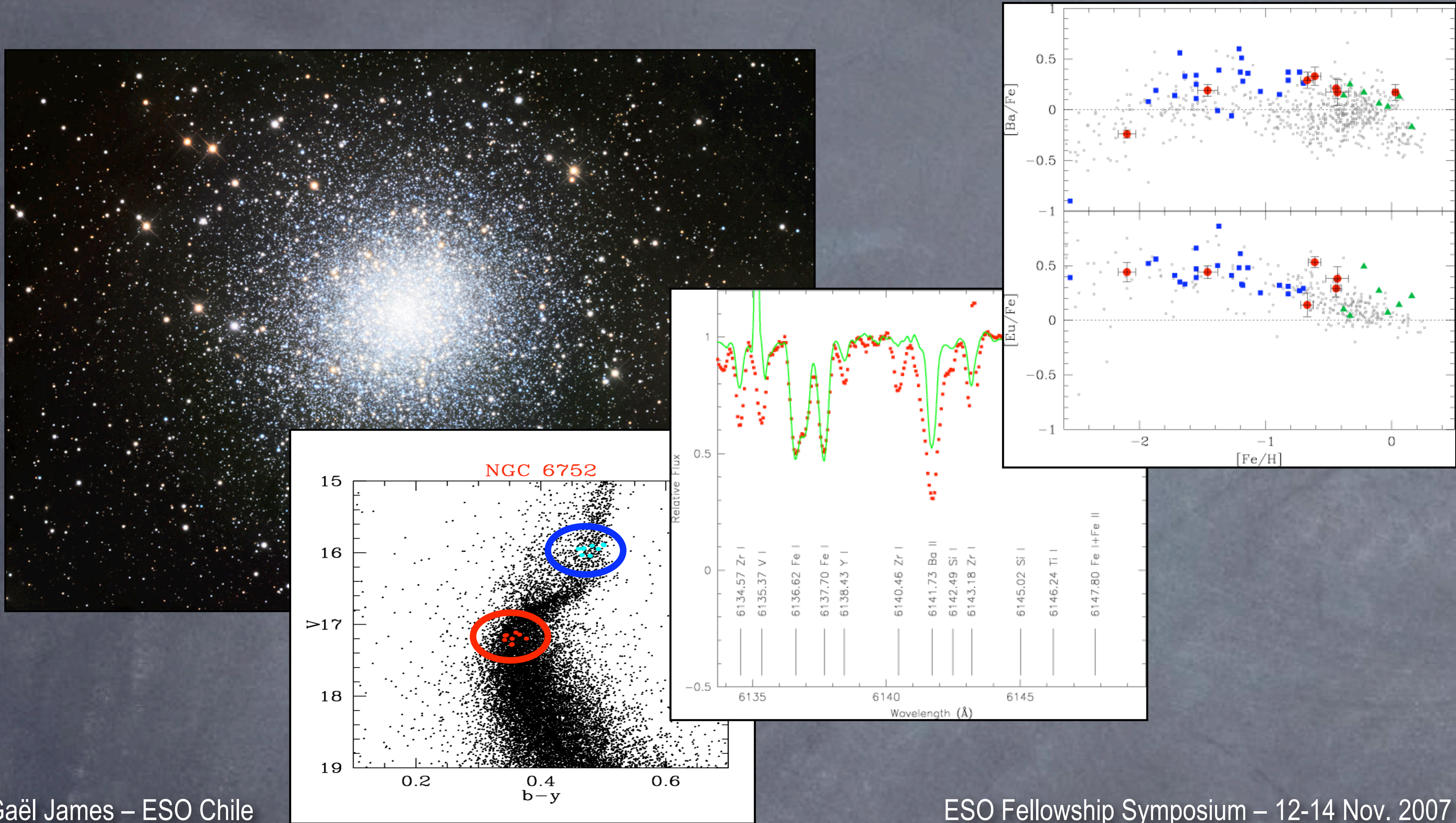
# Heavy element abundances
# in
# Galactic globular clusters



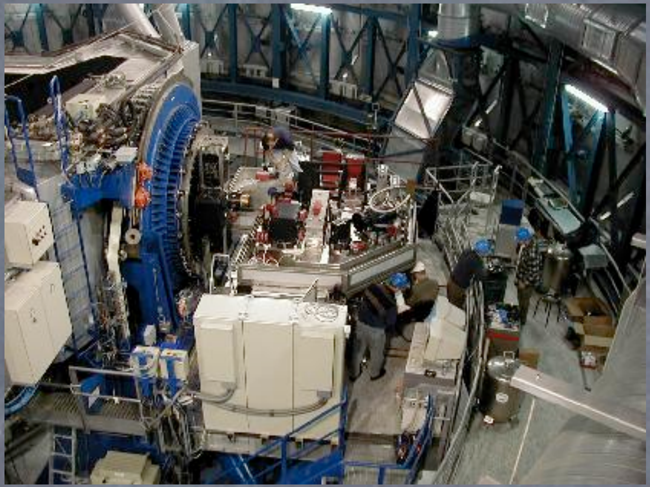

Gaël James – ESO Chile

ESO Fellowship Symposium – 12-14 Nov. 2007

# About me…

- 2000-2005: Master + PhD + 1-year position at the Paris-Meudon Observatory

- Since Oct. 2005: ESO fellowship in Chile



UVES Instrument Fellow…
(UV-Visual Echelle Spectrograph @ VLT-UT2)

# Globular clusters in the Galaxy…

NGC 6397 (ESO-MPI 2m20 + WFI)

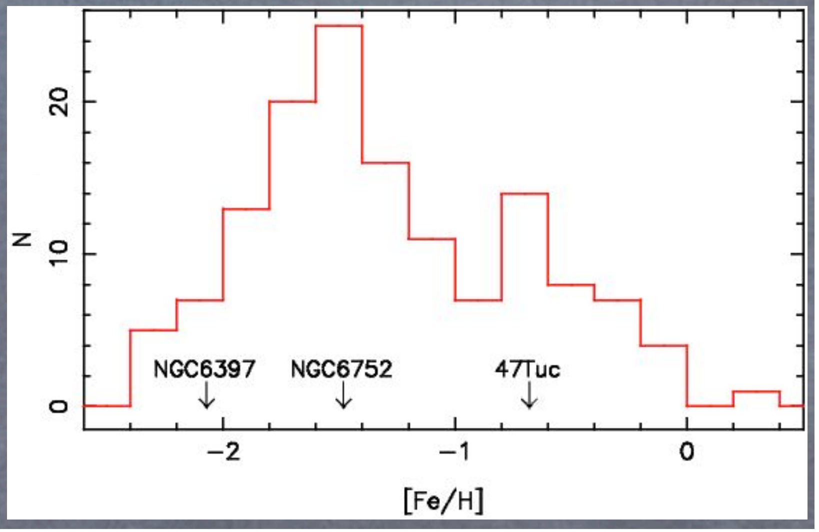
- ~ $10^4$-$10^6$ stars
- ~ 150 GCs in our Galaxy
- Spherical distribution in the Halo + disk, bulge…
  - Shapley (1918) : determined the position of the Galactic center
  - Baade (1944) : “Population II”
- Fossils / witnesses of the 1st phases of the evolution of our Galaxy
- “Ideal” natural labs to test different theories of chemical evolution in stars

