# Supergiant Stars - Extragalactic Probes of Cosmic Abundances and Distances

Rolf Kudritzki

UNIVERSITY OF HAWAII ◆ INSTITUTE FOR ASTRONOMY

in collaboration with

Miguel Urbaneja

Zach Gazak

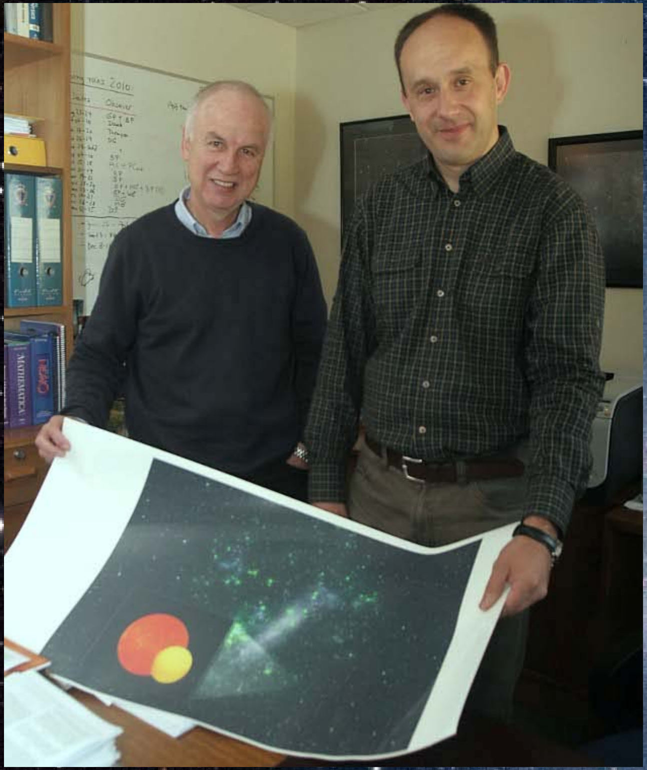
Fabio Bresolin

Ben Davies

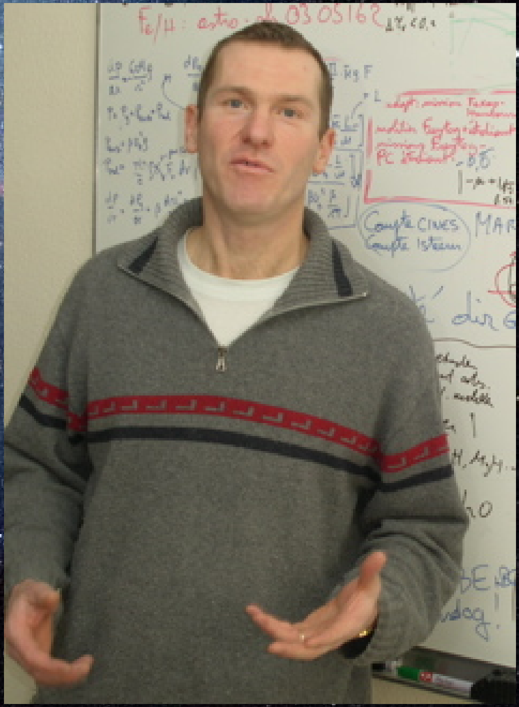
Matt Hosek

Chris Evans

in collaboration with



Norbert Przybilla



Maria
Bergemann

Wolfgang Gieren
Grzegorz Pietrzynski

Bertrand Plez

# ΛCDM-universe → metallicity of galaxies depends on their mass

**metal-rich**

M81

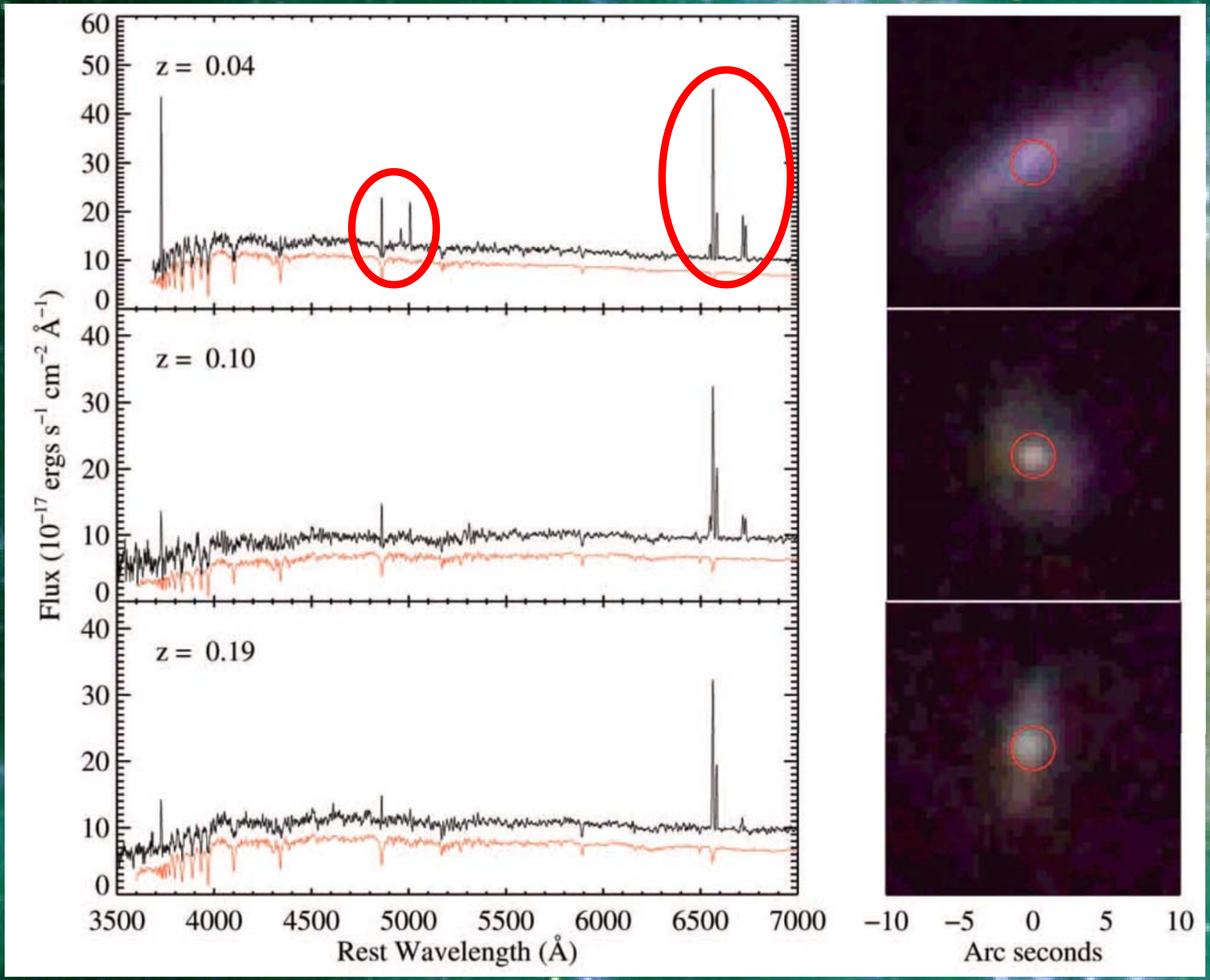
**metal-medium**

NGC 300

**metal-poor**

WLM

Tremonti et al., 2004, ApJ 613, 898

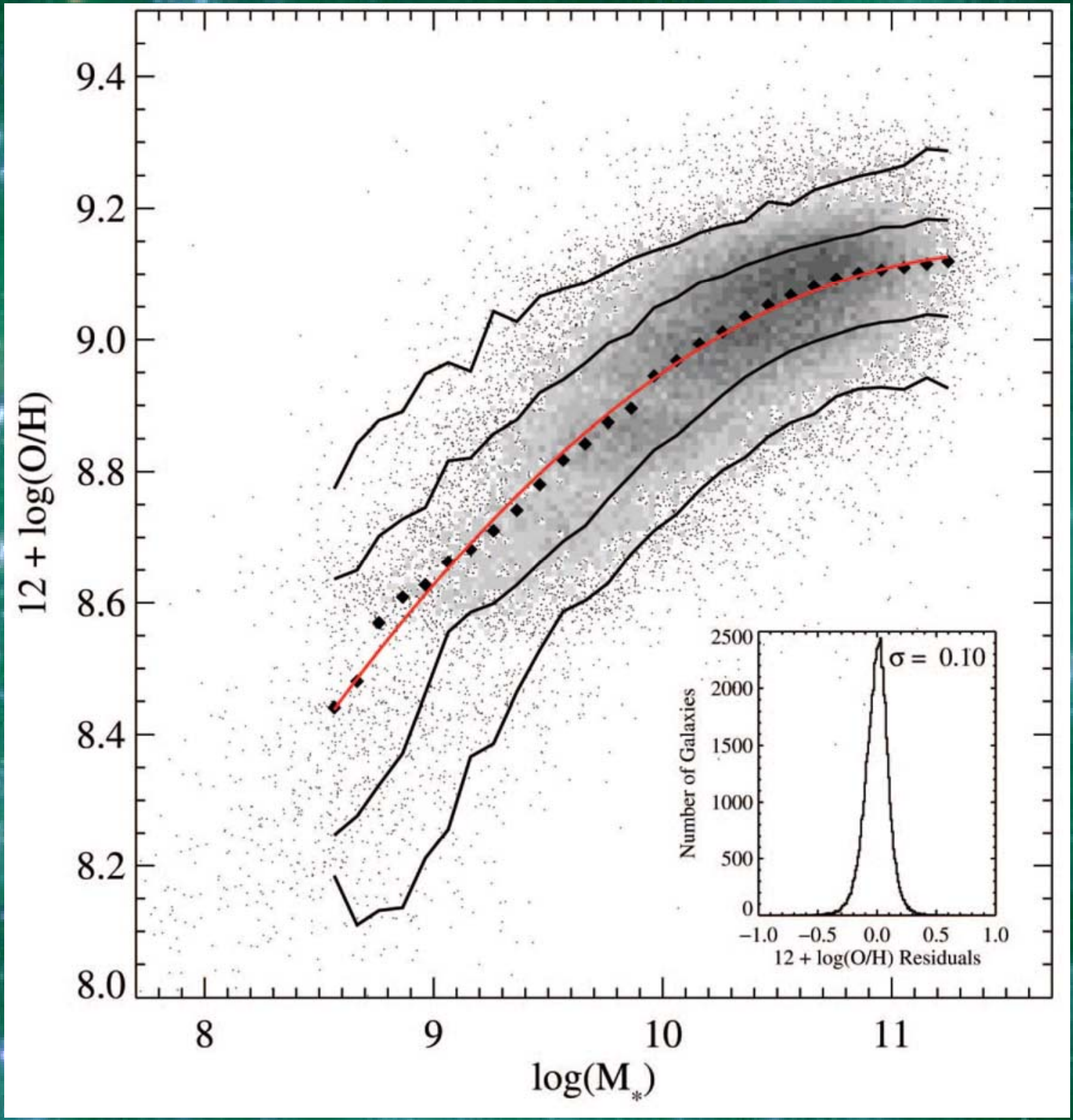



strong nebular emission lines: hydrogen, oxygen, nitrogen

50,000 starforming galaxies with Sloan spectra

# mass-metallicity relationship

Rosetta stone
to understand
galaxy formation
and
chemical evolution!



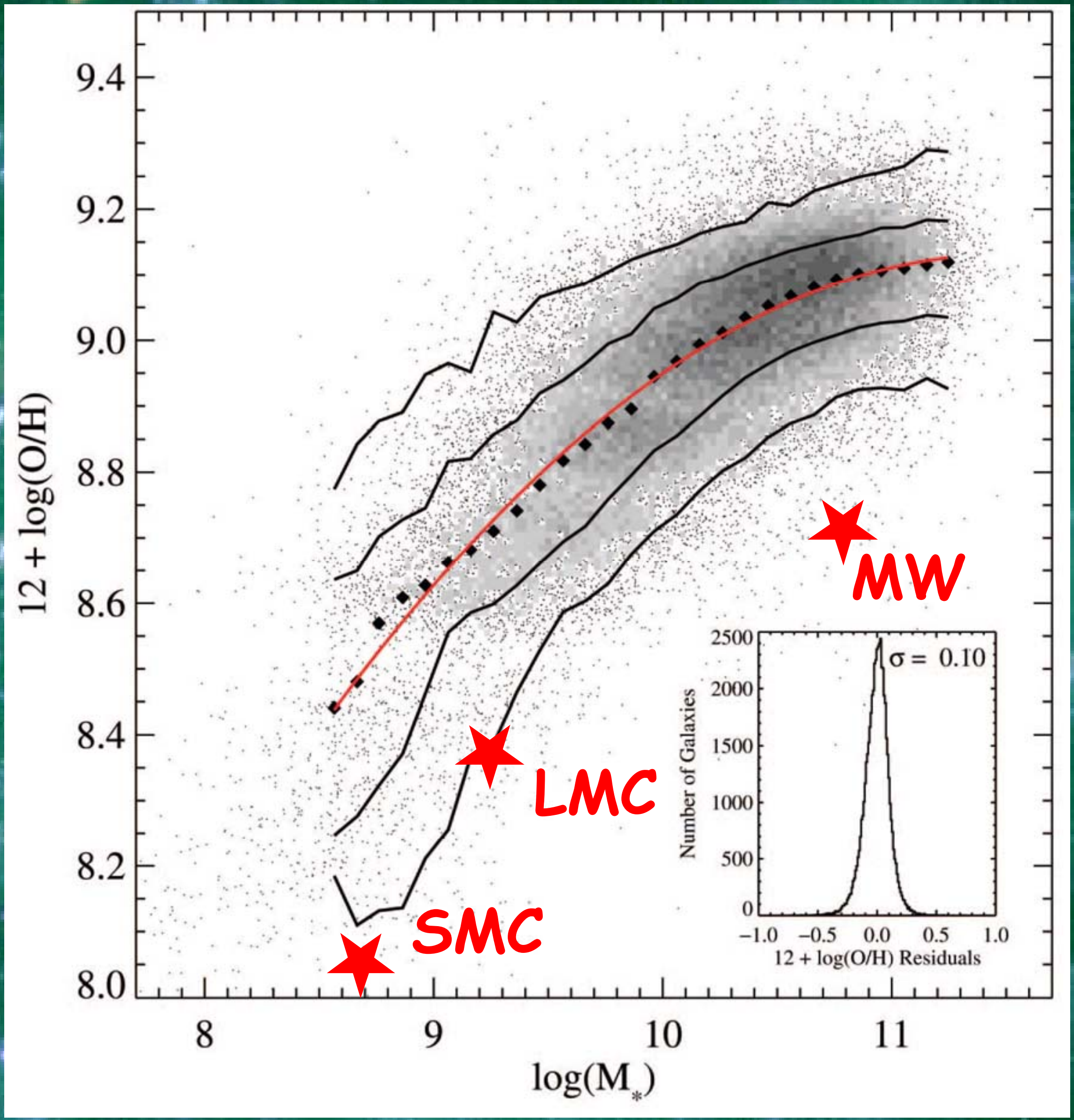

Tremonti et al., 2004, ApJ 613, 898

mass-metallicity relationship

# However…

Something must be wrong….

It's based on very simplified emission line analysis….



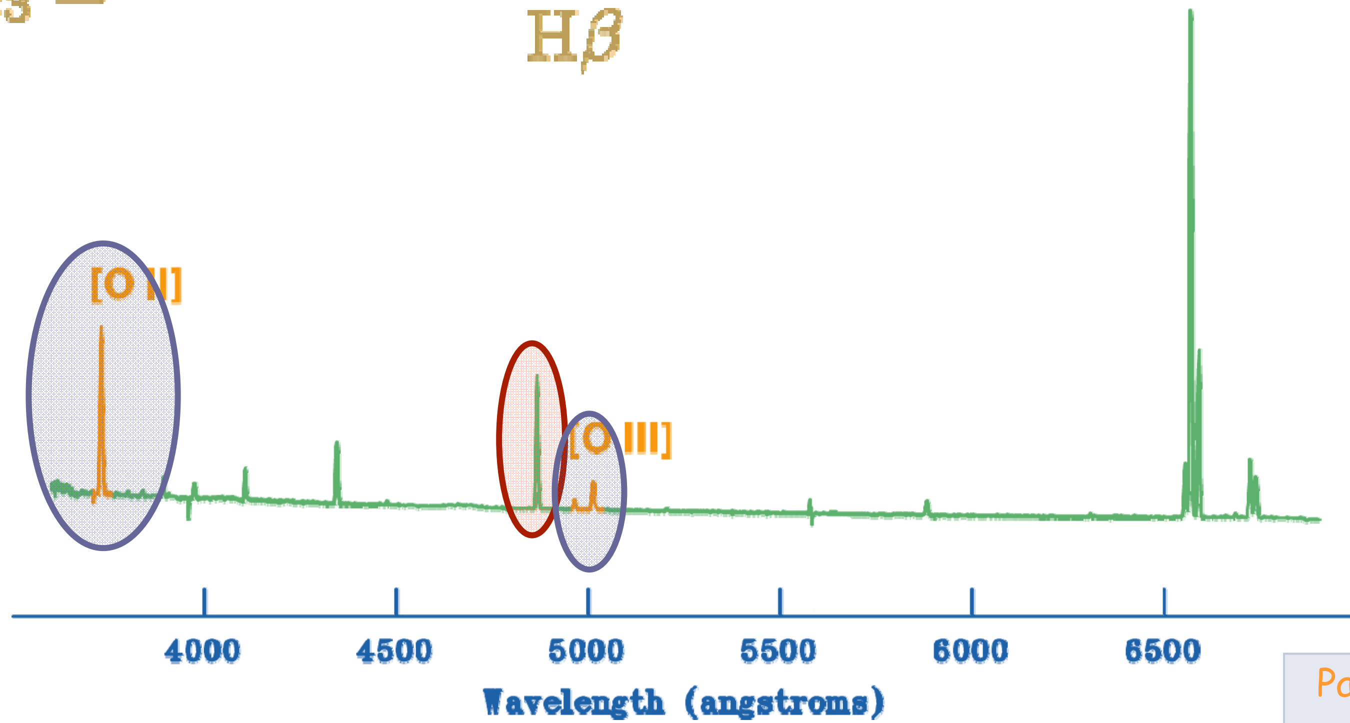

Tremonti et al., 2004, ApJ 613, 898

# strong line method: $R_{23} = f[N(O)/N(H)]$

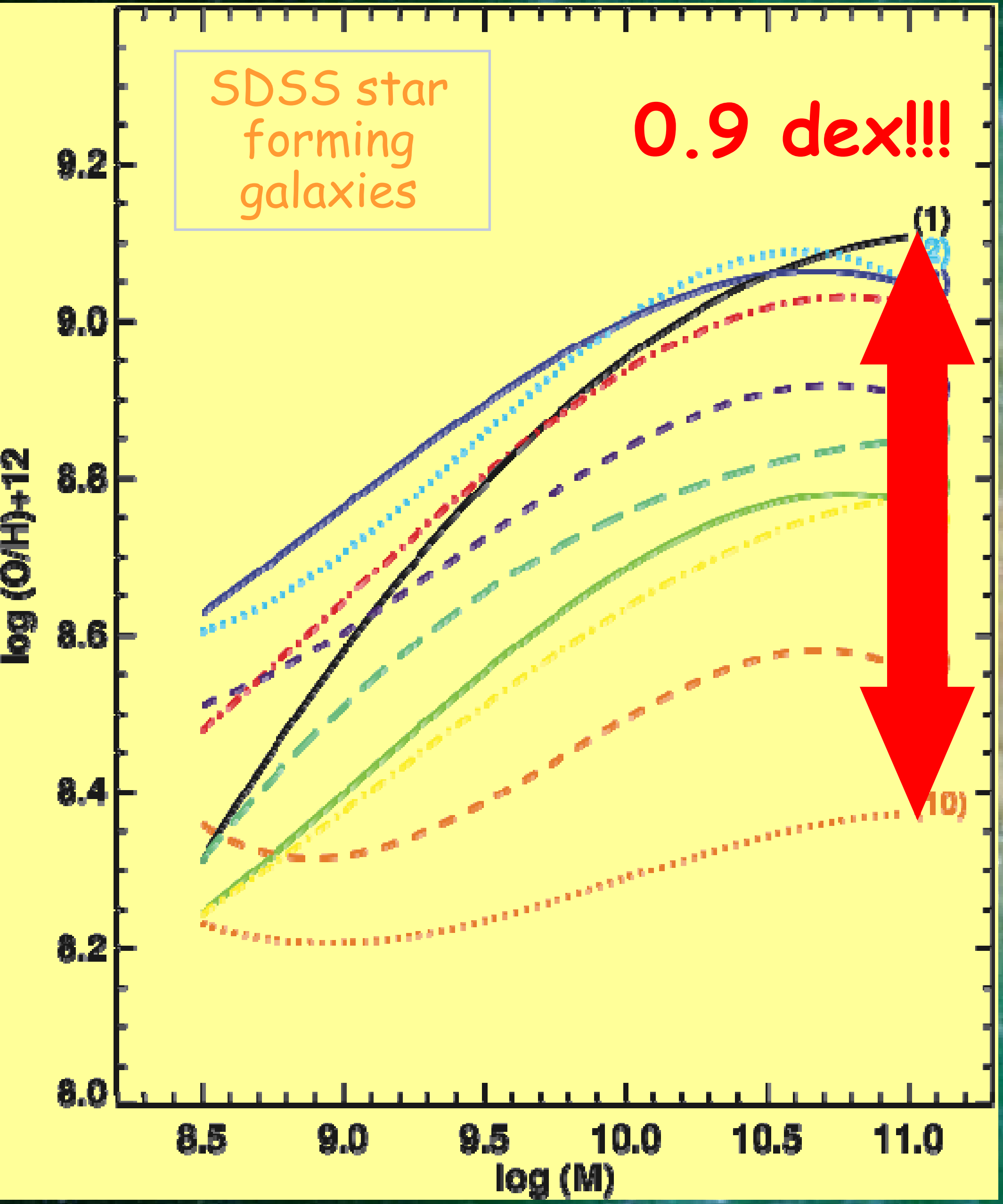
simple empirical calibration
but…

$R_{23}$ depends on
- $T_{electron}$
- $n_{electron}$
- nature of ionizing stars
- gas imhomog.
- filling factors
- depletion into dust…..

$$R_{23} = \frac{[\mathrm{O\,II}]3727 + [\mathrm{OIII}]4959,5007}{\mathrm{H}\beta}$$




Pagel, Edmunds, Blackwell et al. 1979




Kewley & Ellison 2008

**mass – metallicity relationship**

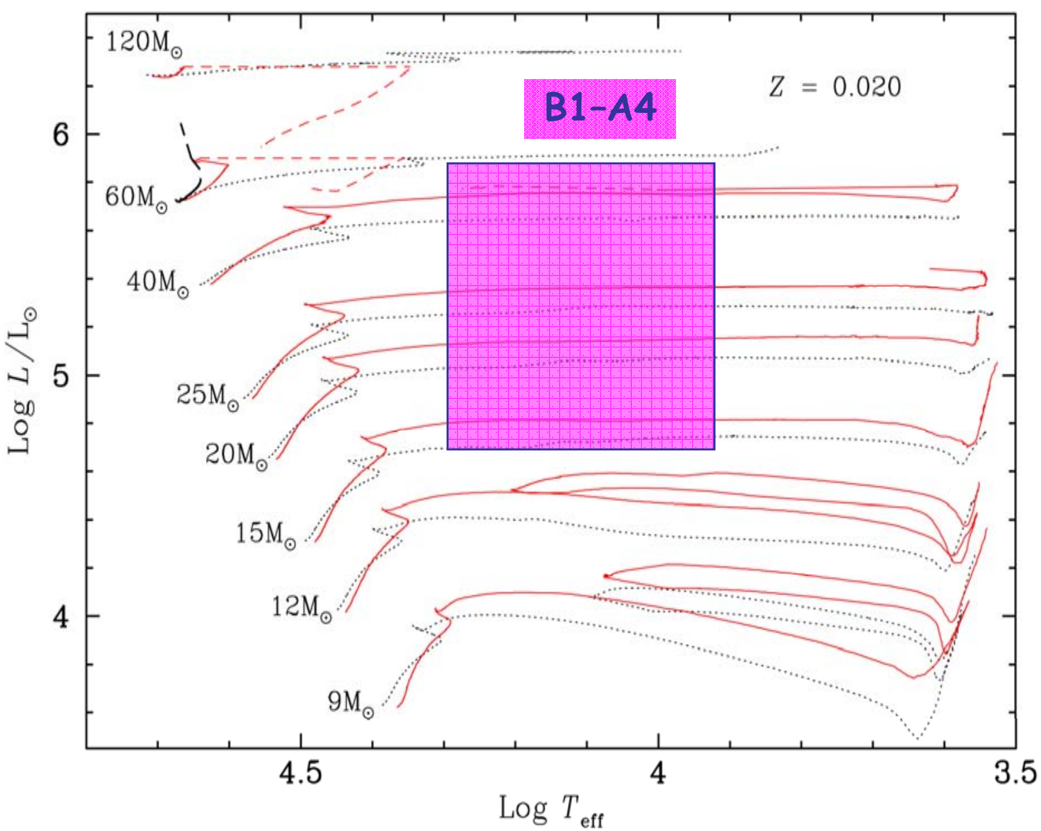
**depends crucially on strong line method calibration**

**supergiant stars will come to rescue !!!!**

# nearby supergiants in Orion

# Blue supergiants – objects in transition

Brightest normal stars at visual light: $10^5..10^6$ $L_{sun}$
$-7 \geq M_V \geq -10$ mag

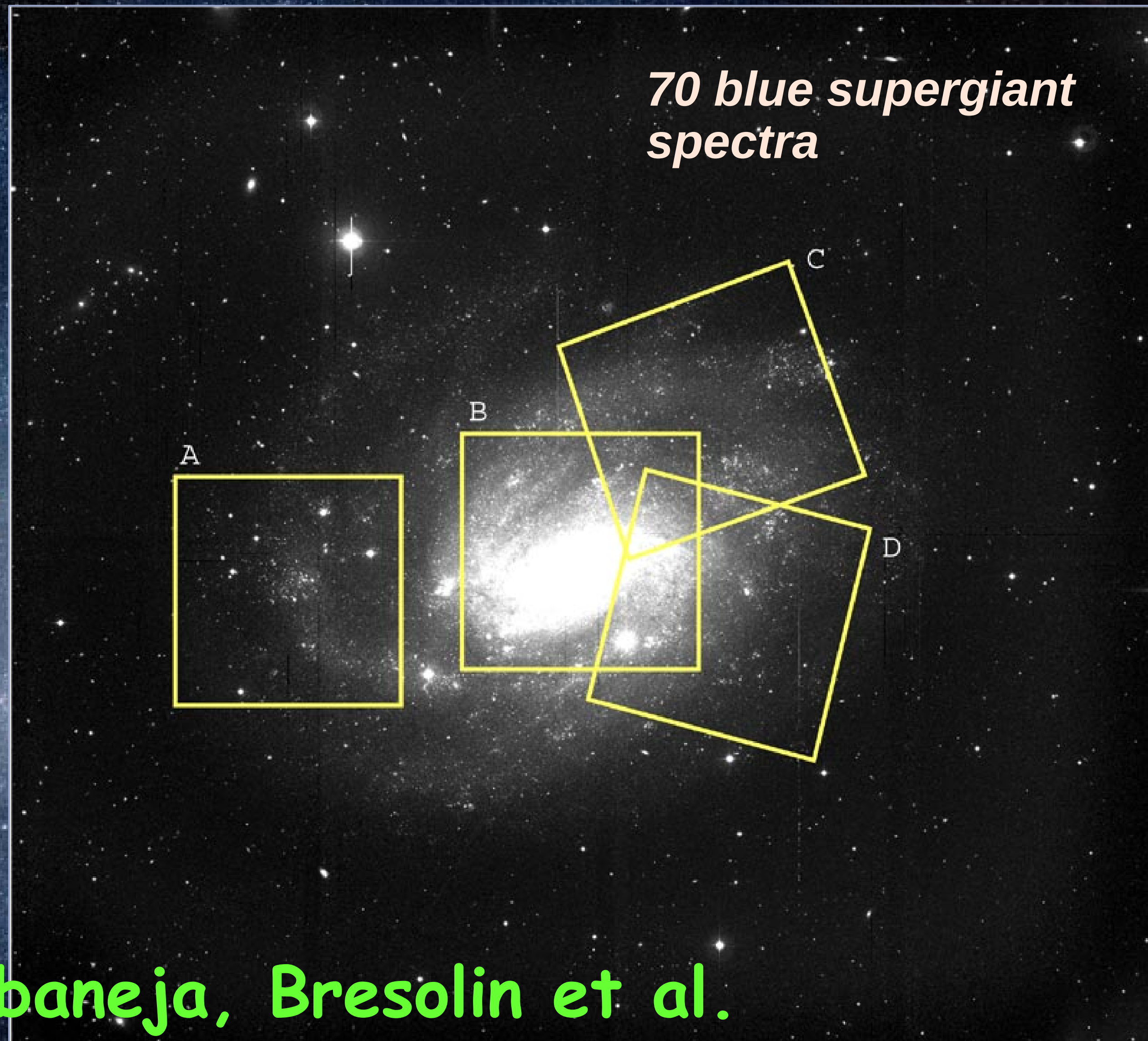



$t_{ev}$ ~ $10^3$ yrs
L, M ~ const.

ideal to determine

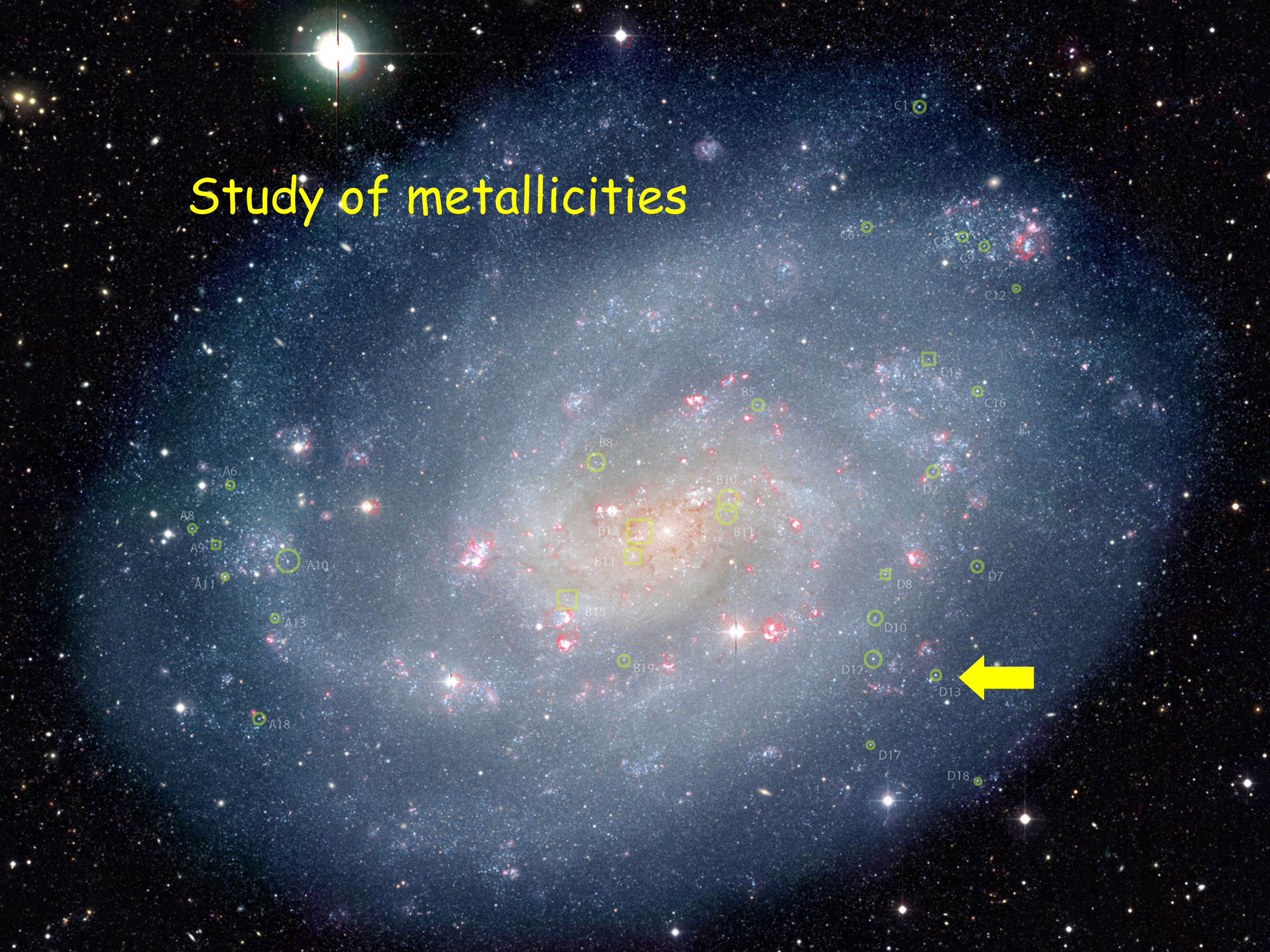
- chemical compos.
- abundance grad.
- SF history
- extinction
- extinction laws
- distances of galaxies

# pilot study




Kudritzki, Urbaneja, Bresolin et al. 2008, ApJ 681, 269

# Study of metallicities



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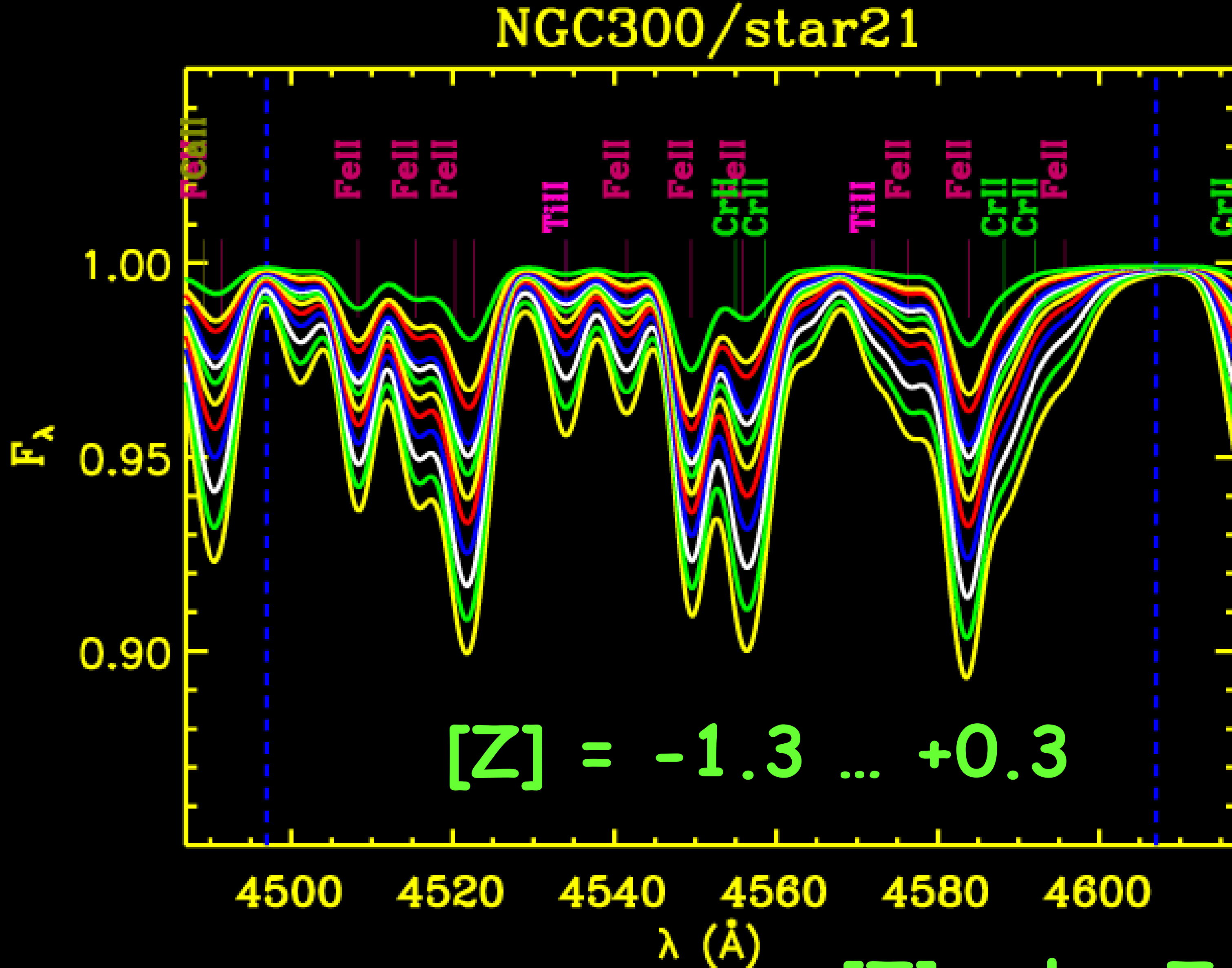
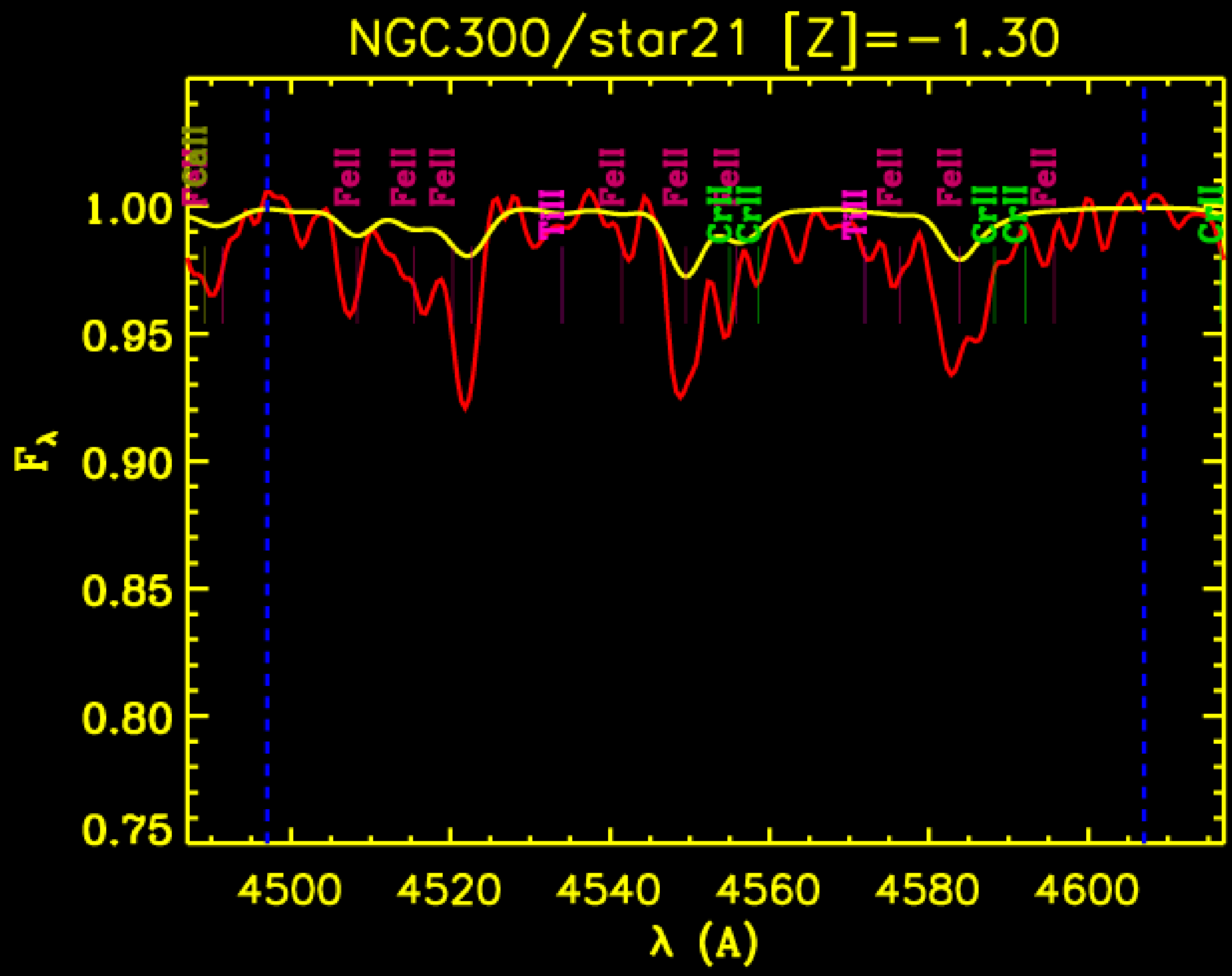
Advanced atmosphere models: ~ $10^6$ lines in NLTE



