MODELING THE MILKY WAY : THE THICK DISC, THE BULGE AND THE OUTER GALACTIC DISC

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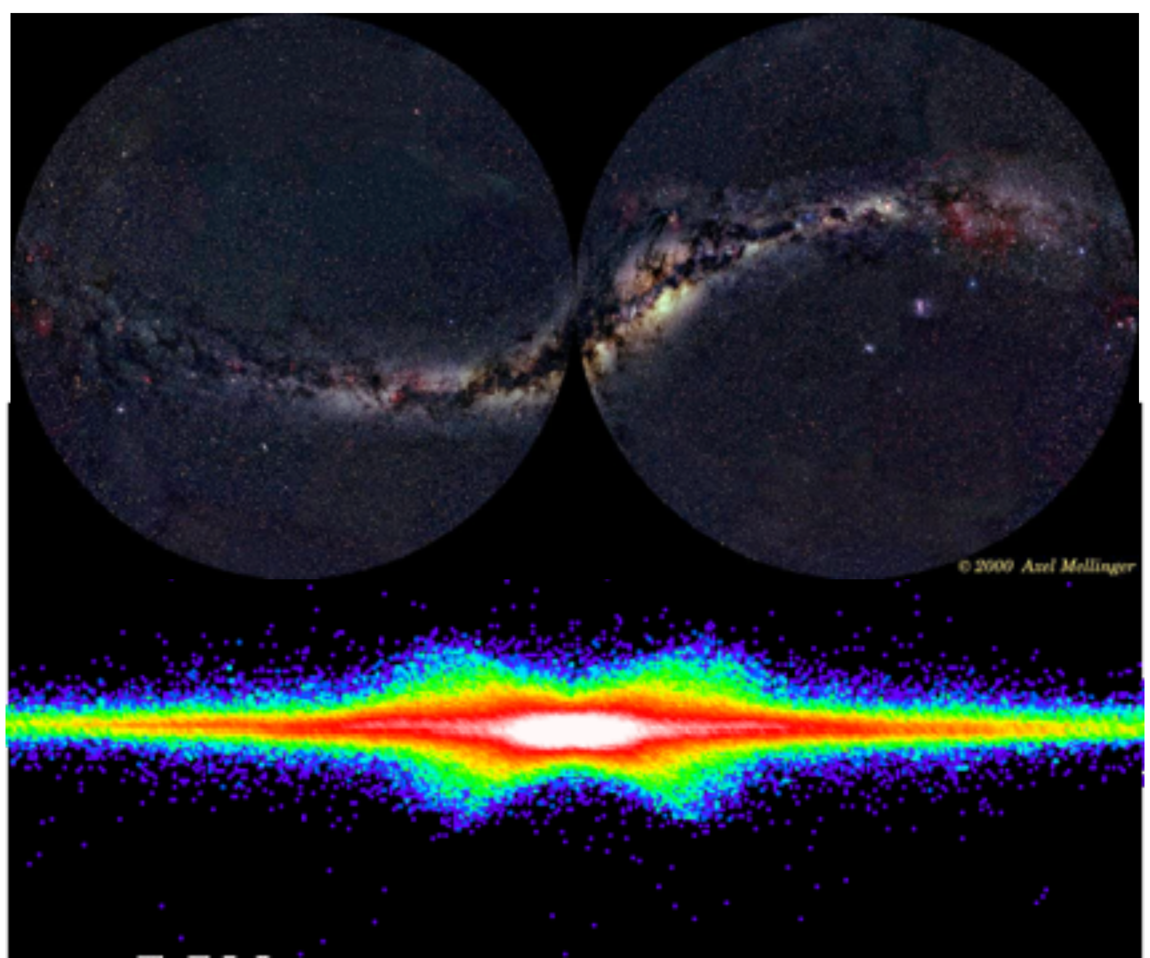
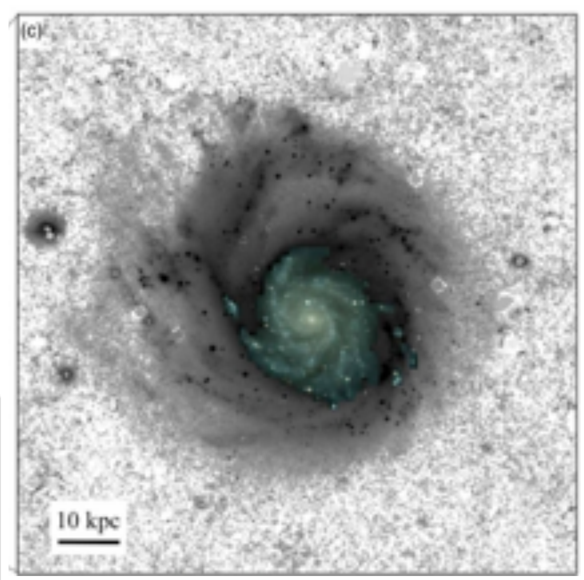
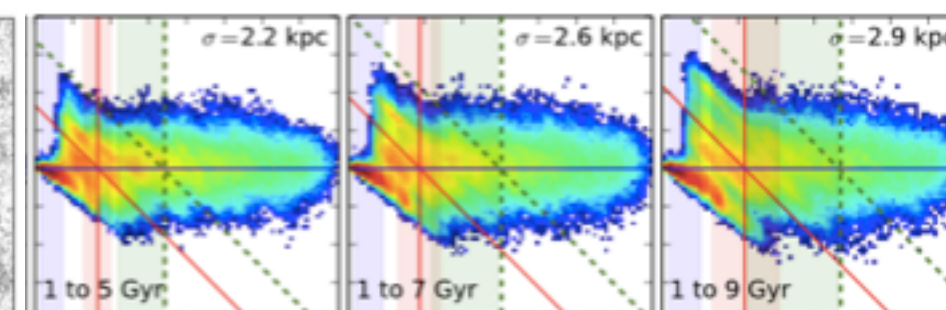
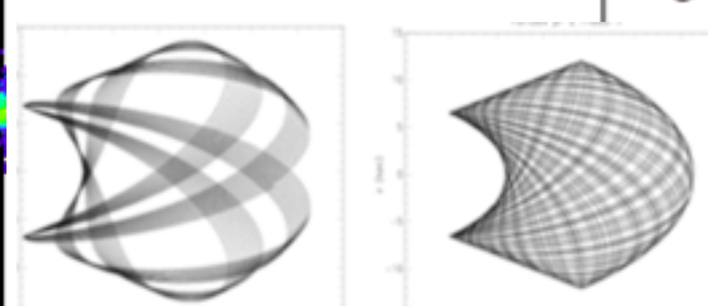
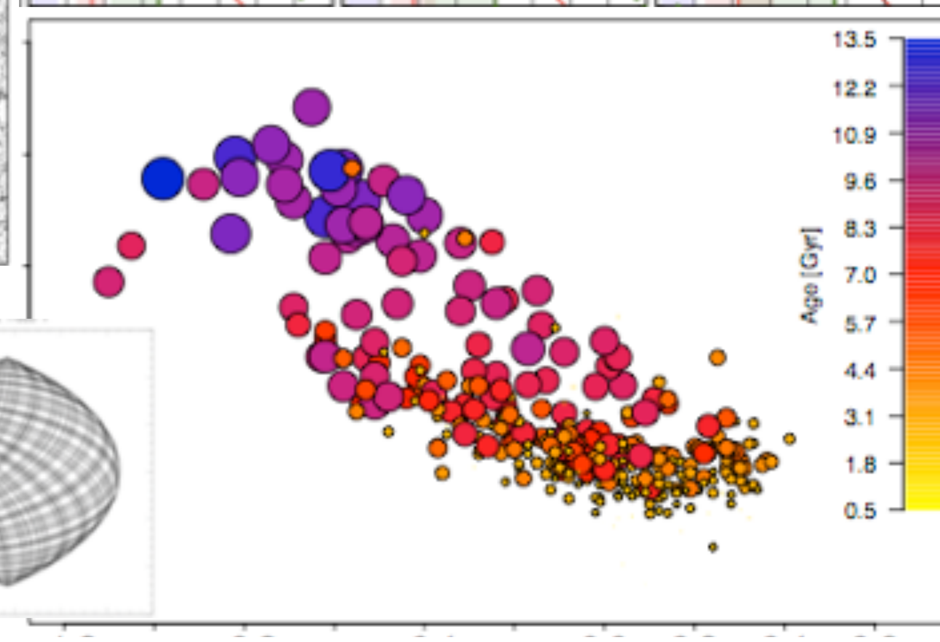
F. Combes, B. Semelin, A. Hallé, I. Jean-Baptiste, E. Pouliasis, M. Ness



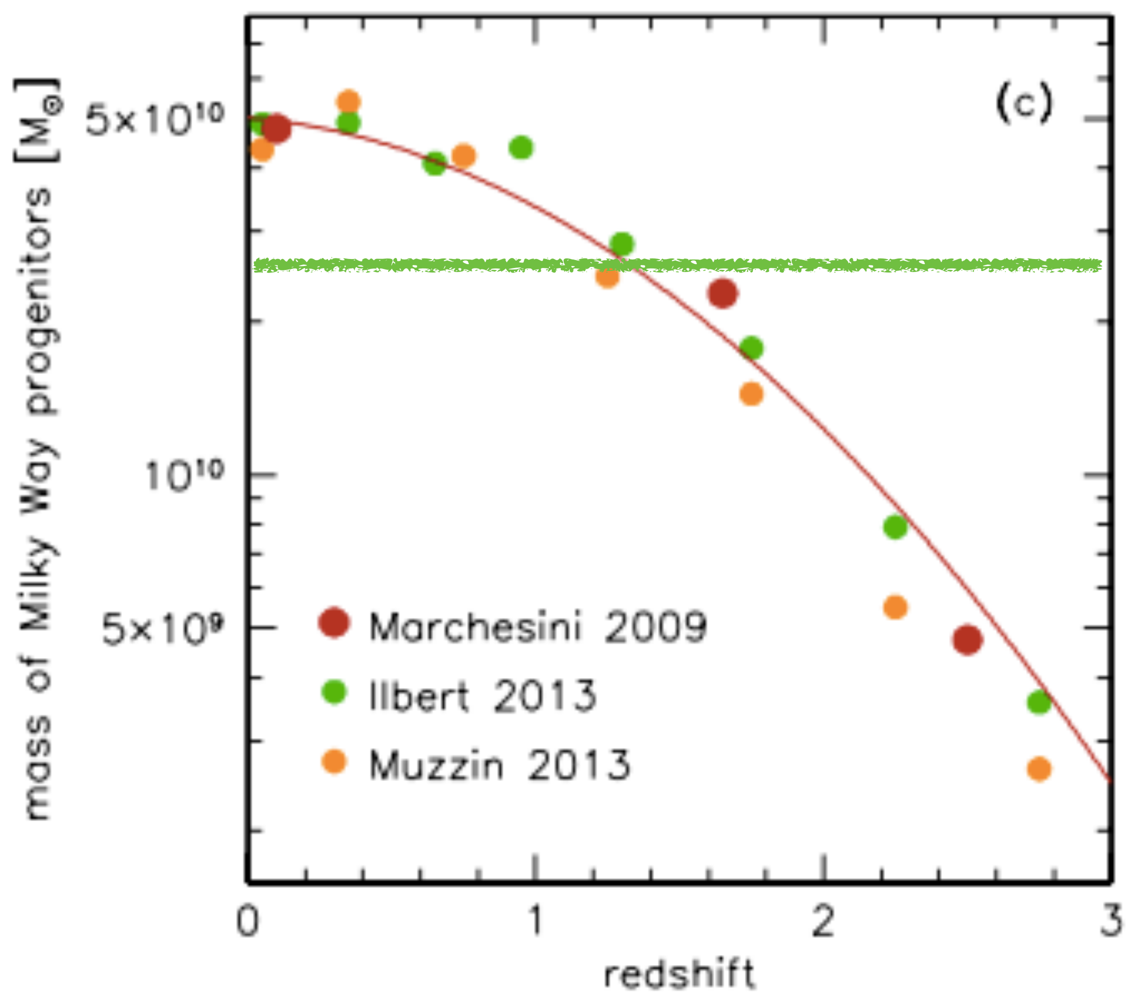




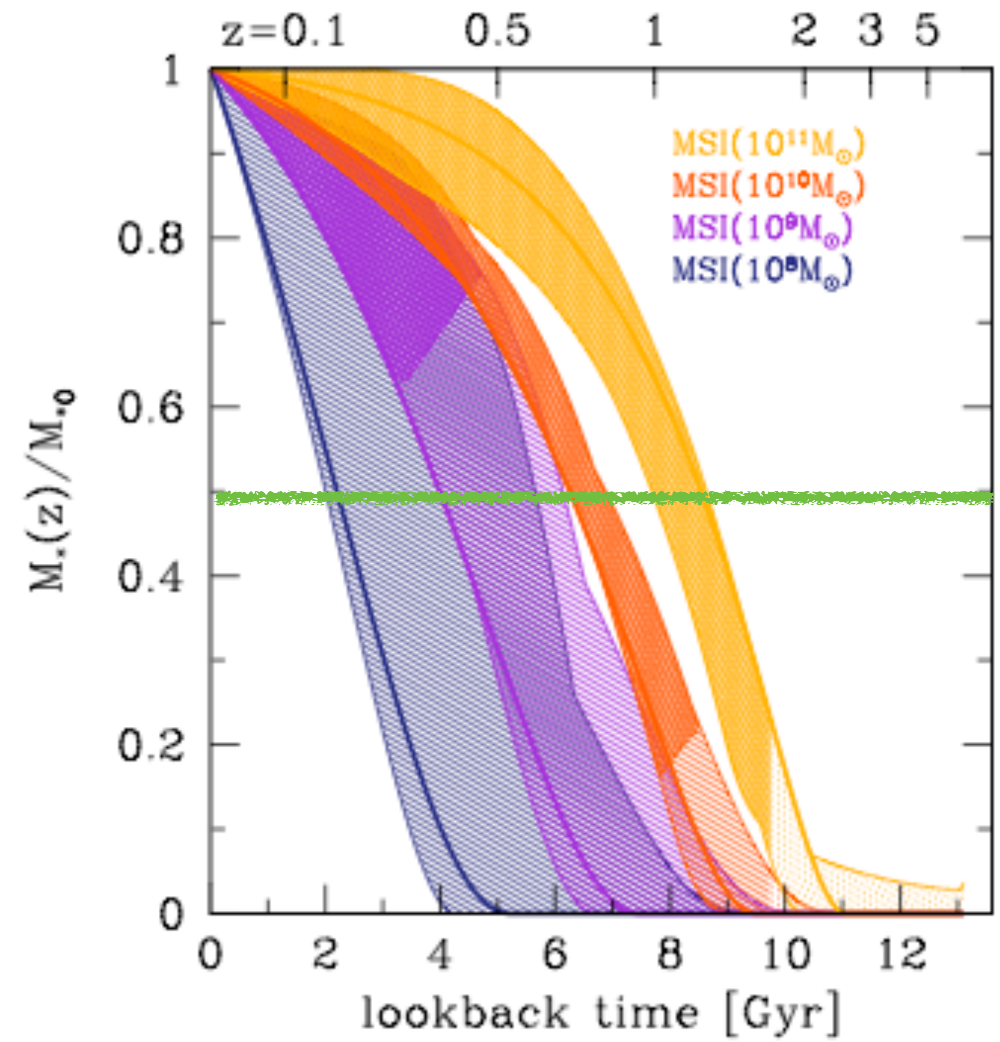




ON THE MASS GROWTH OF MW-TYPE GALAXIES



van Dokkum et al 2013



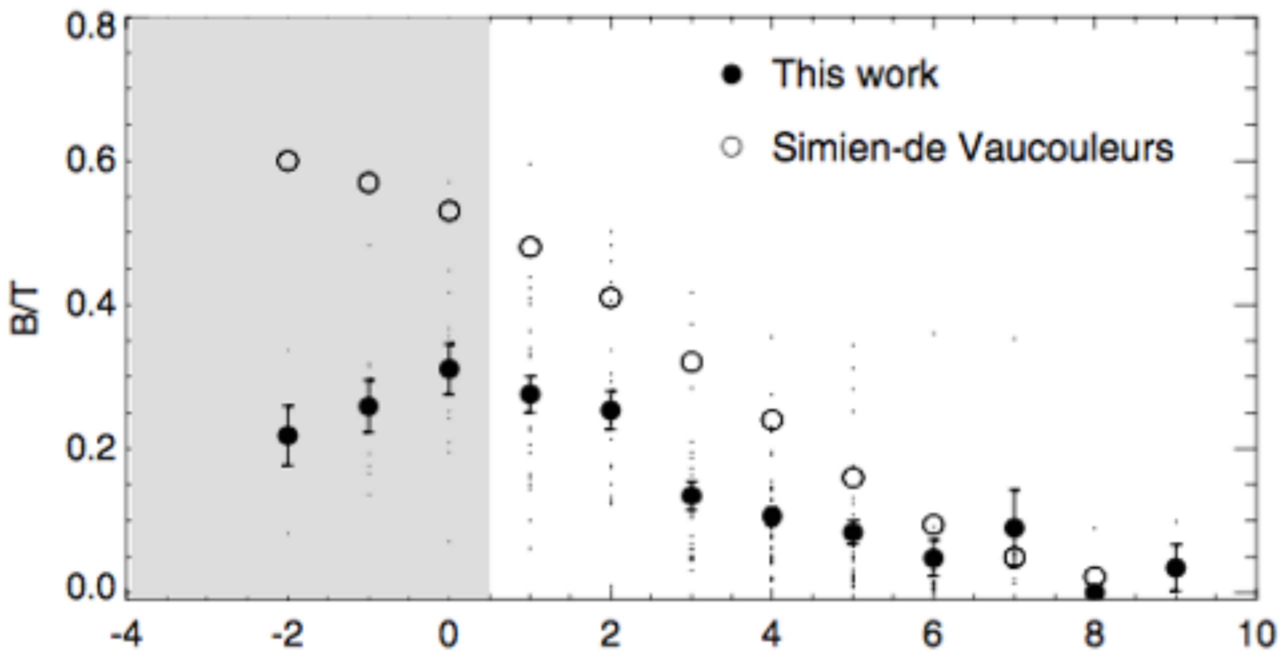
Leitner, 2012, ApJ

For MW-type galaxies about half of the stellar mass formed in the first 4-5 Gyr of evolution (~z=1)

Where does this mass reside nowadays ?

CLASSICAL BULGES IN DISC GALAXIES

Laurikainen et al 2007



Hubble type index

- *Laurikainen et al 2007* : Revision of the classical bulge to total stellar mass ratio along the Hubble sequence. Classical bulges considerably smaller than previous estimates
- *Kormendy et al 2010* : Giant galaxies closer than 8 Mpc distance lack classical bulges

see also Laurikainen et al 2014, Fisher & Drory 2011, ..

Bulge, Pseudobulge, and Disk Inventories in Giant Galaxies Closer Than 8 Mpc Distance

Galaxy (1)	Type (2)	D (Mpc) (3)	S (4)	M_K (5)	M_V (6)	V_{circ} (km s^{-1}) (7)	S (8)	B/T (9)	PB/T (10)	S (11)
NGC 6946	Scd	5.9	a, b	−23.61	−21.38	210 ± 10	a, b	0	0.024 ± 0.003	a
NGC 5457	Scd	7.0	c, d, e	−23.72	−21.60	210 ± 15	c, d, e	0	0.027 ± 0.008	a
IC 342	Scd	3.28	f, w	−23.23	−21.4 :	192 ± 3	a, f	0	0.030 ± 0.001	c, e, f
NGC 4945	SBcd	3.36	g	−23.21	−20.55	174 ± 10	e	0	0.073 ± 0.012	b
NGC 5236	SABc	4.54	d, i, j	−23.69	−21.0	180 ± 15	e, i	0:	0.074 ± 0.016	c, e
NGC 5194	Sbc	7.66	h	−23.94	−21.54	240 ± 20	a, i, j	0:	0.095 ± 0.015	d, e
NGC 253	SBc	3.62	g, k	−24.03	−20.78	210 ± 5	a, f	0:	0.15	c
Maffei 2	SBbc	3.34	l	−23.0 :	−20.8 :	168 ± 20	f	0:	0.16 ± 0.04	b
Galaxy	SBbc	0.008	m, n, o	−23.7	−20.8 :	220 ± 20	k, l	0:	0.19 ± 0.02	g, h
Circinus	SABb:	2.8	a	−22.8	−19.8	155 ± 5	o, p	0:	0.30 ± 0.03	b, e
NGC 4736	Sab	4.93	h, p	−23.36	−20.66	181 ± 10	e, q	0:	0.36 ± 0.01	d, e
NGC 2683	SABb	7.73	h	−23.12	−19.80	152 ± 5	g, h	0.05 ± 0.01	0:	b
NGC 4826	Sab	6.38	h, u	−23.71	−20.72	155 ± 5	m, n	0.10	0.10	d, e, f, i, j
NGC 2787	SB0/a	7.48	h	−22.16	−19.19	220 ± 10	r, s, t	0.11	0.28 ± 0.02	d, k
NGC 4258	SABbc	7.27	g, h, q	−23.85	−20.95	208 ± 6	e, u	0.12 ± 0.02	0:	b, d, e, l
M 31	Sb	0.77	c, h, r	−23.48	−21.20	250 ± 20	e	0.32 ± 0.02	0	b, m, n
M 81	Sab	3.63	d, r, s	−24.00	−21.13	240 ± 10	e, v	0.34 ± 0.02	0	d, e, f, i, o, p
Maffei 1	E	2.85	l	−23.1 :	−20.6 :	(264 ± 10)	w	1	0	q
NGC 5128	E	3.62	e, h, t, v	−23.90	−21.34	(192 ± 2)	x	1	0:	q

Kormendy et al 2010

CLASSICAL BULGES IN DISC GALAXIES

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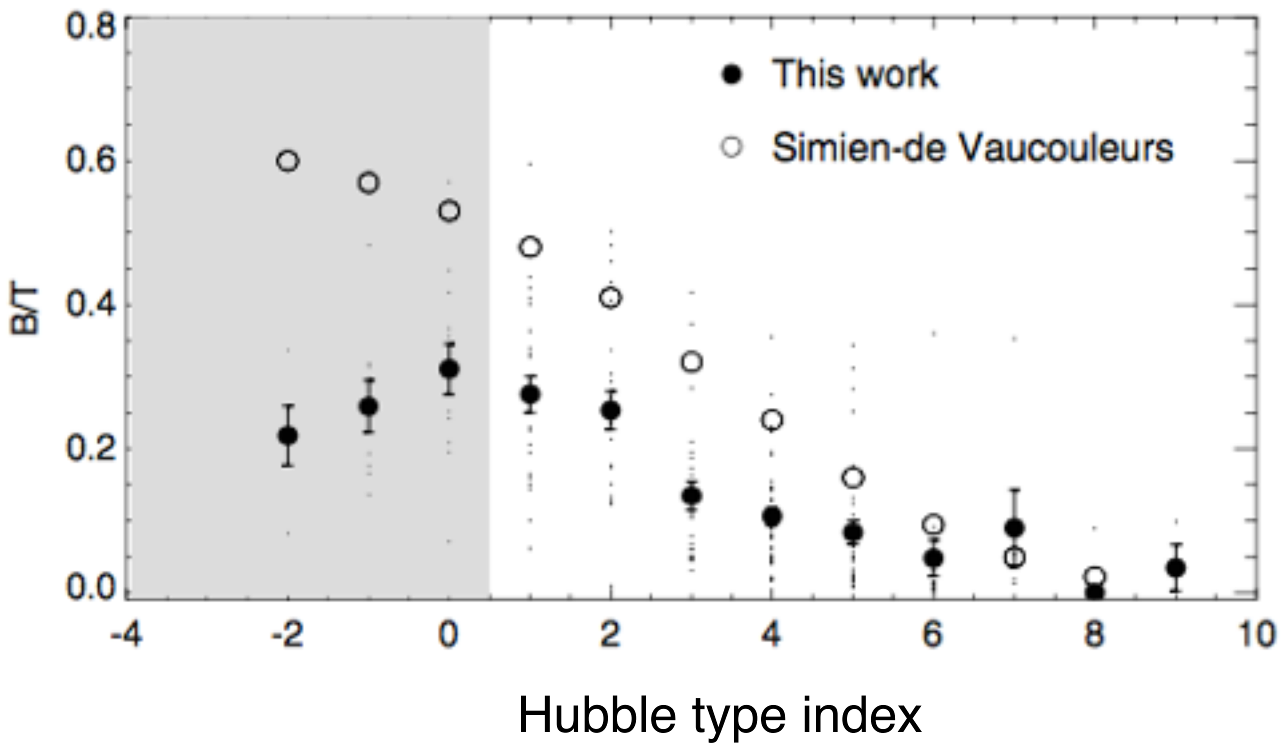

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see also Laurikainen et al 2014, Fisher & Drory 2011, ..

