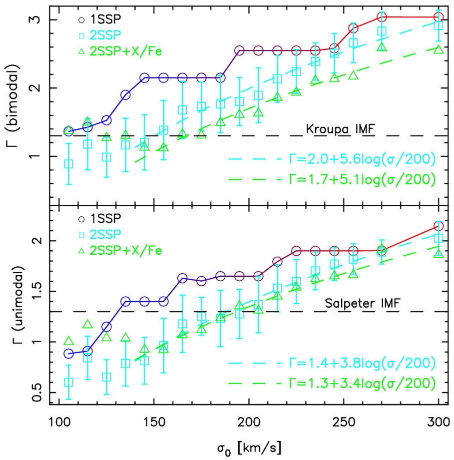
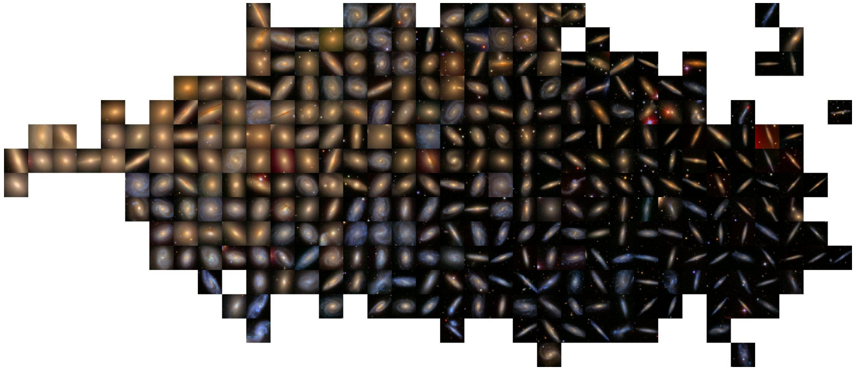
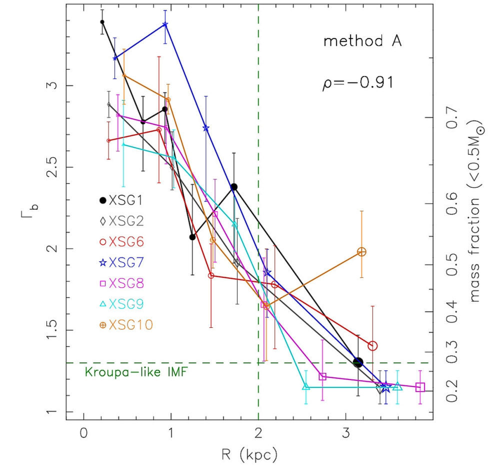
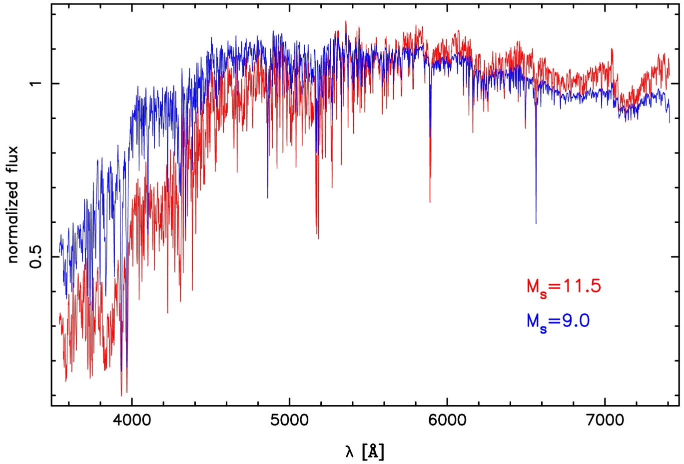


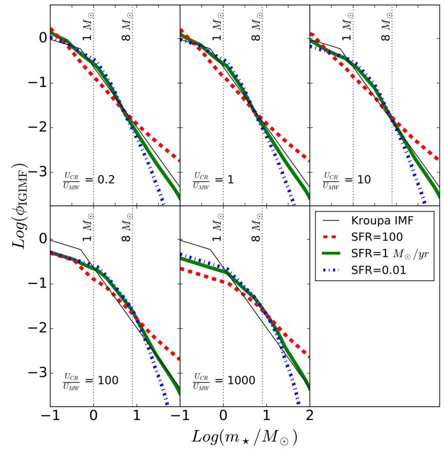


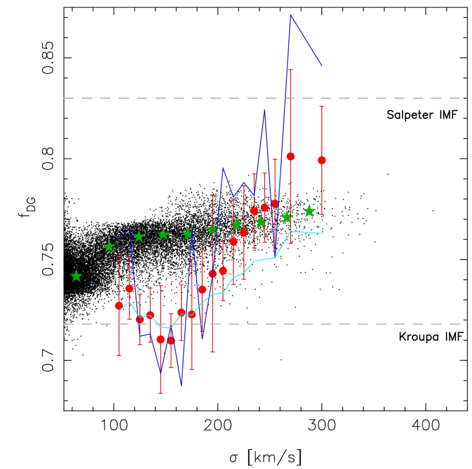


A non-universal IMF with updated stellar population models from FUV through NIR

Francesco La Barbera
INAF-Osservatorio Astronomico di Capodimonte







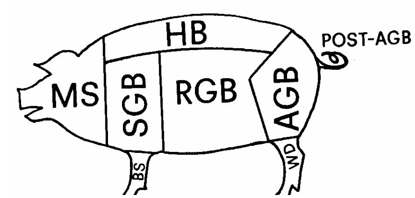
LAYOUT

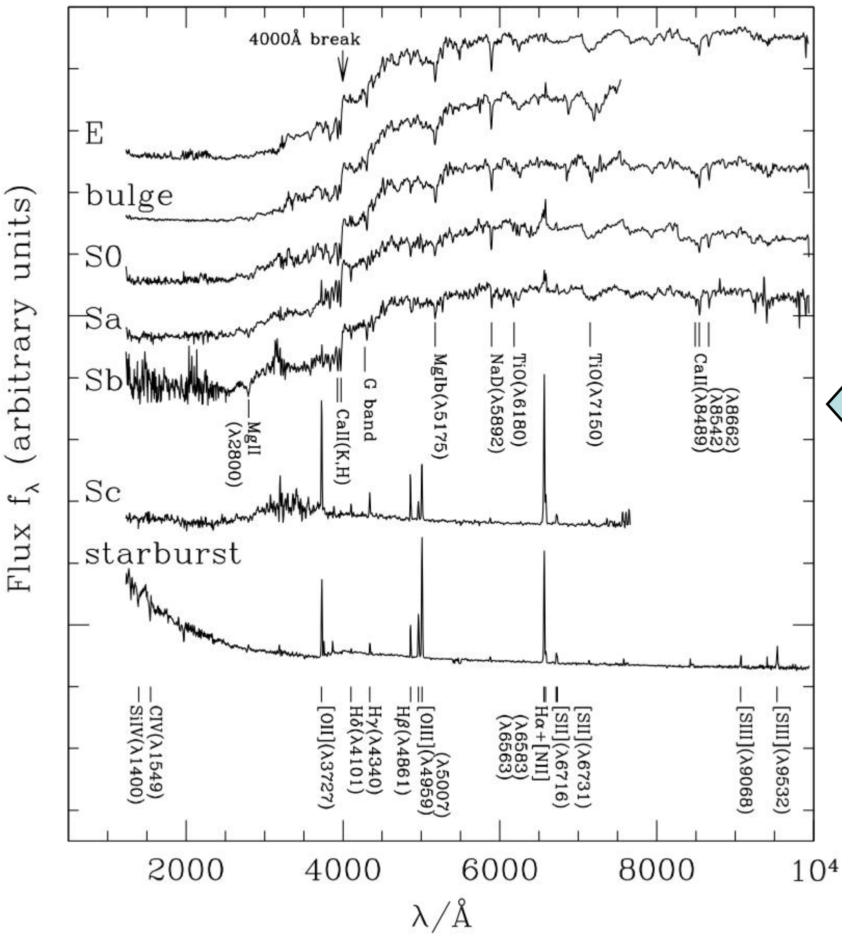
- EMILES models from FUV through NIR
- The non-universal IMF of (massive) galaxies

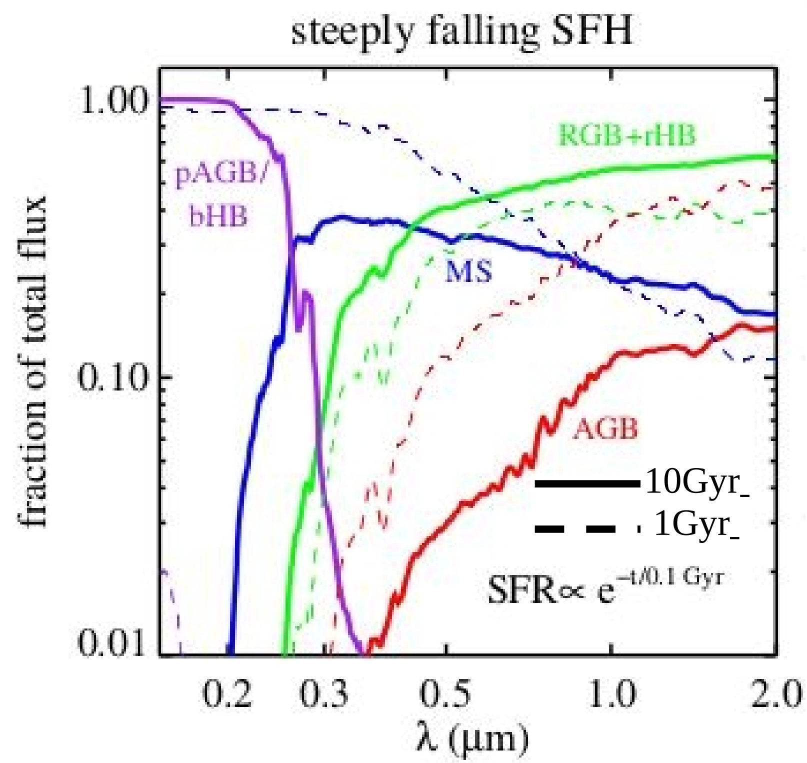
Unresolved stellar populations

Most galaxies are too far to resolve their individual stars, hence we have to rely on the analysis of their integrated spectra.

