Kilonova: An electromagnetic signal of heavy element nucleosynthesis

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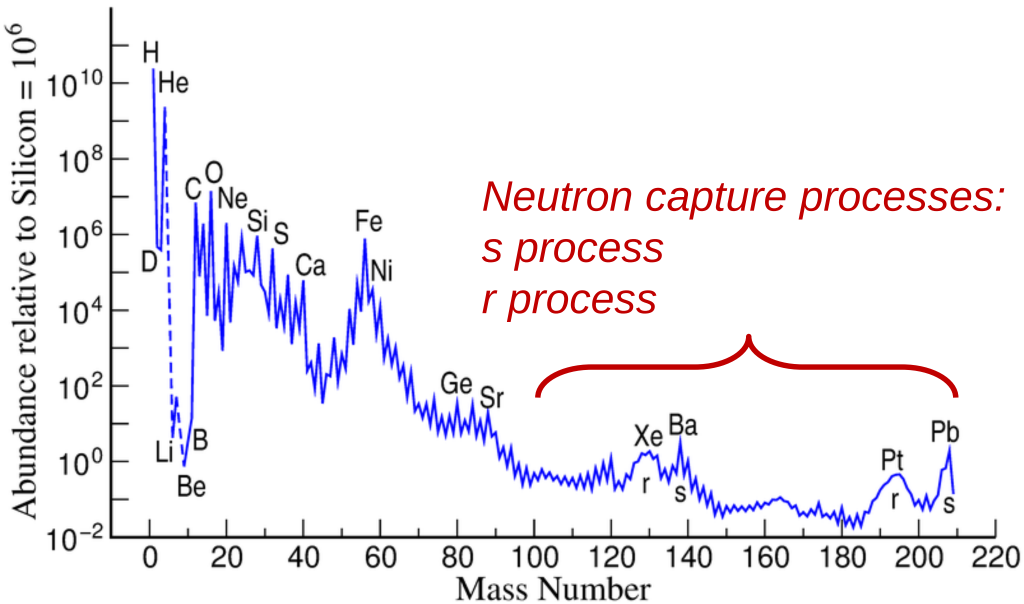
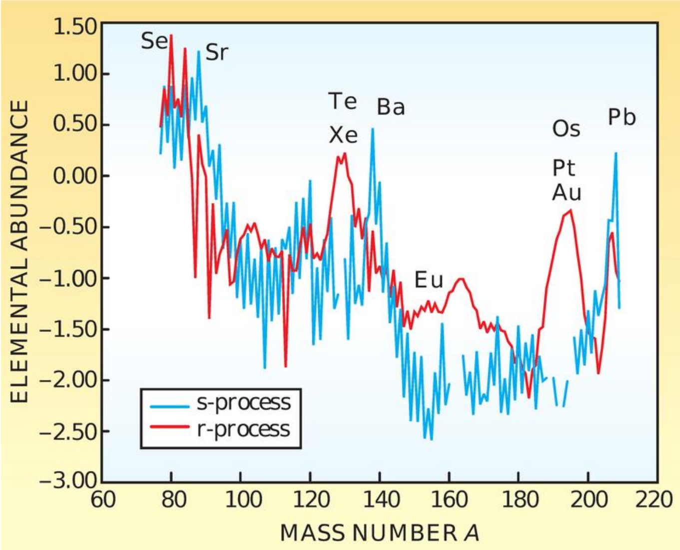
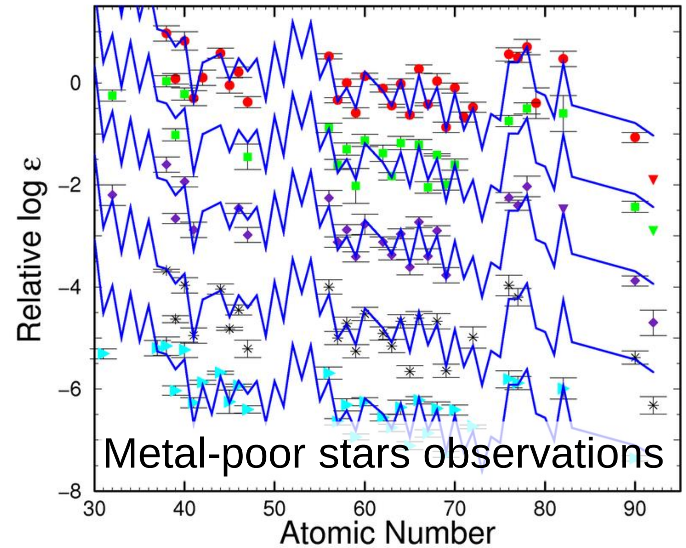
(Structure and Reactions for Nuclear Astrophysics, Strasbourg, 22-24 November 2017)

Signatures of nucleosynthesis







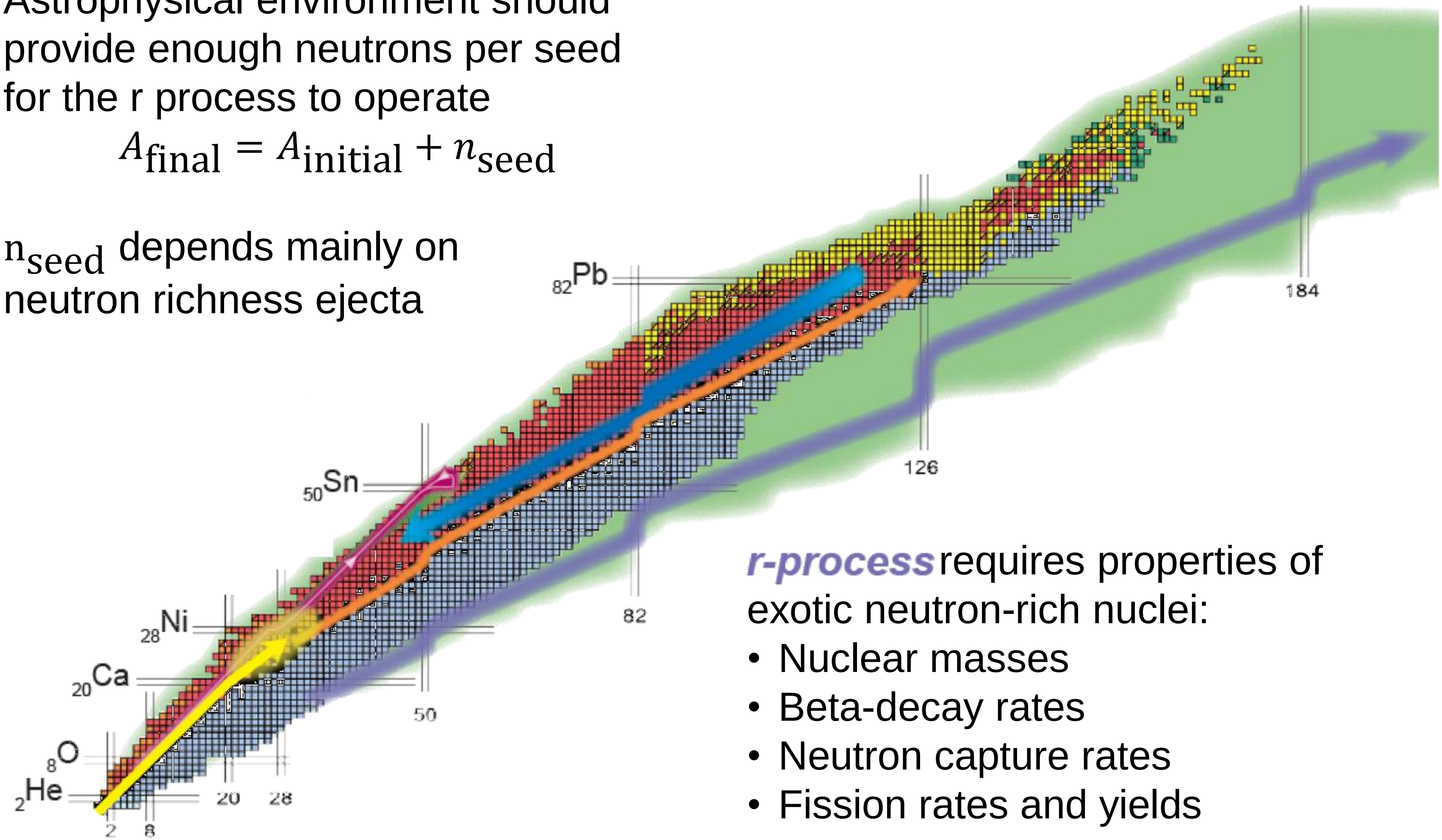
- Heavy elements produced in neutron capture processes
- r process operates at early Galactic history
- Observations favor a low frequency/high yield site

