Early Cosmic Evolution of Europium from Core Collapse Supernovae and/or Neutron Star Mergers

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ABSTRACT

Context. The rapid neutron-capture process, or r-process, is known to be of fundamental importance for explaining the origin of approximately half of the > 60 stable nuclei observed in nature. Despite important efforts, the astrophysical site of the r-process remains unidentified. The two most promising astrophysical sites of the r-process, namely Core Collapse SuperNovae (CCSN) and Neutron Star Mergers (NSM), are considered in the context of the early cosmic chemical evolution through the origin and evolution of a typical r-process element, Eu.

Aims. While both scenarios are known to be at the origin of the bulk galactic r-process content, different histories for the galactic enrichment may be expected. The Eu abundance in very-low-metallicity stars is used to shed light on the possible CCSN and NSM contributions in the early Universe.

Methods. Predictions are made here using a hierarchical model for structure formation for which a special attention is paid to a proper description of the stellar formation rate. Eu yields from NSM are taken from recent nucleosynthesis calculations. Observations of Eu in ultra-metal-poor stars are considered to constrain the model.

Results. We find that the bulk of Eu observations at [Fe/H] > −2.5 is rather well fitted by both CCSN and NSM scenarios. However, at lower metallicity, the Eu cosmic evolution tends to favor NSM as the main astrophysical site for the r-process since CCSN overproduce Eu at high redshift (corresponding to very low metallicities). Our calculations allow to constrain the coalescence timescale in the NSM scenario: typical timescales of ∼ 0.1–0.2 Gyr are found to be compatible with observations. The observed evolution of Eu abundances puts also a constraint on the merger rate, which allows an independent prediction of the expected merger rate in the horizon of the gravitational wave detectors advanced Virgo/ad LIGO, as well as a prediction for the expected rate of electromagnetic counterparts to mergers (“kilonovae”) in large NIR surveys.

Conclusions. While our model favors NSM as the main r-process site, more observations at very low metallicity and improved predictions from the nucleosynthetic evolution of massive stars are needed to confirm this result.

Key words. cosmology: dark ages, reionization, first stars – stars: abundances, gamma-ray bursts, neutron, Population III – galaxies: evolution

1. Introduction

The rapid neutron-capture process, or r-process, of stellar nucleosynthesis is invoked to explain the production of the stable (and some long-lived radioactive) neutron-rich nuclides heavier than iron that are observed in stars of various metallicities, as well as in the solar system (for a review, see Arnould et al. 2007). In recent years, nuclear astrophysicists have developed more and more sophisticated r-process models, trying to explain the solar system composition in a satisfactory way by adding new astrophysical or nuclear physics ingredients.

The r-process remains the most complex nucleosynthetic process to model from the astrophysics as well as nuclear-physics points of view. The site(s) of the r-process is (are) not identified yet, all the proposed scenarios facing serious problems. Complex—and often exotic—sites have been considered in the hope of identifying astrophysical conditions in which the production of neutrons is large enough to give rise to a successful r-process.

Progress in the modelling of type-II supernovae and γ-ray bursts has raised a lot of excitement about the so-called neutrino-driven wind environment. However, until now a successful r-process cannot be obtained ab initio without tuning the relevant parameters (neutrino excess, entropy, expansion timescale) in a way that is not supported by the most sophisticated existing models (Wanajo et al. 2011; Janka 2012).

Early in the development of the theory of nucleosynthesis, an alternative to the r-process in high-temperature supernova environments was proposed (Tsuruta & Cameron 1963). It relies on the fact that at high densities (typically $\rho > 10^{10}$ g/cm³) matter tends to be composed of nuclei lying on the neutron-rich side of the valley of nuclear stability as a result of free-electron captures. The astrophysical plausibility of this scenario in accounting for the production of the r-nuclides has long been questioned. It remained largely unexplored until the study of the de-
compression of cold neutronised matter resulting from tidal effects of a black hole (BH) on a neutron star (NS) companion (Lattimer & Schramm, 1974; Lattimer et al., 1977; Mewe, 1989).

Recently, a special attention has been paid to NS-NS or NS-BH mergers, as they are the most promising sources of gravitational waves for ground-based detectors such as advanced Virgo/ad Ligo (Phinney, 1991; Narayan et al., 1991; Virgo collaboration, 2009; Abadie et al., 2010; LIGO Scientific collaboration, 2011; Aasi et al., 2014; Belczynski et al., 2014) and because several evidence (see Berger, 2014, for a recent review) suggest in addition that these are the progenitors of short gamma-ray bursts (Paczynski, 1986; Eichler et al., 1989; Narayan et al., 1992; Mochnikovitch et al., 1993). Recent simulations show that, after the merger, the relic BH-torus system can produce an ultra-relativistic ejection along its rotation axis (Rezzolla et al., 2011), potentially leading to a short GRB. The similarities between the properties of the prompt emission in short and long GRBs (see e.g. Guiriec et al., 2010) suggest that the same dissipation process is at work in these two classes of bursts (Bošnjak & Daigne, 2014) and that the main differences are the lifetime of the central engine, leading to shorter events, and the density of the circumburst medium, leading to weaker afterglows (Nakar, 2007). In addition, hydrodynamic simulations have confirmed that a non-negligible amount of matter, typically about $10^{-3}$ to $10^{-2}$ $M_\odot$, can be ejected quasi-isotropically (Janka et al., 1999; Rosswog et al., 1999, 2004; Oechslin et al., 2007; Goriely et al., 2011; Bauswein et al., 2013; Goriely et al., 2013; Just et al., 2014; Wanao et al., 2014).

In contrast to the supernova site, investigations with growing sophistication have also confirmed NSM ejecta as viable sites for strong r-processing (Arnaud et al., 2007; Goriely et al., 2011; Bauswein et al., 2013; Goriely et al., 2013; Just et al., 2014; Freiburghaus et al., 1999; Goriely et al., 2009; Metzger et al., 2010; Roberts et al., 2011; Korobkin et al., 2014; Wanao et al., 2014). In particular, recent nucleosynthesis calculations (Just et al., 2014) show that the combined contributions of both the dynamical (prompt) ejecta expelled during the binary NS-NS or NS-BH merger and the neutrino and viscously driven outflows generated during the post-merger remnant evolution of the relic BH-torus systems lead to the production of r-process elements from $A > 90$ up to thorium and uranium with an abundance distribution that reproduce extremely well the solar distribution, as well as the elemental distribution spectroscopically determined in very-low-metallicity stars. The ejected mass of r-process material, combined with the predicted astrophysical event rate (around $10^{-5}$ yr$^{-1}$ in the Milky Way, Dominik et al., 2012), can account for the majority of r-material in our Galaxy (Goriely et al., 2011; Bauswein et al., 2013; Just et al., 2014). Nearly all of the ejecta are converted to r-process nuclei, whose radioactive decay heating leads to potentially observable electromagnetic radiation in the optical and infrared bands (Li & Paczynski, 1993; Metzger et al., 2010) with 100–1000 times fainter peak brightnesses than those of typical supernovae and durations of only days (Goriely et al., 2011; Roberts et al., 2011; Bauswein et al., 2013). These “macronovae” or “kilonovae” are intensely searched for (with a recent, possible first success in association with the short GRB 130603B, see Berger et al., 2013; Tauris et al., 2013). Their unambiguous discovery would constitute the first detection of r-material in situ.

However, despite a growing wealth of observations of r-process-rich stars of different metallicities, including in very low metallicity stars (François et al., 2007; Spedden et al., 2008; Ren et al., 2012; Roederer et al., 2012, 2014b,c) (and references therein), and increasingly more sophisticated r-process models, the astrophysical site of r-process is not clearly identified. Although core collapse supernovae (CCSN) remain promising, especially in view of their potential to significantly contribute to the galactic enrichment (Argast et al., 2003), they remain handicapped by large uncertainties associated mainly with the still incompletely understood mechanism that is responsible for the supernova explosion and the persistent difficulties to obtain suitable r-process conditions in self-consistent dynamical explosion and neutron-star cooling models (Janka, 2012; Hifdepoli et al., 2010; Fischer et al., 2014). In addition, nucleosynthesis predictions of the detailed composition of the ejected matter remain difficult due to the remarkable sensitivity of r-process calculation to the still unknown initial properties of the ejecta.

