Bulge Formation in the Milky Way and in High Redshift Galaxies

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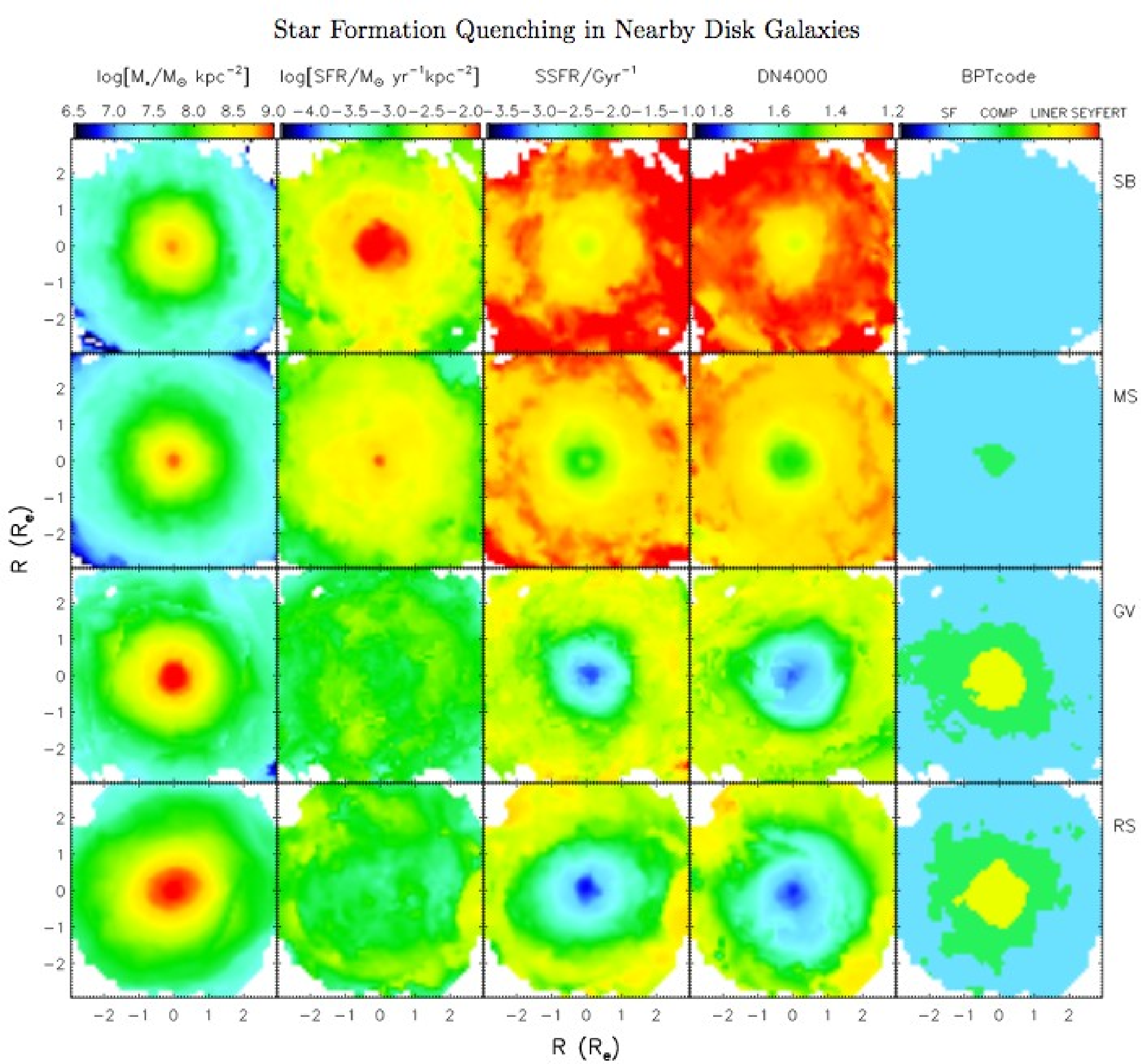
Outline:

- Structure and kinematics of the MW bulge
- Its stellar population content: ages and metallicities
- Lookback ~10 Gyr (at z~2) to see galaxies while brewing their bulges
- Hints on the formation of the MW bulge (and other bulges)

IPMU, April 18, 2019

Starforming and quenched bulges in nearby galaxies (MANGA, Guo+2018)



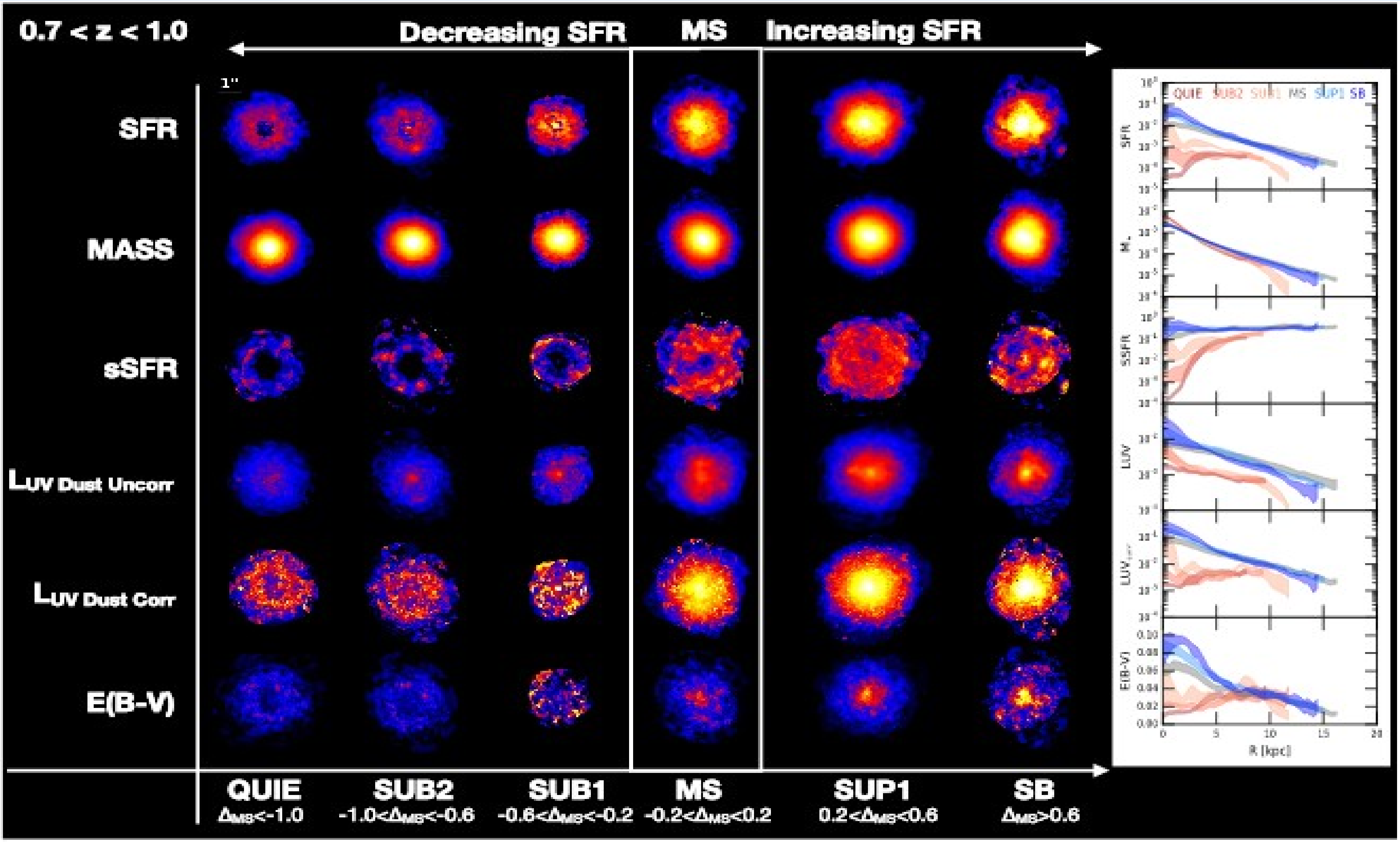
Starbursters

Main Sequence

Green Valley

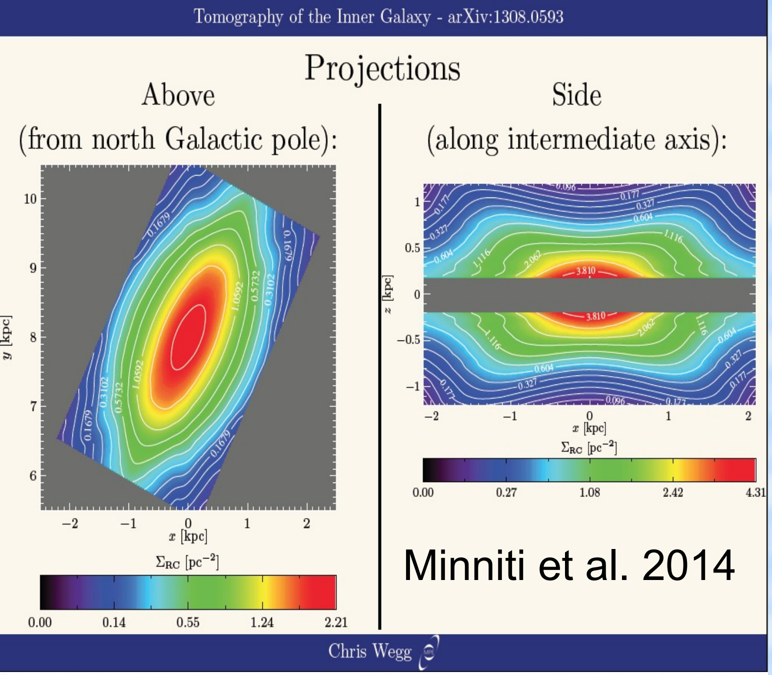
Fully Quenched

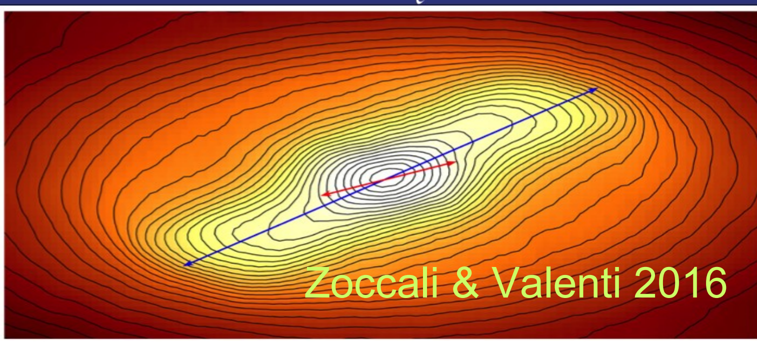
Starforming and quenched bulges in nearby galaxies (SDSS, Morselli+2018)