R process nuclear needs

Astrophysical environment should provide enough neutrons per seed for the r process to operate

$$A_{\mathrm{final}} = A_{\mathrm{initial}} + n_{\mathrm{seed}}$$

n_{seed} depends mainly on neutron richness ejecta

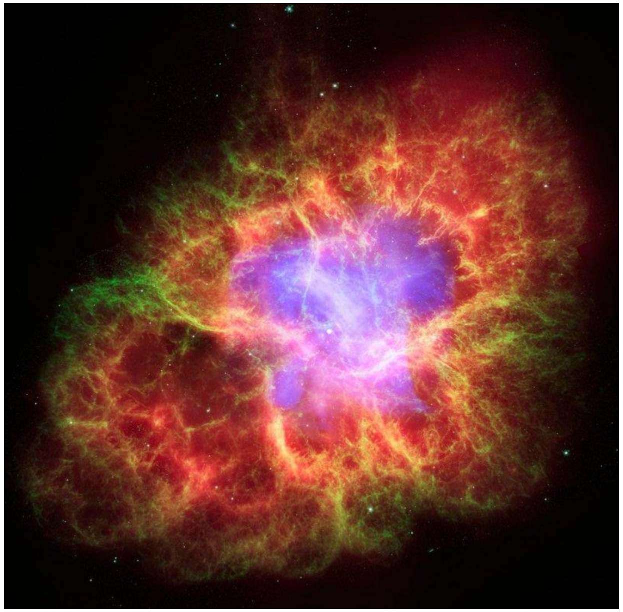


r-process requires properties of exotic neutron-rich nuclei:

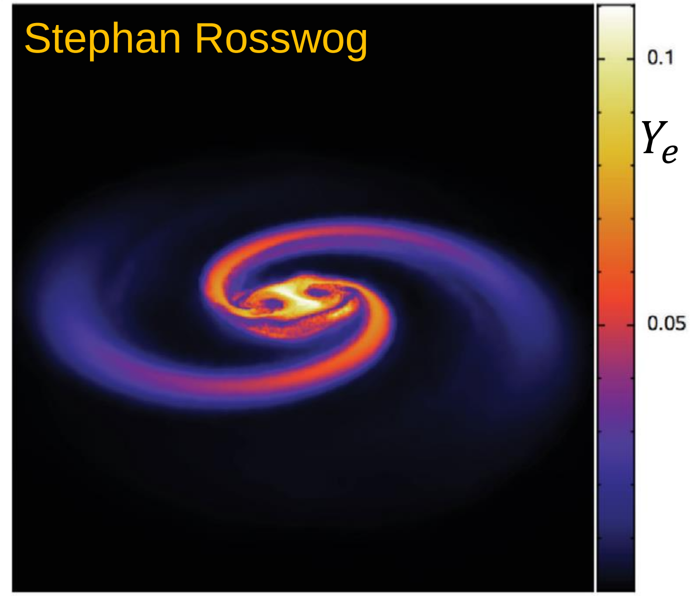
- Nuclear masses
- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

Astrophysical sites

Core-collapse supernova



Compact binary mergers

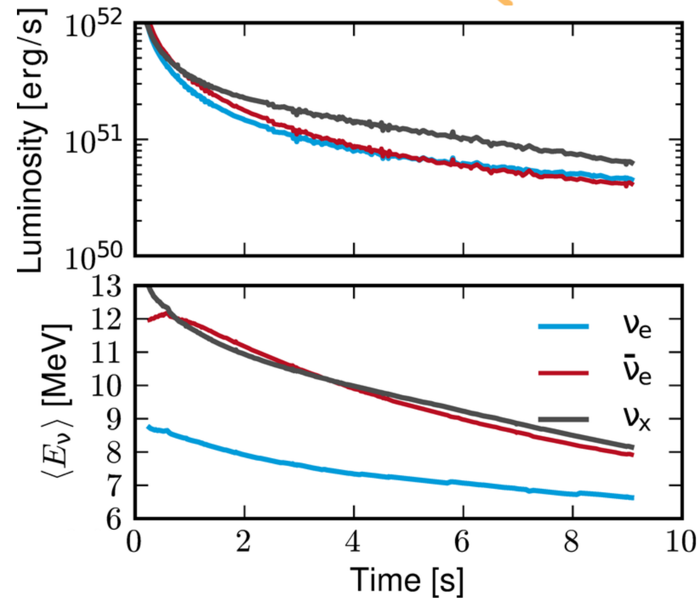


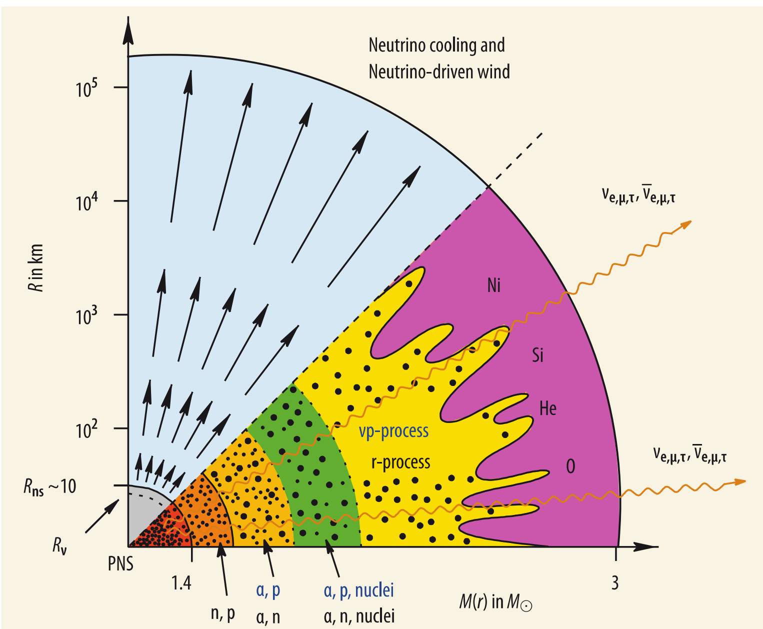
	Supernova	Mergers
Optimal conditions	☹	☺
Yield / Frequency	😐	☺
Direct signature	☹	☺

Supernova nucleosynthesis

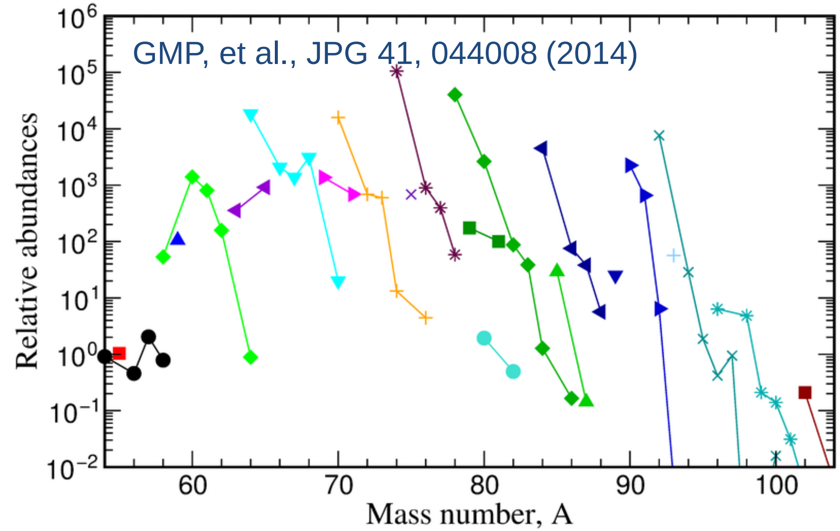
Heavy elements produced in neutrino winds from protoneutron star cooling. Neutrino interactions determine proton-to-nucleon ratio, Y_e

