Neutron star mergers, r process elements, gravitational waves and kilonovae

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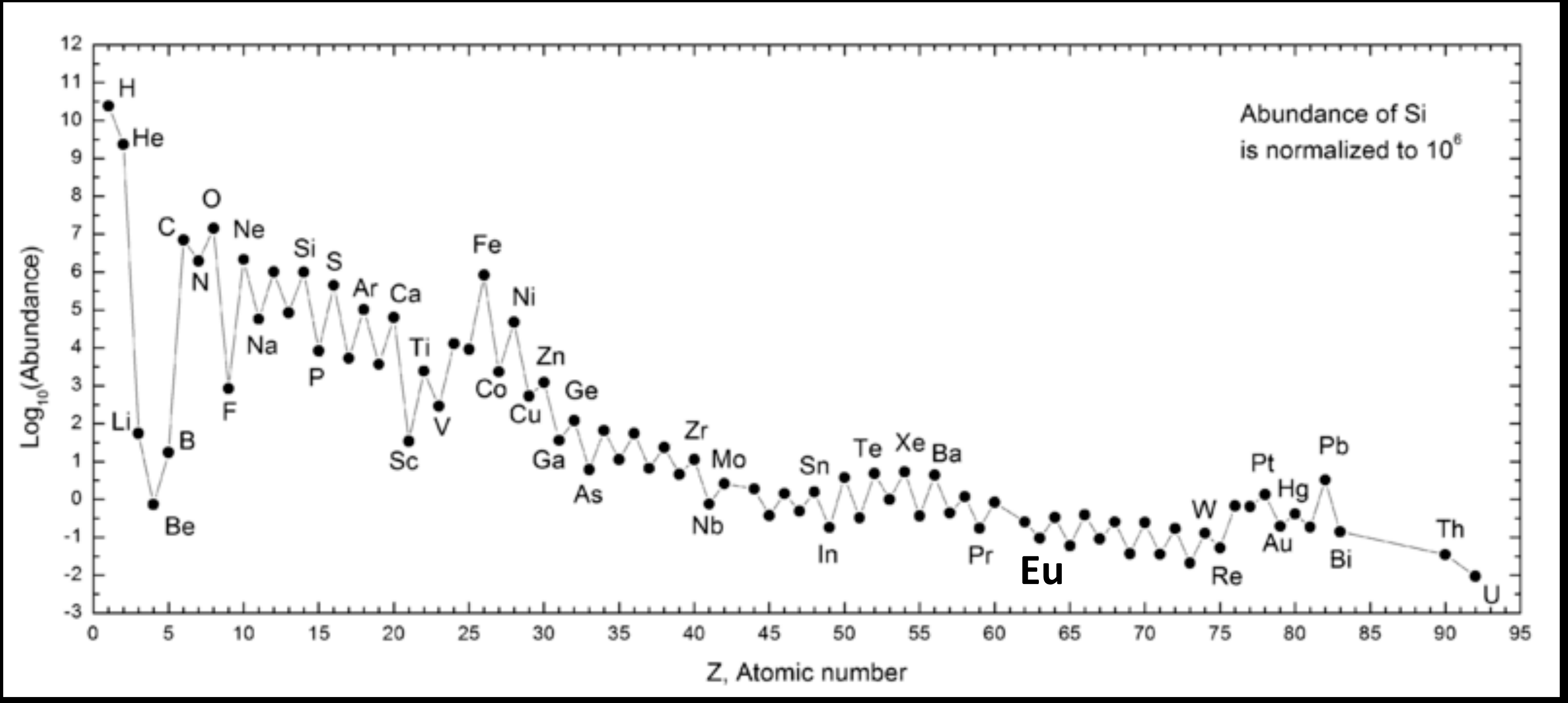
Heavy elements and r process

The chemical composition of the Universe



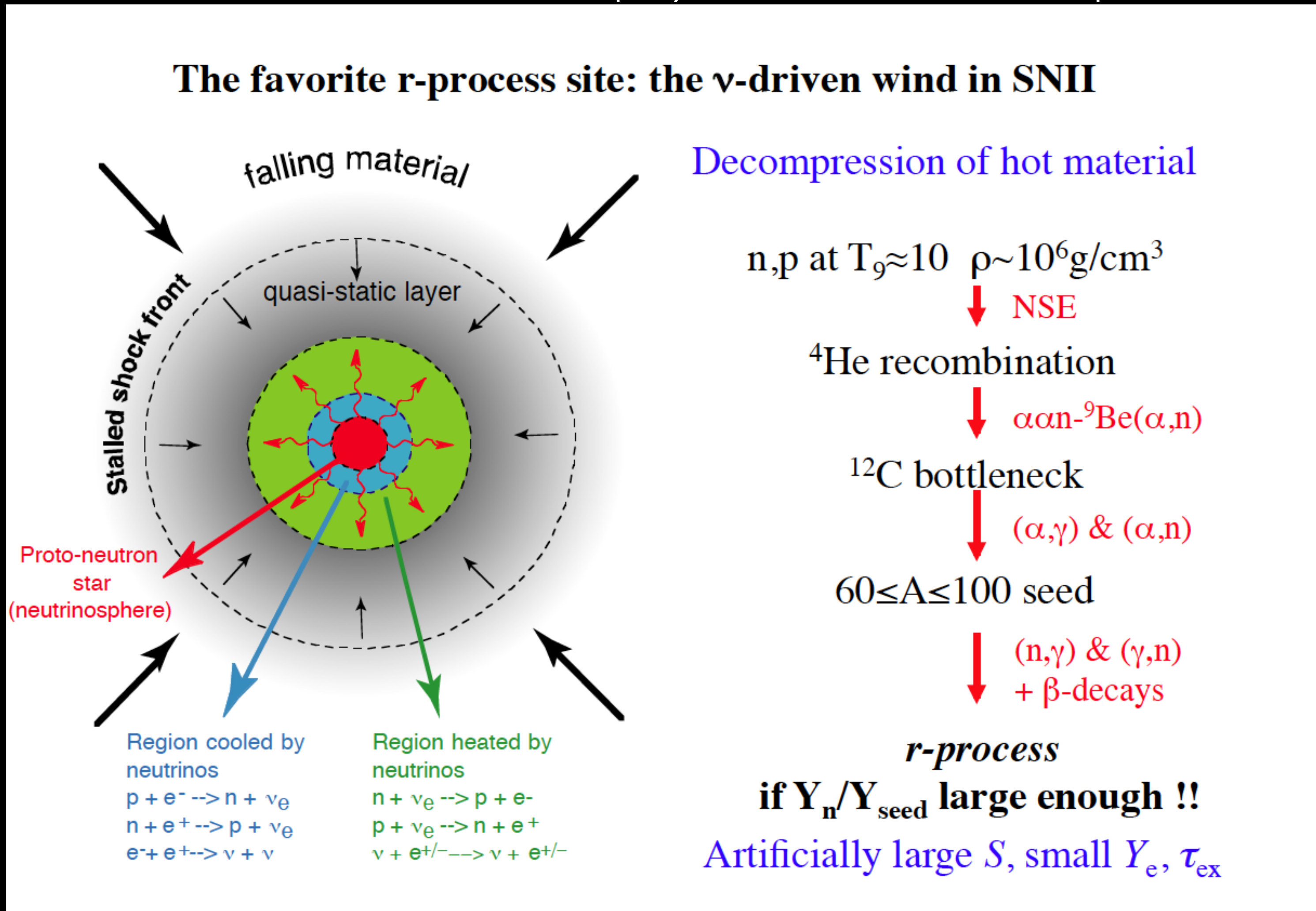
Lodders (2003)

r-process nucleosynthesis: very specific physical conditions (density, temperature, neutron fraction)

Which astrophysical site ?

The r-process nucleosynthesis: cc SNae ?

Main candidate for the astrophysical site: core-collapse Snae

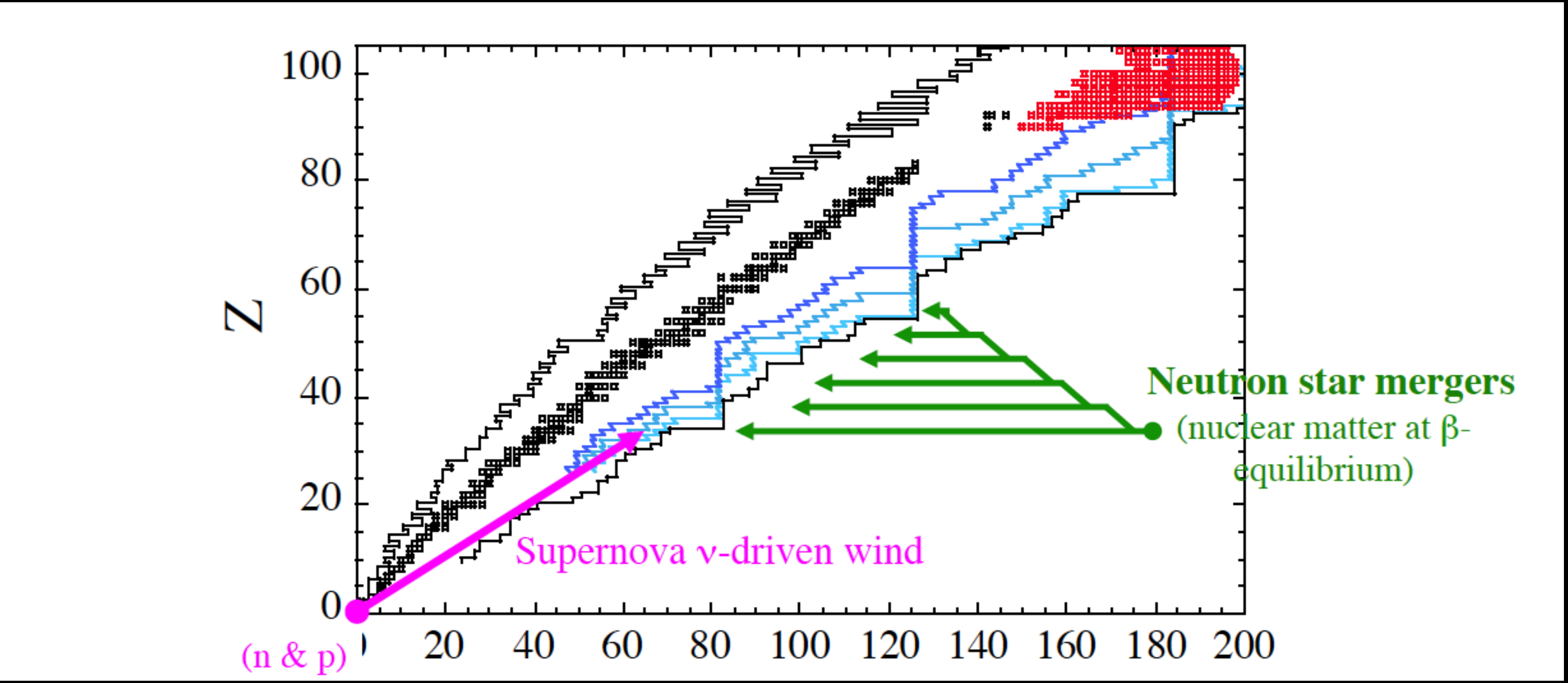


However: recent cc SN simulations are still unable to yield the extreme conditions for forming the heaviest elements.

(Hoffmann et al. 2008 ; Janka et al. 2008 ; Roberts et al. 2010 ; Hüdepohl et al. 2010 ; Fischer et al. 2010 ; Wanajo et al. 2011 ; Arcones & Martinez-Pinedo 2011)

The r-process nucleosynthesis: NS-NS mergers ?

An alternative scenario : NS-NS mergers



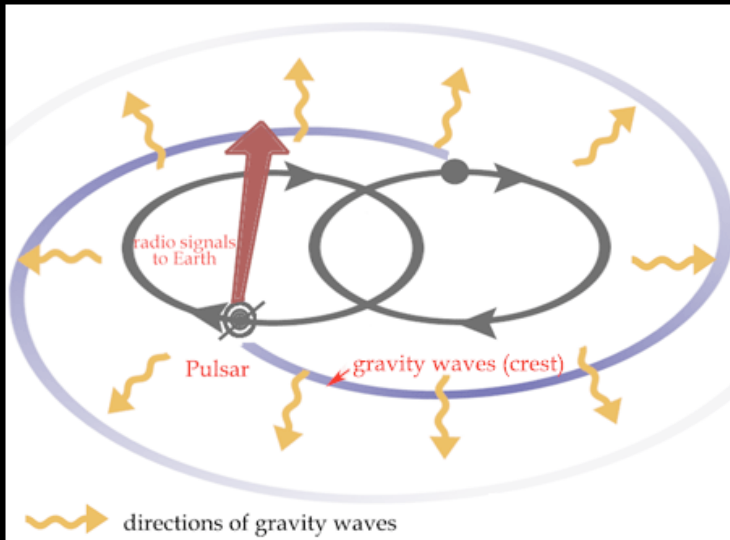
Ejection of NS matter : r-process occurs during expansion

Recent simulations confirm that NS-NS mergers are a a viable r-process site.

(Freiburghaus et al. 1999 ; Goriely et al. 2005 ; Arnould et al. 2007 ; Metzger et al. 2010 ; Roberts et al. 2011 ; Goriely et al. 2011 ; Korobkin et al. 2012 ; Bauswein et al. 2013 ; Goriely et al. 2013)

