Binary neutron stars and production of heavy elements

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A decade of AGILE:results, challenges and prospects of gamma-ray astrophysics

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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)

- (3-15)x10^{-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 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 semplicity we use three different timescales: 1 Myr, 10 Myr 100 Myr. A more realistic approach would require a distribution of a's
- Belczynski et al. (2002) finds that a large fraction of systems would merge in <1 Myr

The theoretical MNS rate in the Galaxy

- 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 α 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:

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

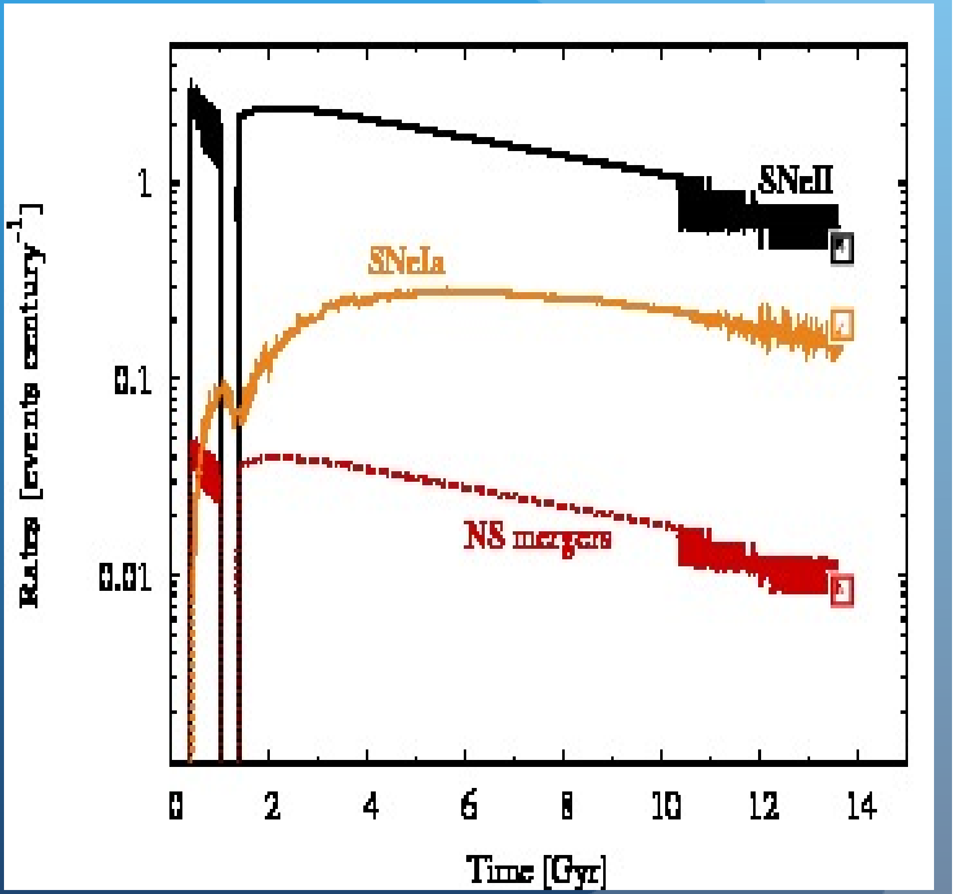
- Kim et al. (2015) suggest [2-210]/ Myr
- Ligo-Virgo estimate at low redshift for GW170817 (Abbott et al. 2017):

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

- Corresponding to 154/Myr
- The upper limit derived for kilonovae is 700 Myr^{-1} (Della Valle, from GW170817)

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 of 0.018
- Chemical evolution can constrain the MNS rate



