Fine Tuning our Understanding of the Stellar Content of Massive Early-Type Galaxies

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Early-Type galaxies

~ 10-20% of the galaxies but contain ~70% of the stellar mass of the Universe.

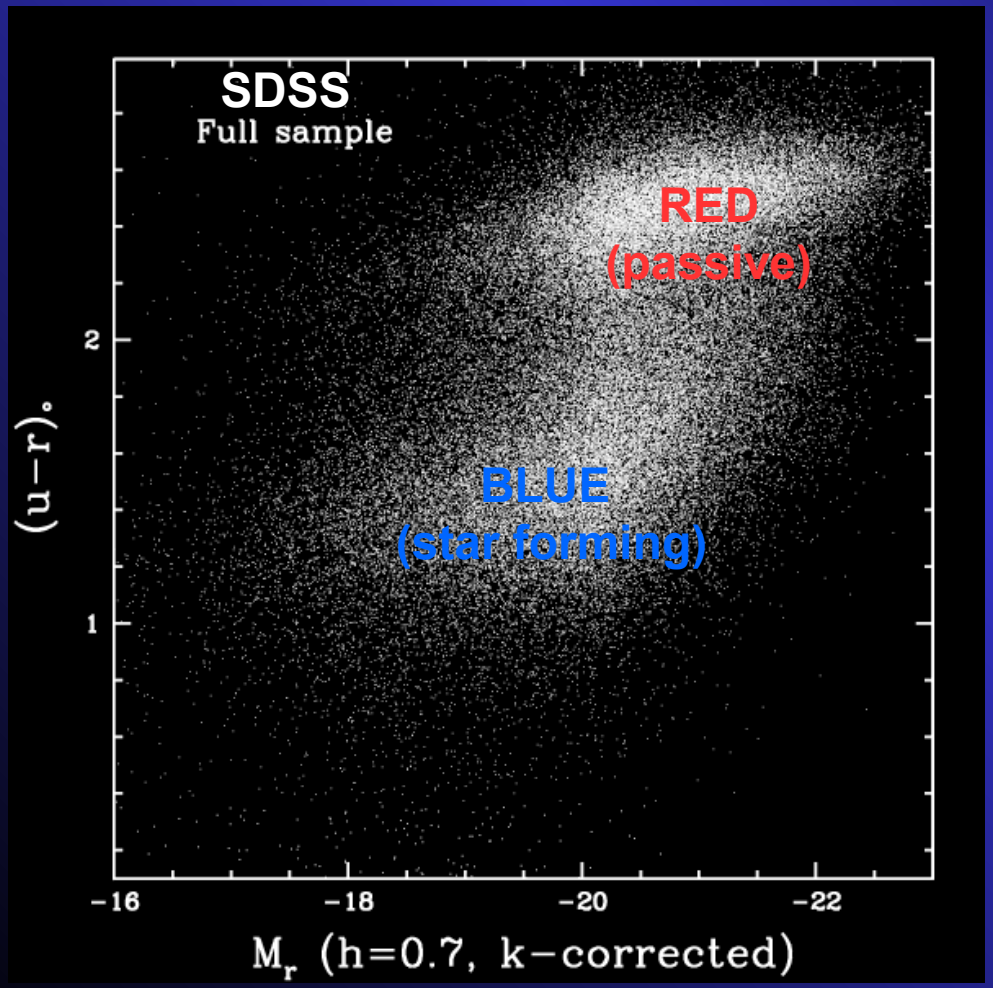
Are thought to be the end-products within a hierarchical galaxy formation framework. In fact they do pose a major challenge to these models

To be constrained by looking at the stellar populations resulting from their Star Formation Histories

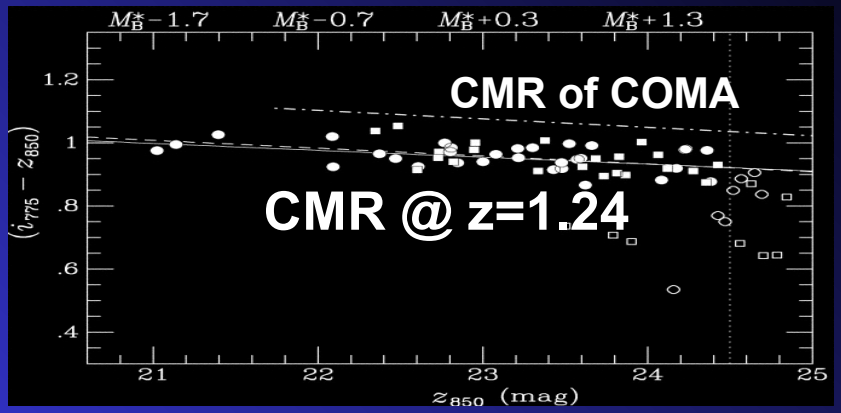
M87 © Anglo-Australian Observatory
Photo by David Malin

The stellar populations of ETGs

Both their photometric and spectroscopic properties follow tight scaling relations

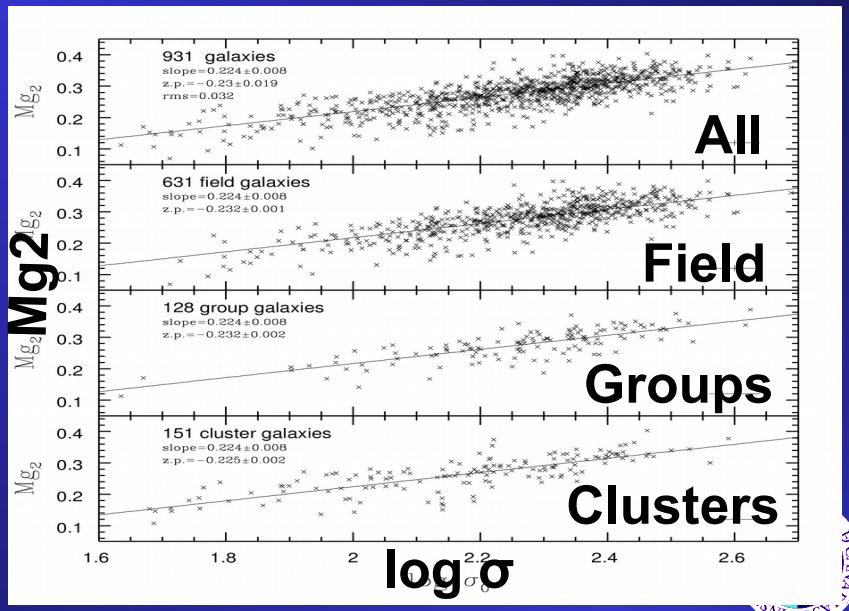


Baldry+04



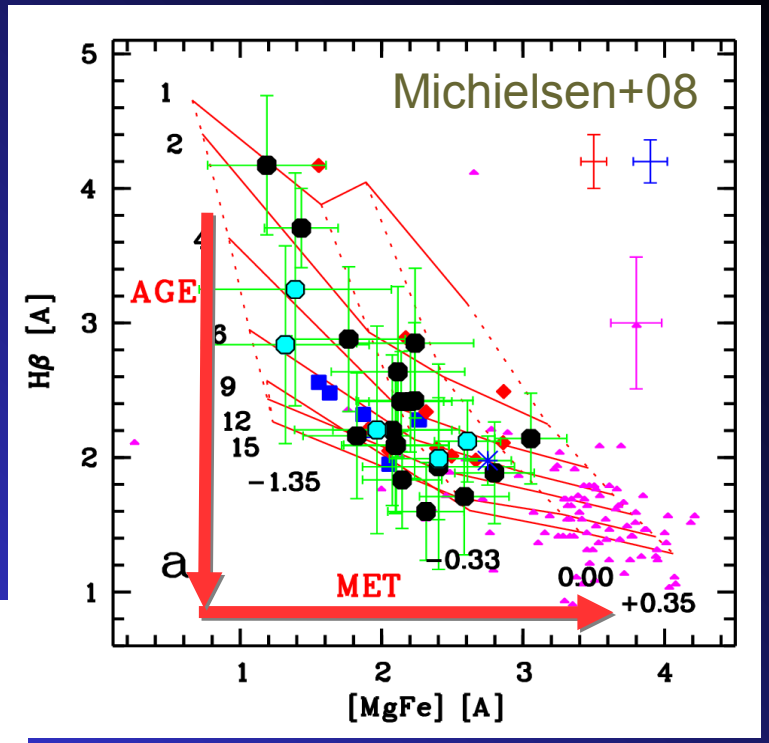
Blakeslee+03

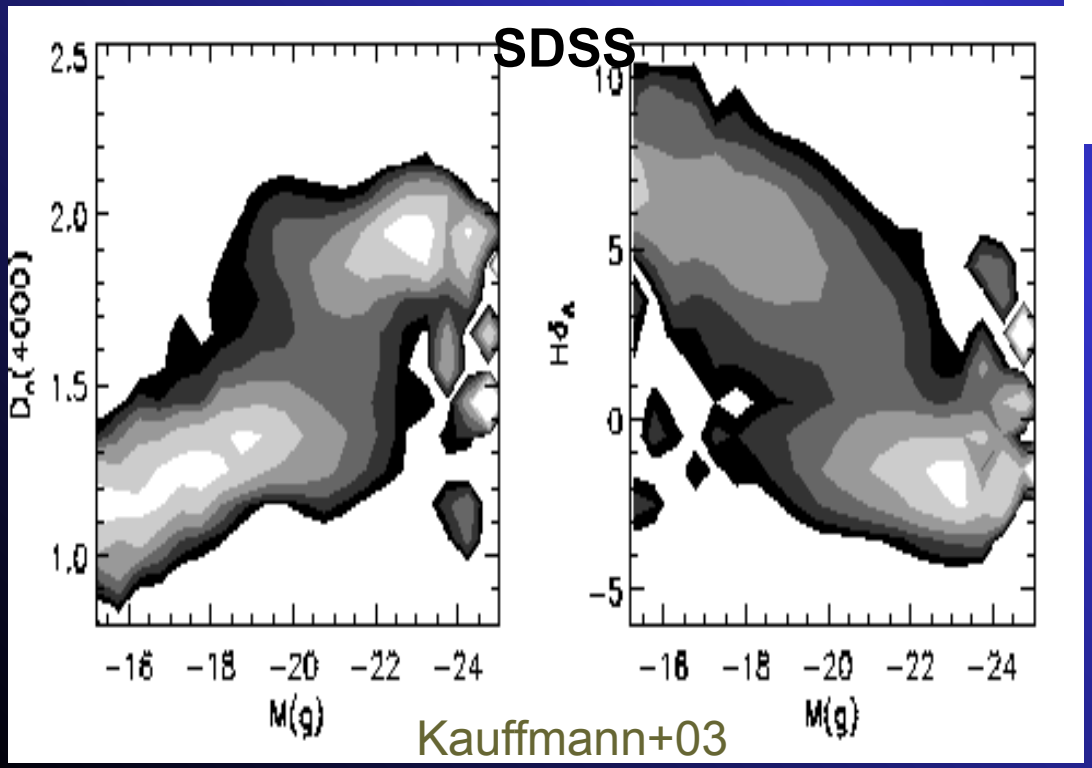
Bernardi+98

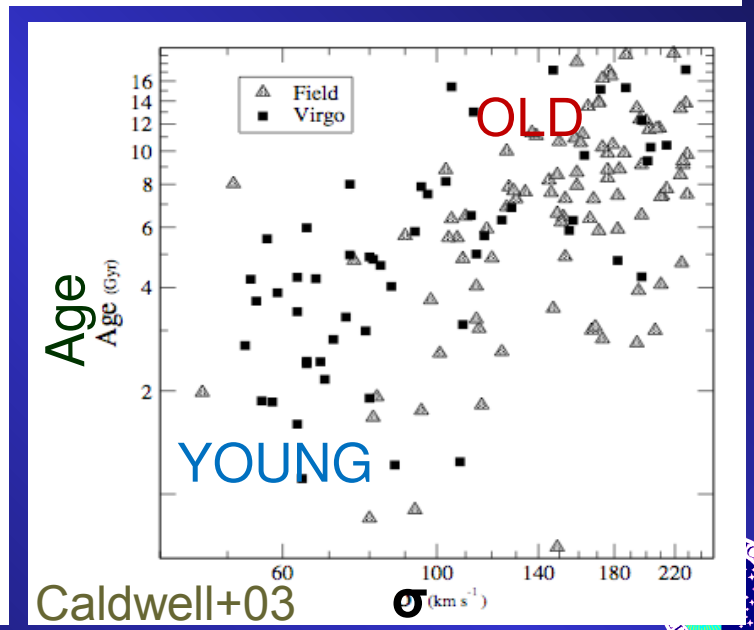


Stellar populations: results from detailed spectroscopic studies

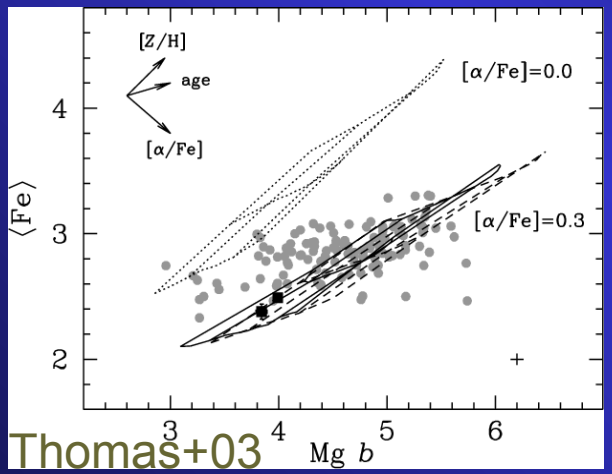
Massive ETGs older (downsizing) and more metal-rich than their lower mass counterparts





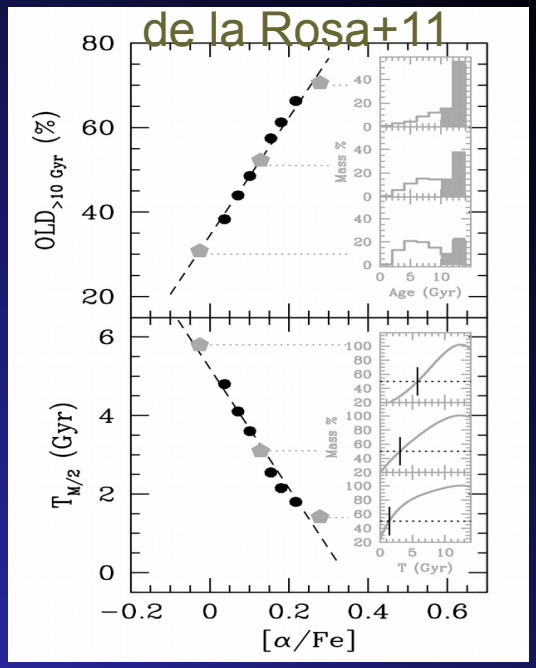


Stellar populations: results from detailed spectroscopic studies

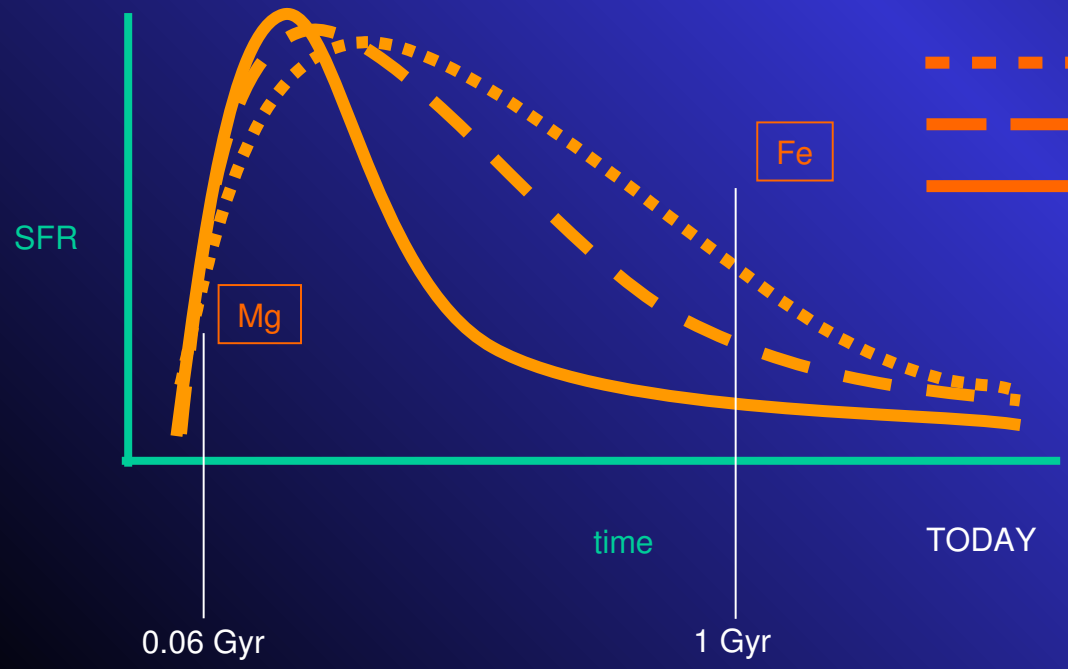


Thomas+03

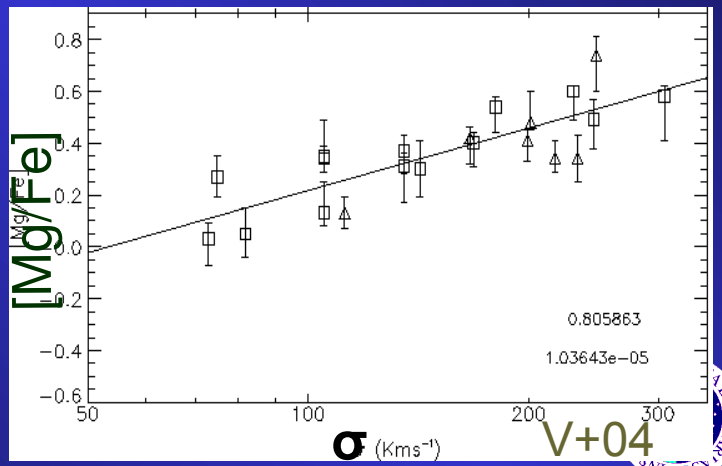
Formation time-scale: massive ETGs not only formed the bulk of their stars earlier but fast (<1Gyr) than their low-mass counterparts



