Star Formation and Chemical Enrichment in the Youngest Galaxies

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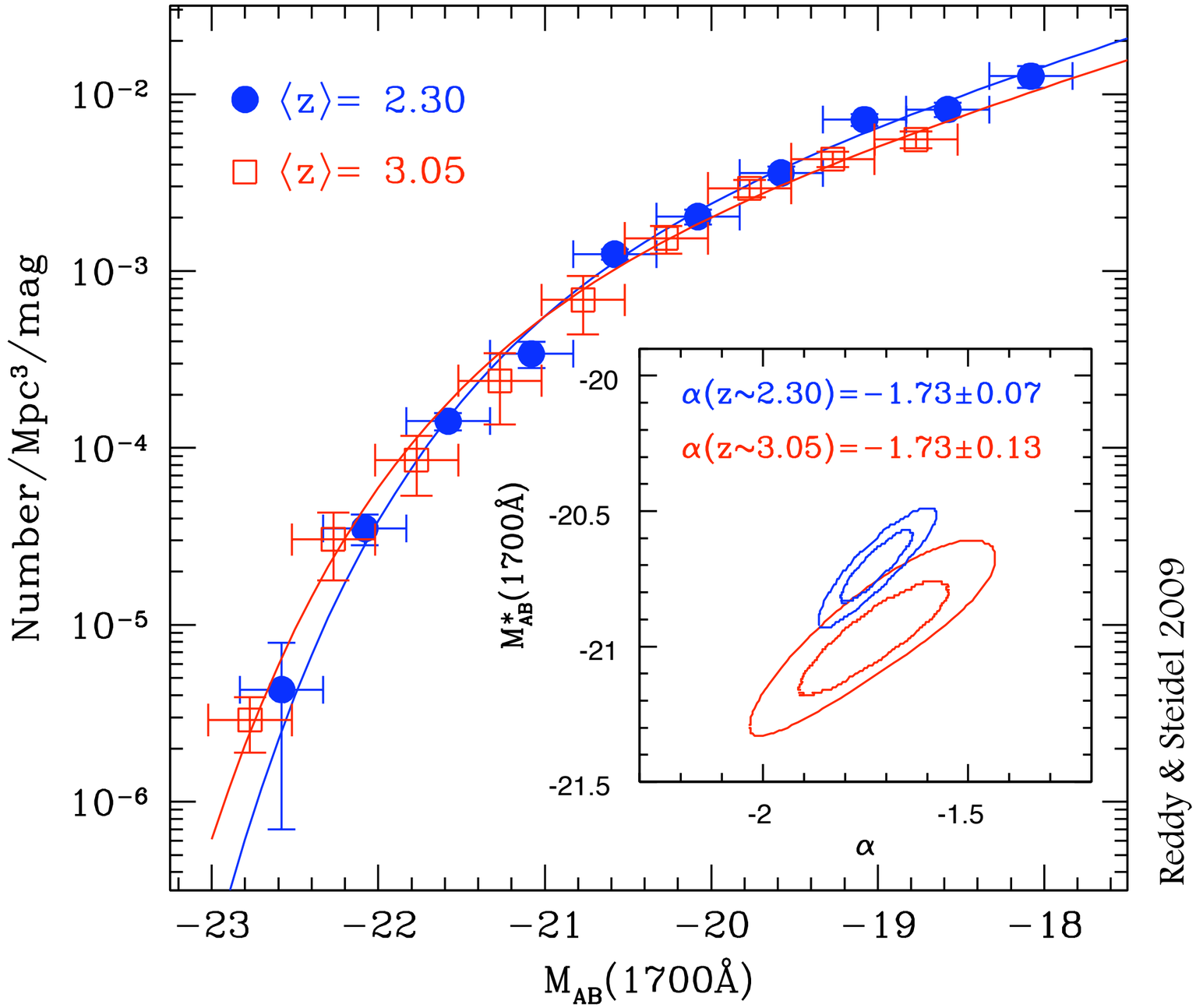
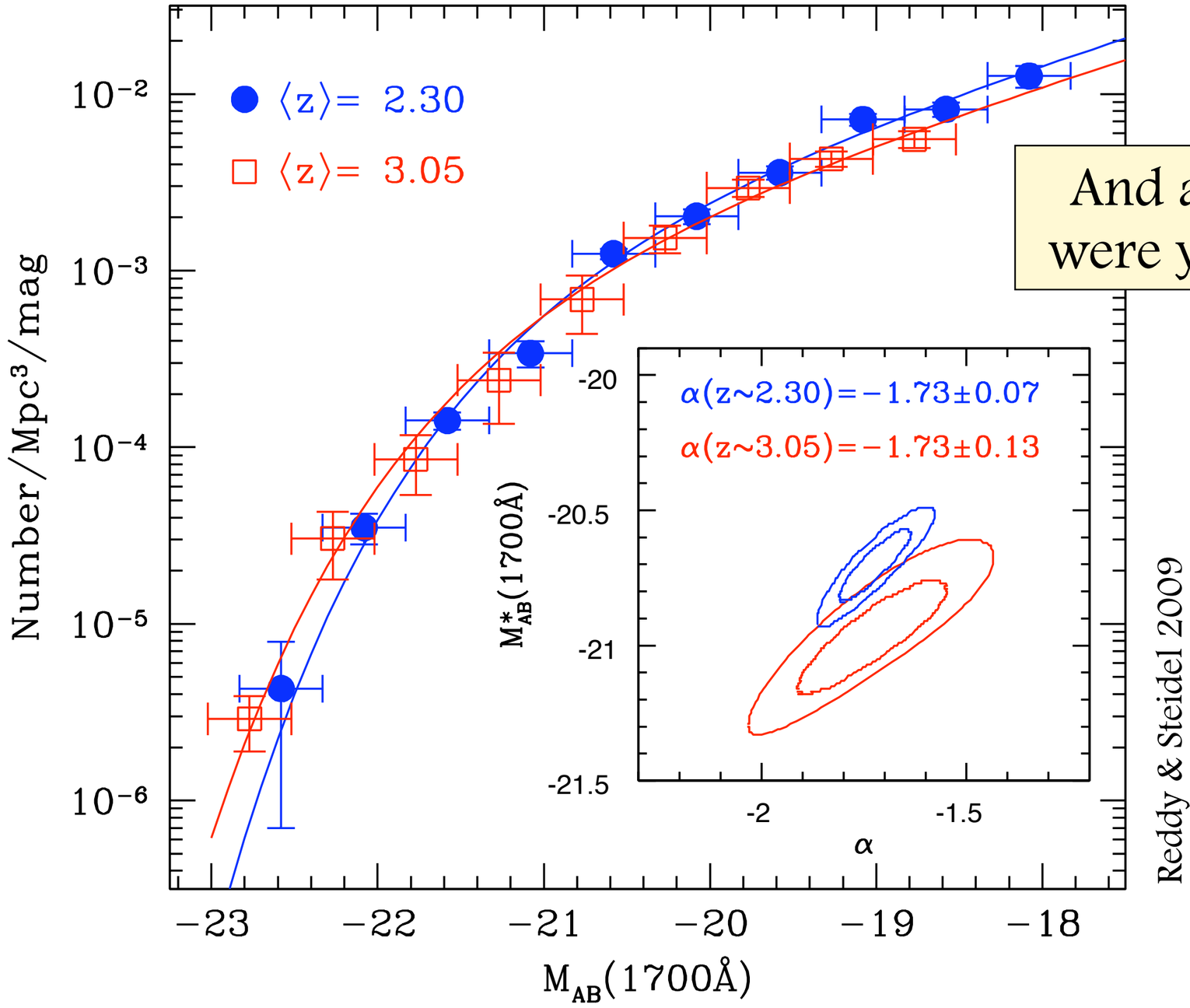
The Importance of Low Mass Galaxies



Low to moderate luminosity galaxies host ~70% of bolometric luminosity, ~25% of stellar mass density at $1.9 < z < 3.4$

The Importance of Low Mass Galaxies



And all galaxies were young once!

