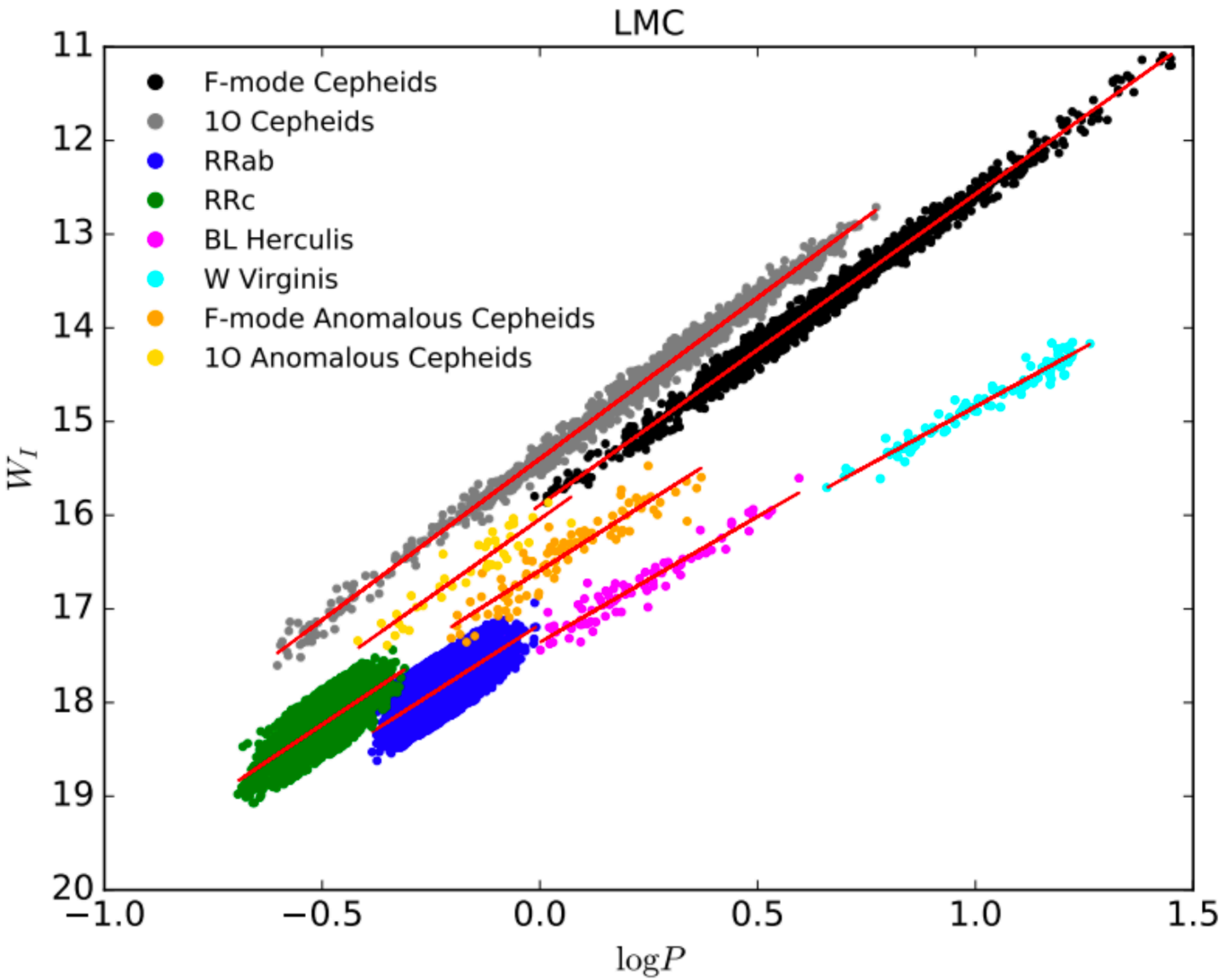
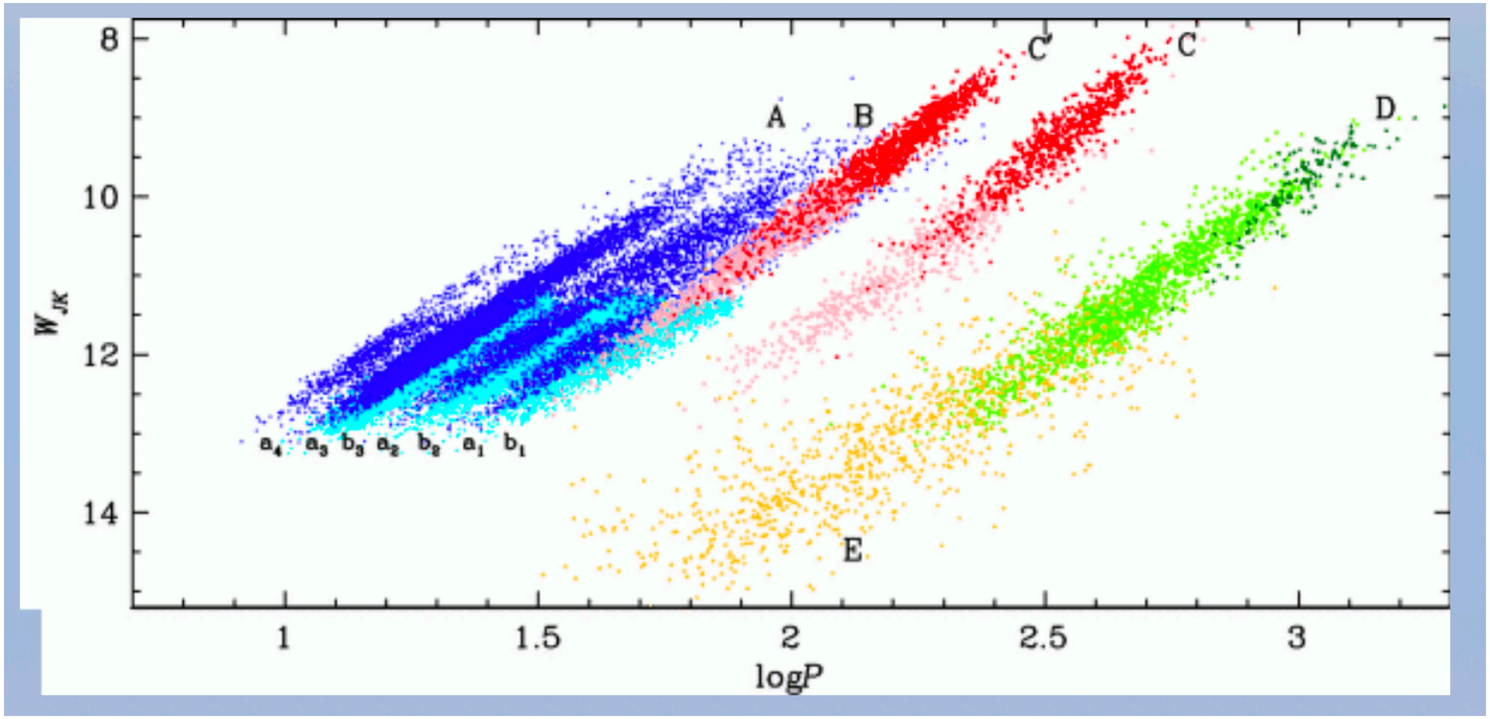
Extragalactic Distance Scale lect. X
TRGB, Supergiants

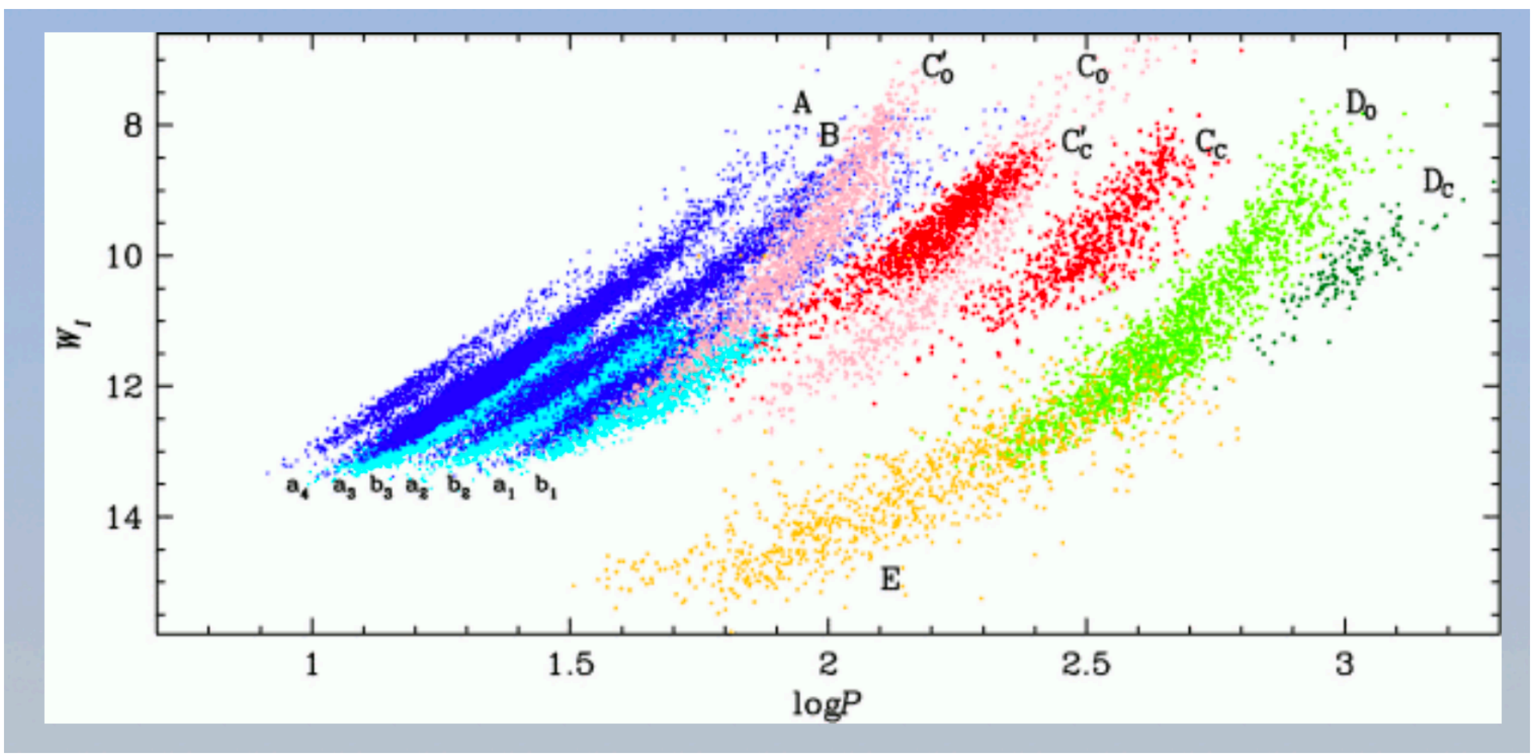
Lectures on /work/chuck/pci/wyklady (Paweł Ciecieląg)
https://www.camk.edu.pl/pl/archiwum/2019/08/14/cosmic-distance-scale/



LMC
F-mode Cepheids
1O Cepheids
RRab
RRc
BL Herculis
W Virginis
F-mode Anomalous Cepheids
1O Anomalous Cepheids
W_I
$\log P$
11
12
13
14
15
16
17
18
19
20
−1.0
−0.5
0.0
0.5
1.0
1.5



8
10
12
14
W_{JK}
1
1.5
2
2.5
3
logP
A
B
C'
C
D
E
a_4 a_3 b_3 a_2 b_2 a_1 b_1



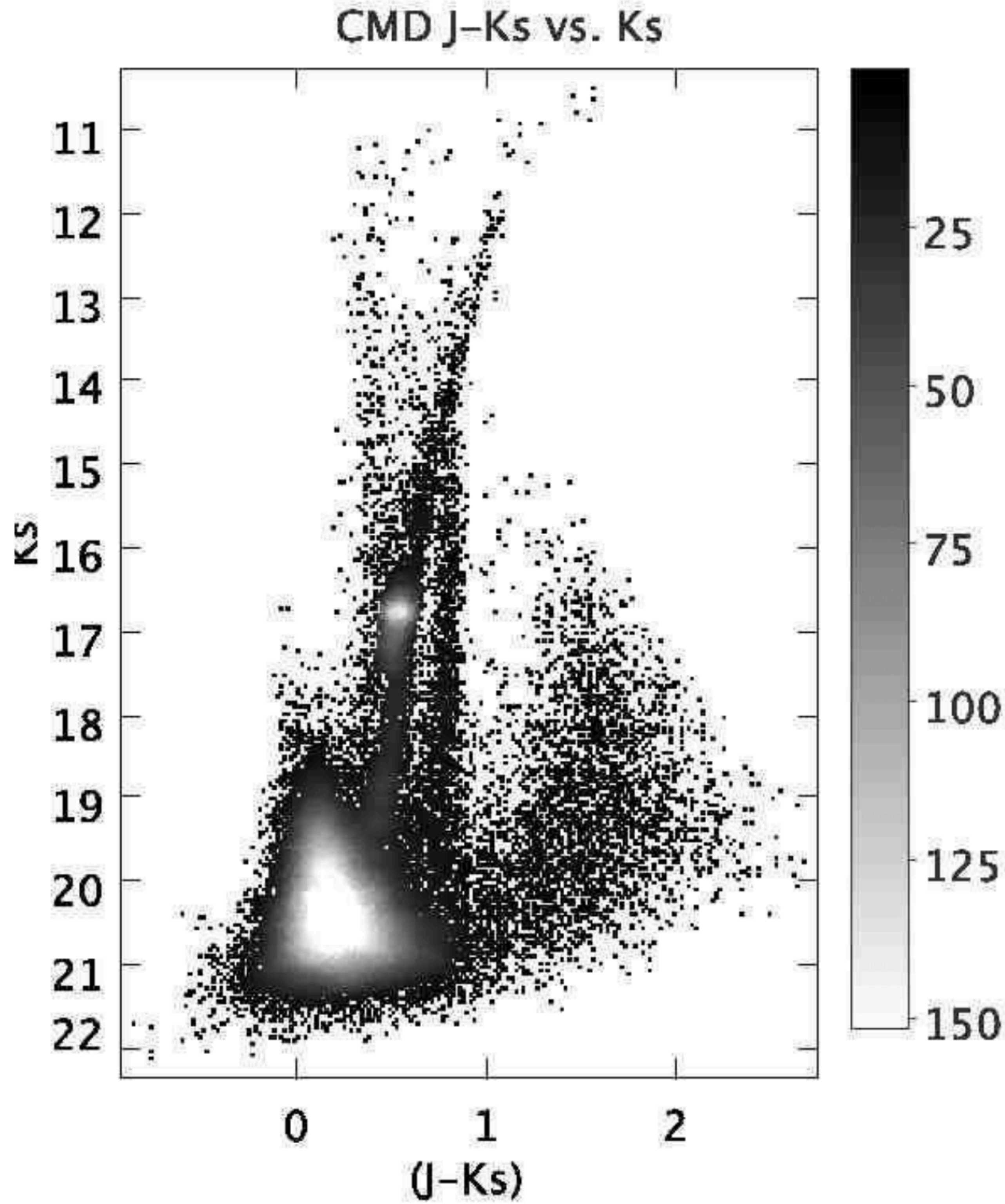
8
10
12
14
W_I
1
1.5
2
2.5
3
logP
A
B
C'_O
C_O
C'_C
C_C
D_O
D_C
E
a_4 a_3 b_3 a_2 b_2 a_1 b_1

Binarity

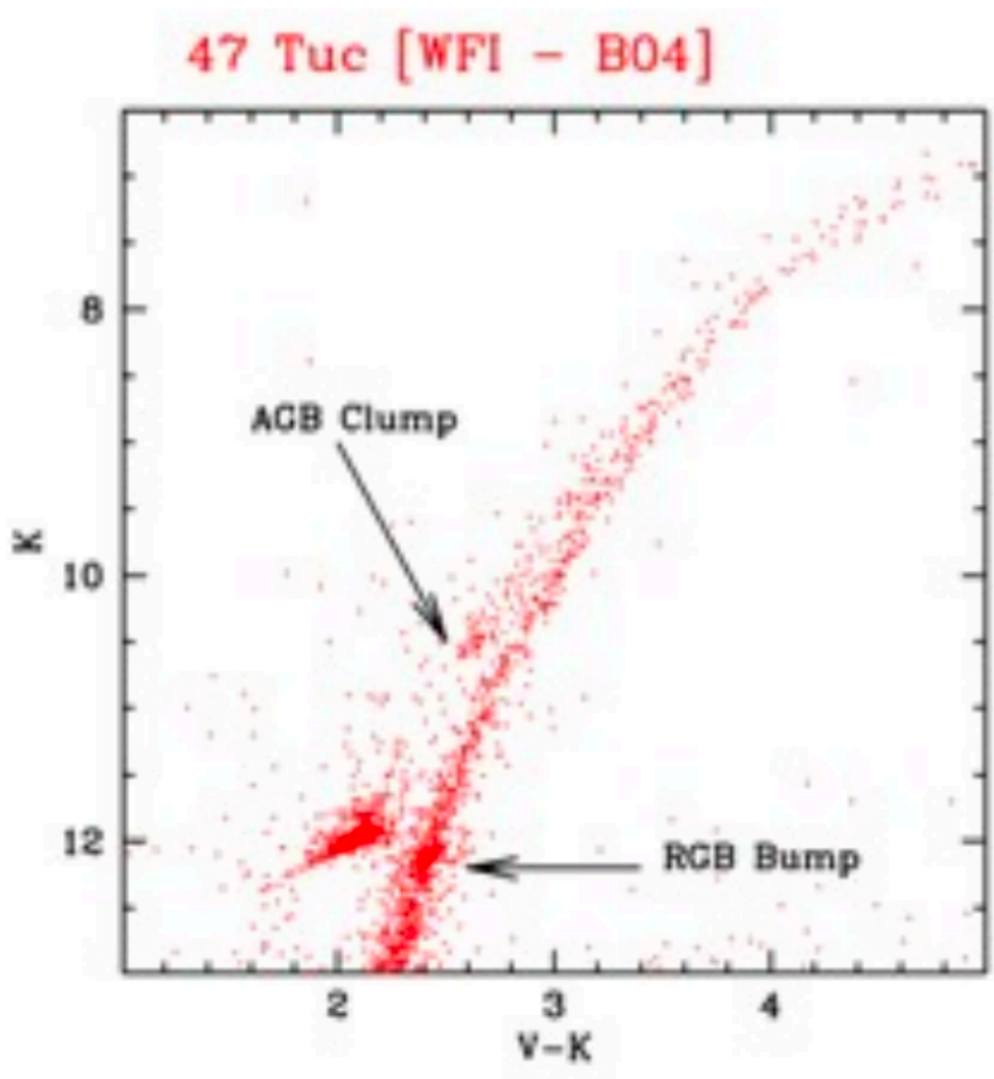
Unique possibility to measure geometrical distances

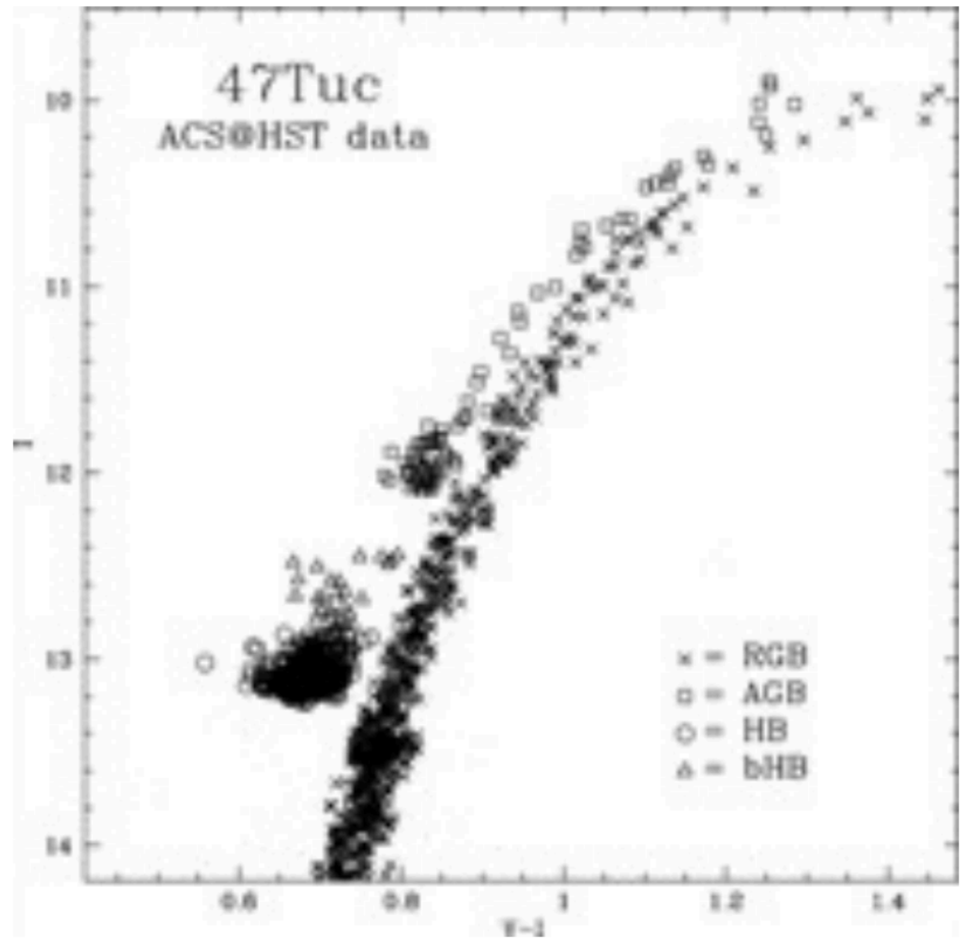
Unresolved blends (bias in distance determination)