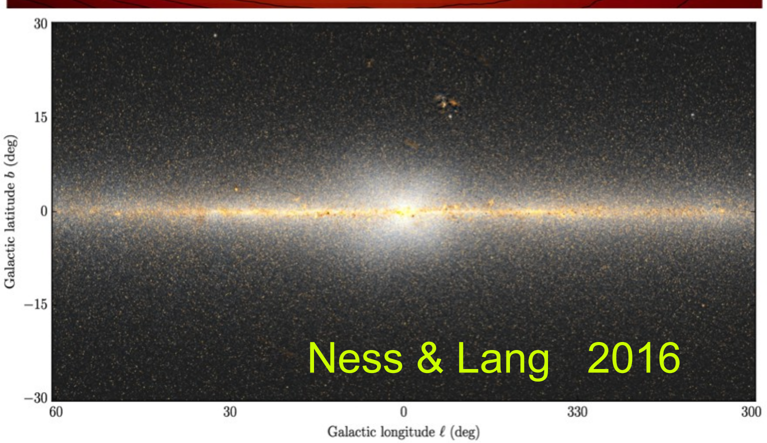


The MW bulge is:

- A bar
- boxy-peanut, X-shaped
- A cylindrical rotator

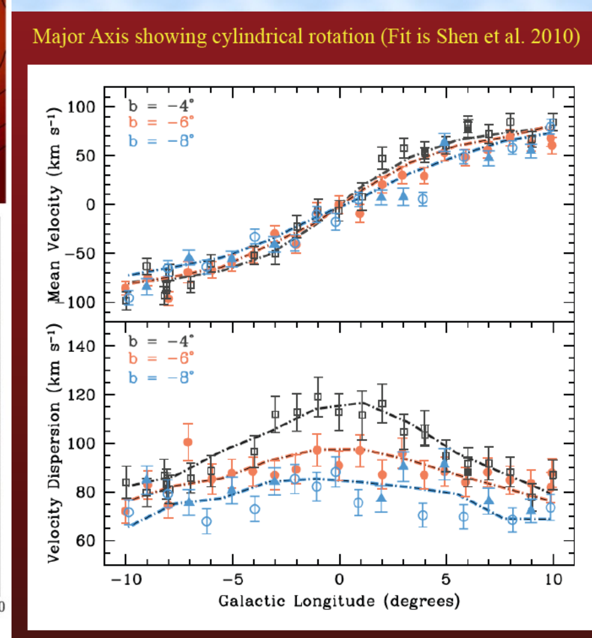


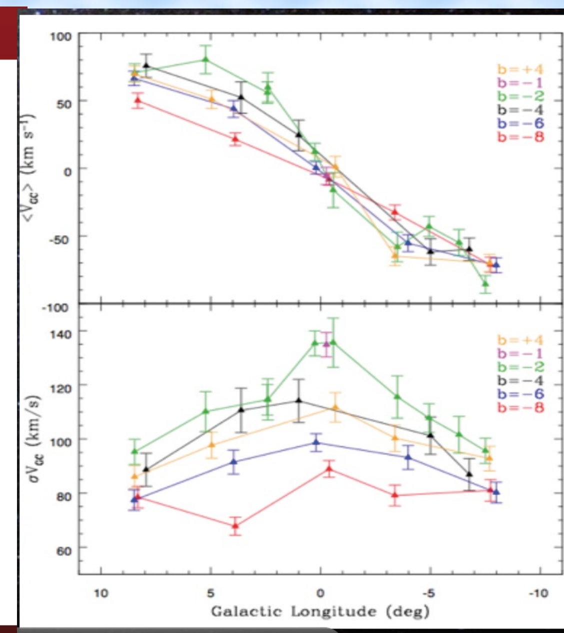




Brava (RM Rich PI)

GIBS (M Zoccali PI)



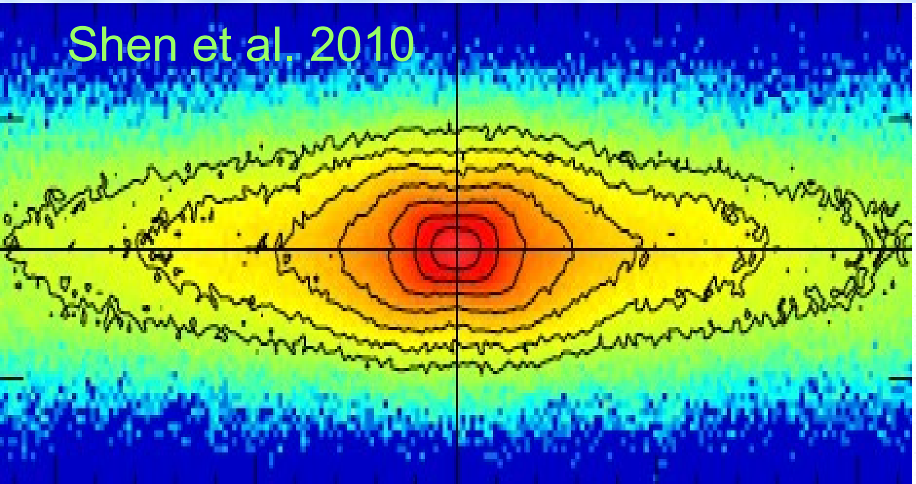


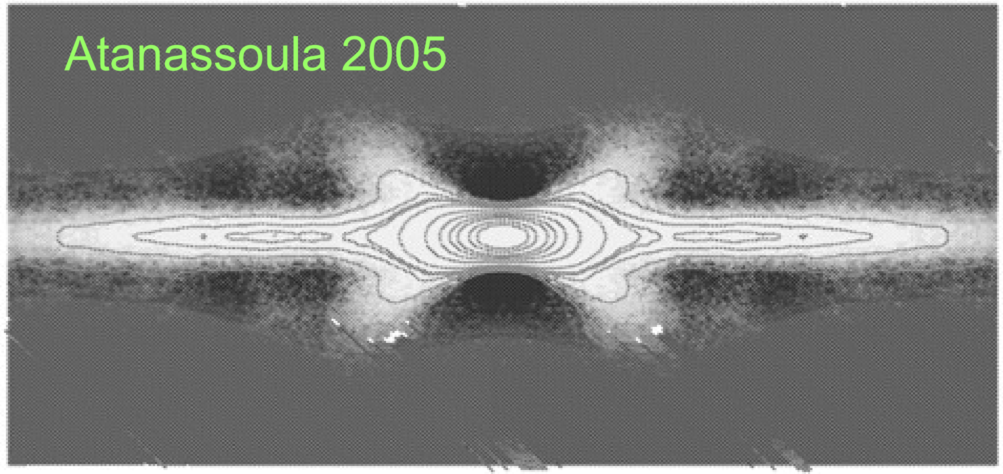
… Just as predicted by N-body simulations in which:

- Starting from a pure, exponential, stellar disk the size of the MW
- The disk develops a bar-formation instability
- Once formed, the bar is subject to buckling instability resulting a:

✓ cylindrically rotating
✓ boxy-peanut, X-shaped bulge
✓ which is a bar

...BUT...