de la Rosa+11



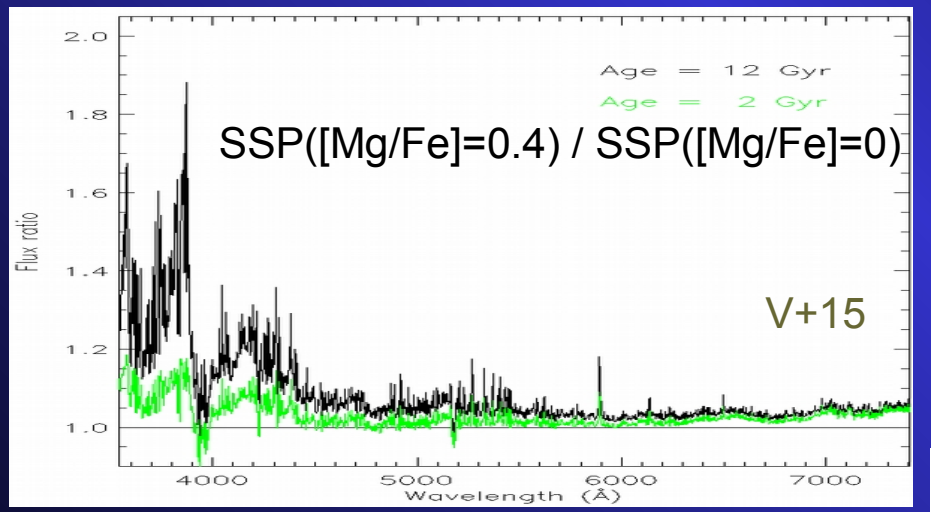
SFR	TIME-SCALE
EXTENDED	LONG
INTERMEDIATE	INTERMEDIATE
EFFICIENT	SHORT

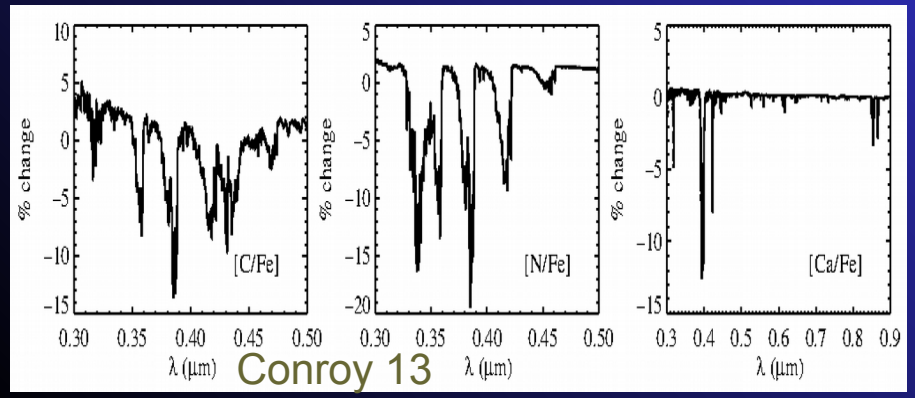


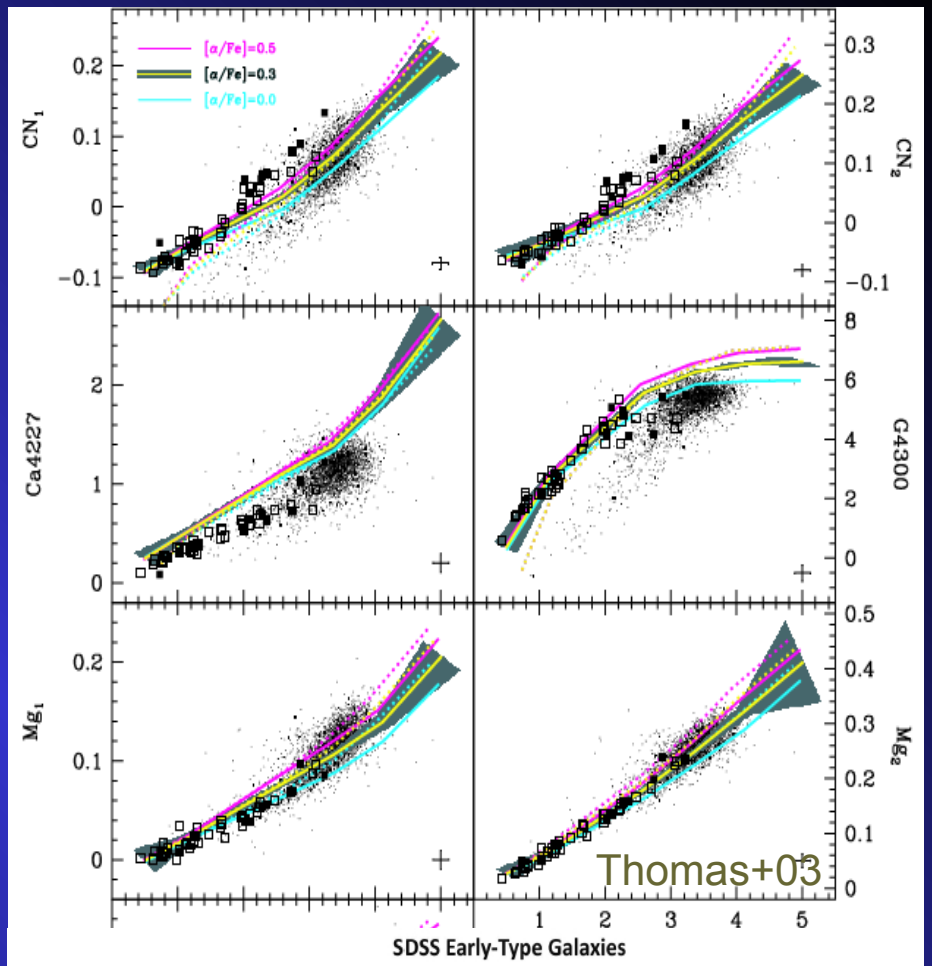
V+04

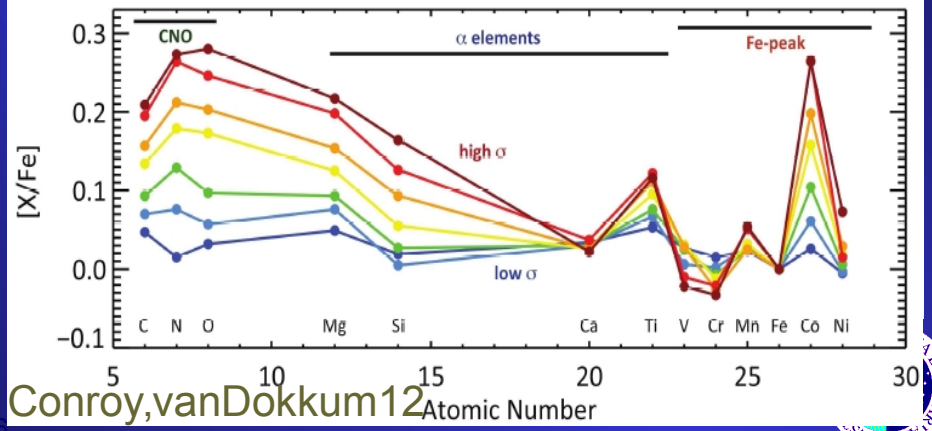
Stellar populations: abundance ratios

New modeling means allowed us to obtain detailed abundance patterns in ETGs: not only Mg but also other elements deviate from scaled-solar!





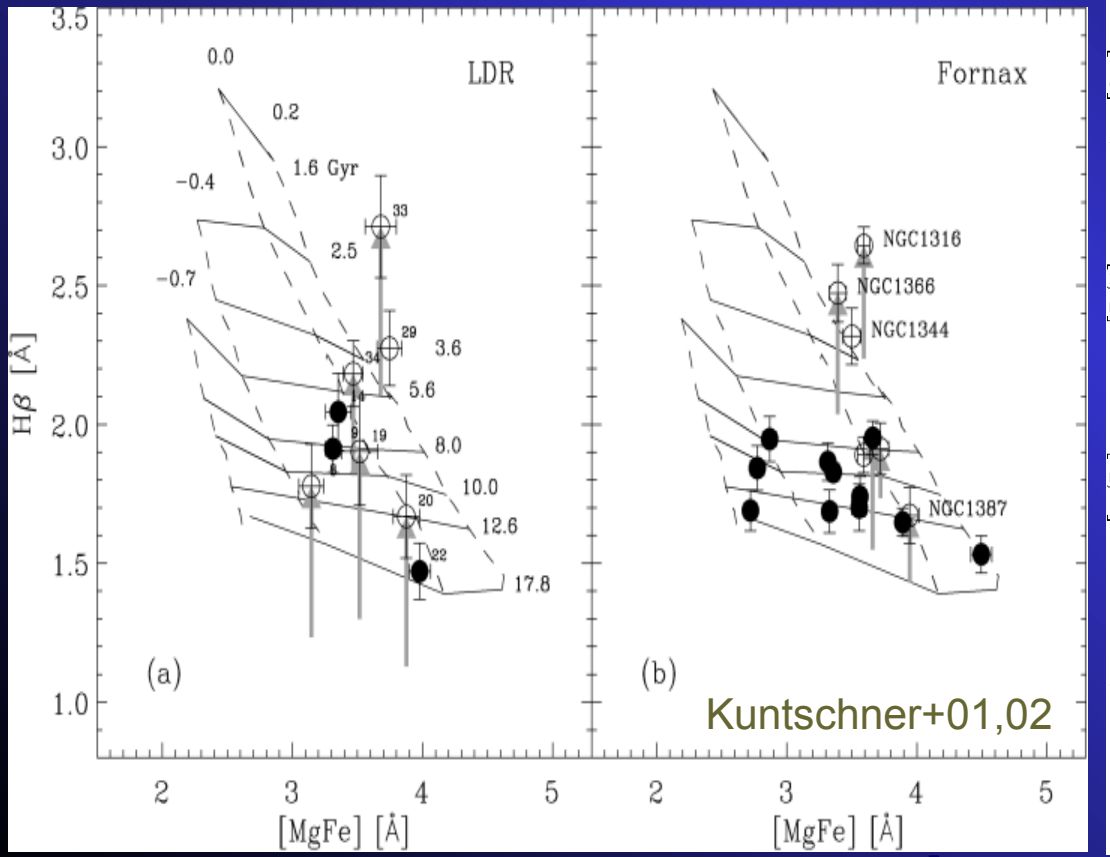


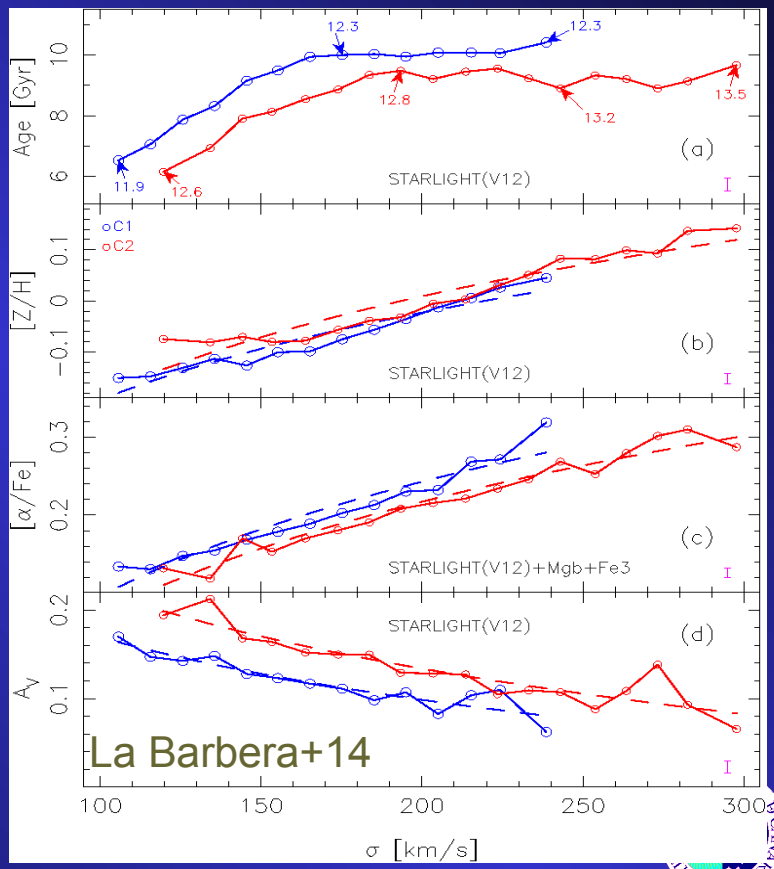


Stellar populations: nature vs. nurture

Mass, as traced by the central velocity dispersion, is the major driver of stellar populations in ETGs. However ISOLATED ETGs show slightly younger (~1-2Gyr) ages than in CLUSTERs

Central galaxies of similar mass in massive halos are slightly younger than those in low mass halos. They show slightly lower [Mg/Fe] too.

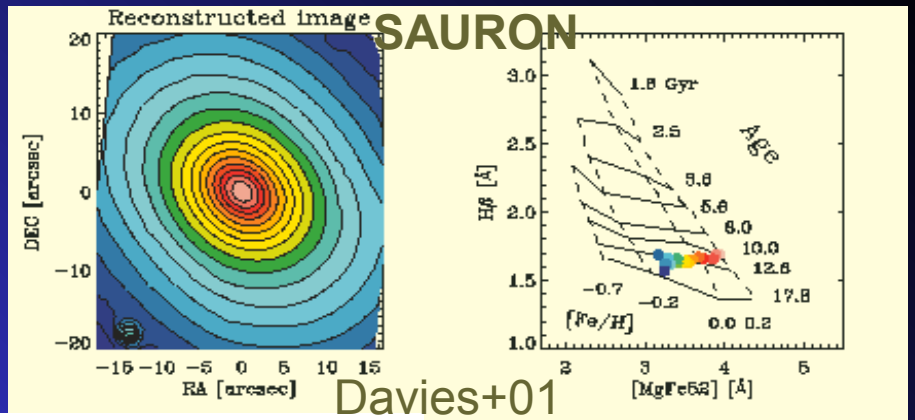




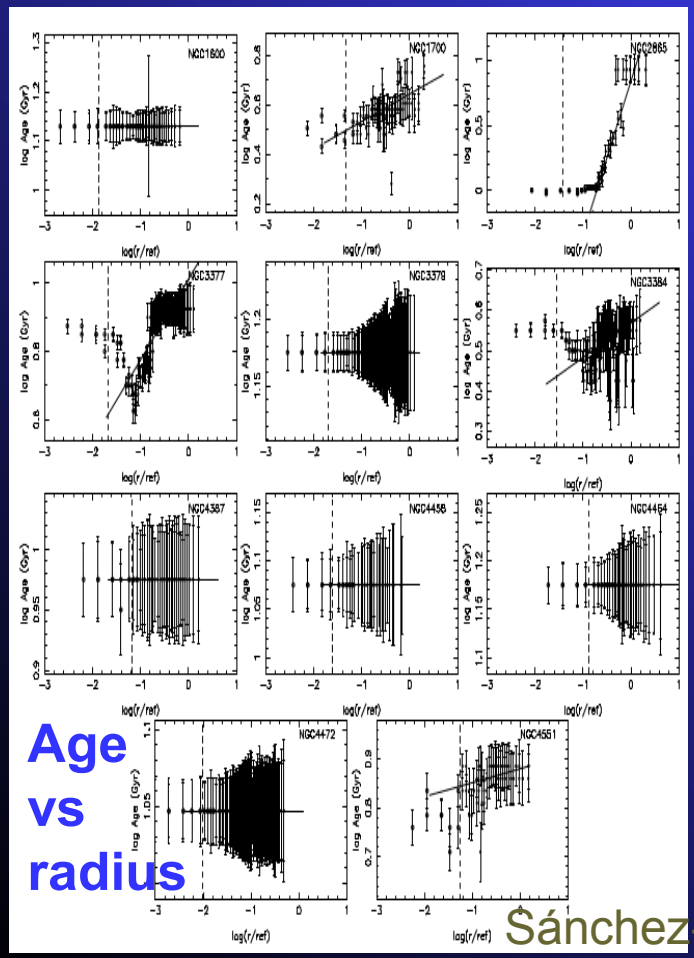
Stellar populations: gradients

Long-slit on 8-10m & IFU on 4m class telescopes allowed us to reach ~1Re.

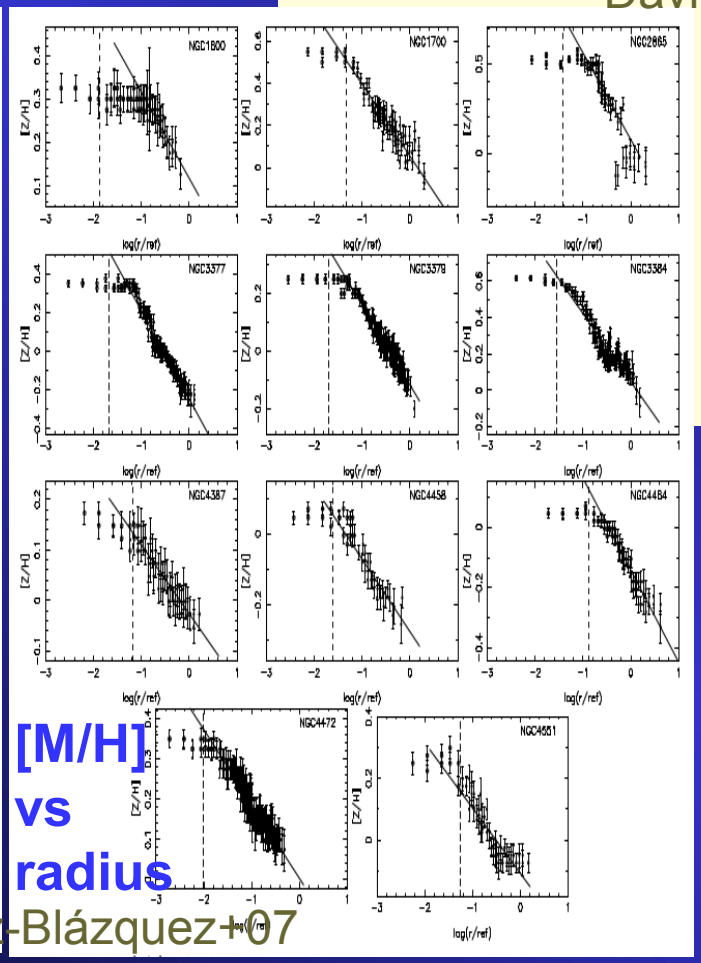
Nearly constant age gradients and strong metallicity decay with radius



