Revealing galaxy evolution through their globular cluster systems

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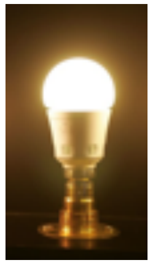
With thanks to:
Søren Larsen
Michele Cantiello
Jean Brodie
Elizabeth Wehner
Jay Strader
João Francisco Santos
Markus Kissler-Patig

Outline

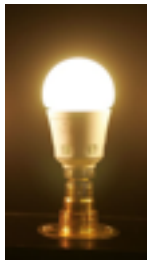
★ Introduction

- ✓literature review
- ✓why bother with GCs?



★Ages

★Metallicity distributions



★Co-evolution of GCs and their host galaxies

Introduction

- ★Goal? ➡ evolutionary history of E+S0
- ★How? ➡ GC systems

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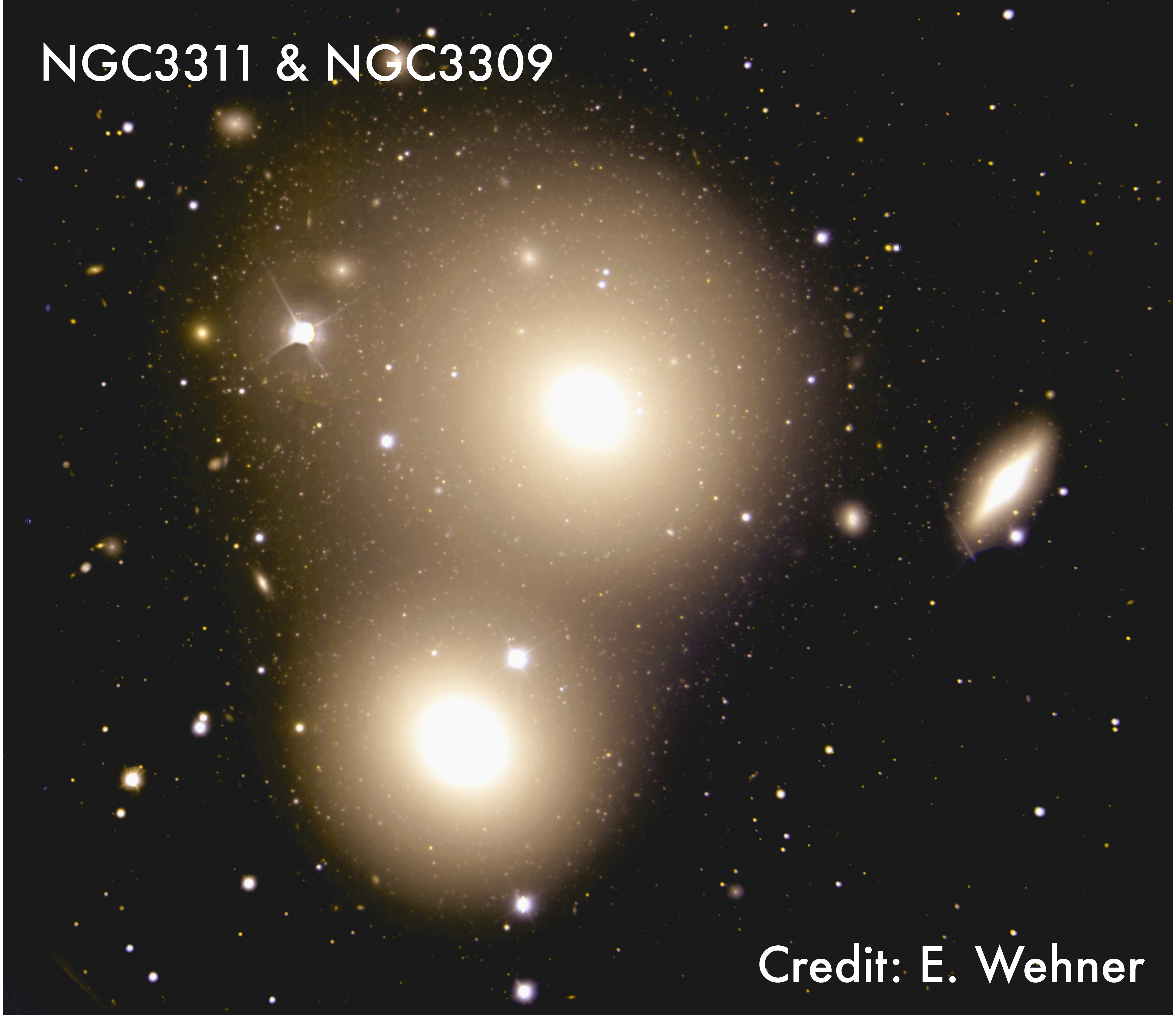
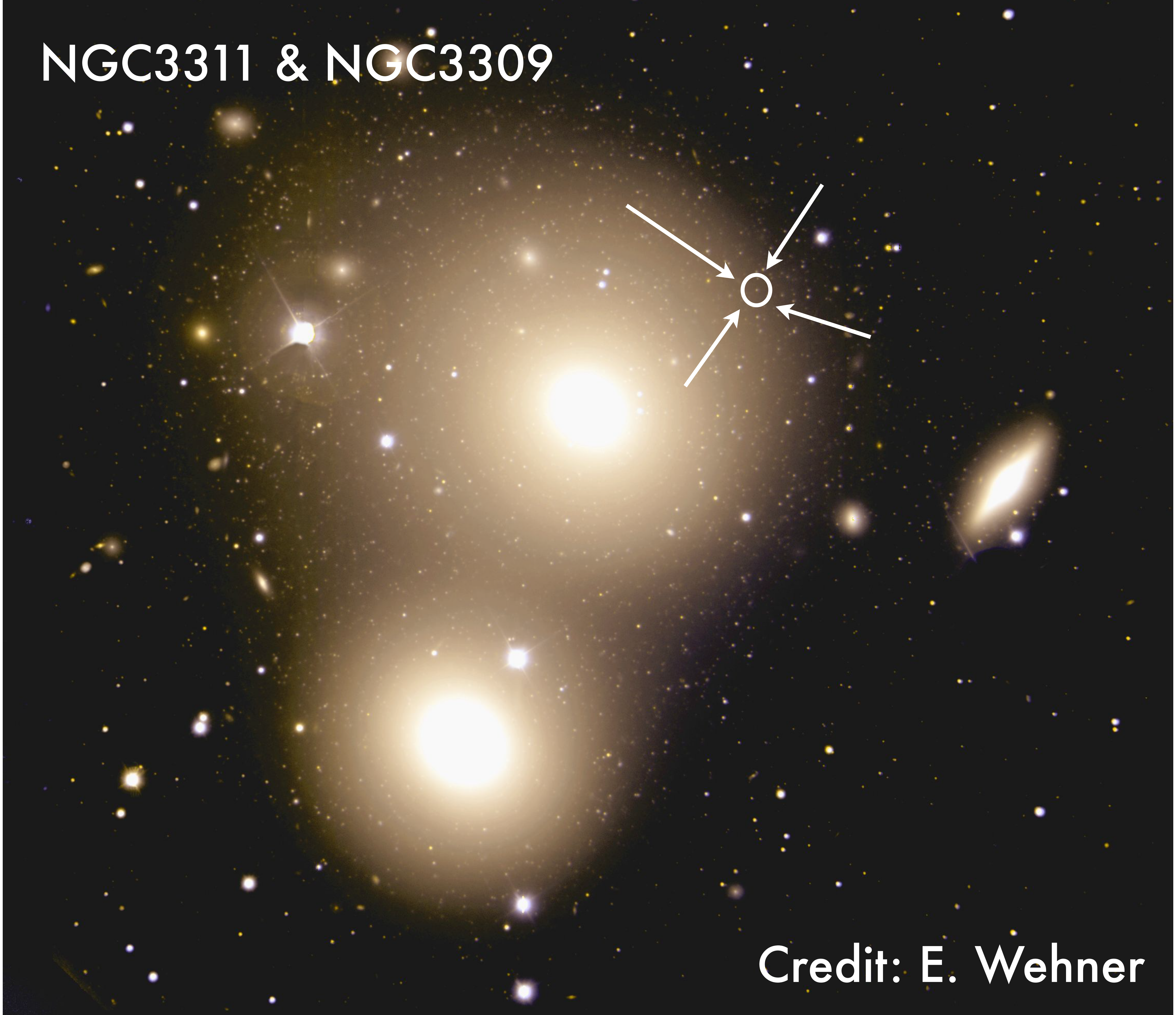
★How? ➡ GC systems

★Why?

- ✓discrete probes of major star formation episodes
- ✓best approximations to SSPs
- ✓marginally resolved up to ≈100Mpc
- ➡ alternative to integrated light studies


NGC3311 & NGC3309
Credit: E. Wehner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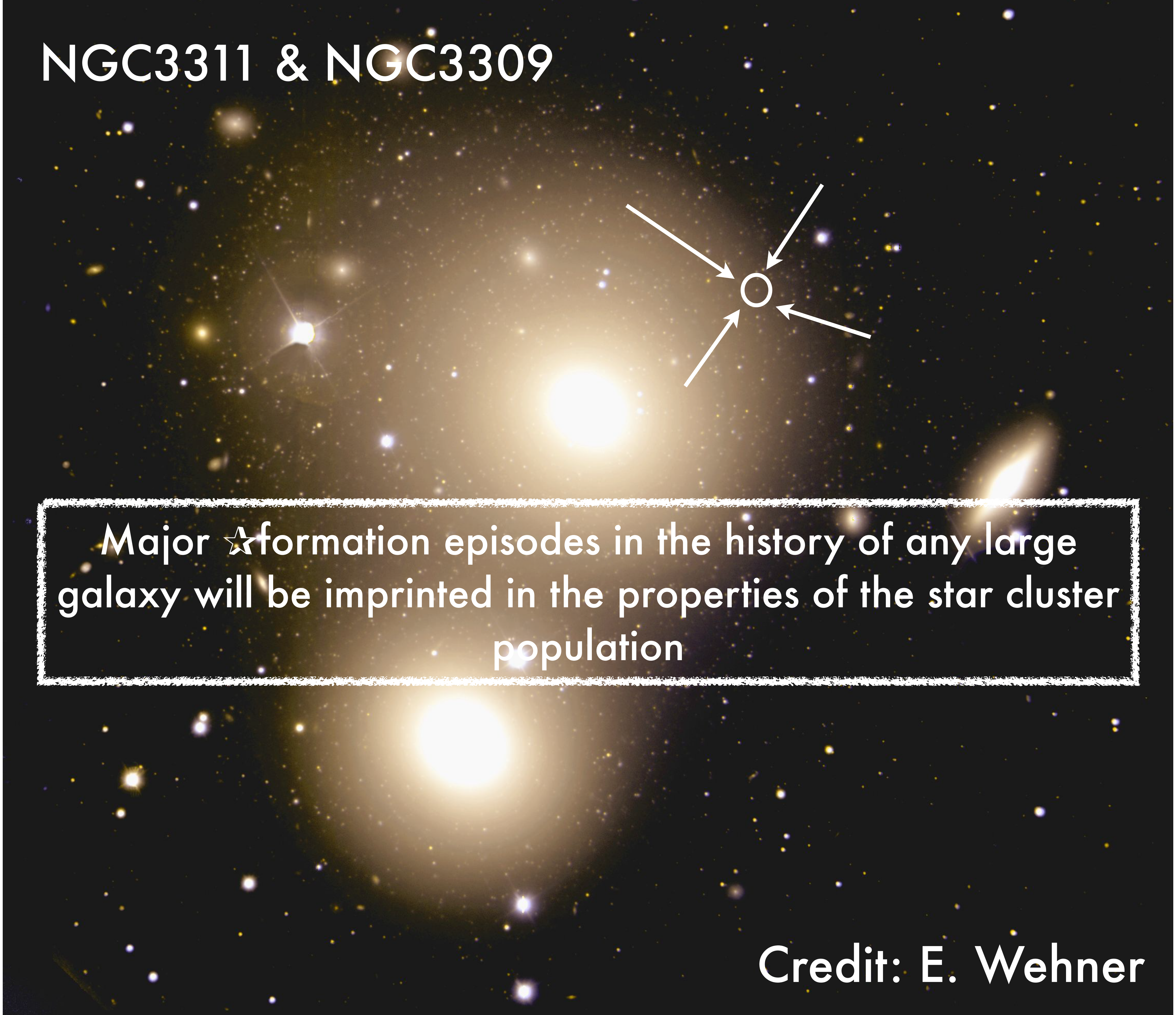
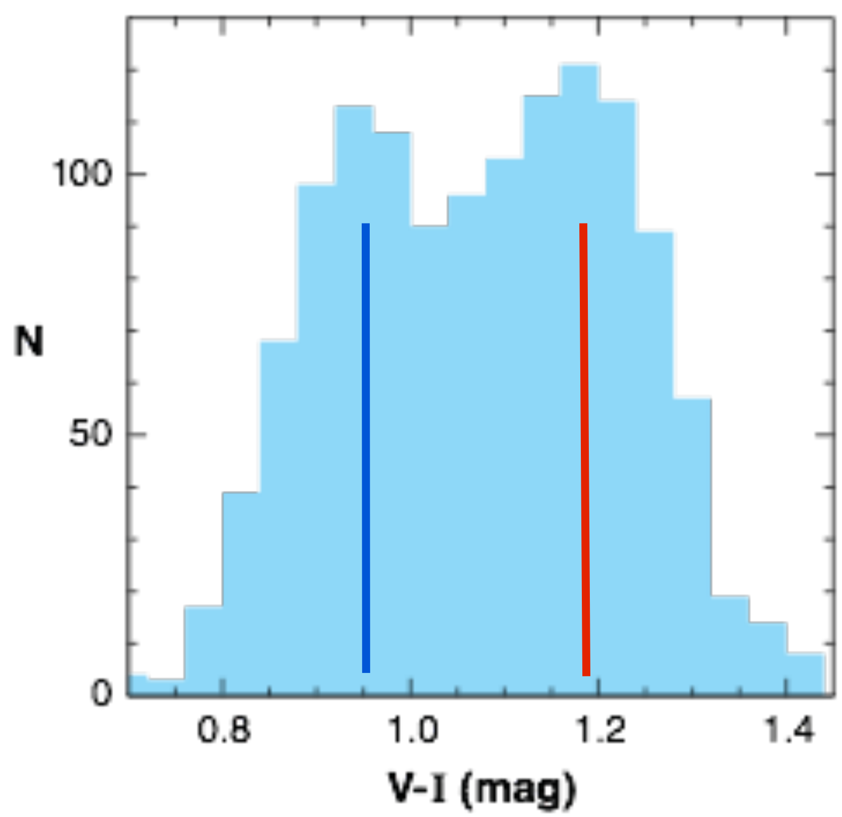

NGC3311 & NGC3309
Major ☆formation episodes in the history of any large galaxy will be imprinted in the properties of the star cluster population
Credit: E. Wehner

blue GCs
red GCs
old ➡ > 10Gyrs
(eg. Strader+05)

Brodie & Strader 06



M87, Larsen+01

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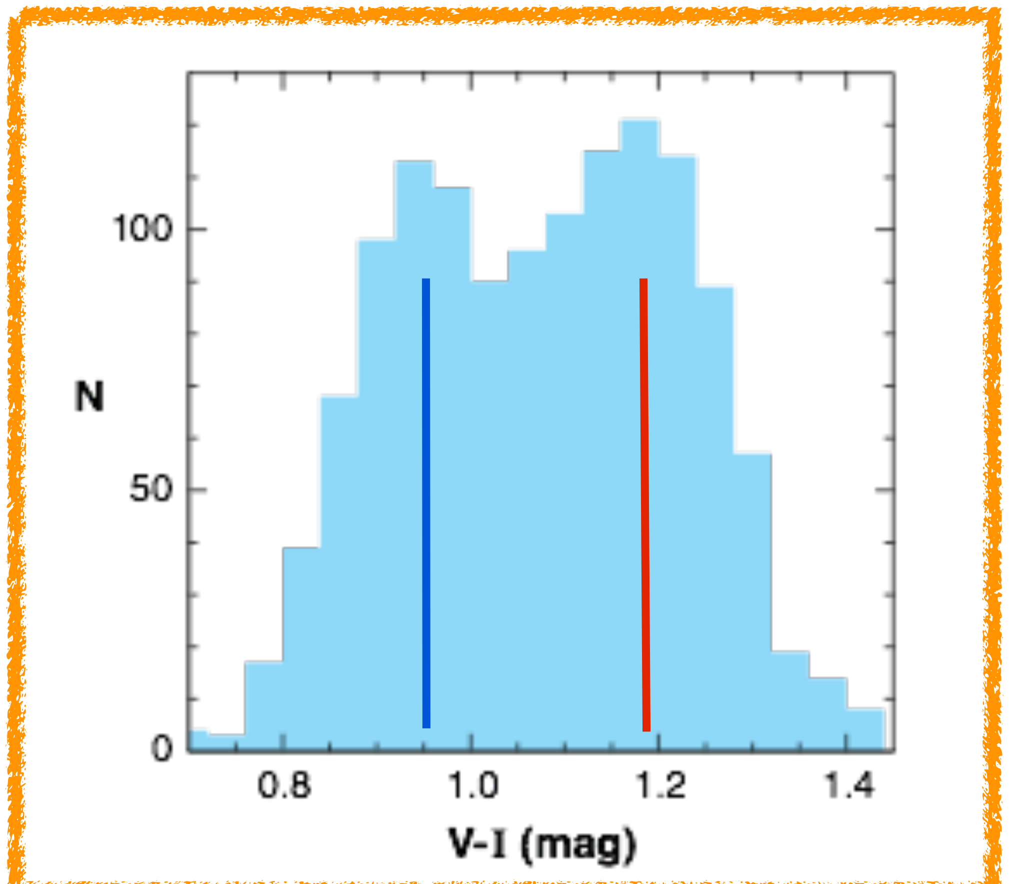

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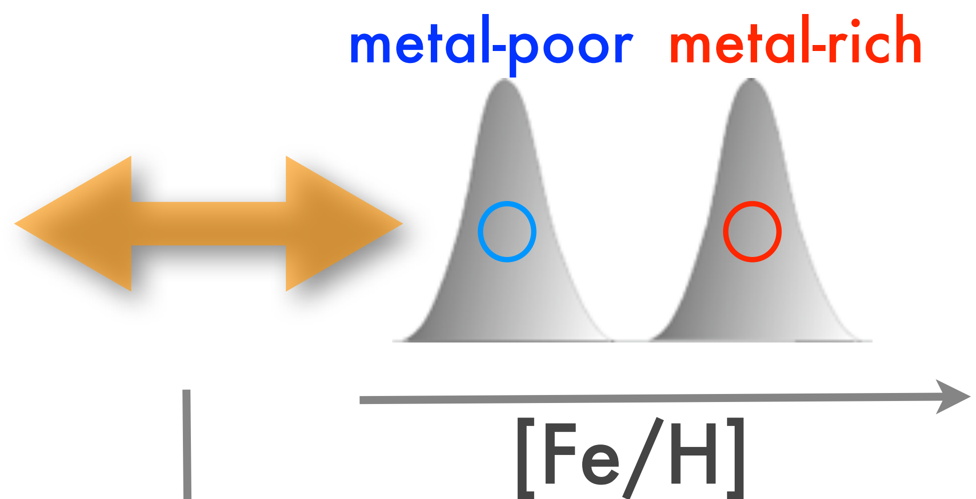
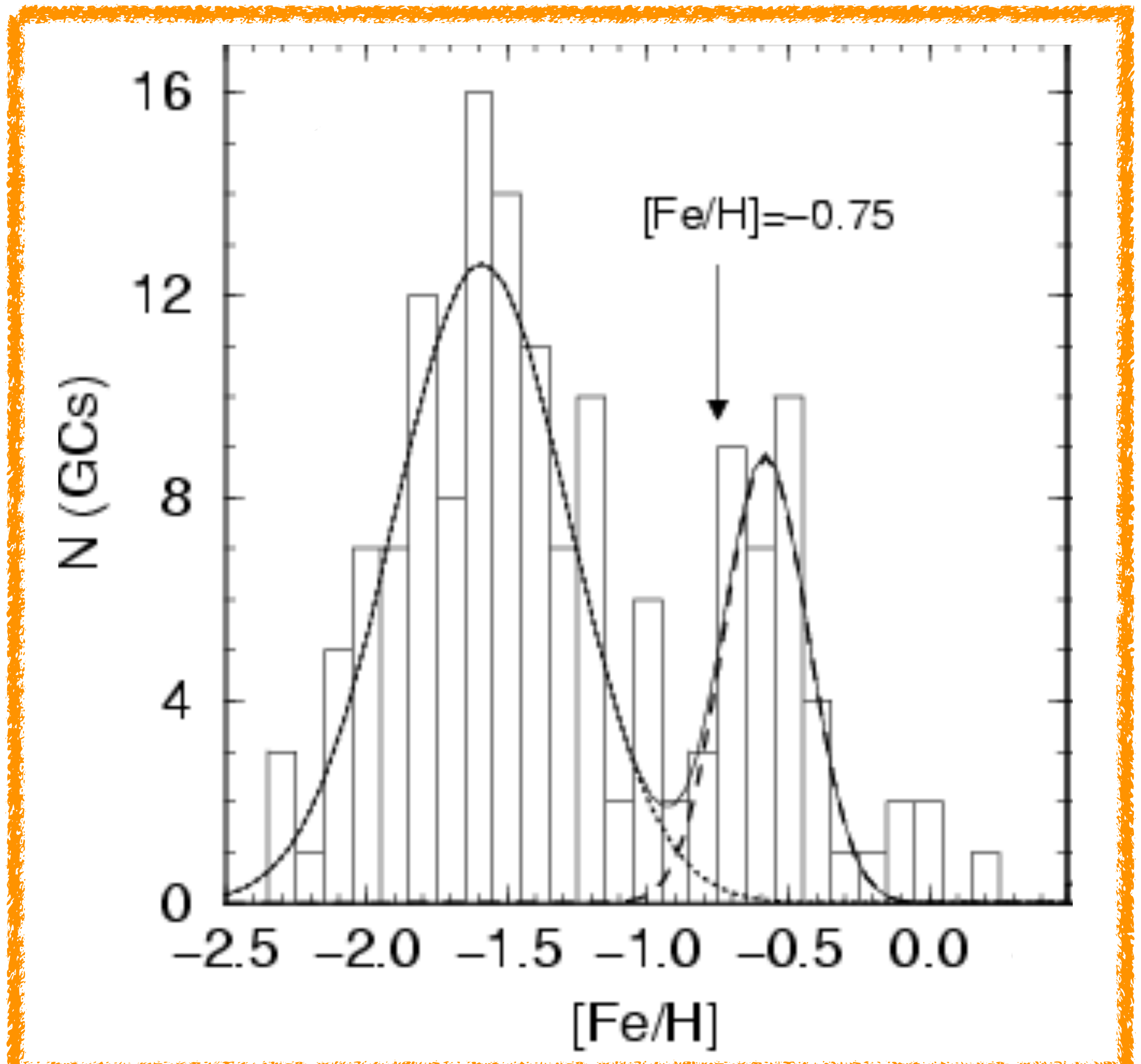


equally old, >10Gyrs

Milky Way metallicity bimodality

★Metallicity bimodality in the Milky Way ➡ Zinn 85, Bica+06



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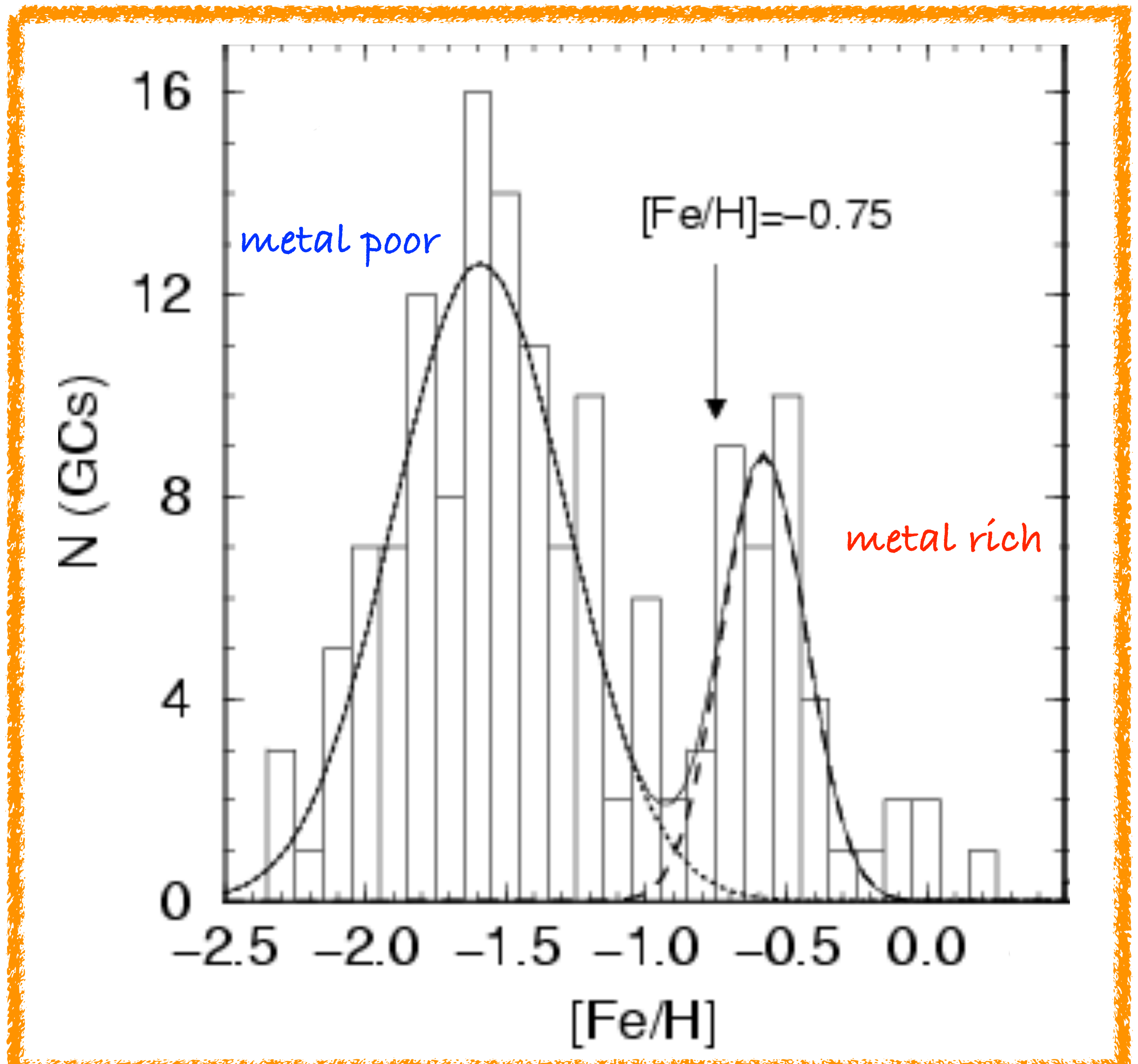
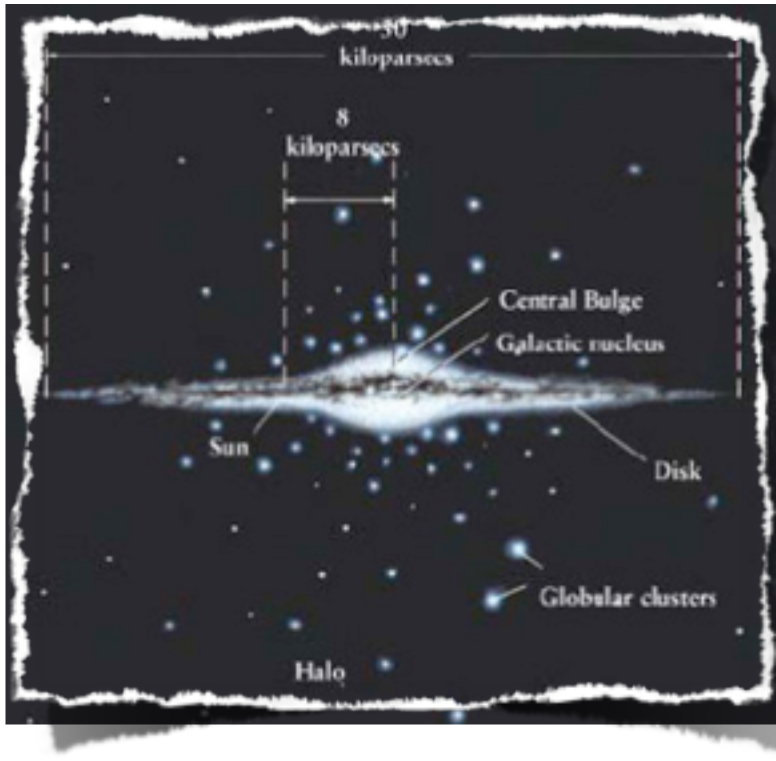
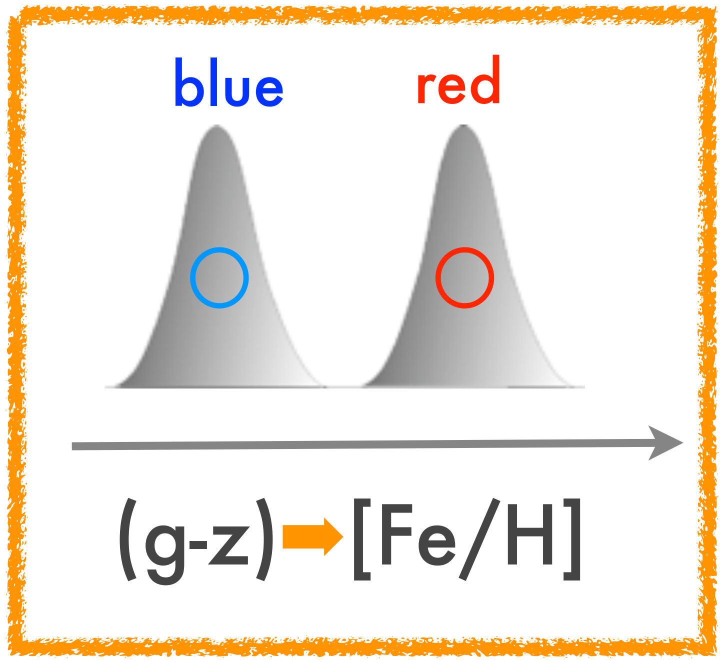




★[Fe/H]~-1.5 & -0.6

★MP halo, MR bulge (Minniti 95)

★For E/S0 GC [Fe/H] bimodality has been derived indirectly through (optical) colours



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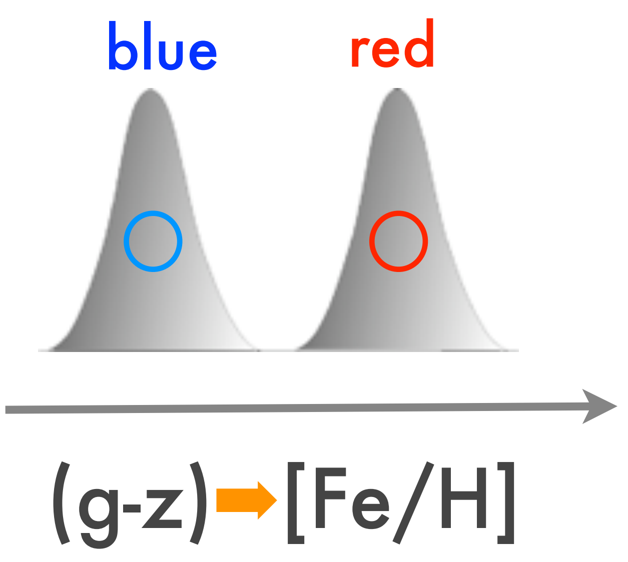
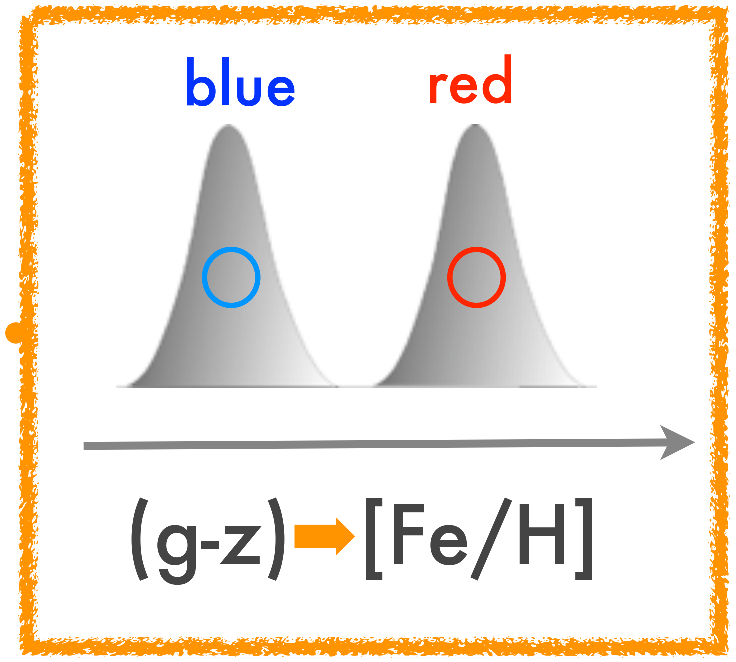


★GCs in closest E's are too faint for the current spectroscopic capabilities ➡ biased samples

GC colour bimodality and galaxy formation



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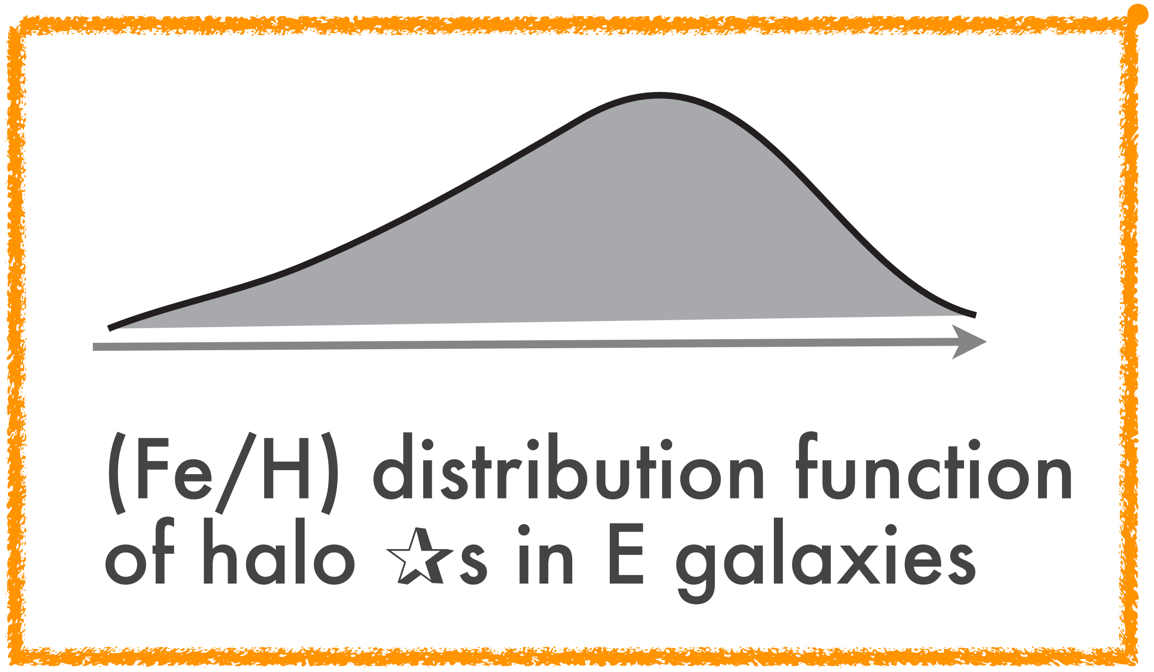

Scenarios

★Mergers of spirals
(Ashman & Zepf 1992)

√GCs ➡ merger event
√GCs ➡ disc galaxies

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√GCs ➡ merger event
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★Multi-phase collapse
(Forbes, Brodie & Grillmair 1997)

GCs ➡ in situ ➡ truncation ➡ GCs

★Accretion
(Côté, Markze & West 1998)

√GCs ➡ in situ
√GCs ➡ dwarf galaxies accreted on to the ellipticals

★Hierarchical merging
(Beasley+02, Strader+05, Rhode+05)

GC formation truncation at z~5

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★Multi-ph
(Forbes, Brodi

➡ GCs

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ted on to the

bimodality is not a natural outcome; scenarios do not account for the all the data

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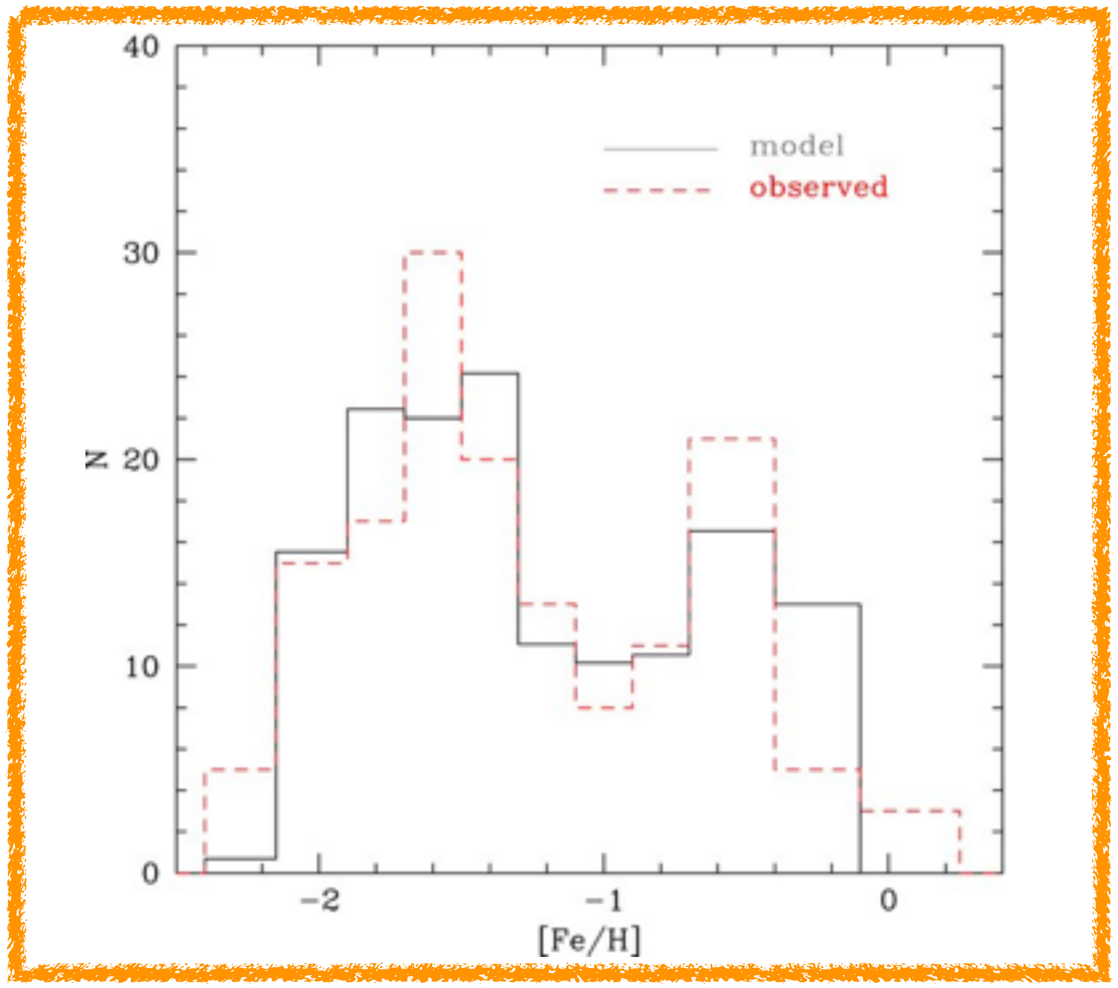
(Beasley+02, Strader+05, Rhode+05)

