R-process nucleosynthesis and its electromagnetic signature

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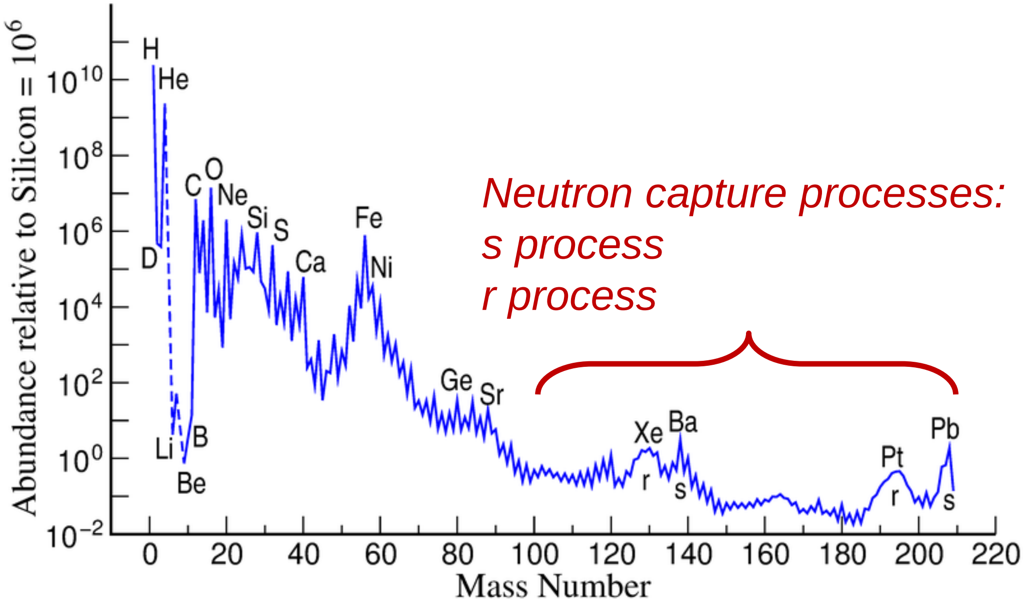
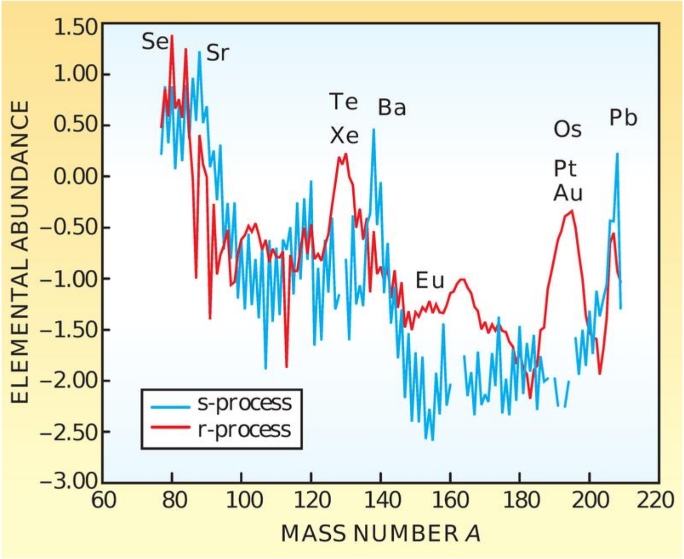
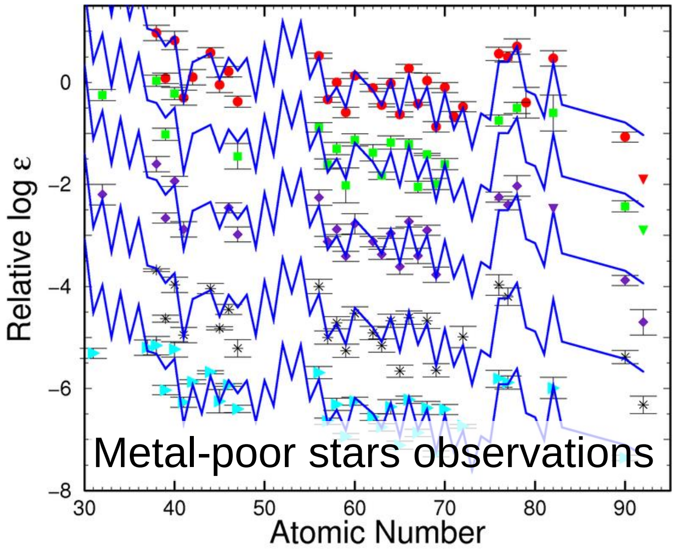
Discoveries and Open Puzzles in Particle Physics and Gravitation,
Humboldt Kolleg June 23-28, 2019, Kitzbühel

Signatures of nucleosynthesis



Neutron capture processes:
s process
r process





Metal-poor stars observations

- Heavy elements produced in neutron capture processes
- Observations indicate that r process operates from early Galactic history in rare (high yield) events

