Short GRBs and production of heavy elements

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Outline of the talk

- Merging of compact objects, such as neutron stars and black holes has important implications for:
- Gravitational wave emission
- Heavy element production
- Short Gamma-Ray bursts
- Kilonovae
- I will discuss predictions about the rate of merging of neutron stars and its implications for the production of Europium in the Milky Way and whether this is consistent with the recent Ligo/Virgo estimate and the upper limit for kilonovae, derived from GW170817

Chemical Evolution Model

- We make use of a chemical evolution model which is an updated version of the two-infall model (Chiappini et al. 1997), as presented in Romano et al. (2010)
- The halo and disk form by means of independent gas accretion episodes
- It computes in detail the evolution of the abundances of 37 elements including very heavy elements such as Europium (r-process)
- Nucleosynthesis from SNe (II, Ia, Ib, Ic), novae and merging neutron stars (MNS) is included

Europium production

- Two main sites have been proposed for r-process elements (e.g. Eu) production:

- SN II, either of low (8-10 M_{sun}) and high (>20 M_{sun}) mass, during explosive nucleosynthesis (Cowan et al. 1991; Woosley et al. 1994; Wanajo et al. 2001) but many uncertainties are still present in the physical mechanisms involved in Eu production. In particular, during explosive nucleosynthesis, there are two few neutrons to produce r-process elements

- MNS producing Eu are more promising (Freiburghaus et al. 1999, Rosswog et al. 1999;2000): we considered two NS of 1.4 M_{sun} ejecting 10^{-3} – 10^{-2} M_{sun} during the event. The Eu mass produced is 10^{-7} – 10^{-5} M_{sun} (Korobkin et al. 2012)

- $(3\text{-}15)\times10^{-6}$ M_{sun} of Eu from GW170817 (Evans et al. 2017; Tanvir et al. 2017;Troja et al. 2017)

Gravitational time delays

- The coalescence time scale depends on gravitational wave emission which causes a loss of angular momentum of the binary system

- The coalescence timescale (gravitational delay) depends on the original separation of the two neutron stars and scales as

$$t_d \propto a^4$$

- Where a is the separation. The common envelope process also influences the coalescence timescale

- For simplicity Matteucci et al. (2014) adopted three different timescales:1 Myr, 10 Myr 100 Myr

- Belczynski et al. (2002) finds that a large fraction of systems would merge in <1 Myr

- A more realistic apronch requires a delay time distribution for a (Simonetti et al. 2019;Greggio et al. 2021)

The theoretical MNS rate in the Galaxy in Matteucci+2014

- We assume that the binary NS are a fraction of all NS and that the rate of NS merger is a fraction (alpha) of the NS formation rate. All stars between 9 and 30 M_{sun} are assumed to leave a NS as a remnant

- This fraction alpha is a free parameter and is fixed by reproducing the present time NS merging rate. It depends on the assumptions on the progenitors of NS

- Another important parameter is the delay between the formation of the NS and their merger, t_d

- As we have seen, this time delay can be less than 1 Myr but it can be also 100 Myr and more

The observed MNS rate

- Kalogera et al. (2004), Belczynski et al. (2002) suggested a rate of MNS for the Milky Way, deduced from binary pulsars, of:

$$R_{MNS} = 83^{+209}_{-66.1} Myr^{-1}$$

- Kim et al. (2015) suggest [2-210]/ Myr
- Ligo-Virgo estimate at low redshift for GW170817 (Abbott et al. 2017):

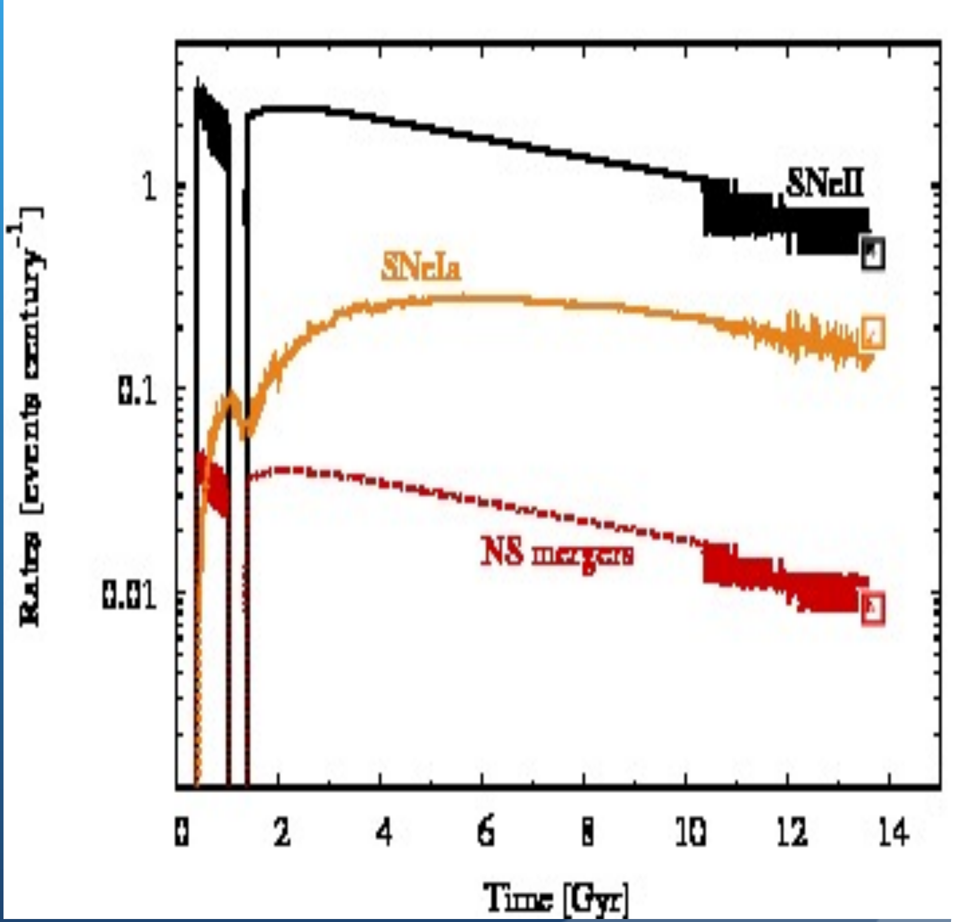
$$1540^{+3200}_{-1220} Gpc^{-3} yr^{-1}$$