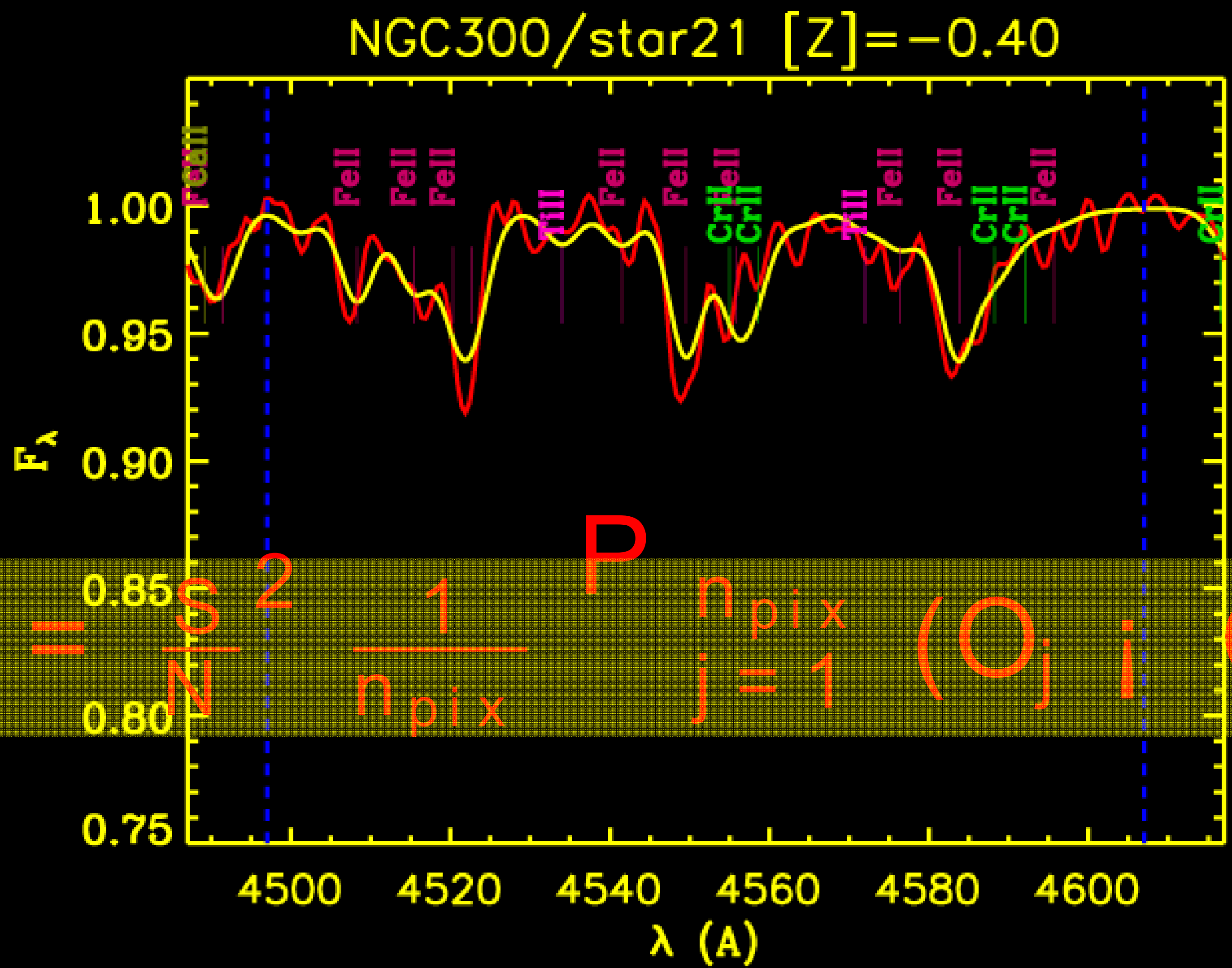

$[Z] = \log Z/Z_{sun}$

Athens 2013

# Spectral window 4497-4607Å

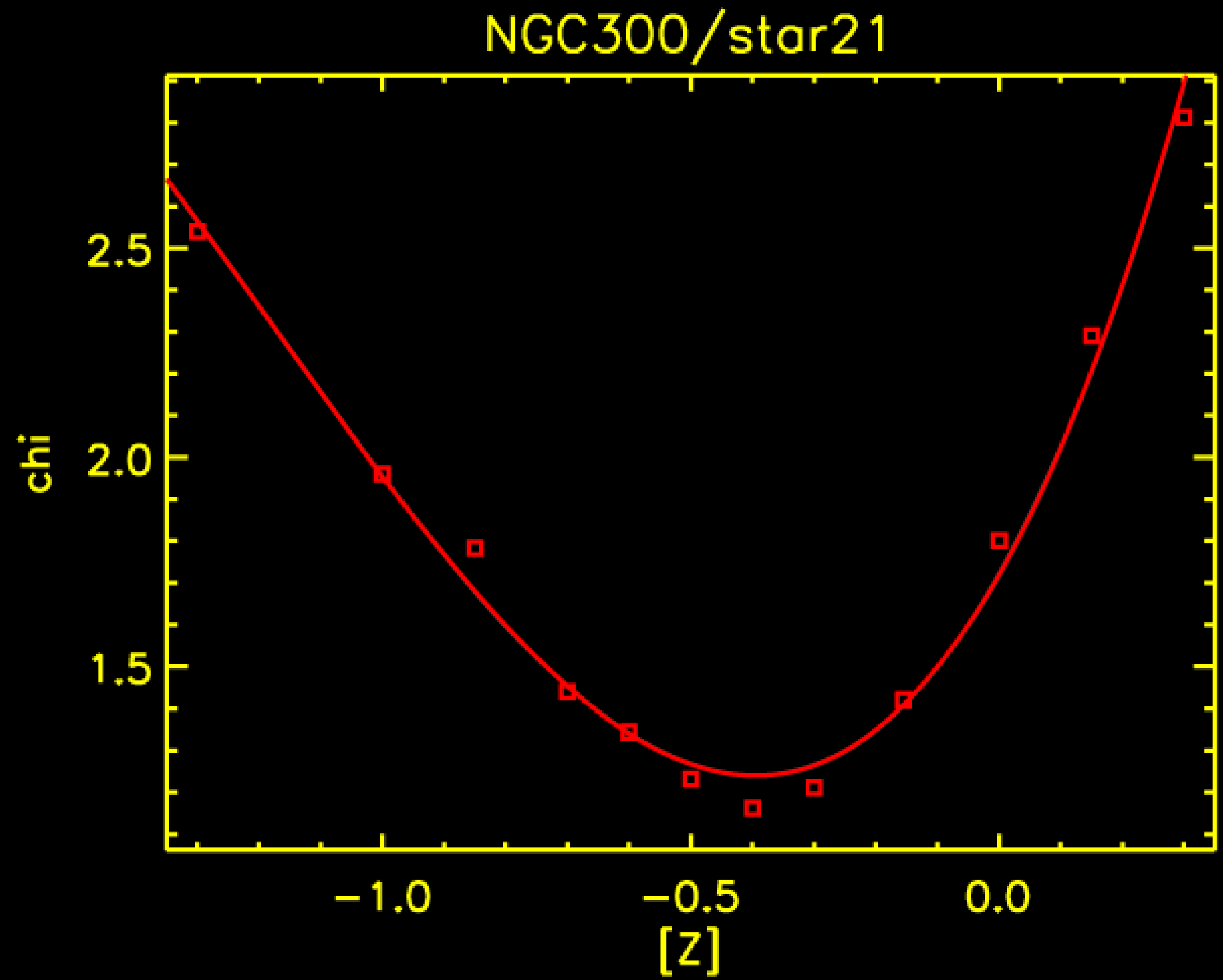


# Spectral window 4497-4607Å

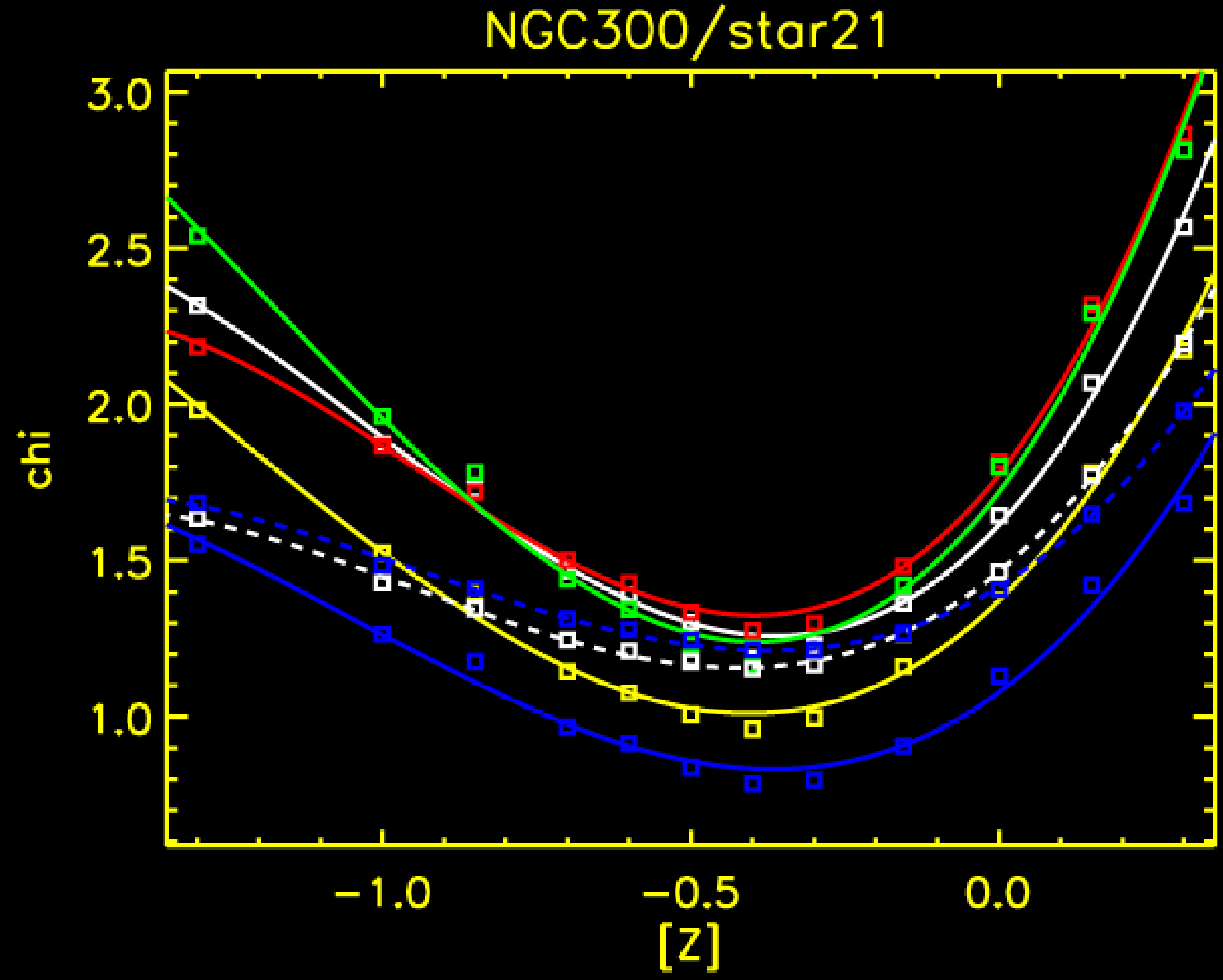



$$\chi_i^2 = \left(\frac{S}{N}\right)^2 \frac{1}{n_{pix}} \sum_{j=1}^{n_{pix}} (O_j - C_j)^2$$

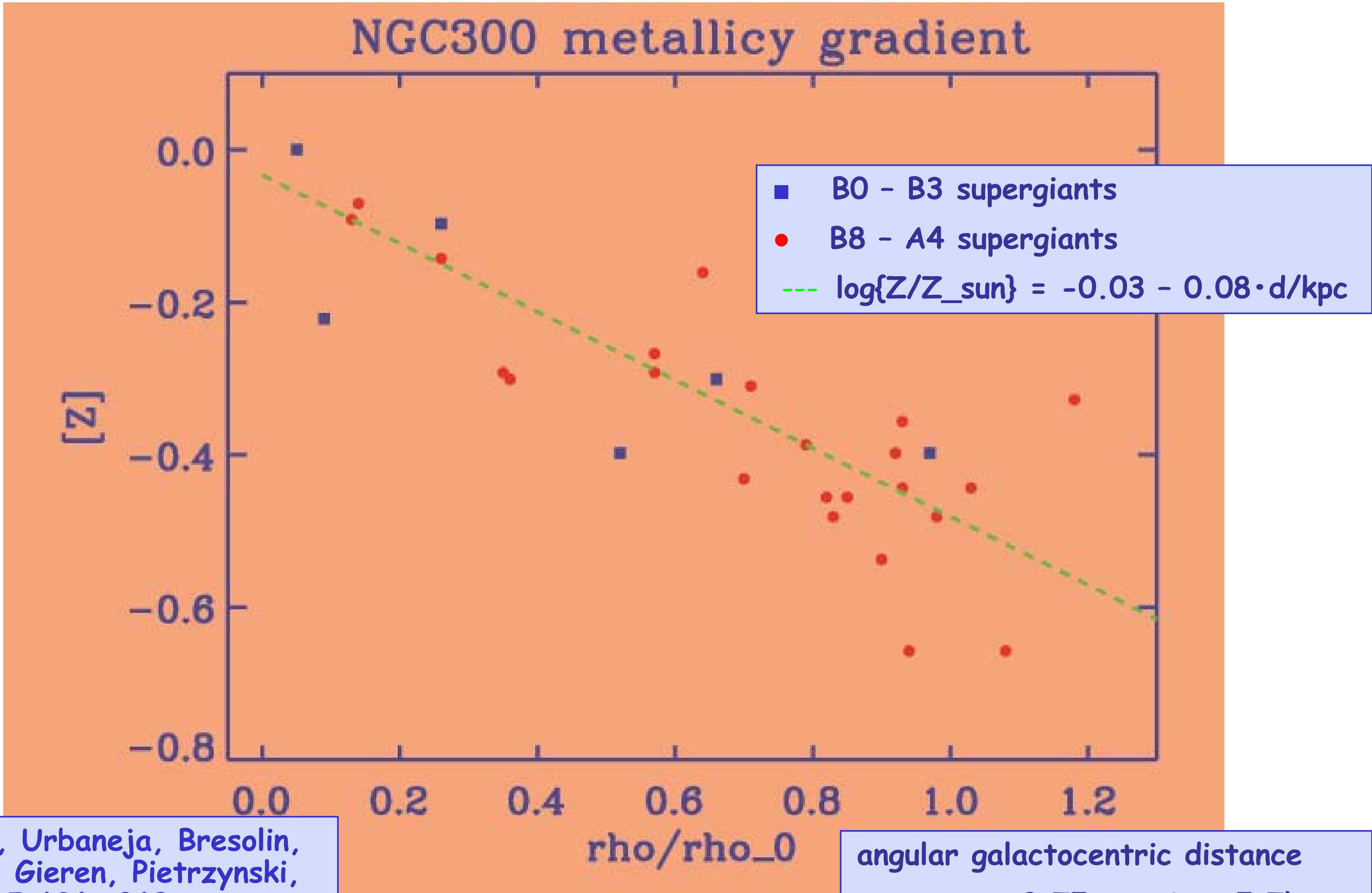
# $\chi_i$ spectral window 4497-4607Å



# $X_i$ all windows → [Z] = -0.4±0.1



# Stellar metallicity gradient in NGC300

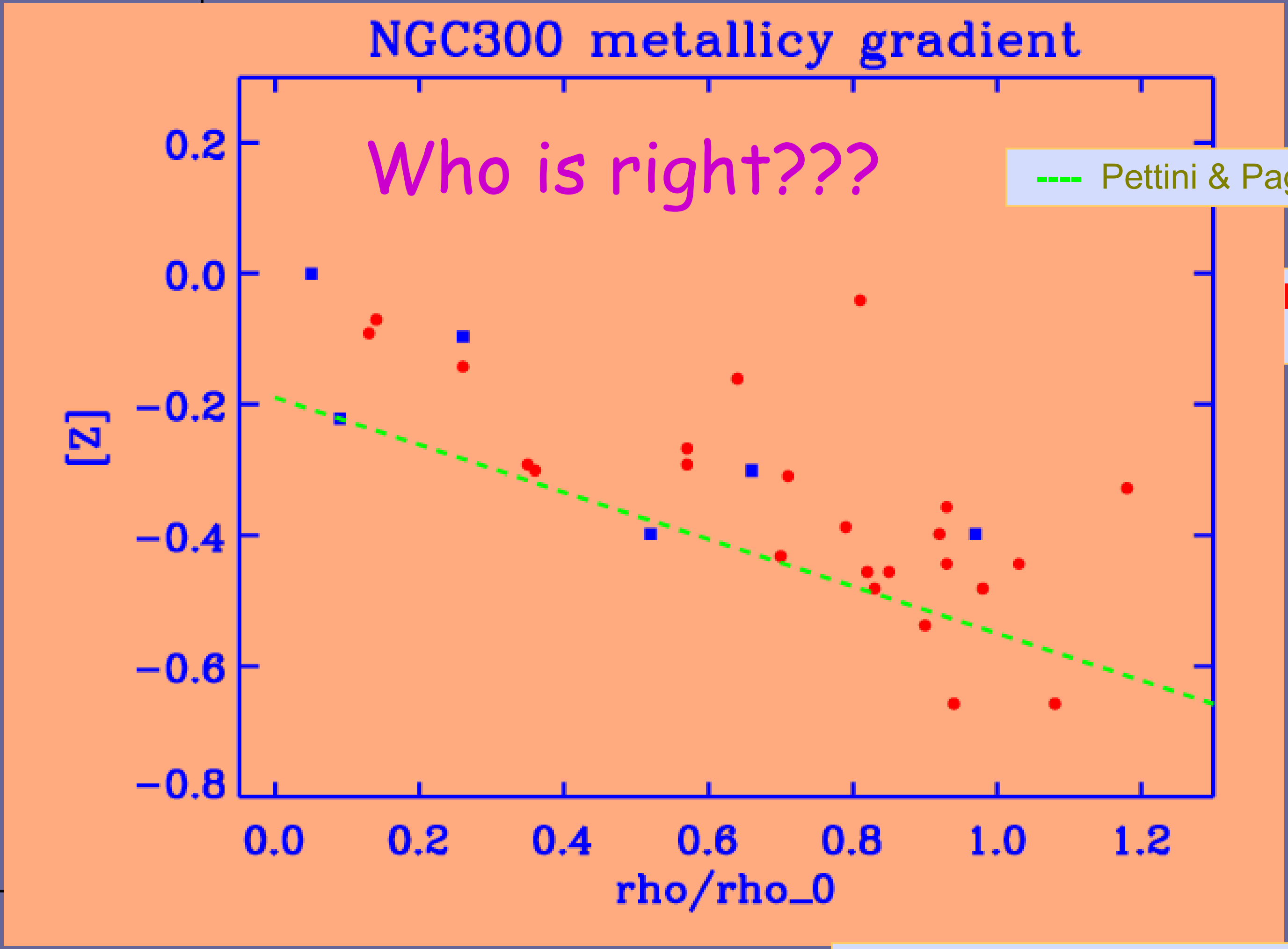



Kudritzki, Urbaneja, Bresolin, Przybilla, Gieren, Pietrzynski, 2008, ApJ 681, 269

angular galactocentric distance

$\rho_0$ = 9.75 arcmin ≈ 5.7kpc

# Stellar vs. HII metallicity gradient

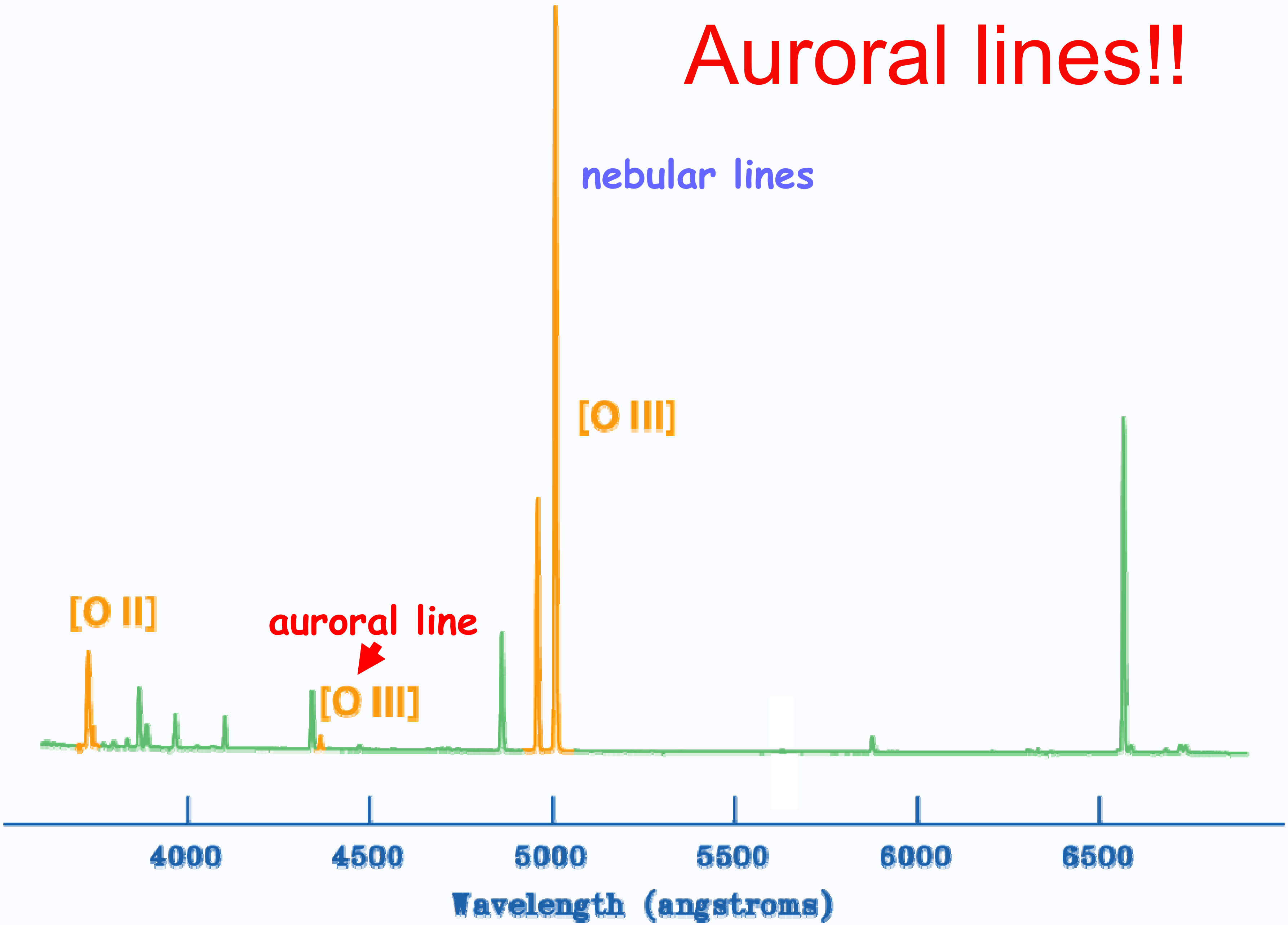



---- Pettini & Pagel (2004)

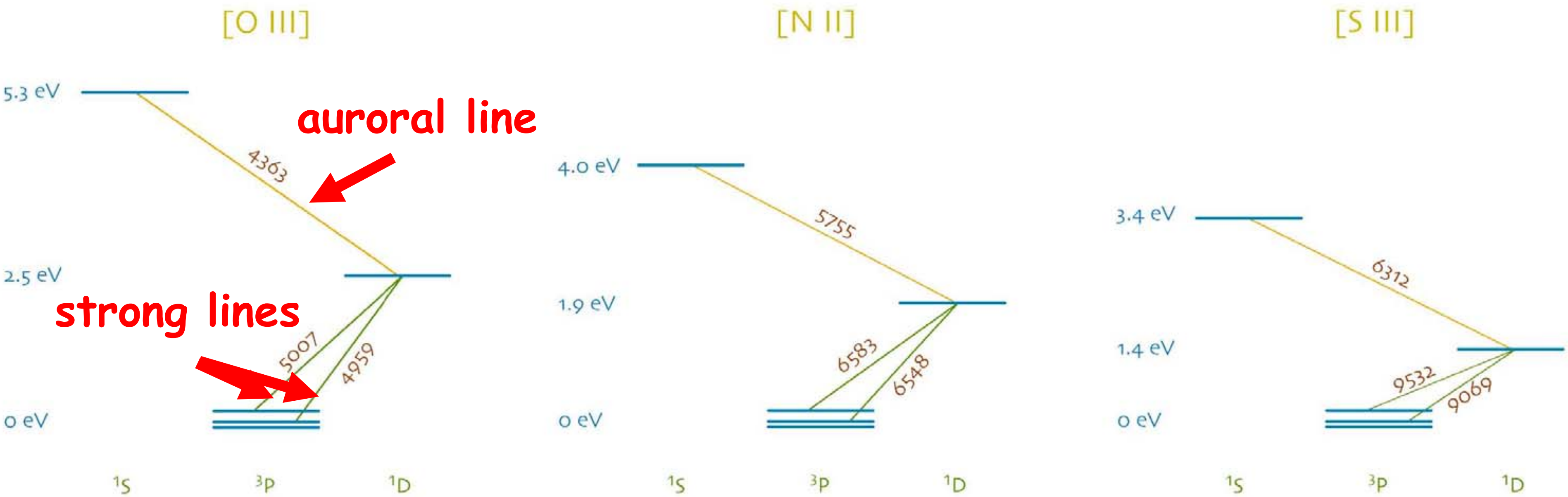
l with stellar

Kudritzki et al., 2008, ApJ 681, 265

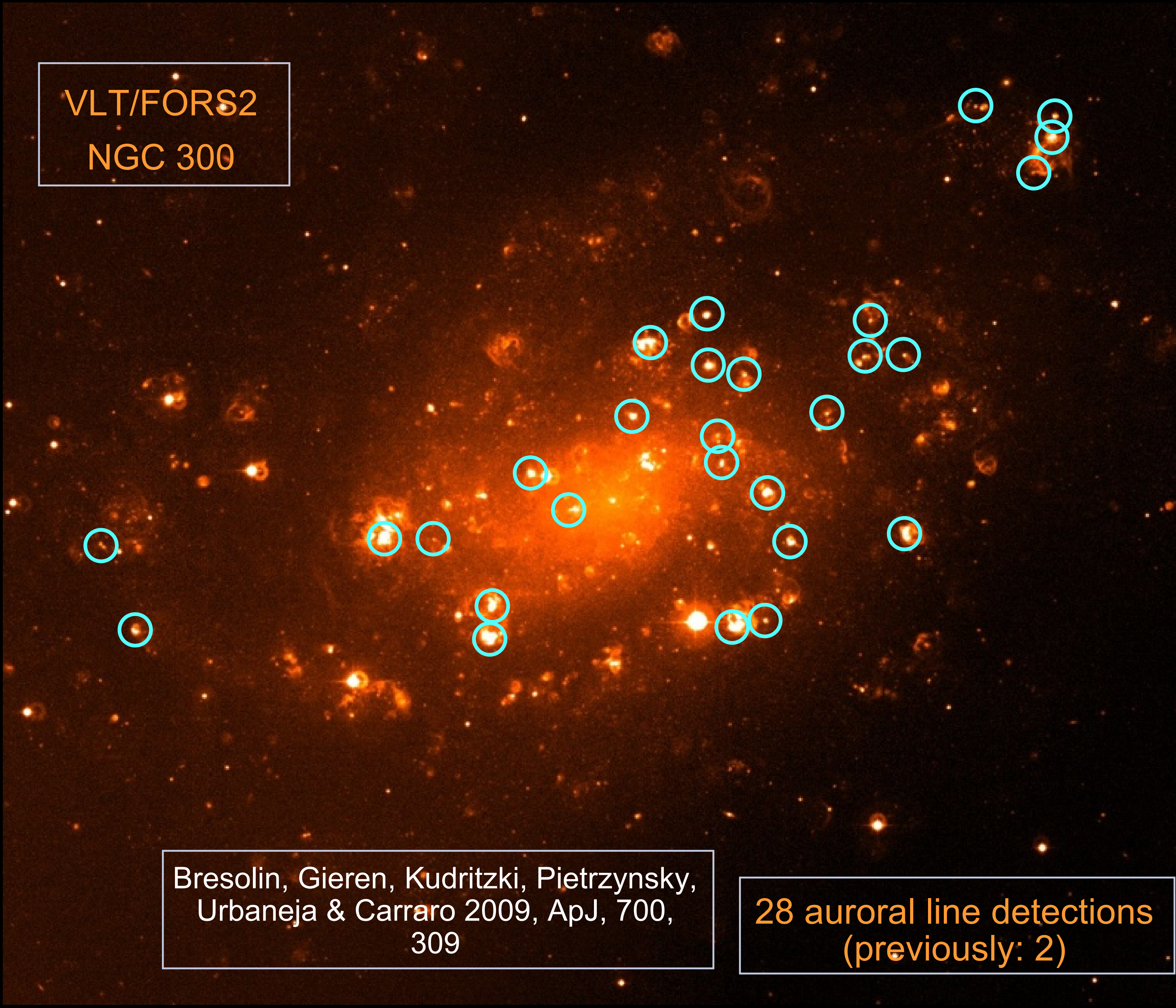
# The solution? Auroral lines!!

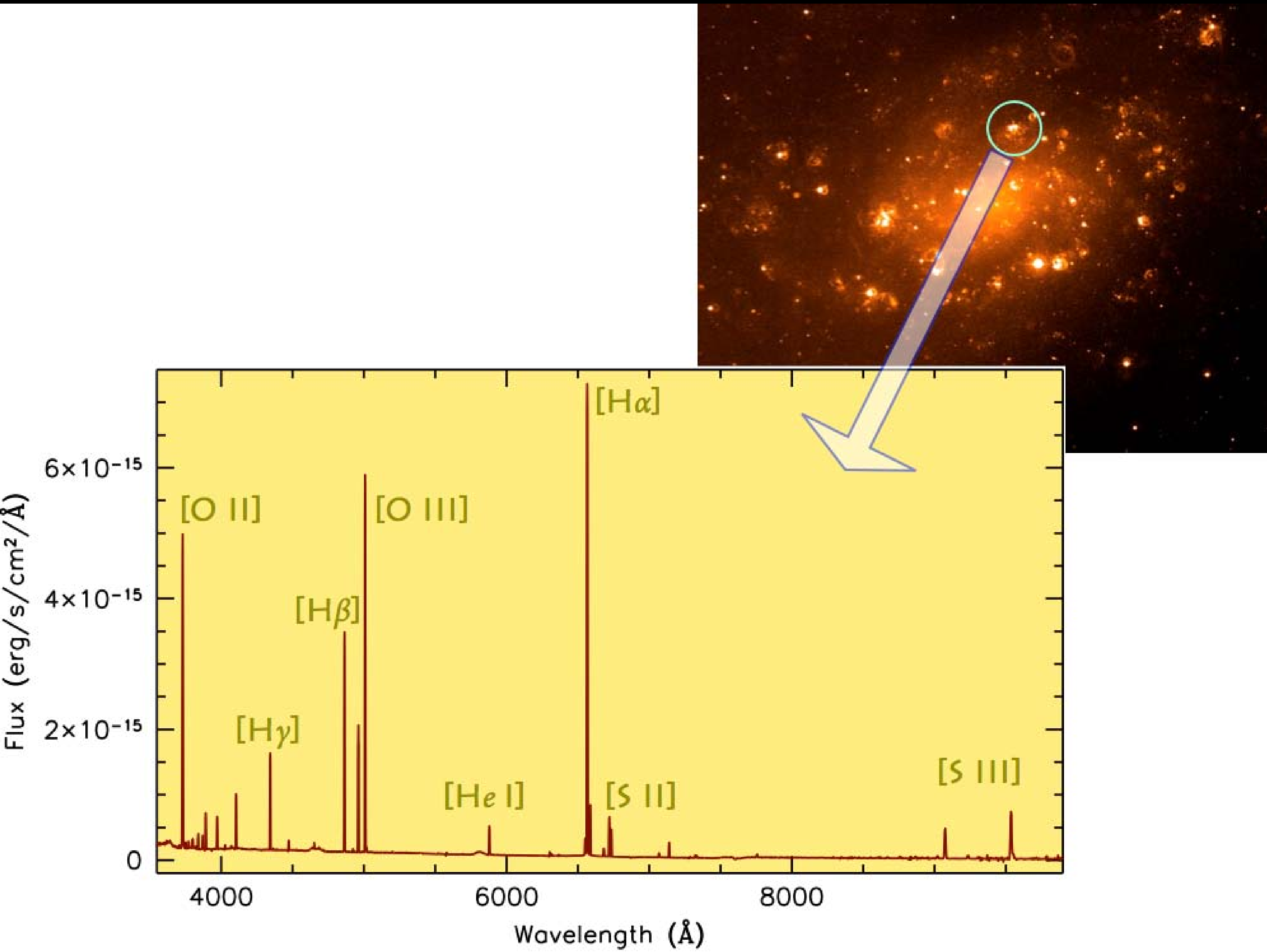


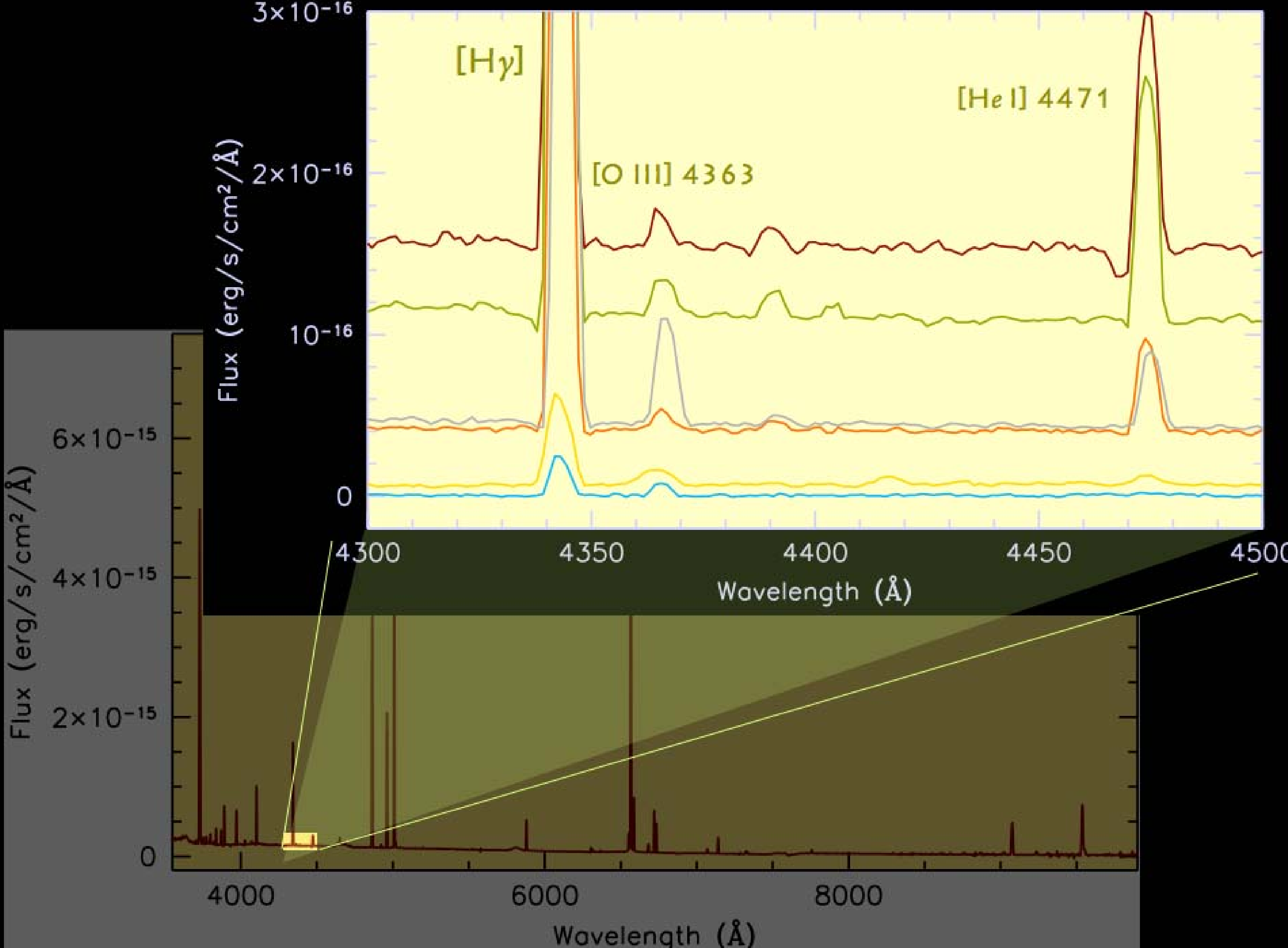
# strong lines and auroral lines




Bresolin, 2009


VLT/FORS2
NGC 300
Bresolin, Gieren, Kudritzki, Pietrzynsky, Urbaneja & Carraro 2009, ApJ, 700, 309
28 auroral line detections (previously: 2)