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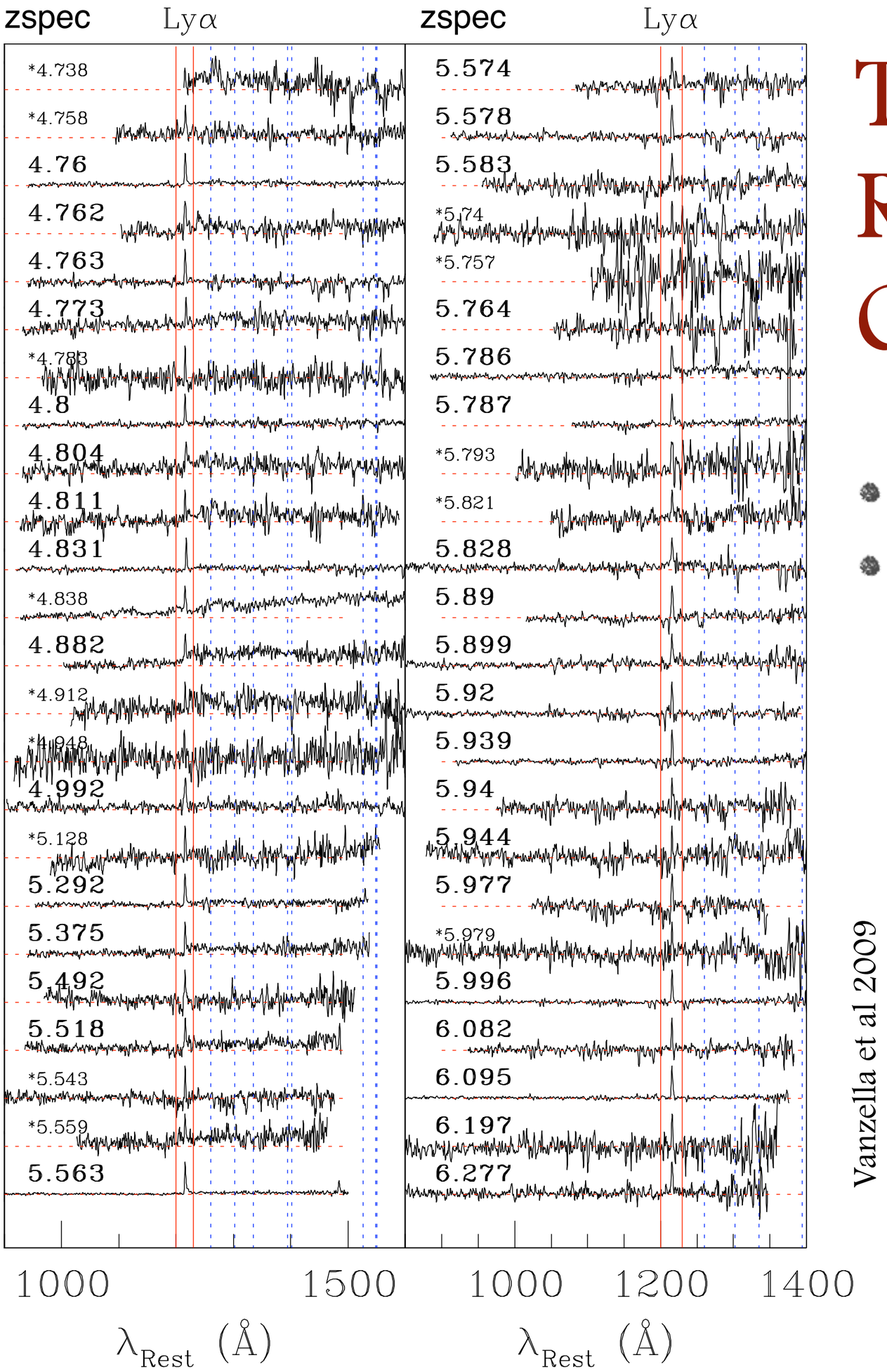
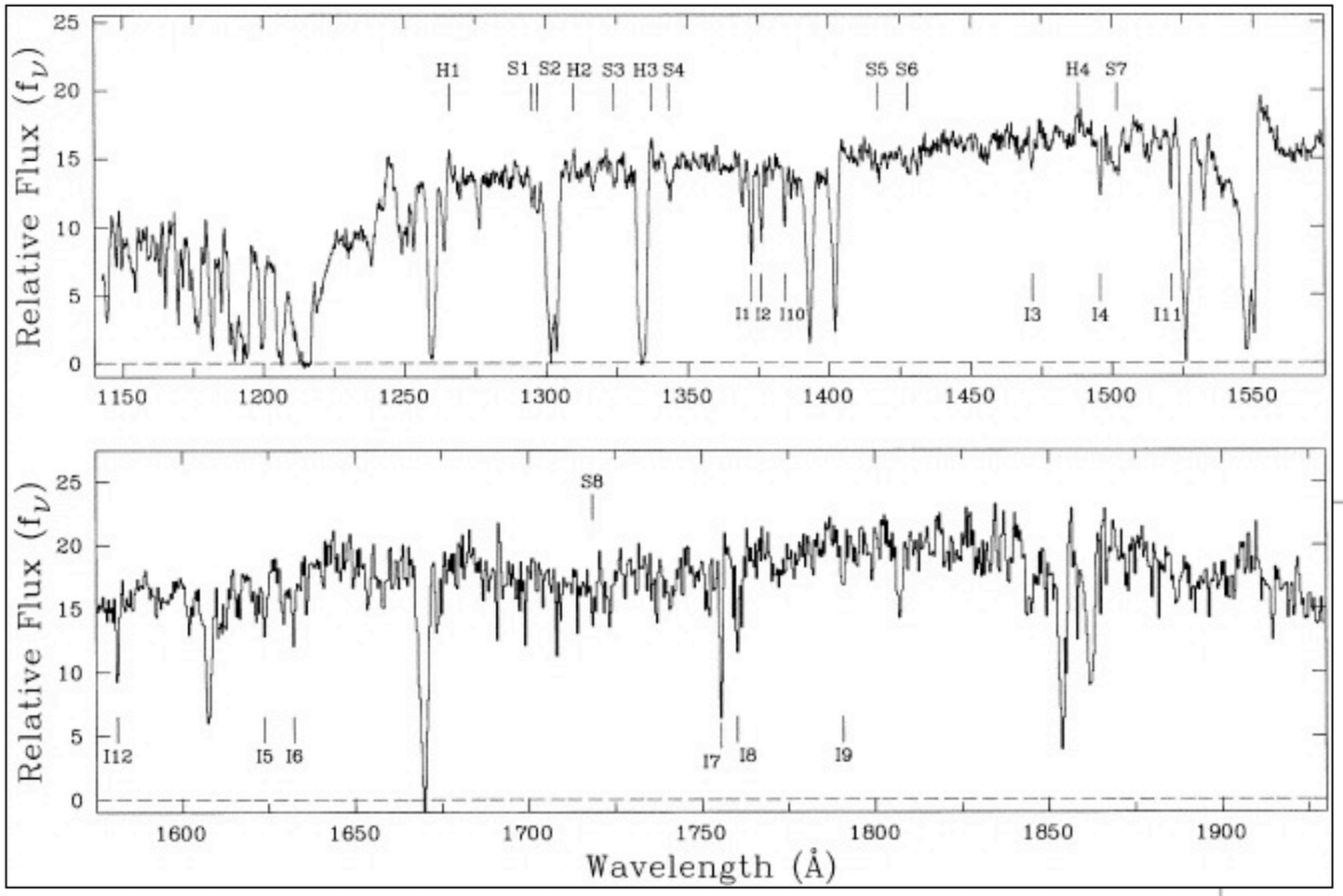


The Highest Redshift Galaxies

- Too faint for detailed study
- Look at plausibly similar galaxies at z~2-3?

