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The Formation of Disk Galaxies Through Galaxy Archaeology

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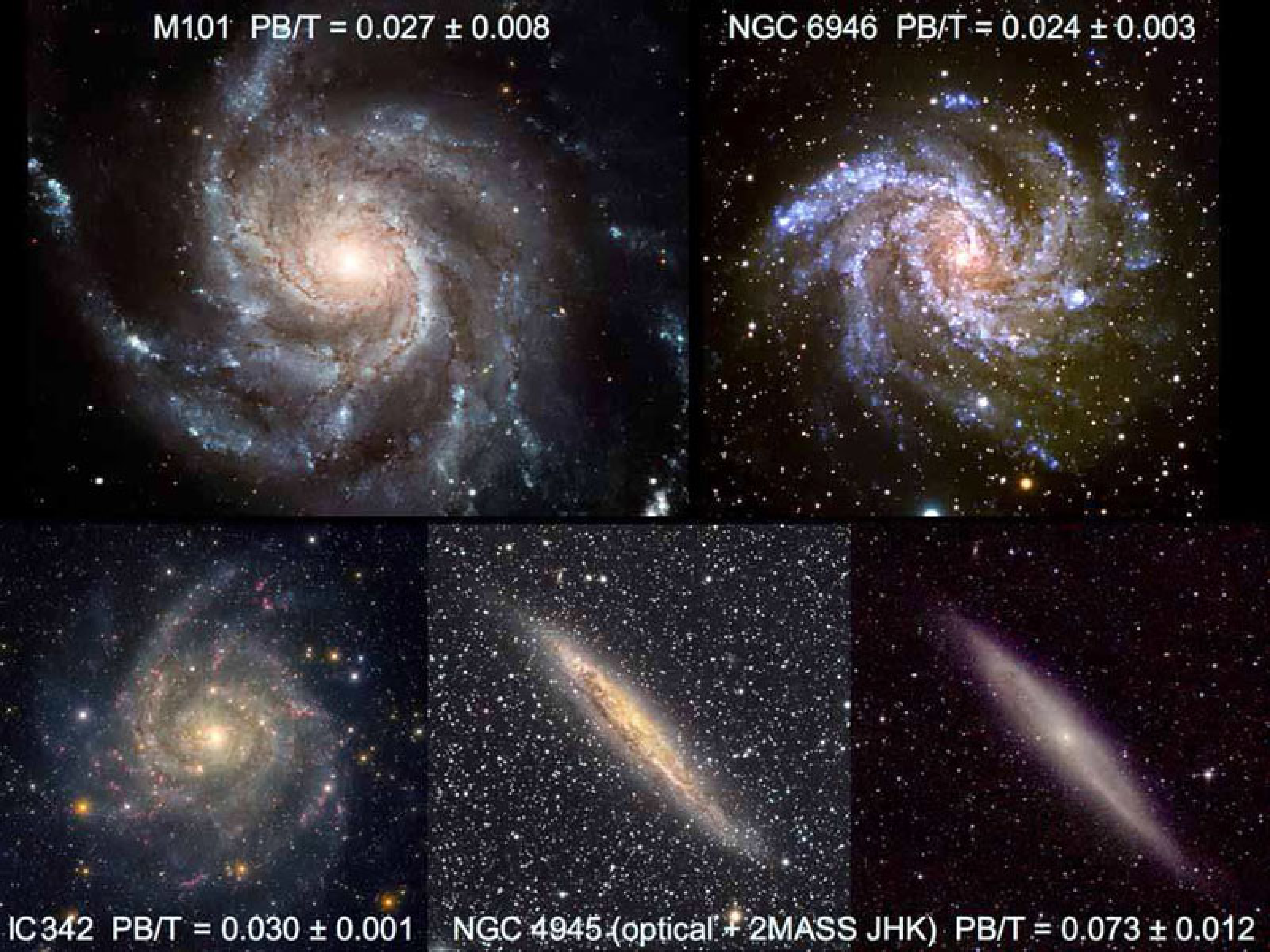
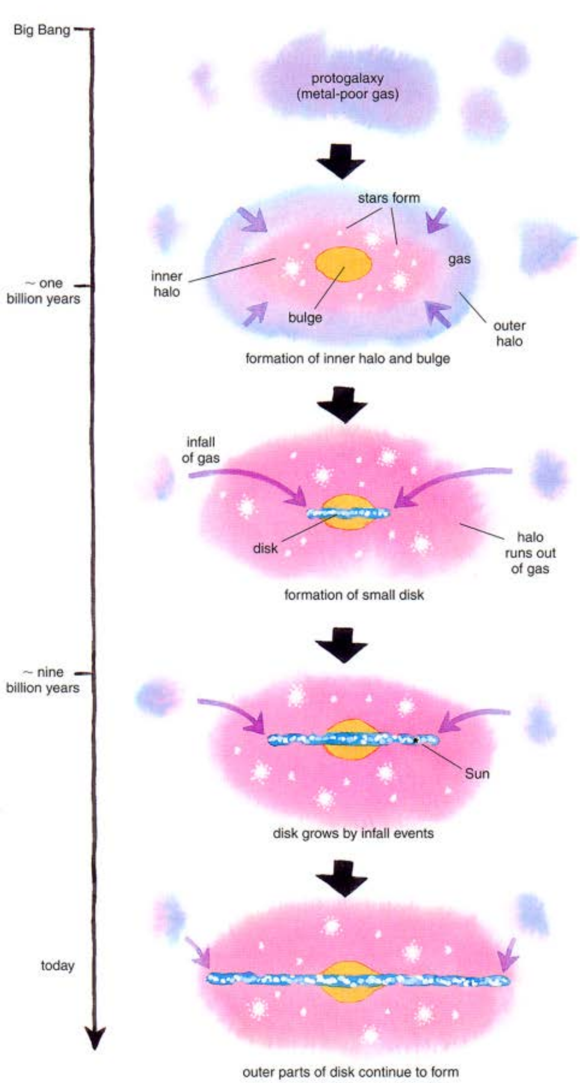

M101 PB/T = 0.027 ± 0.008
NGC 6946 PB/T = 0.024 ± 0.003
IC 342 PB/T = 0.030 ± 0.001
NGC 4945 (optical + 2MASS JHK) PB/T = 0.073 ± 0.012

The two phases fo disk formation

Chiappini (2010)



The two epochs formation

(1) Early "**violent phase**" : stars in the (classical) bulge and halo are formed and maybe also in the thick disk

(2) "**secular**" phase: when the disk growths inside out and become dynamically unstable bars can growth .

- Bars drive gas flows to the center and a (*pseudo)bulge* may form
- Bars can produce redistribution of angular momentum and material in the stellar disks

Outline

- Do the disk form inside-out?
- How important secular processes relative to mergers in producing the observed bulges and pseudobulges?
- How important is the redistribution of material in the disk?
- Evolution of the metallicity gradient as a constrain to the numerical simulations

Archaeology

"The scientific study of past human cultures by analyzing the material remains (sites and artifacts) that people left behind"

Astro-Archaeology

"The scientific study of past galaxies history by analyzing the material remains (old stars)"

Previous works

Most of our knowledge come from resolved stellar populations (MW, M31, M33.. (e.g., Bland-Hawthorn & Freeman 2003; Gogarten et al. 2010; William et al. 2009)

Some other works using colors (de Jong 1996; MacArthur+2004; Muñoz-Mateos + 2007) → highly degenerate

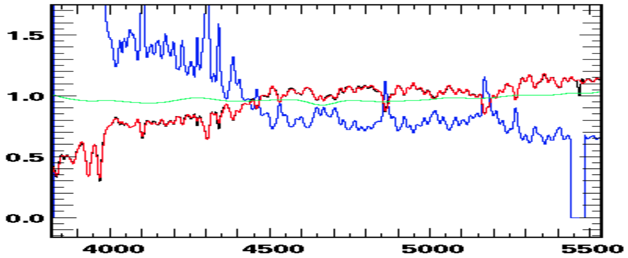
- Very few spectroscopic studies of stellar populations in the disk (long slit –only inner disk -MacArthur et al. 2009, PSB et al. 2011)
- We lack studies relating the stellar properties in the disk region with other properties of the galaxies