GC formation truncation at z~5

Scenarios

★Muratov & Gnedin 10 ➡ [Fe/H] bimodality is a natural outcome of the hierarchical theory of galaxy formation in some, bot not all range of model realizations

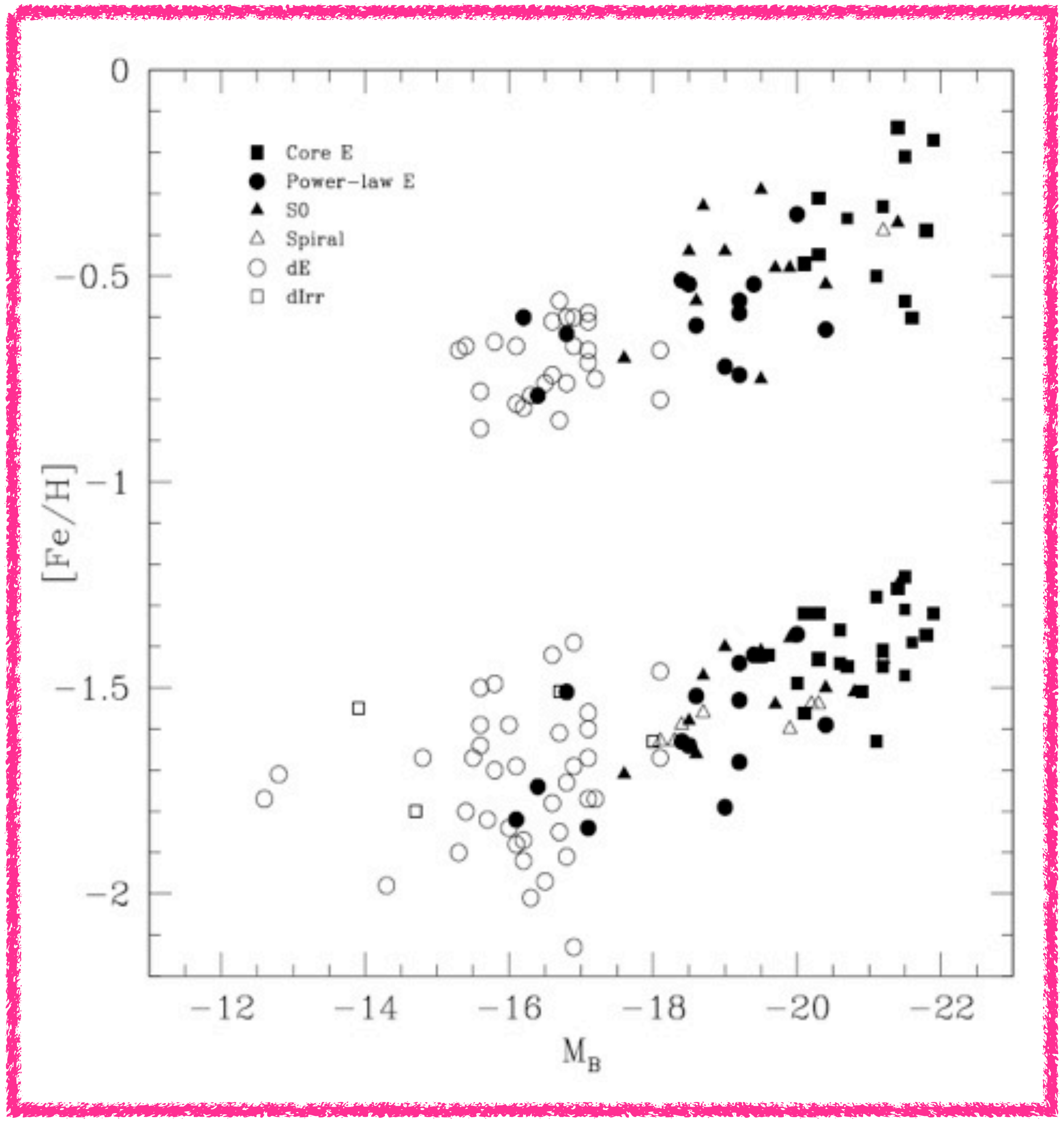


√GCs ➡ only through major mergers
√GCs ➡ minor mergers

GC obs. properties

★GC peak metallicity vs. galaxy luminosity

e.g. Brodie & Strader 06



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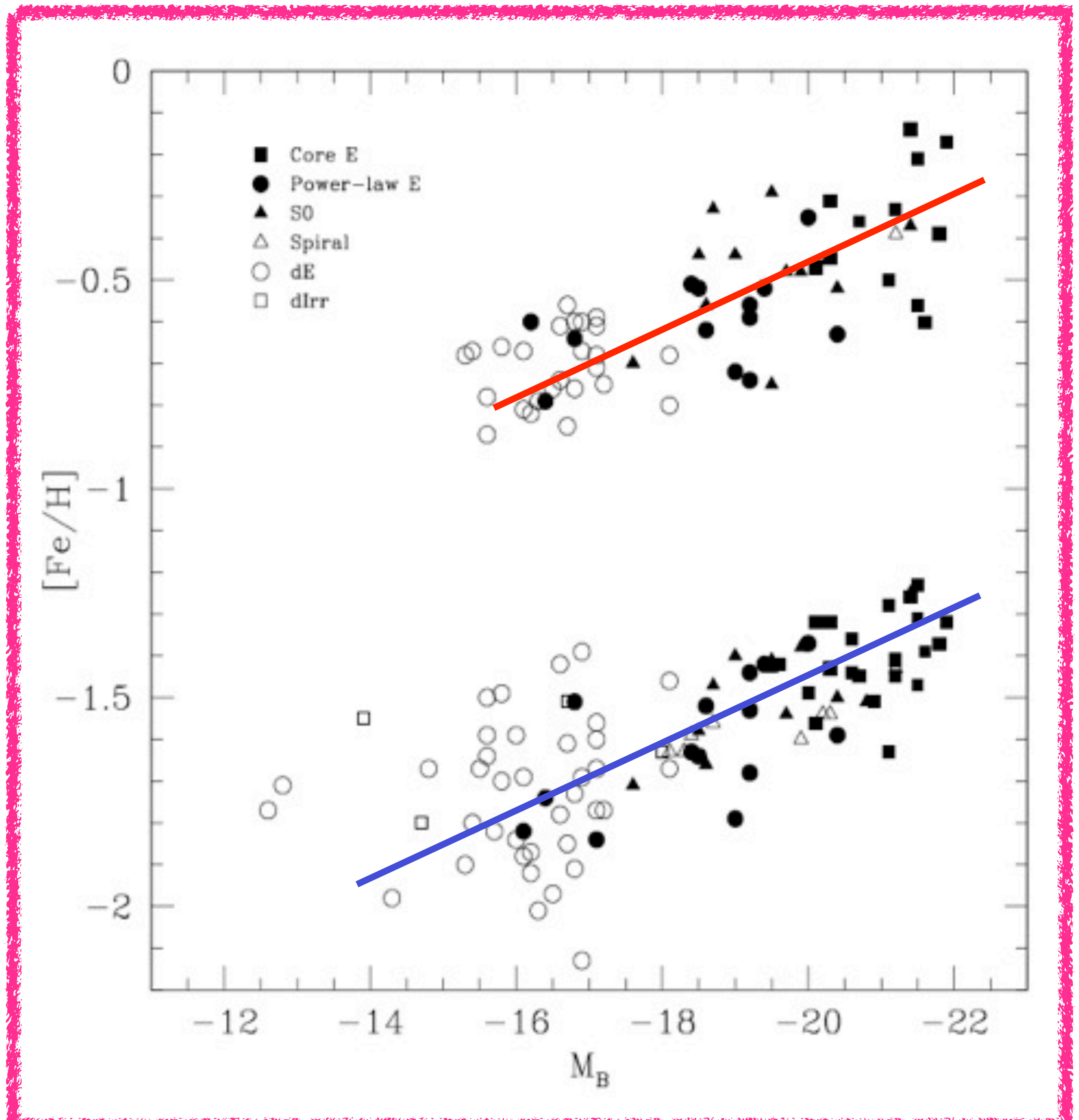

★Color (metallicities) of both red and blue GC peaks correlate with galaxy luminosity

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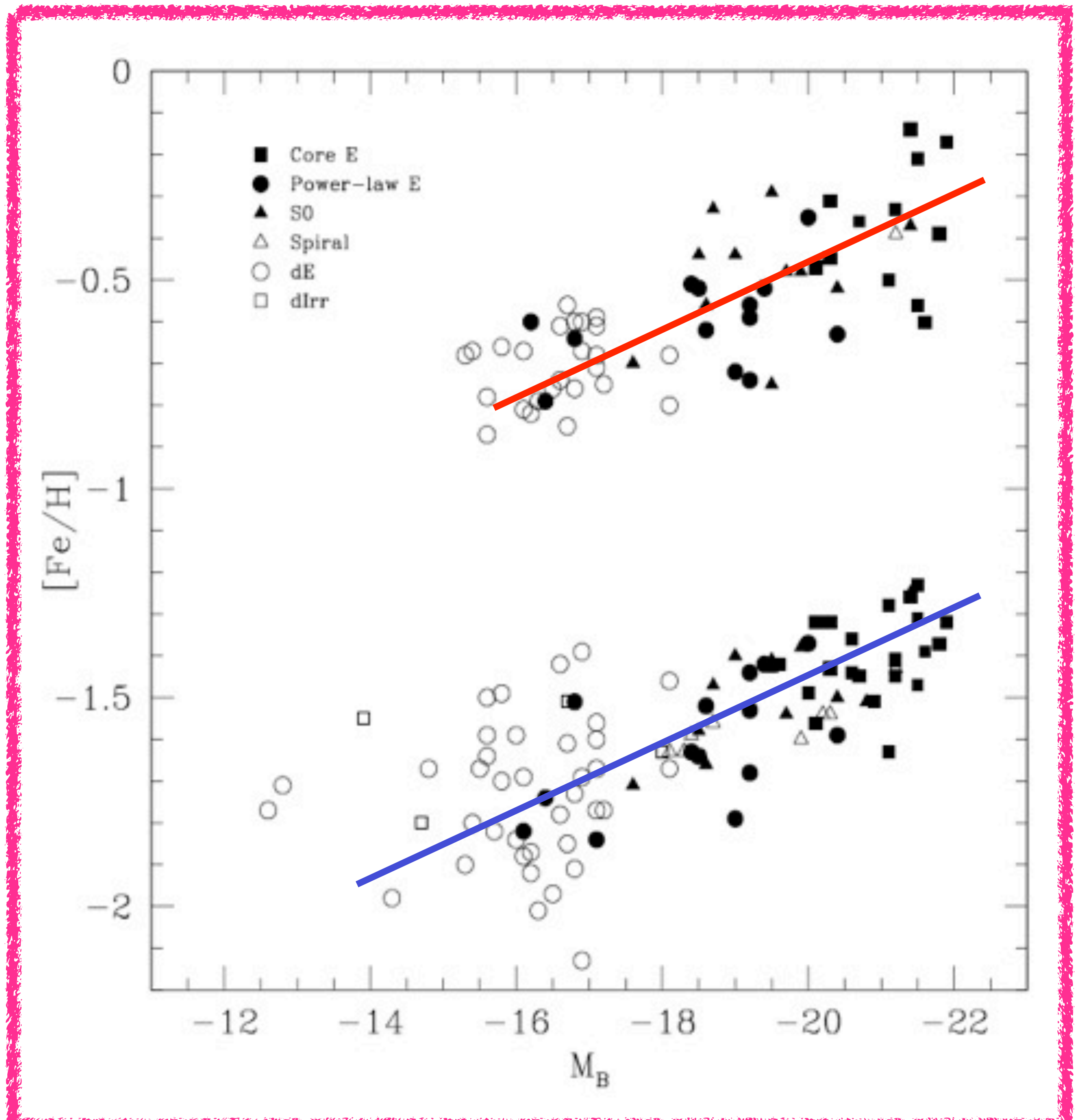
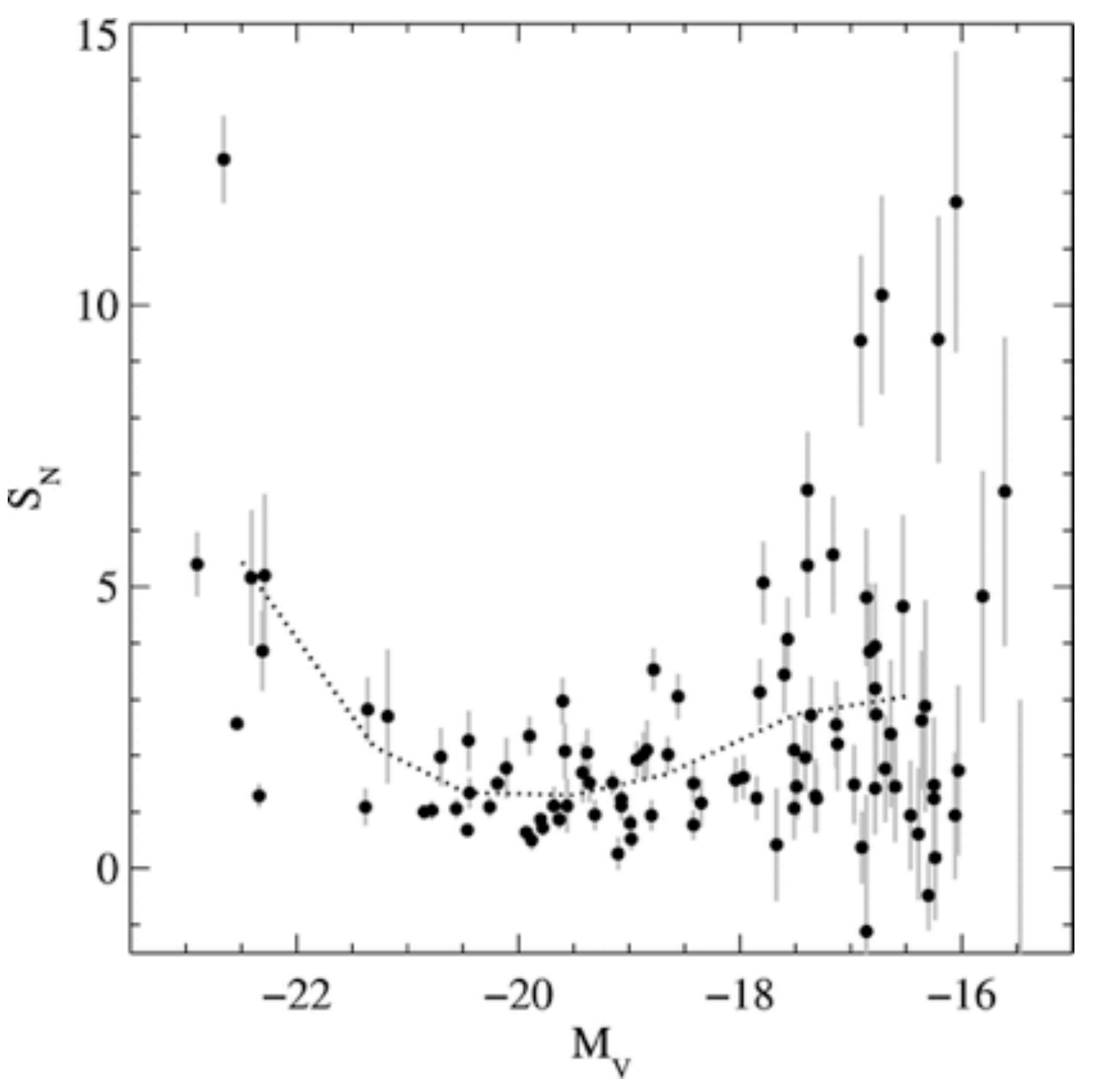


★Color (metallicities) of both red and blue GC peaks correlate with galaxy luminosity

★dwarf galaxies MP GCs are more metal poor than the MP GCs of more massive galaxies

★Number of GCs normalised per host galaxy luminosity Mv=-15 (S_N) vs. M_V (Peng+08)



$$S_N = N_{GC} \times 10^{0.4(M_V+15)}$$

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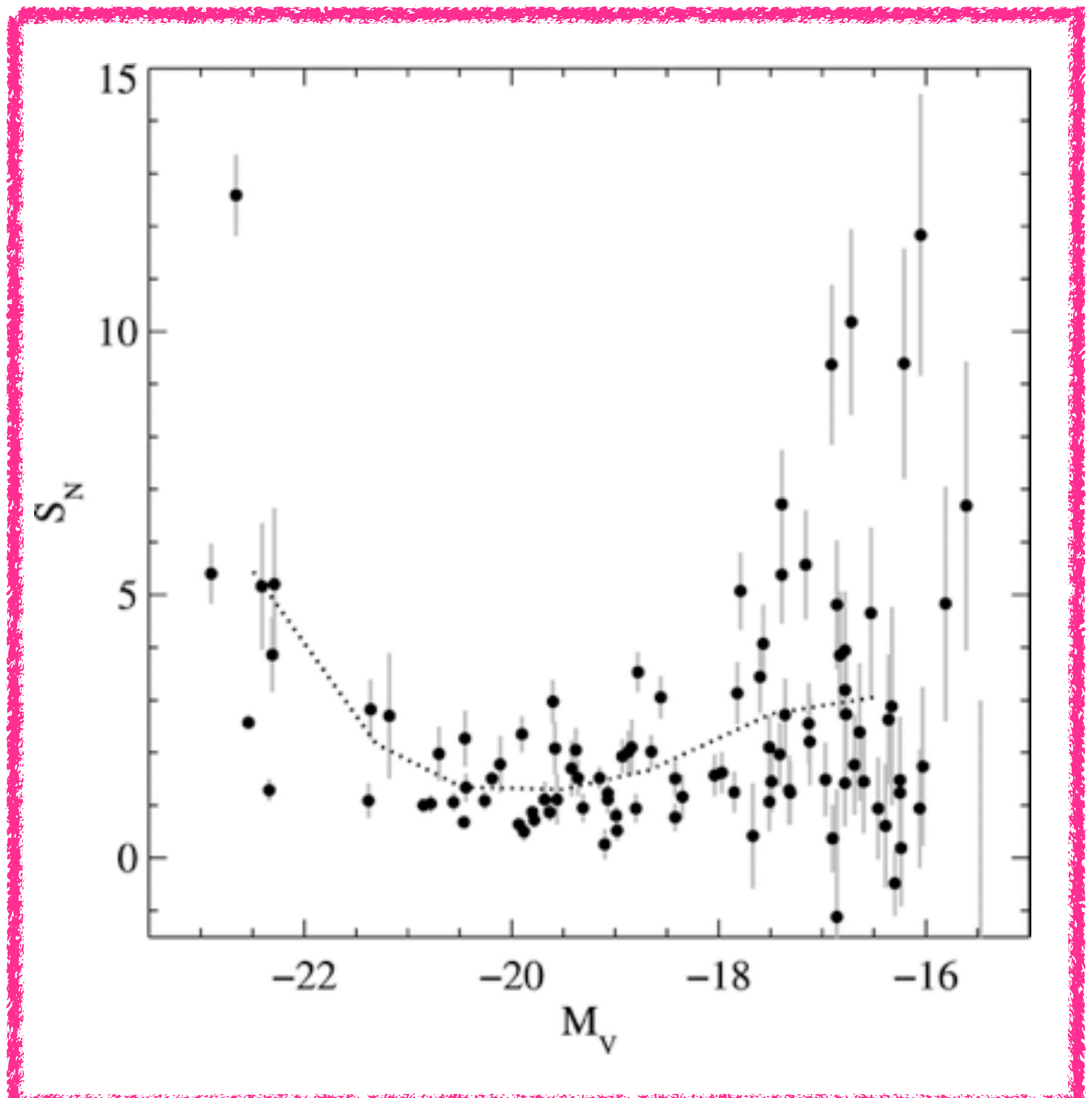
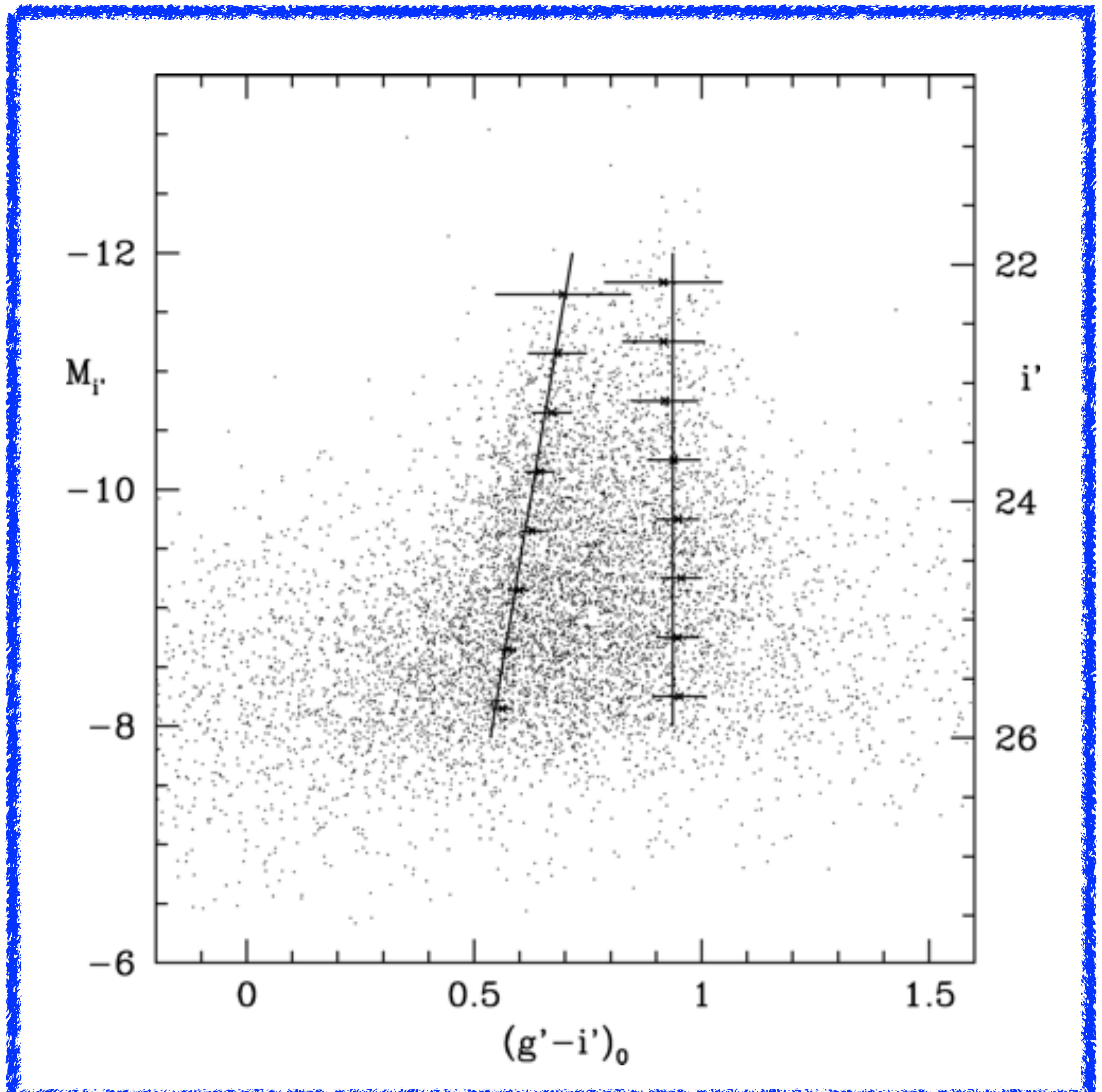


$$S_N = N_{GC} \times 10^{0.4(M_V+15)}$$

★S_N can be high in both giants and dwarfs ➡ but is low in intermediate luminosity galaxies

★no clear distinction between blue and red clusters

★*Blue-Tilt* or mass-metallicity relation for NGC3311 (Wehner+08)



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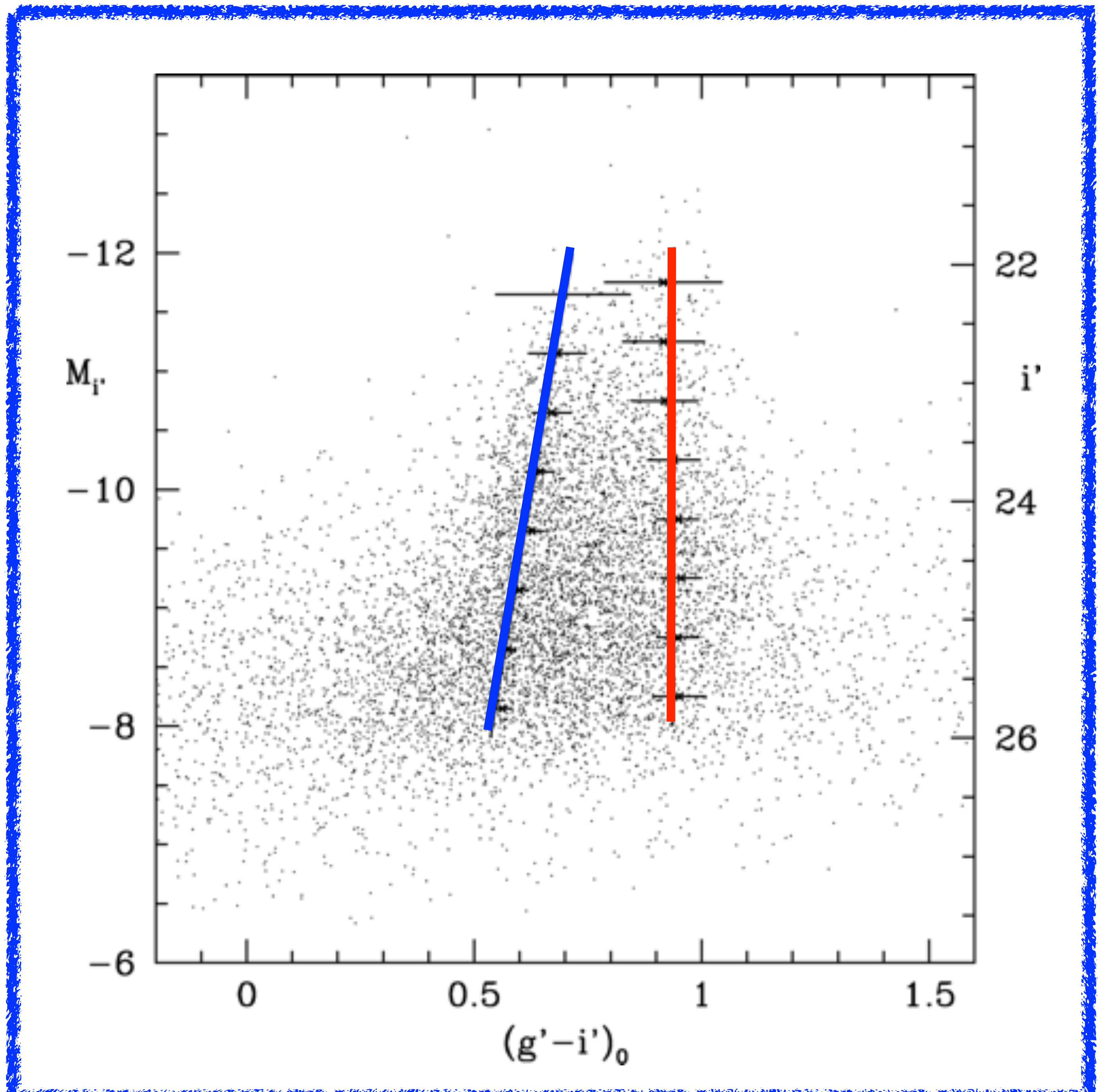
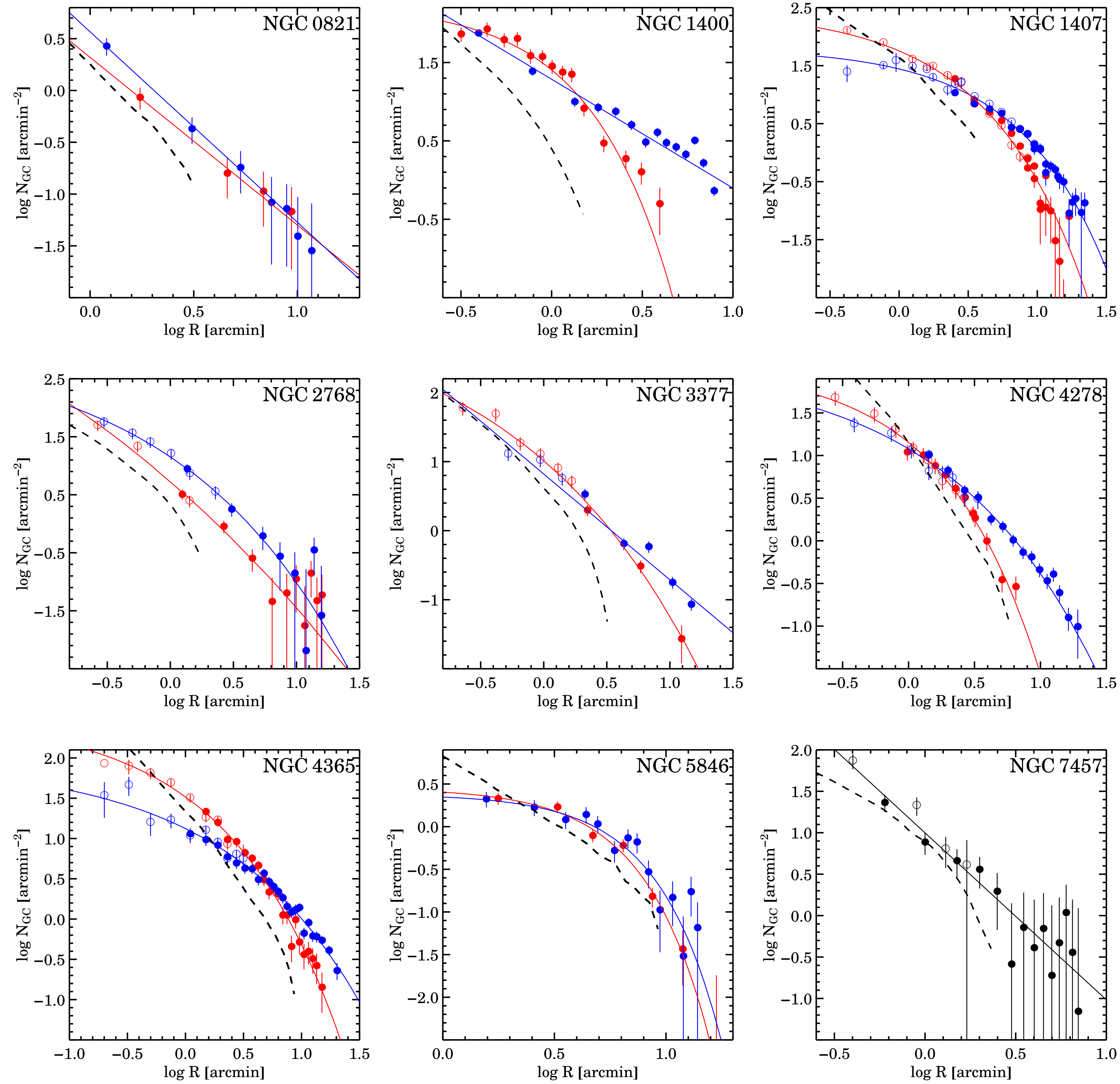


★Blue GCs of certain Es have redder colours at brighter magnitudes

★self-enrichment (e.g. Bailin & Harris 2009)

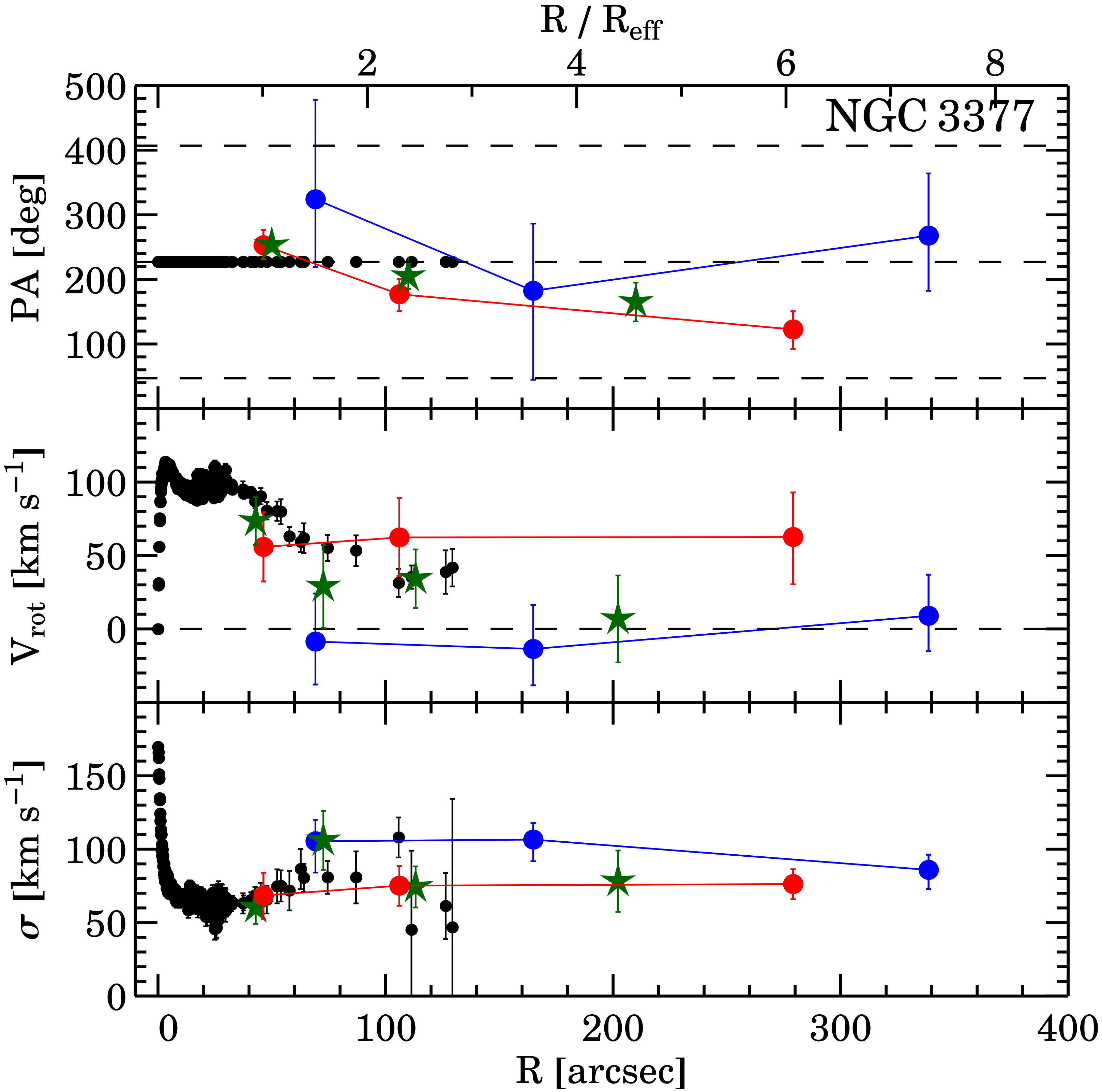
★Wide Field Imaging

✓Pota+2012



✓surface density distribution

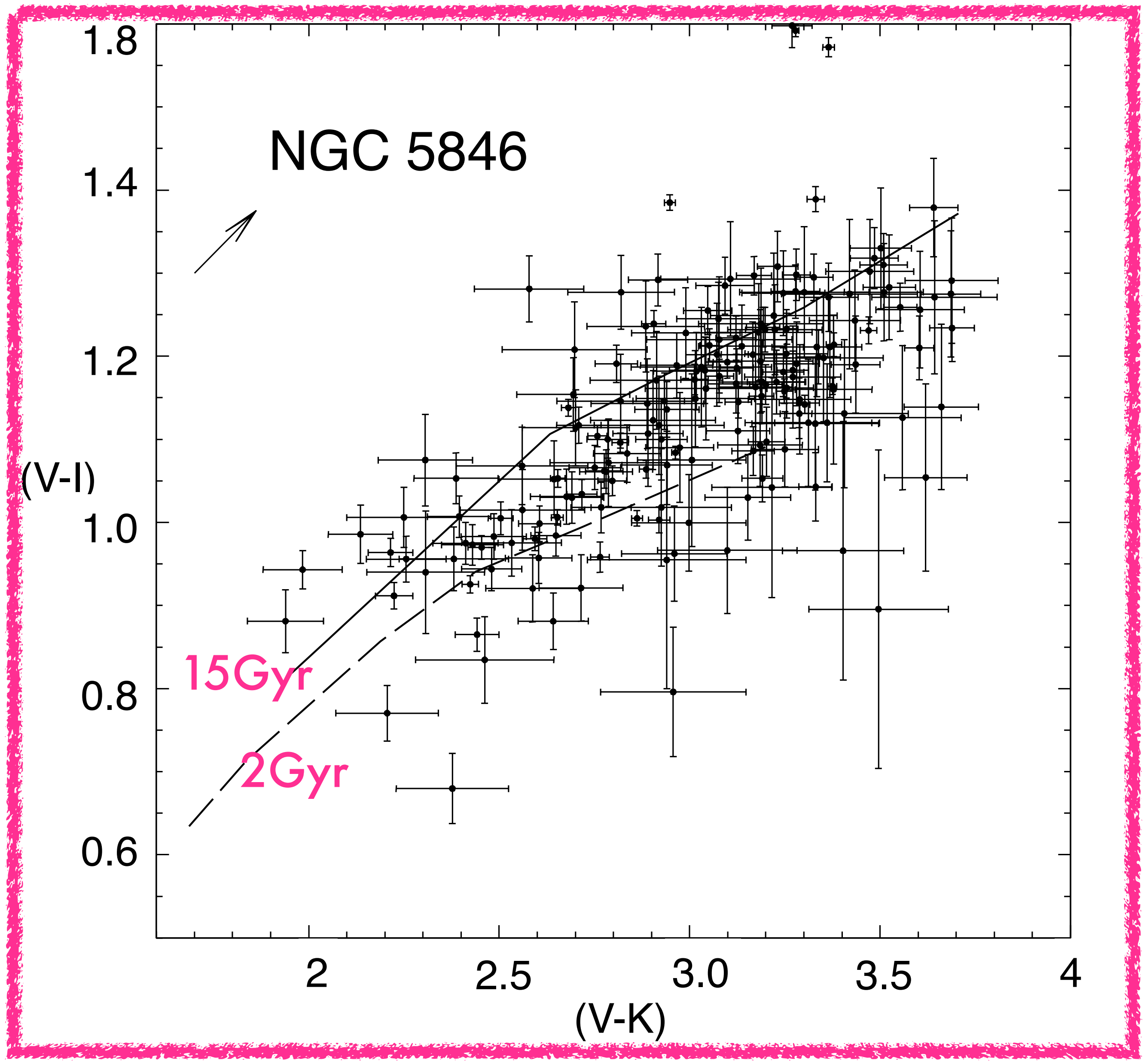
√ Pota+2012



Challenges in dermining ages & [Fe/H] of GCSs

"Ages problem"

