Supergiants in the E-ELT era

Extragalactic Stellar Astronomy

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$$n_i \sum_{j\neq i}(R_{ij}+C_{ij}) = \sum_{j\neq i} n_j(R_{ji}+C_{ji})$$

$$\mu\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu$$

Blue Supergian

Extragalacti

Nor

national PhD School "F. Lucchin" - XIV Cycle II Course

nd Technology with E-ELT

cily, 8-20 October 2015

and stellar populations:

mical abundances

Bologna, Italy

ectors:

Tor Vergata)

ncaster University)

thern Observatory)

015.html

Erice, Sicily, 8-20 October, 2015

International PhD School "F. Lucchin": Science and Technology with E-ELT

- XIV Cycle II Course

Stellar variability in the E-EL

INAF

Instrumentation

Extremely

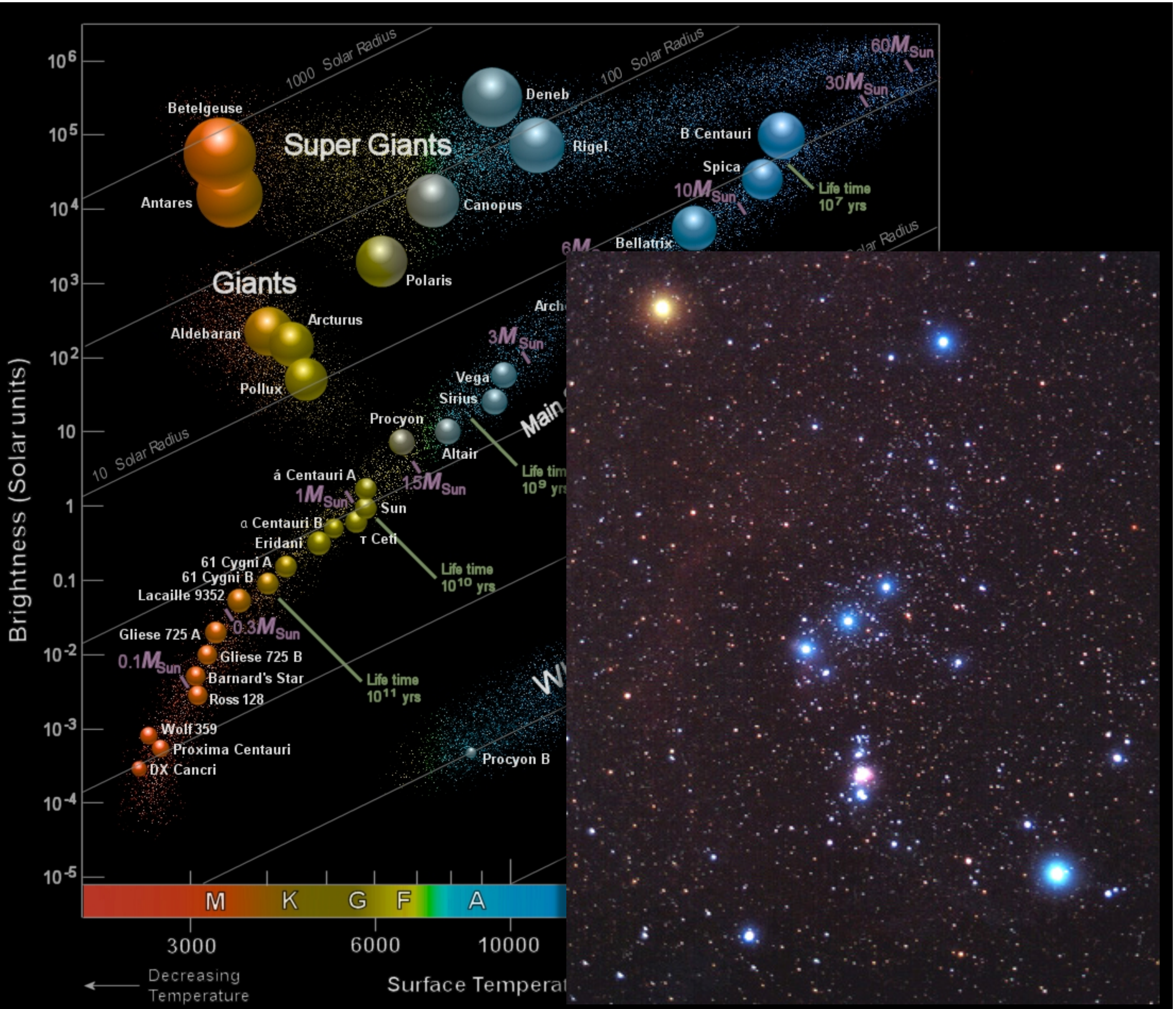
Science and Technology

Erice, October 2

Suzanne Ramsay (sramsay@e

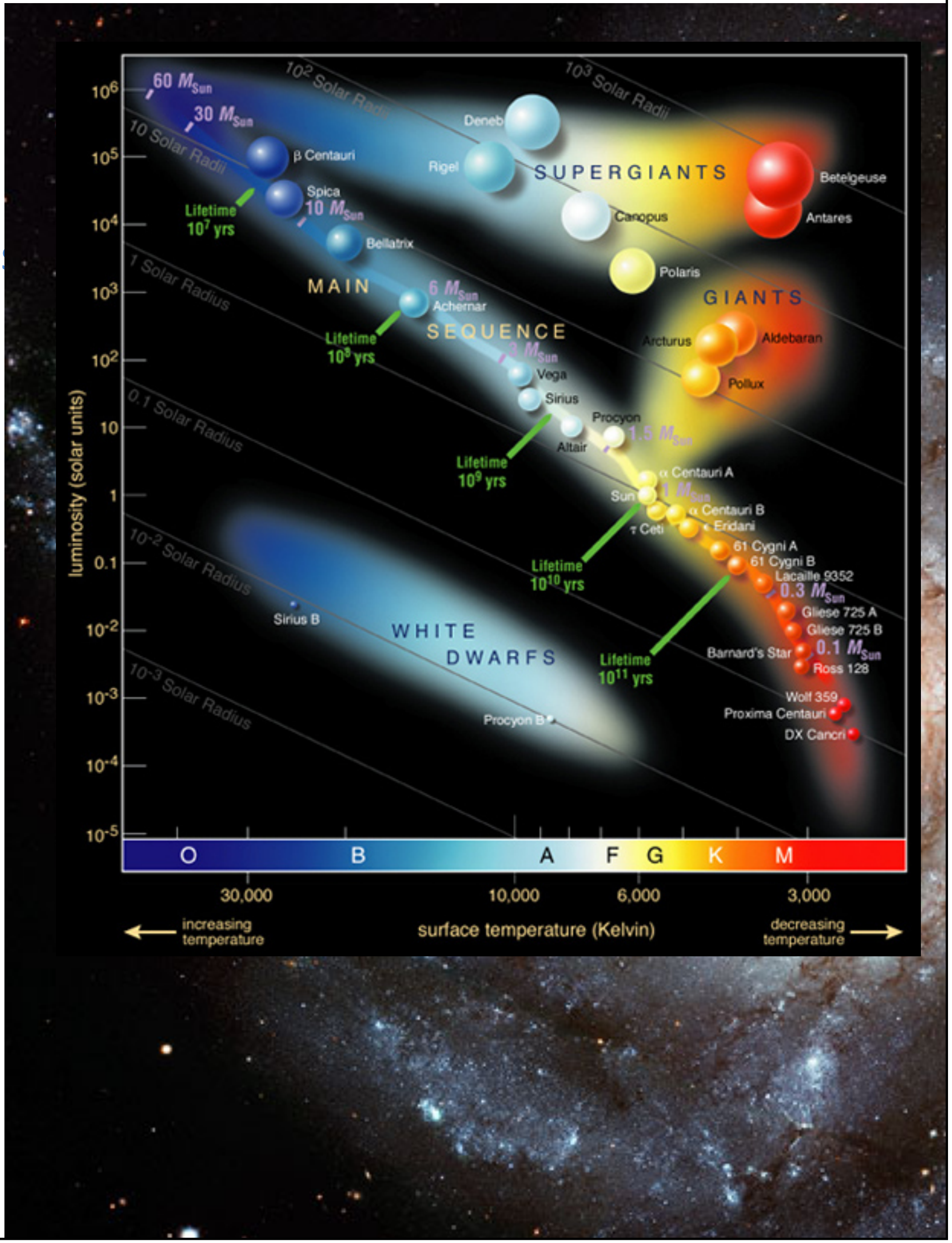
Precision Measurements for not very precise Cosmology in the E-ELT Era

Jochen Liske


Brightness (Solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
1000 Solar Radius
100 Solar Radius
10 Solar Radius
Super Giants
Giants
Main
Betelgeuse
Antares
Deneb
Rigel
Canopus
Polaris
B Centauri
Spica
Bellatrix
Arcturus
Aldebaran
Pollux
Vega
Sirius
Procyon
Altair
á Centauri A
Sun
α Centauri B
τ Ceti
Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Procyon B
60M Sun
30M Sun
10M Sun
6M
3M Sun
1.5M Sun
1M Sun
0.3M Sun
0.1M Sun
Life time 10^7 yrs
Life tim 10^9 yrs
Life time 10^10 yrs
Life time 10^11 yrs
M
K
G
F
A
3000
6000
10000
Decreasing Temperature
Surface Temperat

Massive Stars

- Massive and young objects
  - Short evolutionary time-scale
- High luminosities
  - Brightest non-transient objects
- Agents of galaxy evolution
  - O, Mg, Si, S, Ti …
  - Mechanical energy
  - Intense radiation fields
- Spectra richly populated by metal lines
  - B Sgs: N, O, Si, …
  - A Sgs : Fe, Ti, Cr, Mg, Si, …
  - Red Sgs: Fe, Ti, Mg, Si, …



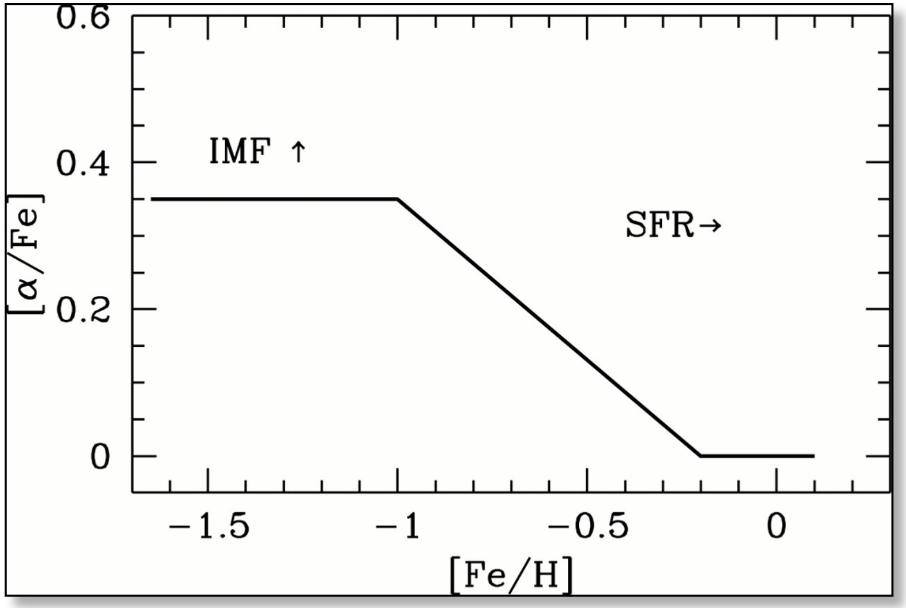
Scientific Drivers

- Physical properties in different environments.
  - Stellar evolution, feedback, early universe …

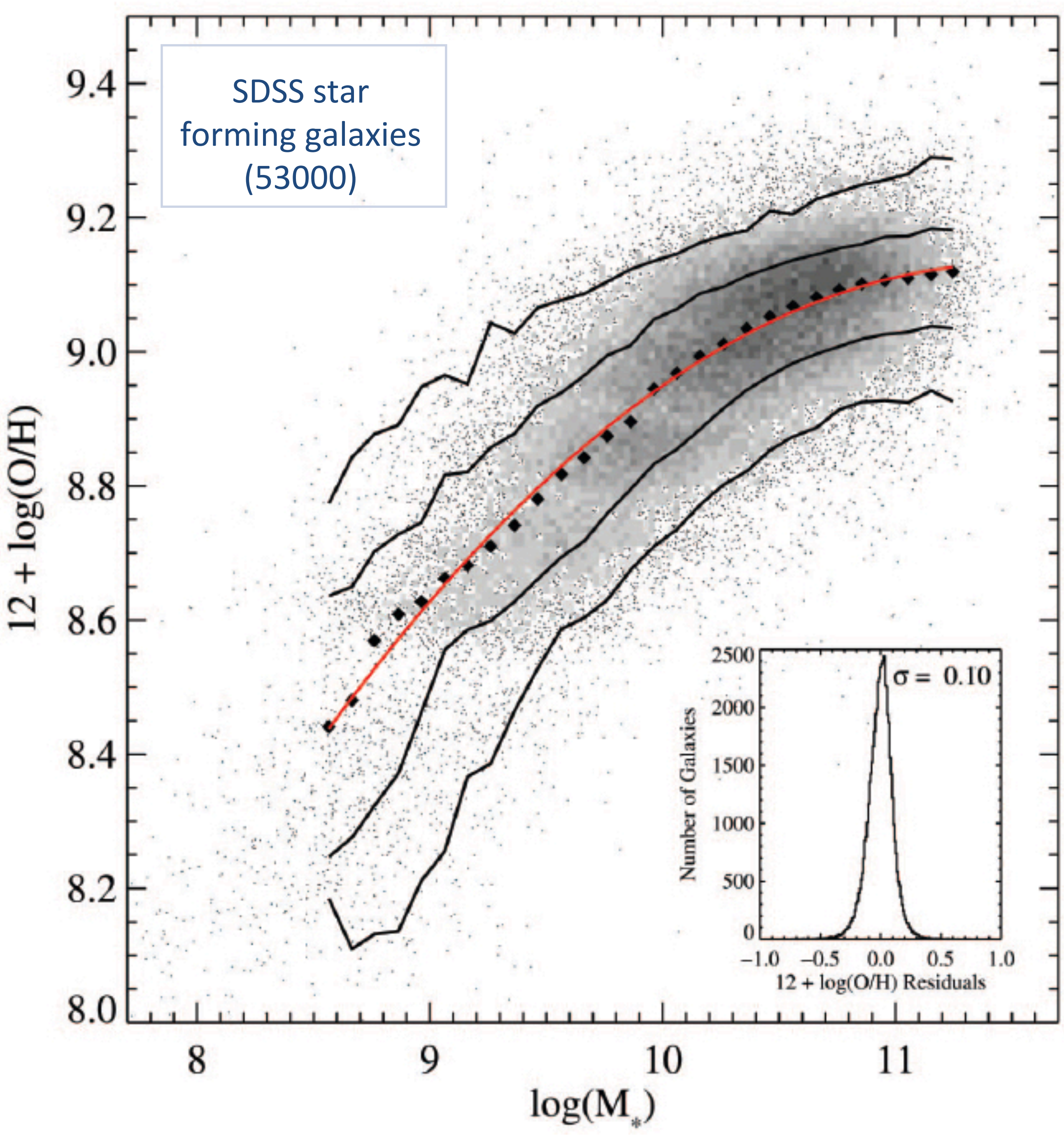
- Present day chemical composition of their host galaxies.
  - Issues related to abundance determinations from ionized gas.
  - Access to many other different species, including Fe and Fe-group elements.

- Distance indicators
  - Investigate the effect of metallicity and reddening.
  - The Flux-weighted Gravity – Luminosity Relationship of Blue Supergiant stars (FGLR, Kudritzki et al. 2003, 2008).

- Oxygen as a proxy for metallicity
  - Extragalactic oxygen abundances
    - Strong Line Methods: dependence upon calibration.
    - Te-SLM : large discrepancies.
    - Te : saturation effects.
    - "Abundance Discrepancy Problem" (CEL vs RL)
  - Is O truly representative of "metallicity" ?



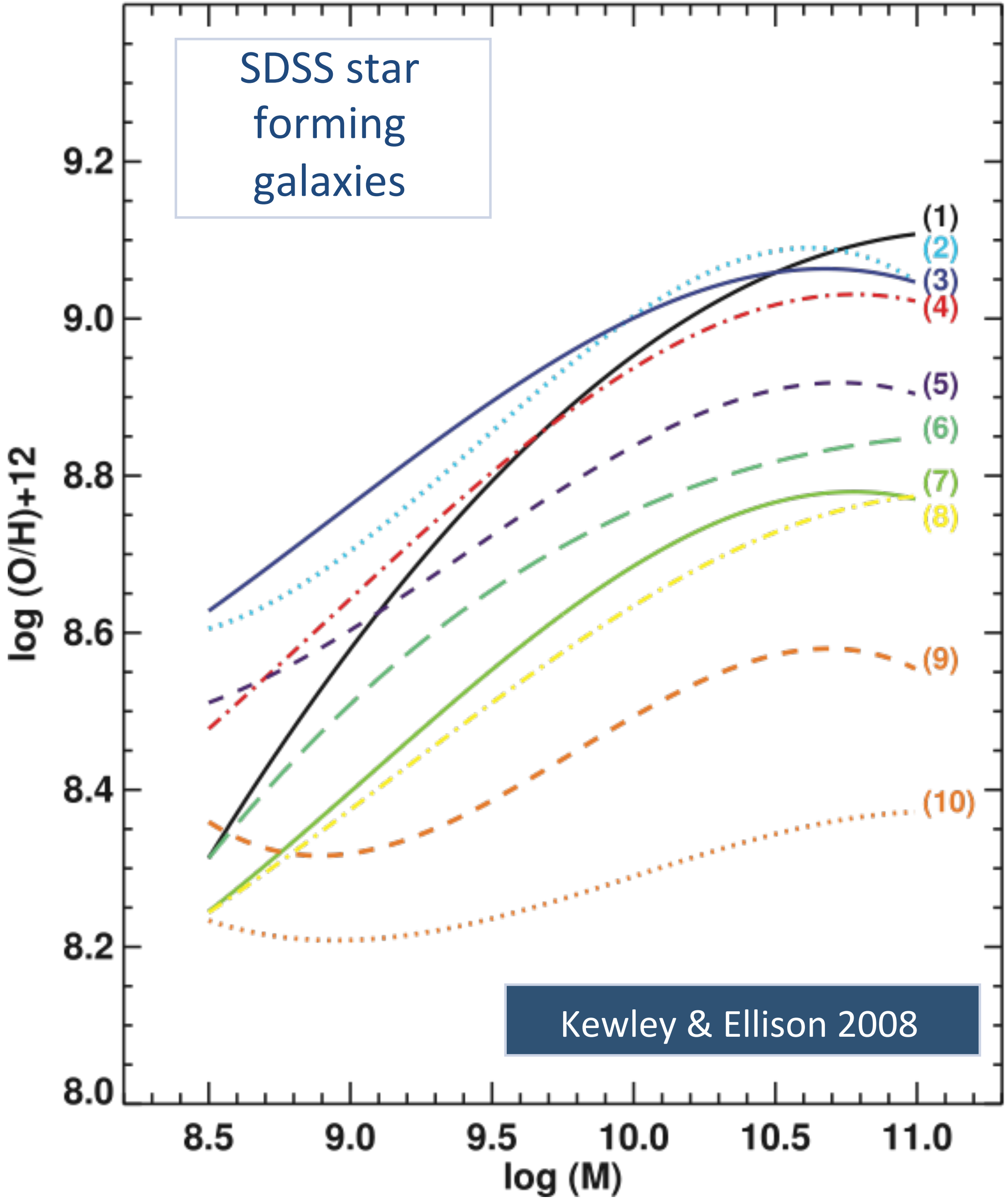
McWilliam (1997)



SDSS star forming galaxies (53000)

Tremonti et al. (2004)

