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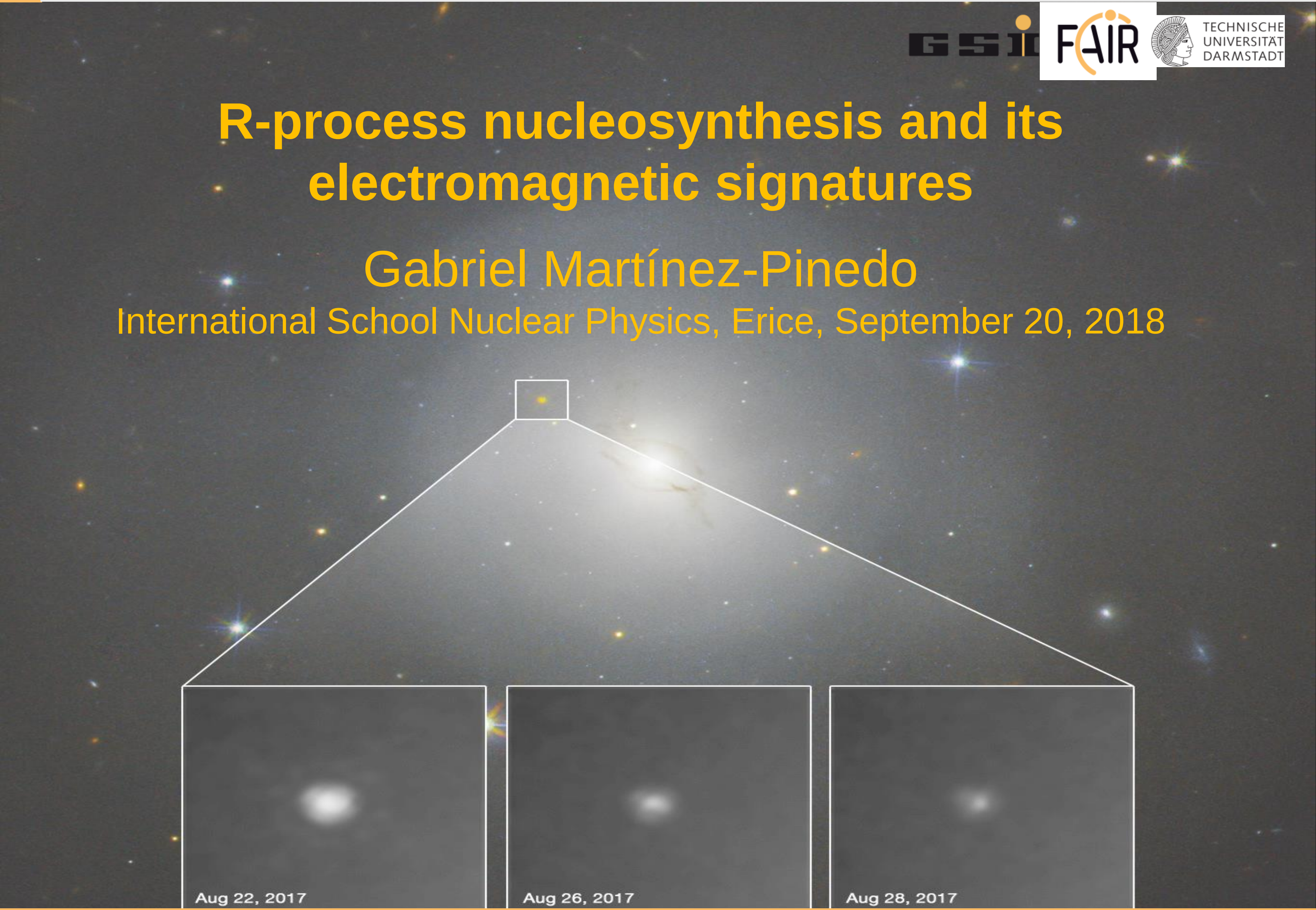
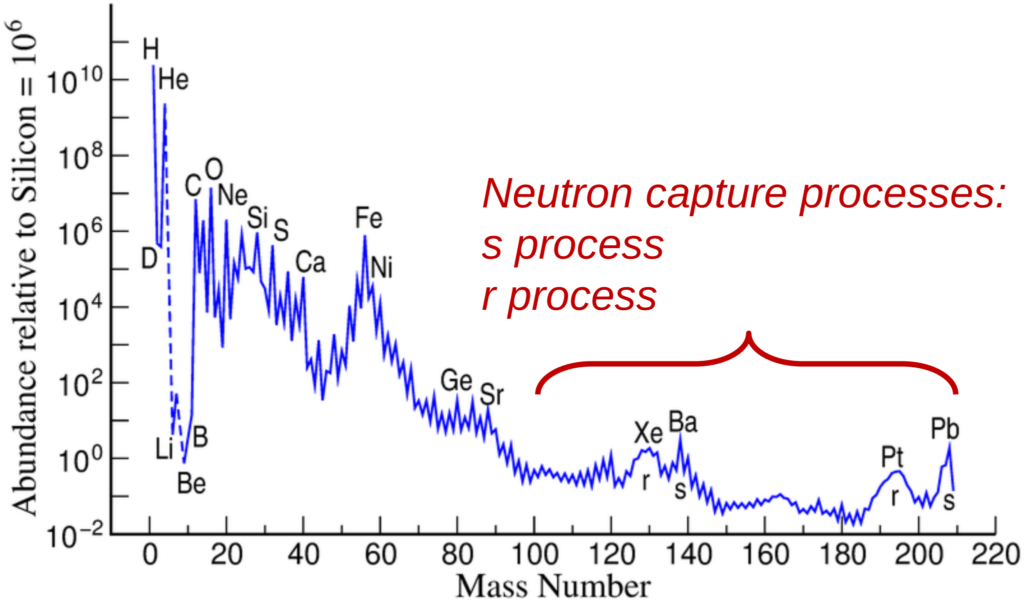
R-process nucleosynthesis and its electromagnetic signatures

Gabriel Martínez-Pinedo

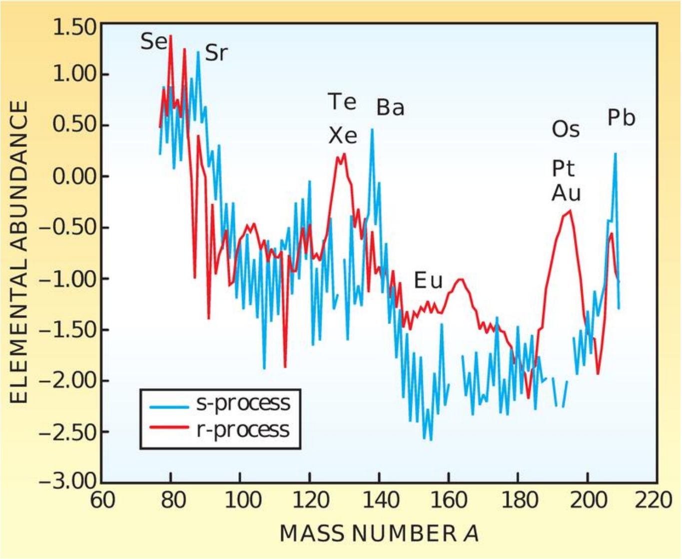
International School Nuclear Physics, Erice, September 20, 2018

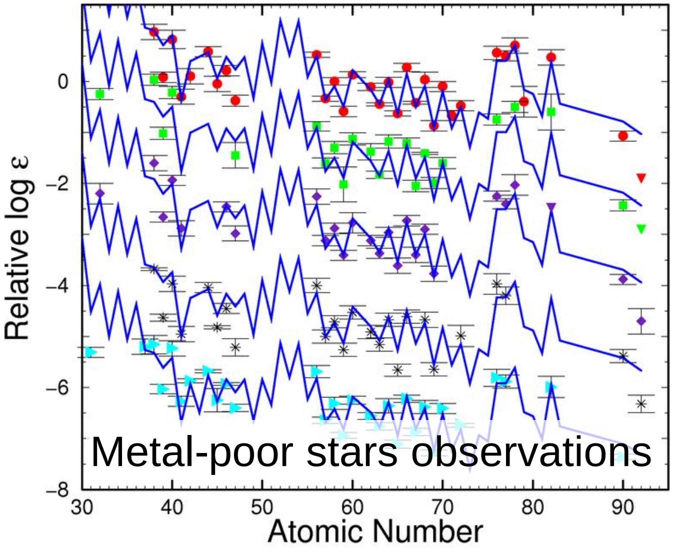


Signatures of nucleosynthesis



Neutron capture processes:
s process
r process



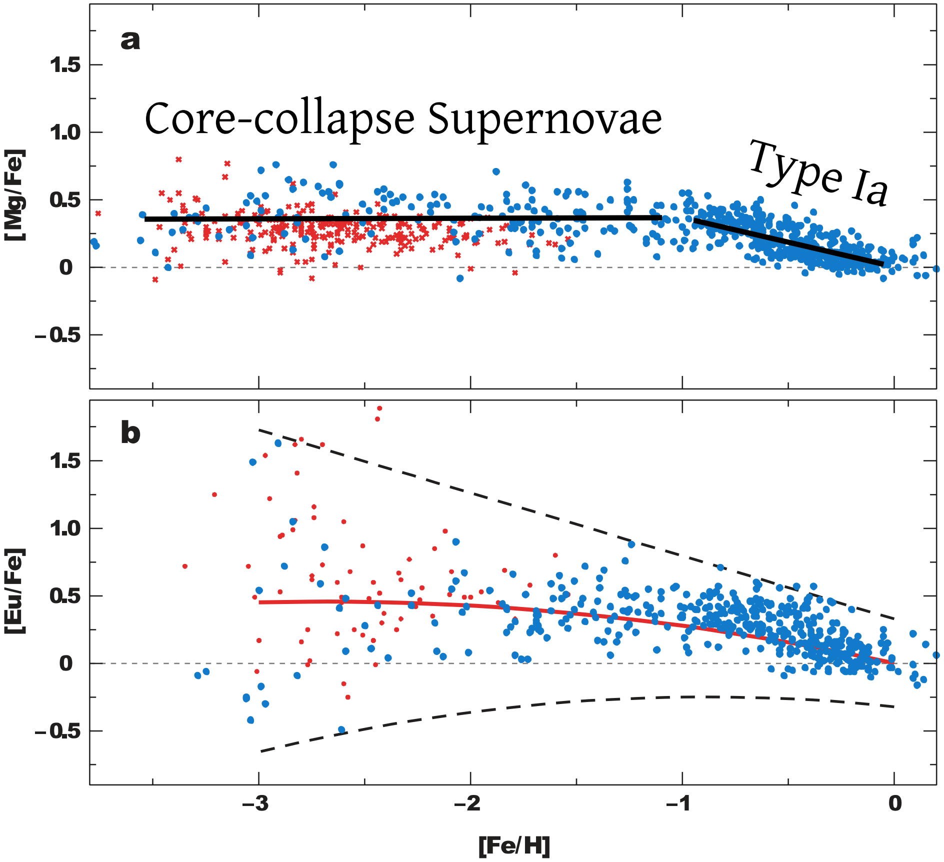


Metal-poor stars observations

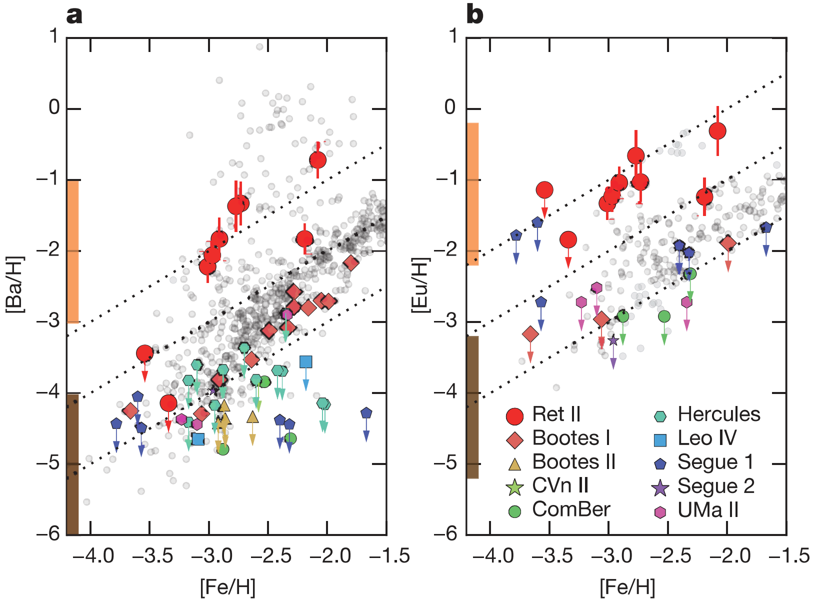
- Old metal-poor stars are enriched in r-process elements with similar relative abundances to our Sun
- r process operates at early Galactic history

Implications from observations

Individual stars, Milky Way Halo
Sneden, Cowan & Gallino, 2008



Ji et al 2016 found that only 1 of 10 ultrafaint dwarf galaxies is enriched in r-process elements



R process related to rare high yield events not correlated with Iron enrichment

Similar results obtained by ^{60}Fe and ^{244}Pu observations in deep sea sediments (Wallner et al, 2015; Hotokezaka et al, 2015)

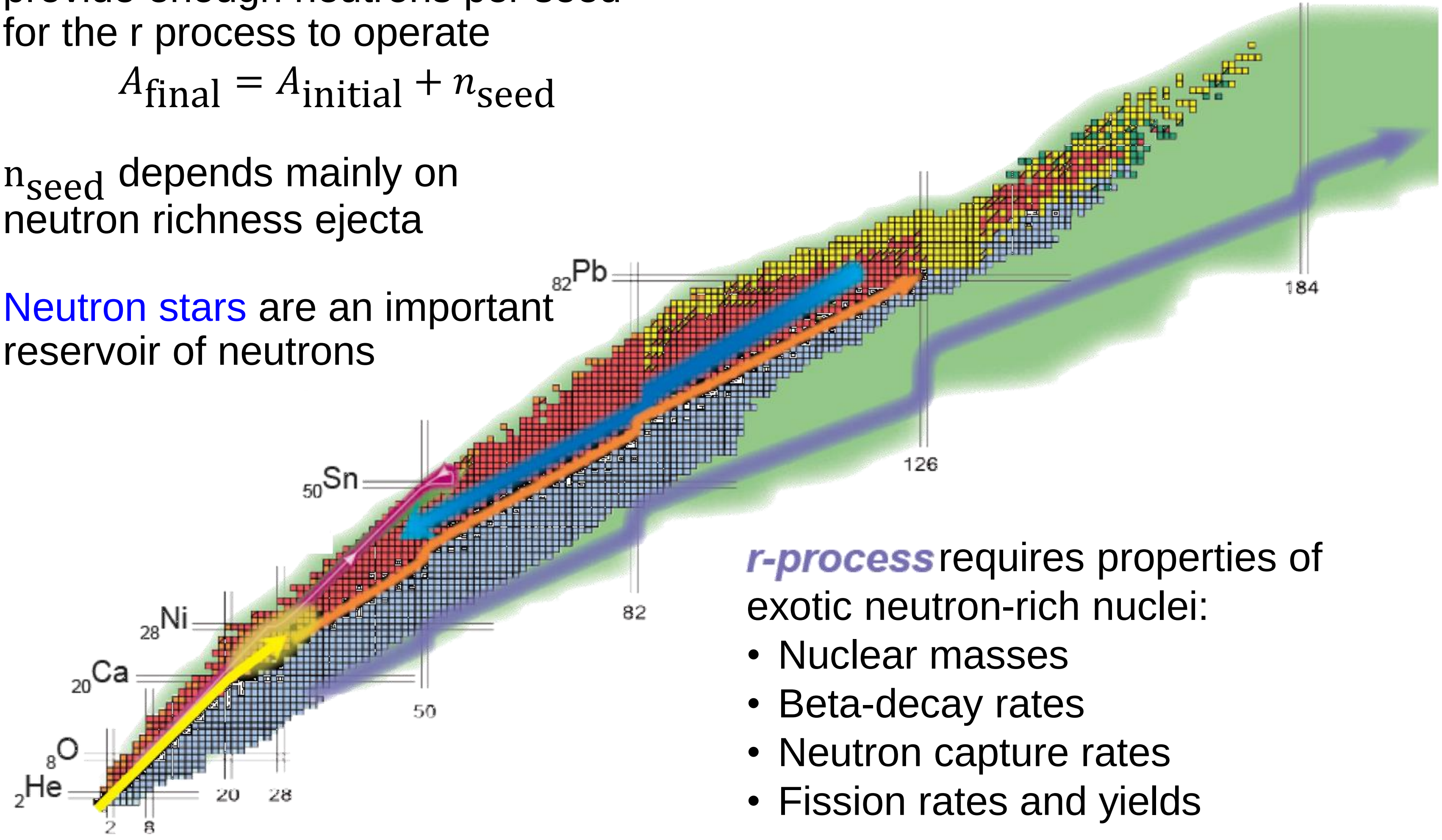
R process nuclear needs

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



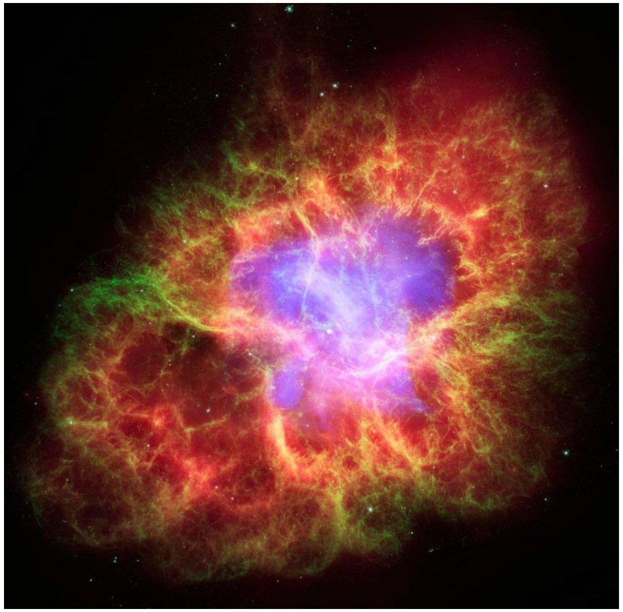
r-process requires properties of exotic neutron-rich nuclei:

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

Astrophysical sites

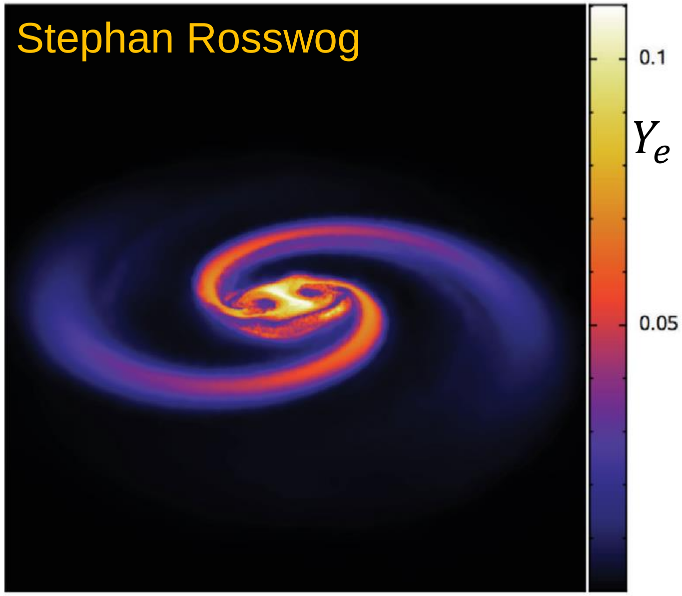
Core-collapse supernova

Woosley+ 94, Takahashi+ 94)



Compact binary mergers

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



Stephan Rosswog

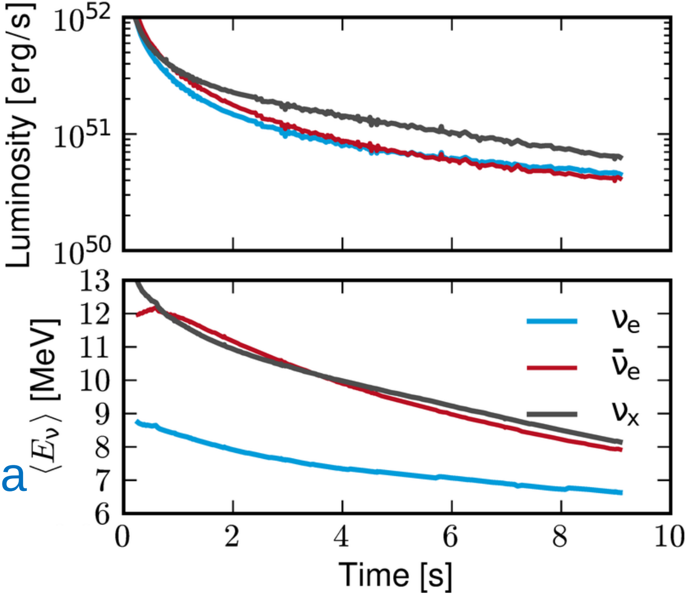
	Supernova	Mergers
Optimal conditions	☹	☺
Yield / Frequency	😐	☺
Direct signature	☹	☺

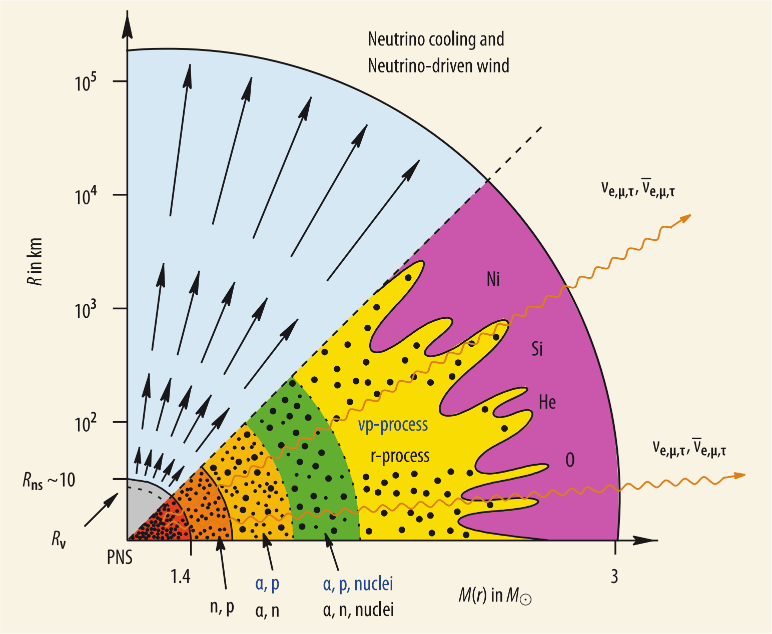
Heavy elements in supernova?

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

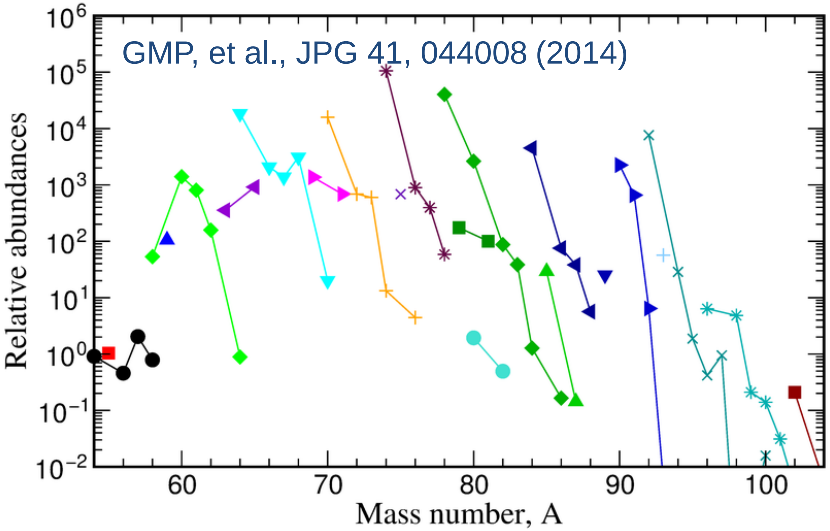
$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Very similar spectra ν_e and $\bar{\nu}_e$ → proton rich ejecta

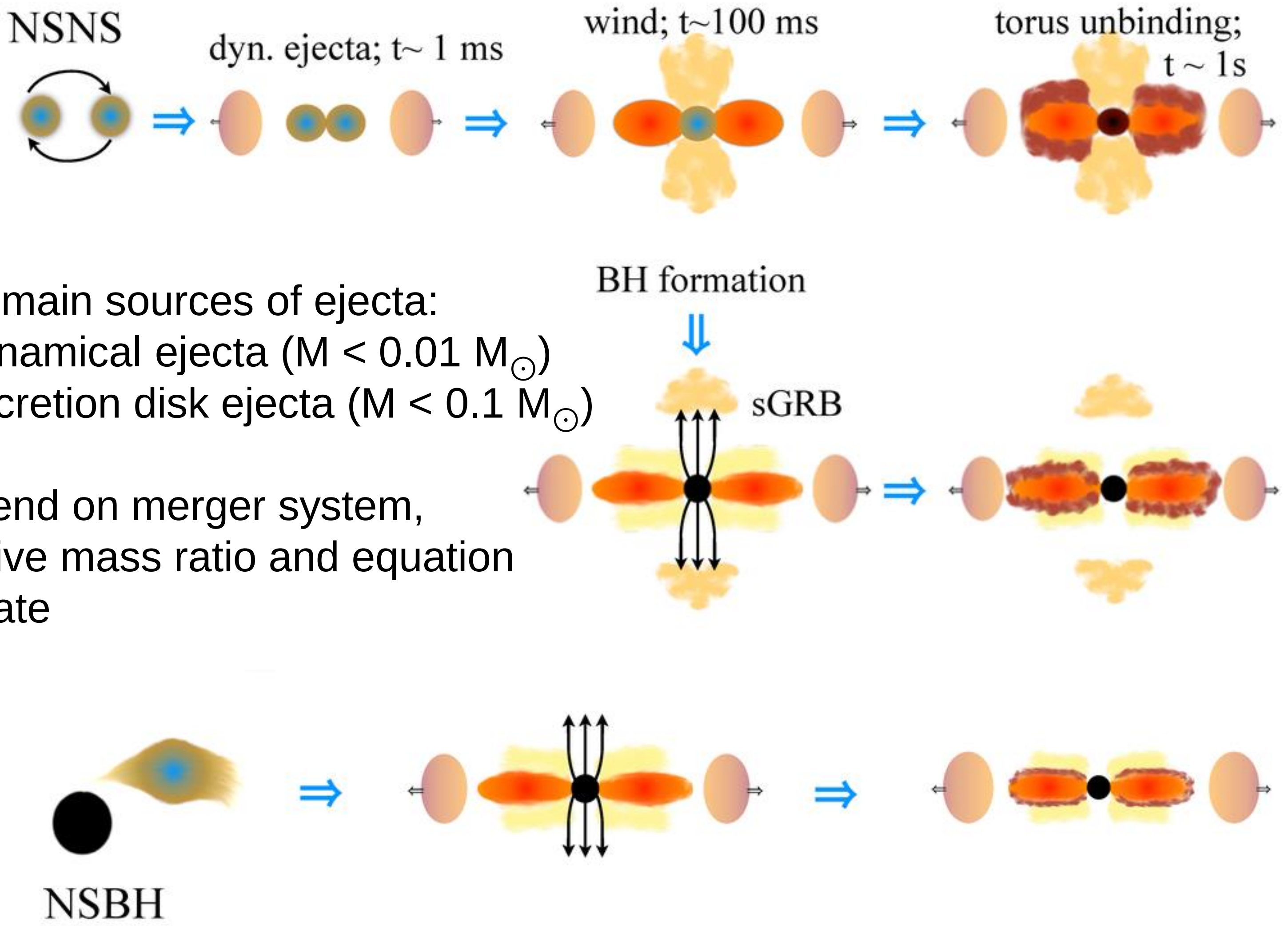




Supernova produce only medium mass nuclei


GMP, et al., JPG 41, 044008 (2014)

Mergers: variety of ejecta



Two main sources of ejecta:

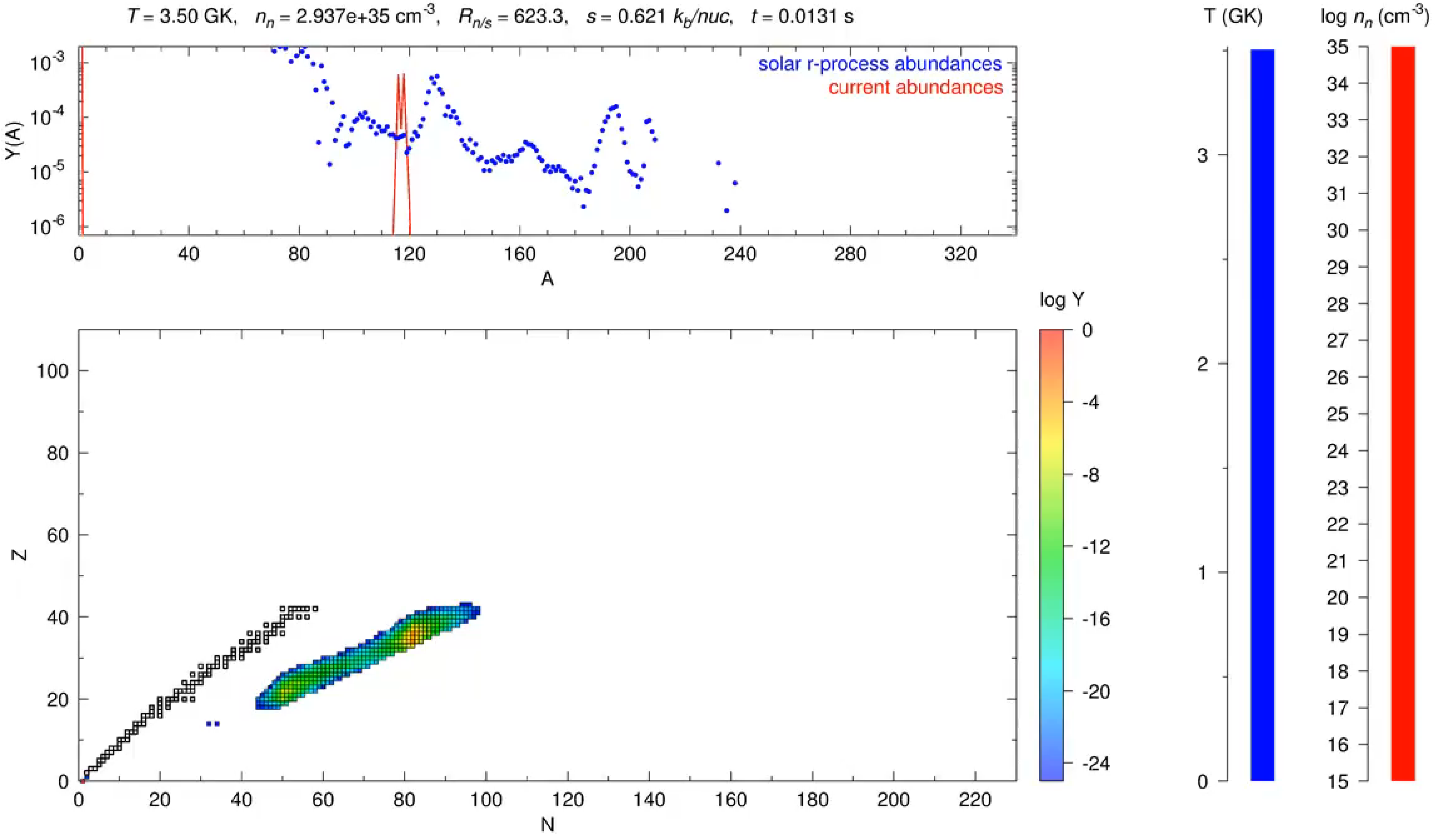
- Dynamical ejecta ($M < 0.01\ M_\odot$)
- Accretion disk ejecta ($M < 0.1\ M_\odot$)

