Simulations of the Formation of Thick Discs in Galaxies

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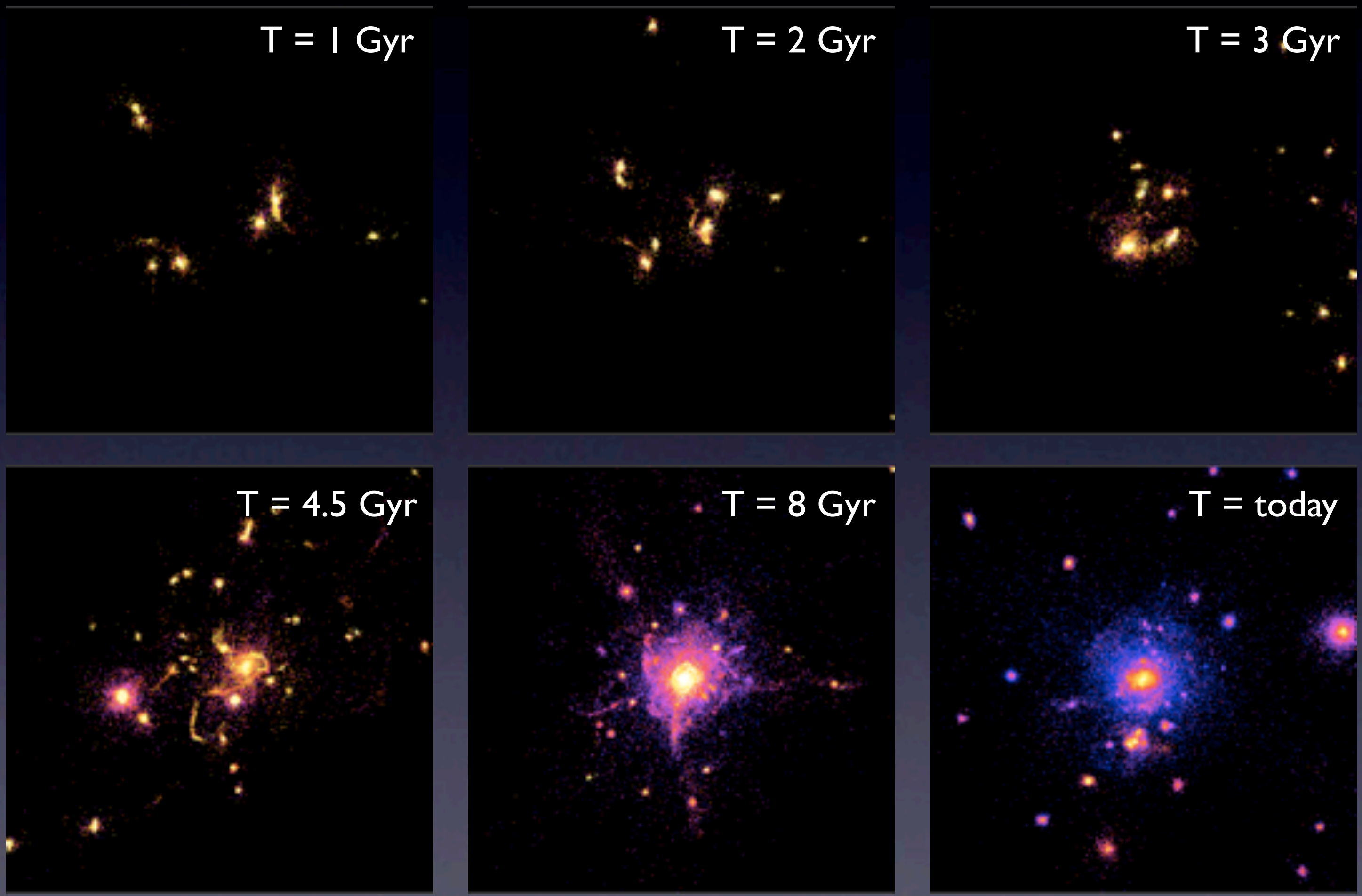
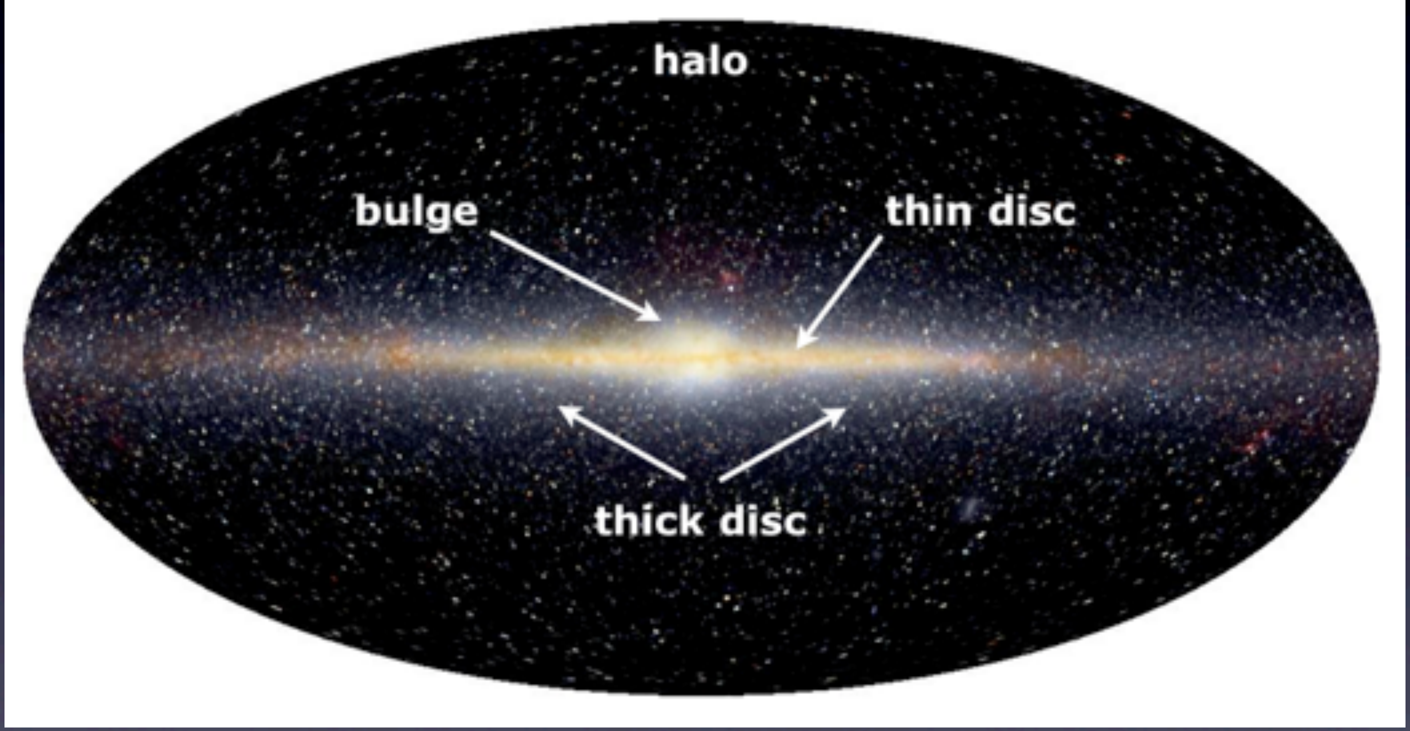
Current paradigm of galaxy formation



Smaller structures merge to form larger systems

simulations by J.P. Gardner

Milky Way structure

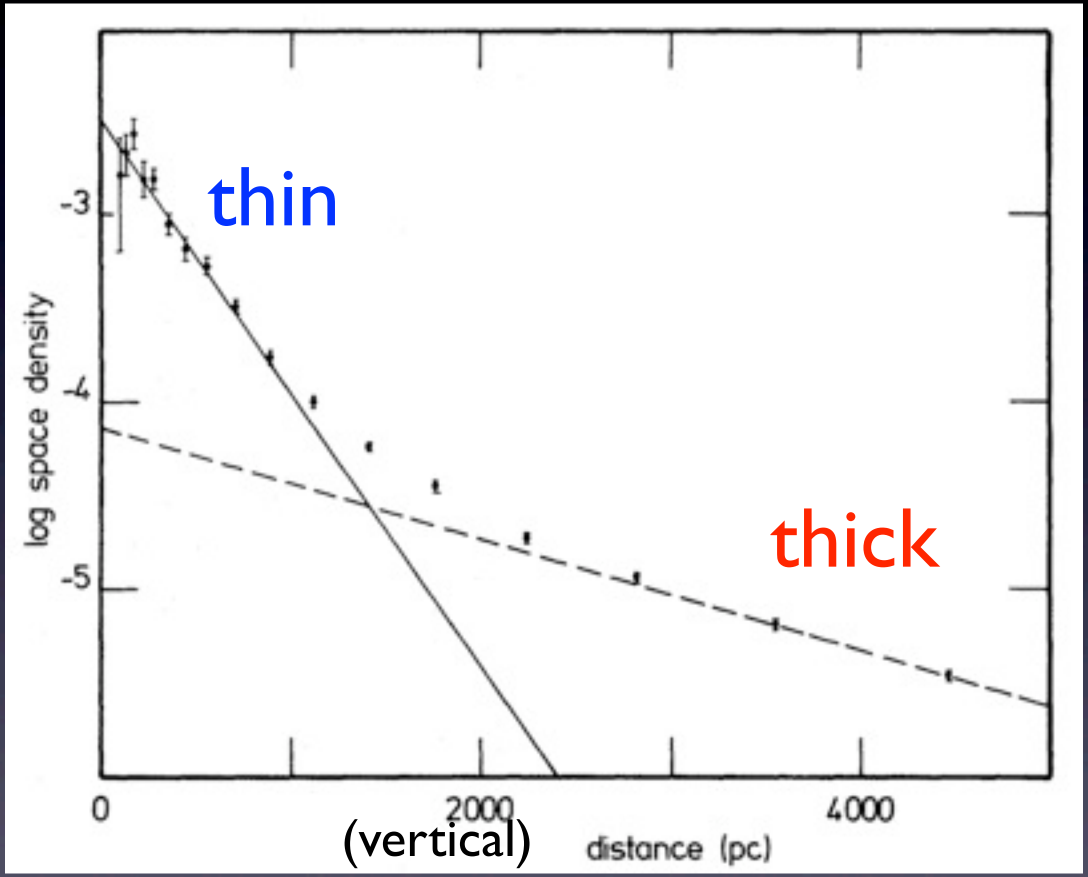


E.L. Wright & The COBE-DIRBE project

MW thick disc in a nutshell

- **Structure**

  scale-height: 0.7-1.5 kpc (2x-3x thin)
  scale-length: 2.8-4.5 kpc (~1x thin)
  normalisation: 2-11%



Gilmore & Reid 1983

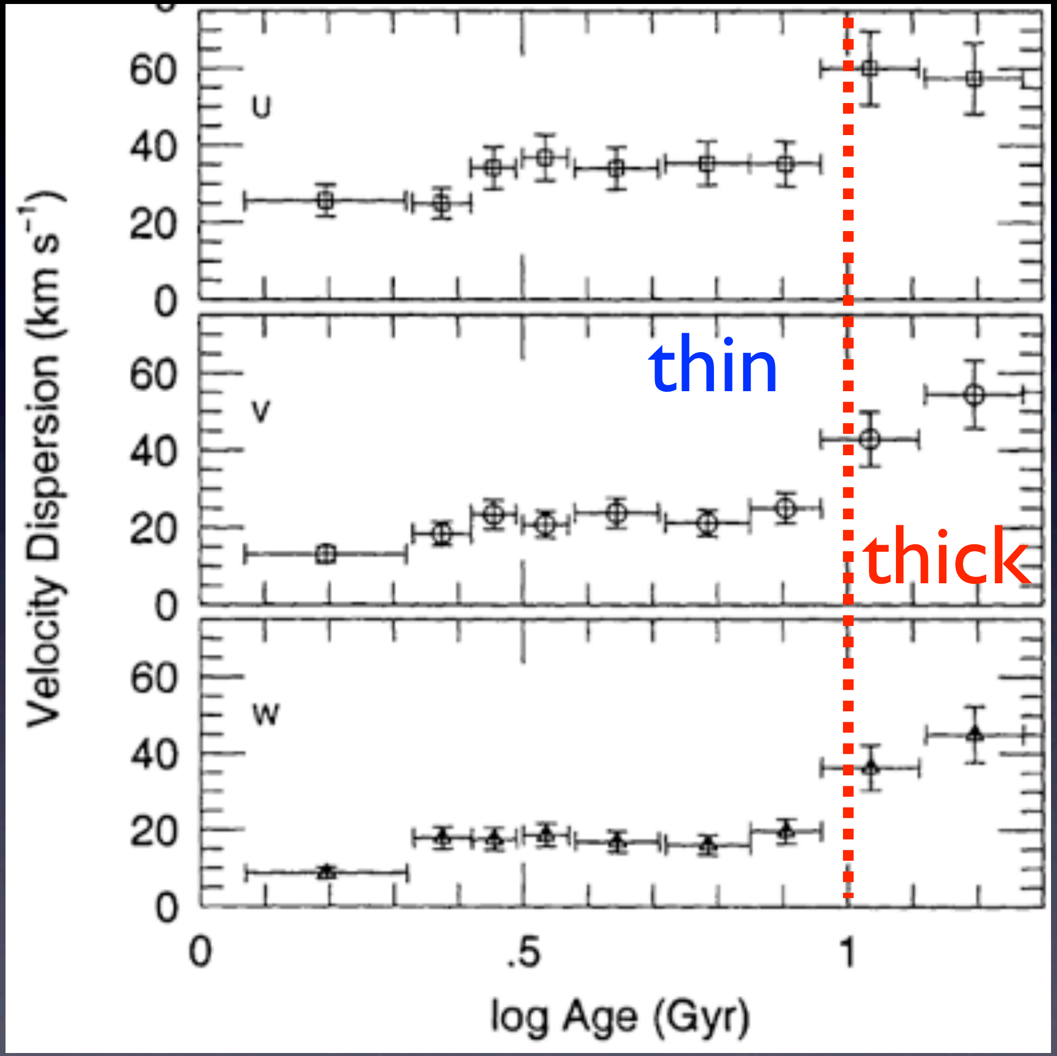
See: Robin et al. 1996, Ojha 2001
Chen et al. 2001, Larsen & Humphreys 2003
Juric et al. 2008

MW thick disc in a nutshell

- **Structure**
  scale-height: 0.7-1.5 kpc (2x-3x thin)
  scale-length: 2.8-4.5 kpc (~1x thin)
  normalisation: 2-11%

- **Kinematics**
  (σ_R , σ_ϕ , σ_z) ~ (65, 54, 38)km/s (2x thin)
  rotates fast ~ 180 km/s

- **Age**
  composed of old stars > 10Gyr



Quillen & Garnett 2000
(but see Holmberg et al. 2007)

See: Chiba & Beers 2001
Nordstrom et al. 2004
Alcobe & Cubarsi 2005
Vallenari et al. 2006
Veltz et al. 2008