- Corresponding to 154/Myr
- The most recent determination (Abbott et al. 2021):
- 320 $^{+490}_{-240} Gpc^{-3} yr^{-1}$

SN rates and MNS rate in the Galaxy

(Matteucci et al. 2014, MNRAS, 438,2177)

- The SN II and Ia rates compared with the MNS rate (100 yr^{-1})
- The predicted present time MNS rate reproduces the observed one of 83/Myr (Kalogera et al. 2004) although the rate could range from 0.1/Myr to 1000/Myr!
- This is obtained with a fraction of binary NS alpha=0.018
- Chemical evolution can constrain the MNS rate



Eu production only from MNS

- Stellar data from Burris et al. (2000); Fulbright(2000);Reddy et al. (2003, 2006); Bensby et al. (2005); Francois et al. (2007); Mishenina et al. (2007); Ramya et al. (2012); Frebel (2010)

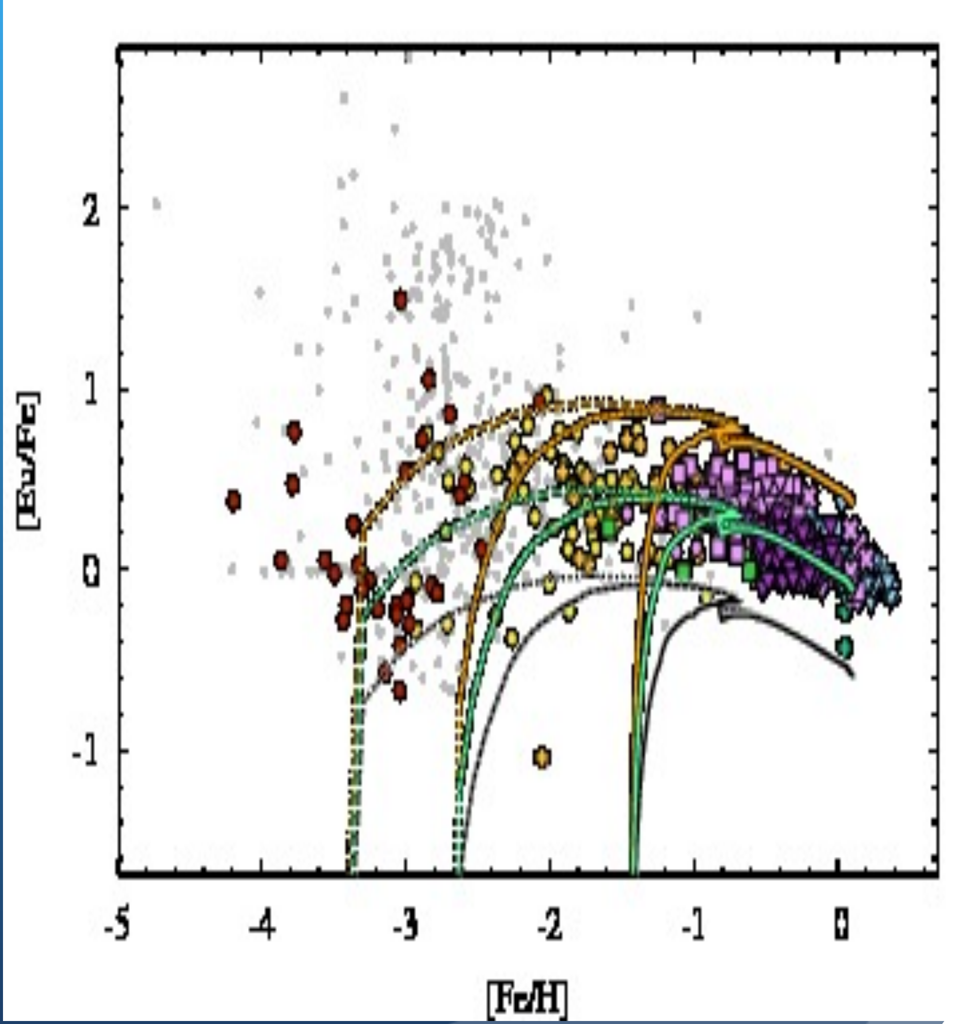
- Solid, dashed and dotted lines refer to 100, 10 and 1 Myr gravitational time delay, respectively

