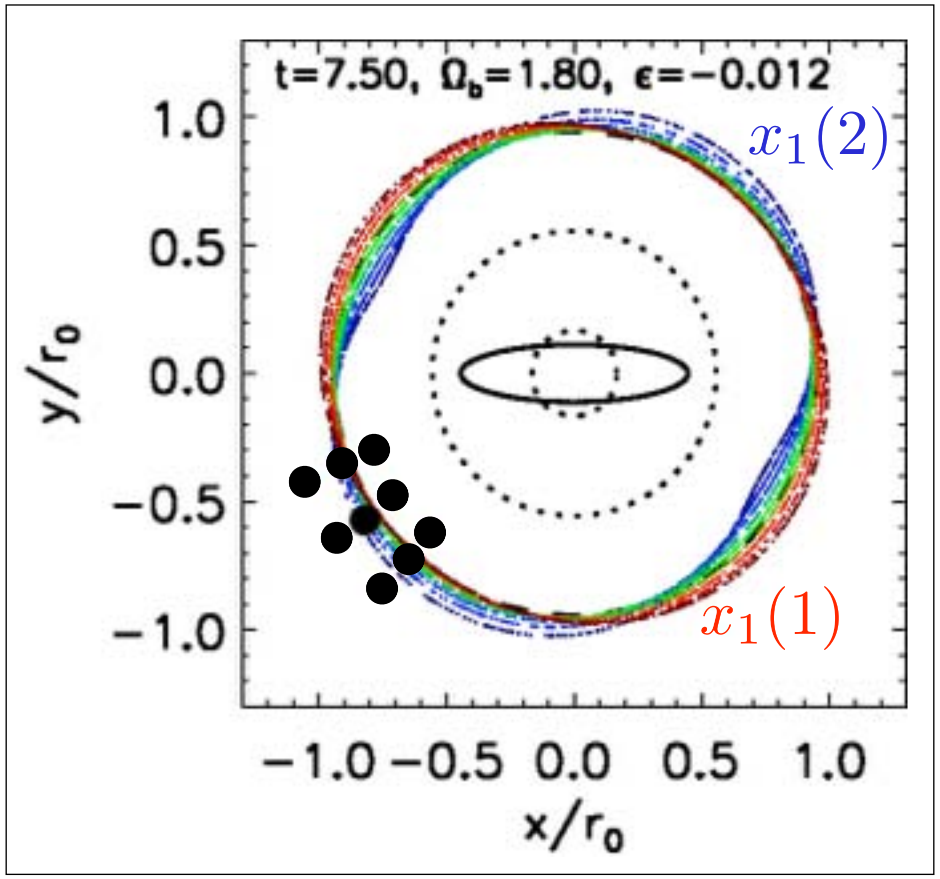
Each region on the u-v plane corresponds to a different family of closed/periodic

Modeling the u-v plane

The effect of the Galactic bar



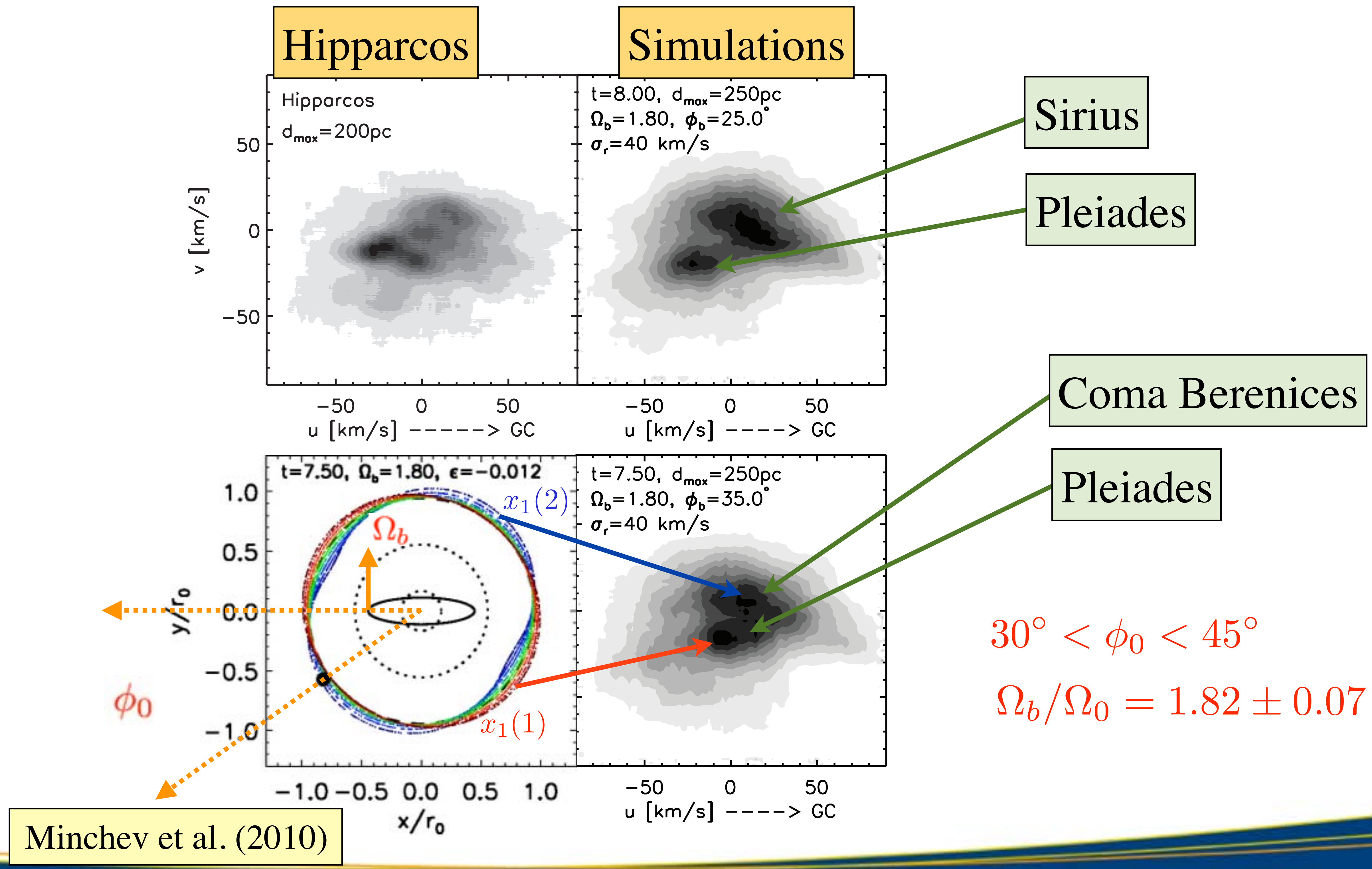
Minchev et al. (2010)



Clumps shift with galactic radius and azimuth

Each region on the u-v plane corresponds to a different family of closed/periodic

Matching to Hipparcos data



$30° < \phi_0 < 45°$

$\Omega_b/\Omega_0 = 1.82 \pm 0.07$

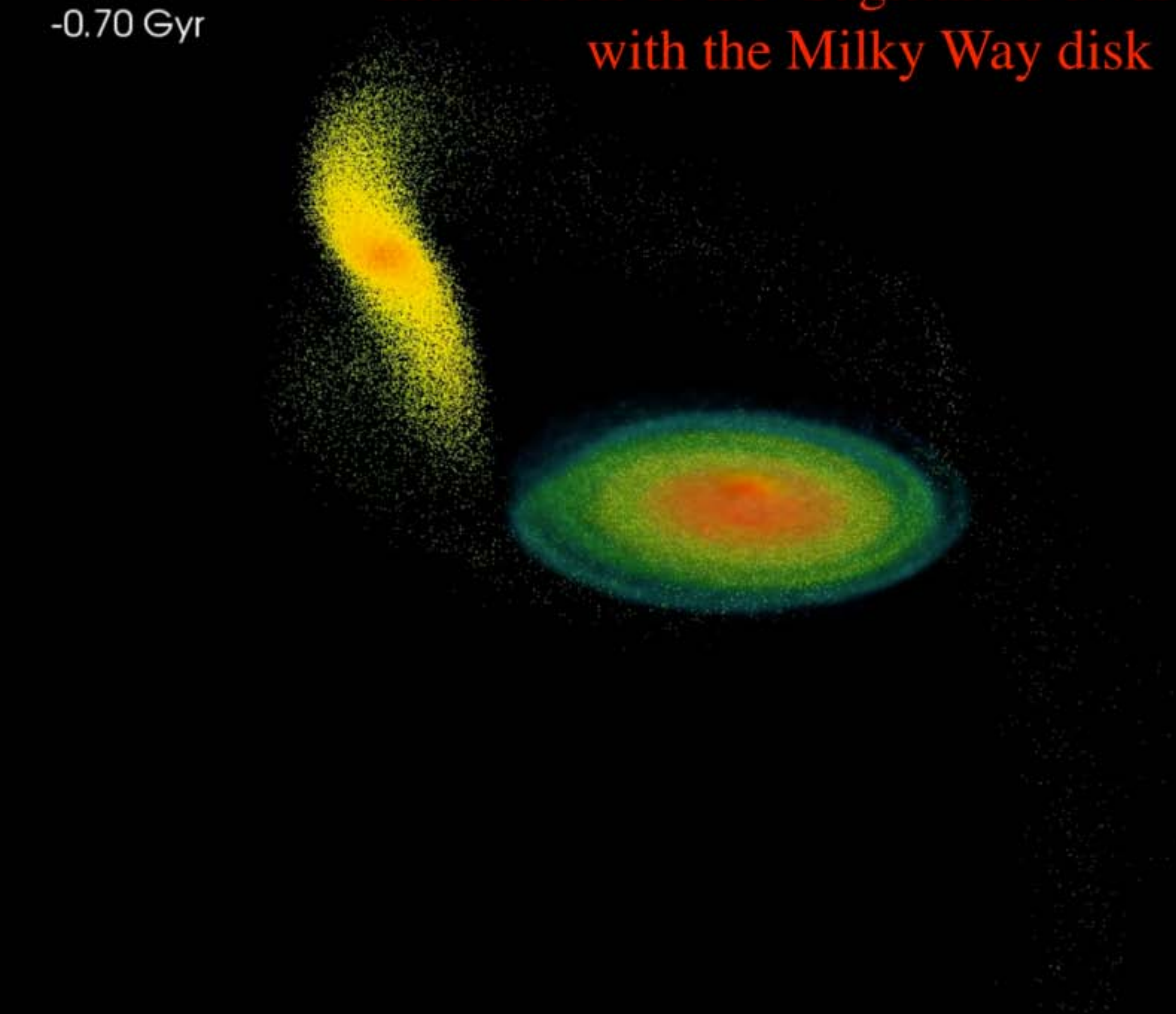
High-velocity streams in the solar neighborhood

- HR1614 at V= - 60 km/s (De Silva PhD thesis)
- An overdensity at V= - 80 km/s (Arifyanto and Fuchs 2006)
- Arcturus at V= - 100 km/s (Mary Williams PhD thesis)
- RAVE at V= - 160 km/s (Klement et al. 2008)

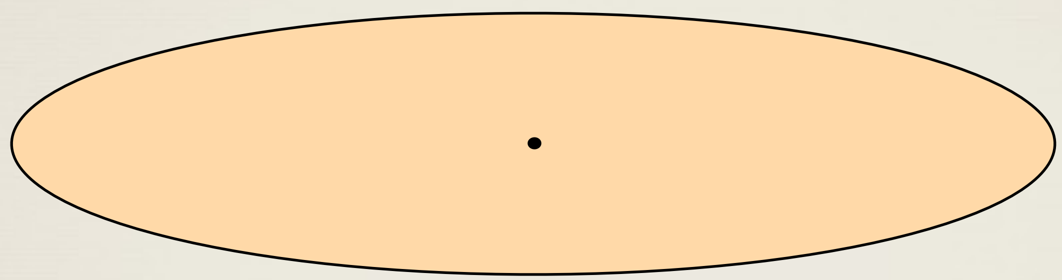
Bar and spirals not able to effect the U-V plane at U, V > ~40 km/s

But perturbations by dwarf galaxies interacting with the Milky Way disk can.

Interaction of the Sagittarius dwarf galaxy with the Milky Way disk

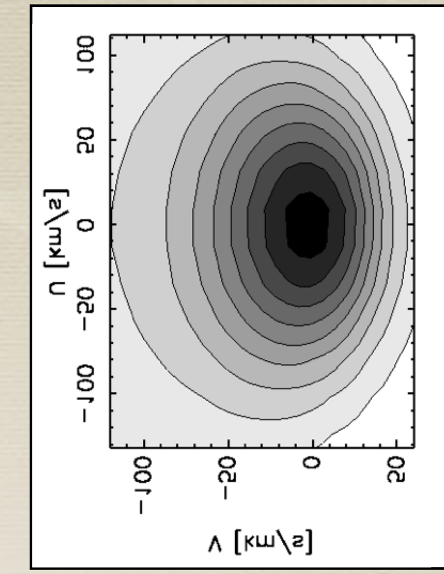


Simulation from Purcell et al. (2011)

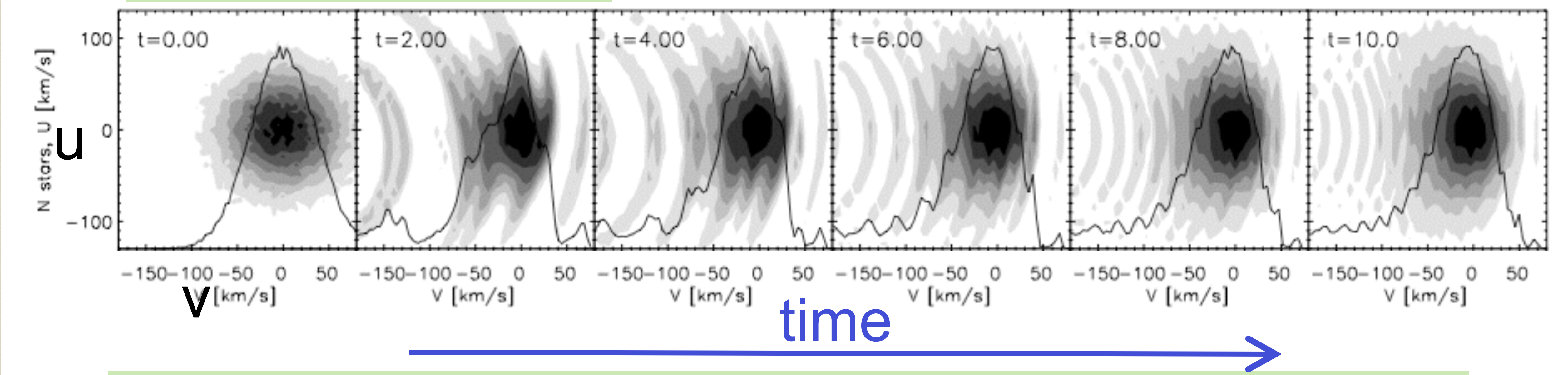


Phase wrapping in the disk

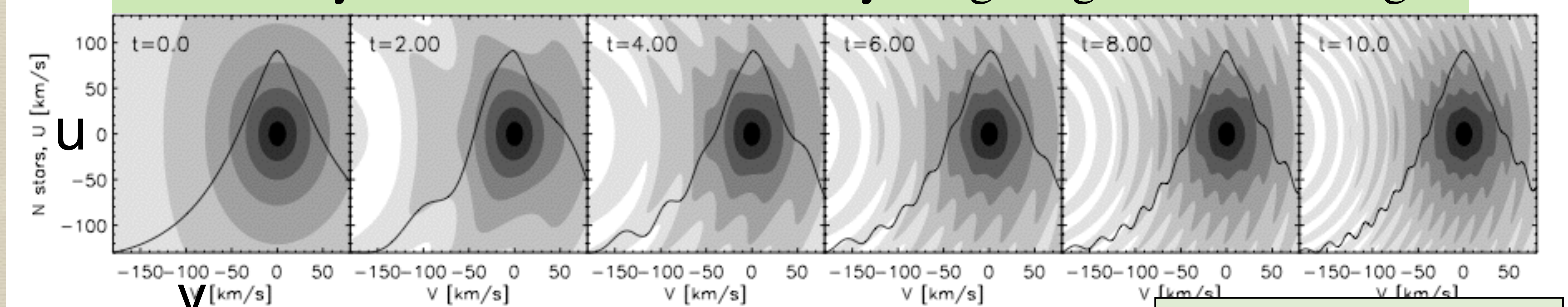
- Following an uneven distribution in epicyclic angle, the thick disk can exhibit streams



