The non-universality of the Initial Mass Function in early-type galaxies

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Why is it important ?

- It governs the matter cycle of galaxies, i.e. how gas is being converted into stars.

- It sets the mass scale of galaxies (both luminous and dark matter), a fundamental ingredient of any galaxy formation theory.

- It drives the energy feedback and the enrichment pattern of the inter-stellar medium (ISM) through the evolution of massive stars.

- The IMF is deeply connected to the physics of star formation.

- Constraining the IMF has deep implications for our understanding of stellar evolution and structure.

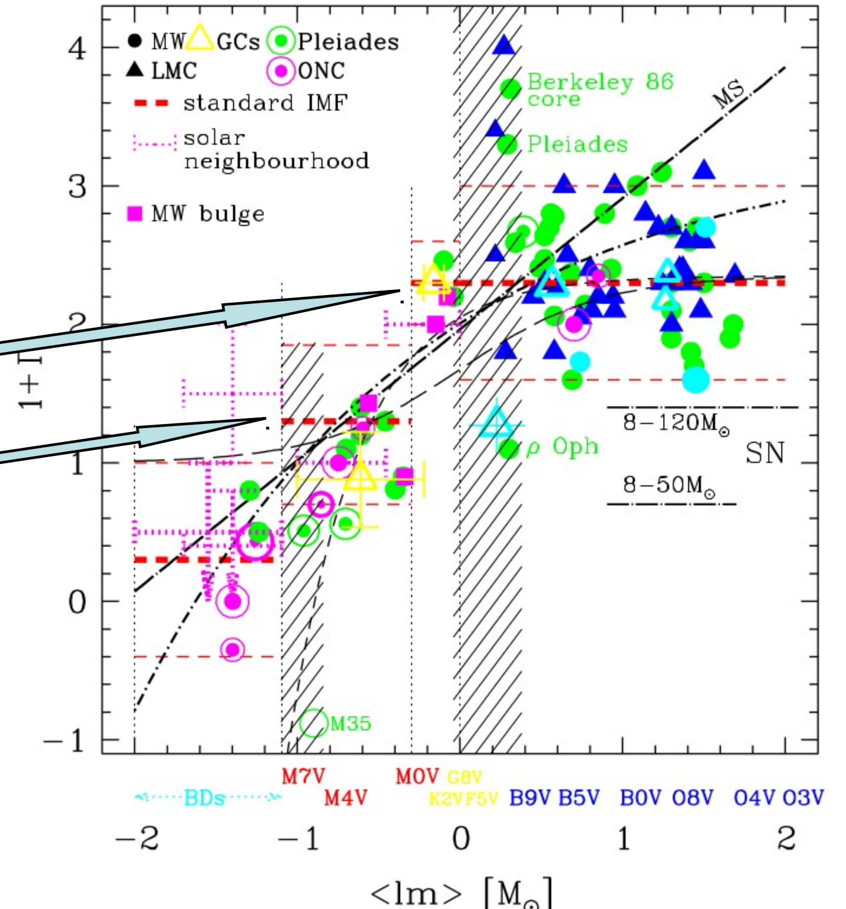
Is the IMF universal ?

IMF slope at different mass scales for star clusters and OB associations in the MW and LMC (from Kroupa 2012; based on data from Scalo 1998 and Kroupa 2001).

- At high mass, the distribution is remarkably consistent with a Salpeter-like universal slope (Kroupa 2001), with a flatter slope at low masses.

Salpeter $\Gamma=1.35$

low-mass slope $\Gamma=0.3$



Central value of the mass range where Γ is estimated.

- The plot is biased towards solar metallicities, and limited to densities $<10^5 M_{Sun}/pc^3$.

The stellar IMF: functional forms

Salpeter (1955), single-segment, **unimodal** IMF →

$$\xi(m) = \frac{dN}{d\log m} = k' \times m^{-\Gamma}$$

with Γ=1.35

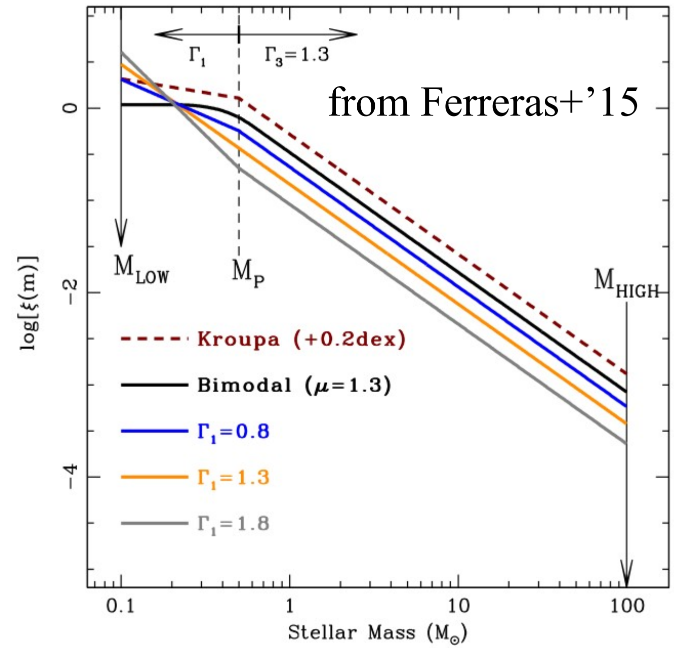
Kroupa (1990, 1991, 1993), two-segment, IMF

⇕

$\Gamma_1 = 0.3$ for $0.1 < m < 0.5 M_{Sun}$ (flatter than Salpeter)

$\Gamma_3 = 1.35$ for $m > 0.5 M_{Sun}$ (Salpeter-like)

very similar to the Chabrier IMF



Bimodal (low-mass tapered) IMF, with slope Γ_b (Vazdekis+'96): Γ_b=1.3 → Kroupa IMF.

Both unimodal and bimodal IMFs seem to be not well justified (either observationally, e.g. Gunawardhana+2011, or theoretically, e.g. Chabrier+2014), but they are a pratical way to change the dwarf-to-giant ratio in the IMF.

EWASS 2015
EUROPEAN WEEK OF ASTRONOMY AND SPACE SCIENCE
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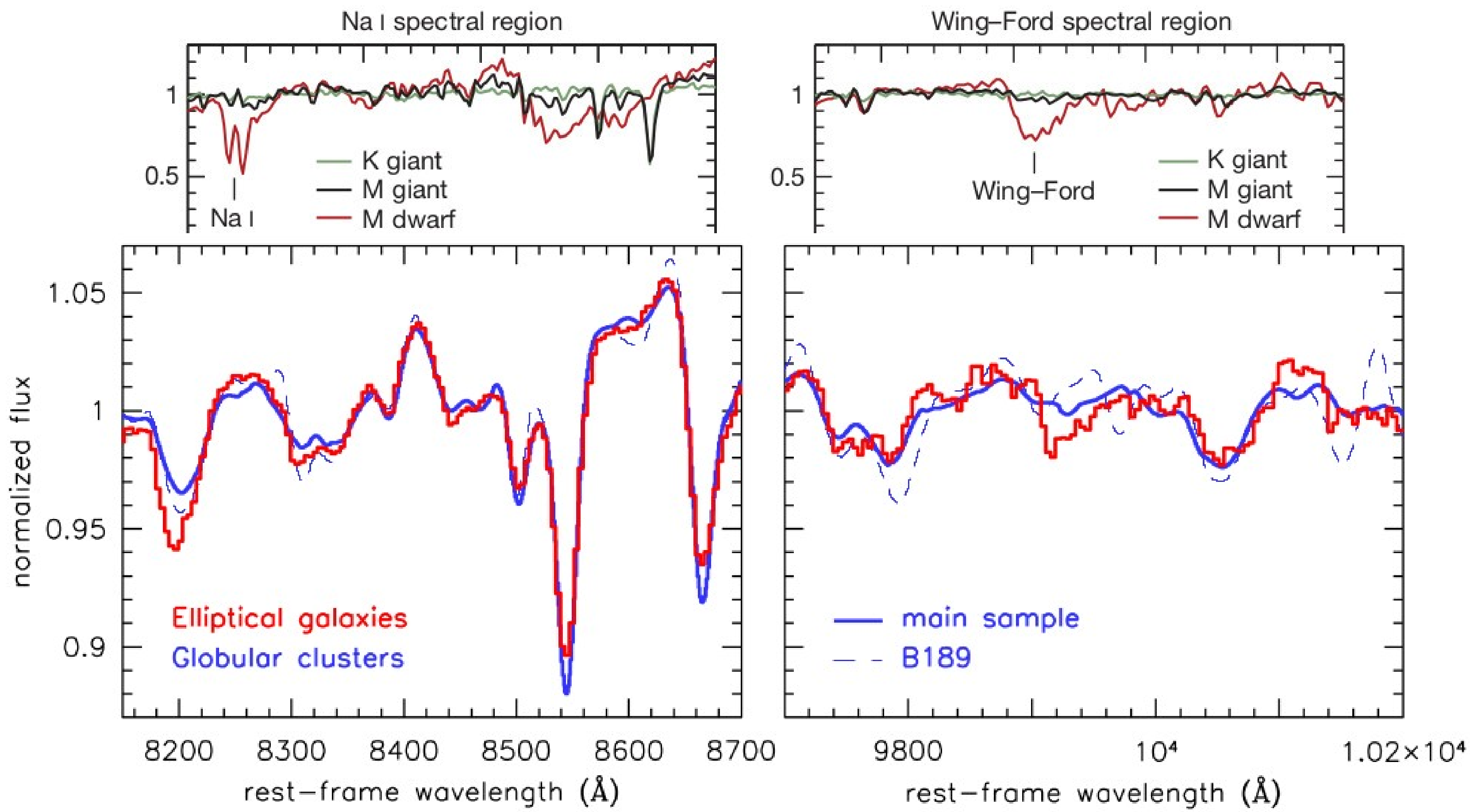
LAYOUT