Davies+01

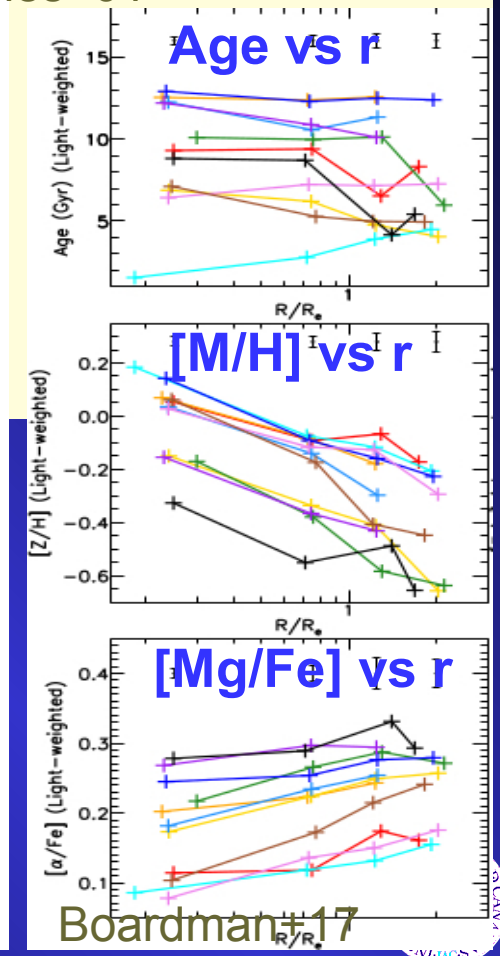


Age vs radius



[M/H] vs radius

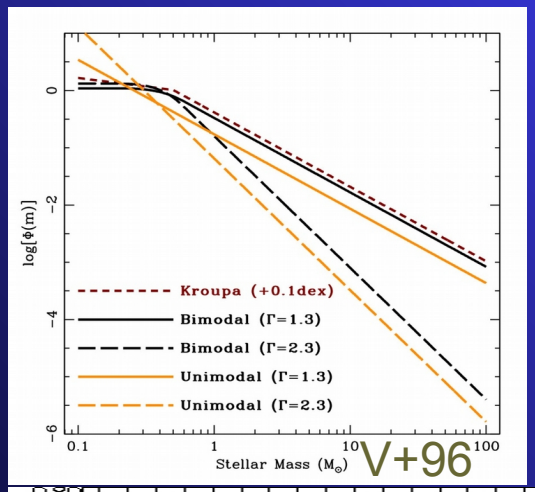
Sánchez-Blázquez+07



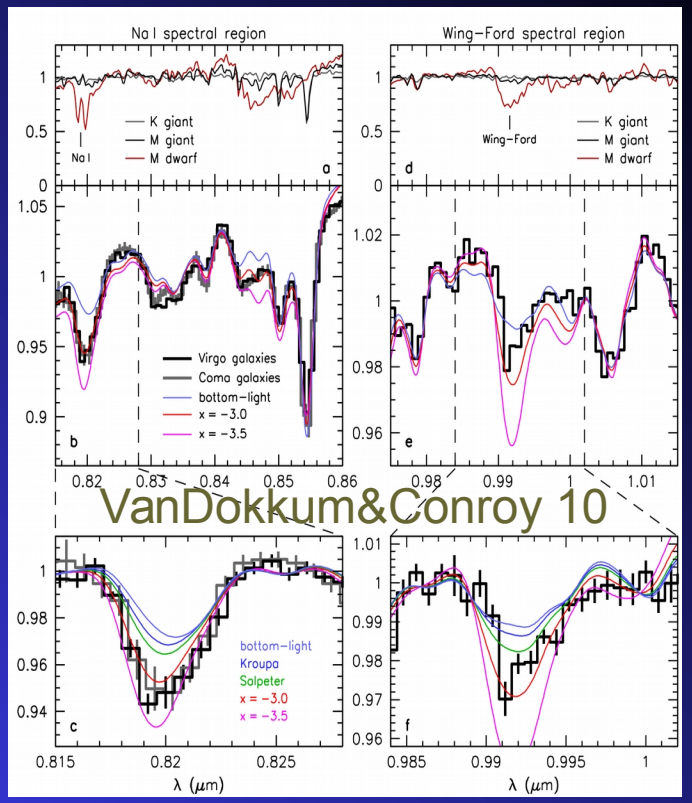
Boardman+17

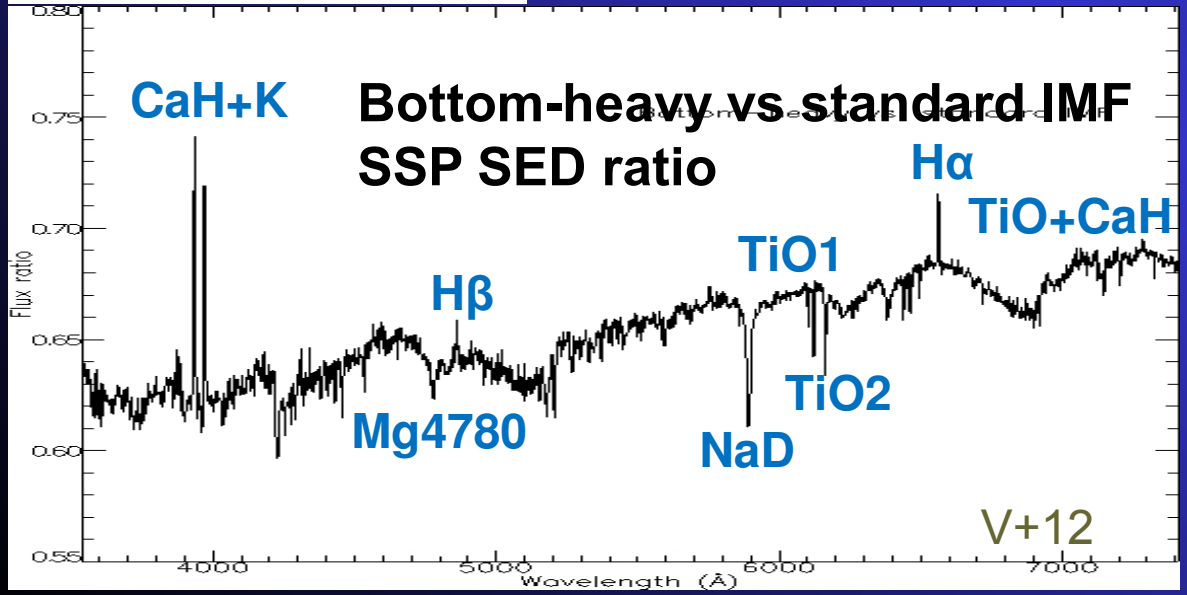
Stellar populations: is the Initial Mass Function universal?

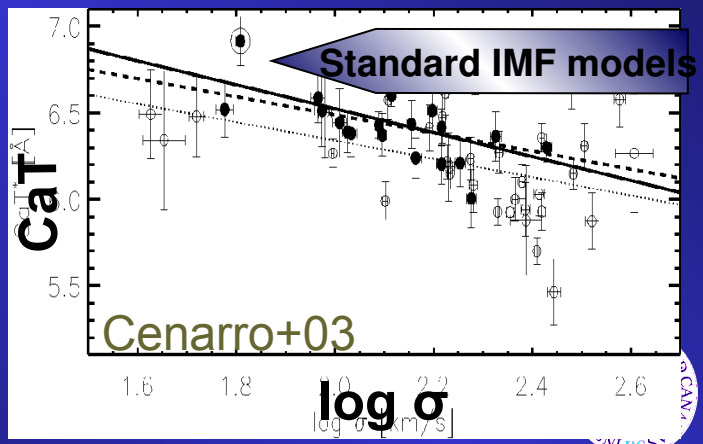
IMF-sensitive atomic & molecular bands can be used to constrain the IMF of ETGs



Massive ETGs cannot be fitted with a standard IMF. The ear-IR Call triplet feature already suggested ~15 years ago that massive ETGs have a larger mass fraction of low-mass dwarfs.

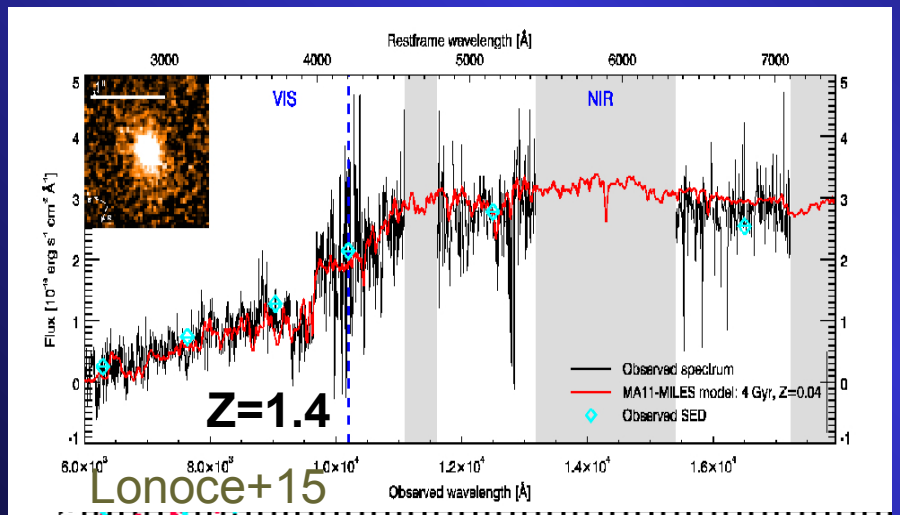




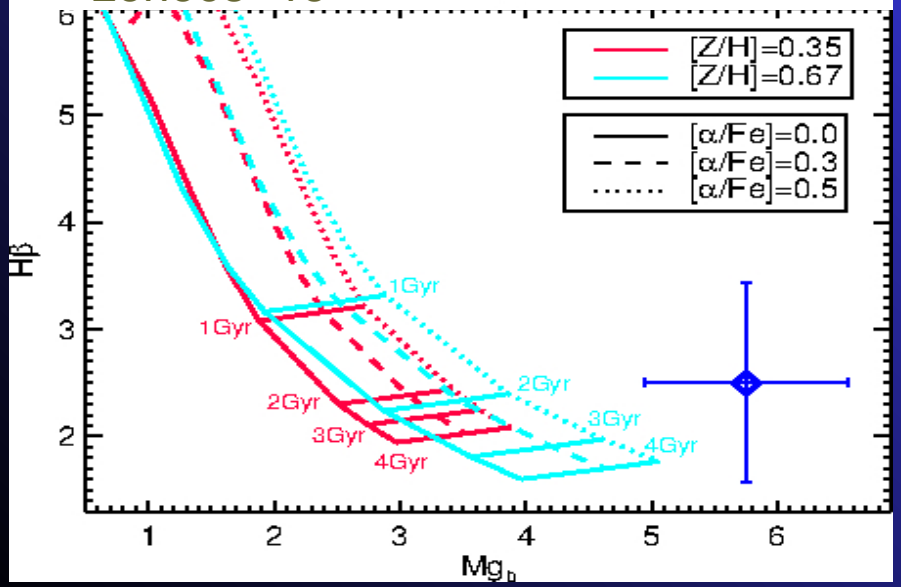


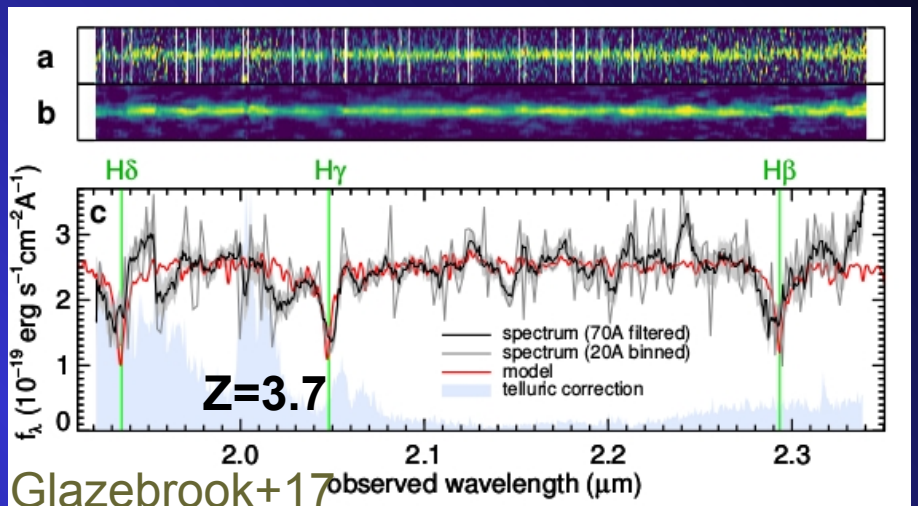
Detailed stellar populations at high redshift

Stellar populations as old as the Universe in red luminous galaxies at z > 1 ?

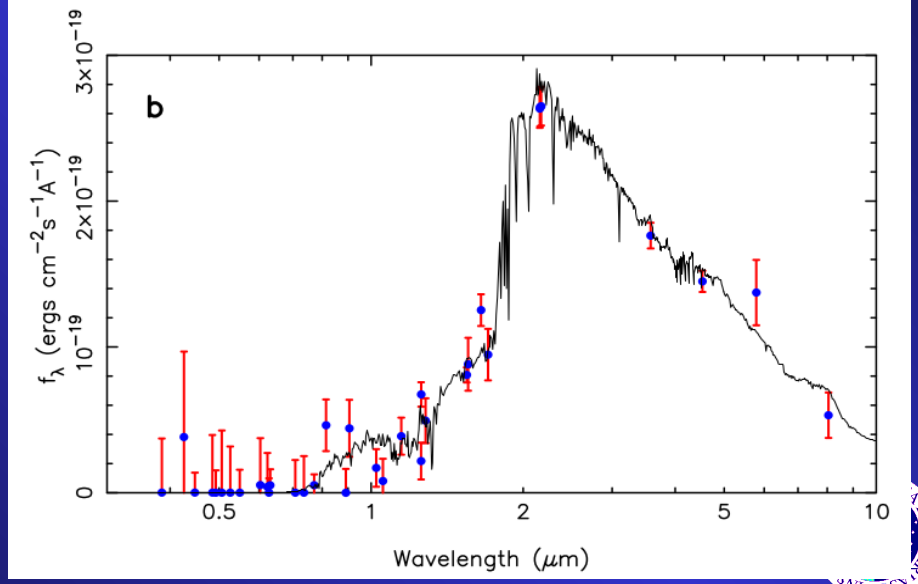


Lonoce+15



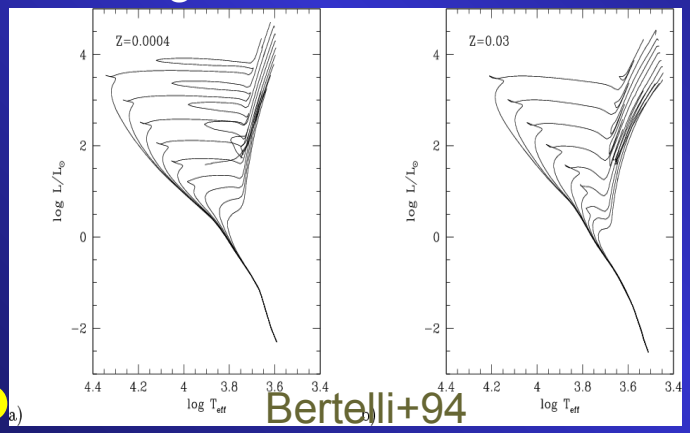


Glazebrook+17



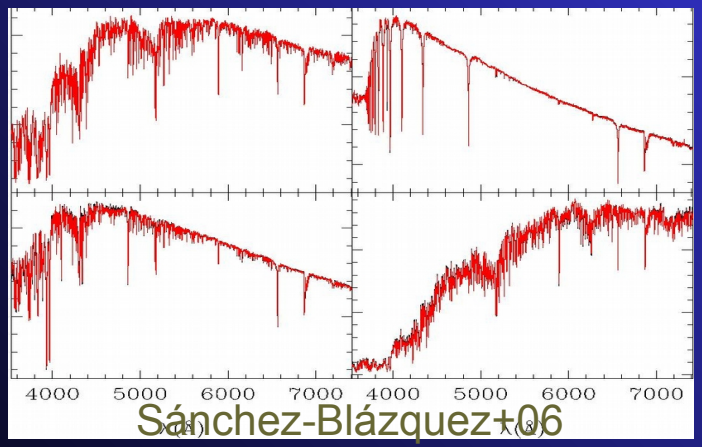
Stellar population synthesis models & main ingredients

ISOCHRONES: Geneva, Padova, BaSTI, Dartmouth, Lyon, Y^2, Victoria-Regina, Weiss+, MIST, …

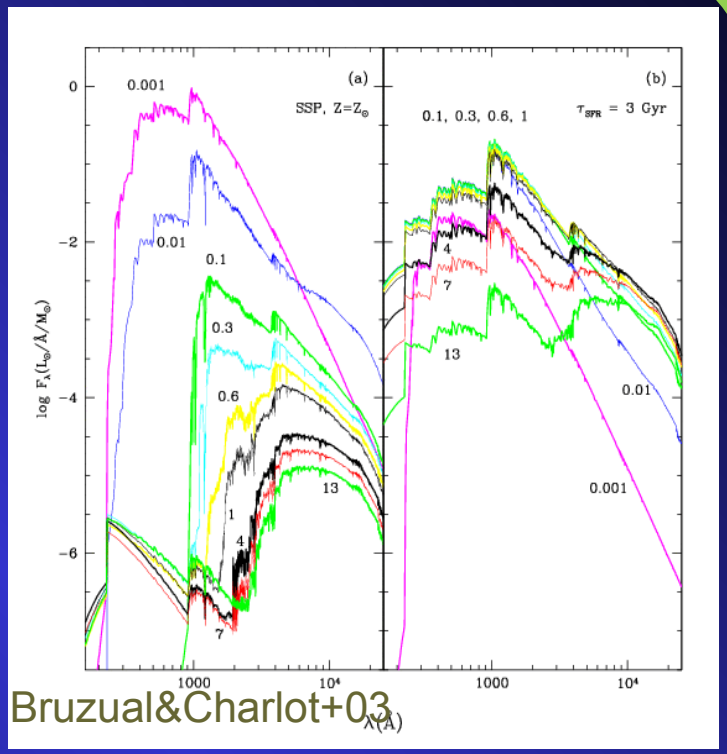


Bertelli+94

$$\int F_{\lambda}(m,T(t_o),g,Z)\,IMF(m)\,dm = SSP$$



Sánchez-Blázquez+06



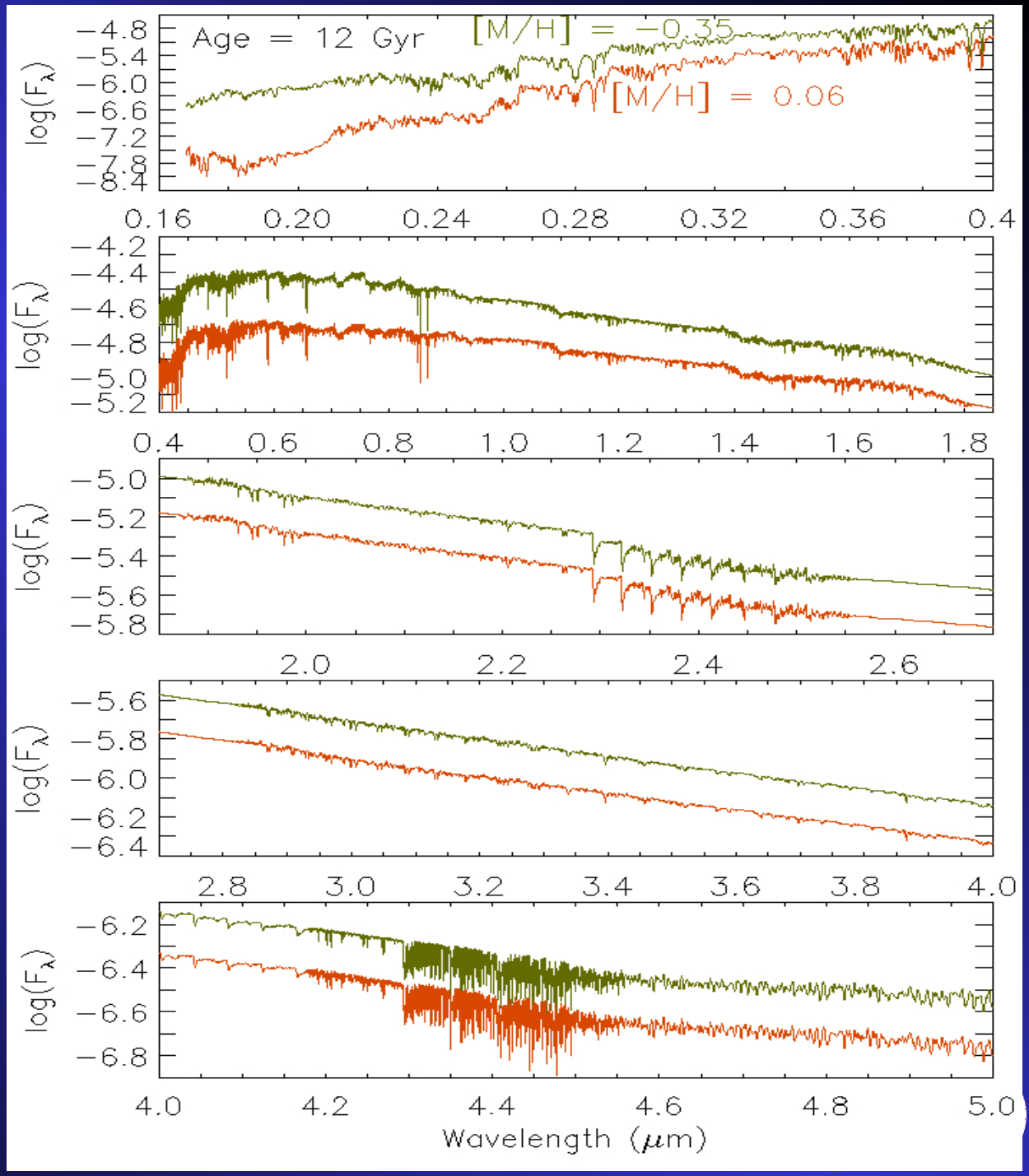
Bruzual&Charlot+03

Bruzual&Charlot, Coelho+, FSPS, GALEV, Kodama&Arimoto, Maraston &Thomas, MILES, Padova, PEGASE, Schiavon,Starburst, Worthey,YEPS…

STELLAR LIBRARIES: Theoretical: Kurucz, Coelho+,PHOENIX... Empirical:Pickles,STELIB, MILES …

