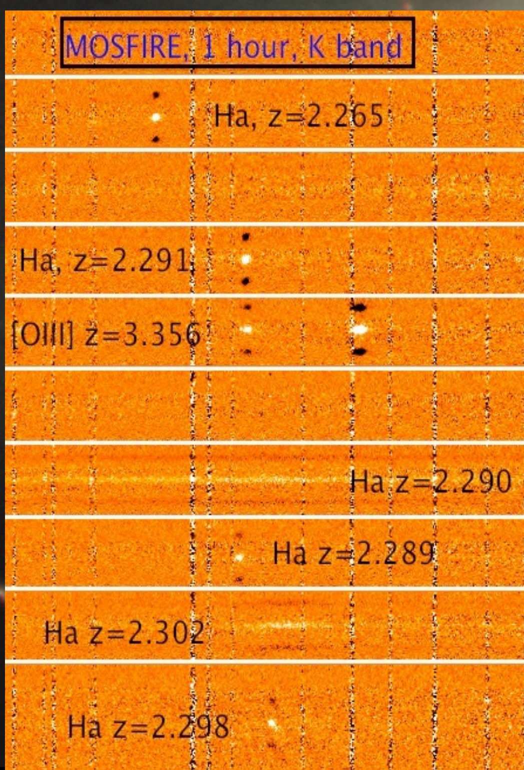
KBSS-MOSFIRE

Reconciling the Far-UV and Nebular Spectra of High Redshift Galaxies

New Constraints on Massive Stellar Populations, Metallicity, and Nebular Diagnostics



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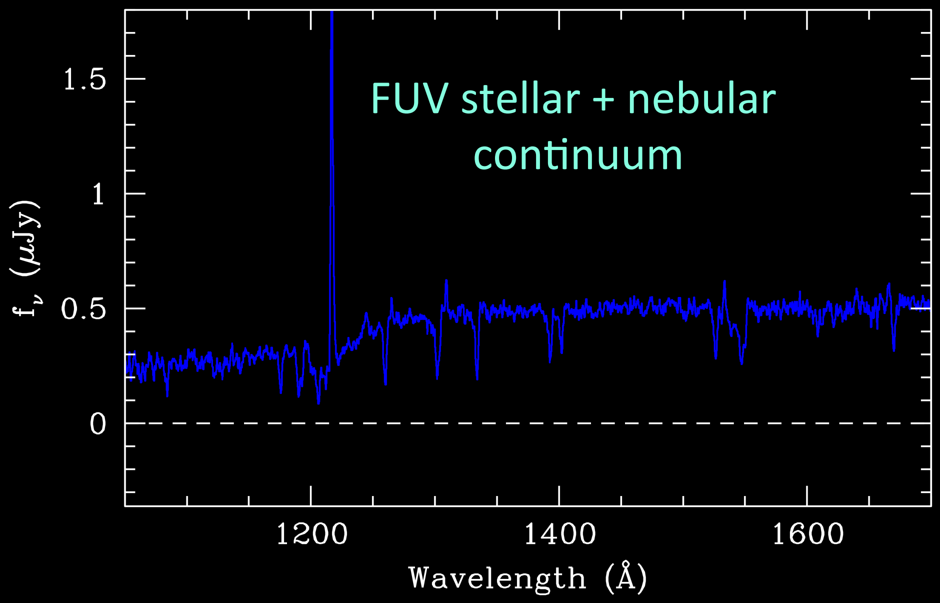
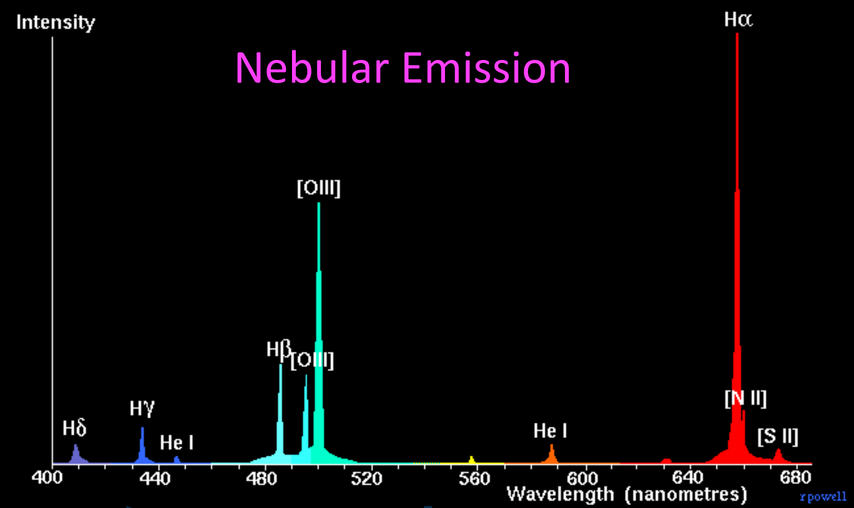
IAP, June 2016

Basic Idea

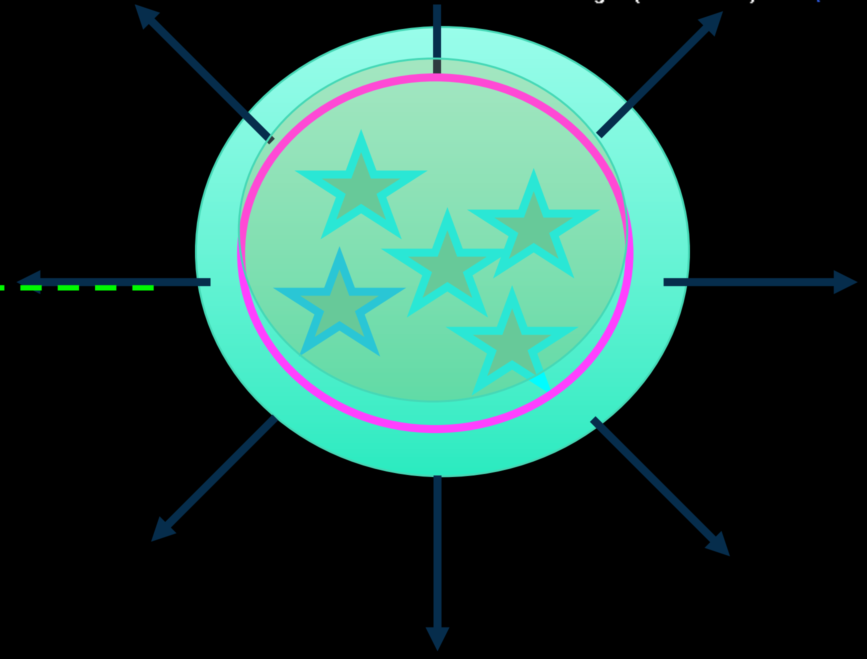
- The most easily-observed features of high redshift galaxies are (a) the far-UV continuum and (b) strong nebular emission lines from HII regions.
  - The same massive stars are responsible for both (a) and (b)
  - A successful model of the ionized gas+ massive stars must consistently and simultaneously reproduce observations of both
- Initial results of KBSS-MOSFIRE follow-up using new, deeper, higher-resolution rest-UV spectra from Keck/LRIS-B+R arxiv:1605.07186
  - Objectives:
    - quantitative comparison iof the spectra of the massive stars with the nebulae they excite
    - attempt to understand what is going on, and how to proceed in the future.
    - Ideally, eliminate dependence on local calibrations of nebular diagnostics