SPECTRA







from Conroy(2013)

the fundamental issue is that of parameters' degeneracies

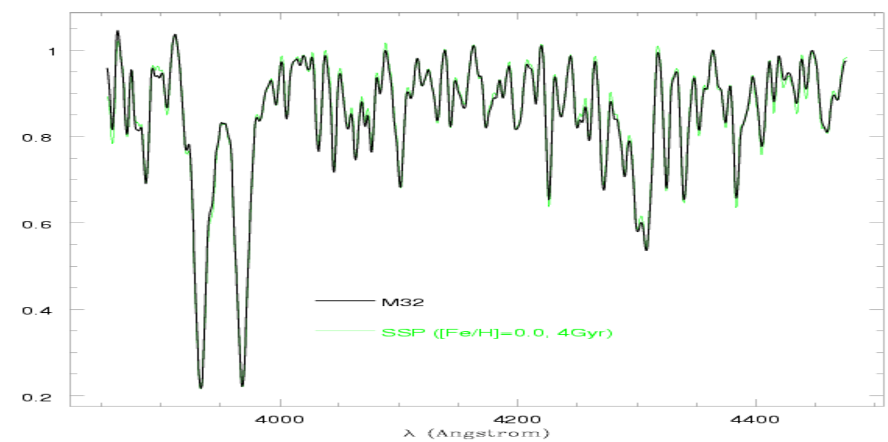
Some history

First attempts based on *empirical* stellar population models: a mixture of stars was combined to match observations, either colors or SEDs (Spinrad & Taylor 1971; Faber 1972; O'Connell 1986)

Table 2. M 31 models — from Faber 1972

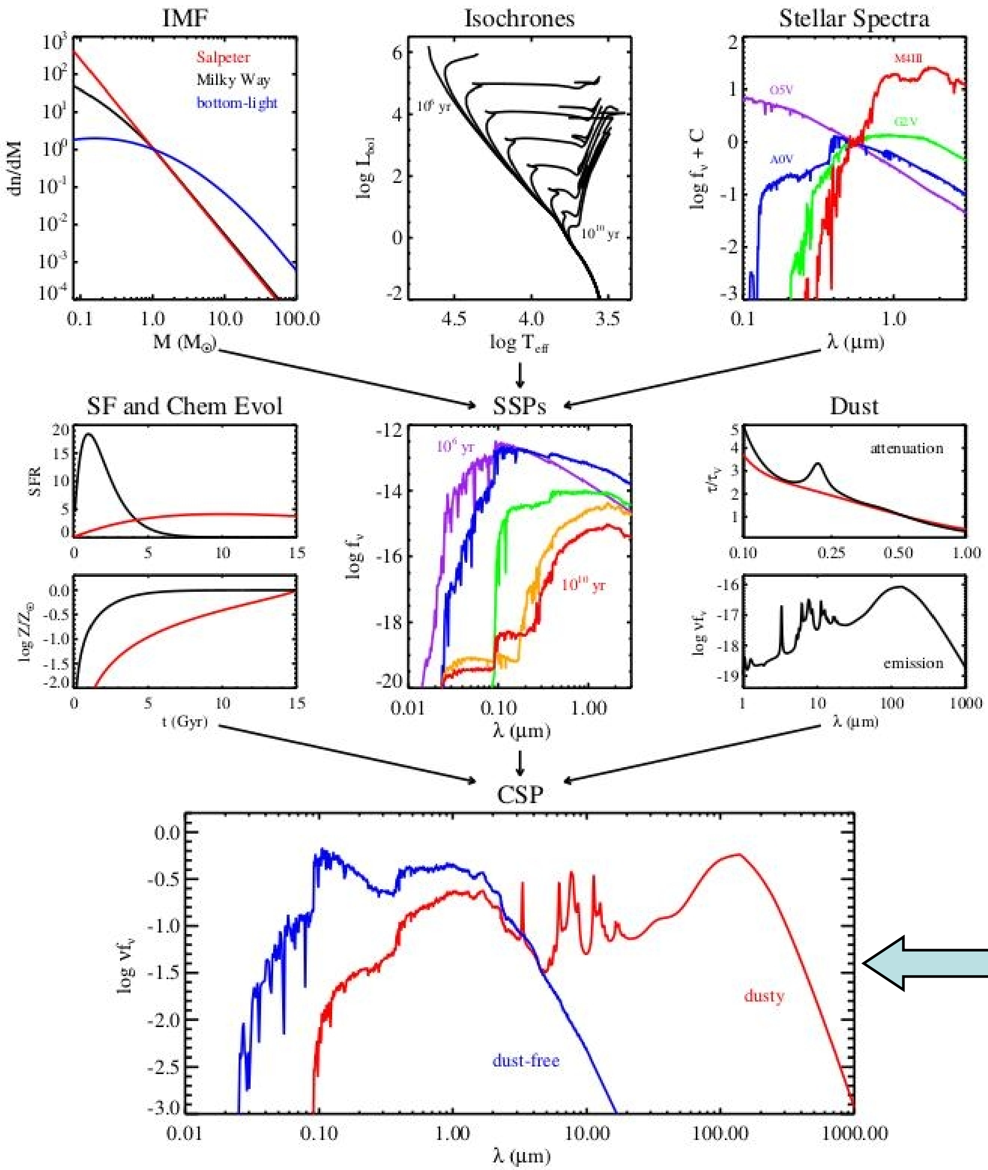
Gr. No.	Group Name	No. of Stars Basic Model
7	Late F Dwarf	
8	Early G Dwarf	0.175 E+03
9	G 5 V–K 0 V	0.355 E+03
10	K 1 V–K 2 V	0.237 E+03
11	K 3 V–K 4 V	0.504 E+03
12	K 5 V–K 7 V	0.787 E+03
13	M 0 V–M 2 V	0.764 E+03
14	M 3 V–M 4 V	0.352 E+05
15	M 5 V–M 6 V	0.235 E+05
16	M 7 V	0.309 E+05
17	M 8 V	0.907 E+06
18	Early G Subgt.	0.117 E+03
19	Late G Subgt.	0.868 E+02
20	SMR K 0–K 1 IV	0.355 E+02
21	SMR K 2 III–IV	0.351 E+02
22	SMR K 3 III	0.984 E+01
23	SMR K 4–5 III	0.315 E+01
31	M 5 III–M 6 III	
38	Hor. Branch	0.135 E+00
	M/L	48.2
	$\Sigma\sigma^2$	241

Nowdays, the "standard" approach is that of *evolutionary* population synthesis (or just stellar population synthesis)



Observed vs. model spectrum for M32 (http://www.iac.es/galeria/vazdekis/)

Evolutionary models in a nutshell



from Conroy(2013)

MAIN INGREDIENTS

- Initial Mass Function (IMF)
- Isochrones
- Stellar spectra (theoretical/empirical)
- Dust
- Star Formation/Chemical Evolution

Composite Stellar Population model

State-of-the-art SP models

- Bruzual&Charlot models (BC03 + updated CB)
  - very wide spectral range (91Å-160μm) ⇒ high-redshift galaxies
- Conroy models (CvD12+CvD18)
  - models with different [X/Fe]'s
  - → varying IMF
- Vazdekis models (V12+V15+V16) – EMILES
  - → varying IMF
  - entirely based on empirical stellar libraries ⇒ NGSL, MILES, IndoUS, CAT, IRTF
- Maraston models (M11-SteLIB + M20-MaStar)
  - 9000, high S/N, empirical stellar spectra

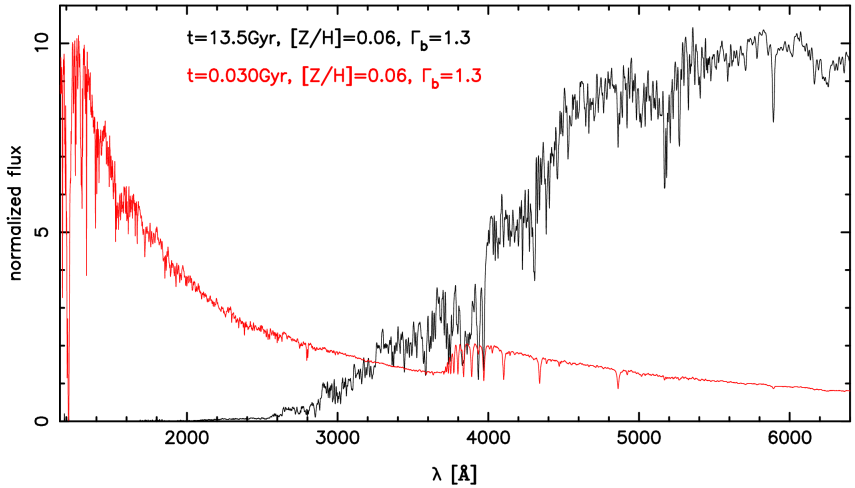
EMILES models: ongoing work

https://archive.stsci.edu/prepds/astral/

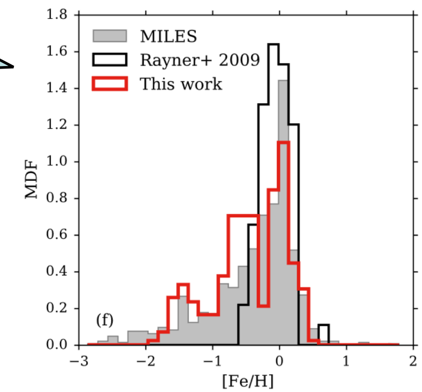
https://ullyses.stsci.edu/

extending the spectral range

FUV: ASTRAL, STARCAT, Ulysses



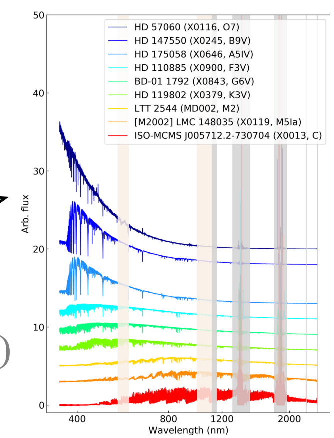
NIR: IRTF-extended



Villaume et al.(2017)

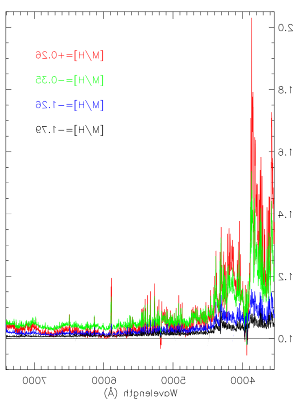
empirical SSP models with the XSL library

Verro et al.(2022a)



