Stellar Populations of Spiral Galaxy Bulges from Integrated Light

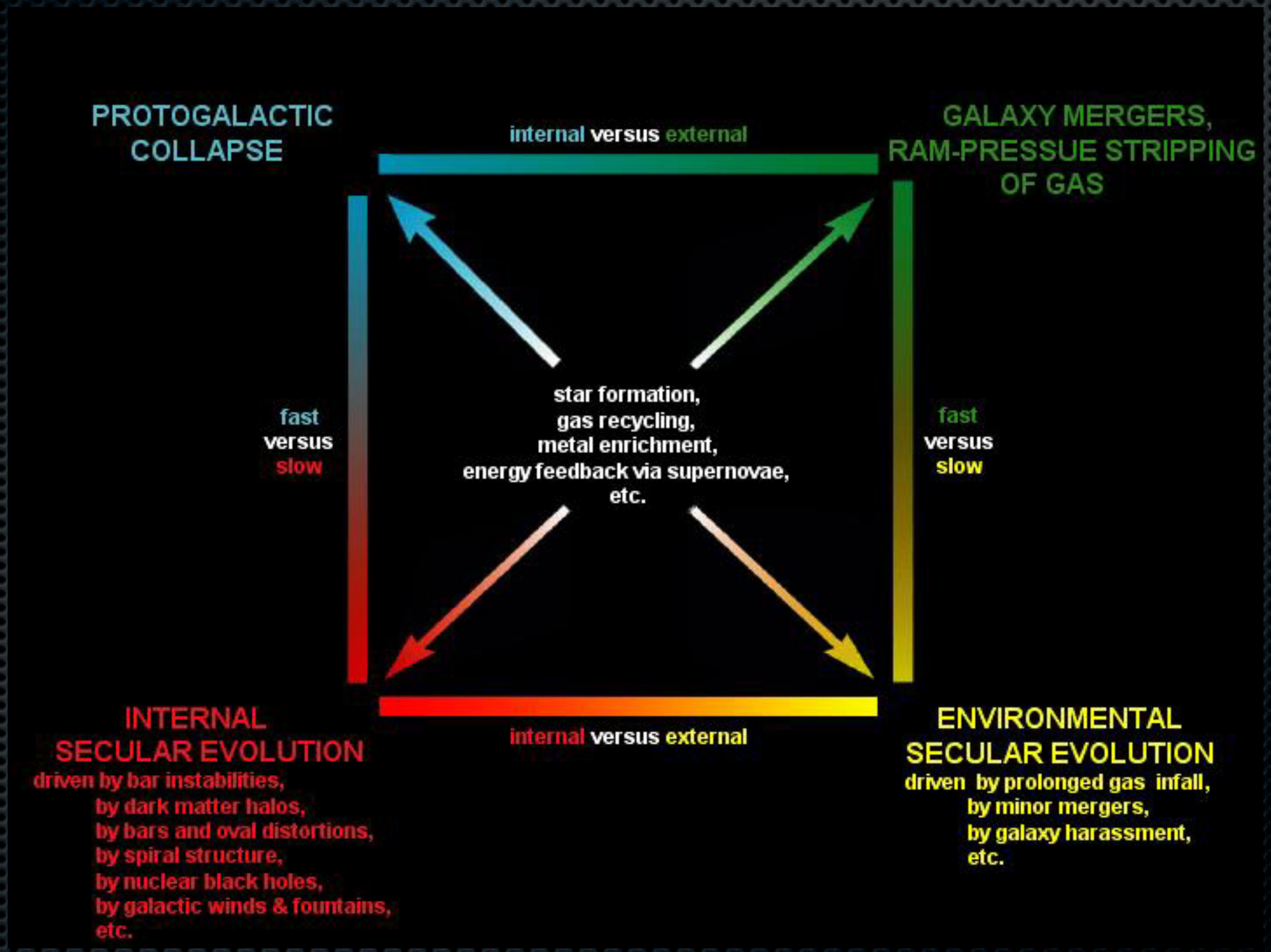
S.C. Trager (Kapteyn Astronomical Institute)

(with thanks to R. Peletier and R. Wyse for helpful suggestions)

What do we *want* to know about bulges?

- How and when do they form?
  - What populations do they contain? What are their compositions?
- What is their connection to other galaxy components (disks, bars, halos)?

Bulge formation scenarios



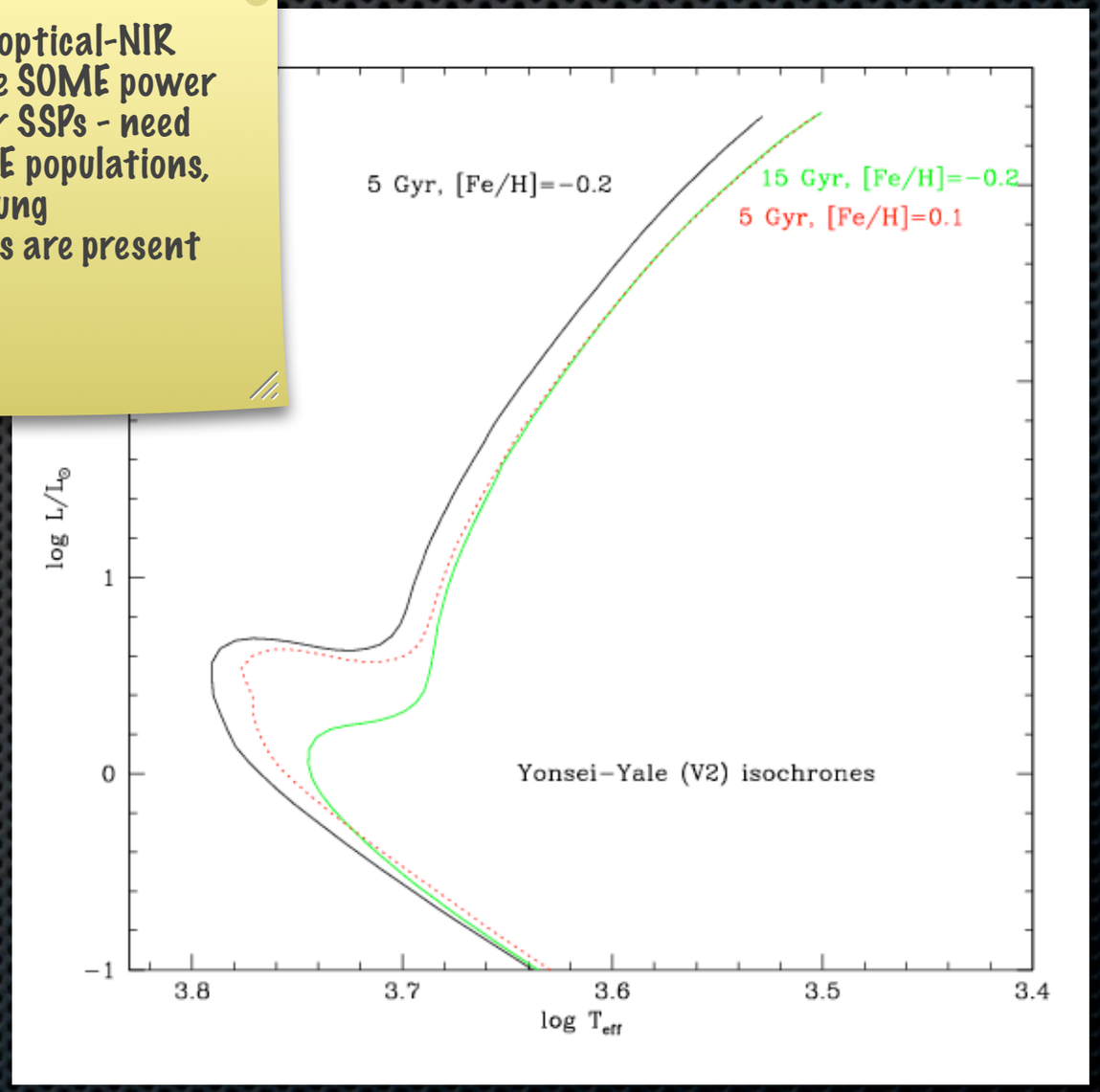
Kormendy & Kennicutt (2004)

Stellar population modeling: basics, caveats, and calibrations

How can we measure the ages of unresolved galaxies?

- Colors don't help!
  - at least not for old galaxies
- Why not?
  - Colors come from *red giant branch* and *main sequence*
  - <u>Degenerate</u> to changes in age and composition!

Note that optical-NIR colors have SOME power but not for SSPs - need COMPOSITE populations, so that young populations are present (Lee+ 07)



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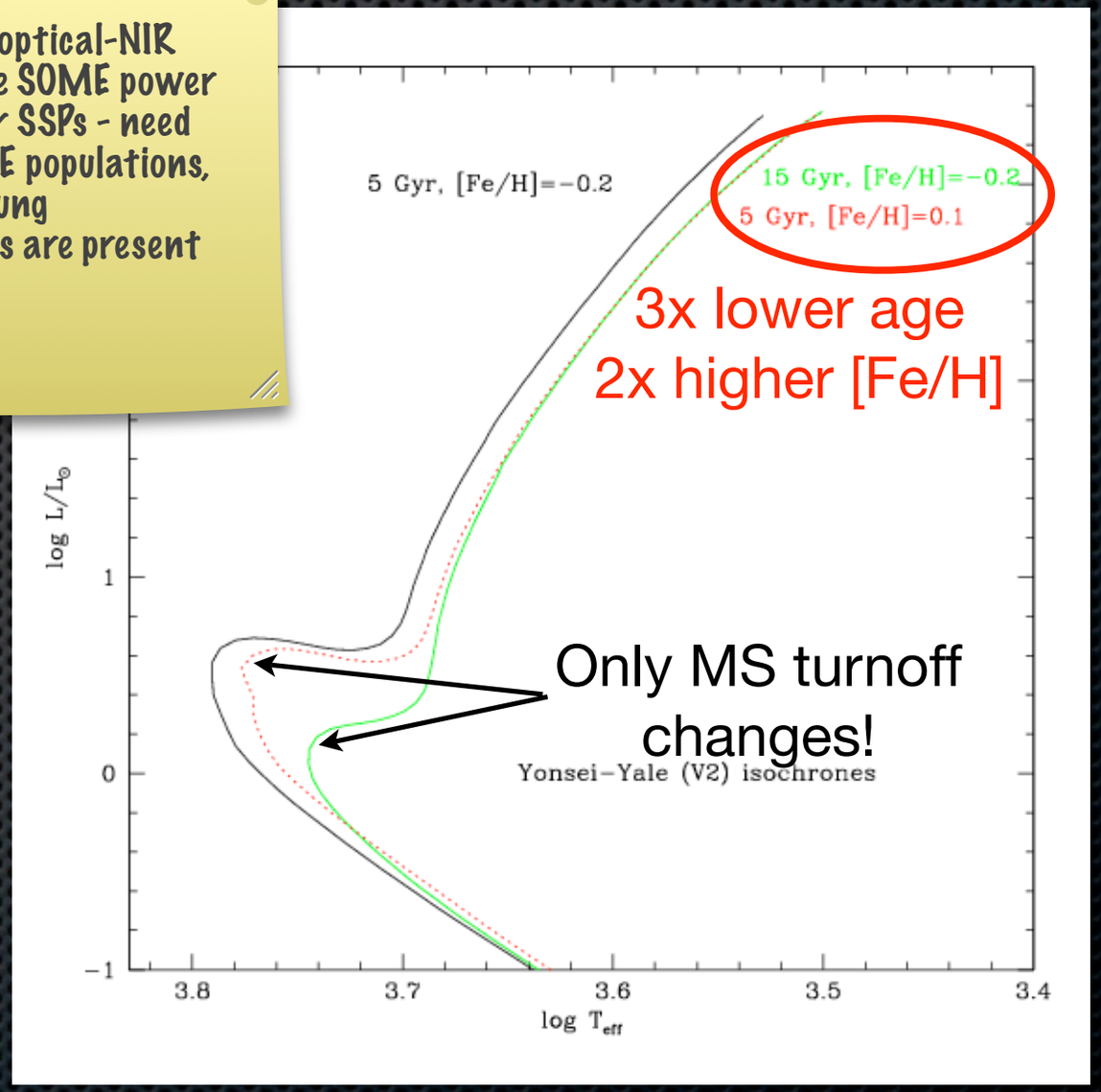
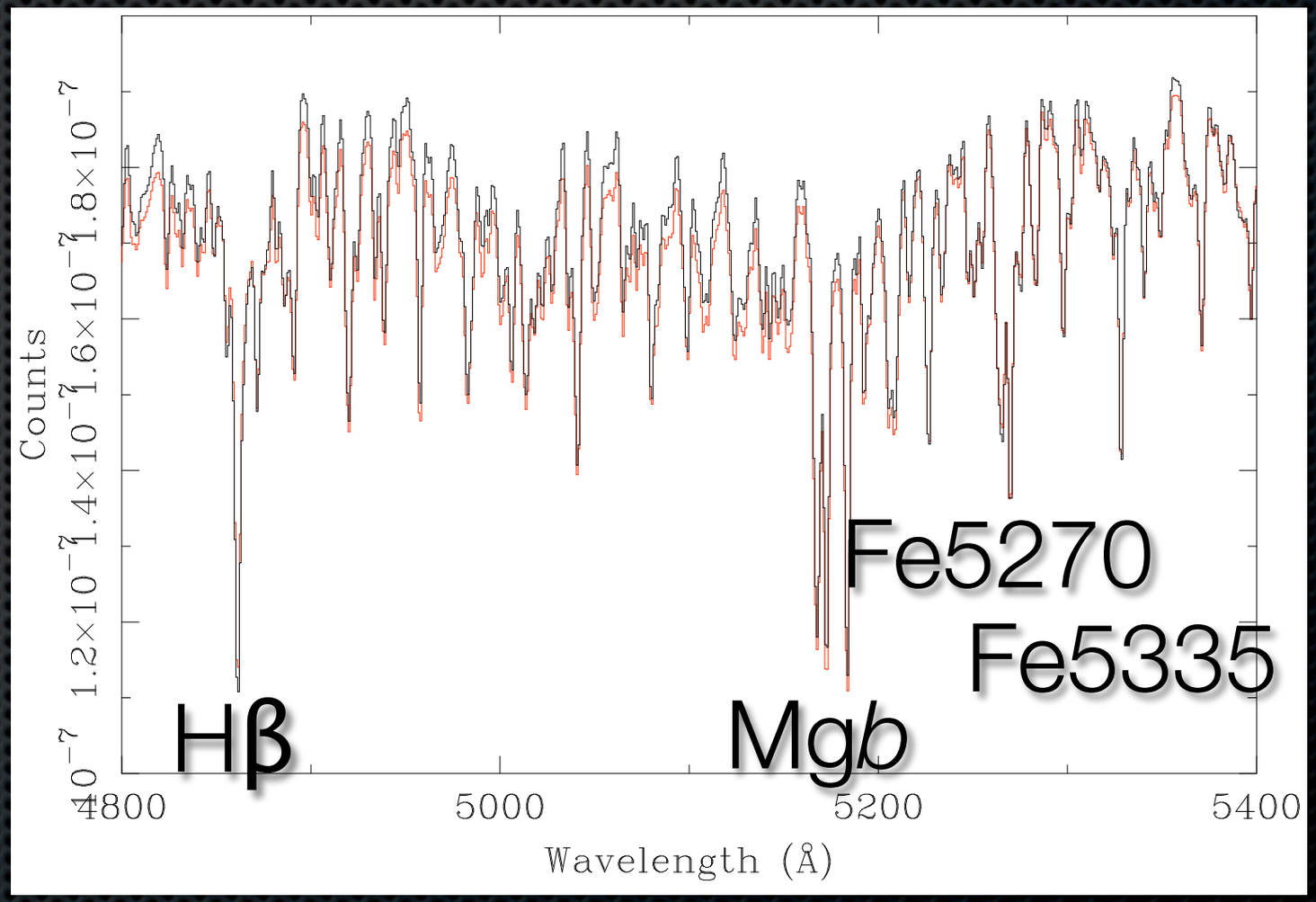


An example of the age-metallicity degeneracy

- Two spectra with
  - 5 Gyr, [Fe/H]=-0.4
  - 15 Gyr, [Fe/H]=-0.7
- Can you tell the difference?