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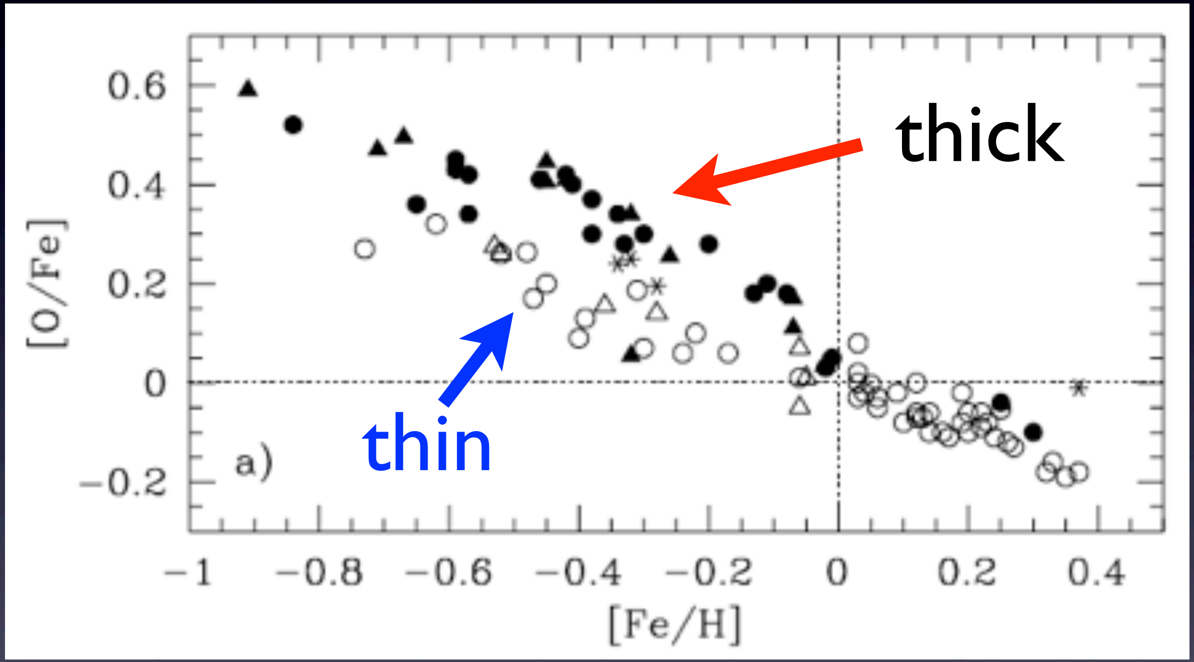
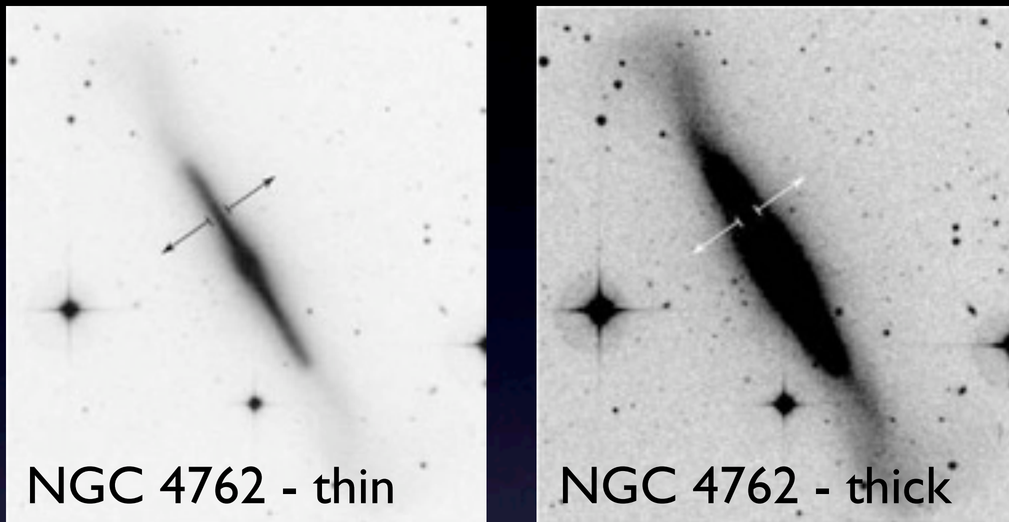
- **Age**
  composed of old stars > 10Gyr

- **Chemistry**
  more metal poor
  higher α-abundance

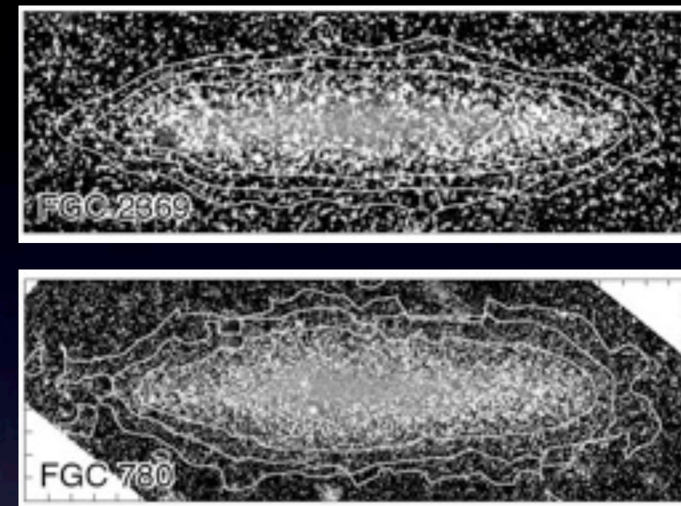


Bensby et al. 2003, 2004, 2005

Thick discs in other galaxies

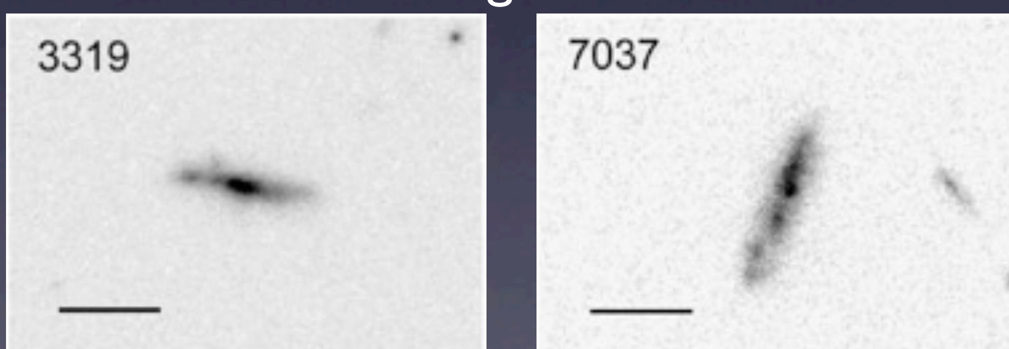


Tsikoudi 1980



Dalcanton & Bernstein 2002

even at high redshift:



Elmegreen & Elmegreen 2006

... and in many other galaxies!

see also:
van der Kruit & Searle 1981
van Dokkum et al. 1994
de Grijs & Peletier 1997
Tikhonov & Galazutdinova 2005

Formation models for thick discs

"born-thick"

Accretion:
Stars accreted from disrupted satellites in coplanar orbits (Abadi et al. 2003)

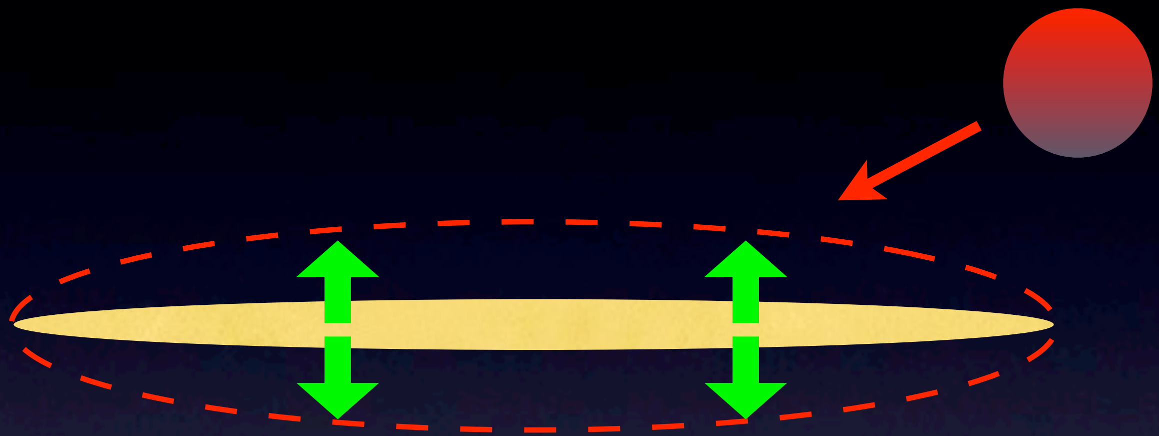
Merger:
Stars form during/after active epoch of gas-rich mergers in early galaxies
(Brook et al. 2005, Bournaud et al. 2007)

"born-thin" (pre-existing disc needed)

Migration:
Stars with "hot" kinematics migrate from the center outwards via spiral arms
(Schoenrich & Binney 2008, Roskar et al. 2008)

Heating:
Disc is dynamically heated during a merger with a satellite
(Quinn et al. 1993, Qu et al. 2011)

Formation model studied: <u>disc-heating</u>



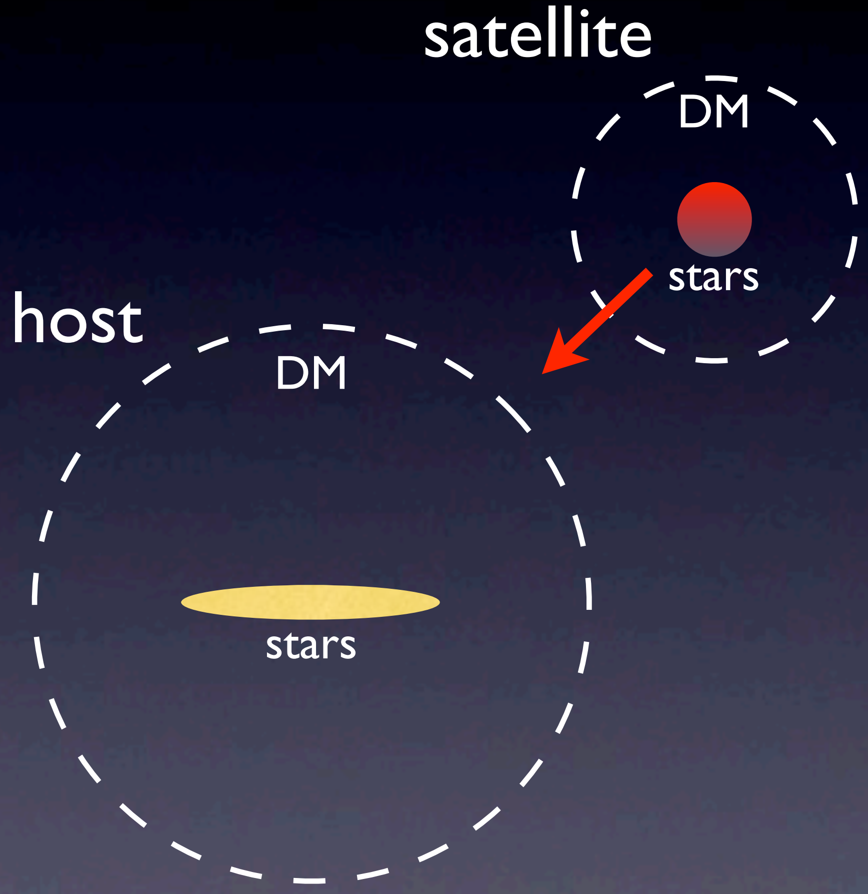
Why the disc-heating scenario?

- such a merger process is <u>unavoidable</u> in ΛCDM

In the case of the Milky Way:

- supported by the presence of <u>substructure in the thick disc</u>
- it naturally explains the <u>high rotation of the thick disc</u>

Set-up of *N*-body simulations



<u>Main features</u>:

- merger mass ratios 5:1 and 10:1
- 3 initial inclinations (0°, 30°, 60°)
- satellite in "cosmological" orbit
- prograde/retrograde orbits
- "discy"/spherical satellites
- mergers at redshifts z=0 and z=1

- gas is not included

Movie

Part I:
General properties of simulated thick discs

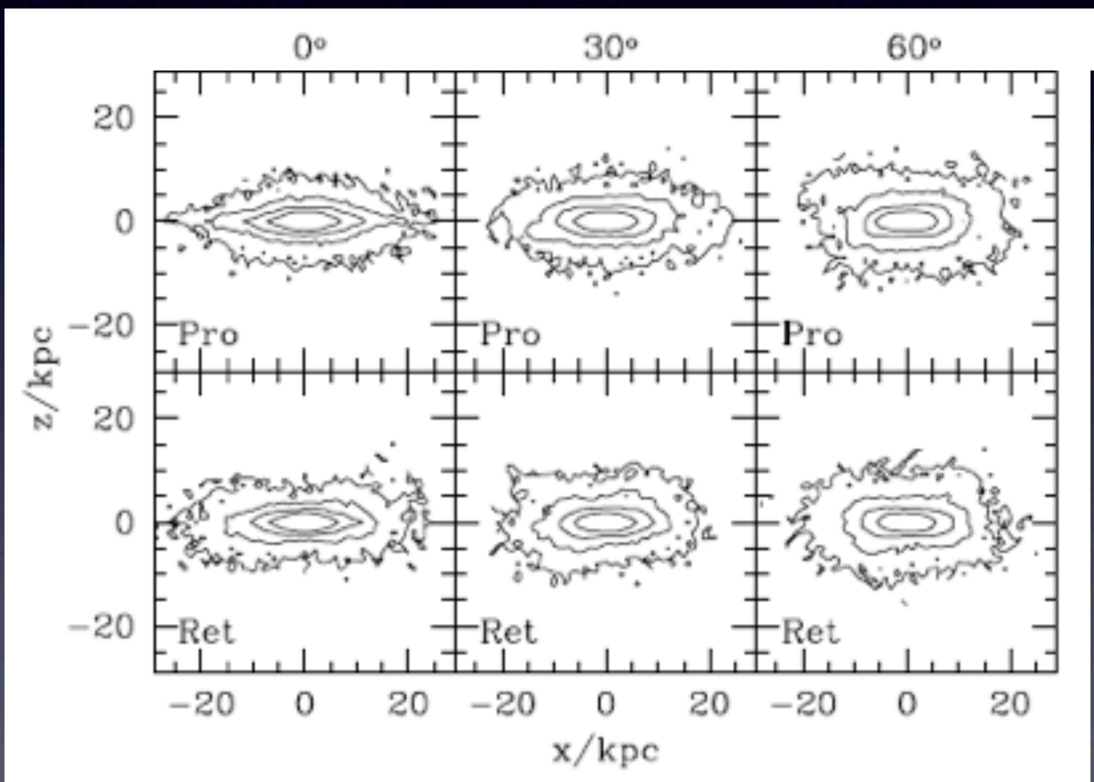
Villalobos & Helmi 2008, MNRAS, 391, 1806

- What are the general predictions of the disc-heating model for structural and kinematical observations in galaxies?
- Is the pre-existing disc fully heated during the merger?
- If the MW's thick disc was formed according to this model, which satellite orbits are favoured?