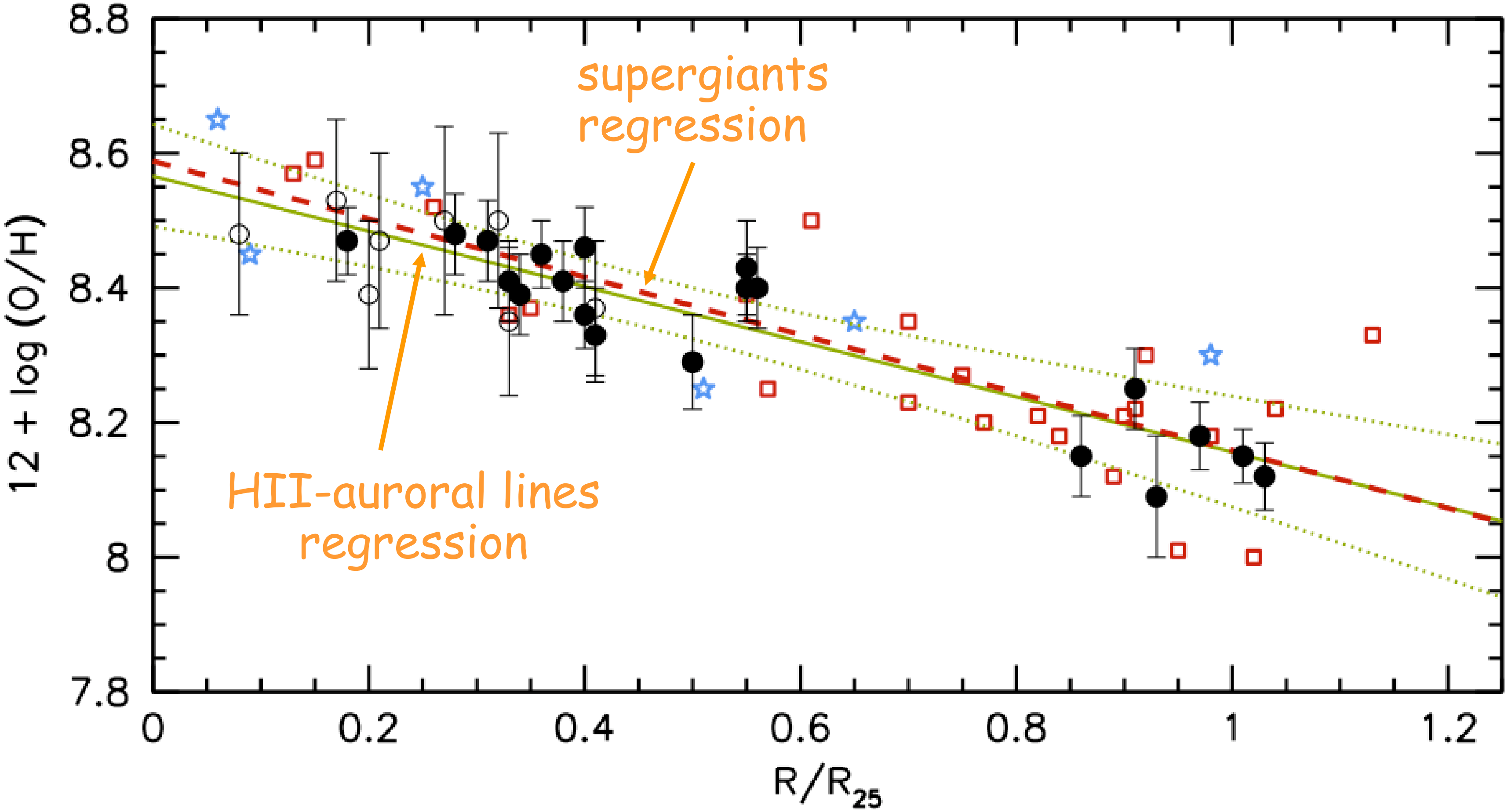

[O II]
[O III]
[Hβ]
[Hγ]
[Hα]
[He I]
[S II]
[S III]
6×10⁻¹⁵
4×10⁻¹⁵
2×10⁻¹⁵
0
Flux (erg/s/cm²/Å)
4000
6000
8000
Wavelength (Å)


[Hγ]
[O III] 4363
[He I] 4471
Flux (erg/s/cm²/Å)
3×10⁻¹⁶
2×10⁻¹⁶
10⁻¹⁶
0
4300
4350
4400
4450
4500
Wavelength (Å)
Flux (erg/s/cm²/Å)
6×10⁻¹⁵
4×10⁻¹⁵
2×10⁻¹⁵
0
4000
6000
8000
Wavelength (Å)

Bresolin, Gieren, Kudritzki et al. 2009

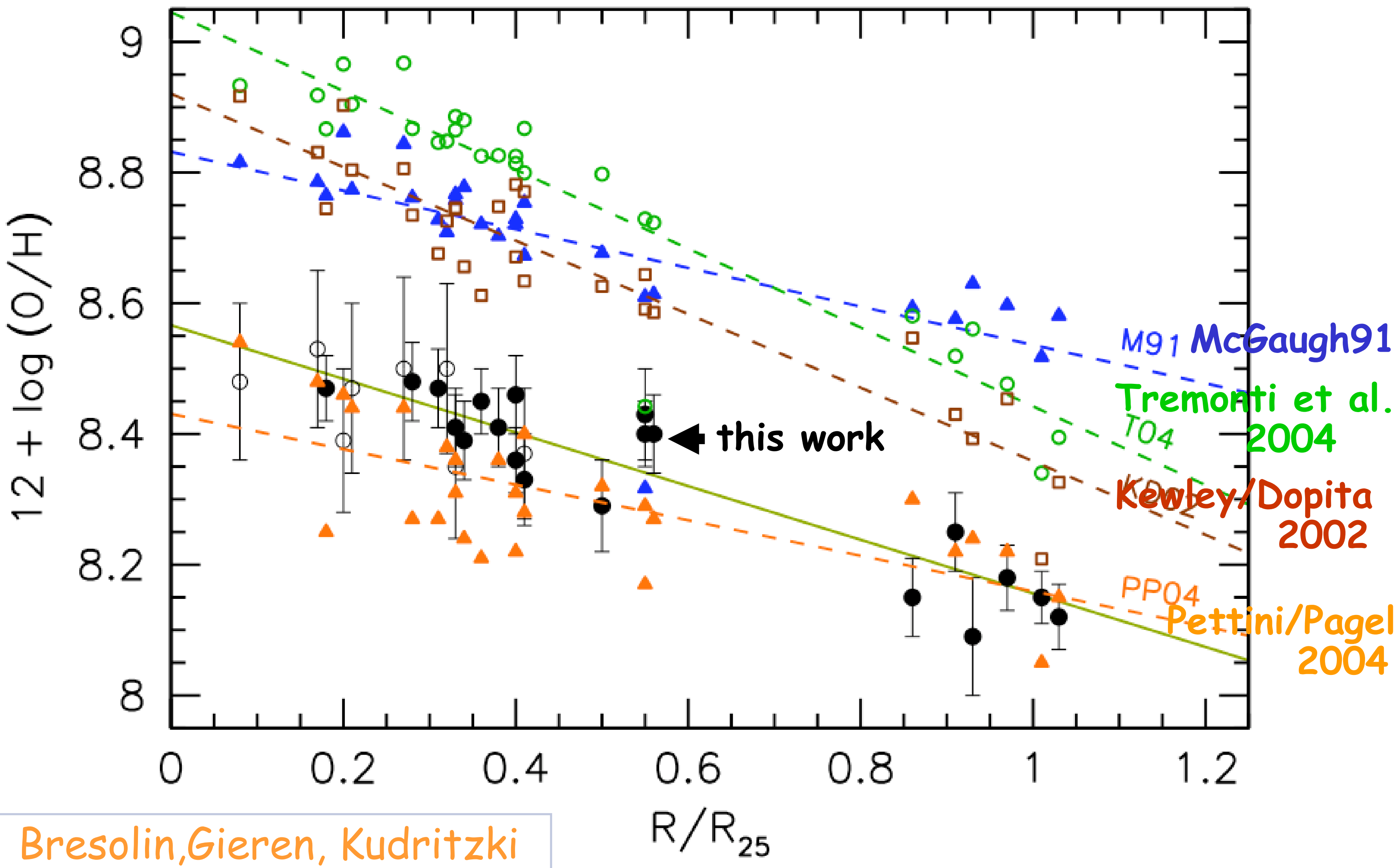
○ ● HII- auroral

□ * supergiants



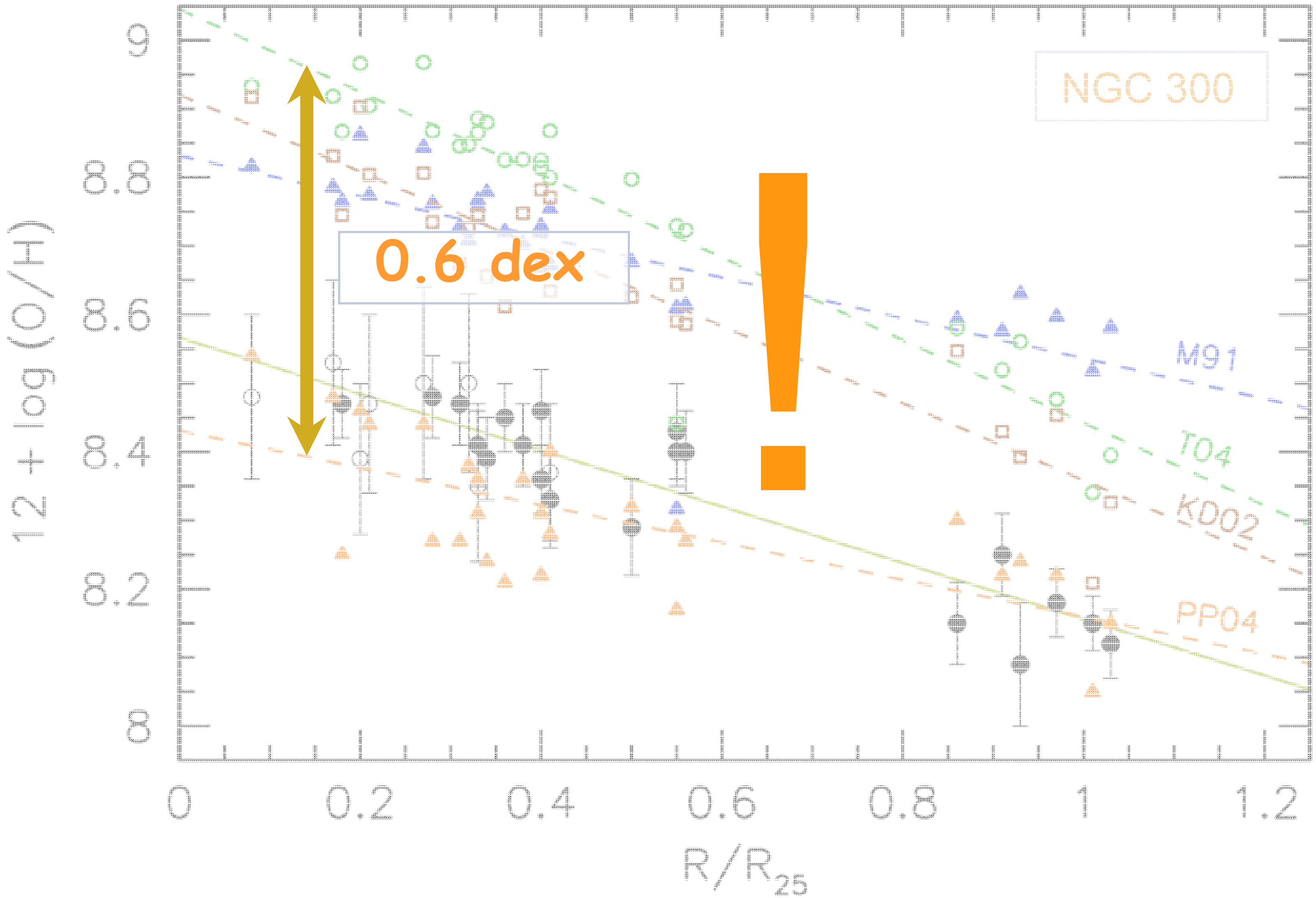

Excellent agreement between auroral lines and supergiants !!

# Auroral lines vs. strong lines calibrations – a horror story !!



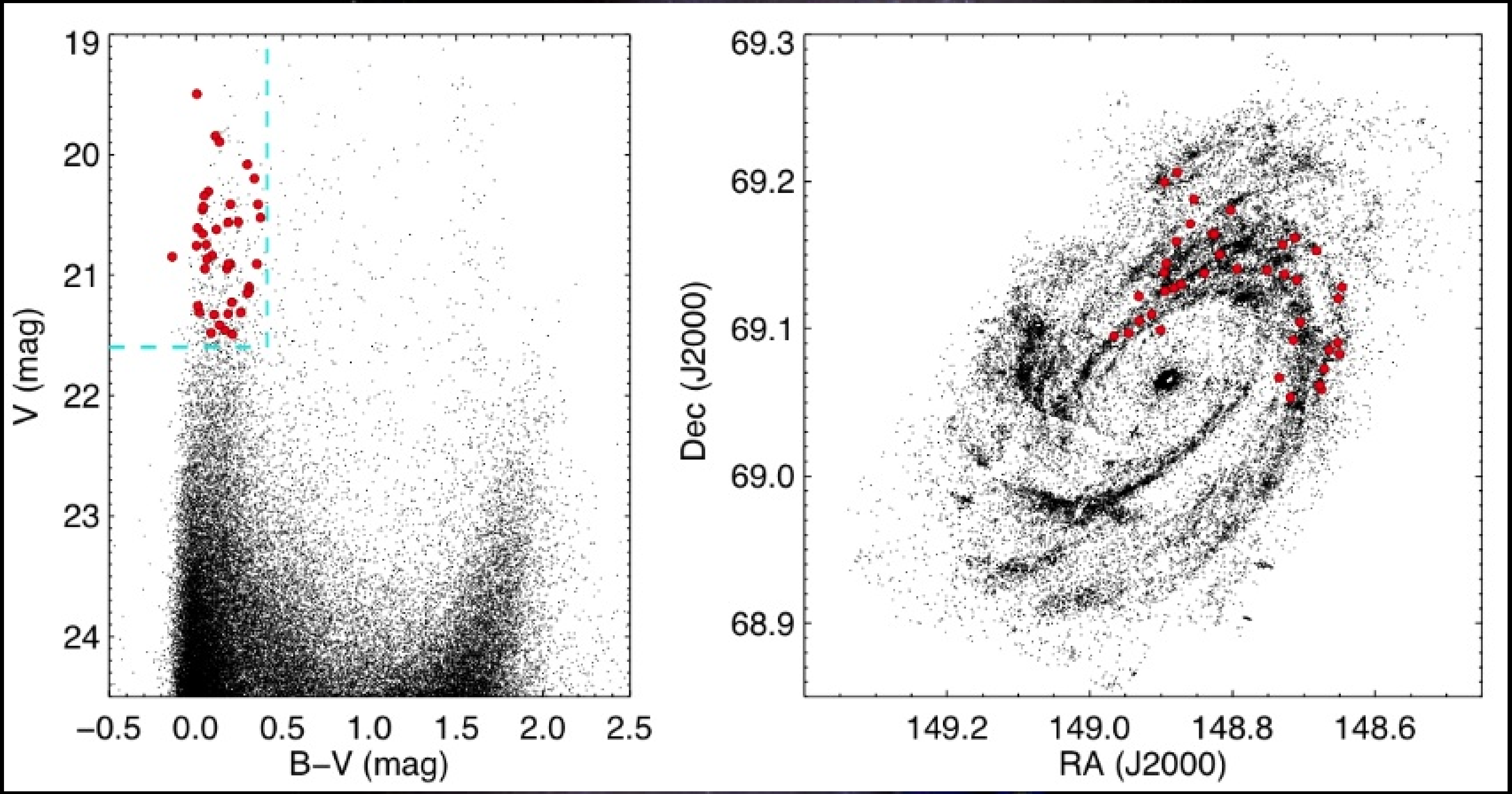

Bresolin,Gieren, Kudritzki et al. 2009

Bresolin, Gieren, Kudritzki,
Pietrzynsky, Urbaneja & Carraro
2009, ApJ, 700, 309



M81

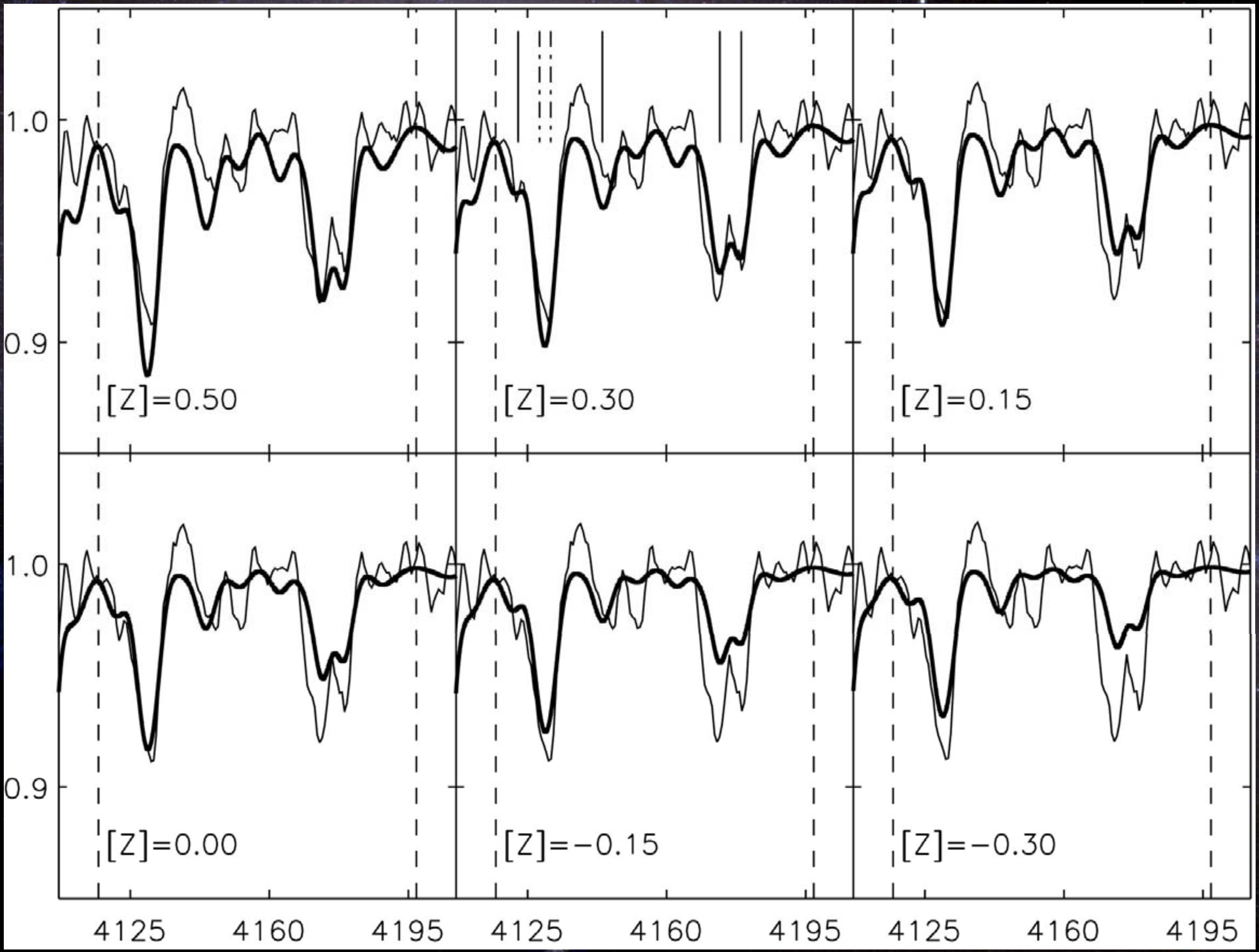
Keck LRIS



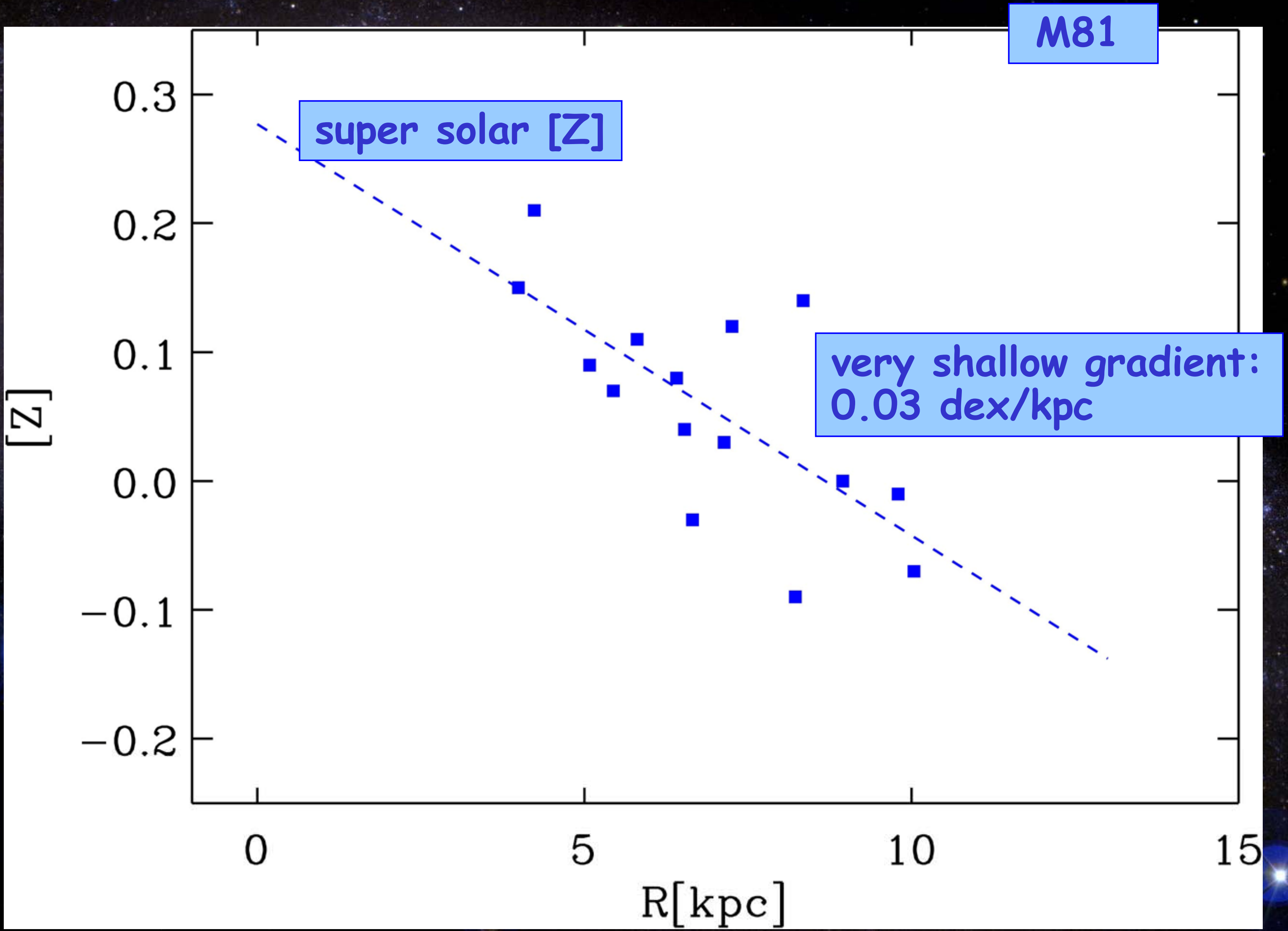

Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15

M81

object C20

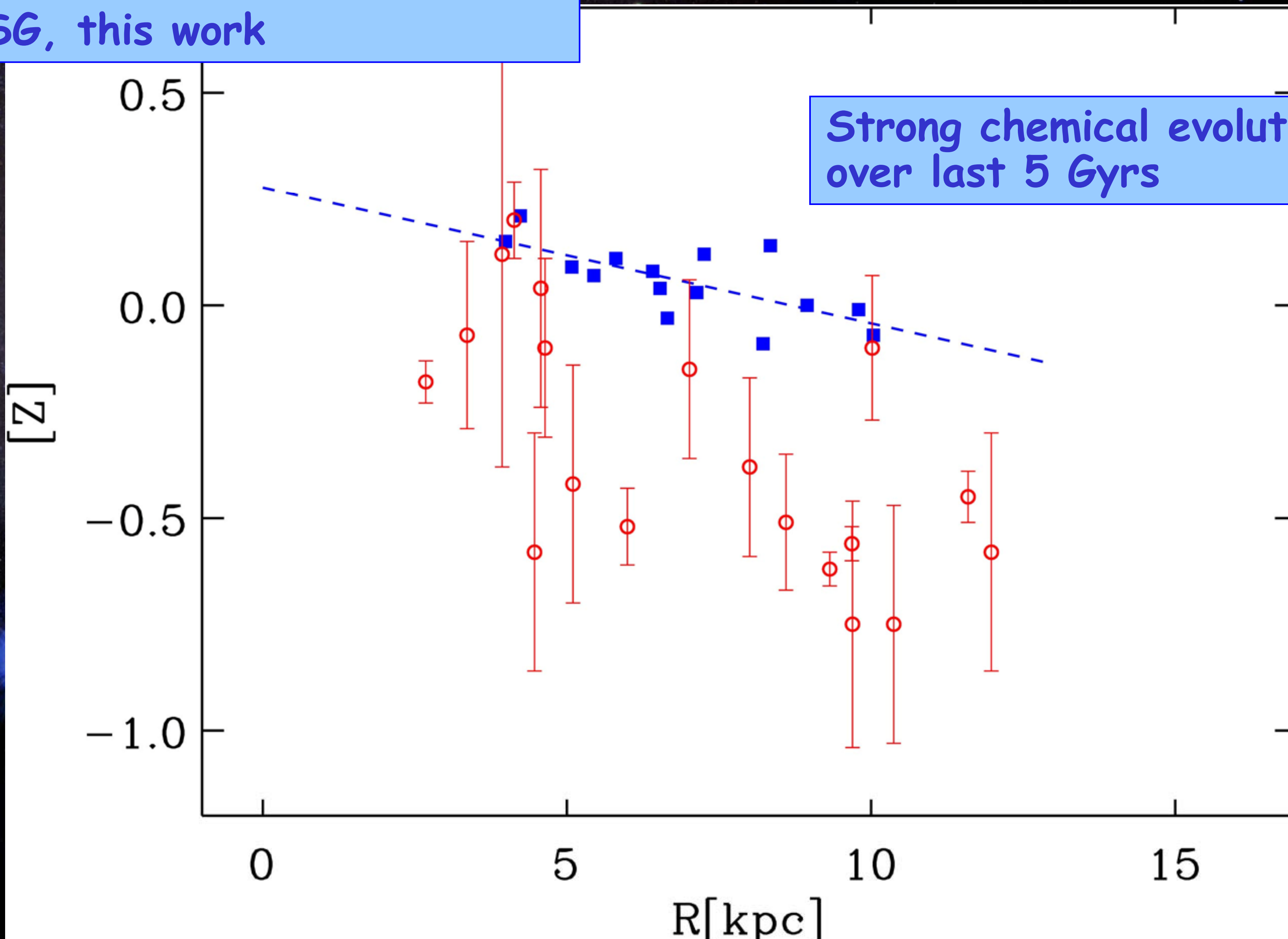



Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15




Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15

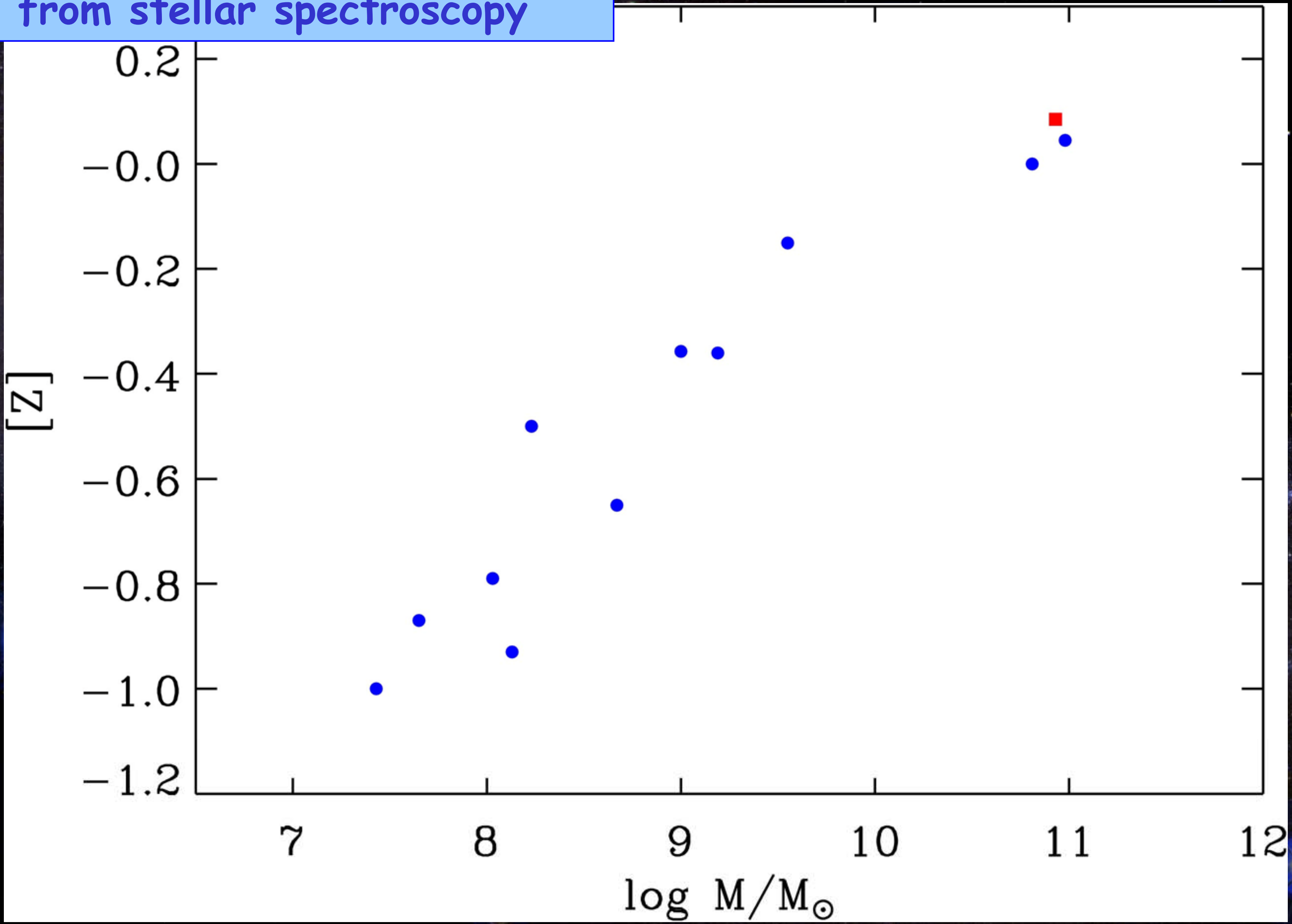
- PNe, Stanghellini et al. 2010
- BSG, this work




Strong chemical evolution over last 5 Gyrs

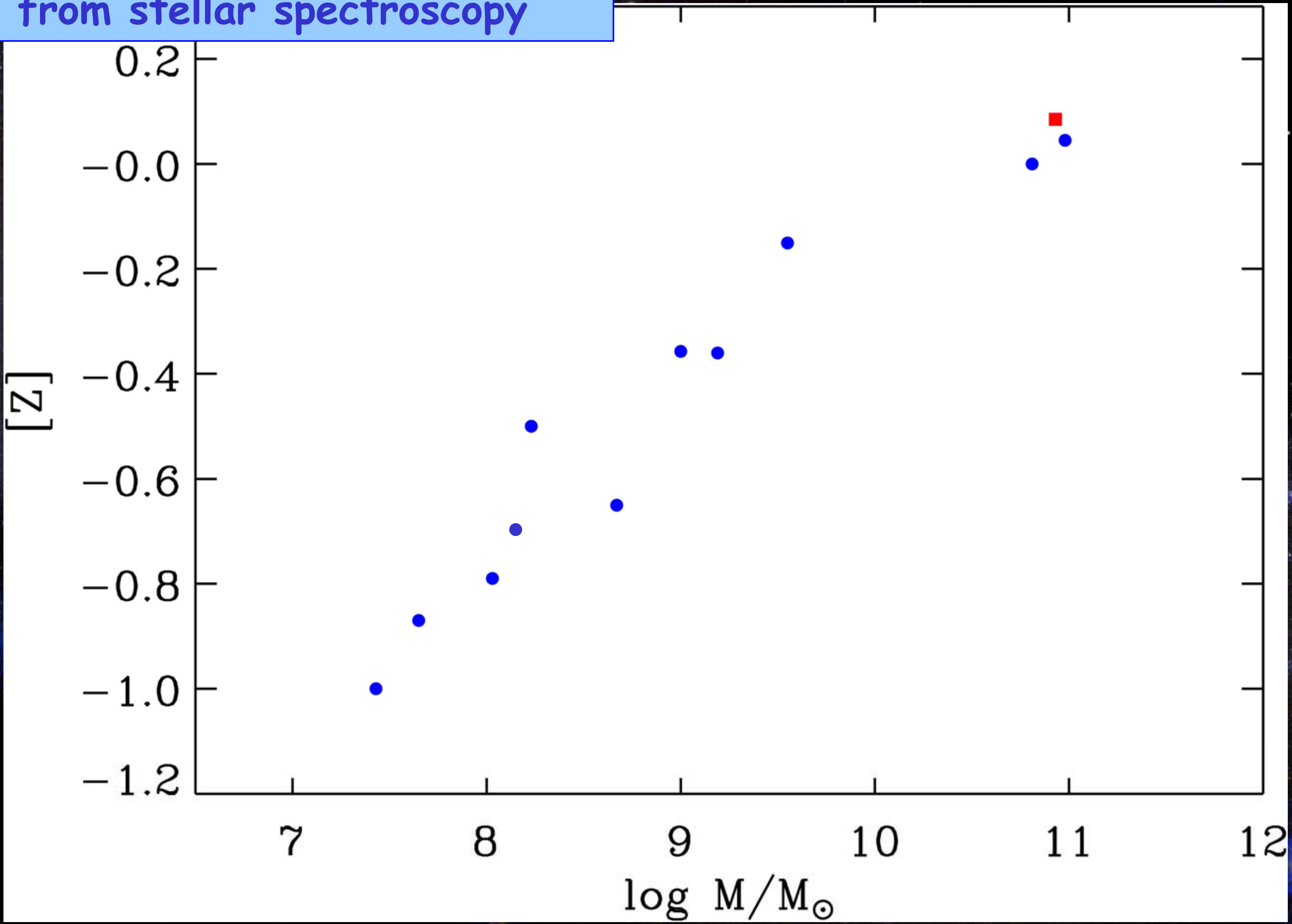
Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15