Vazdekis MILES models

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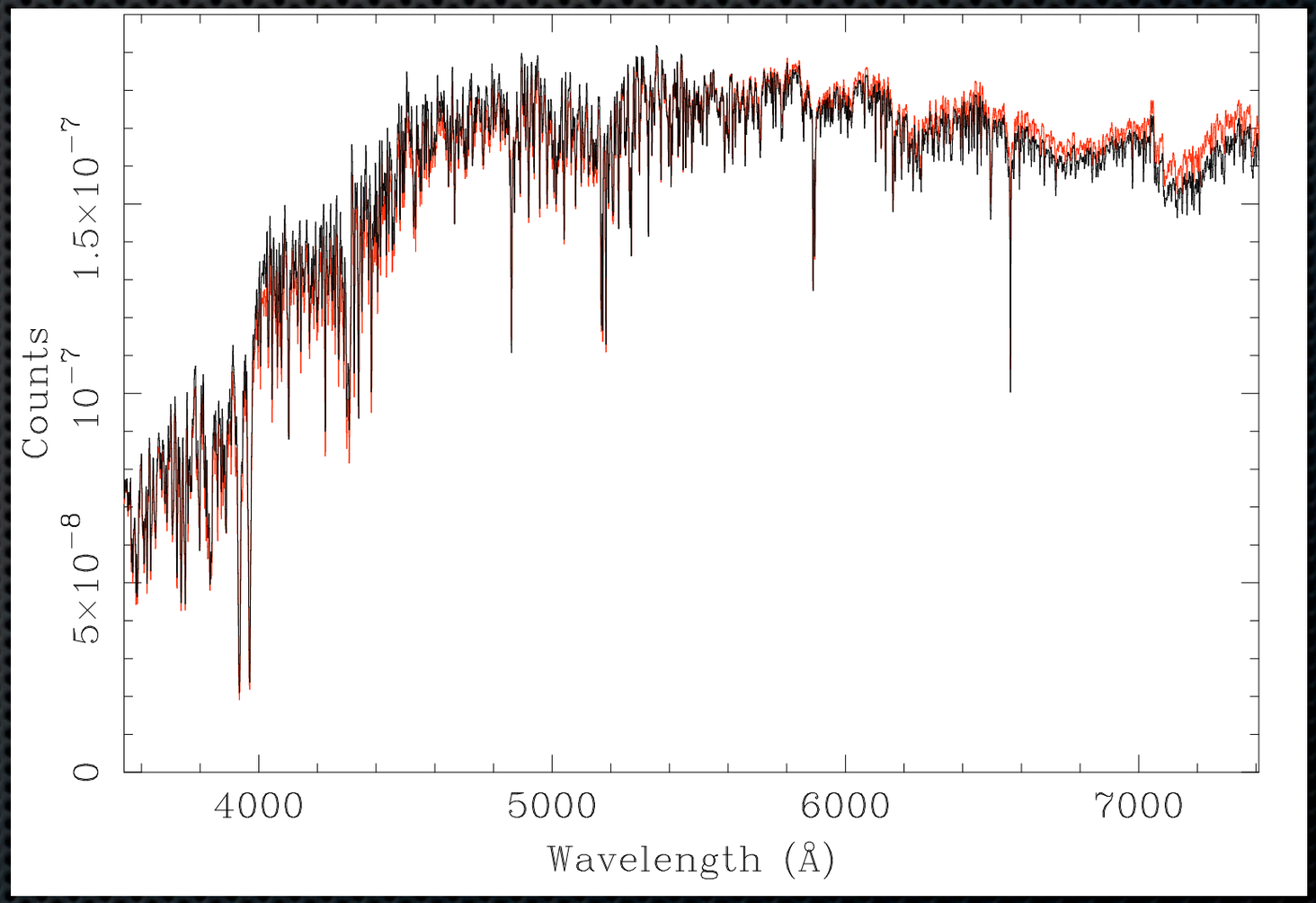


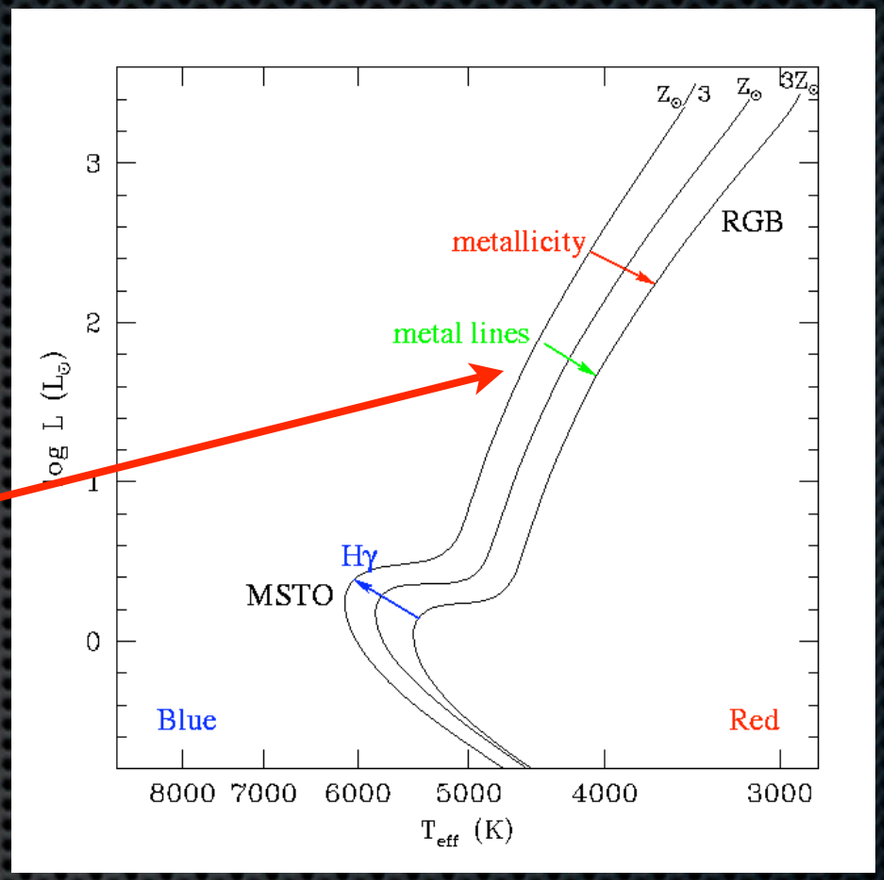
Vazdekis MILES models

How can we break the t-Z degeneracy?

Isochrones from Worthey (1994)

How can we break the t-Z degeneracy?

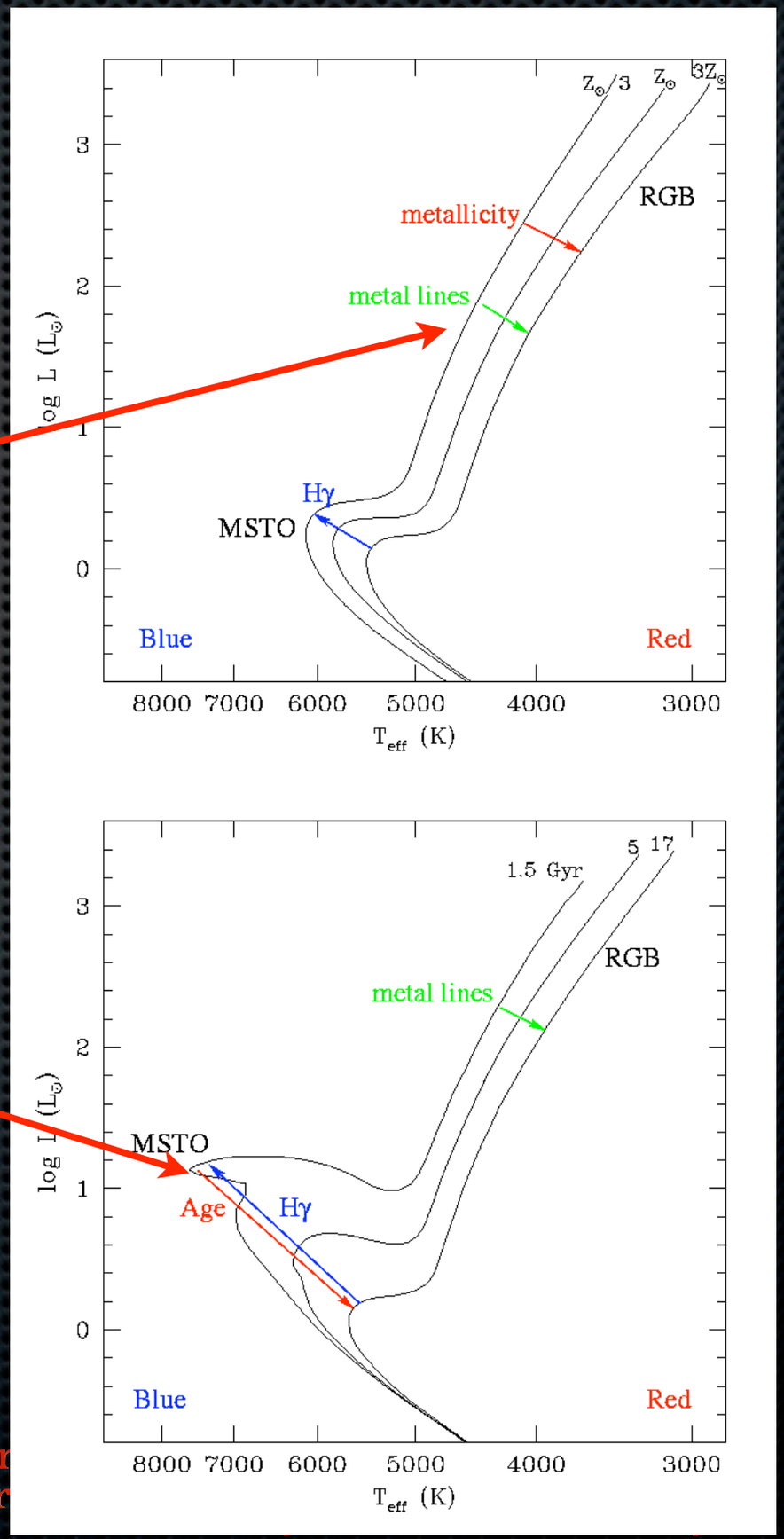
- Metal lines arise from *coolest* stars: RGB & lower MS (invisible at optical wavelengths)



Isochrones from Worthey (1994)

How can we break the t-Z degeneracy?

- Metal lines arise from *coolest* stars: RGB & lower MS (invisible at optical wavelengths)
- Balmer lines of H arise from *hottest* stars (cooler than mid-B): main-sequence turn-off (MSTO)
  - *nonlinearly* sensitive to temperature



Isochrones from Worthey (1994)

A historical note

- Rabin (1980,1982) and Gunn, Stryker & Tinsley (1981) independently pointed out that Balmer line strengths allowed for accurate age-dating of single stellar populations
- Rabin (1982) made first index-index diagram to decouple age and metallicity: the “hydrogen-metals diagnostic diagram”

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- Rabin (1981)
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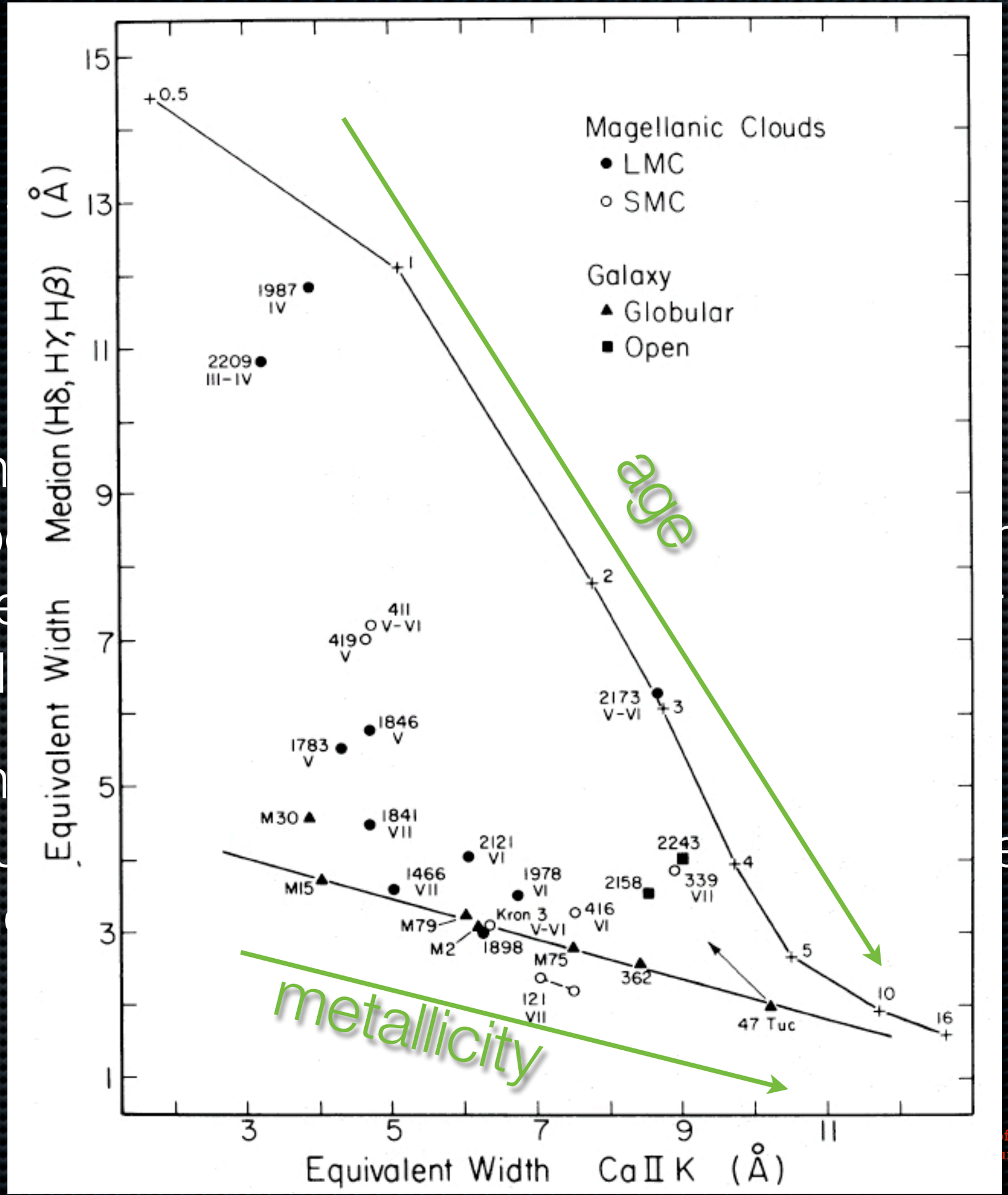
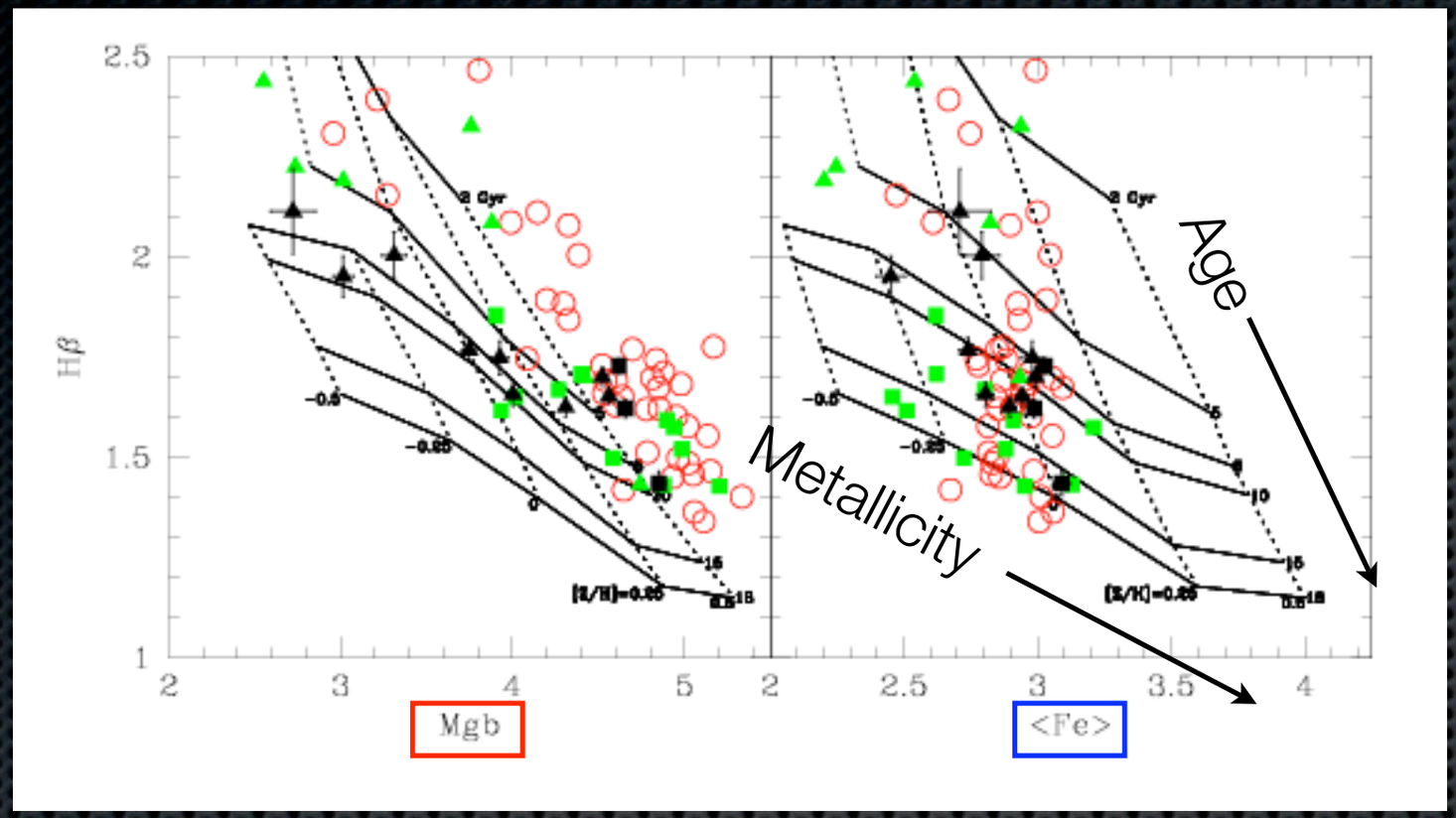


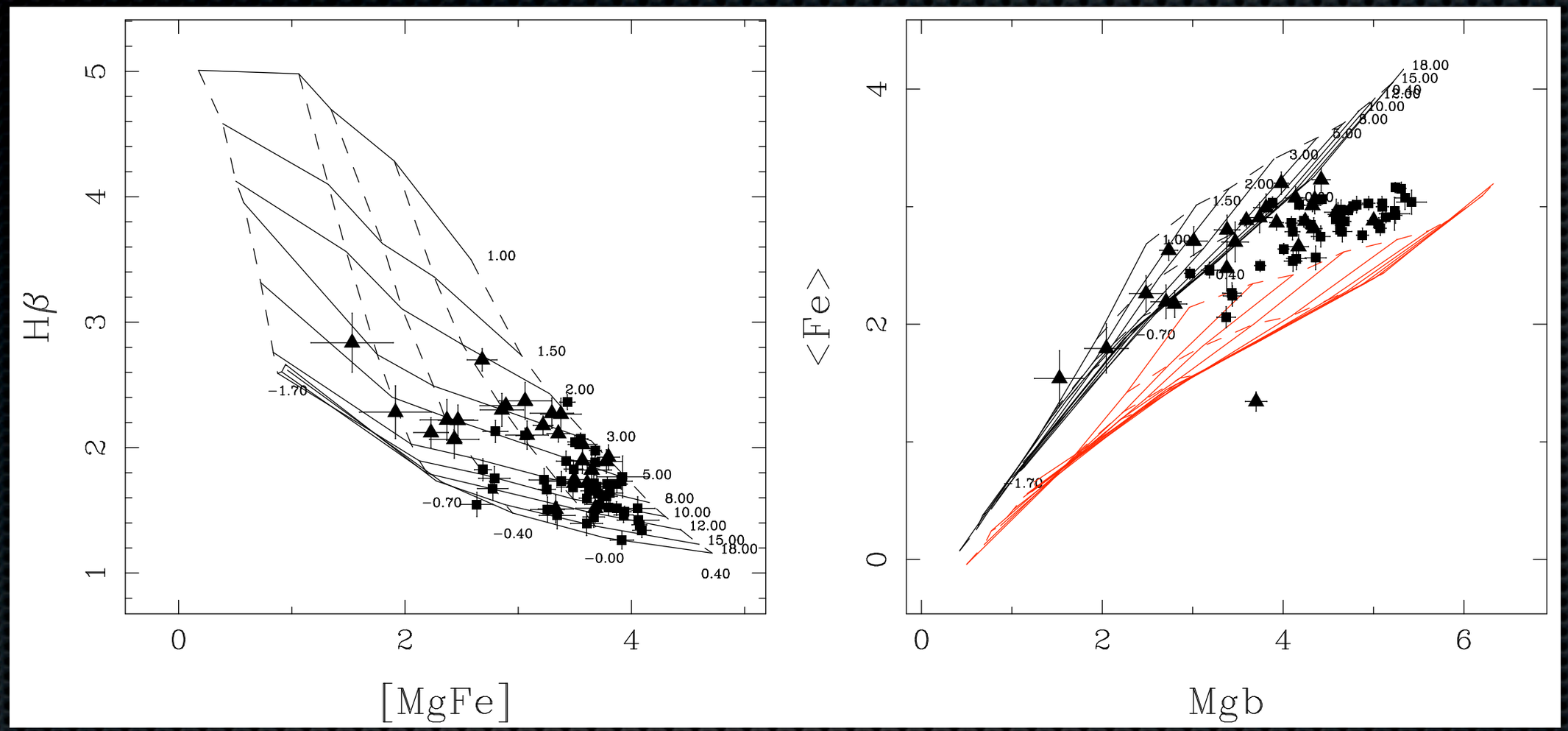
How do we analyze unresolved stellar populations?