SSP models with varying abundance ratios

Vazdekis et al.(2015), La Barbera et al.(2017), Knowles et al.(2023)

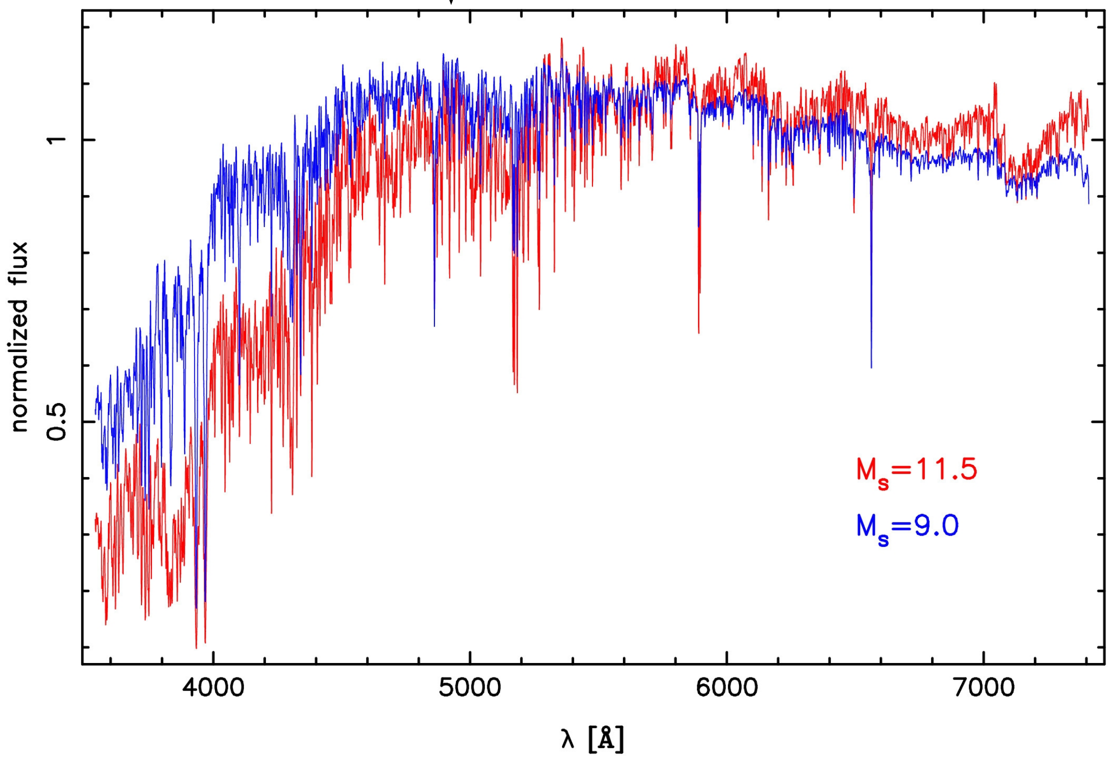


EMILES models and GAEA

11	-0.3500000	11.00000	8.039924
11	-0.3500000	11.50000	7.409225
11	-0.2500000	10.00000	7.662535
11	-0.2500000	10.50000	7.546865
11	-0.2500000	11.00000	7.919477
11	5.9999999E-02	9.500000	7.323114
11	5.9999999E-02	10.00000	7.281787
11	5.9999999E-02	10.50000	7.260445
11	5.9999999E-02	11.00000	7.236448
11	5.9999999E-02	11.50000	8.288659
12	-0.9600000	11.50000	8.301329
12	-0.9600000	12.00000	8.939809
12	-0.9600000	12.50000	7.625126
12	-0.6600000	10.50000	9.272826
12	-0.6600000	11.00000	8.989711
12	-0.6600000	11.50000	9.647057
12	-0.6600000	12.00000	9.450498
12	-0.6600000	13.00000	7.101978
12	-0.3500000	10.00000	9.599819
12	-0.3500000	10.50000	9.754812
12	-0.3500000	11.00000	9.265563
12	-0.3500000	11.50000	8.249346
12	-0.3500000	12.00000	8.015349
12	-0.2500000	10.00000	9.333031
12	-0.2500000	10.50000	9.654995
12	-0.2500000	11.00000	8.776909
12	-0.2500000	11.50000	8.038465
12	5.9999999E-02	9.000000	8.518901
12	5.9999999E-02	9.500000	9.066126
12	5.9999999E-02	10.00000	9.297407
12	5.9999999E-02	10.50000	9.417618
12	5.9999999E-02	11.00000	8.997580
12	5.9999999E-02	11.50000	7.582573
12	0.1500000	9.500000	8.708903
12	0.1500000	10.50000	8.610087
12	0.4000000	4.000000	8.373673
12	0.4000000	6.000000	9.351814
12	0.4000000	6.500000	9.145329
12	0.4000000	7.000000	9.206287
12	0.4000000	7.500000	9.167029
12	0.4000000	8.000000	9.754007
12	0.4000000	8.500000	9.190743
13	-0.2500000	10.00000	10.44812
13	5.9999999E-02	9.000000	10.59584
13	5.9999999E-02	9.500000	10.82231
13	5.9999999E-02	10.00000	10.26530
13	0.1500000	9.000000	10.47457
13	0.1500000	9.500000	9.676993
13	0.1500000	10.50000	8.647026
13	0.2600000	2.750000	9.311671
13	0.2600000	8.500000	9.618090
13	0.2600000	9.000000	10.16858
13	0.4000000	5.000000	8.840903
13	0.4000000	5.500000	9.154140
13	0.4000000	7.500000	8.900314
13	0.4000000	8.500000	10.32324
18	-2.270000	12.00000	7.493665
18	-2.270000	12.50000	8.289596
18	-2.270000	13.00000	8.042631
18	-1.790000	12.00000	7.637281
18	-1.790000	12.50000	8.453043
18	-1.790000	13.00000	7.932449
18	-1.490000	12.00000	7.309945
18	-1.490000	12.50000	7.614112
18	-1.490000	13.00000	6.879154
18	-1.260000	12.00000	7.699543
18	-1.260000	12.50000	8.102407
18	-0.9600000	11.50000	8.319077
18	-0.9600000	12.00000	8.419543
18	-0.9600000	12.50000	8.765631
18	-0.6600000	11.00000	7.099240
18	-0.6600000	11.50000	8.387415
18	-0.6600000	12.00000	8.759751
18	-0.6600000	12.50000	8.145297
18	-0.3500000	11.50000	8.085496

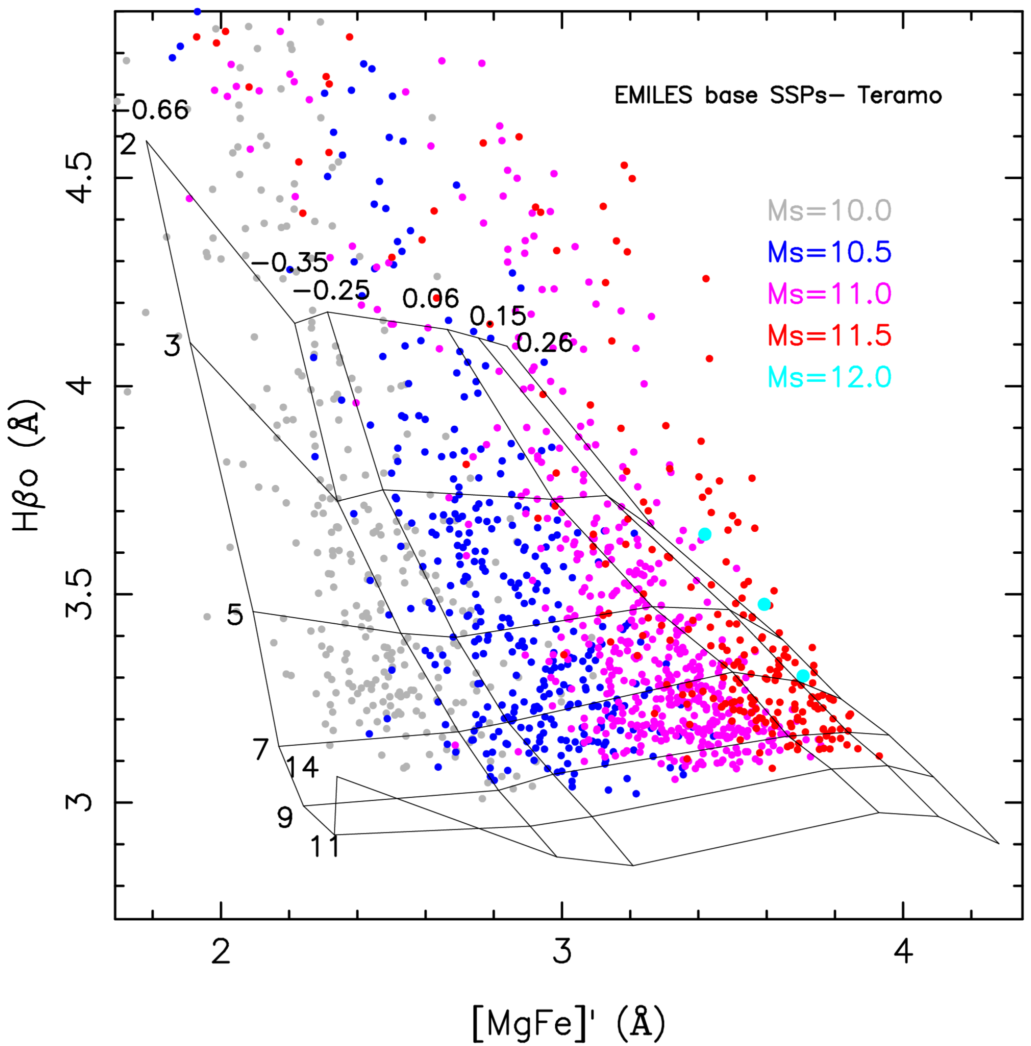
table with SFH of each model galaxy (IMF, [Z/H], Age, M_s)

summing up the spectra
(only MILES range)