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

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

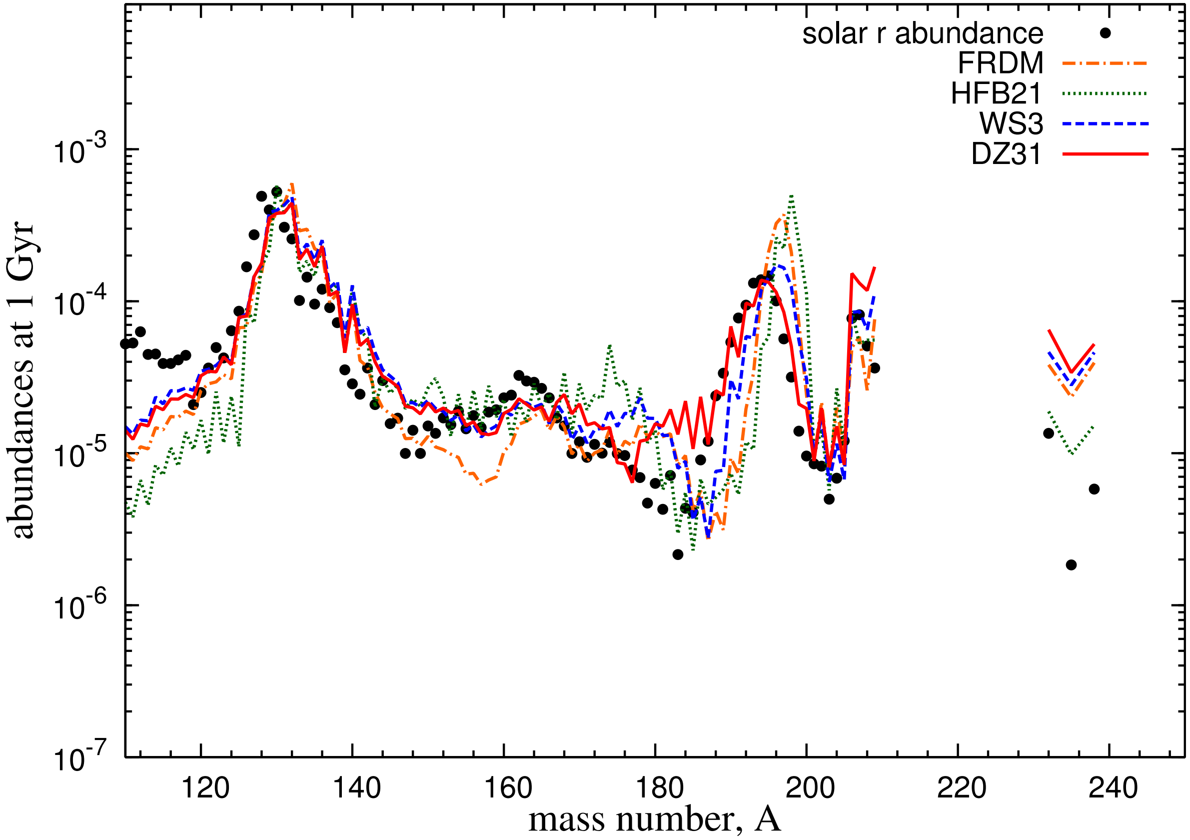
R process in merger ejecta

Heavy elements produced in merger ejecta. Radioactive decay liberates energy



Dependence on nuclear masses

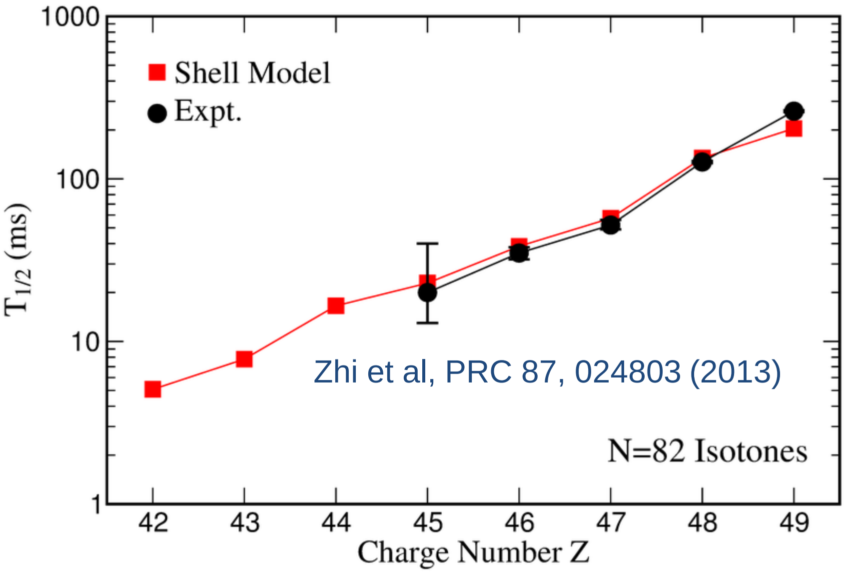
Mendoza-Temis, et al, PRC 92, 055805 (2015)



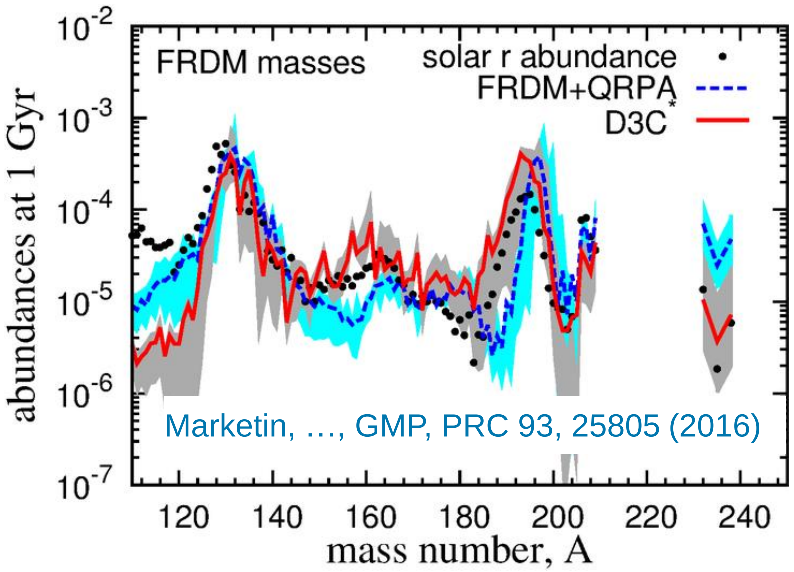
- Robustness astrophysical conditions, sensitive nuclear physics
- Second peak (A ~ 120) sensitive to fission yields (Goriely, 2015)
- Third peak (A ~ 195) sensitive to masses and half-lives
- Elements lighter than A ~ 120 are not produced

Impact beta-decay half-lives

- Beta-decay half-lives determine the speed at which heavy elements are build starting from light ones
- Theoretical advances allow for fully microscopic calculations



Zhi et al, PRC 87, 024803 (2013)

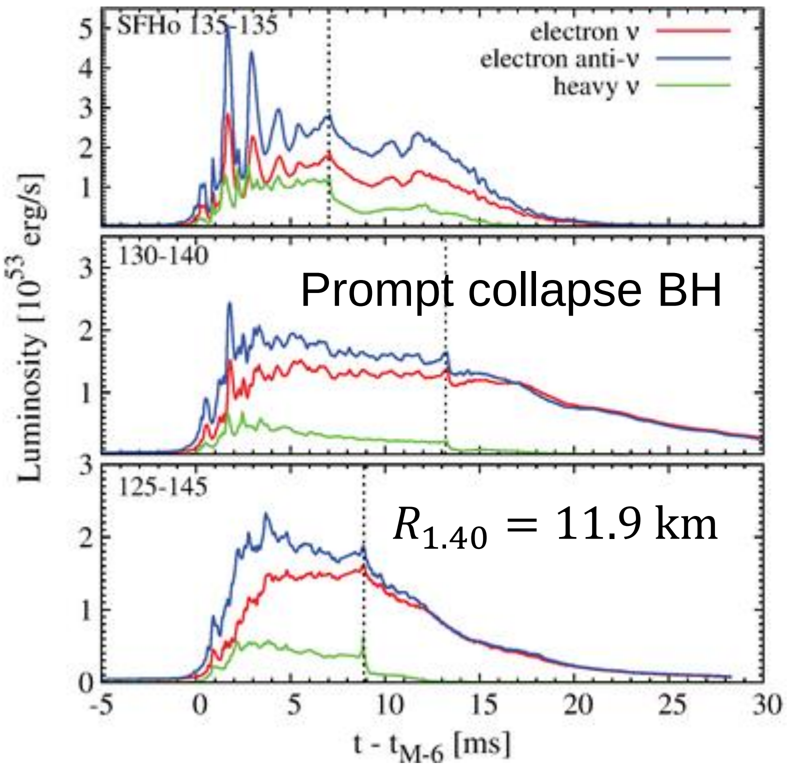


Marketin, …, GMP, PRC 93, 25805 (2016)

- Microscopic calculations reproduce available data
- Predict shorter half-lives for nuclei $Z > 80$ having a strong impact on the position of the A ~ 195 peak [Eichler et al, ApJ 808, 30 (2015)]

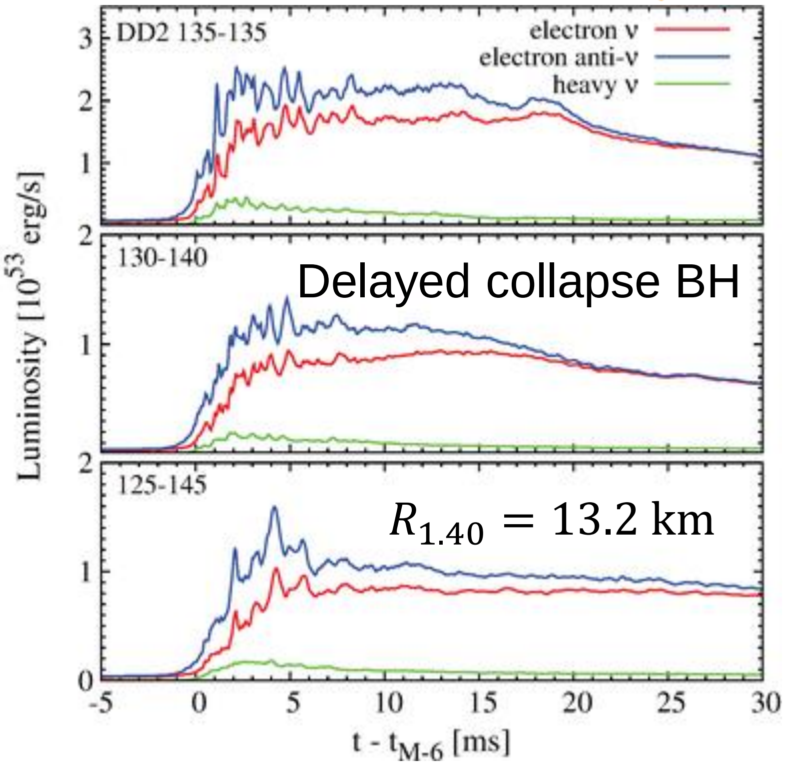
Impact of neutrinos on NS-NS mergers

Sekiguchi, et al, 2016



Prompt collapse BH

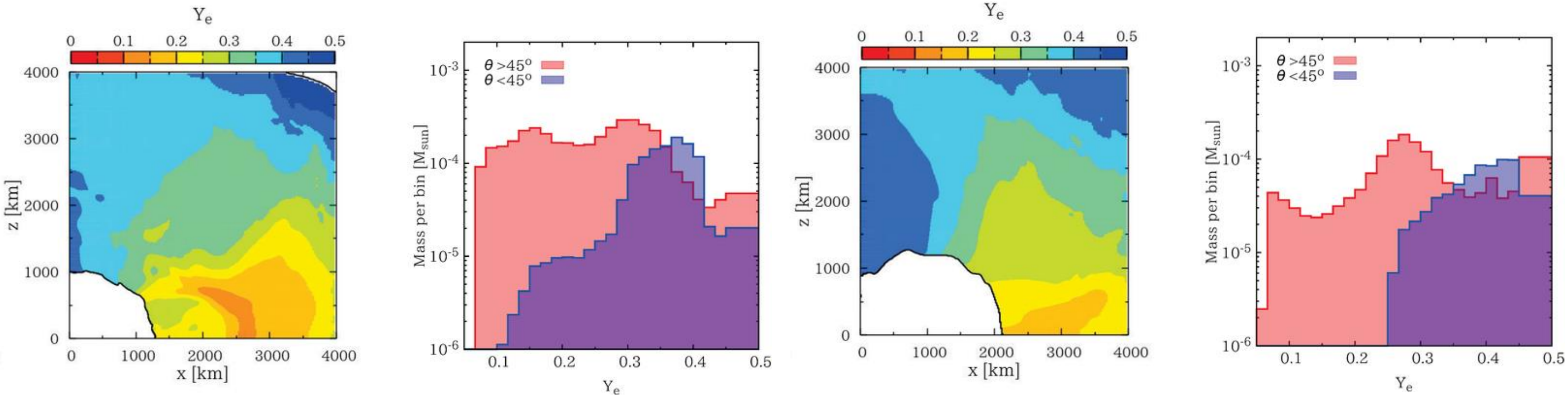
$R_{1.40} = 11.9$ km



Delayed collapse BH

$R_{1.40} = 13.2$ km

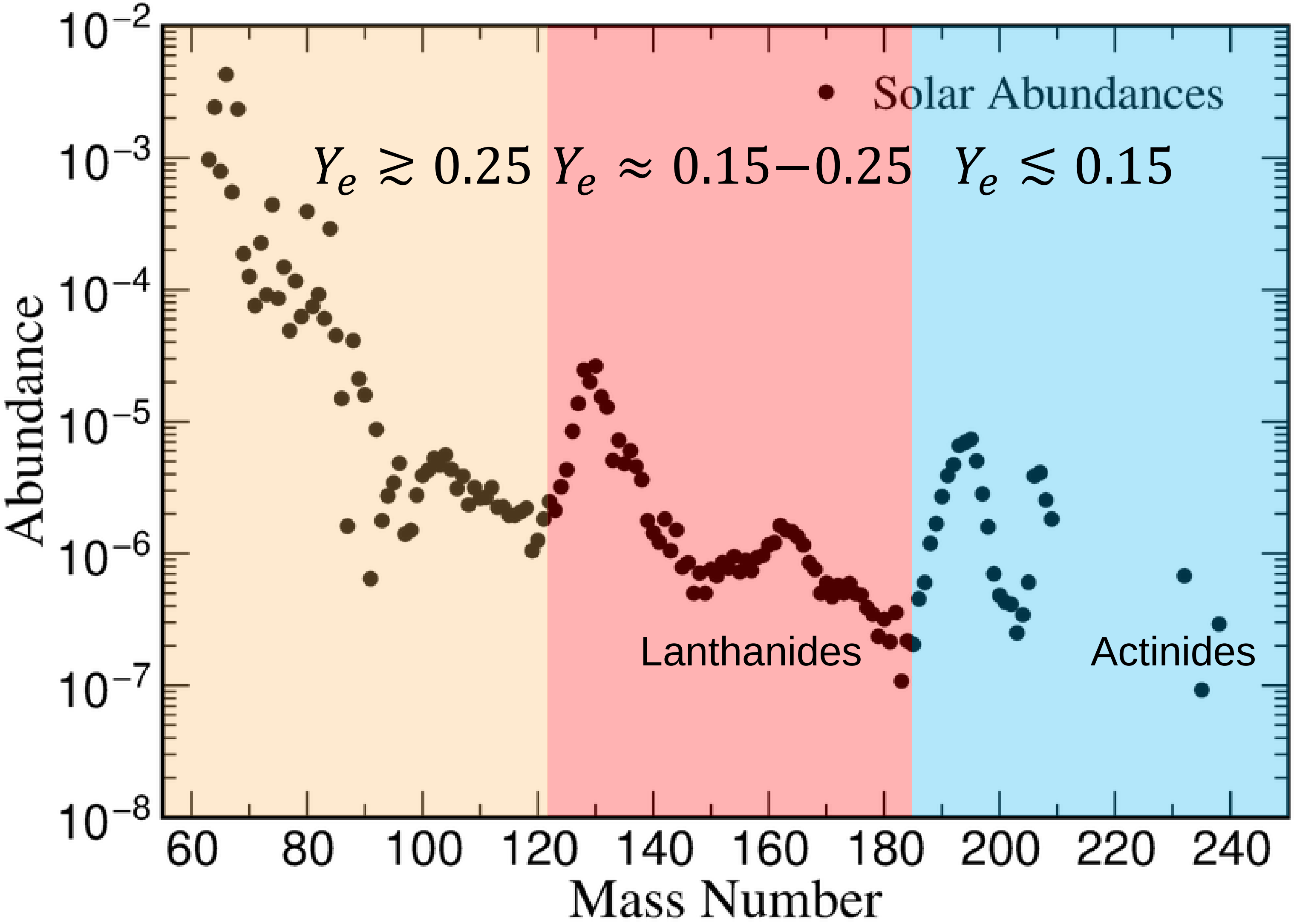
Shibata, et al, 2017



Nucleosynthesis dependence on Y_e

Nucleosynthesis mainly sensitive to proton-to-nucleon ratio, $Y_e = n_n/(n_n + n_p)$

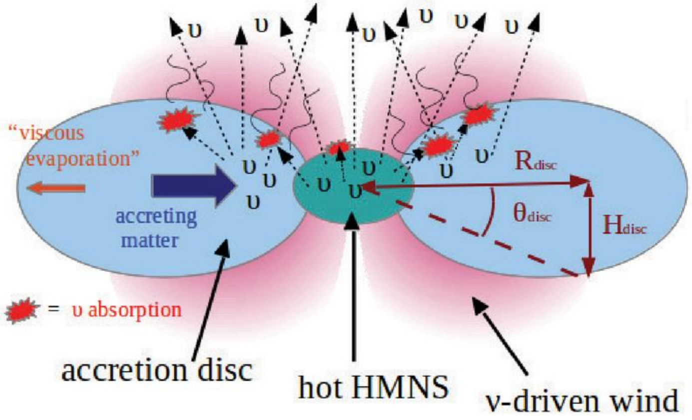
$\nu_e + n \rightleftarrows p + e^-$ vs $\bar{\nu}_e + p \rightleftarrows n + e^+$