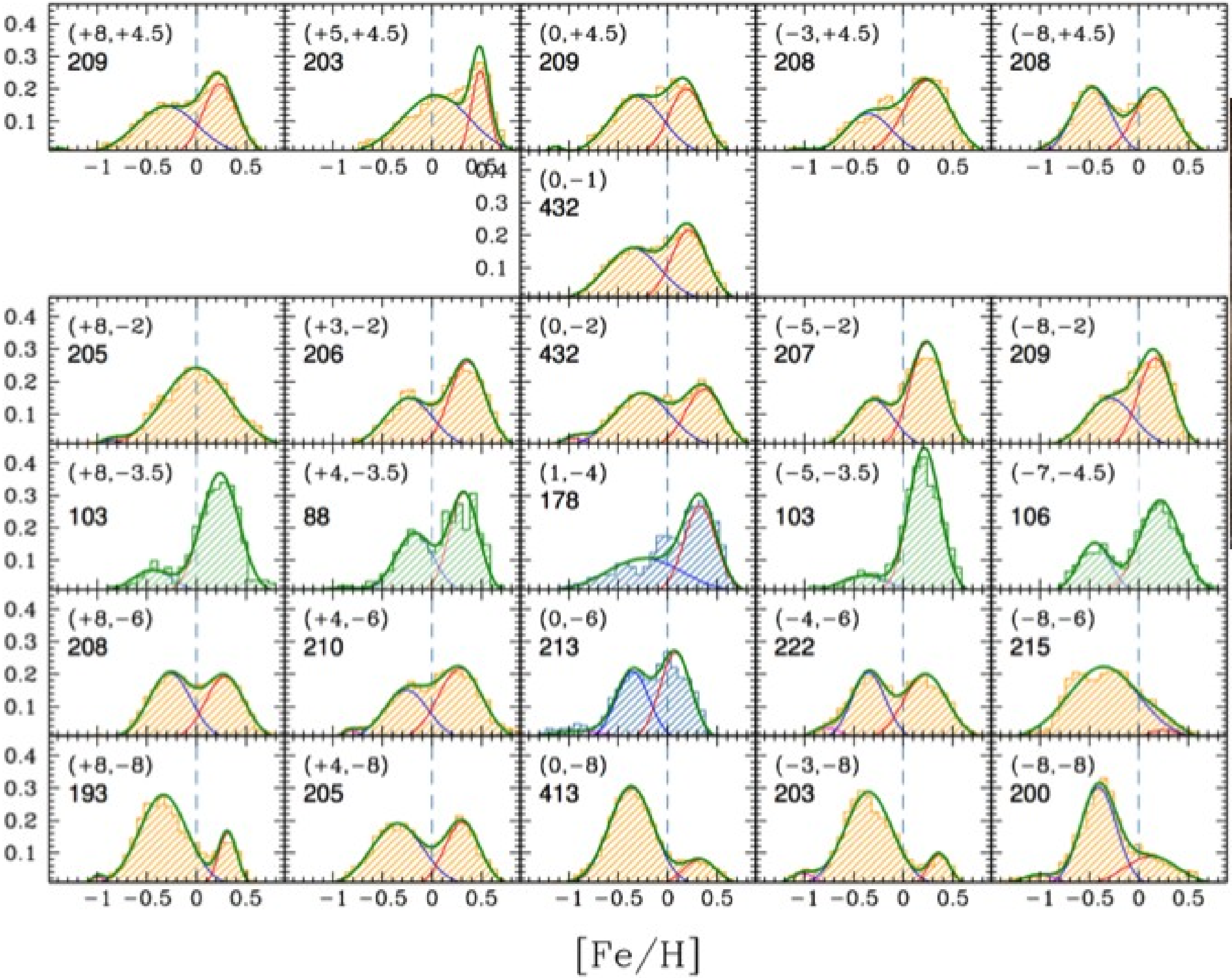


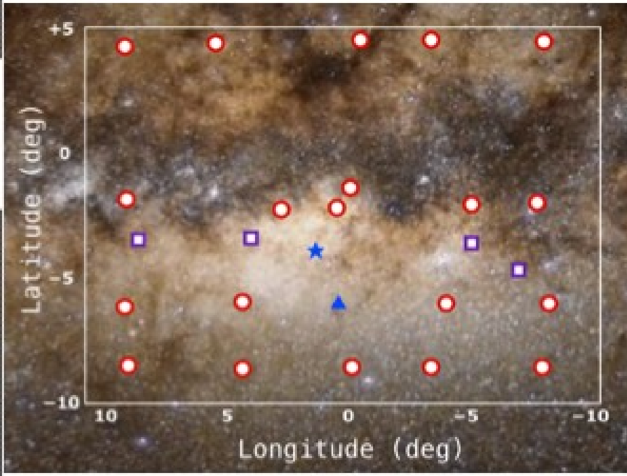
So far so good for structure and dynamics, but what about the bulge stellar population content, i.e.,

Ages and Metallicities?

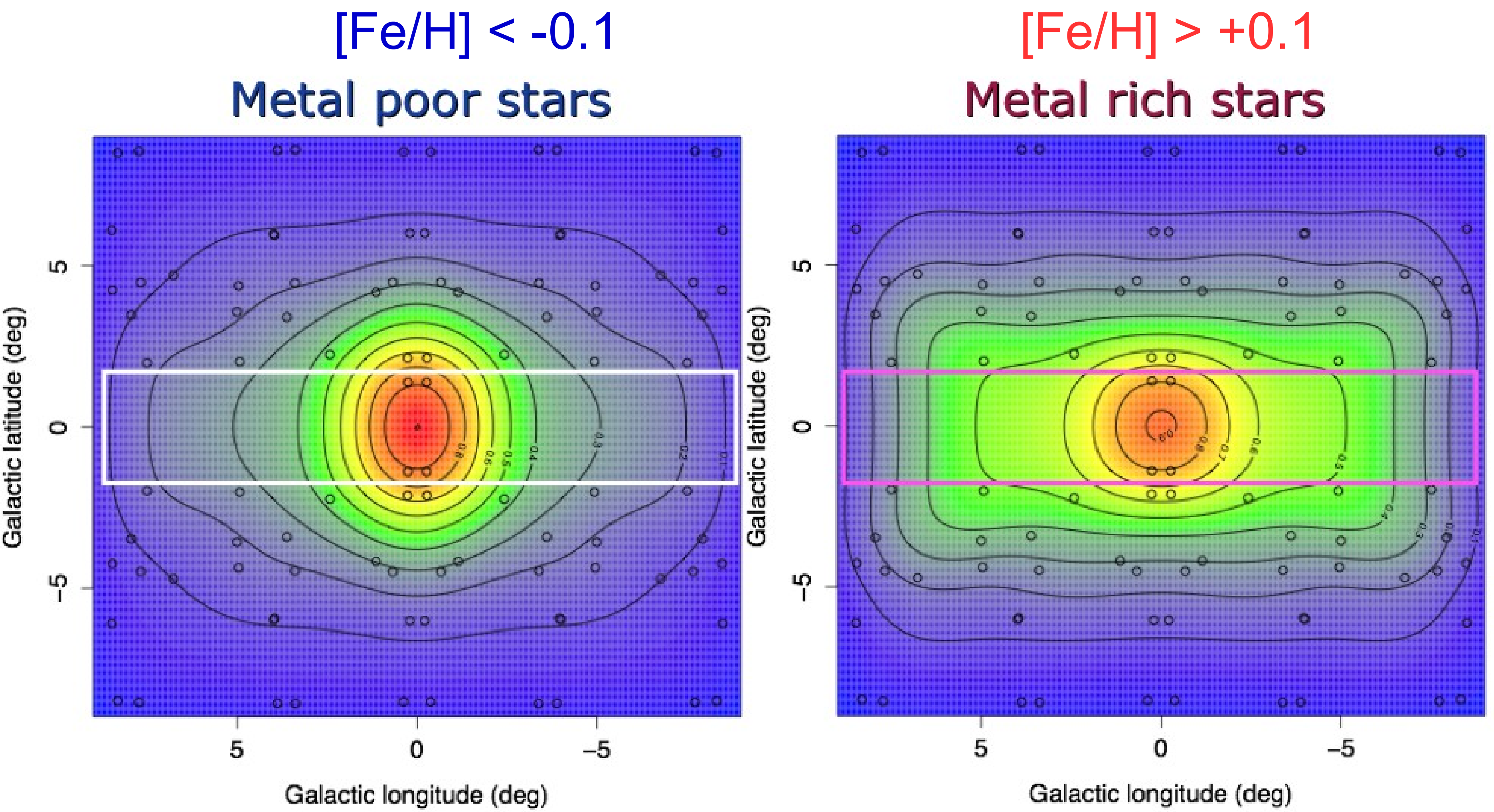
GIBS – Metallicity Distribution Functions

Zoccali et al. (2017, A&A)





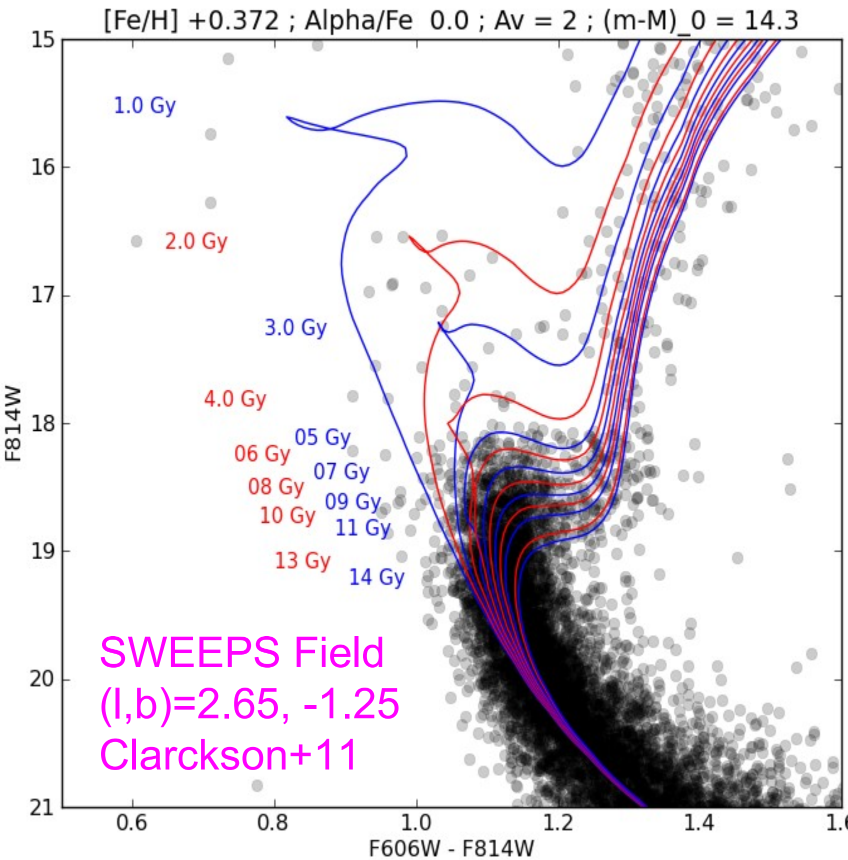
Bulge Density maps for:

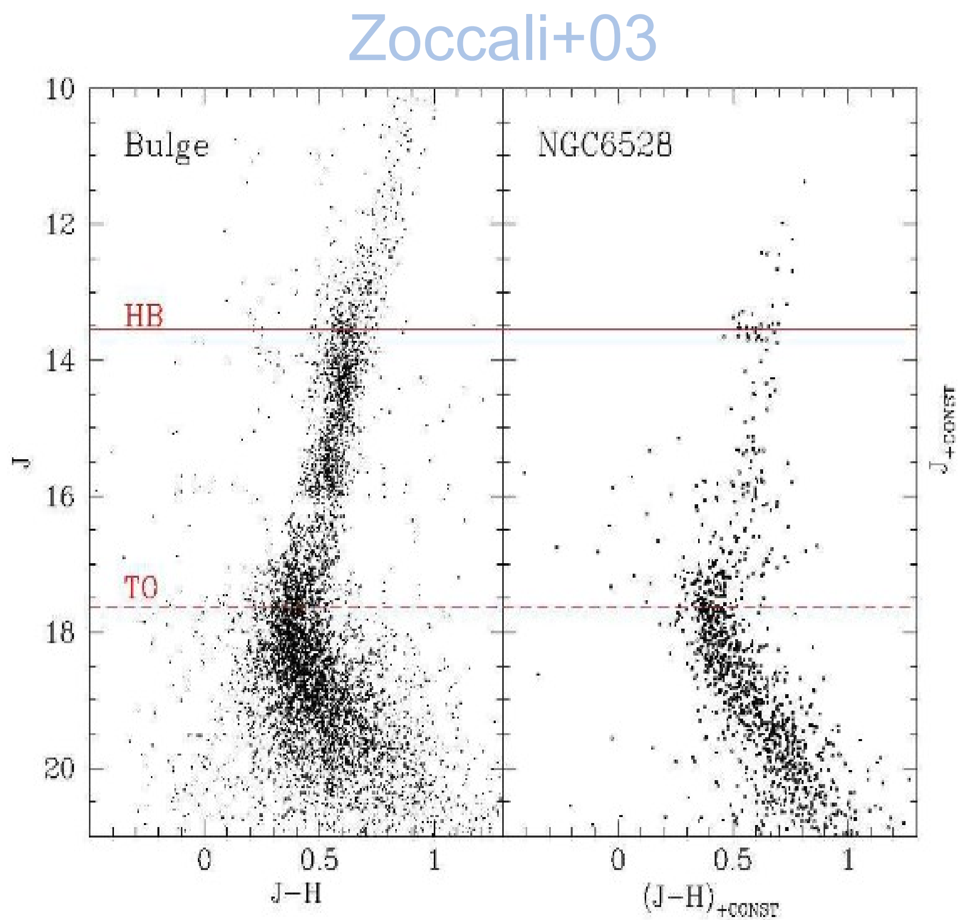


Zoccali et al. 2017

With CMDs we never found other than ~10 Gyr old stars

(Ortolani+95, Kuijken & Rich 2002, Zoccali+2003, Clarckson+11, Valenti+13, Gennaro+14)

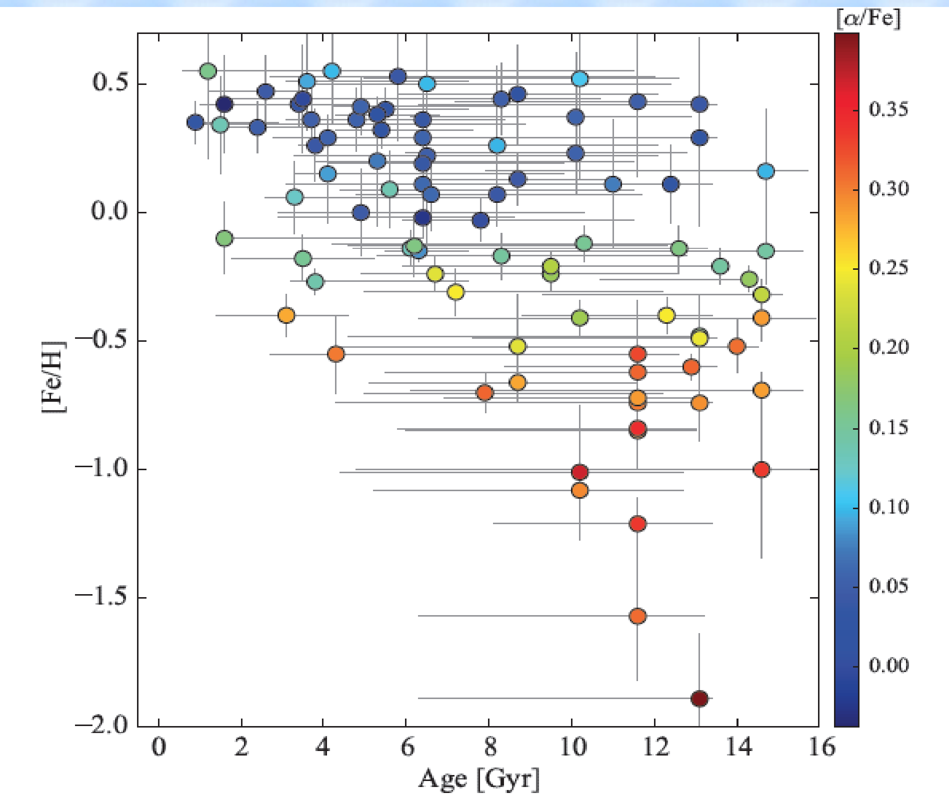


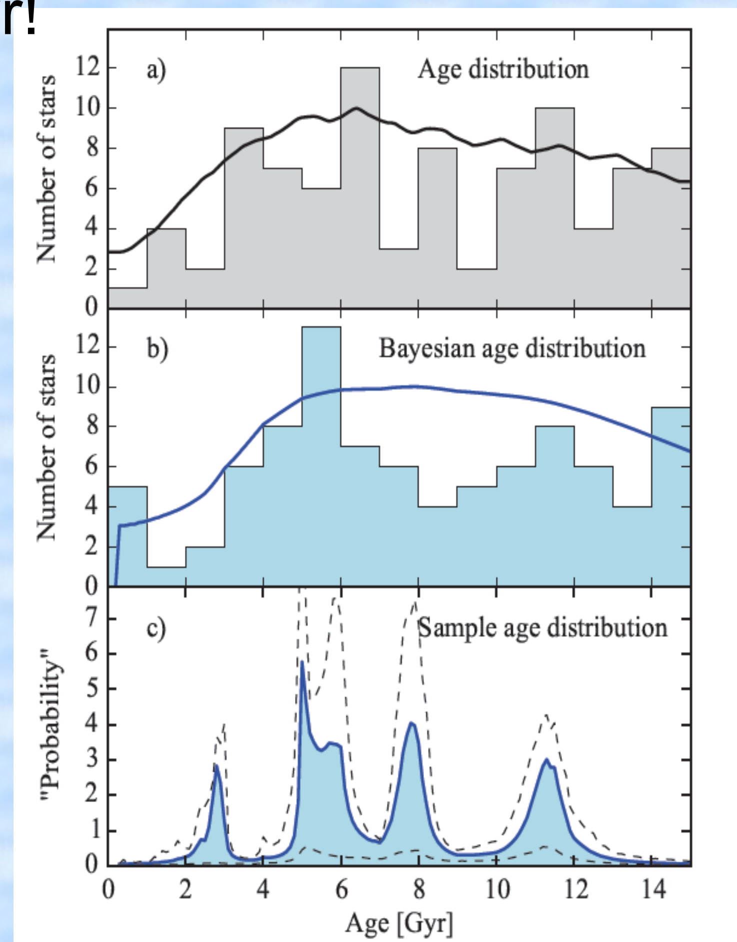


Ages for 90 MS, TO and SGB bulge stars (>~100 x) amplified by microlensing (Bensby et al. 2017).

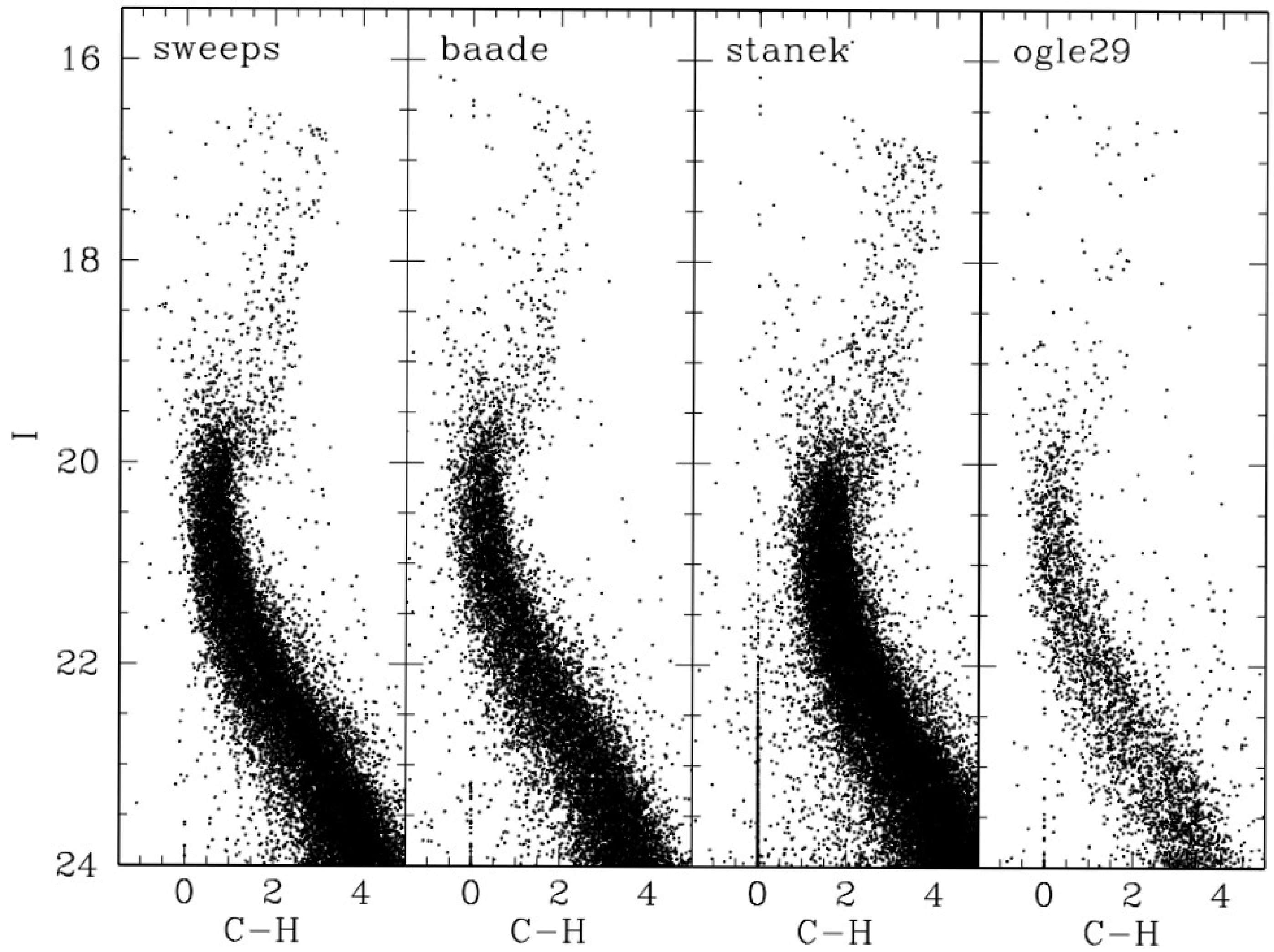
- Metallicities from high resolution spectroscopy
- Ages of individual stars from position in the log(g)-log(Teff) plane

