Star Formation History of Early Type Galaxies

Ricardo Schiavon

Liverpool John Moores University

RASPUTIN

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Content

1. Why do we care about SFH of ETGs?
2. Methods (ages, chemical abundances)
3. Key results at $0 \lesssim z \lesssim 1$
4. How E-ELT can contribute

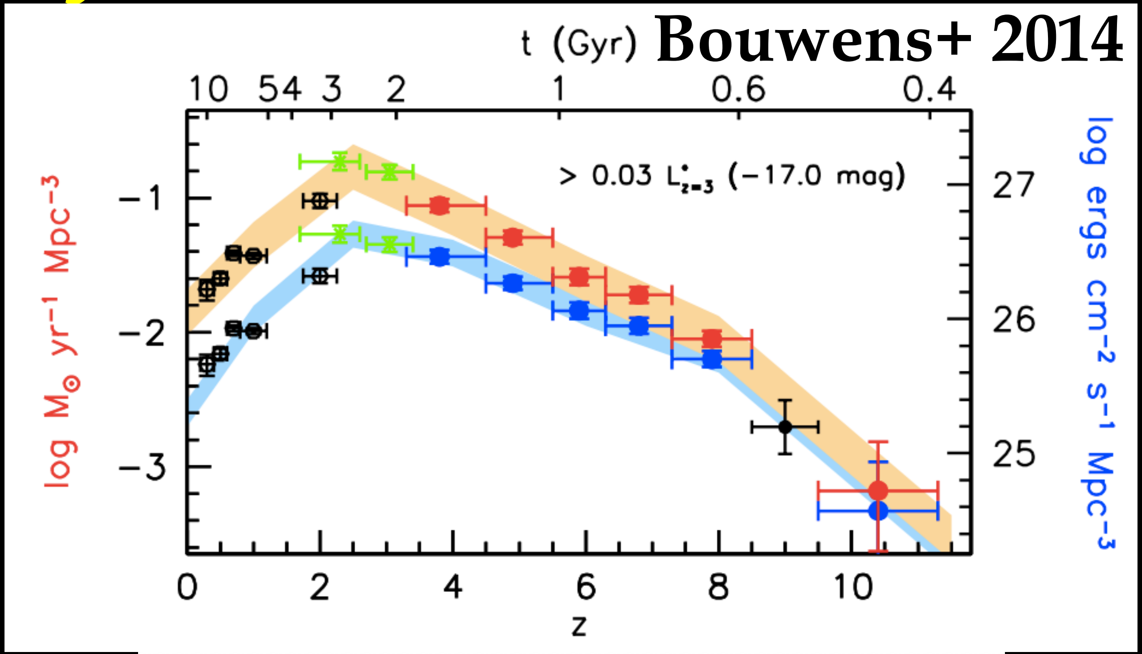
Cosmic History of Star Formation

We have a fairly good idea about the cosmic star formation history

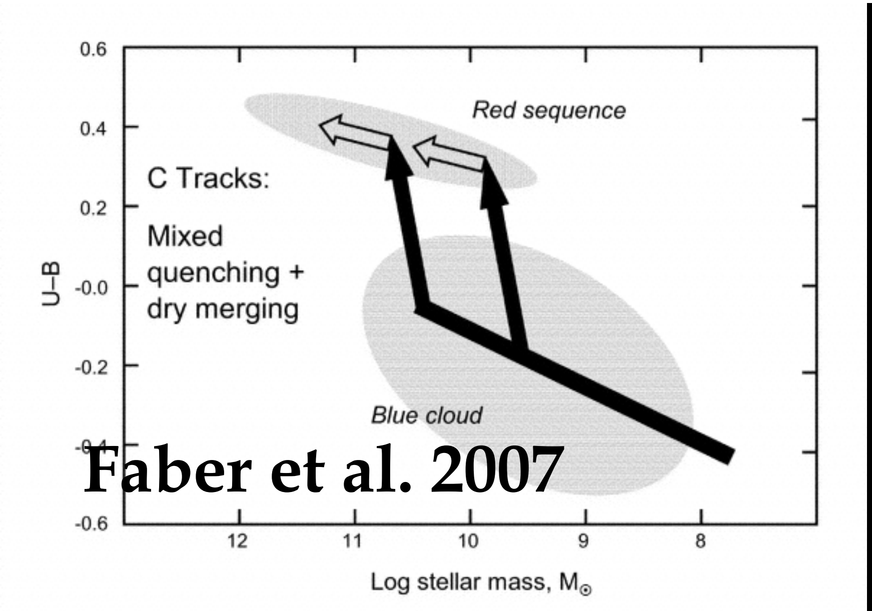
And we know that ETGs are the by-product of quenching of SF galaxies

Therefore, we know in broad strokes the SFH of ETGs!

But the devil is in the details.



Bouwens+ 2014



Faber et al. 2007

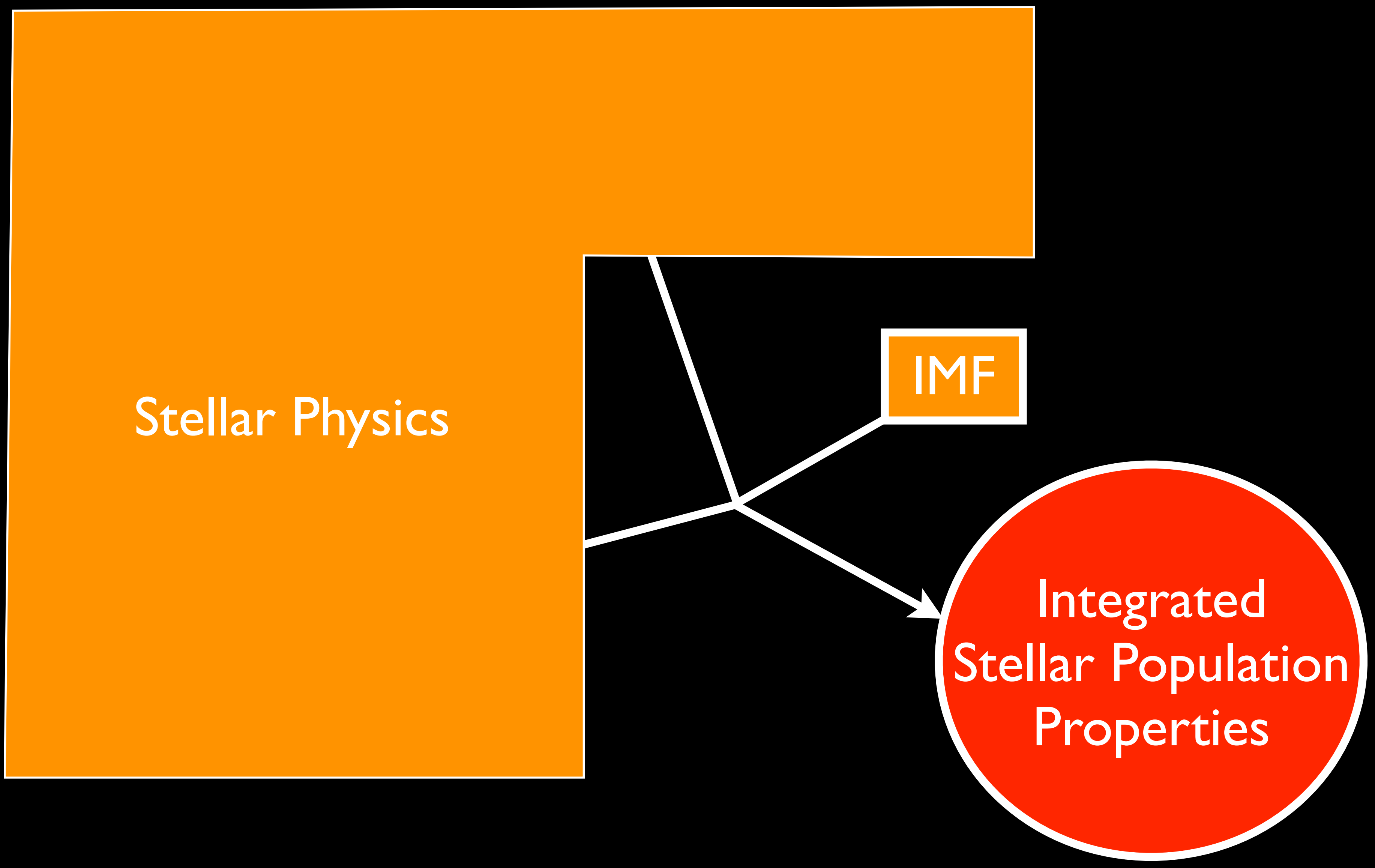
Constraining SF with SP synthesis

- “Direct” method: ages of stars
  - → Mean ages
  - → Age distributions

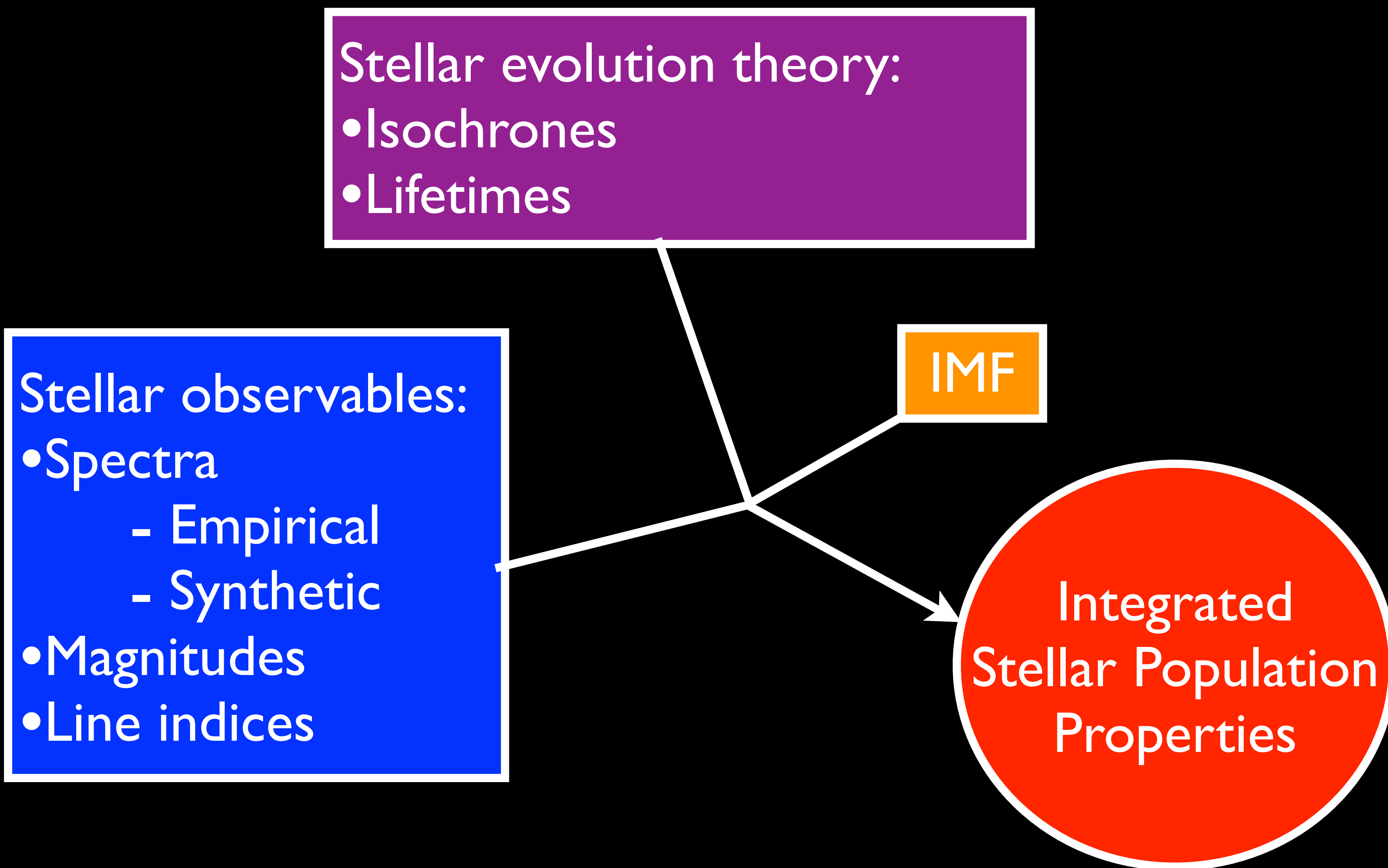
- Indirect method: Chemical compositions (detailed abundance patterns)