Rest-Frame UV Spectra

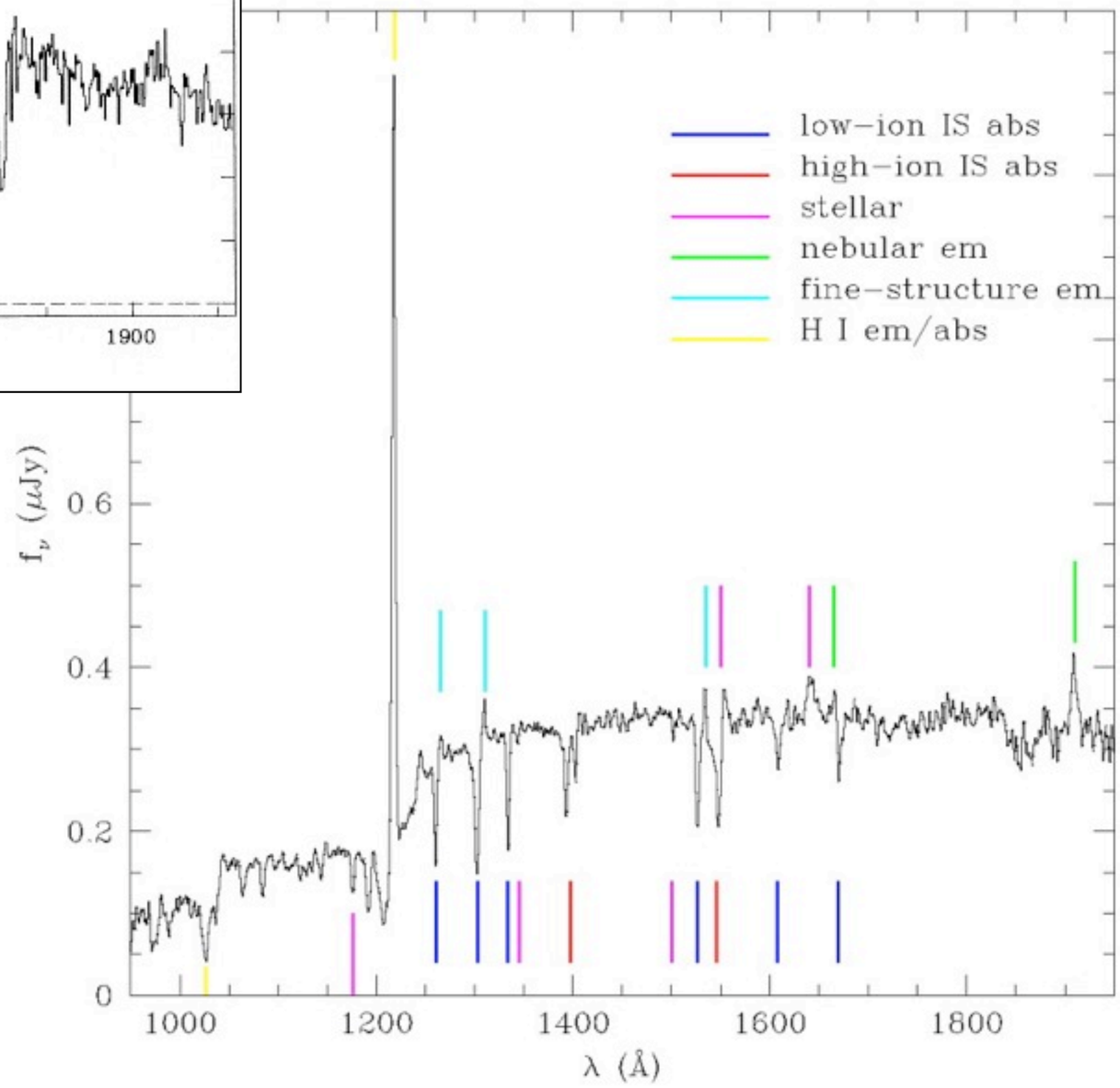


Pettini et al 2000

Lensed z=2.7 LBG cB58

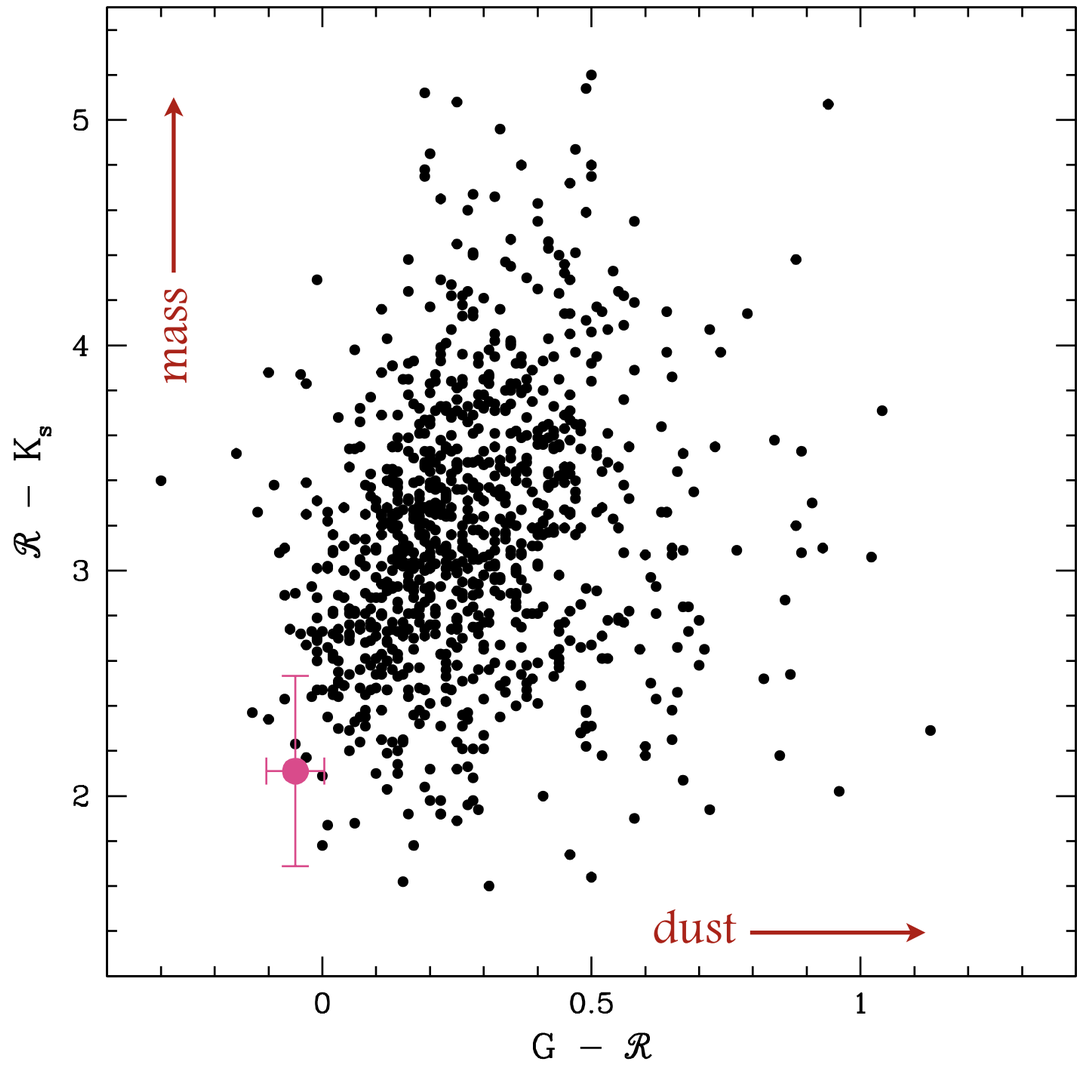
z~3 LBG
composite spectrum

Shapley et al 2003

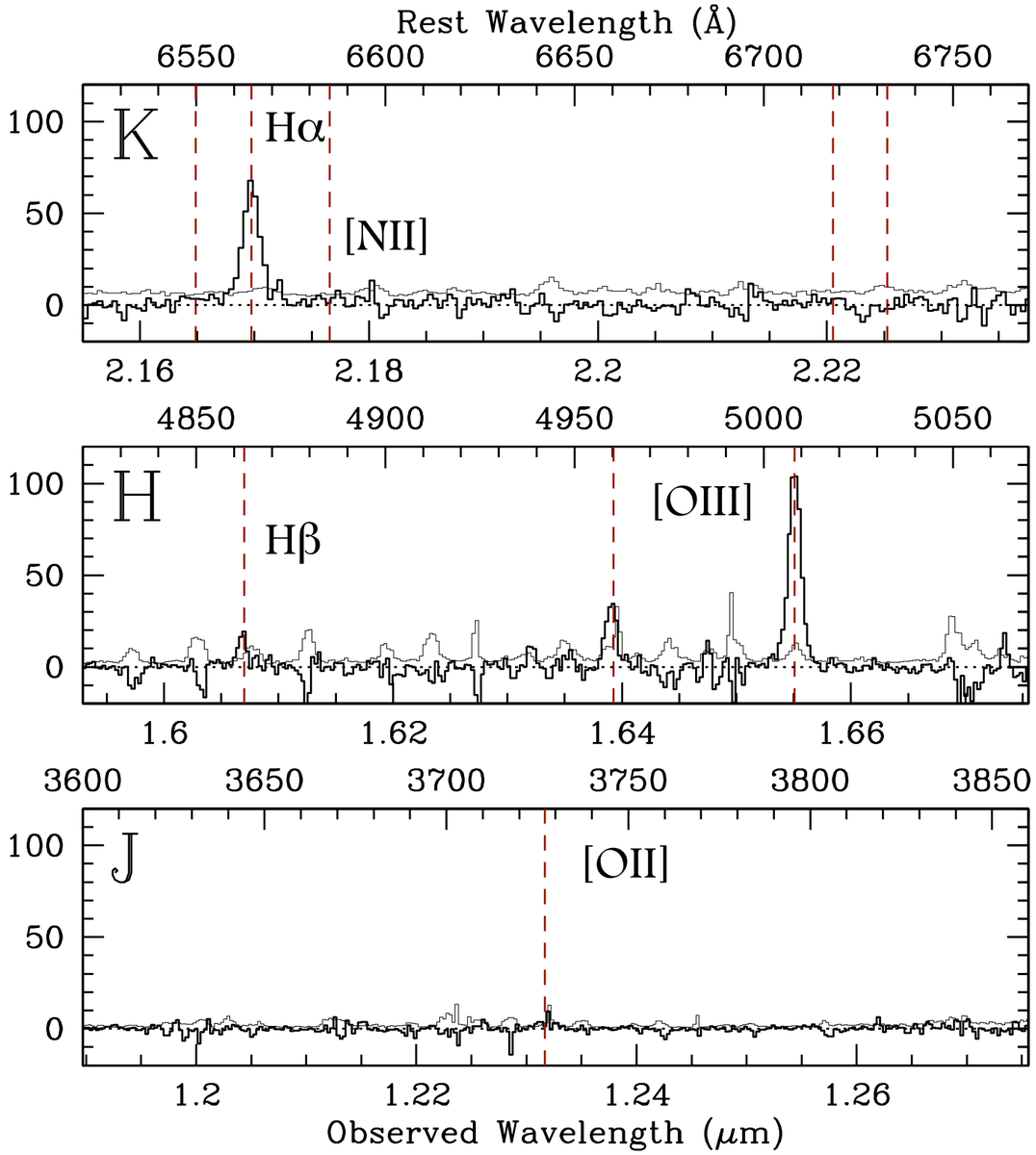


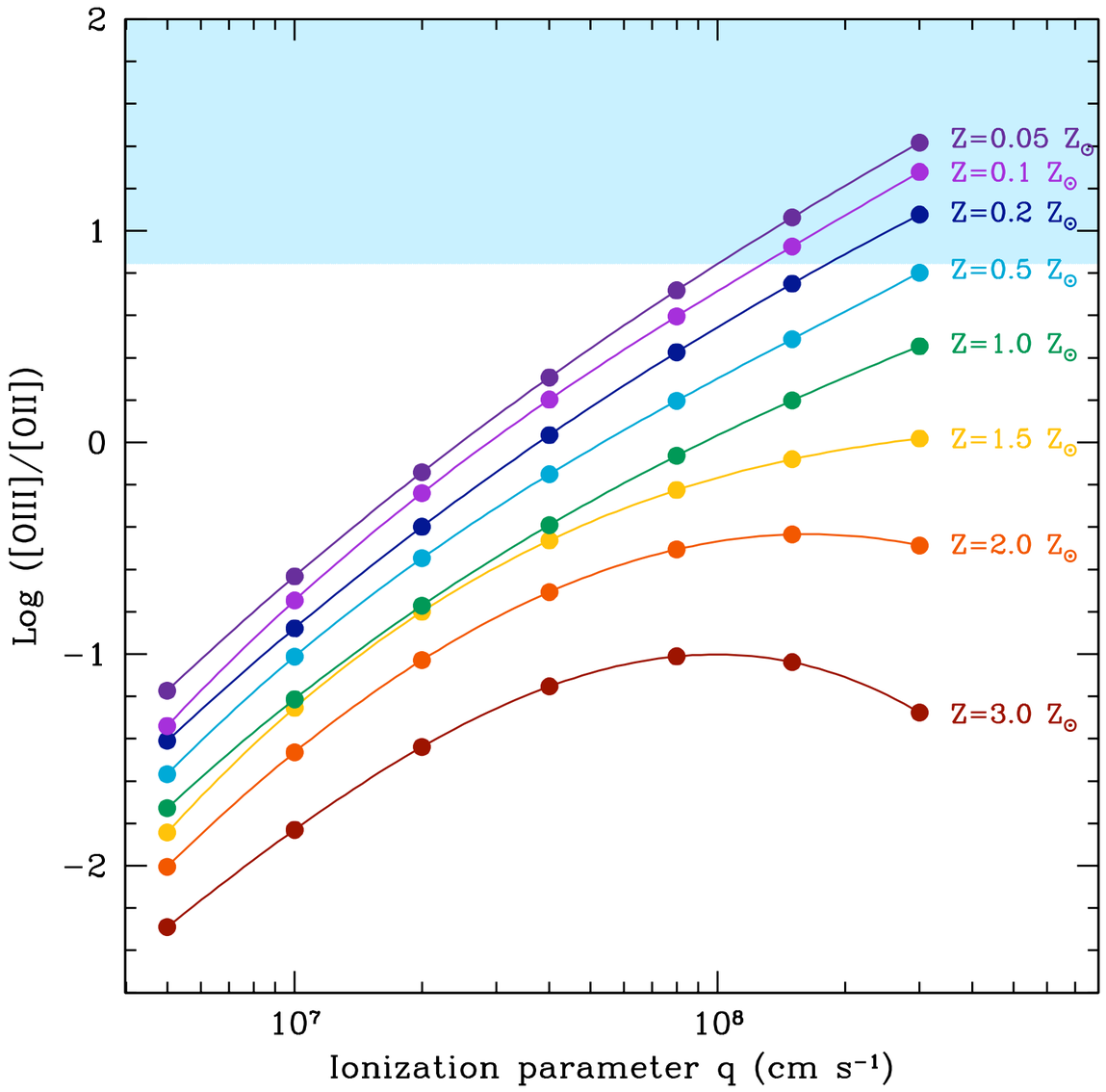
A Low Mass, Low Metallicity Galaxy at z=2.3

- Strong Lyα emitter: $W_{Ly\alpha}$ ~ 60 Å
- Very little dust
  - Hα/Hβ ~ 3
  - E(B-V) ~ 0.03
  - β = -2.1, among bluest in sample
  - Undetected in deep 24 μm data