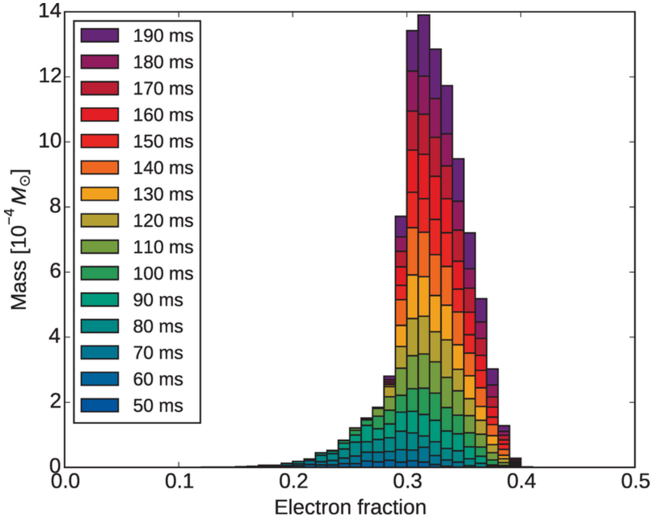


Nucleosynthesis delayed BH case

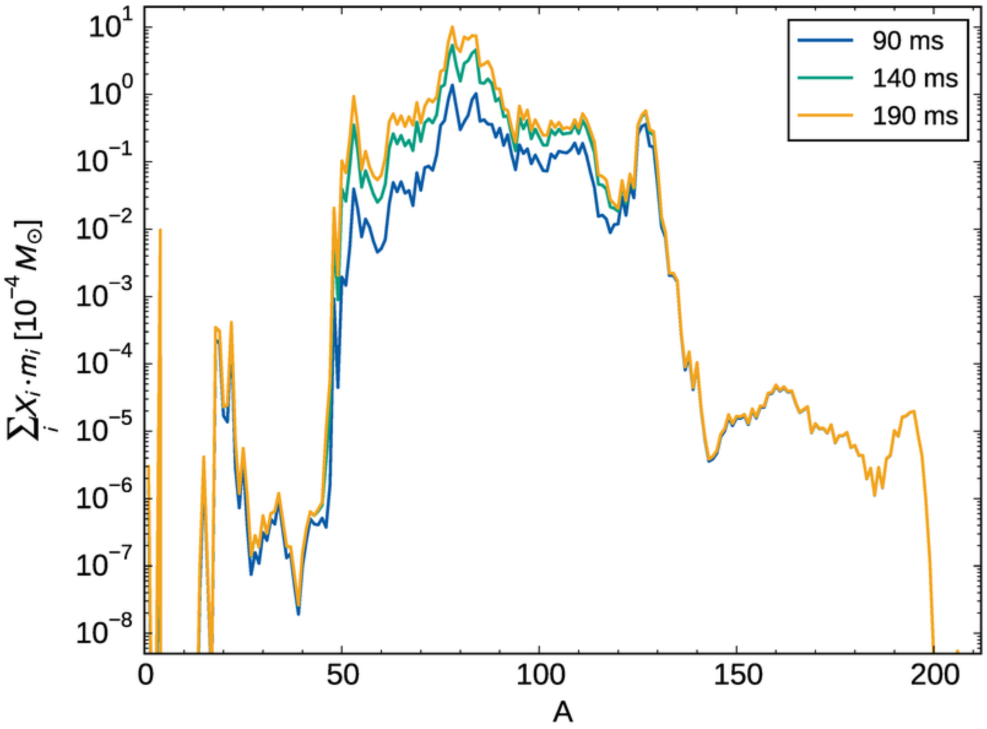
An HyperMassive Neutron Star produces large neutrino fluxes that drive the nucleosynthesis to light elements

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





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

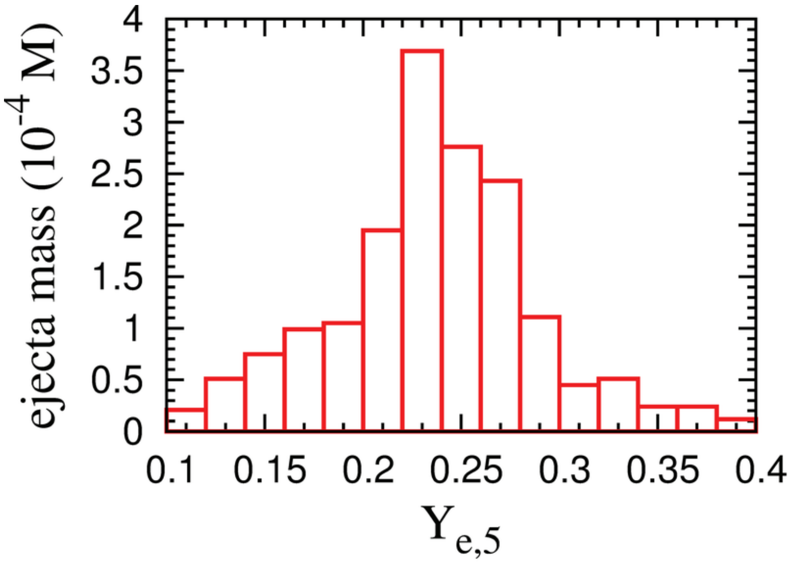


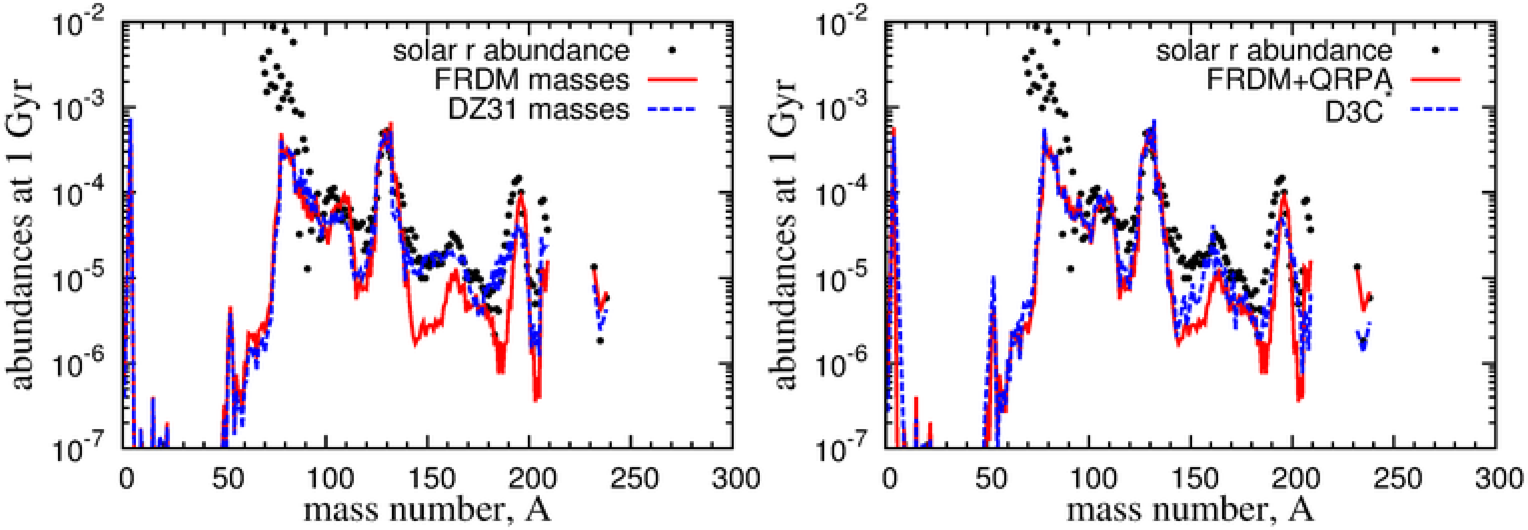
No Lanthanides are produced

See also Lippuner, et al MNRAS 472, 904 (2017).

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)]

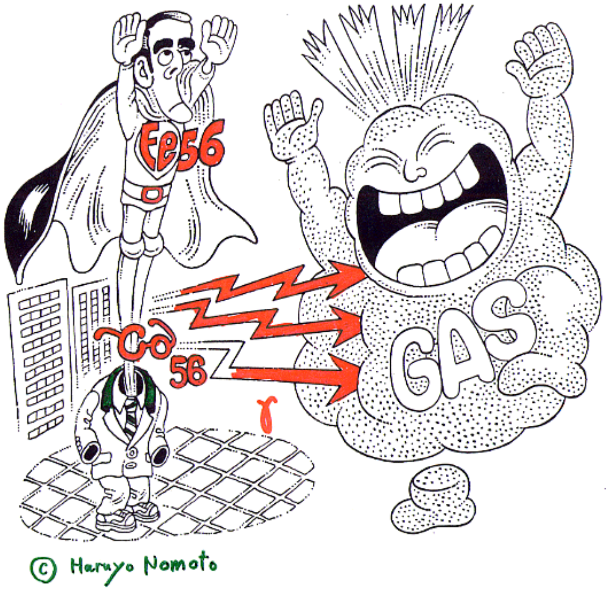


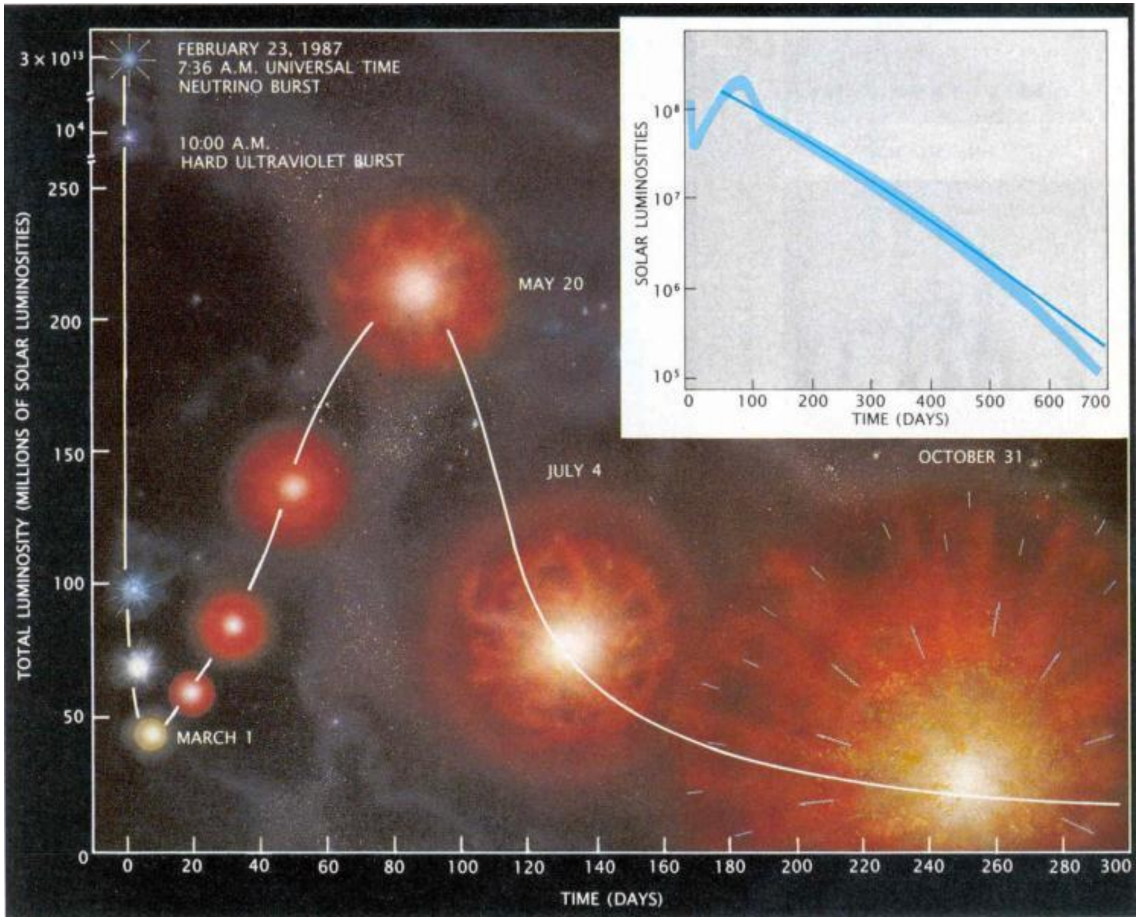


See also Just et al, MNRAS **448**, 541 (2015), Siegel and Metzger PRL **119**, 231102 (2017).

Supernova light curve: *signature of nucleosynthesis*

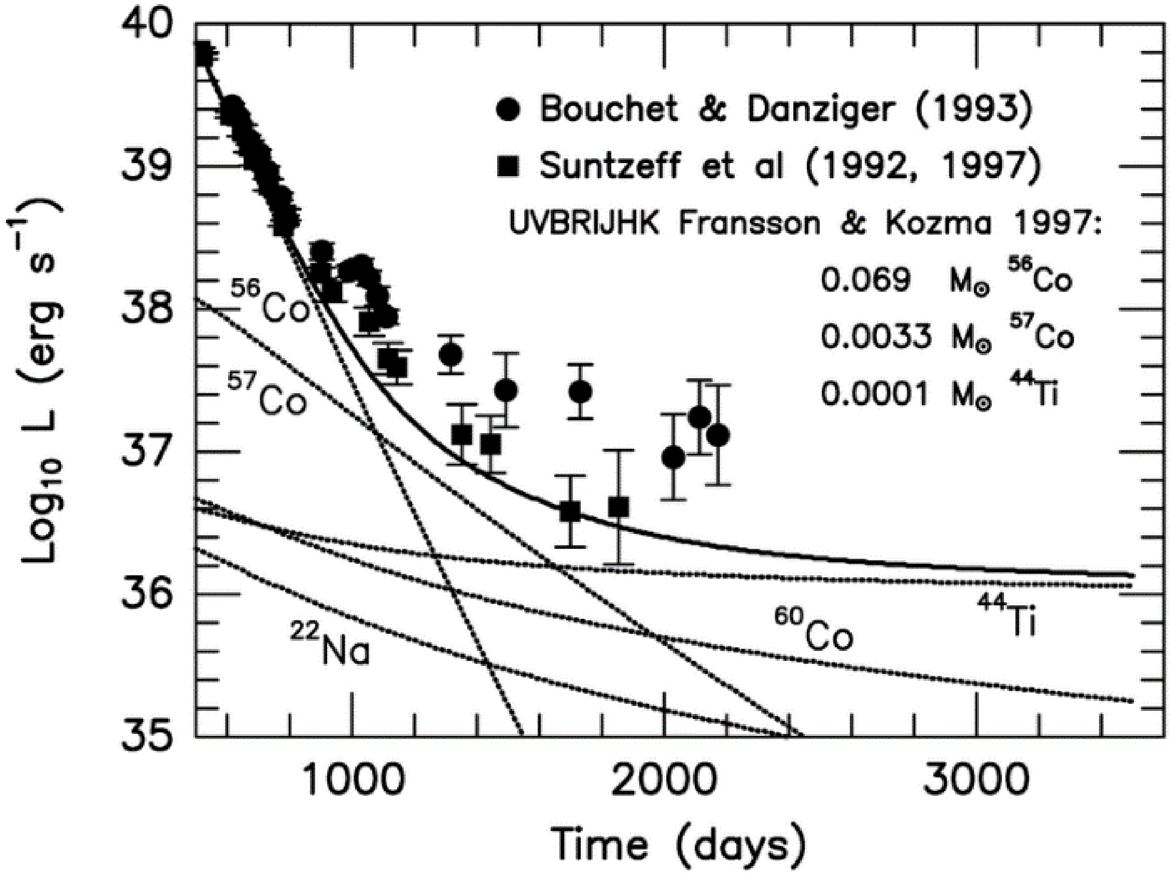
Supernova light curves follow the beta decay of ^{56}Ni ($t_{1/2} = 6\ \mathrm{d}$) and later ^{56}Co ($t_{1/2} = 77\ \mathrm{d}$)





Woosley & Weaver, Scientific American 261, 1989

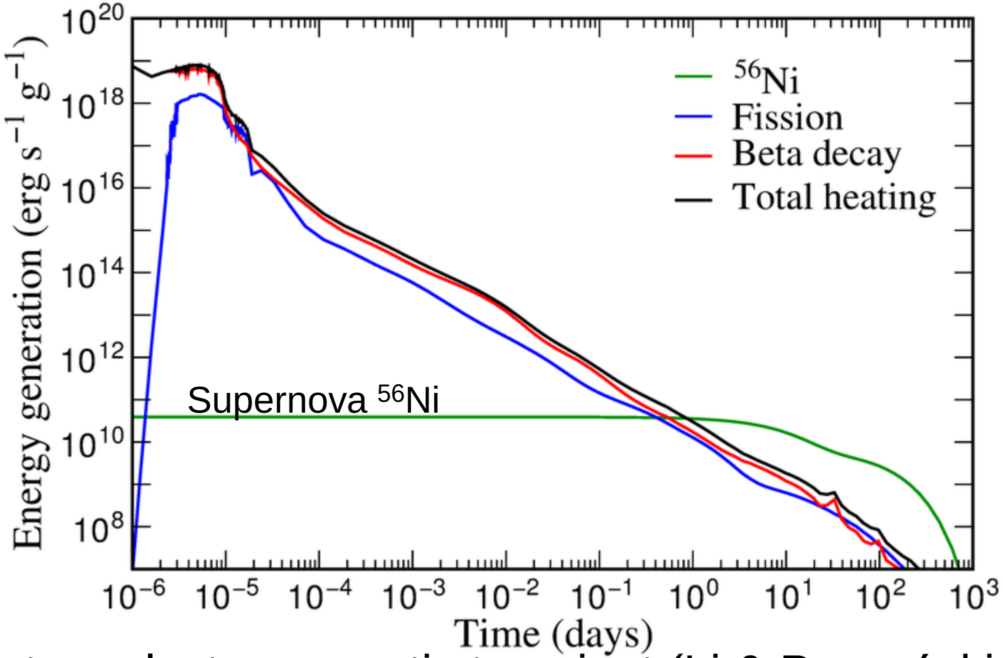
Supernova light curve: *signature of nucleosynthesis*



