PROBING THE ORIGIN OF GLOBULAR CLUSTERS AND THEIR MULTIPLE POPULATIONS

THE KEY ROLE OF HRMOS

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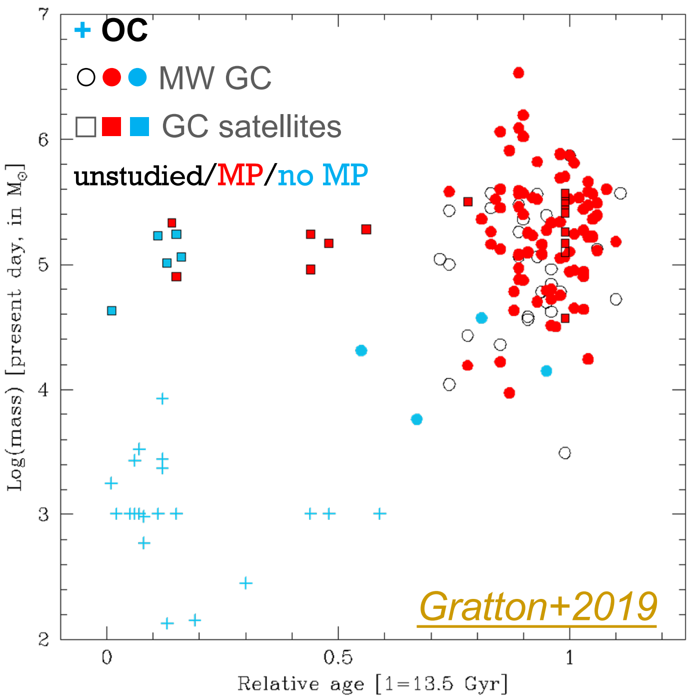
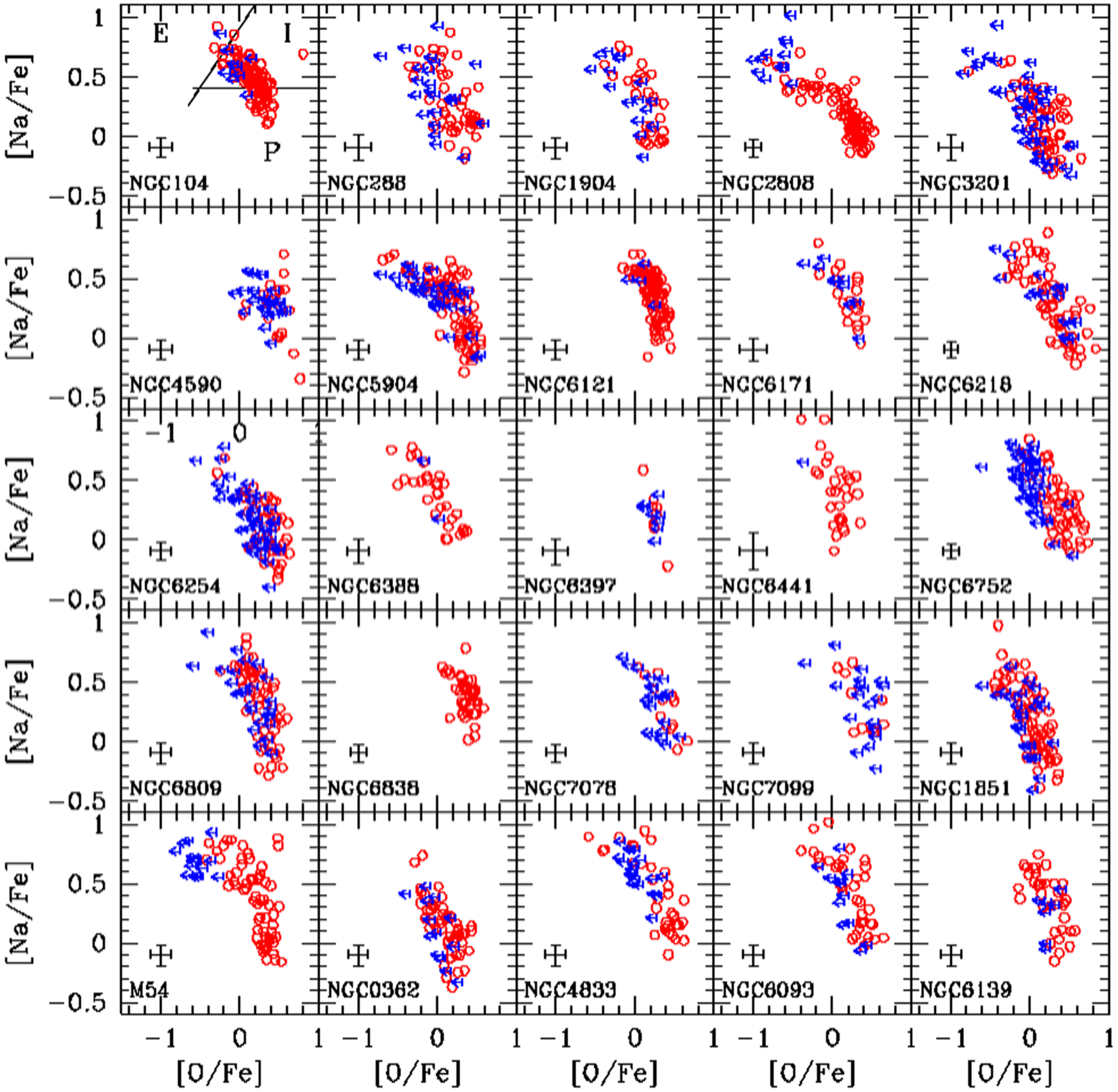
HRMOS SCIENCE WORKSHOP (18° - 22° OCTOBER 2021-FIRENZE/SYDNEY)

WHAT WE KNOW

*Virtually *ALL* Galactic GCs and massive clusters in LMC/Fornax exhibit multiple populations*



Gratton+2019



(see reviews by Bastian and Lardo 2018, Gratton et al. 2019 & new works on MC clusters)