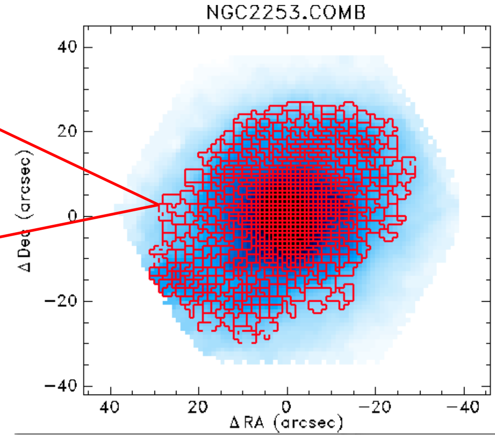
BaLROG (Bars in Low Redshift Optical Galaxies)

TIMER: Time Inference with MUSE in Extragalactic Rings

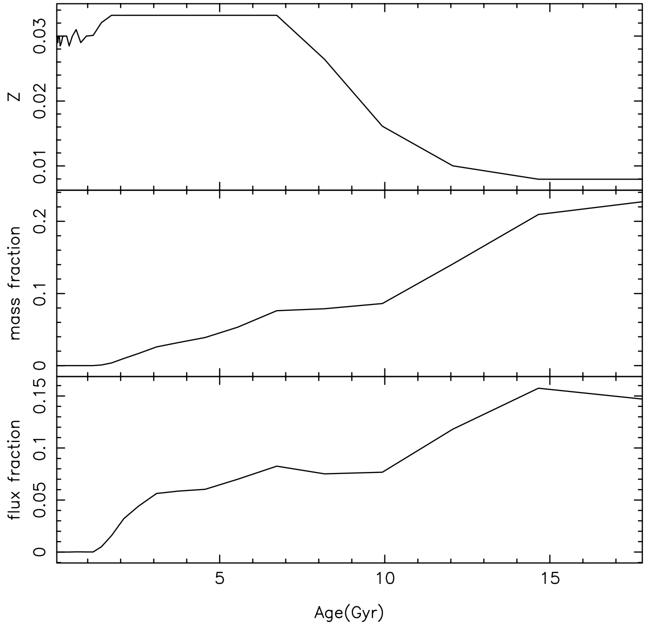
CALIFA: The Calar Alto Legacy Integral Field Area Survey

S/N~40 per Å (@ 5800Å)





Inversion algorithm



Mean values

$$< \log age >_{MW} = \frac{\sum_i mass(i) \log age_i}{\sum_i mass(i)}$$

$$< \log age >_{LW} = \frac{\sum_i flux(i) \log age_i}{\sum_i flux(i)}$$

PSB et al. (2014)

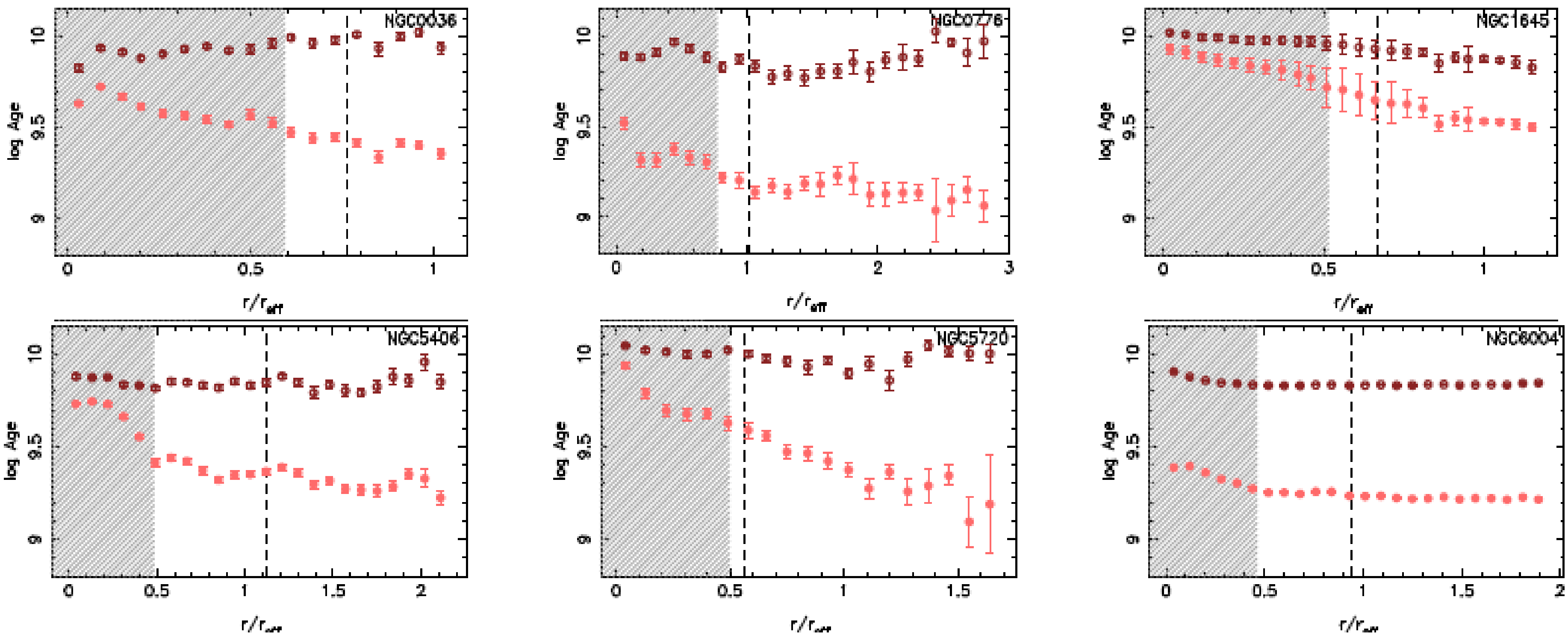
Do the disk form inside-out?

Age gradients

Luminosity weighted values

Mass weighted values

reff = 1.67835rd



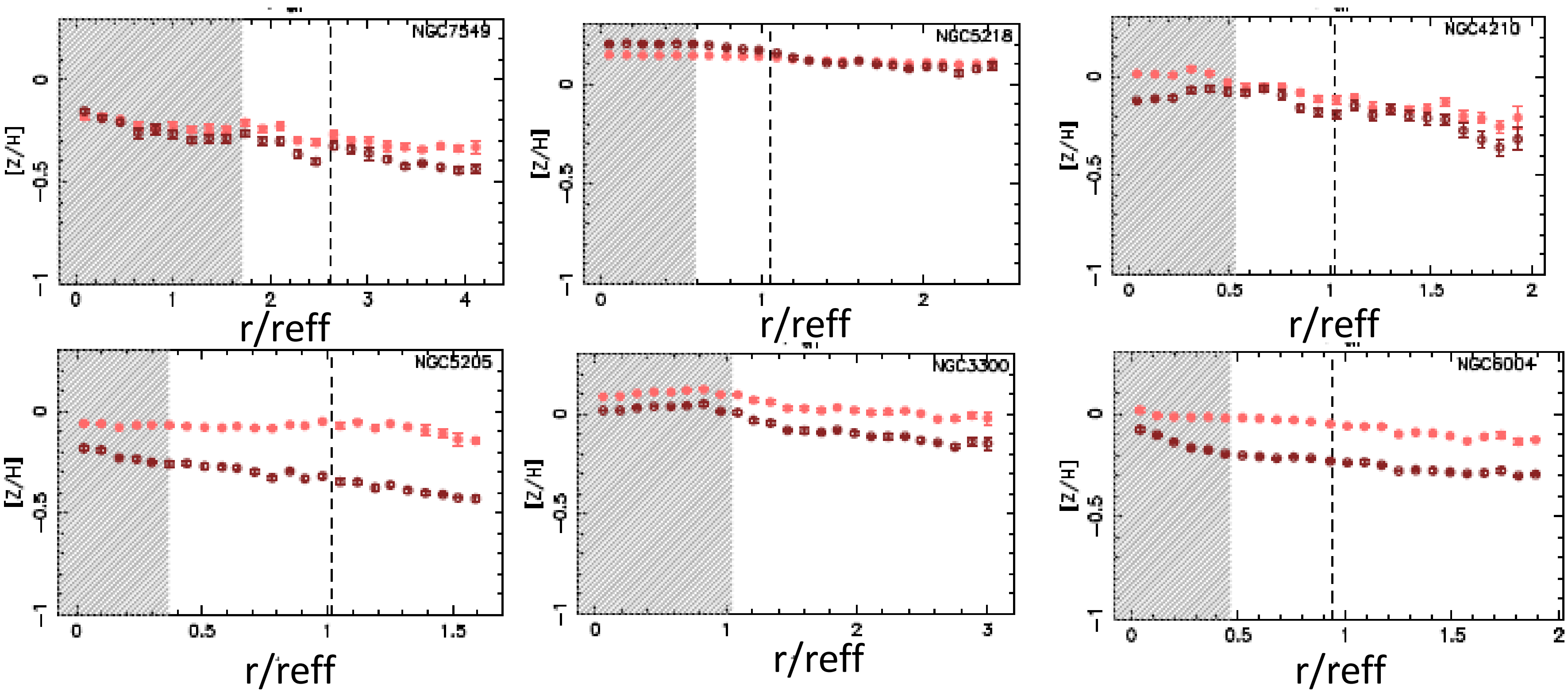
- Results:
- Mass-weighted age gradient reflect **old stellar populations** at all sampled radii
- Lum-weighted age gradient is always negative in the disk region (although very mild)

