Galactic evolution of r-process elements: the role of compact binary mergers

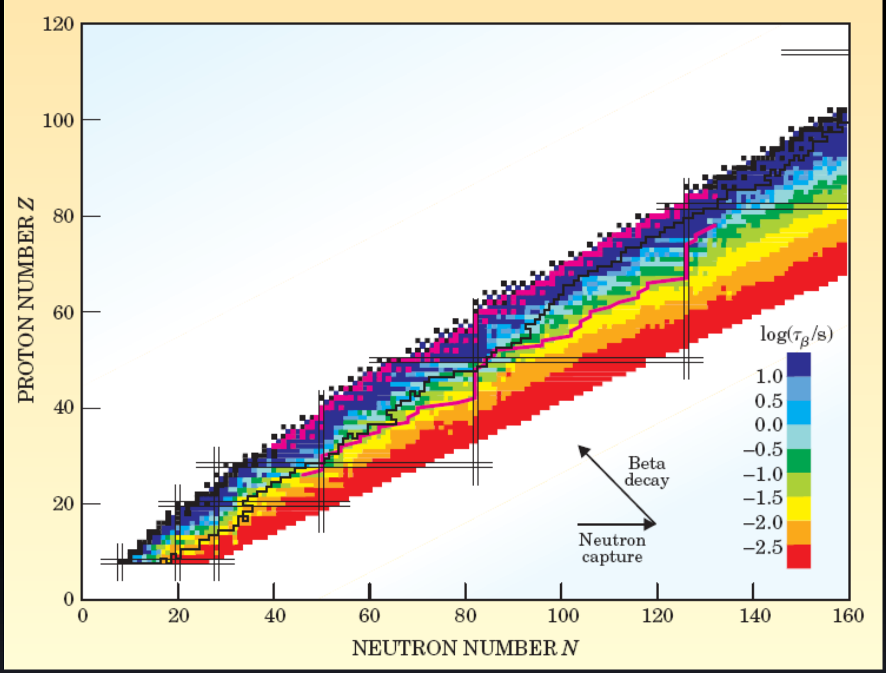
Donatella Romano
(INAF—OABo)

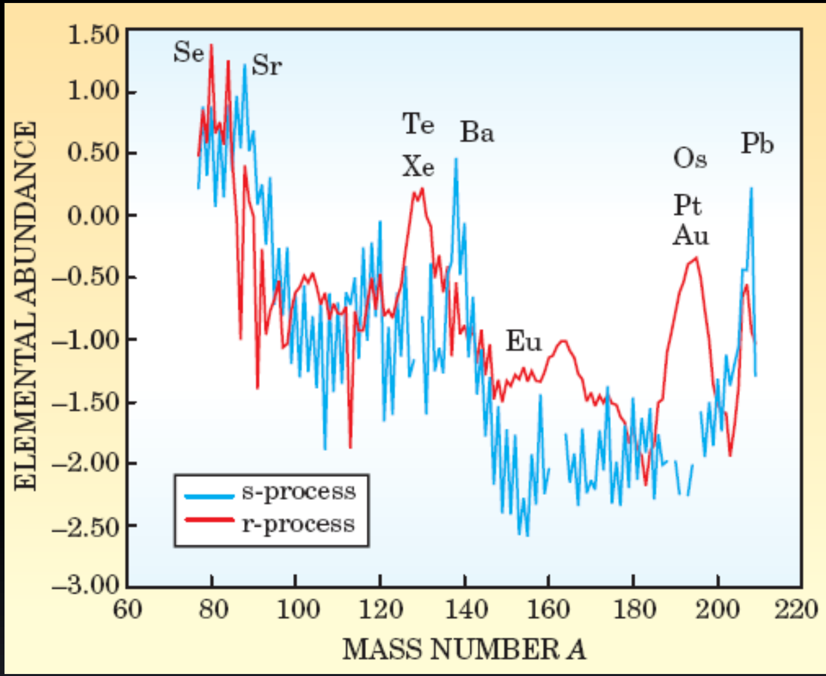
In collaboration with (in alphabetical order): A. Arcones *(IKP, Darmstadt Univ., DE)*, G. Cescutti *(AIP, Potsdam, DE)*, C. Chiappini *(AIP, Potsdam, DE)*, R. Hirschi *(Keele Univ., UK)*, O. Korobkin *(OKC, Stockholm Univ., SE)*, F. Matteucci *(Trieste Univ., IT)*, S. Rosswog *(OKC, Stockholm Univ., SE)*

