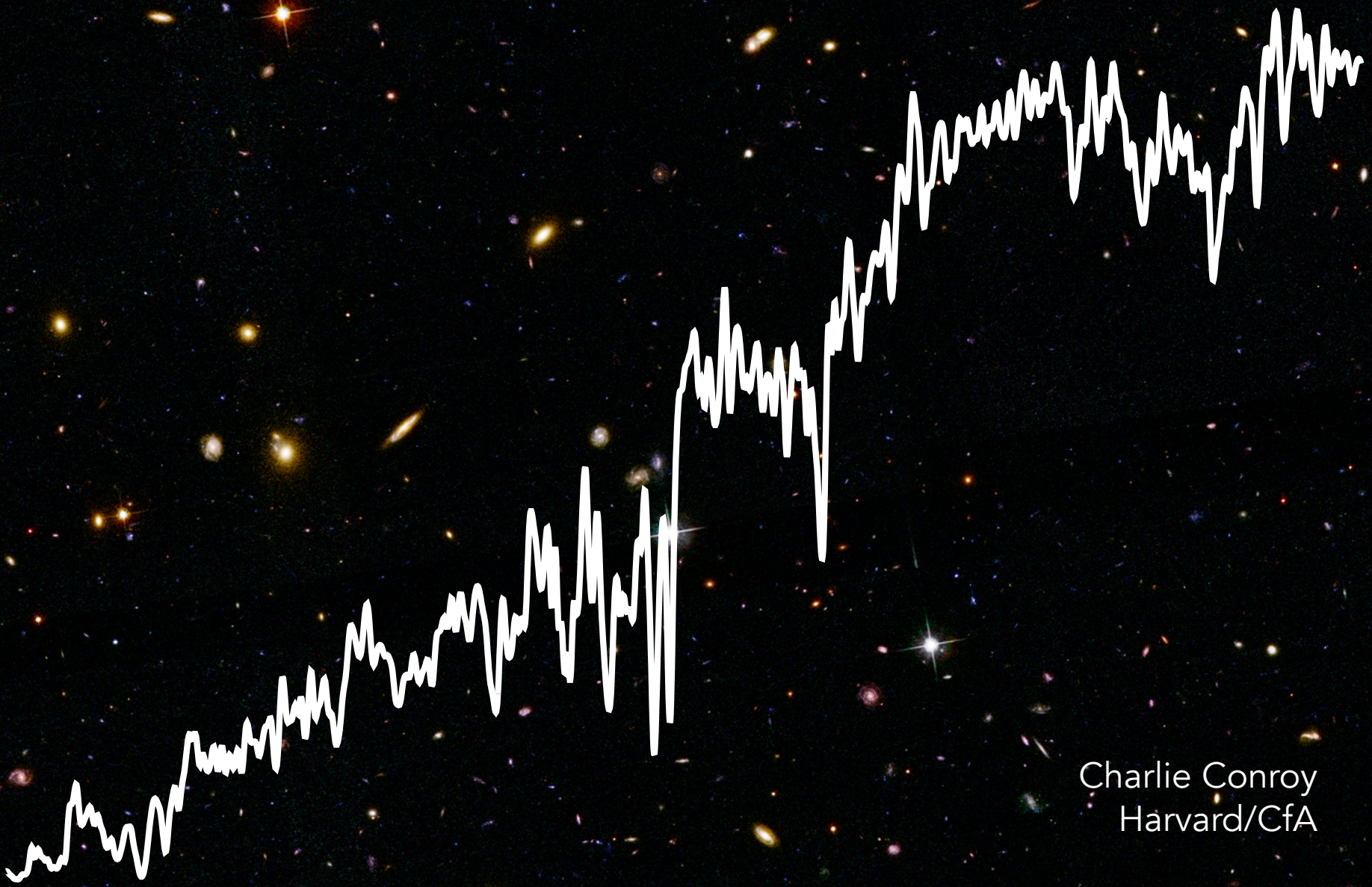
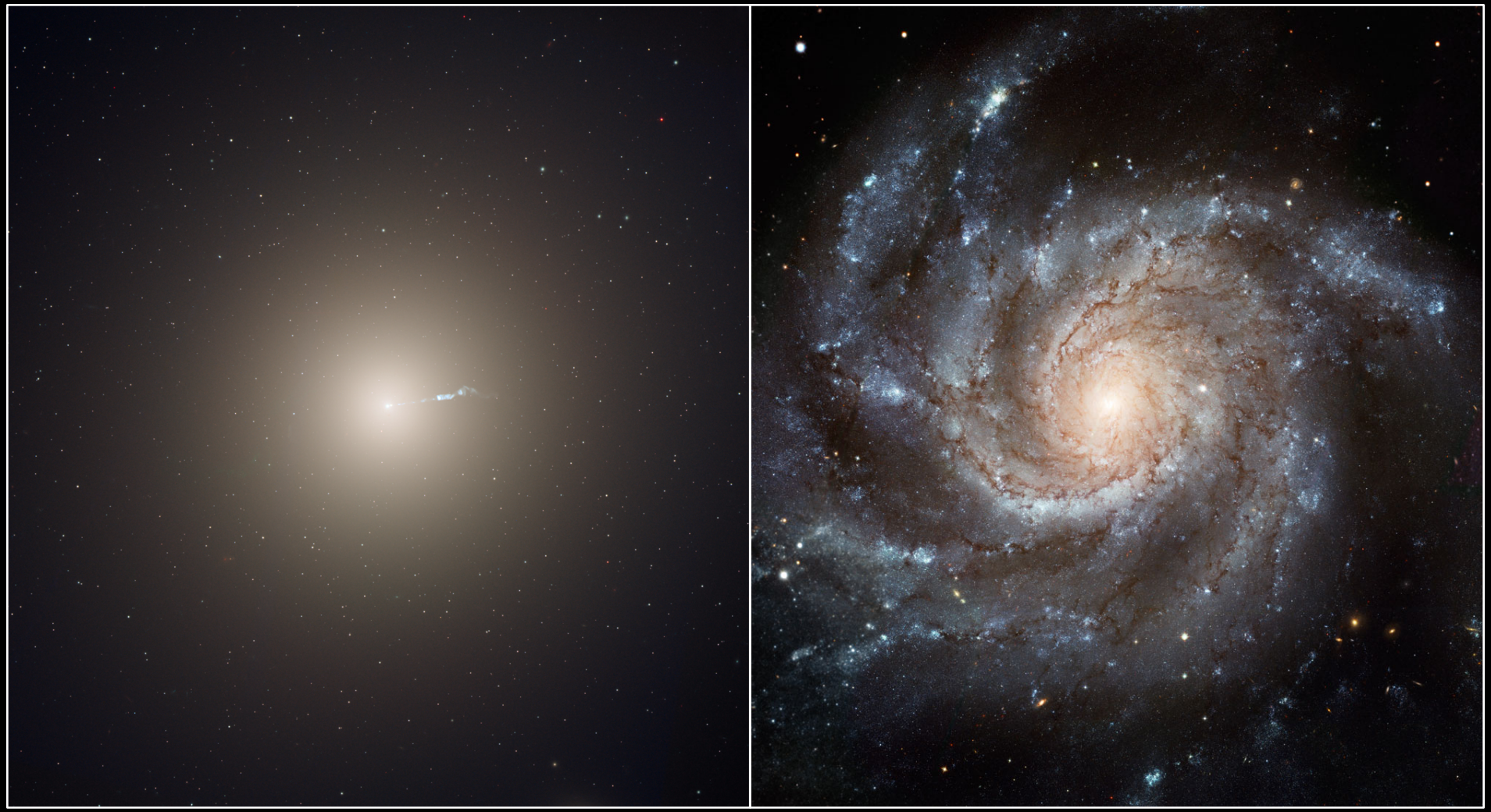
Extragalactic Archeology



Charlie Conroy
Harvard/CfA

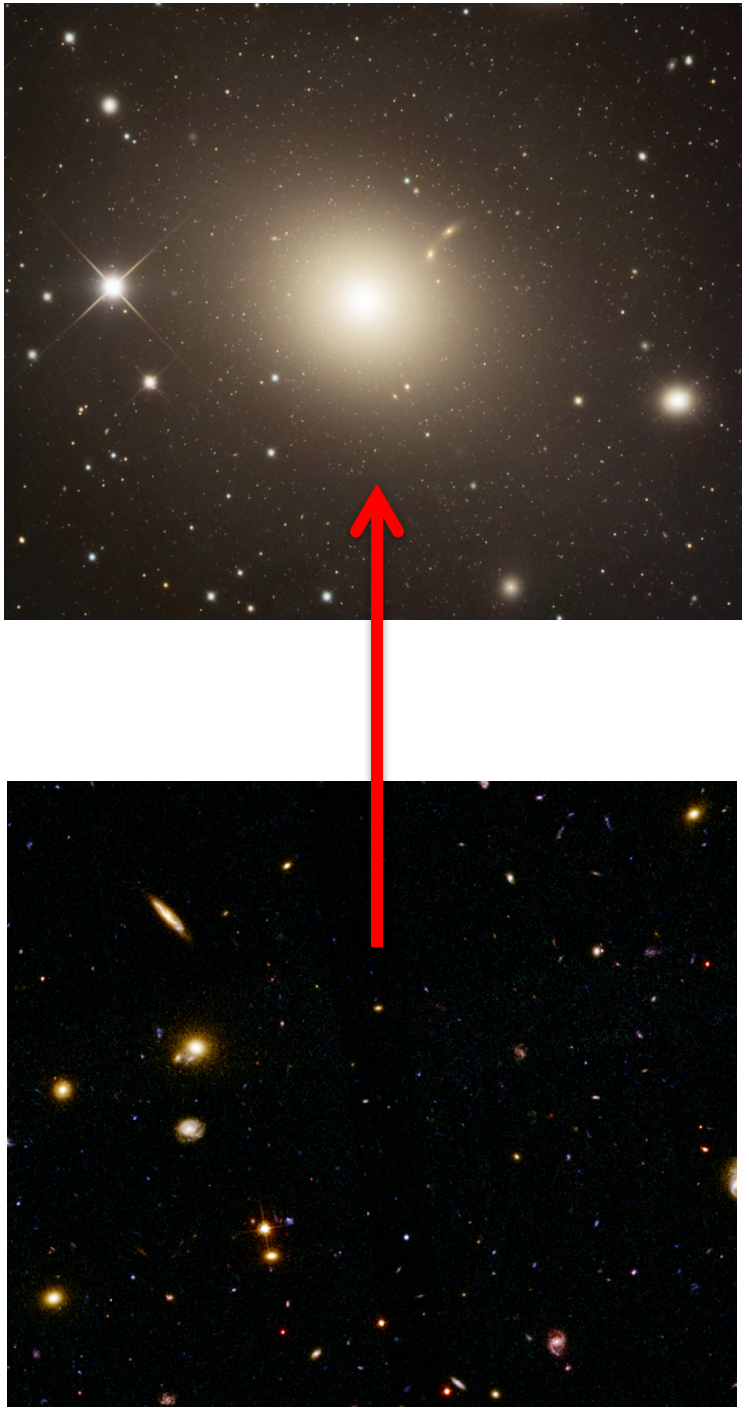


Quiescent Galaxies: Formation & Evolution

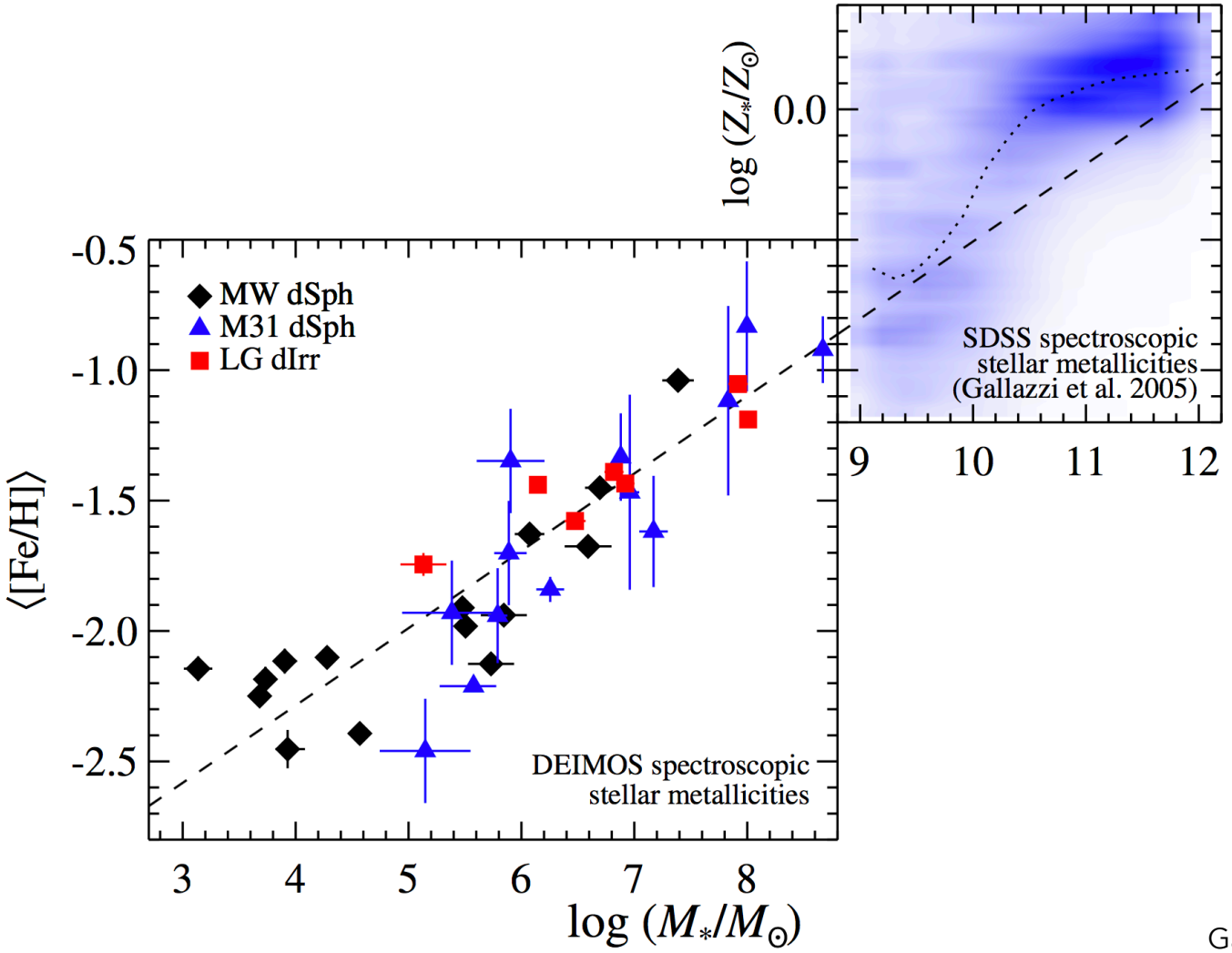
Big Questions

1. How do they form?
2. How do remarkably uniform objects emerge from such violent histories?
3. What information is stored in the radial variation in stellar properties?