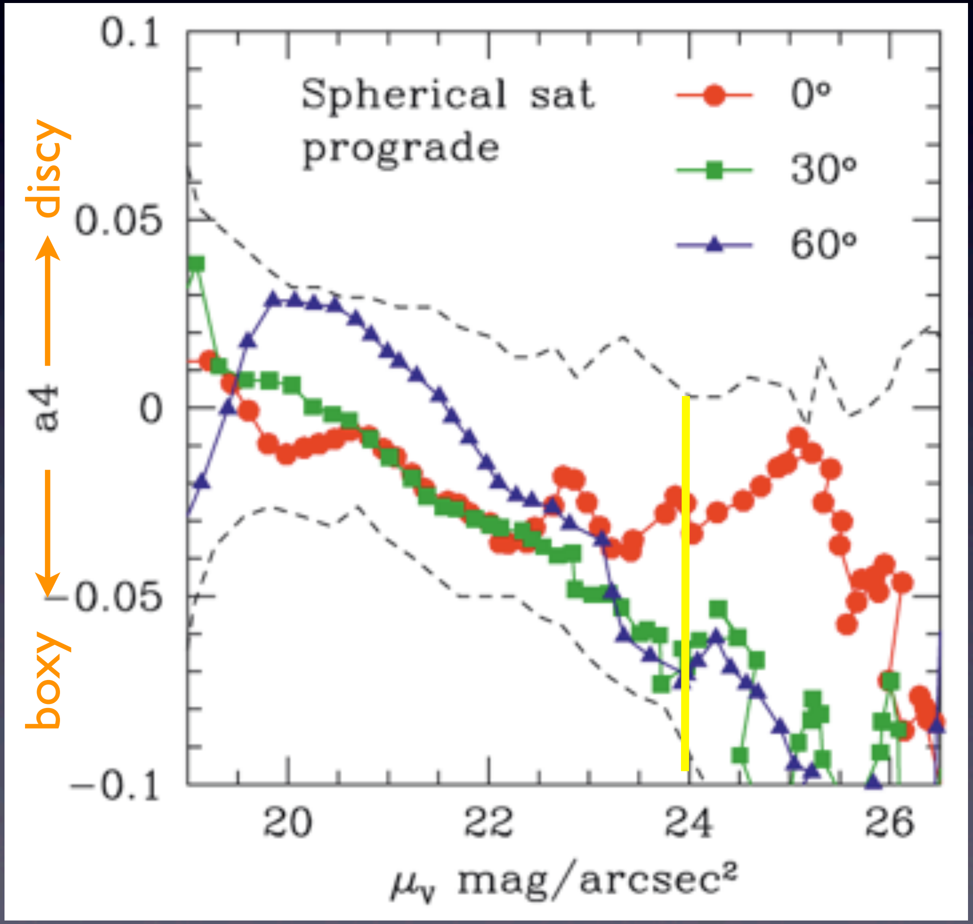
Morphological properties of simulated thick discs

disc-heating scenario predicts boxy surface brightness contours in the outskirts

(edge-on views)



22.5 to 27.7 mag arcsec^2 in V



6 mag below central surface brightness

Morphological properties of simulated thick discs

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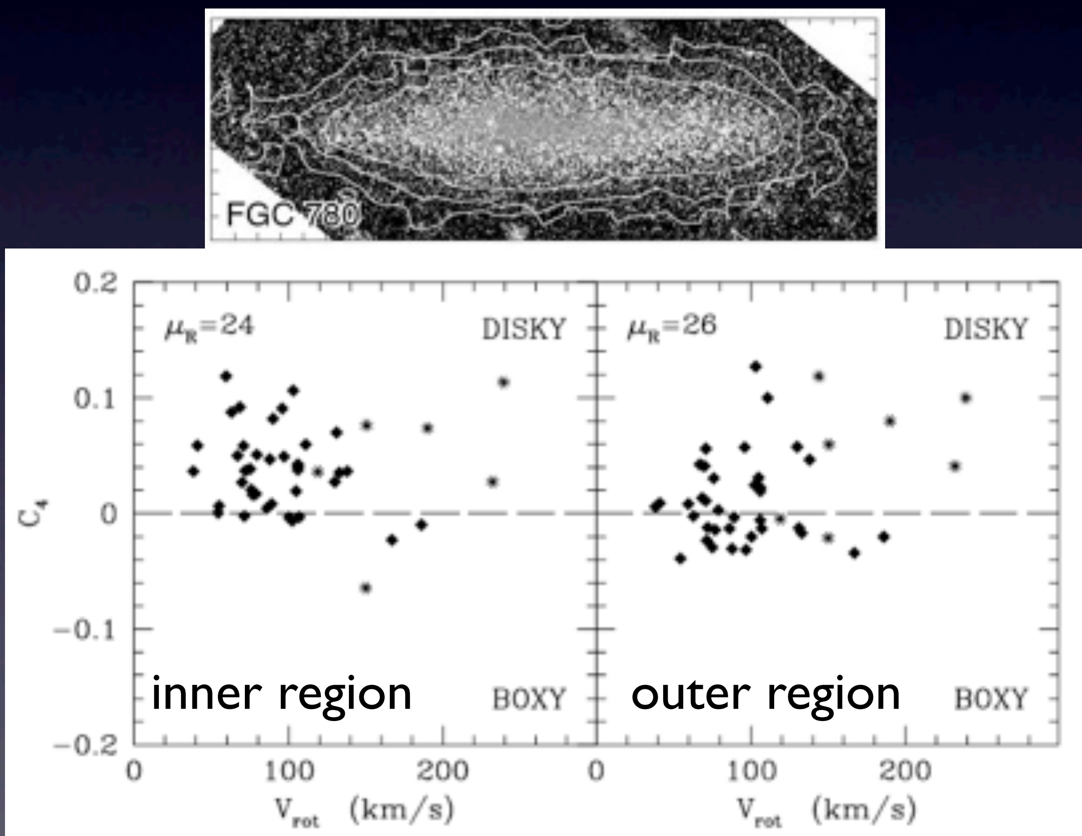
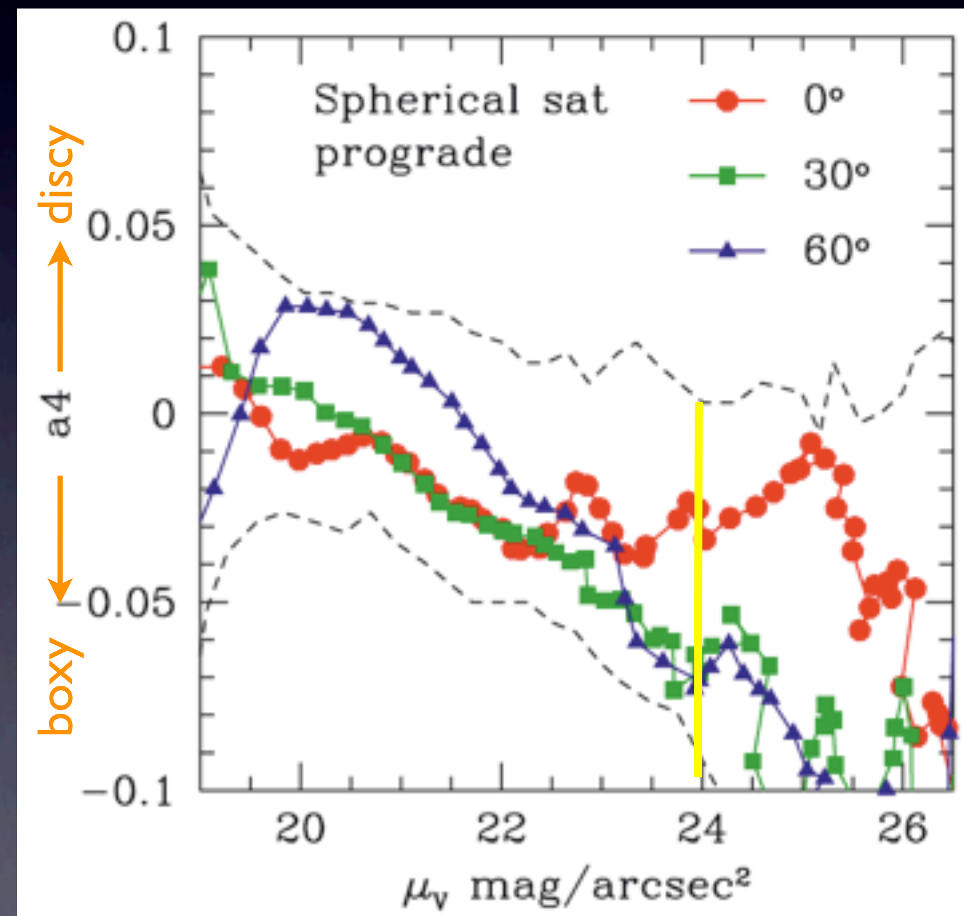


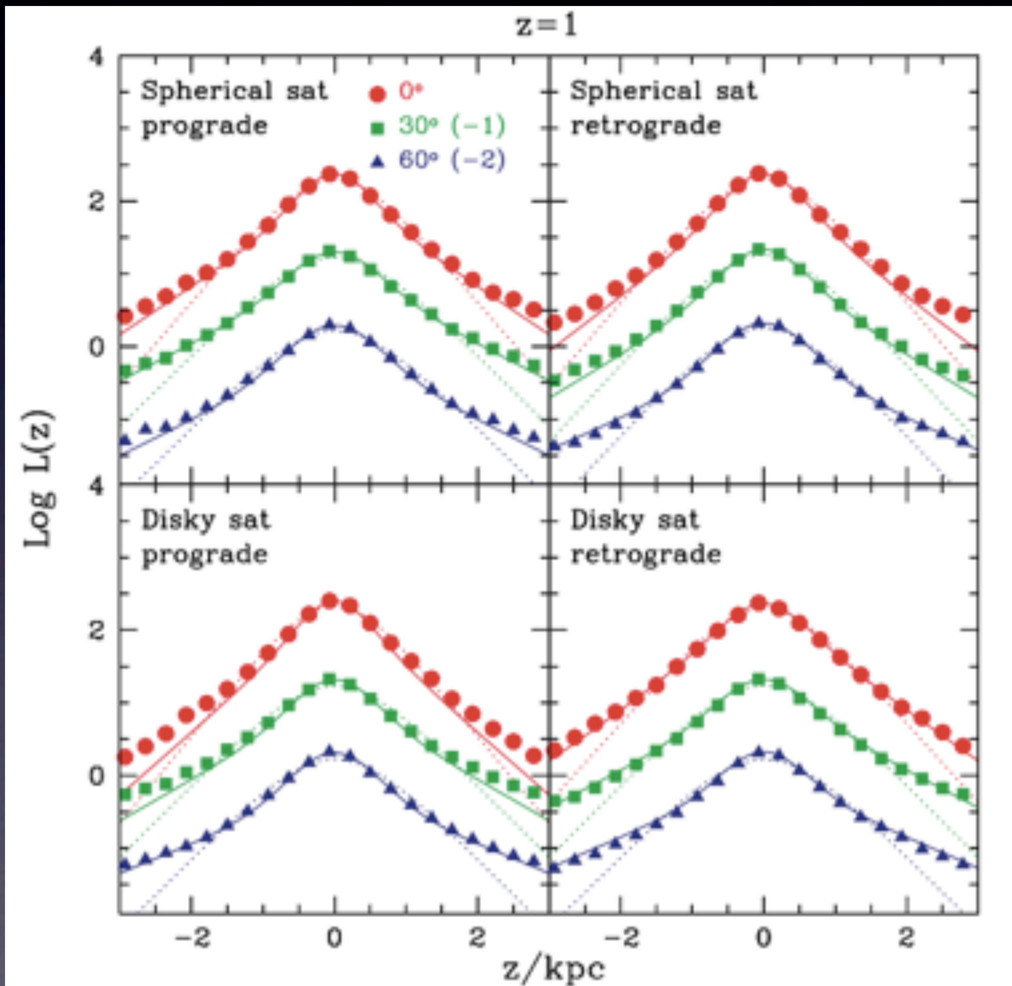
Dalcanton & Bernstein 2002

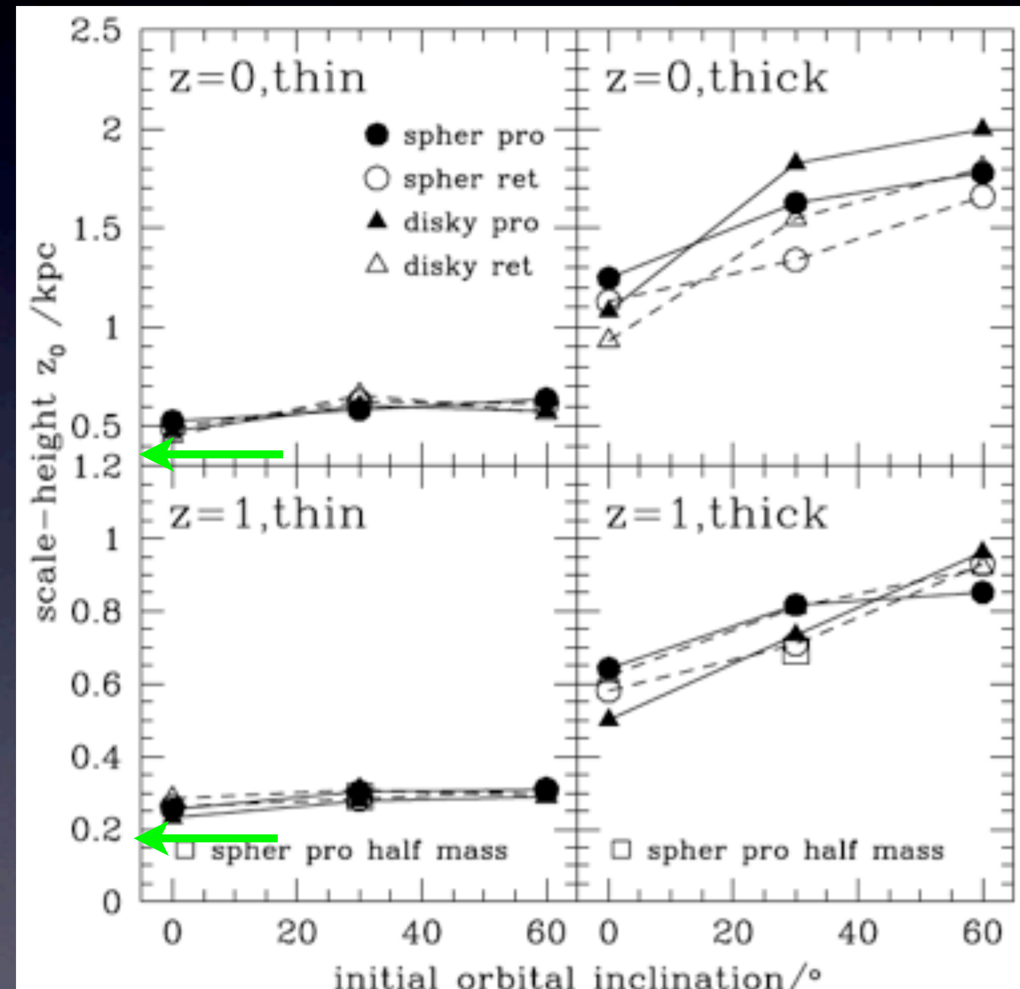


6 mag below central surface brightness

Structural properties of simulated thick discs

vertical structure of the remnants: 2 $sech^2$ components give better fit ("thin" + thick)