- $M_{star} = 9 \times 10^8\ M_\odot$
- Age ~ 35 Myr ~ t_{dyn}
- SFR ~ 15 $M_\odot$ yr^{-1}
- $M_{gas} \sim M_{dyn} \sim 3 \times 10^9\ M_\odot$
- Gas fraction μ ~ 0.8 from K-S law
- Z ~ 1/6 $Z_\odot$ from R_{23}, N2 limit
- Unusual in current samples at z~2, but more typical at fainter limits and in early universe?



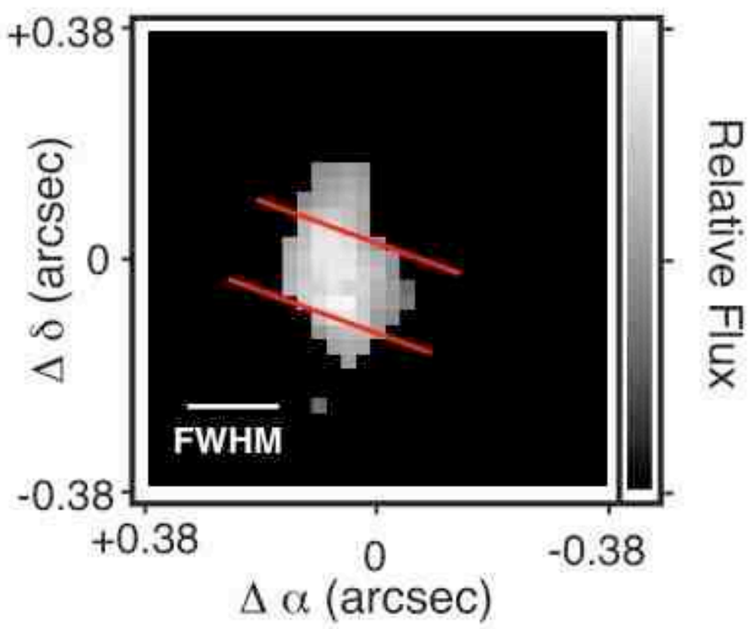
Rest-Frame Optical Spectra



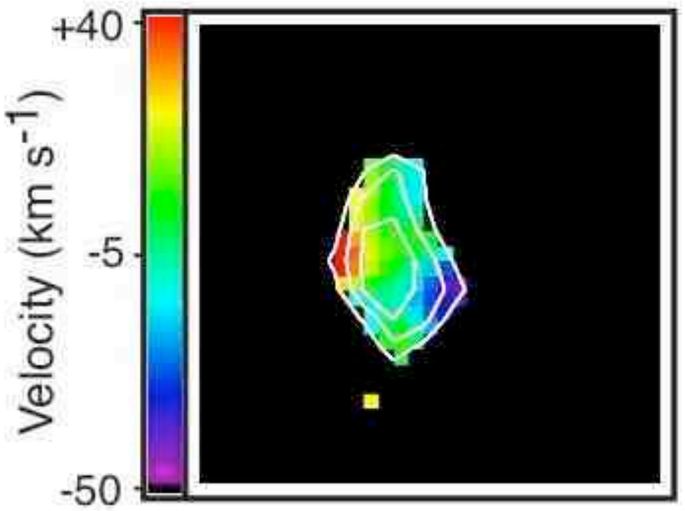


- Low metallicity: 12 + log (O/H) = 7.9 ~ 1/6 $Z_\odot$
- High ionization parameter