examples of model spectra for early-type galaxies

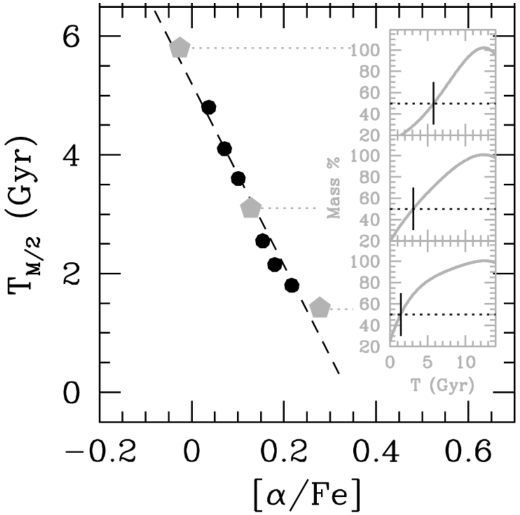
EMILES models and GAEA



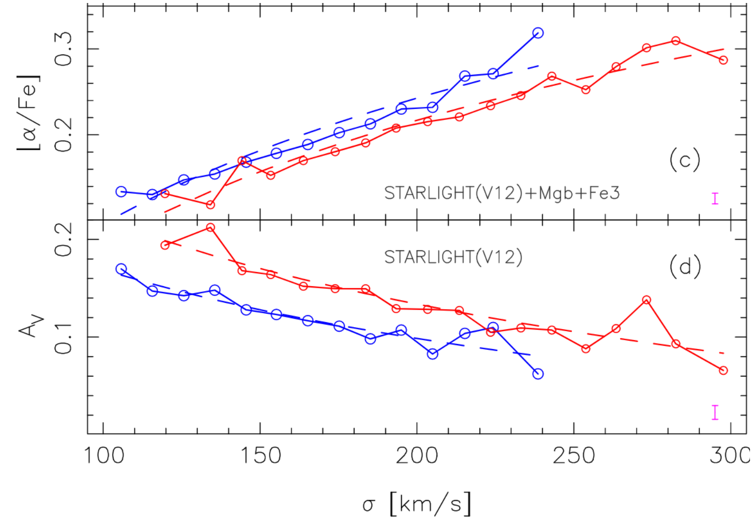
Hβ-[MgFe]’ (age-metallicity) diagram for model early-type galaxies

Abundance ratios

So far, most studies have focused on [Mg/Fe]:

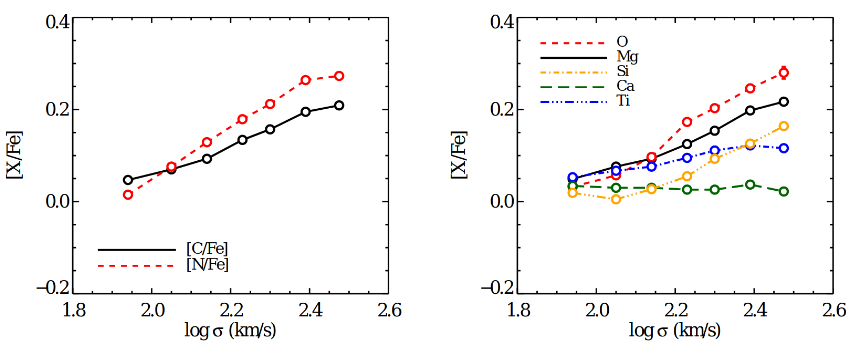


de La Rosa et al. (2011)



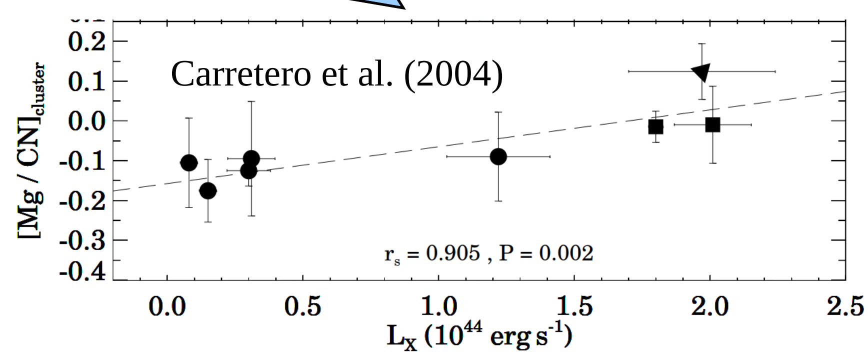
La Barbera et al. (2014)

SP models with varying [X/Fe] are becoming available:



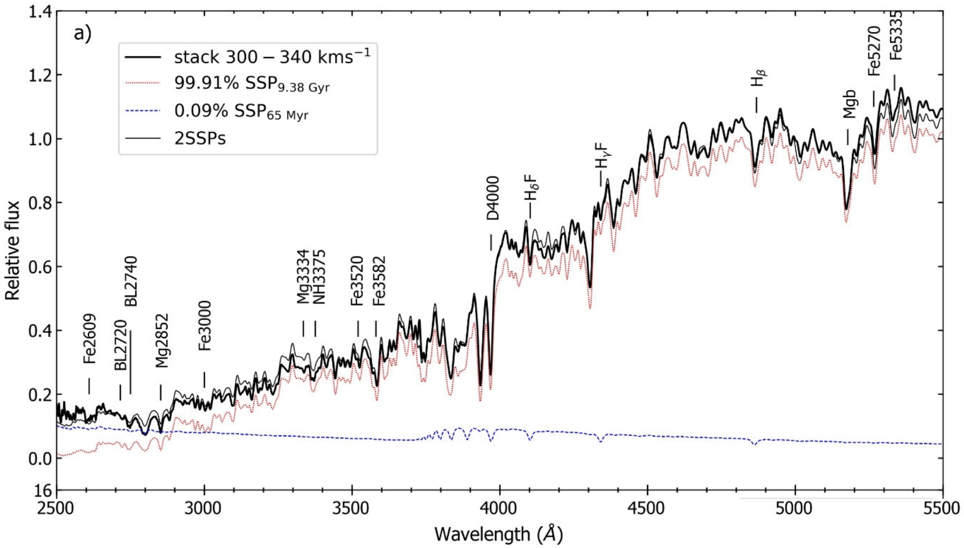
Conroy, Graves, van Dokkum (2013)

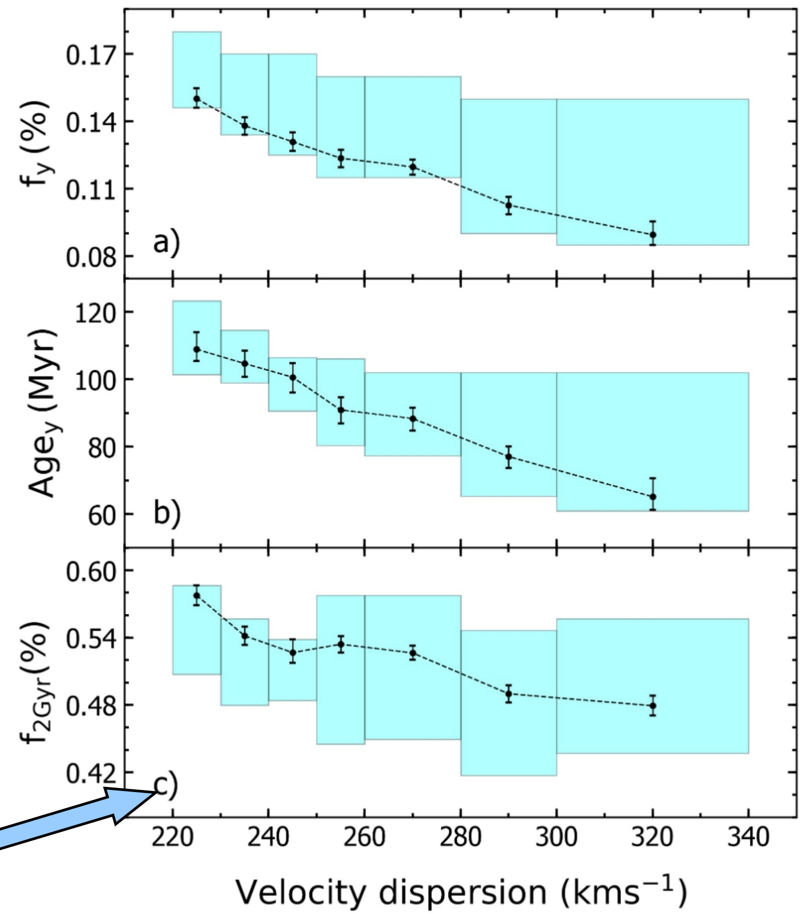
Different SF time-scales



Sub-percent young populations

(Salvador-Rusiňol et al. 2019)





- Recent star-formation is ubiquitous in ETGs, with 0.5% mass fraction formed in past 2Gyr

- The fraction shows a decreasing trend with galaxy mass

LAYOUT

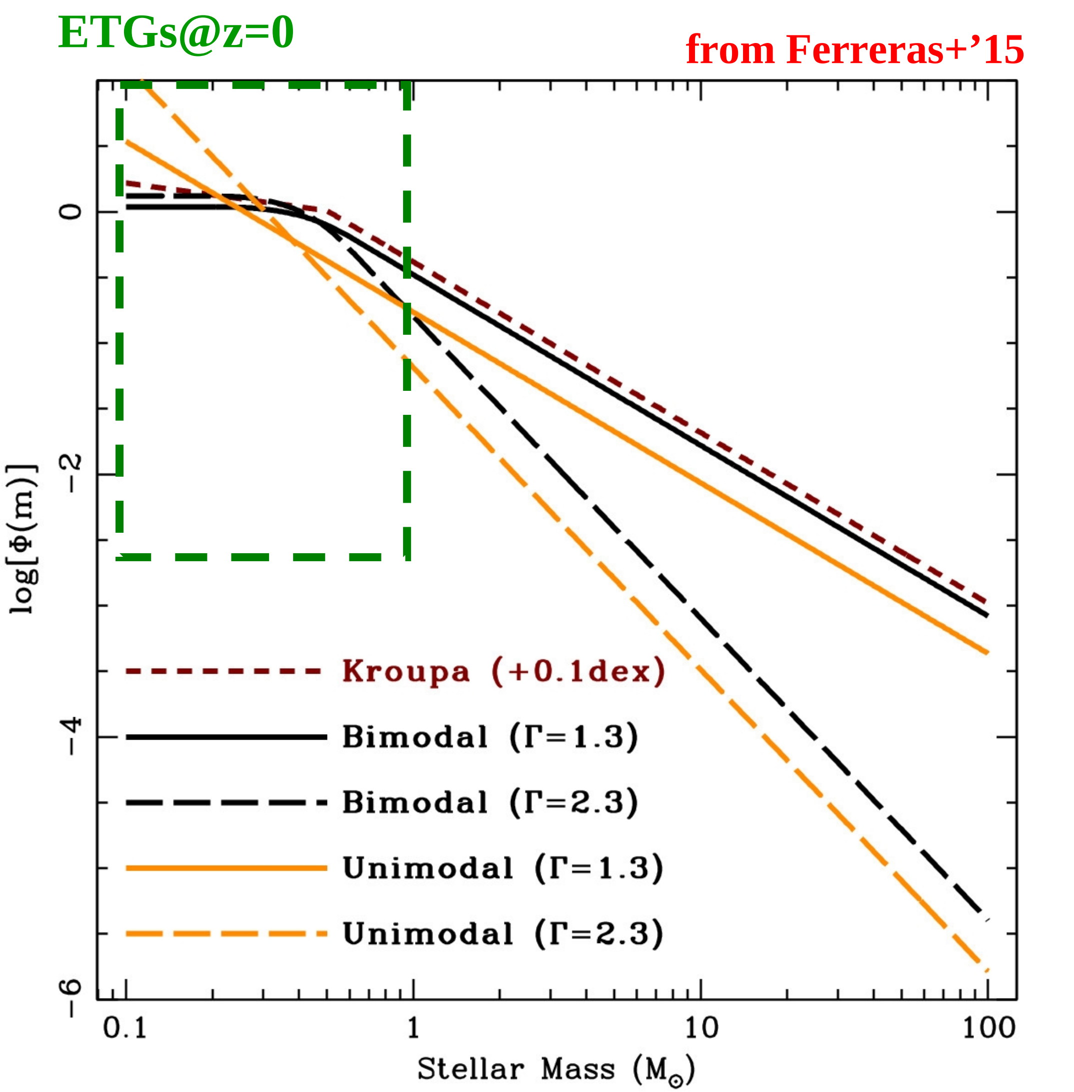
- EMILES models from FUV through NIR
- The non-universal IMF of (massive) galaxies