As a function of mass, environment, redshift

SP Synthesis in a nutshell

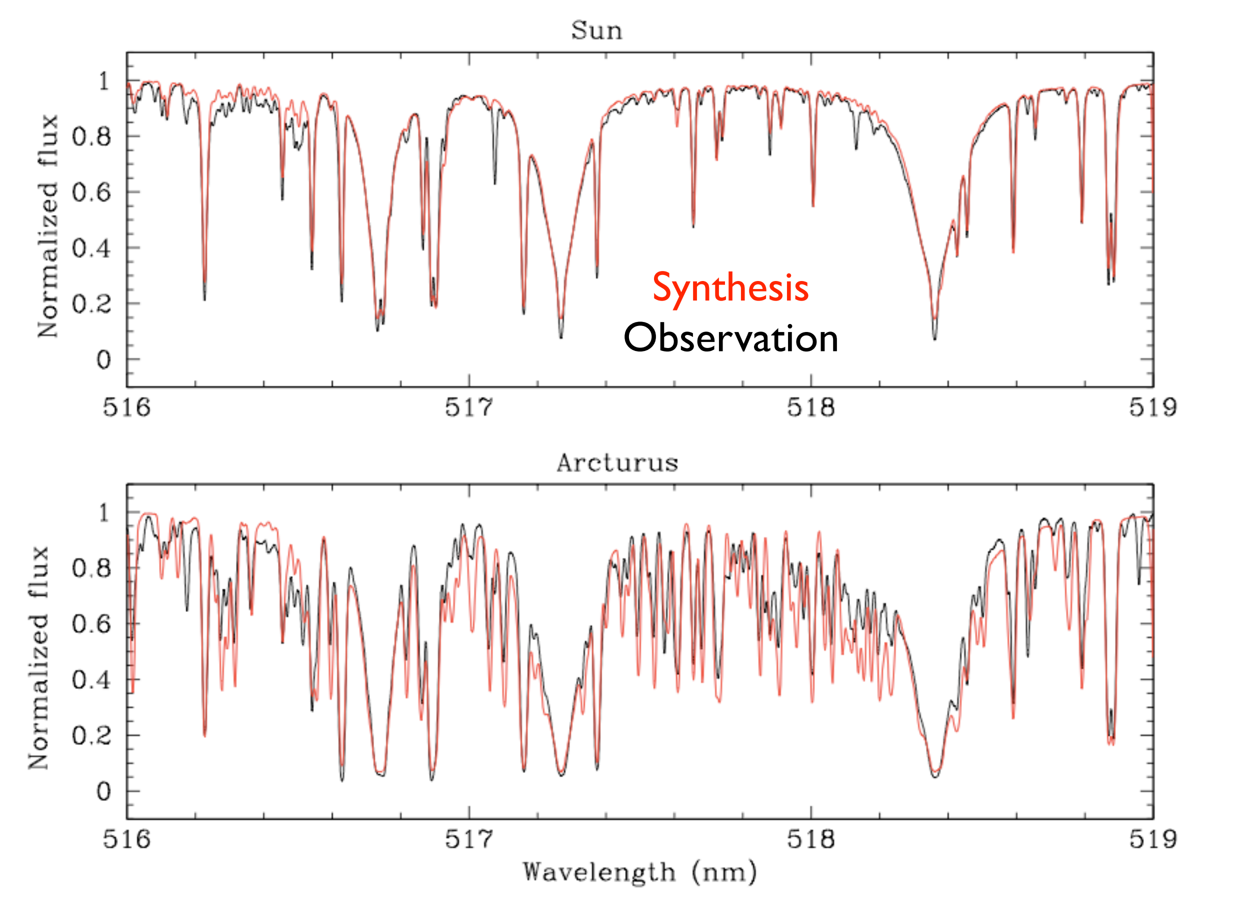


SP Synthesis in a nutshell



Uncertainties in synthetic spectra

Uncertainties in log gfs (mostly) and model atmospheres prevent adoption of purely synthetic models to be used in accurate abundances

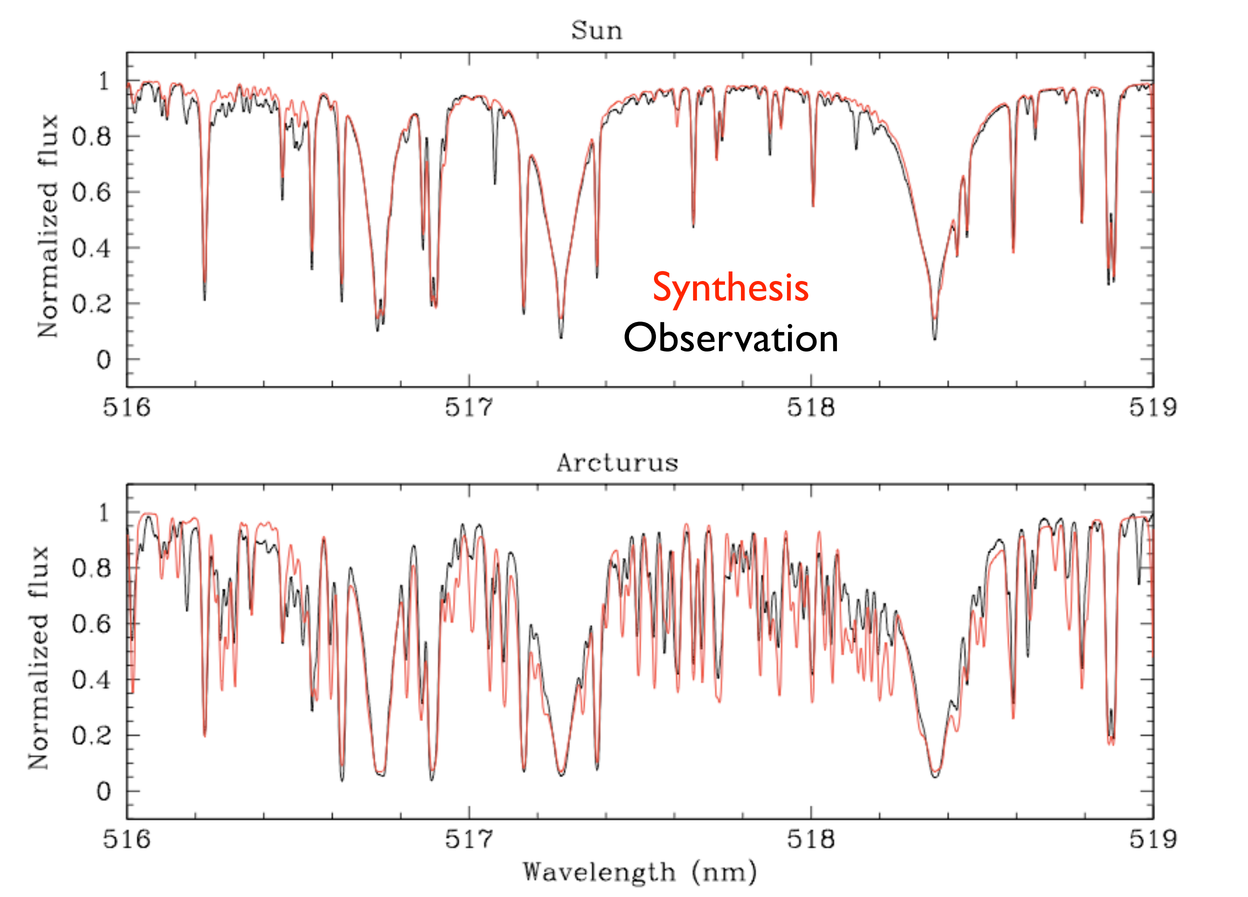


Spectrum synthesis of the Sun

Coelho et al. (2005)

Uncertainties in synthetic spectra

A hybrid approach combines observed stellar libraries with differential spectrum synthesis (Trager et al. 2000, Proctor & Sansom 2002, Thomas et al. 2003,2011, Schiavon 2007, Conroy & van Dokkum 2012, among others)



Spectrum synthesis of the Sun

Coelho et al. (2005)

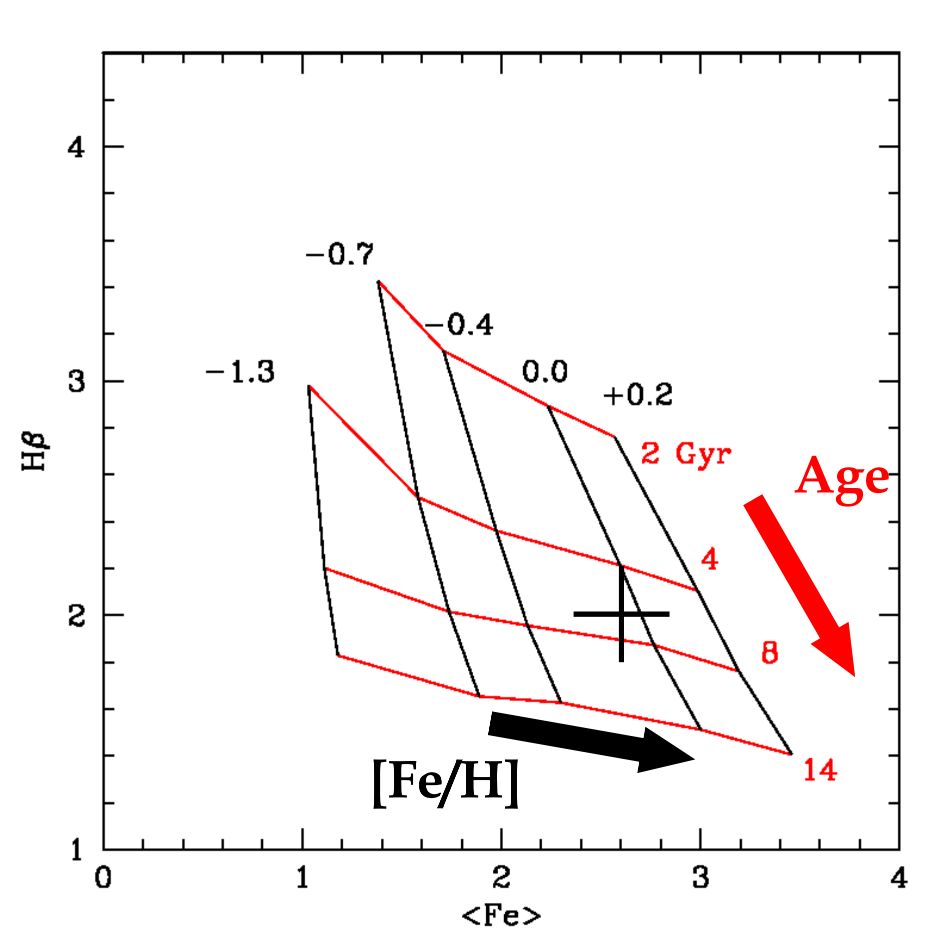
Line Indices

Isolate spectral dependence on specific parameters (e.g., age, elemental abundance, IMF)