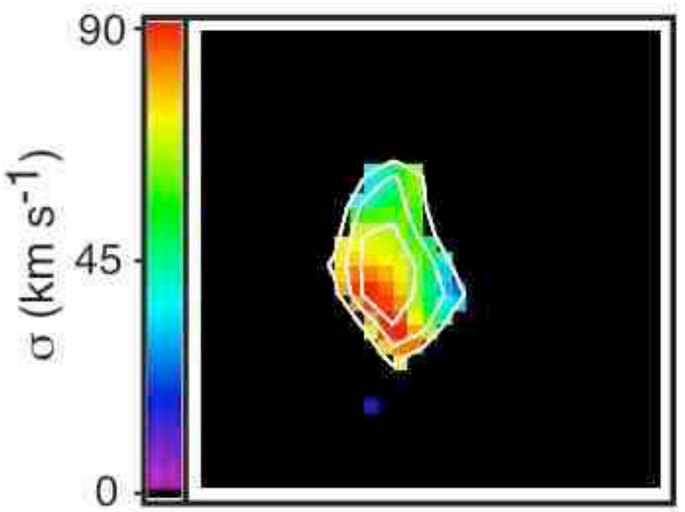
Kinematics with OSIRIS



Hα flux map



Relative velocity



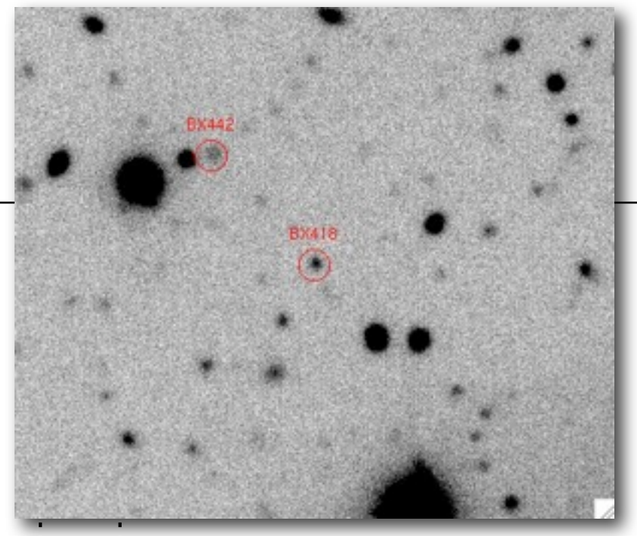
Velocity dispersion

Law et al 2009

- Integral field spectroscopy with Keck OSIRIS, LGS AO
  - ~0.15" resolution
- Compact: r ~ 1 kpc
- Kinematics dominated by random motions, not rotation
  - v ~ 33 km s^{-1}, σ ~ 60 km s^{-1}
  - v/σ ~ 0.5, typical of low to average mass galaxies
- Σ_{SFR} ~ 12 $M_\odot$ yr^{-1} kpc^{-2} → Σ_{gas} ~ 2000 $M_\odot$ pc^{-2}

Outflow Kinematics

- Lyα redshifted by ~300 km s^{-1}
  - FWHM ~ 800 km s^{-1}
- Interstellar lines blueshifted by ~200 km s^{-1}
  - Unresolved (spectral resolution ~350 km s^{-1})
- Typical values, except narrowness of absorption
  - S/N issue?



Lyα and C IV absorption from BX442
z=2.176, impact parameter 17" ~ 135 kpc

Normalized Flux

Rest Wavelength (Å)

Keck LRIS, 11.6 hr integration

Absorption from Outflowing Gas

BX418

z~2 composite

Low ionization lines:
Si II ratio → saturated
weak → low covering fraction

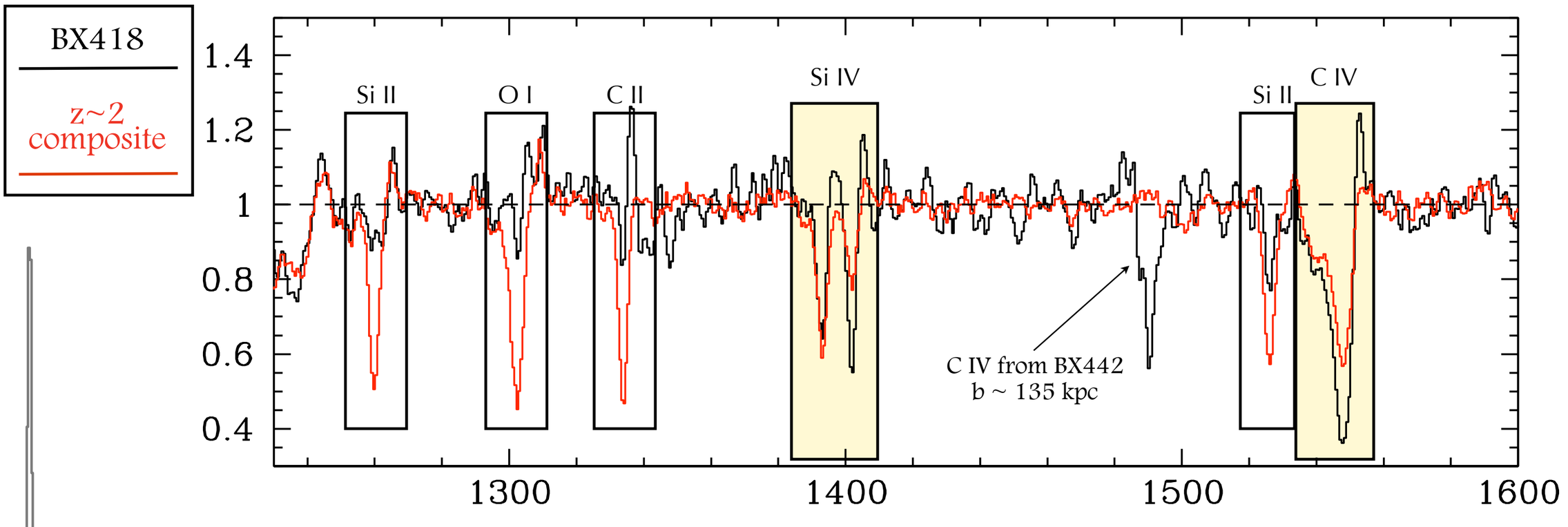
Si II
O I
C II
Si II
Fe II
Al III

Normalized Flux

Rest Wavelength (Å)

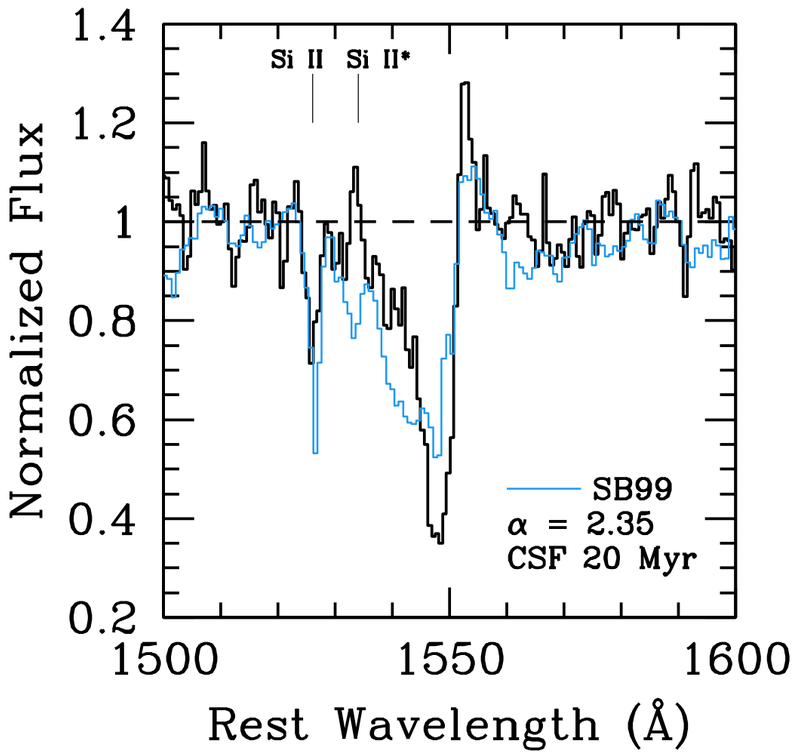
Rest-frame UV spectrum:
11.6 hrs Keck LRIS