Neutron Star Mergers

Hulse & Taylor Binary Pulsar PSR B 1913+16

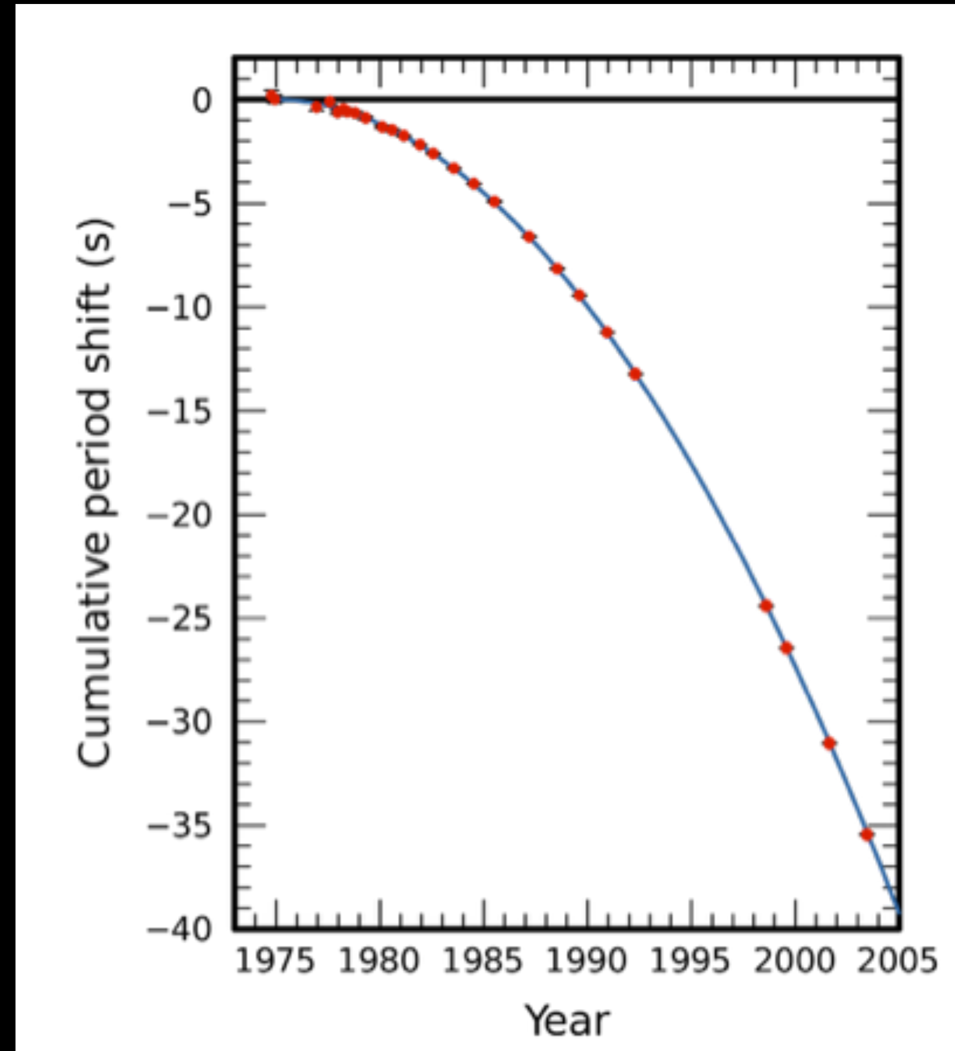


D = 7.1 kpc
M_1 = 1,4414 ± 0,0002 $M_\odot$
M_2 = 1,3867 ± 0,0002 $M_\odot$

$d\omega/dt$ = 4.23°/yr

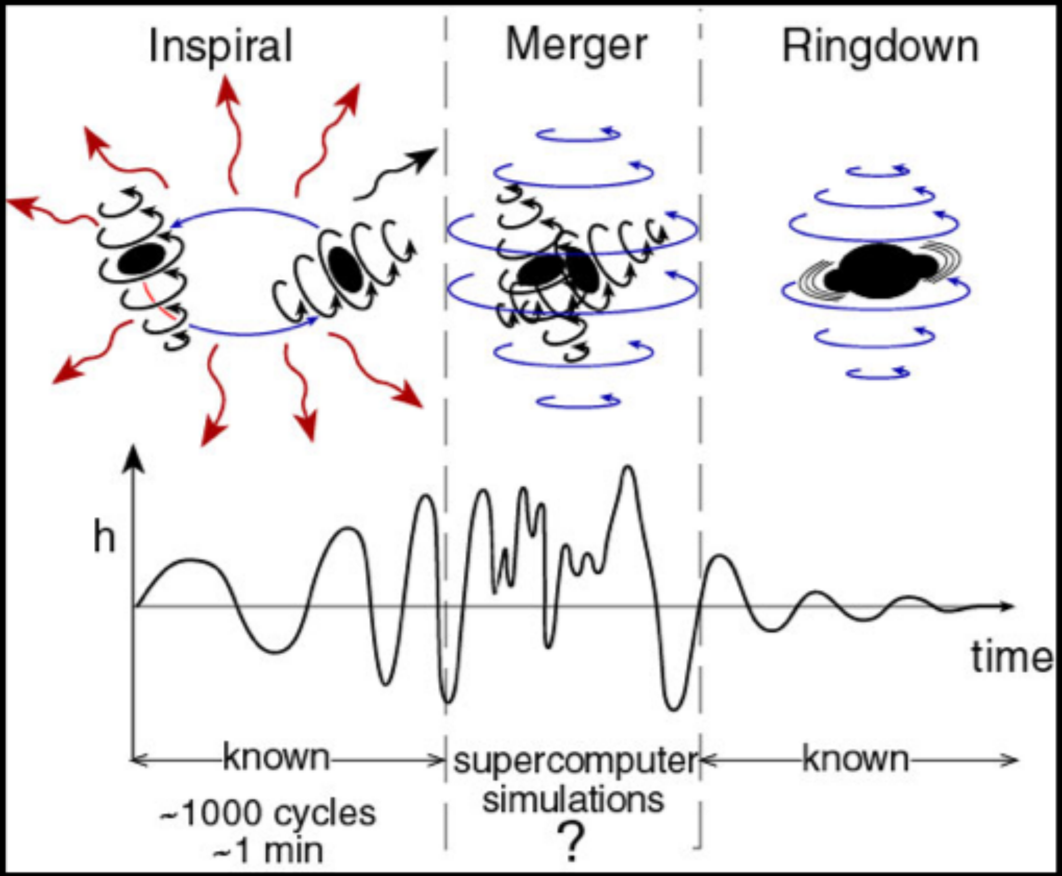
Orbital period:
T = 77.5 h (precision: ns)
dT/dt = -2.42 x 10^{-12} = 76.5 μs/yr

Semi-major axis:
a = 13.0 mUA
da/dt = 3.5 m/yr



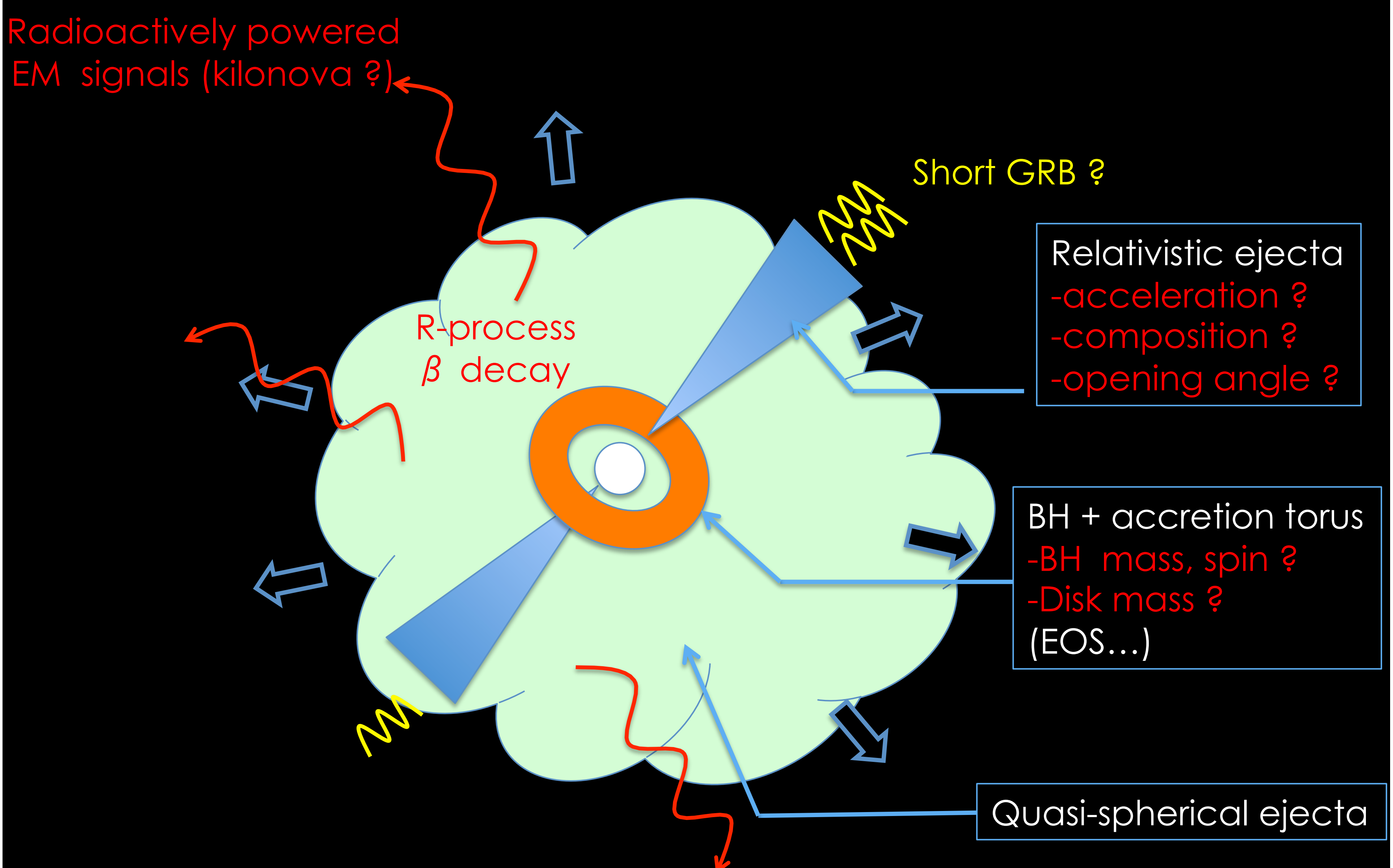
Merger in 300 Myr !

Neutron Star Mergers: gravitational waves



The main expected source of GW for advanced Virgo/LIGO

Neutron Star Mergers: electromagnetic counterparts



Original figure by B. Hotokezaka + M. Shibata

Neutron Star Mergers: electromagnetic counterparts

Electromagnetic emission from the non-relativistic ejecta ?

Relativistic simulations predict weaker counterparts than Newtonian

- Optical transient (radioactive decay of the product of r-process):
  a few 10^{40} to a few 10^{42} erg/s
  T_{eff} ~ 10 000 to 20 000 K after a few hours

  (Li & Paczynski 1998)

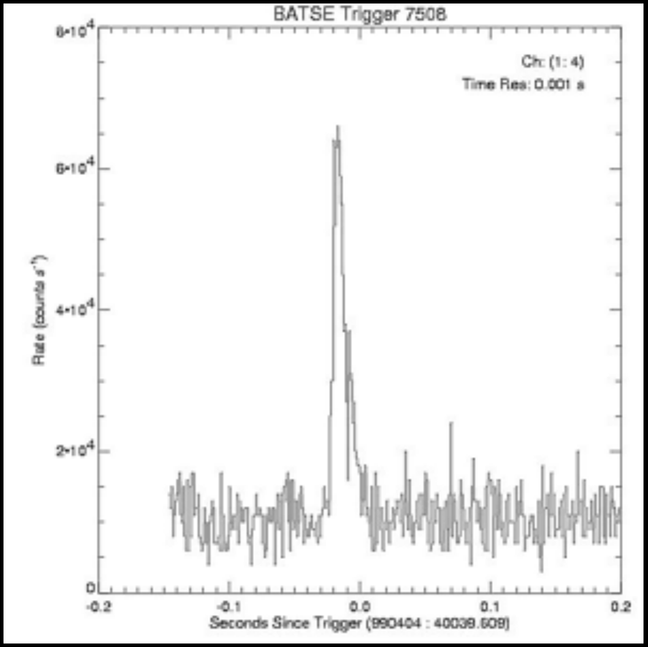
- Radio transient (deceleration of the ejecta by external medium):
  depends on velocity (0.15 to 0.5 c) – kinetic energy (5×10^{49} to 10^{51} erg)

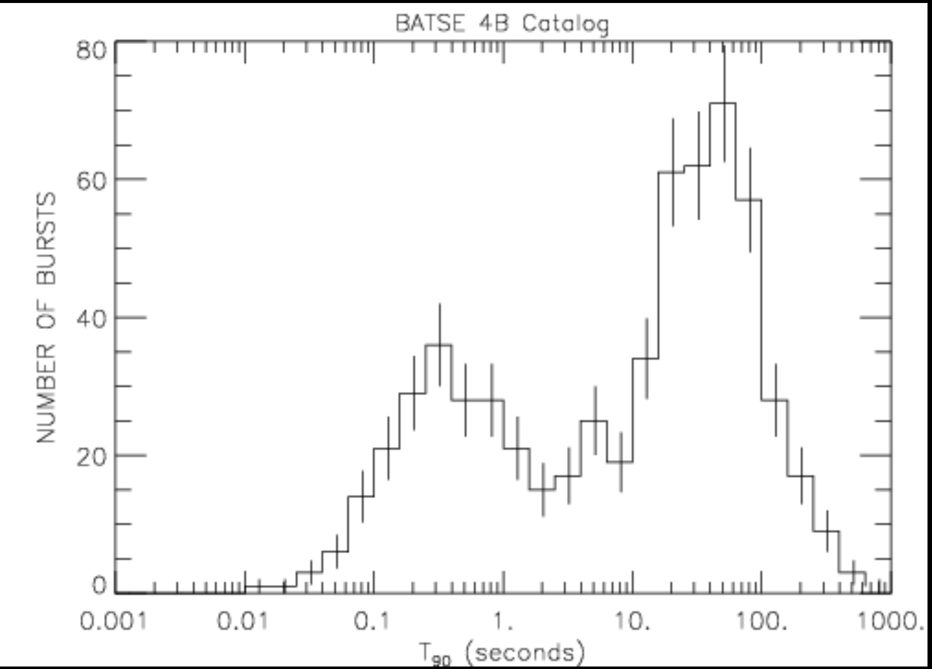
Short GRB from an ultra-relativistic ejecta ?

Seen only if the observer is on-axis: what is the beaming angle ?

Short Gamma-Ray Bursts:

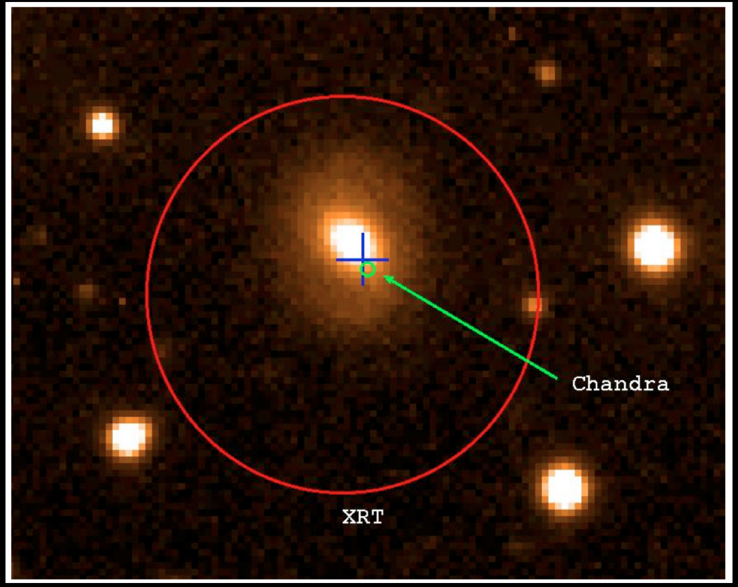
Compared to long GRBs:
-less frequent
-shorter, harder
-weaker afterglow
-less localizations, less redshift measurements





Short GRBs: association with mergers ?