The stellar Initial Mass Function (IMF)

The stellar IMF is the mass distribution of stars collectively born in one event of star formation.

"One event" means a gravitationally-driven collective process of transformation of the interstellar gaseous matter into stars on a spatial scale of about one pc and within about one Myr (Kroupa+2012, "Stellar Systems and Galactic Structure").

The stellar IMF: functional forms

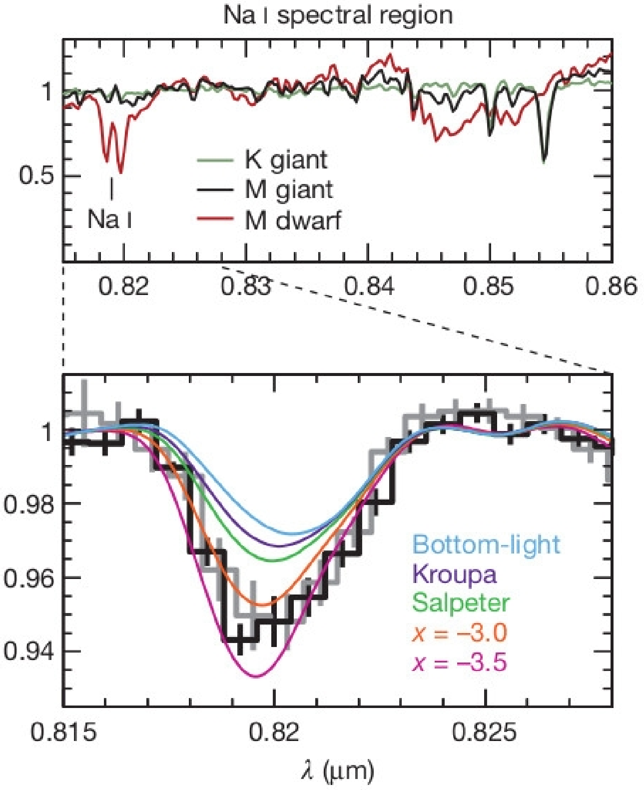


A bottom-heavy IMF in luminous ETGs ?

- Early studies plagued by small sample sizes, low S/N and R, uncertain SP models
  (Spinrad'62; Cohen'78; Faber&French'80; Carter+'86; Hardy&Couture'88; Delisle&Hardy'92)

- The issue was raised up again by Cenarro+(2003). However, the interpretation of CaT was hampered by the lack of model predictions for non-solar abundance ratios (Saglia+2002).

- The interest to use gravity-sensitive features to constrain the IMF low-mass end has been boosted up by van Dokkum & Conroy(2010).



IMF-σ relation

(Ferreras+'13; La Barbera+'13)

SPIDER sample of 39,993 *bright* (M_r<-20) ETGs (SDSS-DR6; La Barbera+'10a)

0.05≤z≤0.095; 70≤σ_0≤420 km s^{-1}; eclass<0, FracDevr>0.8, E(B-V)<0.1, S/N>15

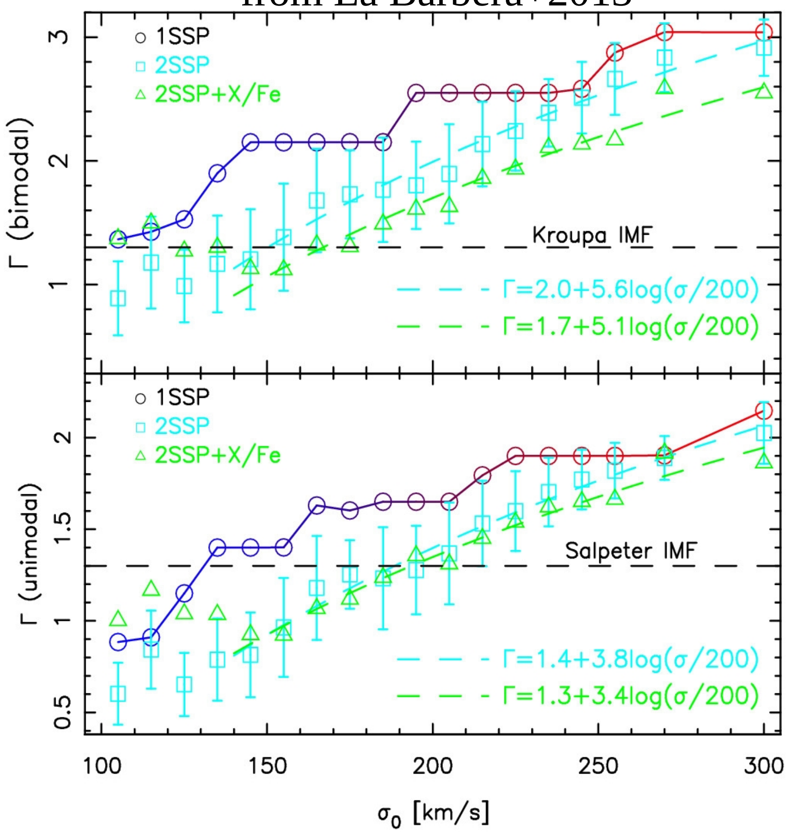
18 median-stacked spectra with 100≤σ_0≤320km/s

➡ Trend from a Kroupa-like IMF (σ≤150km/s), to a bottom-heavy IMF at high σ.

➡ Different indices give different results, but the presence of a trend is very robust!

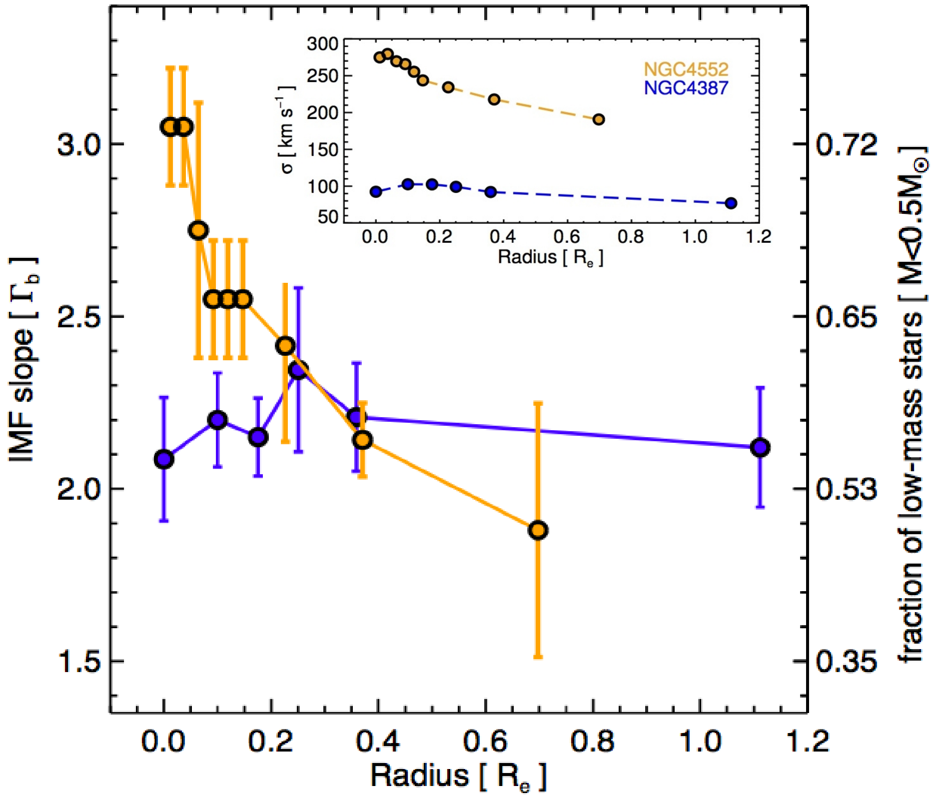
➡ The presence of an IMF-σ trend is very robust (Spiniello+'14,'15a) !

from La Barbera+2013



A bottom-heavy IMF in the cores of ETGs ?

