Formation of globular clusters with abundance spreads in r-process elements: evidence of neutron star merging ?

Relation ?

GW170817 (Credit: APOD)

M15(Credit: APOD)

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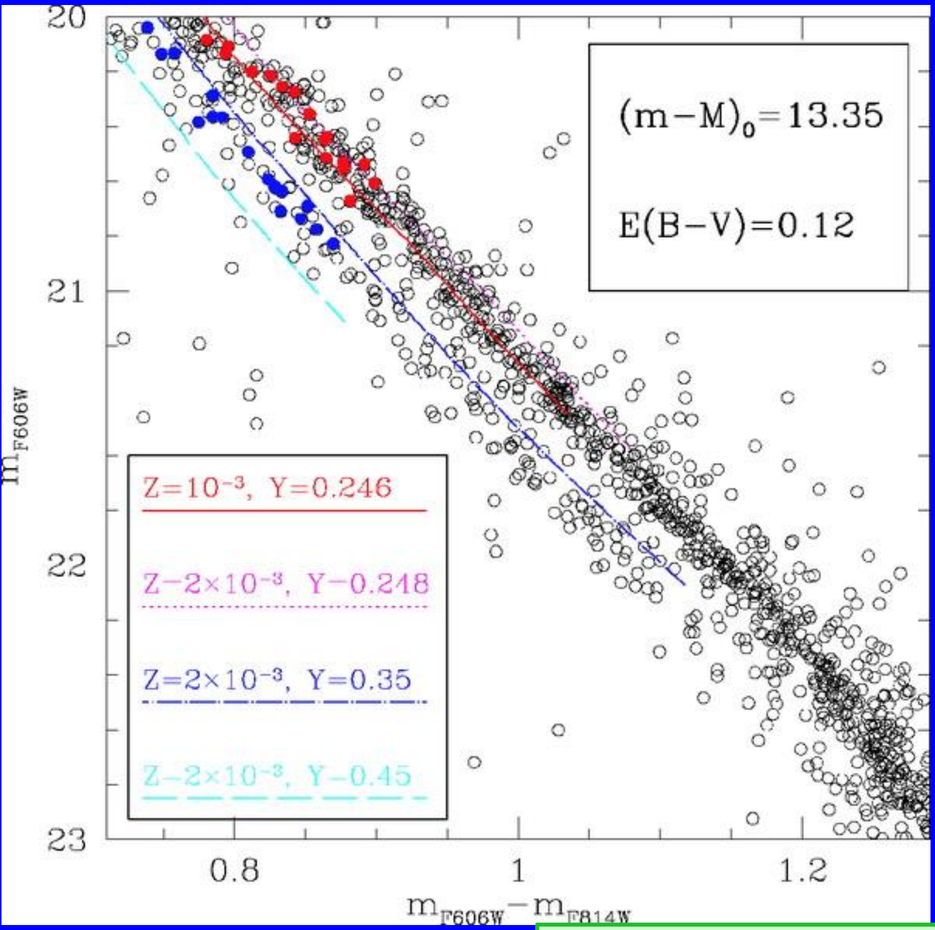
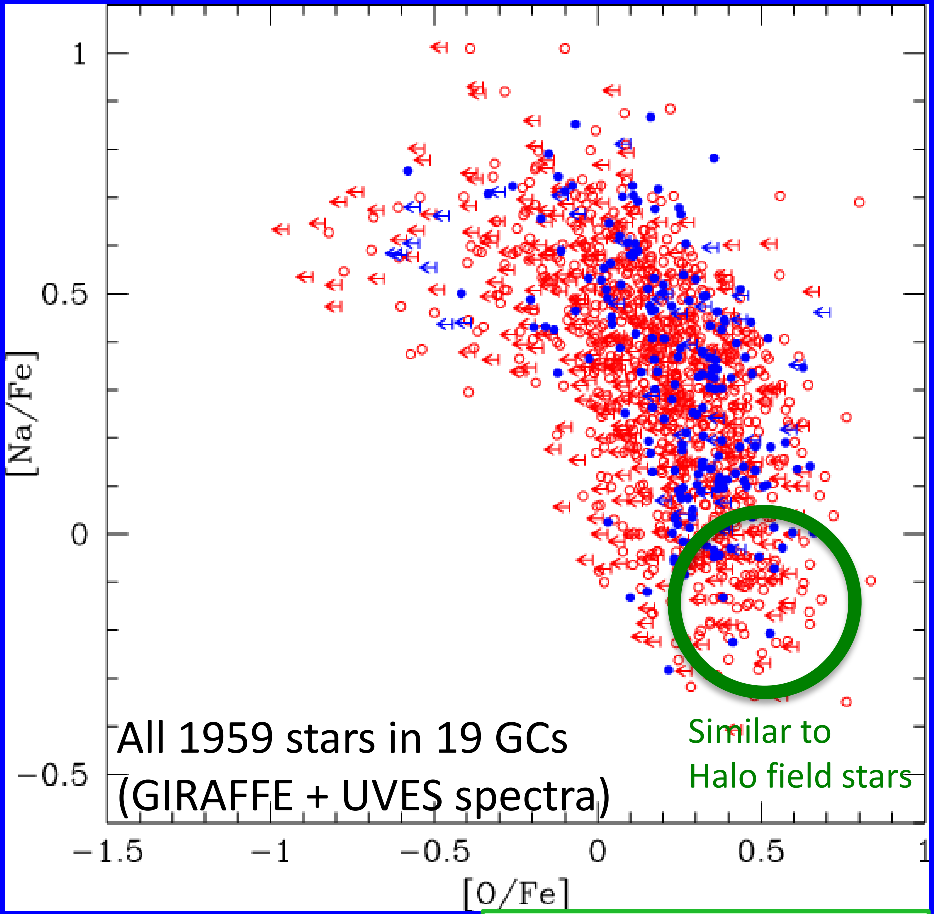
Star-to-star abundance variations in He and light elements (e.g., O-Na anti-correlation)

~ 70% of GC stars are second generation !