- First, build stellar population model
  - Stellar interiors: compute *isochrone* and populate using initial mass function (IMF)
    - theoretical
      - be sure to include mass loss!
    - calibrate using globular and open clusters
  - Stellar atmospheres: determine flux distribution and absorption-line strengths
    - mostly empirical (libraries of stellar spectra)



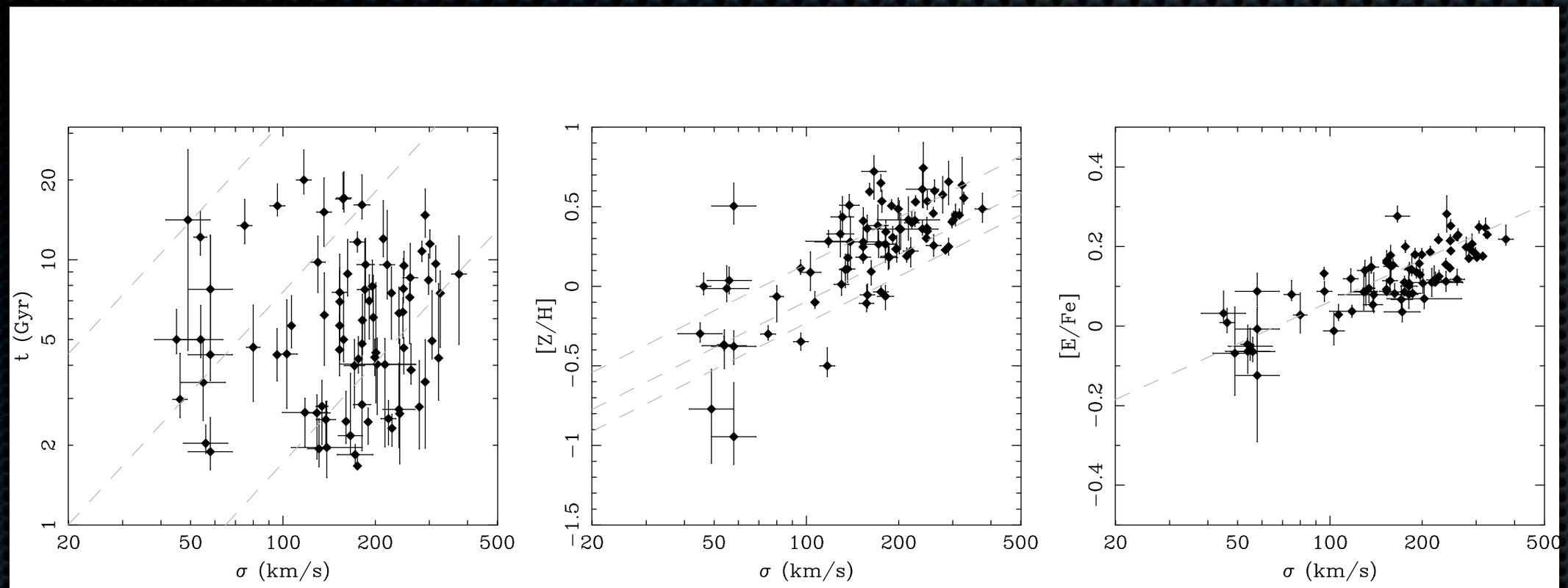
Galaxy data from González93, Fisher+95, Trager+08
Models from Worthey94

- Predict line strengths and compare to observed galaxies
- Note **inconsistency** between stellar populations using different *metal*-line strengths!
  - due to [α/Fe]≠0 in massive early-type galaxies
    - α-elements include Mg, Si, Na, S, and other even-numbered elements



Early-type galaxy data from González93 & Fisher+95, models from Bruzual&Charlot03 & Trager+08

- Can separate out [α/Fe] effect from age and metallicity by combining indexes cleverly (González93, Tantalo+96, Trager+00b, Thomas+03)
  - roughly reflects SNeII/SNeIa ratio: <u>duration of star formation</u>



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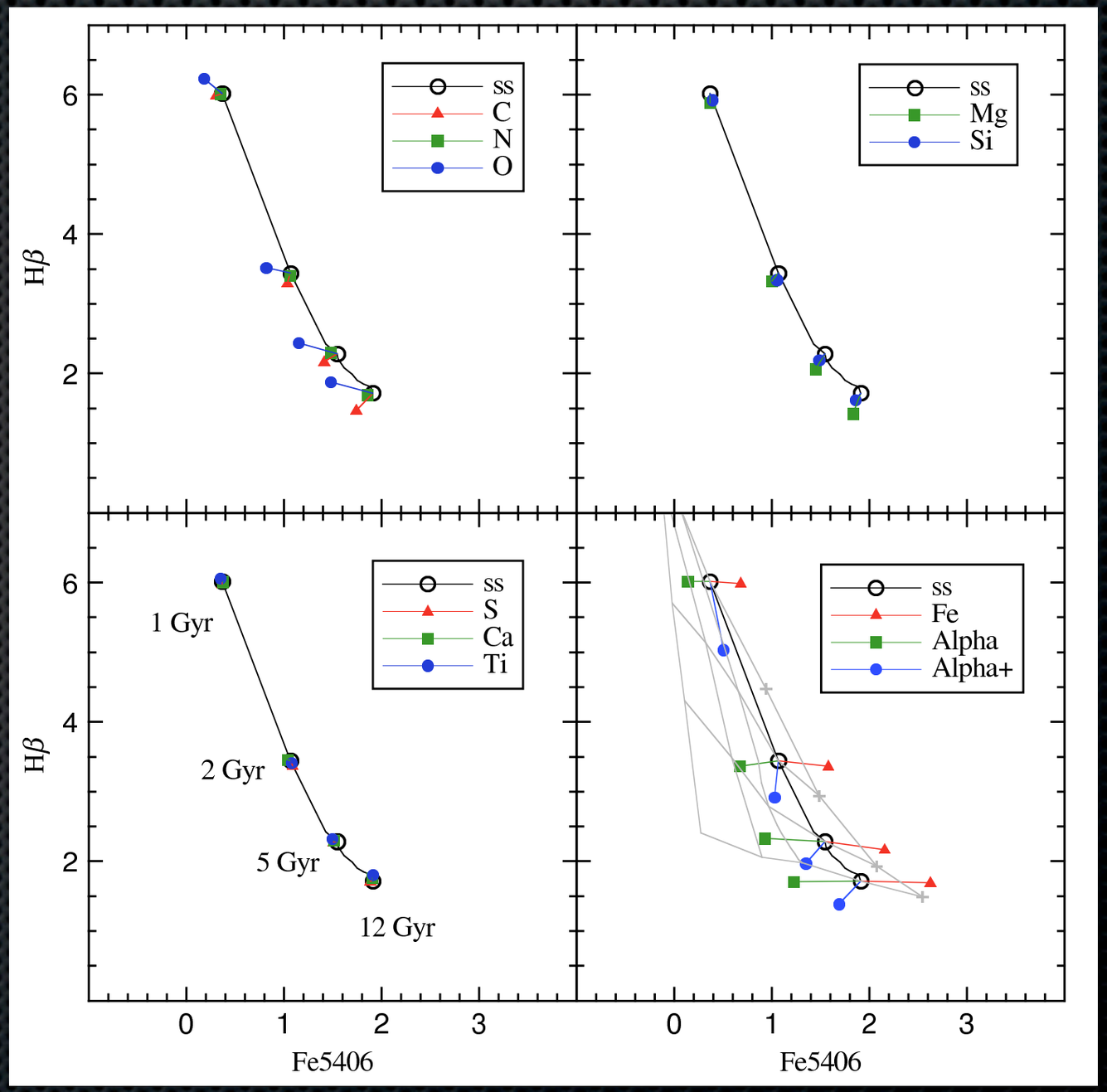
- SSP models with [α/Fe]≠0 are now a big industry
  - Trager+ (2000a): Worthey (1994) models + Tripicco & Bell (1995) -- only three stars with [α/Fe]≠0, scaled-solar isochrones
  - Thomas+ (2005): Maraston (2005) models + Korn+ (2005) -- three stars with [α/Fe]≠0 *per metallicity*, scaled-solar isochrones
  - Schiavon (2007): scaled-solar *or* [α/Fe]≠0 isochrones*, three stars with [α/Fe]≠0 *per metallicity* (Korn+05); **also allows** [X/Fe] ≠0
  - Coelho+ (2007): new [α/Fe]≠0 evolutionary tracks + new [α/Fe]≠0 synthetic spectra at *each isochrone point* (but not fully calibrated yet)

- Dotter+ (2007) + Lee+ (2008): *fully self-consistent* stellar interiors+atmospheres with any of 11 elemental mixes, based on deviations from empirical stellar spectra
  - **but** only solar metallicity so far,
  - and only indices

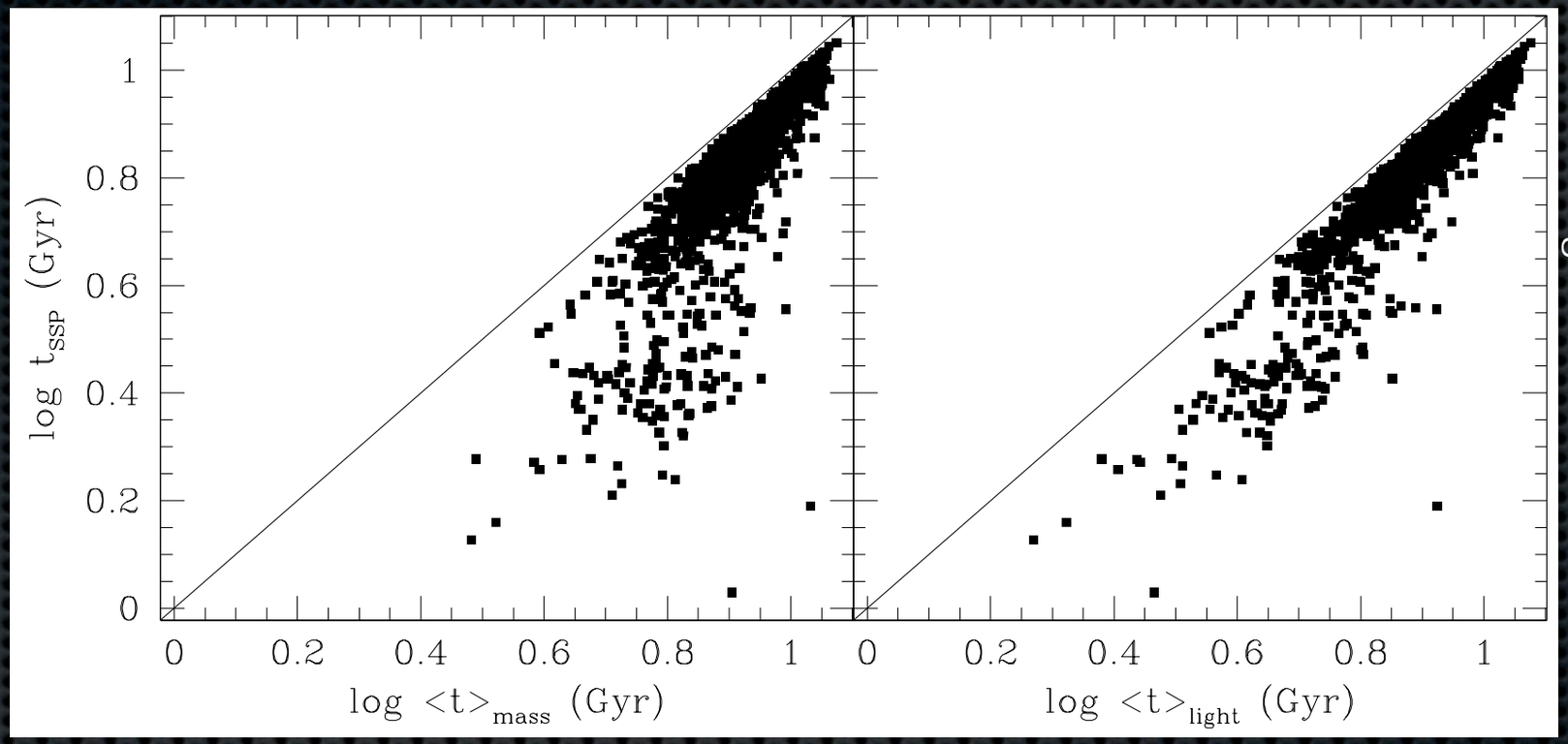


Lee+ (2008)

Caveats

- Note that “ages”, “metallicities” and “enhancement ratios” are *line-strength-weighted* quantities
- We compute these parameters **assuming** the population is a **single-burst stellar population**
  - Our parameters are therefore “SSP-equivalent” parameters
- Trager & Somerville (2009) use **semi-analytic models** (Somerville+08) to generate **mock line-strength catalogs** to understand the properties of these SSP-equivalent parameters

What do SSP-equivalent ages represent?



Trager&Somerville09

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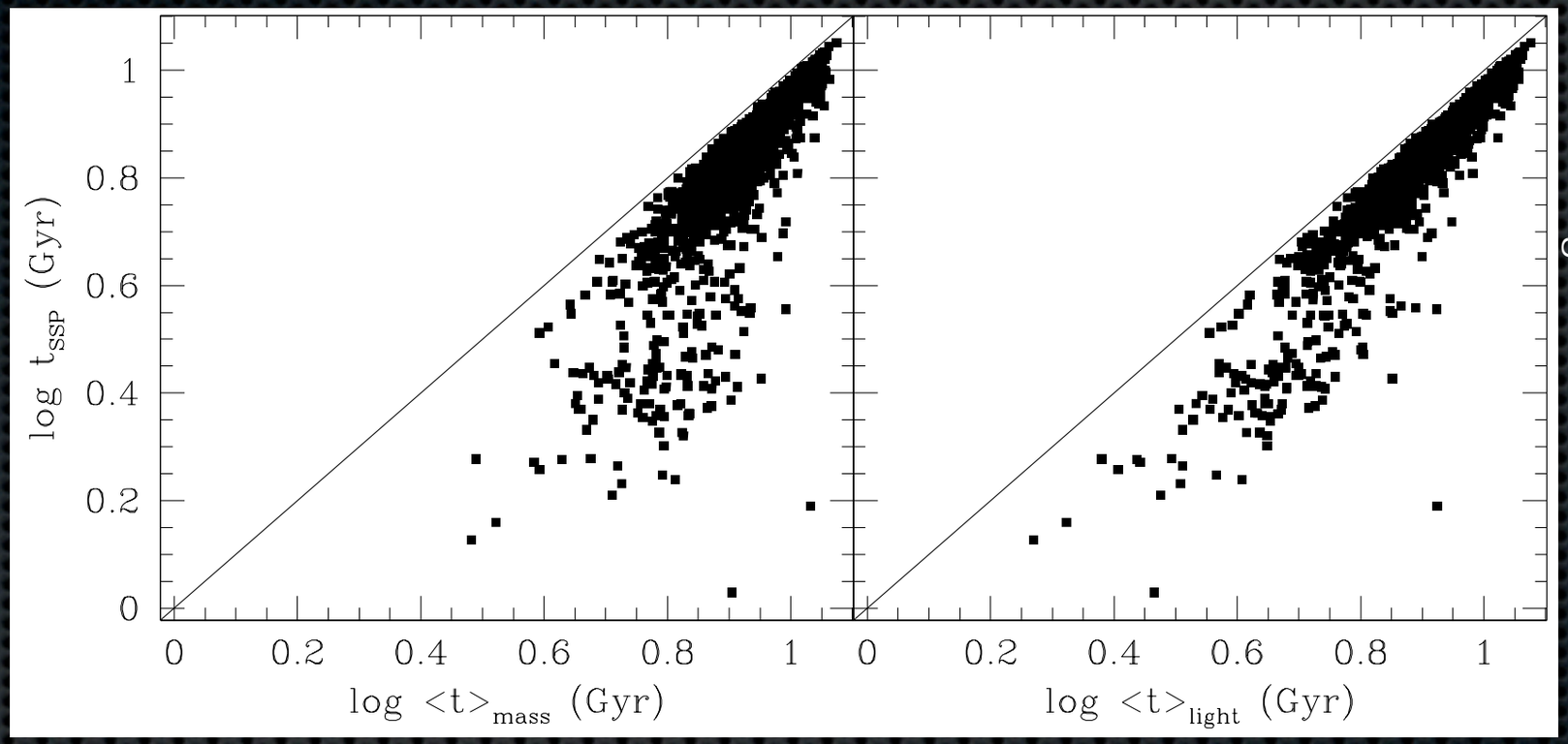
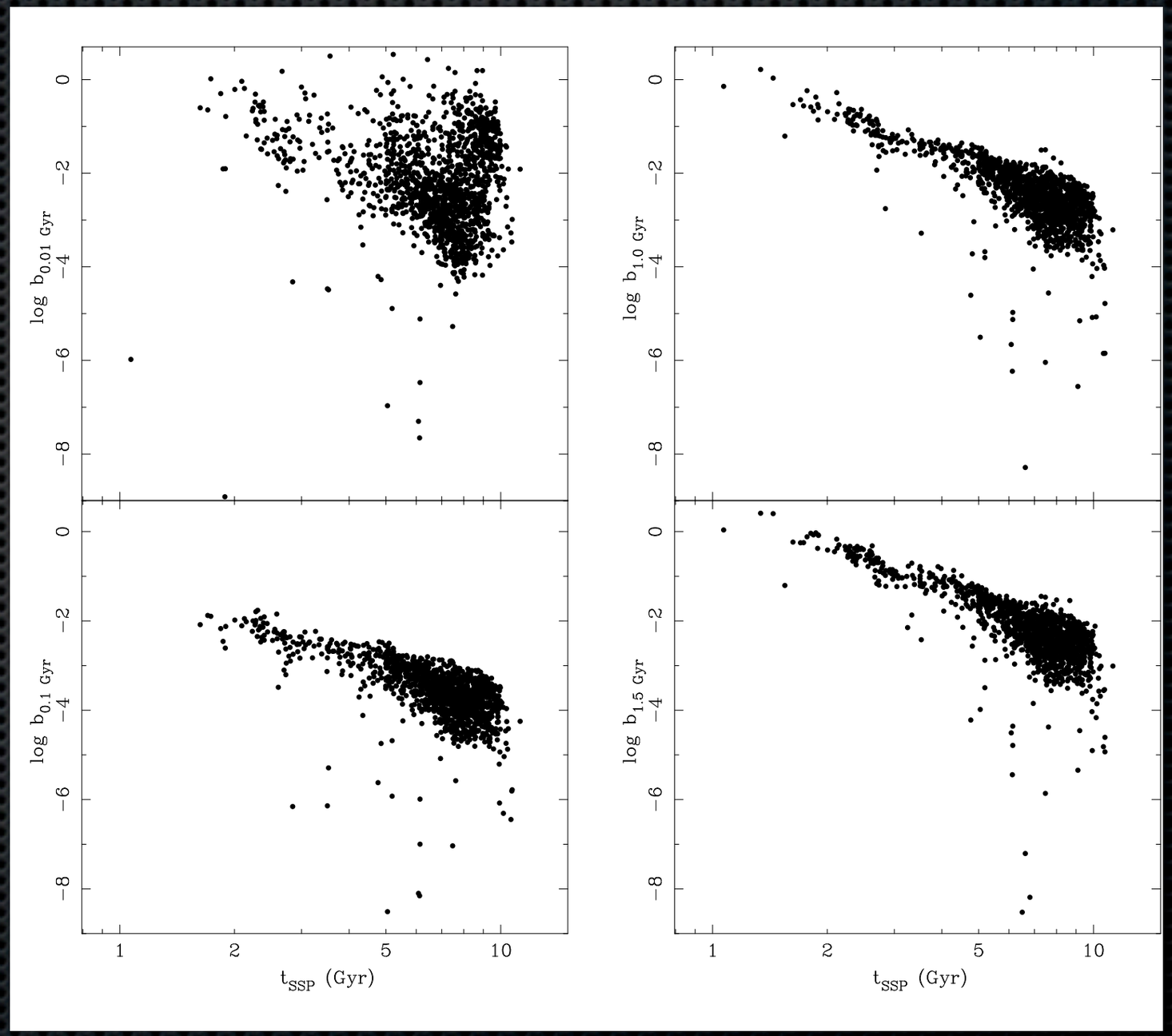