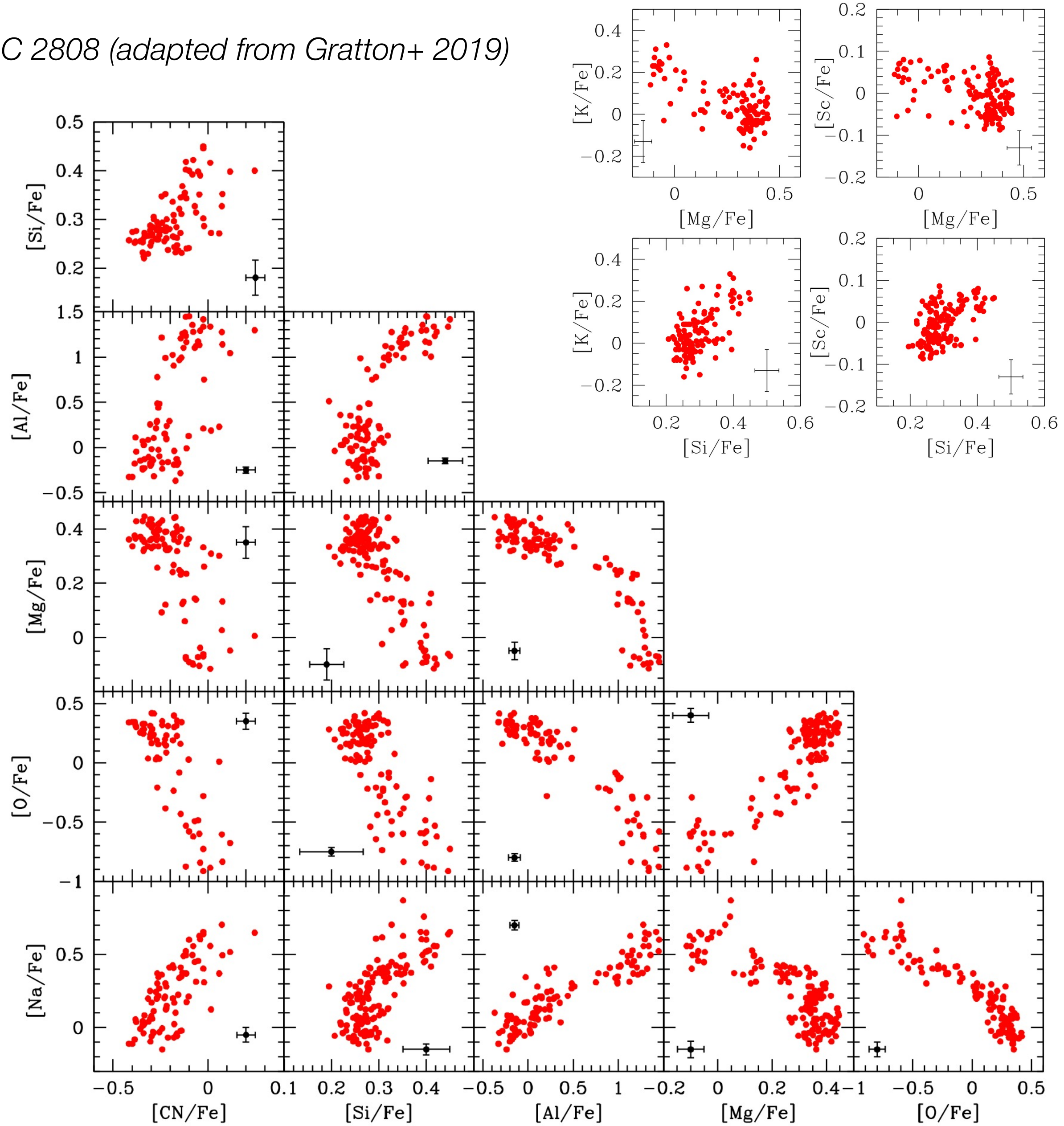
WHAT WE KNOW

ligh-element variations (positive and negative correlations) including He,C,N,O,Na,Mg,Al

-(plus Li, in several cases Si,Ca,Sc,K)

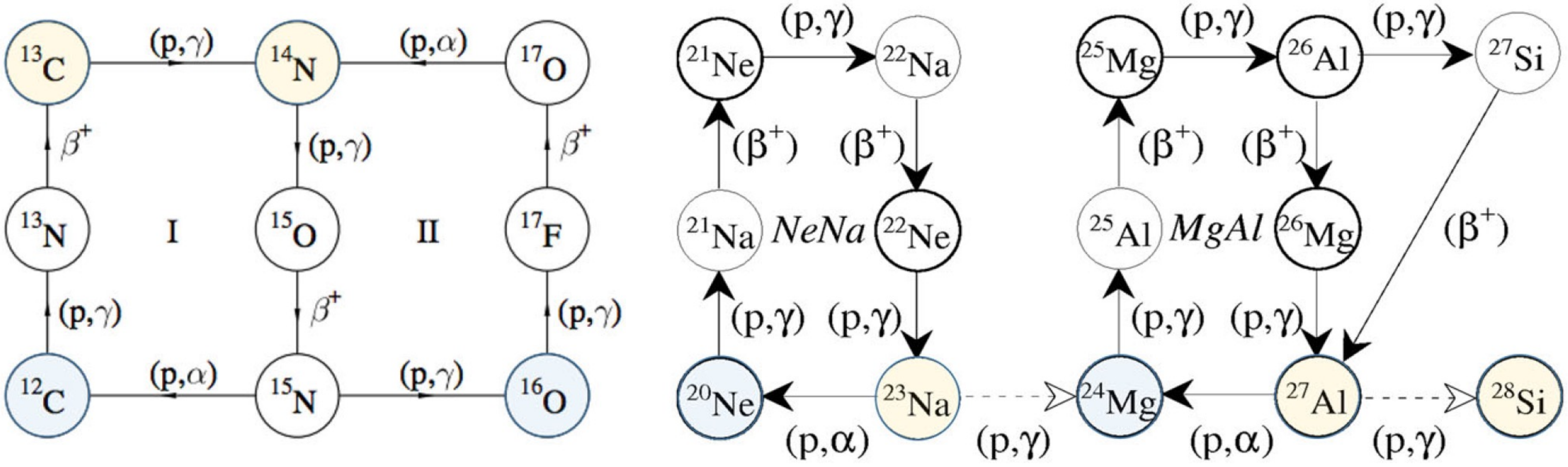
WARNING: Several cases of iron-peak and heavy element abundance variations, TypeI vs TypeII GCs (see seminal papers by A. Milone and collaboratos + C. Johnson)
+ cf Anna Marino's talk in this workshop

NGC 2808 (adapted from Gratton+ 2019)



WHAT WE KNOW

Signature of the activation of hot H burning via CNO



10 MK **40 MK** **70 MK** **80-180 MK**

Burning Temperature

Gratton+ 2019, originally adapted from Salaris+ 2002

WHAT WE DO NOT KNOW

- *Does «multiple populations» mean multiple stellar generations ?*

→*YES (Decressin+ 2007, D'Ercole+ 2008, Krause+ 2013) «cooling flow»*

→*NO (De Mink+ 2009, Bastian+ 2013, Gieles+ 2018) accretion on first-generation stars*

The Occam's razor + previous evidence

↓

A fraction of first-generation (FG) stars have activated CNO,NeNa,MgAl cycles and provided polluted material from which the SG formed

(but see Bastian+ 2015, 2018 for a different view)

At first approximation we think of:

- ○ *First-generation stars: C-rich, O-rich, N-poor , Na-poor [Mg-rich/Al-poor]*
- ○ *Second generation stars: C-poor, O-poor, N-rich, Na-rich [Mg-poor~ish/Al-rich]*

WHAT WE DO NOT KNOW

- *Different clusters have different correlations (elements involved, shape and extent of abundance variations):*

→ relationship with global cluster parameters such as e.g., mass, metallicity, HB morphology and/or location in the Galaxy (environment!)

- *What about the binary fraction and the formation scenarios?*

→Consensus on a more concentrated second generation of stars (Lardo+ 2011, D'Alessandro+ 2019, Milone et al 2020, Sollima+ 2021 in prep)

WHAT WE DO NOT KNOW

What is the stellar source of internal pollution ?*

- *Fast rotating massive stars (Decressin+ 2007)*
- *Intermediate-mass AGB stars (Ventura+ 2001)*

- *Massive binaries (de Mink+ 2009)*
- *Super massive stars (Denissenkov & Hartwick 2013; Gieles+ 2018)*

*Note that the hardest thing is not to reproduce Na, Al production but O/Mg depletion !

LITHIUM

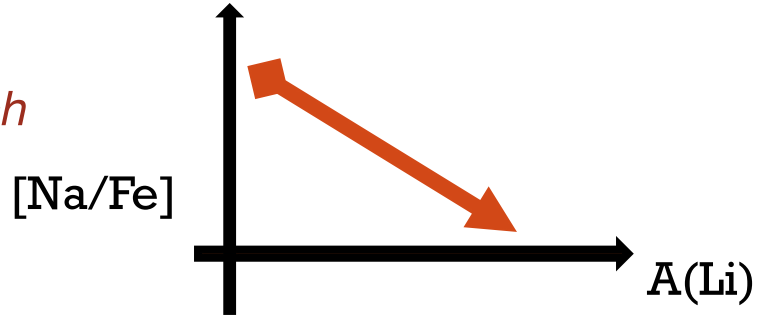
It is expected that at CNO/NeNa cycle temperatures occur NO Li is left (Li burns at T~ 2.5 MK)

→ Polluting material (ejected from the first generation stars) has Li ~ 0

(under the assumption that there is NO Li production within the polluters)