- Gravity-sensitive features
- IMF-slope trends → "mass", radius, time
- Challenges to IMF variations

A bottom-heavy IMF in luminous ETGs

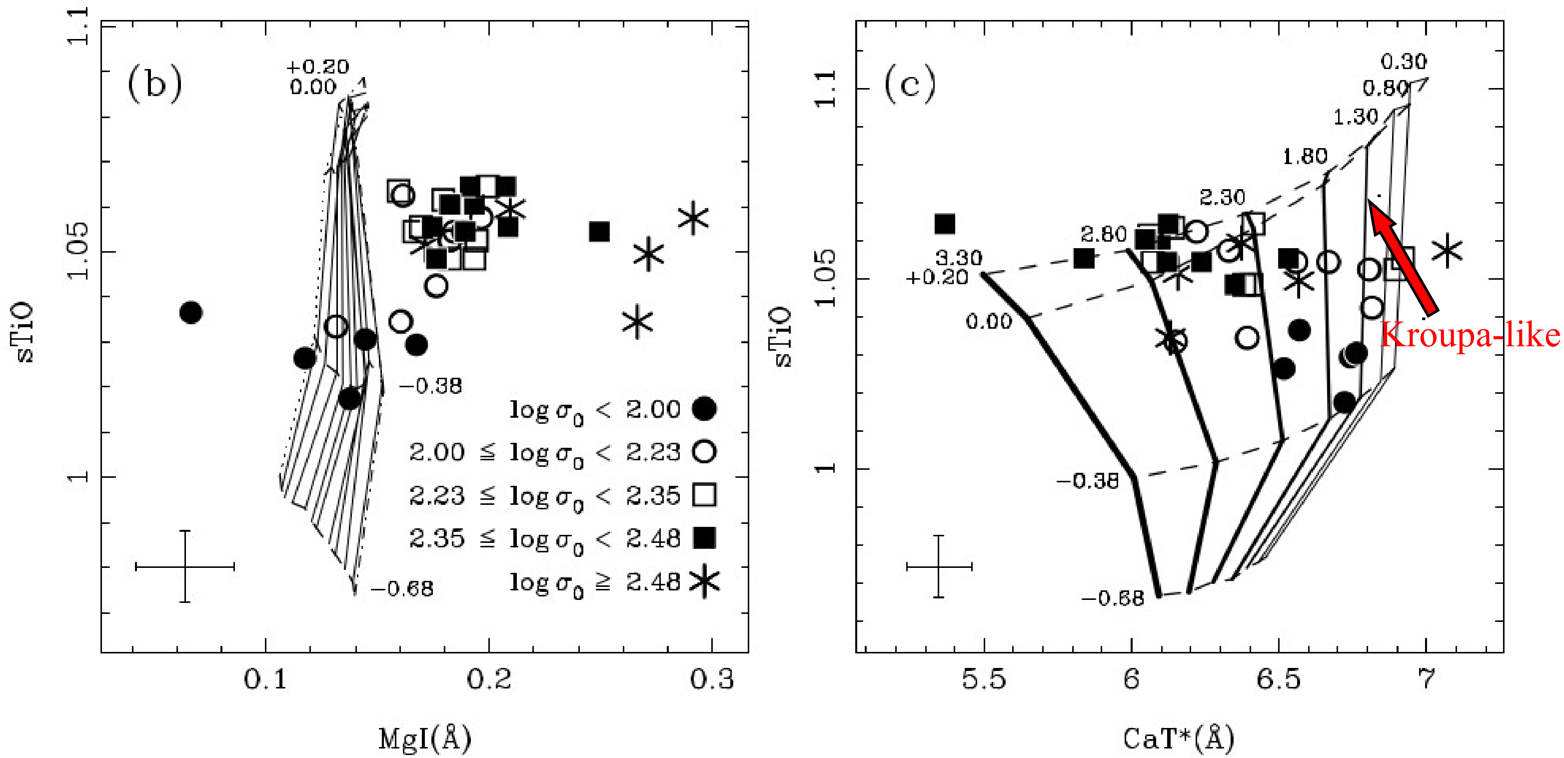
The interest to use gravity sensitive features to constrain the IMF low-mass end has been recently raised up by van Dokkum&Conroy(2010).



Comparison to GCs with similar ages, metallicities, abundance ratios as ETGs (van Dokkum&Conroy 2011).

A bottom-heavy IMF in massive ETG?

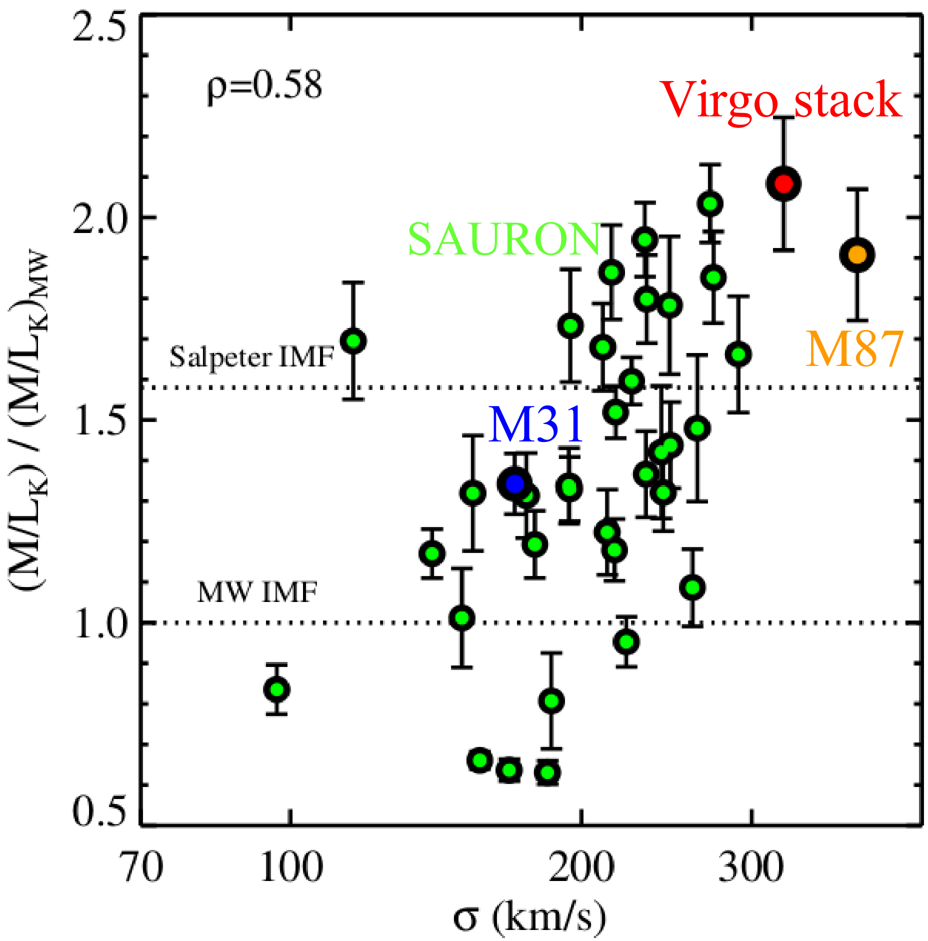
- Early studies plagued by small sample sizes, low S/N and R, uncertain SP models (Spinrad'62; Cohen'78; Faber&French'80; Carter+'86; Hardy&Couture'88; Delisle&Hardy'92)



The issue was raised up again, after more than 10yrs, by Cenarro+(2003). However, the interpretation of the CaT line was hampered by the lack of model predictions for non-solar abundance ratios (Saglia+2002).

