Are NS-NS mergers the main astrophysical site for the r-process?

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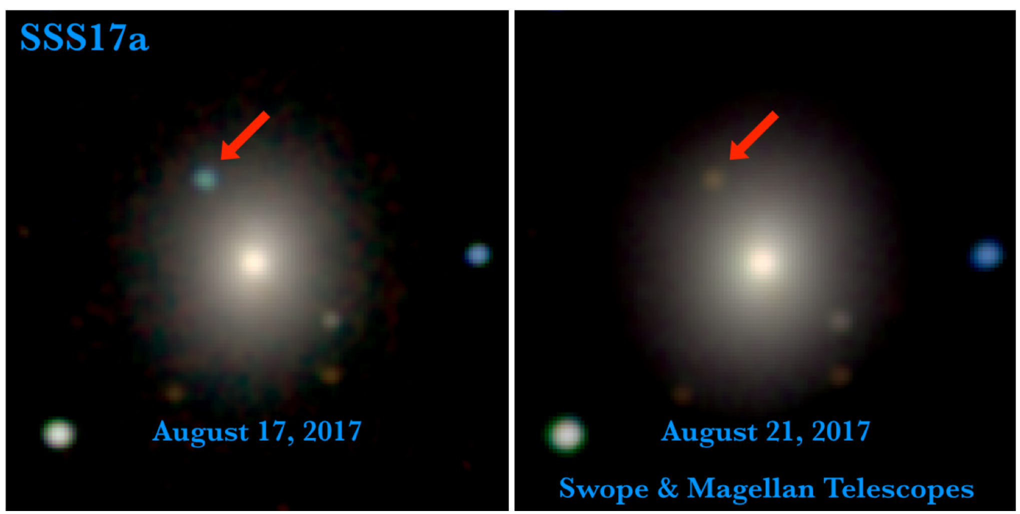


Réunion groupes de travail GdR Resanet et OG – Observatoire de Paris, 24-25 Septembre 2018

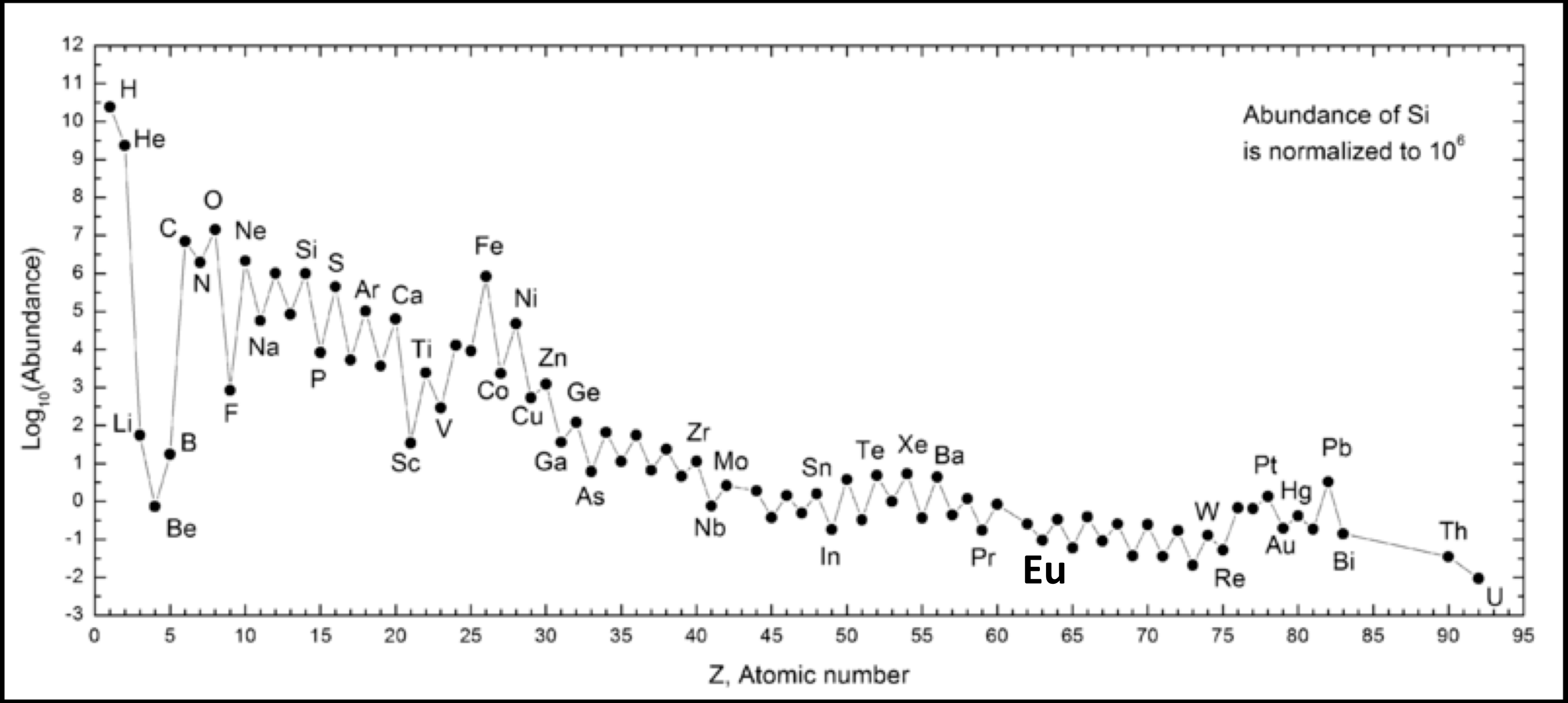
Are NS-NS mergers the main astrophysical site for the r-process?

1- The point of view of the cosmic chemical evolution
(Vangioni, Goriely, Daigne, François & Belczynski 2015)

2- The consequences of GW170817 and associated kilonova

Heavy elements and r process

The chemical composition of the Universe

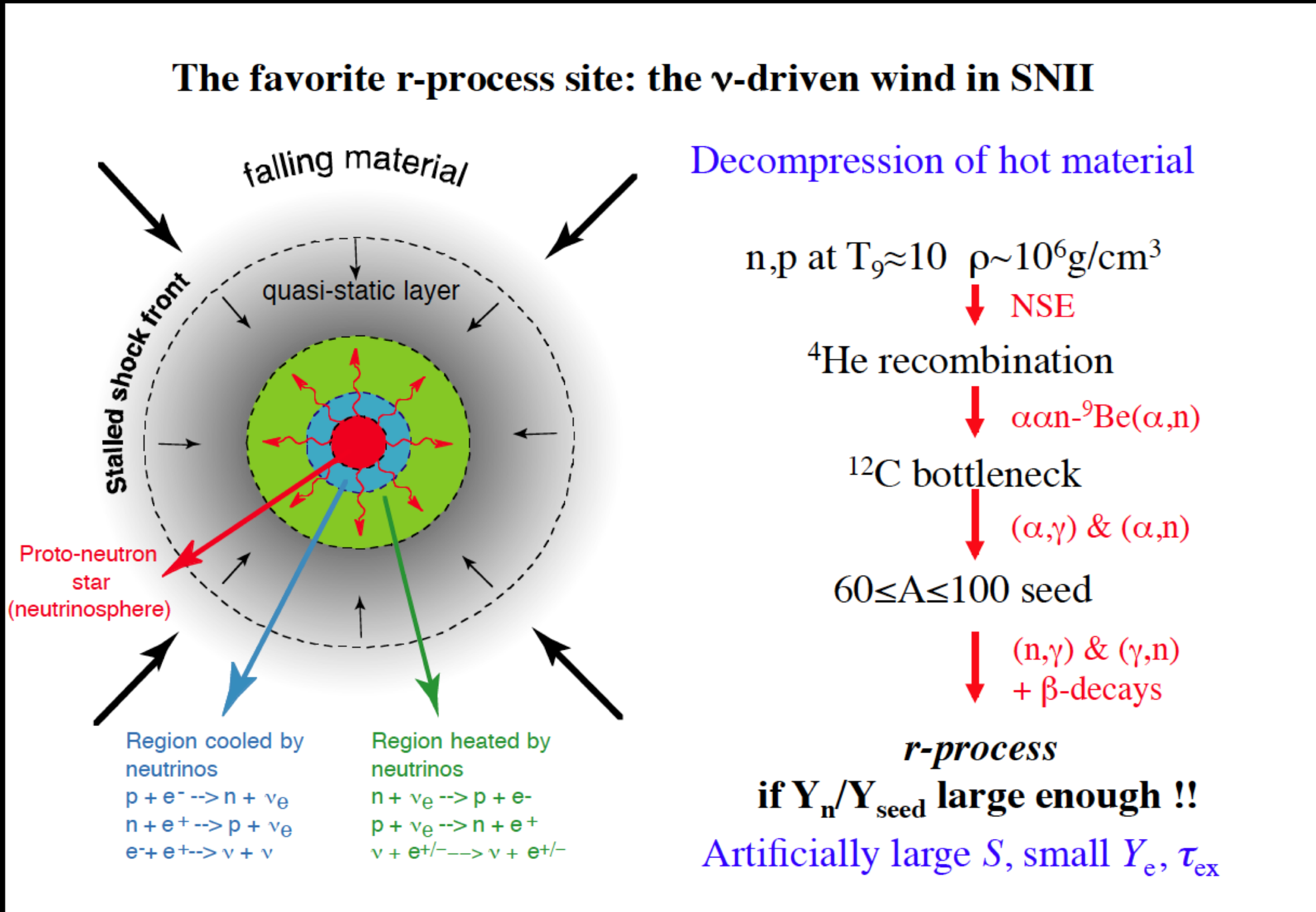


Lodders (2003)

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

Which astrophysical site?

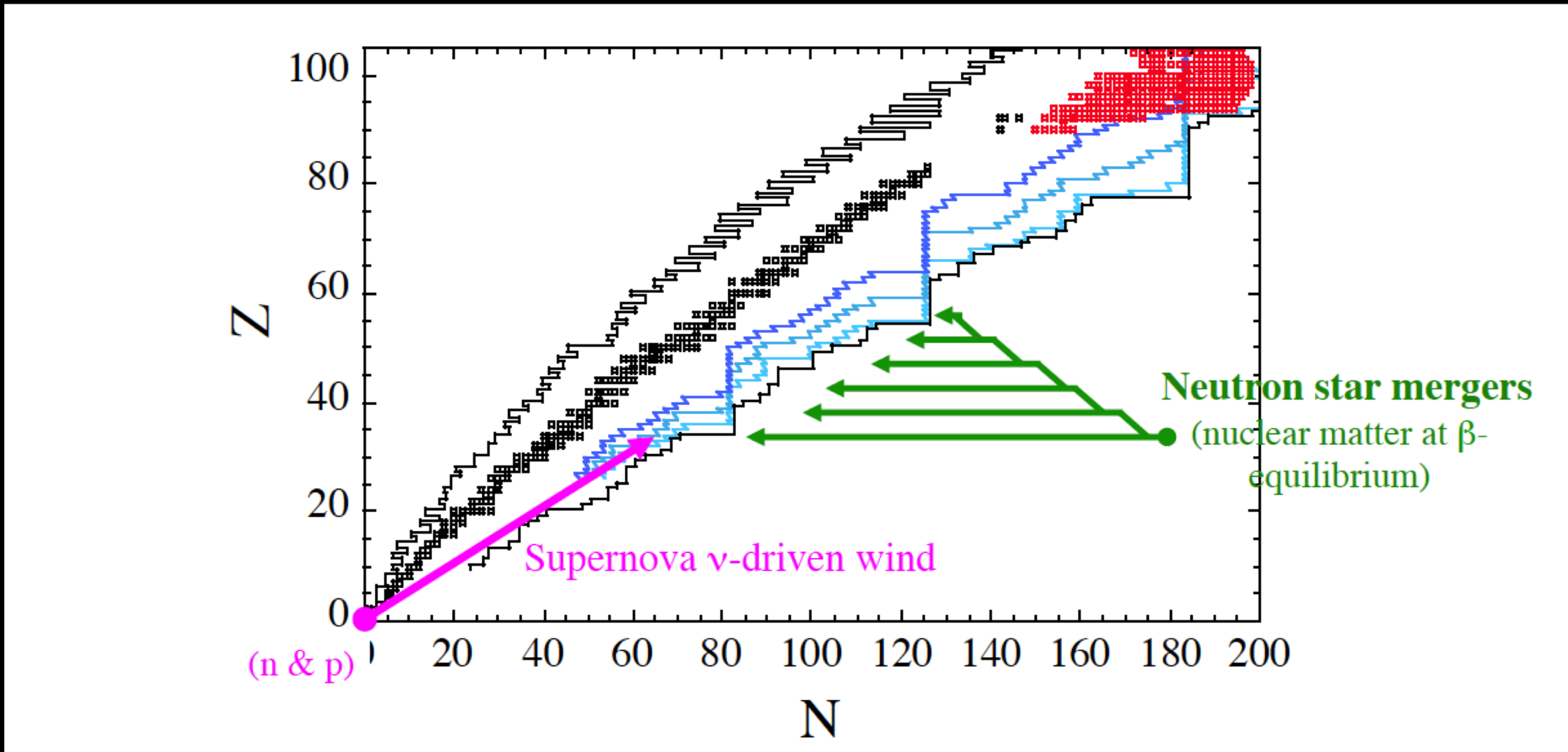
The r-process nucleosynthesis: cc SNae?



However: recent cc SN simulations seem 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?