Na-poor, O-rich stars (FG stars) should be (they actually are) Li-rich

Na-rich, O-poor stars (SG stars) should be Li poor



Lithium and sodium ANTI-CORRELATED
lithium and oxygen correlated

While Massive Stars can only destroy Li, the IM-AGB stars can also produce it via THE CAMERON-FOWLER MECHANISM (“^{7}Be transport” mechanism, Cameron & Fowler 1971)

[Any production of Lithium tends to erase the Li–O(Na) (anti–)correlation]

LITHIUM ABUNDANCES IN GC STARS*

(AND CONNECTION TO THE MP SCENARIO)

- ☐ *M92 (Bonifacio+ 2002, some scatter but no Na/O available)*
- ☐ *NGC 6752 (Pasquini+ 2005; Shen+ 2010; Gruyters+ 2014)*
- ☐ *NGC 6397 (Lind+ 2009)*
- ☐ *47 Tuc (Bonifacio+ 2007; D’Orazi+ 2010; Dobrovolskas+ 2014)*
- ☐ *NGC 6121 (D’Orazi & Marino 2010; Mucciarelli+ 2011, Monaco+ 2012, Spite+ 2016)*
- ☐ *NGC 5904, NGC 6218 (D’Orazi+ 2014)*
- ☐ *NGC 1904, NGC 2808, NGC 362 (D’Orazi+ 2015a,b)*
- ☐ *NGC 7099 (Gruyters+ 2016)*
- ☐ *Omega Centauri (Mucciarelli+ 2018)*
- ☐ *NGC 4590, NGC6809, NGC6656, NGC 3201, NGC 6838 (Aguilera-Gómez+ 2021)*

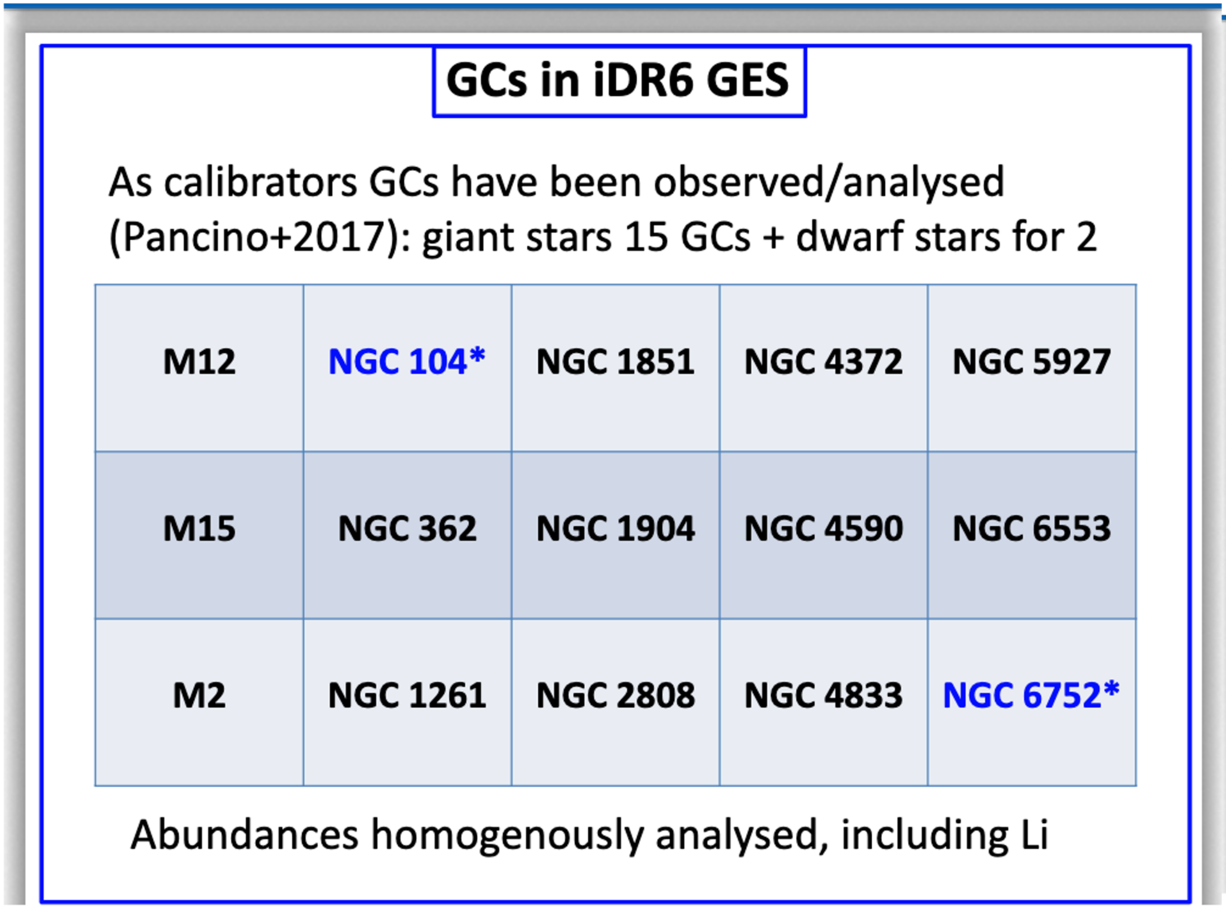
17 GCs in total**

*MS and RGB stars below the bump) :

**(NGC 1261 from Gaia-ESO –Sanna+ 2020)

*LITHIUM ABUNDANCES IN GC STARS**
(AND CONNECTION TO THE MP SCENARIO)

GES: n1261 n6553 n7089 n4833 n1851 n4372 n5927 … new GC
cf N. Sanna in "Star Clusters: the Gaia Revolution (5-7 October) 2021
https://zenodo.org/record/5554008 - .YWLA6EYzalY