PSB et al. (2014)

Metallicity gradients

Luminosity weighted values

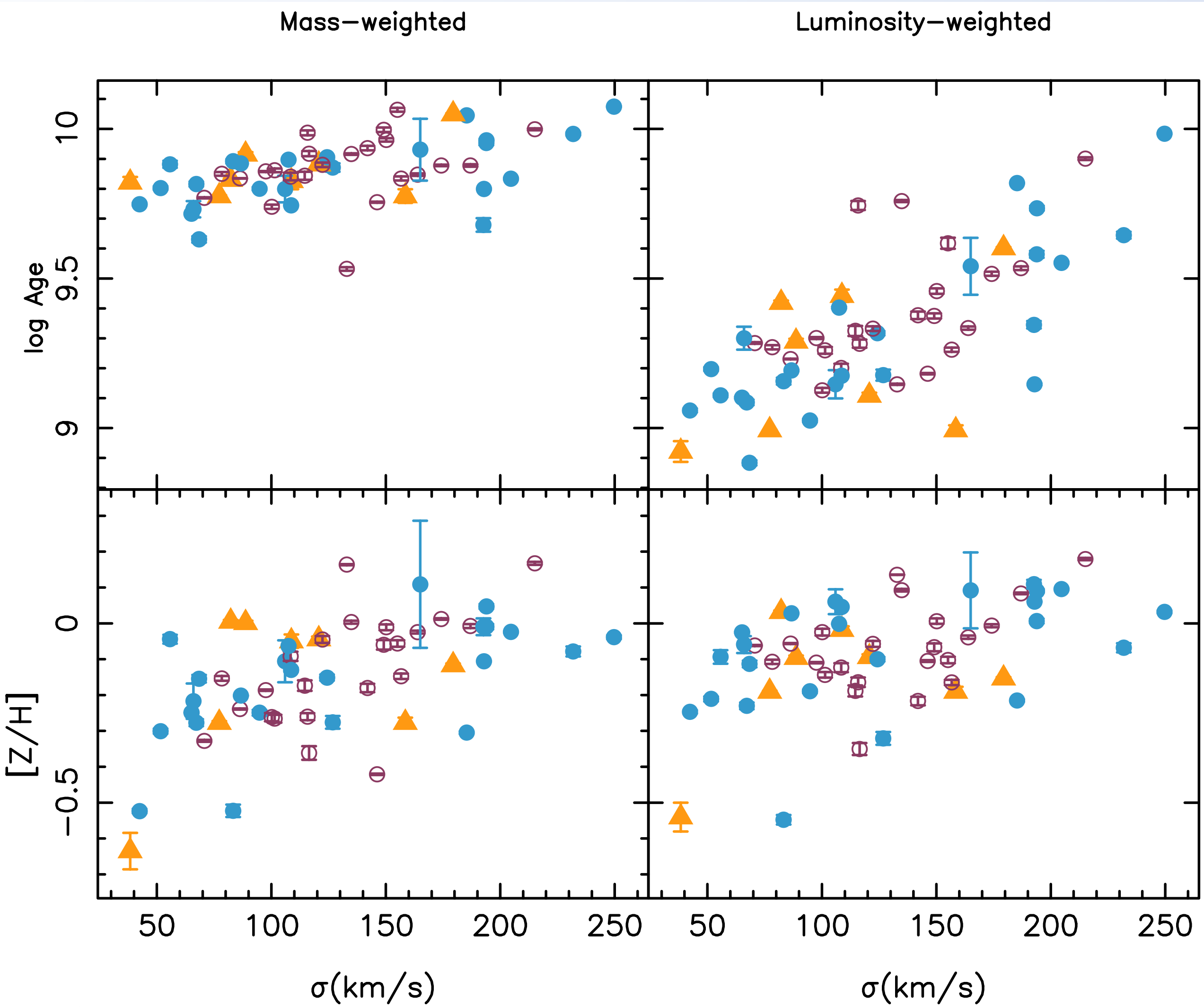
Mass weighted values



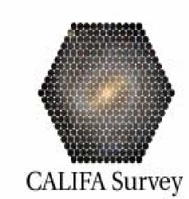
Results:

- •The LW metallicity is always larger than the MW
- •In general, metallicities are very high in the disk region
- •The slopes of the MW and LW metallicities are very similar

Values at 2 scale-length vs central σ



PSB et al. (2014)

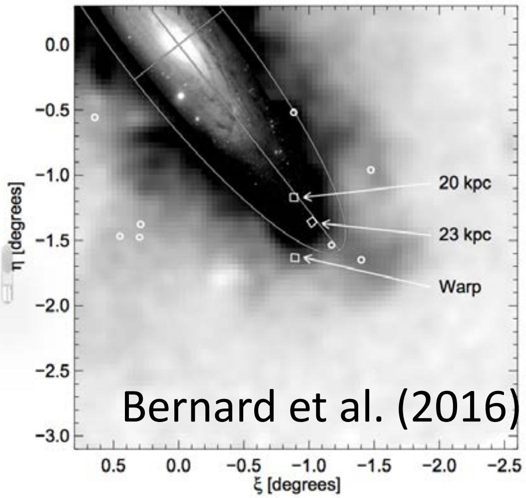


Do the disk form inside-out?

→The flat mass-weighted age gradient and the high metallicity values suggest an early and rapid formation of the disk (similarly to what is seen in resolved stellar population studies (e.g., Gorgarten 2010; William et al. 2009, Bernard et al. 2016).

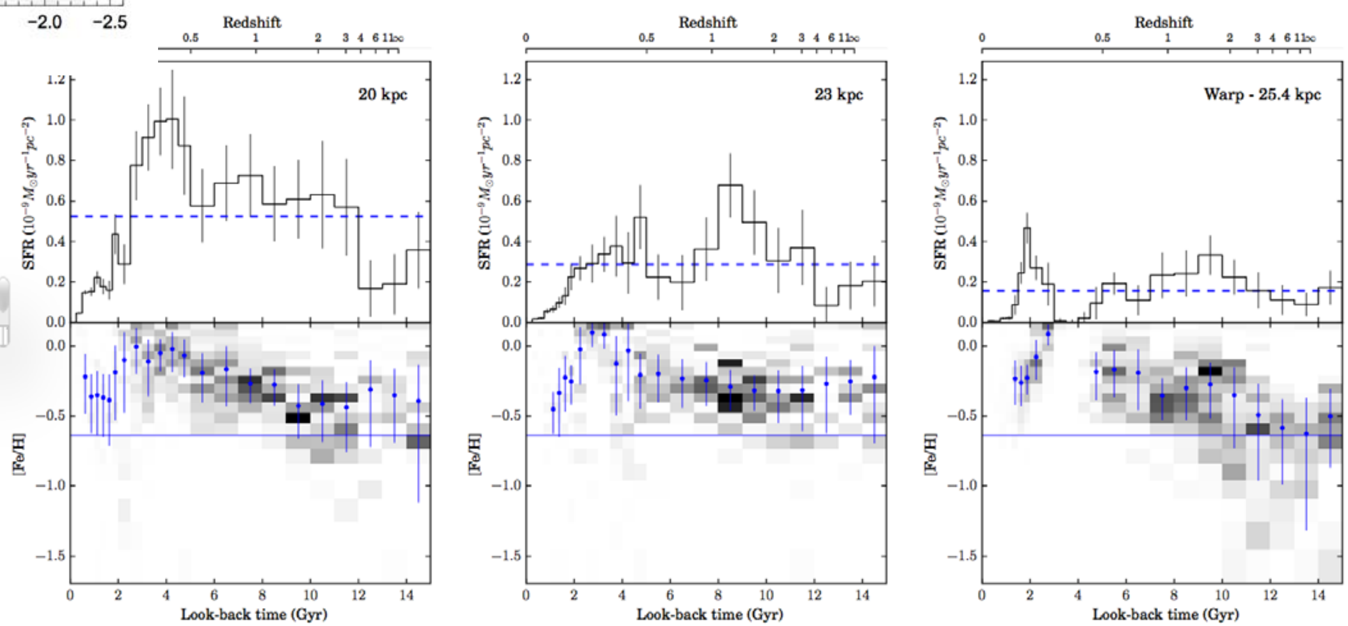
→The comparison of the luminosity- and mass-weighted age gradients suggest that disks 'quench' inside-out, but that disks were already extended at high redshift.