- Black lines: $M_{eu}=10^{-6}\, M_{sun}$ and $t_d=1$, 10 and 100 Myr

- Green $_{lines}$: $M_{eu}=3\text{x}10^{-6}\, M_{sun}$,Yellow lines: $M_{eu}=9\text{x}10^{-6}\, M_{sun}$

- Predicted $(X_{eu})_{sun}=1.04\text{x}10^{-10}$

- Observed $(X_{eu})_{sun}=3.5\ \text{x}10^{-10}$ Asplund et al. (2009)



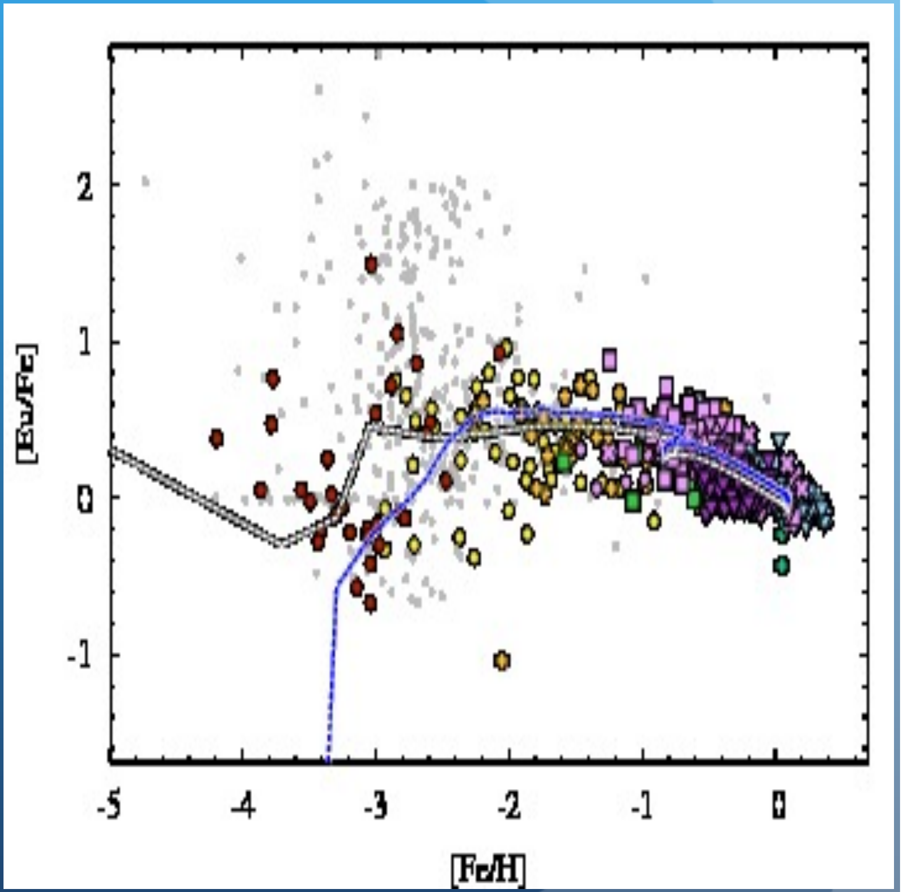
Toward a best model with CC-SNe

- Here the white line represents a model with Eu production from massive stars (Type II SNe) with the yields of Argast et al. (2004) from 20 to 50 M_{sun} and from MNS with M_{eu}=2x 10^{-6} M_{sun} .Progenitor of NS from 9 to 30M_{sun}

- Predicted solar :