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$





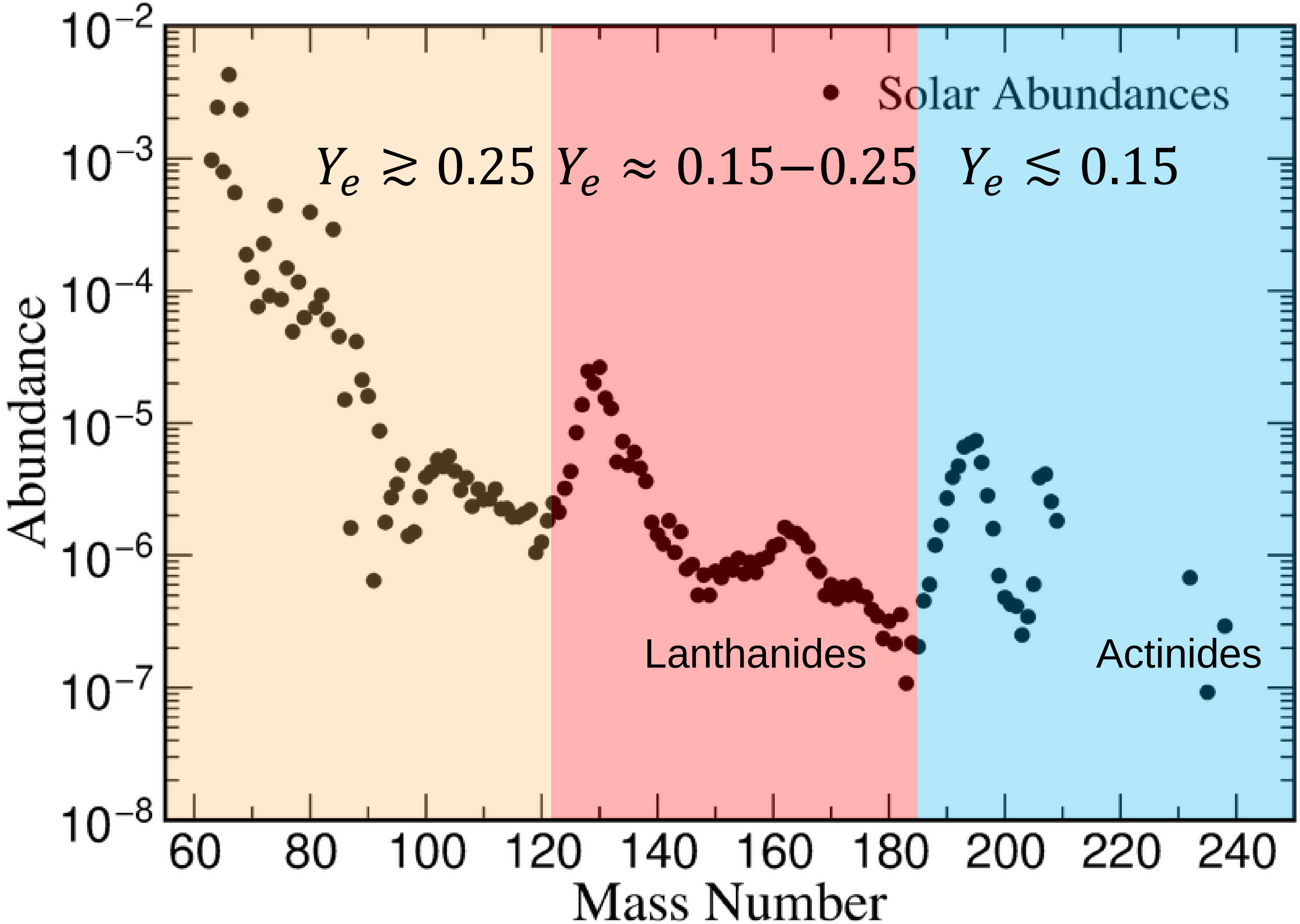
Supernova produce only medium mass nuclei



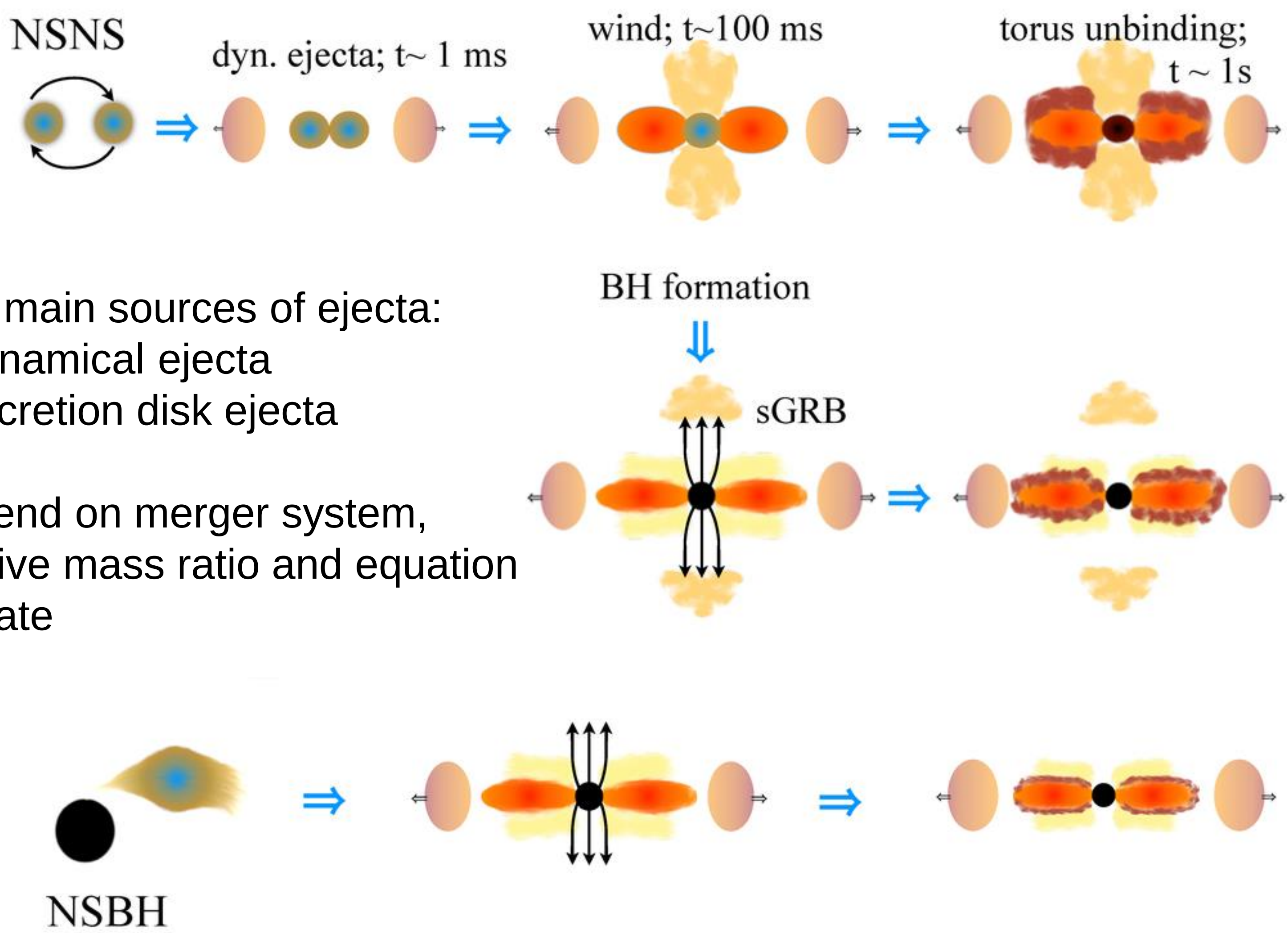
Nucleosynthesis dependence on Y_e

Nucleosynthesis mainly sensitive to proton-to-nucleon ratio, Y_e

$\nu_e + n \rightleftarrows p + e^-$ vs $\bar{\nu}_e + p \rightleftarrows n + e^+$



Mergers: variety of ejecta



Two main sources of ejecta:

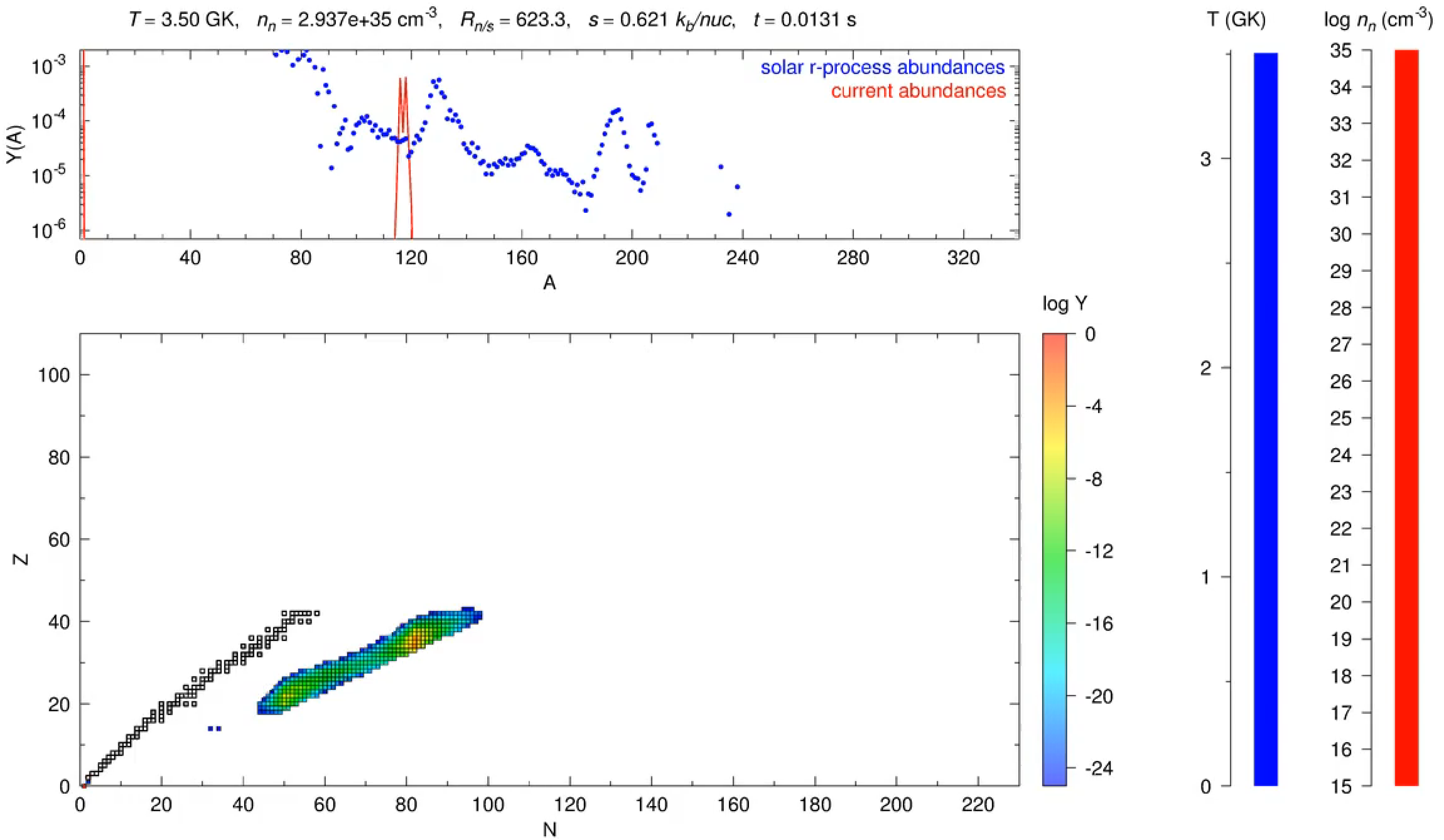
- Dynamical ejecta
- Accretion disk ejecta

Depend on merger system, relative mass ratio and equation of state

S. Rosswog, et al, Class. Quantum Gravity 34, 104001 (2017).

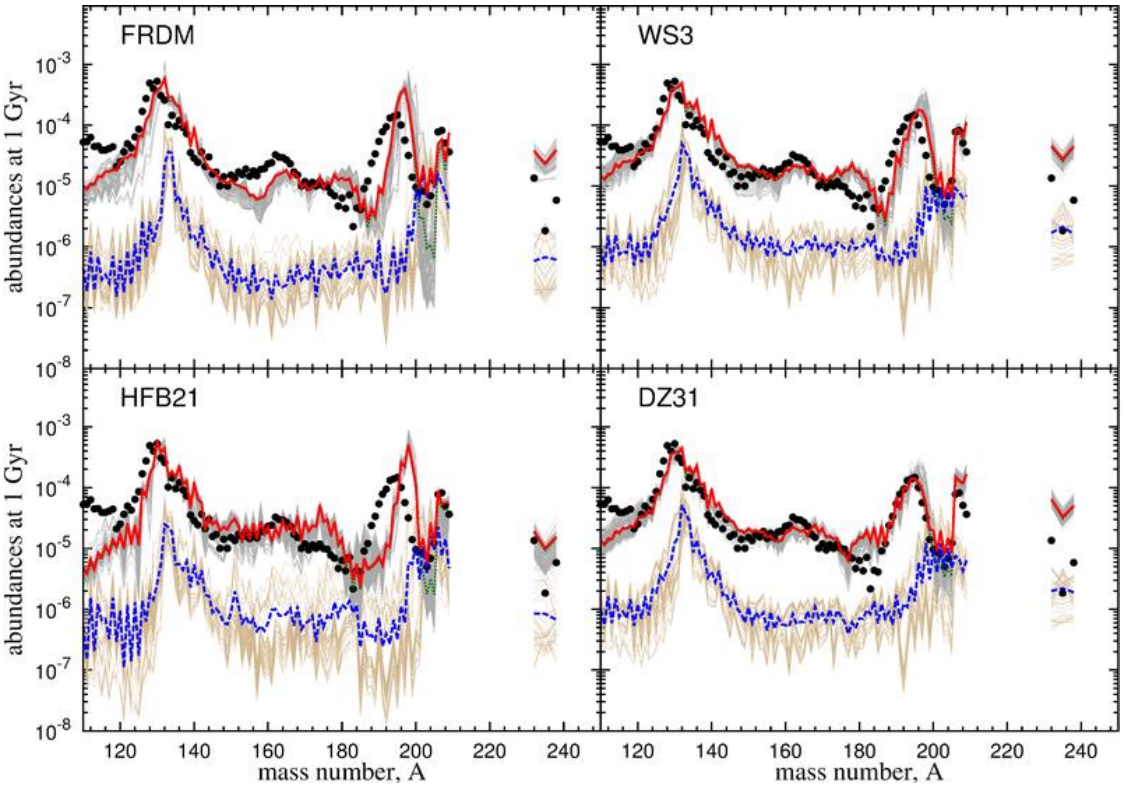
Neutron rich ejecta

BH-NS ejecta and NS-NS ejecta in the equatorial plane is very neutron rich

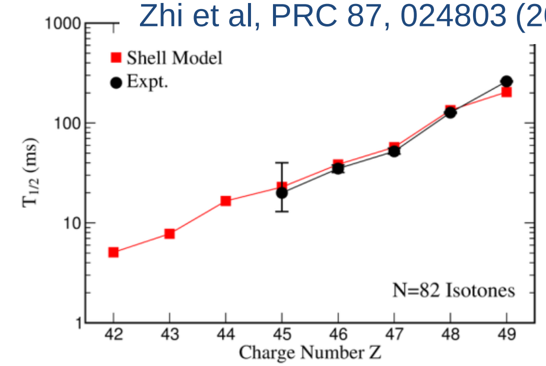


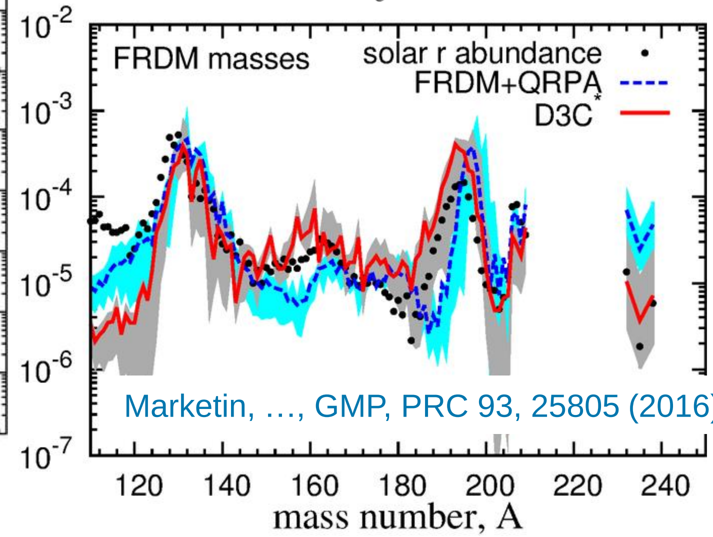
Dependence on nuclear masses

Mendoza-Temis, et al, PRC 92, 055805 (2015)



Zhi et al, PRC 87, 024803 (2013)