A bottom-heavy IMF in luminous ETGs

The analysis was extended to 34 SAURON ETGs by Conroy&vanDokkum(2012b)



Conroy&vanDokkum(2012a) SP models

spectral fitting (400→1020nm)

Table 1 from CvD12b

Parameter	Prior
v_z	(−1,000,10,000)
σ	(20,400)
[Fe/H]	(−0.4,0.4)
[O,Ne,S/Fe]	(−0.4,0.6)
[C/Fe]	(−0.4,0.4)
[N/Fe]	(−0.4,0.8)
[Na/Fe]	(−0.4,1.3)
[Mg/Fe]	(−0.4,0.6)
[Si/Fe]	(−0.4,0.4)
[Ca/Fe]	(−0.4,0.4)
[Ti/Fe]	(−0.4,0.4)
[Cr/Fe]	(−0.4,0.4)
[Mn/Fe]	(−0.4,0.4)
age	(4,15.0)
$\log(f_y)$	(−5.0,−0.3)
α_1	(0.0,3.5)
α_2	(0.0,3.5)
α_3	2.3
$\Delta(T_{\rm eff})$	(−50,50)
log(M7III)	(−5.0,−0.3)
$\log(f_{\rm hot})$	(−5.0,−0.3)
$T_{\rm hot}$	(1,3)

21 free fitting parameters

(11 abundance ratios, 3-segment IMF)

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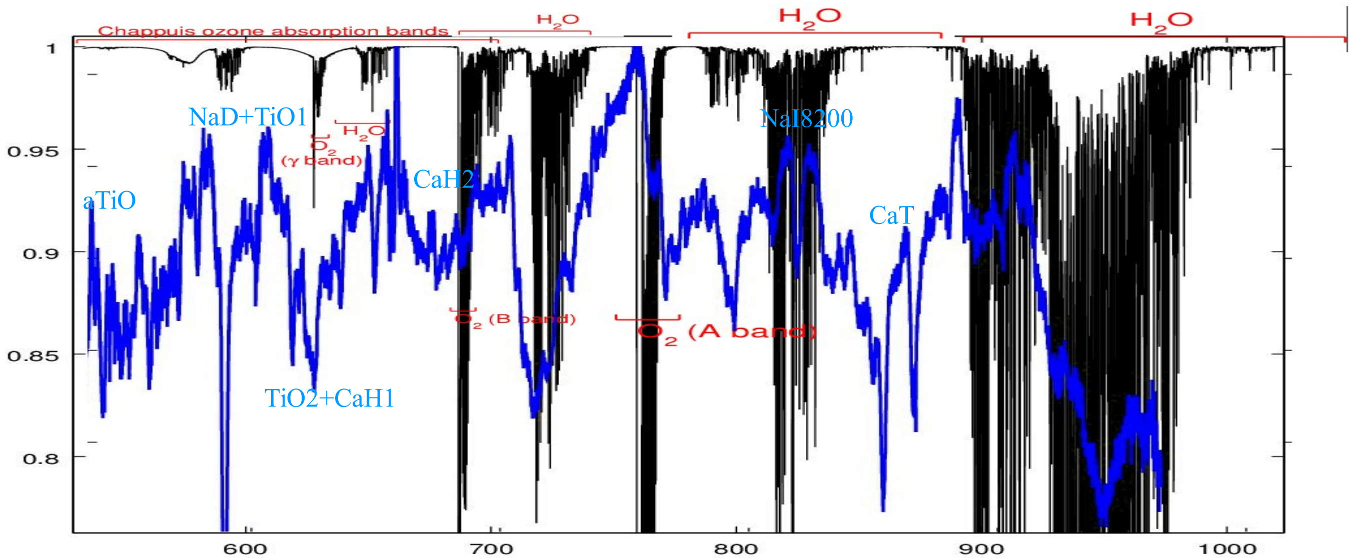
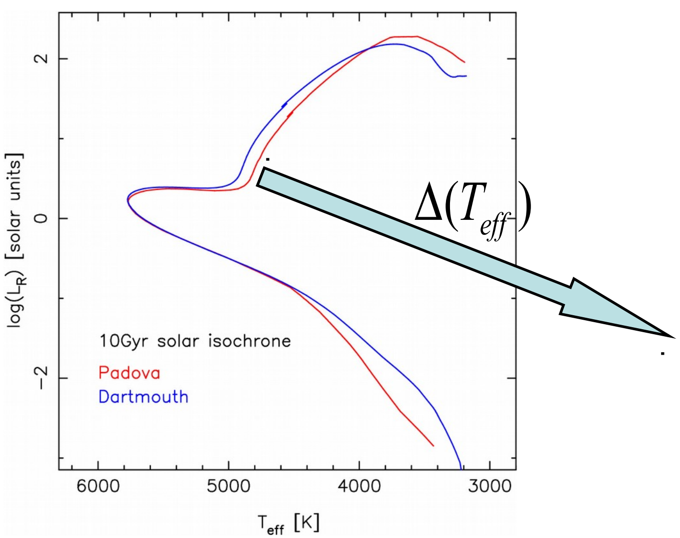
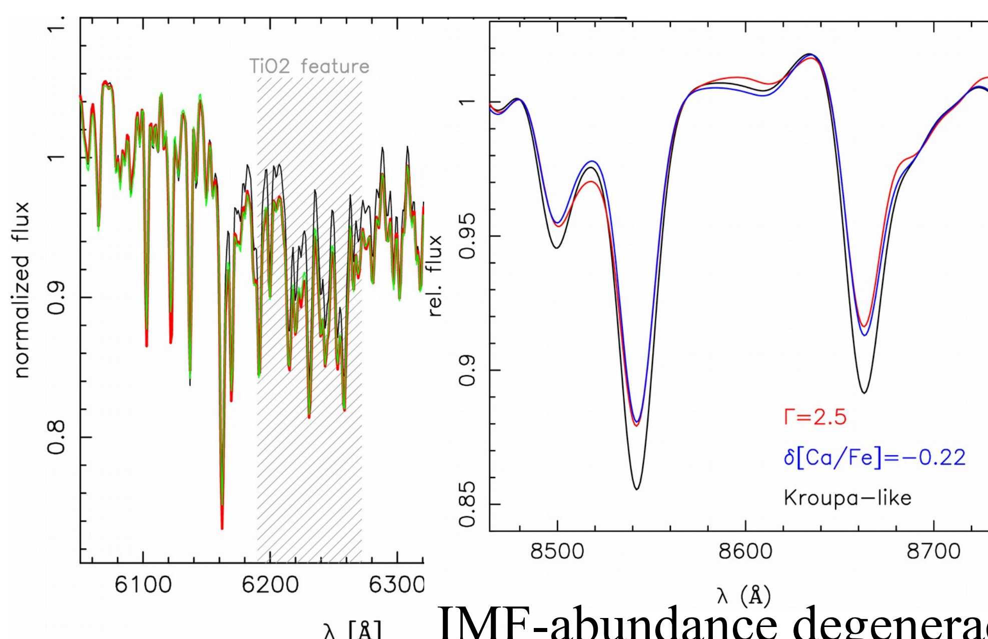
A difficult task !!





SP modeling uncertainties



IMF-abundance degeneracy

LAYOUT

- Gravity-sensitive features
- IMF-slope trends
  - "mass"
  - radius
  - time
- Challenges to IMF variations

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Carsten Weidner (IAC, ES)
Jesús Falcón Barroso (IAC, ES)
Ignacio G. de la Rosa (IAC, ES)
Anna Pasquali (ARI, DE)
Marina Trevisan (INPE, BR)
Beatriz Barbuy (IAG, BR)
Elena Ricciardelli (Valencia, ES)
……..

