Constraints on the stellar IMF of early-type galaxies from a variety of spectral features

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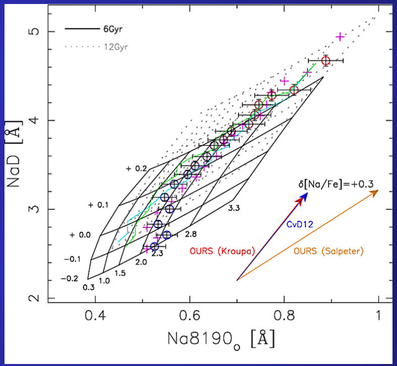
The stellar IMF

It is a crucial ingredient of any theory of star formation, sets the mass-scale of galaxies, controls the intensity of stellar feedback processes, drives chemical enrichment patterns of the ISM

Gravity-sensitive features

- 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)
- Trend towards a bottom-heavier, than MW, IMF in massive galaxies
  (Cenarro+'03; van Dokkum&Conroy'10,'11; Conroy&van Dokkum'12a,b)
- Trend is in place for the whole population of ETGs
  (Ferreras+'13; La Barbera+'13; Spiniello+'13)
- Abundance patterns vs. IMF degeneracy (Spiniello+'12)



(from La Barbera+'13)

- Independent constraints from dynamical models/lensing
  (Ferreras+'08,'10; Thomas+'11, Cappellari+'12a, b; Dutton+'12; Tortora+'13).
  Are these consistent with spectral features (Barnabé+13, Conroy+'13; Smith&Lucey'13) ?

LAYOUT

- Stacked spectra (σ_0) – spectral features
- [α/Fe] stacks at fixed σ_0
- Fitting age-, metallicity-, IMF-sensitive features
- Constraints to M/L's and mass fractions

Sample selection

SPIDER volume-limited sample (Miller+' 03) of <u>39,993 ETGs from SDSS-DR6</u>

M_r<-20 (*bright* ETGs; Capaccioli+' 92)

spectroscopy available → $0.05 \leq z \leq 0.095$, $70 \leq \sigma_0 \leq 420$ km s^{-1}

ETGs → eclass<0, $FracDev_r > 0.8$

match to UKIDSS-LAS DR4 → <u>5,080 ETGs with grizYJHK</u>

→ $100 \leq \sigma_0 \leq 320$km/s (18 bins, each 10km/s width, but the two at highest σ_0, i.e. 260–280 and 280–320 km/s, respectively)

→ low internal reddening, E(B-V)<0.1 (estimated from spectral fitting)