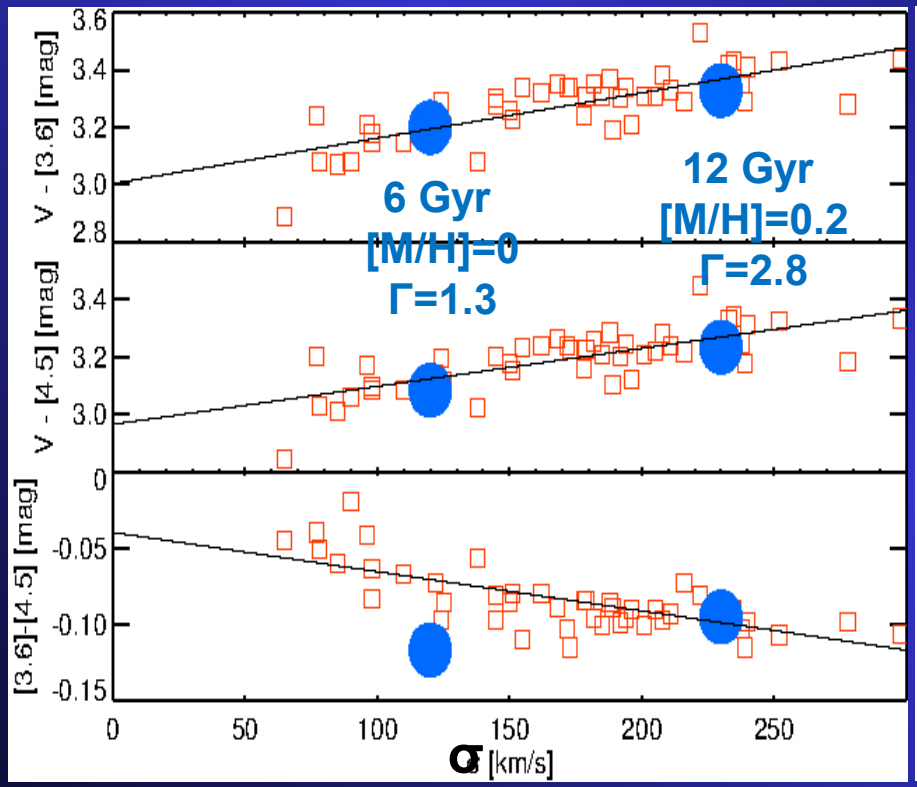
Extended E-MILES models (miles.iac.es)

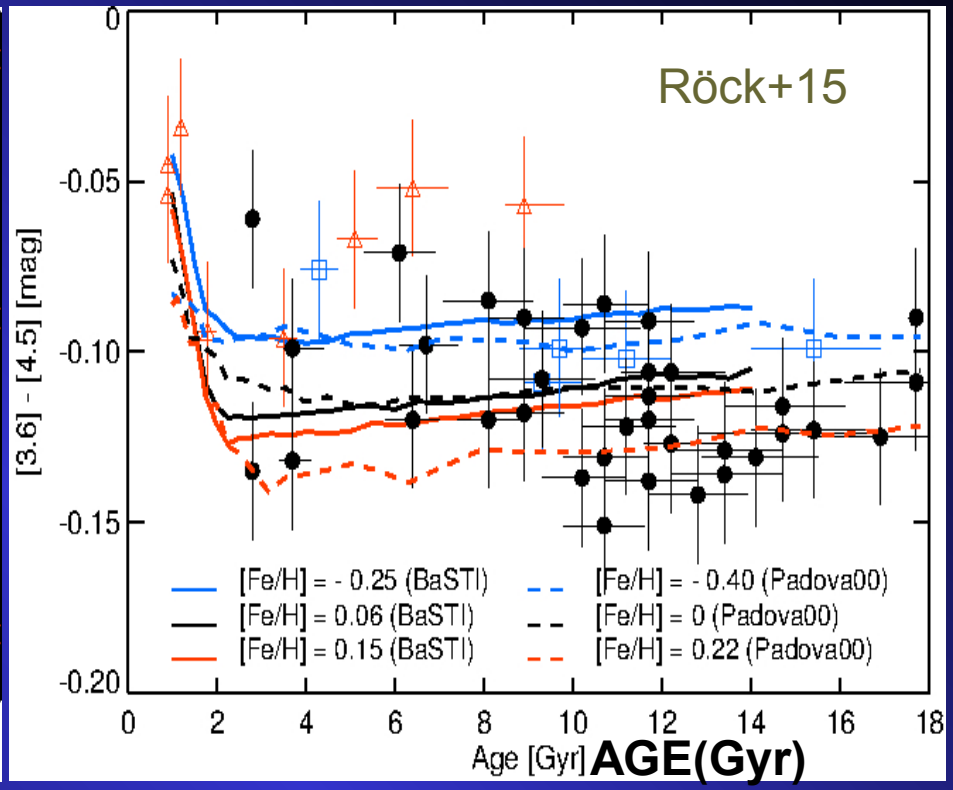
- Based on extensive fully empirical stellar spectral libraries (NGSL, MILES, Indo-US, CaT, IRTF)
- Spectral range: 0.17-5μ
- Resolution: FWHM~2.5Å (λ<0.9μ) σ ~ 60 Kms^{-1} (λ>0.9μ)



V+16

Spitzer Mid-IR colours: confirm that massive ETGs are well fitted by single-burst like old stellar populations as in the visible

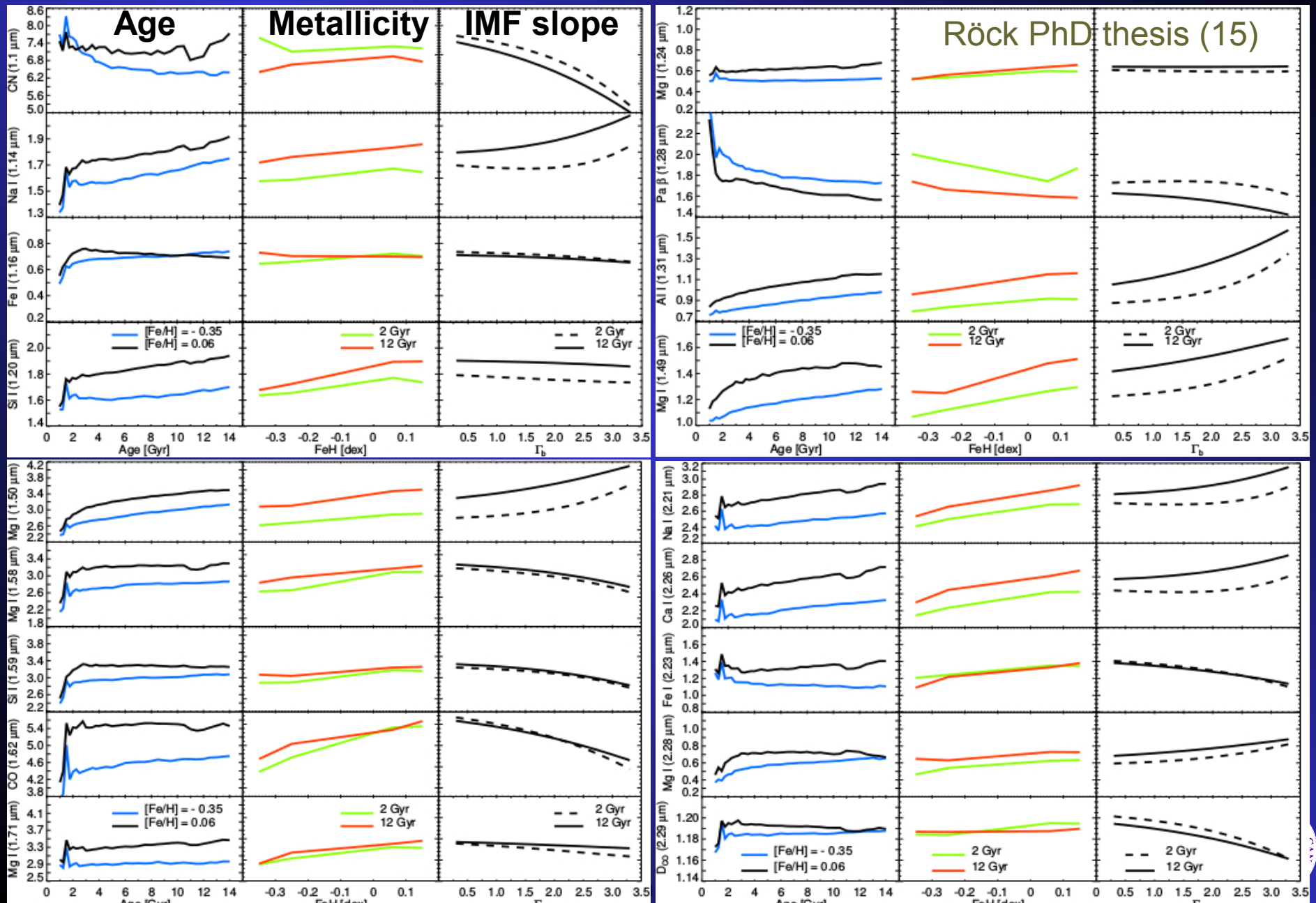




- V - [3.6] & V – [4.5]: Single-burst SSP models are in good agreement with Spitzer colours of massive ETGs.
- On the contrary, SSP models do not match low-mass galaxies: the presence of younger components redden their [3.6] – [4.5] colours

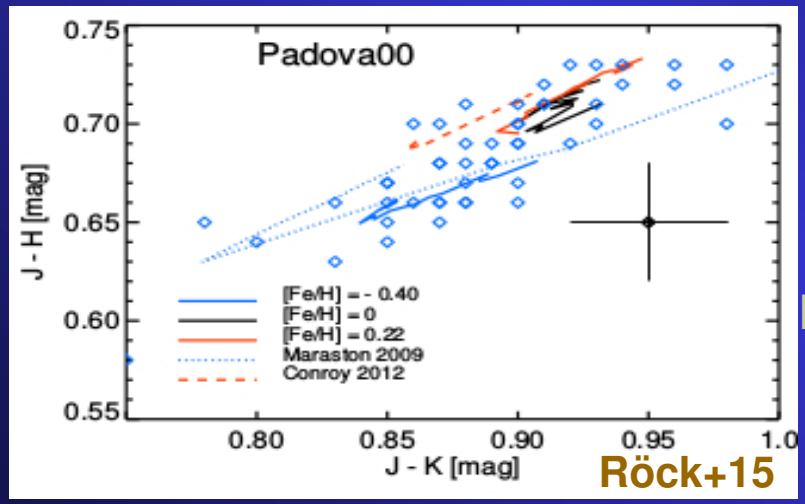
No need for a 1~Gyr red component with an emphasized contribution of AGB stars to fit massive ETGs, but the low-mass ETGs!

Line-strength indices in the J,H,K bands:

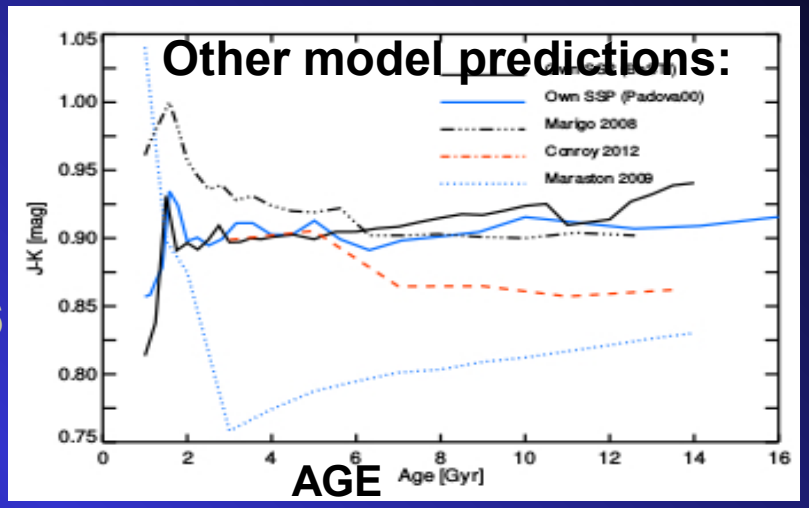


The Near-IR: are there intermediate-aged (AGB-dominated) stellar populations that go unnoticed in the optical range?

→ as claimed from Near-IR colours: we obtain good fits with just single-burst like old stellar populations



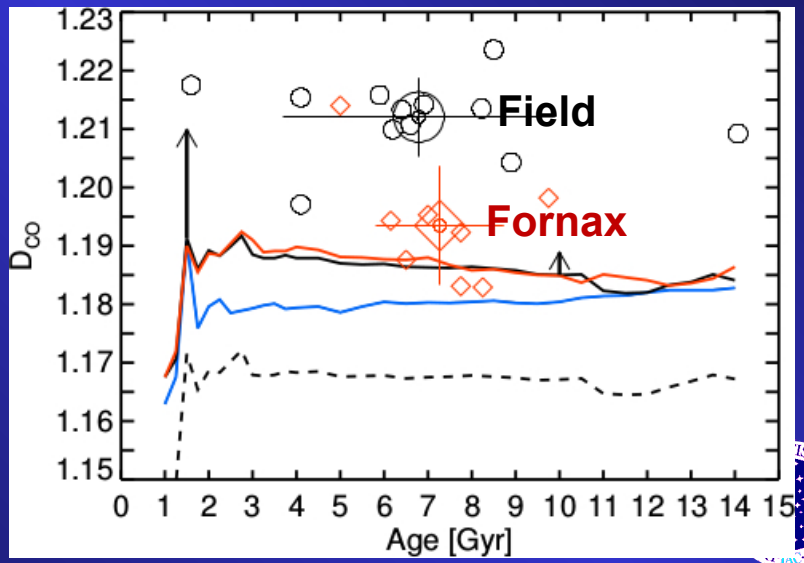
Röck+16



→ as claimed from near-IR indices:

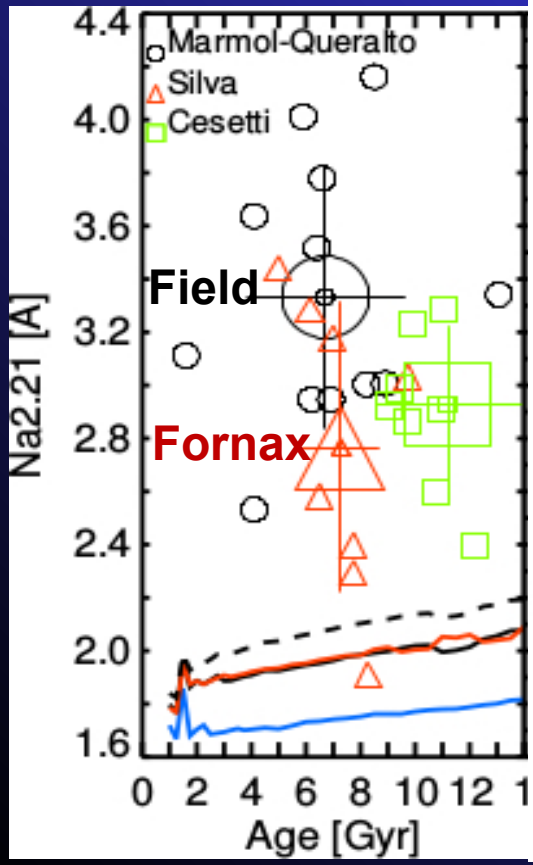
- OLD + 3%(1Gyr + AGB-enhanced to 70% contribution) doesn't fit.

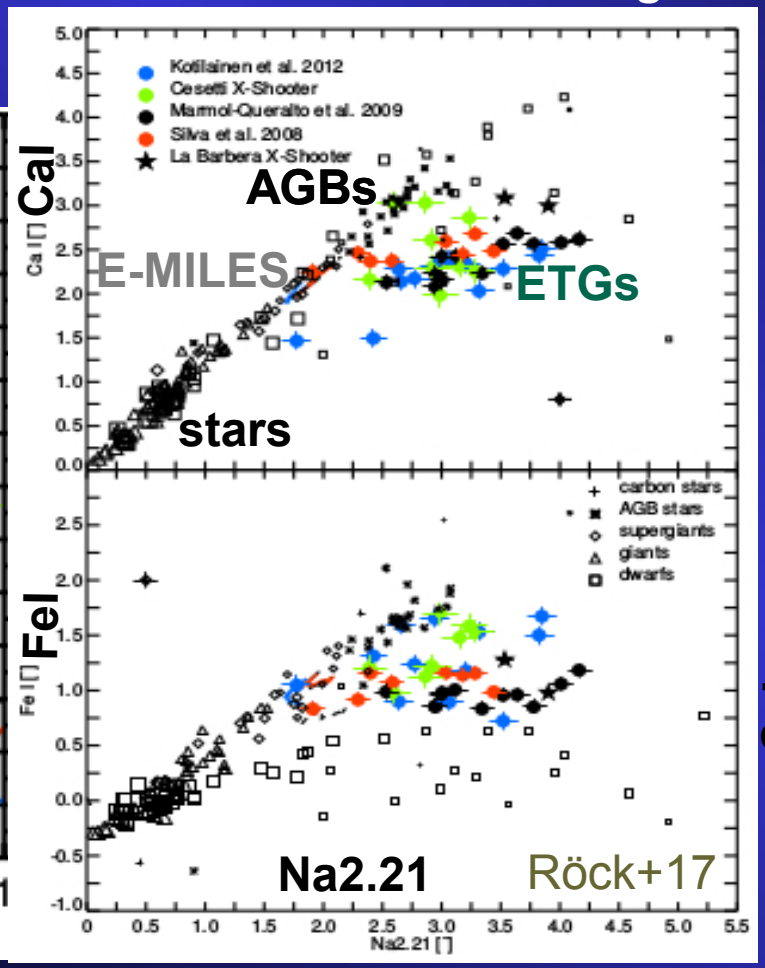
- Field ETGs could be fitted with 100% 1Gyr (however such a model doesn´t fit optical indicators (e.g. Hβ)



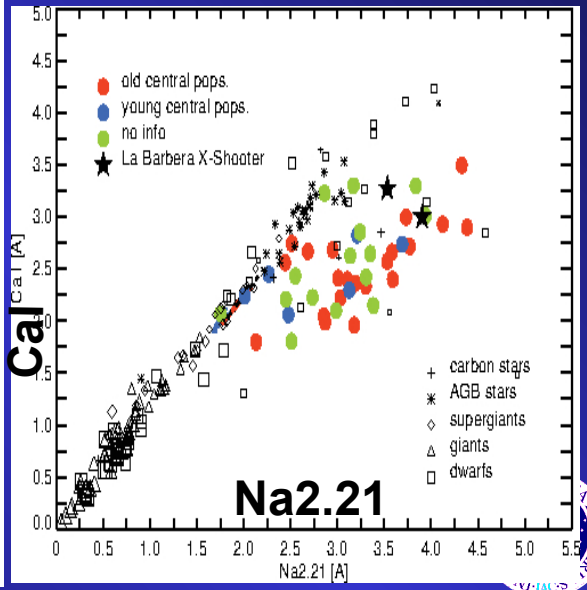
Abundance element ratios at work

- Na2.21 behaves similarly to the CO 2.3μ. Although a bottom-heavy IMF improves the results it is not enough to match the data.
- Cluster galaxies display smaller index values than those in the field. CO & NaI2.21 indices show an unprecedented sensitivity to the environment!
- ETGs don´t fall on the star's locus. Increasing the AGB contribution doesn't solve it