SFH in the external parts of M31



Bernard et al. (2016)

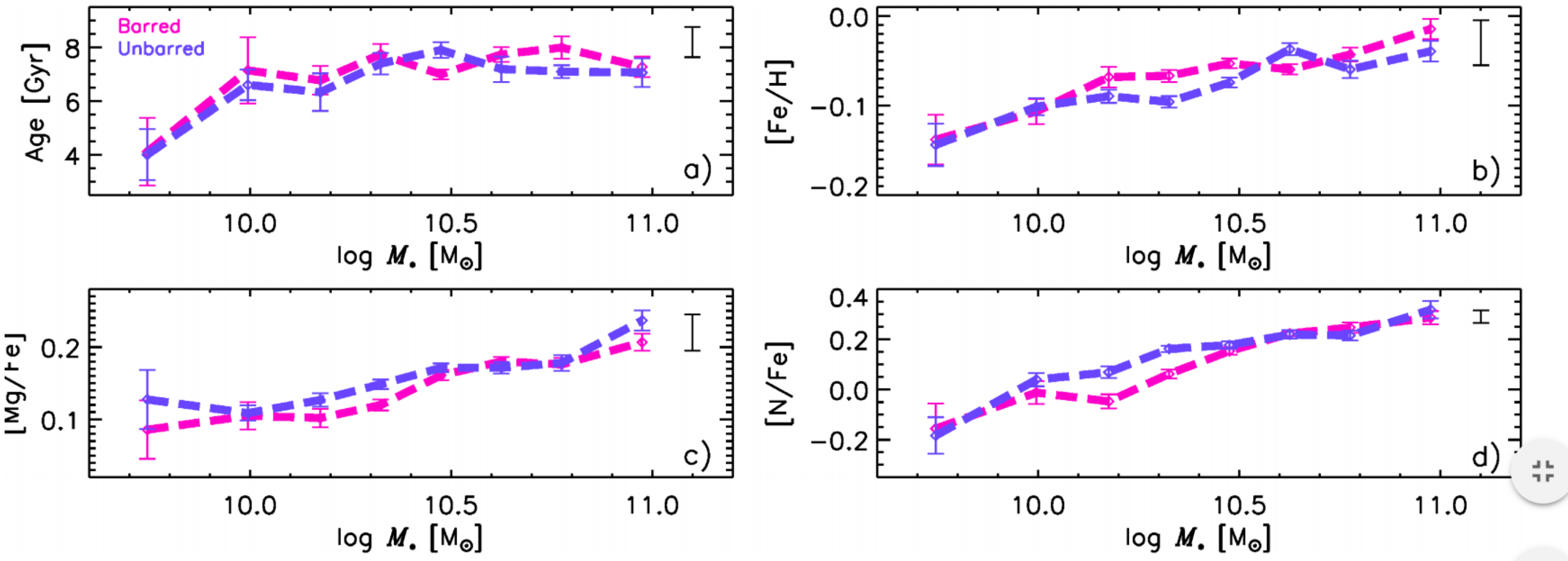
M31 was already a large disc at z> 2



The median stellar ages in the three fields is > 7.5 Gyr

How important secular processes relative to mergers in producing the observed bulges and pseudobulges?

How important are bars in creating pseudobulges?



Cheung et al. (2015)
(see also Cacho et al. 2014)

Bas do not seem to influence the stellar population in the galaxy bulges

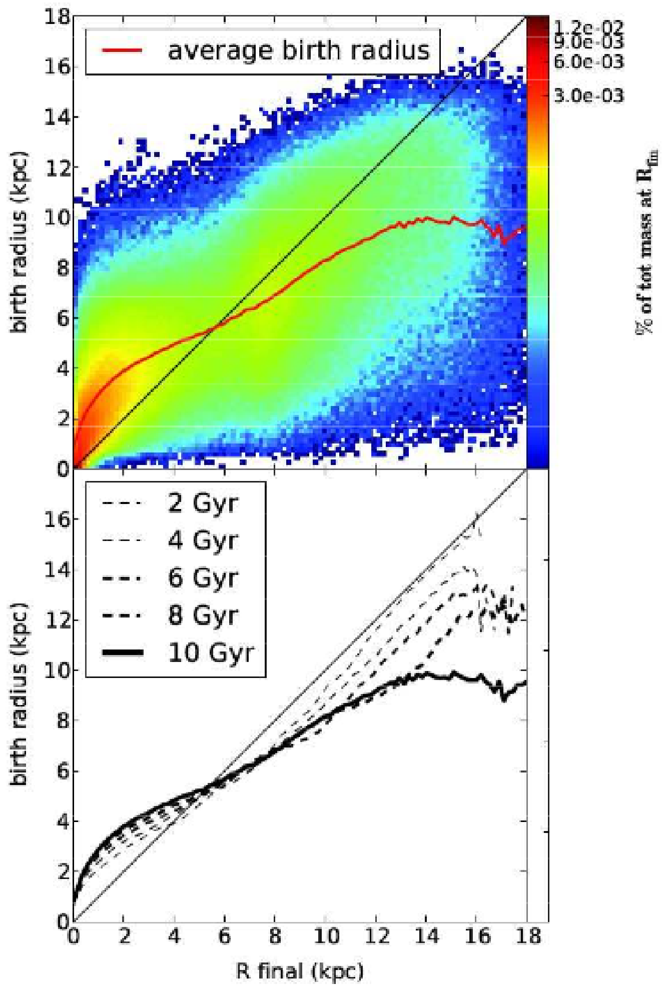
How important secular processes relative to mergers in producing the observed bulges and pseudobulges?

Bars do not seem to influence the stellar population in the galaxy bulges

How important is the redistribution of material by bars?

Radial redistribution of stars due to bars

Kubryk et al. (2013)



•In numerical simulations, stars do not remain where they were born (e.g., Sellwood & Binney 2002; Roskar et al. 2008; PSB et al. 2009)

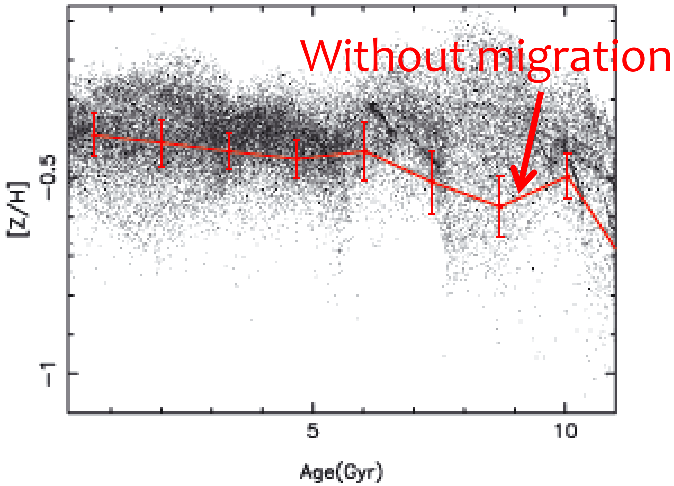
See Friedli et al. (1998), Minchev & Famey (2010), Minchev et al. (2011, 2012); Shevchenko et al. (2011), Brunetti et al. 2011, Grand et al. (2012)

Importance of studying radial migration

→ Ongoing and upcoming surveys (SEGUE, RAVE, HERMES, APOGEE, 4MOST) designed to study the structure of the MW structure require the understanding of the dynamical processes affecting the stellar distribution