Constraining IMF from SDSS spectra

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

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

$0.05 \leq z \leq 0.095$; $70 \leq \sigma_0 \leq 420$ km s^{-1}; eclass<0, FracDevr>0.8, E(B-V)<0.1, S/N>15

18 median-stacked spectra with $100 \leq \sigma_0 \leq 320$km/s

MILES extended (MIUSCAT) SSP models (Vazdekis+'12)

- 0.06<Age<17.78Gyr; -2.23<[Z/H]<+0.22
- unimodal (single power-law) IMF
- **bimodal** (low-mass tapered; Vazdekis+'96) IMF

IMF-σ trend for the population of ETGs as a whole, with optical+NIR features

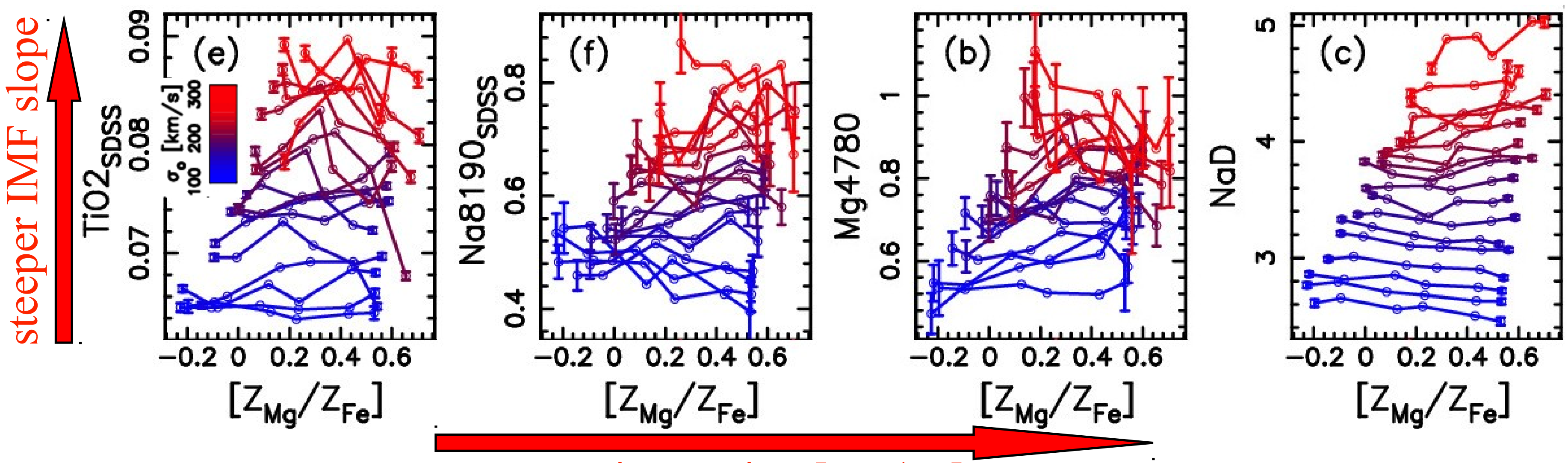
24,781 ETGs, S/N>200/Å, no sky contamination issues

Spectral indices vs. σ and [α/Fe]

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

age and metallicity [Z/H]	IMF (4700<λ<8800Å)	elemental abundances
Hβo, HγF, [MgFe]'	Mg4780, TiO1, TiO2, NaI8190, CaT	CaHK, NaD

Abundance ratios:

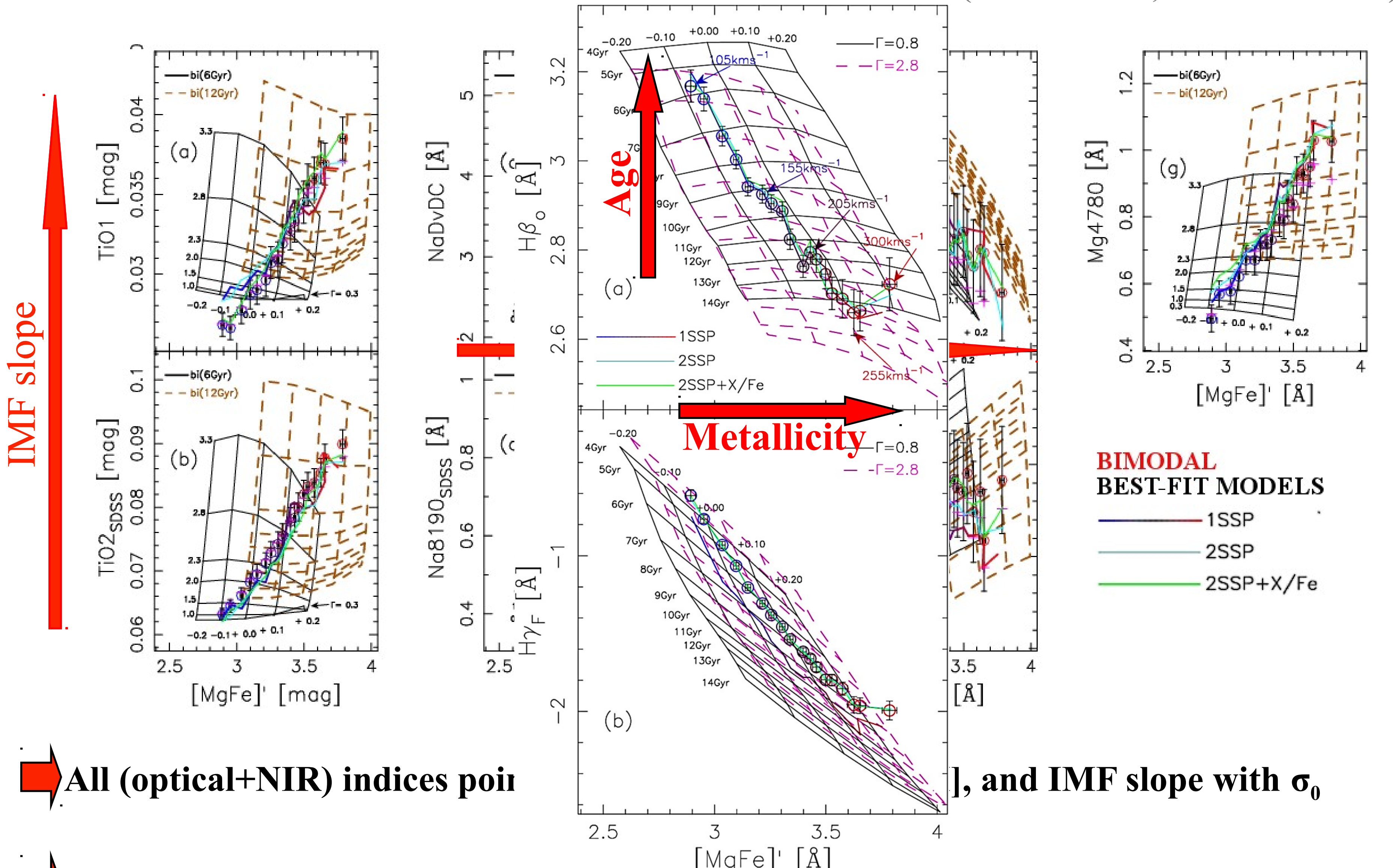


increasing [Mg/Fe]

At fixed σ (age/[Z/H]), IMF-sensitive features do not vary much with [Mg/Fe]

