The Kavli Institute for Astronomy and Astrophysics at Peking University
北京大学科维理天文与天体物理研究所

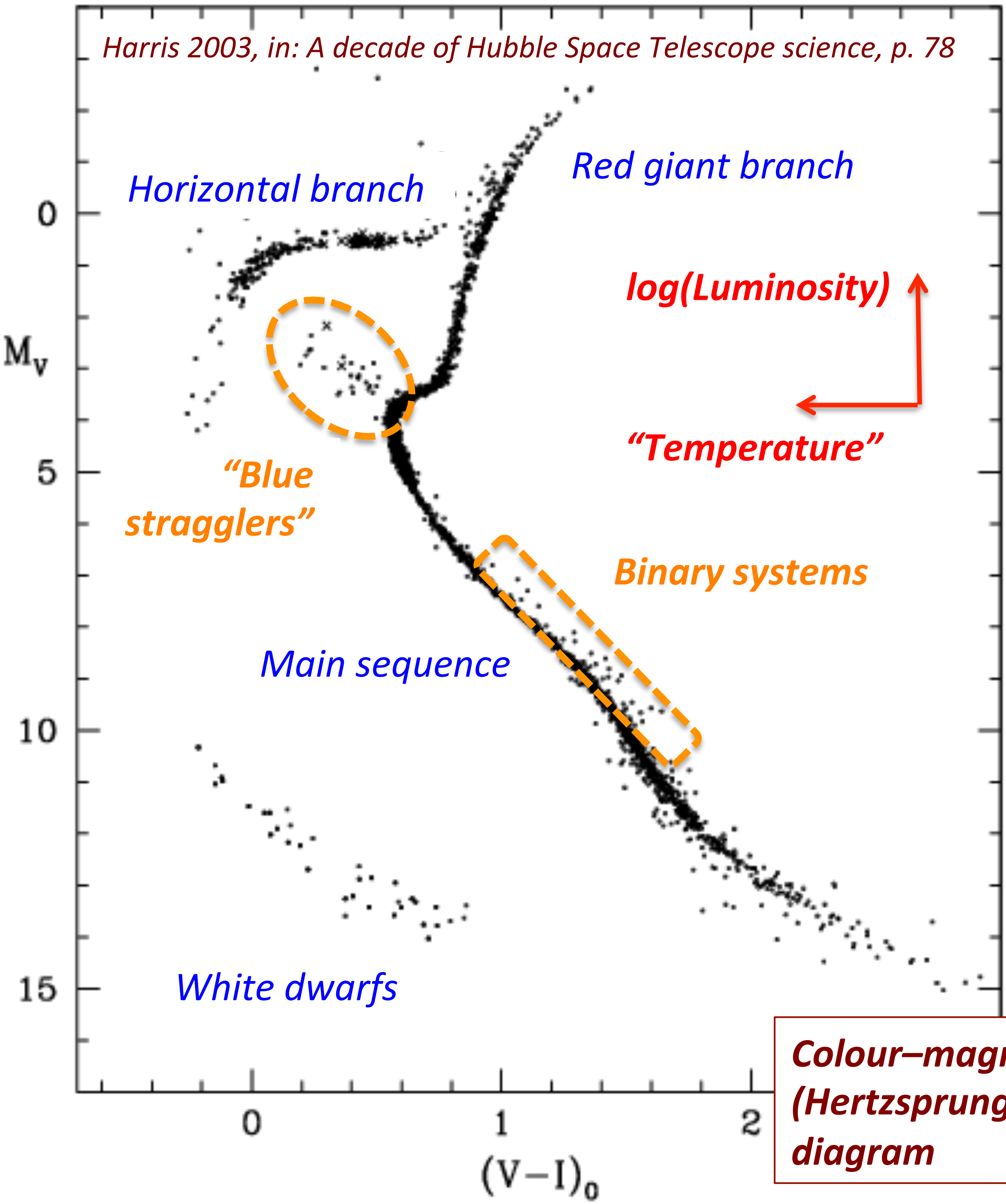
Not-so-simple stellar populations in middle-aged massive star clusters

Richard de Grijs | 何锐思
Kavli Institute for Astronomy and Astrophysics
Peking University, China

Main collaborators:
Chengyuan Li (KIAA, PKU; now Macquarie Univ., AUS),
Licai Deng (NAOC)

Simple stellar populations?

Single age: sharp, narrow MSTO
Single metallicity: narrow CMD
Mass range given by the IMF
… but for ***single stars*** only!



Colour–magnitude (Hertzsprung–Russell) diagram

$M_V = -2.5 \log L_V\ [L_\odot]$ + constant at D = 10 pc (*absolute magnitude*)

$(V\!-\!I) = m_V - m_I = -2.5 \log L_V/L_I$

Subscript "**0**": corrected for the effects of extinction (dust)

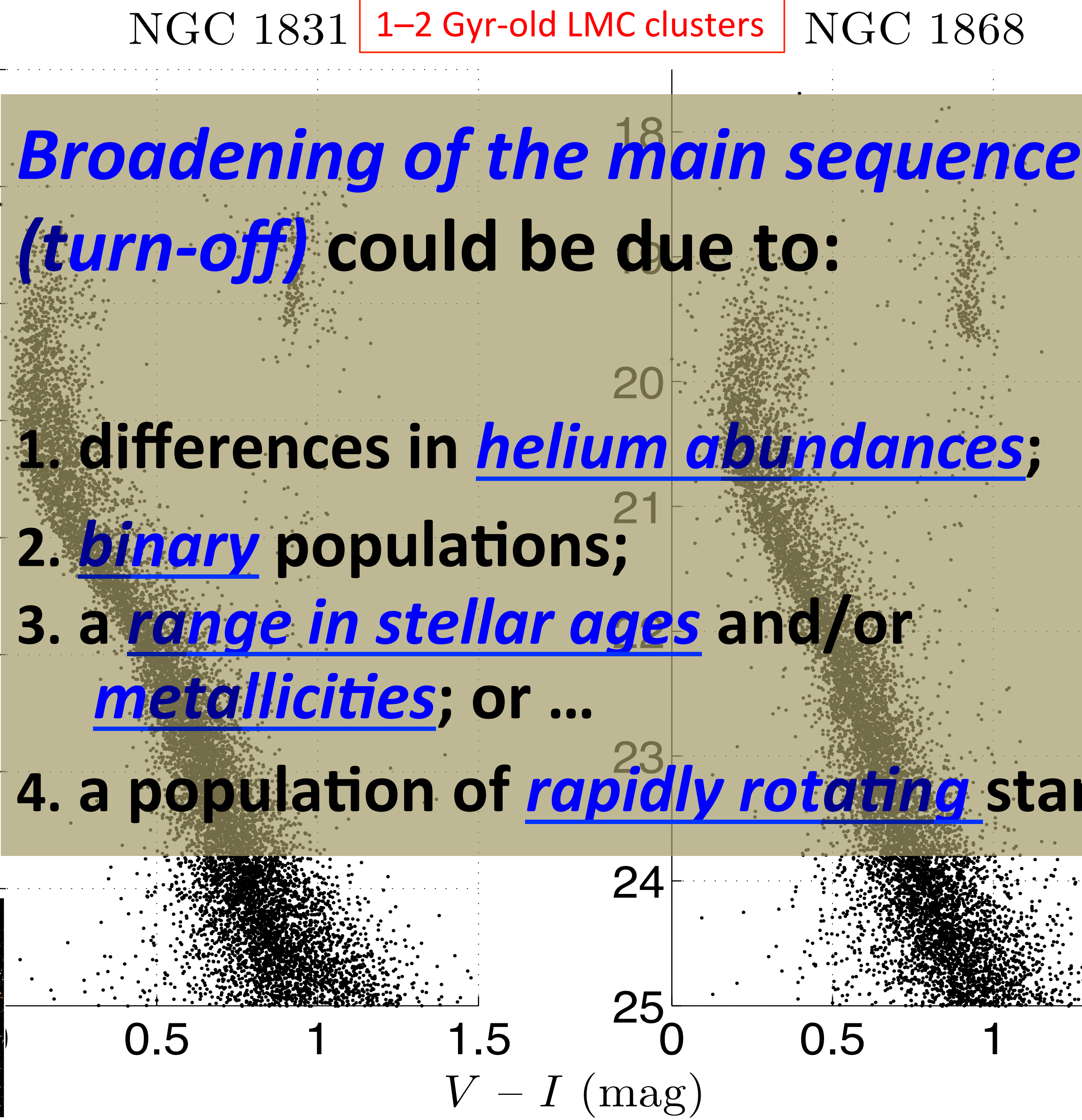
M3, M55, M68, NGC 6397, NGC 2419

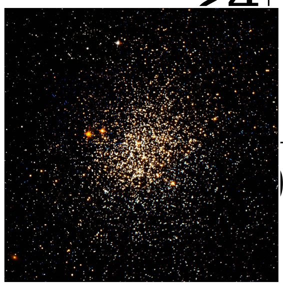
"Blue" ← → **"Red"**

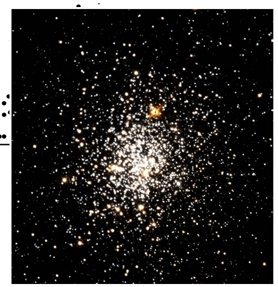
1–2 Gyr-old LMC clusters

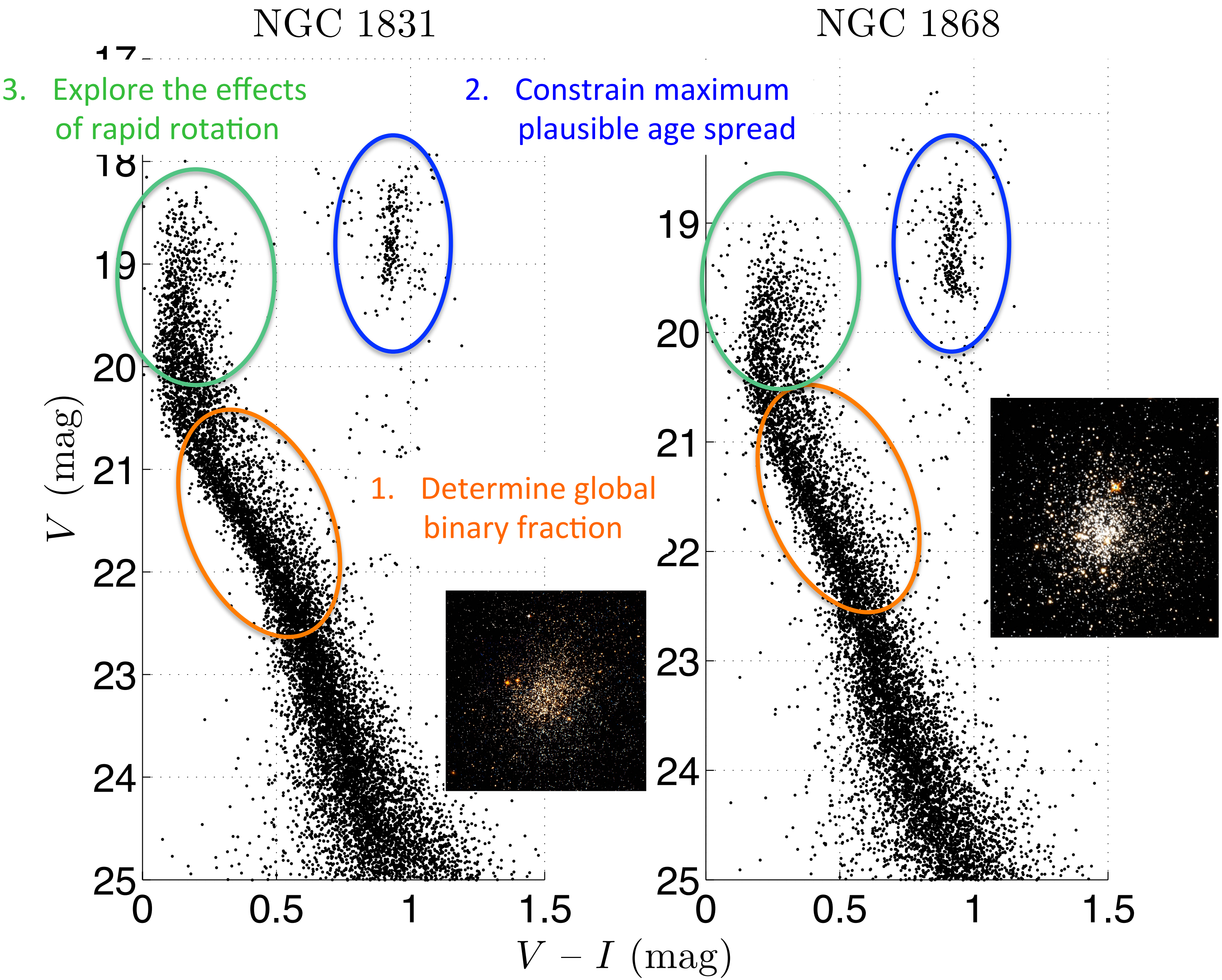
Broadening of the main sequence (turn-off) could be due to:

