Simulations of the Formation of Thick Discs in Galaxies

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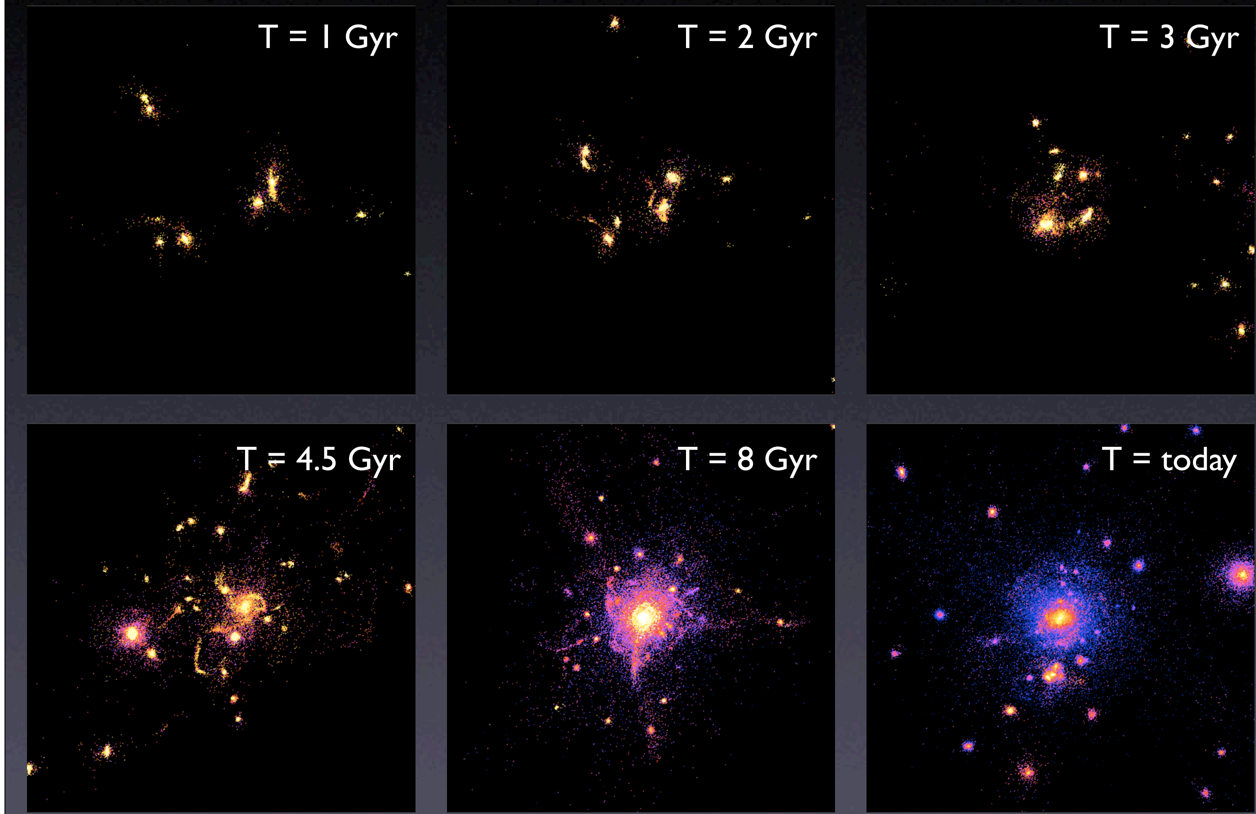
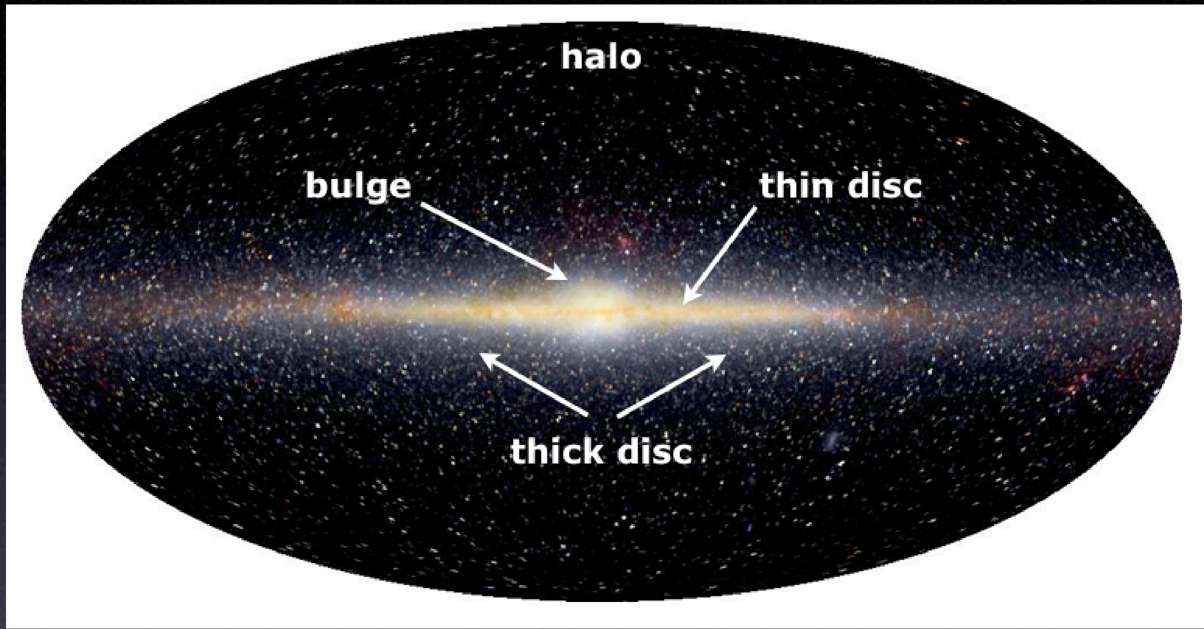
Current paradigm of galaxy formation