Matteucci, DR, et al. (2014, MNRAS, 438, 2177)
Cescutti, DR, et al. (2015, arXiv:1503.02954)

Heavy element synthesis

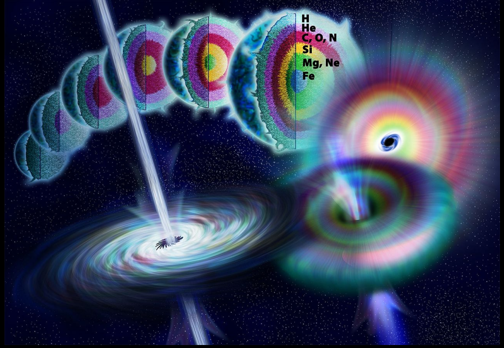
- Heavy elements (i.e. elements beyond the iron peak) cannot be efficiently produced by charged-particle interactions, owing to the large Coulomb repulsion between nuclei. Temperatures high enough to overcome the Coulomb barrier lead to photodisintegration of the iron-peak nuclei (see e.g. Woosley & Weaver 1995).
- Heavy elements can be synthesized by successive neutron captures onto iron peak nuclei, followed by β decays (Burbidge et al. 1957).
- Two characteristic abundance patterns are observed, depending on whether the neutron captures occur on a time scale long enough for all β decays to occur (*s*-process), or on a time scale that is short compared to β decay (*r*-process).





- In a steady flow of neutrons the abundance of each isotope is inversely proportional to its neutron capture cross section. The closed neutron shells with 50, 82, and 126 neutrons have small neutron capture cross sections, leading to abundance peaks for these nuclei. Similarly, even-numbered nuclei have smaller neutron capture cross sections than odd-numbered nuclei, resulting in higher abundances for the even nuclei; this is called the odd-even effect. The *s*-process abundance pattern is characterized by abundance peaks near mass numbers 87, 138, and 208 neutrons and a strong odd-even effect. The *r*-process abundance pattern is characterized by the abundance peaks shifted to mass numbers near 80, 130, and 195 with no odd-even effect.

Astrophysical *r*-process sites



- The dominant production site of the *r*-process elements has not yet been unambiguously identified (e.g. Thielemann et al. 2010).

- Heavy element abundance patterns in extremely metal-poor stars ([Fe/H]<−3.0 dex) involve only *r*-process products (e.g. Truran 1981) ➞ *r*-process nucleosynthesis associated with the environments provided by the evolution of massive stars

  - Neutrino-driven winds from proto-NS following the delayed explosions of m > 20 $M_\odot$ stars (Takahashi et al. 1994; Woosley et al. 1994; Wanajo et al. 2001)

  - Prompt explosions of 8–10 $M_\odot$ stars (Wheeler et al. 1998)

  - Highly-rotating massive stars with strong magnetic fields (Winteler et al. 2012)

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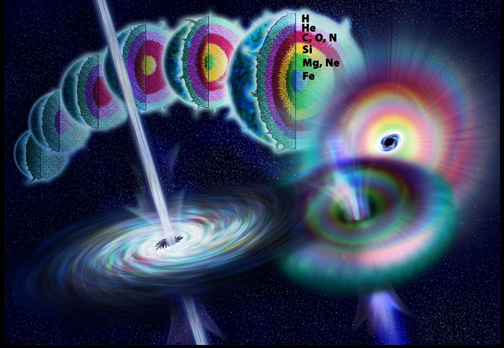

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  😦 Winds are proton-rich (e.g. Liebendoerfer et al. 2003; Arcones et al. 2007; Hüdepohl et al. 2010)

  – Prompt explosions of 8–10 $M_{\odot}$ stars (Wheeler et al. 1998)

  😳 Do they occur?