For MW-type galaxies, classical bulges are small (on average 10% of the total stellar mass).

Most (~80%) of the old stellar mass is not in classical bulges. Where is this mass ?

NGC 4945	SBcd	3.36	g	−23.21	−20.55	174 ± 10	e	0	0.073 ± 0.012	b
NGC 5236	SABc	4.54	d, i, j	−23.69	−21.0	180 ± 15	e, i	0:	0.074 ± 0.016	c, e
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M 31	Sb	0.77	c, h, r	−23.48	−21.20	250 ± 20	e	0.32 ± 0.02	0	b, m, n
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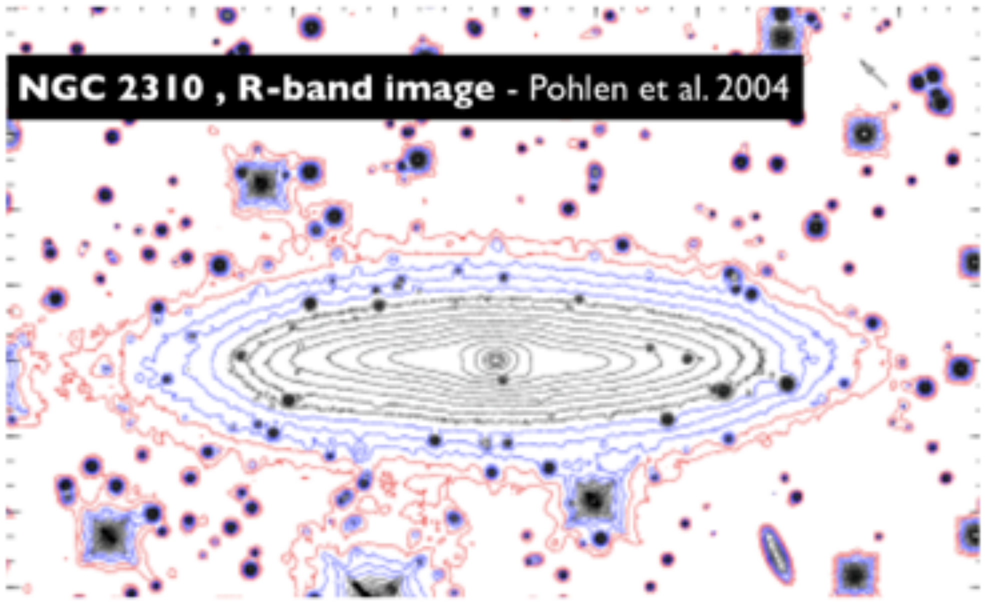
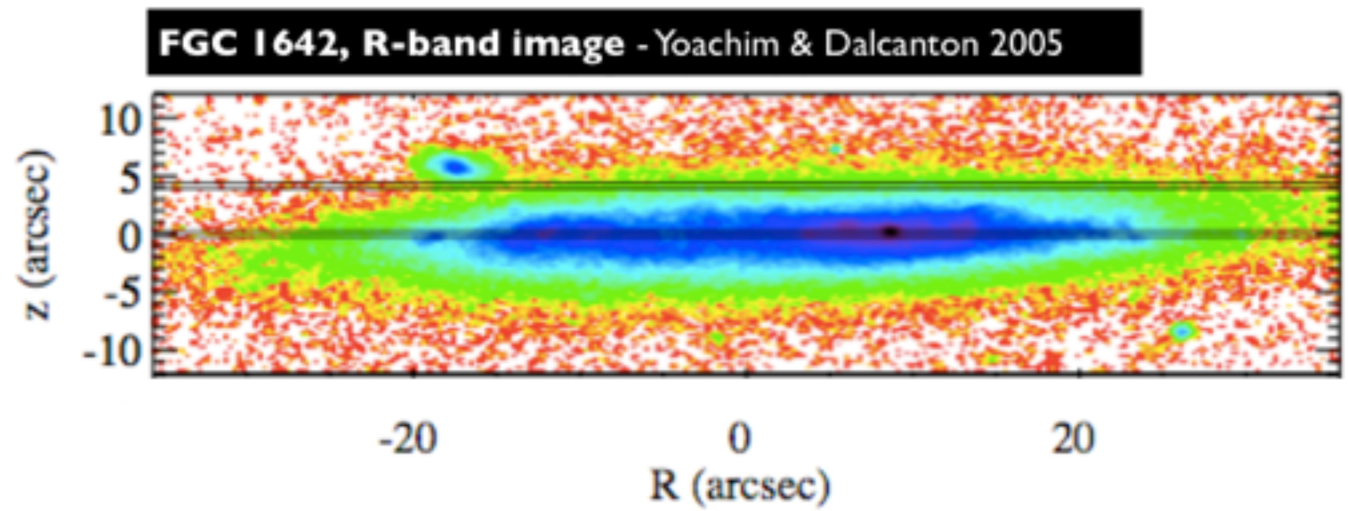
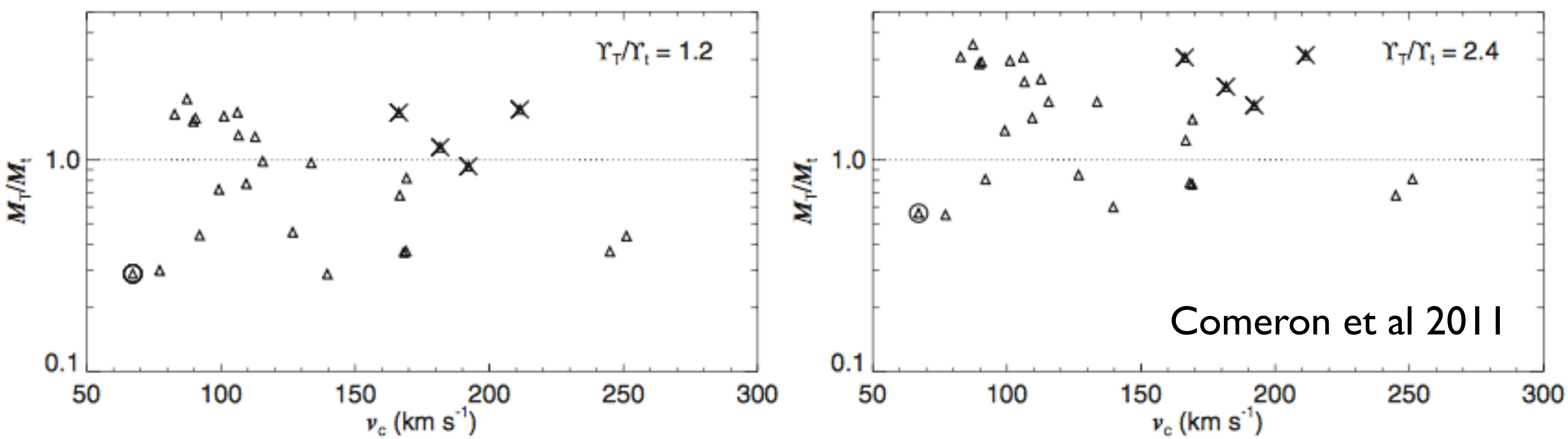
THICK STELLAR DISCS



Observed all along the Hubble sequence, from S0 to late-type discs





Comeron et al 2011: Studied ~20 edge-on disc galaxies of late-type in the S4G sample and found that "… **Typically, the thin and thick disks have similar masses.** "

Extragalactic studies :
small classical bulges & massive thick discs.
Does the MW fit in this scheme ?

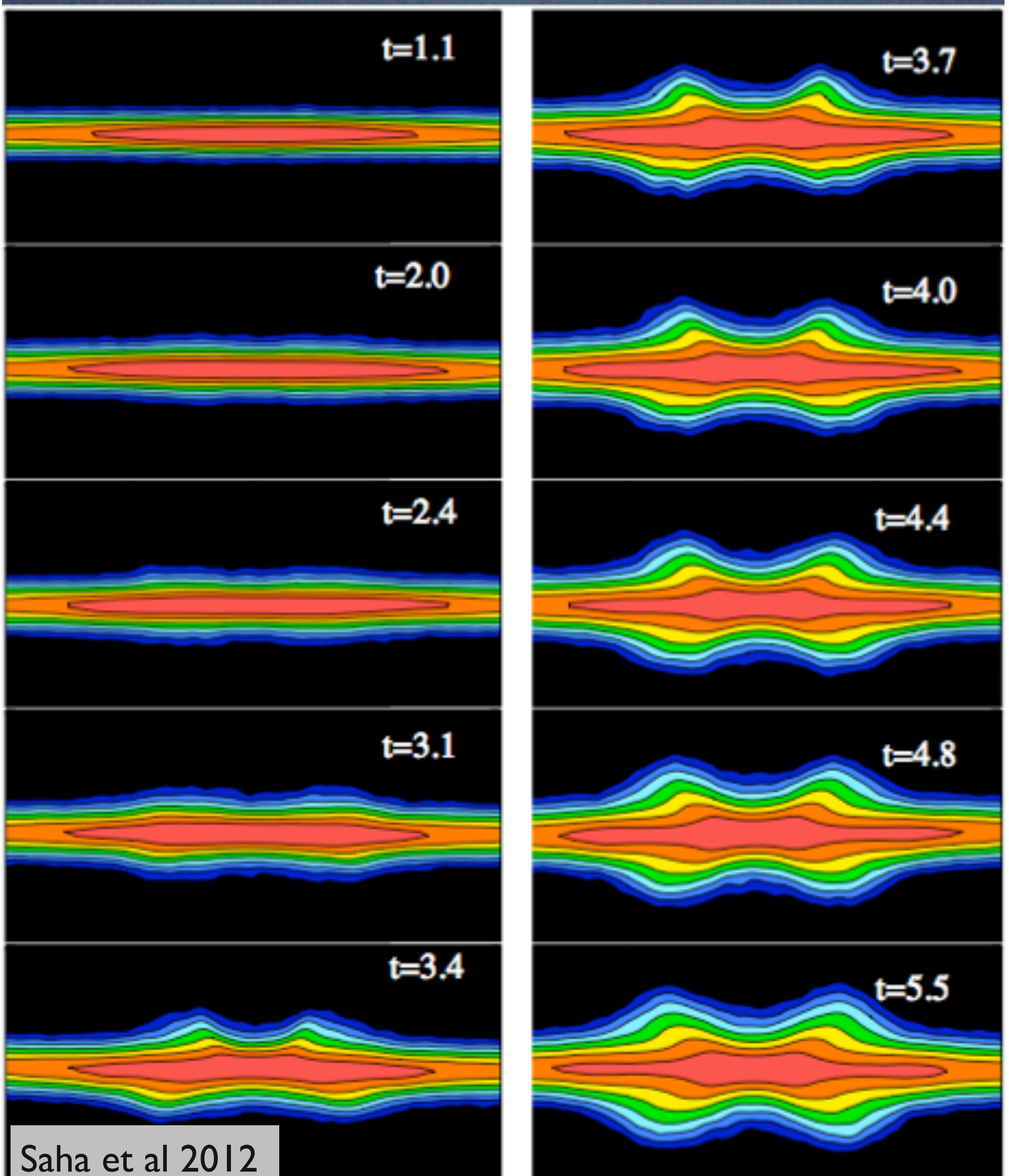
Yes, The Milky way is not exceptional in this picture

1/ It has either a small or a not existent classical bulge (Shen et al 2010, Kunder et al 2012, Di Matteo et al 2014a)
2/ It has a massive thick disc (Snaith et al 2014a,b)

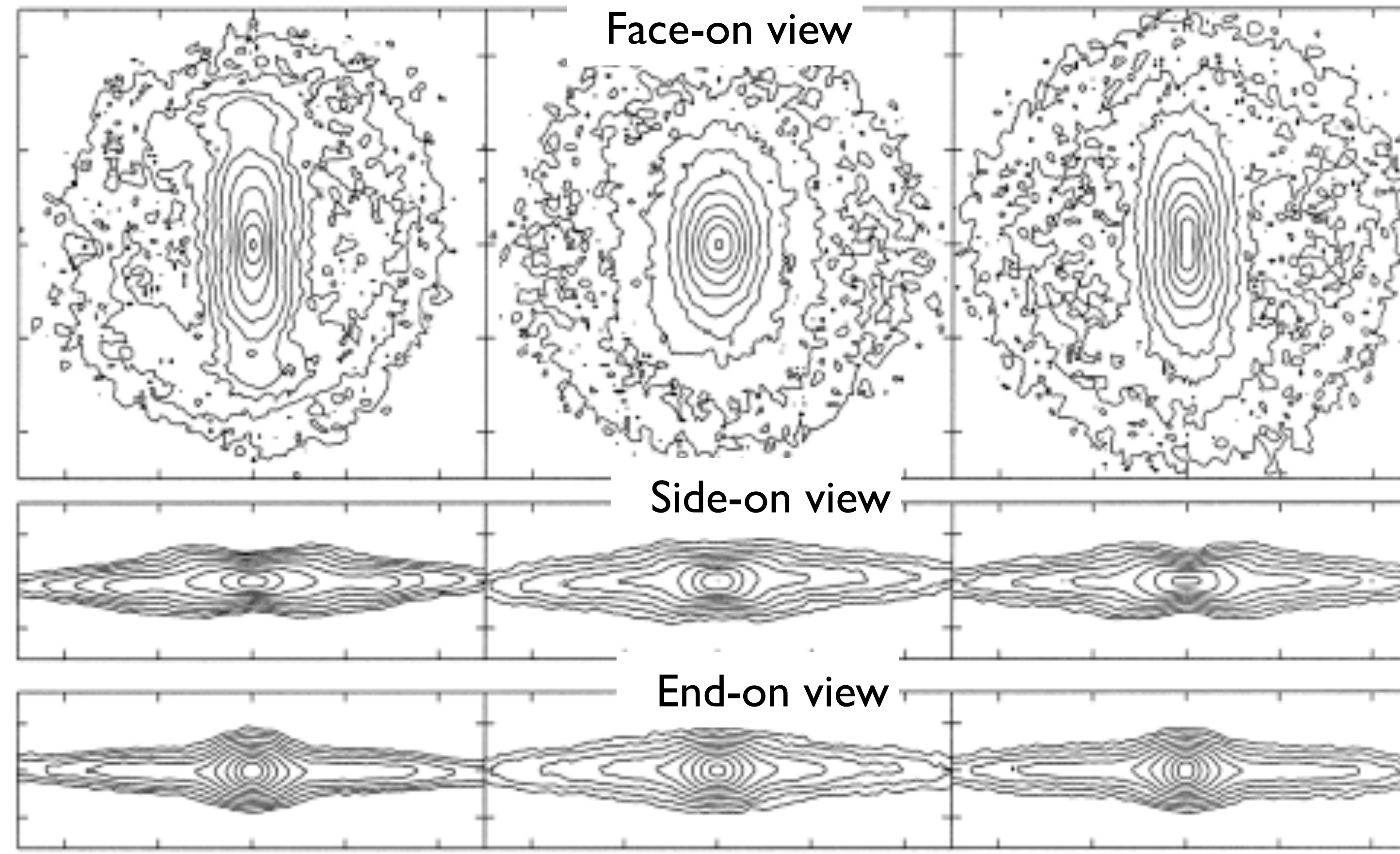
Note that these two results are linked.

THE CLASSICAL BULGE IN THE MW IS SMALL

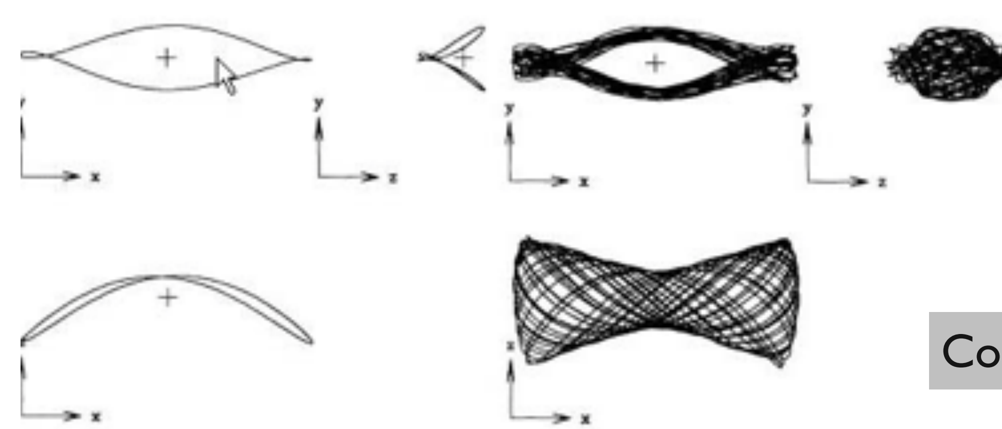
THE MILKY WAY BULGE IS SECULAR



Saha et al 2012



Athanassoula & Misiriotis 2002

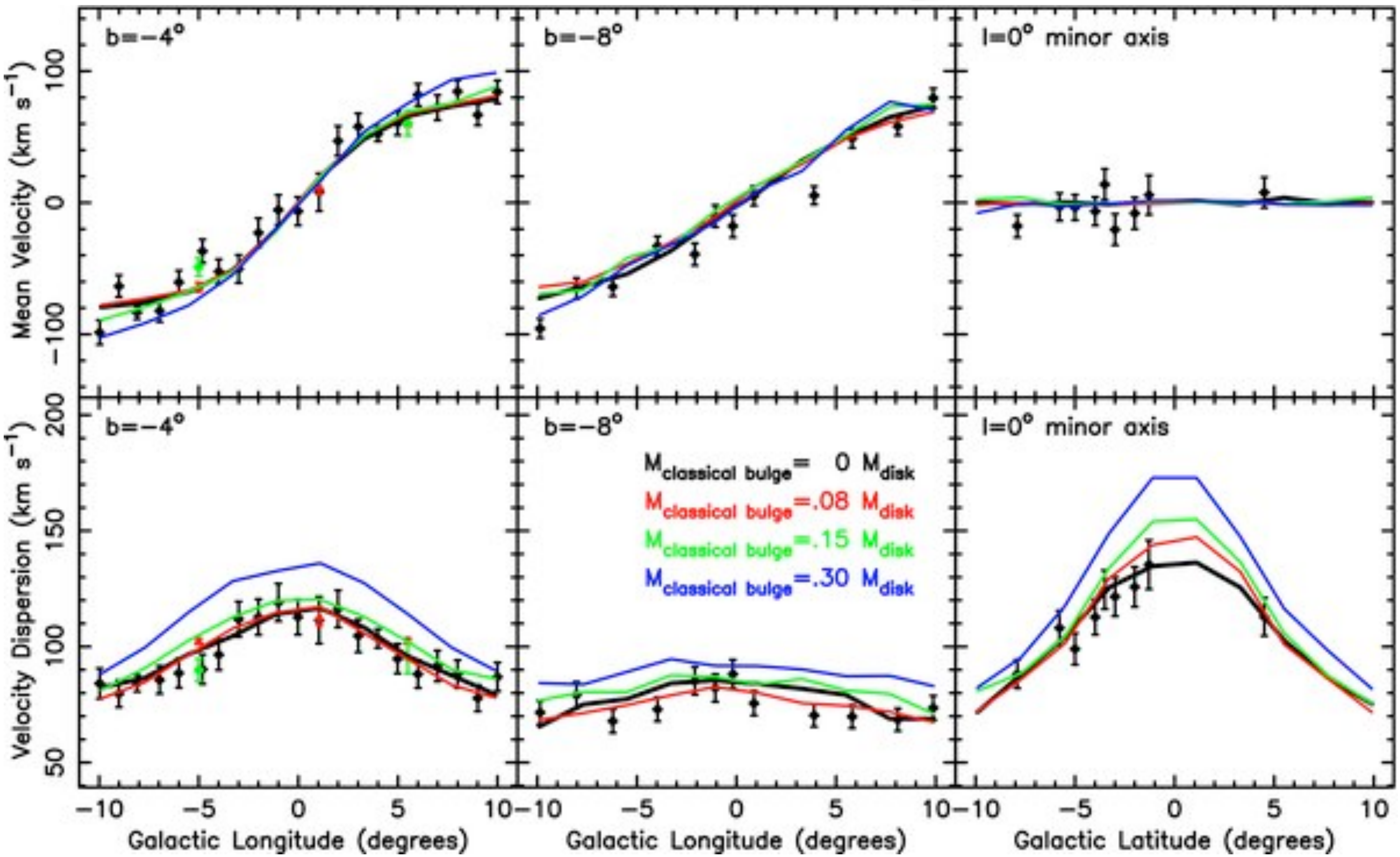


Combes et al 1990

+ Wegg et al, see Ortwin Gerhard talk this morning

THE CLASSICAL BULGE IS SMALL OR NOT EXISTENT

Global bulge kinematics



Shen et al 2010: "**The MW as a pure thin disk galaxy,** any classical bulge contribution cannot be larger than ~8% of the disk mass."