Mass – metallicity relationship



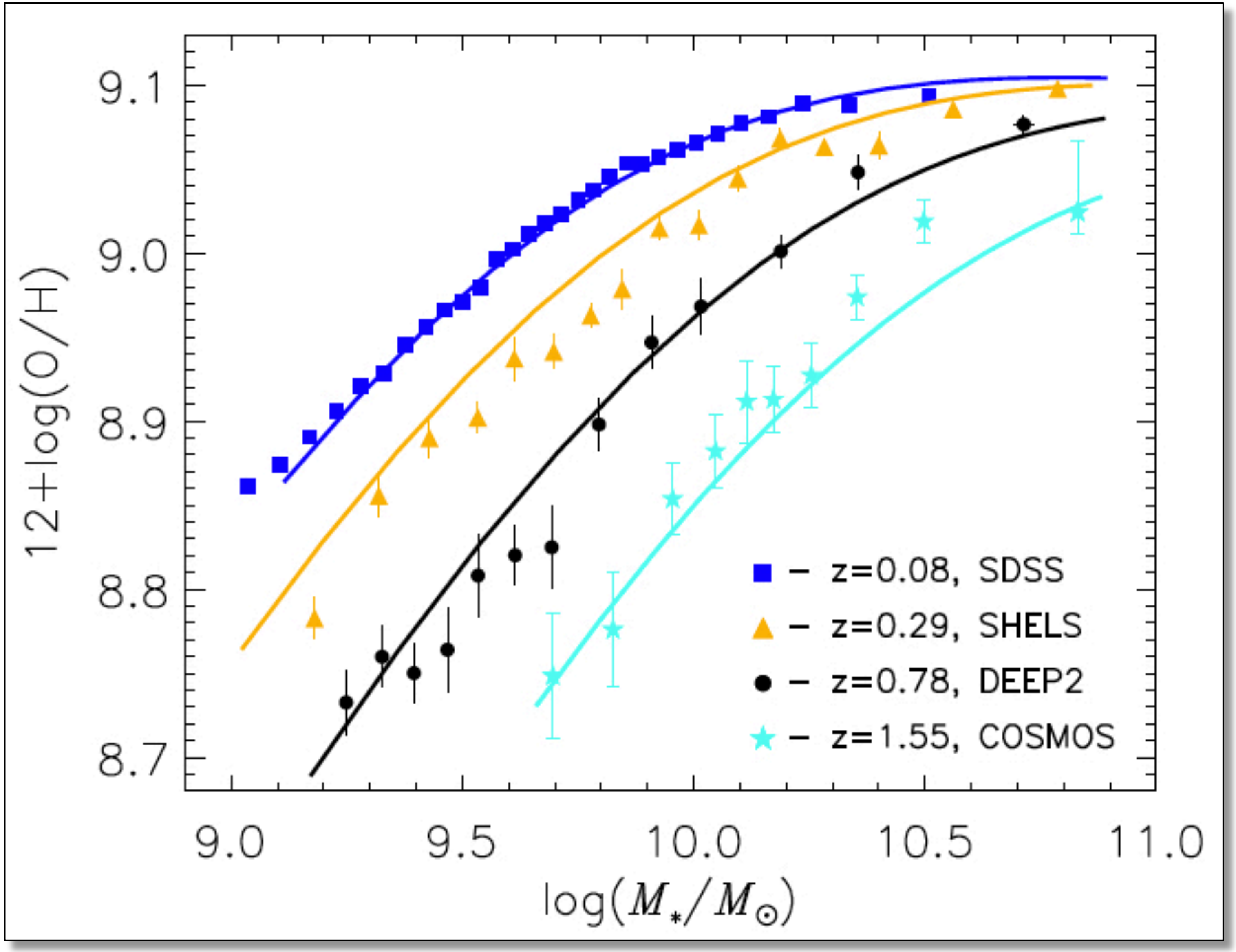
SDSS star forming galaxies

Kewley & Ellison 2008

depends crucially on strong line method calibration

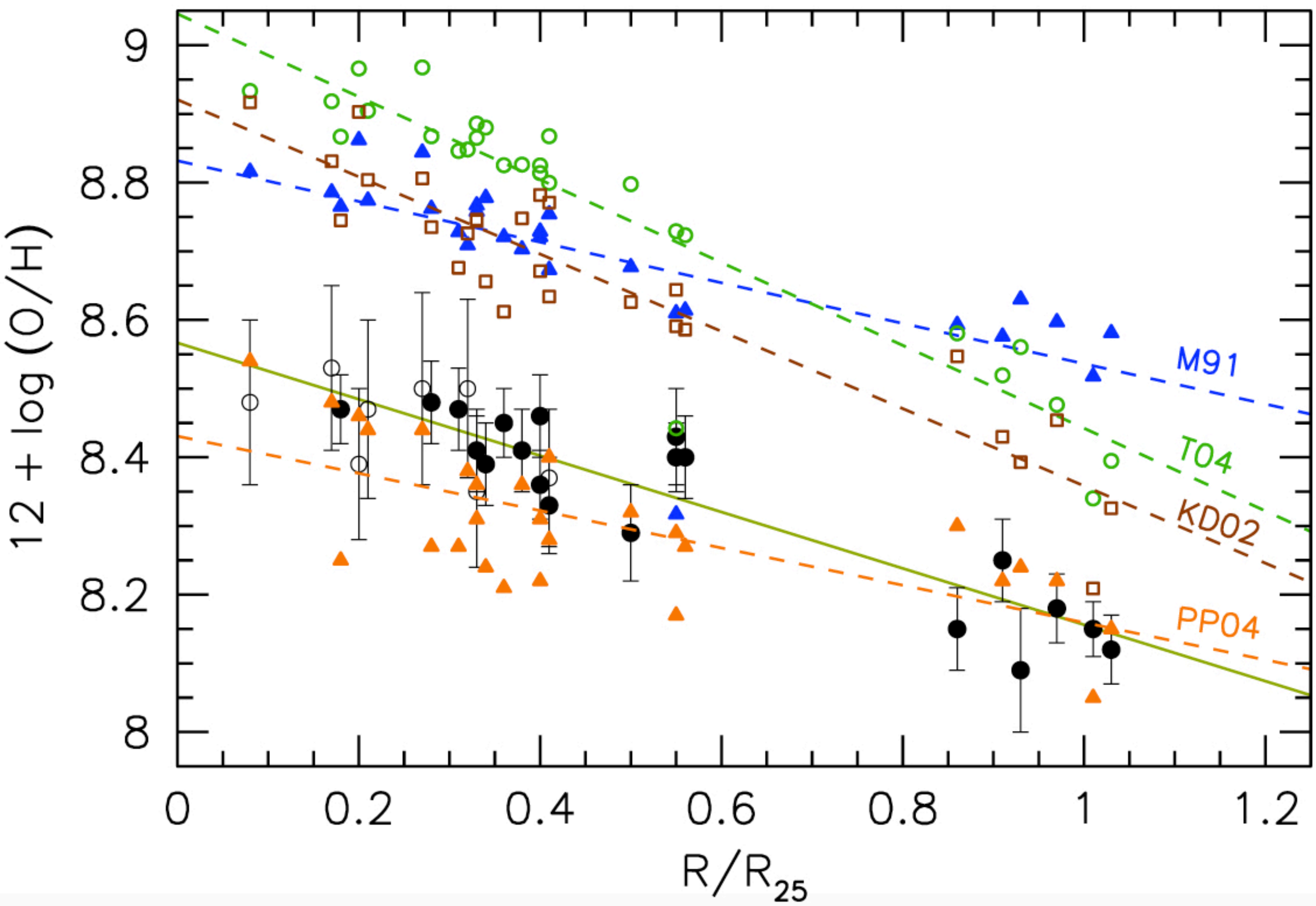
(1) Tremonti et al. (2004)
(2) Zaritzki et al. (1994)
(3) Kobulnicky & Kewkey (2004)
(4) Kewley & Dopita (2002)
(5) McGaugh (1991)
(6) Denicolo et al. (2002)
(7) Pettini & Pagel (2004) - N2O3
(8) Pettini & Pagel (2004) - N2
(9) Pilyugin (2001)
(10) Pilyugin & Thuan (2005)

Zahid et al. (2014)



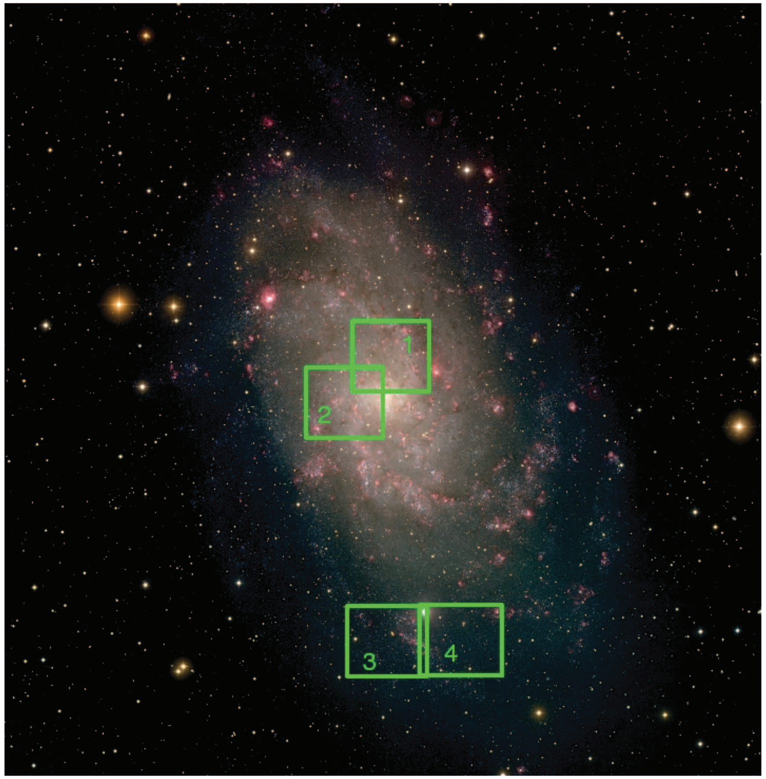
NGC300 - HII regions

Bresolin et al. (2009)

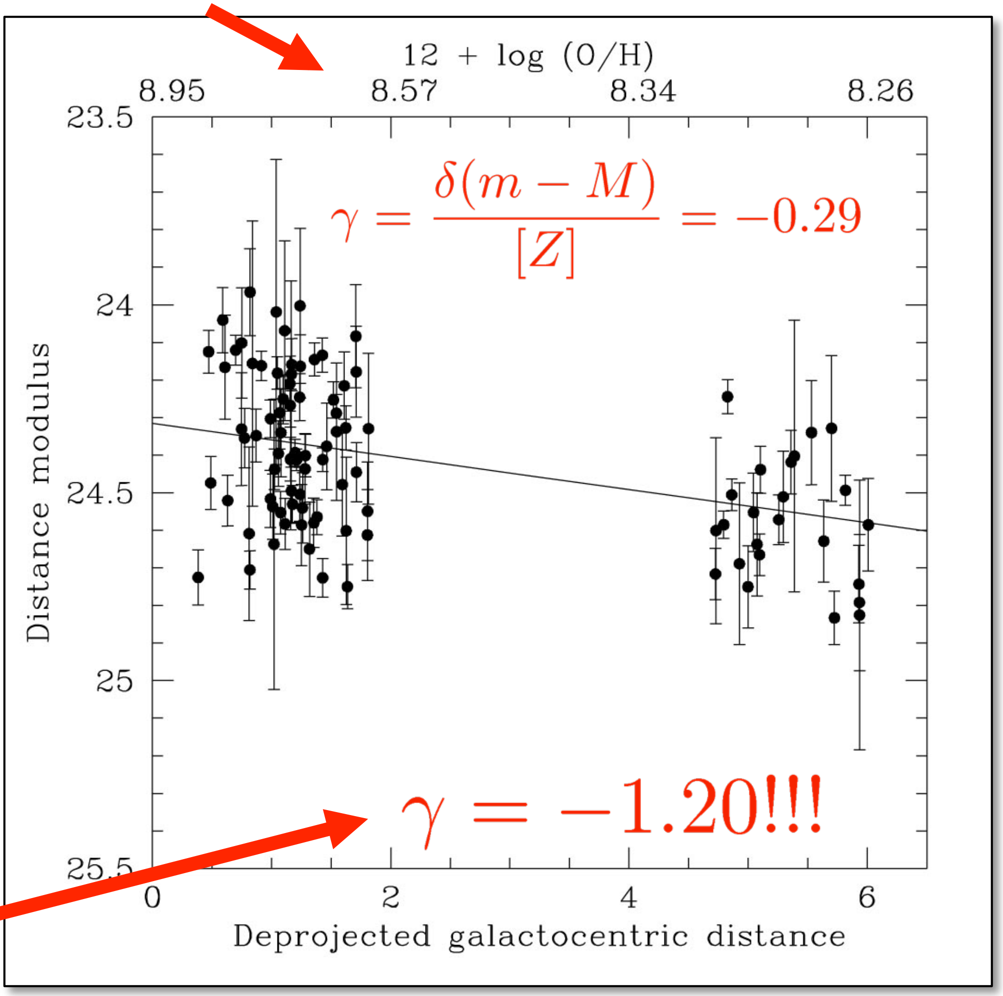


Cepheids in M33

Scowcroft et al. (2009)



Magrini et al. (2007)



$$\gamma = \frac{\delta(m-M)}{[Z]} = -0.29$$

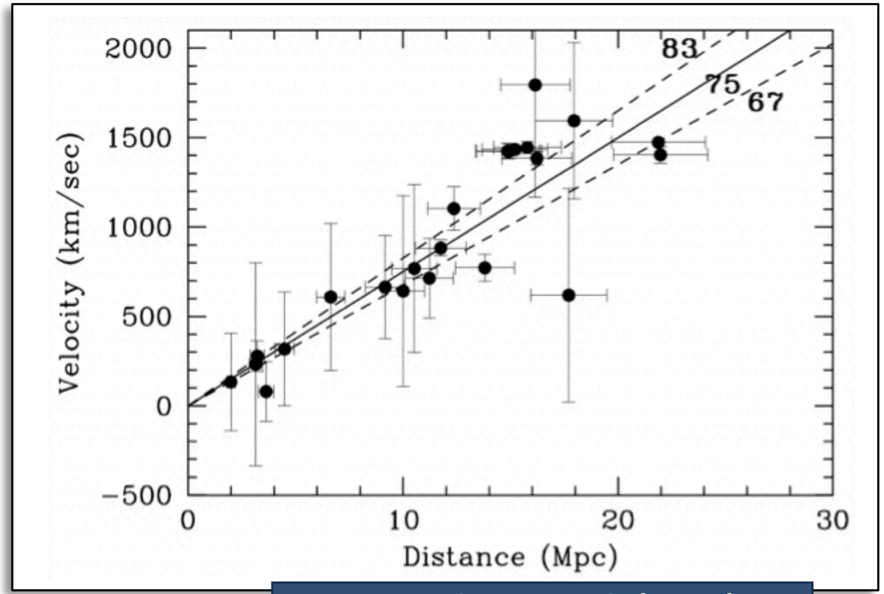
$$\gamma = -1.20!!!$$

Bresolin (2011)

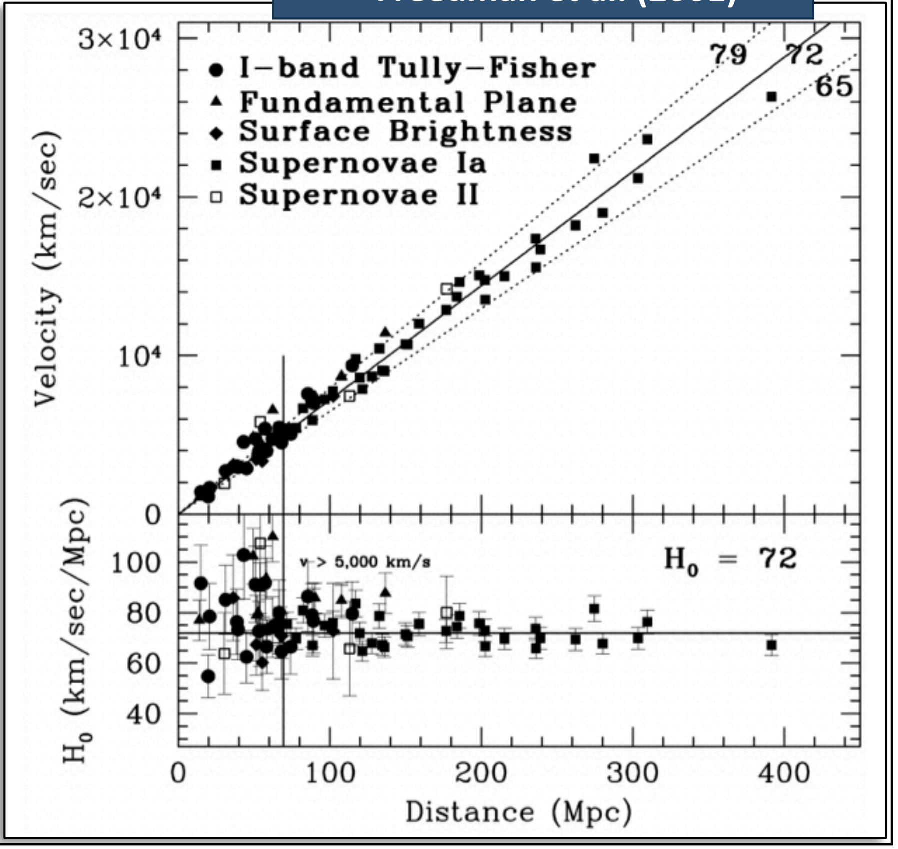
- Cepheids
  - First step in the ladder

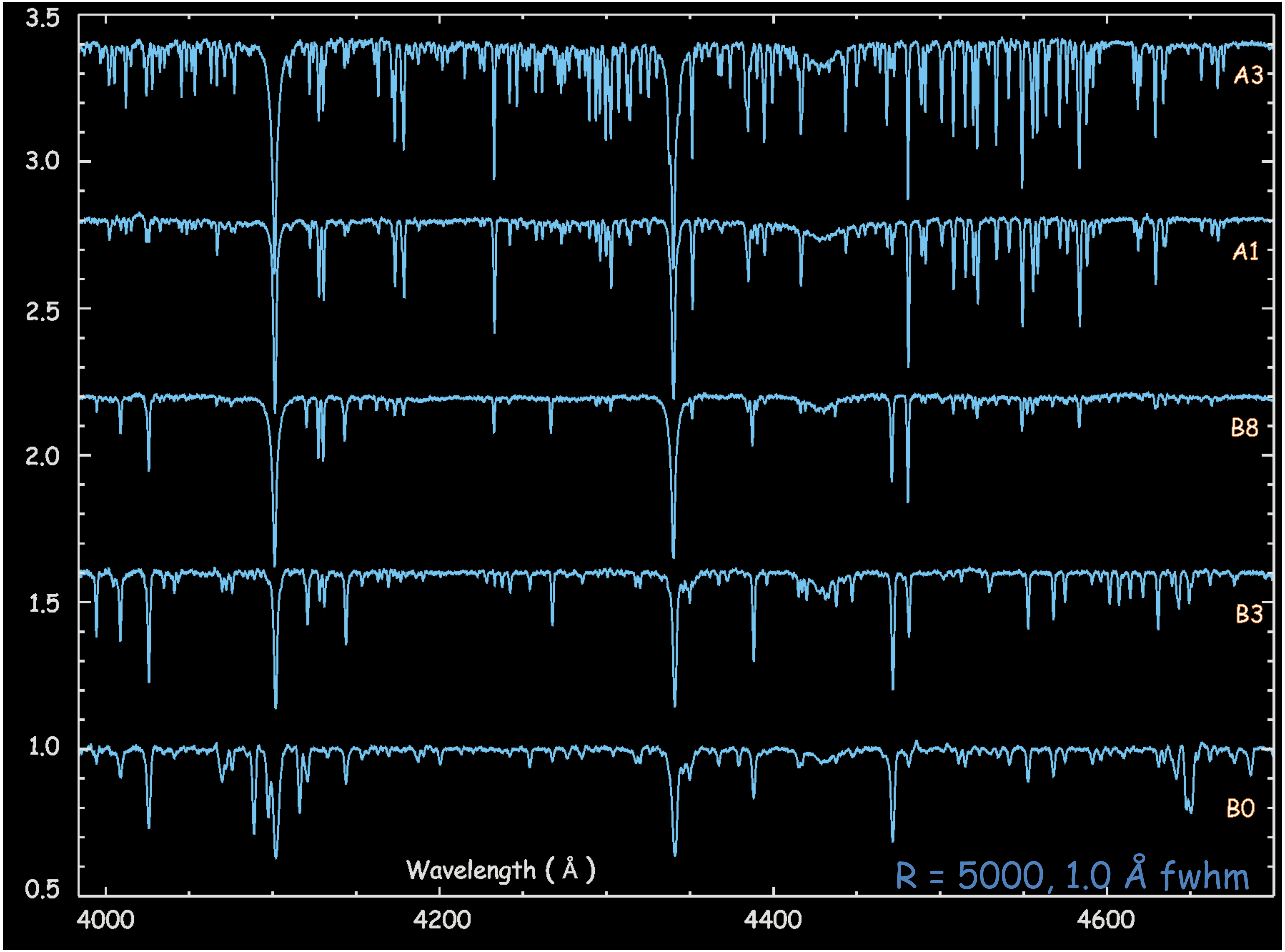
- Secondary distance indicator are calibrated w.r.t Cepheids
  - SN Ia
  - Tully-Fisher relationship
  - SBF

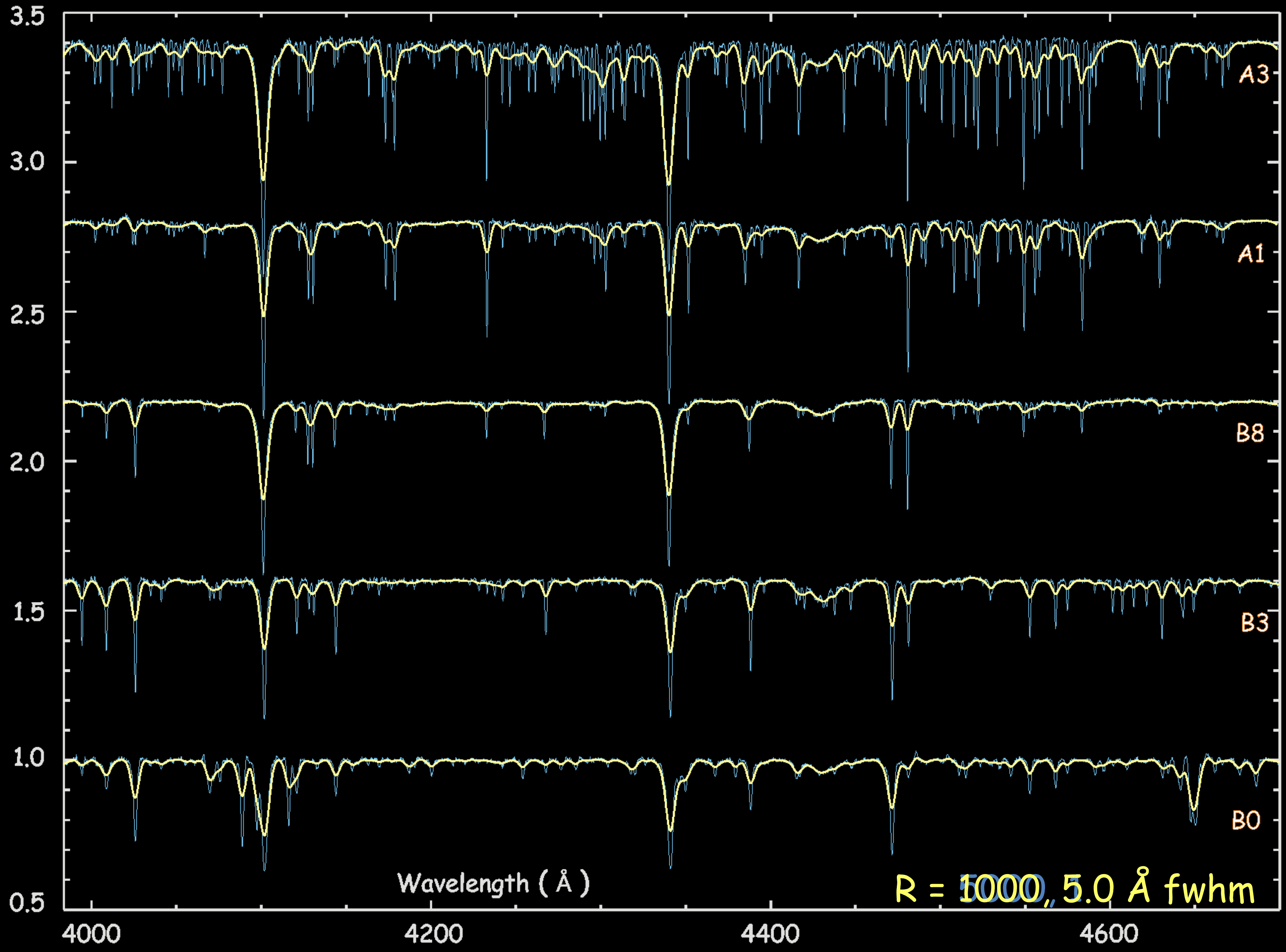
$$\frac{\delta \mathrm{w}}{\mathrm{w}} \approx 2\frac{\delta H_0}{H_0}$$

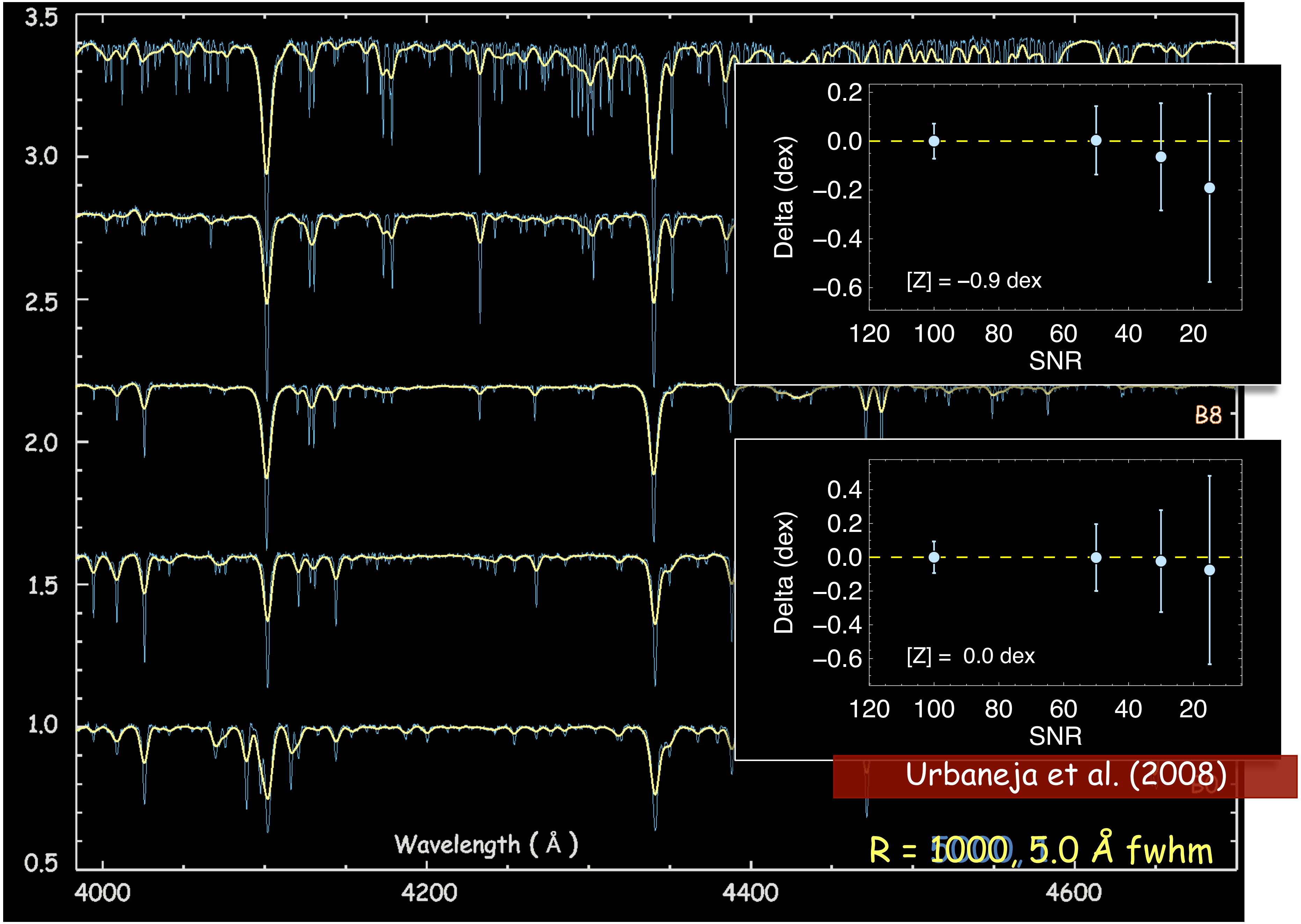


Freedman et al. (2001)