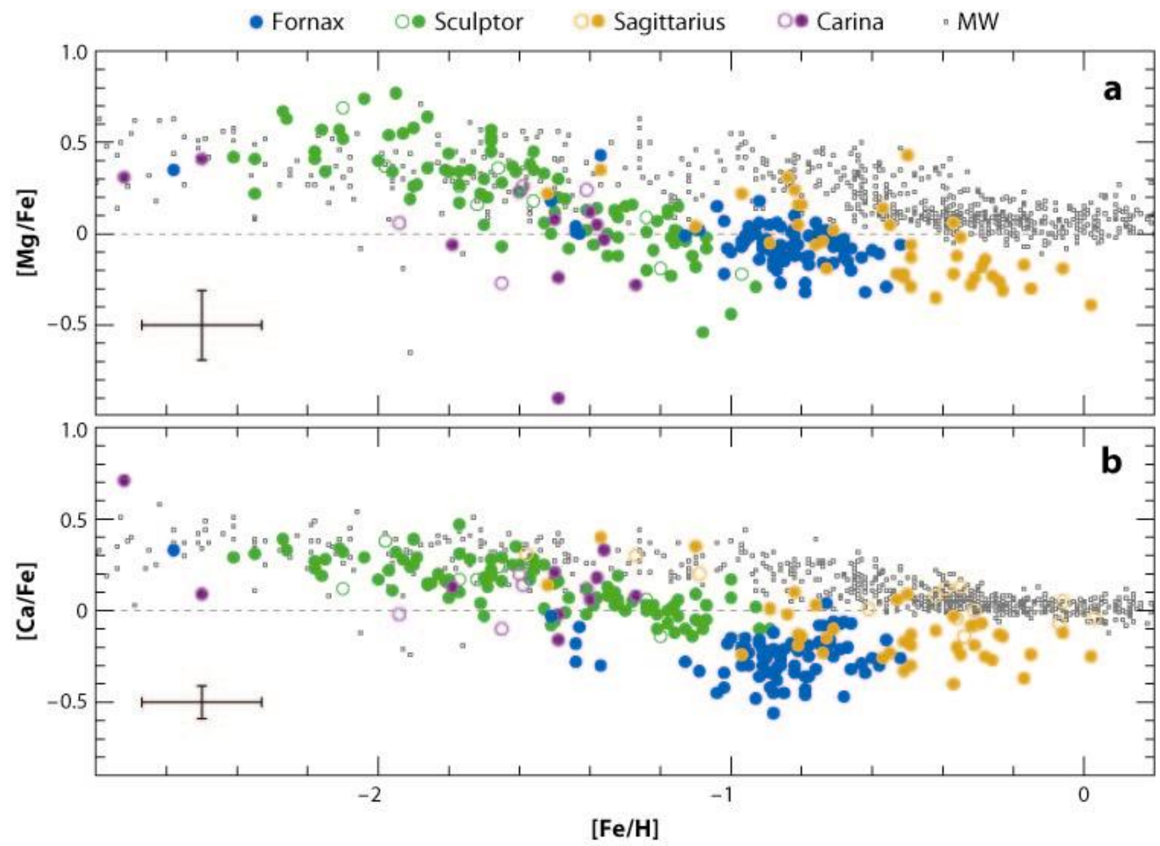
  – Highly-rotating massive stars with strong magnetic fields (Winteler et al. 2012)

  😱 They are rare!!