Trager&Somerville09

- SSP-equivalent age poorly correlated with mass- **and** light-weighted ages (in early-type galaxies)

- SSP-equivalent age correlates best with **birthrate** of stars in last 0.1-2 Gyr



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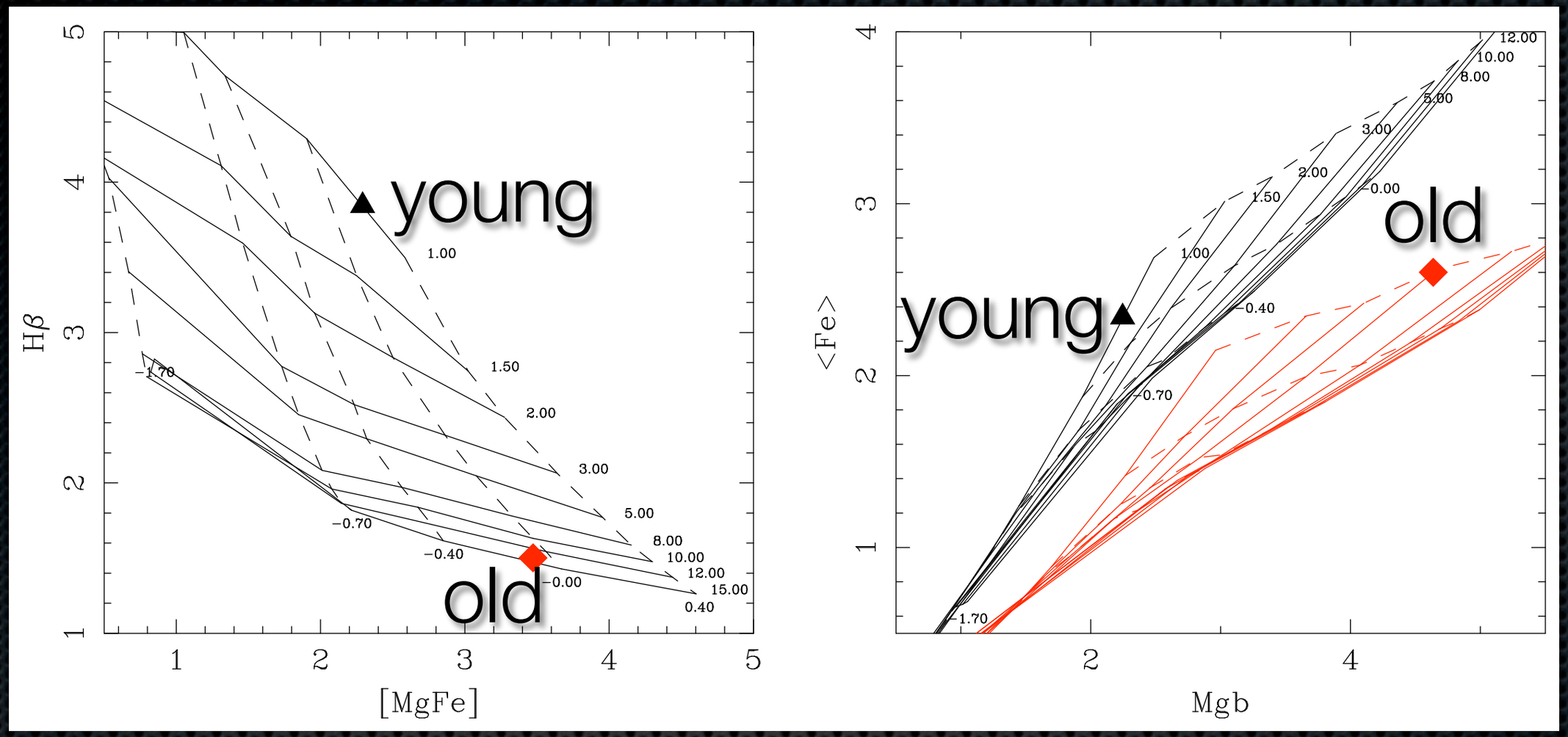
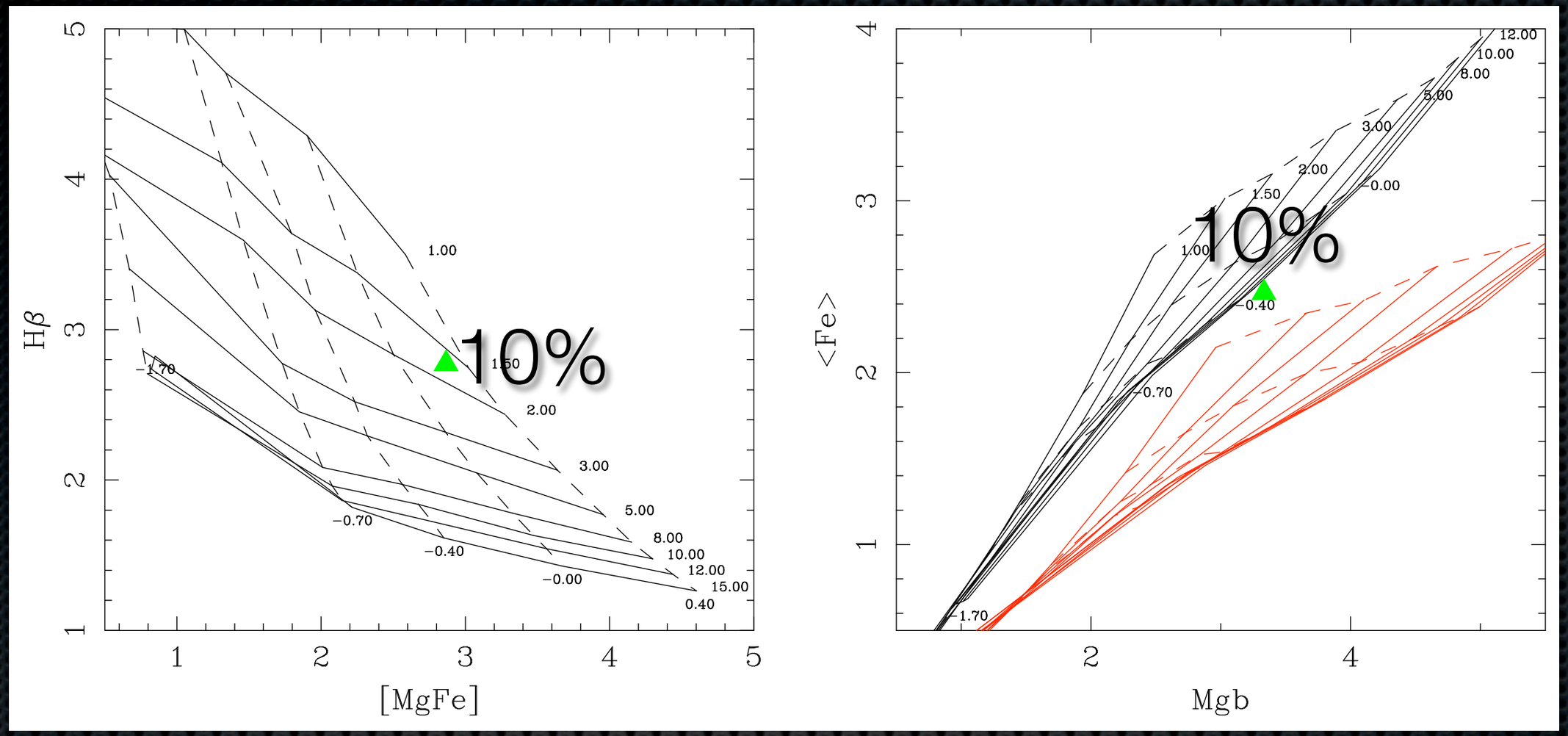


- Reason is simple:
  - Late **bursts** of star formation (RSF=residual star formation) make Hβ ages *much* **younger** than 'true' mass-weighted ages (see Trager+00b, Serra & Trager07)



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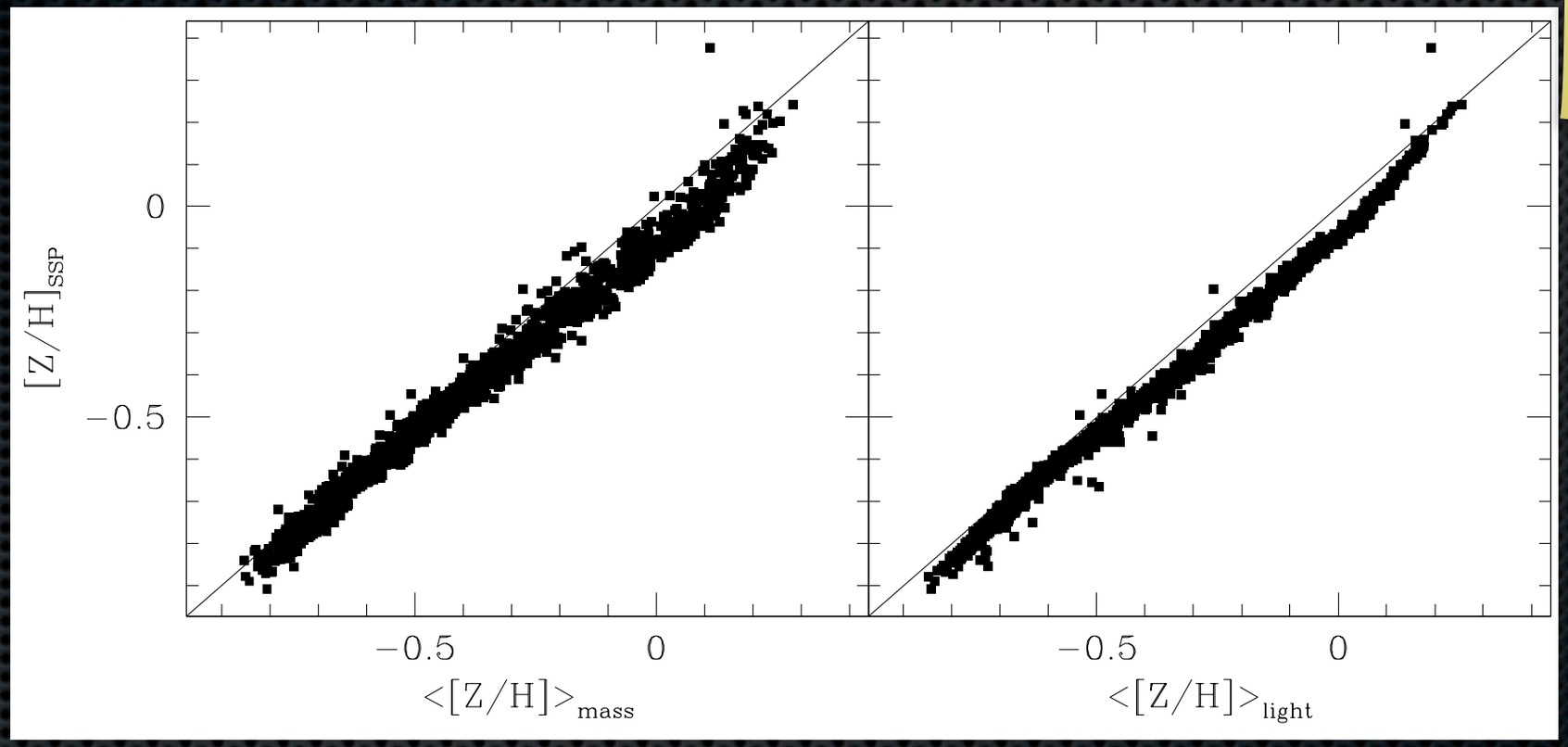
What do SSP-equivalent metallicities represent?

note slight offset due to metal-poor stars contributing more to indices than to light



Trager&Somerville09

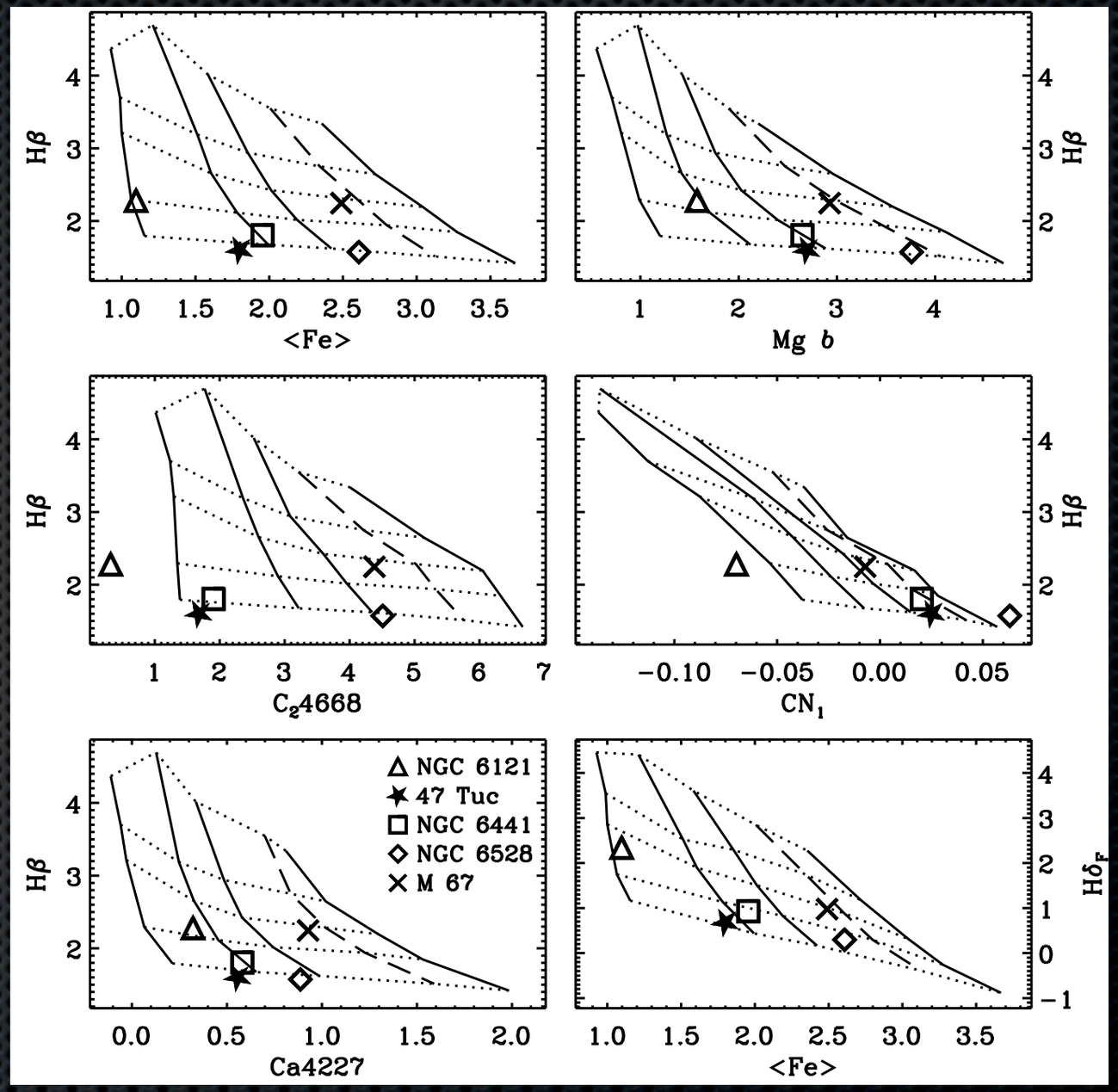
- SSP-equivalent metallicity is basically equivalent to mass- or light-weighted metallicity

Calibration of stellar population models

- Ricardo Schiavon and his collaborators have pushed *very* hard to calibrate SSP models using globular and open cluster spectra
  - Schiavon+ 2002a,b; Schiavon 2007; Graves & Schiavon 2008
  - thanks Ricardo!