→ excluding spectra in the lowest quartile of the S/N distribution

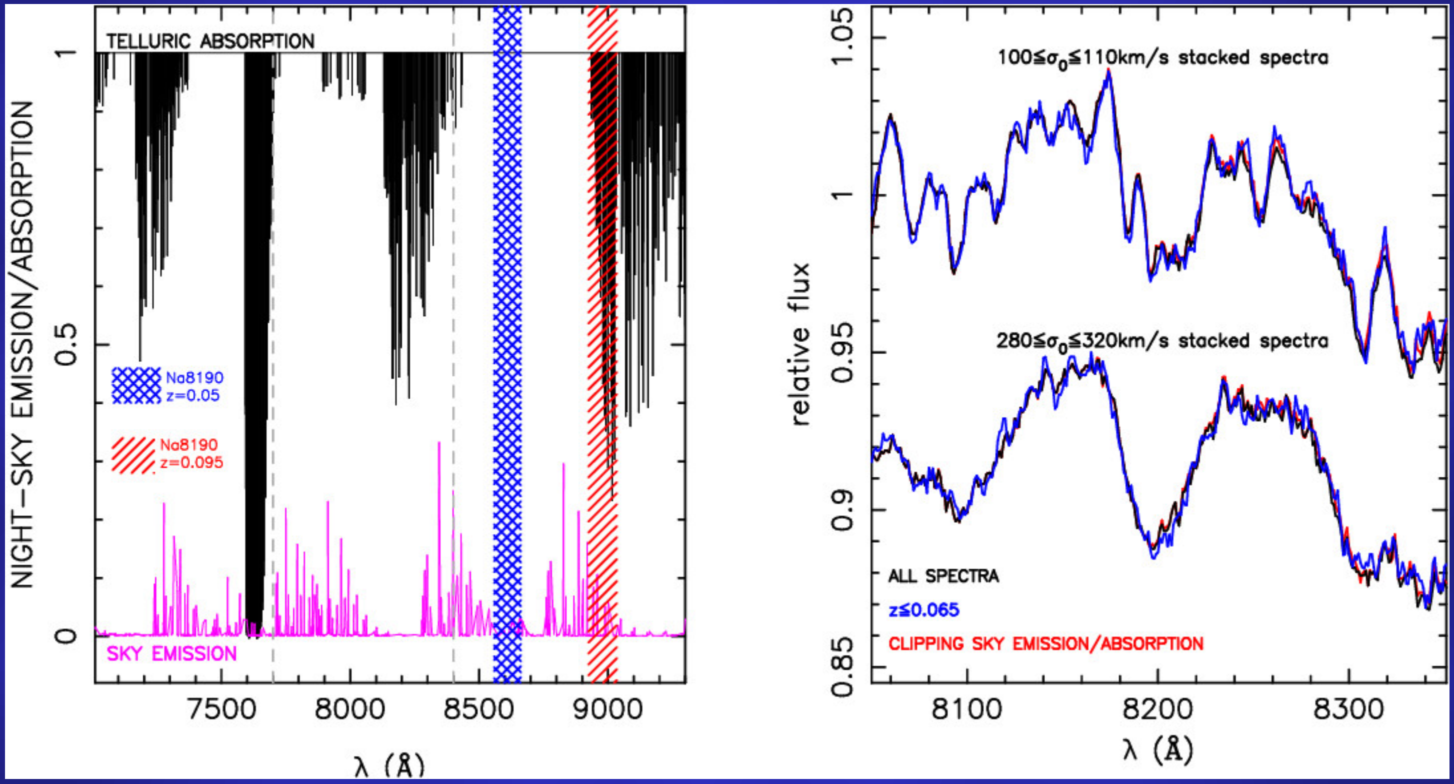
↓

24,781 ETGs (Ferreras+'13; La Barbera+'13)

First time the IMF trend has been analyzed for the whole population of ETGs with a variety of features