Larger structures are formed after mergers of smaller systems

simulations by J.P. Gardner

Milky Way structure

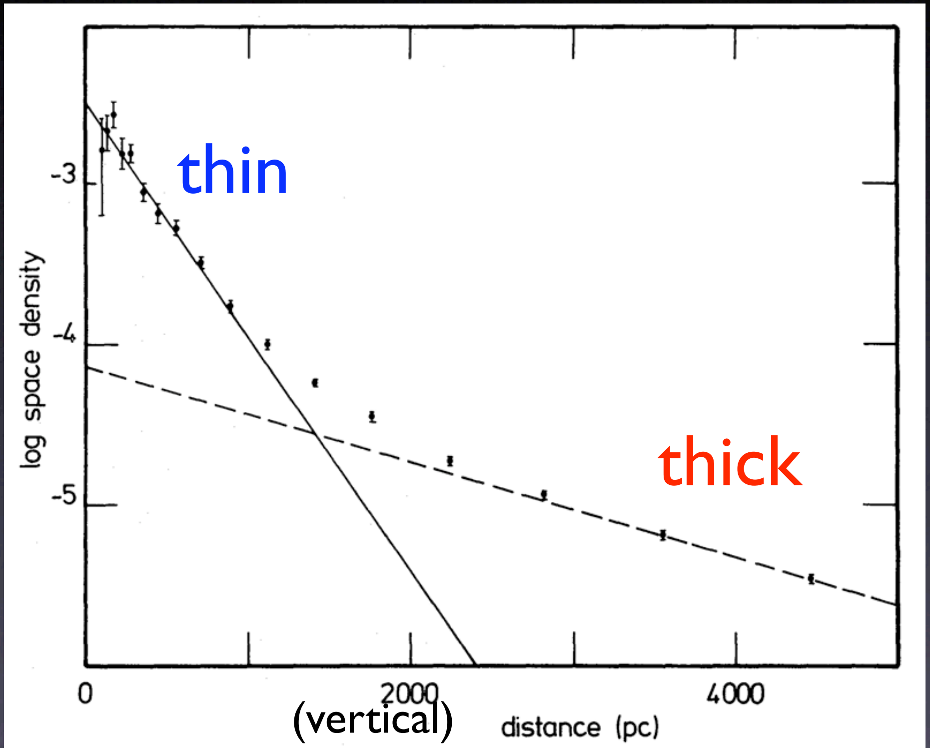


E.L. Wright & The COBE-DIRBE project

	$\times 10^{10}\ M_{sun}$	R kpc
thin disc	5	15
thick disc	1	~15 (?)
bulge	1.6	3
stellar halo	0.1	3 (1/2 mass)
dark halo	100	150 (1/2 mass)

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

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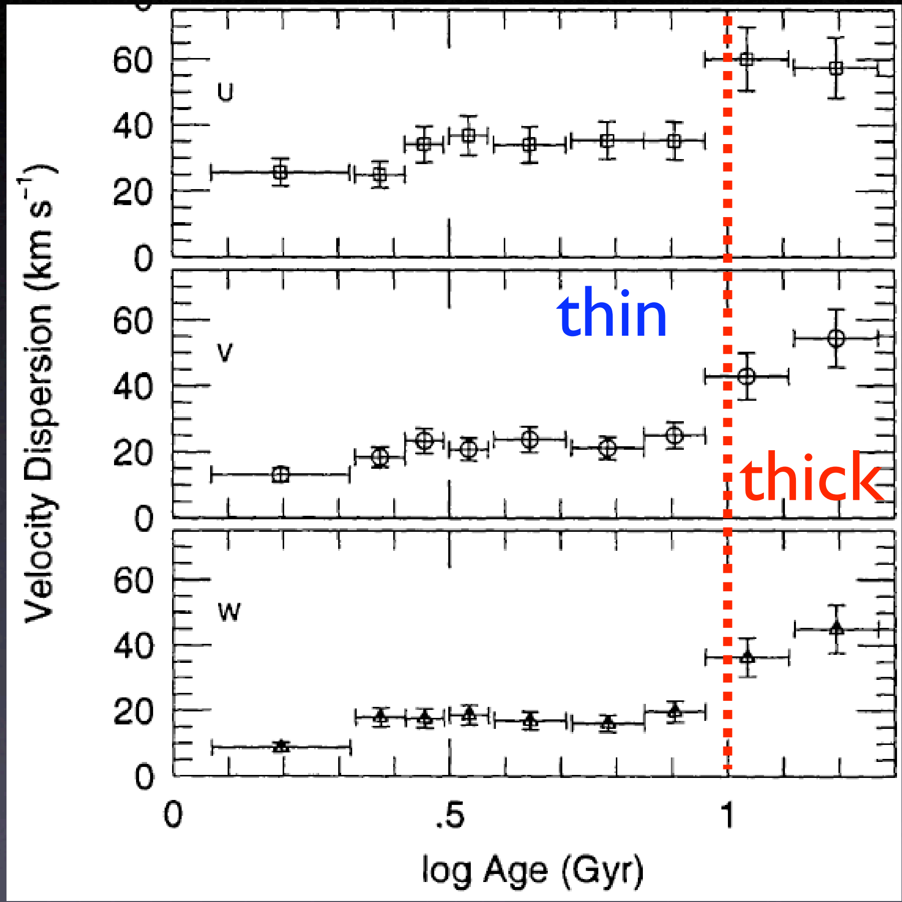
- **Kinematics**
  (σ_R , σ_ϕ , σ_z) ~ (65, 54, 38)km/s (2x thin)
  rotates fast ~ 180 km/s

- **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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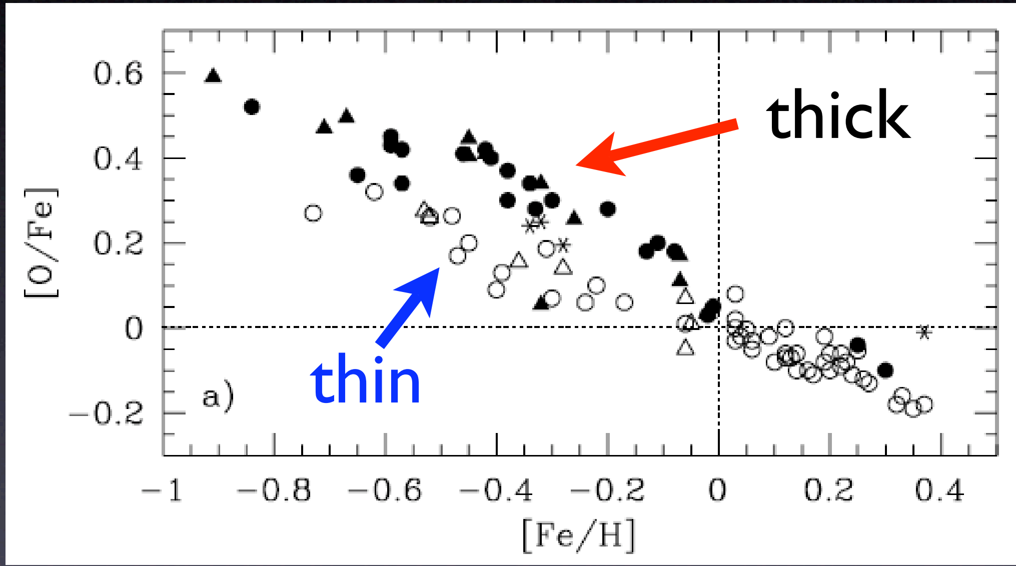
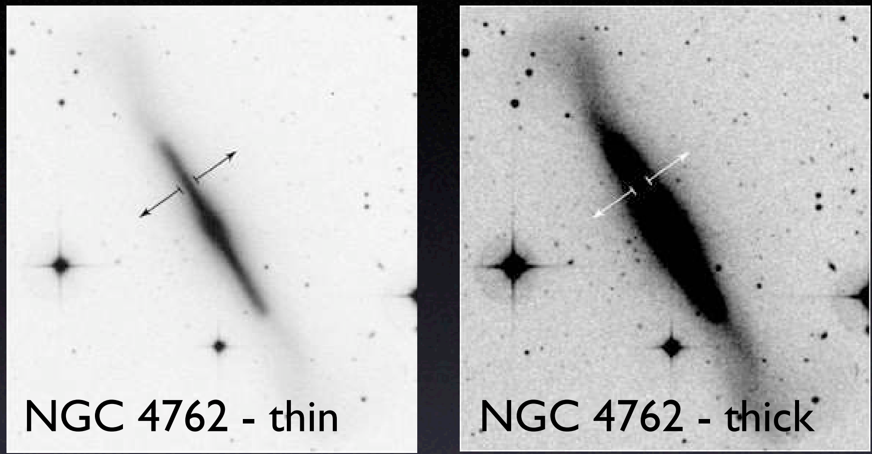
- **<u>Chemistry</u>**
  more metal poor
  higher α-abundance