# From the first observations to the abundance "anomalies"

- 1st abundance determinations in GC stars: Helfer et al. (1959)
  - 50h of exposure time / star on the Mt Palomar 5 m telescope!
    ⇒ clusters can be metal-poor ~ field stars in the Halo

- Very small dispersion in Fe abundance inside a given GC

- Zinn et al. (1985)
  - Bimodal metallicity distribution : 2 pics → [Fe/H] ~ –1.5 and –0.7
    ⇒ 2 populations (Halo + Disk)
  - Peculiar [Fe/H] distribution: there is NO cluster with [Fe/H] < –2.5 ≠ Halo field stars → -5.4 !!!

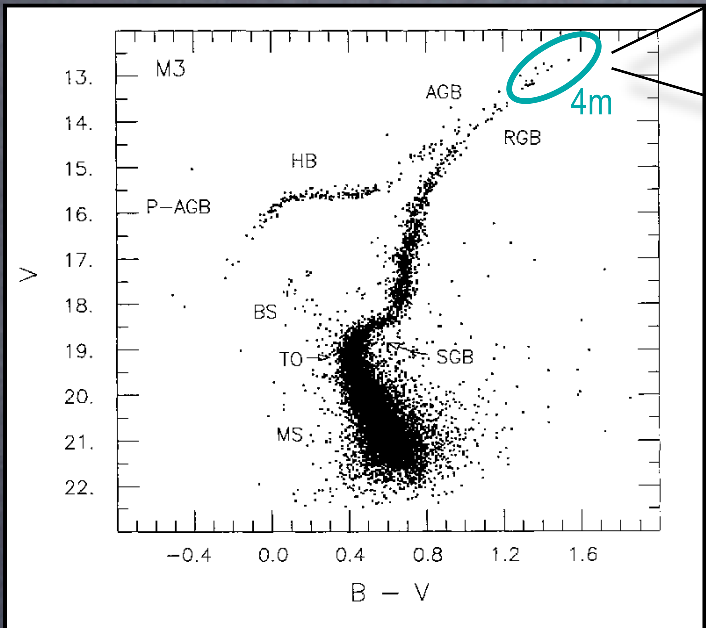


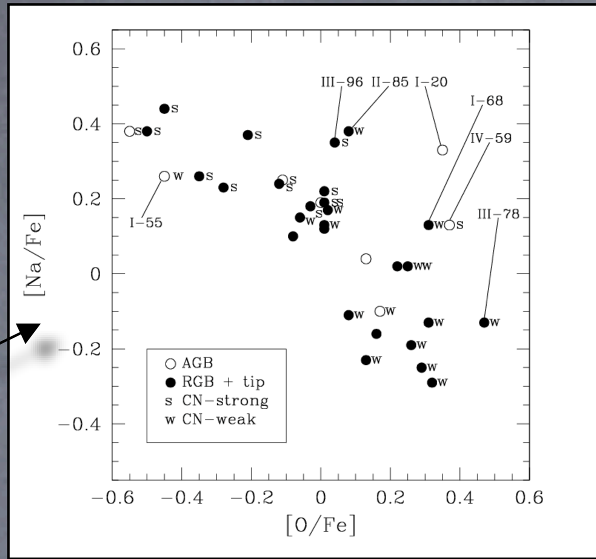

Abundance of element X : log (X) = log (X/H) + 12
[X/H] = log (X/H) – log (X/H)$_\odot$

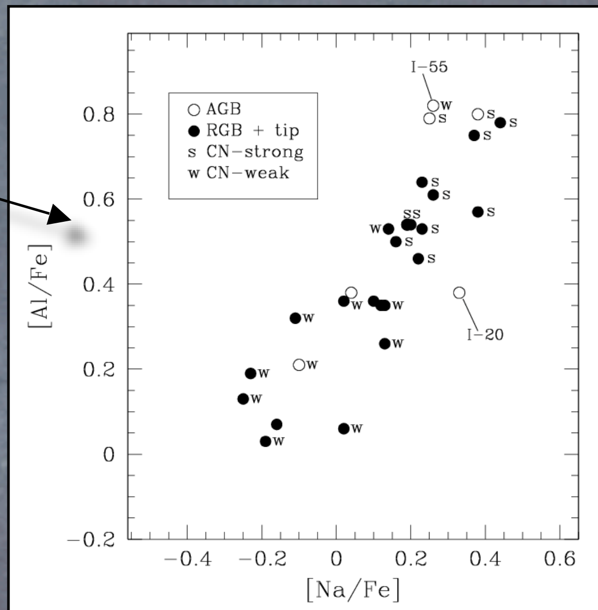
- Before large telescopes:

  → high-resolution spectroscopy only for bright giants

  - No star-to-star variation of [Fe/H] in a given GC
  - But abundance “anomalies”: large dispersion in CN, CH, O, Na, Mg, Al… never seen in field stars!
  - O-Na, Mg-Al anticorrelations and Na-Al correlations in giants