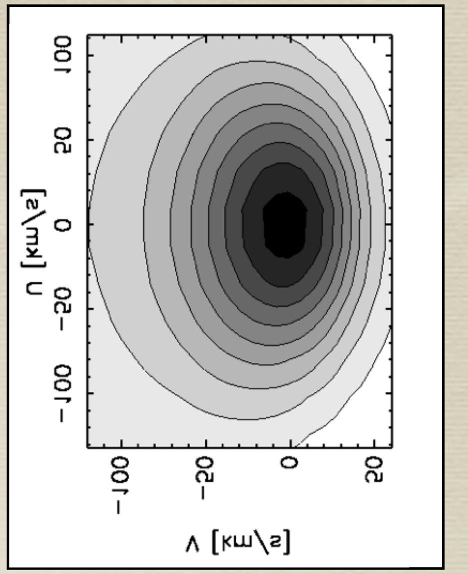
Stellar disk simulations



Semi-analytical model constructed by weighting with radial angle

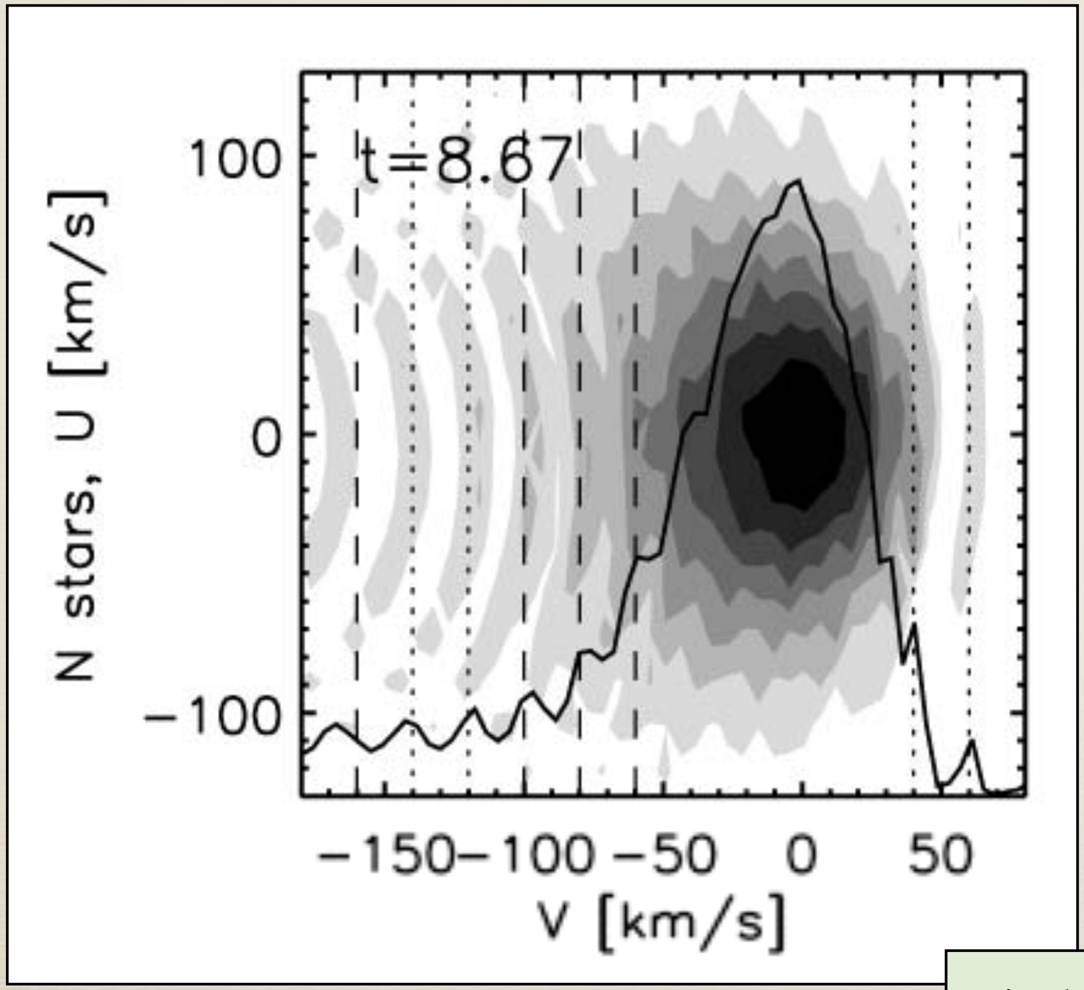


Minchev et al. (2009)



Is the Milky Way ringing?

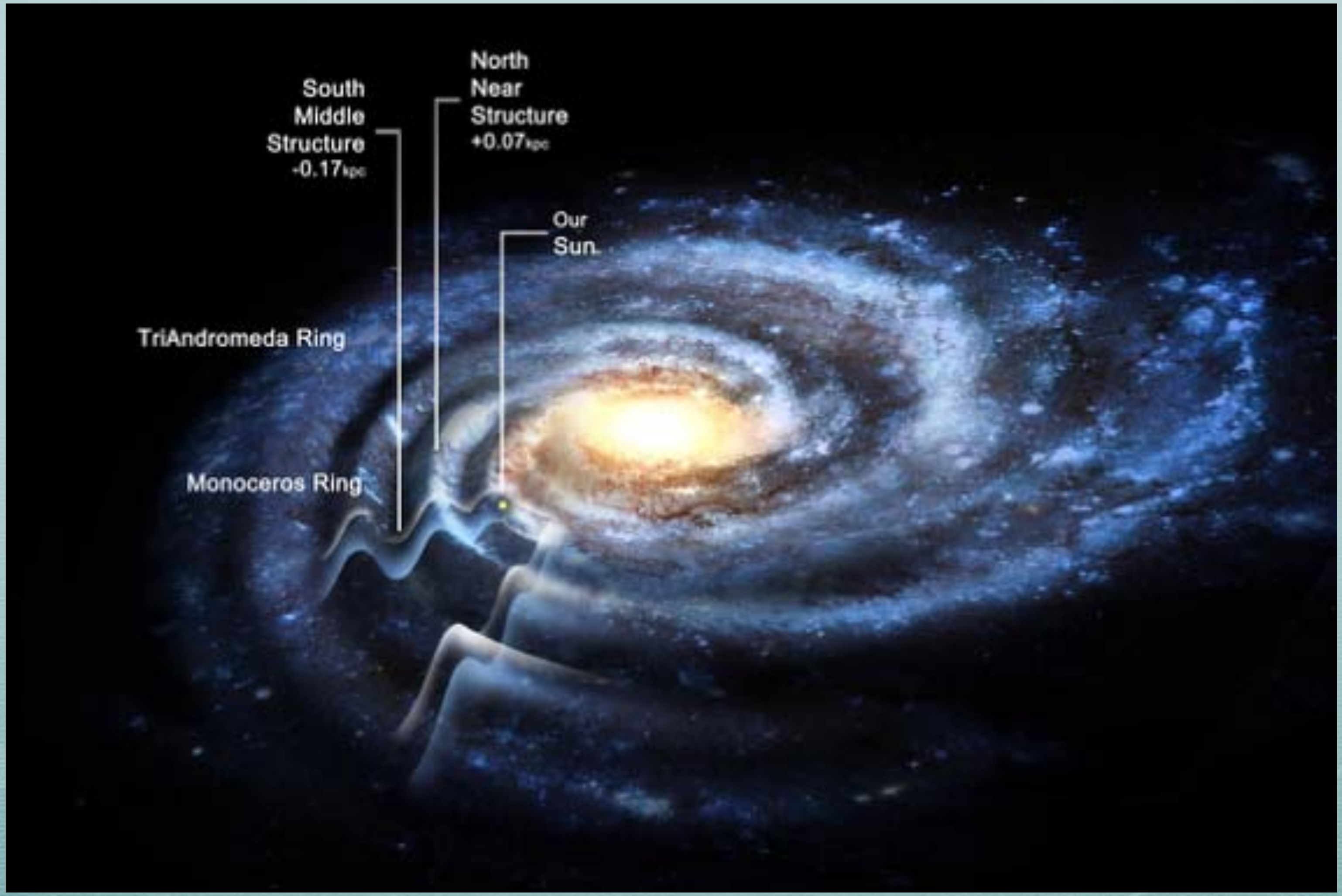
- Match stream positions to known high-velocity streams in the solar neighborhood velocity distribution.



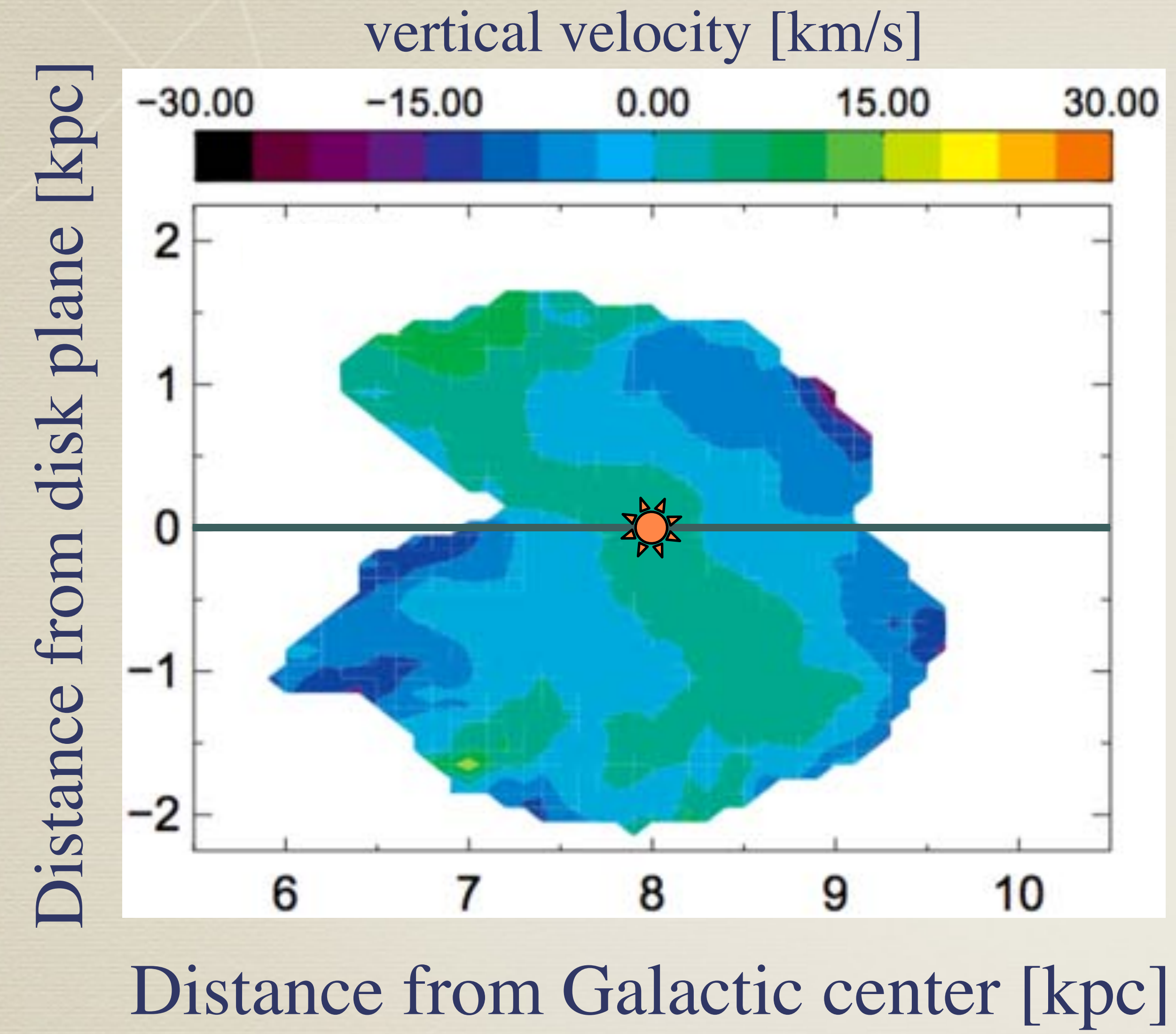
Minchev et al. (2009)

- Consistent with a minor merger ~2 Gyr ago.