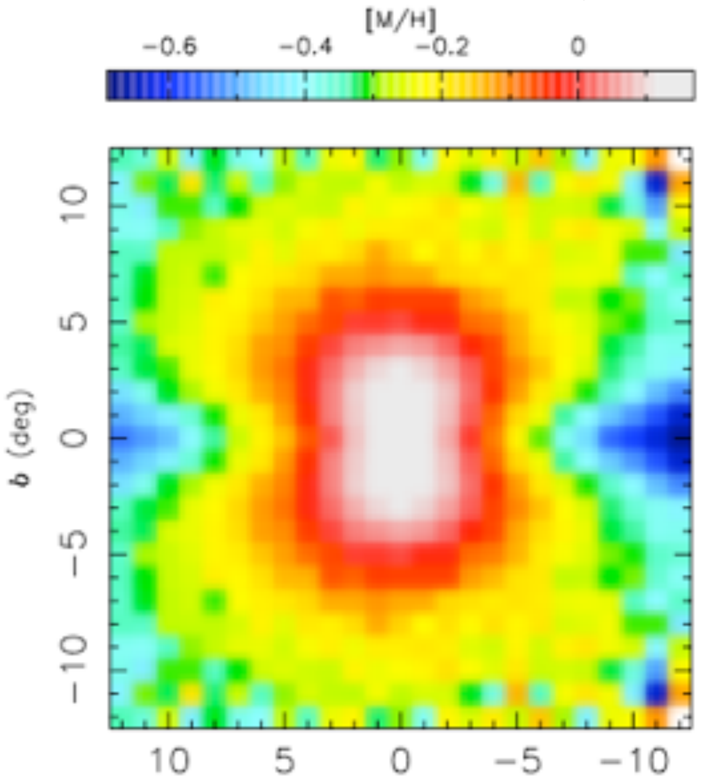
Zoccali et al 2014: "The very good agreement between this model and the data supports the conclusion presented in Shen et al. (2010), extending it to the inner bulge at b = –2"

THE CLASSICAL BULGE IS SMALL OR NOT EXISTENT

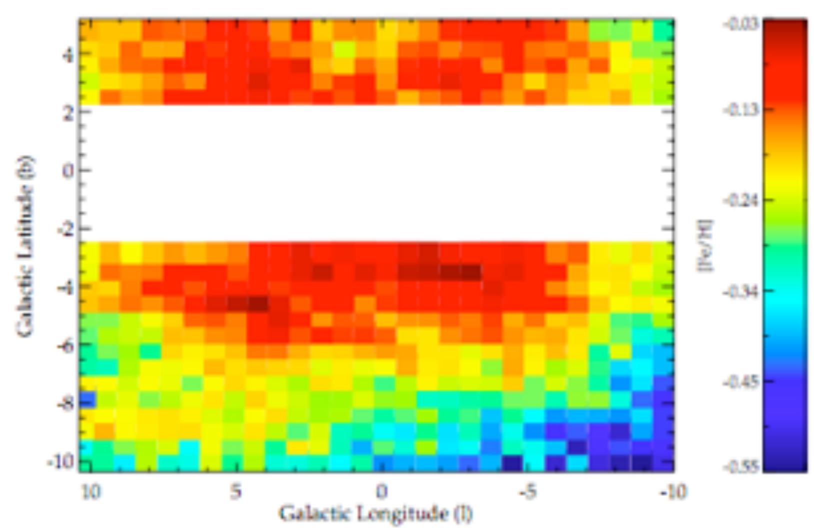
Global bulge metallicity

If the initial negative radial metallicity gradient in the stellar disc is steep enough (~-0.4 dex/kpc) a vertical negative metallicity gradient similar to those measured in the bulge can be produced
(*see Martinez-Valpuesta & Gerhard 2013; confirmed by Di Matteo et al 2014b*)

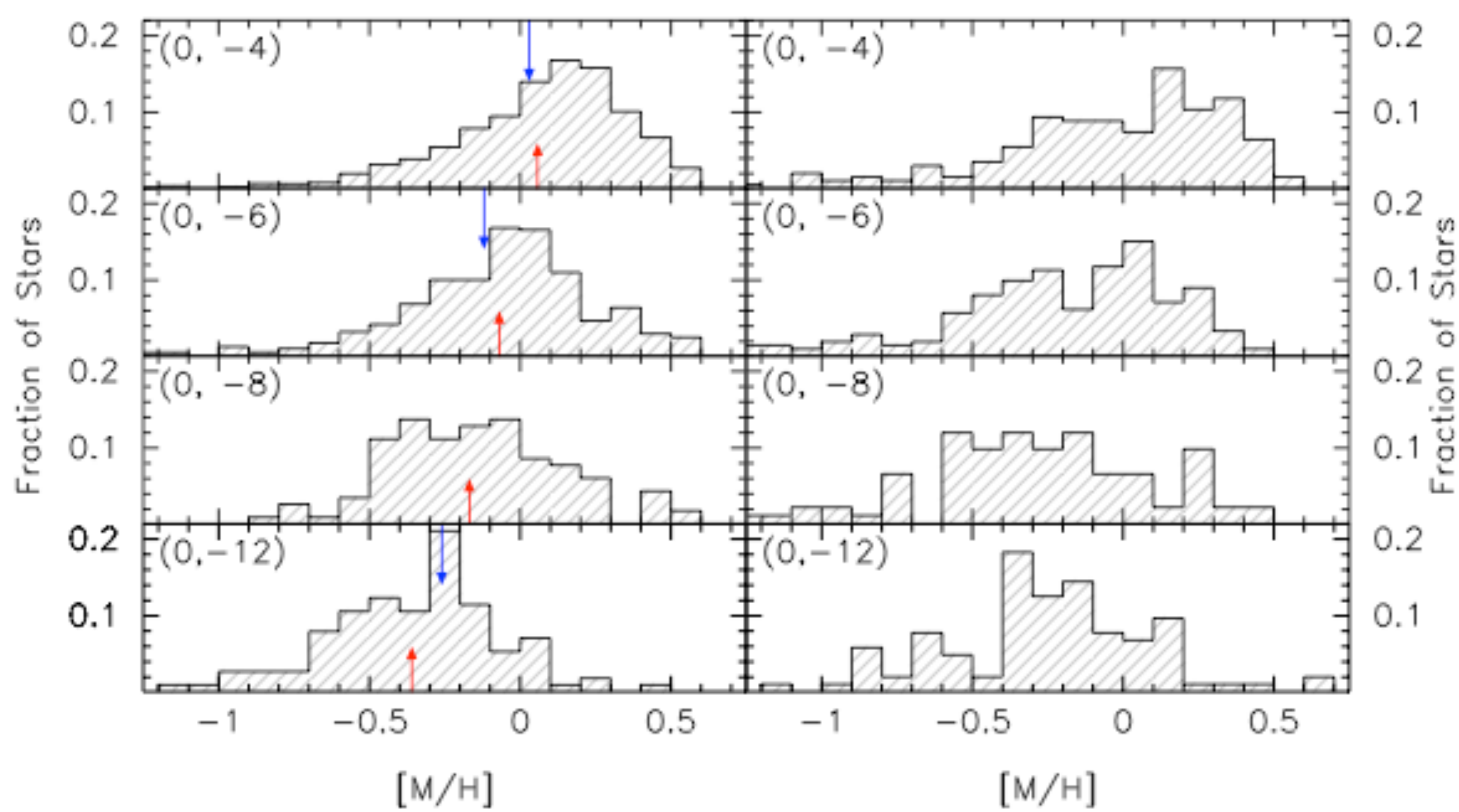
Simulation by MV&G13



VVV Survey, Gonzalez et al 2013



Simulations from MV & G 2013 data from Zoccali et al 08



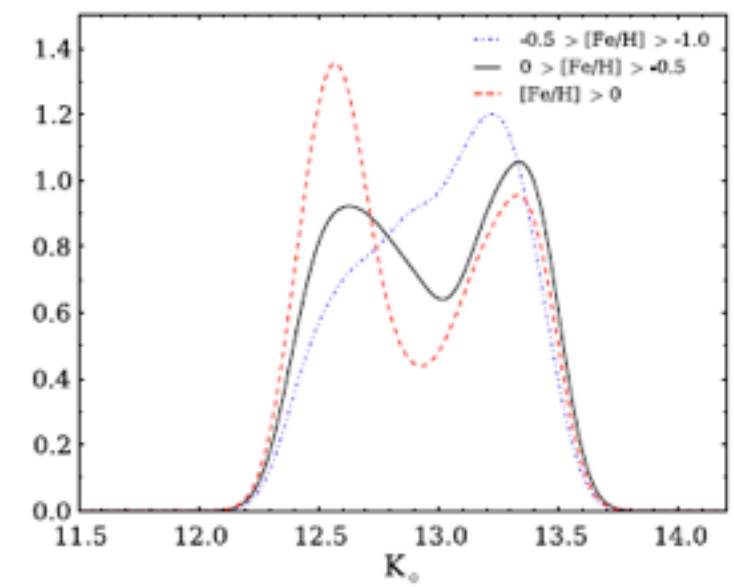
HOWEVER THE MILKY WAY IS NOT A PURE THIN DISC GALAXY

Observational findings :

1/ Multiple stellar populations in the bulge (A, B & C following Ness et al)

2/ Continuous of properties, the weight of these populations changes with latitude

$b°$	A	B	C
-5	0.39	0.37	0.22
-7.5	0.22	0.43	0.30
-10	0.11	0.50	0.31

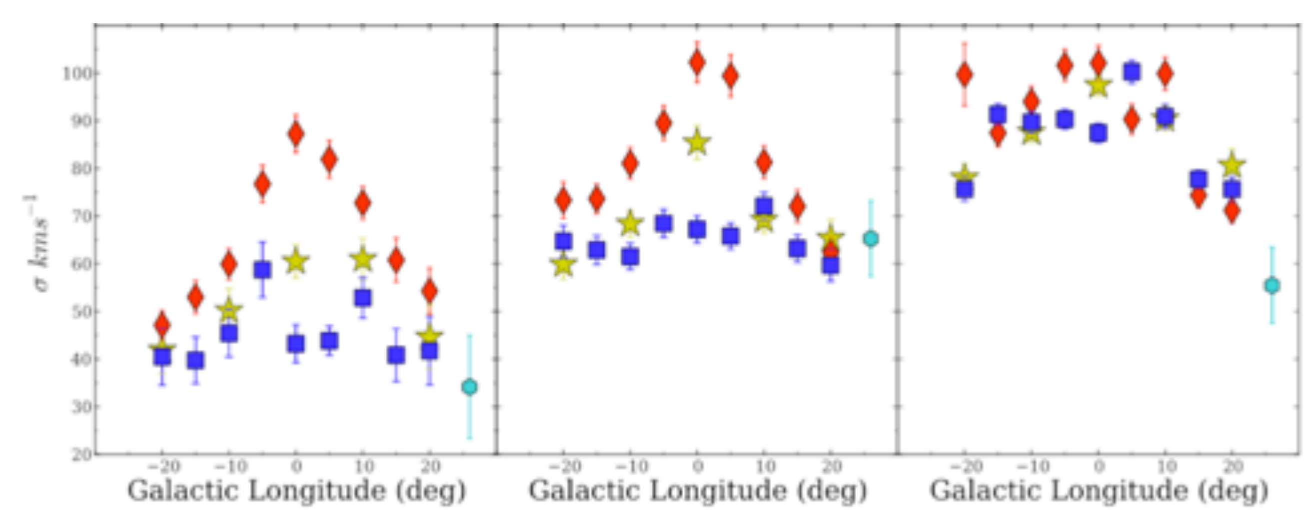


Ness et al 2012

3/ A & B part of the peanut structure, C is not

4/ A, B & C similar rotational velocities

5/ A & B similar trends in velocity dispersions profiles, but different absolute values, while C has a flat velocity dispersion.



FAILURES OF A PURE THIN DISC SCENARIO FOR THE MW BULGE

(see Di Matteo et al 2014b, A&A in press)

A pure thin disc scenario for the formation of the MW bulge would imply:

1/ Multiple stellar populations in the bulge
(see Martinez-Valpuesta & Gerhard 2013)

2/ Continuous of properties, the weight of these populations changes with latitude (Di Matteo et al 2014a)

BUT (see Di Matteo et al 2014b, A&A in press)

3/ A, B & C should all have a boxy-peanut shaped morphology at low latitudes *not observed*

4/ The rotational velocity should increase from A to C *not observed*

5/ The velocity dispersion profiles should be the same, only the absolute values should change *not observed*

THICK DISC AS A MAJOR COMPONENT OF THE MW

1. The (alpha-enhanced) thick disk as a short scale length
(Bensby et al 2011; Bovy et al 2012; Anders et al 2014)

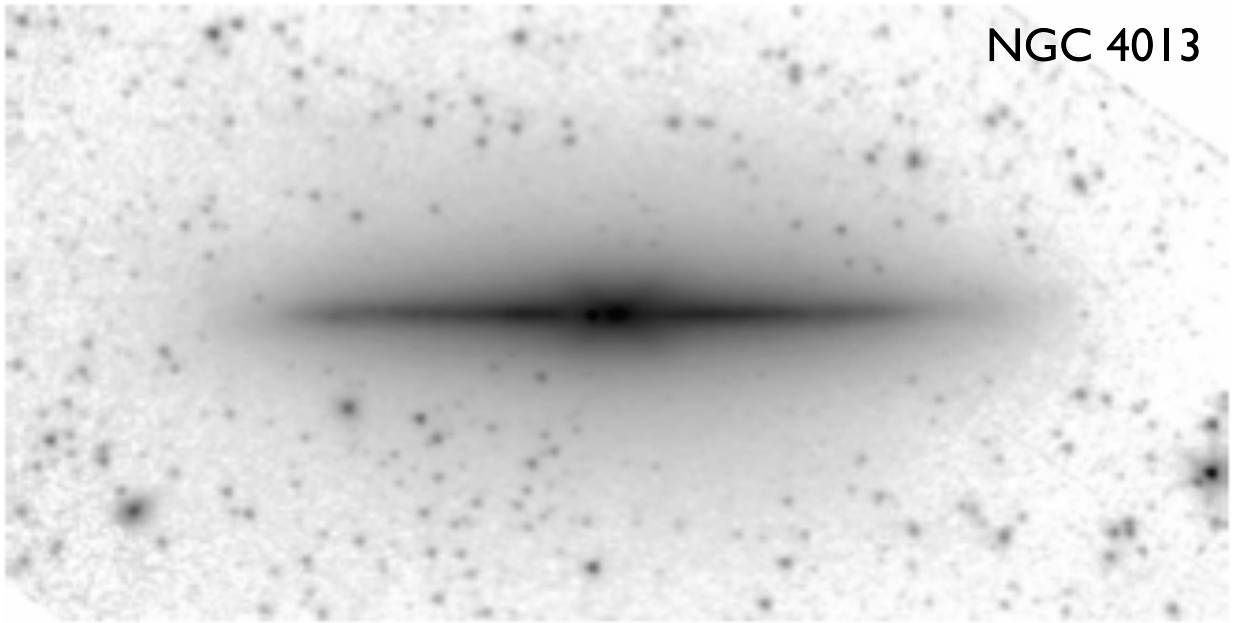
2. The (alpha-enhanced) thick disk is massive, as massive as the thin disc
(Snaith et al 2014a,b)

It is impossible to avoid a dominant contribution of the thick disc to the inner MW regions

3. Moreover, the thick disk at the solar vicinity
and the old, alpha-enhanced, metal poor component in the bulge
almost perfectly overlaps in [alpha/Fe]-[Fe/H]
(Gonzalez et al 2011; Bensby et al 2013)

See Misha Haywood's talk yesterday, but also Michael Rich's talk this morning

ORIGIN OF POPULATIONS A, B & C: MAPPING OF A (THIN+THICK) DISC INTO A BOXY BULGE



The thick disk is a major component of many of the extragalactic boxy/peanut bulges

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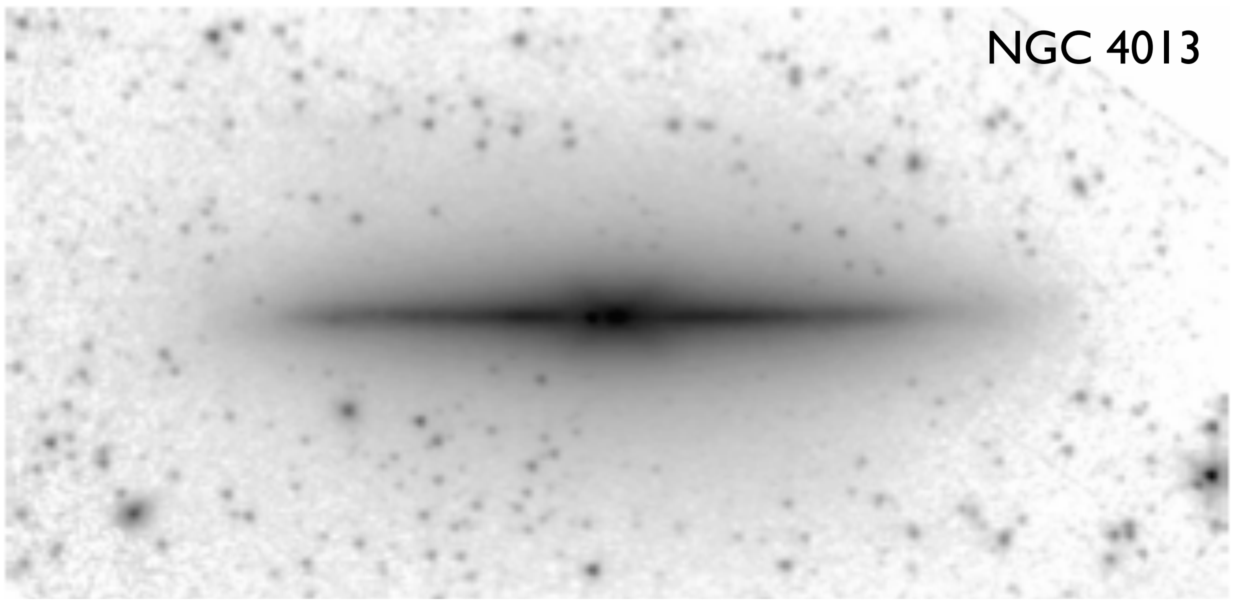

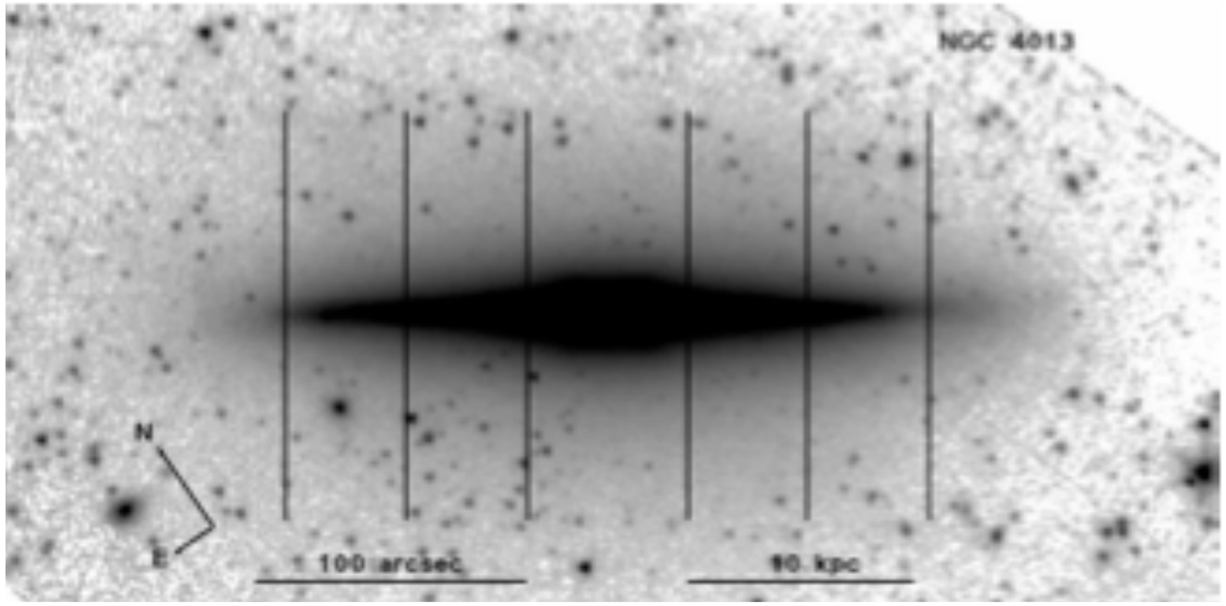

(see Comeron et al 2011, 2014, S^4G survey)