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)

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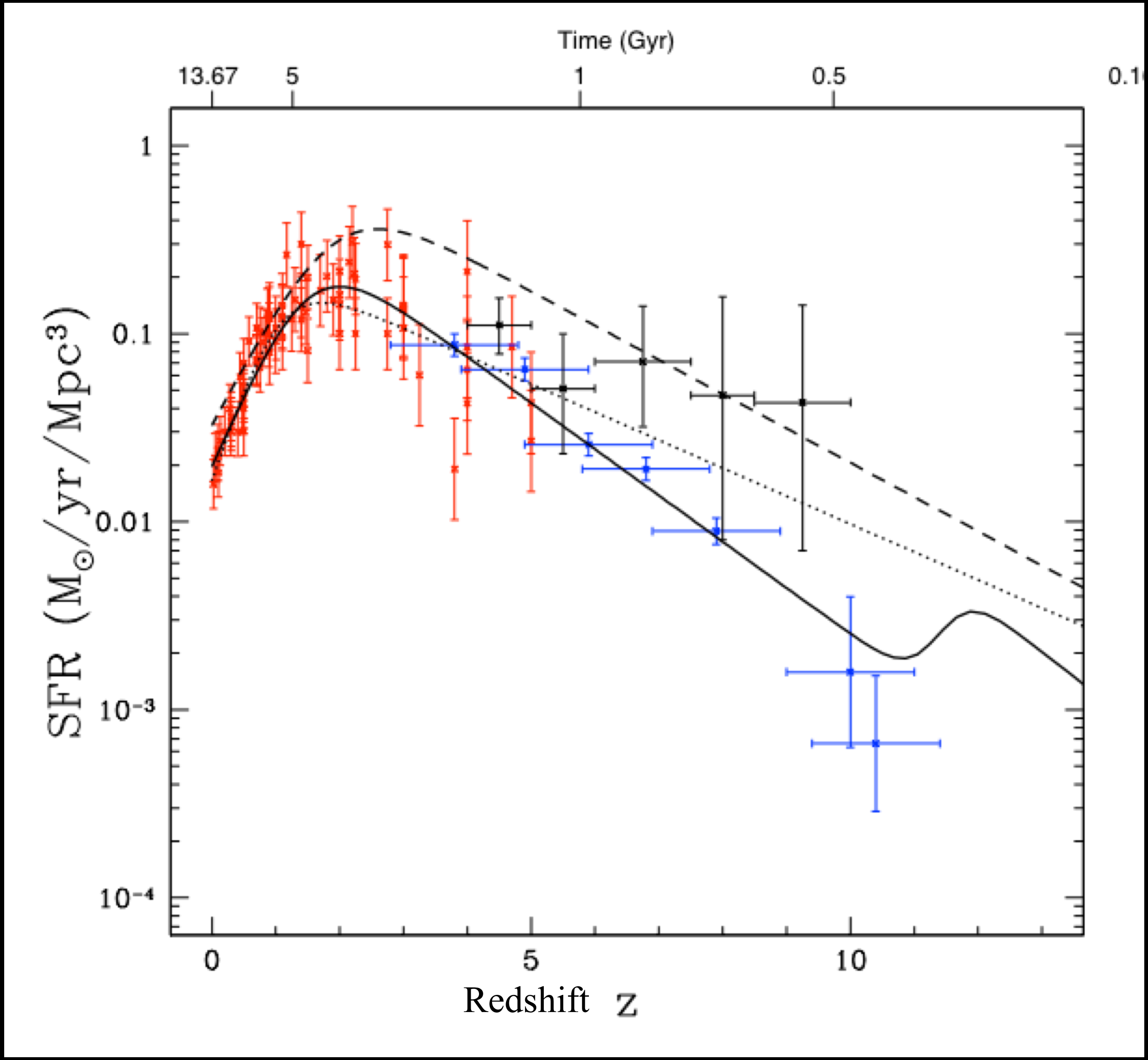
Predicting core-collapse supernovae and BNS merger rates in the Universe

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 cosmic star formation rate:

The NS birth rate is known, but **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)

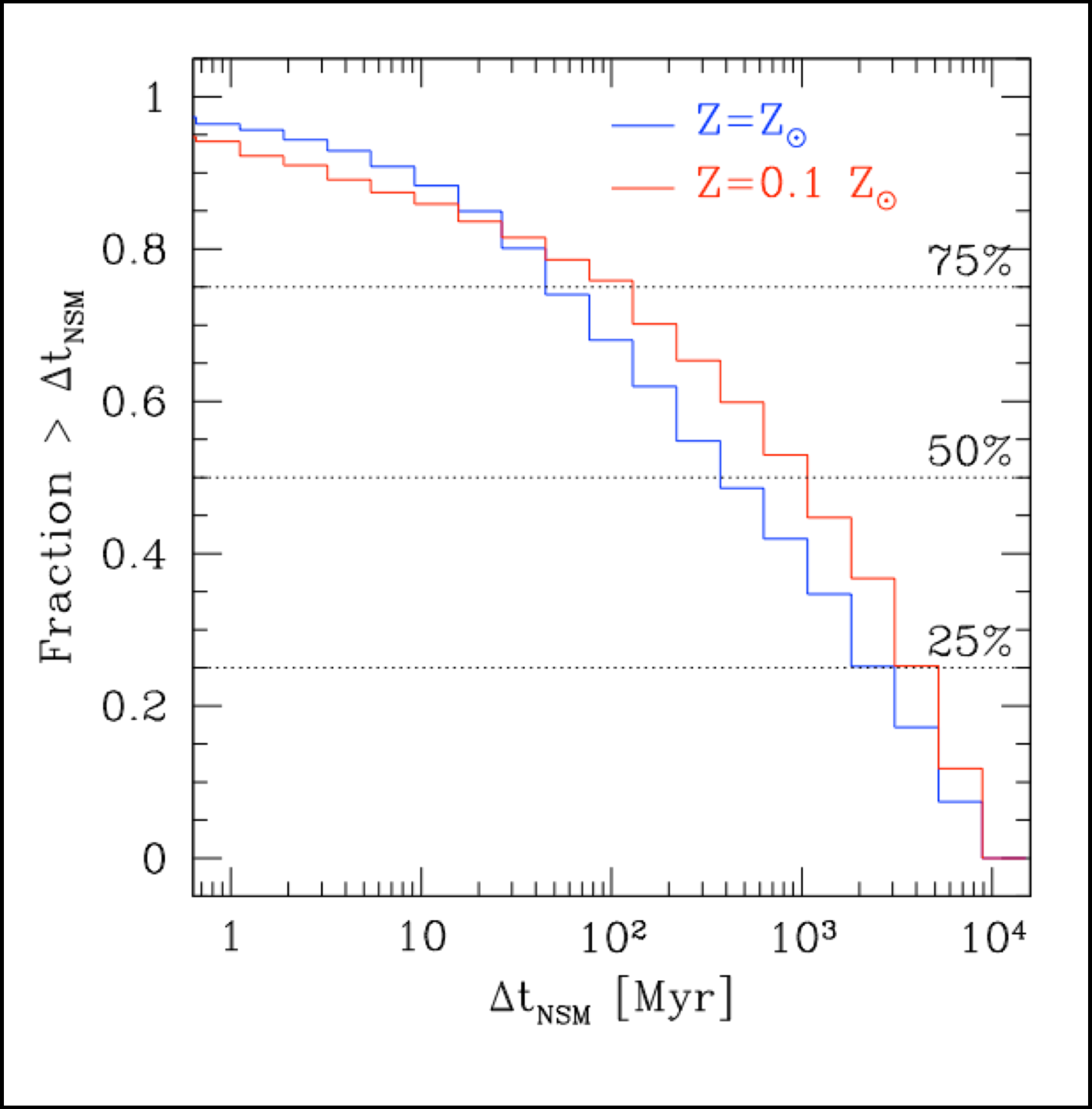
* with measured mass → remaining time before merger
* with one NS detected as a pulsar → age of the system

* 4 systems with 100 < Δt_{NSM} < 400 Myr
* 3 systems with Δt_{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)



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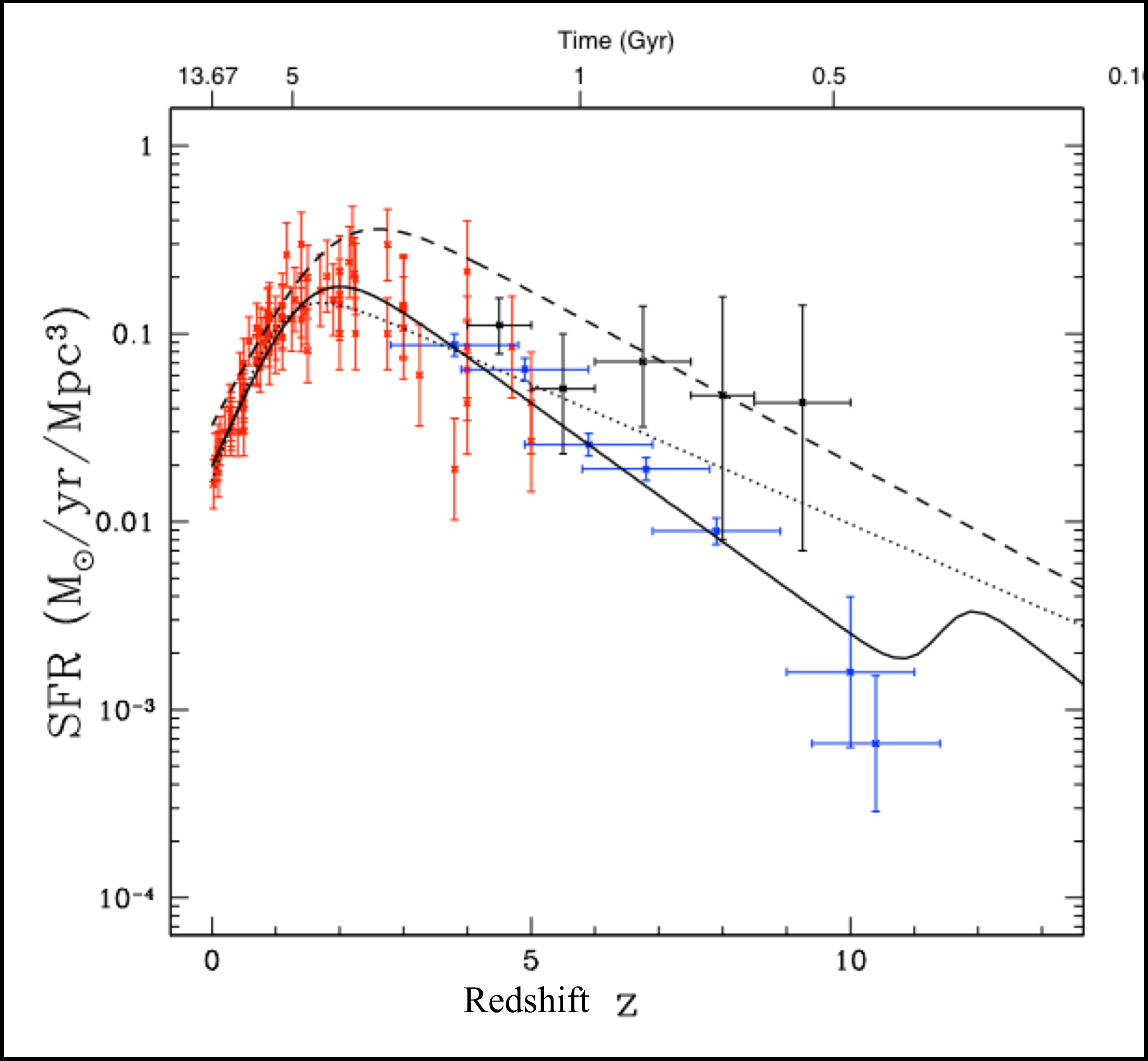
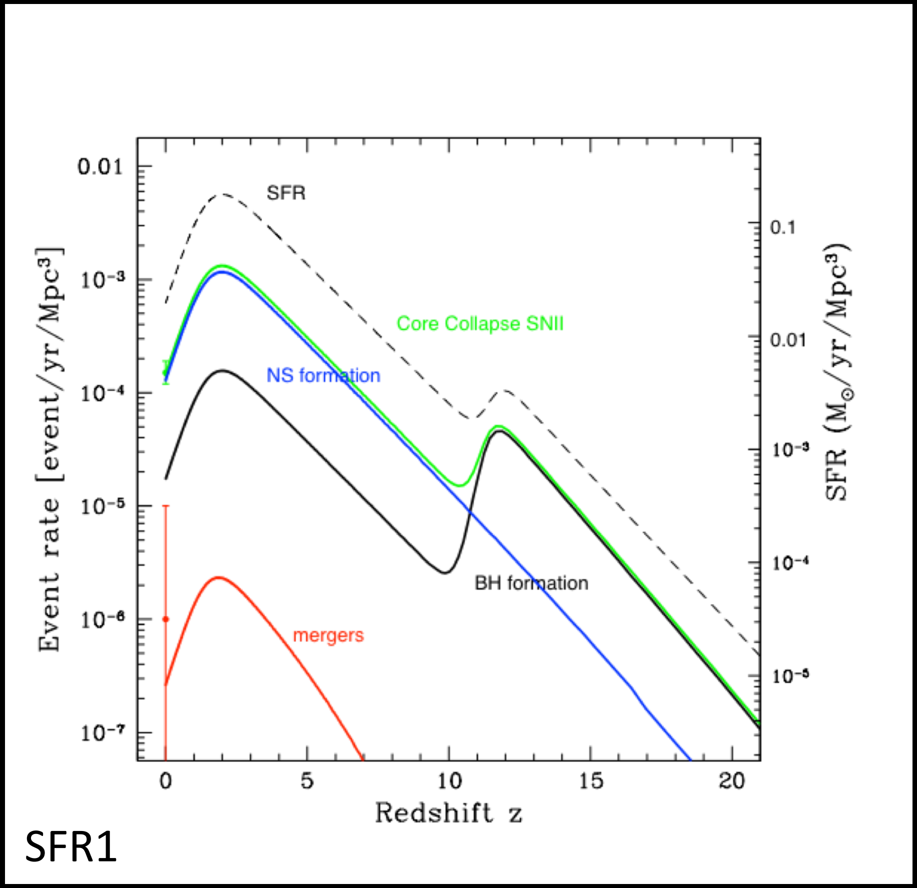
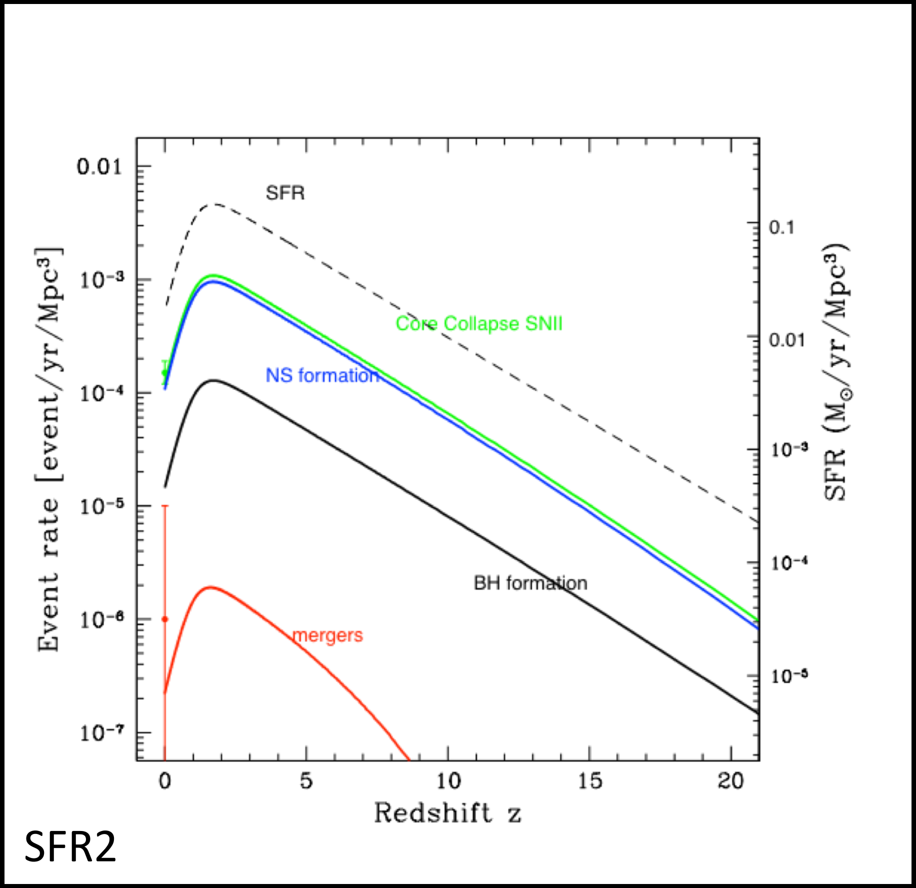