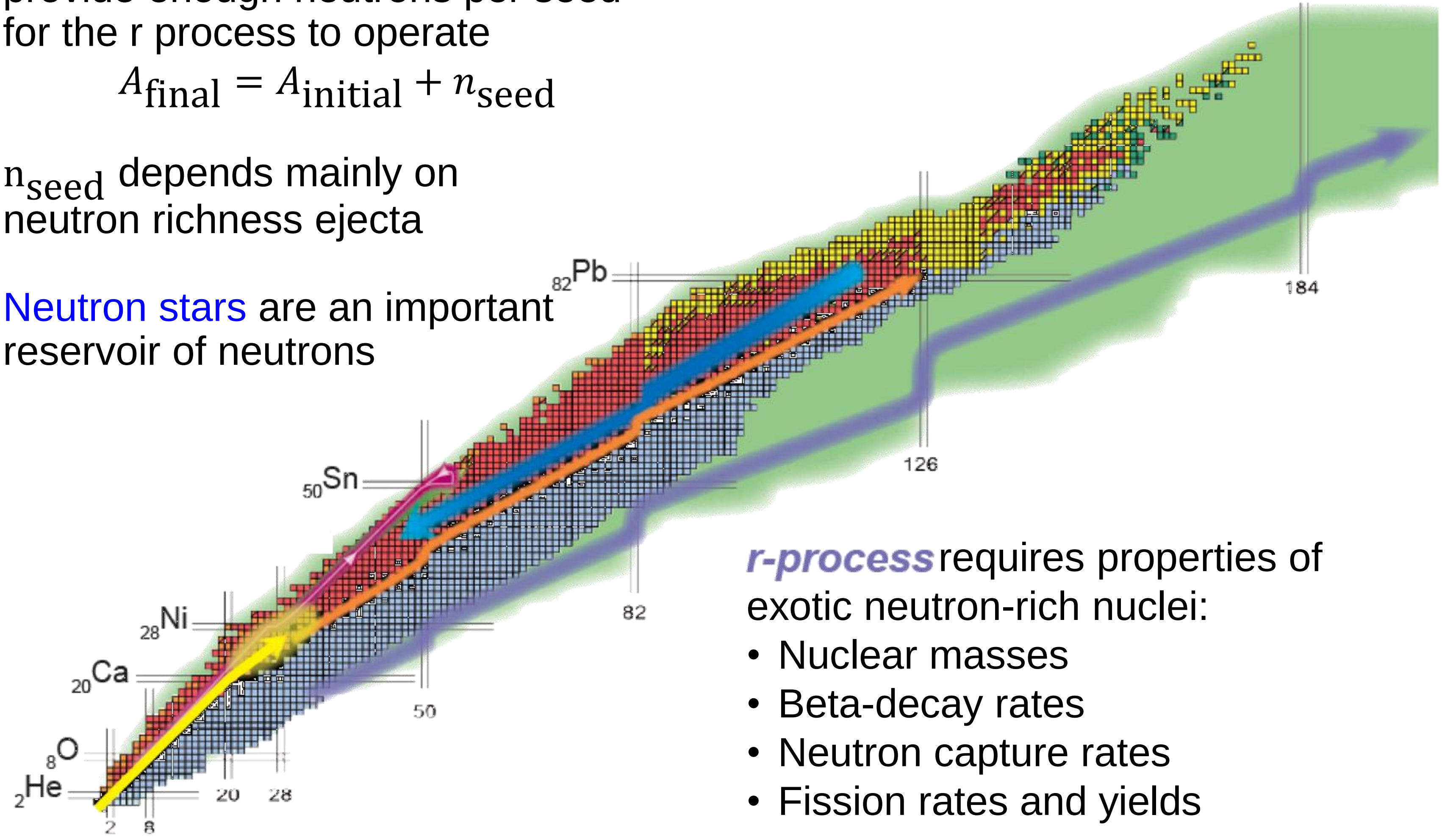
R process nuclear needs

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

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

n_{seed} depends mainly on neutron richness ejecta

Neutron stars are an important reservoir of neutrons



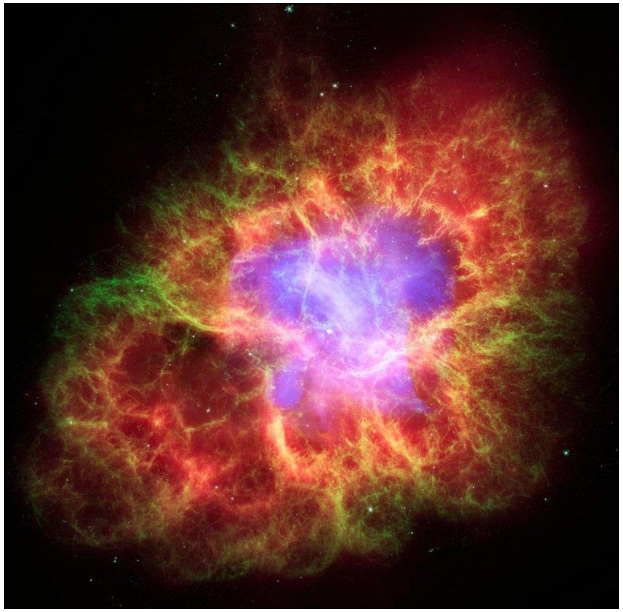
r-process requires properties of exotic neutron-rich nuclei:

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

Astrophysical sites

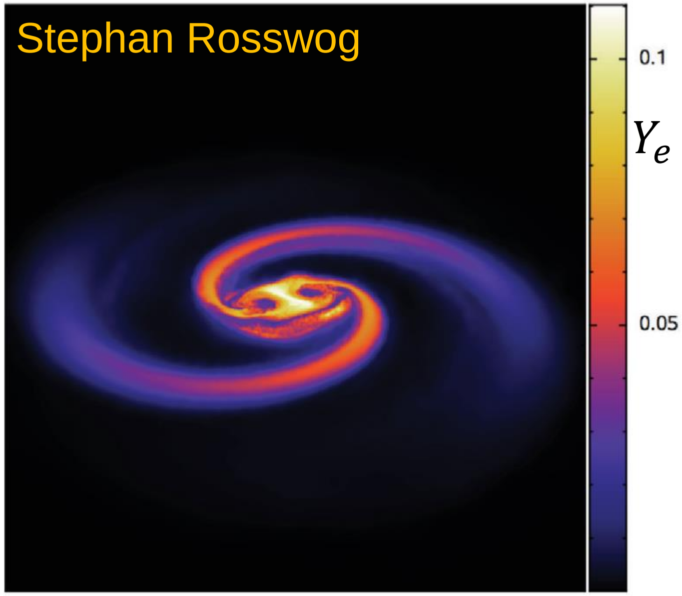
Core-collapse supernova

Woosley+ 94, Takahashi+ 94



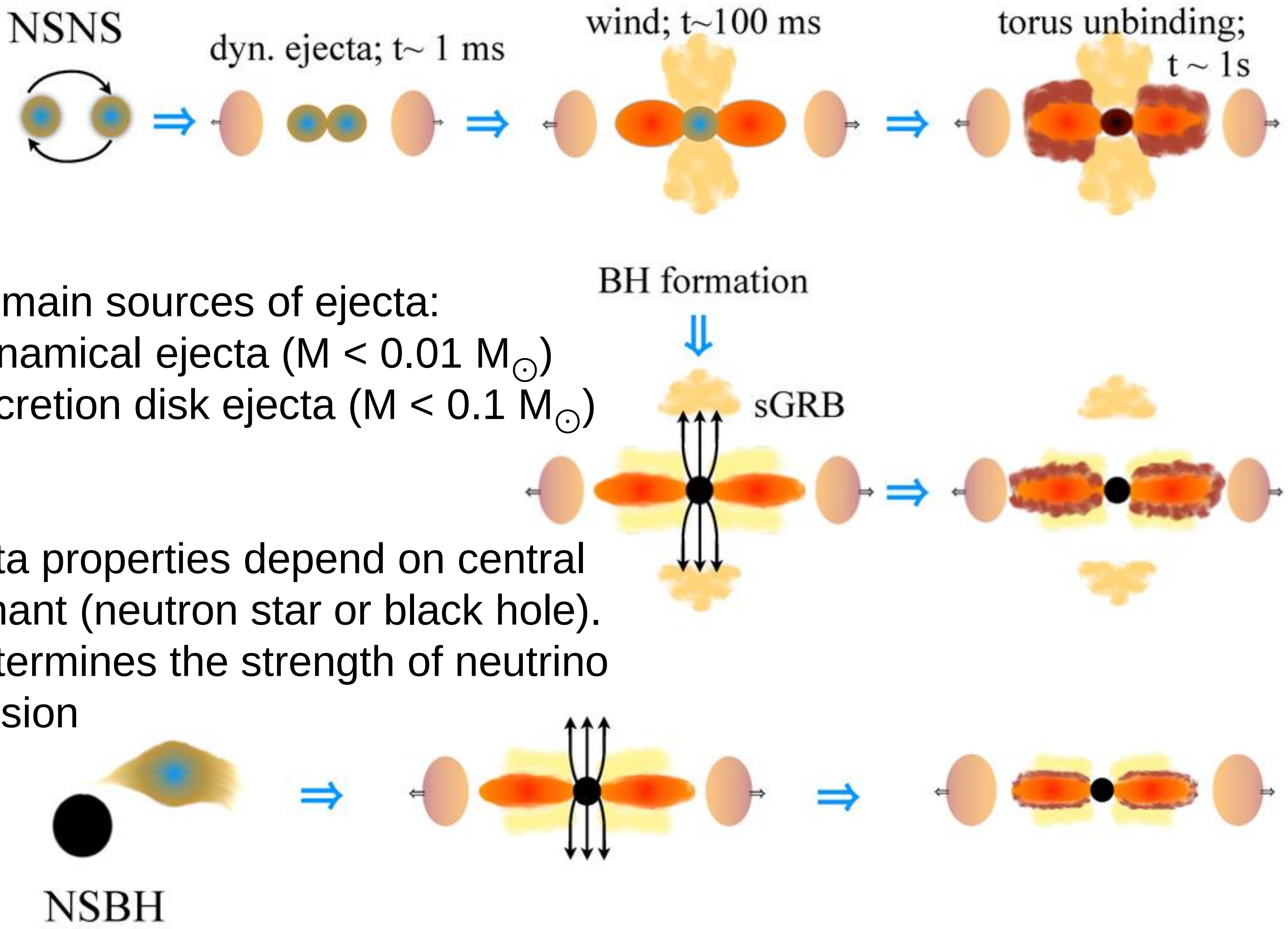
Compact binary mergers

Lattimer & Schramm 74, 76. Eichler+ 89, Freiburhaus+ 99



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

Mergers: variety of ejecta



Two main sources of ejecta:

- Dynamical ejecta (M < 0.01 $M_\odot$)
- Accretion disk ejecta (M < 0.1 $M_\odot$)