BEPs − peculiar stars mimicking classical pulsators

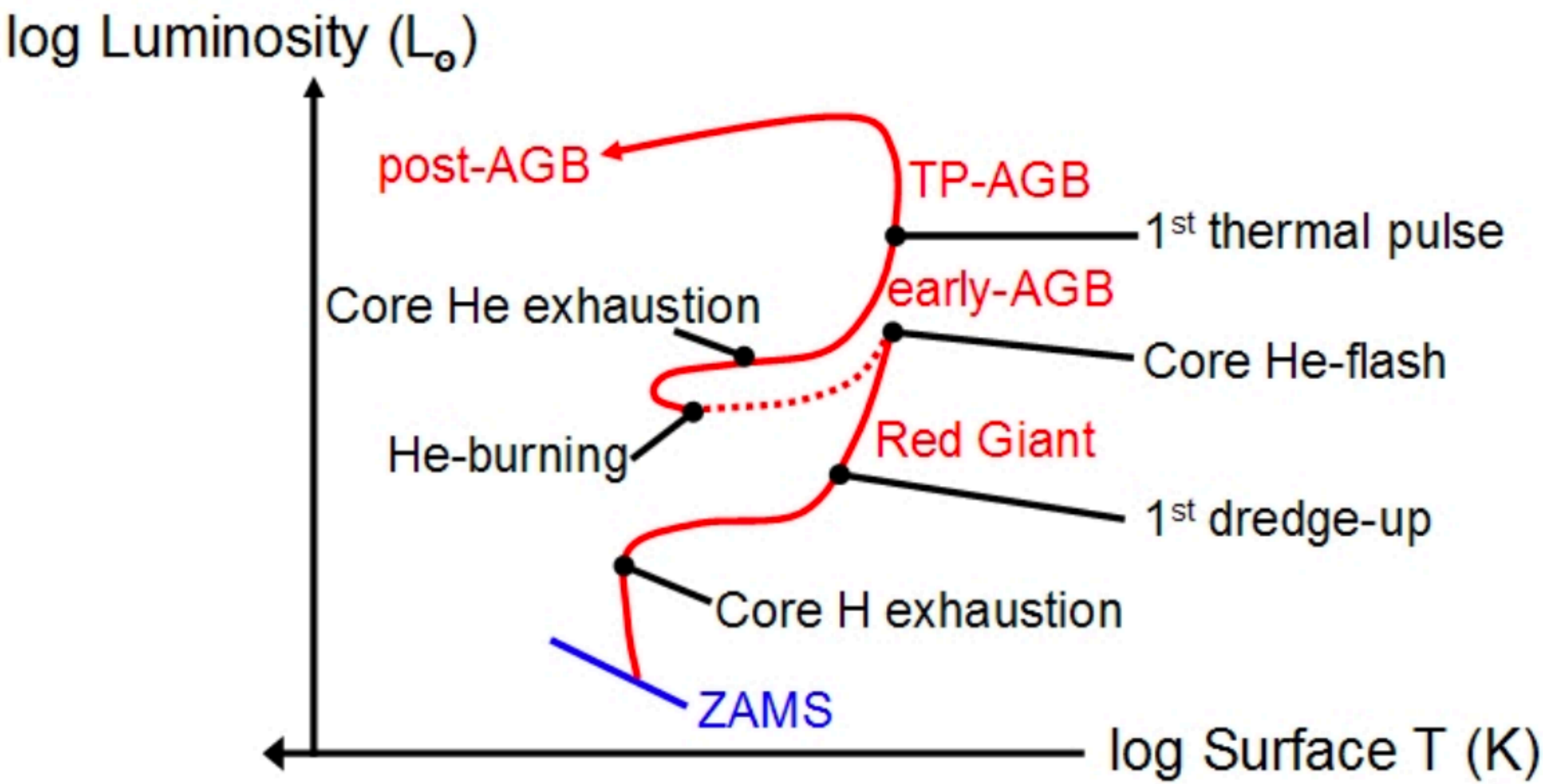

CMD J-Ks vs. Ks
Ks
11
12
13
14
15
16
17
18
19
20
21
22
0
1
2
(J-Ks)
25
50
75
100
125
150

Structures on the CMD

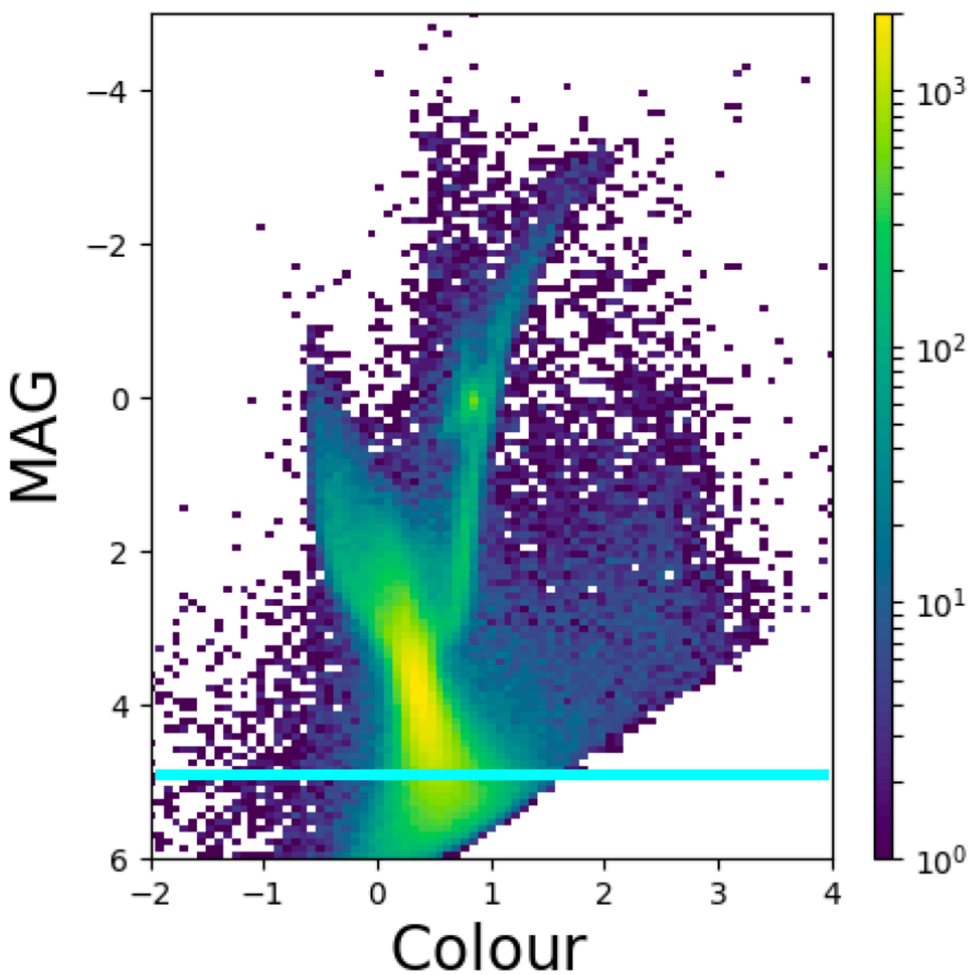


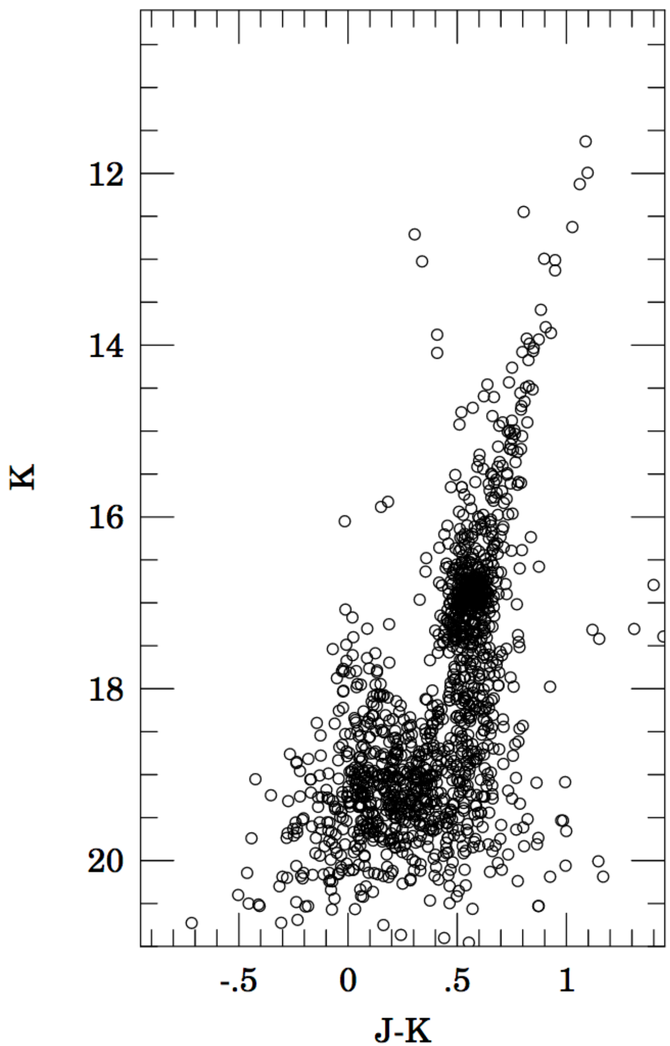


Tip of the Red Giant Branch (TRGB)



Detection technique





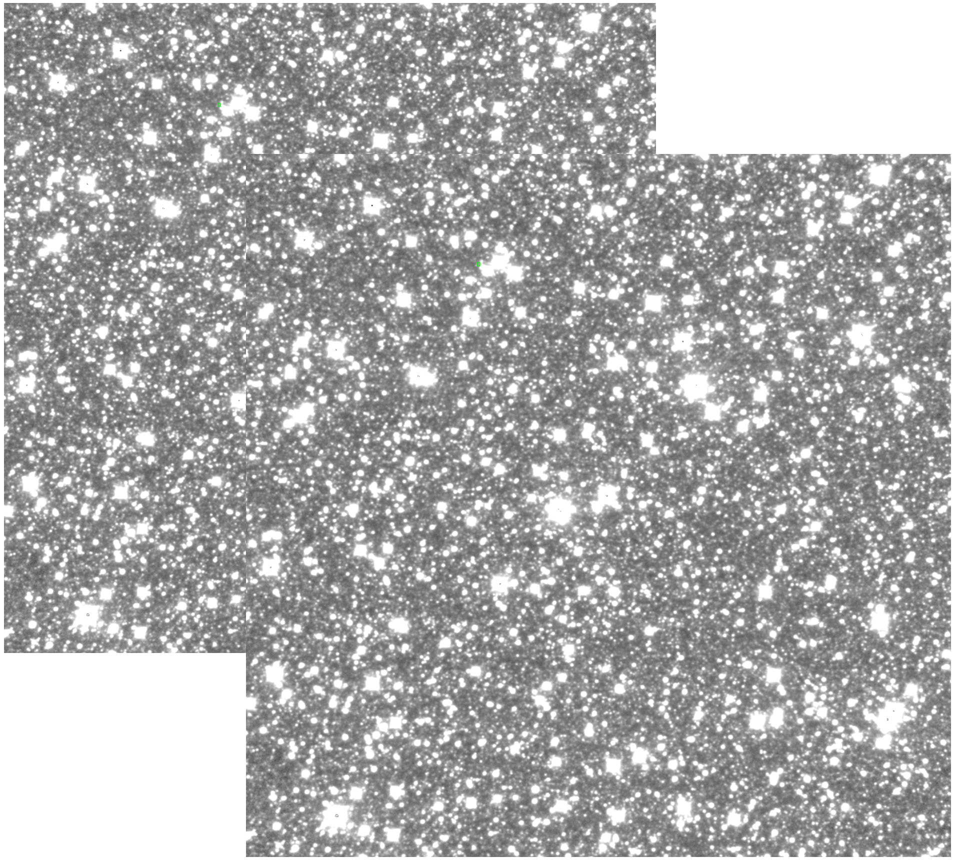
Detection technique

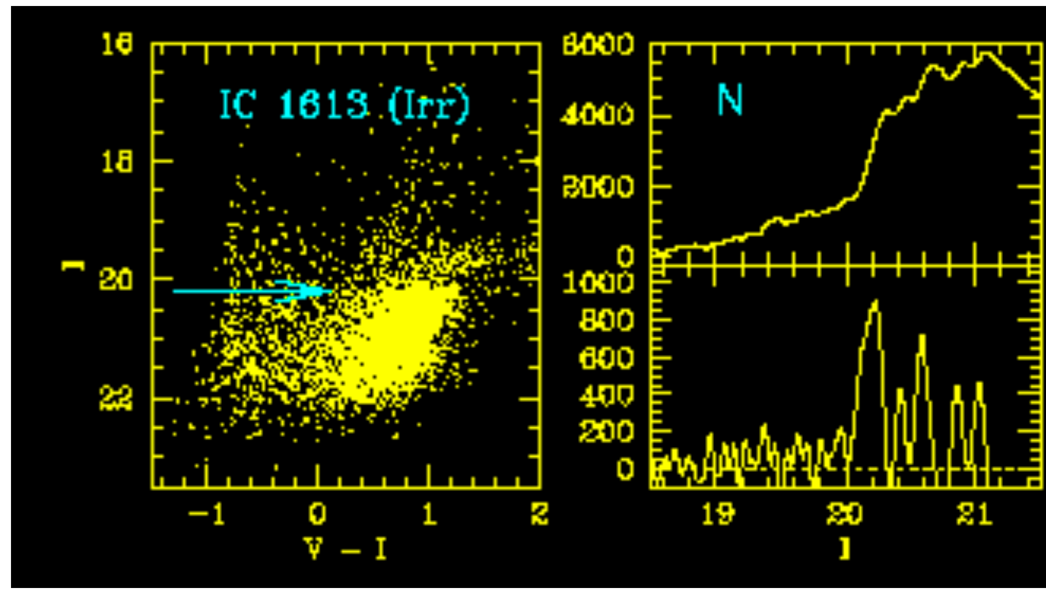
1) Sobel filter (Lee Freedman Madore 1993)

with several modifications (Sakai et al. 1996)

2) Maximum Likelihood Algorithm (MLA) Malendez et al. 2002, Makarov et al. 2006.

3) Poisson noise weighted method (PN) Gorski et al. 2018





$$M_I^{\mathrm{TRGB}} = a + b(V - I),$$

TRGB - short history

Technique known since 1940s (e.g. Baade 1944)

First good optical calibration by Lee et al. (1993)

First near-IR calibrations (e.g. Valenti et al. 2004)

First near-IR distances (Pietrzynski, Gorski, Gieren 2005)

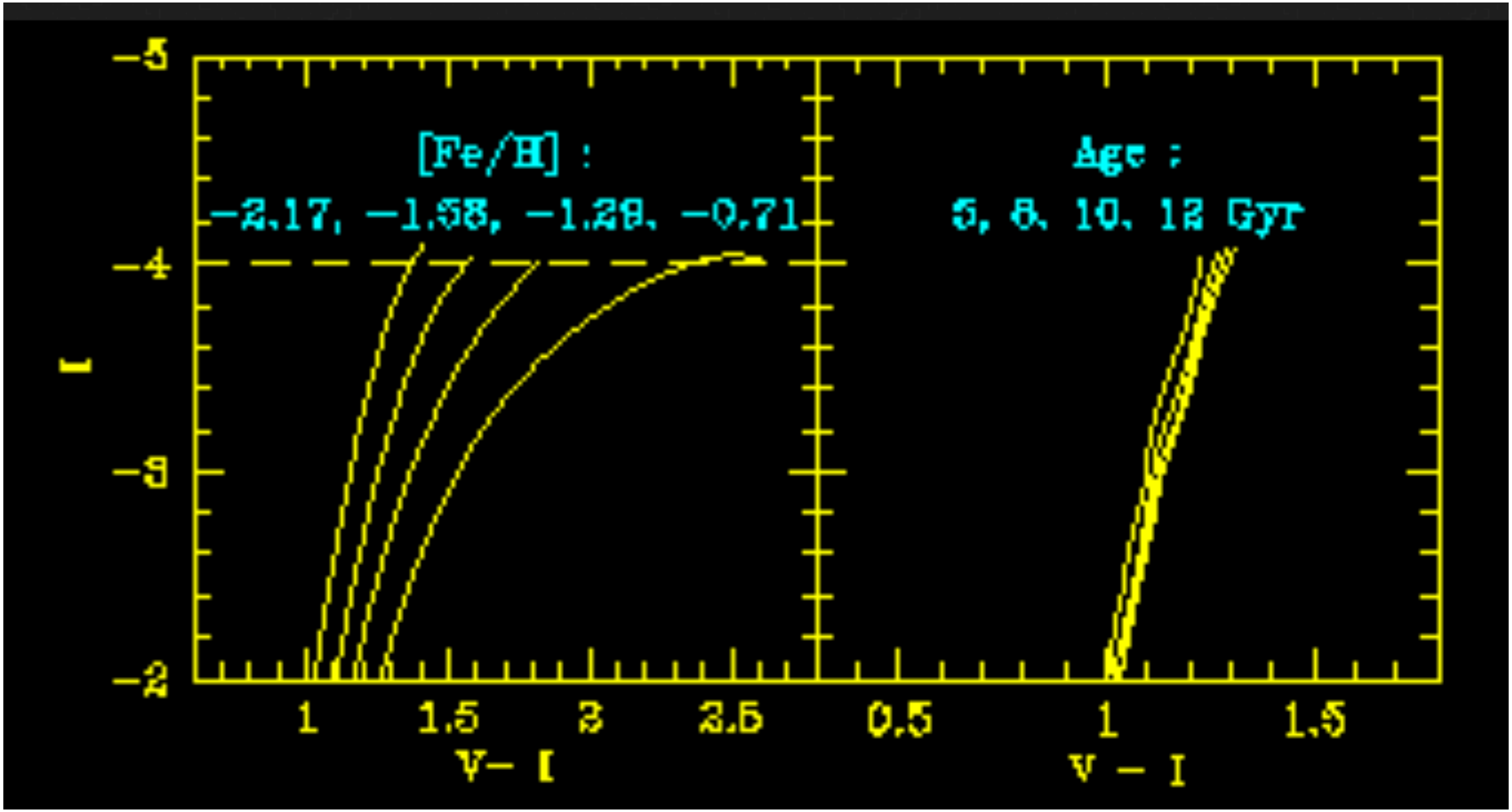
Improved calibration of TRGB I band (Rizzi et al. 2001)

TRGB distances for 300+ galaxies up to 16 Mpc (Tully et al. 2016)

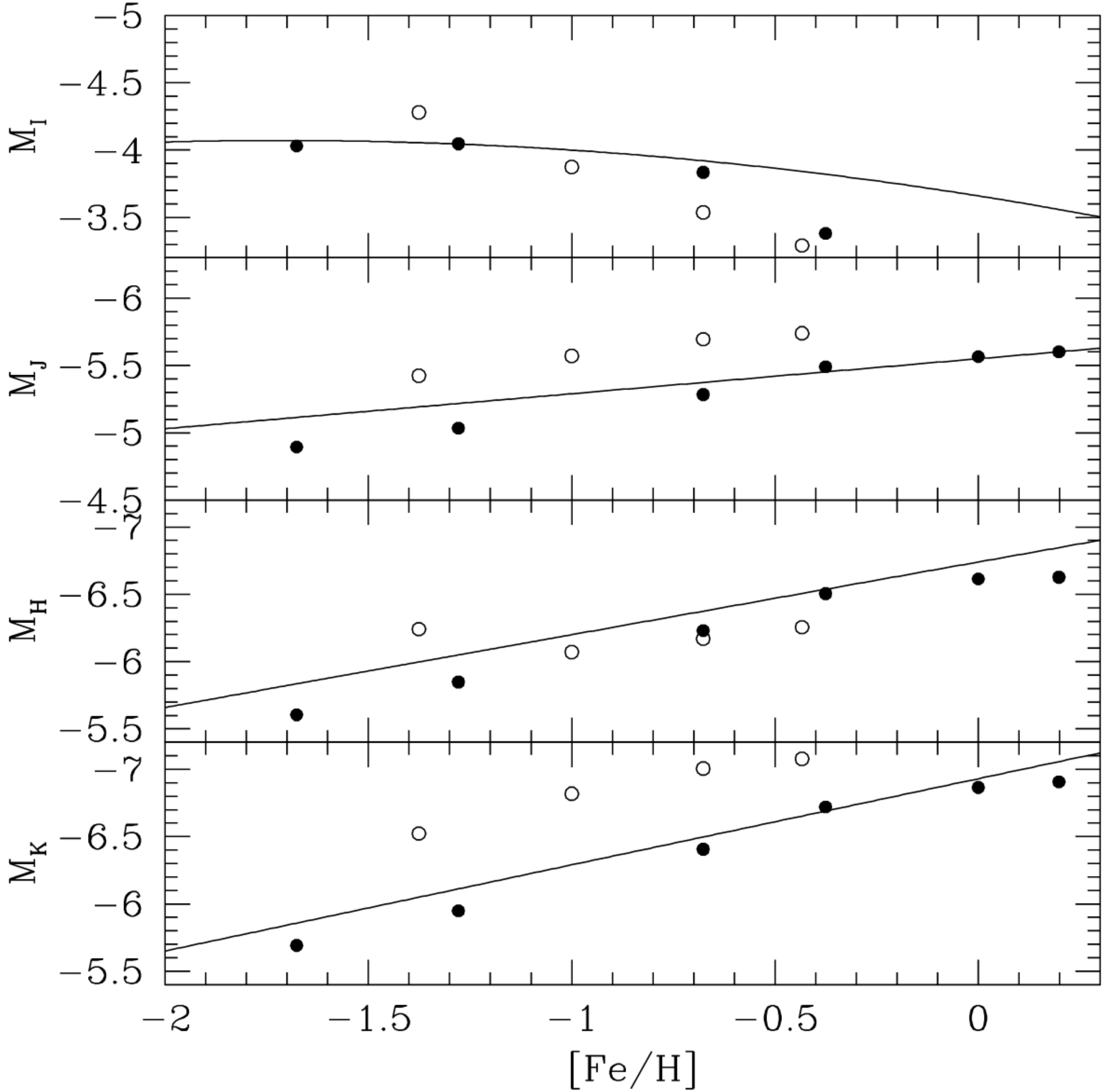
Solid theoretical calibrations (e.g. Serenelli et al. 2017)

Near-IR calibrations: (Madore et al. 2018, Gorski et al. 2018)

Many comparisons against Cepheids, RC stars, RR Lyrae stars etc ...



