r-Process nucleosynthesis and kilonovae from neutron star mergers

Jonas Lippuner

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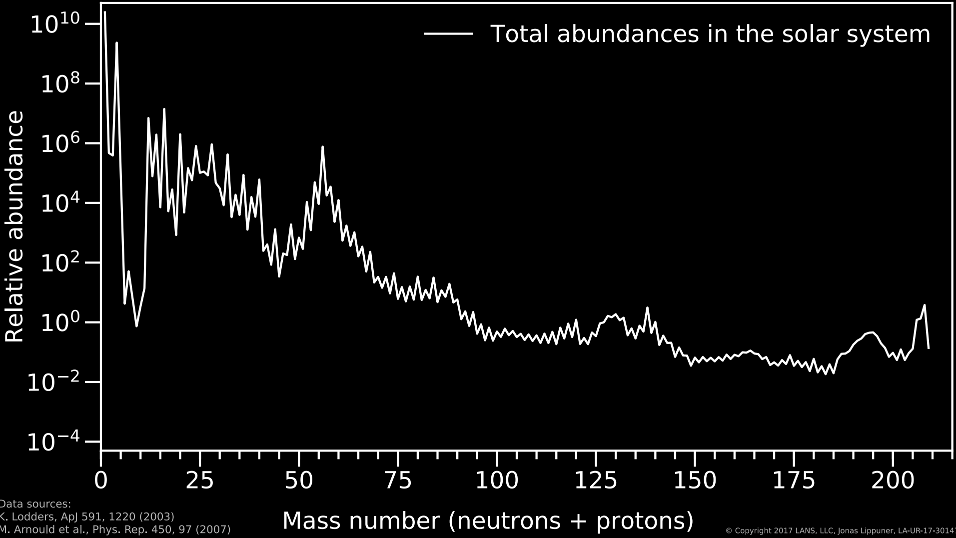
Multi-Messenger Astrophysics
in the Gravitational Wave Era
YITP, Kyoto, Japan

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

Outline

1. Very brief nucleosynthesis overview
2. The SkyNet nuclear reaction network
3. r-Process in neutron star mergers
4. Observational signature and first detection

Solar system abundances



Data sources:
K. Lodders, ApJ 591, 1220 (2003)
M. Arnould et al., Phys. Rep. 450, 97 (2007)

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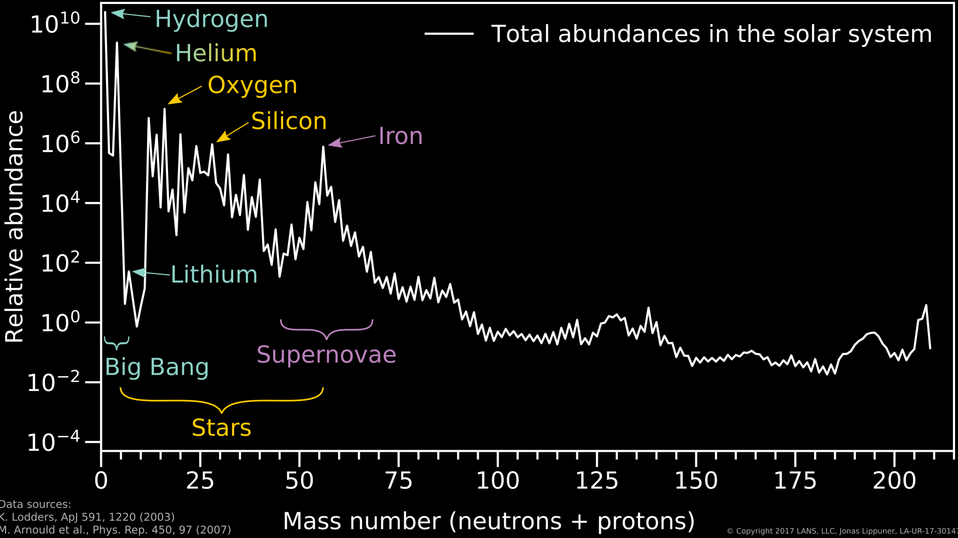