Host galaxies:



GRB 050724 : VLT observation

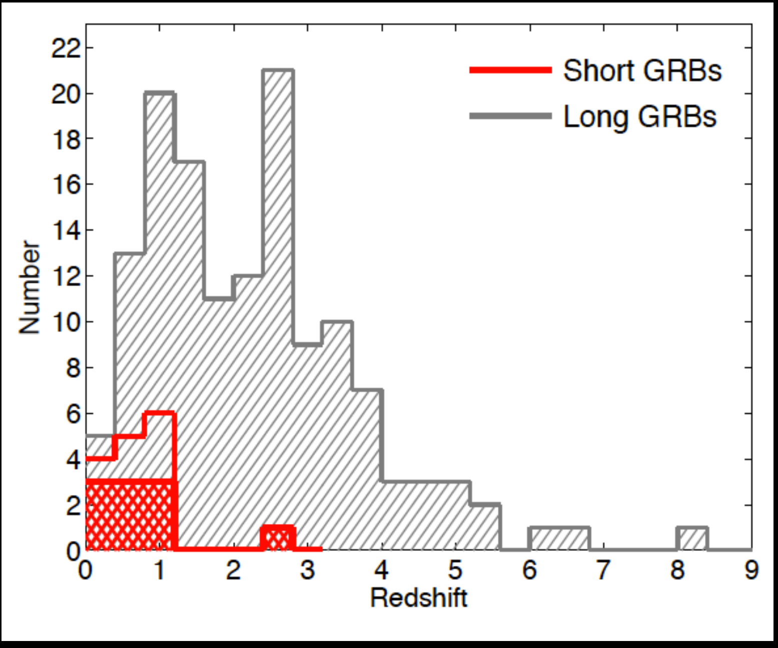
Barthelmy et al. 2005

Short GRBs: no correlation with star formation – offsets (see recent review by Berger)

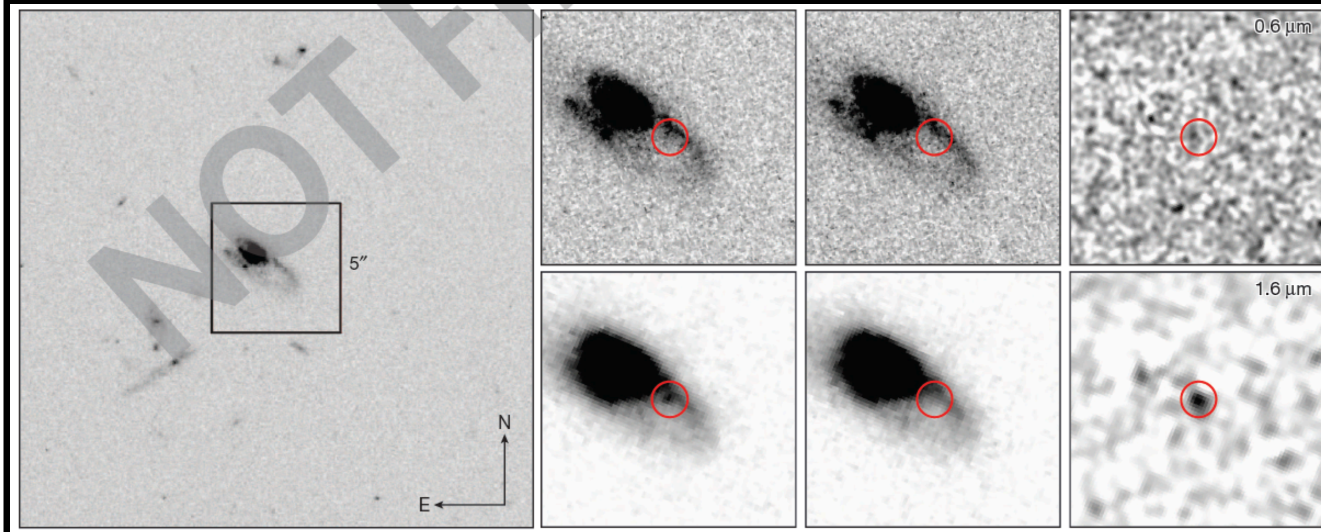
Long GRBs: star forming hosts
association with SNae

Redshift distribution:

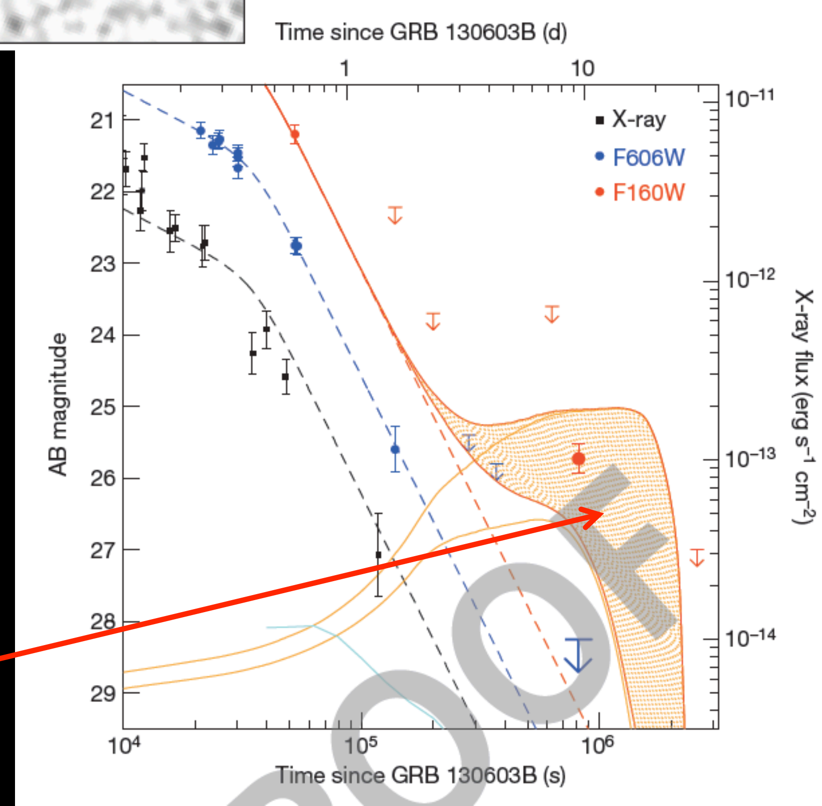
Berger et al. 2011



Kilonovae ?



Tanvir et al. 2013



Short GRB 130603B

See also another candidate found by Fan et al. in association with GRB 060614

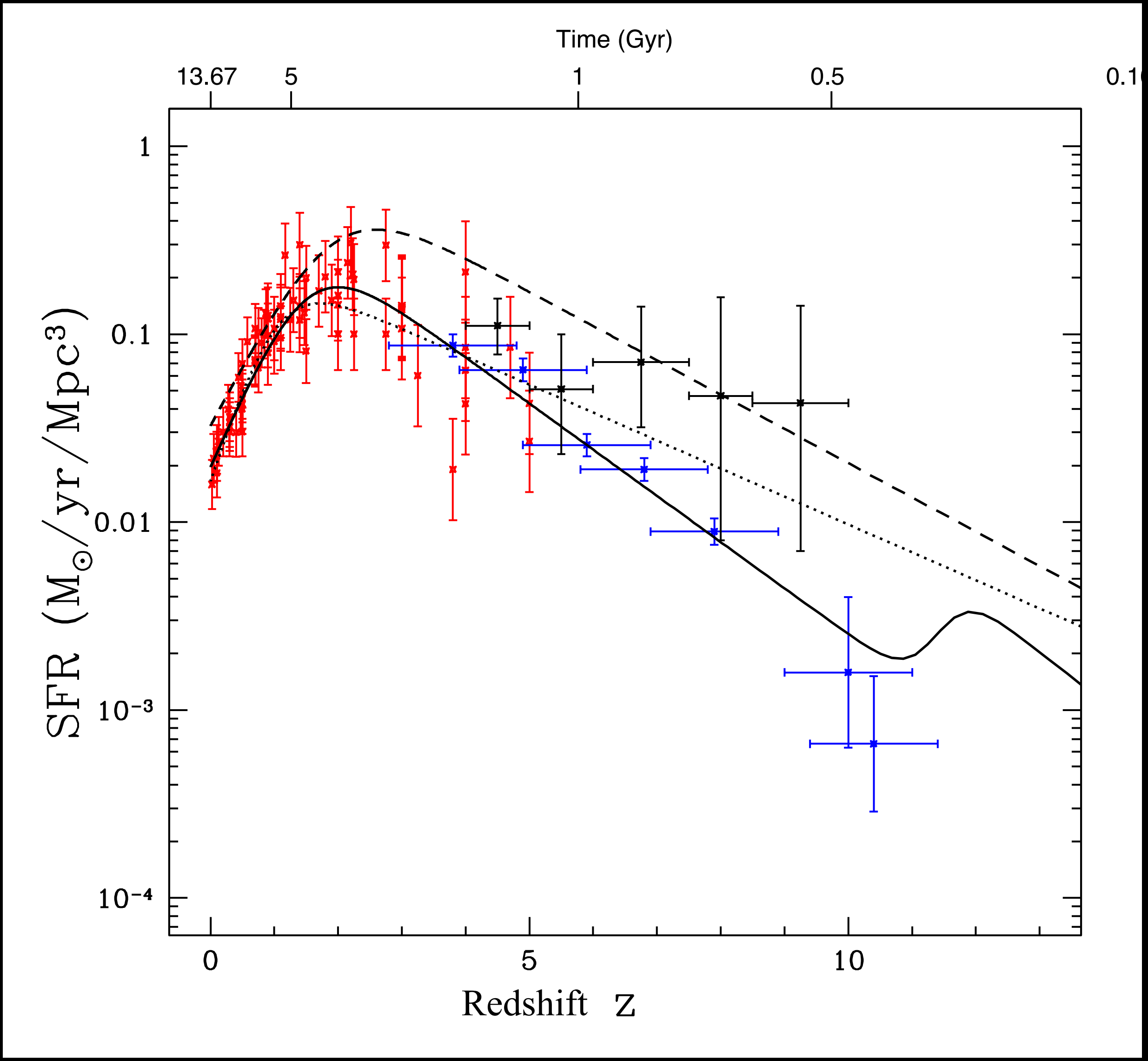
Kilonova ?

Predicting the Neutron Star Merger Rate in the Universe

Cosmic Star Formation Rate Density

Observations:

Behroozi et al. (2014)
Bouwens et al. (2014)
Oesch et al. (2014)
Kistler et al. (2013)



SFR1 (low)
SFR2 (mid)
SFR3 (high)

Core-collapse Supernova Rate

Stellar models: mass range of stars forming NS or BH in core collapse [uncertainties…]

The core collapse rate can be deduced directly from the star formation rate without new assumptions.

Massive stars have short lifetimes : strong correlation !

Neutron Star Mergers:

The merger rate cannot be deduced so easily from the SFR:

The NS birth rate is known.

Two more parameters:

- -fraction of NS in a binary system with a NS/BH ?
- -distribution of coalescence timescale ?

Neutron Star Mergers: coalescence timescale

Large dependence on initial separation $\Delta t_{\mathrm{NSM}} \propto a^4$ (Peter & Mathews 1963)

Exemple:
NS+NS 1.4 $M_\odot$+1.4 $M_\odot$ and a = 0.01 AU : T=5.2 h and Δt_{NSM} = 64 Myr

7 systems known in the MW: (Lorimer 2005, 2008)

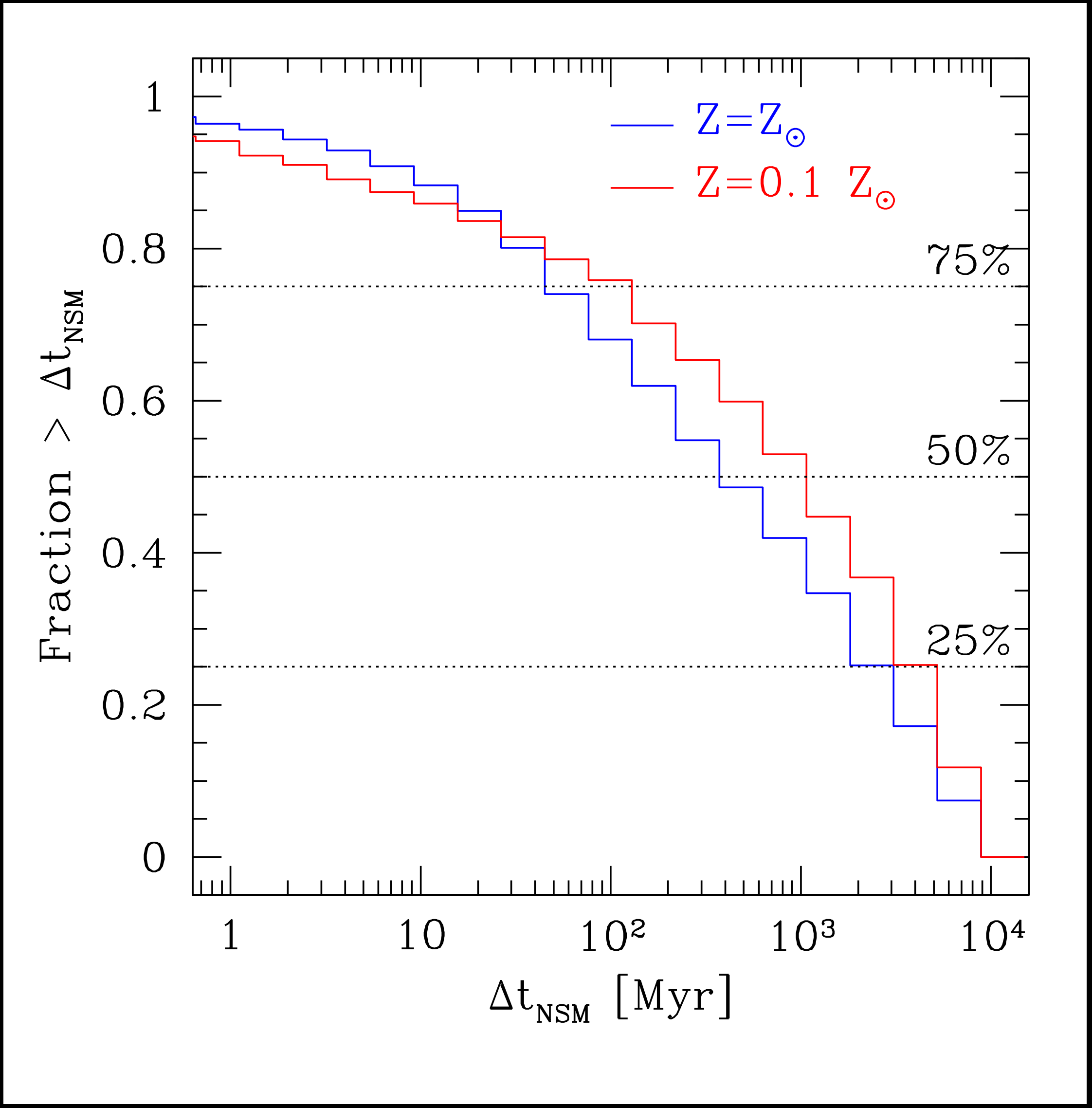
* with measured mass → remaining time before merger
* with one NS detected as a pulsar → age of the system

* 4 systems with $100 < \Delta t_{NSM} < 400$ Myr
* 3 systems with $\Delta t_{NSM} > 1$ Gyr

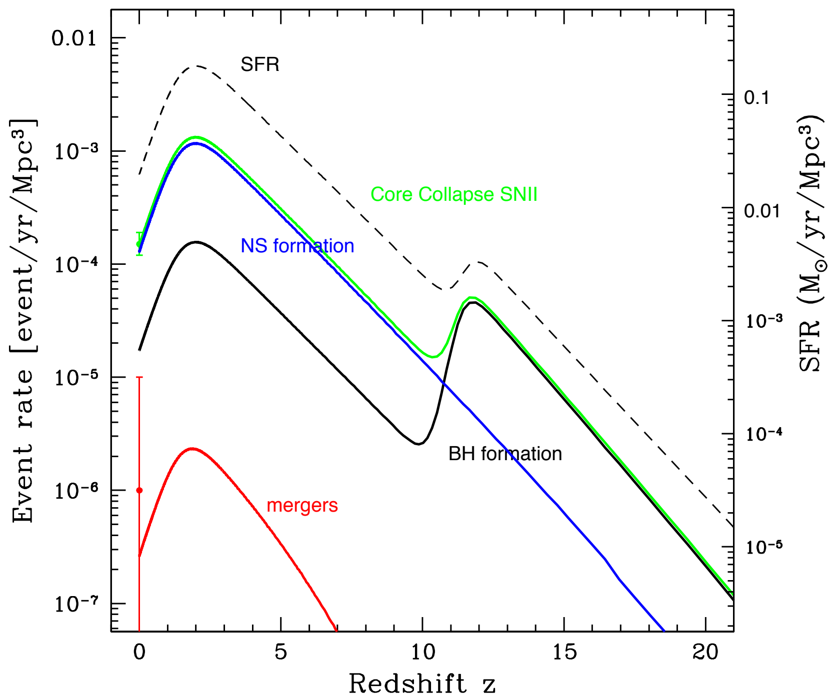
Double pulsar PSR J037-3039 : 180 Myr (lowest value)
Hulse & Taylor binary pulsar PSR B1913+16 : 420 Myr

Neutron Star Merger Rate: coalescence timescale (NS/NS)