SFR1 (low) ———
SFR2 (mid) ········
SFR3 (high) – – – – –

Core collapse & merger rate





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

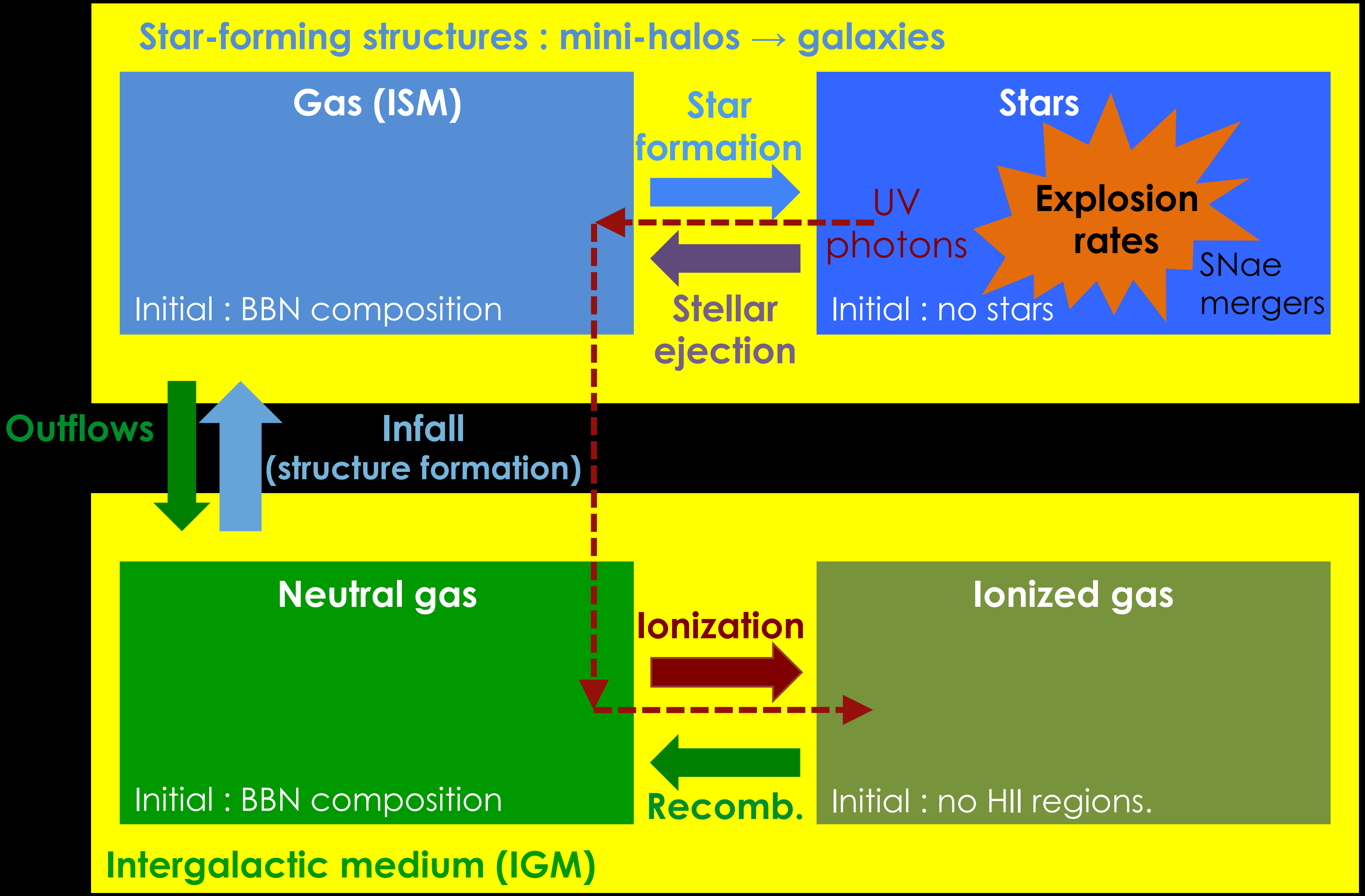
Local core collapse rate: Mattila et al. 2012

Local merger rate: estimate from Abadie et al. 2010

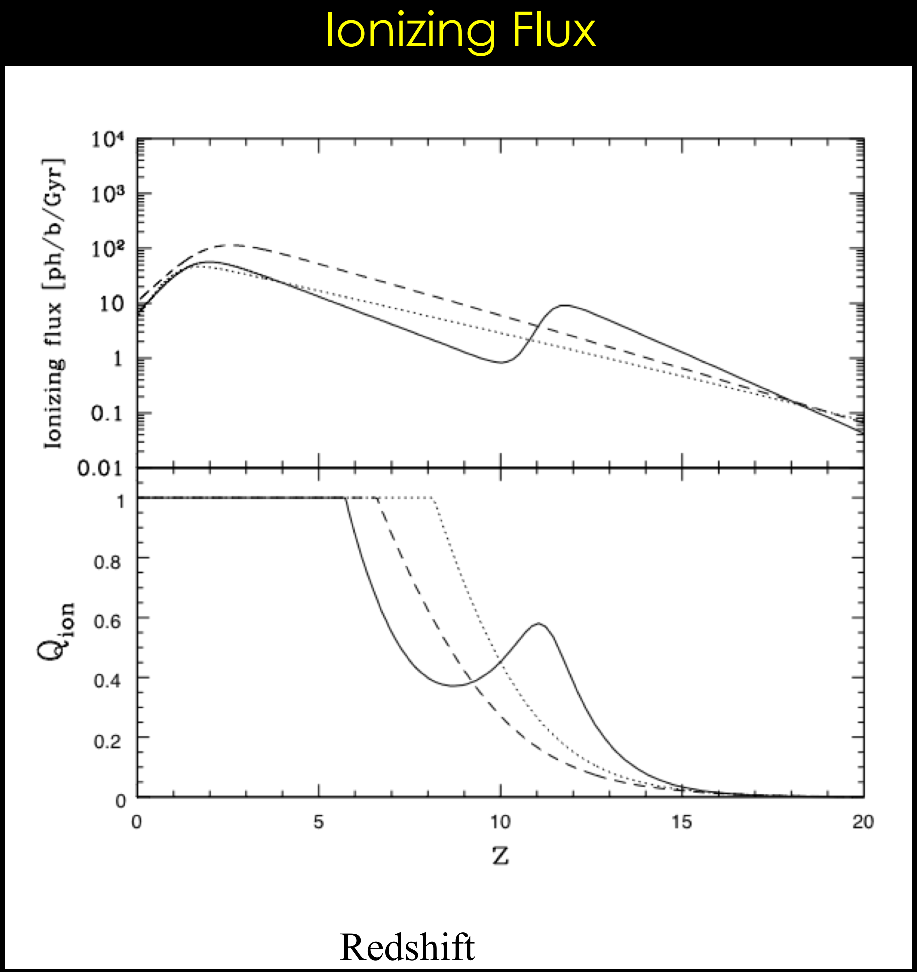
Cosmic Chemical Evolution

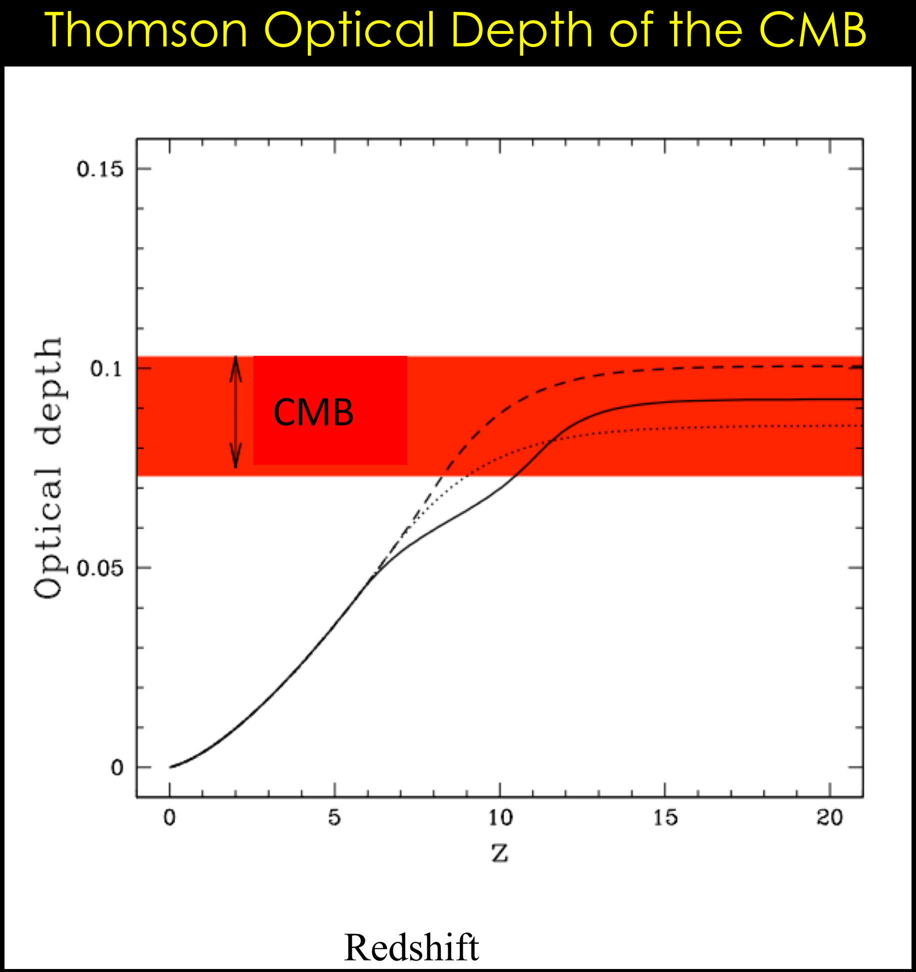
Modeling the cosmic chemical evolution

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



Constraints (1) Reionization





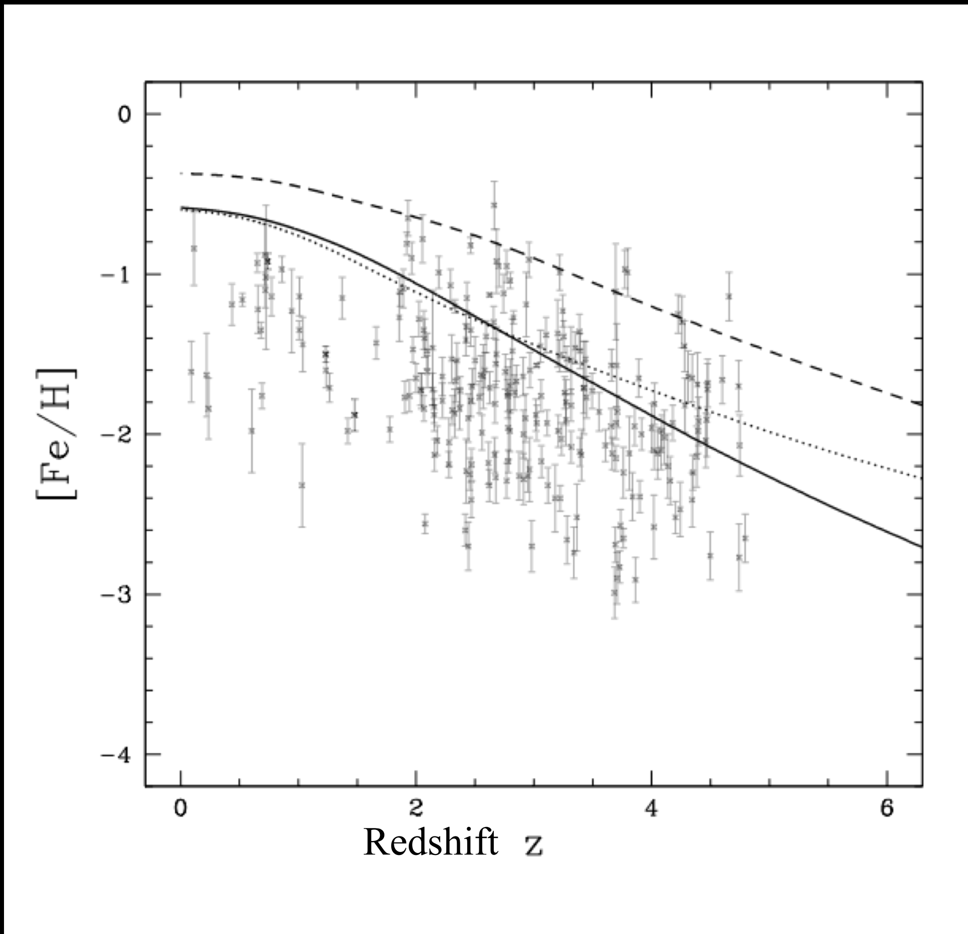
Q_{ion} = volume filling fraction of the ionized regions