gravitational wave emission events in the Galaxy

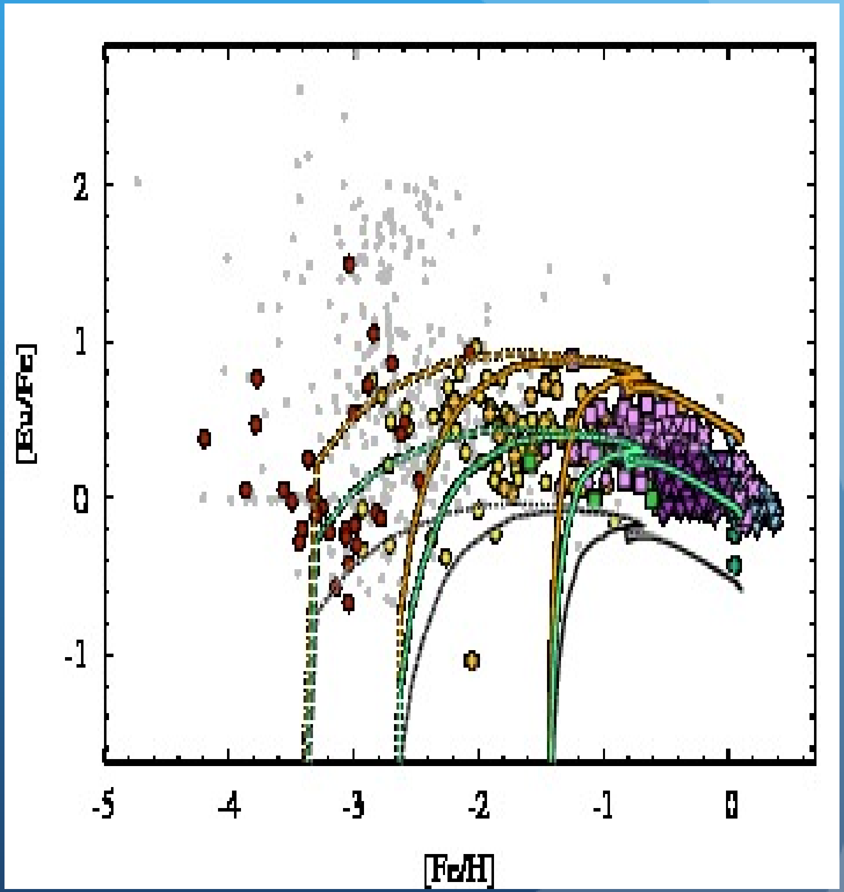
- We have integrated our predicted rate of MNS in time and found the total number of mergers during the Galaxy lifetime (13.7Gyr)

- 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:

$$2.95 \cdot 10^6$$

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 $_{lines}$: $M_{eu}=3x10^{-6} M_{sun}$,Yellow lines: $M_{eu}=9x10^{-6} M_{sun}$
- Predicted $(X_{eu})_{sun}=1.04x10^{-10}$



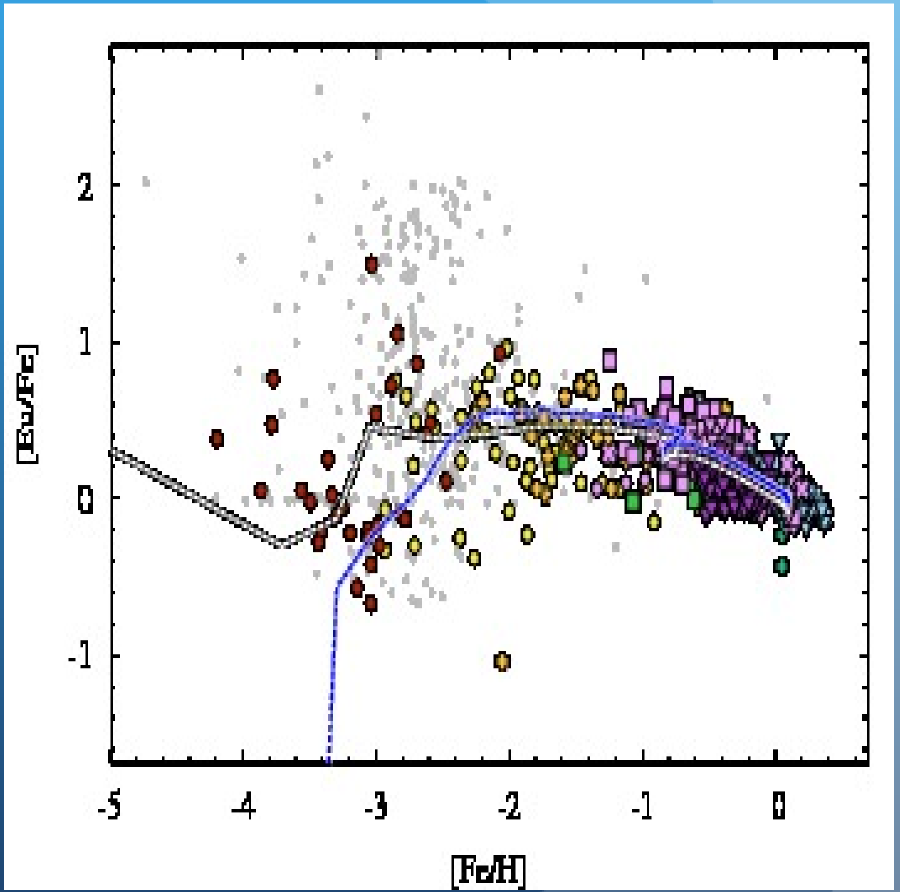
Observed $(X_{eu})_{sun}$ =3.5 x10^{-10}