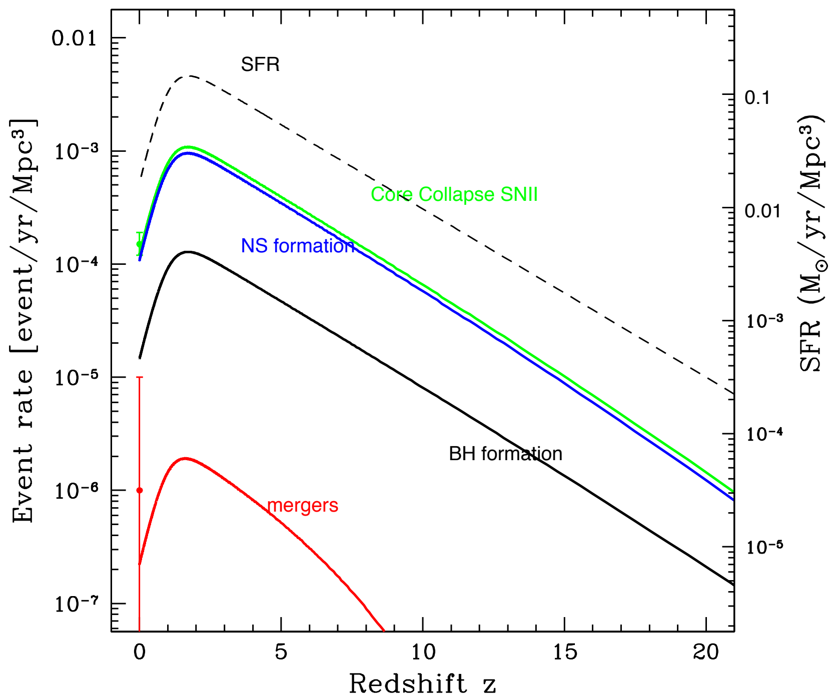
Population Synthesis Model by Belczynski et al. (2002)



Core collapse & merger rate



SFR1

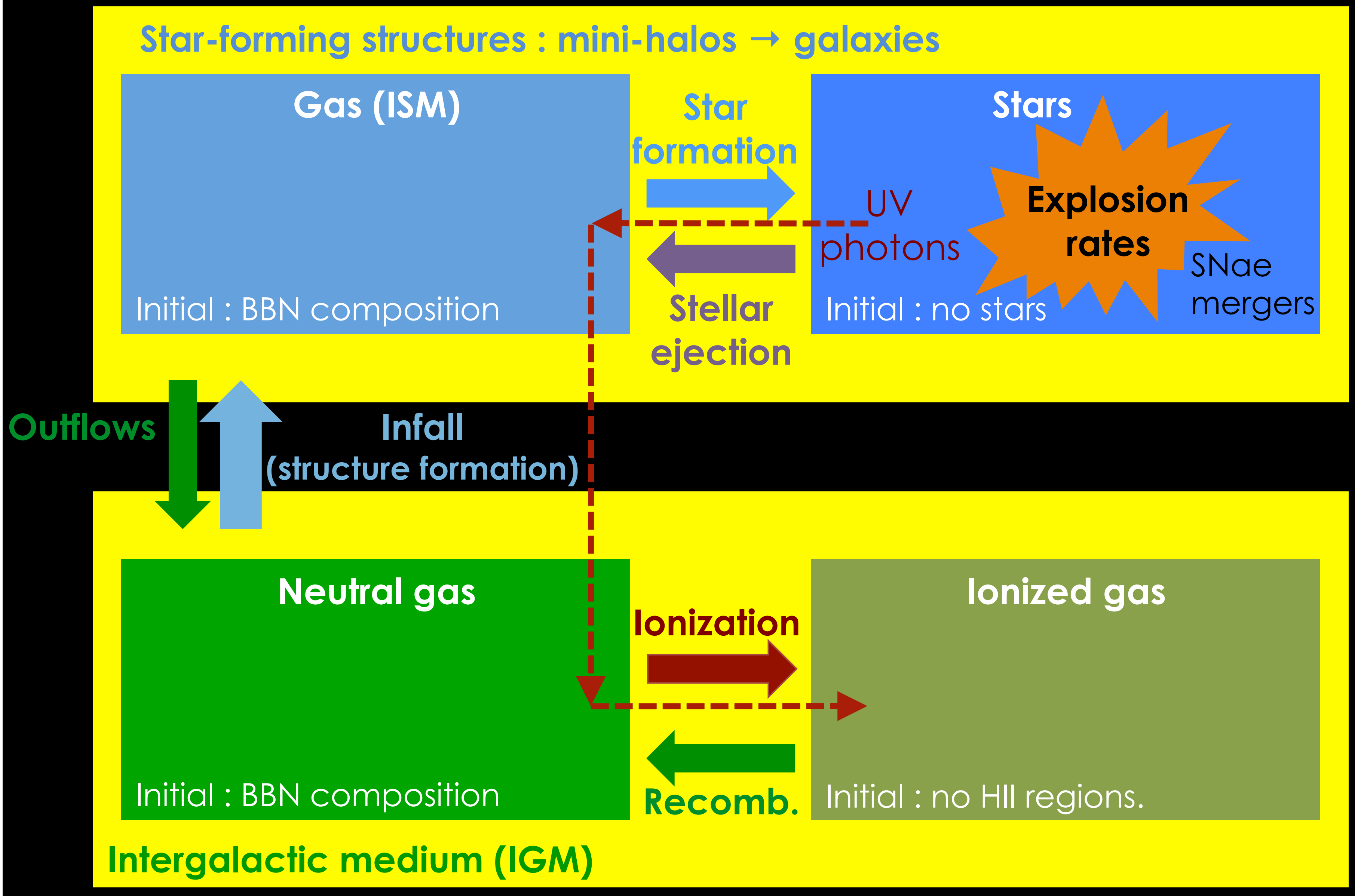


SFR2

Cosmic Chemical Evolution

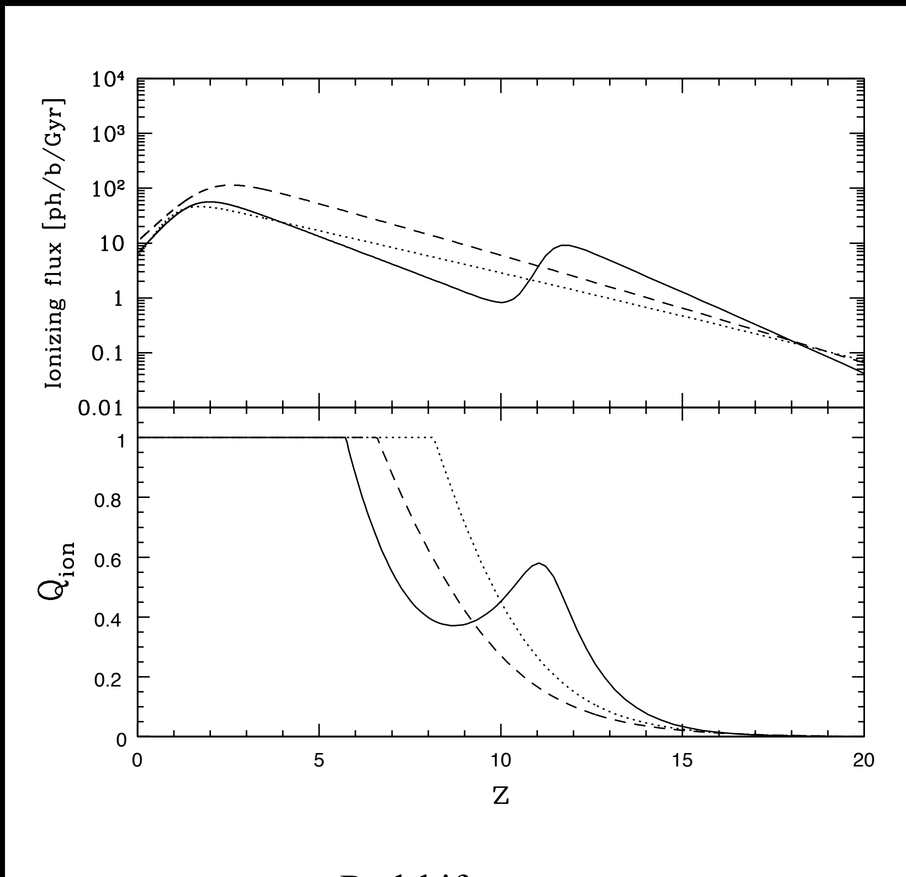
Modeling the cosmic chemical evolution

Daigne, Olive, Vangioni-Flam, Silk & Audouze 2004
Daigne, Olive, Silk, Stoehr & Vangioni 2006
Rollinde, Vangioni, Maurin, Olive, Daigne, Silk & Vincent 2009

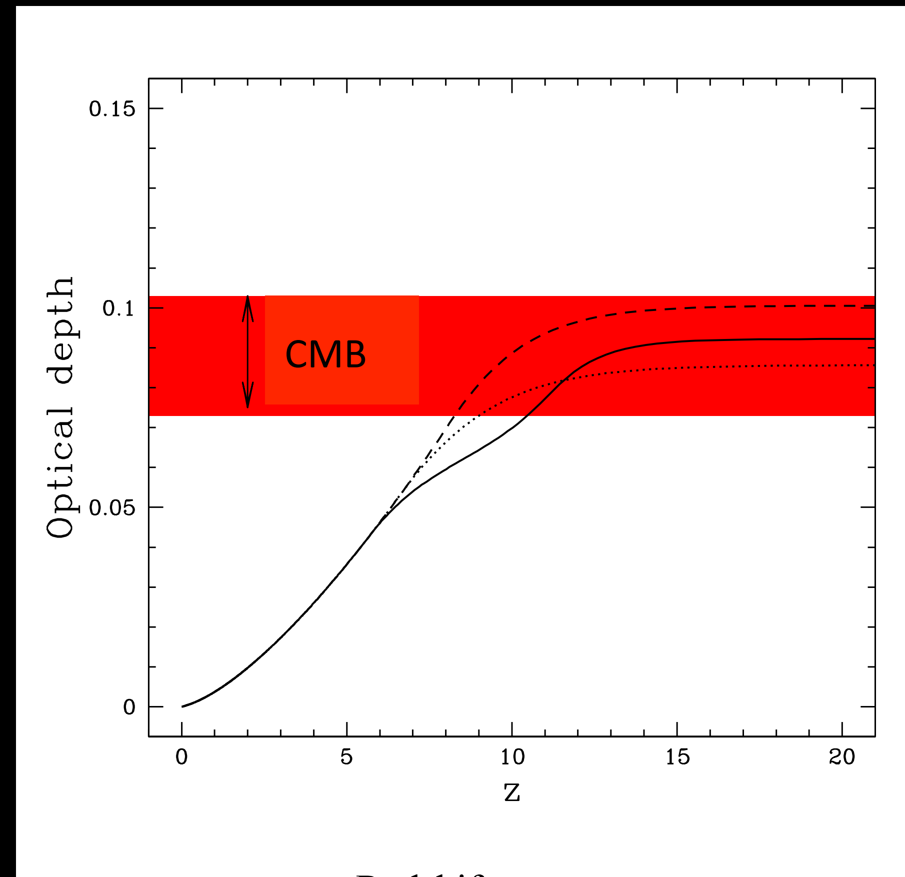


Constraints (1) Reionization

Ionizing Flux



Thomson Optical Depth of the CMB



Q_{ion} = volume filling fraction of the ionized regions

SFR1 (low) ———

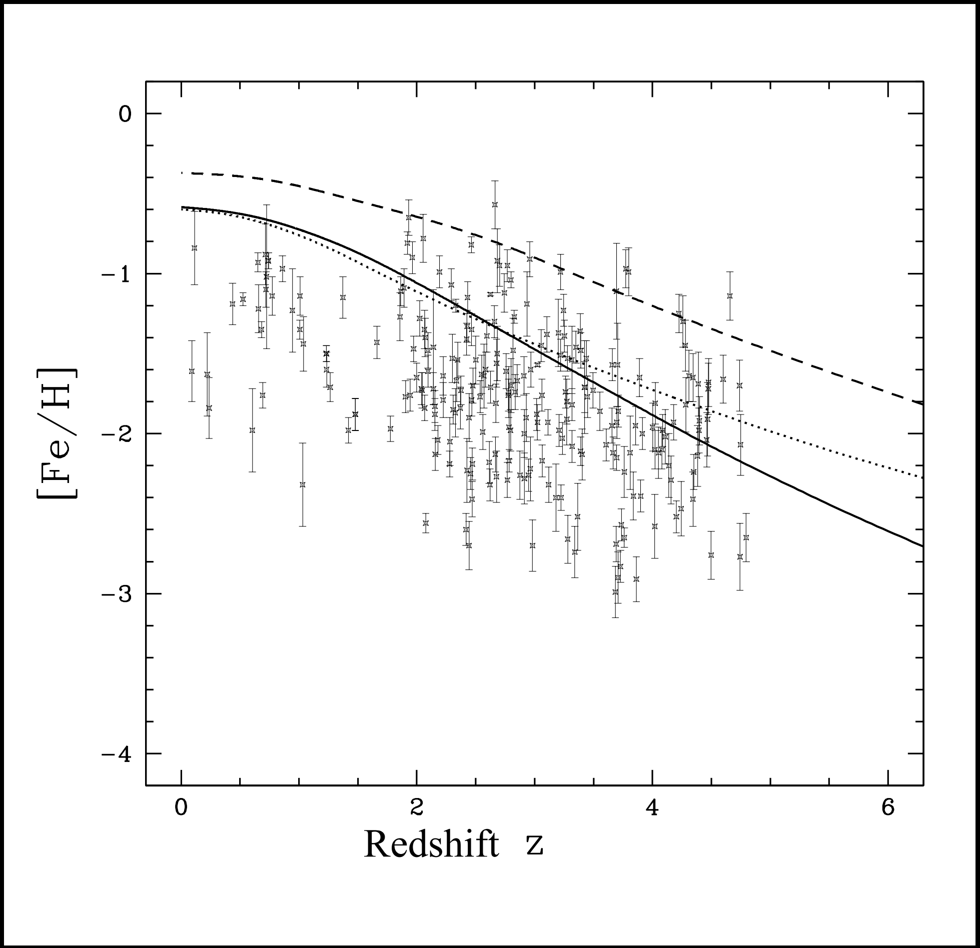
SFR2 (mid) ········

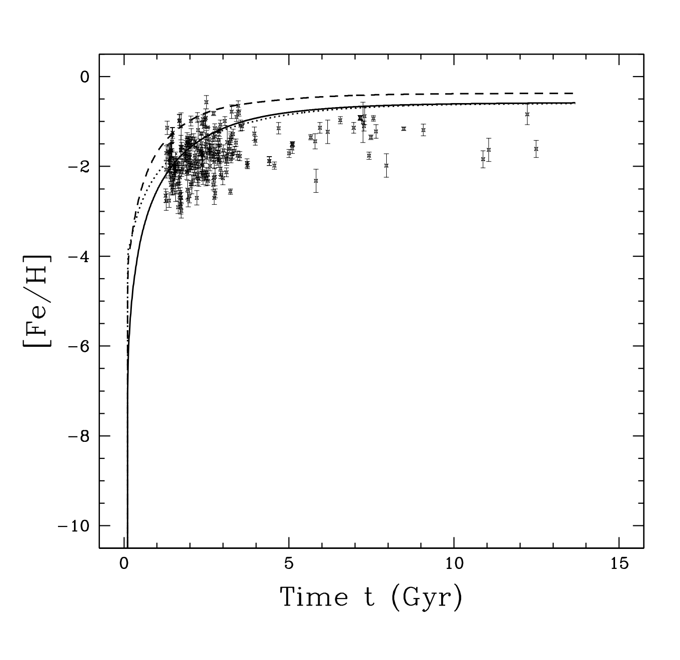
SFR3 (high) – – – – –

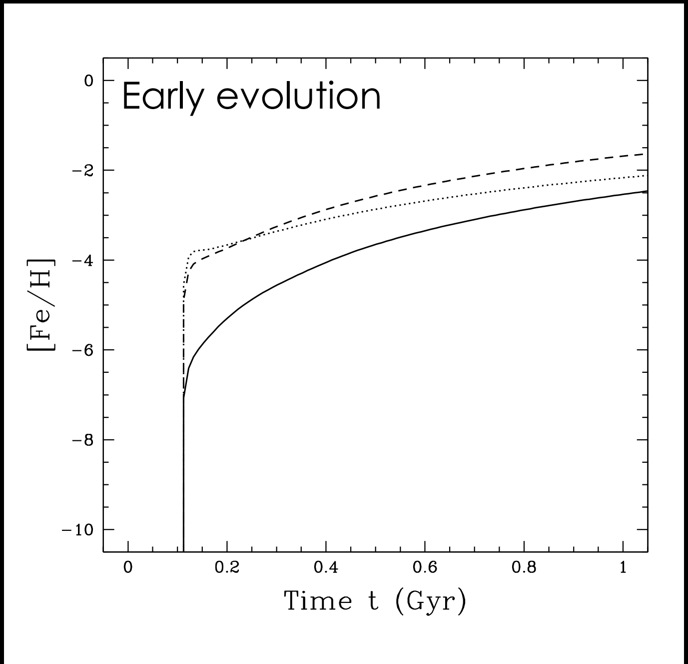
$$\tau = c\,\sigma_{\mathrm{T}}\,n_{\mathrm{b}} \int_0^z \mathrm{d}z'\, Q_{\mathrm{ion}}(z')\,(1+z')^3 \left|\frac{\mathrm{d}t}{\mathrm{d}z}(z')\right|$$