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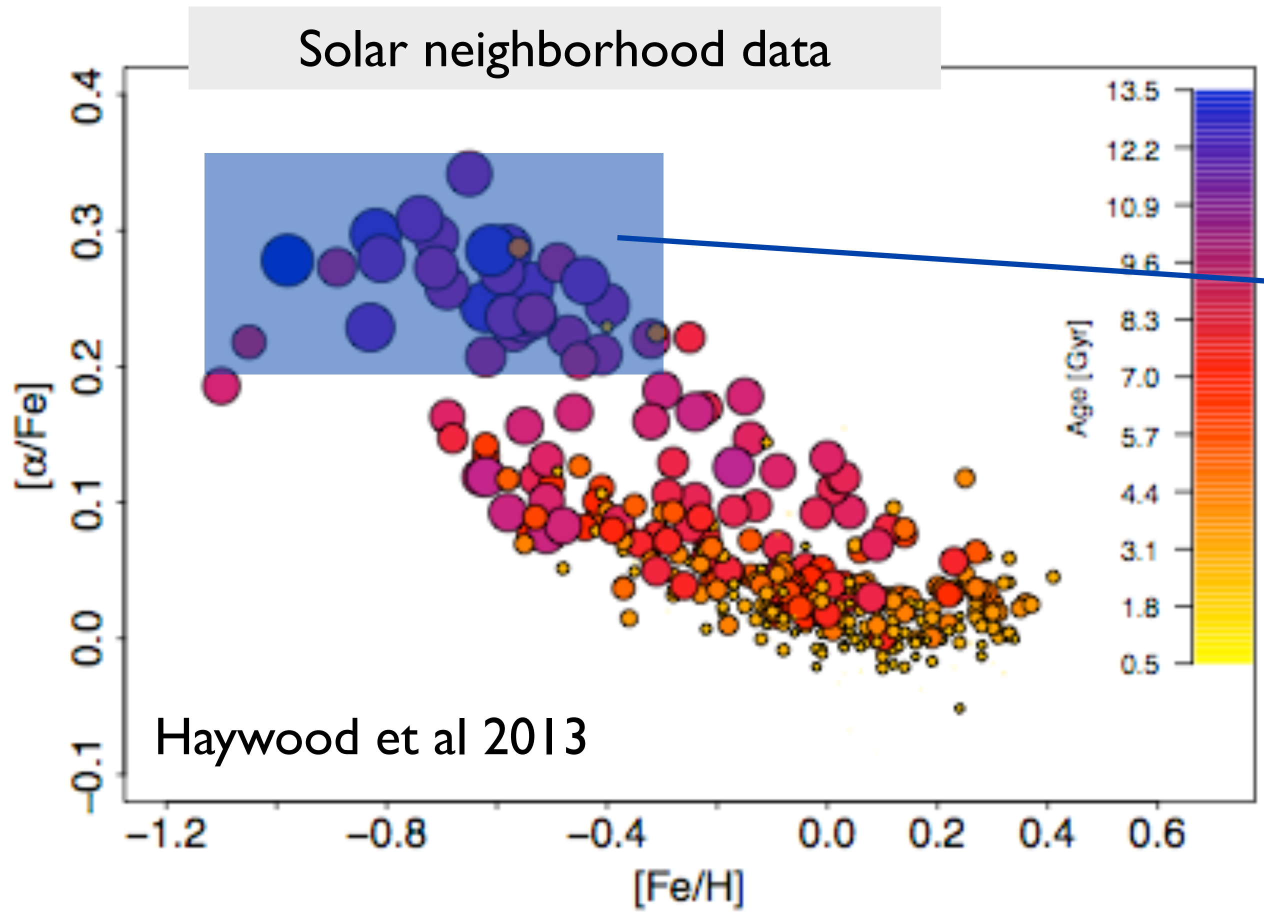
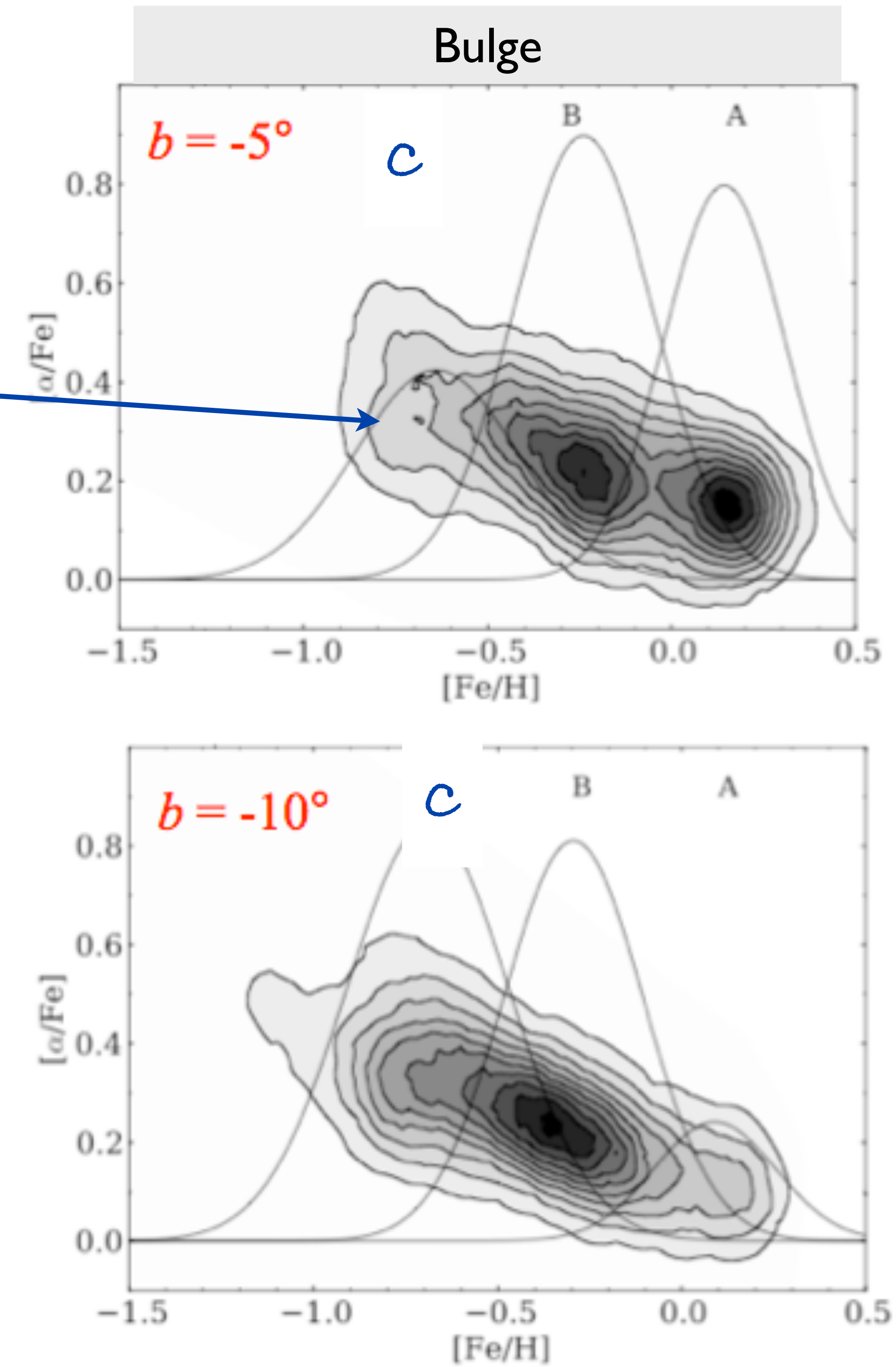


The MW bulge has a pure (thin+thick) disc origin.
Its stellar components are indistinct from those of the MW inner disc
(Di Matteo et al 2014a,
see also discussion in ARGOS papers)

A= inner thin disc
B= young thick disc
C= old thick disc



Ness et al 2013

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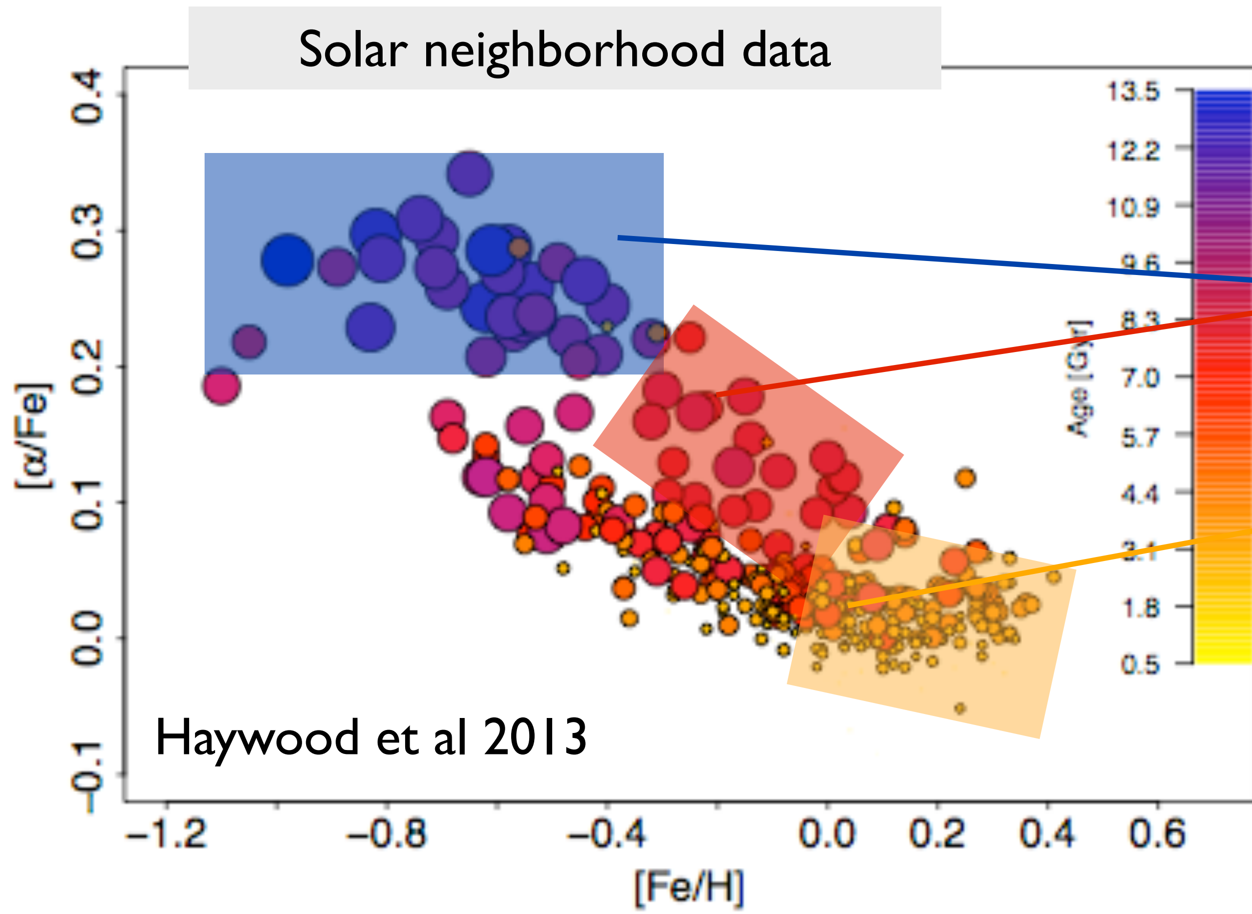

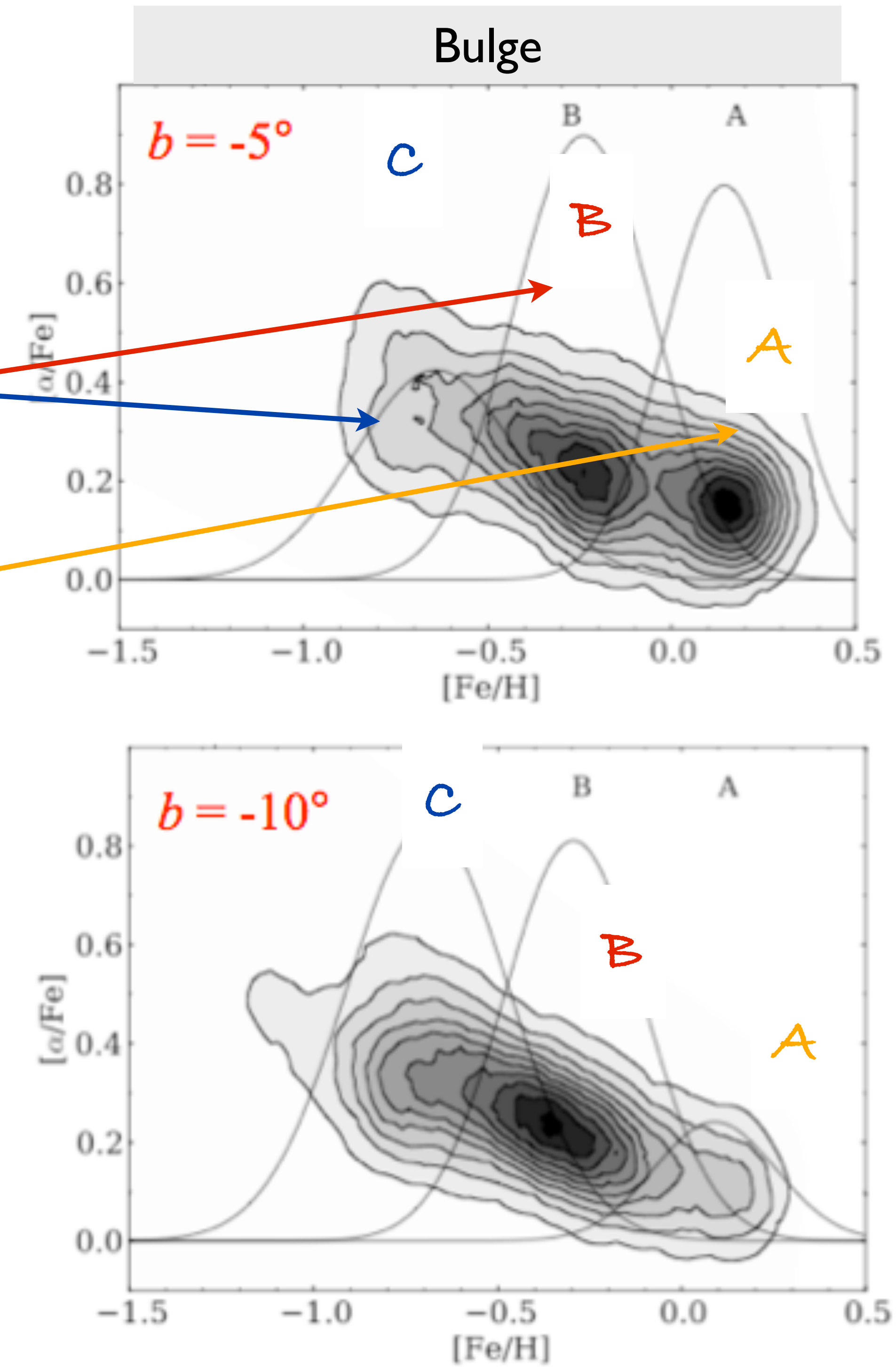

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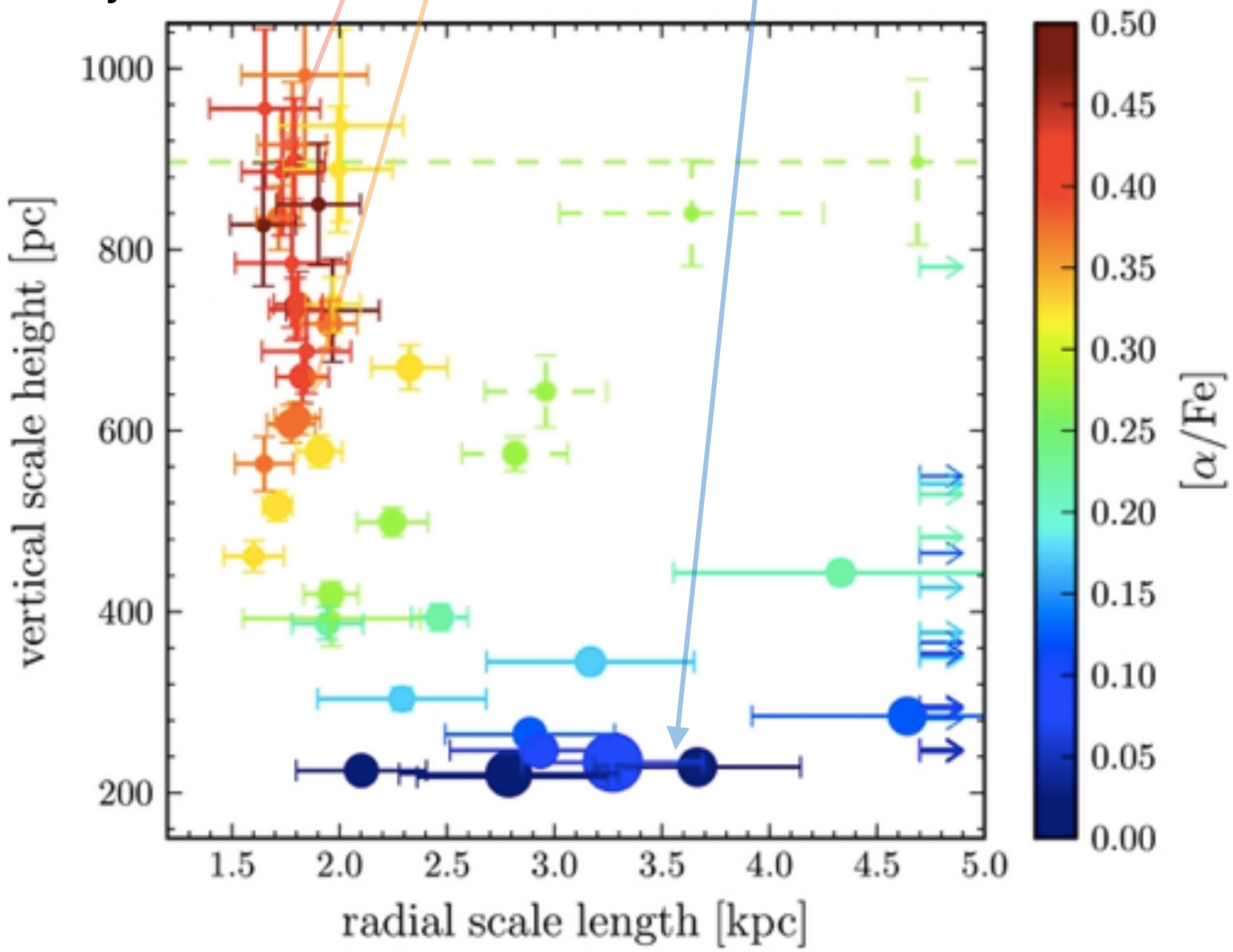
SIMULATION OF A MILKY WAY-TYPE GALAXY

1.5 Millions particles (1M stars, 500K dark matter)

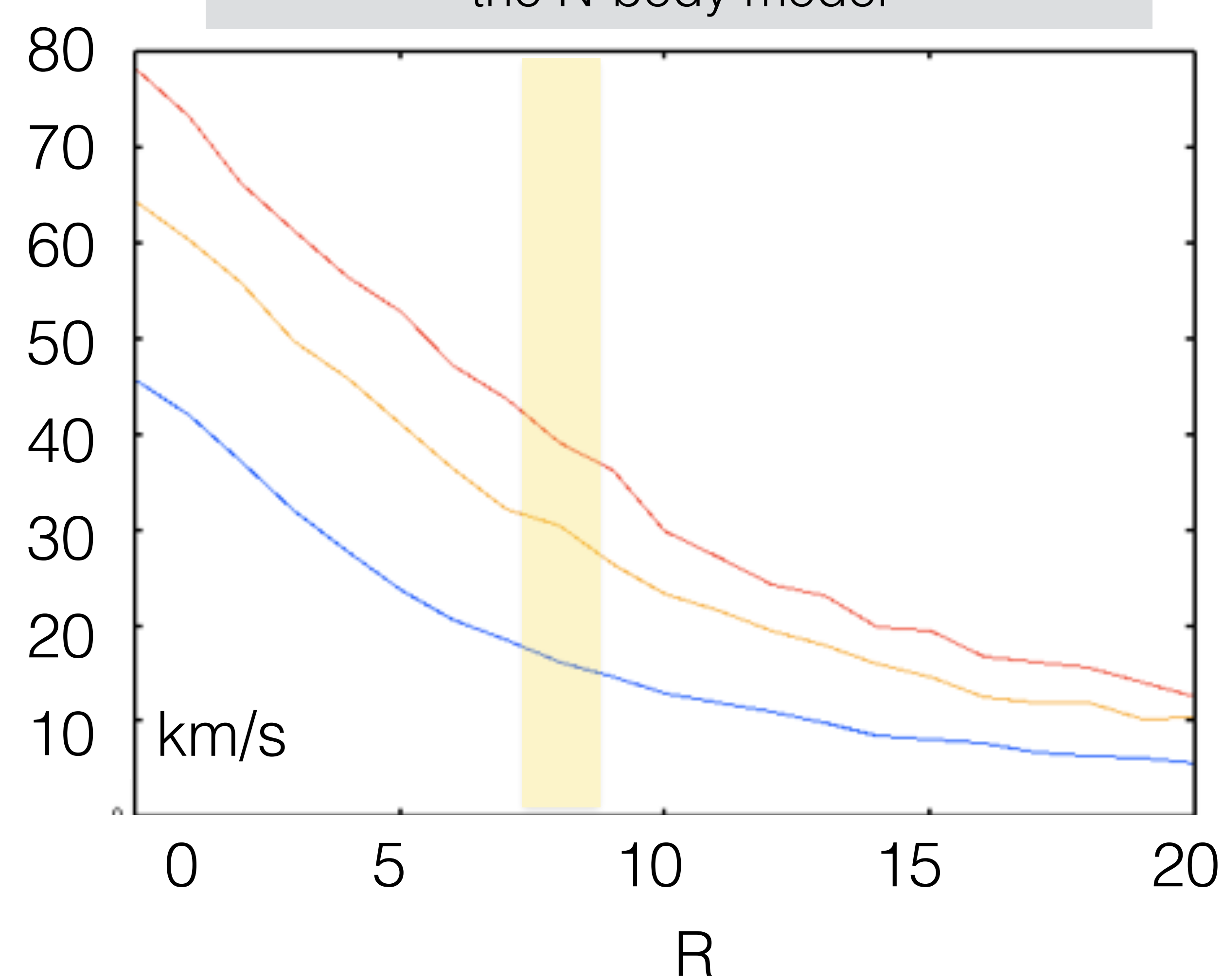
Stellar particles redistributed in 3 discs,

1. a thick stellar disc (old thick disc), r_d=1.8kpc, h_z=0.9 kpc, 0.2$Mtot_*$
2. an intermediate disc (young thick disc), r_d=1.8 kpc, h_z=0.6 kpc, 0.3$Mtot_*$
3. a thin stellar disc, r_d=3.6 kpc, h_z=0.3 kpc, 0.5$Mtot_*$