Disk wobbling or corrugations

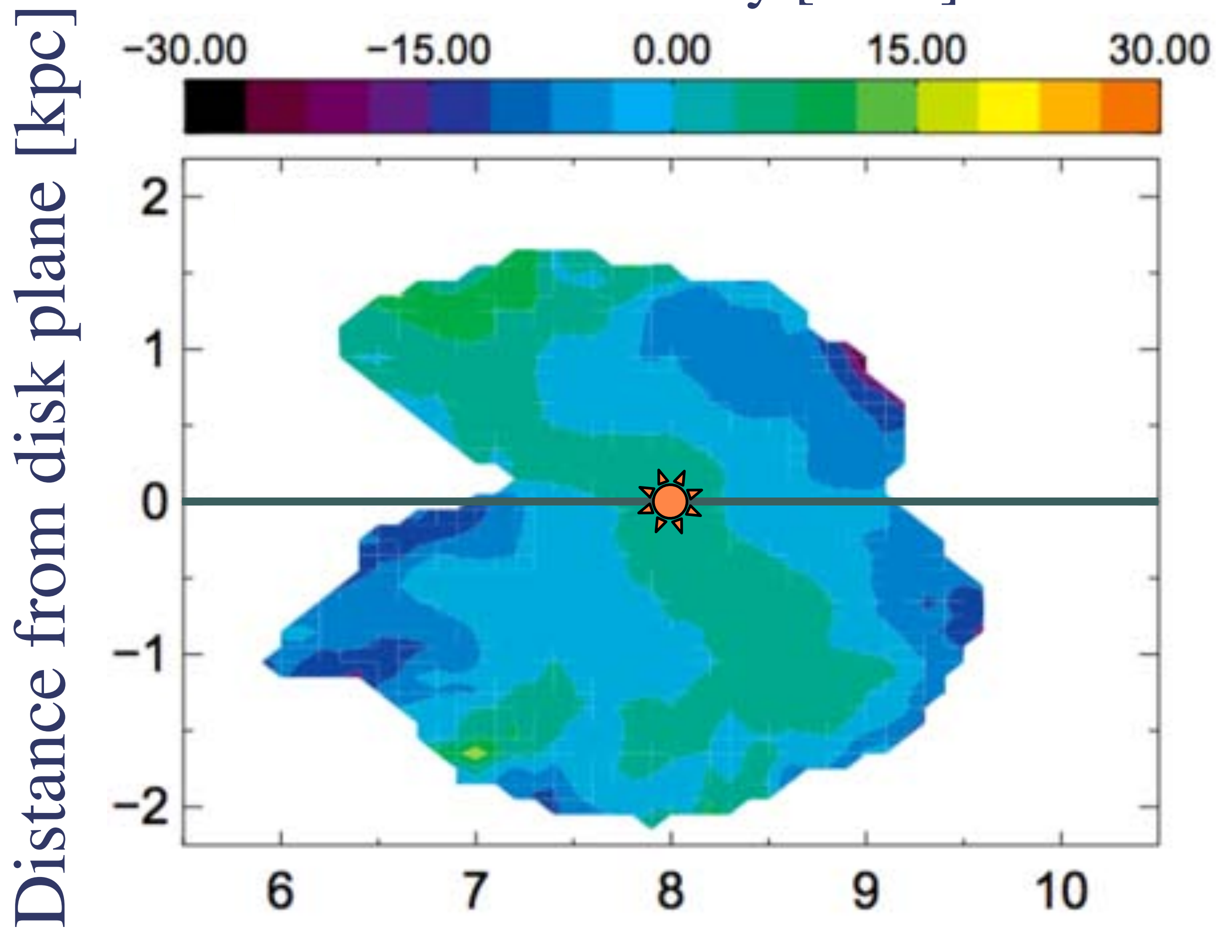


Vertical disk waves found in RAVE data



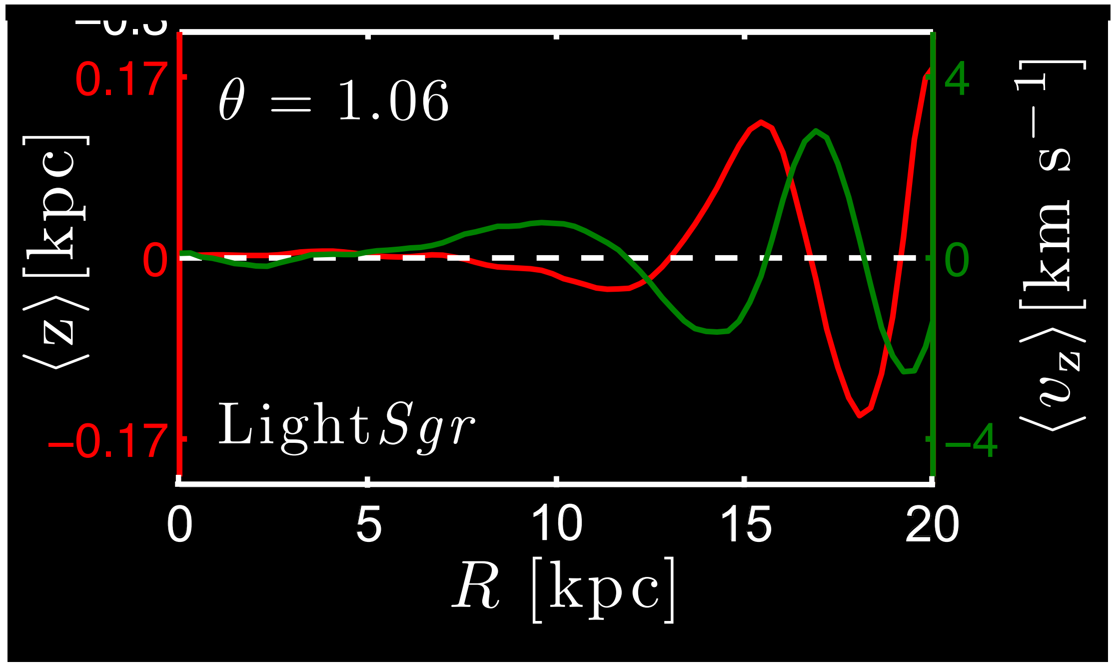
Williams + RAVE (2013)

Vertical disk waves found in RAVE data



Distance from Galactic center [kpc]

Simulations

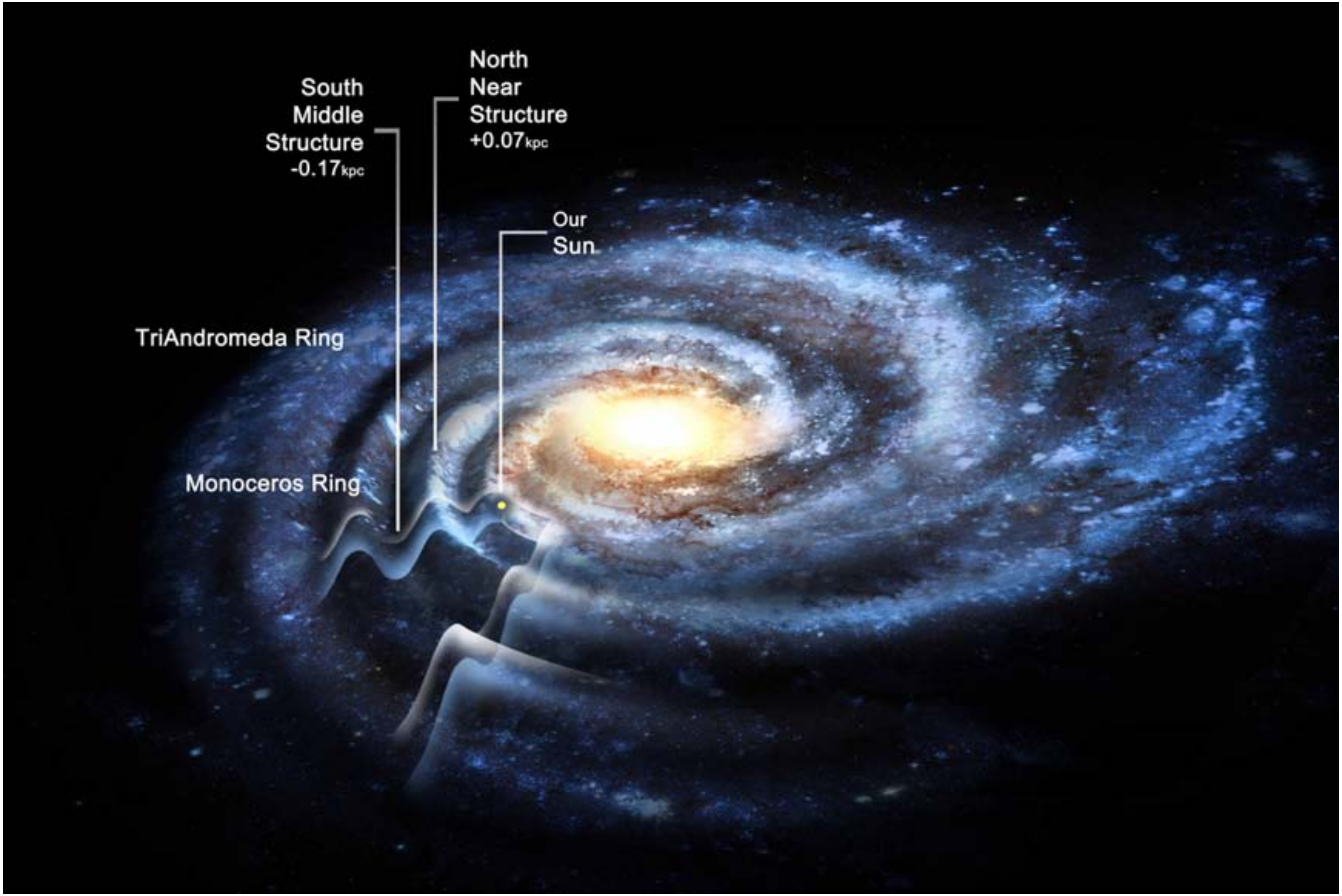


Distance from Galactic center [kpc]

Williams + RAVE (2013)

Gómez, Minchev et al. (2013)

Explained by the effect of the Sagittarius dwarf galaxy

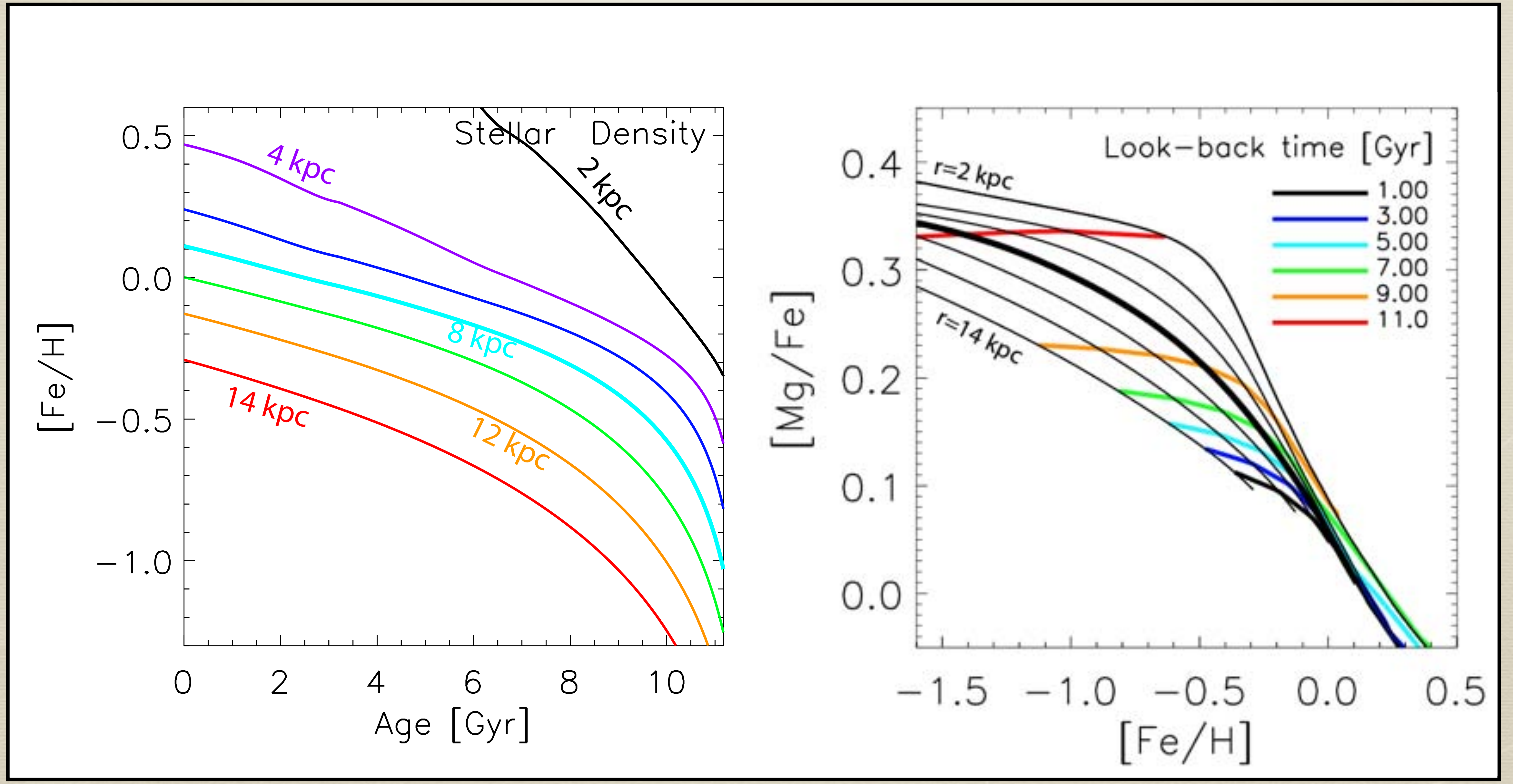

North
Near
Structure
+0.07kpc
South
Middle
Structure
-0.17kpc
Our
Sun
TriAndromeda Ring
Monoceros Ring

A chemo-dynamical evolution model for the Milky Way

Minchev, Chiappini & Martig (2013, 2014)

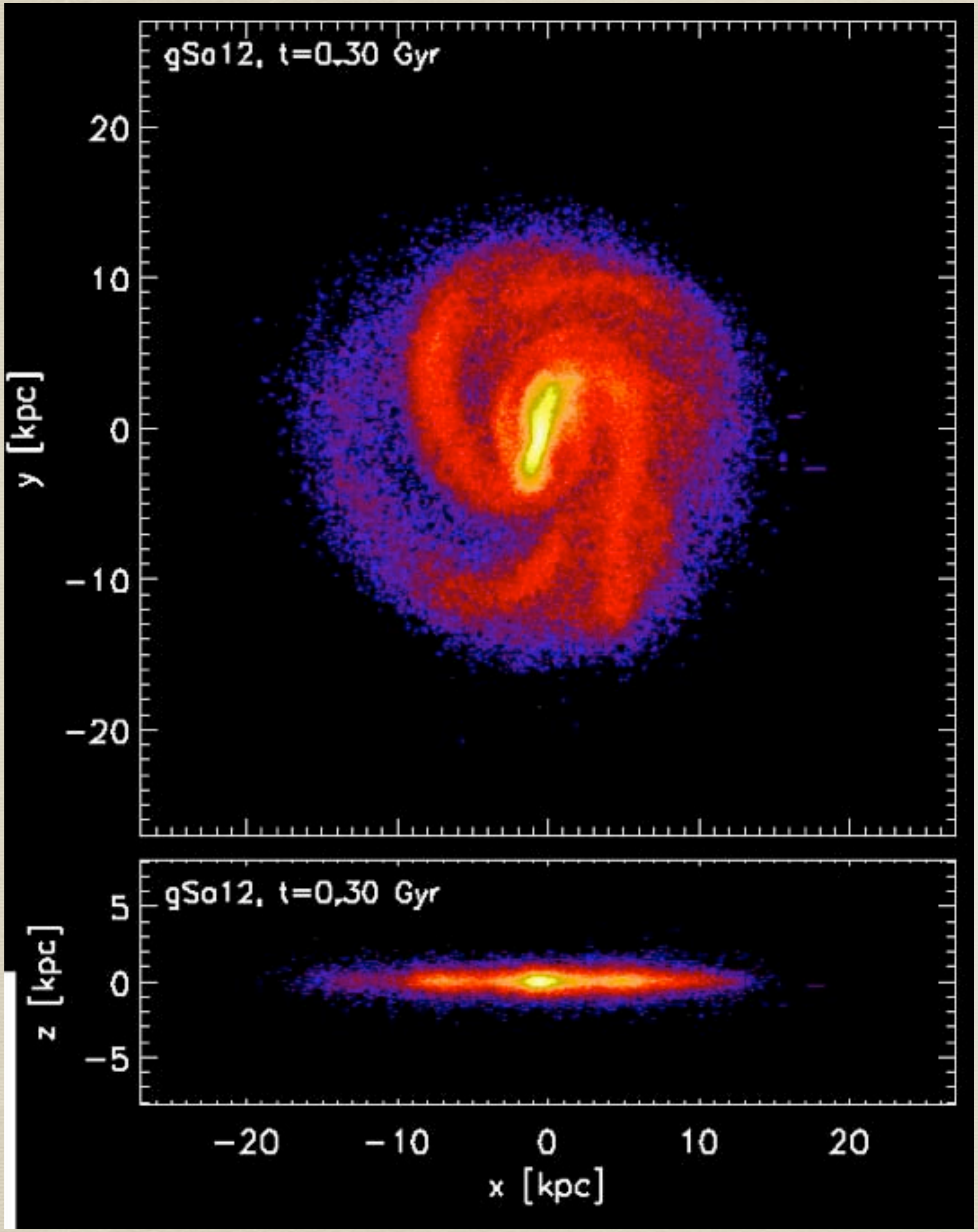
Classical chemical evolution modeling

- Semi-analytical chemical evolution models (Matteucci & Francois 1989; Prantzos & Aubert 1995; Chiappini et al. 1997, 2001).
- Stars assumed to remain close to their birth places.