Constraints (2) Chemical evolution

Cosmic evolution of iron as a function of redshift





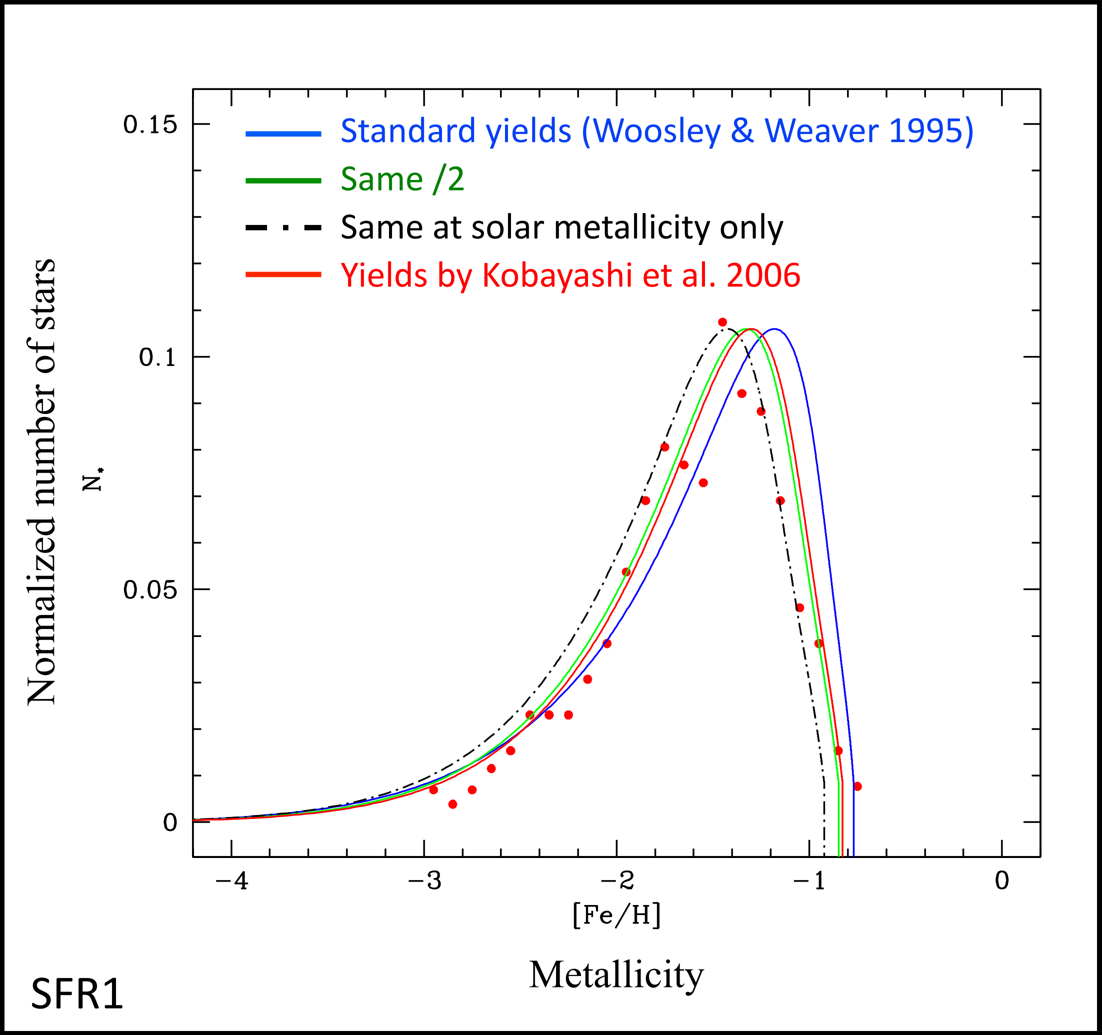


SFR1 (low)	———
SFR2 (mid)	········
SFR3 (high)	– – – – –

Observations:
DLAs (Rafelski et al. 2012)

Constraints (2) Chemical evolution

Local metallicity distribution function



Obs: ● SDSS (An et al. 2013)

More constraints not shown here

Evolution of more chemical elements (CNO…)

Evolution of the stellar mass in galaxies

Etc.

Predicting the evolution of r process elements: uncertainties for the yields

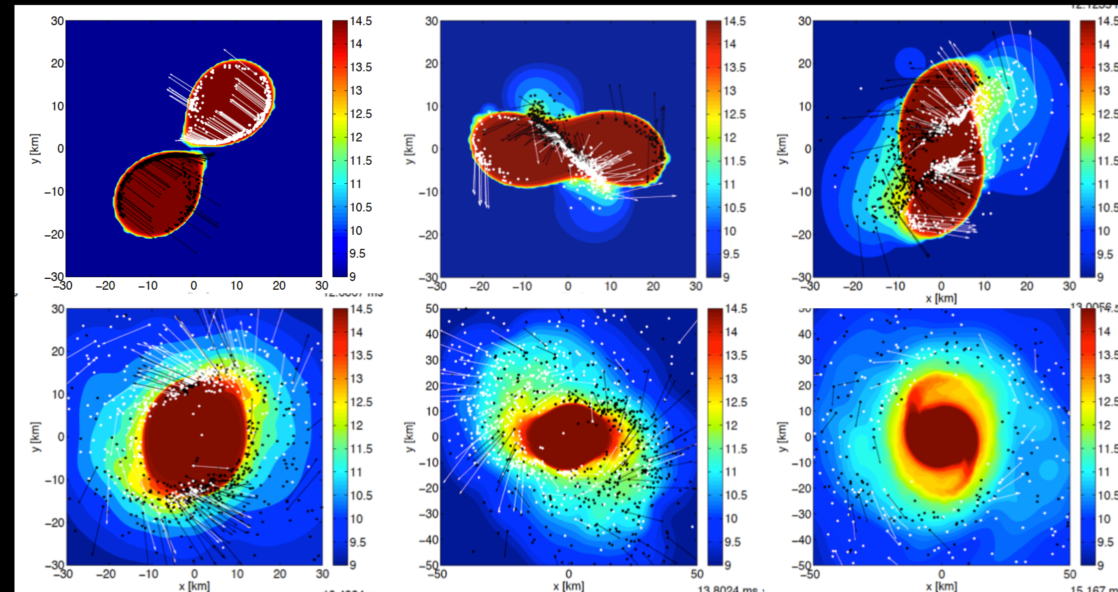
- Core-collapse scenario: yield = uncertain

  We assume for Eu : $10^{-7}\ M_\odot$ per CCSN
  calibrated on the Milky Way (Lodders 2003, Asplund et al. 2009)

- Merger scenario: yield = detailed calculations available

Mergers: uncertainties

Ejected mass



Bauswein, Goriely & Janka 2013

from a few 10^{-3} to a few 10^{-2} $M_{\odot}$.
Depends on
- EoS of NS matter
- dynamical parameters

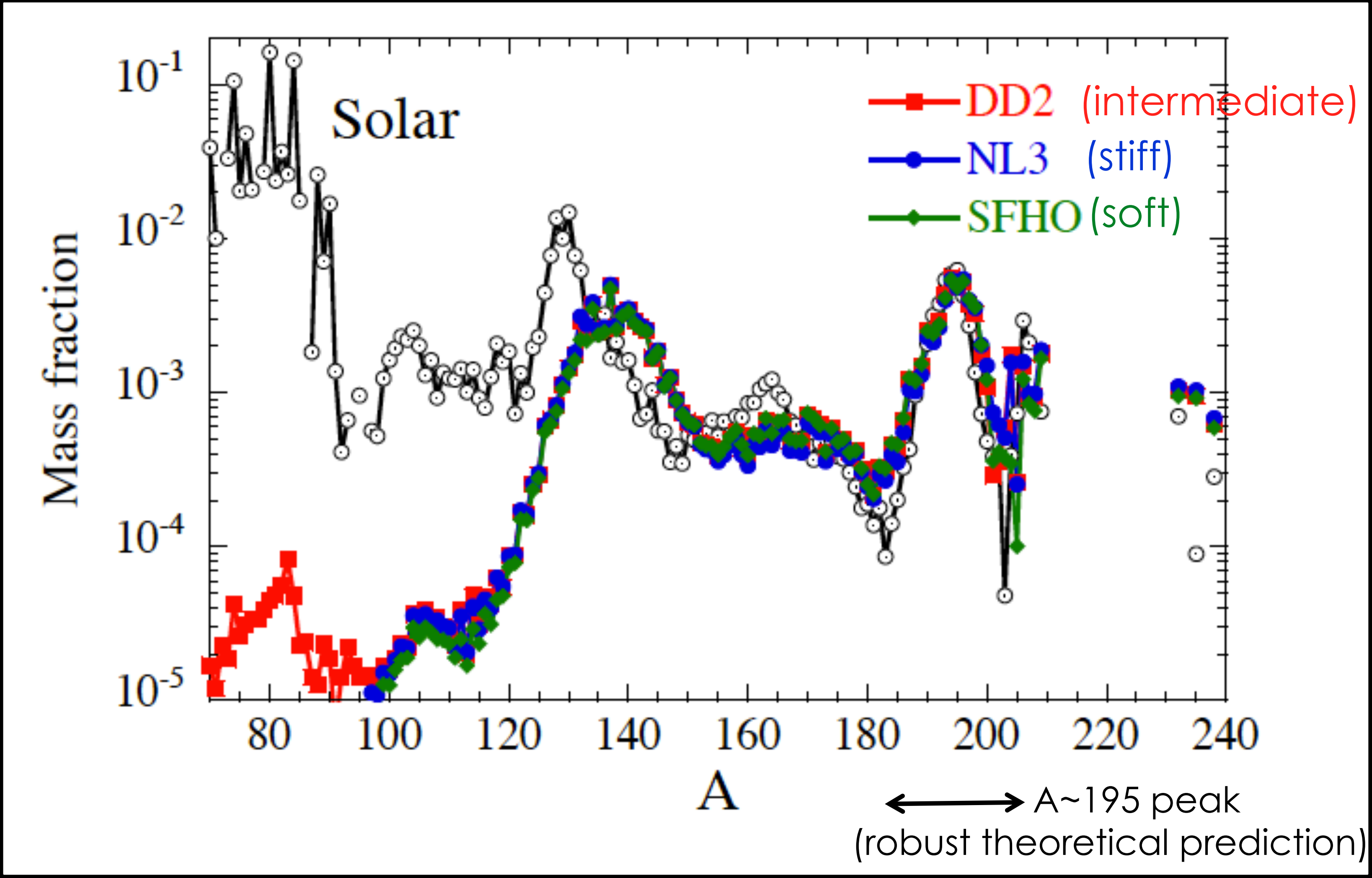
Production of r elements

typical yield for elements like Eu :
7×10^{-5} to 2×10^{-4} $M_{\odot}$ (Goriely et al. 2013, Just et al. 2014)

r-process in the ejecta from NS-NS mergers

symmetric merger (1.35-1.35 $M_\odot$)

Similar patterns for NS/NS, NS/BH, …



Bauswein, Goriely & Janka 2013

A~140 peak due to fission recycling
(large theoretical uncertainties)

Europium production

- Core-collapse scenario: yield = uncertain

We assume for Eu: 10^{-7} $M_{\odot}$ per CCSN
calibrated on the Milky Way (Lodders 2003, Asplund et al. 2009)

In our reference case, we do not assume a dependence on the mass or metallicity of the progenitor star

- Merger scenario: yield = detailed calculations available

Weak sensitivity to the EOS of dense matter,
Weak sensitivity to M_{BH}, M_{torus}, …

Main uncertainty: ejected mass, viscosity

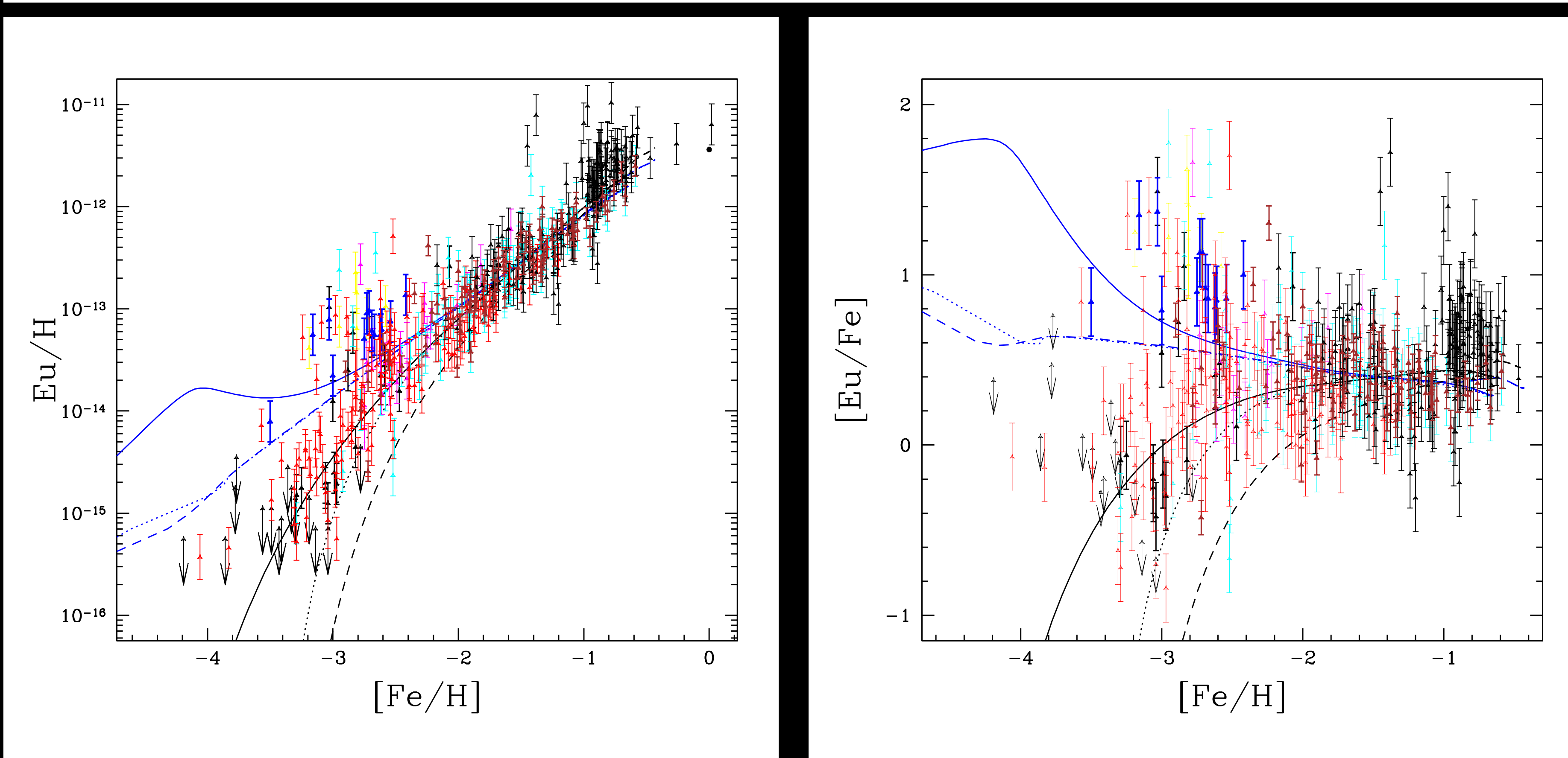
Just et al. 2014: 7 10^{-5} $M_{\odot}$ to 2 10^{-4} $M_{\odot}$ per merger