Martín-Navarro et al. 2015a



IMF-slope radial gradients with optical+NIR (OSIRIS@10.4m-GTC) spectroscopy

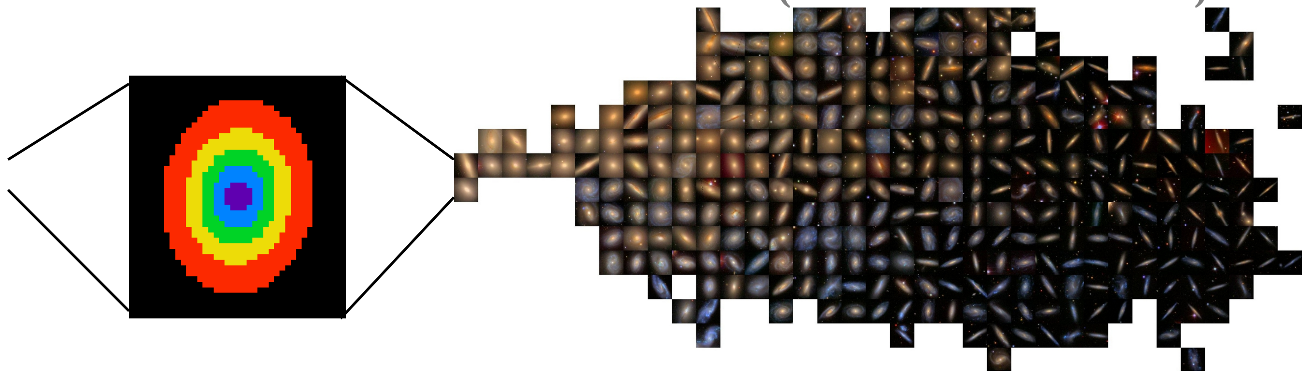
⇨ IMF gradient detected, for the first time, in the high-σ ETG NGC4552

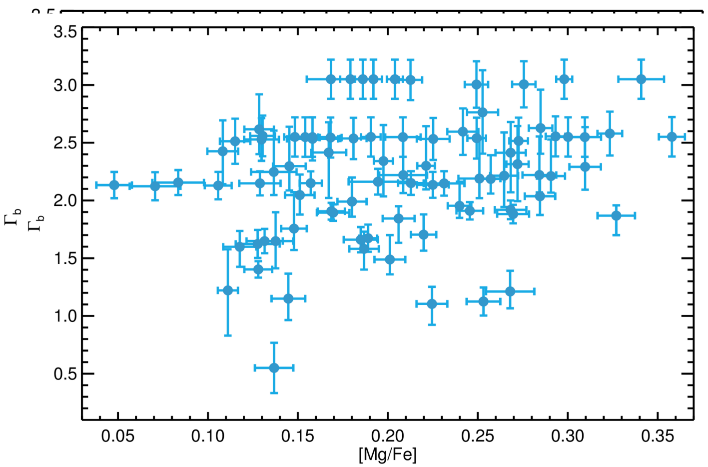
⇨ No IMF radial gradient for NGC4387 (σ~100km/s; see also Spiniello et al.2015c)

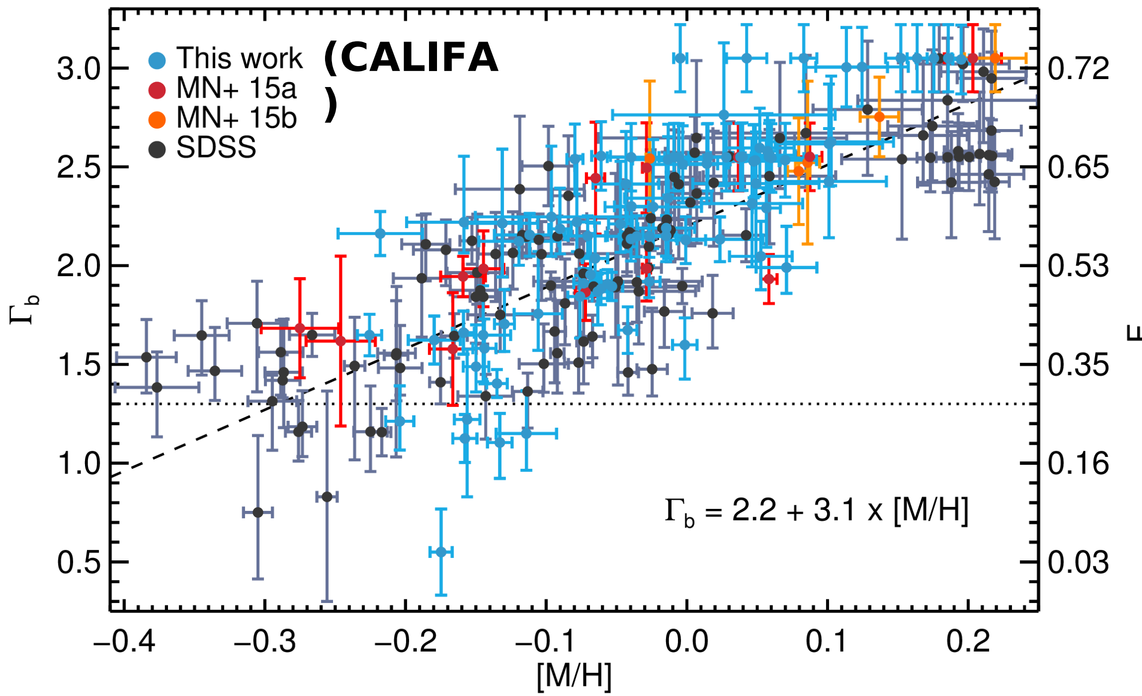
IMF variations vs. σ, [α/Fe], **and** metallicity

(Martìn-Navarro+'15d)

24 ETGs at 0.018 < z < 0.030 from the CALIFA survey







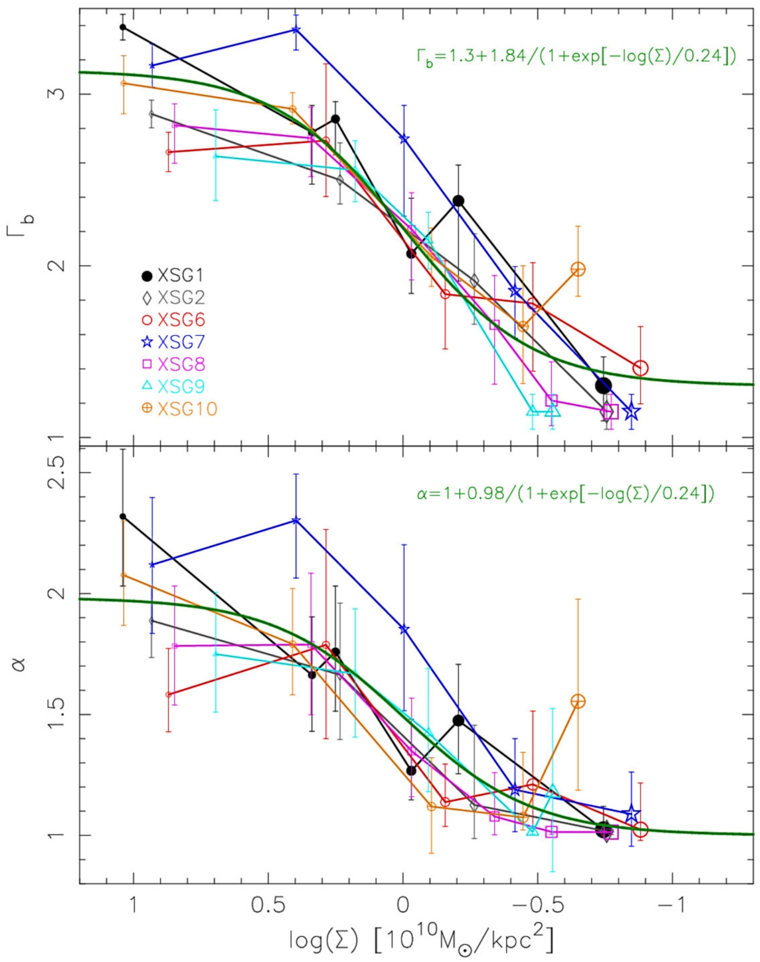
- No <u>local</u> correlation with dynamical properties
- No <u>local</u> correlation with [Mg/Fe].

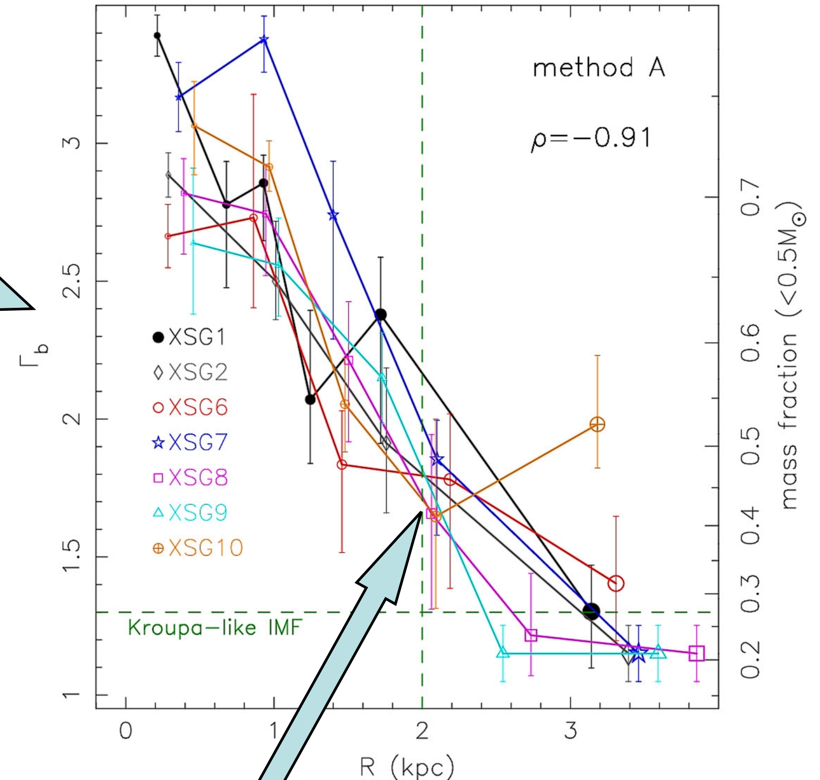
Good correlation with metallicity ([M/H])

See Lyubenova+'16 (MNRAS, 463, 3220L) for an homogeneous comparison of dynamical/spectroscopic constraints.