  $(X_{eu})_{sun}$=3.65 x10^{-10} to be compared with the observed one of

  $(X_{eu})_{sun}$=3.5 x10^{-10}



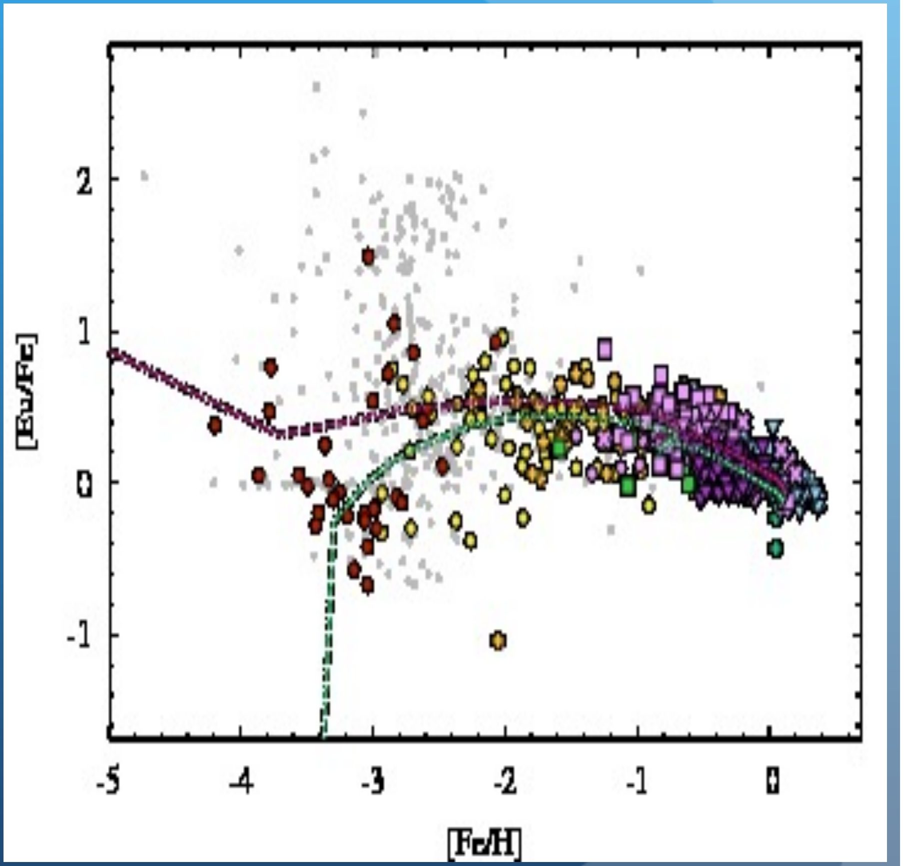
Toward a best model with only MNS

- We run a model (violet line) where we assumed that neutron stars form from 9 to 50 M_{sun} and not only to 30Msun and that Eu comes only from MNS with a t_d = 1Myr and $M_{eu}=3\times10^{-6}\ M_{sun}$

- Green line corresponds to a maximum progenitor for NS of 30M_{sun}

- The best model is the violet line (NS maximum progenitor 50 M_{sun}) and it demonstrates that Eu can indeed be produced all by MNS if all of these conditions are fulfilled

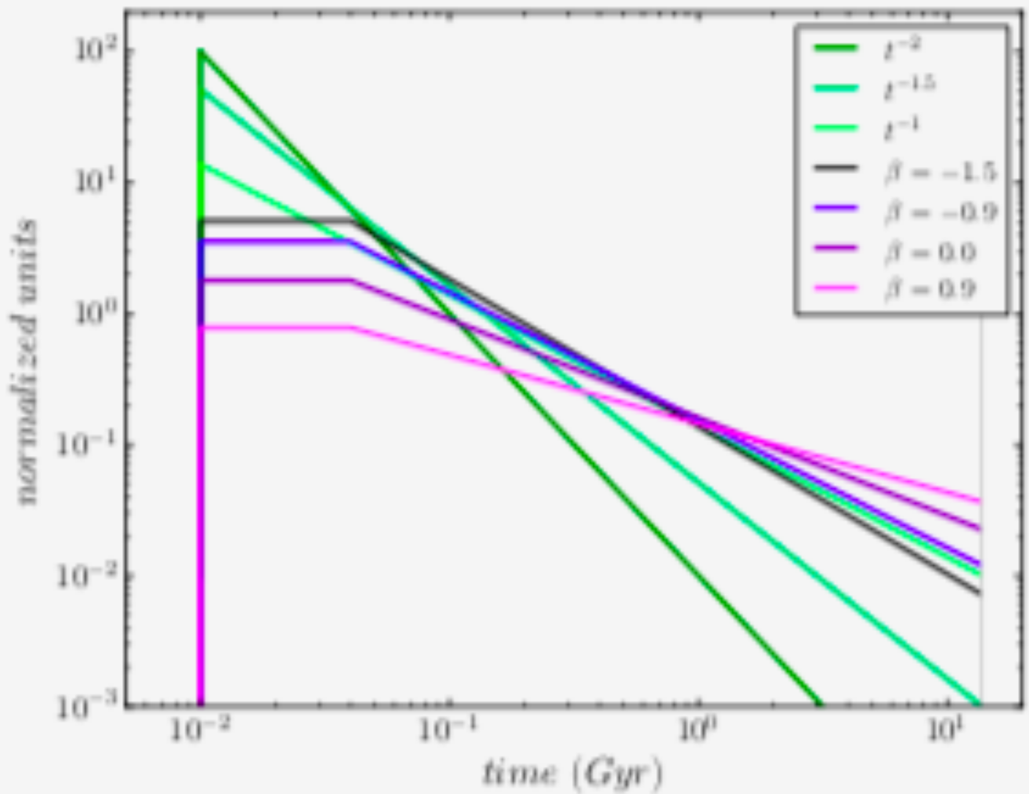
- Predicted solar Europium by the best model $(X_{eu})_{sun}=4.2\ \mathrm{x}10^{-10}$