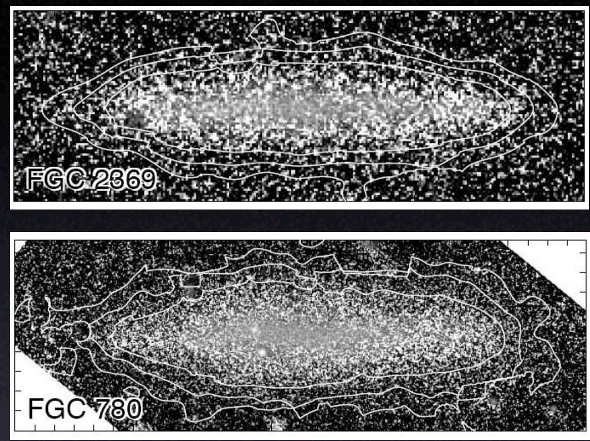


Bensby et al. 2003, 2004, 2005

Thick discs in other galaxies

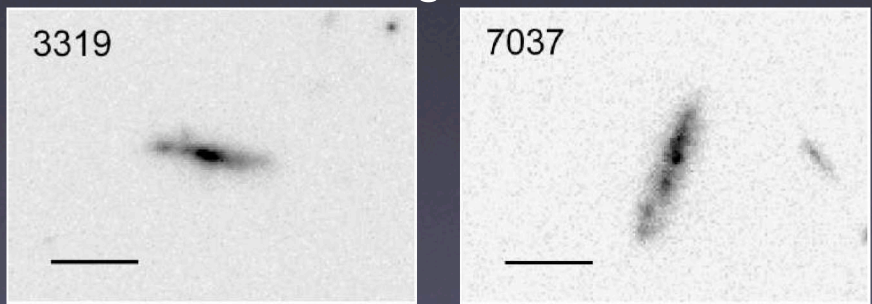


Tsikoudi 1980



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"

Star formation during gas-rich mergers
(Brook et al. 2004)

Collapse of large gaseous clumps in turbulent early gas-rich discs
(Bournaud et al. 2007)

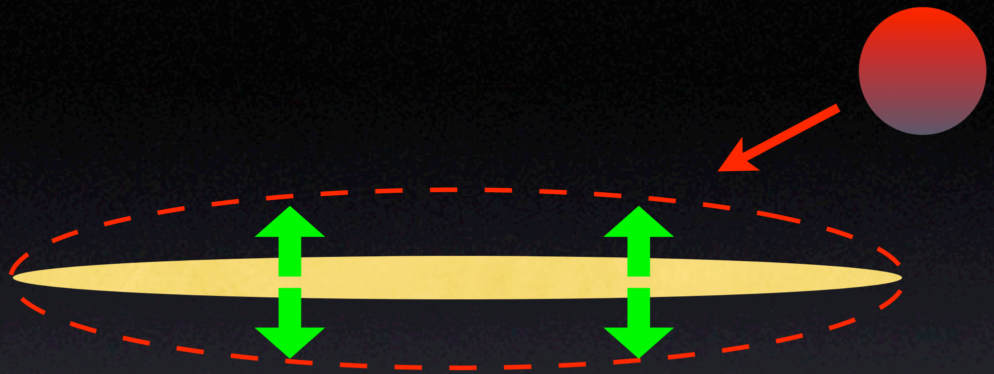
"born-thin" (pre-existing disc needed)

Radial mixing of stars by spiral arms
(Schoenrich & Binney 2008)
(Roskar et al. 2008)

Disc heated during merger with a satellite
(Quinn et al. 1993)

Accretion of several small satellites
(Abadi et al. 2003)

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



Why the disc-heating scenario?

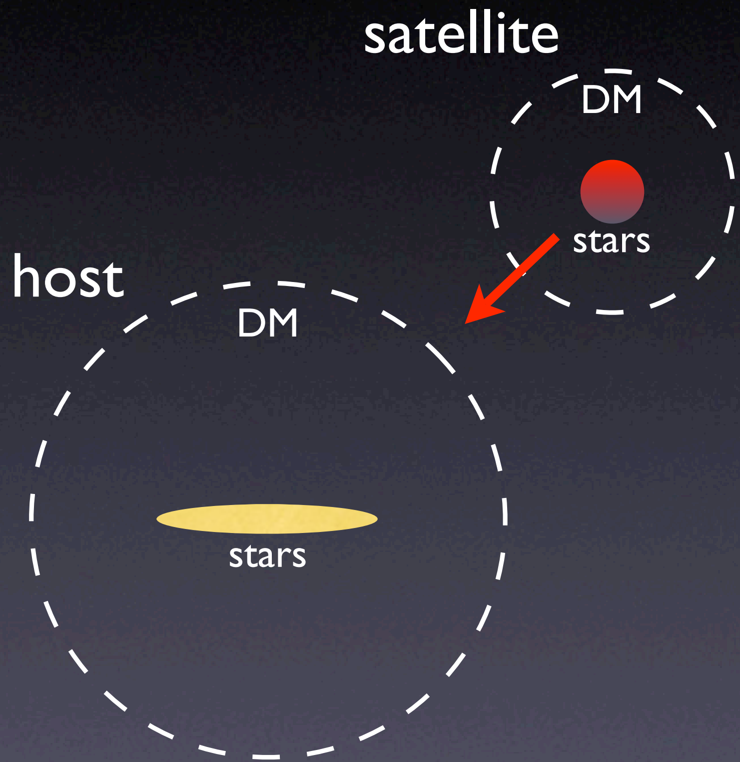
- such a merger process is <u>unavoidable</u> in ΛCDM

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>

ÁV & Helmi 2008, MNRAS, 391, 1806
ÁV & Helmi 2009, MNRAS, 399, 166
ÁV, Kazantzidis & Helmi, 2010, ApJ, in press (arXiv:0912.2250)

Set-up of *N*-body simulations



Main features:

- 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

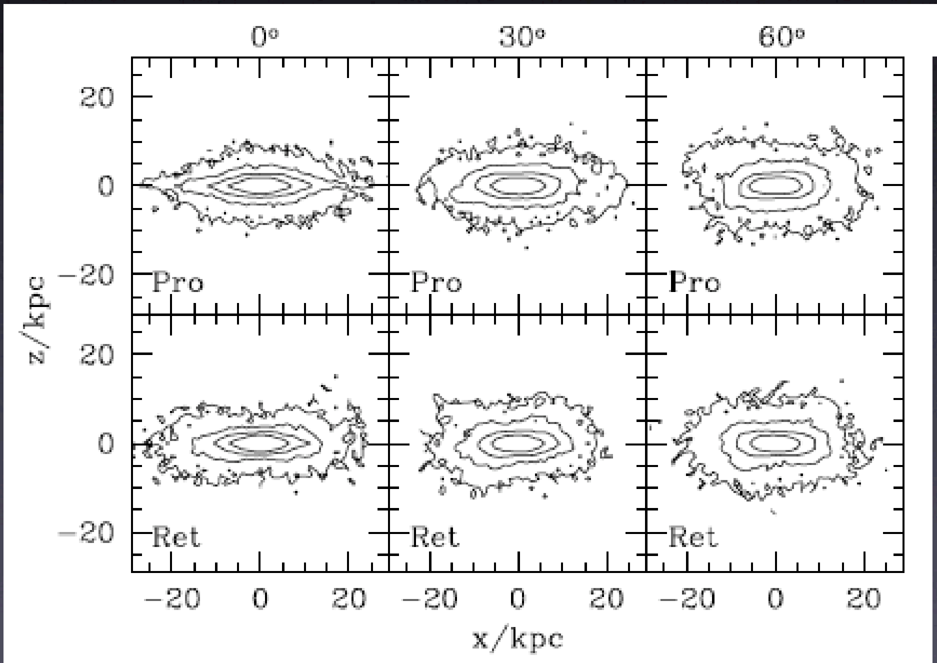
- gas is not included

Movie

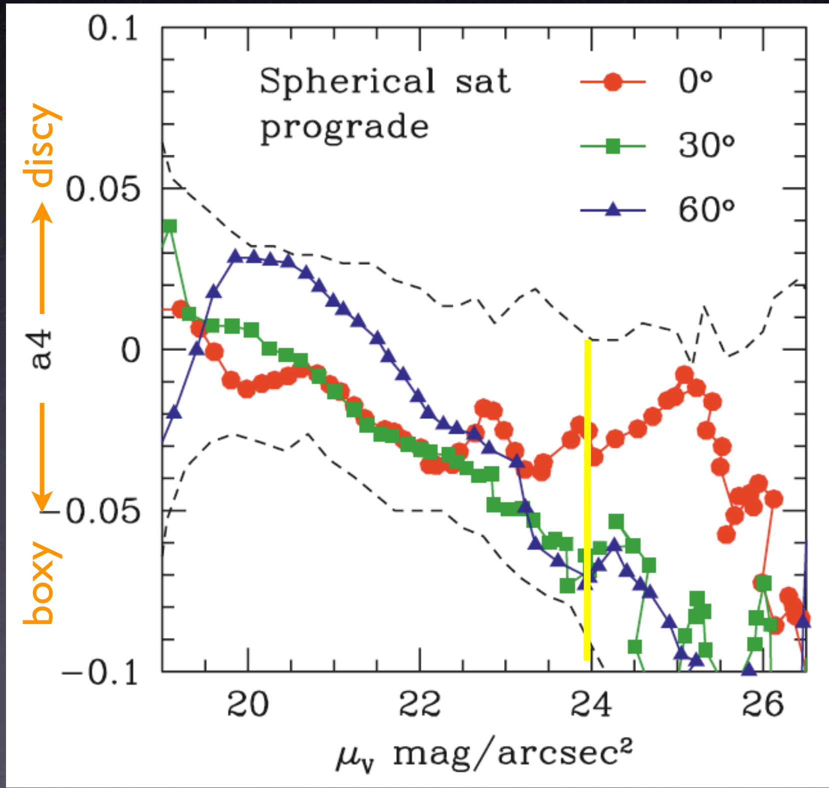
Morphological properties of simulated thick discs

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

(edge-on views)



22.5, 24.2, 26, 27.7 mag arcsec^2 in V



6 mag below central s.b.

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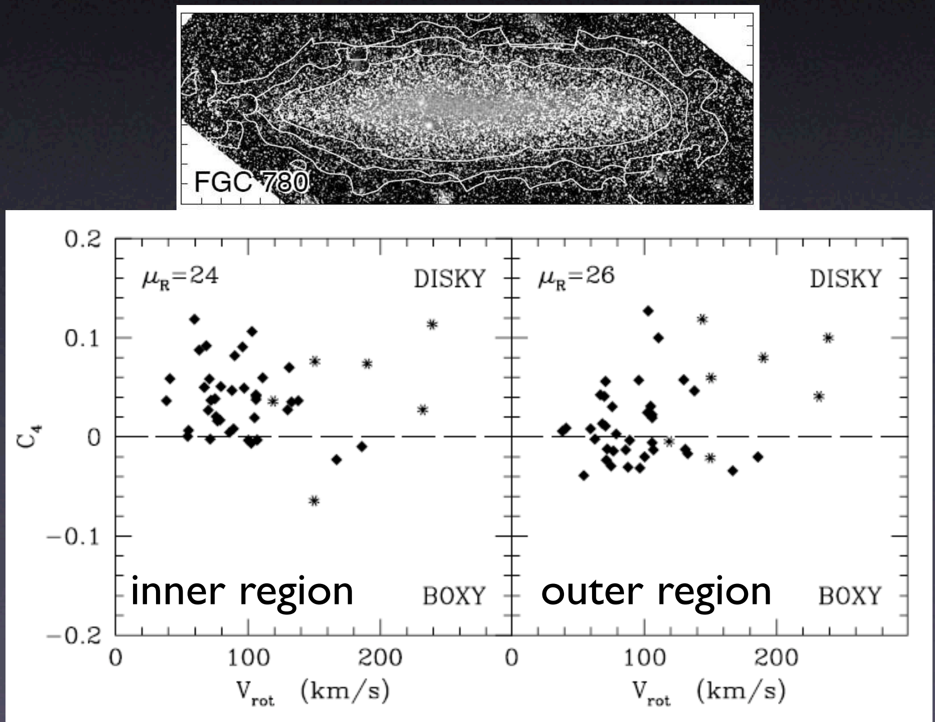
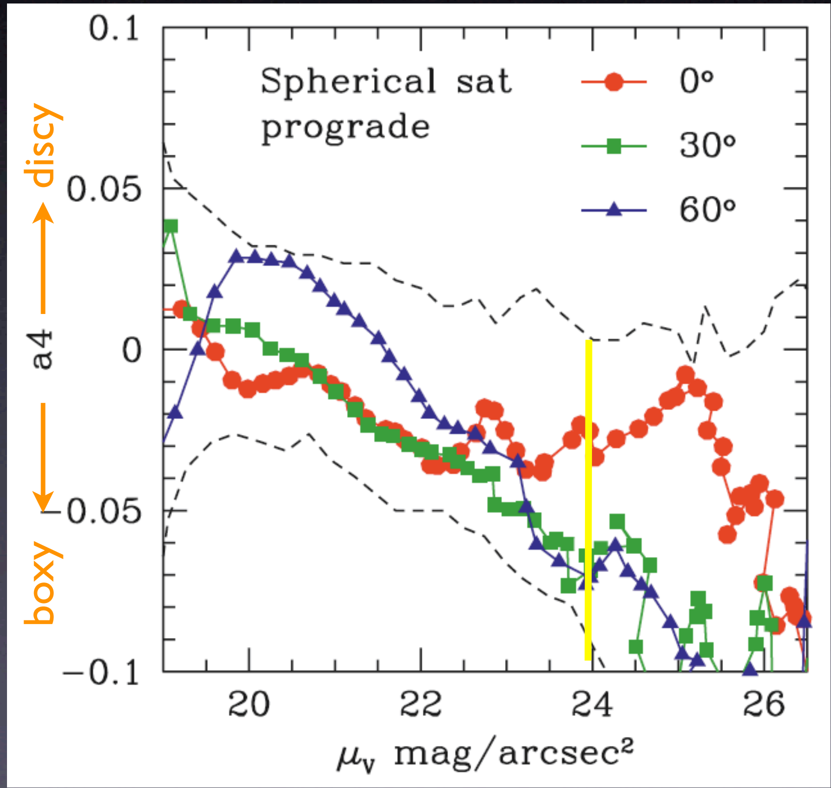