In contrast, NS-NS or NS-BH mergers, which today are clearly favored from a nucleosynthesis point of view, have been claimed to be ruled out as the dominant r-process source by early studies on the basis of inhomogeneous chemical evolution models (Argast et al., 2004), due to their low rates of occurrence which seem to be inconsistent with observations of low-metallicity r-process-rich stars. In addition, the significant amount of r-process material ejected by a single NSM leads to a large scatter in r-process enrichment at later times that does not seem to be confirmed by observations.

A few more recent studies (Matteucci et al., 2014; Komiya et al., 2014; Cescutti & Chiappini, 2014; Mennekens & Vanbeveren, 2014; Tsujimoto & Shigeyama, 2014a,b; Shen et al., 2014; van de Voort et al., 2014) have reconsidered the chemical evolution of r-process elements in different evolutionary contexts, but have reached rather different conclusions. More specifically, Matteucci et al. (2014) explored the Eu production in the Milky Way using a local chemical evolution model. Their observational constraints at low metallicity come essentially from the observations of Eu in metal-poor stars by (François et al., 2007), without including the related error bars and upper limits. The relevance of the NSM scenario on the production of Eu has been studied by testing the effect of (i) the coalescence timescale of the binary system (ii) the Eu yield expected to be ejected from NSM and (iii) the range of the initial mass of the NS progenitors. Similarly, the CCSN scenario has been explored by considering different possible Eu yields assuming a strong r-process taking place in CCSN. In this framework, NSM is found to be potentially a major r-process source if the coalescence timescale is of the order of 1 Myr and the ejected Eu yield of the order of $3 \times 10^{-7} M_\odot$ for a mass range of progenitors of NS ranging between 9 and 50 $M_\odot$. The scenario where both CCSN and NSM contribute to the Eu synthesis is also compatible with observations provided NSM produce $2 \times 10^{-7} M_\odot$ of Eu per system and each CCSN with progenitors in the range of 20–50 $M_\odot$ produce around $10^{-8} - 10^{-9} M_\odot$ of Eu.
In parallel, Komiva et al. (2014) investigated the chemical enrichment of r-process elements using a hierarchical galaxy formation model. The CCSN scenario is found to reproduce the scatter of observed r abundances in low metallicity stars if about 10% of CCSN in the low-mass end (i.e. for progenitor mass of the order of 10 M⊙) is the dominant r-process source and the star formation efficiency amounts to about 0.1 per Gyr. For NSM to be the main r-process site, a coalescence timescale of about 10 Myr with an event rate about 100 times larger than currently observed in the Galaxy need to be considered. We note that the coalescence timescale in the studies by Matteucci et al. (2014) and Komiva et al. (2014) is constrained to be surprisingly short compared to known systems in our Galaxy and theoretical predictions by stellar population models (see Sect. 4).

Cescutti & Chiappini (2014) computed inhomogeneous chemical evolution models for the galactic halo, taking into account the contribution of electron-capture and magnetorotationaly driven supernovae (including fast-rotating progenitors), but not NSM, to explain the Eu scatter in metal-poor stars.

Mennekens & Vanbeveren (2014) also studied the temporal evolution of the galactic population of double NS binaries, mixed systems with a NS and BH component, and double BH binaries. They conclude that, except for the first 100 Myr of the evolutionary phase of the Galaxy, double compact star mergers may be the major production sites of r-process elements, and it is probable that the mixed NS-BH systems dominate over double NS binary mergers.

Finally, Shen et al. (2013) and van de Voort et al. (2014) estimated the enrichment history of r-process elements in the Galaxy, as traced by the [Eu/Fe] ratio, using a high resolution cosmological zoom-in simulation. Unlike previous studies, it was found that the nucleosynthetic products from compact binary mergers can be incorporated into stars of very low metallicity and at early times, even with a minimum time delay of 100 Myr and that compact binary mergers could be the dominant source of r-process nucleosynthesis in the Galaxy.

In the present paper, we revisit the origin and the evolution of a typical r-process element, Europium, taking into account (i) the last observational data in halo stars and in external galaxies (for corresponding references see Sect. 2), (ii) the recent nucleosynthetic analysis for ejecta of compact binary mergers (Goriely et al., 2011; Bauwein et al., 2013; Just et al., 2014), and (iii) the recent new observational constraints obtained on the global cosmological star formation rate (SFR) (Bebrozo et al., 2013; Bebroszo & Silk, 2014; Oesch et al., 2014; Bouwens et al., 2014; Kistler et al., 2014; Tenti et al., 2013). The Eu evolution is studied for both astrophysical scenarios, CCSN and NSM, in a cosmological context, using a model of the cosmic chemical evolution from the first stars to the present Universe (Daigne et al., 2006; Rollinde et al., 2009; Vangioni et al., 2014) based on a hierarchical model for structure formation (Press & Schechter, 1974; Sheth & Tormen, 1999; Jenkins et al., 2001; Wyithe & Loeb, 2003). In Sect. 2 we analyse the Eu observational constraints, specifically at low metallicities. In Sect. 3 the cosmological evolutionary model is described and confronted to some observational constraints such as the Thomson optical depth of the CMB and the [Fe/H] evolution, for three possible evolutions of the cosmic SFR suggested by the most recent measurements at high redshift and following the study of Vangioni et al. (2014). In Sect. 4 the CCSN and NSM Eu production sites are discussed, including the large uncertainties affecting the various input parameters needed in our cosmic chemical evolution model. The resulting evolution of the Eu enrichment in the Universe is discussed in Sect. 5 for each of the three cosmic SFR scenarios. Both astrophysical sites (CCSN, NSM) are considered separately and their capacity to explain observations, especially at low metallicities are discussed. The sensitivity of our results with respect to the various input, in particular the Fe production in massive stars and the mass range of the initial mass function (IMF) of stars are also studied. Finally, the cosmic binary compact object merger rate as a function of redshift is estimated in Sect. 6 leading to a prediction of the expected merger rate in the horizon of advanced Virgo/ad LIGO. This allows us also to compute the expected kilonova rate as a function of the limiting magnitude and to discuss the expected rates for the Euclid and LSST surveys. Conclusions are drawn in Sect. 7.

2. Eu observations

We have gathered most of the recent observations on Eu abundance (Eu/H and [Eu/Fe] as a function of [Fe/H]) in metal poor stars (Francois et al., 2007; Honda et al., 2008; Barklem et al., 2003; Simmerer et al., 2004; Roederer, 2011; Roederer et al., 2010, 2012; 2014; Ren et al., 2012; Worlev et al., 2013) together with the abundances found in dwarf spheroidal systems (Shertone, Coté & Stetson, 2001; Shertone, et al., 2003; Geilsler et al., 2005; Cohen and Huang, 2009; Letarte et al., 2010; Starkenburg et al., 2013; McWilliam et al., 2013). It is interesting to note that the bulk of data coming from external dwarf galaxies is embedded in galactic ones. The solar abundances are taken from Lodders (2003).

The determination of Eu abundance suffers from the fact that only few transitions are visible in the spectrum of metal poor stars. The strongest transitions are rather weak and it becomes particularly difficult to detect and estimate the abundance of this element at low metallicities. Typically, the strongest Eu line becomes almost undetectable below [Fe/H] ≃ -3.5 dex. Although we cannot fully rule out the existence of few stars below [Fe/H] ≃ -3.5 dex for which the Eu abundance has been measured is small. The sample used in the present paper does not represent an unbiased sample of stars, so the distribution function of [Eu/Fe] vs [Fe/H] has no significance. In several stars, the upper limit of the Eu abundance has been computed. These upper limits are useful as they complement the real measurement and show that, so far, no star below [Fe/H] ≃ -3.5 dex has a very high [Eu/Fe] ratio, i.e. of the order of what is found in stars at [Fe/H] ≃ -3.5 dex. Although we cannot fully rule out the existence
of such stars with $[$Eu/Fe$] \geq 1.2$ dex, the present sample seems to indicate that the upper envelope of the $[$Eu/Fe$]$ stops to rise at $[$Fe/H$] \approx -3.0$ dex. This hypothesis receives support from the recent study of Hansen et al. (2014b) who analyzed 4 stars with $[$Fe/H$] \leq -4.00$ dex and did not report any measurement of the Eu abundance although the wavelength range of the spectra used in this study covers the Eu transitions wavelength.