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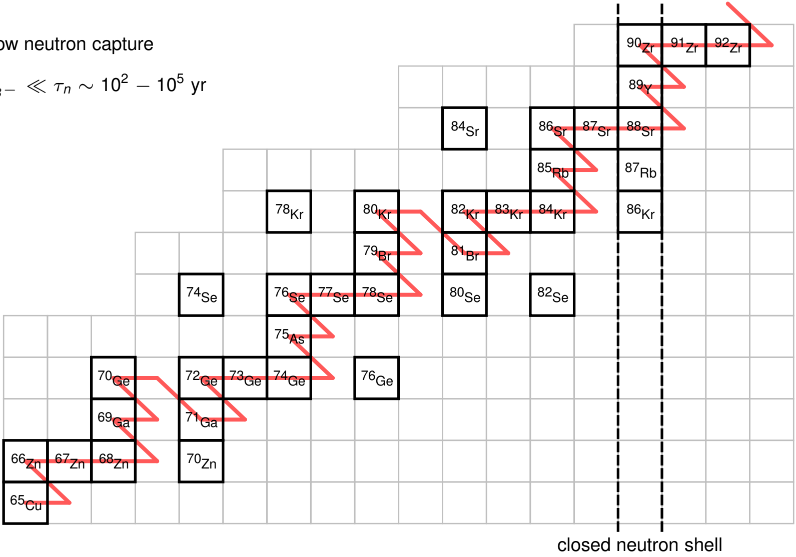
The s-process

slow neutron capture

$\tau_{\beta-} \ll \tau_n \sim 10^2 - 10^5$ yr



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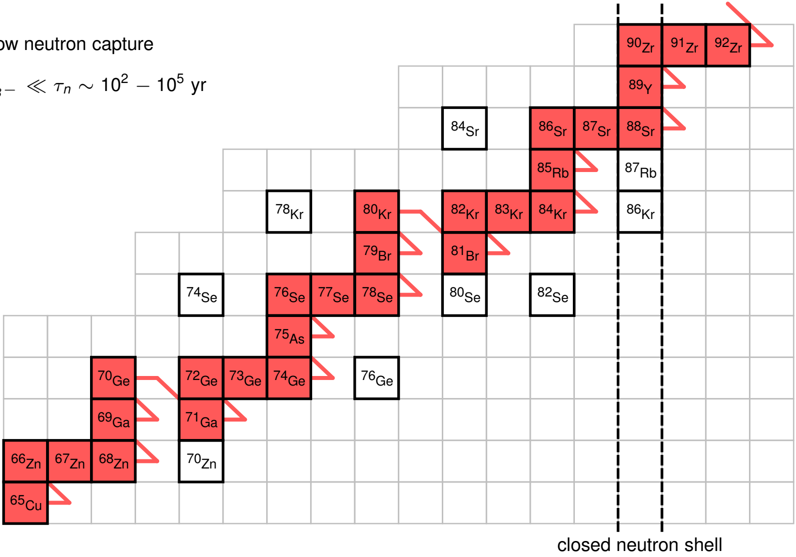
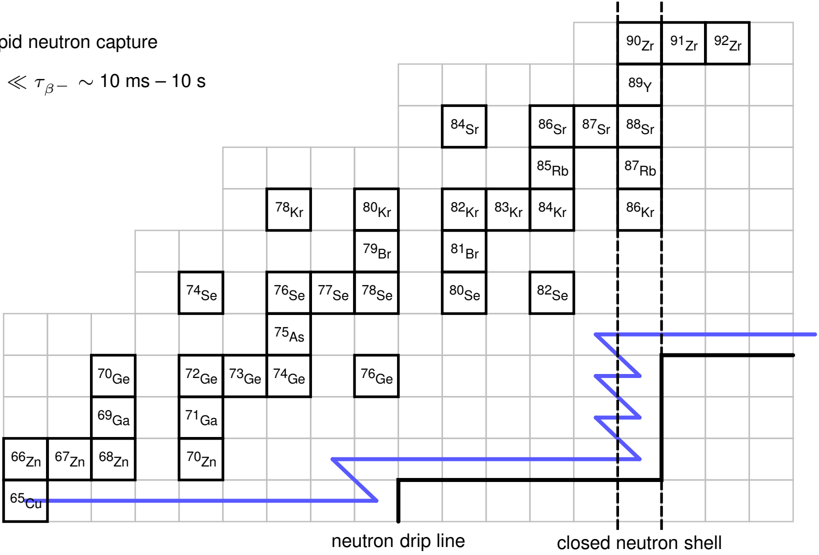