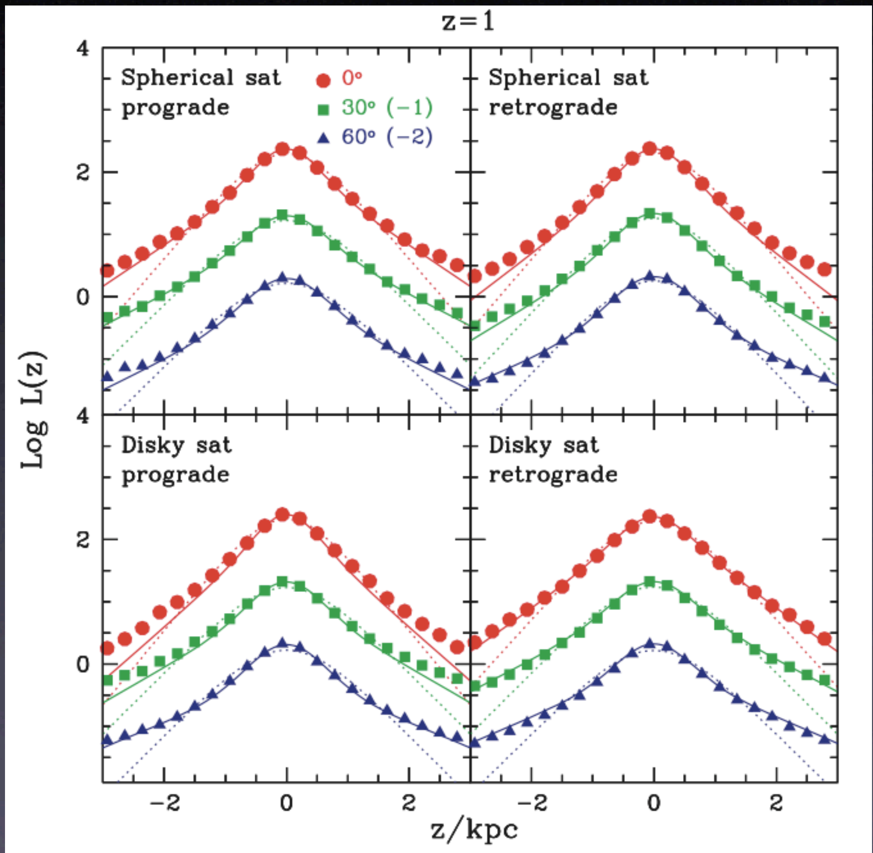
Dalcanton & Bernstein 2002

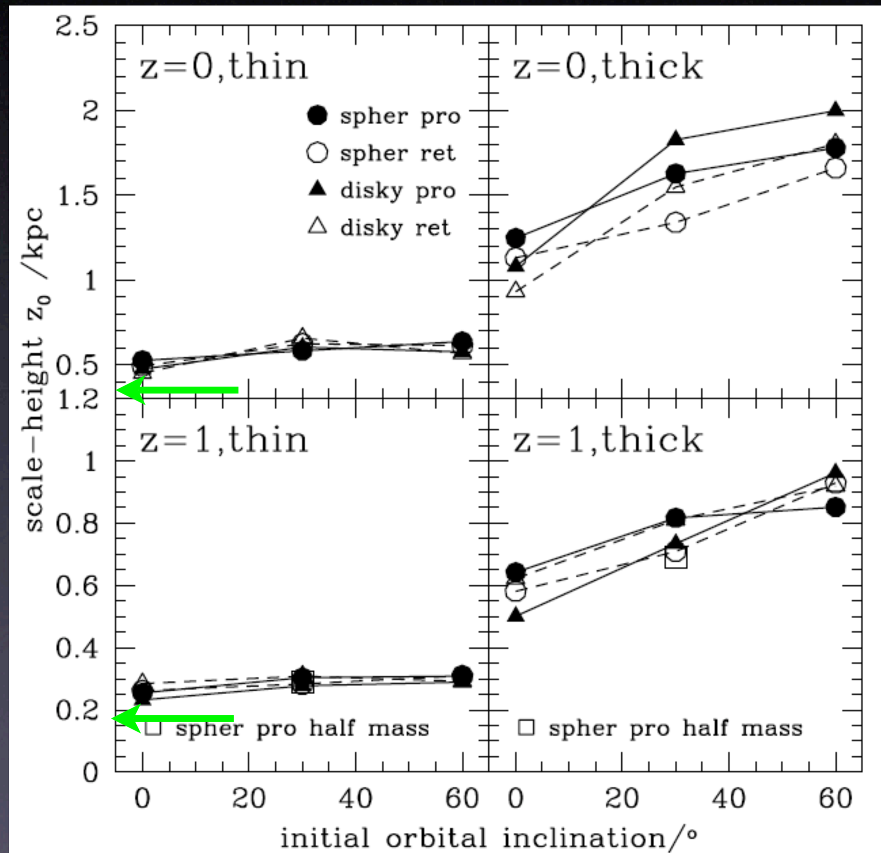


6 mag below central s.b.