The Simonetti et al.(2019, MNRAS, 486, 2896) model

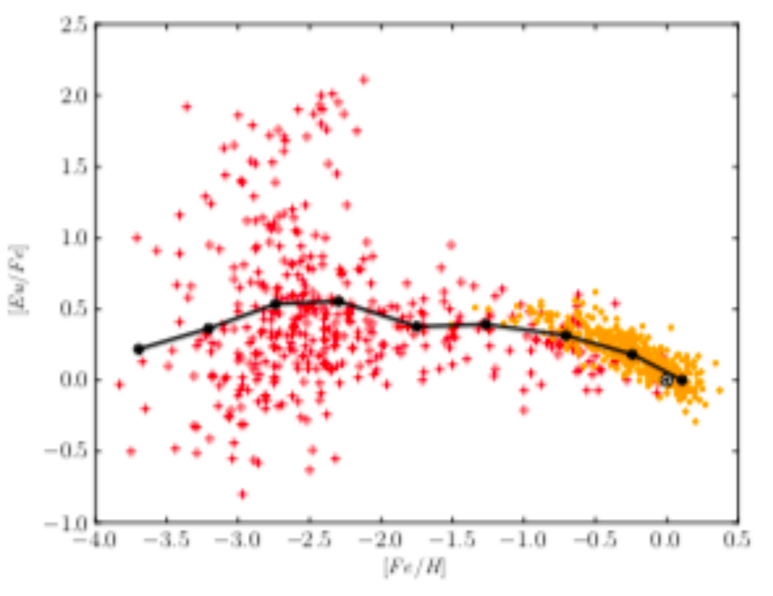
- A DTD function for the gravitational coalescence time was assumed: a flat distribution for NS stellar masses in binary systems and a power law for initial separations with exponent beta
- Four different values of beta were tested (0.9; 0.0;-0.9;-1.5). Beta=-1.5 produces a DTD similar to that of SNeIa
- We tested these DTDs on the Cosmic Short Gamma Ray Burst rate and on the [Eu/Fe] vs. [Fe/H] relation in the Milky Way

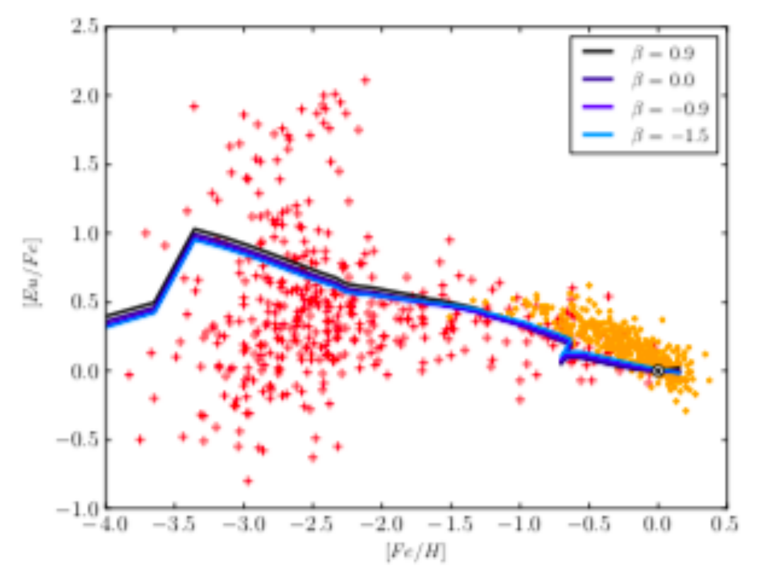
The various DTDs adopted by Simonetti+2019



The Simonetti+2019 model results: MNS+CC-SNe

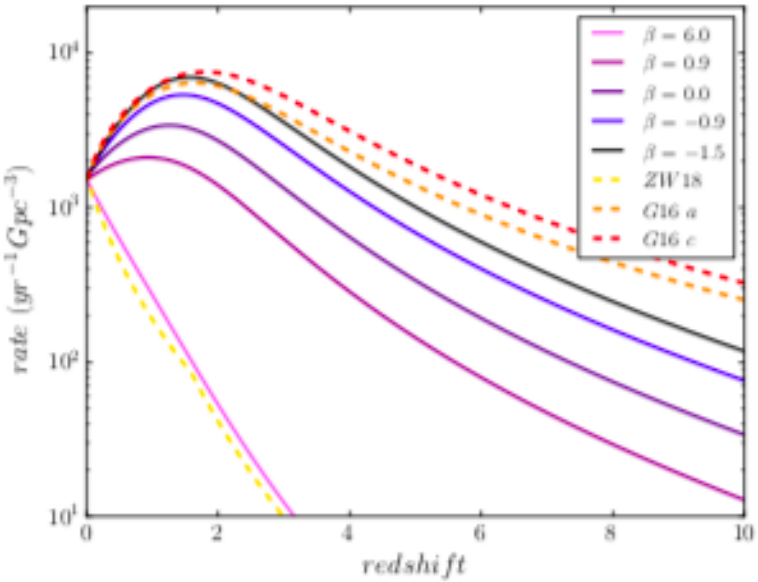
- On the left the best fit of [Eu/Fe] data, on the right the model results for different values of the beta parameter. Several values of beta can allow to reproduce the data, suggesting an average merging time of 300-500 Myr, but only beta=-1.5 allows to reproduce also the cosmic rate of SGRBs. Eu is produced by MNS and CC-SNe, alpha=0.01