The inspection of observed abundances (see below in Fig. 5) shows the apparent existence of two branches starting below $[$Fe/H$] \approx -2.8$ dex, the first one with high values of $[$Eu/Fe$]$ as high as $+2.0$ dex, the second one with decreasing values down to $[$Eu/Fe$] \approx -1.0$ dex at $[$Fe/H$] \approx -3.2$ dex. As the sample is biased, it is difficult to be fully confident about the reality of this two branches. The plot could also well be interpreted as an increase of the dispersion as the metallicty decreases.

The origin of the stars with a high level of r-process elements like Eu is still a matter of debate. A recent analysis by Roederer et al. (2014b,c) has shown and confirmed that this overabundance is also found in main-sequence turn-off stars rejecting the hypothesis that the star would have produced itself such overabundances. They also did not find any compelling evidence to suggest that a noticeable high fraction of highly r-process enriched stars are members of binary systems, assigning the origin of the r-process enhancement to a companion star. They also confirmed that these peculiar stars do not present a different α-element chemical signature from the bulk of the other metal poor stars. Therefore, the site responsible for the production of this r-process enhancement is not expected to produce any chemical anomalies for light elements.

### 3. Cosmological evolution model

We follow the cosmic chemical evolution using the model developed by Daigne et al. (2006), Rollinde et al. (2009), Vangioni et al. (2014), which is based on a hierarchical model for structure formation (Press & Schechter, 1974; Sheth & Tormen, 1999; Jenkins et al., 2001; Wyithe & Loeb, 2003). Assuming a given evolution of the cosmic SFR, the model tracks baryons i) in stars and their remnants (white dwarfs (WD), NS, BH) within structures, ii) in gas within structures (the interstellar medium, ISM), and iii) in gas outside structures (the intergalactic medium, IGM). The model includes mass (baryon) exchange between the IGM and ISM, the ionizing flux from stars, the ionization state of the IGM and the Thomson optical depth of the CMB.

#### 3.1. Cosmic SFR

A key ingredient to all evolution models is the cosmic SFR, whose evolution with redshift is constrained by many observations. Recent data from the Hubble Ultra Deep Field have significantly extended the range of redshift for its determination, from $z = 4$ up to 10 (Bouwens et al., 2007; Bouwens et al., 2008, 2011, 2013; Oesch et al., 2012, 2013). Even more recent observations of high $z$ galaxies and GRBs tend to favor a large amount of still unseen SFR at $z > 9$ (Kistler et al., 2013; Wang, 2013). This last study suggests that SFR density may only decline out at $z = 11$ and that GRBs may be useful in exploring the unseen faint dwarf galaxies at high redshift. Behroozi et al. (2013) re-analyzed the average star formation histories from $z = 0$ to 8 and obtained consistent results with observed galaxy stellar mass functions, specific star formation rates and SFR. Moreover, high-redshift galaxy evolution has also been predicted by Behroozi & Silk (2014) who, including recent constraints (Behroozi et al., 2013; Oesch et al., 2013; Kistler et al., 2013; Trenti et al., 2013), probed the unobserved $z > 8$ galaxy populations. The resulting observationally constrained SFR is illustrated in Fig. 1 as a function of the redshift.

The evolution of the cosmic SFR as a function of redshift can be parametrized by the following form proposed by Springel & Hernquist (2003).

$$\psi(z) = \nu \left[ \frac{a \exp[b(z-z_m)]}{a - b + b \exp[a(z-z_m)]} \right],$$

(2)

where $\nu$ (in $M_\odot$/yr/Mpc$^3$) and $z_m$ correspond to the star formation rate and the redshift at the SFR maximum, respectively, while $b$ and $a - b$ fix the SFR slope at low and high redshifts, respectively.

Due to the fundamental importance of the SFR in the chemical evolution model, we consider for the present analysis SFR modes which reproduce the low redshift SFR measurements and take into account their uncertainties at high redshift. We impose in addition that the cosmic evolution of $[$Fe/H$]$ and the Thomson optical depth of the CMB.

A specific analysis of the observational constraints on the parameters of different possible SFR modes has been presented in Vangioni et al. (2014). We use their results for the two first SFR modes considered in the present study, namely SFR1, which corresponds to a standard SFR with an additional Population III star component at high redshift, and SFR2, which is a SFR enhanced at high $z$. The third mode considered here, SFR3, is chosen as the upper limit of the SFR at high redshift obtained from the constraint of the Thomson optical depth of the CMB (see Fig. 2).

As shown in Fig. 1, SFR1 fits the observational constraints from Behroozi et al. (2013), Bouwens et al. (2013) and Oesch et al. (2014), whereas SFR2 and SFR3 take into...
For each mode, the IMF slope is set to the Salpeter value, Vangioni et al. (2014).

in the two next subsections. A detailed description of the parameters: 

\[ \nu = 0.15, \ z_m = 1.7, \ a = 2.8, \ b = 2.45; \]

SFR2 includes a unique mode of star formation between 0.1 M\(_\odot\) and 100 M\(_\odot\), with the following parameters:

\[ \nu = 0.36, \ z_m = 2.6, \ a = 1.92, \ b = 1.5. \]

For each mode, the IMF slope is set to the Salpeter value, i.e. \( x = 1.35 \). These three scenarios for the cosmic SFR are not only compatible with the direct measurements described above (Fig. 1), but lead to a cosmic evolution that is compatible with two fundamental observations discussed in the two next subsections. A detailed description of the cosmic evolution model used for these calculations can be found in Daigne et al. (2006); Rolinde et al. (2009); Vangioni et al. (2014).

3.2. Reionisation

Concerning the ionization history, the evolution of the volume filling fraction \( Q_{\text{ion}}(z) \) of ionized regions at redshift \( z \) is given by

\[ \frac{d Q_{\text{ion}}(z)}{dz} = \frac{1}{n_b} \frac{dn_{\text{ion}}(z)}{dz} - \alpha_B n_b C(z) Q_{\text{ion}}^2(z) (1 + z)^3 \left| \frac{d z}{dz} \right|, \]

where \( n_b \) is the comoving density in baryons, \( n_{\text{ion}}(z) \) the comoving density of ionizing photons, \( \alpha_B \) the recombination coefficient, and \( C(z) \) the clumping factor. This last factor is taken from Greif & Bromm (2006) and varies from a value of 2 at \( z \leq 20 \) to a constant value of 10 for \( z < 6 \). The escape fraction, \( f_{\text{esc}} \), is set to 0.2 for each of our SFR modes. The number of ionizing photons emitted by massive stars is calculated using the tables given in Schaerer (2002). Finally, the Thomson optical depth between redshifts \( z' = 0 \) and \( z \) is computed following Greif & Bromm (2006), i.e.

\[ \tau = c \sigma_T n_b \int_0^z dz' Q_{\text{ion}}(z') (1 + z')^3 \left| \frac{d z'}{dz} \right|, \]

where \( \sigma_T \) is the Thomson scattering cross section. Fig. 2 shows the evolution of the volume filling fraction \( Q_{\text{ion}} \) and the ionizing flux for the three SFR histories, and the resulting Thomson optical depth, the value of which is found to agree well with the measurement from CMB observations by WMAP (Hinshaw et al., 2013) at high redshift. As mentioned above, the SFR1 scenario without the Pop III mode at high redshift would not fulfill this constraint (Vangioni et al., 2014).

3.3. Cosmic chemical evolution

Our model includes the lifetimes estimated by Maeder & Meynet (1980) for intermediate mass stars with \( 0.9 < M/M_\odot < 8 \) and by Schaerer (2002) for more massive stars. Lifetimes of low mass stars \( (M/M_\odot < 0.9) \), such as the old halo stars where abundances of Eu are measured at low metallicity, are long enough for the star to be still observed today, whatever the redshift of formation. Stars formed at redshift \( z \) inherit their initial chemical composition from the abundances in the ISM at the same redshift. Thus, the observed abundances in stars reflect, in a somewhat complex way, the yields of all massive stars that have exploded earlier. The stellar yields adopted in our model depend on the stellar mass and metallicity. We use the tables of yields from Woosley & Weaver (1995) for massive stars \( (M/M_\odot < 40) \). These tables also provide the remnant type (NS, BH). An interpolation is made between the different metallicities \( (Z = 0, 0.0001Z_\odot, 0.001Z_\odot, 0.1Z_\odot, Z_\odot) \) and masses, and tabulated values are extrapolated for stars beyond 40 M\(_\odot\).