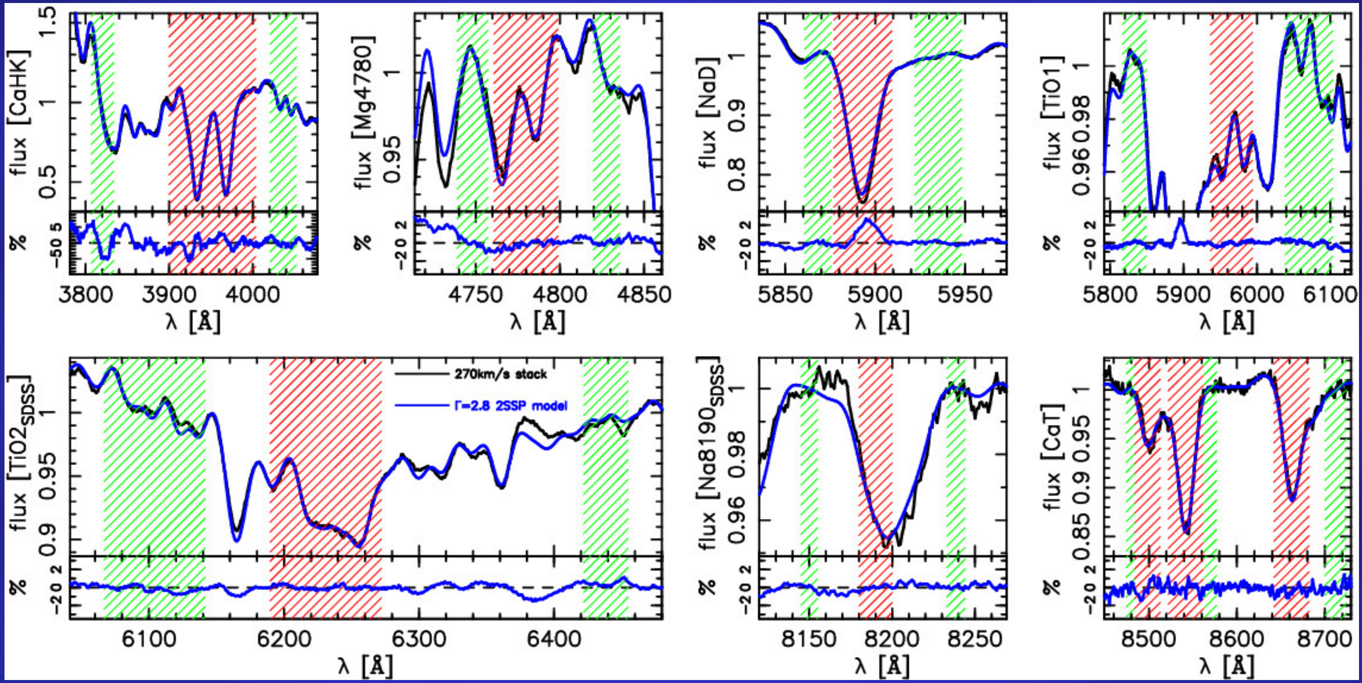
Stacking SDSS spectra

- we median-combine spectra in each σ_0 bin, excluding pixels with flags on.
- stacked spectra have <u>high S/N</u> (from 100 to 2000, depending on σ_0 and λ)
- extensive tests show that sky contamination does not affect at all our results.



Selection of spectral features

- IMF-sensitive features: **Mg4780** (Serven+'05), **TiO1 (Trager+'98)**, **$TiO2_{SDSS}$** (Trager+'98 modified), **$NaI8190_{SDSS}$** (Vazdekis+'12 modified), **CaT** (Cenarro+'01)
- abundance-sensitive features (leading elements): **CaHK** (Serven+'05), **NaD** (Trager+'98)



- age+metallicity indicators: **$H\beta_o$** (Cervantes & Vazdekis '09), **$H\gamma_F$**, **[MgFe]'**

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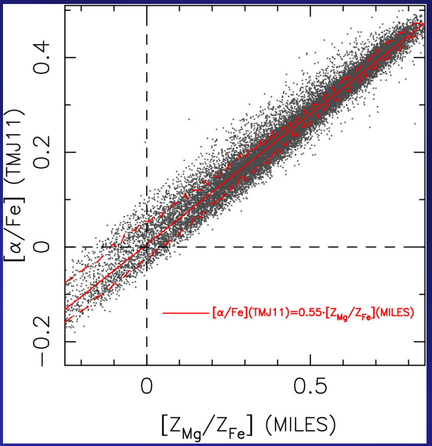
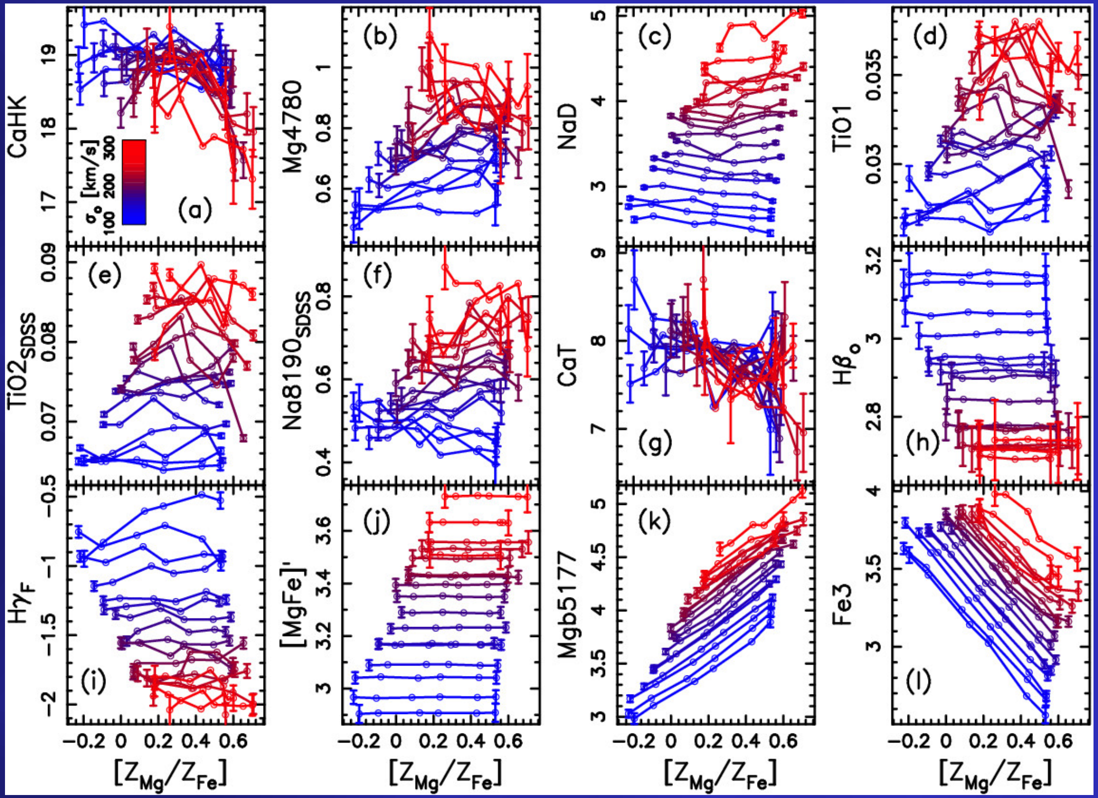
Spectral indices vs. [α/Fe], at fixed σ_0