Observational Constraints on Stars + Gas

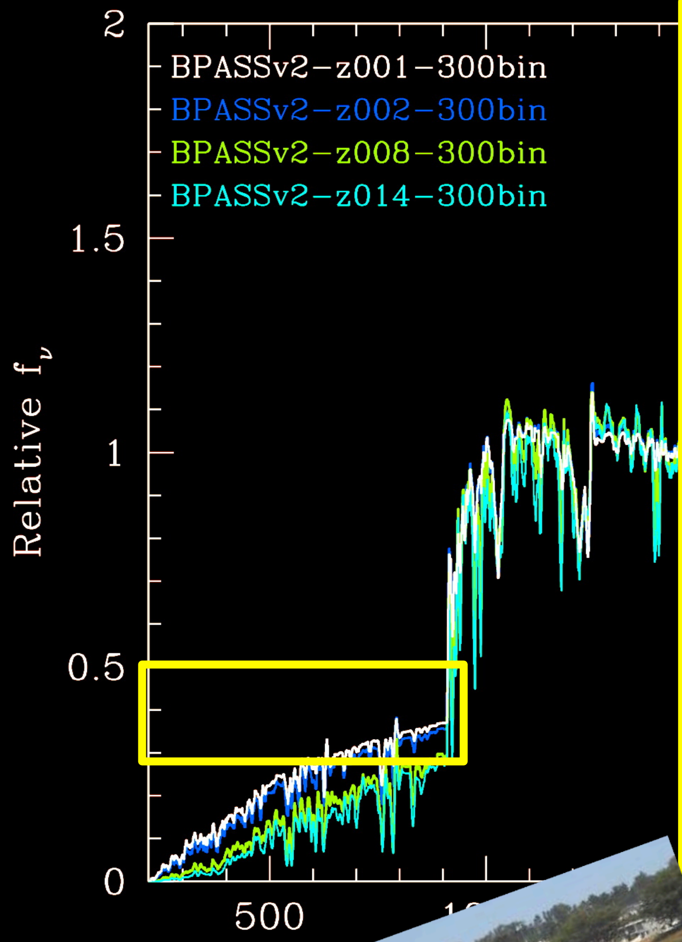


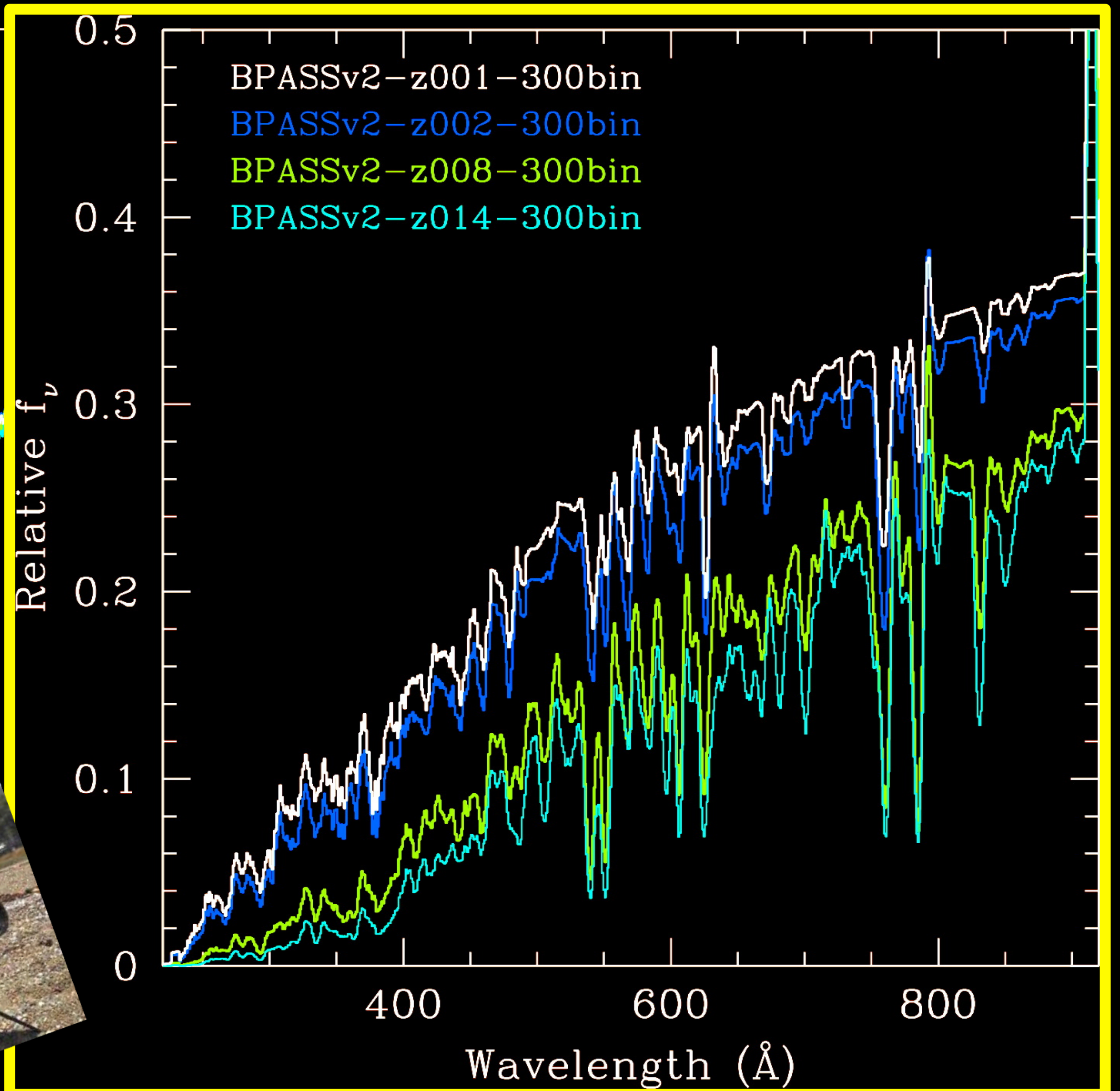


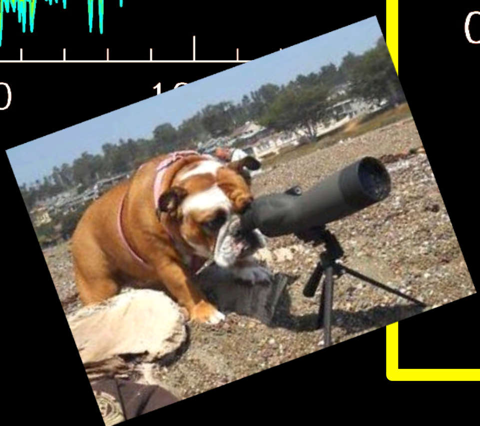
observer



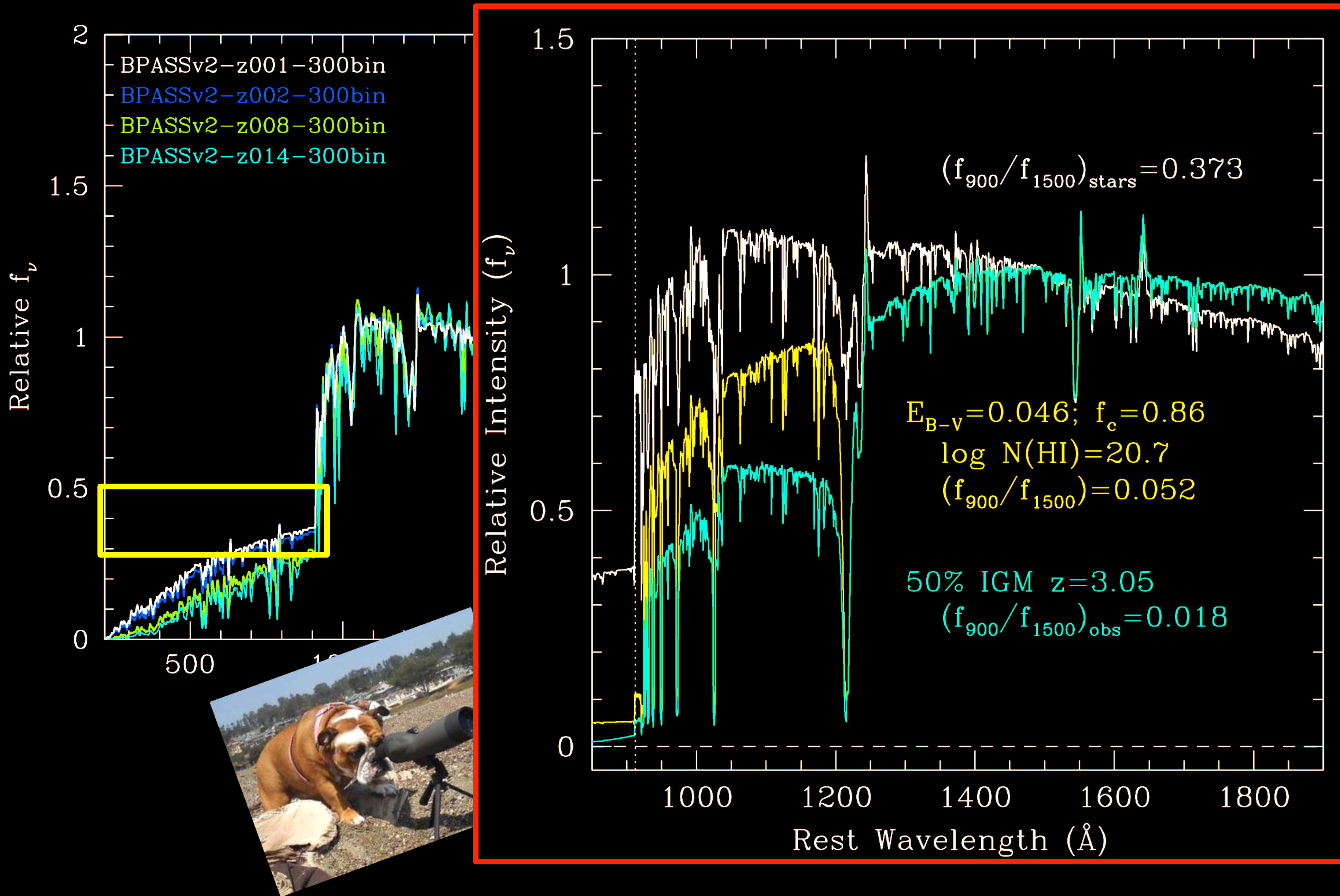
Observational Constraints on Gas and Stars





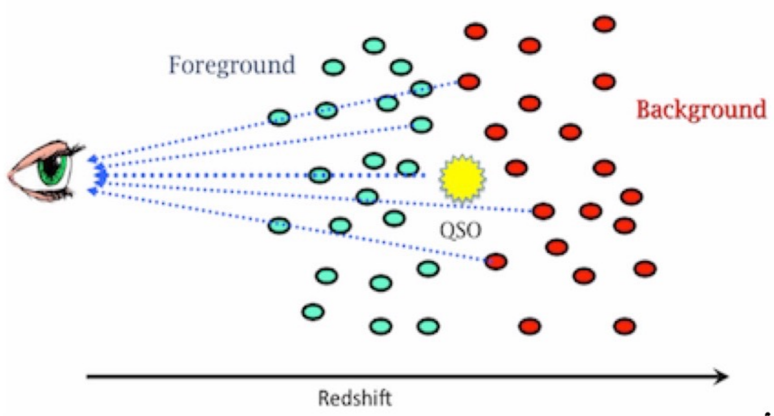


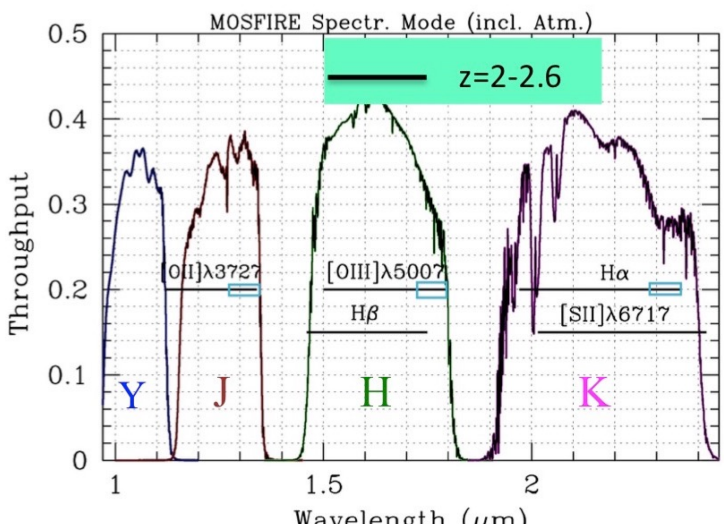
Observational Constraints on Gas and Stars