Absorption from Outflowing Gas

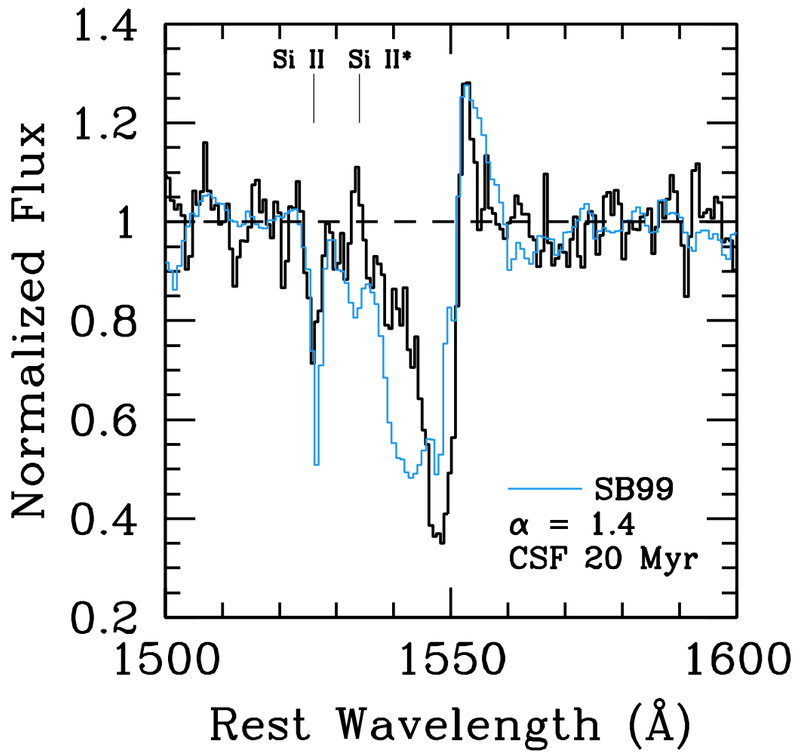


- High ionization lines as strong or stronger than average spectrum
- Si IV ratio indicates ionized gas optically think
  - This is unusual!
  - Covering fraction ~50%
- Compare very low covering fraction of neutral gas (~10%)
- Higher fraction of the outflowing gas is highly ionized?

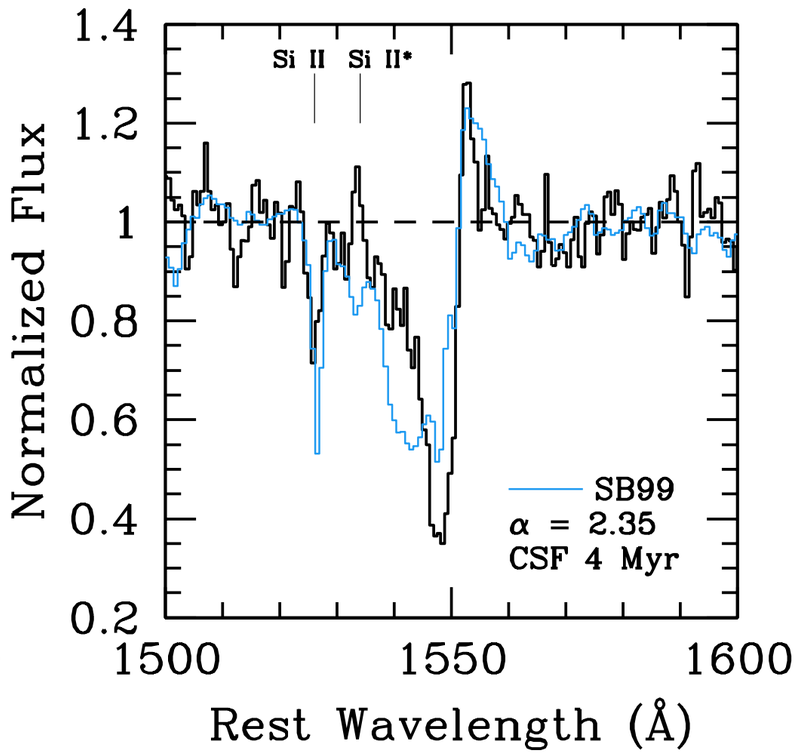
C IV P Cygni Emission and the IMF



Standard Salpeter



Top-heavy IMF



4 Myr W-R dominated

- Sensitive to age, metallicity, top end of IMF
- Unlike other measured high redshift galaxies, not well-fit with Salpeter IMF
  - Requires either flatter top end slope or domination by young W-R stars
  - Trends in composite spectra suggest young stars dominate

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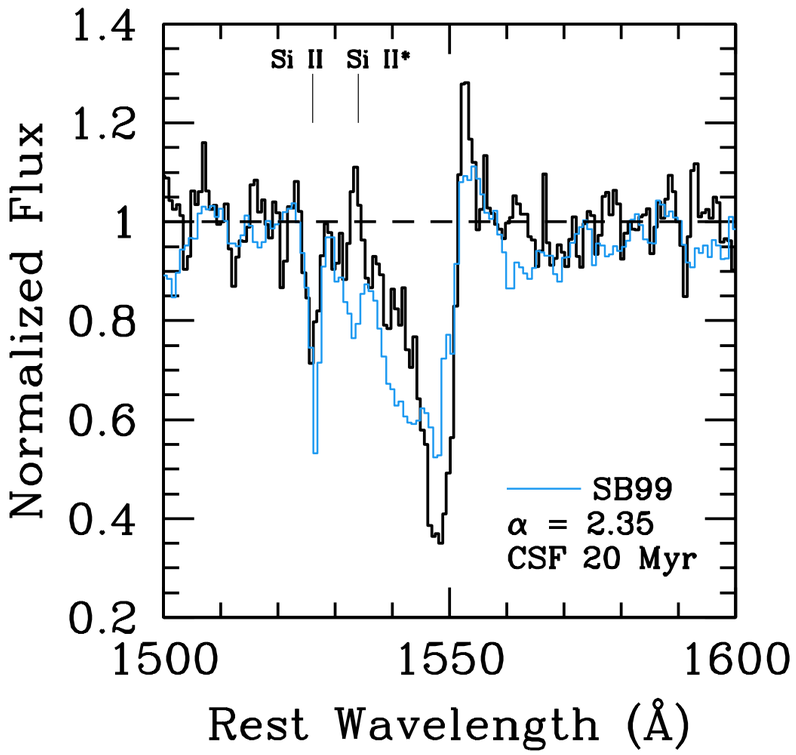

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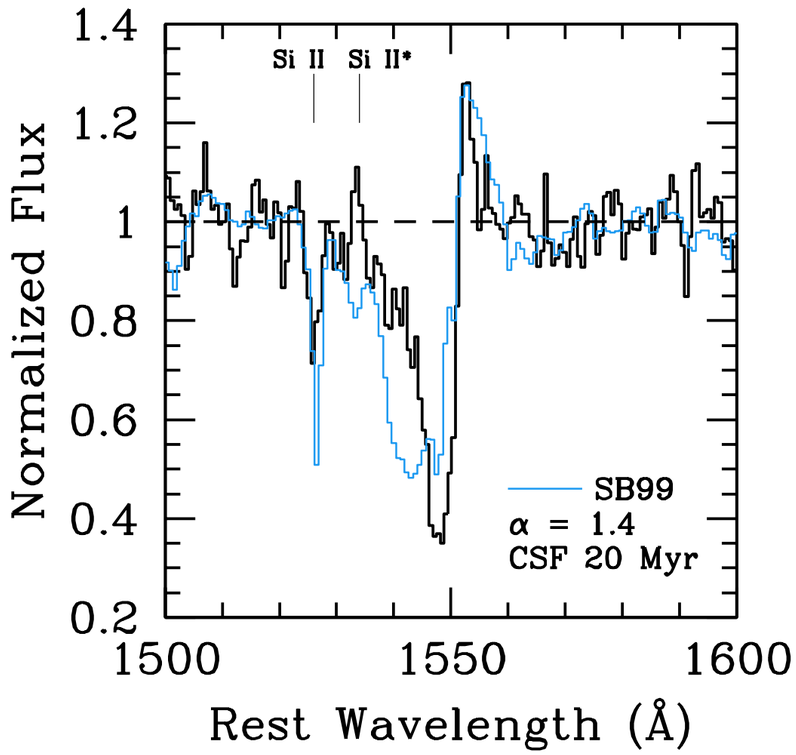