When applied to stellar clusters: ages and elemental abundances

Galaxies: luminosity-weighted mean ages and elemental abundances

Method has many many caveats, but it basically works



Worthey, Maraston+Thomas, Schiavon, Vazdekis, and many many others

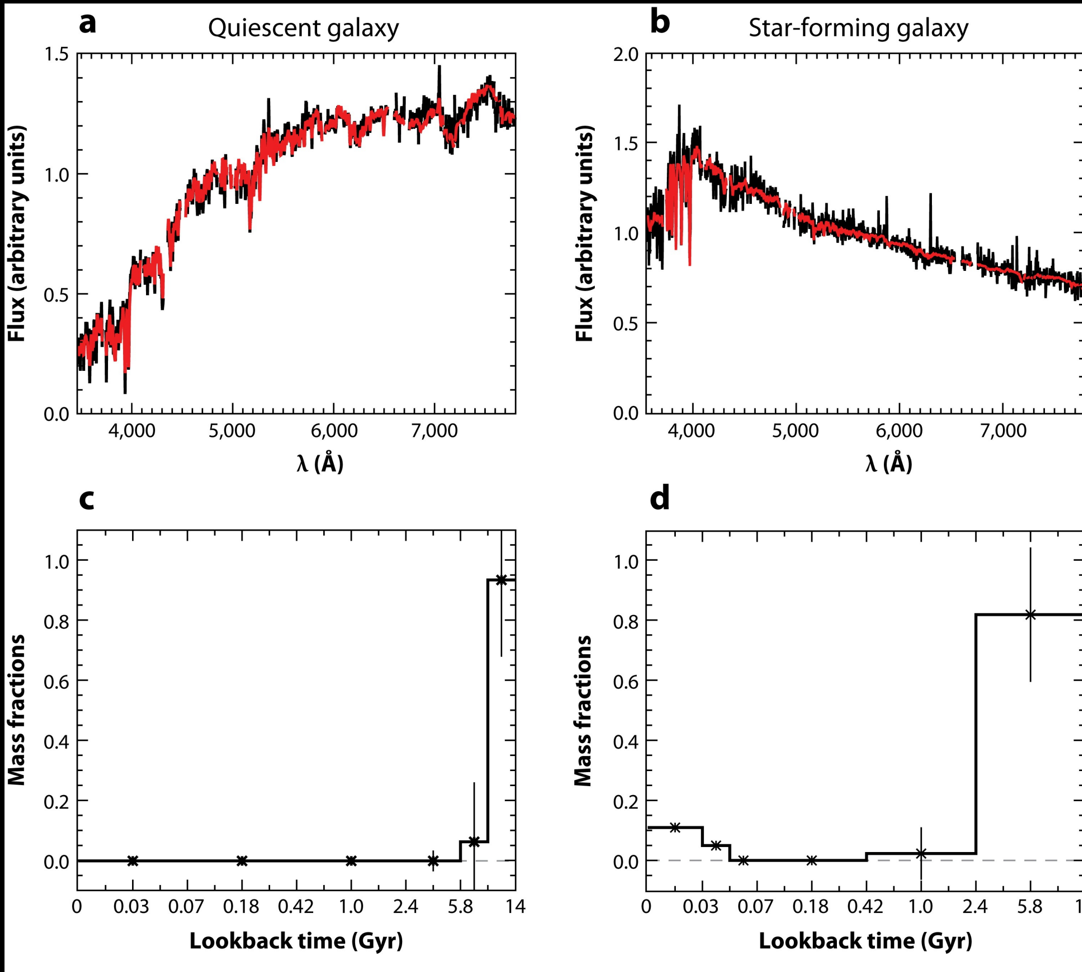
Spectral Fits

Maximizes use of spectral pixels, so can use lower S/N/pixel

Requires wider spectral coverage, which is observationally costly

In principle can constrain age distribution, but that depends on spectral coverage

Recently capable of yielding detailed elemental abundances

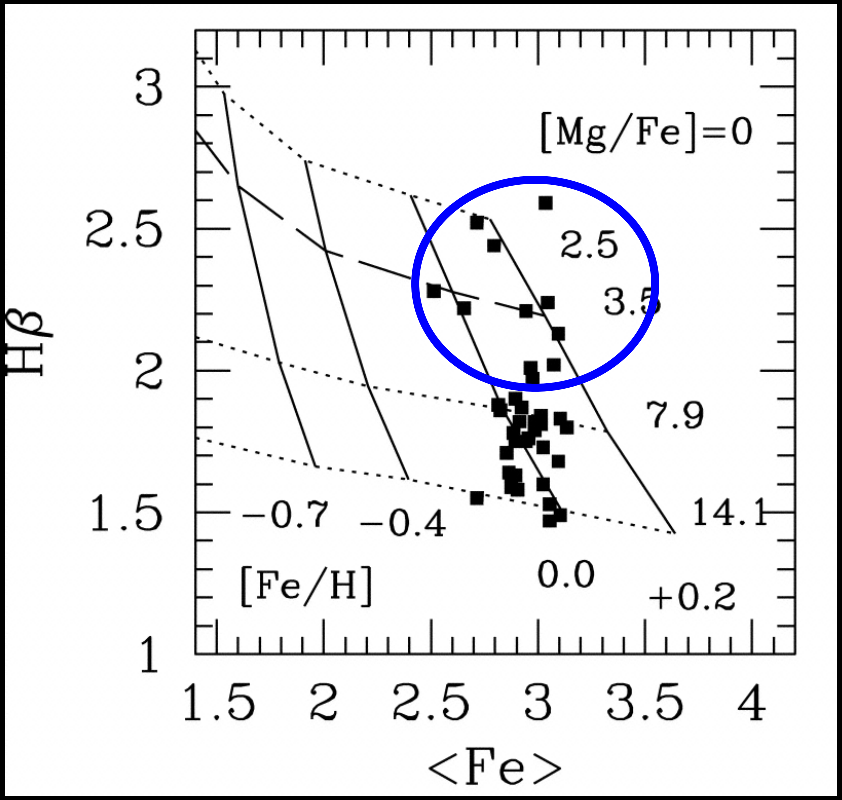


Conroy C. 2013. Annu. Rev. Astron. Astrophys. 51:393–455

Based on Tojeiro et al. 2009

Cid Fernandes, Tojeiro, Heavens, Conroy, Walcher, Coelho, Ocvirk, Koleva, and others

"Luminosity-weighted" ages for some galaxies are fairly low



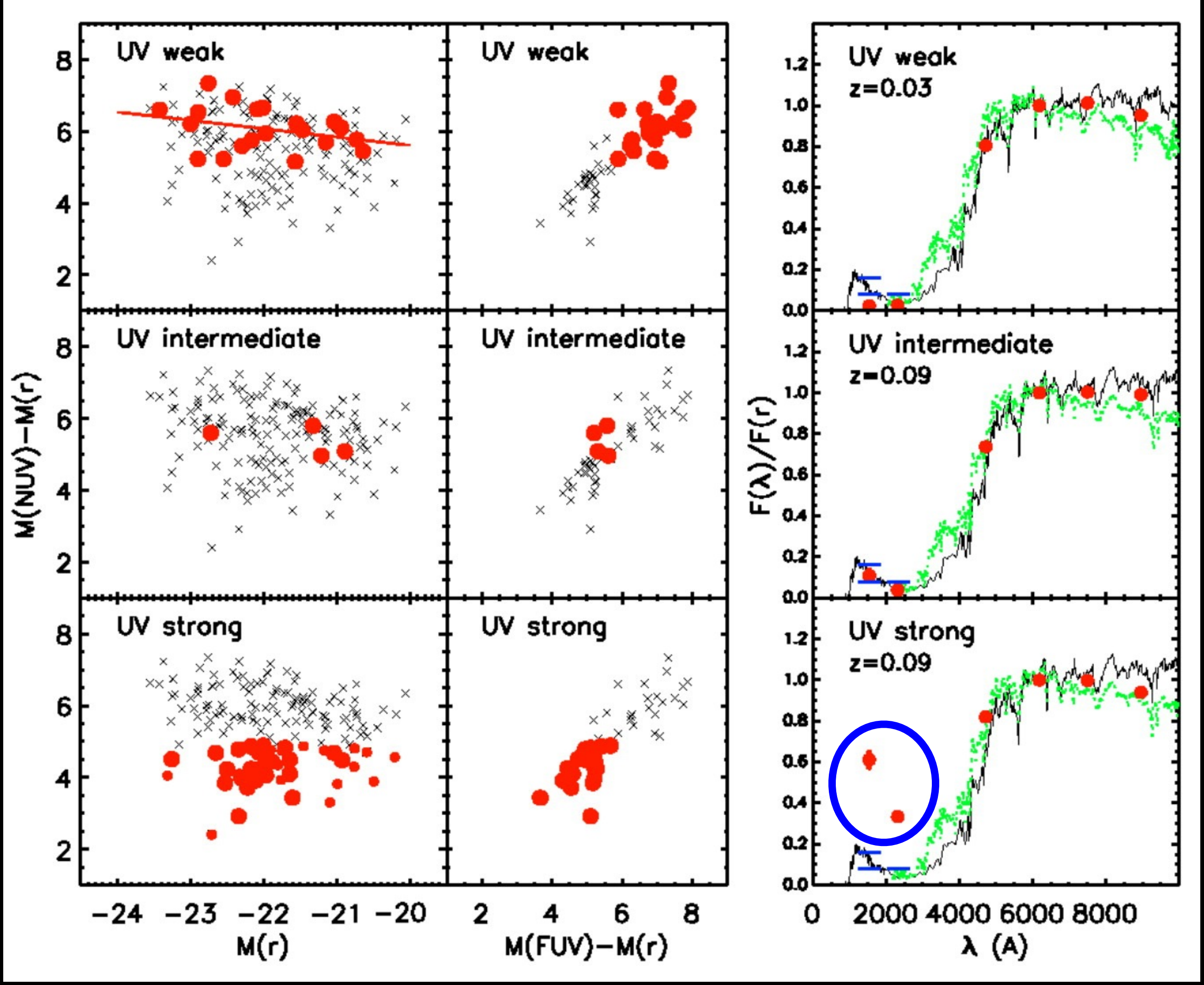
Schiavon (2007)