Just take nacient population, metal poor, and assume no internal E(B-V)



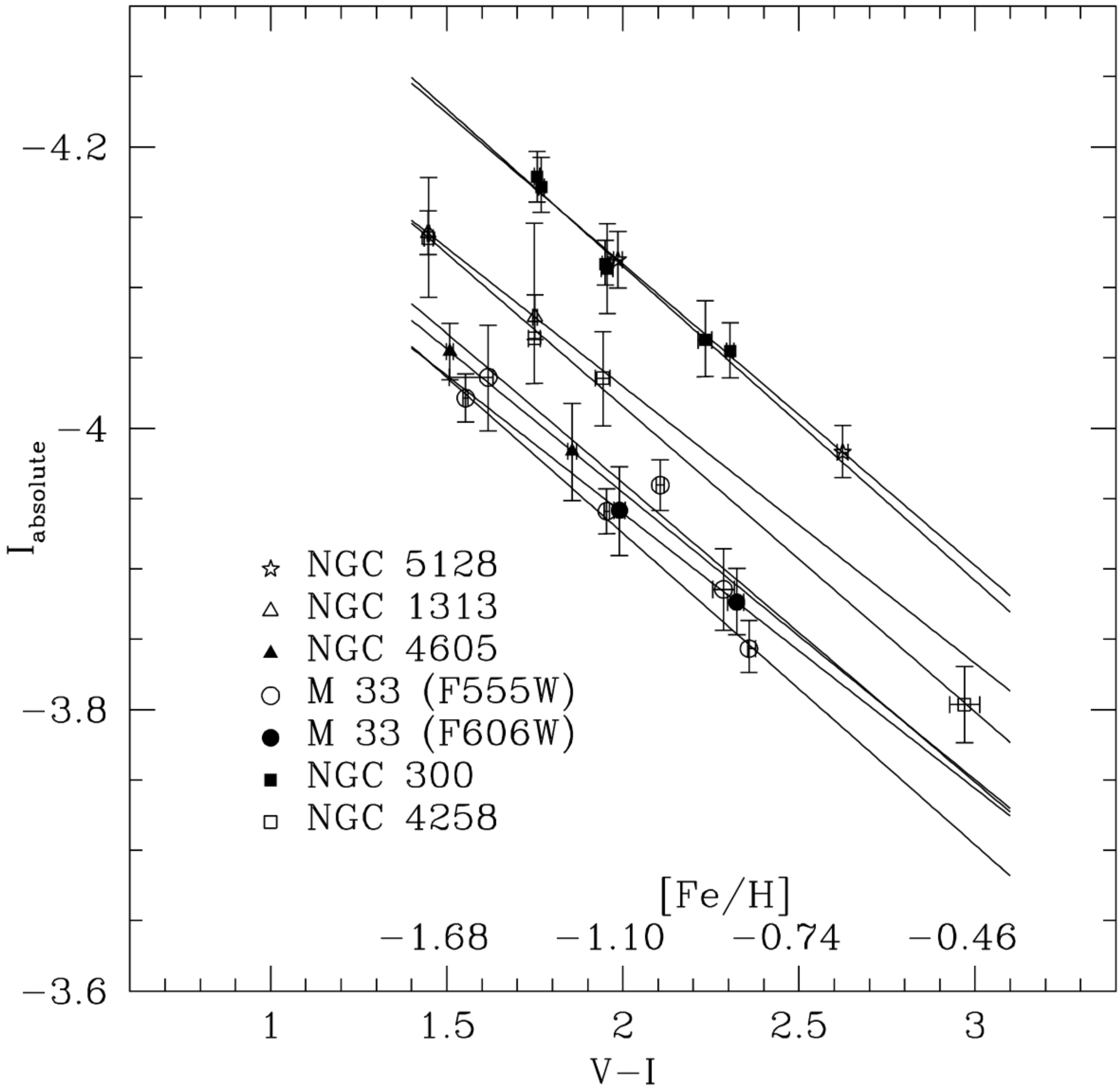
M_I
M_J
M_H
M_K
−5
−4.5
−4
−3.5
−6
−5.5
−5
−4.5
−7
−6.5
−6
−5.5
−7
−6.5
−6
−5.5
−2
−1.5
−1
−0.5
0
[Fe/H]

$$M_{\rm bol}^{\rm TRGB} = -3.81 – 0.19[{\rm Fe/H}],$$

$$\mathrm{BC_I} = 0.881 – 0.243(V - I)_0.$$

$$[{\rm Fe/H}] = -15.16 + 17.0(V - I)_{0,-3} - 4.9[(V - I)_{0,-3}]^2.$$

$$M_I^{\rm TRGB} = a + b(V - I),$$



−4.2
−4
−3.8
−3.6
I_absolute
1
1.5
2
2.5
3
V−I
[Fe/H]
−1.68
−1.10
−0.74
−0.46
NGC 5128
NGC 1313
NGC 4605
M 33 (F555W)
M 33 (F606W)
NGC 300
NGC 4258

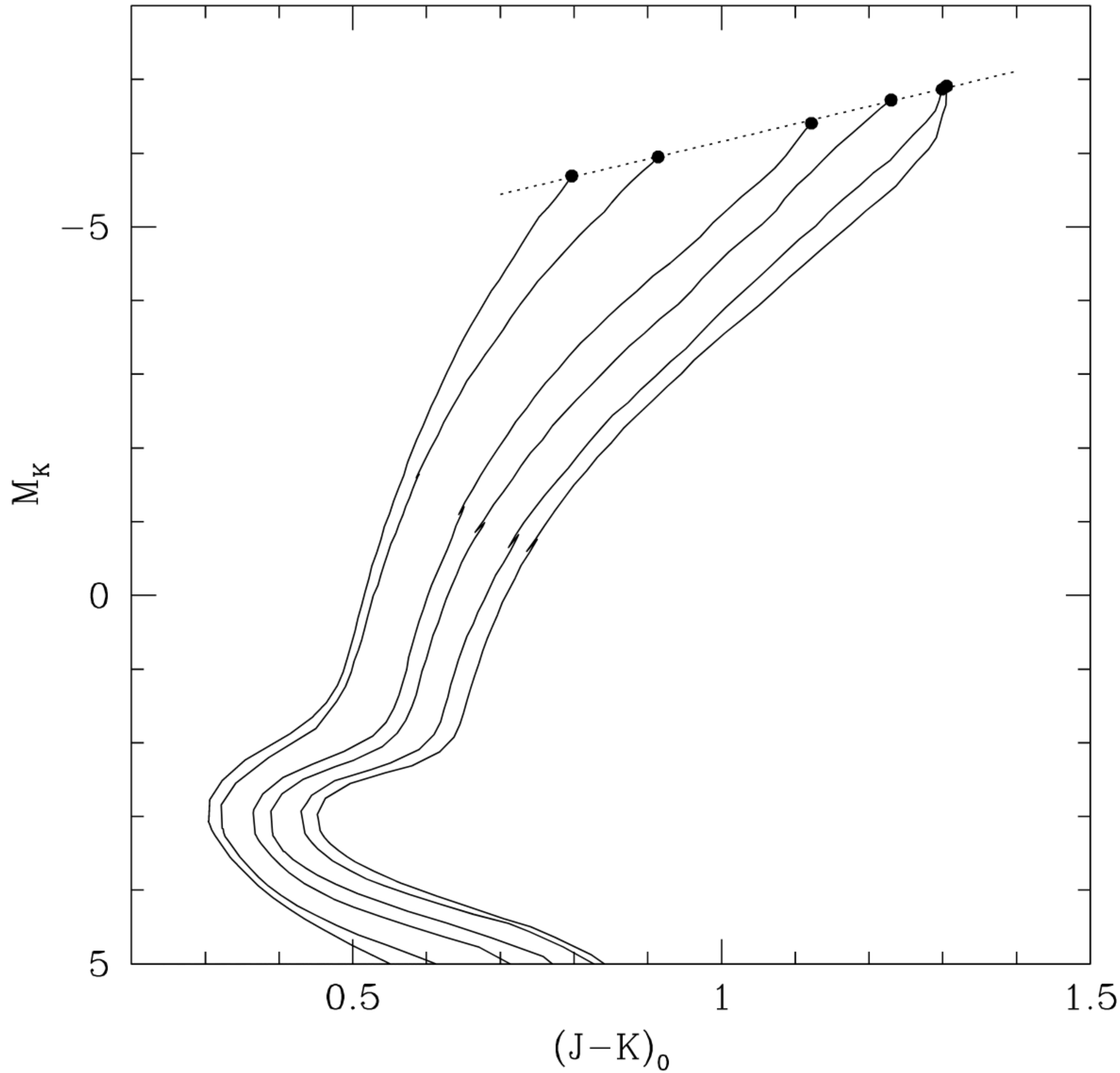
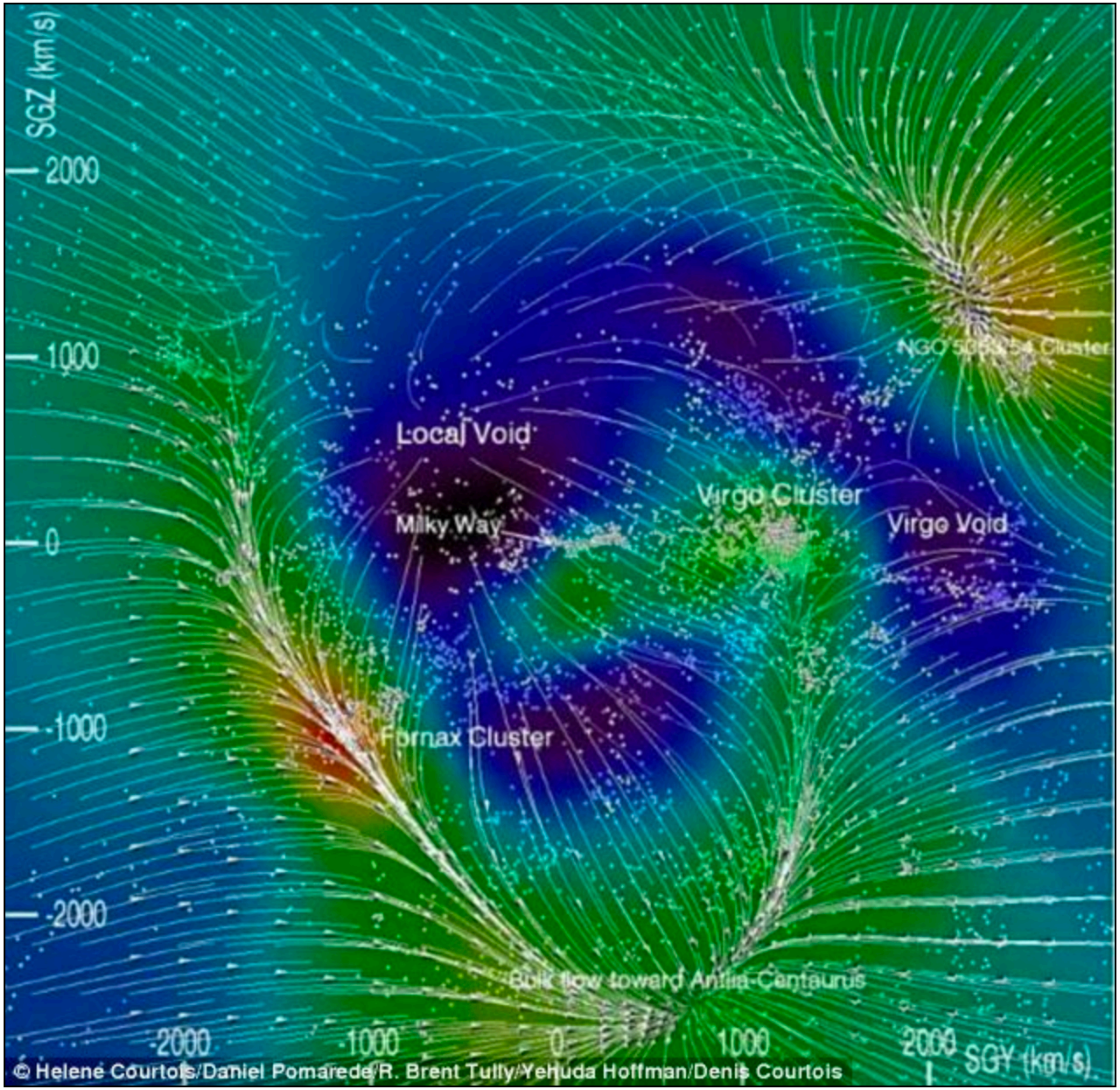
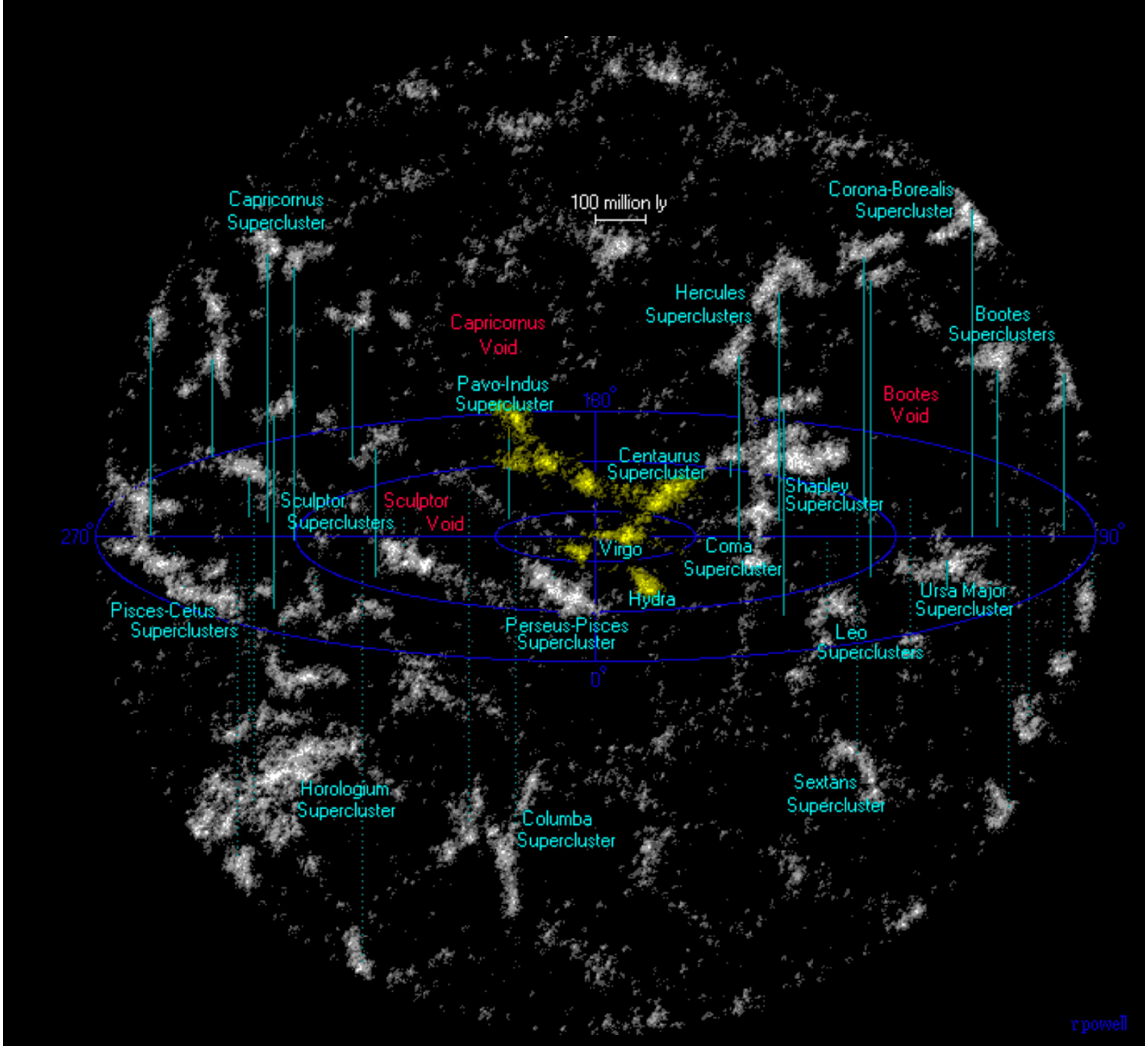
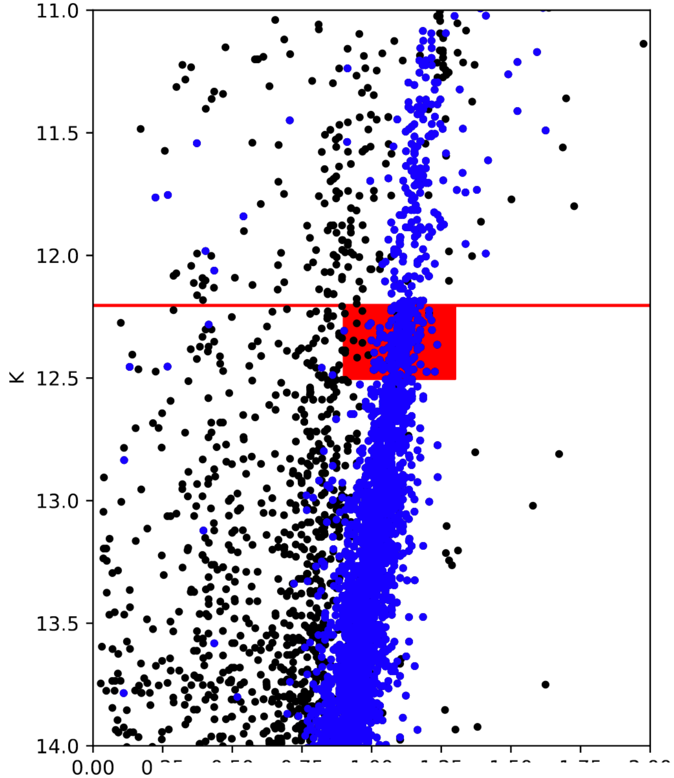


FIG. 1.—Isochrones in IR passbands from the library of Girardi et al. (2002) with dots marking the position of the TRGB. The curves (*left to right*), correspond to increasing values of metallicity; $Z = 0.004$, 0.001, 0.004, 0.008, 0.19, and 0.30.