We assume for Eu: 7 10^{-5} $M_{\odot}$ per merger

Constraints on the Merger Rate from the cosmic evolution of Eu

Cosmic evolution of Europium: ccSNae vs NS mergers
Evolution as a function of metallicity

Black: Neutron Star Mergers　　Blue: Core-collapse Supernovae Scenario



Black points/upper limits: François et al. 2007
[old metal poor stars in the MW]
Other observations: many sources

Mergers: Δt_{NSM} = 200 Myr ; Binary fraction 0.002

SFR1 (low) ————
SFR2 (mid) ········
SFR3 (high) – – – – –

Cosmic evolution of Europium: ccSNae vs NS mergers
Evolution as a function of metallicity

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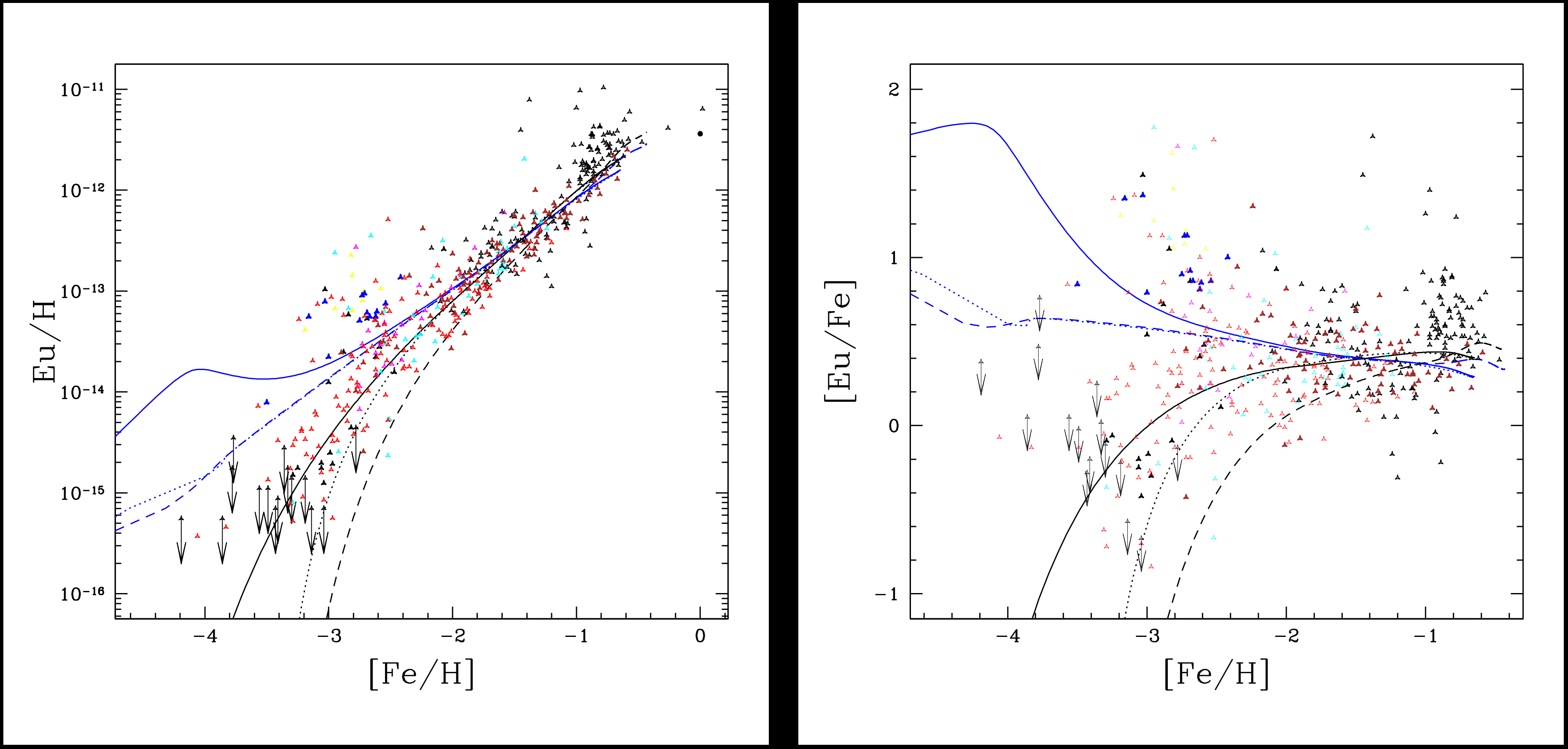


Black points/upper limits: François et al. 2007
[old metal poor stars in the MW]
Other observations: many sources

SFR1 (low)

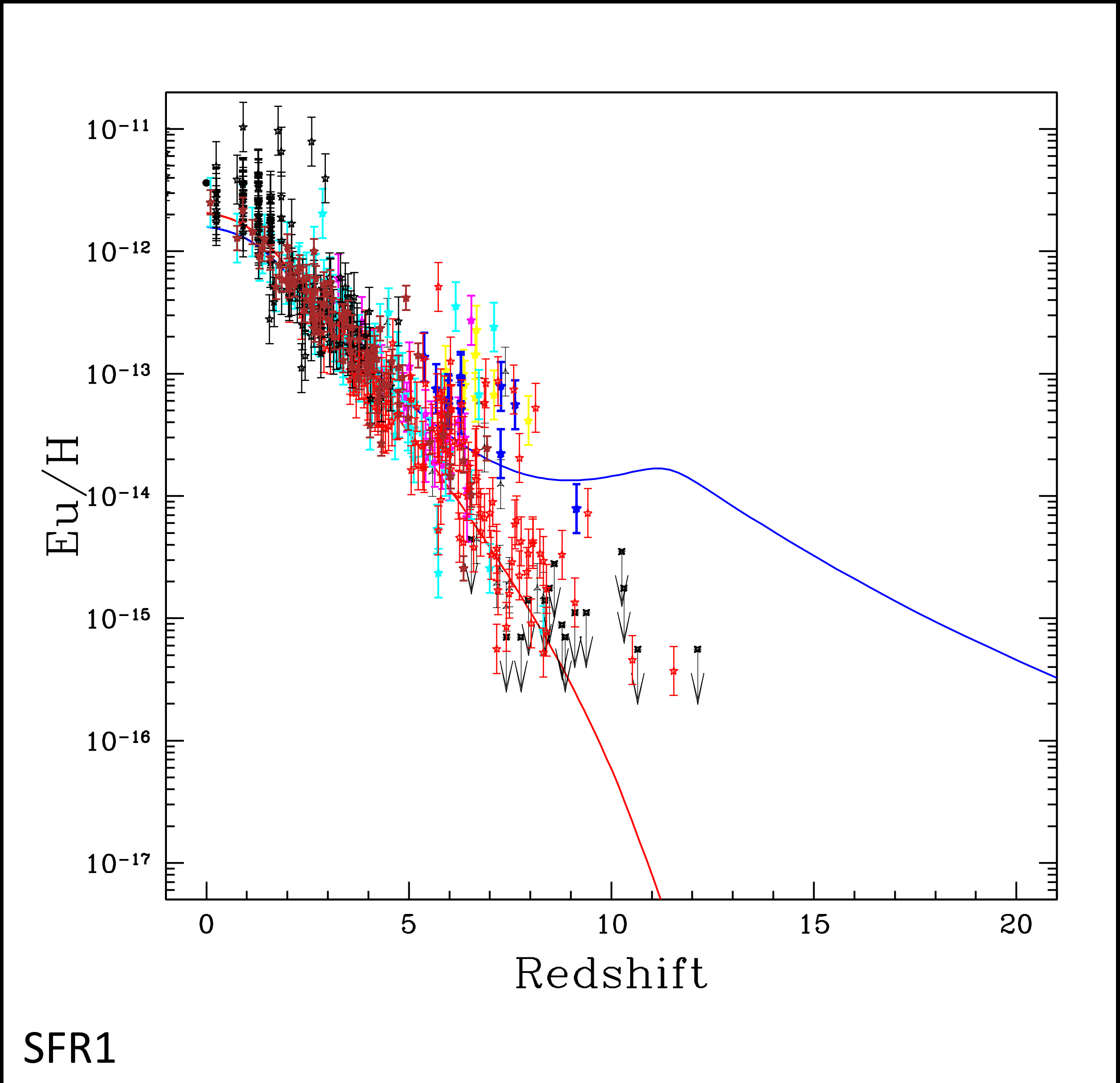
SFR2 (mid)

SFR3 (high)

Mergers: Δt_{NSM} = 200 Myr ; Binary fraction 0.002

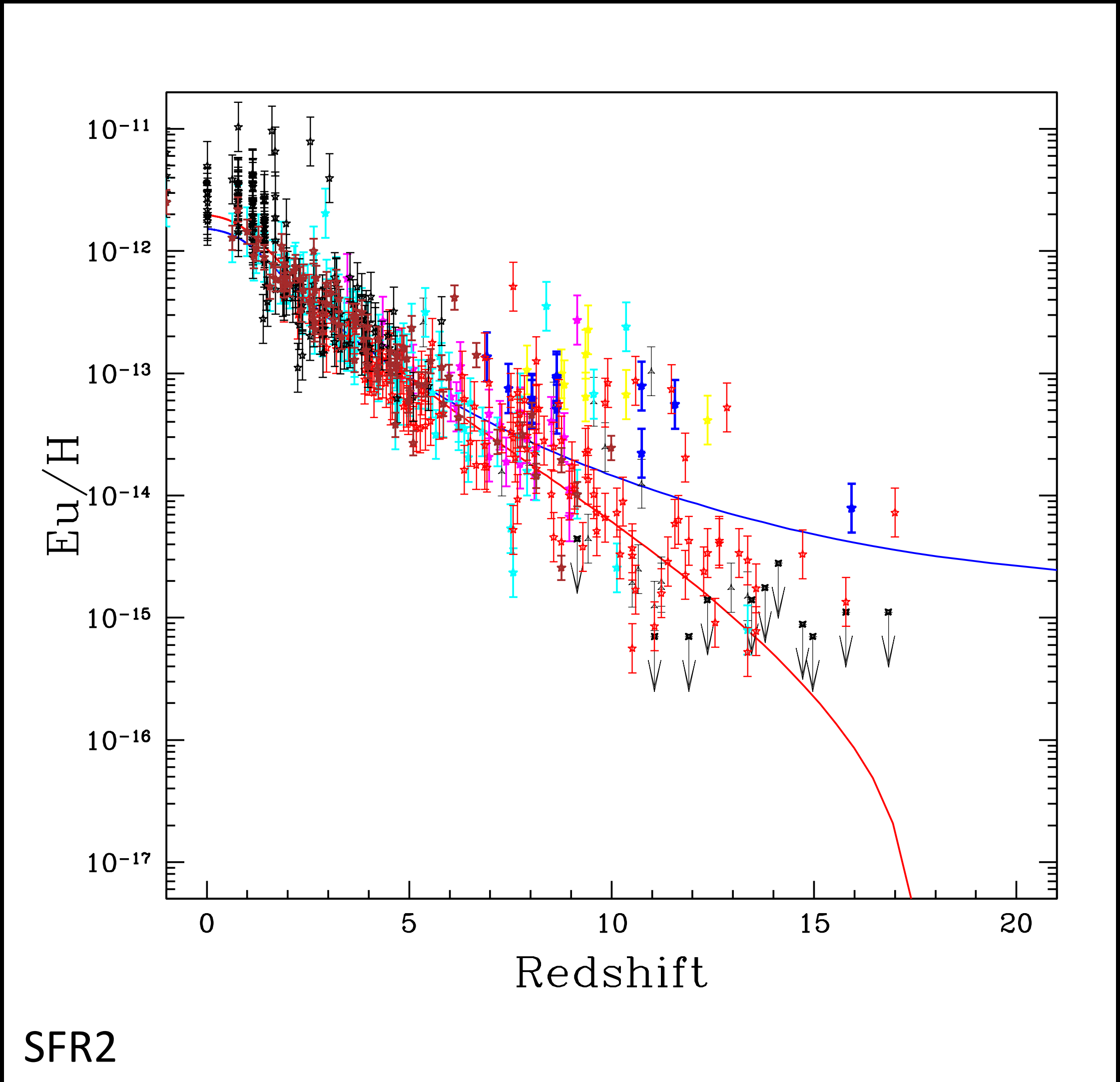
Cosmic evolution of Europium: ccSNae vs NS mergers
Evolution as a function of redshift

Red: Neutron Star Mergers   Blue: Core-collapse Supernovae Scenario



Cosmic evolution of Europium: ccSNae vs NS mergers
Evolution as a function of redshift

Red: Neutron Star Mergers Blue: Core-collapse Supernovae Scenario



Cosmic evolution of Europium: ccSNae vs NS mergers
Evolution as a function of redshift