A mass-metallicity relationship only from stellar spectroscopy



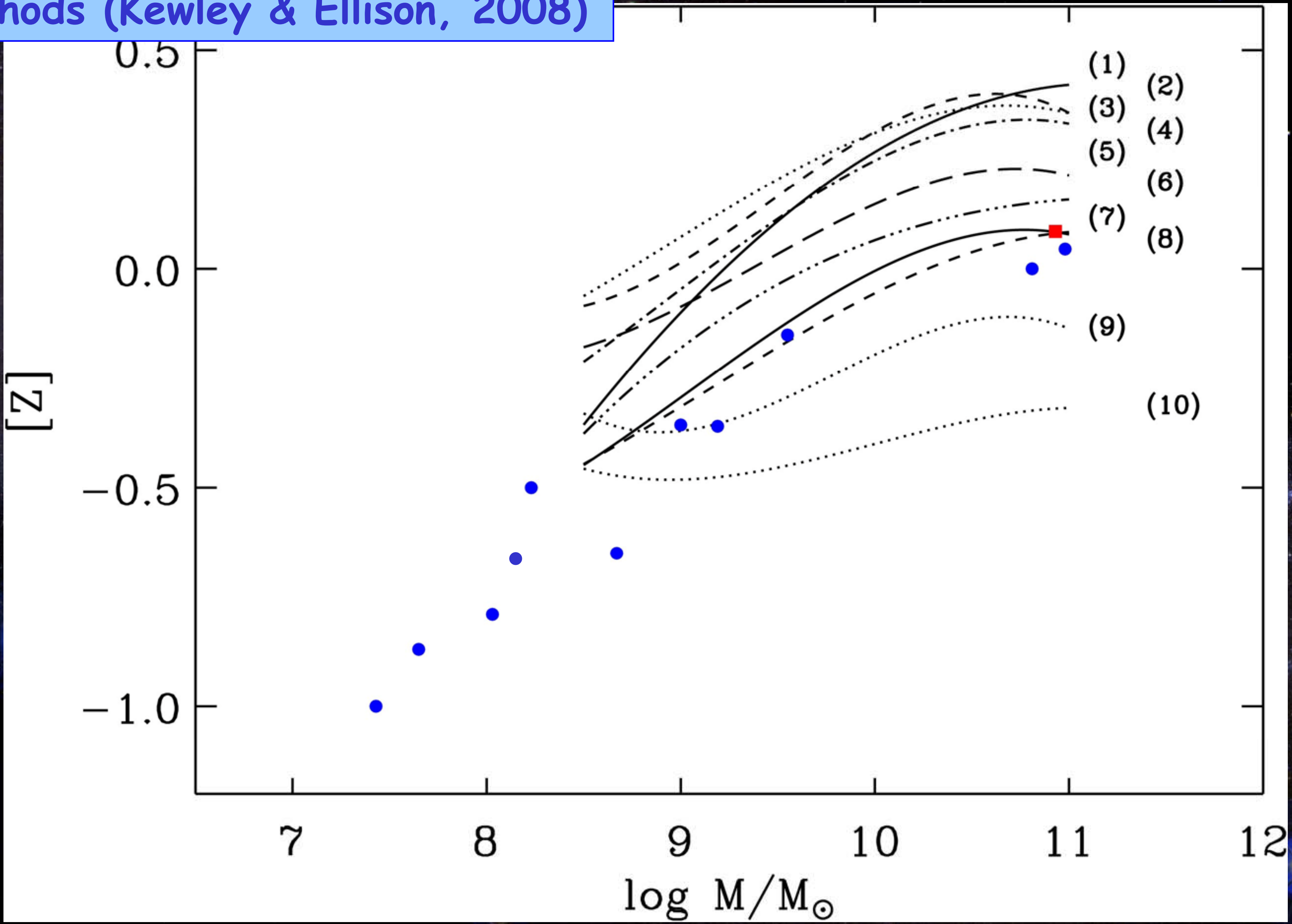

Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15

# A mass-metallicity relationship only from stellar spectroscopy



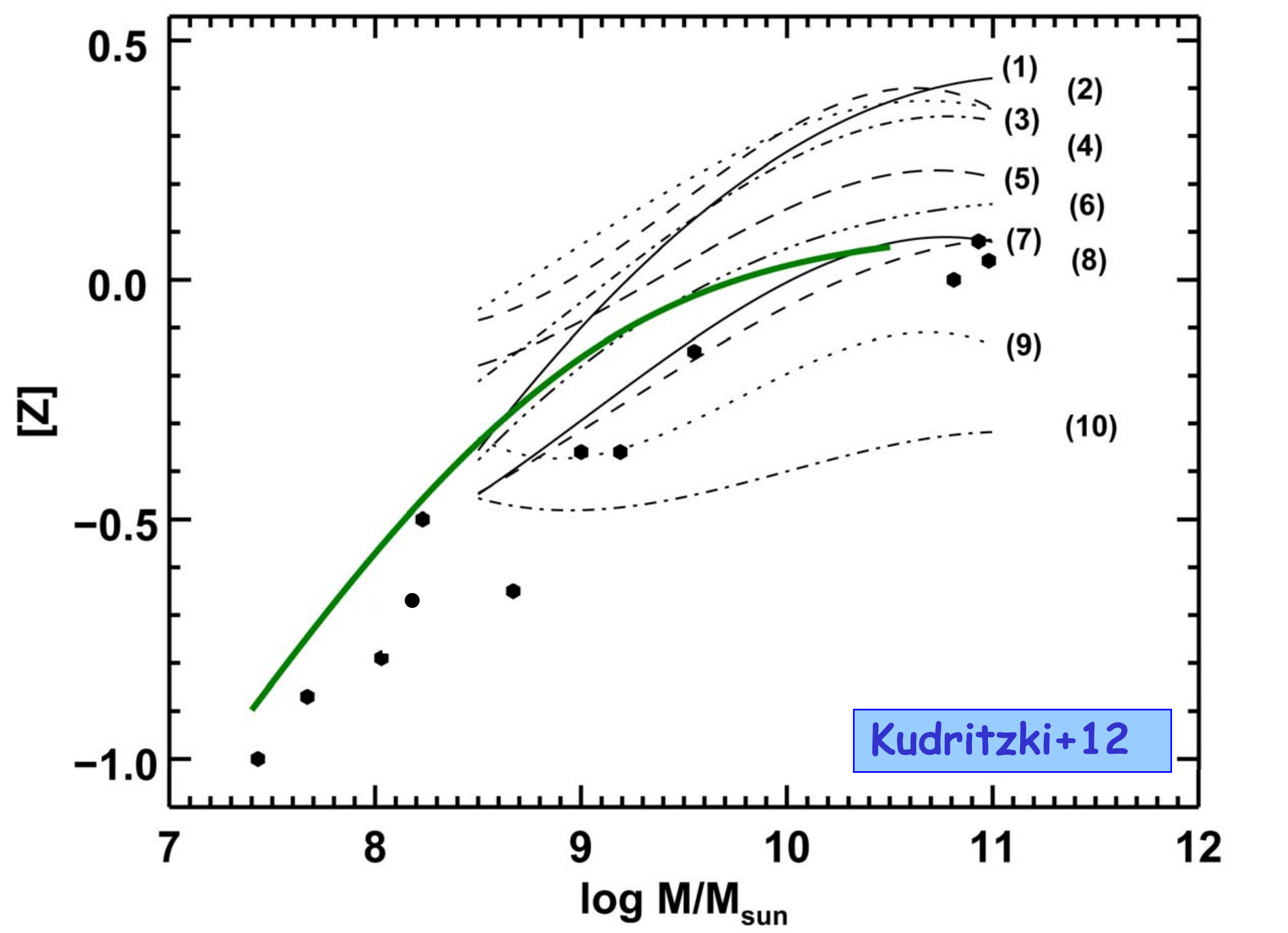

Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15

# Comparison with HII strong line methods (Kewley & Ellison, 2008)




Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15

# HII auroral line method –staggered SDSS spectra
Andrew & Martini, 2013



# $H_0$ uncertainty and universe equation of state

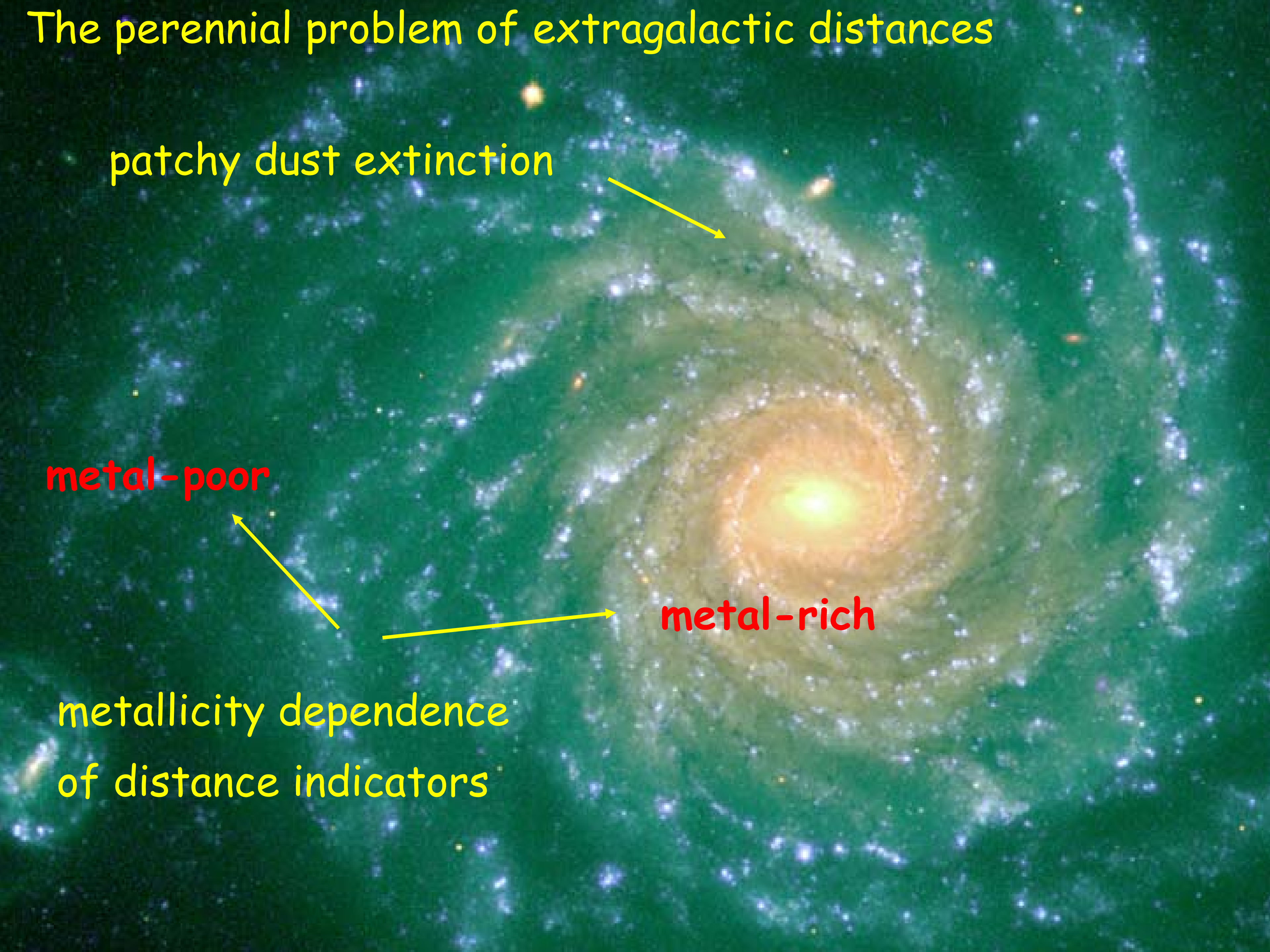
Hubble constant uncertainty →
EoS parameter w

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

$$w = \frac{p}{c^2\rho}$$

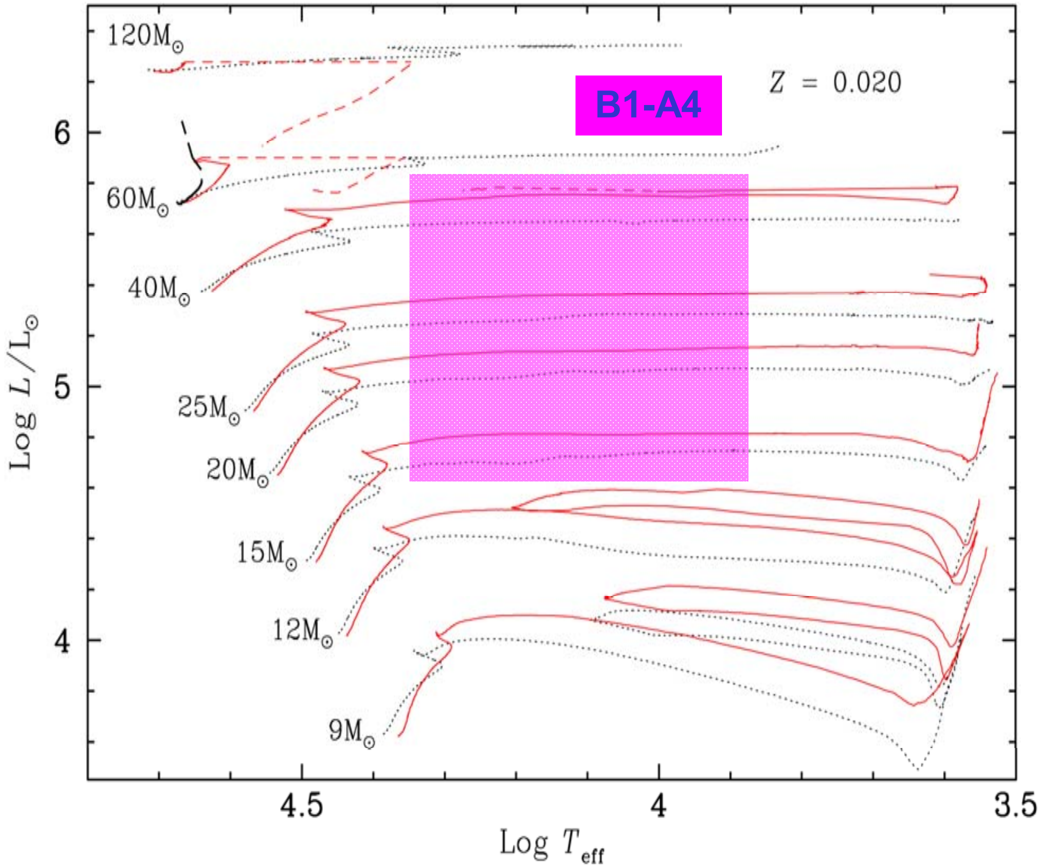
despite enormous effort still: $\delta H_0$ ~ 10% → $\delta w$ ~ 0.2

compare
Freedman et al., 2001
Saha et al., 2001, Sandage et al., 2006
Mould & Sakai, 2008, 2009ab
Riess et al., 2009, 2011, 2012 → $\delta H_0$ ~ 3%


The perennial problem of extragalactic distances
patchy dust extinction
metal-poor
metal-rich
metallicity dependence
of distance indicators

# Flux weighted Gravity - Luminosity Relationship (FGLR)

Kudritzki, Bresolin, Przybilla, ApJ Letters, 582, L83 (2003)




L,M ~ const.

$M \sim g \times R^2 \sim L \times (g/T^4) = const.$

const.

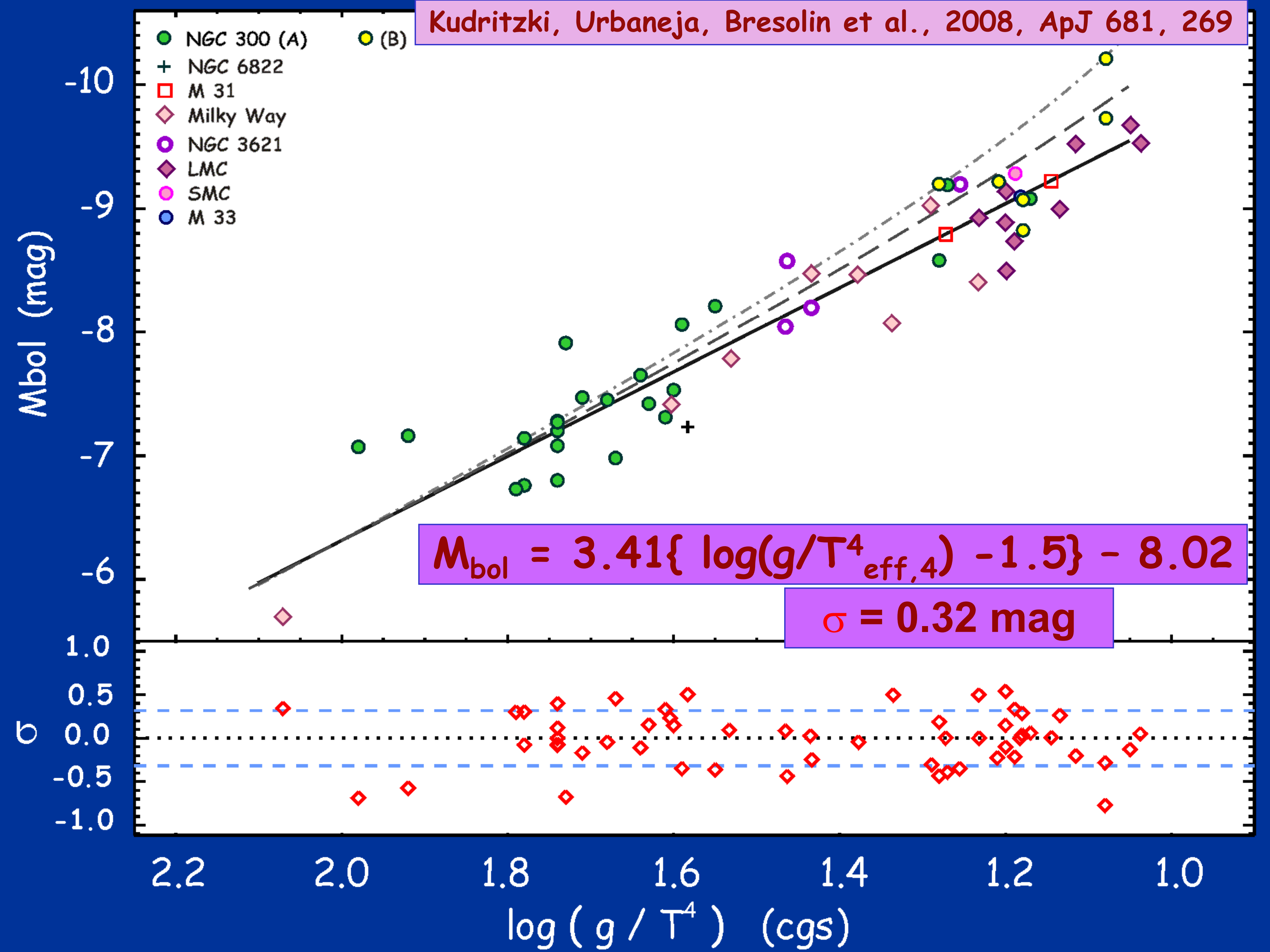
with $L \sim M^x \sim L^x (g/T^4)^x$, $x \sim 3$

$\rightarrow L^{1-x} \sim (g/T^4)^x$

or with $M_{bol} \sim -2.5 \log L$

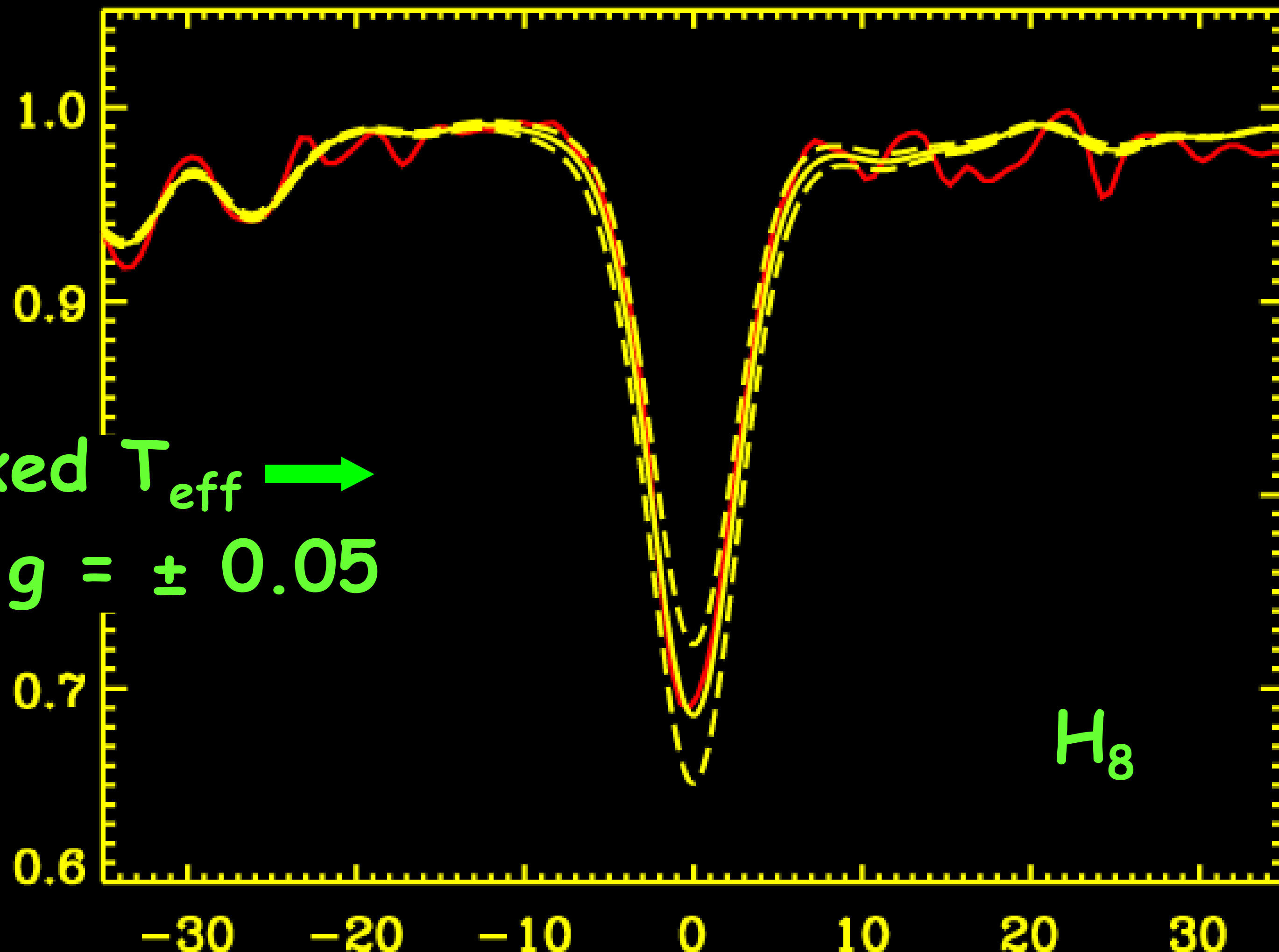
$M_{bol} = a \log(g/T^4) + b$ FGLR

$a = 2.5\, x/(1-x) \sim 3.75$



Kudritzki, Urbaneja, Bresolin et al., 2008, ApJ 681, 269
NGC 300 (A)
(B)
NGC 6822
M 31
Milky Way
NGC 3621
LMC
SMC
M 33
Mbol (mag)
-10
-9
-8
-7
-6
$M_{bol}$ = 3.41{ log(g/$T^4_{eff,4}$) -1.5} - 8.02
σ = 0.32 mag
σ
1.0
0.5
0.0
-0.5
-1.0
2.2
2.0
1.8
1.6
1.4
1.2
1.0
log ( g / $T^4$ ) (cgs)

# Balmer series fitting: log $g$ = 1.55±0.1



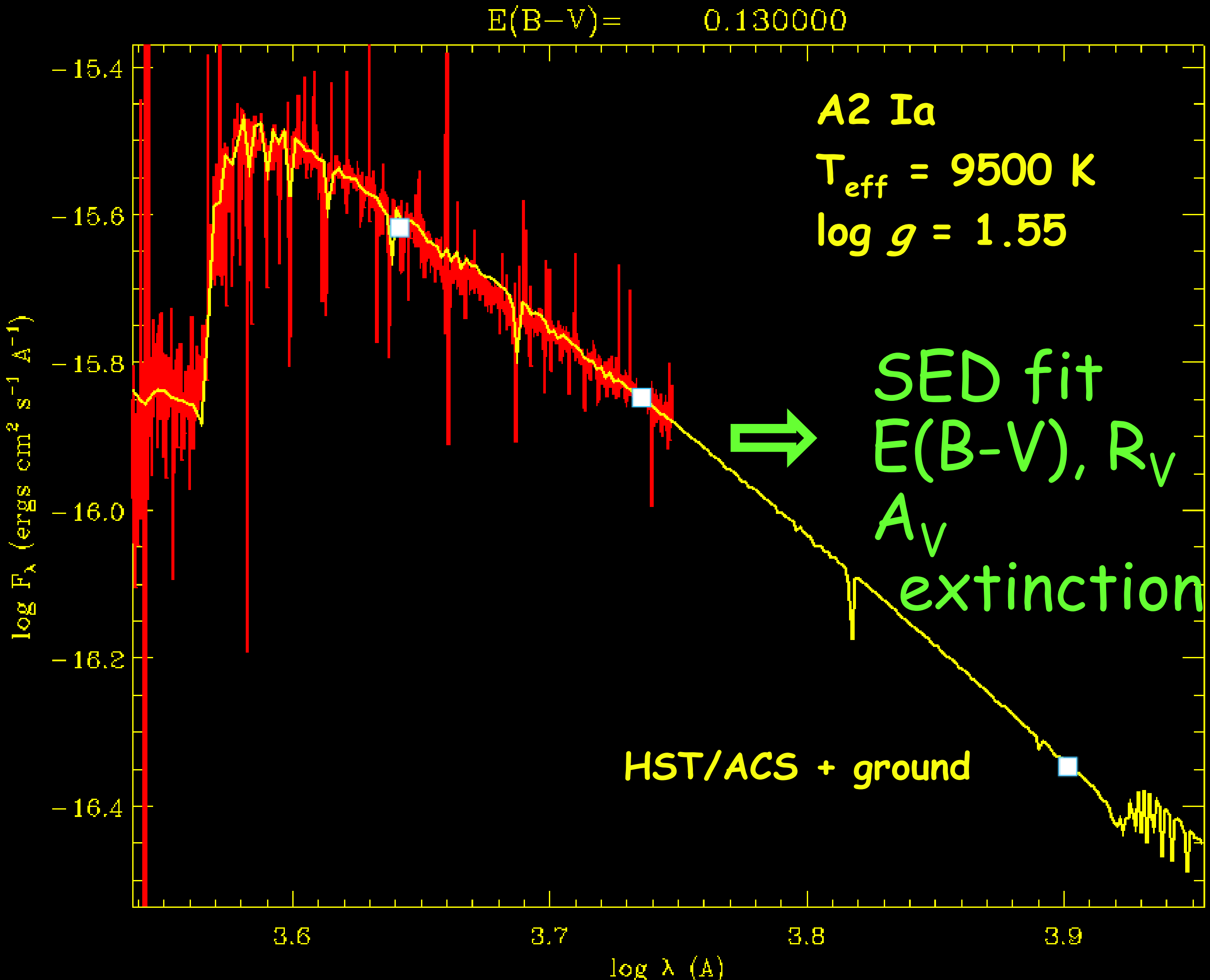

At fixed $T_{eff}$ →

$\Delta$ log $g$ = ± 0.05

Athens 2013

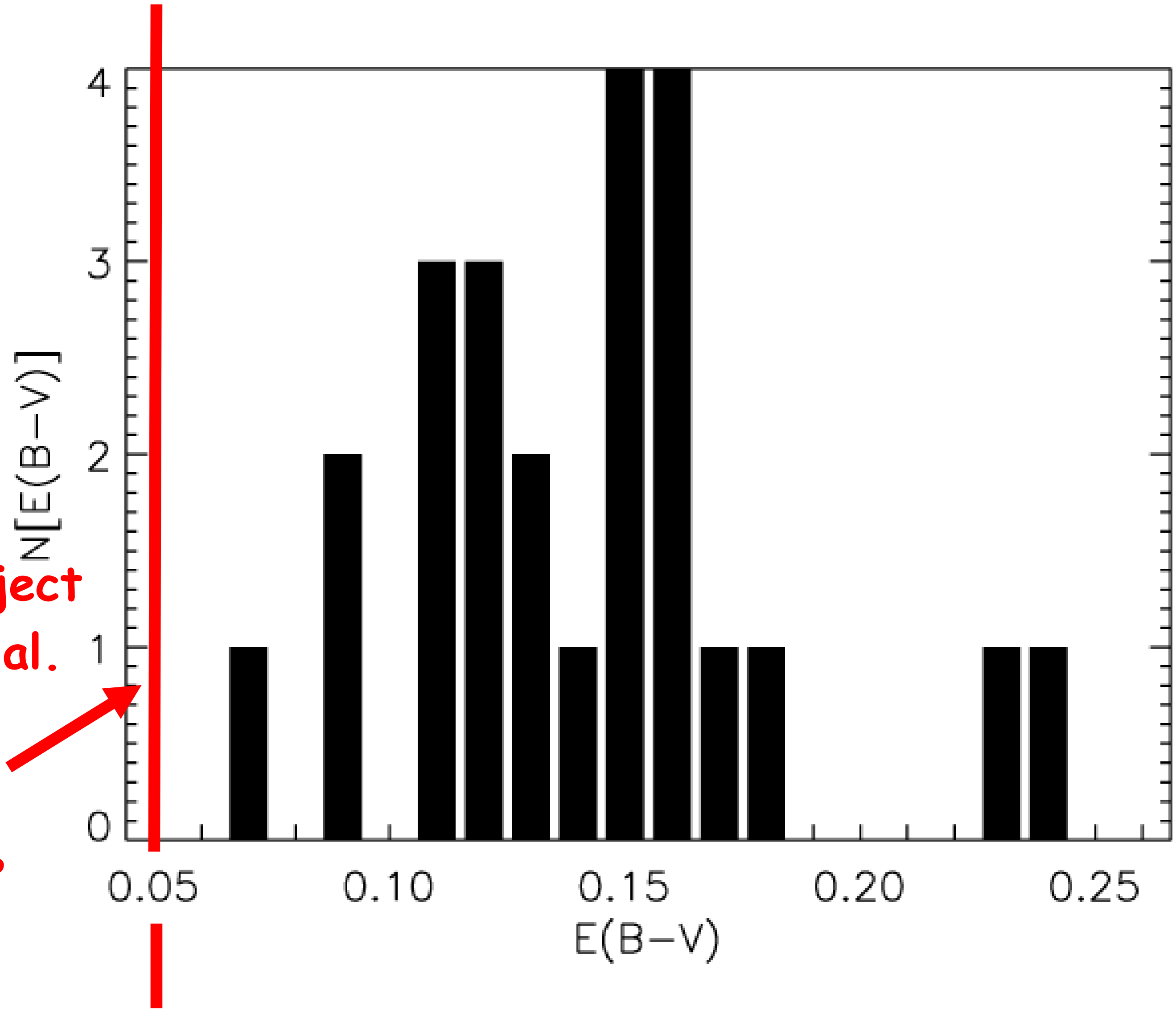
# A supergiant SED

Kudritzki, Urbaneja & Bresolin et al. 2008



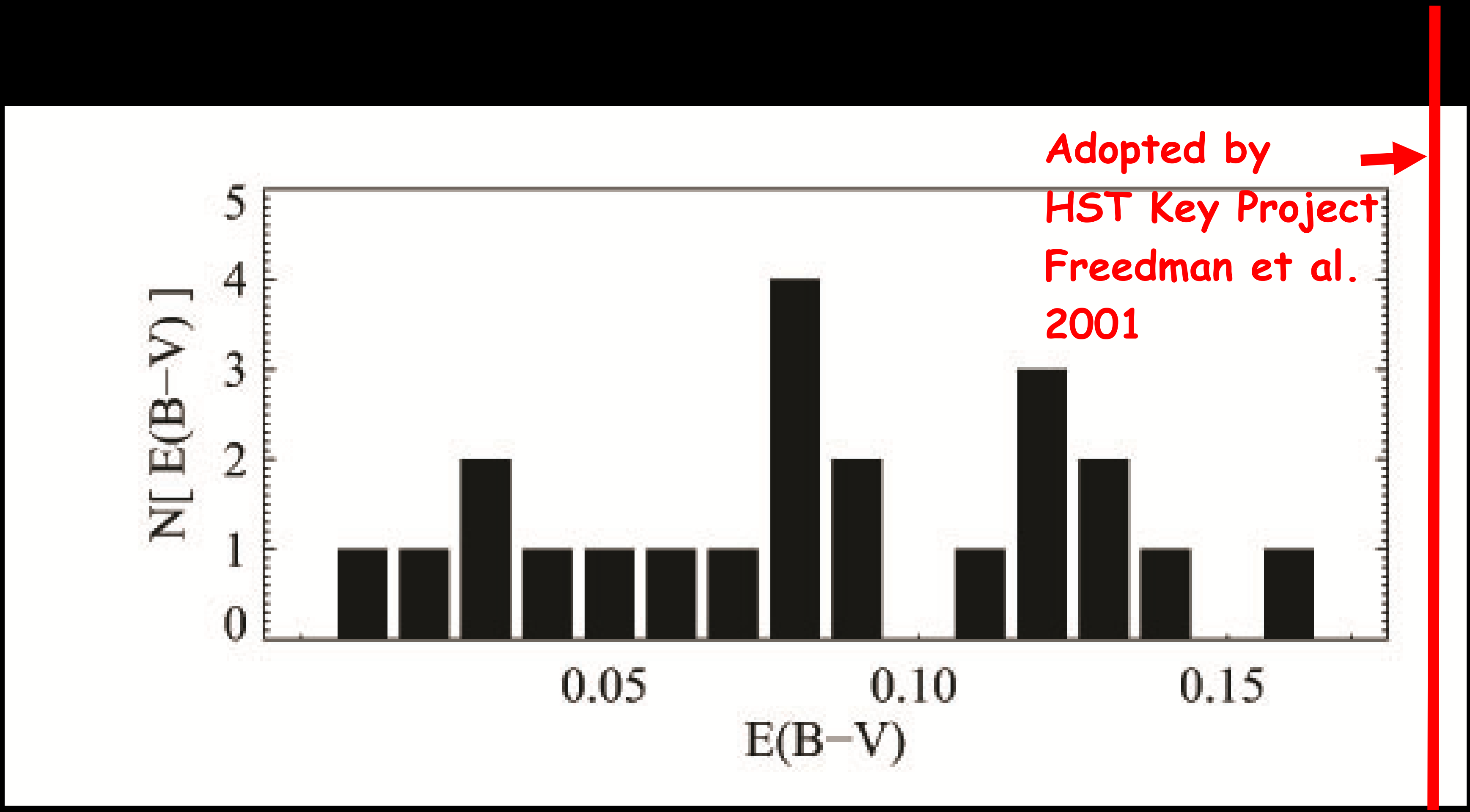

⇒ SED fit
E(B-V), $R_V$
$A_V$
extinction law

# E(B-V) distribution in NGC 300



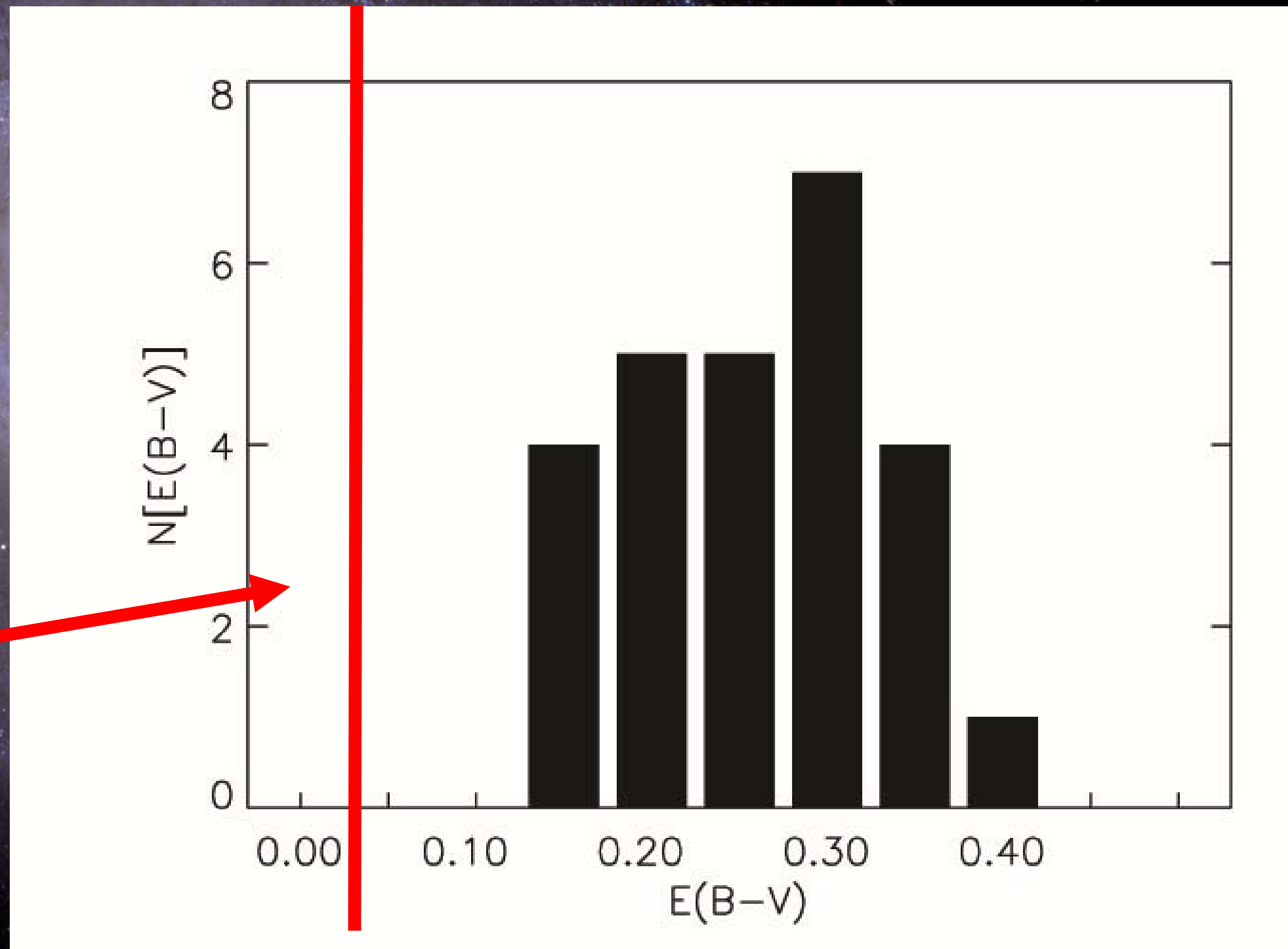

Adopted by HST Key Project Freedman et al. 2001 → Distance 15% too large

# B&A supergiants in M33 - reddening




Vivian U, Urbaneja, Kudritzki, Jacobs, Bresolin, 2009, ApJ 740, 1120

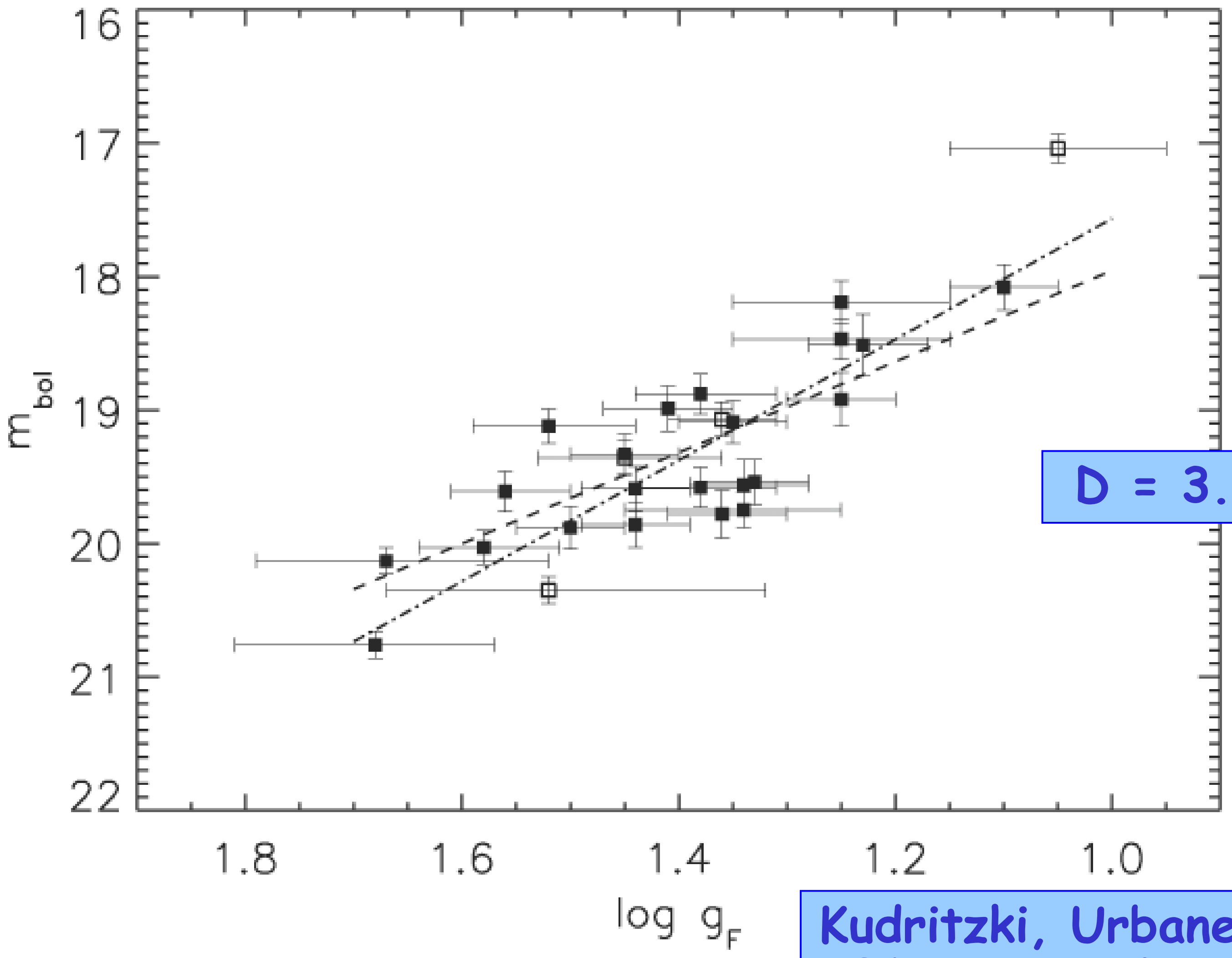
## M81 extinction




Adopted by
HST Key Project
Freedman et al.
1994
→
Distance too large

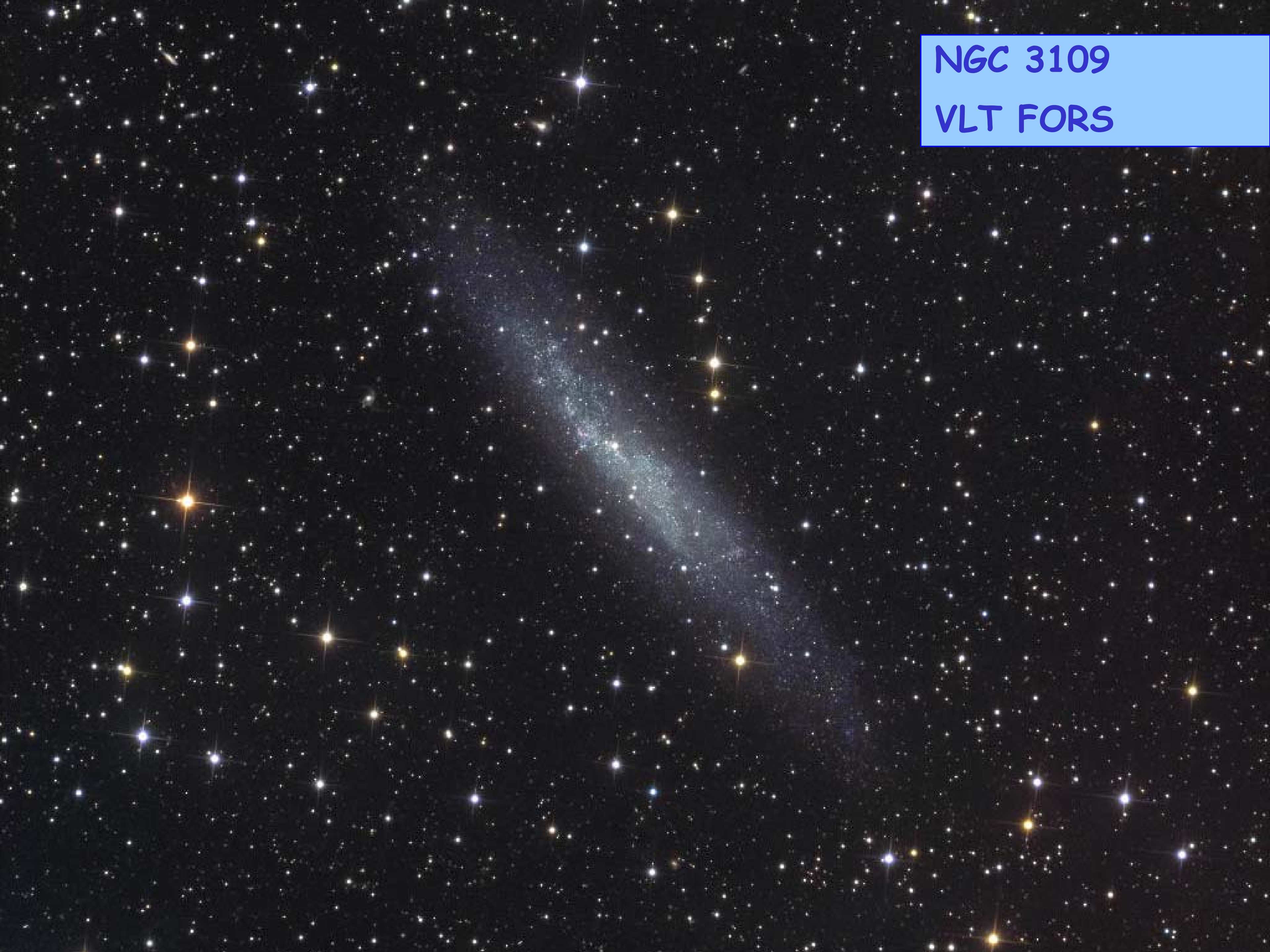
Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15