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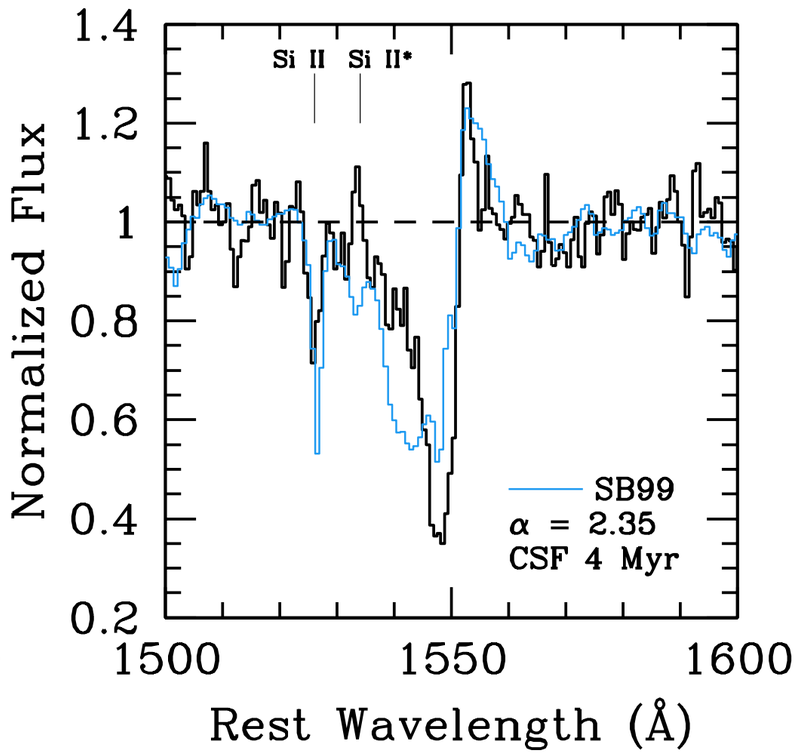

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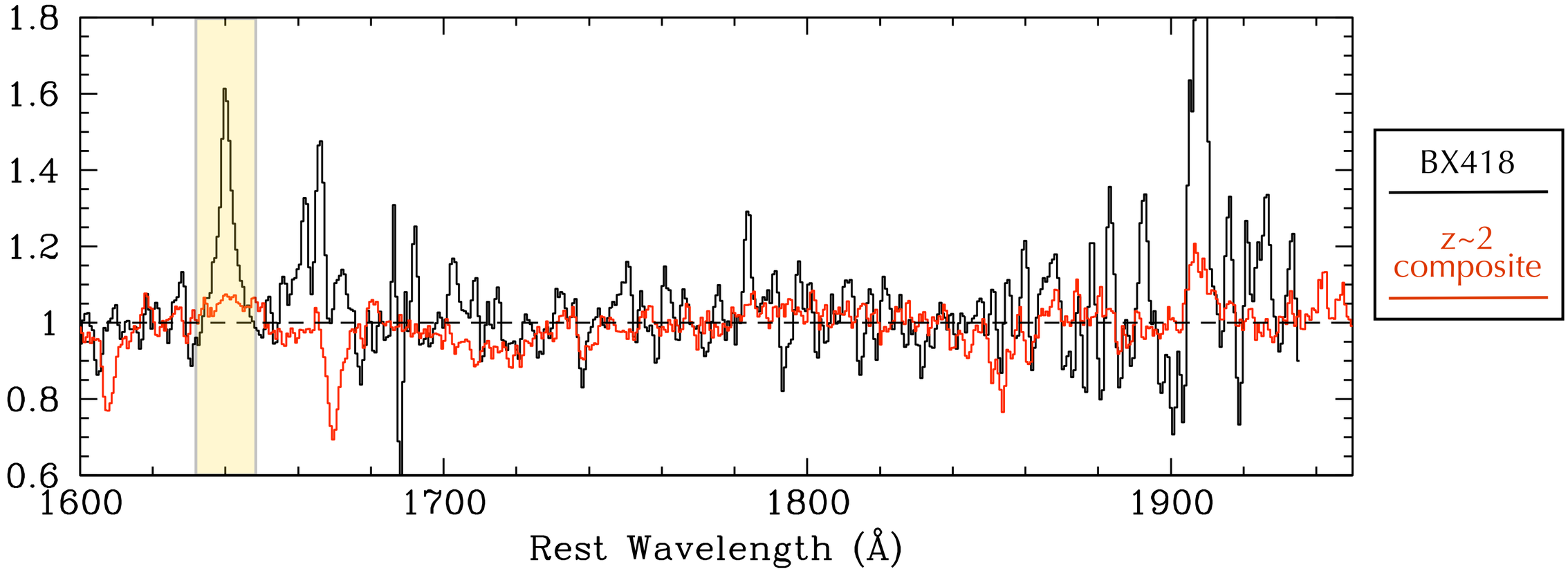
Emission Lines: He II



- Very strong He II λ1640 emission
  - Produced only by hottest O and W-R stars
  - Best fit with broad stellar component (FWHM ~ 1100 km s^{-1}) + narrow nebular emission
  - Harder ionizing spectrum from low metallicity W-R stars
  - Stellar wind line hard to explain at low metallicities?
  - Most z~2-3 galaxies show only broad stellar emission

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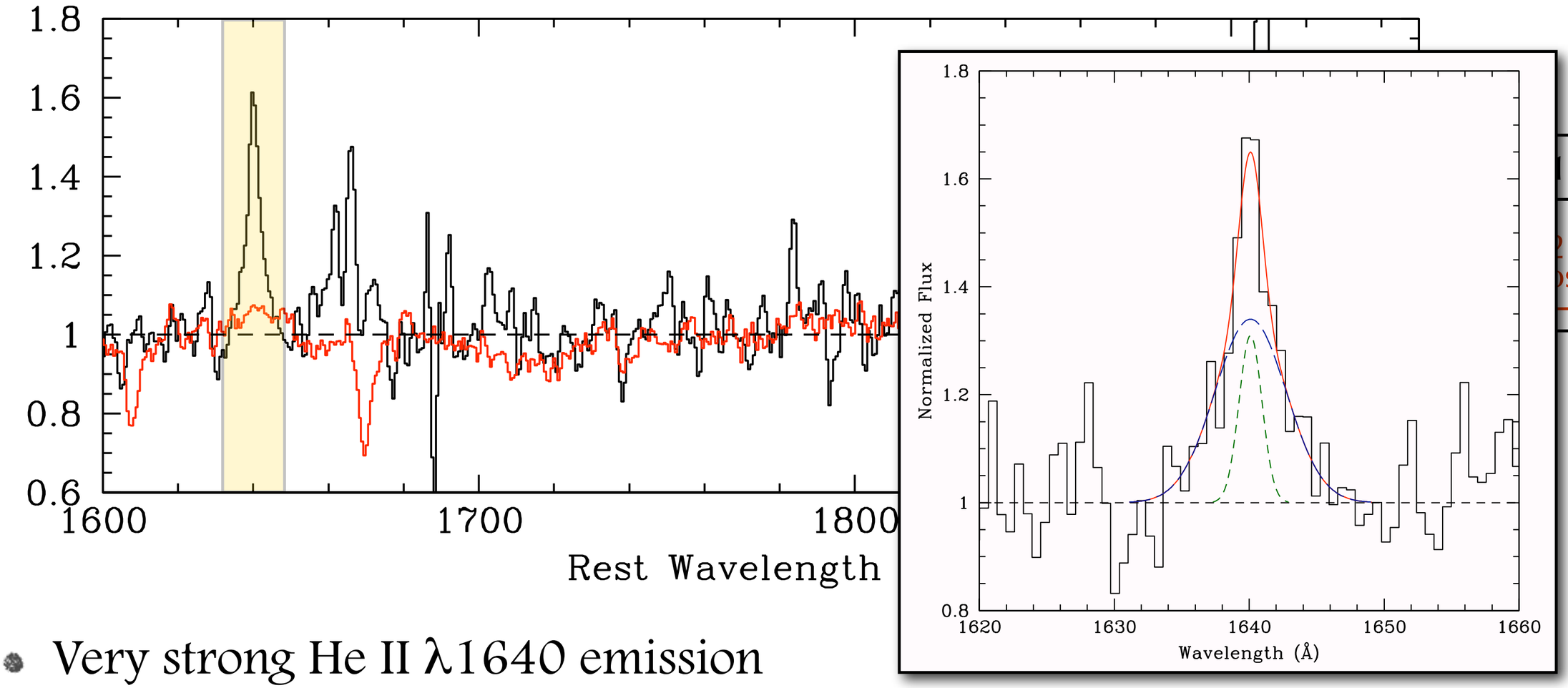