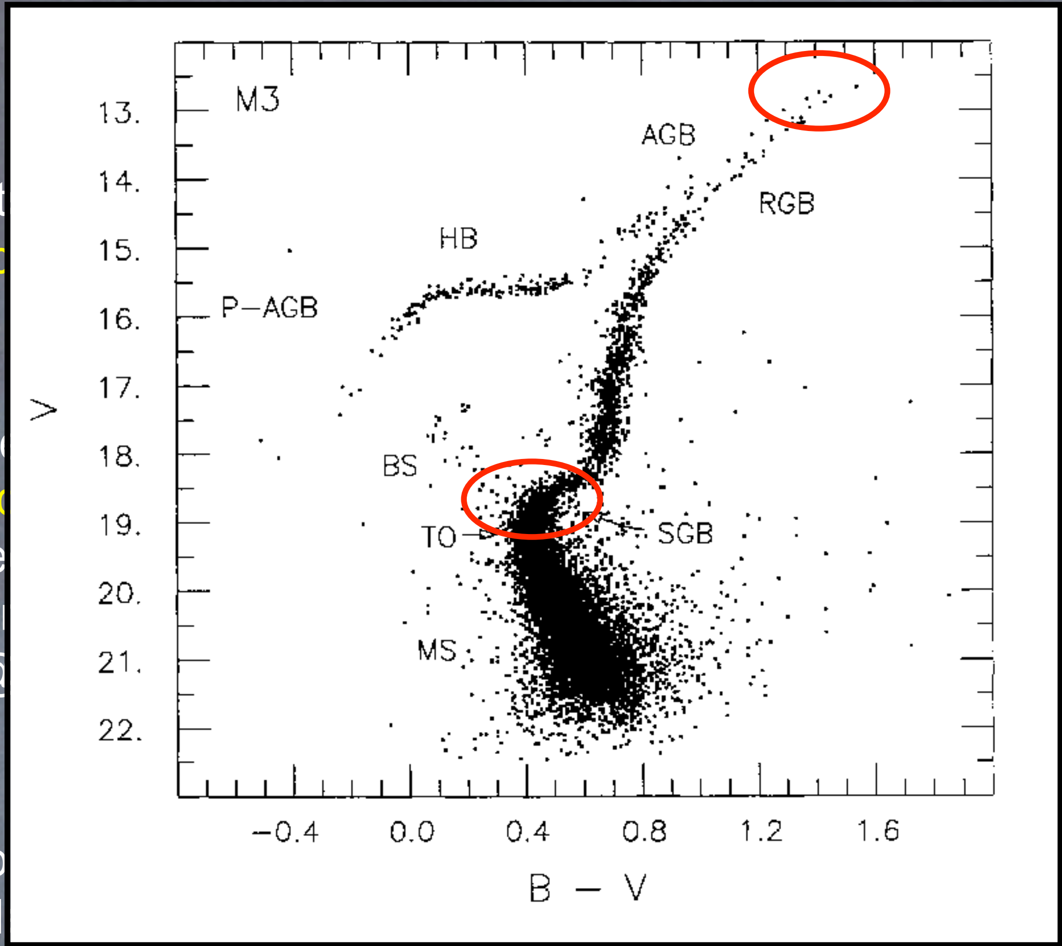



# Some issues about chemical evolution in GCs

- Observations in GC giants
  ⇒ theories of chemical evolution
  – "Anomalies" seen for the element
  – Homogeneity in [Fe/H] : self-enric

- Testing the deep mixing scenario
  – Spectroscopical analysis at differe
    ⇒ Stars less bright / less evolved
  – 3–4 m telescopes + high-res. spe
  – 8–10 m class + efficient spectrogr
    ⇒ UVES @ VLT-UT2 / HIRES @



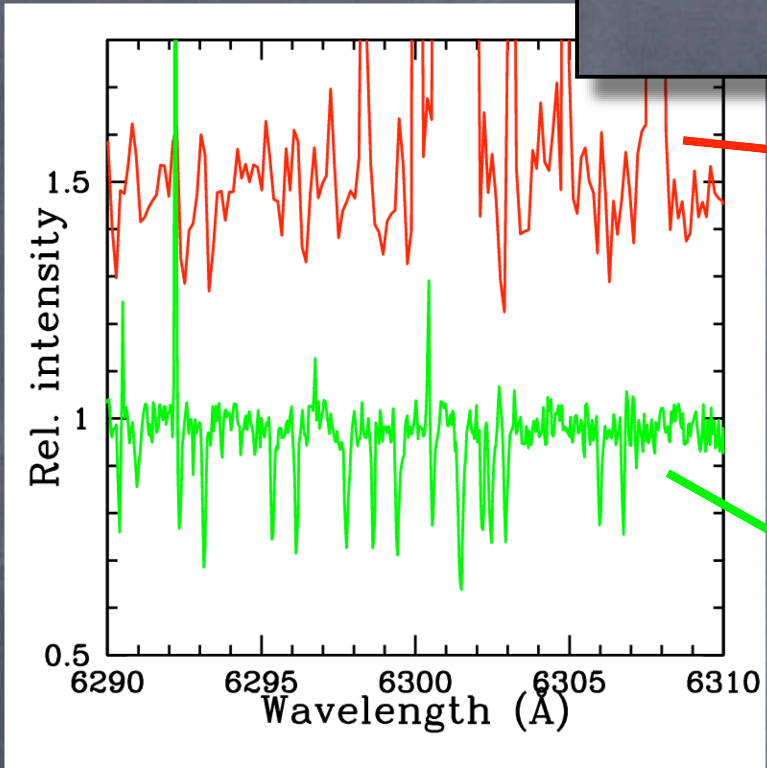

- Origin of the clusters' metallicity
  – Test the self-enrichment scenario
  – What about the abundances of el
    - *n*-capture element abundances in giants not precise
      ⇒ Access to blue part of the spectrum & unsaturated lines…