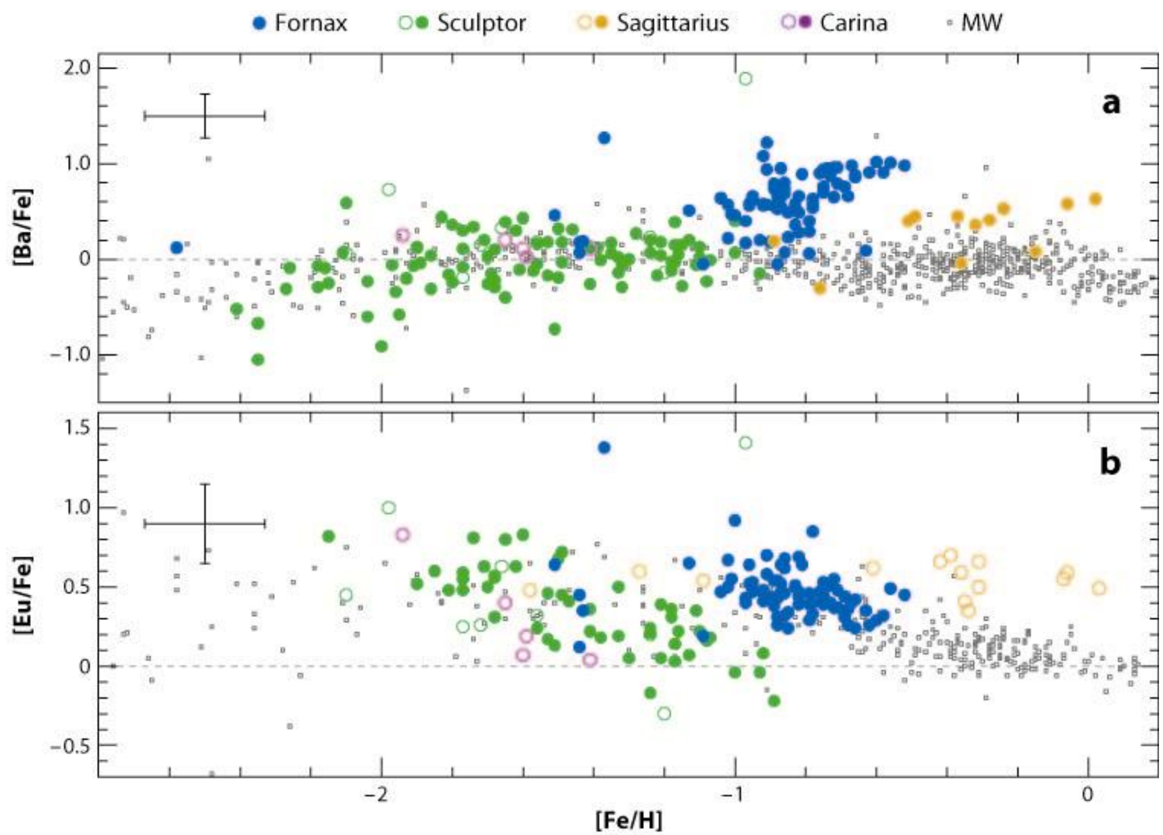
Astrophysical *r*-process sites

- Another major source of r-process elements might be NS-NS or NS-BH mergers (Lattimer & Schramm 1974, 1976; Freiburghaus et al. 1999; Goriely et al. 2011; Roberts et al. 2011).
- The resulting abundance patterns are extremely robust with respect to varying the parameters of the merging binary system (e.g. Korobkin et al. 2012).
- Up to 10^{-2} $M_\odot$ of *r*-process matter may be ejected in a single coalescence event (Rosswog et al. 1999, 2000; Oechslin et al. 2007; Bauswein et al. 2013; Rosswog 2013; Hotokezaka et al. 2013; Kyutoku et al. 2013)

→ Out of these, 10^{-5}–10^{-7} $M_\odot$ are Europium



Tolstoy E, et al. 2009.
Annu. Rev. Astron. Astrophys. 47:371–425



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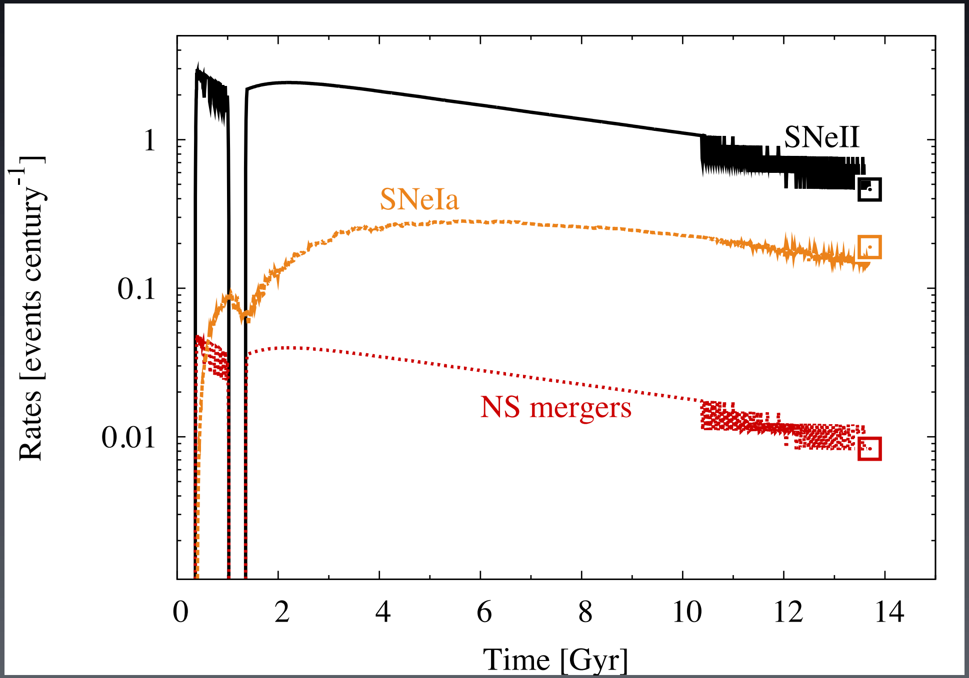
Chemical evolution models