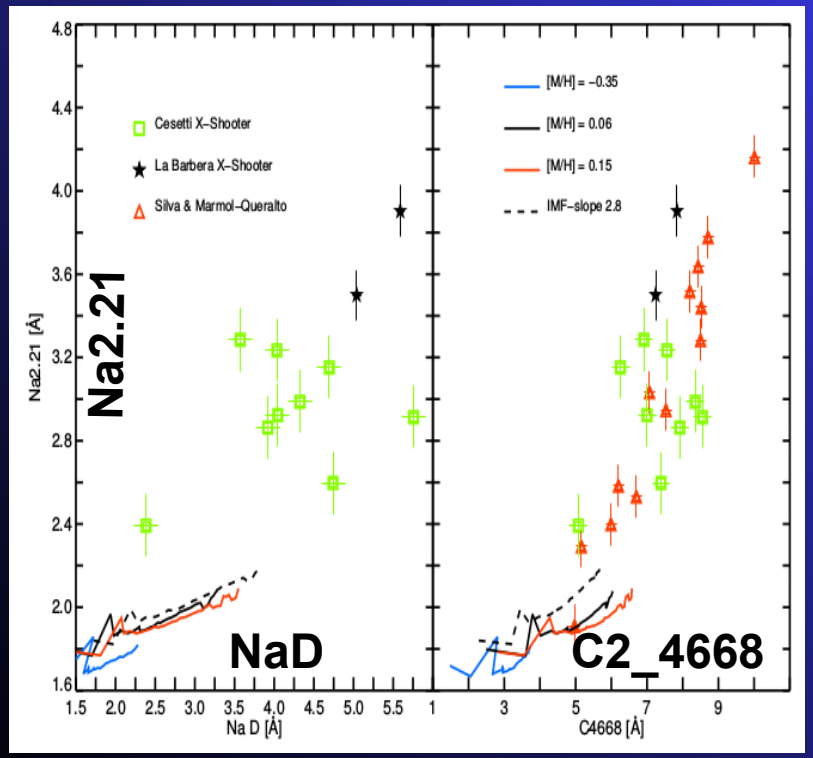


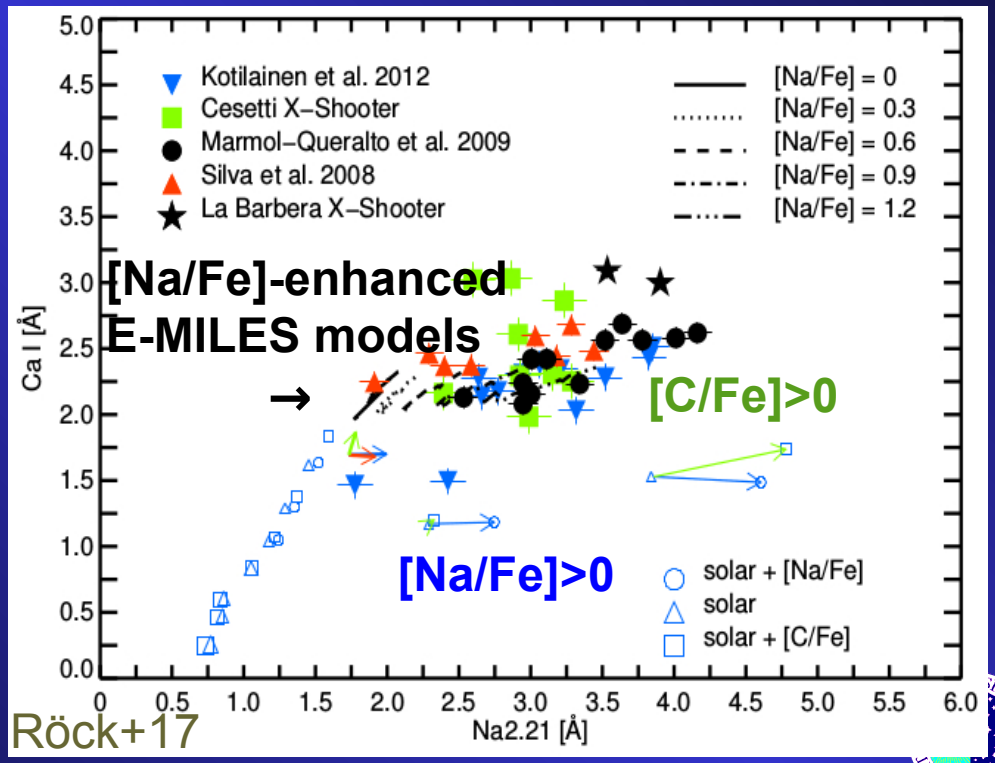
AGN host galaxies, both YOUNG & OLD, fall on the ETG's locus!



- Na2.21 correlates with C
- From theoretical star spectra:
  - [Na/Fe] enhancement increases Na2.21 at all temperatures
  - [C/Fe] enhancement increases Na2.21 only at very low temperature

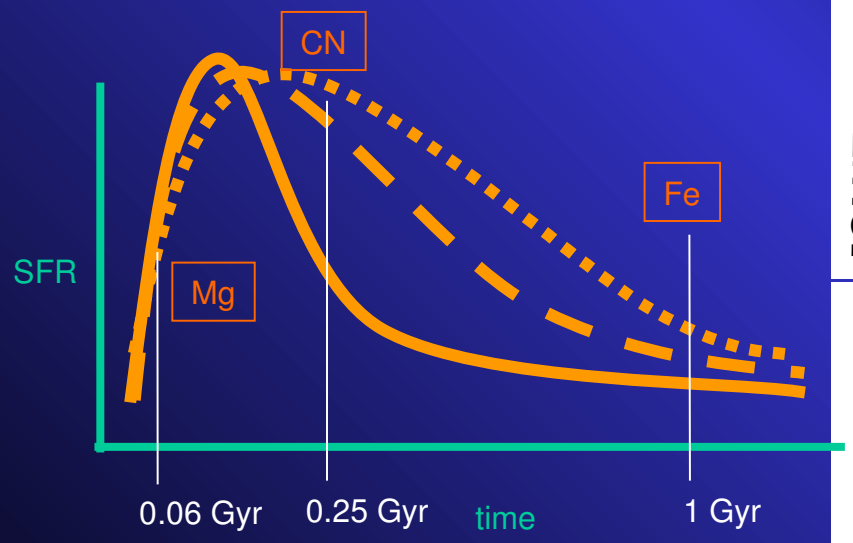
→ A bottom-heavy IMF burst these effects and E-MLES models fit!



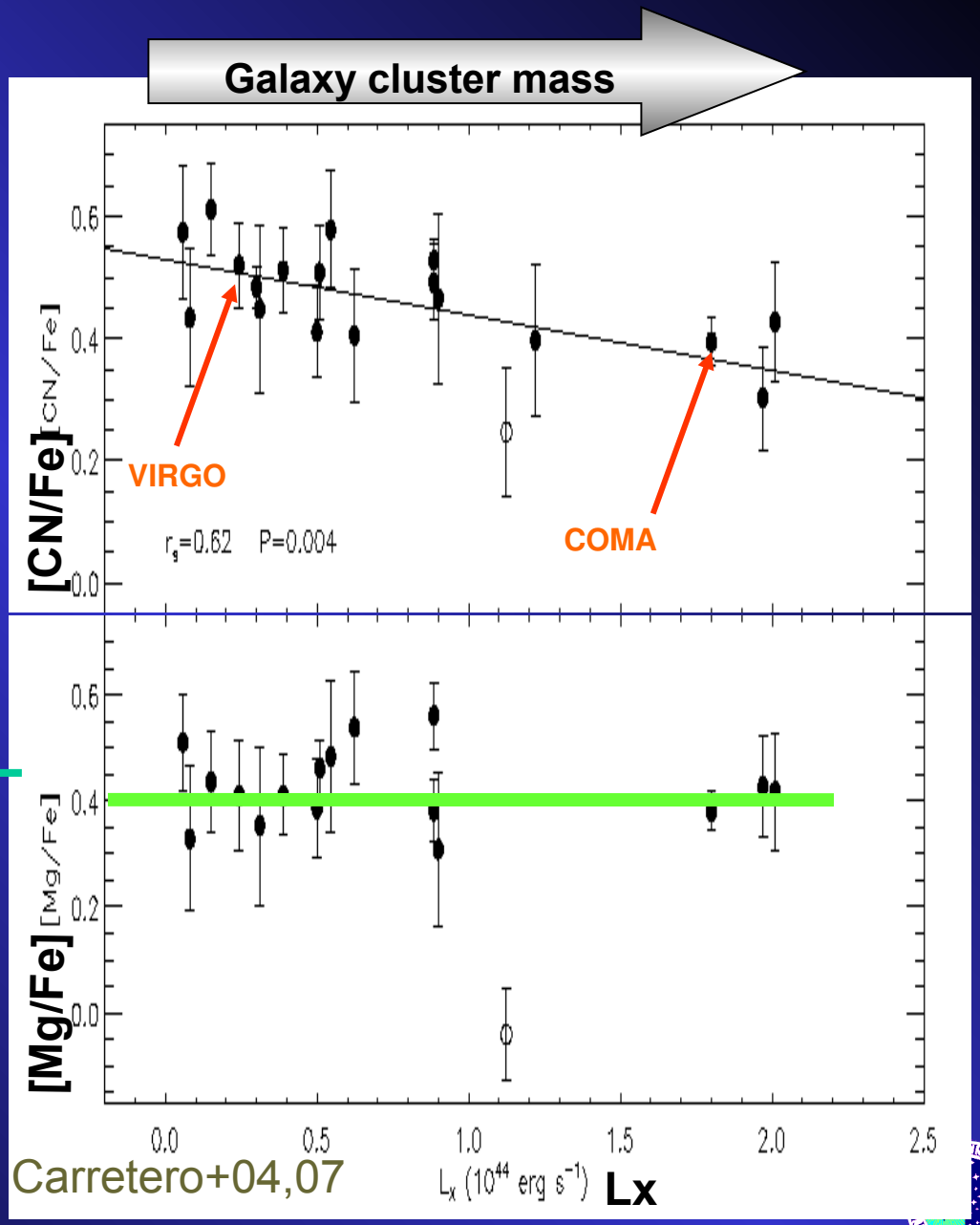


An alternative scenario:

From the optical range: [CN/Fe] correlates with Lx for ETGs of σ~200 km/s. [Mg/Fe]>0 insensitive



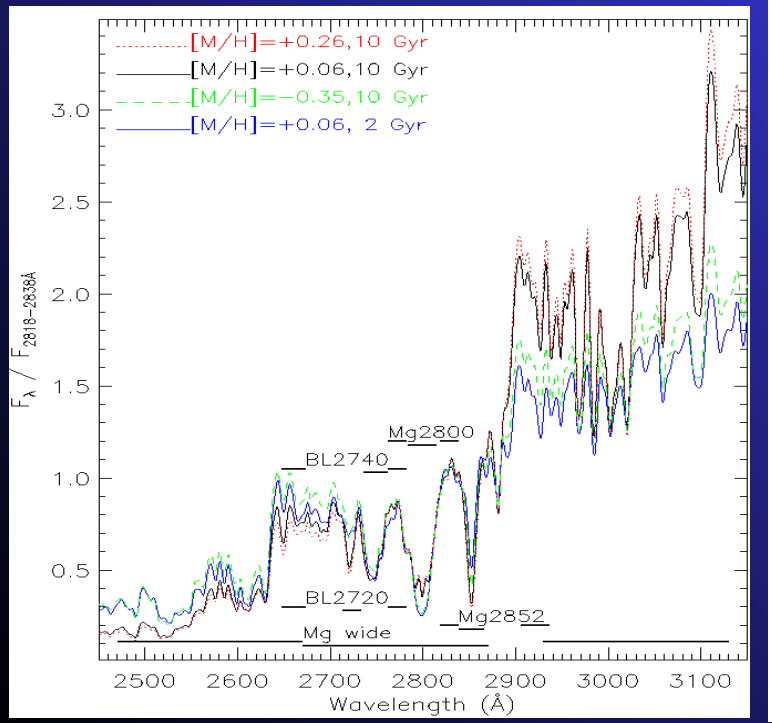
- **TG < 1 Gyr**
- **TG(rich cluster) < TCN**
- **TG(poor cluster) > TCN**

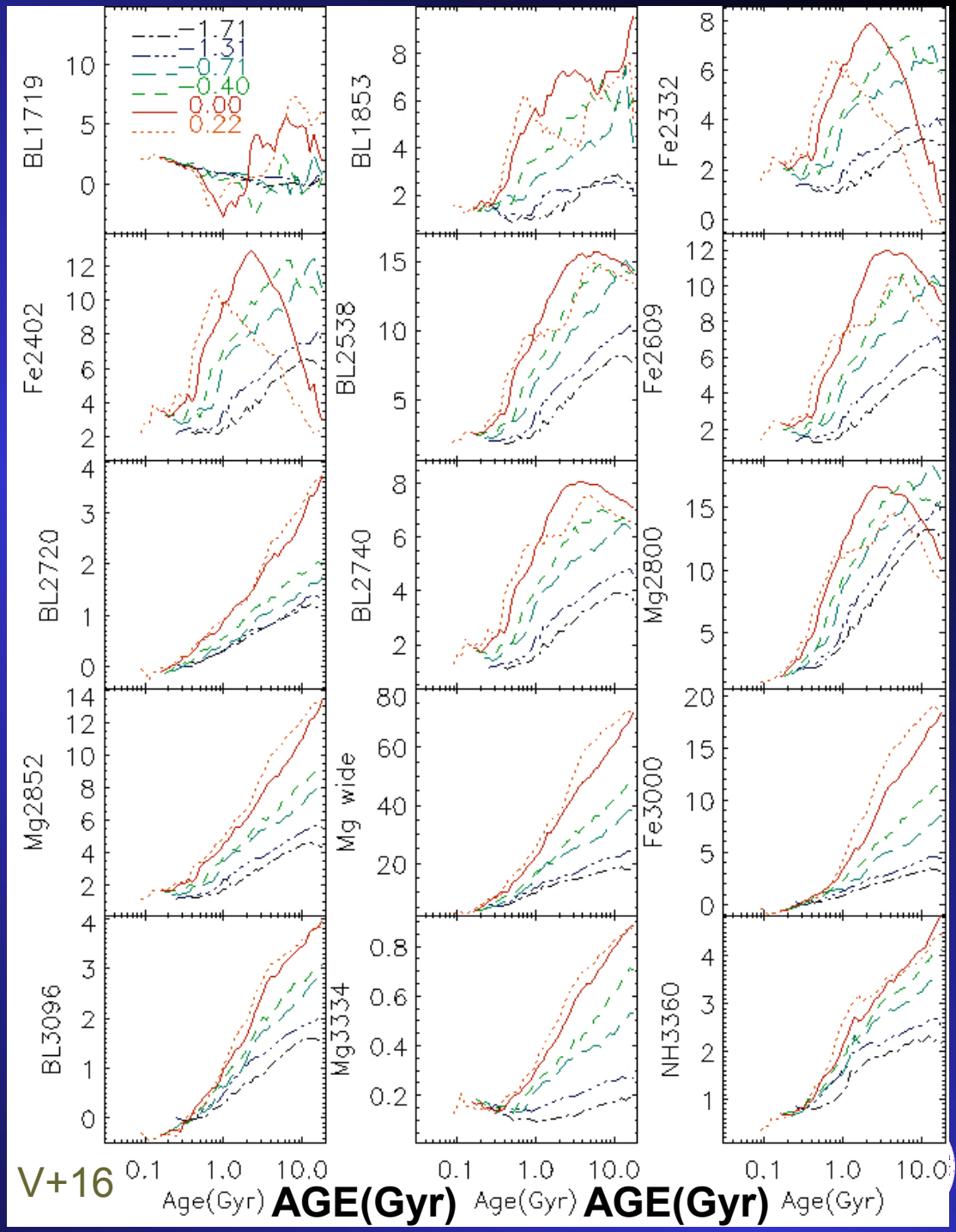


Carretero+04,07

UV line-strength indices

- Redder indices, e.g. Fe3000 strengthen with age much faster than in the optical
- Some (not all) indices below 3000Å peak around 2-3 Gyr (e.g., Mg2800, BL2402) for metal-rich stellar populations
- Varying behaviours offer new means to constrain the SFHs!

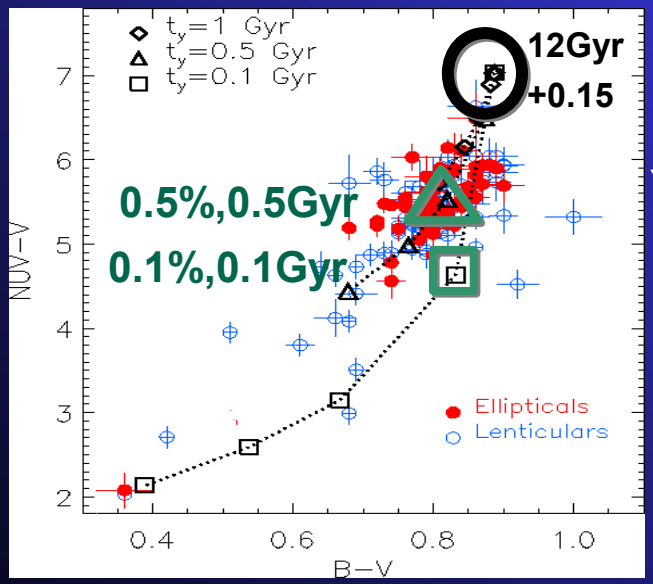




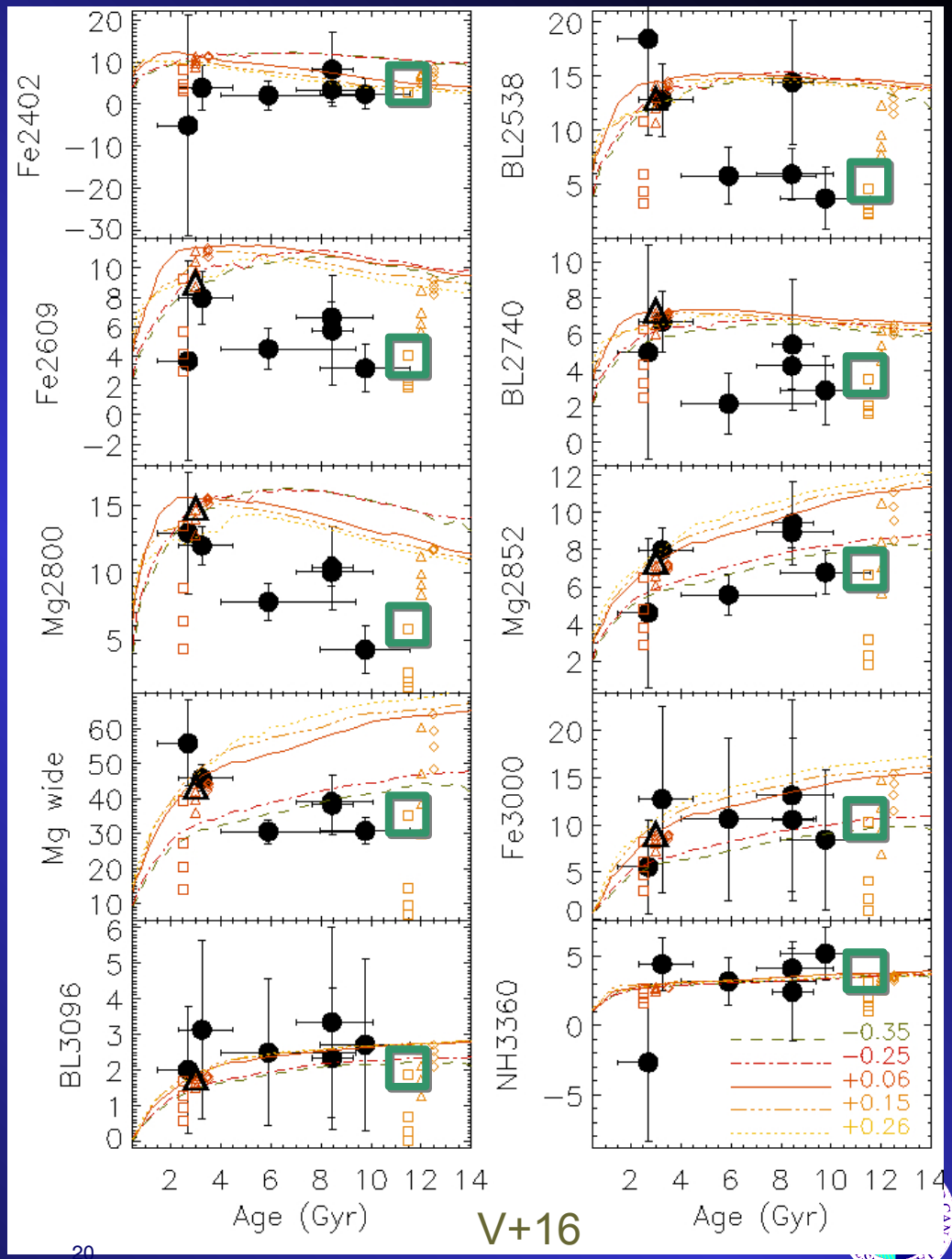
V+16

What about the UV?