# Sometimes… size does really matter!

**EMMI @ NTT (LSO, 3m60)**

$t_{exp}$ ~ 12 h    *R* ~ 28 000

⇒ *S/N* ~ 20




Turn-off (dwarf) star (V ~ 17) in NGC 6397

**UVES @ VLT-UT2 (Paranal, 8m20)**

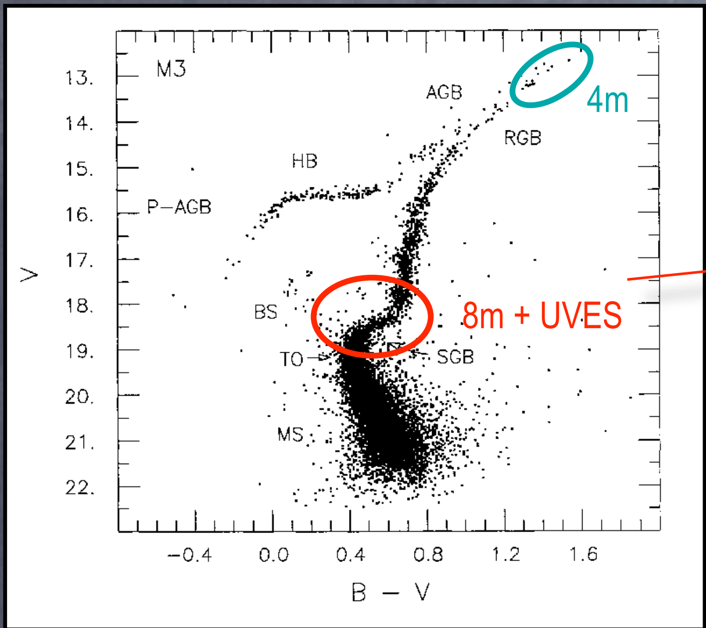
$t_{exp}$ ~ 4 h    *R* ~ 45 000

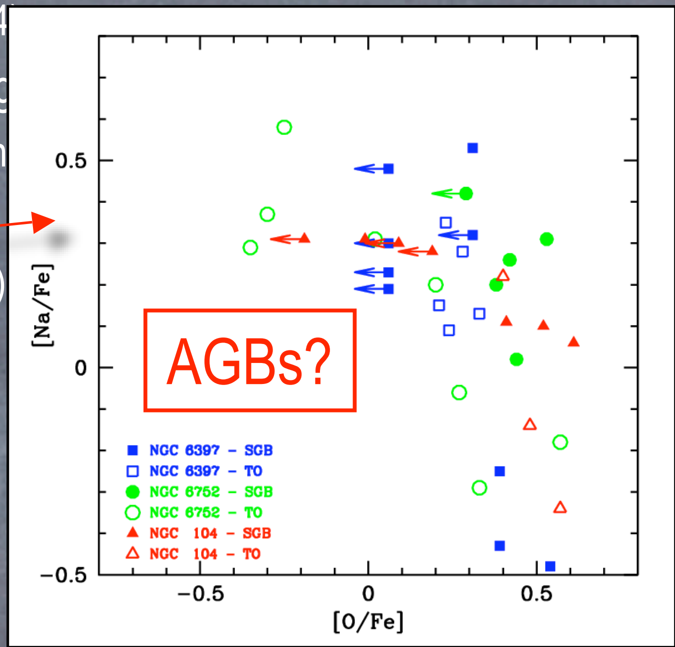
⇒ *S/N* ~ 45

# Recent progresses (part I)

- Large telescopes + efficient spectrographs
  - Abundances along the RGB and even down to MS!

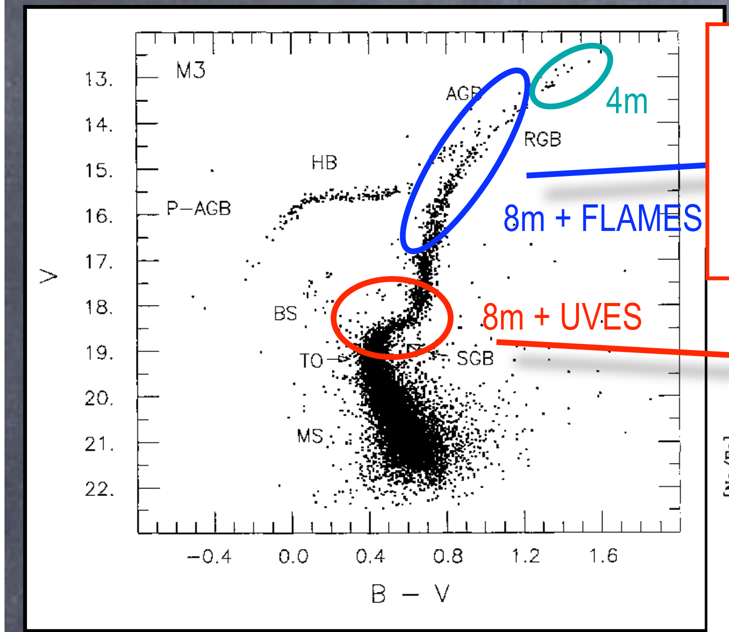
- Observations of the ESO-LP “*Globular Cluster Distances, Ages and Metallicities*”
  - PI: R. Gratton, Padova Obs., started in 2000
  - UVES – 3 clusters: subgiants + TO
  - Testing the deep-mixing scenario with different evolutionary phases + at different metallicities
  - O-stars), Carretta et al. (2004
  - nario for the formation of g
  - lements and chemical enrich
  - ular cluster stars
  - 07 (Li in 47 Tuc turnoff stars)



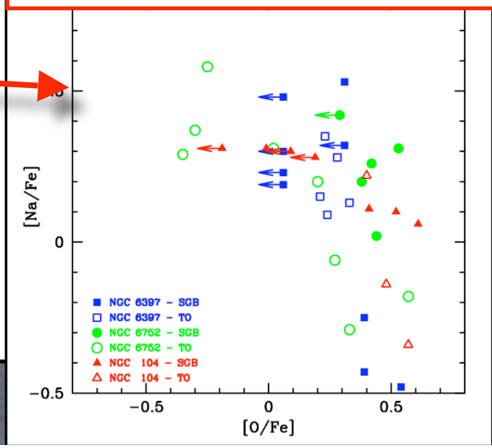



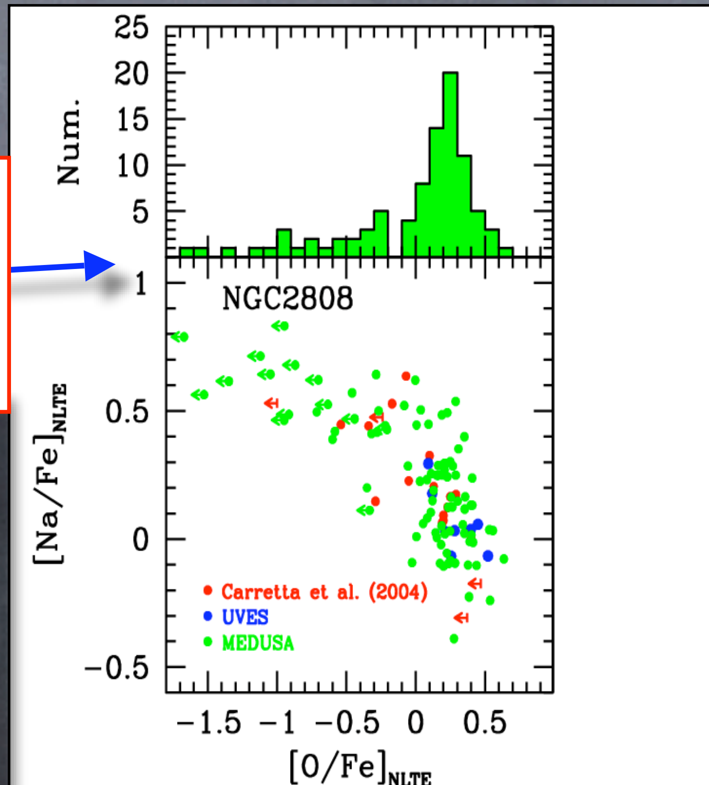
# Recent progresses (part II)

