Stellar population models to constrain the stellar IMF and galaxy stellar content

Francesco La Barbera
INAF-Osservatorio Astronomico di Capodimonte

Stellar populations in galaxies

Understanding the stellar population content of galaxies is essential for constraining how galaxies form and evolve.

⇨ Ages and star-formation histories (when and how stars were formed)

⇨ Metallicity (chemical enrichment, inflows/outflows)

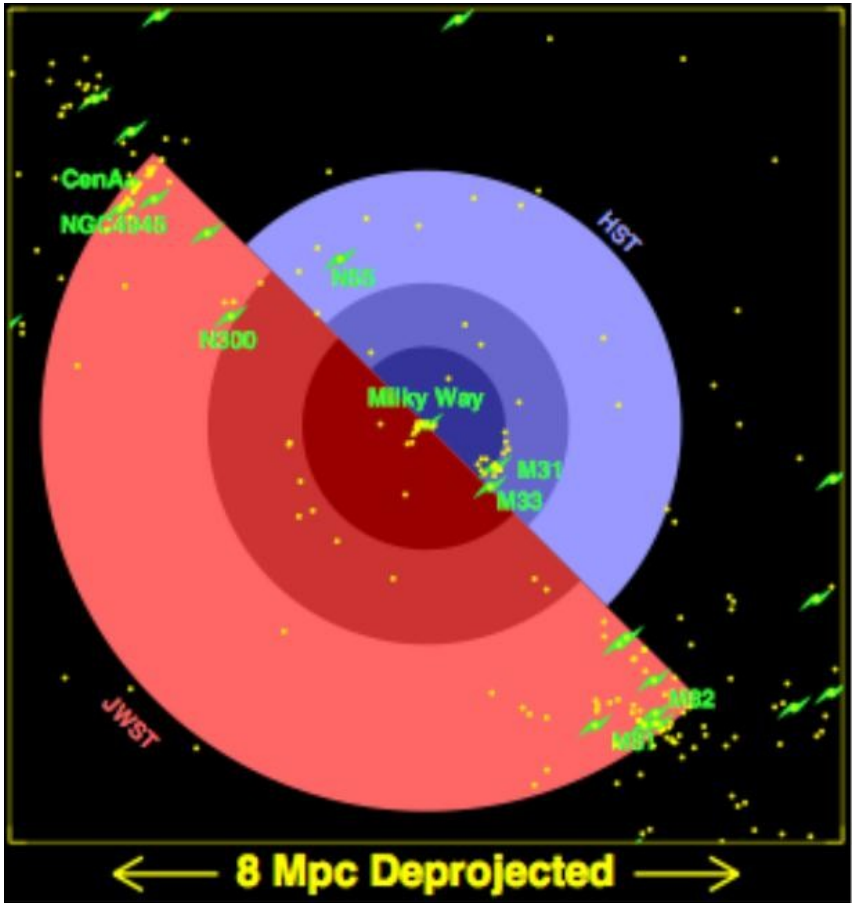
⇨ Abundance ratios of individual elements (star-formation time-scales, stellar yields)

⇨ Stellar IMF (physics of star formation, M/L)

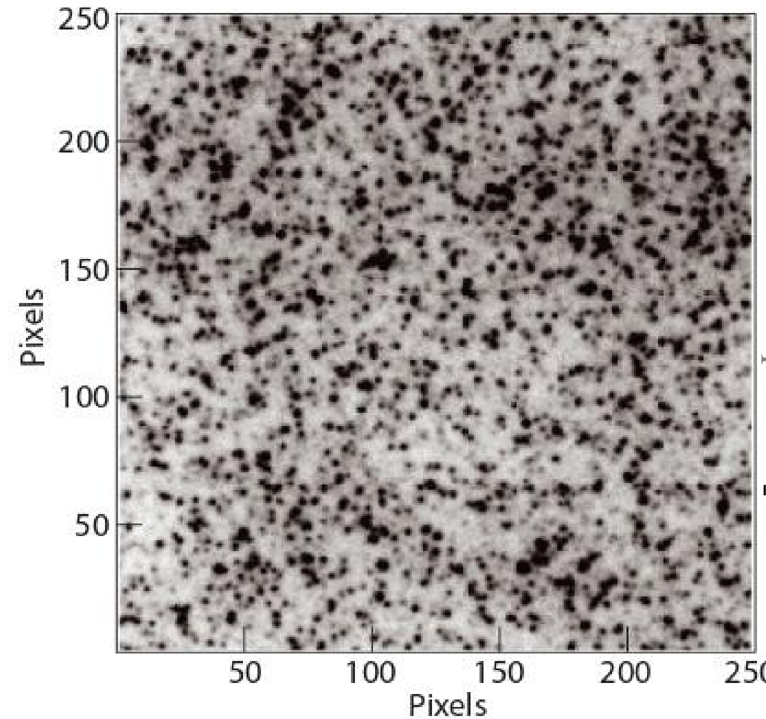
Radial gradients inform on different processes of galaxy formation and evolution (merging vs. closed-box, feedback processes, inside-out vs. outside-in formation).

Unresolved stellar populations

For most galaxies, stellar populations can only be studied via <u>integrated light</u>.
For VLMS, this will remain the case even with next-generation telescopes and instrumentation.