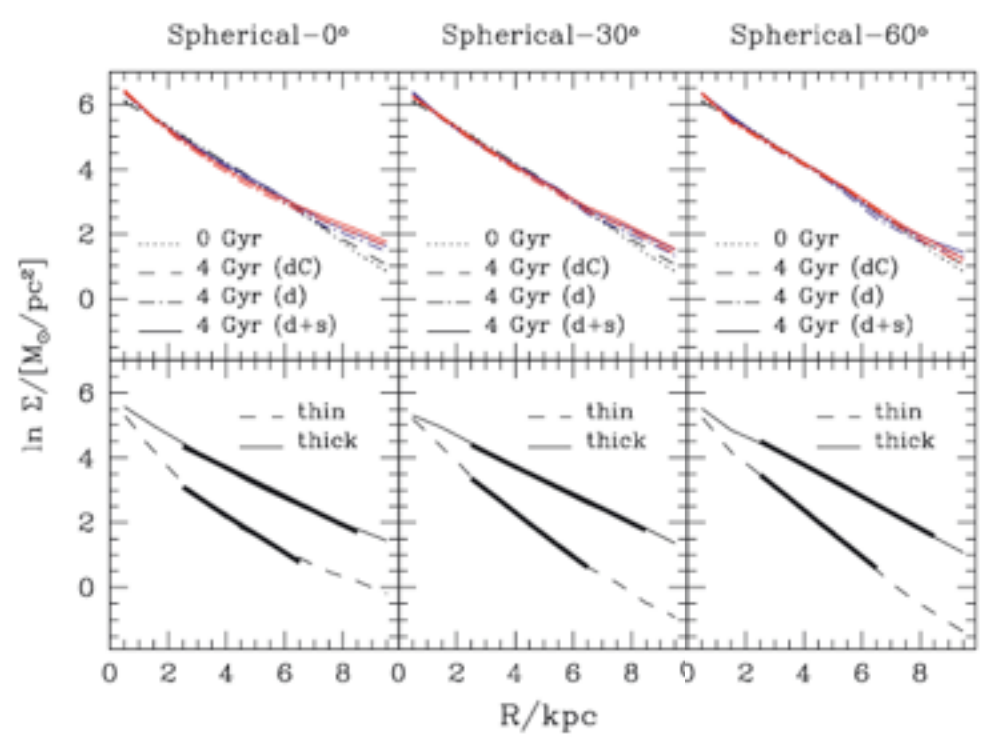
fit: 1 component

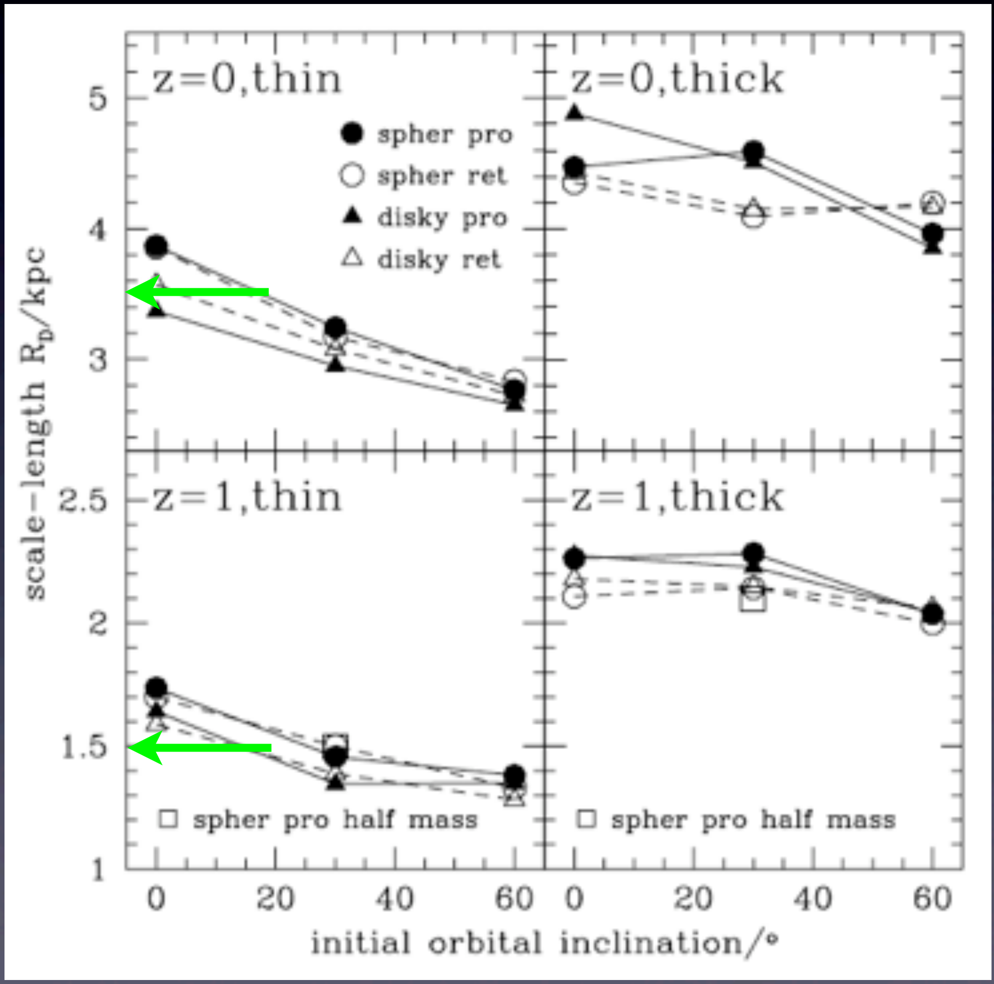
fit: 2 components

: scale-height of initial disc

Structural properties of simulated thick discs

radial structure of the remnants: decomposition into "thin" and thick components





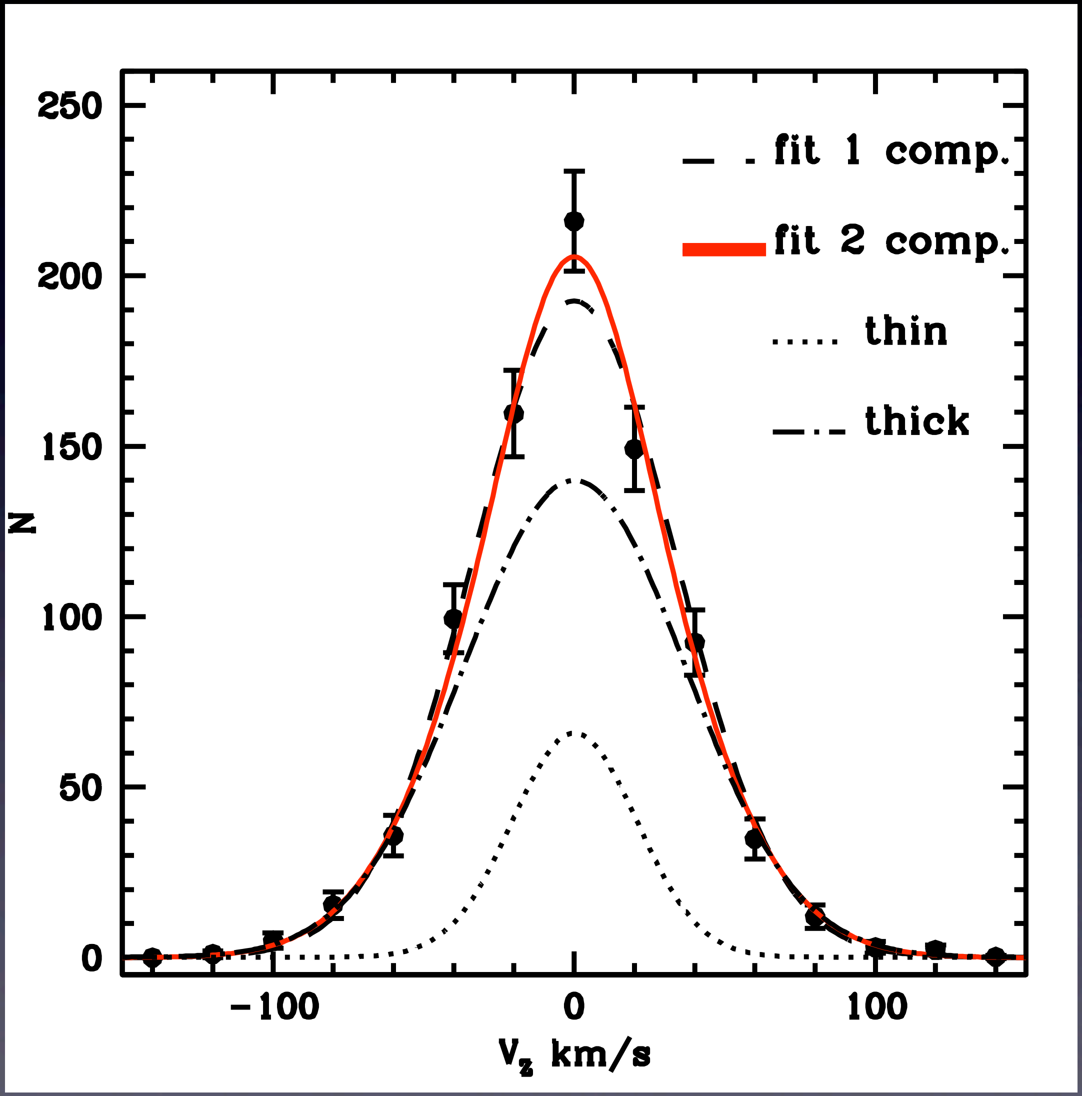
- "thin" component defined as: $|z| < 0.5\ z_{o,thin}$
- thick component defined as: $z_{o,thin} < |z| < 3$ kpc

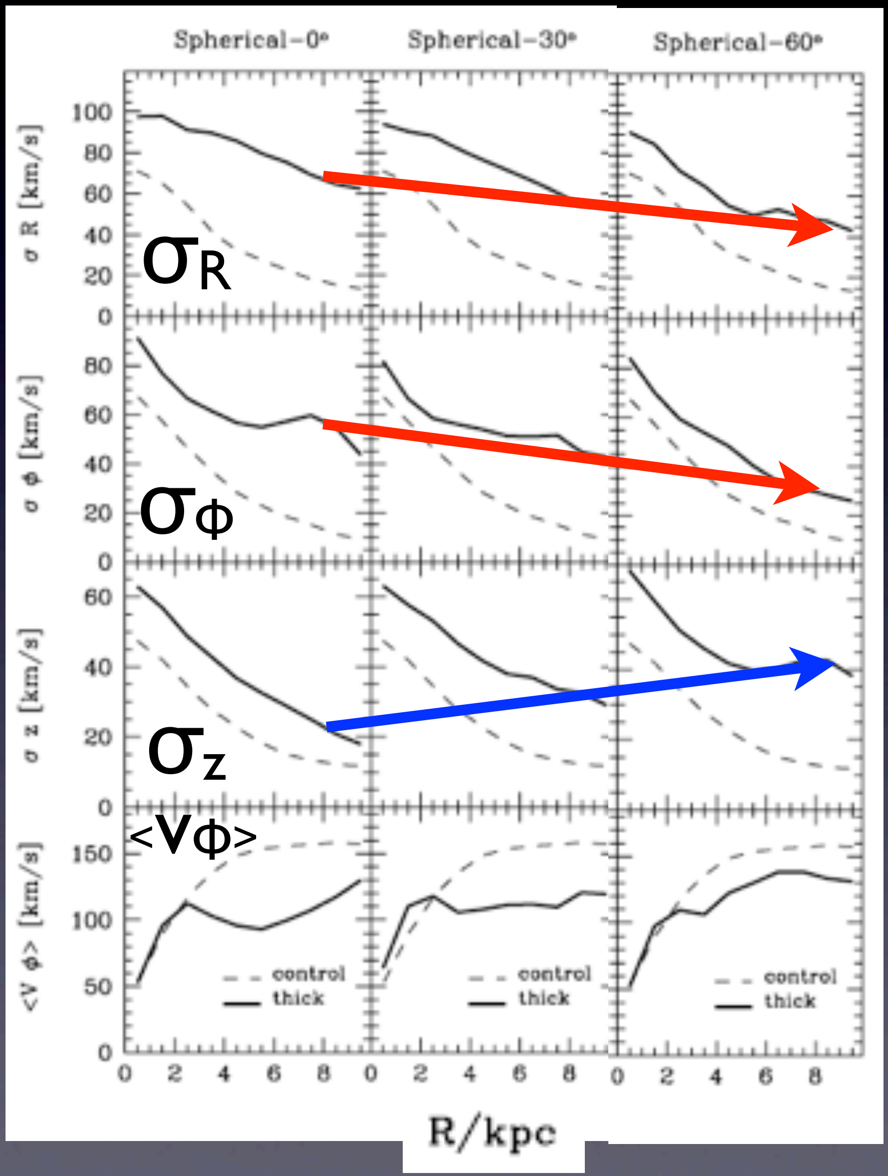
$\boxed{M_{thin} = 15\% - 25\% \text{ of } M_{thick}}$