- Extended statistical analysis of the abundance dispersion/anomalies in globular clusters
  - Ongoing project: "*Na-O Anticorrelation and Horizontal Branches*" (FLAMES – 19 clusters observed with GIRAFFE + UVES @ VLT-UT2)
  - Recent results:
    - Detection of He-rich/He-poor stellar populations in NGC 6218 (Carretta et al. 2007, A&A 464, 939)
    - O-Na anticorrelation in NGC 6441 (Gratton et al. 2007, A&A 464, 953)
    - Chemical composition of the peculiar bulge globular cluster NGC 6388 (Carretta et al. 2007, A&A 464, 967)



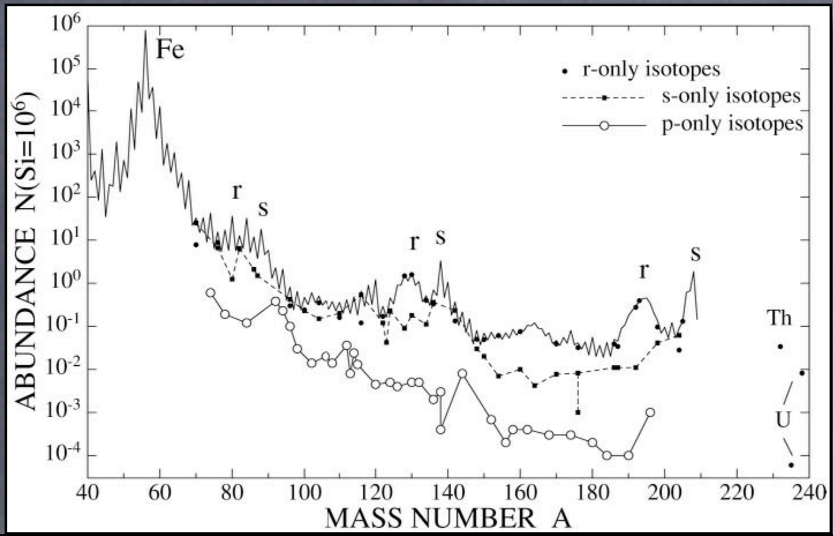

Pollution by AGBs...




NGC 2808 (FLAMES Science Verification)

# Why do we look for *s*-process elements in GCs?



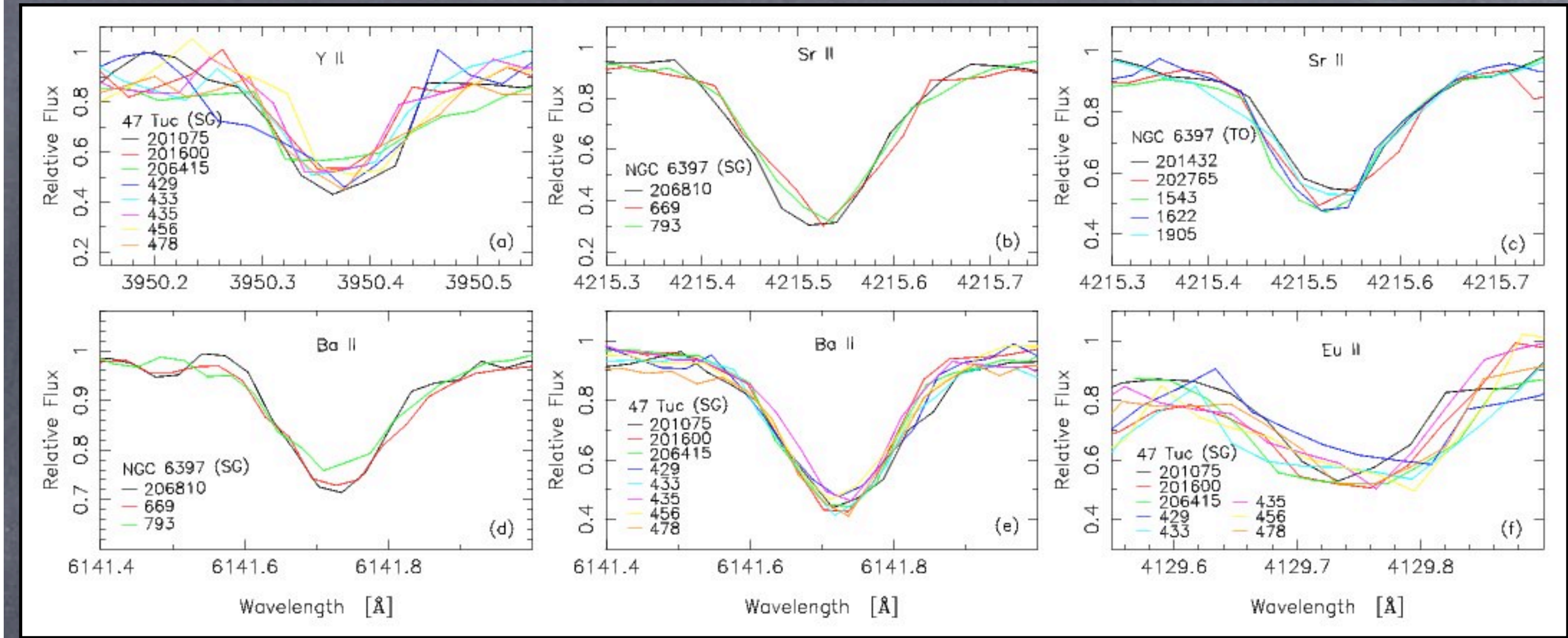

- The *s*-process
  - Slow neutron captures ($\tau_{cap} >> \tau_{\beta}$)
  - Two components: *weak* / *main*
    - *weak-s* process (A < 90)
      - He-core burning / C and N shell burning in massive stars ($M \geq 15\ M_{\odot}$)
    - *main-s* process

What else can we learn from heavy metals in GCs?

→ Is there a variation as a function of the evolutionary phase? As a function of [Fe/H]?