Stellar (gas) Radial migration

hampers classical chemical evolution modeling



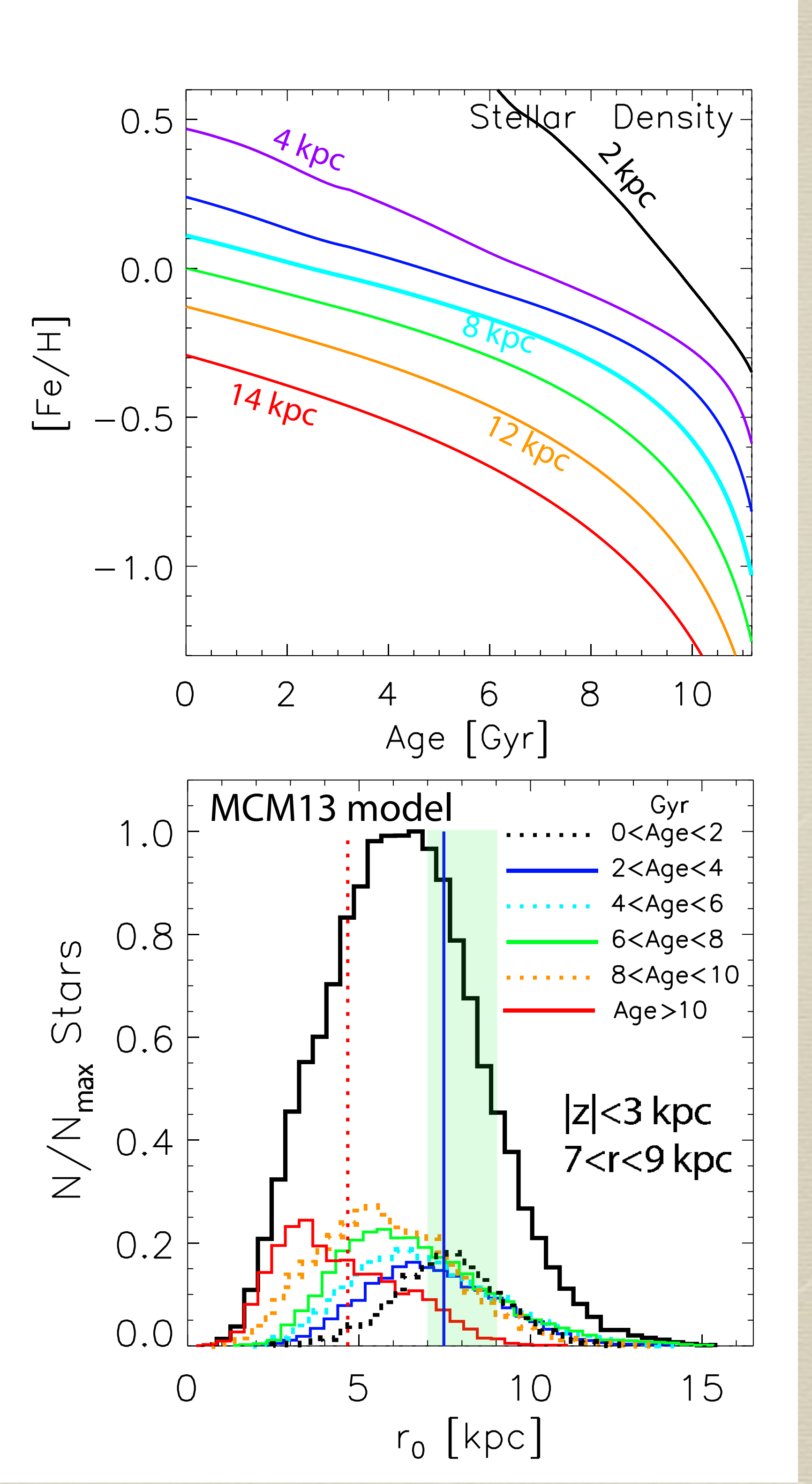
Disk expands due to strong angular momentum transport outwards.

Disk thickens

N-Body Simulations by P. Di Matteo

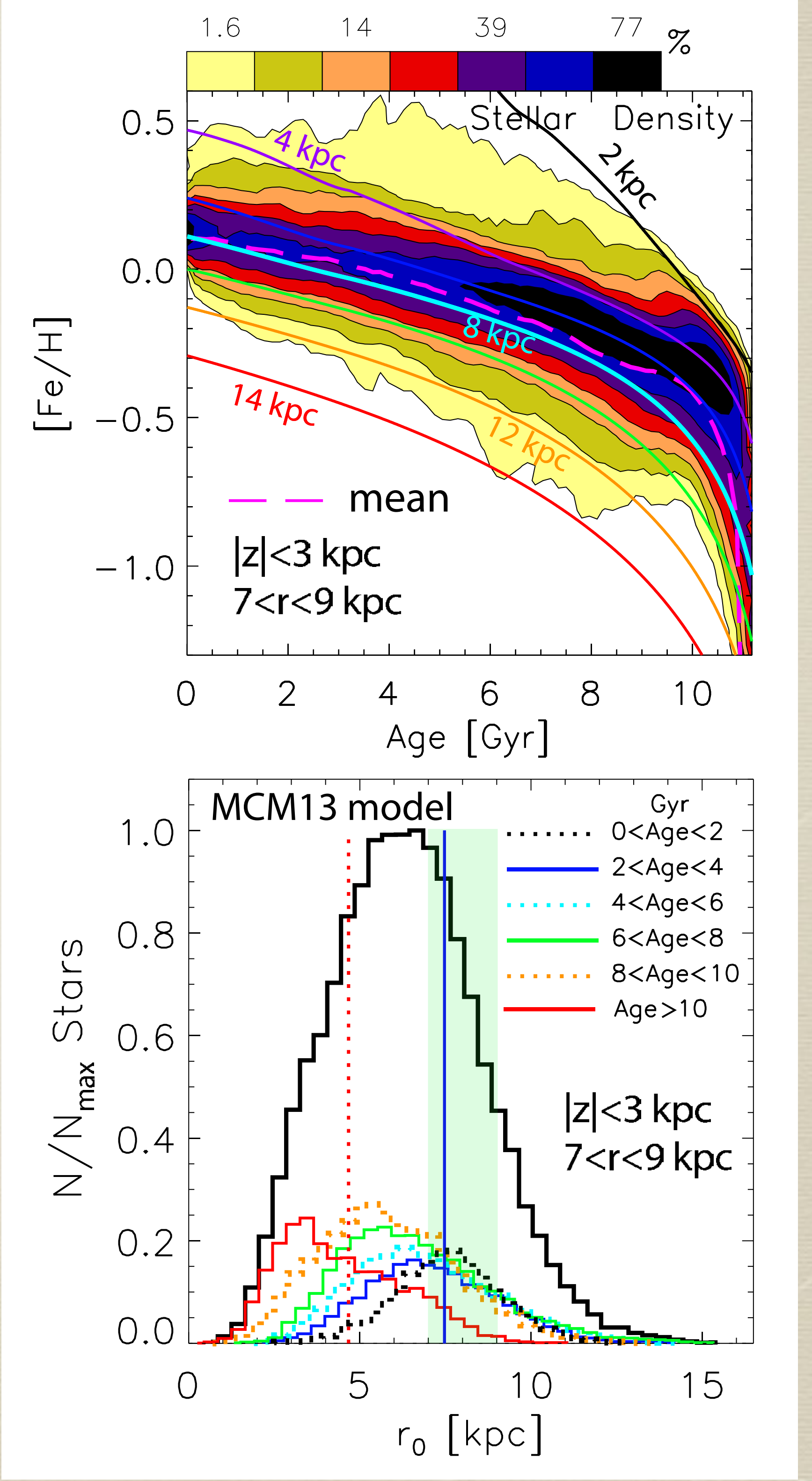
Classical chemical evolution modeling hampered by radial migration

- Stars move away from their birth places (e.g., Sellwood and Binney 2002, Roskar et al. 2008, Minchev & Famaey 2010).



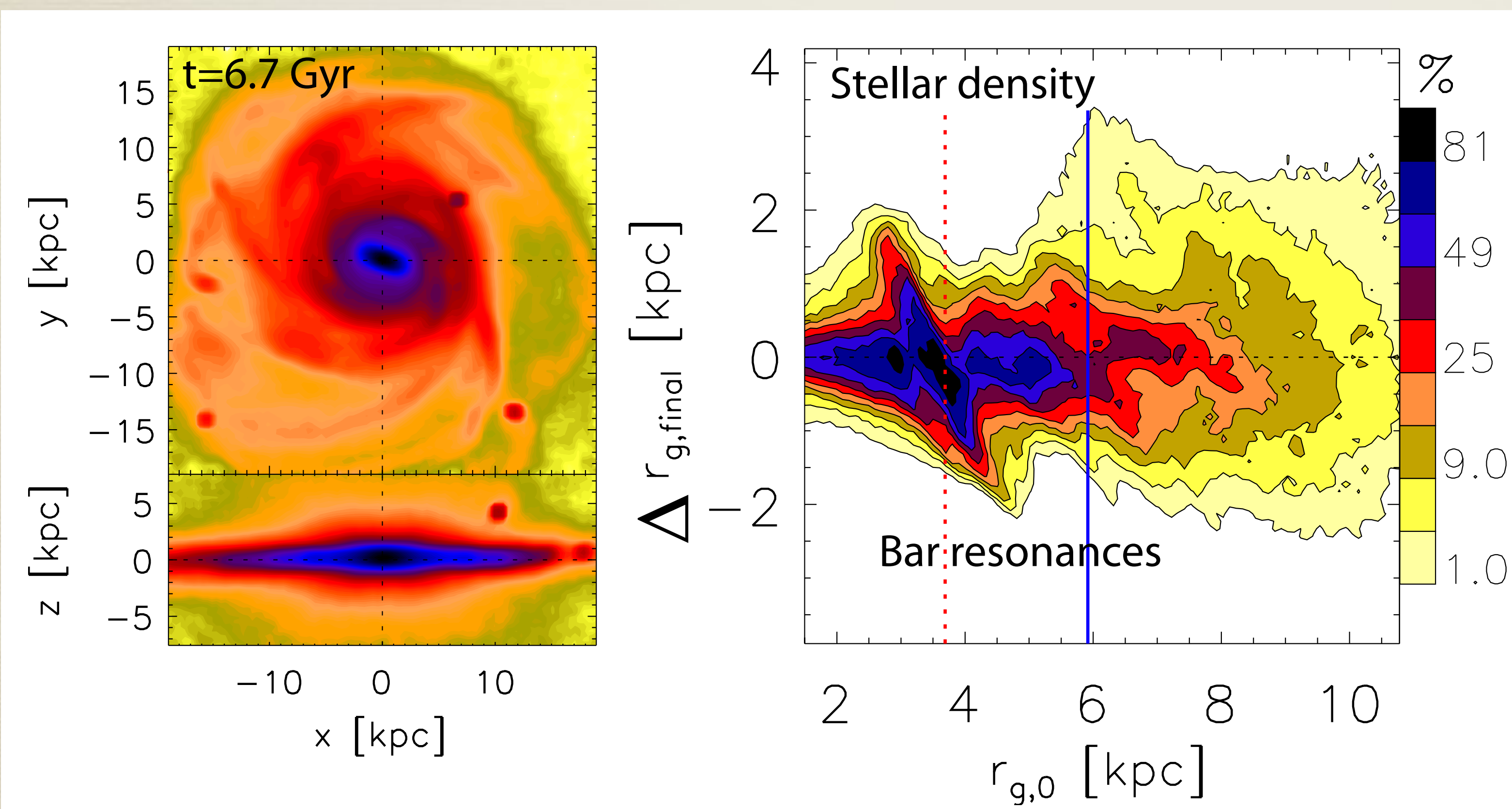
Classical chemical evolution modeling hampered by radial migration

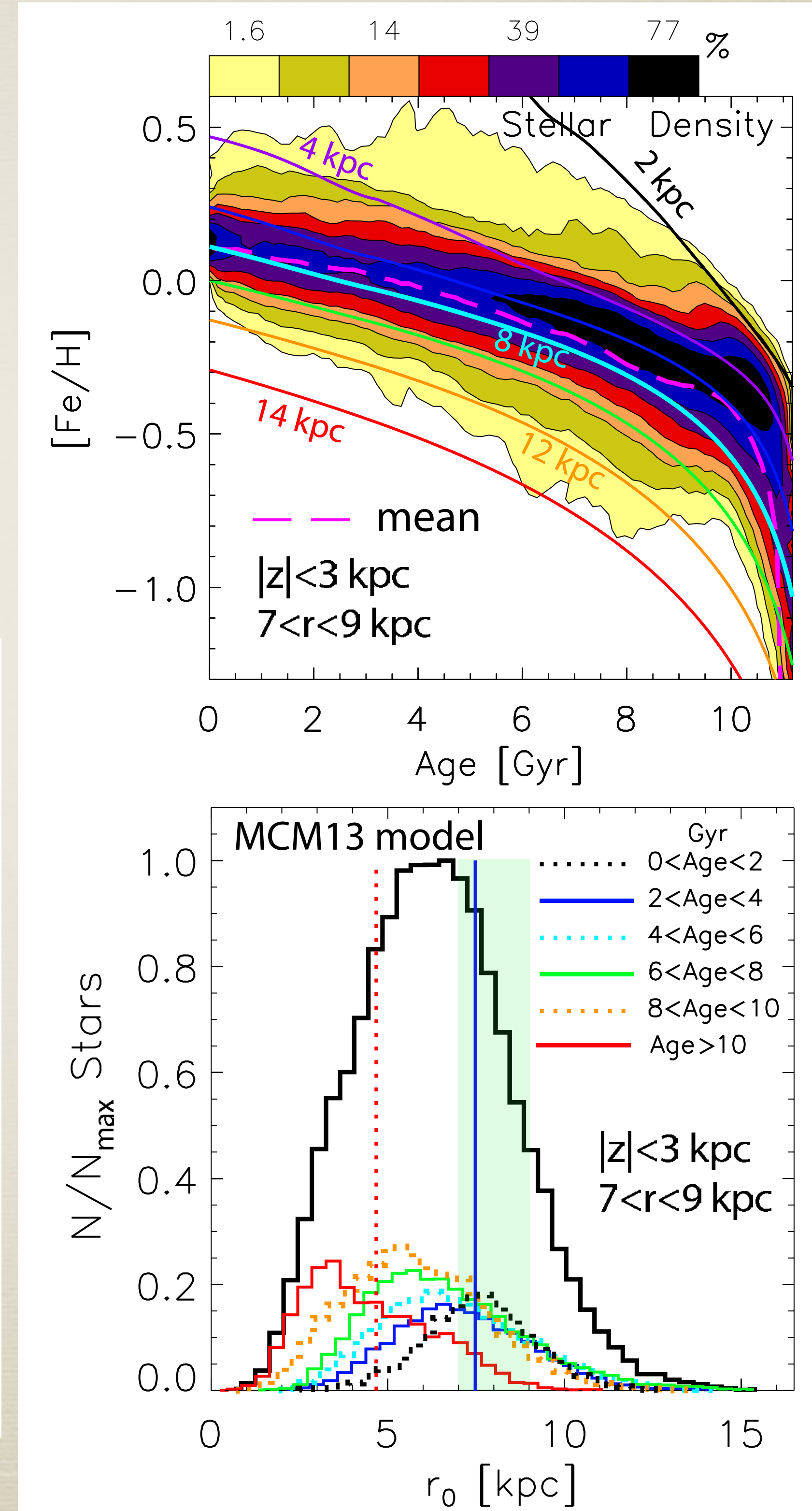
- Stars move away from their birth places (e.g., Sellwood and Binney 2002, Roskar et al. 2008, Minchev & Famaey 2010).



Classical chemical evolution modeling hampered by radial migration

- Stars move away from their birth places (e.g., Sellwood and Binney 2002, Roskar et al. 2008, Minchev & Famaey 2010).
- We need to recover the migration efficiency as a function of Galactic radius and time.