Bovy et al 2012



Vertical velocity dispersion profiles of the N-body model



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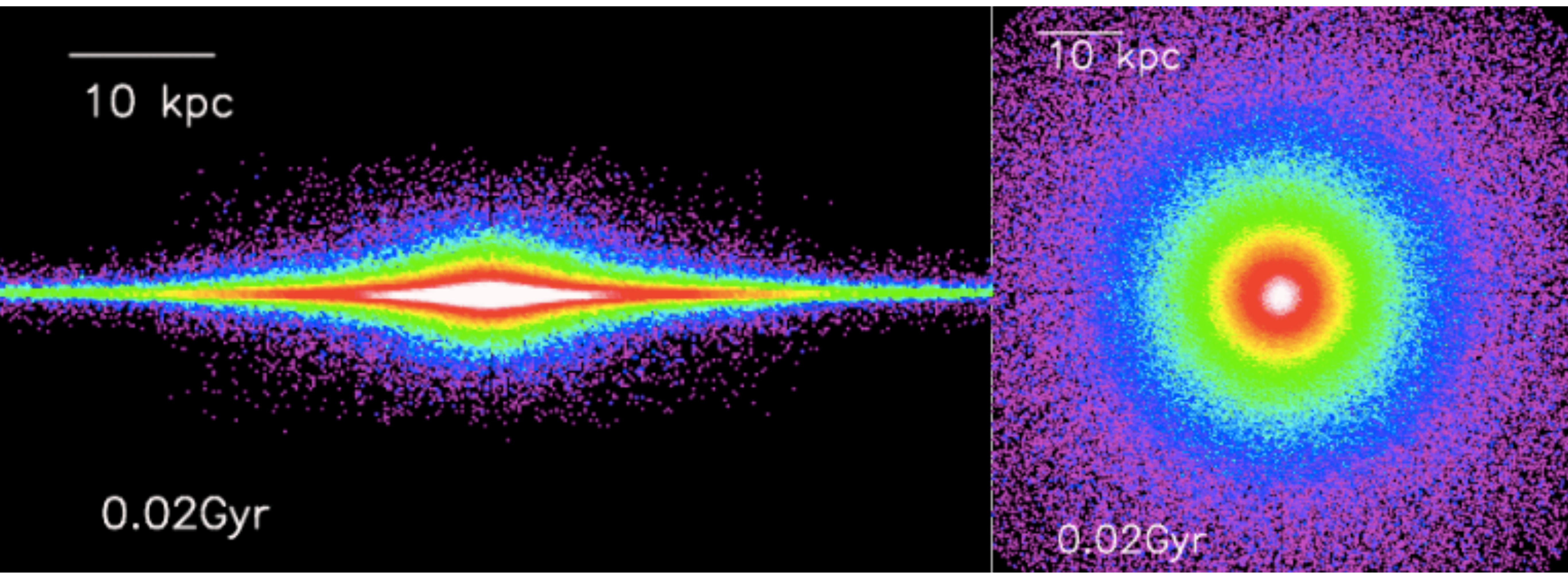

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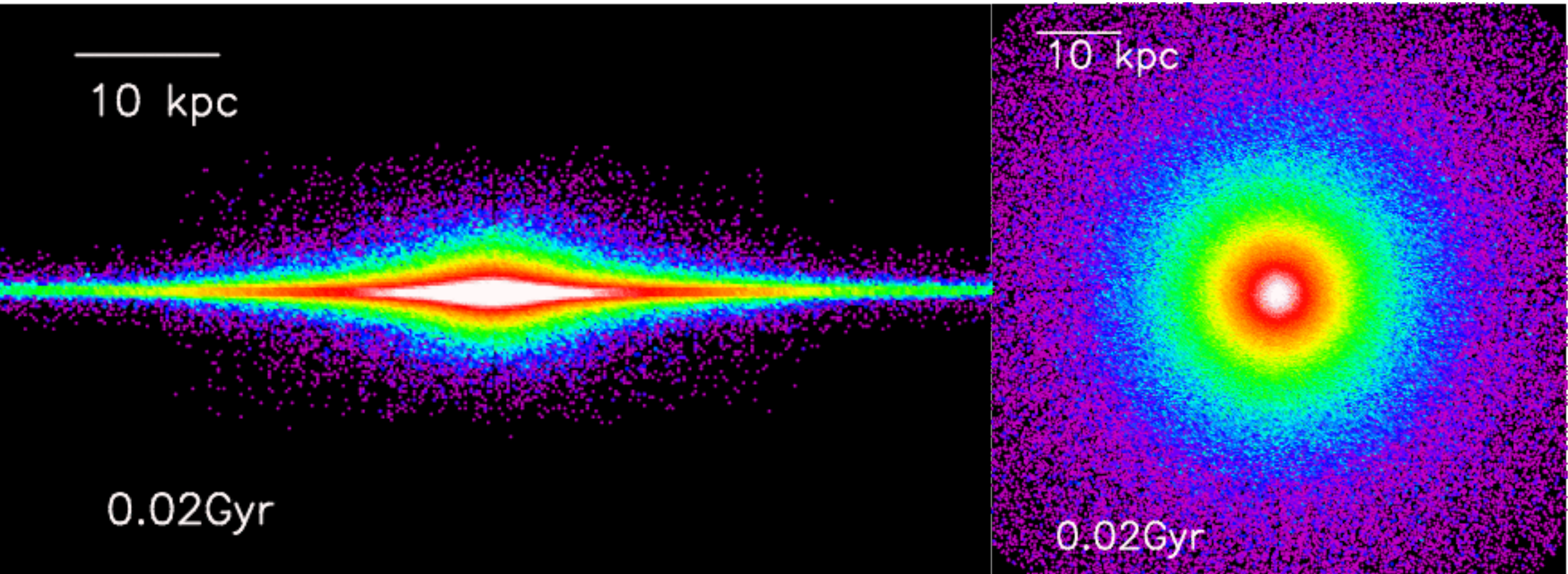
Di Matteo et al, in prep



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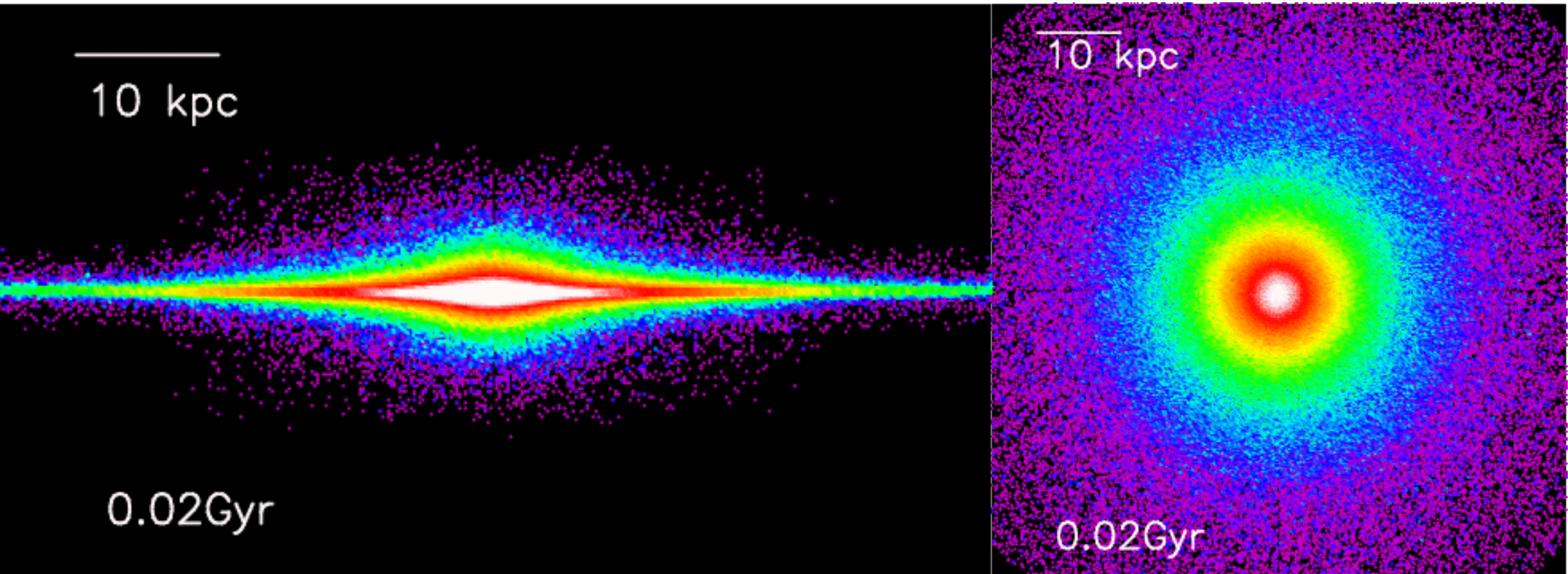

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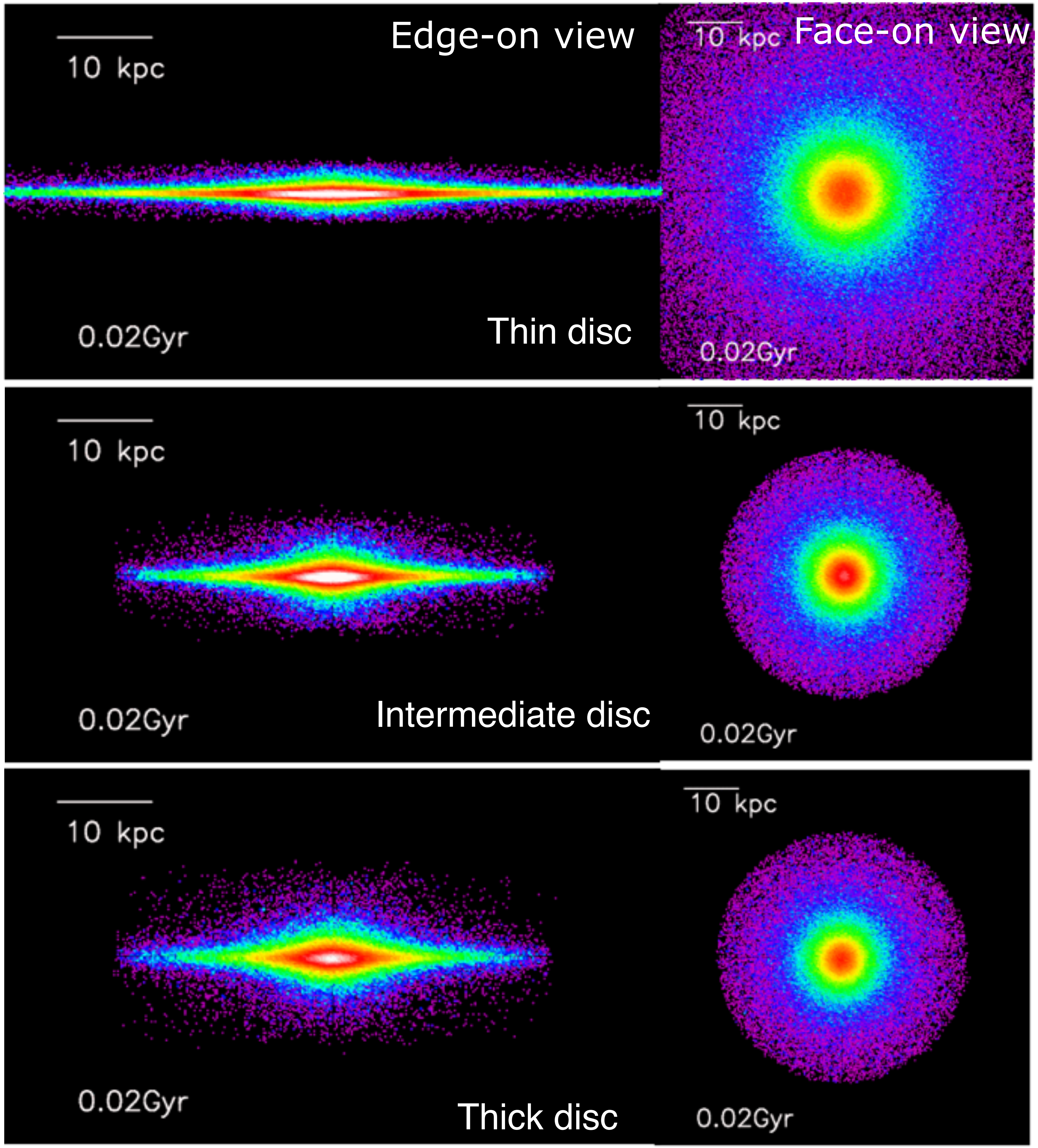

The stellar bar is present in the thin disc, as well as in the intermediate & thick discs

However, the peanut-shaped structure is mostly associated to the thin and intermediate disc. Weak for the thick disc, where it is apparent mostly at high latitudes

Di Matteo et al, in prep

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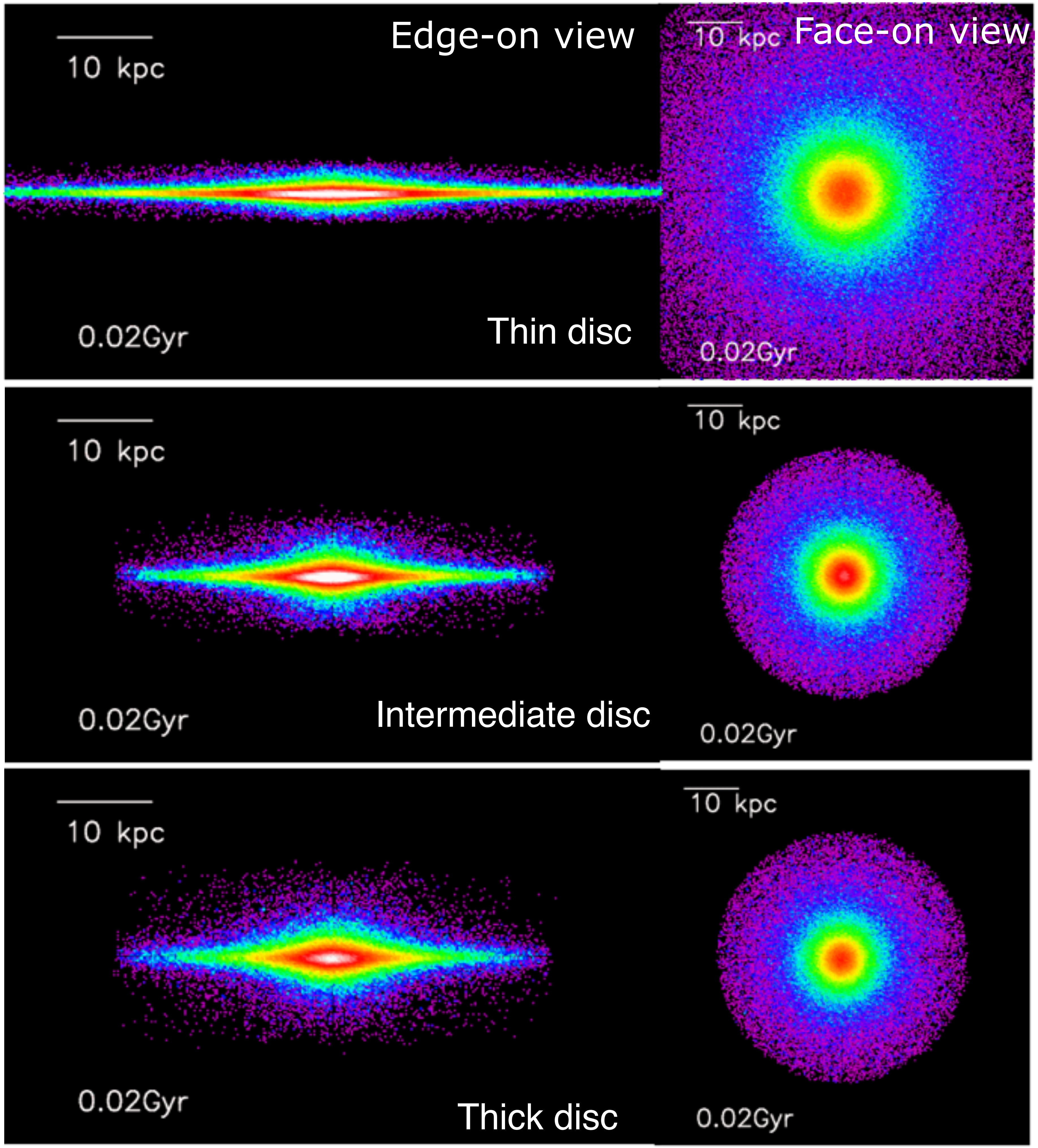

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Di Matteo et al, in prep

N-BODY MODELS OF THIN+THICK DISC GALAXIES

- 16 simulations of thin+thick disc galaxies, with varying M_{thick}/M_{thin} mass ratio and disc scale lengths
- Each simulation : 1.5 millions particles (1M stars, 0.5M dark matter)
- 9 Gyr of evolution

	M_{thick}/M_{thin}	$r_{d,thin}$	$r_{d,thick}$	$h_{z,thin}$	$h_{z,thick}$
thick0	0.	3.6	—	0.3	—
thick0.1S	0.1	3.6	1.8	0.3	0.9
thick0.1E	0.1	3.6	3.6	0.3	0.9
thick0.1G	0.1	3.6	4.3	0.3	0.9
thick0.3S	0.3	3.6	1.8	0.3	0.9
thick0.3E	0.3	3.6	3.6	0.3	0.9
thick0.3G	0.3	3.6	4.3	0.3	0.9
thick0.5S	0.5	3.6	1.8	0.3	0.9
thick0.5E	0.5	3.6	3.6	0.3	0.9
thick0.5G	0.5	3.6	4.3	0.3	0.9
thick0.7S	0.7	3.6	1.8	0.3	0.9
thick0.7E	0.7	3.6	3.6	0.3	0.9
thick0.7G	0.7	3.6	4.3	0.3	0.9
thick0.9S	0.9	3.6	1.8	0.3	0.9
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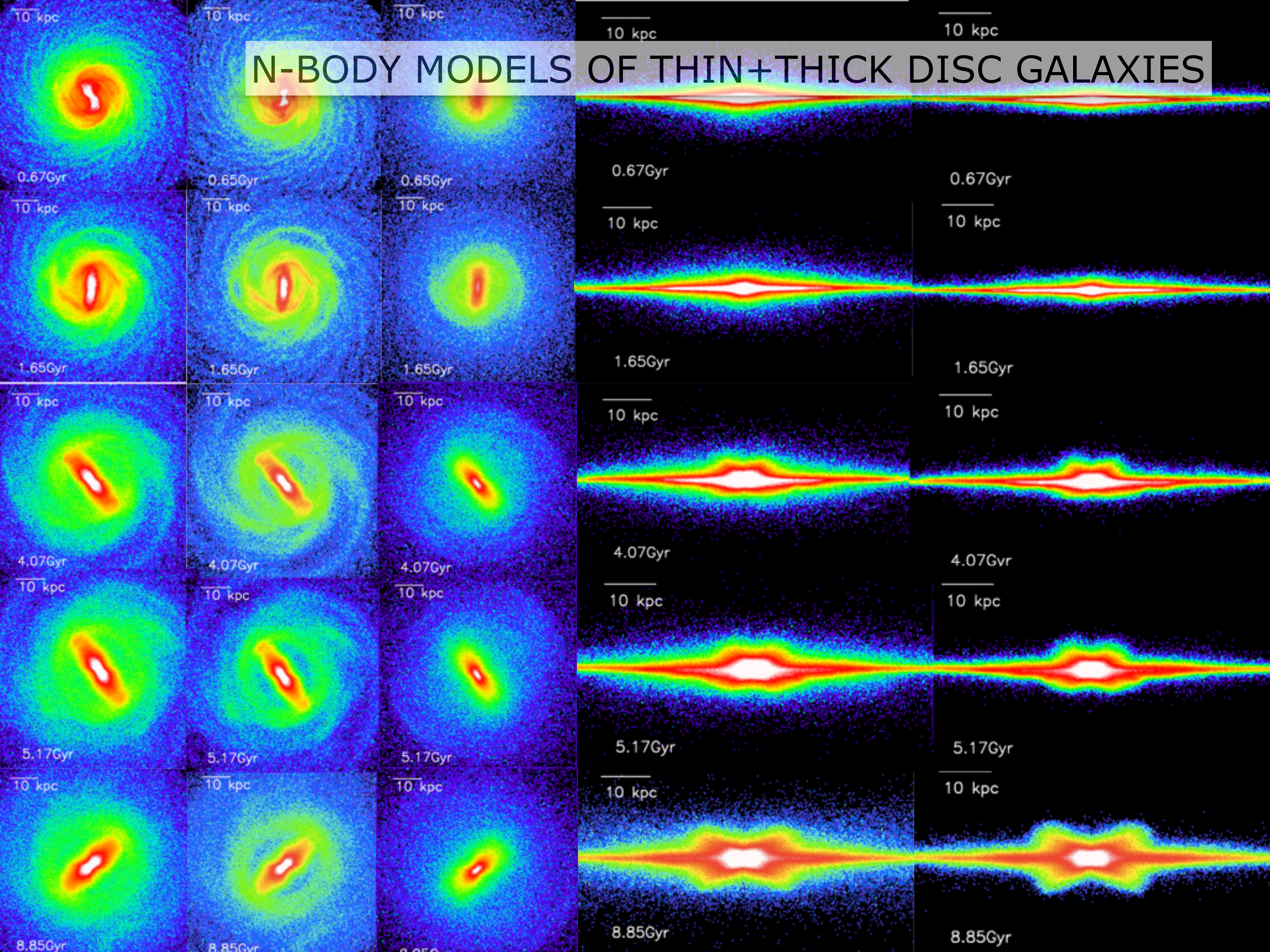


CONCLUSIONS

1/ MW-type galaxies formed ~50% of their stellar mass above z=1. Only a small fraction (~10%) of this mass contained in classical bulges.

2/ In external galaxies, thick discs are found to be significantly more massive than what previously thought (Comeron et al 2011)

3/ **The MW is not exceptional : very small (if any) classical bulge and a massive thick disc** (Snaith et al 2014a,b)

4/ **The MW bulge did not all originate in a thin disc** (Di Matteo et al 2014b)

Di Matteo et al, in prep (preliminary results !) :

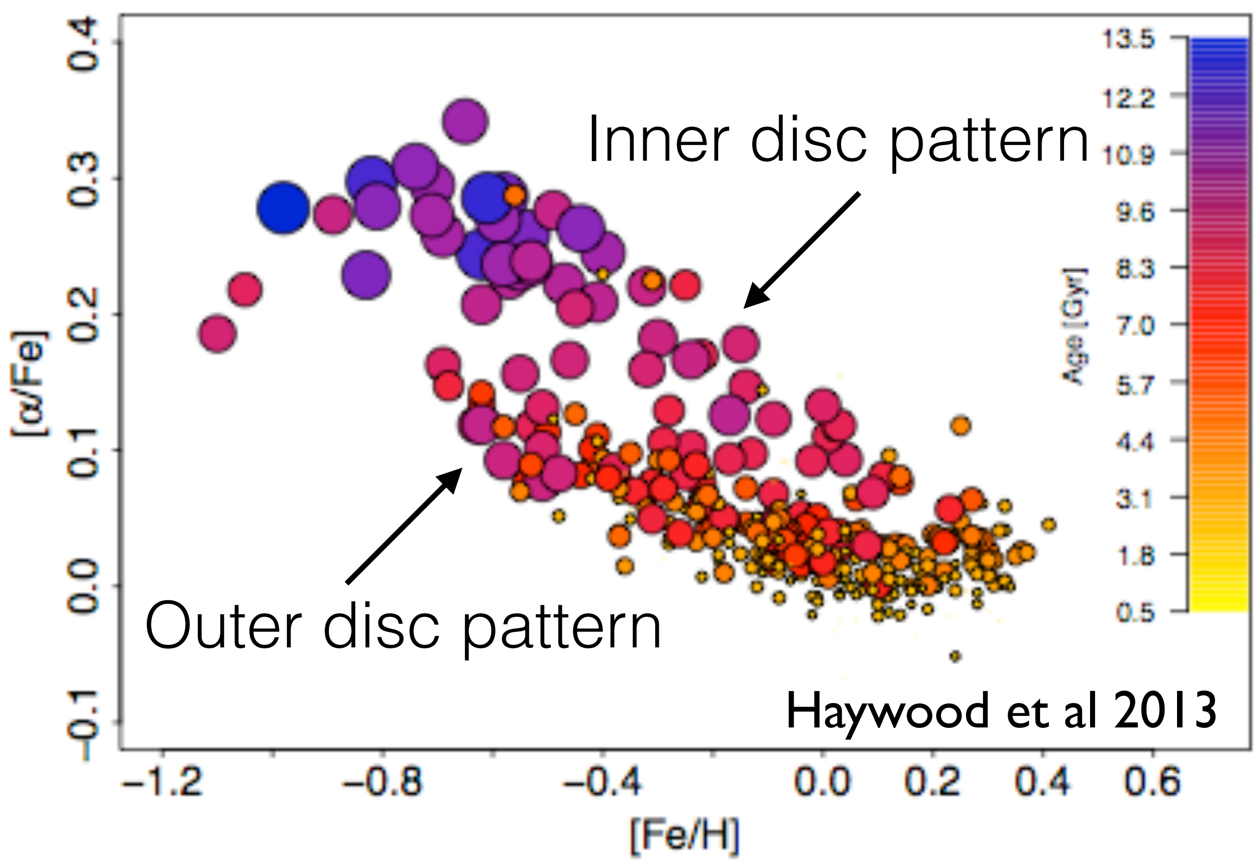
5/ First results of thin+thick disc models show that when a stellar bar forms, the thick disc is barred, but only very weakly boxy/peanut-shaped.