Flatten the age-metallicity relation and increase the scatter

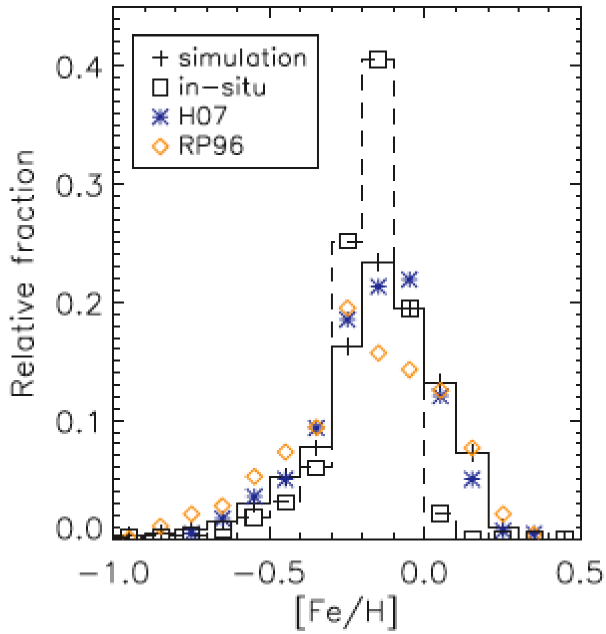
PSB et al. 2009



Flattening of the AMR

Widen the metallicity distribution funcion

Roškar et al. 2008b

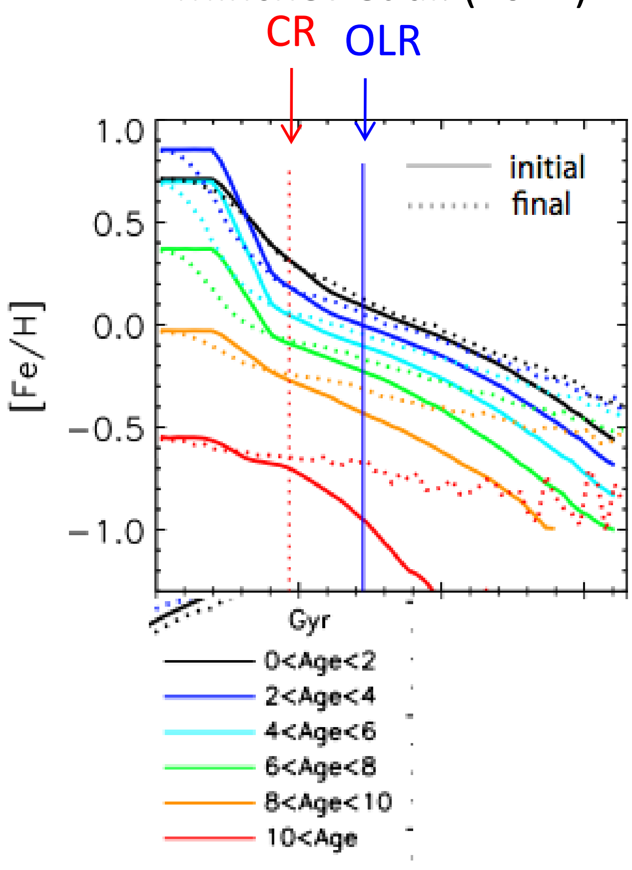


Widening of the MDF

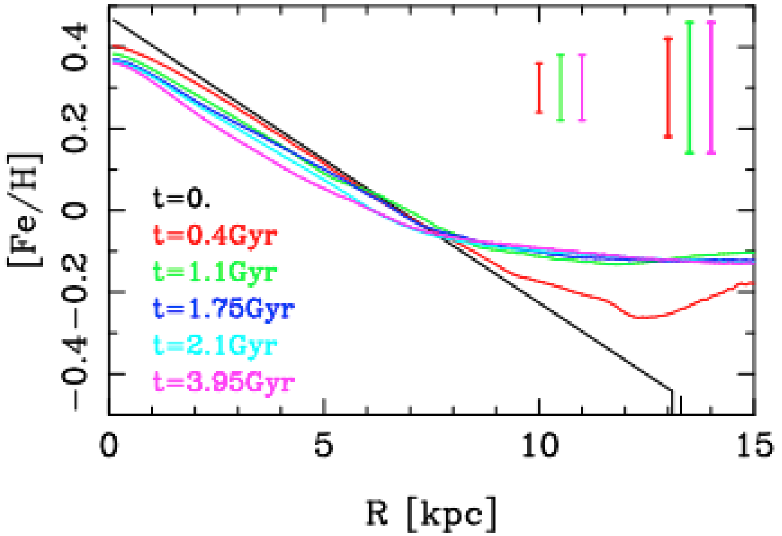
Metallacity gradient flattening due to bars

Numerical simulations predict a flattening in the stellar metallicity gradient of more than 50% in 4 Gyr

Minchev et al. (2012)



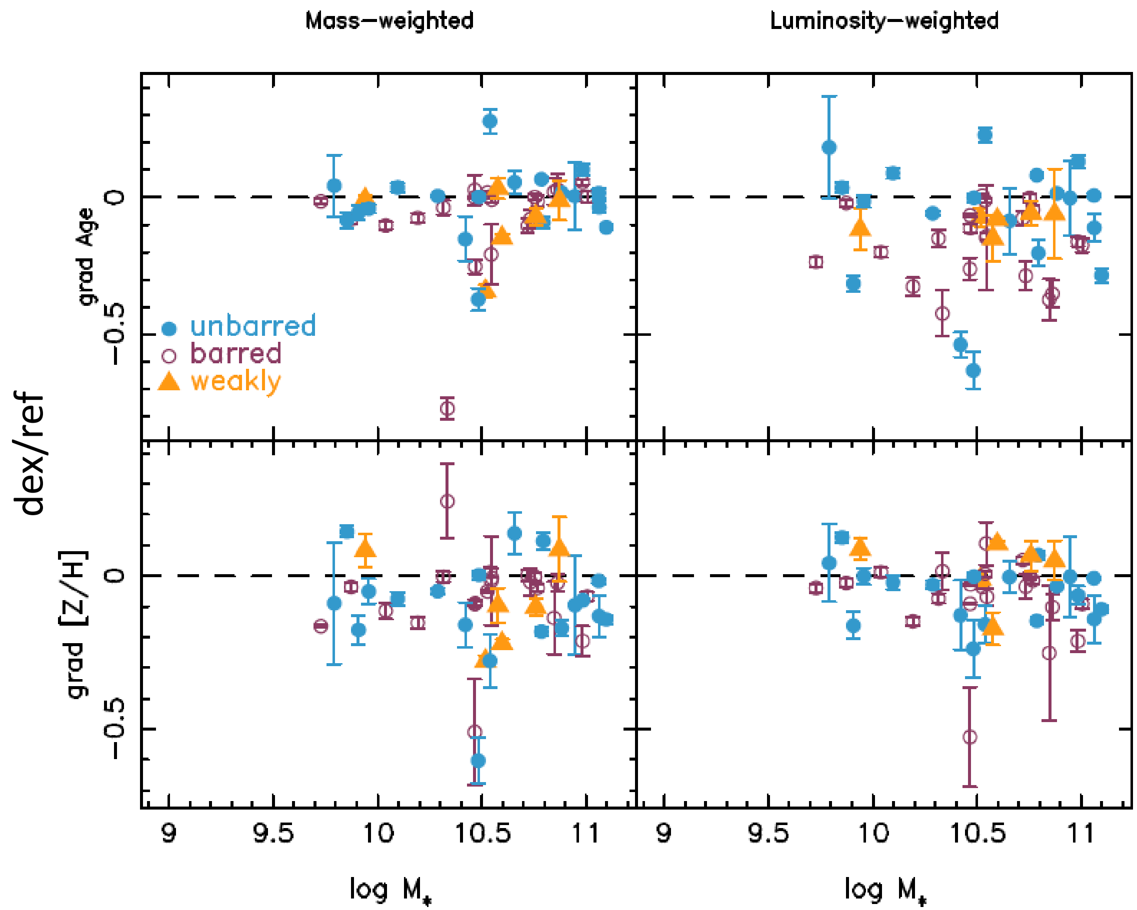
Di Matteo et al. (2013)



(see also Friedli 1998; Minchev & Famaey 2010; Brunetti et al. 2011; Minchev , Chiappini & Martig 2012)