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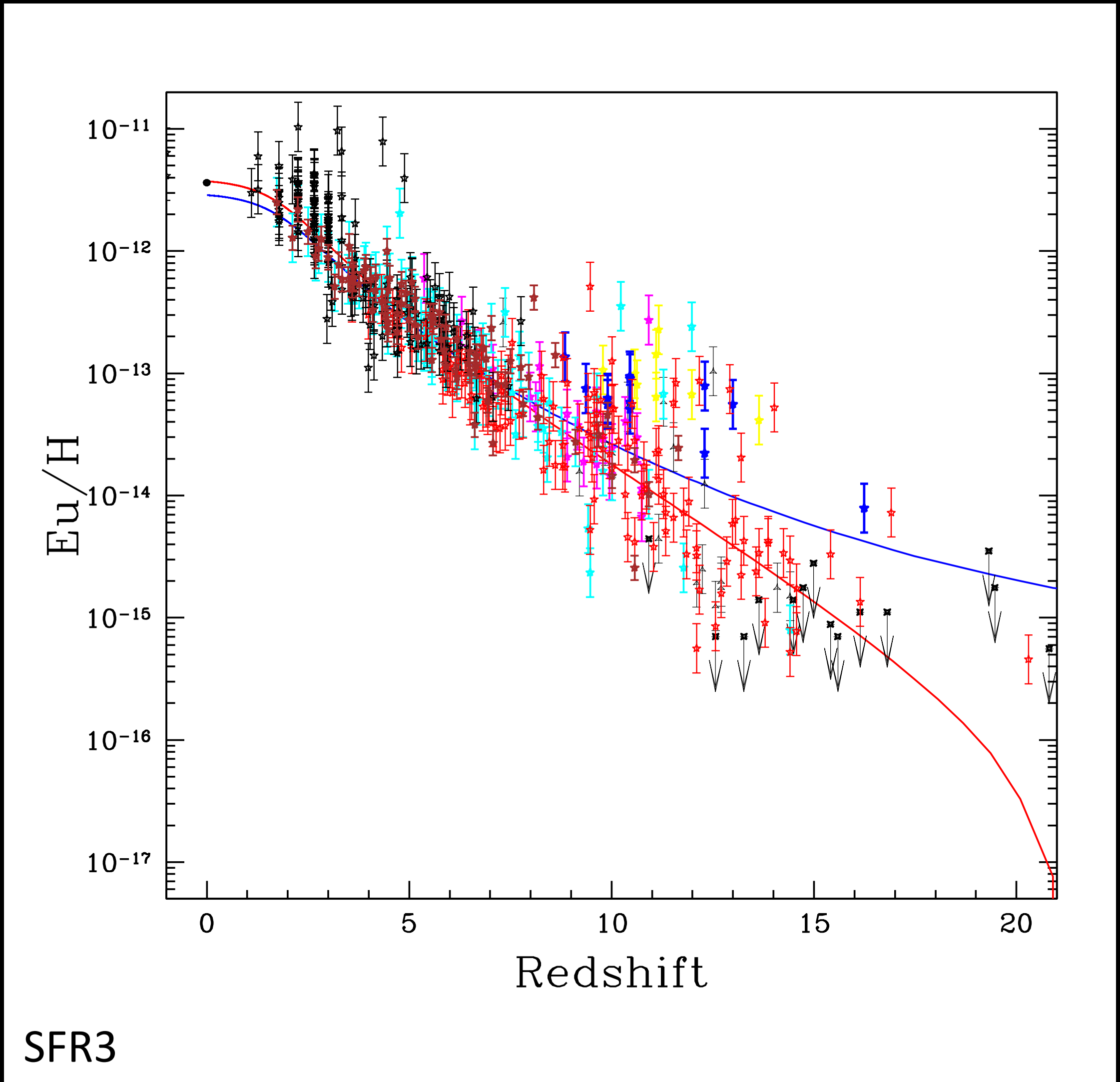
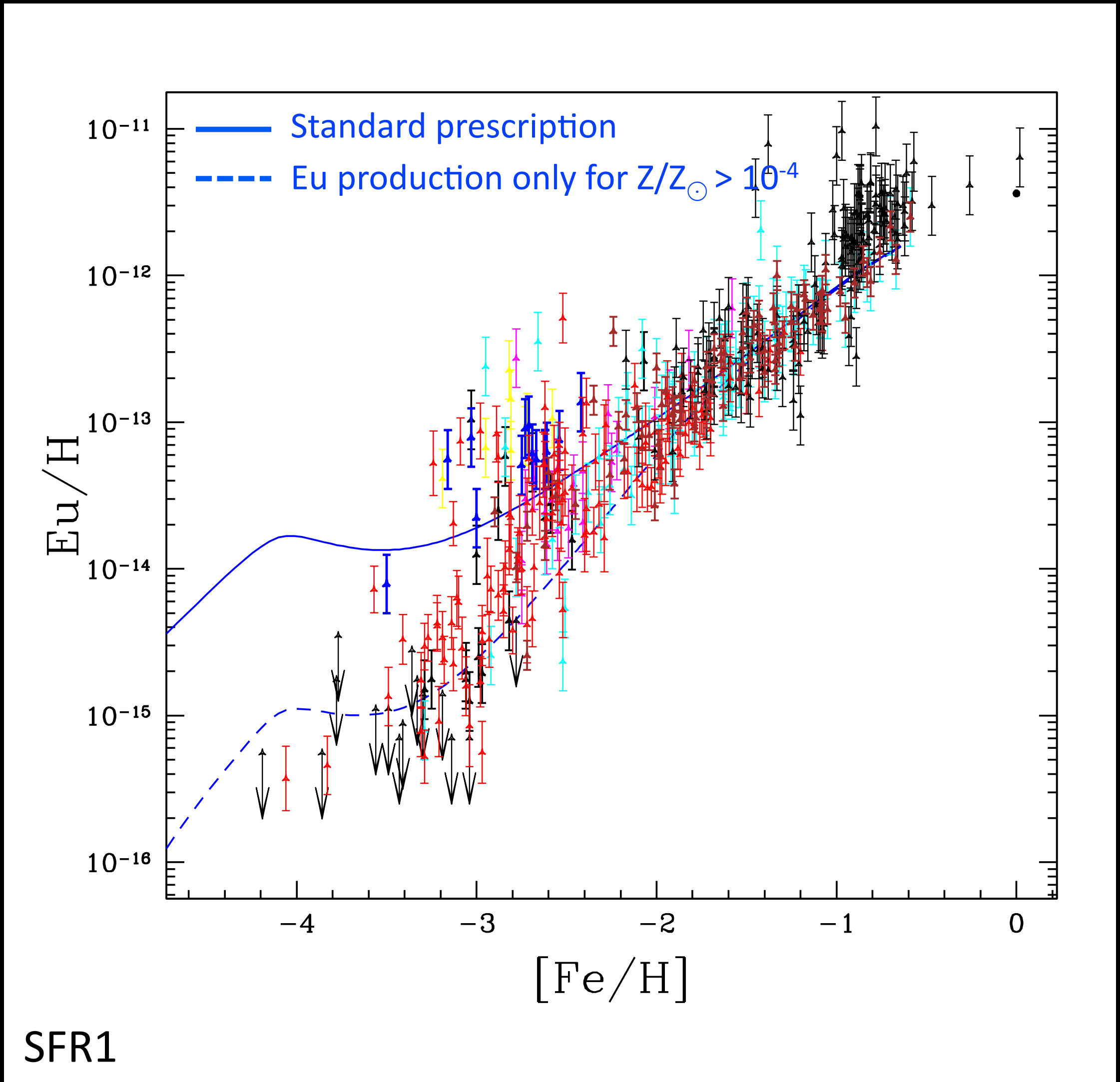
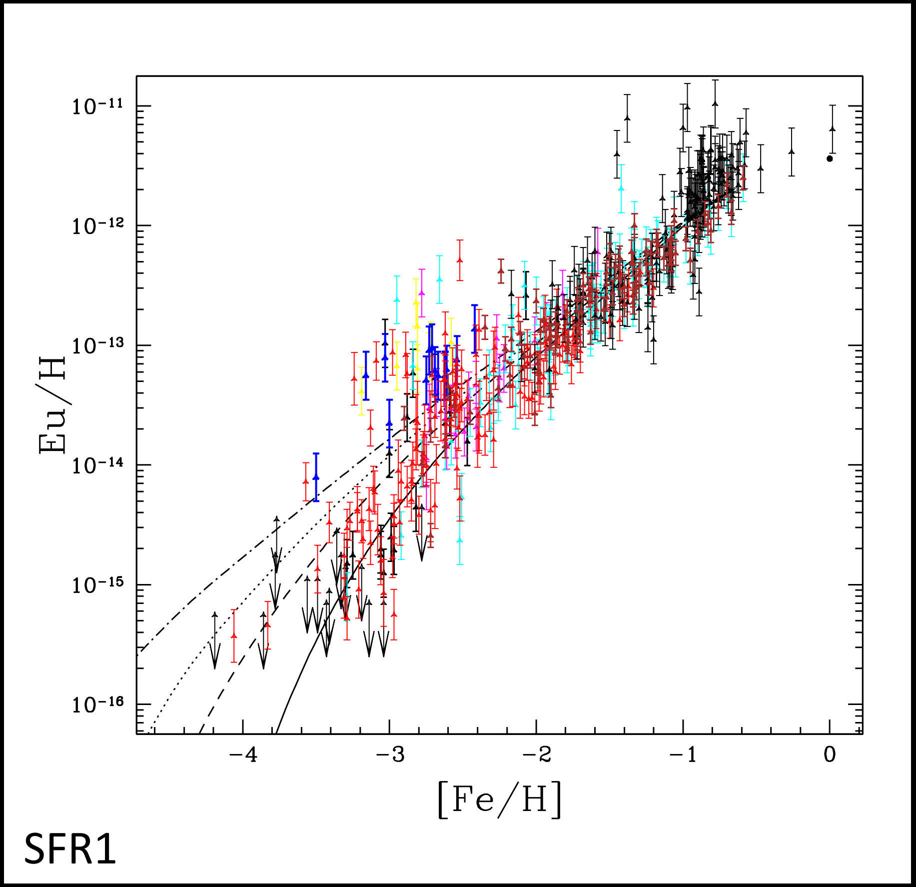
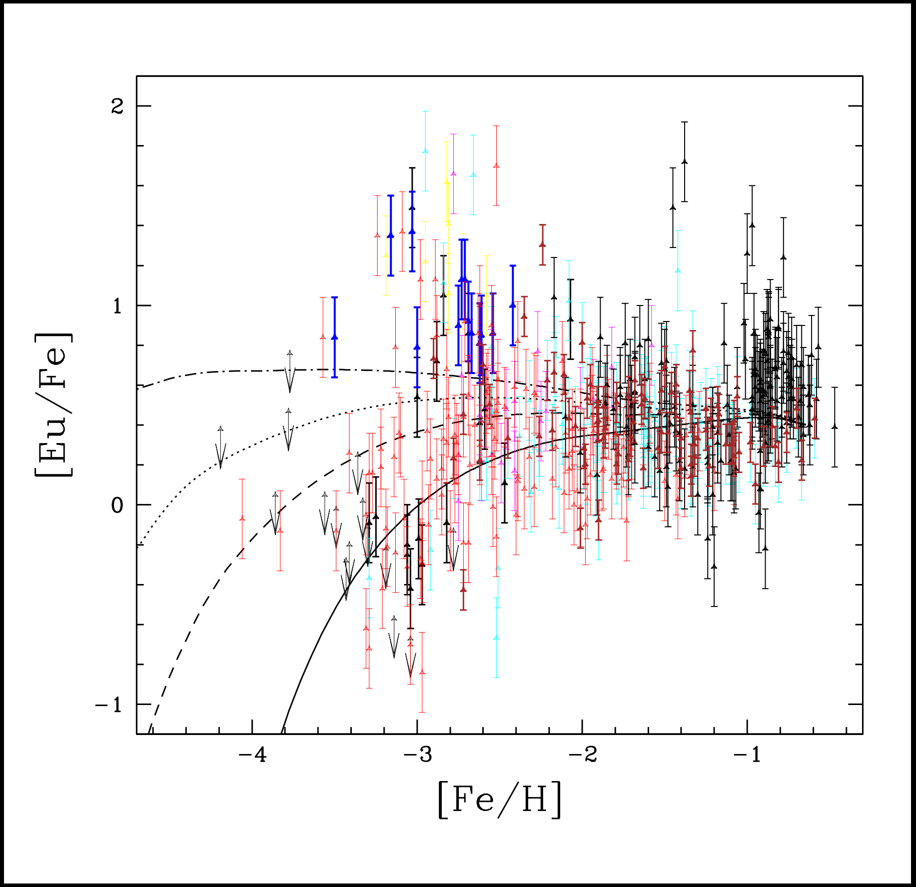


Cosmic evolution of Europium: core collapse scenario
Uncertainties on the Eu yield



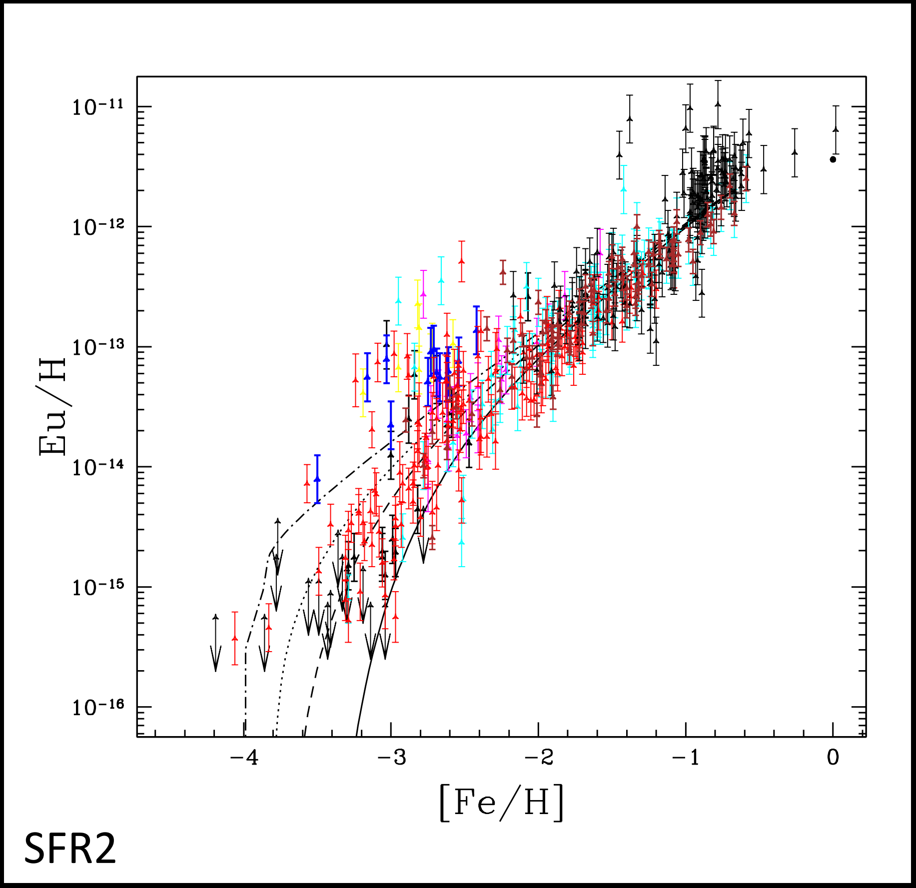
Cosmic evolution of Europium: merger scenario
Effect of coalescence timescale