Structural properties of simulated thick discs

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





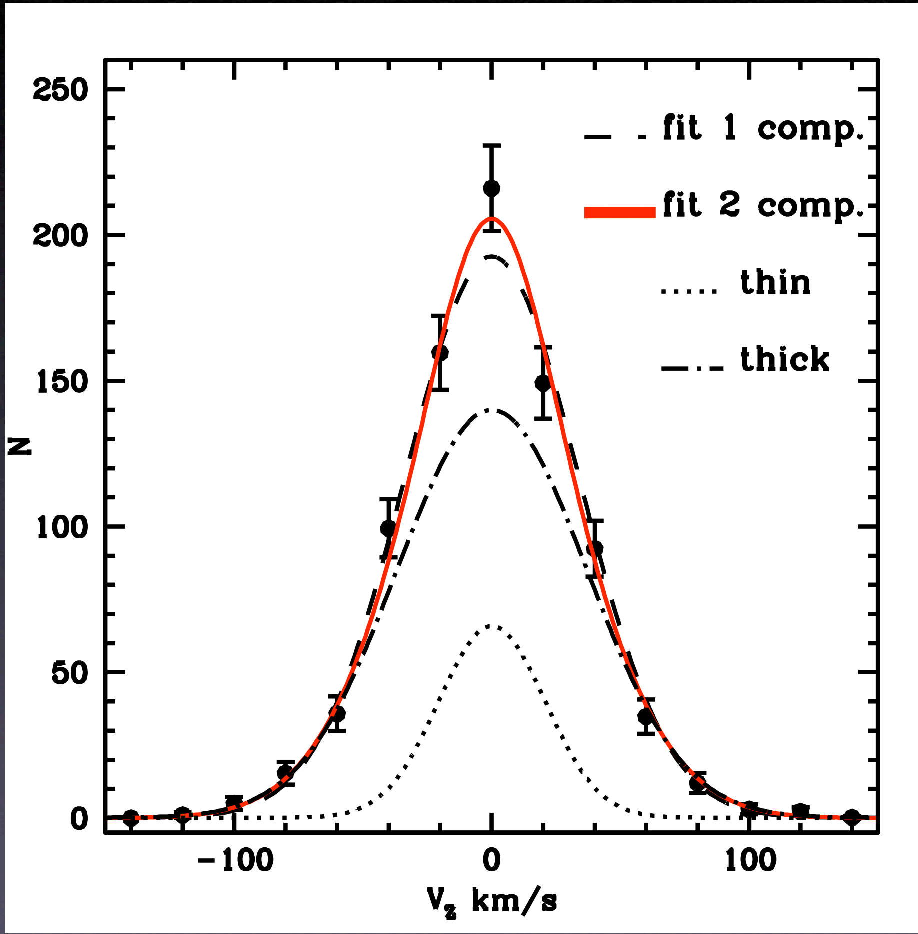
.... fit: 1 component

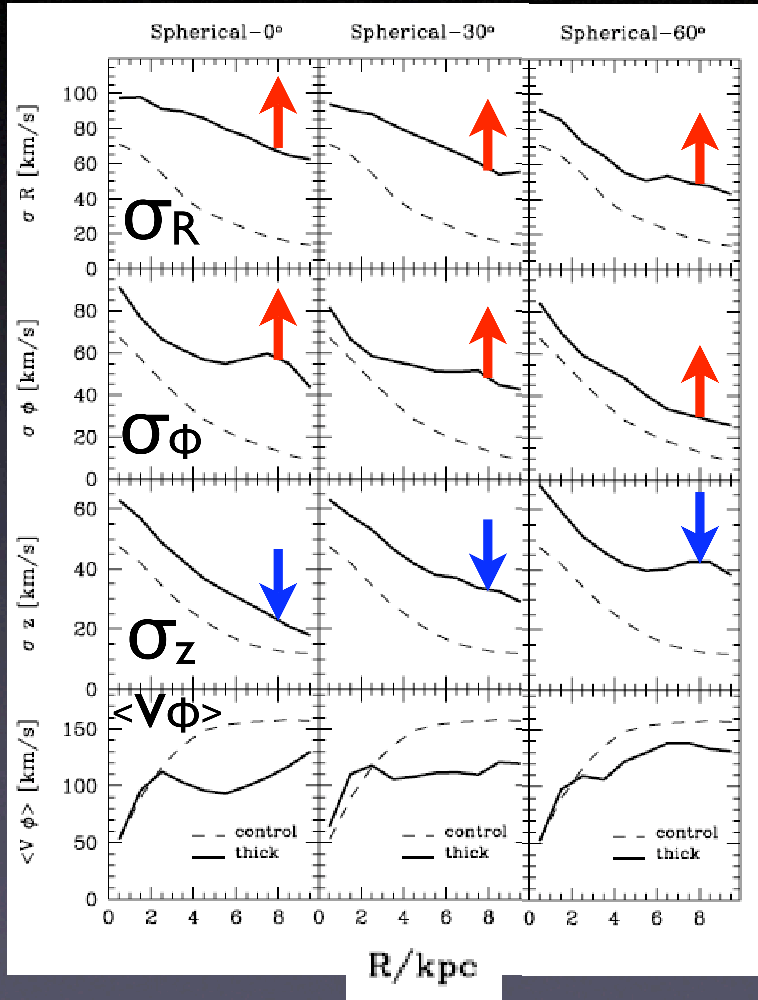
——— fit: 2 components

←— : scale-height of initial disc

Kinematical properties of simulated thick discs

decomposition of velocity distributions into “thin” and thick components

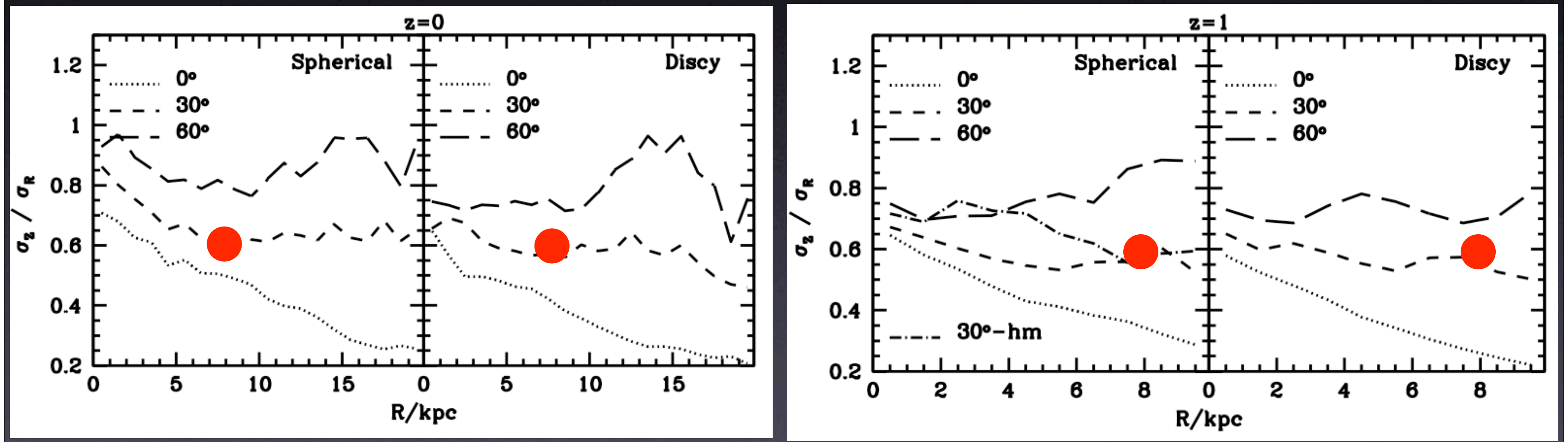




- fit 1 component, $\chi^2 = 0.68$
- fit 2 component, $\chi^2 = 0.47$

Kinematical properties of simulated thick discs