→ *r*-process: test the self-enrichment scenario for the formation of globular clusters!
(Cayrel, 1986; Truran et al., 1991; EASE scenario…)

# Neutron-capture elements in GCs: first results in TO stars…



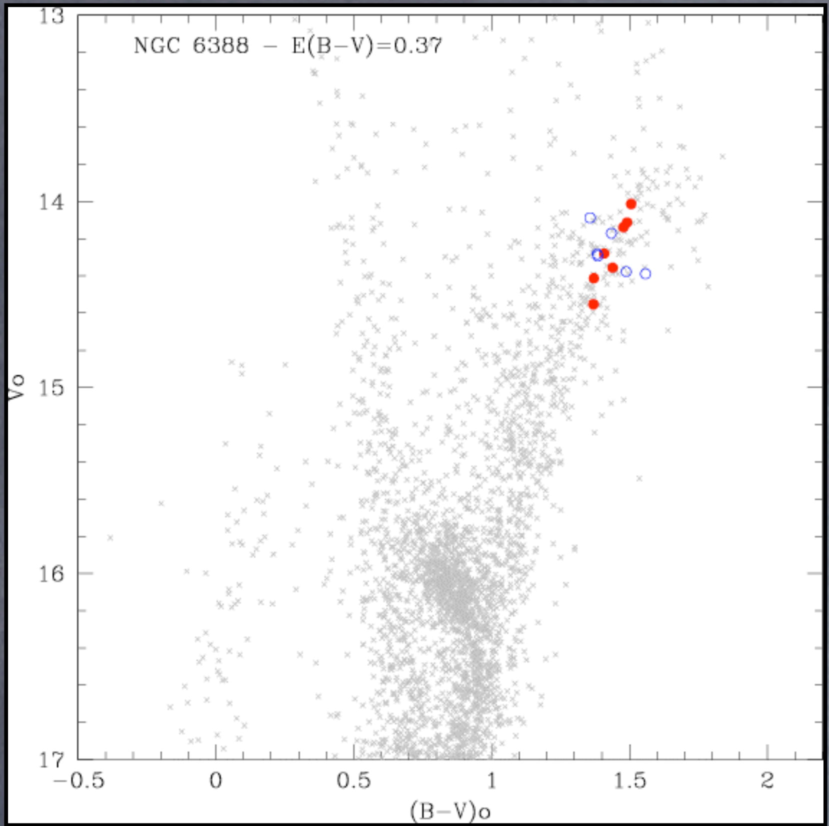

- 3 GCs at different metallicities → 47 Tuc (-0.70), NGC 6752 (-1.40) and NGC 6397 (-2.0)
  - ➔ NO variation in *n*-capture element abundances (star-to-star + evolutionary phase)
  - ➔ NO correlation with O, Na, Mg, Al "anomalies"
    - ➔no detectable influence of AGB pollution / *s*-process elements…

➔ GCs formed out of matter already enriched in neutron-capture elements

(James et al. 2004a, b)

# FLAMES-UVES Observations of NGC 6388

Carretta et al. (2007)




- One of the 10 more massive GCs
- Luminous (*Mv* = -9.42, Harris 1996 on-line catalog)
- Location
  - 3 kpc from the Galactic center
  - 10 kpc from the Sun
  - 1 kpc from the Galactic plane
- Nothing known about orbit + age…
  - no proper motion info!
- Extended Blue Horizontal Branch!
  - Rich et al. 1997
- Large population of RR Lyrae
  - Pritzl et al. 2002; Corwin et al. 2006

➔ Chosen to study the possible link between chemical anomalies vs. global parameters (e.g. HB morphology)

➔ Try to observe a signature of self-enrichment (predicted e.g. by Cayrel 1986 + many others…)

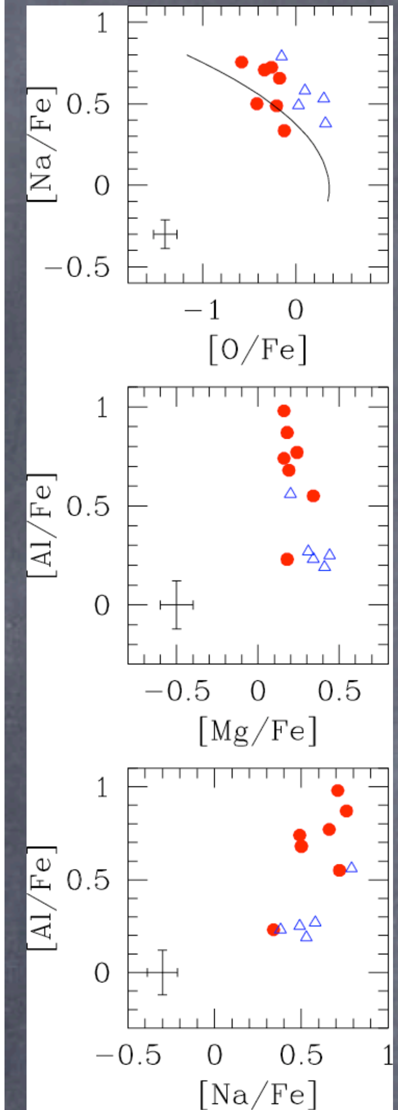
- Observations:
  - BVI photometry from Wide Field Imager @ ESO/MPI 2.20m (Momany et al. 2003)
  - 100 stars with FLAMES-GIRAFFE @ VLT-Kueyen (analysis in progress…)
  - 7 stars with FLAMES-UVES (S/N~40-80 @ 500nm, R~40,000) → membership by Rad. Vel. (Harris 1996)

