TL3: Binary inspiral electromagnetic counterparts / ejecta

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Compose and WG 2 + WG 3 meeting

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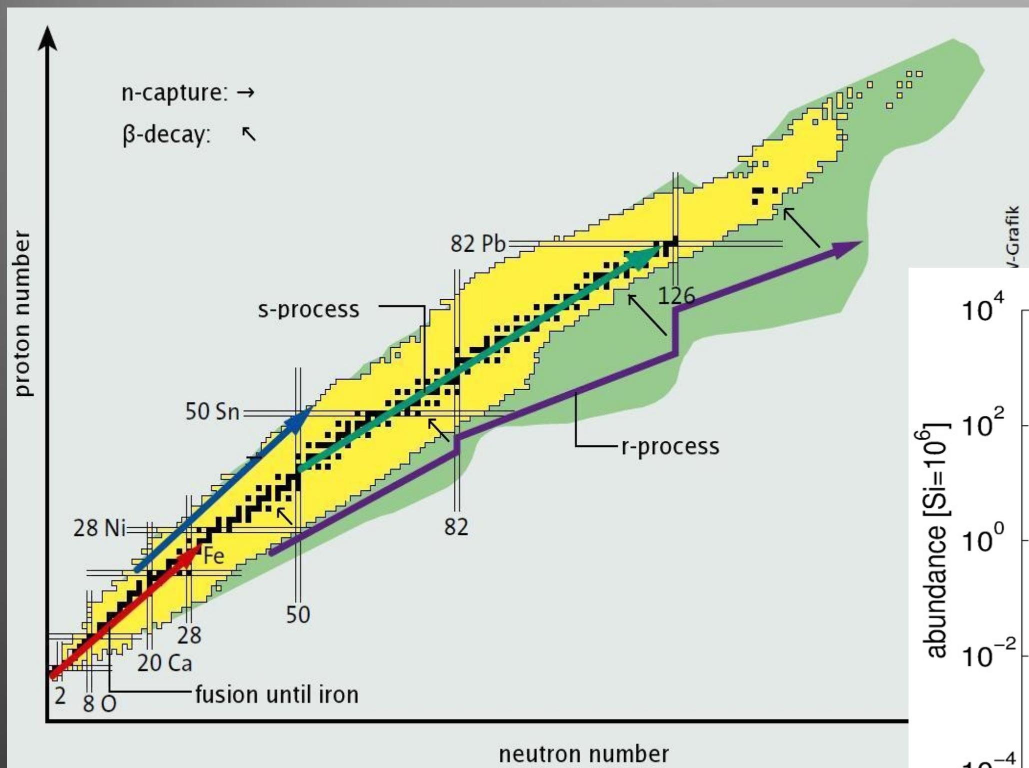
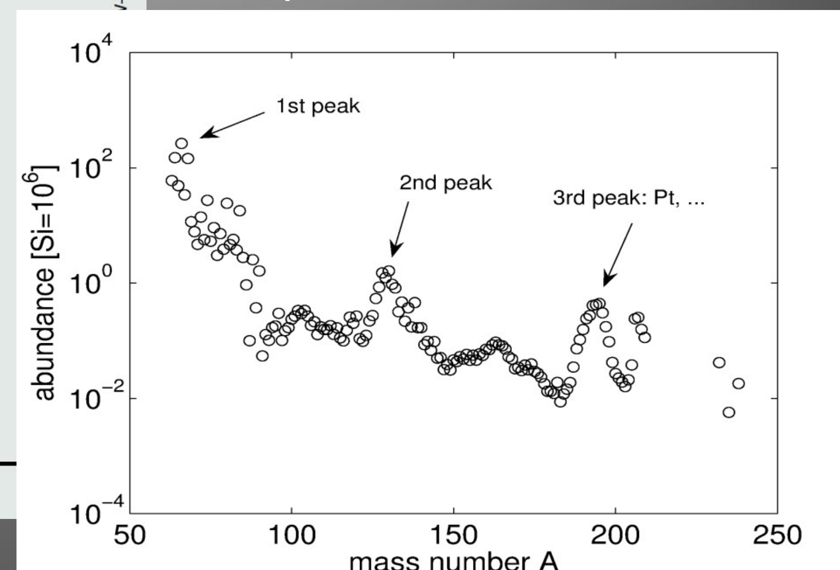
Outline

- Origin of heavy elements: r-process
- R-process in compact binary mergers: achievements and challenges (mostly NSNS but NSBH similar)
- Overview: electromagnetic counterparts
- Focus: ejecta powered transients – models and observations
- Merger rates and nucleosynthesis
- Summary and conclusions

Motivation: origin of r-process elements



Observed abundance of r-process elements



Astrophysical production site unknown

Search for explosive, neutron-rich environment, fast expansion

→ Ejecta of compact binary mergers ???

Lattimer & Schram 1974, 1976, Lattimer et al. 1977, Eichler et al. 1989, Freiburghaus et al.1999

Neutron capture processes

n-capture versus β-decay

rapid neutron-caputre process	slow neutron-capture process
(r-process)	(s-process)
n-capture timescale << beta-decay timescale	n-capture >> beta-decay
→ high neutron densities required	→ moderate neutron densities
→ explosive event	→ He burning in Red Giants
	→ terminates at Pb, Bi

r-process elements

We don't know where they are produced.

But we have some clue how they are formed.*

* A nuclear physicist may not even agree on this (many details unclear).

Where does the r-process takes place?

Key parameters: neutron-richness, entropy, expansion timescale

Core-collapse supernovae

- consistent with chemical evolution model
- most recent SN models disfavor this site (Y_e too high) *e.g. Fischer et al.. 2010, Huedepohl et al. 2010*
- third peak ?

NS-NS or NS-BH mergers

- robust r-process for heavy elements
- merger rate and ejecta masses?
- chemical evolution model?

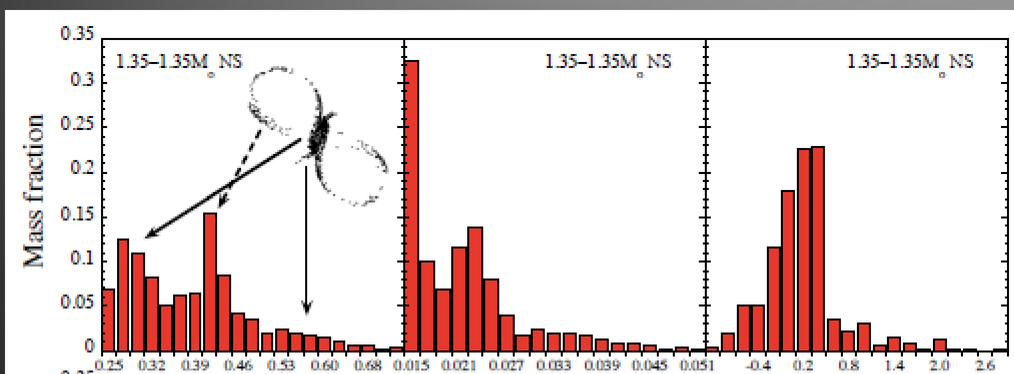
… several other ideas: e.g. MHD jet, quark nova, He shells, ...

e.g. Winteler et al. 2012, Ouyed et al 2011, Banerjee et al 2011, ...

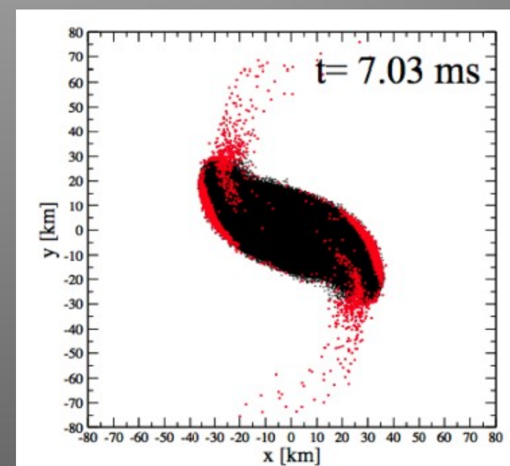
… different sources could contribute to the final abundance at different mass ranges and different times

Unbound matter in NS mergers

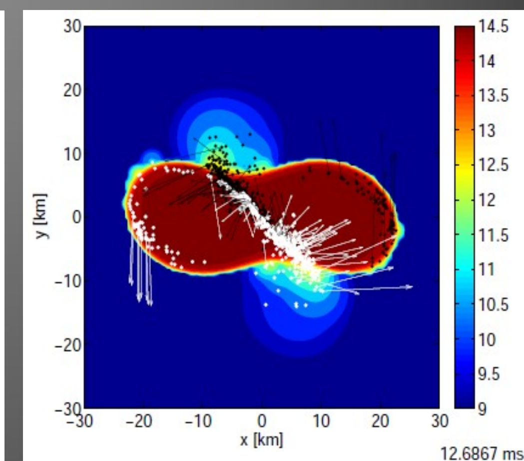
Dynamical mass ejection found in Newtonian and relativistic hydrodynamical models: *e.g. Ruffert & Janka 1999, Rosswog et al. 1999, Freiburghaus et al. 1999, Oechslin et al. 2007, Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011, Hotokezaka et al. 2013, Bauswein et al. 2013, Rosswog et al. 2013, Piran et al. 2013, Wanajo et al. 2014, …* (with and without nucleosynthesis calculations; different degrees of sophistication regarding EoS, gravity, neutrinos)