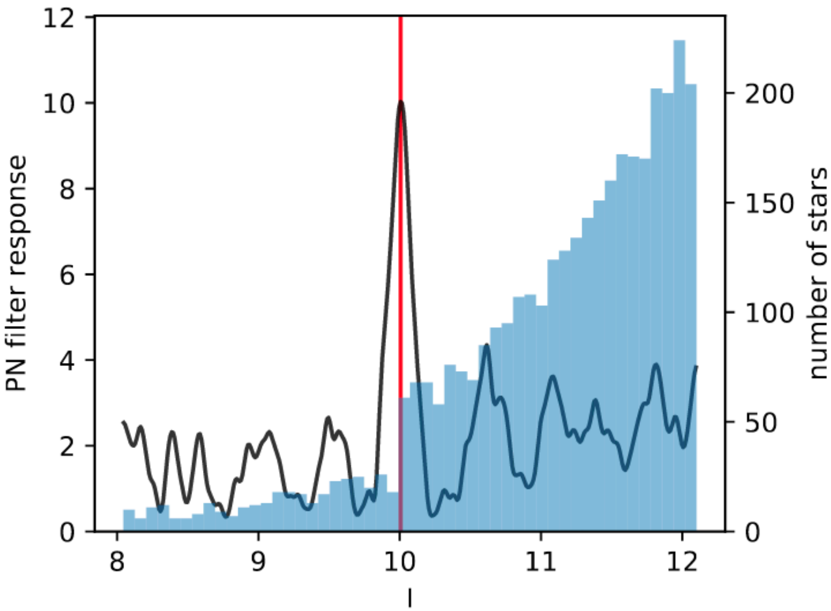
Massive applications of TRGB

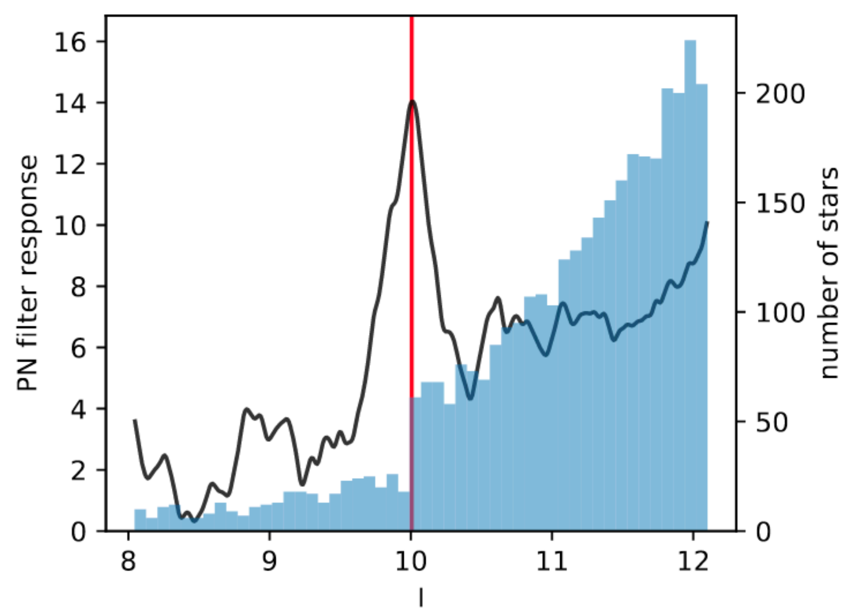



Capricornus Supercluster
100 million ly
Corona-Borealis Supercluster
Hercules Superclusters
Bootes Superclusters
Capricornus Void
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster
r powell



TRGB precision (multiband) calibration





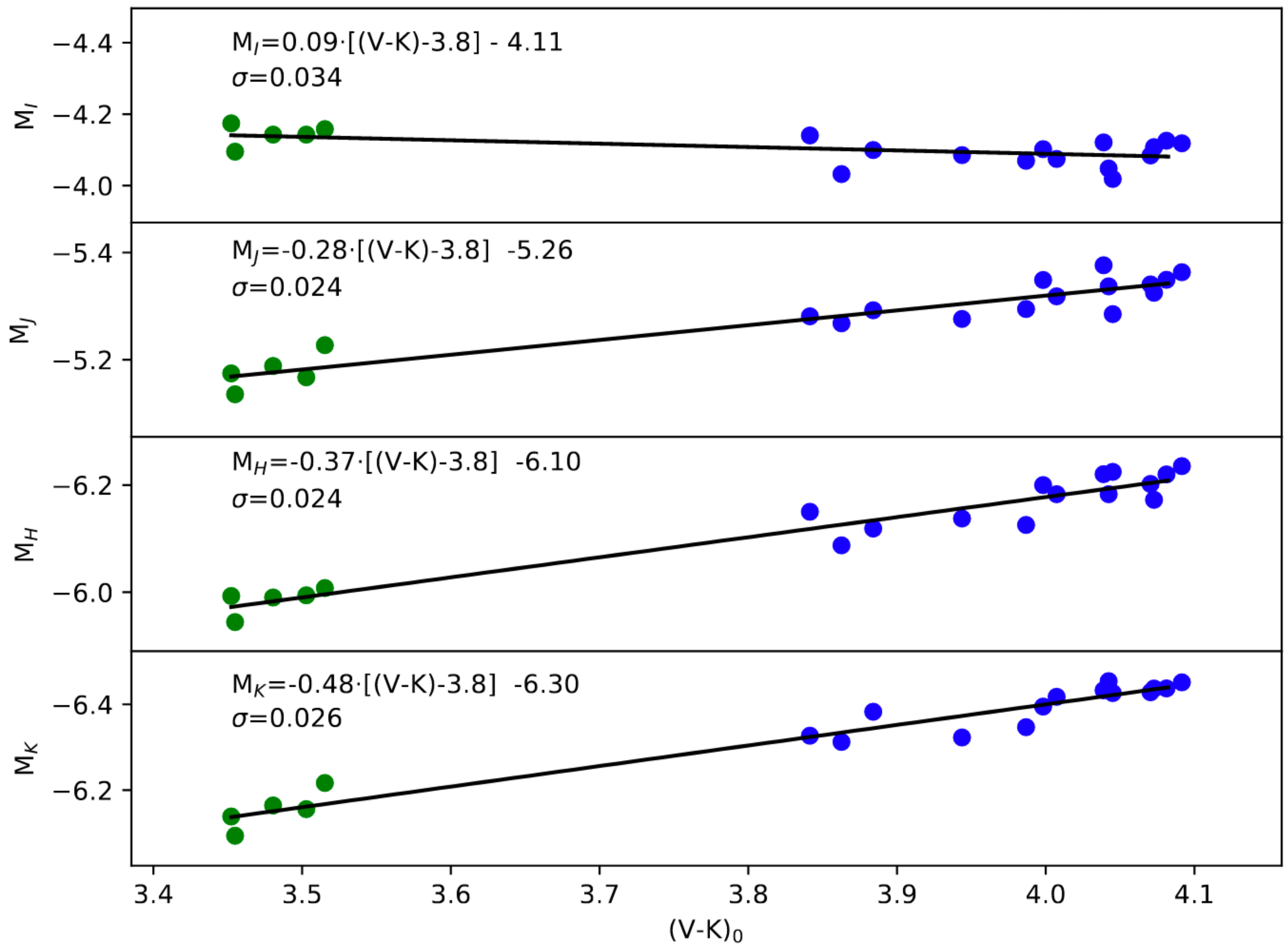


Fig. 6.— Absolute magnitudes of the TRGB as a function of the tip $(V\text{-}K)_0$ color. Green points come from 5 fields in the SMC, blue points from 14 fields in the LMC. Black solid line is the best fit to the data.

$$M_I = 0.09 \cdot ((V-K)_0 - 3.8) - 4.11$$

$$M_J = -0.28 \cdot ((V-K)_0 - 3.8) - 5.26$$

$$M_H = -0.37 \cdot ((V-K)_0 - 3.8) - 6.10$$

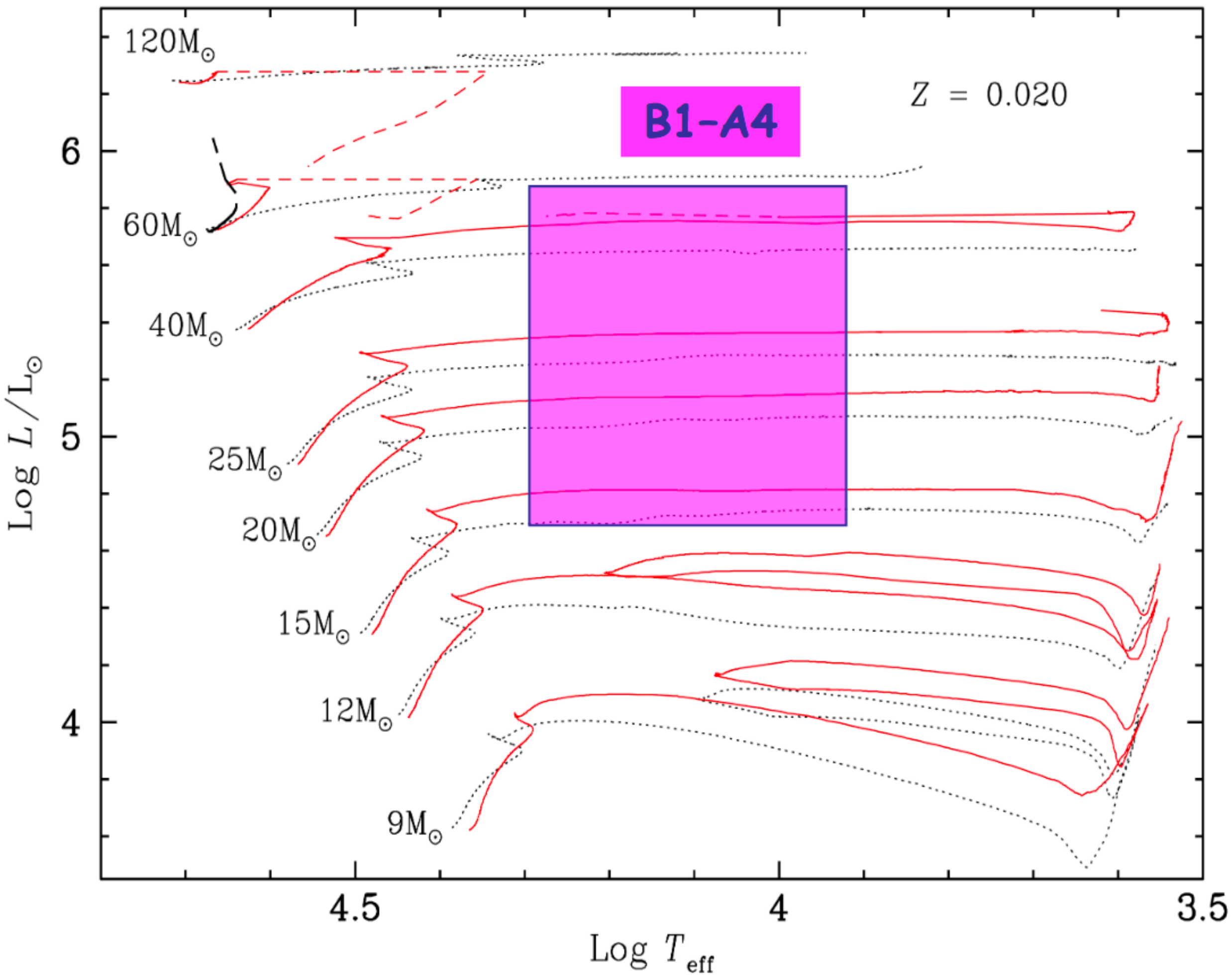
$$M_K = -0.48 \cdot ((V-K)_0 - 3.8) - 6.30$$

3-5 % precison !

We can use TRGB instead of Cepheids and calculate H_0 from LMC + TRGB + SN Ia

blue supergiants - objects in transition

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



$t_{ev} \sim 10^4$ yrs
L, M ~ const.

ideal to determine

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

nearby supergiants

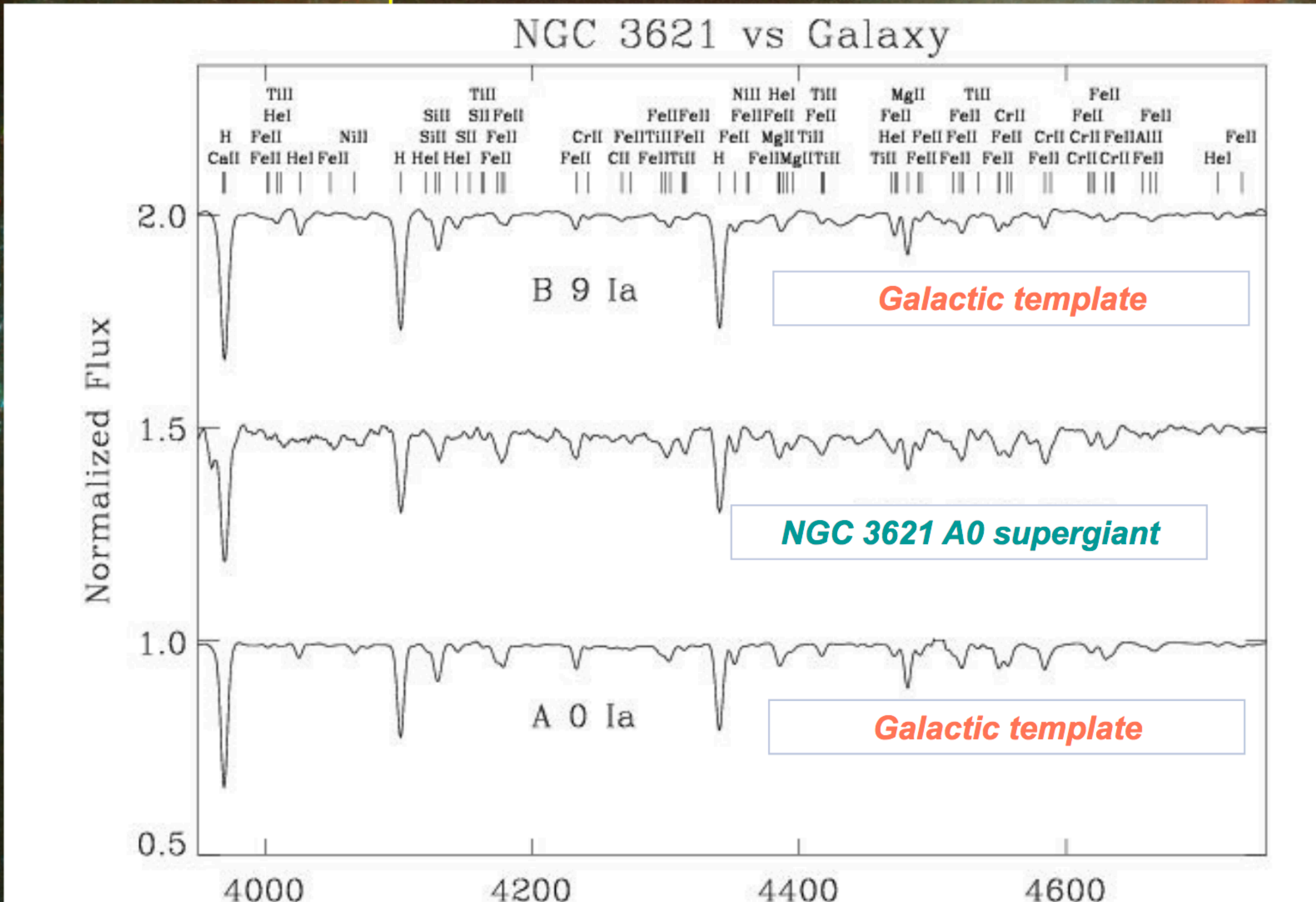
in Orion

1000 Lyrs away

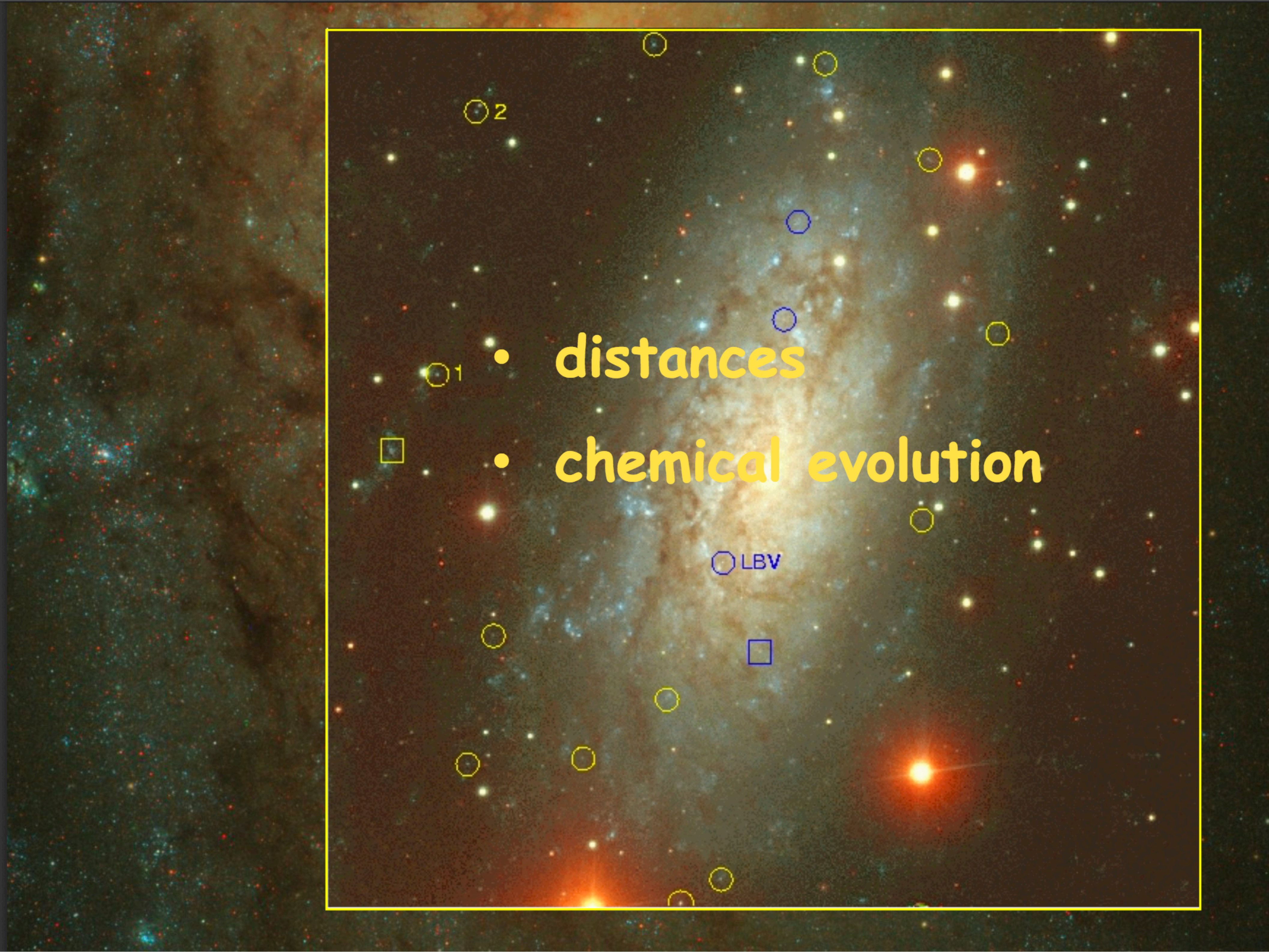
Rigel

NGC 3621 at 6.5 Mpc

stellar spectroscopy at 6.5 Mpc



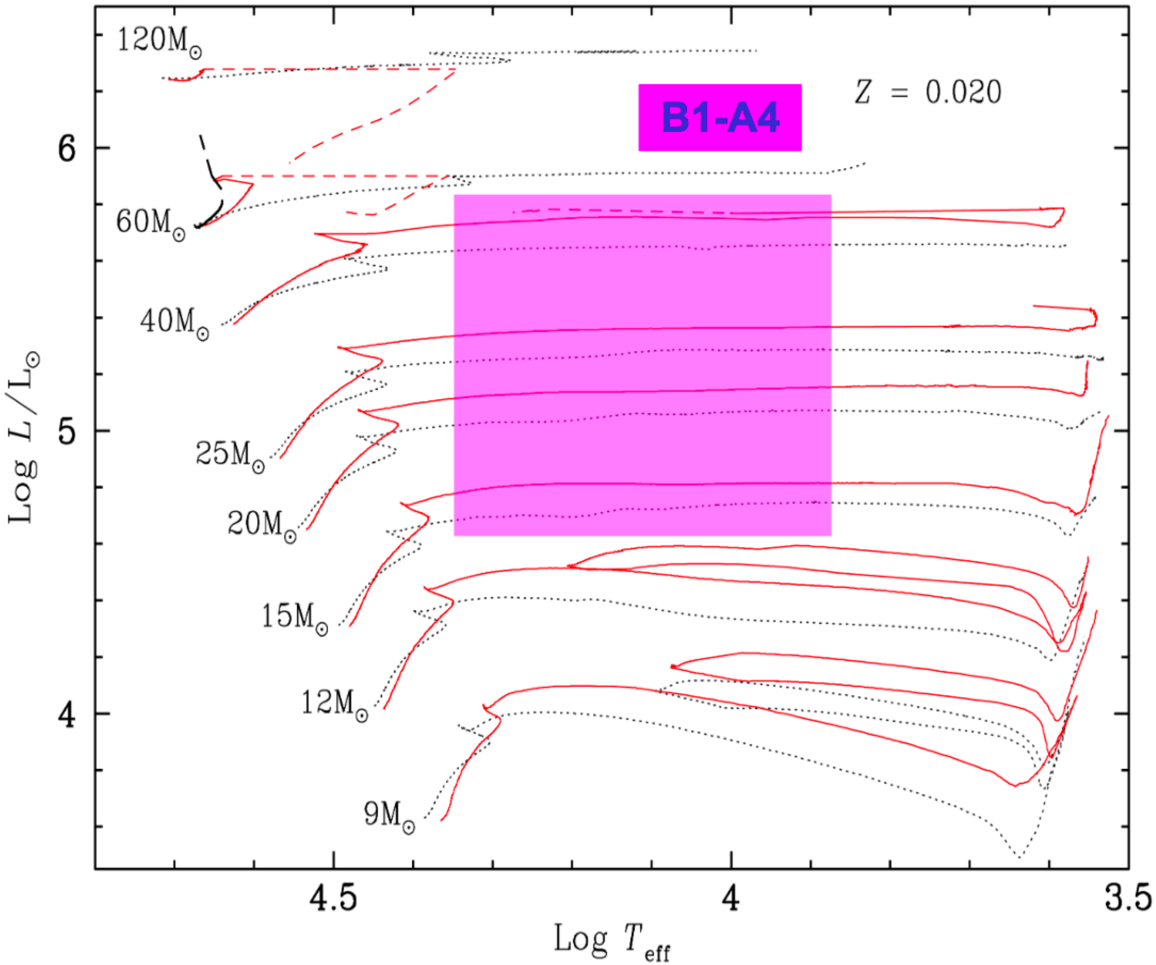
Bresolin, Kudritzki et al., 2001



2
1
LBV
• distances
• chemical evolution

Flux weighted Gravity – Luminosity Relationship (FGLR)

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



L,M ~ const.