# M81 FGLR

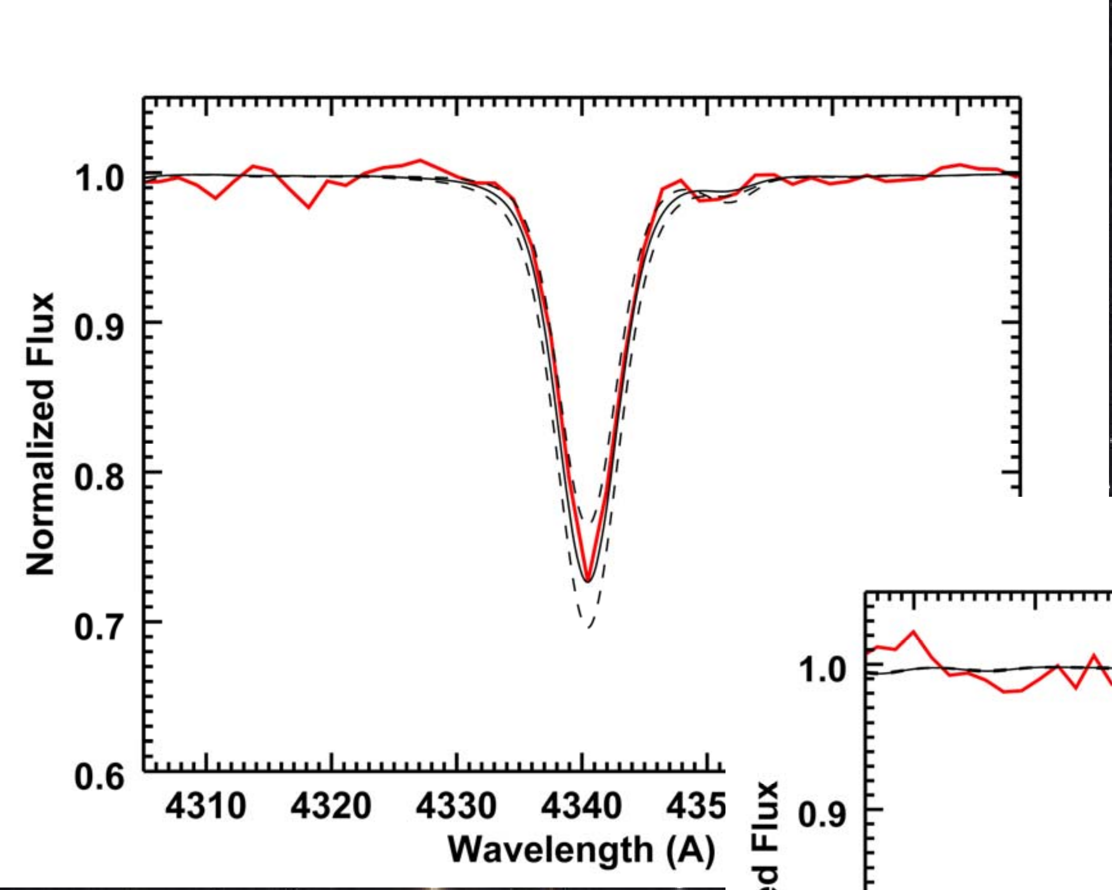


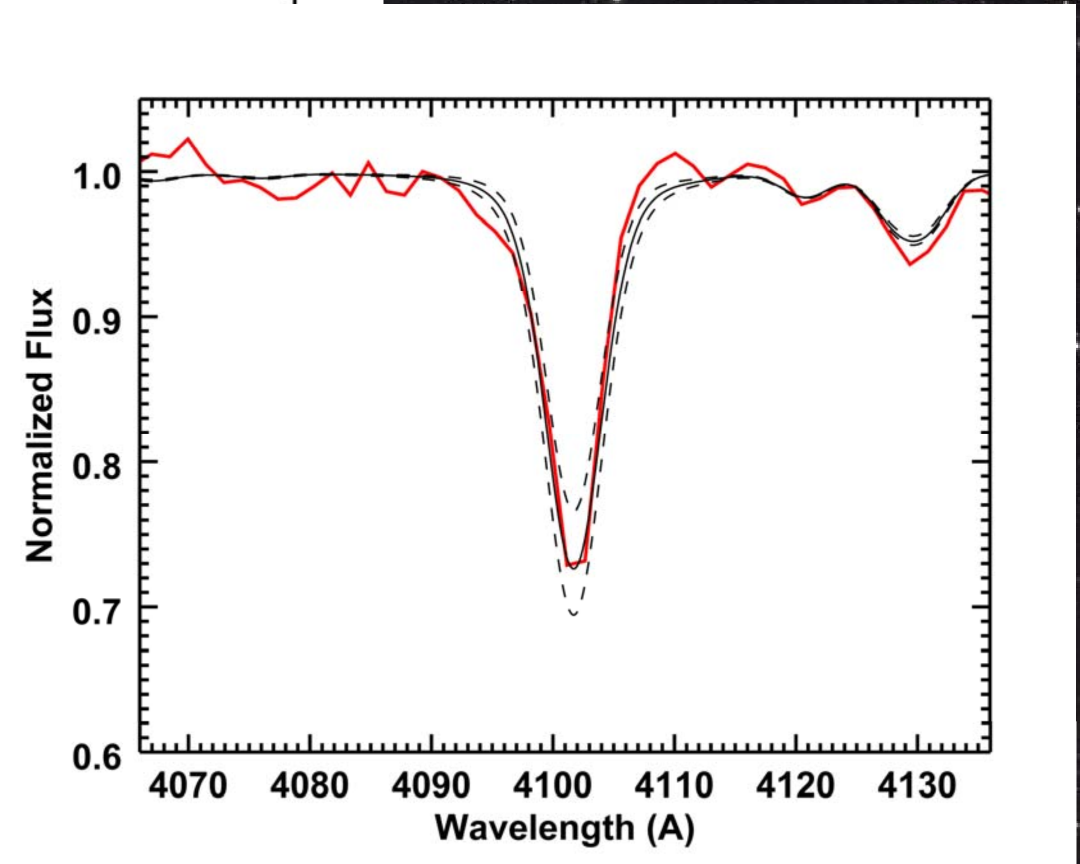

D = 3.47 ± 0.16 Mpc

Kudritzki, Urbaneja, Gazak et al.
2015, ApJ 747, 15


NGC 3109
VLT FORS

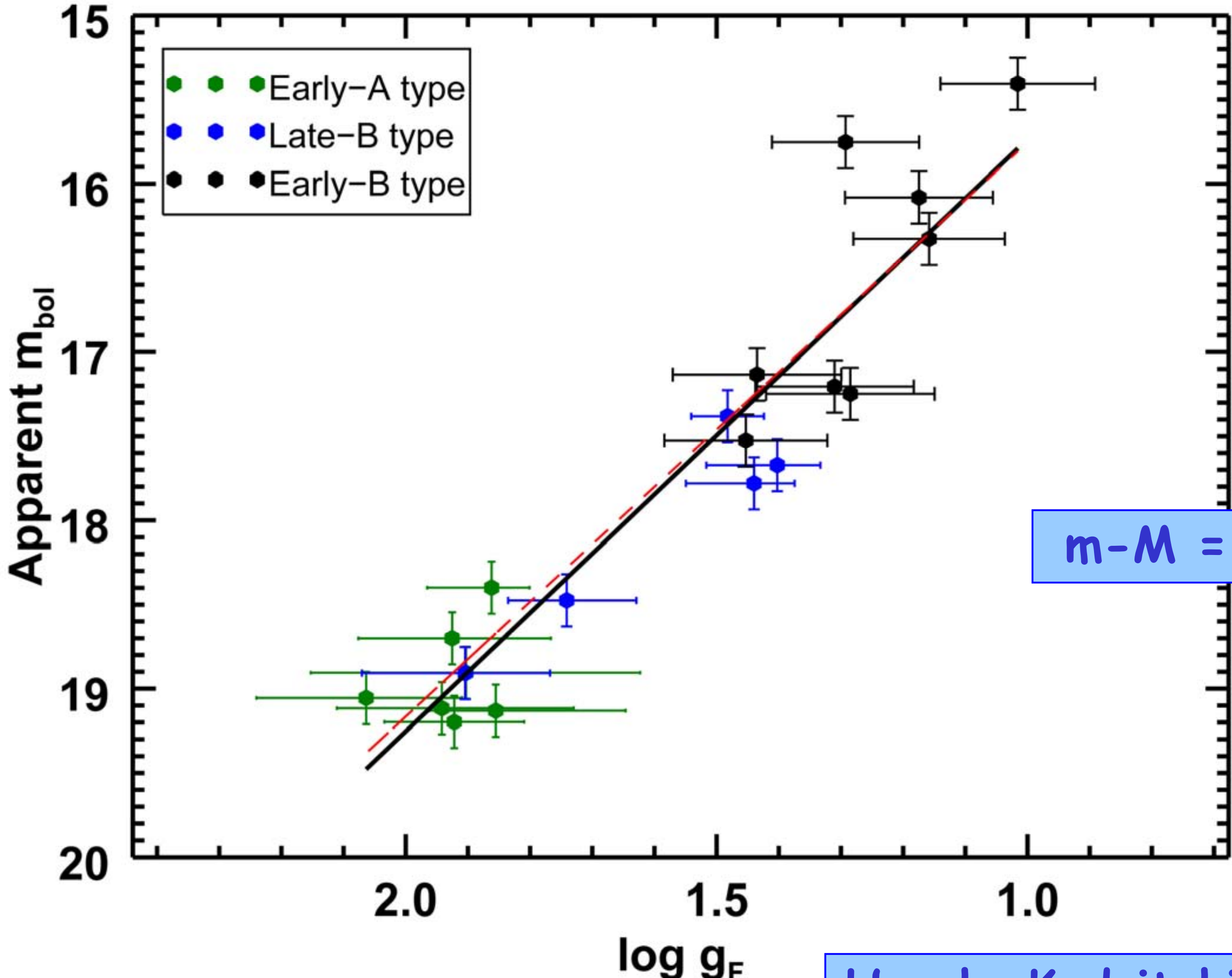
NGC2403 fit of Balmer lines




Hosek, Kudritzki, Bresolin et al., 2013, ApJ subm.

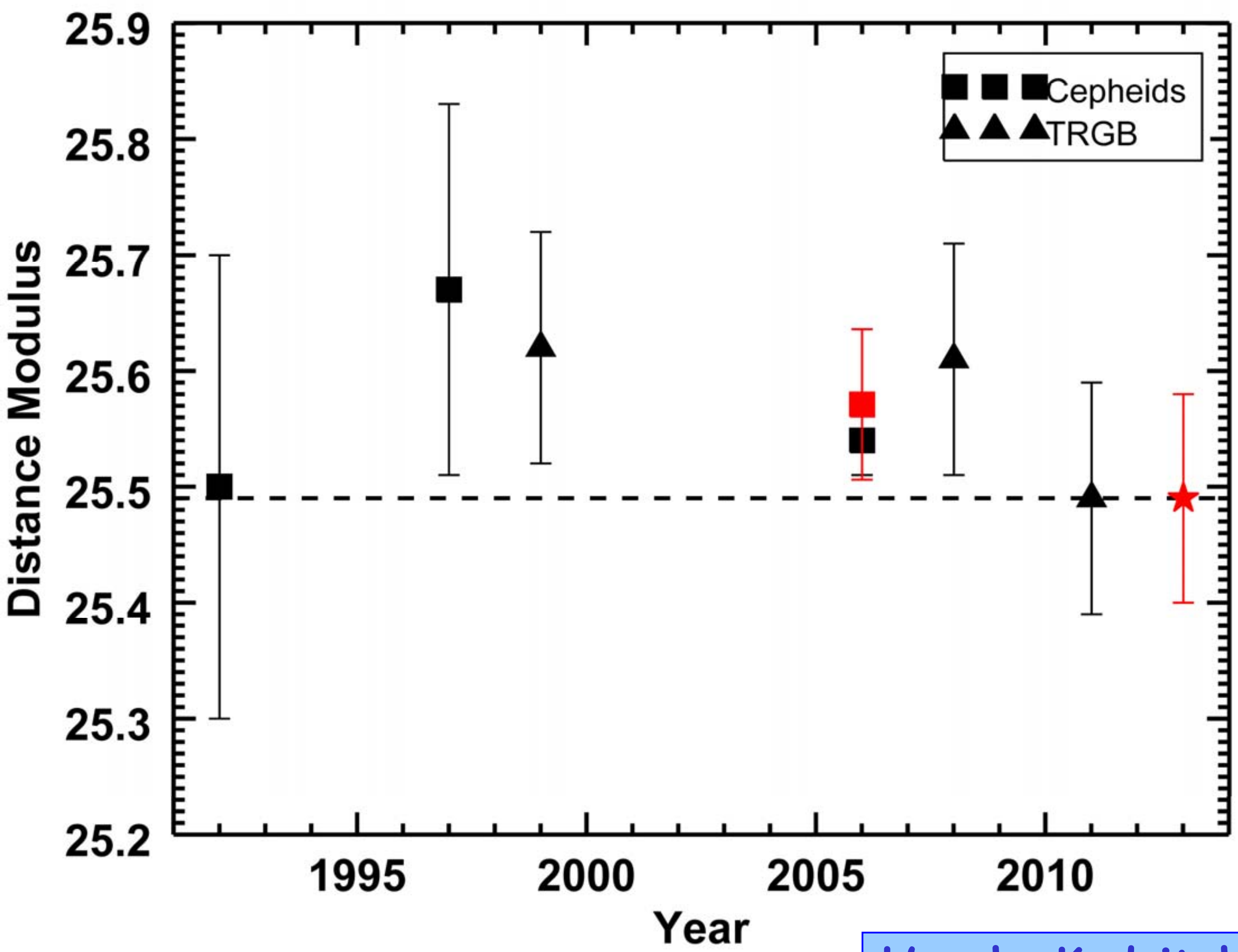
## NGC 3109 FGLR




m-M = 24.50 ± 0.09 mag

Hosek, Kudritzki, Bresolin et al., 2013, ApJ subm.

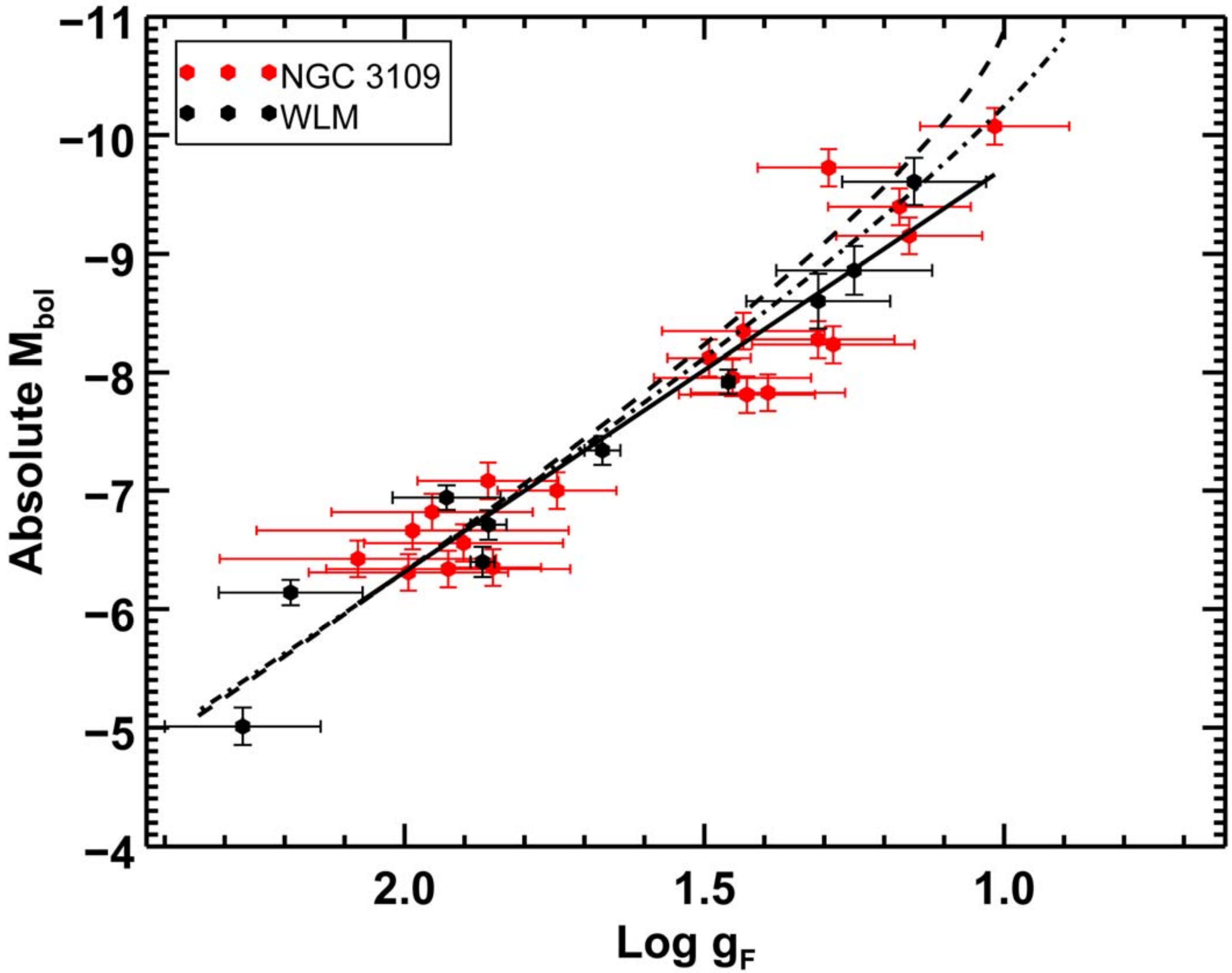
# NGC3109 distances




Hosek, Kudritzki, Bresolin et al., 2013, ApJ subm.

# NGC 3109 & WLM FGLR

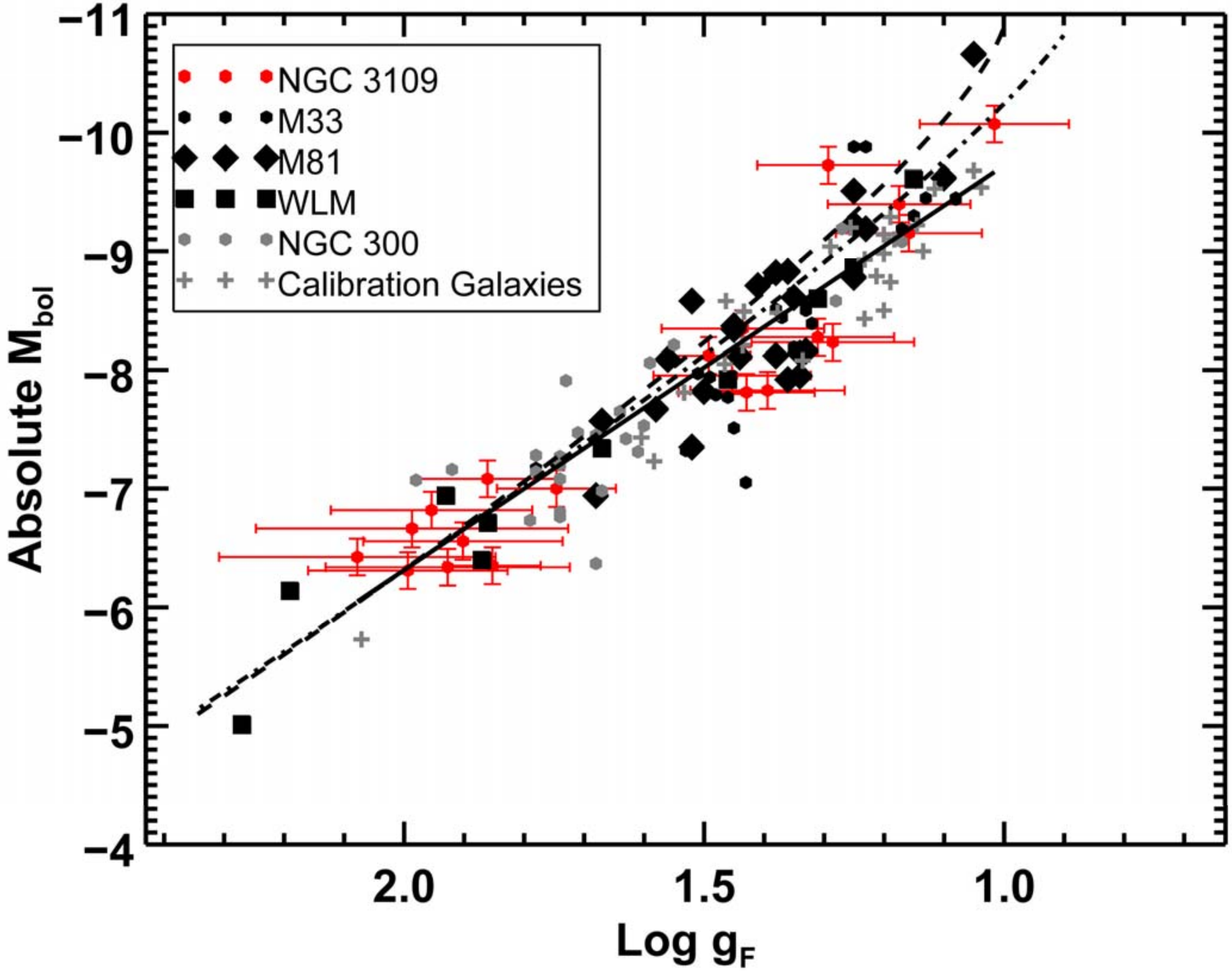
two metal poor LG galaxies




Urbaneja, Kudritzki,Bresolin et al., 2008, ApJ 684, 118

Hosek, Kudritzki, Bresolin et al., 2013, ApJ subm.

## FGLR all galaxies

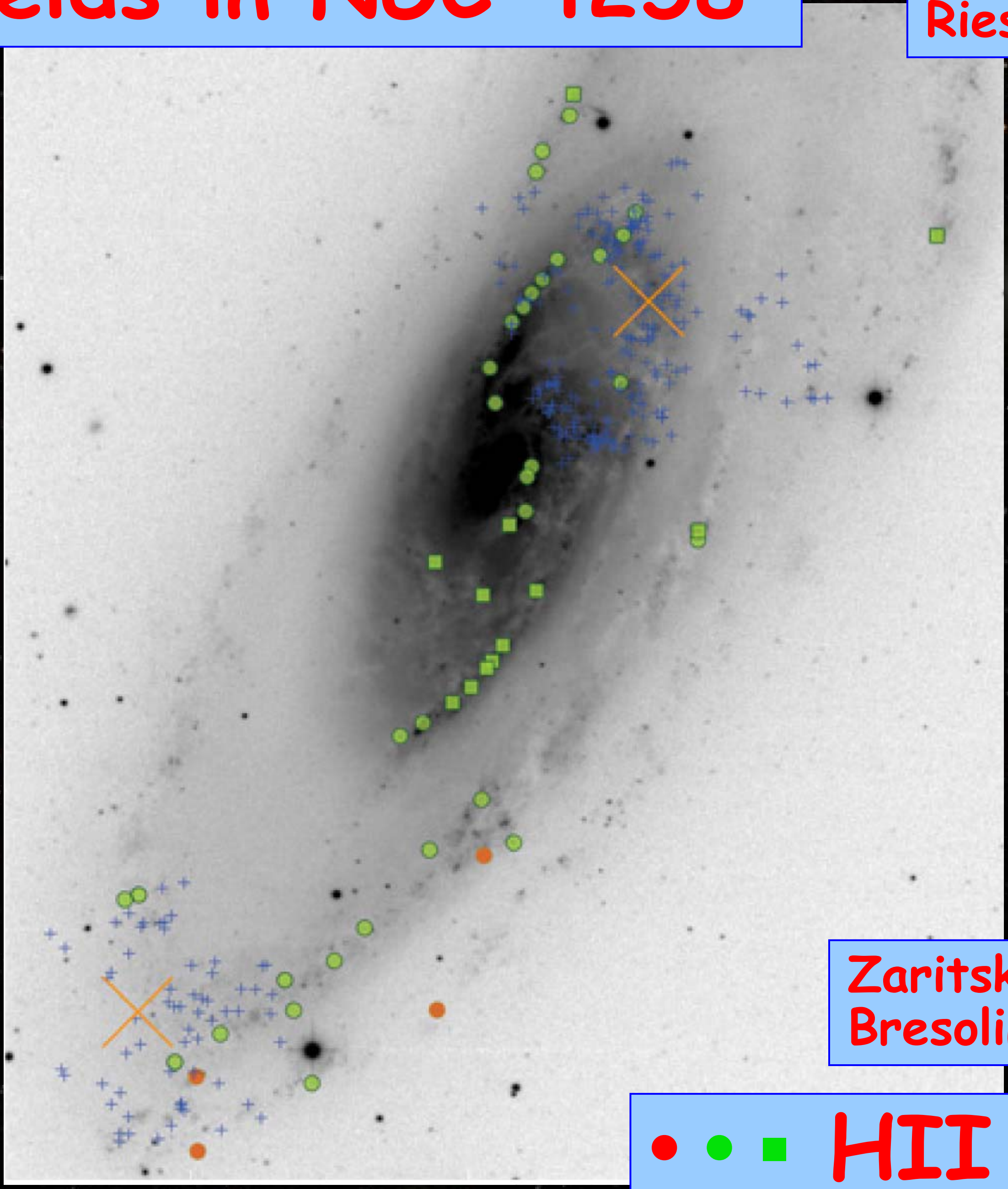



Hosek, Kudritzki, Bresolin et al., 2013, ApJ subm.


Keck LRIS
NGC 4258 7±0.2 Mpc
"Maser Galaxy"