Diehl & Timmes, PASP 110, 637 (1998)

Energy production from r process ejecta

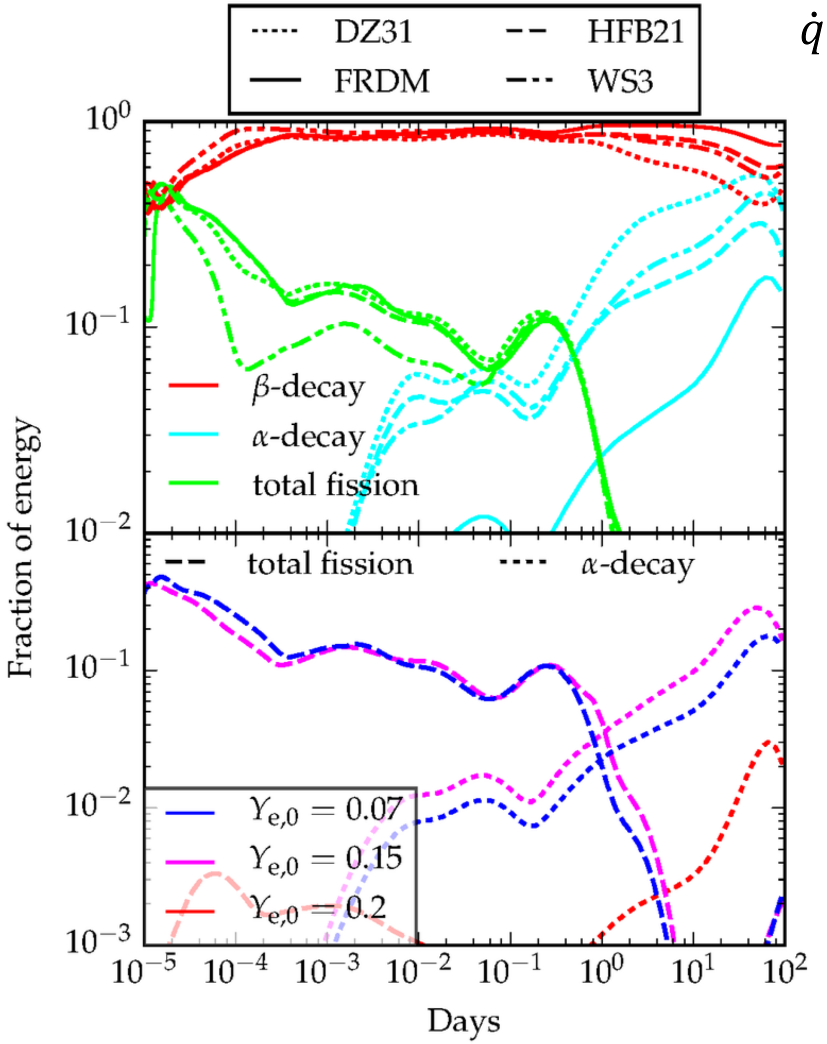
At early times (days), the decay of r process products produces energy following a power law $\dot{\varepsilon} \sim t^{-1.3}$ (Way & Wigner 1948, Metzger et al 2010). Many nuclei decaying at the same time heating up the ejecta



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)

Energy production and thermalization

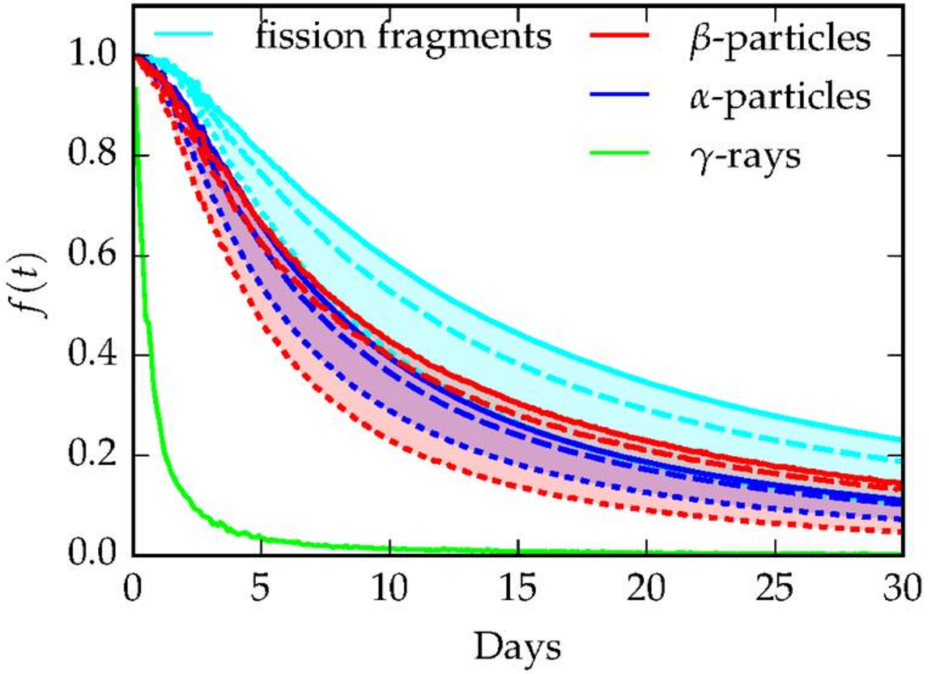


$$\dot{q}(t) = \sum_k f_k(t)\dot{\epsilon}_k(t)$$

$\dot{\epsilon}_k(t)$ energy emitted in particle k

$f_k(t)$ thermalization efficiency particle k

Thermalization depends on particle, ejecta dynamics, magnetic field, …



See Barnes, Kasen, Wu, GMP, ApJ 829, 110 (2016); Kasen & Barnes, arXiv:1807.03319

Impact of opacity

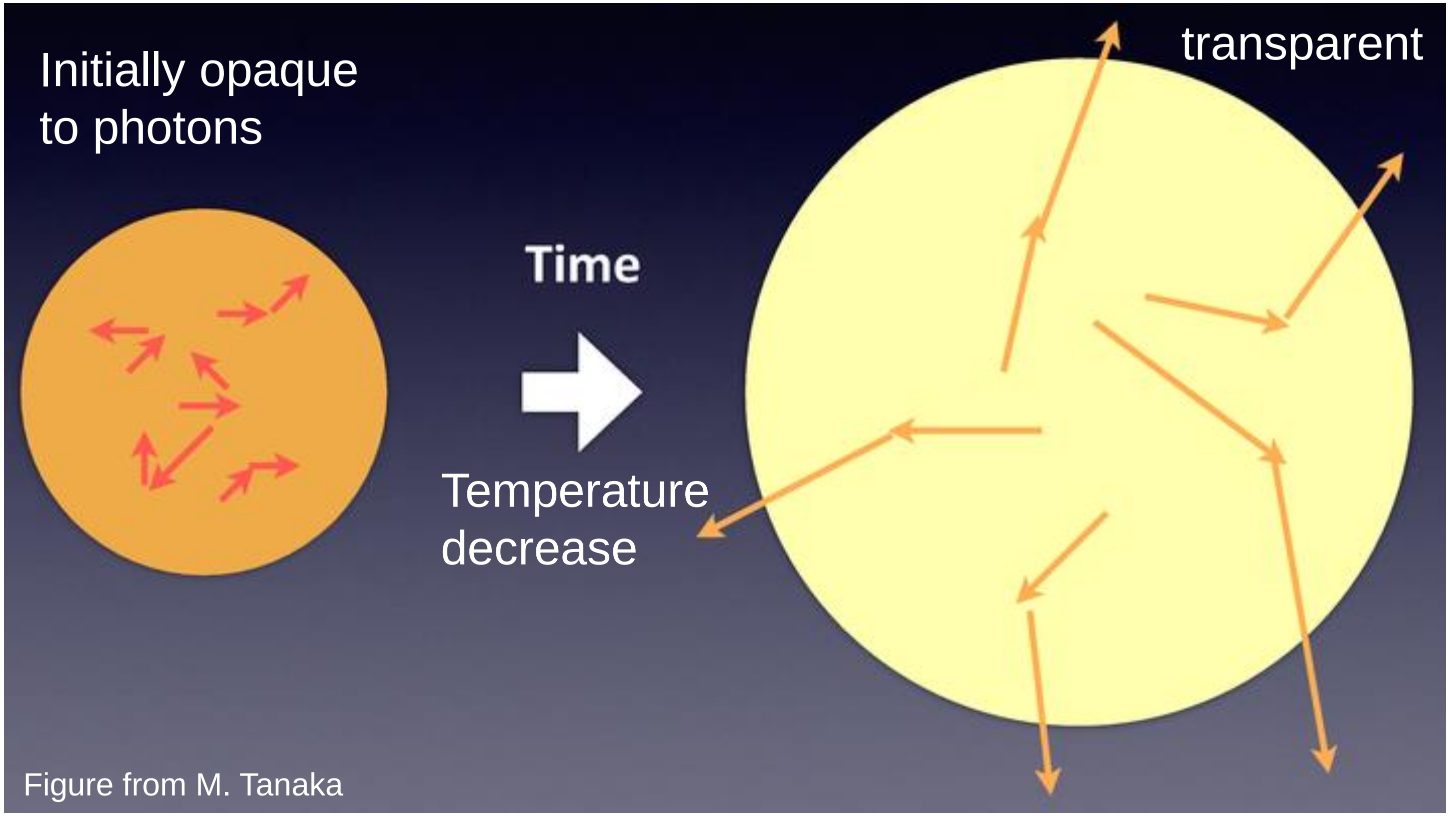


Figure from M. Tanaka

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

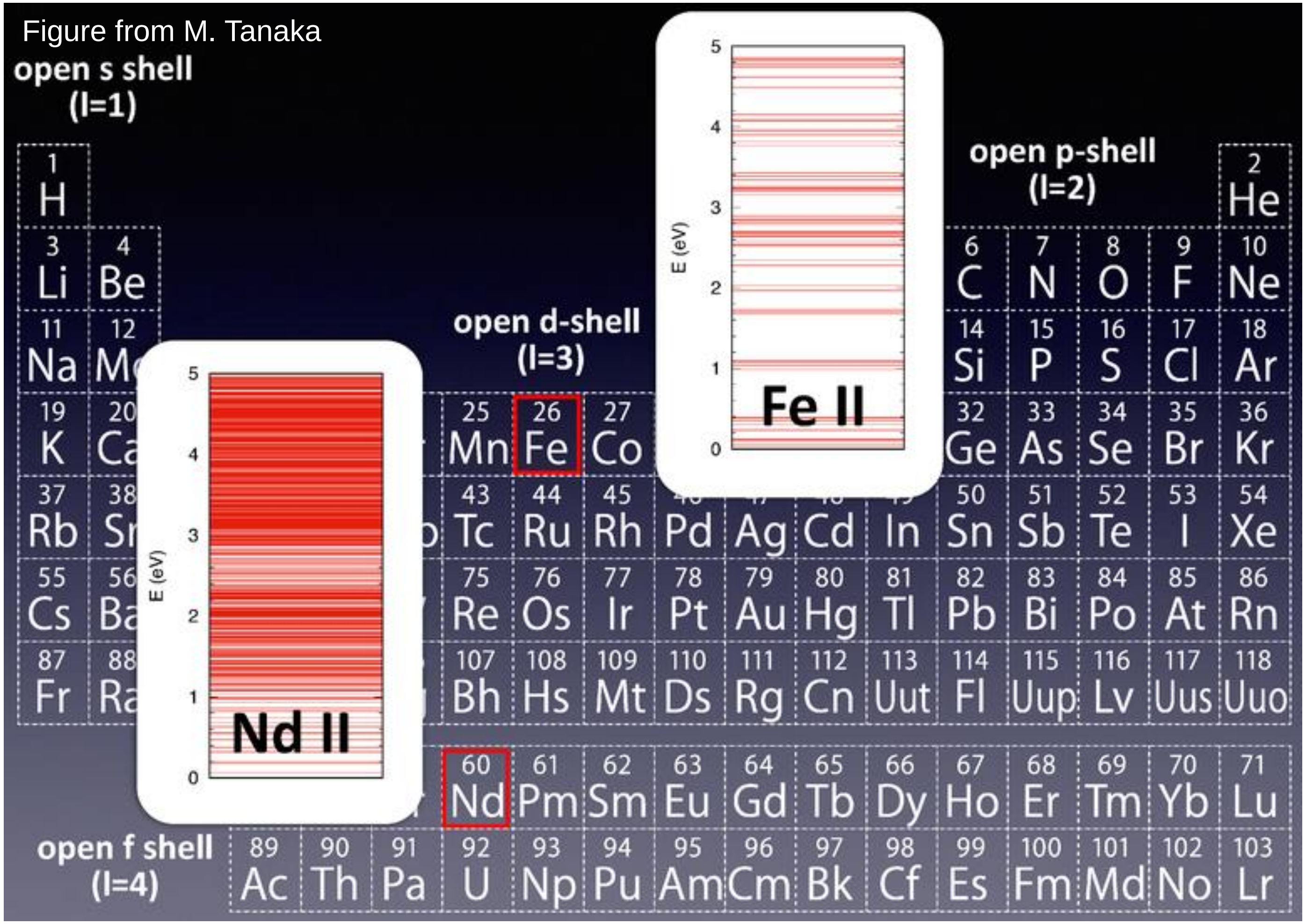
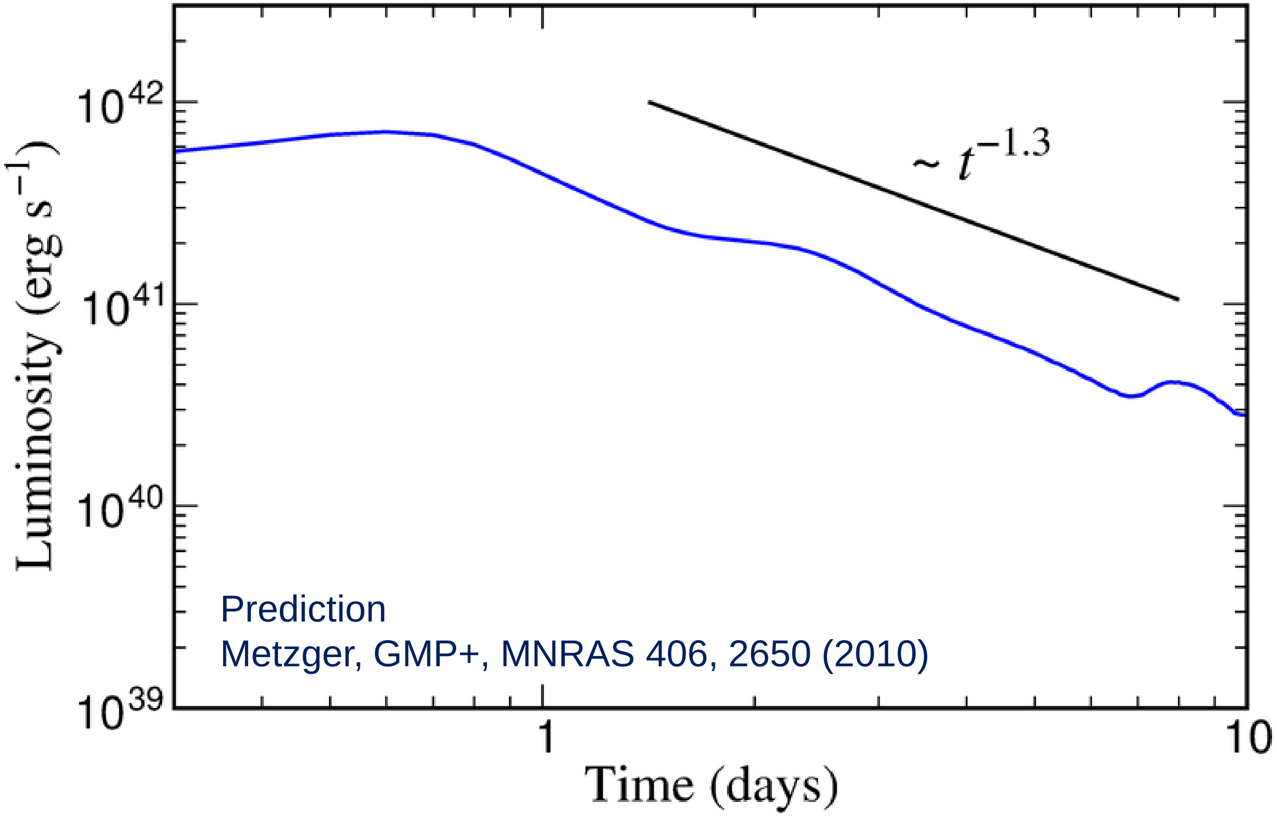


Figure from M. Tanaka

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 signature of the r process



Prediction
Metzger, GMP+, MNRAS 406, 2650 (2010)

Luminosity equivalent to 1000 novas (kilonova) in timescales of days.
Depends on amount of ejected material, velocity and composition.