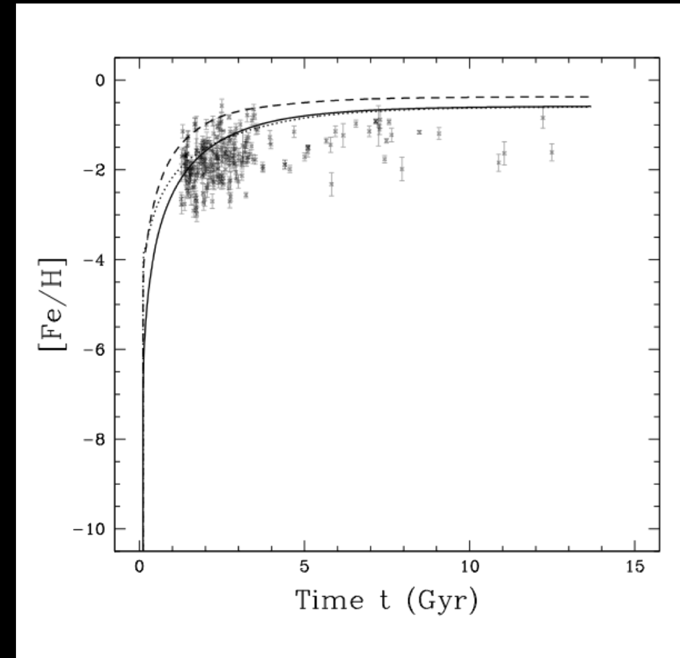
SFR1 (low)	———
SFR2 (mid)	....
SFR3 (high)	- - - - -

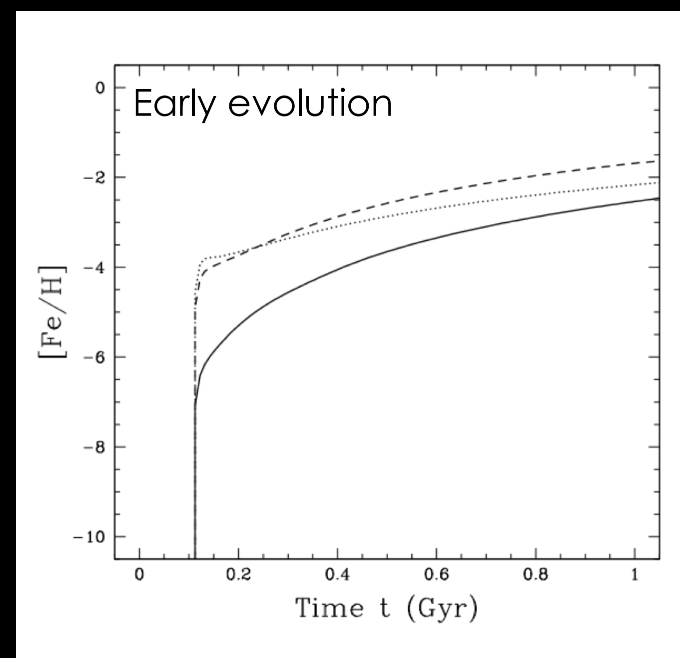
$$\tau = c\,\sigma_T\,n_b \int_0^z dz'\,Q_{ion}(z')\,(1+z')^3 \left|\frac{dt}{dz}(z')\right|$$

Constraints (2) Chemical evolution

Cosmic evolution of iron as a function of redshift





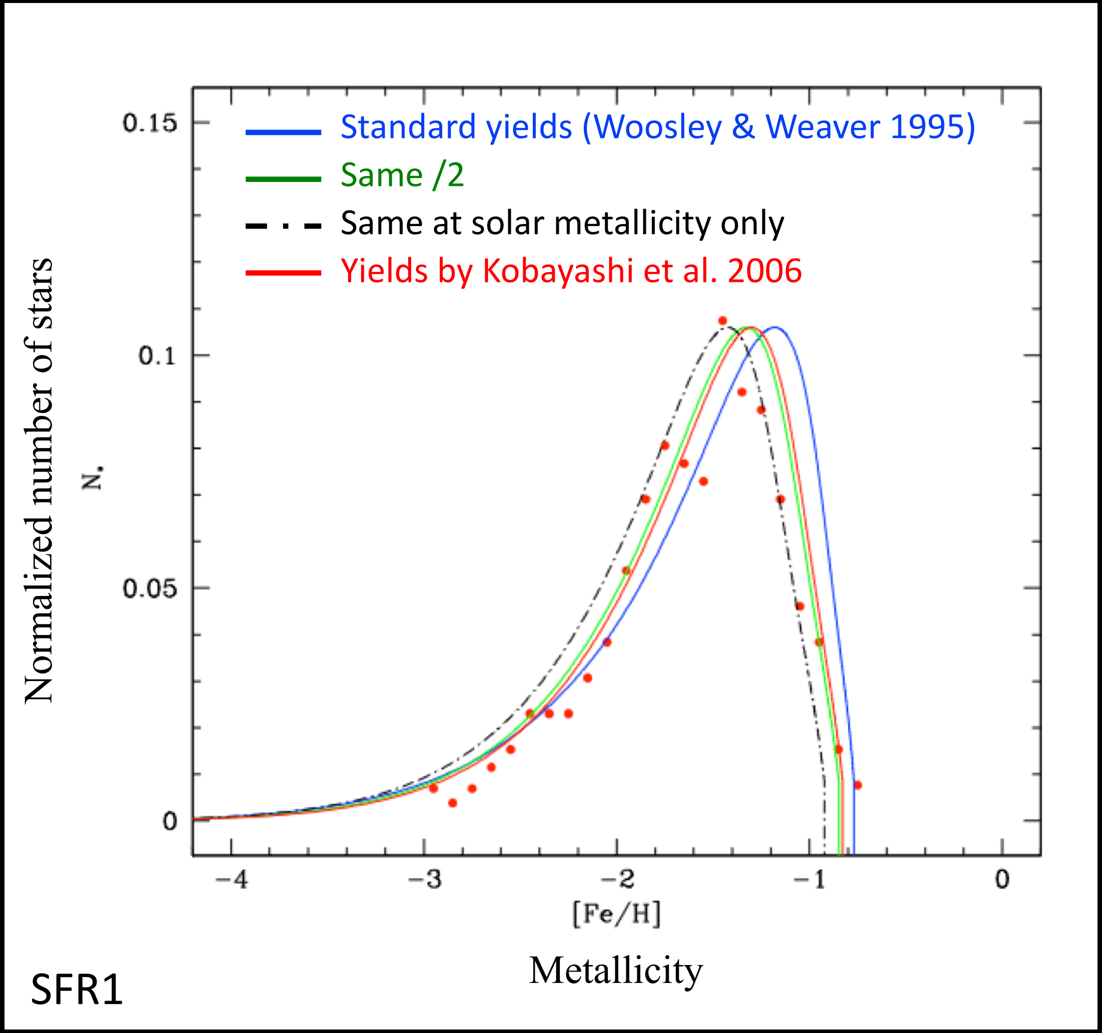


SFR1 (low)	————
SFR2 (mid)	....
SFR3 (high)	- - - - -

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

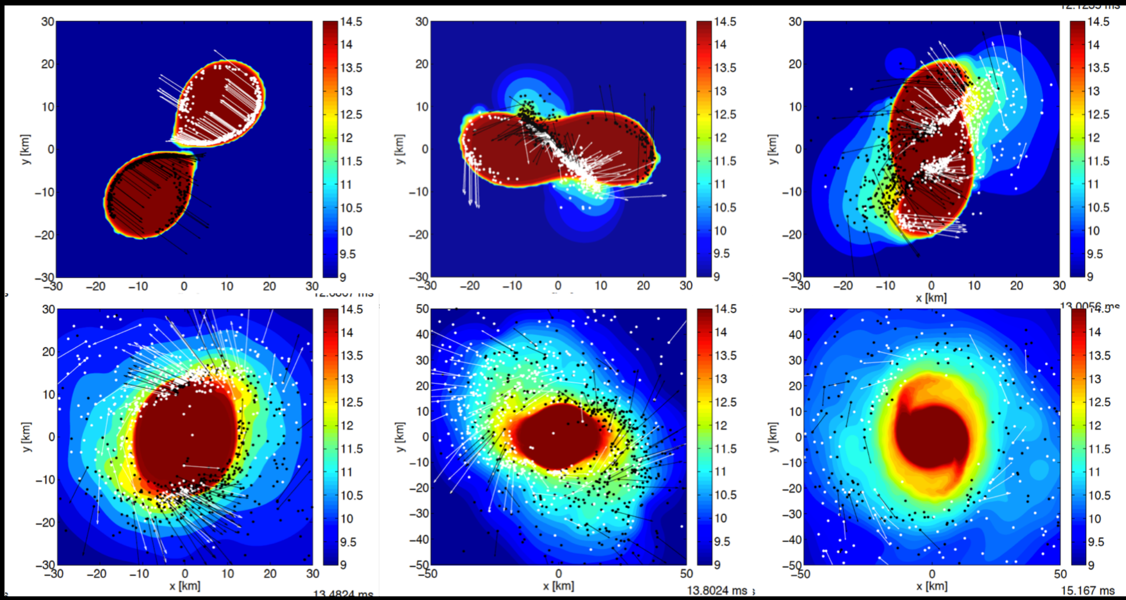
  We assume for Eu : 10^{-7} $M_{\odot}$ per CCSN
  calibrated on the Milky Way (Lodders 2003, Asplund et al. 2009)

- Merger scenario: yield = detailed calculations available

Mergers: uncertainties

Ejected mass

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



Bauswein, Goriely & Janka 2013

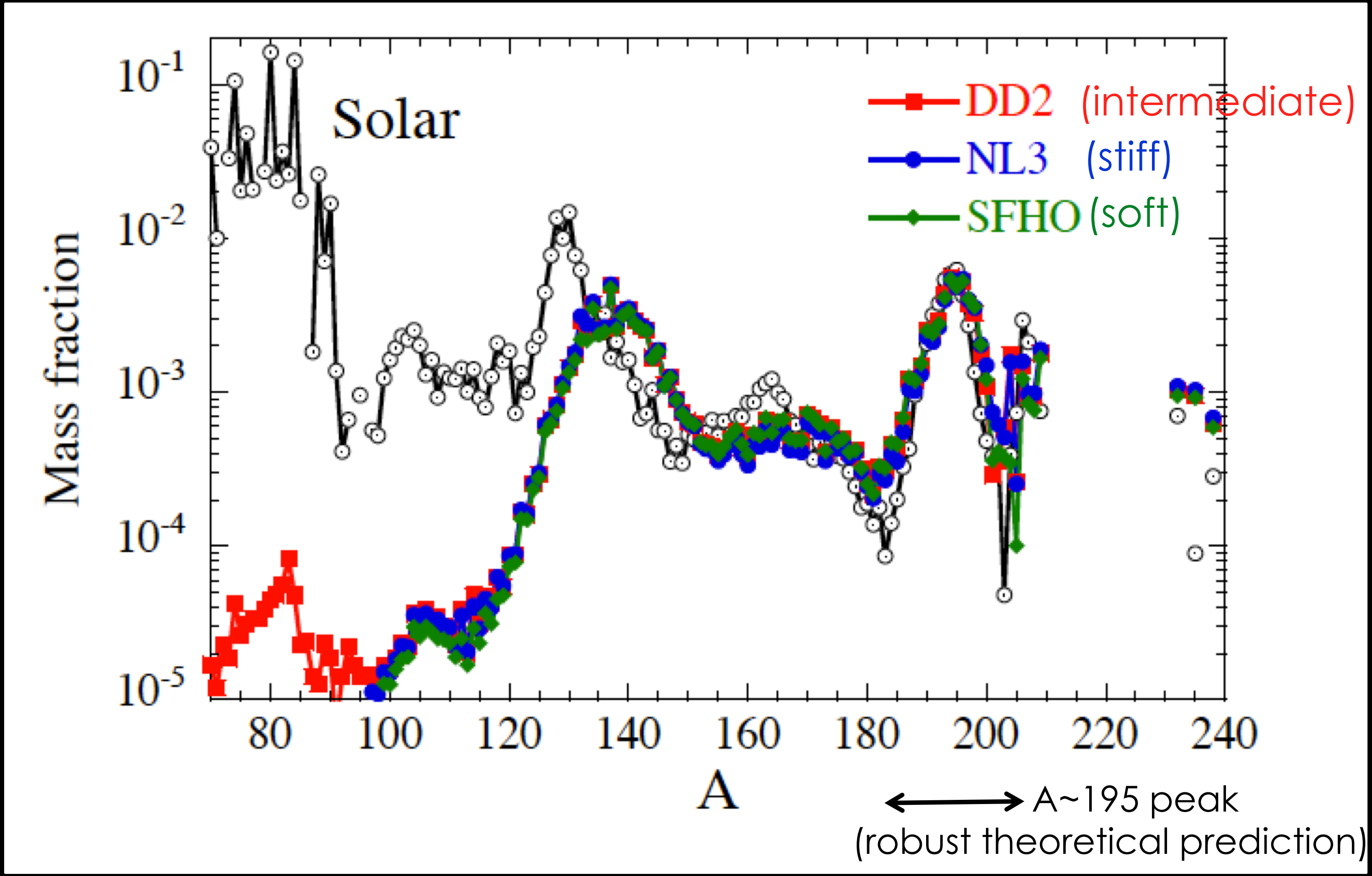
Production of r elements

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

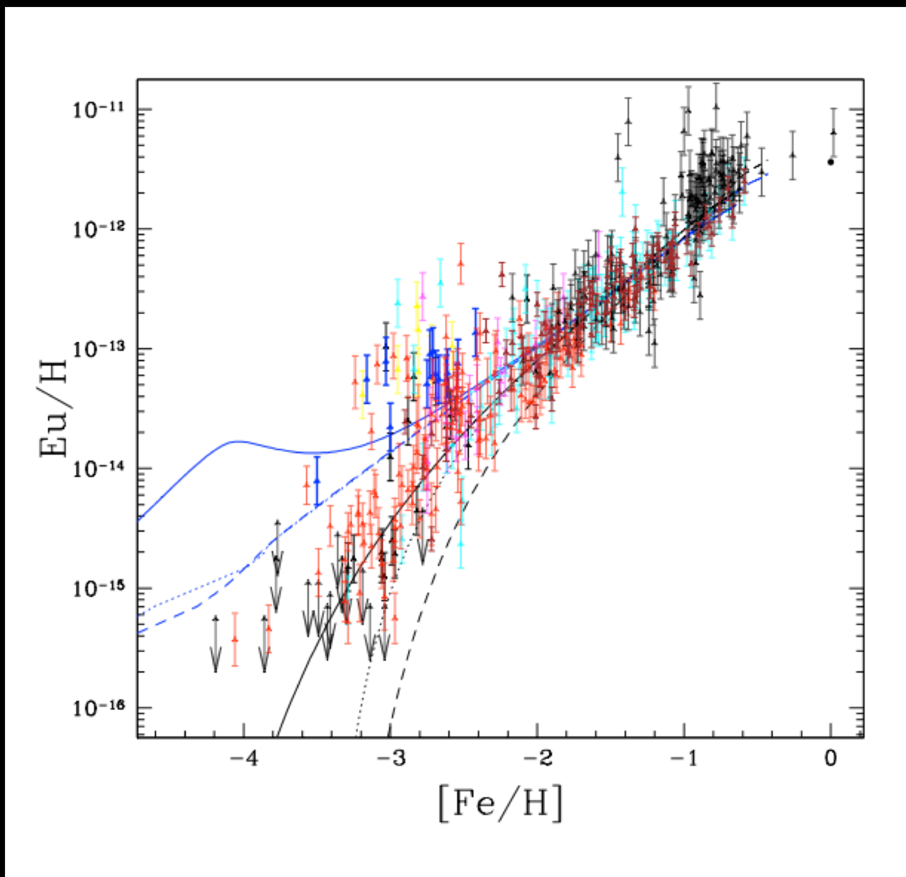
  Just et al. 2014: 7 10^{-5} $M_{\odot}$ to 2 10^{-4} $M_{\odot}$ per merger