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

const.

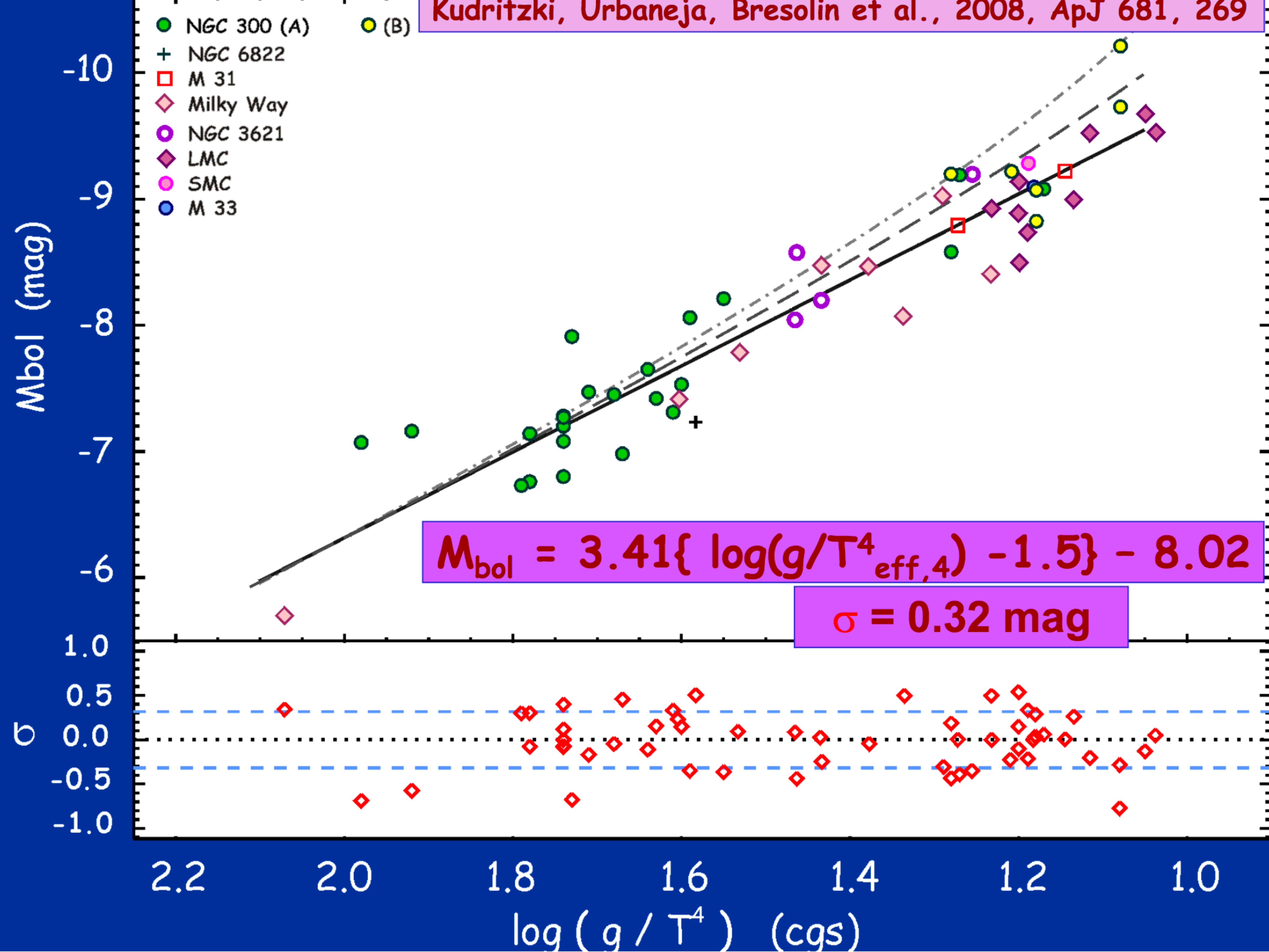
with $L \sim M^x \sim L^x (g/T^4)^x$, $x \sim 3$

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

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
1.0
0.5
σ 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)

Spectroscopic studies beyond the Local Group

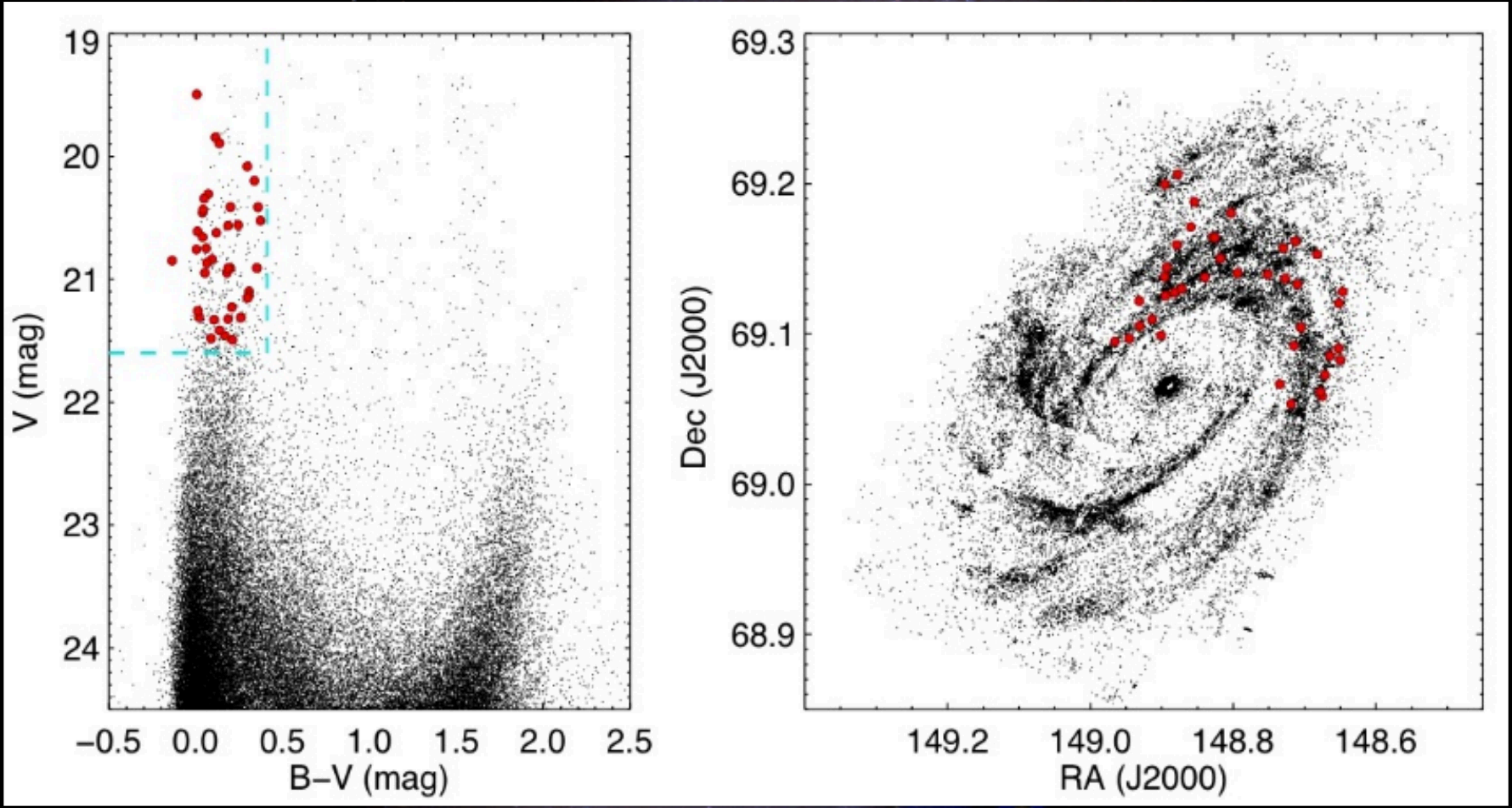
- selection of targets from wide field CMDs
- HST ACS imaging
- multi-object spectroscopy
  $\Delta\lambda$ ~ 4-5 A with FORS @ VLT
  LRIS @ Keck

→ T_{eff} ~ 4%, Δ log g ~ 0.05,
metallicity ~ 0.1 dex

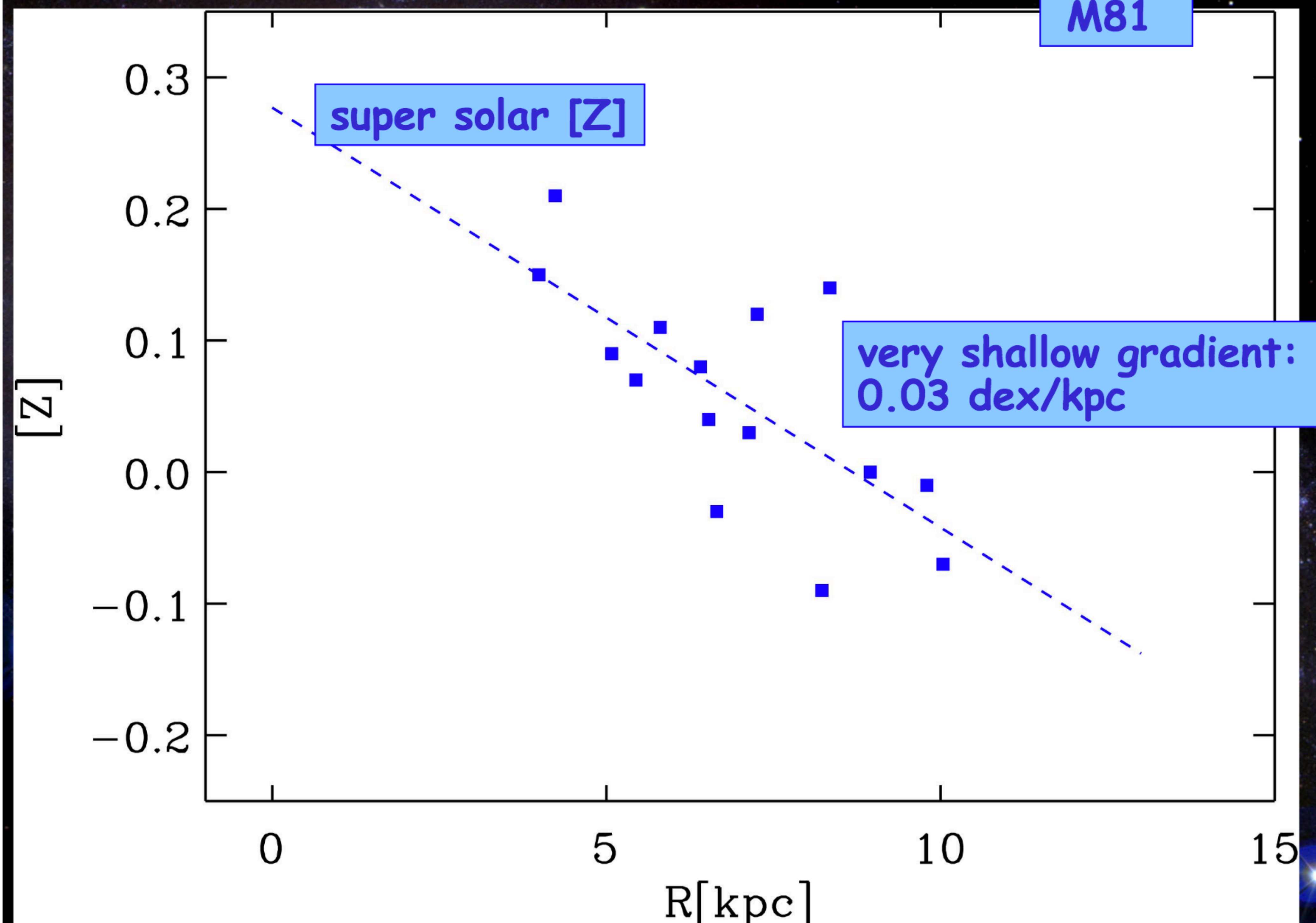
- galaxies out to 10 Mpc

M81

Keck LRIS

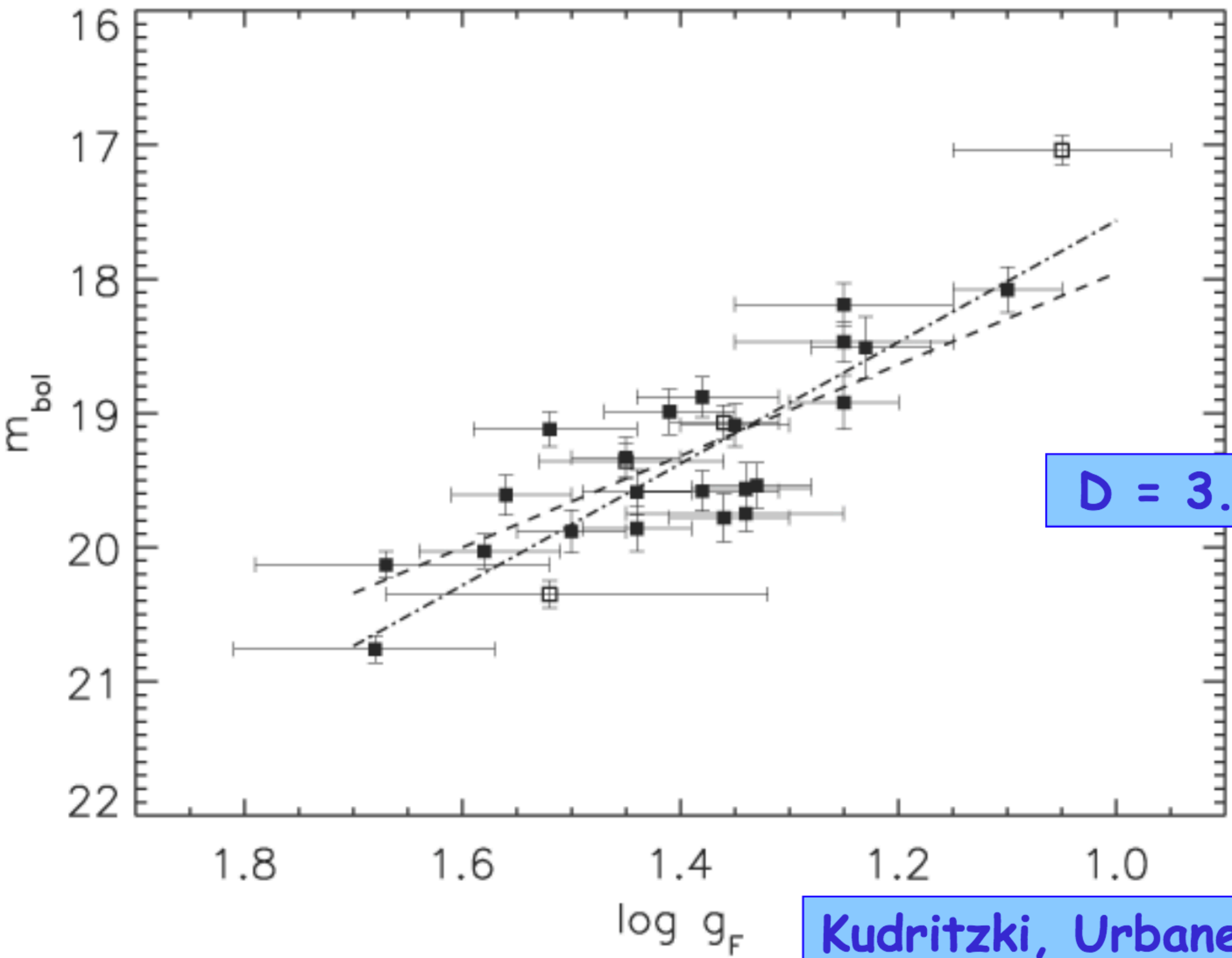


Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15



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

M81 FGLR



D = 3.47 ± 0.16 Mpc

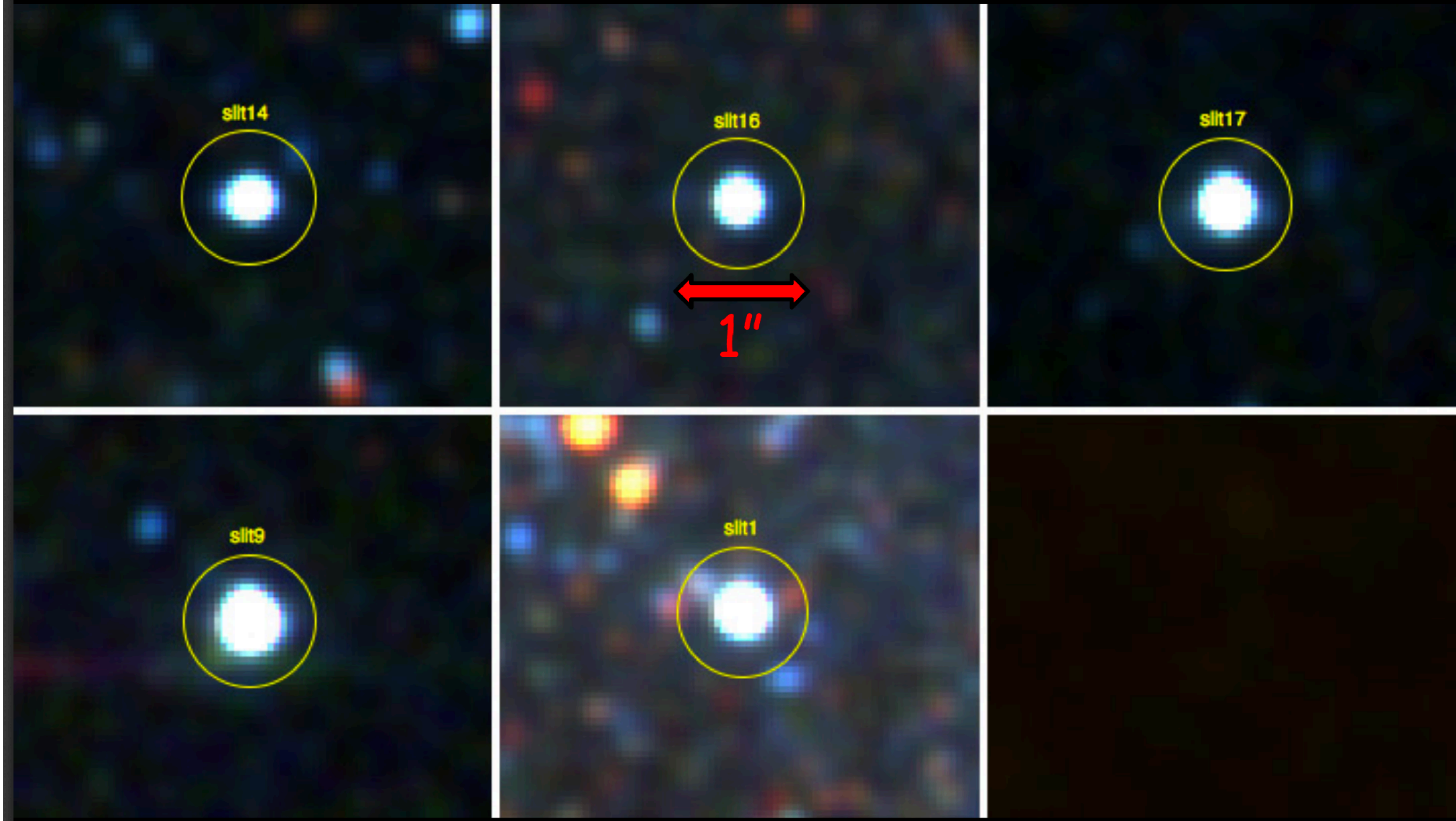
Kudritzki, Urbaneja, Gazak et al. 2012, ApJ 747, 15