: scale-length of initial disc

Kinematical properties of simulated thick discs

decomposition of velocity distributions into “thin” and thick components

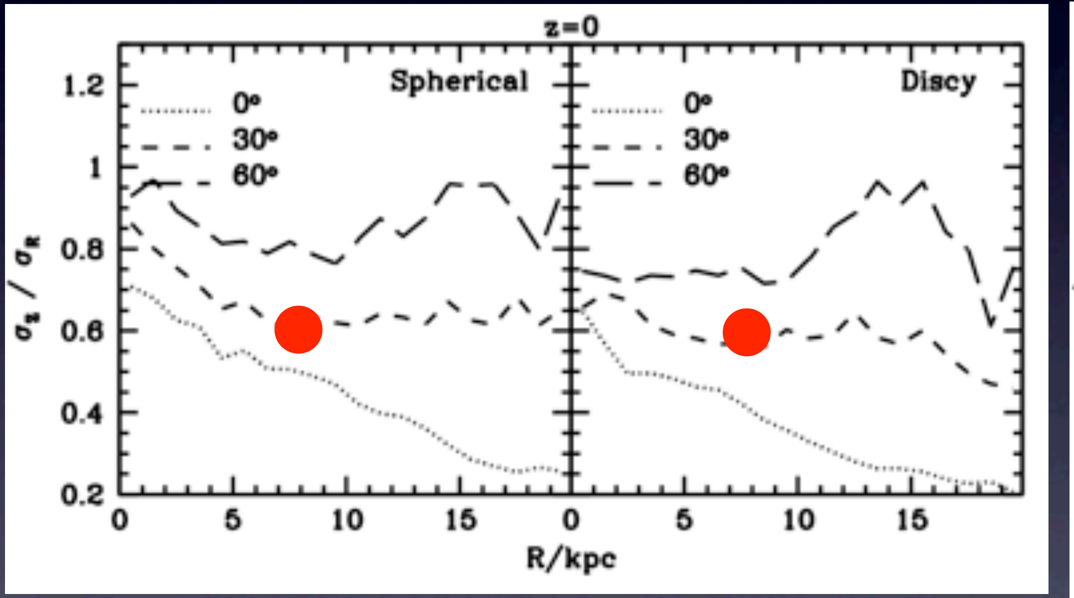


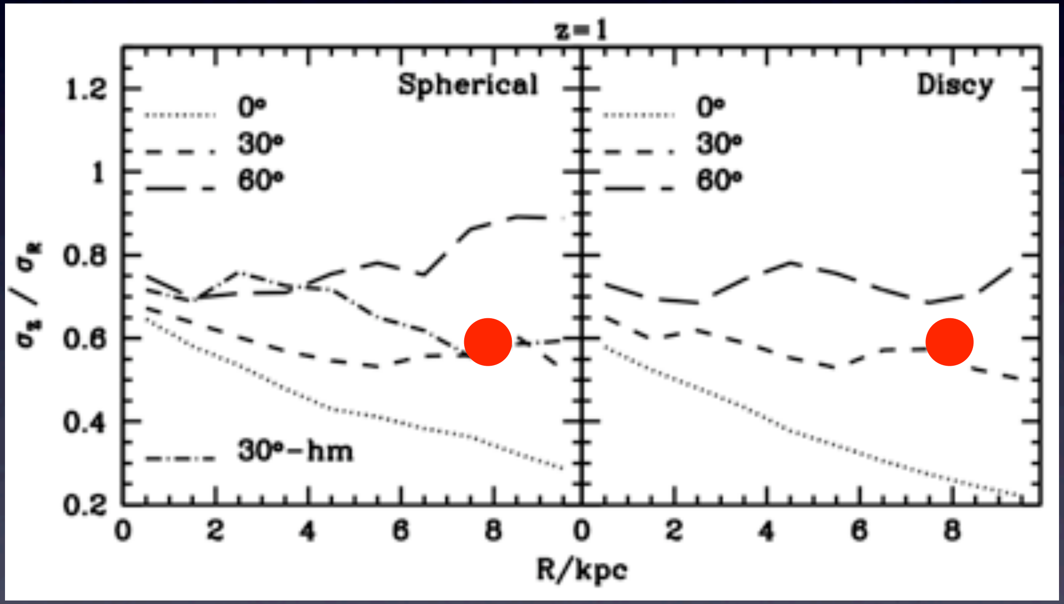


- fit 1 component, $\chi^2 = 0.68$
- fit 2 component, $\chi^2 = 0.47$

Kinematical properties of simulated thick discs

ratio σ_z / σ_R of thick disc stars could be a good indicator of the initial inclination of the satellite

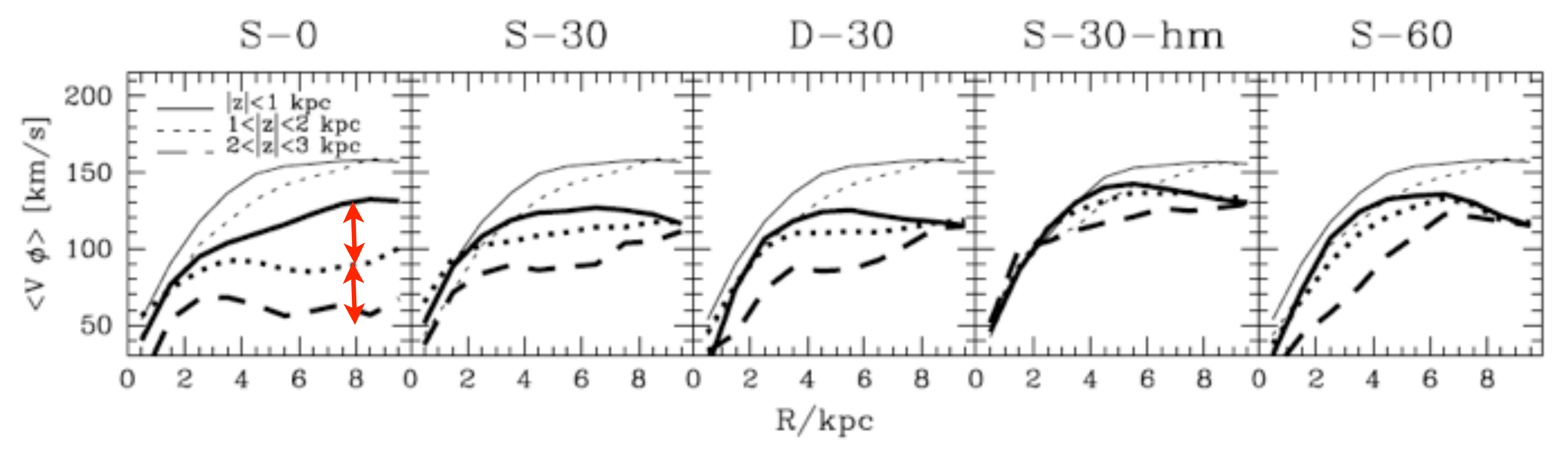




● Observed in Solar neighbourhood: $\sigma_z / \sigma_R \sim 0.6$
(Chiba & Beers 2001, Soubiran et al. 2003, Vallenari et al. 2006)

Kinematical properties of simulated thick discs

vertical gradient of rotational velocity in thick disc is stronger for lower initial inclinations of the satellite.



- Observed gradient in the MW's thick disc in the range -18 to -30 km/s/kpc (Chiba & Beers 2000, Girard et al. 2006, Ivezic et al. 2008)

Conclusions. I

- What are the general predictions of the disc-heating model for structural and kinematical observations in galaxies?

  - boxiness of low surface brightness contours
  - value of σ_z/σ_R in the solar neighbourhood
  - presence of strong vertical gradient of mean rotation

- Is the pre-existing disc fully heated during the merger?

  - No. There is a cold/thin remnant with 15-25% of the total mass

- If the MW's thick disc was formed according to this model, which orbits of the satellite are favoured?

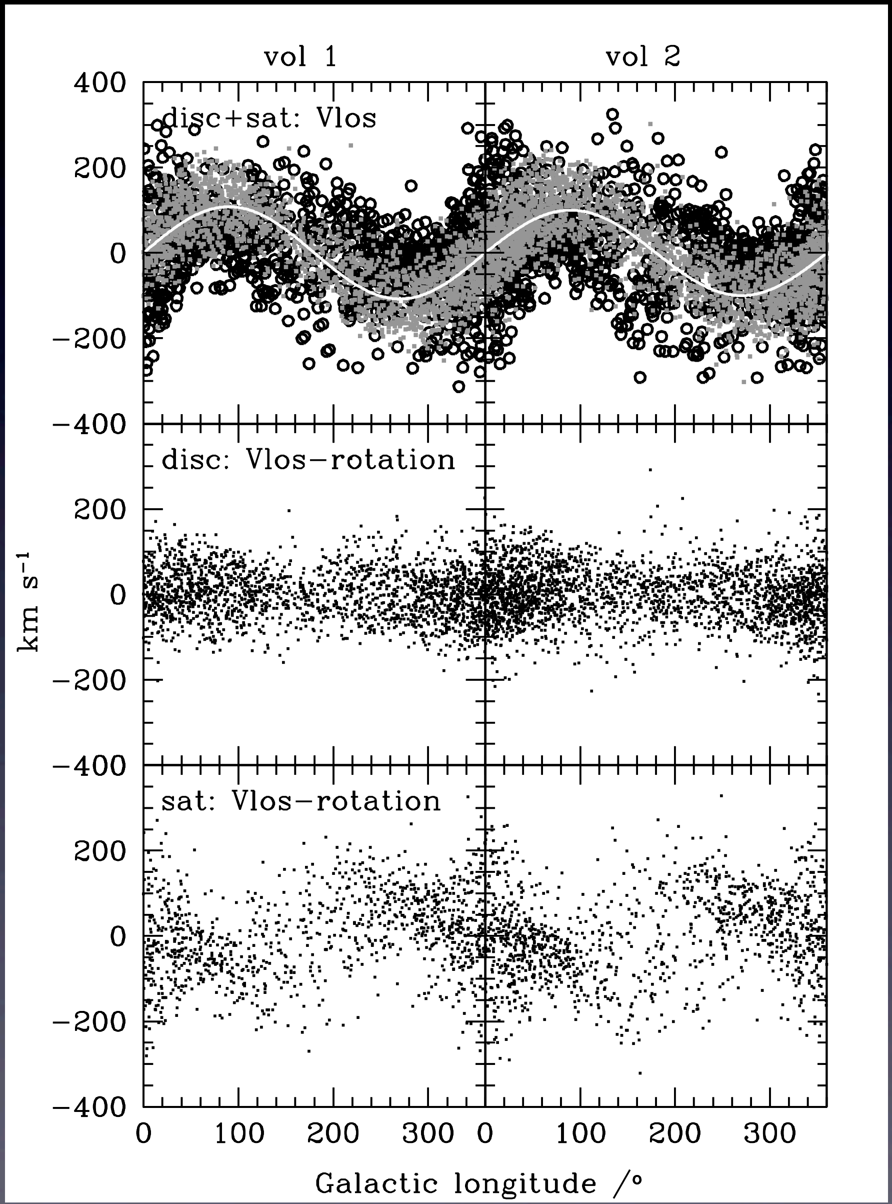
  - this model favours a merger with low/intermediate inclination (~0-30°) based on value of σ_z/σ_R and the presence of strong vertical gradient of mean rotation

Part II:
Phase-space properties of thick discs stars

Villalobos & Helmi 2009, MNRAS, 399, 166

- What kind of evidence of the disc-heating scenario is imprinted in the phase-space structure of thick disc stars, especially within small spatial volumes resembling the Solar neighbourhood?

Heliocentric line-of-sight velocities, V_{los}

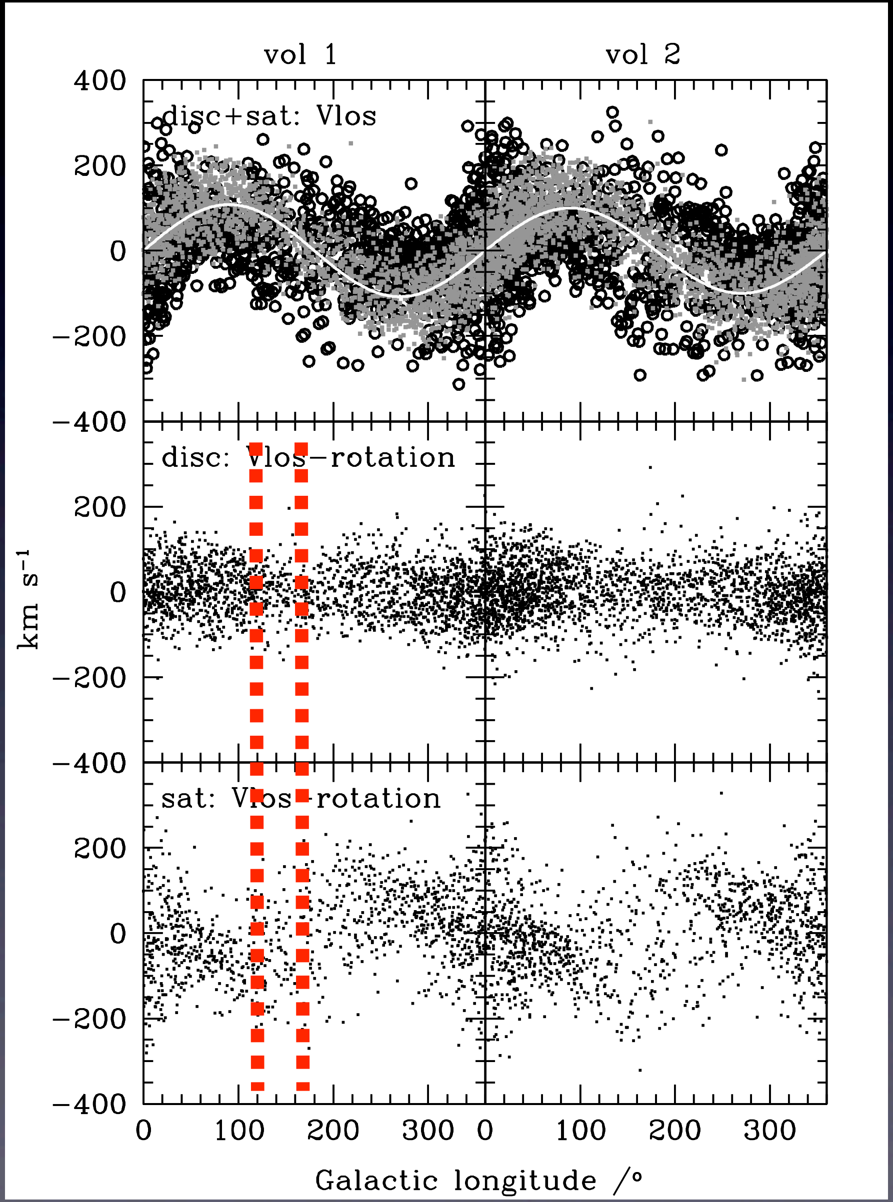


grey: heated disc
black: satellite

- sinusoidal shape:
thick disc stars retain the nearly circular orbits from the pre-existing disc

- the different behaviour of heated disc and satellite stars is clear after subtracting the rotation.