# + Cepheids in NGC 4258

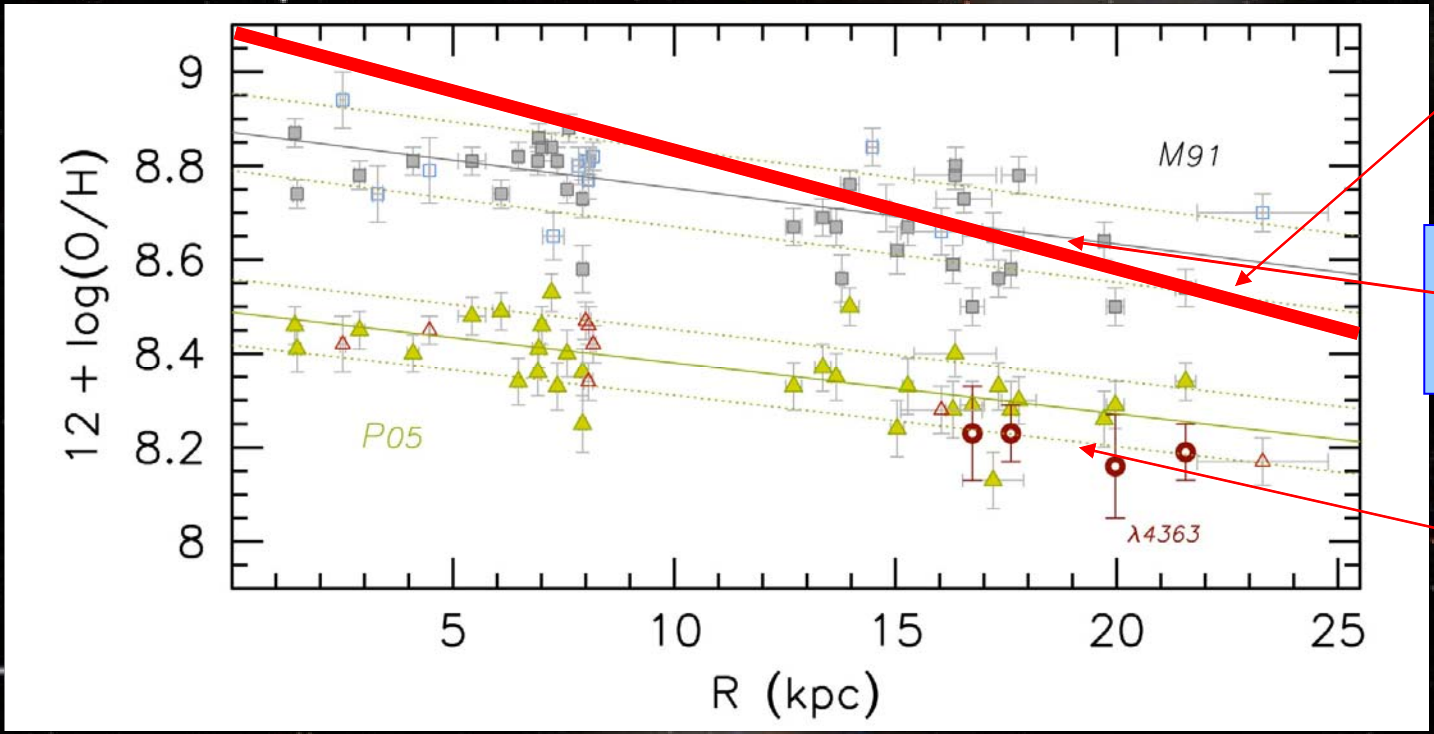
Macri et al.,2006
Riess et al., 2012



Zaritsky et al., 1994
Bresolin et al., 2011

• • ▪ HII regions

# Metallicity of NGC 4258




Zaritsky et al., 1994

strong lines

McGaugh, 1991

strong lines

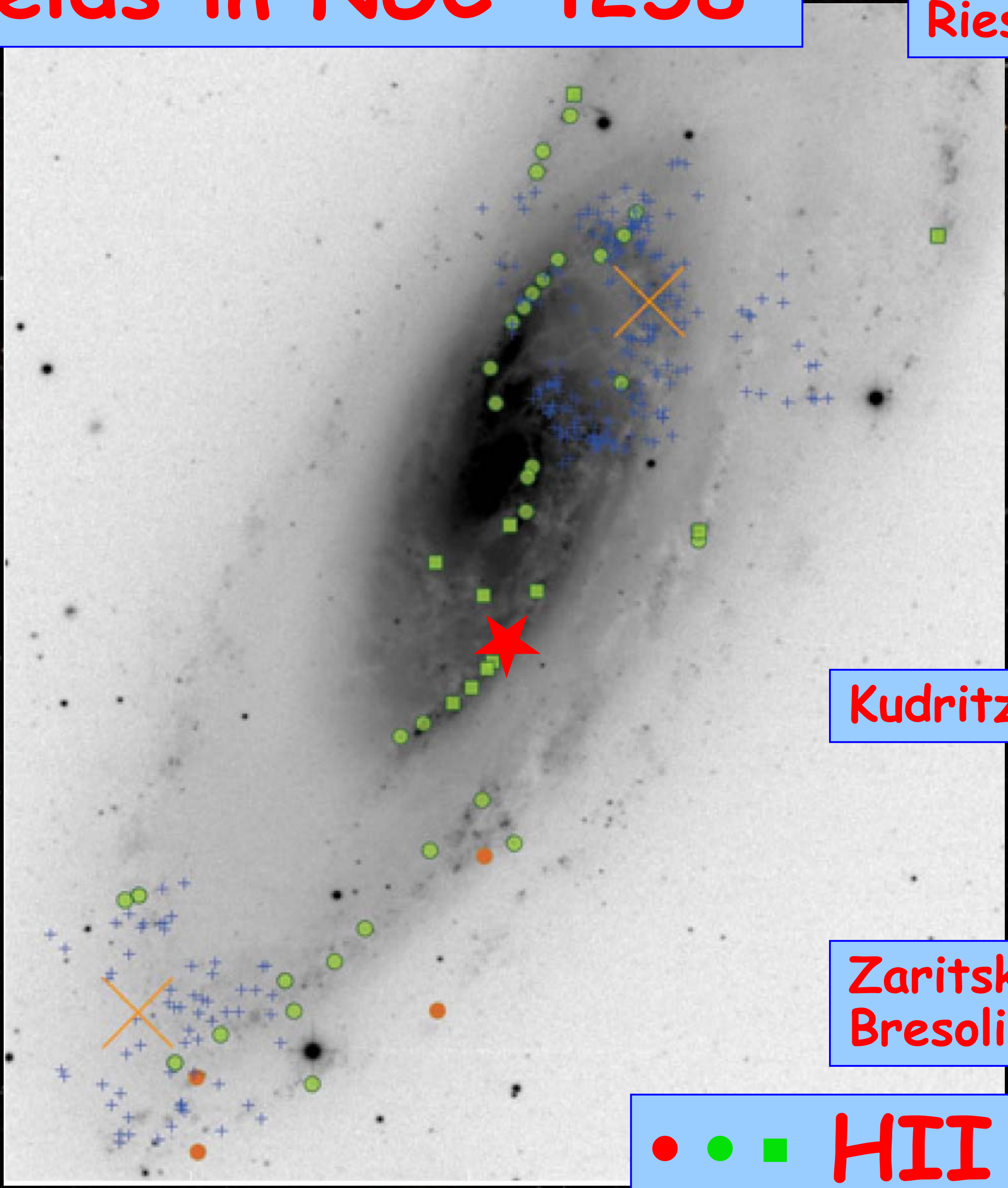
Bresolin, 2011

auroral lines


Operating at 4,200 m

# + Cepheids in NGC 4258

Macri et al.,2006
Riess et al., 2012

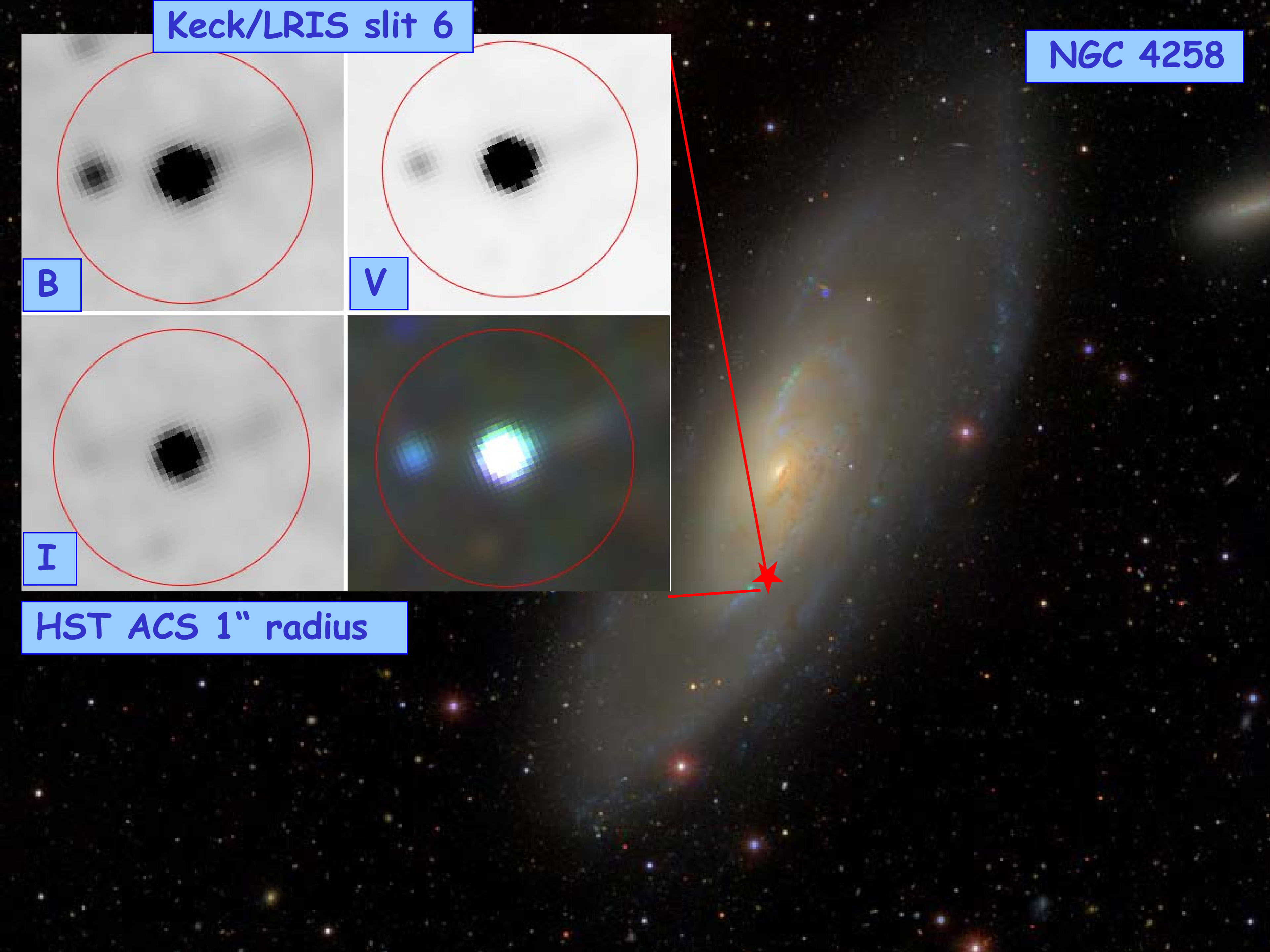


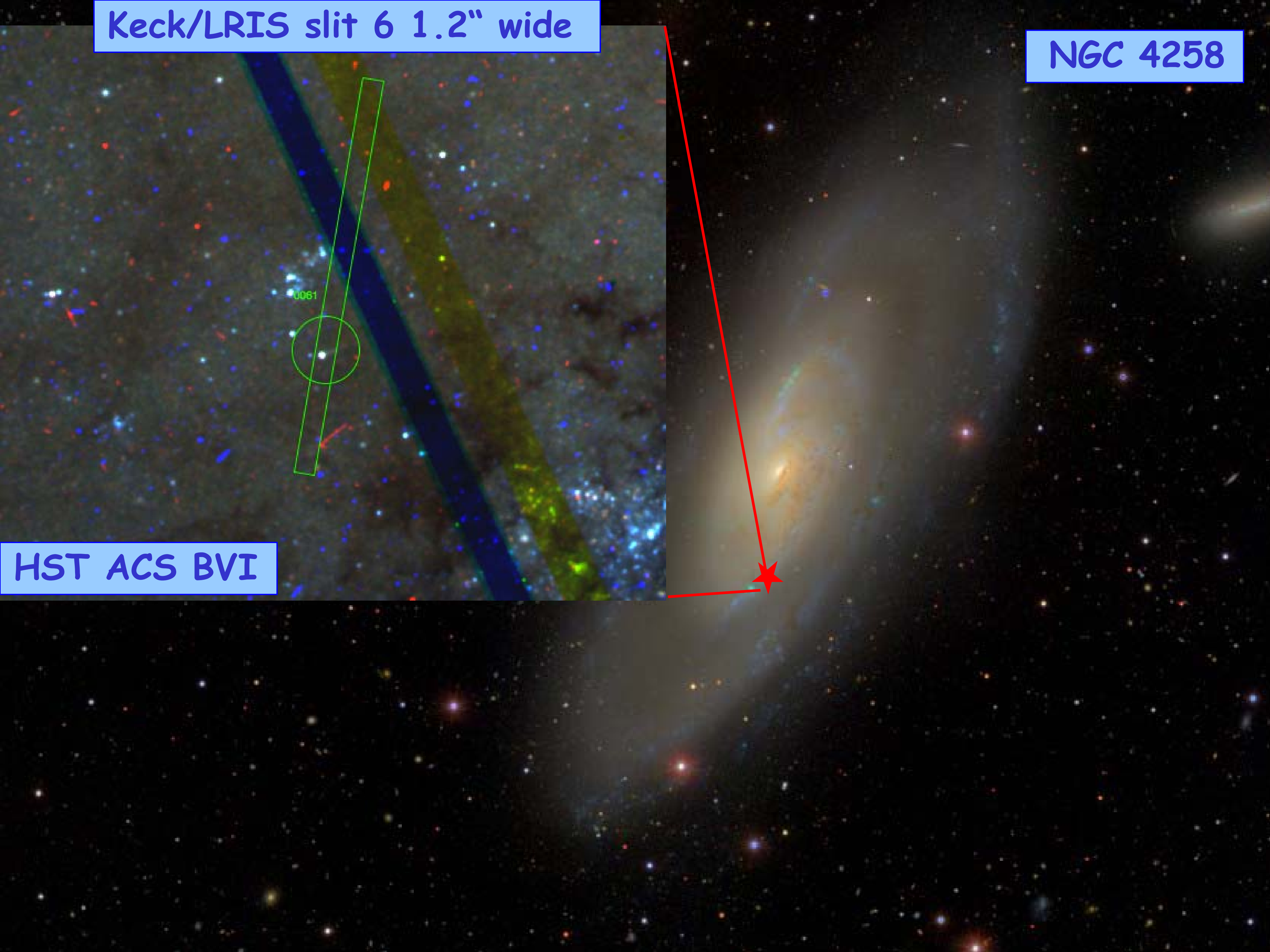
BSG

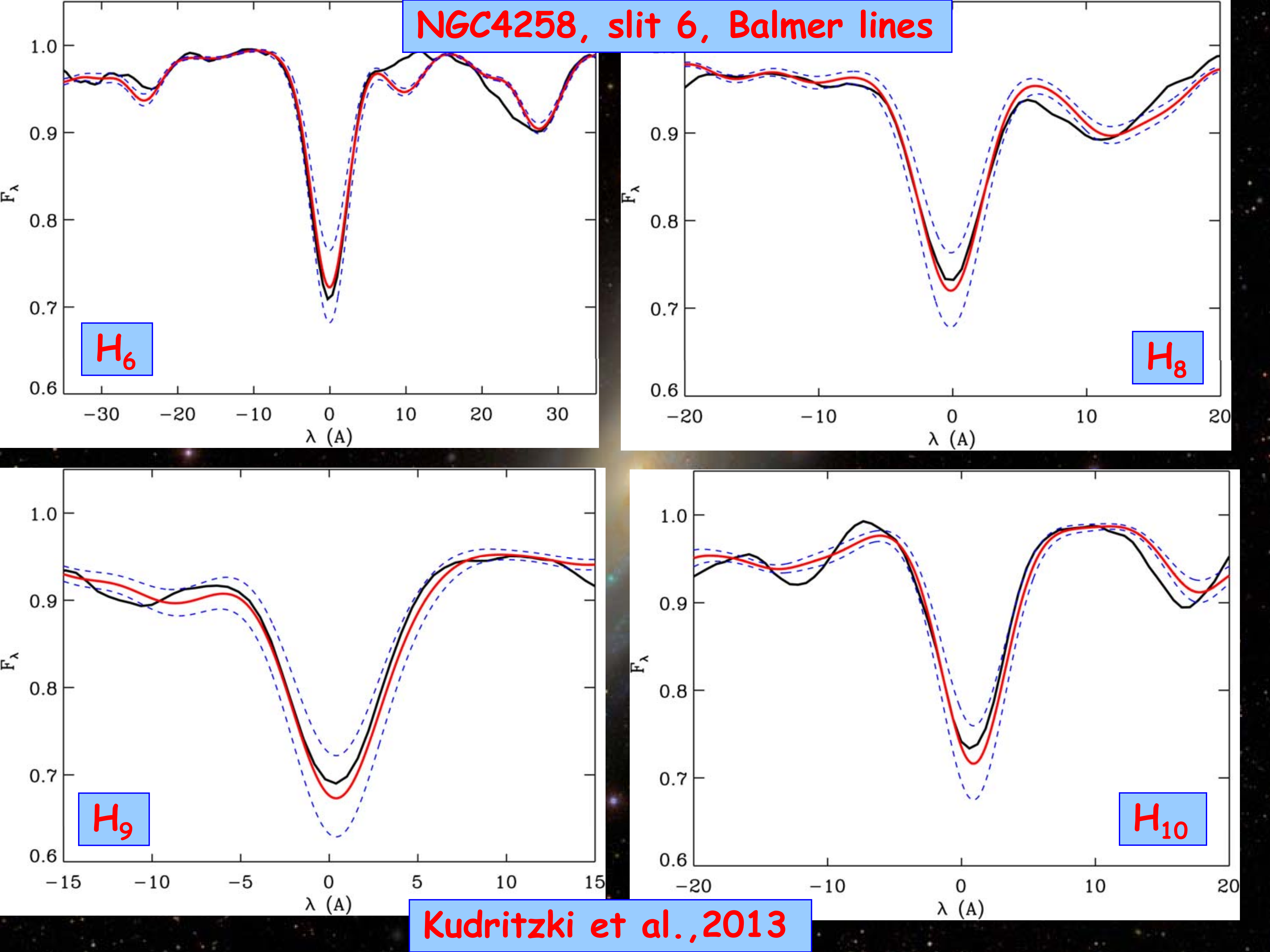
Kudritzki et al.,2013

Zaritsky et al., 1994
Bresolin et al., 2011

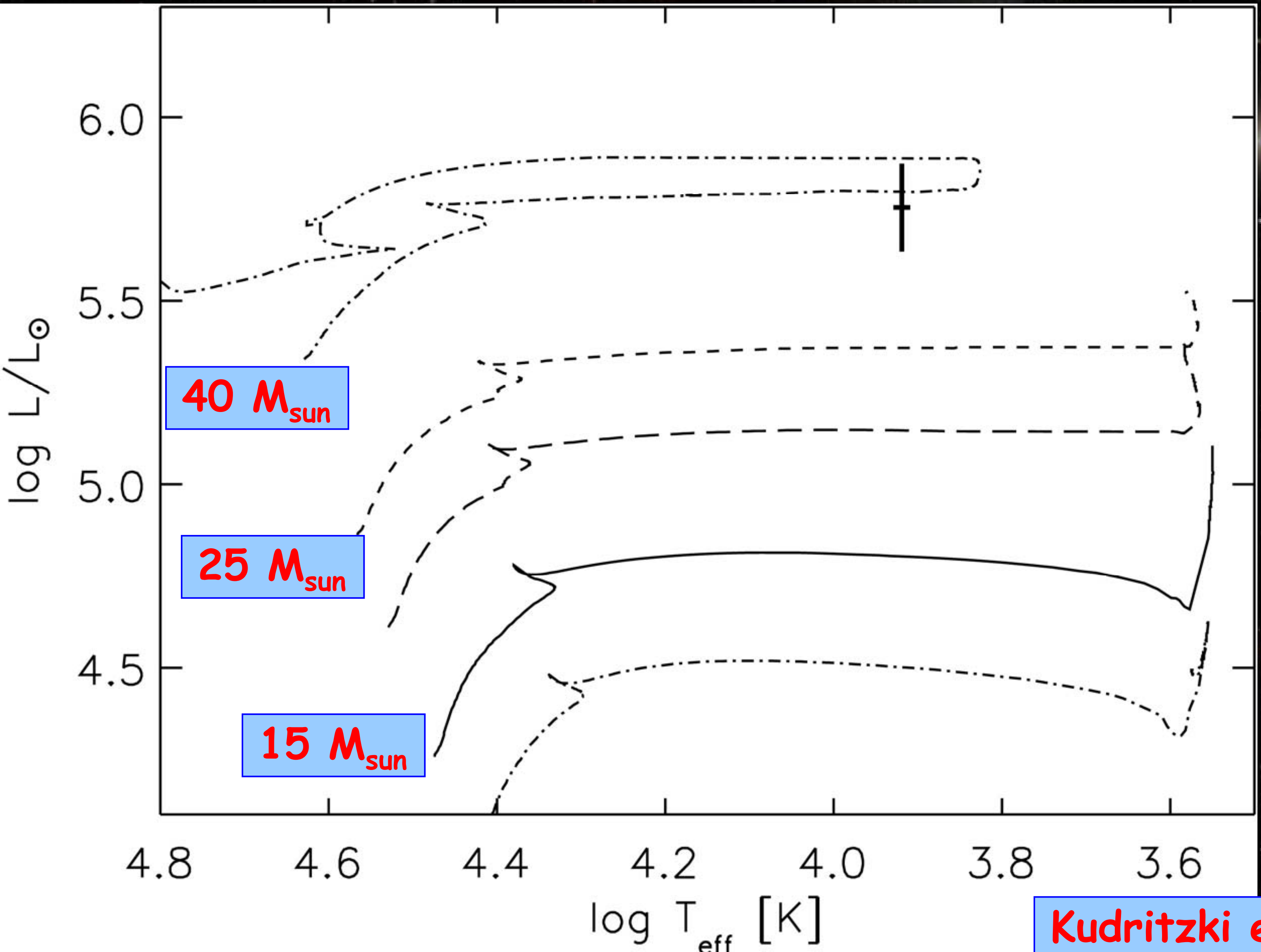
• • ▪ HII regions


Keck/LRIS slit 6
NGC 4258
B
V
I
HST ACS 1" radius


Keck/LRIS slit 6 1.2" wide
NGC 4258
HST ACS BVI

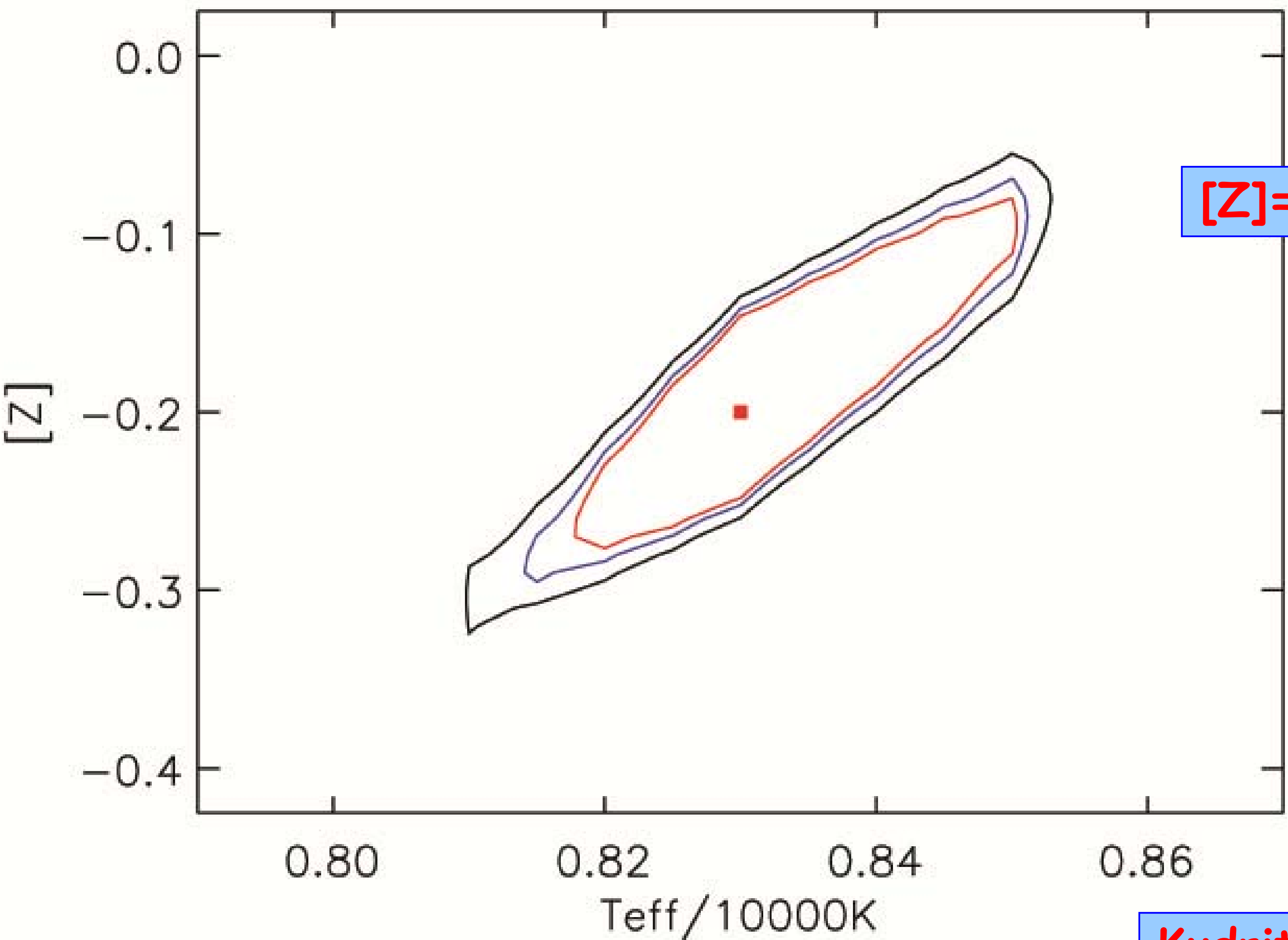

NGC4258, slit 6, Balmer lines
$H_6$
$H_8$
$H_9$
$H_{10}$
$F_\lambda$
λ (A)
Kudritzki et al.,2013

# HRD




Kudritzki et al.,2013

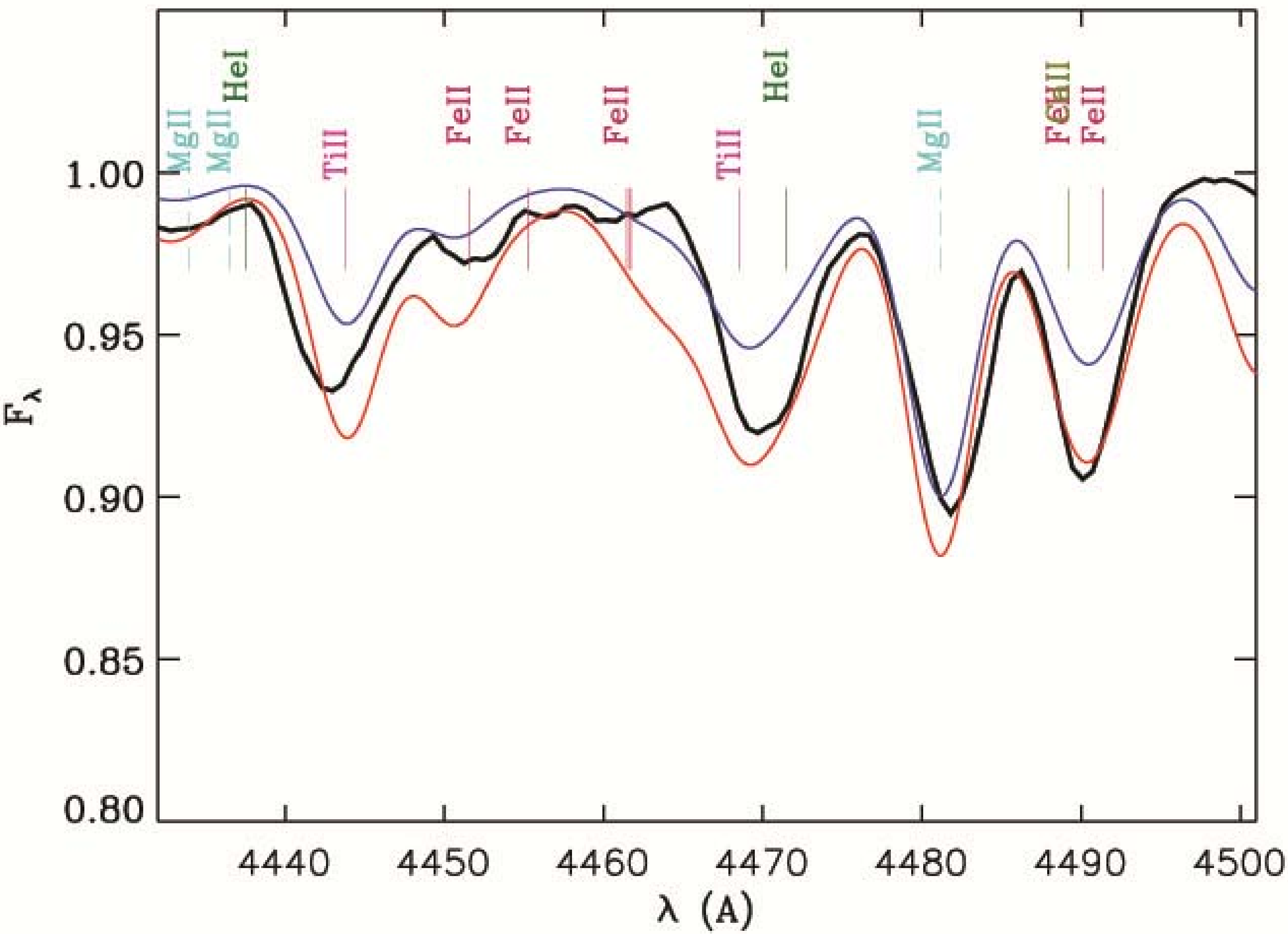
# stellar metallicity



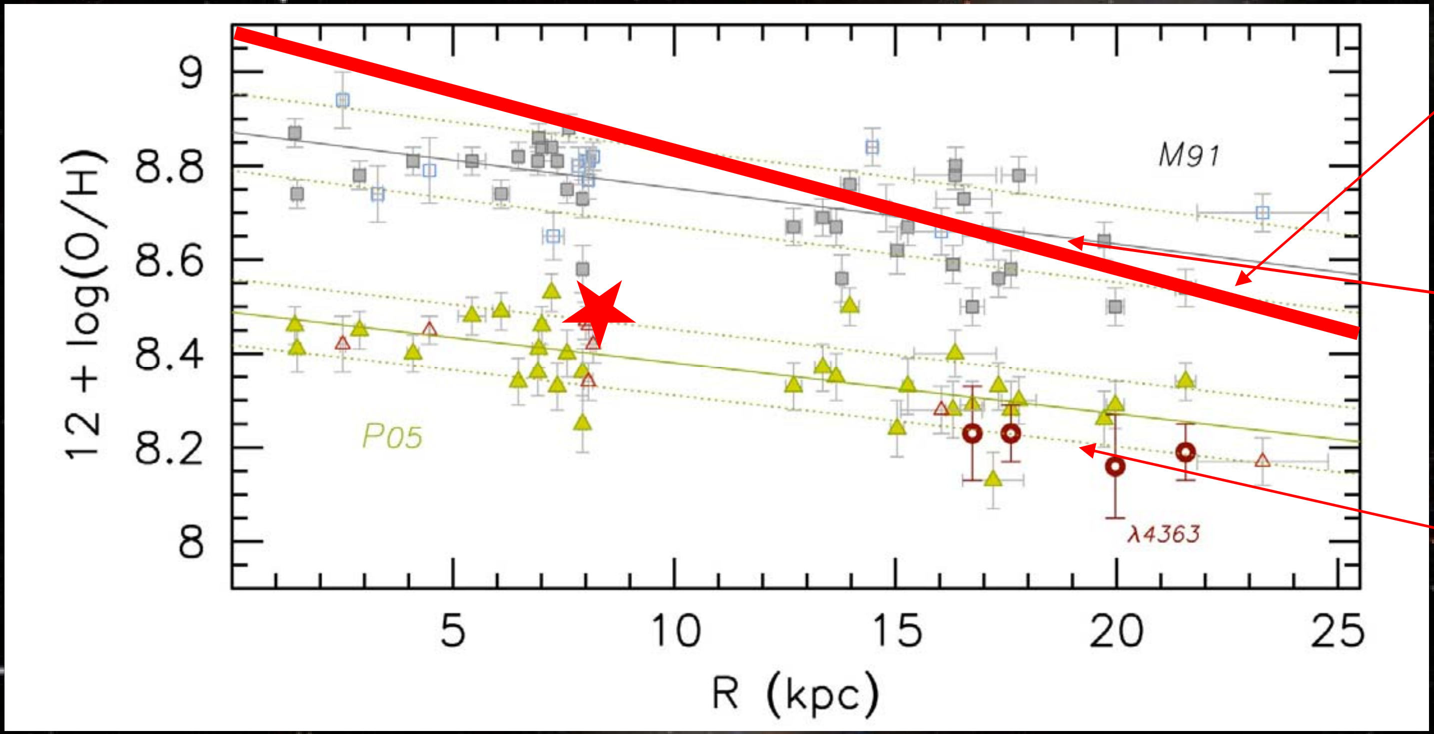

[Z]=-0.20±0.12

Kudritzki et al.,2013

# stellar metallicity



# Metallicity of NGC 4258




Zaritsky et al., 1994

strong lines

McGaugh, 1991

strong lines

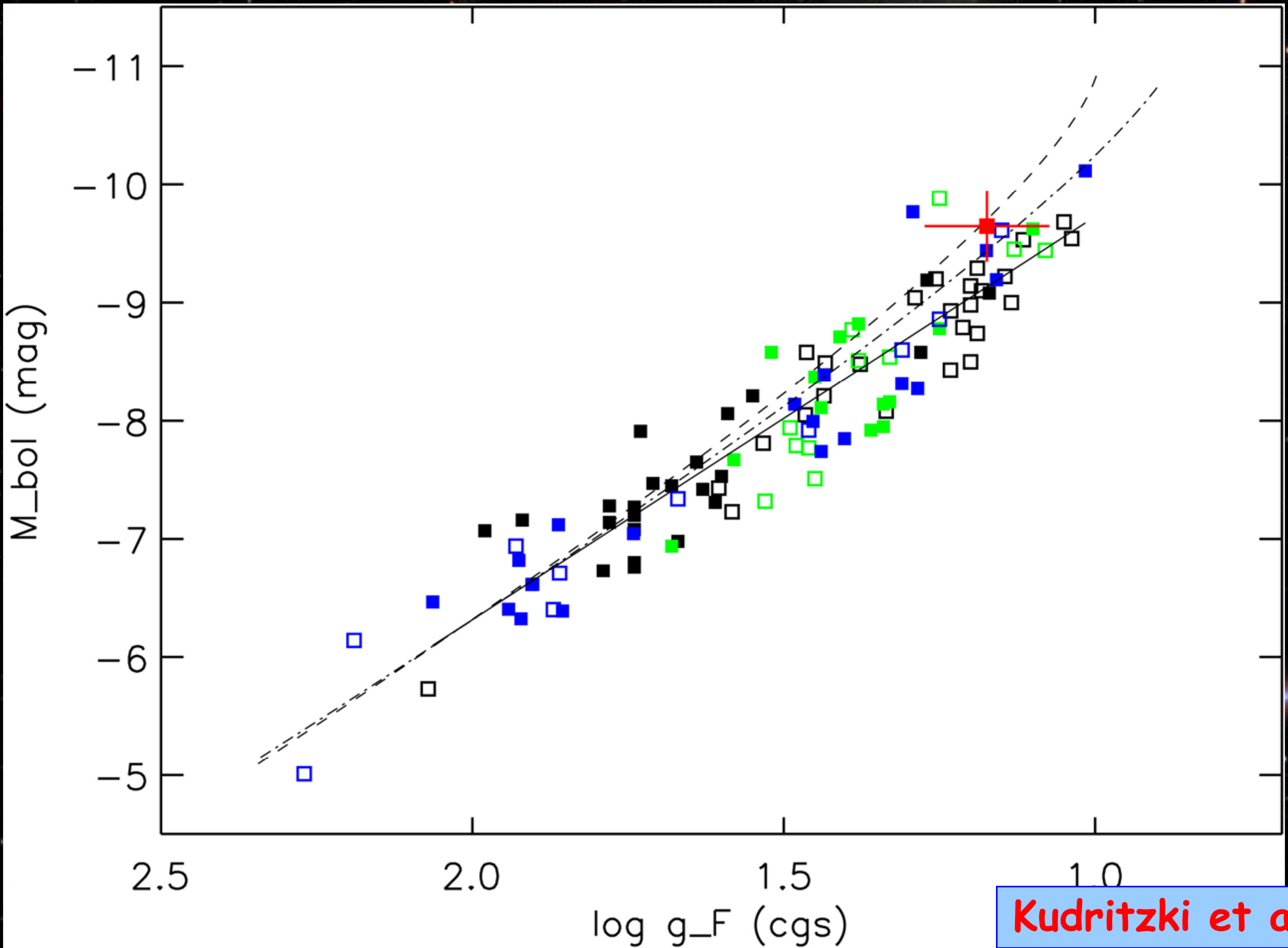
Bresolin, 2011

auroral lines

★ BSG in NGC 4258

Kudritzki et al.,2013

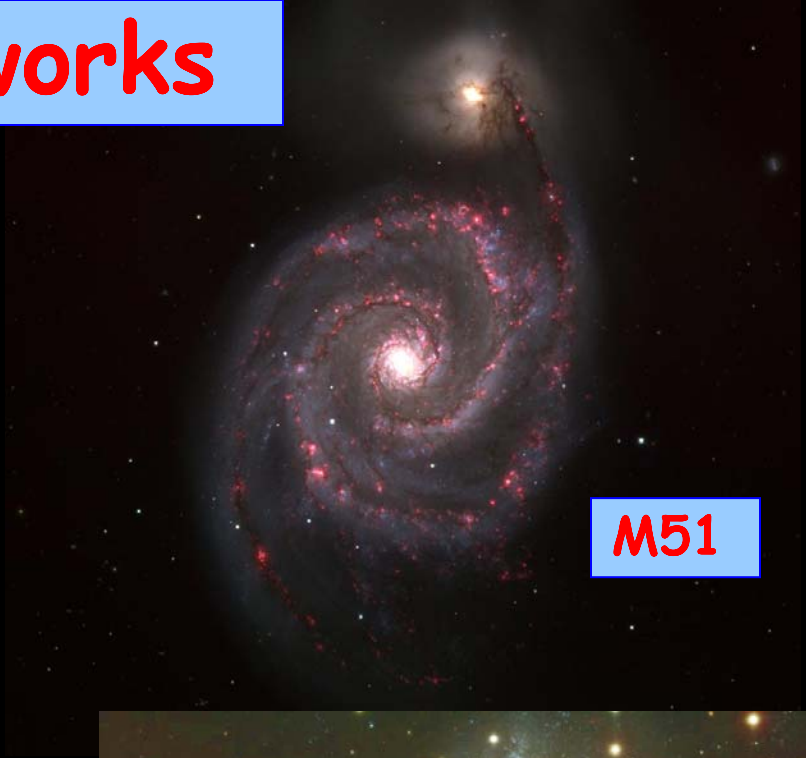
# FGLR of NGC 4258 BSG




Kudritzki et al.,2013

# galaxies in the works


NGC2403


M51


M83


NGC3621

# BSGs and TMT/ELT perspectives

WFOS → quantitative spectroscopy
possible down to $m_V \sim 24.5$ mag

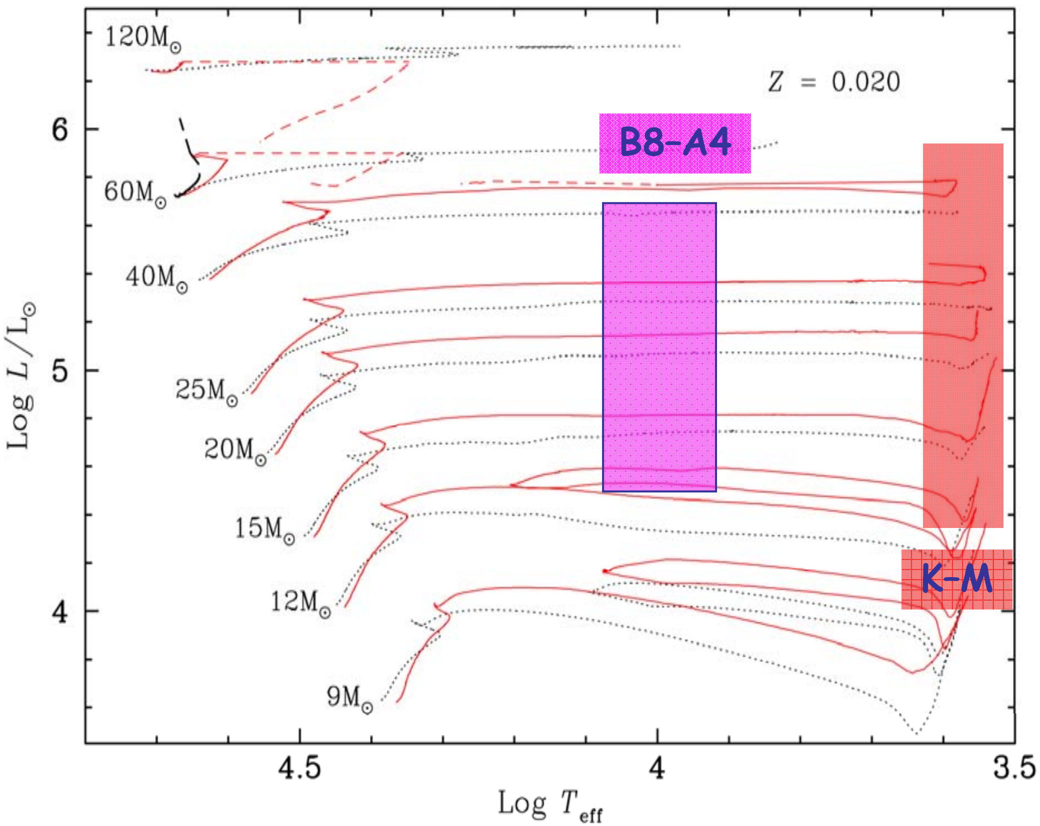
→ with objects $M_V \leq -8$ mag

$m - M \sim 32.5$ mag ~ 30 Mpc possible

chemical evolution studies
SF
ISM, extinction, extinction laws
distances
10 objects per galaxy
→ $\Delta(m-M) \sim 0.1$ mag

# Alternative method: red supergiants

**Brightest stars at infrared light: $-8 \geq M_J \geq -11$ mag**




Advantage: AO supported
MOS possible

Problems at H- and K-band:
forest of molecular lines
→high res. spectra needed

→ even with E-ELT no chance beyond Local Group

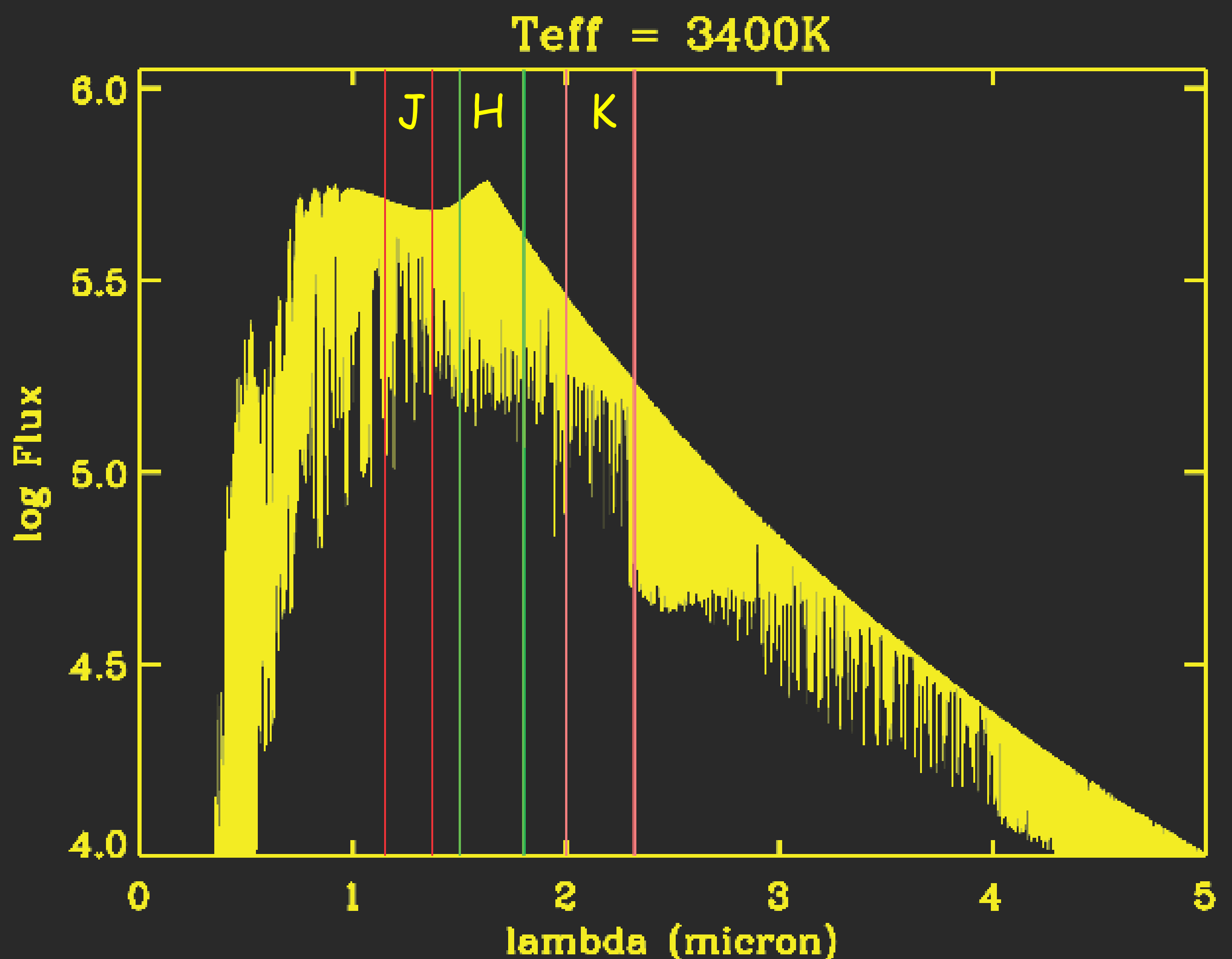
Advantage of J-band:
atomic lines dominate
→medium res. spectra ok