- ★≈2-8Gyrs GCs in "old" ellipticals (>10Gyrs)
- ★NGC 4365 and NGC 5846



★Hempel+03

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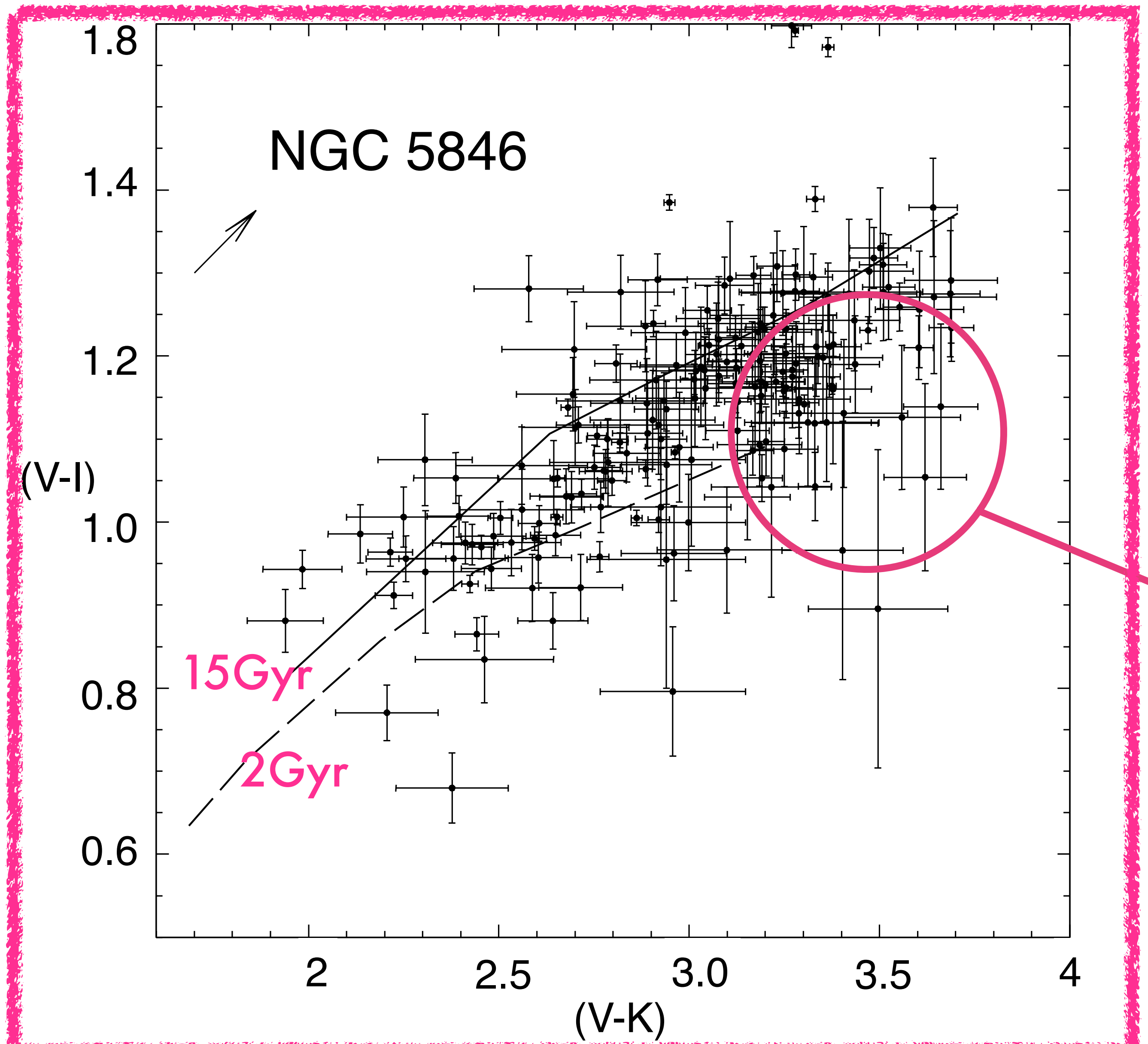
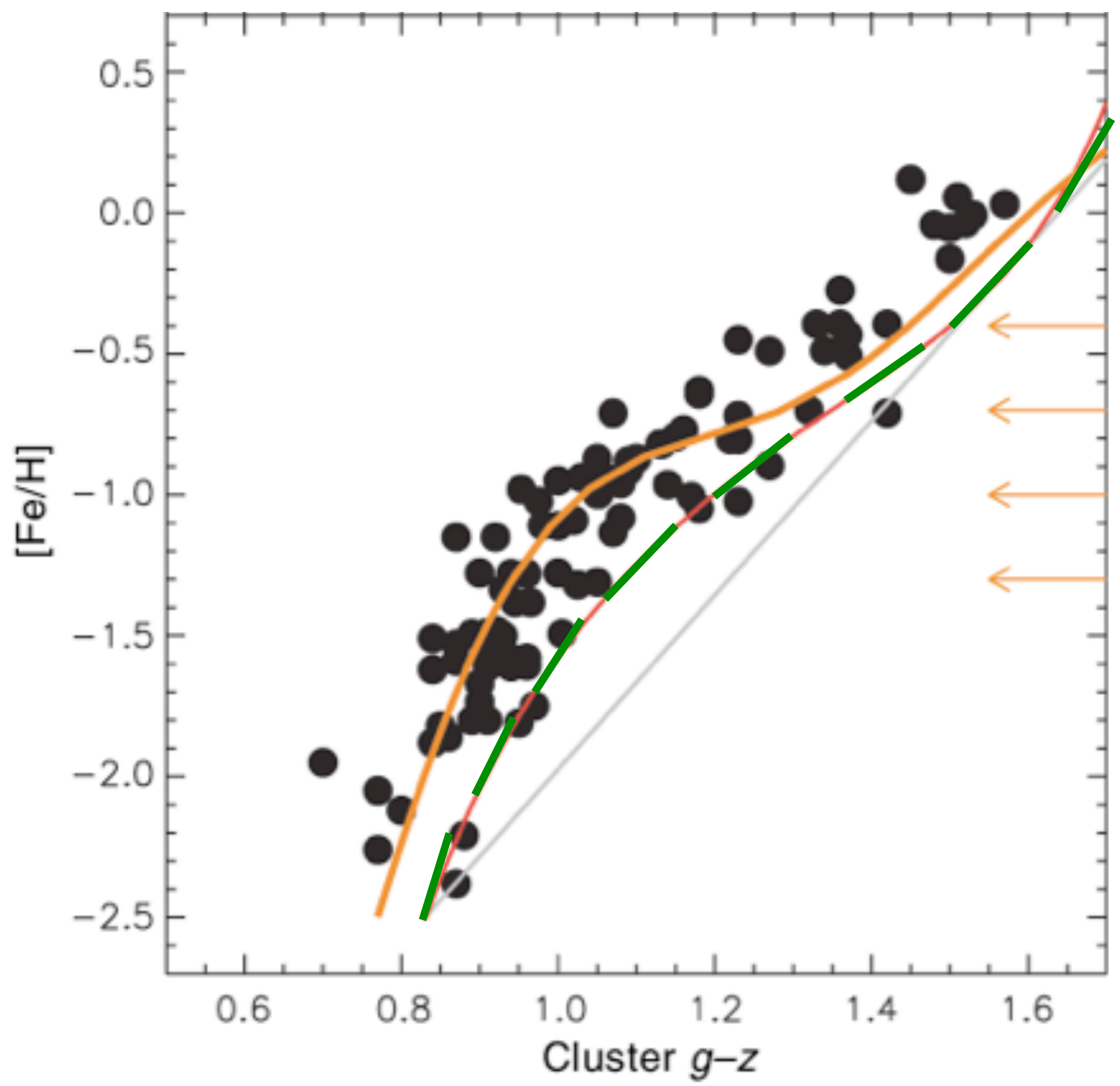


★Hempel+03

★ Intermediate ages?

“Metallicity bimodality problem”

★Yoon, Yi, Lee 06 ➡ YEPS, metallicity bimodality is artifact of HB morphologies

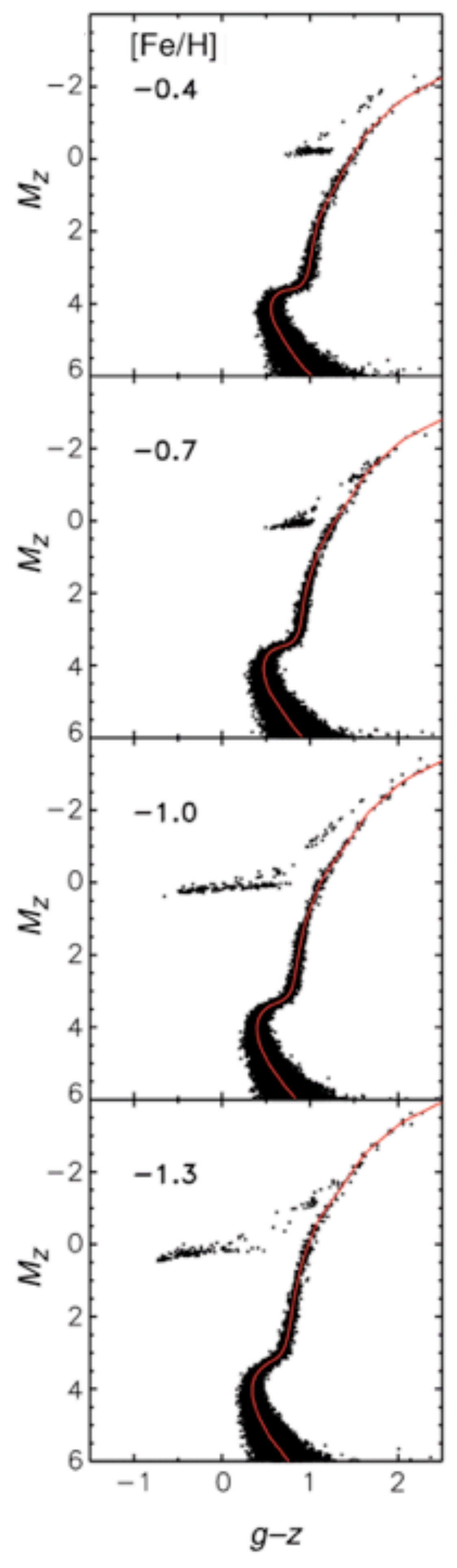


● GCs: MW+ M49+M87

~ YEPS CMR 13Gyr SSP WITH HB

– BC03 CMR 13 Gyr SSP WITHOUT HB

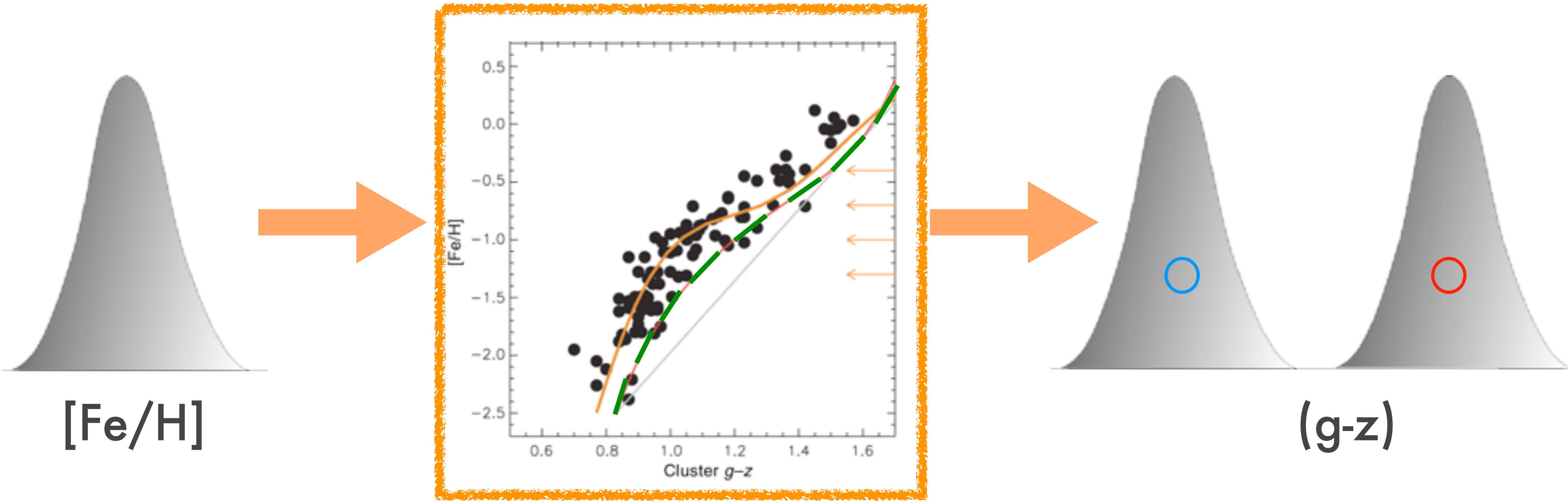
★BHB to RHB ➡ Wavy feature in the CMR



★Yoon, Yi, Lee 06

★YEPS models ➡ systematic variation in the mean colour of HB stars as a function of [Fe/H]

★Yoon+ Scenario



Data

optical/NIR survey of GCs in early-type galaxies

Chies-Santos+ 2011a,b 2012a

- ★GCS of 14 galaxies ➡ sub-sample of SAURON (de Zeeuw+02)
- ★(m-M)<32 (≈25Mpc)
- ★M_B<-19

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★NIR ➡ LIRIS/WHT (FOV=4.2′x4.2′) ➡ Ks-band (2.2μm)
✓3 runs (07, 08, 09)
★Optical ➡ Archival ACS/HST (FOV= 3.4′x3.4′) ➡ g(4750Å), z(8400Å) bands

Data

- ★Large number of galaxies
- ★Homogeneous
- ★Deep K-band imaging (≈3.4 hrs)
- ★Aided by HST/ACS ➡ decontamination

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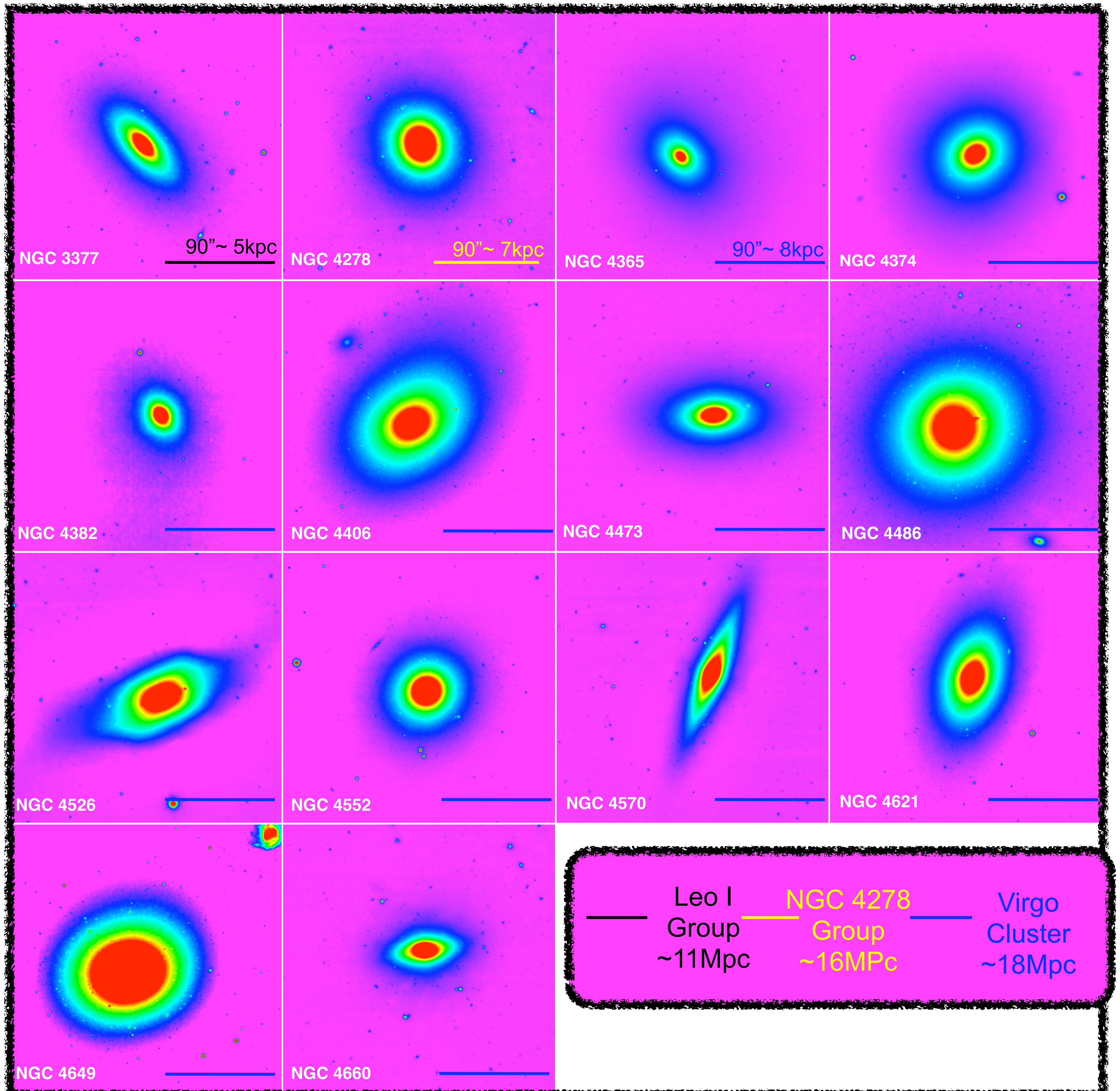

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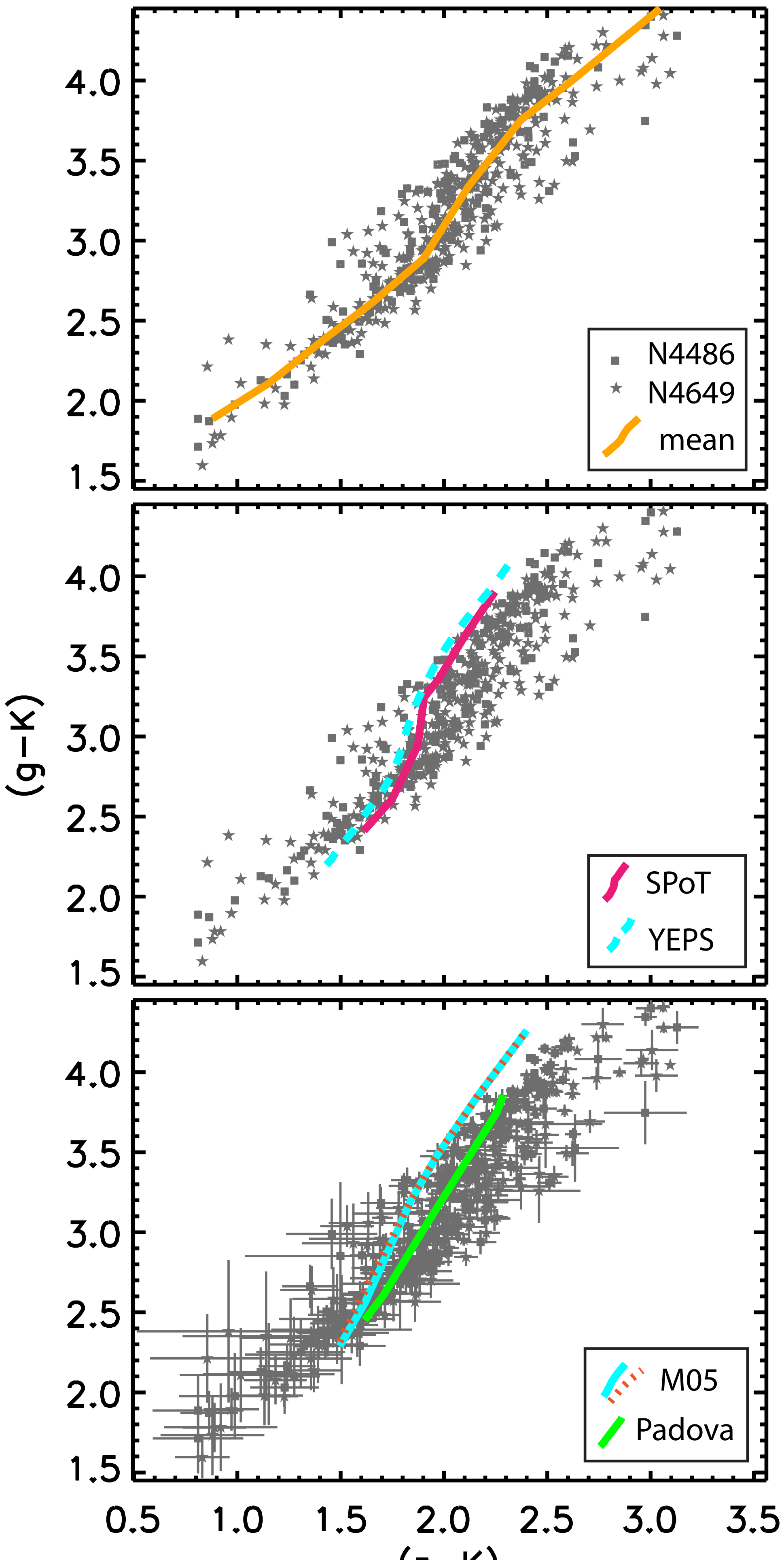

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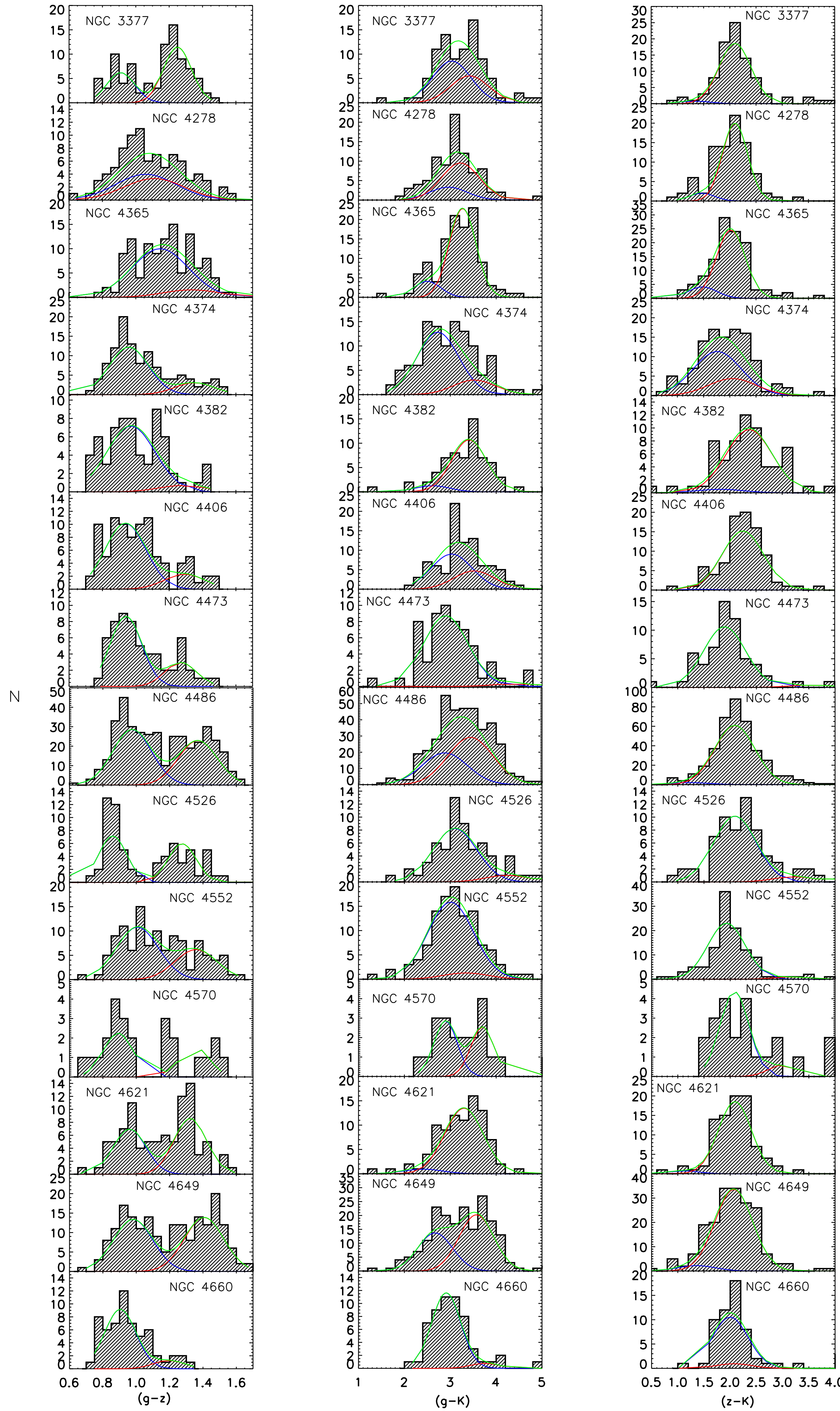
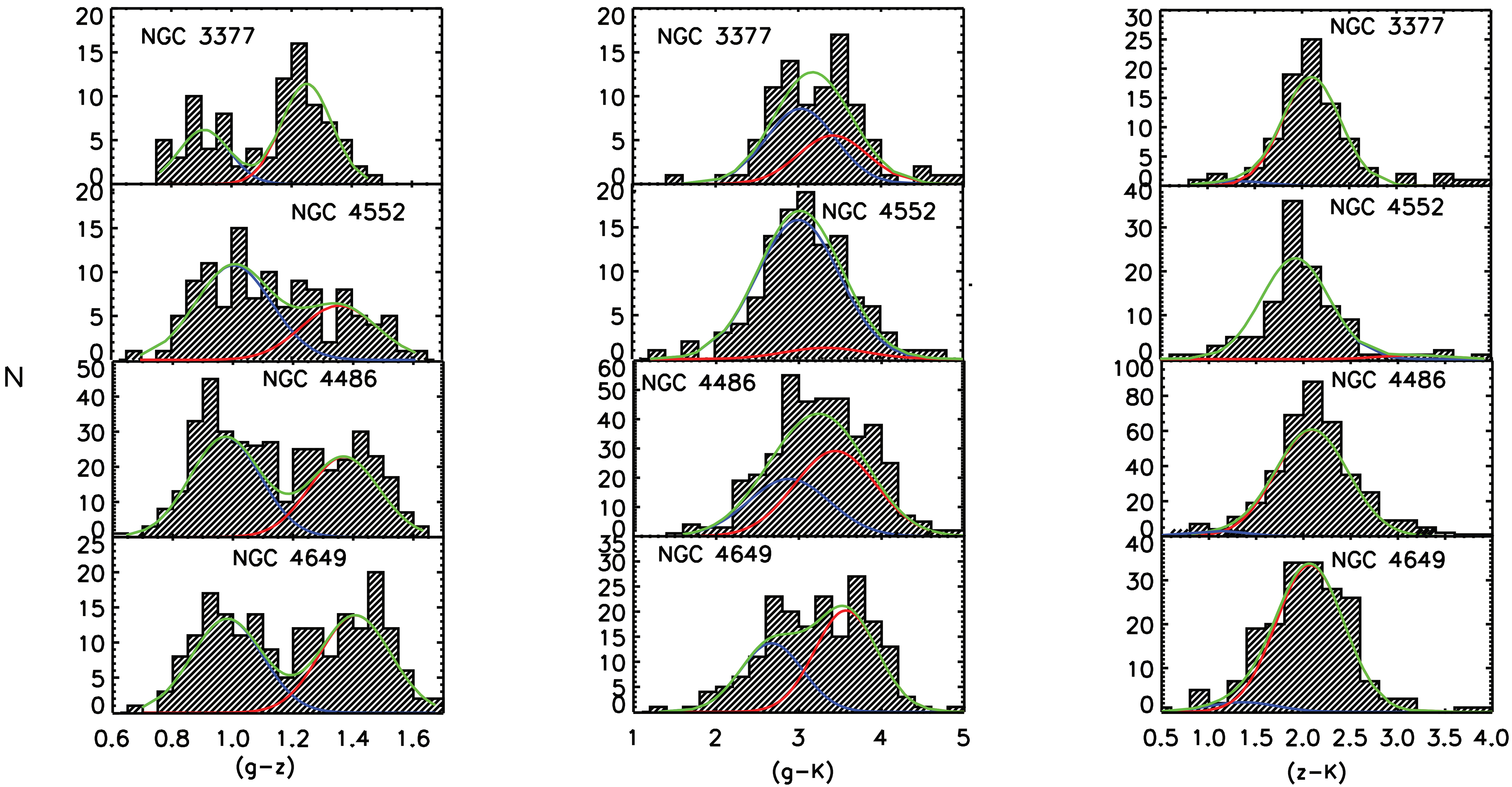


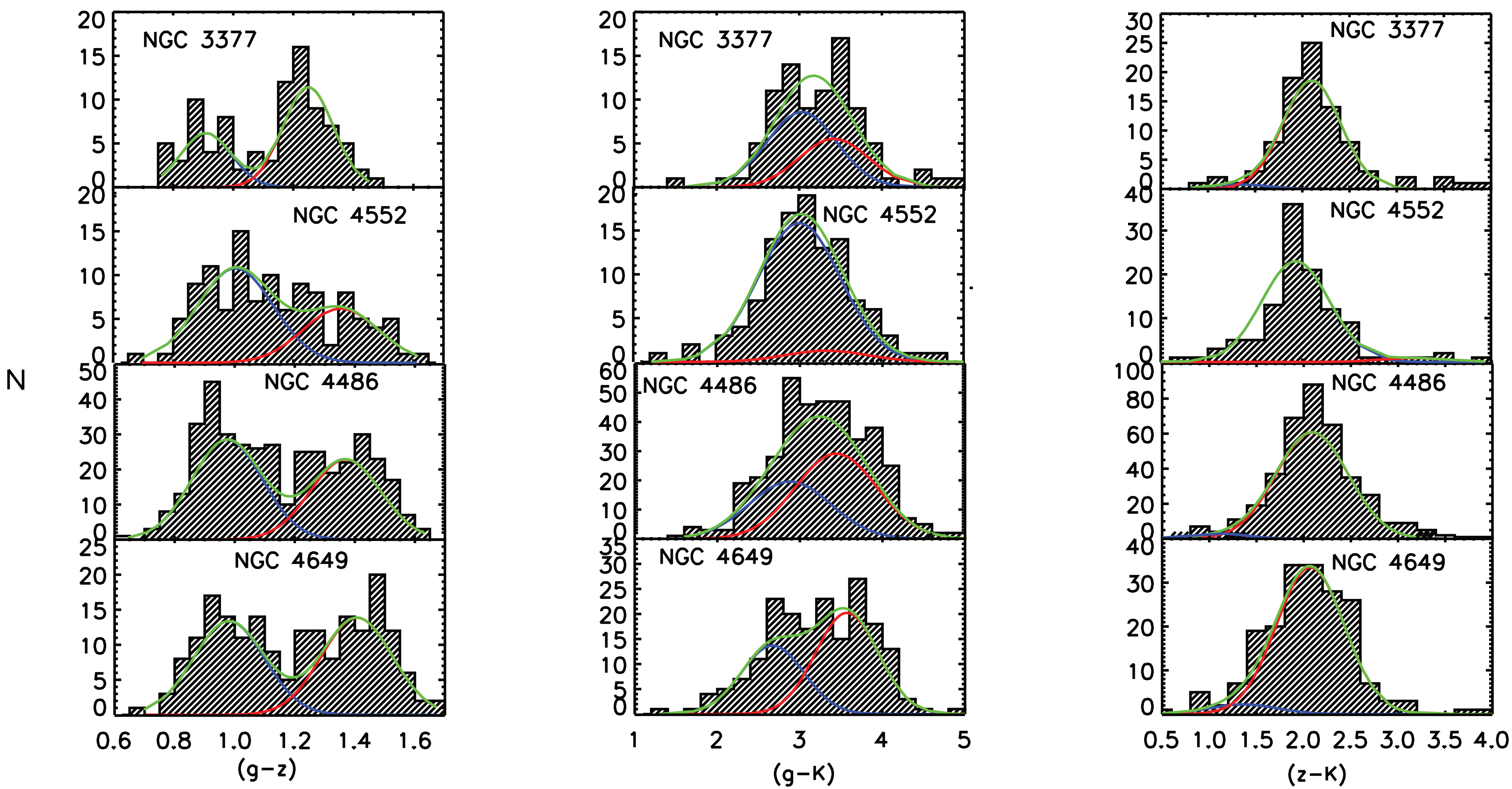
✓Chies-Santos+2012a

(g-z) **(g-K)** **(z-K)**

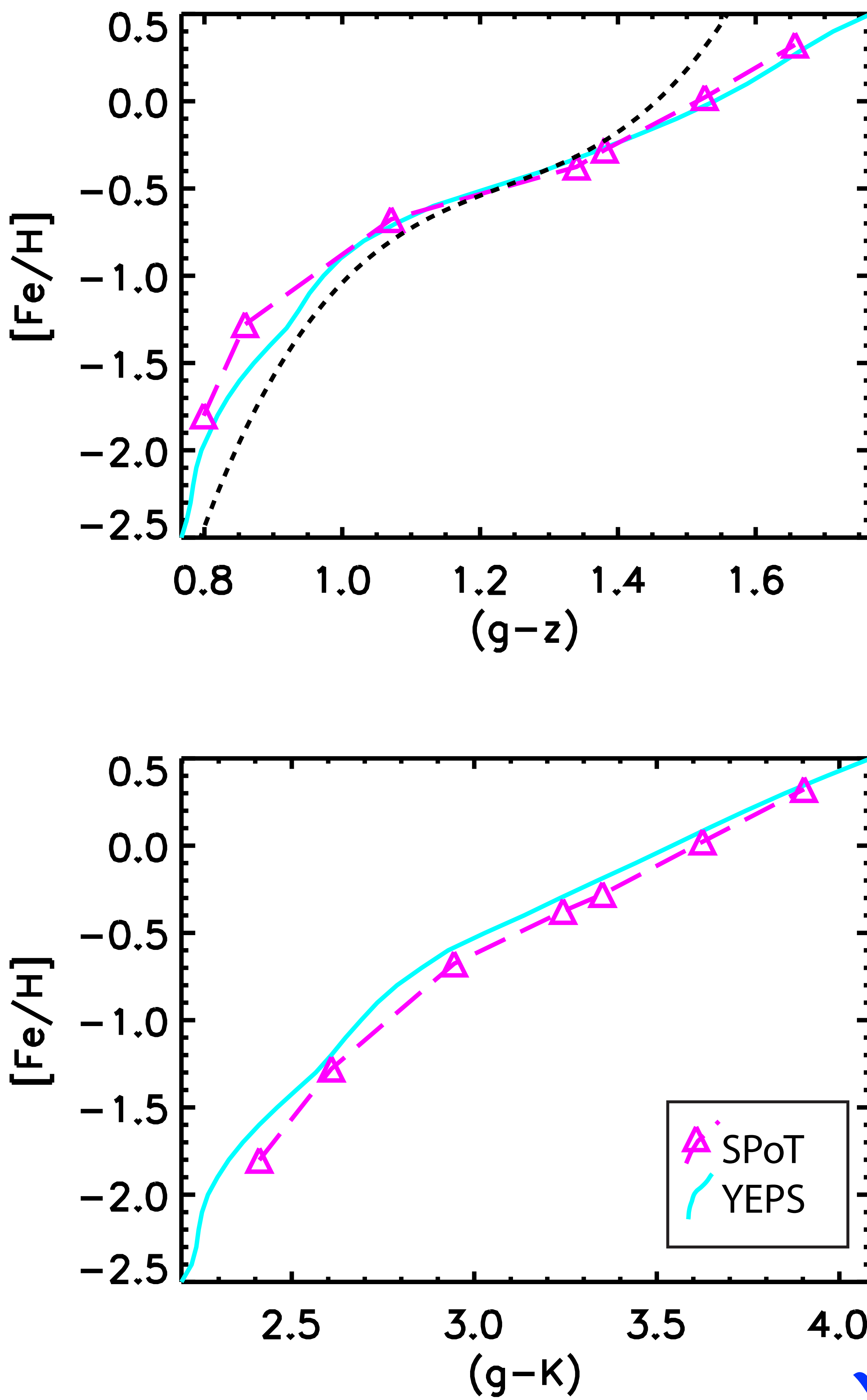


✓ Chies-Santos+2012a

(g-z) | (g-K) | (z-K)