Observed vs. model indices

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

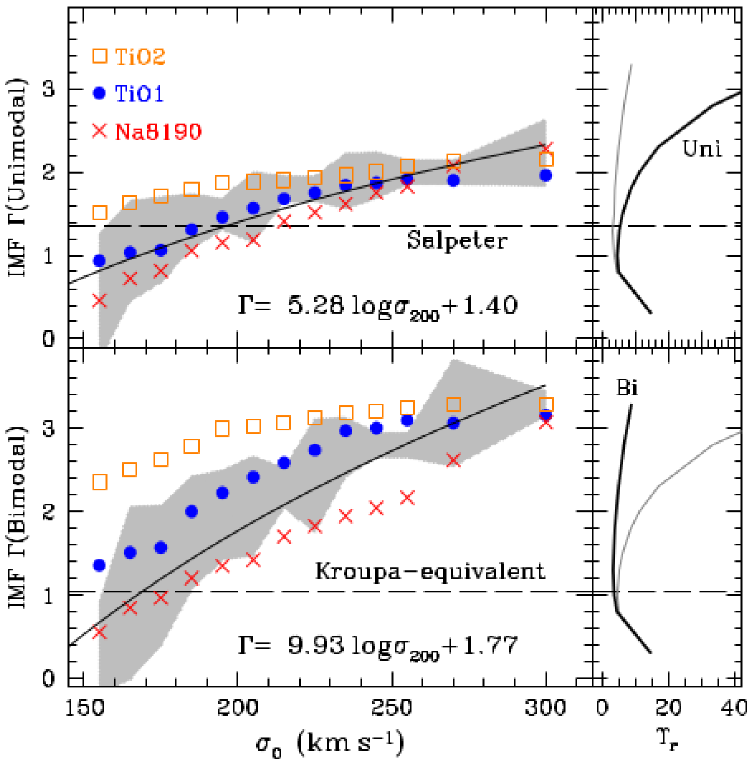


- All (optical+NIR) indices poi], and IMF slope with σ_0
- Unimodal and bimodal models fit equally well (i.e. cannot be singled out from indices)

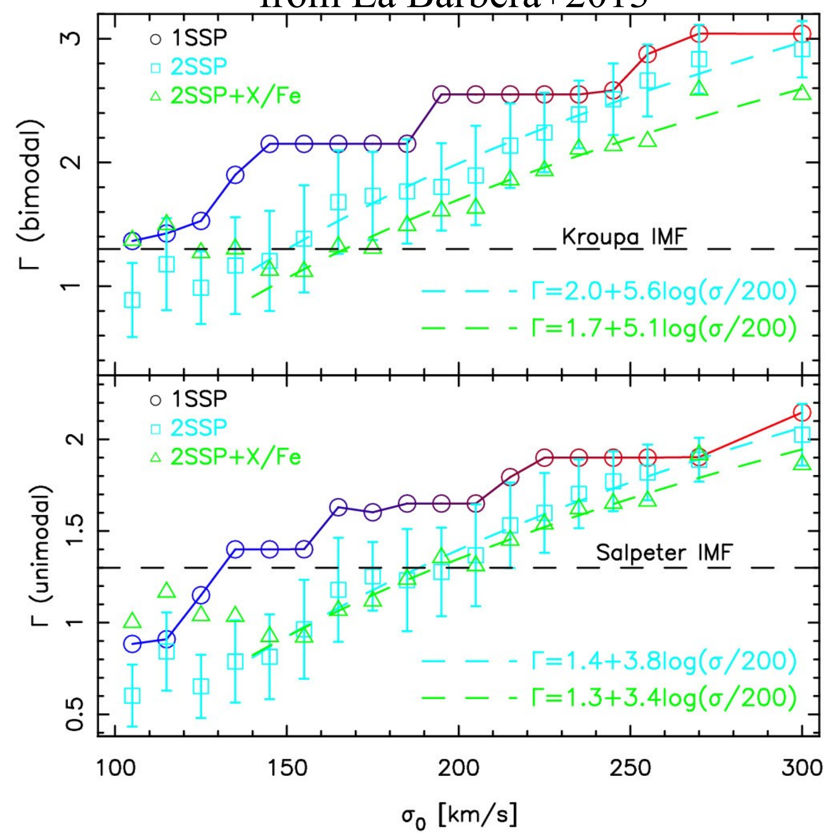
IMF-σ relation

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

from Ferreras+2013



from La Barbera+2013

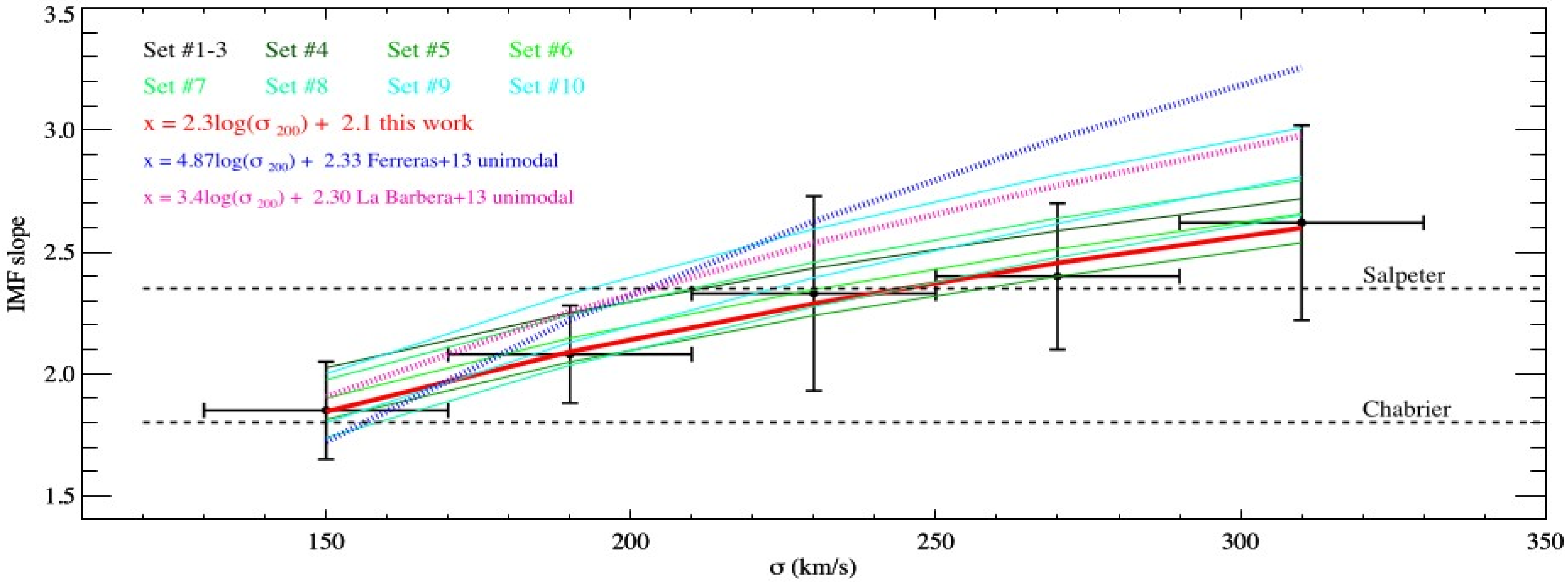


- Trend from a Kroupa-like IMF (σ≤150km/s), to a bottom-heavy IMF at high σ.
- Different indices give different results, but the presence of a trend is very robust!
- see Martìn-Navarro talk for correlations with other galaxy properties in CALIFA

Constraining IMF from SDSS spectra

IMF-sensitive features from Spiniello et al.(2014)

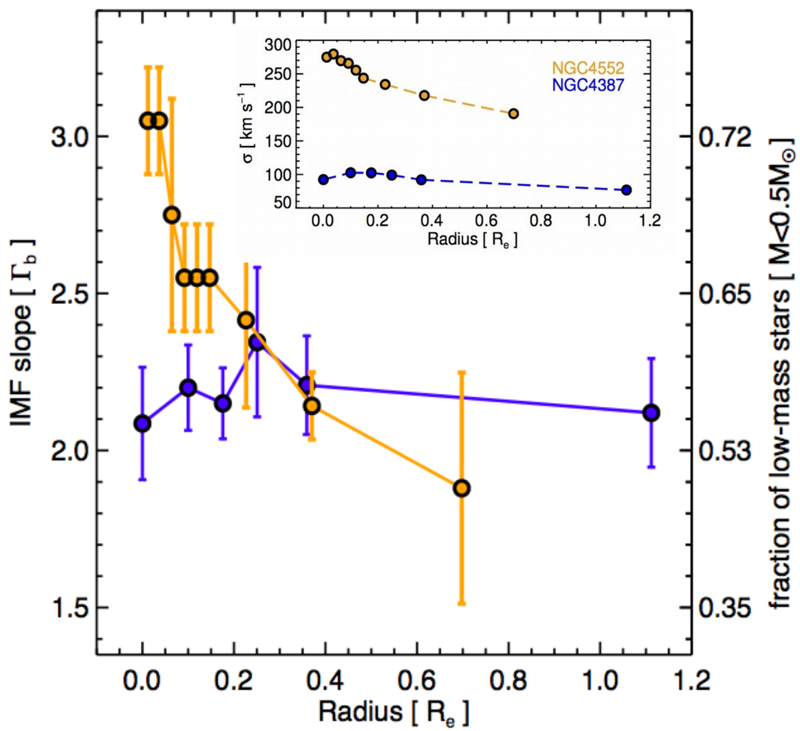
bTiO (aka Mg4780), TiO1, TiO2, aTiO, NaD, CaH1, CaH2