1. differences in ***helium abundances***;
2. ***binary*** populations;
3. a ***range in stellar ages*** and/or ***metallicities***; or …
4. a population of ***rapidly rotating*** stars

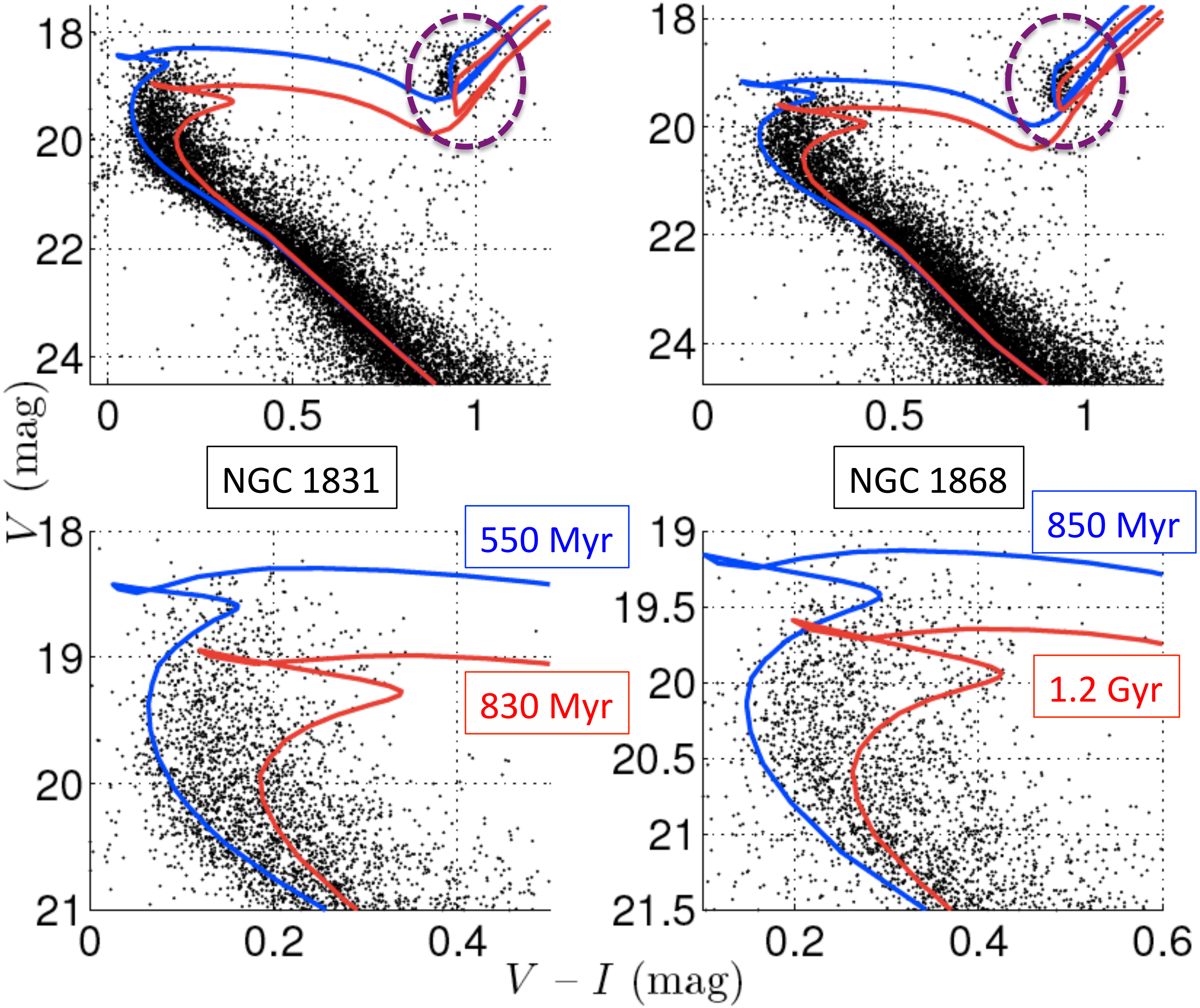






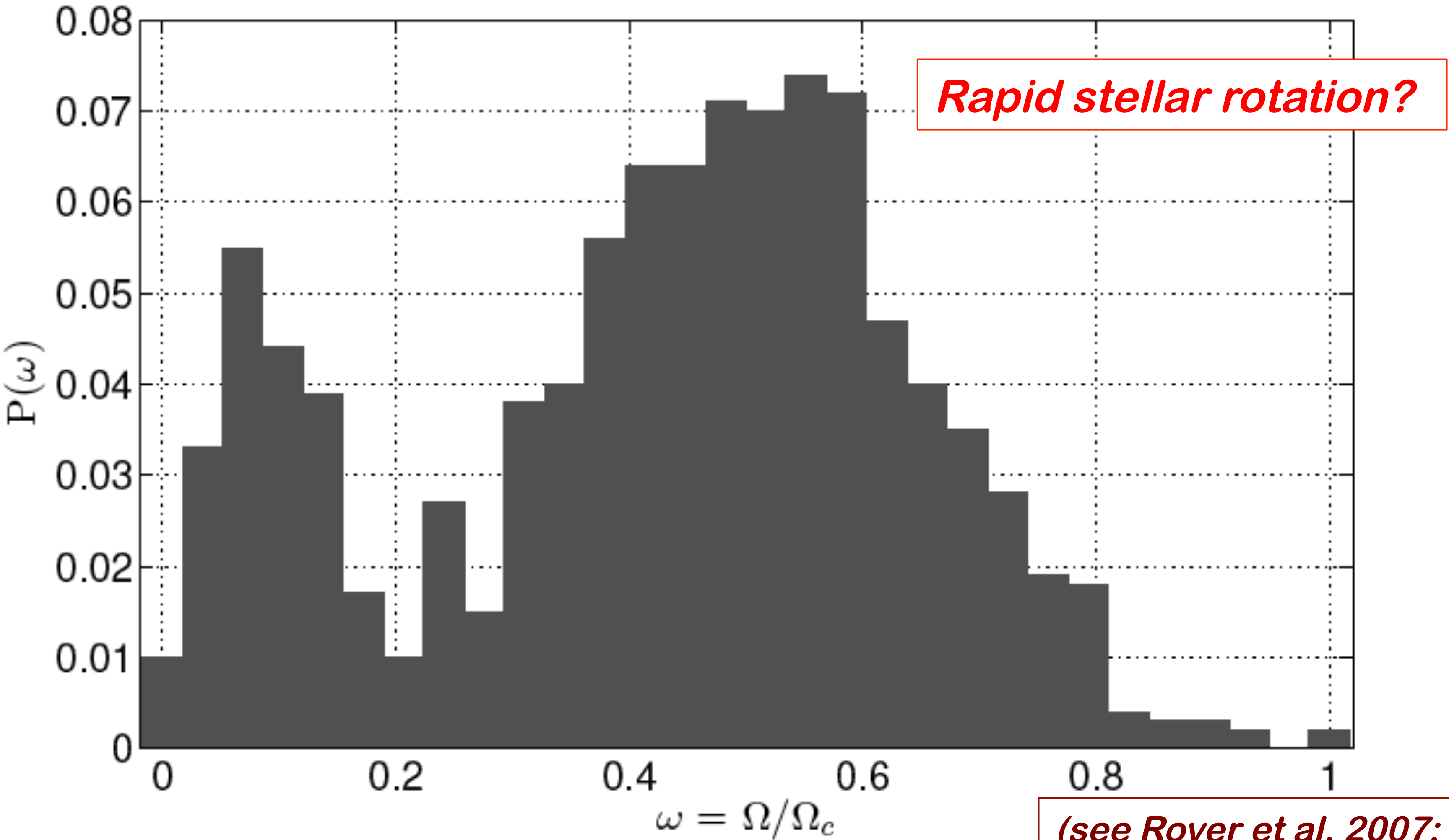


NGC 1831
NGC 1868
3. Explore the effects of rapid rotation
2. Constrain maximum plausible age spread
1. Determine global binary fraction
V (mag)
V − I (mag)
17
18
19
20
21
22
23
24
25
0
0.5
1
1.5



(Li, de Grijs, & Deng, 2014, ApJ, 784, 157)

(Li, de Grijs, & Deng, 2014, ApJ, 784, 157)



(see Royer et al. 2007; Bastian & de Mink 2009)

Fig. 15.— ω (fraction of the critical break-up rate) distribution of rotating stars, with double Gaussian peaks at 0.10 and 0.50, and standard deviations of 0.05 and 0.15, respectively.

(Li, de Grijs, & Deng, 2014, ApJ, 784, 157)