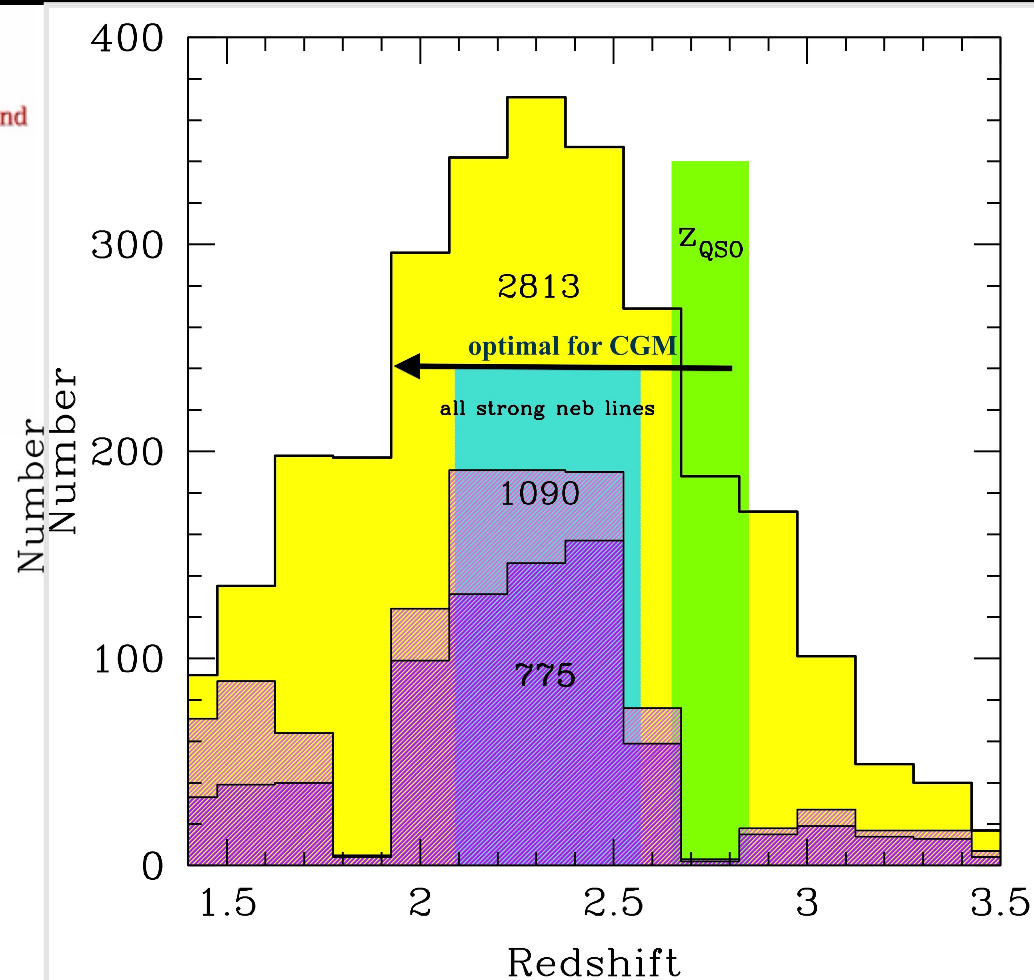


KBSS-MOSFIRE

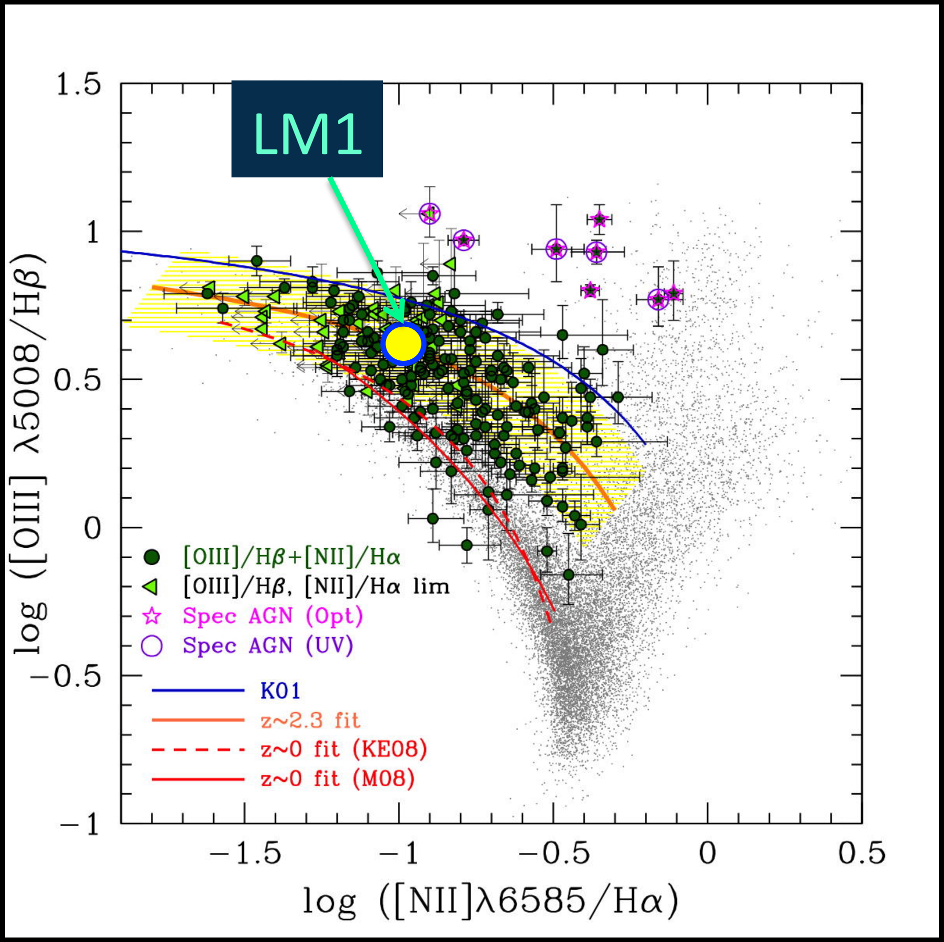
15 fields, 0.25 sq. degrees, ~2800 spectra <z>=2.4
~2300 UV spectra
~1100 rest-optical (MOSFIRE) spectra