- we measure the difference of Mgb and Fe3 metallicities (with MILES SSPs), at fixed age ($H\beta_o$): $[Z_{Mg}/Z_{Fe}]$.
- The $[Z_{Mg}/Z_{Fe}]$ shows a tight correlation with [α/Fe] estimated with Thomas+'11 models.





Line strengths of $[Z_{Mg}/Z_{Fe}]$-binned spectra at fixed σ_0 (after removing Age and Z variations among bins).

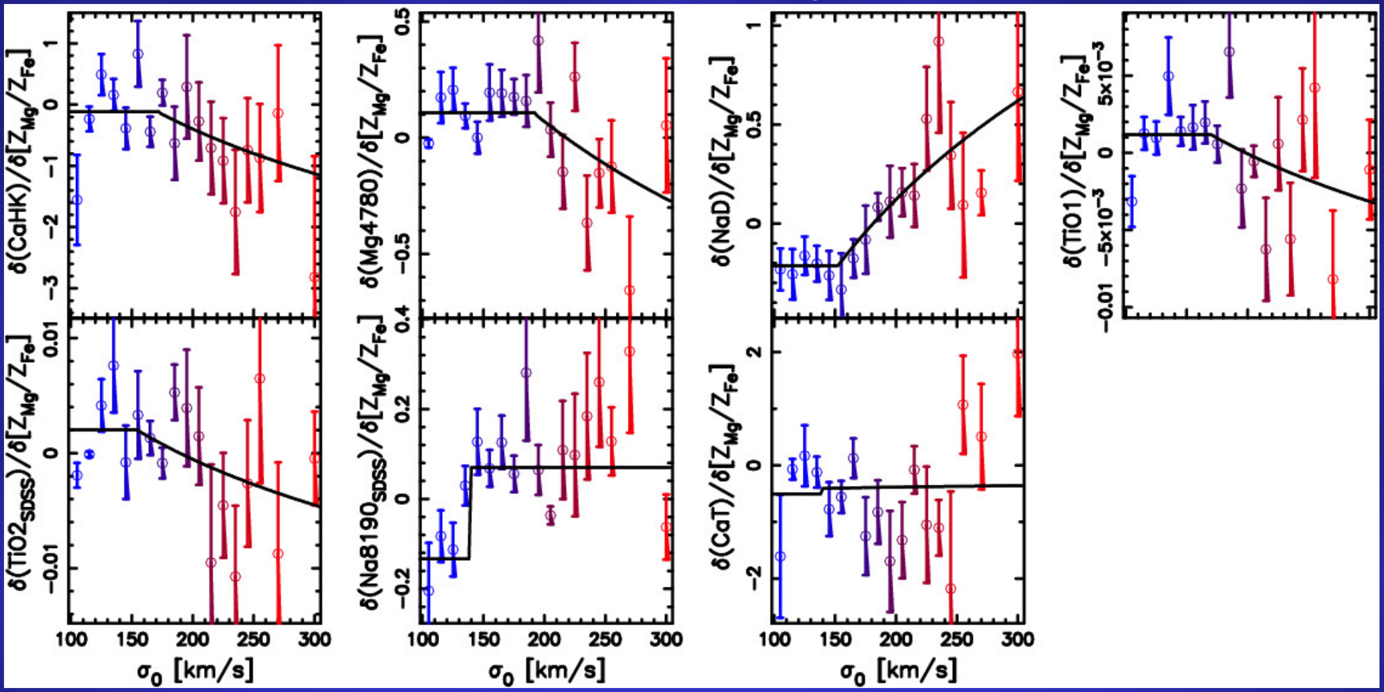
Gravity-sensitive features exhibit only a mild variation with [α/Fe]