- In principle, chemical evolution studies offer a way to discriminate among different sites for *r*-process element production.
- SN and CBM rates constrained by observations:



Squares: ‘observed’ present-time values from Li et al. (2011; SNe II and Ia) and Kalogera et al. (2004; CBM)

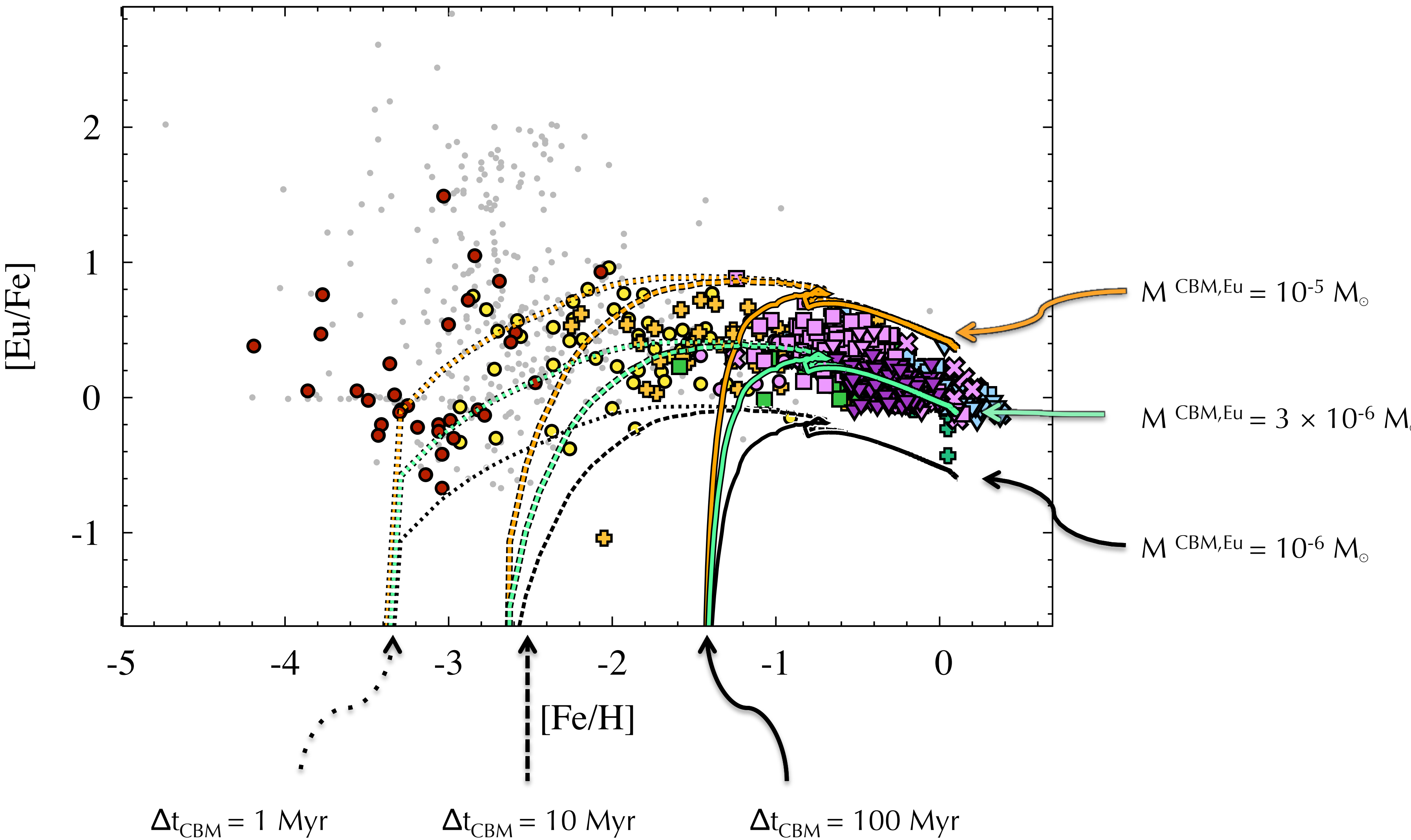
Lines: model predictions (Matteucci et al. 2014)