40% of [Fe/H]>0 stars younger than 5 Gyr!

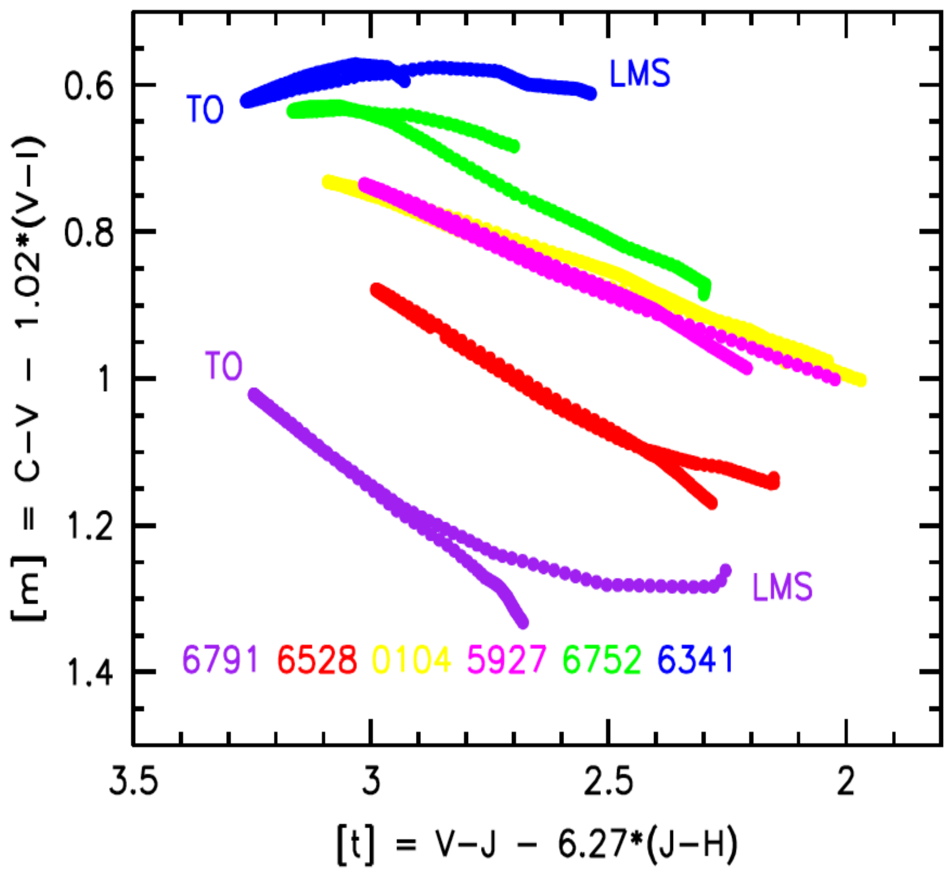


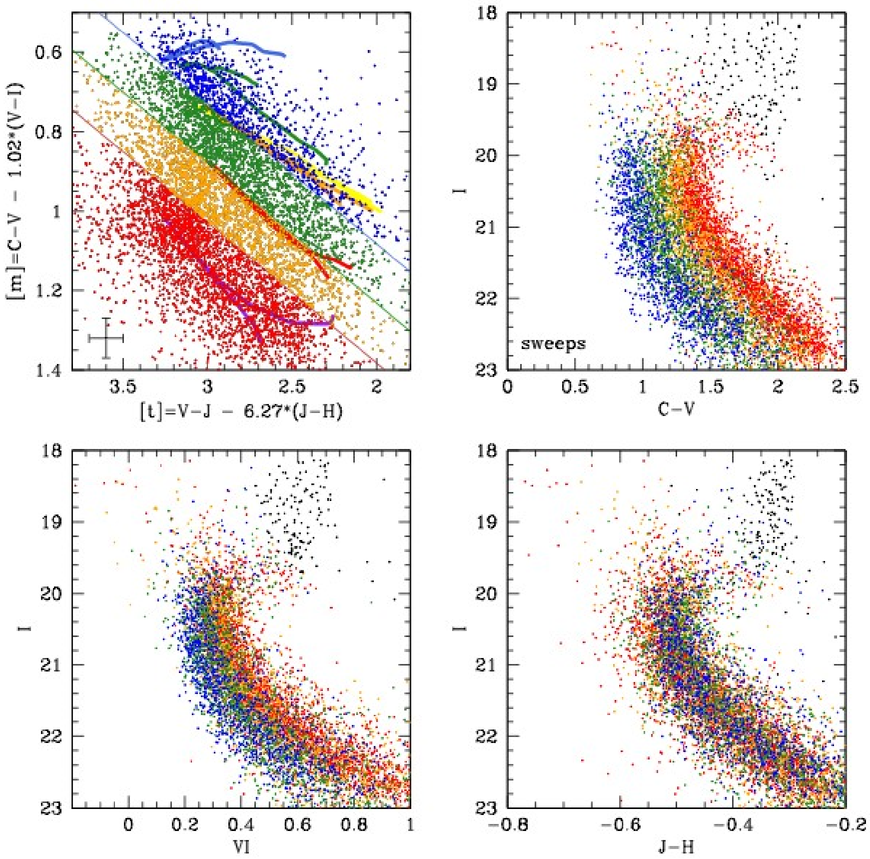


Metallicities from reddening-free 2 color plots from 5-band HST/WFC3 photometry of proper motion-selected bulge stars in 4 separate fields (Brown+2010; AR+2018)



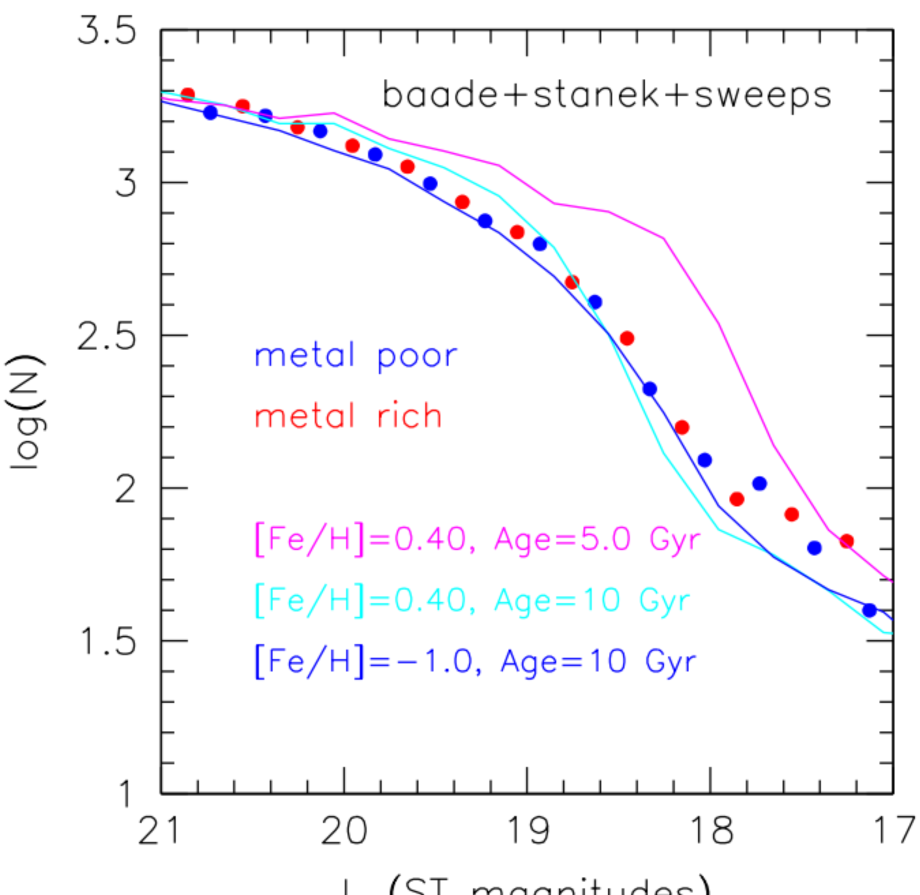
Metallicities from reddening-free 2 color plots from 5-band HST/WFC3 photometry of proper motion-selected bulge stars in 4 separate fields (Brown+2010; AR, Gennaro, Zoccali, Brown, Anderson, Minniti, Valenti, VandenBerg 2018)