★ Yoon+06 effect? ➡ (g-K) and (z-K) ➡ less affected by the HB



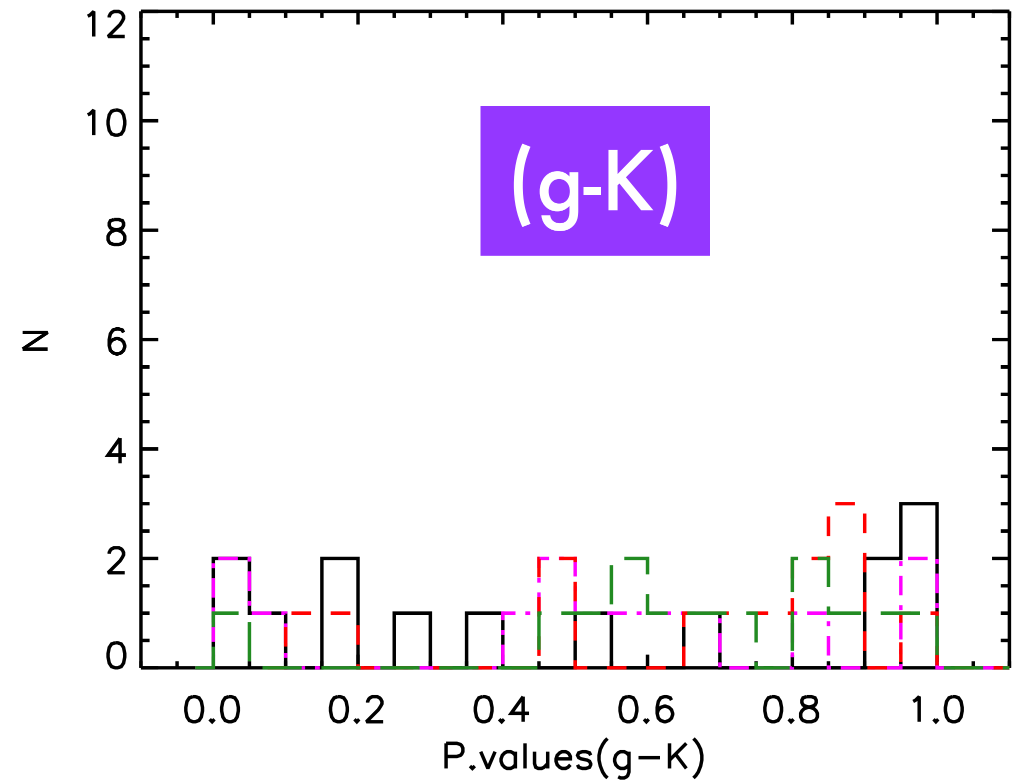
✓ Chies-Santos+2012a

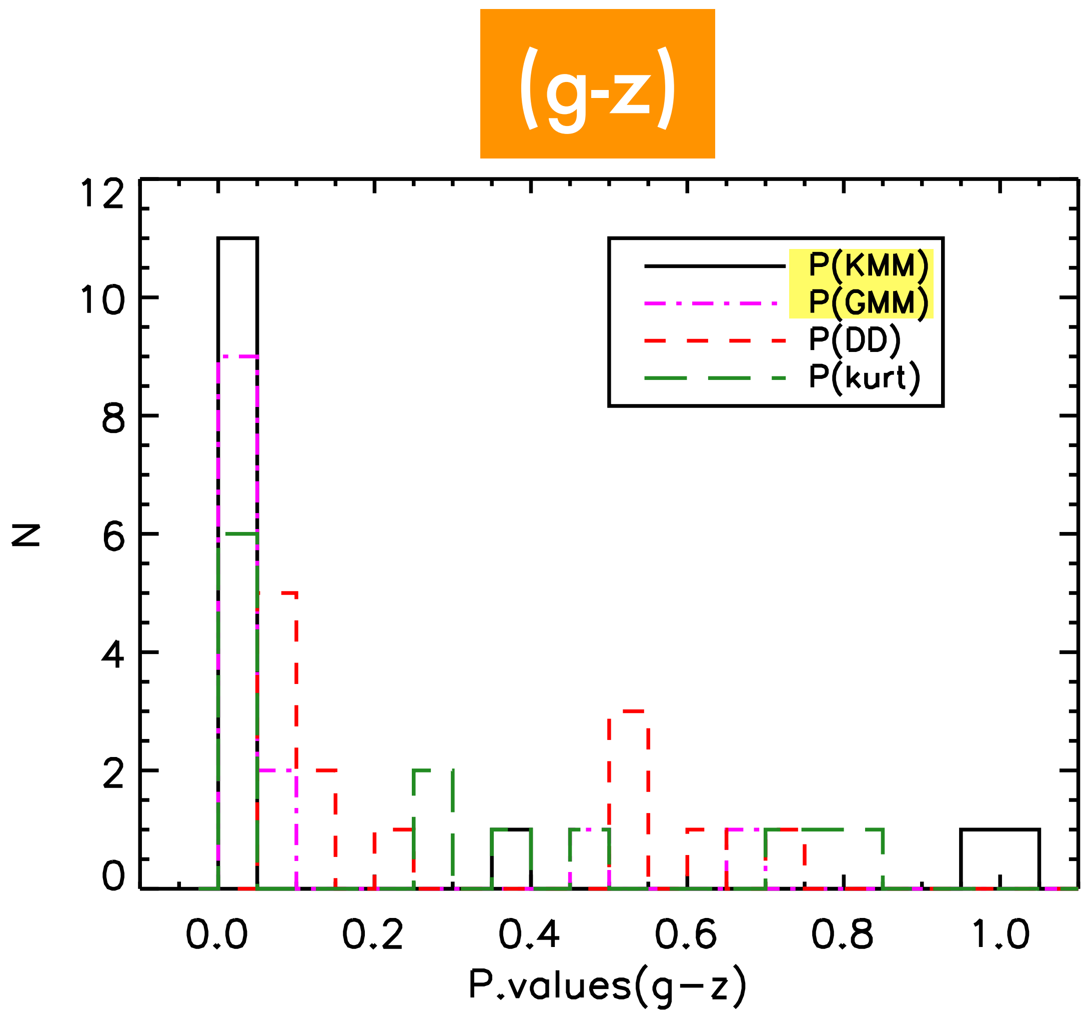
¿ bimodality ? - HB effect - Yoon+06?

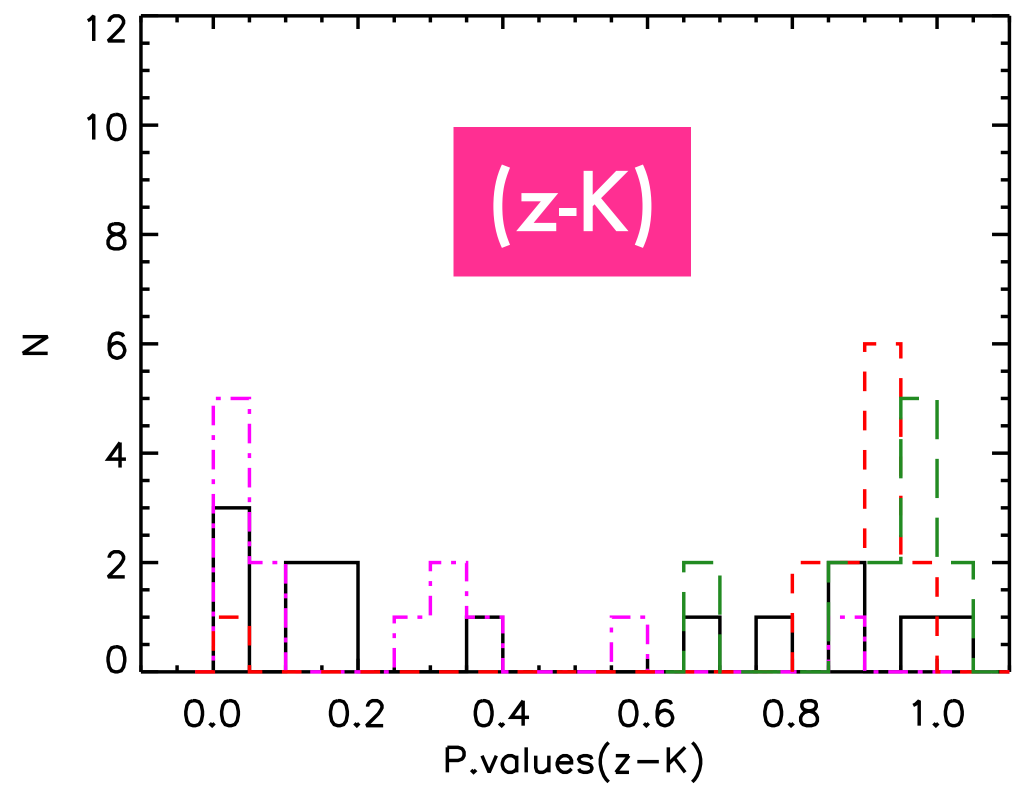
★check if bimodality could be blurred in (g-k) ➡ (z-k) due to K-band errors which are non-negligible

★Simulations ➡ bimodal (g-z) ➡ transforming linearly (g-z) ➡ (g-K) and (z-K) ➡ +++ randomly realistic magnitude dependant scatter (2 X that of PHOT)

P ➡ 0 ➡ more likely bimodal distribution (KMM & GMM)







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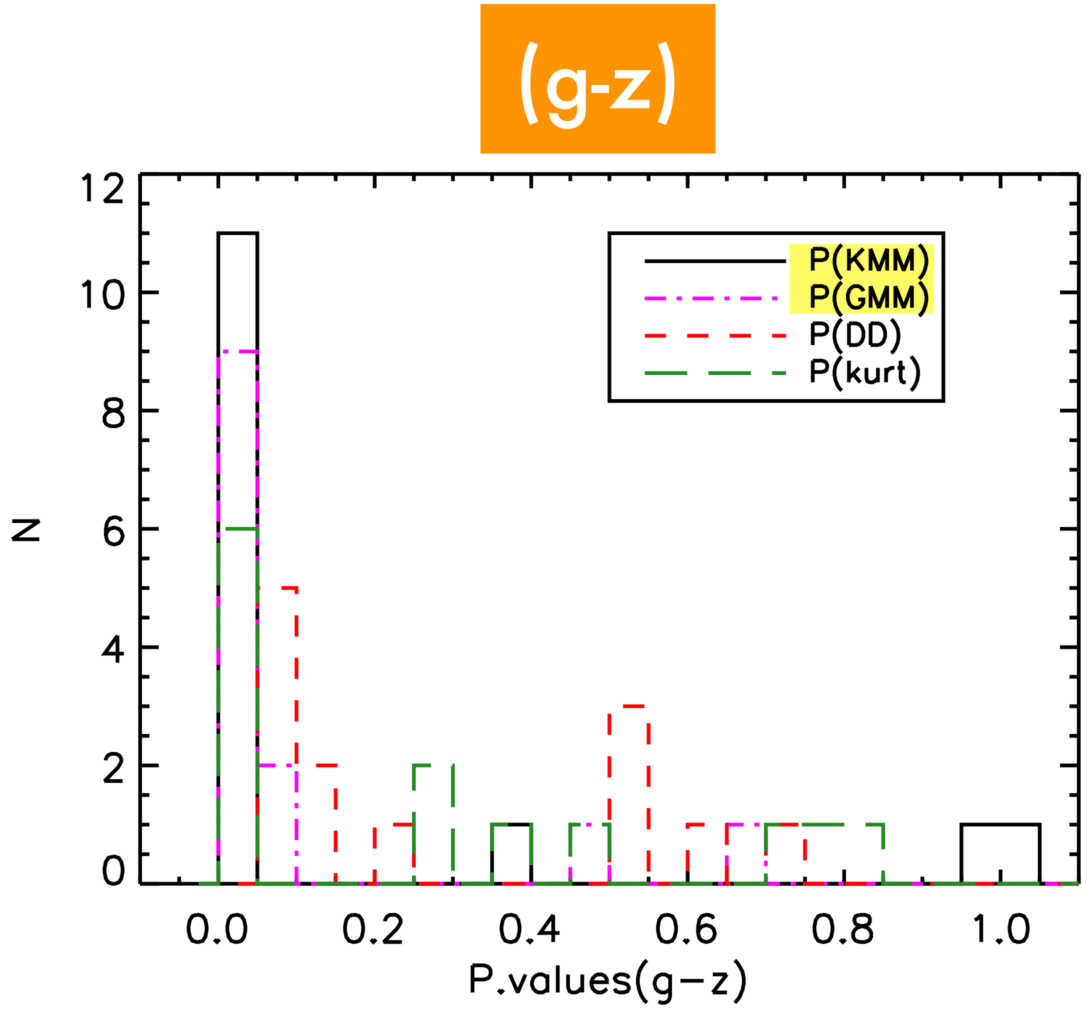
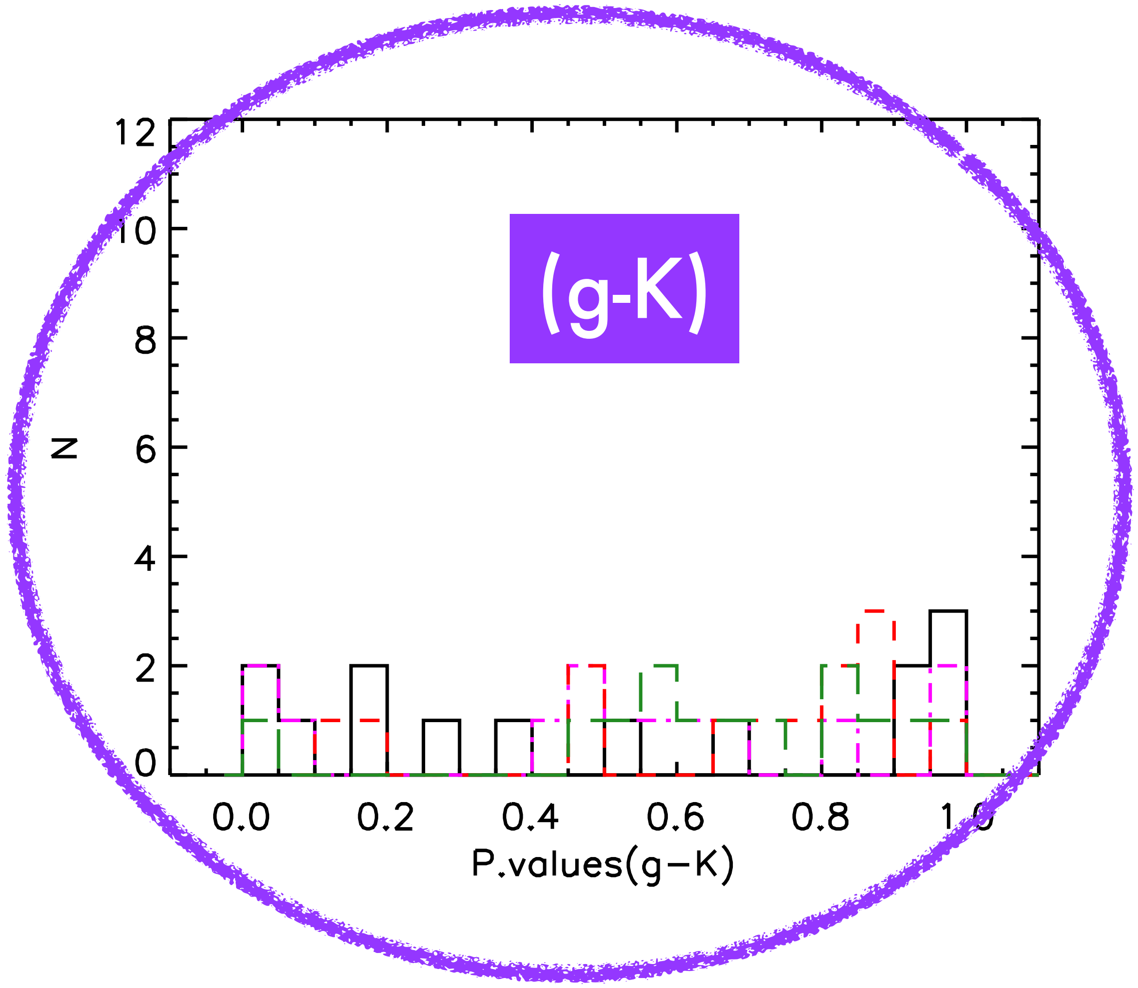
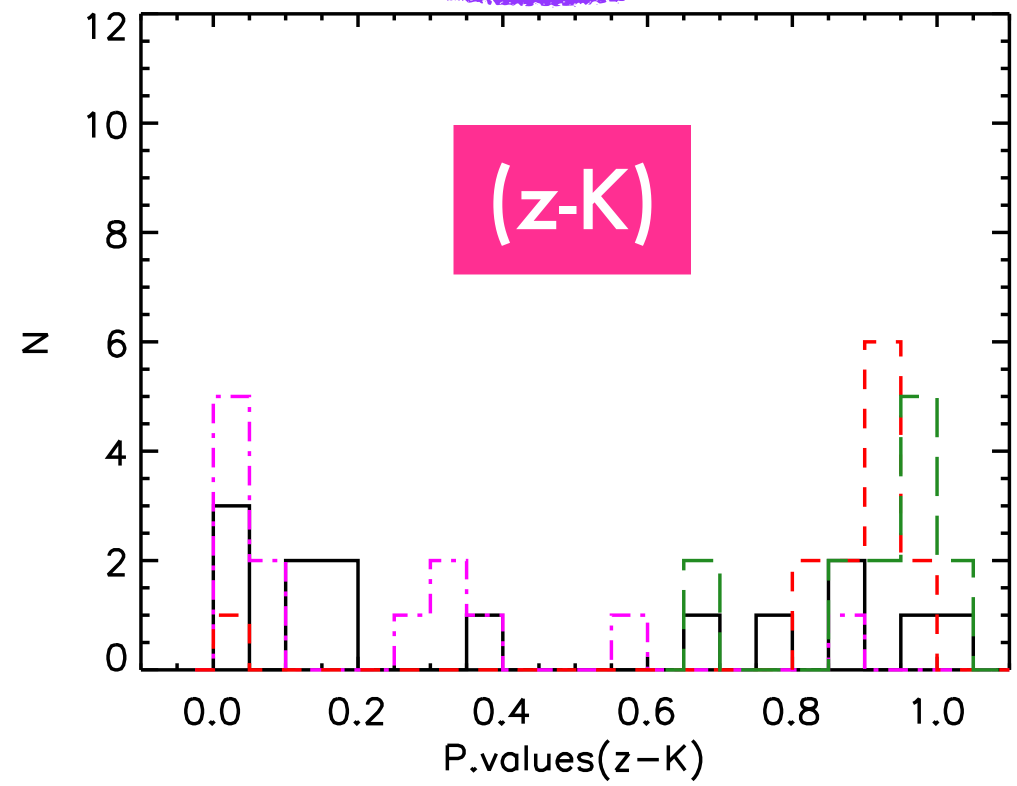




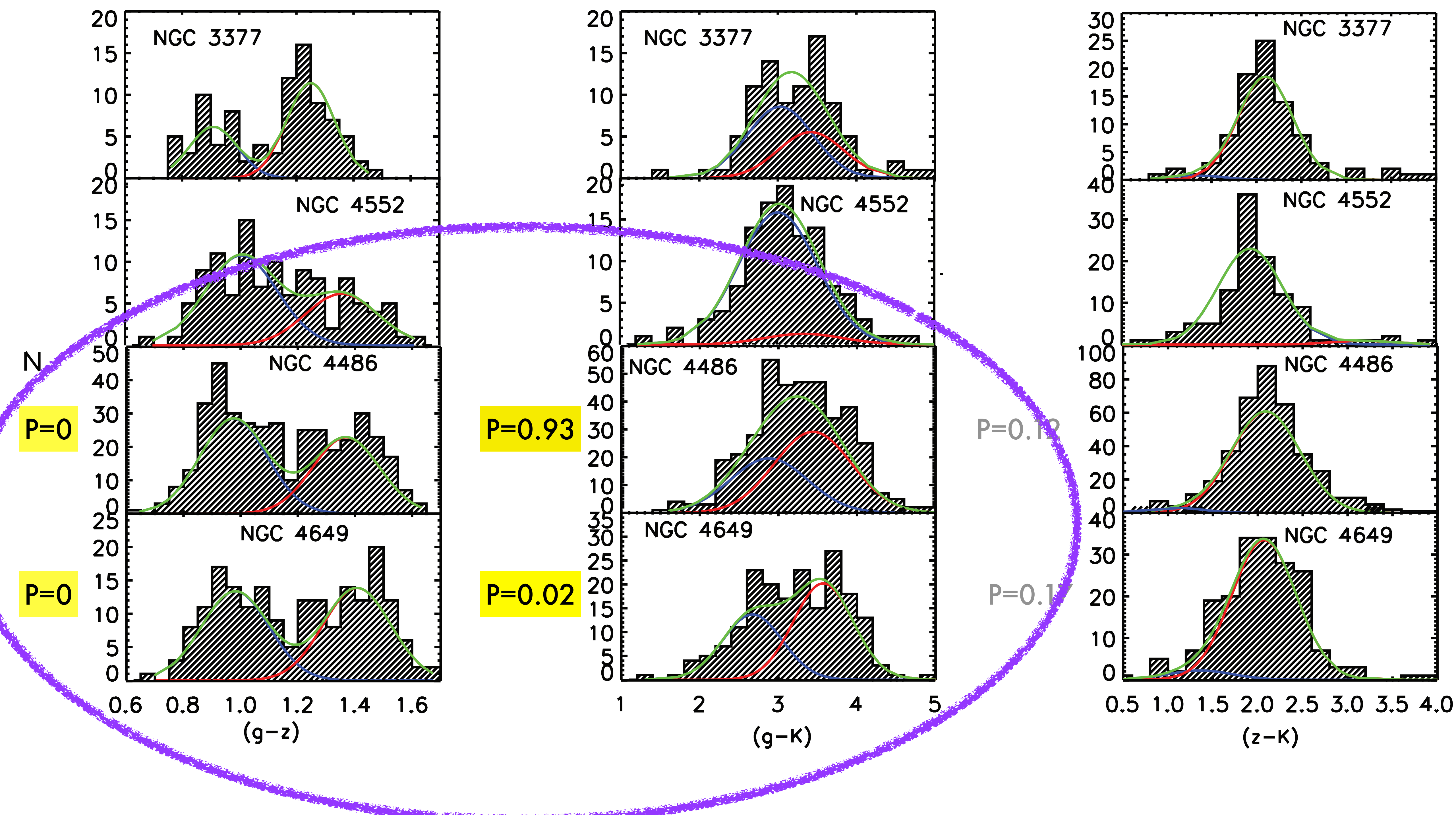


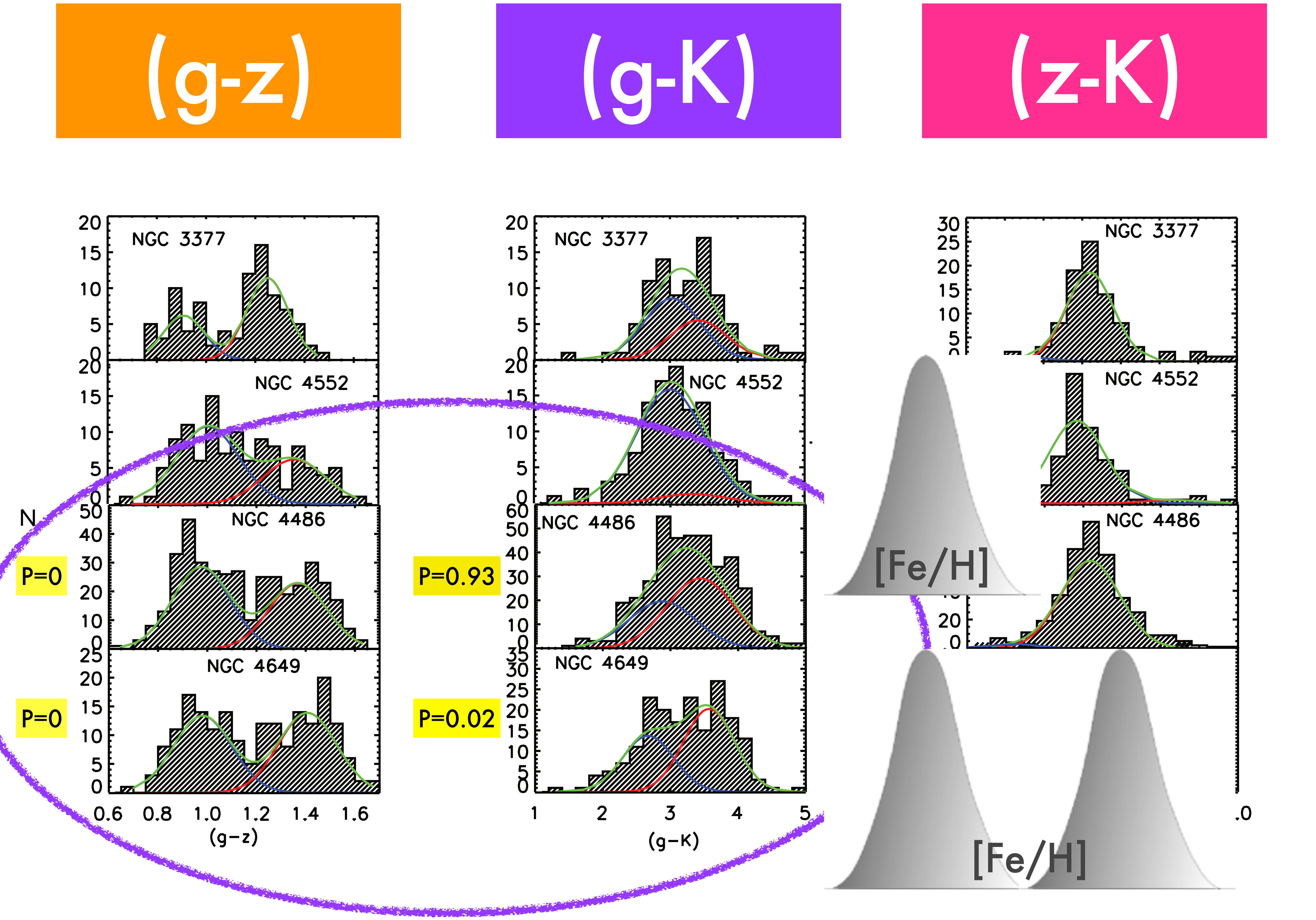
✓Chies-Santos+2012a

(g-z)

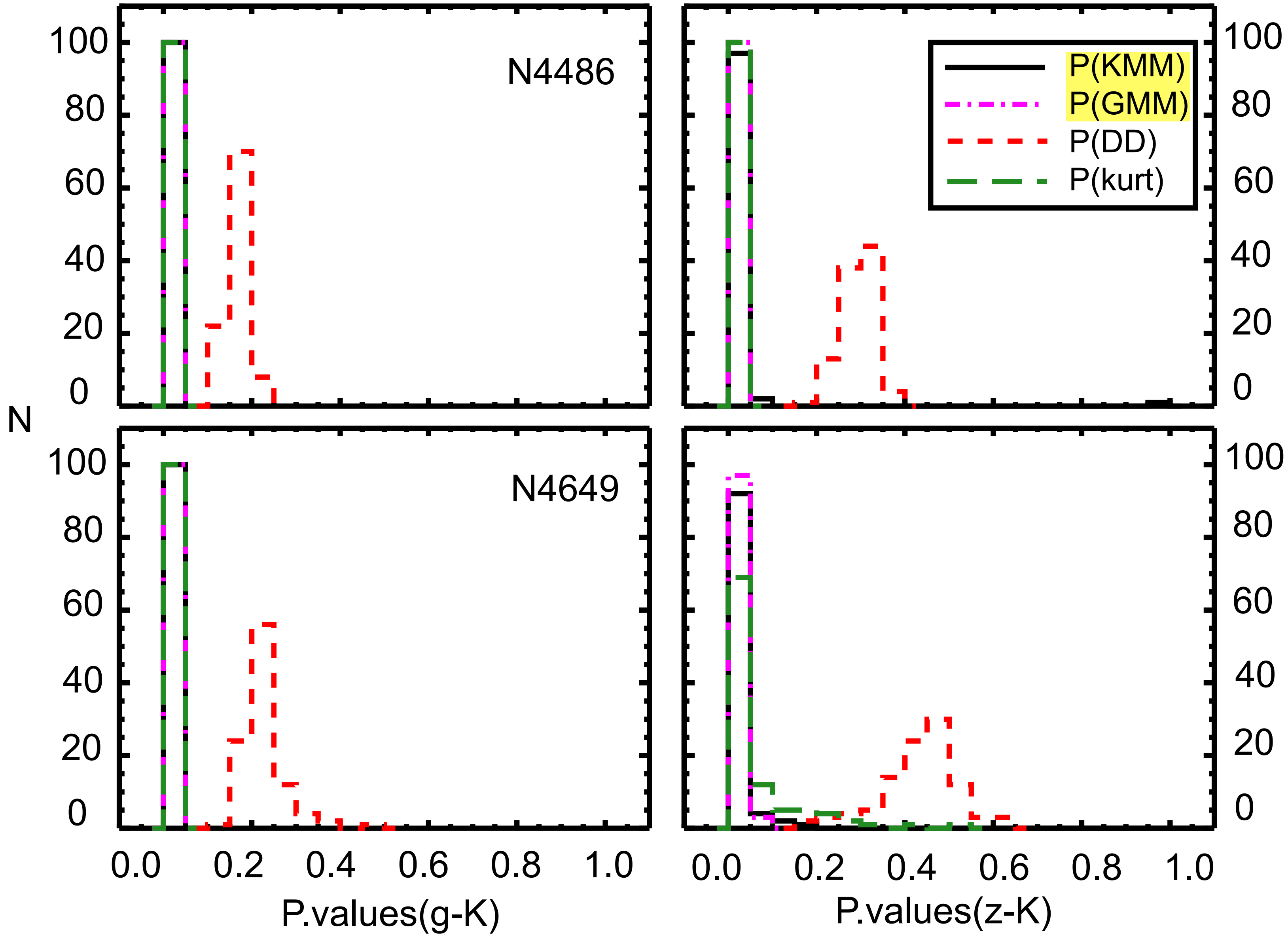
(g-K)

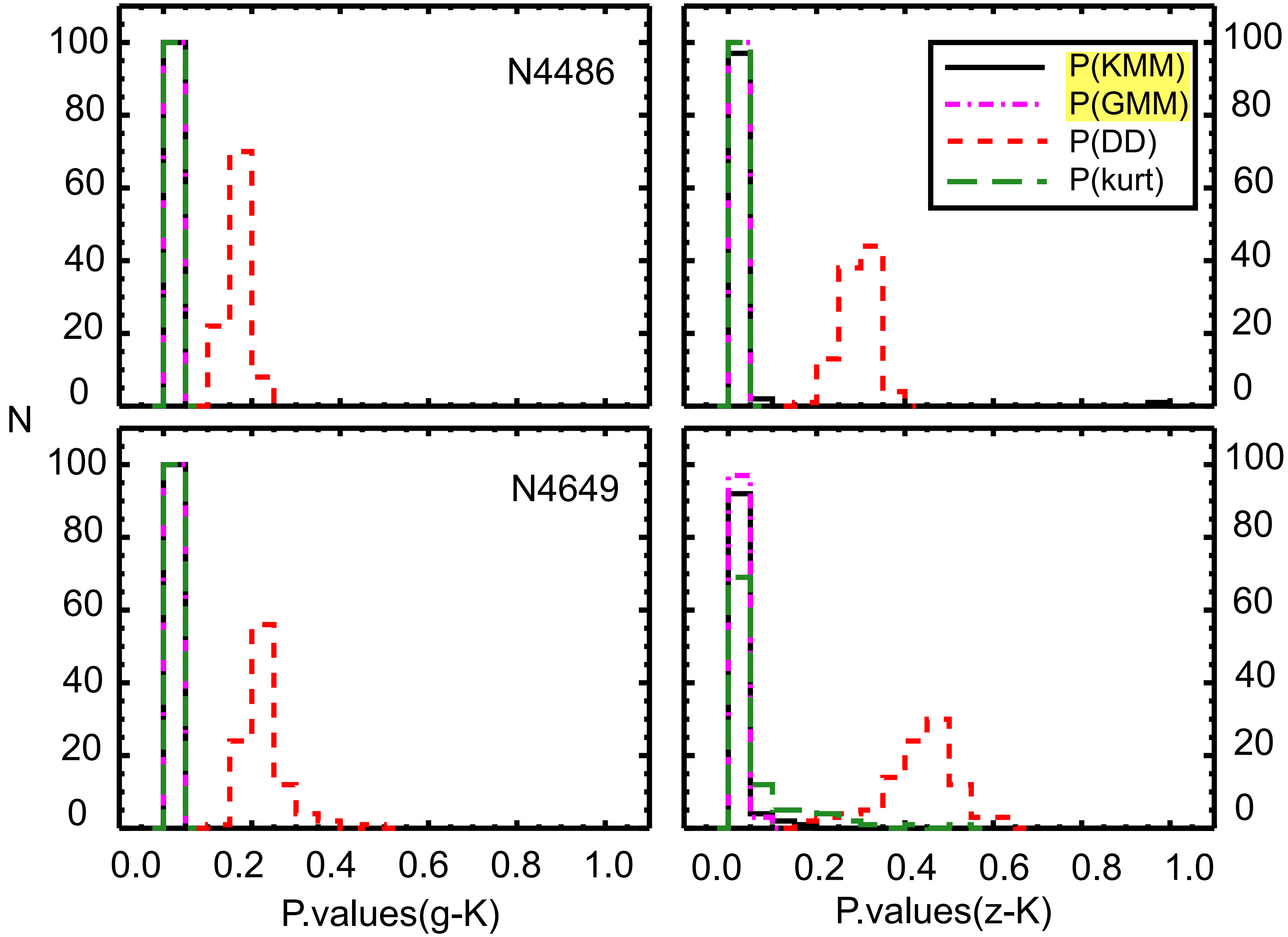
(z-K)



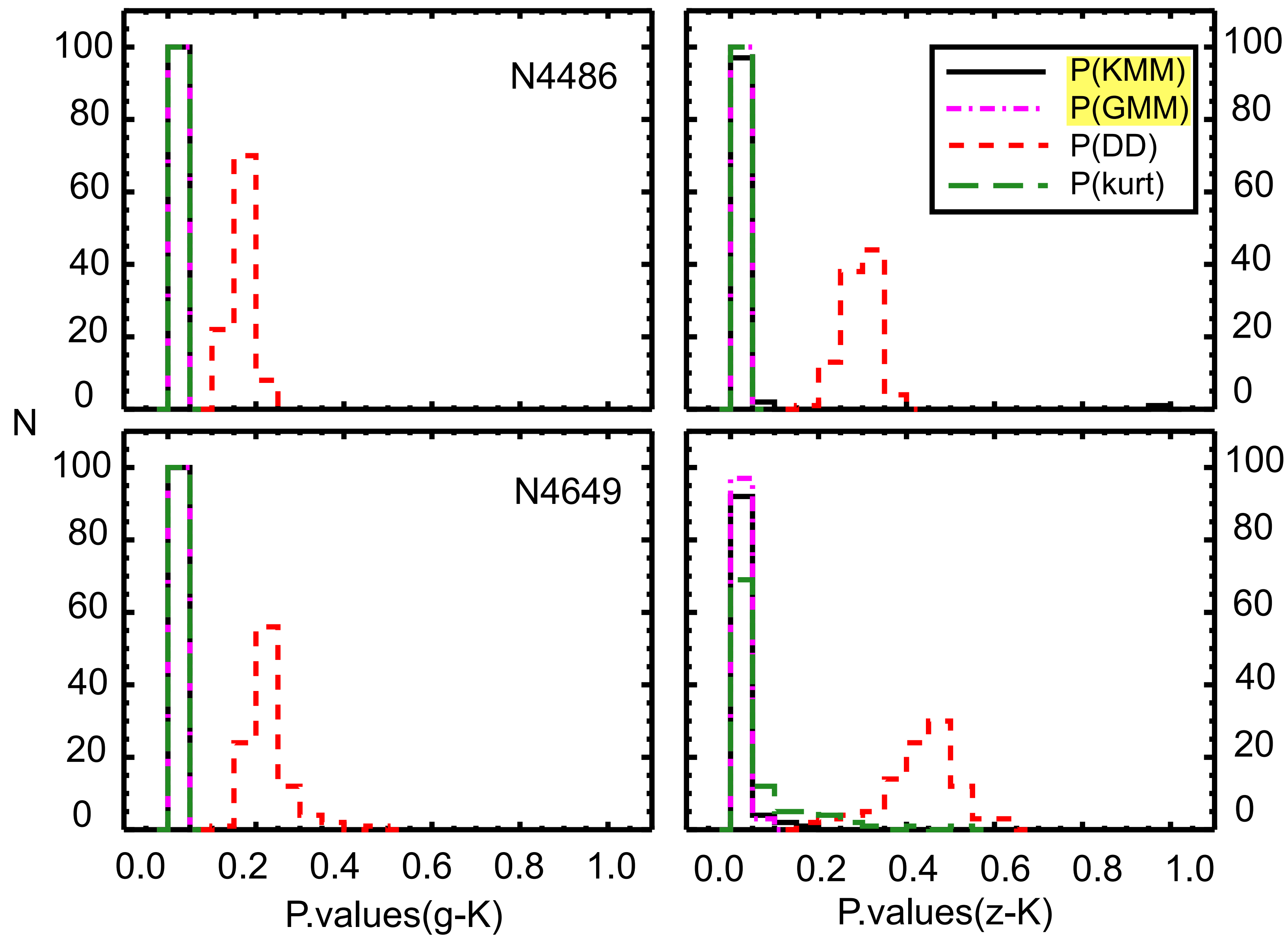


(g-z)
(g-K)
(z-K)
NGC 3377
NGC 4552
NGC 4486
NGC 4649
N
P=0
P=0
P=0.93
P=0.02
(g−z)
(g−K)
[Fe/H]
[Fe/H]


N4486
N4649
P(KMM)
P(GMM)
P(DD)
P(kurt)
N
P.values(g-K)
P.values(z-K)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100



★bimodality does not get blurred due to K-band scatter!!!
at least not in the GC-rich galaxies...