The r-process

rapid neutron capture

$\tau_n \ll \tau_{\beta-} \sim 10$ ms – 10 s



The r-process

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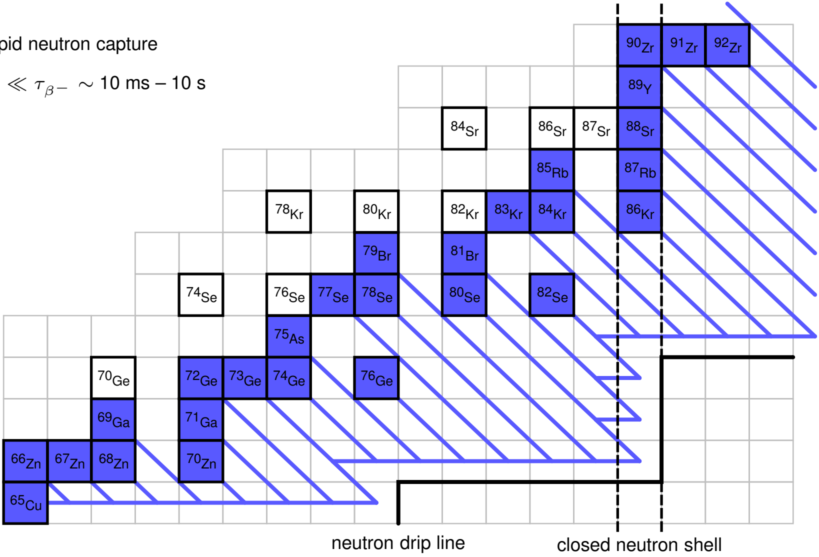
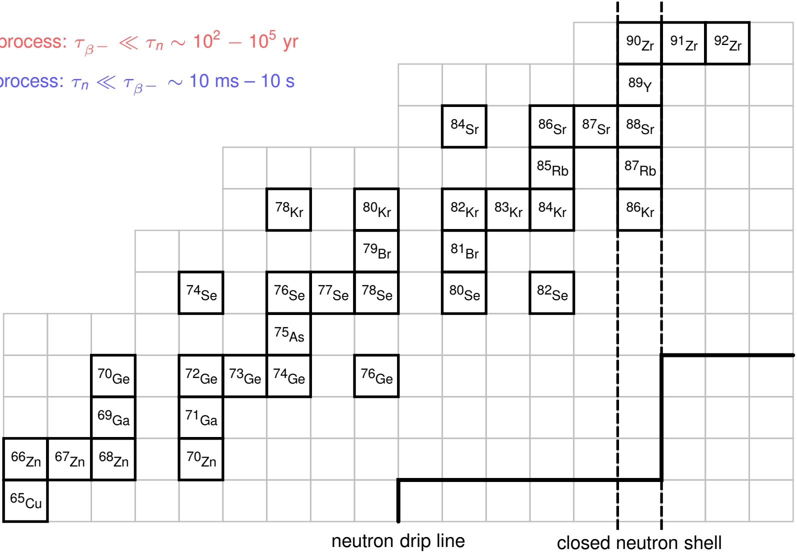


Double peaks due to closed neutron shells

s-process: $\tau_{\beta-} \ll \tau_n \sim 10^2 - 10^5$ yr

r-process: $\tau_n \ll \tau_{\beta-} \sim 10$ ms – 10 s



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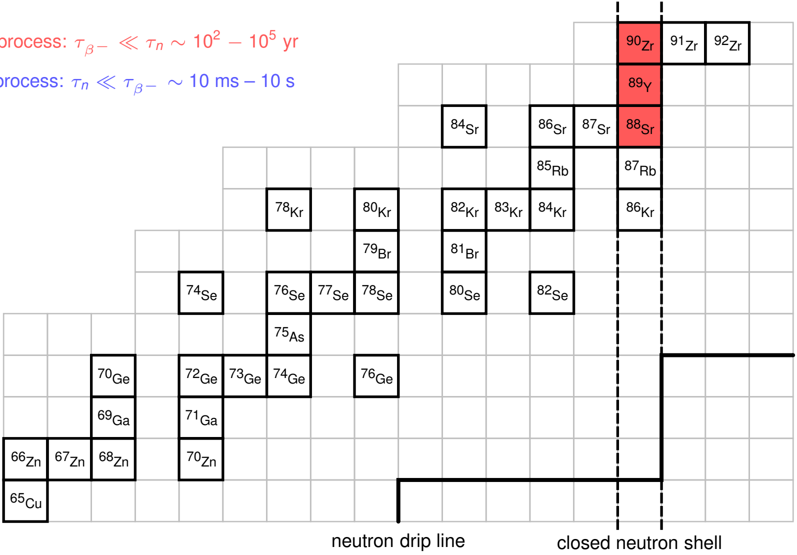