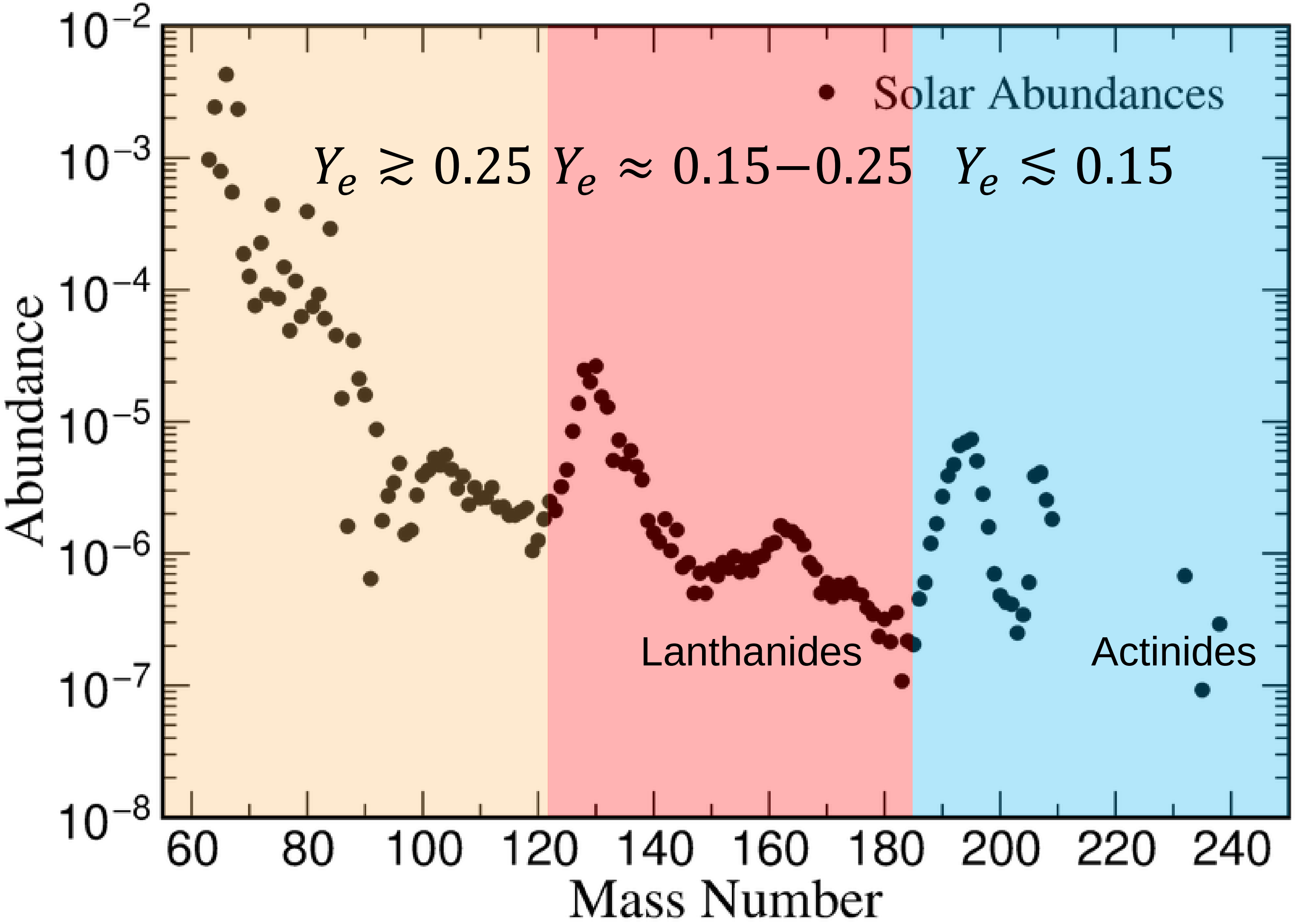
Ejecta properties depend on central remnant (neutron star or black hole). It determines the strength of neutrino emission

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

Nucleosynthesis dependence on Y_e

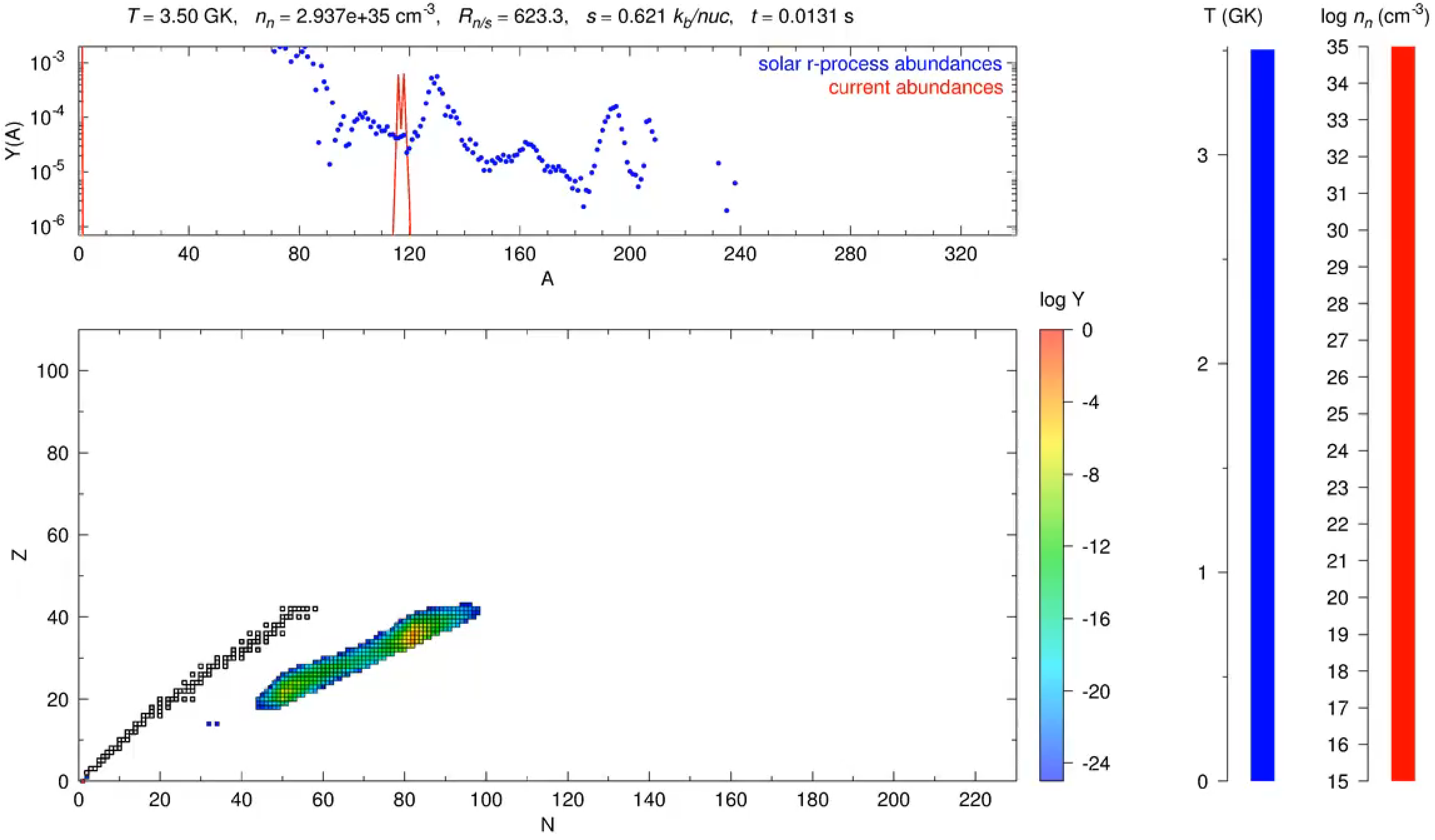
Nucleosynthesis mainly sensitive to proton-to-nucleon ratio, Y_e