NGC 3621

Key Project galaxy at 6.5 Mpc

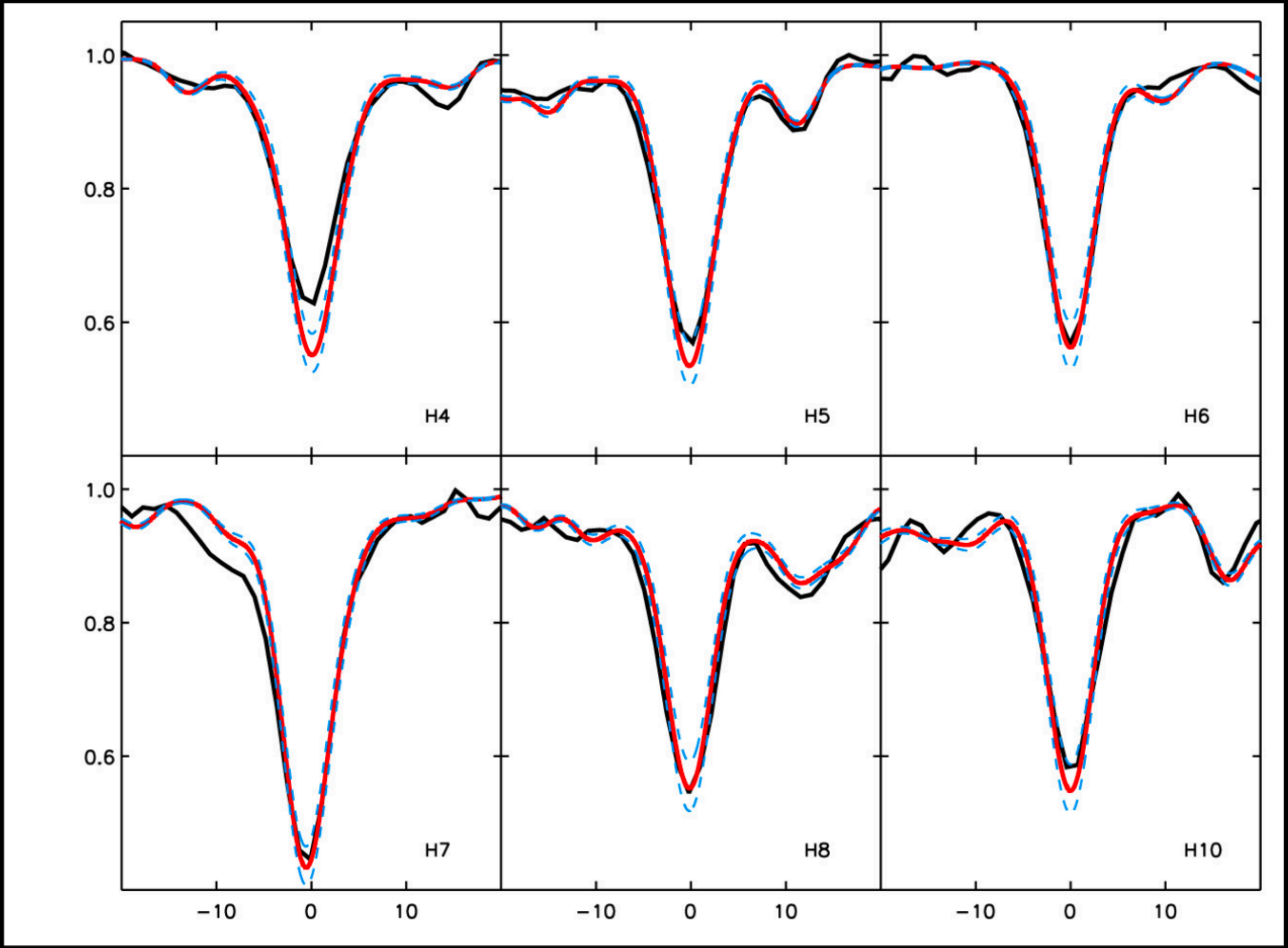
Tully-Fisher calibrator

BSGs in NGC 3621: HST ACS



Fit of Balmer lines ⟶ log g

NGC 3621 slit 17



best log g fit

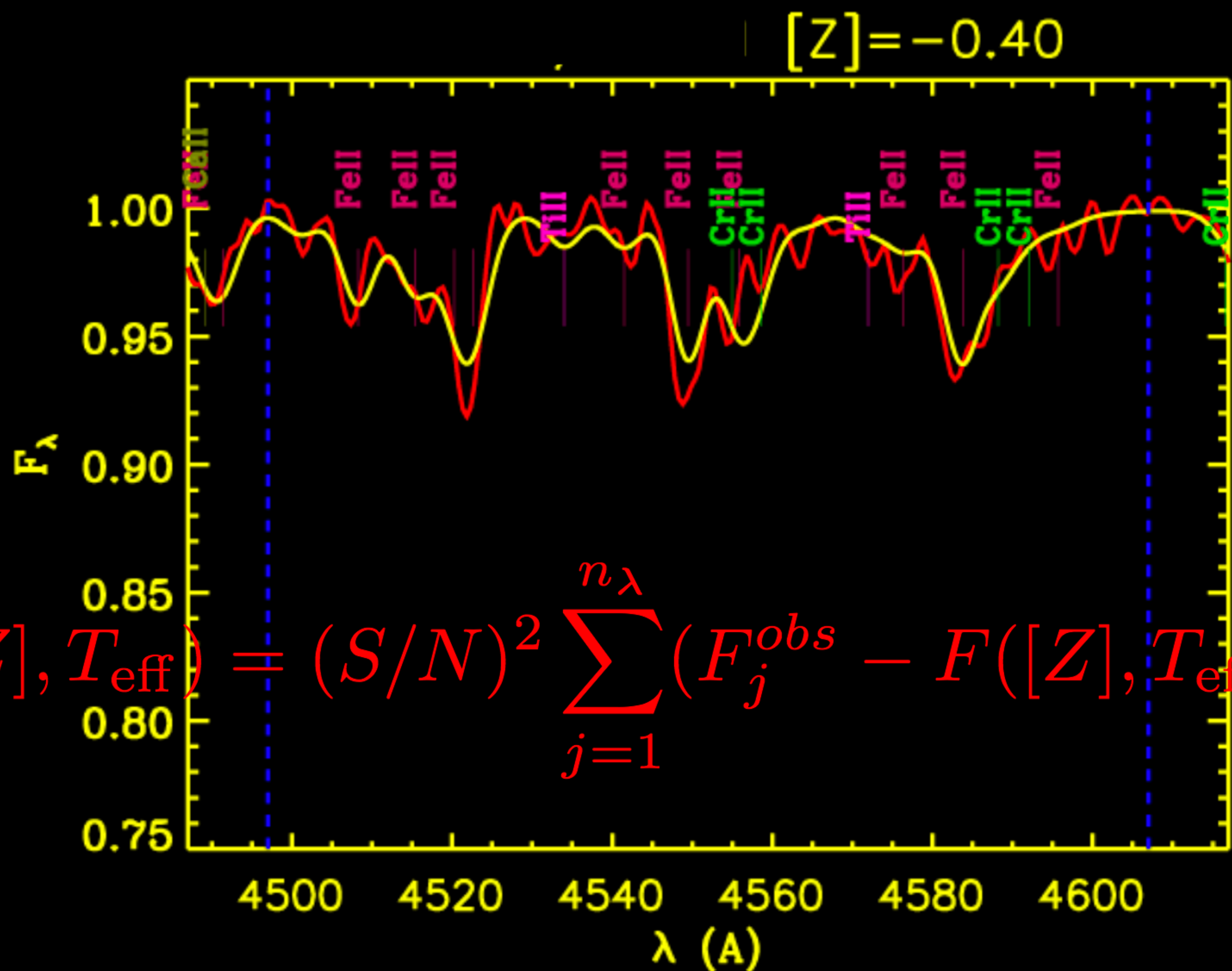
--- $\Delta \log g = \pm 0.05$

At fixed T_{eff}

$\Delta \log g \leq \pm 0.05$

MIAPP 2014

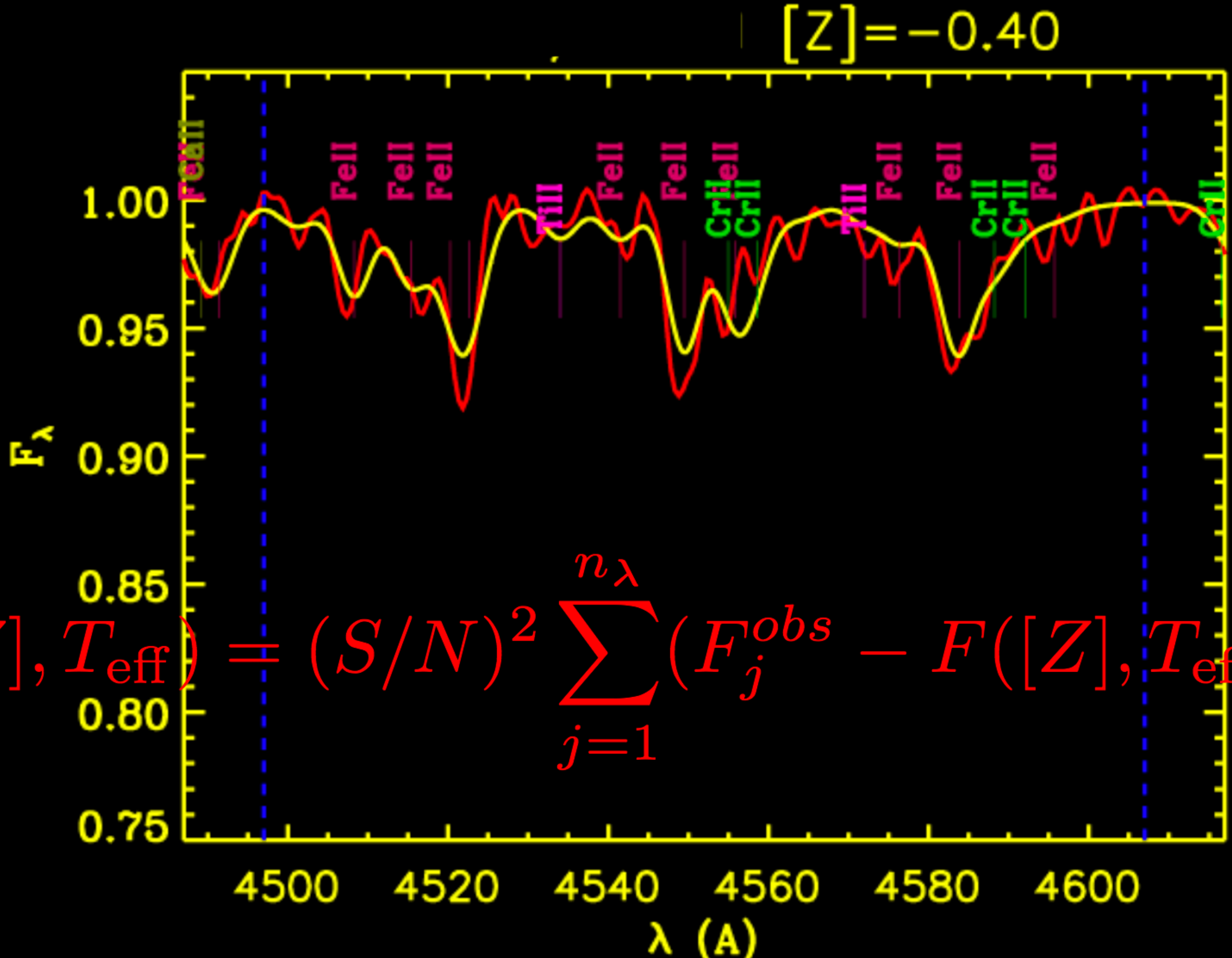
Spectral window 4497-4607Å



$$\chi^2([Z],T_{\rm eff}) = (S/N)^2 \sum_{j=1}^{n_\lambda} \left(F_j^{obs} - F([Z],T_{\rm eff})_j^{calc}\right)^2$$

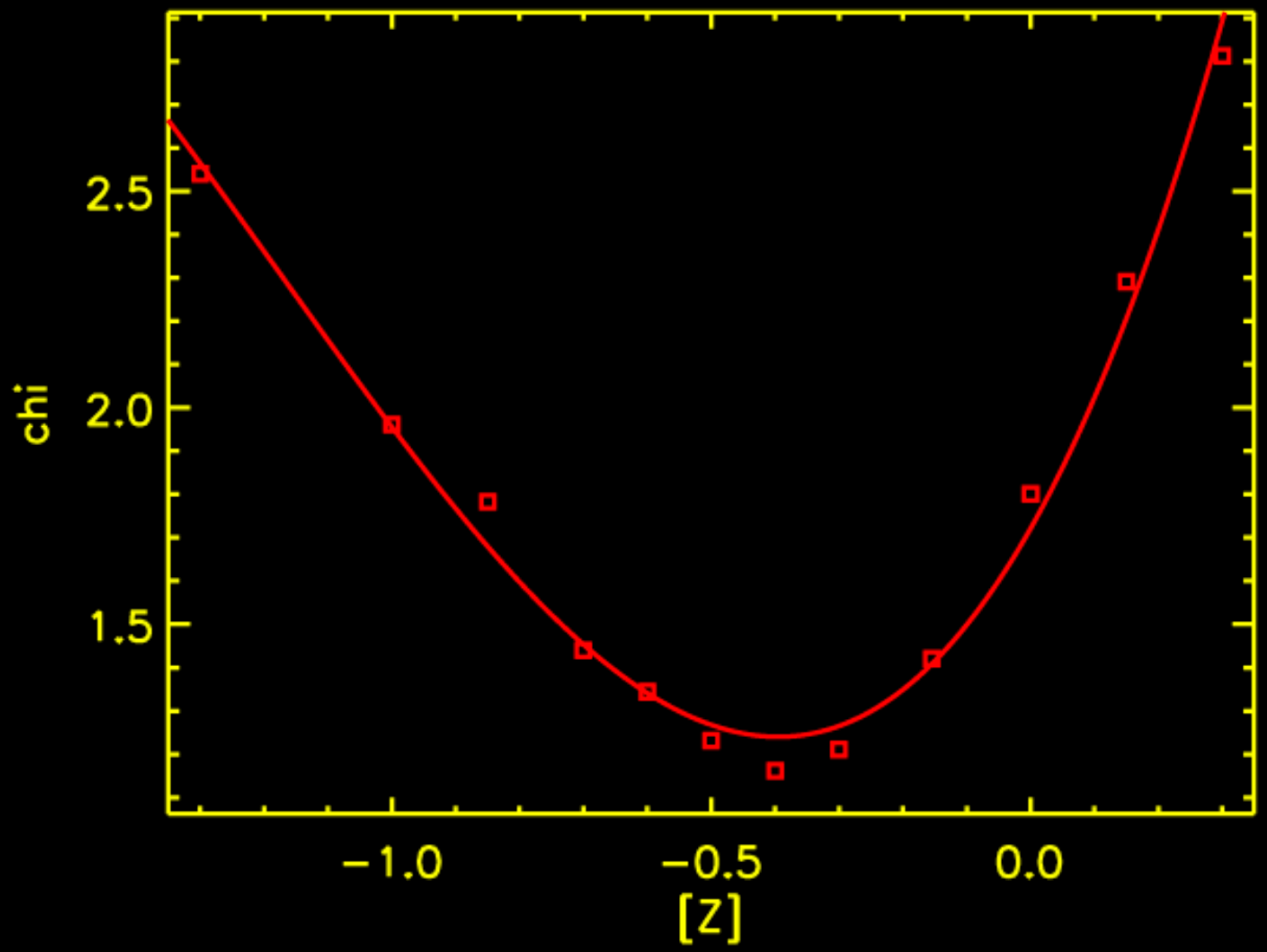
MIAPP 2014

Spectral window 4497-4607Å

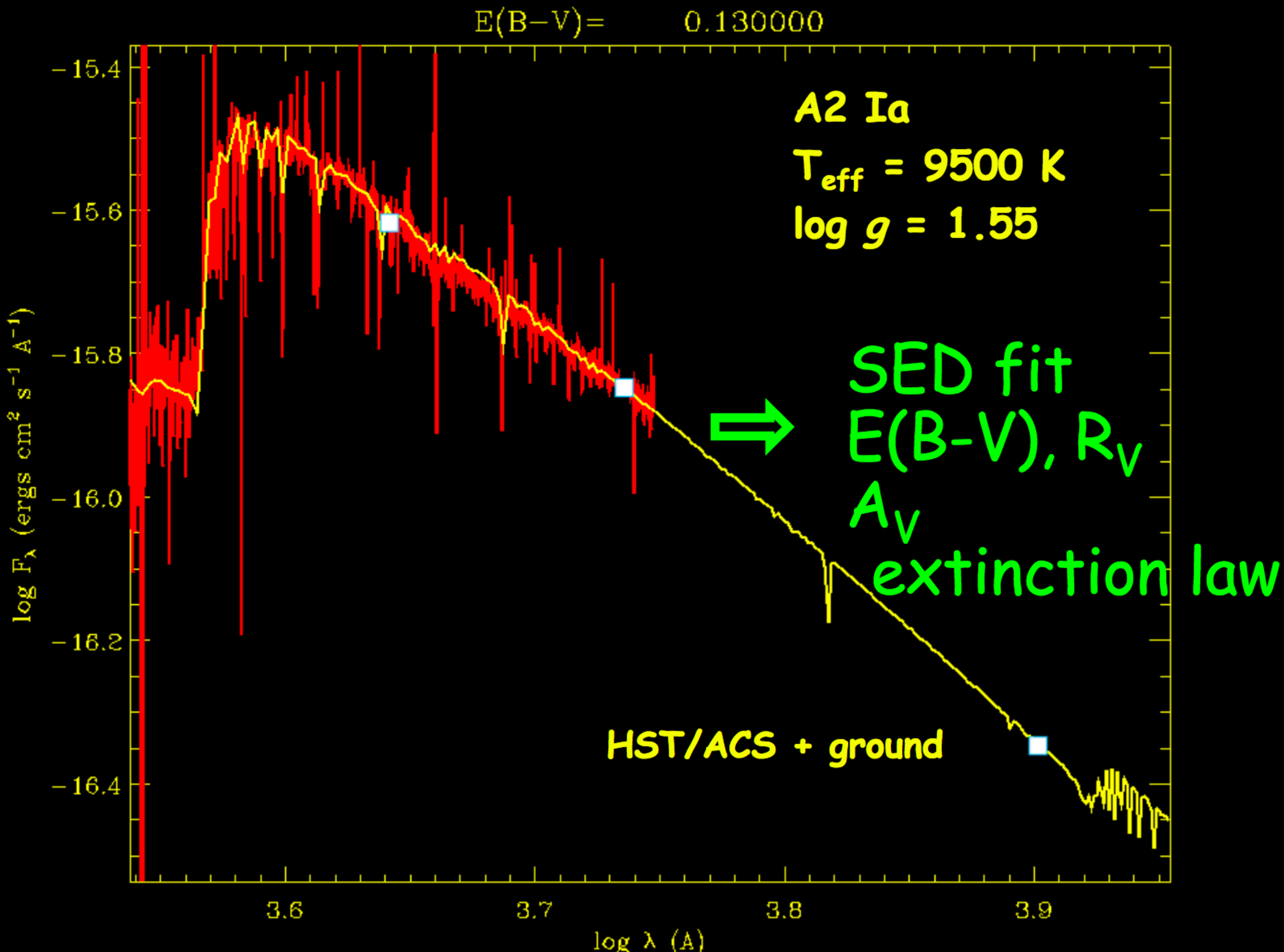


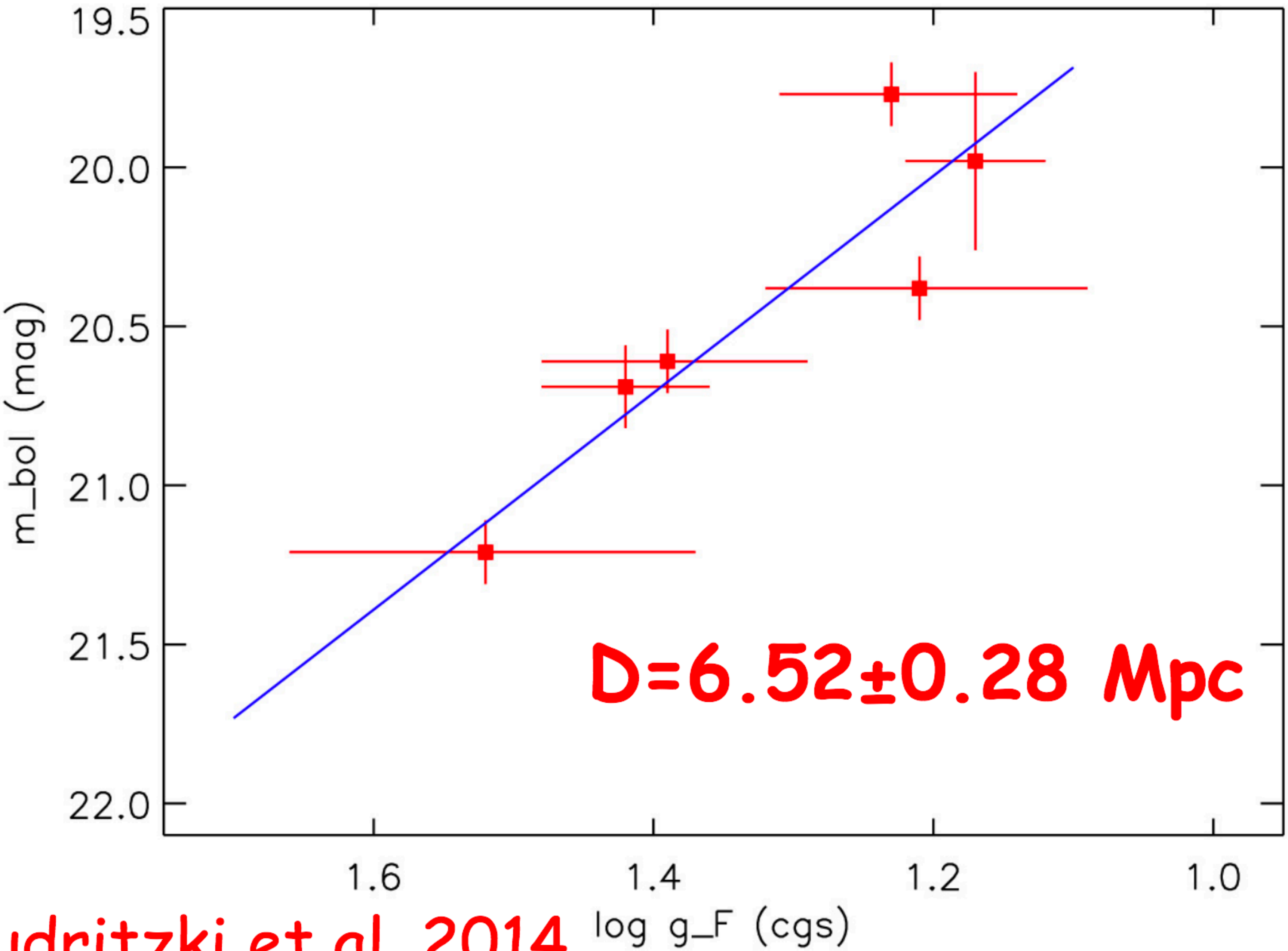
$$\chi^2([Z],T_{\rm eff}) = (S/N)^2 \sum_{j=1}^{n_\lambda} (F_j^{obs} - F([Z],T_{\rm eff})_j^{calc})^2$$