Projected region, around the MW, where JWST can resolve stars 0.5mag below the TO for an old stellar population (from Brown+2008 White Paper)



from Deep+2011

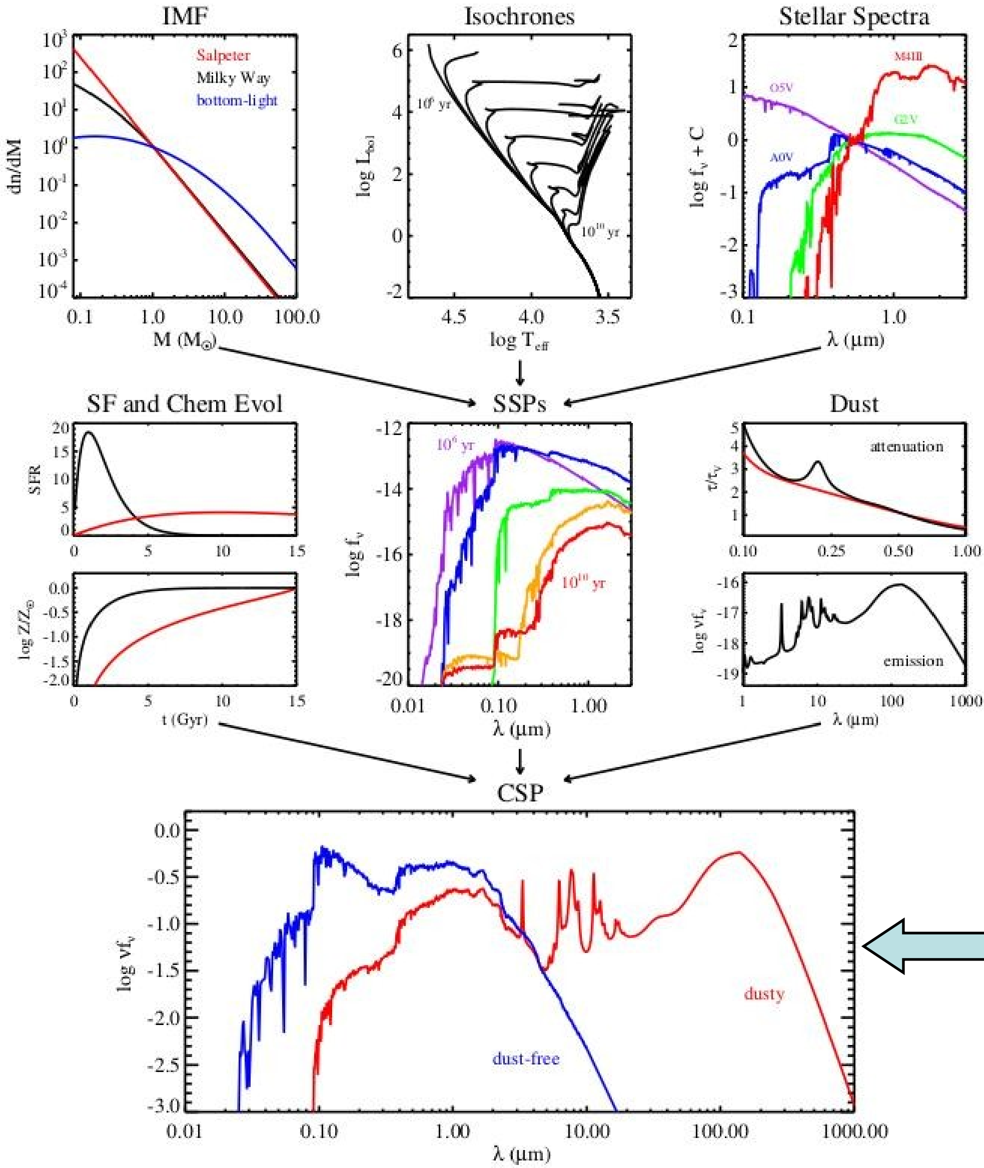
Fig. 6. A simulated MICADO/MAORY I filter image of a stellar field in an old galaxy at the distance of Virgo (17 Mpc). The field size is 0.75 arcsec square, with a pixel scale of 3 mas. The surface brightness of the galaxy at this position is $\mu_V \sim 19.0$ mag/arcsec^2. The image assumes an exposure time of 1 h.

(see Greggio+2012; Schreiber+2015)

LAYOUT

- Stellar population models
- Constraining the IMF
- Open avenues

Evolutionary models in a nutshell



MAIN INGREDIENTS

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

Composite Stellar Population model

from Conroy(2013)

Stellar spectral libraries - theoretical

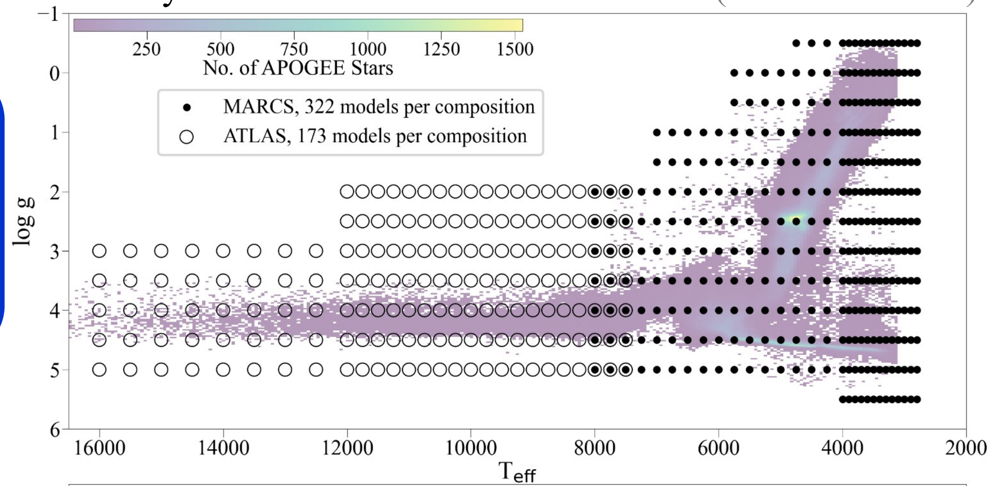
Theoretical libraries

stellar-atmosphere model (e.g. ATLAS, MARCS)

+

radiative transfer code (e.g. SYNTHE, Asset)