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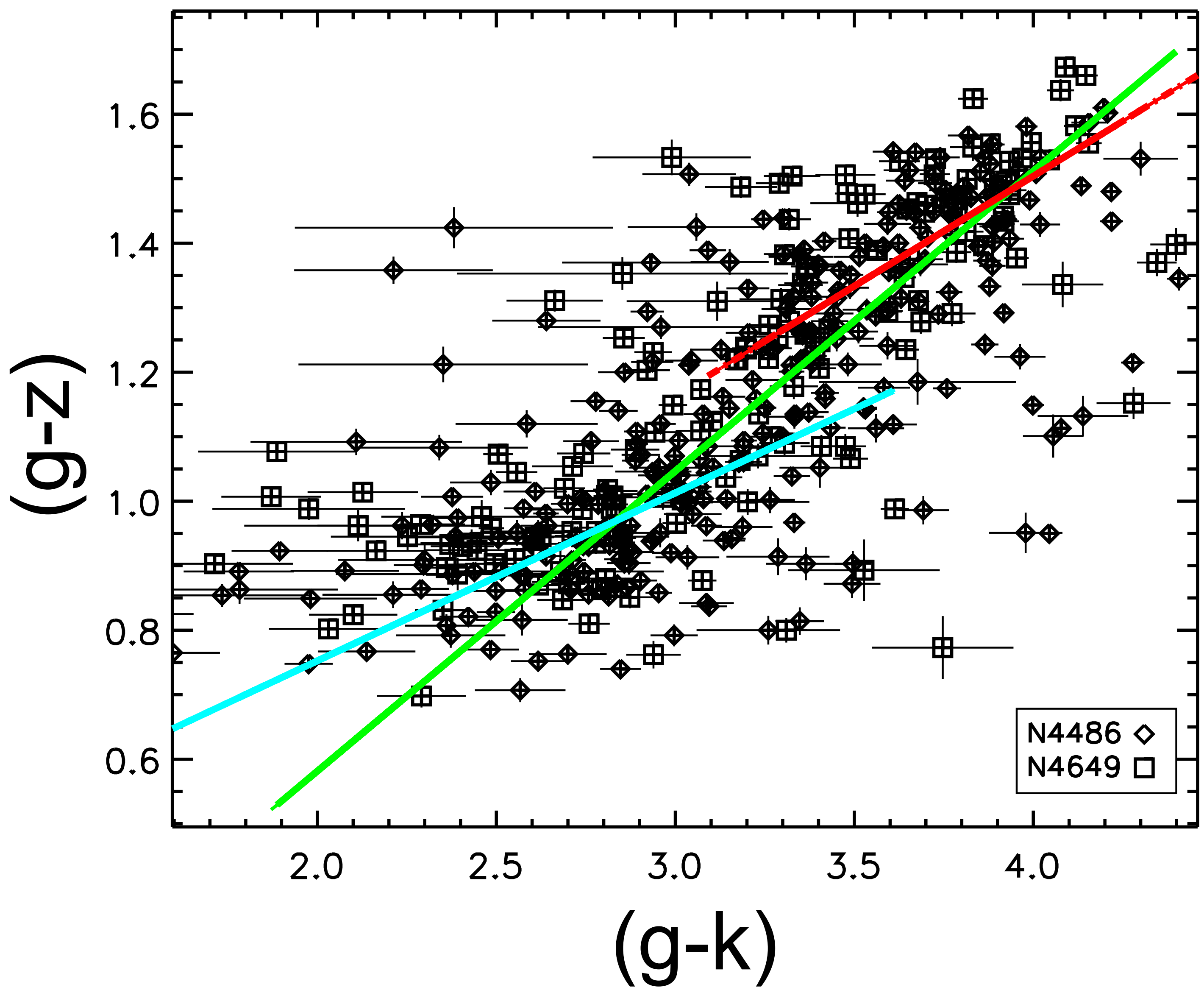
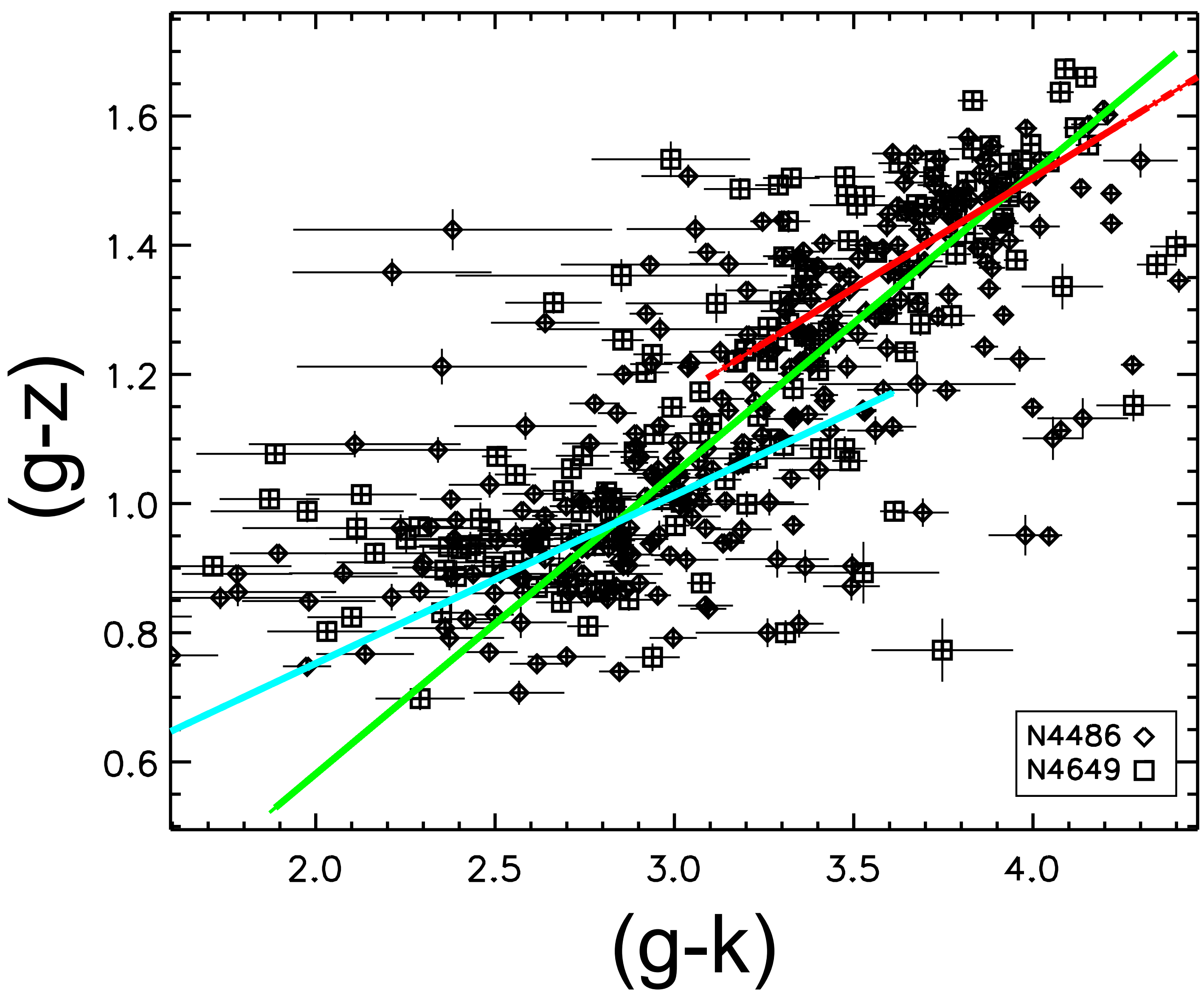
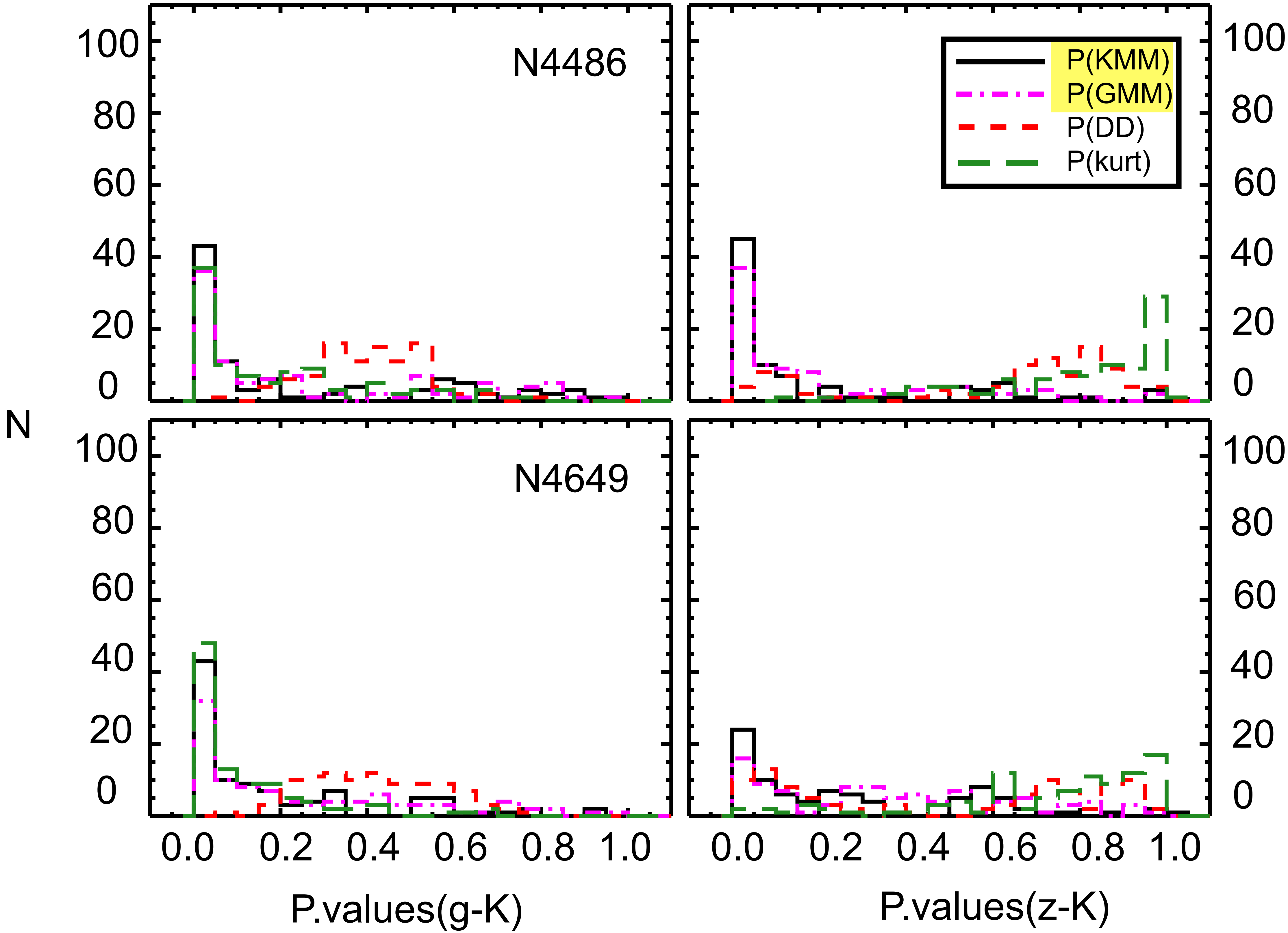
BUT



(g-z)
1.6
1.4
1.2
1.0
0.8
0.6
2.0
2.5
3.0
3.5
4.0
(g-k)
N4486
N4649

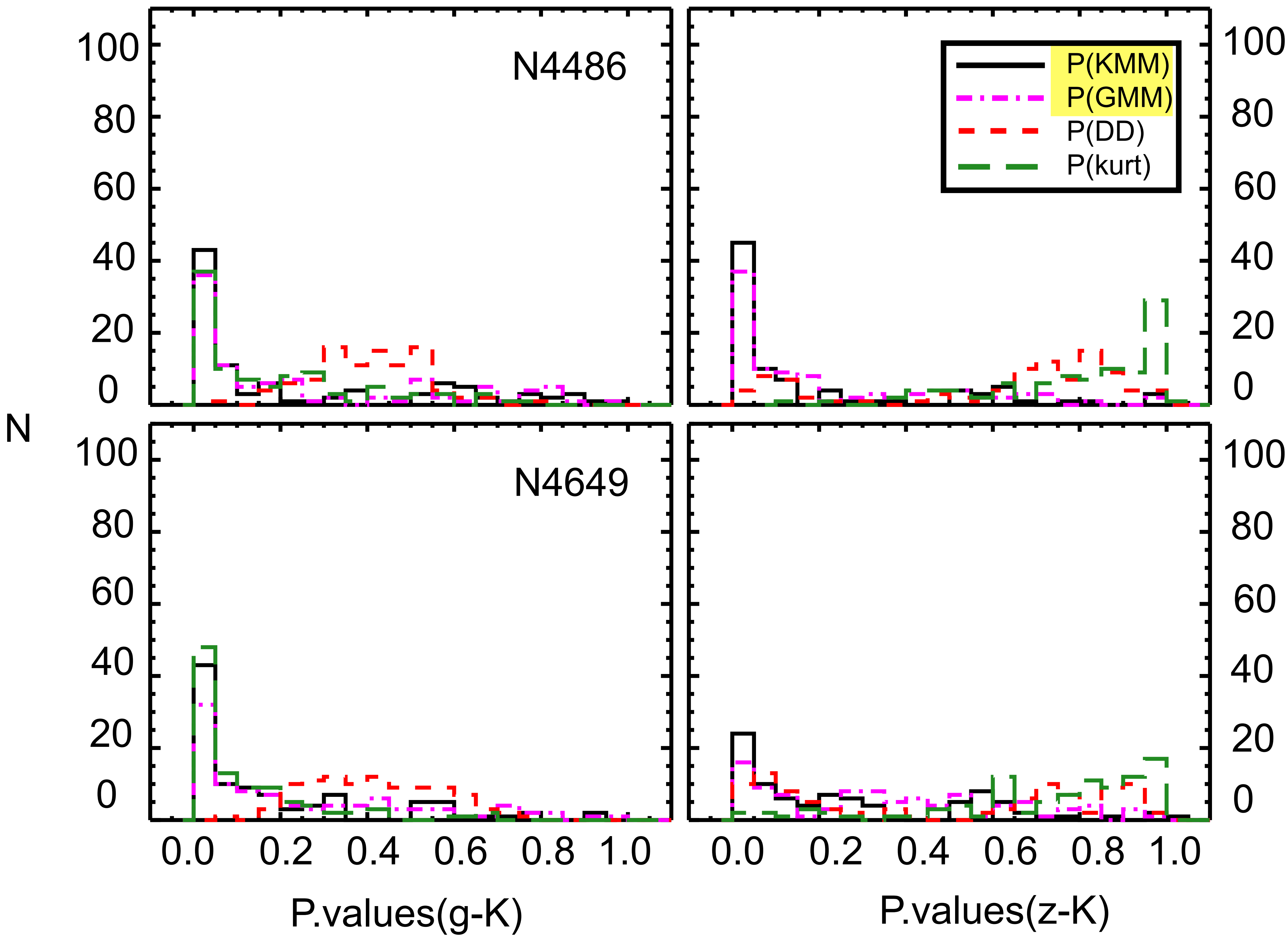


★Simulations ➡ transforming (g-z) ➡ (g-K) and (z-K) ➡ +++ randomly to the transformed distribution the residuals from the transformation relation



N4486
N4649
P(KMM)
P(GMM)
P(DD)
P(kurt)
N
100
80
60
40
20
0
0.0
0.2
0.4
0.6
0.8
1.0
P.values(g-K)
P.values(z-K)

★bimodality is blurred due to this scatter in the 2-colour diagrams for over half the cases



Summary "bimodality"

★colour bimodality does get less pronounced in optical/ NIR colours

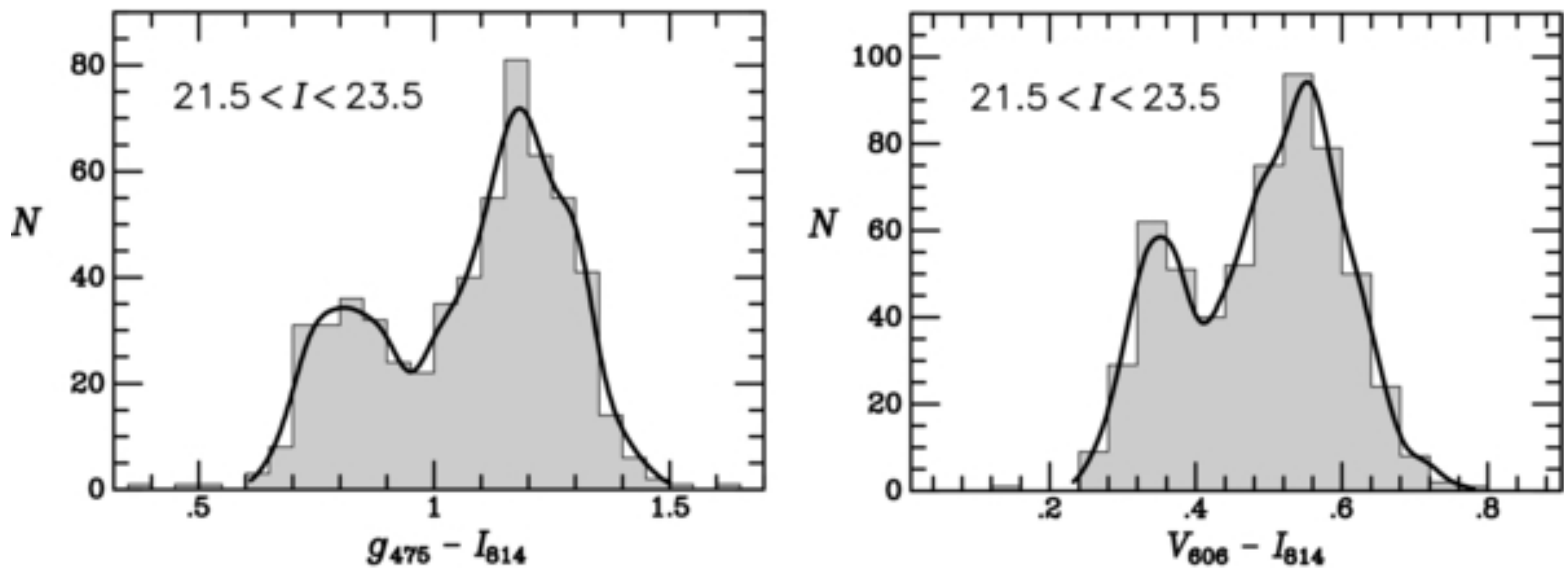
- ✓(g-K) N4486
- x (g-K) N4649

★Formally K-band errors are not responsible for blurring bimodality in the red colours BUT (instrinsic?) scatter in 2-colour diagrams

★need better K data
- ✓HAWK-I
- ✓Flamingos-2

★metallicity bimodality is NOT universal

★Blakeslee+12 ➡ GC colour distribution NGC1399 (ACS+WFC3)



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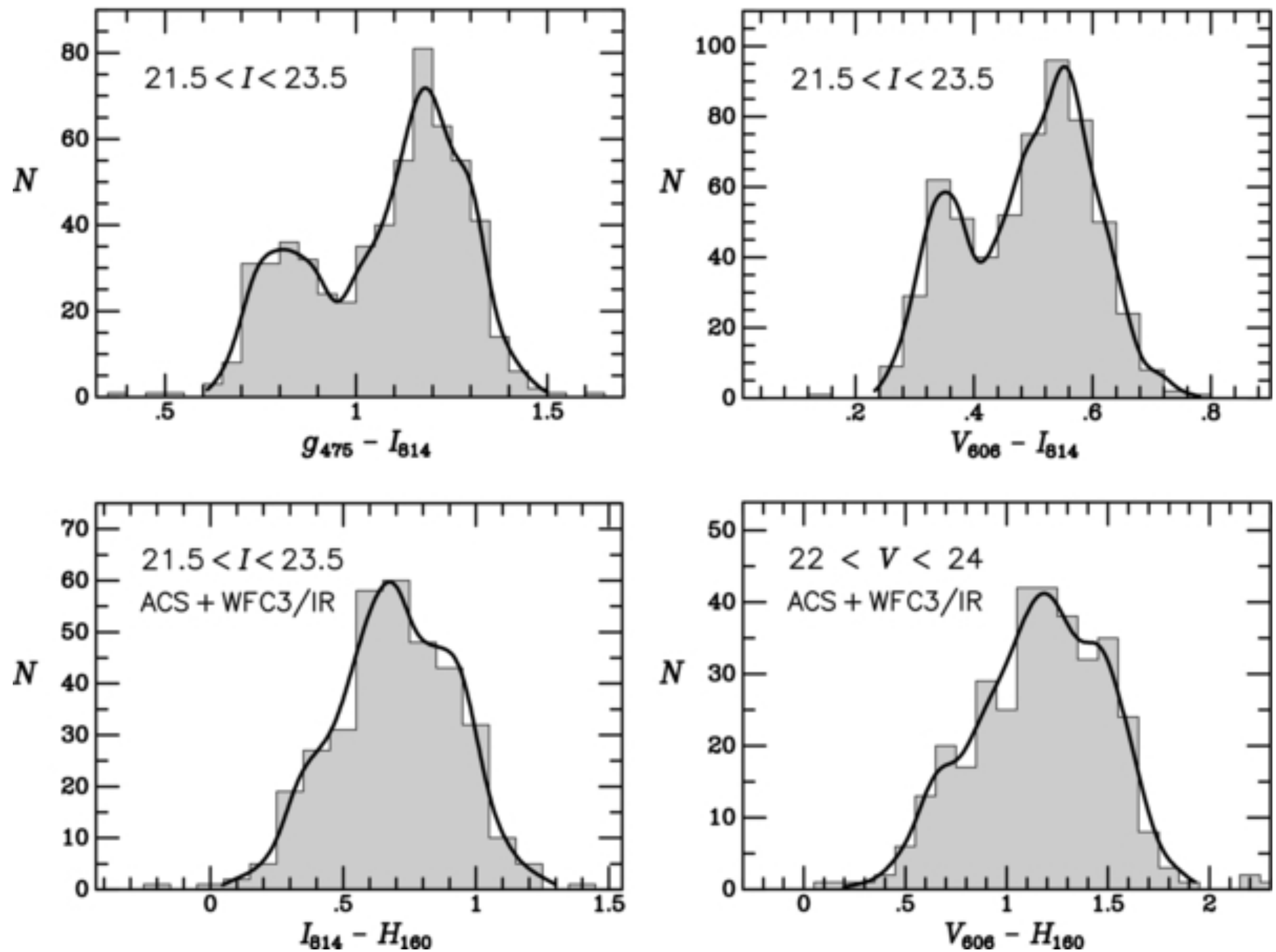
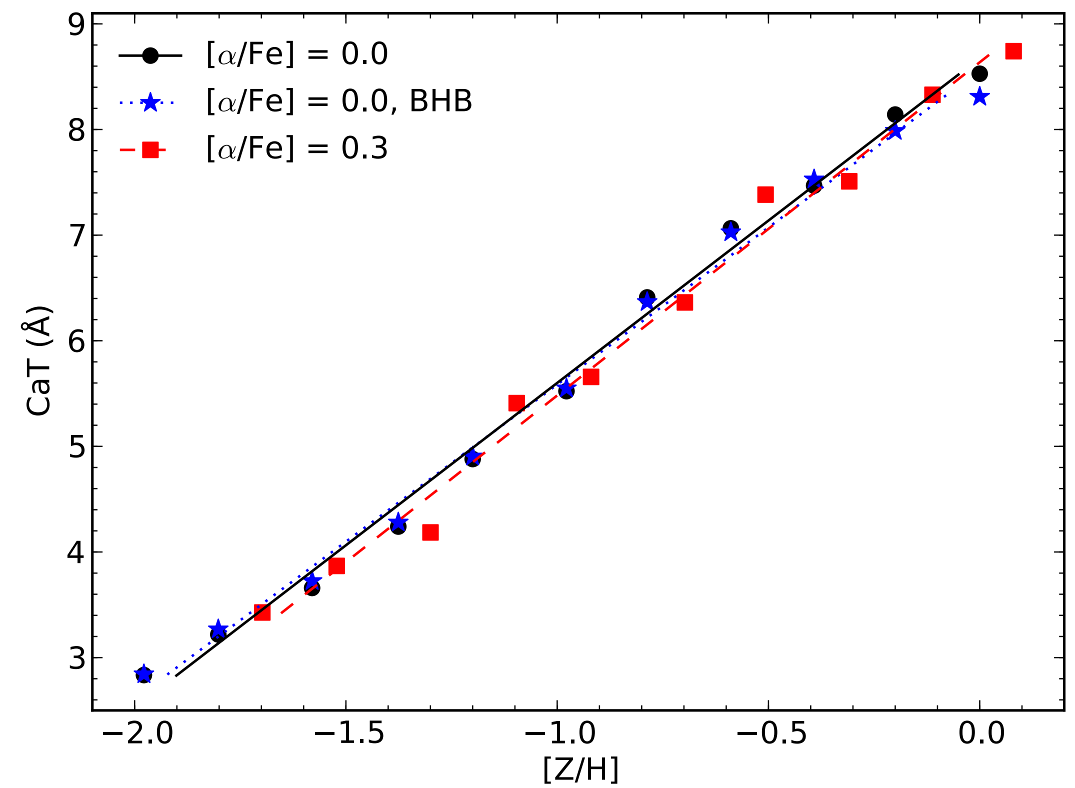
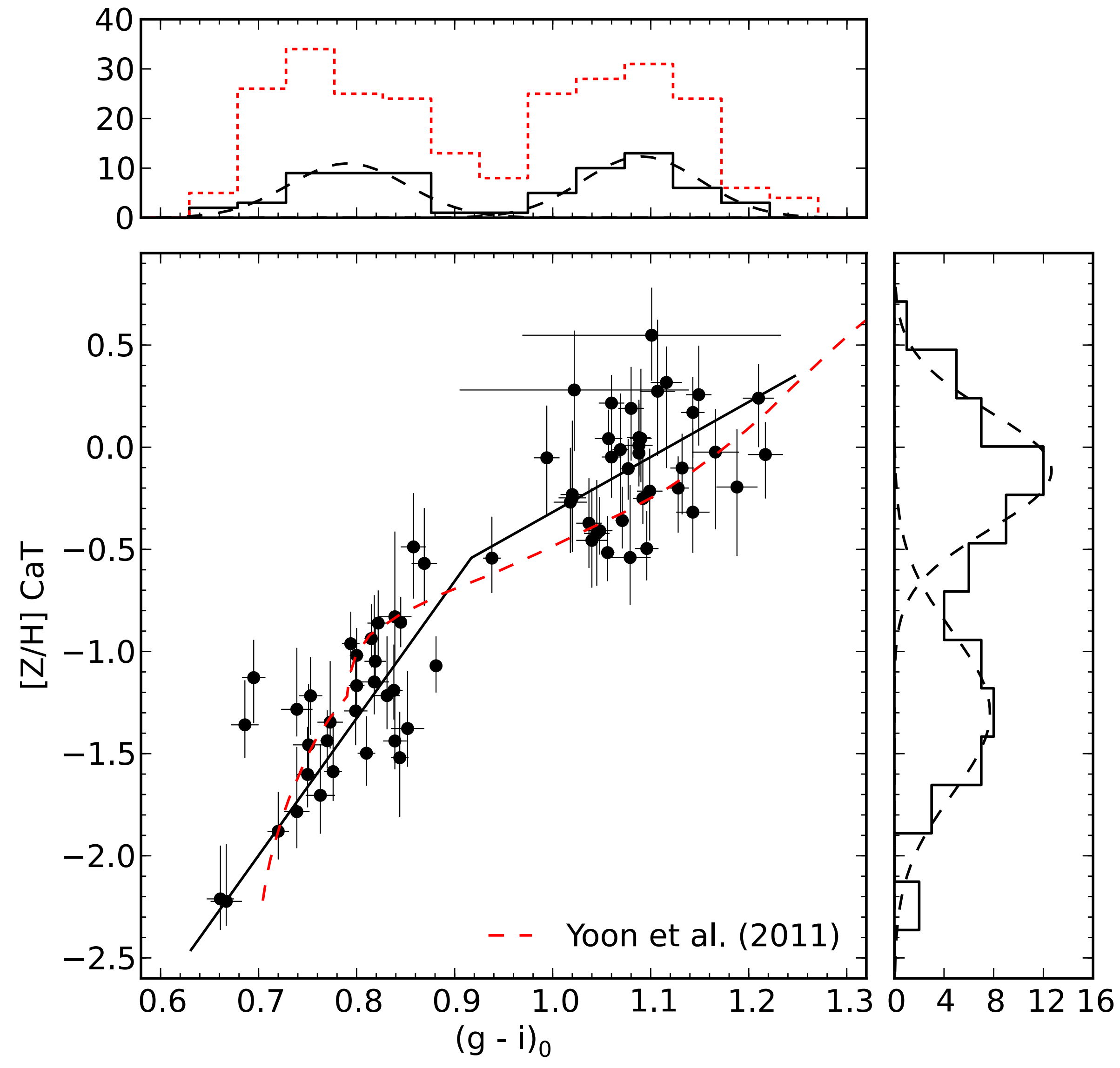
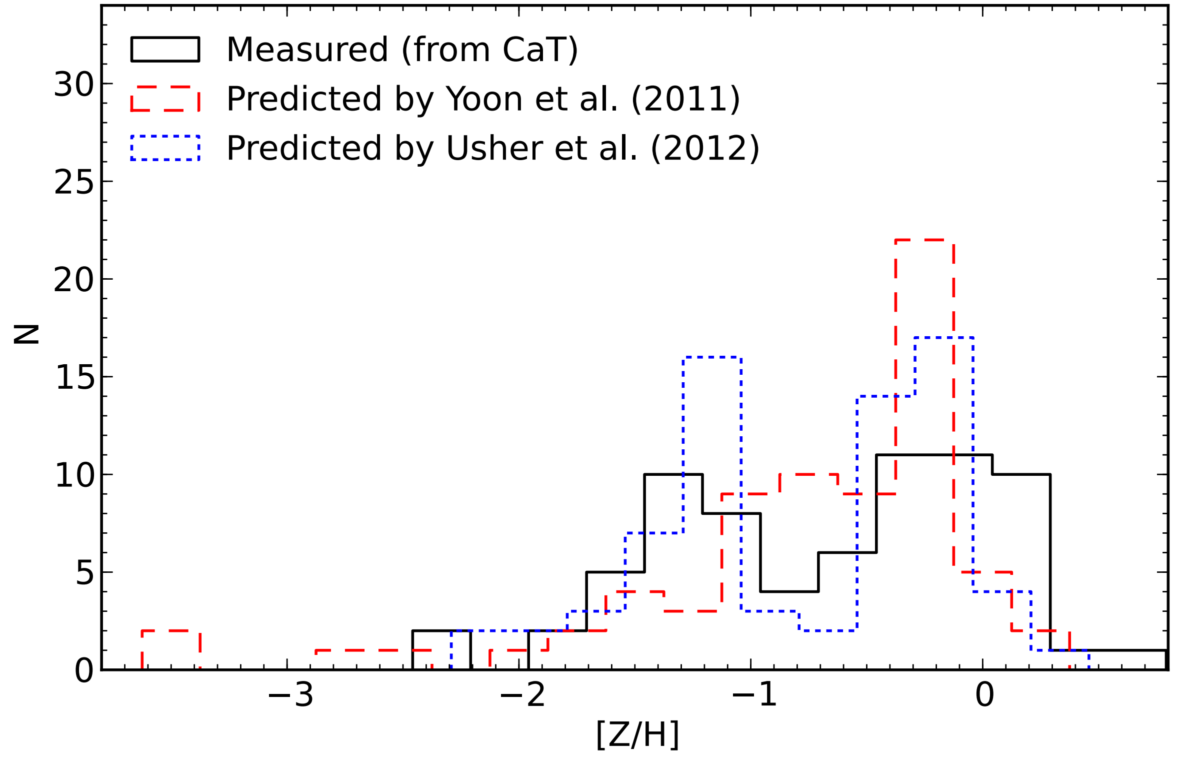


★Brodie +2012

✓N3115, nearest S0

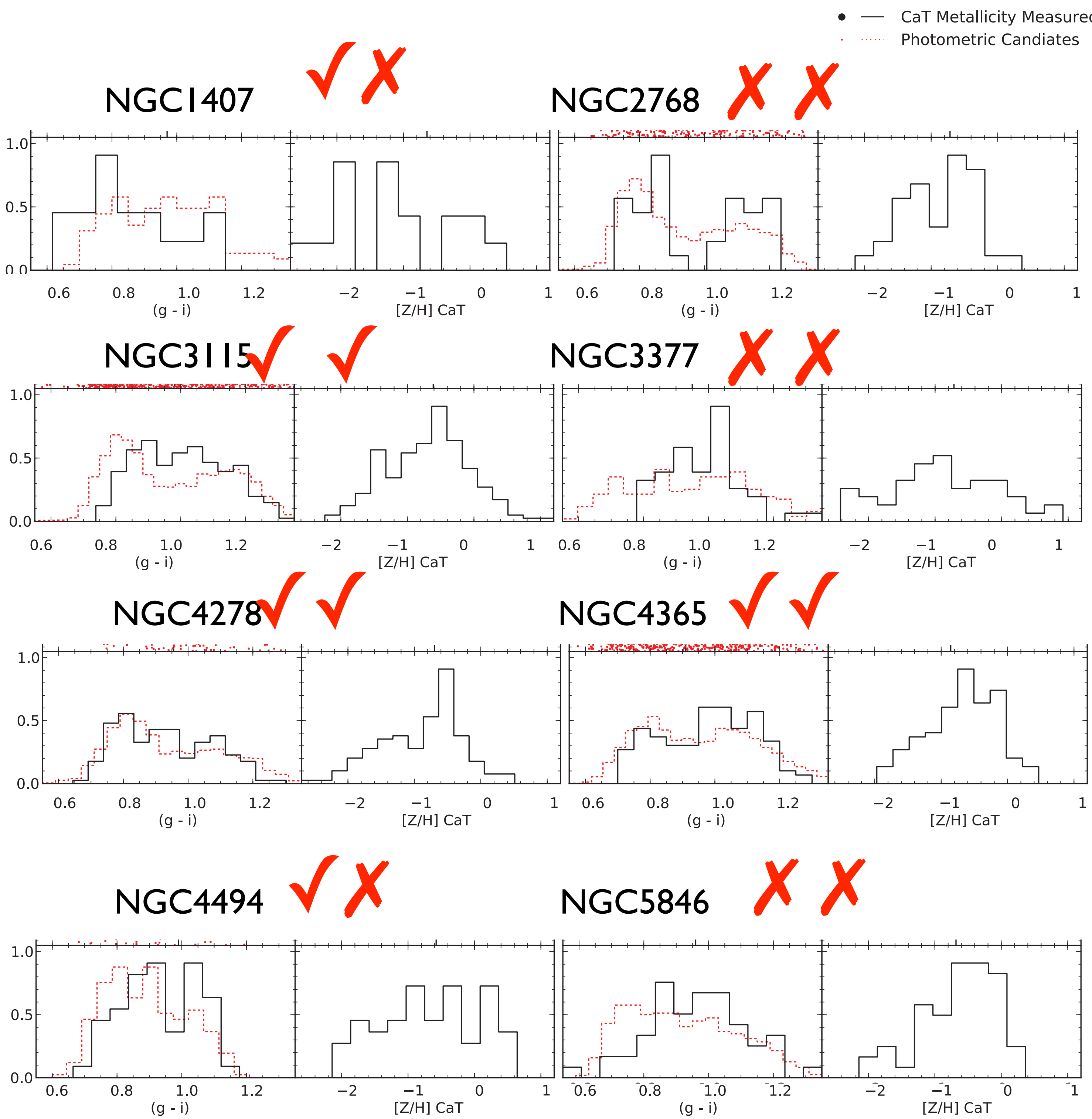






★Usher +2012

✓CaT metallicities



GMM

(g-i)	p=0.001	p=0.355
CaT	p=0.059	p=0.859
(g-i)	p=0.001	p=0.097
CaT	p=0.002	p=0.090
(g-i)	p=0.005	p=0.001
CaT	p=0.001	p=0.049
(g-i)	p=0.045	p=0.159
CaT	p=0.181	p=0.075

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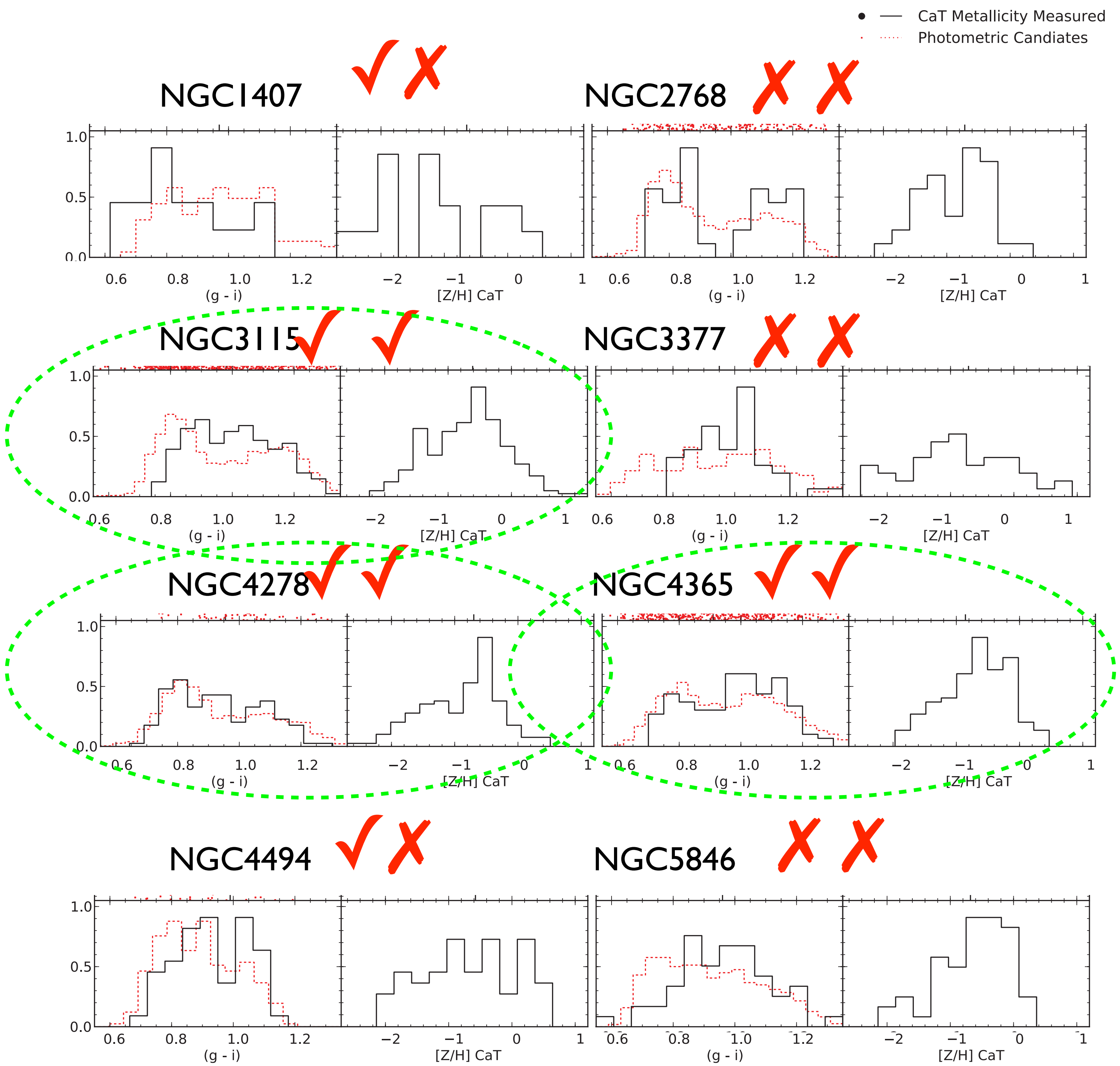

<u>GMM</u>

(g-i)	p=0.001	p=0.355
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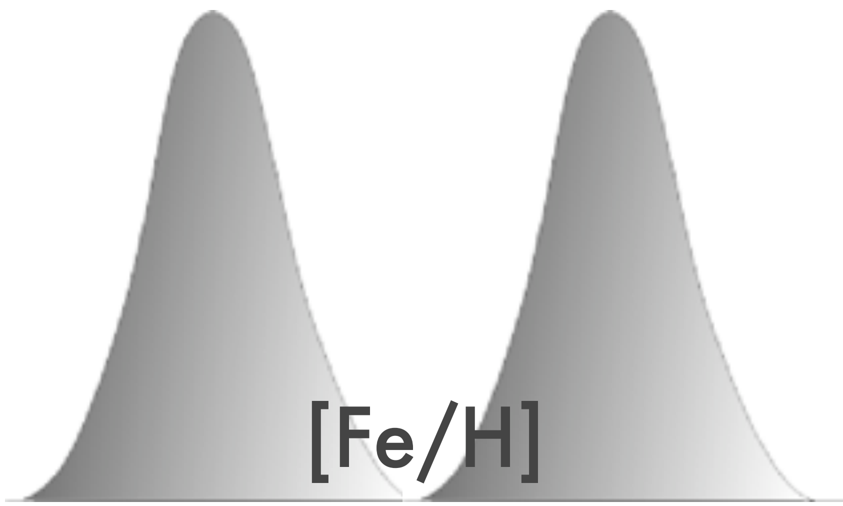
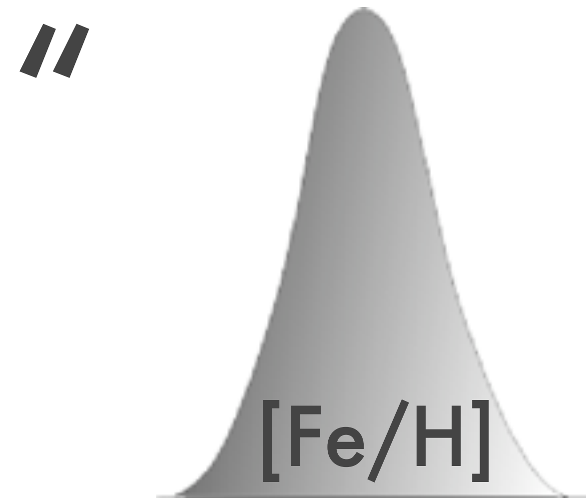
Conclusions “bimodality"

★Metallicity bimodality is NOT universal!