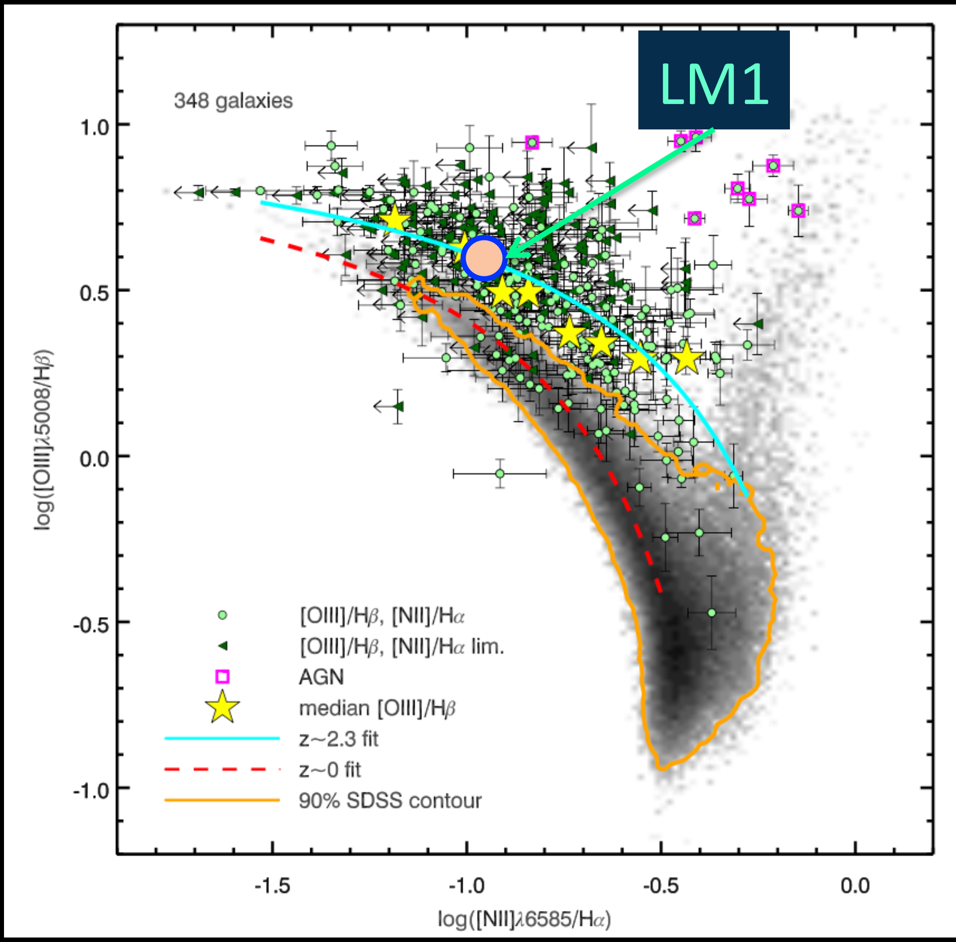




KBSS-MOSFIRE, KBSS-LM1 @ z=2-2.6

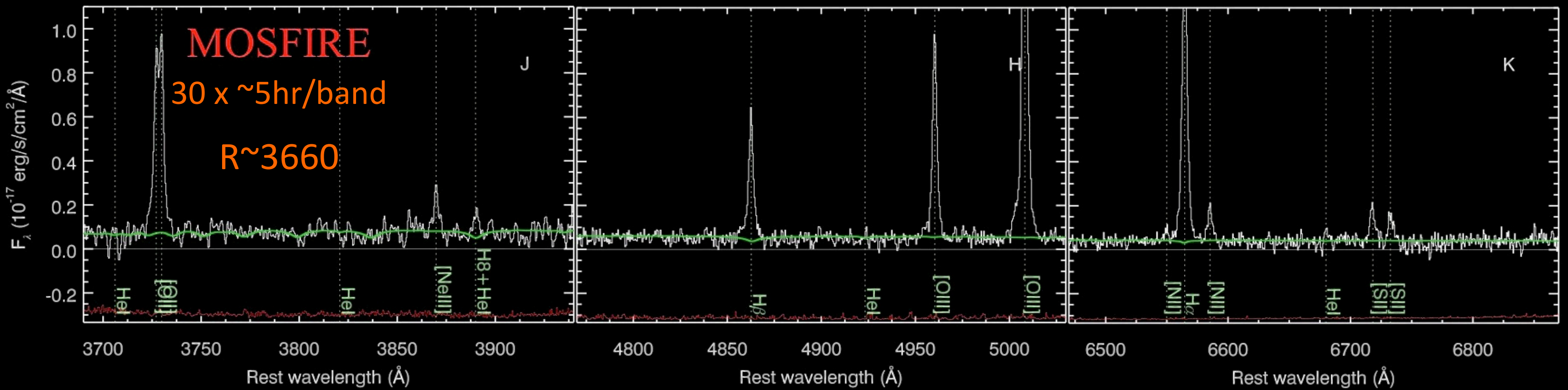


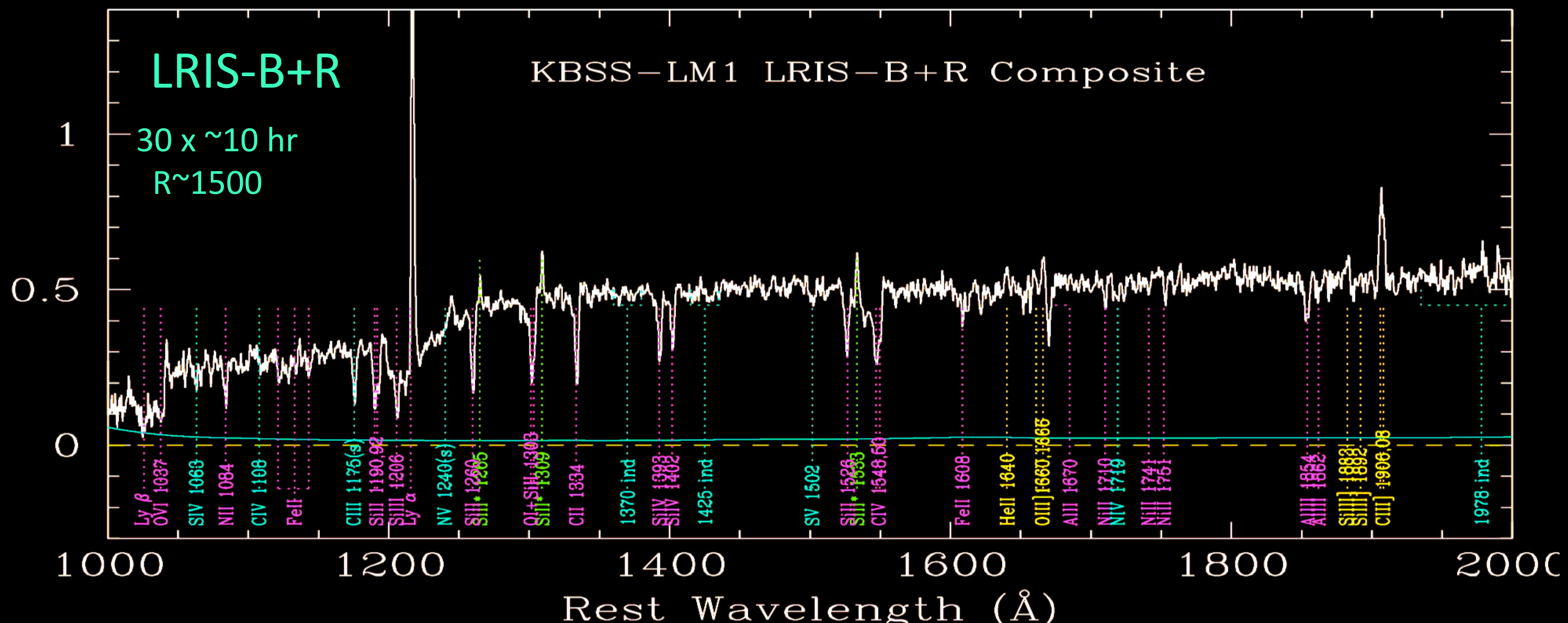
CS, Rudie, Strom+2014



Strom, CS, Rudie, Trainor, Pettini, Reddy 2016

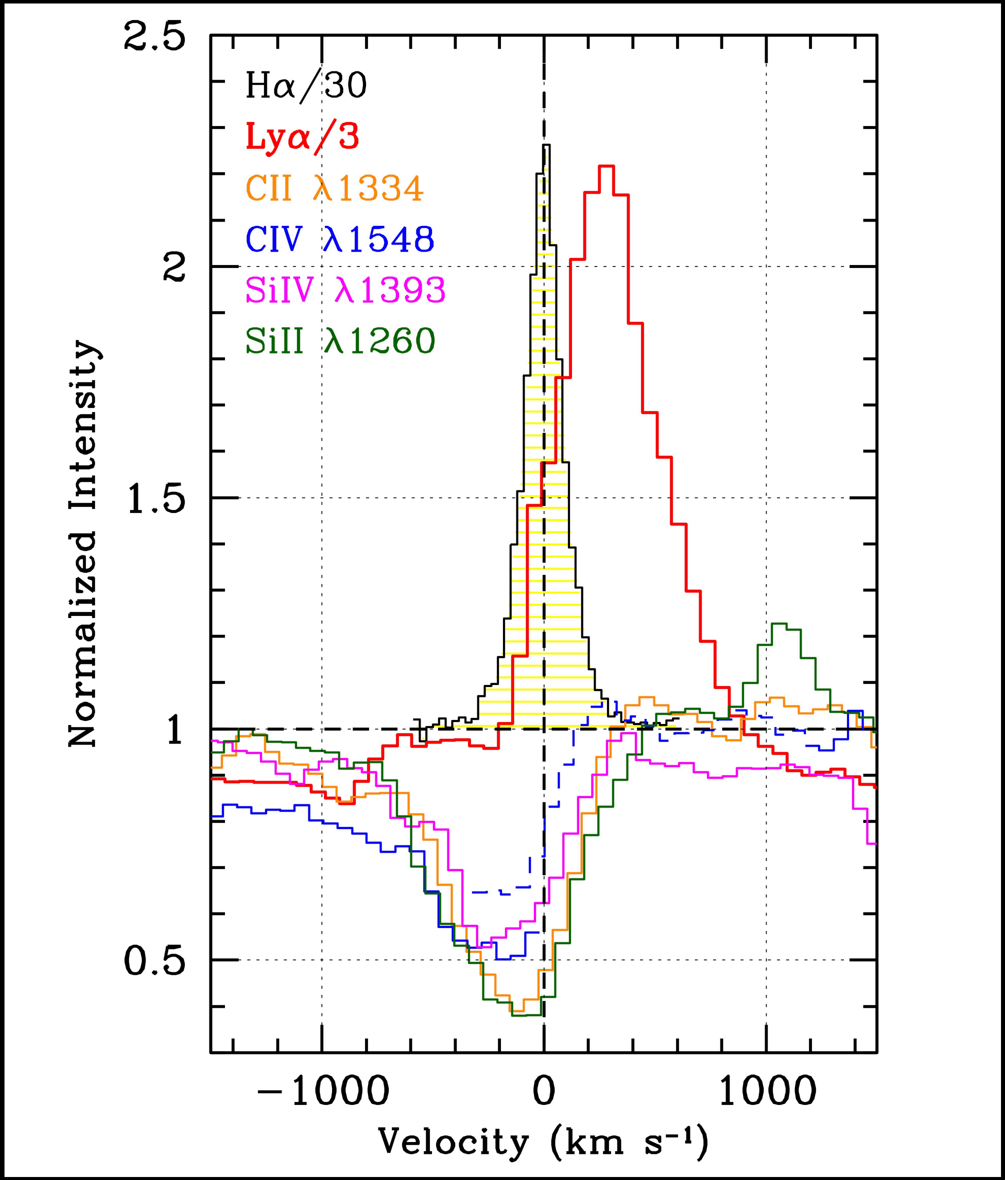
KBSS-LM1: the same 30 galaxies @z~2.4:





CS, Strom, Rudie+2016

The View "Down the Barrel" (30 KBSS galaxies @ z~2.4)

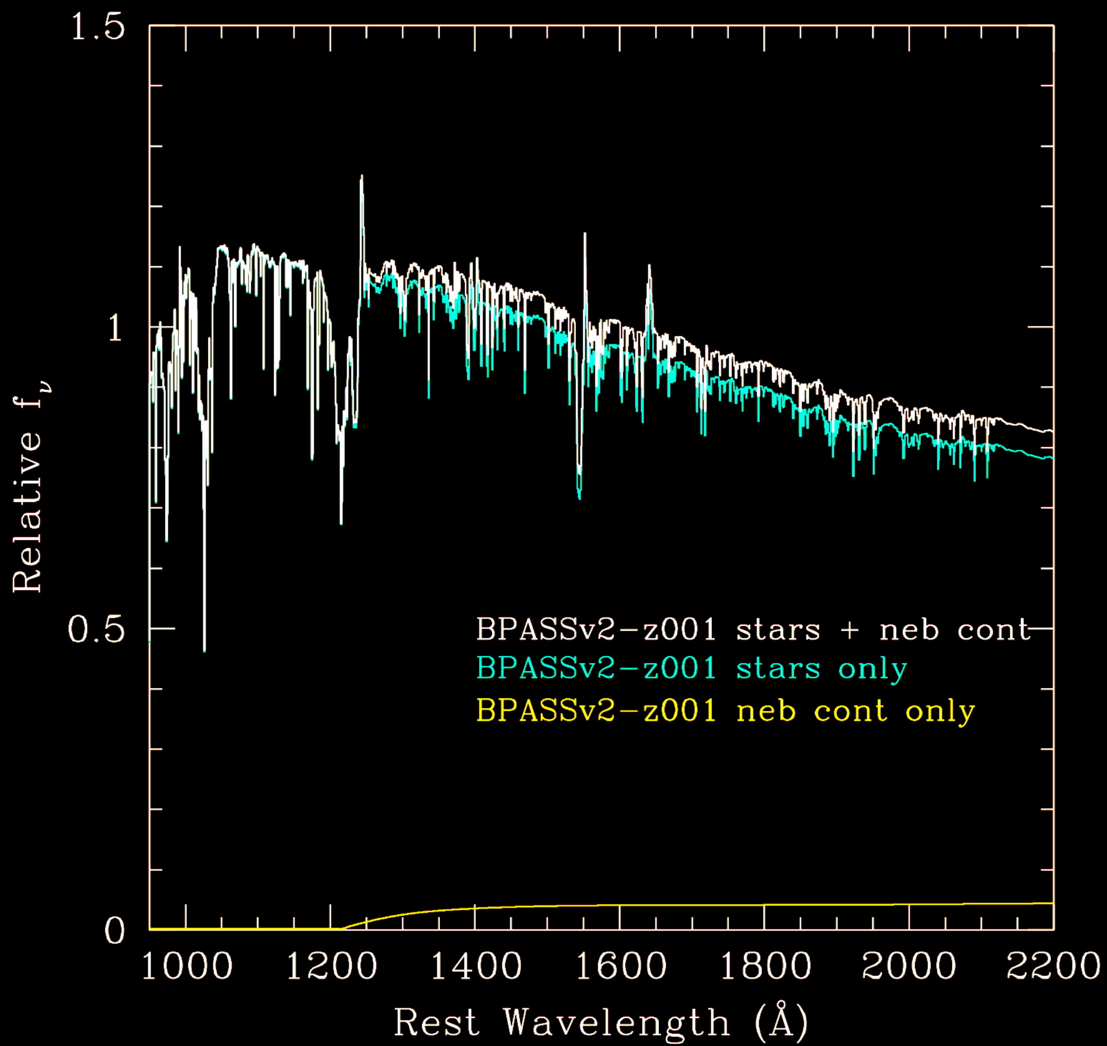


- SFR ≈ 30 $M_\odot$/yr
- $M_* \approx 10^{10}\ M_\odot$; $M_{DM} \approx 10^{12}\ M_\odot$
- $V_c \approx 150$ km/s
- $M_{gas} > M_*$ (gas-dominated)
- Gas-phase metallicity ≈ 0.5 solar (oxygen)
- Outflow:
  - extends to $v_{max} \approx -1000$ km/s
  - $\langle v_{out} \rangle = -190$ km/s
  - $\langle v_{lya} \rangle = +290$ km/s

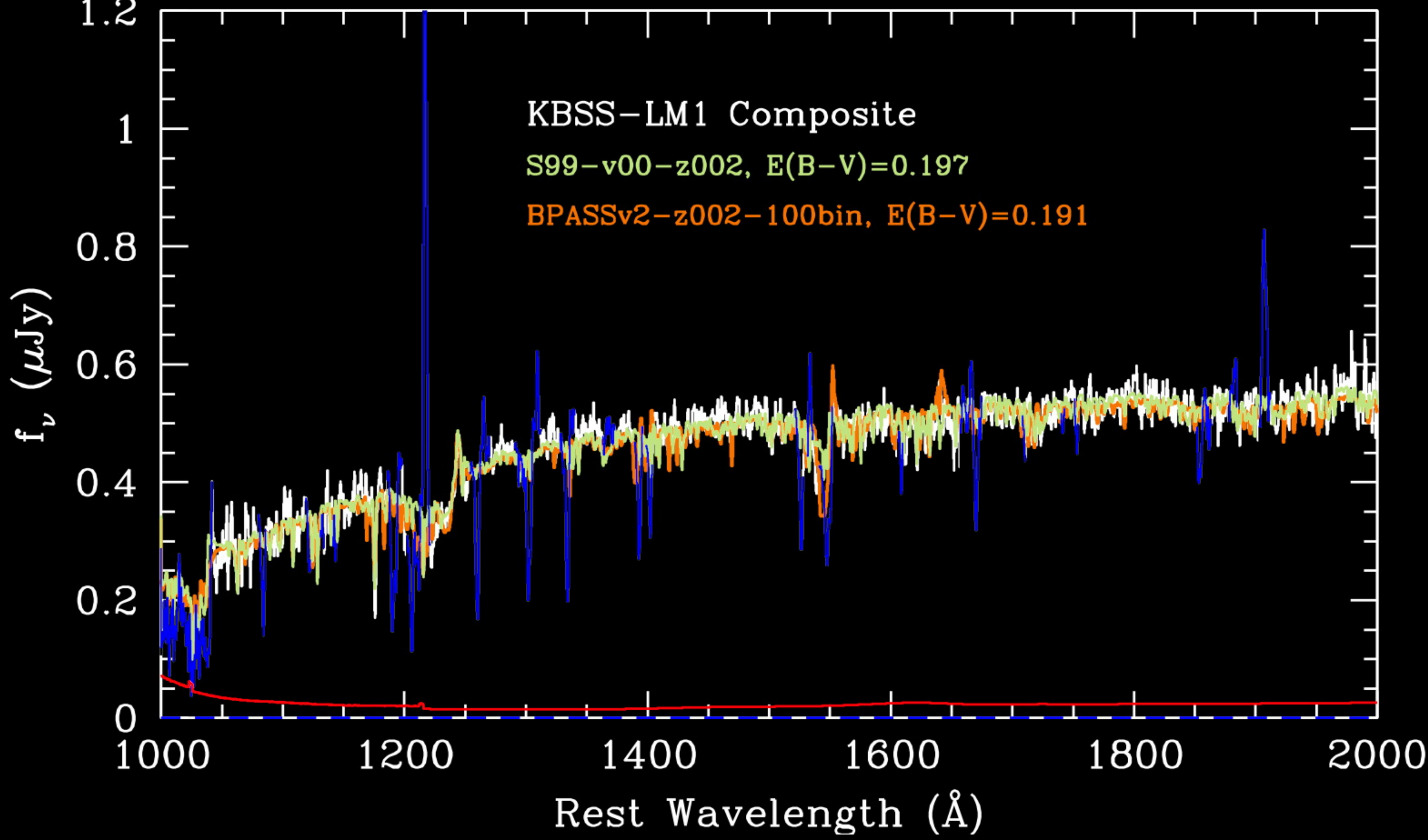
Table 6
Excited Fine Structure Emission Lines[a]