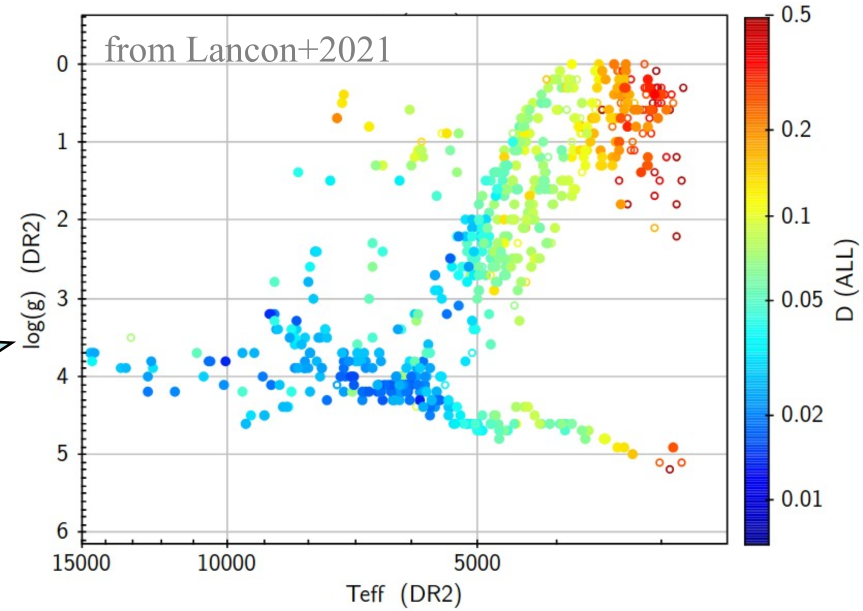
BOSZ synthetic vs.APOGEE observed stars (Mészáros+2024)



ADVANTAGES

- large statistics/coverage of paramater space
- known abundance pattern
- high spectral resolution
- large wavelength range

Comparison of PHOENIX (synthetic) vs. XSL (observed) stellar spectra



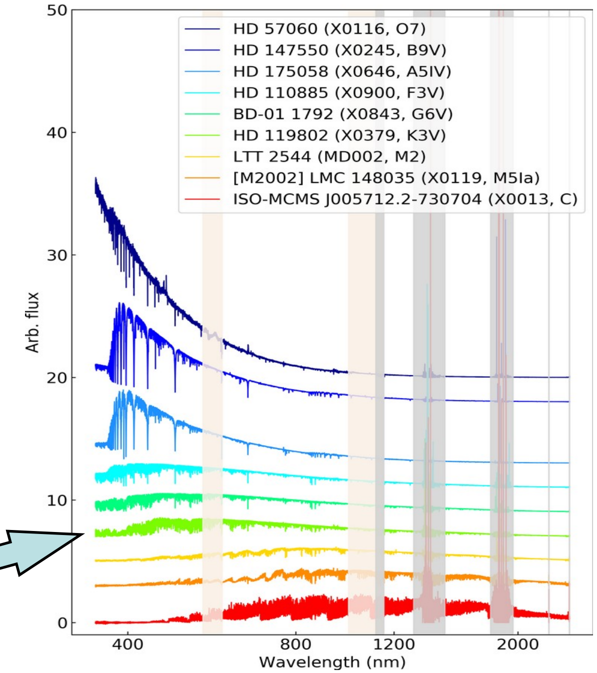
DRAWBACK

- empirical is better, the stars are real!

Stellar spectral libraries - empirical

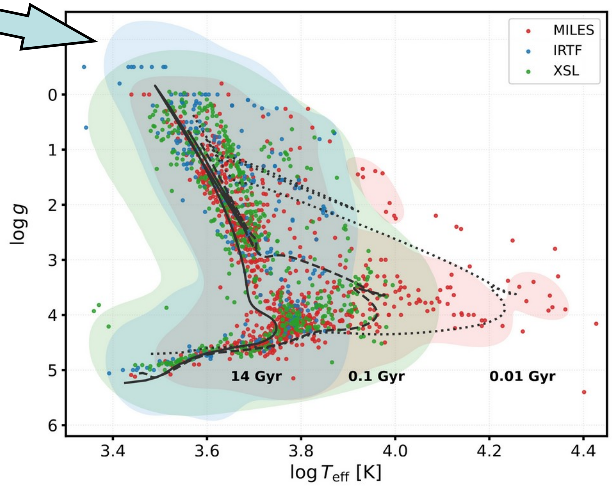
Empirical libraries consist of observed spectra for solar-neighborhood stars.
For population synthesis, we need:
•accurate relative flux calibration (few percent level)
•accurate correction for tellurics/sky lines are requied
•accurate stellar parameters, Teff, logg, [Fe/H] (and [X/Fe]) - derived with theoretical stellar spectra!
•S/N, spectral resolution (R≳1500) and λ coverage

Examples of stellar spectra from the XSL (Verro+2022)

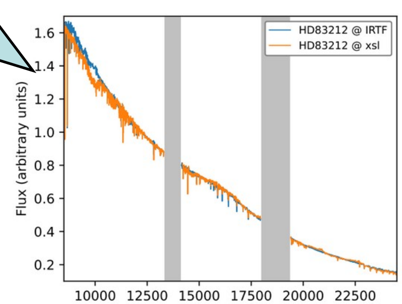


Latest generation empirical libraries

UV: ULLYSES (N~500), NGSL (N~370)
Optical: MILES (N~980), MaSTAR (N~12000)
NIR: IRTF (N~320), XSL (N~680), TIRMA (N~500)



Besides population synthesis, stellar libraries are relevant for many fields, e.g. atmospheric parameters, chemical abundances, exoplanets, variability, surveys' calibration, distance scale, etc...



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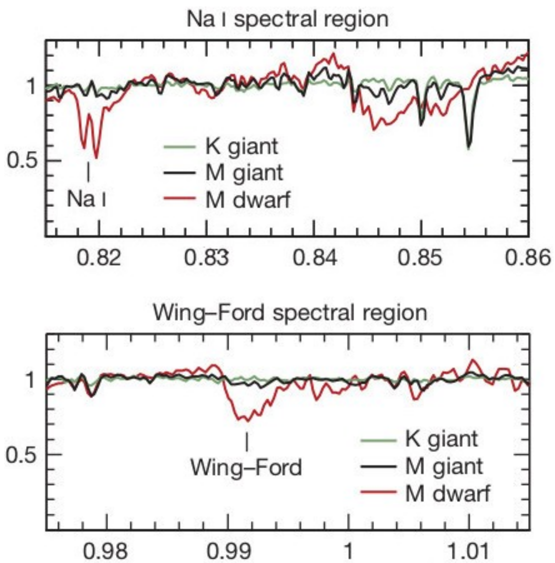
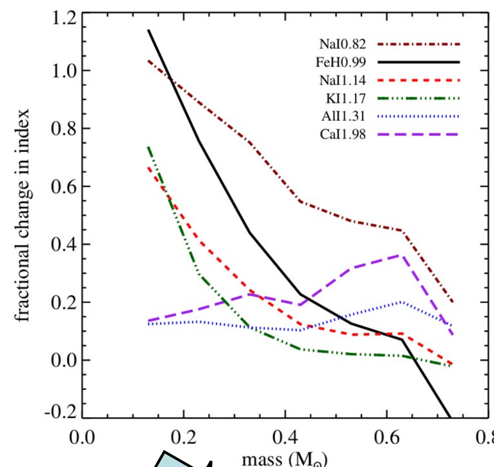
IMF-sensitive features