3.5
3.0
2.5
2.0
1.5
1.0
0.5
4000
4200
4400
4600
Wavelength (Å)
A3
A1
B8
B3
B0
R = 5000, 1.0 Å fwhm


3.5
3.0
2.5
2.0
1.5
1.0
0.5
A3
A1
B8
B3
B0
Wavelength (Å)
4000
4200
4400
4600
R = 1000, 5.0 Å fwhm



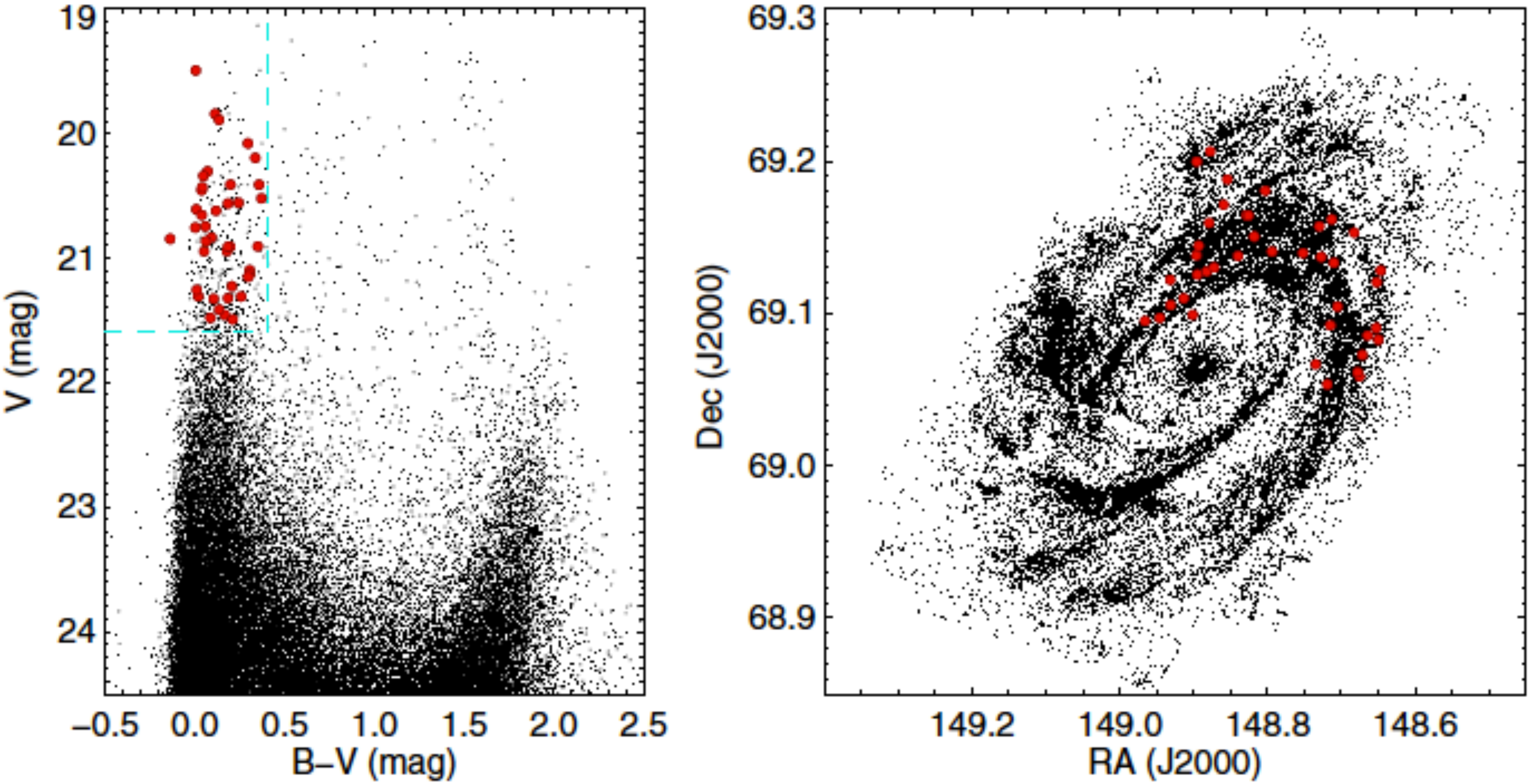
Urbaneja et al. (2008)

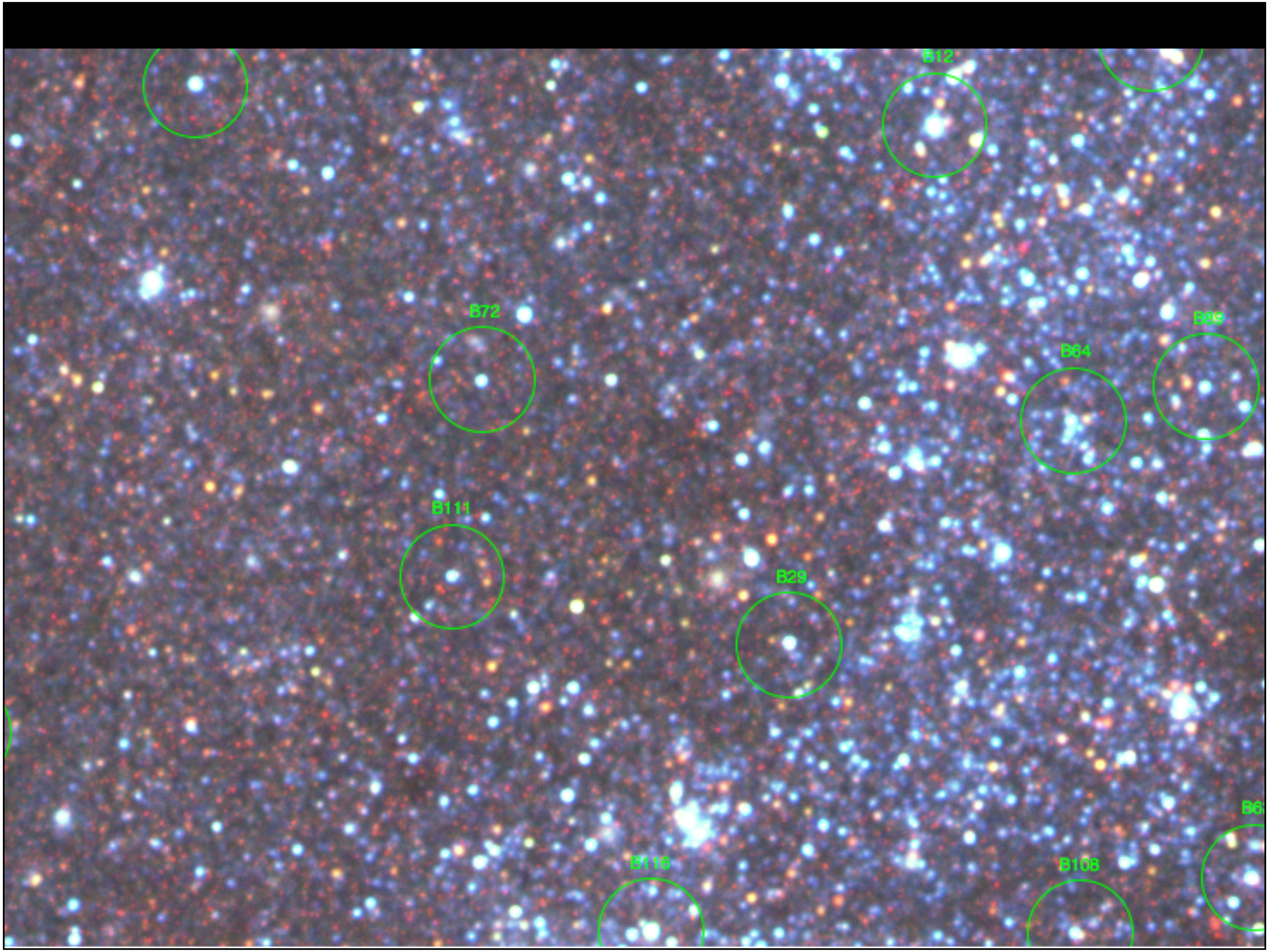
R = 1000, 5.0 Å fwhm

- Intrinsically bright targets   Mv ~ -8.0^{mag}
    - D ~ 1 Mpc m_v ~ 18.0^{mag} M 33, M31, IC1613
    - D ~ 7 Mpc m_v ~ 22.0^{mag} M 51, NGC4258
    - D ~ 10 Mpc m_v ~ 30.0^{mag} M 74

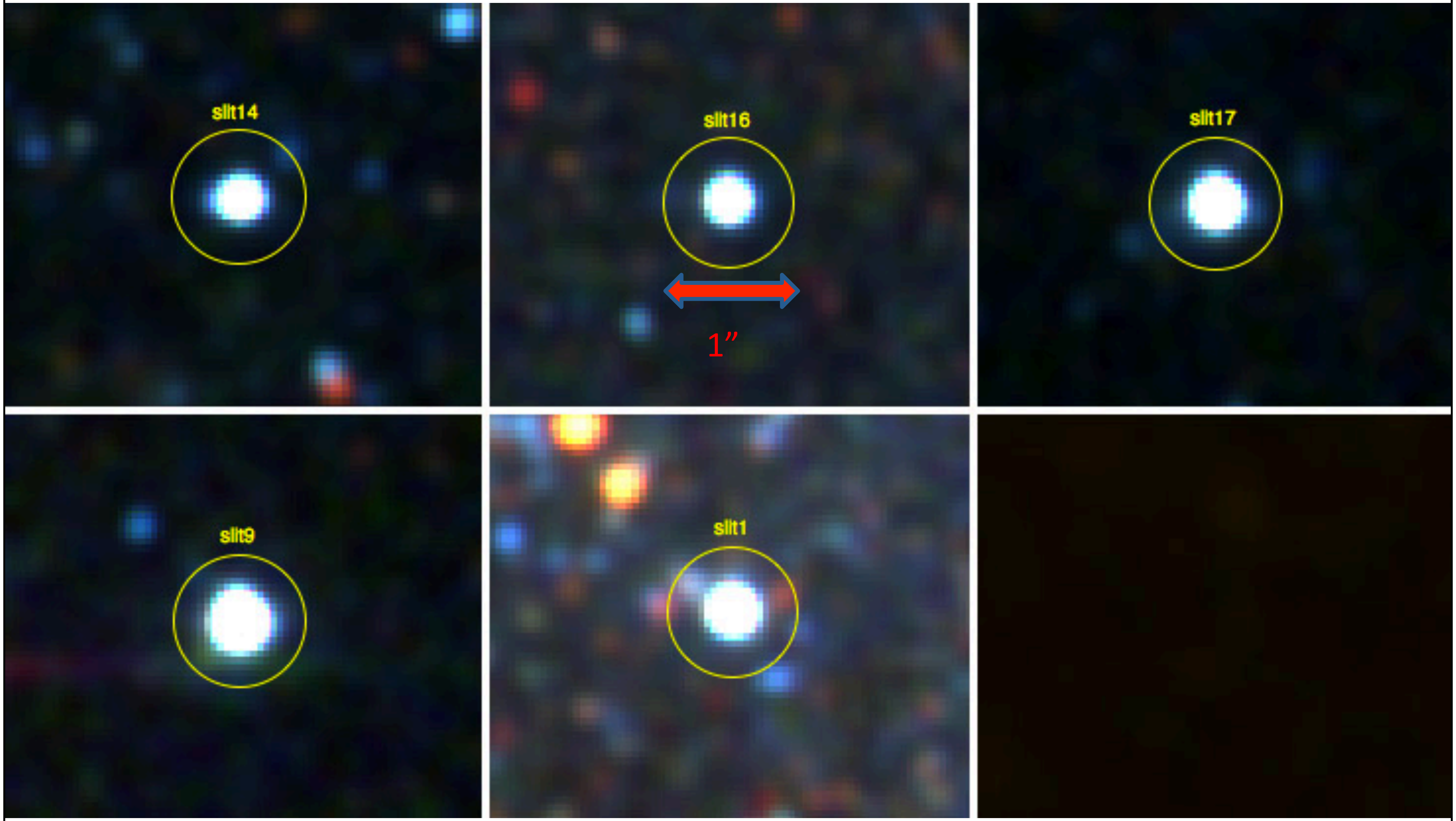
- MOS feasible with 10m-class telescopes
    - Low / intermediate spectral resolution
        - DEIMOS / Keck II   Δλ ~ 2 Å fwhm
        - LRIS / Keck I   Δλ ~ 5 Å fwhm
        - FORS2 / VLT   Δλ ~ 5 Å fwhm
        - MODS1 / LBT   Δλ ~ 5 Å fwhm
    - Wide spectral coverage
        - High / mid res   400 - 700 nm   R > 2500
        - Low res   350 - 700 nm   R < 2500

Kudritzki et al. (2012)



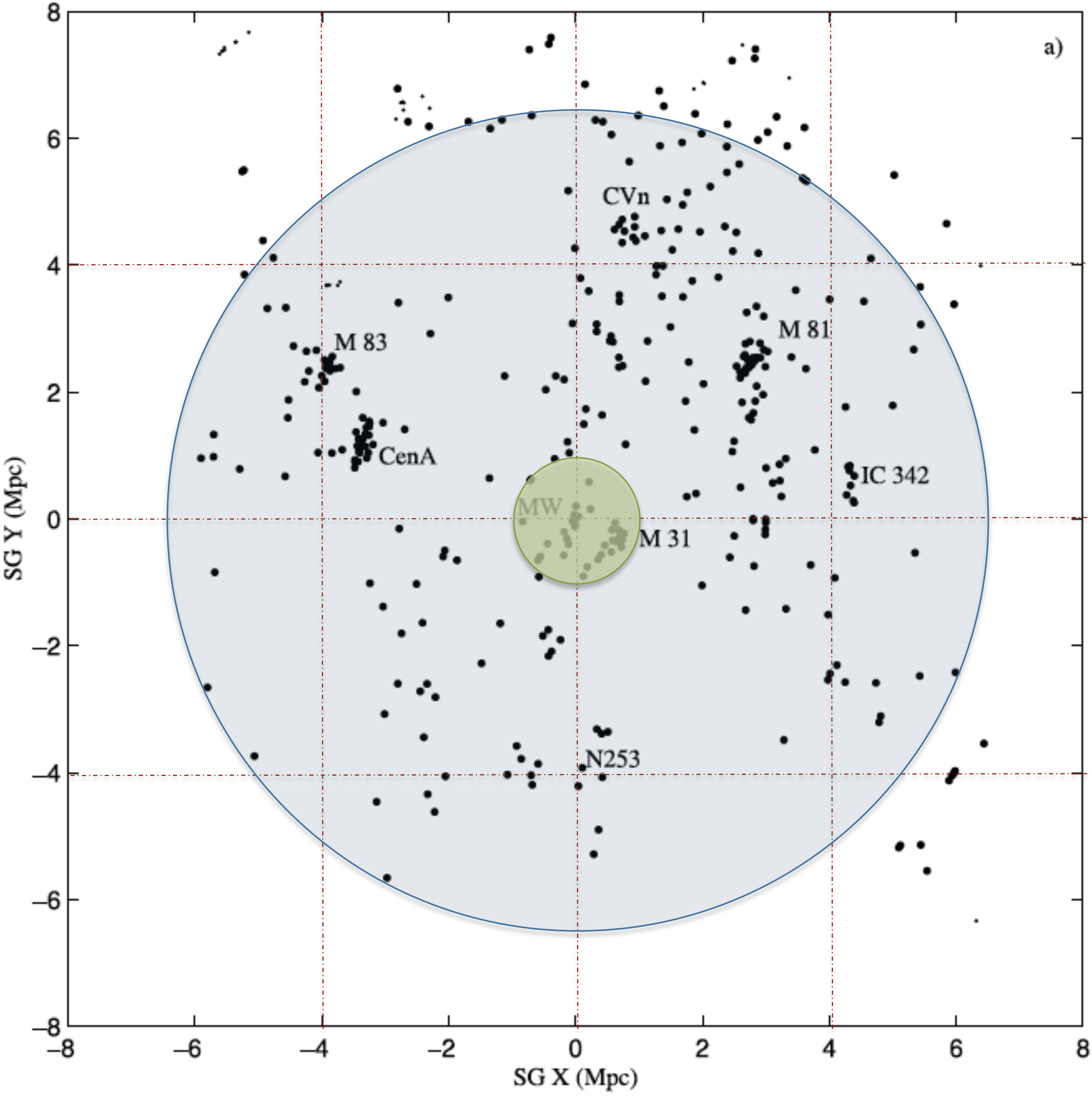

B12
B72
B89
B64
B111
B29
B116
B108
B6

BSGs in NGC 3621: HST ACS

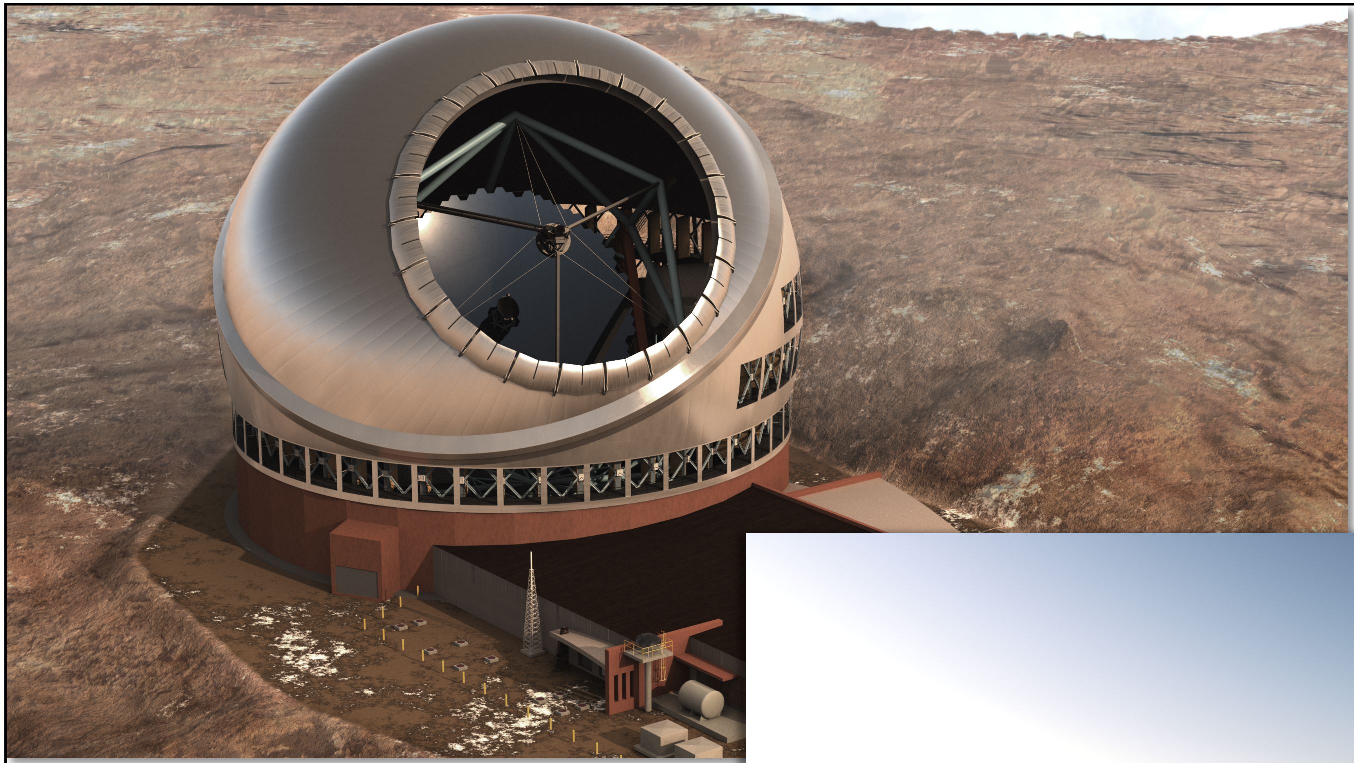


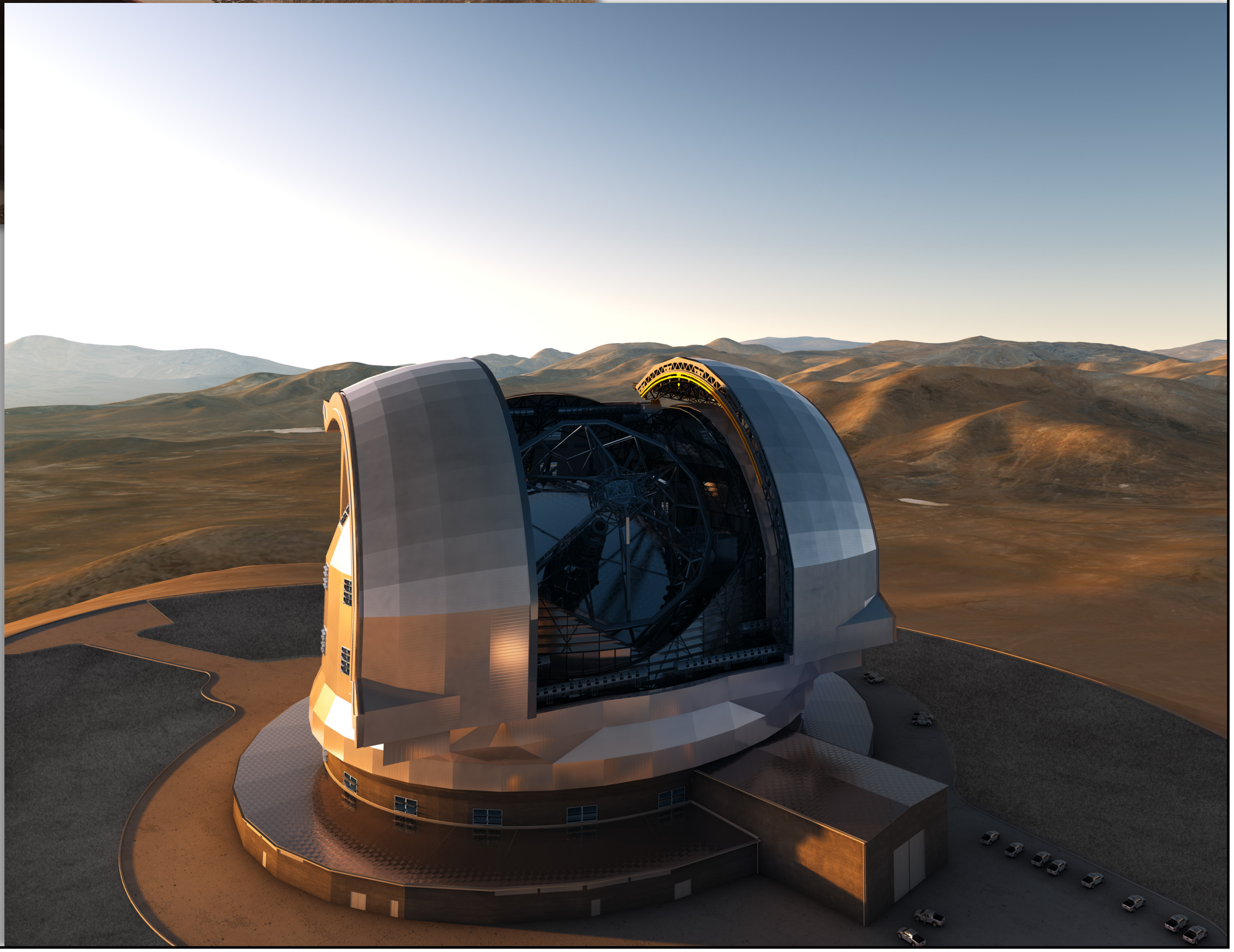
- NGC 6822 (0.45 Mpc): Muschielok et al. (1999), Venn et al. (2001)
- IC1613 (0.7 Mpc): Bresolin et al. (2007); García et al. (2014); Bouret et al. (2015)
- WLM (0.9 Mpc): Venn et al. (2003); Bresolin et al. (2006); Urbaneja et al. (2008)
- Sex A (1.4 Mpc): Kaufer et al. (2004)
- NGC 3109 (1.3 Mpc): Evans et al. (2007); Hosek et al. (2014)