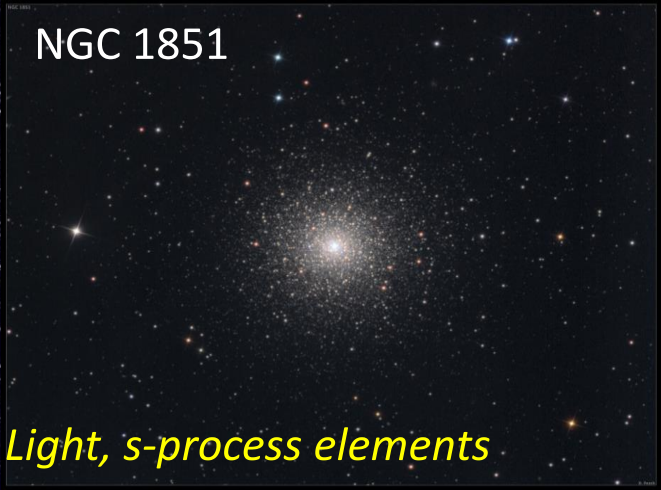


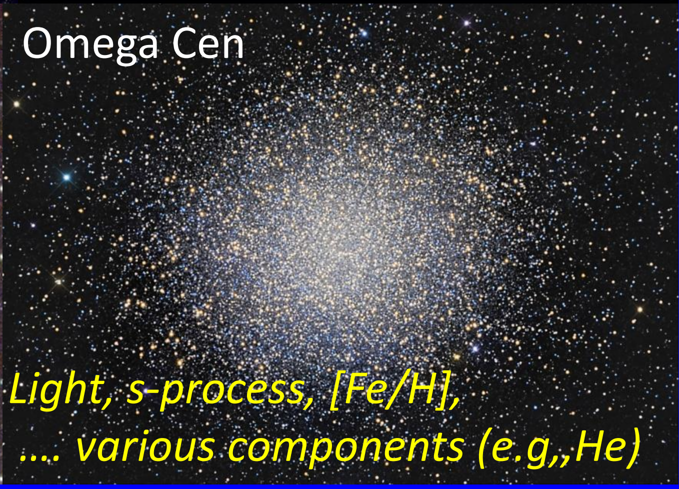
(Piotto et al. 2005)



(Carretta et al. 2009)

Globular cluster zoo (Different levels of abundance inhomogeneity)



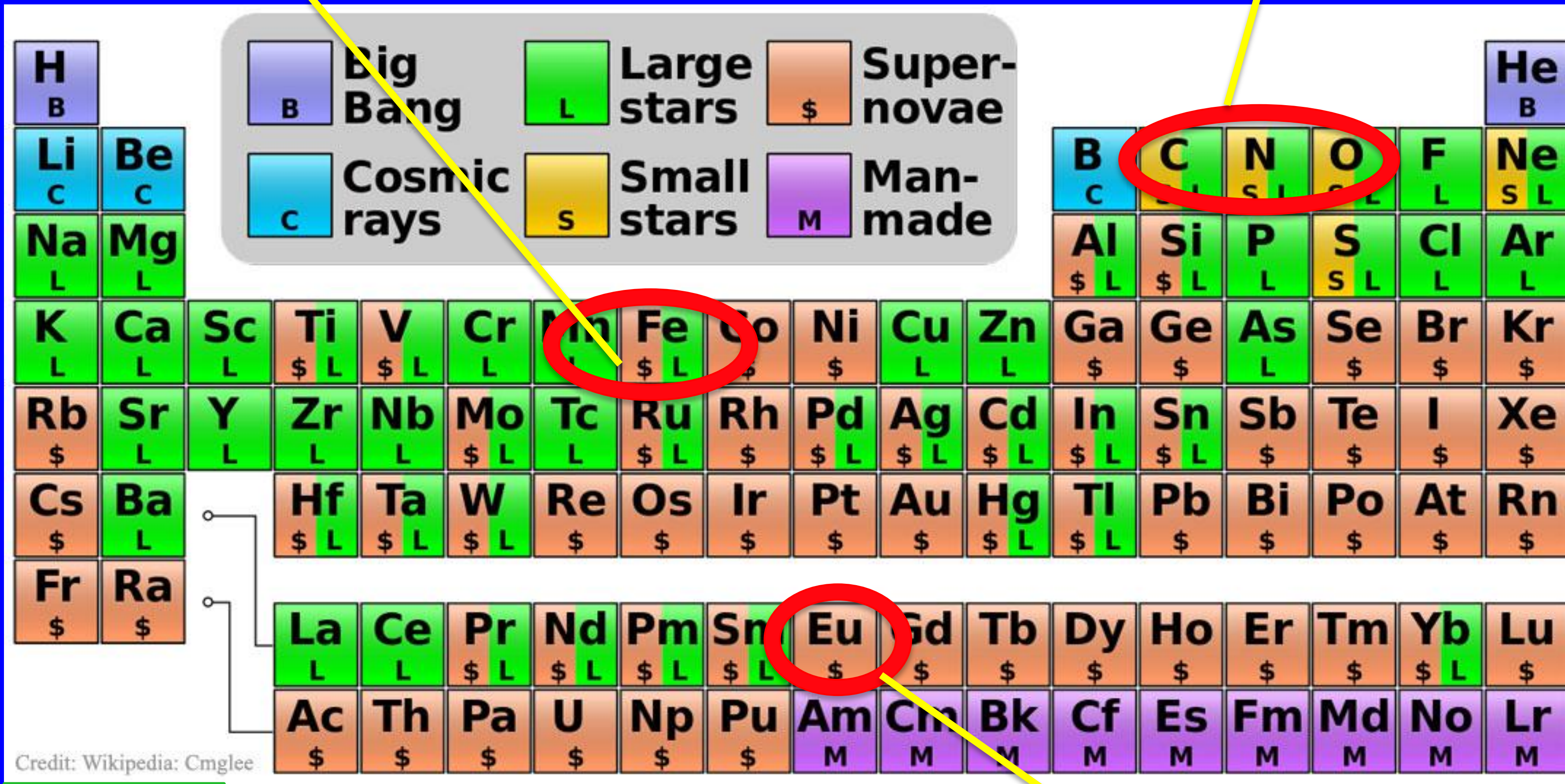


(Credit: APOD & Damian Peach)

Abundance spreads in r-process elements

8 Galactic GCs show [Fe/H] spreads (``anomalous GCs)

``Normal'' GCs shows spreads in light elements (e.g., M4)