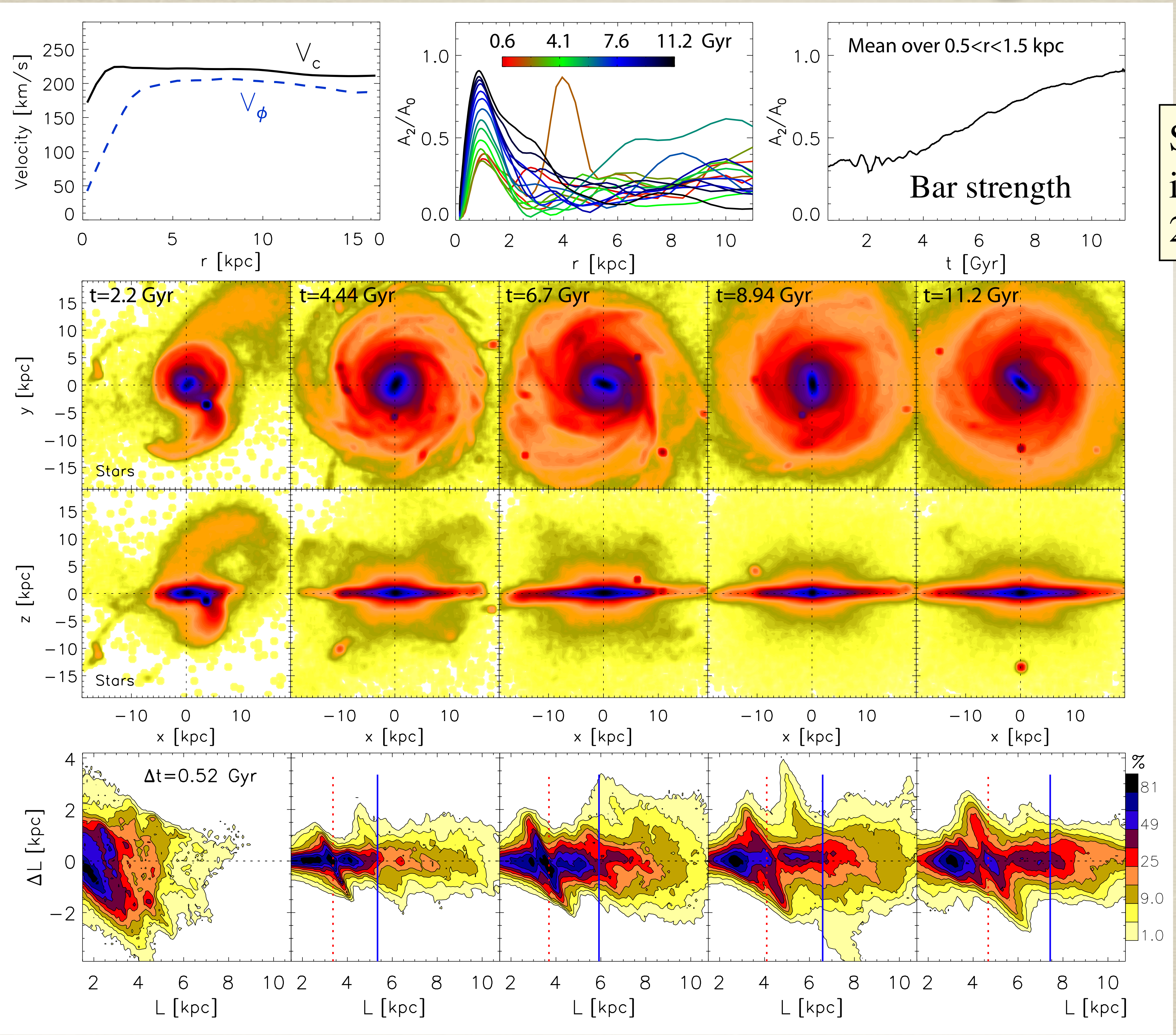




Our chemo-dynamical model

- Not easy to match Milky Way chemo-kinematic relations with cosmological simulations which include chemical enrichment (see Calura et al. 2012).
- We resorted to **a hybrid approach** using a high-resolution simulation of a disk assembly in the cosmological context:
  - Gas infall form filaments and gas-rich mergers
  - Merger activity decreasing toward redshift zero
  - Disk properties at redshift zero consistent with the dynamics and morphology of the Milky Way:
    - The presence of a Milky Way-size bar
    - A small bulge
    - Bar's Outer Lindblad Resonance at ~2.5 disk scale-lengths
  - A detailed chemical evolution model:
    - Matching several observational constraints in the Milky Way.

Disk evolution in the cosmological context



Simulations described in Martig et al. (2009, 2012)

Stars born hot at high redshift:

Similar to

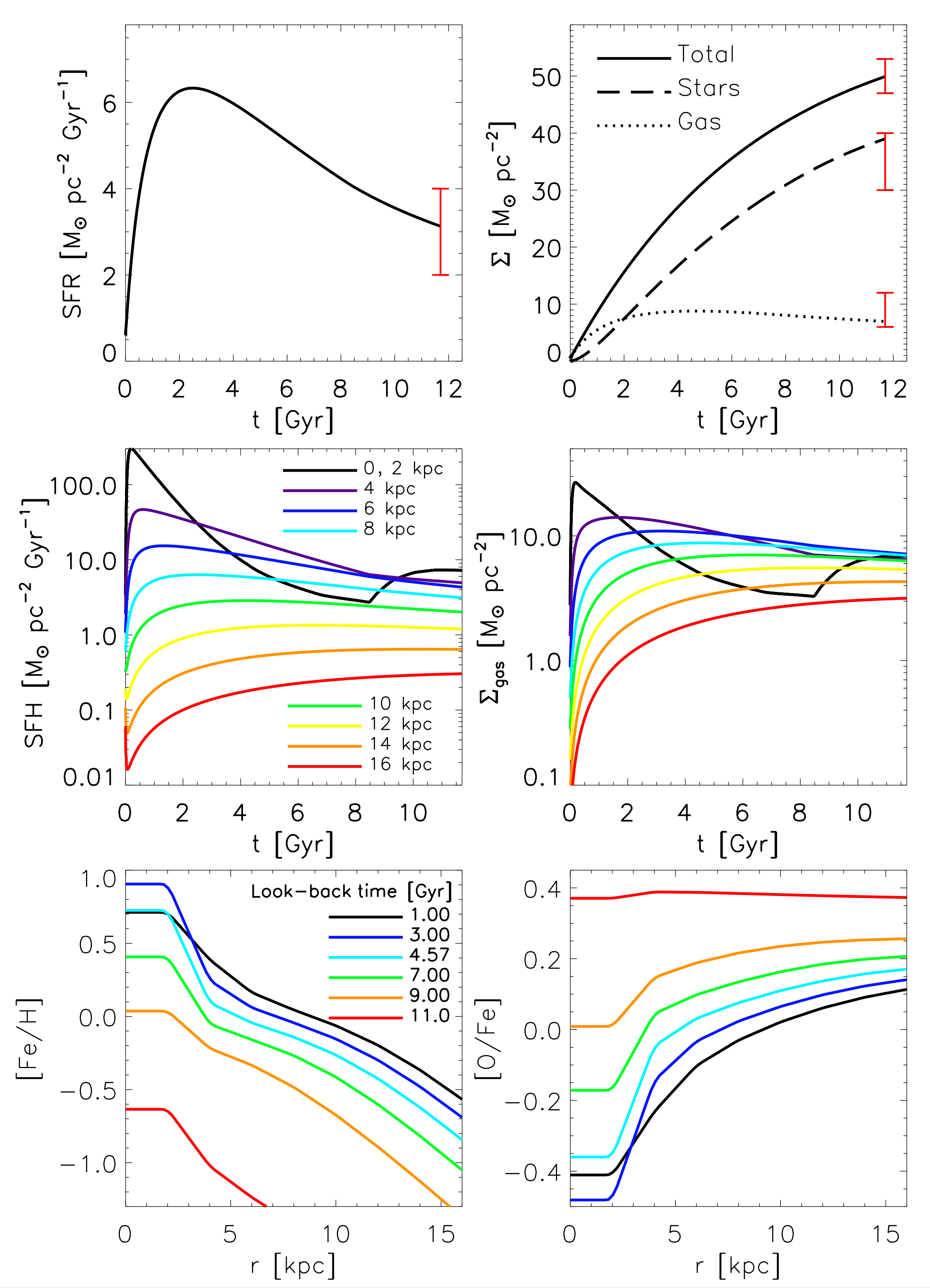
Brook et al. (2012),

Stinson et al. (2013),

Bird et al. (2013)

Chemical model

assigned to simulation a posteriori



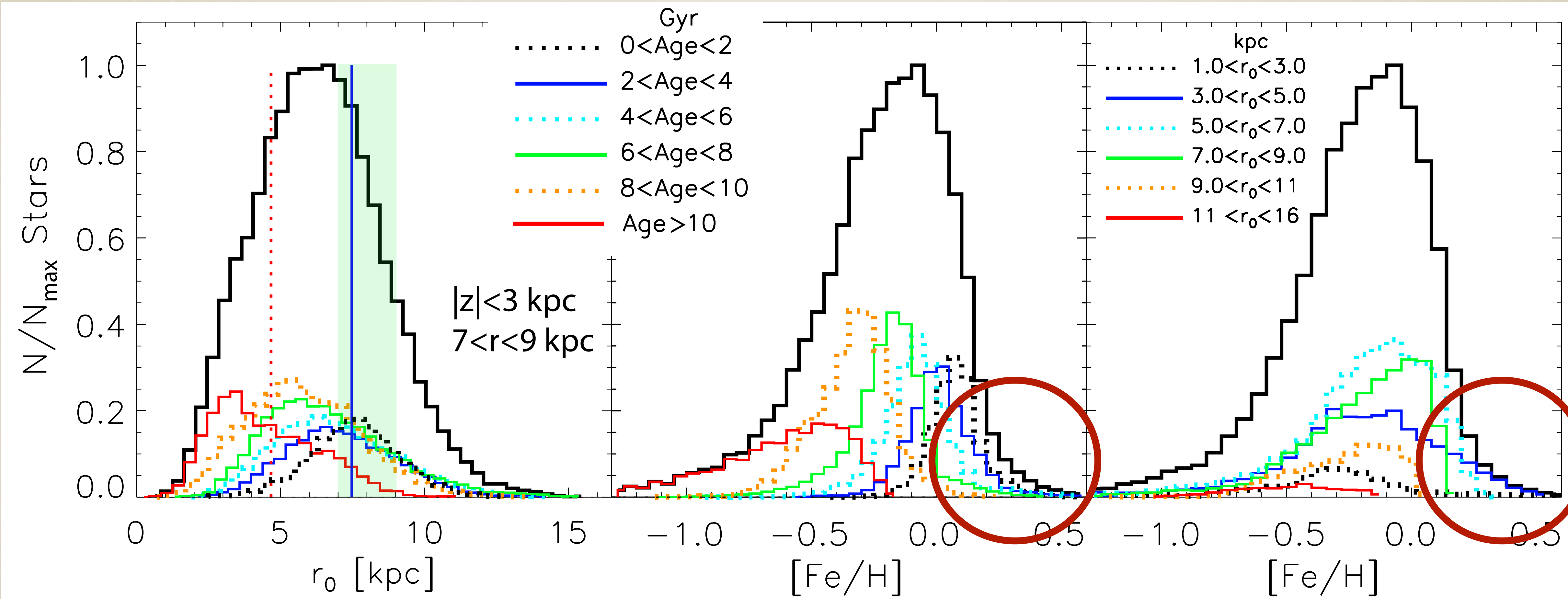
Similar to Chiappini (2009)

Constrained by:

- The solar and present day abundances of more than 30 elements
- The present SFR
- The current stellar, gas and total mass densities at the solar vicinity
- The present day supernovae rates of type II and Ia
- The metallicity distribution of G-dwarf stars

- Only thin disk chemistry used!

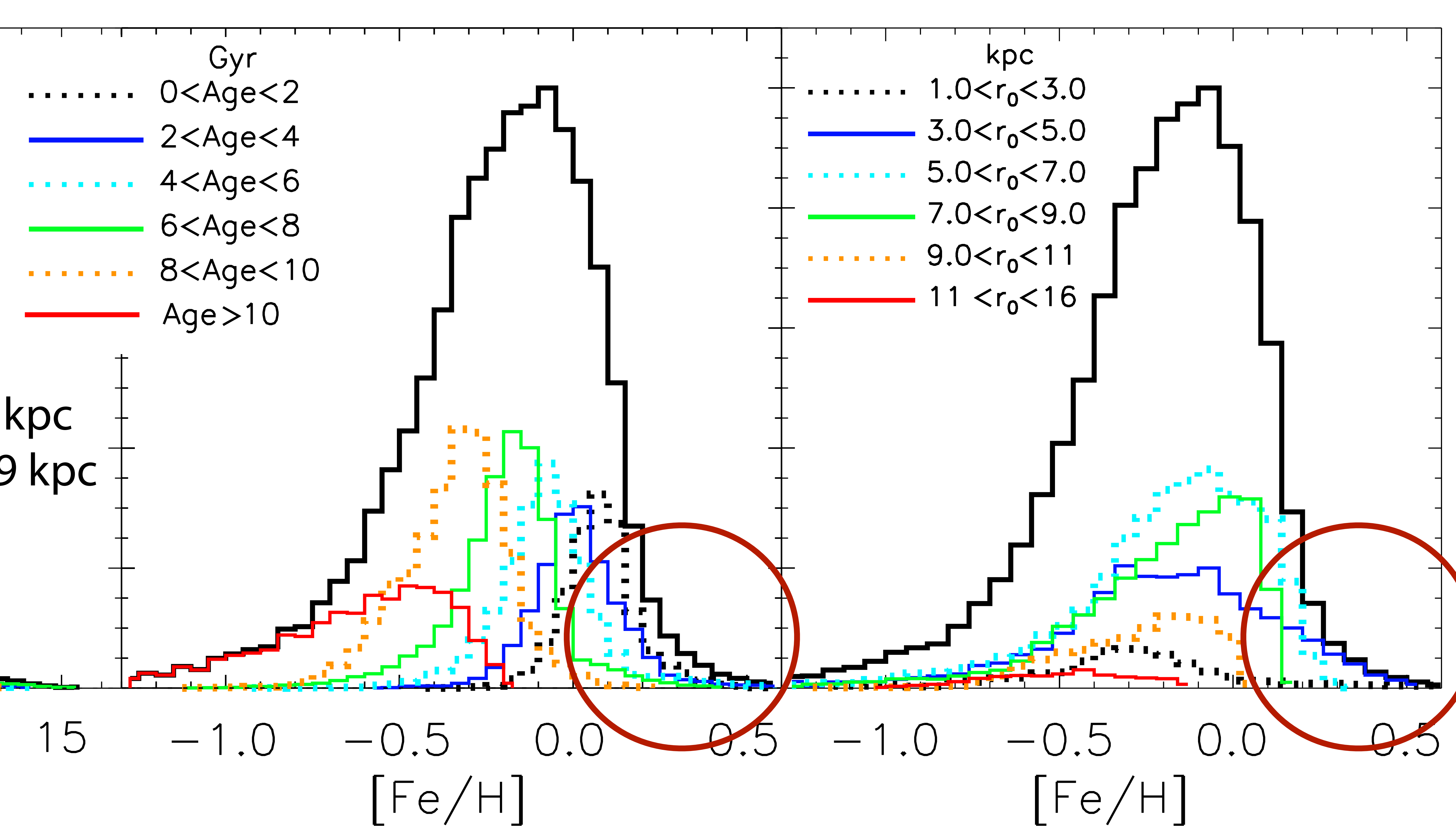
Origin and metallicity distributions of local stars



Minchev, Chiappini & Martig (2013)

Older populations arrive from progressively smaller galactic radii due to their longer exposure to migration.