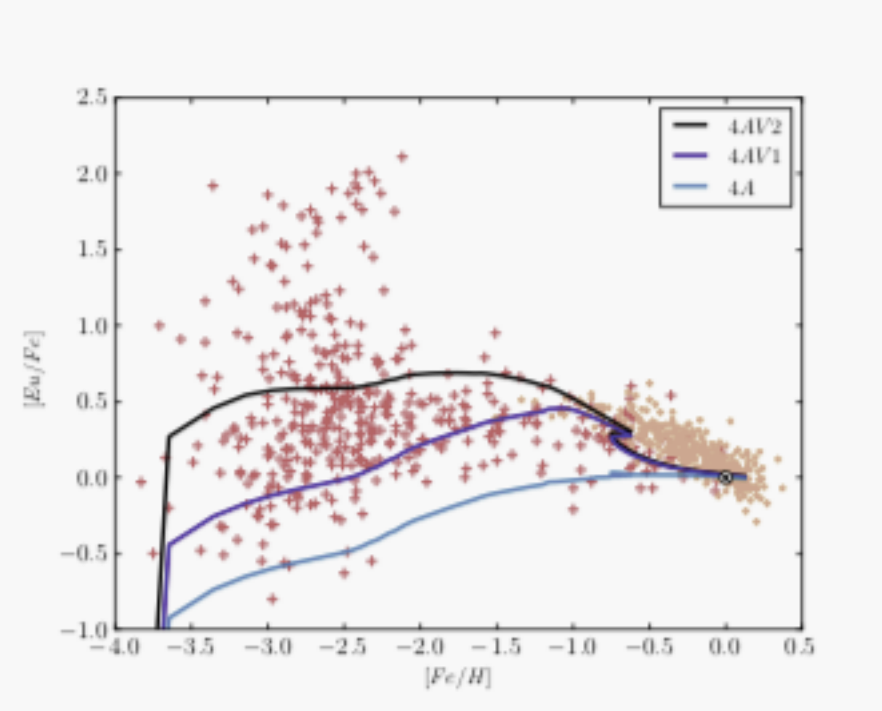
Cosmic rate of Short Gamma Ray Bursts : Ghirlanda+2016 compared with MNS rates with DTDs

- The DTDs of Simonetti+2019 convolved with CSFR of Madau & Dickinson (2014). A constant t_d does not fit
- To fit the CSGRB rate Zhang&Wang2017 needs a top-heavy distribution of separations



Variable alpha and contribution only from MNS (Simonetti+2019)

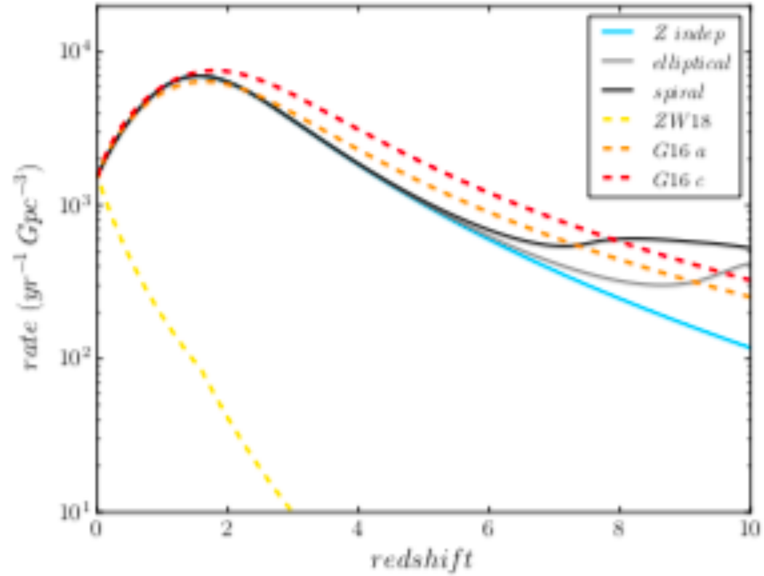
- The only way to reconcile a DTD for the merging coalescence time and Eu produced only from MNS is to assume a variable alpha parameter, being higher at early times
- In the figure the predictions for different assumptions about the variation of alpha with metallicity. Metallicity can play a crucial role in the formation of binary systems (Giacobbo+Mapelli2018) but…
- In this case, we can reproduce also the cosmic rate of SGRBs
- Beniamini&Piran (2019) suggests more MNS at early times



CSGRB rate with alpha variables with metallicity (Simonetti+2019)

- We computed the metallicity evolution in ellipticals and spirals and assumed alpha varying with metallicity in these systems and only MNS as Eu producers. The real cosmic metallicity evolution is in between the spiral and elliptical ones

- The we recomputed the CSGRB rate and this alpha variable does not substantially changes the results obtained with constant alpha and the best DTD