Young ages (Worthey 1994) inferred from Hβ because younger populations dominate over old ones in the optical. Mass weighted ages are older (Trager & Somerville 09)

Results

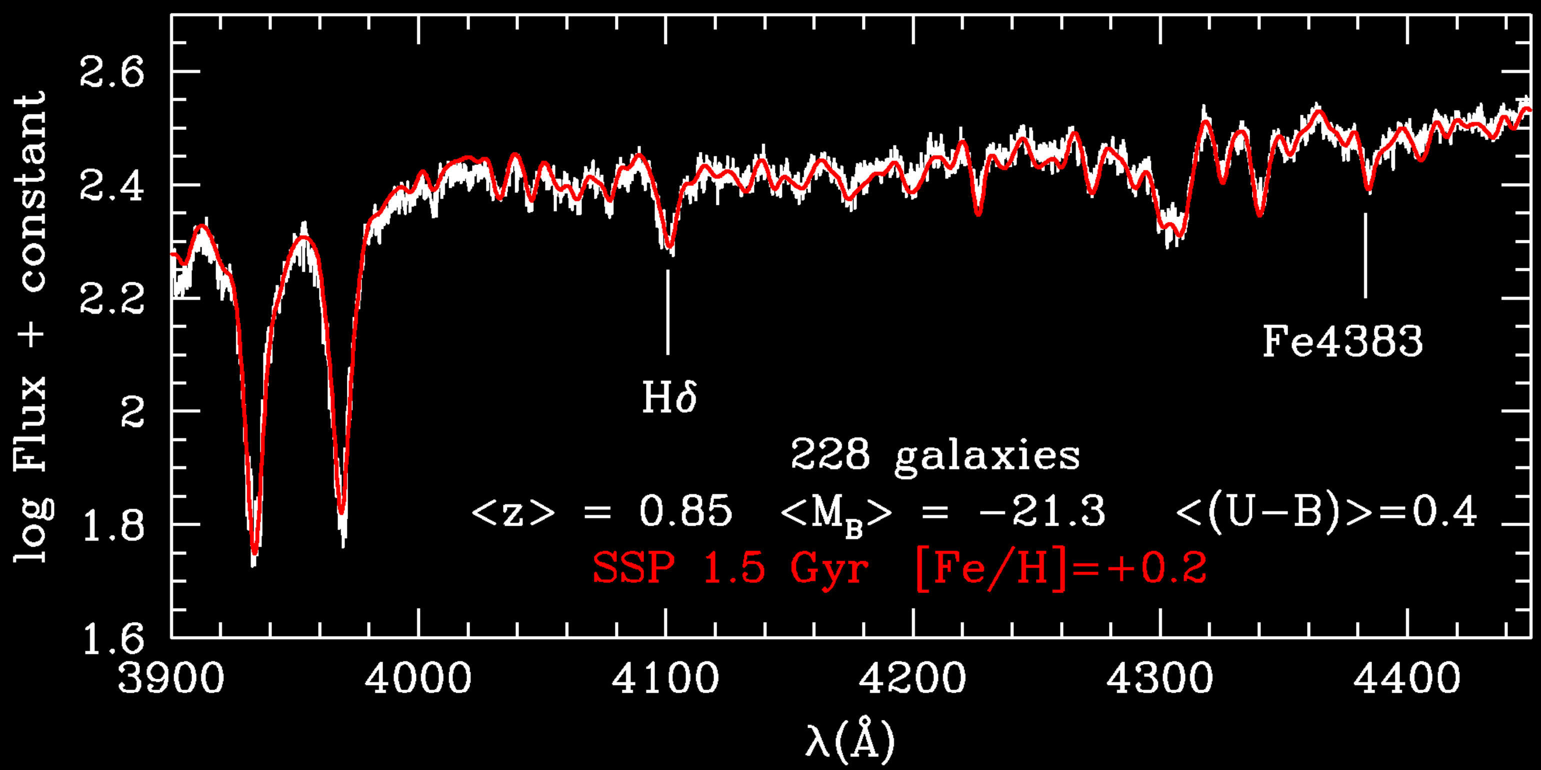
Galex+SDSS provide smoking gun

Galex UV colors of early-type galaxies from SDSS
Yi et al. (2005)



UV too bright for old stellar populations. Consistent with a few % by mass in young populations

DEEP2 Stacked Spectra vs. Models



Schiavon et al. (2006)

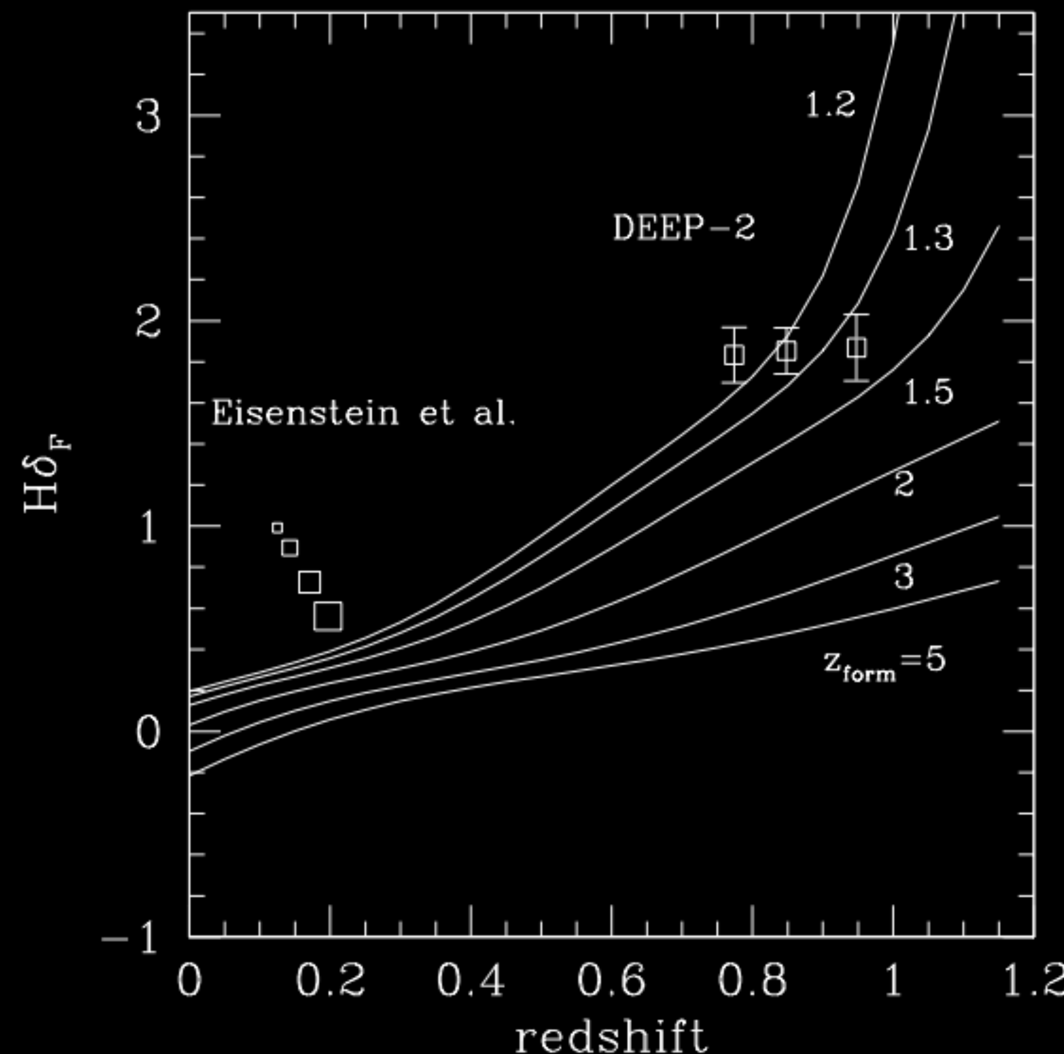
Mean luminosity-weighted ages are "young" at intermediate redshift

Results: Stellar Ages

Red field galaxies at z~0.9 and z~0.1 are NOT connected by lines of passive evolution

Due to steady incorporation of quenched newcomers from the blue cloud?

In overall agreement with results at z~0



Schiavon et al. (2006)

ATLAS-3D results

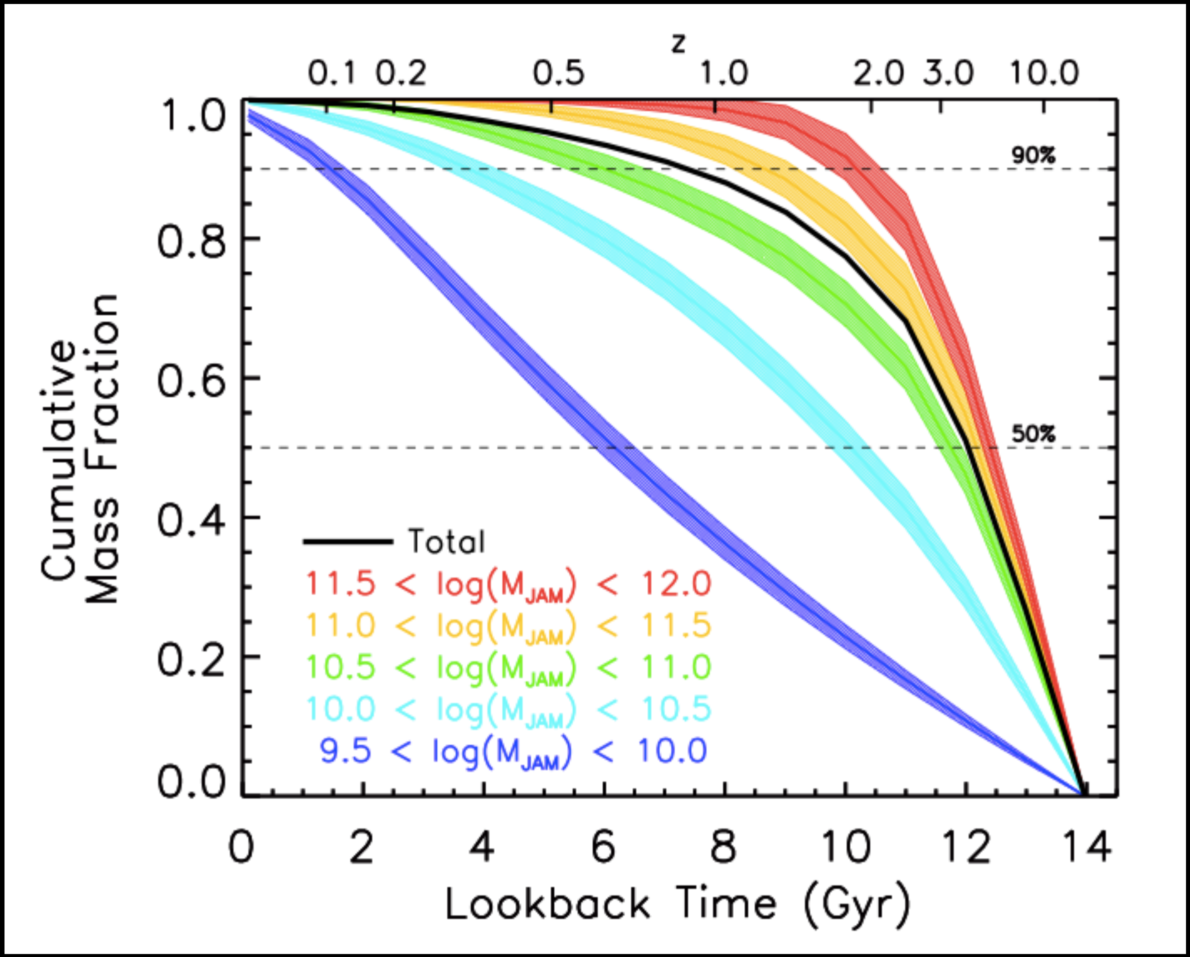
A more nuanced picture emerges from ATLAS-3D