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



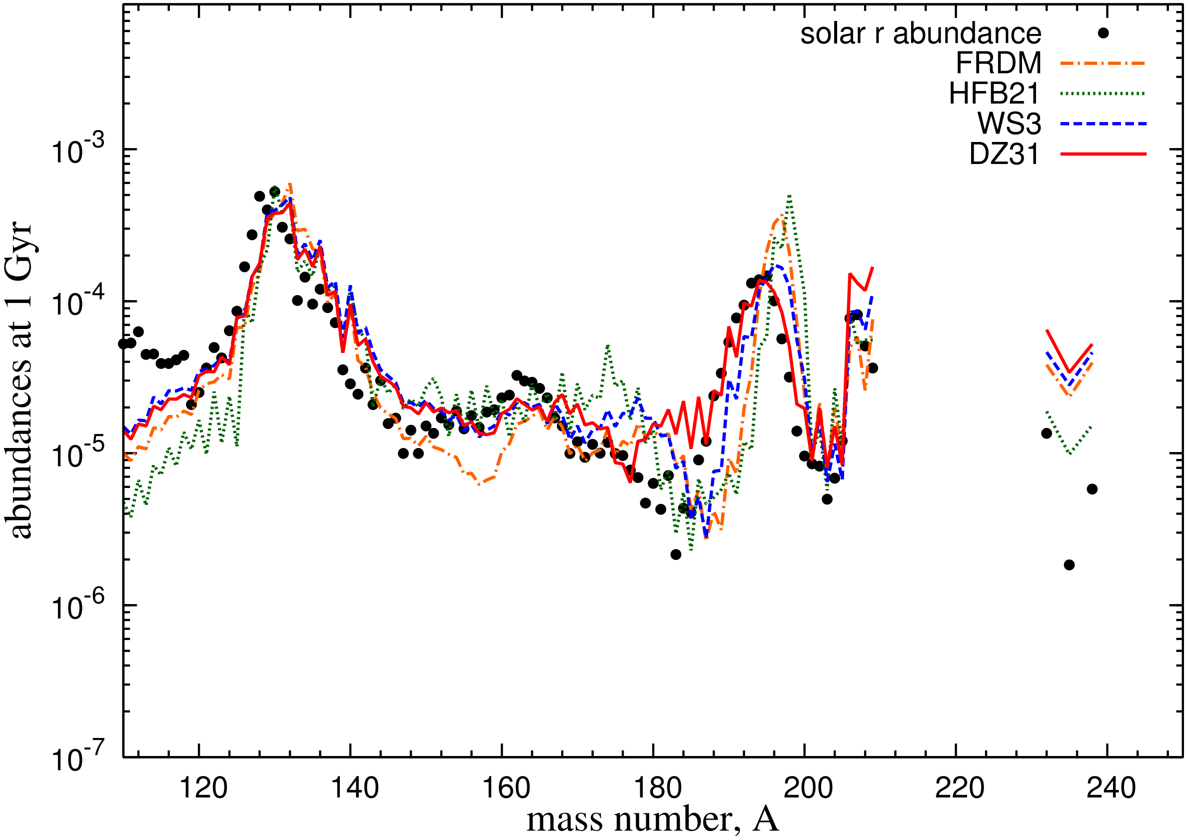
Neutron rich ejecta

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



Dependence on nuclear masses

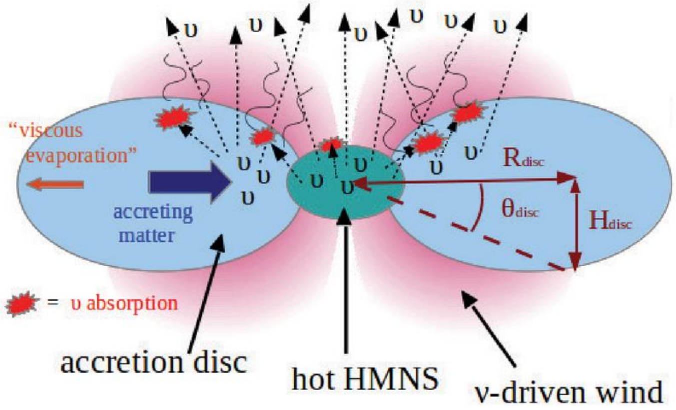
Mendoza-Temis, et al, PRC 92, 055805 (2015)



- Robustness astrophysical conditions, sensitive nuclear physics
- Second peak (A ~ 120) sensitive to fission yields (Goriely, 2015)
- Third peak (A ~ 195) sensitive to masses and half-lives

Impact of the merger remnant

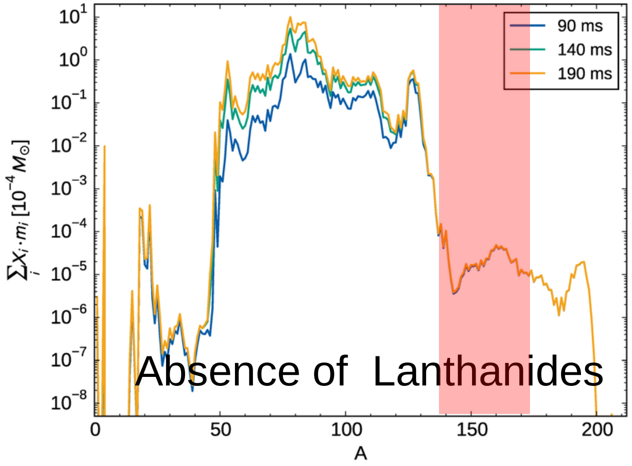
After the merger an hyper massive neutron star is formed that can be temporarily stable before collapsing to a black hole



Large neutrino fluxes mainly in polar region decrease neutron-to-proton ratio by reactions

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

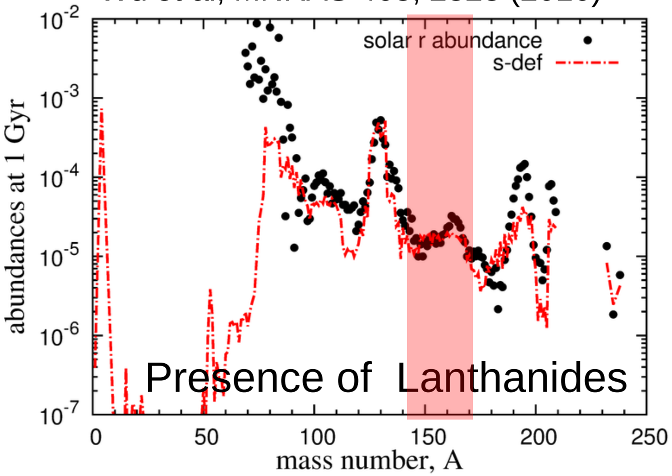
Martin, et al, ApJ 813, 2 (2015)



Absence of Lanthanides

Once neutron star collapses to a black hole neutrinos emission ceases. Larger neutron-to-proton ratio

Wu et al, MNRAS 463, 2323 (2016)



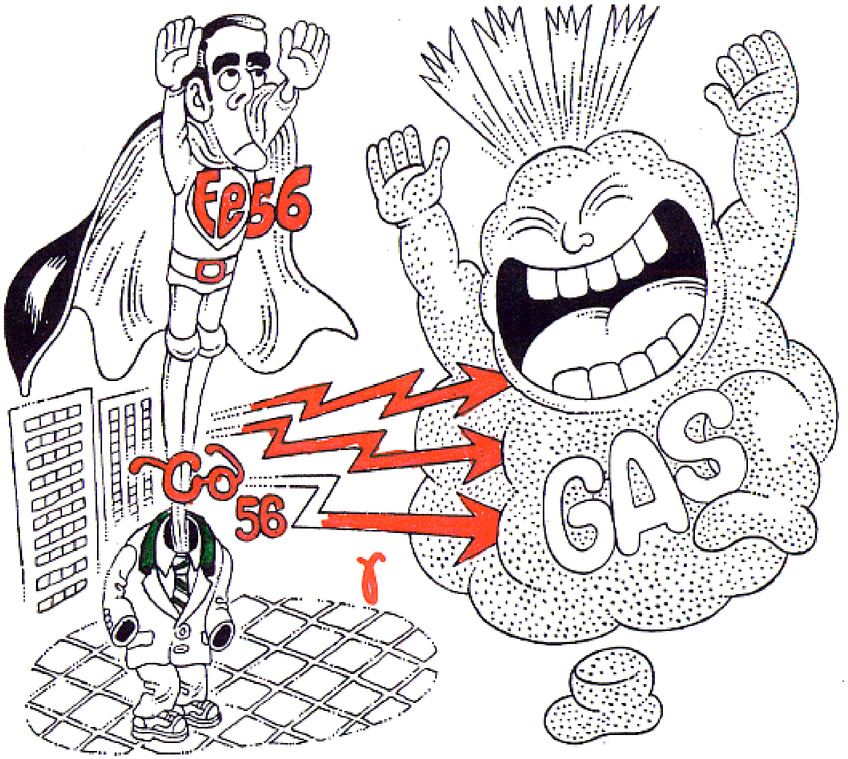
Presence of Lanthanides

see also Lippuner et al, MNRAS 472 904 (2017)

See also Just et al, MNRAS **448**, 541 (2015), Siegel and Metzger PRL **119**, 231102 (2017).