Ion	λ_0 (Å)	λ_{obs} (Å)	W_λ (Å)	Δv^a (km s^{-1})
SiII*	1197.39	1197.37	...	−6.0
SiII*	1265.00	1265.06	0.23	+14.2
SiII*	1309.28	1309.20	0.42	−18.3
SiII*	1533.43	1533.45	0.43	+3.9
				$\langle \Delta v \rangle = 1.3 \pm 12.1$ km s^{-1}

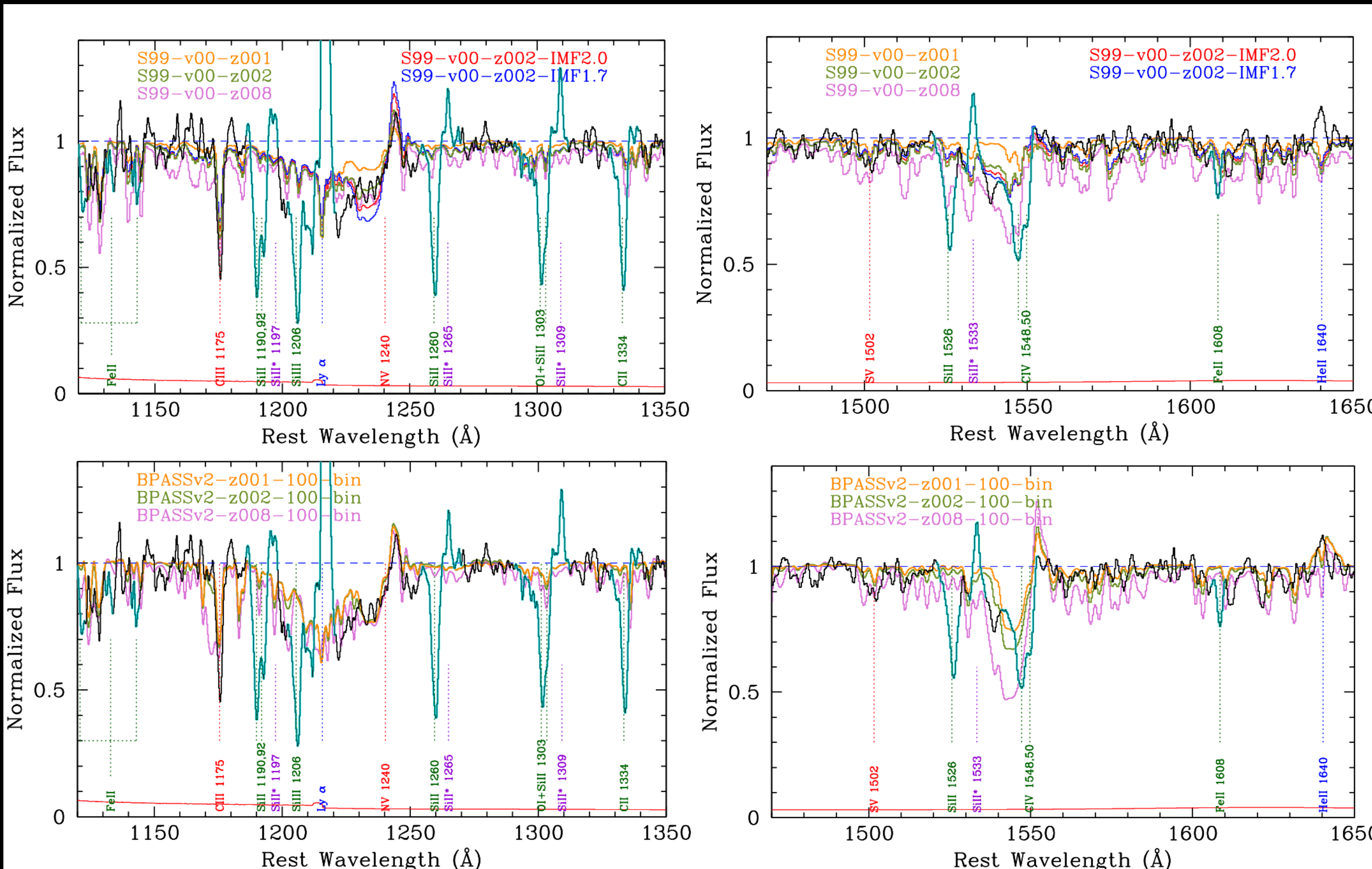
[a] Redshift of observed feature relative to z_{neb} defined by strong rest-optical nebular lines.



Model	$Z_*/Z_\odot$ [a]
Mask1 (Global	
BPASSv2-z001-100bin	0.07
BPASSv2-z002-100bin	0.14
BPASSv2-z003-100bin	0.21
BPASSv2-z004-100bin	0.28
BPASSv2-z006-100bin	0.42
BPASSv2-z008-100bin	0.56
BPASSv2-z001-300bin	0.07
BPASSv2-z002-300bin	0.14
BPASSv2-z003-300bin	0.21
BPASSv2-z004-300bin	0.28
BPASSv2-z006-300bin	0.42
BPASSv2-z008-300bin	0.56
BPASSv2-z001-300	0.07
BPASSv2-z002-300	0.14
BPASSv2-z003-300	0.21
BPASSv2-z004-300	0.28
BPASSv2-z006-300	0.42
BPASSv2-z008-300	0.56
S99-v00-z001	0.07
S99-v00-z002	0.14
S99-v00-z008	0.56
S99-v00-z001-IMF2.0	0.07
S99-v00-z002-IMF2.0	0.14
S99-v00-z008-IMF2.0	0.56
S99-v00-z001-IMF1.7	0.07
S99-v00-z002-IMF1.7	0.14
S99-v00-z008-IMF1.7	0.56

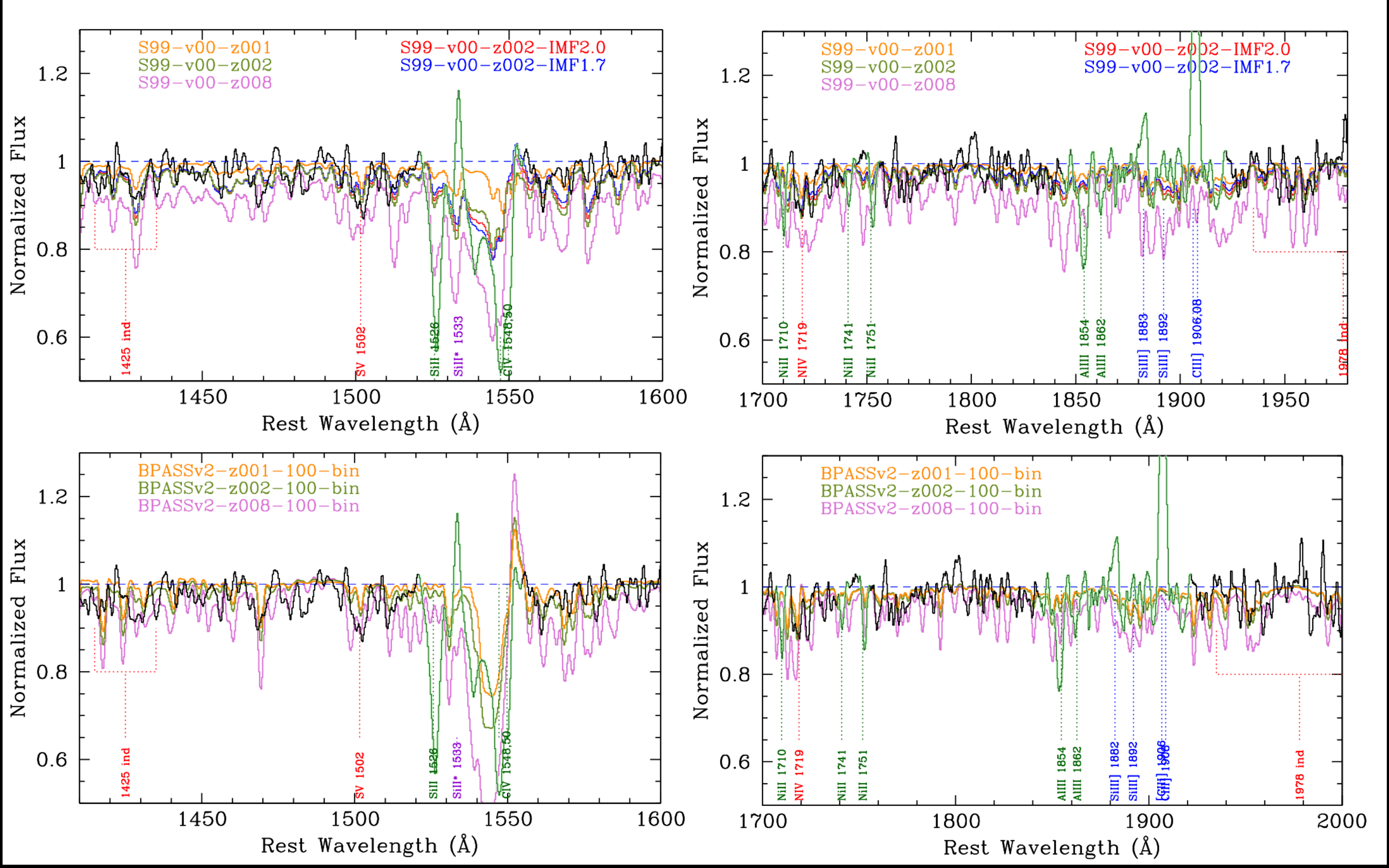

KBSS-LM1 Composite
S99-v00-z002, E(B-V)=0.197
BPASSv2-z002-100bin, E(B-V)=0.191
f_ν (μJy)
Rest Wavelength (Å)
0
0.2
0.4
0.6
0.8
1
1.2
1000
1200
1400
1600
1800
2000

Metallicity Dependence of Wind Lines



CS, Strom, Pettini, Rudie+16 arXiv:1601.07186

Metallicity Dependence of FUV Stellar Spectra



CS, Strom, Pettini, Rudie+16 arXiv:1601.07186

- All classes of models strongly favor $Z_*/Z_\odot \approx 0.1$
- $Z_*/Z_\odot \geq 0.2$ ruled out at $> 3\sigma$ significance
- Focus on successful models as input to models of nebular emission (both UV and optical)