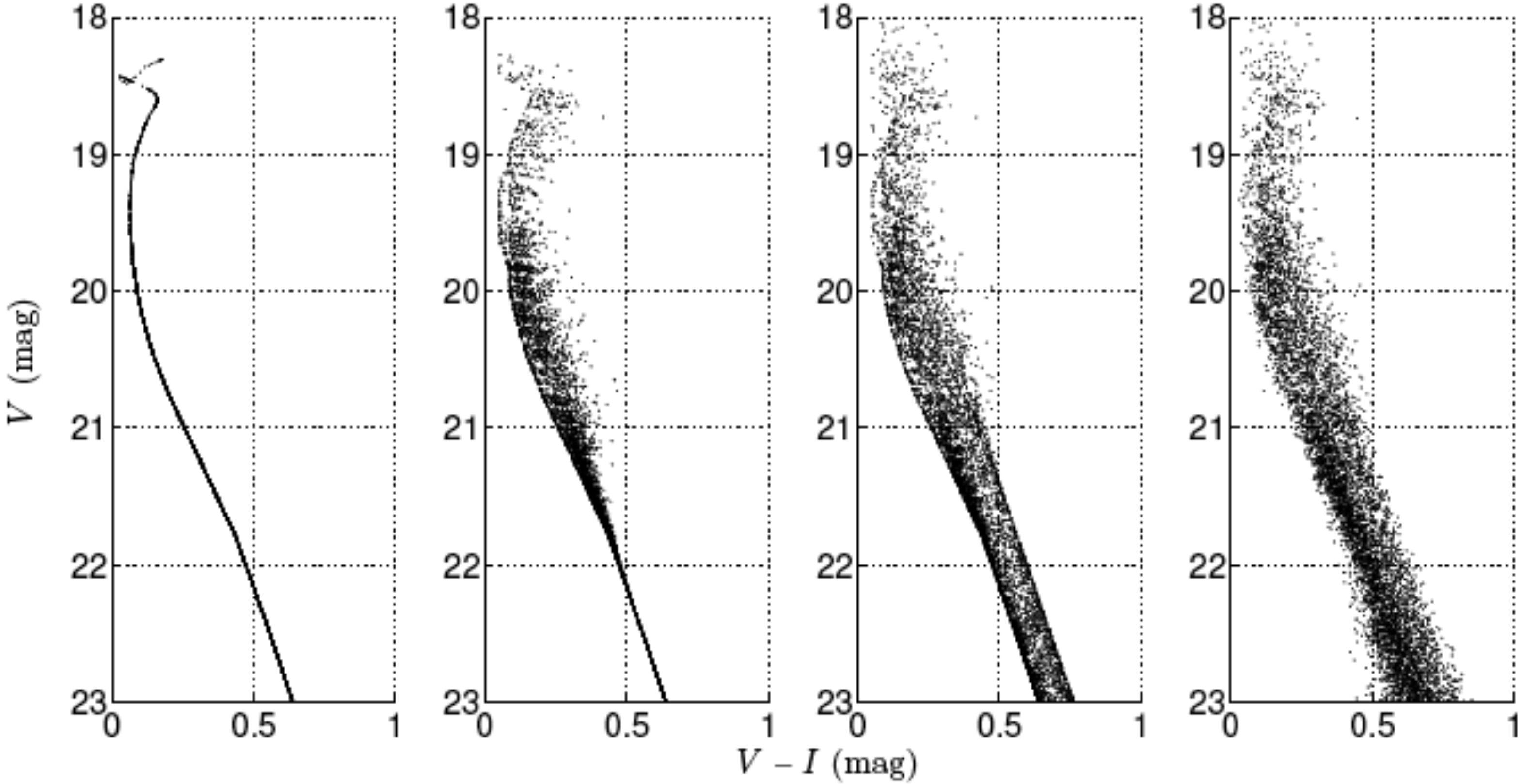
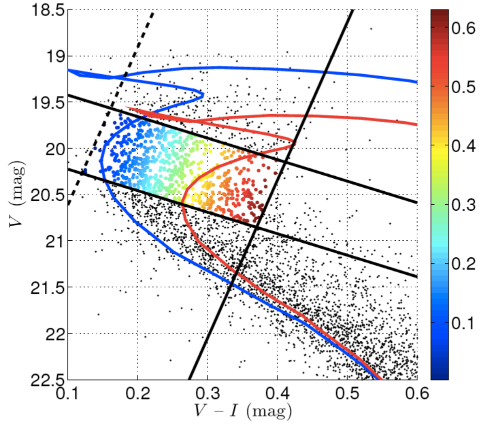
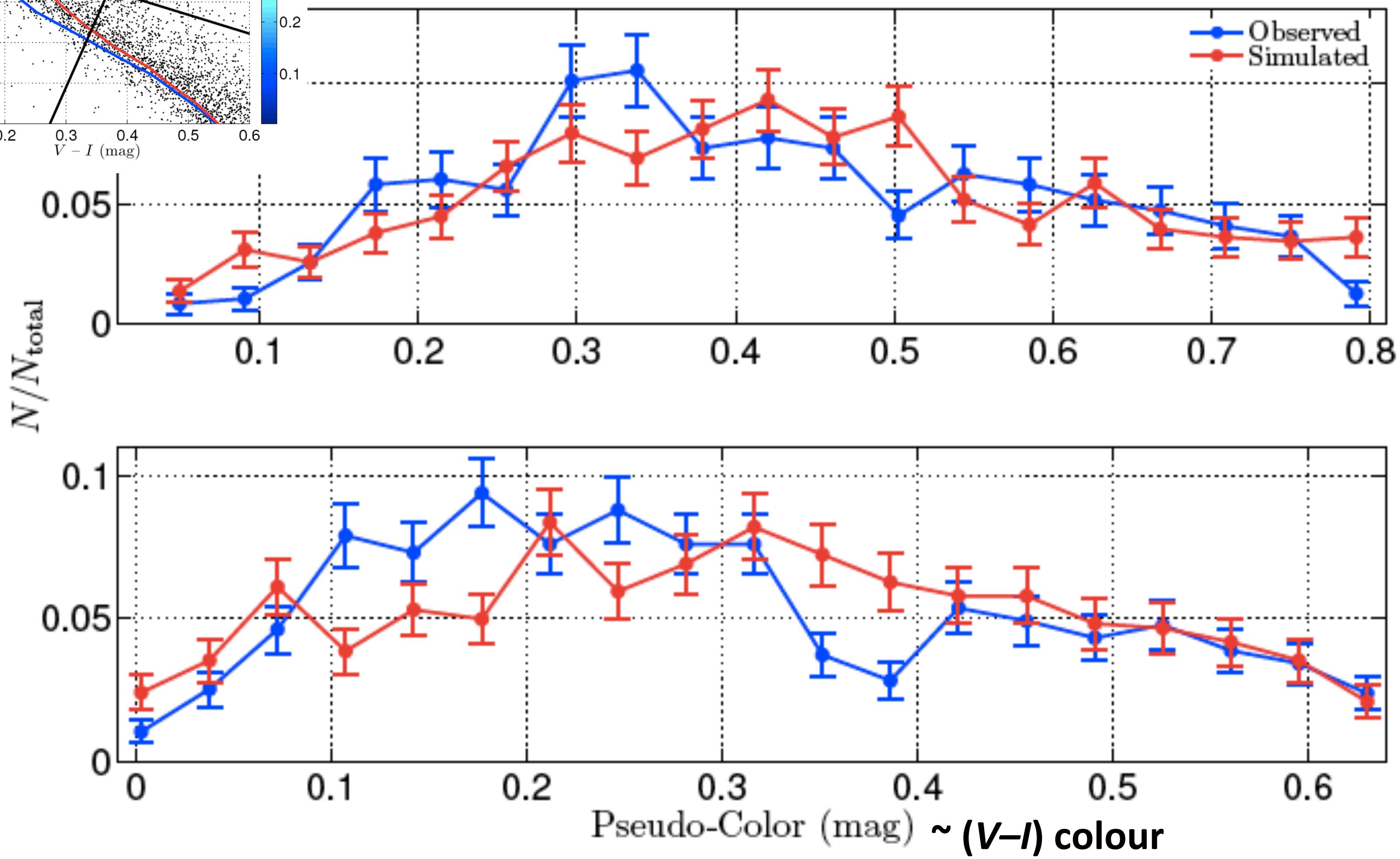


Fig. 16.— Steps to generate our simulated NGC 1831 CMD. From left to right: (1) We generate stars that exactly match the parameters given by the adopted isochrone. (2) For stars more massive than $1.2M_{\odot}$, we randomly assign rotation velocities, based on the ω distribution of Fig. 15. (3) We assign 'binary status' to 70% of the artificial stars and adjust their photometry based on the adopted binary properties. (4) We adopt the appropriate photometric uncertainties according to Eq. (1).



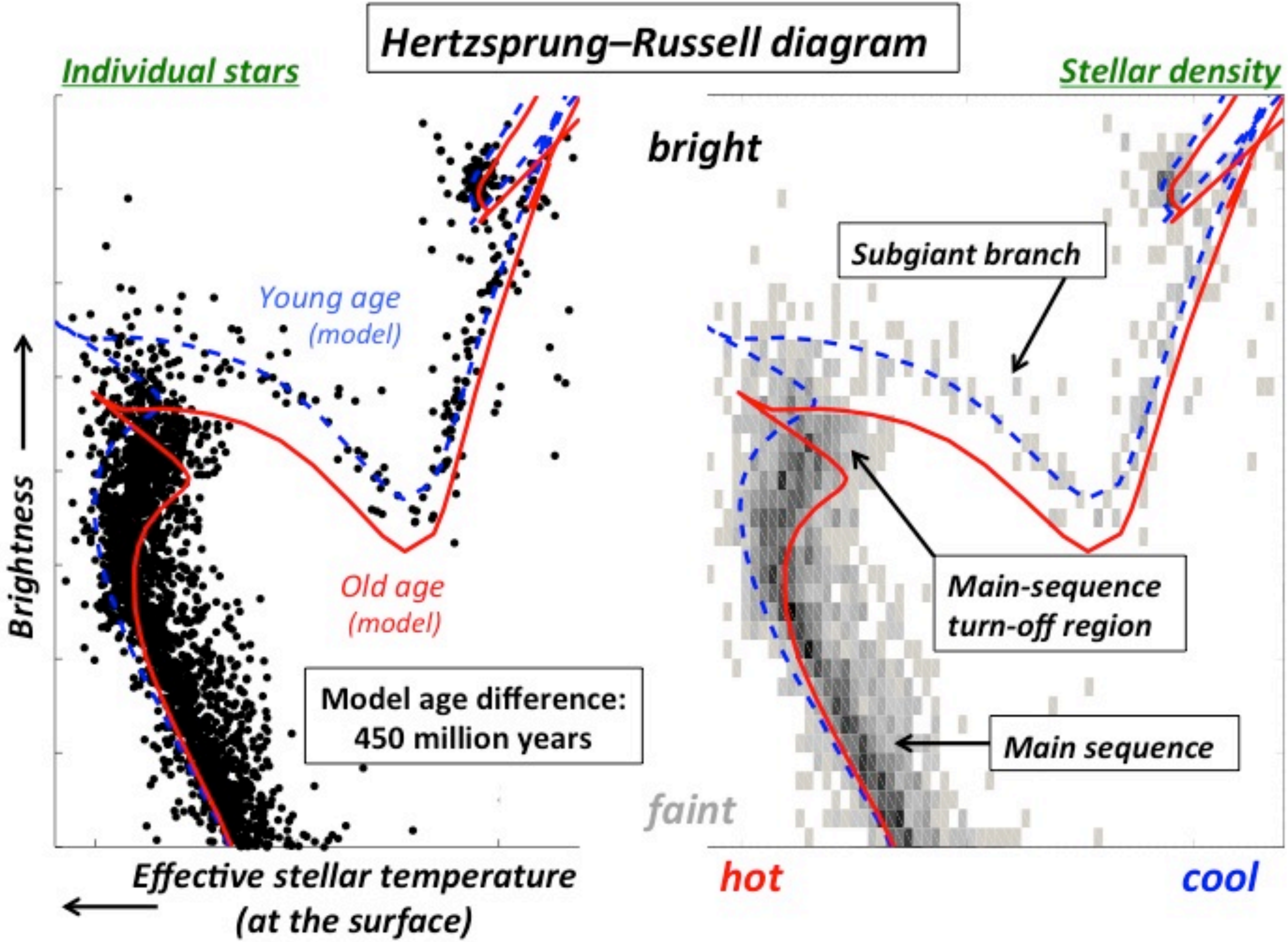
(Li, de Grijs, & Deng, 2014, ApJ, 784, 157)