Massive galaxies formed >90% of their mass at z > 2

At log M < 10, 50% of the mass was formed at z < 0.7

Also, more compact galaxies tend to be older and more metal-rich

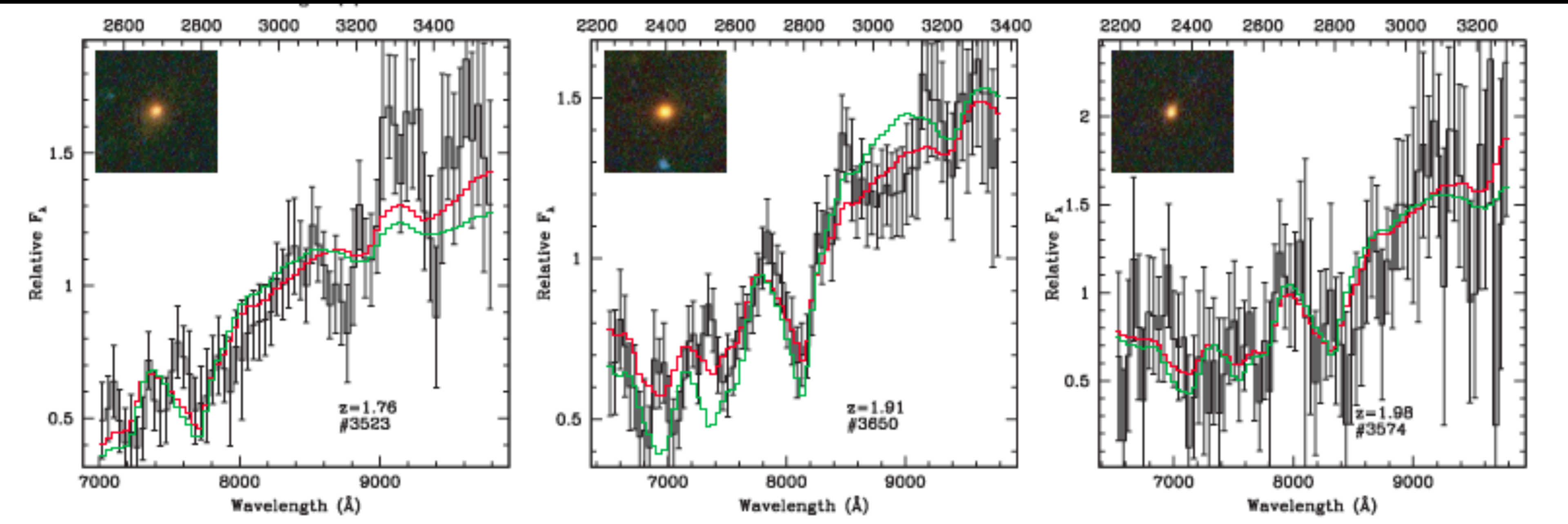
Environment mostly unimportant



McDermid et al. (2014, submitted)

At higher z

Daddi et al. (2005)



Galaxies at z~2 host "old" metal-rich stellar populations, indicating that bulk of star formation happened at higher redshift

Summing up age results

- Evidence from local and intermediate z samples suggests bulk of ETG stars were formed before z ~ 2 (as expected!)
- Small fraction (5-10%) formed since z ~ 1 (e.g., Yi et al. 2005)
- We have an increasingly good idea of what triggers and quenches this residual SF (e.g., Schawinski et al. 2014)

Summing up age results

- What about the remaining 90-95%, formed beyond z ~ 2?
- Two approaches:
    - Lookback studies
    - Fossile record
- E-ELT will contribute on both fronts

Stellar Abundances

From integrated light studies

◇ History of chemical enrichment
◇ Can constrain SF time scales
◇ May constrain characteristic masses of SF systems
◇ May constrain IMF
◇ May constrain history of mass assembly

State of the art

Elements that have been studied so far:

1. α elements: Mg, Ca, Ti, O
2. C, N, Na, Ba, Sr (in galaxies) and r-process elements in extragalactic GCs

See Choi et al. (2014), Worthey et al. (2014), Conroy et al. (2013,2012), Thomas et al. (2011), Schiavon (2007), Thomas et al. (2005), Proctor & Sansom (2002), Worthey (1994), among others

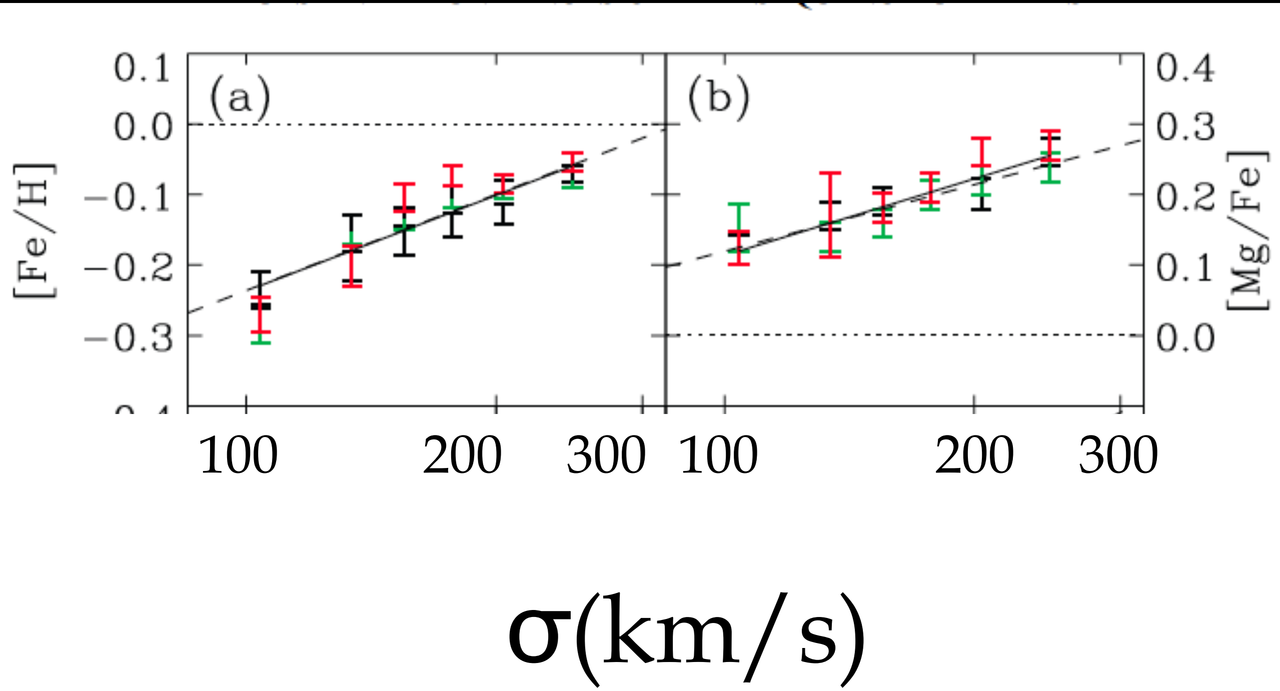
We will focus on α and nitrogen

Mg and Fe abundances as a function of σ

Analysis of stacked spectra of SDSS galaxies using EZ_Ages

Oxygen seems to follow the same behavior, but that's not the case of Ca and also perhaps Ti

Behaviour as a function of mass and environment well documented



Graves et al. (2007)

And many many other people before and since (Peletier, Worthey, Trager, Tantalo, Bressan, Thomas, Maraston, Gorgas, Sanchez-Blazquez, Conroy…)

[Mg/Fe]

Possible (qualitative) scenarios

◇ Duration of SF shorter than ~ 1 Gyr (σ-dependent quenching by SN+AGN feedback or gas exhaustion?)

◇ Variable IMF, top-heavy for high σ

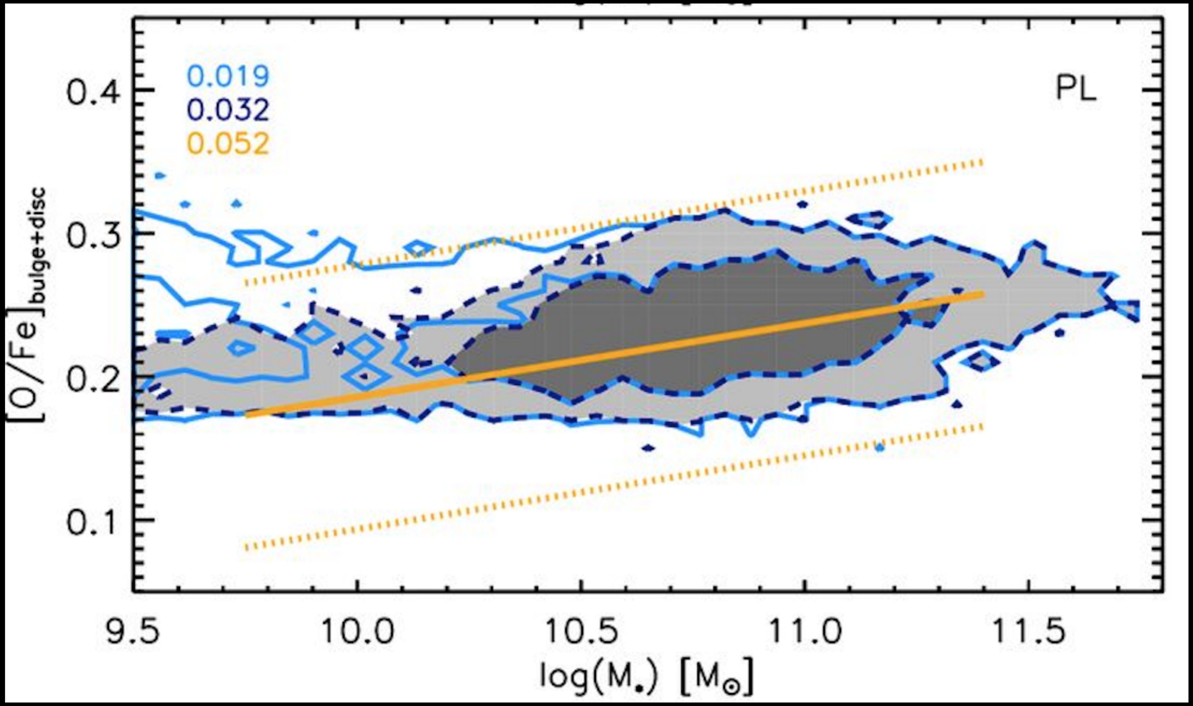
◇ "Selective" winds

◇ Other scenarios that vary SN II/SN Ia as a function of σ

Comparison with models

[O/Fe] vs mass well matched by semi-analytic models incorporating refined GCE prescription