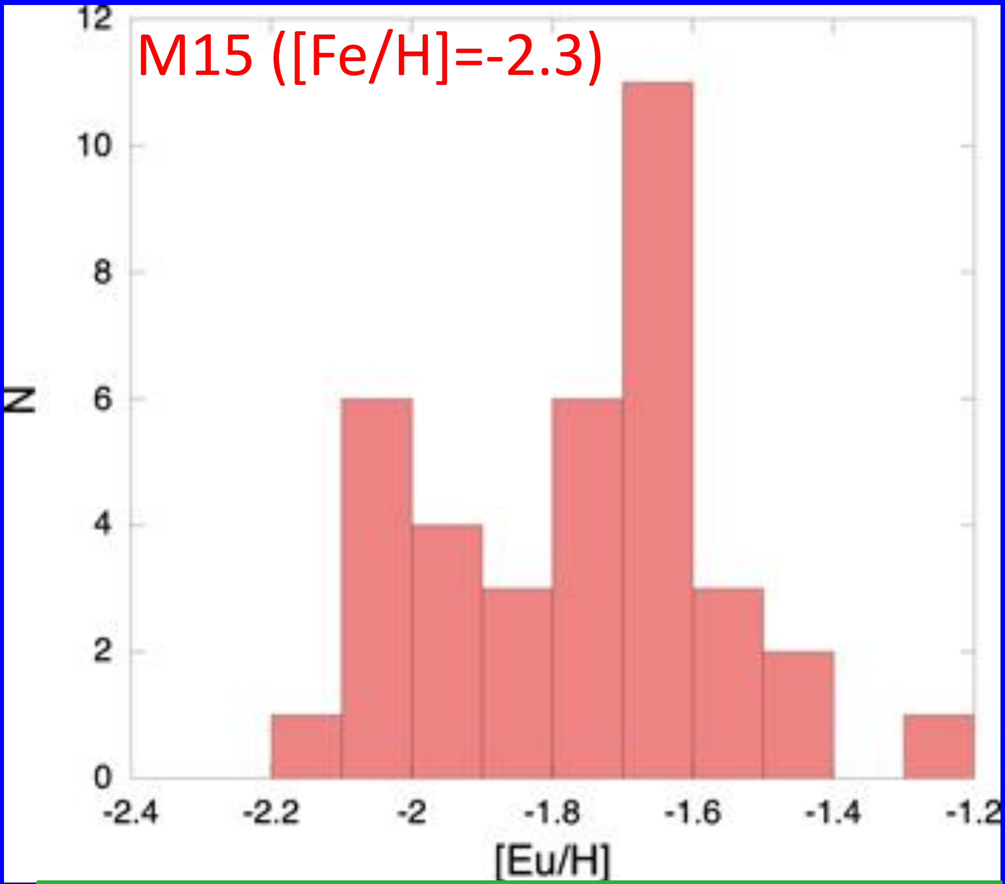


(Credit: APOD)

r-process: rapid neutron capture by heavy seed nuclei

``Today's elements''

Evidence for Eu spread in GCs

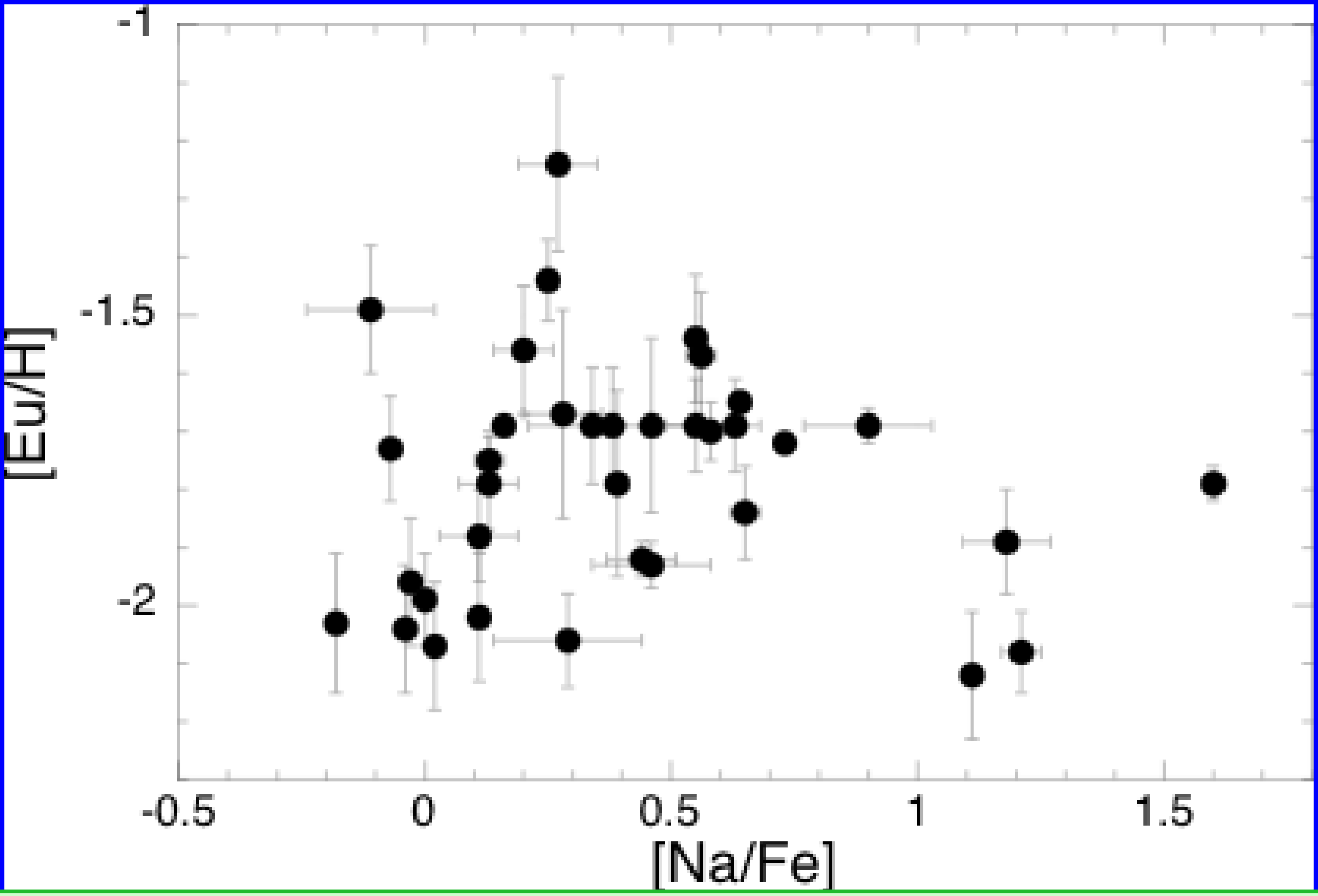


(Bekki & Tsujimoto 2017: produced from data by Sobeck et al. 2011 and Worley et al. 2013)

- At least 6 Galactic GCs show larger (0.3-1 dex) spreads in [Eu/H] (e.g., Snedin et al. 1997; Roederer 2011).
- The bimodal [Eu/H] distribution of M15 indicates two distinct epochs of star formation.

(M5, M15, M92, NGC3201, M3, & M13)

A large spread in [Na/Fe] in M15: where does Na come from ?