- ★Milky Way (Zinn 85)
- ★Sombrero (Alves-Brito+11)
- ★N3115 (Brodie+12)
- ★M60?



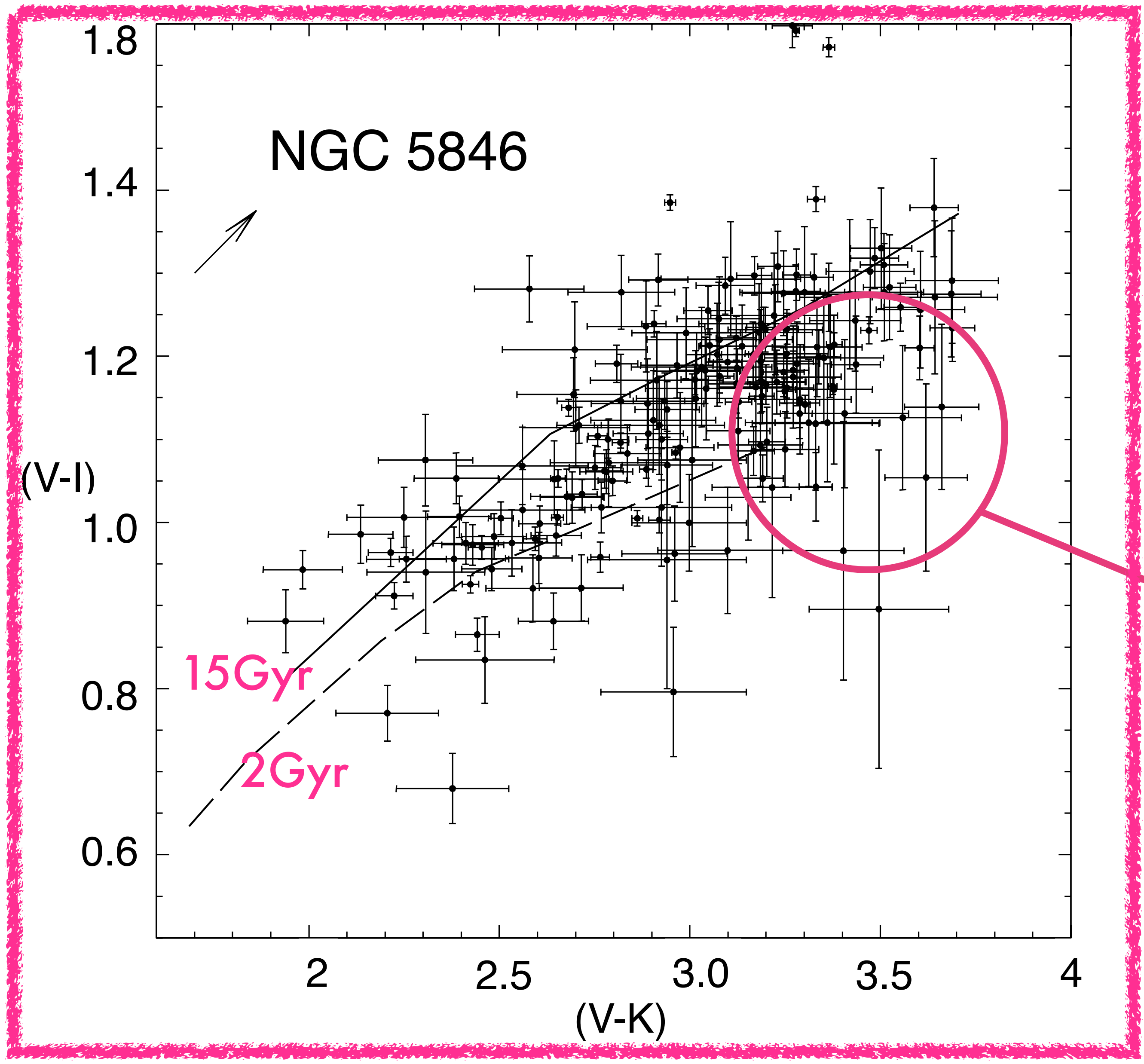
- ★N1399 (Blakeslee+12)
- ★M87?
- ★N1407 (Foster+10a)
- ★M31 (Caldwell+11)
- ★CenA (e.g. Woodley10)

★Fits much better with the hierarchical merging paradigm

"Age Problem"

★≈2-8Gyrs GCs in "old" ellipticals (>10Gyrs)

★NGC 4365 and NGC 5846



★Hempel+03

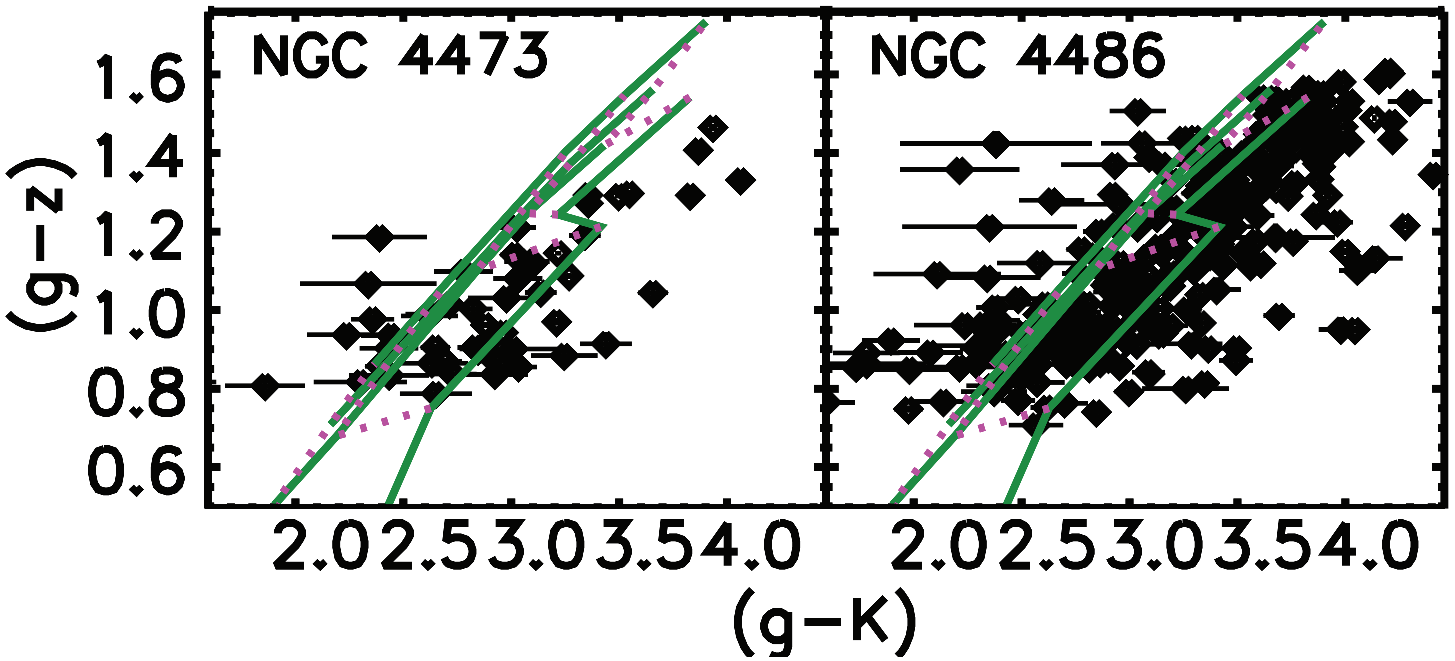
★ Intermediate ages?

Deriving ages ✔ SSP

Deriving ages SSP

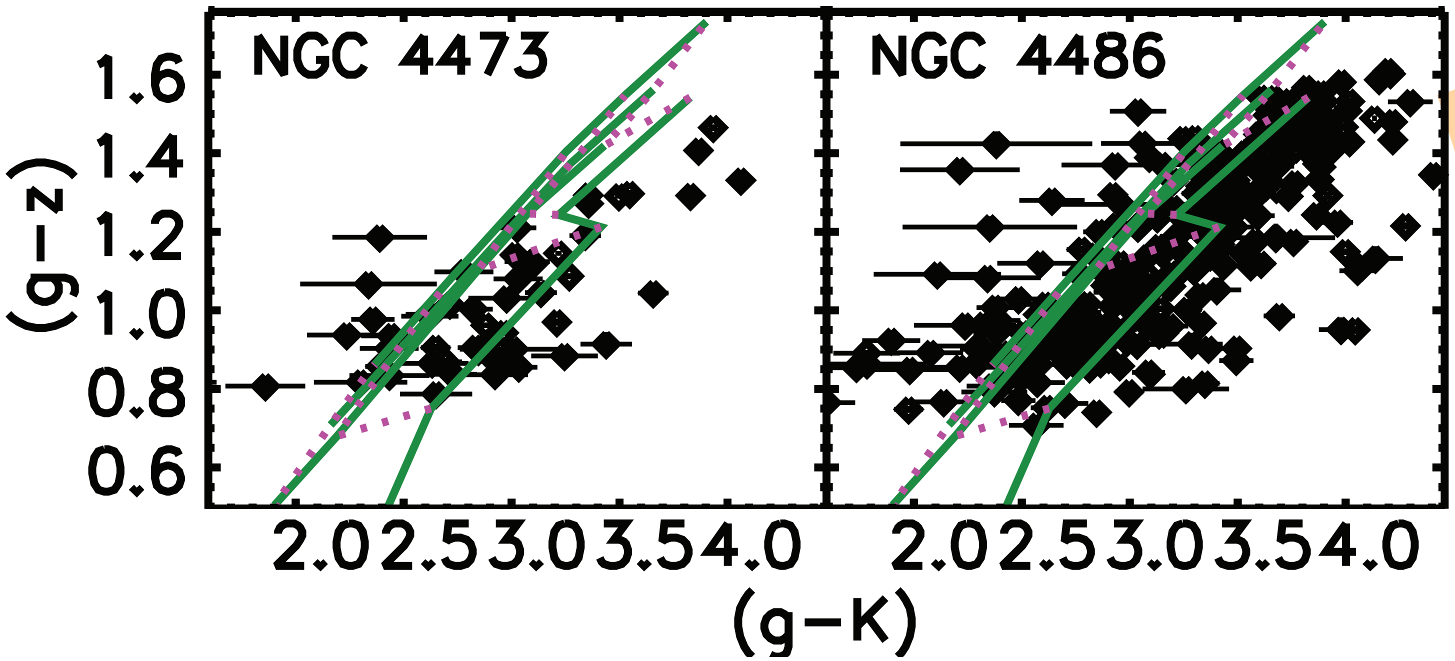
and its problems

Maraston05



✓Chies-Santos+2011b

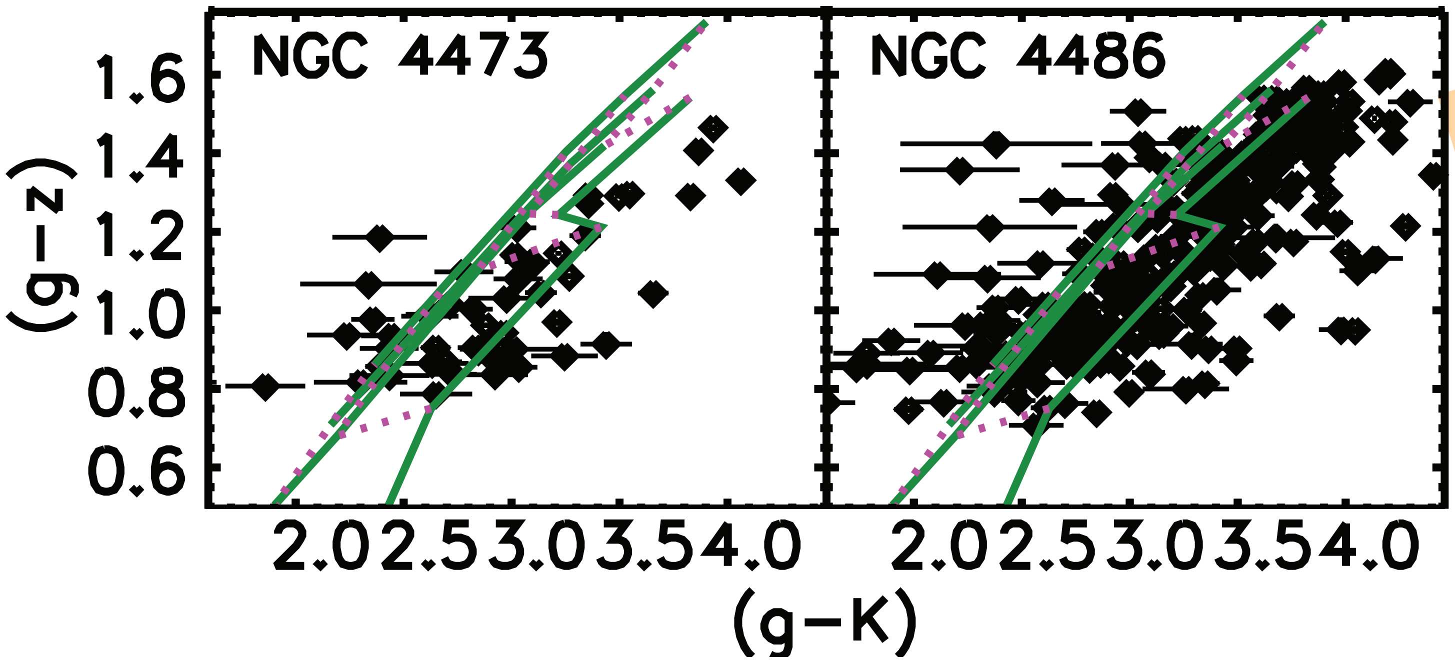
Maraston05



2<ages(Gyrs)<3 Gyrs

✓Chies-Santos+2011b

Maraston05

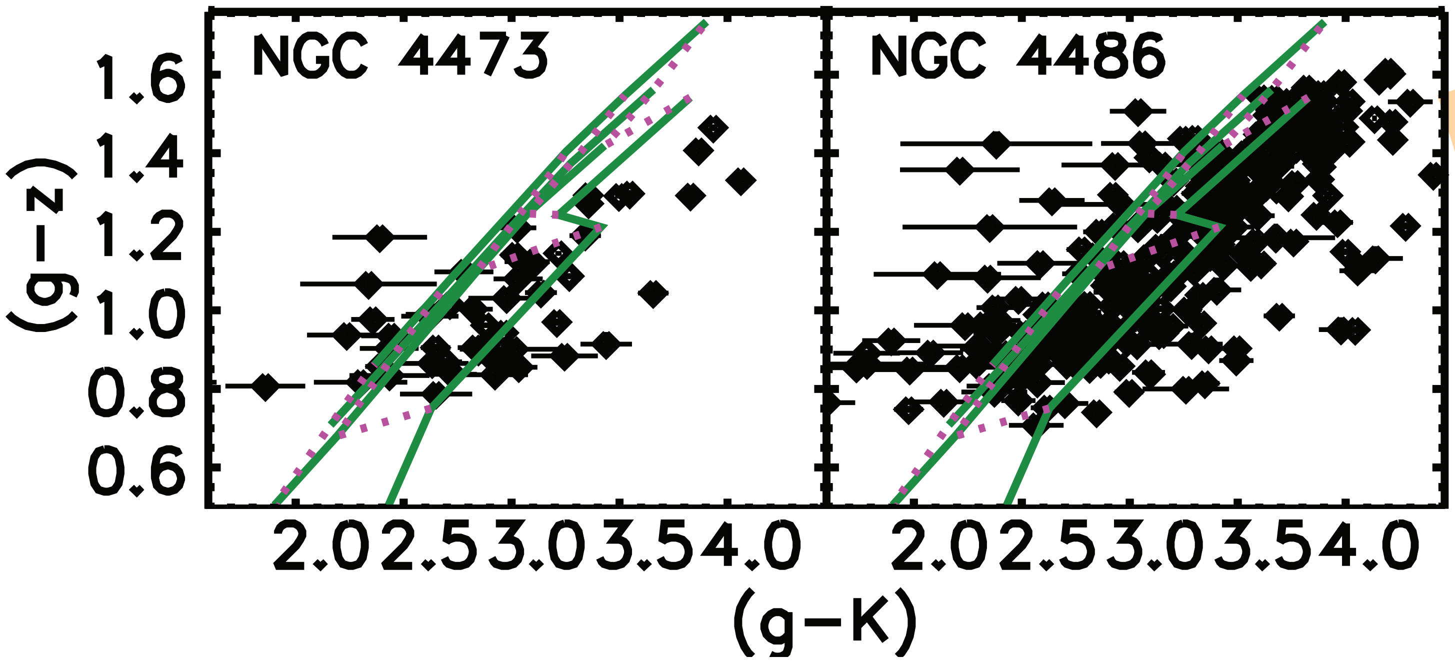


2<ages(Gyrs)<3 Gyrs

also Charlot & Bruzual and Maraston11

✓Chies-Santos+2011b

Maraston05



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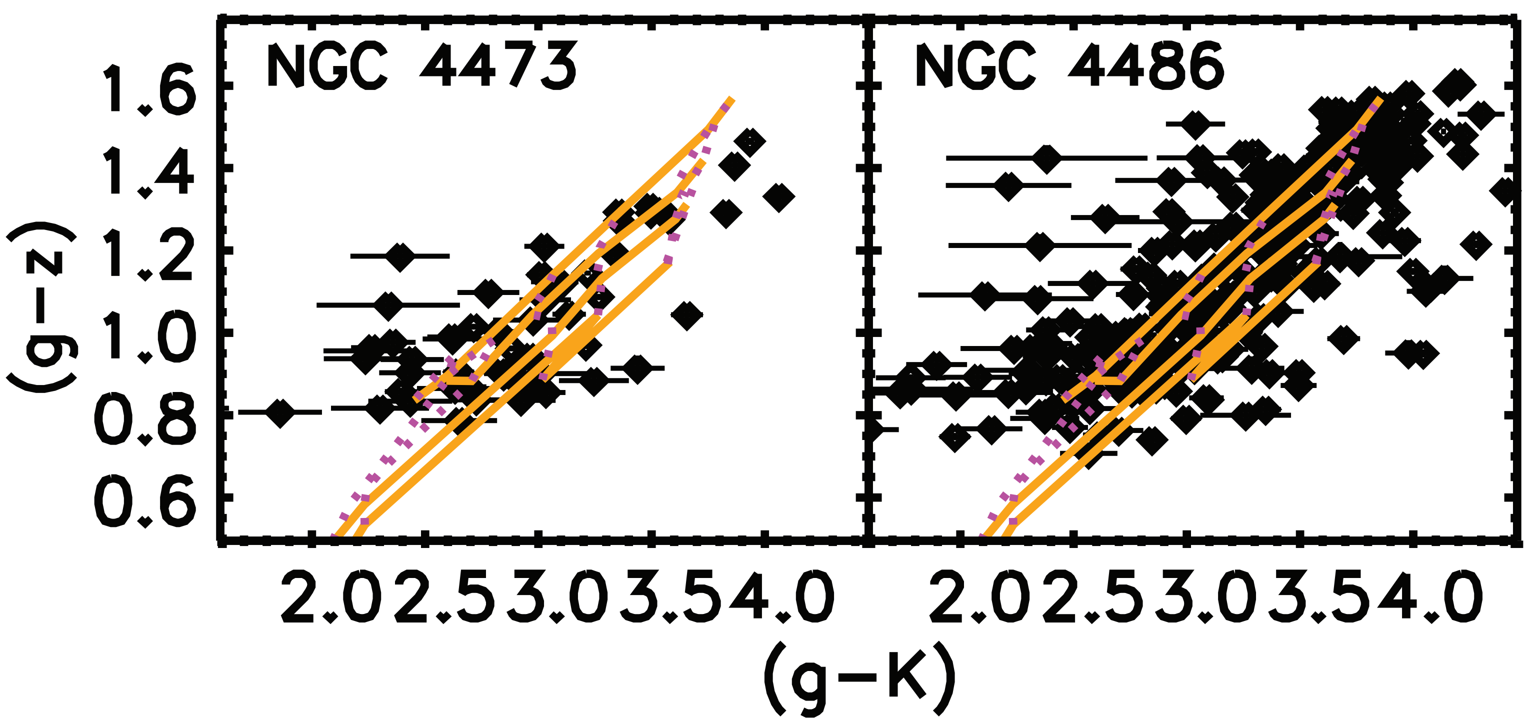
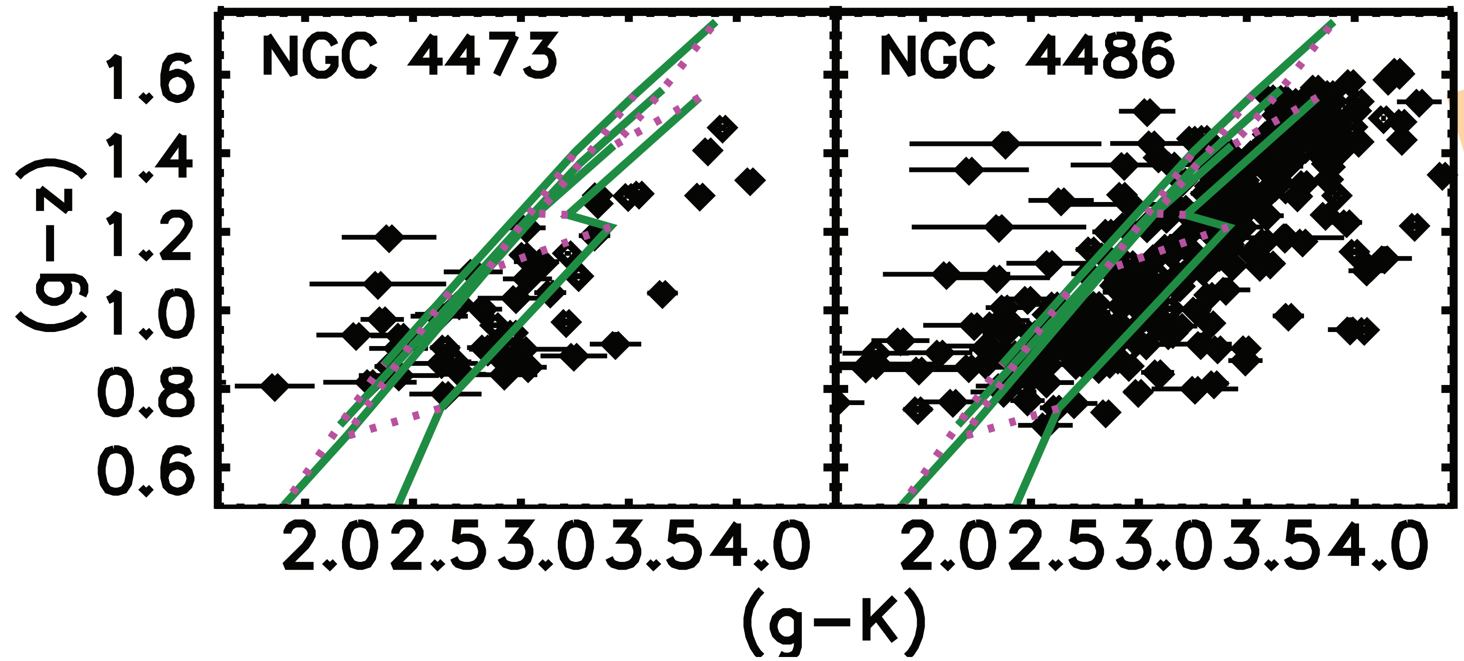
Padova SSPs, Marigo+08 isochrones



✓Chies-Santos+2011b

Maraston05



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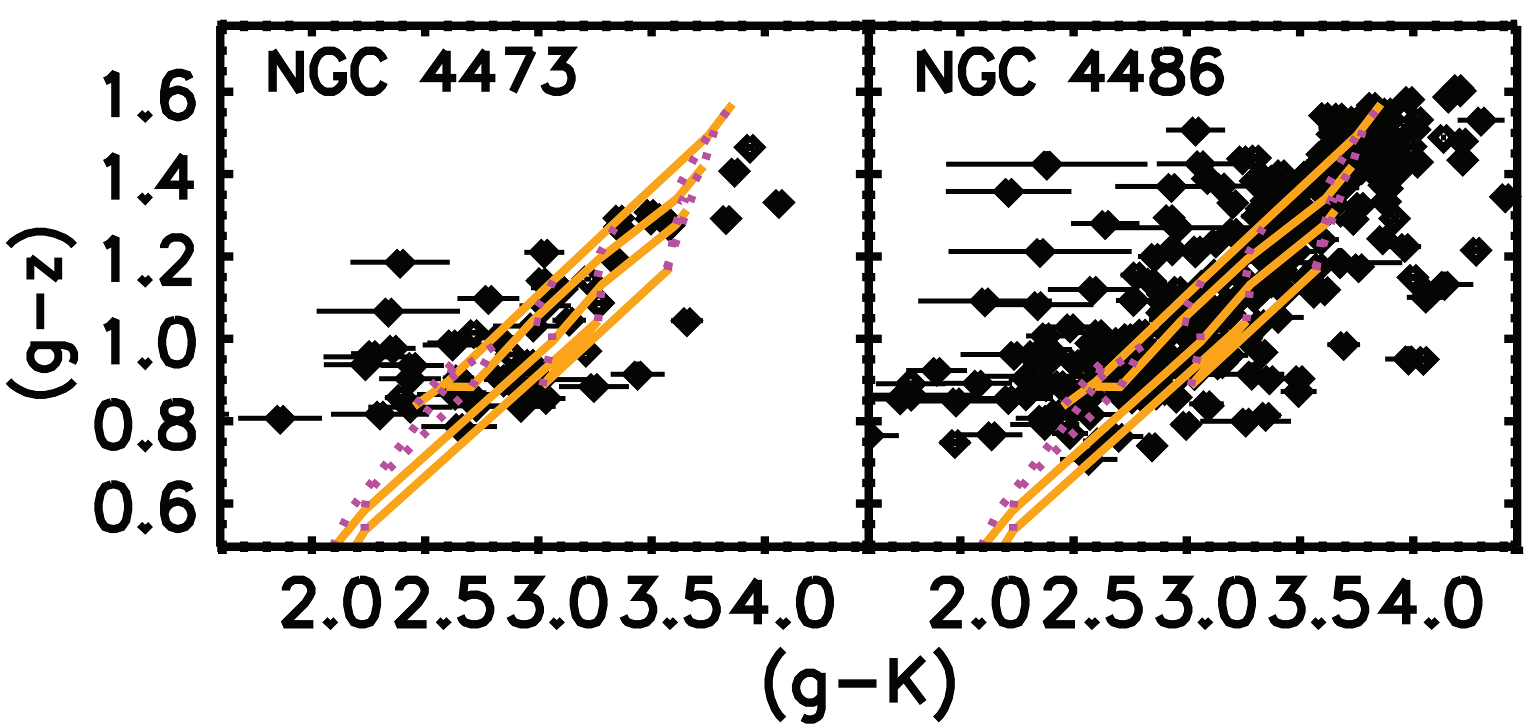
Padova SSPs, Marigo+08 isochrones



formal fit ➡ intermediate ages!