- The stellar IMF is the mass distribution of stars born in one event of star formation.
- In the MW and LMC star clusters, we do not see much variation (see Kroupa 2013).
- Measuring the low-mass end ($<1M_{Sun}$) is crucial to constrain galaxies' M/L.
- For distant galaxies, we rely on IMF-sensitive features in their unresolved spectra:

vanDokkum&Conroy2010





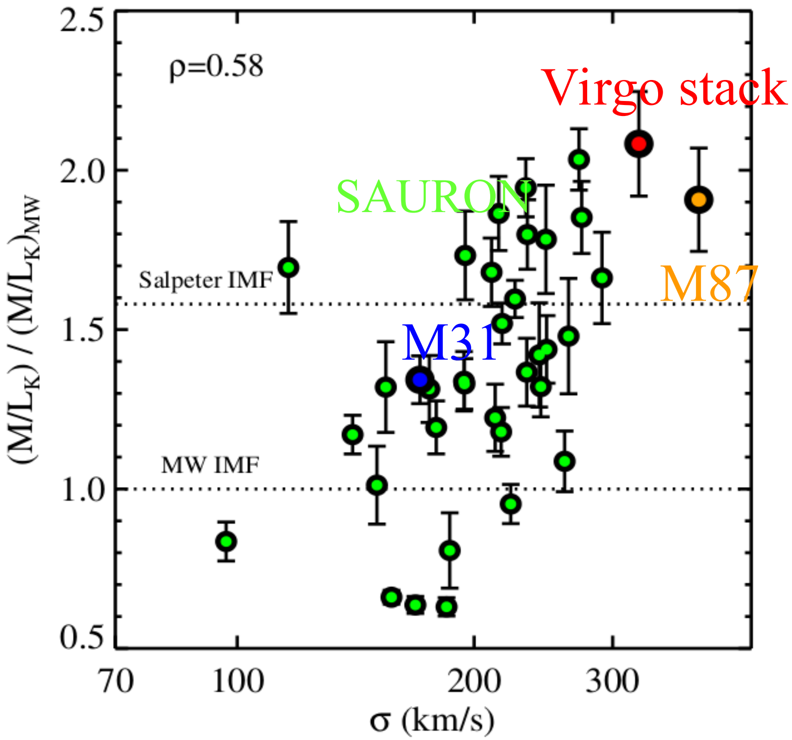
Conroy&vanDokkum2012a

Possibility of constraining the IMF shape

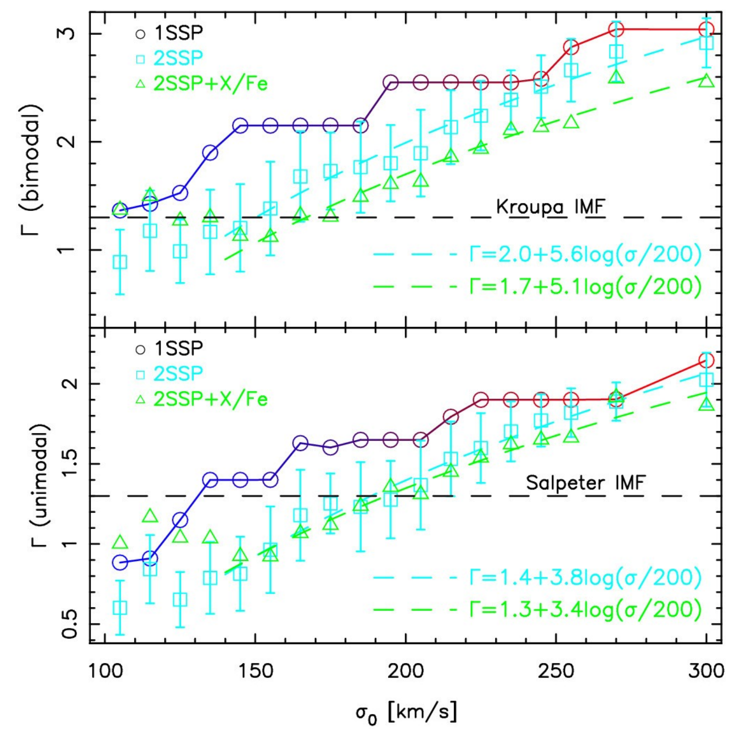
Early studies plagued by small sample sizes, low S/N and R, uncertain SP models
(Spinrad'62; Cohen'78; Faber&French'80; Carter+'86; Hardy&Couture'88; Delisle&Hardy'92)

A bottom-heavy IMF in luminous ETGs

34 nearby ETGs at z~0
CvD SSP models
(van Dokkum&Conroy 2010; Conroy+2012b)



SDSS stacked spectra of 39993 ETGs @z<0.1
Vazdekis+ SSP models
(Ferreras+2013: La Barbera+2013)