• Proton-capture elements

→ O-Na, Mg-Al anticorrelation / Al-Na correlation

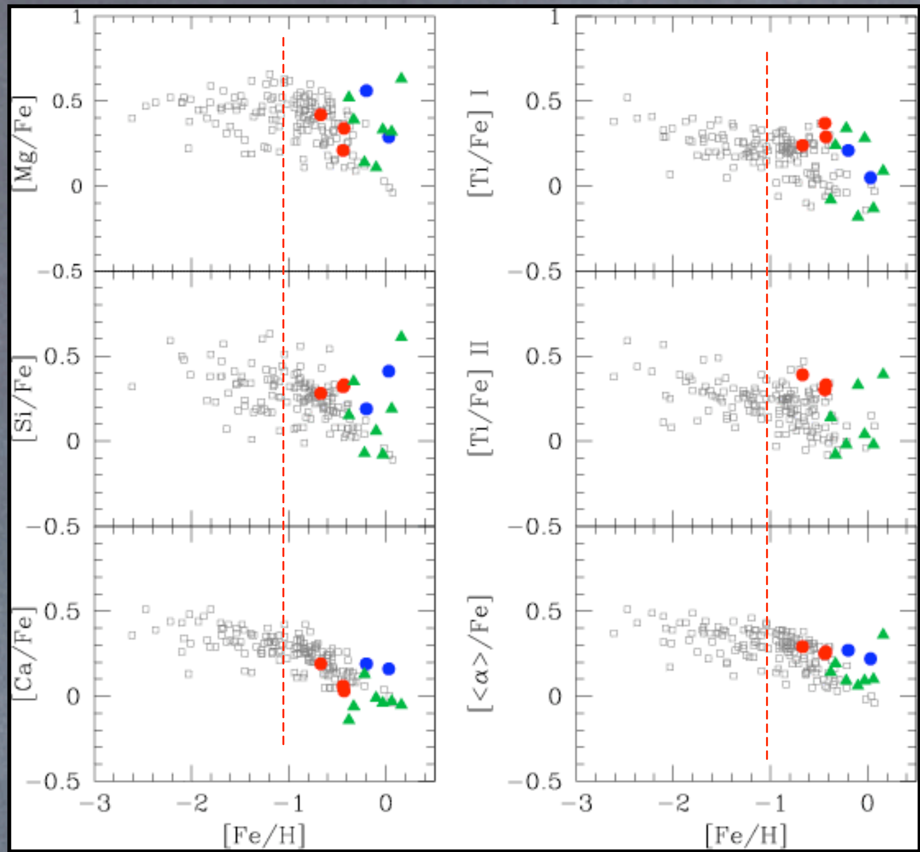
- compatible with ~400 stars in ~20 studied GCs

➔ [Fe/H] = -0.44 ± 0.01 (star-to-star scatter…)




(open symb. = UVES stars from NGC 6441)

- O-Na in a forthcoming paper (GIRAFFE)
- Mg-Al and Na-Al:
  → H-burning at high T involving NeNa and MgAl cycles…




• α-elements

- overabundance / solar
- test the scenario where dense objects may retain the ejecta of core-collapse SNe + maintain independ chemical evolution → self-enrichment
- Type Ia SNe contribution…

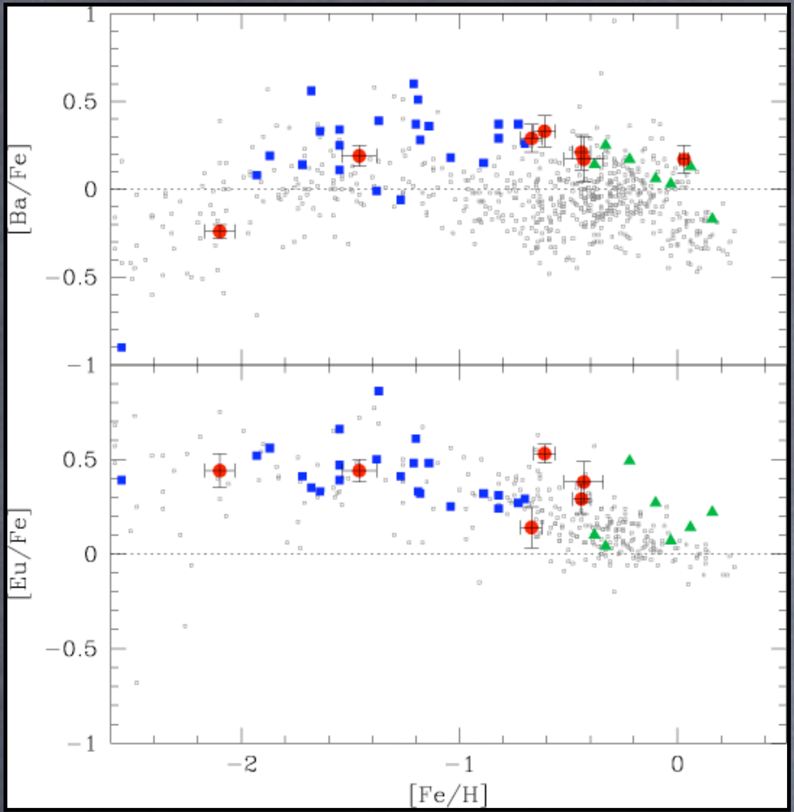
# *n*-capture vs. $\alpha$-elements vs. self-enrichment

- $\alpha$-elements
  → test the relative contribution of core-collapse SNe II / lower mass SNe Ia

- *n*-capture elements
  → contribution + metallicity dependence in yields from massive vs. intermediate-mass stars
  - *r*-process + "*weak*" *s*-process elements → high-mass stars (SNe II)…
  - "*main*" *s*-process elements → He-burning shell of low- and intermediate-mass AGBs
  - constraints on models of formation and early evolution of GCs (James et al. 2004 → needed more metal-rich clusters!)

→ NGC 6388 is one of the most metal-rich GCs

→ Perfect complement to test the self-enrichment




- Cluster to cluster dispersion for *n*-capture elements

- But… "universal" [Eu/Fe] ratio in GCs
  - Very small dispersion: <[Eu/Fe]> = +0.42 ± 0.09 (cluster-to-cluster!)
  - Confirmed by litterature: 20 GCs ➔ +0.40 ± 0.13
  
  → Confirms James et al. (2004): Eu abundance has been fixed in the ISM before the formation of GCs…

- Eu follows same evolution as field stars until [Fe/H] ~ -0.70
  
  → Change at higher metallicity (NGC 6388 > overabundance)

- Ba evolution more complex
  - *r*-process + progressive enrichment by *s*-process nucleosynthesis

• Heavy elements' abundance ratios: relative weight of the *r*- / *s*-process

• [Eu/Ba] ~ solar scaled pure *r*-process value at low [Fe/H]

- NGC 6397 (James et al. 2004)
- M 15, M 92 (Sneden et al. 1999)