Toward a best model

- 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}
- Predicted solar :

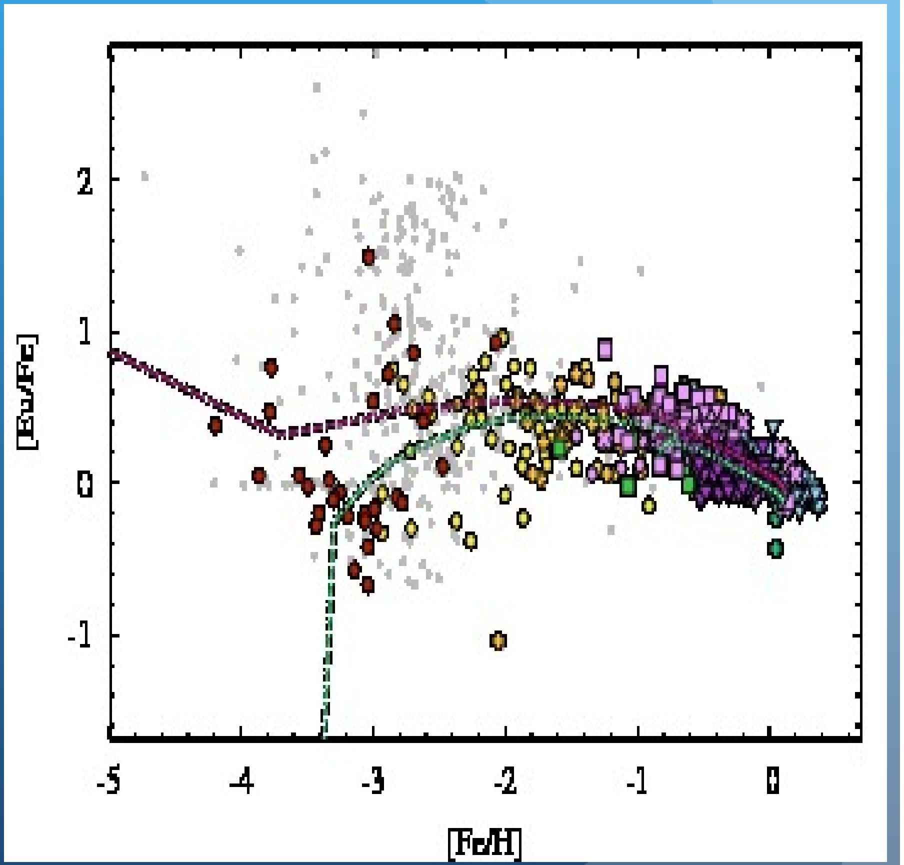
$(X_{eu})_{sun}$=3.65 x10^{-10} to be compared with the observed one of

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



Toward a best model

- 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 $M_{eu}=3x10^{-6}$ 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 $(X_{eu})_{sun}=4.2 \times 10^{-10}$



Conclusions

- Europium 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

- A more realistic (?) situation suggests that both SNeII and MNS can produce Eu. The best model in this case assumes that MNS produce M_{eu}= 2x 10^{-6} M_{sun} and the delay times can be various. The SNe II should produce Eu in a range 20-50 M_{sun}, but the production from MNS should be predominant

- 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 chemical models

- If GW170817 is a representative event, then MNS can be considered as the main r-process element sites

Type Ib,c supernovae and long cosmic GRB rate

cosmic predicted SN Ib/c rates (black and red lines) computed by means of various CSFRs and the number of observed GRBs at various redshifts provided by Wanderman + Piran (2010), Swift data (black circles with error bars) and Matsubayashi et al. (2005) (magenta dashed–dotted line). The short-dashed and the double-dotted blue lines, below the Matsubayashi et al. (2005) rate, represent the best fit and the upper and lower limits, respectively, of the cosmic GRB rate obtained by Salvaterra et al. (2012). Ratio GRB/SN Ib/c is 3×10^{-3}