3.1.1 *The neutron star merger rate*

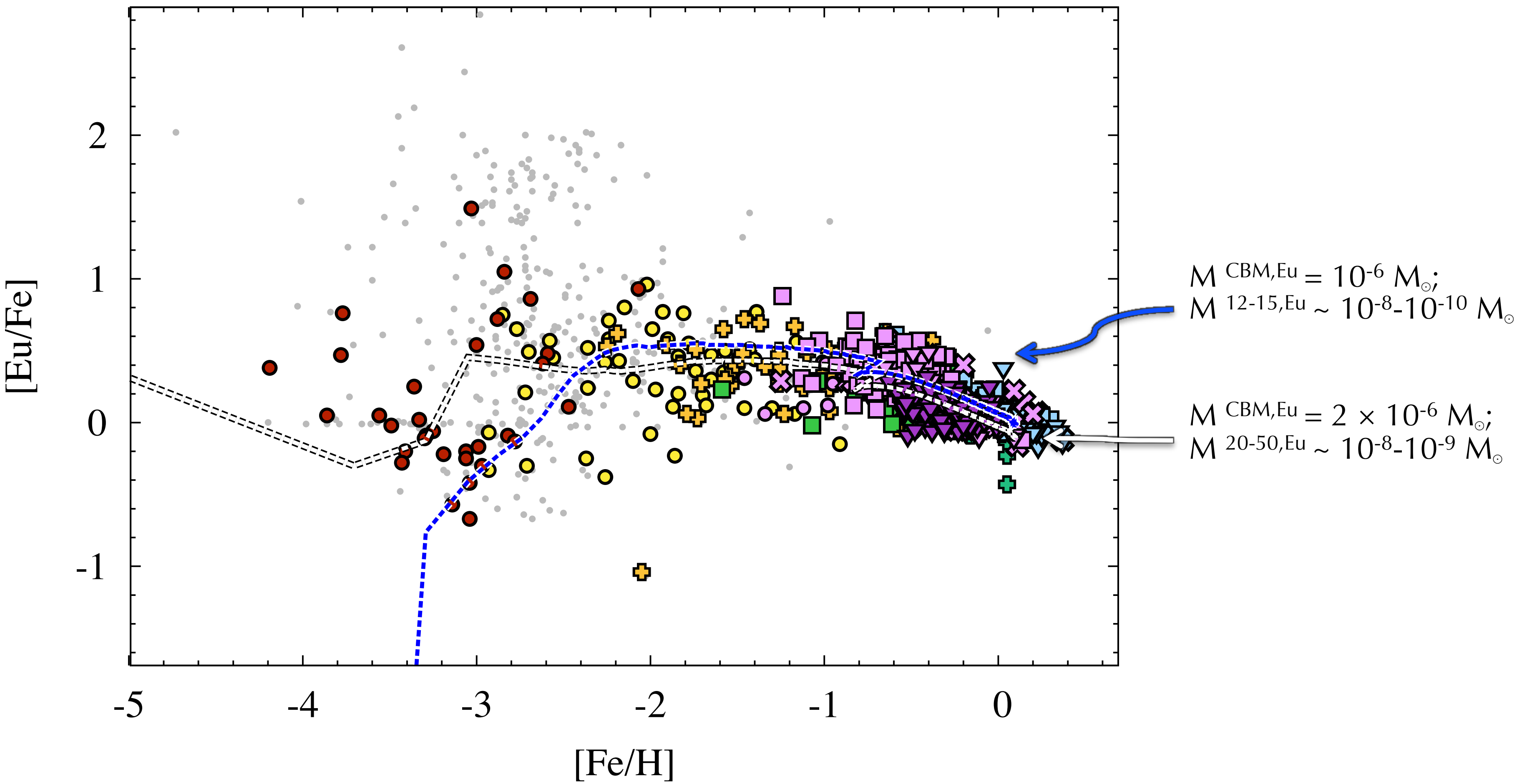
In our model, the rate of CBM at the time t is computed under the assumption that the rate of formation of double neutron star systems, which will eventually coalesce, is a fraction $\alpha_{\rm CBM}$ of the neutron star formation rate at the time $t - \Delta t_{\rm CBM}$:

$$R_{\rm CBM}(t) = \alpha_{\rm CBM} \cdot \int_{M_{ns,1}}^{M_{ns,2}} \psi(t - \tau_m - \Delta t_{\rm CBM})\phi(m)dm, \quad (3)$$

where $M_{ns,1} = 9$ and $M_{ns,2} = 30$ $\rm M_{\odot}$ are the canonical lower and upper masses, at birth, which can leave a neutron star as a remnant (we will come back to the issue of the choice of the upper mass limit in Sections 4 and 5). Stars with $m > 30$ $\rm M_{\odot}$ probably leave black holes as remnants but the situation is quite uncertain and depends on the assumed rate of mass loss in massive stars and its dependence upon stellar metallicity (e.g. Meynet & Maeder, 2002a,b). The value of the parameter $\alpha_{\rm CBM}$ is chosen by imposing that equation (3) reproduces the present-time rate of neutron star merging in the Galaxy. Several observational estimates of this rate appeared in the literature (van den Heuvel & Lorimer 1996; Kalogera & Lorimer 2000; Belczynsky et al. 2002; Kalogera et al. 2004). Here, we take that of Kalogera et al. (2004), $R_{\rm CBM}(t_{\rm now}) = 83^{+209.1}_{-66.1}$ $\rm Myr^{-1}$, and find $\alpha_{\rm CBM} = 0.018$.