- Some rules of thumb for constructing and calibrating SSP models from Schiavon's work:
  - Use the same isochrones for SSP models as used for measuring ages of clusters
  - Make sure the LFs of the observed and model RGB and AGB match (e.g., check mass loss!)
  - Make sure the atmospheric parameters of the stellar library are **homogeneous** and cover the appropriate part of (T_{eff}, log *g*, [Fe/H]) space
    - If possible, make sure CN weak/strong stars properly represented as well

- Calibration of Schiavon07 models by Graves & Schiavon (2008)
  - Only significant problem is NGC 6121, which has strong BHB
  - *Be careful* with models at [Fe/H]<-1!
    - cf. Maraston & Thomas (2000), Trager+ (2005)



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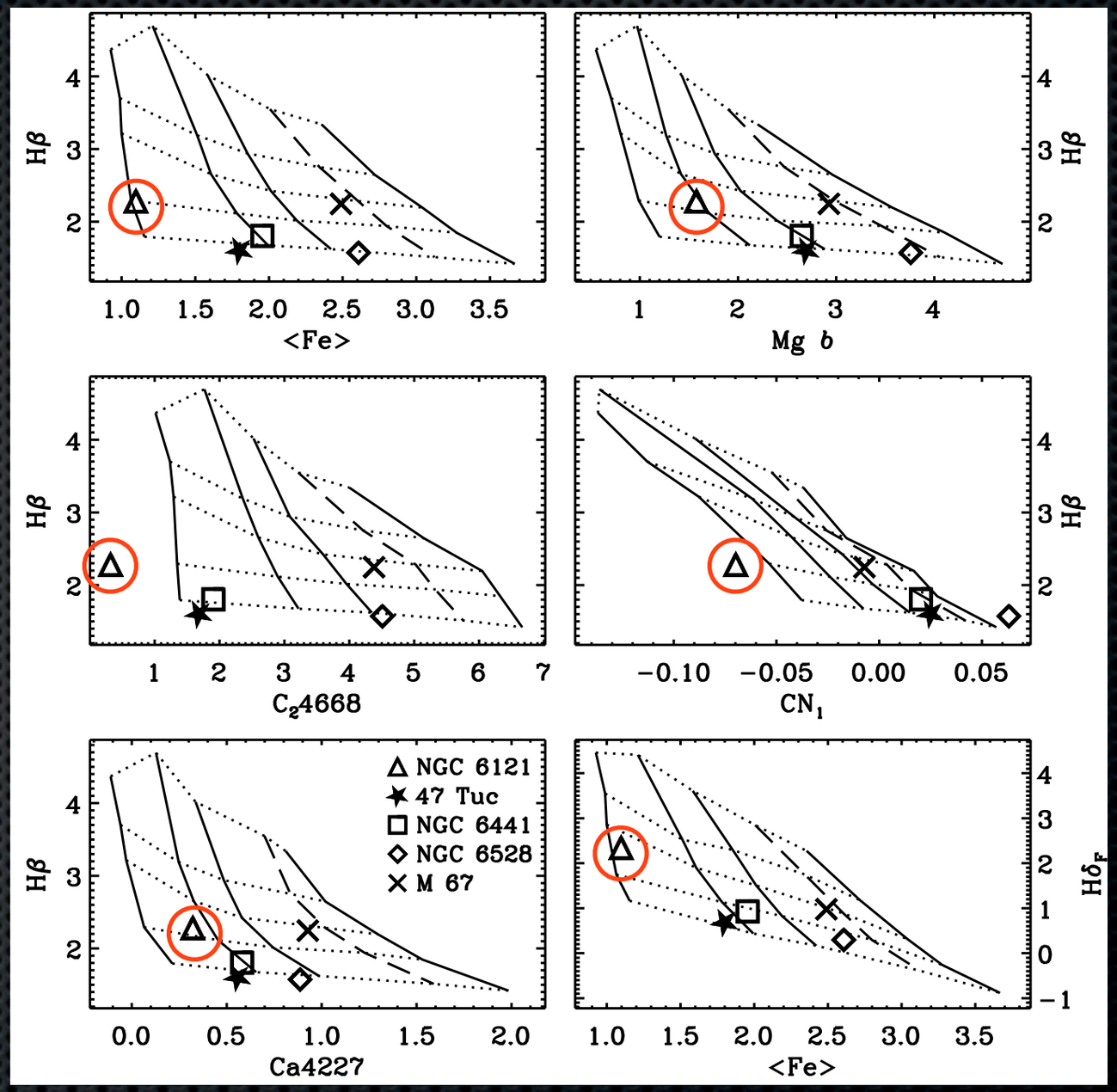
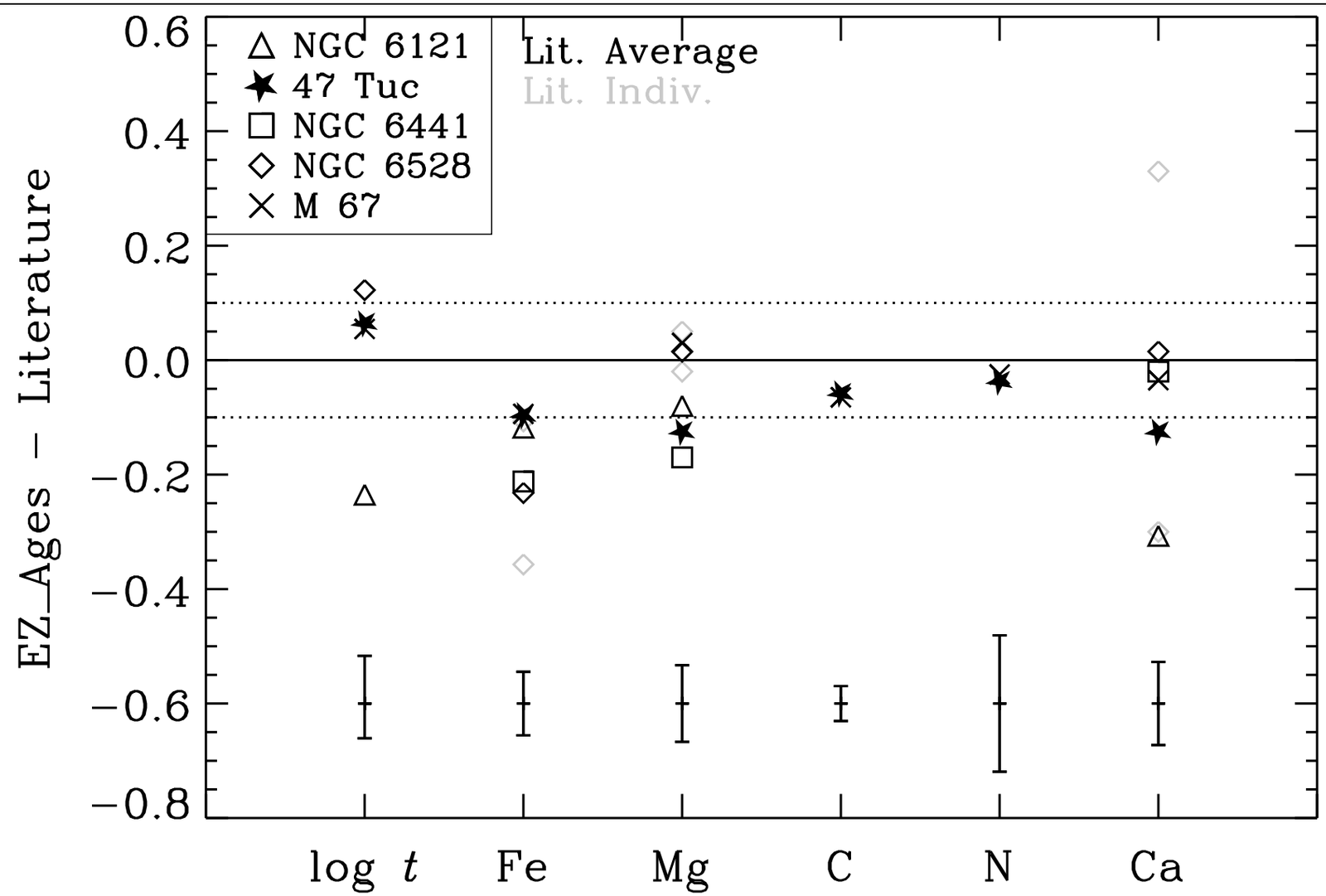


Graves & Schiavon (2008)

TABLE 3

EZ_Ages Cluster Abundances Compared to Literature

Cluster	Source	Age[a]	[Fe/H]	[Mg/Fe]	[C/Fe]	[N/Fe]	[Ca/Fe]	Reference
NGC 6121	EZ_Ages	$7.6^{+0.8}_{-0.7}$	-1.30 ± 0.09	$+0.36 \pm 0.11$	-0.12 ± 0.02	0.15 ± 0.15	-0.05 ± 0.10	...
	Literature	13[b]	-1.18 ± 0.00	$+0.44 \pm 0.02$	...	...	$+0.26 \pm 0.02$	1, 2
47 Tuc	EZ_Ages	$13.9^{+\max c}_{-3.0}$	-0.80 ± 0.09	$+0.28 \pm 0.05$	-0.16 ± 0.03	$+0.66 \pm 0.08$	$+0.08 \pm 0.03$	...
	Literature	12	-0.7 ± 0.05	$+0.4 \pm 0.1$	$-0.2/0.0$[d]	$+1.1/+0.3$[d]	$+0.2 \pm 0.1$	3, 4, 5
NGC 6441	EZ_Ages	$11.5^{+1.9}_{-1.5}$	-0.64 ± 0.07	$+0.17 \pm 0.08$	-0.20 ± 0.05	$+0.54 \pm 0.13$	$+0.01 \pm 0.08$	...
	Literature	...	-0.43 ± 0.08	$+0.34 \pm 0.09$	...	...	$+0.03 \pm 0.04$	6
NGC 6528	EZ_Ages	$14.6^{+\max c}_{-2.0}$	-0.26 ± 0.06	$+0.12 \pm 0.06$	-0.04 ± 0.04	$+0.31 \pm 0.08$	-0.07 ± 0.05	...
	Literature	11	$-0.15/+0.1$[e]	$+0.07/+0.14$[e]	...	...	$-0.40/+0.23$[e]	7, 8, 9, 10
M67	EZ_Ages	$4.0^{+1.0}_{-0.58}$	-0.09 ± 0.05	0.03 ± 0.05	-0.07 ± 0.03	-0.01 ± 0.05	-0.03 ± 0.07	...
	Literature	3.5	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.1	11, 12, 13



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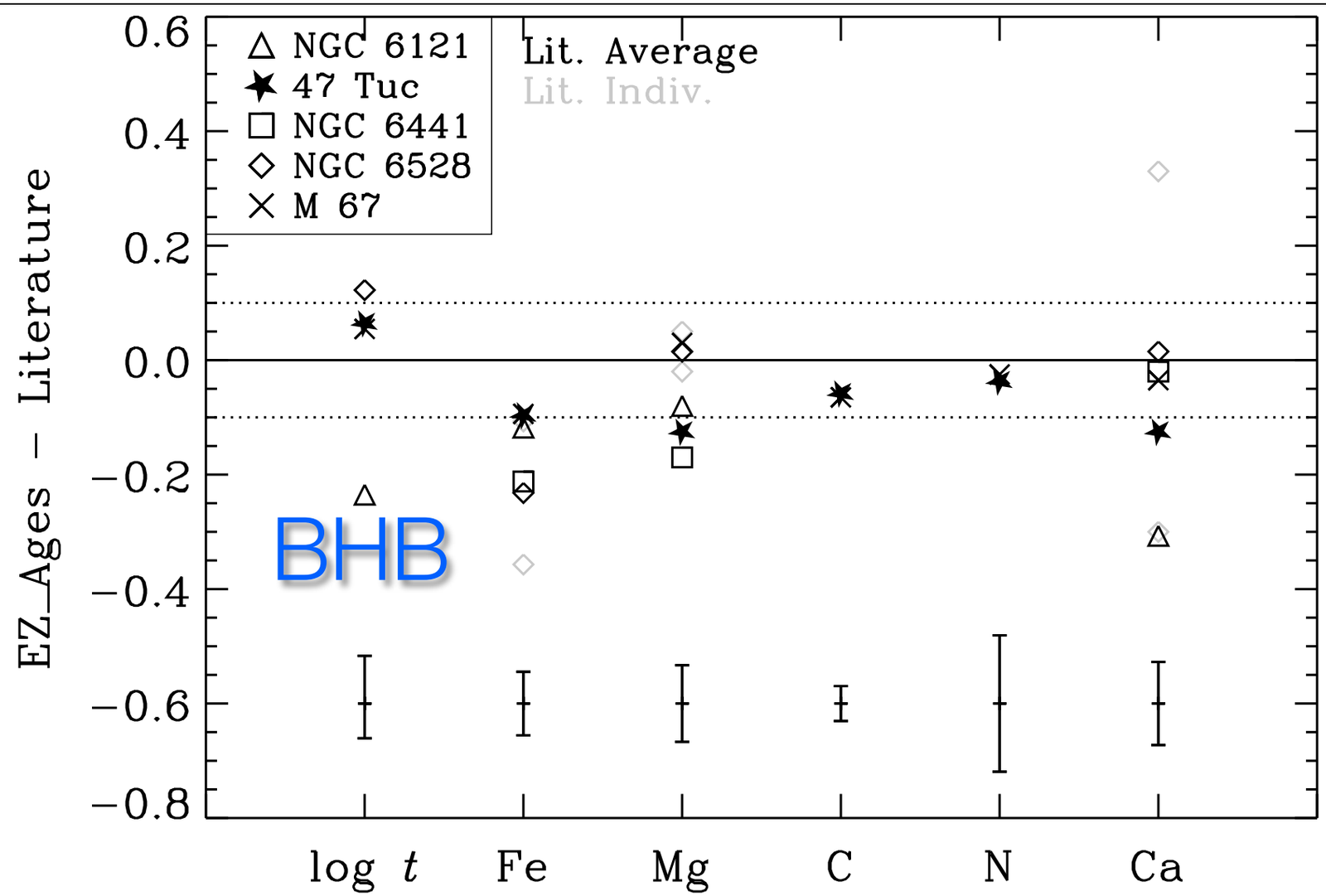


Graves & Schiavon (2008)

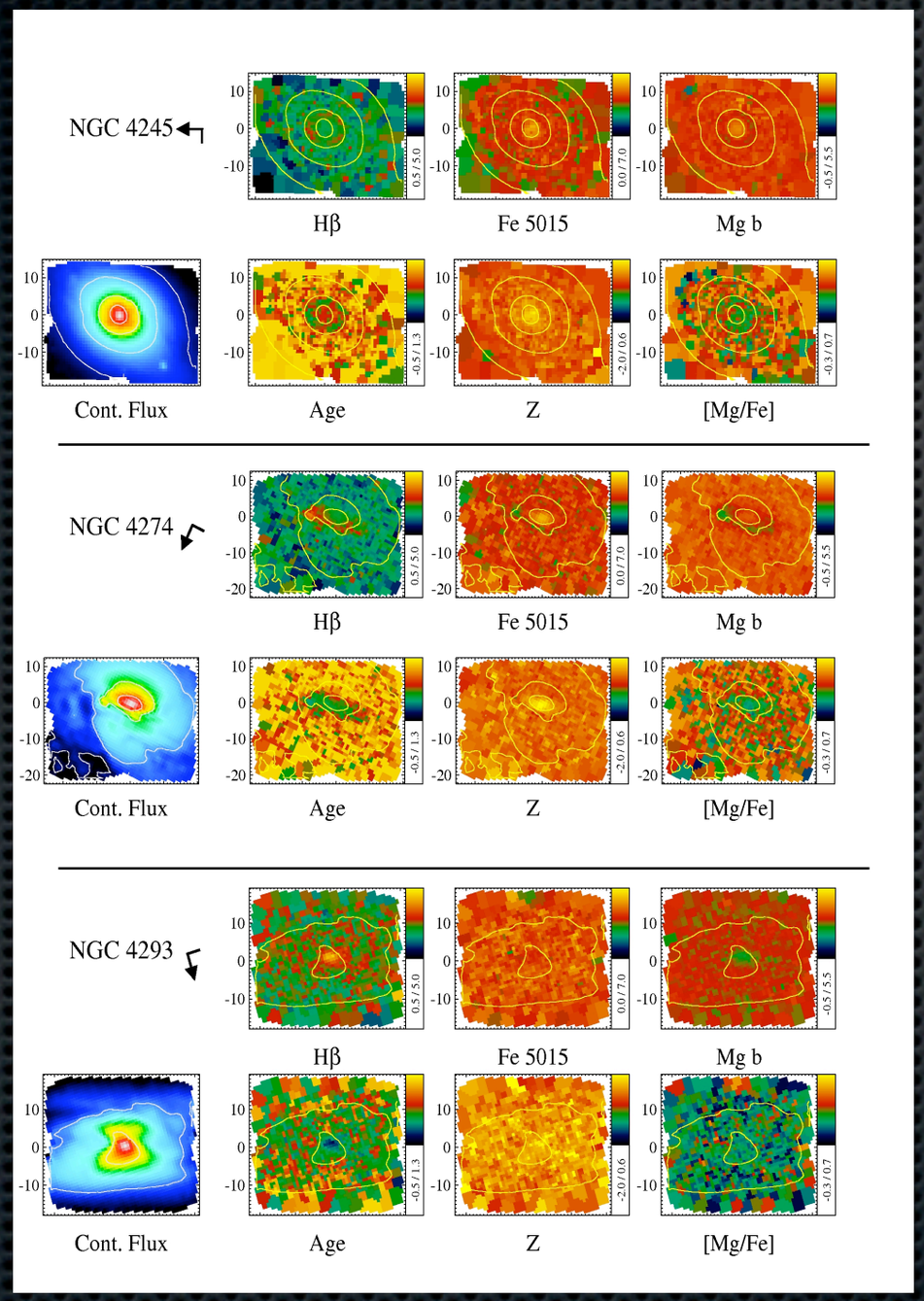
The stellar populations of spiral galaxy bulges