σ, not [α/Fe], drives the (IMF) trend

Sensitivity of line indices to [α/Fe]

For each σ_0 bin, we derive line strength vs. $[Z_{Mg}/Z_{Fe}]$ slopes with linear fits.

Slopes vs. σ_0



- the $[Z_{Mg}/Z_{Fe}]$ slopes depend on σ_0 → different enrichment patterns of high- relative to low-mass ETGs

- <u>“empirical” corrections of observed line strengths to solar scale, i.e. $[Z_{Mg}/Z_{Fe}]=0$</u>

  Crucial!! since predictions of line strength sesntivities to $[Z_{Mg}/Z_{Fe}]$ vary dramatically among models (Coelho+’07, Cervantes+’07, Thomas+’11, CvD12).

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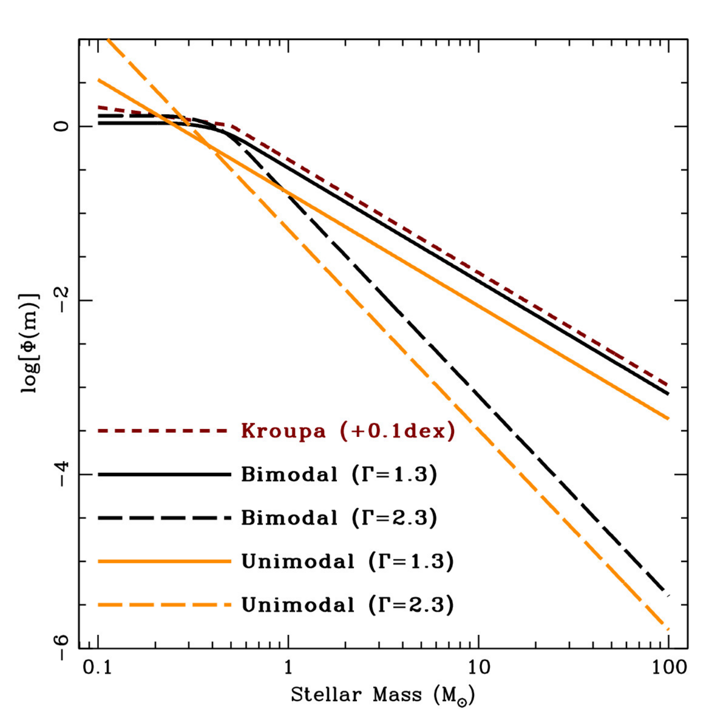
Fitting approaches

$$\chi^2\left[\Gamma; p_j\right] = \sum_{indices} \frac{\left(I_{corr} - I_{\mathrm{mod}}\right)^2}{\sigma^2 + (s_{corr})^2}$$

I_{mod} computed from MILES (nearly solar-scale) extended (MIUSCAT) SSPs (Vazdekis+' 12), with

- **unimodal** (single power-law) IMF (Salpeter: Γ_=1.35)
- **bimodal** (low-mass tapered) IMF (Vazkedis+' 96; Kroupa IMF: Γ=1.3)



mod

- 1SSP: p_j={Age,[Z/H]}
- 2SSP: p_j={Age_1,$[Z/H]_1$,Age_2,$[Z/H]_2$}
- 2SSP+X/Fe : p_j={Age_1,$[Z/H]_1$,Age_2,$[Z/H]_2$, [Ca/Fe], [Na/Fe], [Ti/Fe]}