Driver of IMF variations in massive ETGs

(La Barbera+2019)



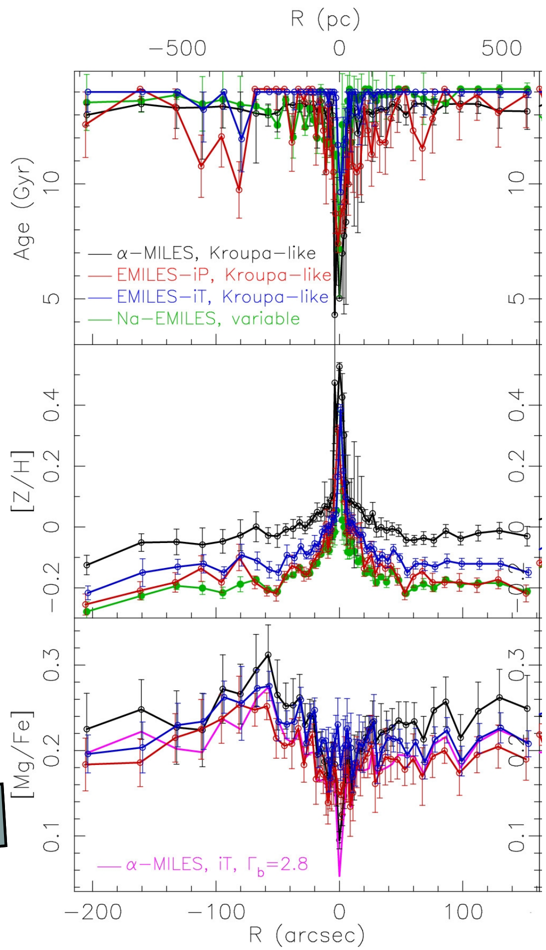


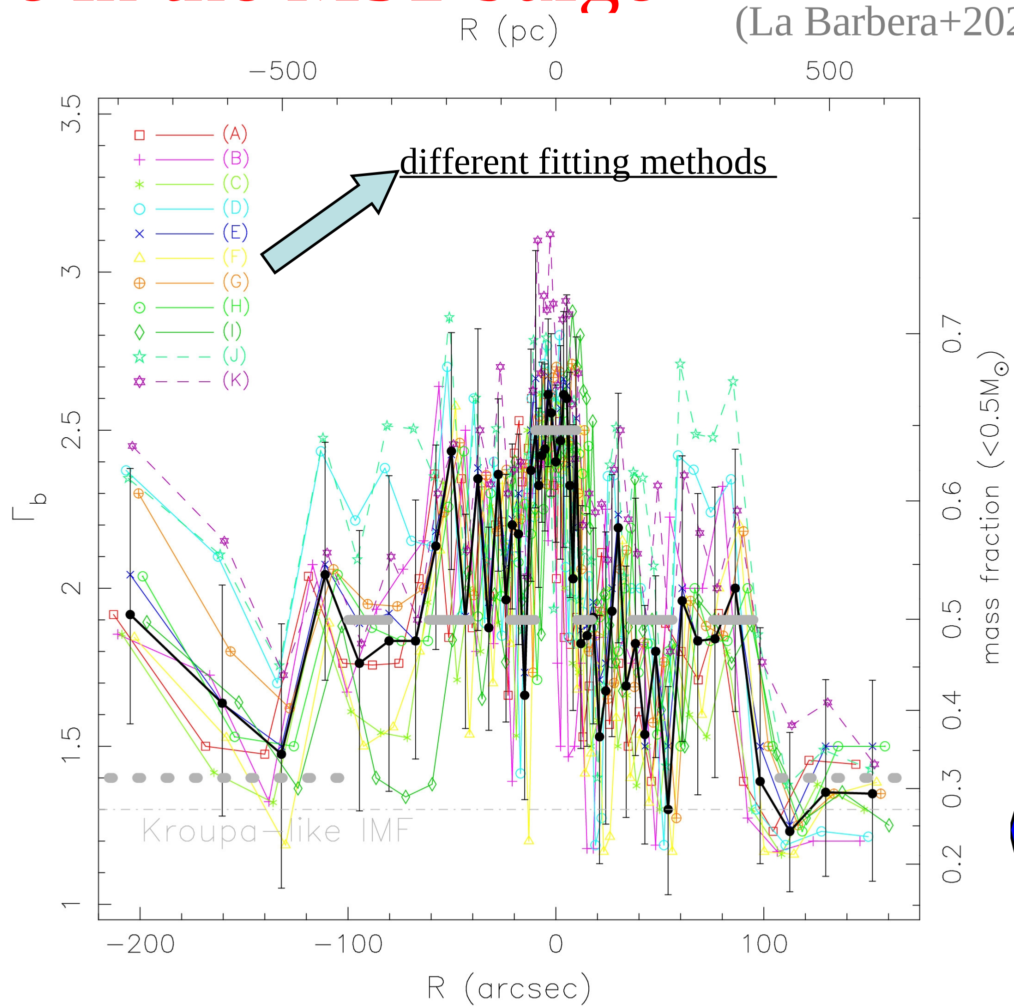
This scale is comparable to the size of massive "red-nuggets" found at high-z by many works (e.g. Trujillo+2007; van Dokkum+2008)

➡ IMF slope correlates with surface mass density (Σ), with a "transition" at $\sim 10^{10} M_\odot/kpc^2$.

IMF slope in the M31 bulge

(La Barbera+2021)





Age, [M/H], and [/Fe] radial trends consistent with previous works (e.g. Saglia et al. 2010)

Radial IMF gradient, with a (mildly) bottom-heavy distribution only in the inner bulge (<10'')

A variable IMF within GAEA

Integrated galaxy-wide IMF (IGIMF)

Weidner & Kroupa (2005); Kroupa et al.(2013)

$$\varphi_{\rm IGIMF}(m) = \int_{M_{\rm cl}^{\rm min}}^{M_{\rm cl}^{\rm max}} \varphi_\star(m \le m_\star^{\rm max}(M_{\rm cl}))\varphi_{\rm CL}(M_{\rm cl})\, {\rm d}M_{\rm cl}.$$

Jeans mass from simulations of a CR-regulated ISM

Papadopoulos+(2011)

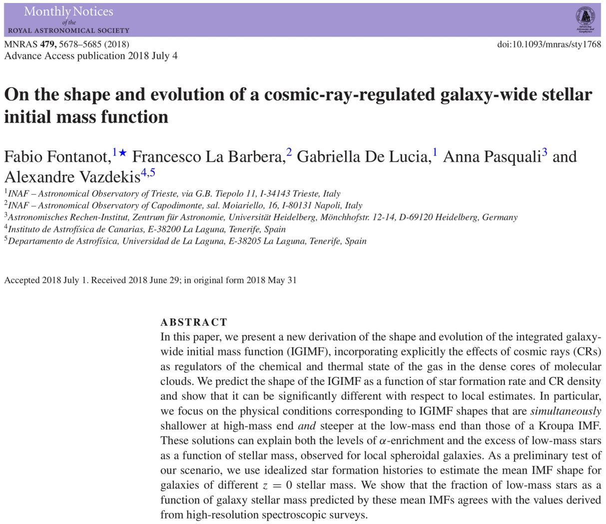
$$\varphi_\star(m) = \begin{cases} \left(\frac{m}{m_{\rm low}}\right)^{-\alpha_1} & m_{\rm low} \le m < m_{\rm br} \\ \left(\frac{m_{\rm br}}{m_{\rm low}}\right)^{-\alpha_1}\left(\frac{m}{m_{\rm br}}\right)^{-\alpha_2} & m_{\rm br} \le m < m_1 \\ \left(\frac{m_{\rm br}}{m_{\rm low}}\right)^{-\alpha_1}\left(\frac{m_1}{m_{\rm br}}\right)^{-\alpha_2}\left(\frac{m}{m_1}\right)^{-\alpha_3} & m_1 \le m \le m_{\rm max} \end{cases}$$

$$m_{\rm br} = M_{\rm J}^\star(\rho_{\rm cl}, U_{\rm CR}).$$

decreases with ρ_{cl}

α_1 and α_2 fixed, while α_3 depends on ρ_{cl}

Marks+(2012)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Advance Access publication 2018 July 4

On the shape and evolution of a cosmic-ray-regulated galaxy-wide stellar initial mass function

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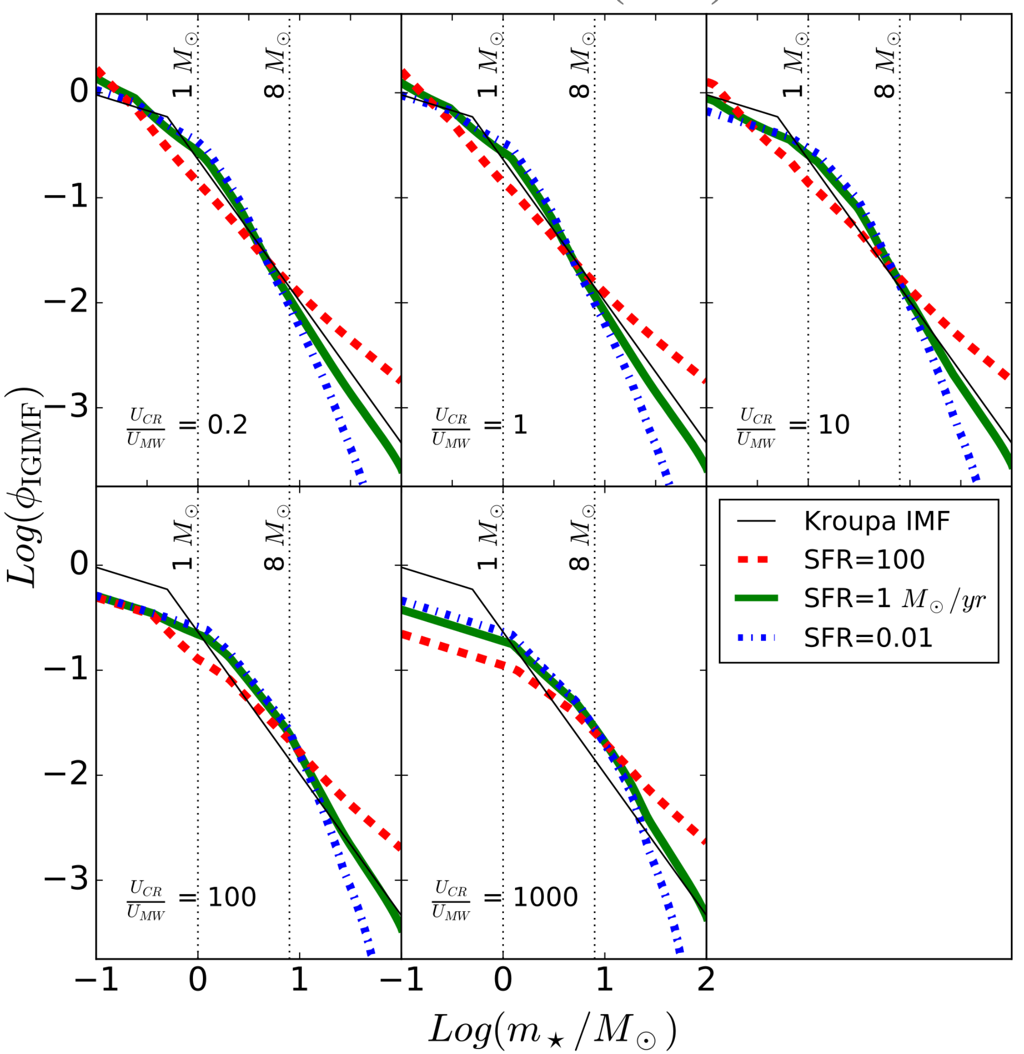
ABSTRACT
In this paper, we present a new derivation of the shape and evolution of the integrated galaxy-wide initial mass function (IGIMF), incorporating explicitly the effects of cosmic rays (CRs) as regulators of the chemical and thermal state of the gas in the dense cores of molecular clouds. We predict the shape of the IGIMF as a function of star formation rate and CR density and show that it can be significantly different with respect to local estimates. In particular, we focus on the physical conditions corresponding to IGIMF shapes that are *simultaneously* shallower at high-mass end *and* steeper at the low-mass end than those of a Kroupa IMF. These solutions can explain both the levels of α-enrichment and the excess of low-mass stars as a function of stellar mass, observed for local spheroidal galaxies. As a preliminary test of our scenario, we use idealized star formation histories to estimate the mean IMF shape for galaxies of different $z = 0$ stellar mass. We show that the fraction of low-mass stars as a function of galaxy stellar mass predicted by these mean IMFs agrees with the values derived from high-resolution spectroscopic surveys.