Electromagnetic signatures of nucleosynthesis

Supernova light curves follow the decay of ^{56}Ni ($t_{1/2} = 6\ \mathrm{d}$) and later ^{56}Co ($t_{1/2} = 77\ \mathrm{d}$)



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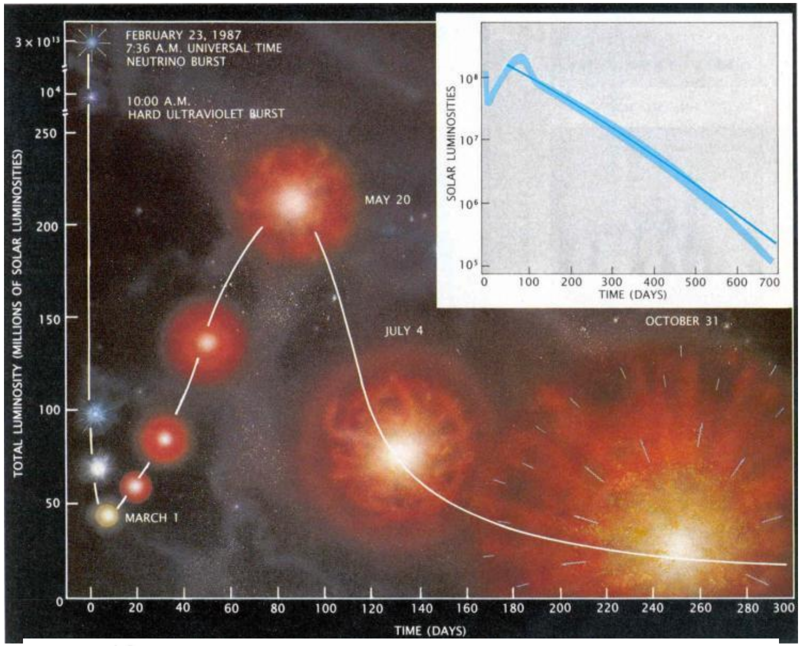
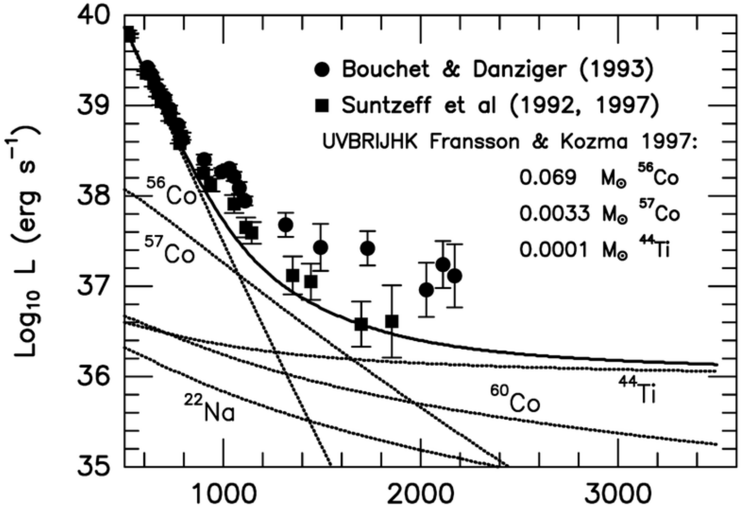
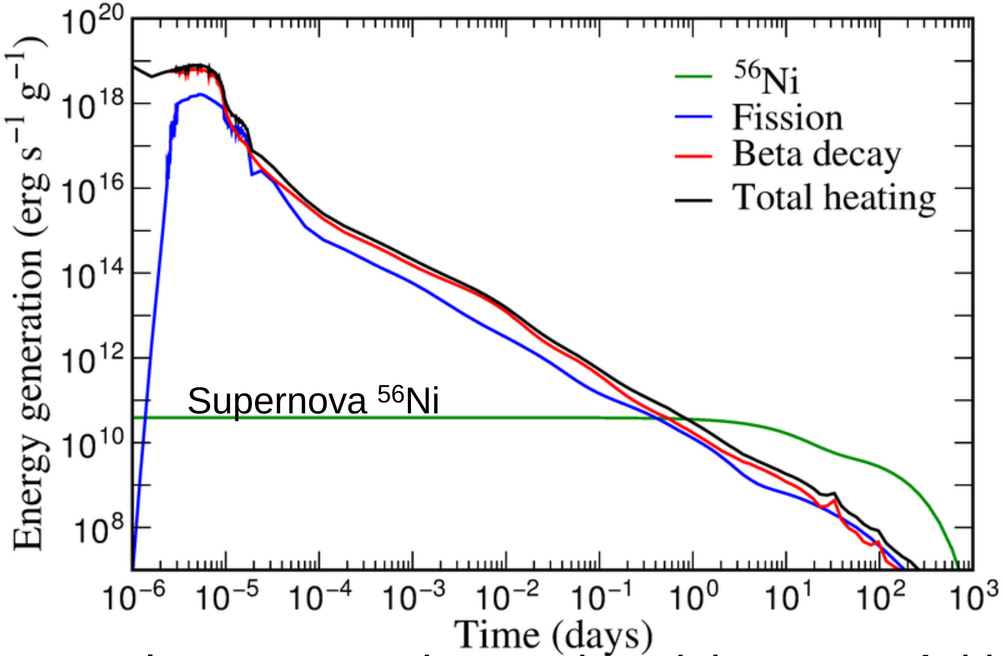




Diehl & Timmes, PASP 110, 637 (1998)

Energy production from r process ejecta

At early times (days), the decay of r process products produces energy following a power law $\dot{\varepsilon} \sim t^{-1.3}$ (Way & Wigner 1948, Metzger et al 2010). Many nuclei decaying at the same time heating up the ejecta



We expect an electromagnetic transient (Li & Paczyński 1998) with properties depending:

- Energy production rate
- Efficiency energy is absorbed by the gas (thermalization efficiency)
- Opacity of the gas (depends on composition, presence of Lanthanides/Actinides)