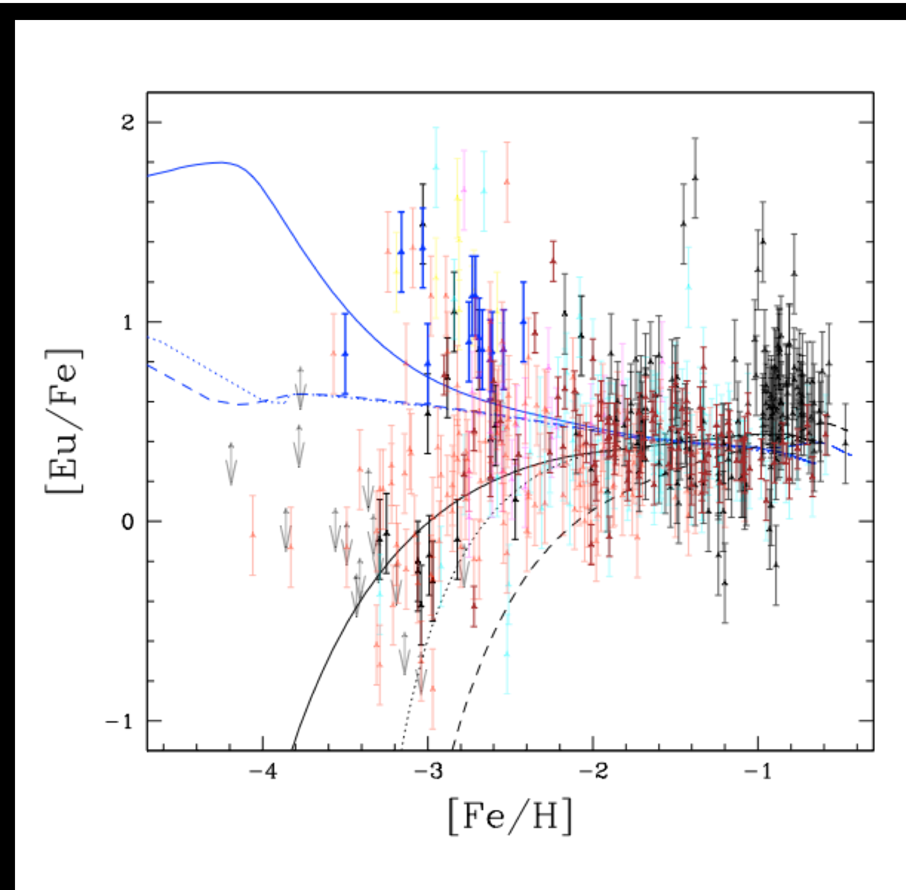
  We assume for Eu: 7 10^{-5} $M_{\odot}$ per merger

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) - - - - -

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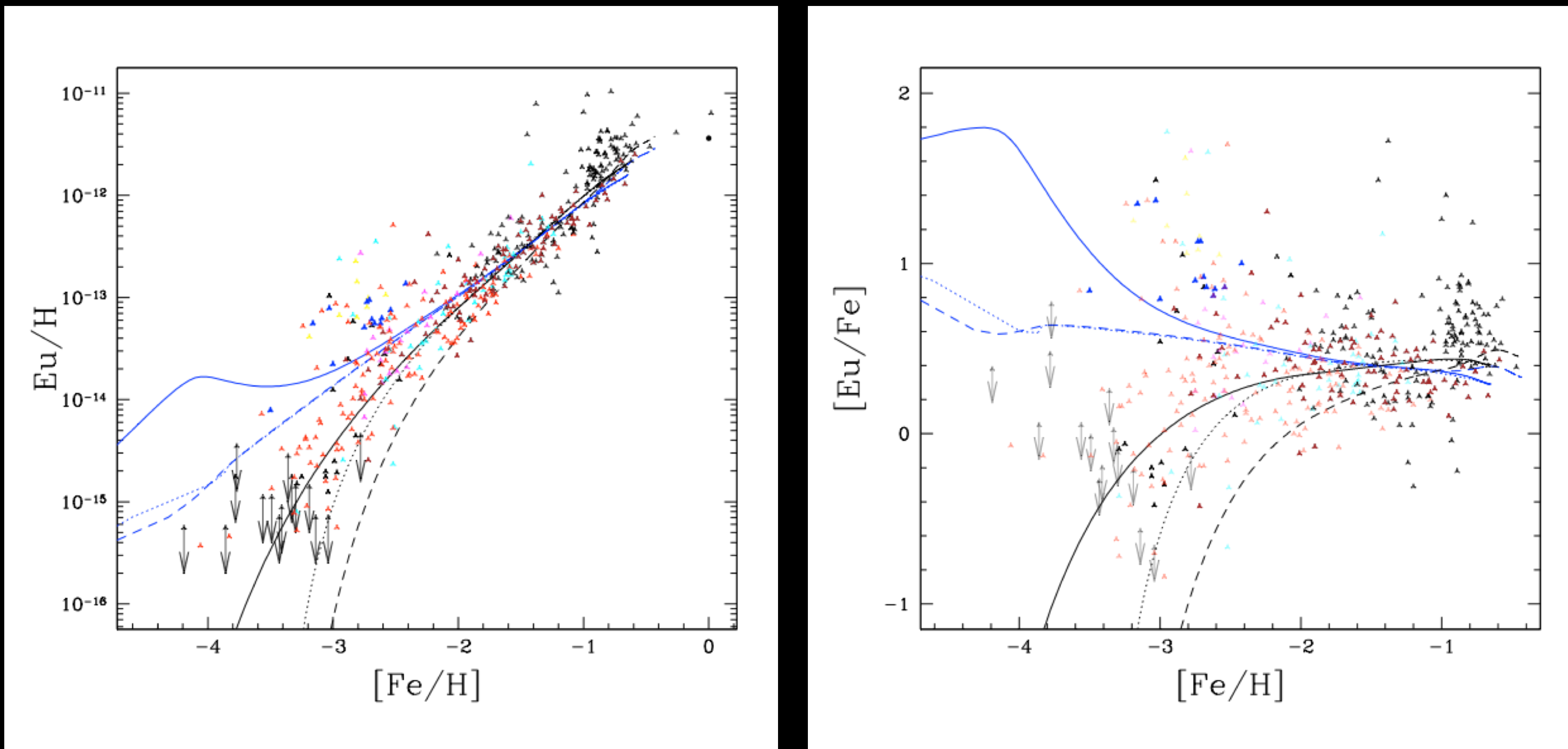

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SFR1 (low) ————
SFR2 (mid) ....
SFR3 (high) – – – – –

Conclusions 1

- The early 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]

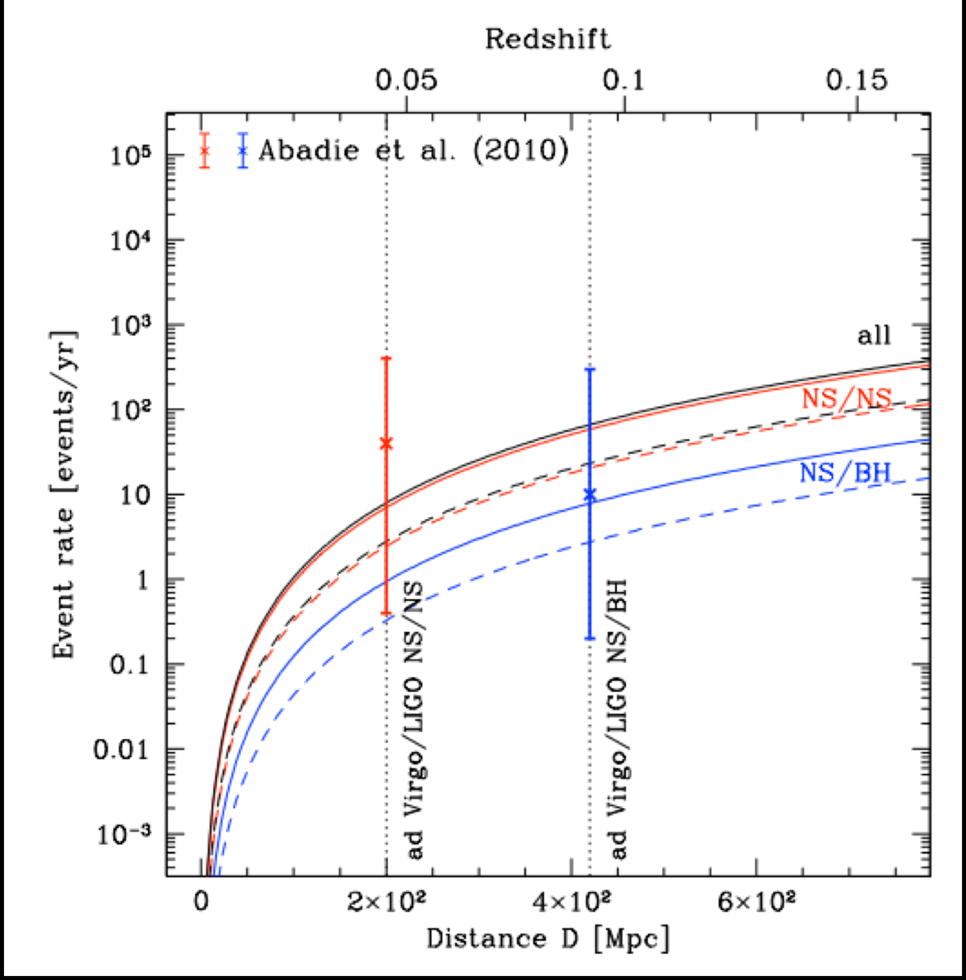
- For mergers : high z / low [Fe/H] observations put a constraint on the delay (typically below 0.4-0.5 Gyr)
- More observations at very low metallicity are needed for a better constraint
- Our conclusions do not depend on the choice of SFR

Consequences:
GW, Kilonovae

Predicted rates assuming BNS mergers as the main site for the r-process

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

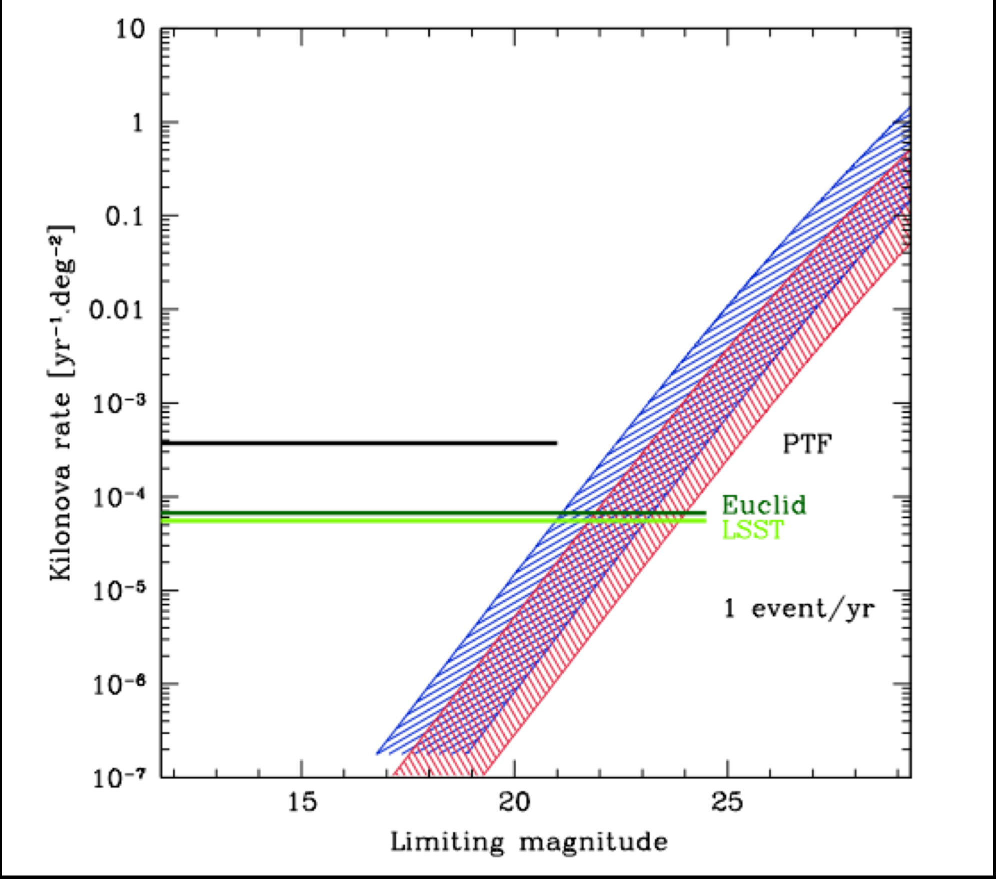


Kilonova Rate

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

	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



Conclusions 2

- The early 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]

- Improved model (dispersion) + new observational constraints: work in progress (Dvorkin et al.)