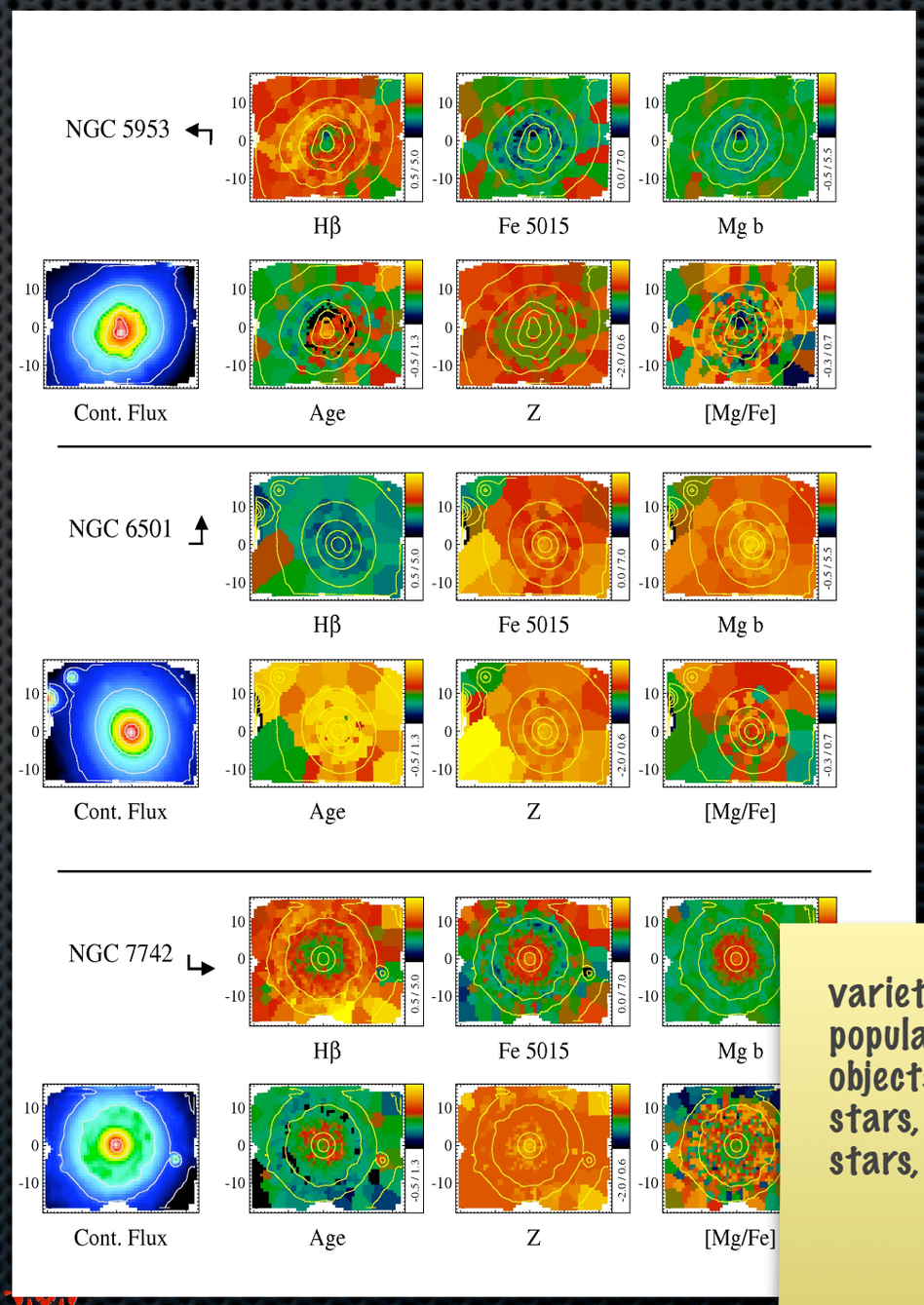
- Lots of studies in this decade:
  - Proctor & Sansom (2002), reanalyzed by Thomas & Davies (2005): edge-on early-type spirals
  - Moorthy & Holtzman (2006): S0-Sc bulges, variety of inclinations
  - Jablonka, Gorgas & Goudfrooij (2007): edge-on S0-Sc spirals
  - **Peletier+ (2007)**: Sa bulges, variety of inclinations
  - **Ganda+ (2007)**: Sb-Sd bulges, mildly inclined
  - Morelli+ (2008): face-on early-type cluster spirals
  - **MacArthur, González & Courteau (2009)**: face-on late-type bulges

Peletier+07: SAURON bulges (Sa)

- 24 Sa galaxies with a variety of inclinations taken with the Integral Field Spectrograph SAURON
  - gives MAPS of line strengths (and emission lines and kinematics, too)
  - can be interpreted as MAPS of SSP-equivalent parameters

A sample of SAURON Sa's



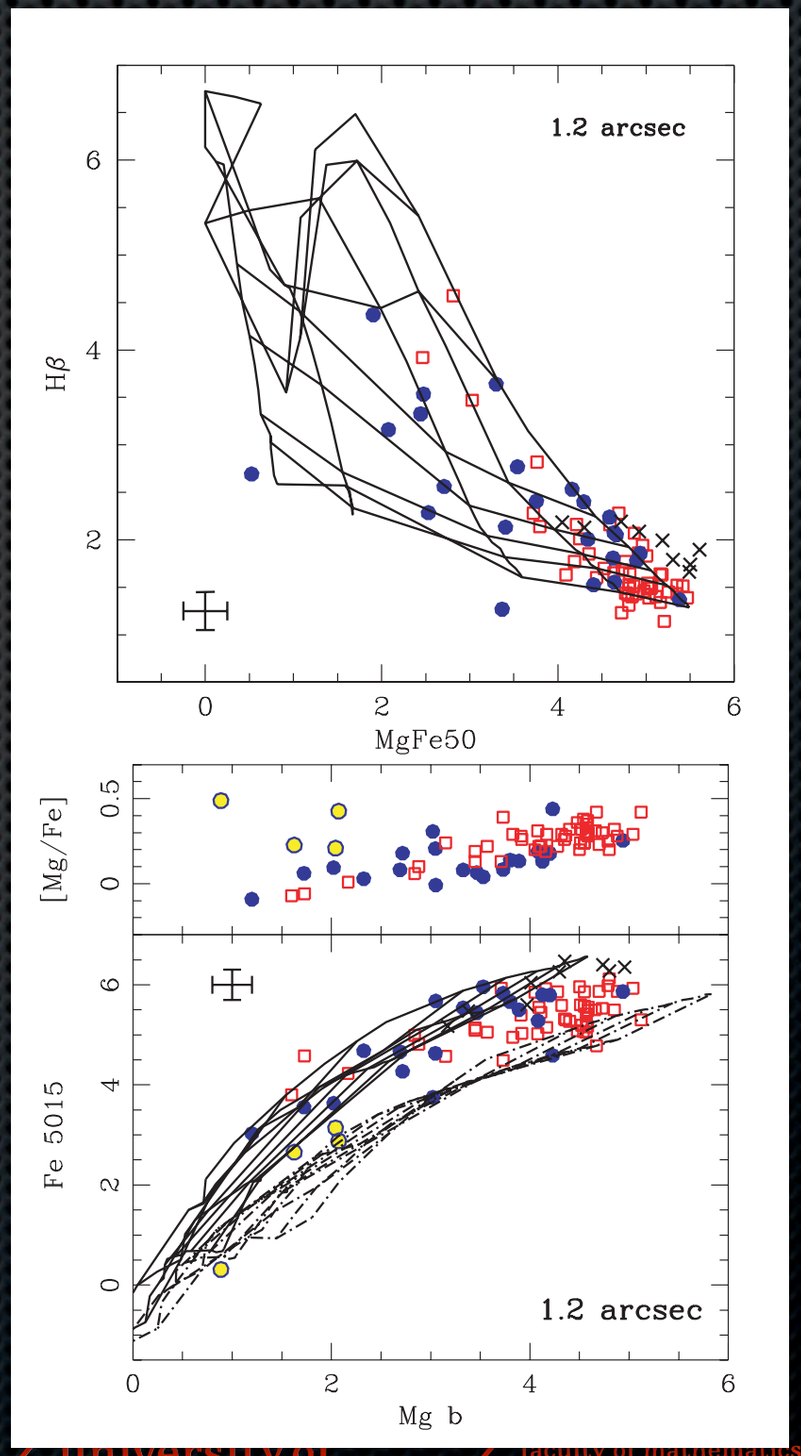


Peletier+07

variety of stellar populations: smoothly old objects, peaked young stars, peaked peaked OLD stars, rings of SF, etc.

Central populations of Sa's

- Sa's are generally younger, more metal-poor, and less α-enhanced than E/S0s
- **but** similar metallicities and [α/Fe] as E/S0s **of same σ** (cf. Thomas & Davies 05)
  - larger scatter in SSP-equivalent age, young populations *common*
- Some galaxies difficult to fit with SSPs



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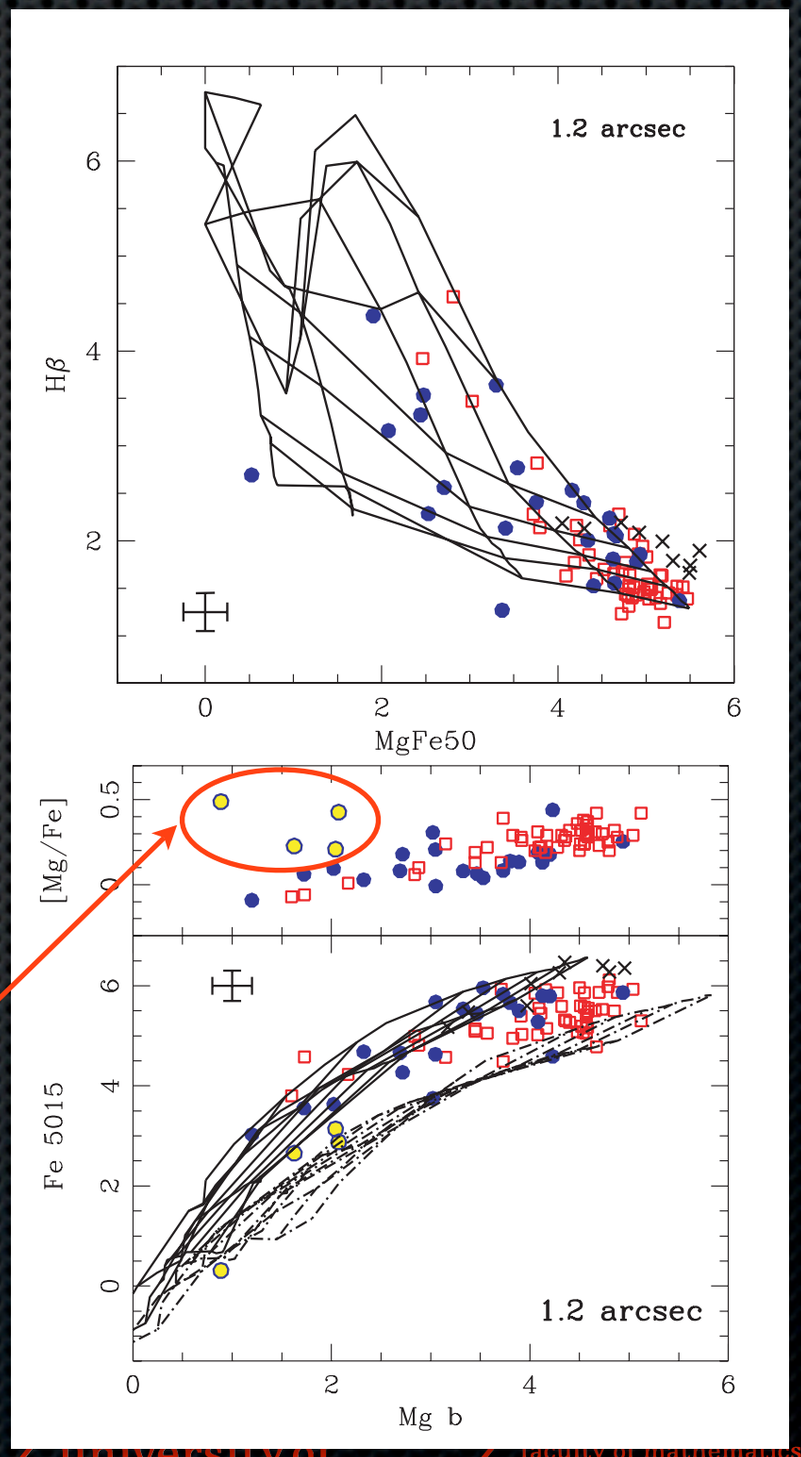
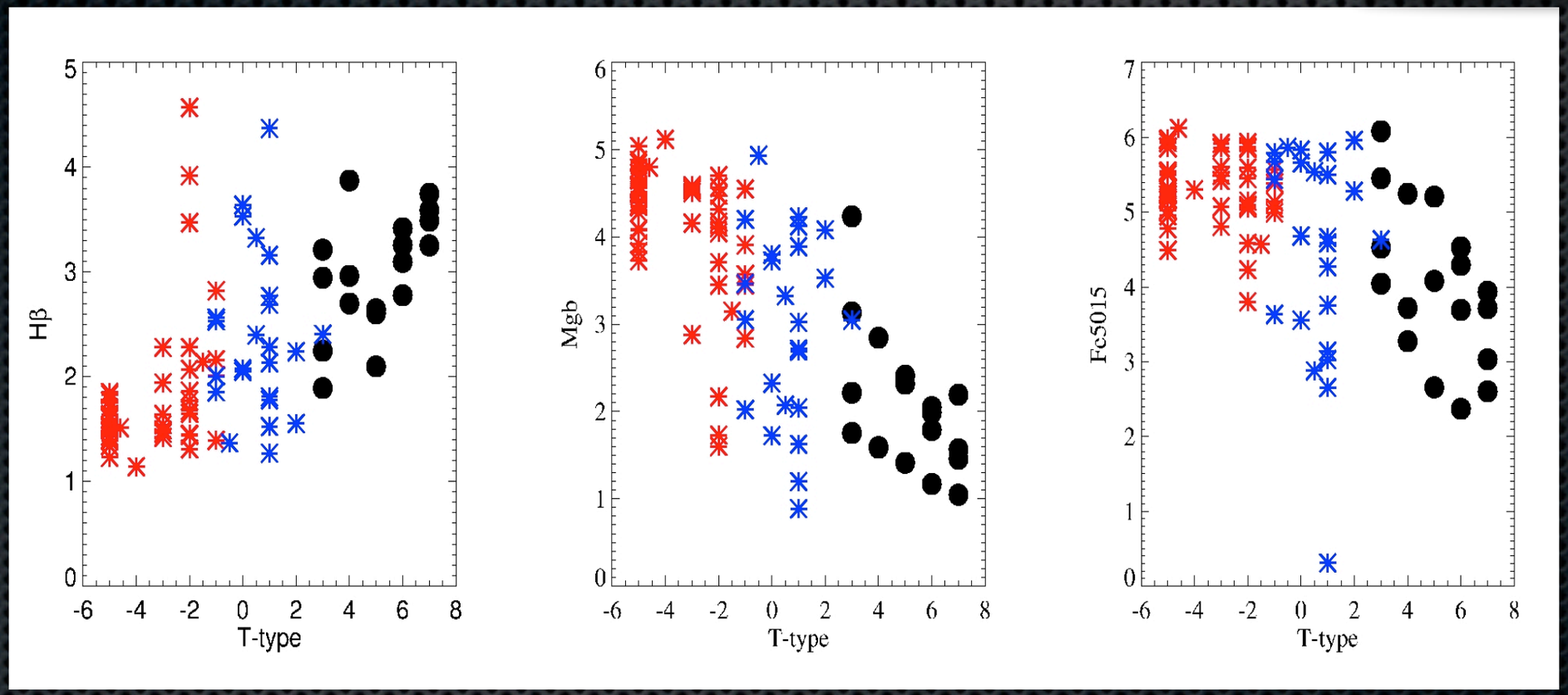


Peletier+07

- So what is going here?
- *Highly-inclined* (edge-on) samples like Falcón-Barroso+ (2002), Jablonka+ (2007) show **older** populations in (outer) bulges than *face-on* samples (cf. Peletier & Balcells 1996)
  - seen (roughly) directly in Peletier+ sample, which has both face-on and (nearly) edge-on galaxies
  - seems to imply **disk** contamination in even *early-type* bulges
    - this may be too simplistic: need at least multiple populations, with young populations confined ~ to disk scale height

Ganda+07: SAURON "bulges" (Sb-Sd)

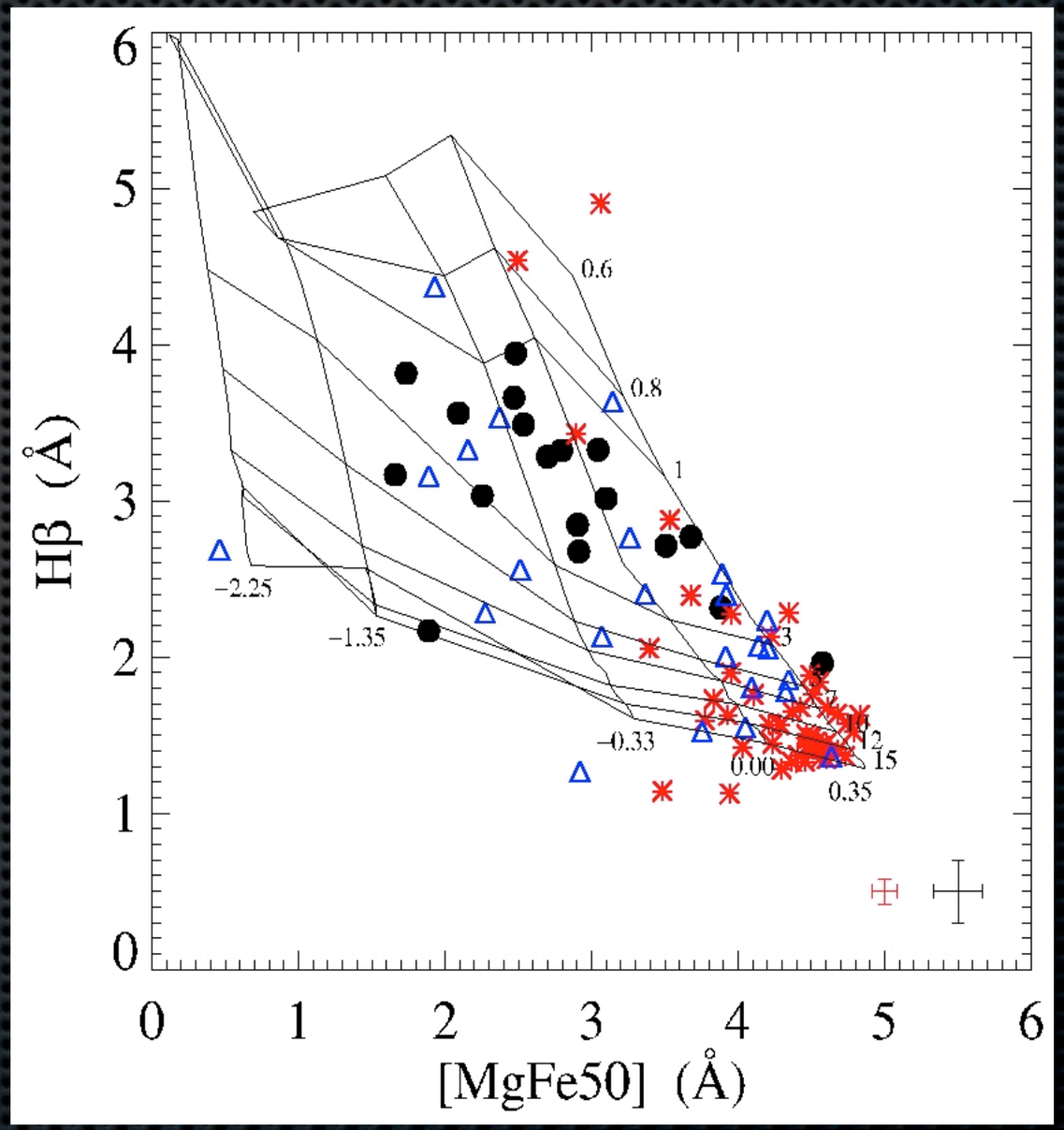
red: SAURON E/S0s
blue: SAURON Sa's
black: SAURON late-types