A variable IMF within GAEA

Fontanot+(2018)

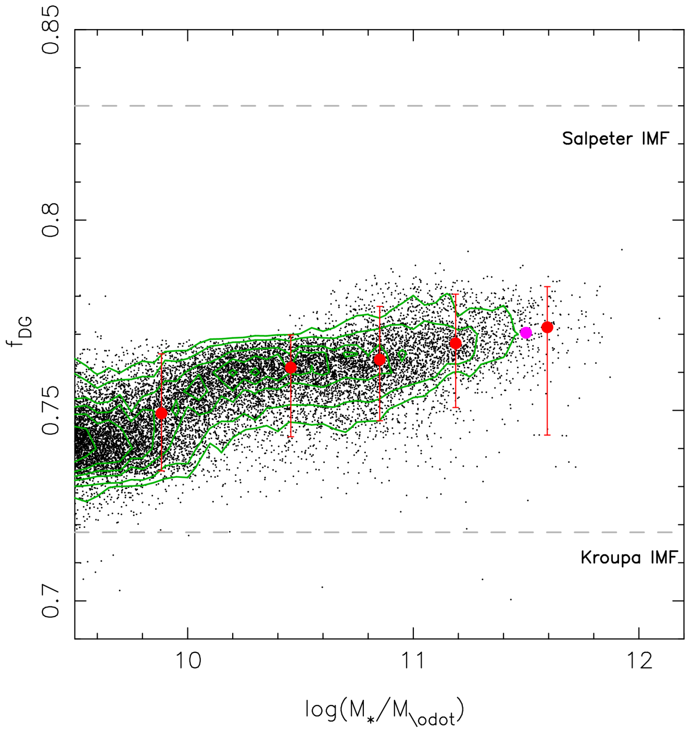


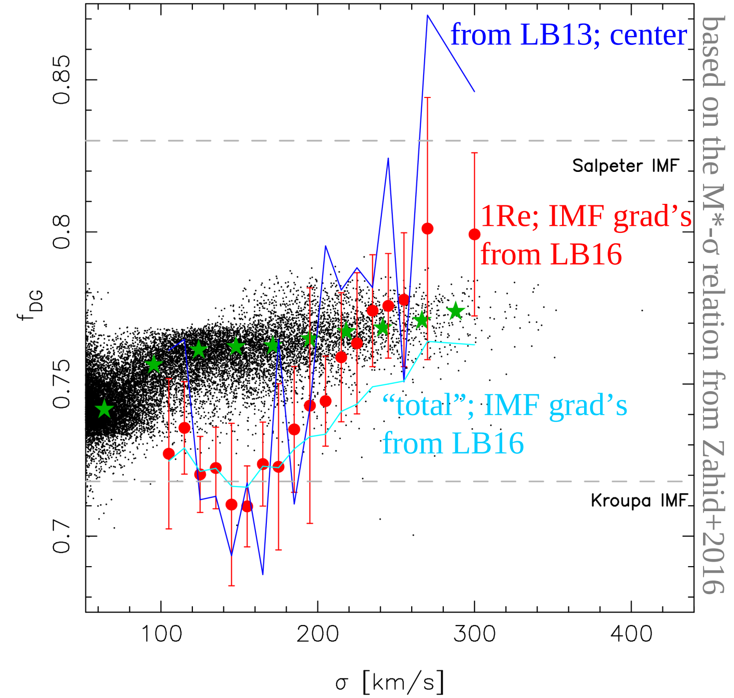
- At low CR density (U_{CR}), the IMF becomes more bottom-heavy (no more than Salpeter!) at high SFR
- At high U_{CR}, the low-mass end does not depend significantly on SFR, and is top-heavy
- We assume $U_{CR}/U_{MW}=\Sigma_{SFR}/\Sigma_{MW}$

A variable IMF within GAEA

We describe IMF variations using the dwarf-to-giant mass ratio in the IMF at z=0, defined as
$f_{DG}=\Phi(m\leq0.6)/\Phi(m\leq1.0)$

Trends of fDG with mass, for "passive" (no $SF_{\leq 2Gyr}$) ETGs in GAEA:



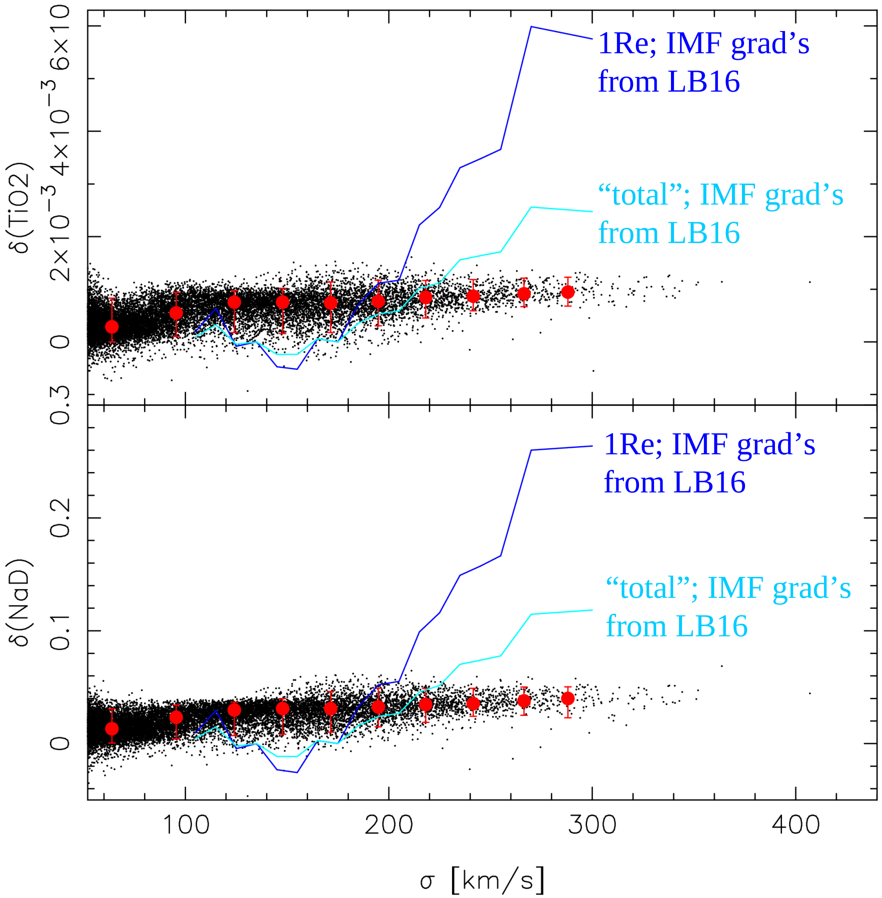


⇨ f_{DG} of model galaxies increases with M* and σ_

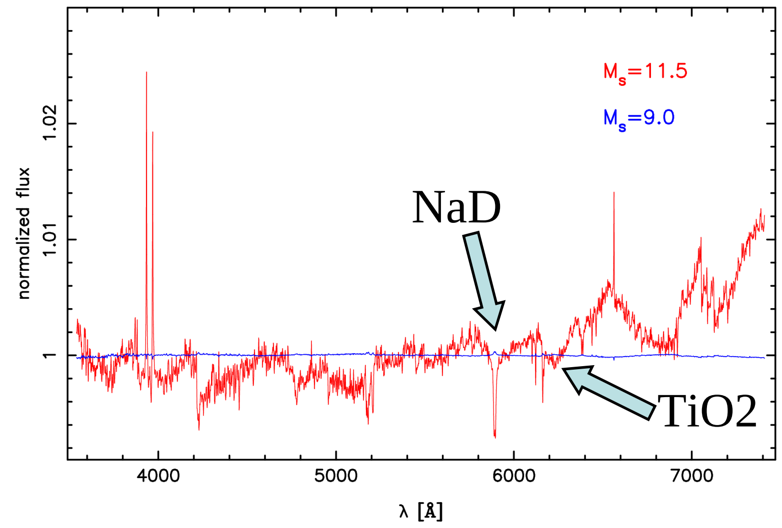
⇨ Observed trend is steeper than models, and the comparison depends on the aperture

A variable IMF within GAEA

Variation of model indices wrt a "canonical" IMF, as a function of σ, for "passive" ETGs in GAEA:



Ratio of model spectra for variable and canonical IMFs:



⇨ Index variations show a (minor) increase with σ

⇨ Observed trends are steeper than those for models

Summary of developments

- Implementation of updated SSP models from FUV through NIR
- Implementation of SSP models with varying abundance ratios, [X/Fe]'s
- How to deal with ETGs having an extended SF…
- Variable IMF: how can we obtain a better match to observations?

  We need
  - IMFs steeper than Salpeter
  - steeper IMF trend with galaxy mass
- Regardless of these implementations, the comparison to observations is hampered by the lack of predictions on spatial variations within galaxies.