Differences in the metallicity gradient between barred and unbarred galaxies

CALIFA Survey

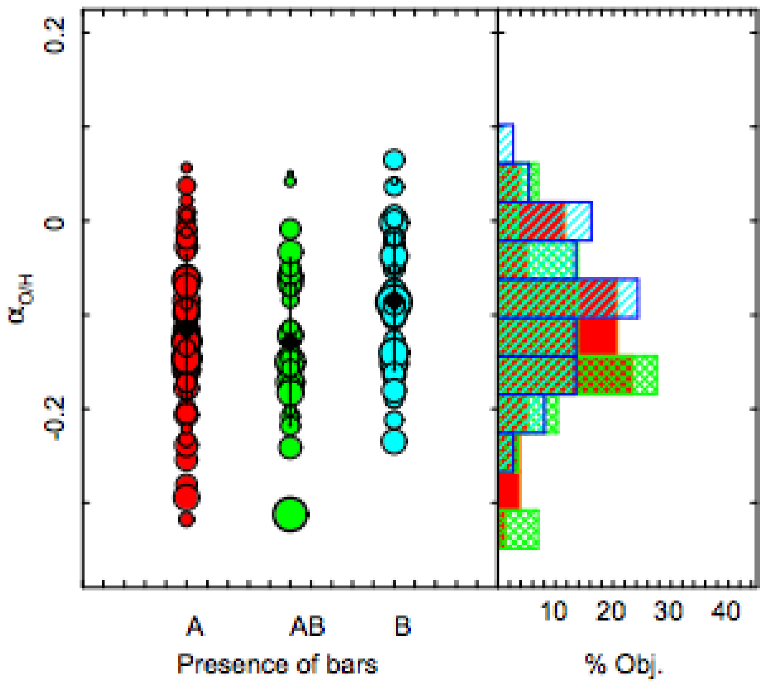


- We do not find any relation between the stellar population gradients and the mass
- We do not find any difference between the gradient of barred and unbarred galaxies

PSB et al. (2014)

Gas Phase metallicity gradient as a function of bar presence

We do not find, also, differences in the gas-phase metallicity gradient of barred and unbarred galaxies



Sánchez et al. (2014)

See also Kaplan et al. 2016

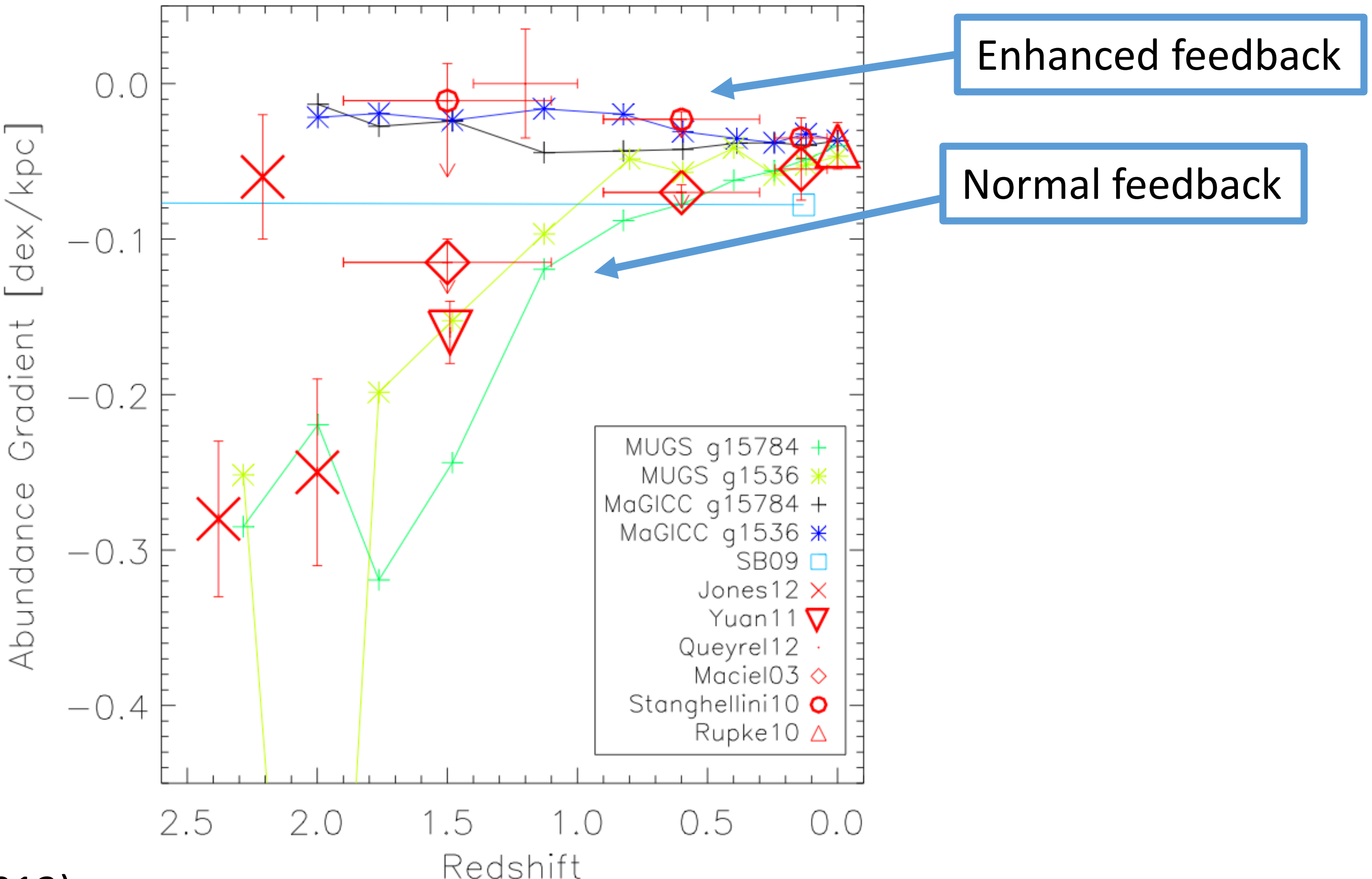
Previous works claim that a different exists:
Vila Costas & Edmunds (1992)
Zaritsky et al. (1994)
Martin & Roy(1994)

How important is the redistribution of material in the disk?

Radial mixing *by bars* does not seem to be as efficient as predicted in simulations

An alternative, is that bars do produce significant radial mixing but this has not have an effect on the gradients (e.g., if the gradients were very flat in the past).

Evolution of the metallicity gradients



Gibson et al. (2013)

Evolution of the metallicity gradient (Observations)

(1) Metallicity gradient using tracers of different ages (OB stars, PN, RGB stars, clusters)
- *Difficult to age date populations older than ~2 Gyr.*

→ Possible flattening with time (e.g., Maciel et al. 2003)
→ Steepening with time (e.g., Sanghellini et al. 2010)

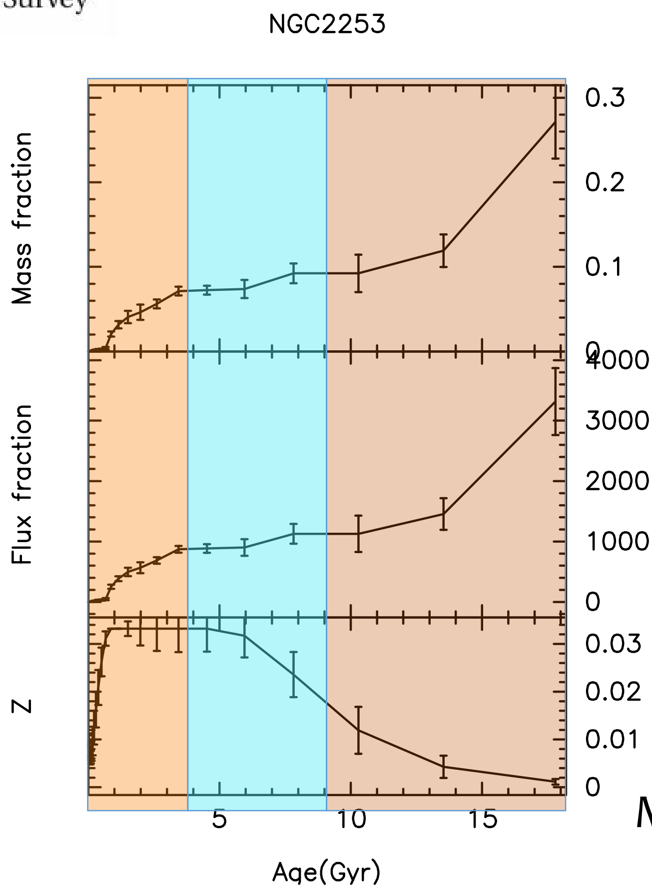
(2) Measuring gradients at different redshifts
- *Difficult due to resolution related problems*