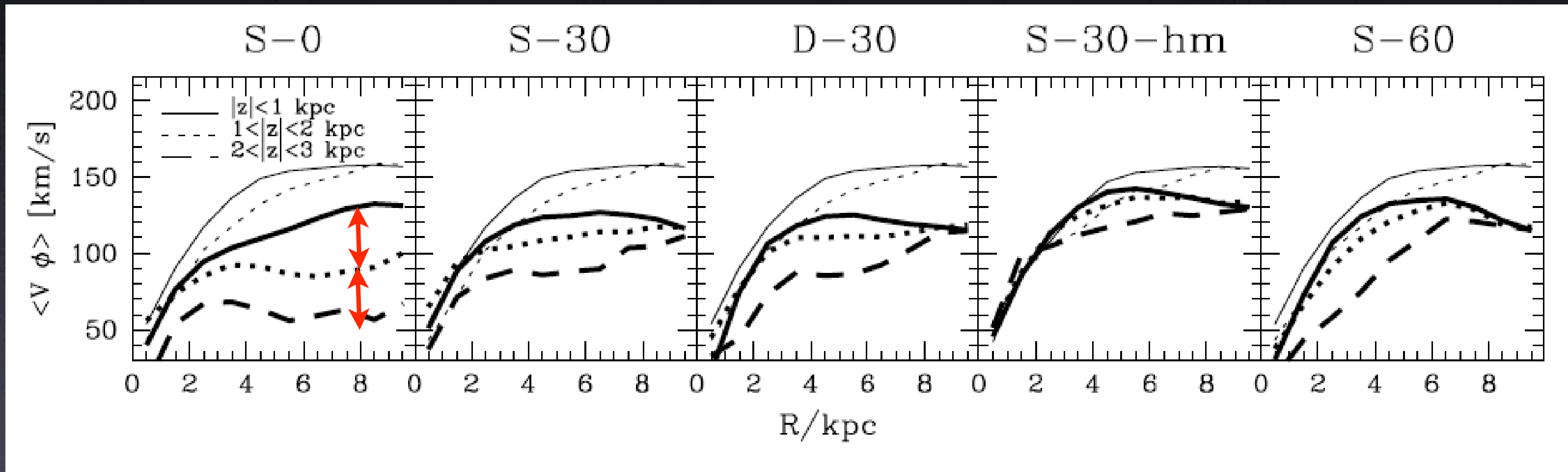
ratio σ_z/σ_R of thick disc stars could be a good indicator of the initial inclination of the satellite



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.

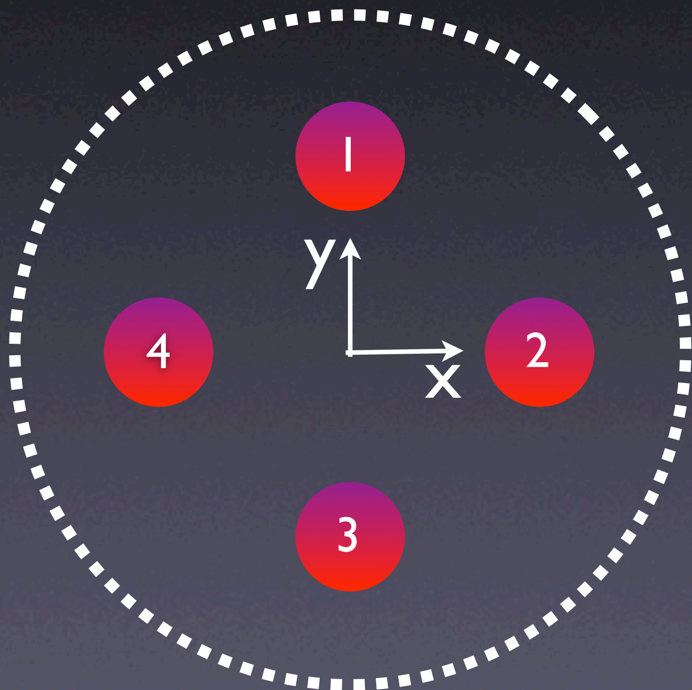


- Observed gradient in the MW's thick disc in the range -18 to -30 km/s/kpc (Chiba & Beers 2000, Girard et al. 2006, Ivezic et al. 2008)

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

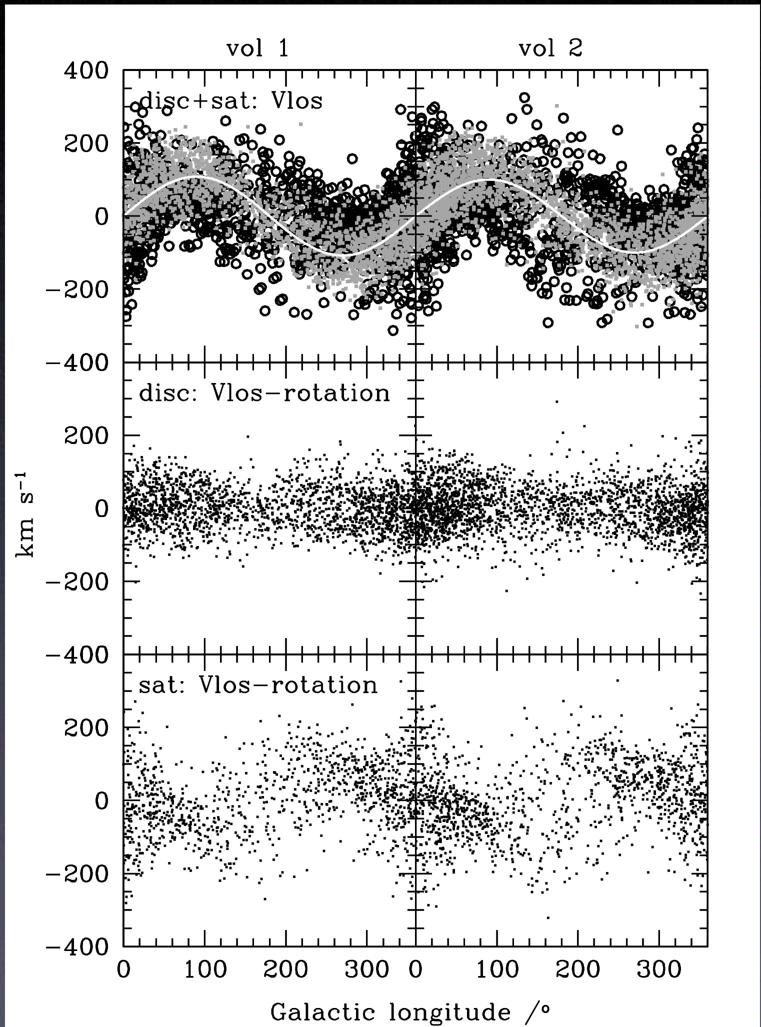
Traces of disc-heating scenario in
the phase-space structure of thick disc stars?