→ enormous potential with Keck/VLT, TMT/E-ELT beyond Local Group

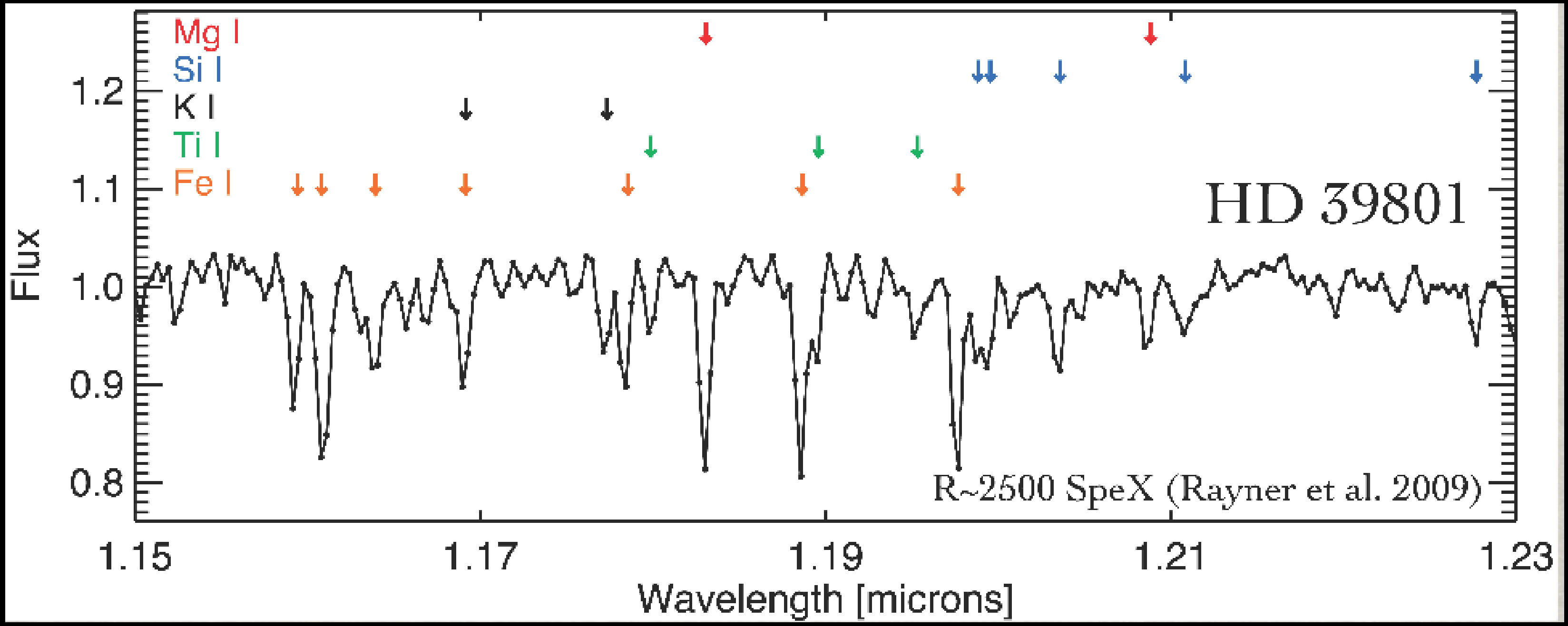
# RSG – SED: $T_{eff}$ = 3400K

*IfA 2012*

MARCS model atmosphere, Gustafsson et al., 2008; Plez, 2011



# RSG: low res J-band spectrum

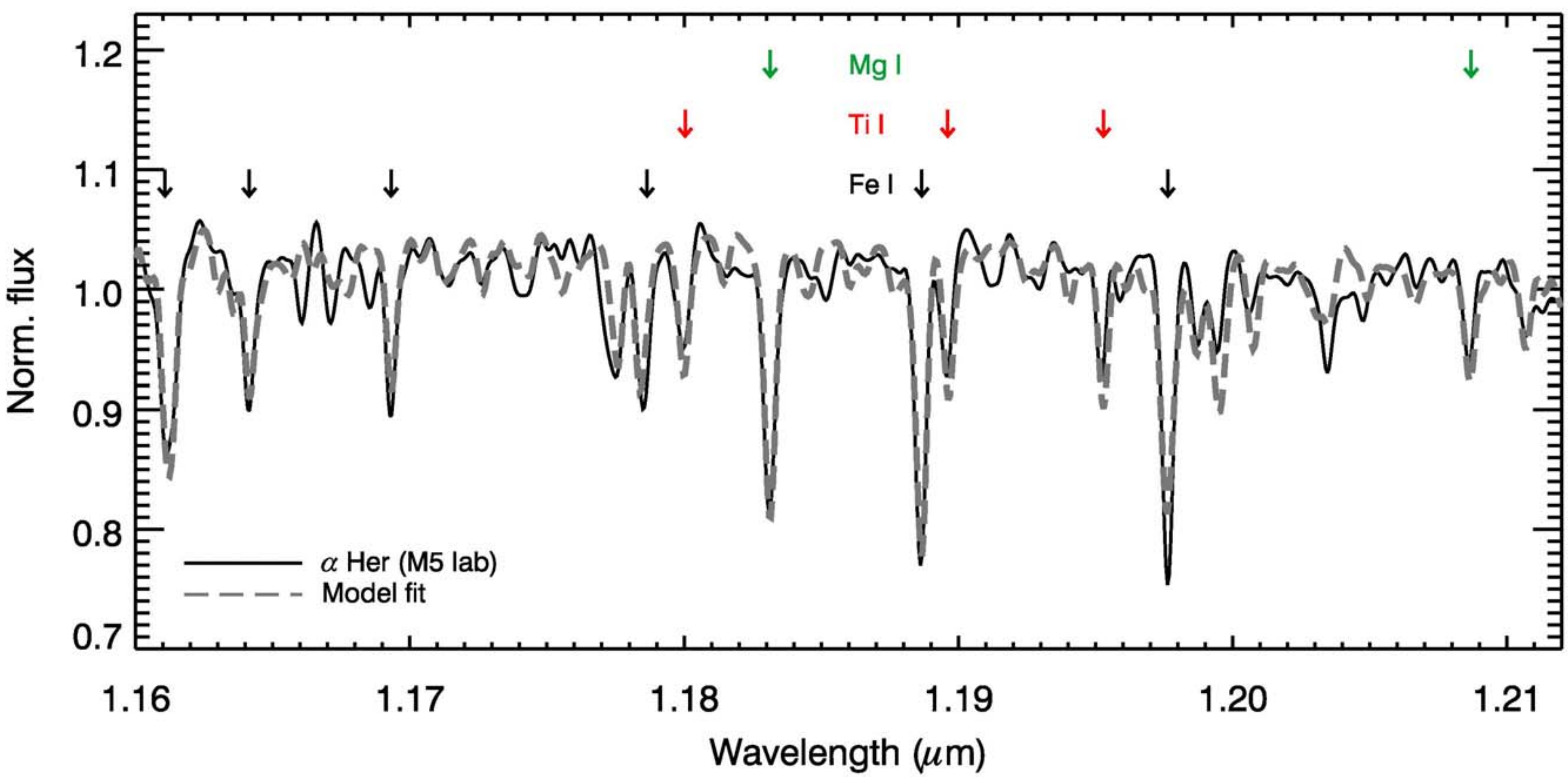



Mauna Kea
IRTF/SpeX

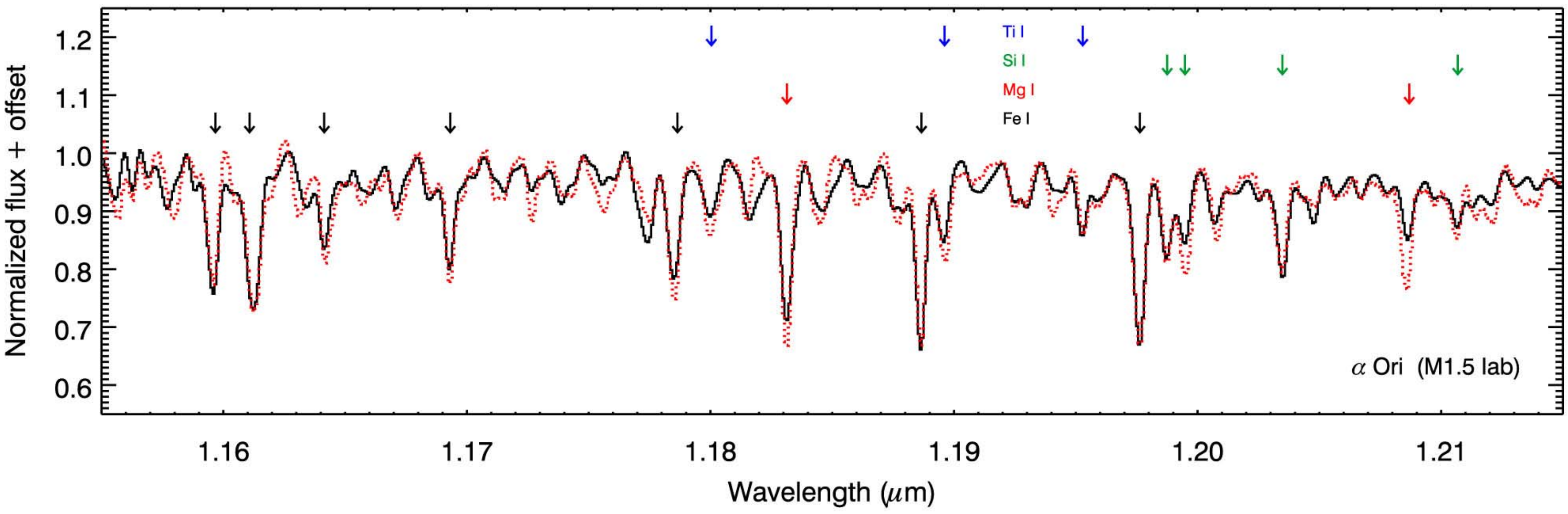

IRTF

# α Her

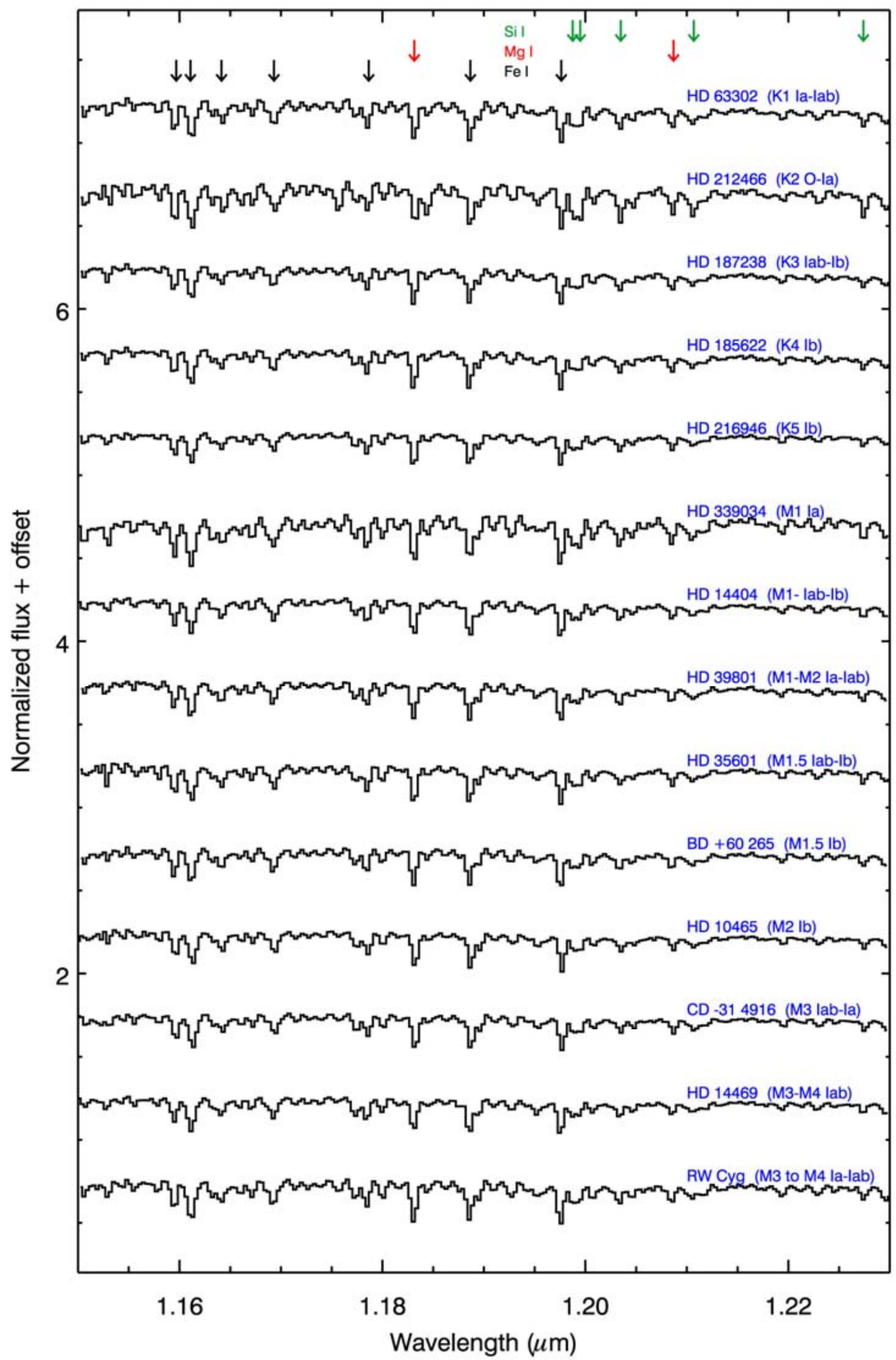
Davies, Kudritzki, Figer, 2010
MNRAS, 407,1203



# α Ori




Davies, Kudritzki, Figer, 2010
MNRAS, 407,1203




SPEX, R=2500

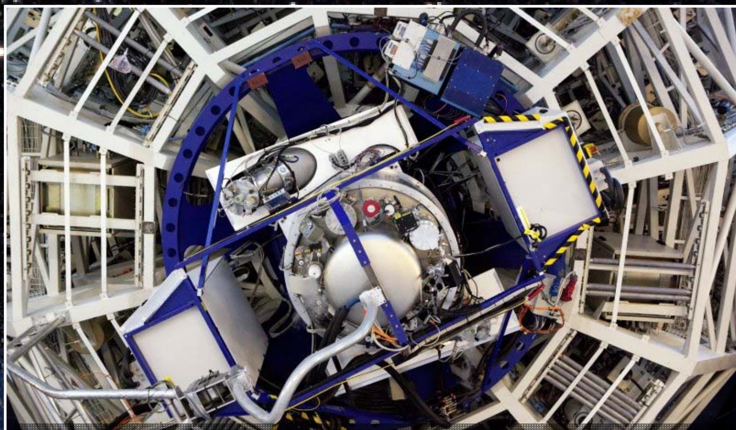
Apply Kudritzki et al.2008 low resolution technique

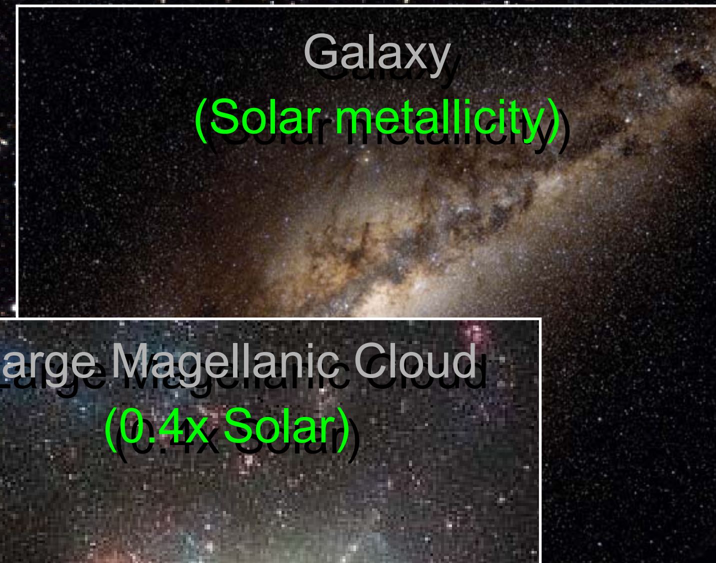
$T_{eff}$ accurate to ± 150 K

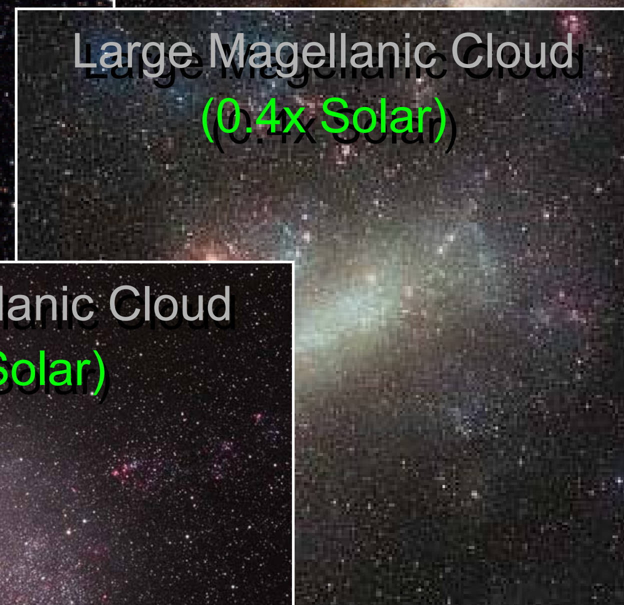
Log Z ± 0.15 dex

Davies, Kudritzki, Figer, 2010
MNRAS, 407,1203

# Road-testing phase

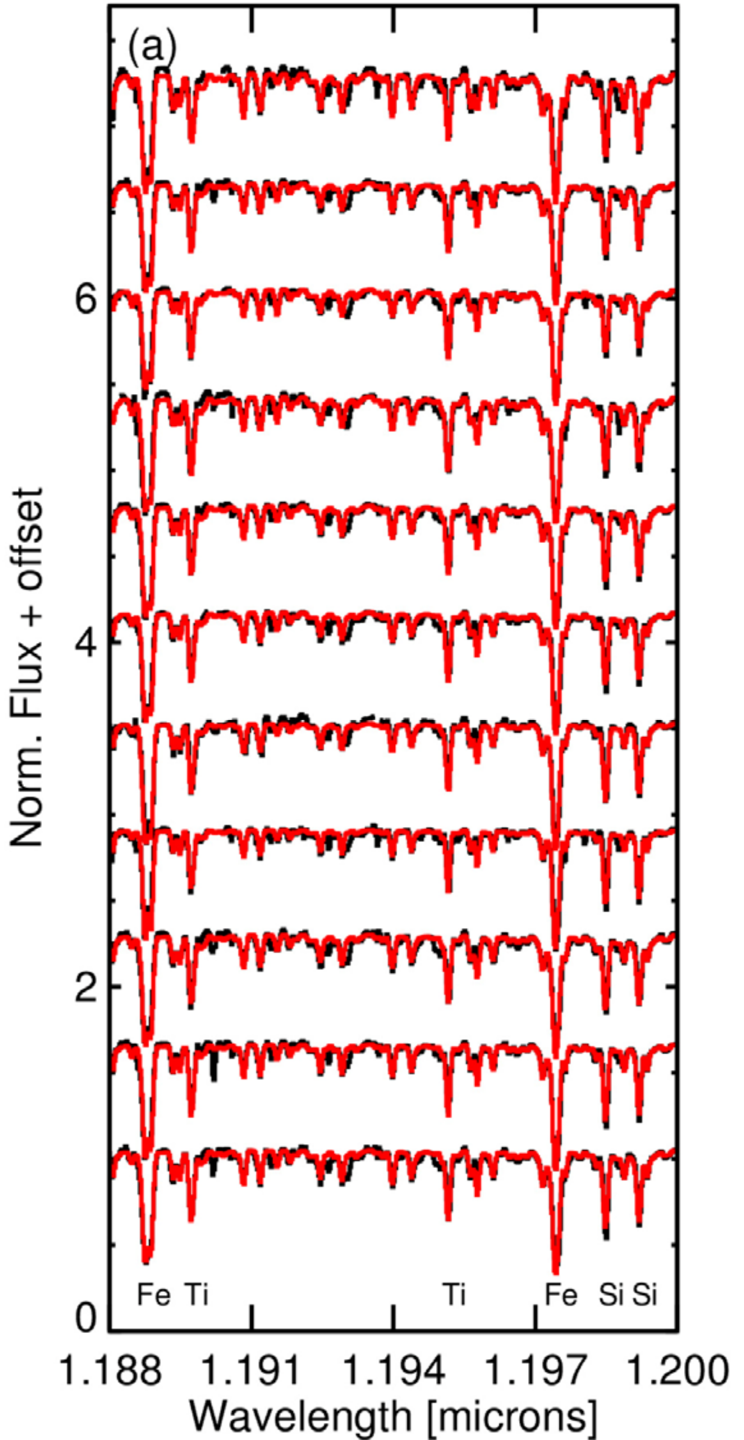

XSHOOTER (VLT instrument)





Per OB-1
20+ RSGs




# Per OB-1

## Spectral fits

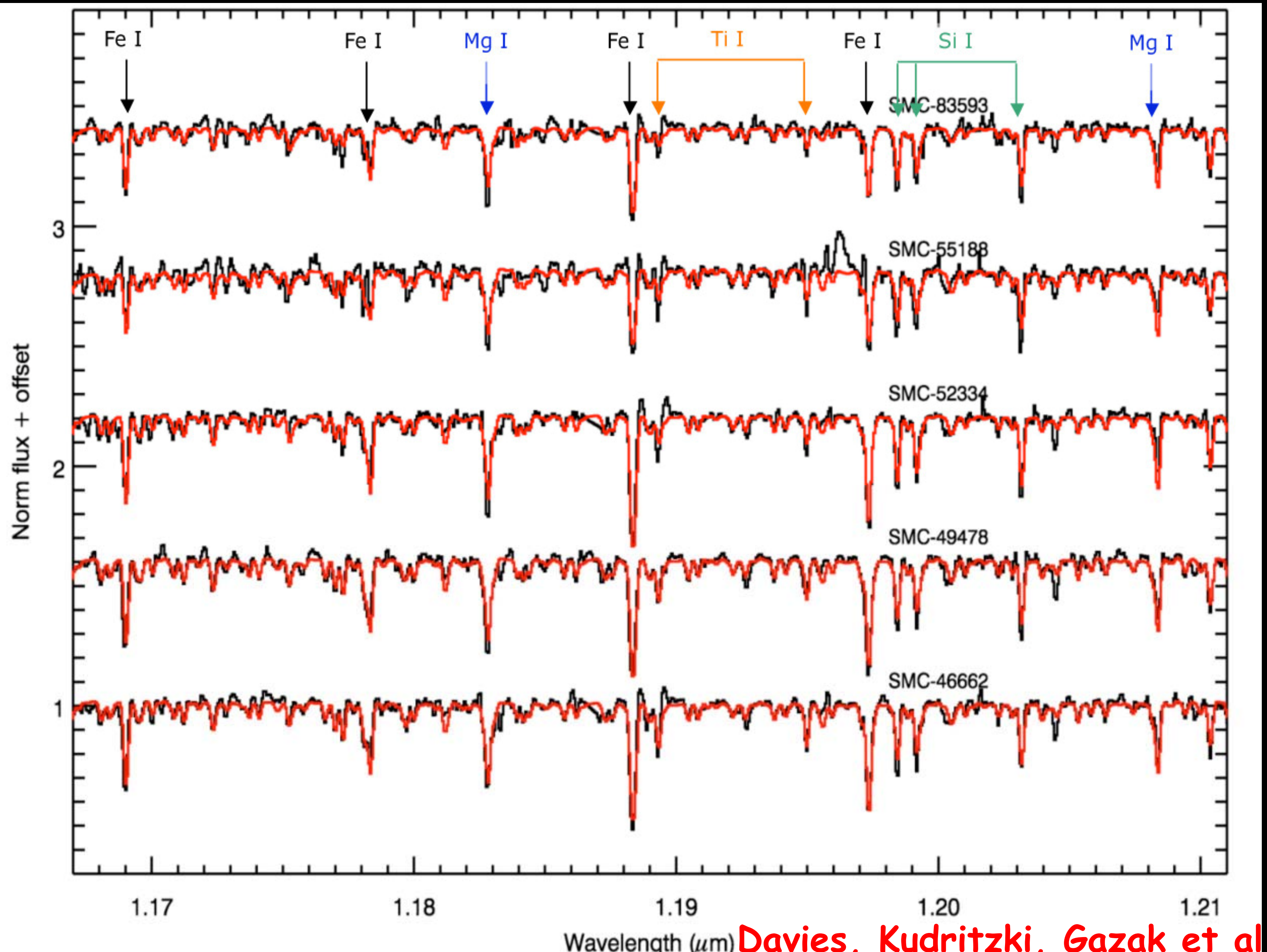
→ [Z]=-0.1±0.1

## Subaru/IRCS

Gazak, Davies, Kudritzki et al., 2013

# SMC → [Z]=-0.6±0.1

VLT/XSHOOTER

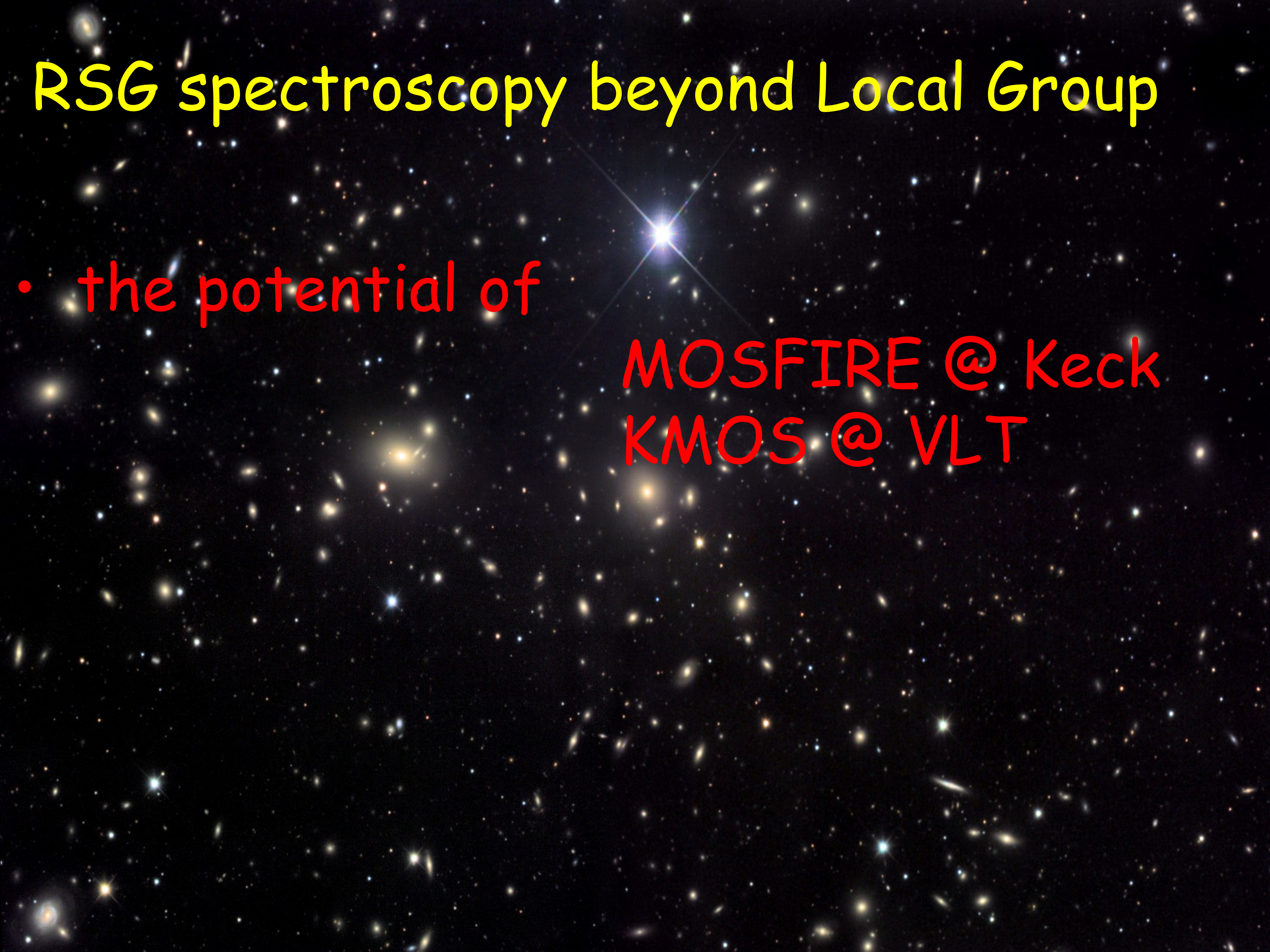



Davies, Kudritzki, Gazak et al., 2013

# RSG spectroscopy beyond Local Group

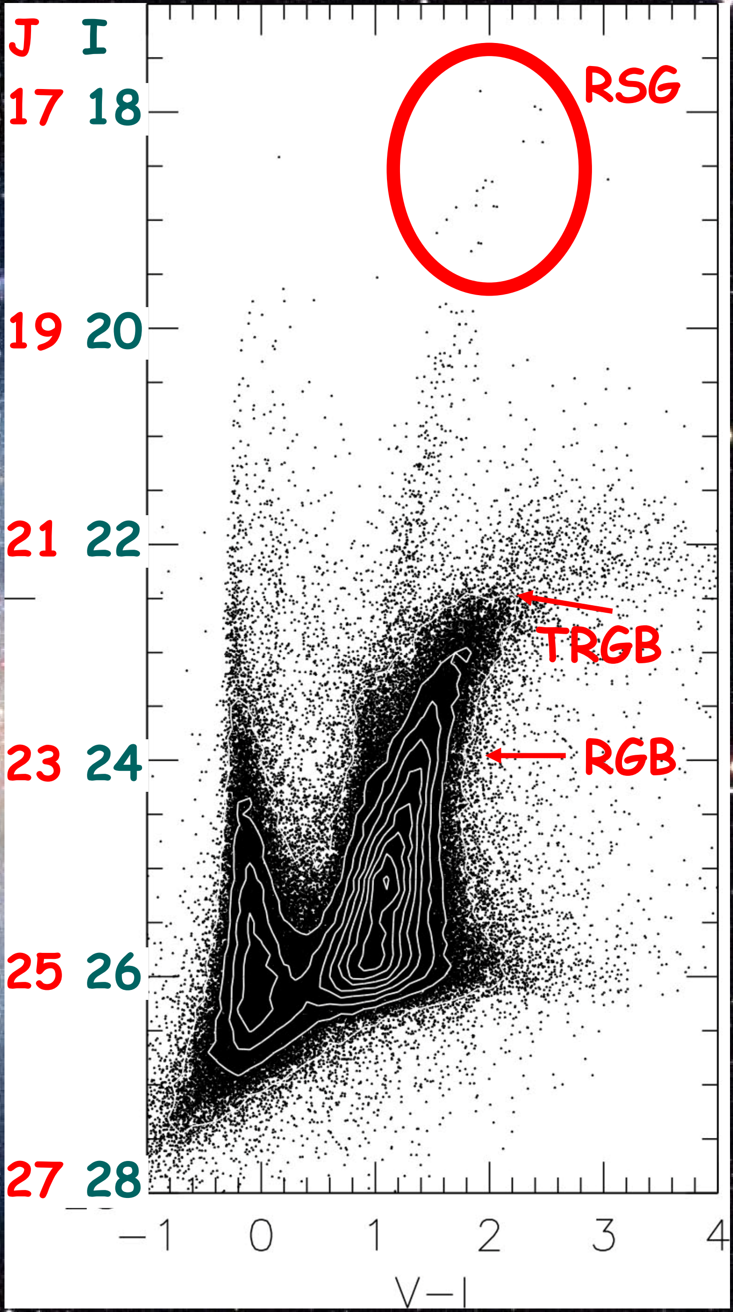
- the potential of

MOSFIRE @ Keck
KMOS @ VLT



# NGC 300 – 2 Mpc

# NGC 300




CMD (HST ACS)
one out of 6 fields
Bresolin et al. (2005)

# Keck/MOSFIRE and VLT/KMOS

[Z] ± 0.1 dex down to $J = 19.5^m$

TRGB: $M_J = -5^m \longrightarrow m - M = 24.5^m$ or $d = 0.8$ Mpc

RSG: $-8^m \geq M_J \geq -11^m$

$\downarrow \qquad \downarrow$

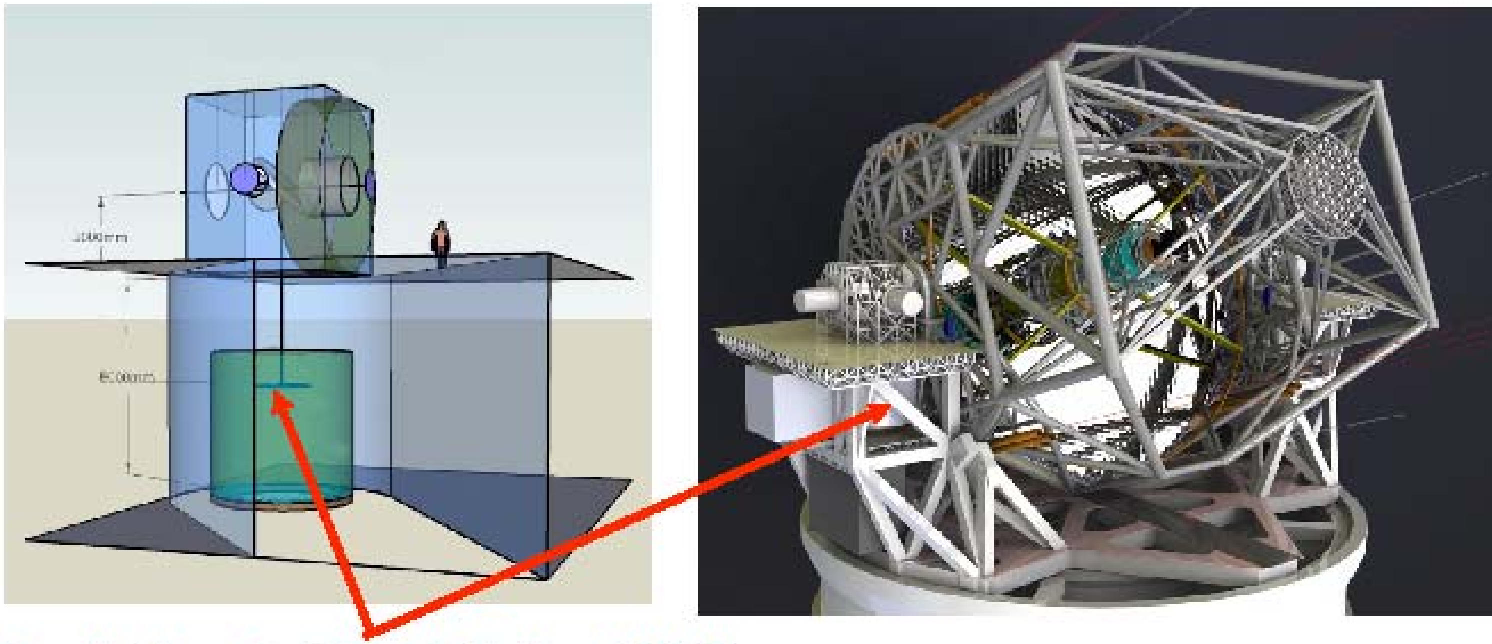
$27.5^m \leq m - M \leq 30.5^m$

$\downarrow \qquad \downarrow$

3.2 Mpc $\leq d \leq$ 12.6 Mpc

# EAGLE @ E-ELT

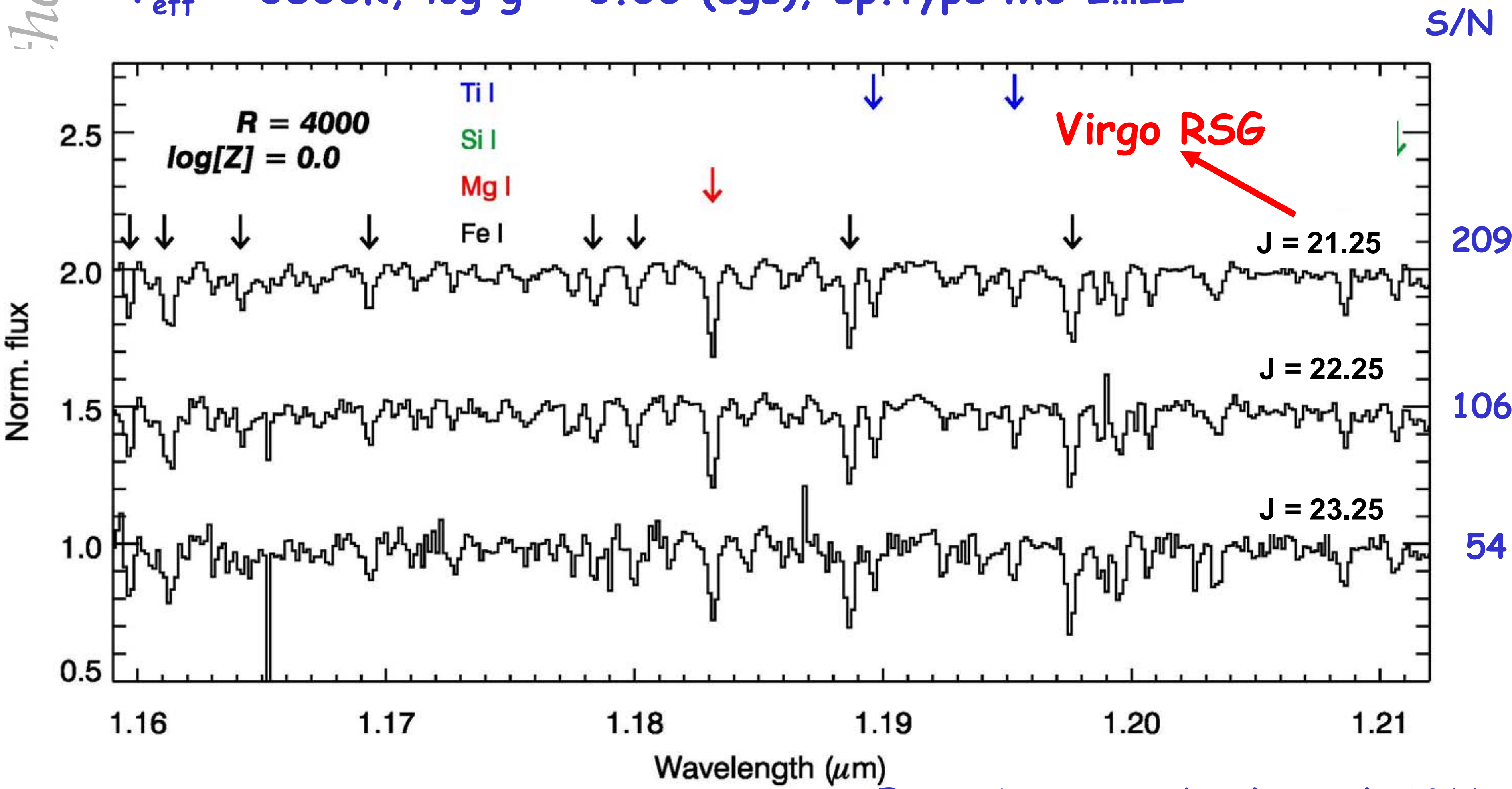
SPIE OP09, San Diego, Aug. 03, 2009



Gravity Invariant Focal Station (GIFS)