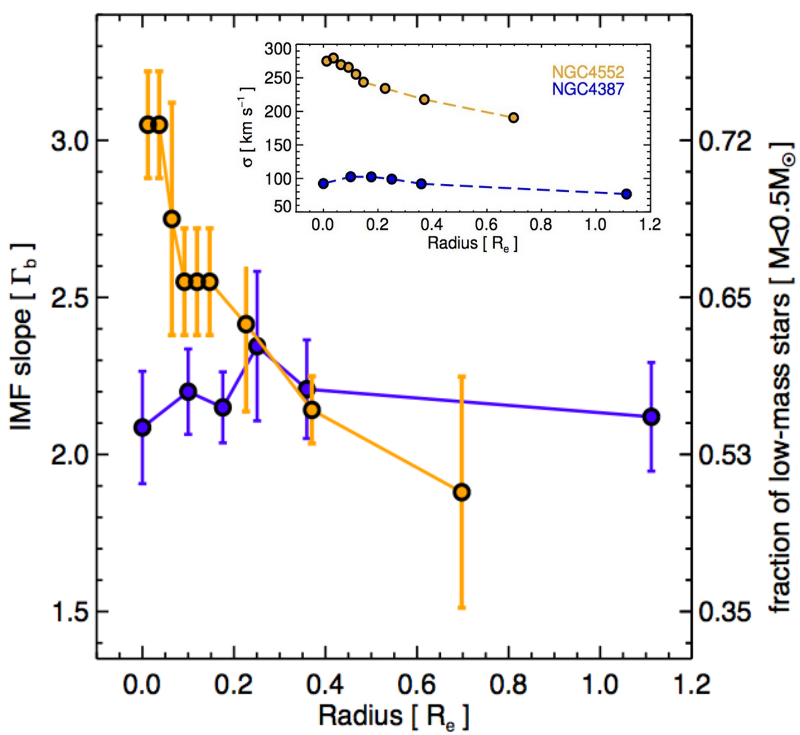
Trend from a Kroupa-like IMF (σ≤150km/s), to a bottom-heavy IMF at high σ.

The relation is consistent with M_*/L trends from
- dynamics (Cappellari+2012, 2013a, J. Thomas+2011, Dutton+2012, Wegner+2012, Tortora+2013)
- lensing (Auger+2010, Treu+2010, Barnabé+2011), but see Smith&Lucey(2013), Smith+2015

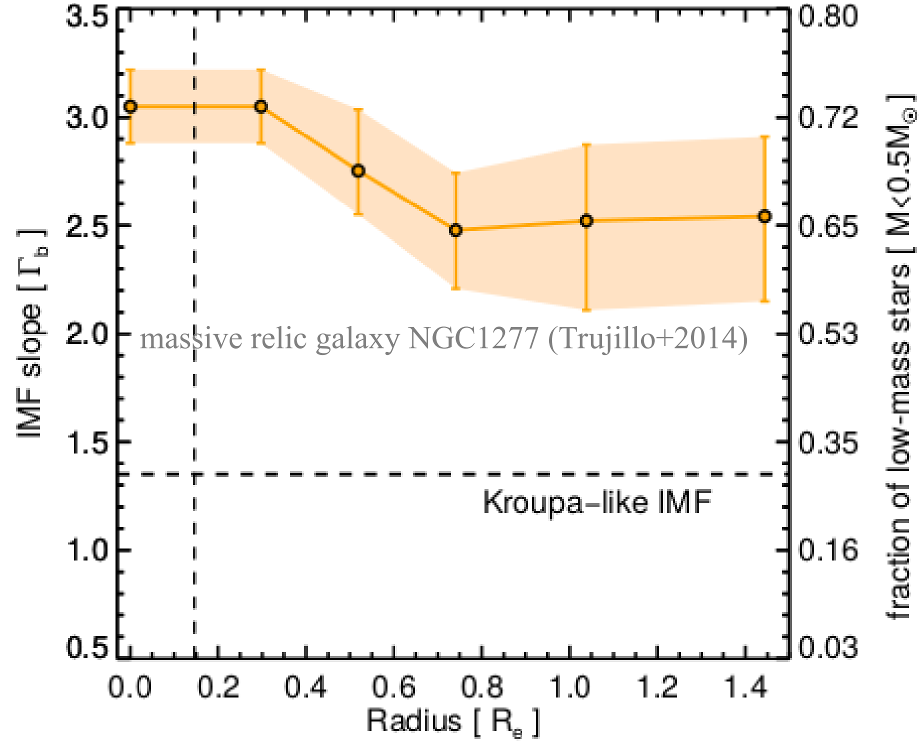
including the contribution of low-mass stars and remnants

A bottom-heavy IMF in the cores of ETGs ?

Martín-Navarro et al. 2015a



Martín-Navarro et al. 2015c



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

Many other papers have found IMF radial gradients at z~0

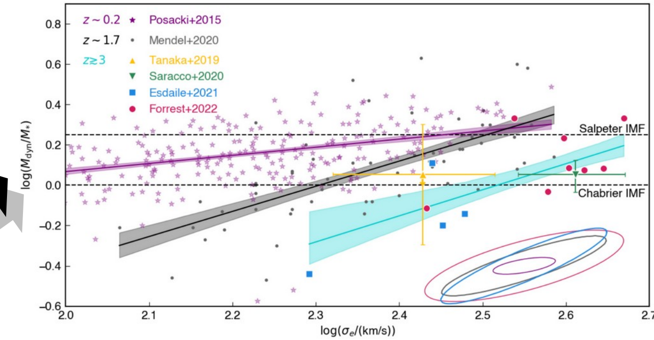
Sarzi+2018; van Dokkum+2017; La Barbera+2016, 2019, 2021; Barbosa+2021; Marti'n-Navarro+2019, 2021; Feldmeier-Kraus+2020, 2021; Parikh+2019; Zhou+2019; Domi'nguez-Sa'nchez+2019; Lonoce+2021 (but see Zieleniewski+2017, 2017; McConnell+2016)