χ_i spectral window 4497-4607Å

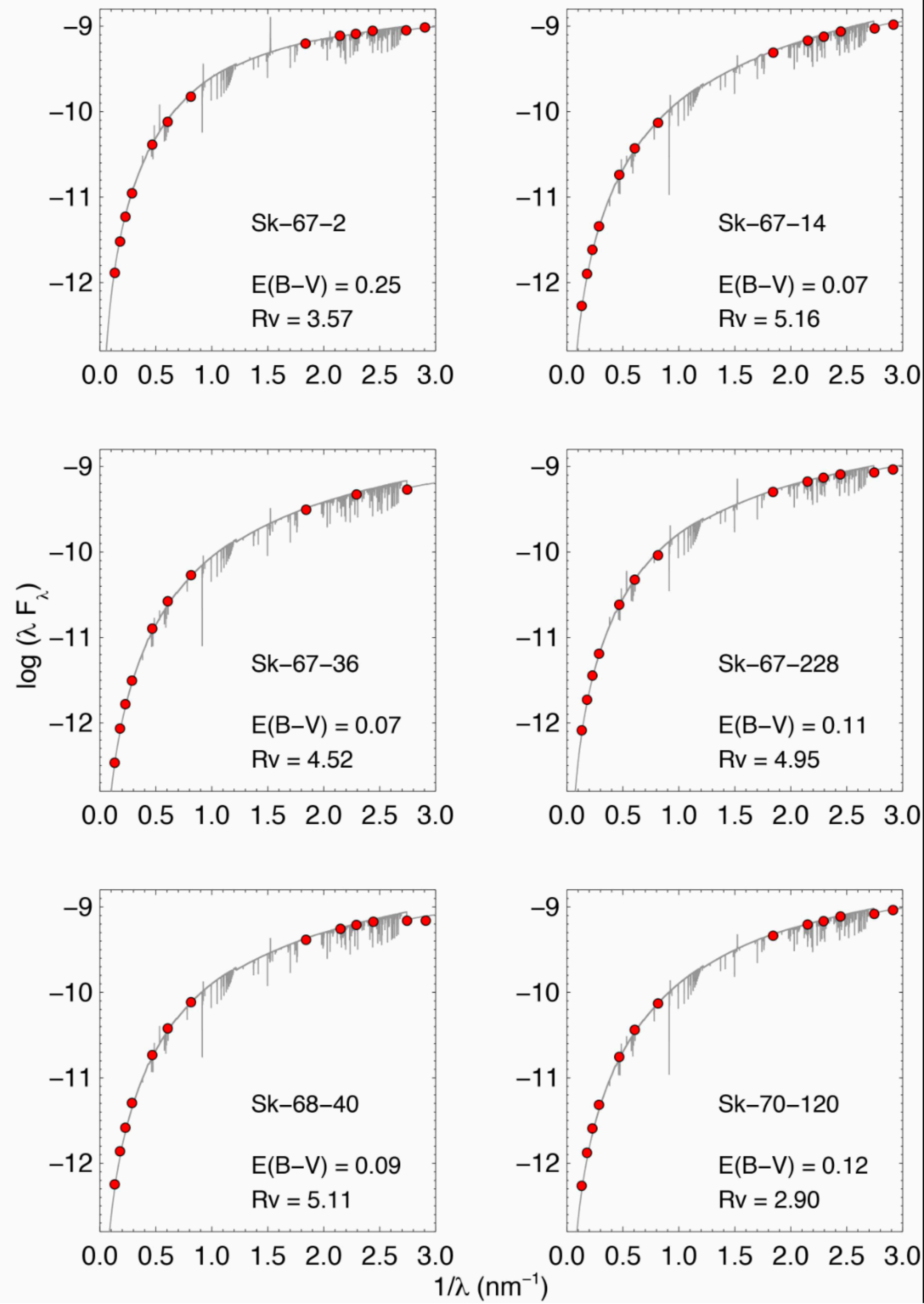


A supergiant SED



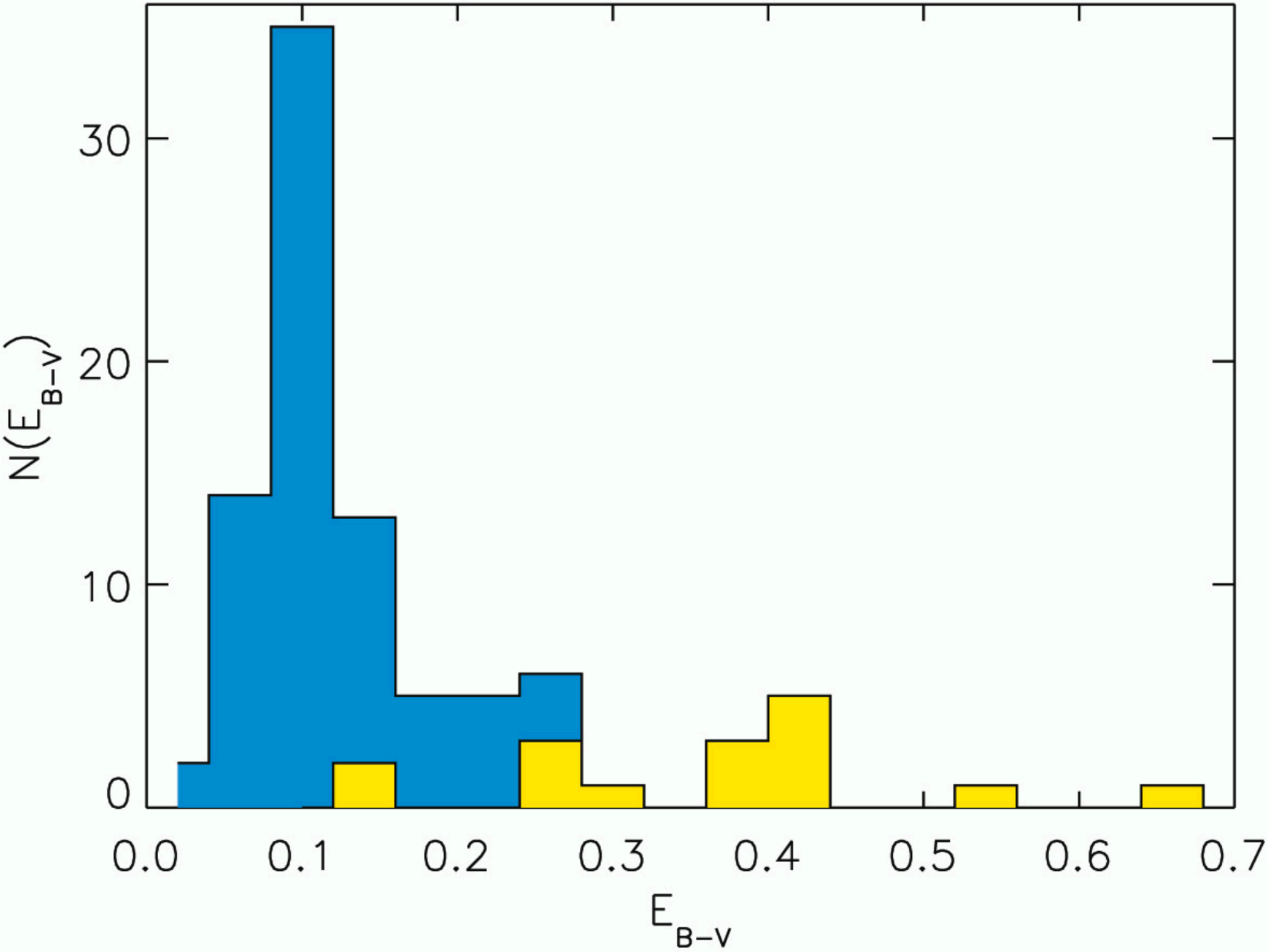


Kudritzki et al. 2014



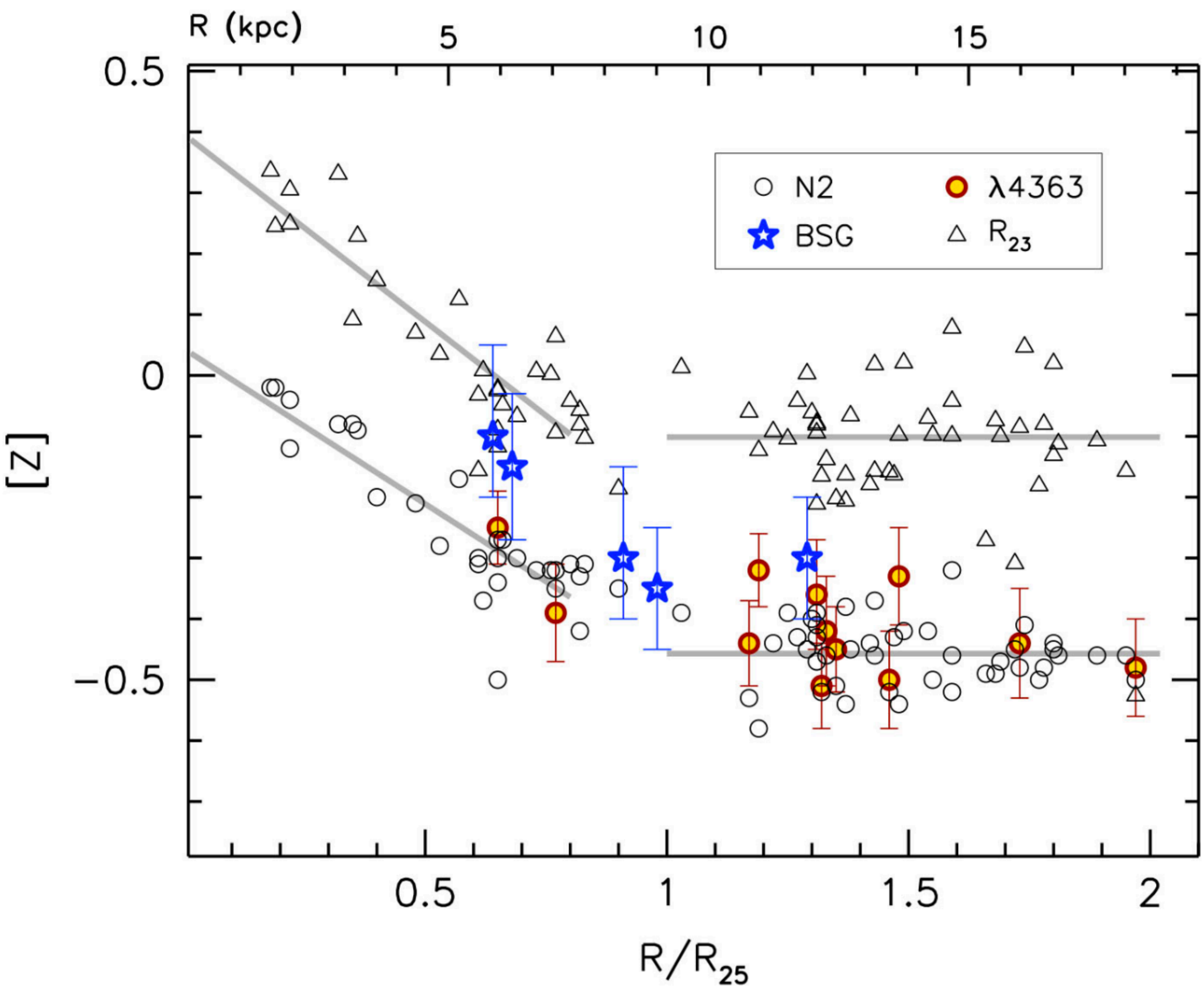
early B Sgs

- E(B-V)
- Rv from E(V-X) and E(B-V)
  - Use B, V, J, H, Ks
  - Spitzer provides a posteriori check



N(E_{B-V})
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
E_{B-V}

NGC 3621 stellar metallicity



comparison with HII
Bresolin et al., 2012

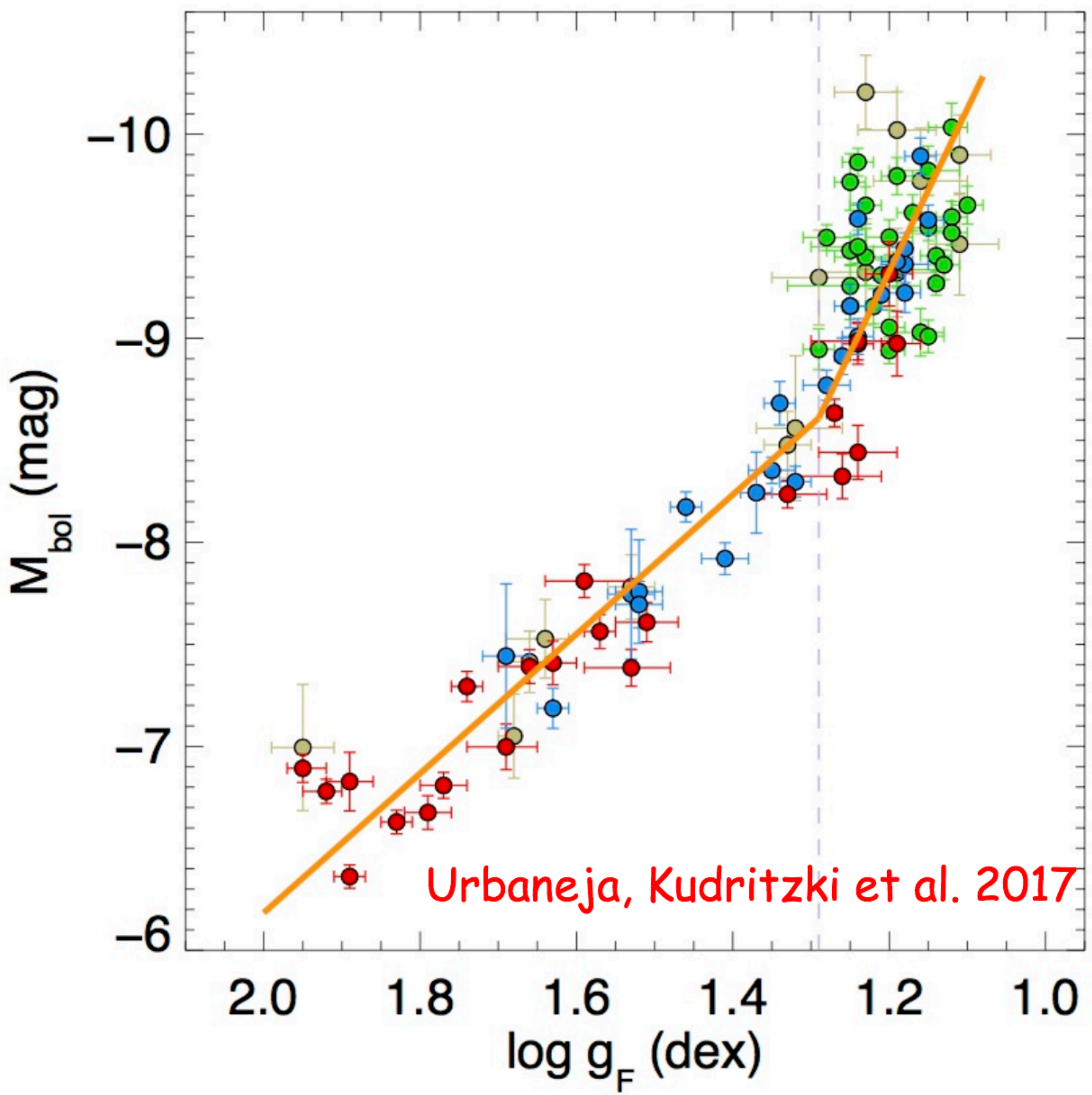
between the two HII
strong line methods

~ 0.1 dex higher than
auroral line method

confirms outer disk flat
metallicity profile

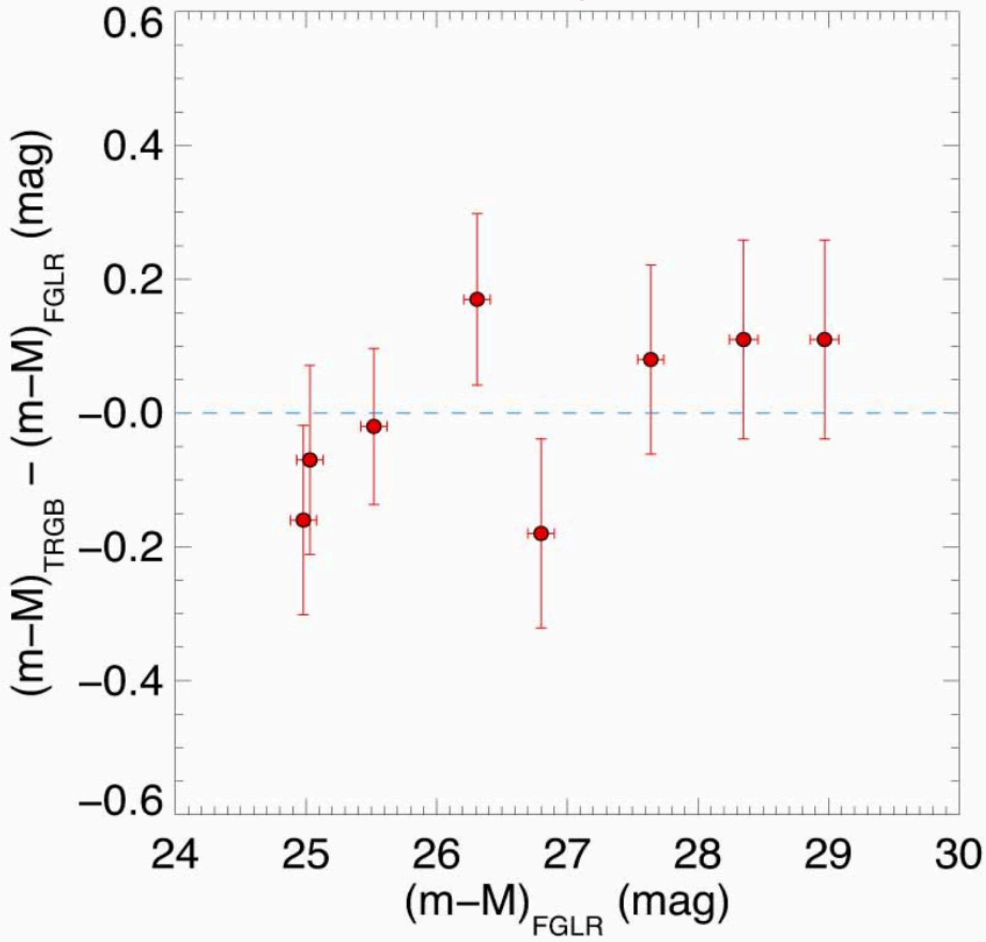
E(B-V) ≈ 0.2 mag in
outer disk

Kudritzki et al. 2014

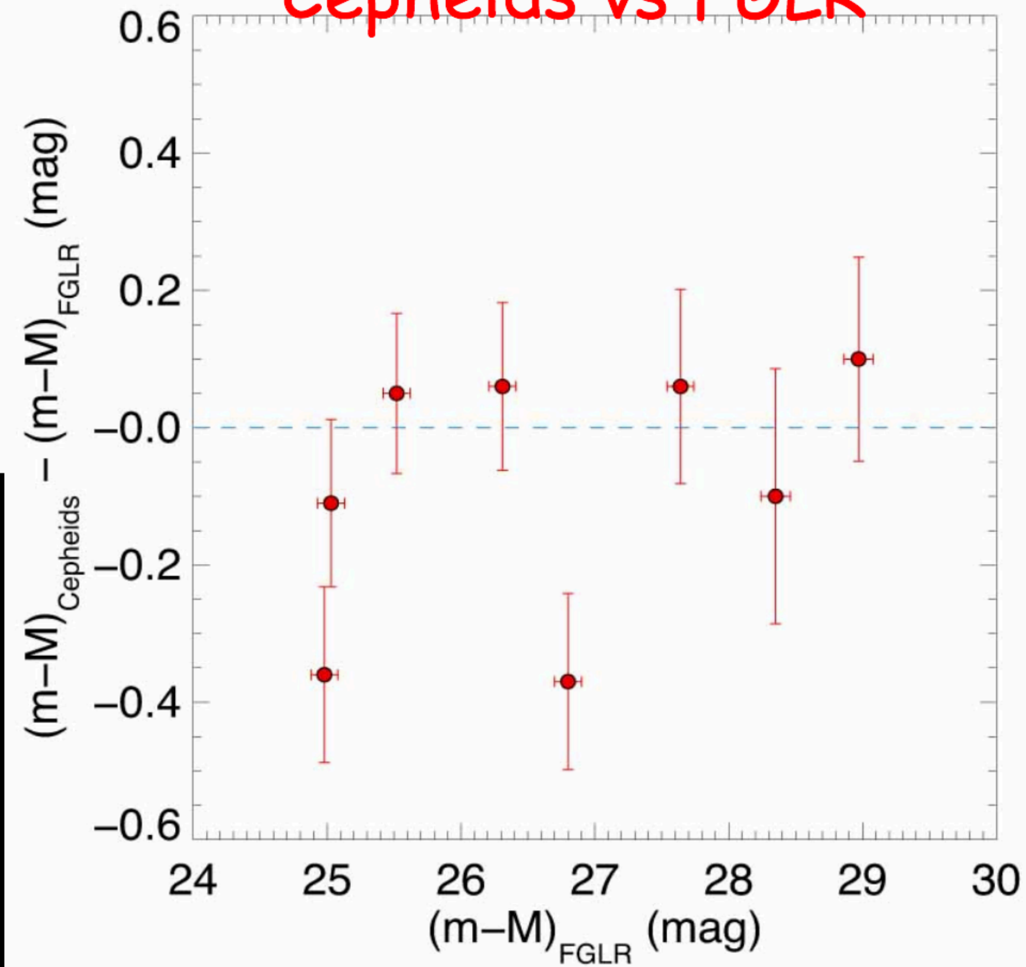


−10
−9
−8
−7
−6
M_bol (mag)
2.0
1.8
1.6
1.4
1.2
1.0
log g_F (dex)
Urbaneja, Kudritzki et al. 2017