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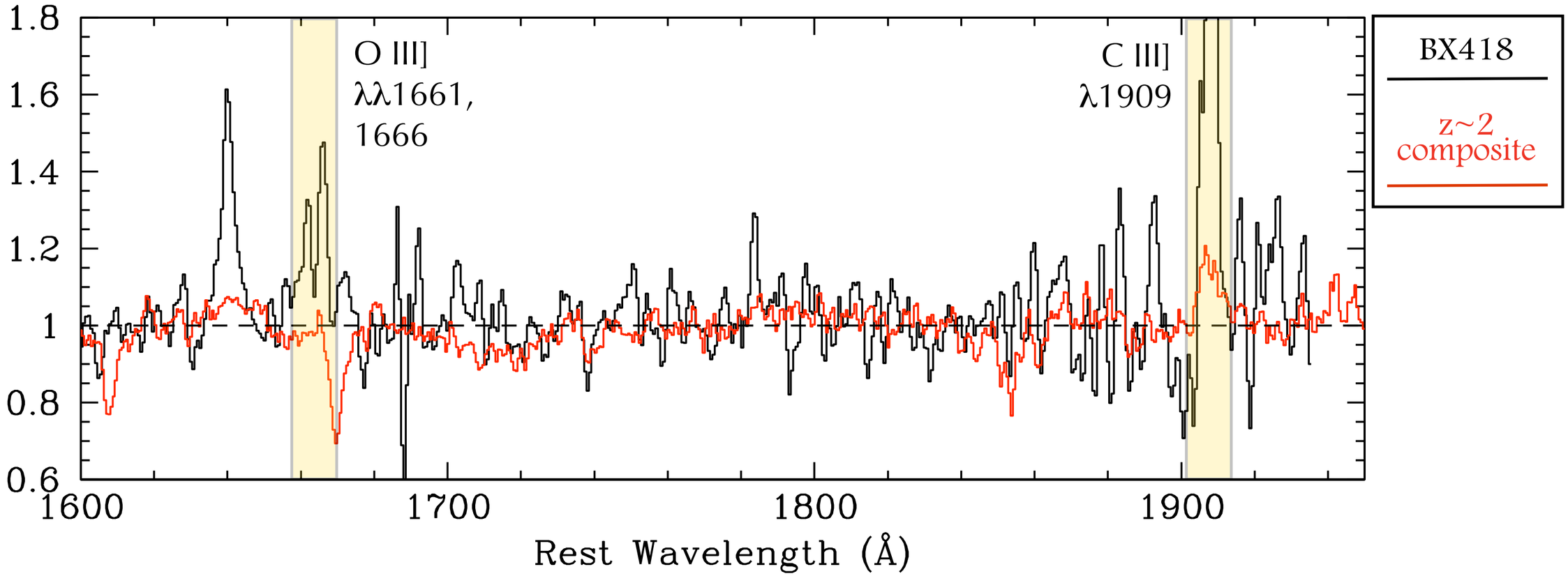
Nebular Emission Lines



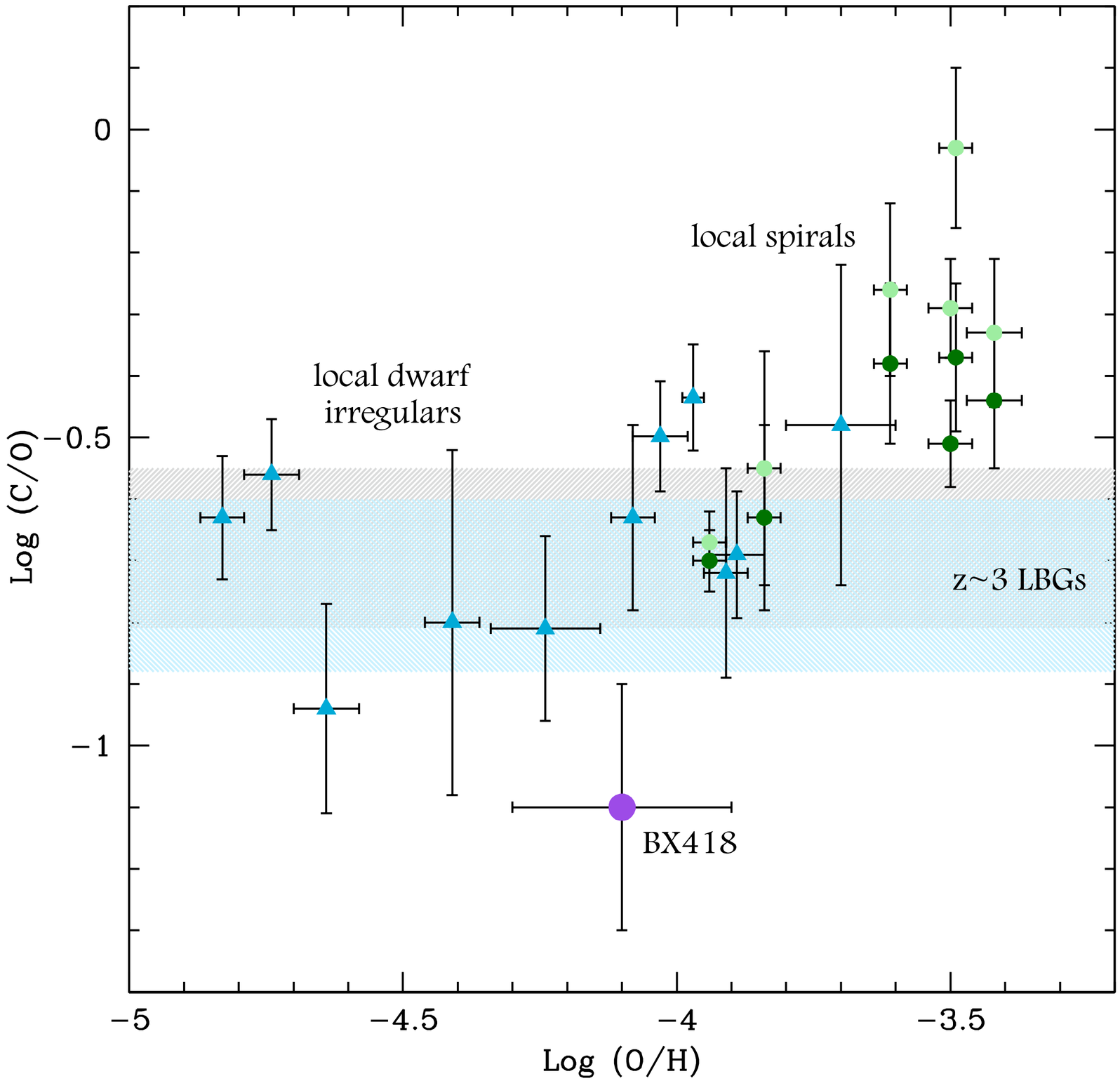
- Nebular emission from O III], C III]
- C III] increases with ionization parameter, peaks at Z ~ 0.2 $Z_\odot$
- One of very few detections of O III] in an individual galaxy at high redshift
  - Weak even in composites
- Use to estimate C/O abundance ratio

C/O Abundance

O produced primarily in massive stars

C from both high and intermediate mass stars

Delayed production of C relative to O in young stellar populations



Conclusions

- Rest-frame UV spectra contain a wealth of information
- Detailed studies of z~2 galaxies may provide insight into galaxies in the very early universe and at lower masses
- Physical conditions in young, nearly dust-free galaxies are different from both local starbursts and more typical high redshift starbursts
  - low metallicities
  - high ionization parameter
  - harder ionizing spectrum indicated by He II recombination line
  - rapid buildup of heavy elements
- Detailed modeling in progress