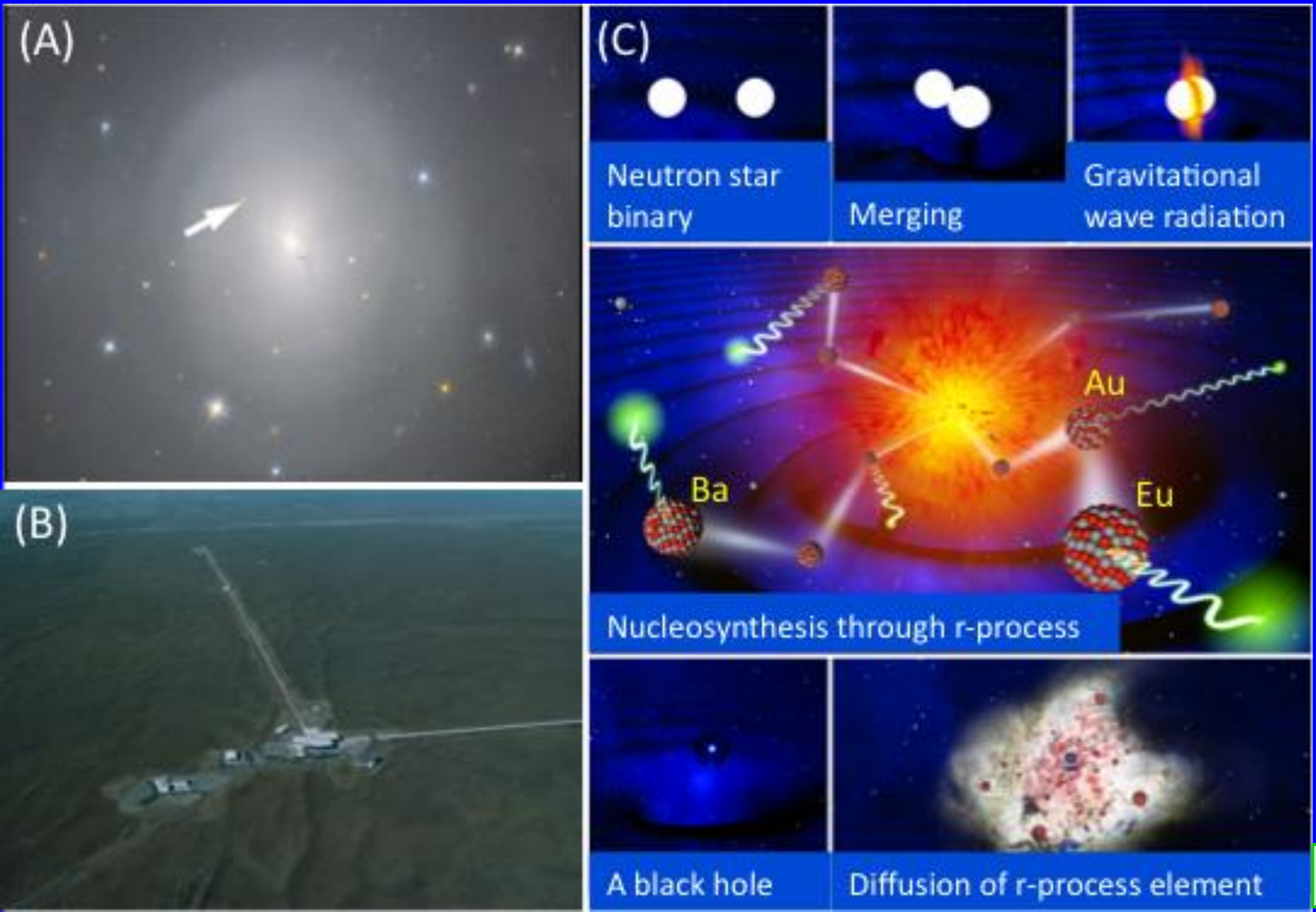
(Bekki & Tsujimoto 2017: produced from data by Sobeck et al. 2011 and Worley et al. 2013)

Five key questions on M15

- Where do r-process elements come from ?
- Why are there Eu-rich and Na-rich stars ?
- What is the most likely scenario for M15 ?
- How could the GC retain Eu-rich ejecta ?
- What does the bimodal [Eu/H] distribution imply ?

Q1: the origin of r-process elements

Ejection of r-process elements from neutron star merging (NSM).



(Credit: NAOJ, APOD, www.ligo.caltech.edu)

Why not from (magnetic) SNe but from NSM ?

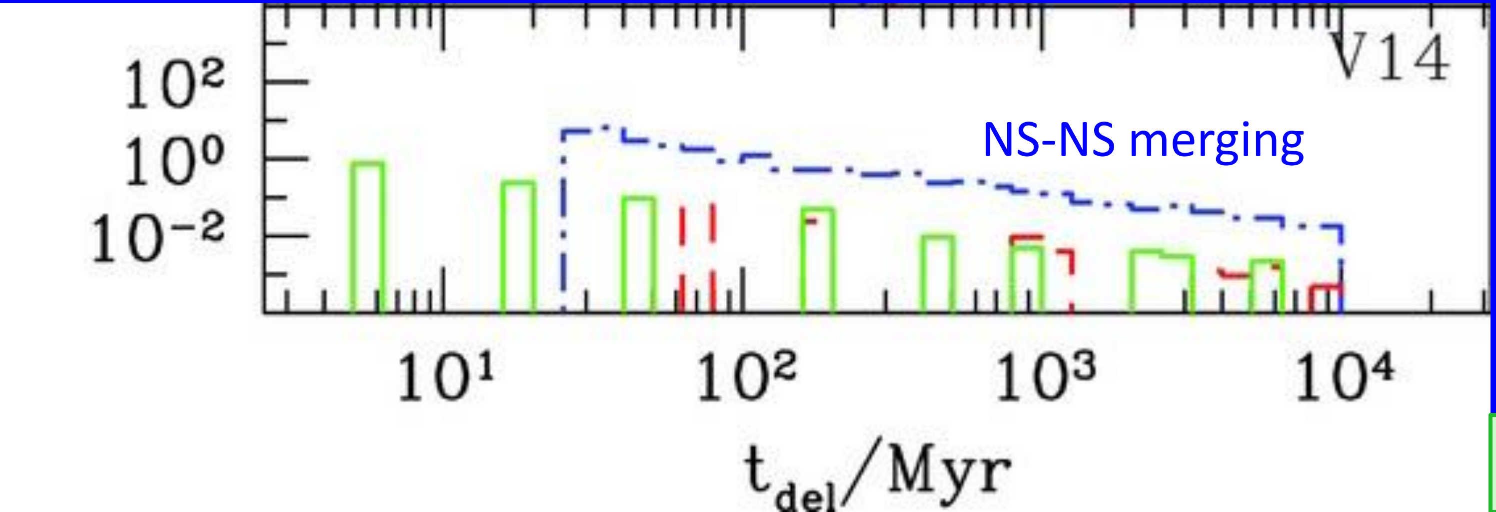
- This is because magnetic SNe II inevitably produce light r-process elements (Sr, Y, Zr) together with Ba and Eu (e.g., Nishimura et al. 2017) → Such spreads in light r-process elements are not observed in M15 (e.g., Sobeck et al. 2011).
- This is also because such SNe II produce Fe and thus introduce [Fe/H] spreads, which are not observed in M15 (e.g., Worley et al. 2013).
- Also, SNe can increase the abundance spreads in α elements (e.g., Ca), but, such spreads are not observed (e.g., Sobeck et al. 2011).

Therefore NSM is the candidate for the polluter !

Q2: the origin of Na-rich stars

Na-rich gas from AGB stars was mixed with gas from NSM ?