Heliocentric line-of-sight velocities, V_{los}



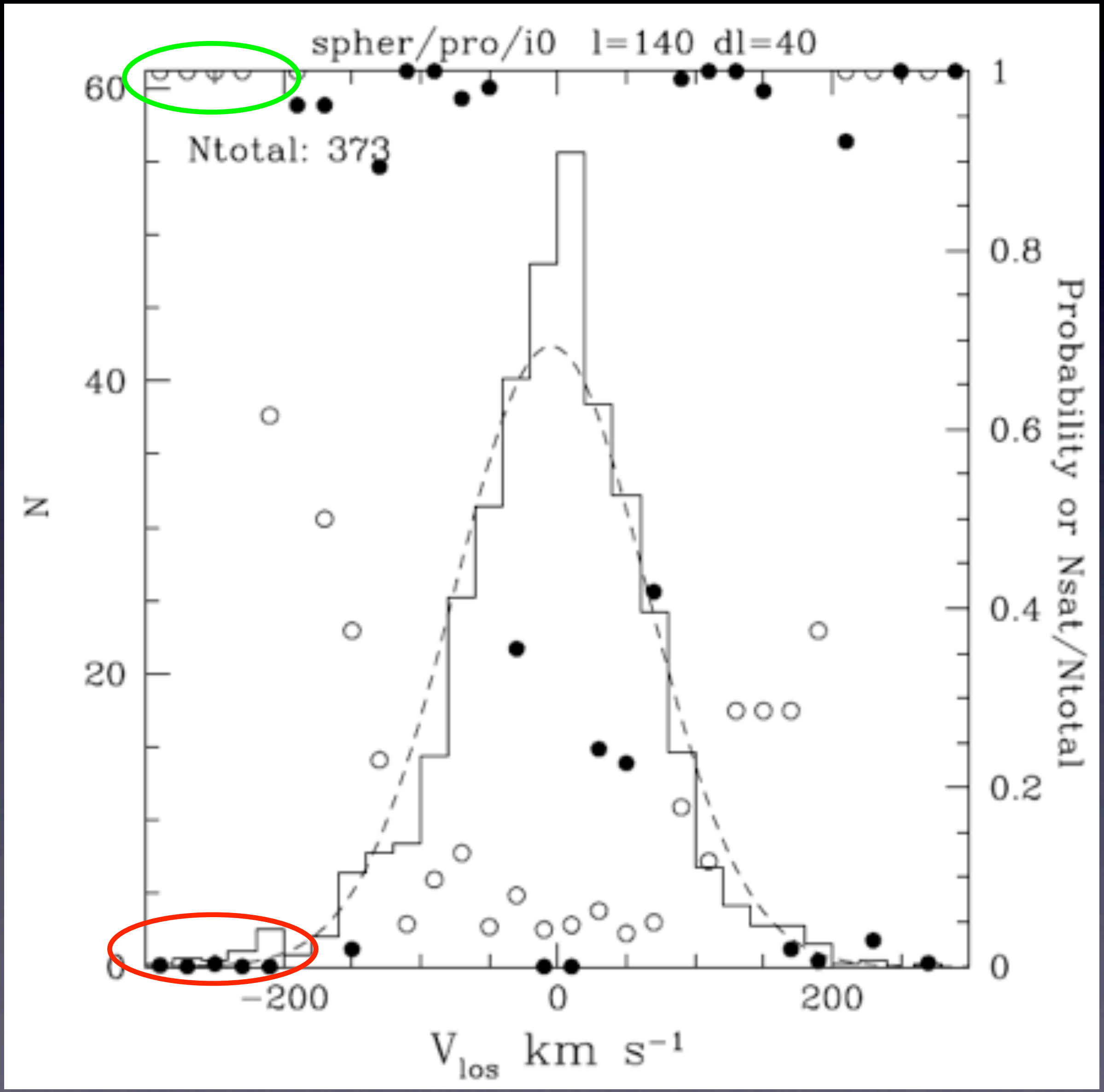
grey: heated disc
black: satellite

- sinusoidal shape:
thick disc stars retain the nearly circular orbits from the pre-existing disc

- the different behaviour of heated disc and satellite stars is clear after subtracting the rotation.

Is it possible to detect the contribution of satellite stars in the wings?

Wings of V_{los} distributions around long. ~ 140°



<u>solid circles</u>: probability that a certain peak occurs by chance.

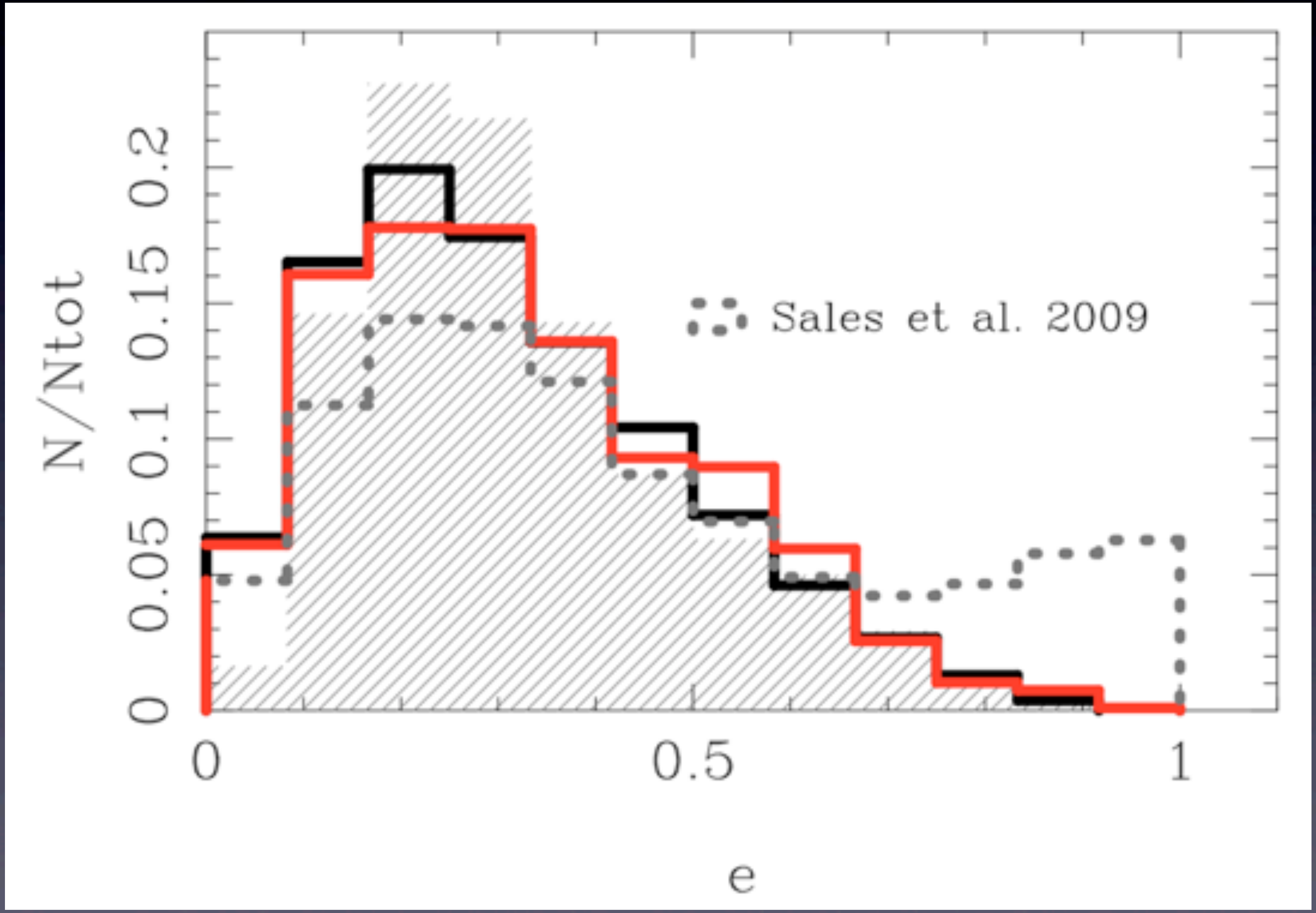
<u>open circles</u>: fraction N_{sat}/N_{total} in each bin.

simple statistical test is able to:

- identify non-Gaussian peaks
- detect presence of accreted stars

Eccentricity distributions

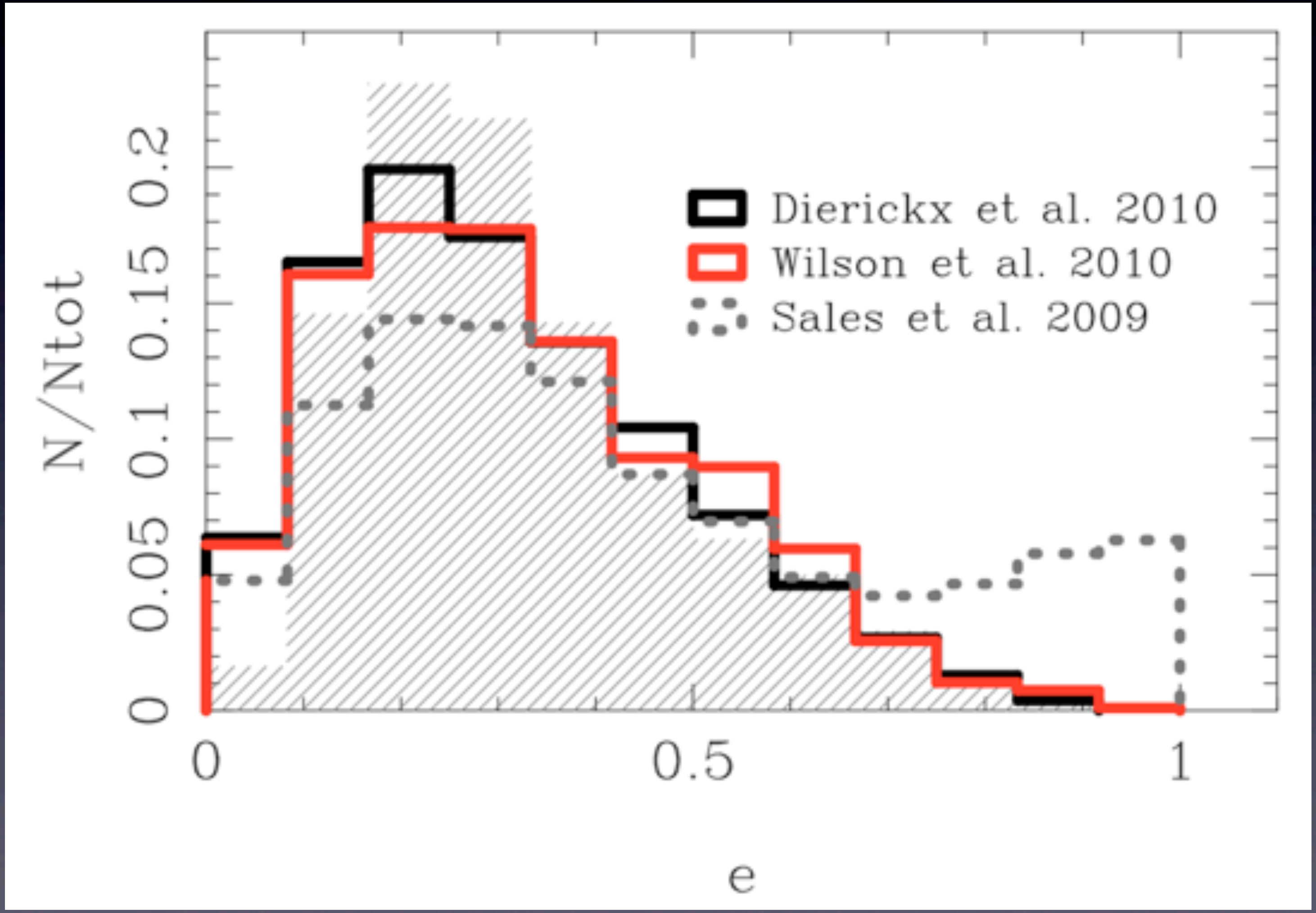
Di Matteo, Lehnert, Qu & van Driel 2011, A&A, 525, L3



(simulation)

Eccentricity distributions

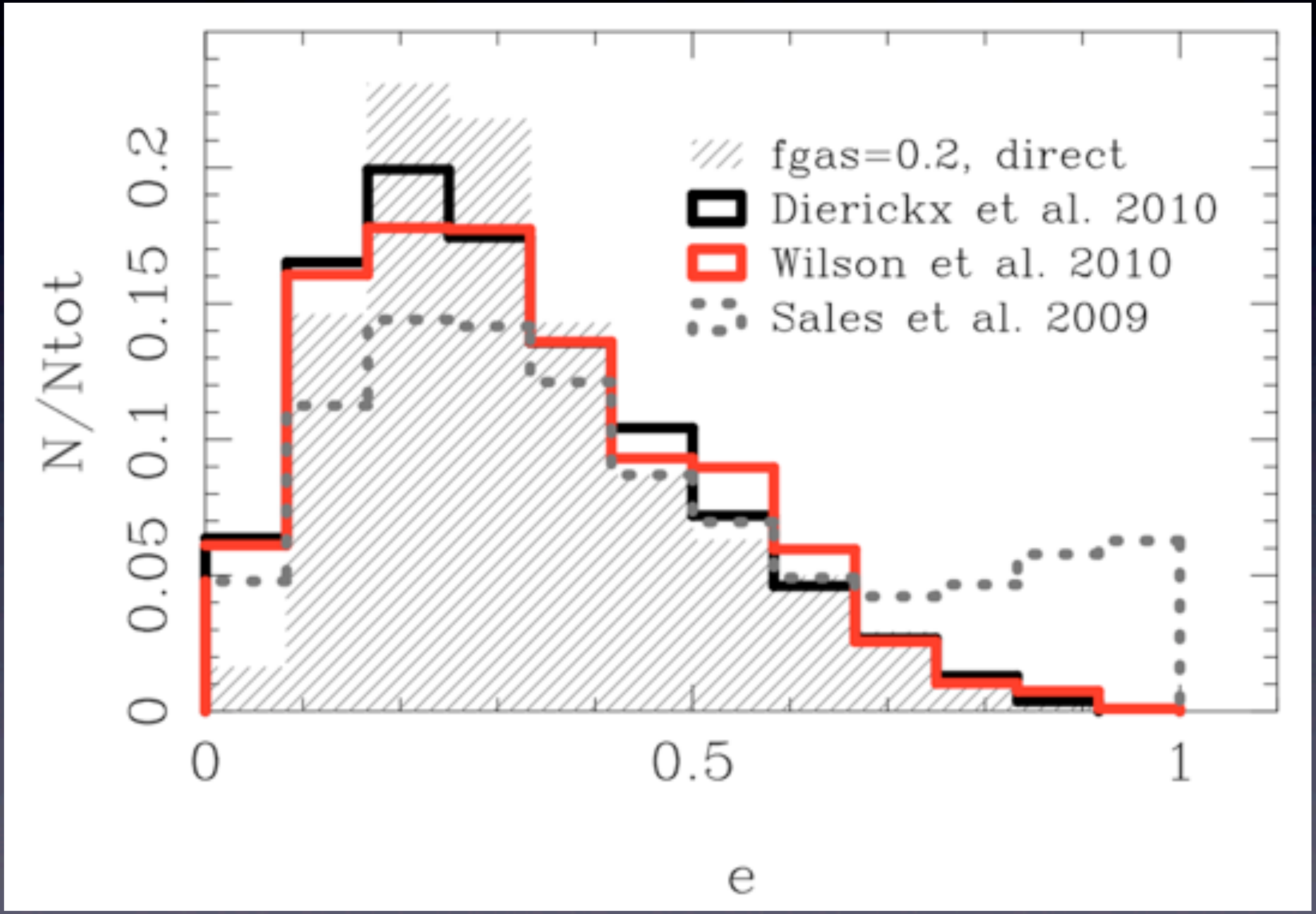
Di Matteo, Lehnert, Qu & van Driel 2011, A&A, 525, L3



(SEGUE)
(RAVE)
(simulation)