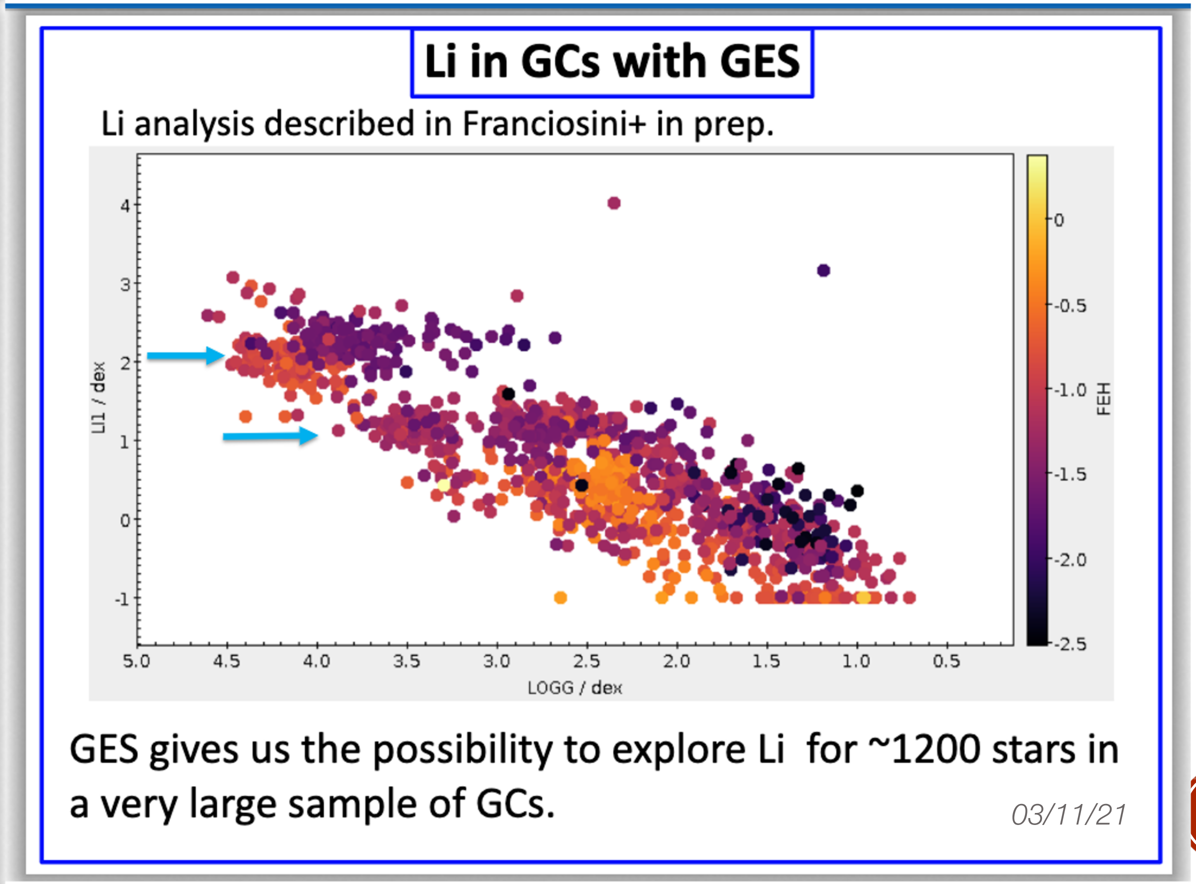


GCs in iDR6 GES

As calibrators GCs have been observed/analysed (Pancino+2017): giant stars 15 GCs + dwarf stars for 2

M12	**NGC 104***	**NGC 1851**	**NGC 4372**	**NGC 5927**
M15	**NGC 362**	**NGC 1904**	**NGC 4590**	**NGC 6553**
M2	**NGC 1261**	**NGC 2808**	**NGC 4833**	**NGC 6752***

Abundances homogenously analysed, including Li

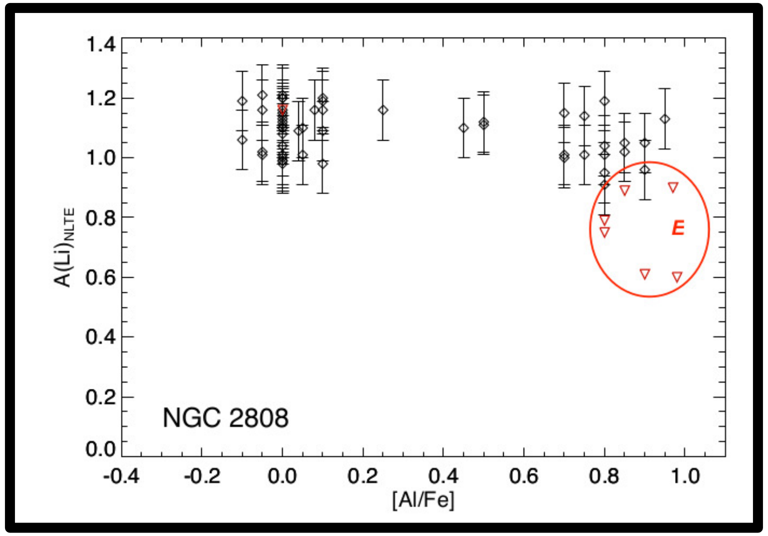


Li in GCs with GES

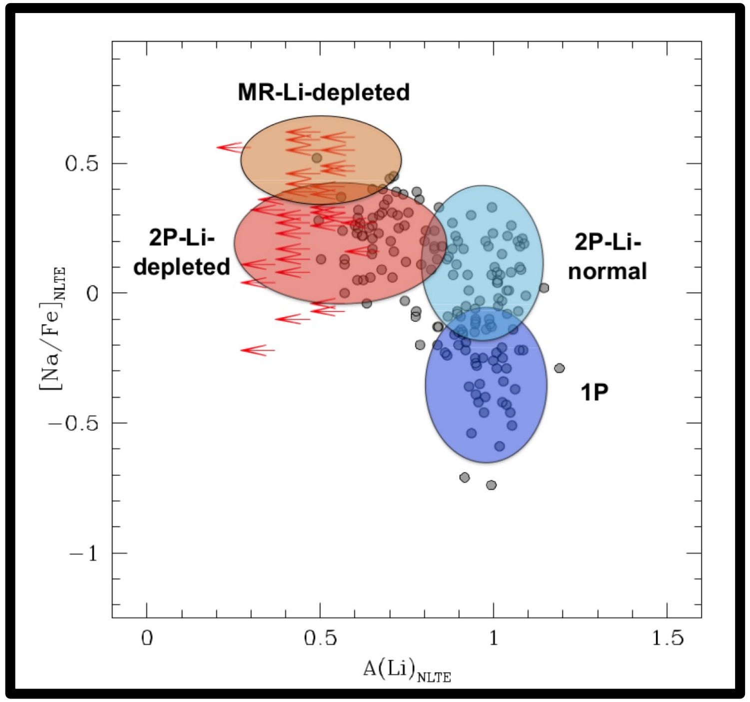
Li analysis described in Franciosini+ in prep.

GES gives us the possibility to explore Li for ~1200 stars in a very large sample of GCs.

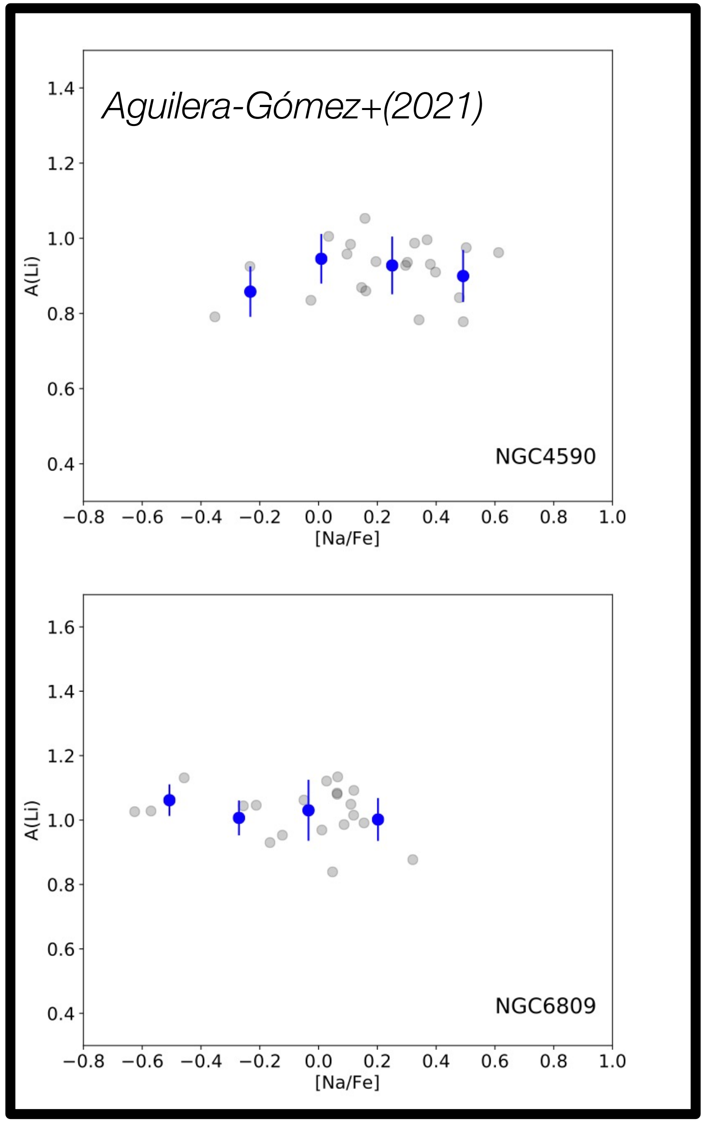
In GCs like M4, M12, NGC 362, NGC 6809, NGC 3201, NGC 6656 NGC 6838:
FG and SG share the same Lithium →
<u>Li production across different stellar generations is unavoidable.</u>
<u>But there are also complex behaviours..</u>



NGC 2808 (D'Orazi+ 2015, Gratton+ 2019)



Omega Cen (Mucciarelli+ 2018)


Aguilera-Gómez+(2021)