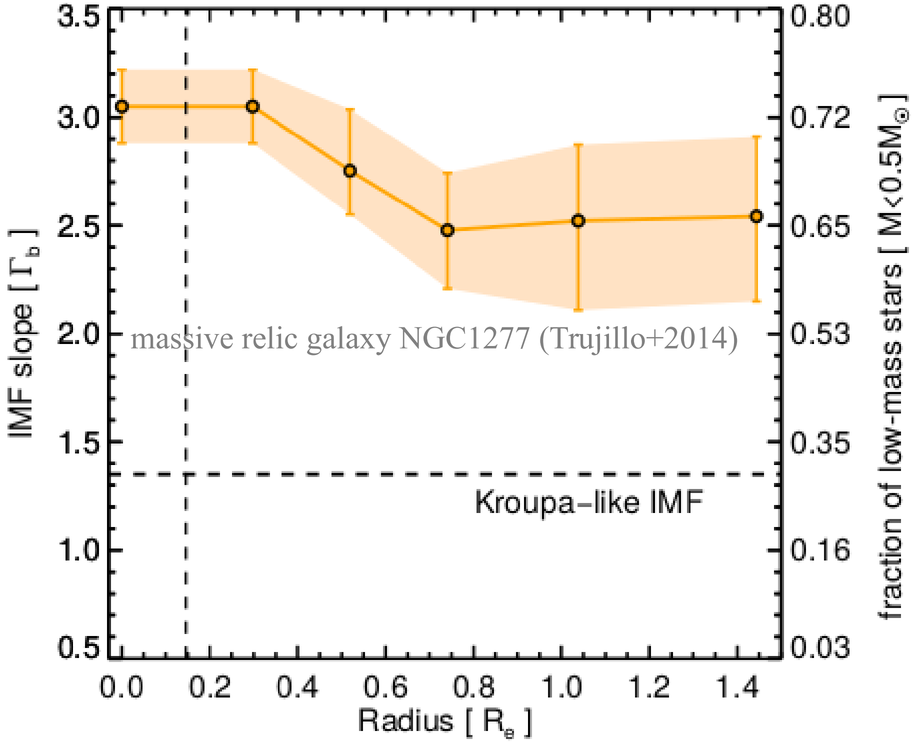
- Trend from a Chabrier-like IMF (σ~150km/s), to a bottom-heavy IMF at high σ (also when including other parameters, e.g. T_{eff}; see also CvD12b).
- The presence of a trend with σ is very robust (see Spiniello+2015a) !

A bottom-heavy IMF in the cores of ETGs ?

Martín-Navarro et al. 2015a



Martín-Navarro et al. 2015c



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

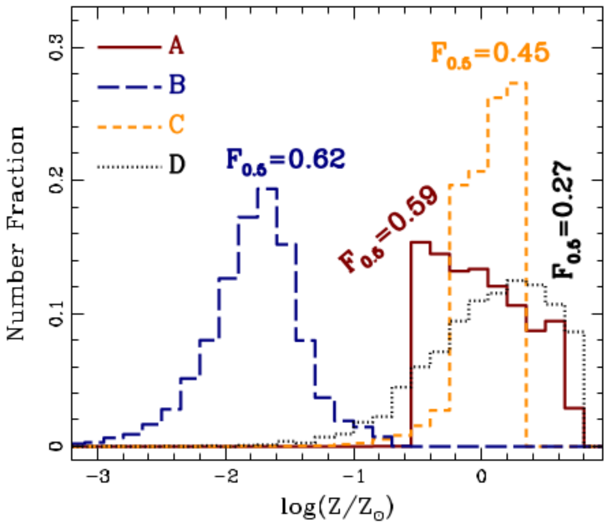
→ IMF gradients relevant to [Z/H] gradients in SLUGGS ETGs (Pastorello+2014)

→ No IMF radial gradient (bulge/disk) for NGC4697 (σ~160km/s; Spiniello et al.2015c)

The time-dependent IMF of ETGs

(Vazdekis+'96,'97; Weidner+'13; Ferreras+15)

Chemical enrichment toy models (Ferreras&Silk2000a,b)

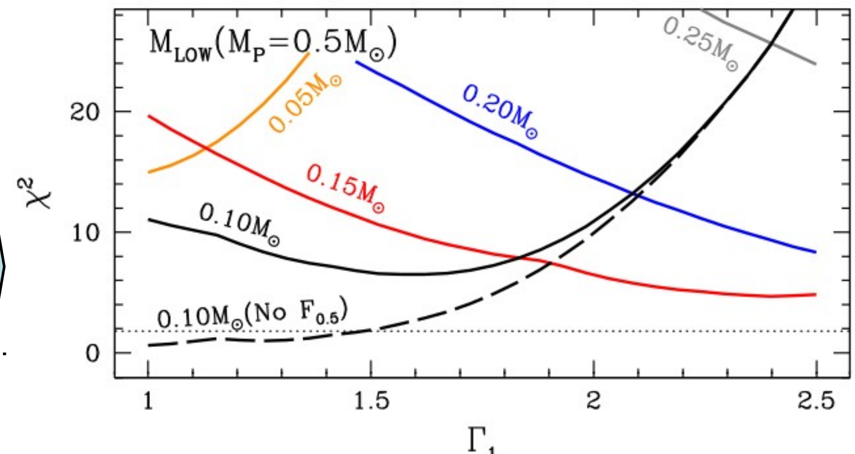


D Kroupa IMF matches age-[Z/H], but not $F_{0.5}$

B bottom-heavy at all times never gets [Z/H]>-1 !!

A **time-dependent IMF is needed** to match all constraints, including fraction of stellar remnants (Peacock+'14)

Observable	Constraint	Reference
Age (Gyr)	[8, 10]	(1)
$[M/H]$	[−0.1, +0.2]	(1)
t_{SF} (Gyr)	[0.5, 2.0]	(2)
$M_s(<Z_\odot/10)$	[0.05, 0.20]	(3)
$F_{0.5}$	[0.6, 0.8]	(4)
$\Upsilon_r/\Upsilon_{r,\odot}$	<7.0	(4)



No parameter (e.g. M_{LOW}) is able to match all constraints for a time-independent IMF