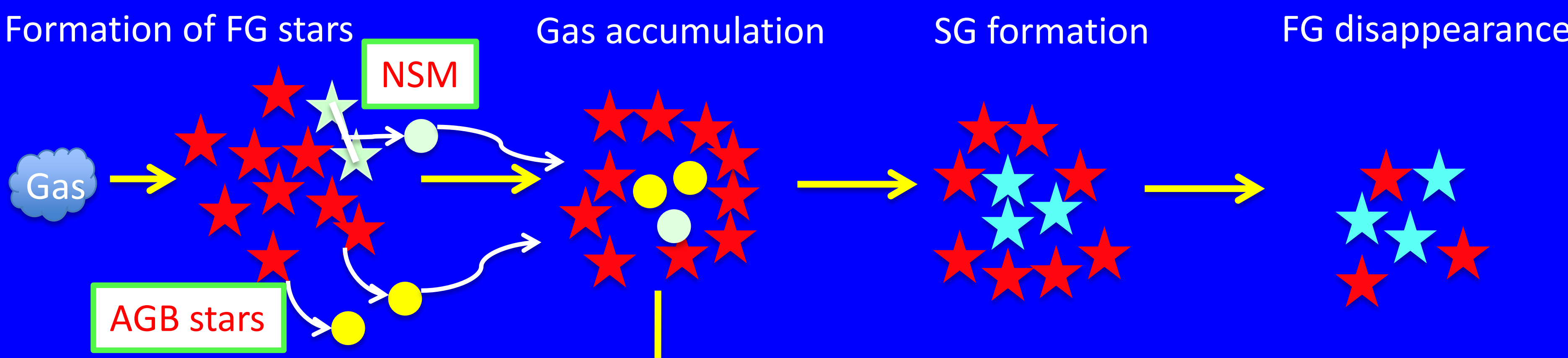
- The delay time (t_{del}) distribution for NSM is approximately proportional to t_{del}^{-1} with a peak around $3*10^7$ yr (e.g., Dominik et al. 2012).
- This means that gas ejected from AGB stars (whose progenitors have lifetimes longer than 30 Myrs) can be mixed with NSM ejecta.
- Thus, stars rich in r-process elements can originate from mixed gas of NSM and AGB stars with high Na abundances.



(Delay-time distribution: Dominik et al. 2012)

Q3: a promising scenario

The AGB scenario



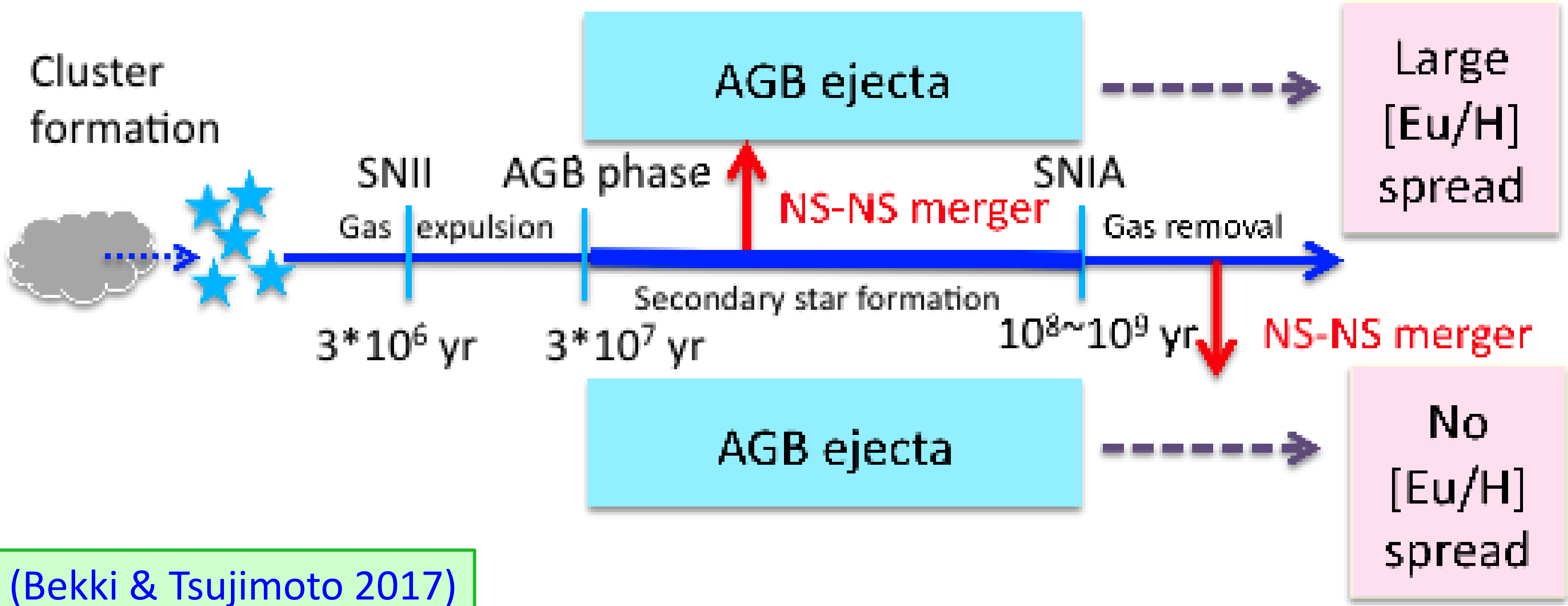
Mixing of ejecta from AGB stars and NSM

FG=First Generation
SG=Second Generation

Multiple stellar populations= Multiple generations
(chemical differences due to star formation from gas from FG)

(D'Antona et al. 2004, 2016; Bekki et al. 2007; D'Ercole et al. 2008; Decressin et al. 2007; Renzini 2008; See Gratton et al. 2012 for a review)

The AGB scenario: how is the mixing of ejecta from AGB stars and NSM possible ?



(Bekki & Tsujimoto 2017)