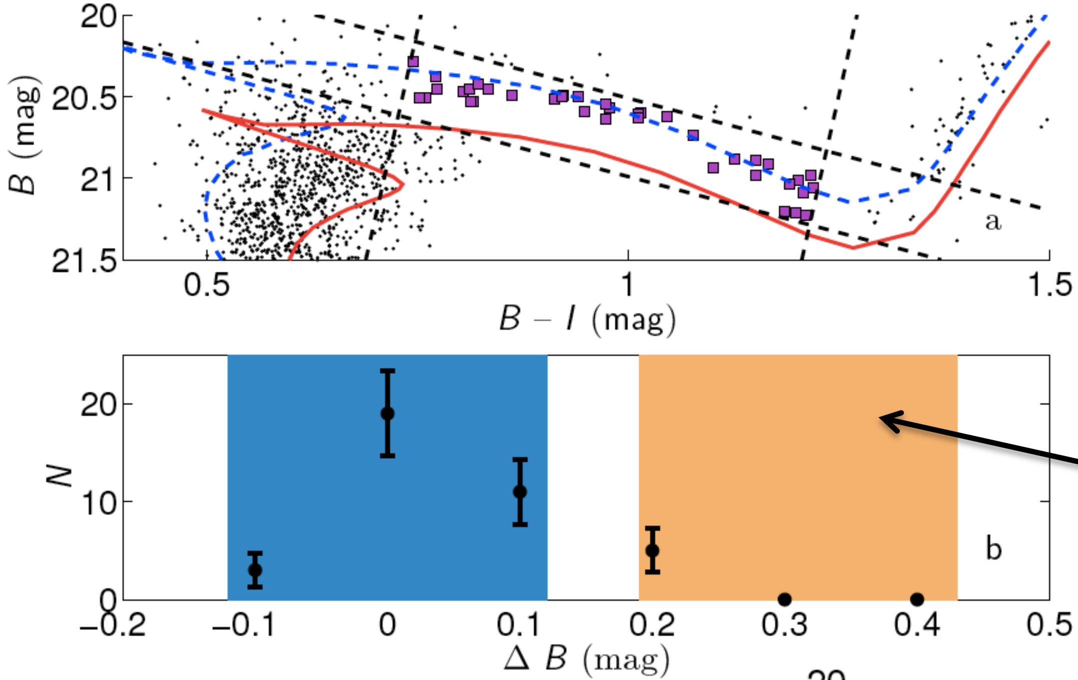
~ (*V–I*) colour

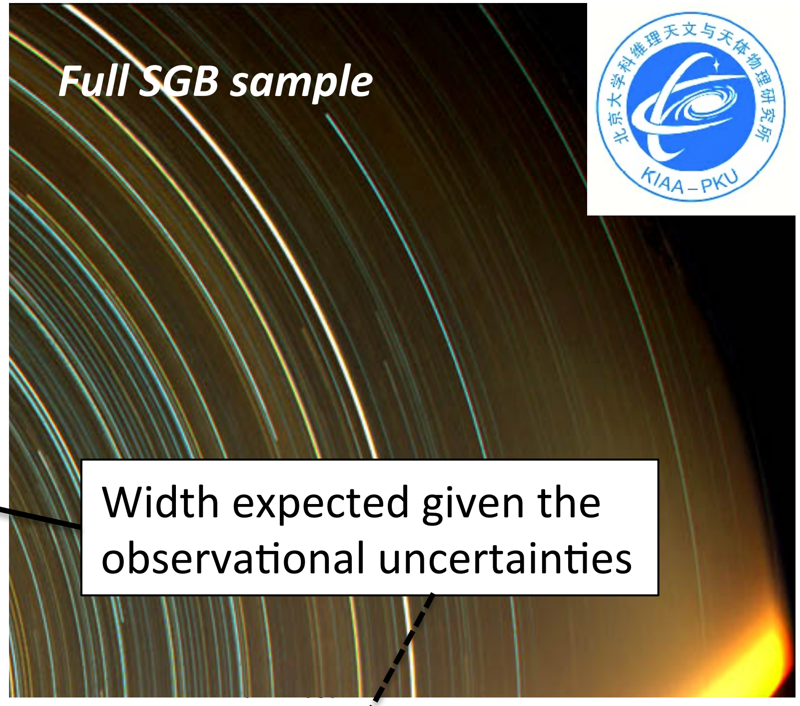
Fig. 19.— Pseudo-color distributions of (red) the simulated MS TO stars and (blue) the observed MS TO stars for (top) NGC 1831 and (bottom) NGC 1868.

NGC 1651: An unexpected discovery

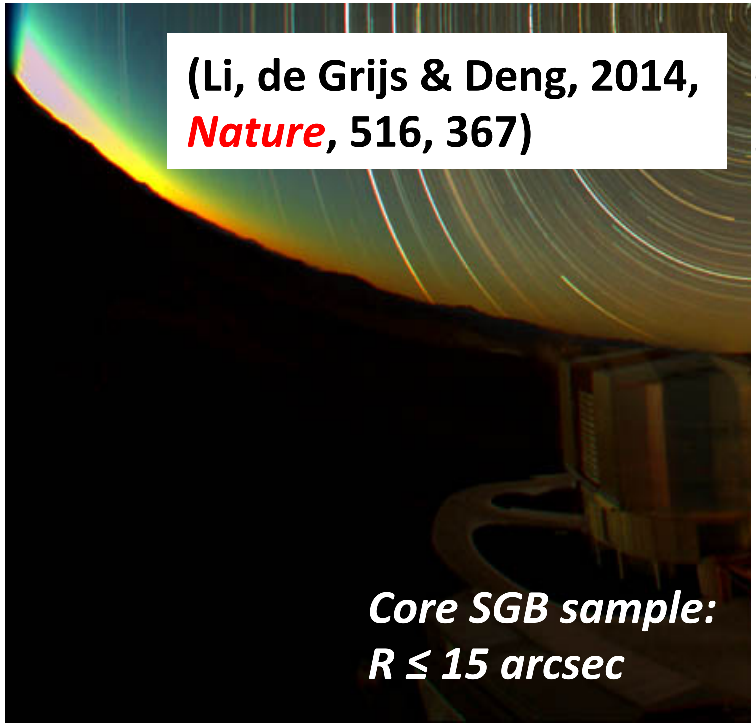


(Li, de Grijs & Deng, 2014, *Nature*, 516, 367)