Impact of opacity

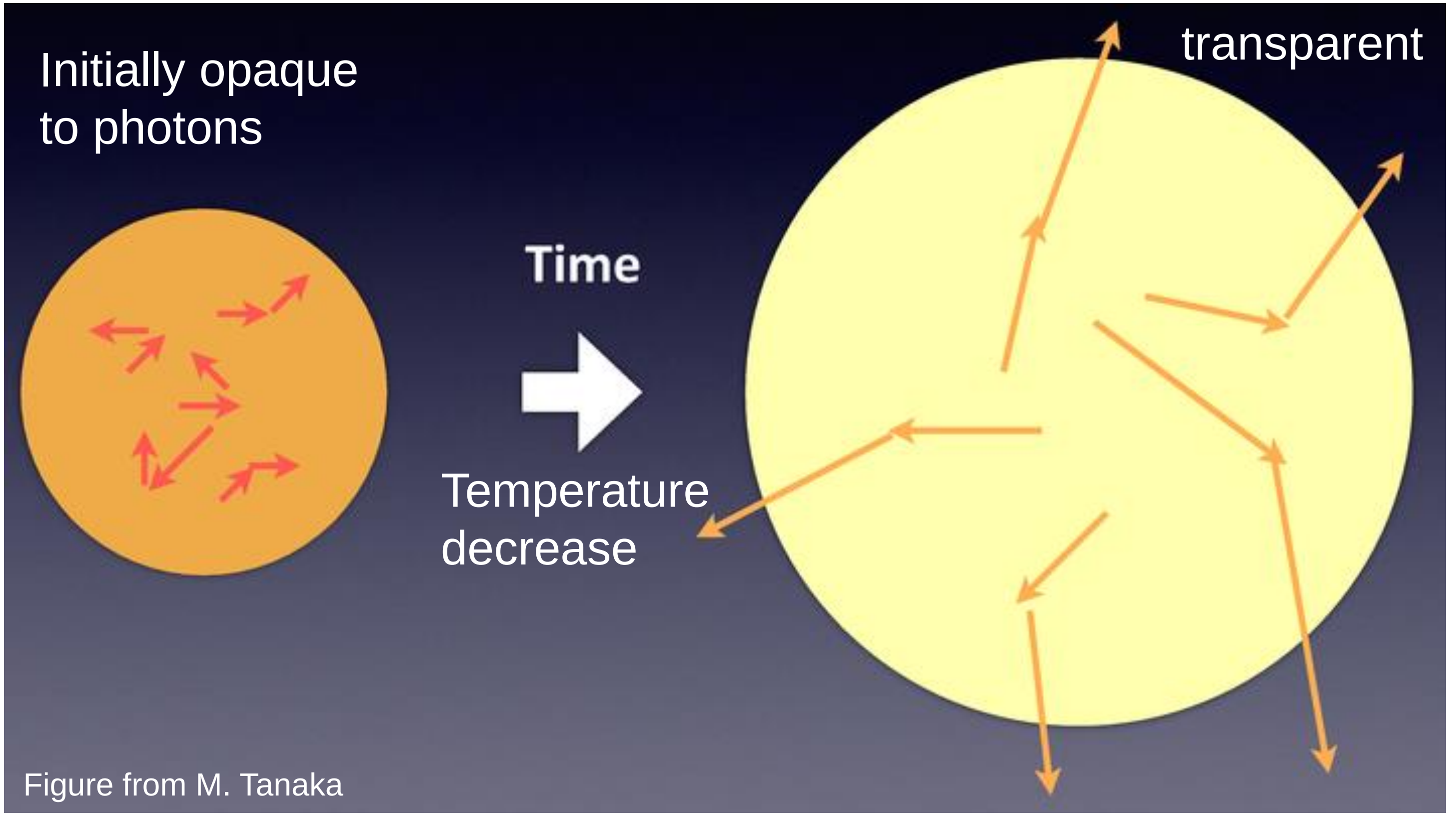


Figure from M. Tanaka

The transition from an opaque to transparent regime depends on the interaction probability of the photons (opacity). Depends on the structure of the atoms.

Low opacity: early emission from hot material at short wavelengths (blue)

High opacity: late emission from colder material at longer wavelengths (red)

Impact Lanthanides

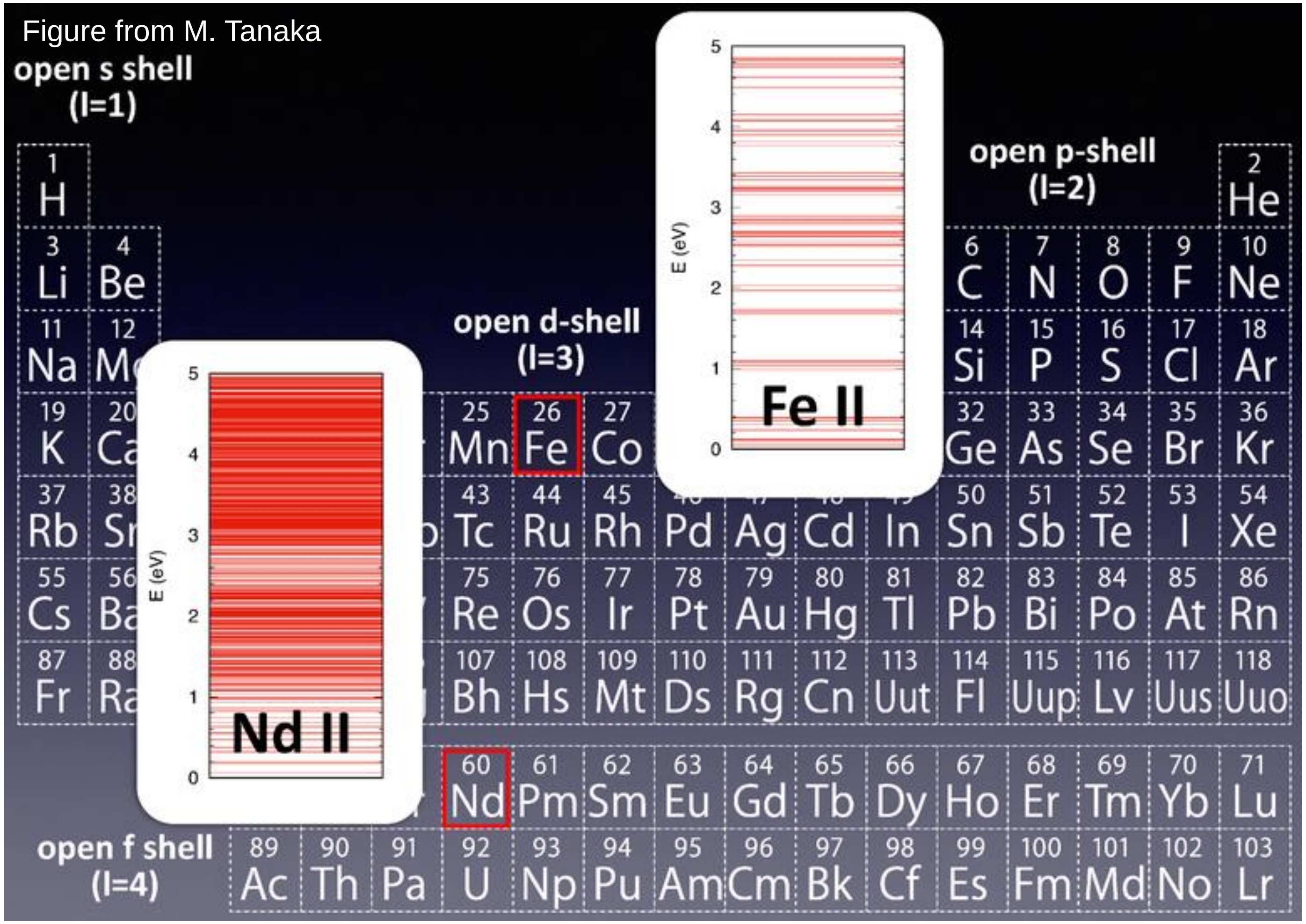
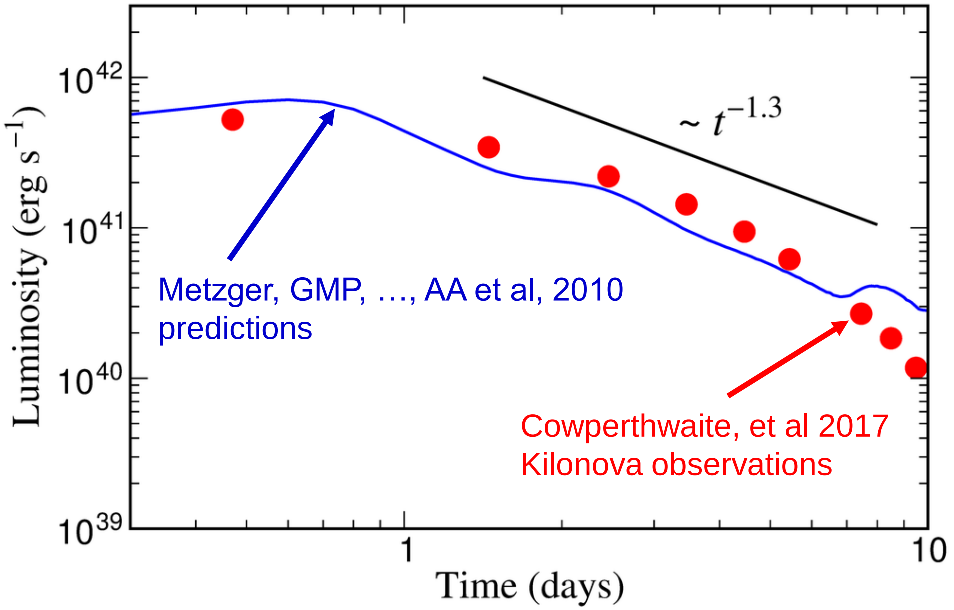


Figure from M. Tanaka

Large number of states of Lanthanides/Actinides leads to a high opacity

Barnes & D. Kasen, Astrophys. J. 775, 18 (2013);Tanaka & Hotokezaka, Astrophys. J. 775, 113 (2013).