Why to push IMF studies at higher redshift

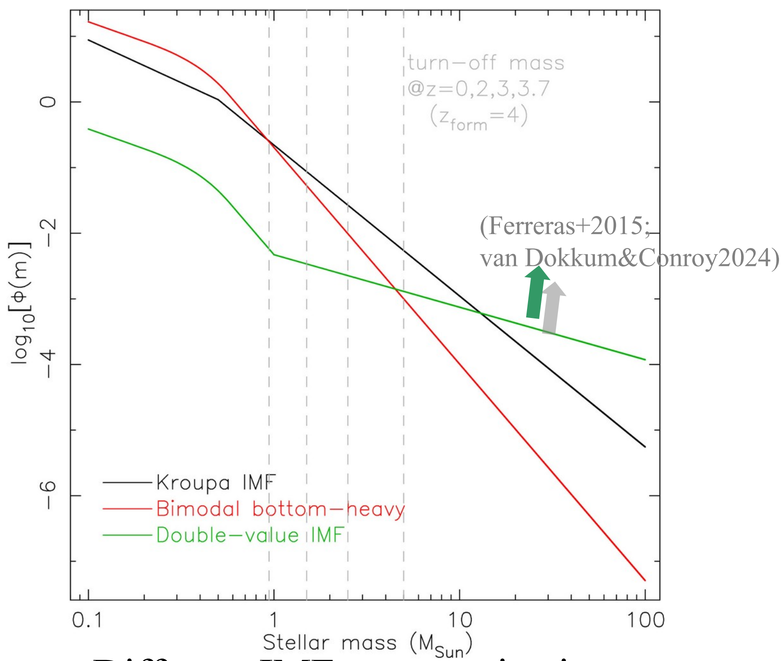
- A bottom-heavy IMF in the center of massive ETGs at z~0 requires that the IMF changes with time (Weidner+2013; Ferreras+2015)

- Theoretical works point to coupled variations at low- and high-mass in the IMF (Fontanot+2018, 2024; Chabrier+2014), or to low-mass star formation modes at later times (Fabian+2024).

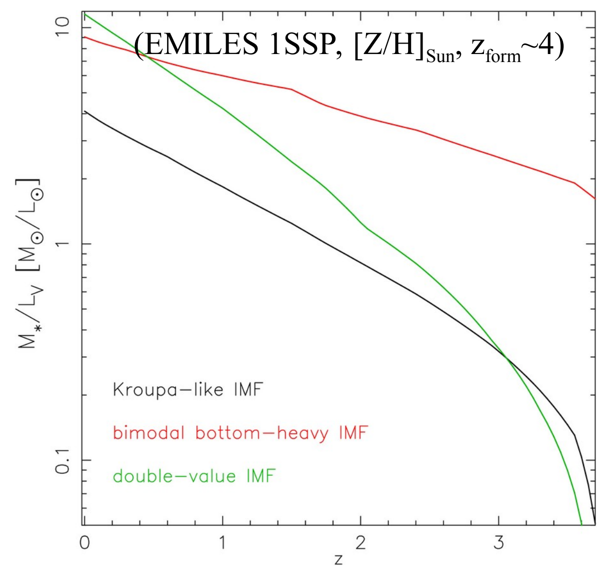
- It seems that Mdyn/M* for high-z massive ETGs leaves little room for M*/L variations wrt a Kroupa-like IMF (e.g. Saracco+2020; Kriek+2024; but see Belli+2017). <u>However, systematics (e.g. rotation) on M_{dyn} should be accounted for</u>!



from Forrest+2022



Different IMF parametrizations



Evolution of the M*/L with z

(Cheng+2026 @z~0.7; to be explored with future facilities at z>1; e.g. SHARP@ELT; see https://sharp.brera.inaf.it/, Saracco+2024)

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Abundance ratios

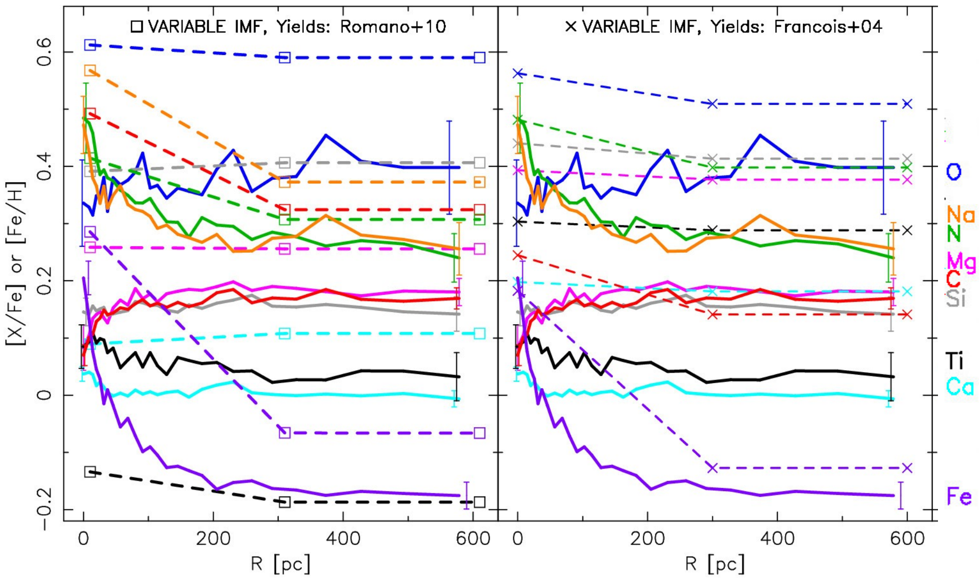
State-of-the-art stellar population models allow abundance ratios to be varied:

•Individual abundances (Conroy&van Dokkum 2012,2018), with solar-scale isochrones

•[α/Fe] (Vazdekis+2015, Knowles+2021, Park+2024) with α-enhanced isochrones, but elements are varied in lockstep.