Conclusions

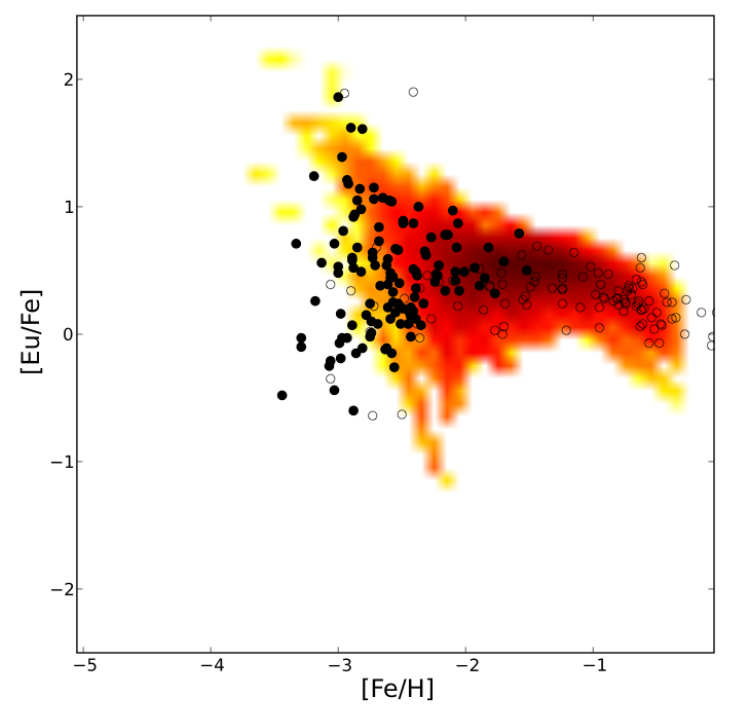
- Matteucci+2014 concluded that Eu production only from MNS can reproduce the evolution of Eu abundance as well as its solar value if: the NS systems explode with a delay no longer than 1 Myr and each event produces $M_{eu} = 3x\ 10^{-6}\ M_{sun}$ and all stars with masses in the range 9-50 M_{sun} leave a NS as a remnant
- Simonetti+2019 proposed a more realistic situation where both CC-SNe and MNS can produce Eu and there is a DTD function for the coalescence times. The best model in this case assumes that MNS produce $M_{eu} = 2x\ 10^{-6}\ M_{sun}$ and the DTD has an exponent beta=-1.5. The CC-SNe should produce Eu in a range 20-50 $M_{sun.}$ This model also reproduces the observed Cosmic SGR Rate (CGRB) by Ghirlanda+2016
- The MNS rate derived by Ligo/Virgo is consistent with a chemical evolution model which explains Eu in the Milky Way. Also the derived heavy element production is consistent with the chemical model
- To have that only MNS produce Eu and at the same time the [Eu/Fe] in the MW and the CSGRB rate well fitted, the fraction of MNS in the IMF should vary with time (Simonetti+2019)

The spread in [Eu/Fe] at low [Fe/H]

- Cescutti et al. (2015) adopted an inhomogeneous model for the evolution of the Galactic halo and reproduced the observed spread of [Eu/Fe]
- Cescutti's model assumes incomplete mixing in the first stages of Galaxy evolution
- The halo is divided in non interacting regions with a radius of 90 pc and in each region stars form by means of a random function weighted on the assumed IMF (Scalo, 1986)
- A model with MNS and SNeII at early stages reproduce the data

Eu only from MNS in a inhomogeneous model (Cescutti et al.,2015, A&A, 577,139)

- Predicted vs. observed [Eu/Fe] in a case similar to the best model of Matteucci et al. (2014). Only halo considered
- Coalescence time constant t_d = 1 Myr
- Only MNS as Eu producers
- Mass range for NS progenitors 9-50 M_{sun}
- Fails in reproducing [Eu/Fe] for [Fe/H]<-3.0 dex

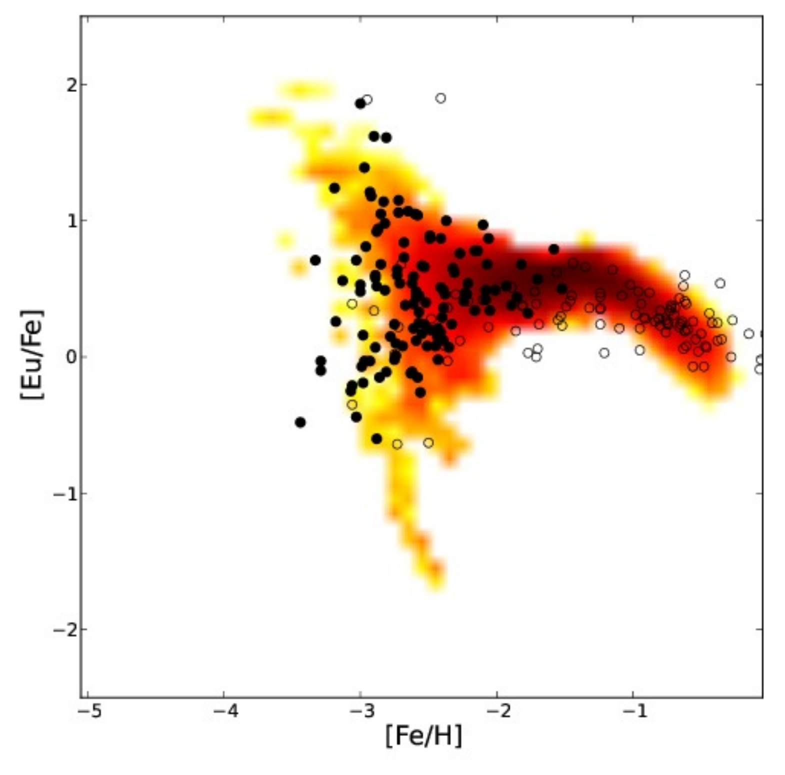


Results for the Galactic halo: MNS+MDR SNe. The best model of Cescutti+2015

- Here Europium originates from NSM plus magneto rotationally driven (MRD) SNe. We consider only the halo ([Fe/H]<-1.0)