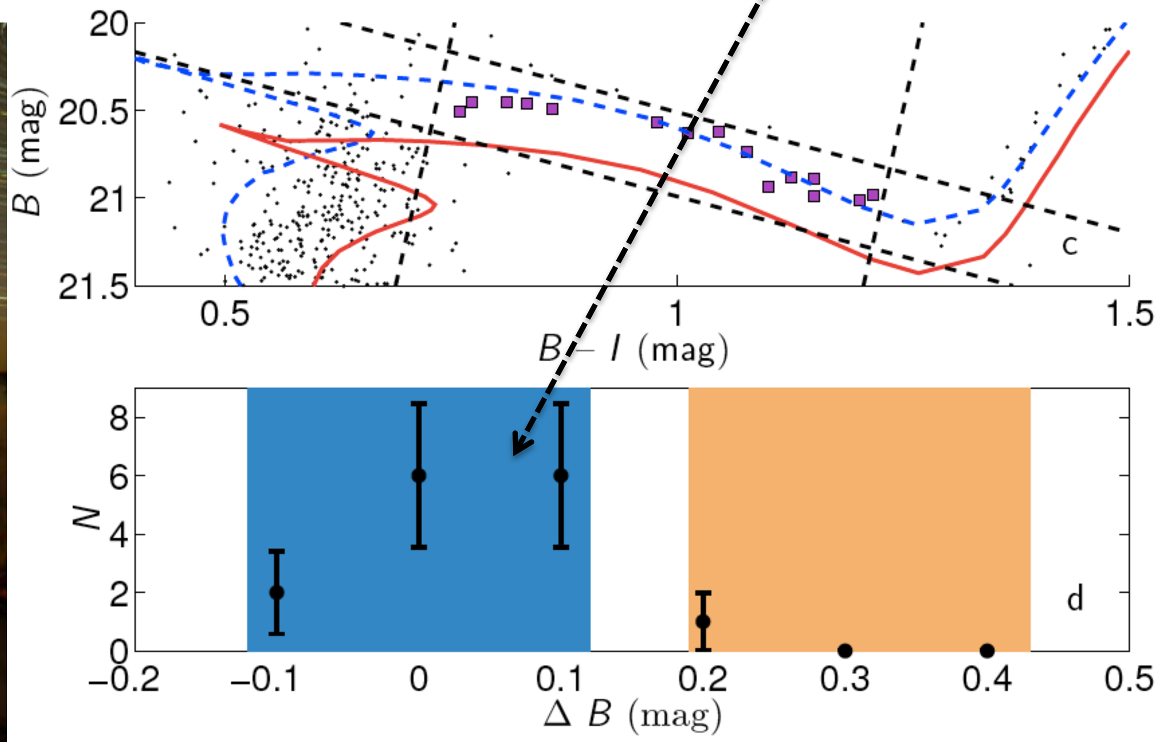


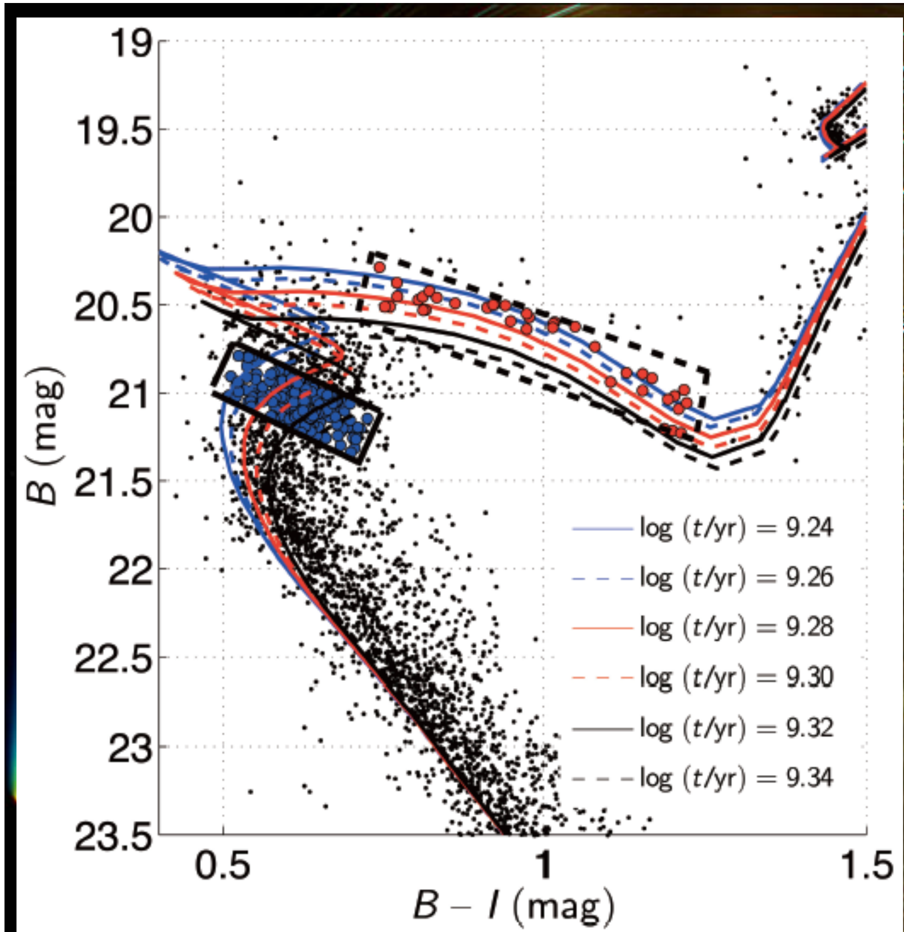


Width expected given the observational uncertainties

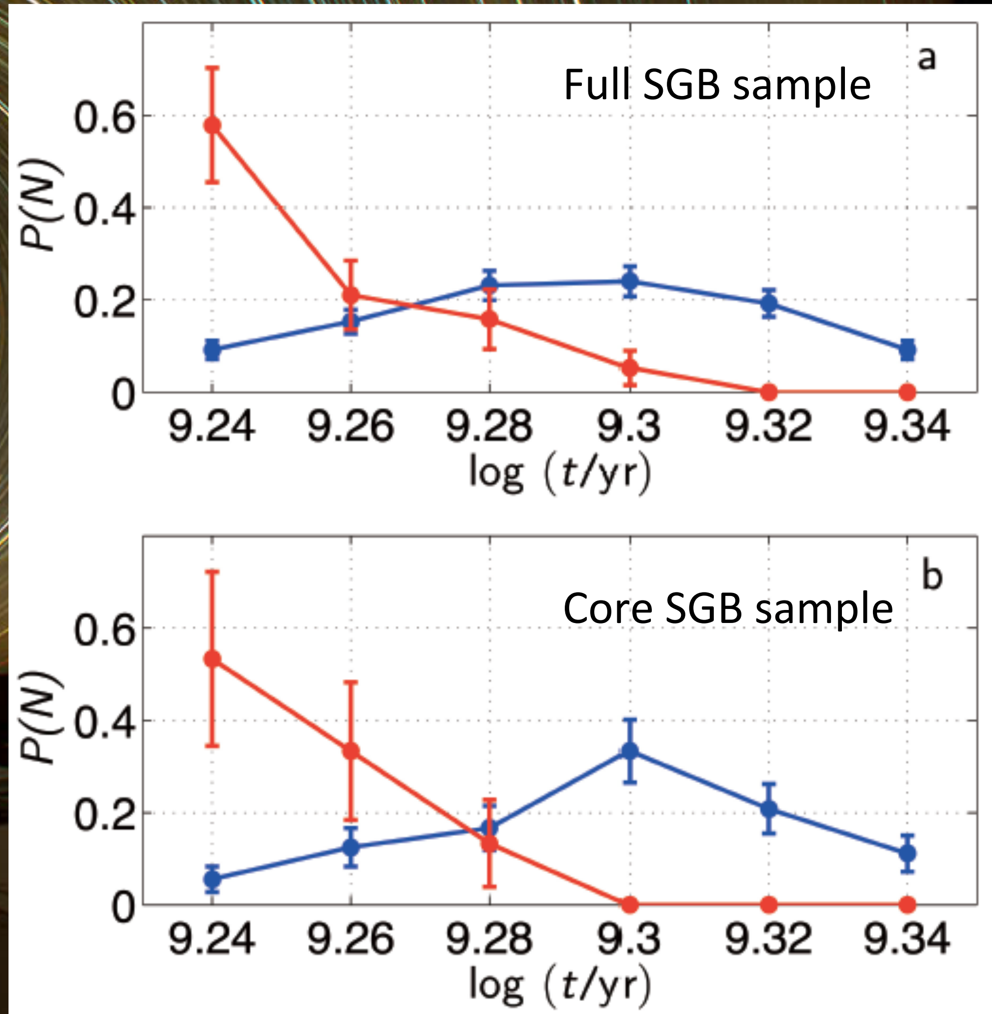


(Li, de Grijs & Deng, 2014, *Nature*, 516, 367)



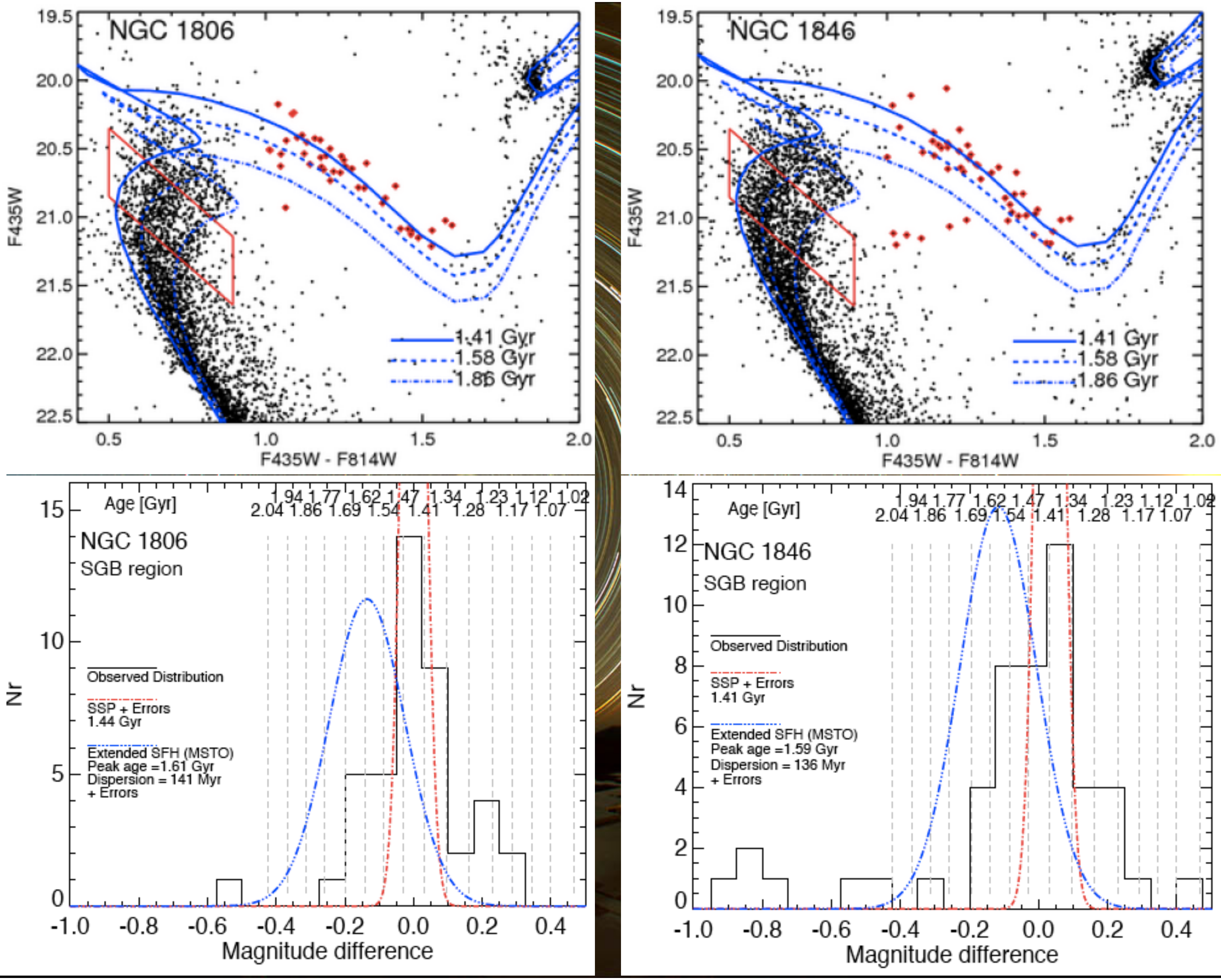


(Li, de Grijs & Deng, 2014, *Nature*, 516, 367)



Maximum plausible age range allowed by the SGB width: 80 Myr

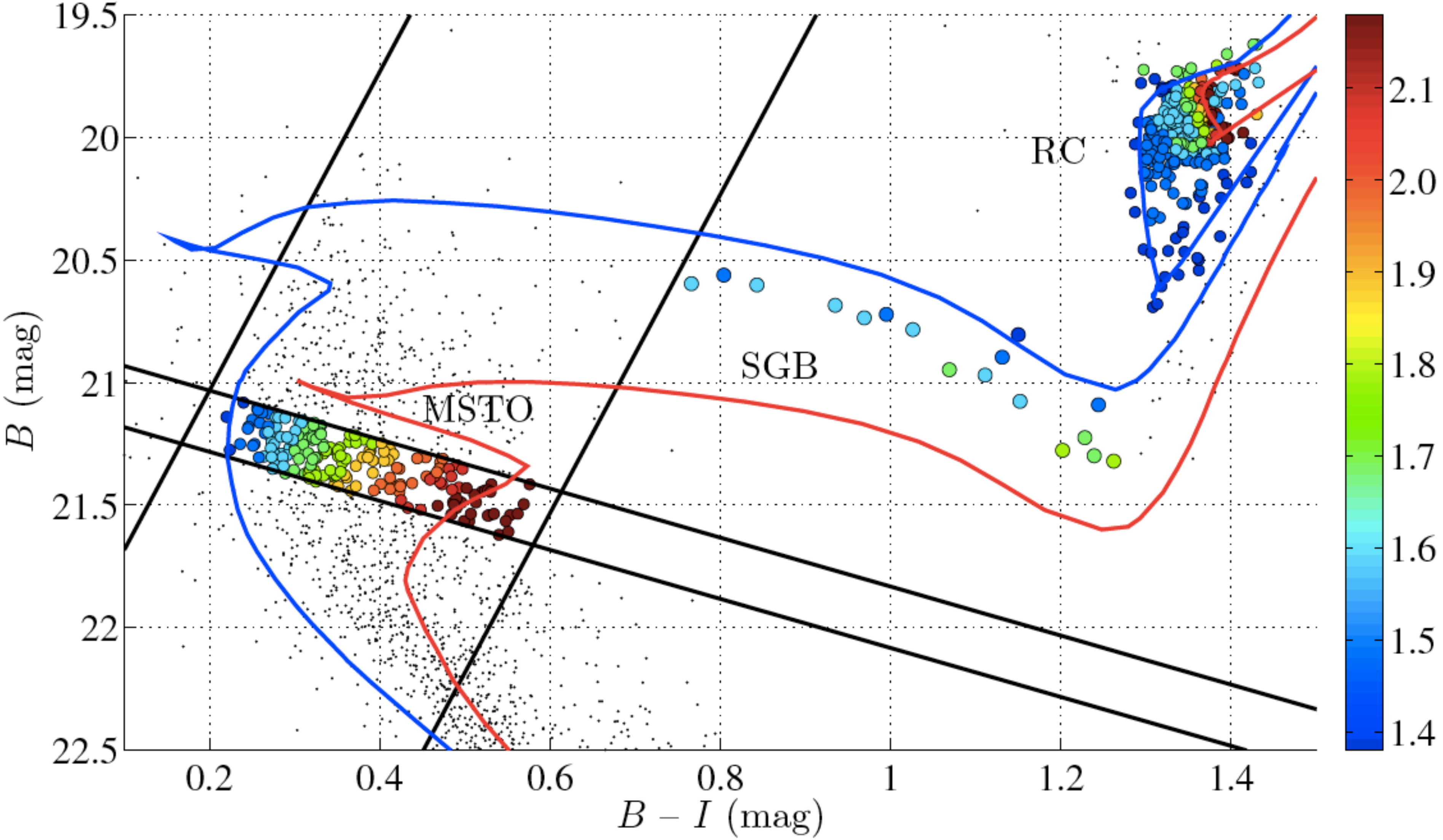
Bastian & Niederhofer 2015, MNRAS, 448, 1863