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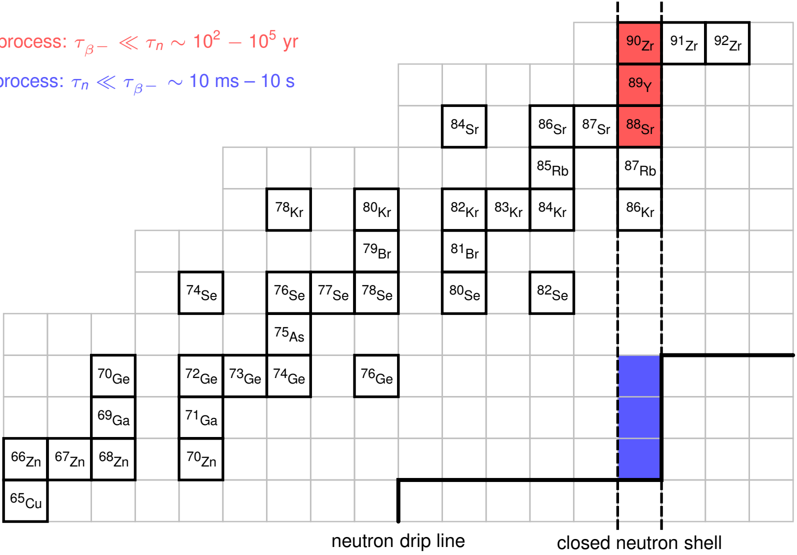

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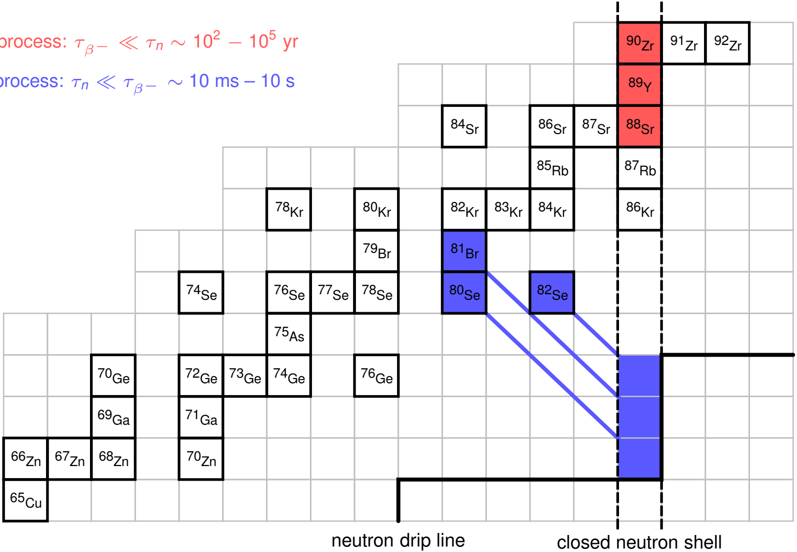
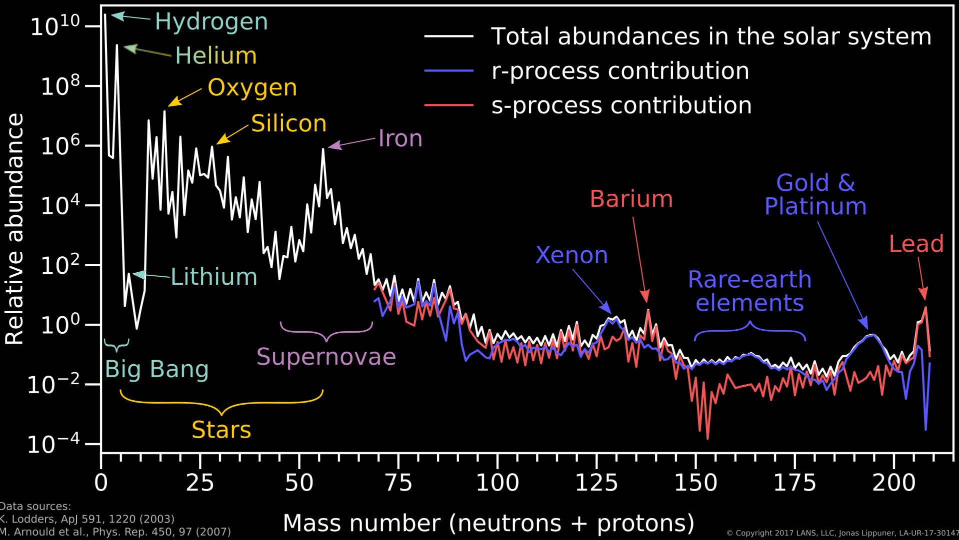