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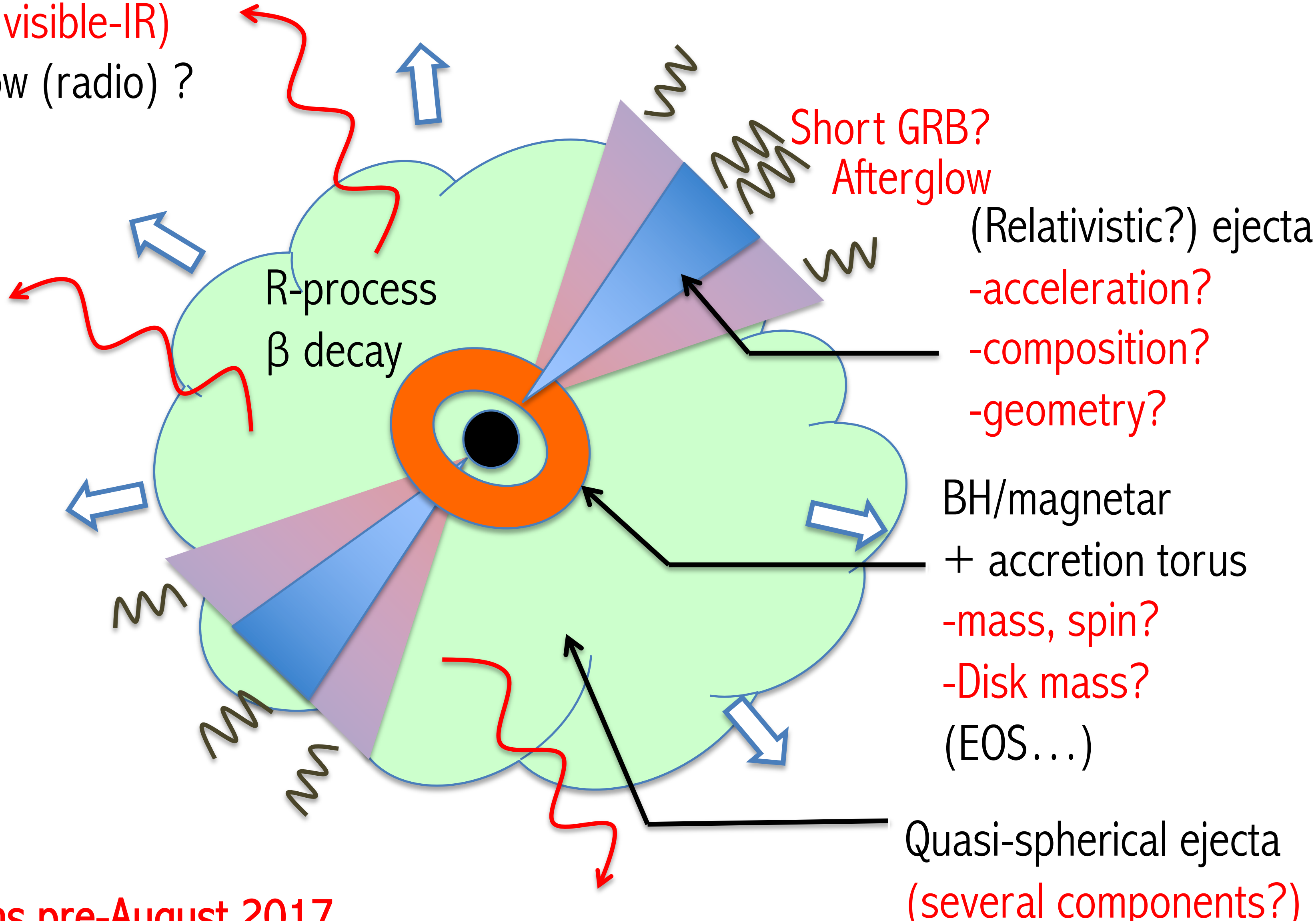
GW 170817 and counterparts

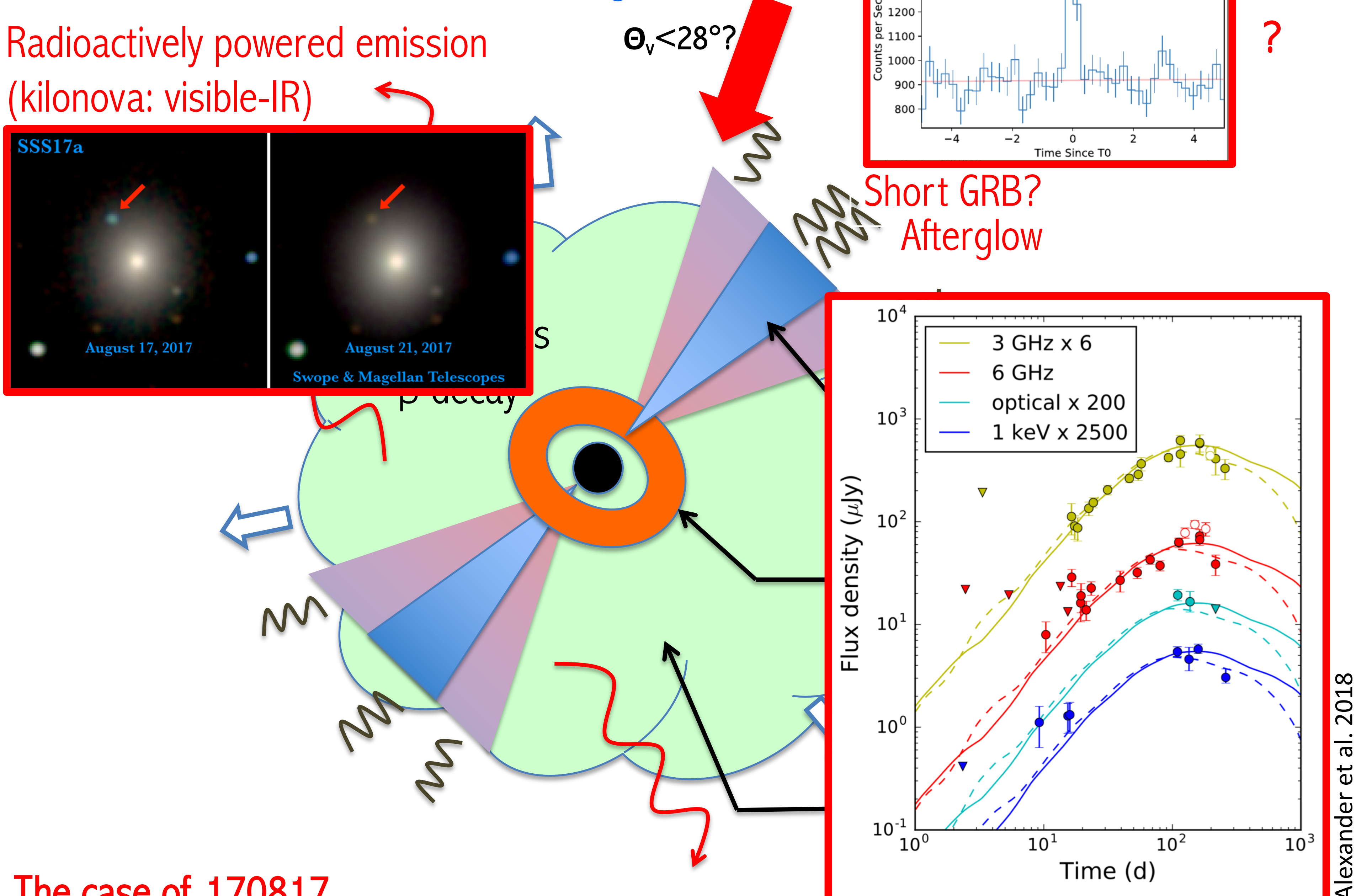
Remnant of a NS+NS merger

Radioactively powered emission
(kilonova: visible-IR)
+ afterglow (radio) ?



Predictions pre-August 2017

Remnant of a NS+NS merger



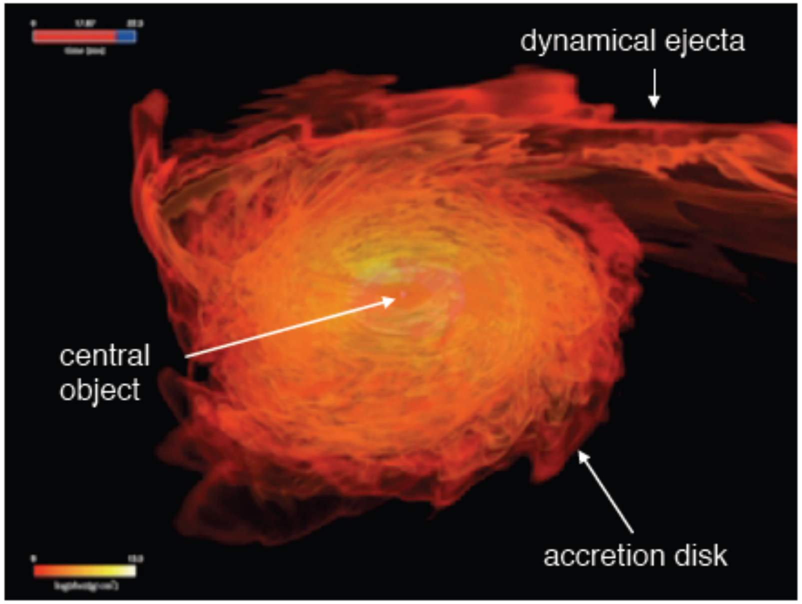
The case of 170817

GW

Gravitational waves

- **Initial system: NS+NS (NS+BH?) with known mass (chirp mass: 1.19 $M_\odot$)**
- **Distance ~40 Mpc**
- **Viewing angle < 28°**
- **Detected signal: inspiral**

Expected post-merger system:
- central object
- torus: a few 0.1 $M_\odot$?
- mass loss (tidal tails, polar outflows): 10^{-2} to 10^{-1} $M_\odot$?



(Rezzolla et al, 2010)

- **Post-merger signal: undetected**
- **Nature of the new-formed compact object?**
  - **Direct/delayed collapse to BH?**
  - **Long-lived massive NS?**

Kilonova

Kilonova:

- **Accurate localization: in NGC 4993**
- **GW+KN: better constraints on distance and viewing angle**

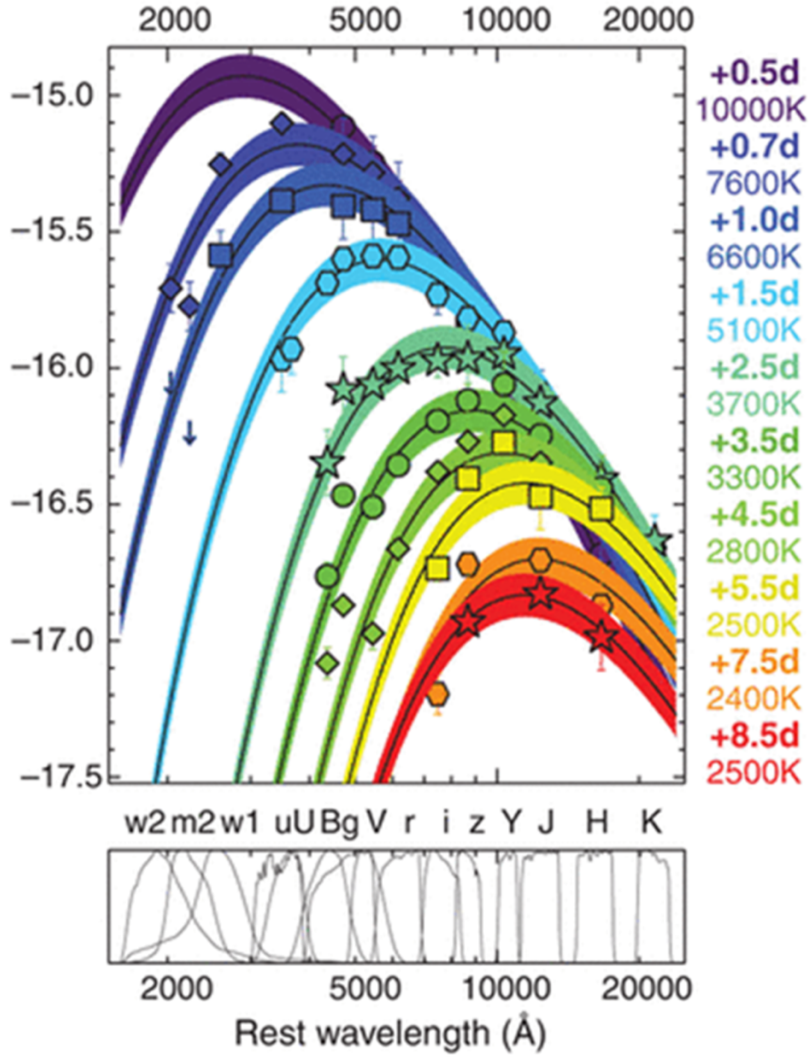
- **Spectro-photometry:**
  ejected mass, opacity, velocity

$$\frac{\mathrm{d}U}{\mathrm{d}t} = -P\frac{\mathrm{d}V}{\mathrm{d}t} + \dot{E} - L$$

$$t_{\mathrm{rad}}\frac{\mathrm{d}L}{\mathrm{d}t} + L = \dot{E} \qquad t_{\mathrm{rad}} \simeq \frac{R^2}{\ell c}$$

$$\dot{E} \simeq At^{-\alpha}$$

Metzger +10 ; Barnes & Kasen 13 ; Kasen +13 ;
Tanaka & Hotokezaka 13 ; Korobkin +12