LAYOUT

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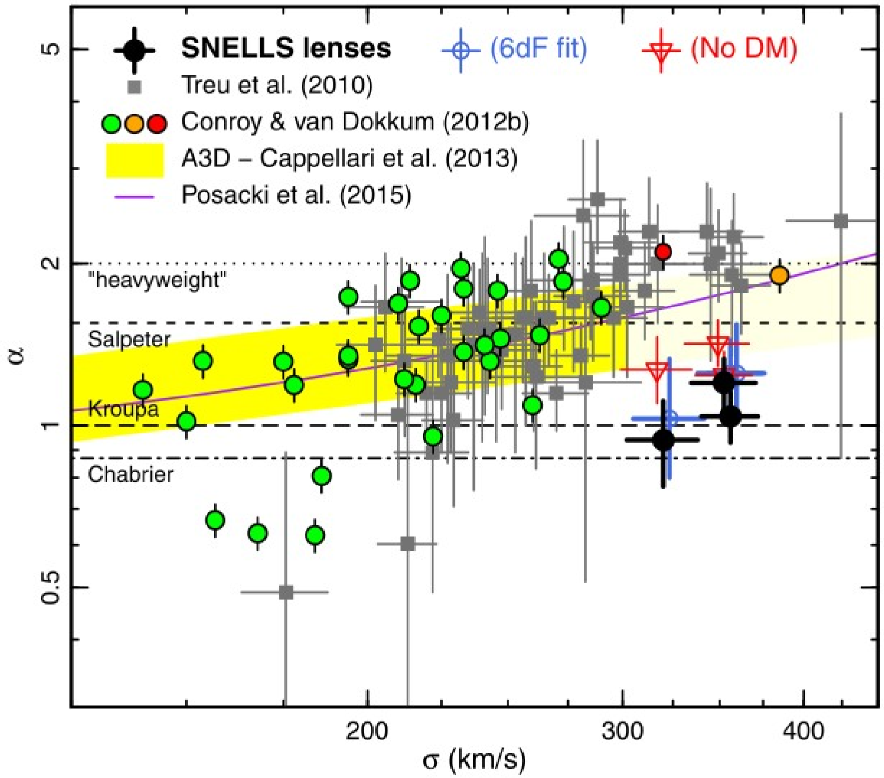
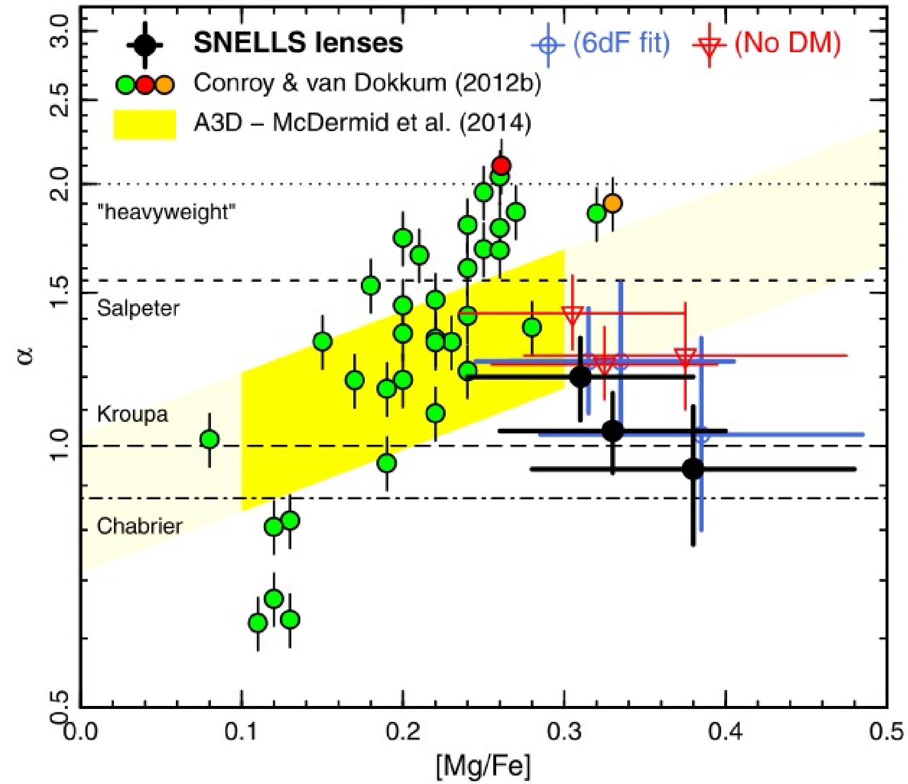
High-σ ETGs with a "light" IMF

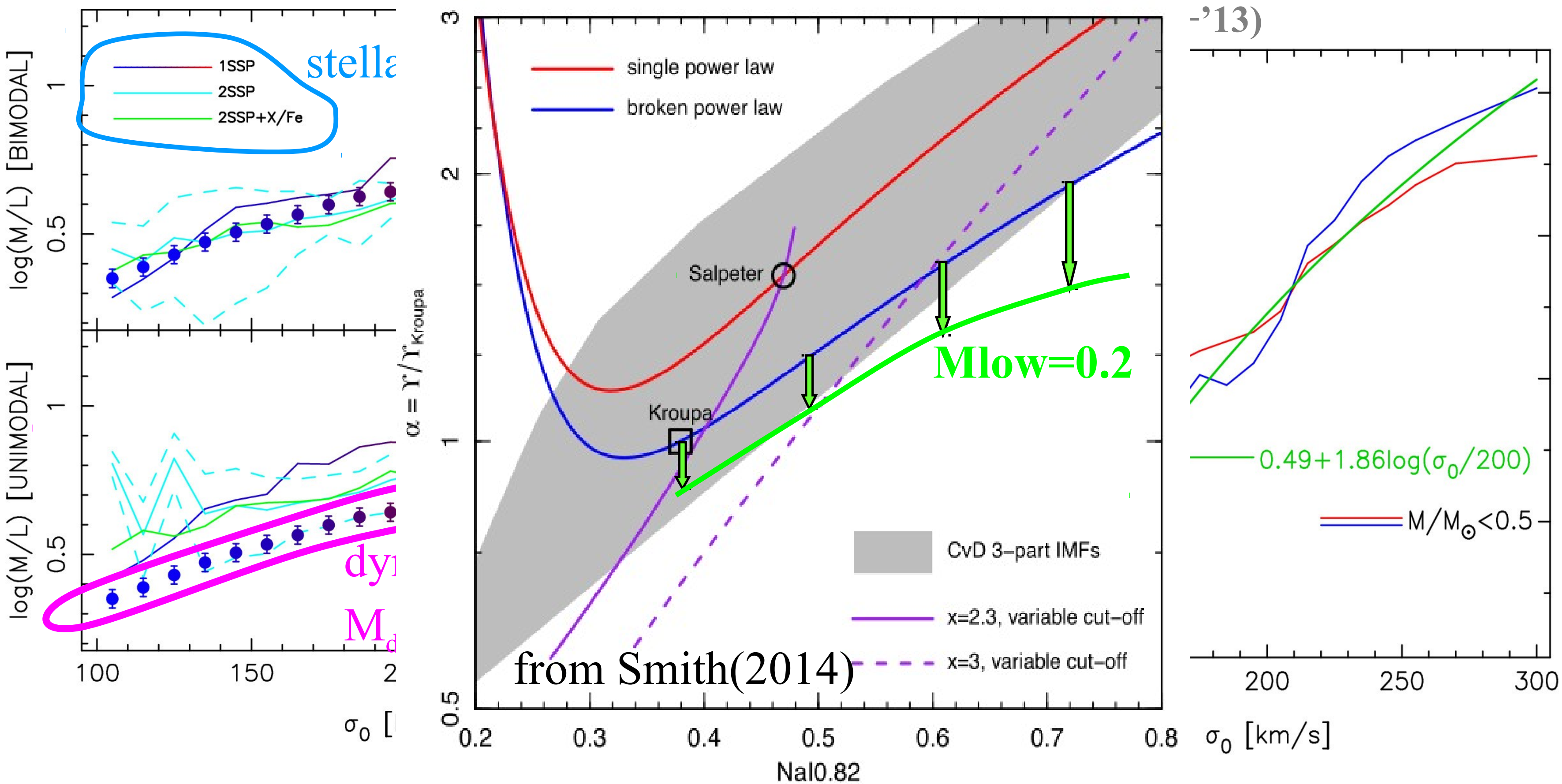
Smith, Lucey and Conroy (2015) have found three nearby (z<0.055), massive (σ>300km/s), ETG lenses, where strong-lensing mass estimates strongly are inconsistent with an "heavy" IMF normalization (see also Smith&Lucey 2013).