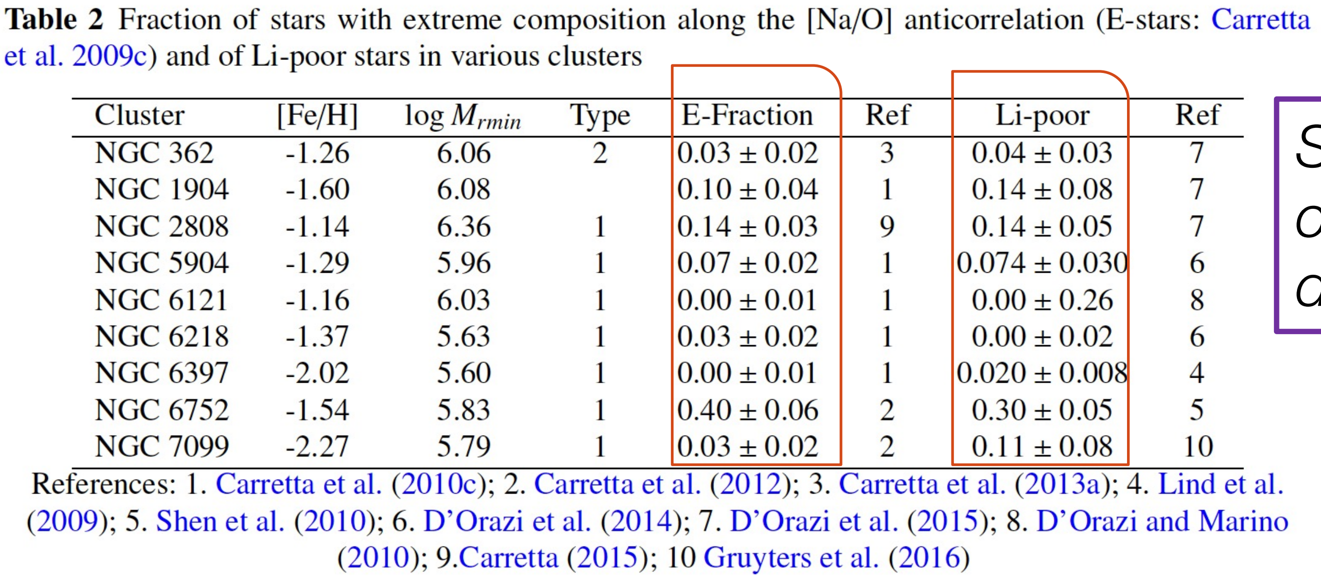
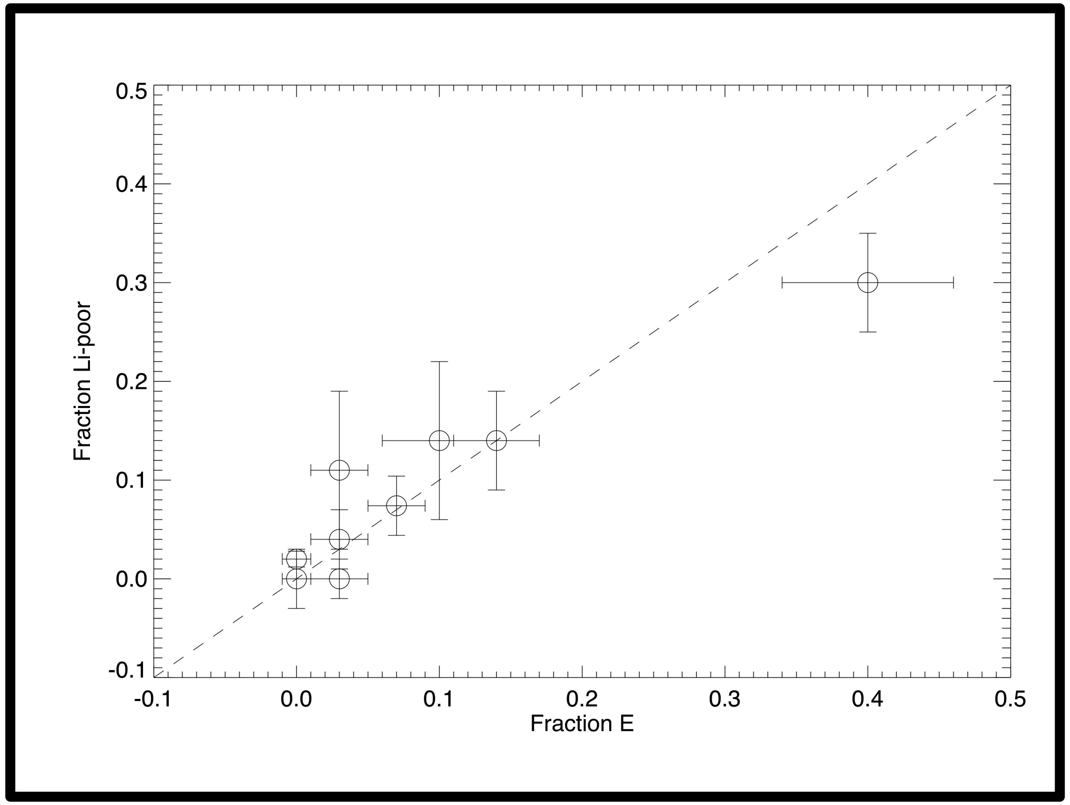


Table 2 Fraction of stars with extreme composition along the [Na/O] anticorrelation (E-stars: Carretta et al. 2009c) and of Li-poor stars in various clusters

Cluster	[Fe/H]	log M_{rmin}	Type	E-Fraction	Ref	Li-poor	Ref
NGC 362	-1.26	6.06	2	0.03 ± 0.02	3	0.04 ± 0.03	7
NGC 1904	-1.60	6.08		0.10 ± 0.04	1	0.14 ± 0.08	7
NGC 2808	-1.14	6.36	1	0.14 ± 0.03	9	0.14 ± 0.05	7
NGC 5904	-1.29	5.96	1	0.07 ± 0.02	1	0.074 ± 0.030	6
NGC 6121	-1.16	6.03	1	0.00 ± 0.01	1	0.00 ± 0.26	8
NGC 6218	-1.37	5.63	1	0.03 ± 0.02	1	0.00 ± 0.02	6
NGC 6397	-2.02	5.60	1	0.00 ± 0.01	1	0.020 ± 0.008	4
NGC 6752	-1.54	5.83	1	0.40 ± 0.06	2	0.30 ± 0.05	5
NGC 7099	-2.27	5.79	1	0.03 ± 0.02	2	0.11 ± 0.08	10

References: 1. Carretta et al. (2010c); 2. Carretta et al. (2012); 3. Carretta et al. (2013a); 4. Lind et al. (2009); 5. Shen et al. (2010); 6. D'Orazi et al. (2014); 7. D'Orazi et al. (2015); 8. D'Orazi and Marino (2010); 9.Carretta (2015); 10 Gruyters et al. (2016)

Strong correlation between the fraction of E stars (according to Na/O, Carretta's definition) and the fraction of Li poor stars