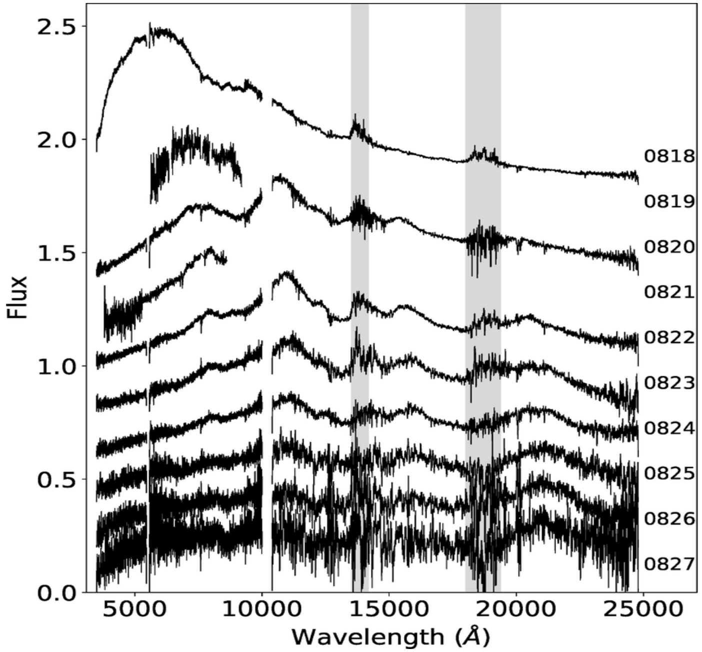
Kilonova: Electromagnetic transient powered by decay of r-process nuclei



Metzger, GMP, …, AA et al, 2010 predictions

Cowperthwaite, et al 2017 Kilonova observations

Pian et al., Nature 551, 67 (2017)



- Time evolution determined by the radioactive decay of r-process nuclei
- Two components (Kasen et al, Nature 551, 80 (2017)
  - Blue dominated by light elements (Z < 50) ($M = 0.025\,M_\odot, v = 0.3c, X_{\text{lan}} = 10^{-4}$)
  - Red due to presence of Lanthanides ($M = 0.04\,M_\odot, v = 0.15c, X_{\text{lan}} = 10^{-1.5}$)
- No direct evidence production of specific nuclei. No spectral features identified

Nuclear fingerprints light curve

Can we identify particular nuclear signatures in the bolometric light curve?

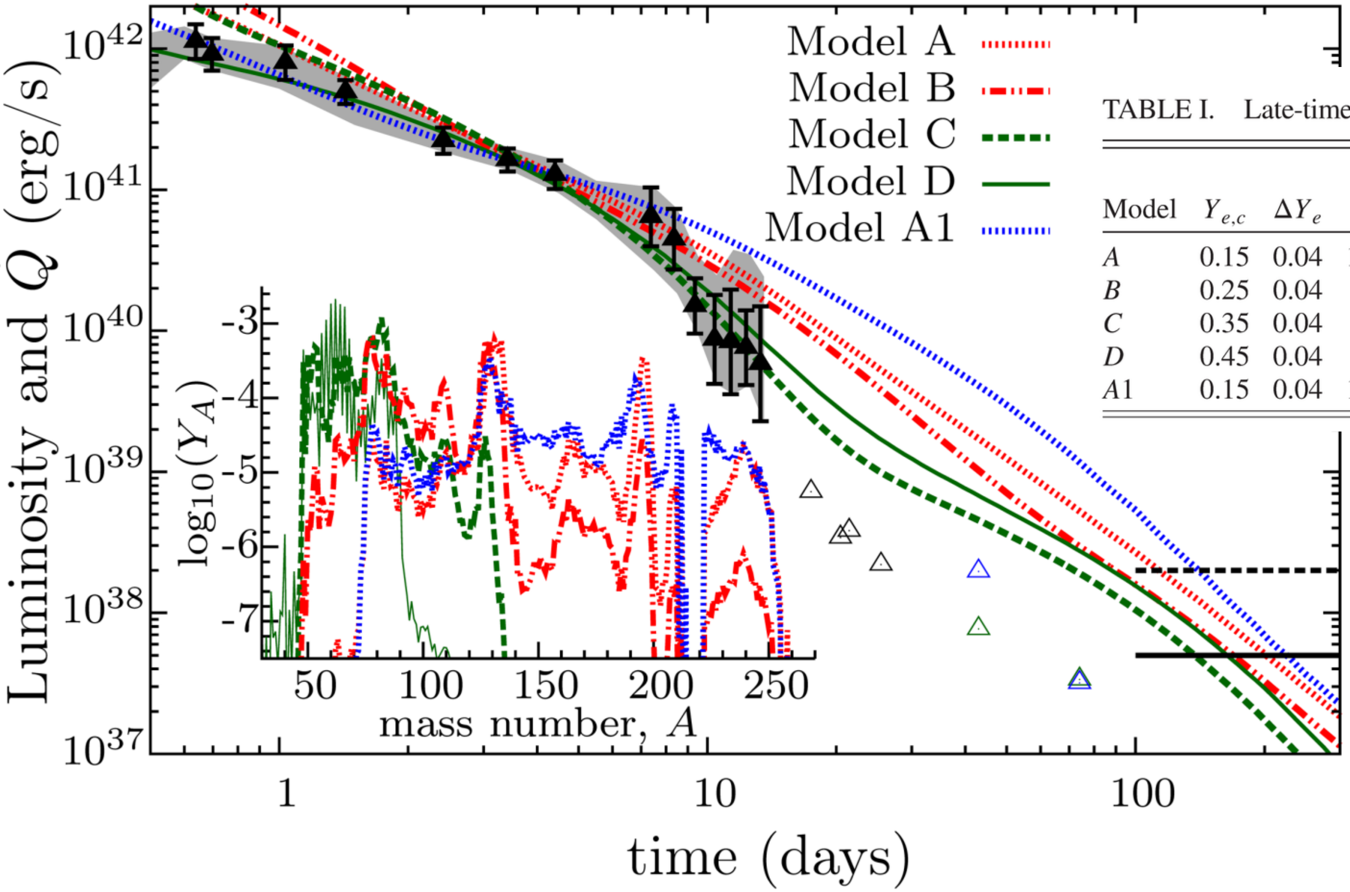


TABLE I. Late-time kilonova models (see text for explanations).

Model	$Y_{e,c}$	ΔY_e	$A_{\rm peak}$	$M_{\rm ej}$ ($M_\odot$)	$v_{\rm ej}$ (c)	Nuclear masses
A	0.15	0.04	130 and 195	0.040	0.1	FRDM
B	0.25	0.04	80 and 130	0.040	0.1	FRDM
C	0.35	0.04	80	0.055	0.1	FRDM
D	0.45	0.04	60	0.030	0.1	FRDM
*A*1	0.15	0.04	130 and 195	0.020	0.1	DZ31

At late times light curve is determined by nuclear heating. Opacity uncertainties do not play a role (ejecta is transparent)