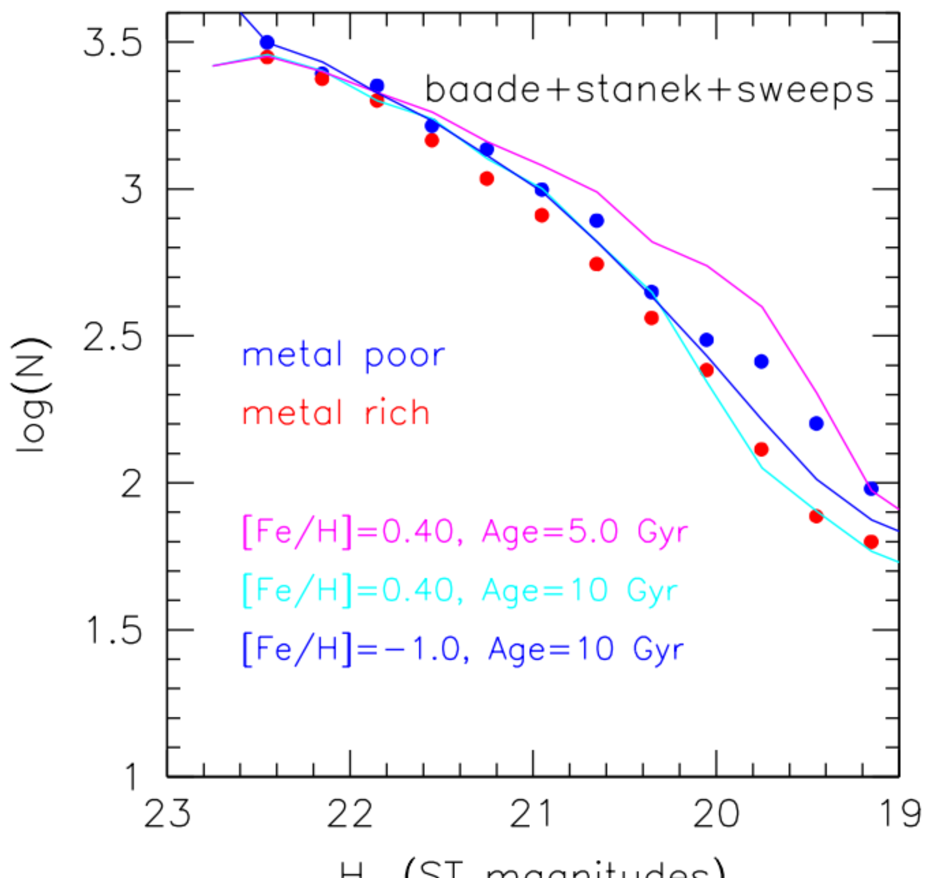




Metallicities from reddening-free 2 color plots from 5-band HST/WFC3 photometry of proper motion-selected bulge stars in 4 separate fields (Brown+2010; AR+18)

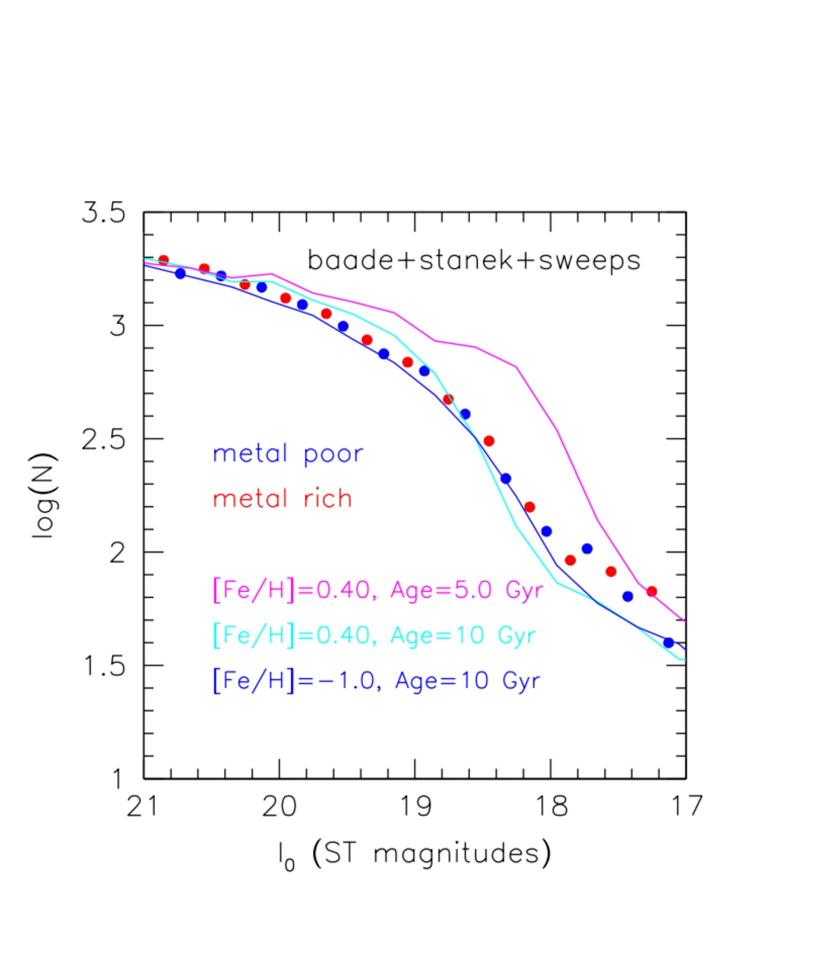
No more than ~3% of metal rich stars ~5 Gyr old, or younger!

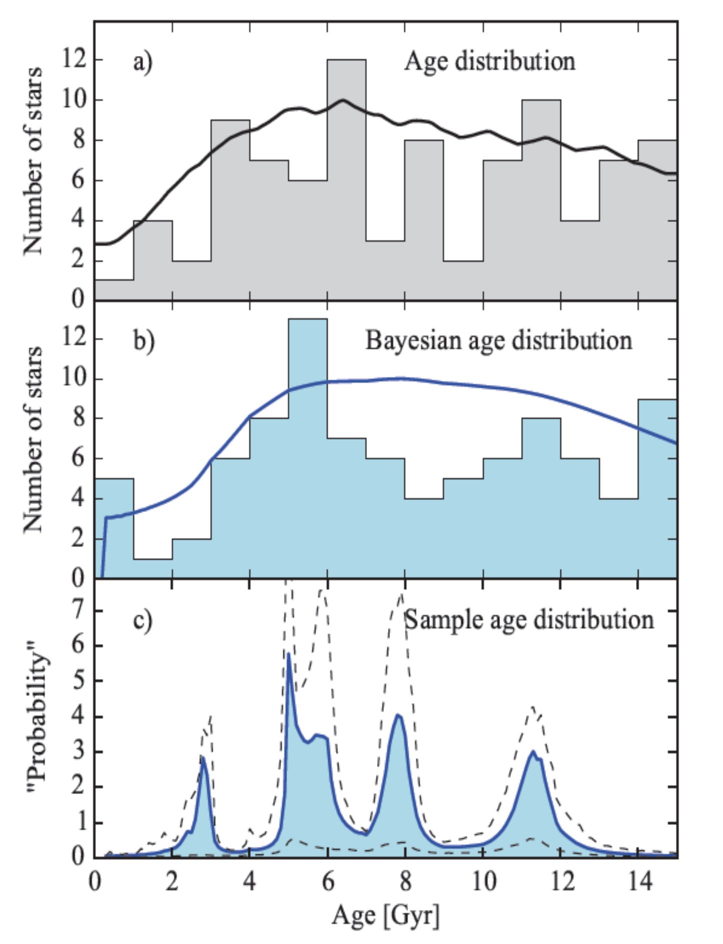




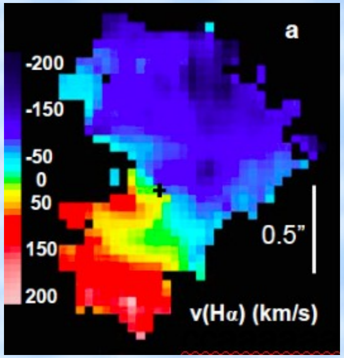
Conclusion: in this study the bulk of stars in the MW bulge are ~10 Gyr old, a young, ~5Gyr component cannot exceed ~3%.

So, the inconsistency between ages from HST CMDs and from HRDs (log g- log T_{eff}) remains!





So, let us LookBack ~10 Gyr, and see how $z \simeq 2$ galaxies look like



Galaxy Scaling Relations as established in the last ~20 years of multiwavelength observations:

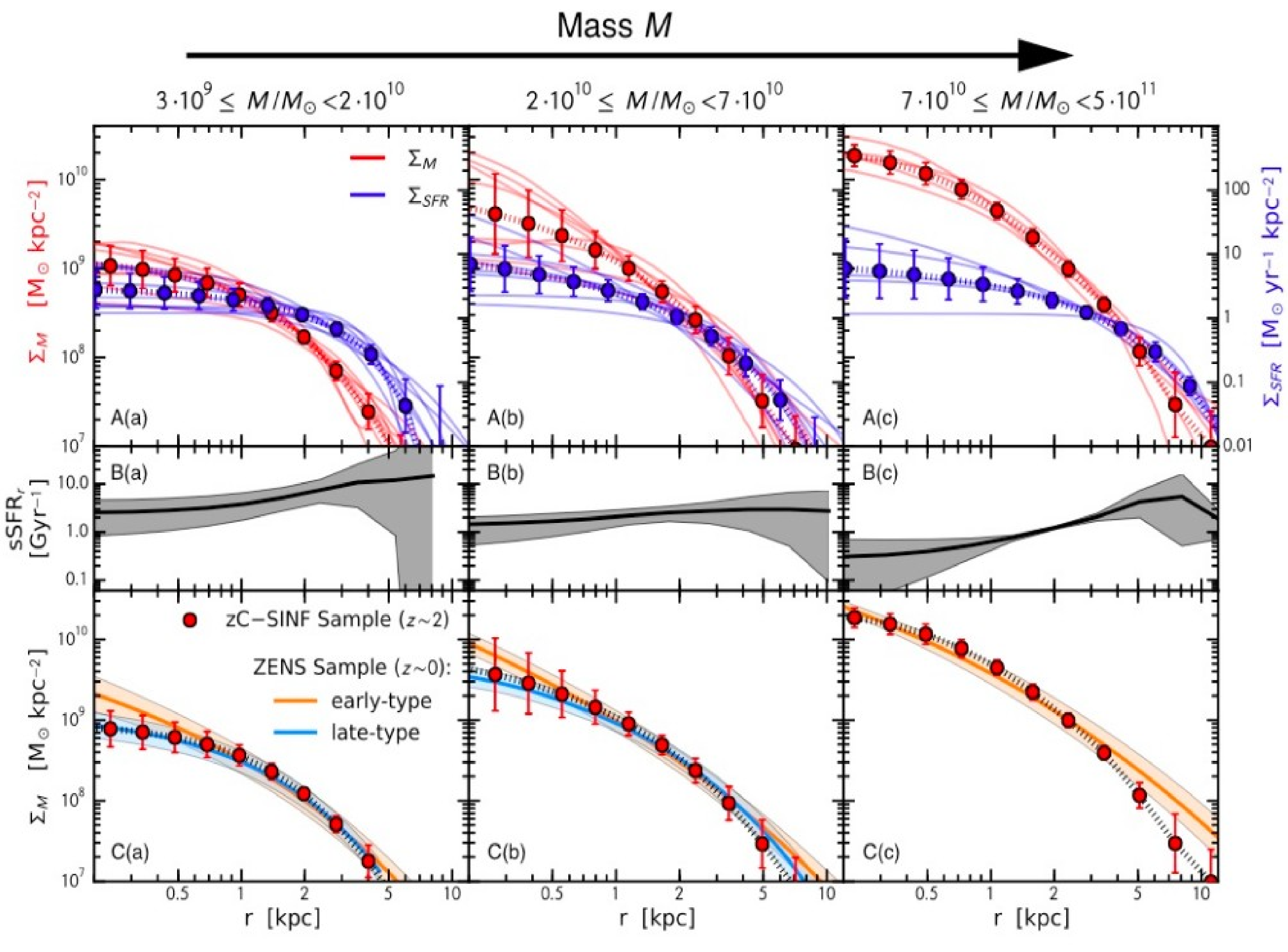
- Majority are rotating disks with high velocity dispersion.

At fixed stellar mass:

Σ_{gas}~150 times higher at z=2!!!

- They are smaller: $R_e \sim (1+z)^{-1}$
- They are gas rich: $f_{gas} \sim (1+z)^{2.6}$
- Their surface mass/gas density is much higher: $\Sigma_{gas} \sim (1+z)^{4.6}$
- Their SFR is much higher: $sSFR \sim (1+z)^{2.8}$
- They are (Toomre unstable) clumpy disks
- They are fully-open boxes (inflows → SF(/AGN) → outflows)
- The most massive ones have already developed their bulge

So, let us LookBack ~10 Gyr, and see how z≃2 galaxies look like



Tacchella+2015

Maps of

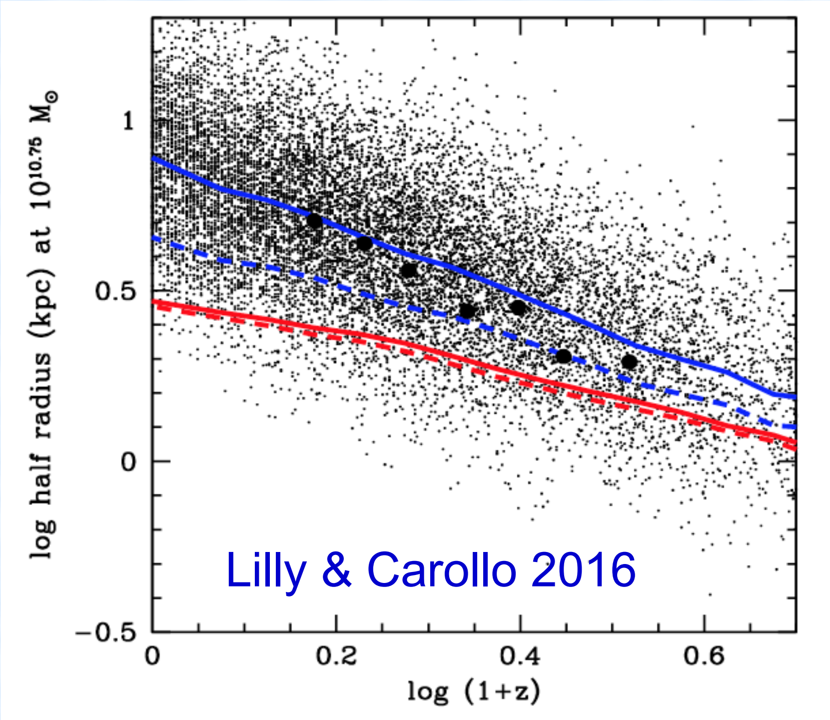
SFR from Hα with SINFONI AO @ VLT

Stellar mass HST H band

Both with ~1.5 kpc resolution

How do we bridge the local, MW evidence with that on High-z galaxies?

- The MW bulge has a mass of ~$2 \times 10^{10}\, M_\odot$ (Valenti+2016)
- At z=2 a typical SF galaxy of $2 \times 10^{10}\, M_\odot$ has an half-mass radius of R_h=~1.5 kpc, just as the MW bulge, today
- And a surface gas density Σ_{gas} ~150 times that of a today galaxy with the same mass



It looks as if at z~2 a $2 \times 10^{10}\, M_\odot$ galaxy is just making its bulge, or little more. Then the disk would have grown later, inside-out

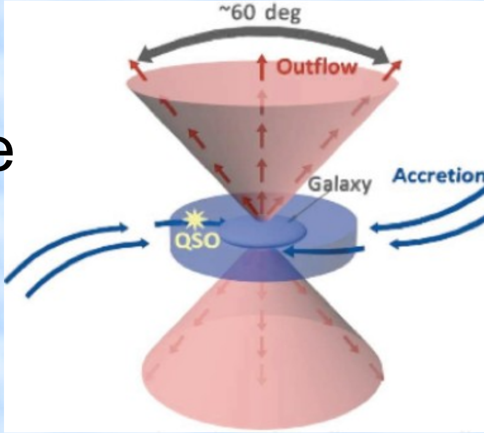
The MW bulge was "quenched" ~ 10 Gyr ago while the disk kept growing via gas accretion and ensuing star formation

Problems and Speculations

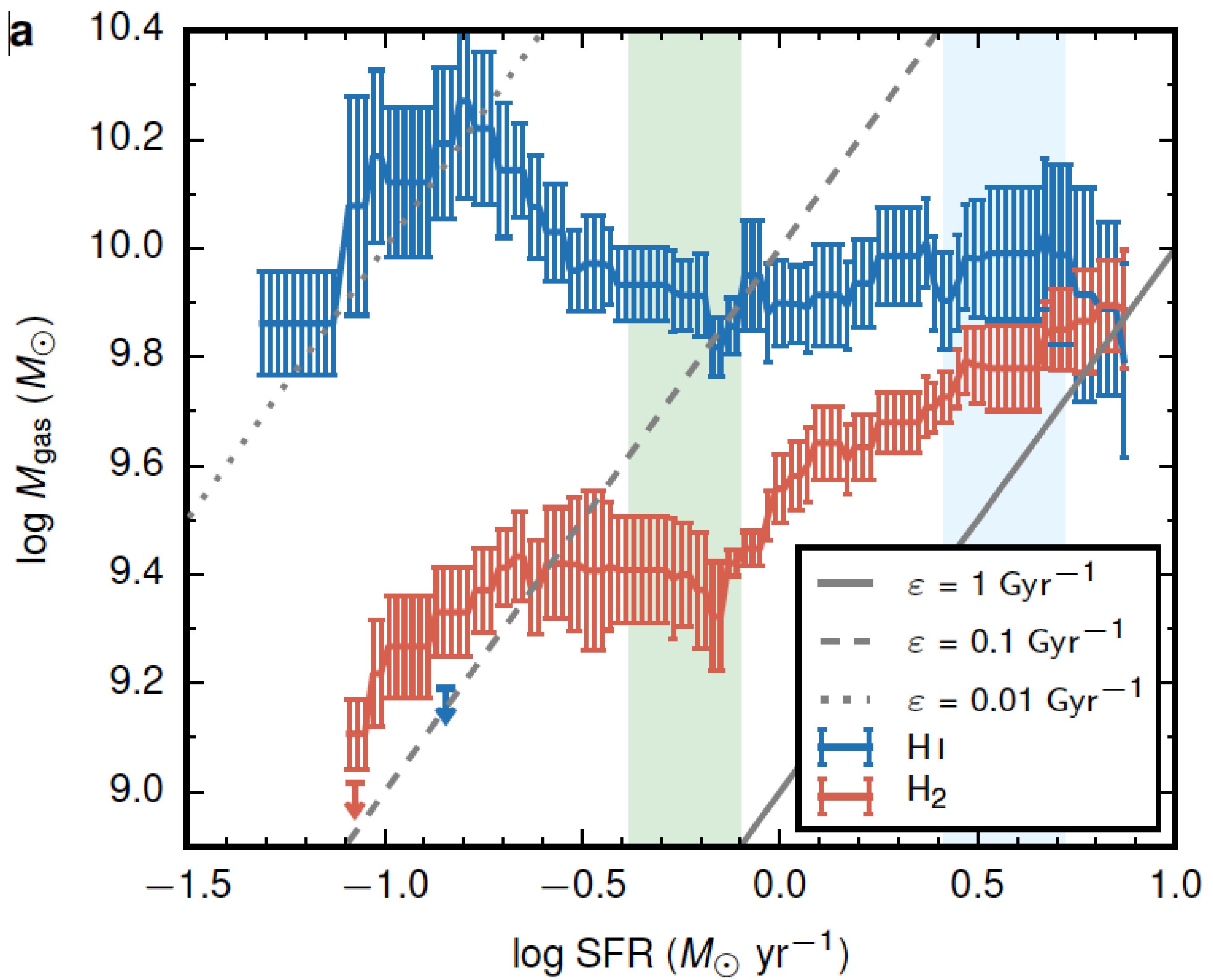
- How was the bulge quenched in the first place?
- How did it manage to remain quenched for the next ~10 Gyr?