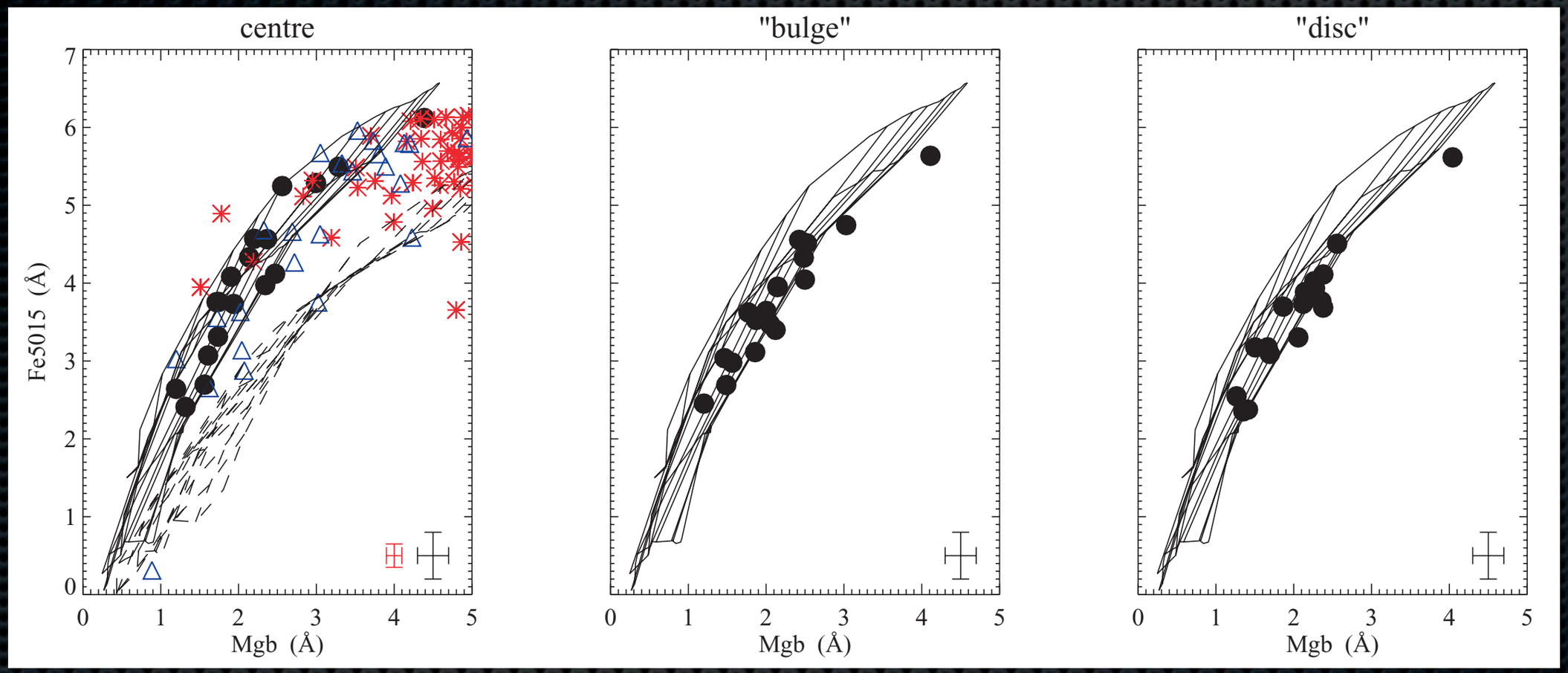
Ganda+ (2007)

- Ganda+ (2007) find that centers of late-type spirals are younger and more metal-poor than the centers of early-type galaxies

- Interestingly, **scatter** in SSP-equivalent parameters *smaller* in centers of late-type spirals
  - much more disk contamination? or more “gentle” SF processes?



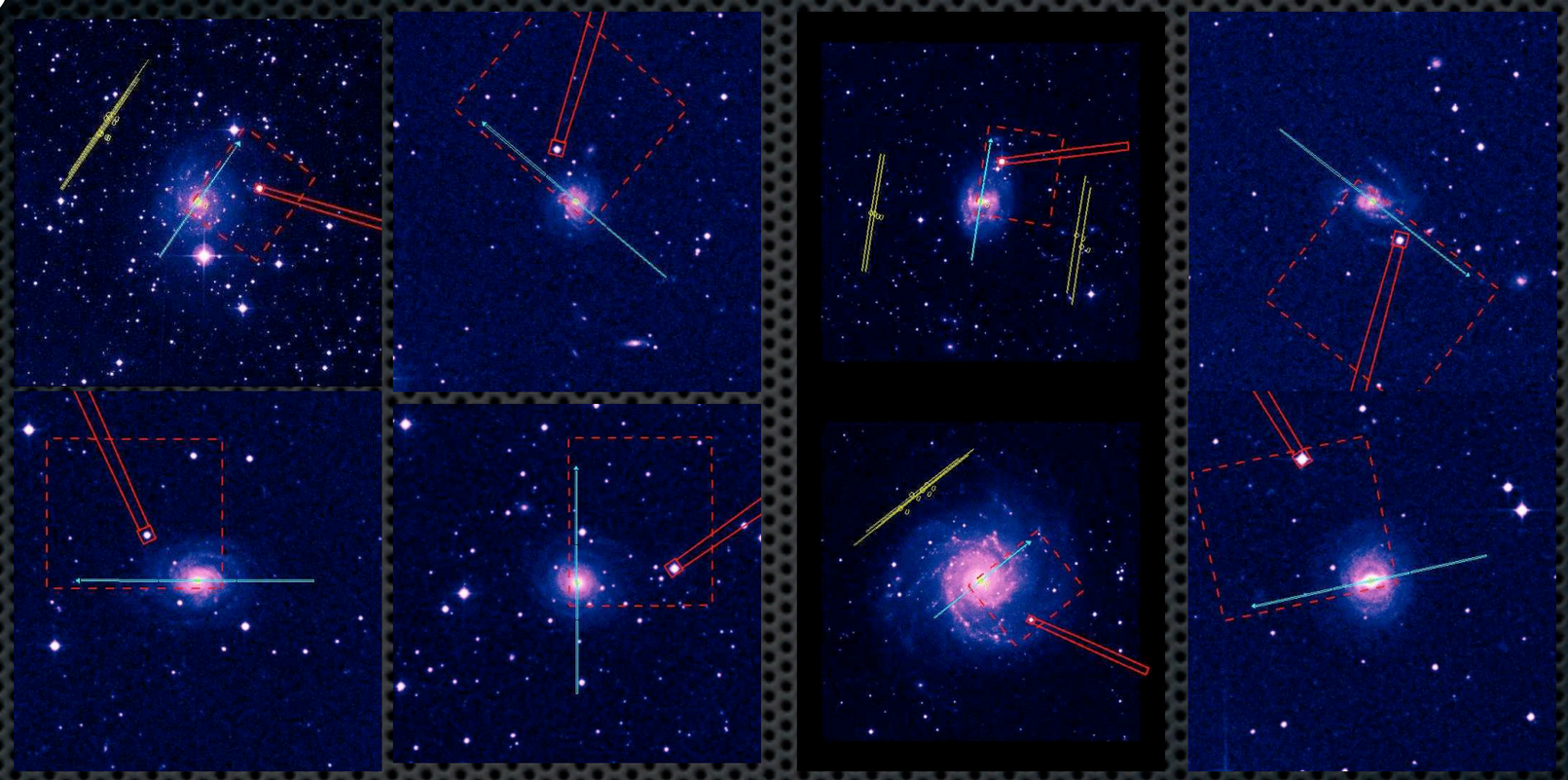
Gandolfi+ (2007)



Ganda+ (2007)

- [α/Fe]~0 for nearly all late-type spirals, (almost) independent of position in galaxy

MacArthur+09: GEMINI bulges

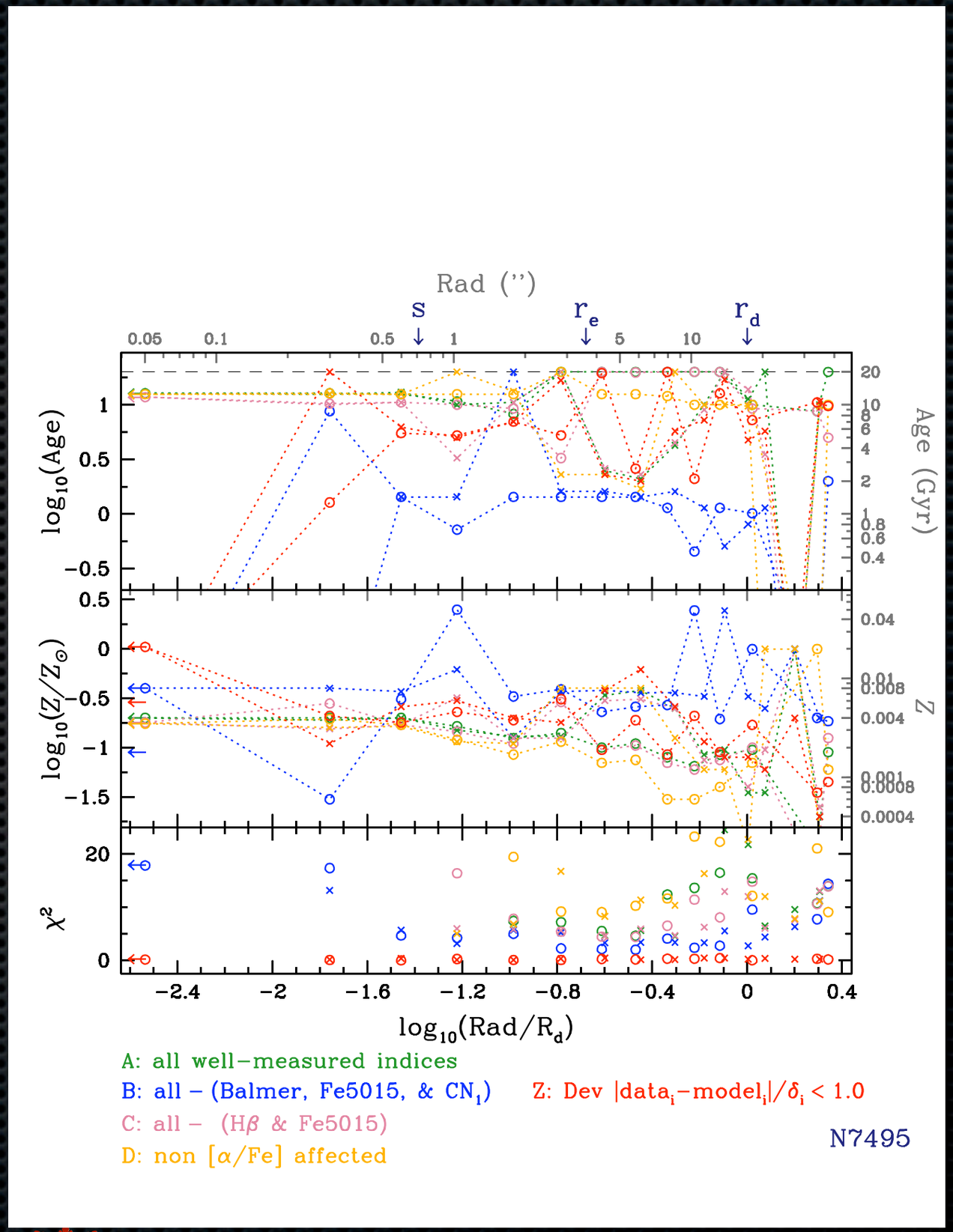


MacArthur+09

- 8 face-on, mostly Sc galaxies taken with GMOS
  - exceptionally high S/N in bulge, long wavelength range

MacArthur+09

- MacArthur+ attempted to fit SSPs to their data and were unimpressed with the results...
  - using line strengths (from BC03)
    - gradients were strongly dependent on exact lines used
  - using (BC03) spectra
    - poor fits and highly age-metallicity degenerate



MacArthur+09

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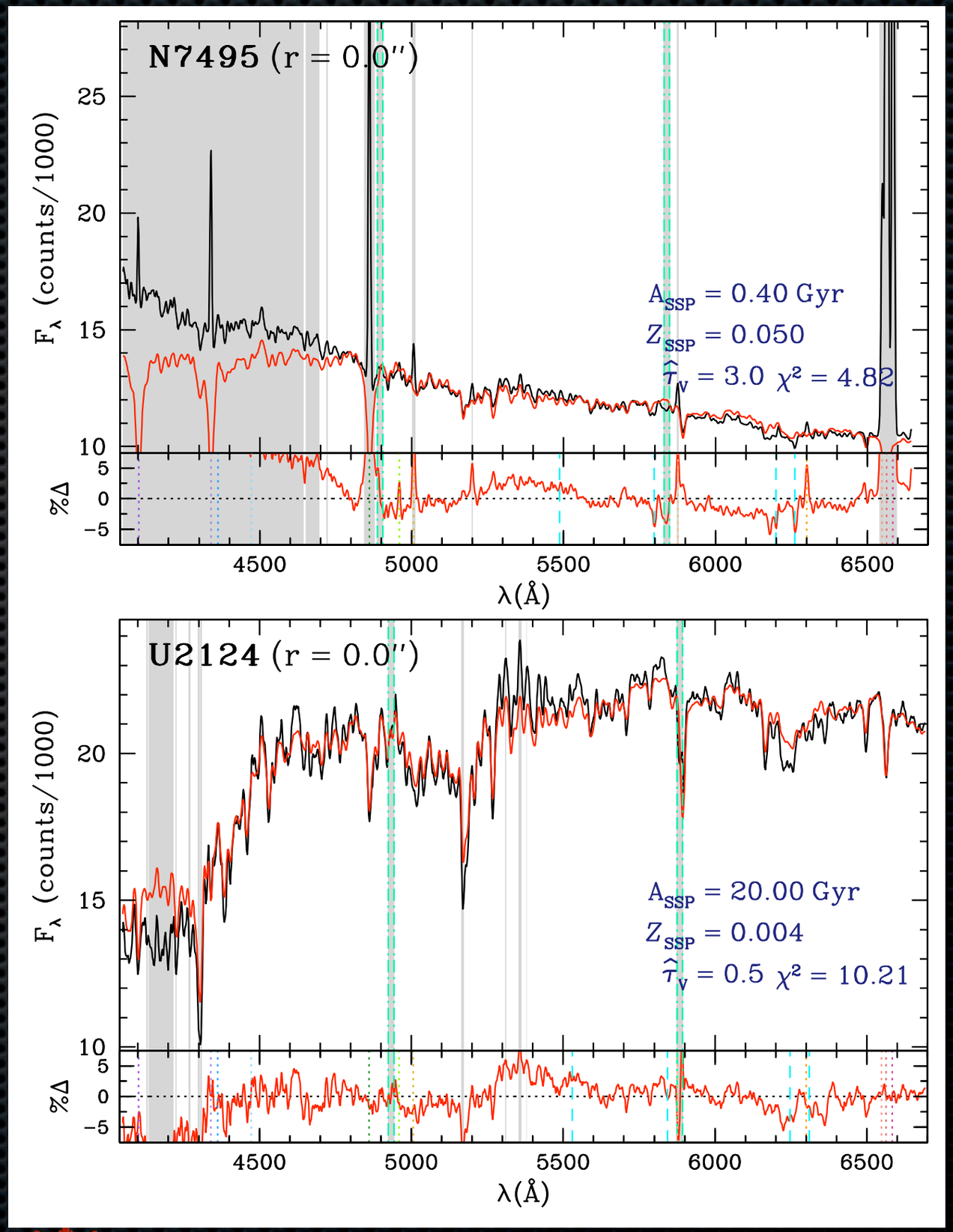
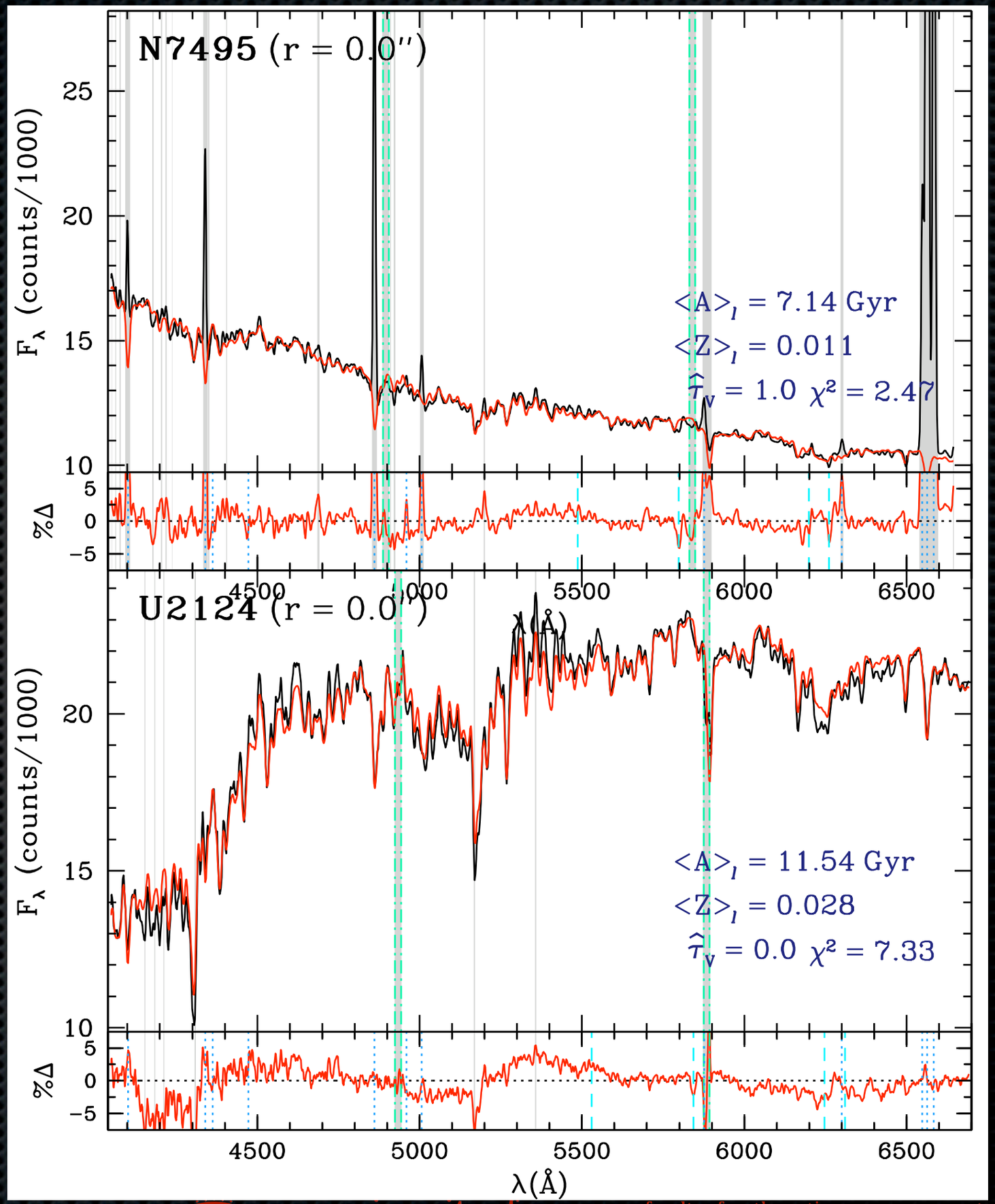
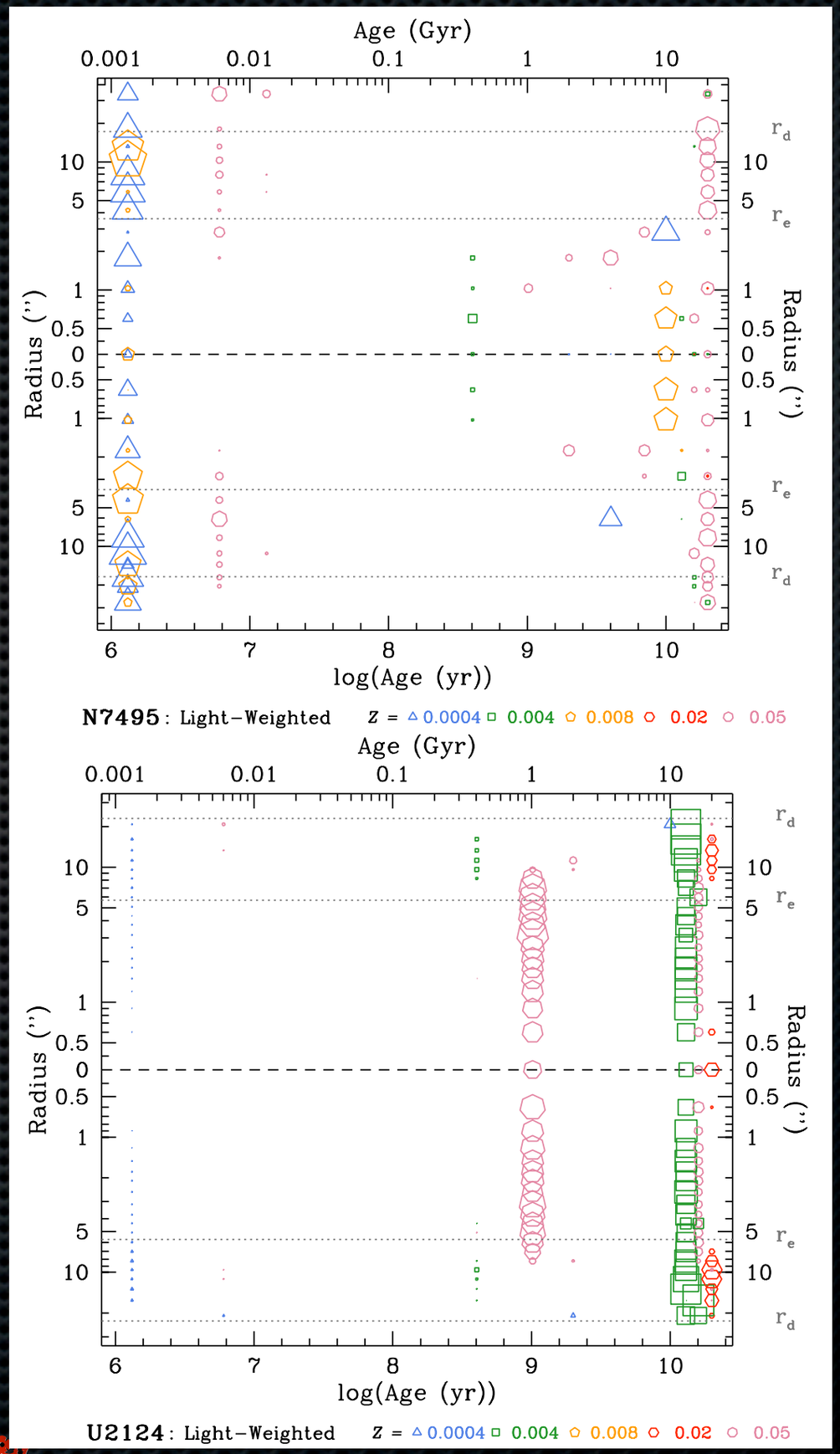