Simple Kilonova model

Light curve is expected to peak when photon diffusion time is comparable to elapsed time (Metzger et al 2010, Kasen et al 2017)

$$t_{\mathrm{diff}} = \frac{\rho\kappa R^2}{c}, \qquad \rho = \frac{M}{4\pi R^3/3}, \qquad R = vt$$

$$t_{\mathrm{peak}} \approx \left(\frac{3\kappa M}{4\pi c v}\right)^{\frac{1}{2}} \approx 2.7\ \mathrm{days}\left(\frac{M}{0.01\ M_\odot}\right)^{\frac{1}{2}}\left(\frac{v}{0.01c}\right)^{-\frac{1}{2}}\left(\frac{\kappa}{1\ \mathrm{cm}^2\ \mathrm{g}^{-1}}\right)^{\frac{1}{2}}$$

The Luminosity is $L(t) \approx M\,\dot{\varepsilon}(t)$, $\dot{\varepsilon}(t) \approx 10^{10}\left(\frac{t}{1\ \mathrm{day}}\right)^{-\alpha}\ \mathrm{erg\ s^{-1}\ g^{-1}}$

$$L_{\mathrm{peak}} \approx 5\times 10^{40} \mathrm{erg\ s}^{-1}\left(\frac{M}{0.01\ M_\odot}\right)^{1-\frac{\alpha}{2}}\left(\frac{v}{0.01c}\right)^{\frac{\alpha}{2}}\left(\frac{\kappa}{1\ \mathrm{cm}^2\ \mathrm{g}^{-1}}\right)^{-\frac{\alpha}{2}}$$

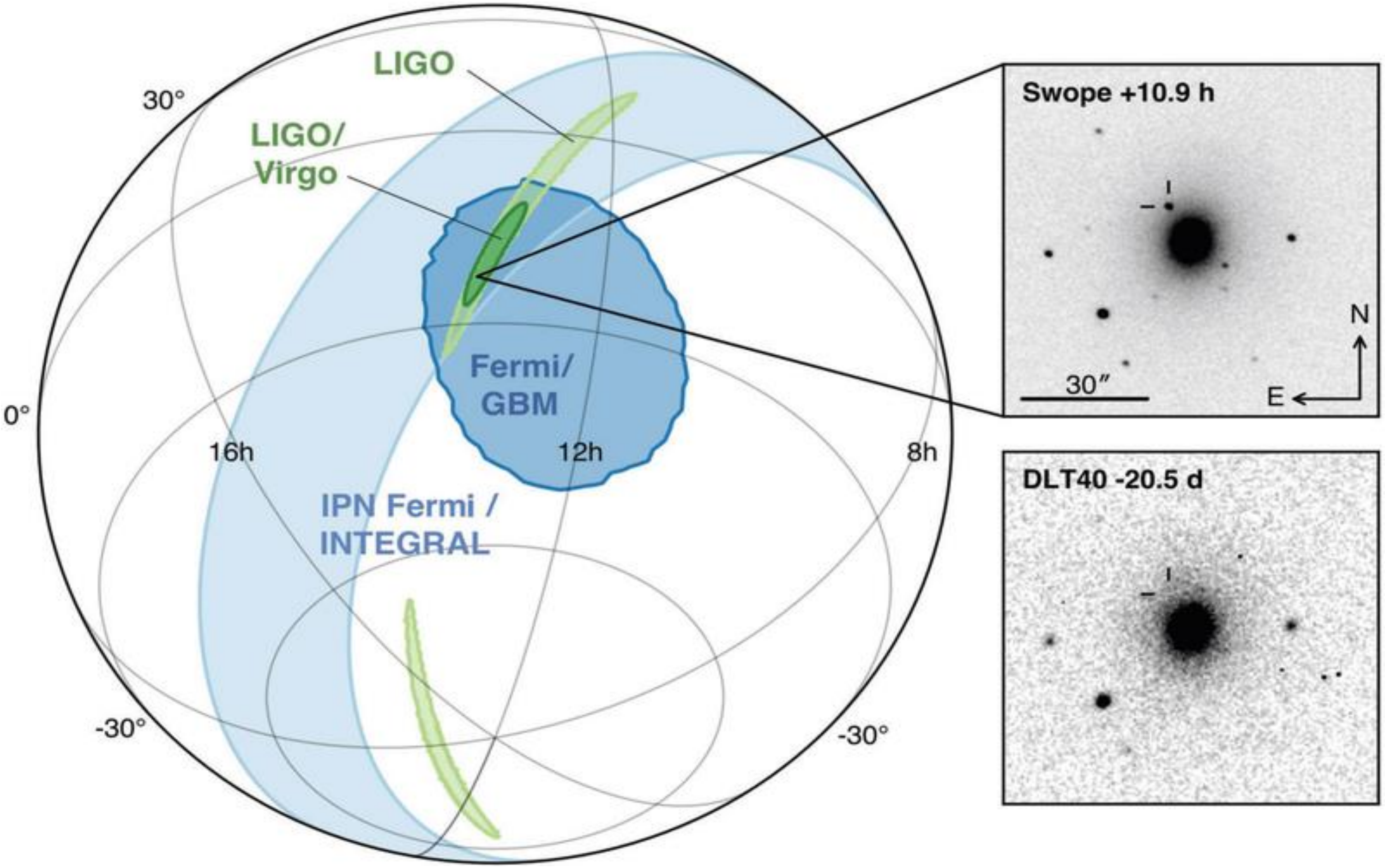
Very sensitive to atomic opacity

$\kappa \approx 1\ \mathrm{cm}^2\ \mathrm{g}^{-1}$, light r process material (blue emission)

$\kappa \approx 10\ \mathrm{cm}^2\ \mathrm{g}^{-1}$, heavy (lanthanide/actinide rich) r process (red emis.)

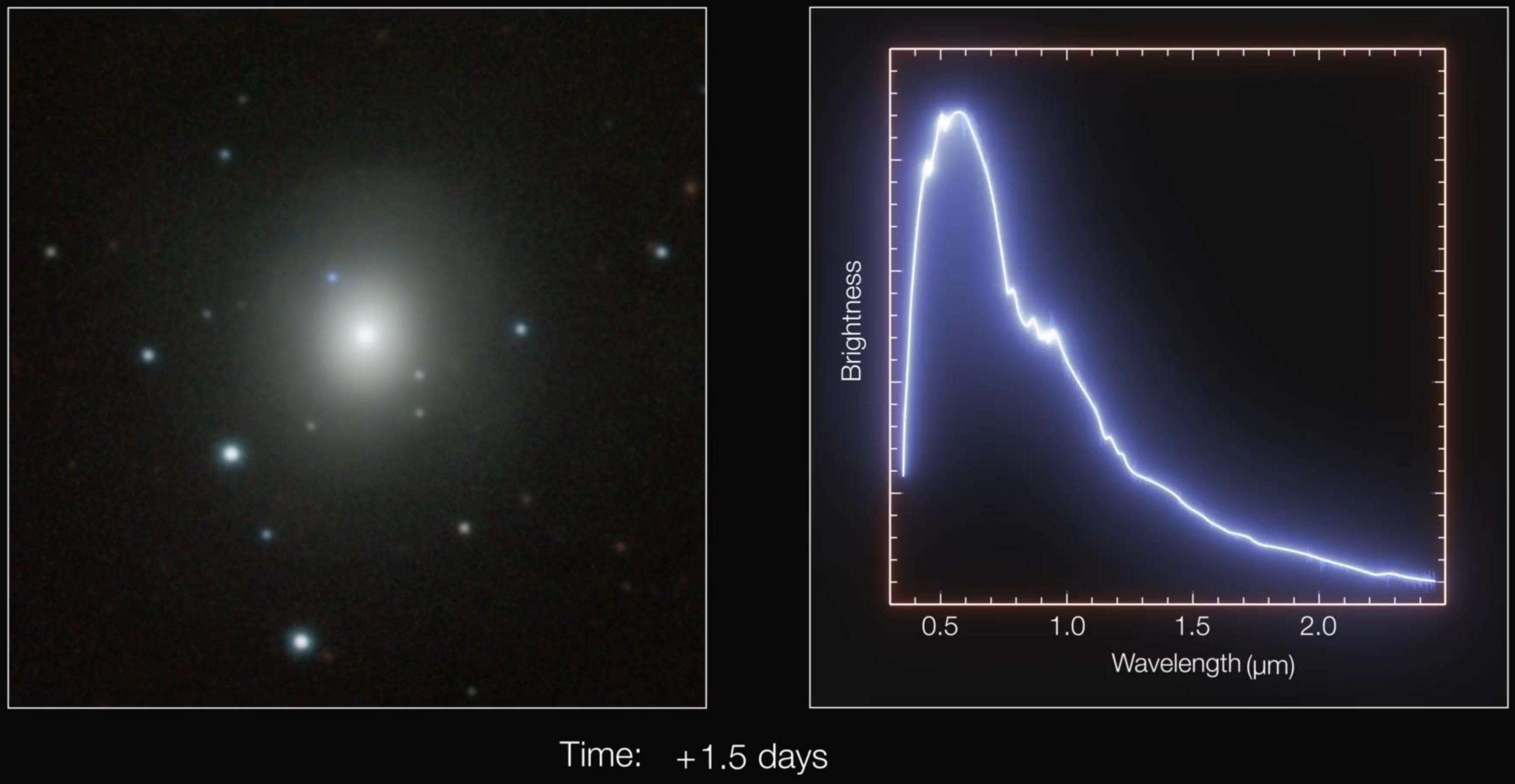
Optical transient identified

Kilonova identified 10.9 hours after the LIGO/Virgo gravitational signal GW170817 on August 17, 2017, in the Galaxy NGC 4993 near the constellation of Hydra (Southern hemisphere). Denoted AT 2017 gfo



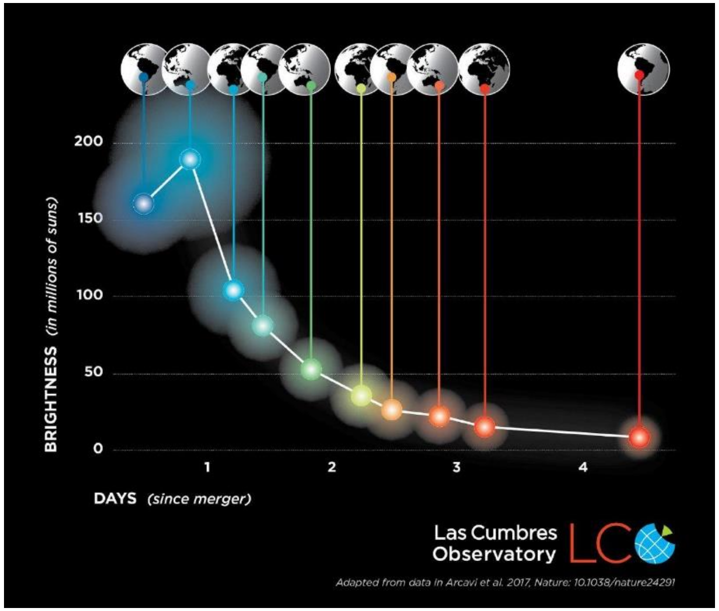
Light curve and spectra evolution

https://youtu.be/kZiCKULA2cE

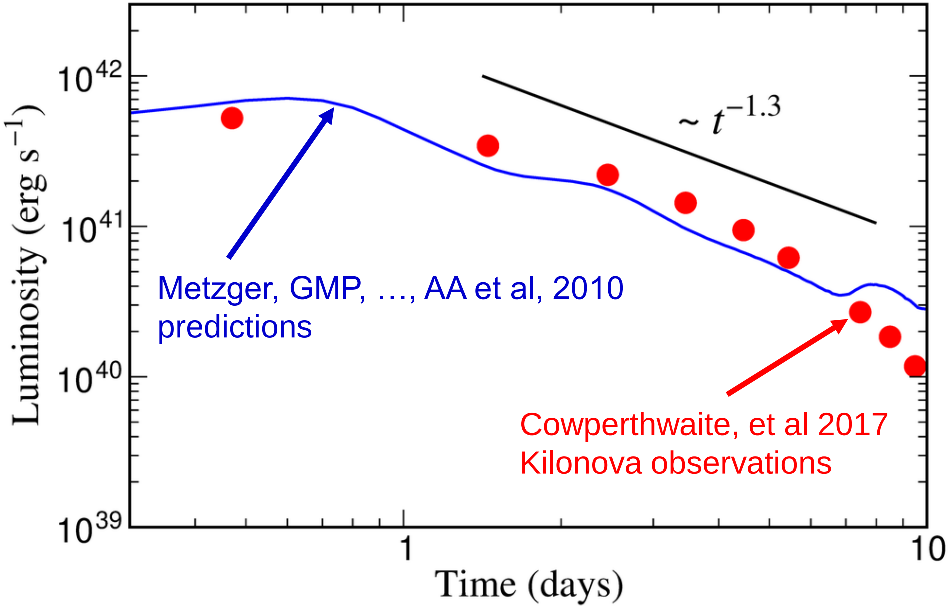


ESO/E. Pian/S. Smartt & ePESSTO/N. Tanvir/VIN-ROUGE, Pian et al, Nature 551, 67, 2017

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



Adapted from data in Arcavi et al. 2017, Nature: 10.1038/nature24291



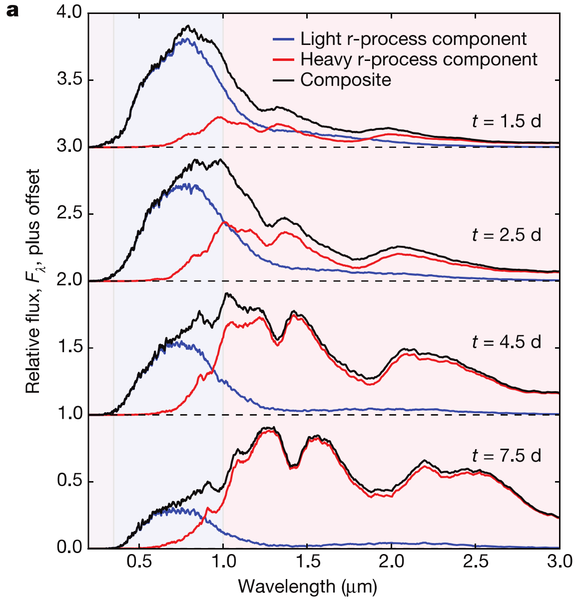
Metzger, GMP, …, AA et al, 2010 predictions

Cowperthwaite, et al 2017 Kilonova observations

- 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

Two components model

Kasen et al, Nature 551, 80 (2017)

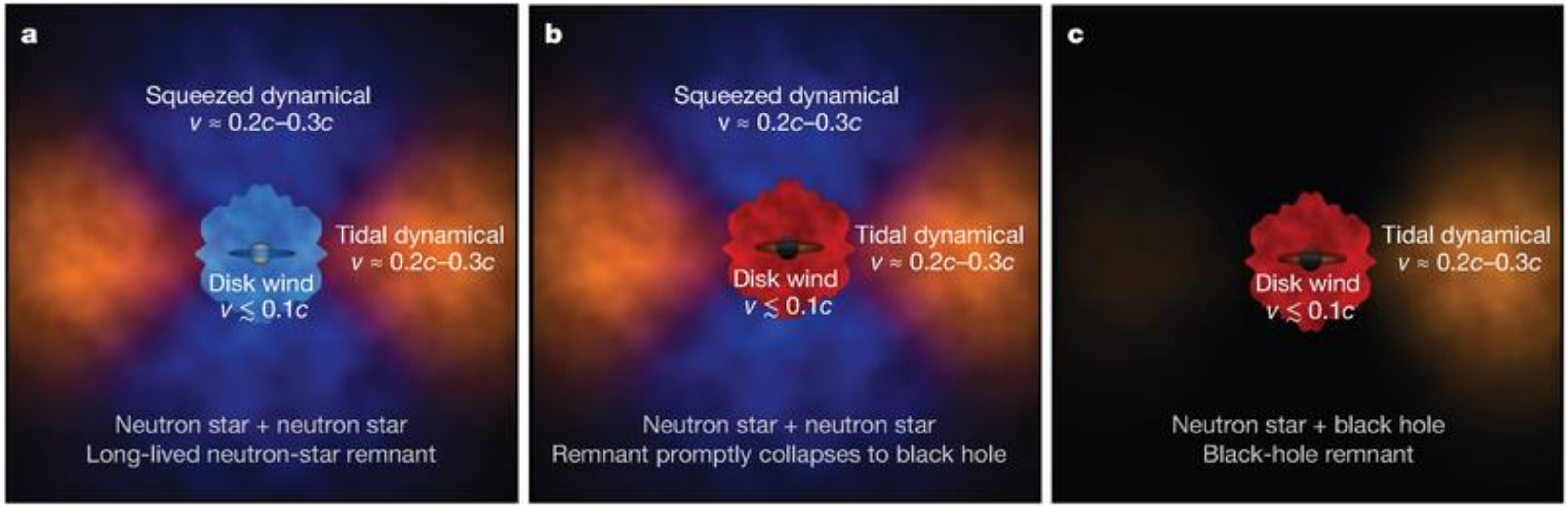


- Blue component from polar ejecta subject to strong neutrino fluxes (light r process)