Needs adjustment of SNIa delayed time distribution for successful fit

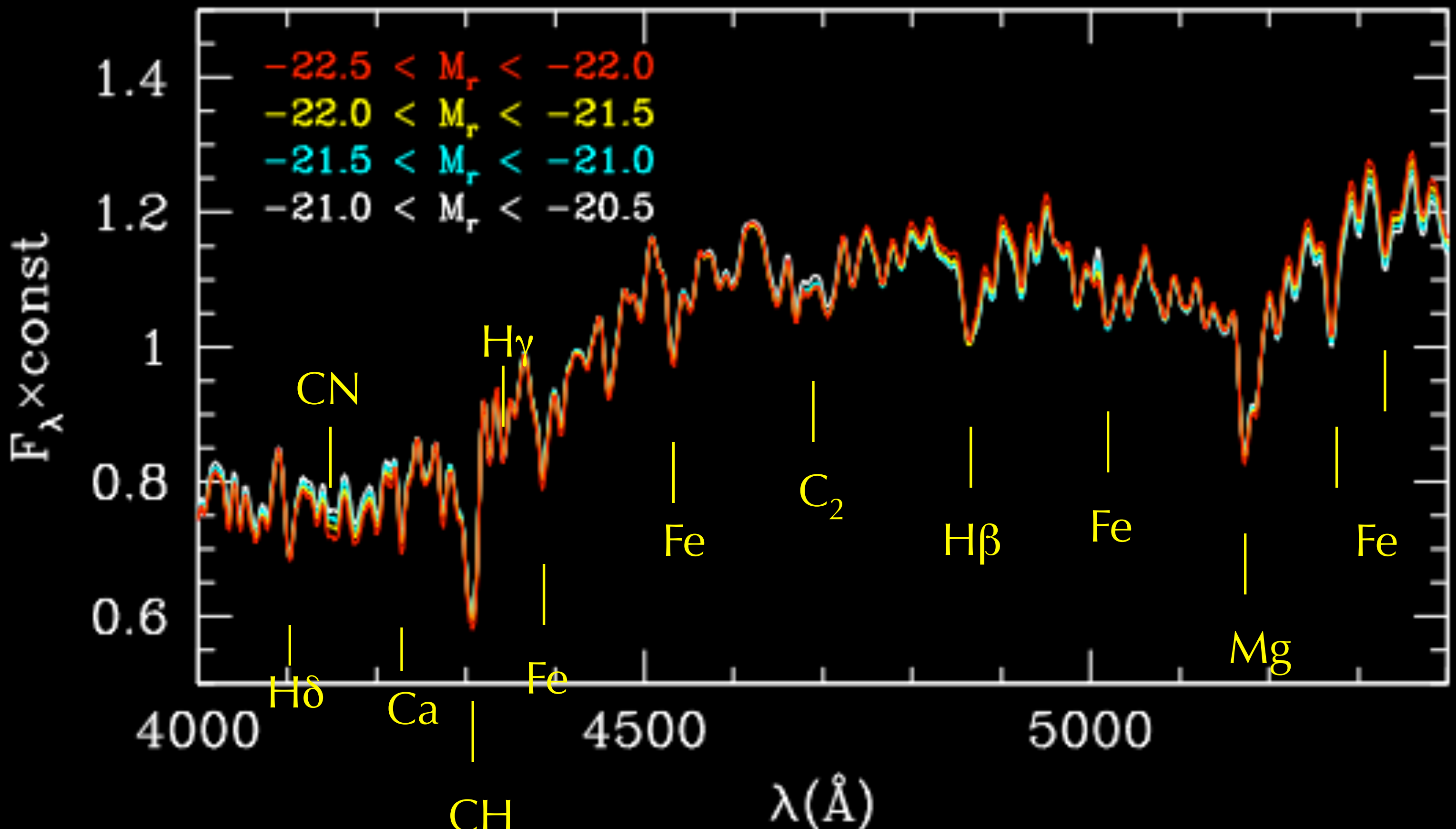


Yates et al. (2013)

Comparisons with data on galaxies are used to shed light on yields from SNIa, rather than to constrain galaxy evolution.

CN variations

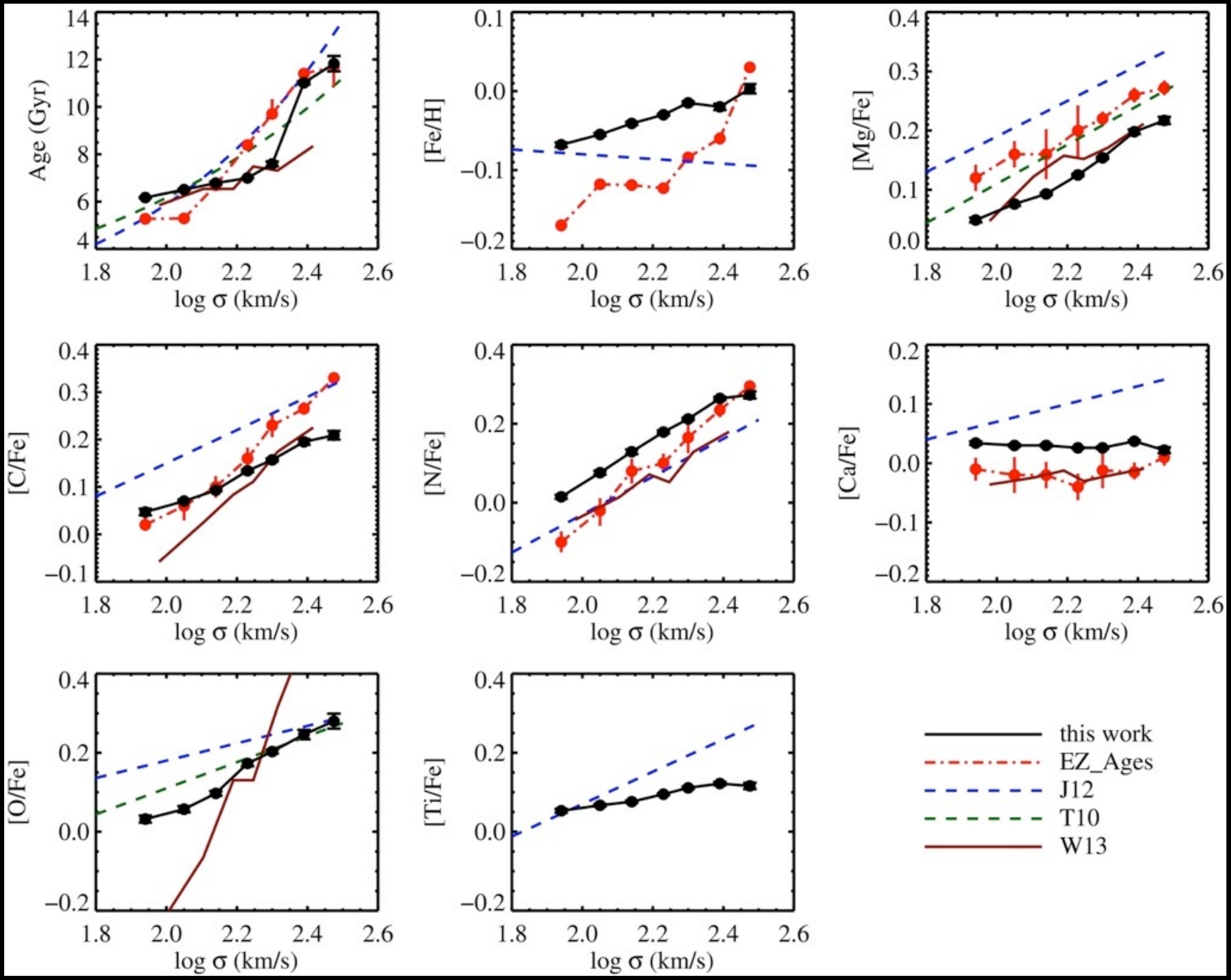
Stacked SDSS spectra from Eisenstein et al. (2003) - z ~ 0.15



The most variable features in blue/green spectra of galaxies are due to CN. Most of it due to nitrogen abundance variations.

True also at z~1 (see Kelson et al. 2006)

Elemental abundances by various groups



Conroy et al. (2014)

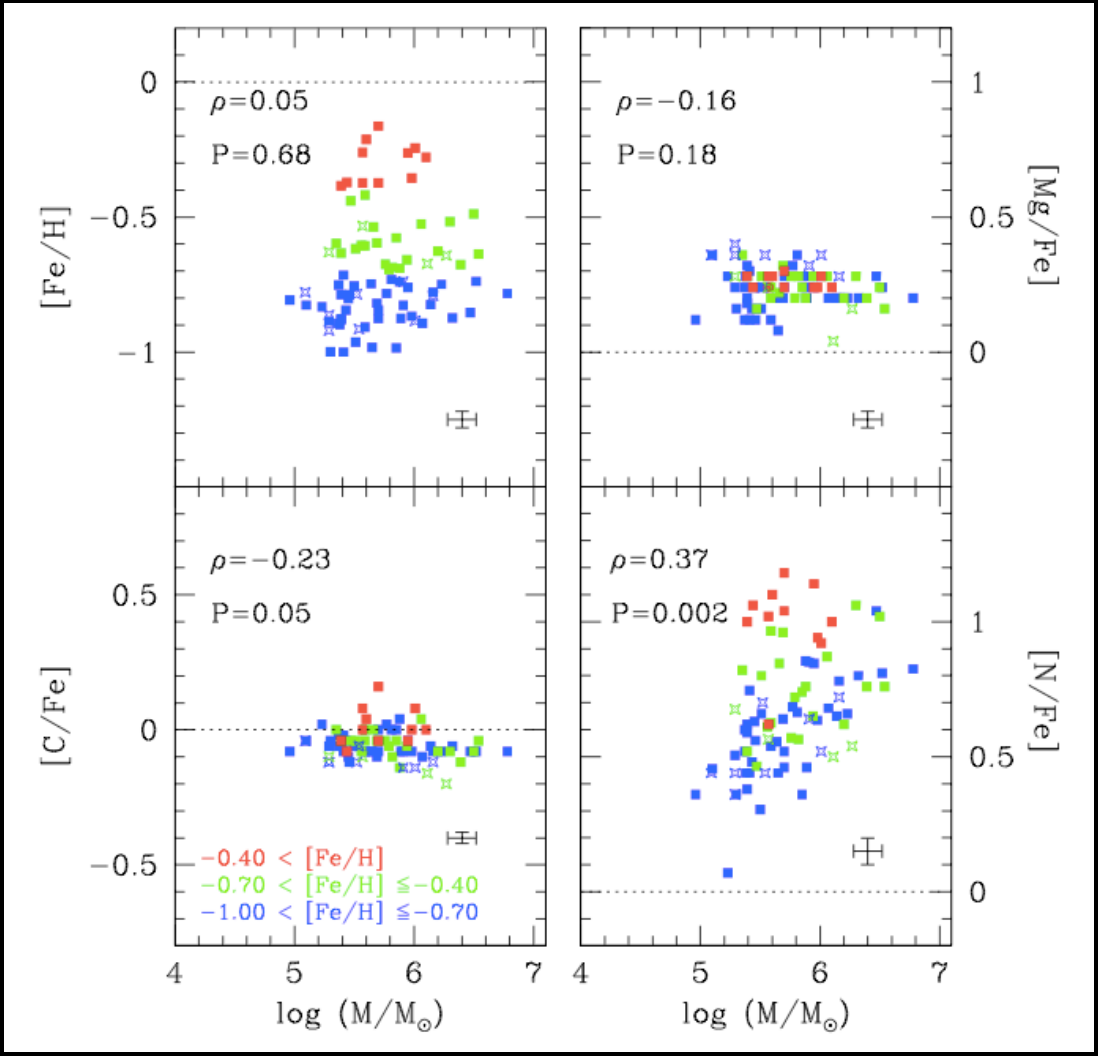
Agreement within 0.1-0.2 dex for abundances and ratios