4. What do their present-day properties tell us about their formation epochs?
   - "extragalactic archeology"
5. How do we connect galaxies across epochs?
   - *"extragalactic chemical tagging"*

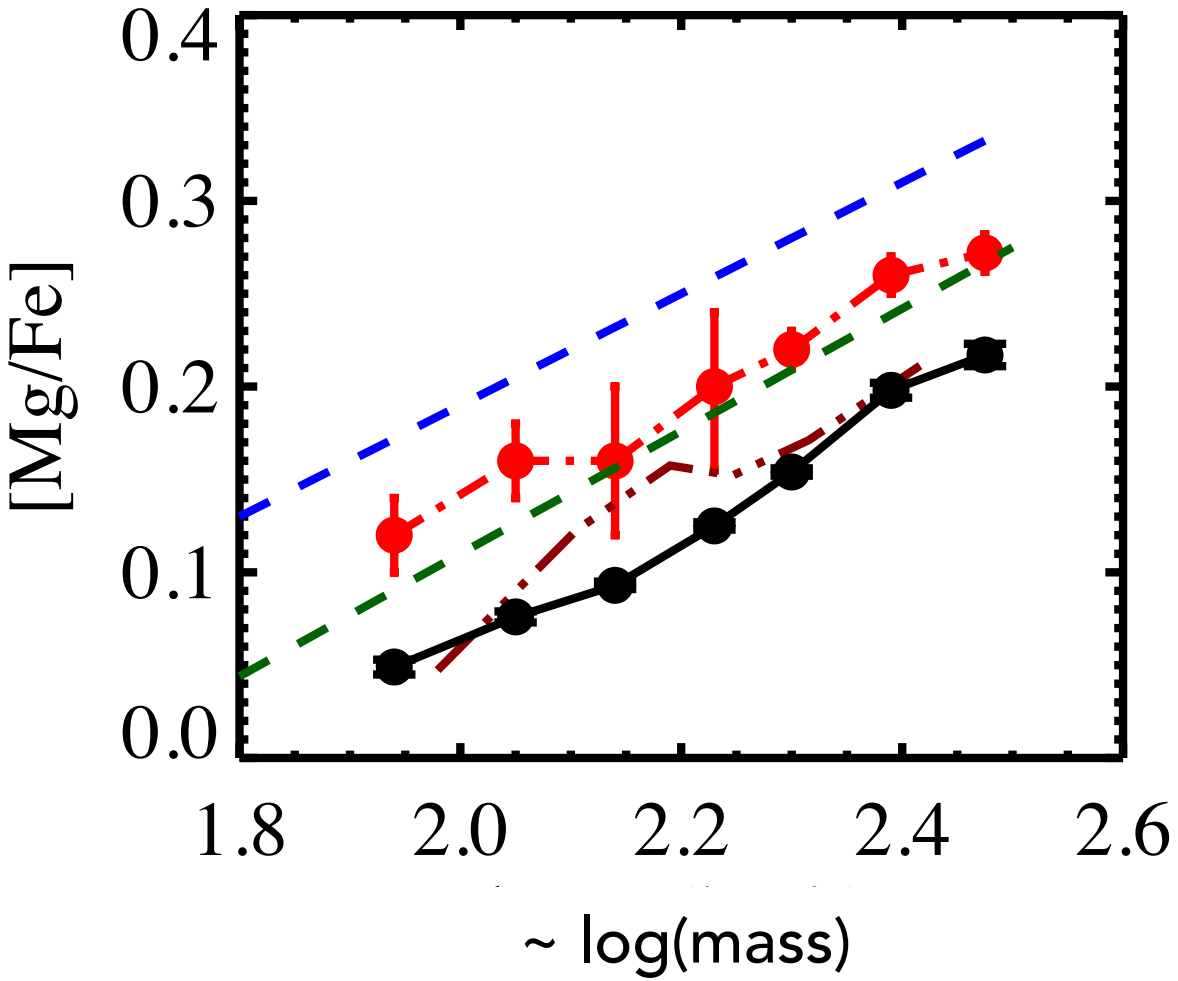


Clues from Element Abundances:
The Stellar Mass-Metallicity Relation



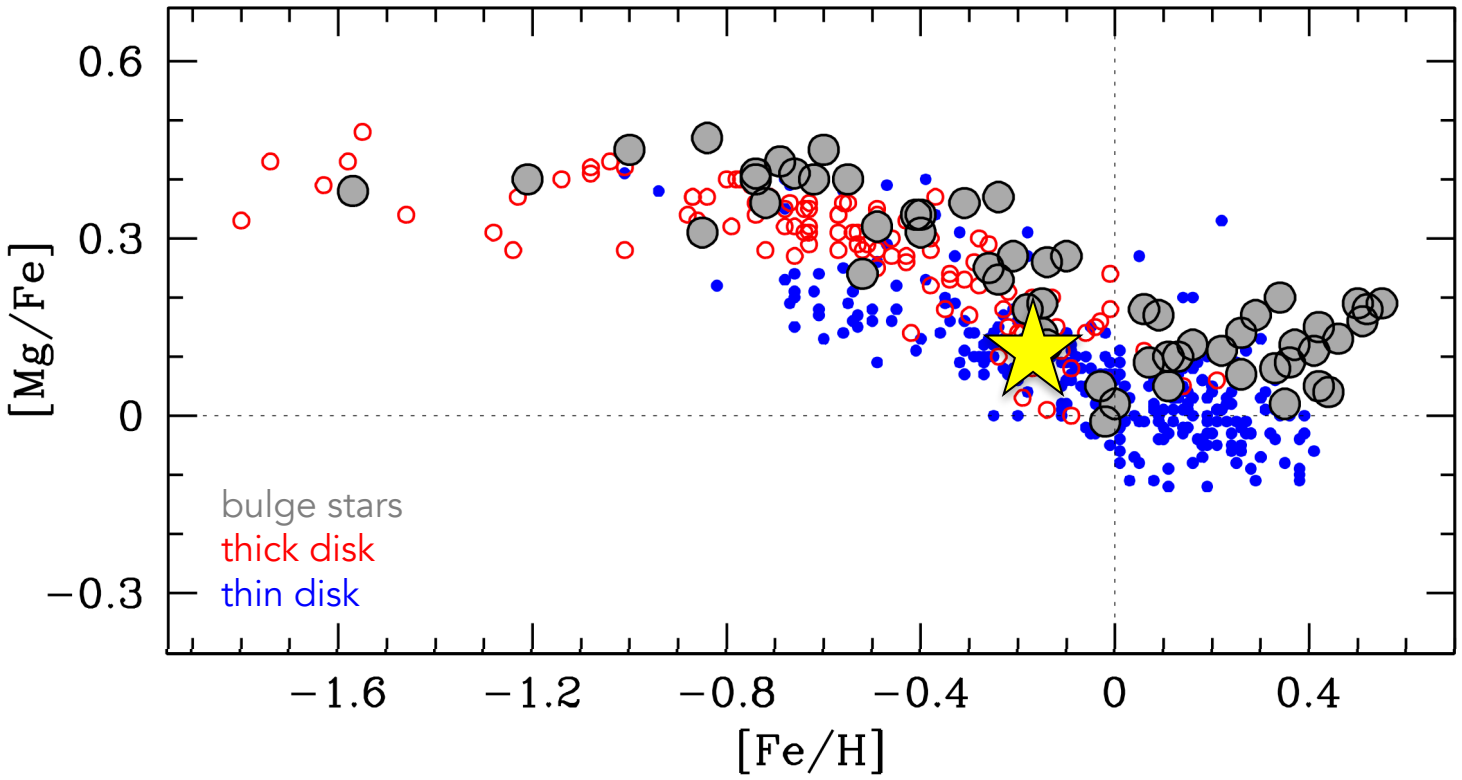
Gallazzi et al. 2005
Kirby et al. 2013

Clues from Element Abundances:
α-enhanced Massive Galaxies



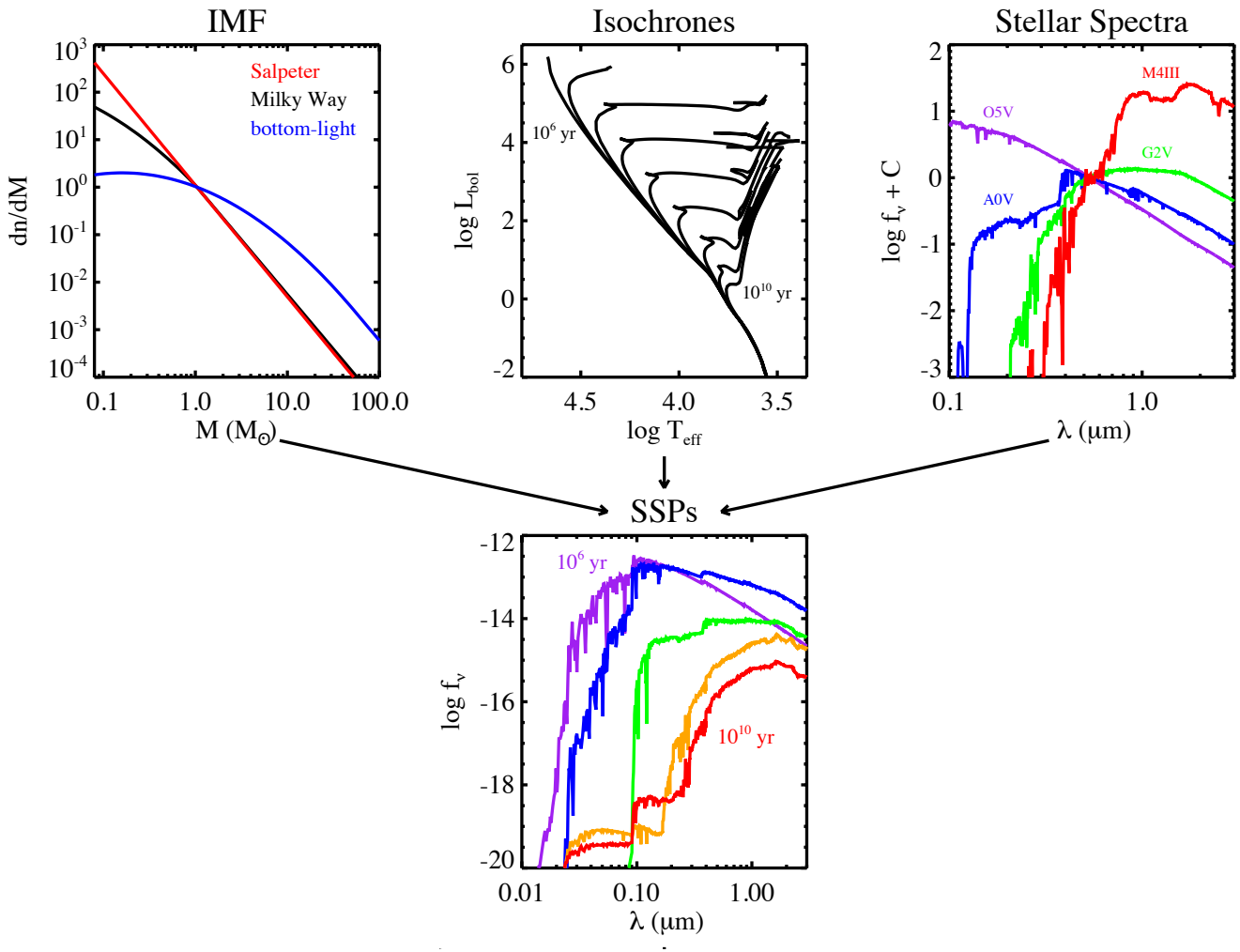
Worthey et al. 1994
Trager et al. 2000
Thomas et al. 2005
Conroy et al. 2014