Solar system abundances



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SkyNet

bitbucket.org/jlippuner/skynet

- General-purpose nuclear reaction network
- $\sim$8000 isotopes, $\sim$140,000 nuclear reactions
- Evolves temperature based on nuclear reactions
- Input: $\rho(t)$, initial composition, entropy
- Open source

Lippuner, J. and Roberts, L. F., ApJS 233, 18 (2017)

SkyNet

Define abundance

$$Y_i = \frac{n_i}{n_B}. \tag{1}$$

Consider reaction

$$\mathrm{p} + {}^7\mathrm{Li} \to 2\,{}^4\mathrm{He} \tag{2}$$

with rate $\lambda = \lambda(T, \rho)$. Then

$$\begin{aligned} \dot{Y}_{^4\mathrm{He}} &= 2\lambda Y_\mathrm{p} Y_{^7\mathrm{Li}} + \cdots\,, \\ \dot{Y}_\mathrm{p} &= -\lambda Y_\mathrm{p} Y_{^7\mathrm{Li}} + \cdots\,, \\ \dot{Y}_{^7\mathrm{Li}} &= -\lambda Y_\mathrm{p} Y_{^7\mathrm{Li}} + \cdots \end{aligned} \tag{3}$$

Need to solve big, stiff, non-linear system of ODEs

SkyNet features

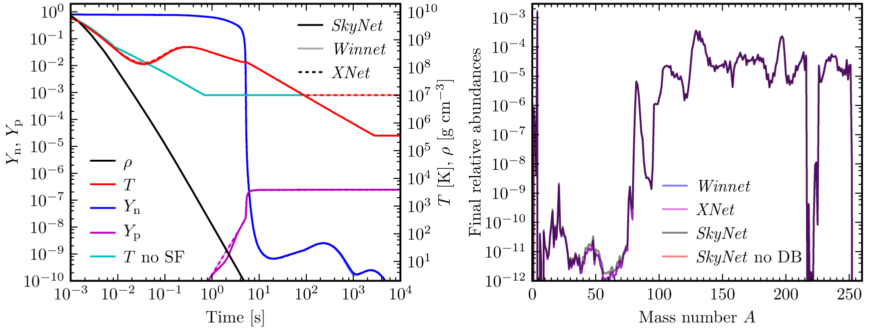
Science

- Extended Timmes equation of state (EOS)
- Calculate nuclear statistical equilibrium (NSE)
- NSE evolution mode
- Calculate inverse rates from *detailed balance* to be consistent with NSE
- Electron screening with smooth transition between weak and strong screening (reactions and NSE)

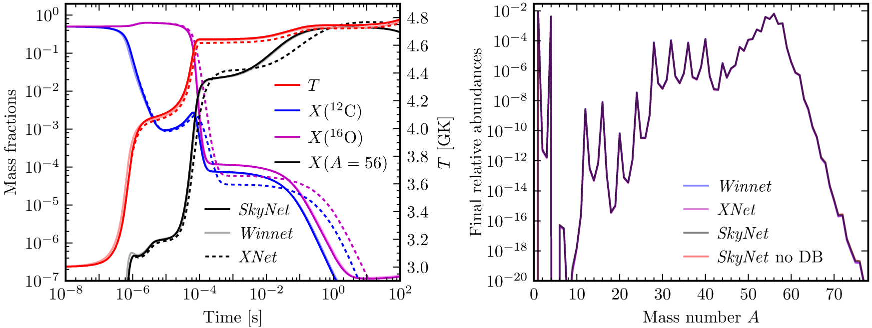
Code

- Adaptive time stepping
- Python bindings
- Modularity
- Extendible reaction class (currently REACLIB, table, neutrino)
- Make movies