- M31 (0.78 Mpc): Venn et al. (2000); Trundle et al. (2002)
- M33 (0.8 Mpc): Monteverde et al. (1998); Urbaneja et al. (2005); U et al. (2009)
- NGC 300 (1.9 Mpc): Urbaneja et al. (2003,2005); Kudritzki, Urbaneja et al. (2008)
- NGC 55 (1.9 Mpc): Castro, Urbaneja et al. (2012)
- M81 (3.7 Mpc): Kudritzki, Urbaneja et al. (2012)
- NGC3621 (6.5 Mpc): Kudritzki, Urbaneja et al. (2014)
- NGC4258 (7.6 Mpc): Kudritzki, Urbaneja et al. (2013)



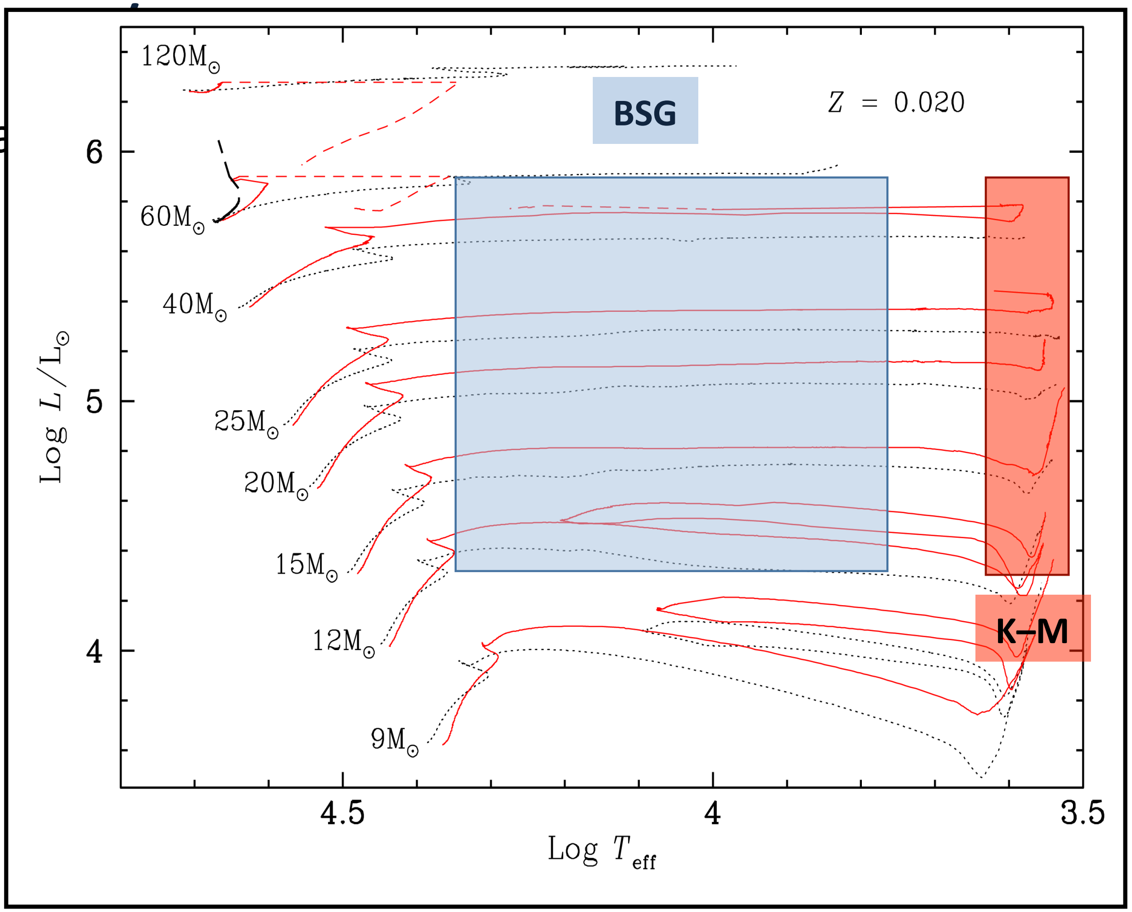
Karachentsev et al. (2004)





Red Supergiants

- Brightest stars at IR light: -8 ≥ M_J ≥ -11 mag
  - [Z] = ±0.2 dex @R~2000-3000 from J-band spectra
- MOSFIRE/Keck, KM
  - Down to J=19.5 ma



Red Supergiants

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  - Down to J=19.5 mag ➔ (m-M) = 30.5 mag (12.6 Mpc)

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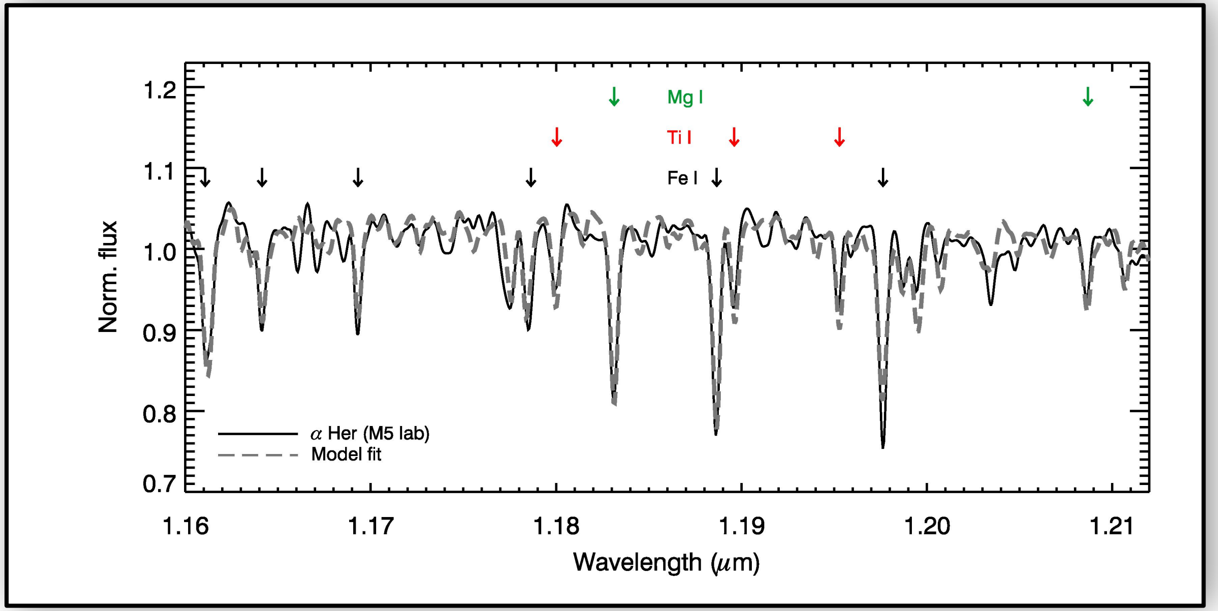
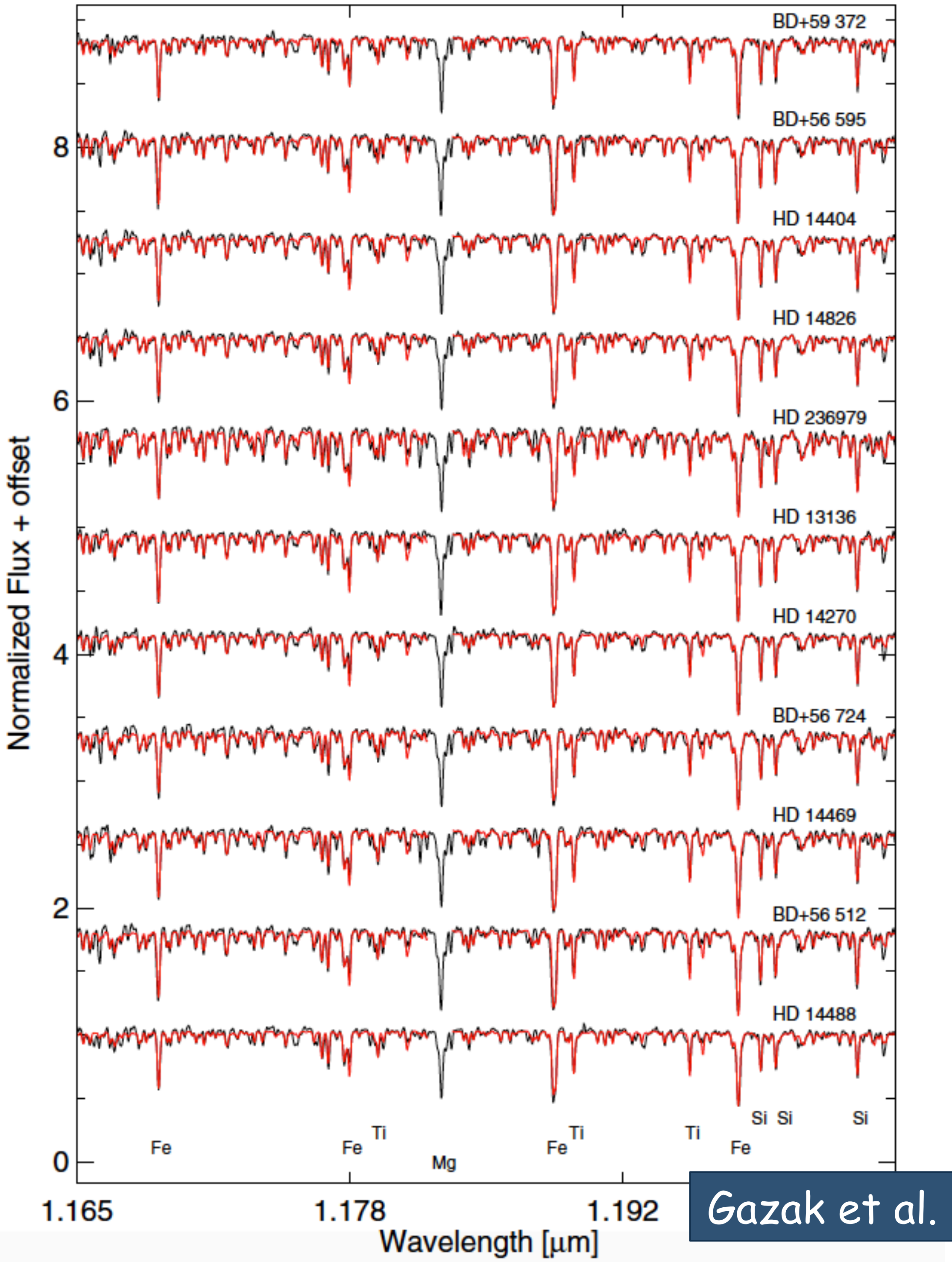
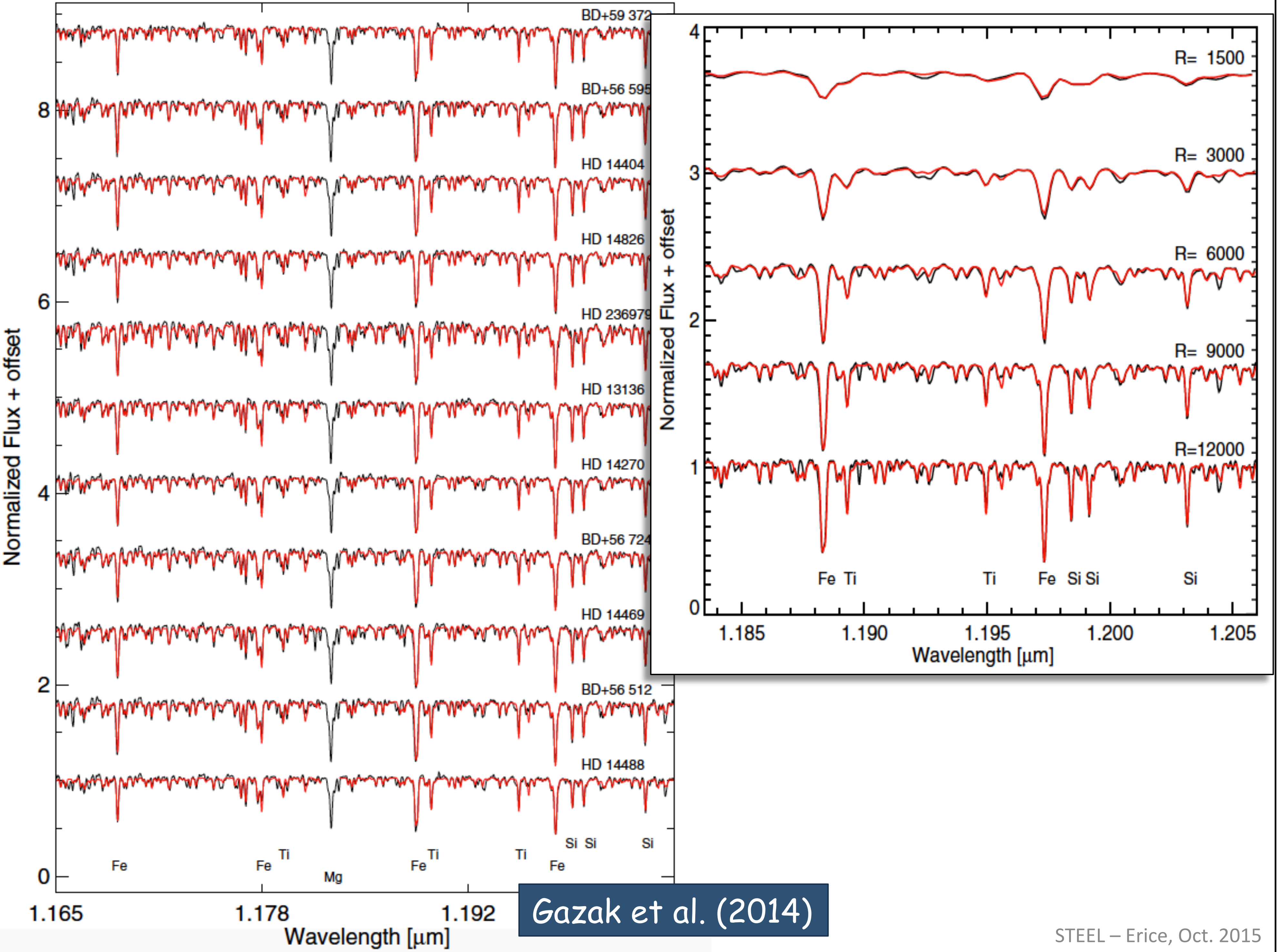


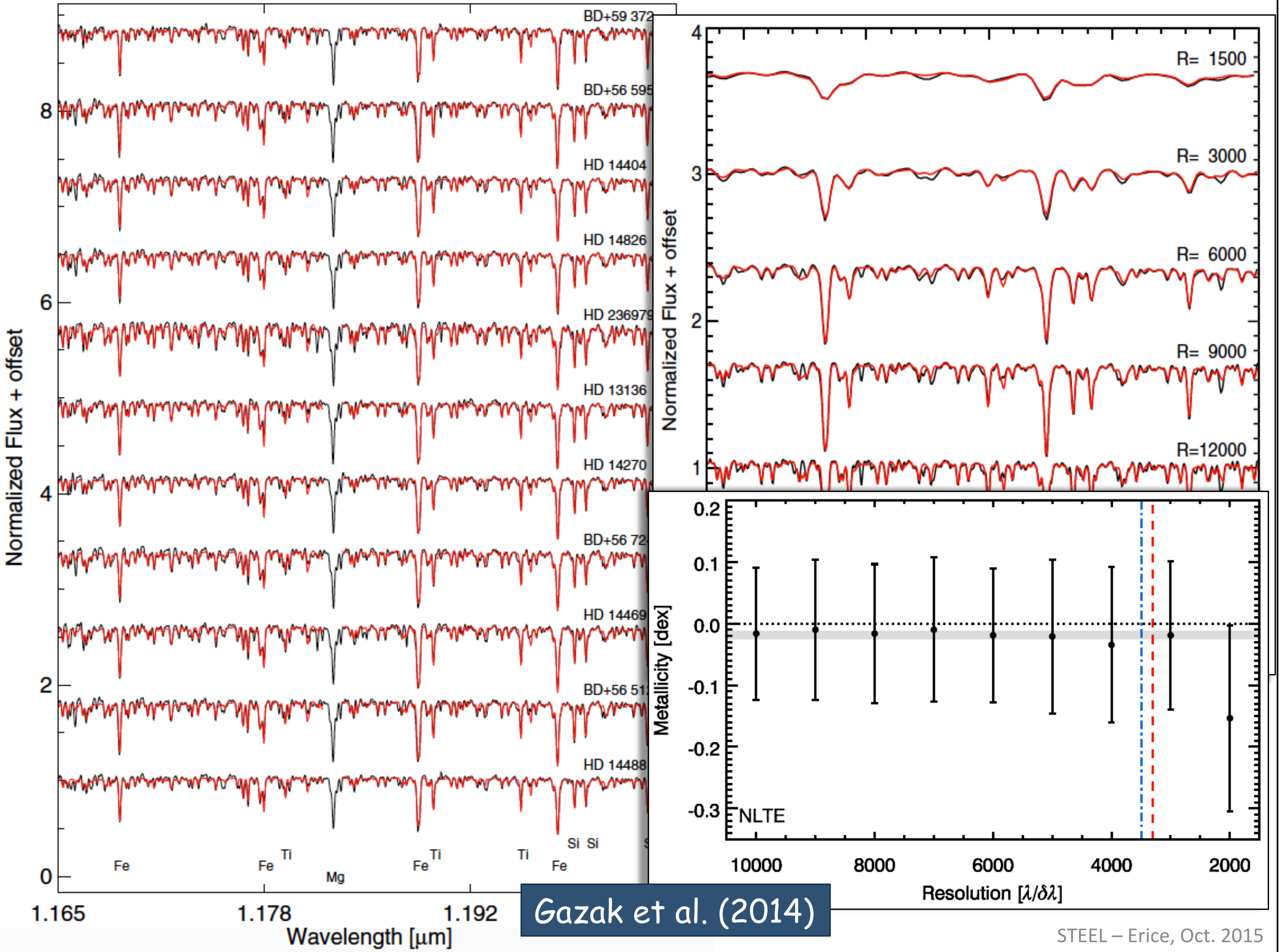
Davies et al. (2010)



Gazak et al. (2014)

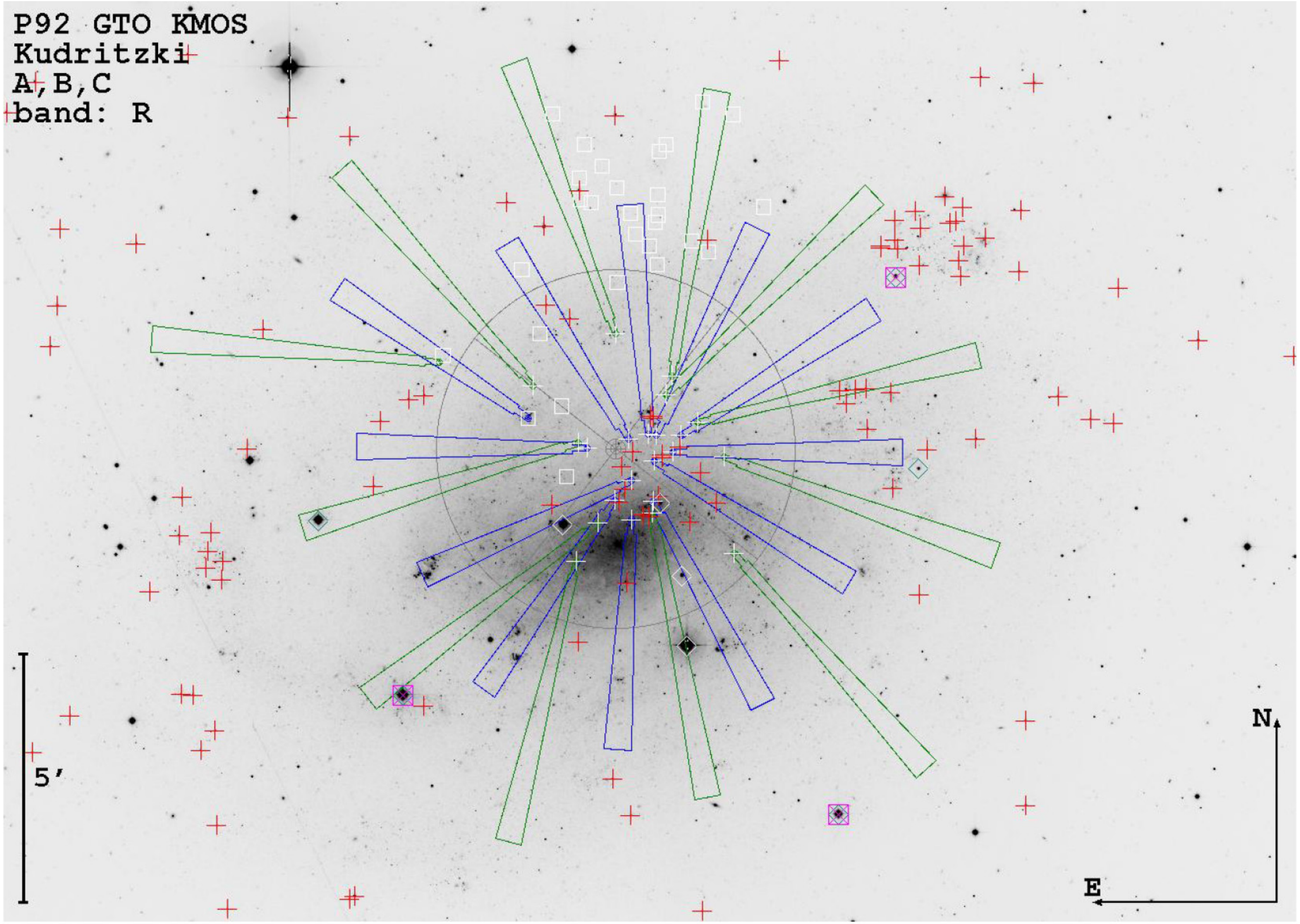


Gazak et al. (2014)