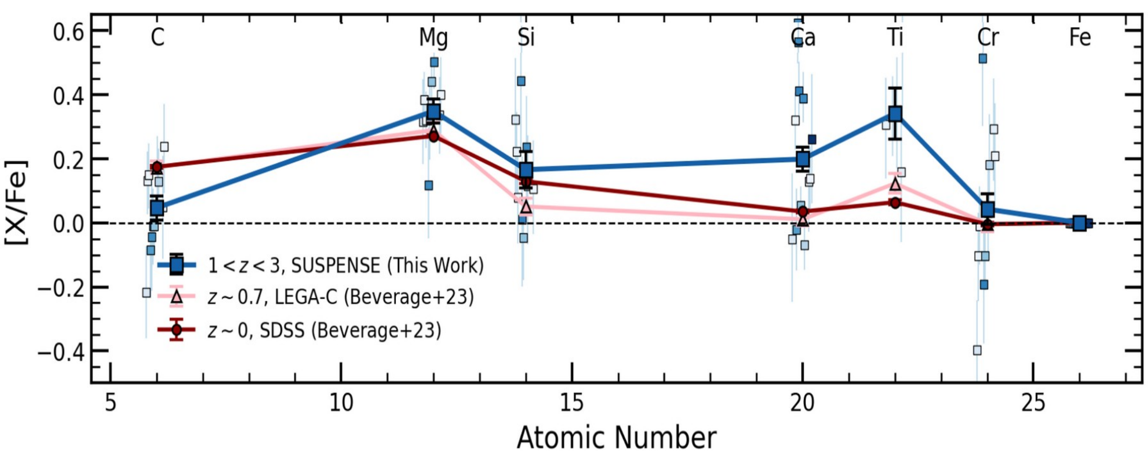
Both are based on theoretical or semi-empirical stellar libraries!

from La Barbera+2026



- Star-formation
- IMF at the high-mass end
- Stellar yields
- IMF at low-mass end (through the effect on gravity-sensitive features)

from Beverage+2025

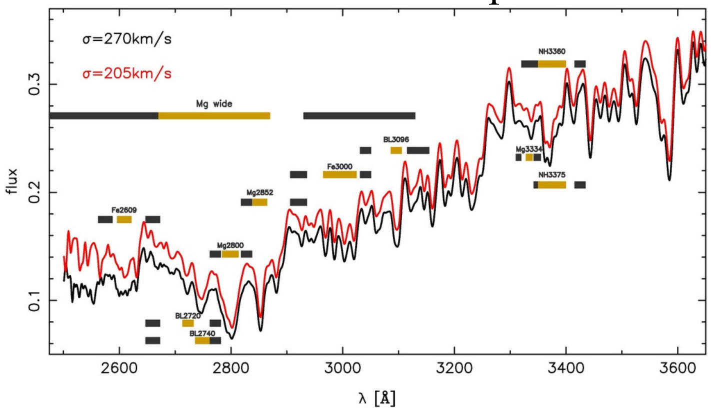


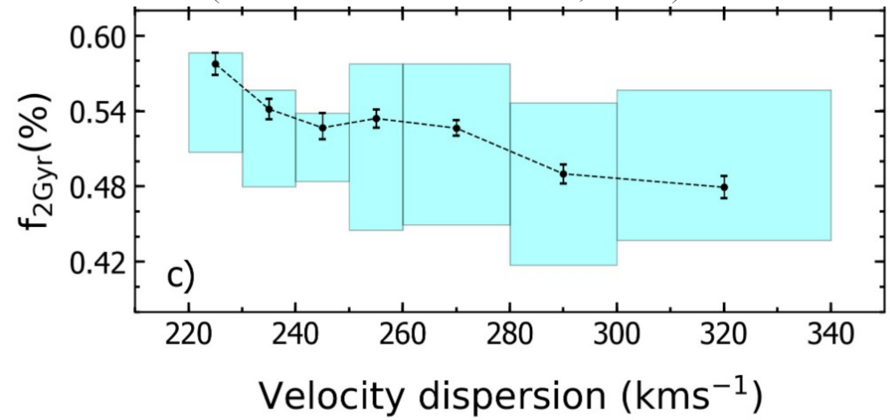
Pushing to high-z with spectroscopic surveys (LEGA-C, DESI, WEAVE/ 4MOST-StePS) and JWST (e.g. Bevacqua+2025, Ditrani+2026)

Abundance effects are important: for young ages, [α/Fe] reddens the spectrum (leading to <u>overestimate galaxy ages</u>; Park+2024).

Exploiting the UV spectral range

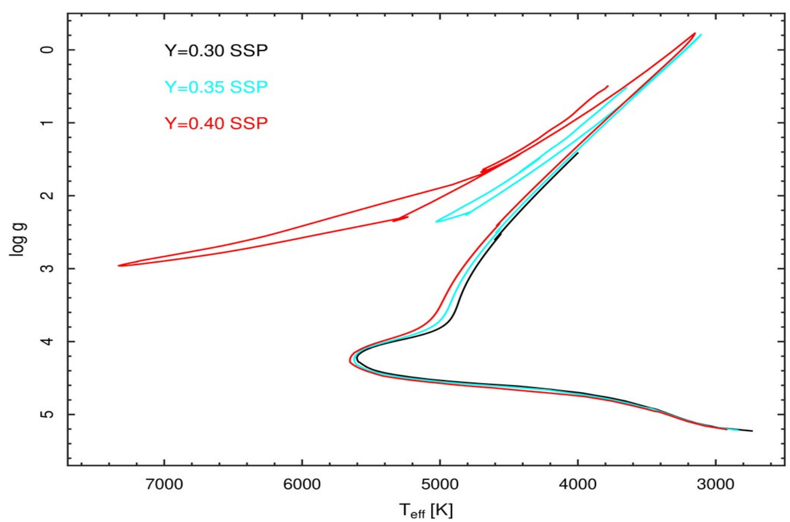
BOSS-stacked spectra of 30k LRGs at z~0.3 (Salvador-Rusinol+2020, 2021)



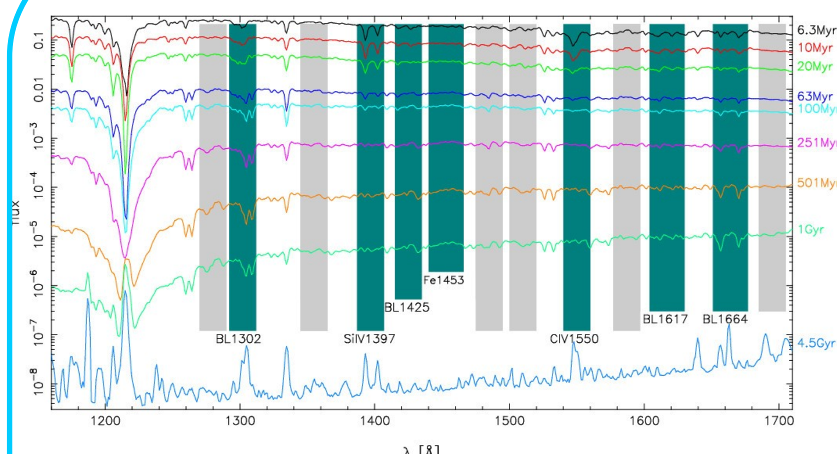


•NUV indices require sub-percent level young stars (few Gyrs) or hot-evolved (e.g. eHB) stars (Le Cras+2016)

from Pasquali+2026 in prep.