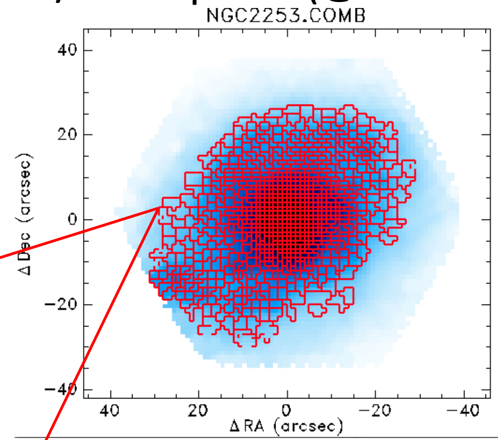
→ Very steep metallicity gradients at high redshift (Yuan et al. 2011; Jones et al. 2012)
→ Mild or even positive metallicity gradients (Cresci et al. 2010; Queyrel et al. 2012)
→ A variety although mostly flat (Leethochawalit et al. 2015)

(3) Astroarchaeology (Tracing the metallicity gradient of stars at different ages)

CALIFA Survey

S/N~40 per Å (@ 5800Å)



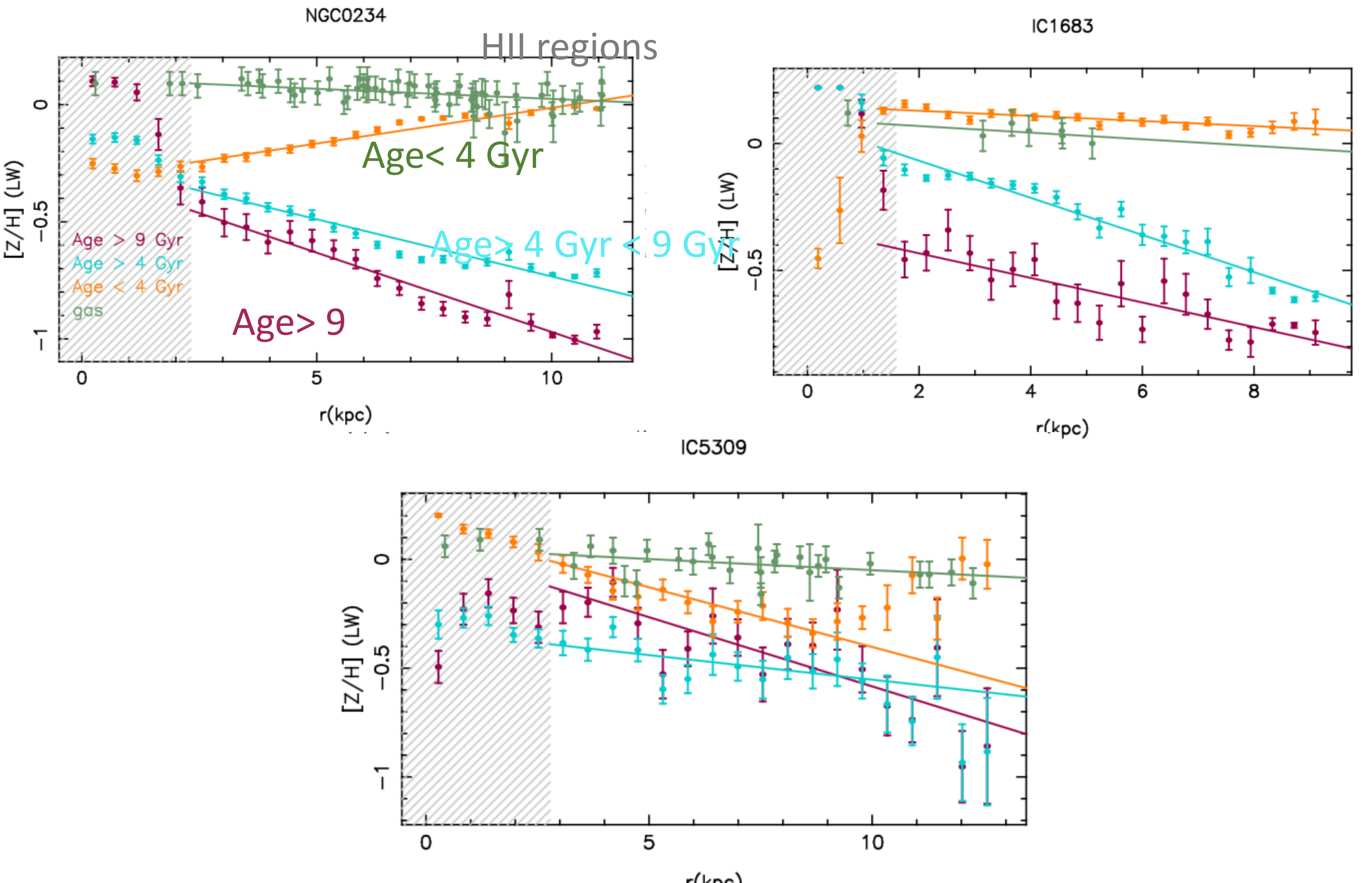


Mean values

$$< [Z/H] >_{LW} = \frac{\sum_I flux(i) \times [Z/H]_i}{\sum_i flux(i)}$$

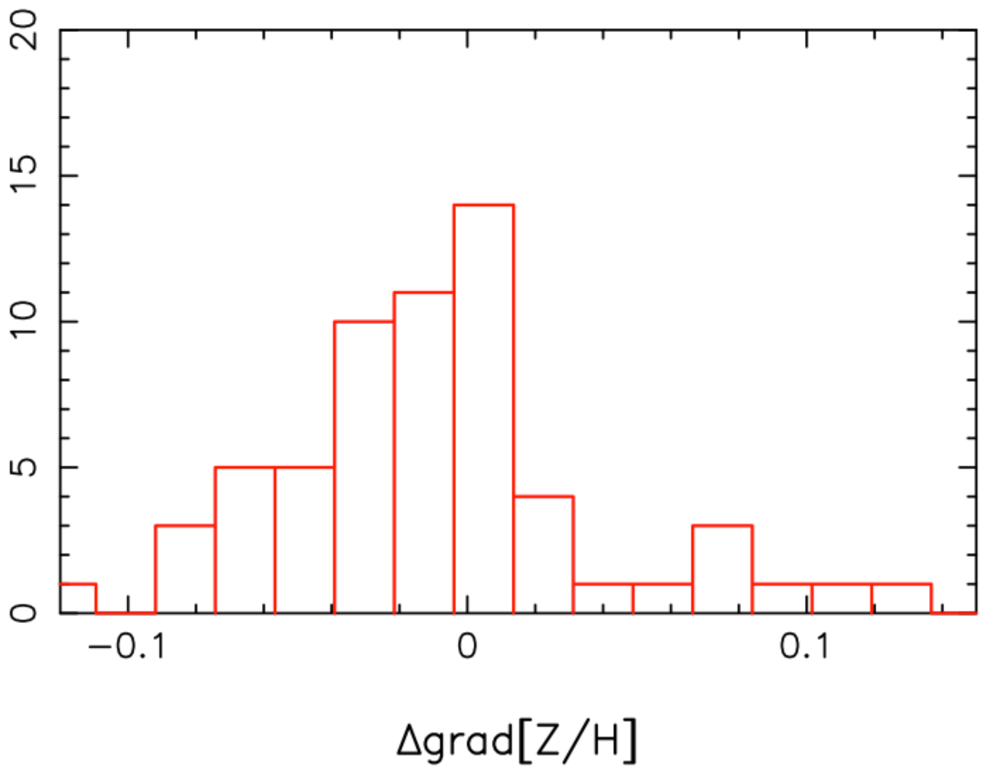
PSB et al. (2014)