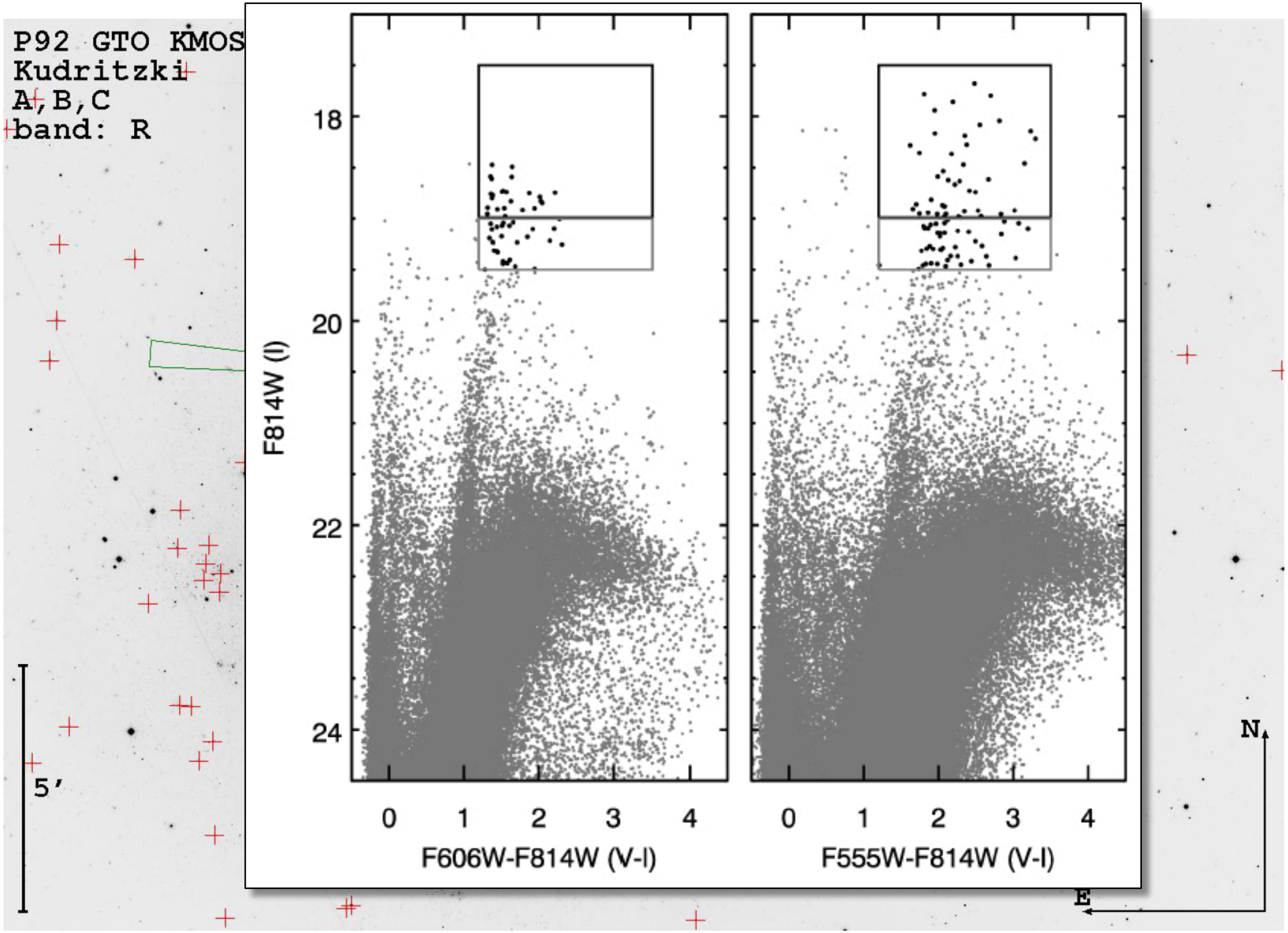


Gazak et al. (2014)

NGC300 – KMOS IFU set-up

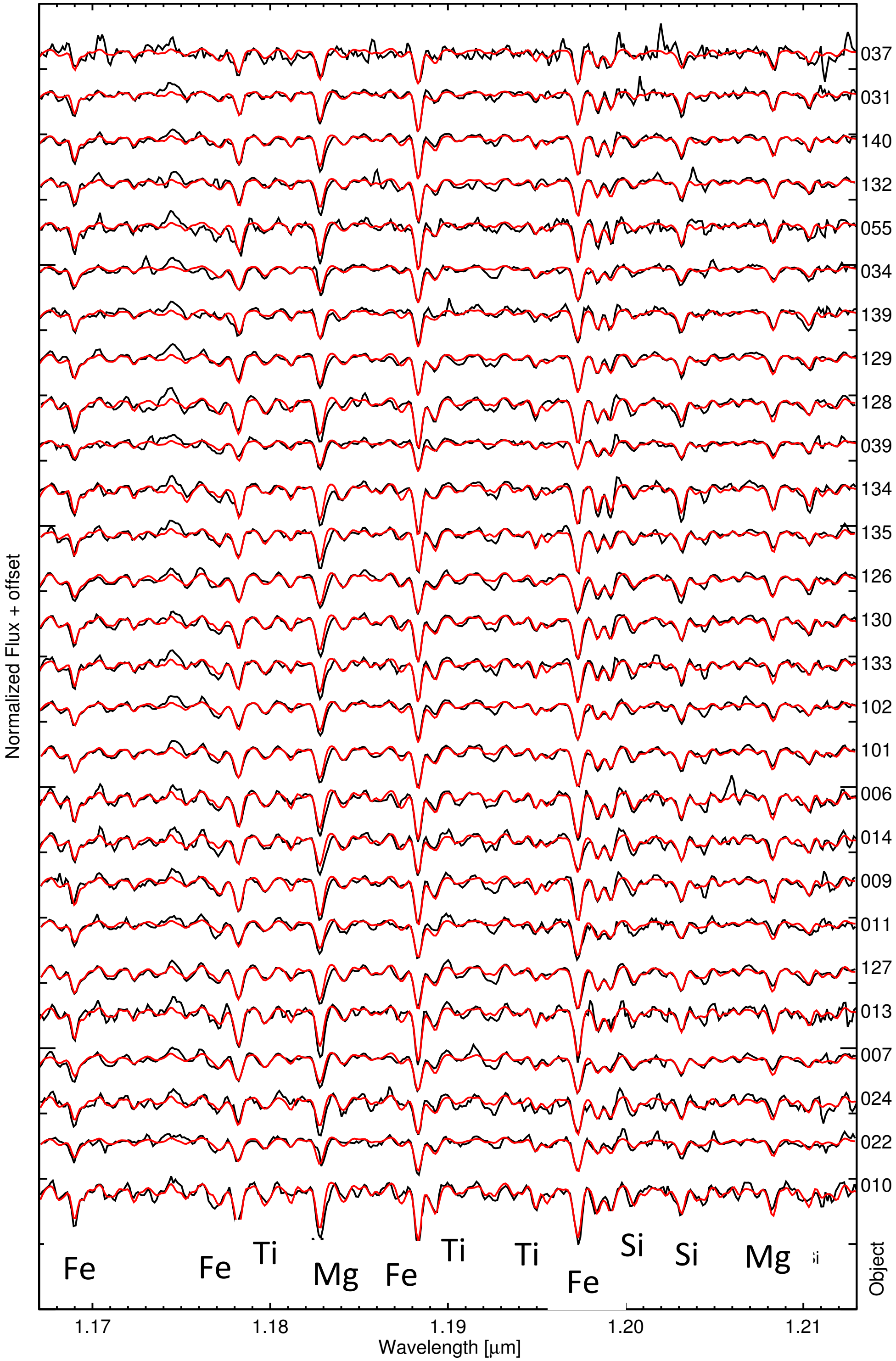


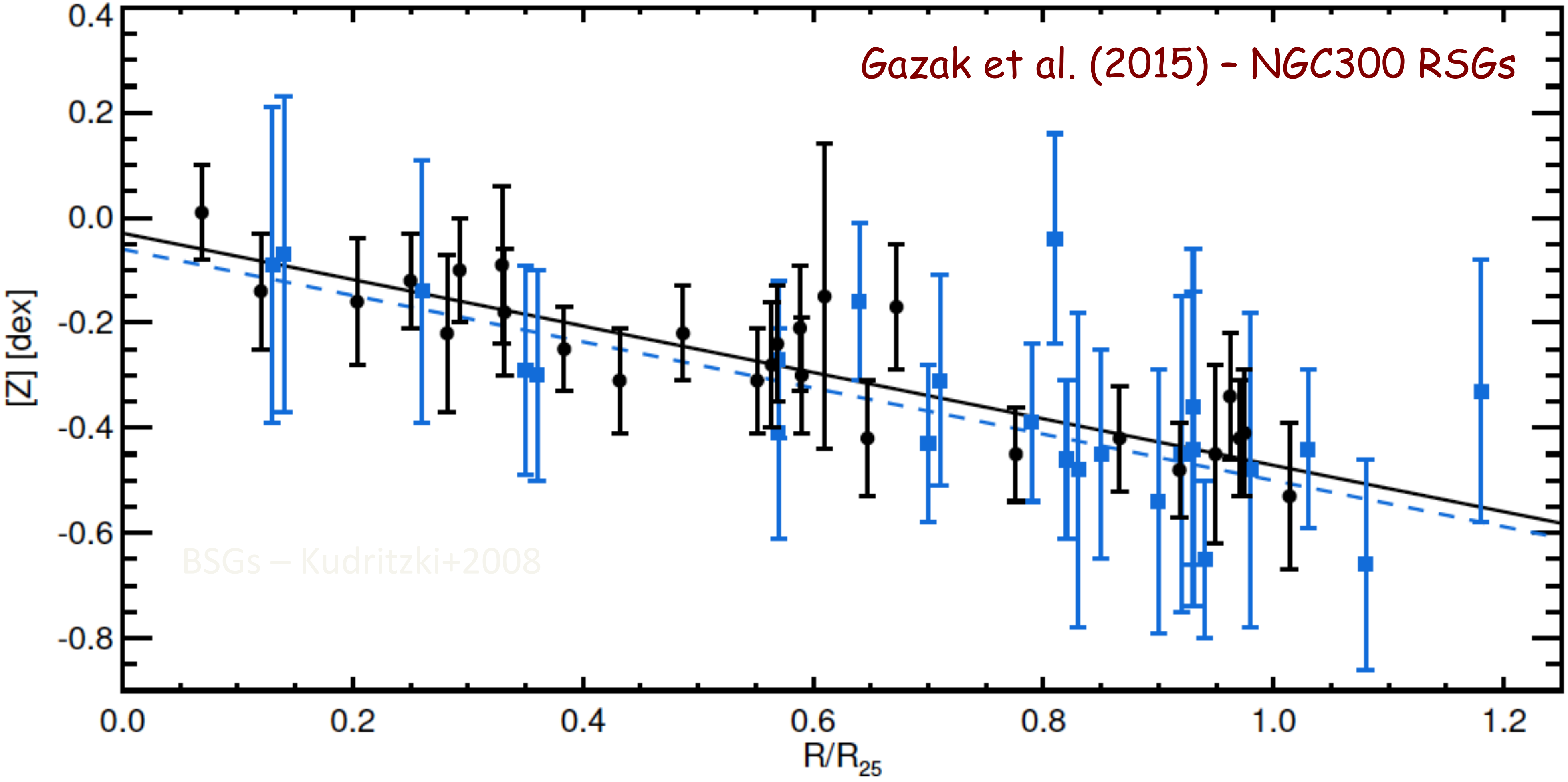
NGC300 – KMOS IFU set-up



NGC300 - KMOS RSGs

Gazak et al. (2015)

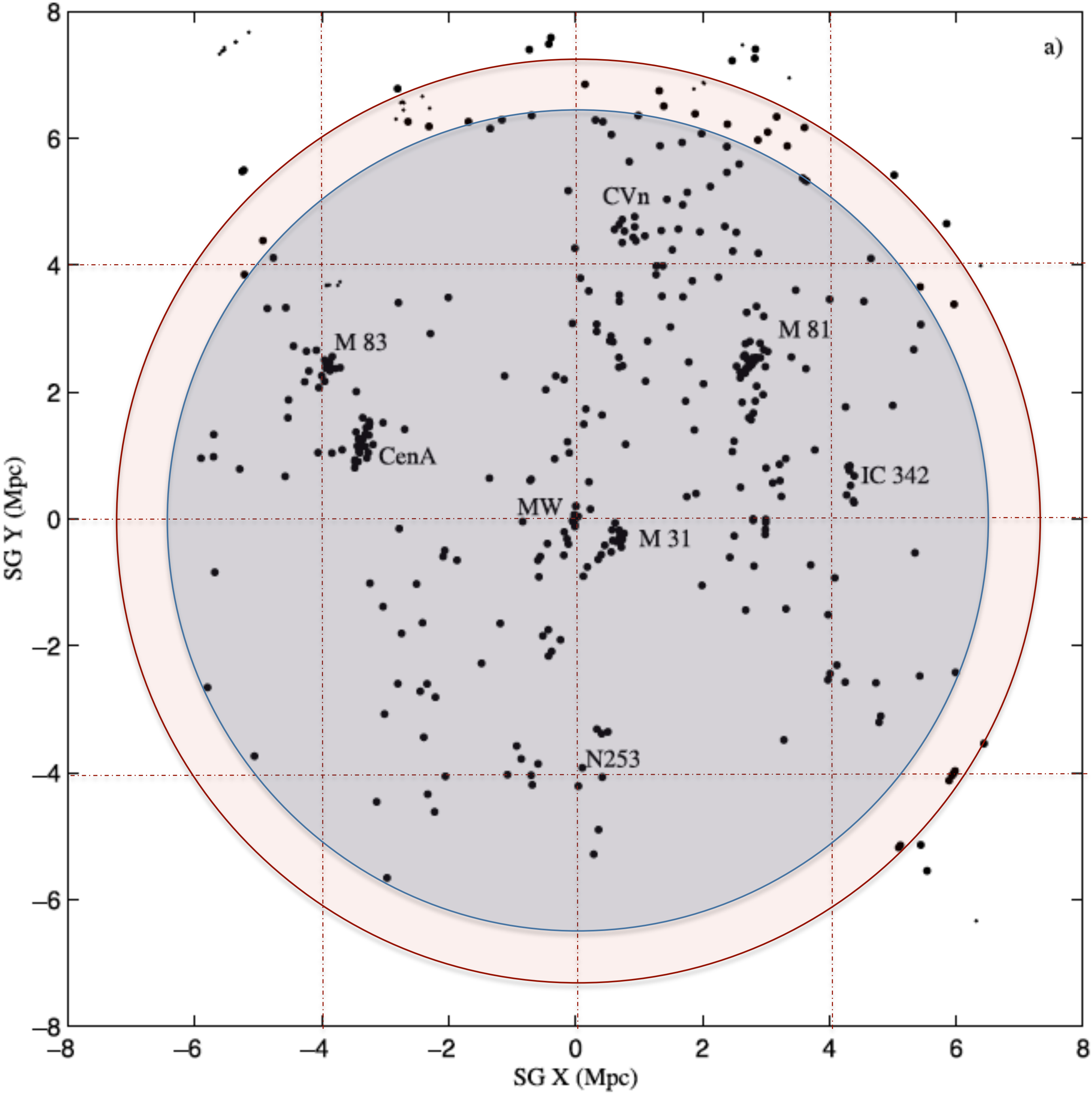




Gazak et al. (2015) – NGC300 RSGs

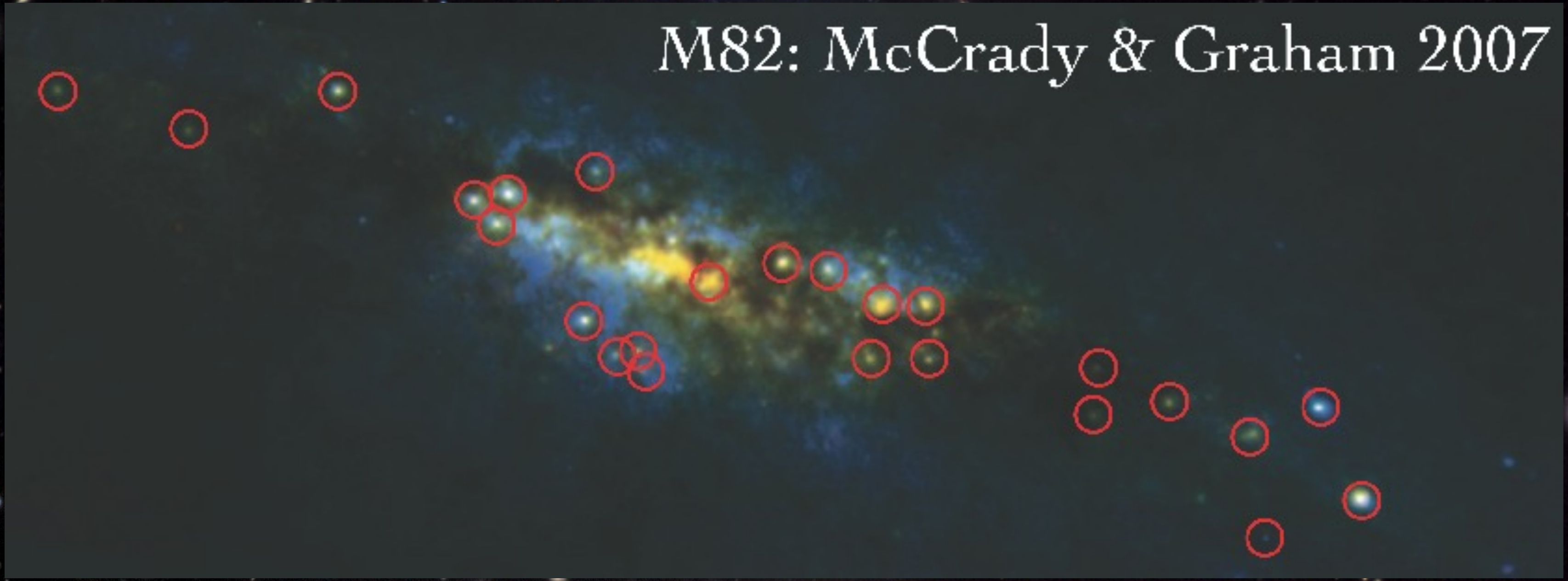
Table 3
Comparison of NGC 300 Metallicity and Gradient Literature

Study	Central Abundance		Metallicity Gradient		Notes
	dex, metals	12+log(O/H)	r/r_{25}	dex kpc^{-1}	
Kudritzki et al. (2008)	-0.07 ± 0.09	...	-0.44 ± 0.06	-0.081 ± 0.011	Blue Supergiants, Metals
Bresolin et al. (2009)	...	8.57 ± 0.02	-0.41 ± 0.03	-0.077 ± 0.006	H II regions, auroral oxygen
This work	-0.03 ± 0.05		-0.44 ± 0.08	-0.083 ± 0.014	Red Supergiants, Metals



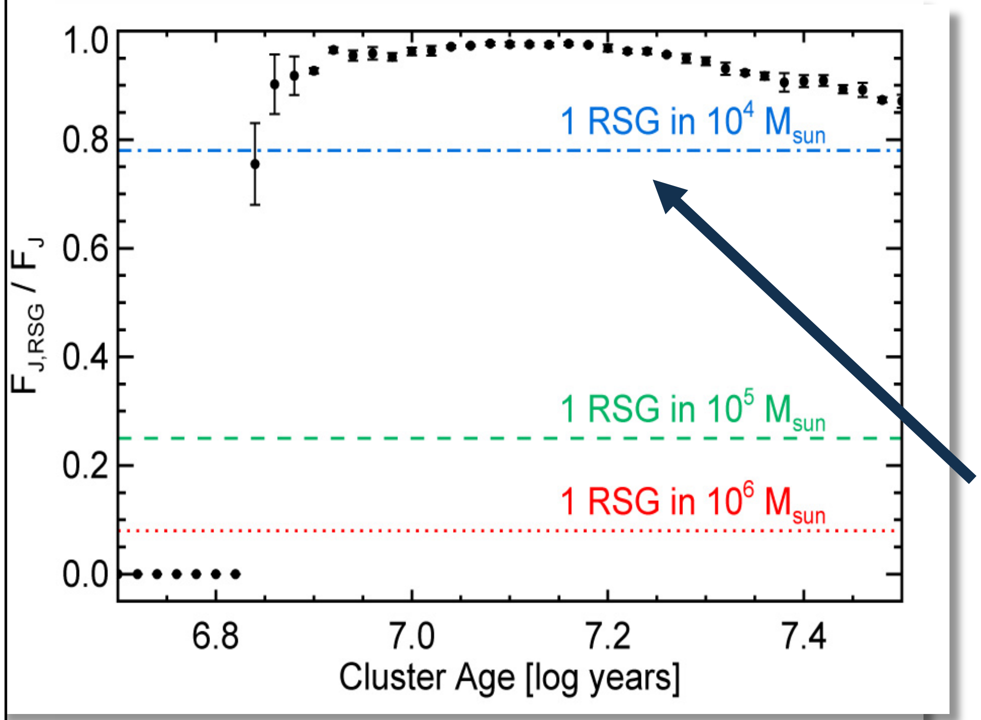
Karachentsev et al. (2004)

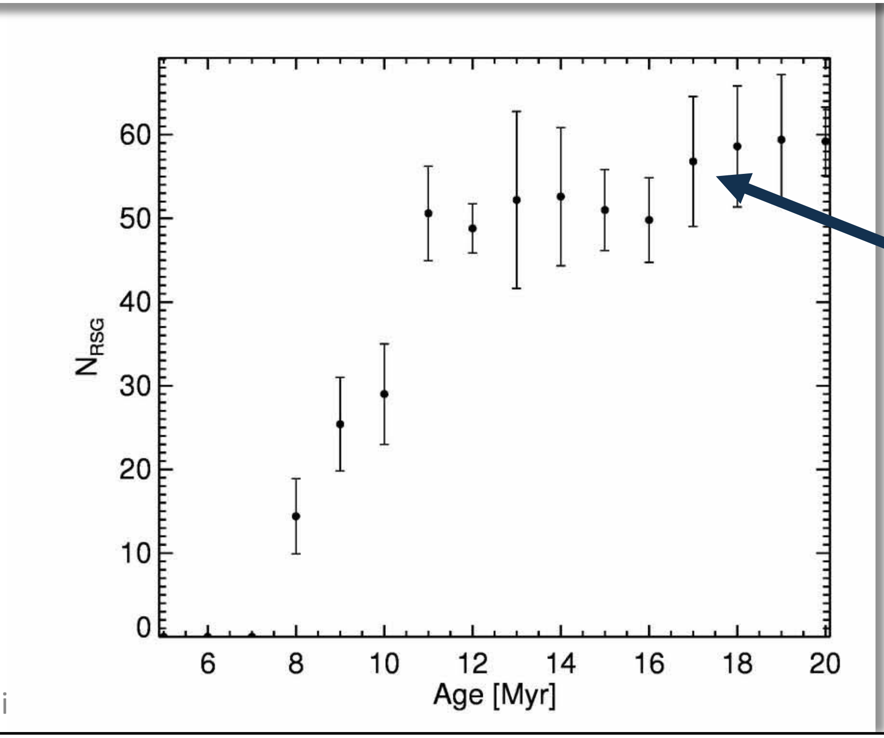
Super Star Clusters (SSCs)



Dense aggregates of young massive stars in
star forming/merging galaxies
(Review by Portegies Zwart et al., 2010, ARAA 48, 431)

$$M \sim 10^5 \ldots 10^6\ M_\odot$$





Gazak et al. (2013)

J-band population synthesis
10^5 M_{sun} cluster

RSG contribution to J-band flux is 95%
Number of RSGs ~ 50

RSGs dominate J-band!!!