Fig. 3 shows the \([Fe/H]\) evolution as a function of time and redshift for the three SFR modes. Data correspond to chemical abundance determinations in about 250 damped Lyα (DLA) systems (Rafelski et al., 2012) (and references therein) as a function of redshift. In their paper, they present 47 DLA systems at \( z > 4 \) observed with the Echelle Spectrograph and Imager and the High Resolution Echelle Spectrometer on the Keck telescopes (for more details see Vangioni et al., 2014). We use Eq. 11 to associate a time with the observed redshift for each observed DLA system. As illustrated in Fig. 3 the cosmic
evolution of the iron abundance is reproduced by each of the three scenarios, passing through the upper limit of the points. However, note that these iron abundances are measured in the gas phase which should be considered as lower limits due to depletion into grains in the ISM. As seen in Fig. 3 (middle panel), the early iron evolution depends strongly on the shape of the SFR at high z. In particular, it can be seen that a cosmic [Fe/H] = −4 enrichment is achieved at the very beginning, Δt = t − t₀ ≃ 0.015 Gyr for SFR2, 0.05 Gyr for SFR3, and 0.4 Gyr for SFR1. This time delay in the early Fe enrichment can have a drastic impact on the interpretation of the cosmic chemical evolution with respect to observations, as discussed in Sect. 5.

4. Properties of the r-process sites

As discussed in the introduction, two possible astrophysical sites for the production of Eu are considered, i.e. CCSN and NSM. Each of these sites may potentially contribute to the galactic r-process enrichment, but we will assume in the present work that they are mutually exclusive, so that the Eu production in the Universe is either originating from CCSN or NSM but not from a mix of both sites. While the Eu production in the CCSN scenario essentially depends on the amount of Eu ejected by the explosion, in the NSM scenario, it is also function of the binary fraction of compact objects and the coalescence timescale of the binary system. These quantities are discussed below.

4.1. Eu yields from CCSN

Since there exists so far no consistent r-process calculation in CCSN, the Eu yields from supernovae remain highly uncertain. The CCSN Eu yields are therefore free parameters that can only be adjusted to reproduce some observables, like the [Eu/Fe] trend as a function of the [Fe/H] observed in galactic stars or the total amount of Eu material in the Galaxy. In particular in this latter case, if we assume that the heavy-element composition in the solar system is representative for the whole Galaxy (as suggested by the small scatter of the Eu abundance in the present-day Milky Way), for a Eu mass fraction of 3.7 × 10⁻¹⁰ (Lodders, 2003; Asplund et al., 2009) and a total galactic baryonic mass of 6 × 10¹⁰ M☉ (McMillan, 2011), this implies a Eu Galactic content of 22 M☉. Assuming that the CCSN events occur at a constant rate identical to the currently observed one, i.e. about one per century during the approximate age of the Galaxy of 1.3 × 10¹⁰ yr, some 1.3 × 10⁶ type-II explosions should be responsible for the 22 M☉ of Eu, i.e. each CCSN event is expected to produce about 1.7 × 10⁻⁷ M☉ of Eu. For this reason, by simplicity, a constant yield of 10⁻⁷ M☉ of Eu is adopted here for all CCSN, regardless of the mass of the progenitor.

4.2. Eu yields from NSM

While a successful r-process cannot be obtained ab initio in CCSN simulations, NSM models consistently predict a significant production and ejection of r-process material. In particular, a mass-weighted combination of the dynamical ejecta from the binary merger phase and the secular ejecta from the BH-torus evolution has been shown (Just et al., 2014) to reproduce the solar r-abundance pattern, and therefore also the elemental one seen in ultra-metal-poor stars, amazingly well in the whole 90 < A ≤ 210 range. This calculation represents today the most consistent estimate of Eu production by NS-NS and NS-BH mergers taking consistently into account both the prompt ejecta as well as the relic BH-torus outflow contributions. For this reason, the Eu yields obtained in such combined models are considered in the present study. More precisely, the three combined systems (merger model plus remnant model) co-
responding to models with torus masses $M_{\text{torus}} = 0.03, 0.1$ and 0.3 $M_\odot$ (see Fig. 19 of Just et al. (2014) are found to eject between $7 \times 10^{-5}$ and $2 \times 10^{-4} M_\odot$ of Eu. A fiducial Eu yield of $7 \times 10^{-5} M_\odot$ is adopted here.

4.3. The NS-NS and NS-BH merger rates

Astrophysical estimates for compact-binary coalescence rates depend on a number of assumptions and unknown model parameters and are still uncertain (Abadie et al., 2010). Among the various estimates, the rate predictions for NS-NS binary systems is the most reliable one since they are based on extrapolations from observed binary pulsars in our Galaxy. These estimates lead to a coalescence rate of about 100 Myr$^{-1}$ per Galaxy, although this rate could plausibly range from 0.1 Myr$^{-1}$ to 1000 Myr$^{-1}$ (Kim et al., 2003; Kalogera et al., 2004; Mennekens & Vanbeveren, 2014).

Due to the lack of observational data, predictions of the frequency of NS-BH mergers remains even more uncertain and rely exclusively on theoretical studies (Tutukov & Yungelson, 1993; Voss & Tauris, 2003; O’Shaughnessy et al., 2008; Dominik et al., 2012; Dominik et al., 2013; Mennekens & Vanbeveren, 2014; Postnov & Yungelson, 2014). These population synthesis models estimate galactic merger rates between $2 \times 10^{-9}$ and $10^{-5}$ per year. The range reflects the challenge in comprehensively modelling the formation and evolution of stellar binaries and their remnants. Bauswein et al. (2014) determined an independent upper limit on the merger rate of NS-BH binaries by comparing the predicted r-process nucleosynthesis yields of such systems with the observed galactic amount of r-process material. A strict upper limit of the average NS-BH merger rate of about $6 \times 10^{-5}$ per year was found. Dominik et al. (2013) calculated the cosmological merger rates of NS-NS, NS-BH, BH-BH systems as a function of redshift assuming different SFR histories. While in most cases NS-NS systems dominate the merger rates in the local universe, BH-BH mergers are found to dominate at high redshift.

In our model (like the one of Matteucci et al. (2014), the merger rate is determined assuming that the formation rate of NS-NS/BH binary systems is a fraction $\alpha$ of the NS birth rate, and that these binary systems merge after a delay $\Delta t_{\text{NSM}}$. The NS birth rate is computed as a function of the redshift and takes into account the dependence of the stellar remnant type on the mass and metallicity. More precisely, for stars above 8 $M_\odot$, the remnant mass is taken from Woosley & Weaver (1995) i.e. the remnant is assumed to be a BH above 30 $M_\odot$ and a NS otherwise.

4.4. The coalescence timescale

The coalescence timescale $\Delta t_{\text{NSM}}$ is defined as the delay between the formation of the binary system of two neutron stars or a neutron star and a black hole (note that it does not include the lifetime of the two star progenitors of the compact objects). It is a key ingredient for chemical evolution models as it is responsible for a different evolution of r-process elements in the NSM compared to the CCSN scenario where there is no additional delay after the formation of a neutron star and the associated supernova.

The angular momentum loss due to the emission of gravitational waves governs the coalescence timescale. Its value strongly depends on the properties of the binary system, and in particular on the initial separation $a$ (or or-
Fig. 4. Distribution of the coalescence timescale $\Delta t_{\text{NSM}}$ for NS/NS binary systems. The coalescence timescale $\Delta t_{\text{NSM}}$ is defined as the delay between the formation of the two neutron stars and the final merger. The plot shows the fraction of mergers with a coalescence timescale above a given value in Myr, for two different metallicities. This distribution has been obtained from an updated version of the population synthesis model described in [Belczynski et al. 2002]. It covers a broad range of values with a distribution falling approximately like $p(\Delta t_{\text{NSM}}) \propto \Delta t_{\text{NSM}}$.