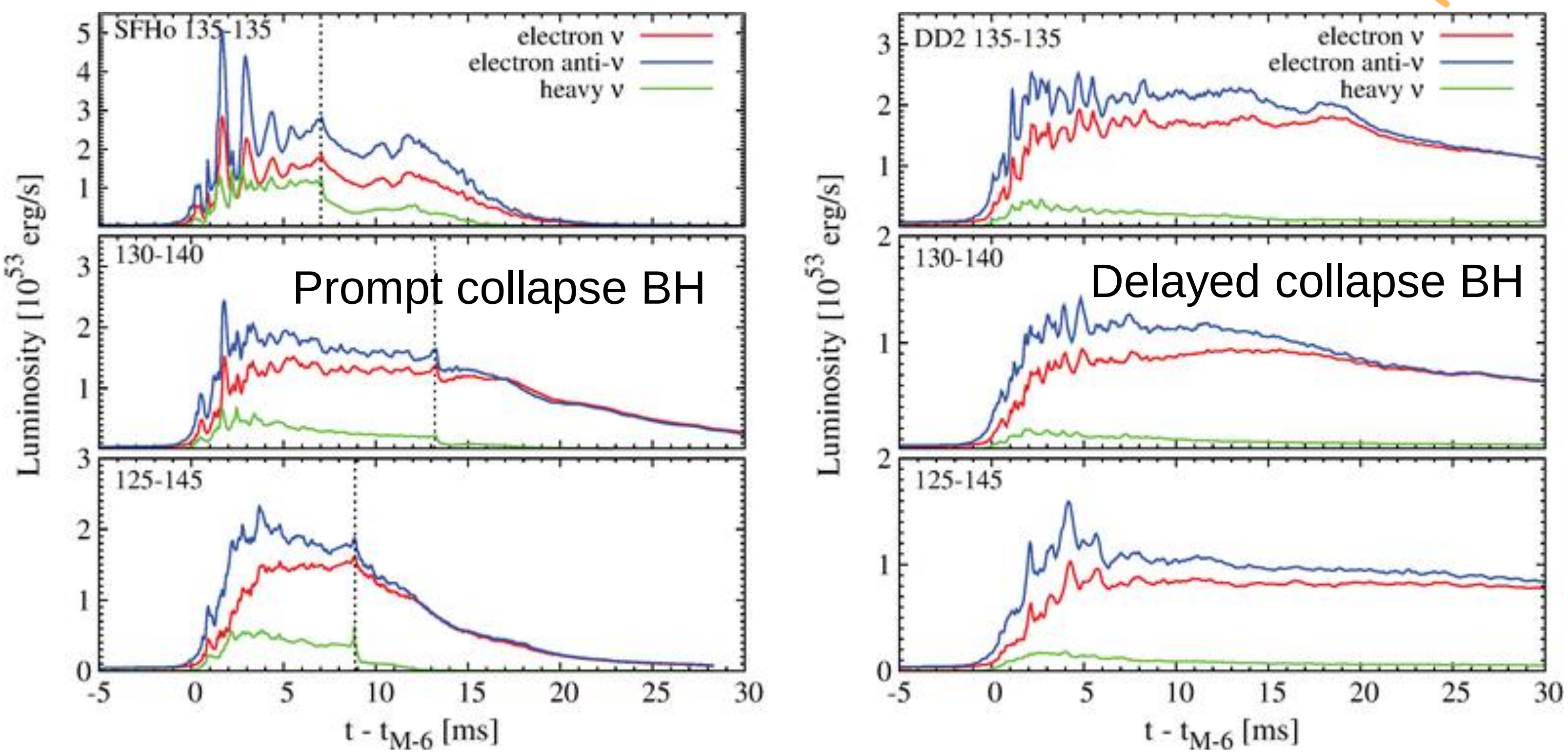


Marketin, …, GMP, PRC 93, 25805 (2016)

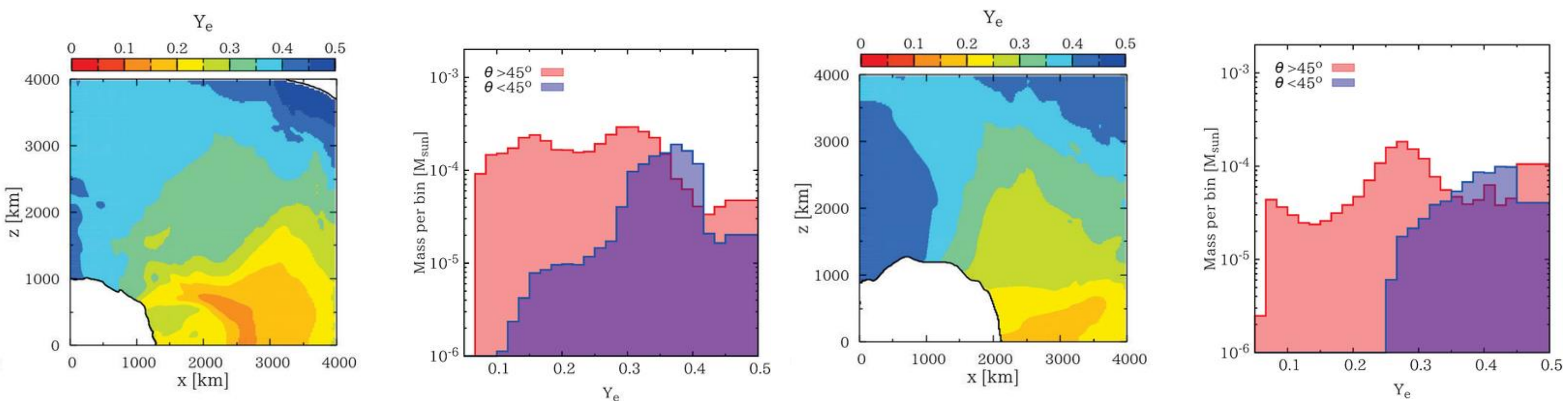
- Robustness astrophysical conditions, sensitive nuclear physics
- Second peak (A ~ 120) sensitive to fission yields
- Third peak (A ~ 195) sensitive to masses and half-lives
- Elements lighter than A ~ 120 are not produced

Impact of neutrinos on NS-NS mergers

Sekiguchi, et al, 2016



Shibata, et al, 2017

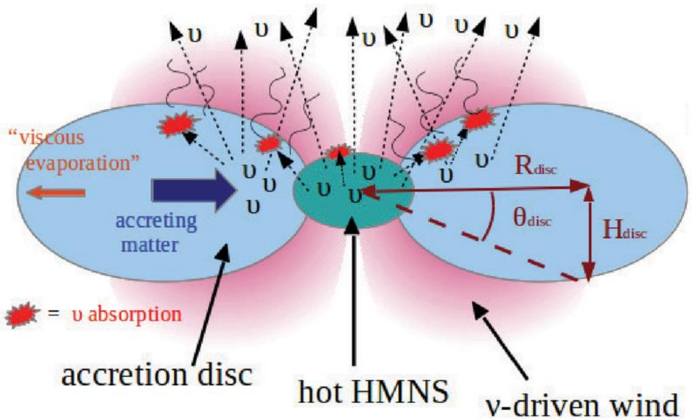


HELMHOLTZ

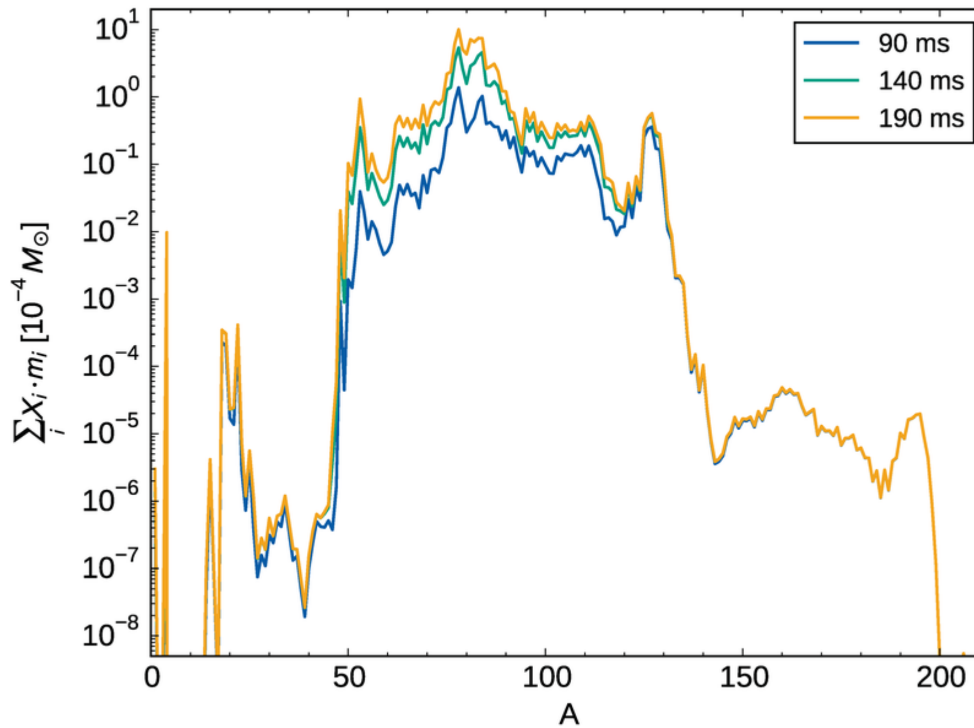
Nucleosynthesis delayed BH case

An HyperMassive Neutron Star produces large neutrino fluxes that drive the nucleosynthesis to light elements