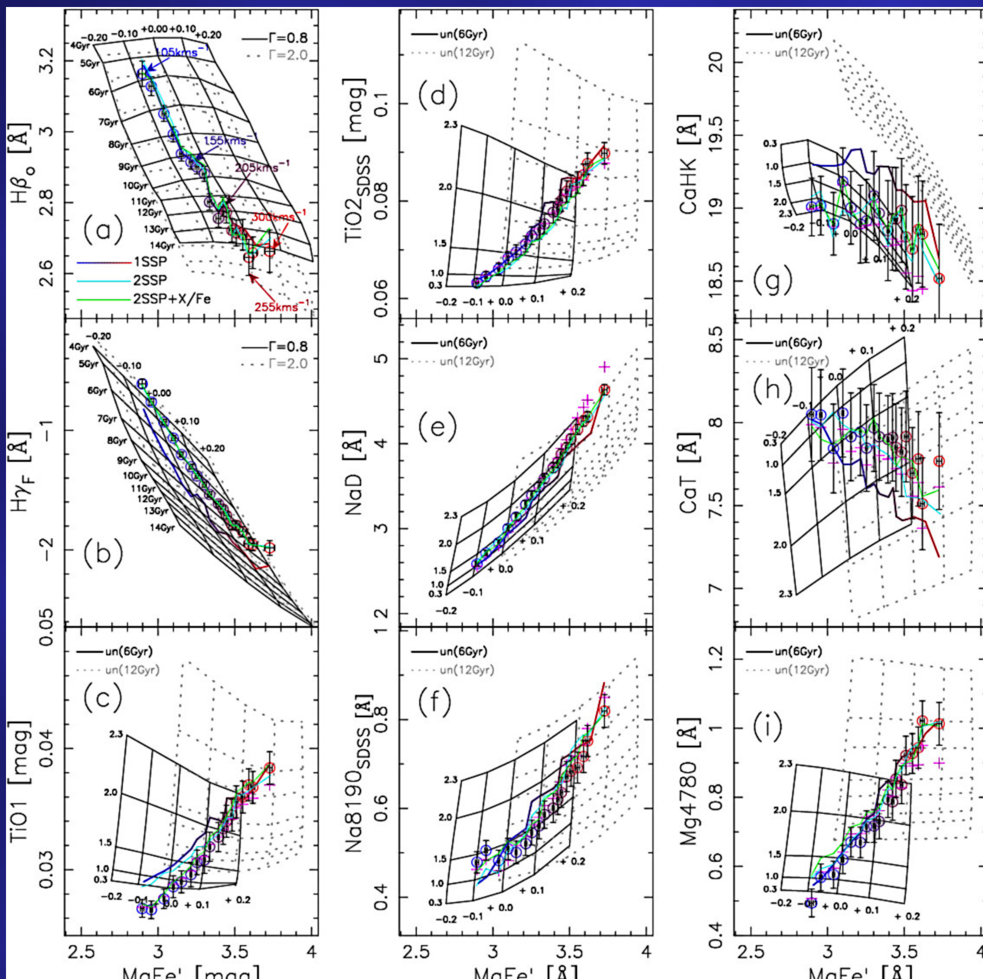
"residual" abundances

with [X/Fe] estimated from CvD12 models

hybrid approach (Ferreras+' 13) where constraints from spectral fitting and line strengths are combined into a single PDF (exploring a wide set of SFHs)

Fitting results – observed vs. model indices

index-index diagrams – data vs. best-fit models
(observed/model indices corrected to 200km/s resolution)



<u>All indices</u> are well described by a simultaneous trend of age, metallicity, and IMF slope, to increase with σ_0.

Fit quality improves significantly for 2(wrt 1)SSP models, while the role of "residual" X/Fe is marginal.

Unimodal and bimodal models cannot be singled out from indices, as both models fit data equally well.