Goriely et al. 2011



Korobkin et al 2012



Bauswein et al. 2013

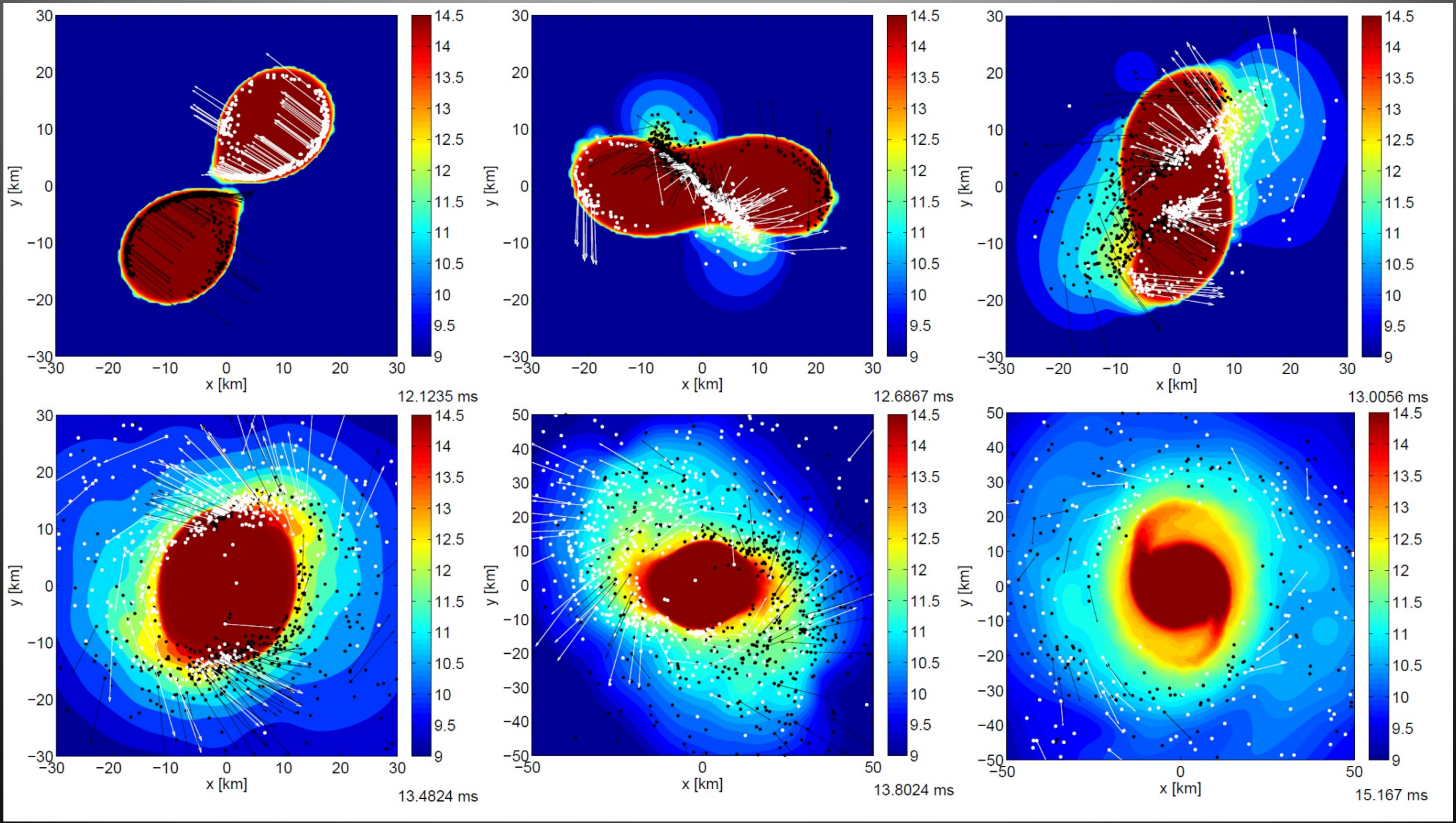
<u>Tendencies:</u>

- typical masses 10^{-3} … 10^{-2} M_{sun}
- asymmetric mergers eject more (tidal)
- Newtonian models favor ejection by tidal forces and produce more ejecta
- relativistic models ejecta mostly from contact interface

(also a number of NSBH simulations and excentric mergers available: typically higher ejecta masses, but rates?)

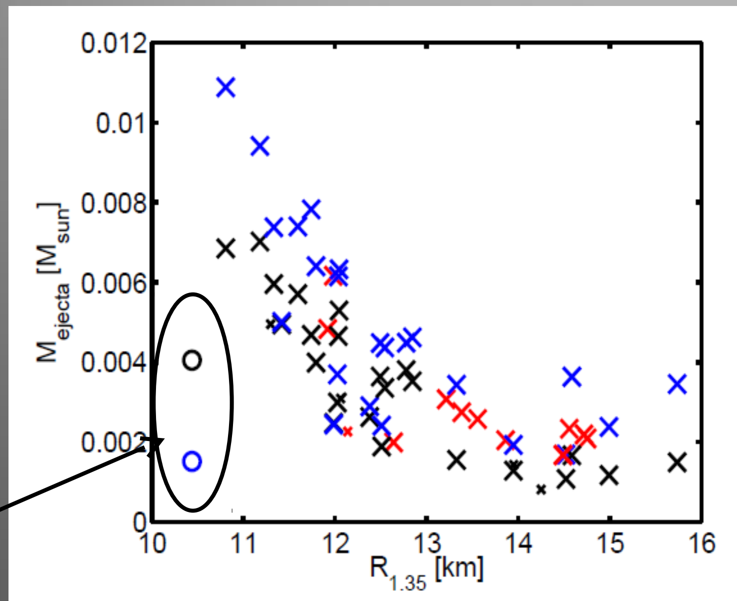
Simulations

Dots trace ejecta (DD2 EoS 1.35-1.35 M_{sun})



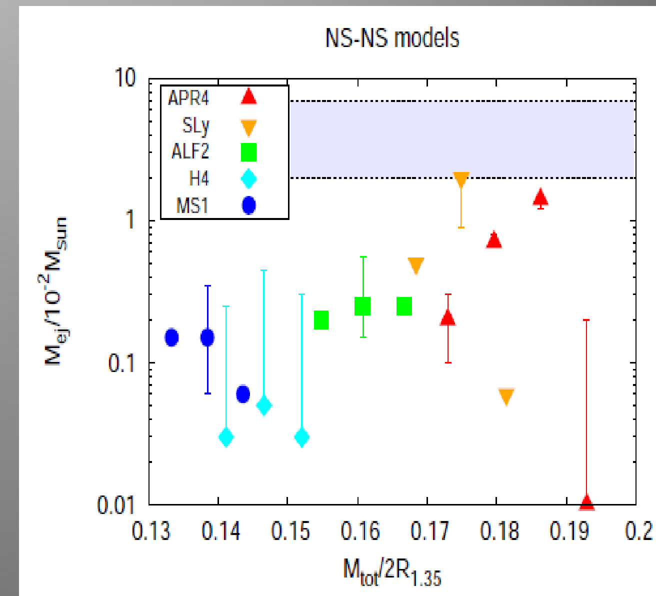
Bauswein et al. 2013

Ejecta mass dependencies: EoS & bin. para.



Prompt collapse

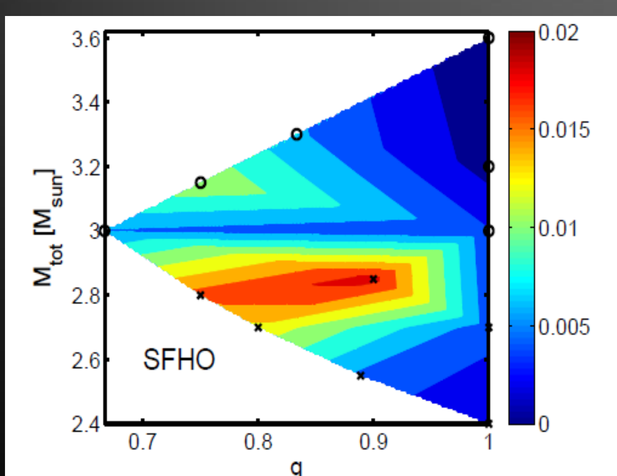
Bauswein et al 2013

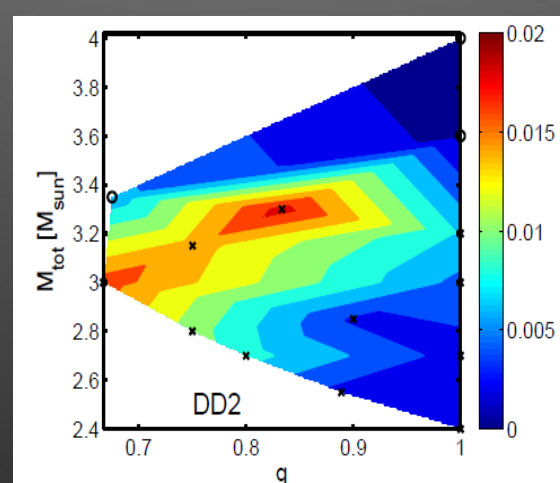


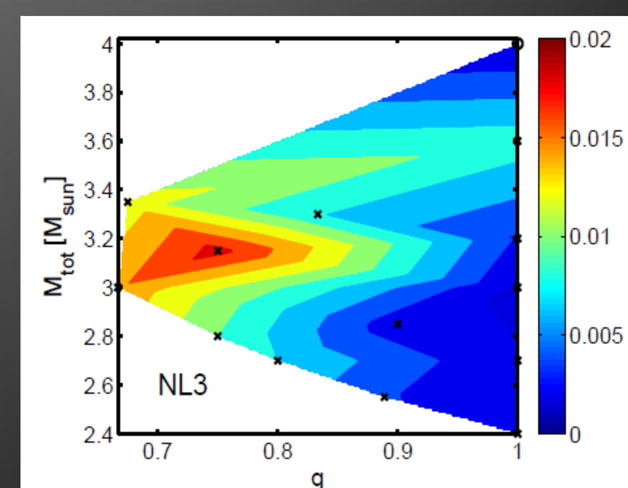
Hotokezaka et al. 2013

Note importance of thermal effects

Stiffness







NSBH merger ejecta

Inverse EoS dependence of ejecta masses compared to NSNS mergers (tidal ejection)