Perego, et al, MNRAS 443, 3134 (2014)



Martin, et al, ApJ 813, 2 (2015)

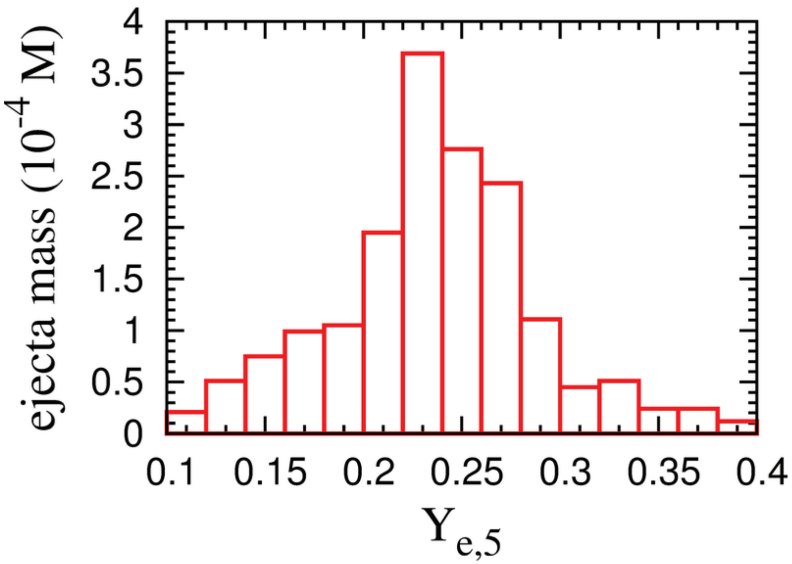


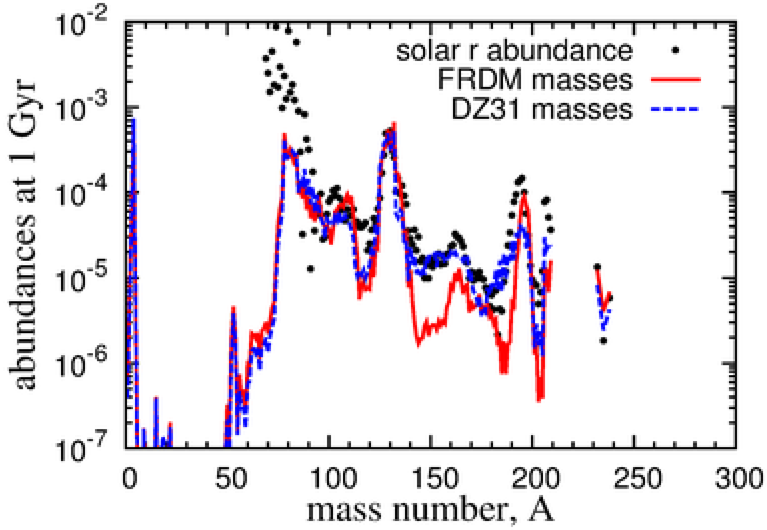
Up to 0.01 $M_\odot$ are ejected.

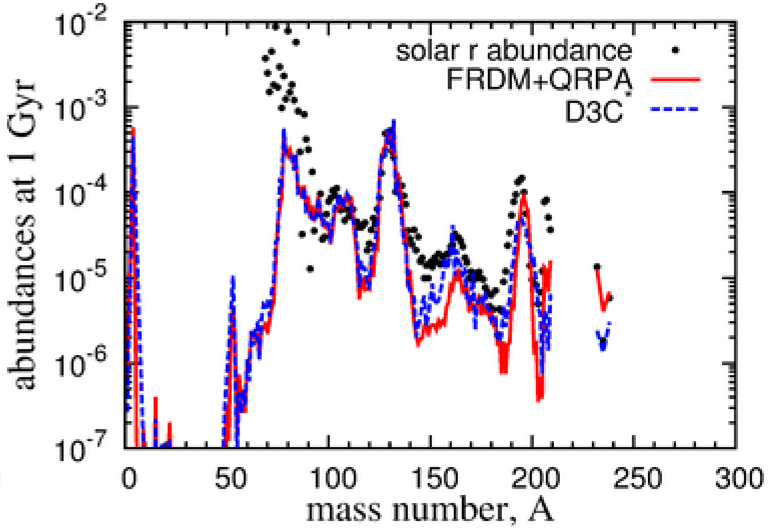
No Lanthanides are produced

Nucleosynthesis after BH formation

- Accretion disk around BH ejects relatively neutron rich matter
  [Fernández & Metzger, MNRAS 435, 502 (2013)]
- Produces all r-process nuclides (Lanthanide rich ejecta)
  [Wu et al, MNRAS 463, 2323 (2016)]

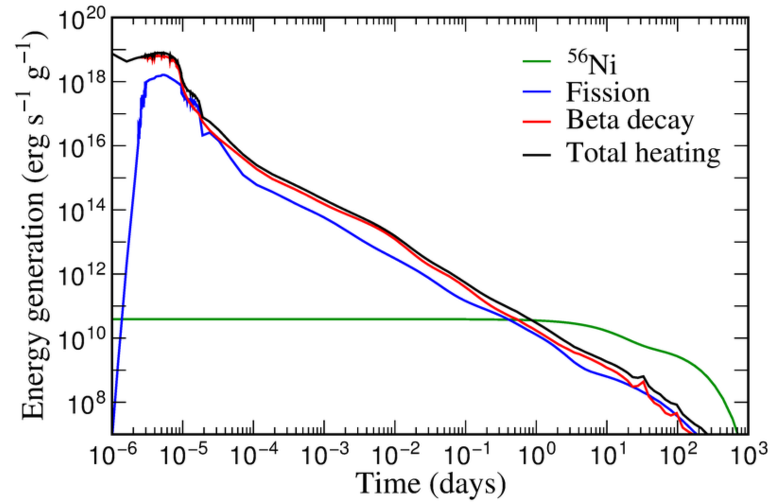


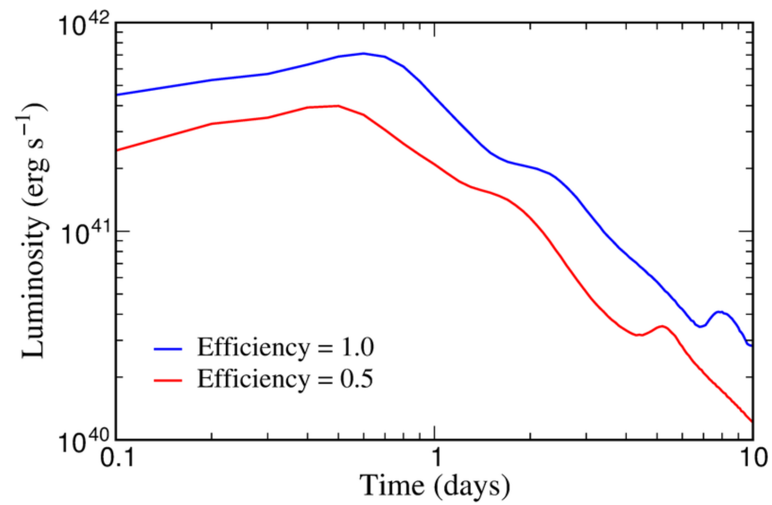




Kilonova: Electromagnetic signature of the r process

- Ejecta produces electromagnetic signatures [Li & Paczyński 1998]
- Transient due to radioactive decay of r-process nuclei [Metzger et al, 2010]
  Heating: $\dot{\varepsilon} \sim t^{-1.3}$
  Luminosity like 1000 novas: Kilonova
  Peak on timescales days in optical/blue
- Presence of Lanthanides reduces luminosity and delays peak to ~ week in red/infrared [Barnes & Kasen, 2013]
- Similar effect due to Actinides [Mendoza-Temis et al, 2015]
- Accurate treatment of thermalization of radioactive products [Barnes, et al, 2016]
- INT Program on "Electromagnetic Signatures of r-process Nucleosynthesis in Neutron Star Binary Mergers" (July 24 – August 18, 2017) [Fernández, Kasen, GMP, Metzger]