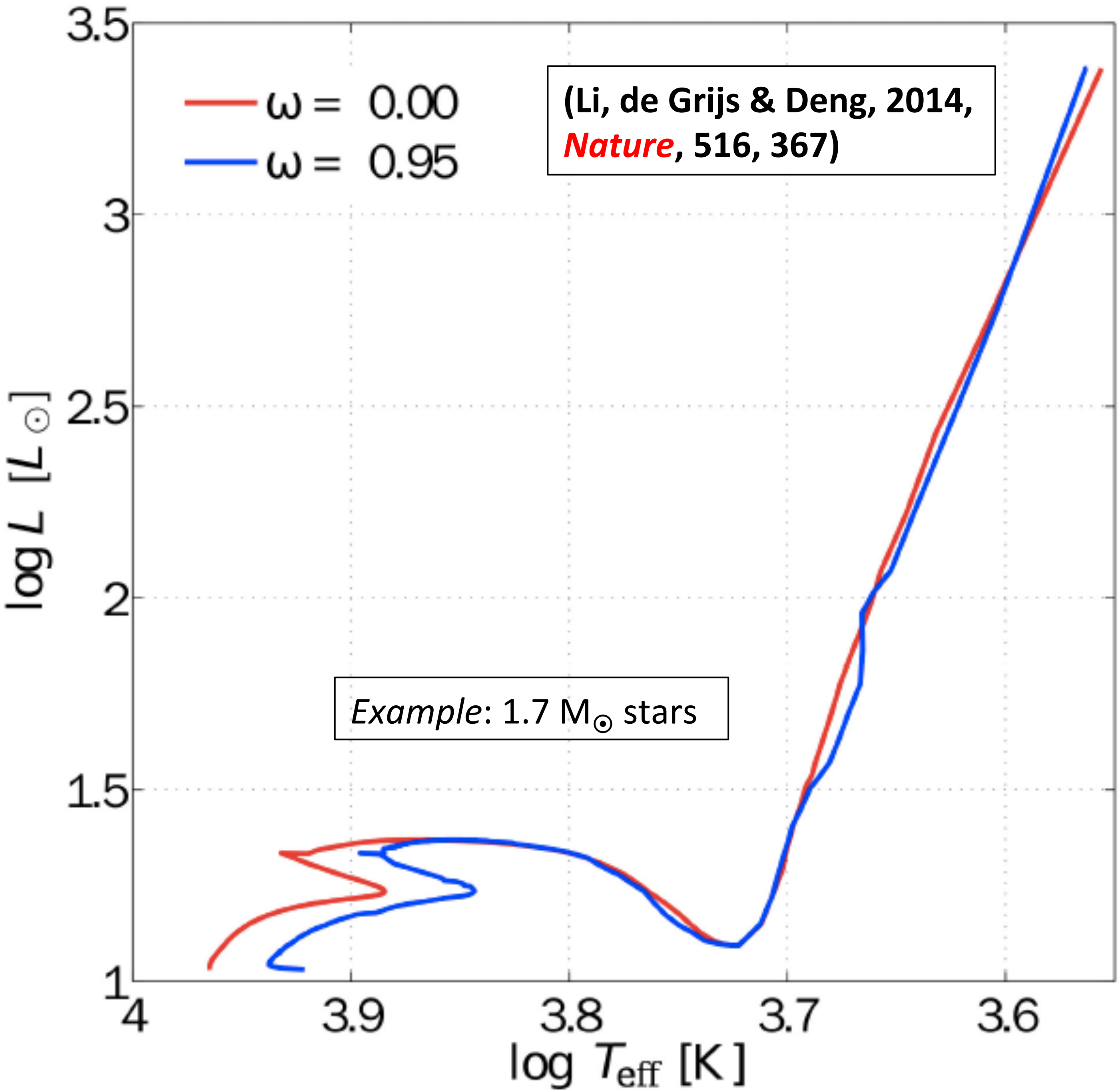


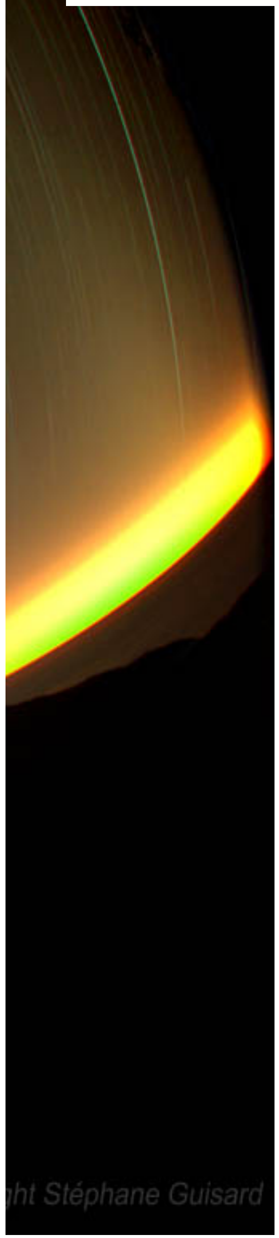
(Li, de Grijs, et al. 2016, MNRAS, 461, 3212)

NGC 411

- Most extended MSTO known
- Lowest escape velocity of an eMSTO cluster



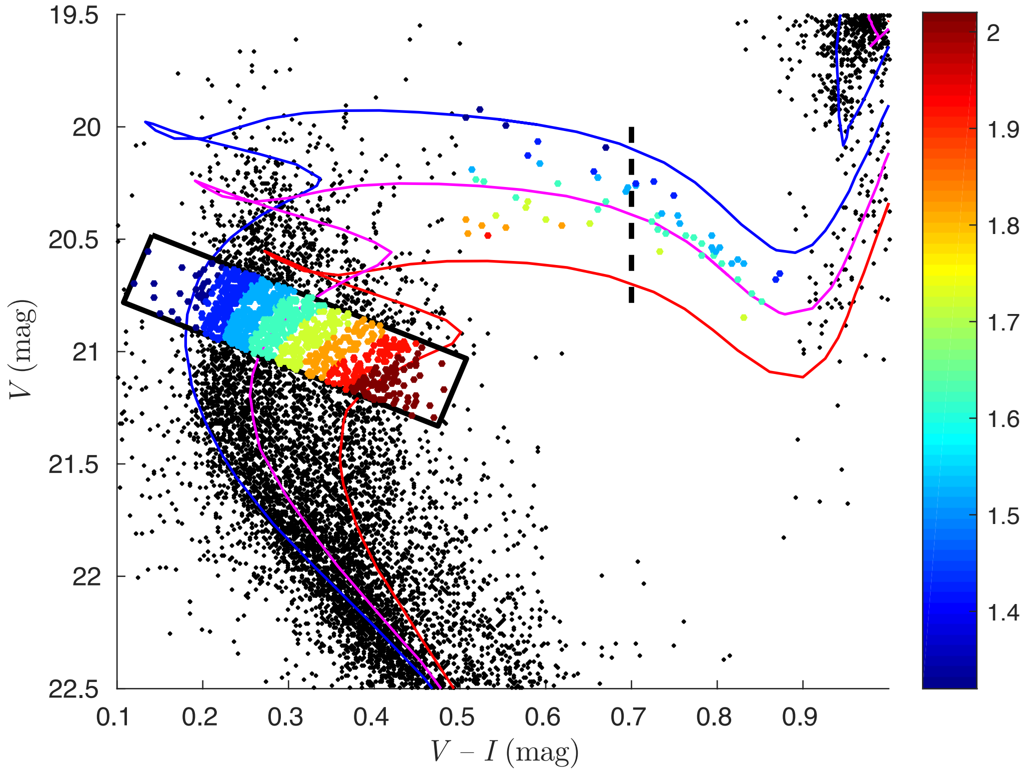

(Li, de Grijs & Deng, 2014,
Nature, 516, 367)
ω = 0.00
ω = 0.95
Example: 1.7 $M_{\odot}$ stars
log L [$L_{\odot}$]
log $T_{\rm eff}$ [K]
3.5
3
2.5
2
1.5
1
4
3.9
3.8
3.7
3.6

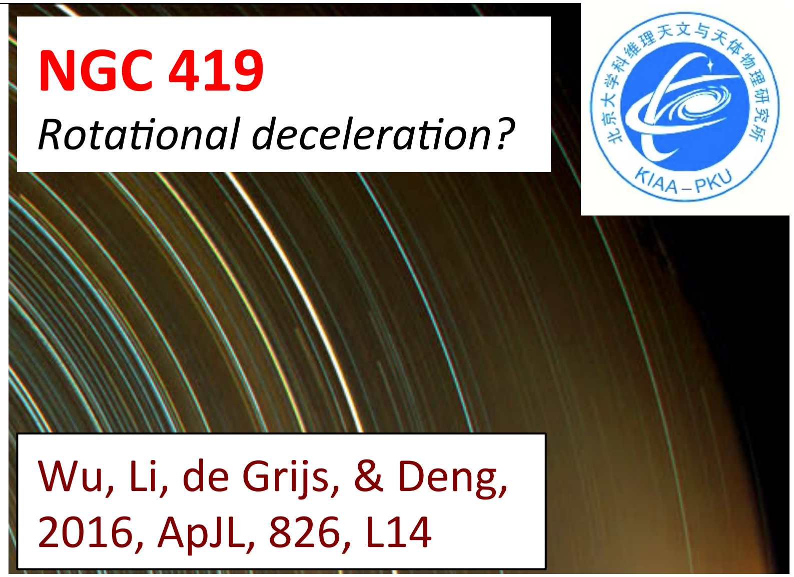

ght Stéphane Guisard

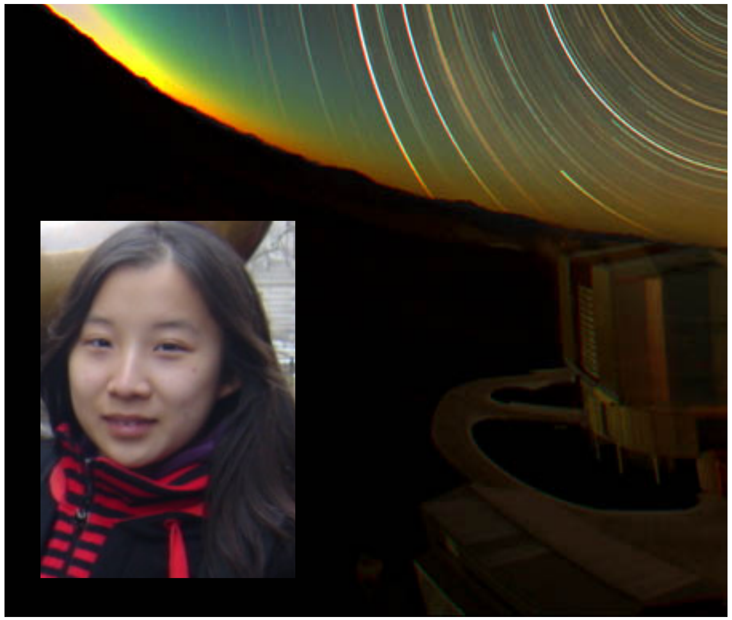
NGC 419

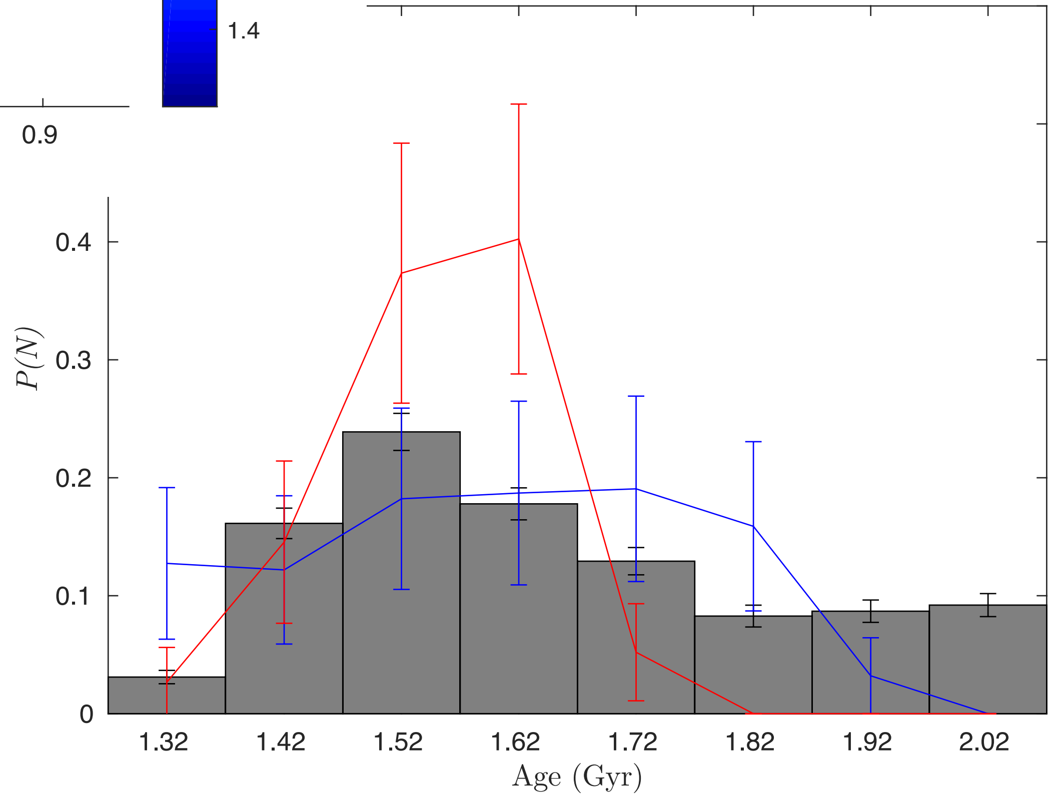
Rotational deceleration?