See Thomas, J., et al., 2015 (IAU311) for more "dynamical" issues…

IMF slope and normalization

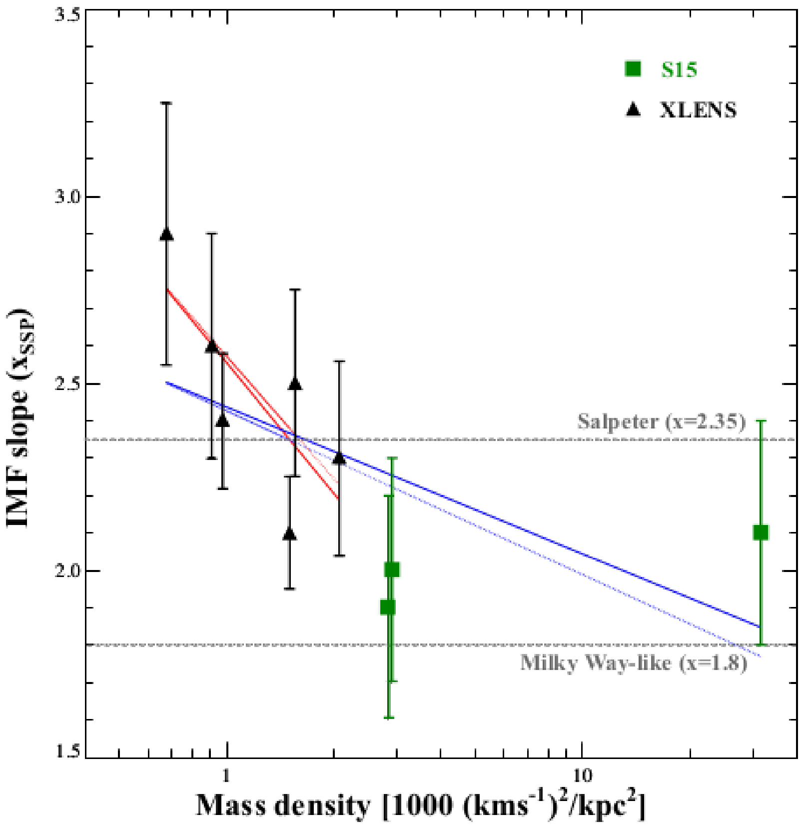


Bimodal 2x smaller than unimodal M*/L.

one can have strong IMF-sensitive features, but “low” M*/L (see Smith&Lucey 2013)

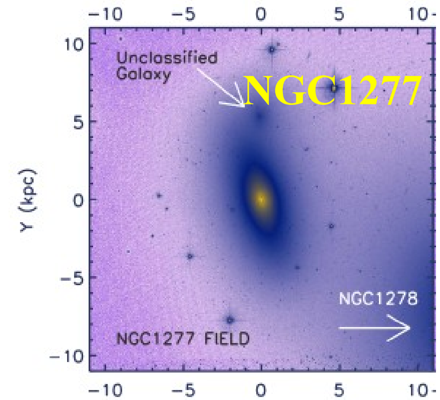
Barnabè+(2013) used this argument to constrain the low-mass end cutoff, assuming a unimodal IMF

IMF variations vs. density/compactness

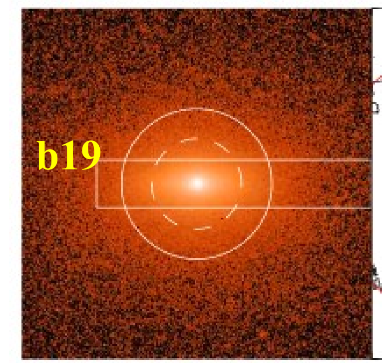


Spiniello+(2015b) have recently suggested an anticorrelation between IMF slope and mass density.

At least two, very dense, ETGs at z~0 have a very bottom-heavy IMF:

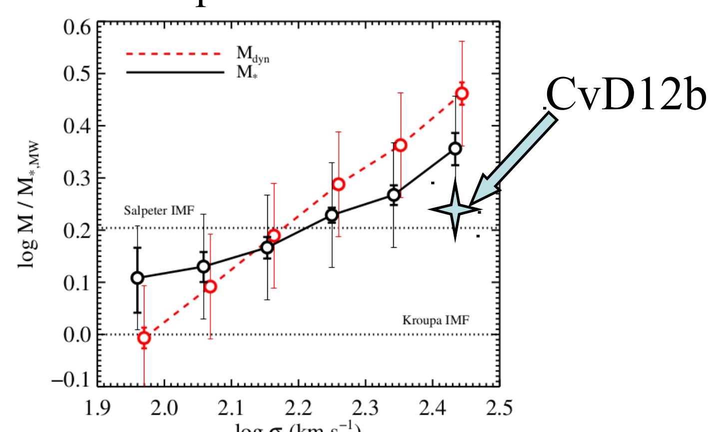


Trujillo+2014;
Martìn-Navarro+2015b



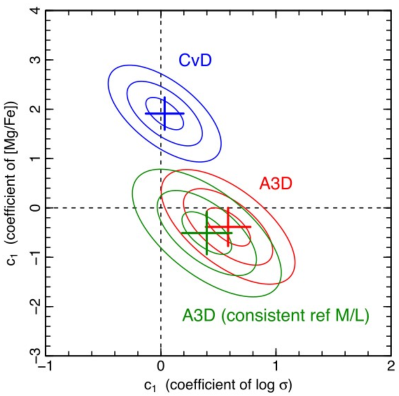
Läsker+2013

Conroy et al. 2013b have found an heavy IMF in compact ETGs from SDSS

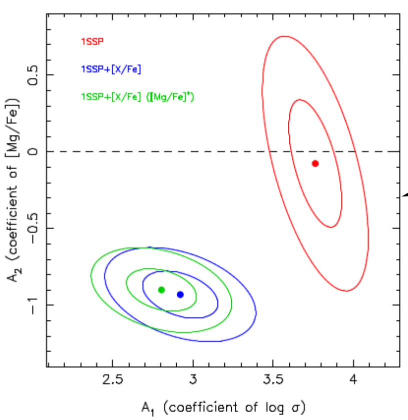


IMF variations vs. σ **and** [α/Fe]

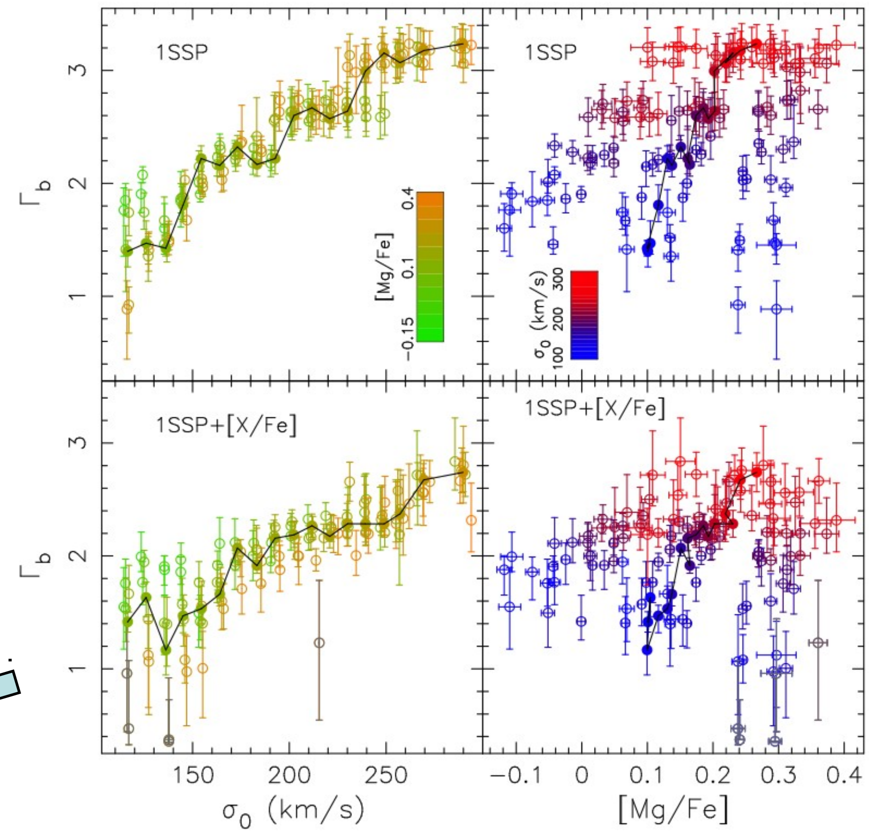
Comparison of spectroscopic and dynamical constraints (Smith 2014):



$$IMF = C_1 \log(\sigma) + C_2 \log([Mg/Fe]) + const$$



anticorrelation with [Mg/Fe] ?



IMF **slope** vs. σ **and** [α/Fe] (La Barbera, Ferreras, Vazdekis 2015) → <u>main correlation with σ</u>

McDermid et al.(2014) found the "dynamical IMF" to have very mild dependence on SP paramaters.

Summary

*Take home message

- Significant trend of IMF slope to increase with σ for the whole population of ETGs. [Mg/Fe] does not drive the trend.

- Consistent IMF trend from different SP studies (it does not mean it is correct, but there is currently no other explanation).

- Significant IMF radial gradients detected in at least some massive ETGs.

- Large uncertainty on M_*/L from spectroscopic indicators alone (but we can constrain the fraction in low-mass stars at birth in the IMF).

- A bottom-heavy IMF at present requires a time-dependent IMF.

- Why high-σ ETGs with a “light” IMF ?