- Both NUV colours & line-strengths show evidence of 0.1-0.5% mass fraction contribution of a 0.1-0.5Gyr component on the top of the old population
- These tiny contributions have little impact on the visible
- ~1Gyr component ruled out!

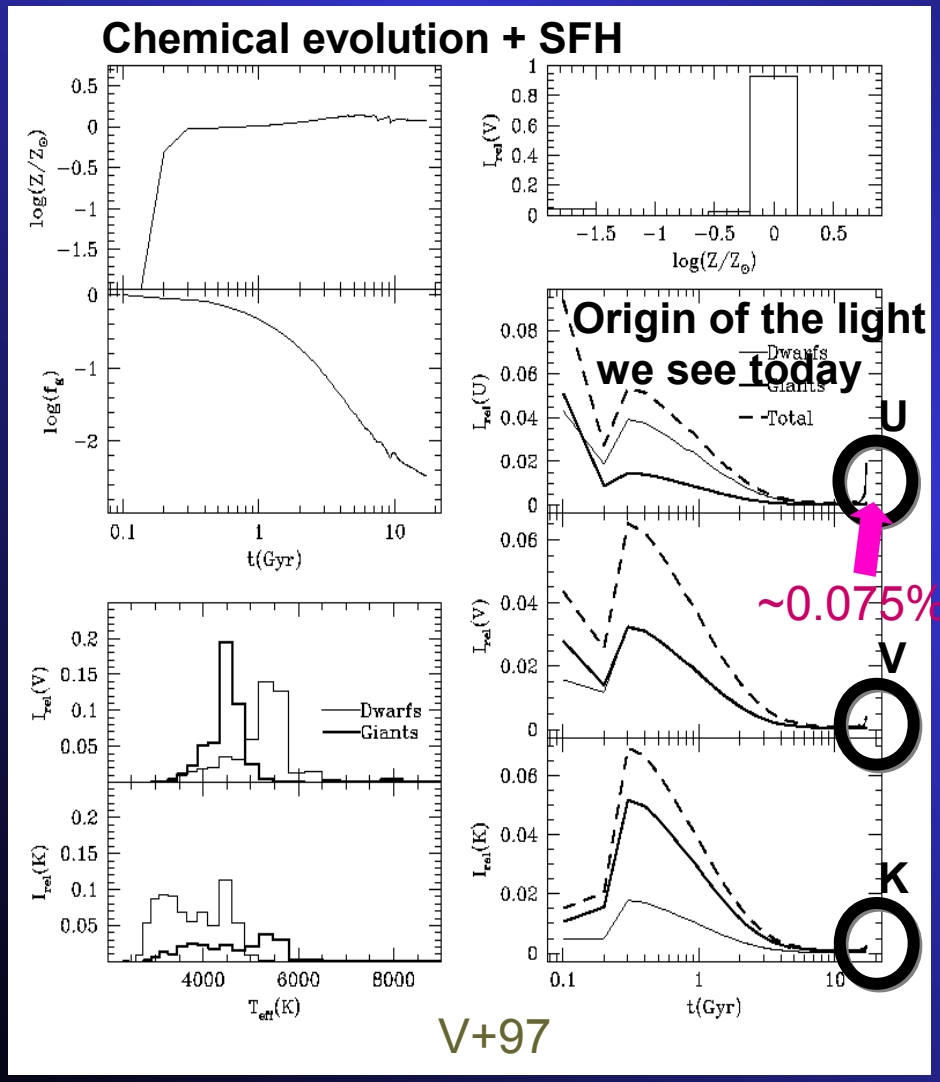


- Fully consistent results with the optical and near-IR !!!

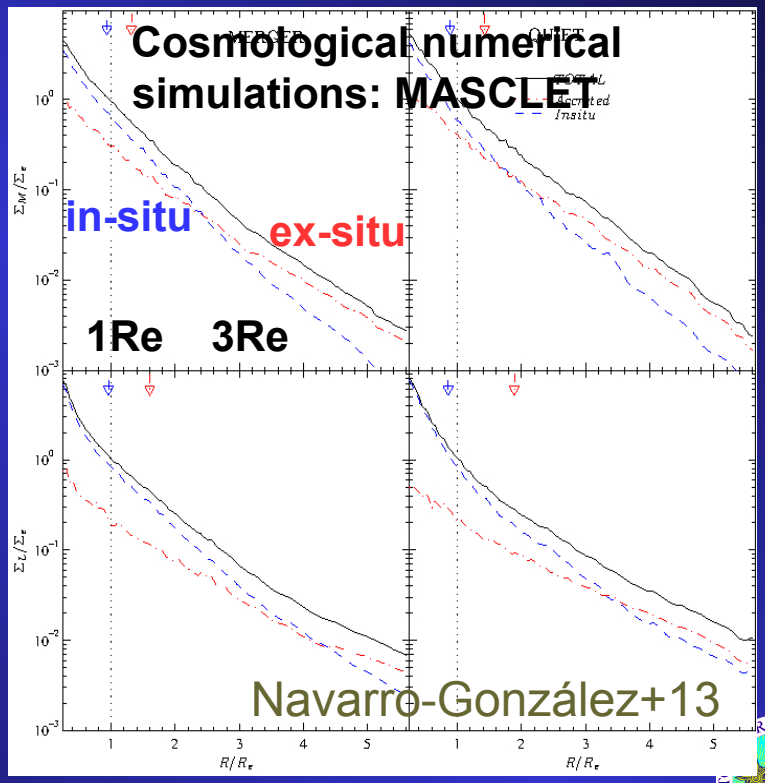


V+16

This result is fully consistent with residual SF within a passive evolution scenario with "no ex-situ" contributions



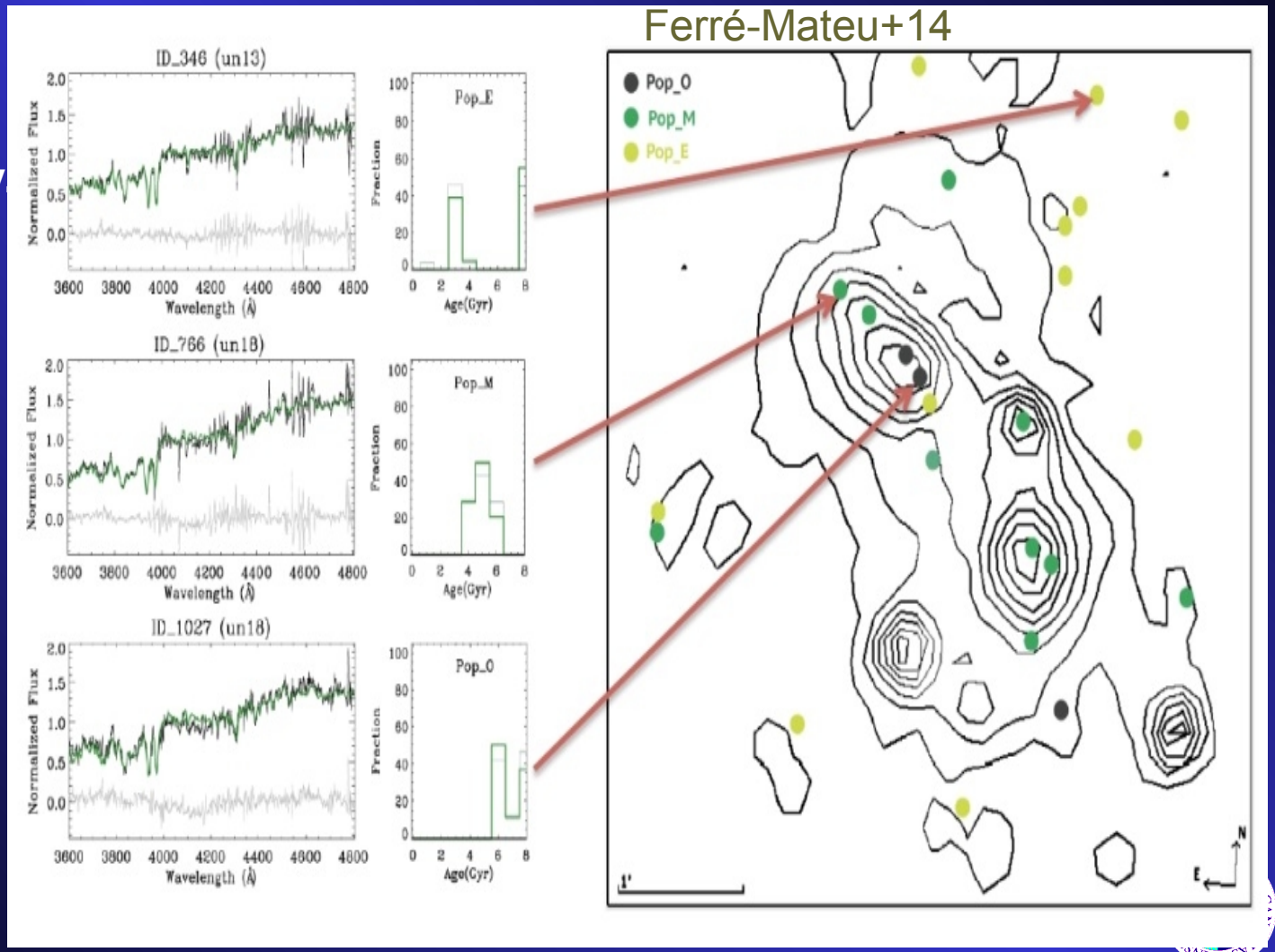
Cosmological numerical simulations: major "in-situ" contribution within < 1-3 Re



Evolution with redshift

Detailed spectroscopic analysis of individual galaxies in a massive cluster at z~0.8 (similar to Coma):

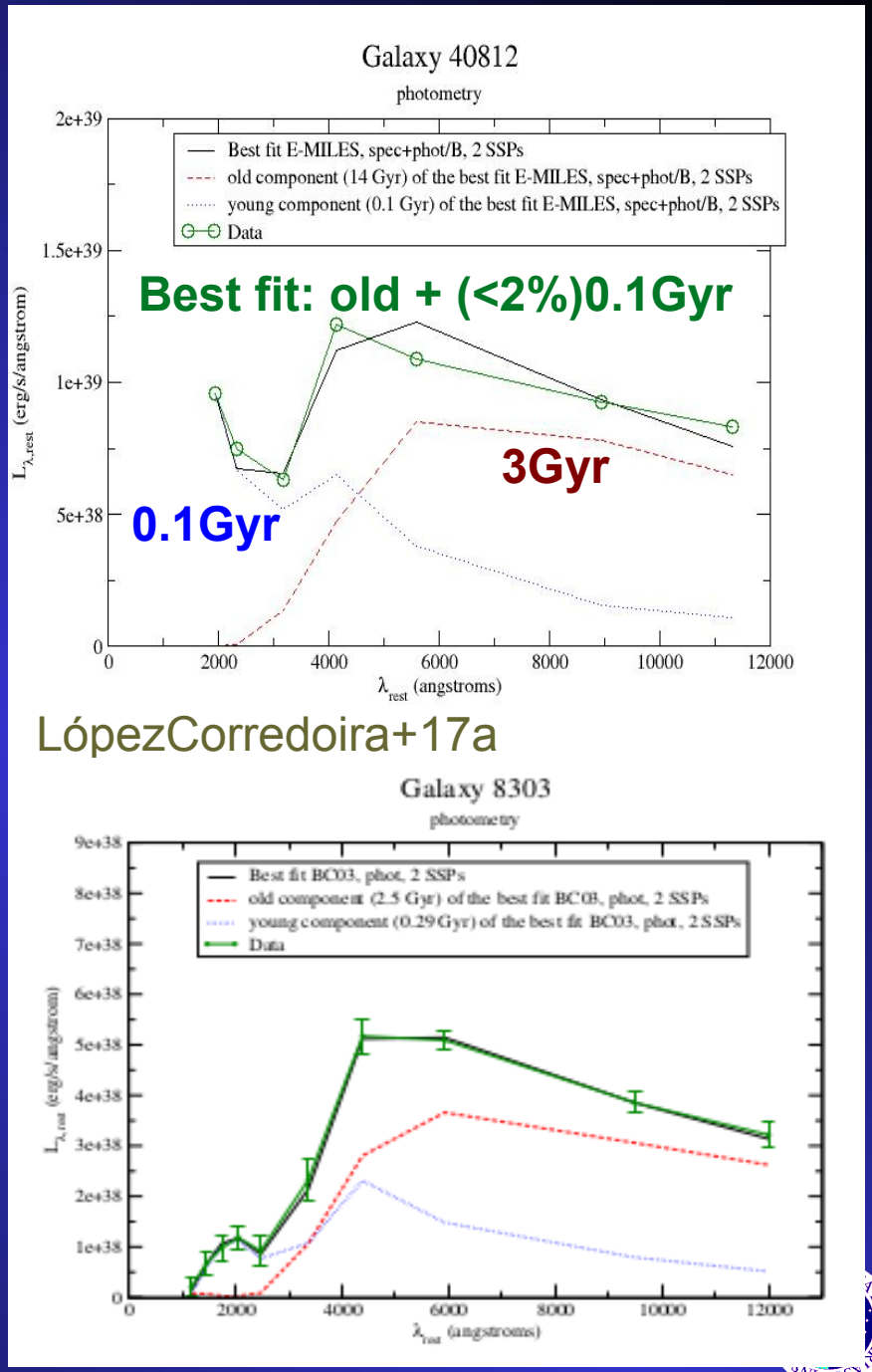
- **Massive galaxies are found in the denser regions evolving passively. Their lower mass counterparts are located on the cluster perifery and their full spectrum-fitting show more extended SFHs.**
- **Their line-strengths show abundance patterns already similar to Coma**



Evolution with redshift

Luminous red galaxies at z~3:

SED fitting: 3Gyr + 2-7%(~0.1Gyr), With more massive galaxies requiring < 2%.
(downsizing already present at z~3)
(LópezCorredoira+17 a,b)



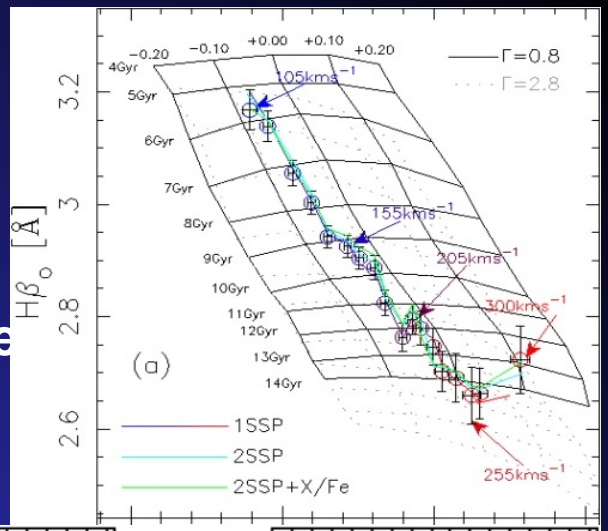
LópezCorredoira+17a

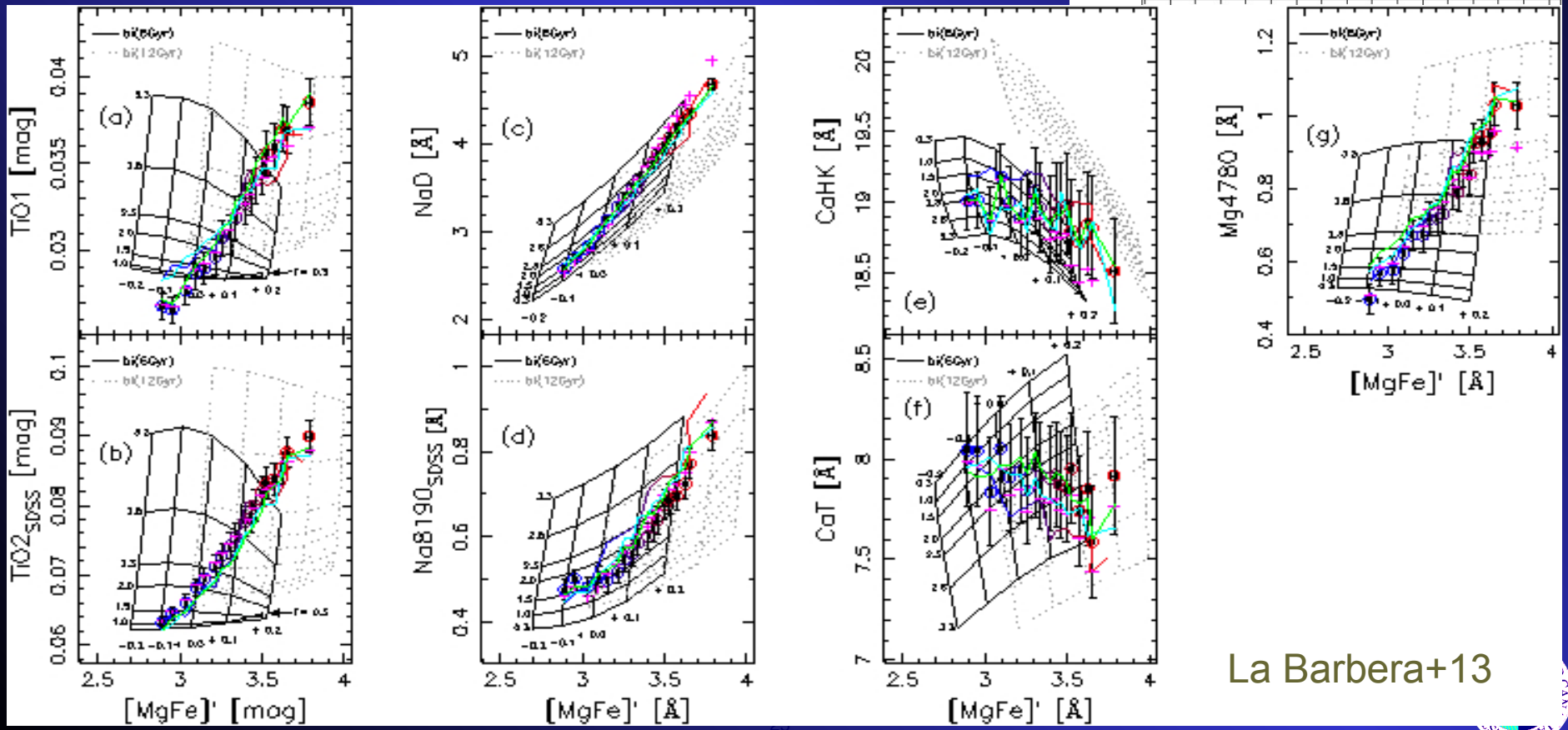
Summary: results from extending the spectral ranges

- The UV is extremely sensitive to very small (< 1%) contributions from stellar populations with ages < 1Gyr, whereas the Near-IR range shows an unprecedented sensitivity to the environment.
- Massive ETGs are well fitted with single-burst like old stellar populations all the way from the Near-UV to 5μ. Smaller ETGs show in general more extended SFHs.
- Tiny mass fractions of 0.1-0.5% of stellar components with ages 0.1-0.5Gyr are required on the top of a dominant old stellar population to be able to fit both the colours and line-strengths in the UV. Such contributions are fully consistent with residual SF.
- Similar result holds for luminous red galaxies out to z~3.
- The claim of a significant component of ~1Gyr with an emphasized AGB-contribution can be safely ruled out.
- Alternative view: the bulk of the stellar populations of intermediate-massive galaxies in denser environments form faster than the massive C-ejection timescale (<0.5Gyr). Field galaxies show enhanced [C/Fe], which when coupled with a bottom-heavy IMF, lead to stronger Near-IR Na2.21 and CO2.3 indices.