The distribution of the coalescence timescale can be estimated using a population synthesis code for binary systems, which can be calibrated with observed systems. The result is plotted for two different metallicities in Fig. 4. It has been obtained using the StarTrack code described in [Belczynski et al. 2002, 2008], where standard stellar evolution models are implemented with the most updated physics regarding the relevant processes for the evolution of binary systems. Fig. 4 has been produced using the results of a recently updated version of the code (Mink & Belczynski in preparation), including new prescriptions for stellar wind mass loss rates [Vink et al. 2011, Vink & Grohener 2012], for supernova models [Fryer et al. 2012], for the common envelope phase of evolution [Dominik et al. 2012], adding electron capture supernovae for NS formation [Belczynski et al. 2008], and taking into account recent observational constraints on massive stars in binary systems [Sana et al. 2012]. Additionally, the evolutionary model included in the code does not allow for the progenitors to undergo a common-envelope phase while one of the massive binary stars is evolving through the Hertzsprung gap (see Belczynski et al. 2007 for more details). This corresponds to a conservative assumption and additional NS-NS mergers may form if this assumption is relaxed. Compared to the results of Belczynski et al. (2002), this updated calculation shows a fraction of undetected galactic merging NS-NS systems which is significantly decreased, now at the level of \( \sim 10\% \). As illustrated in Fig. 4, the distribution of coalescence timescales predicted by such a detailed calculation shows a broad range of values: at solar metallicity \( Z = Z_\odot \) (resp. at metallicity \( Z = 0.1 Z_\odot \)), it is found that 29\% (resp. 28\%) of systems have $\Delta t_{\text{NSM}}$ \( \leq 100 \) Myr, 13\% (resp. 16\%) have $100 < \Delta t_{\text{NSM}} \leq 300 \) Myr, 15\% (resp. 14\%) have $0.3 < \Delta t_{\text{NSM}} \leq 1 \) Gyr, 17\% (resp. 16\%) have $1 < \Delta t_{\text{NSM}} \leq 3 \) Gyr, and 26\% (resp. 26\%) have $\Delta t_{\text{NSM}} > 3 \) Gyr. The impact of the metallicity is small. It appears clearly that a significant fraction of systems has a coalescence timescale of a few 100 Myr or less. These systems will dominate the early evolution of Eu in the NSM scenario.

In our cosmic chemical evolution model, both the fraction \( \alpha \) of binary systems and the coalescence timescale $\Delta t_{\text{NSM}}$ are taken as free parameters and are adjusted to reproduce the evolution of Eu as a function of metallicity (or redshift) deduced from the observations described in Sect. 2. The merger rate at time \( t \) is given by

$$ R_{\text{NSM}}(t) = \alpha \int \text{dm} \Phi(m) \Psi(t) \Xi(m, Z(t)) $$

where $\Phi(m)$ is the IMF integrated over the whole stellar mass range, $\Psi(t)$ the SFR, $t_*$ the formation time of the progenitor, such that $t_* + \tau(m, Z(t_*)) + \Delta t_{\text{NSM}} = t, Z(t_*)$ the metallicity at the epoch of formation of the progenitor, $\tau(m, Z(t_*))$ the lifetime of a star formed with mass \( m \) and metallicity $Z(t_*)$, and $\Xi(m, Z(t_*))$ is 1 if the stellar remnant is a NS, 0 otherwise. The lifetimes of stars come from Maeder & Meynet (1989) and the stellar remnants, depending of metallicity, are taken from Woosley & Weaver (1995).

As described in the next section, the late cosmic evolution of Eu is not constraining for the coalescence timescale. On the other hand, $\Delta t_{\text{NSM}}$ has a strong impact on the early evolution. Therefore, we focus in Sect. 5.4 on results obtained with values taken in the lower end of the range of $\Delta t_{\text{NSM}}$. 

Only seven NS/NS binary systems are known with measured masses [Lorimer 2005, 2008]. The current orbital parameters and the measured mass allow to estimate the remaining time before the merger. As at least one of the two neutron stars is observed as a pulsar, the measurement of the pulsar period and its time derivative allow to estimate the current age of the binary system. The sum of these two times gives an estimate of $\Delta t_{\text{NSM}}$. Using the values listed in Lorimer (2008), coalescence timescales between 100 and 400 Myr are found in four cases, and values larger than 1 Gyr in the three other cases. The double pulsar PSR J0379-3039 corresponds to the lowest value, $\Delta t_{\text{NSM}} \approx 180$ Myr. The famous binary pulsar PSR B1913+16, which has been studied in details for years as a test of general relativity [Hulse & Taylor 1975, Weisberg, Nice and Taylor 2010] has a coalescence timescale $\Delta t_{\text{NSM}} \approx 420$ Myr.
\[ \Delta_{\text{NSM}} \], i.e. a few 100 Myr. In \S\ 5.1, we discuss results obtained with a more realistic distribution of \[ \Delta_{\text{NSM}} \] also including longer values above 1 Gyr. As expected, it does not affect the early evolution, which justifies our approach.

5. Cosmic evolution of Eu

5.1. Standard results

5.1.1. Evolution of Eu as a function of [Fe/H]

The Eu cosmic evolution is computed for the three SFR modes. Figs. 5 and 6 (with and without error bars) show the evolution of [Eu/H] and [Eu/Fe] as a function of [Fe/H] for both r-process sites, separately, the CCSN (blue lines) and NSM (black lines). Observations come from different sources as described in Sect. 2.

Concerning the CCSN scenario, the Eu yield of \( 10^{-7} \ M_\odot \) is seen to reproduce fairly well the spectroscopic data for [Fe/H] > \(-2.5\). At lower metallicity, Eu is clearly overproduced by CCSN, specifically if we consider Eu data at lowest metallicity, as pointed in Sect. 2. In the SFR1 mode, where a Pop III contribution is included, the overproduction is even more significant due to the lack of iron production at very low metallicities in the models of Woosley & Weaver (1995) (Case B), whereas Eu is assumed to be produced in all mass ranges of massive stars.

Regarding the NSM scenario, with the fixed value of \( 7 \times 10^{-5} \ M_\odot \) for the Eu yield (see \S\ 1.2), observations at [Fe/H] > \(-2.5\) are seen to be in good agreement with the predicted evolution for a fraction of binary compact objects \( \alpha = 0.002 \) and a coalescence timescale \( \Delta_{\text{NSM}} = 0.2 \ Gyr \). A larger Eu yield of \( 2 \times 10^{-4} \ M_\odot \) would logically imply a lower value of \( \alpha \approx 0.0007 \), both parameters being degenerate in this approach. The agreement with the observations of Eu at low metallicity depends strongly on the coalescence timescale, which can therefore be constrained for each SFR mode, as illustrated in Figs. 4, 5, and 6 where we compare four coalescence time scales \( \Delta_{\text{NSM}} = 0, 0.05, 0.1, 0.2 \ Gyr \) for each SFR mode. The best fit is obtained for a typical coalescence timescale of 0.2 Gyr for SFR1 (Fig. 4), 0.1 Gyr for SFR2 (Fig. 5) and 0.05 Gyr for SFR3 (Fig. 6).

The difference stems from the [Fe/H] evolution which differs significantly for the three SFR modes, as already pointed out in \S\ 5.3 (see Fig. 4). The more iron produced at early time, the shorter coalescence timescale needed to explain the low-metallicity r-process-rich stars. An important conclusion, illustrated by these results, is that a coalescence timescale larger than typically 0.3 Gyr is excluded by the observations of Eu at low [Fe/H] for all SFR. Note that the production of iron from type Ia supernovae is included in our calculation but their contribution becomes efficient in the production of iron at very low metallicities in the models of Woosley & Weaver (1995), more specifically their case B (for which low-metallicity high-mass stars do not produce iron), have been used. Note that Heger & Woosley (2010), which follow the evolution and the explosion of zero-metallicity stars in the 10 – 100 M\odot range, obtain the same results regarding the production of iron. However, other studies find different conclusions; in particular, Kobayashi et al. (2006) predict higher iron yields than Woosley & Weaver (1995) for massive stars regardless of the metallicity. Fig. 12 illustrates the impact of Fe yields on the Eu evolution when considering the yields of Kobayashi et al. (2006). Note that we have also modified the lower end of the IMF from 0.1 to 0.8 M\odot to increase the gas processing in stars and favor again the iron production.