Wu, Li, de Grijs, & Deng, 2016, ApJL, 826, L14

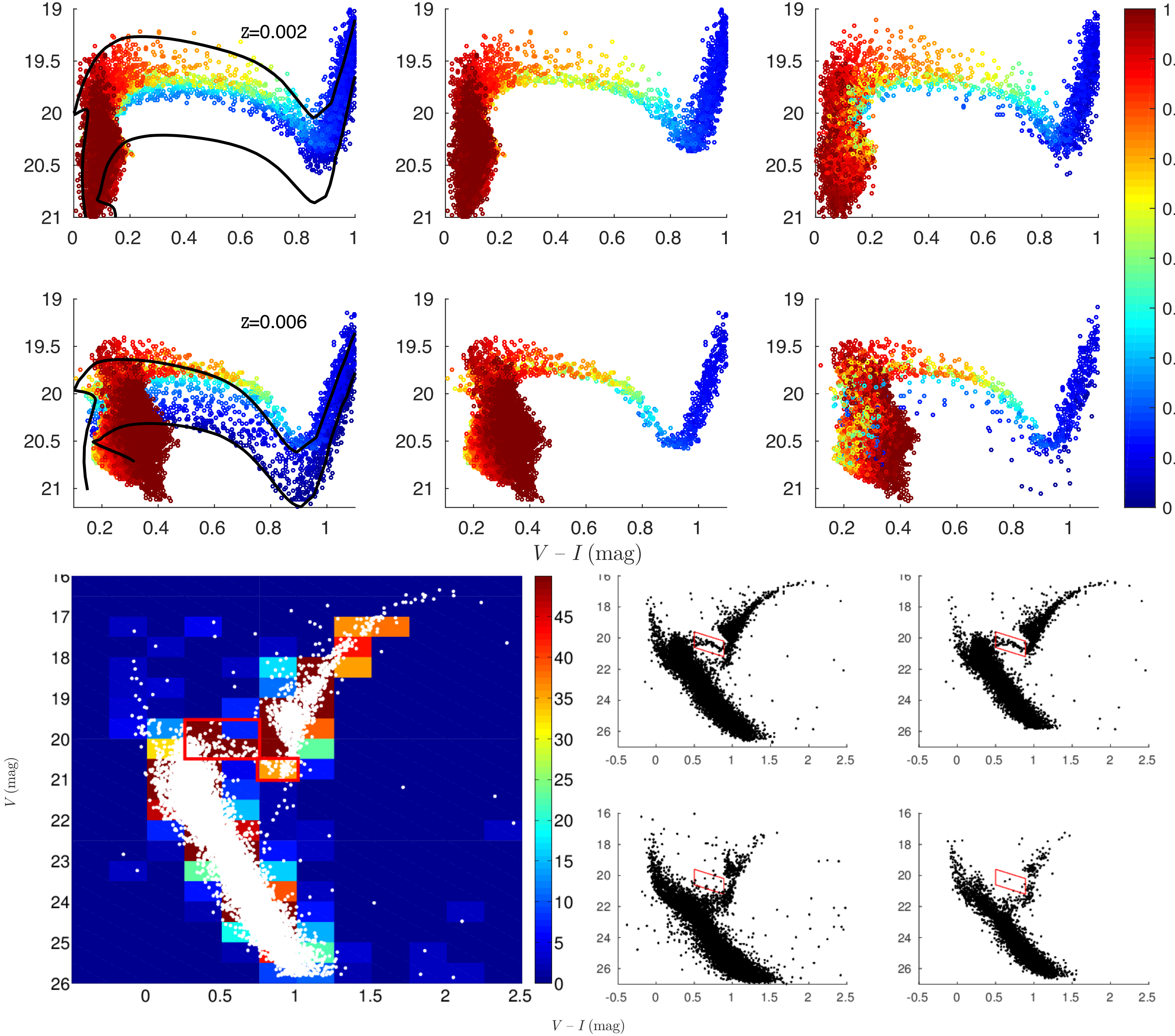


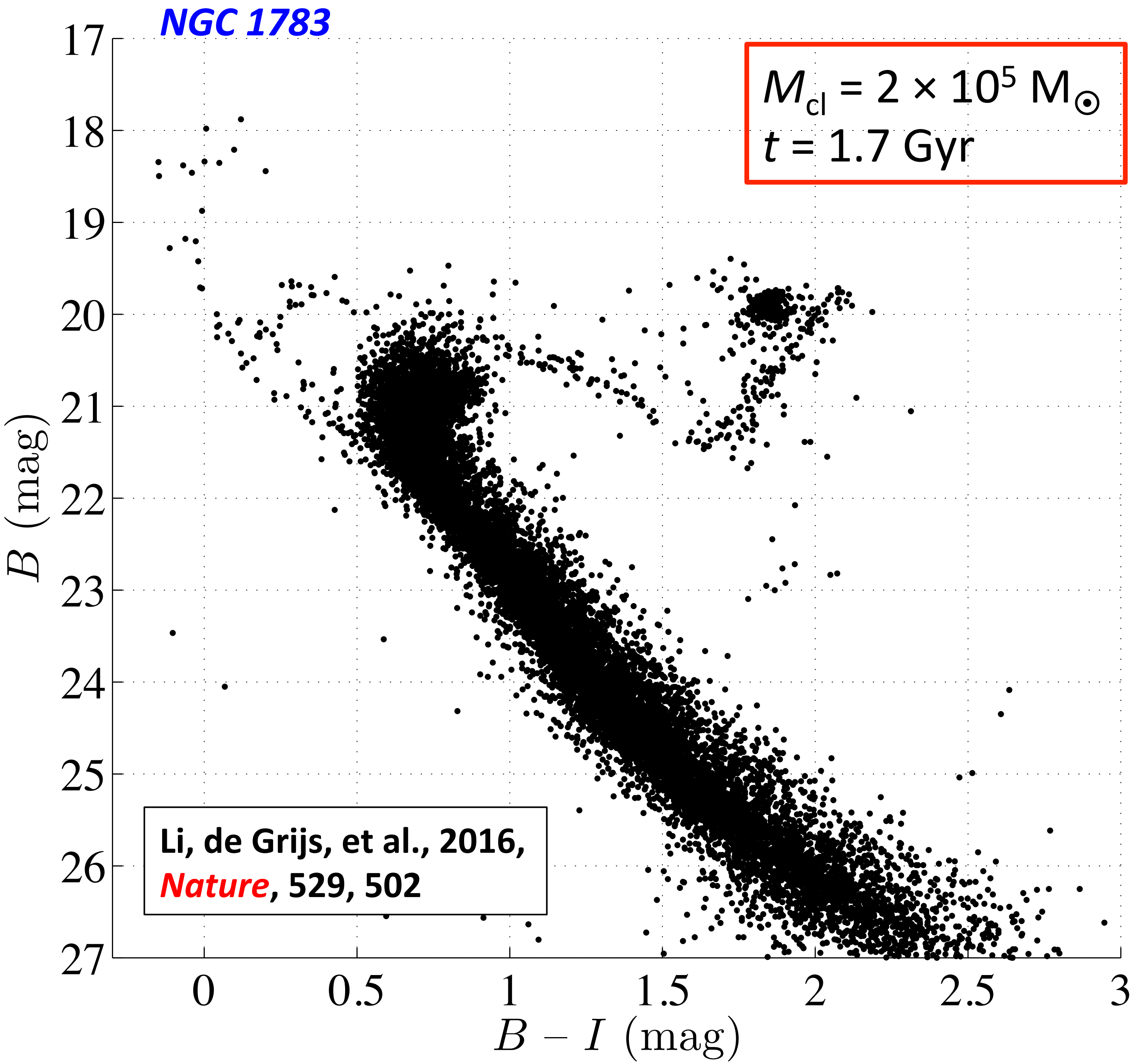


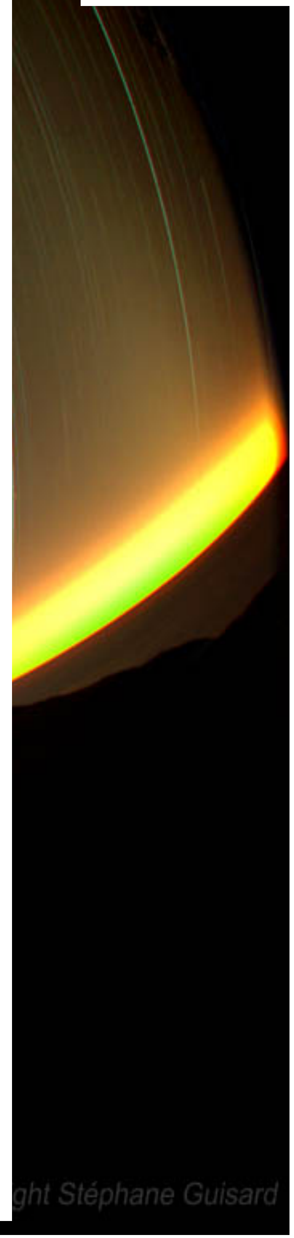


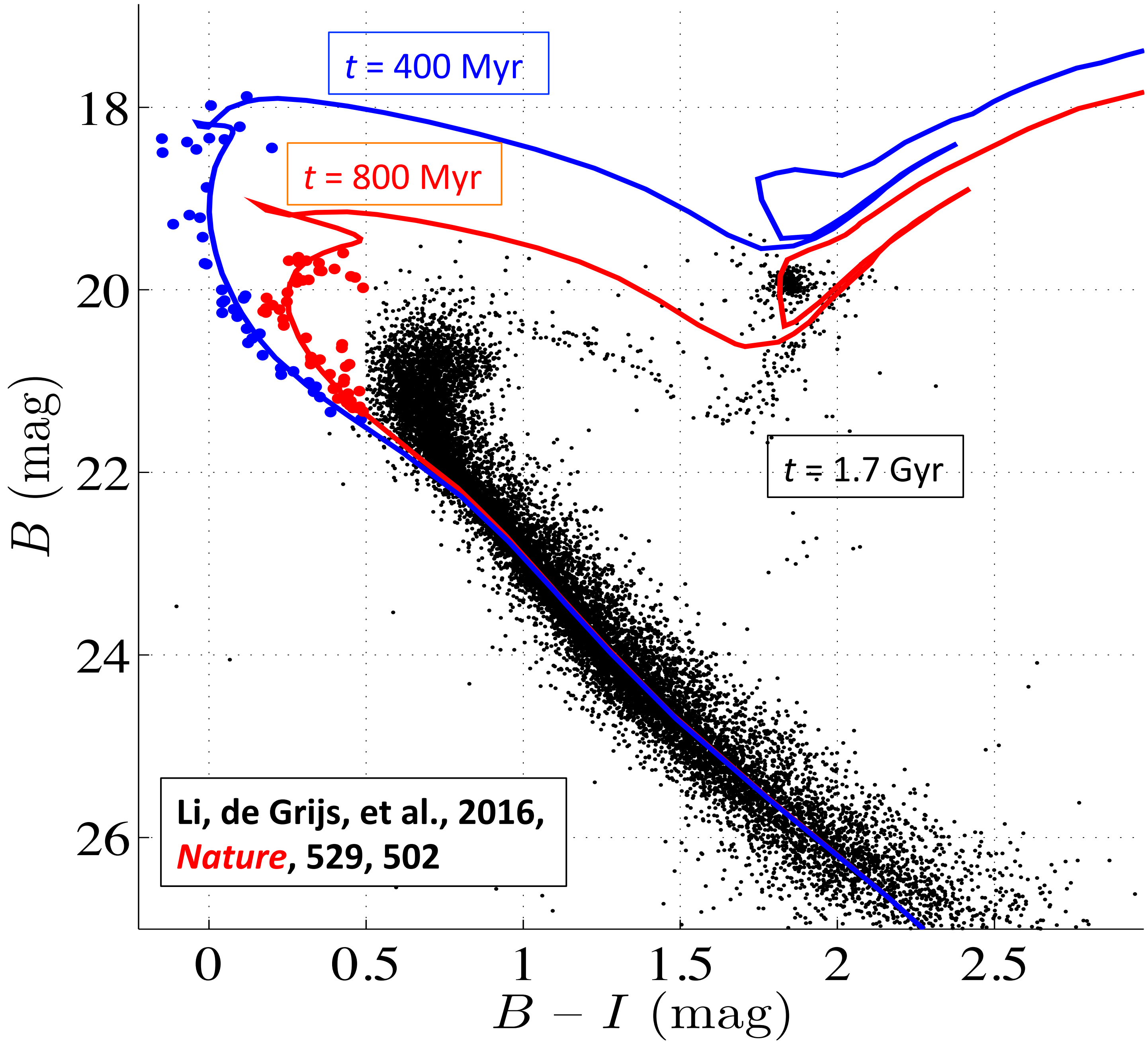


Wu, Li, de Grijs, & Deng, 2016, ApJL, 826, L14

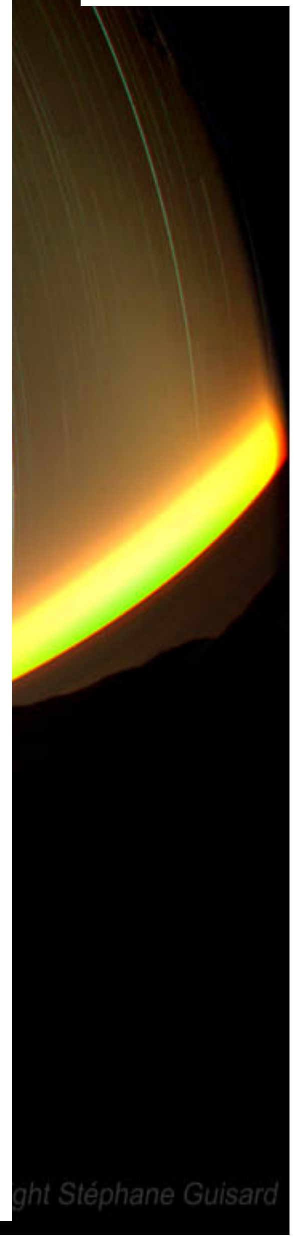



NGC 1783
M_{cl} = 2 × 10^5 $M_\odot$
t = 1.7 Gyr
Li, de Grijs, et al., 2016,
Nature, 529, 502
17
18
19
20
21
22
23
24
25
26
27
B (mag)
0
0.5
1
1.5
2
2.5
3
$B - I$ (mag)


ght Stéphane Guisard



t = 400 Myr
t = 800 Myr
t = 1.7 Gyr
18
20
22
24
26
0
0.5
1
1.5
2
2.5
B (mag)
B − I (mag)
Li, de Grijs, et al., 2016,
Nature, 529, 502



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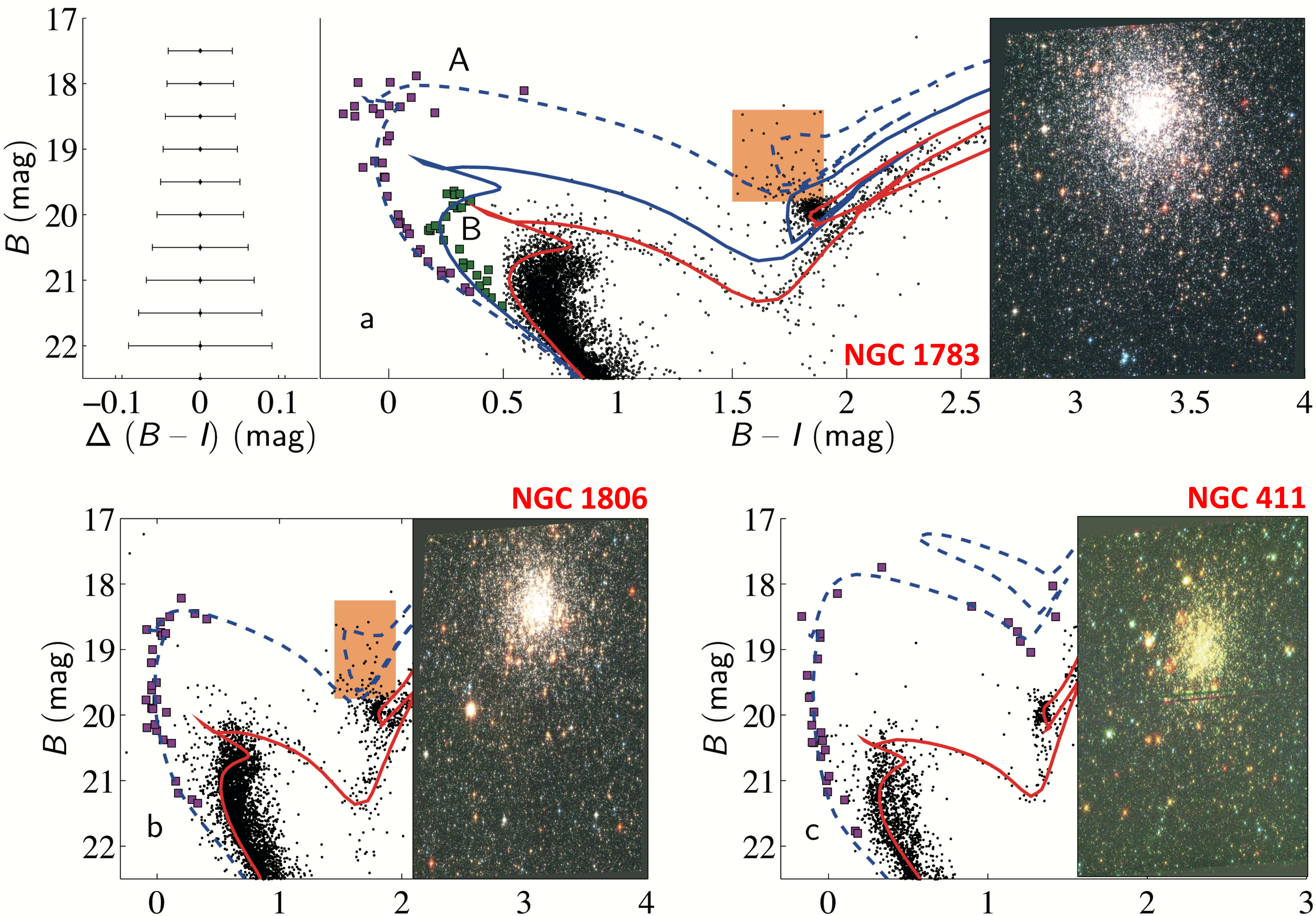
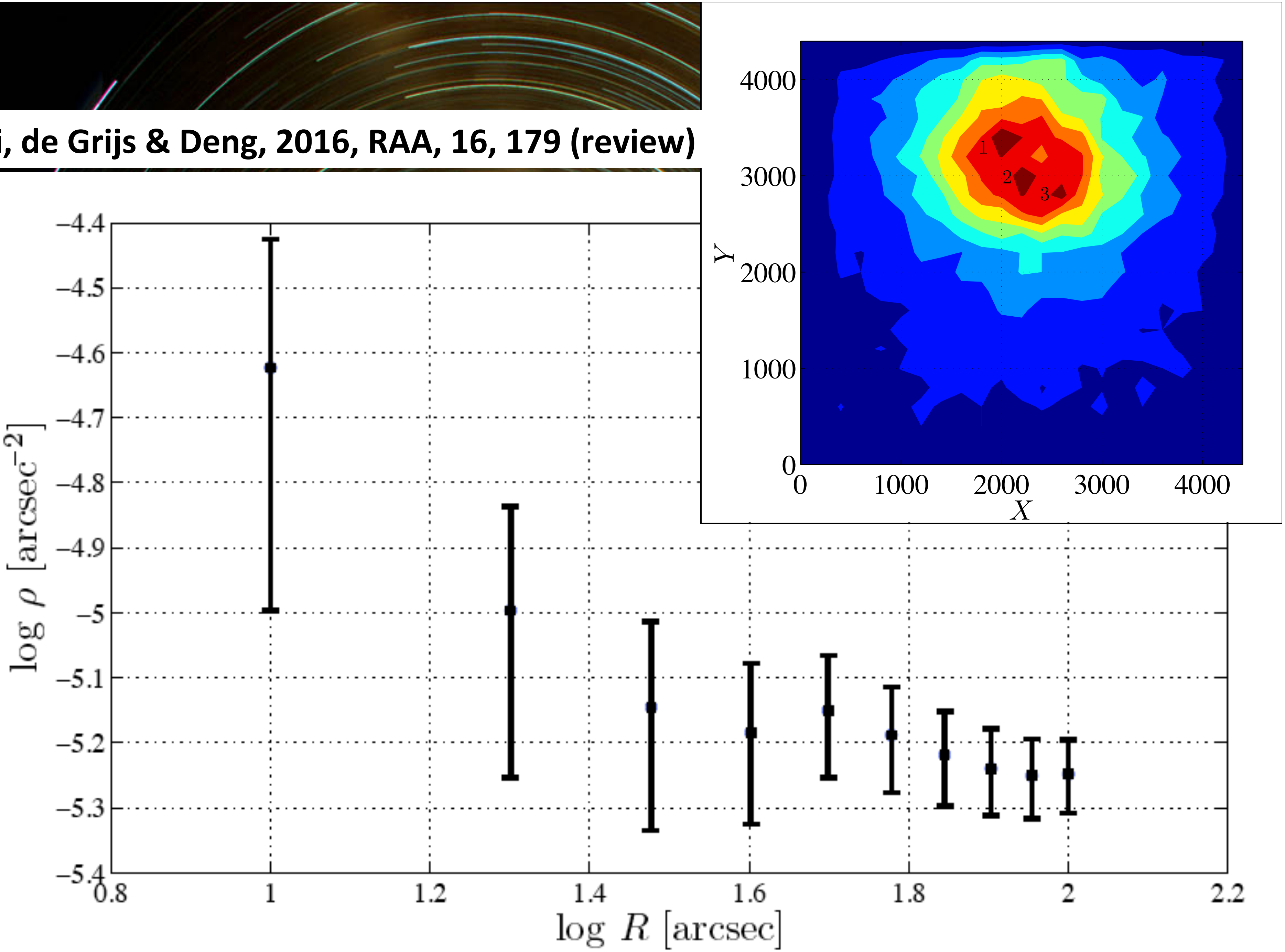


Li, de Grijs, et al., 2016, *Nature*, 529, 502

Li, de Grijs & Deng, 2016, RAA, 16, 179 (review)



Rebuttal:

1. A **centrally concentrated** population, clearly peaking in the cluster core – <u>unlikely for a field population</u>

2. Tightly constrained to a **single-age isochrone** – <u>unlikely for a field population</u>

3. Careful **choice of field region**: in our *Nature* paper, we pointed out that part of the nearby region from which the field was selected was contaminated by active star formation – <u>willfully ignored by the critics</u>

4. Young features obvious for **a wide range of CMD cell sizes**, not affected by "negative" numbers – <u>incorrect claim by the critics</u>

Take-home messages

1–3 Gyr

- At intermediate ages, *extended Main-Sequence Turn-Offs* imply the presence of an *age spread* or a population of *rapidly rotating* MSTO stars.

- A *simple stellar population* including rapidly rotating stars seems the "best" match to intermediate-[…] clusters

No age range needed!

- The presence of an exte[…] MSTO *does not necessarily imply* an age spread

- Our most recent results suggest that a *major reassessment* of the *multiple stellar population paradigm* is sorely needed!