Gas ejection velocity: ~ 10 km/s for AGB stars

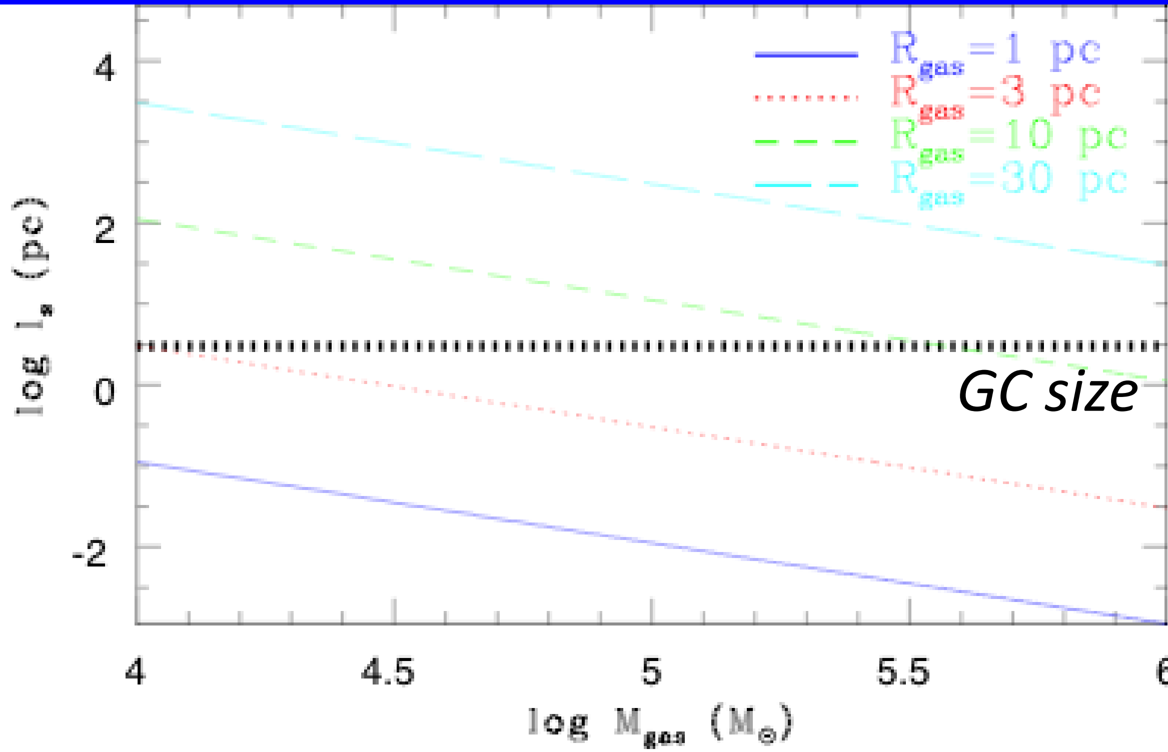
~ 0.1*c ($3*10^4$) km/s for NSM.

Q4: a mechanism for retaining NSM ejecta in ICM

The stopping length (l_s) constraint.

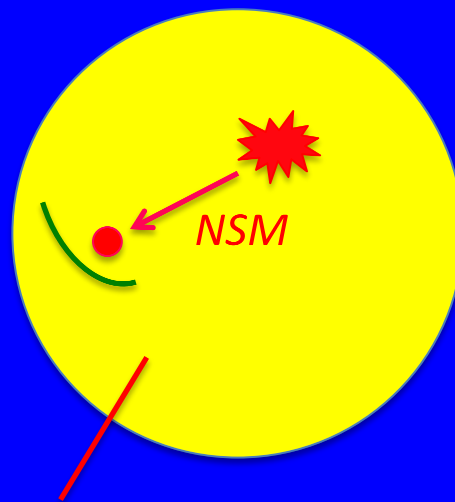
l_s=2.6(n_{H1}/1 atom cm^{-3})$^{-1}$ kpc (Komiya et al. 2016)

(through Coulomb scattering)



l_s –M_{gas} relation

Intra-cluster gas (AGB ejecta)

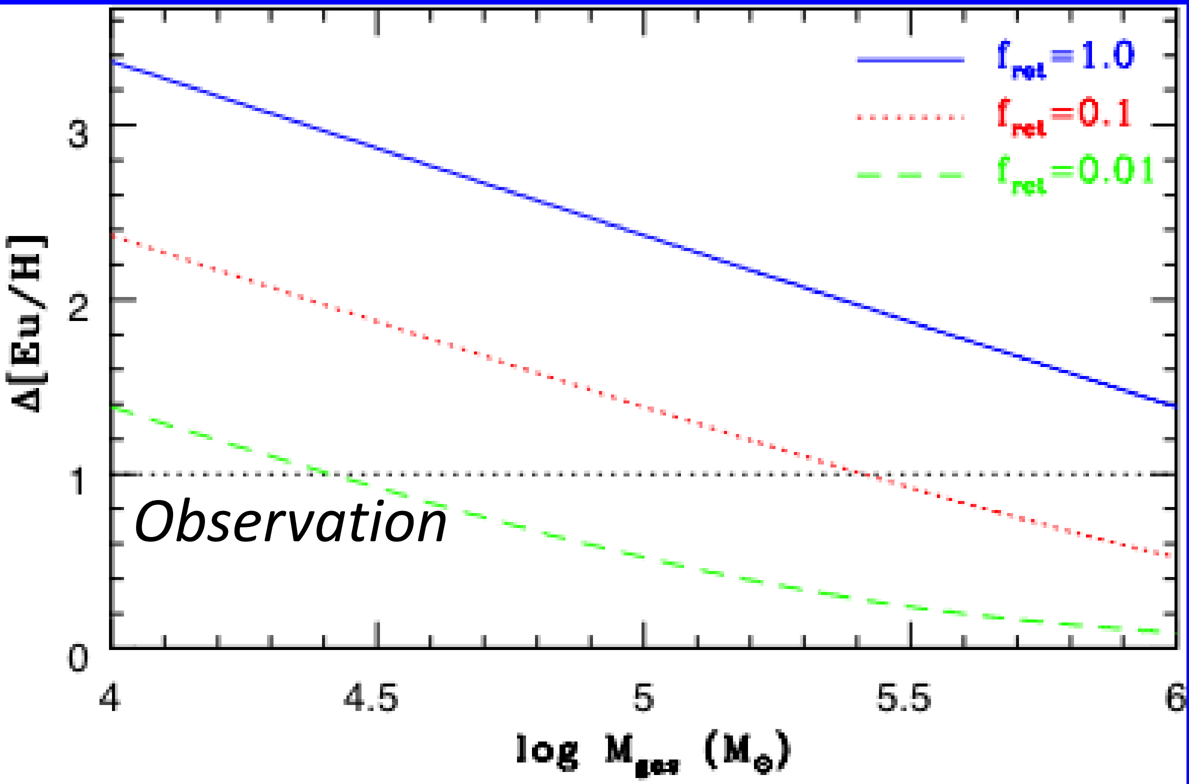


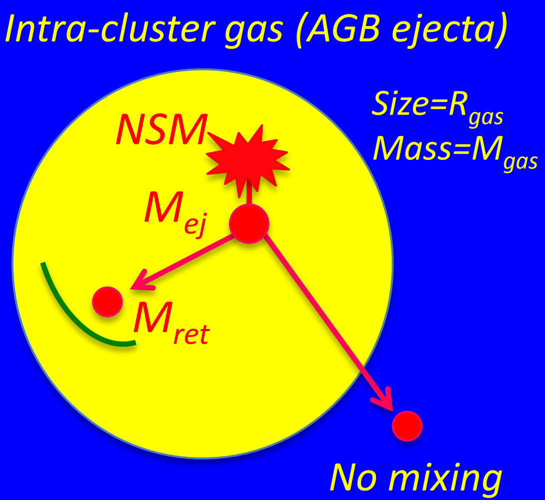
Size=R_{gas} , Mass=M_{gas}

(Bekki & Tsujimoto 2017)

For example, if M_{gas} is 10^4 (10^5) M_{sun} , then R_{gas} should be < 3pc (7pc) so that l_s can be less than the GC size.

How much should the NSM ejecta be retained in a GC to explain [Eu/H] spreads ?





$f_{ret}=M_{ret}/M_{ej}$, $M_{ej}=0.01M_{sun}$ Per NSM (only 1% of this is Eu).