With the yields of Kobayashi et al. (2006), iron at the very beginning of the evolution is seen to be synthesized earlier than in our standard model, leading to an overall abundance more than 10 times higher (Fig. 12 upper panel). We compare in Fig. 12 (lower panel) our standard SFR2 model with \( \Delta_{\text{NSM}} = 0.1 \ Gyr \) (solid black line) with the results obtained with the yields of Kobayashi et al. (2006) and three different coalescence timescales, namely 0.1 Gyr (dashed line), 0.01 Gyr (dotted line) and 0.001 Gyr as a function of \( z \), each [Fe/H] value needs to be associated with a corresponding redshift. In our approach, the iron abundance increases monotonically with time, so that there exists a unique relation between [Fe/H] and \( z \), using equation 1, but this relation is however function of the adopted SFR since the Fe evolution depends on the SFR, as shown in Fig. 3 (lower panel). For this reason, the three modes are shown in different panels. In the NSM scenario, the coalescence timescale adopted for each SFR mode is \( \Delta_{\text{NSM}} = 0.2, 0.1, 0.05 \ Gyr \) for SFR1, SFR2, SFR3, respectively, as discussed above.

5.2. Eu from CCSN and the Pop III star component

As already mentioned, the Eu nucleosynthesis by CCSN remains highly uncertain. In our standard calculations (§ 5.1), it was assumed that each CCSN produces \( 10^{-7} \ M_\odot \) of Eu regardless of the mass and metallicity of its progenitor. If we consider in the SFR1 mode the existence of a Pop III star component, as required to explain the Thomson optical depth of the CMB measured by WMAP9 (see Fig. 2), Fig. 5 clearly shows a large overproduction of Eu at low metallicity. So, would the r-process successfully take place in CCSN, the observation of Eu in ultra-metal-poor star could be a discriminant indicator highlighting the existence or not of Pop III stars. However, if we assume that Pop III stars, or more generally \( Z < 10^{-4} \ Z_\odot \) stars, do not produce r-process elements significantly (less than typically 5 \( 10^{-5} \ M_\odot \)), the Eu evolution curve in SFR1 model, becomes almost equivalent to the predictions obtained with SFR2 and SFR3, as shown in Fig. 11.

5.3. Sensitivity to the early iron production

As already mentioned, the cosmic Fe enrichment plays a fundamental role in the interpretation of the chemical abundance evolution. To analyse the impact of this input on the determination of the NSM coalescence timescale, the Fe yield produced by massive stars has been varied in the SFR2 case. The standard yields of Woosley & Weaver (1995), more specifically their case B (for which low-metallicity high-mass stars do not produce iron), have been used. Note that Heger & Woosley (2010), which follow the evolution and the explosion of zero-metallicity stars in the 10 – 100 M\odot range, obtain the same results regarding the production of iron. However, other studies find different conclusions; in particular, Kobayashi et al. (2006) predict higher iron yields than Woosley & Weaver (1995) for massive stars regardless of the metallicity. Fig. 12 illustrates the impact of Fe yields on the Eu evolution when considering the yields of Kobayashi et al. (2006). Note that we have also modified the lower end of the IMF from 0.1 to 0.8 M\odot to increase the gas processing in stars and favor again the iron production.
Fig. 5. Cosmic evolution of Eu: comparison between the two possible astrophysical sites (1) Eu/H and [Eu/Fe] vs [Fe/H]. Evolution of Eu/H and [Eu/Fe] as a function of [Fe/H] either in the CCSN (blue lines) or in the NSM (black lines) scenario. The evolution is computed for the three SFR modes considered in the present study, SFR1 (solid lines), SFR2 (dotted lines), SFR3 (dashed lines). In the CCSN scenario, the Eu yield is $10^{-7} \ M_\odot$ per supernova. In the NSM scenario, the Eu yield is $7 \times 10^{-5} \ M_\odot$ per merger, the fraction of binary compact objects is $\alpha = 0.002$ and the coalescence timescale is $\Delta t_{\text{NSM}} = 0.2 \ Gyr$. Data points come from different references: black points and upper limits at low metallicity from François et al. (2007), brown points at higher metallicity from Simmerer et al. (2004), yellow from Barklem et al. (2005), magenta from Ren et al. (2012), red from Roederer et al. (2010, 2014a,b), heavy blue points from Roederer et al. (2014c). The bulk of black points at high metallicity come from dwarf spheroidal systems (Shetrone, Côté & Stetson, 2001; Shetrone, et al., 2003; Geilser et al., 2005; Cohen and Huang, 2009; Letarte et al., 2010; Starkenburg et al., 2013; McWilliam et al., 2013).

Fig. 6. Same as Fig. 4 but without error bars.

(dot-dash line). Consequently, a significant reduction of the coalescence timescale ($\Delta t_{\text{NSM}} = 1 \ Myr$) needs to be applied to compensate for the early increase in the Fe production in this context. It should be recalled that it is close to the scenario obtained by Matteucci et al. (2014) using the same Fe yields from Kobayashi et al. (2006) and an IMF with
Fig. 7. Cosmic evolution of Eu in the NSM scenario: effect of the coalescence timescale (SFR1 case). Same as Fig. 5 in the NSM scenario and SFR1 case. We compare four different coalescence timescales: $0$ (dot-dash line), $0.05$ (dotted line), $0.1$ (dashed line) and $0.2$ Gyr (solid line).

Fig. 8. Cosmic evolution of Eu in the NSM scenario: effect of the coalescence timescale (SFR2 case). Same as Fig. 7 in SFR2 case.

Fig. 9. Cosmic evolution of Eu in the NSM scenario: effect of the coalescence timescale (SFR3 case). Same as Fig. 7 in SFR3 case.
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Fig. 10. Cosmic evolution of Eu: comparison between the two possible astrophysical sites (2) Eu/H vs redshift. Evolution of Eu/H as a function of $z$ either in the CCSN (blue lines) or in the NSM (red lines) scenario. The evolution is computed for the three SFR modes considered in the present study, SFR1 (upper panel), SFR2 (middle), SFR3 (lower panel). The three SFR modes are shown in different panels because the observations expressed in terms of [Fe/H] do not correspond to the same redshift $z$ when different SFR are considered. The yields in the two scenarios are the same as in Fig. 11. In the NSM scenario, the binary fraction is $\alpha = 0.002$ and the coalescence timescale is 0.2 Gyr for the SFR1 mode, and 0.1 Gyr for the SFR2 and 0.05 Gyr for SFR3.

Fig. 11. Cosmic evolution of Eu in the CCSN scenario: effect of the Eu yield (SFR1 case). Evolution of Eu/H as a function of [Fe/H] in the CCSN scenario for the SFR1 mode, assuming either the standard prescription for the Eu yield (solid line), i.e. $10^{-7} M_{\odot}$ per supernova for massive stars at all metallicities, or a modified prescription (dashed line) where Eu is produced in supernovae only for massive stars with a metallicity $Z > 10^{-4} Z_{\odot}$.

$M_{\text{inf}} = 0.8 M_{\odot}$. Clearly, the more iron is produced at early time, the shorter the predicted coalescence timescale required to explain the Eu abundance in the ultra-metal-poor stars.

5.4. Time delay distribution and dispersion in data

When fitting the observed early cosmic evolution of Eu in the NSM scenario, the coalescence timescale $\Delta t_{\text{NSM}}$ is constrained to be short, typically in the range 50–200 Myr depending on the SFR (see §5.1.1), as binary systems with longer timescales are not merging at large redshifts. As discussed in Sect. 4.4, such systems with a relatively low value of $\Delta t_{\text{NSM}}$ represent a significant fraction of all the systems, but not all of them. In Fig. 14 we show the evolution of Eu using a broader, and more realistic, distribution of coalescence timescales. Based on the distribution plotted in Fig. 4, we assume 13% of the NSM in the 0–10 Myr range ($\Delta t_{\text{NSM}} = 5$ Myr), 10% in the 10–100 Myr range ($\Delta t_{\text{NSM}} = 30$ Myr), 15% in the 100–500 Myr range ($\Delta t_{\text{NSM}} = 300$ Myr), and 62% with a coalescence timescale above 500 Myr ($\Delta t_{\text{NSM}} = 1$ Gyr). The calculation is carried out for the SFR1 mode and we present the result for both $\alpha = 0.002$ (solid line) and $\alpha = 0.004$ (dotted line). When compared to Fig. 7, the early evolution is slightly modified due to the contribution of systems with even shorter coalescence timescales than in our reference case. As mergers are rare events with large Eu yields (compared to core-collapse supernovae which are more frequent but produce less Eu), a large dispersion can be expected at low metallicity when only a small number of mergers affected the local environ-
6. Cosmic evolution of the merger rates

Once the fraction $\alpha$ and the coalescence timescale $\Delta t_{\text{NSM}}$ have been adjusted to reproduce the cosmic evolution of Eu, as described in the previous section, the cosmic evolution of the merger rate can be determined. It is plotted as a function of the redshift in Fig. 14 for the SFR1 and SFR3 modes, together with the CCSN rate and the NS and BH birth rates. The SFR evolution is shown for comparison. We also plot the local observational constraints for the CCSN and merger rates from Mattila et al. (2012) and Abadie et al. (2010).