$$M = 0.025\, M_{\odot}, v = 0.3c, X_{\text{lan}} = 10^{-4}$$

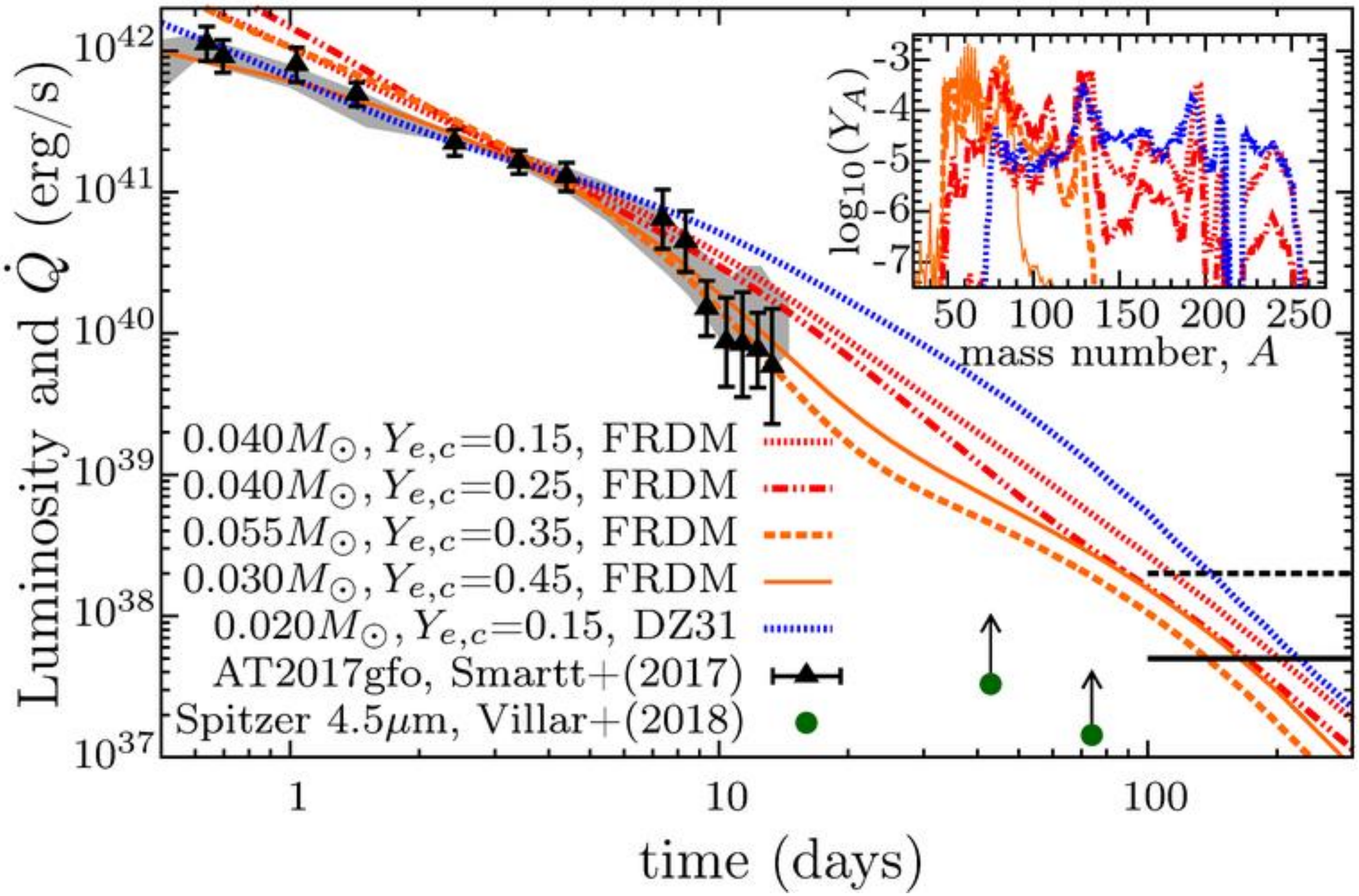
- Red component disk ejecta after NS collapse to a black hole (includes both light and heavy r process)

$$M = 0.04\, M_{\odot}, v = 0.15c, X_{\text{lan}} = 10^{-1.5}$$



Nuclear fingerprints light curve

Can we identify particular nuclear signatures in the light curve?



Wu, Barnes, GMP, Metzger, arXiv:1808.10459

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

Dominating decay chains

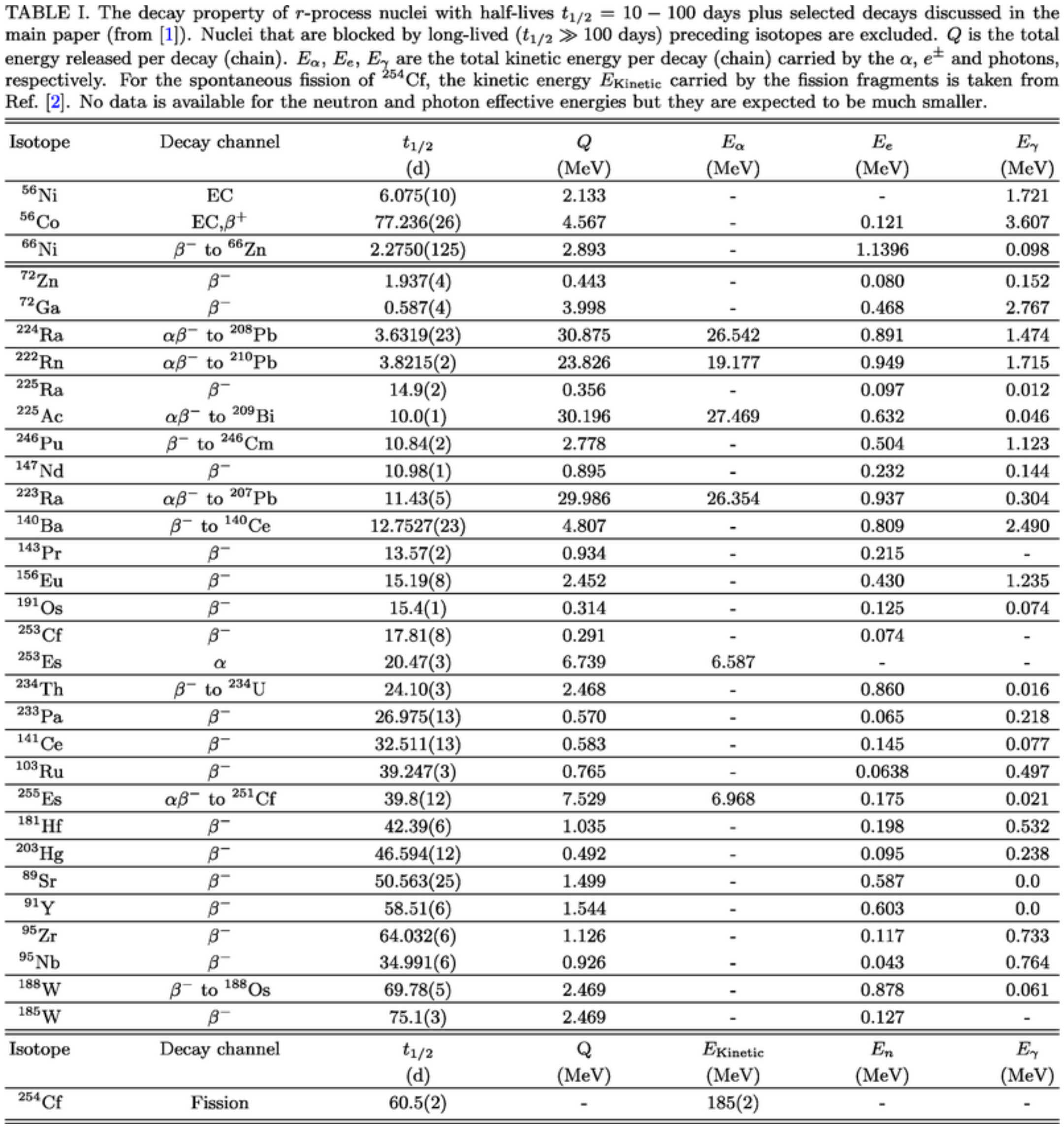


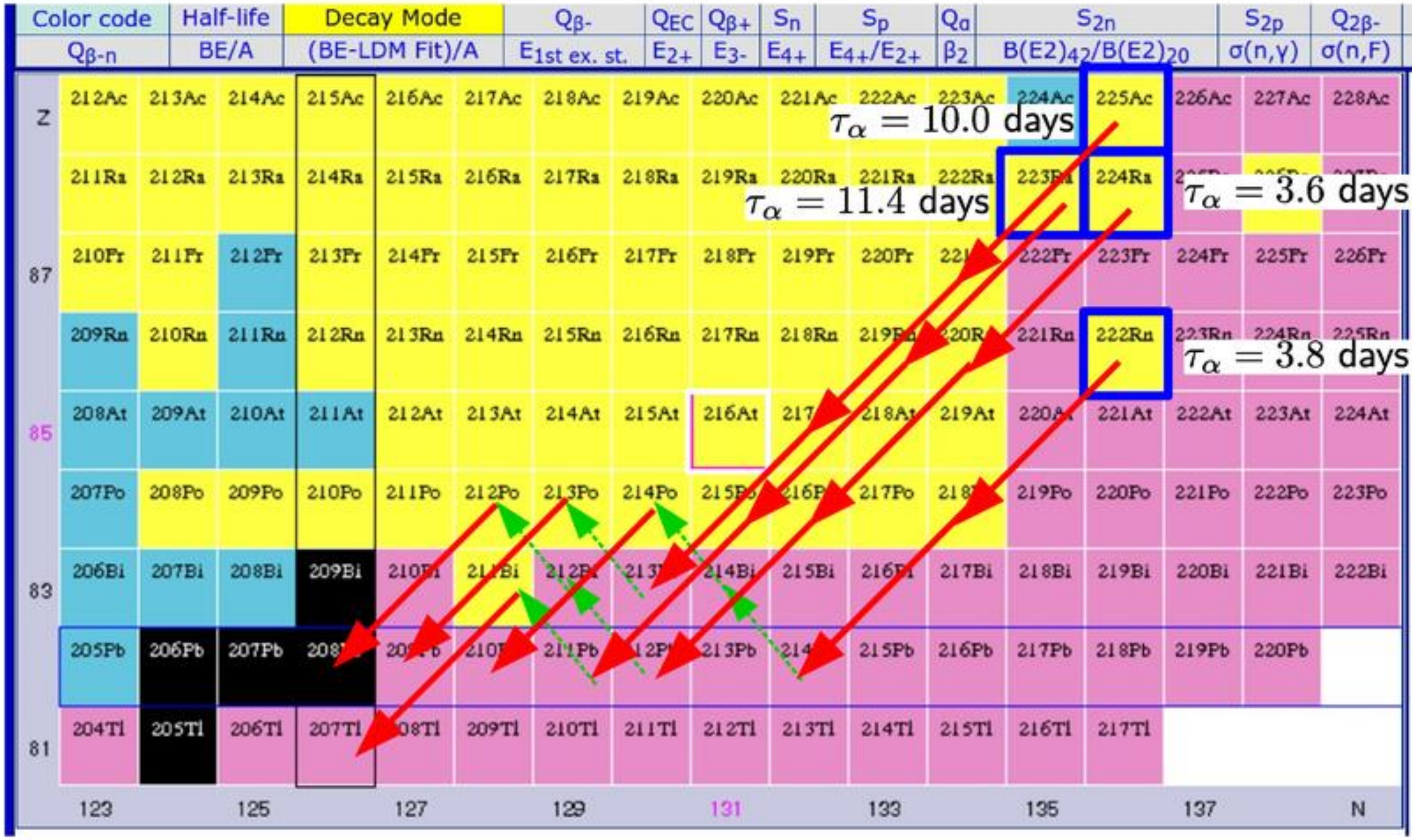
TABLE I. The decay property of r-process nuclei with half-lives $t_{1/2} = 10 - 100$ days plus selected decays discussed in the main paper (from [1]). Nuclei that are blocked by long-lived ($t_{1/2} \gg 100$ days) preceding isotopes are excluded. Q is the total energy released per decay (chain). E_α, E_e, E_γ are the total kinetic energy per decay (chain) carried by the α, $e^\pm$ and photons, respectively. For the spontaneous fission of ^{254}Cf, the kinetic energy $E_{\rm Kinetic}$ carried by the fission fragments is taken from Ref. [2]. No data is available for the neutron and photon effective energies but they are expected to be much smaller.

Isotope	Decay channel	$t_{1/2}$ (d)	Q (MeV)	E_α (MeV)	E_e (MeV)	E_γ (MeV)
^{56}Ni	EC	6.075(10)	2.133	-	-	1.721
^{56}Co	EC,β^+	77.236(26)	4.567	-	0.121	3.607
^{66}Ni	β^- to ^{66}Zn	2.2750(125)	2.893	-	1.1396	0.098
^{72}Zn	β^-	1.937(4)	0.443	-	0.080	0.152
^{72}Ga	β^-	0.587(4)	3.998	-	0.468	2.767
^{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
^{246}Pu	β^- to ^{246}Cm	10.84(2)	2.778	-	0.504	1.123
^{147}Nd	β^-	10.98(1)	0.895	-	0.232	0.144
^{223}Ra	$\alpha\beta^-$ to ^{207}Pb	11.43(5)	29.986	26.354	0.937	0.304
^{140}Ba	β^- to ^{140}Ce	12.7527(23)	4.807	-	0.809	2.490
^{143}Pr	β^-	13.57(2)	0.934	-	0.215	-
^{156}Eu	β^-	15.19(8)	2.452	-	0.430	1.235
^{191}Os	β^-	15.4(1)	0.314	-	0.125	0.074
^{253}Cf	β^-	17.81(8)	0.291	-	0.074	-
^{253}Es	α	20.47(3)	6.739	6.587	-	-
^{234}Th	β^- to ^{234}U	24.10(3)	2.468	-	0.860	0.016
^{233}Pa	β^-	26.975(13)	0.570	-	0.065	0.218
^{141}Ce	β^-	32.511(13)	0.583	-	0.145	0.077
^{103}Ru	β^-	39.247(3)	0.765	-	0.0638	0.497
^{255}Es	$\alpha\beta^-$ to ^{251}Cf	39.8(12)	7.529	6.968	0.175	0.021
^{181}Hf	β^-	42.39(6)	1.035	-	0.198	0.532
^{203}Hg	β^-	46.594(12)	0.492	-	0.095	0.238
^{89}Sr	β^-	50.563(25)	1.499	-	0.587	0.0
^{91}Y	β^-	58.51(6)	1.544	-	0.603	0.0
^{95}Zr	β^-	64.032(6)	1.126	-	0.117	0.733
^{95}Nb	β^-	34.991(6)	0.926	-	0.043	0.764
^{188}W	β^- to ^{188}Os	69.78(5)	2.469	-	0.878	0.061
^{185}W	β^-	75.1(3)	2.469	-	0.127	-
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)	-	-

Wu, Barnes, GMP, Metzger, arXiv:1808.10459

Main heating sources late times

Relevant α-decays

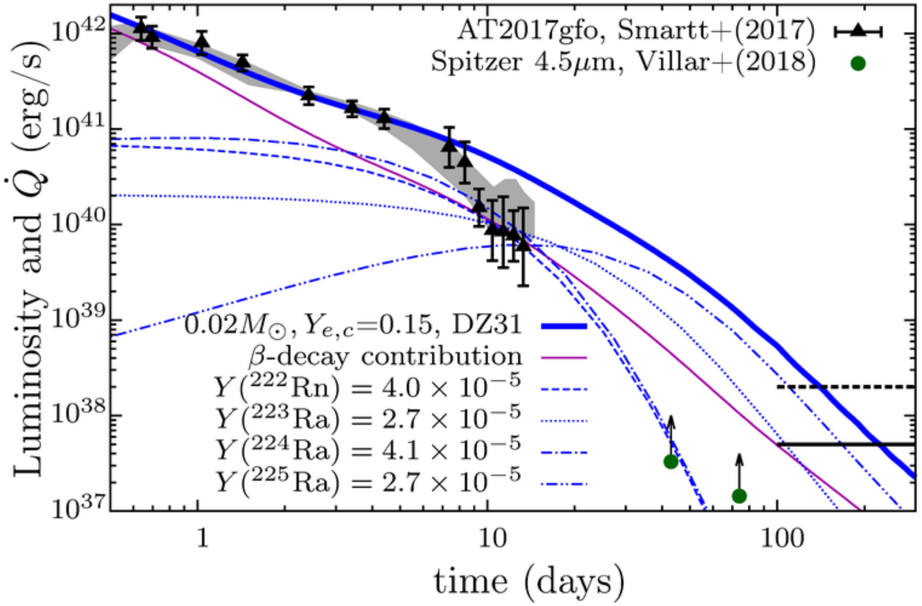


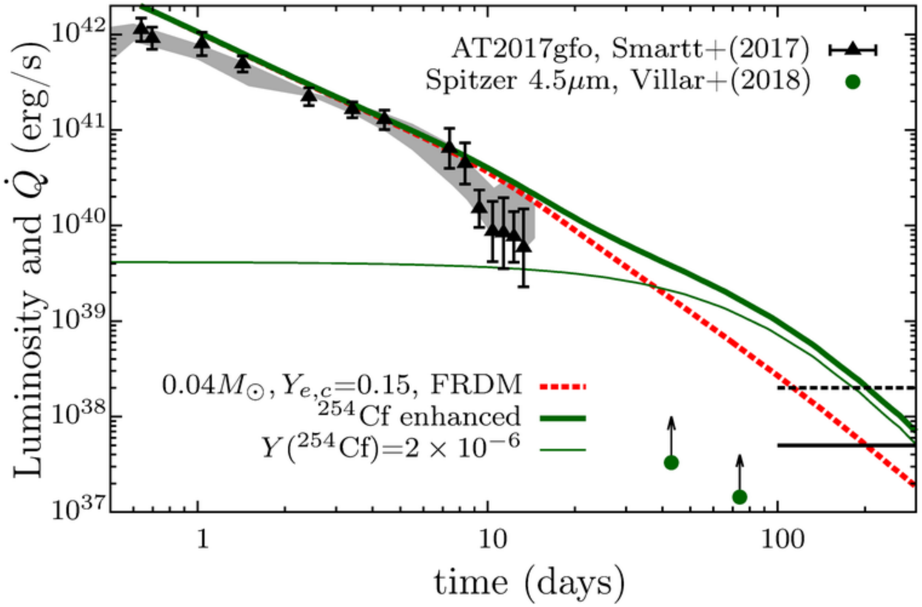
Plus fission of ^{254}Cf

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_{Kinetic} (MeV)	E_n (MeV)	E_γ (MeV)
^{254}Cf	Fission	60.5(2)	-	185(2)	-	-