Typical ejecta masses are higher compared to NSNS (~ 0.1 … 0.2 M_{sun} for appropriate binary parameters); ejecta can also be absent (e.g. low spin – high mass cases)

Strong spin impact on ejecta masses (also dependence on spin orientation)

See e.g. Kyutoku et al. 2013, Rosswog et al. 2013, Foucart et al. 2013, Deaton et al. 2013, Foucart et al. 2014, Just et al. 2014, Bauswein et al. 2014 (only recent results, see Living review by Shibata & Taniguchi)

Ejecta properties – nuclear network calculations

- Robust features: fast expansion, neutron rich (neutrinos may somewhat increase Y_e, see Wanajo et al. 2014)
- Originating from inner neutron crust (initial Y_e very low)
- Matter heated to NSE and frozen out at neutron drip $4*10^{11}$ g/cm^3
- Ejecta expansion typically followed for a few 10 ms by simulations, then extrapolation (outcome insensitive)
- Post-processing hydrodynamical trajectories with nuclear network

  - Properties of ~5000 nuclei (mostly theoretical models)

  - Theoretical and experimental reaction rates: beta-decays, neutron captures, photodissosication, multiple-particle reactions (n,2n)

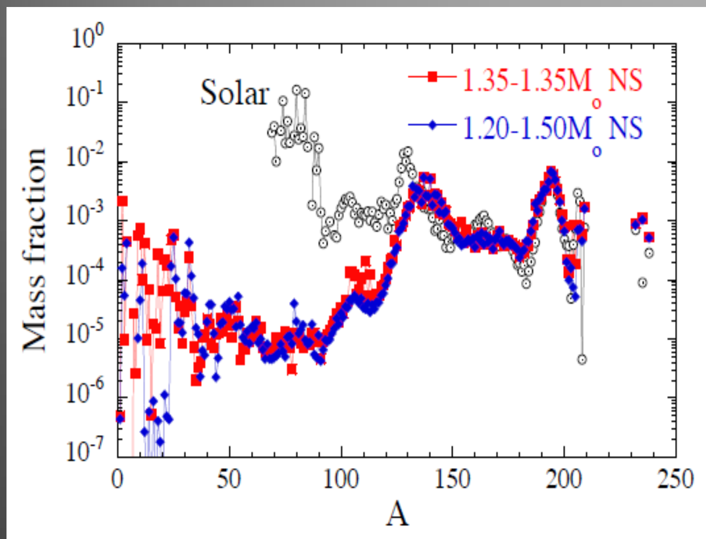
  - Neutron-induced fission, spontaneous fission, beta-delayed fission, photofission, beta-delayed neutron emission

  - Heating due to beta-decays, fission, alpha decays

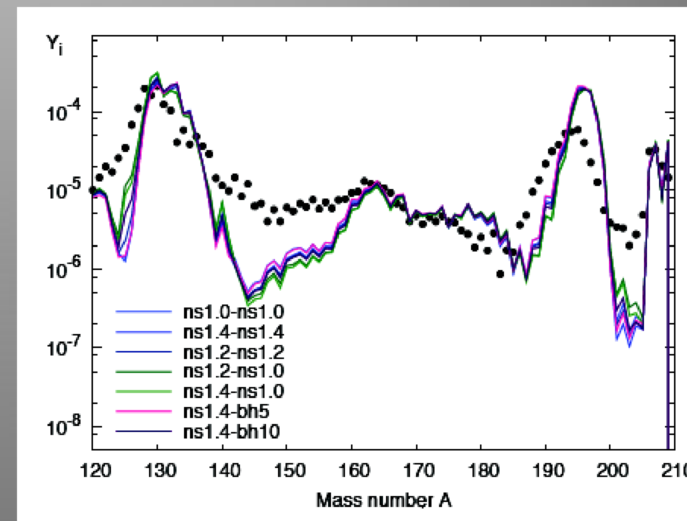
Nucleosynthesis results

Some recent results: different hydrodynamical models, different nuclear network codes, different NS EoS, different binary systems → robust pattern

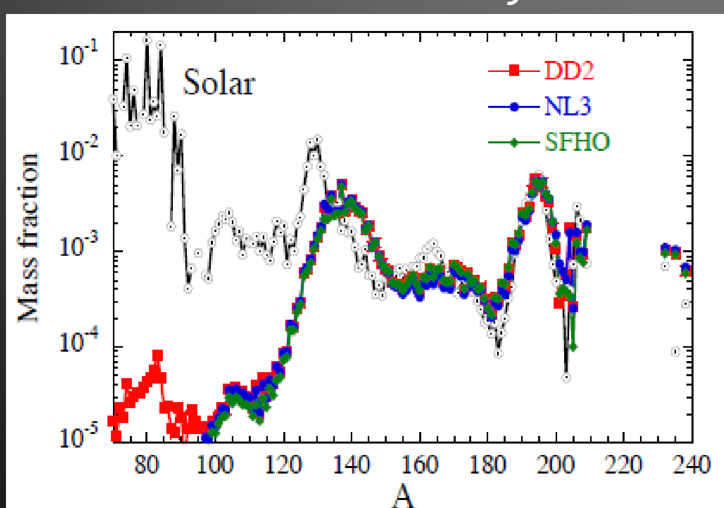
Black dots: observed abundances (results scaled)



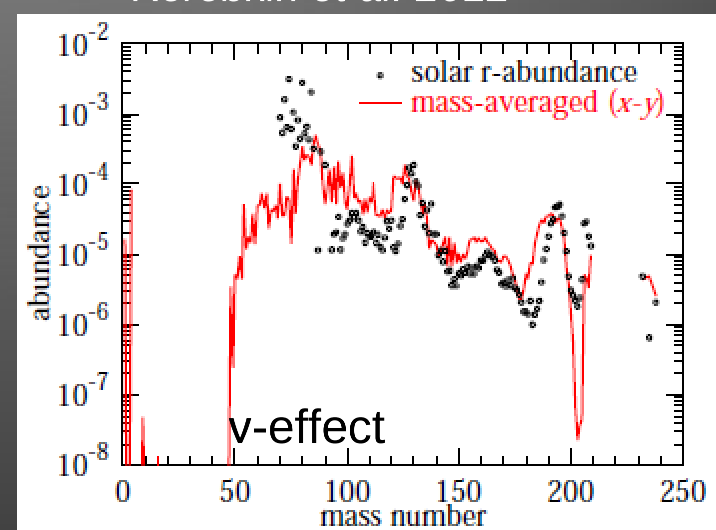
Goriely et al 2011



Korobkin et al. 2012



Bauswein et al 2013



Wanajo et al. 2014

See also Freiburghaus et al 1999, Metzger et al. 2010, Roberts et al. 2011,...