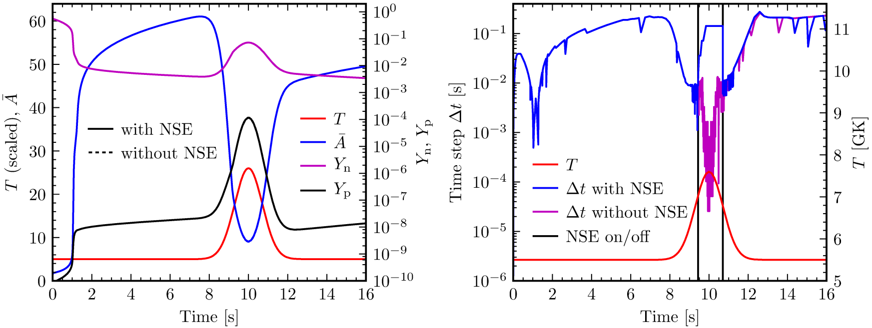
Code comparison: Neutron-rich r-process



Initial conditions: NSE with $T = 6.1$ GK, $\rho = 7.4 \times 10^9$ g cm^{-3}, $Y_e = 0.07$, screening and self-heating on*



Fixed $\rho = 10^7$ g cm^{-3}, initial $T = 3$ GK, initial $X_C = X_O = 0.5$, screening and self-heating on



Fixed $\rho = 10^8$ g cm^{-3}, initial NSE with $T = 5.5$ GK, $Y_e = 0.1$, screening and self-heating off

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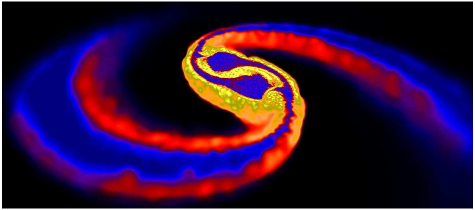
Merger ejecta: Dynamical

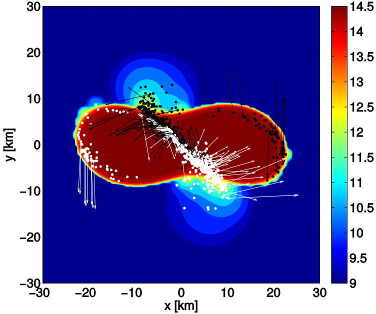
Tidal tails or collision interface

NS–NS: $M_{\rm ej} \sim 10^{-4} - \text{few} \times 10^{-2}\, M_\odot$, $Y_e \sim 0.05 - 0.45$
NS–BH: $M_{\rm ej} \sim 0 - 10^{-1}\, M_\odot$, $Y_e \lesssim 0.2$

Bauswein+13, Hotokezaka+13, Foucart+14, Sekiguchi+15, Kyutoku+15, Radice+16



From Price+06



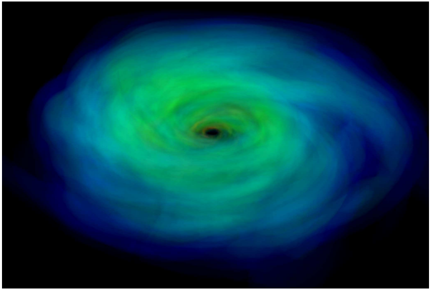
From Bauswein+13

Merger ejecta: Disk outflow

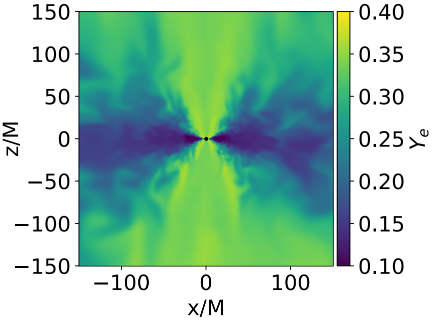
Neutrino-driven wind or outflow due to MHD, viscous heating, and α recombination

$M_{\rm ej} \sim$ few $\times\, 10^{-3}\, M_\odot$, $Y_e \sim 0.2 - 0.45$

Surman+08, Wanajo+11, Fernández+13, Perego+14, Just+15, Foucart+15, Siegel+17, Siegel+18, Miller+19