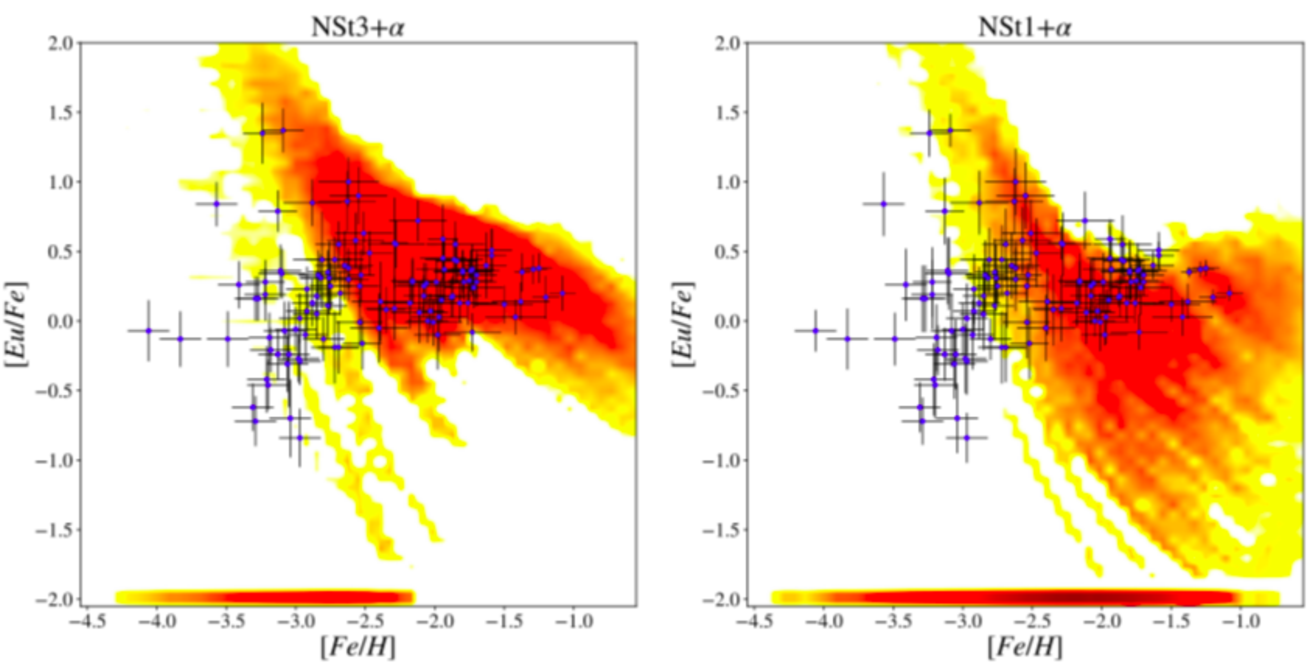
- The merging events have a fixed delay of 100 Myr

- The MRD SNe are assumed to be 10% of the total number of CC-SNe but only for $Z<10^{-3}$



Cavallo+2021(MNRAS,503,1) stochastic model: DTD for merging times, no CC-SNe and variable alpha

- In the left is DTD prop.$t^{-1.5}$, in the right DTD prop. t^{-1}, in both alpha variable. A problem of no stars below [Fe/H]<-3.0 dex. Different observational data (Abohalima&Frebel, 2018) from Cescutti+2015



Final remarks and warnings

- The meaning of the alpha parameter: the fraction of massive stars in the IMF that end up as binary merging neutron stars. Clearly is a free parameter fixed by reproducing the observed present time MNS rate (very uncertain)
- But we can constrain alpha also by means of the Eu yields from MNS. In fact, not any alpha value is acceptable, but only those which imply an Eu yield inside the theoretical and observational range. Degeneracy alpha-yields
- CC-SNe are not very likely producers of Eu but to reproduce all the MW Eu only with MNS, we need alpha higher at early times or very short coalescence times. Nugent+2022 finds that SGRB occurs preferentially in star forming galaxies (short coalescence time?)

Predicted number of gravitational wave emission events in the Galaxy

- We have integrated our predicted rate of MNS in time and found the total number of mergers during the Galaxy lifetime (13.7Gyr)
- We found that for our rate reproducing the local MNS rate of Kalogera et al. (2004) of 83 events/Myr, the number of events of gravitational wave emission in the Milky Way during the Hubble time should have been:

$$2.95 \cdot 10^6$$