Nucleosynthesis results

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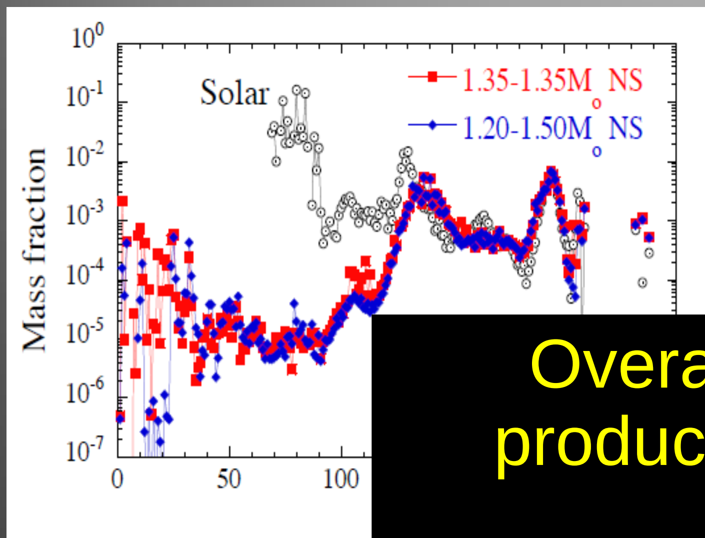
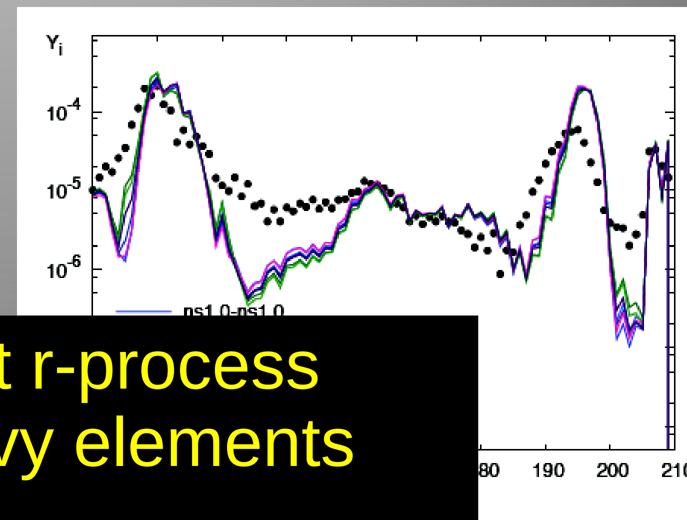
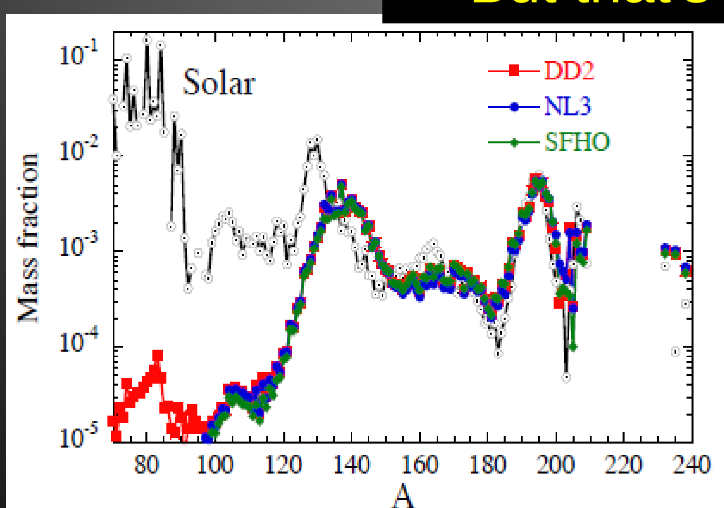


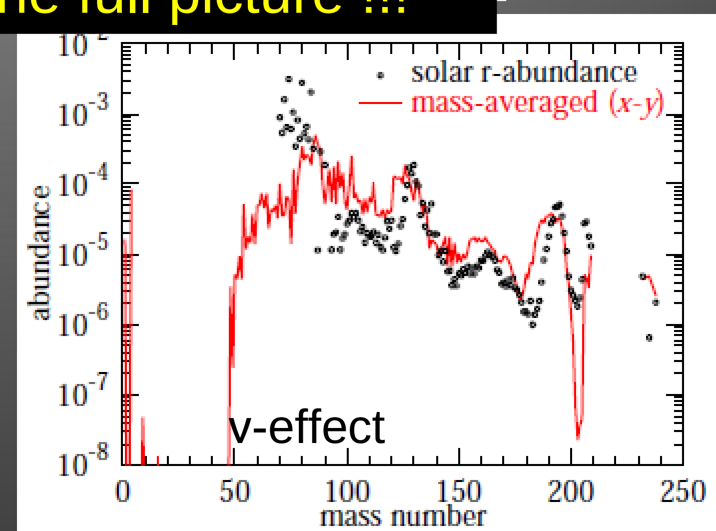


Overall robust r-process producing heavy elements

But that's not yet the full picture !!!



Bauswein et al 2013



Wanajo et al. 2014

See also Freiburghaus et al 1999, Metzger et al. 2010, Roberts et al. 2011,...

Secular ejecta

But: NS mergers leave a remnant

- Long-lived NS remnant
- BH-torus system (also from NSBH binary)

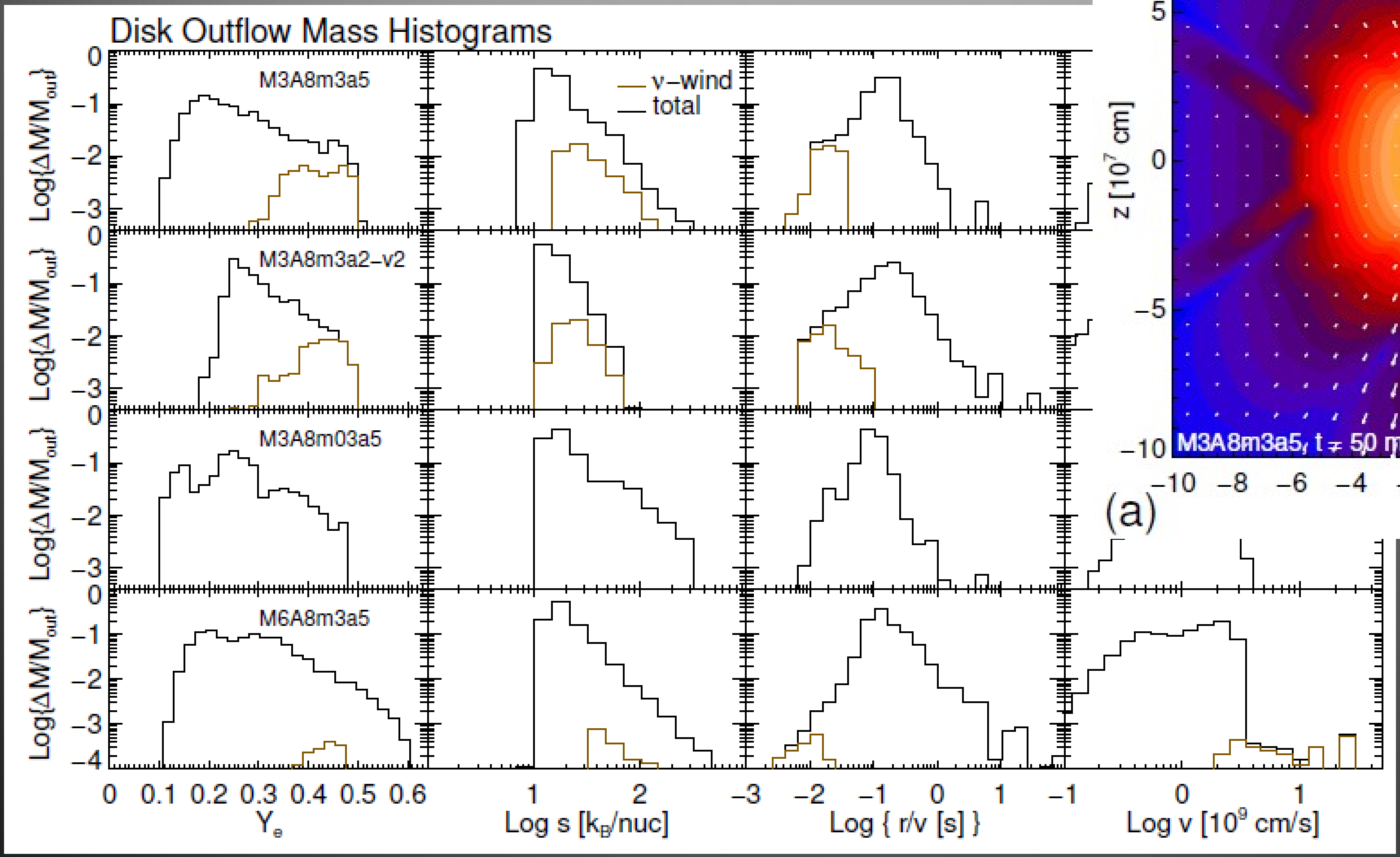
→ neutrino-driven, magnetically driven, viscosity-driven ejecta on longer timescales

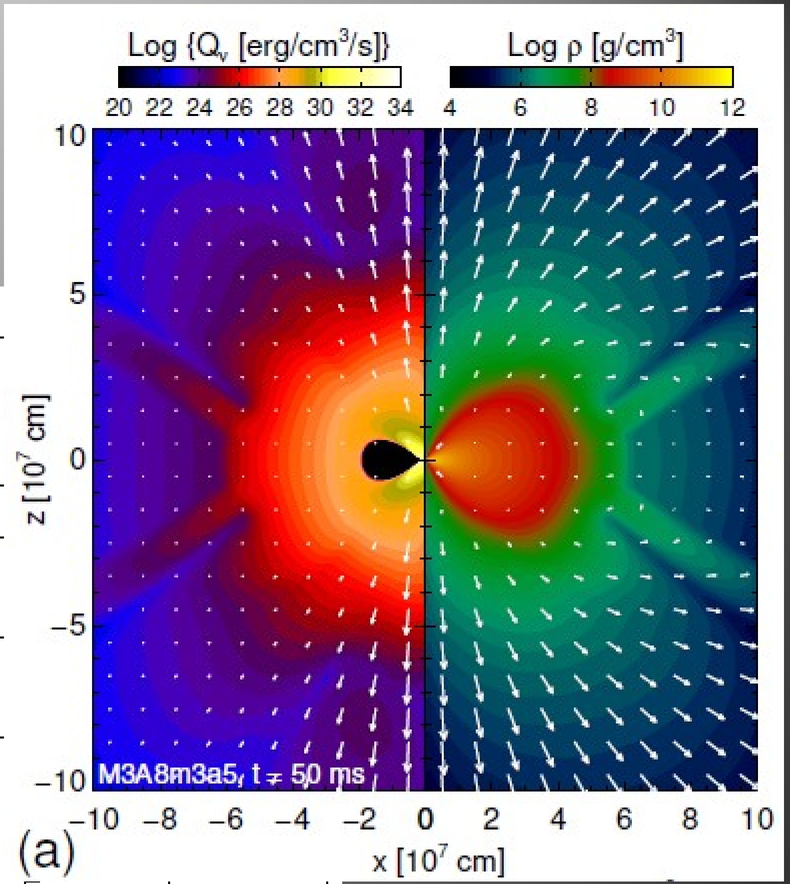
→ neutron-rich outflow for r-process (light r-process elements)