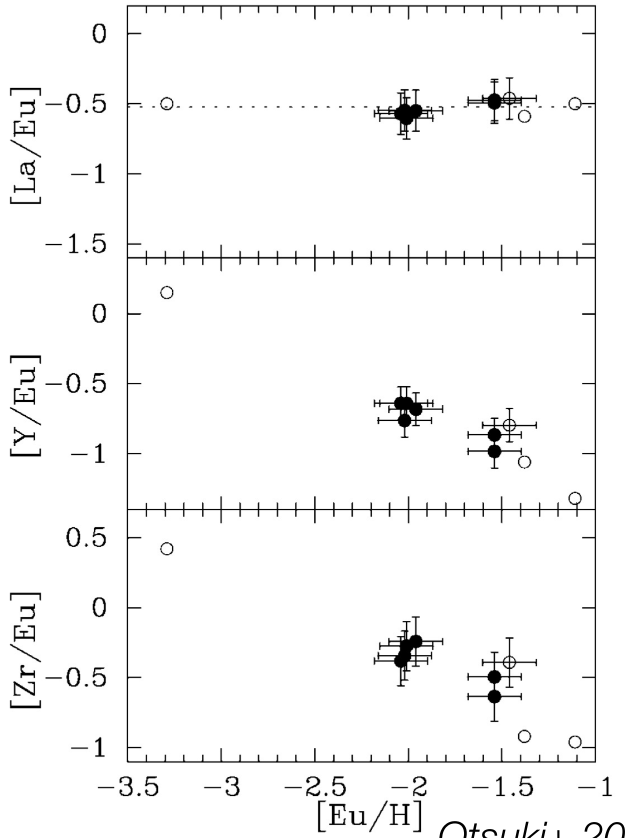
1. *The more massive the cluster, the larger the Li variation →Li production is more efficient in low-mass GCs*
2. *Metallicity plays a role (NGC 362 vs NGC 1904)*
3. *Anti-correlation between dilution factor Na/O for I stars and the fraction of Li-poor stars → the larger is the fraction of Li-poor stars, the lower is the dilution of the Intermediate population (so these two populations are not independent)*

**Different story for Omega Cen*

N-CAPTURE ELEMENTS

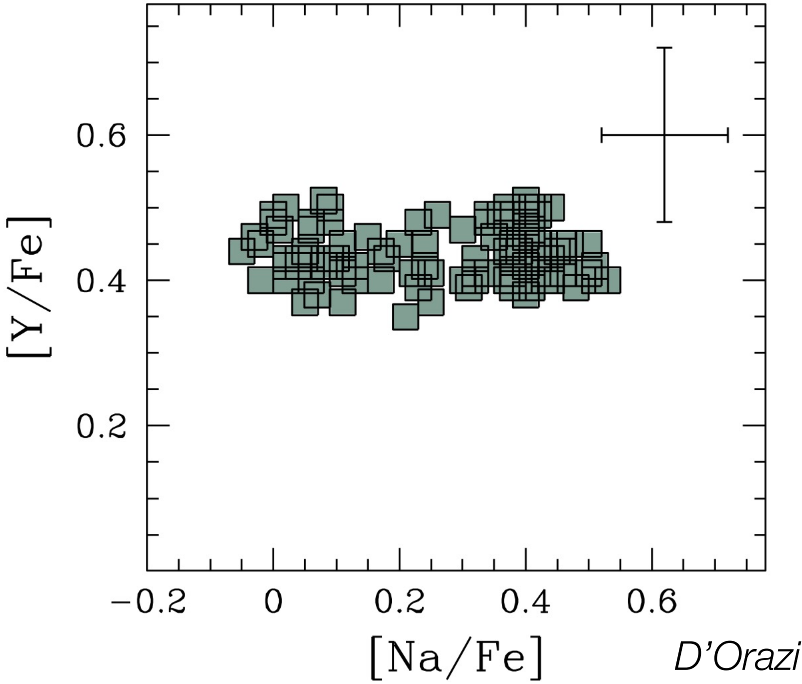
In general GCs are homogeneous as far as n-capture elements are concerned (Armosky+ 1994, James et al. 2004, D'Orazi+ 2010) although anomalous Type II clusters (e.g., NGC 1851, M22, Omega Cen) exhibit internal variations (Marino+ 2009, 2011, 2015, 2017, this workshop)

Exotic case: M15
Variation of Ba and Eu
(Sneden+ 1997,
Worley+ 2013)



Otsuki+ 2006

M4 primordially enriched in n-capture (Ivans+ 1999)



D'Orazi+ 2013

N-CAPTURE ELEMENTS

- *Large observational uncertainties affecting Ba II lines (e.g., D'Orazi+ 2010, 1200 stars but errors of ~0.25 dex, Carretta+ 2011)*
- *Lanthanum is proven to be a better tracer of the s-process than Ba but higher resolution than FLAMES is required (and bluer coverage !) some work by e.g., Yong and collaborators*
- *No information on third-peak s-process elements (only the main component can produce Pb)*
- *Rubidium is a key diagnostics (high resolution and red spectral coverage)*

RUBIDIUM

Some preliminary works by Yong et al. 2006, 2007, D'Orazi+ 2013 but very limited samples

Due to a critical branching point in the s-process path at ^{85}Kr, the abundance of Rb relative to Sr, Y, or Zr can differ by a factor of 10 depending upon the neutron density at the s-process site.

In the standard picture, two neutron sources are present in the He-rich shell of AGB stars (Gallino et al. 1998).

The $^{13}C(\alpha,n)^{16}O$ reaction is activated in low-mass ($< 4\ M_\odot$) AGB stars in radiative conditions and produces low neutron densities ($\sim 10^8$ n/cm3), resulting in negative [Rb/Sr] and [Rb/Zr] ratios.

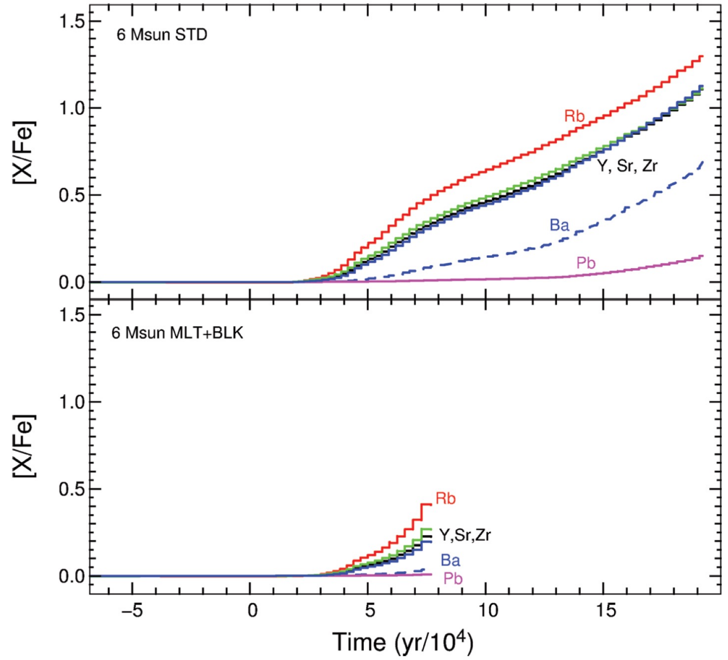
The $^{22}Ne(\alpha,n)^{25}Mg$ reaction is activated in the convective thermal pulses of IM-AGB stars and produces high neutron densities (up to $\sim 10^{13}$ n/cm3) → positive [Rb/Sr] and [Rb/Zr] ratios.

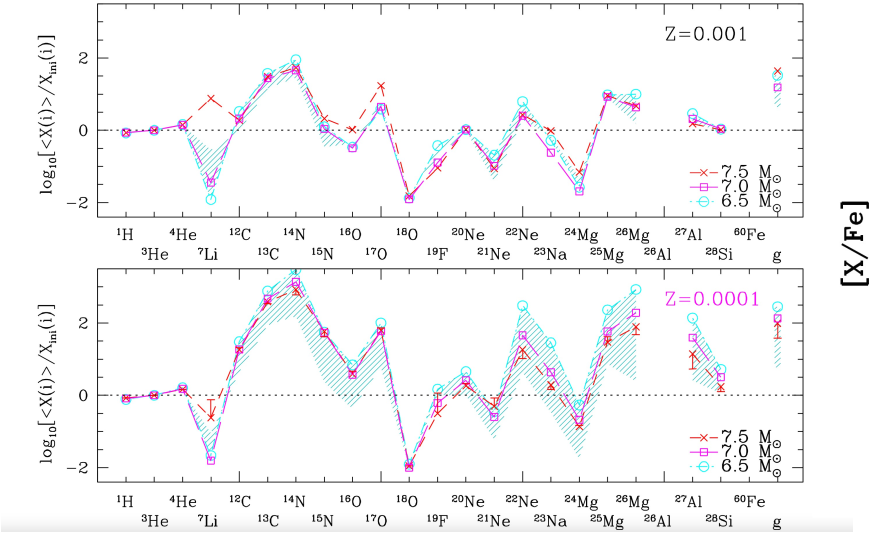
The picture is more complicated than that..