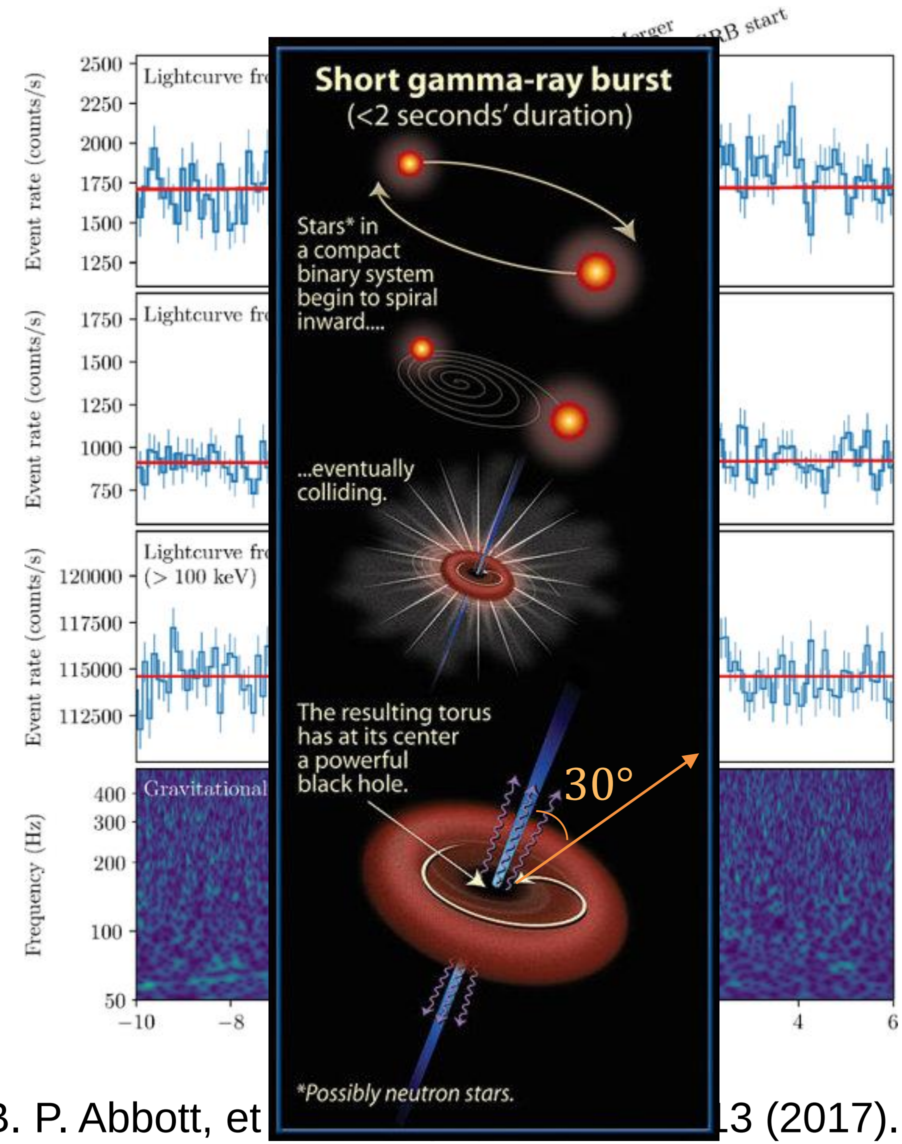




Metzger, GMP, Darbha, Quataert, Arcones et al, MNRAS 406, 2650 (2010)

GW170817: A big reveal from the cosmos

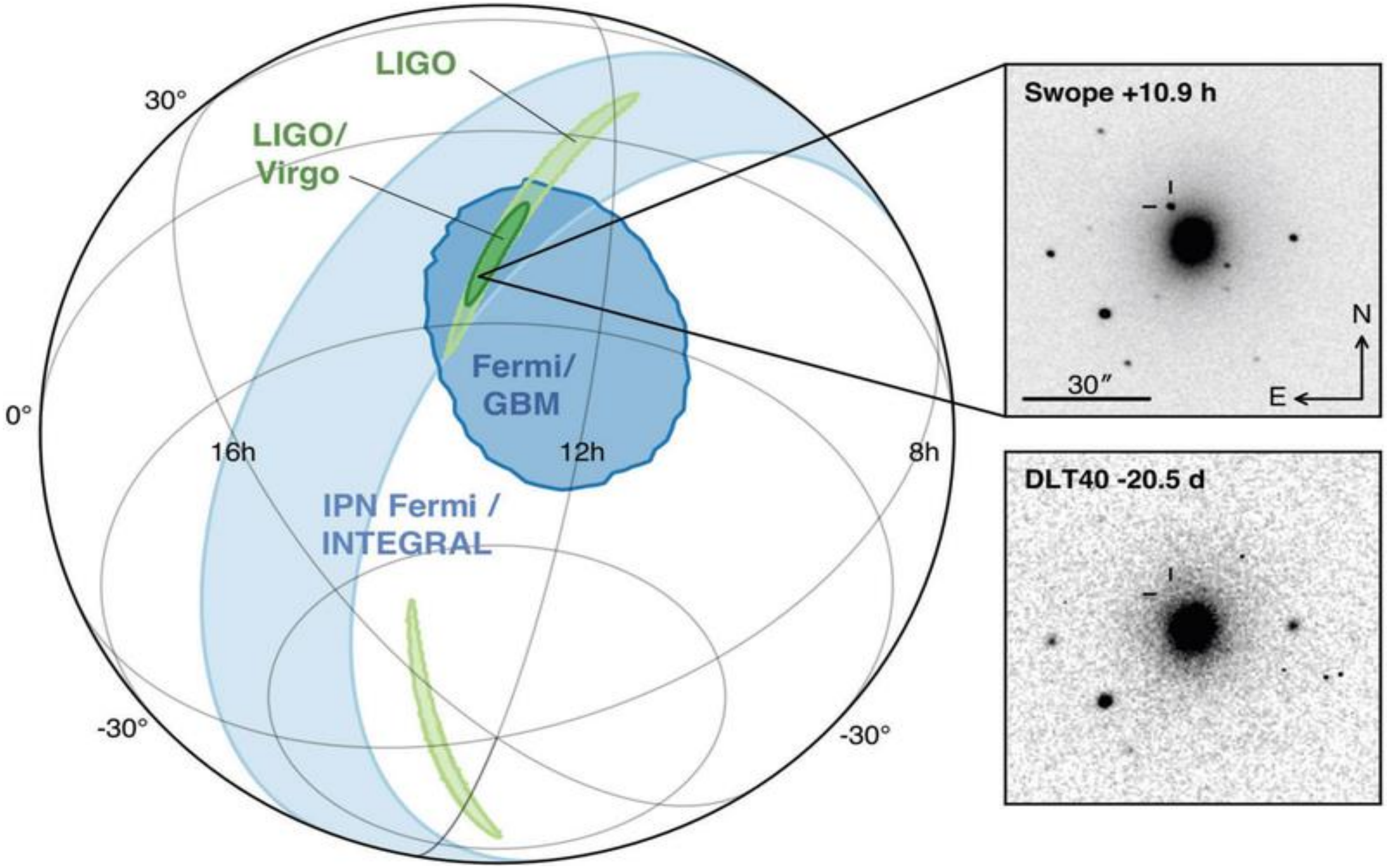
- On August 17, 12:41:04 UTC advanced LIGO and Virgo detect the first GW signal from a binary neutron star inspiral
- Key properties
  Chirp mass: $\mathcal{M} = 1.188^{+0.004}_{-0.002}\ \mathrm{M}_{\odot}$
  Total mass: $M = 2.74^{+0.04}_{-0.01}\ \mathrm{M}_{\odot}$
  Primary mass: $m_1 \in (1.36\text{–}1.60)\ \mathrm{M}_{\odot}$
  Secon. mass: $m_2 \in (1.17\text{–}1.36)\ \mathrm{M}_{\odot}$
  Distance: 40^{+8}_{-14} Mpc
- 1.7 s later Fermi and INTEGRAL detected the short GRB 170817 A
- Despite being the closest SGRB is 2-6 order of magnitude weaker than typical SGRBs.
- Explained assuming jet forms ~ 30° with line of view.
- Combined analysis favors formation BH on timescales $\lesssim 100$ ms.