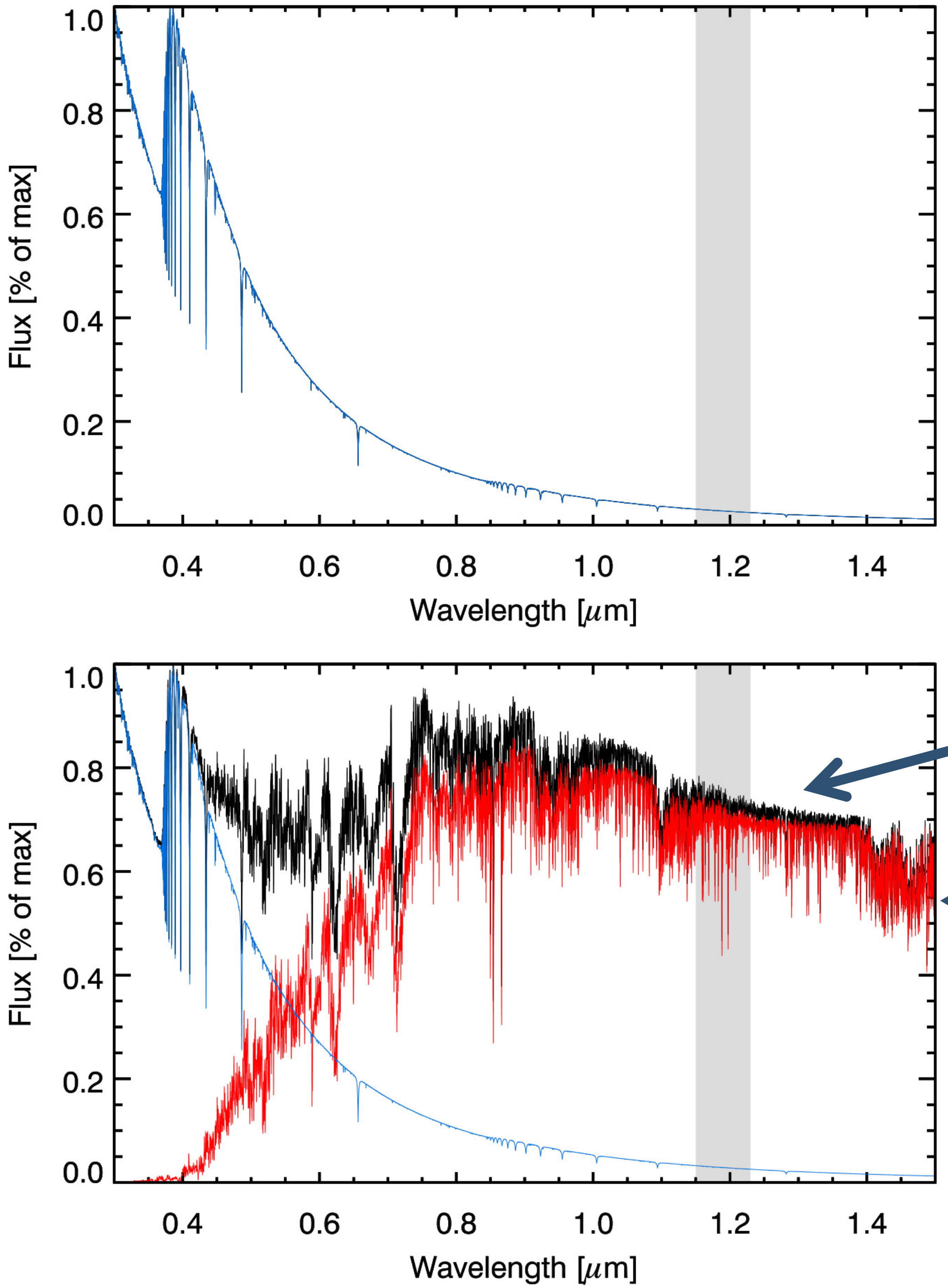
SSC J-band low R ideal for metallicity!!!!!

Mi

Gazak et al. (2014)

Predicted SSC spectrum

15 Myr

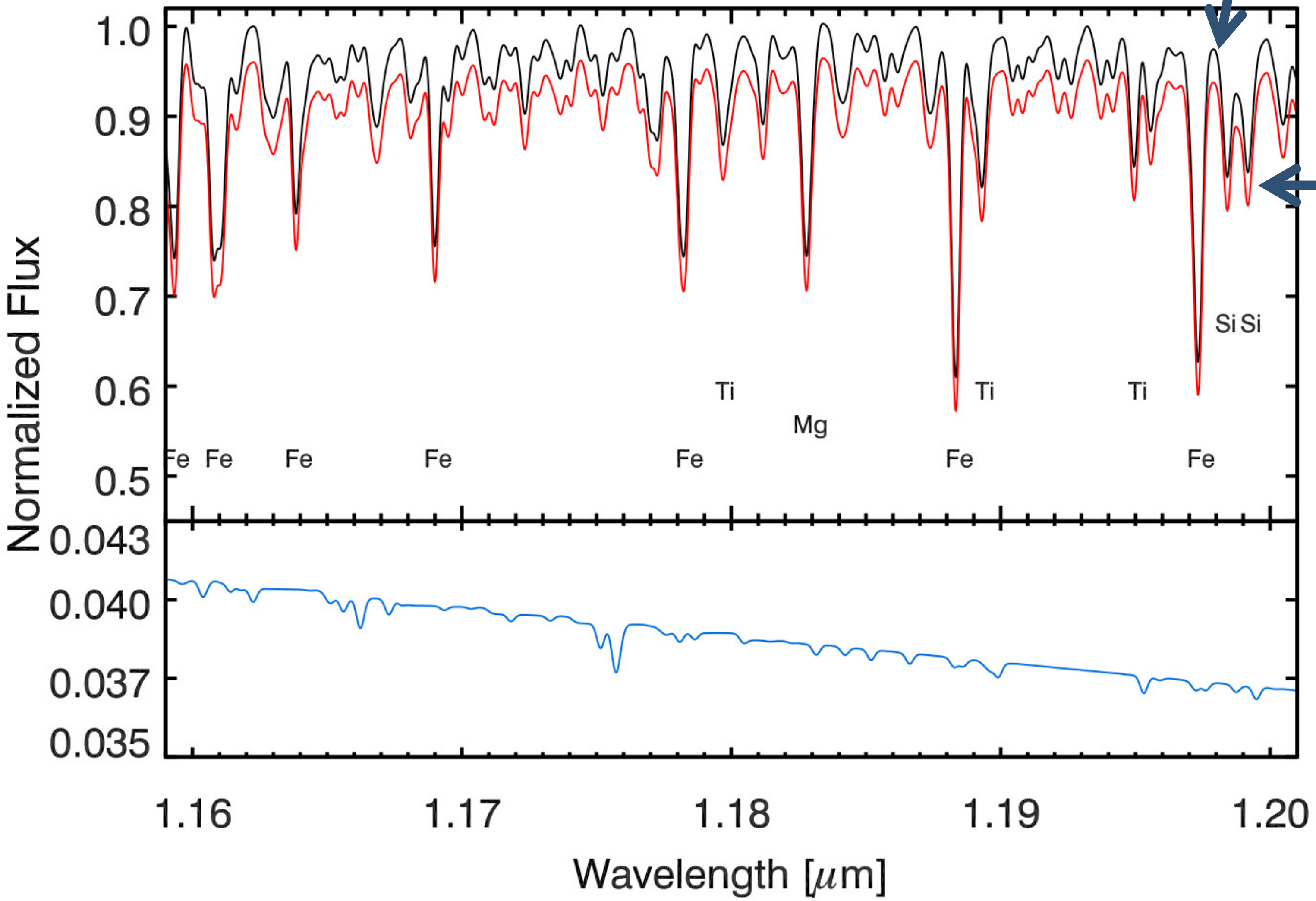


total SSC

RSGs only

Predicted SSC J-band spectrum at 15 Myr in J-band

Gazak et al. (2014)

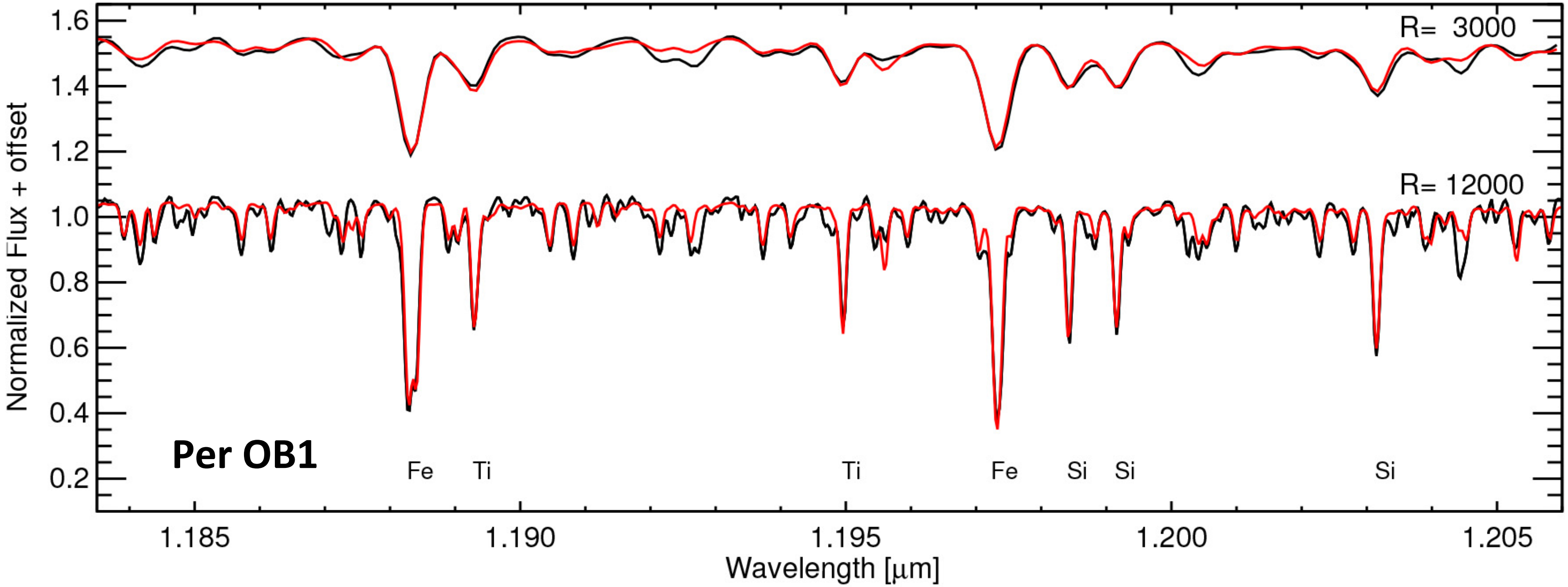


total SSC

RSGs only

Gazak et al. (2014)

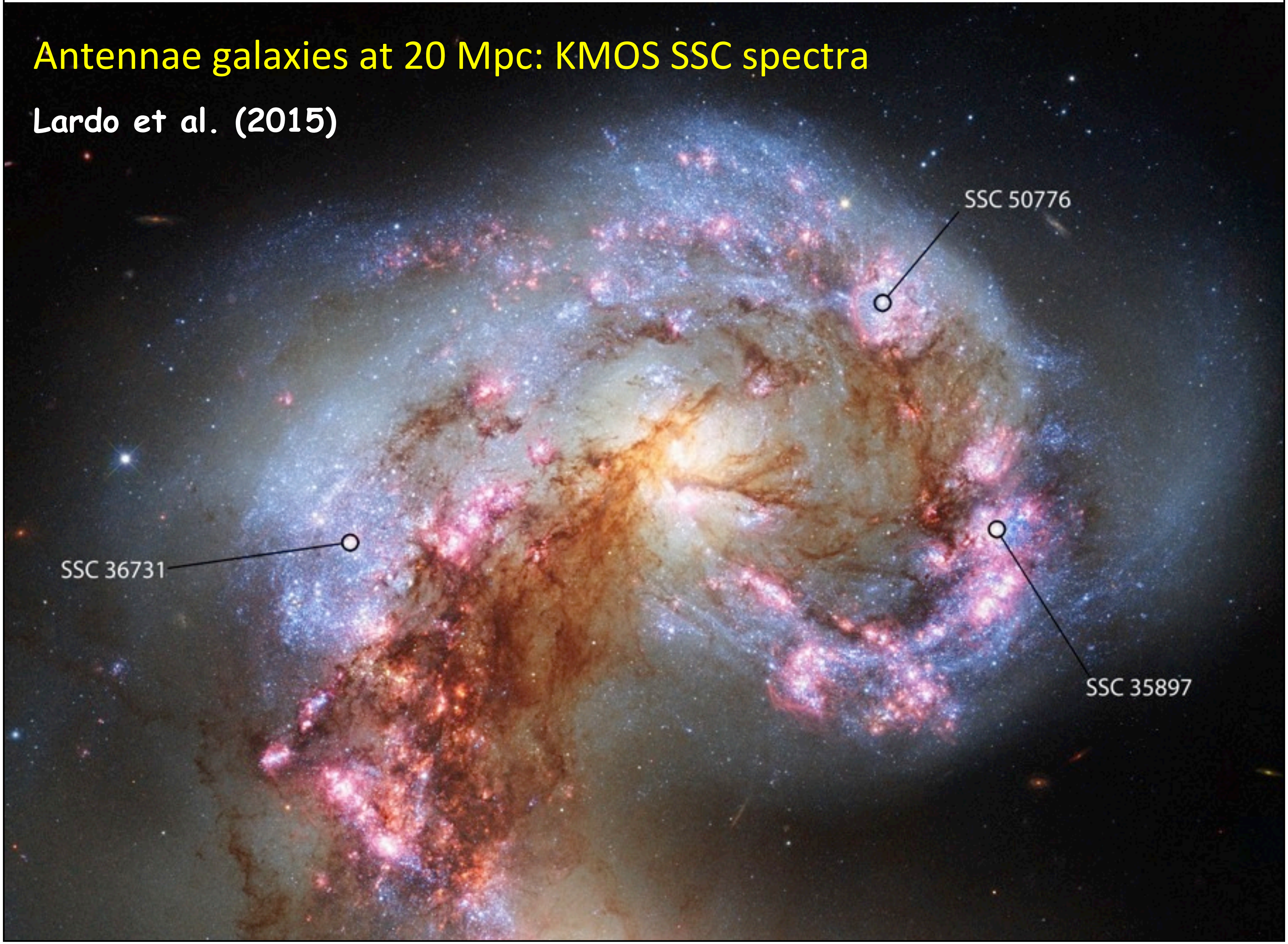
individual RSG spectra → simulated cluster spectrum



Simulated integrated cluster spectrum → same metallicity as for individual cluster objects

Antennae galaxies at 20 Mpc: KMOS SSC spectra

Lardo et al. (2015)



Lardo et al. (2015)

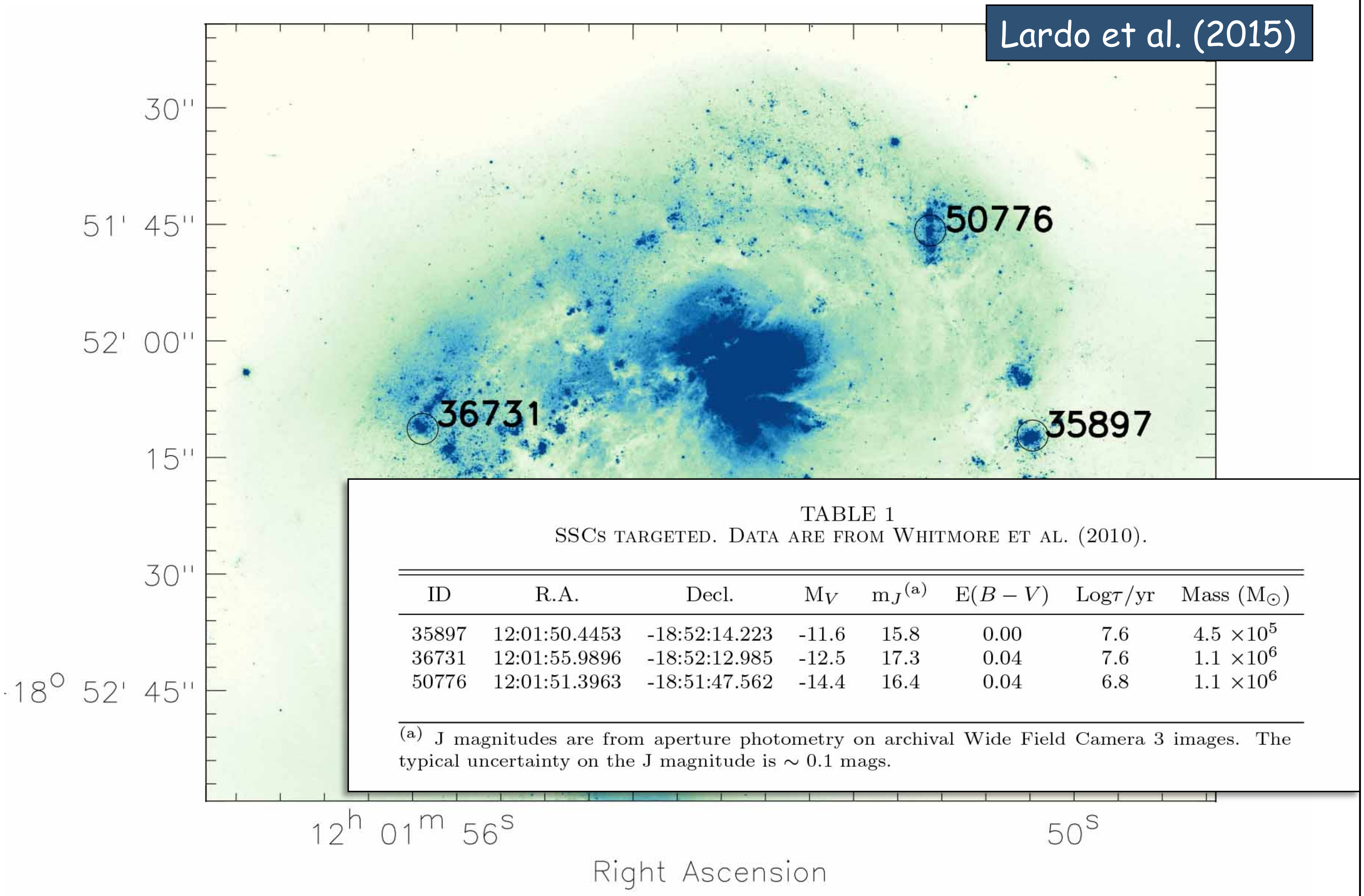
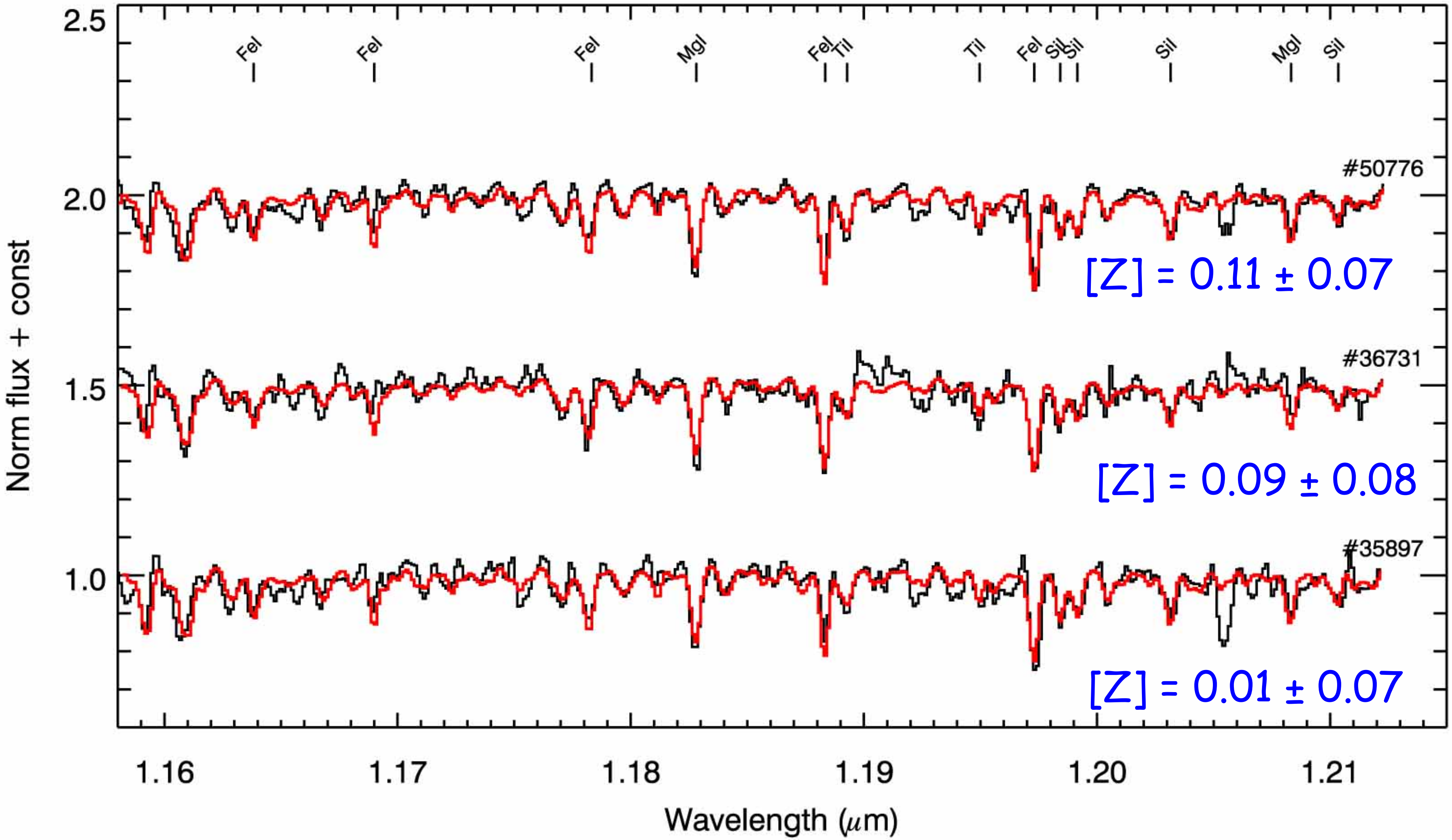


TABLE 1
SSCs targeted. Data are from Whitmore et al. (2010).

ID	R.A.	Decl.	M_V	m_J [a]	$E(B-V)$	Logτ/yr	Mass ($M_\odot$)
35897	12:01:50.4453	-18:52:14.223	-11.6	15.8	0.00	7.6	4.5×10^5
36731	12:01:55.9896	-18:52:12.985	-12.5	17.3	0.04	7.6	1.1×10^6
50776	12:01:51.3963	-18:51:47.562	-14.4	16.4	0.04	6.8	1.1×10^6

[a] J magnitudes are from aperture photometry on archival Wide Field Camera 3 images. The typical uncertainty on the J magnitude is ∼ 0.1 mags.