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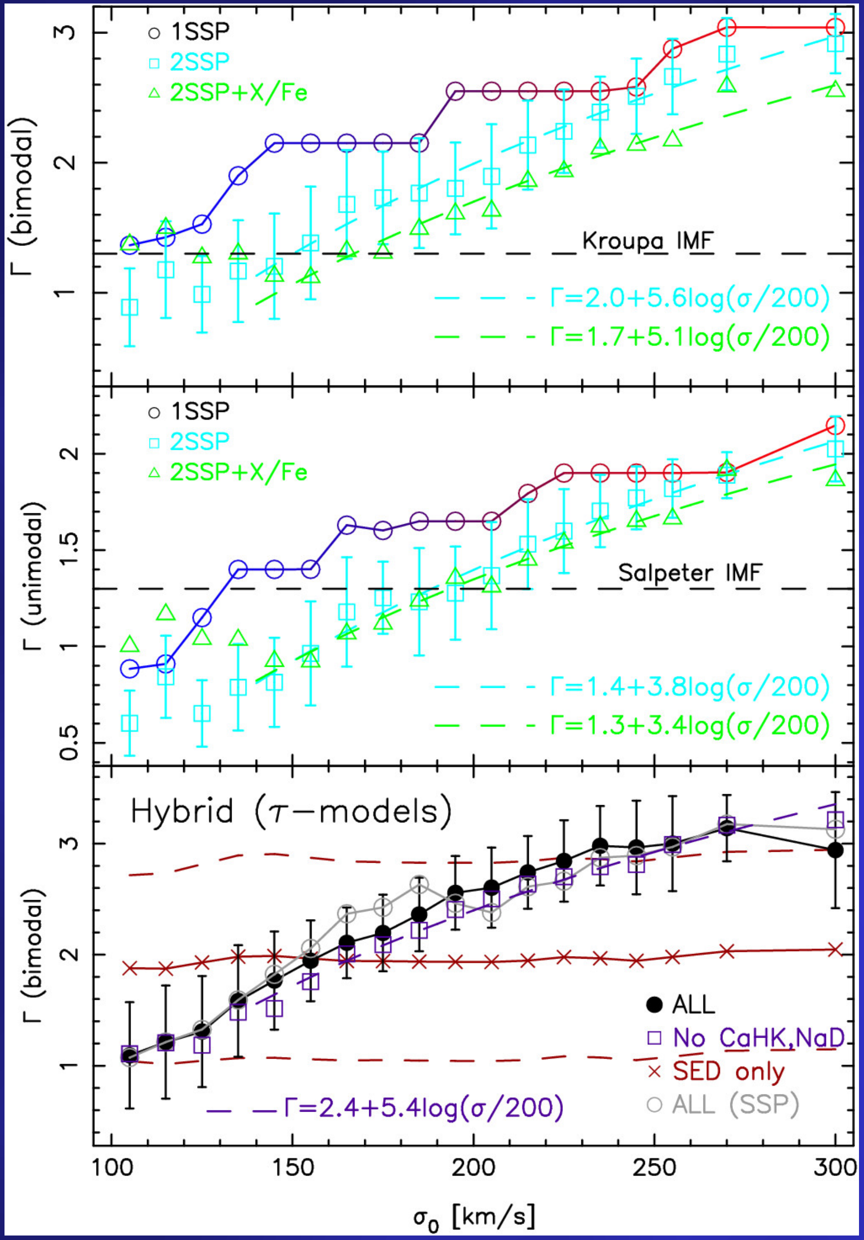
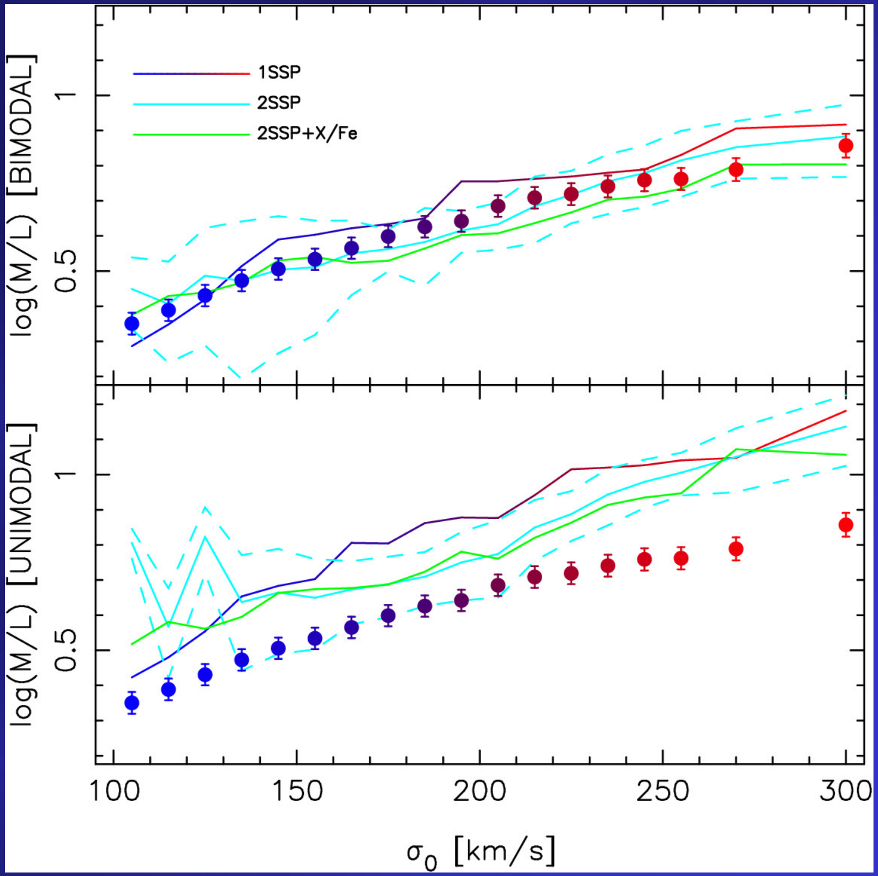
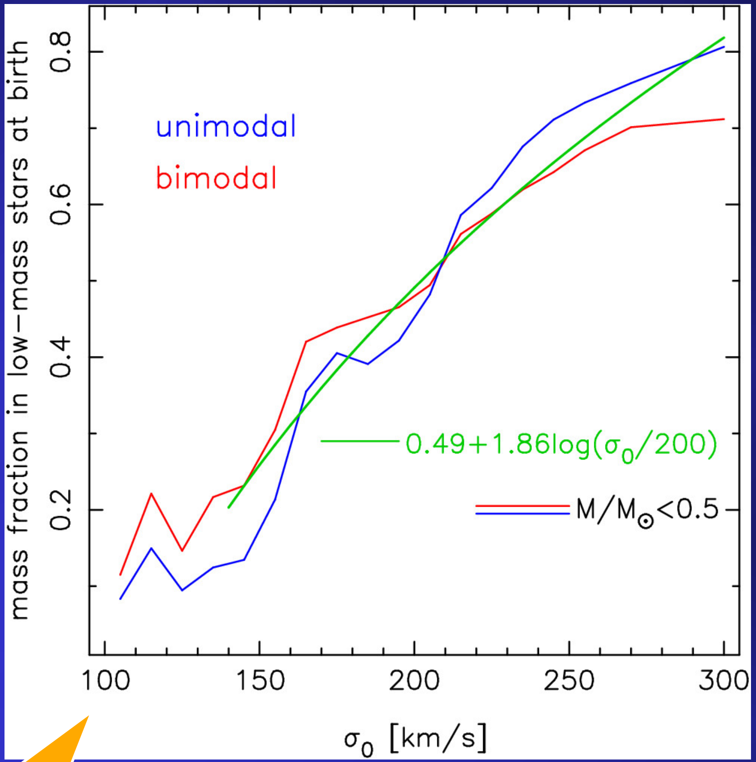
IMF slope vs. σ_0