→ because of timescales neutrino effects are important

e.g. Surman et al. 2008, Metzger et al. 2008, Lee et al. 2009, Metzger et al. 2009, Dessart et al. 2009, Lee et al. 2009, Wanajo & Janka 2012, Surman et al 2013, Fernandez & Metzger 2013, Rosswog et al. 2014, Grossmann et al. 2014, Metzger & Fernandez 2014, Siegel et al. 2014, Perego et al. 2014, Just et al 2014, Kasen et al. 2014

Secular ejecta properties



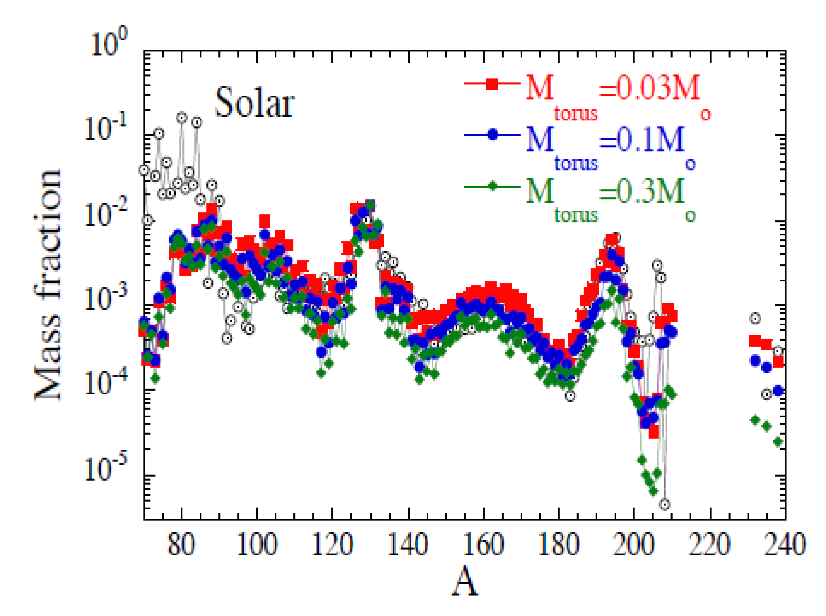


neutrino-driven
vs. total ejecta

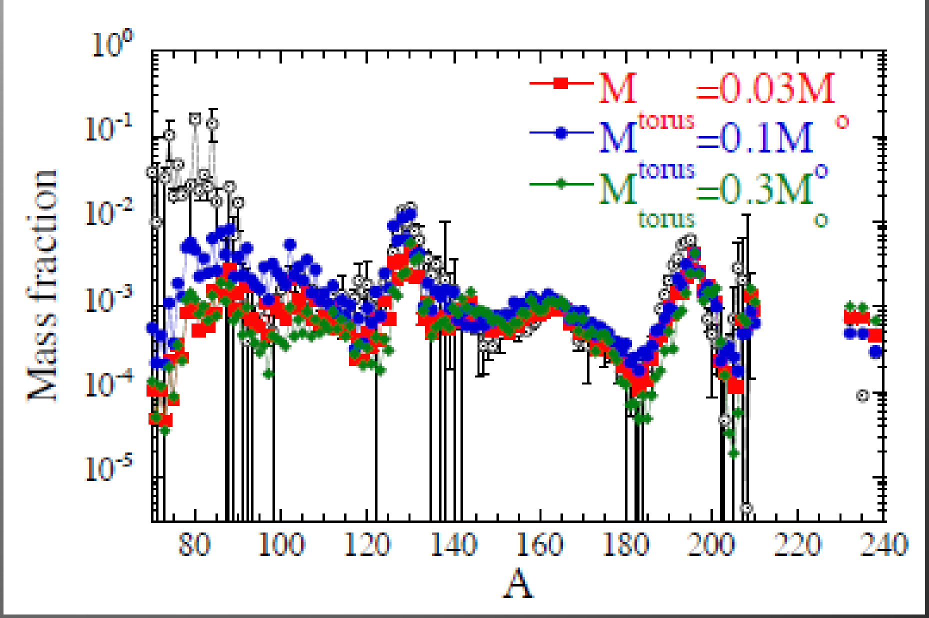
Just et al. 2014.

Long-term torus evolution including detailed neutrino transport (connected with merger simulations)

Nucleosynthesis of secular ejecta



Only secular ejecta



Secular and dynamical ejecta
(merger and disk ejecta)

Just et al. 2014.

Mergers produce also the low A r-process elements

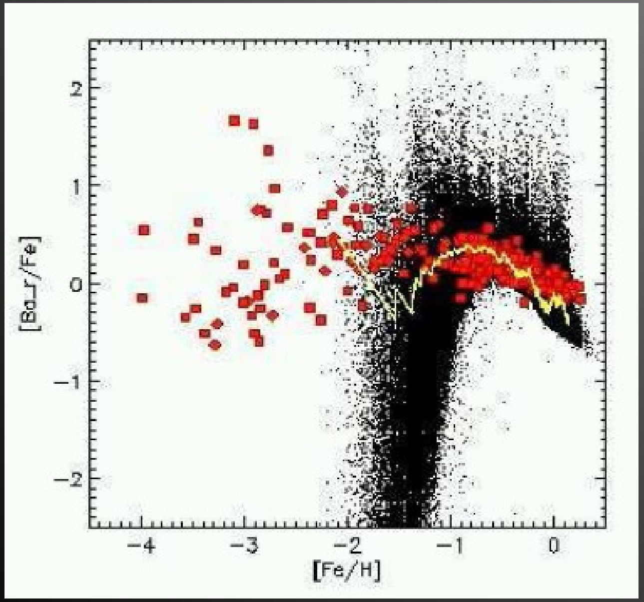
Observations

Ejecta masses and merger rates are roughly consistent with NS mergers being the dominant source of heavy r-process elements (details later, see e.g. Bauswein et al. 2014 for a detailed analysis)

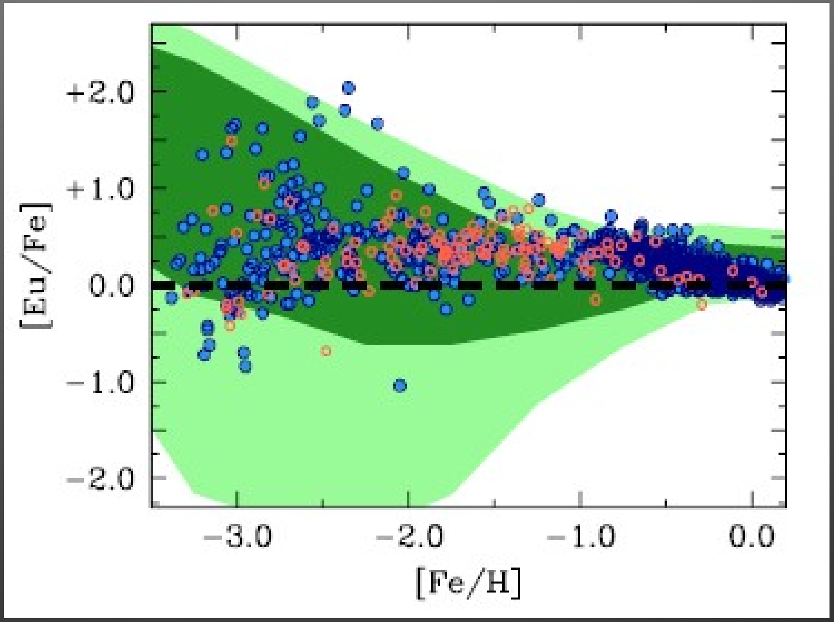
R-process elements are observed in metal-poor (=old) stars with robust abundance pattern (see e.g. Sneden et al. 2008); with large star-to-star scatter

Formation of NS binary followed by inspiral time of 100...1000 Myrs => merger is delayed

→ Do mergers occur sufficiently "early" to explain the Galactic enrichment → chemogalactical models *Qian 2000, Argast et al. 2004, Ishimaru & Wanajo 1999, Cescutti et al 2006, Mennekens & Vanbeveren 2014, Matteucci et al. 2014, Shen et al 2014, van de Voort et al 2014.* ... (different models available currently no consensus whether the early enrichment could be due to mergers)



Argast et al. 2004
(one-zone mdoel)