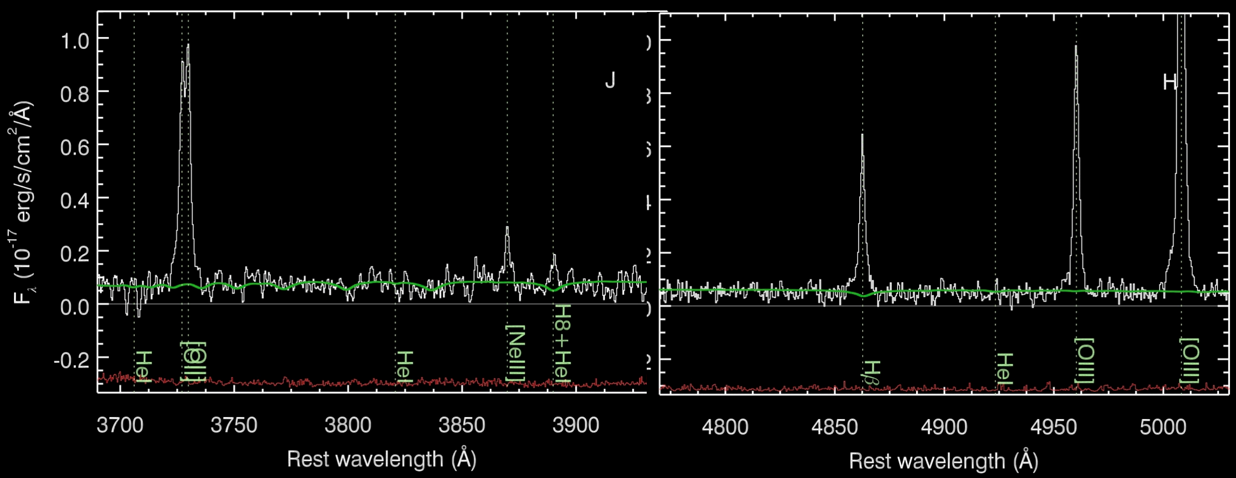
Table 4
Results of χ^2 Minimization for Stellar Models

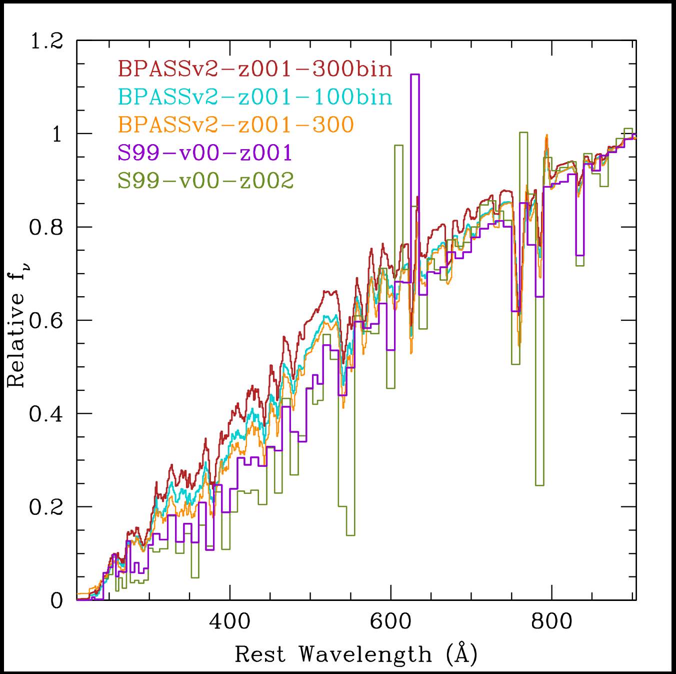
Model	$Z_*/Z_\odot$ [a]	E(B-V) [b]	χ^2/ν	$\Delta\chi^2/\nu$ [c]	$\Delta\sigma$ [d]
Mask 2 fit ($\nu = 1710$)					
BPASSv2-z001-100bin	0.07	0.203	1.089	0.038	0.97
BPASSv2-z002-100bin	0.14	0.201	1.126	0.075	1.92
BPASSv2-z003-100bin	0.21	0.203	1.181	0.130	3.33
BPASSv2-z004-100bin	0.28	0.202	1.270	0.219	5.62
BPASSv2-z006-100bin	0.42	0.183	1.393	0.342	8.77
BPASSv2-z008-100bin	0.56	0.177	1.533	0.482	12.36
BPASSv2-z001-300bin	0.07	0.205	1.107	0.056	1.43
BPASSv2-z002-300bin	0.14	0.205	1.140	0.089	2.28
BPASSv2-z003-300bin	0.21	0.204	1.187	0.136	3.49
BPASSv2-z004-300bin	0.28	0.200	1.261	0.210	5.39
BPASSv2-z006-300bin	0.42	0.187	1.367	0.316	8.10
BPASSv2-z008-300bin	0.56	0.183	1.508	0.457	11.72
BPASSv2-z001-300	0.07	0.186	1.051	0.000	0.00
BPASSv2-z002-300	0.14	0.187	1.093	0.042	1.08
BPASSv2-z003-300	0.21	0.190	1.166	0.115	2.95
BPASSv2-z004-300	0.28	0.189	1.264	0.213	5.46
BPASSv2-z006-300	0.42	0.177	1.383	0.332	8.51
BPASSv2-z008-300	0.56	0.176	1.529	0.478	12.26
S99-v00-z001	0.07	0.204	0.986	0.000	0.00
S99-v00-z002	0.14	0.193	1.024	0.038	0.98
S99-v00-z008	0.56	0.196	1.502	0.516	13.41
S99-v00-z001-IMF2.0	0.07	0.200	0.994	0.008	0.20
S99-v00-z002-IMF2.0	0.14	0.188	1.004	0.018	0.46
S99-v00-z008-IMF2.0	0.56	0.187	1.439	0.453	11.77
S99-v00-z001-IMF1.7	0.07	0.192	1.005	0.019	0.50
S99-v00-z002-IMF1.7	0.14	0.180	1.004	0.018	0.47
S99-v00-z008-IMF1.7	0.56	0.182	1.360	0.374	9.71

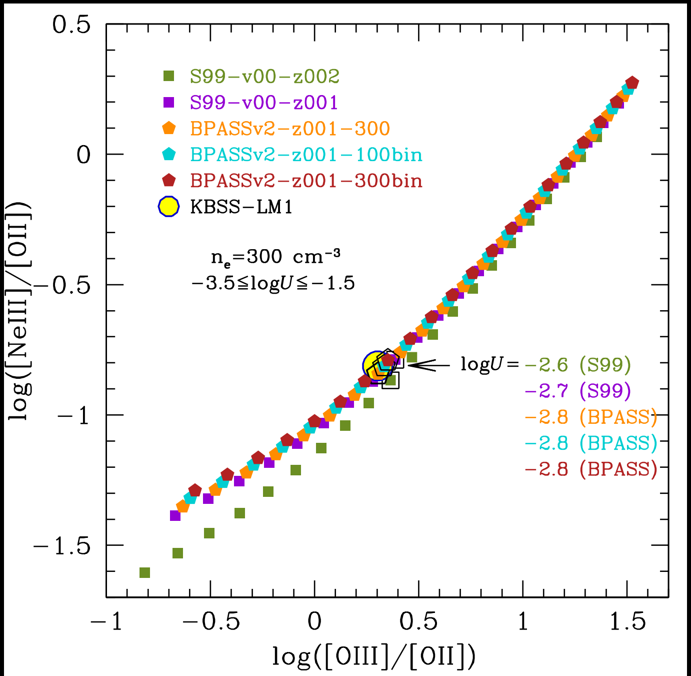
[a] Stellar metallicity relative to solar, where $Z_\odot = 0.0142$ (Asplund et al. 2009).
[b] Value of $E(B\text{-}V)_{cont}$ that minimizes χ^2.
[c] Difference in χ^2/ν compared to best-fitting model within group (BPASSv2 or S99).
[d] Number of σ deviation from best-fitting models within group (BPASSv2 or S99).

CS, Strom, Pettini, Rudie+16 arXiv:1601.07186

Constrain Normalization of the EUV (1-4 Ryd) Spectrum using [OIII]/[OII], [NeIII]/[OII]