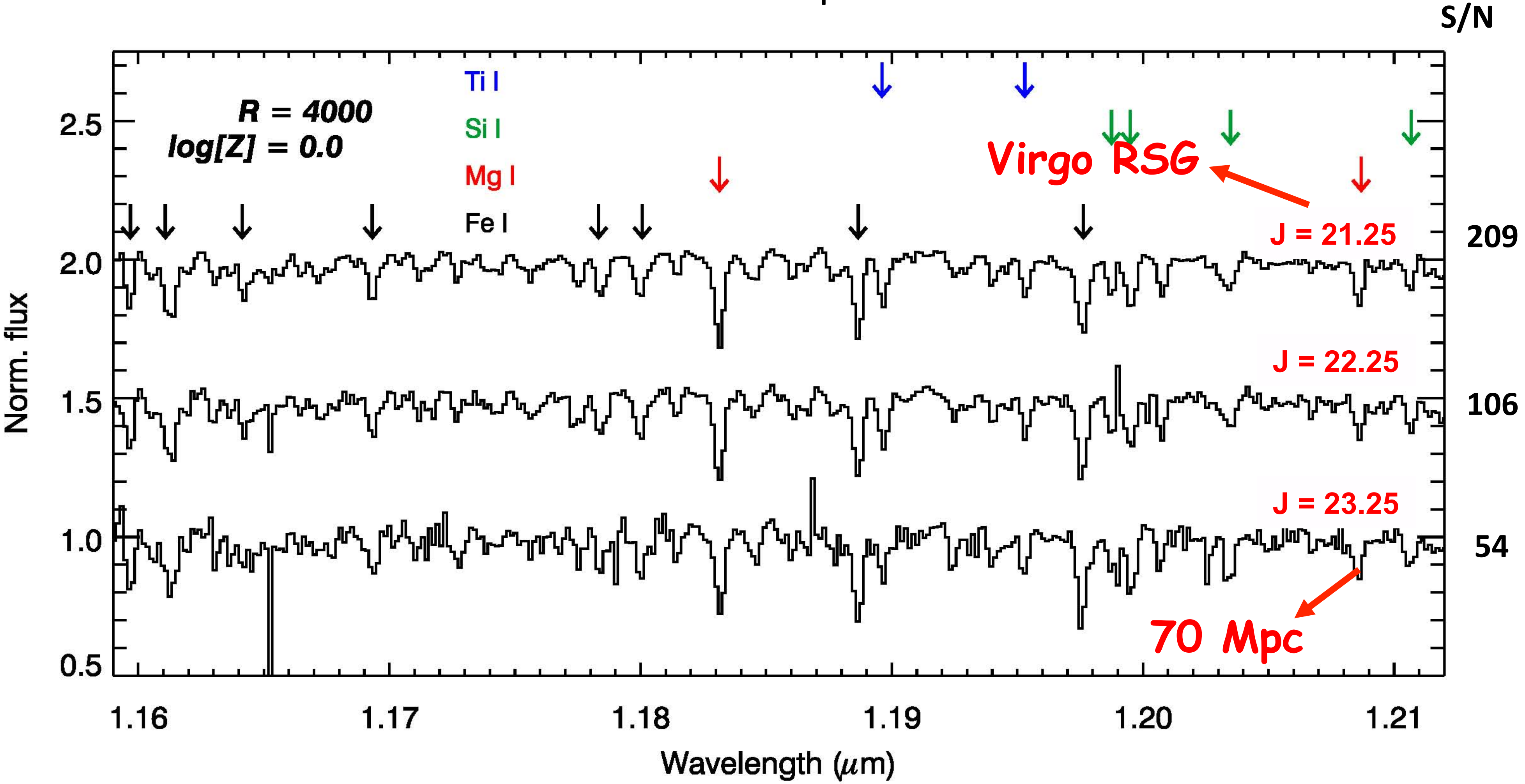
Lardo et al. (2015)



RSG J-band technique: E-ELT perspectives

Evans et al. (2011)

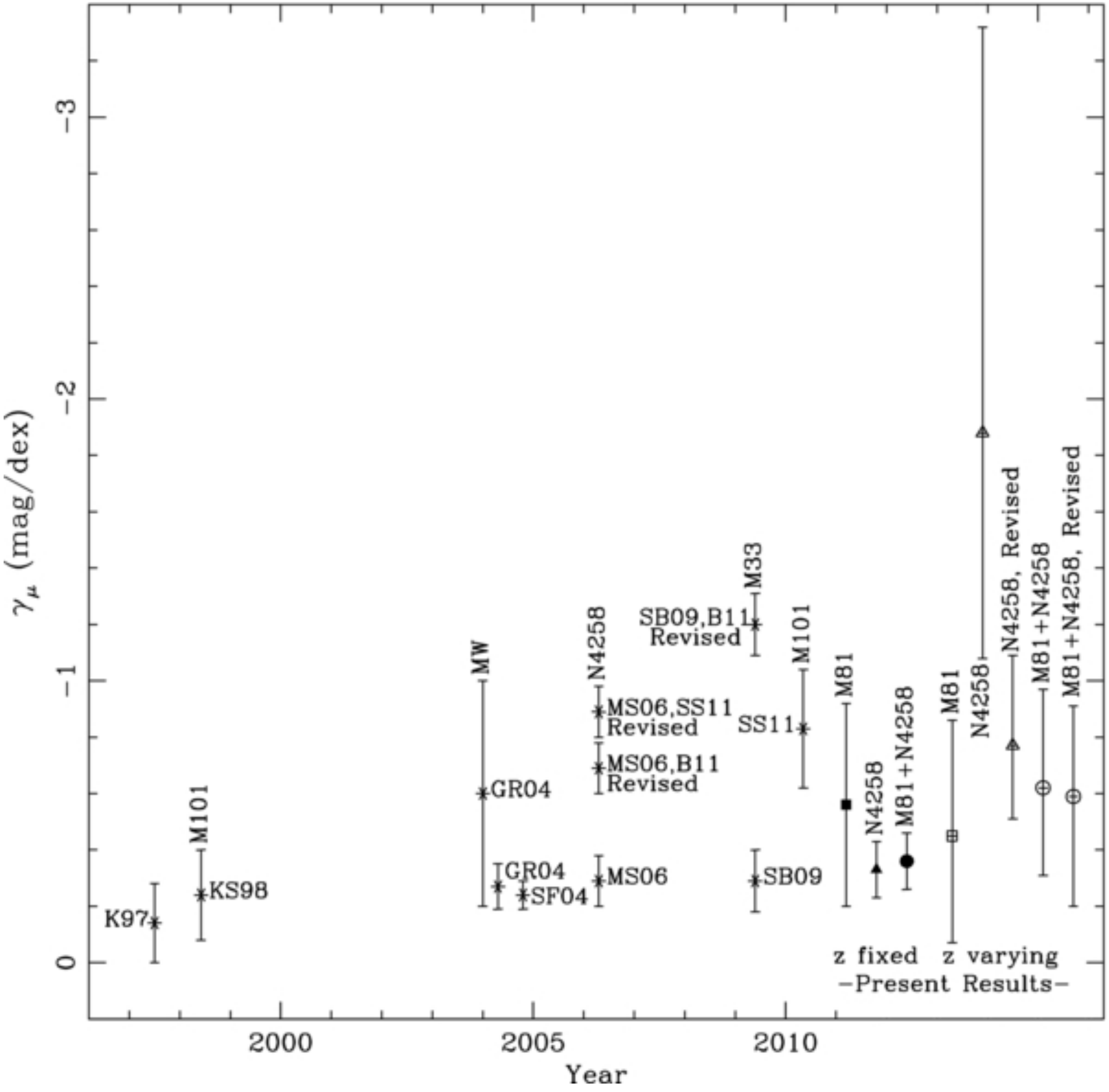
Simulated EAGLE observations: 10h exposure

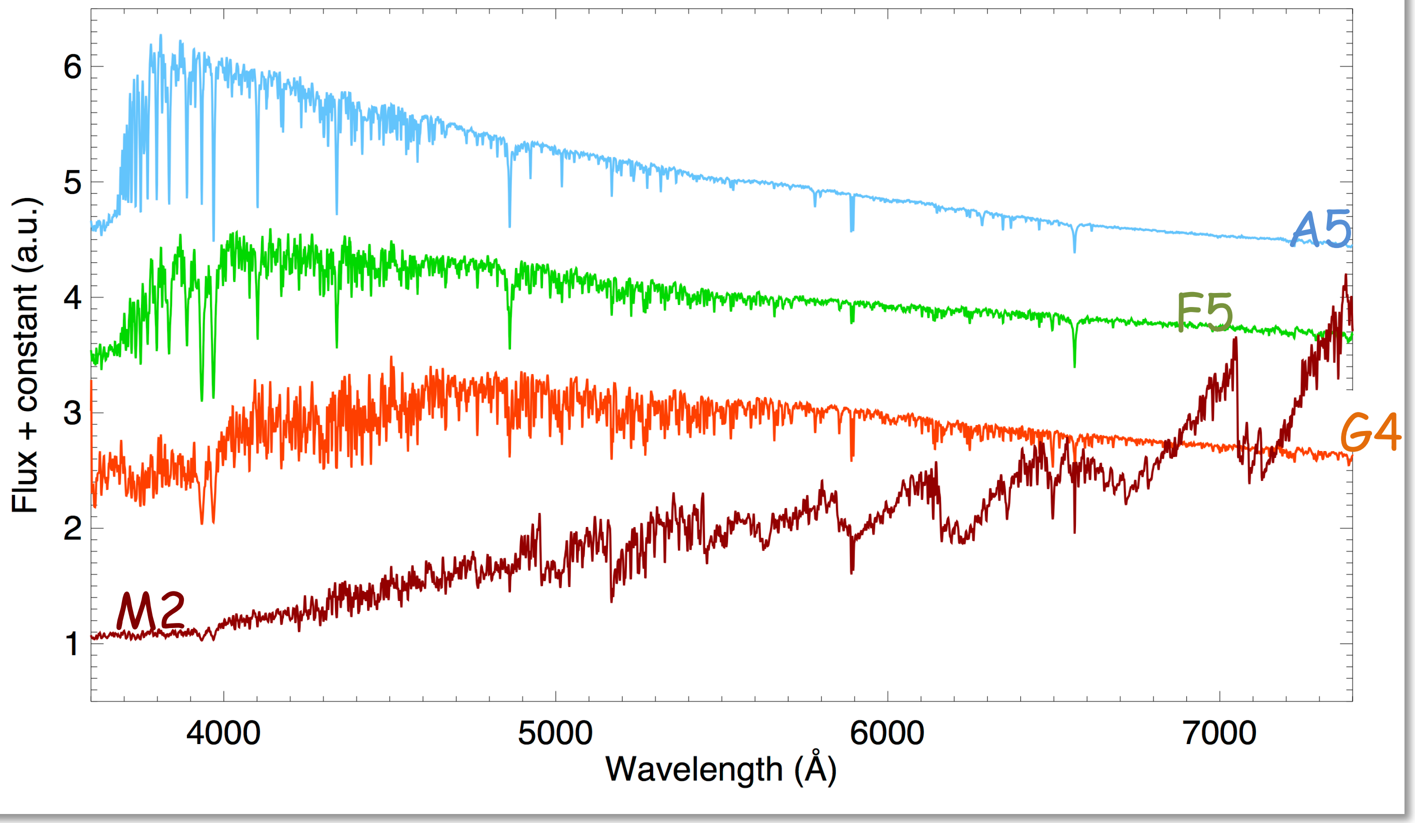


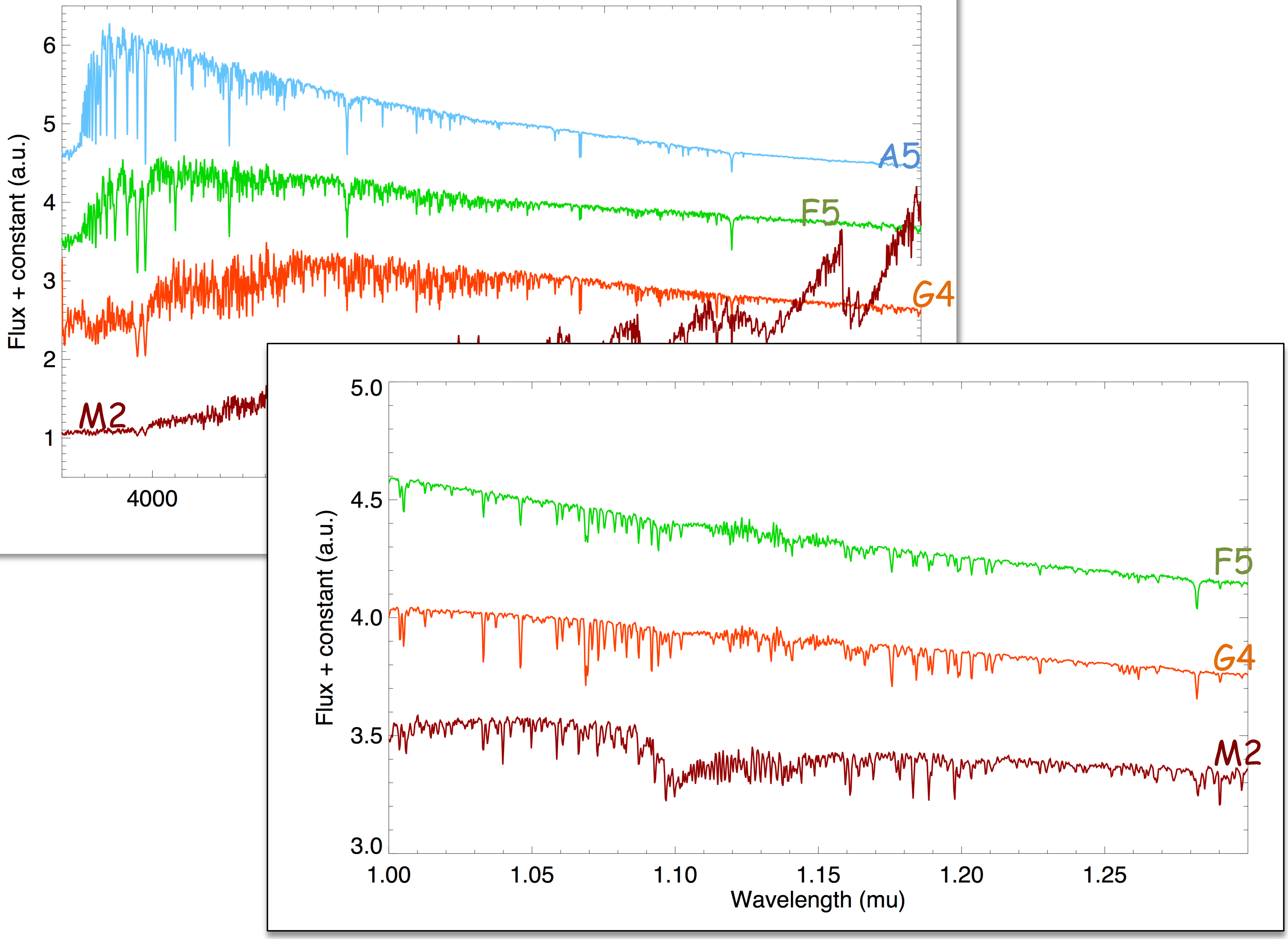
Quantitative Spectroscopy of RSGs (MOS)

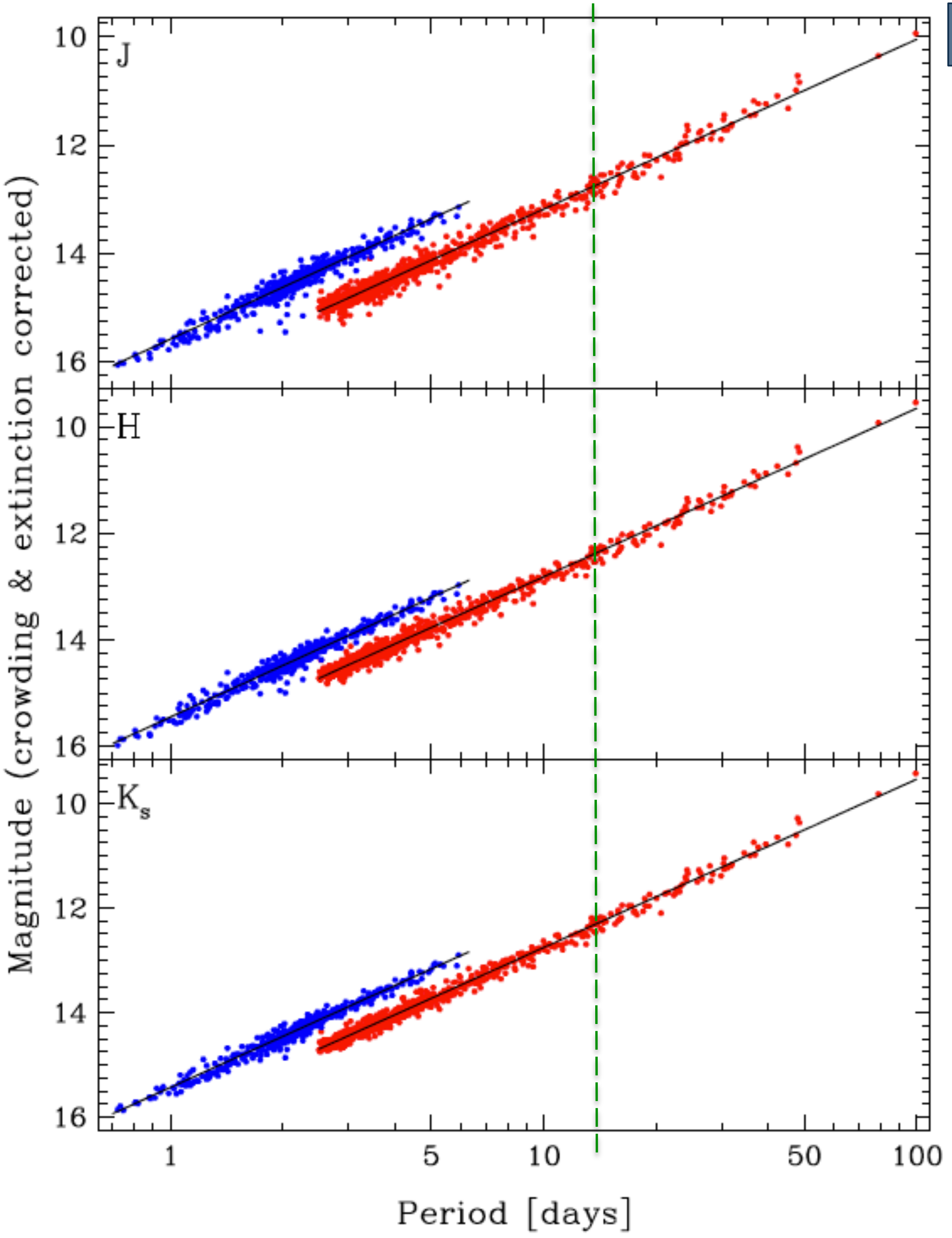
J band @R3000	**SSC**	**RSgs**
Abs. Mag. (J)	-13 to -15.5 mag	-8 to -11 mag
VLT/Keck (J=19)	~ 73 Mpc	~ 9 Mpc
E-ELT/TMT (J=22)	~ 291 Mpc	~ 35 Mpc

Gerke et al. (2011)

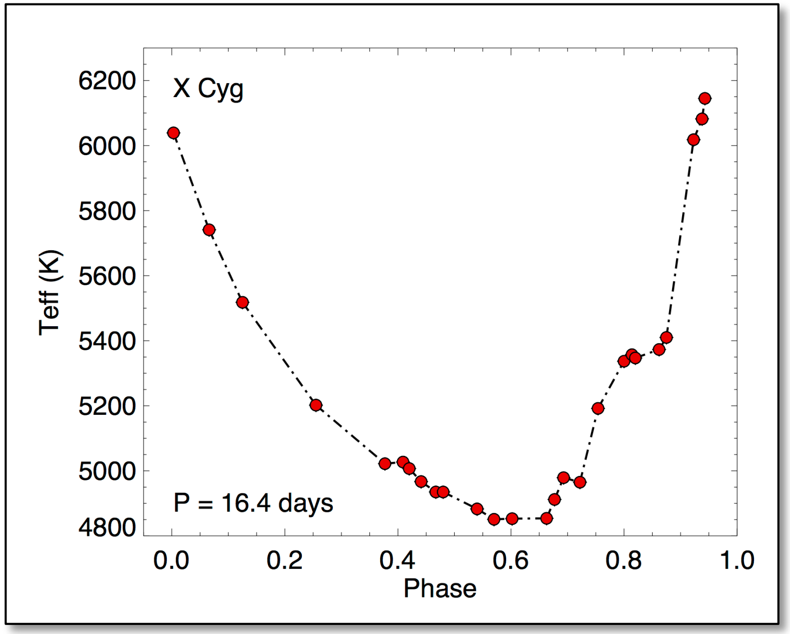



Flux + constant (a.u.)
1
2
3
4
5
6
4000
5000
6000
7000
Wavelength (Å)
A5
F5
G4
M2

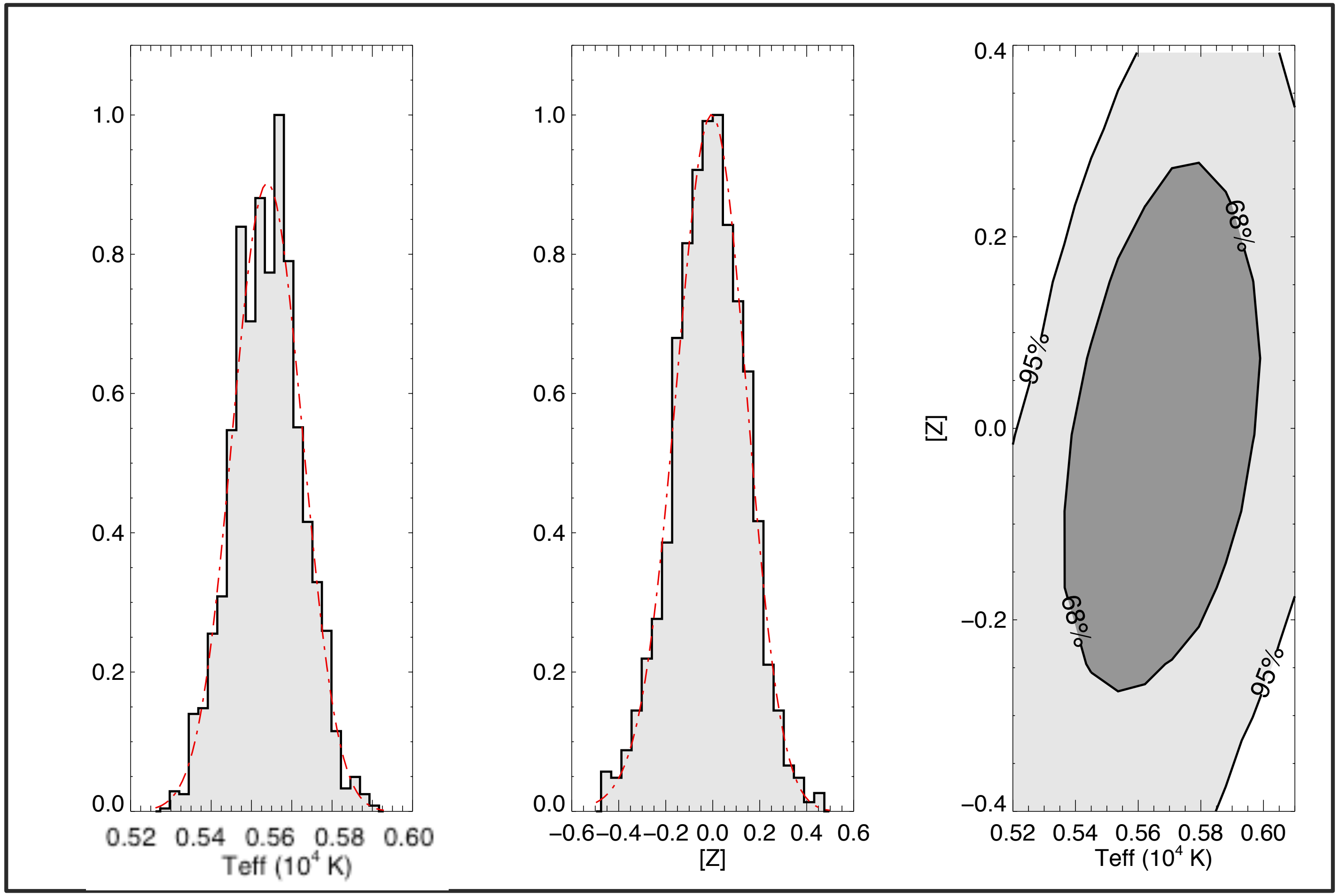

6
5
4
3
2
1
4000
Flux + constant (a.u.)
A5
F5
G4
M2
5.0
4.5
4.0
3.5
3.0
1.00
1.05
1.10
1.15
1.20
1.25
Wavelength (mu)
Flux + constant (a.u.)
F5
G4
M2