Beware of wild speculative behavior

Mean N/Fe in M31 GCs

- It's been known that GCs have multiple stellar populations for about a decade now
- [N/Fe] in M31 GCs correlate strongly with mass

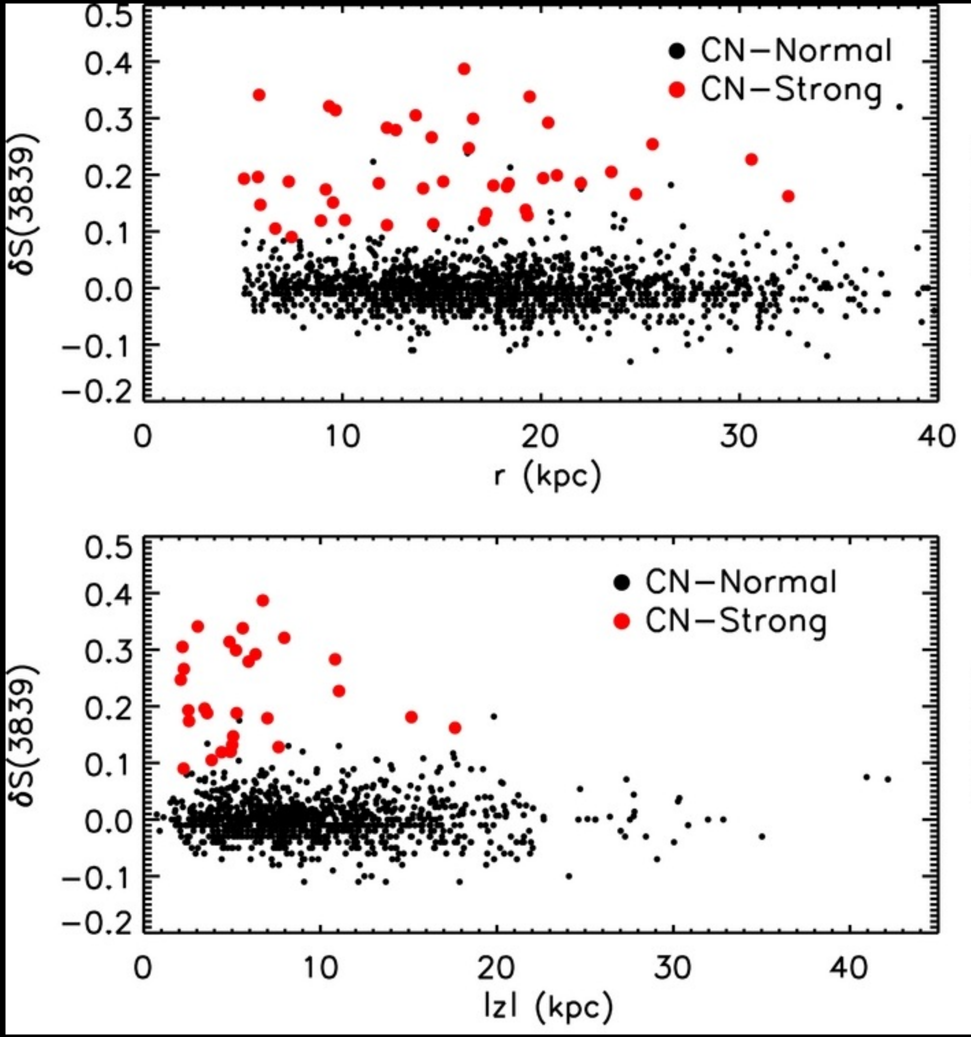
Feedback-regulated SF history and chemical enrichment in GCs?



Schiavon et al. (2013)

CN strong stars in MW halo

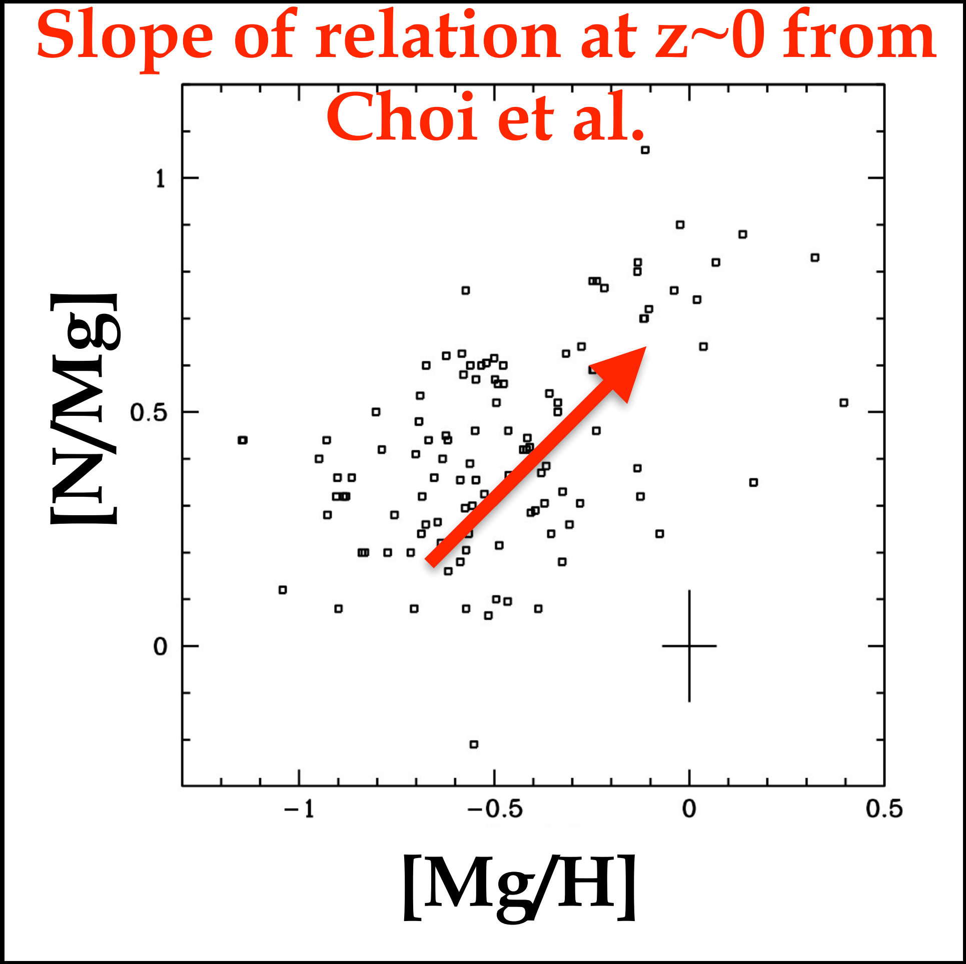
- CN-strong stars, believed to be formed within globular clusters, are found in the field of the Galactic halo
- Dissolved GCs may contribute as much as 50% of the stellar mass of the halo (Martell et al. 2011, Martell & Grebel 2010)



Carollo, Martell et al. (2013)