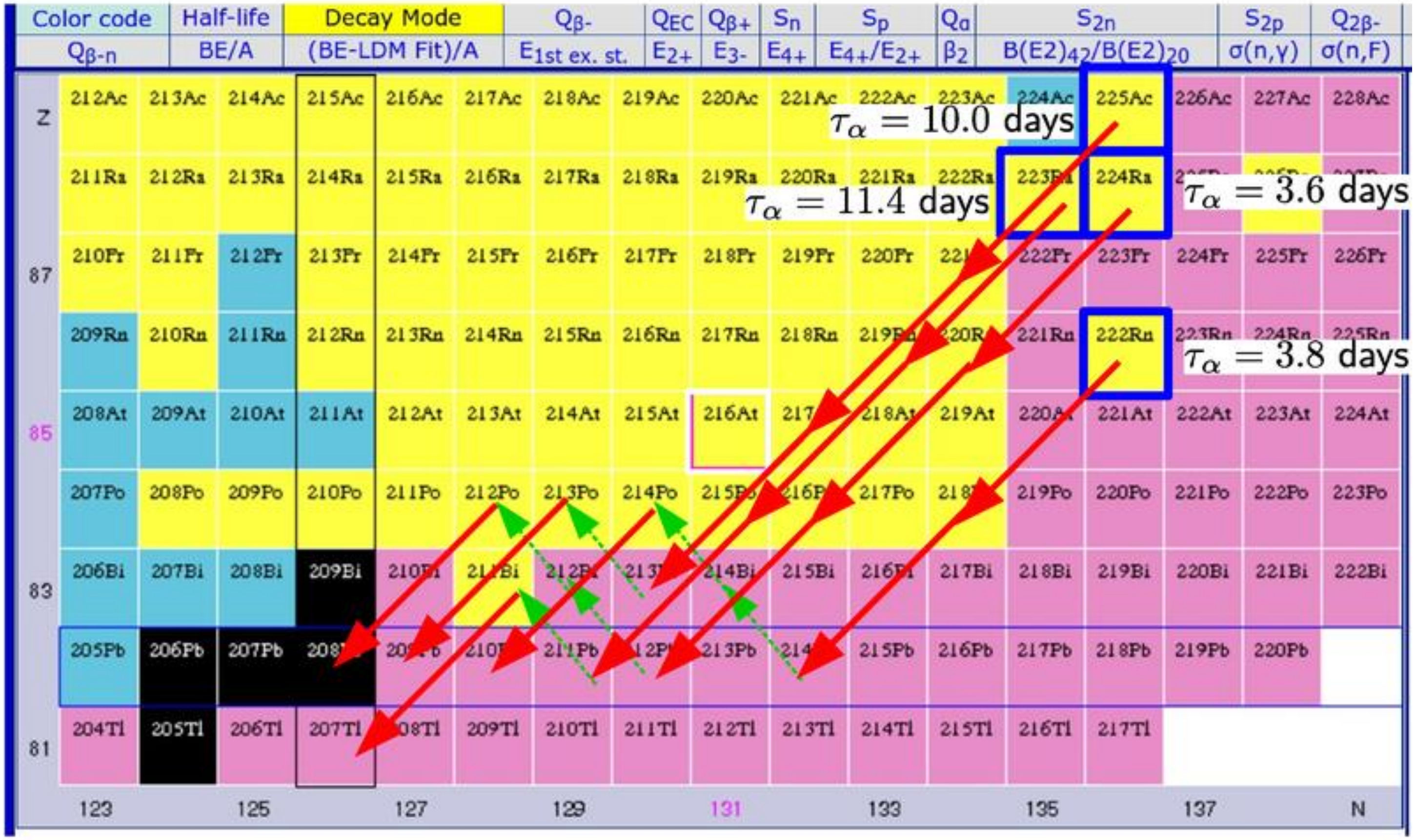
Observations between 10 and 100 days are sensitive to composition.
Light curve becomes dominated by individual decays

Wu, Barnes, GMP, Metzger, PRL 122, 062701 (2019)

Main heating sources late times

Relevant α-decays

Wu, Barnes, GMP, Metzger, PRL 122, 062701 (2019)



Plus fission of ^{254}Cf

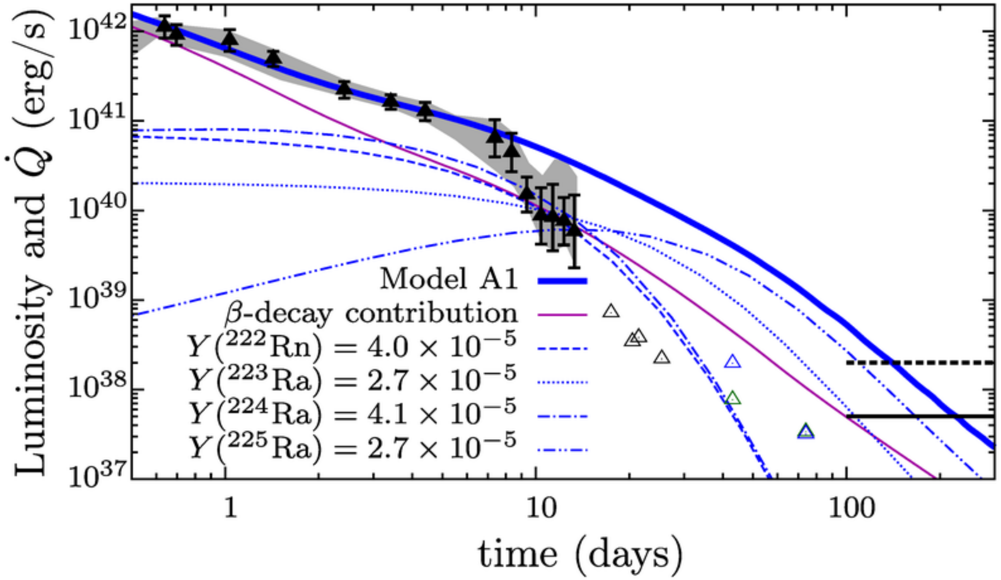
See also:

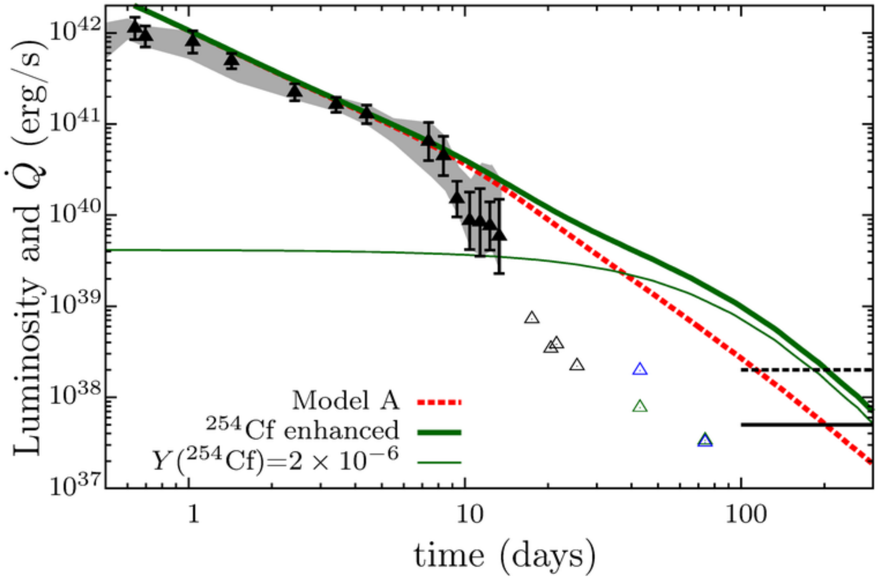
Zhu et al., ApJ 863, L23 (2018), Wanajo, ApJ 868, 65 (2018).

Signature dominating decay chains

Isotope	Decay channel	$t_{1/2}$ (d)	Q (MeV)	E_α (MeV)	E_e (MeV)	E_γ (MeV)
^{224}Ra	$\alpha\beta^-$ to ^{208}Pb	3.6319(23)	30.875	26.542	0.891	1.474
^{222}Rn	$\alpha\beta^-$ to ^{210}Pb	3.8215(2)	23.826	19.177	0.949	1.715
^{225}Ra	β^-	14.9(2)	0.356	-	0.097	0.012
^{225}Ac	$\alpha\beta^-$ to ^{209}Bi	10.0(1)	30.196	27.469	0.632	0.046
^{223}Ra	$\alpha\beta^-$ to ^{207}Pb	11.43(5)	29.986	26.354	0.937	0.304

Isotope	Decay channel	$t_{1/2}$ (d)	Q (MeV)	$E_{\rm Kinetic}$ (MeV)	E_n (MeV)	E_γ (MeV)
^{254}Cf	Fission	60.5(2)	-	185(2)	-	-





At late times alpha decay chains of ^{223}Ra and ^{225}Ac and ^{254}Cf fission dominate

Wu, Barnes, GMP, Metzger, , PRL 122, 062701 (2019)

Summary

- Kilonova from GW170817 originates from the statistical radioactive decay of heavy elements
- (One) Astrophysical site of the r process is identified
- Signatures of individual decays not yet identified
- Observations in time scale 10-100 days may contain signatures of such decays.

Collaborators: J. Barnes (Columbia, USA), A. Bauswein (GSI, Darmstadt), R. Fernandez (U Alberta, Canada),S. Giuliani (MSU, USA), H.-Th. Janka (MPA, Garching), D. Kasen (UC Berkeley, USA), T. Marketin (U Zagreb, Croatia), B. Metzger (Columbia, USA), L. Robledo (UAM, Madrid), T. R. Rodriguez (UAM, Madrid), M.-R. Wu (A Sinica, Taiwan)