Individual Stars vs. Integrated Light

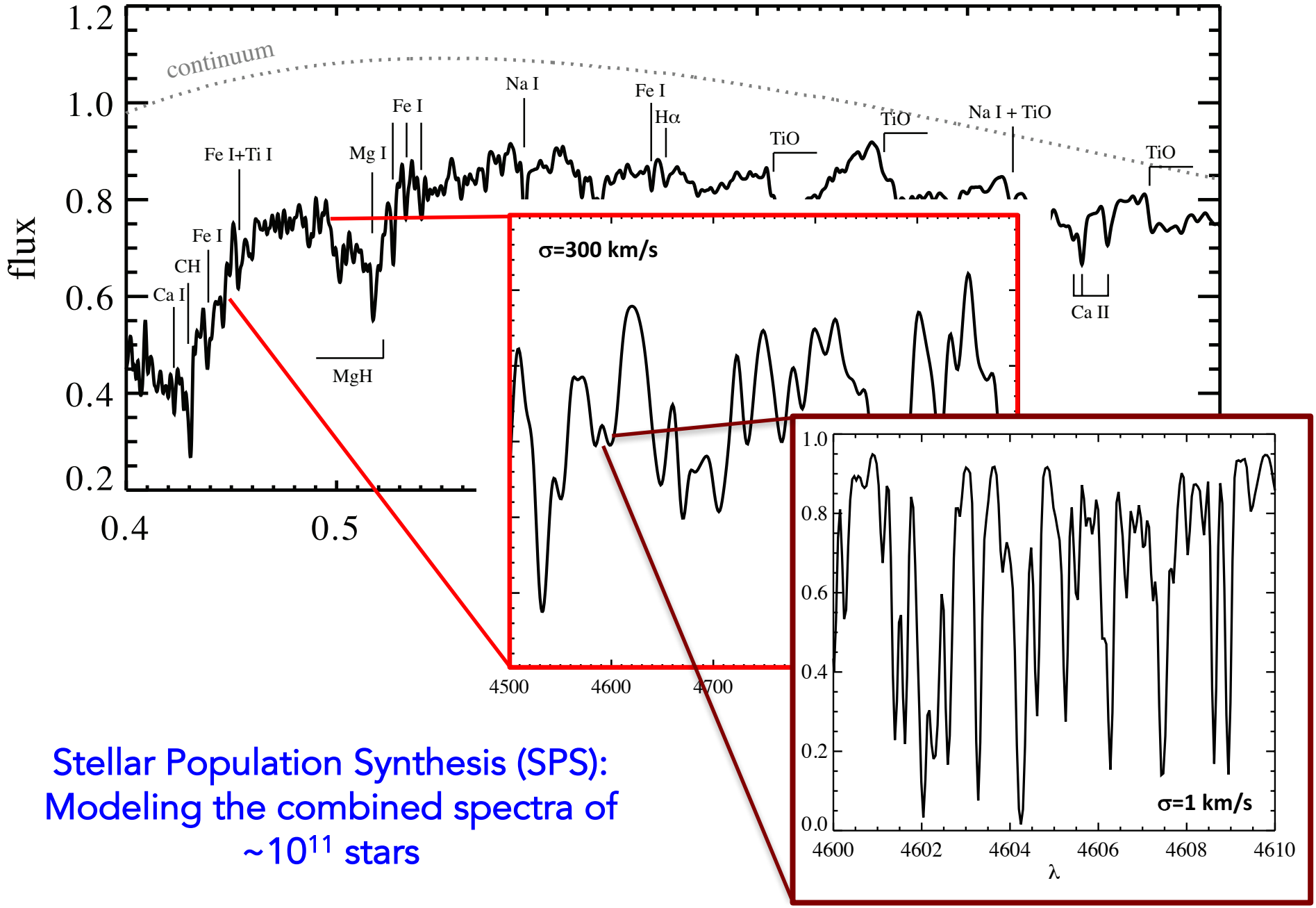


Bensby et al. 2012

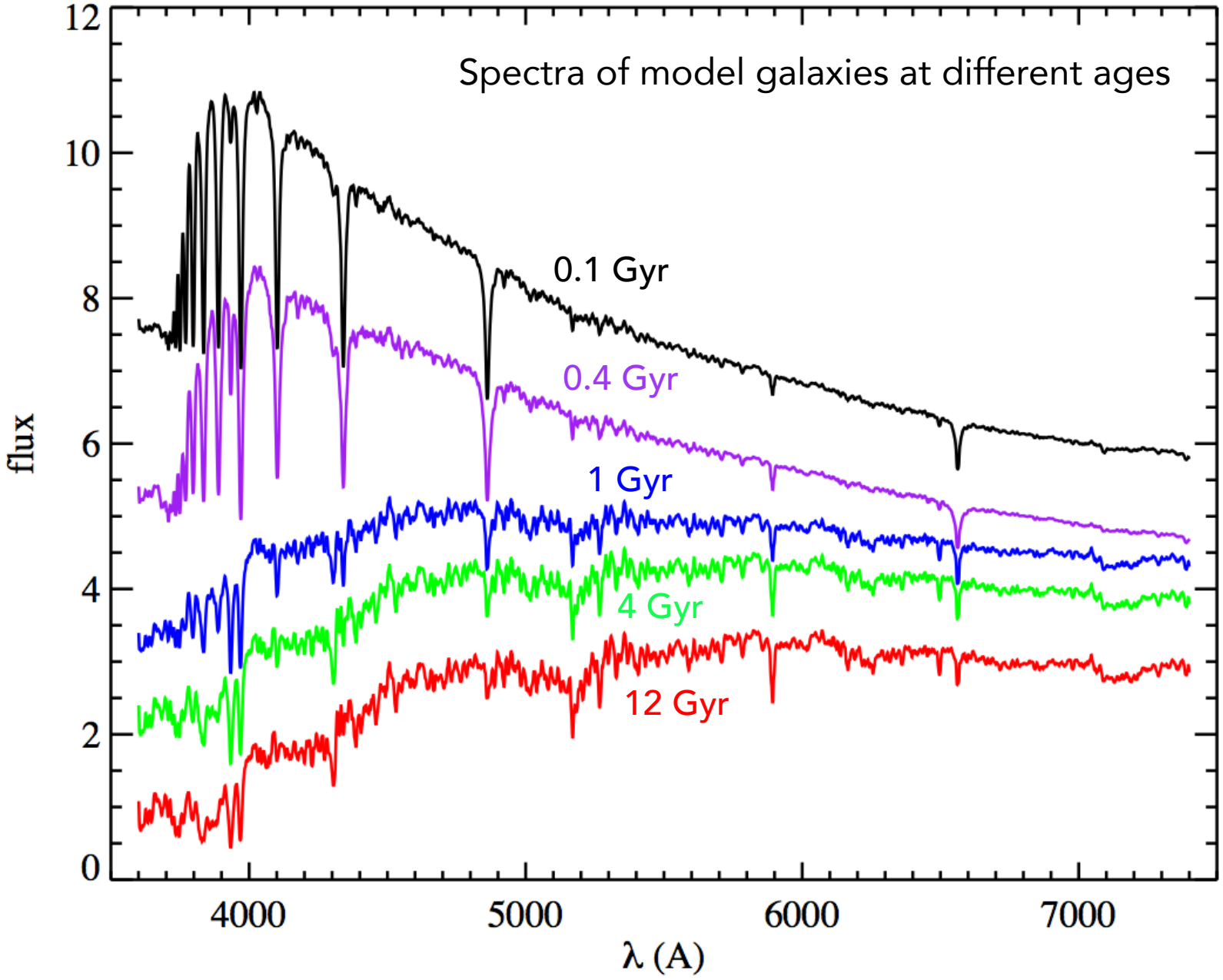
Stellar Population Synthesis



Conroy, ARAA (2014)

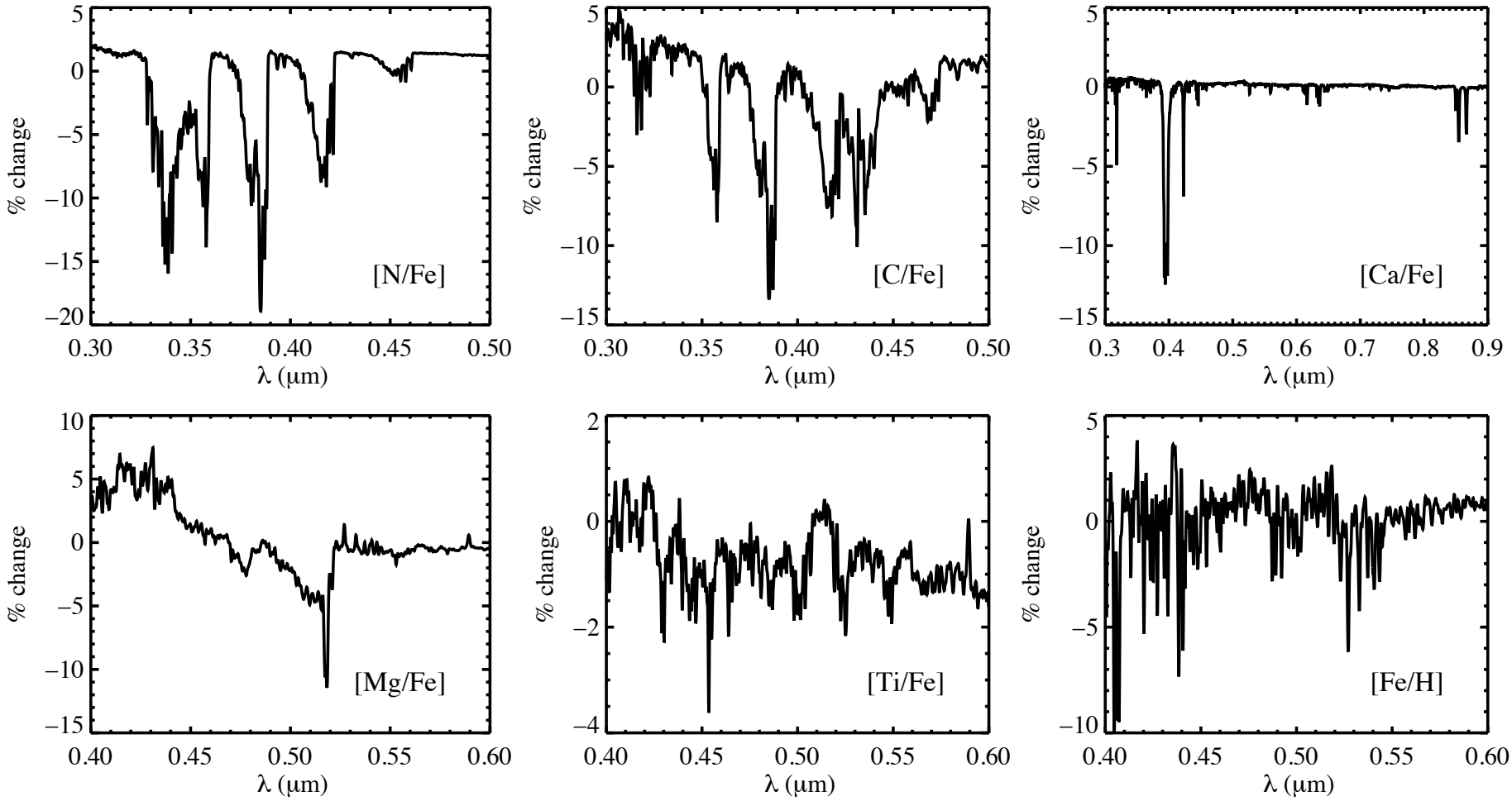


Stellar Population Synthesis (SPS):
Modeling the combined spectra of
~10^{11} stars


Spectra of model galaxies at different ages
0.1 Gyr
0.4 Gyr
1 Gyr
4 Gyr
12 Gyr
flux
λ (A)
0
2
4
6
8
10
12
4000
5000
6000
7000

Element sensitivity

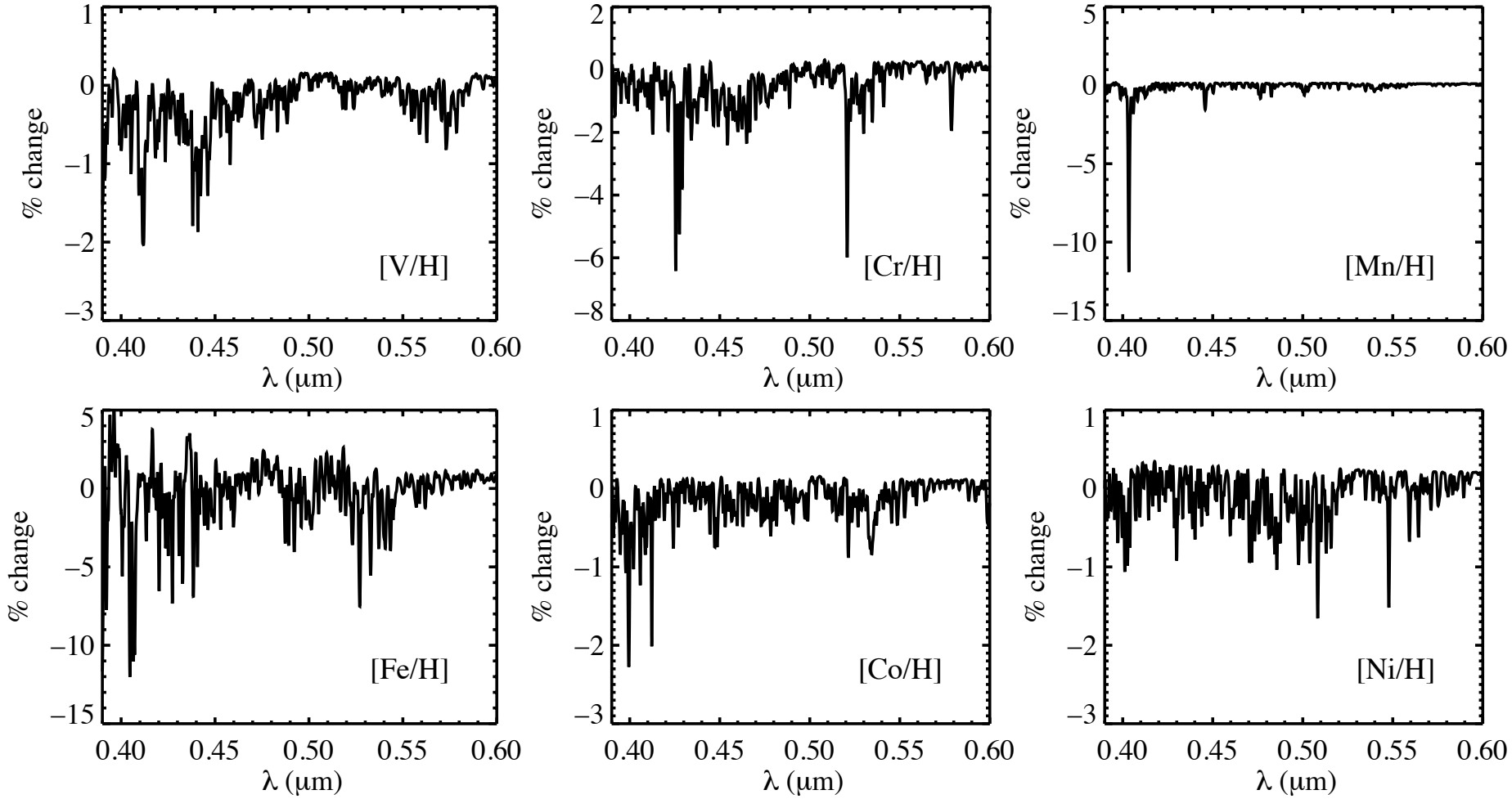
Change in model galaxy due to 2x abundance increase:



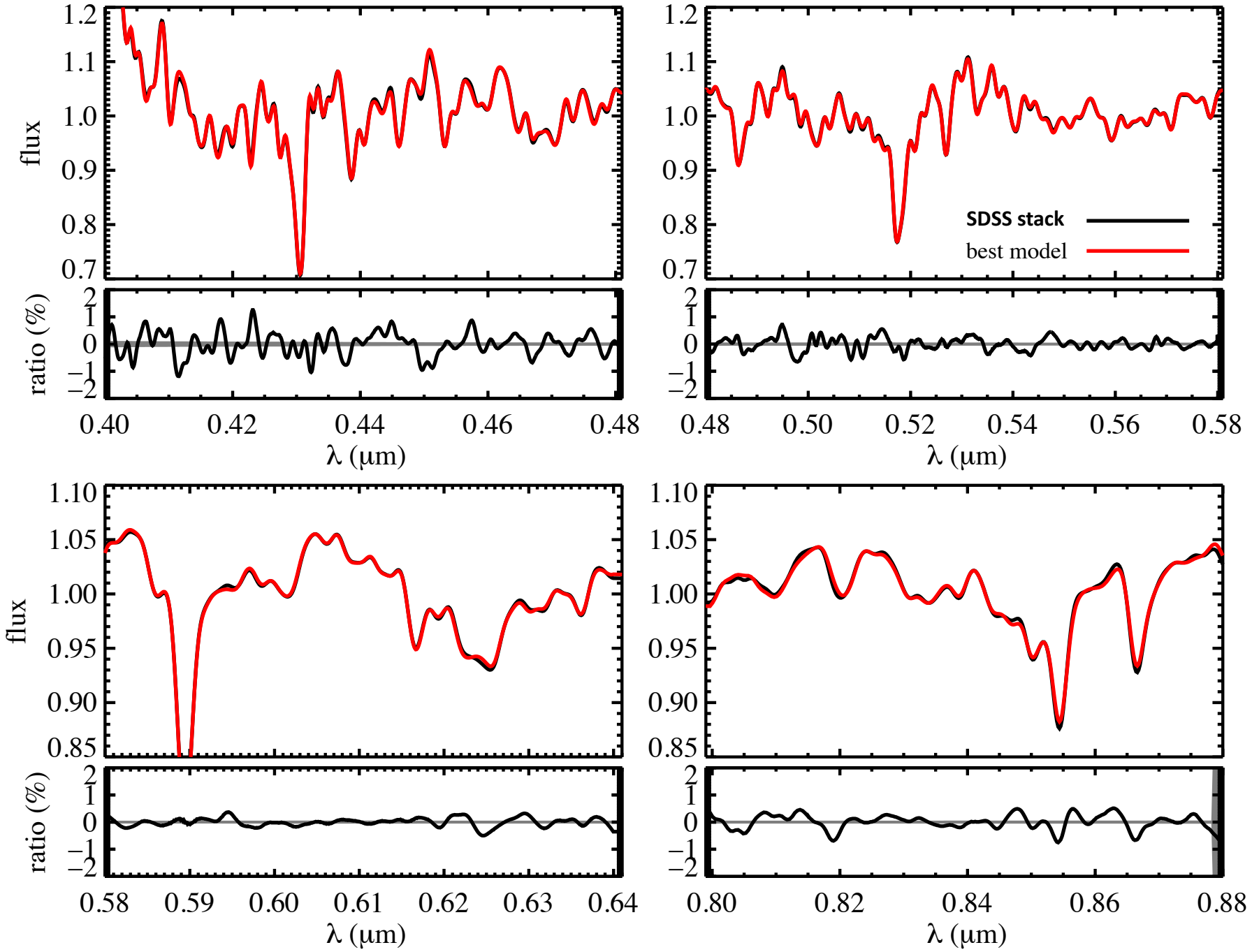
σ=150 km/s; R~1000

Element sensitivity

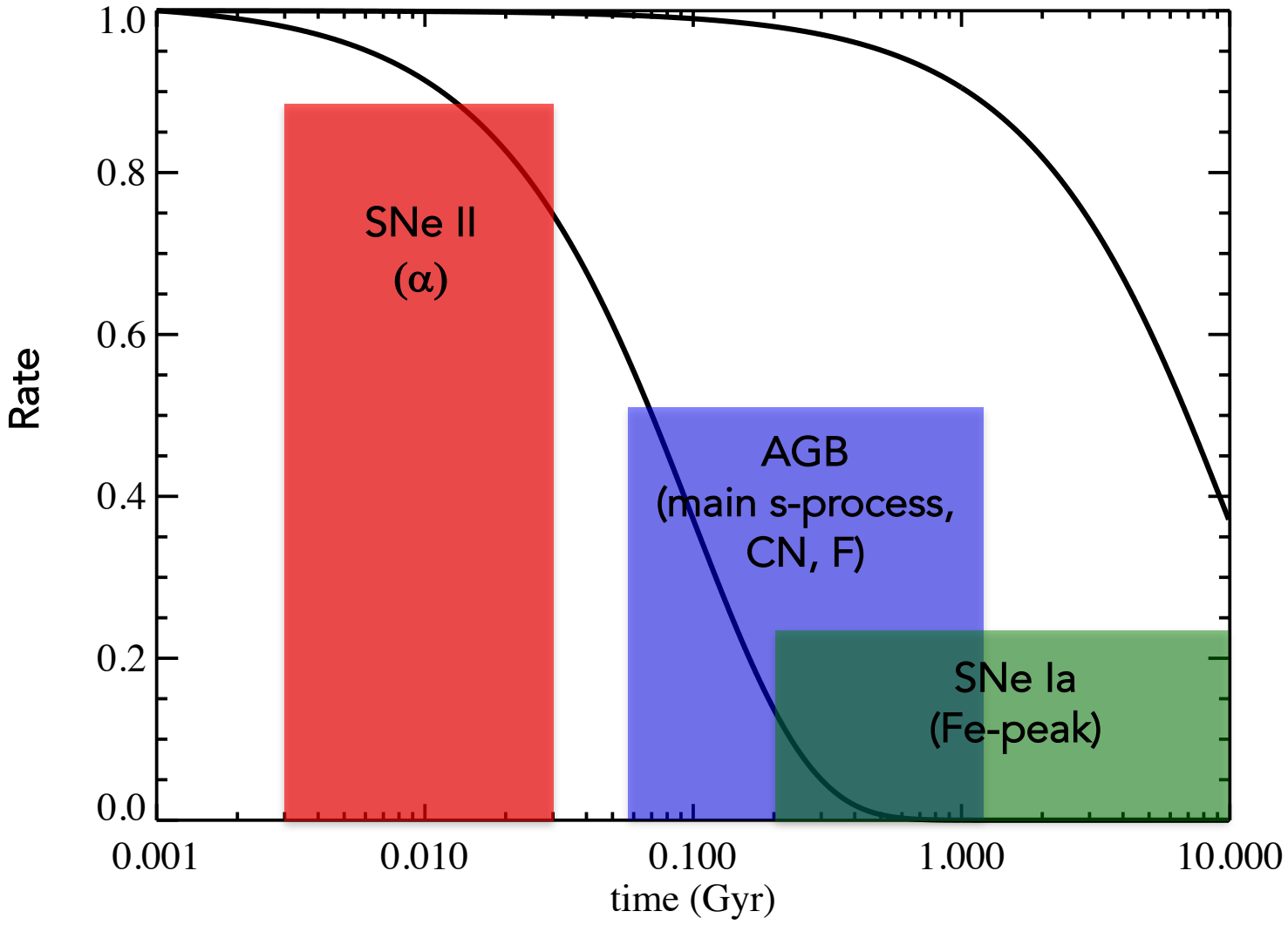
The Iron Peak Elements:



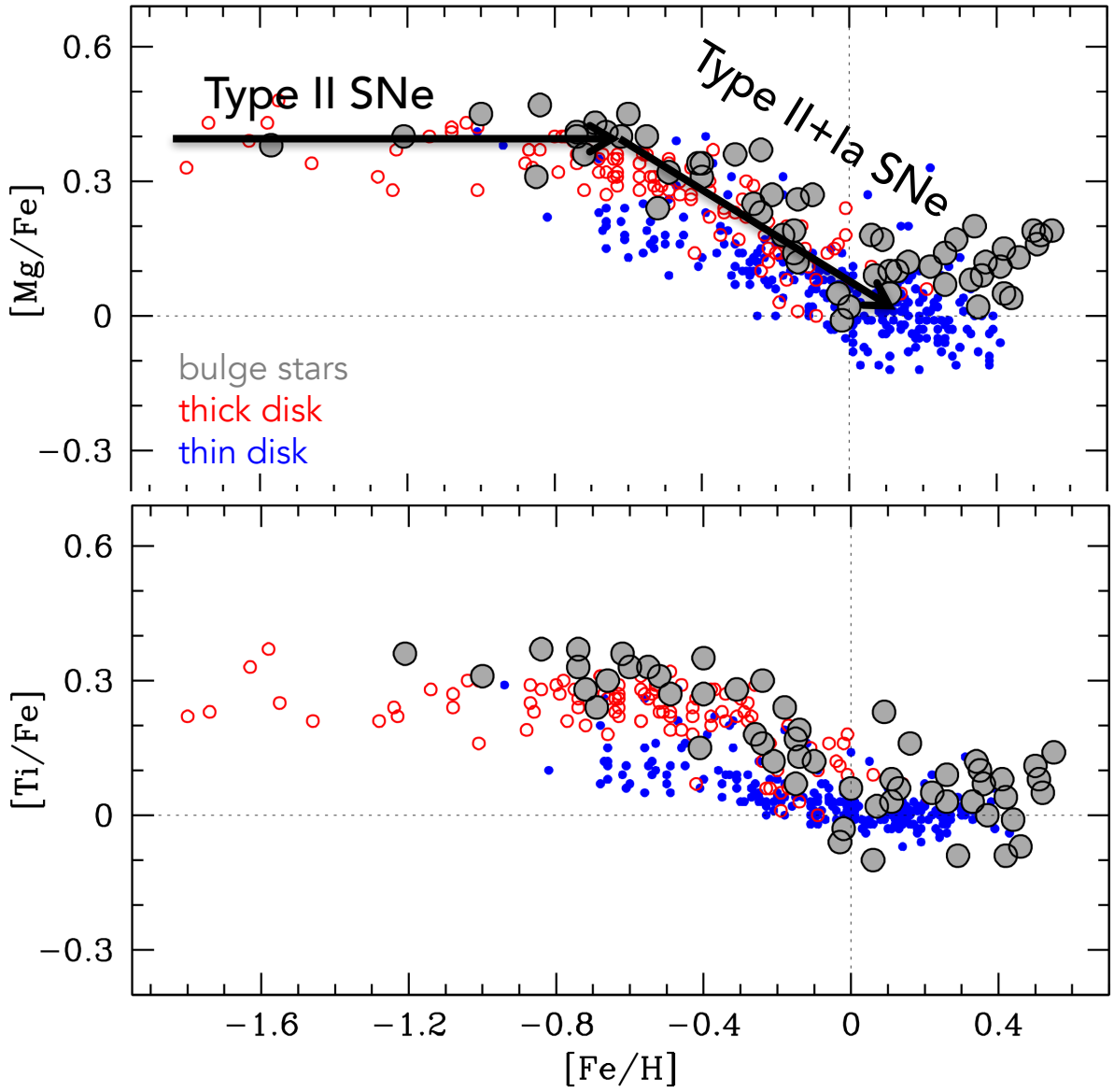
σ=150 km/s; R~1000


flux
ratio (%)
λ (μm)
SDSS stack
best model

Insights from Abundance Patterns



Milky Way Stars

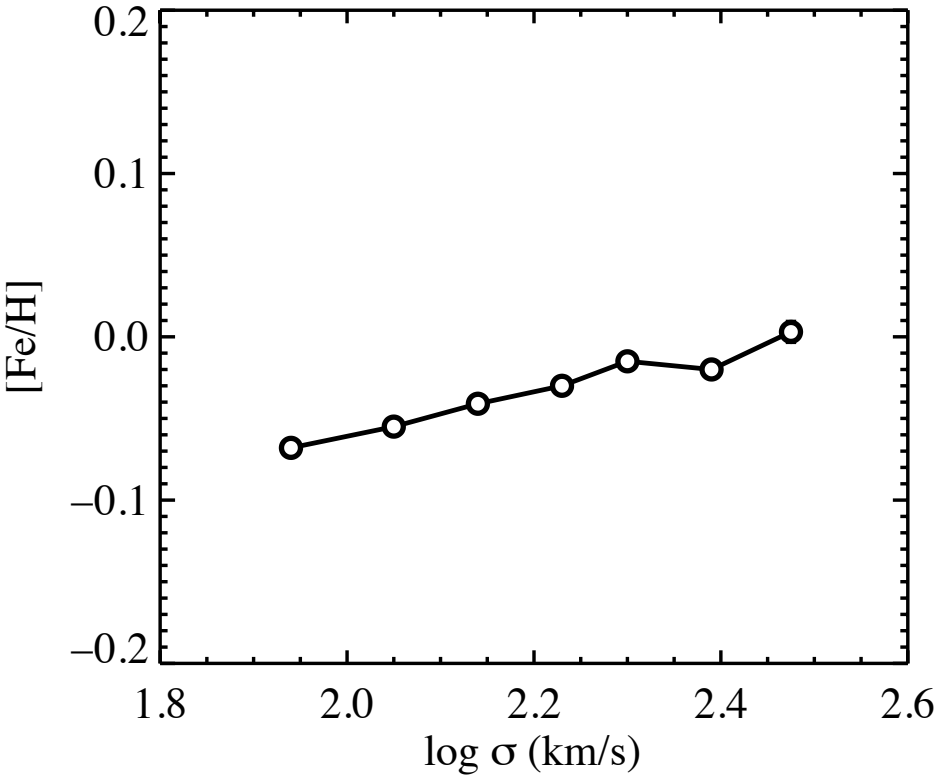


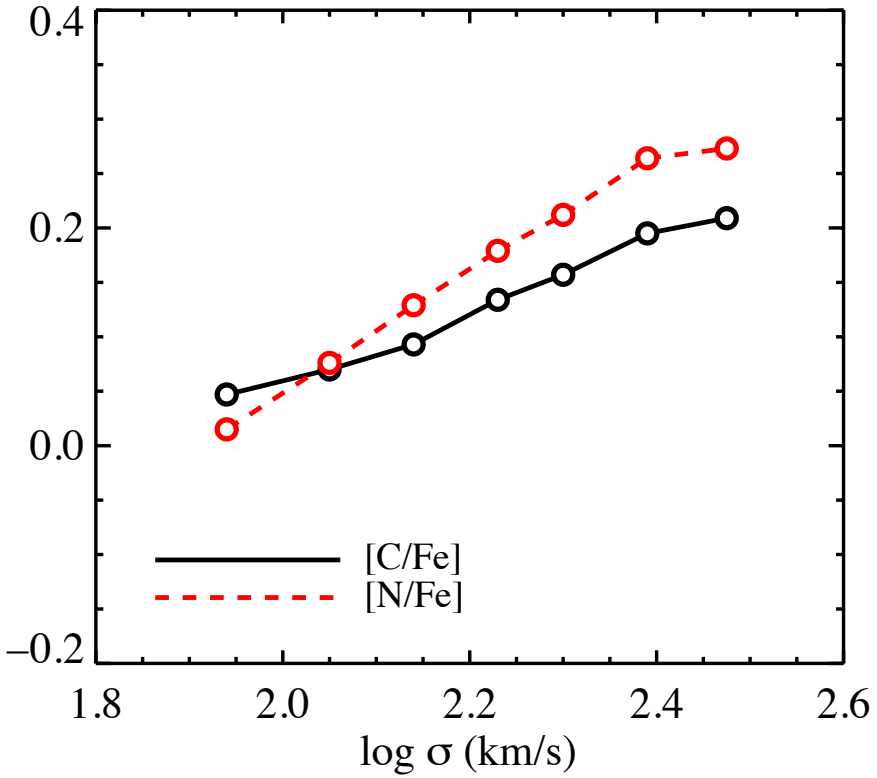
"Chemical Evolution Modeling"