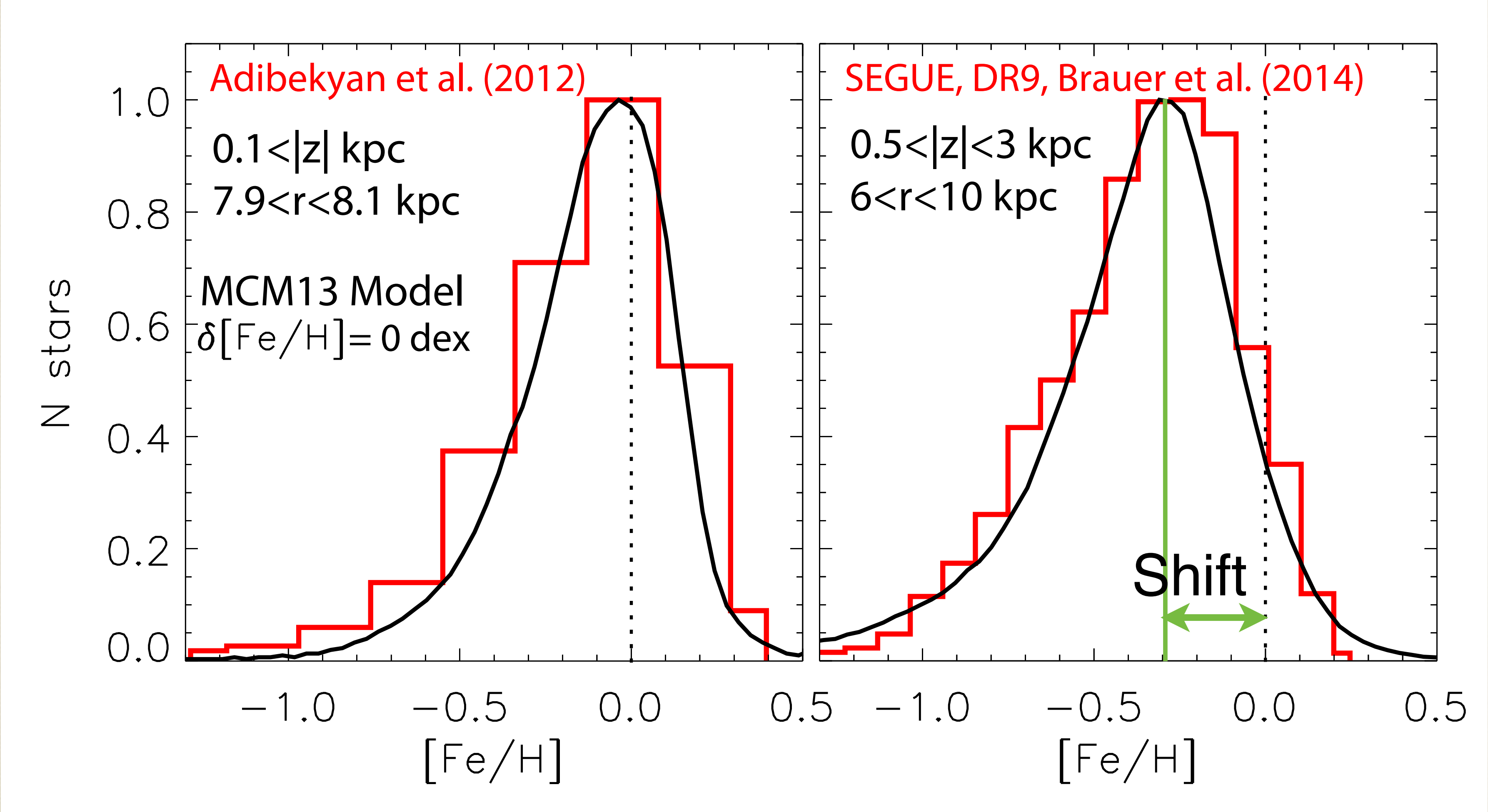
Origin and metallicity distributions of local stars



The metallicity distribution

|z| < 40 pc

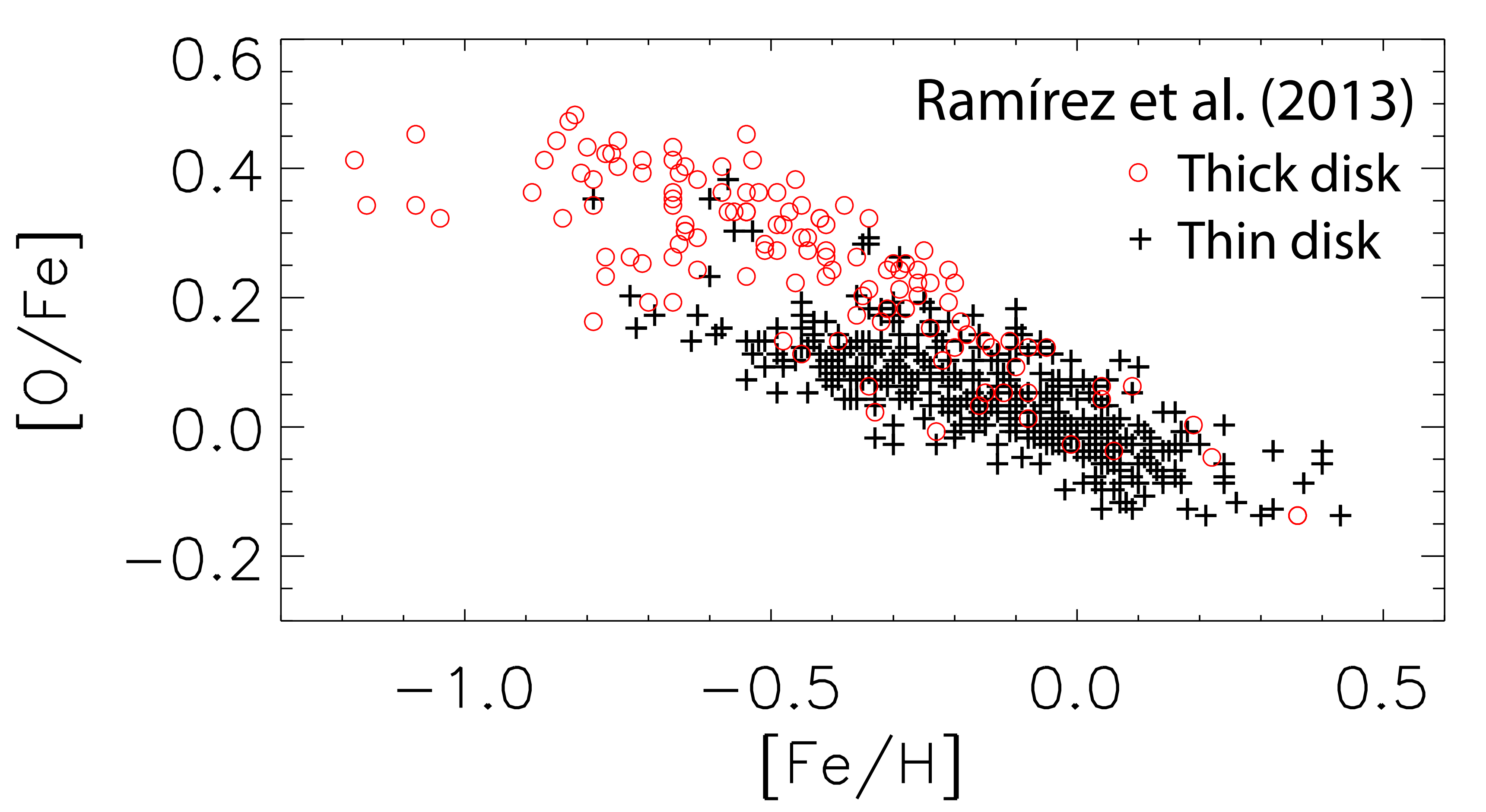
|z| > 500 pc



For both model and observations the MDF peak shifts to lower [Fe/H] with distance from the disk plane

The [Fe/H]-[O/Fe] relation

Kinematical selection of thin- and thick-disk populations



The [Fe/H]-[O/Fe] relation

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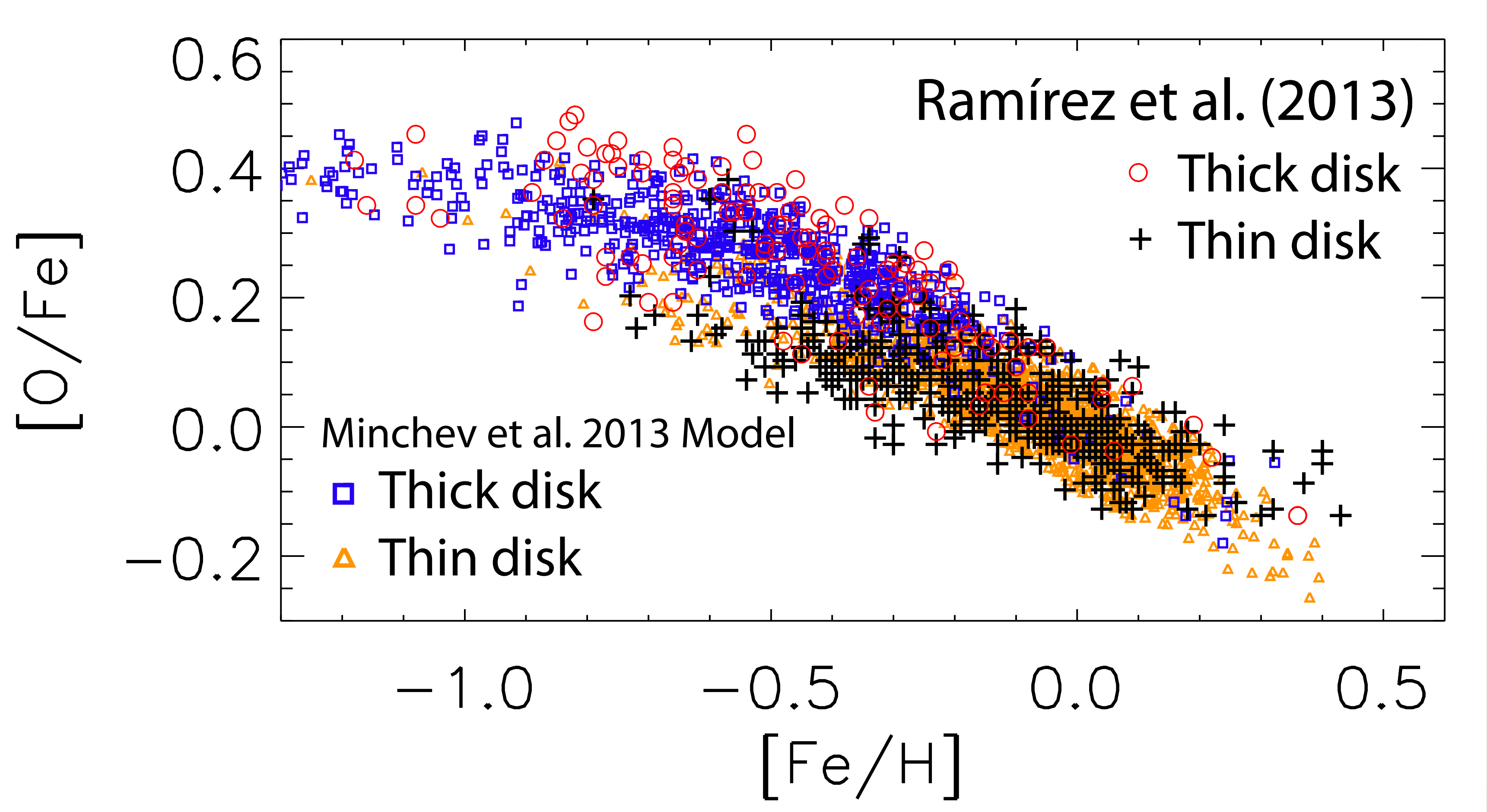
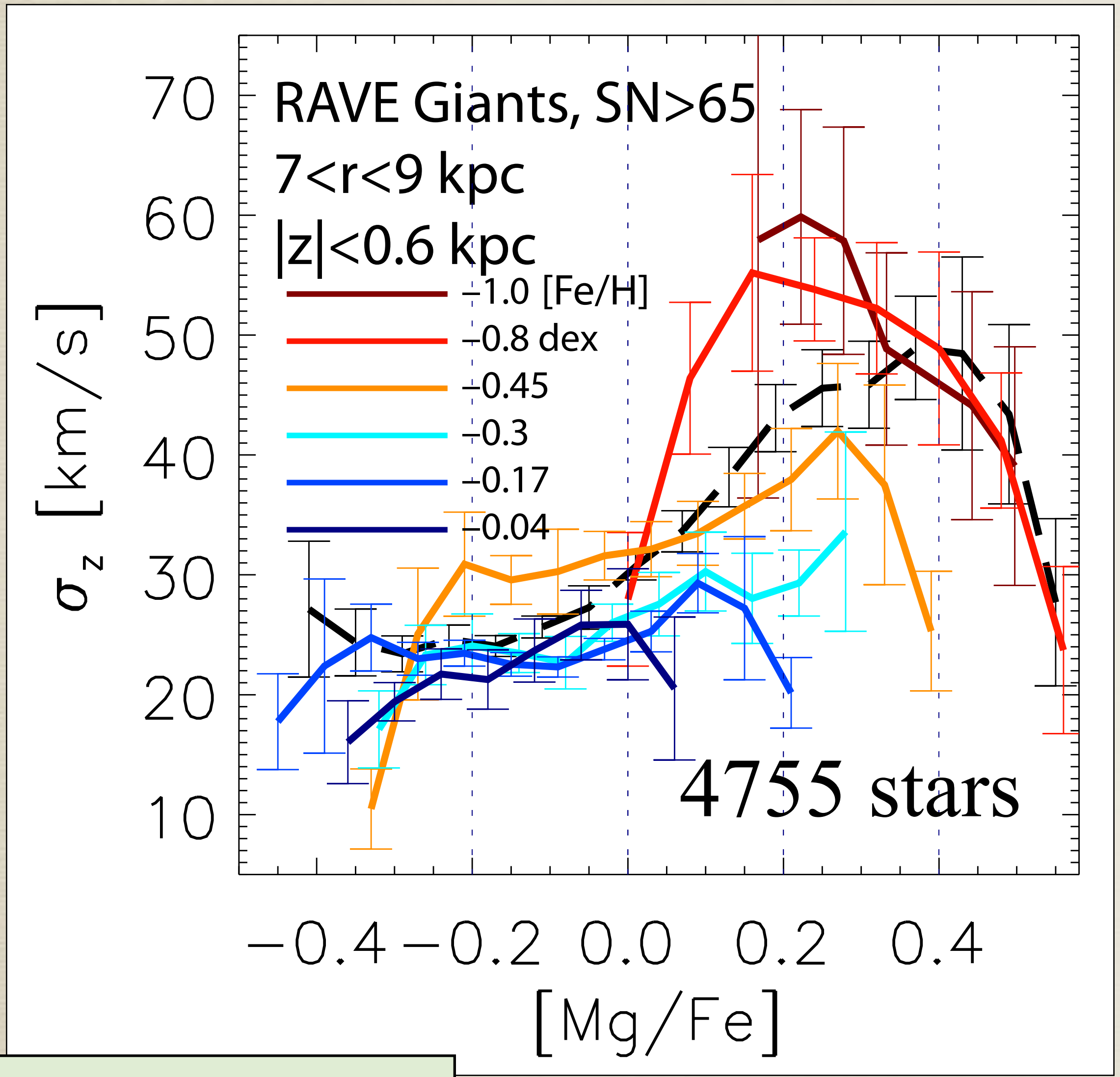
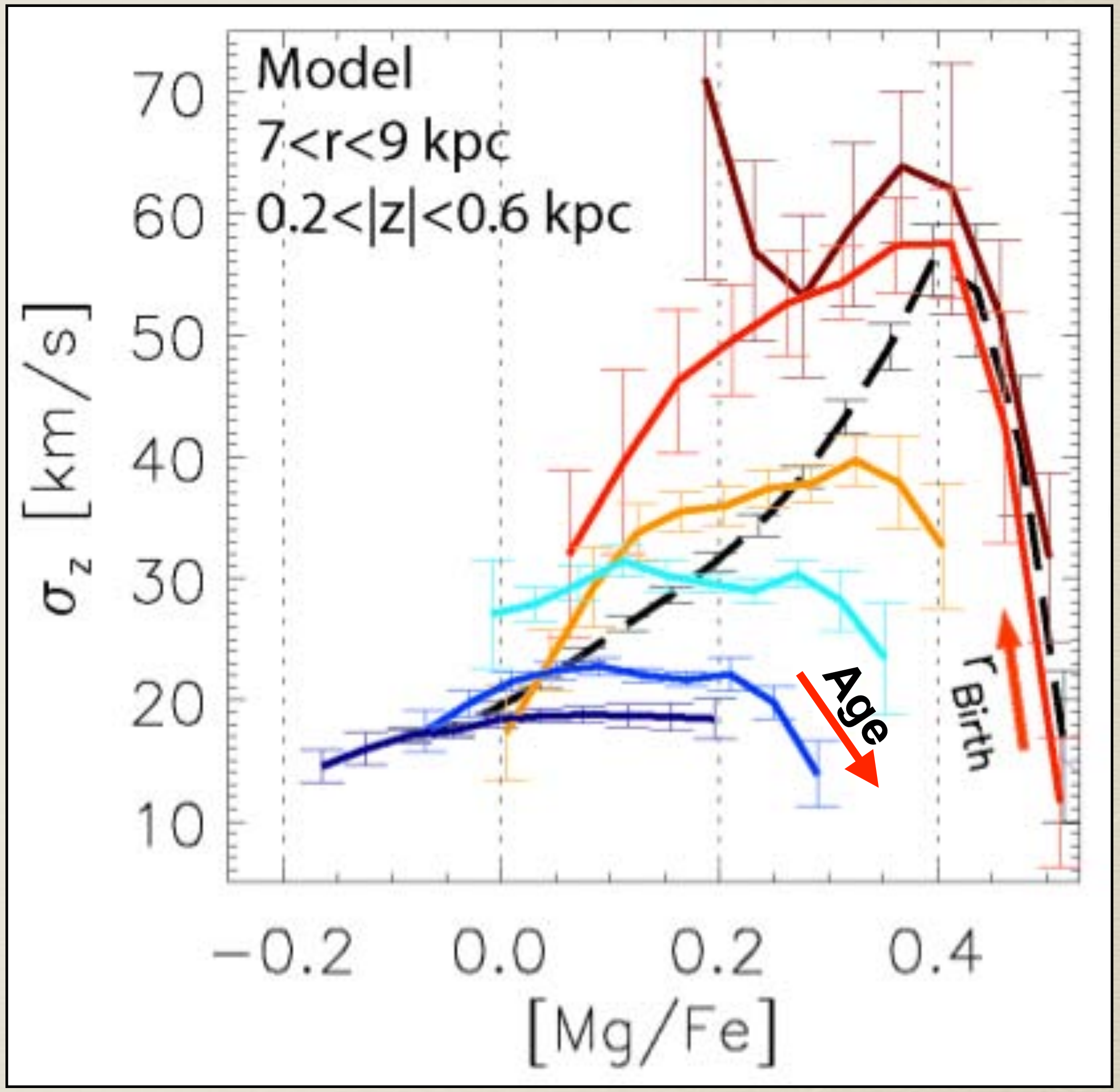