Eu pure r-process element

Based on galaxy simulation, *Shen et al. 2014*

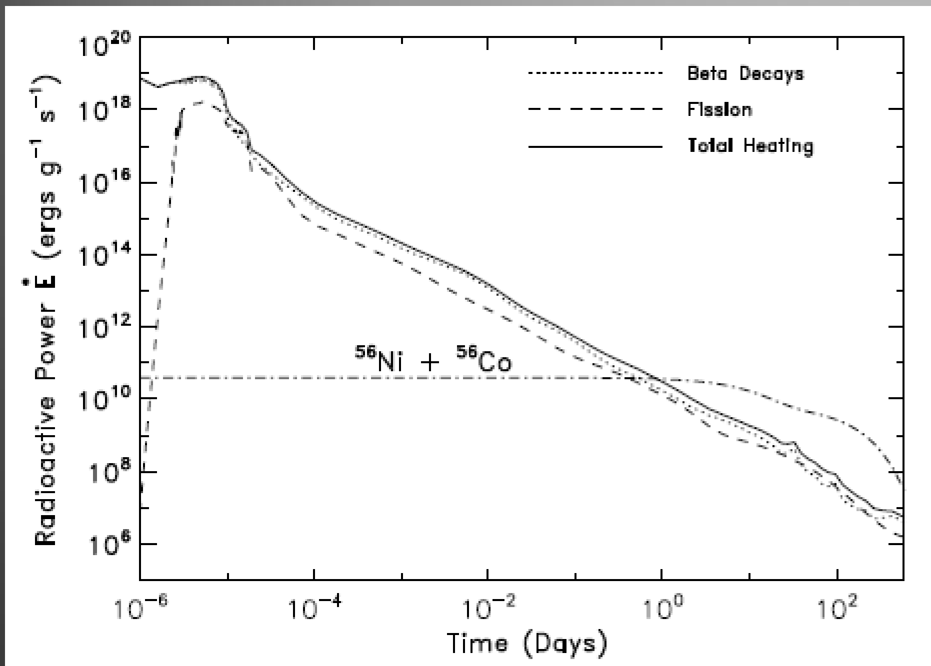
Electromagnetic counterparts

Overview: em counterparts

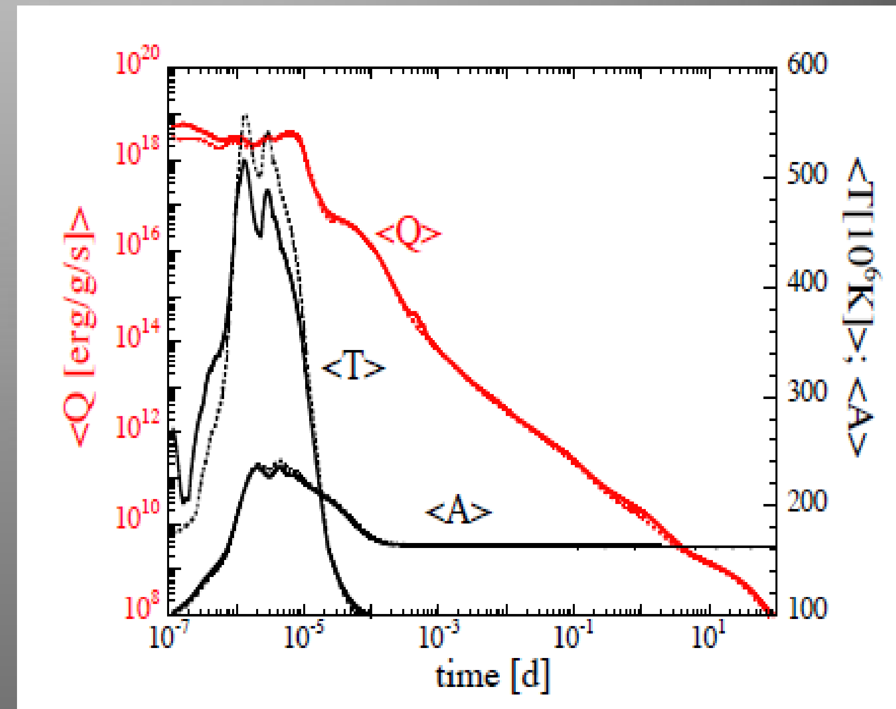
- short gamma-ray bursts (prompt emission, X-ray plateaus, afterglows, precursors) (Paczynski 1986, Eichler et al. 1989) – smoking gun = simultaneous GW detection (in particular with postmerger) (see e.g. Clark et al. 2014)
- Radioactively powered transients (Li & Paczynski 1998, Kulkarin 2005, Metzger et al. 2010, …) = kilonova, macronova
- Radio transient – synchrotron rad. (Nakar & Piran 2011, Rosswog et al. 2013, Piran et al. 2013)
- Pulsar revival (Lipunov & Panchenko 1996)
- Magnetospheric interaction → radio, x-rays (Vietri 1996, Hansen & Lyutikov 2001, Piro 2012, Lai 2012, Palenzuela et al. 2013, Paschalidis et al. 2013, Ponce et al. 2014)
- Remnant magnetic fields x-ray, optical, radio (Shibata et al. 2011, Zhang 2013, Gao et al. 2013, Rezzolla & Kumar 2014, Siegel & Ciolfi 2014)
- Crust shattering (Tsang et al. 2012)
- Ultrarelativistic shock breakout → synchrotron x-rays .. radio (Kyutoku et al. 2012)
- See also Bruno's talk

Only grouping the models (partially different mechanisms and phenomena); some work also with NSBH

Radioactive heating by r-process



Metzger et al. 2010



Goriely et al. 2011

Heating by beta-decays, fission and alpha-decays: about 3 – 4 MeV per nucleon

Most energy released within seconds

hydro models with nucleosynthesis (mostly dynamical ejecta): *Freiburghaus et al. 1999, Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011, Korobkin et al. 2012, Bauswein et al. 2013, Rosswog et al. 2013, Grossmann et al. 2013, Wanajo et al. 2014, Just et al. 2014*

Electromagnetic counterparts

Li & Paczynski 1998, Kulkarni 2005, Metzger et al. 2010

Radioactive decays during r-process (beta, alpha, fission) heat ejecta → electromagnetic thermal emission, adiabatic expansion

optically thick at early times – estimate peak properties via photon diffusion timescale

Peak luminosity:

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

Peak timescale:

$$t_{\rm peak} \approx 5 \ {\rm d} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{M_{\rm ej}}{10^{-2} M_{\odot}}\right)^{1/2}, \quad (2)$$

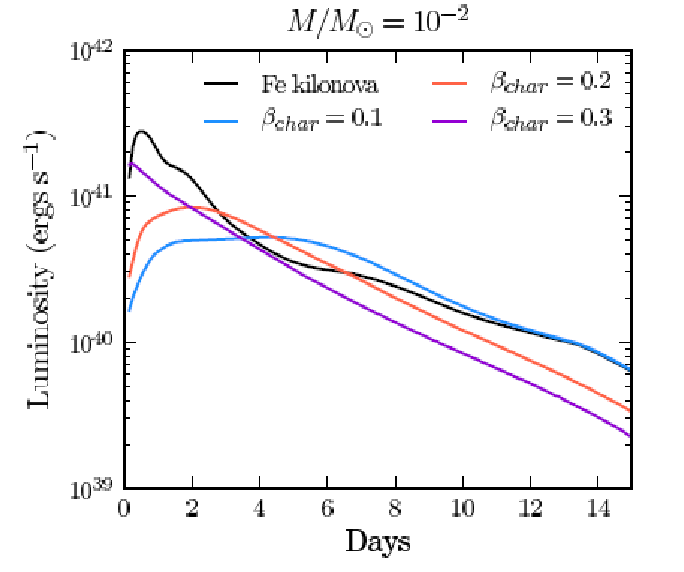
Effective temperature:

$$T_{\rm peak} \approx 0.25 \times 10^{4} {\rm K} \left(\frac{f}{10^{-6}}\right)^{1/4} \left(\frac{v}{0.1c}\right)^{-1/8} \left(\frac{M_{\rm ej}}{10^{-2} M_{\odot}}\right)^{-1/8} \quad (3)$$

Formulae adopted from Metzger et al. 2010 with high r-process opacities of r-process elements 10 cm^2/g (*see Kasen et al. 2013,Barnes & Kasen 2013, Tanaka & Hotokezaka 2013*)

Key parameters: ejecta mass, ejecta velocity, (heating efficiency)

More advanced models



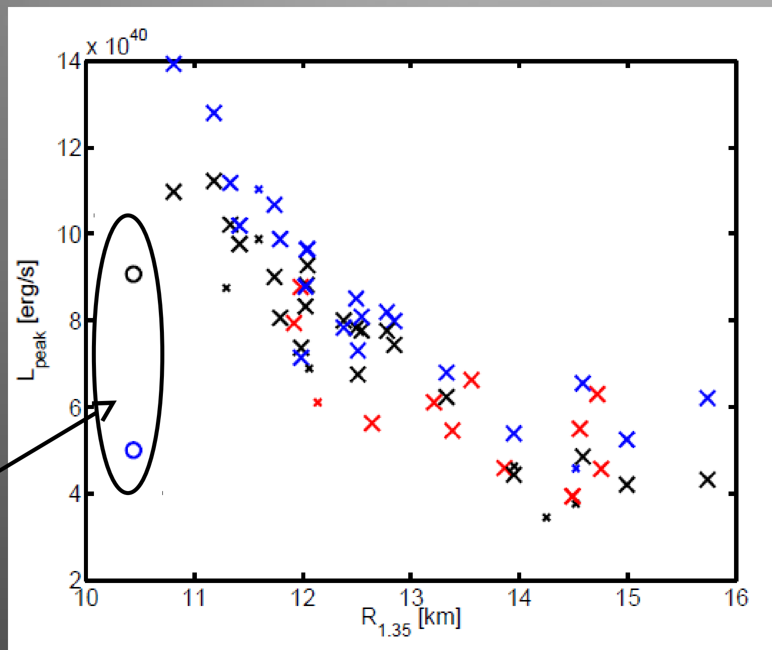
Detailed radiative transfer with r-process opacities → redder (IR) and later than originally thought, Barnes & Kasen 2013 (see also Kasen et al. 2013, Tanaka & Hotokezaka 2013)