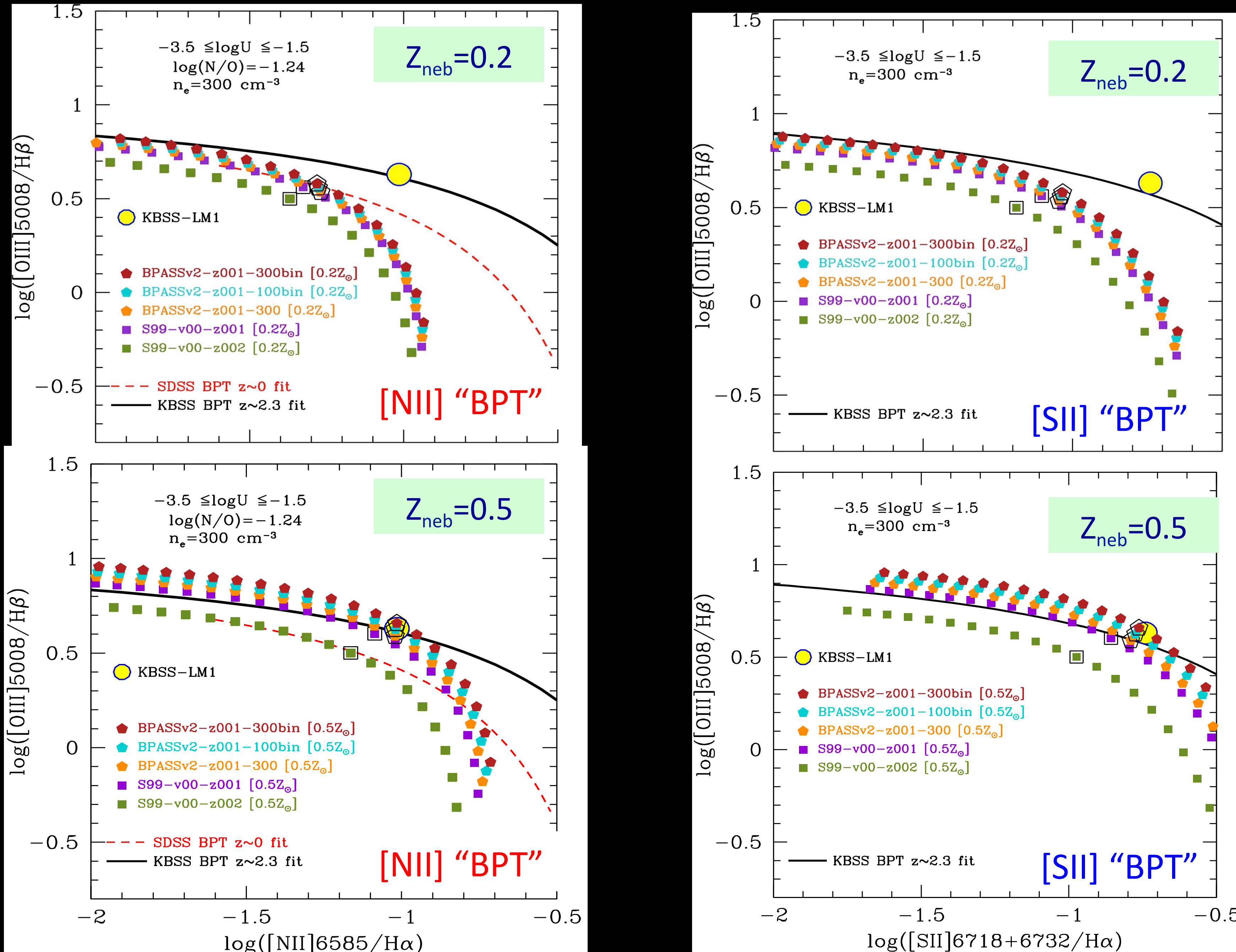






log U = -2.8

CS, Strom, Pettini, Rudie+16 arXiv:1601.07186



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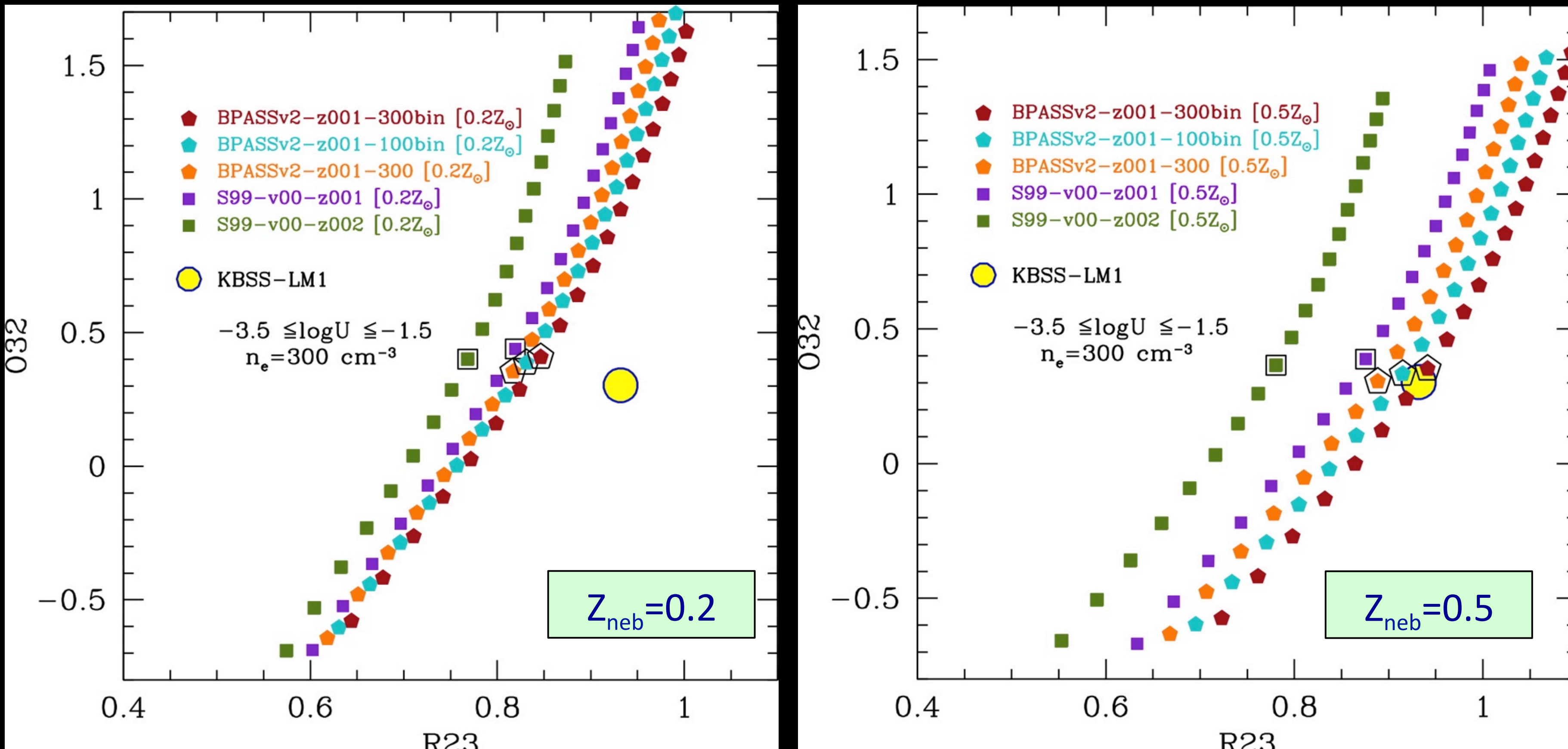

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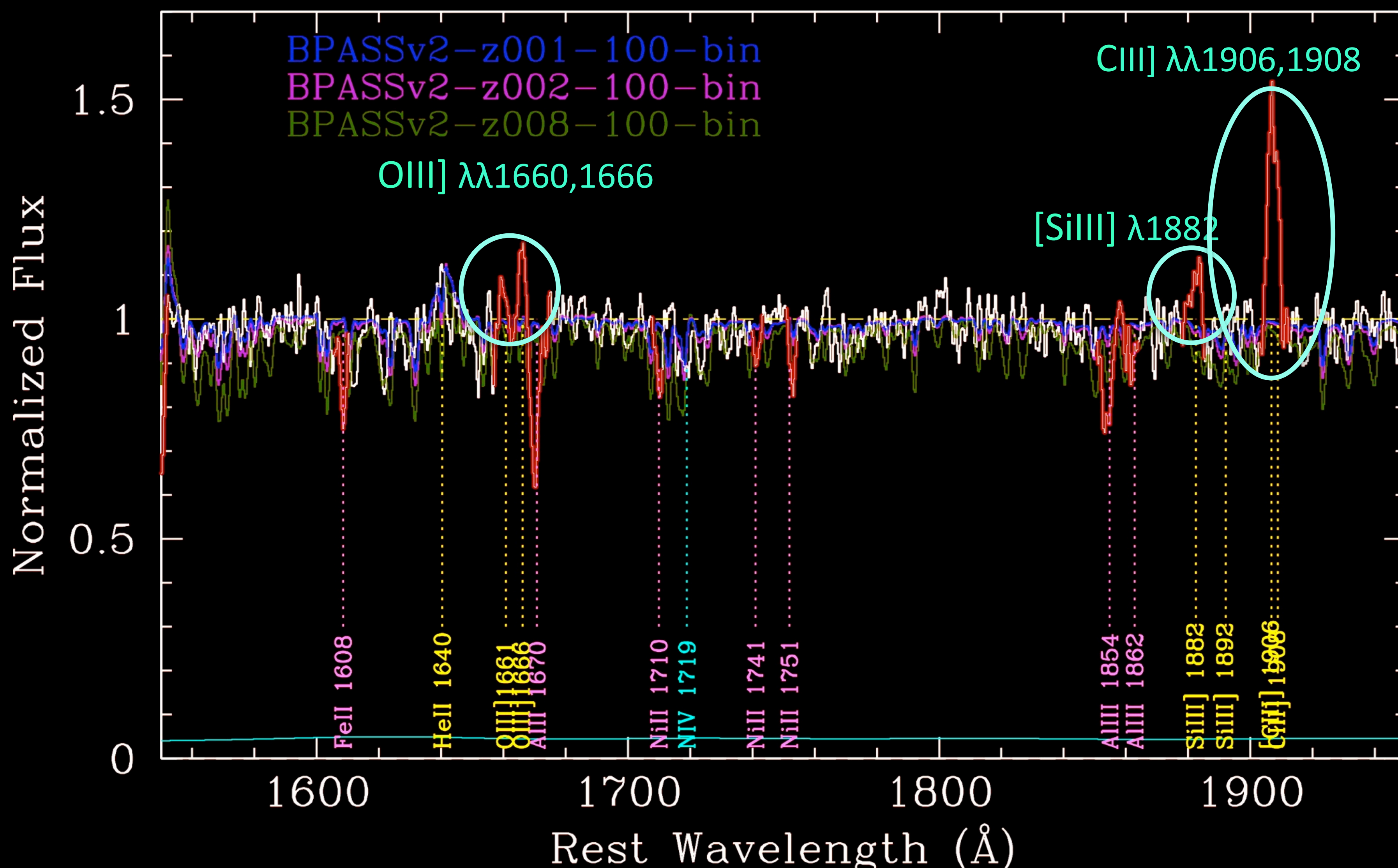
UV nebular emission lines complementary to rest-optical



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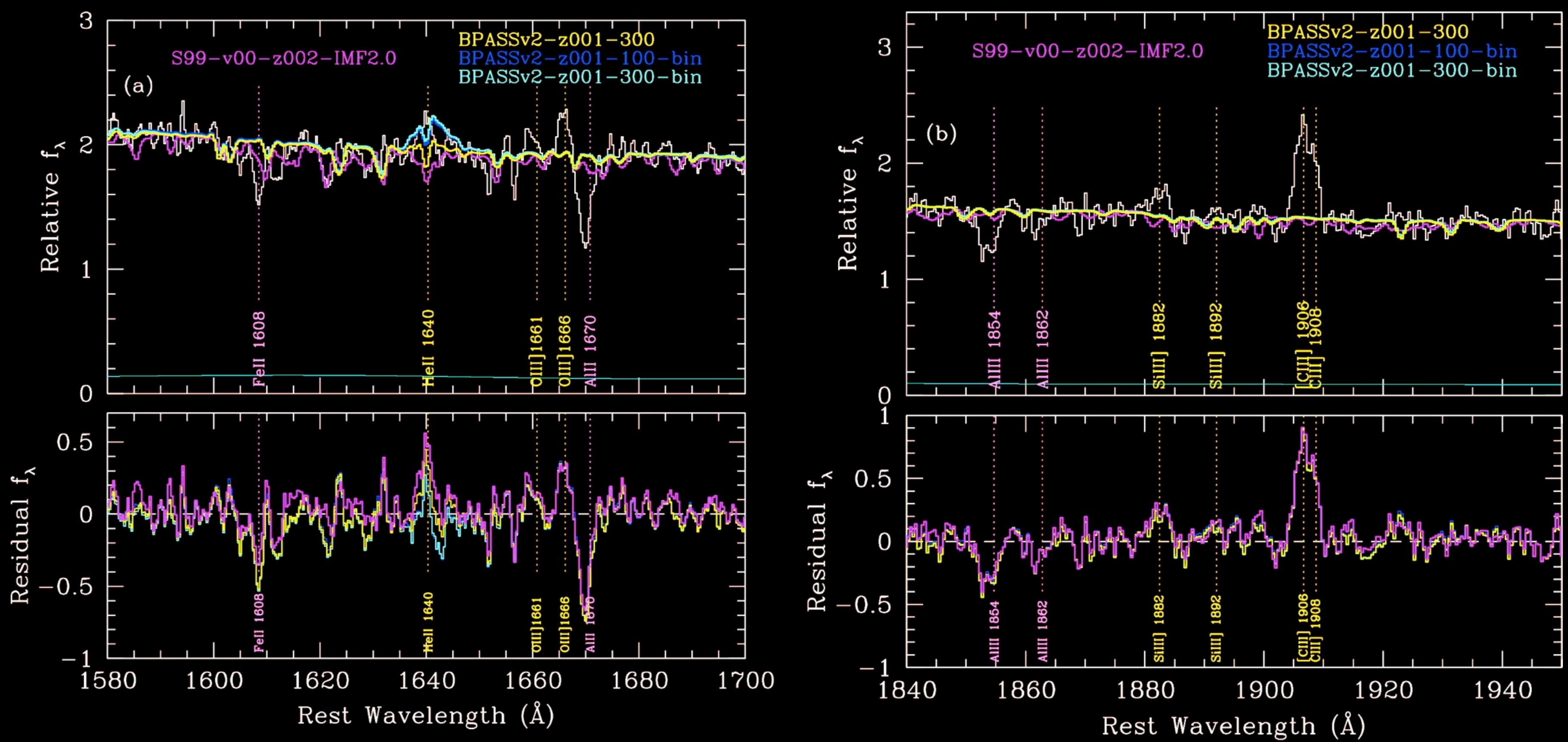
UV nebular emission complementary to rest-optical



→ C/O, Si/O in conjunction with best pop. synth. +photoionization models

CS, Strom, Pettini, Rudie+16 arXiv:1601.07186

KBSS-LM1 z=2.4 Composite: Summary of Properties

- $\log M_* \approx 10$
- SFR≈30 $M_\odot$/yr
- $\log$ sSFR ≈ 0.54 Gyr^{-1} (i.e., "main sequence"™ @z=2.4)
- $L_{uv} \approx 0.4 L^*_{uv}$; $L_{bol} \approx L^*_{bol}$