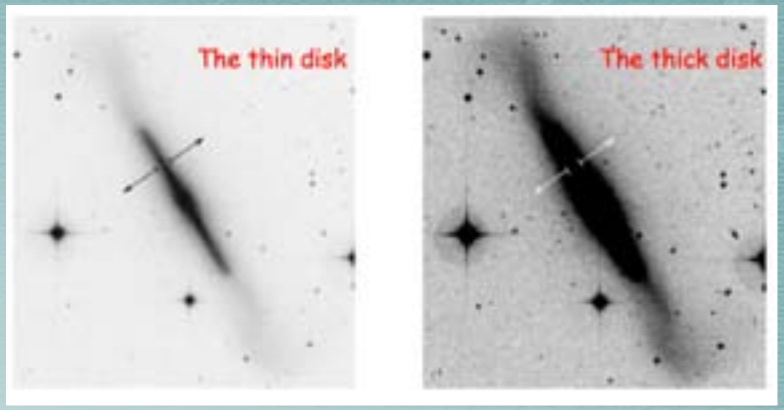
Variation of velocity dispersion with [Mg/Fe]



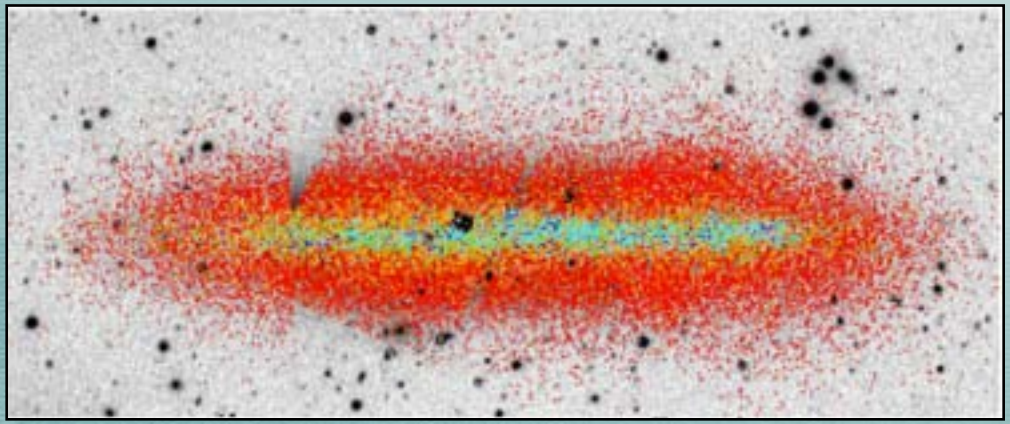


Minchev + RAVE (2014)

Velocity dispersion drops at the high-[Mg/Fe] end for each metallicity sub-population

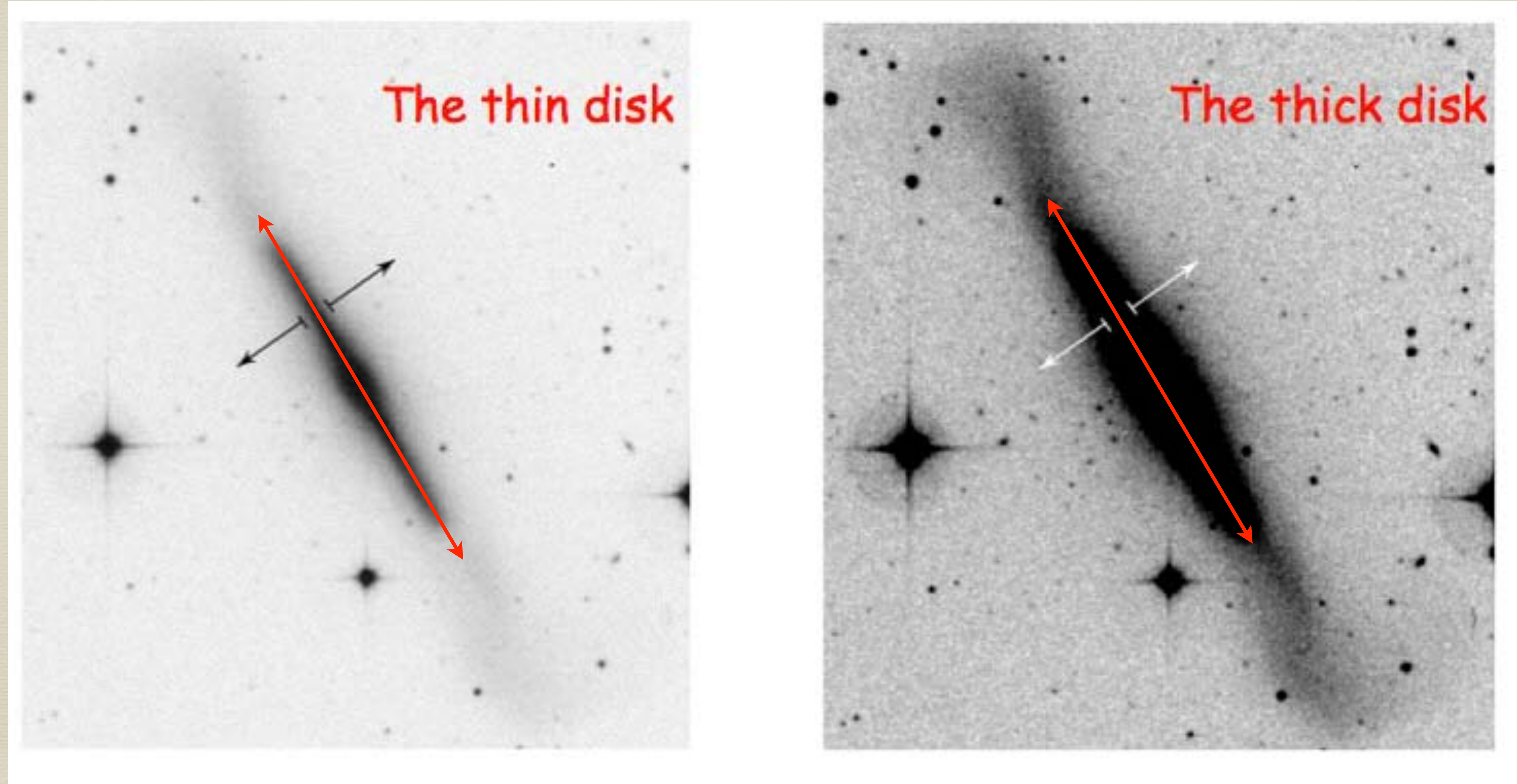


On the formation of galactic thick disks



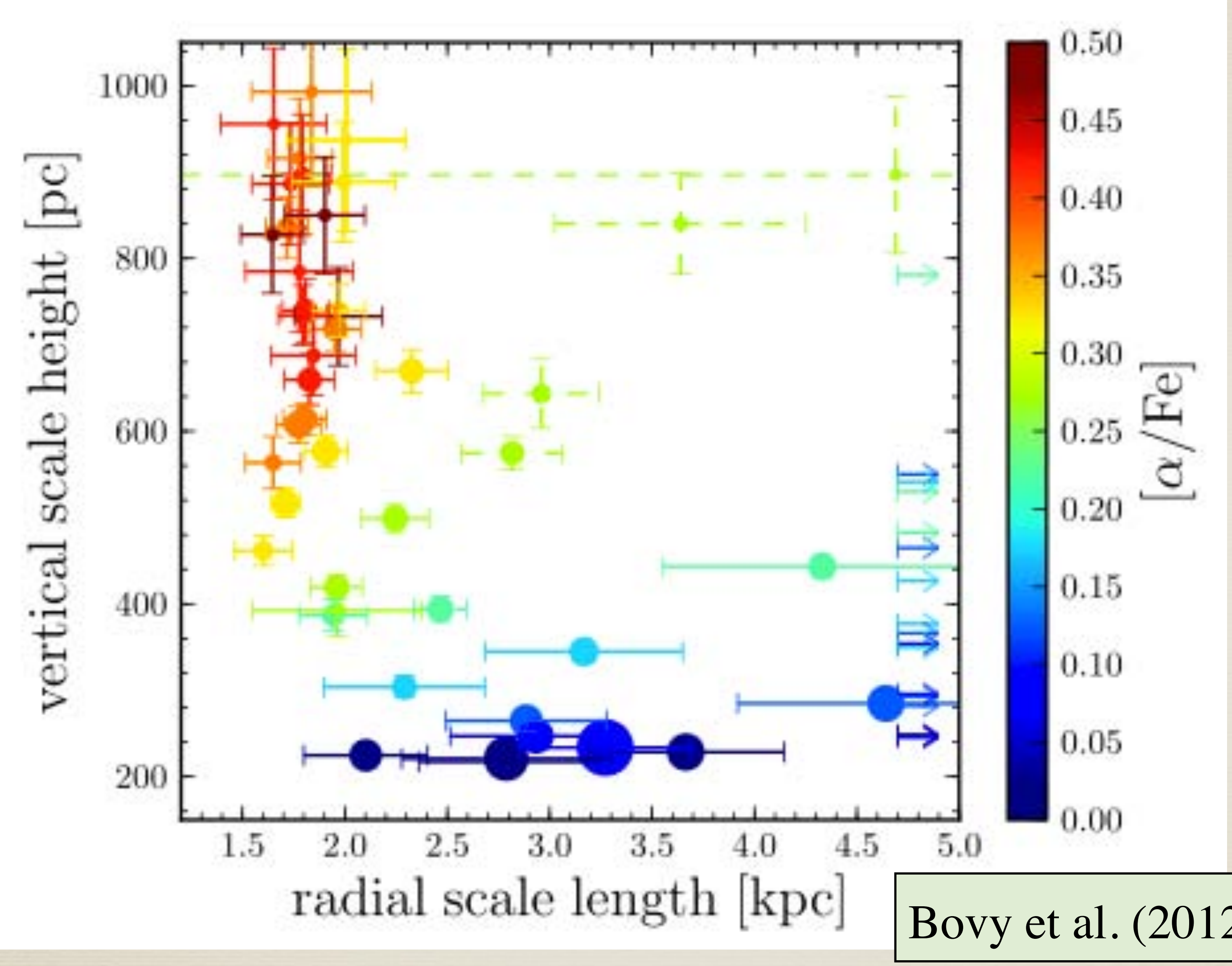
Thick disks are **extended**

NGC 4762 - a disk galaxy with a bright thick disk (Tsikoudi 1980)



Also argued by Yoachim and Dalcanton (2006); Pohlen et al. (2007); Comerón et al. (2012)

Chemically/Age defined Milky Way thick disk **centrally concentrated** (e.g., not extended)

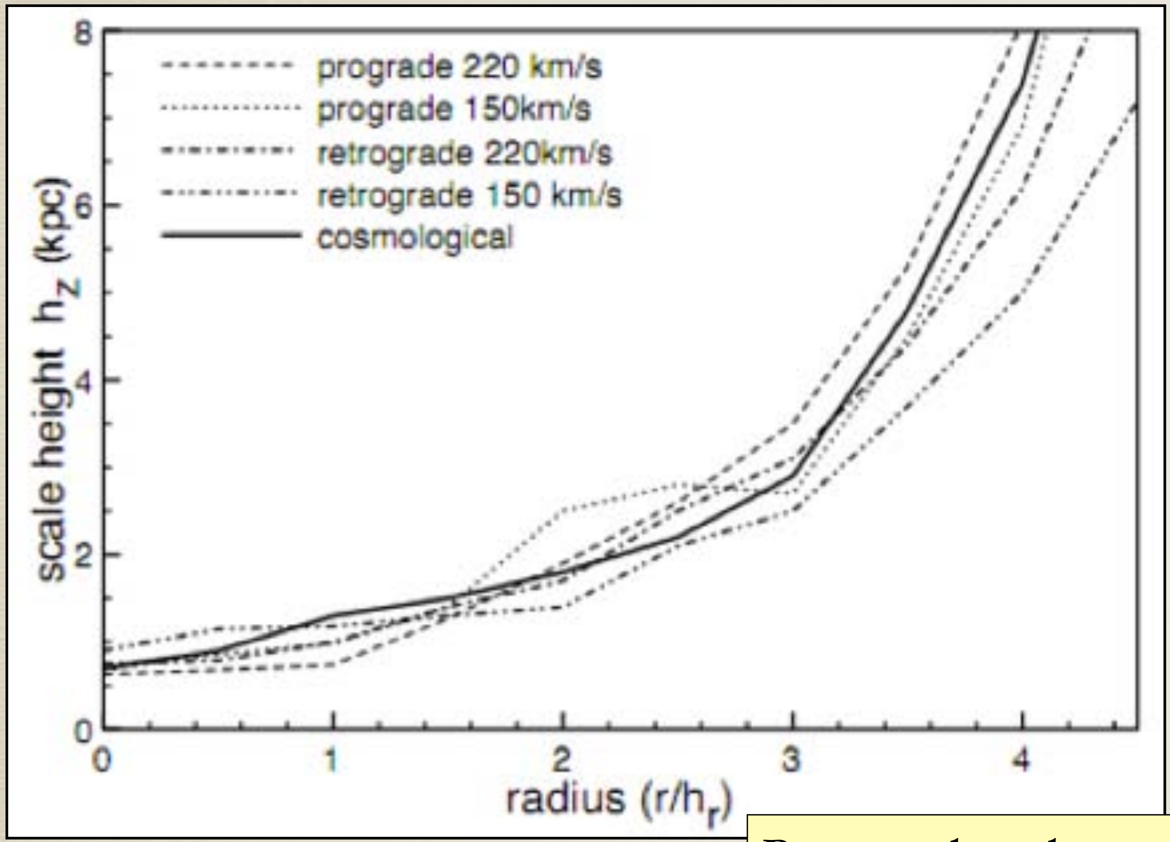


Bovy et al. (2012)

Found already earlier by Bensby et al. (2011) and Cheng et al. (2012)