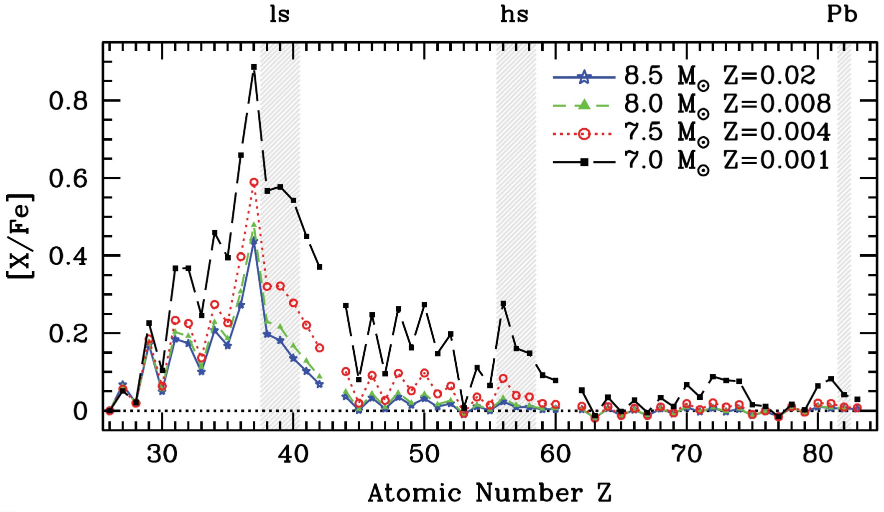
THEORETICAL PREDICTIONS

«Some contend that IM-AGBs also synthesize s-process nuclides and then one might expect to see star-to-star variations in the Rb and Pb abundances as well as correlations with light element abundances» (Yong+ 2007)

Massive AGB models for heavy elements







Doherty+ 2014,2015, 2017

D'Orazi et al. 2013
(AGB stars modeled «a la Monash» vs Ventura's group –no heavy!)

PAST/CURRENT SURVEYS

- *NO SIMULTANEOUS determination of Li and heavy-element abundances*
- *NO Pb & Rb measurements for significant samples.*

GAIA-ESO (R = 20 000 / 48 000) Li I line included but not blue spectral coverage for best lines of n-capture elements, no Pb, Rb..

APOGEE (R = 22 500) H band No Lithium and no n-capture elements

GALAH+ (R= 28 000) Lithium and several n-capture (including Rb but no Pb) but limited resolution + not blue spectral coverage (bright targets, a few GCs)

NEXT-COMING SURVEYS

WEAVE : R=20000 max, but will have Li and several n-capture elements but R not enough for Pb, La, and Rb

MOONS : no Li, low resolution (except in H, same problem as APOGEE)

4MOST : same as WEAVE in resolution & WL coverage

Under construction (telescope, instrument, survey)
MSE = Maunakea Spectroscopic Explorer
will have (maybe) higher resolution
R=30000, 40000 under discussion
WL coverage under discussion

WEAVE has ~1000 fibers
(plus 20 mIFUs, 1 lIFU)
@WHT, FoV 2 deg ∅
R~5000: 366-959 nm
R~20000: in 2 (of 3) WL regions

MOONS has ~1000 fibers
@VLT, FoV 25 arcmin ∅
R~5000: 0.6-1.8 μ
R~9000: at CaT
R~20000: in H band

4MOST has ~2400 fibers
(1600 LR, 800 HR at same time)
@VISTA, FoV 4 sq.deg
R~5000 + R~20000