IMF in ETGs

- 40000 ETGs from the SDSS. Stacked galaxy spectra according to velocity dispersion (σ)
- More massive galaxies, with larger σ, are olde and more metal-rich.
- Use of IMF-sensitive indices:



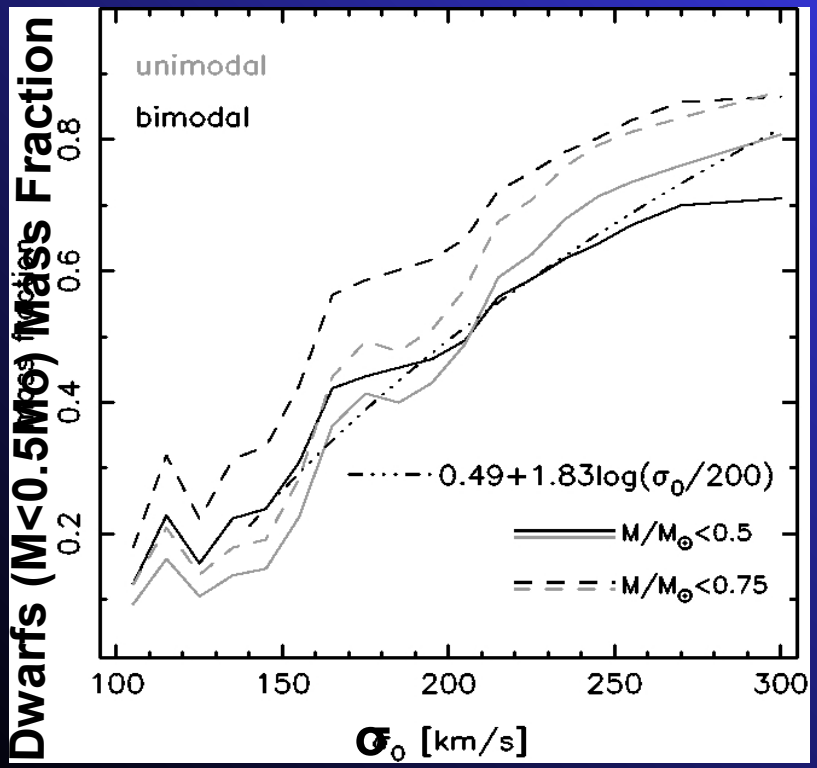


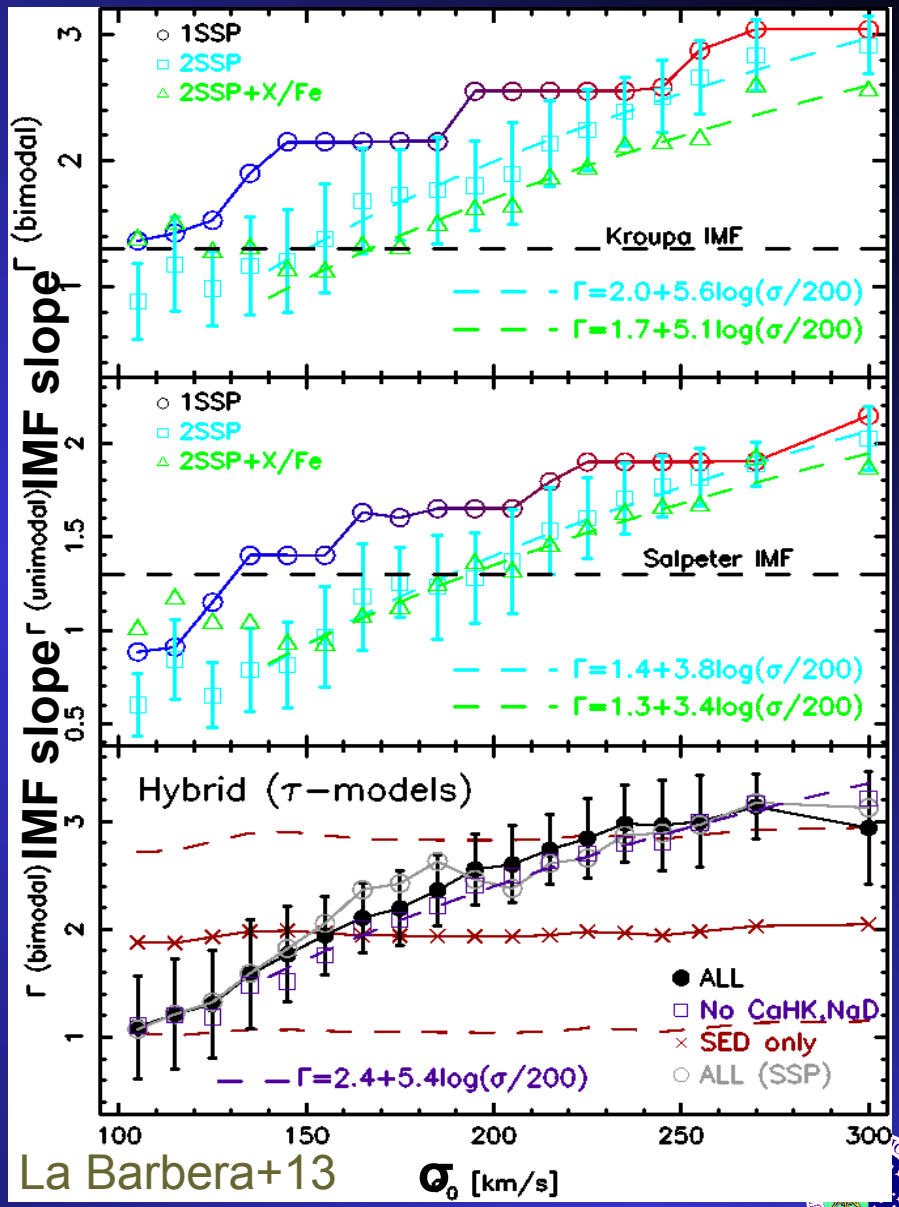
La Barbera+13

IMF in ETGs: IMF-σ relation

IMF slope steepens withincreasing σ (galaxy mass).

Massive galaxies have a larger mass fraction of stars with M<0.5Mo (~70%) than in the Milky Way (~30%).

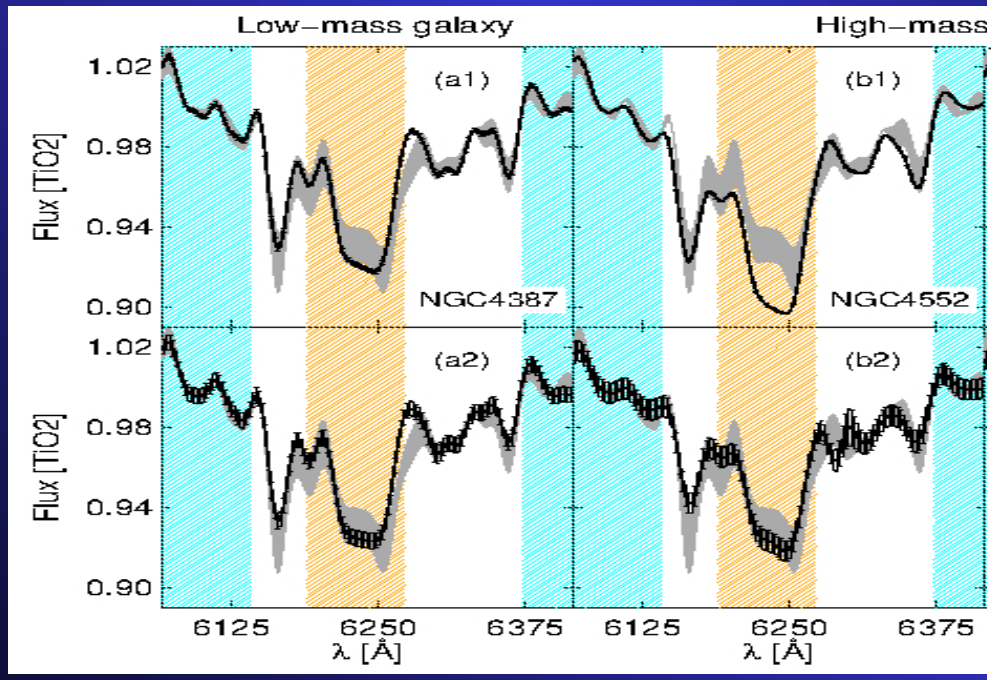


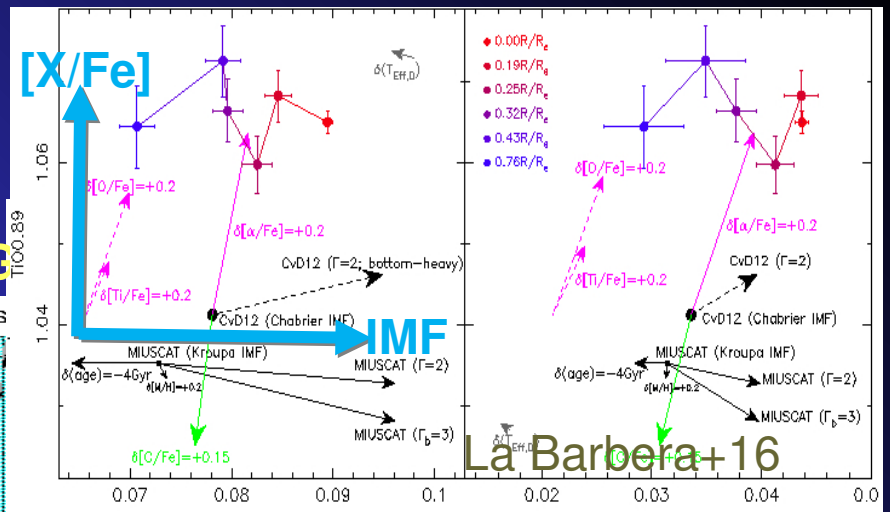


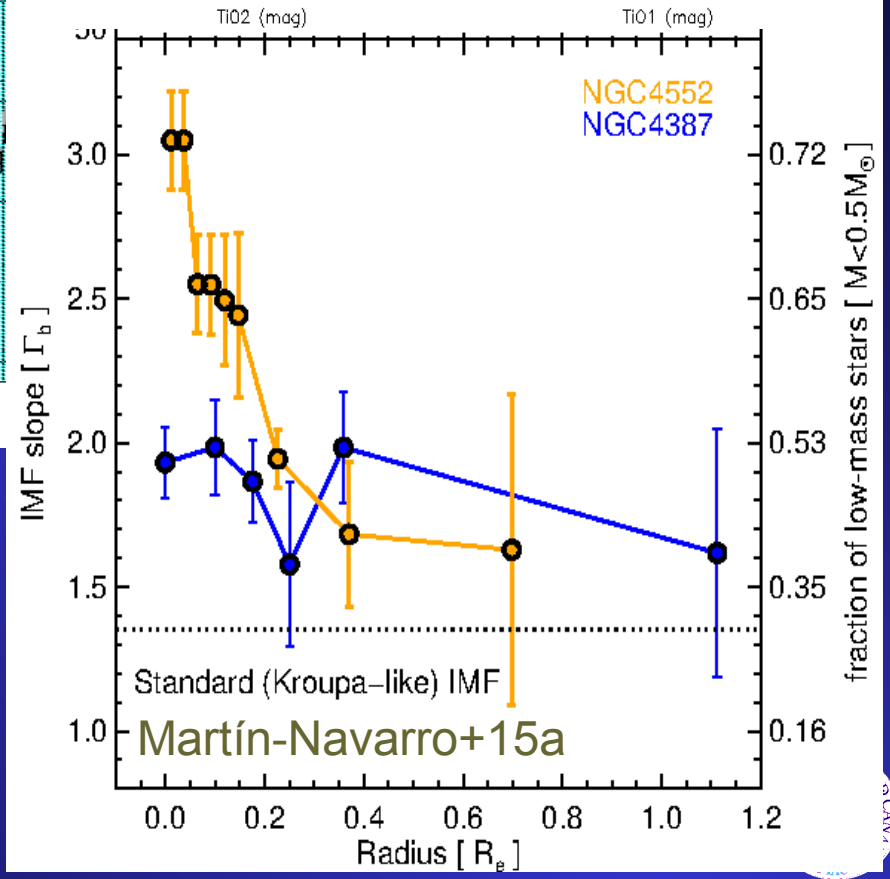
La Barbera+13

IMF in ETGs: radial profiles

Models with varying age/metallicity and standard IMF do not fit IMF-sensitive features in central regions of massive ETG





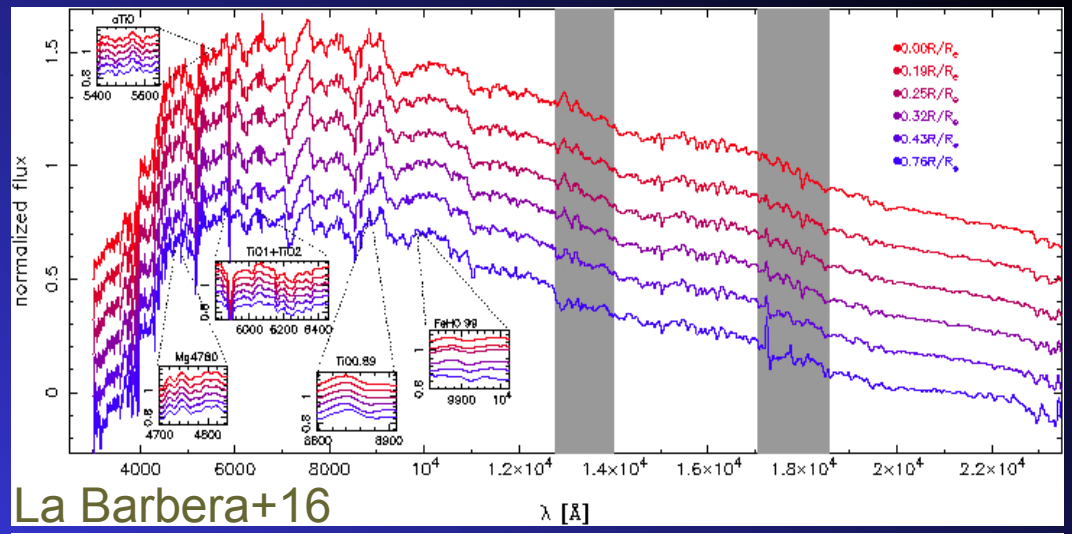


IMF varies with radius for massive ETGs: it is a local property!. Bottom-heavy in the center & MW-like at ~1Re (Martín-Navarro+15a;La Barbera+16a)

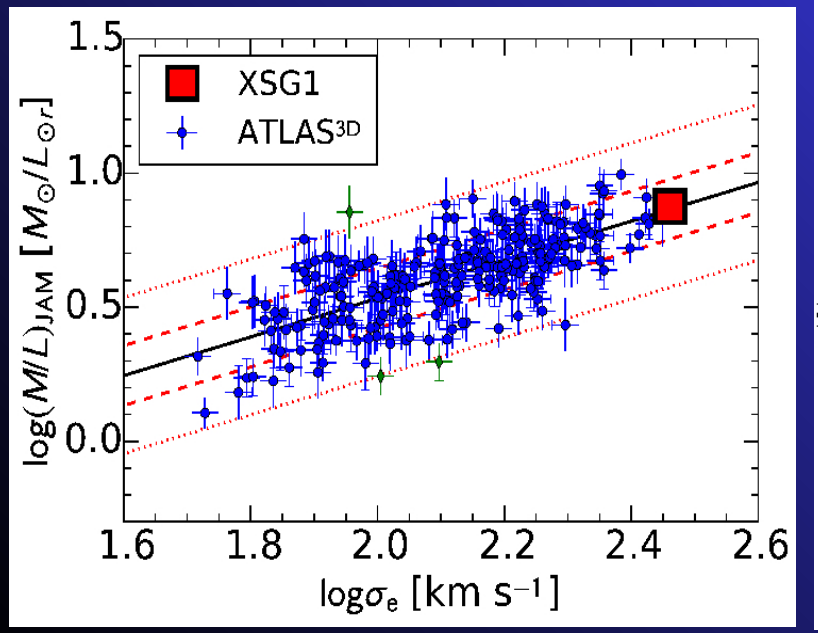
It suggests different formation scenarios for the inner/outer parts

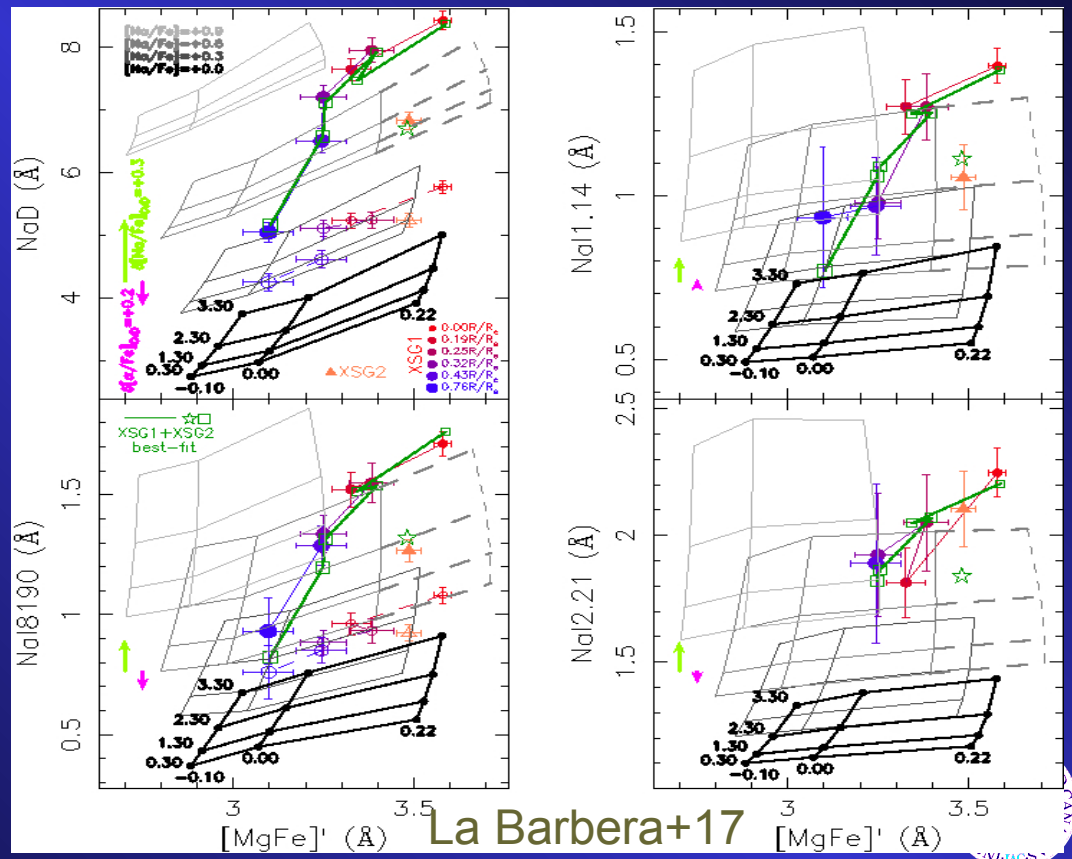
IMF gradients from Na lines of very massive ETGs:

- Extremely high S/N (>400) X-shooter@VLT spectra.
- Extreme galaxy in the Mass-Size and M/L – σ planes
- The four Na line indices in the R, I, J and K bands can be fit well with a bottom-heavy IMF and [Na/Fe]~0.6.