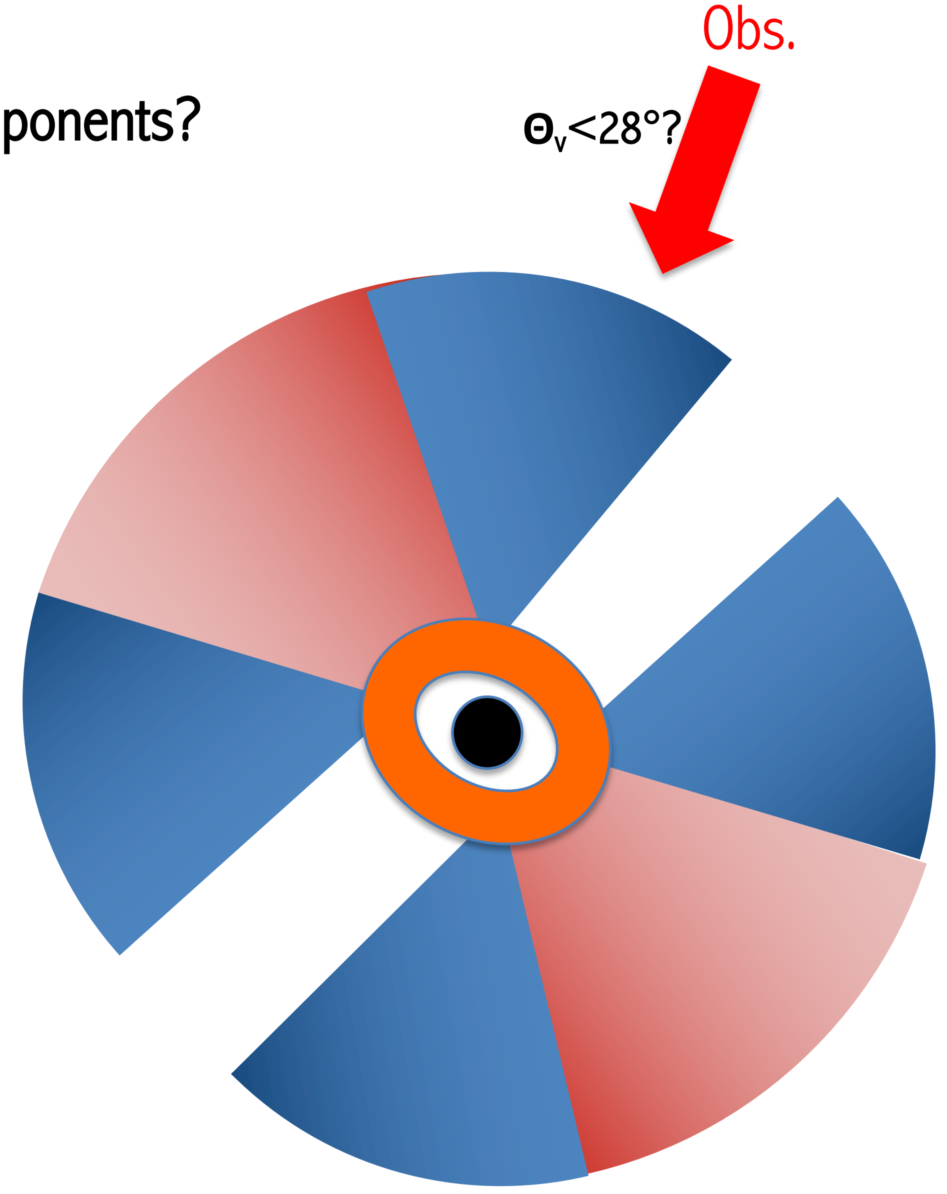


Drout et al., Science, 2017

M_{KN} ~ 0.03 – 0.05 $M_{\odot}$; v_{exp} ~ 0.1 - 0.2 c

Kilonova:

at least two components?



Dynamical ejecta?

Neutrino wind from the disk?

Kilonova:

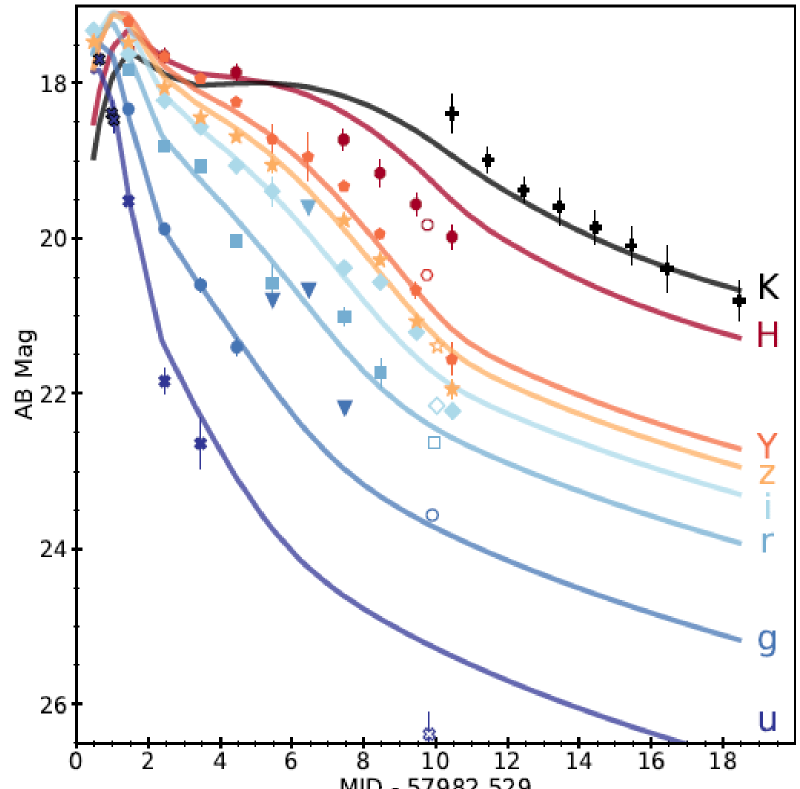
- **Accurate localization: in NGC 4993**
- **GW+KN: better constraints on distance and viewing angle**

- **Spectro-photometry:**
  ejected mass, opacity, velocity

- Large opacities: heavy nuclei
  (r process)

$$\frac{\mathrm{d}U}{\mathrm{d}t} = -P\frac{\mathrm{d}V}{\mathrm{d}t} + \dot{E} - L$$

$$t_{\mathrm{rad}}\frac{\mathrm{d}L}{\mathrm{d}t} + L = \dot{E} \qquad t_{\mathrm{rad}} \simeq \frac{R^2}{\ell c}$$



(Cowperthwaite et al, 2017)

Blue component:

M=0.014 $M_{\odot}$; v_{exp}=0.27c ; k= 0.5 $cm^2\, g^{-1}$; t_0 =1.3 days (light r-process elements?)

Red component:

M=0.036 $M_{\odot}$; v_{exp}=0.12c ; k= 3.5 $cm^2\, g^{-1}$; t_0 =6.5 days (lanthanides A≳140 ?)

Kilonova:

- Accurate localization: in NGC 4993
- GW+KN: better constraints on distance and viewing angle

- Spectro-photometry:
  ejected mass, opacity, velocity

- Large opacities: heavy nuclei
  (r process)

- **Heaviest elements (gold, platinium)?**

Early KN emission is not sensitive to these elements.
Late evolution? (JWST?)
(see e.g. Wu et al. 1808.10459)

Kilonova:

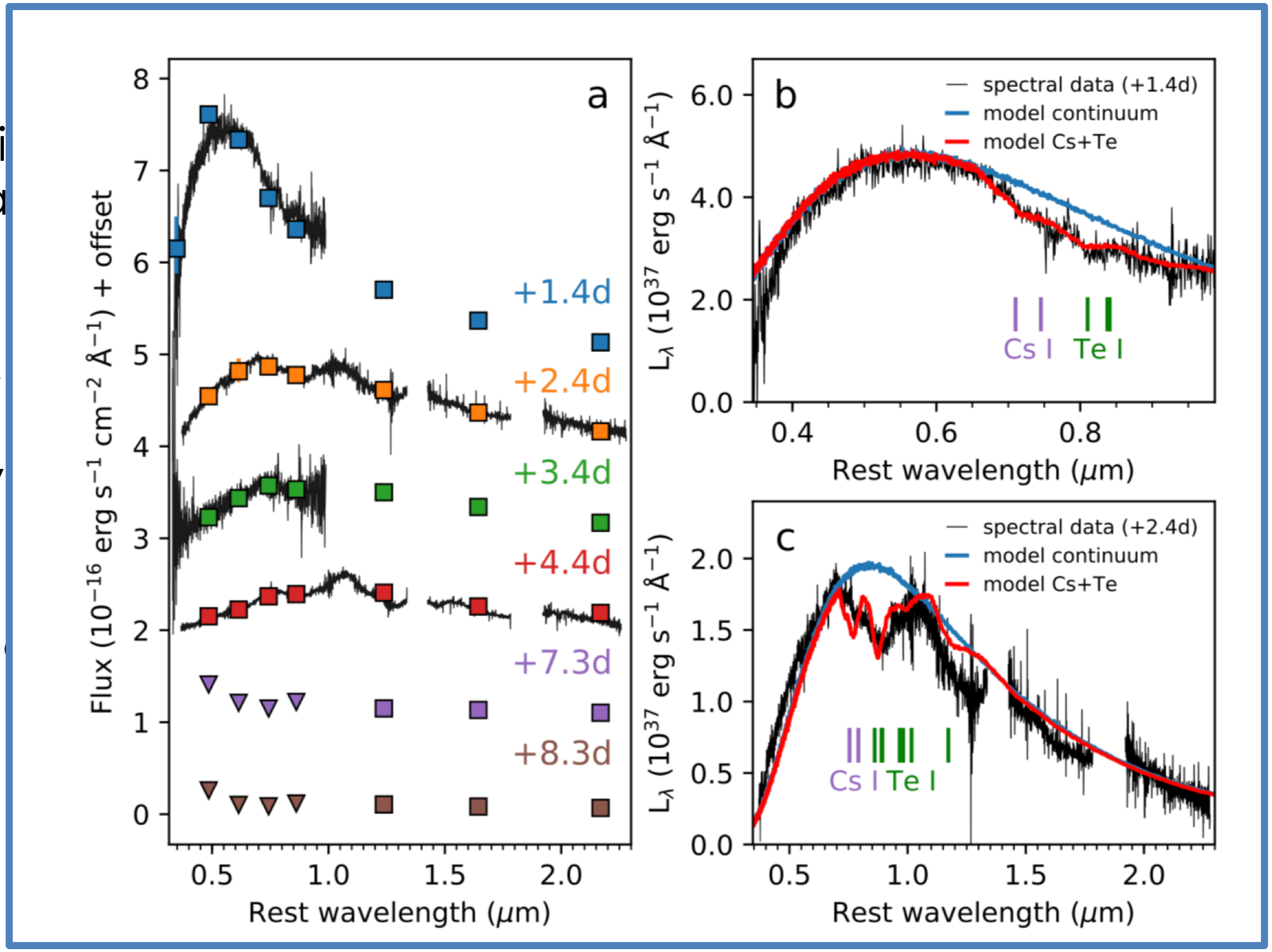
- Accurate localization: i
- GW+KN: better constra

- Spectro-photometry: ejected mass, opacity,

- Large opacities: heavy (r process)

- Heaviest elements (gol

- **Direct spectroscopic signature?**
  Difficult.
  (see Smartt et al. 2017, Pian et al. 2017)



Smartt et al. 2017

Line features consistent with light r-process elements?
Need for more accurate and complete atomic data

Kilonova:

- Accurate localization: in NGC 4993
- GW+KN: better constraints on distance and viewing angle

- Spectro-photometry:
  ejected mass, opacity, velocity

- Large opacities: heavy nuclei
  (r process)

- Heaviest elements (gold, platinium)?

- Direct spectroscopic
  signature?

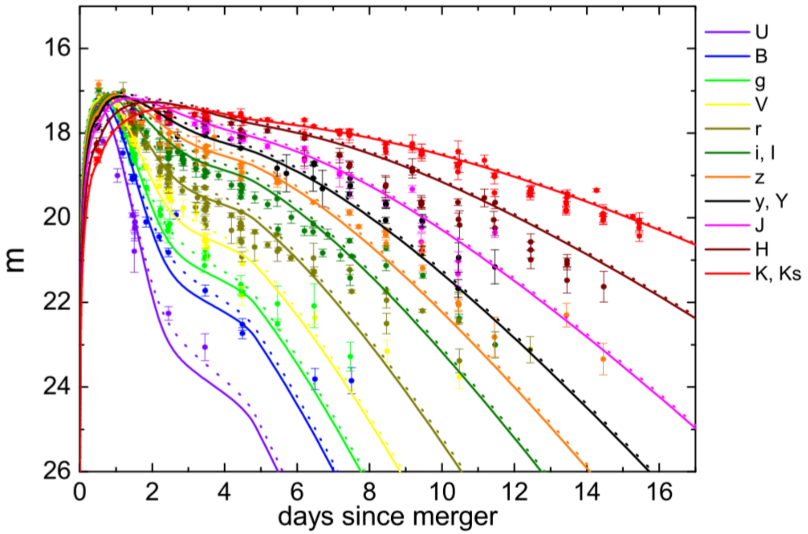
- **Ejected mass: indirect constraint on EOS of ultra-dense matter and nature of the final object**
  See e.g. Bauswein et al. 2017, Margalit et al. 2017 :
  For the 170817 event, high ejected mass favors the formation of a NS, possibly followed by a collapse to a BH.

Kilonova:

- **Ejected mass: indirect constraint on EOS of ultra-dense matter and nature of the final object**

- **See e.g. Bauswein et al. 2017, Margalit et al. 2017 :**
  For the 170817 event, high ejected mass favors the formation of a NS, possibly followed by a collapse to a BH.

  BUT
  - how robust is the theoretical prediction? (physics of the ν wind in simulations)
  - how accurate is the ejected mass measurement?
  If a long-lived NS is formed, energy can be continuously injected in the ejecta: affect the physics of the kilonova.

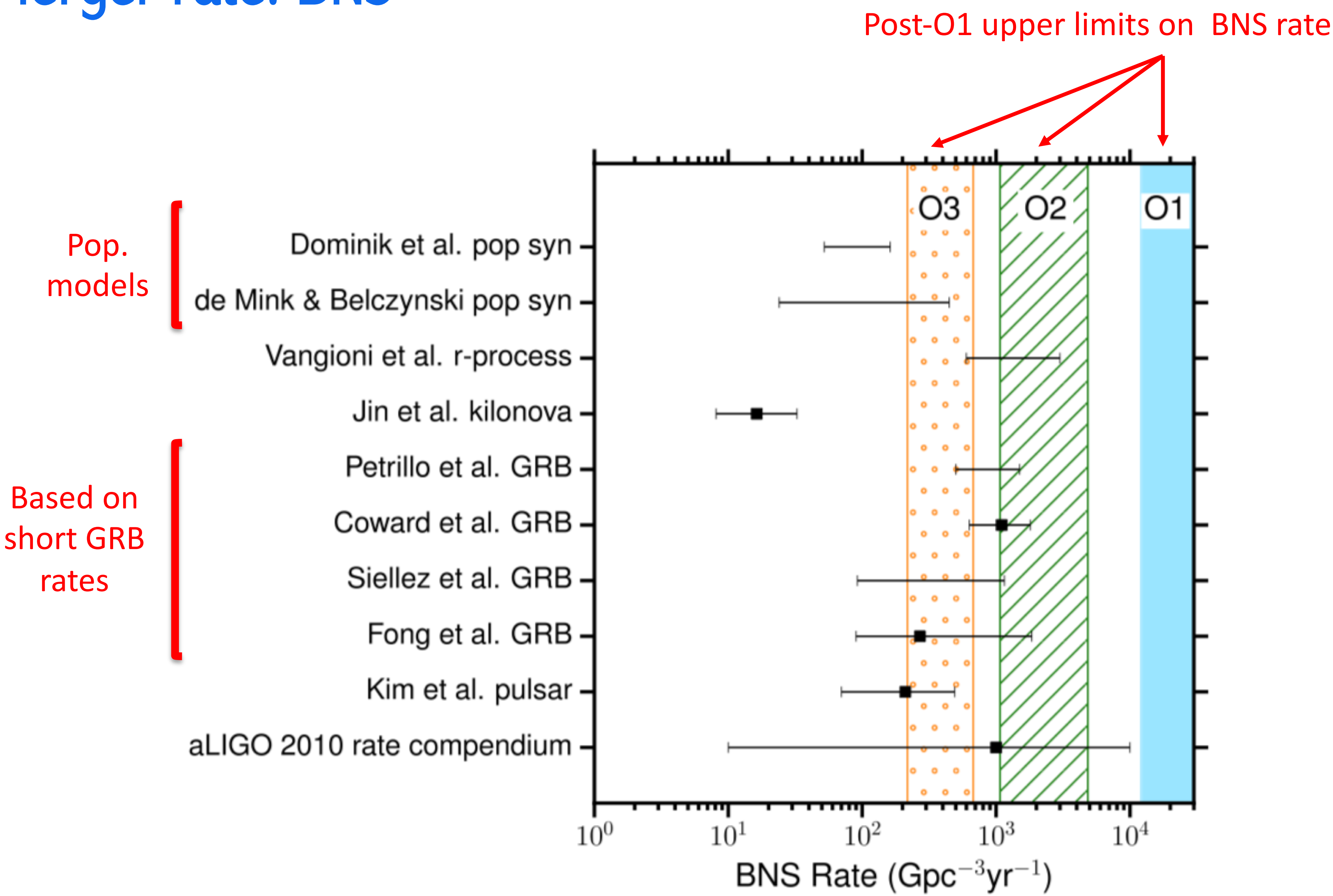


Li et al. 2018: kilonova model with long-lived NS: ejected mass is reduced by a factor 10…

Self-consistent analysis?