6/ At low vertical distances from the plane, most of the boxy/peanut shaped structures related to the thinner (and more metal-rich) stellar populations.

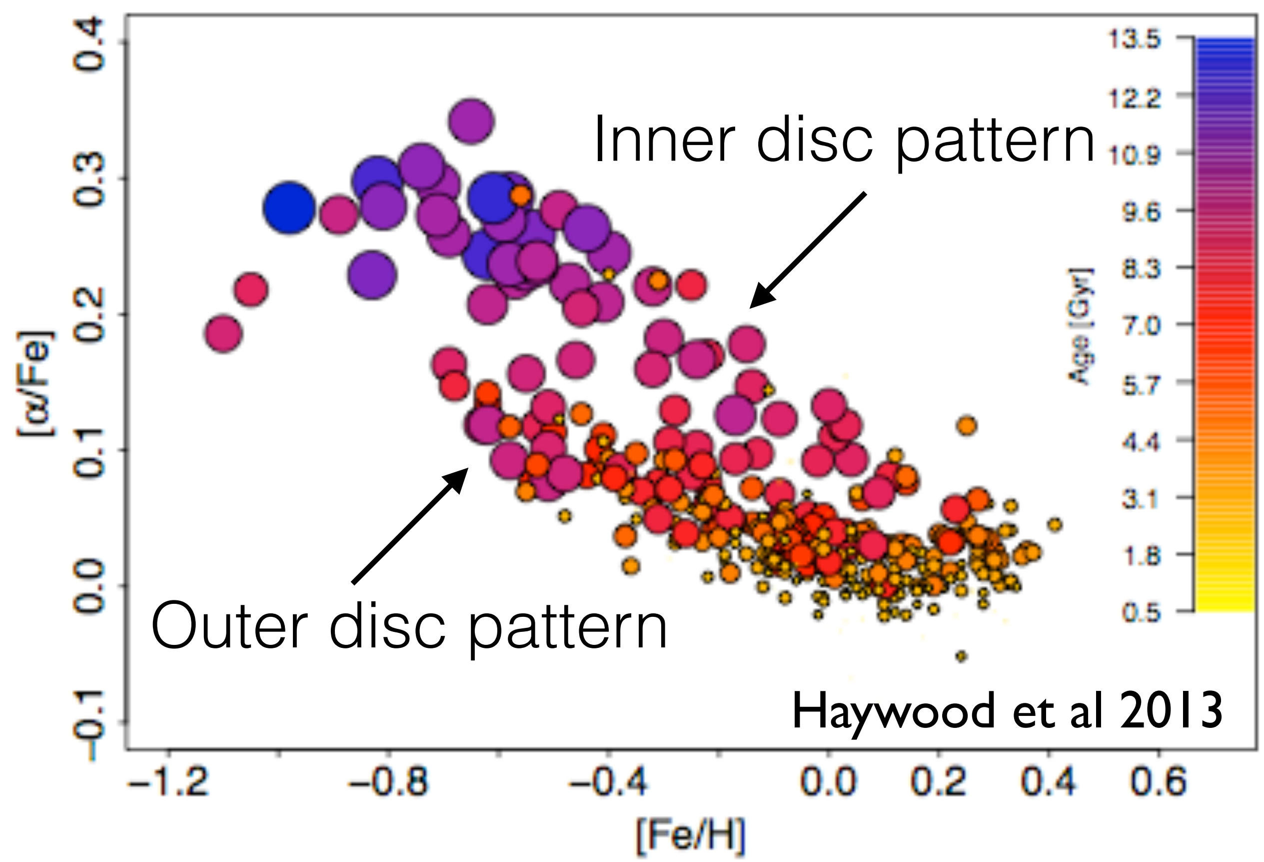
7/ At larger vertical distances, the thick disc shows a weak boxy/peanut-shaped morphology. **It is not excluded that population C may have a weak peanut-shaped morphology at b < -10.**

STARS WITH BORDERS :
RADIAL MIGRATION & THE OUTER GALACTIC DISC

THE OUTER DISC OF THE MILKY WAY



➡ From solar vicinity studies : old stars in the outer (R_g>~ 10 kpc) disc. Their metallicity is up to 0.4 dex lower than that of inner disc stars formed at the same time



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How is possible to maintain the inner & outer discs chemically separated for ~10 Gyr ?

Gas : Why there is chemical discontinuity between the gas in the inner & outer disc ?

Stars : Why radial migration has not been effective in mixing the two ?

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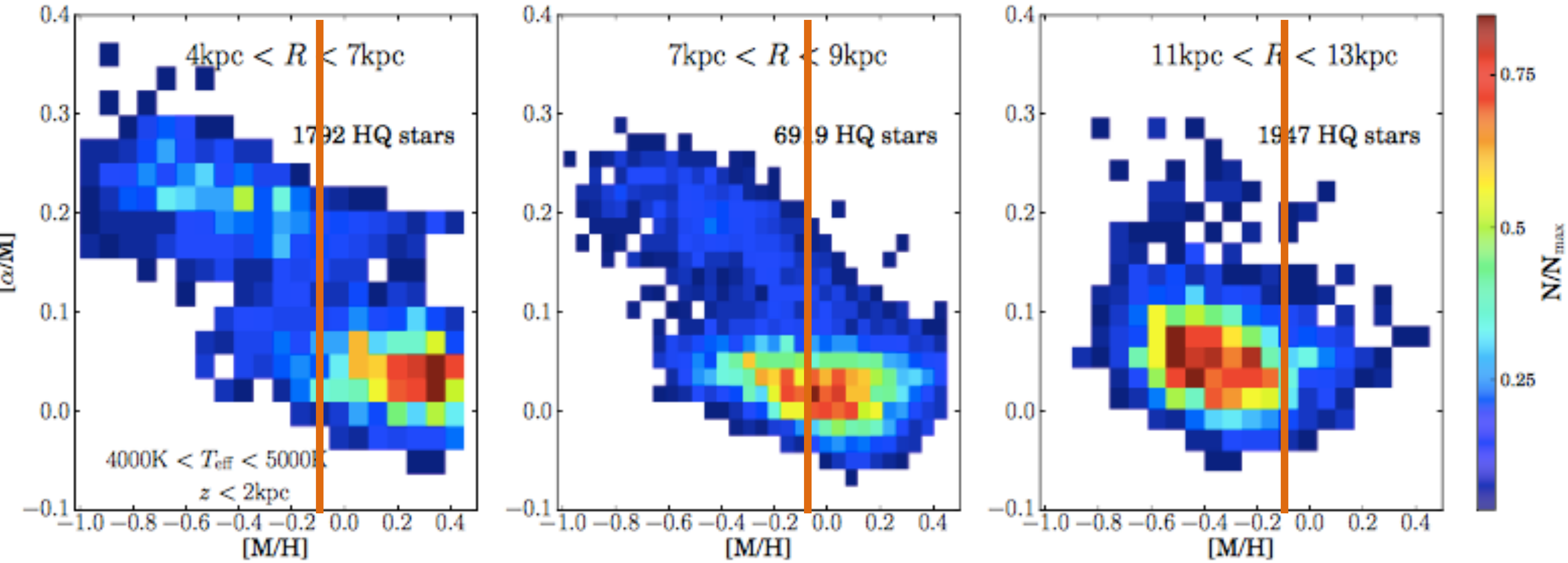
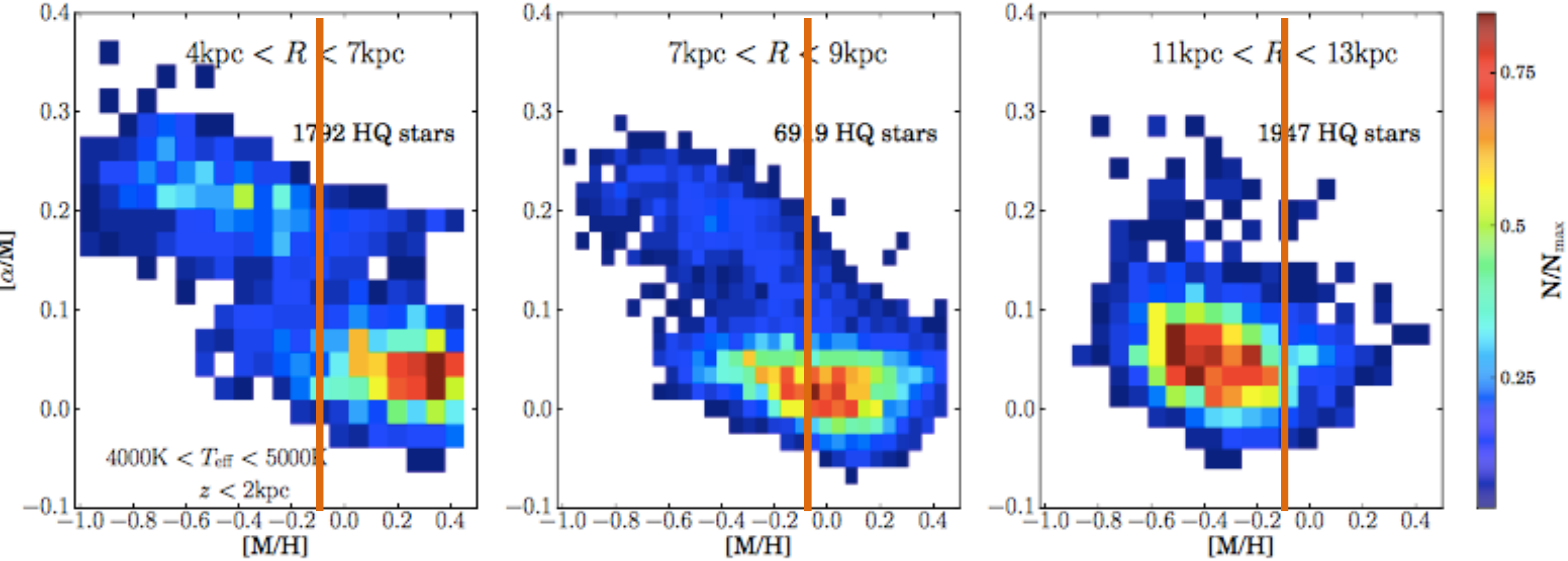


Anders et al 2014

➡ From larger scale studies (lack of age information) : inner and outer disc are made of substantially different populations



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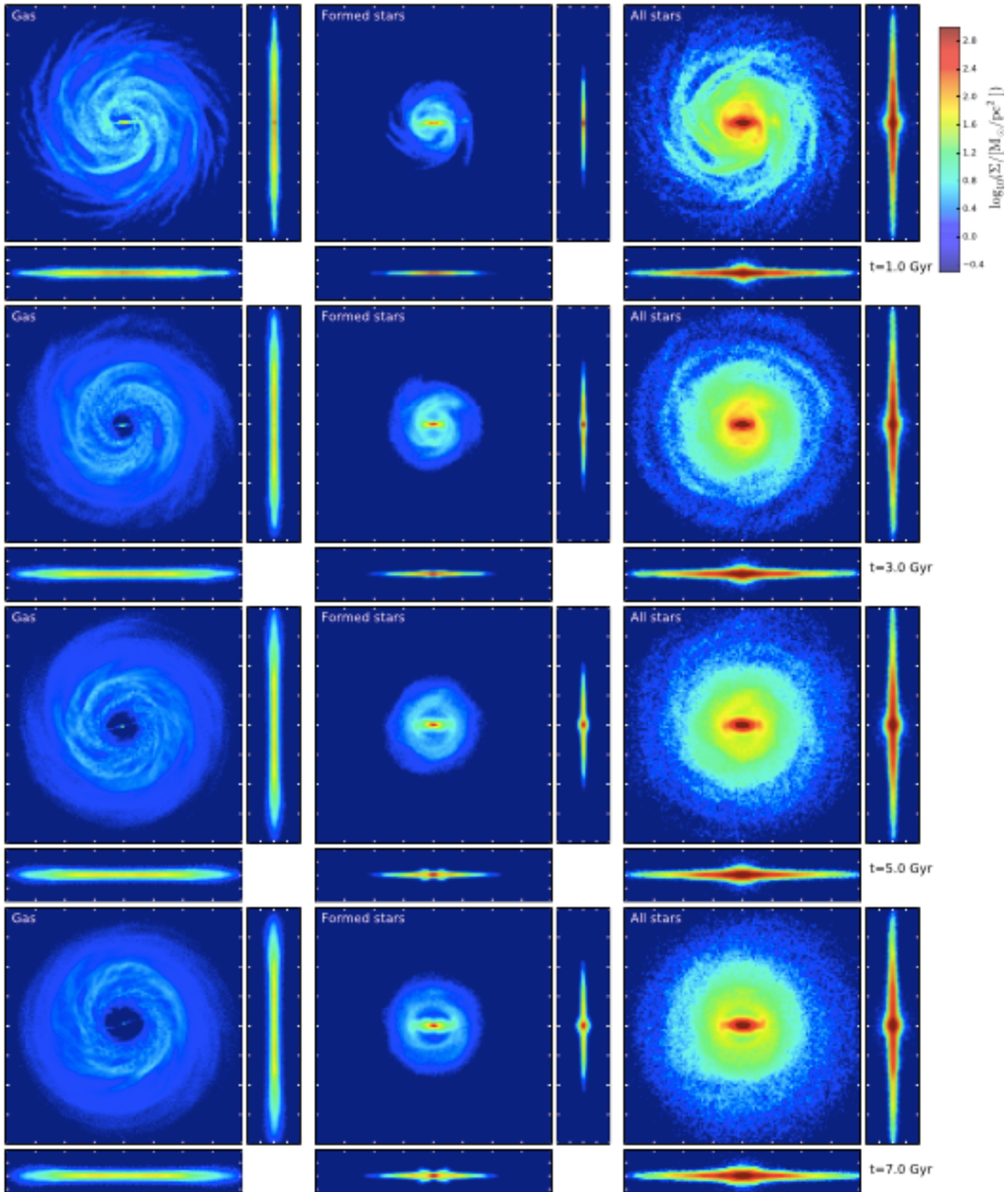
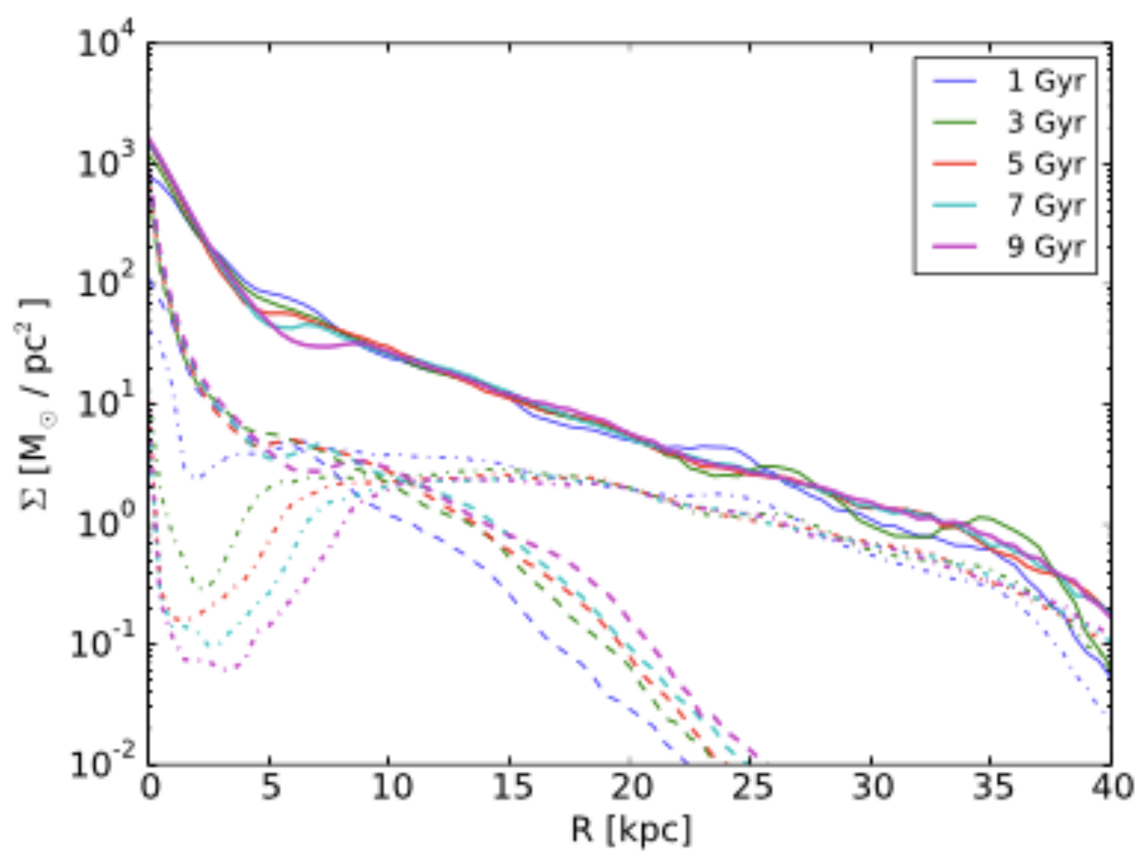
THE ACTION OF THE GALACTIC STELLAR BAR

on the stars, see Hallé et a 2015, astro-ph/1501.00664



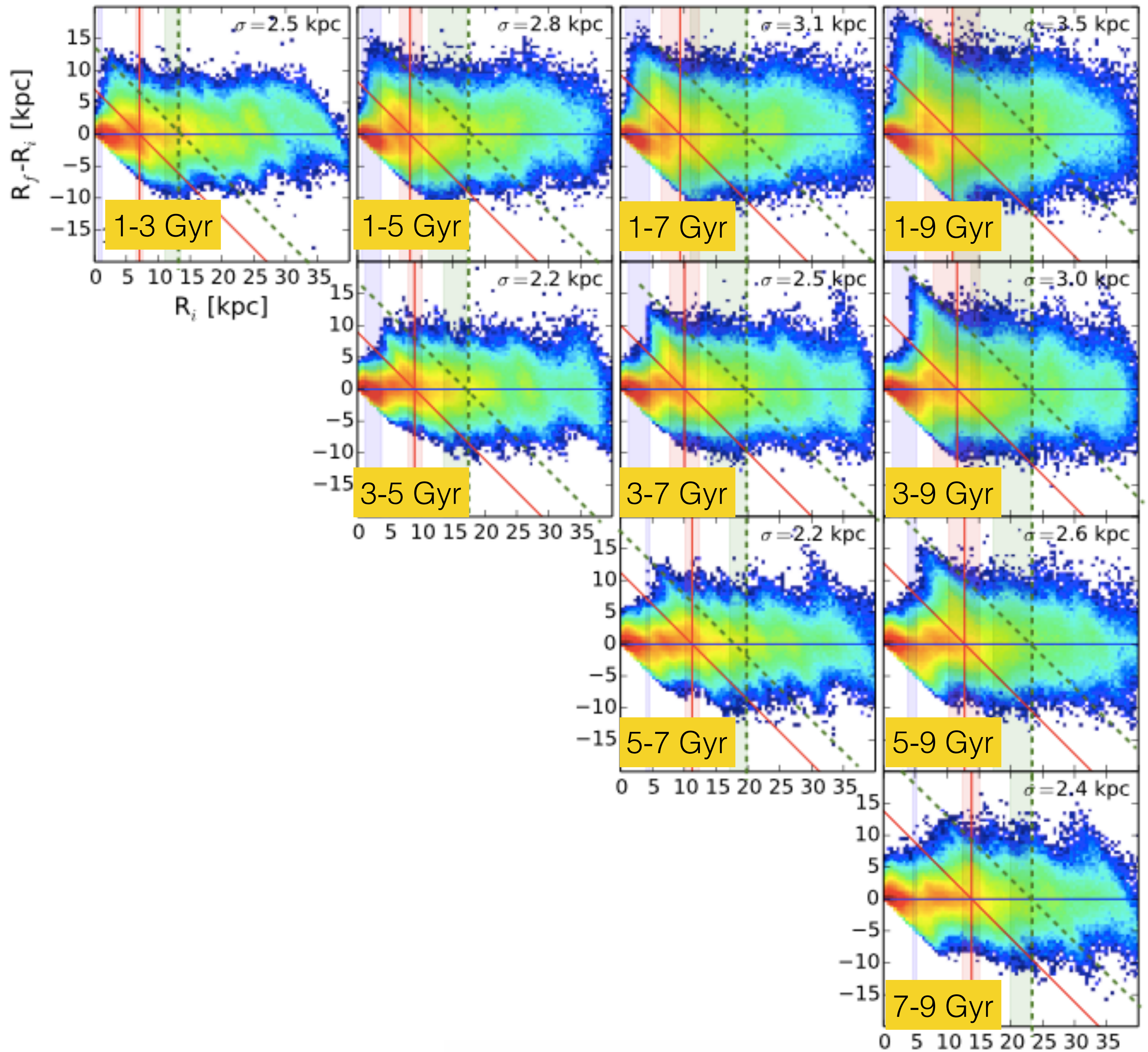
1.2 M particles, equally distributed among stars, gas and dark matter