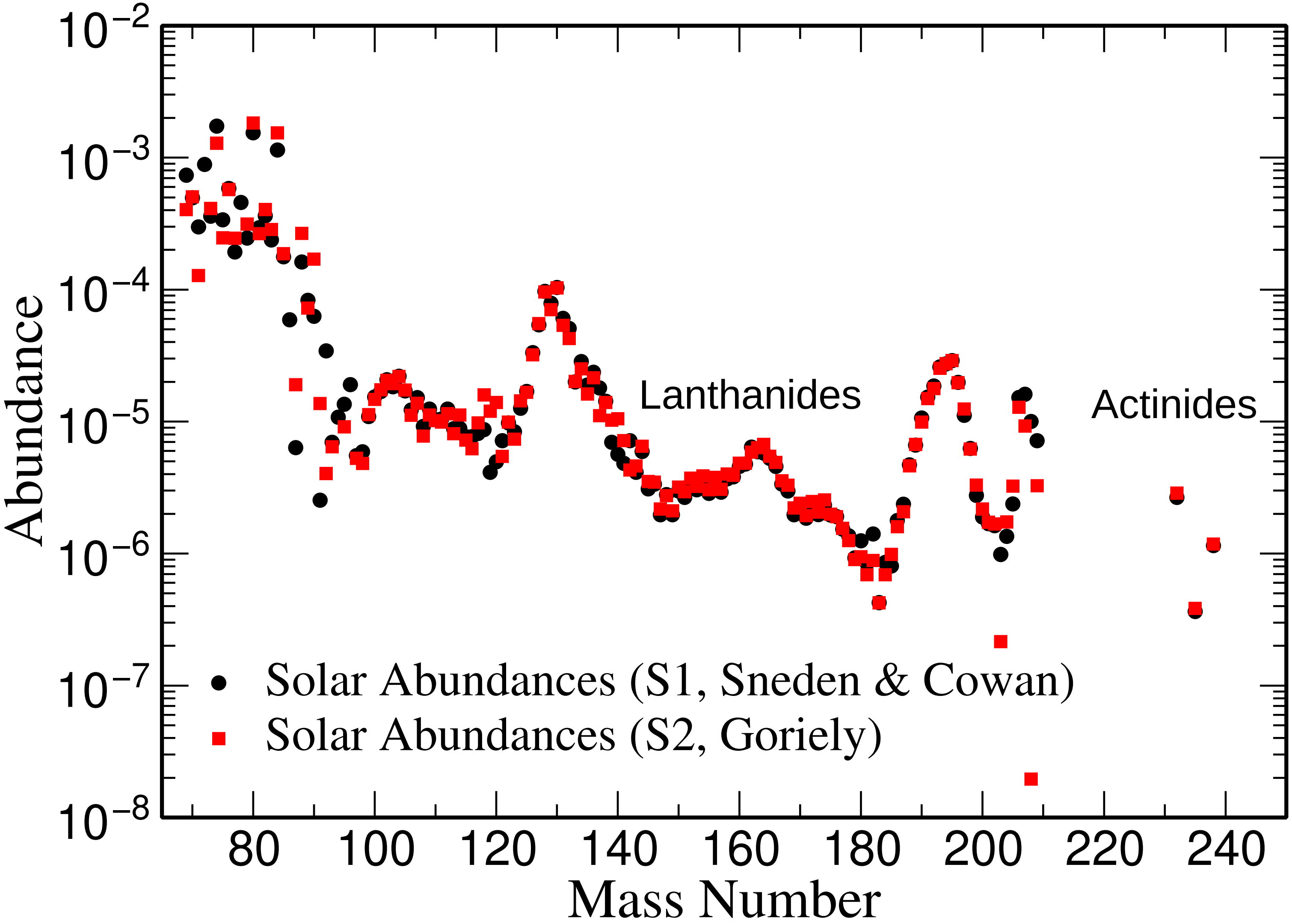


Decline observed light curve at 10 days suggest an upper limit of 0.01 $M_\odot$ of U and Th

Wu, Barnes, GMP, Metzger, arXiv:1808.10459

Sensitivity to solar abundances

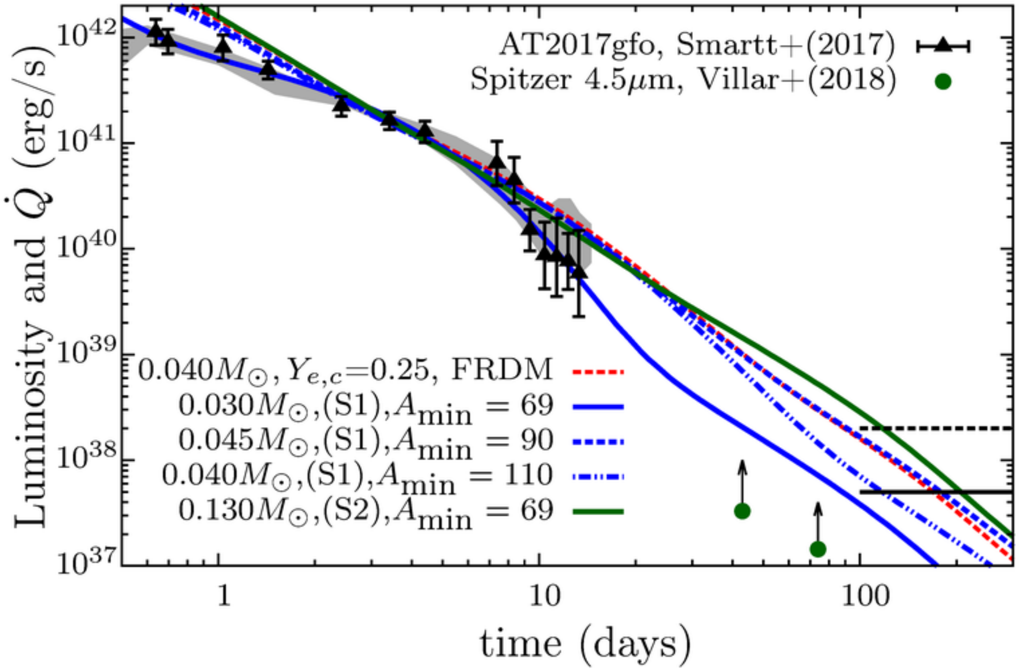
Inferred solar system abundances show large differences for light elements



Is the light curve sensitive to the Solar abundances used?

Consistency with solar r abundances

- Is the light curve consistent with the production of a Solar r-process abundance pattern?
- Large mass fraction of Lanthanides, $10^{-3} - 10^{-2}$, requires production of all r-process nuclei up to a minimum $A \sim 70$



Light curve favors production all R-process nuclei down to A ~ 69

Sensitive to Solar abundance set S1 (Sneden & Cowan), S2 (Goriely)

Very different abundances of A=72 nuclei. ^{72}Zn half-life 1.92 days.

Wu, Barnes, GMP, Metzger, arXiv:1808.10459

Summary

- Kilonova from GW170817 originates from the radioactive decay of heavy elements
- Astrophysical site of the r process is identified
- Further observations necessary to confirm variability with respect to merging system and viewing angle
- Observations in time scale 10-100 days can provide signatures of individual nuclear decays

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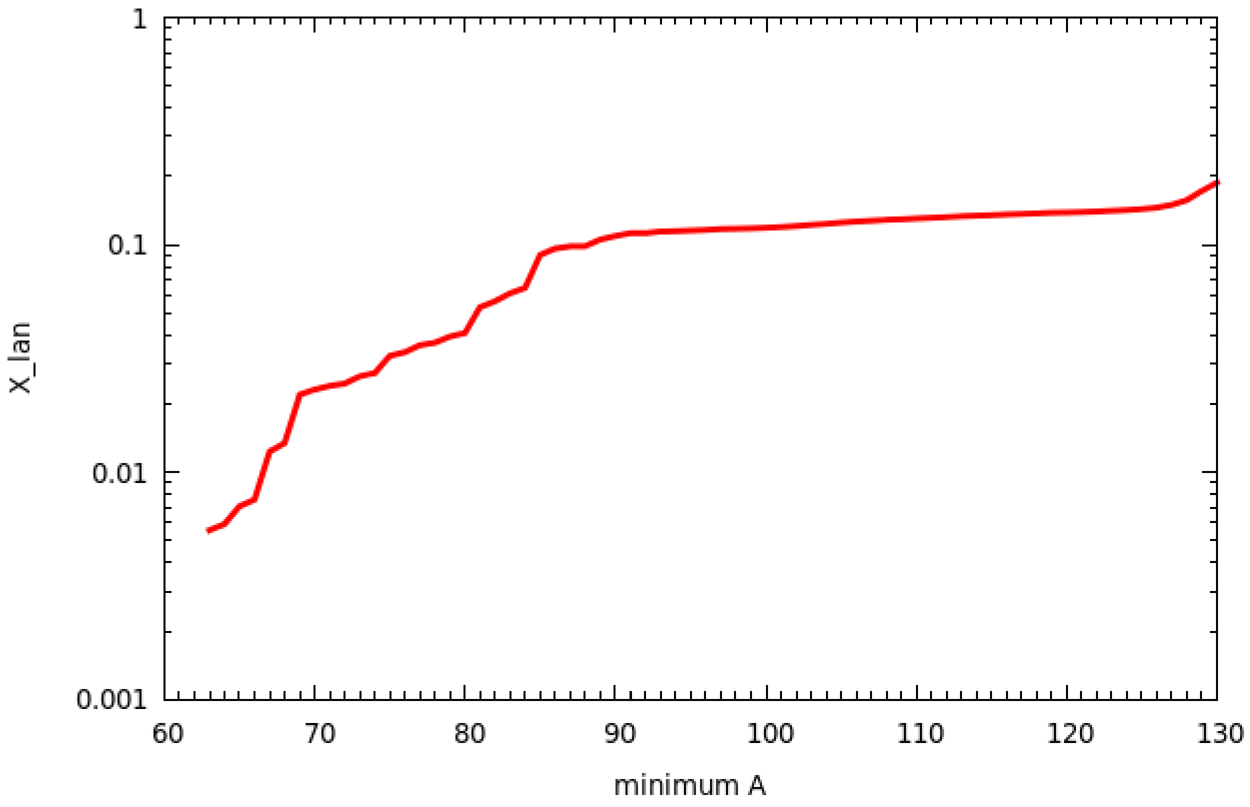
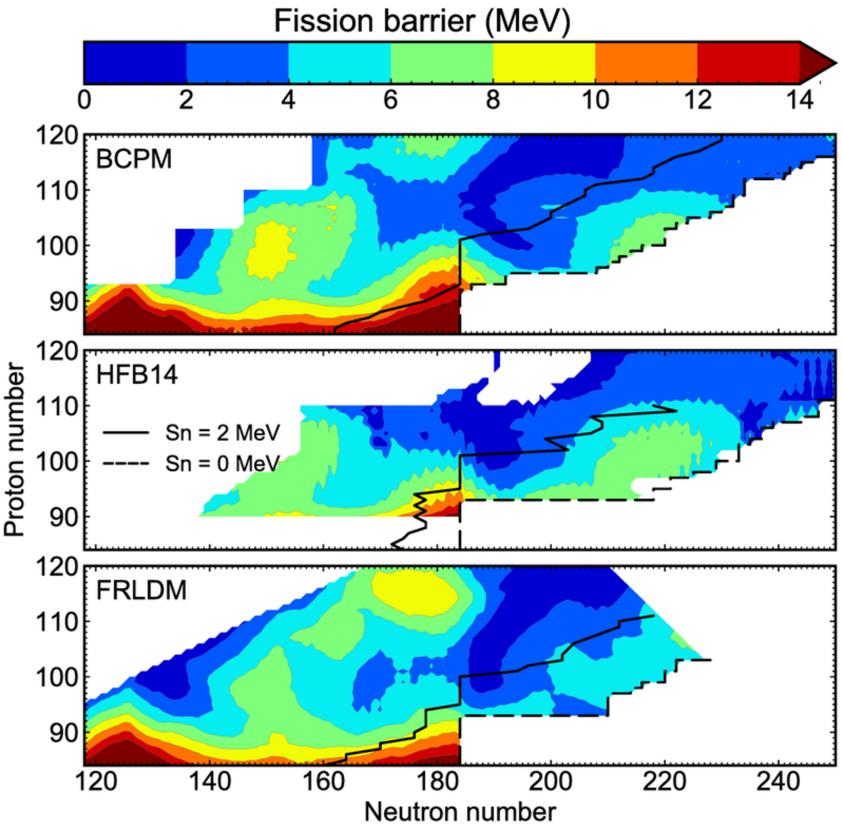
Collaborators: J. Barnes (Columbia, USA), R. Fernandez (U Alberta, Canada), D. Kasen (UC Berkeley, USA), T. Marketin (U Zagreb, Croatia), B. Metzger (Columbia, USA), L. Robledo (UAM, Madrid), T. R. Rodriguez (UAM, Madrid), S. Giuliani (MSU, USA), M.-R. Wu (A Sinica, Taiwan)

Lanthanide mass fraction

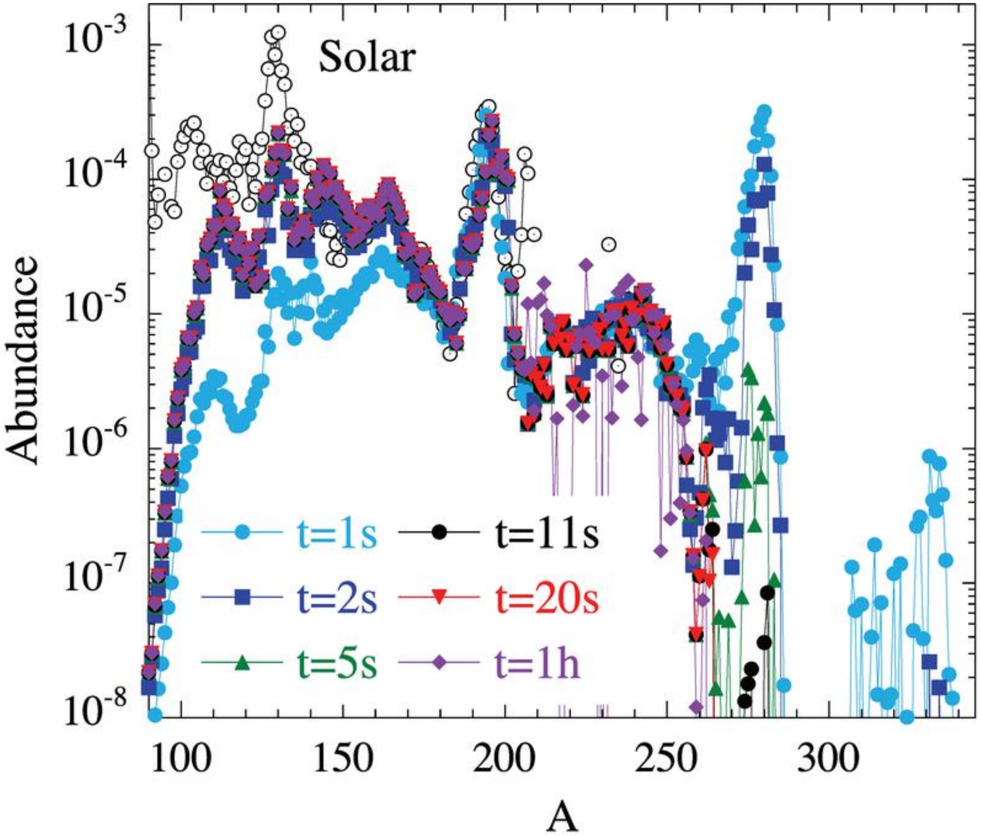


Are superheavy elements produced?

- All models predict low fission barriers beyond N= 184
- The heaviest nuclei substantially produced have A ~ 280 and Z ~ 96
- Non long-lived nuclei remain



Giuliani, GMP, Robledo, PRC 97, 034323 (2018)



Goriely, GMP, NPA 944, 158 (2015)
Petermann et al , EPJA 48, 122 (2012)