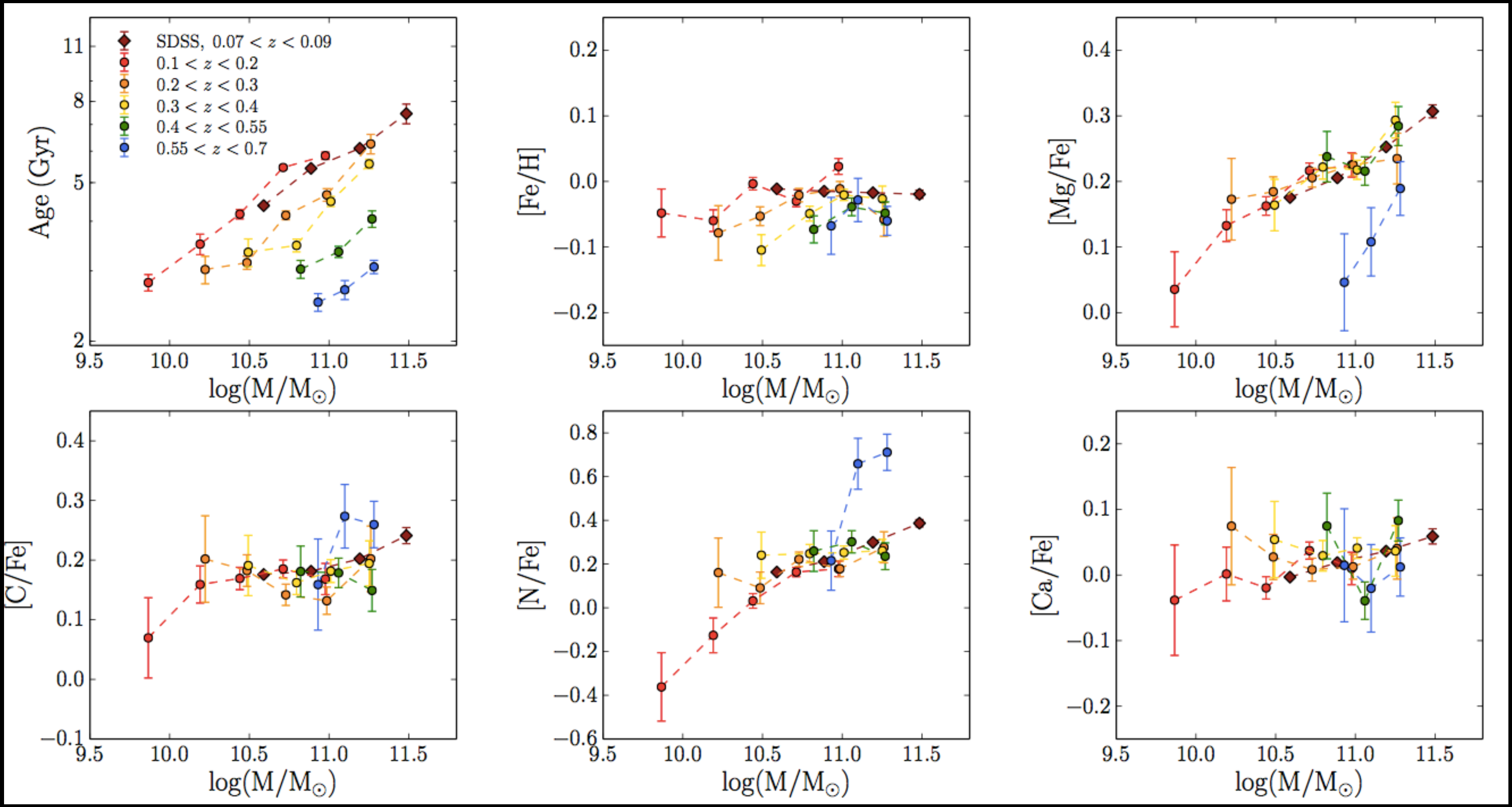
Chemical Enrichment

- The slope of the [N/Mg] vs [Mg/H] relation is approximately the same in GCs and early-type galaxies
- Does all that mean that a substantial fraction of ETG stellar mass come from (the precursors of) GCs?
- Can chemistry constrain the masses of the SF units that make up galaxies?
- See Schiavon (2010)



Schiavon et al. in prep

Abundance ratios



Choi et al. (2014)

Relations between abundance ratios and mass were already in place at z ~ 0.8 (see also Jørgensen & Chiboucas 2014, Sanchez-Blazquez et al. 2009, Kelson et al. 2006)

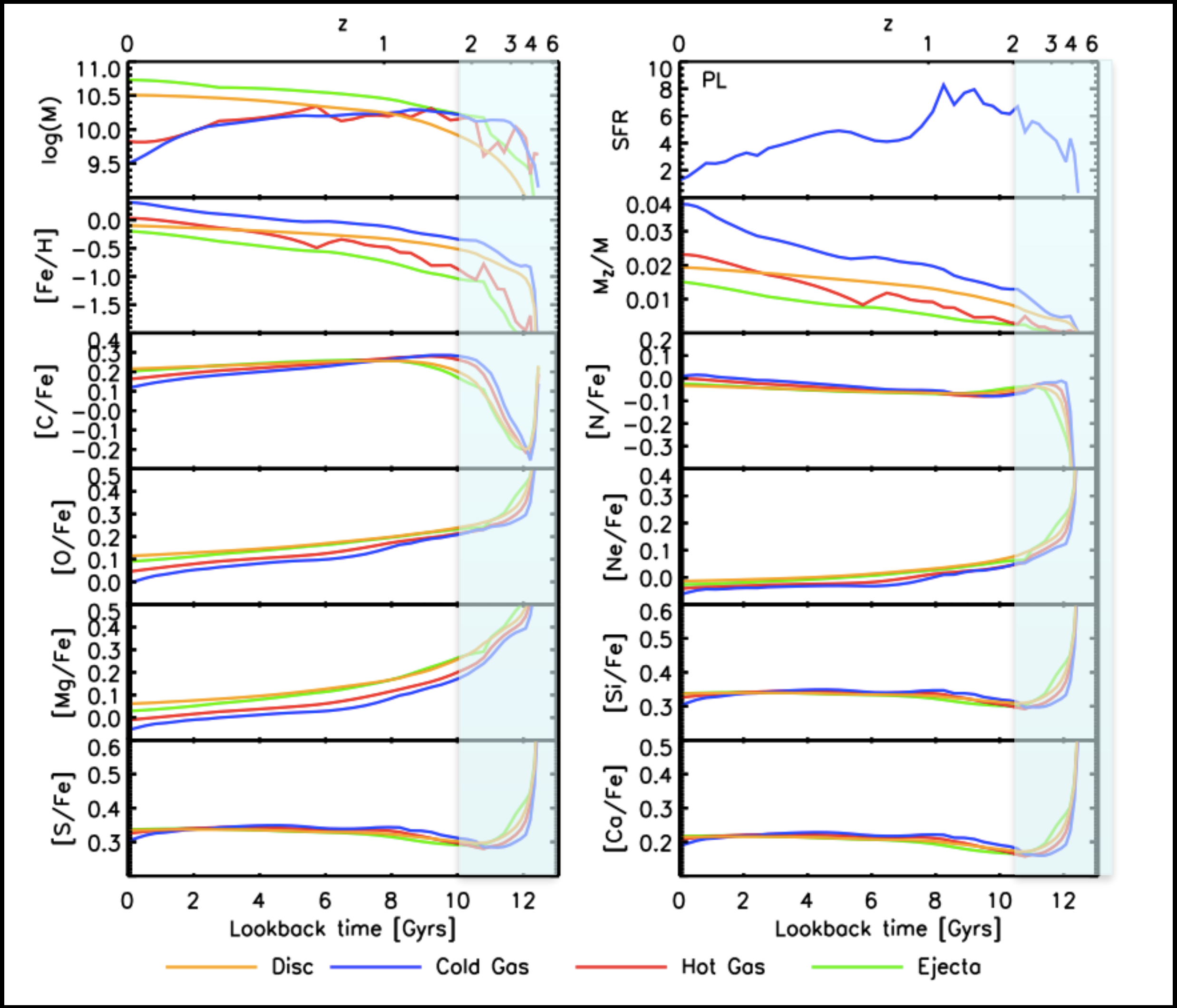
Future

Theoretical Predictions

Models now make testable predictions for the run of elemental abundances with time.

Important variations occur beyond z~2.

Tests require statistically significant samples at those redshifts

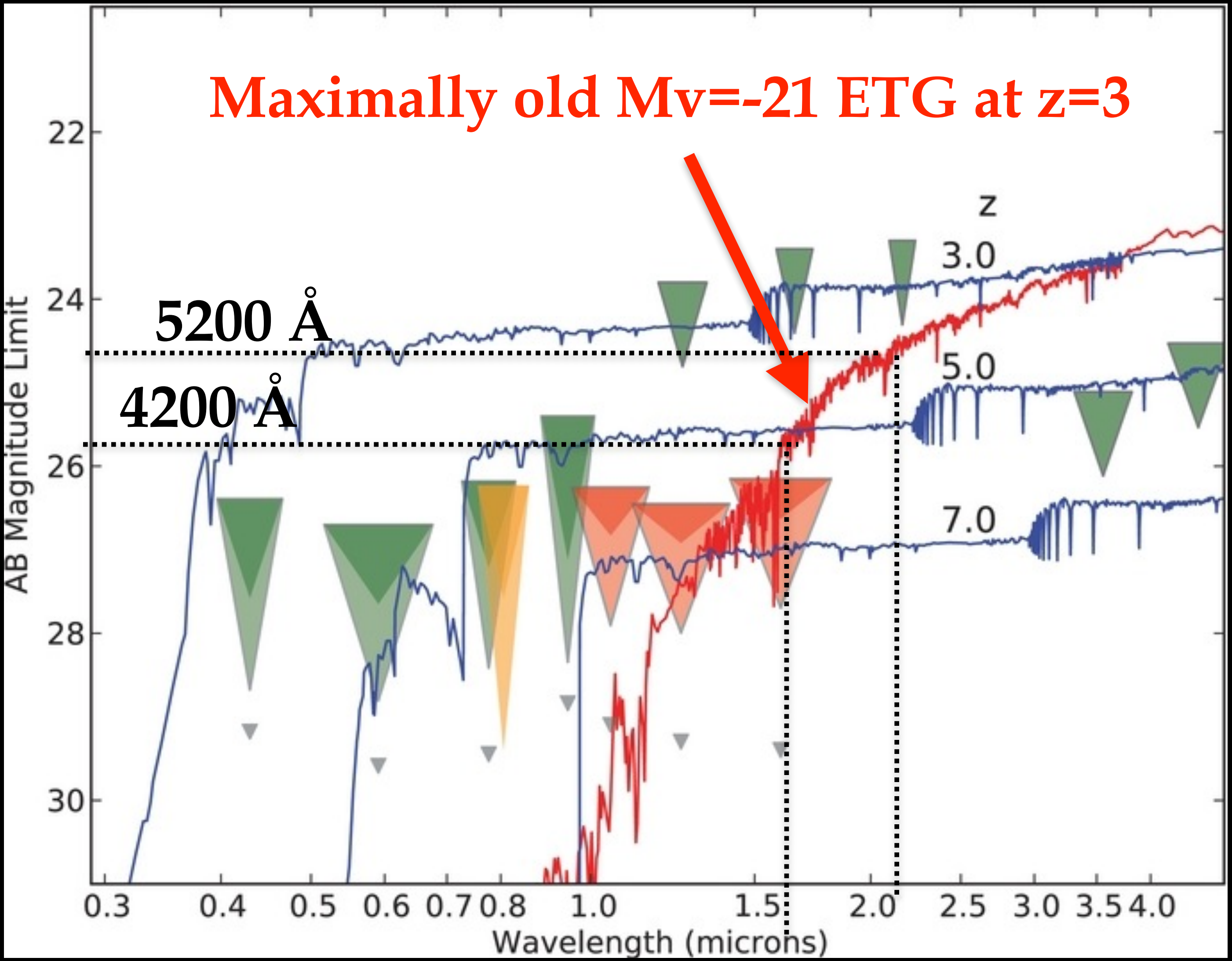


Yates et al. (2013)

E-ELT contribution

- E-ELT will make a transformational contribution to the field
- With MOSAIC, a survey of several 10^4 galaxies can access galaxy populations at $z \gtrsim 2$ with enough S/N through stacking to allow elemental abundances to be measured, so as to test model predictions

Magnitude limits



Grogin et al. (2011)

E-ELT contribution

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- With MOSAIC, a survey of several x10^4 galaxies can access galaxy populations at $z \gtrsim 2$ with enough S/N through stacking to allow elemental abundances to be measured, so as to test model predictions
- Requires reaching S/N ~ a few/pixel in the continuum at H ~ 26, K ~ 25, for 1 hr exposure.
- Simple scaling from known performance of 10 m class telescope-based MOS spectrographs suggests that this is feasible.

תודה

Dankie Gracias

Спасибо شكراً

Merci Takk

Köszönjük

Terima kasih

Grazie Dziękujemy Dėkojame

Ďakujeme Vielen Dank Paldies

Kiitos Täname teid 谢谢

Thank You

Tak

感謝您 Obrigado Teşekkür Ederiz

감사합니다

Σας Ευχαριστούμ

ขอบคุณ

Bedankt Děkujeme vám

ありがとうございます

Tack