- SNe yields
- Initial mass function
- Chemical mixing
- Star formation histories
- Inflows and outflows

Bensby et al. 2012

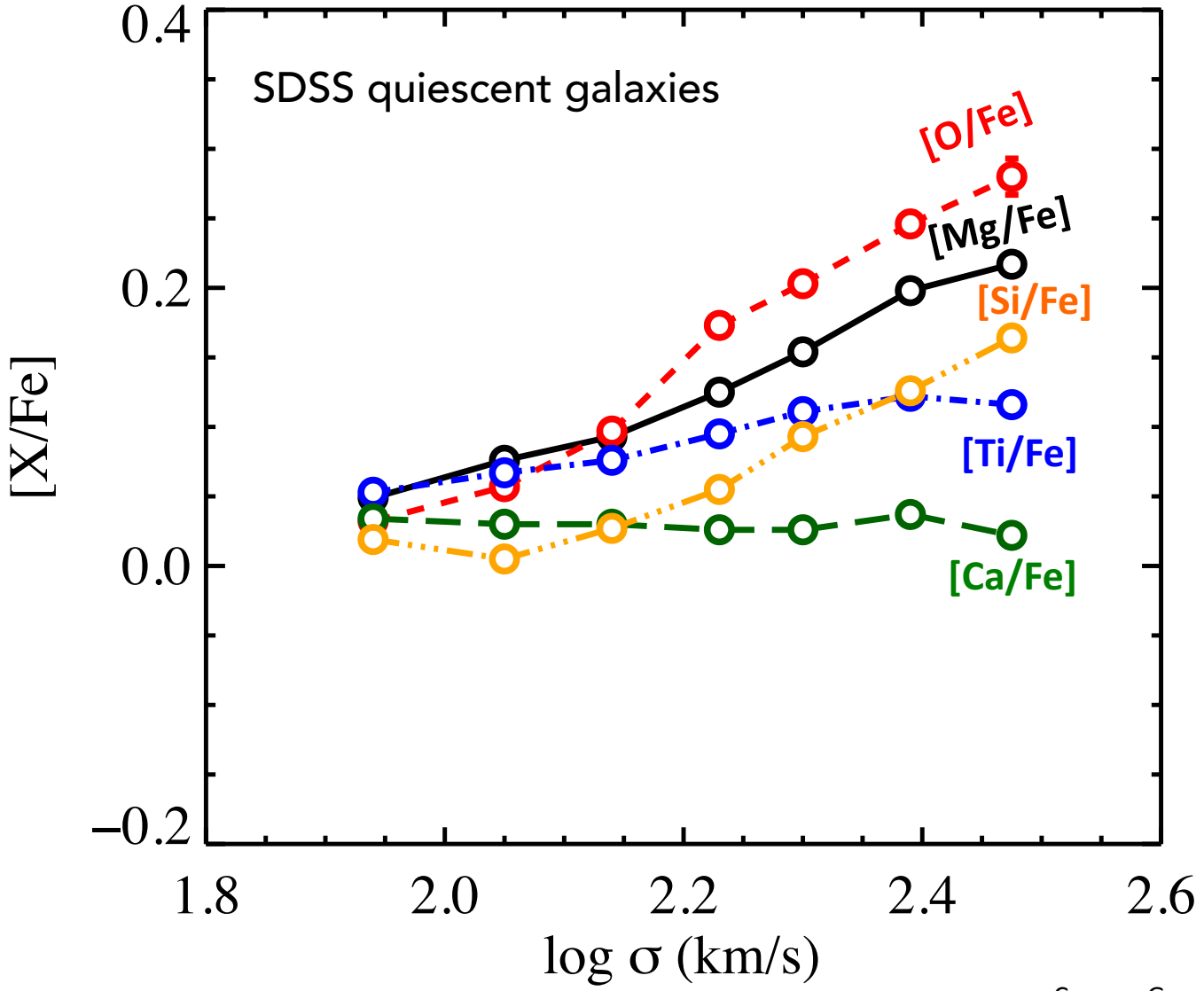
Fe, C, N





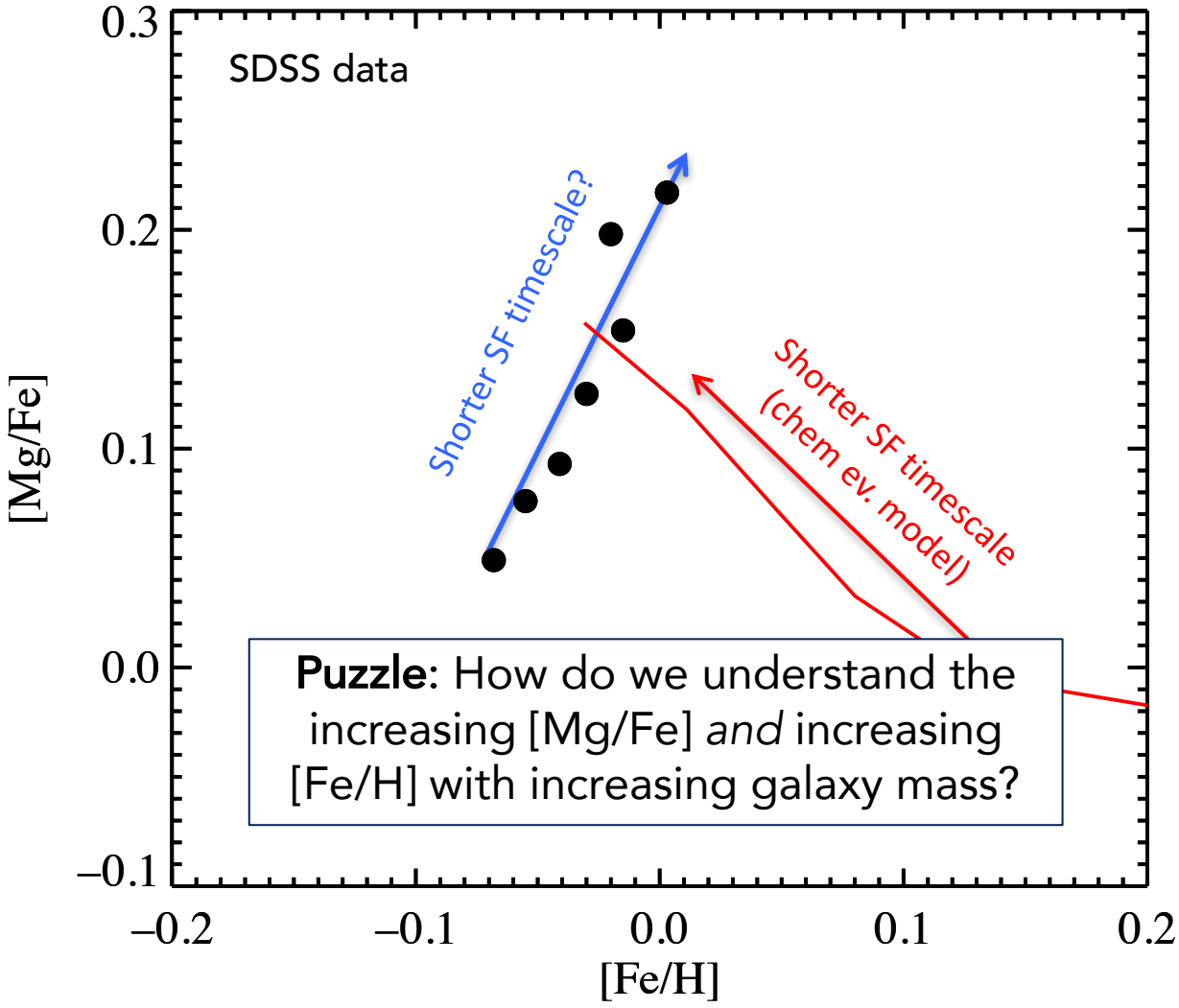
Conroy, Graves, van Dokkum 2014

The α-elements

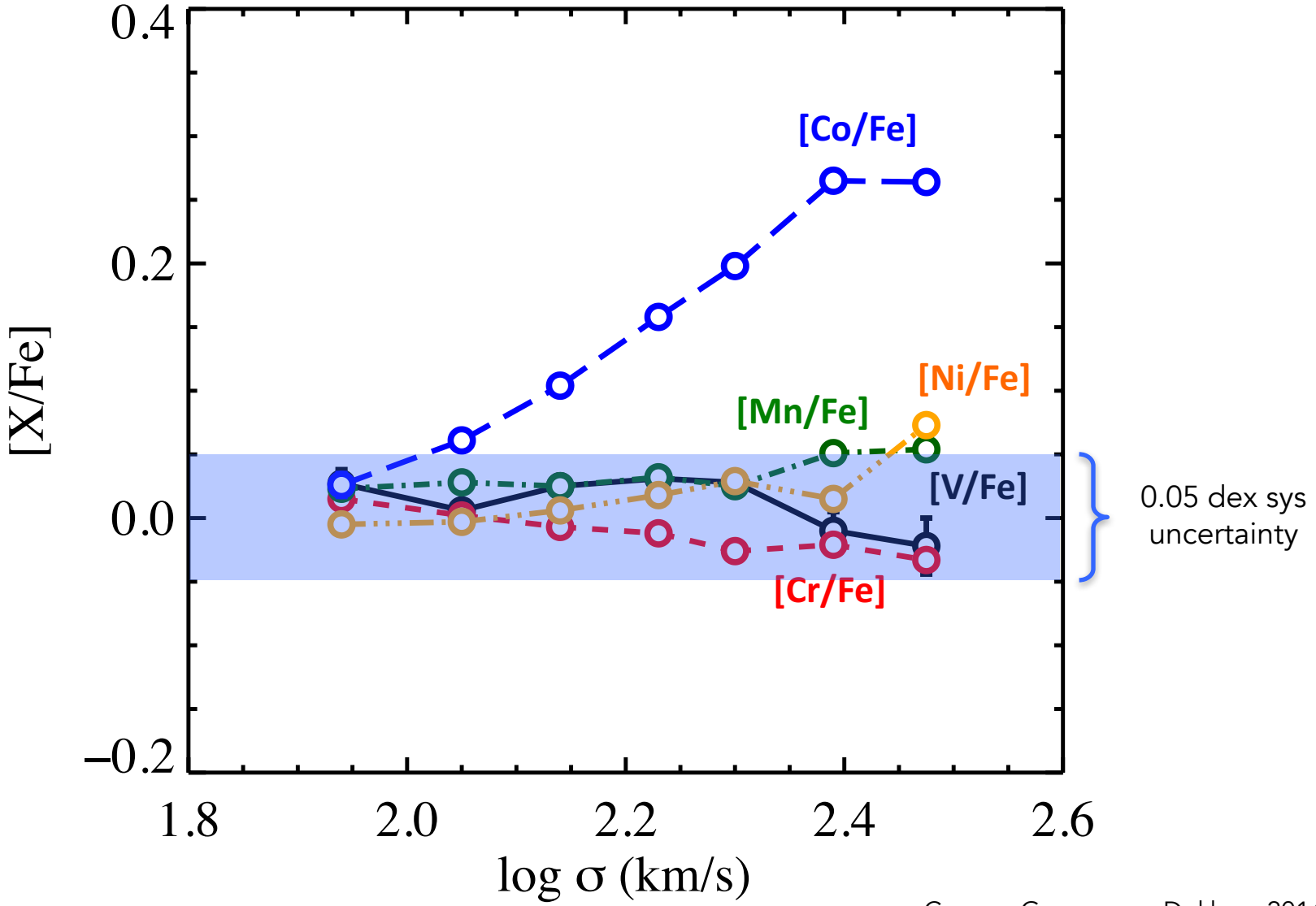


Conroy, Graves, van Dokkum 2014

[α/Fe] –> SF Timescale?