✓Chies-Santos+2011b

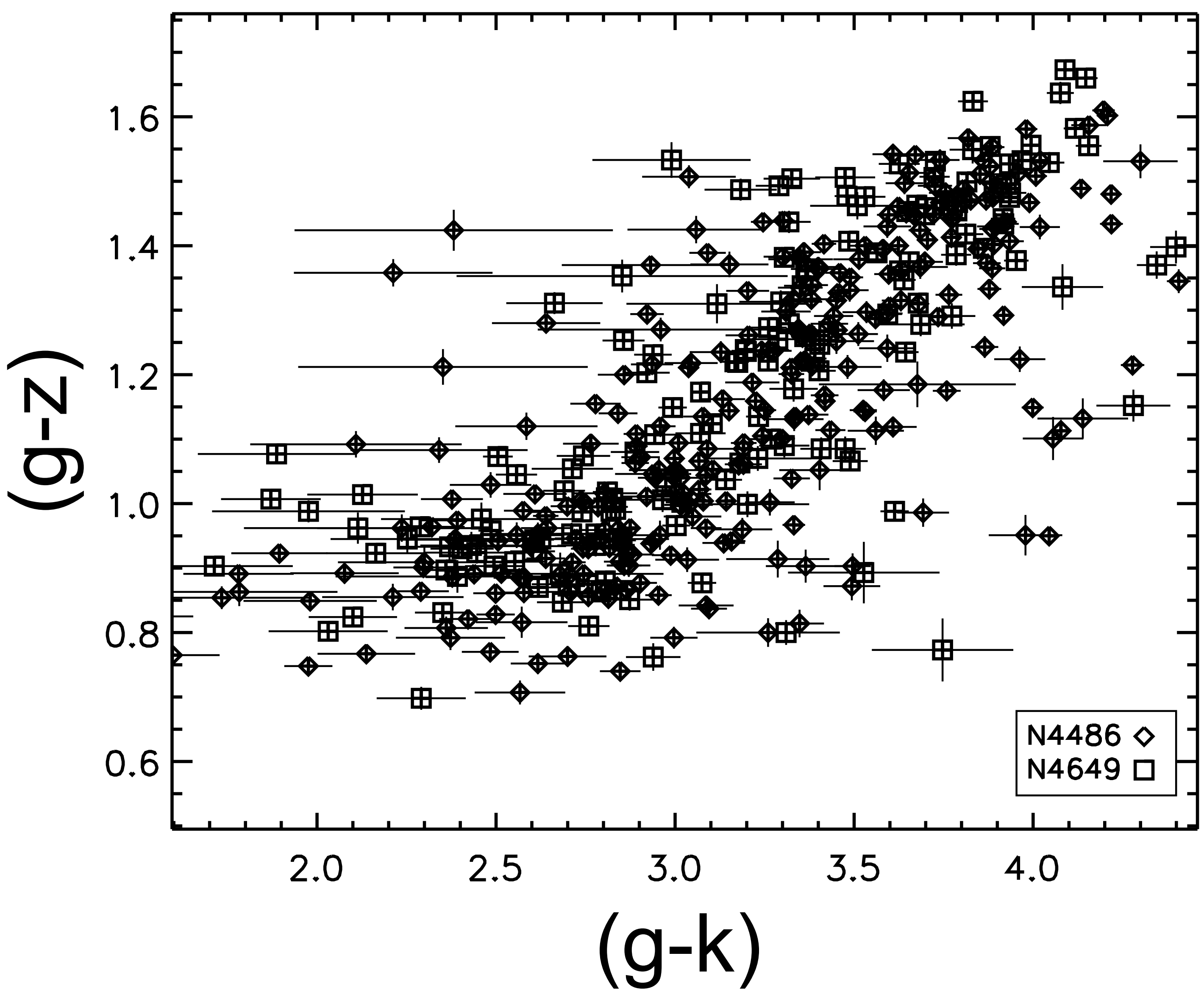
Deriving ages SSP

Deriving ages ~~SSP~~

Differential Comparison

➡ <u>relative</u> ages

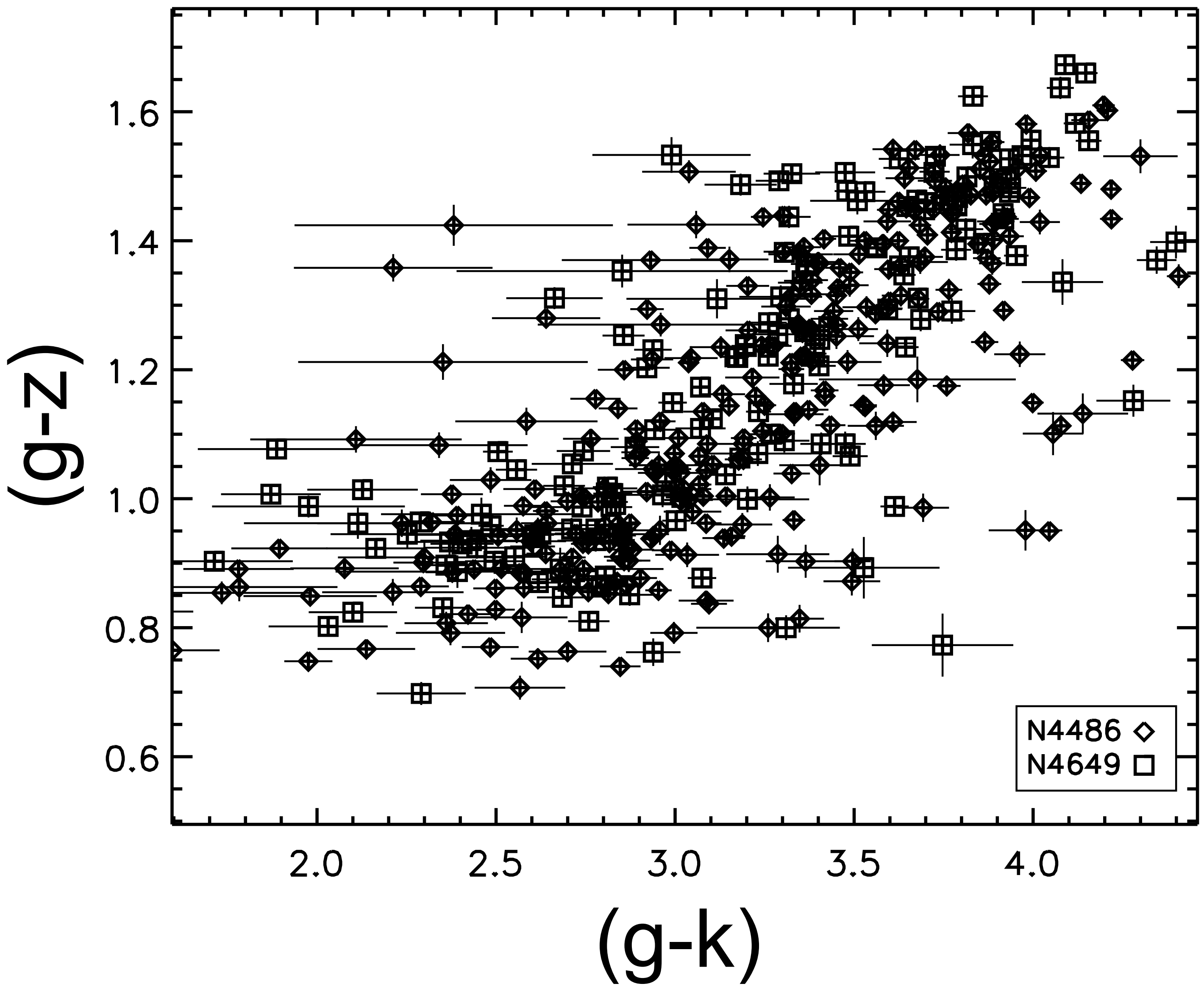
The method



★GC spectra of NGC 4486 GCs Cohen+98 ≈13 Gyrs

✓Chies-Santos+2011b

The method



Fiducial old GCs

★GC spectra of NGC 4486 GCs Cohen+98 ≈13 Gyrs

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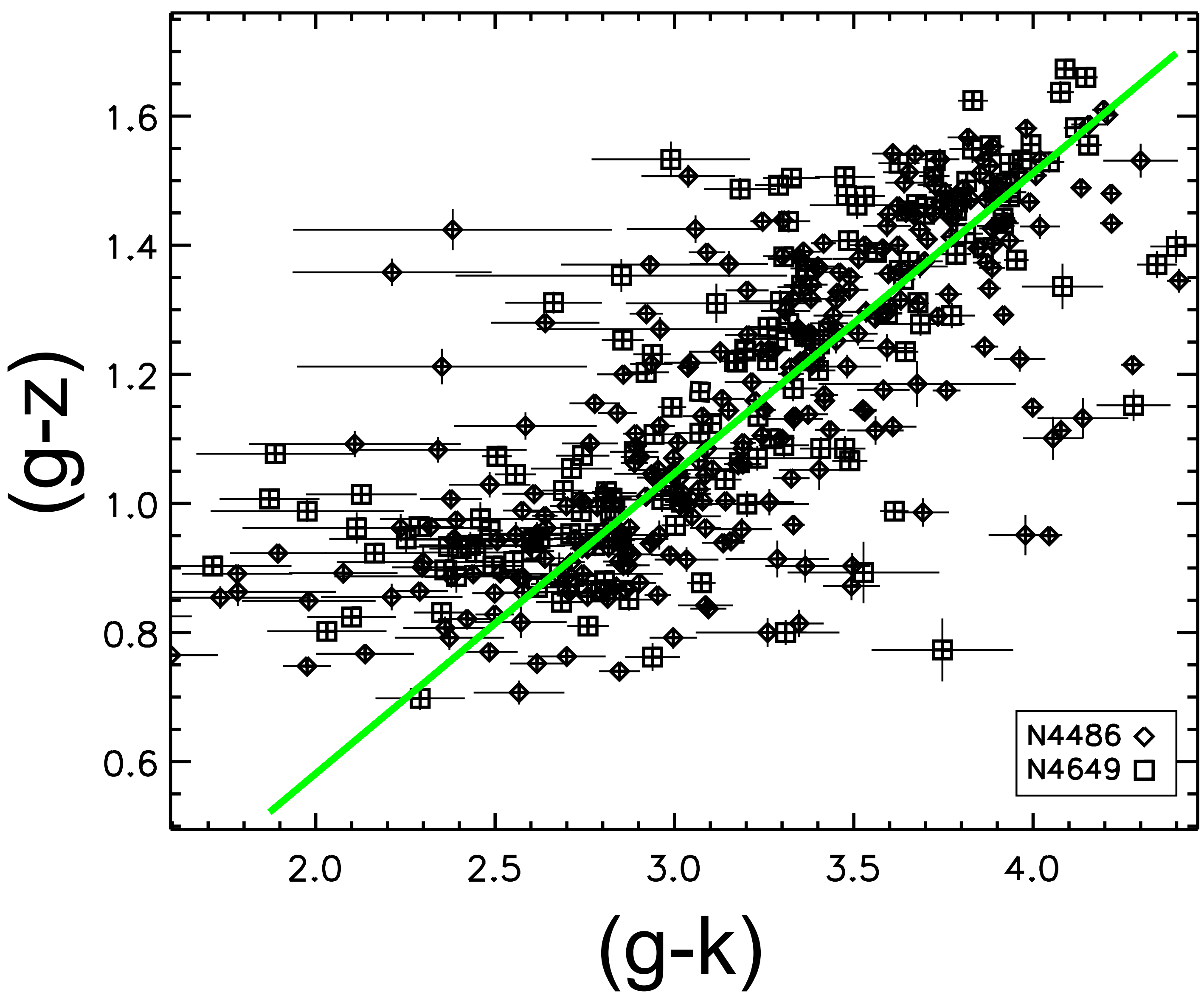
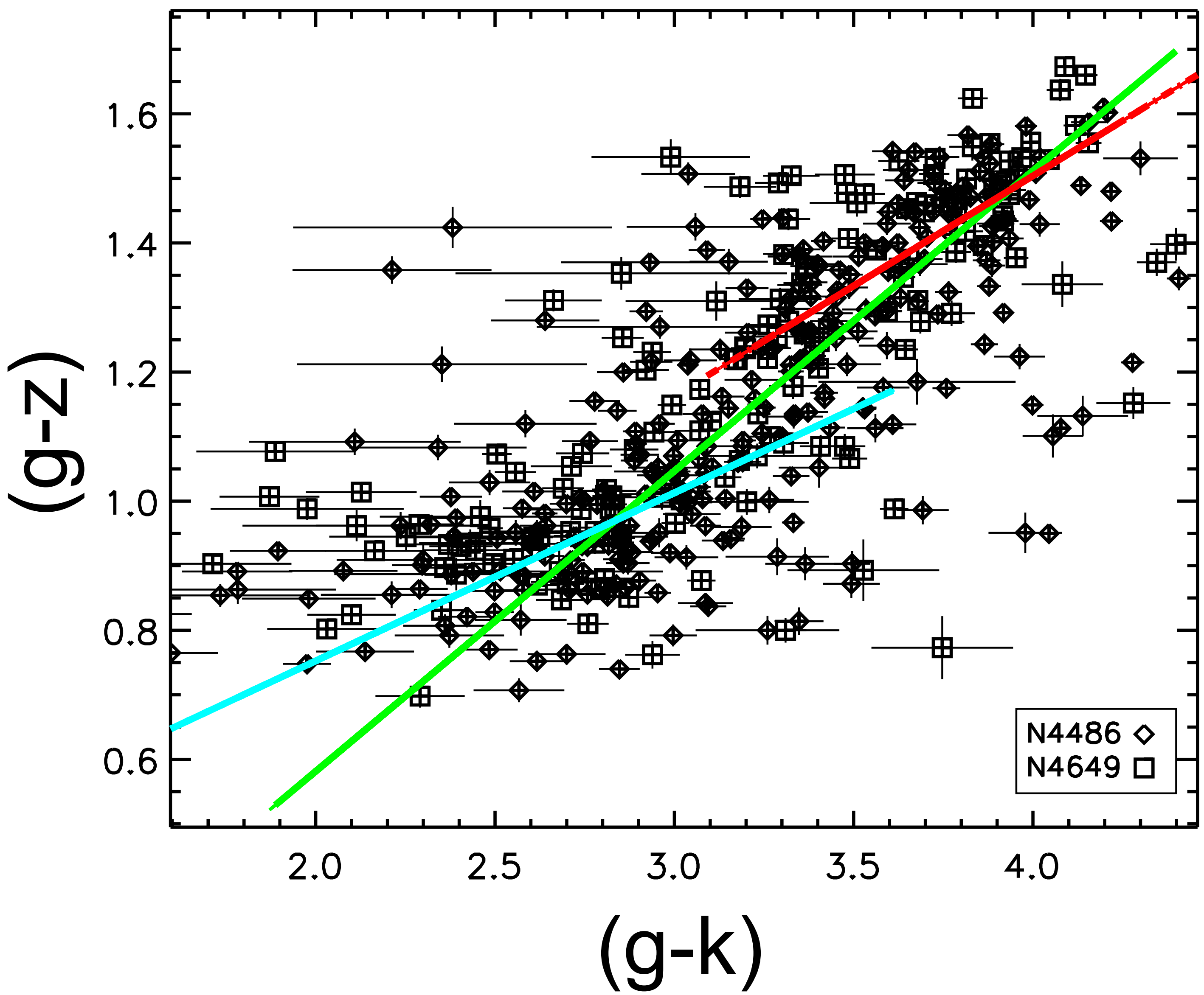
The method



$$(g - z) = 0.465 * (g - K) - 0.349$$

✓ Chies-Santos+2011b

The method



$$(g-z) = 0.465 * (g-K) - 0.349$$

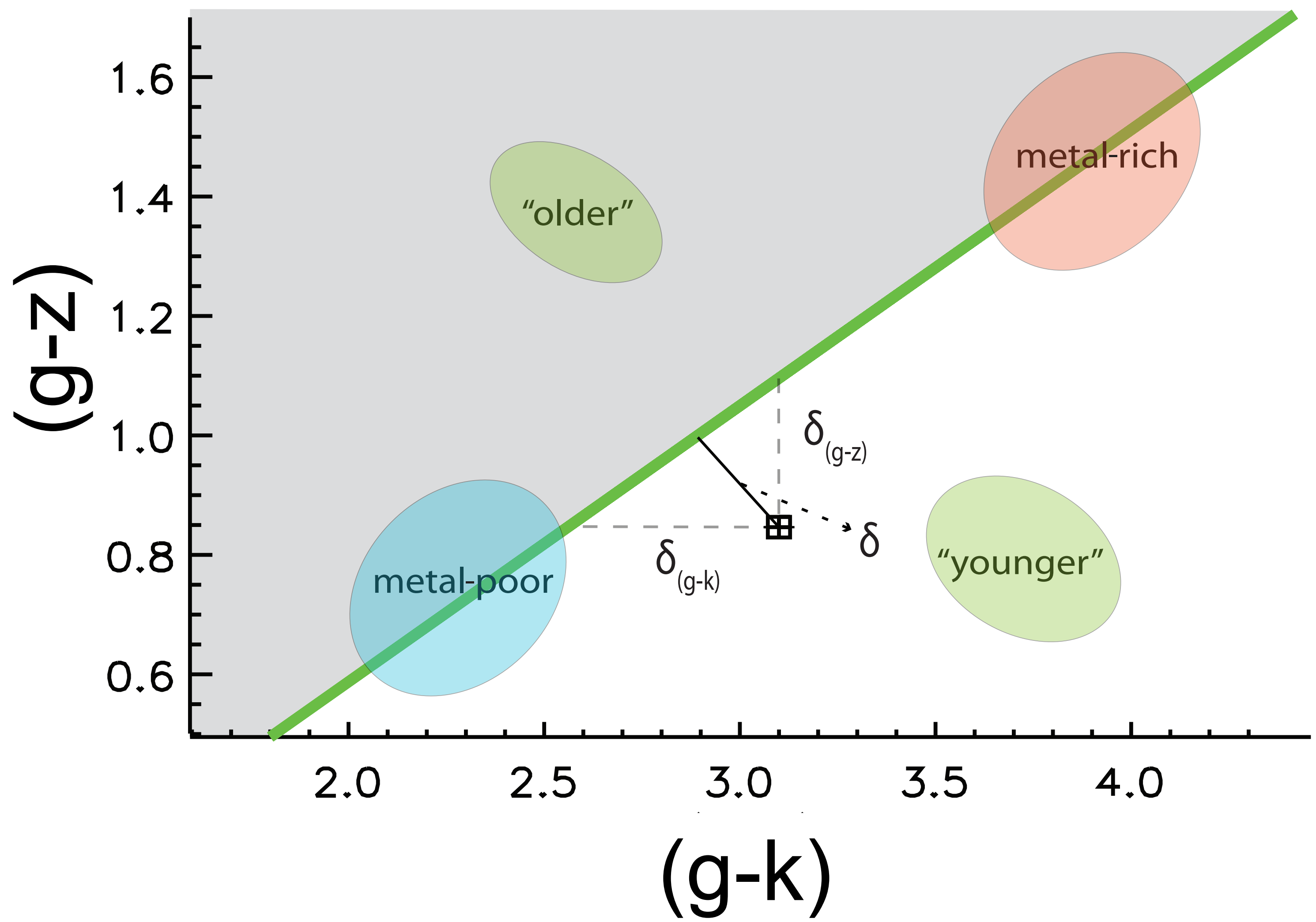
$$(g-z)_b = 0.260 * (g-K)_b + 0.232$$

$$(g-z)_r = 0.340 * (g-K)_r + 0.140.$$

✓Chies-Santos+2011b

"δ" parameter

★ distance from the best fit line

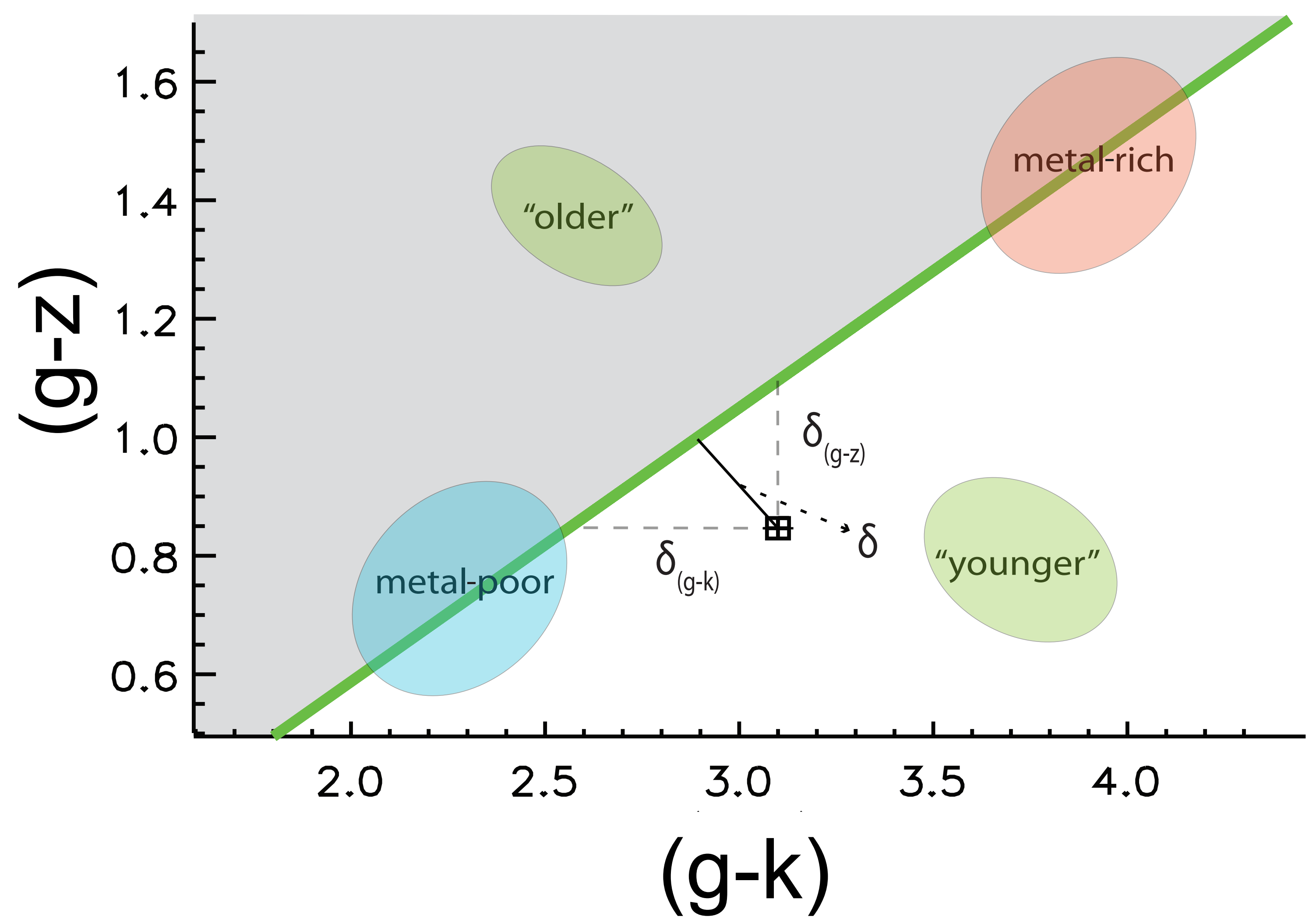


✓Chies-Santos+2011b

"δ" parameter

age indicator

★ distance from the best fit line



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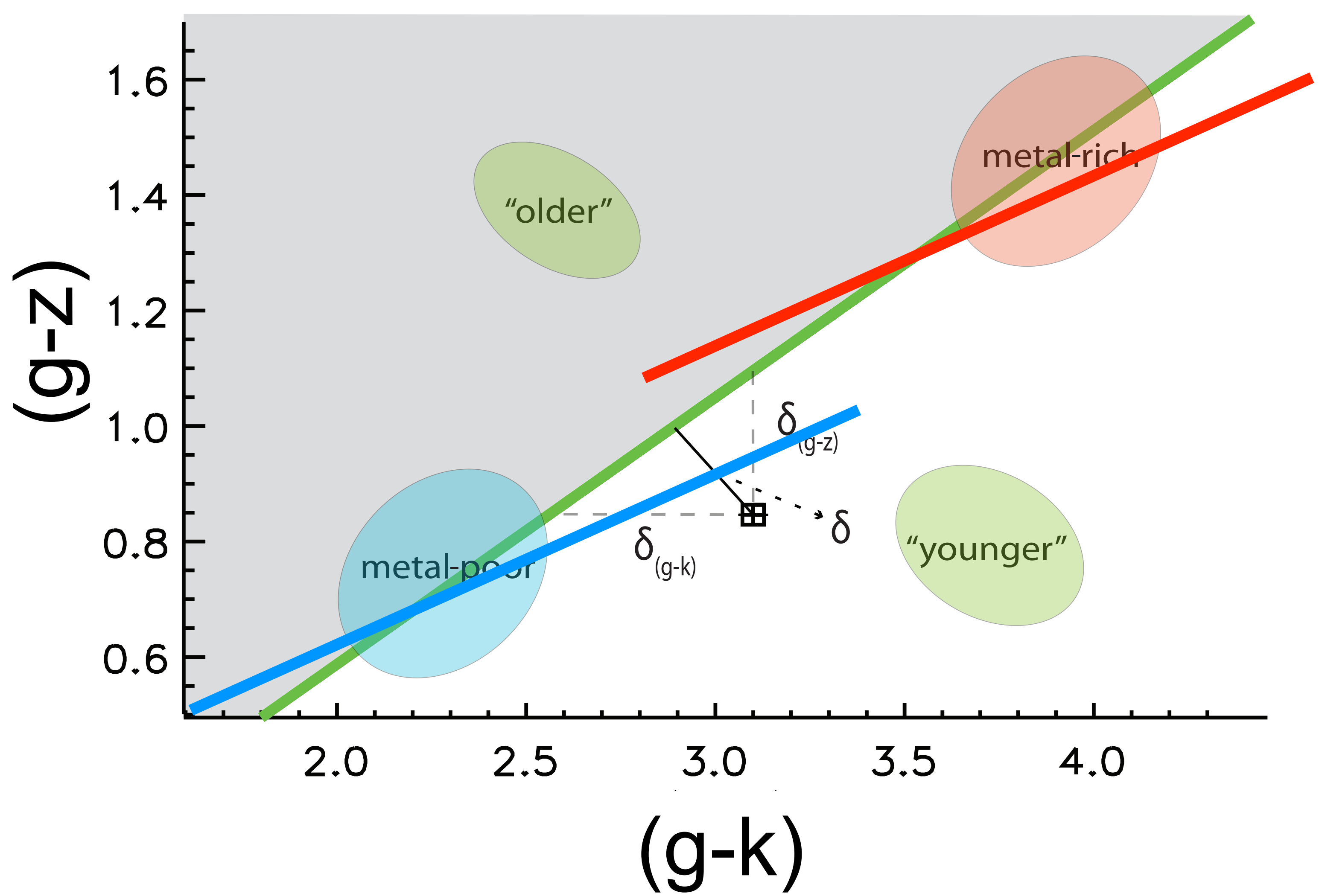
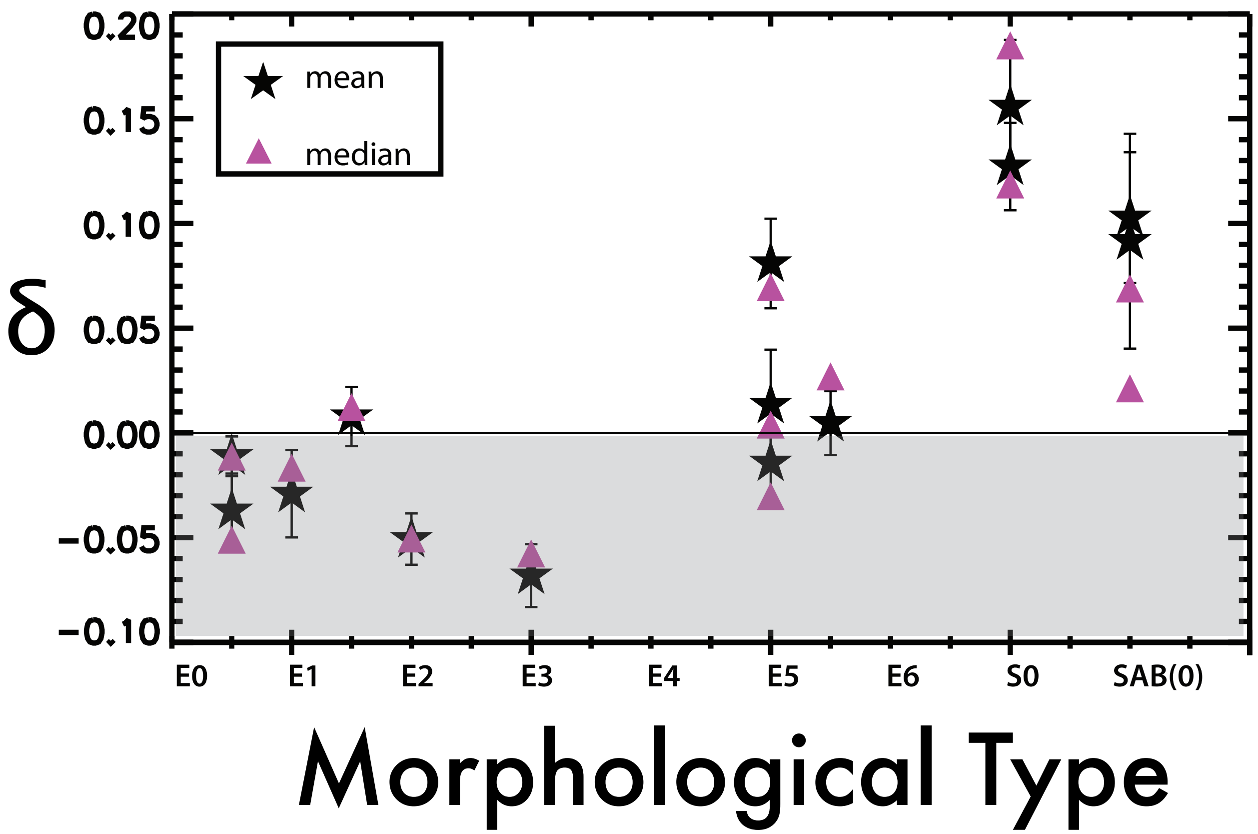


δ_{blue}

δ_{red}

✓Chies-Santos+2011b

Ages & galaxy morphology



✓Chies-Santos+2011b

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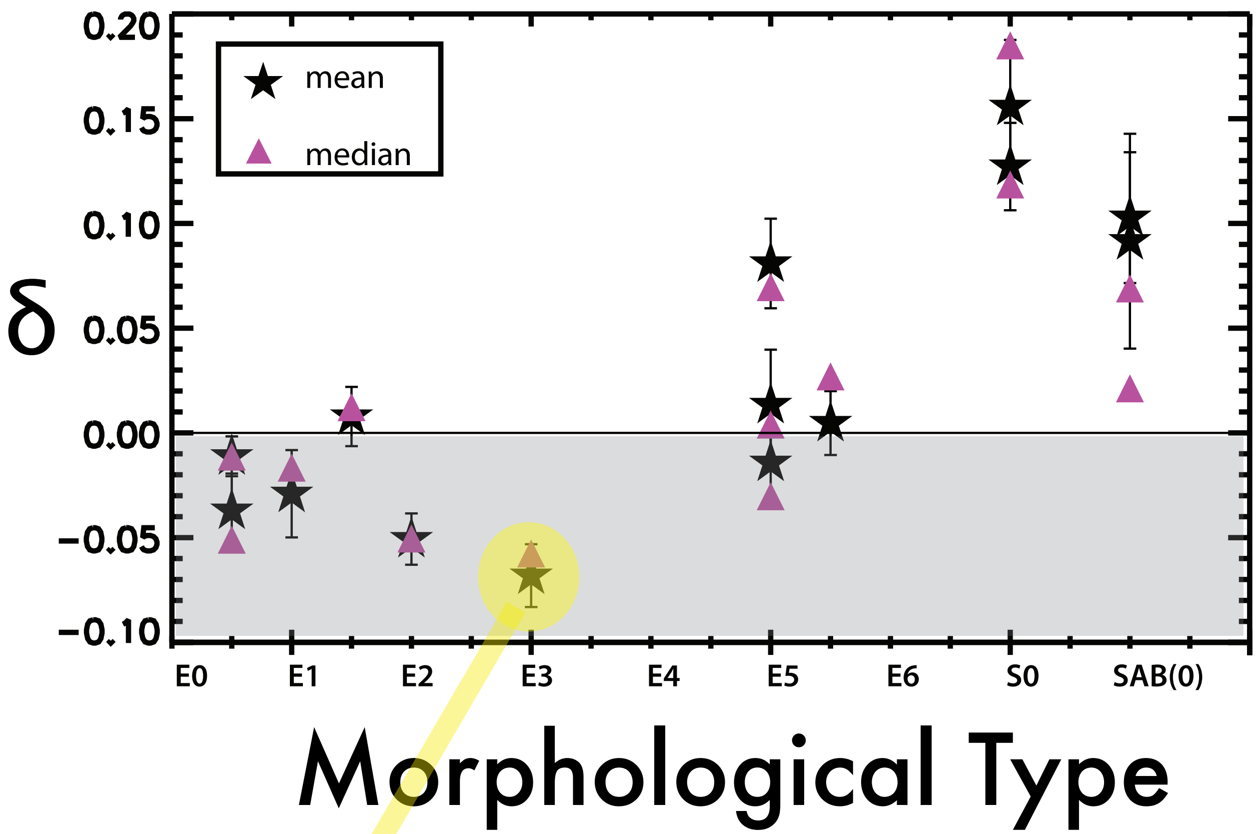
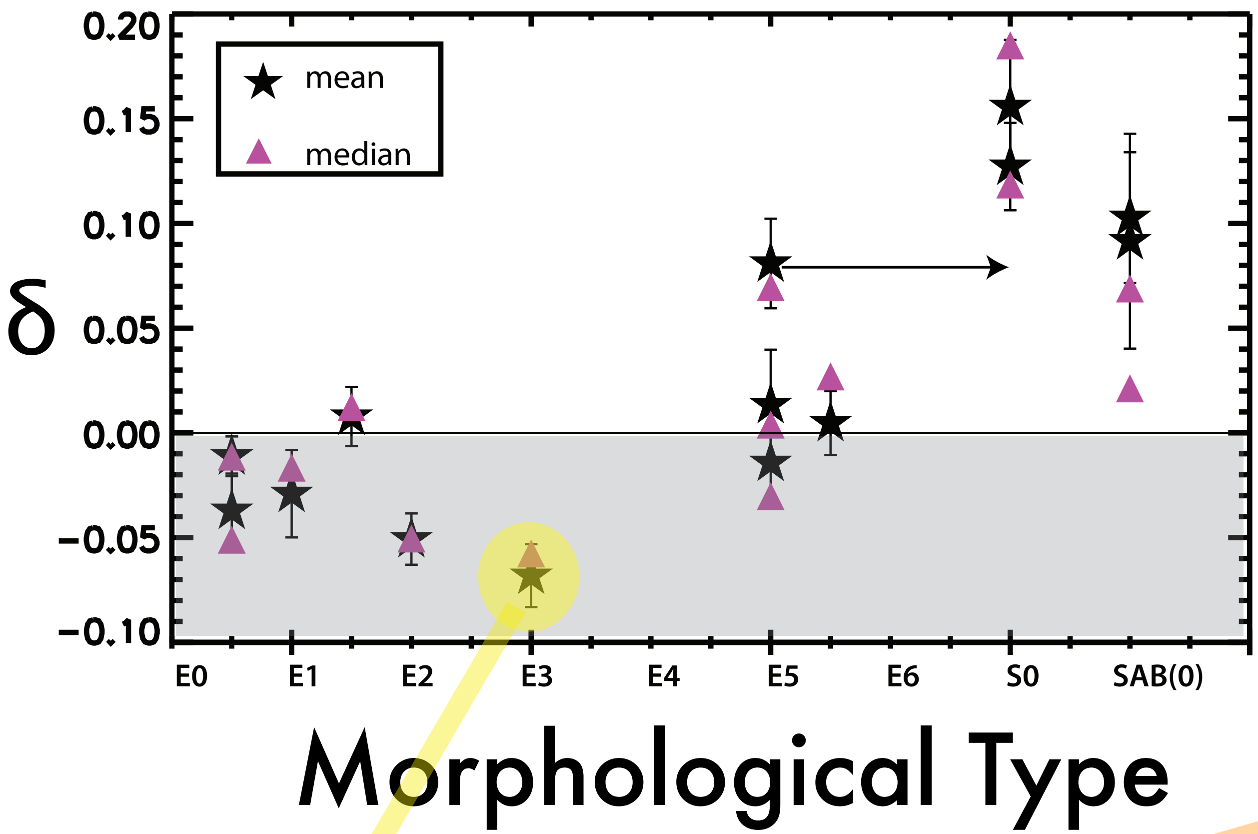


NGC 4365

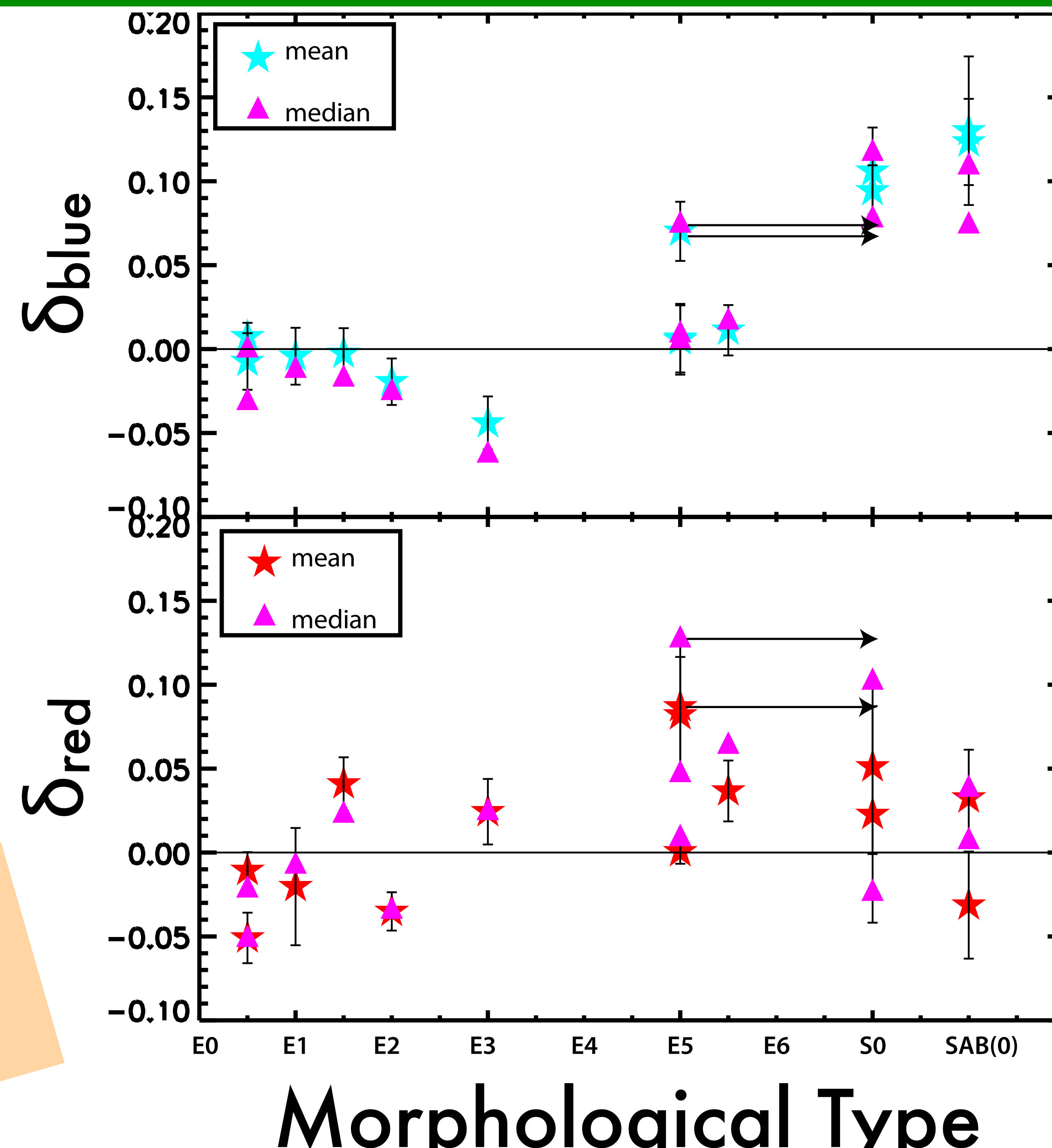
✓Chies-Santos+2011b

Ages & galaxy morphology



NGC 4365

relation stronger for blue GCs



✓Chies-Santos+2011b

δ

★ galaxy mass?