- I don't know, but e.g., in Tacchella+2016 hydro-simulations quenching follows *naturally* from gas consumption, with short depletion time, following a *compaction* event (Dekel & Burkert 15).

- If so, maybe equatorial accretion streams came in with too high angular momentum to feed the bulge that then remained starving (plus occasional *AGN maintenance*?)



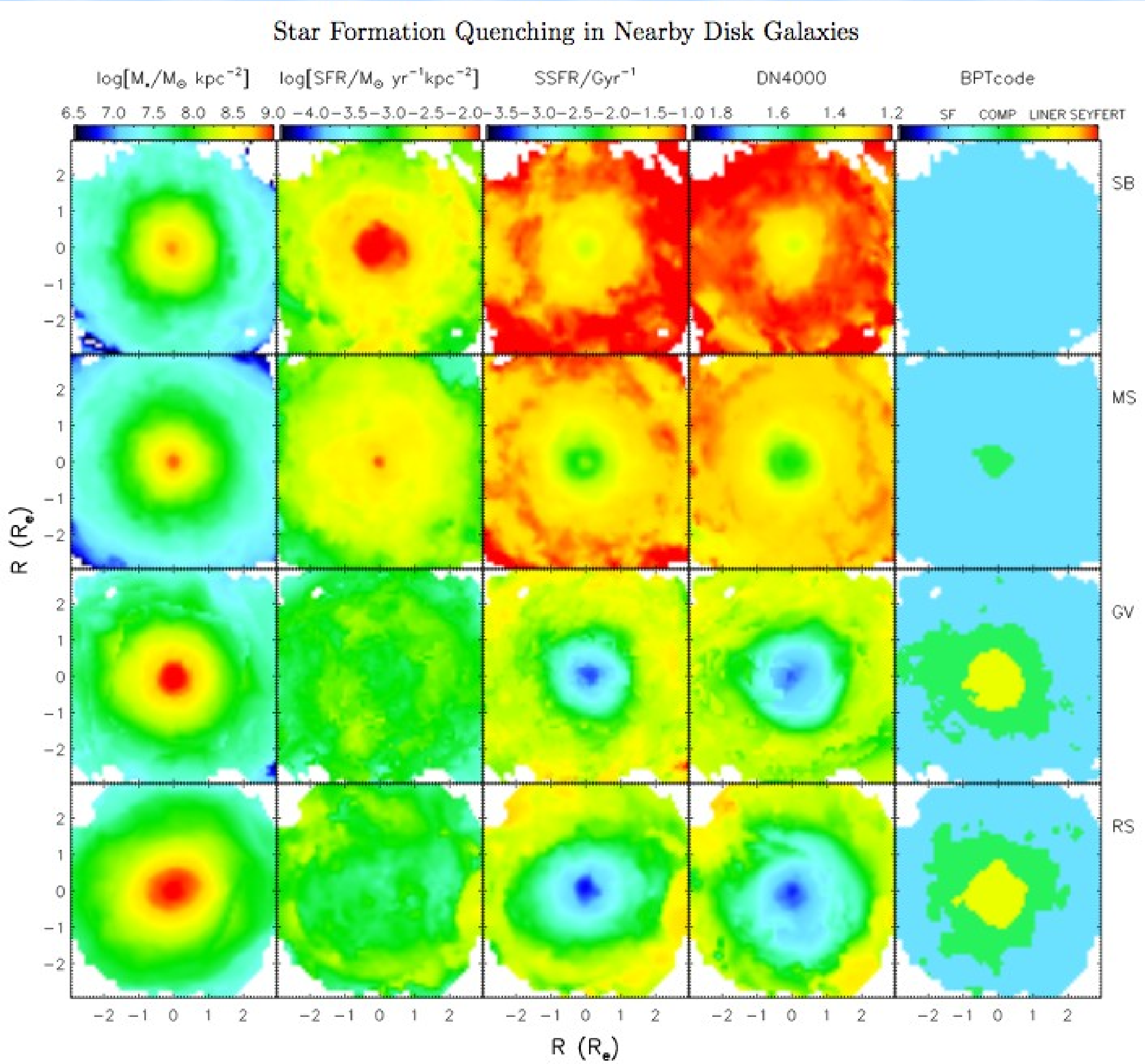
The cold gas content of local disks



10.5<logM*<11

Peng+2019

With JWST similar maps will be done for galaxies up to z~2 and beyond



Starbursters

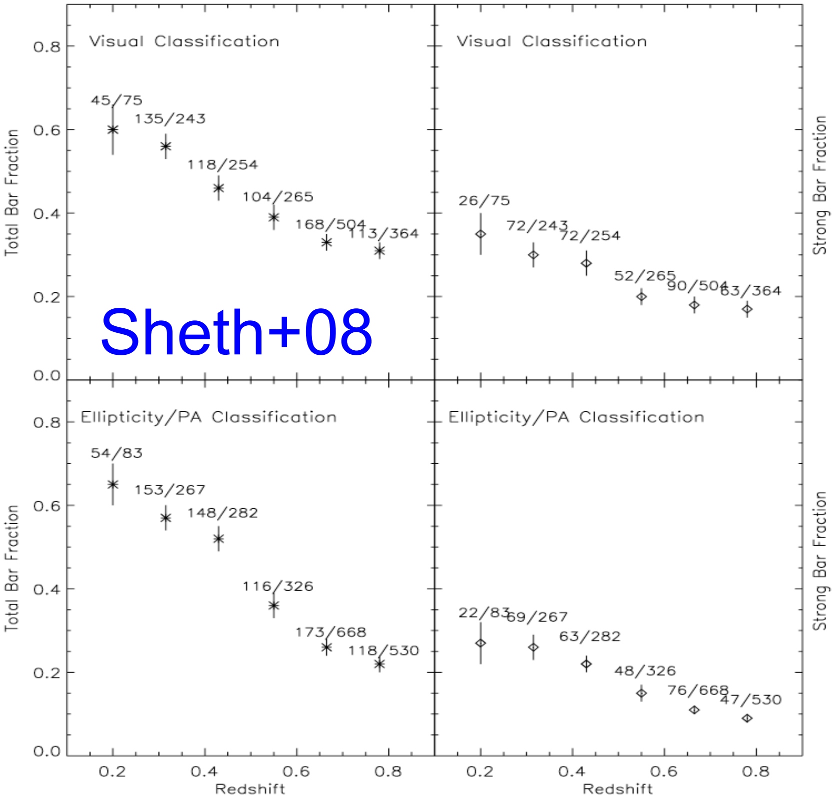
Main Sequence

Green Valley

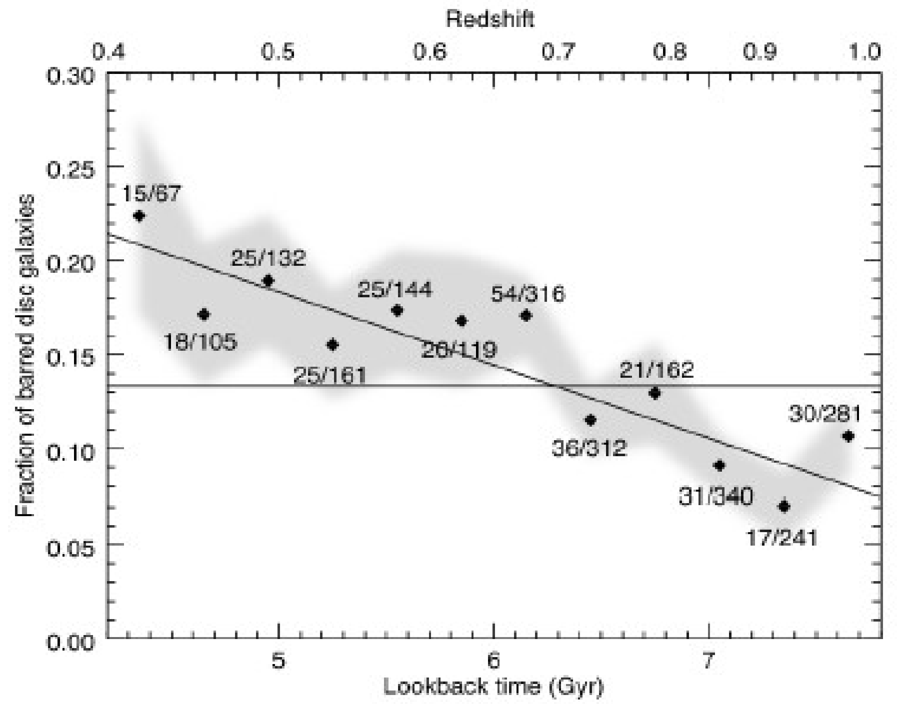
Fully Quenched


Thank You!

Bars seem to disappear at high z: there were no bars when most of the bulge stars formed: bars make bulges or bulges later become bars?



8 *Thomas Melvin et al.* 2014



Bars make bulges or (some) bulges later become bars?

A final speculation/question:

- As the MW disk grew bigger $(1+z)^{-1}$ and progressively more gas poor $(1+z)^{2.6}$, it became more and more stellar dominated, hence prone to bar-formation+buckling instabilities leading to a
  - ✓ cylindrically rotating
  - ✓ boxy-peanut, X-shaped bulge
  - ✓ which is a bar

- Does this make sense to you???