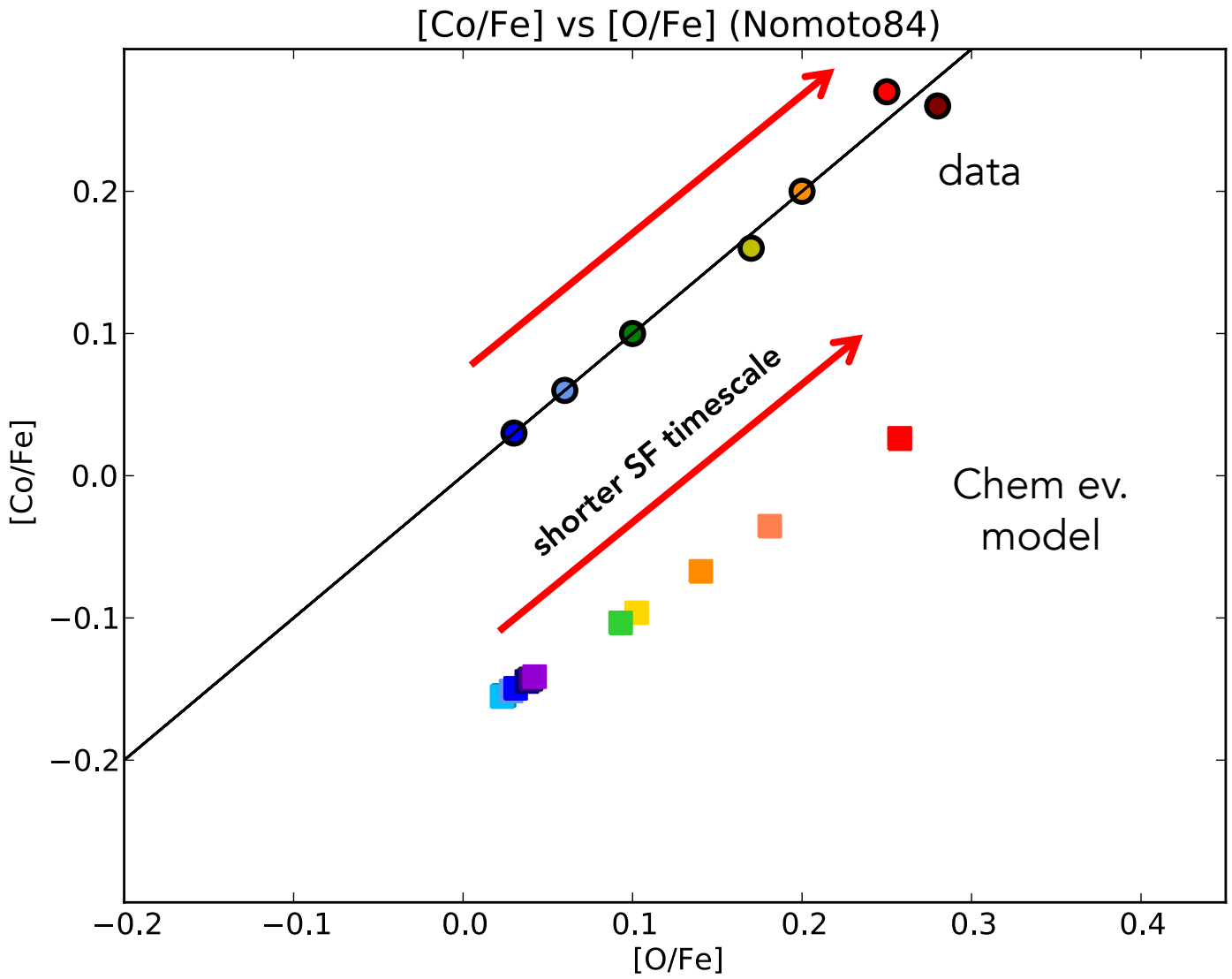


The iron-peak elements



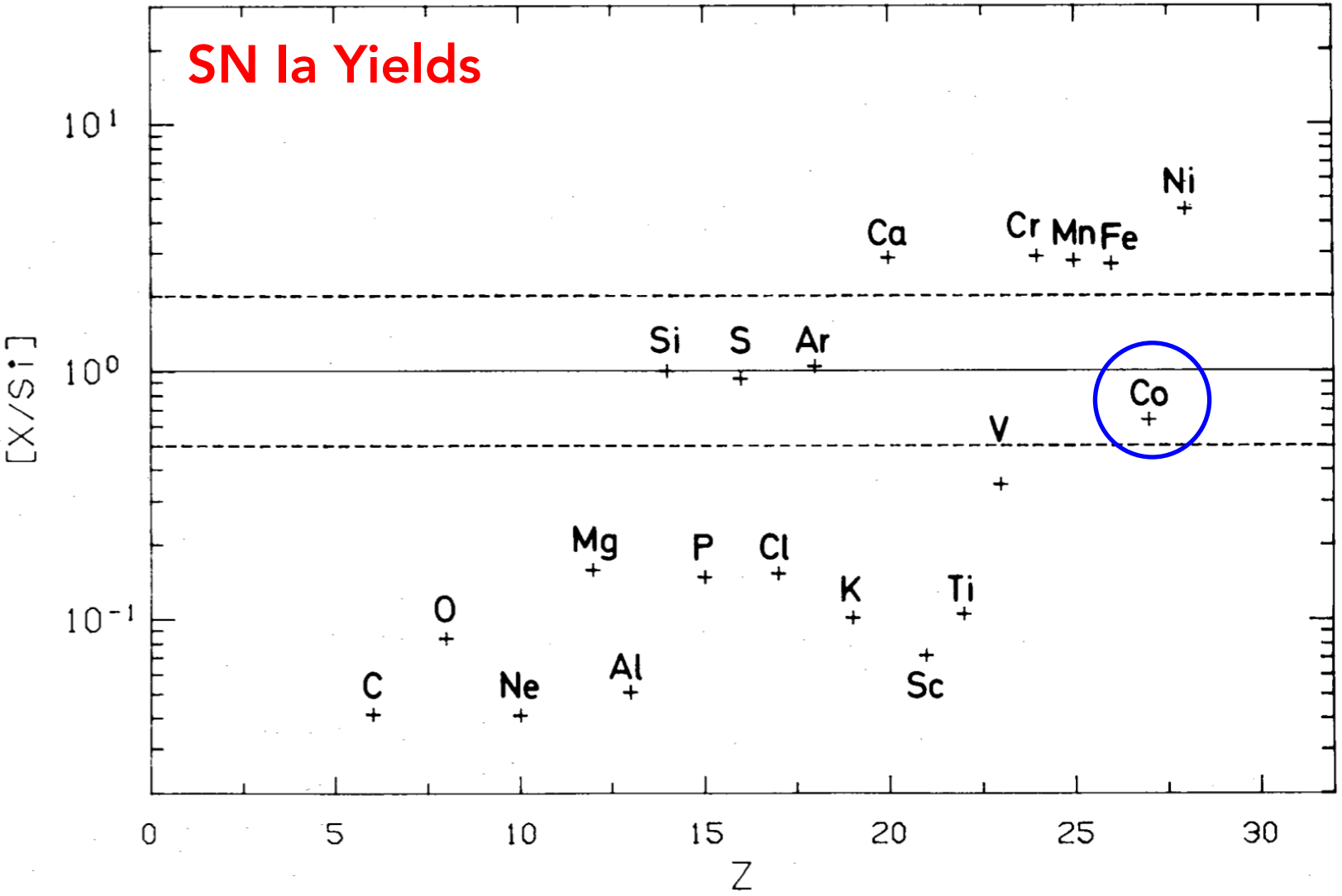
Conroy, Graves, van Dokkum 2014

Chemical Evolution Models



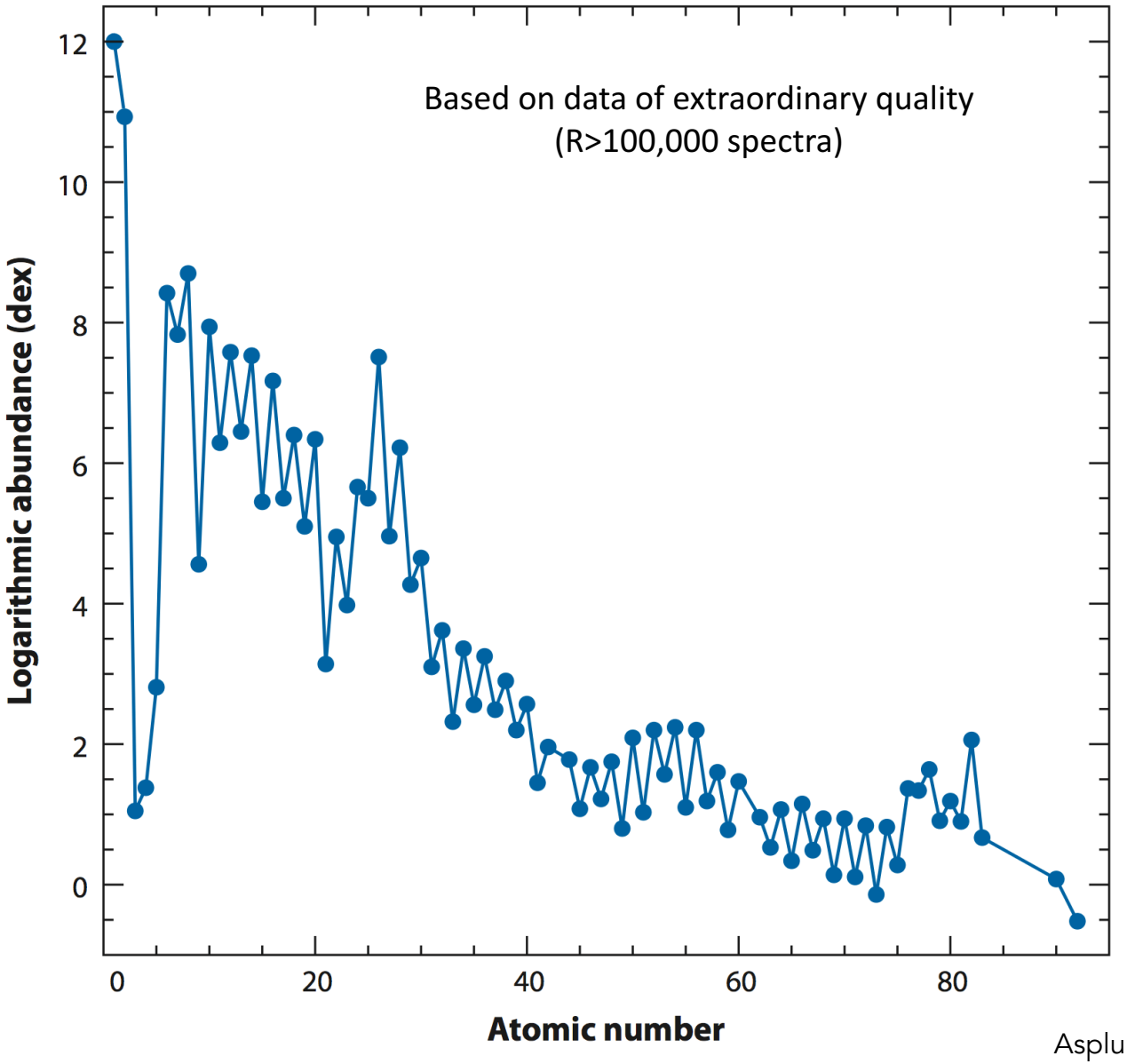
Leibler, Conroy, Ramirez-Ruiz, in prep

SN Ia Yields



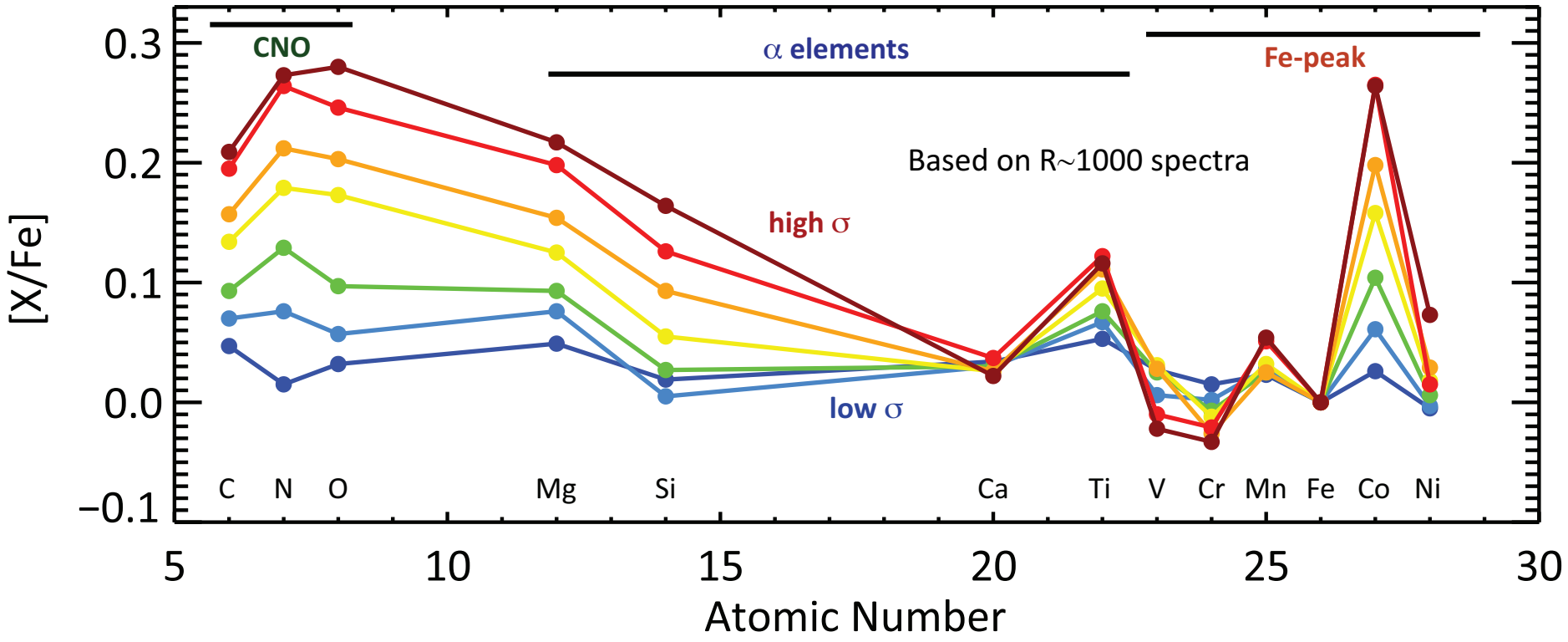
Nomoto et al. 1984

The abundance pattern of the Sun



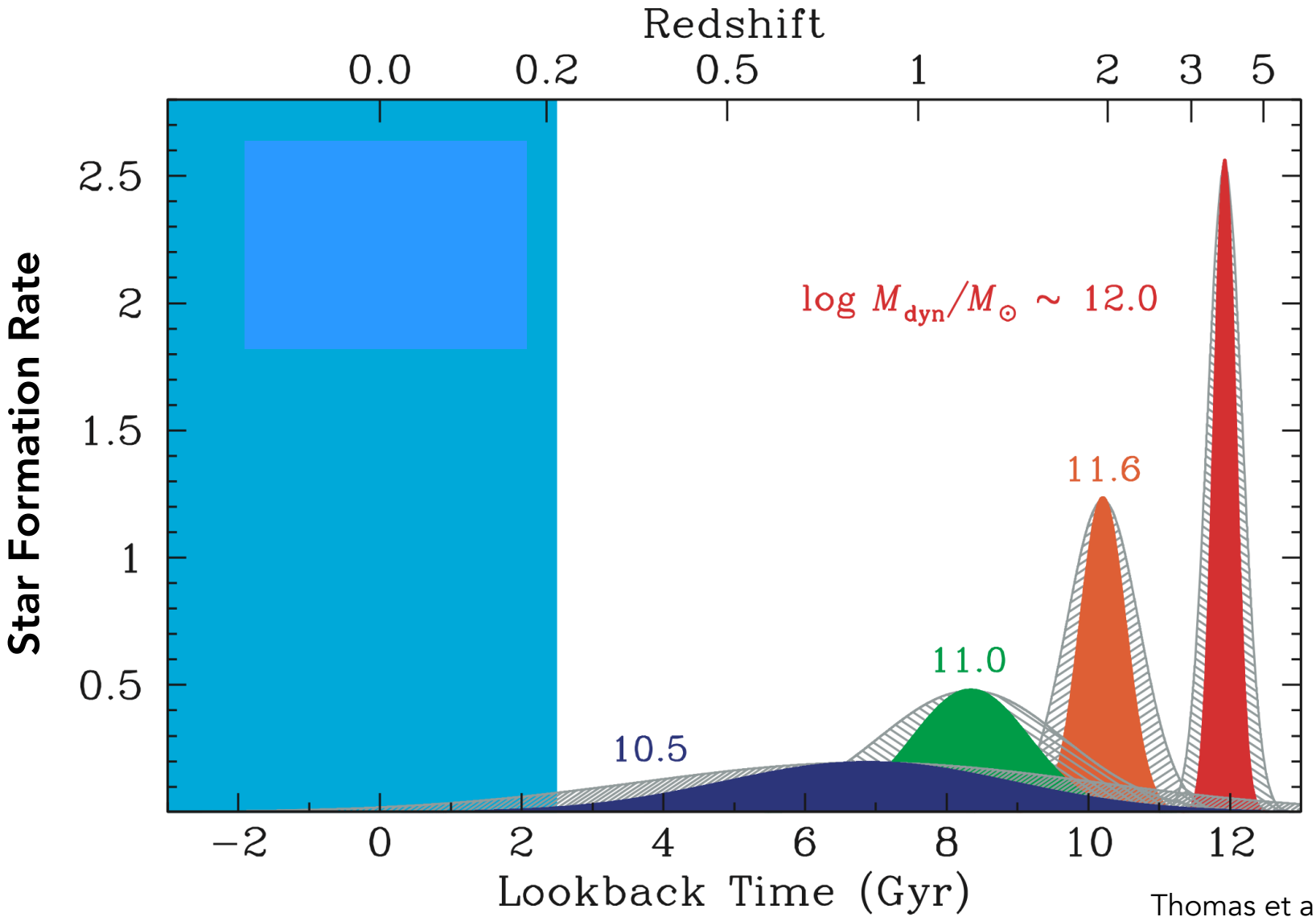
Asplund et al. 2009 (ARAA)

The abundance pattern of quiescent galaxies



Conroy, Graves, van Dokkum 2014

- Simple picture of shorter star formation timescale for more massive galaxies qualitatively explains this trend. No quantitative comparison to models yet.

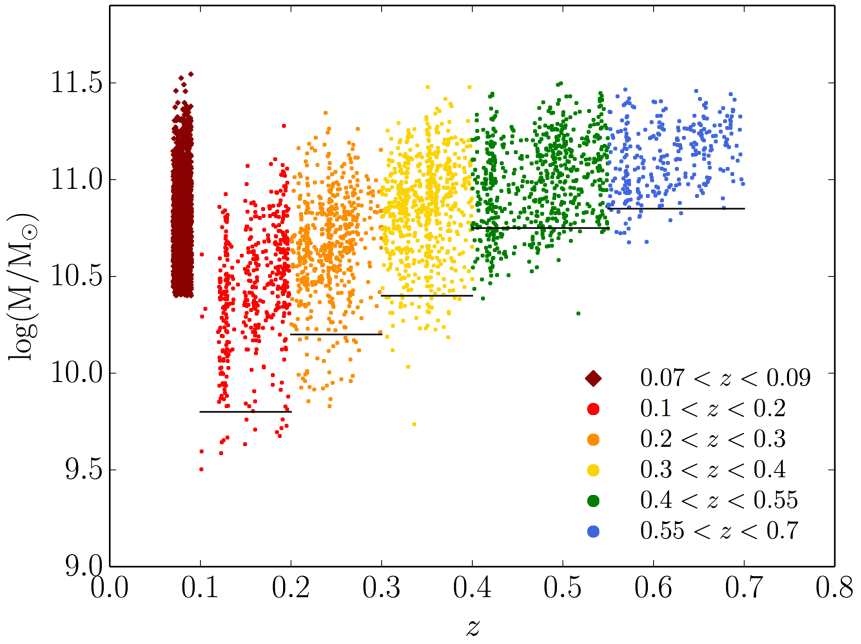


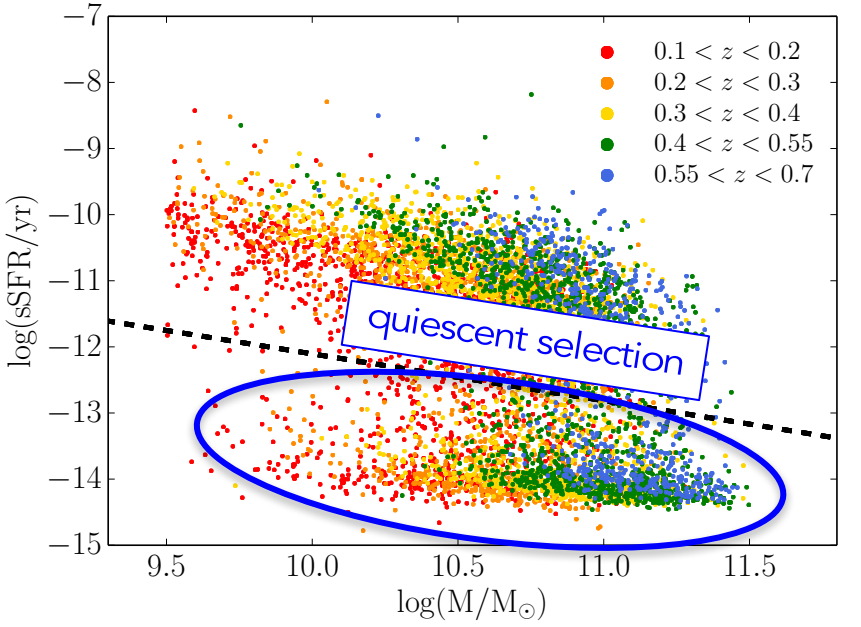
Thomas et al. 2010

The AGES Survey

- 7.7 sq deg spectroscopic survey of the Bootes field in the NOAO Deep-Wide Field Survey