TRGB vs FGLR



Cepheids vs FGLR



Kudritzki, Urbaneja et al., 2017

Conclusions and TMT/ELT perspectives

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

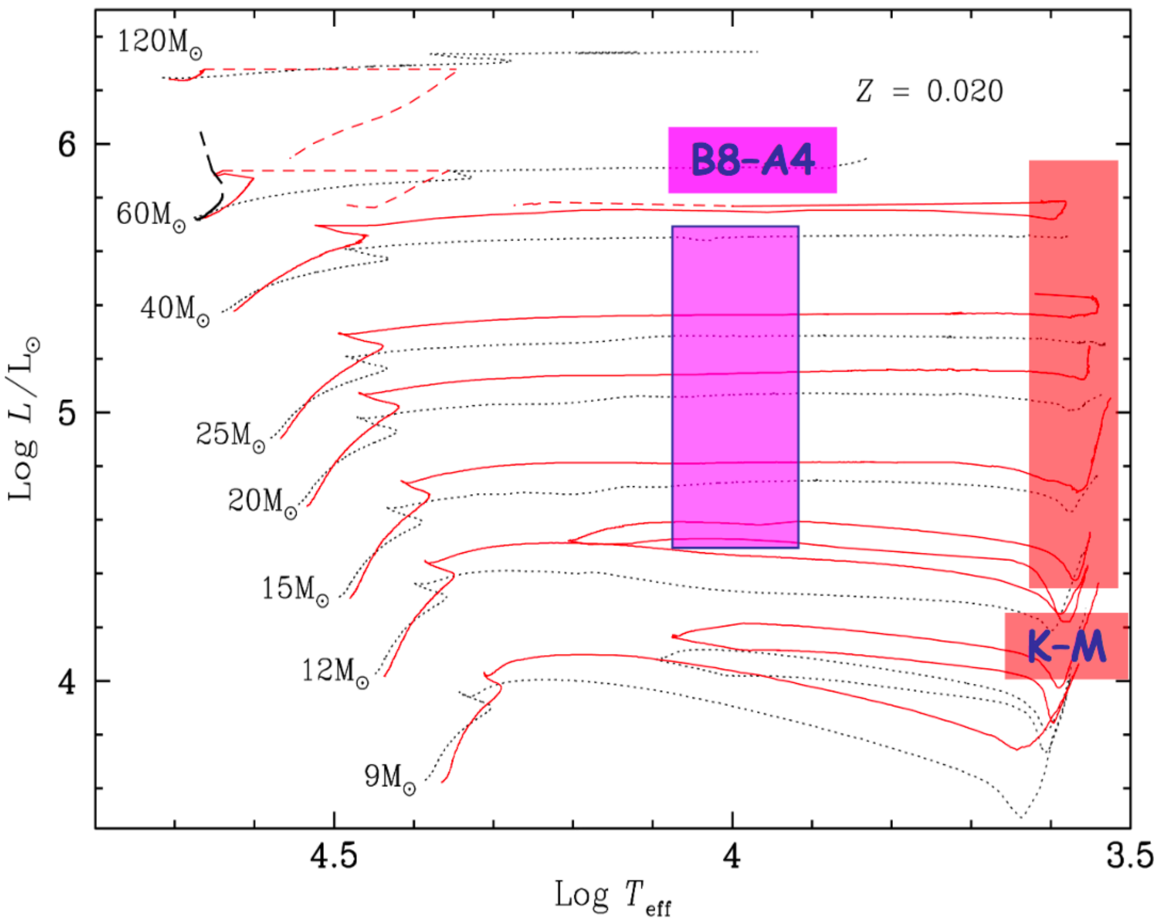
→ with objects $M_V \leq -8$ mag

m - M ~ 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

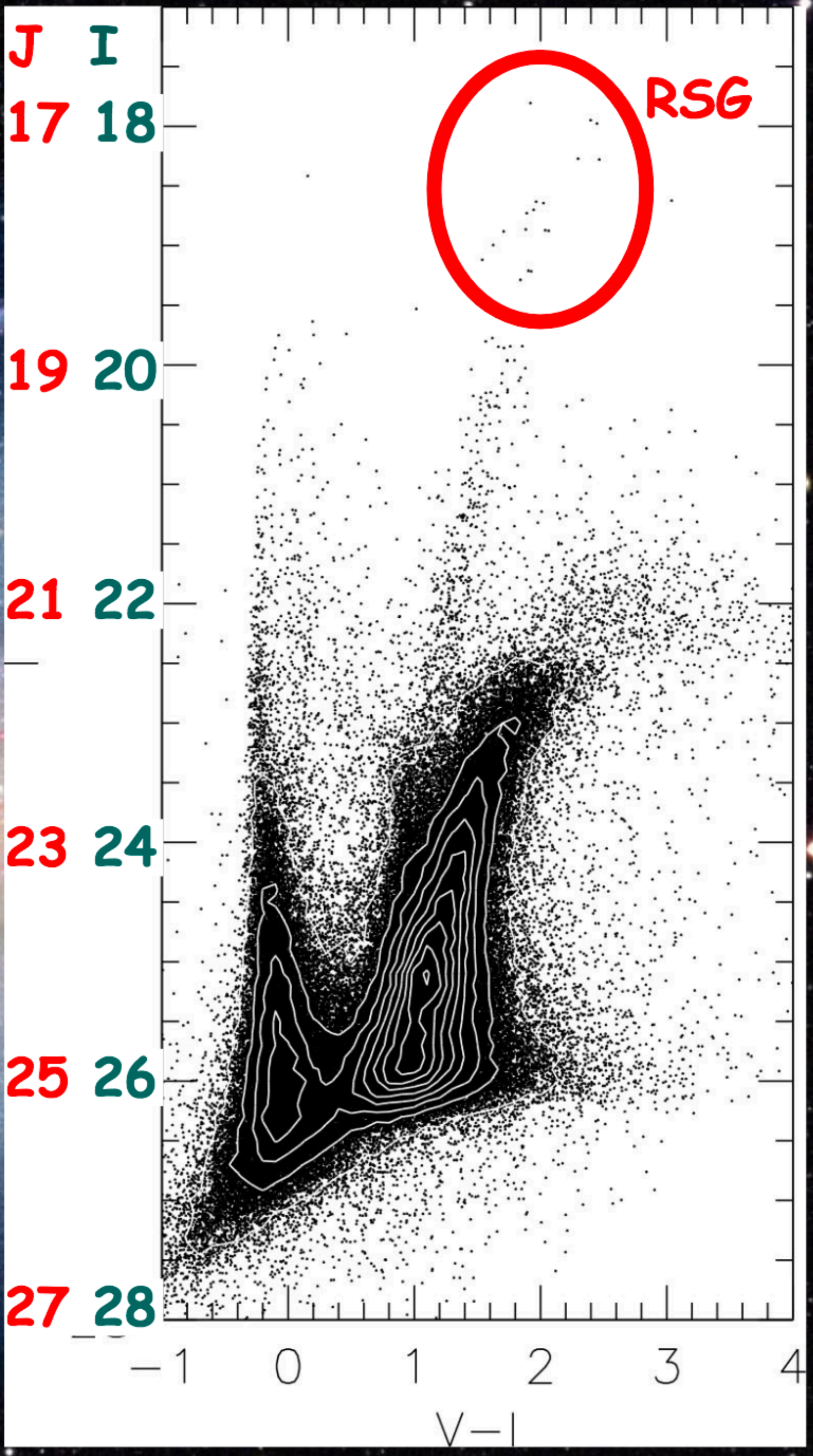
medium resolution J-band spectroscopy:

atomic lines dominate

→medium res. spectra ok

→ enormous potential with Keck/VLT, TMT/E-ELT beyond Local Group out to Coma cluster

NGC 300



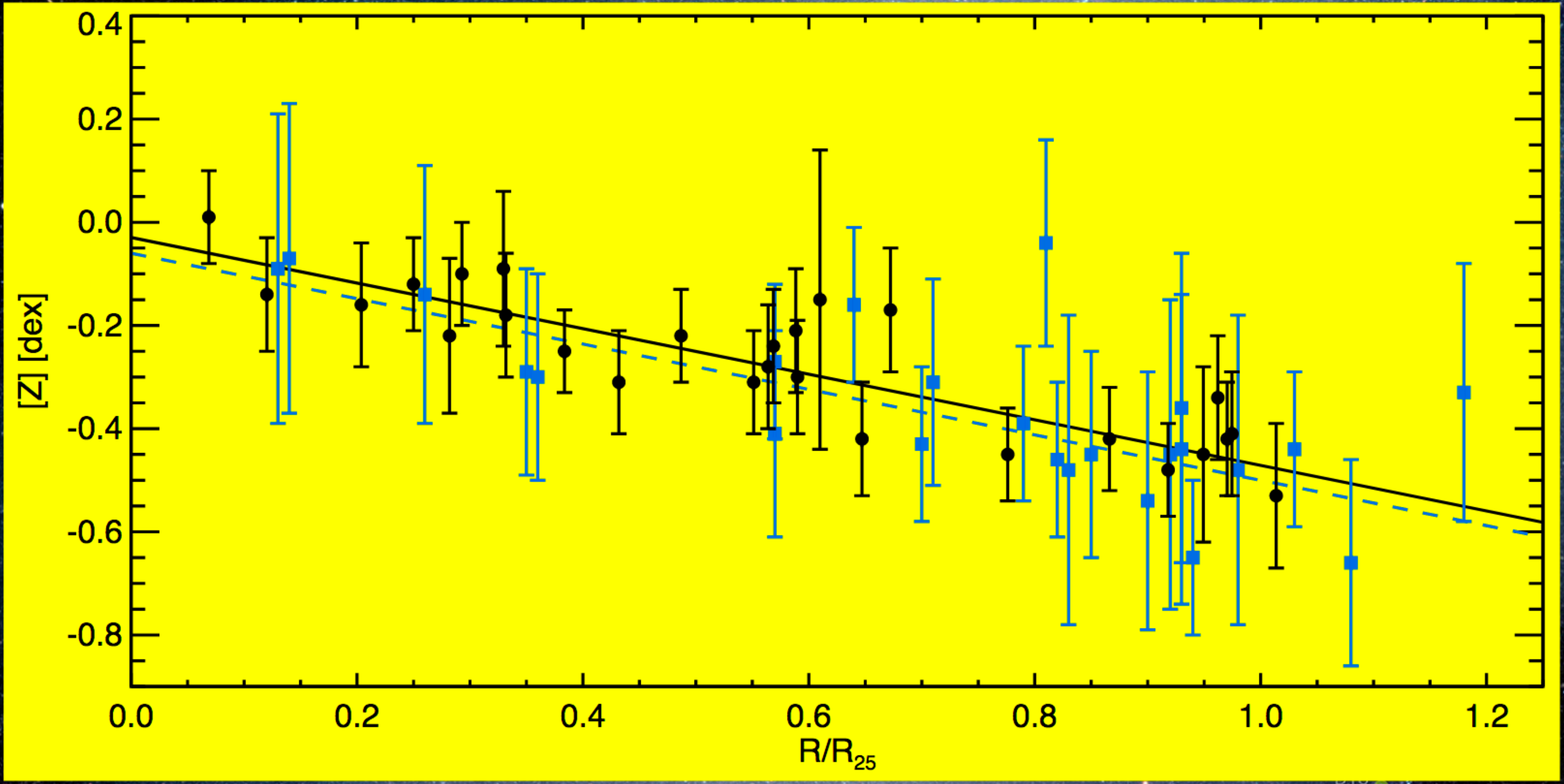
CMD (HST ACS)
one out of 6 fields
Bresolin et al. (2005)

NGC300
KMOS RSG spectra

final fits

Gazak, Kudritzki, Evans et al., 2015, ApJ 805, 182

NGC 300 : blue and red supergiant stars



Kudritzki, Urbaneja, Bresolin et al. 2008, ApJ 681, 269
Gazak, Kudritzki, Evans et al., 2015, ApJ 805, 182

Keck/MOSFIRE and VLT/KMOS

[Z] ± 0.1 dex down to J =19.5^m

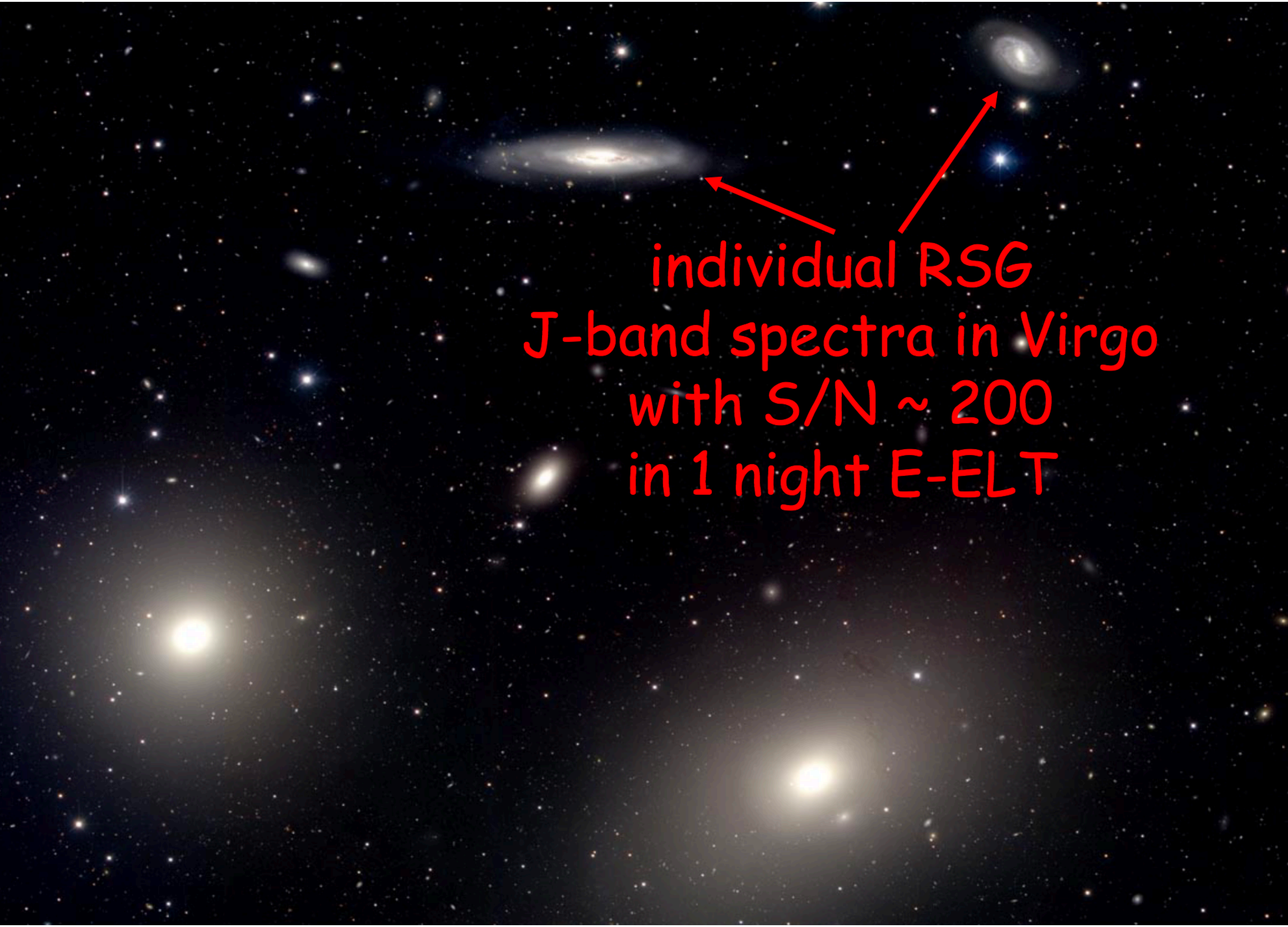
RSG: $-8^m \geq M_J \geq -11^m$

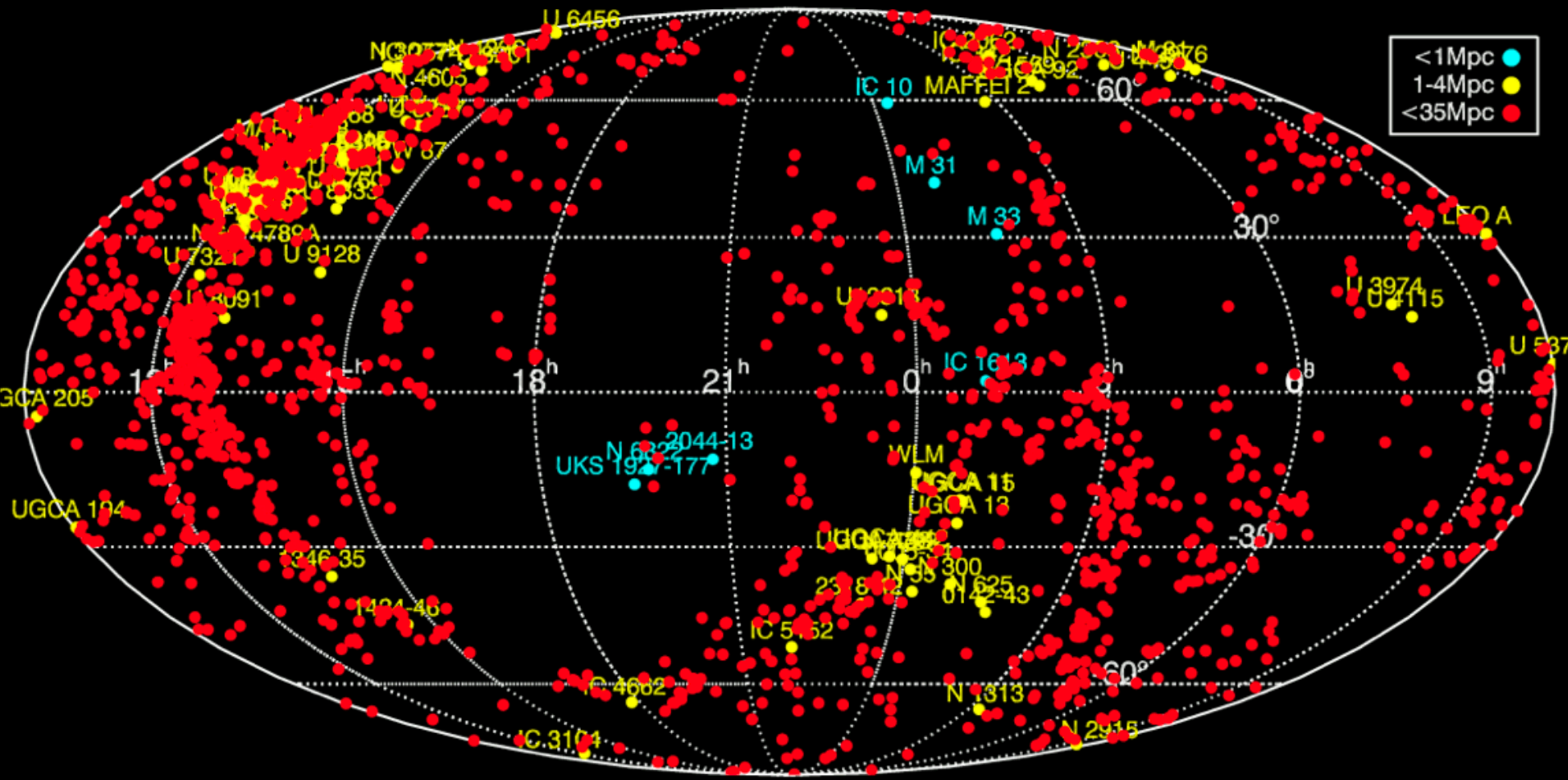
↓ ↓

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

↓ ↓

3.2 Mpc ≤ d ≤ 12.6 Mpc


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



- E-ELT: galaxies out to 35Mpc (modest…)
- number of observable targets increased to ~1500!!