6.1. Merger rate in the horizon of gravitational wave detectors

On the basis of the cosmic evolution of the merger rate, it is possible to estimate the rate expected in the horizon of the gravitational wave detectors advanced Virgo and ad LIGO and to compare those rates with independent predictions, as compiled by Abadie et al. (2010). The result is plotted in Fig. 15 for the SFR1 scenario. When considering the production of Eu in the NSM scenario, both parameters, the Eu yield and the fraction of binary mergers $\alpha$, are degenerate when adjusted on the cosmic evolution of Eu. This is not the case for the calculation of the event rates. Therefore, we present in Fig. 15 the results for two sets of parameters: either our standard Eu yield of $7 \times 10^{-5} M_\odot$ and a binary fraction $\alpha = 0.002$ (solid lines), or a larger Eu yield of $2 \times 10^{-4} M_\odot$ (as found in NSM simulations, see Sect. 4.2) and a lower binary fraction $\alpha = 0.0007$ (dashed lines), both leading to exactly the same cosmic evolution of Eu. The predicted rates are given in Tab. 1 for the two extreme sets of parameters.

Interestingly, the integrated merger rate in the horizon of gravitational wave detectors obtained in the present study using our standard value for the Eu yield from NSM ($7 \times 10^{-5} M_\odot$) is close to the central value of the predictions compiled by Abadie et al. (2010). In contrast the upper value of the Eu yield tends to disfavor the upper half of the predicted range given by Abadie et al. (2010), as clearly illustrated in Fig. 15.

6.2. Kilonova rate

As discussed in the introduction, NS-NS/BH mergers can potentially have two types of electromagnetic counterparts, short GRBs and kilonovae. Short GRBs are associated to the production of an ultra-relativistic outflow along the polar axis of the post-merger BH-torus system, with large uncertainties on the beaming angle of the jet. Therefore, the prediction of the short GRB rate from the merger rate requires a specific treatment (see e.g. Guetta & Piran, 2006; Wanderman & Piran, 2014), which we do not include in the present study. On the other hand, kilonovae are associated with a quasi-isotropic non-relativistic ejection that should be present in all systems. The luminosity of the kilonova is powered by the radioactive decay of freshly synthesized elements and is consequently directly related to the nucleosynthesis of r-process nuclei. Therefore, the detection of a kilonova would represent a major step to probe the contribution of NS-NS/BH mergers to the synthesis of heavy elements in the Universe (see also Metzger et al., 2013). There is only one tentative detection to date, in association with the short GRB 130603B (Berger et al., 2013; Tanvir et al., 2013). However, this observation is not detailed enough (only a single photometric measurement) to prove firmly its kilonova nature. More detections, with a photometric and spectroscopic follow-up, will be required to progress further. The peak of the kilonova is expected in the near-infrared range a few days after the merger (it may be bluer in the case of NS/BH mergers, Tanaka et al., 2014). The long-term evolution of the ejecta, which is decelerated by the ambient medium, also leads to emission over weeks. This signal is not considered here though it may also become detectable by future radio surveys (Nakar & Piran, 2011; Piran et al., 2013).

Our model allows to constrain the expected rate of kilonovae for a given large survey as a function of the limit magnitude in the optical/NIR range. Following Metzger et al. (2010), the peak luminosity scales as

$$ L_{\text{KN, peak}} \simeq 5 \times 10^{49} \frac{v}{10^{-6}} \left(\frac{f}{0.1c}\right)^{1/2} \left(\frac{M_{ej}}{10^{-2} M_\odot}\right)^{1/2} ,$$

where $v$ and $M_{ej}$ are the velocity and mass of the ejecta respectively and $f$ is the heating efficiency (Arnett, 1982; Li & Paczynski, 1998; Metzger et al., 2010). Compared to Metzger et al. (2010), the normalization in Eq. 6 has been corrected for a more realistic opacity of the r-process elements, which is expected to be $\sim 10^4$ times larger compared to the opacity of iron group elements considered in previous studies (Kasen et al., 2013) (see also Kasen et al., 2014). Using the extreme values obtained in the systematic study of the dynamics of the ejecta carried out by Bauswein et al. (2013), this leads to $L_{\text{KN, peak}} \simeq (2.0 - 14) \times 10^{49} \text{erg/s}$ (see also Grossman et al., 2014).

Assuming that all kilonovae have similar peak luminosities $L_{\text{KN, peak}}$, we can deduce from the merger rate the number of kilonovae per year above a given flux. This leads to the results plotted in Fig. 16, where the rate of kilonovae per year and per square degree is plotted as a function of the limiting magnitude of a given survey, in the SFR1 case with the two same sets of parameters (Eu yield, compact binary fraction $\alpha$) as in Fig. 15. The width of the shaded area takes into account the range of $L_{\text{KN, peak}}$, discussed above. Horizontal lines indicate the limit above which at least one event per year is expected for different surveys, taking into account their magnitude limit and their field of view. The results are listed in Tab. 1 for each SFR and for the two extreme values of the yield of Eu. It appears that the current Palomar Transient Factory (PTF) survey (limiting magnitude of 21 and area of 2700 deg$^2$) fails to detect kilonovae, whereas the predictions are more optimistic for future surveys like the Large Synoptic Survey Telescope (LSST, limiting magnitude of 24.5, area of 18000 deg$^2$) and mostly Euclid (limiting magnitude of 24.5, area of view of 15000 deg$^2$) with a well adapted spectral range, for which typically $\sim 2 - 100$ events per year can be expected.

7. Conclusions

The early evolution of a typical r-process element such as Eu is now constrained by observations in metal poor halo
stars. It gives a possible diagnostic to distinguish among the two main astrophysical scenarios for the r-process nucleosynthesis, namely CCSN et NS/NS or NS/BH mergers. Indeed, supernovae directly trace the star formation rate, whereas an additional delay due to the coalescence timescale is expected for mergers. Therefore different early evolutions of Eu are expected in these two scenarios.

We have calculated the predicted evolution for each possible astrophysical site of the r-process using a model of the cosmic chemical evolution in the cosmological context which is calibrated to reproduce a large set of observational constraints coming from our Galaxy and external dwarf galaxies. We obtain the following results:

(i) Current measurements (or upper limits) of the abundance of Eu in metal-poor stars disfavor the CCSN scenario for the r-process, as it overproduces Eu at very early times. The only way to reconcile this scenario with observations is to assume that the r-process is inefficient in supernovae with progenitors having a metallicity below $Z/Z_\odot \sim 10^{-4}$. Moreover, Eu yields from CCSN remain highly uncertain, since up to now, CCSN simulations have failed to predict a successful r-process nucleosynthesis;

(ii) The evolution predicted in the merger scenario is in good agreement with observations, assuming that the early evolution is dominated by mergers of binary systems with a coalescence timescale of the order of $\Delta t_{NSM} \sim 100$ Myr. Such mergers represent a significant fraction of all mergers according to recent estimations obtained with detailed population synthesis codes;

(iii) In the merger scenario, the explosive events responsible for the production of r-process elements are more rare than in the supernova scenario, but each event yields more Eu. Therefore, a larger scattering in the r-process abundance is expected in metal-poor stars enriched by mergers. We present calculations of the early evolution of Eu obtained when summing up contributions of mergers with a broad range of coalescence timescales according to predictions of population synthesis models and we find a reasonable agreement with the level of scatter observed. At high metallicities, the cumulative effect leads to a low sensitivity with respect to the coalescence timescale;