final thick disc
(face-on view)



sampling thick
disc stars within
small spherical
volumes

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

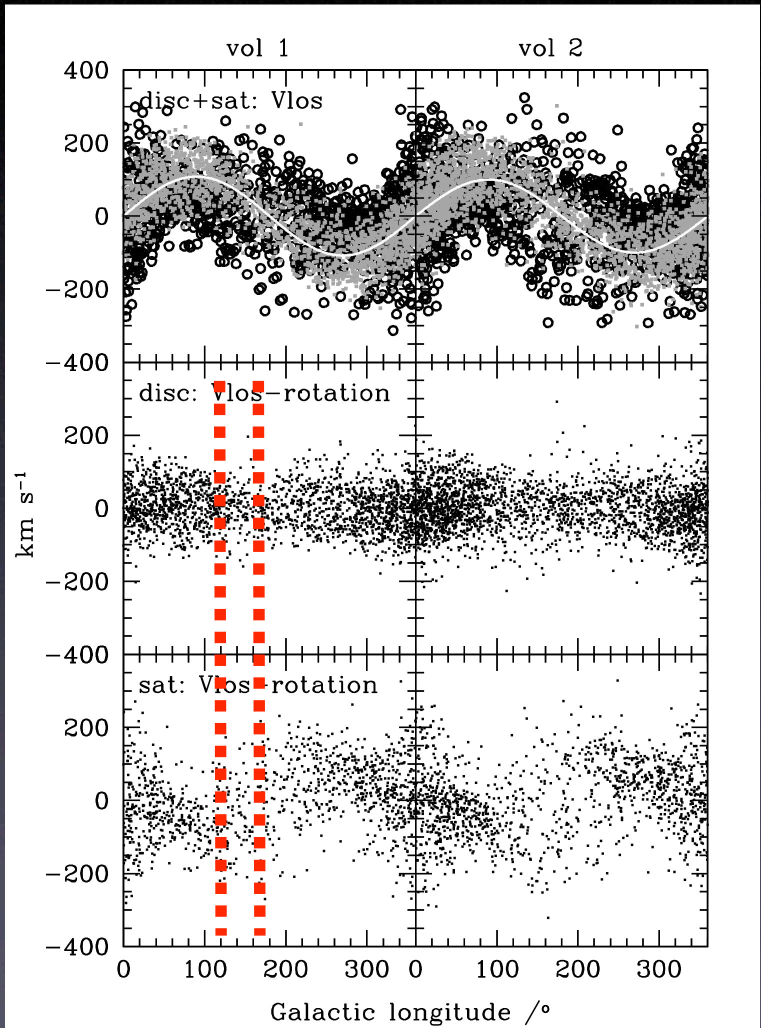


grey: heated disc
black: satellite

- 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}



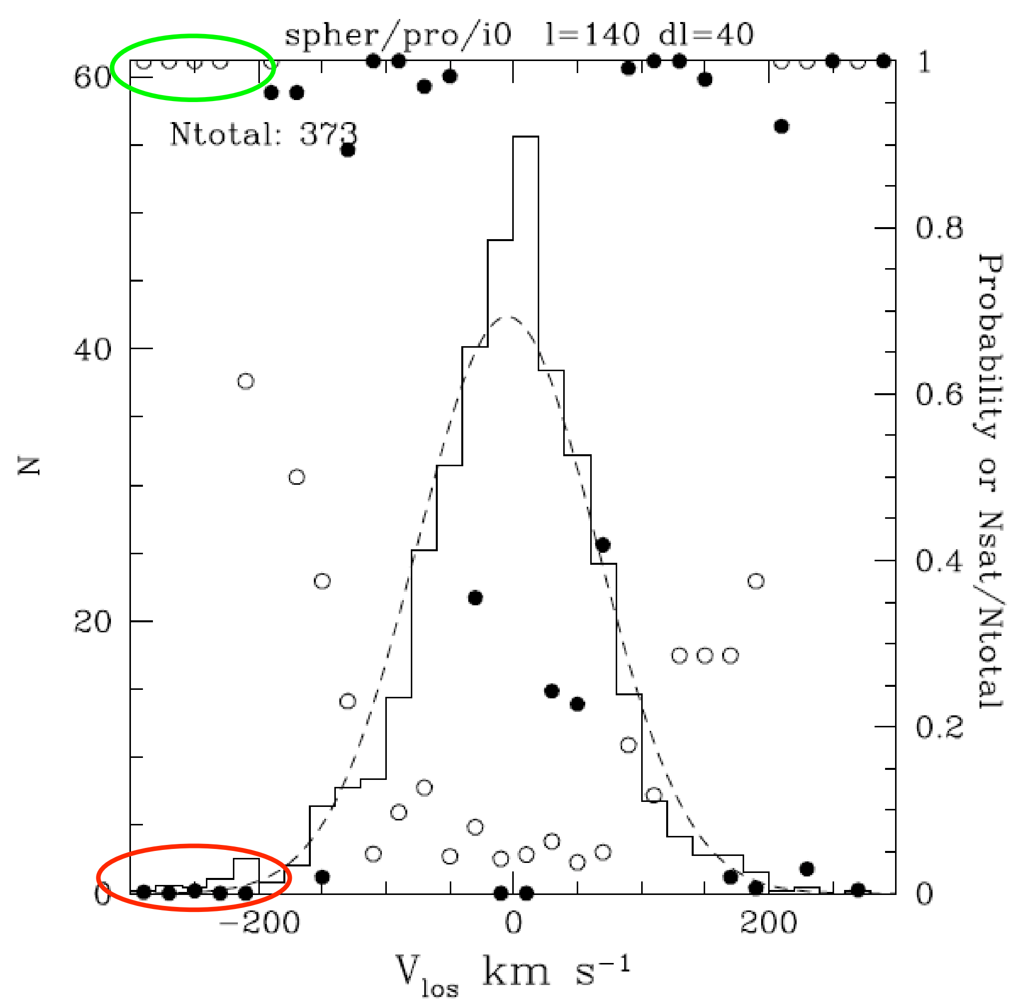
grey: heated disc
black: satellite

- 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°



solid circles: probability that a certain peak occurs by chance.

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

simple statistical test is able to:

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

Conclusions

- *What general structural and kinematical observations could support the disc-heating scenario?*
  - 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 (old thin disc?)

- *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 (~30°) based on value of σ_z / σ_R and the presence of strong vertical gradient of mean rotation

- *Are there traces of disc-heating scenario in the phase-space structure of thick disc stars?*
  - sinusoidal shape of V_{los} as a function of Galactic longitude
  - wings of V_{los} distributions are mainly populated by satellite stars