Star formation, SNe feedback and gas cooling included (see Hallé & Combes 2013)

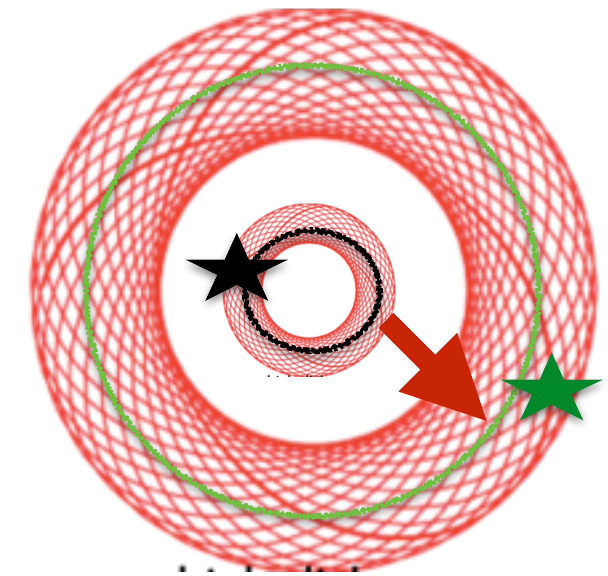


THE ACTION OF THE GALACTIC STELLAR BAR

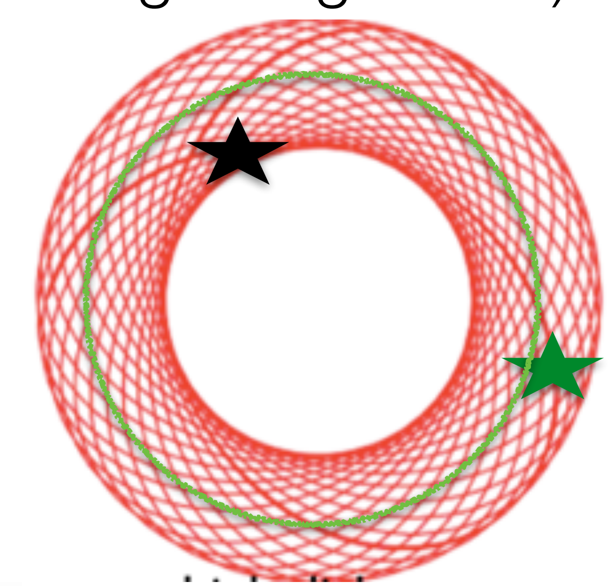
on the stars



Migrators by churning (change in the guiding radius)



+ migrators by blurring (only excursions around a fix guiding radius)



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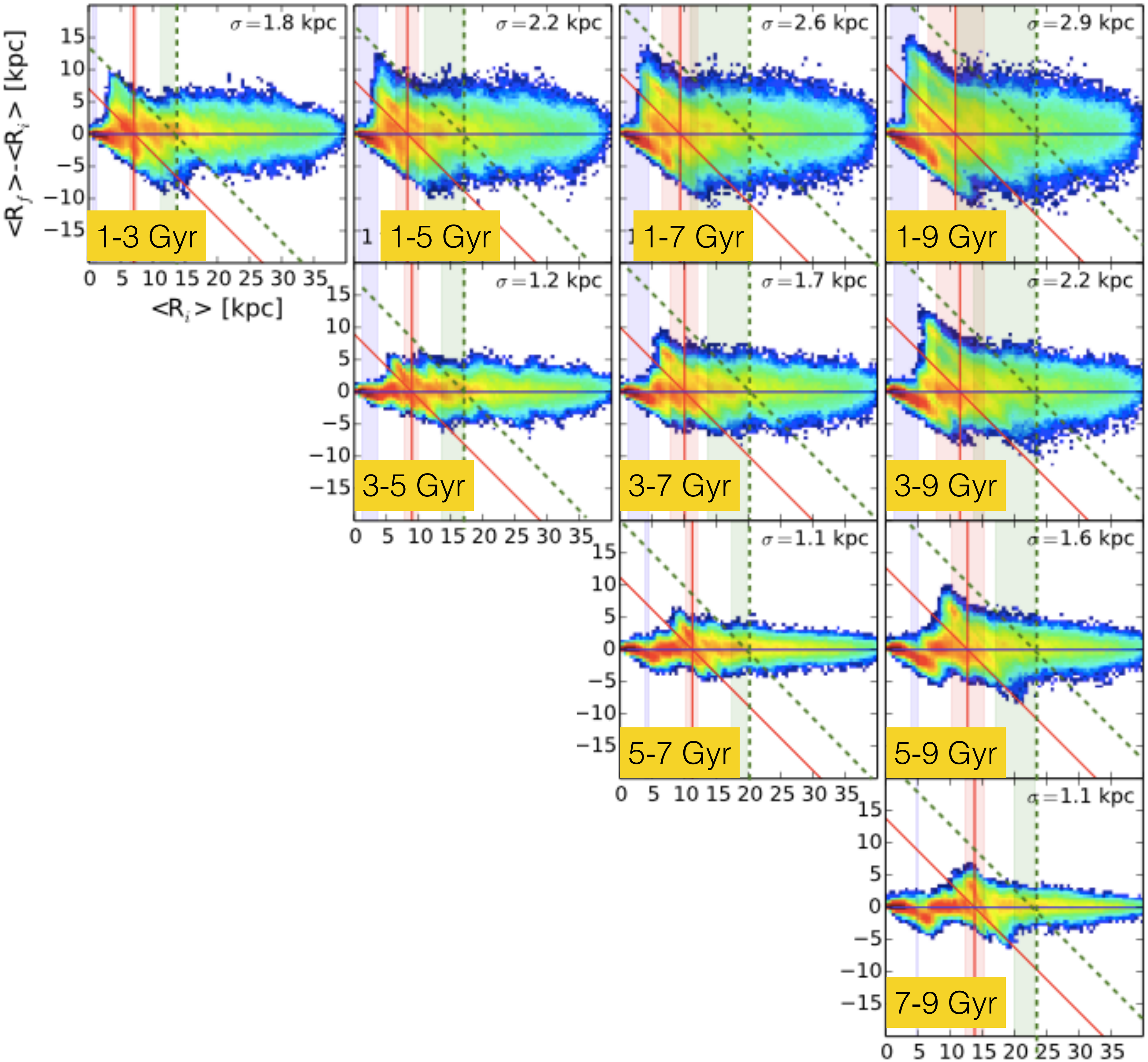
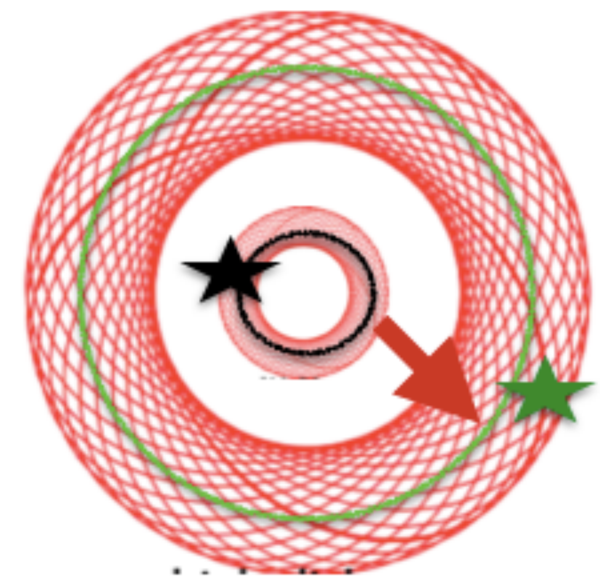


Migrators by churning alone (change of their guiding radii)



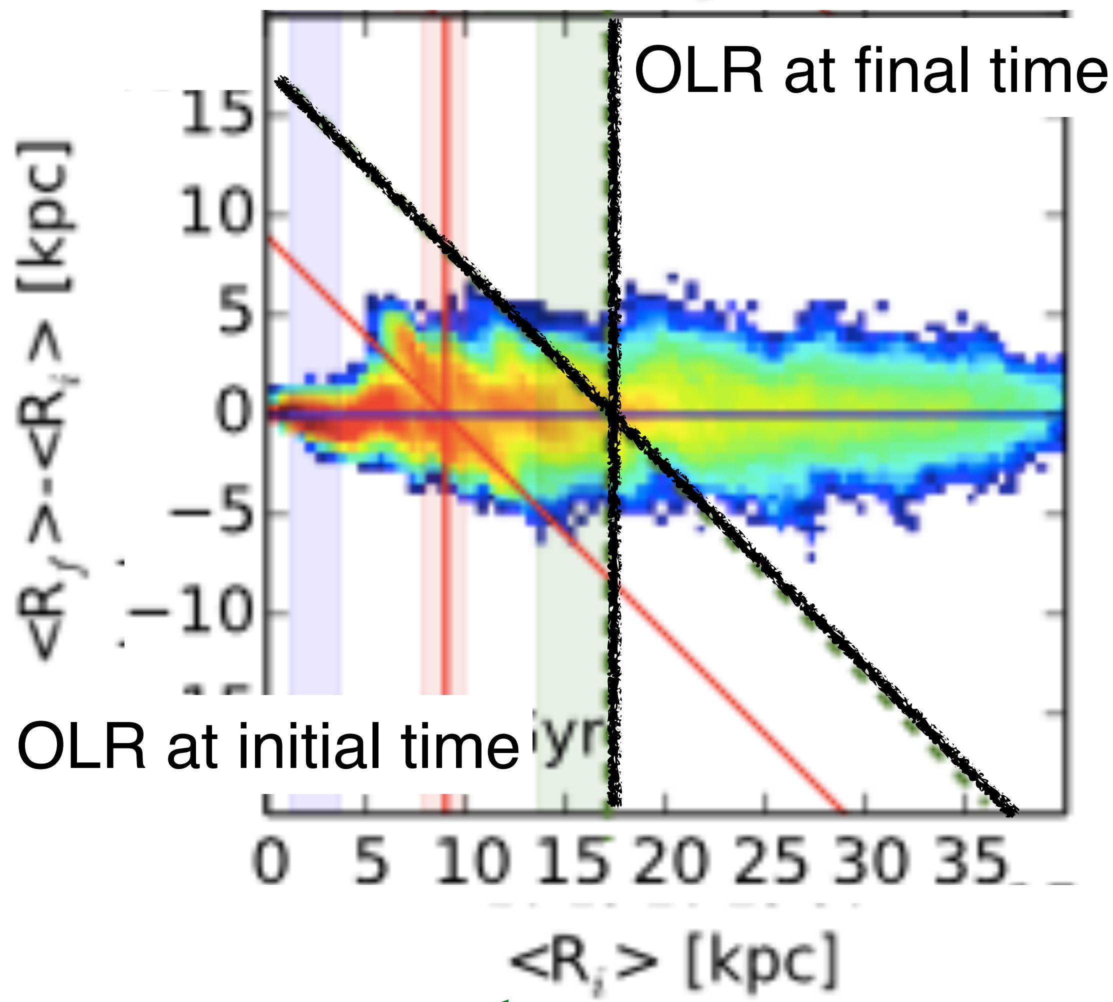
The amplitude of migration decreases significantly once migrators by blurring are removed *on the stars*

Outward migrators which cross the OLR

Stars from the inner disc do not cross the OLR by churning

Stars from the outer disc do not penetrate the OLR

The region spanned by the OLR is a transition region for the disc, the only region where churning between the inner and outer disc is allowed



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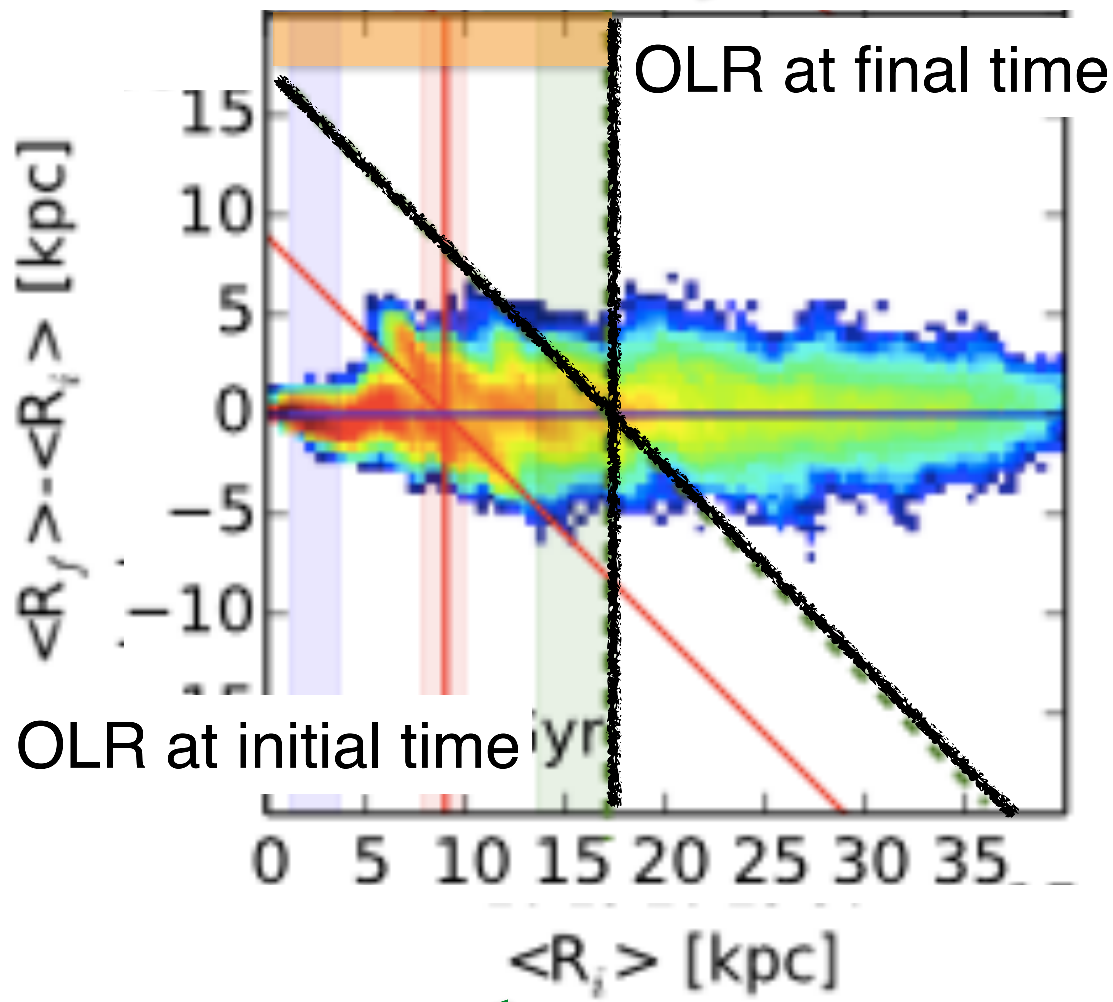

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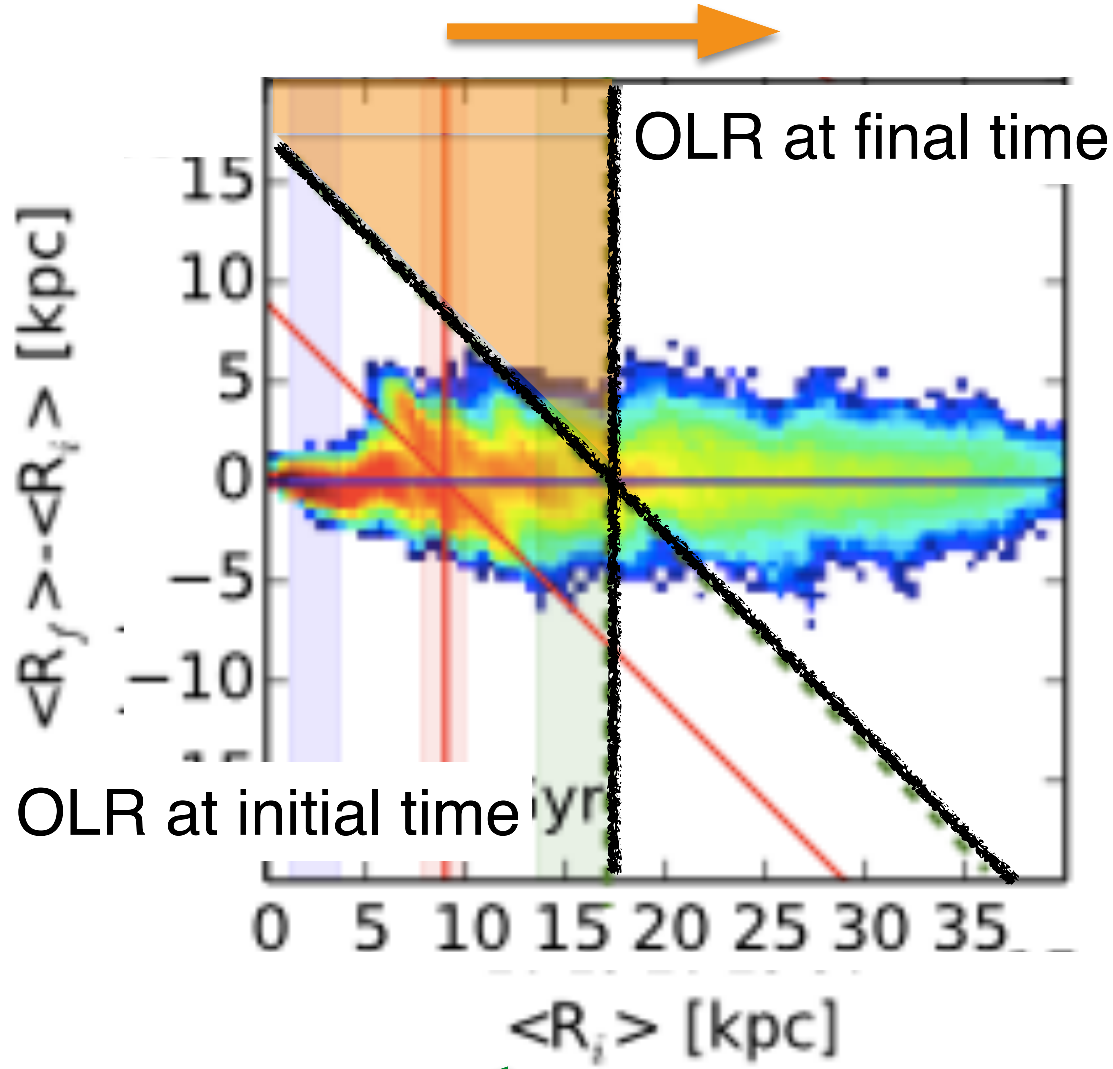

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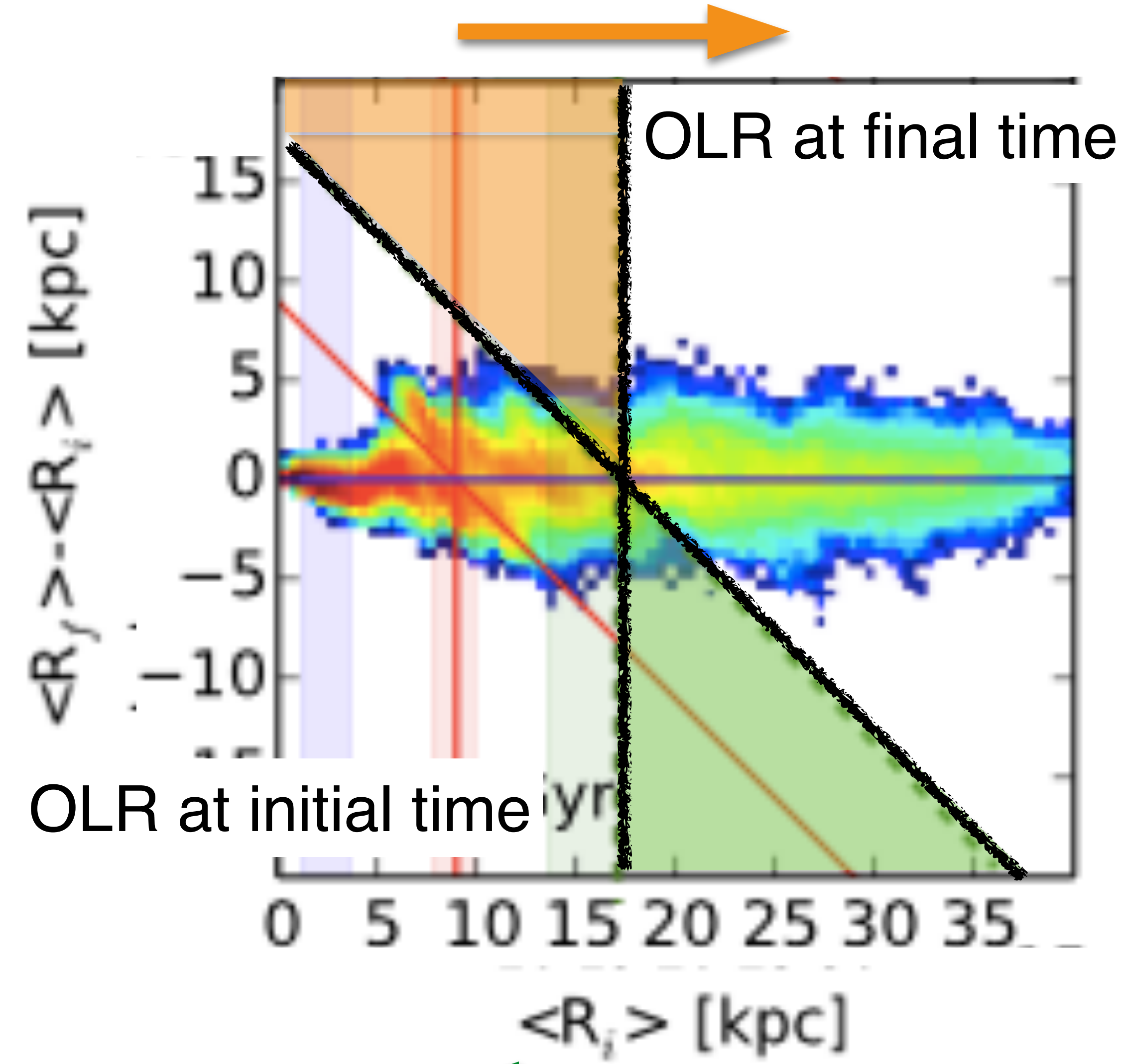