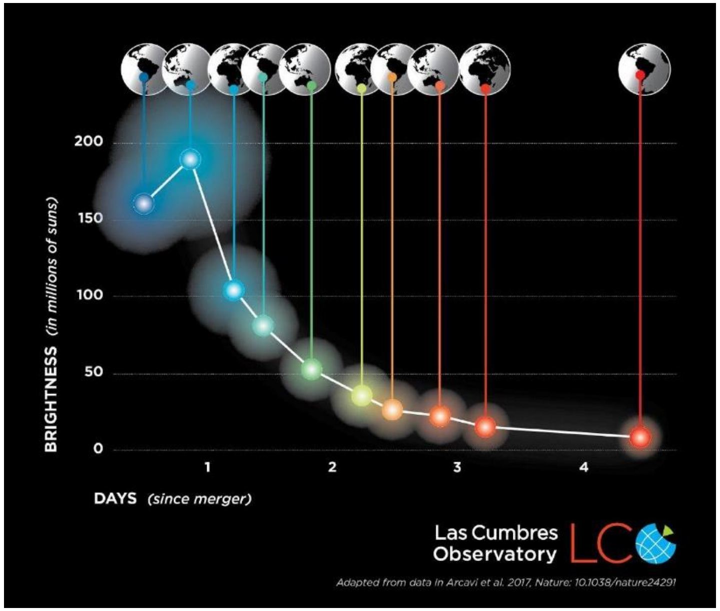
B. P. Abbott, et ... 13 (2017).

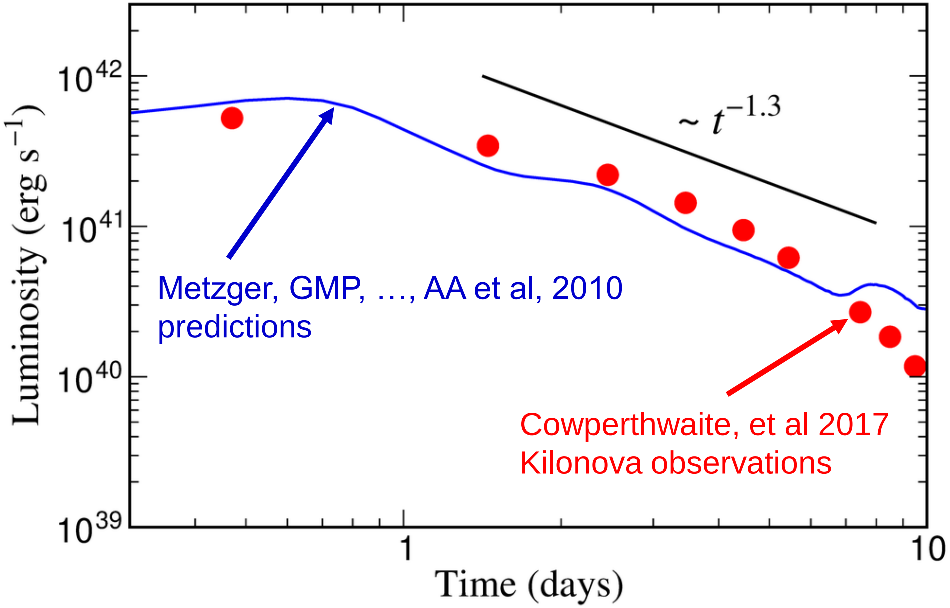
Optical transient identified

Kilonova identified 10.9 hours after the merger in the Galaxy NGC 4993 near the constellation of Hydra (Southern hemisphere)



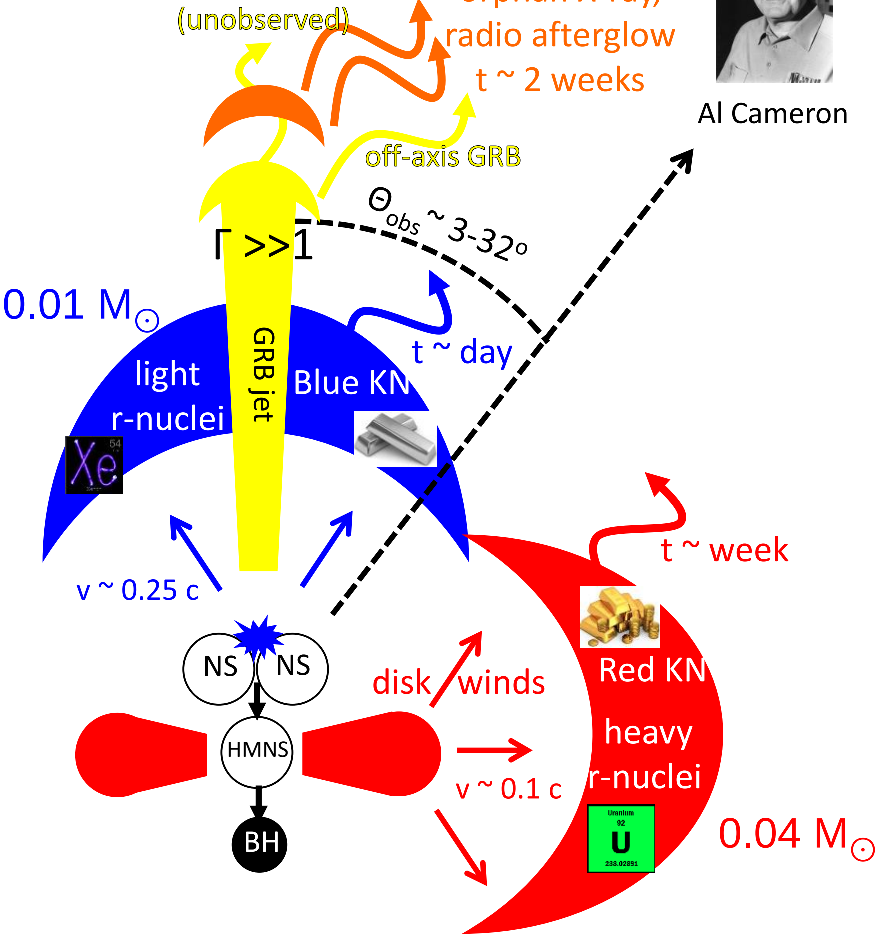
Kilonova: An electromagnetic signal of r-process nucleosynthesis





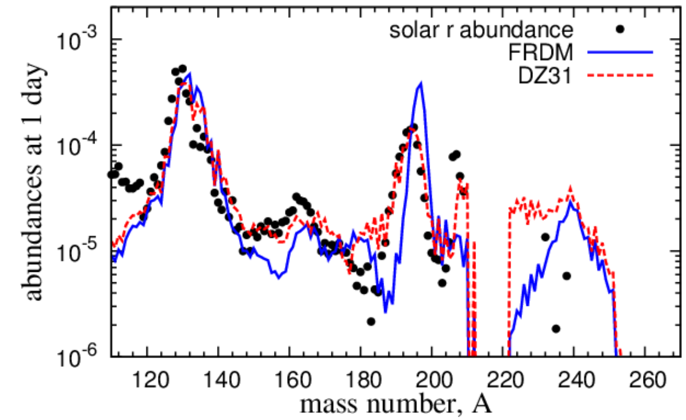
- Time evolution determined by the radioactive decay of r-process nuclei
- Two components:
  - blue dominated by light elements (Z < 50)
  - Red due to presence of lanthanides (Z = 57-71) and/or Actinides (Z = 89-103)
- Likely source of heavy elements including Gold, Platinum and Uranium

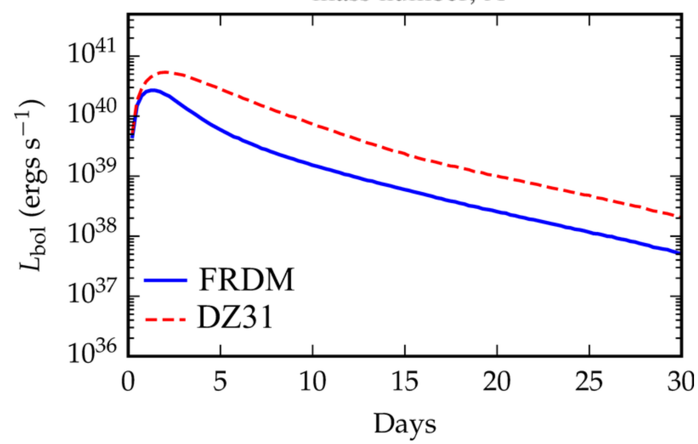
Unified scenario EM counterparts



Al Cameron

- Late red emission is interpreted as due to Lanthanides (A ~140). No direct evidence of heavier elements.
- Is there a signature of Actinide production?





Barnes, Kasen, Wu, GMP, ApJ 829, 110 (2016)

Sketch from B. Metzger

Luminosity sensitive abundances alpha decaying Actinides

Summary

- Kilonova from GW170817 originates from the radioactive decay of heavy elements
- Signature of r-process nucleosynthesis in ejecta from neutron star mergers
- Astrophysical site of the r process is identified
- Further observations necessary to confirm the expected large variability depending on the merging system and viewing angle.