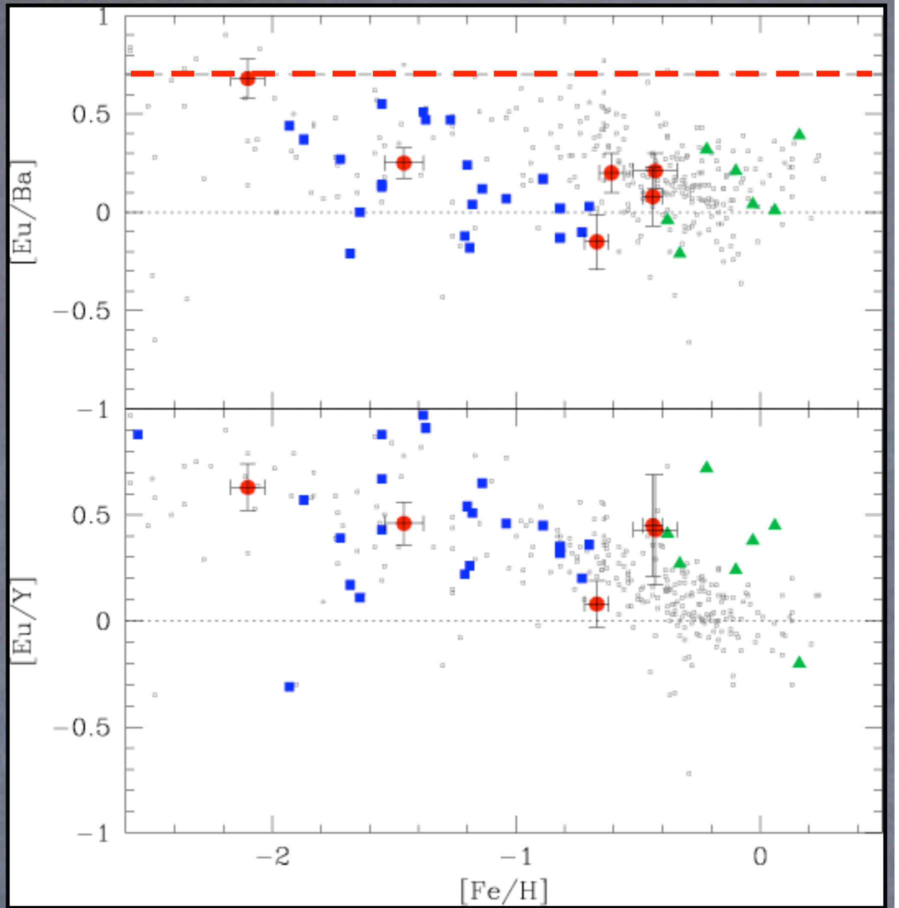
• [Eu/Ba] ≠ pure-*r* value: *s*-process contribution at high [Fe/H]

- 47 Tuc (James et al. 2004)
- NGC 6388 (Carretta et al. 2007)

• BUT: NGC 6388, NGC 6441 and Bulge stars (from Gratton et al. 2003) show a very high [Eu/Y] ratio…

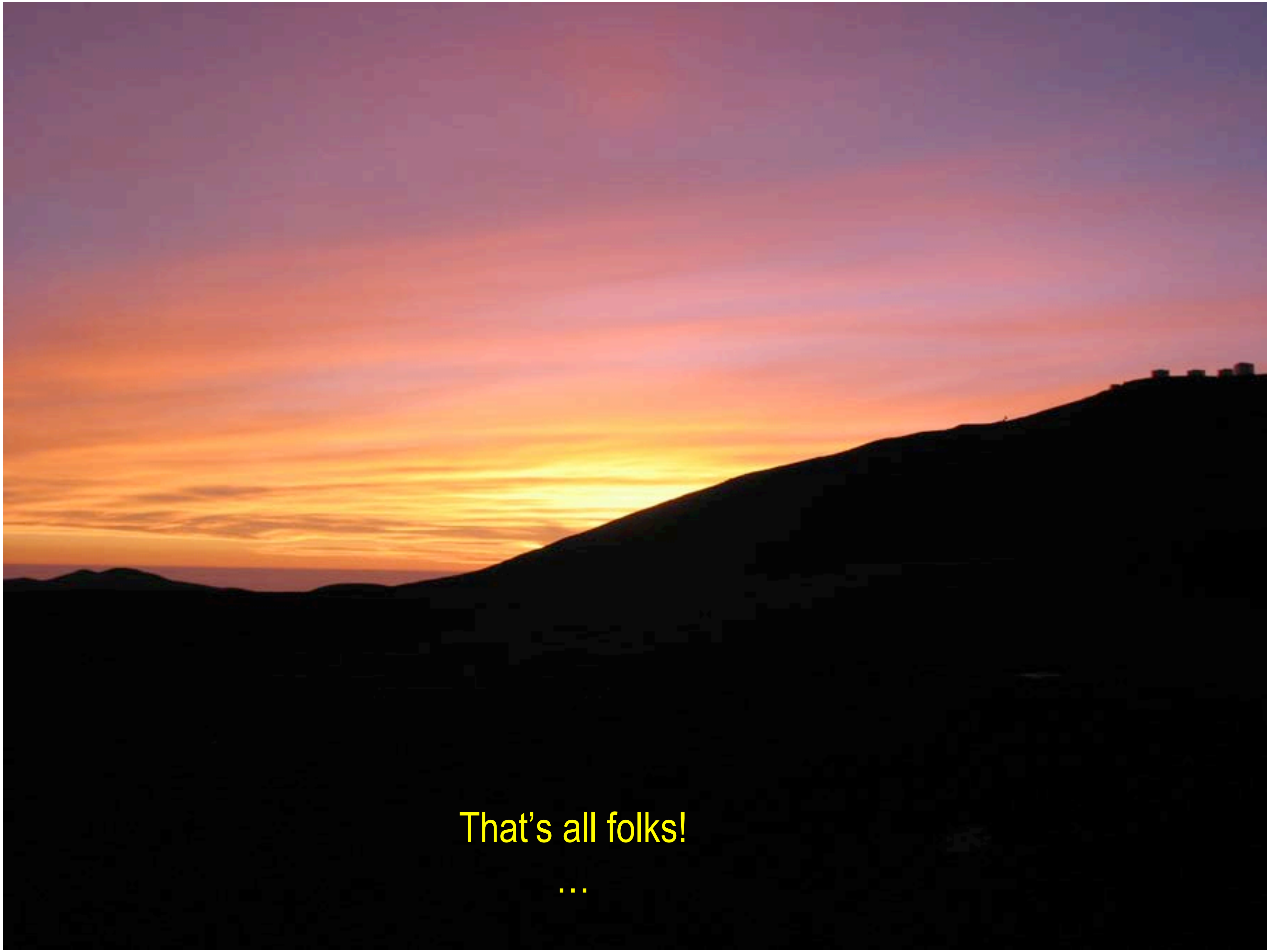
→ Bulge stellar populations dominated by contribution of massive star nucleosynthesis?

→ "*Weak*" *s*-process plays also a role for Y, Sr…




• Eu → 91 % *r*-process in the Sun
• Ba → 81 % *s*-process in the Sun
• Y → 74 % *s*-process in the Sun

➔ Clear limits to the primordial pure self-enrichment scenario for the formation of globular clusters!


That’s all folks!
…