Macri et al. (2015)



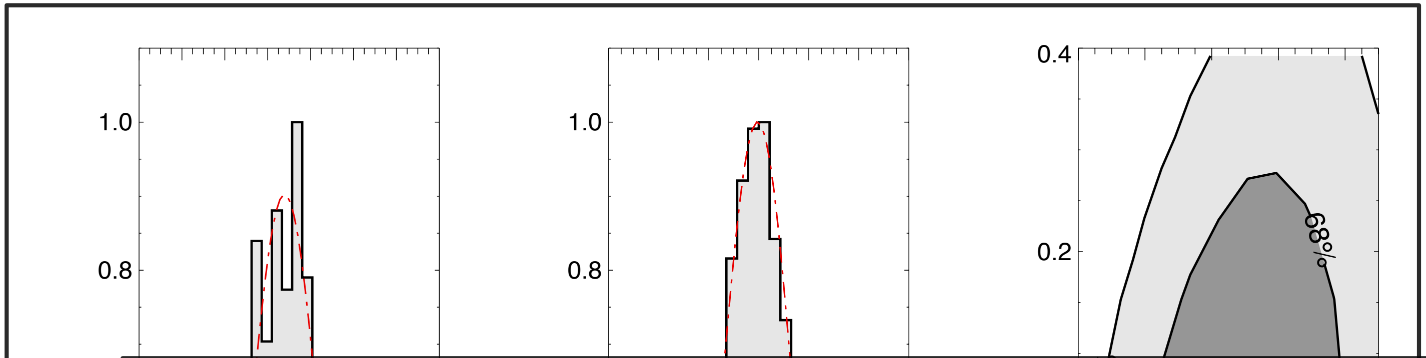
Kovteyukh et al. (2005)

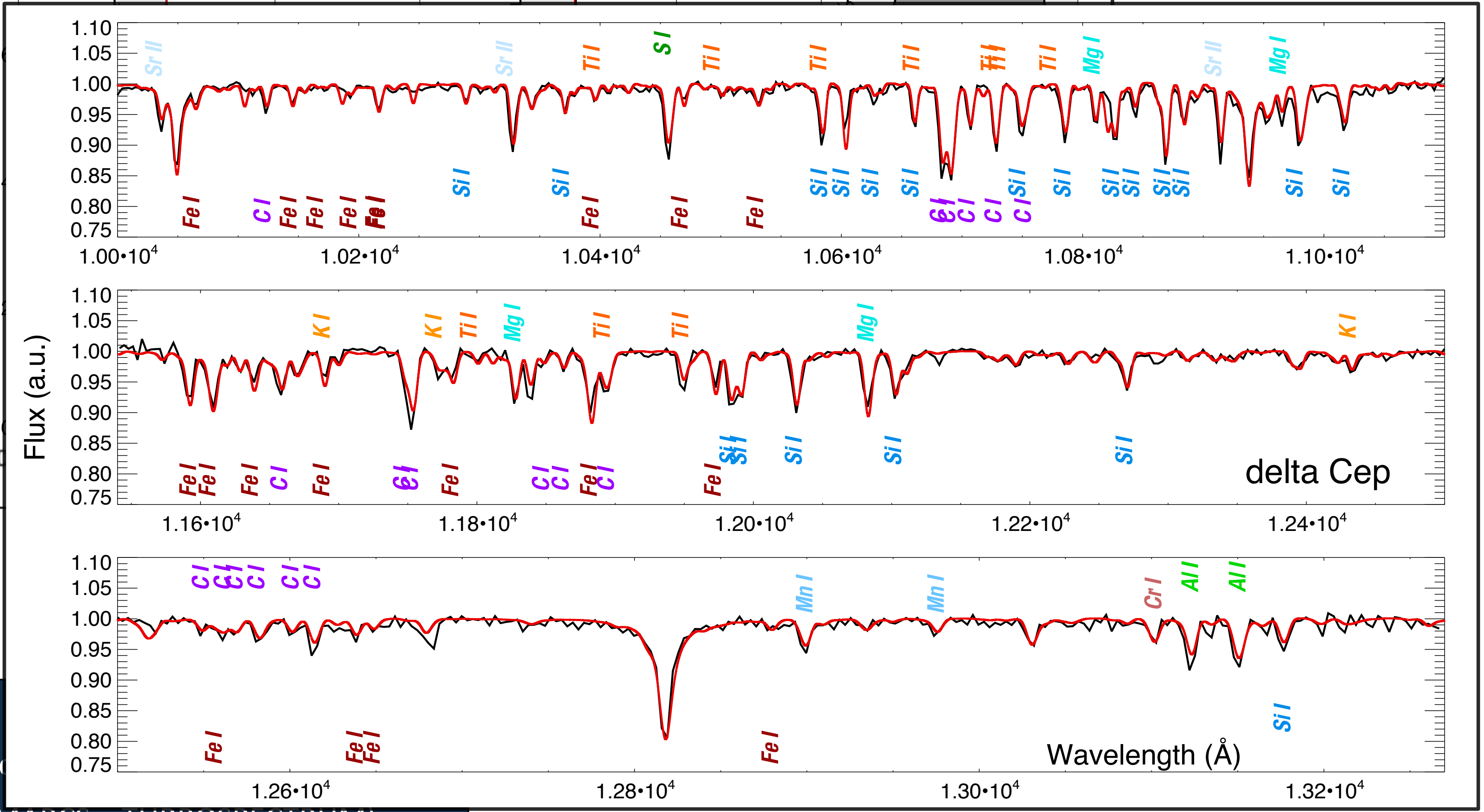


1D LTE

hydrostatic model atmospheres

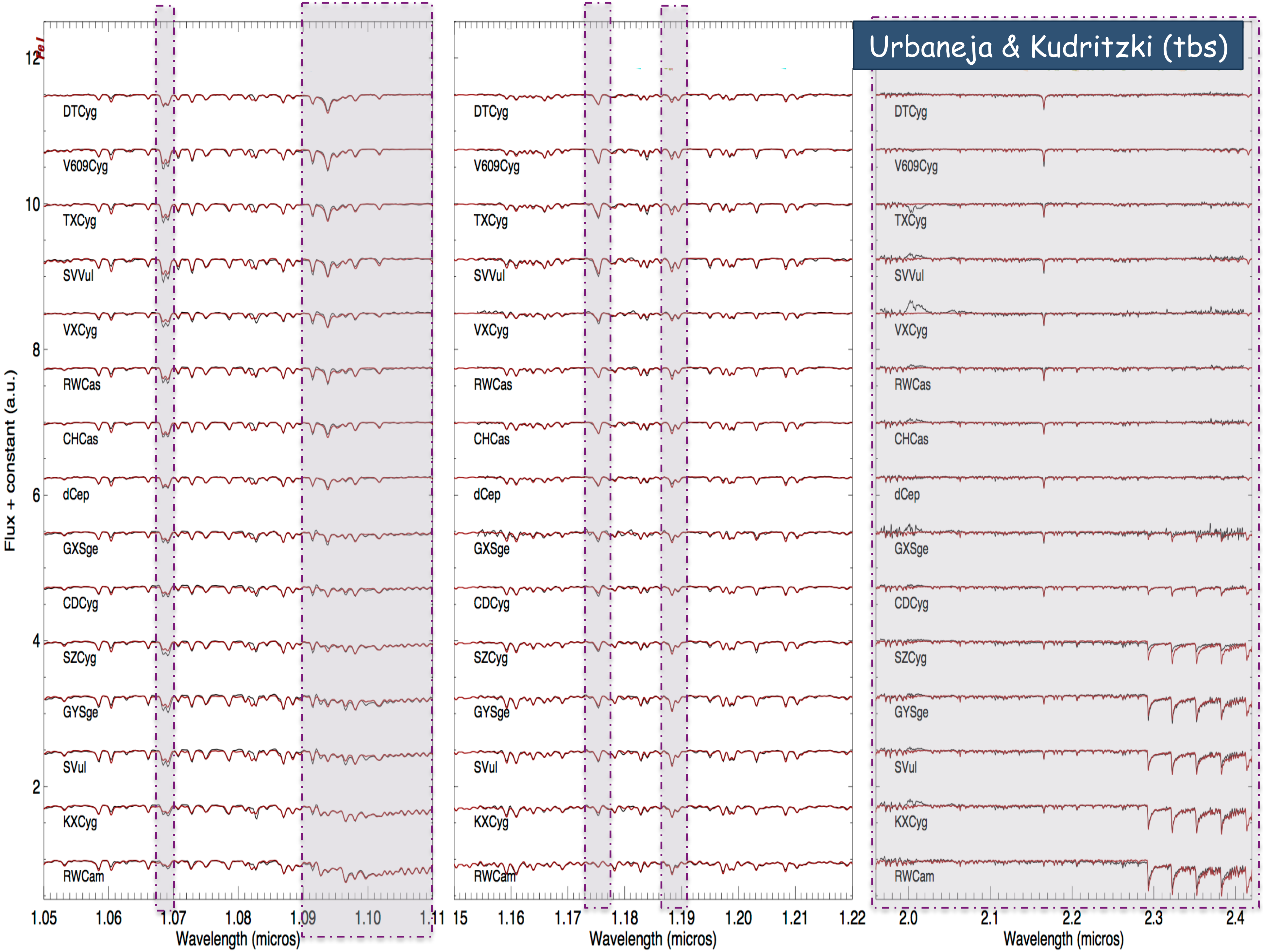
(MARCS + TURBOSPECTRUM)



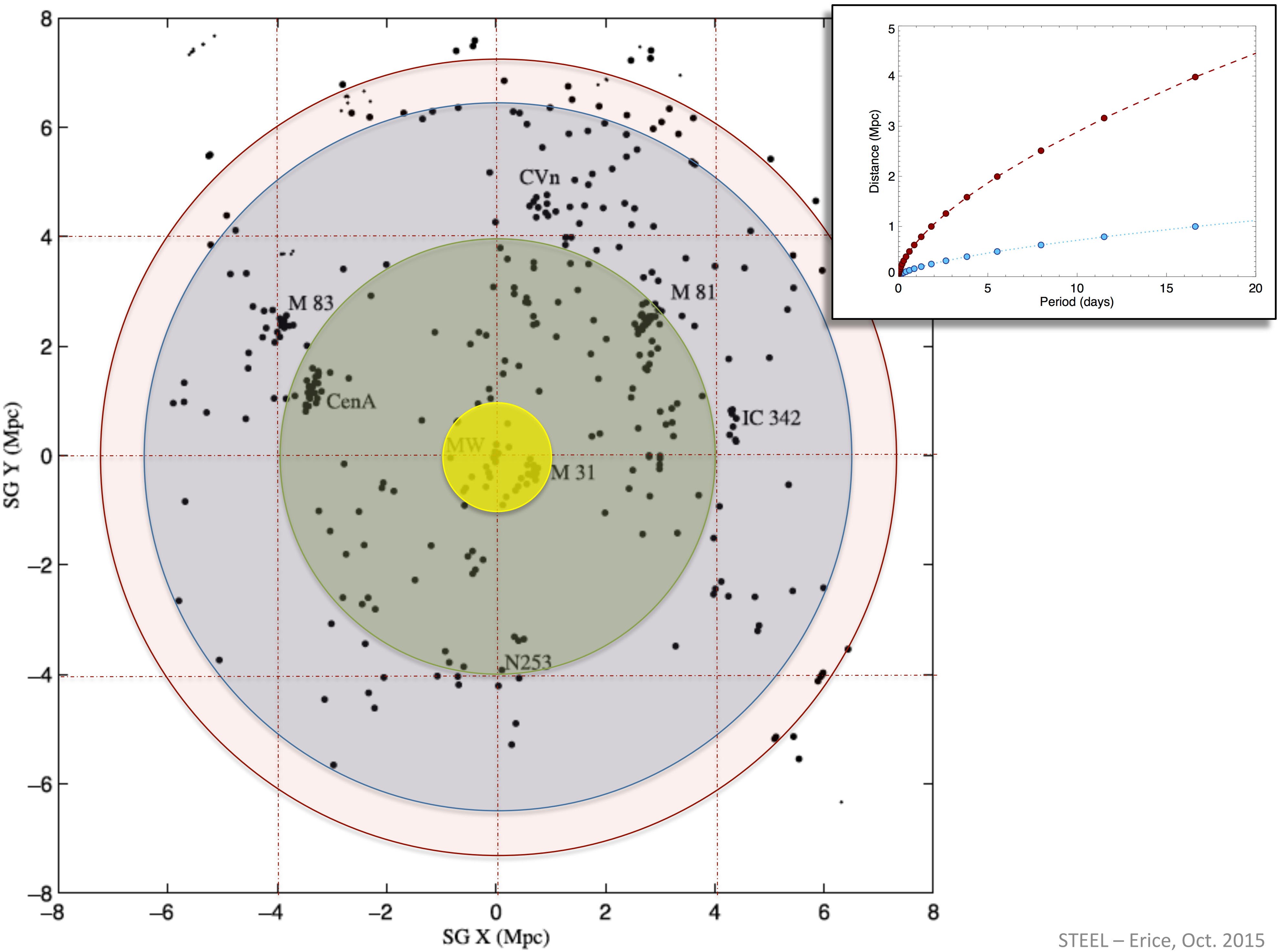


hy

(MARCS + TURBOSPECTRUM)



Urbaneja & Kudritzki (tbs)


SG Y (Mpc)
SG X (Mpc)
8
6
4
2
0
−2
−4
−6
−8
CVn
M 83
M 81
CenA
IC 342
MW
M 31
N253
Distance (Mpc)
Period (days)
0
1
2
3
4
5
0
5
10
15
20

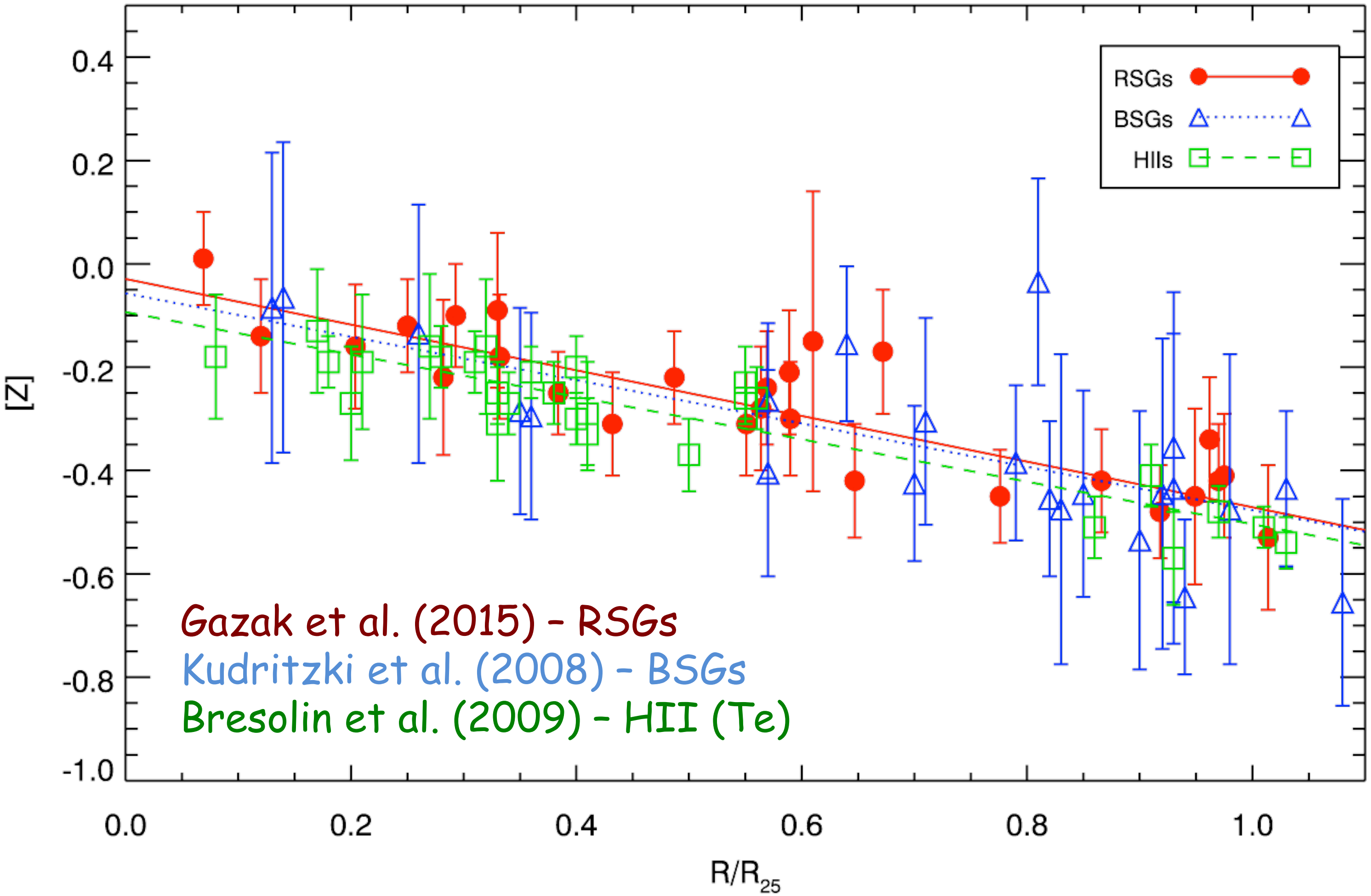
Quantitative Spectroscopy

- Inference of the physical parameters that (uniquely and completely?) characterize an astronomical object based on:
  - observed spectrum,
  - theoretical spectra, and
  - comparison metrics

What should one worry about?

- Information encoded in the observed data (both quantity and quality)
  - Spectral range coverage, SNR, …
- Physics incorporated in the models
  - Assumptions/simplifications
- Atomic data
- Comparison metrics

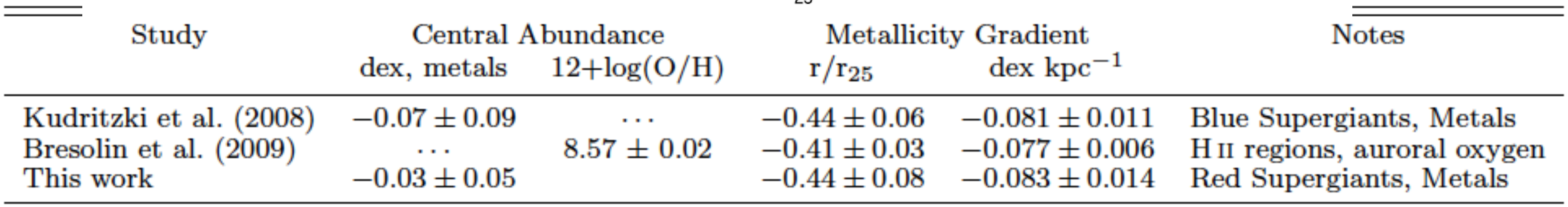
NGC 300 : blue and red supergiant stars vs. HII regions



Gazak et al. (2015) – RSGs

Kudritzki et al. (2008) – BSGs

Bresolin et al. (2009) – HII (Te)



Study	Central Abundance		Metallicity Gradient		Notes
	dex, metals	12+log(O/H)	r/r$_{25}$	dex kpc^{-1}	
Kudritzki et al. (2008)	-0.07 ± 0.09	...	-0.44 ± 0.06	-0.081 ± 0.011	Blue Supergiants, Metals
Bresolin et al. (2009)	...	8.57 ± 0.02	-0.41 ± 0.03	-0.077 ± 0.006	H II regions, auroral oxygen
This work	-0.03 ± 0.05		-0.44 ± 0.08	-0.083 ± 0.014	Red Supergiants, Metals

Quantitative Spectroscopy of SGs (MOS)

	Blue (BA)	**Cepheids (FGK)**	**Red (KM)**	**SSC**
Abs. Magnitude	-9.5 (V, J)	-6.5 for P> 20 days (J)	-8 to -11 (J)	-13 to -15.5 (J)
VLT/Keck	~ 8 Mpc (V=22.5)	~ 1 Mpc (J=19.0)	~ 9 Mpc (J=19.0)	~ 73 Mpc
E-ELT/TMT	~ 18 Mpc (J=21.5)	~ 4 Mpc (J=21.5)	~ 35 Mpc (J=21.5)	~ 291 Mpc
Requirement		YJ band @R≥3000	J band @R≥3000	J band @R≥3000
Information @R~3000	C, N, O, Mg, Si, Ti, Fe	C, Mg, Si, Ti, Fe	Mg, Si, Fe	
+ Photom.	E(B-V), Rv	Ages		

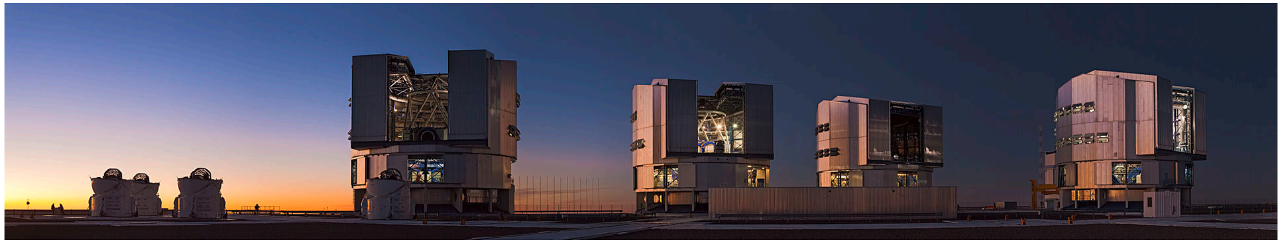
Red Supergiant Stars:

Davies et al. 2010, MNRAS, 407, 1203
Davies et al. 2013, ApJ, 767, 3
Gazak et al. 2014, ApJ, 788, 58
Patrick et al. 2015, ApJ, 803, 14
Davies et al. 2015, ApJ, 806, 21

Super Star Clusters:

Gazak et al. 2013, MNRAS, 430, L35
Gazak et al. 2014, ApJ, 787, 142
Lardo et al. 2015, arxiv150904937

"… these stars may be used to determine metallicities …"
Quantitative Spectroscopy of Luminous Blue Stars in Distant Galaxies
Kudritzki, Lennon and Puls (1995, "Science with the VLT")



Antu (UT1) – 1998

Bresolin et al. (2001)

… it is possible to determine individual abundances (such as Fe, Ti, Cr, O, Mg …) up to 6-7 Mpc …

"… {Introduce your bold idea here} …"
Catchy title for your talk
Introduce your name here (2021, "Science with the E-ELT")

E-ELT starts operation – 2024