(iv) The precise constraint on the dominant coalescence timescale relevant for the early evolution of Eu depends on the adopted SFR at high redshift, for which we have tested three scenarios representative of the current uncertainties, and on the iron yields of stars at low metallicity, for which we have compared two theoretical predictions made by either Woosley & Weaver (1995) or Kobayashi et al. (2006). The conclusion is that shorter coalescence timescales are favored by scenarios for which the production of iron at early times is more intense, i.e. for larger SFR at high redshift and larger iron yields coming from CCSN. In the standard conditions, we constrain the coalescence timescale $\Delta t_{NSM}$ to be in the range of 50-200 Myr;

(v) In the merger scenario which is favored by observations at low metallicity, two additional parameters are degenerate: the fraction $\alpha$ of NS in a binary system with another NS or a BH and the yield of Eu per merger. This second parameter is constrained to be in the range $7 \times 10^{-5} - 2 \times 10^{-4} M_\odot$ per merger in the most recent nucleosynthesis calculations. Adopting these two values leads to an upper and a lower limit on $\alpha (0.002 - 0.0007)$ which constrain the merger rate as a function of the redshift in the Universe;

Table 1. Predictions for the merger rate within the horizon of advanced Virgo/LIGO obtained with the constraint from the cosmic evolution of Eu using SFR1, SFR2, SFR3 models. For each SFR, the lower and higher values of the predicted rate correspond to the higher and lower limits on the yield of Eu in mergers, i.e. $2 \times 10^{-4} M_\odot$ and $7 \times 10^{-5} M_\odot$, respectively. The range of independent predictions compiled by Abadie et al. (2010) is given on the first line for comparison. Following Abadie et al. (2010), we adopt 200 Mpc (resp. 420 Mpc) for the size of the horizon for NS-NS (resp. NS-BH) mergers.

| SFR   | Lower limit | Upper limit |
|-------|-------------|-------------|
| SFR1  | 2.4 - 6.7   | 2.7 - 7.7   |
| SFR2  | 3.8 - 10.9  | 4.3 - 12.4  |
| SFR3  | 3.8 - 10.9  | 4.3 - 12.4  |

Table 2. Predictions for the kilonova rate for three different surveys: Palomar Transient Factory (PTF, limiting magnitude of 21 and area of 50000 deg$^2$), Large Synoptic Survey Telescope (LSST, limiting magnitude of 24.5, area of 180000 deg$^2$), and Euclid (limiting magnitude of 24.5, area of 150000 deg$^2$) for SFR1, SFR2, SFR3 models. For each SFR, we consider either the most pessimistic case (‘low’) or the most optimistic case (‘high’) corresponding to the highest and lowest possible values of the yield of Eu, as in Table 1. For each case, the range of predicted rates corresponds to the lowest and highest values of the peak luminosity of a kilonova (see text).

| Survey | PTF | LSST | Euclid |
|--------|-----|------|--------|
| SFR1 low | 0.0018 - 0.034 | 1.4 - 22.9 | 1.2 - 19.1 |
| SFR1 high | 0.005 - 0.096 | 4.1 - 65.4 | 3.3 - 54.5 |
| SFR2 low | 0.0014 - 0.028 | 1.2 - 20.1 | 1.0 - 16.7 |
| SFR2 high | 0.004 - 0.08 | 3.5 - 57.4 | 2.9 - 47.9 |
| SFR3 low | 0.003 - 0.054 | 2.3 - 36.4 | 1.9 - 30.3 |
| SFR3 high | 0.008 - 0.16 | 6.6 - 103.9 | 5.5 - 86.6 |
We use the previous calculation to predict the expected rate of mergers within the horizon of gravitational wave detectors. We find that the predicted rate as constrained by the cosmic evolution of Eu falls well within the range of predictions by other independent methods compiled by Abadie et al. (2011) but clearly favors the mid or lower values, and not the most optimistic predictions. We predict typically 2 to 10 NS-NS mergers per year and an equivalent number of NS-BH mergers per year.

(vii) Considering the most recent estimates of the opacity of r-process elements, we also predicted the rate of kilonovae in current and future optical/near-infrared large surveys. Our results are compatible with the lack of kilonova detections by PTF and are optimistic for the future LSST and Euclid projects, though with a large uncertainty: from 1 kilonova per year in the most pessimistic case to 100 events per year in the most optimistic case.

Our results can be improved in the future in several ways. Successful r-process in CCSN with well-defined Eu yields, including a possible dependence with metallicity, would be very useful to definitively check the consistency of the SFR at large redshift and a convergence of theoretical predictions for iron yields in primordial CCSN would also strongly reduce the uncertainties on the parameters of the model in the merger scenario. In addition, more measurements of the abundance of r-process elements in stars at even lower metallicity ([Fe/H] < −3.5) would also allow to better constrain the model parameters. Finally, the predictions for the kilonova detection rate in future surveys could be improved by taking into account the correction for the spectral range of the instruments. Additional predictions for the rates of other transients associated with mergers, i.e. short gamma-ray bursts and radio flares, could also be deduced from the predicted merger rate to provide new diagnostics in the future.

Our results clearly demonstrate the importance of taking into account the early cosmic chemical evolution to distinguish between the possible astrophysical sites for the r-process and lead to promising prospects for solving in the coming years this long standing mystery.

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Fig. 12. Cosmic evolution of Eu in the NSM scenario: sensitivity to the iron production and to the lower end of the IMF. Upper panel: evolution of [Fe/H] as a function of time in the SFR2 case, computed either with our standard prescription (solid line: Fe yields from Woosley & Weaver (1995), case B, and $M_{\text{inf}} = 0.1 M_\odot$ for the IMF), or with a modified prescription (dashed line: Fe yields from Kobayashi et al. (2006), hypernova case, and $M_{\text{inf}} = 0.8 M_\odot$ for the IMF); Lower panel: corresponding evolution of [Eu/Fe] as a function of [Fe/H]: our standard prescription for iron production (solid line) with a coalescence timescale of $\Delta t_{\text{NSM}} = 0.1$ Gyr is compared with the modified prescription for three values of the time delays, i.e. 0.1 Gyr (dashed line), 0.01 Gyr (dotted line), 0.001 Gyr, (dot-dash line).

Fig. 13. Eu evolution with a time delay distribution. Same as in Fig. 7 (SFR1 case) for a distribution of coalescence timescales corresponding to Fig. 4 (see text for more details). Solid and dotted curves correspond to two NSM fractions, of 0.002 and 0.004, respectively.
Fig. 14. NS and BH birth rate and CCSN and merger rates as a function of the redshift for SFR1 (upper panel) and SFR2 (lower panel). Green and red points represent the local CCSN rate Mattila et al. (2012) and the total local merger rate Abadie et al. (2010), respectively. The SFR evolution is also plotted for comparison.

Fig. 15. The integrated merger rate (NS-NS, red line, NS-BH, blue line, and total, black line) as a function of the distance (lower axis) and the redshift (upper axis). Two vertical lines indicate the size of the horizon of the gravitational wave detectors advanced Virgo/LIGO. For comparison, the central value and range of the predicted rates within this horizon compiled by Abadie et al. (2010) is also indicated for both types of mergers. The calculation corresponds to the SFR1 mode with the standard prescription (solid line: Eu yield of $7 \times 10^{-5}$ M$\odot$ and binary fraction $\alpha = 0.002$) and with a modified prescription (dashed line: $2 \times 10^{-4}$ M$\odot$ and binary fraction $\alpha = 0.0007$), both leading to exactly the same cosmic evolution of Eu plotted in Fig. 5.
**Fig. 16.** The integrated kilonova rate per deg$^2$ as a function of the limiting magnitude for the two same cases as in Fig. 15, i.e. SFR1 with the standard prescription (blue) or the modified prescription (red) for the Eu yield. The width of the shaded area in each case takes into account the theoretical uncertainties on the peak luminosity of the kilonova (see Eq. (6)). For comparison, horizontal yellow and green lines indicate the limit of 1 event per year for three surveys (PTF, LSST and Euclid, see Sect. 6.2 and Tab. 2 for the limiting magnitude and area of each survey).