*Eu (Sun)=3.8*10^{-10}*

(Bekki & Tsujimoto 2017)

For example, if M_{gas} is 10^5 M_{sun} , then f_{ret} should be ~ 0.03 so that the observed Eu spread can be explained.

Animations of the AGB scenario

$M_{mc}=10^7\ M_{sun}$, $R_{mc}=200$ pc (Bekki 2017)

Gas in a fractal molecular cloud

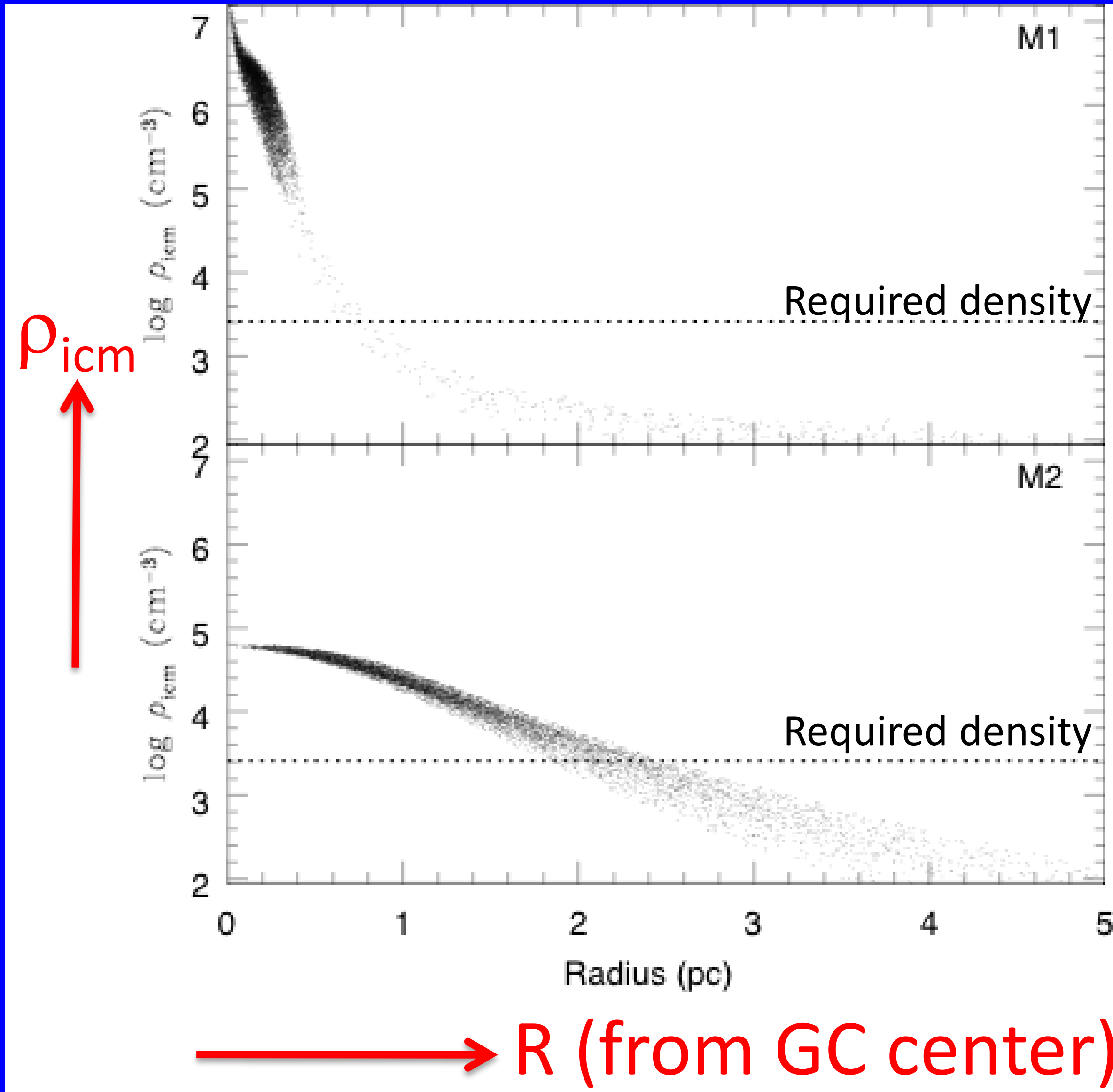
First generation new stars

Animations of the AGB scenario

AGB ejecta

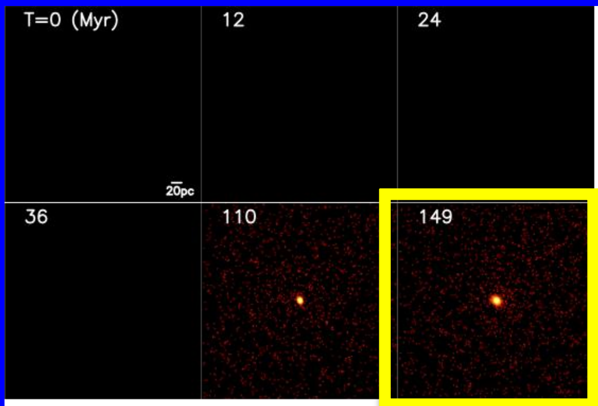
Second generation stars from AGB ejecta

Densities of intra-cluster gas (ρ_{icm})