La Barbera+16



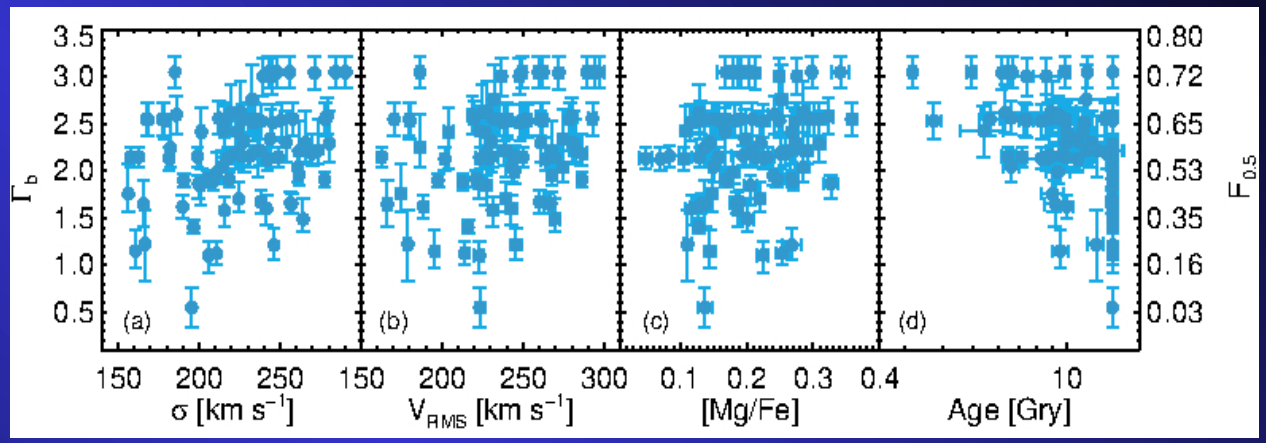


La Barbera+17

IMF in ETGs: behind the IMF variations

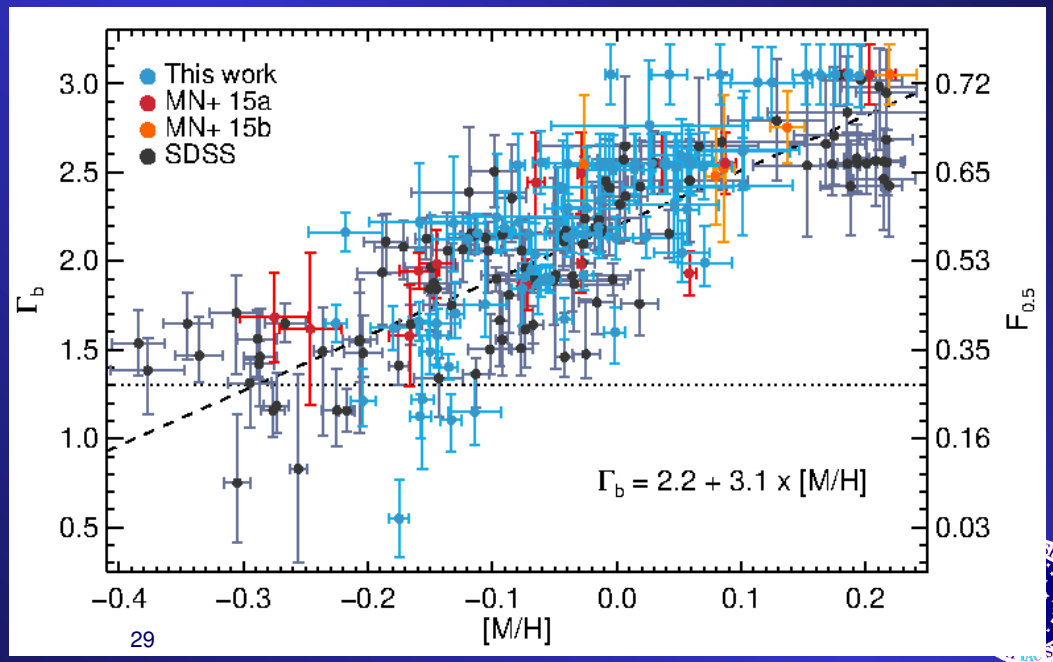
Integral Field CALIFA survey including 24 ETGs with varying mass:

- **local IMF**
- **stellar population parameters**
- **kinematical properties**



The IMF does not correlate with any of these parameters

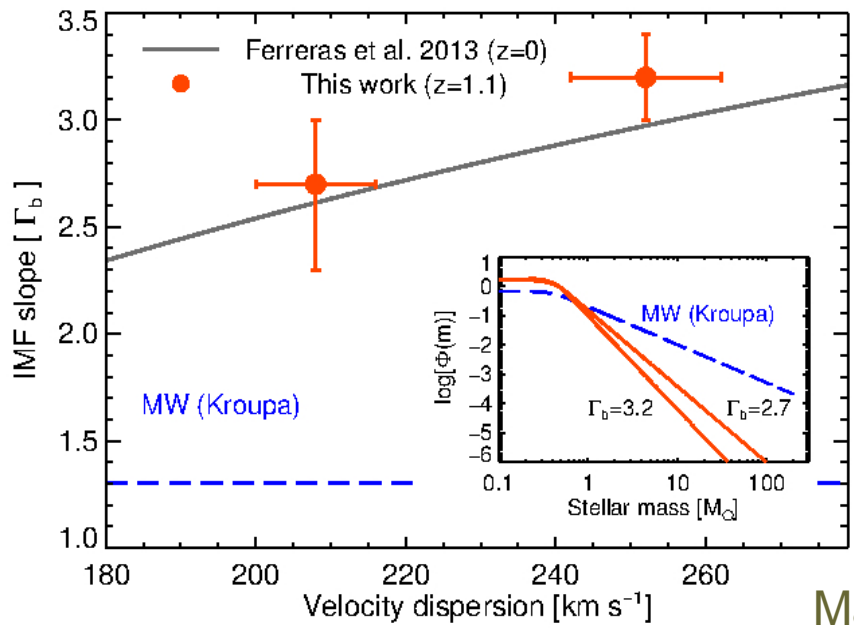
but the IMF does correlate with the local metallicity!!!

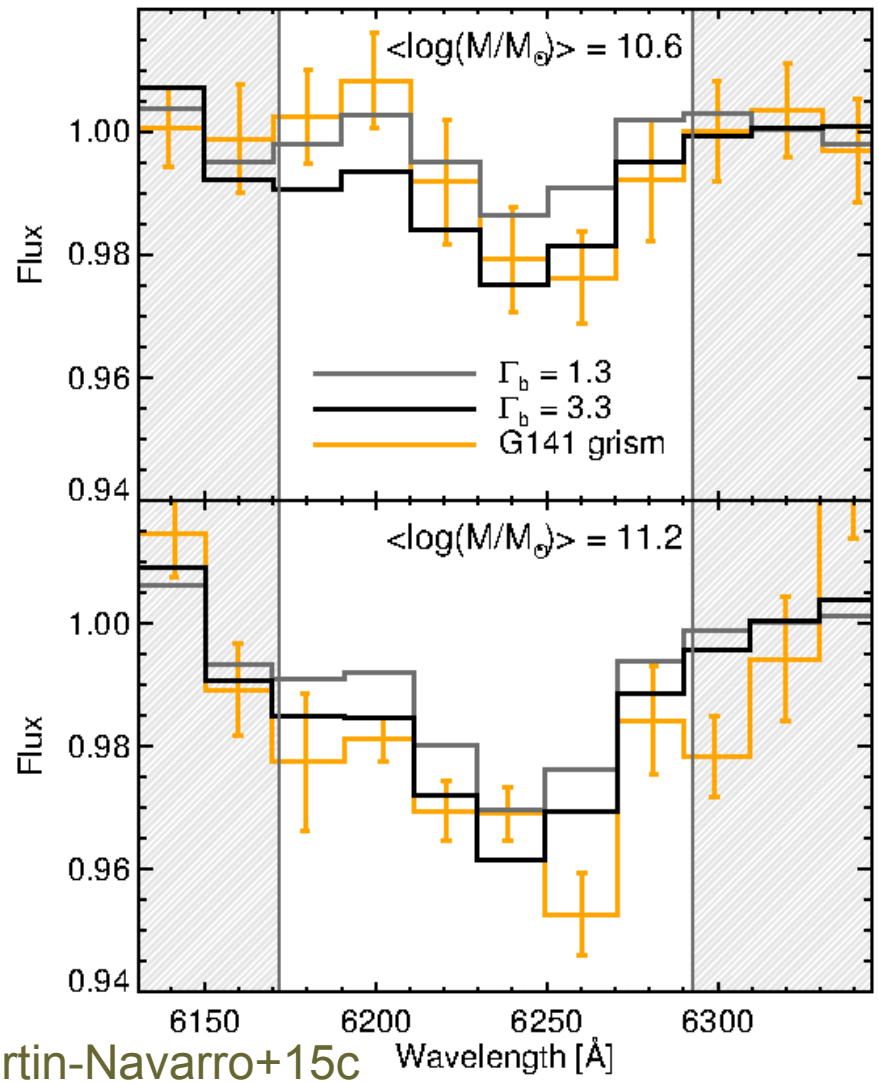


Martin-Navarro+15b

IMF in ETGs: IMF at z~1.2 (~ 1/3 the age of Universe)

Massive and intermediate-massive galaxy stacks with SHARDS@GTC show similar IMF trends as found in nearby galaxies

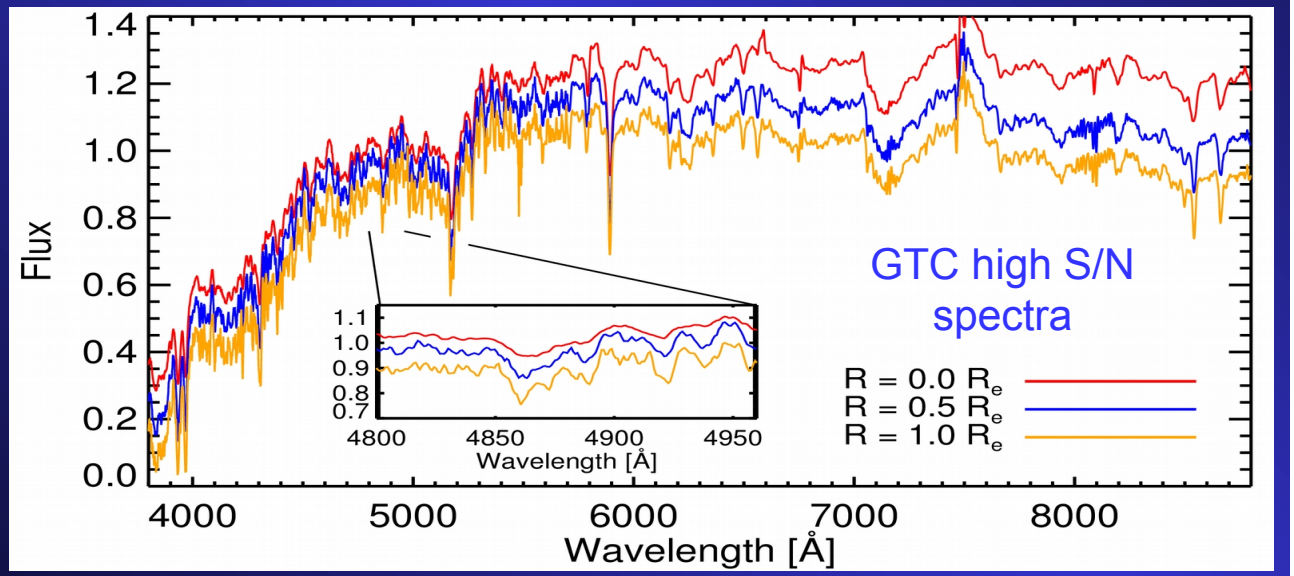


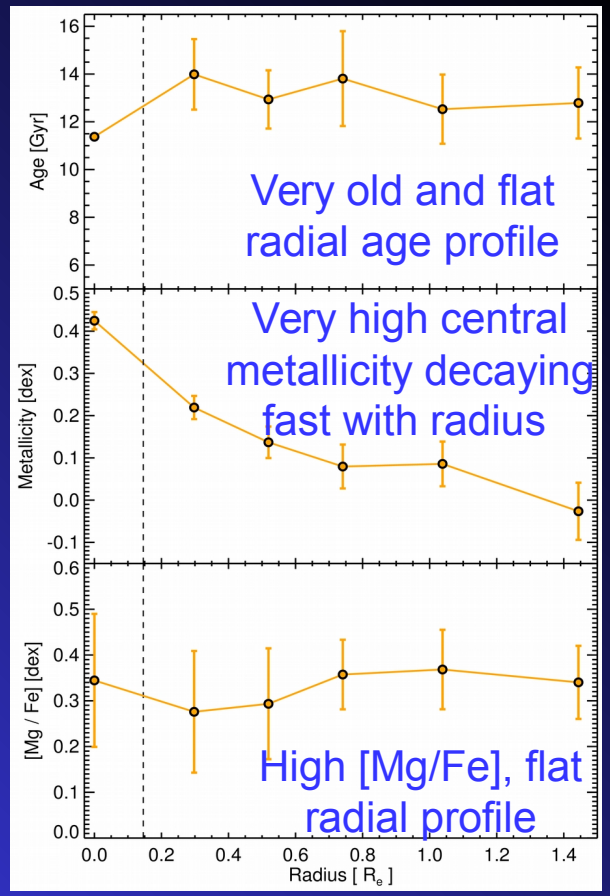


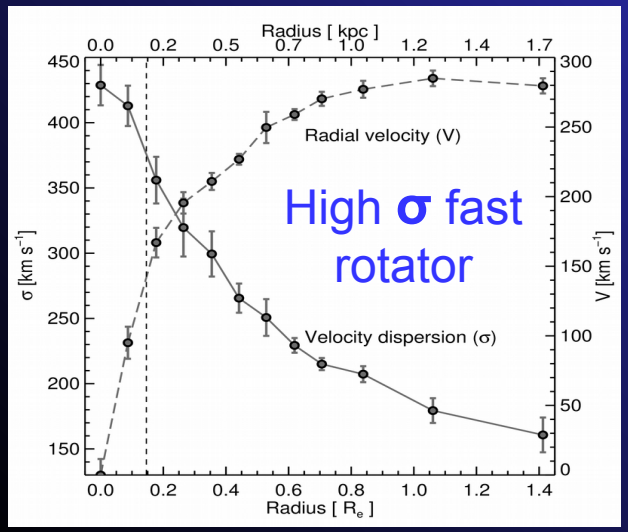
Martin-Navarro+15c

IMF of a massive compact relic galaxy

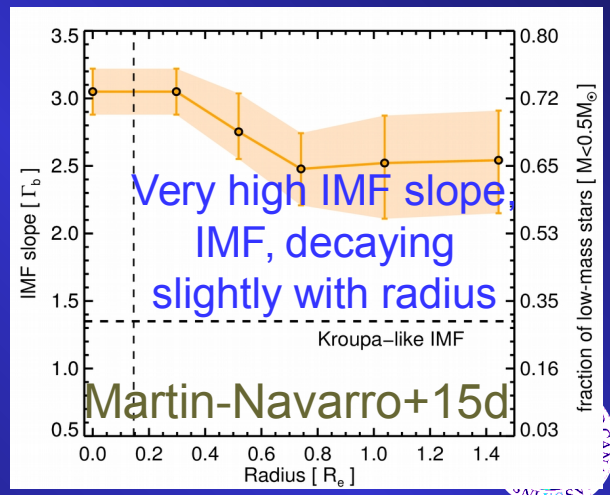
(NGC 1277 in the core of Perseus cluster)





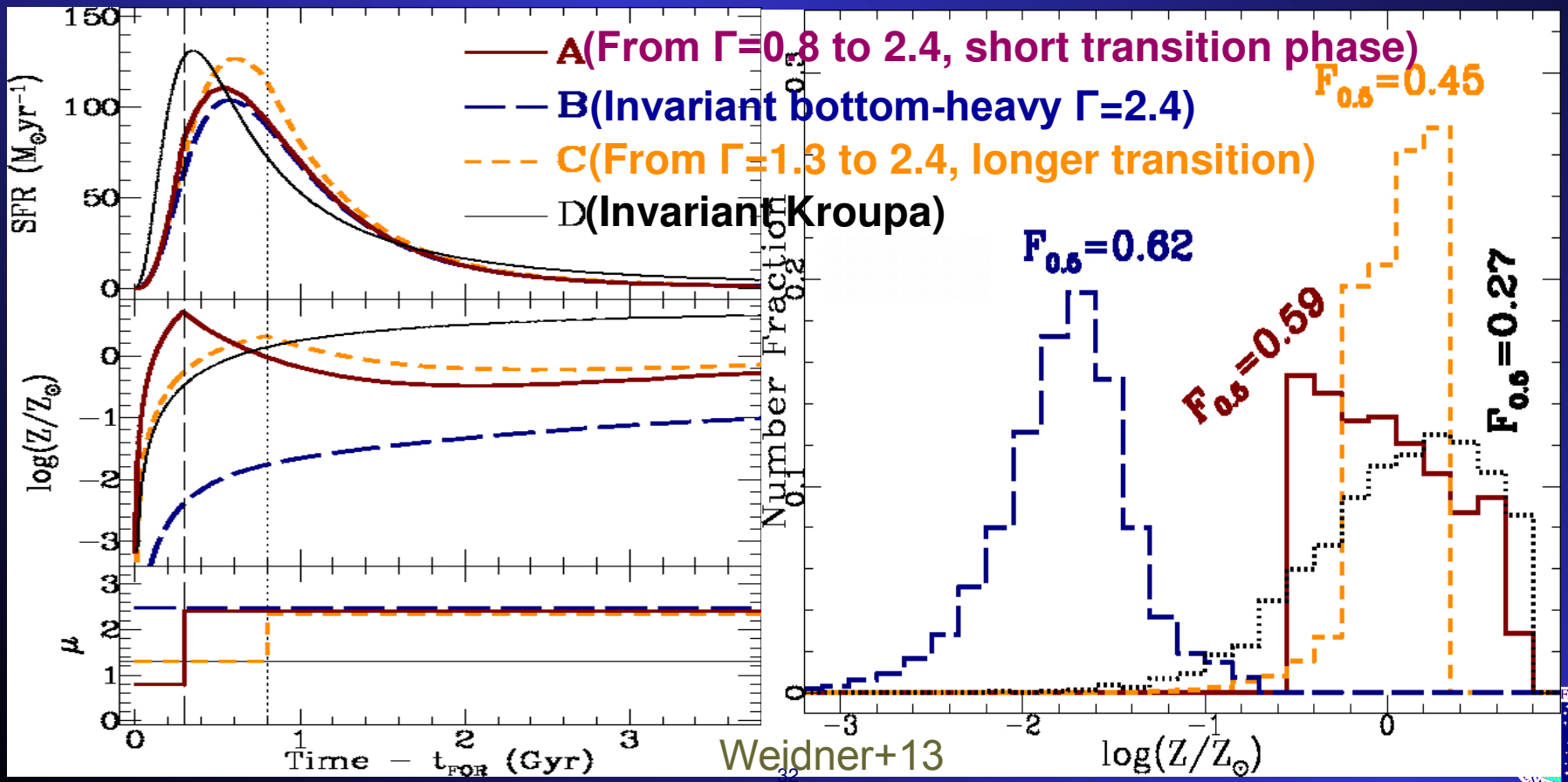


A truly old massive compact galaxy in the nearby Universe, similar to those found at high z. Progenitors of nowadays normally sized massive ETGs ?



IMF in ETGs: time varying IMF

An invariant bottom-heavy IMF prevents reaching solar metallicity (or higher) as showed by massive ETGs: if it is bottom-heavy it should have evolved with time: from top- to bottom-heavy (V+97;Weidner+13;Ferreras+15).



Weidner+13

Summarizing IMF results

Varies with galaxy mass: massive ETGs are enhance in low-mass dwarfs (<0.5Mo), i.e. IMF slope - σ relation (Cenarro+03; Ferreras+13; LaBarbera+13)

Varies locally within massive galaxies: bottom-heavy in the center & MW-like at ~1Re (Martín-Navarro+15a;LaBarbera+16[a])

Correlates with metallicity: both global and locally (Martín-Navarro+15b)

It varies with time: from top to bottom-heavy (V+96,97;Weidner+13;Ferreras+15)

These results favour a two phase galaxy formation scenario: a monolitic-like in-situ phase followed by a later accretion of less massive satellites (with standard IMF), which settle in galaxy perifery.