Eccentricity distributions

Di Matteo, Lehnert, Qu & van Driel 2011, A&A, 525, L3

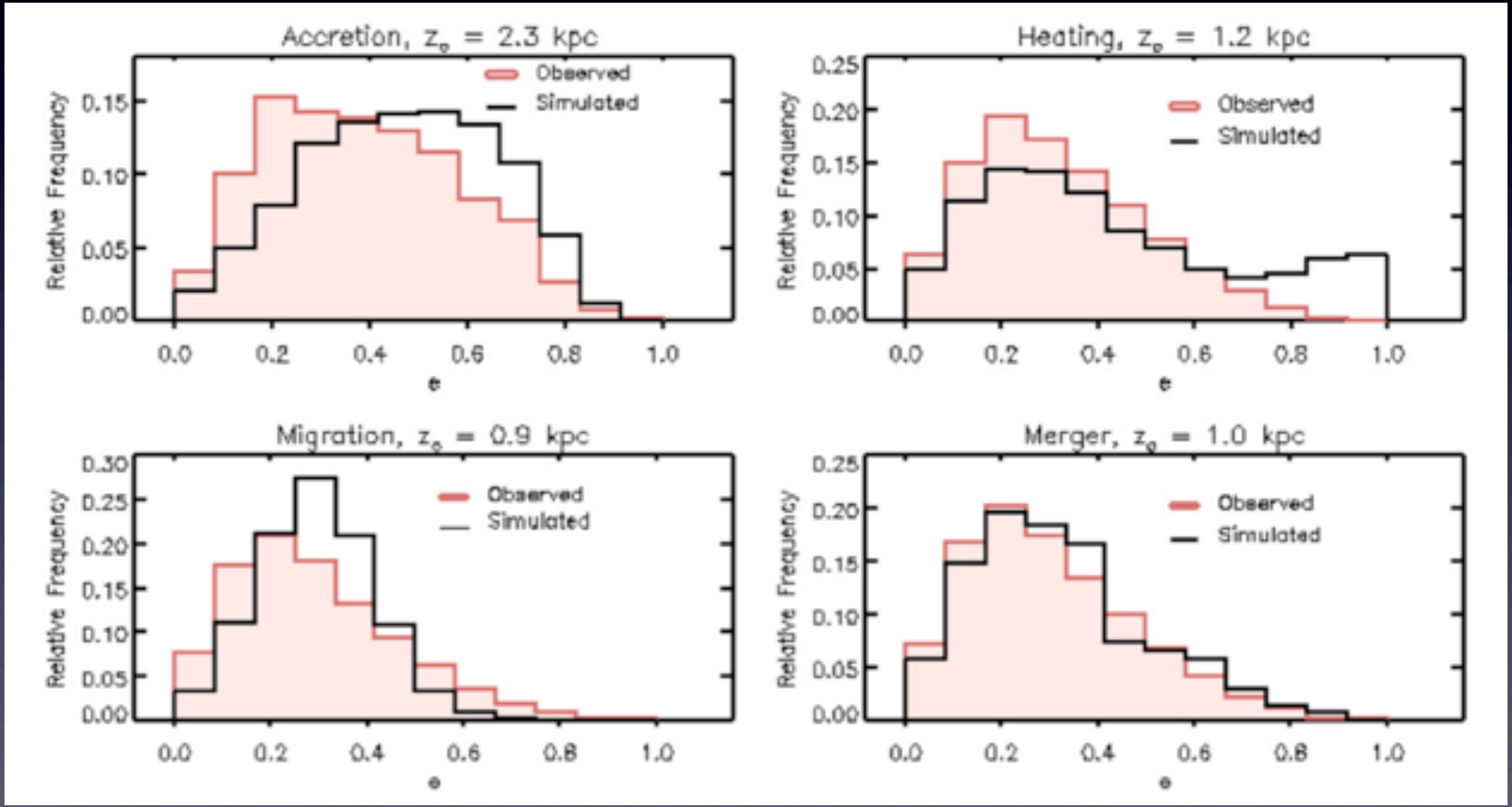


(simulation)
(SEGUE)
(RAVE)
(simulation)

Eccentricity distributions

disc heating vs other models vs observations

Dierickx et al. 2010, ApJL, 725, L186



Conclusions. II

- What kind of evidence of the disc-heating scenario is imprinted in the phase-space structure of thick disc stars, especially within small spatial volumes resembling the Solar neighbourhood?

- sinusoidal shape of V_{los} as a function of Galactic longitude
- wings of V_{los} distributions are mainly populated by satellite stars
- eccentricity distributions could discriminate between formation models

Part III:
Evolution of thick discs after slow growth of a thin disc

Villalobos, Kazantzidis & Helmi 2010, ApJ, 718,314

- How does a thick disc evolve due to the slow growth of a new embedded thin disc?
- What are the most relevant aspects of the growth that affect this evolution?
- Which of the previous results (Part I and II) are still in place after the growth of the new disc?

Simulating the growth of a new thin disc

explored features of the new thin disc:

- total mass: 2 M_{thick} and 5 M_{thick} *
- scale-length: 1 kpc and 3 kpc *
- scale-height: 25 pc and 125 pc

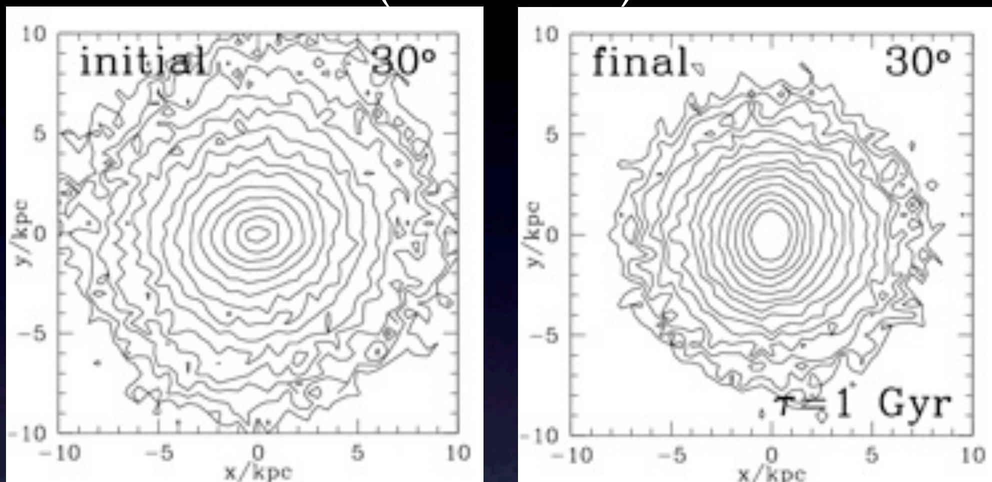
- growth time-scales: 0, 1 and 5 Gyr

- $\vec{L}_{thin}$ aligned with $\vec{L}_{thick}$ or halo spin
- thin disc counter-rotating w.r.t. thick disc

Thick disc response to the growth of thin disc: **structural contraction**

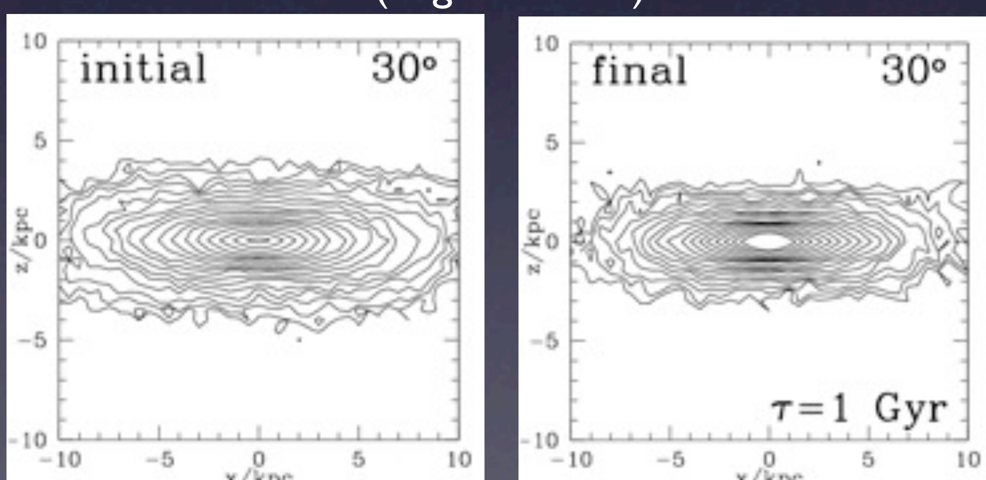
(face-on view)

contours: 20.25-25.35 mag arcsec^2



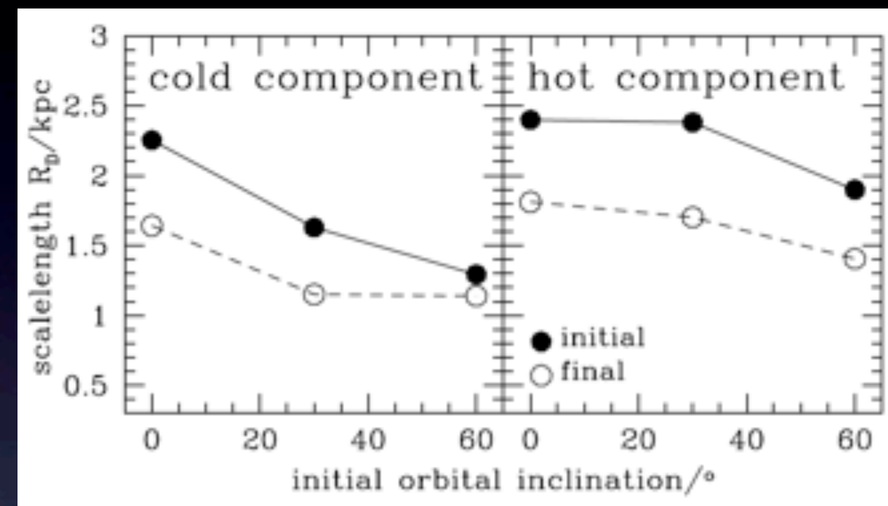
(edge-on view)

contours: 19.09-25.35 mag arcsec^2

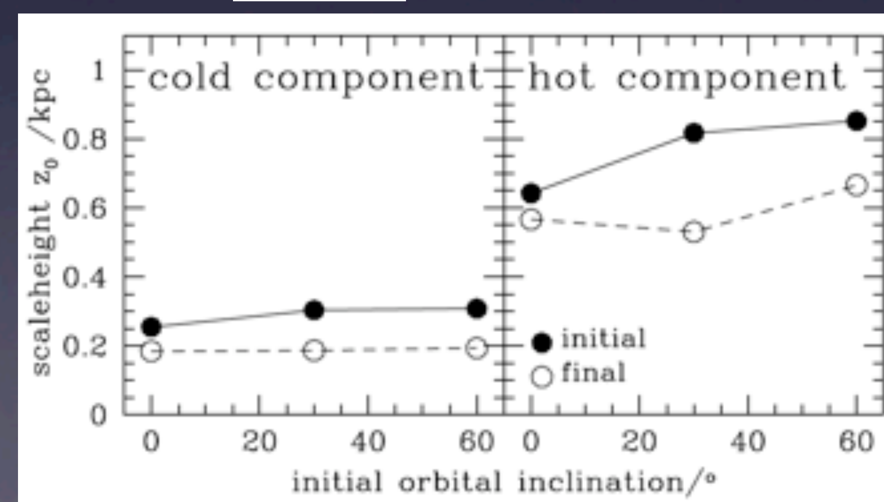


$M_{thin}=5M_{thick}$; scale-length=3 kpc ; scale-height=125 pc

<u>radial</u> contraction

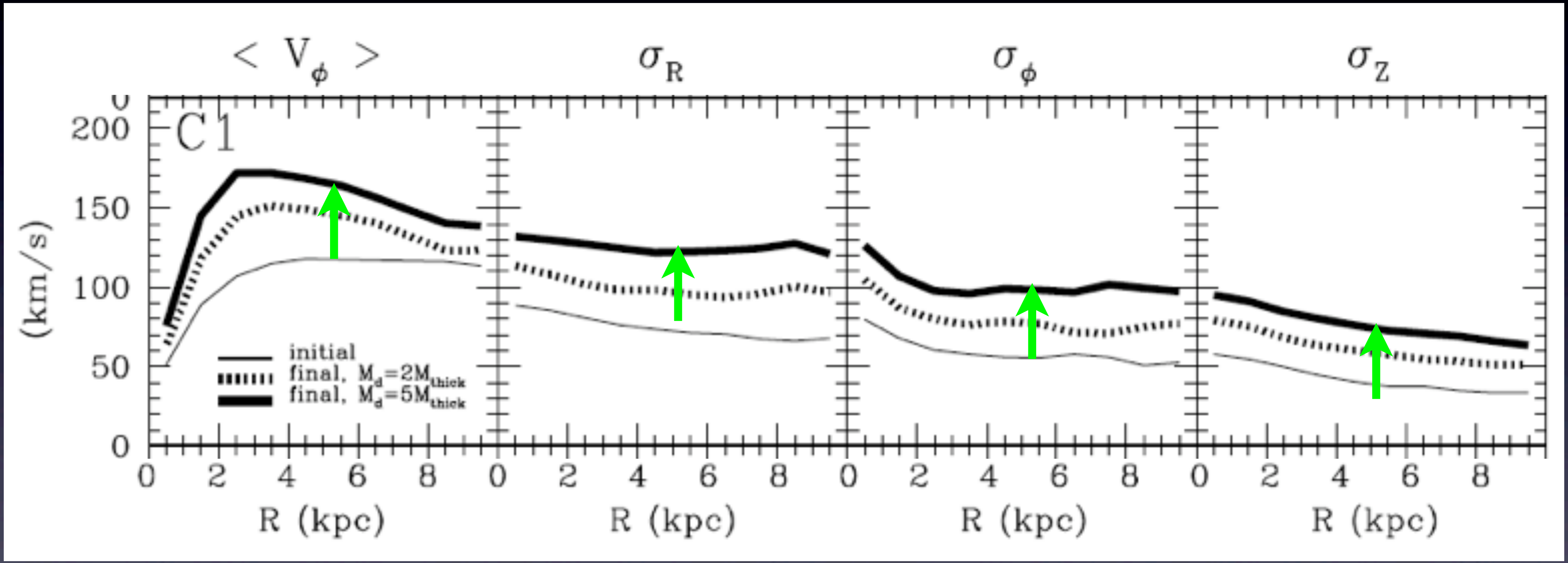


<u>vertical</u> contraction



Thick disc response to the growth of thin disc:

increasing mean rotation and vel. dispersions

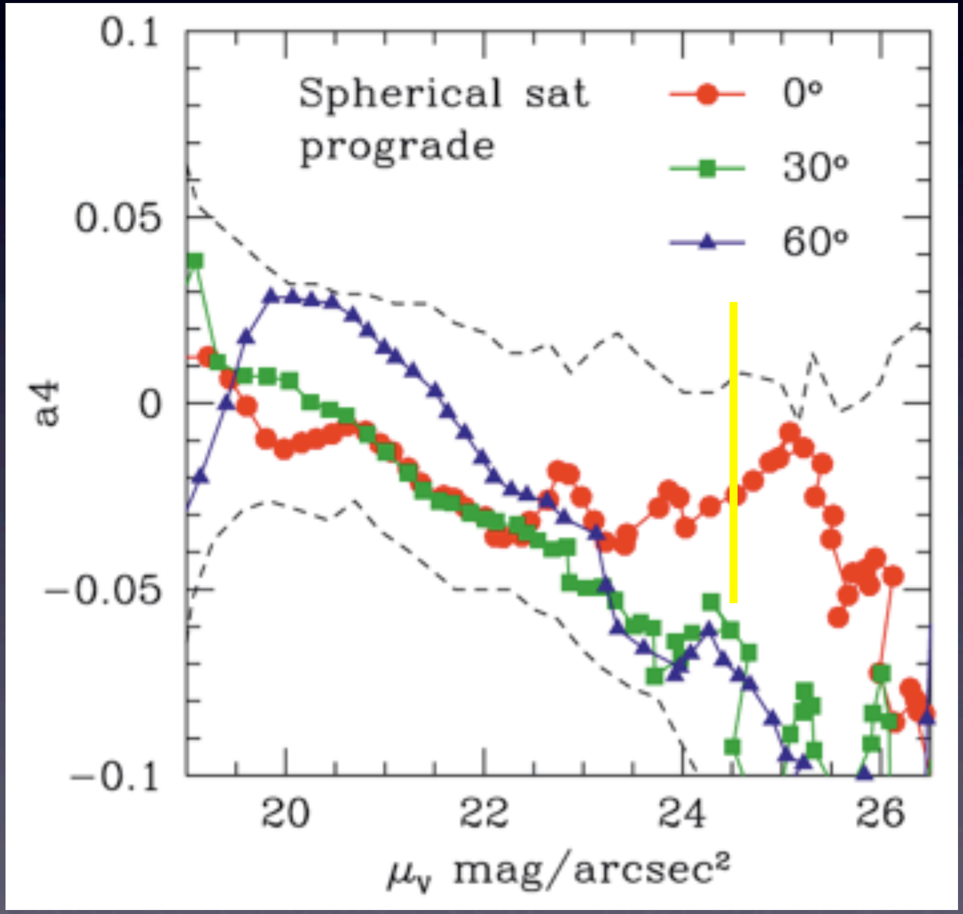


new thin disc:
growth time-scale=1 Gyr
scale-length=3 kpc
scale-height=125 pc

Comparison to some results of **Part I** and **II**

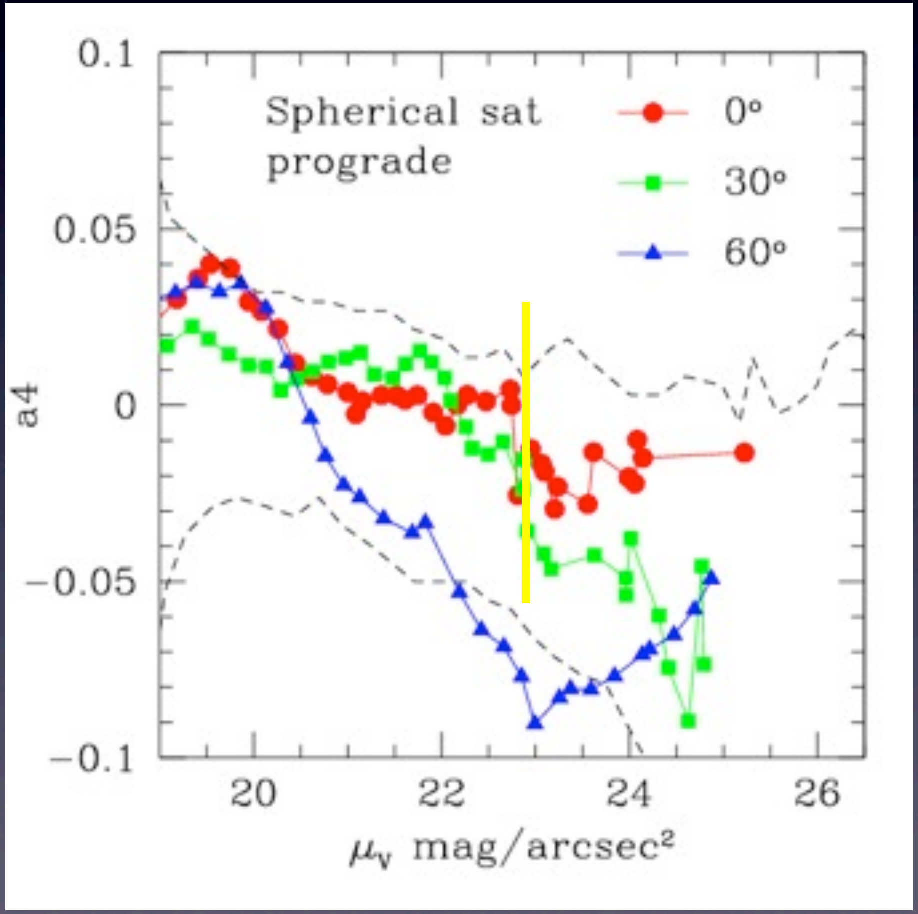
contours remain boxy at low surface brightness

before new thin disc



6 mag below central peak

after new thin disc

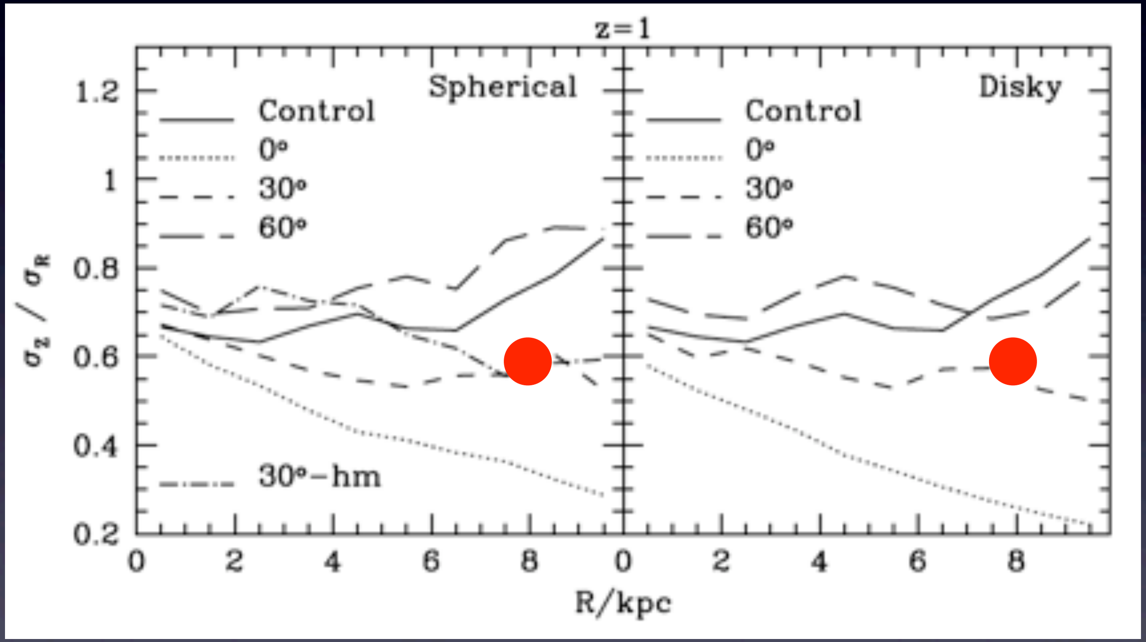


6-7 mag below central peak

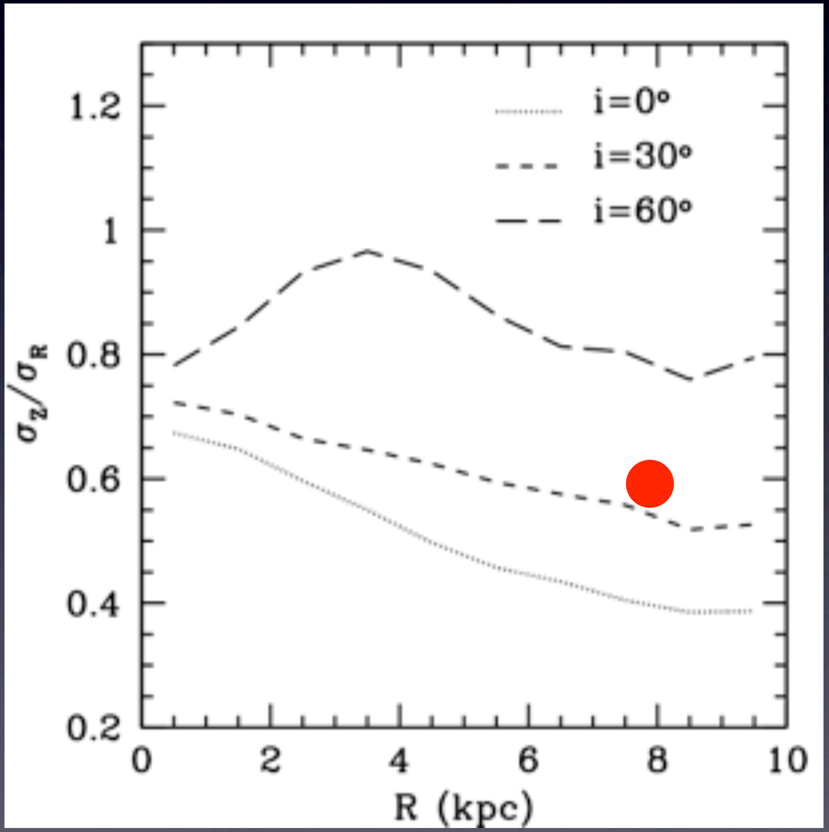
Comparing to some results of **Part I** and **II**

ratio σ_z/σ_R of thick disc stars <u>remains</u> a good indicator of the initial inclination of the satellite

<u>before</u> new thin disc



<u>after</u> new thin disc

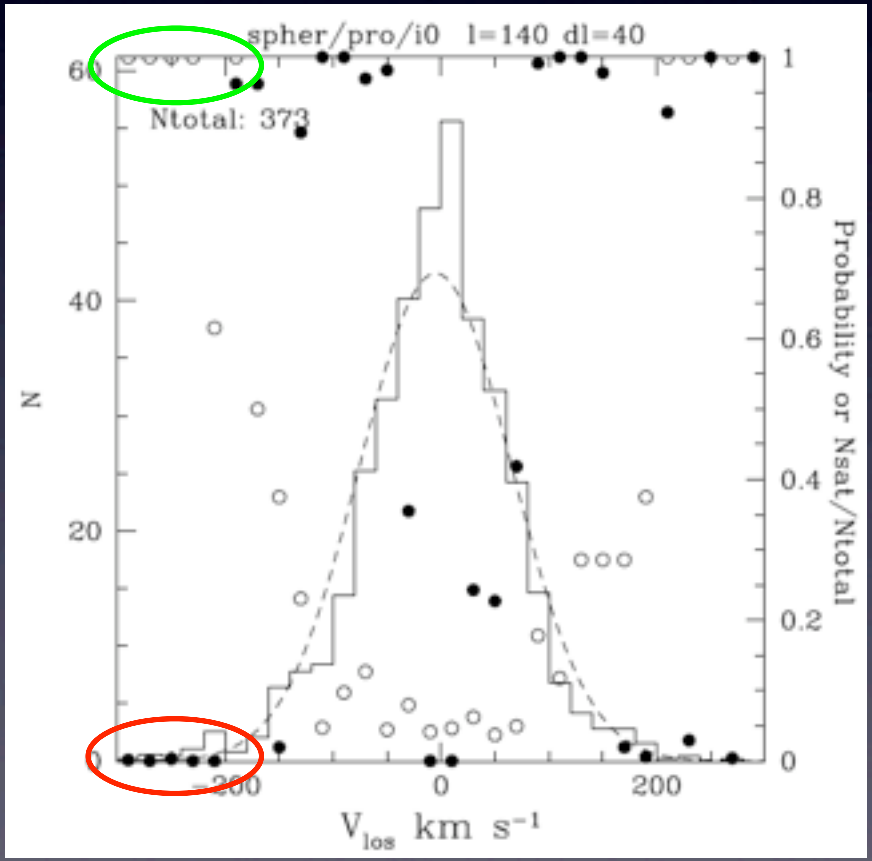


● $\sigma_z/\sigma_R \sim 0.6$ Chiba & Beers 2001, Soubiran et al. 2003, Vallenari et al. 2006

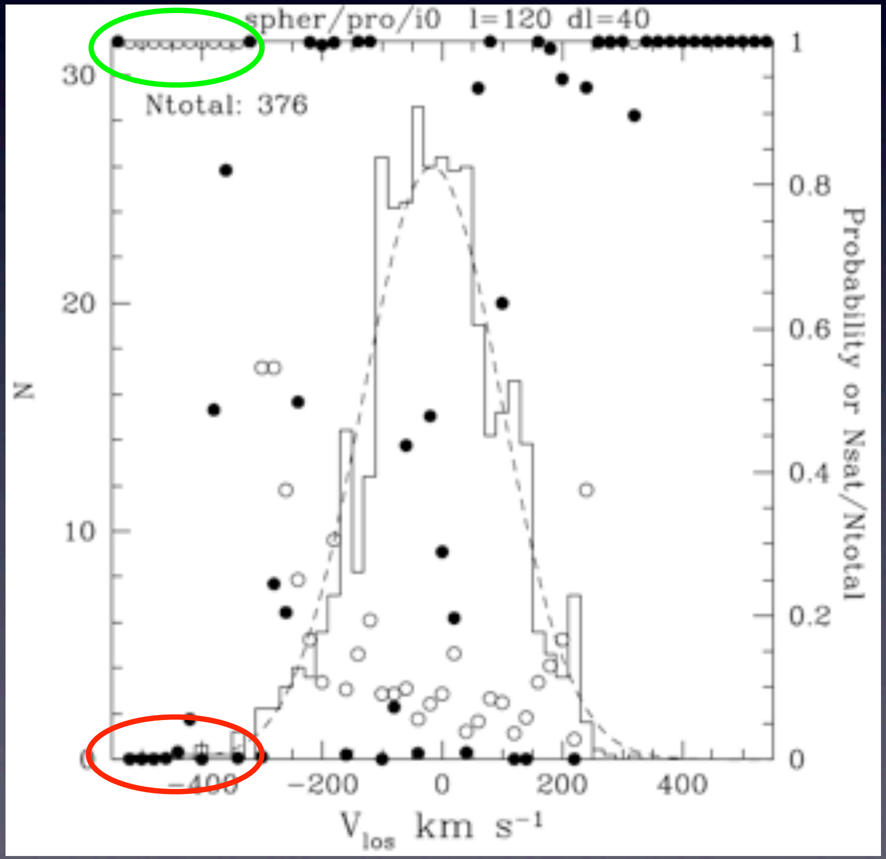
Comparing to some results of **Part I** and **II**

simple statistical test <u>is still</u> capable to:
- identify non-Gaussian peaks
- detect presence of accreted stars

<u>before</u> new thin disc



<u>after</u> new thin disc



solid: probability open: N_{sat}/N_{total}

Conclusions. III

- How does a thick disc evolve due to the slow growth of a new embedded thin disc?

  - thick discs' structure contracts but rotation and dispersion increase

- What are the most relevant aspects of the growth that affect this evolution?

  - the total mass and scale-length of the new thin disc

- Which of the previous results (Part I and II) are still in place after the growth of the new disc?

  - contour's boxiness, vertical gradient of rotation, σ_z / σ_R, and satellite stars populating the wings of V_{los}