- At low σ (≤150km/s), the slope is consistent with a Kroupa-like IMF.
- The slope exceeds the Salpeter value at ~200km/s, becoming significantly bottom-heavy at high σ.
- Slopes among different methods are consistent, but significant offsets exist (e.g. 1SSP wrt 2SSP+X/Fe)

Constraining M/L's ?





$$\frac{M_*}{L}(indices) \text{ vs. } \frac{M_{dyn}}{L} = 5\frac{\sigma_e^2 R_e}{G \cdot L}$$ (Cappellari+'06;+'12b)

Unimodal, wrt bimodal, models predict M_*/L's a factor of 2x larger (Ferreras+'13), still both fit the indices equally well !!

Both models predict nearly identical mass fractions in low-mass stars, f(M<$0.5M_{Sun}$).

Summary

- Significant steepening of IMF slope with σ for the average population of ETGs. After the "empirical" correction to solar scale, all selected indices can be well described by an increase of age, metallicity, **and** IMF slope with σ.

- It's σ_0, not [α/Fe], the main driver of the trend.

- Unimodal and bimodal models cannot be singled out, implying that M/L's are poorly constrained with indices alone.

- In contrast, the fraction in low-mass ($<0.5M_{Sun}$) stars at birth in the IMF is robustly constrained, varying from 20% at σ~100km/s, to 70% at σ~300km/s.