$Z_*/Z_\odot \approx 0.1$ → [Fe/H] ≈ -1.0

$Z_{neb}/Z_\odot \approx 0.5$ → [O/H] = -0.31

[N/O] = -0.38

[C/O] = -0.34 → (C/H) ≈ 0.25 $(C/H)_\odot$

[Si/O] = -0.63 → depletion

(~80% of Si is in dust)

Inferred Gas-Phase Abundance Ratios		
log(N/O)	-1.24 ± 0.04	[N/O] = -0.38 ± 0.04; Eqs. 1, 2, §8.1.2
log(C/O)	-0.60 ± 0.09	[C/O] = -0.34 ± 0.09; Eq. 17
log(Si/O)	-1.81 ± 0.08	[Si/O] = -0.63 ± 0.08; Eq. 18

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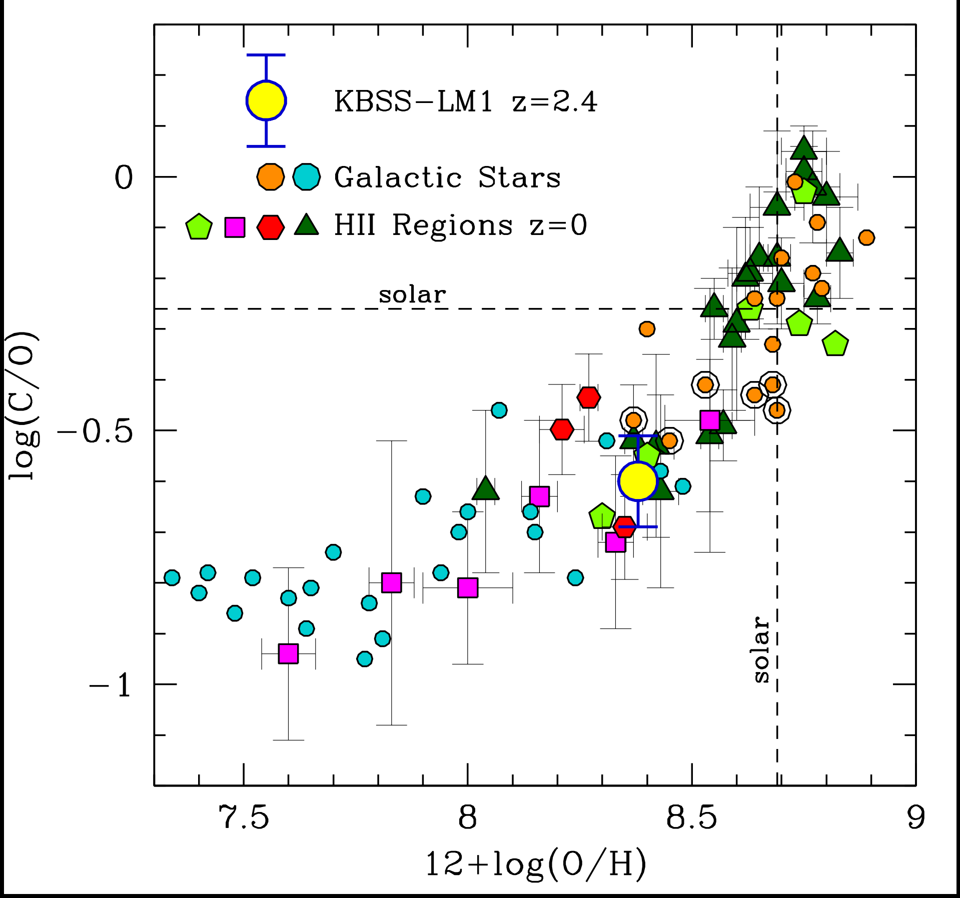
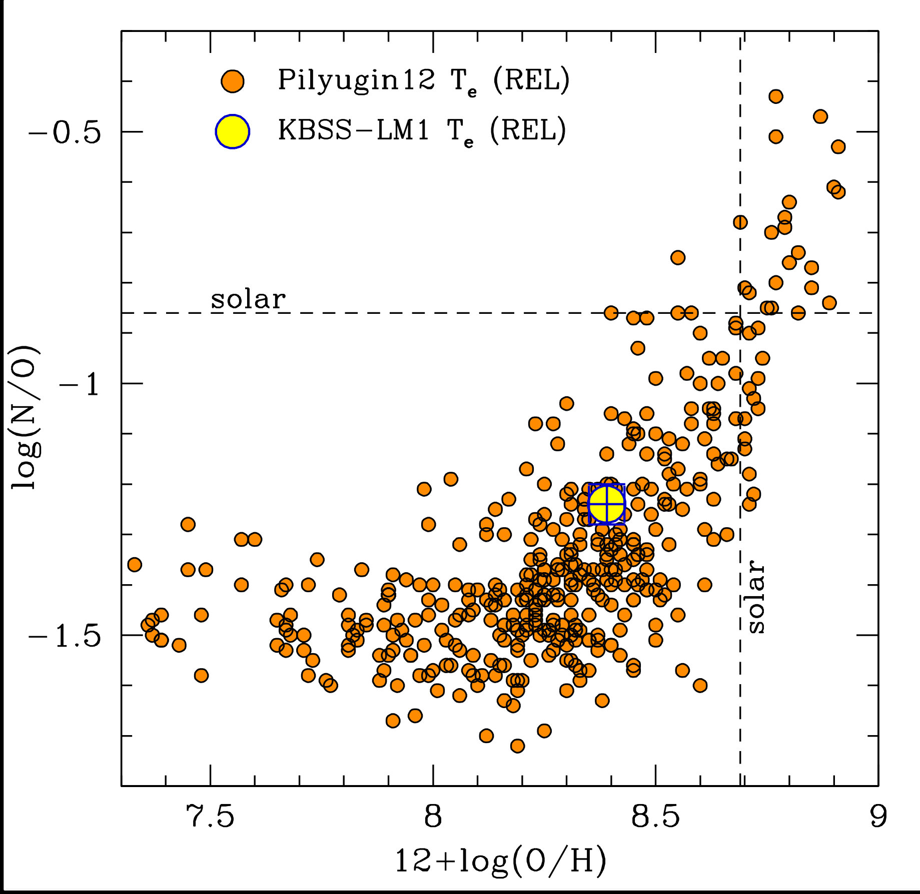
Abundance Patterns vs. Oxygen Abundance

C/O vs. O/H



N/O vs. O/H



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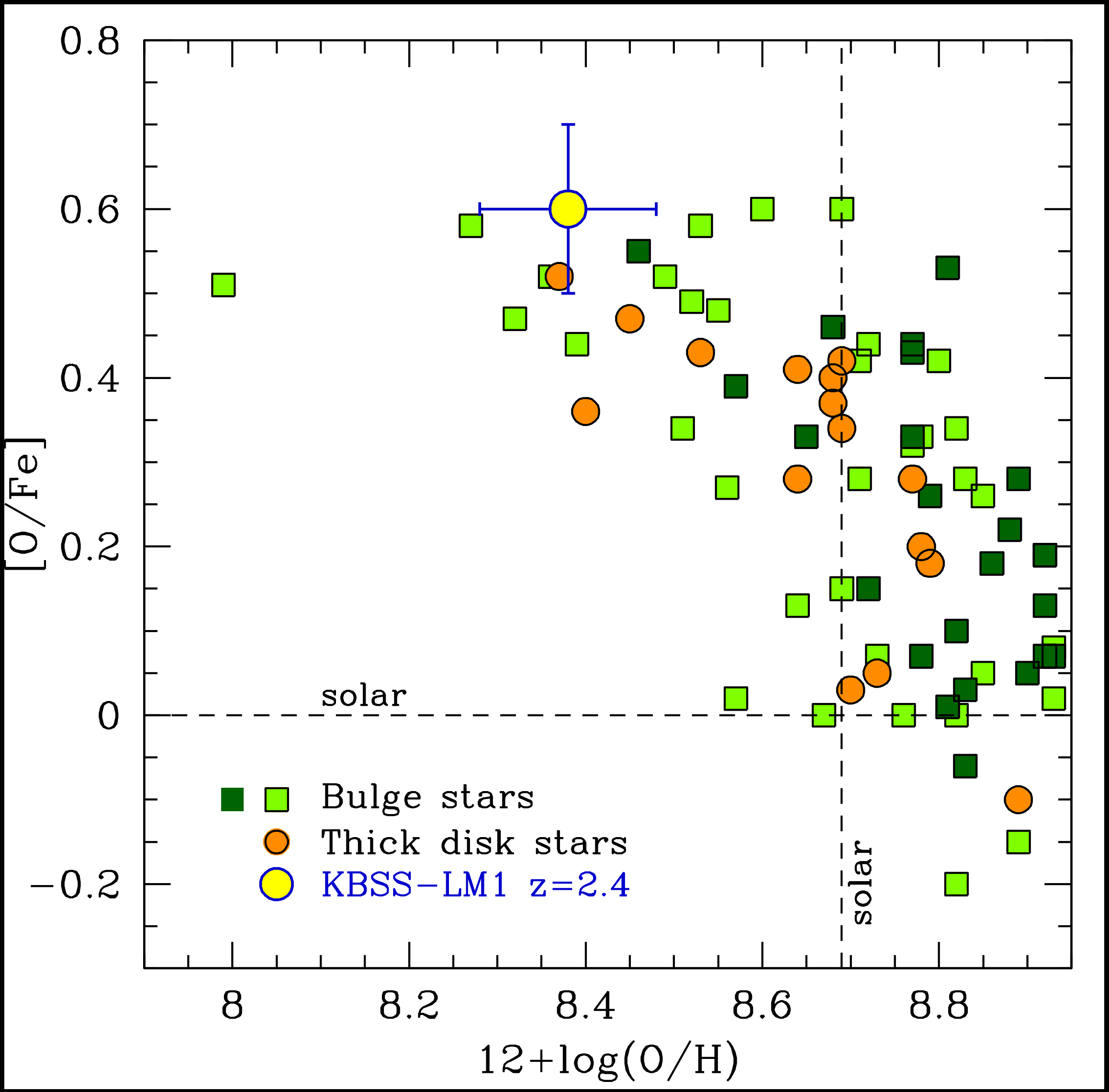

At z~2.4, a typical SF galaxy with $M^*=10^{10}\ M_\odot$

- has “stellar metallicity “ of 0.1 solar
- “gas-phase metallicity” of 0.5 solar

CS, Strom, Pettini, Rudie+16 arXiv:1601.07186

Why You Should Take Massive Binaries Seriously

- This is (apparently) the way massive stars are born (whether we approve or not)
- Naturally produces hard EUV spectra in moderately metal-poor stellar populations ([Fe/H]≤-0.3) over long SF timescales
  - Crucial to LyC escape from local ISM! (see e.g. Ma+2016)
  - $f_{900}/f_{1500} \approx 0.37$ instead of "canonical" 0.14
- Naturally explains observations (stellar+nebular spectra) in EUV+FUV+Optical at z=2.4 (including stellar HeII 1640)
- Nearly all z>>2 galaxies likely to be affected by the same spectral characteristics

Last Slide

- Joint modeling of FUV and nebular spectra seems extremely promising: very easily done at z~2-3; harder but possible at z>>2.
  - Most of the high redshift galaxies are in the regime where nebular spectra are more sensitive to the ionizing stars than to nebular abundances.
  - "Metallicity" inferences tend to be lower in the UV, likely because abundance ratios are not solar, and stellar and nebular spectra depend on different elements!
  - Can account for systematic differences between z~2.4 and z~0 in nebular diagnostics: at fixed O/H, high z galaxies have higher excitation– we think because O/Fe ~ 4-5x solar.

Observational Constraints on Gas and Stars