- Decided to fit **composite populations** to entire spectra
  - note: Ganda+07 also found that composite population fits better match their data

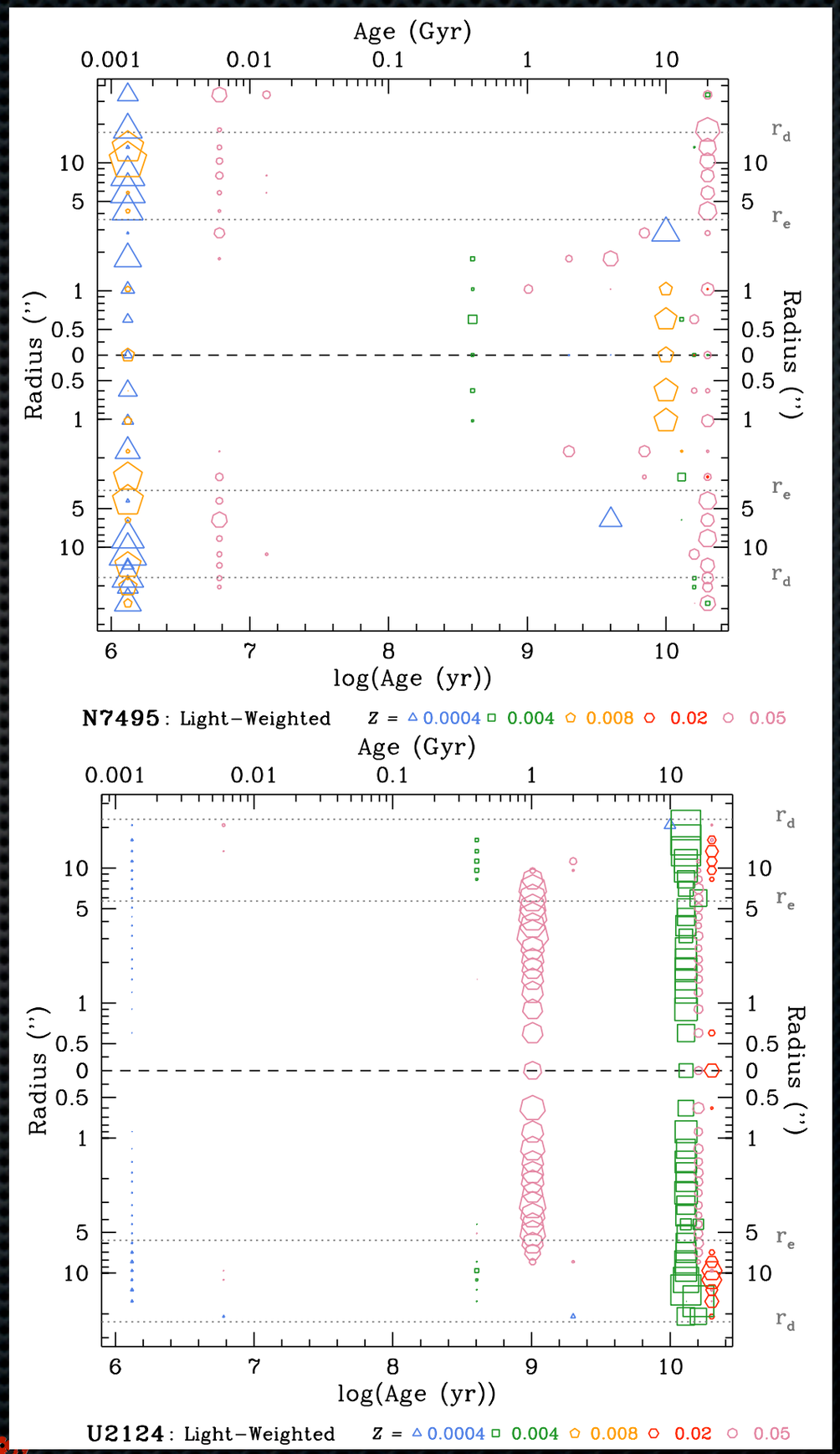


MacArthur+09



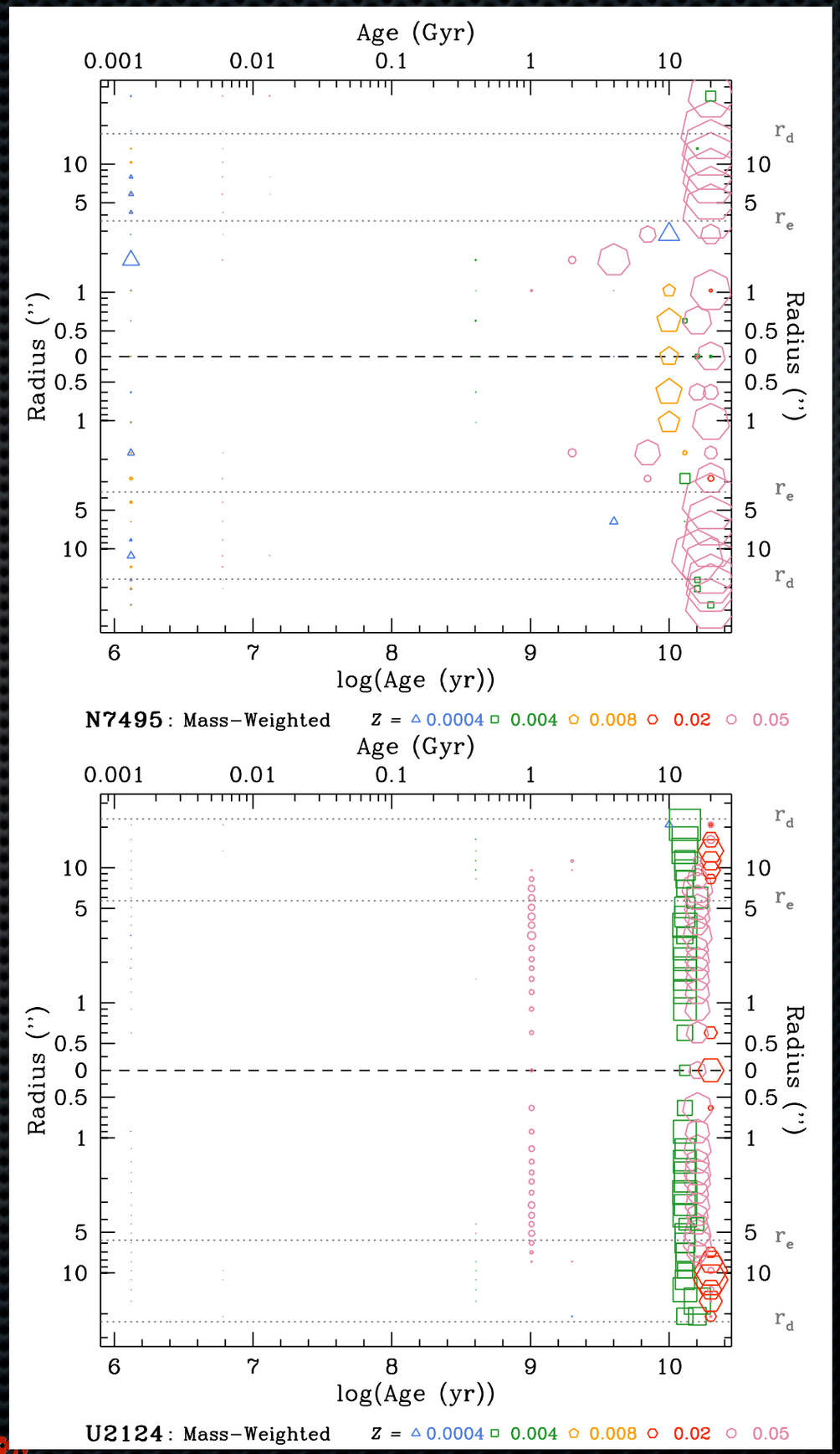
MacArthur+09

- Need multiple populations to fit spectra: old + young, little intermediate age, some very young
  - **light** usually dominated by young populations



MacArthur+09

- Need multiple populations to fit spectra: old + young, little intermediate age, some very young
  - **light** usually dominated by young populations
  - but **mass** *always* dominated by **old** population (>70%, typically ~90%)



MacArthur+09

- **Question:** are these fits unique?
  - Cf. MOPED (e.g., Panter+07), VESPA (Tojeiro+07), STEC(K)MAP (Ocvirk+06ab)
- Some problems with these fits:
  - Emission lines *ignored*, not fit: lose Balmer line information and depend on spectral shape
  - No [α/Fe]-enhancement (but probably only important in UGC 2124)
  - Dust must be (and is) included in fit: modeled correctly?
  - Full-spectrum fits notoriously sensitive to missing or badly-modeled stellar phases: e.g., Maraston+ 2006 and Conroy+ 2008

Summary of bulge stellar populations

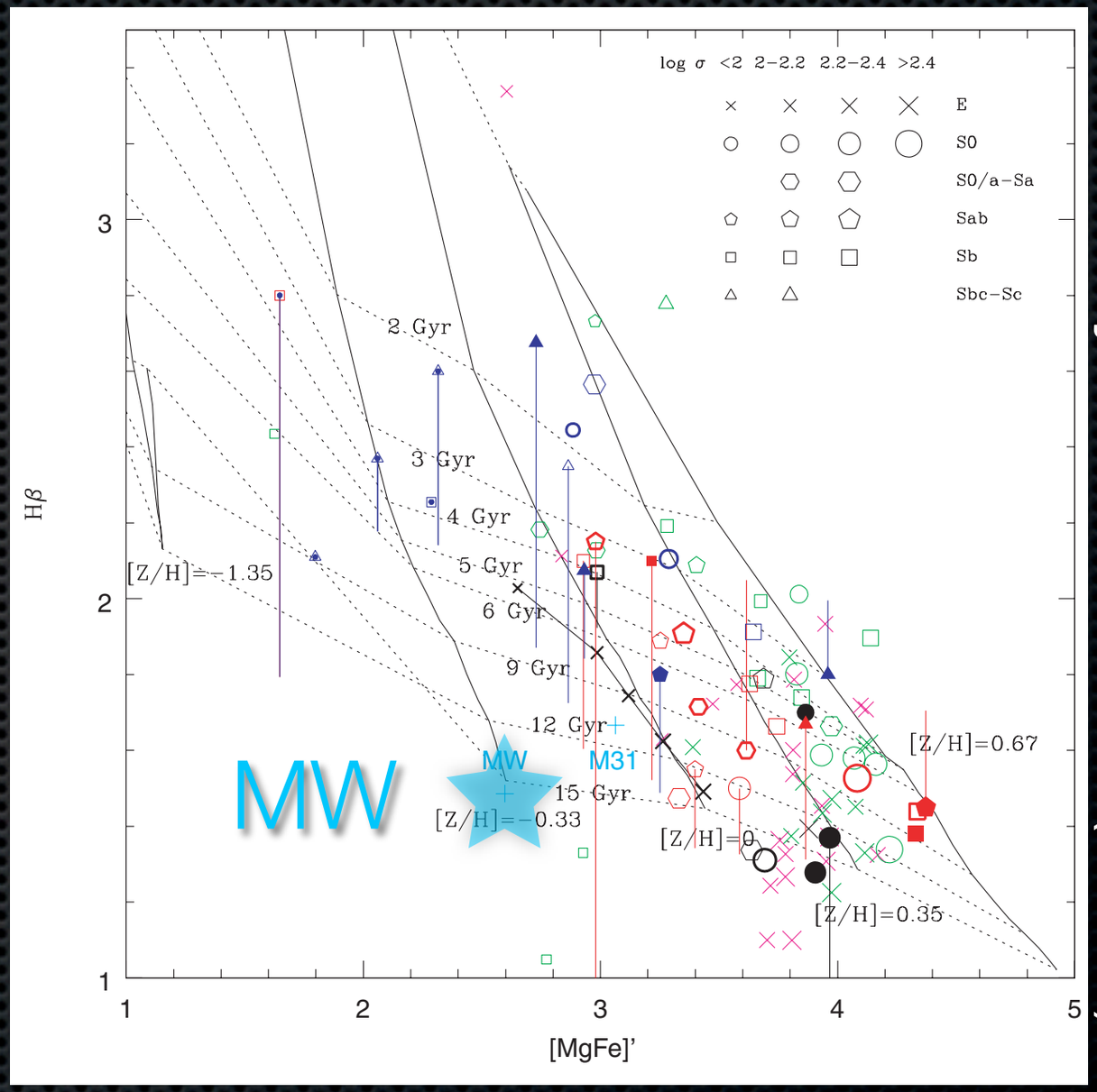
- Face-on bulges/centers:
  - **light** dominated by young/intermediate-age populations
  - **mass** *probably* dominated by old populations
- Edge-on bulges/centers
  - **light** and **mass** dominated by old populations (excepting boxy/peanut or blue bulges)

- Metallicity and [α/Fe] decrease with decreasing central σ
  - just like ellipticals and S0s at the same σ's
- ... and with increasing T-type
  - i.e., late-type bulges are metal-poor and have ~solar abundance ratios

What do we still not know?

- How do bulges form?
  - How important are secular processes? Mergers?
- Balance between “bulge” and “inner disk”
  - Are the young stars “disk” populations or some other, bulge-like (pseudo-bulge?) population?
  - Peletier+ associate “sigma-drops” in bulges, caused by dynamically cold structures, with young populations, but connection is unclear: there are *old* sigma-drop galaxies

- What's going on in the Milky Way?
  - MW is **old** in its light *and* mass for its size
- Thomas & Davies (2005) suggest MW may have a *positive* age gradient: we're only seeing the **old**, outside edge of the bulge
  - seen in ~1/3 of Sc galaxies (Moorthy & Holtzman06, MacArthur +09)



Moorthy & Holtzman (2006)

APOGEE: what we need from you!

- Age and composition of inner disk and any age gradient in the bulge
  - Can we reconcile the old MW bulge with other bulges of similar mass?
- Good NIR spectra of TP-AGB stars (please)!
  - ...and any other high-metallicity, cool giants you can give us