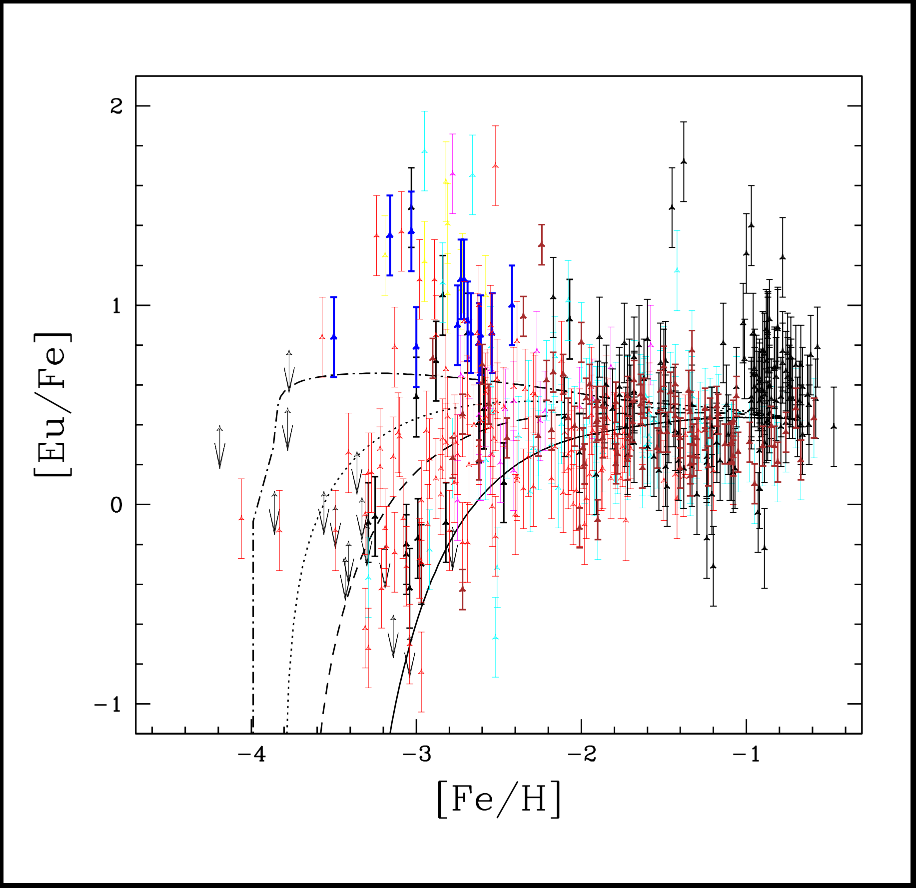




Δt_{NSM} = 0, 50 Myr, 100 Myr, 200 Myr

Cosmic evolution of Europium: merger scenario
Effect of coalescence timescale





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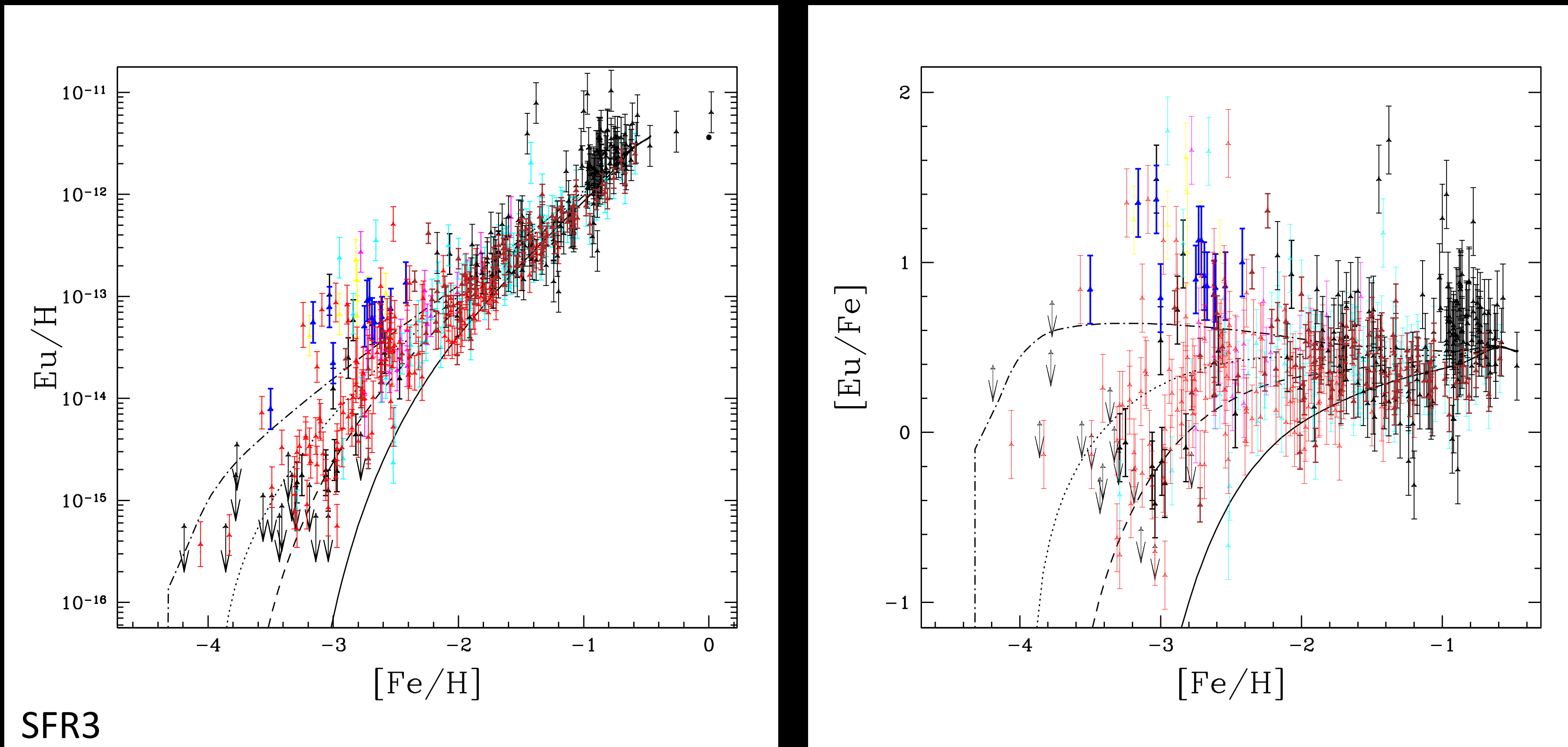
Effect of coalescence timescale



Δt_{NSM} = 0, 50 Myr, 100 Myr, 200 Myr

Conclusions 1

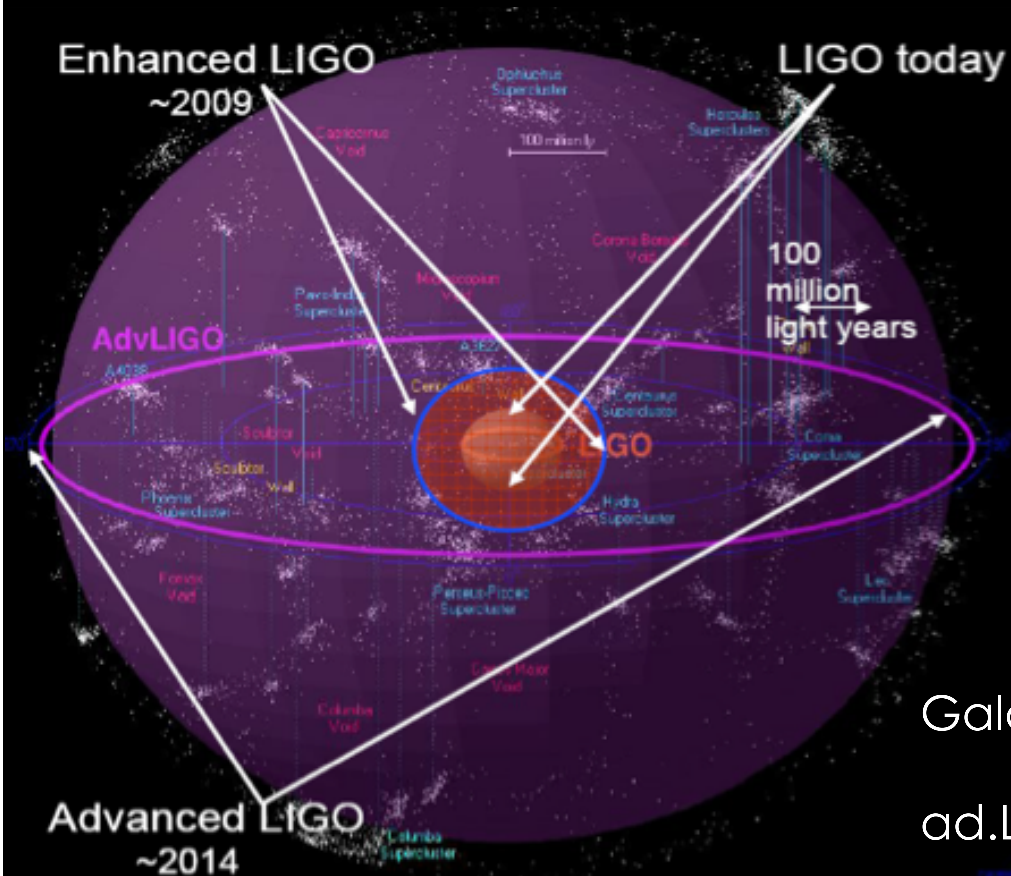
- The cosmic evolution of Europium (pure r element) favors mergers as the main astrophysical site for the r process

- Supernovae over produce Eu at high z / low metallicity
[Note: other heavy elements, like Ba, are observed at [Fe/H]<-3]
- For mergers : high z / low [Fe/H] observations put a constraint on the delay (typically below 0.4-0.5 Gyr)
- More observations at very low metallicity are needed for a better constraint
- Our conclusions do not depend on the choice of SFR

Consequences:
GW, KNae

Merger rate and GW detectors

The local rate has been studied in details in Abadie et al. 2010
(compilation of predictions for advanced Virgo / enhanced LIGO).



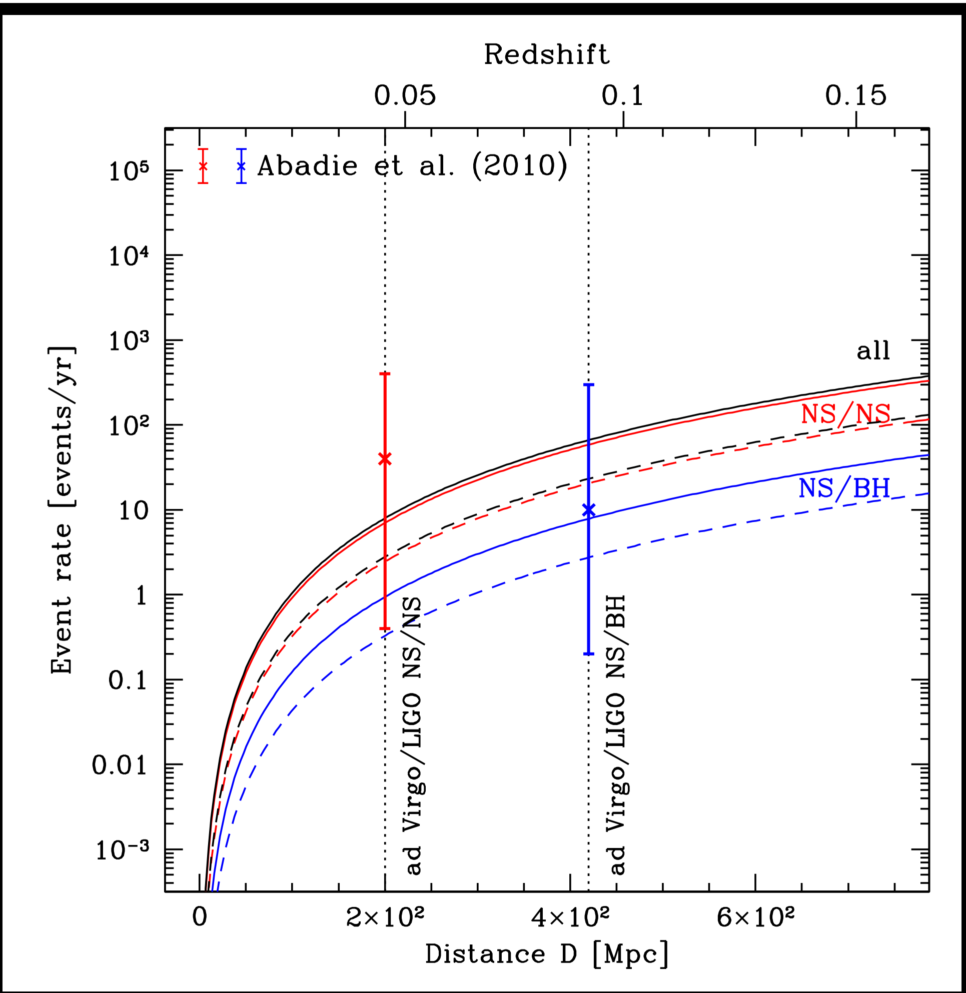
Galaxy: 4×10^{-6} to 4×10^{-3} mergers/yr

ad.LIGO/ad.Virgo volume:

NS+NS	200 Mpc	40 yr^{-1}	0.4 to 400 yr^{-1}
NS+BH	420 Mpc	10 yr^{-1}	0.2 to 300 yr^{-1}

Merger rate within adVirgo/LIGO horizon

	NS-NS merger rate (yr^{-1})	NS-BH merger rate (yr^{-1})
Abadie et al. (2010)	40 (0.4–400)	10 (0.2–300)
SFR1	2.4 – 6.7	2.7 – 7.7
SFR2	2. – 5.7	2.3 – 6.87
SFR3	3.8 – 10.9	4.3 – 12.4

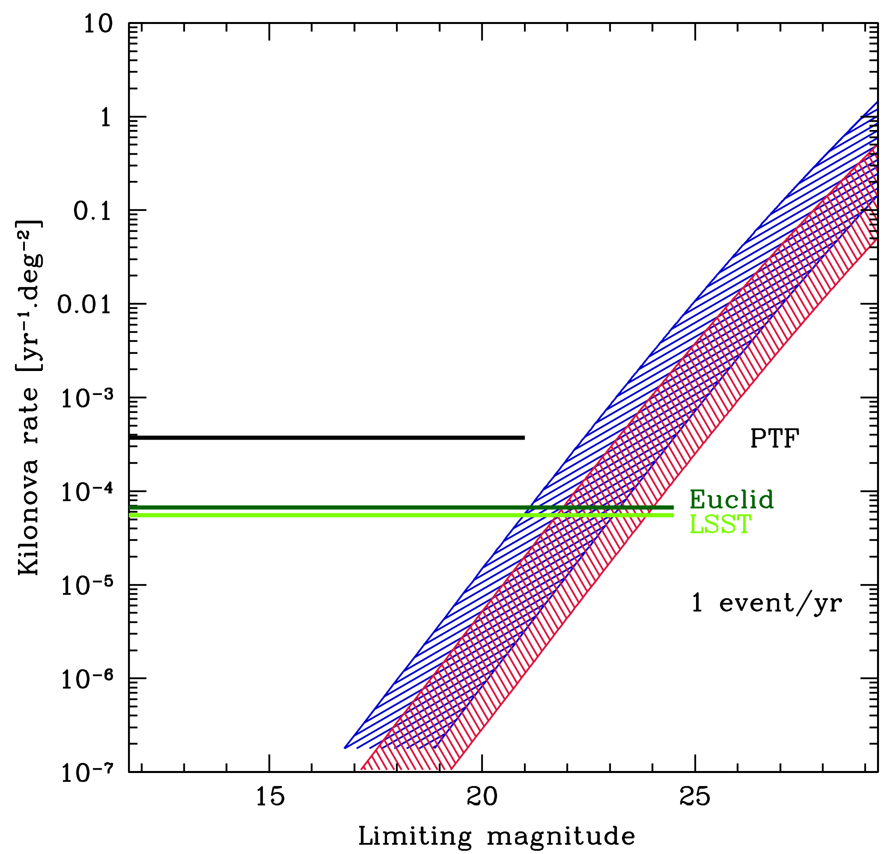


Kilonova Rate

$$L_{\mathrm{KN,peak}} \simeq 5\times10^{40}\,\mathrm{erg/s}\left(\frac{f}{10^{-6}}\right)\left(\frac{v}{0.1c}\right)^{1/2}\left(\frac{M_{\mathrm{ej}}}{10^{-2}\,M_{\odot}}\right)^{1/2}$$

	Kilonova rate (yr^{-1})		
	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

Metzger et al. 2010
Recent r-process opacity
by Kasen et al. 2013,2014



Short GRB rate

Work in progress…

Many additional uncertainties

-geometric beaming of the relativistic ejecta
-luminosity function

Rare data for a comparison
(small number of short GRBs with measured redshift
no observed short GRB within 400 Mpc…)

Summary

Conclusions 2

- The cosmic evolution of Europium (pure r element) favors mergers as the main astrophysical site for the r process

- The early evolution is dominated by neutron star mergers with coalescence timescale ~100 Myr (range 50-200 Myr)
- Compared to core-collapse supernovae, mergers are more rare but expected yields of r process elements are larger
- The precise constraints on the coalescence timescale is sensitive to the uncertainties on stellar iron iron yields at low metallicity
[larger production of iron: smaller coalescence timescales]

- One can deduce a lower and upper limit on the merger rate from Eu obs. [degeneracy Eu yields/NS binary fraction]
- Predicted rate within the horizon of advance Virgo/LIGO is consistent with low/mid values of Abadie et al. (population synthesis models)
- The associated kilonova rate can be deduced: additional uncertainty related to the opacity of r process elements
- Results are compatible with no KN detection for PTF and are more optimistic for LSST or Euclid (1 to 100 per year)