Without star formation from AGB ejecta

With star formation from AGB ejecta

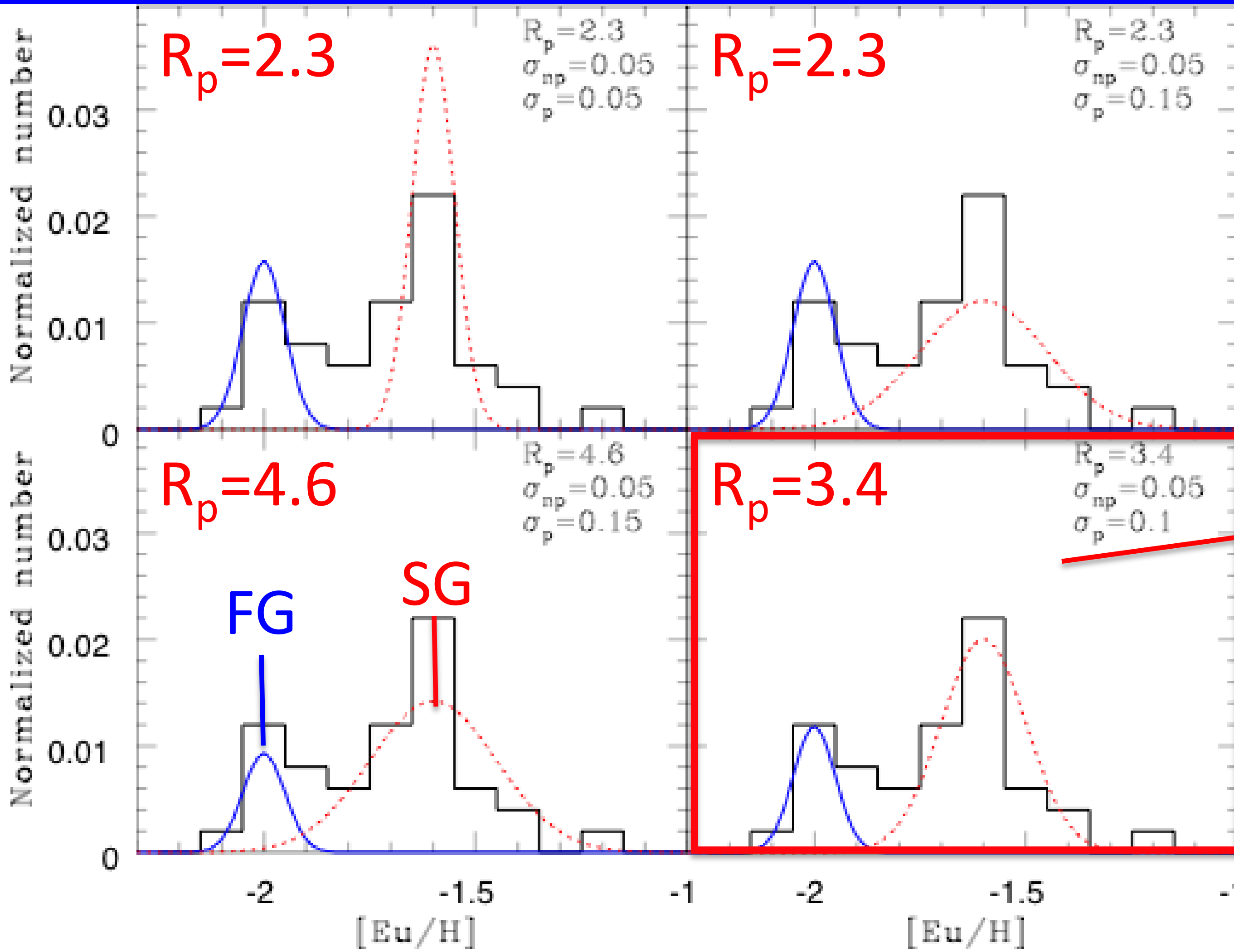


$M_{mc}=3*10^6\ M_{sun}$, $R_{mc}=100$ pc
(Bekki & Tsujimoto 2017)

Q5: Implications of the bimodal [Eu/H] distribution

Analytic models for [Eu/H] distributions

$$N([\mathrm{Eu/H}]) = \frac{N_0}{(2\pi\sigma^2)^{3/2}} \exp\left(\frac{-(Z - Z_{\mathrm{m}})^2}{2\sigma^2}\right),$$



$R_p=M_{SG}/M_{FG}$ ($M_{polluted}$ divided by $M_{not\text{-}polluted}$)

The best model:

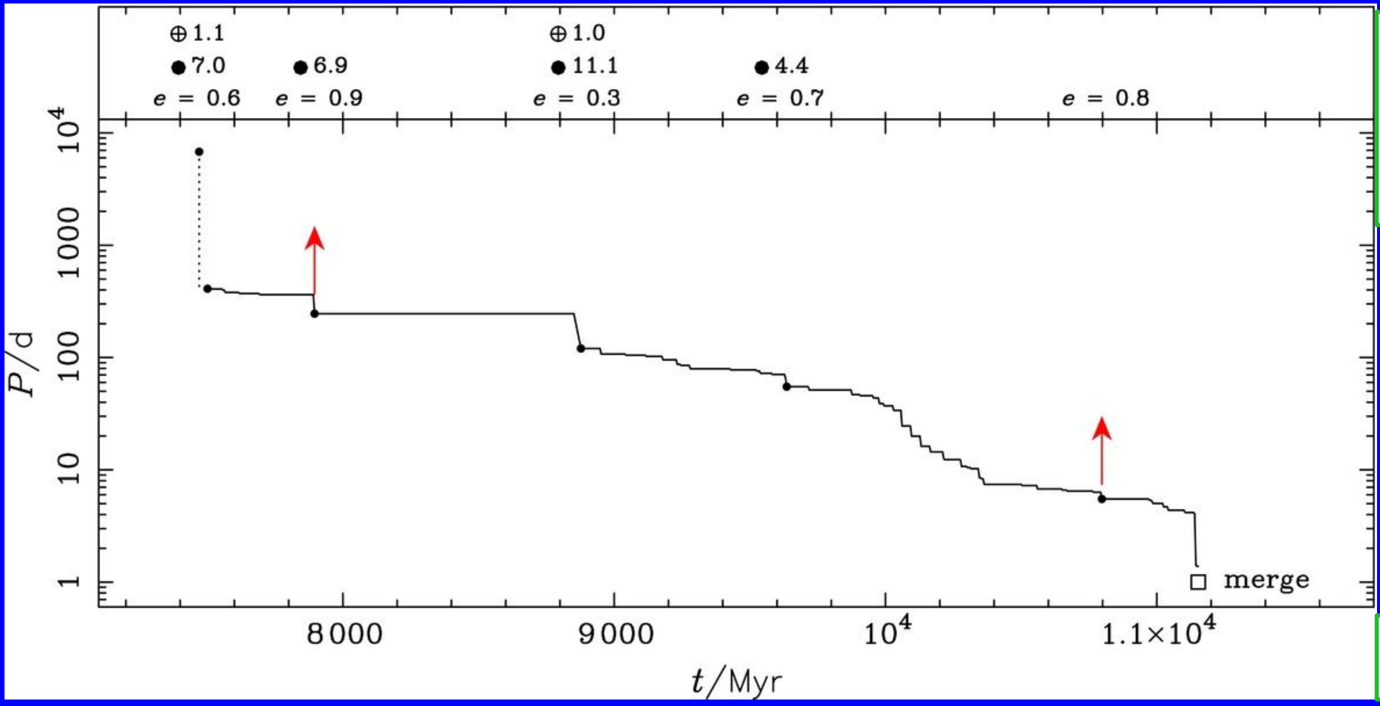
This means that SG population is three times more massive than FG. Why is it possible ?

Conclusions

- The observed chemical abundances of GCs with spreads in r-process elements and Na can be explained by the AGB scenario.
- This means that star formation timescales of these GCs are longer than 300 Myrs (evidence for prolonged SF).
- The densities of AGB ejecta in forming GCs can be high enough to retain NSM ejecta, however, it is not clear whether star formation can really occur from mixed gas of NSM and AGB ejecta → we need to run a fully self-consistent simulation.
- Eu-rich population is more massive than Eu-poor one: a new mass budget problem for these GCs.

Future work

- Is it really possible for NSM to occur when AGB ejecta is accumulated enough ? → A new hydrodynamical simulations that combine Nbody 6 with a hydrodynamical code is required (Bekki & Hurley in preparation).



Evolution of orbital period of BH-BH binary in a GC.

(Hurley et al. 2017)