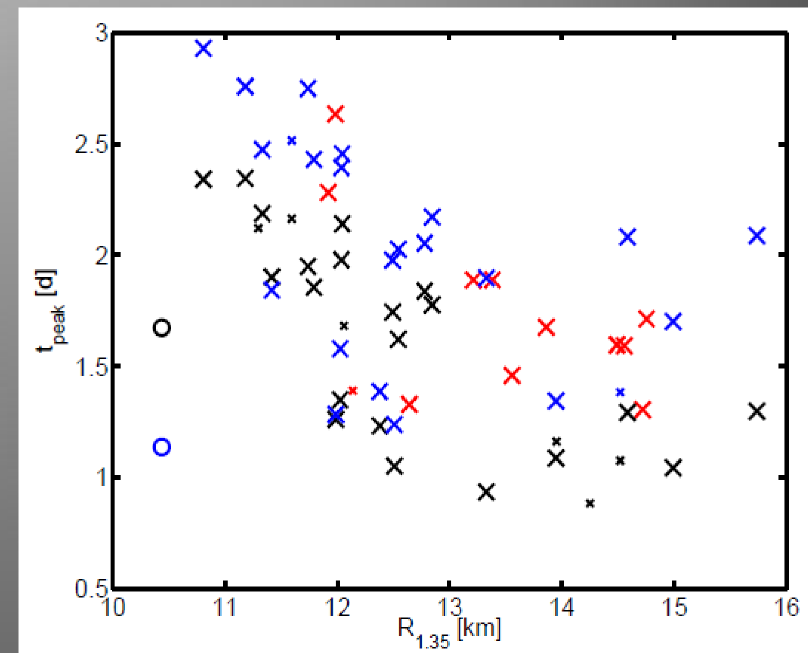
- for a delayed remnant collapse secular ejecta may lead to early blue bump (~ 6 hr) because of Lanthanide-free polar region (weak interactions) Metzger & Fernandez 2013, see also Perego et al. 2014, Kasen et al. 2014

- long-term hydrodynamical expansion models → homologous expansion (Grossmann et al. 2013, Rosswog et al. 2013)

EoS dependence

Prompt collapse





Bauswein et al. 2013

→ potential constraint for NS radius from observations

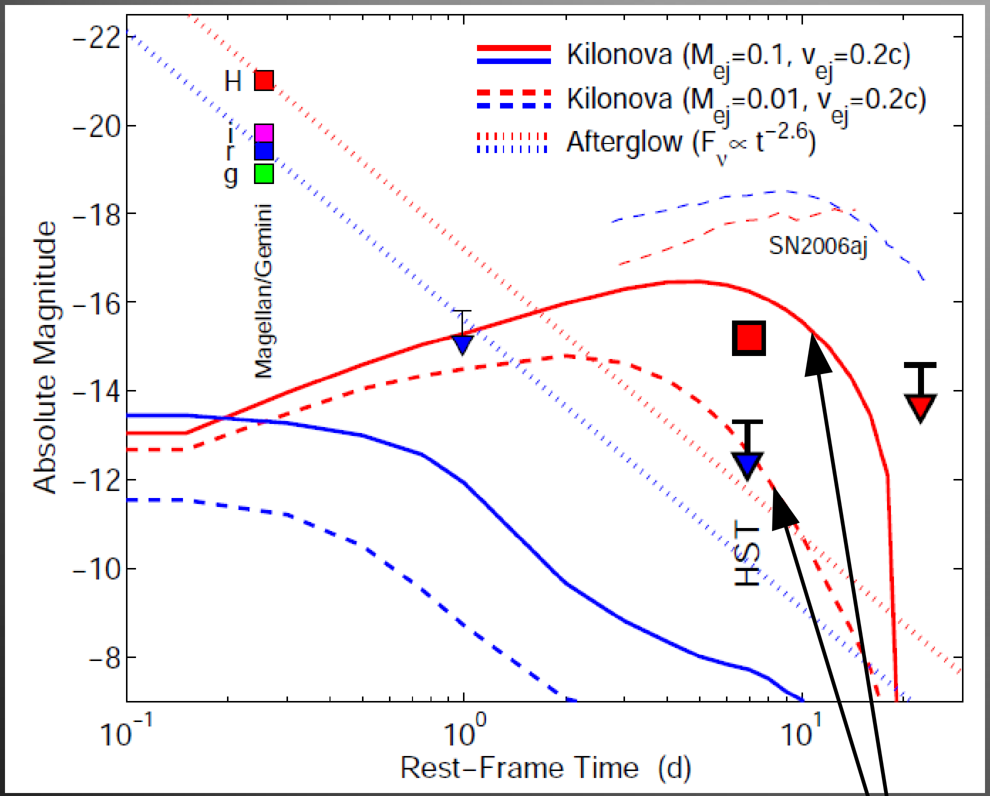
(similar findings for asymmetric binaries; also effective temperature shows characteristic behavior)

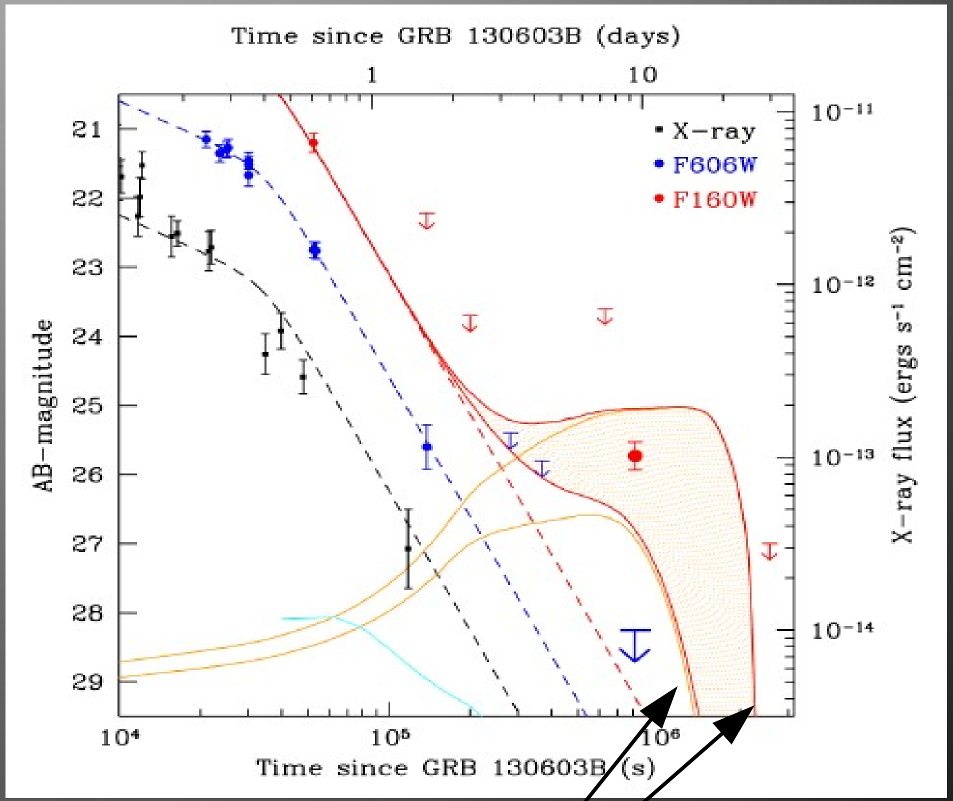
(derived from scaling models with updated opacities)

See also Hotokezaka et al. 2013, also for an interpretation in the context of GRB130603B; see Kyutoku et al. 2013, Tanaka et al. 2014 for NS-BH mergers

A possible em counterpart observation associated with GRB130603B

in near IR on top of the GRB afterglow





Gemini and HST observations
Berger et al. 2013

HST Tanvir et al. 2013

0.01 and 0.1 M_{sun} ejecta

Prospects for existing and upcoming surveys and wide-field facilities (Pan-STARRS, DECam, Subaru, LSST, ZTF, ...)