- I<20 selection; 0.1<z<0.7
- 23,000 redshifts via MMT/Hectospec
- Typical continuum S/N of 5-10

- Stack spectra in bins of z, logM

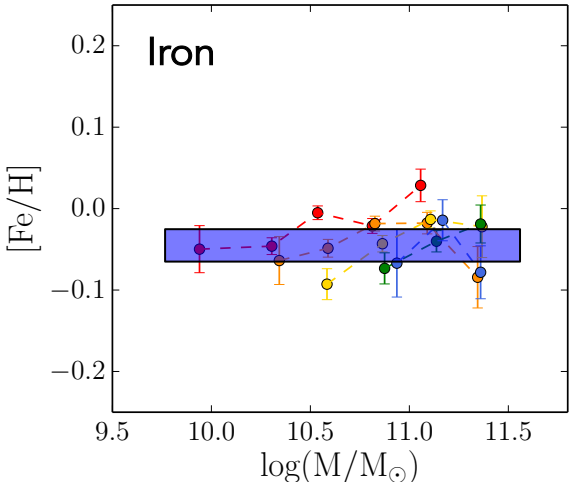


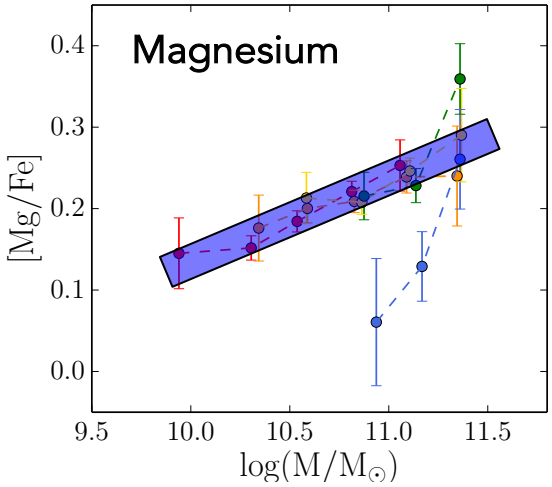


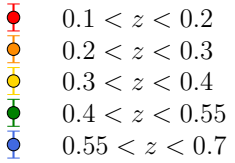
Kochanek et al. 2012

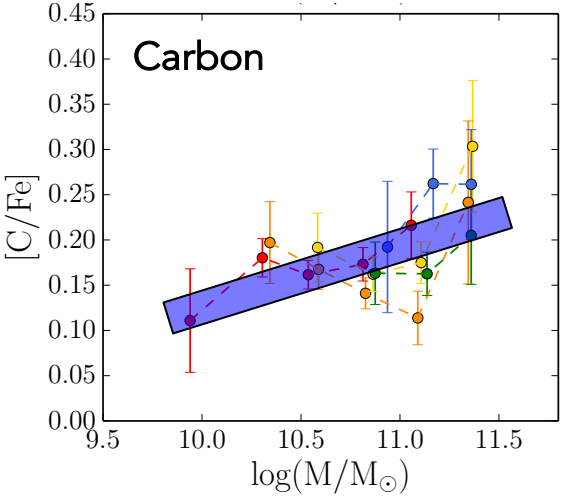
Evolution of Quiescent Galaxies to z=0.7

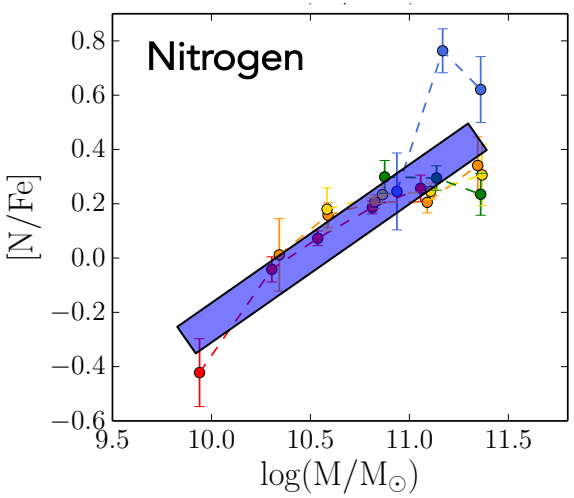
- No evidence for evolution in abundance patterns at fixed mass since z=0.7

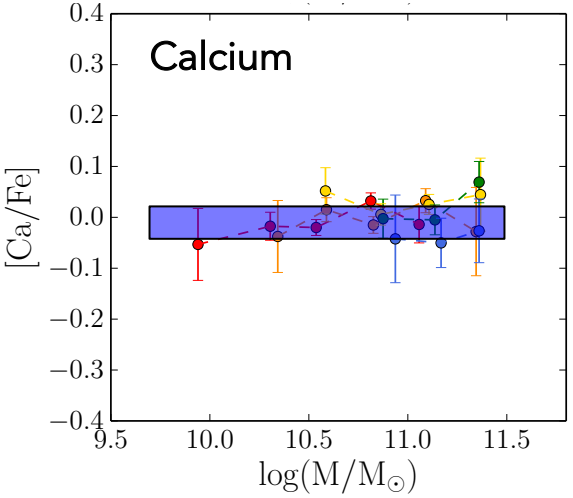






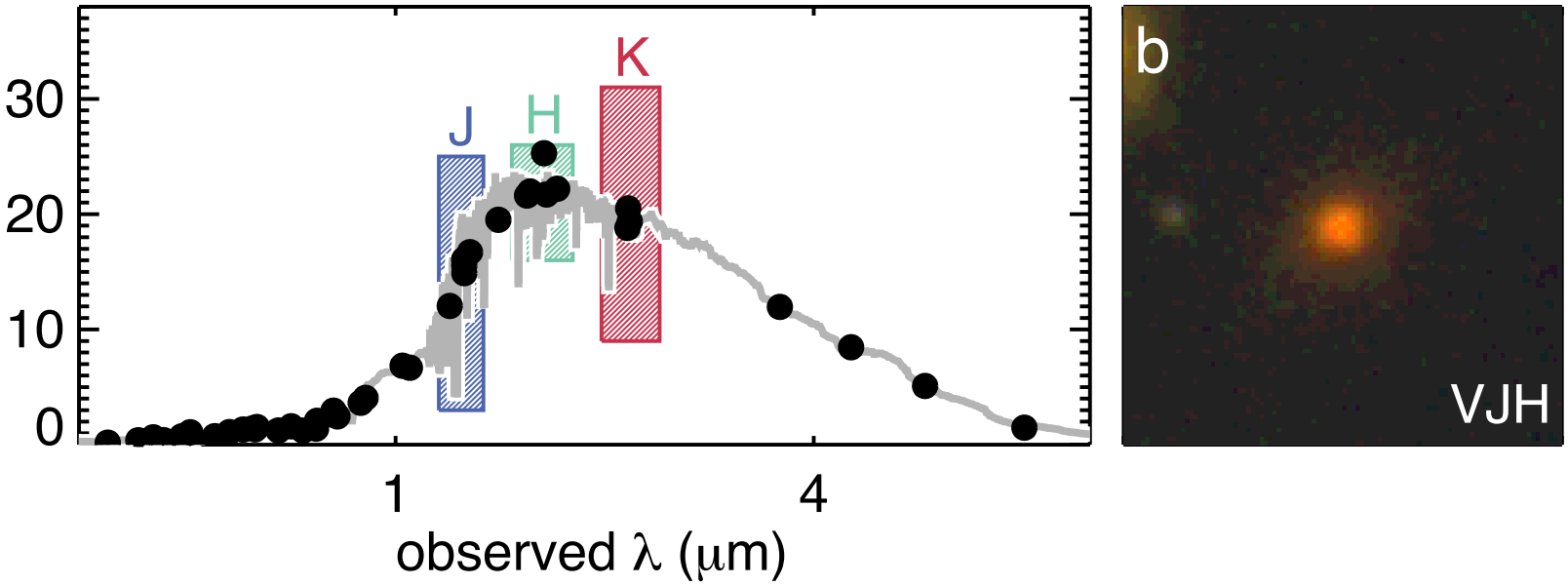






J. Choi, Conroy et al. 2014

A Massive Quiescent Galaxy at z=2.1



Selected from the 3D-HST grism survey
z=2.1; H=20.8 (extremely bright)
Stellar mass ~ $10^{11.5}$ M_{sun}
R_e = 2.1 kpc
SED shows no evidence for young stars (*quiescent*)