# simulated EAGLE observations: 10h exposure

$T_{eff}$ = 3800K, log g = 0.00 (cgs), sp.type M0 I...II

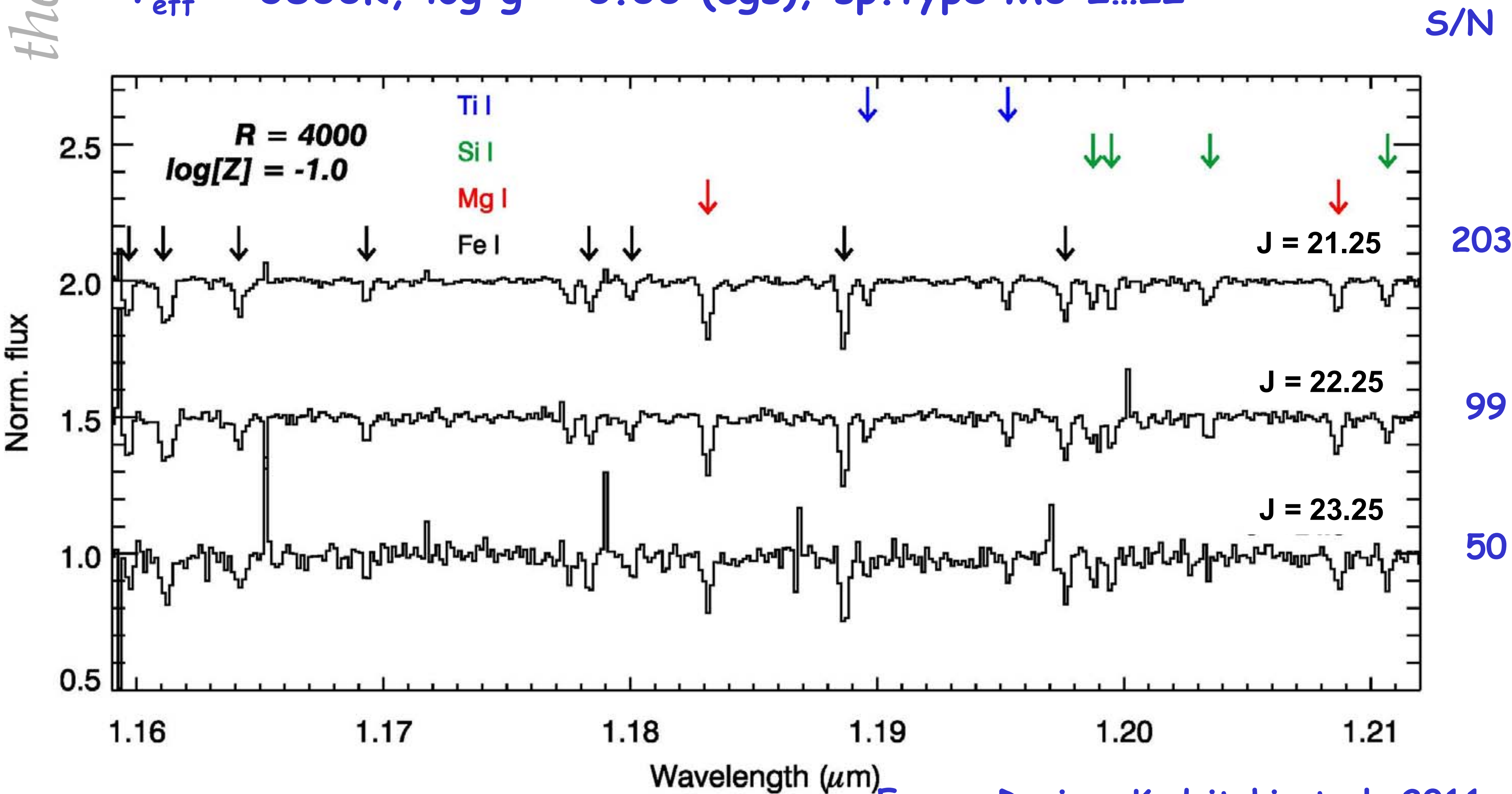



Evans, Davies, Kudritzki et al. 2011
A&A, 527, 50


RSG J-band spectra in Virgo
with S/N ~ 200
in 1 night E-ELT

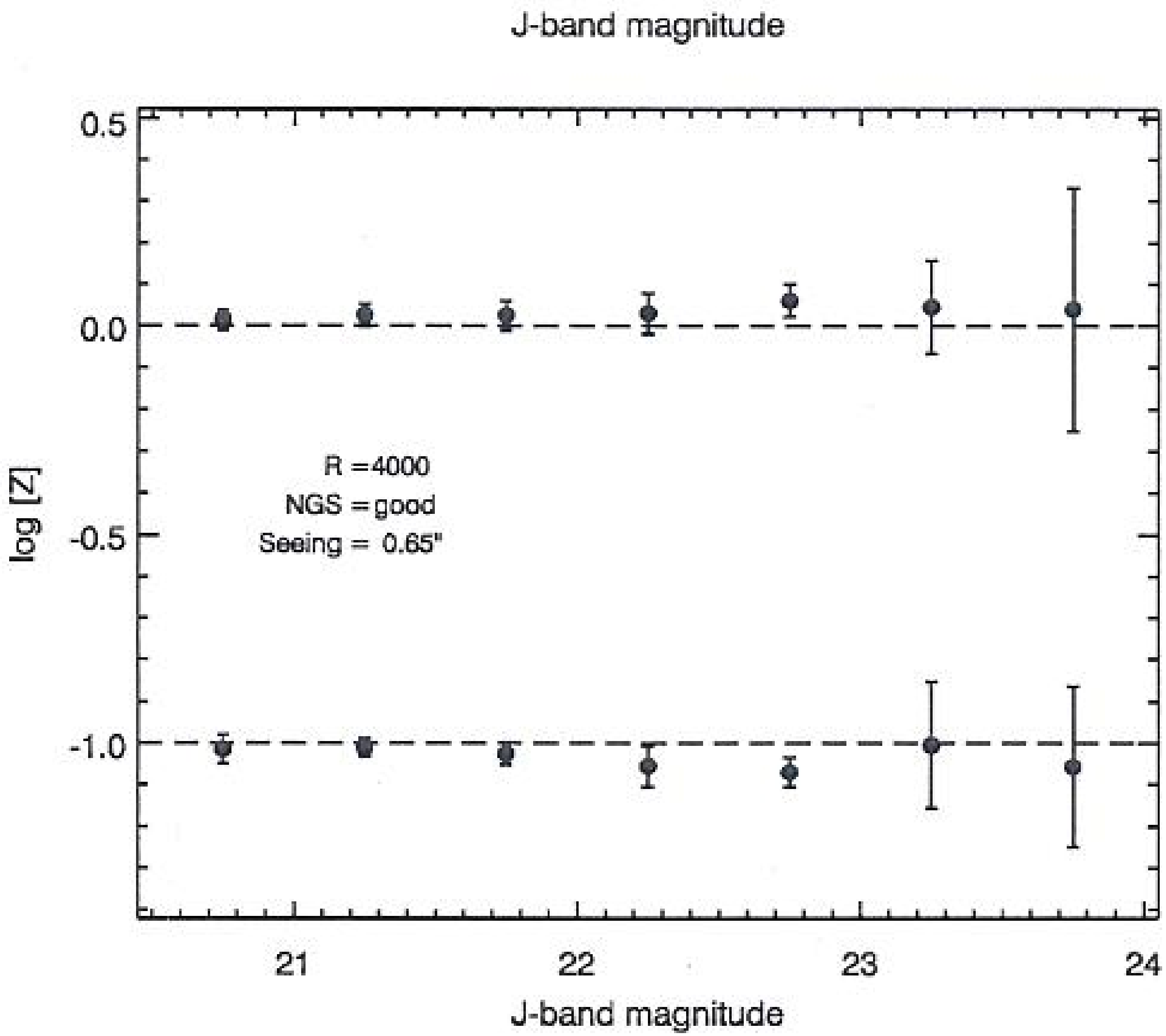
# simulated EAGLE observations: 10h exposure

$T_{eff}$ = 3800K, log g = 0.00 (cgs), sp.type M0 I…II




Evans, Davies, Kudritzki et al. 2011
A&A, 527, 50

# perfect recovery of metallicity!!!!

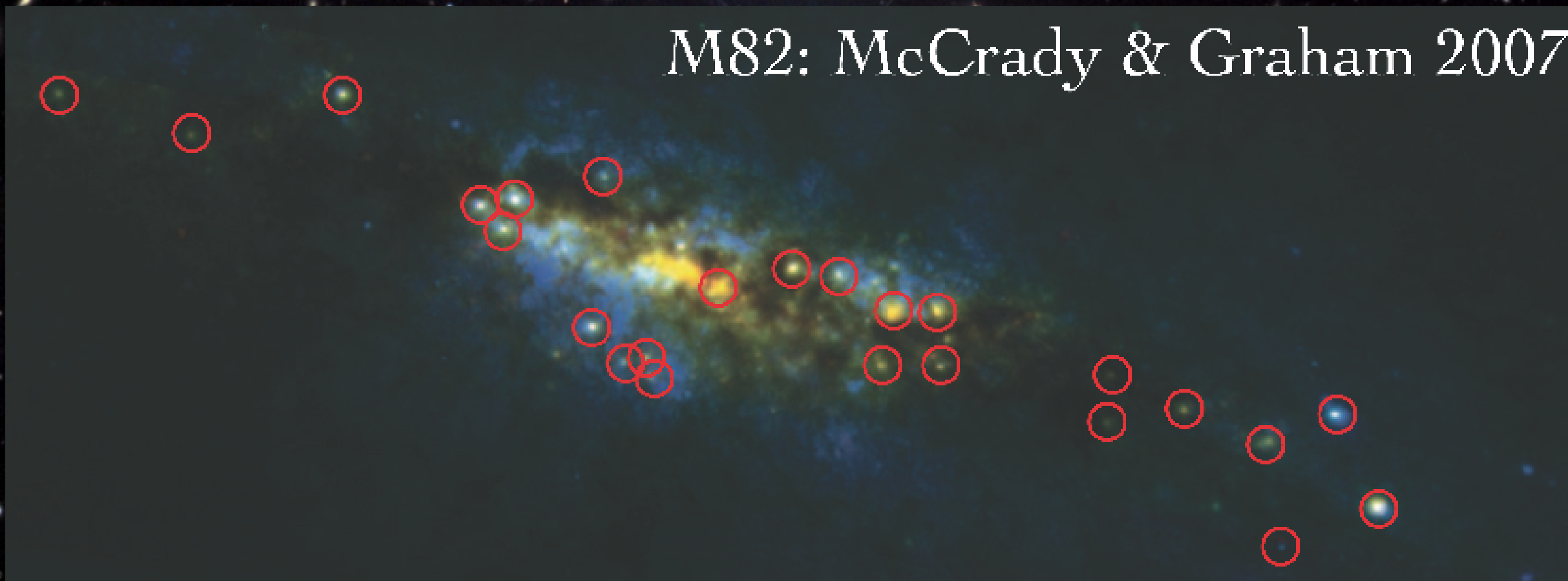



Evans, Davies, Kudritzki et al. 2011
A&A, 527, 50

# Potential: E-ELT and EAGLE

[Z] ± 0.1 dex down to J =$24^m$

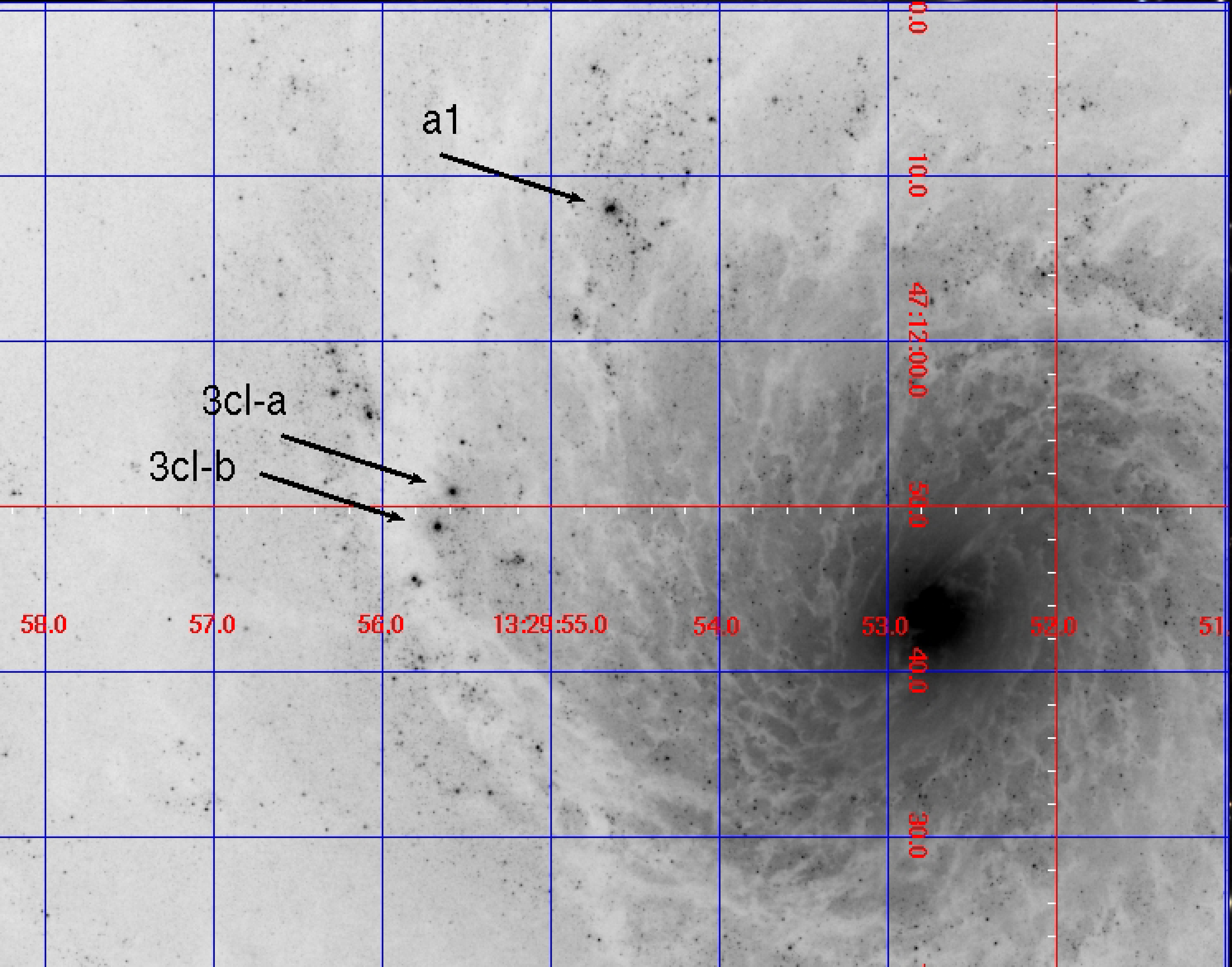

# Super Star Clusters (SSCs)



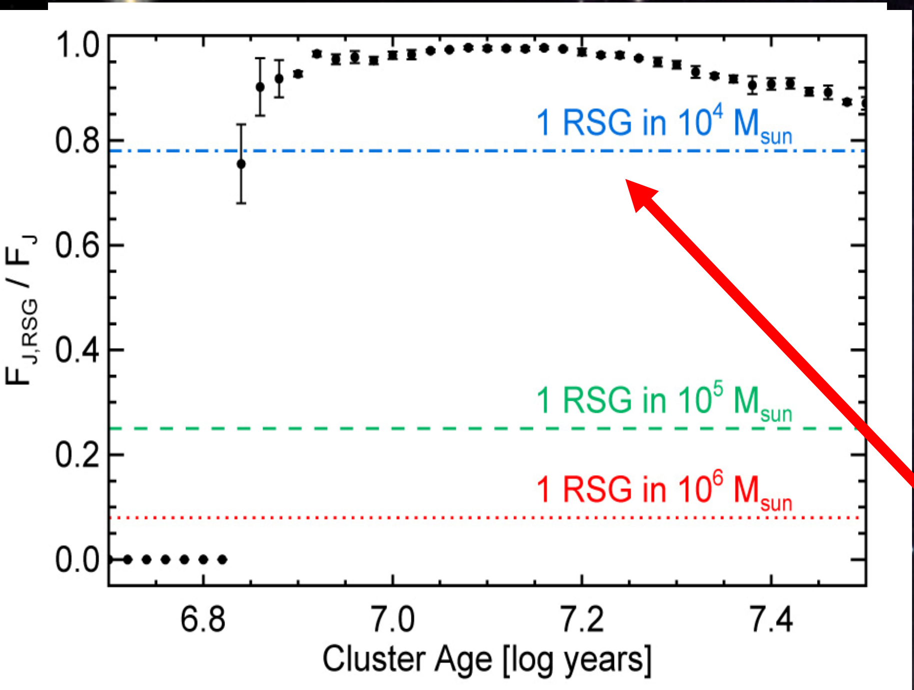

Dense aggregates of young massive stars in
star forming/merging galaxies
(Review by Portegies Zwart et al., 2010, ARAA 48, 431)

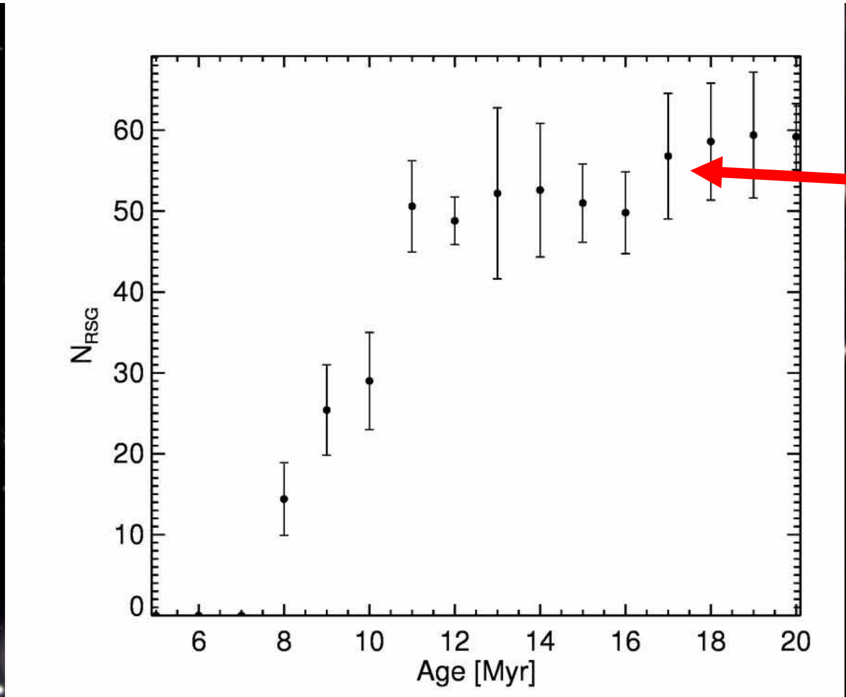
$M \sim 10^5 \ldots 10^6\ M_{sun}$

# Super Star Clusters (SSCs)




M51
Bastian et al. 2005




Gazak, Bastian, Kudritzki et al. 2013, MNRAS Letters, 430,35

J-band population synthesis

$10^5$ $M_{sun}$ cluster

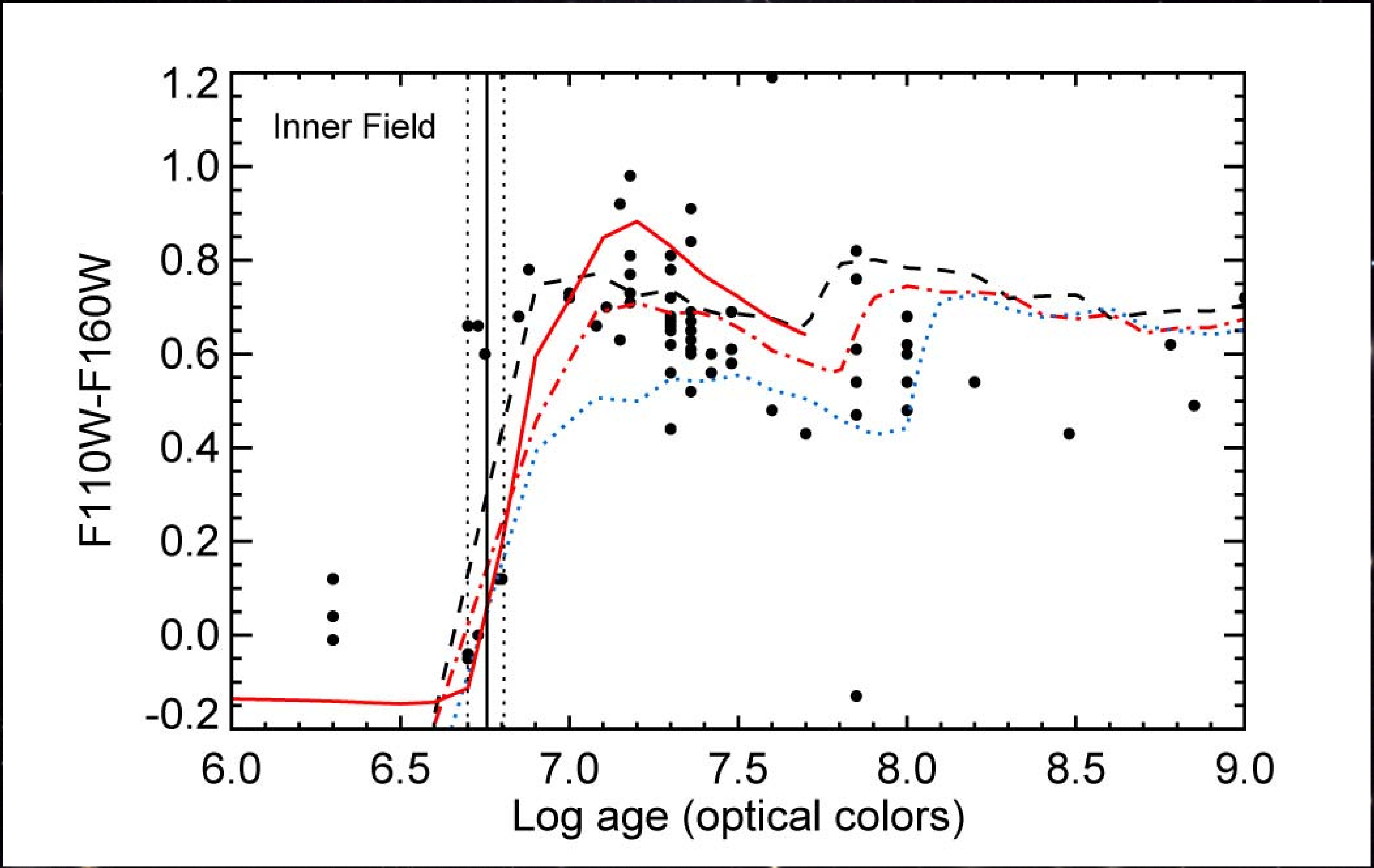
RSG contribution to J-band flux is 95%

Number of RSGs ~ 50

RSGs dominate J-band!!!

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

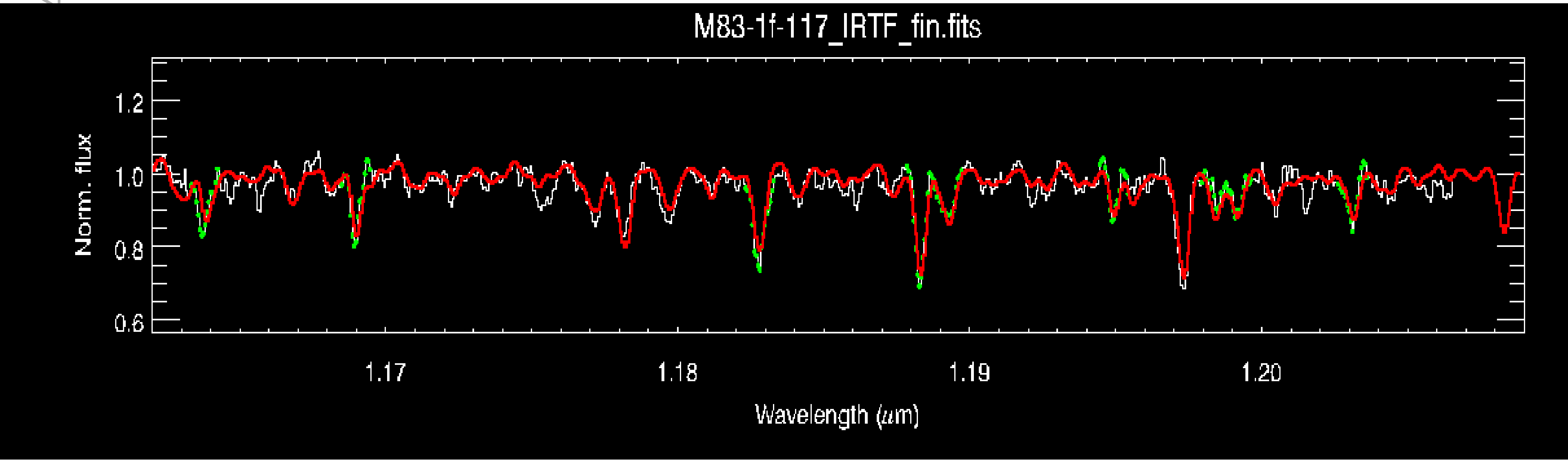
# HST photometry of M83 SSCs
# dramatic change of IR-color with age




Gazak, Bastian, Kudritzki et al., 2013

# SSC in M83

## Proof of concept: 3h VLT/ISAAC, J- band

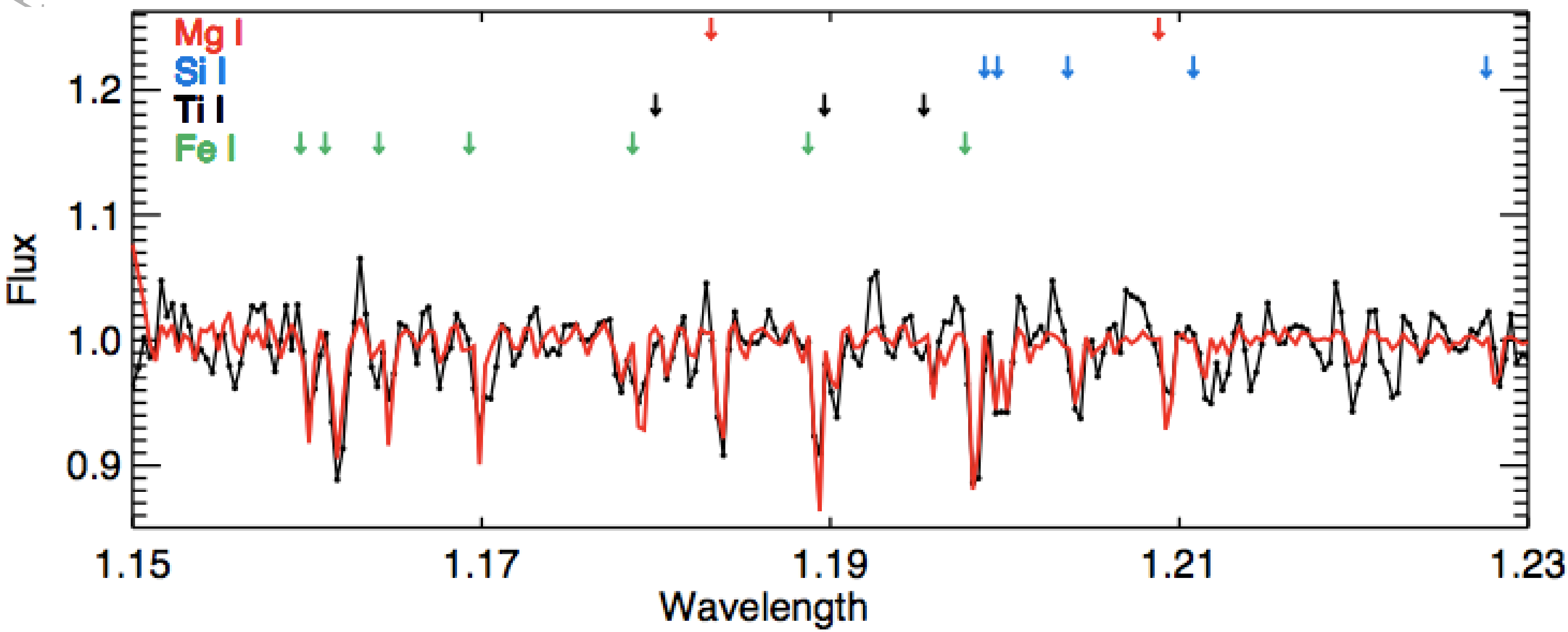



**[Z] ~ 0.3**

Gazak, Davies, Kudritzki et al., in prep.

# SSC 1447 in NGC 6946

## Proof of concept: 1 night with IRTF, J- band

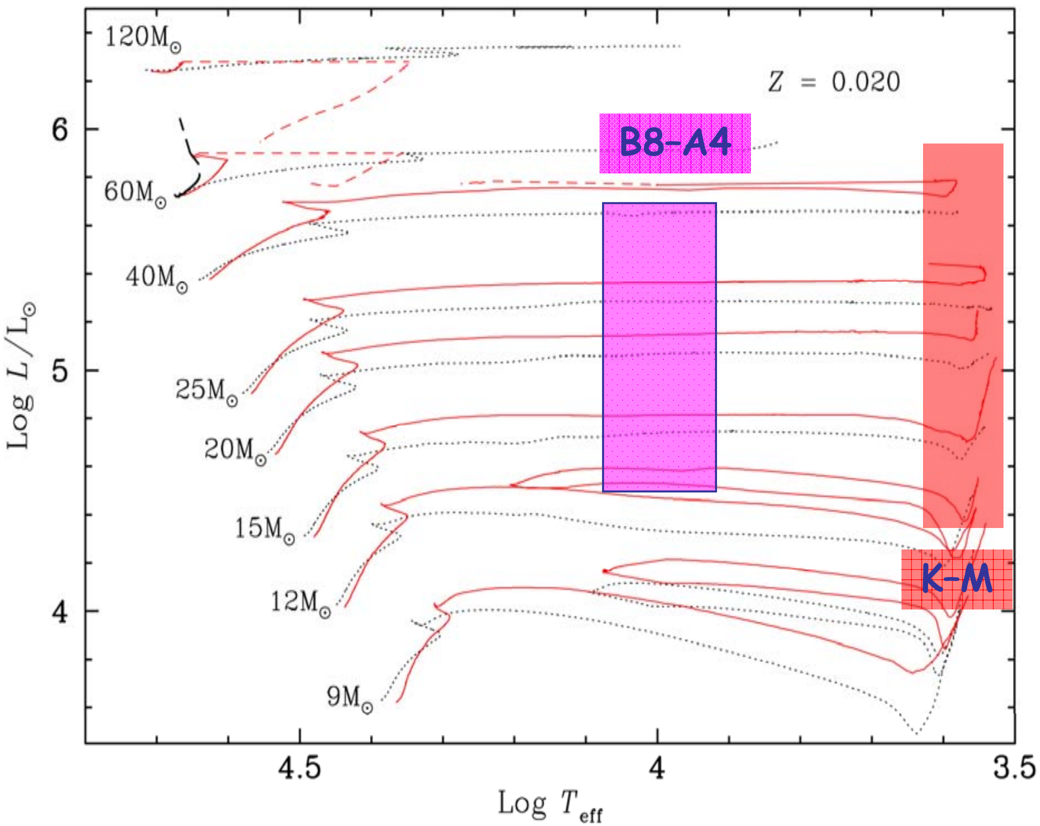



**[Z] = -0.5 ± 0.15**

Gazak, Davies, Kudritzki et al., in prep.

# red supergiants J-band spectroscopy

**Brightest stars at infrared light: $-8 \geq M_J \geq -11$ mag**



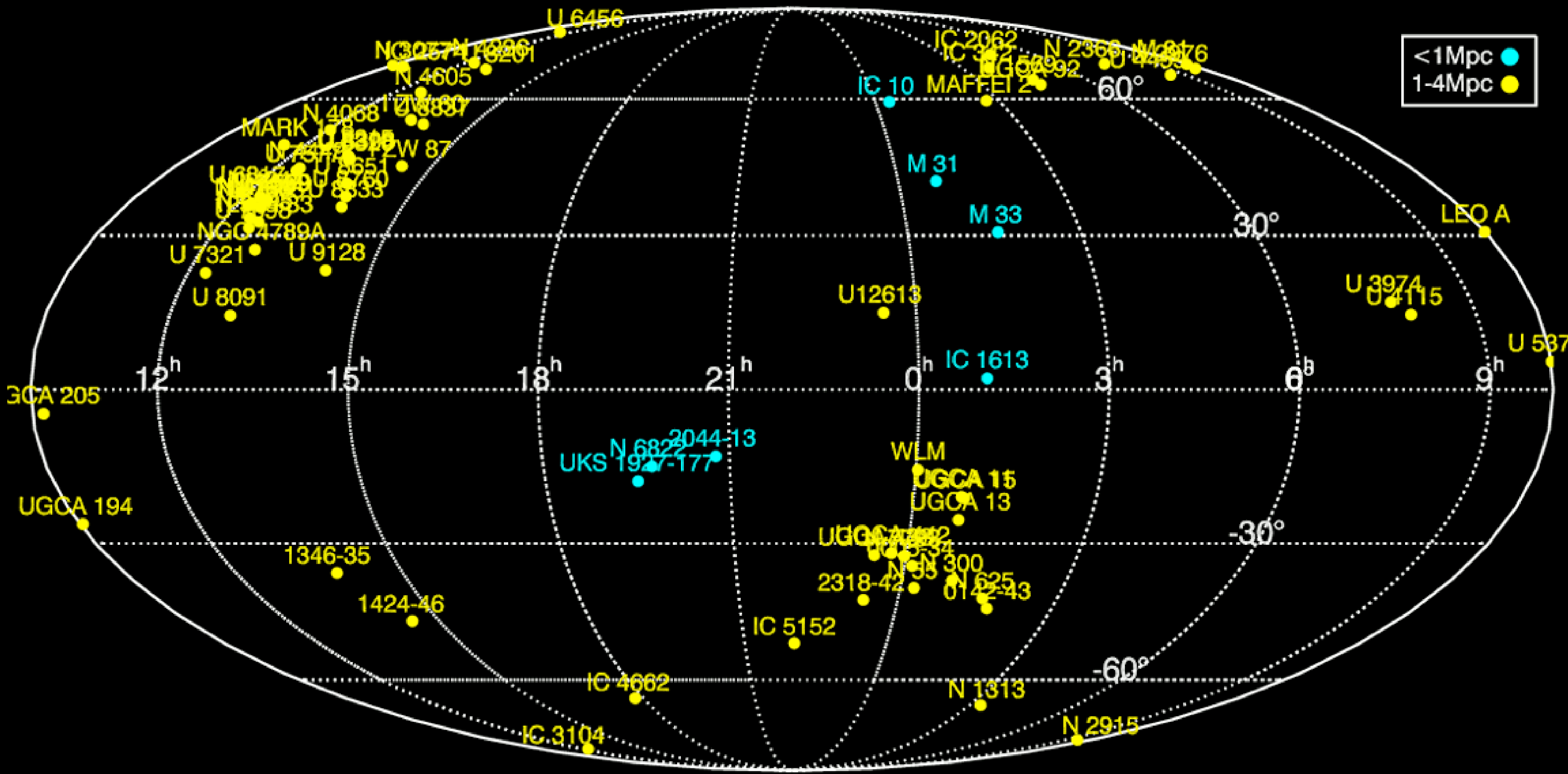

Davies, Kudritzki, Figer, 2010 MNRAS, 407,1203

Evans, Davies, Kudritzki et al. 2011 A&A, 527, 50

Keck/MOSFIRE, VLT/KMOS: 10 Mpc

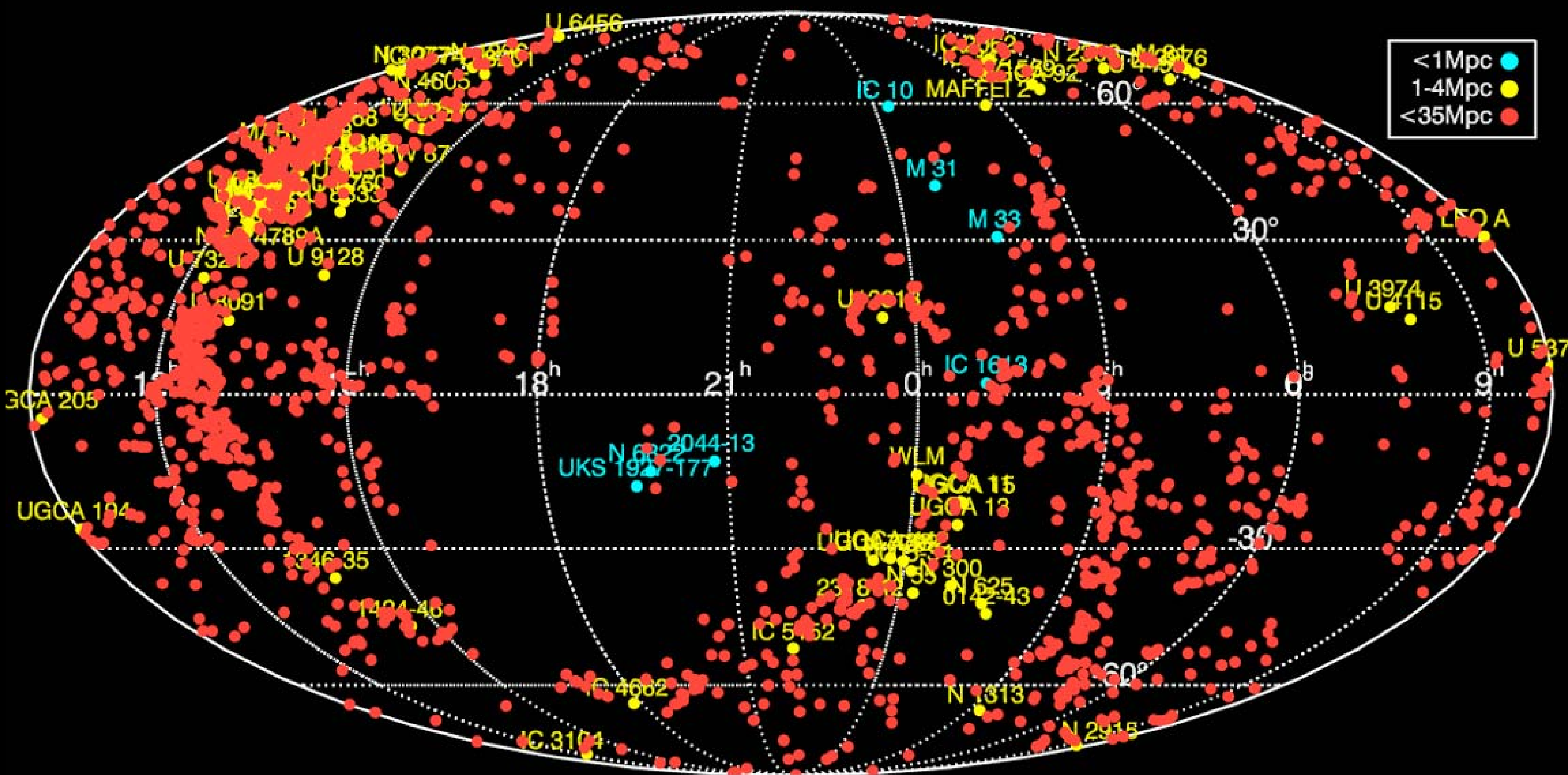
TMT/IRMS, E-ELT/EAGLE: 100 Mpc

Star Super Clusters: ~10 times further out




galaxies out to 4Mpc

➡ number of observable targets ~100




➡E-ELT: galaxies out to 35Mpc (modest...)

➡number of observable targets increased to ~1500!!