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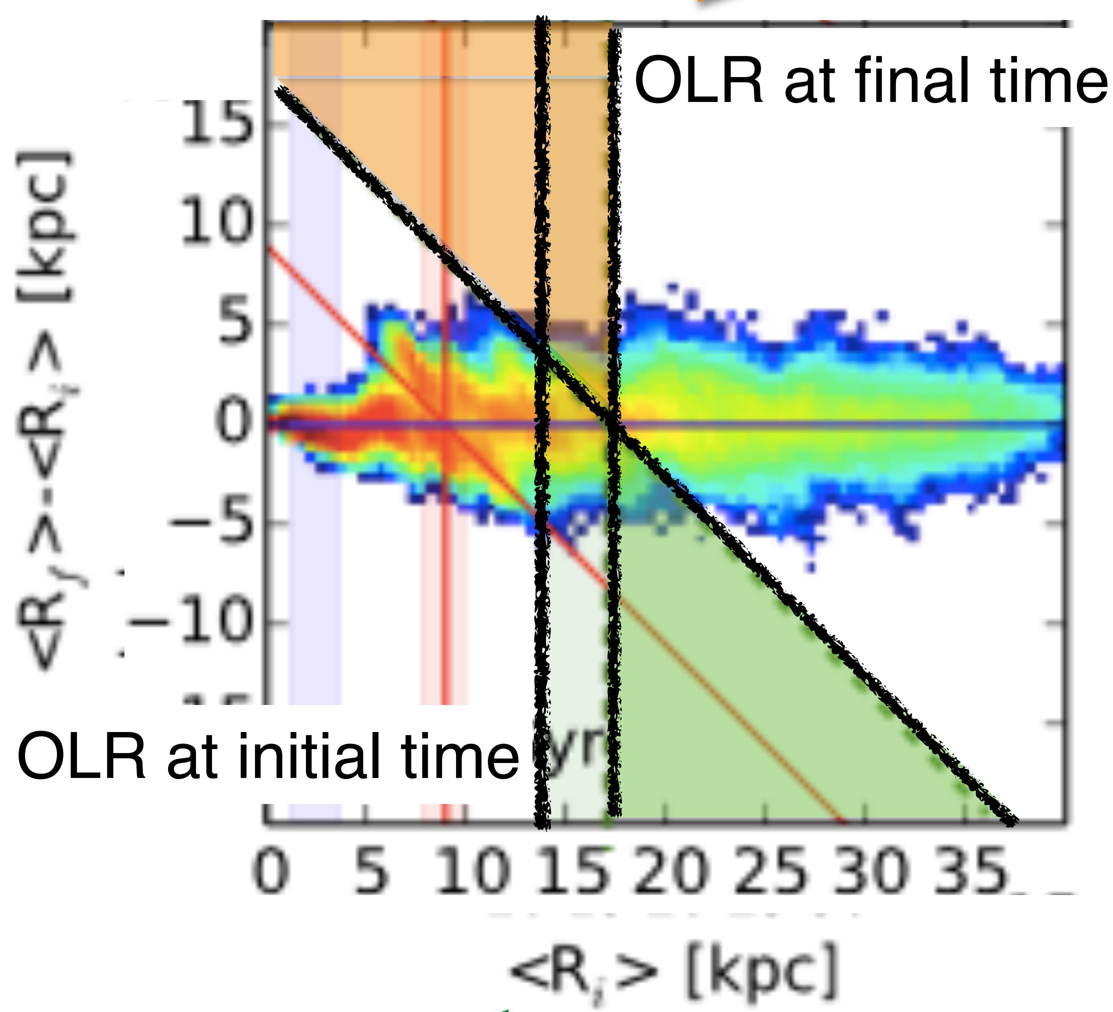

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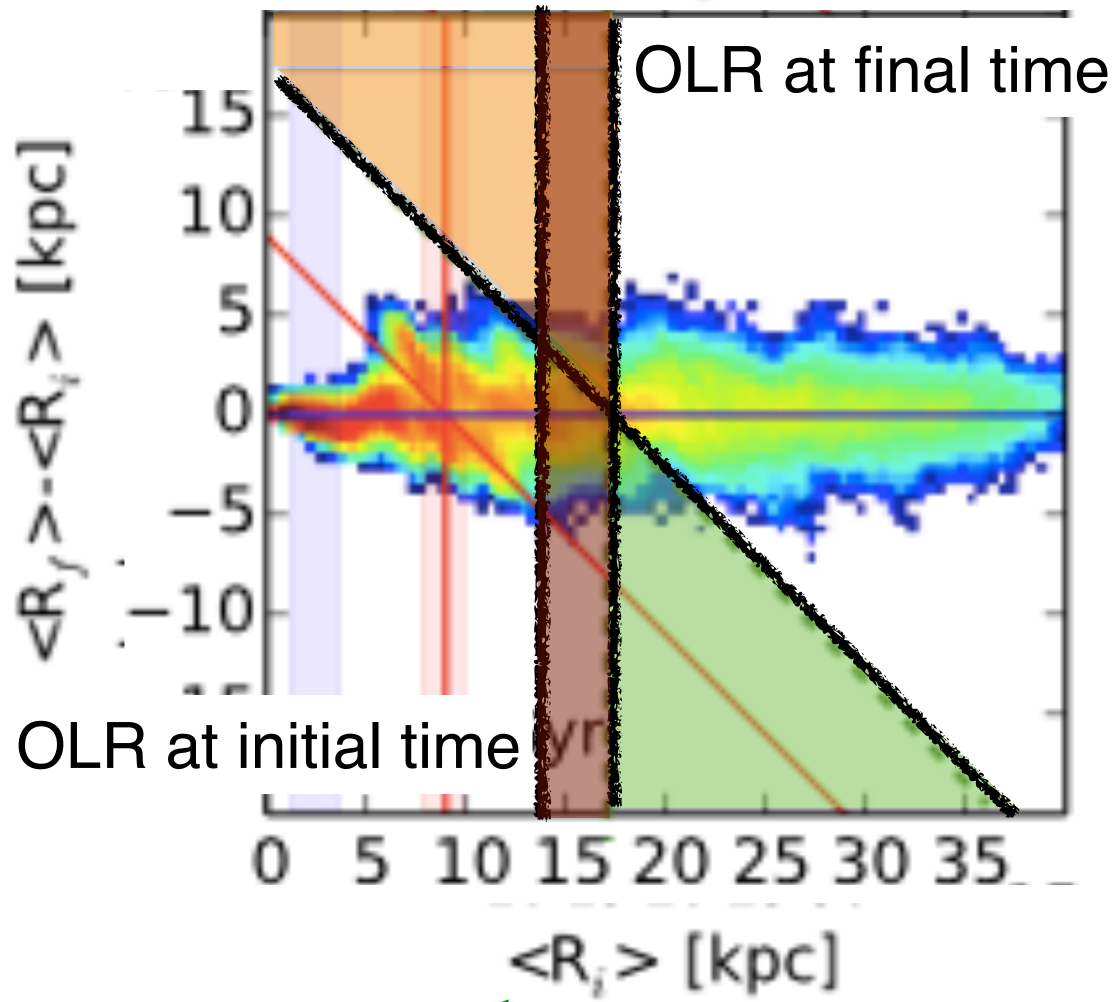

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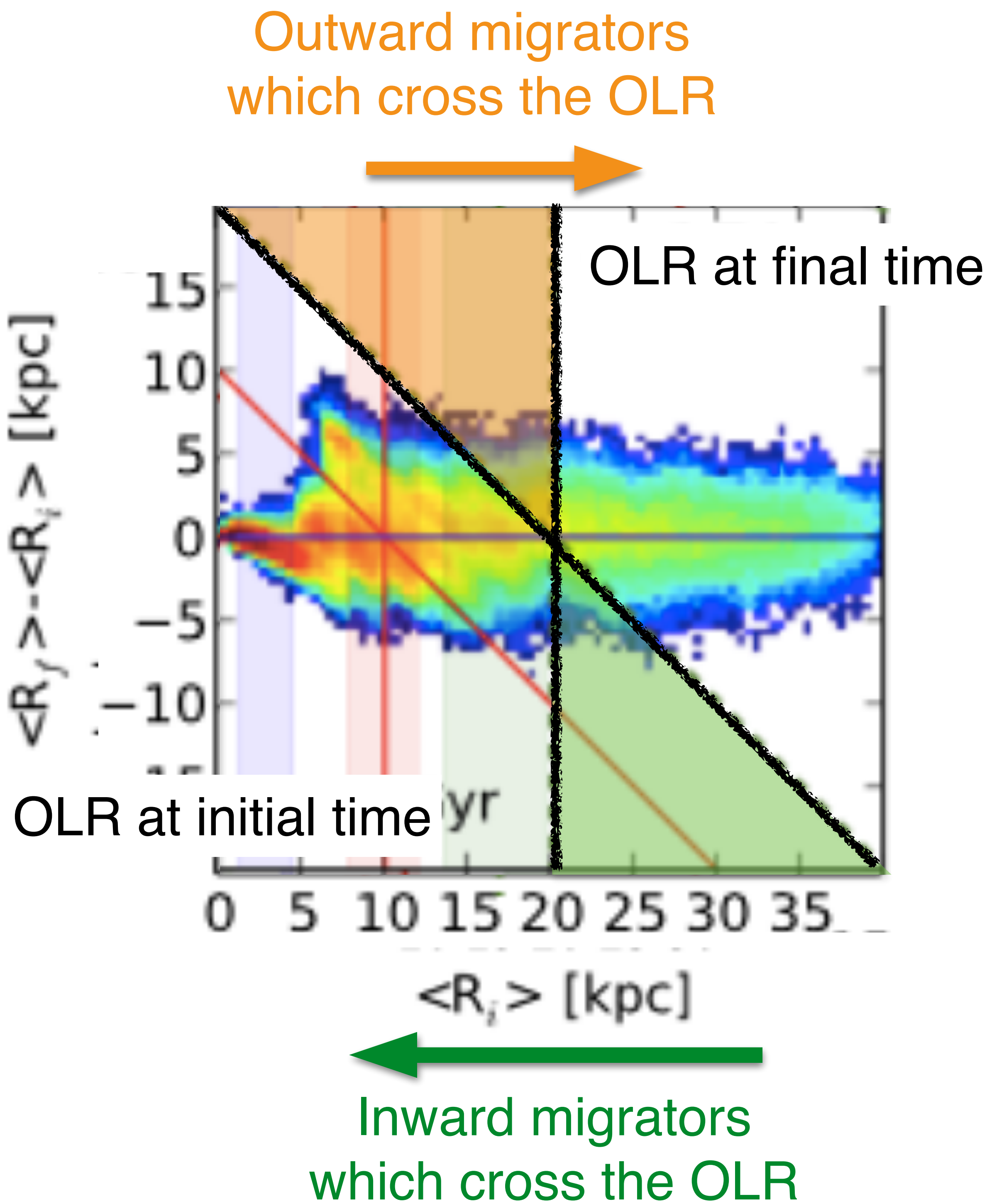

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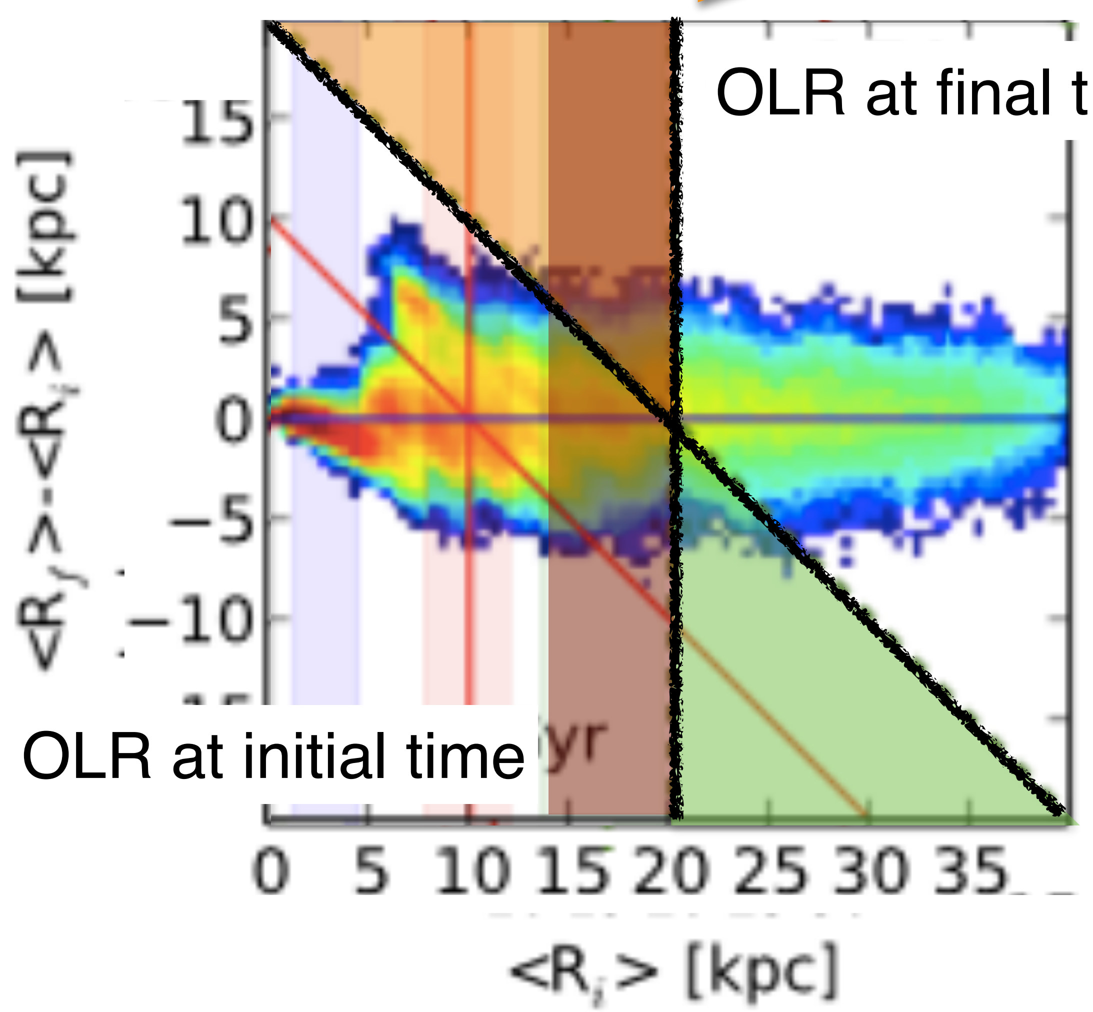

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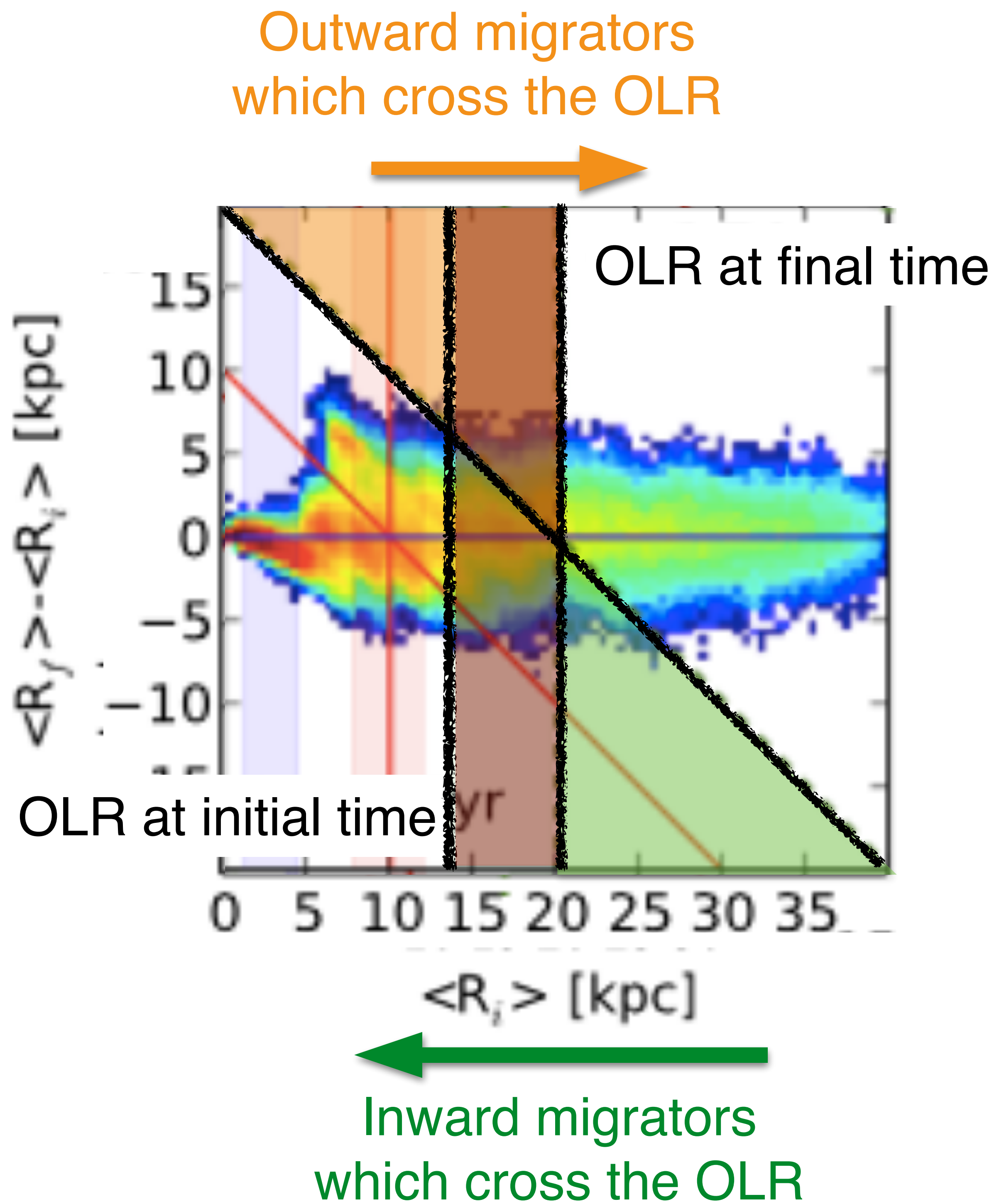

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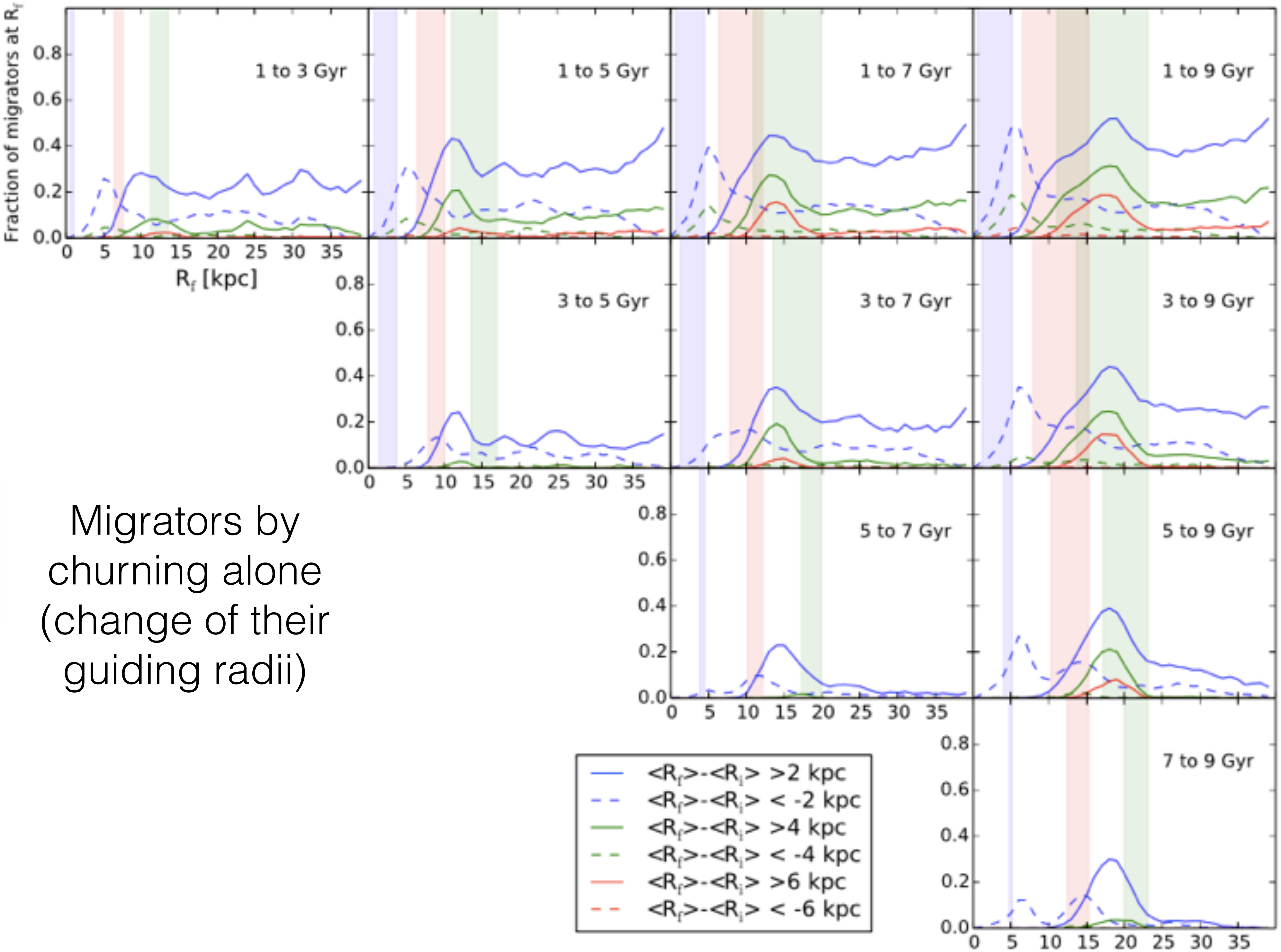

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The maximum contribution of migrators by churning is expected inside the OLR

CONCLUSIONS

The stellar bar defines borders in the disc that structure chemical evolution. In particular, the OLR can be responsible of the chemical discontinuity observed between the inner & the outer Galactic disc (Haywood et al 2013, Nidever et al 2014).

For gas :

1/ Any gas accreted in the Galactic disc after the formation of the bar may have been confined at the OLR without penetrating in the inner disc (Combes 1988, Schwarz 1981). This may determine the discontinuity in the ISM chemistry.

For stars (Hallé et al 2015, arXiv) :

2/ **The OLR acts as a barrier separating the disc in two distinct parts with no exchange of stars by churning**, except in the transition zone delimited by the position of the OLR at the epoch of the formation of the bar, and at the final epoch.

3/ Consequences of these findings for our understanding of the structure of the Milky Way disc: if the Sun is outside the OLR, **we suggest that the solar vicinity may have experienced very limited churning from the inner disc.**