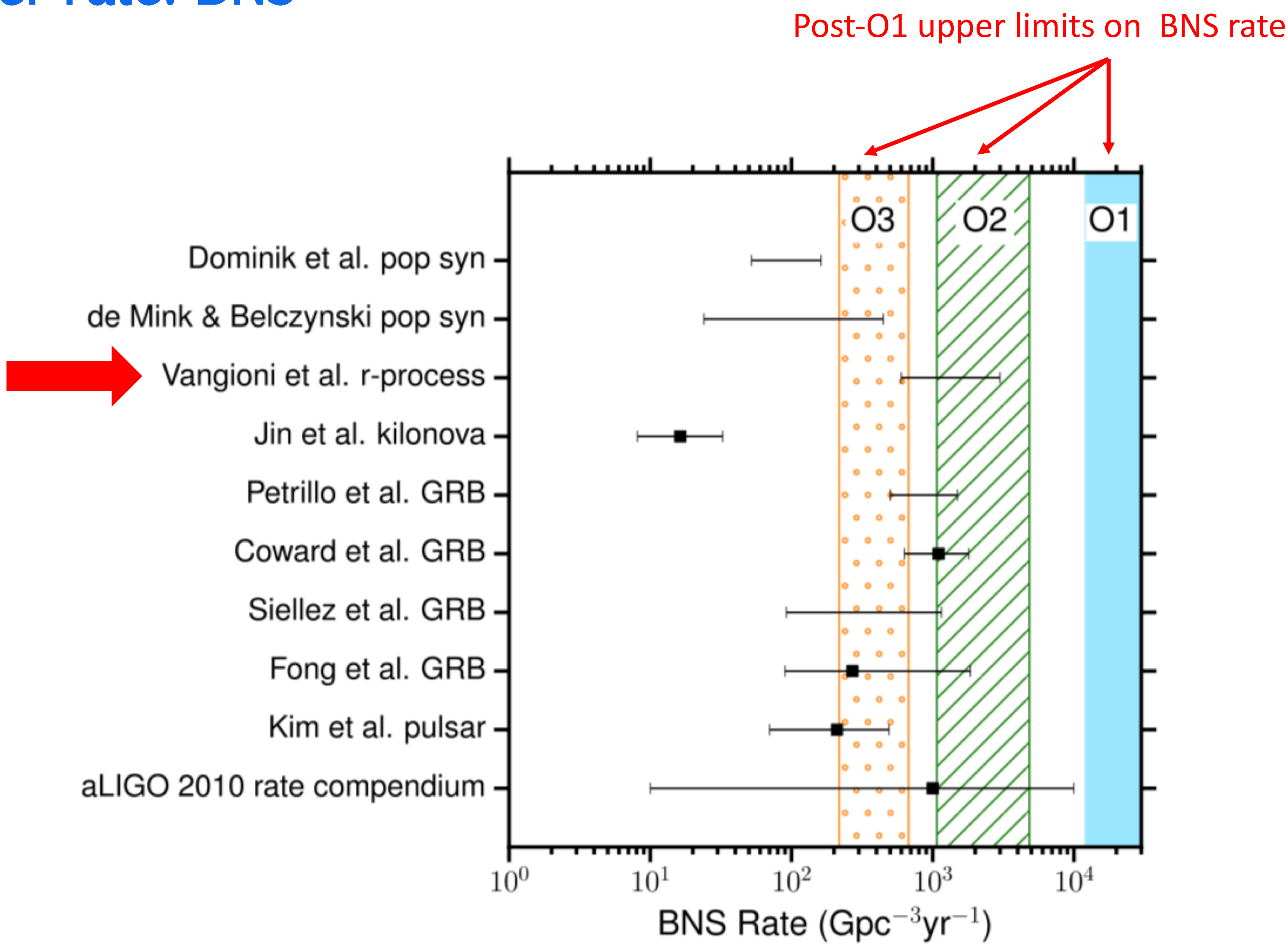
Merger rates

Merger rate: BNS



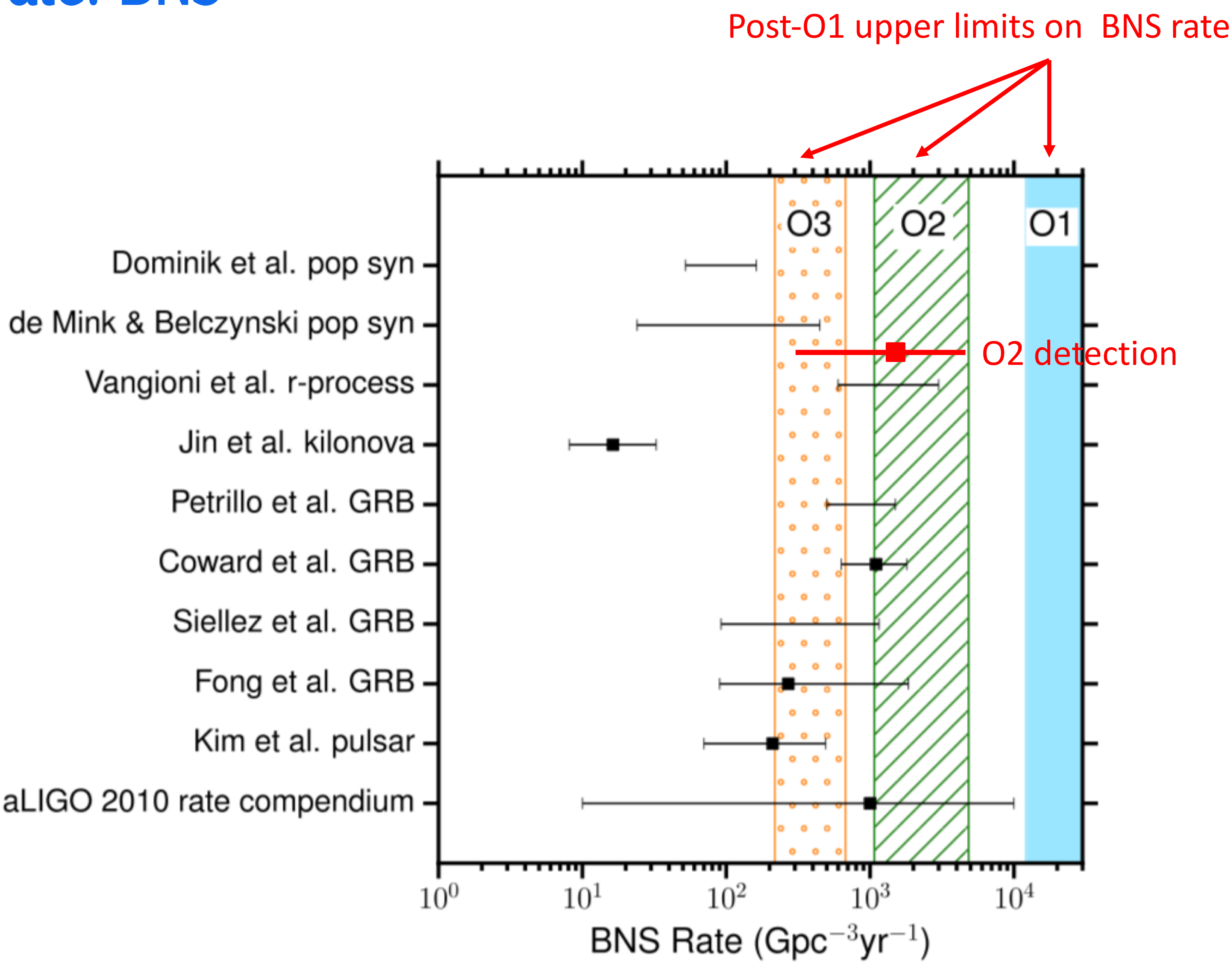
Abbott et al. 2016, post-O1

Merger rate: BNS



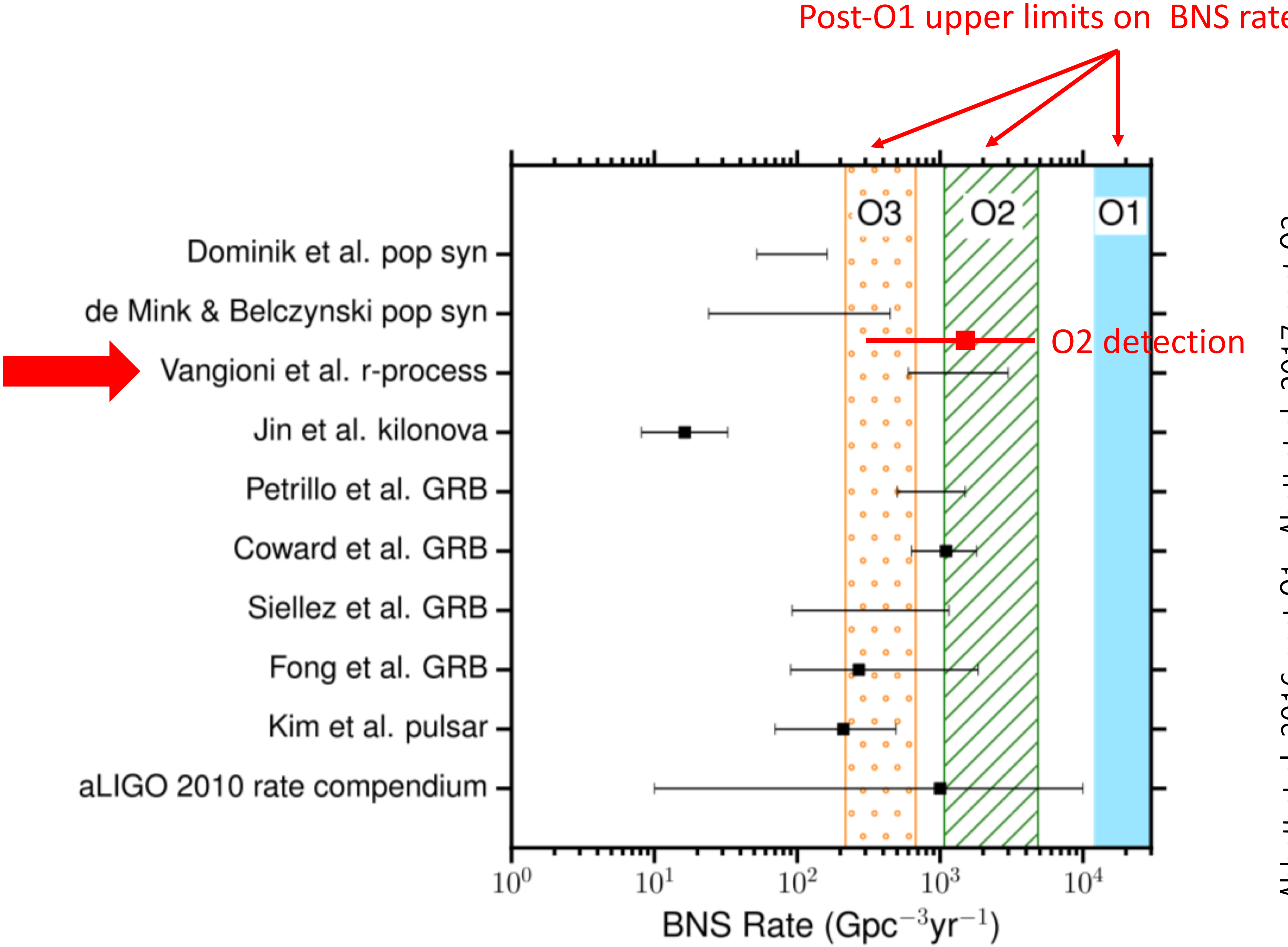
Abbott et al. 2016, post-O1

Merger rate: BNS



Abbott et al. 2016, post-O1

Merger rate: BNS



Abbott et al. 2016 post-O1, Abott et al. 2017 post-O2

To confirme that mergers are the main contributers of r-process elements: more evidence for heavy elements formation, estimate of the ejected mass, …

Summary

Summary

- Pre-2017:
  The cosmic evolution of Europium (pure r element) favors mergers as the main astrophysical site for the r process

- **The deduced BNS merger rate assuming mergers as the main site for the r-process is consistent with post-GW17087 detection direct estimates**

- The counterpart AT2017gfo associated to GW170817 is the first kilonova identified with confidence.

- The observed evolution gives good evidence for at least two ejected components with different opacities
  - blue component: light r-process elements (low opacity)?
  - red component: heavier elements (lanthanides) (higher opacity)?

  =strong evidence for r-process occurring in a BNS merger

- Direct spectroscopic evidence for r-process elements is difficult
- Evidence for the synthesis of the heaviest elements is difficult (late evolution)

- **Next steps: rates, distribution of ejected mass, better understood geometry, etc. New detections during O3?**