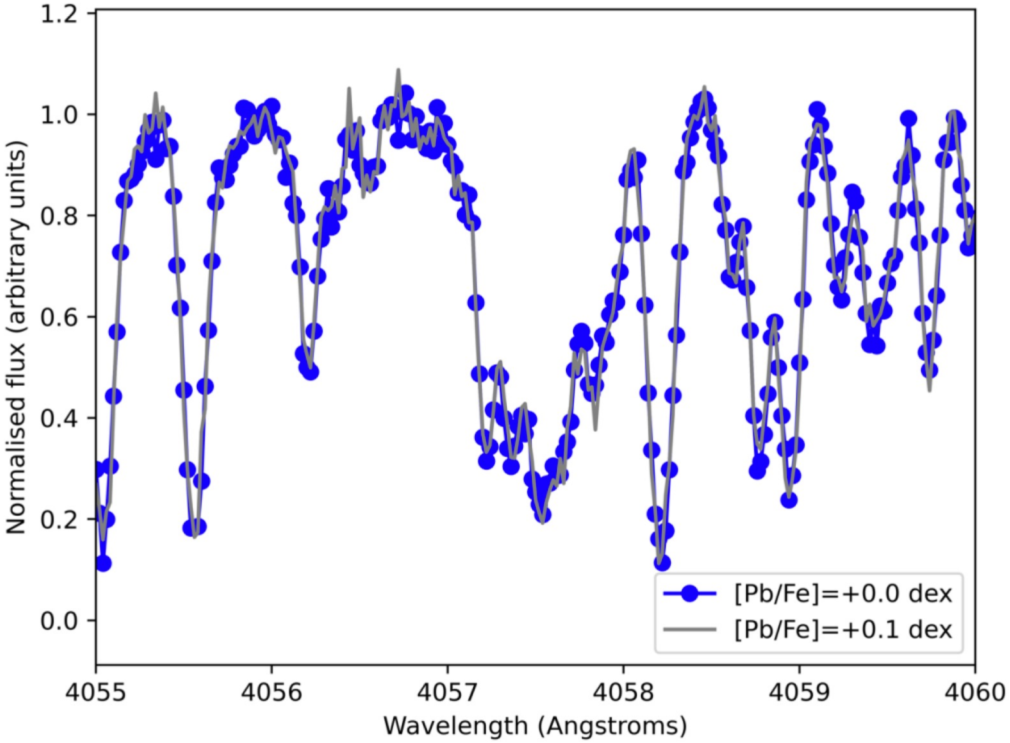
THE UNIQUENESS OF HRMOS

1. SPECTRAL COVERAGE (blue coverage < 4200 Å and Li at 6708 Å + possibly Rb at 7800 (and C isotopes at 8000?)

2. VERY HIGH RESOLUTION (R > 50 000)

3. MULTIPLEXING CAPABILITIES (50+)

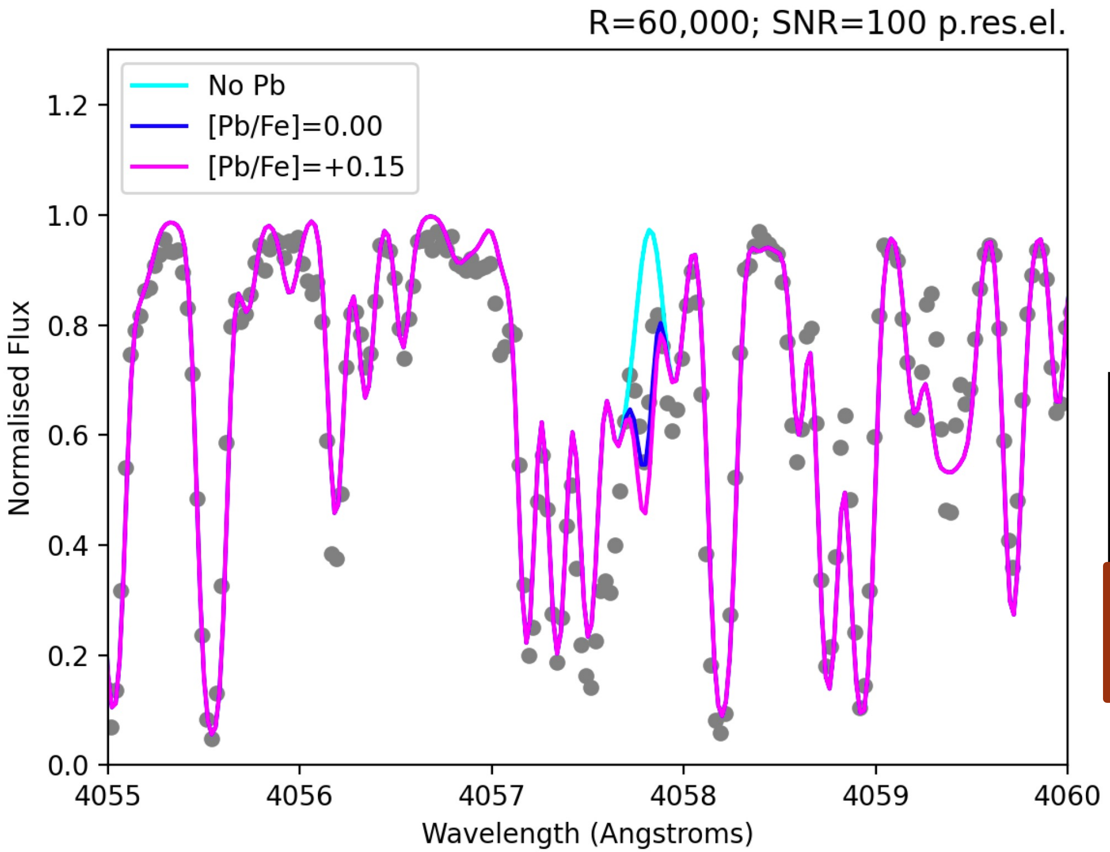
SCIENCE CASES & SIMULATIONS (BLUE)



At R = 40 000 severe blending with Mn I line at 4057.9

Resolving power R	SNR per resol. element	σ(EW) in mÅ	Δ([Pb/H]) in dex
40,000	100 (58 per pixel)	8.0	± 0.20
40,000	300 (173 per pixel)	4.4	± 0.10
60,000	100 (58 per pixel)	5.6	± 0.13
60,000	300 (173 per pixel)	3.2	± 0.07

SCIENCE CASES & SIMULATIONS (BLUE)



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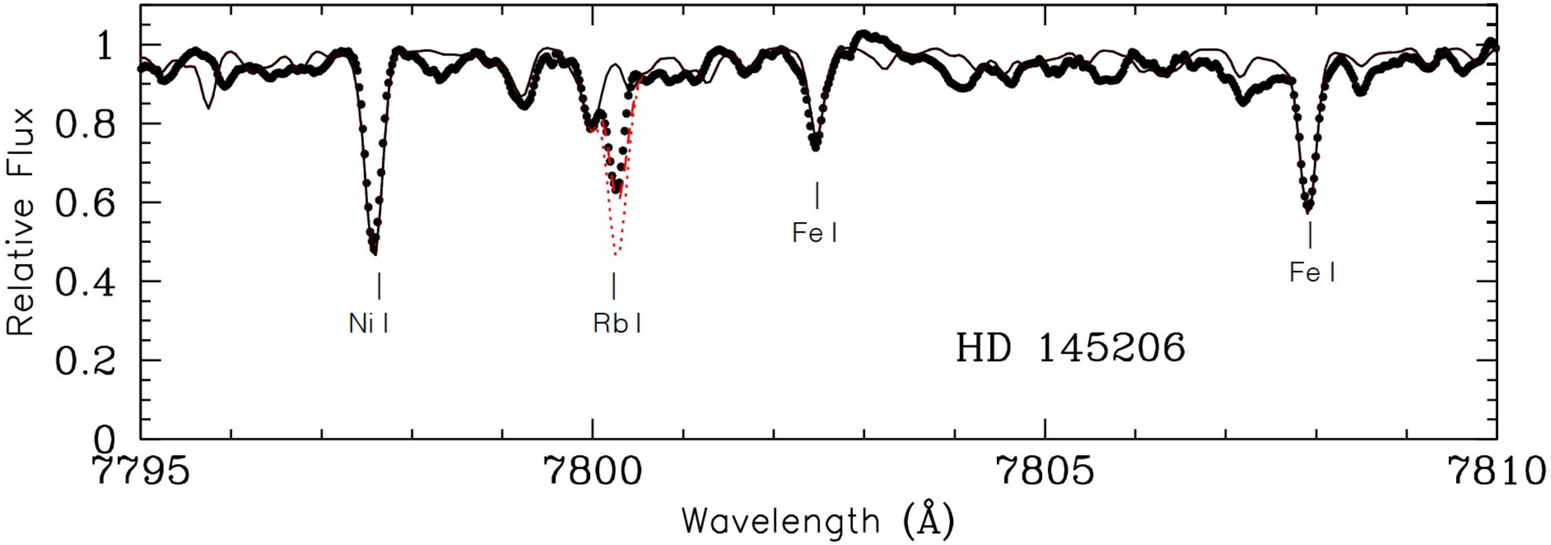
60,000	300 (173 per pixel)	3.2	± 0.07

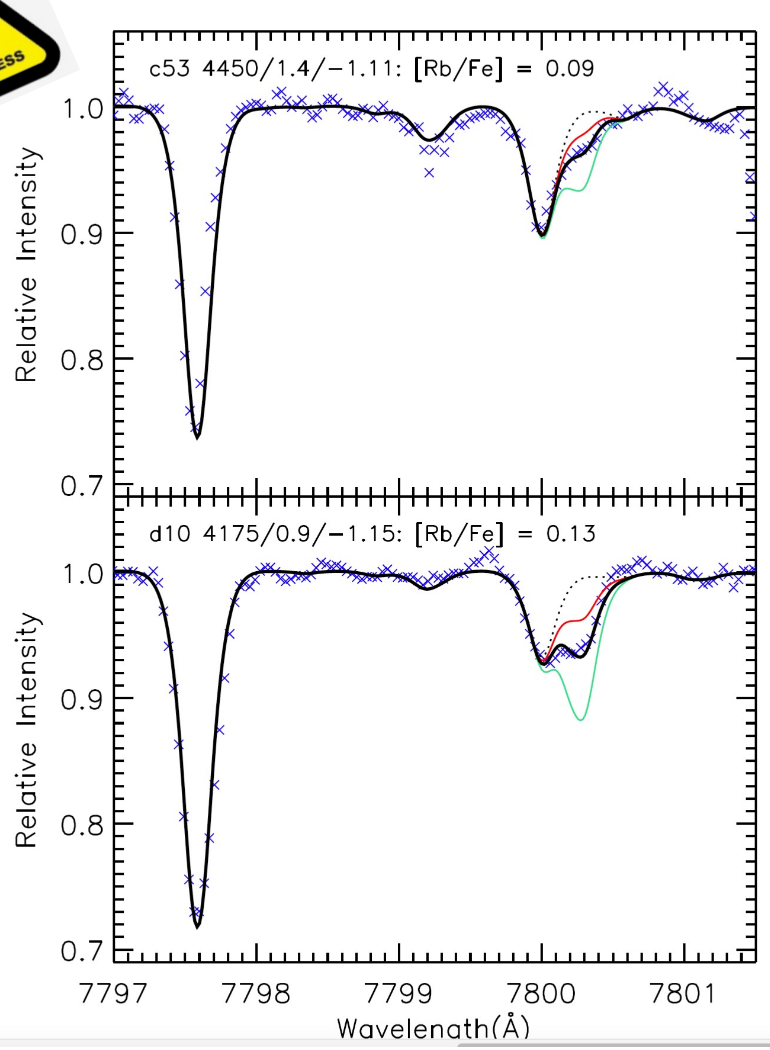
SCIENCE CASES & SIMULATIONS (RED)

WORK IN PROGRESS

TO BE DONE ..



Abia+ (2021)



Yong+ (2014)