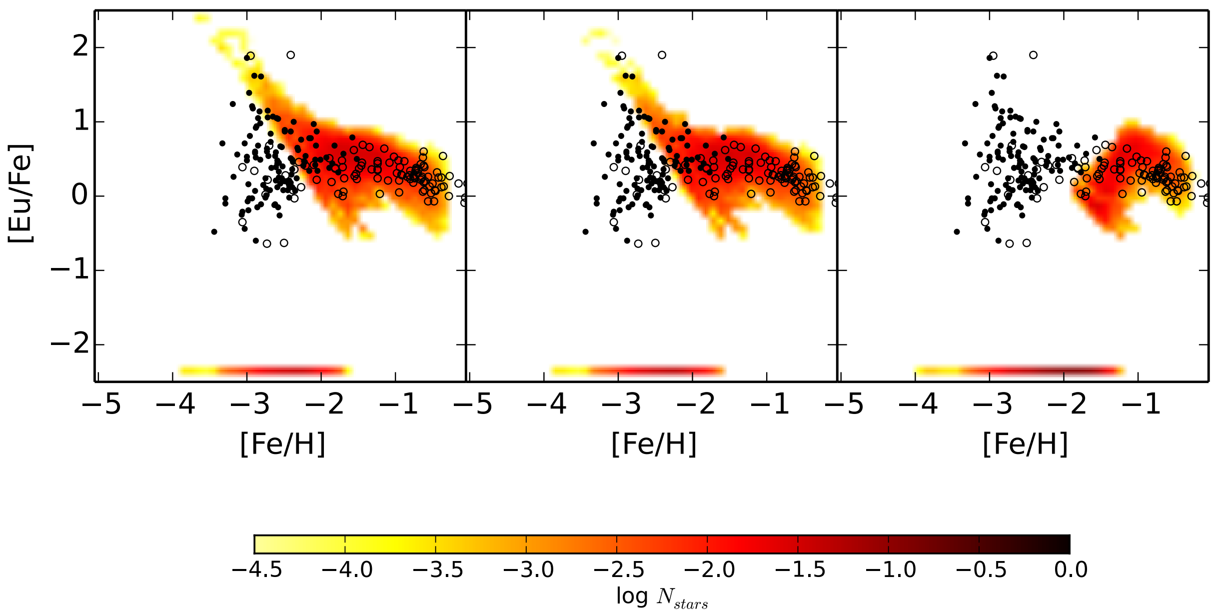


Predicted (lines) and observed (symbols) [Eu/Fe] vs [Fe/H] relations for solar neighborhood stars. **CBM are the only Eu producers.** Figure from Matteucci et al. (2014).



Predicted (lines) and observed (symbols) [Eu/Fe] vs [Fe/H] relations for solar neighborhood stars. **Eu is produced by both CBMs and massive stars.** Figure from Matteucci et al. (2014).

Inhomogeneous chemical evolution model by Cescutti et al. (2015):



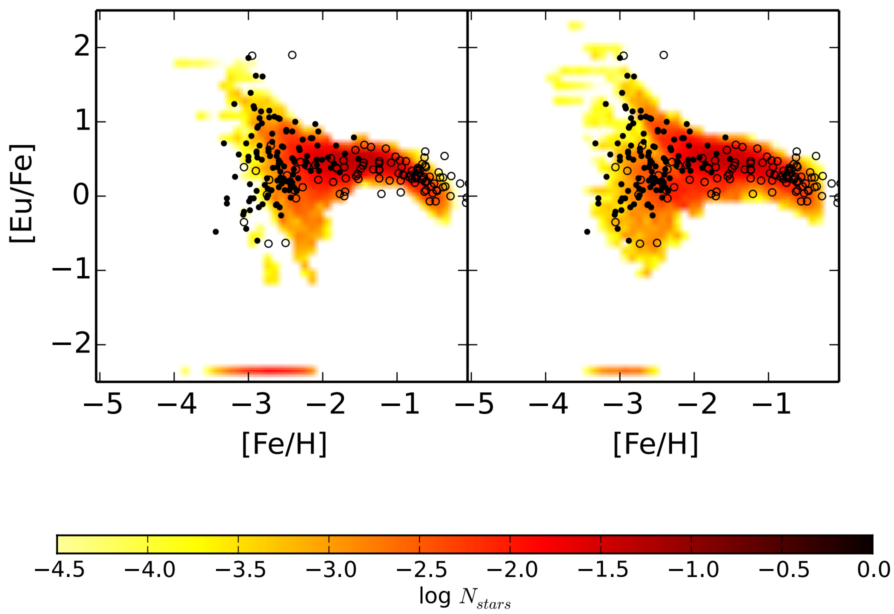
$M^{CBM,Eu} = 5 \times 10^{-6} M_\odot$;

$\Delta t_{CBM} = 1, 10, 100$ Myr

(from left to right)

Predicted (density maps) and observed (circles) [Eu/Fe] vs [Fe/H] relations for halo stars. **Eu is produced by CBMs only.**

Inhomogeneous chemical evolution model by Cescutti et al. (2015):



Predicted (density maps) and observed (circles) [Eu/Fe] vs [Fe/H] relations for halo stars. **Eu is produced by CBMs + 20-50 $M_\odot$ stars (left) or CBMs + MRD SNe (10% of 8-80 $M_\odot$ stars, right).**

Conclusions

- The history of Eu enrichment in the Galaxy is explained by models in which both compact binary mergers and massive stars are responsible for Eu production.
- As for the massive star channel, magneto-rotational driven SNe (Winteler et al. 2012) seem to be a promising source, while more 'classic' scenarios do not work (Arcones et al. 2007; Wanajo et al. 2011; Arcones & Thielemann 2013, and refs. therein).
- Not only the average trend, but also the observed dispersion are well explained by the models.
- Chemical evolution is a useful test bed for hydrodynamical simulations of both massive star explosions and coalescence of compact binary systems.