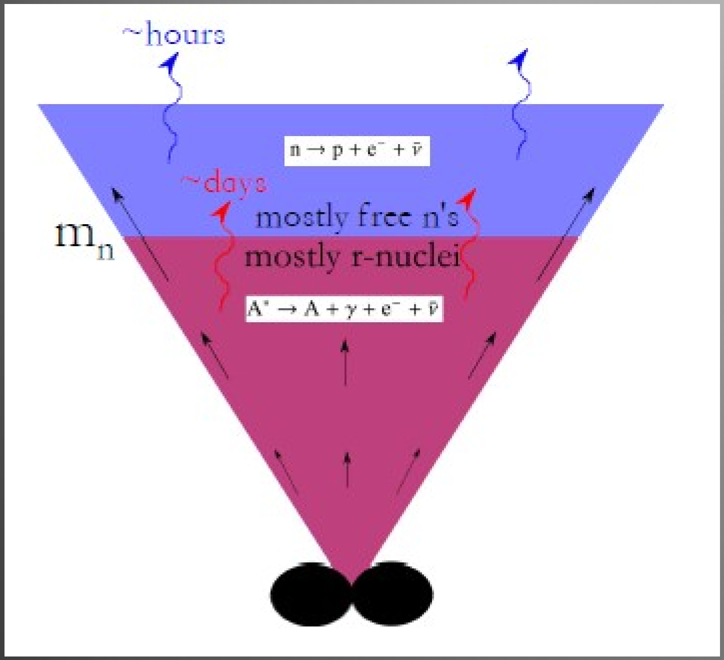
Perspective: Multimessenger

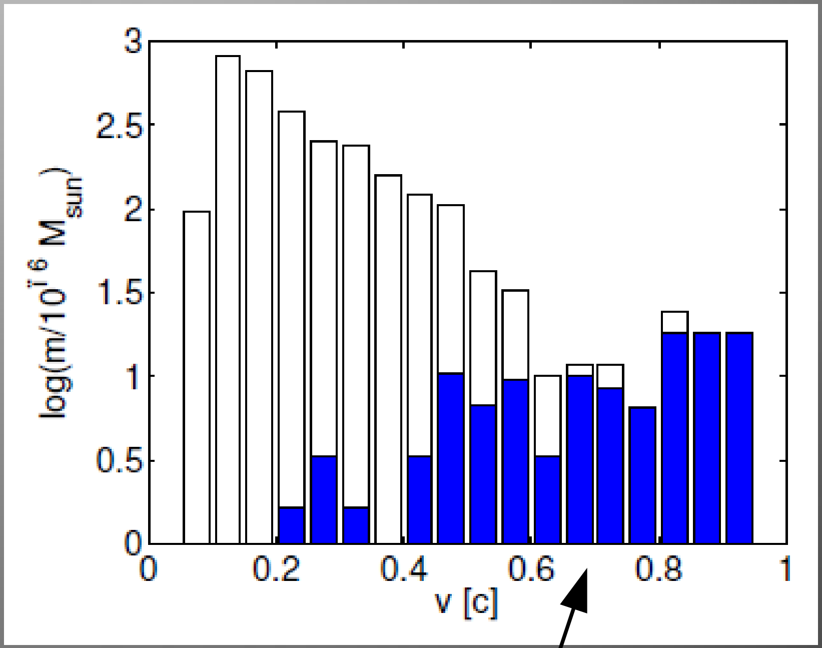
Kilonova for GW follow-up / blind survey → host galaxy, sky localization of GW events, demographics, sensitivity, interpreting kilonova properties

GW – GRB coincidence → GRB progenitor models

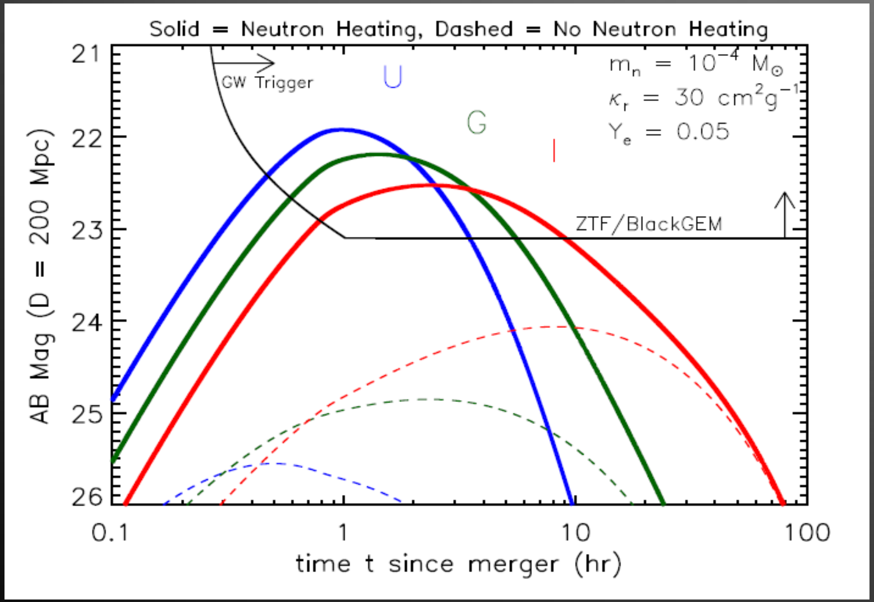
e.g. Metzger & Berger 2012, Nissanke et al. 2013, Kasliwal & Nissanke 2014, Singer et al. Clark et al. 2014, ...

Kilonova precursors





Neutrons left about 10-4 Msun



Neutron decay leads to early, bright, optical emission

→ easier to detect, interesting for GW follow up

Metzger et al. 2014

Are ejecta masses and mergers rates compatible ?

(earlier rough estimates: Lattimer & Schramm 1974, Freiburghaus et al. 1999, Qian 2000, Metzger et al. 2010, Goriely et al. 2011, Korobkin et al. 2012, Rosswog et al. 2013, Bauswein et al. 2013, Piran et al. 2014)

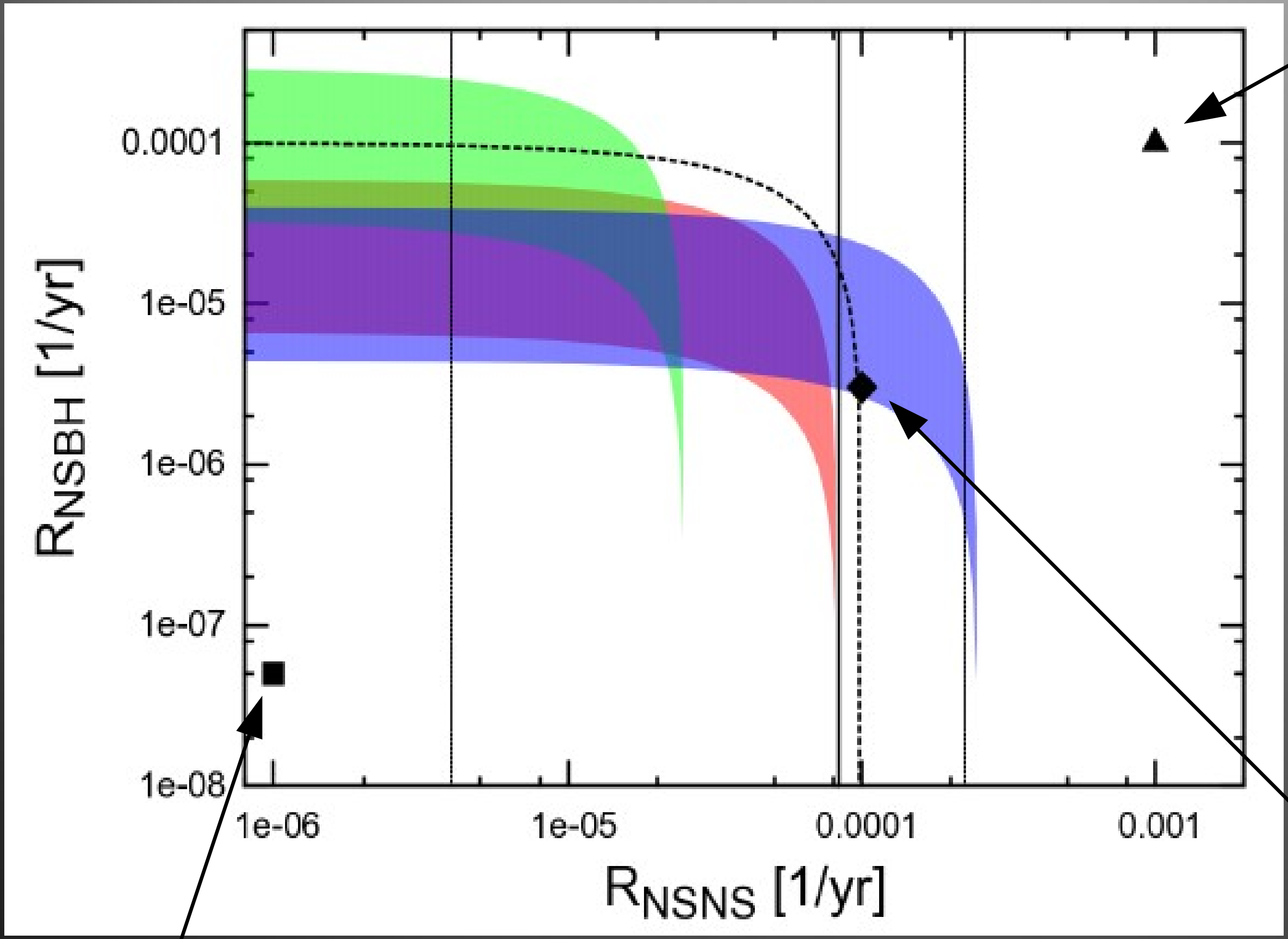
Consider observed amount of r-process elements → derive merger rates from know ejecta masses → uncertainty factor of a few (detailed analysis, Bauswein et al. 2014)

→ mergers are compatible with being the dominant source of r-process elements

→ in turn one can estimate merger rates assuming that all r-process matter was produced by mergers (→ GW and counterpart detection rates)

Galactic merger rates

40 detections per yr (with Ad. LIGO-Virgo network)



Optimistic detection rate (ruled out by our study, but compatible with constraints from recent science runs)

10 detections per yr

“realistic” detection rate

Bauswein et al. 2014

Pessimistic detection rate (only if additional r-process source)

Symbols taken from Abadie et al. (2010) (complied mostly from pop. synthesis studies)

Summary, conclusions, outlook

Ejecta is robustly produced in binary mergers

Heavy r-process elements are robustly produced (solar abundance)

Compatible with mergers being the dominant source of heavy r-process elements

Merger remnants produce additional ejecta by secular processes

Different types of counterparts discussed

Radioactively powered em counterparts are expected

Emission properties encode bin. para, EoS

Possible detection of a counterpart (GRB130603B)

early, bright, optical emission by neutron decay

Perspective for multimessenger astronomy

…. and