What is producing the hot-evolved component?
High He abundance? Likely not...(but see Ali+2018, 2021)



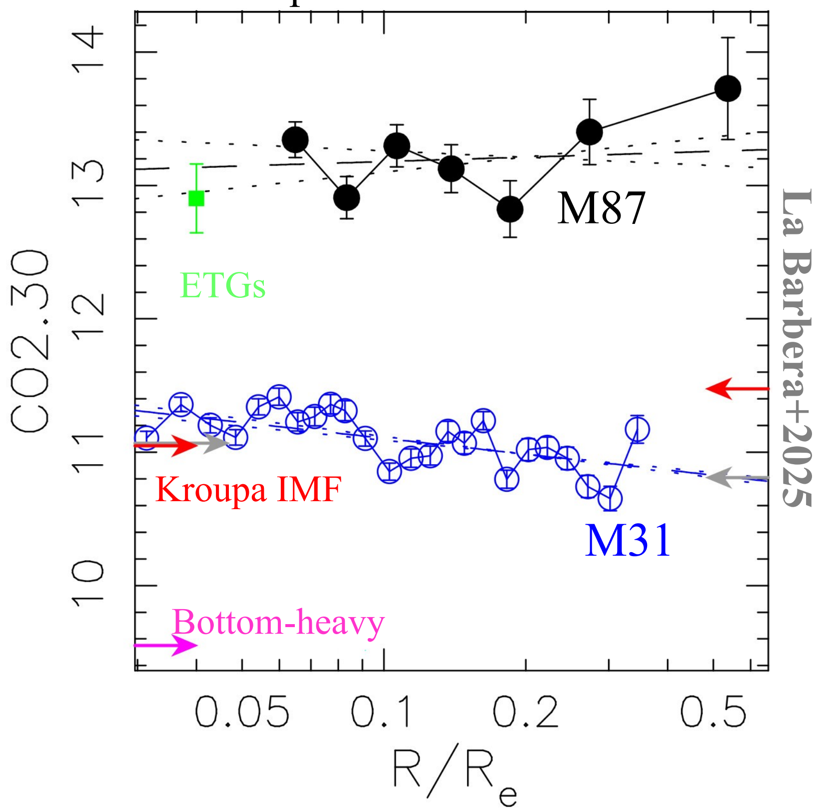
The degeneracy can be broken with FUV indices (but we need SSP models! Vazdekis+2026 in prep.)

NIR spectral features

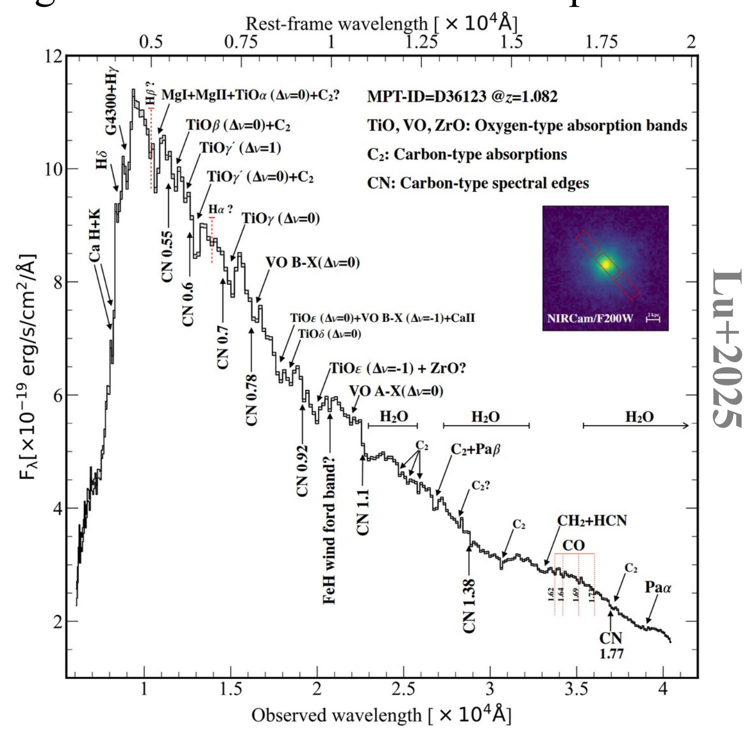
NIR spectroscopy is still a comparatively young area of research (Eftekhari+2021a, 2022b; Gasparri+2021):

- JWST now enables high signal-to-noise, high-quality spectra in the NIT restframe even for galaxies at z>1.
- Yet, the physical origin of many NIR absorption features remains poorly constrained.

CO mismatch problem in massive ETGs at z~0



Strong contribution from C-/O-absorptions at z~1-2



However, no evidence for PSBs at z~0.2 (Zibetti+2013)

➡ To date, the best-quality empirical stellar library in the NIR is the IRTF(extended) with ~300 stars, with relatively limited coverage in [Fe/H] and T_{eff}.

➡ No SSP model is able to match NIR absorption features with similar accuracy as in the optical! (see e.g.Bevacqua+2025)

Summary

*Take home message

Stellar population (SP) models are the key tool to constrain the galaxies' unresolved stellar population content. Significant effort should be done to further expand/characterize stellar spectral libraries for SP synthesis.

Applying state-of-the-art SSP models, we have found that the the stellar IMF is not universal, with a bottom-heavy distribution in the center of massive ETGs. What is driving these variations? What is the evolution with cosmic time?

Some key applications of next-generation SP models:

-constraining elemental abundances of unresolved populations;

-assessing the origin of UV spectral features/colors in (massive) galaxies;

-taking advantage of the NIR spectral range.