Metallicity gradients for populations with different ages

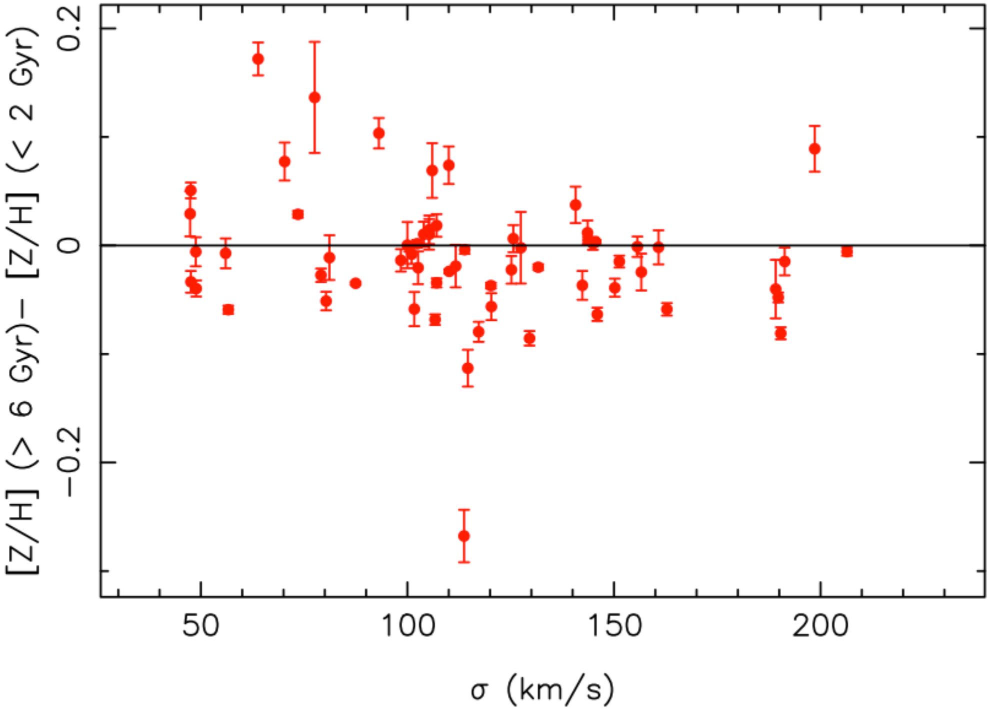


Comparison of young and old stellar metallicity gradients

grad[Z/H] (old) – grad[Z/H] (young)

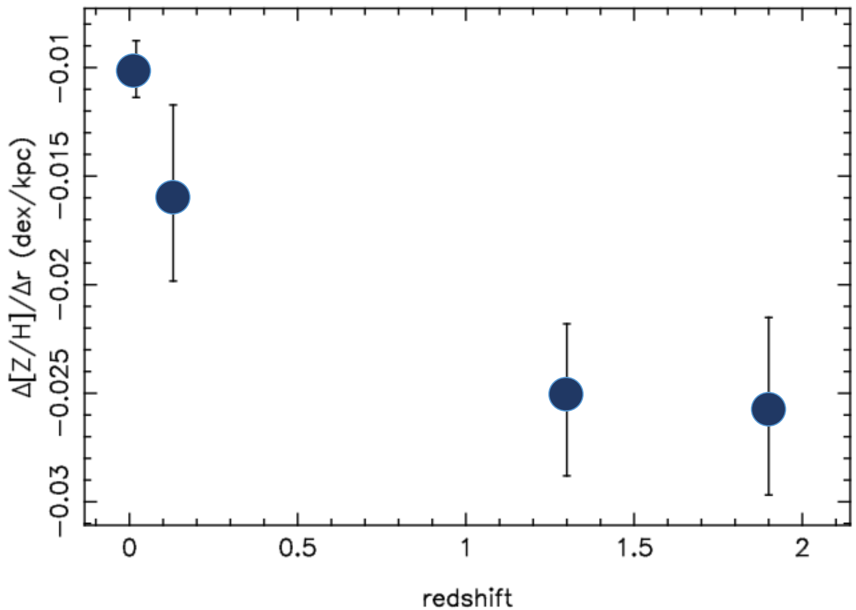


Differences in the metallicity gradients for different stellar populations

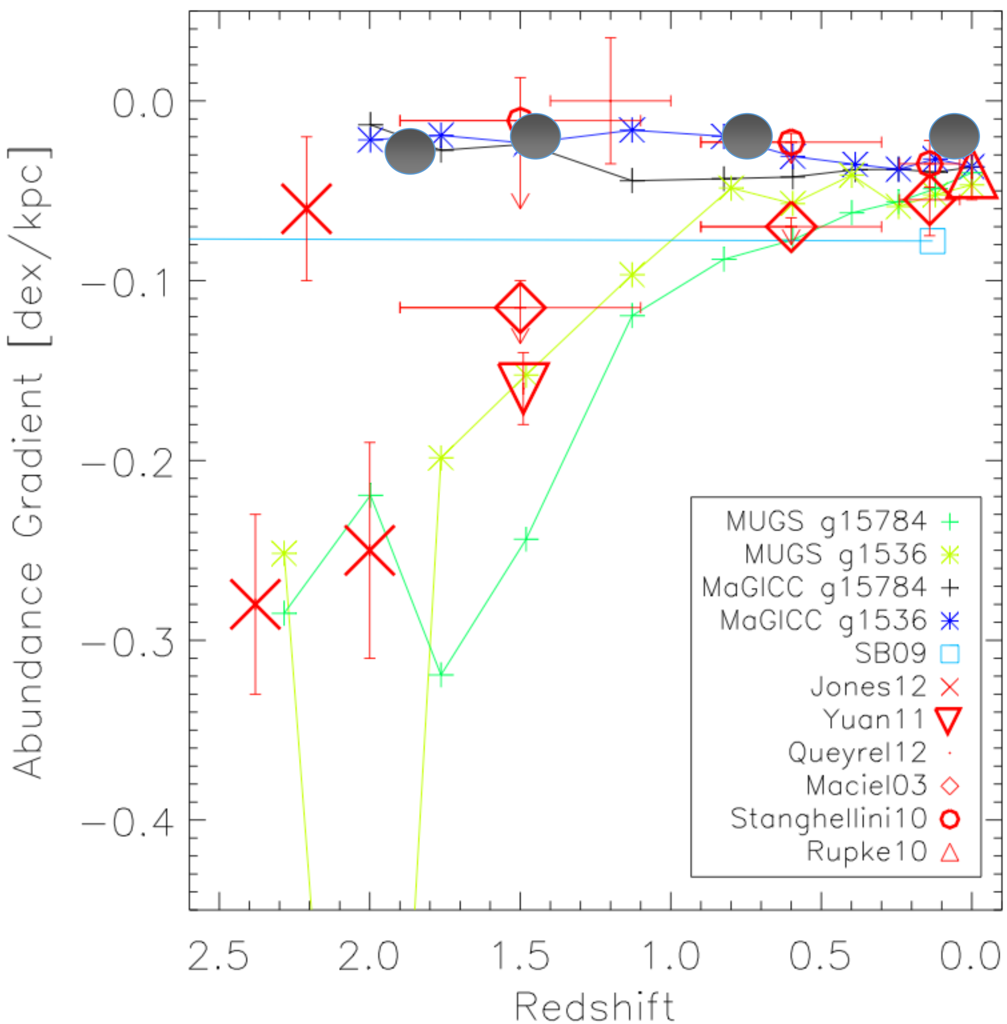


Evolution of the metallicity gradient

Gradients were steeper in the past, but the evolution is mild



Evolution of the metallicity gradients with time



We find little evolution in the metallicity gradient compatible with **cosmological simulations with enhanced feedback**

See also Magrini et al. (2016) Leethochawalit et al. (2016)

Summary

We are studying the **stellar populations** in disk galaxies trying to disentangle the epoch of formation of their different components and the importance of internal (secular) evolution processes in shapping them:

(1) Stellar population gradients in disks indicate a mild, negative, age and metallicity gradients. When weighted by mass thought, the age gradients are flat and the ages high. Combined with the high metallicity seems to indicate, again, and early and rapid formation of the disks → **inside out quenching more than inside-out forming**

(2) **Bars have little influence in building up central components** through dynamical redistribution of material.

(4) We find very **little evolution of the metallicity gradient** with time but the trend is that gradient **become flatter** (less negative) **with time**.

Summary

We are studying the **stellar populations** in disk galaxies trying to disentangle the epoch of formation of their different components and the importance of internal (secular) evolution processes in shapping them:

(1) Stellar population gradients in disks indicate a mild, negative, age and metallicity gradients. When weighted by mass thought, the age gradients are flat and the ages high. Combined with the high metallicity seems to indicate, again, and early and rapid formation of the disks → inside out quenching more than inside-out forming

(2) Bars do not modify the stellar or gaseous metallicity gradients.

(6) We find very little evolution of the metallicity gradient with time but the trend is that gradient **become flatter** (less negative) **with time**.

(7) The gradients may have been steeper in the past and flatten due to dynamical processes (but comparing the results using integrated spectra with those of direct metallicity measurements we can constrain the importance of radial migration.

Secular evolution does not seem to be as important as predicted in simulations