δ

- ★ galaxy mass? ✗

δ

★ galaxy mass? ✗

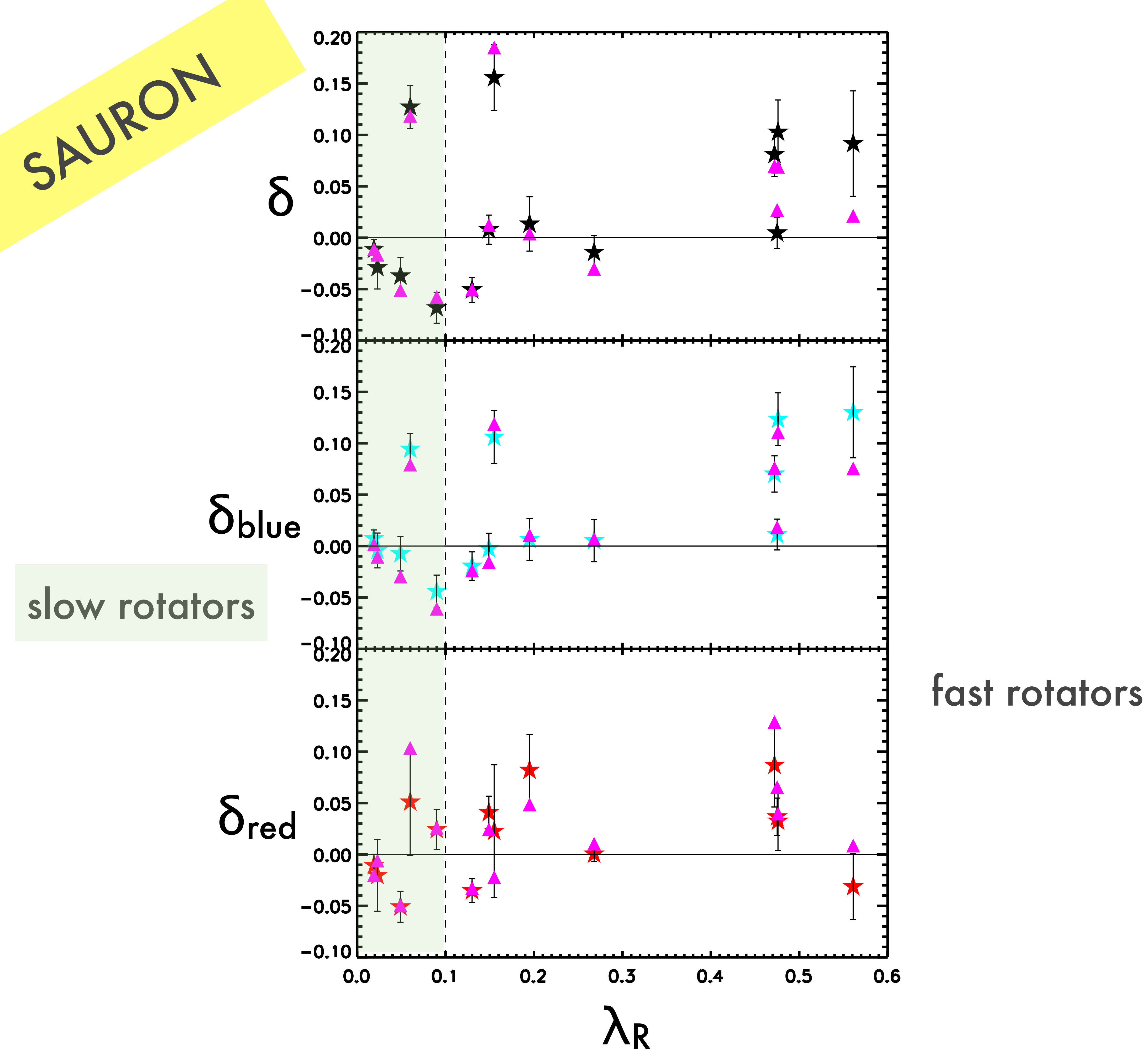
SAURON

λ_R ➡ proxy for angular momentum

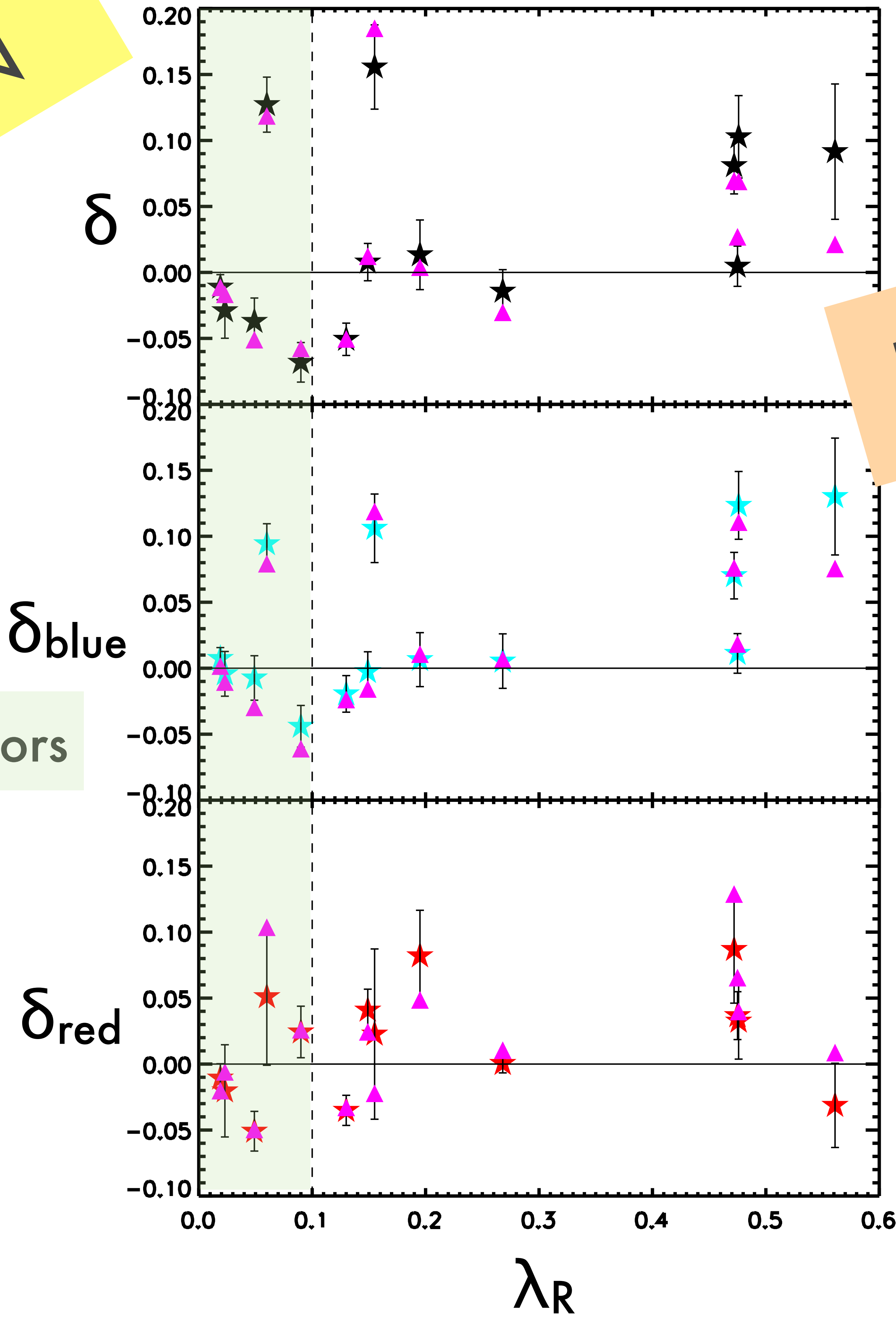
Emsellem+07

λ_R<0.1 ➡ slow rotators

λ_R>0.1 ➡ fast rotators


SAURON
δ
δblue
δred
slow rotators
fast rotators
λR
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
0.0
0.1
0.2
0.3
0.4
0.5
0.6

SAURON

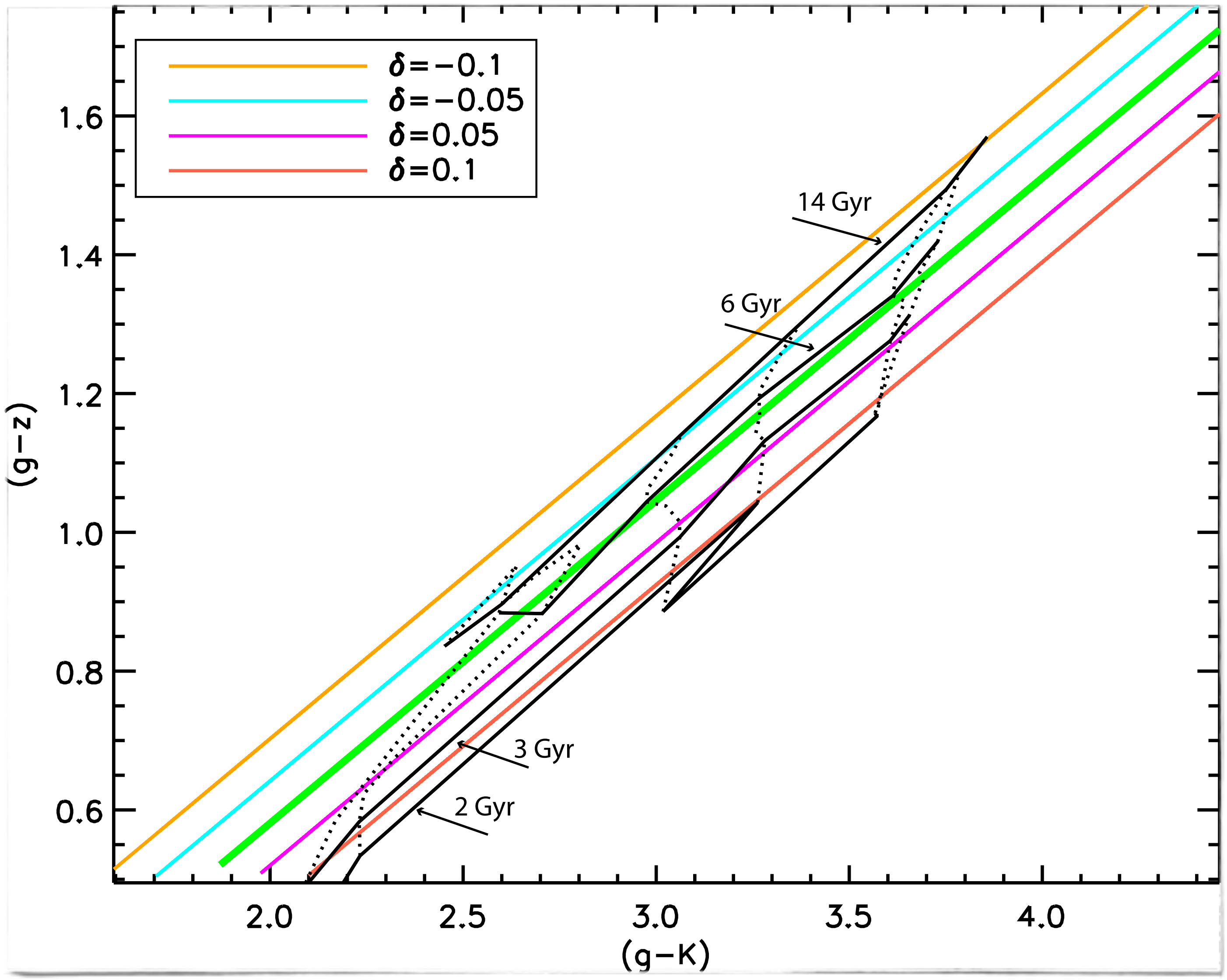


not as clear as the δ-morphology!

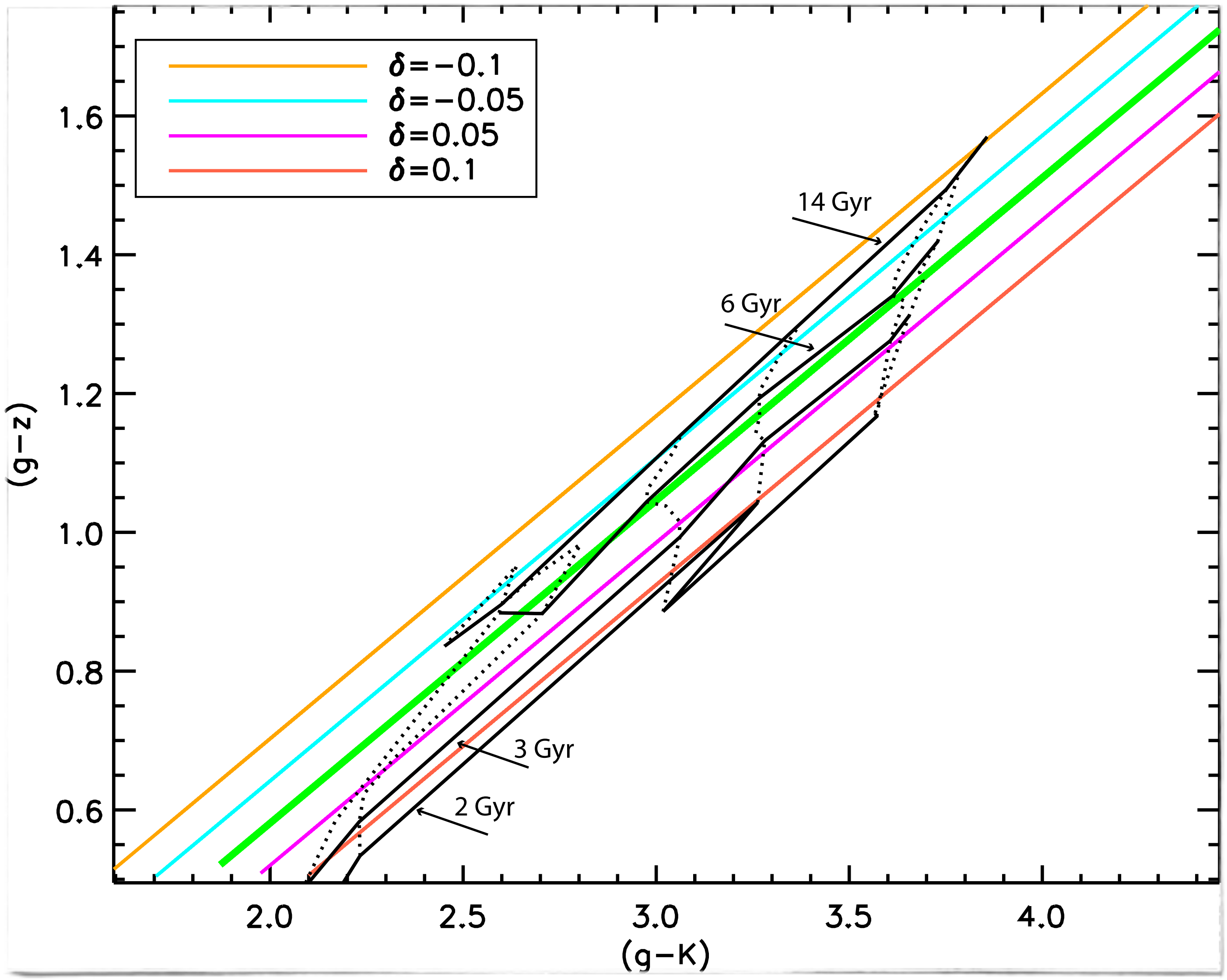
slow rotators

fast rotators

δ≟age difference



δ ≟ age difference

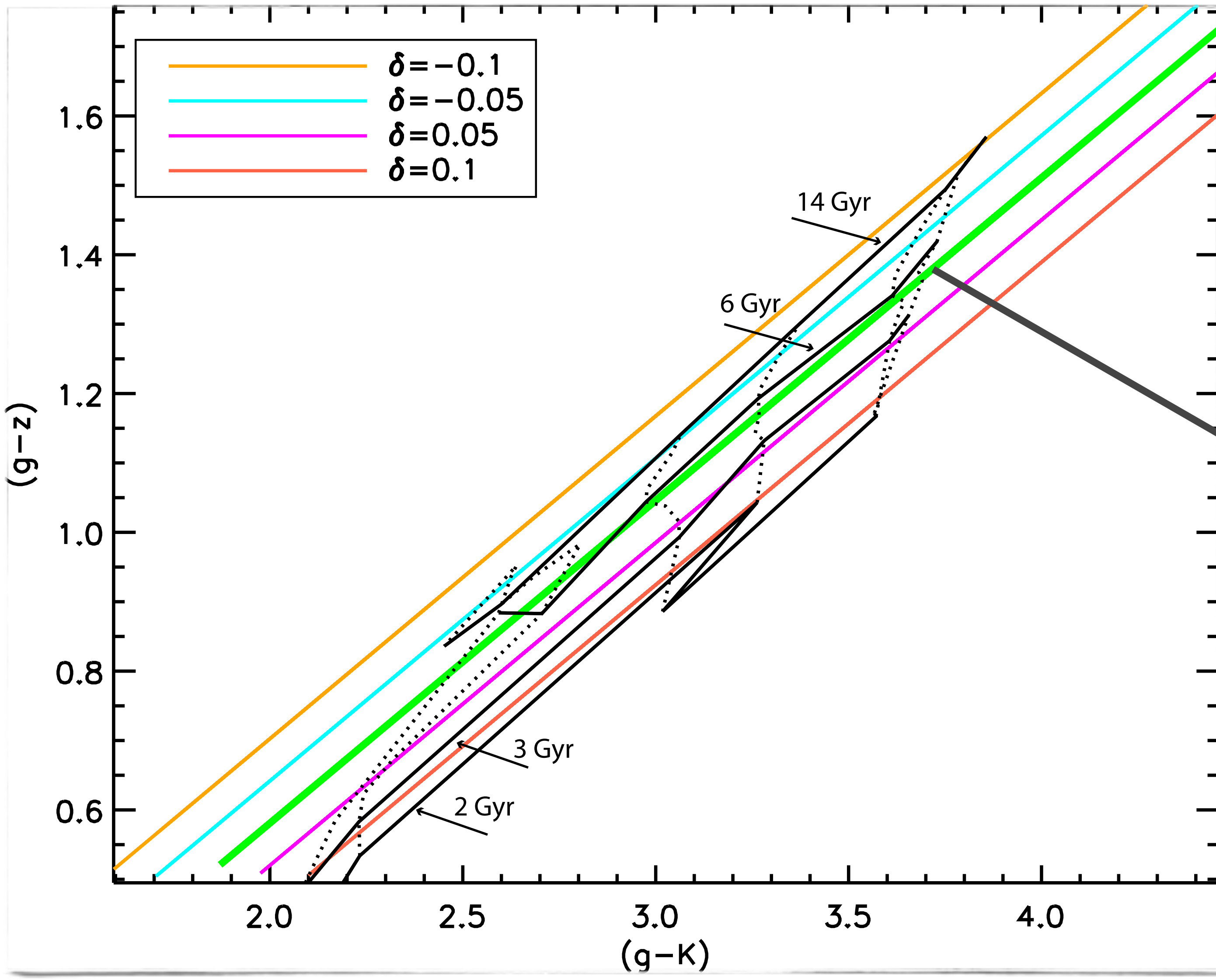


δ=0.1 ➡ age diff=4-8Gyrs

↓

Padova SSPs

δ ≟ age difference



δ=0.1 ➡ age diff=4-8Gyrs

↓

Padova SSPs

if δ=0 ➡ 13Gyrs for E0's

↓

Cohen+98 NGC4486

S0's ➡ 5-9Gyrs

Interpretation “δ - morphology"?

GC system age ⇔ galaxy morphology

★younger GC systems in S0s

★E assembled most of their GCs in a shorter and earlier period than S0s

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★E assembled most of their GCs in a shorter and earlier period than S0s

★S0s have a more extended period of GC formation/assembly

★minor mergers affected more strongly the GC system of S0s?

Interpretation “δ - morphology"?

GC system age ⇔ galaxy morphology

★drivers metal-poor GCs ➡ result of minor mergers

★dwarf galaxies
- ✓have a more extended SFH than more massive galaxies (eg. Tolstoy+09)
- ✓contain almost exclusively metal-poor GCs (Forbes+00)

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1.GCs formed in the accreted host galaxy (Côté+98)

2.GCs formed during the merger event from a metal-poor gas reservoir of the accreted dwarfs. Muratov & Gnedin 10 ➡ mergers of smaller hosts create exclusively blue clusters.

GCS NGC 4365 old? young?

- ★Larsen+03 ➡ intermediate ages, lower S/N on LRIS Keck
- ★Brodie+05 ➡ old ages, higher S/N on LRIS Keck
- ★FORS2 sample, the best of 3!

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✗

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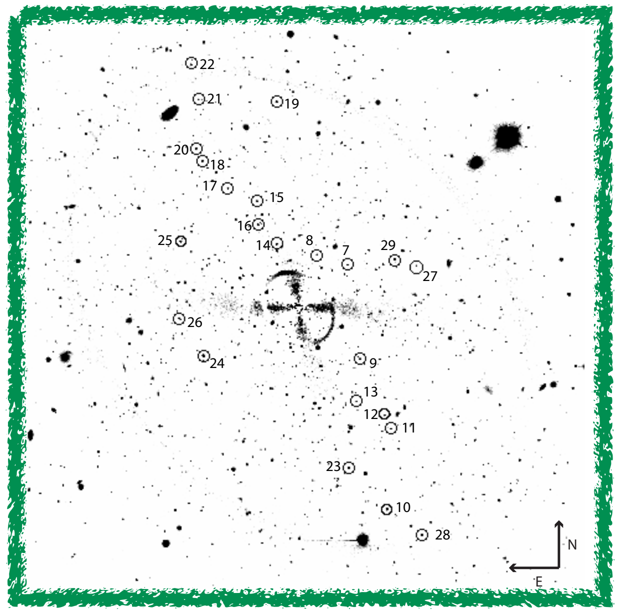
Spectroscopy



★ 22 GC candidates, ≃9 hours

★ VLT/FORS2 MXU

★ ESOREX

✓fors_calib

✓fors_science

★Lick_Indices

✓Lick_EW/EZ_ages (Graves & Schiavon 08)

★Ages & [Fe/H]

✓Schiavon+07

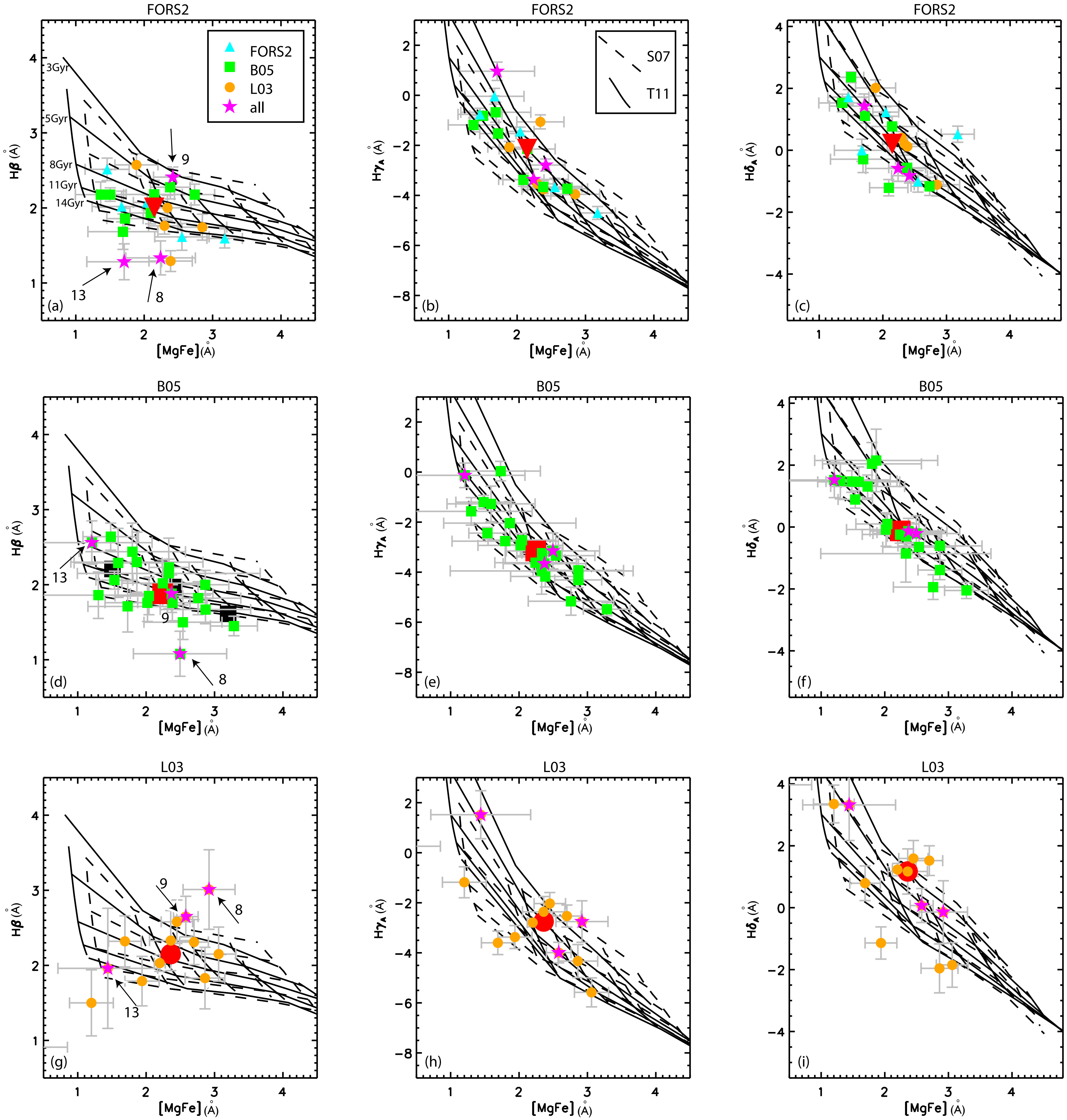
✓ Thomas+11

✓Chies-Santos+2012b

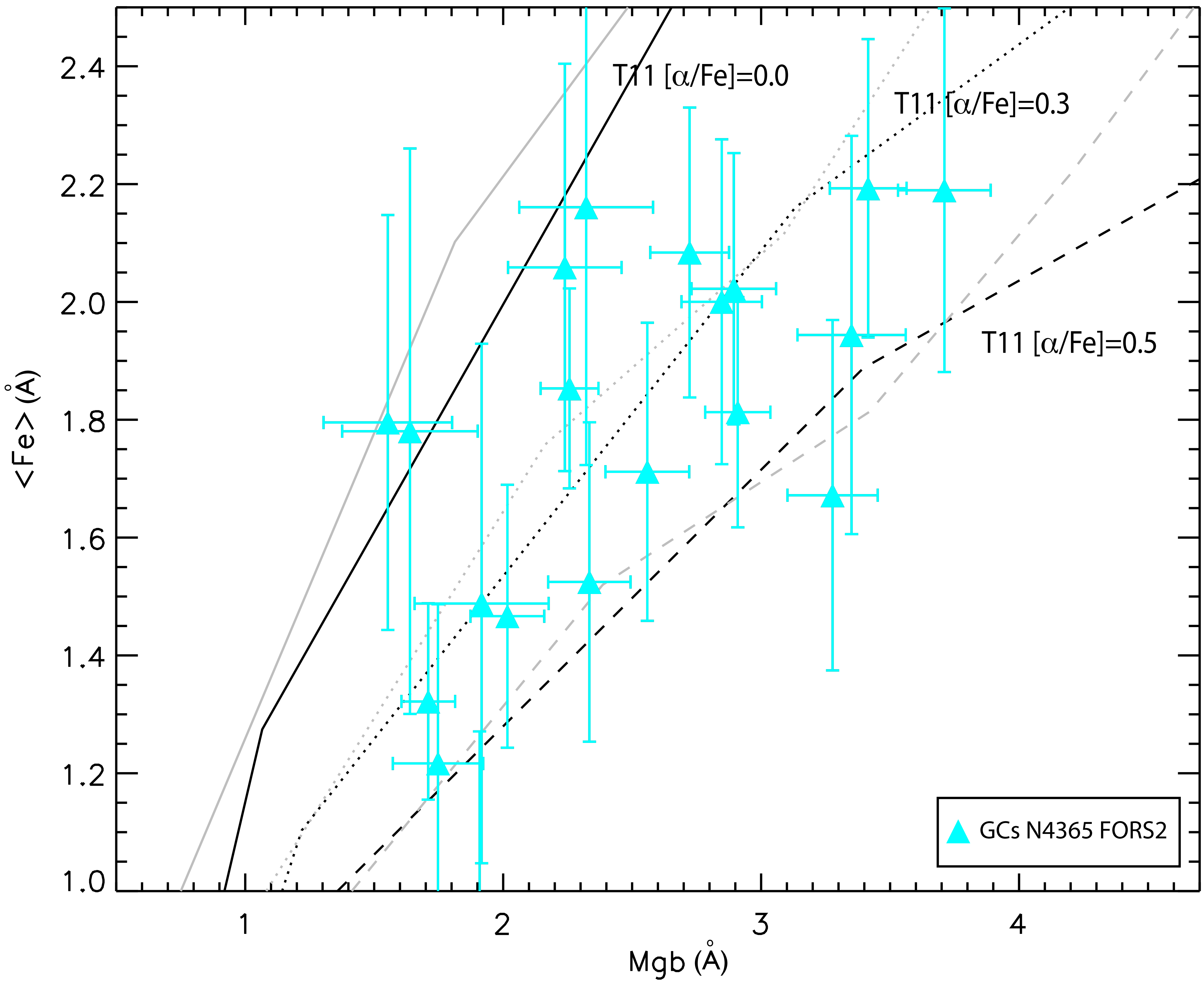
✓FORS2

✓B05

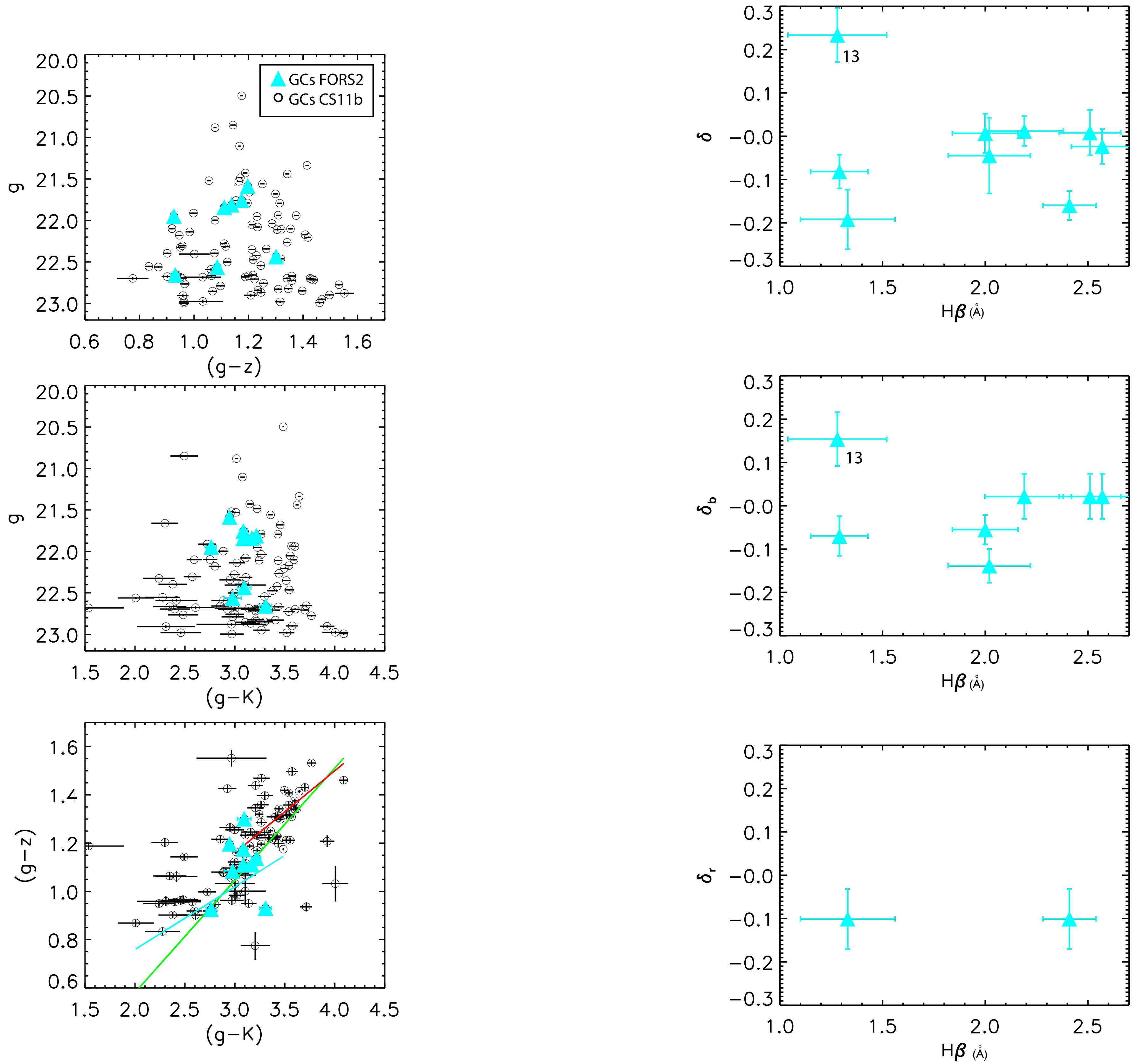
✓L03



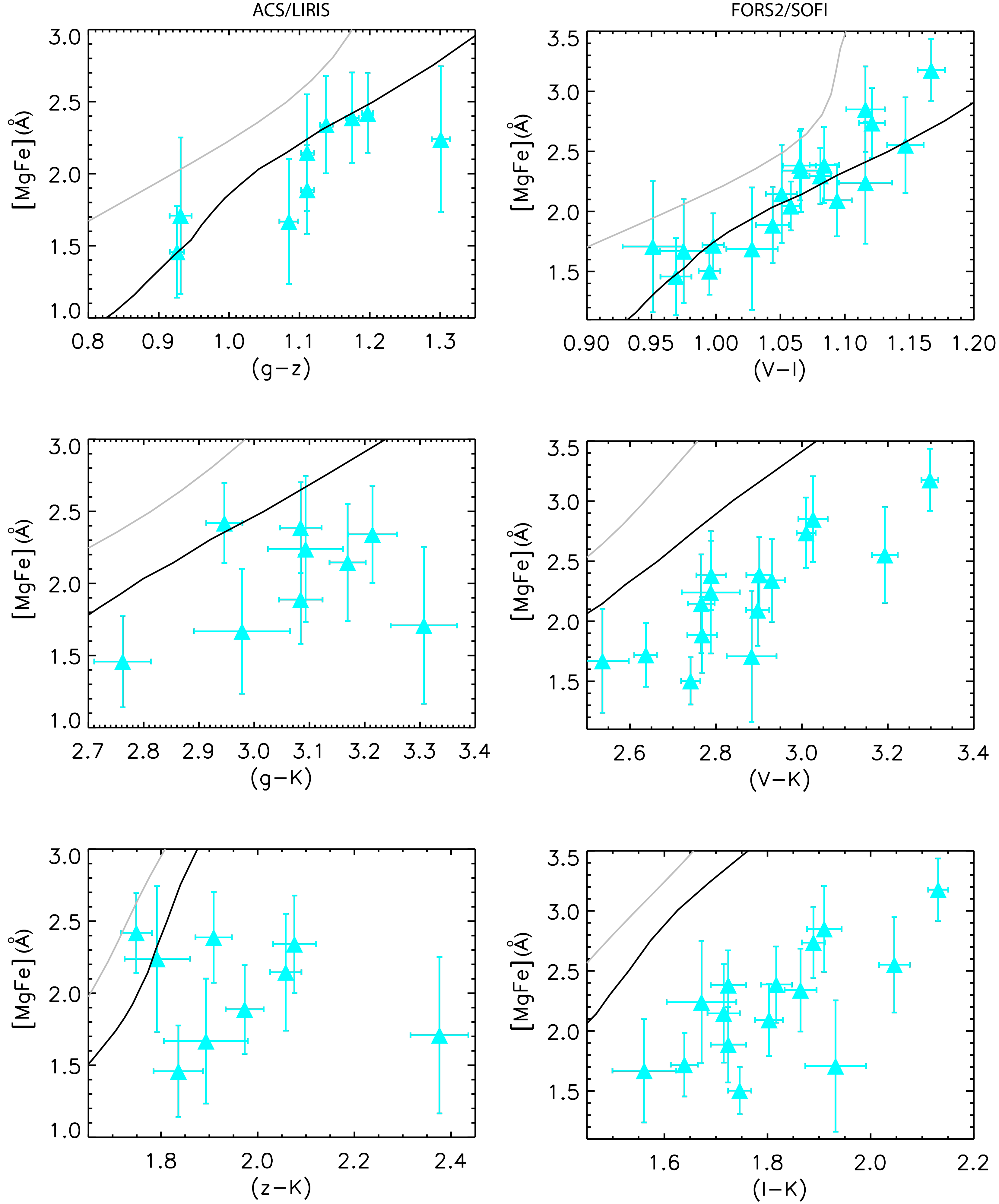
✓Chies-Santos+2012b



T11 [α/Fe]=0.0
T11 [α/Fe]=0.3
T11 [α/Fe]=0.5
GCs N4365 FORS2
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
1
2
3
4
<Fe> (Å)
Mgb (Å)



GCs FORS2
GCs CS11b
g
(g−z)
(g−K)
δ
δ_b
δ_r
Hβ (Å)
13



ACS/LIRIS
FORS2/SOFI
[MgFe] (Å)
(g−z)
(V−I)
(g−K)
(V−K)
(z−K)
(I−K)

Summary "ages"

★Padova SSPs + Marigo+08 isochrones for old ages (14Gyr) ➡ better match than previous models ➡ but still not there yet!

★avoiding SSPs ➡ relative ages

★NGC4365 has an old GC system, old as NGC4486 + NGC4649

★relation between δ (the ages of the GC systems) and galaxy morphology

✓driven by metal-poor clusters

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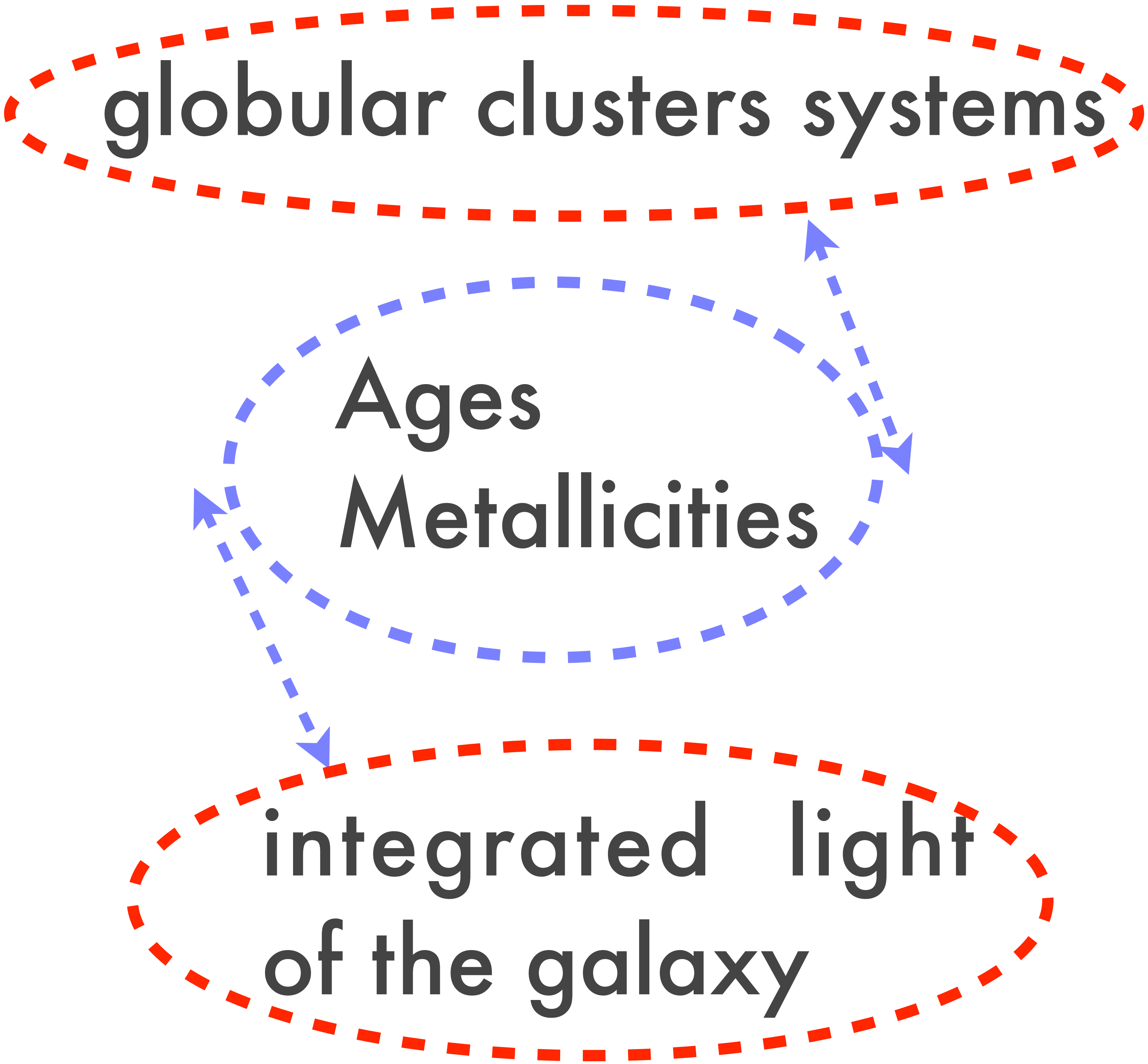
★old ages, consistent with Brodie+05 & photometric part Chies-Santos +11b

Conclusion


globular clusters systems
Ages
Metallicities
integrated light
of the galaxy

Obrigada