Kriek, Conroy, van Dokkum, et al. (Nature, 2016)

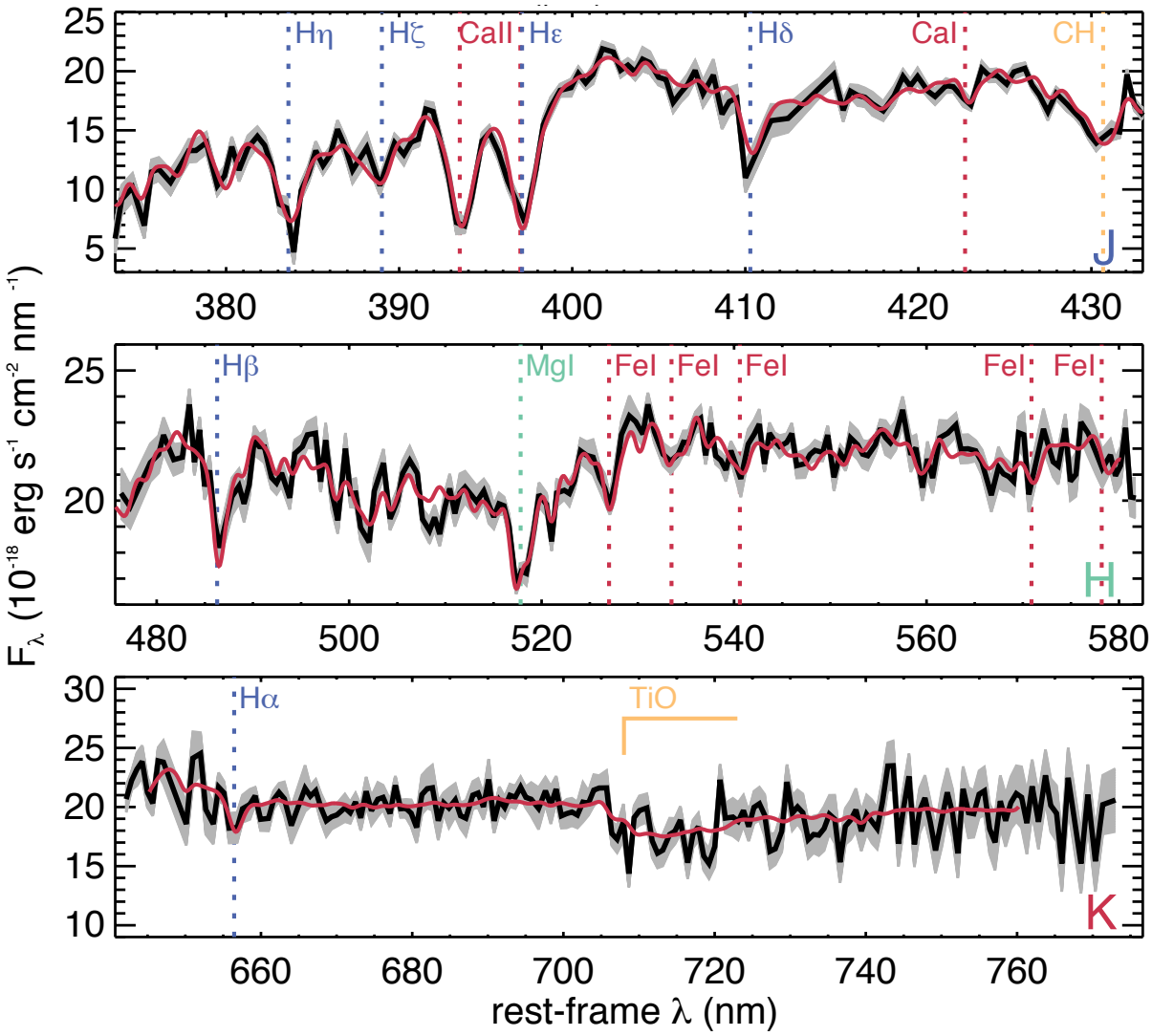
Keck/MOSFIRE Observations

Data

- ~33 hr total observations
- Deepest NIR spectrum to-date of a quiescent galaxy at z>2
- S/N~10-20 per pix

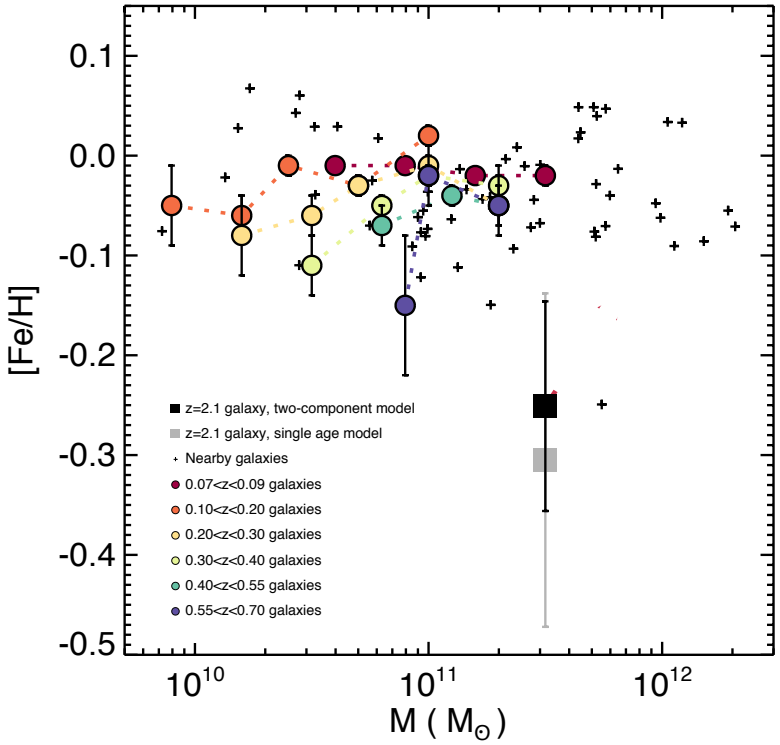
Modeling

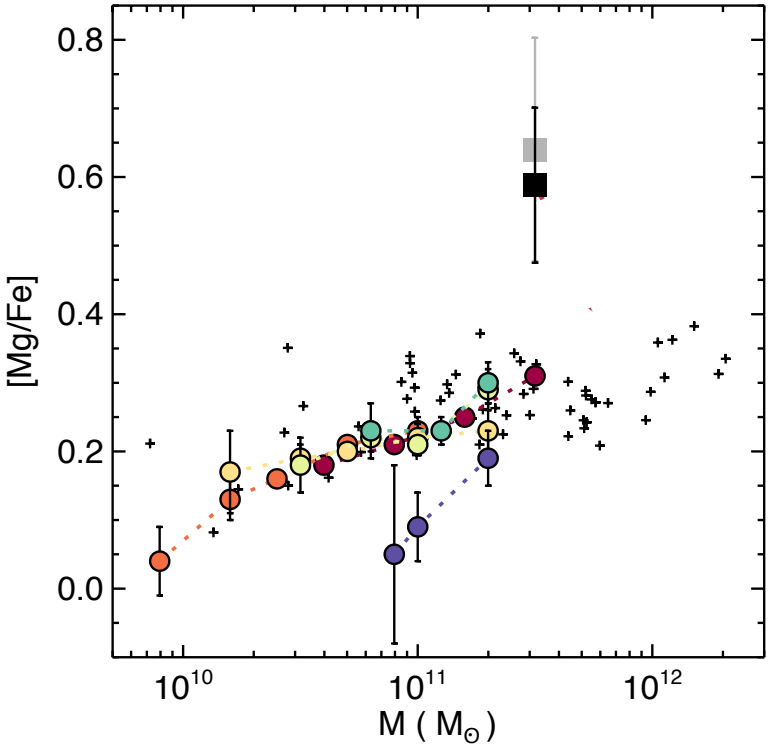
- Parameters include: z, σ, age, metallicity, abundances of C, N, Mg, Ca, Ti, Fe



Kriek, Conroy, et al. (Nature, 2016)

A chemically-extreme stellar population





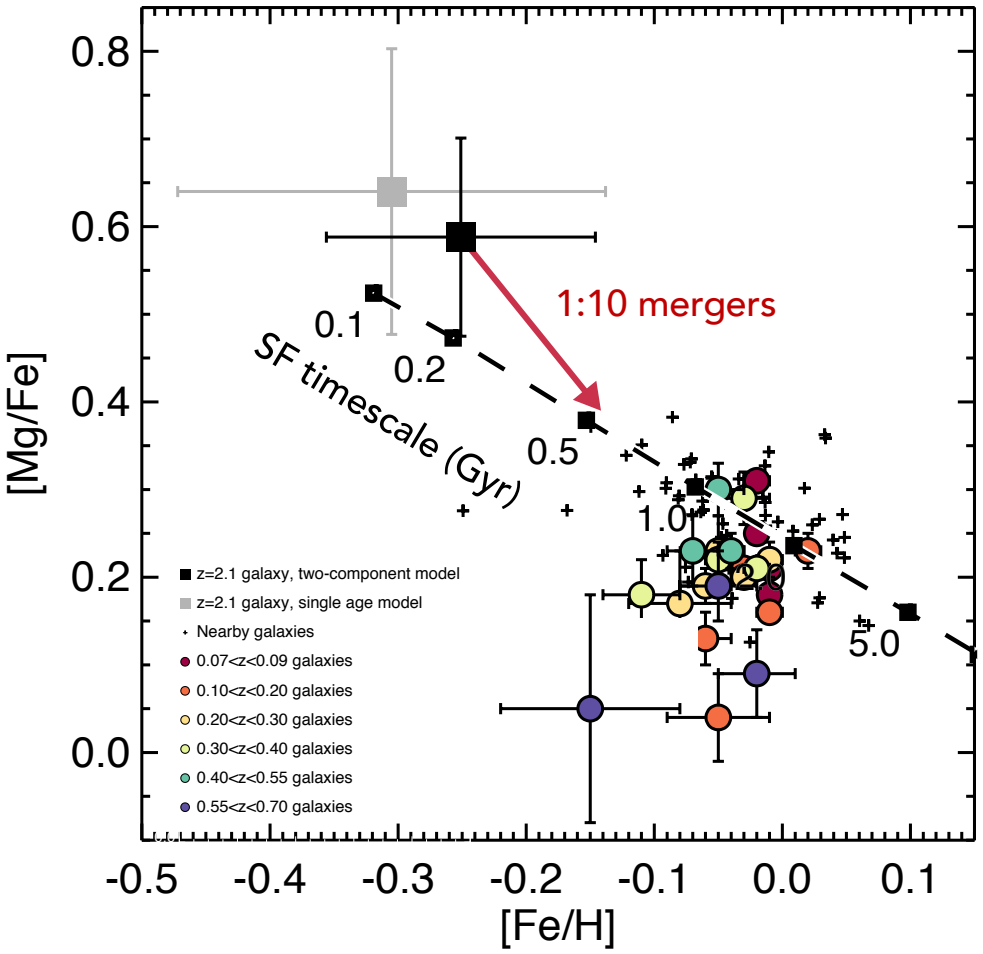
The highest [Mg/Fe] ratio measured from the integrated light of a galaxy to date

Kriek, Conroy, et al. (Nature, 2016)

Extremely Rapid Mass Buildup

Abundance pattern consistent with star formation occurring over ~0.1 Gyr

SFR ~ 10^3 M_{sun}/yr



Kriek, Conroy, et al. (Nature, 2016)

Summary & Connections

- Modeling absorption line spectra has revealed that massive quiescent galaxies are both metal-rich and α-enhanced
  - Suggests very short star formation timescales (<1 Gyr!)
  - *Puzzle: explain positive correlation between [Fe/H] and [Mg/Fe]*

- Measurement of element abundances of quiescent galaxies across cosmic time places strong constraints on formation pathways
  - Suggests that the inner regions of massive galaxies assembled early (z~2-3?); subsequent evolution was "passive"

- Abundance ratios within the quiescent galaxy population offer a unique constraint on stellar yield tables (e.g., Co vs. O vs. Ca).

- Quantitative, accurate models for converting abundance ratios into star formation timescales would be a tremendous advance in this field. We are still (mostly) in the "back of the envelope" era