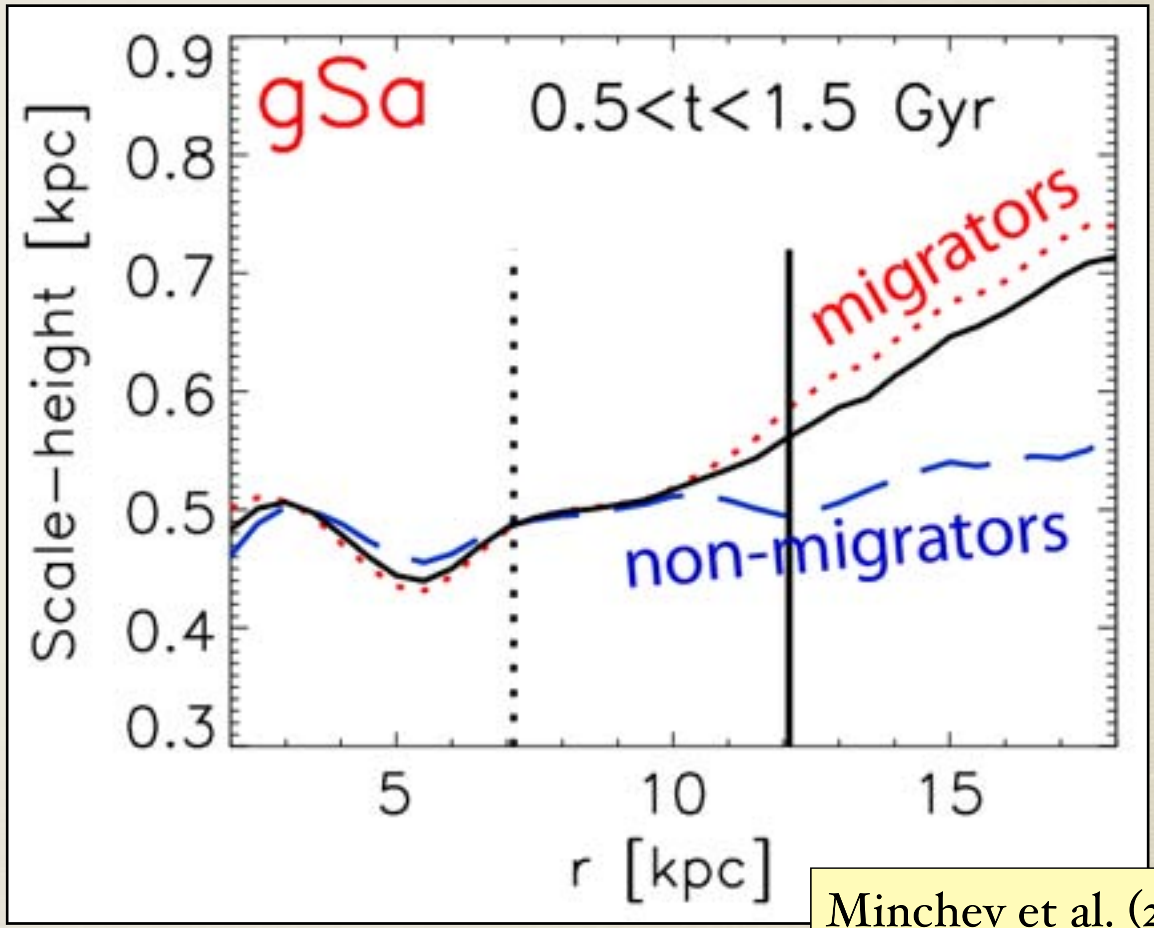
Simulated disks **always flare** (for a single stellar population)

Mergers flare disks



Bournaud et al. 2009

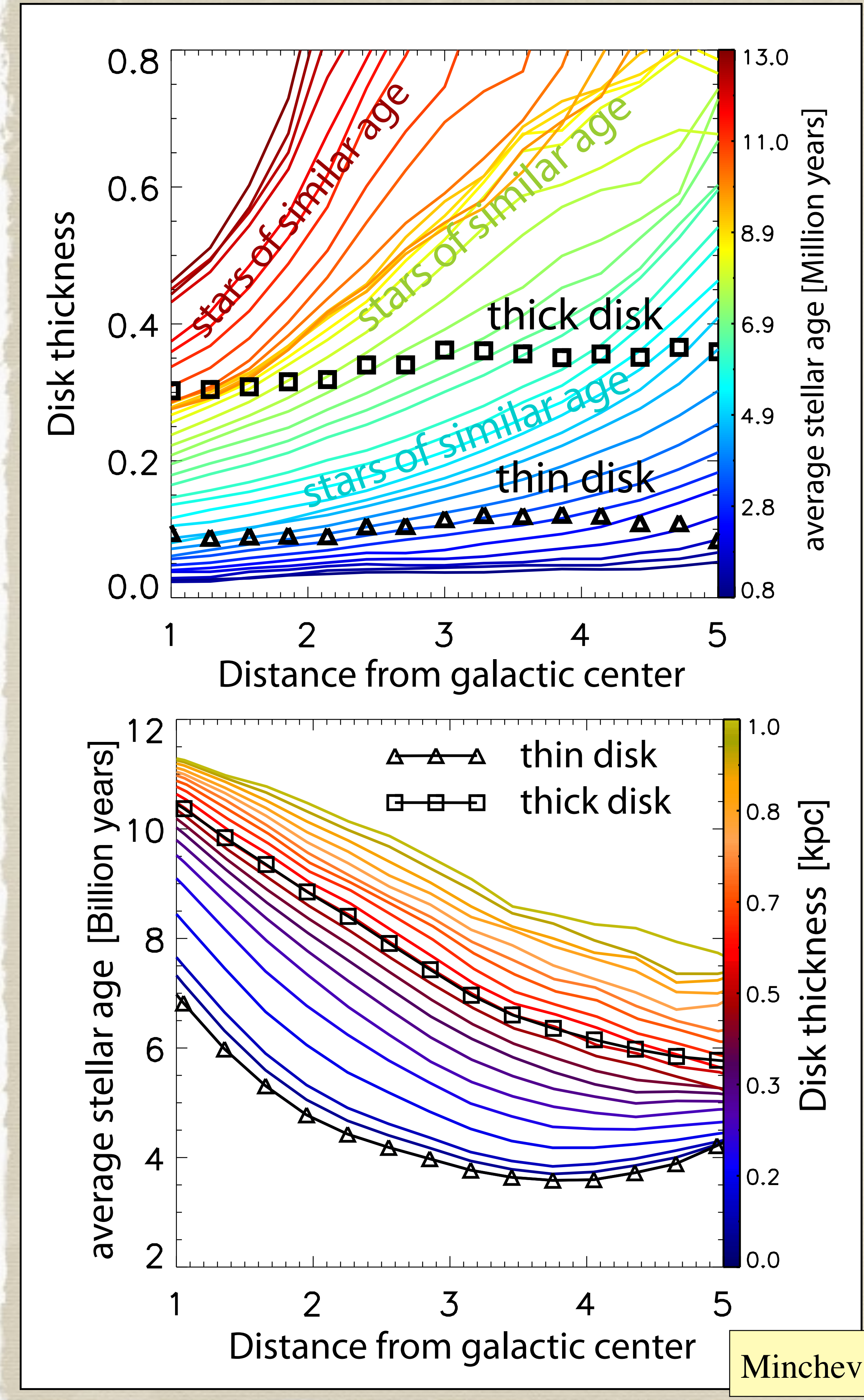
Migration flares disks



Minchev et al. (2012)

But observed edge-on disks do not flare (de Grijs 1998; Comerón et al. 2011)!

Disk flaring in inside-out galaxy formation

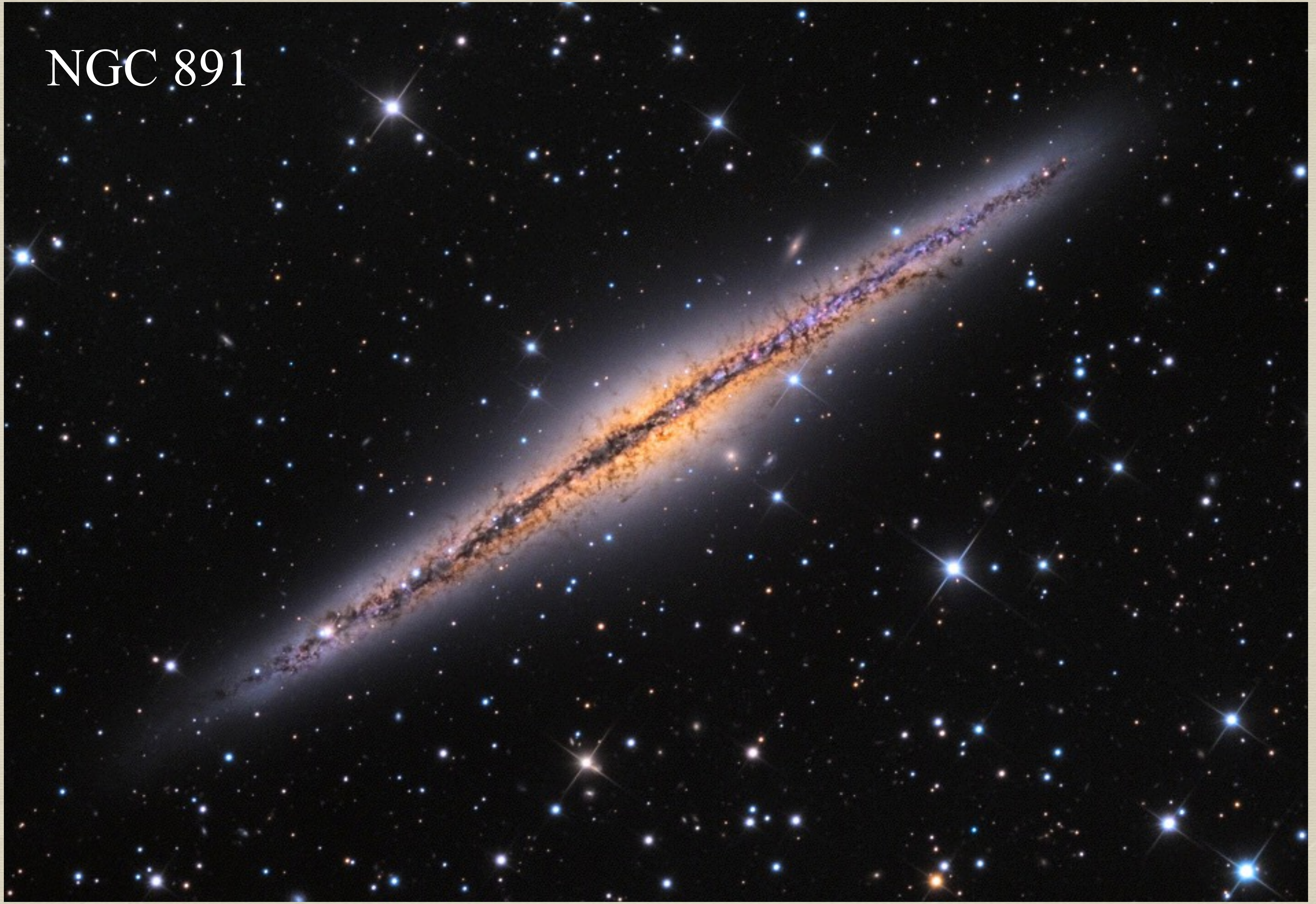


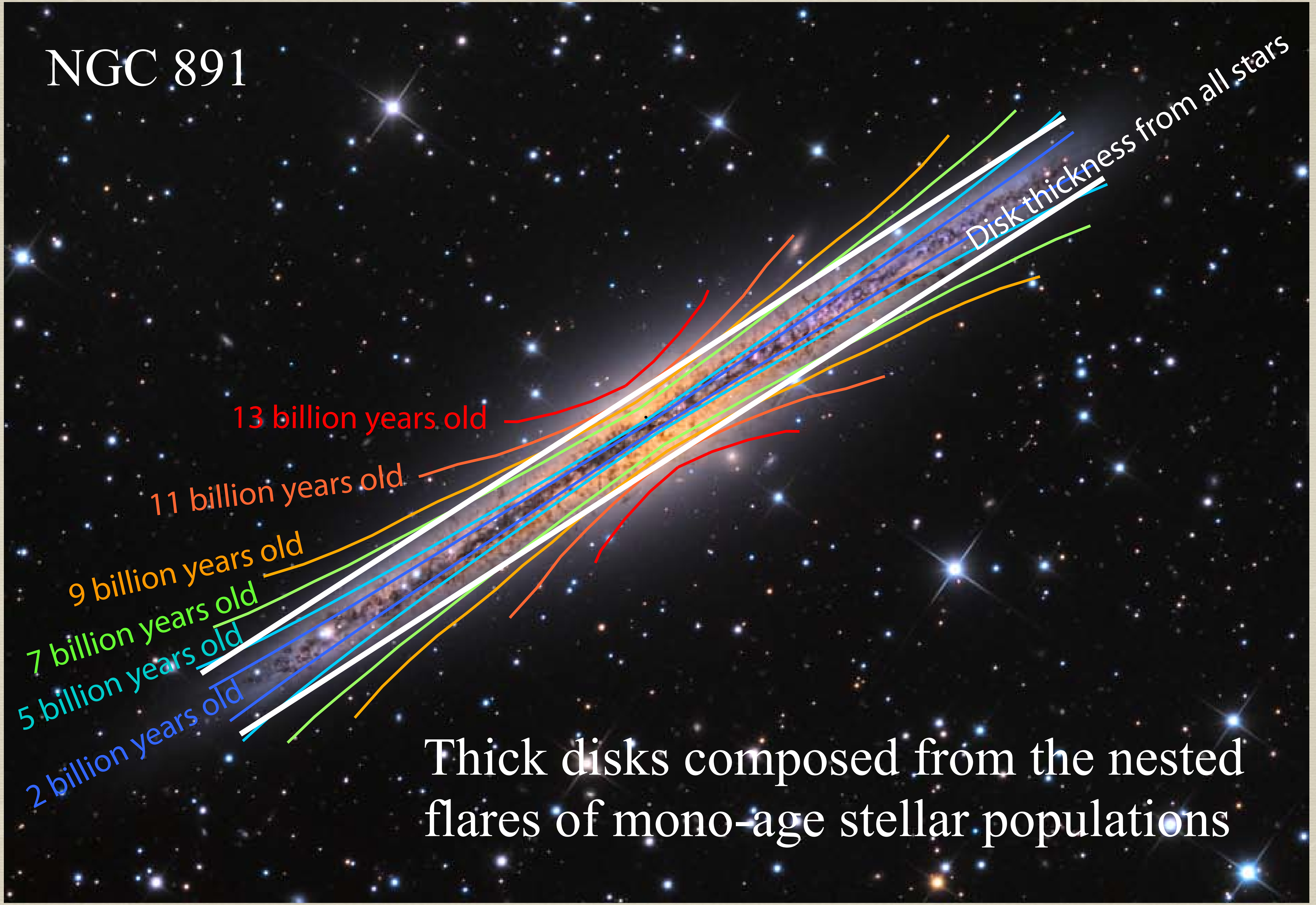
Minchev et al. (2015)

Age decline with radius in thick disk predicted

Chemical thick disk ≠ Morphological thick disk

Simulation by Scannapieco/Aumer


NGC 891


NGC 891
Disk thickness from all stars
13 billion years old
11 billion years old
9 billion years old
7 billion years old
5 billion years old
2 billion years old
Thick disks composed from the nested
flares of mono-age stellar populations

Summary

- **Galactic disks must be modeled as non-equilibrium systems!**
- **Signatures of merging satellites can be found in the disk phase space.**
  - can last for up to 4-5 Gyr.
  - can constrain time of merger event.
  - can we detect the effect of several mergers?
- **A novel approach to chemo-dynamical modeling:**
  - more than 30 chemical elements available for doing **Galactic Archeology**.
  - matching a number of observation and making prediction for future ones.
- **Thick disks composed of the flares of populations of different ages:**
  - explains extended morphologically defined thick disks in external galaxies.
  - explains the centrally concentrated older populations in the MW.
- **Models to be tested in the MW with forthcoming Gaia data +4MOST!**