Credit: Jonah Miller



Credit: Jonah Miller

Parametrized r-process

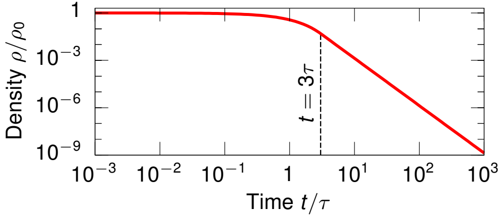
Lippuner & Roberts, 2015, ApJ, 815, 82, arXiv:1508.03133

Parameters

$0.01 \leq Y_e \leq 0.50$	initial electron fraction
$1\,k_B\,\text{baryon}^{-1} \leq s \leq 100\,k_B\,\text{baryon}^{-1}$	initial specific entropy
$0.1\,\text{ms} \leq \tau \leq 500\,\text{ms}$	expansion time scale

Density profile

$$\rho(t,\tau) = \begin{cases} \rho_0 e^{-t/\tau} & t \leq 3\tau \\ \rho_0 \left(\frac{3\tau}{te}\right)^3 & t \geq 3\tau \end{cases}$$

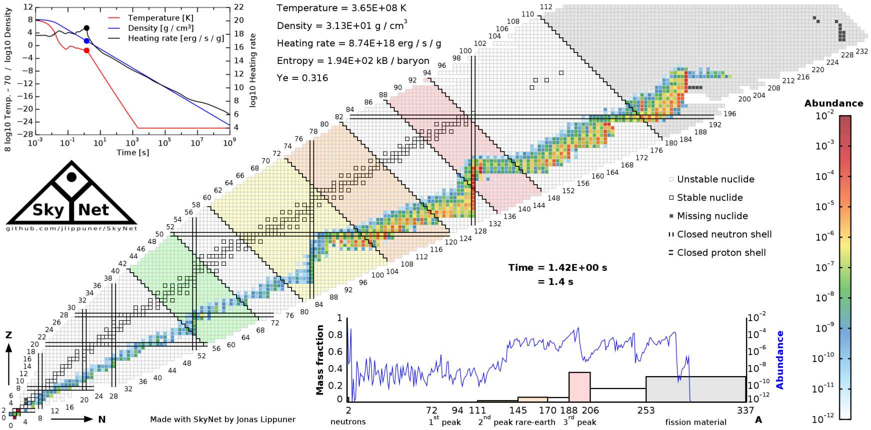


Initial conditions

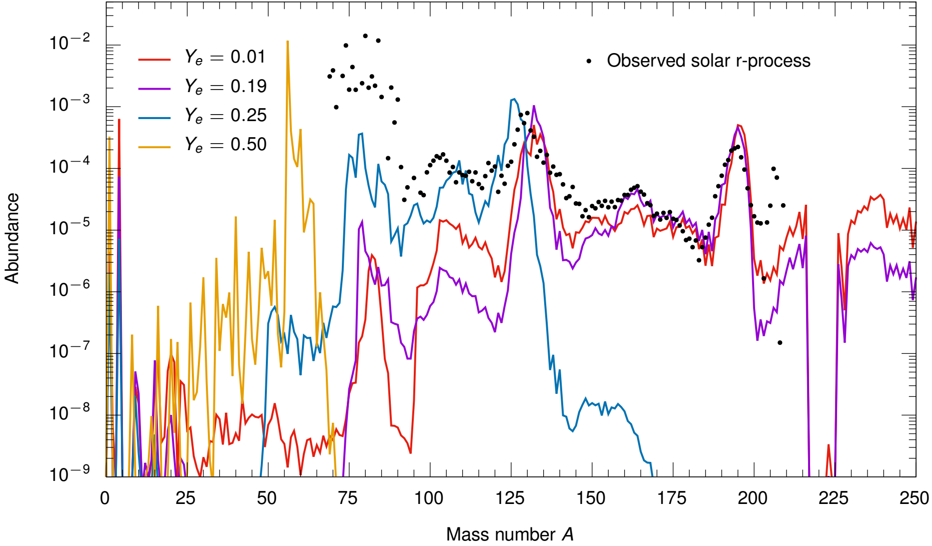
- Choose initial temperature $T_0 = 6\,\text{GK}$
- Find ρ_0 by solving for NSE at T_0 and Y_e that produces specified s

Movie

http://jonaslippuner.com/skynet/SkyNet_Ye_0.010_s_010.000_tau_007.100.mp4
http://jonaslippuner.com/skynet/SkyNet_Ye_0.250_s_010.000_tau_007.100.mp4

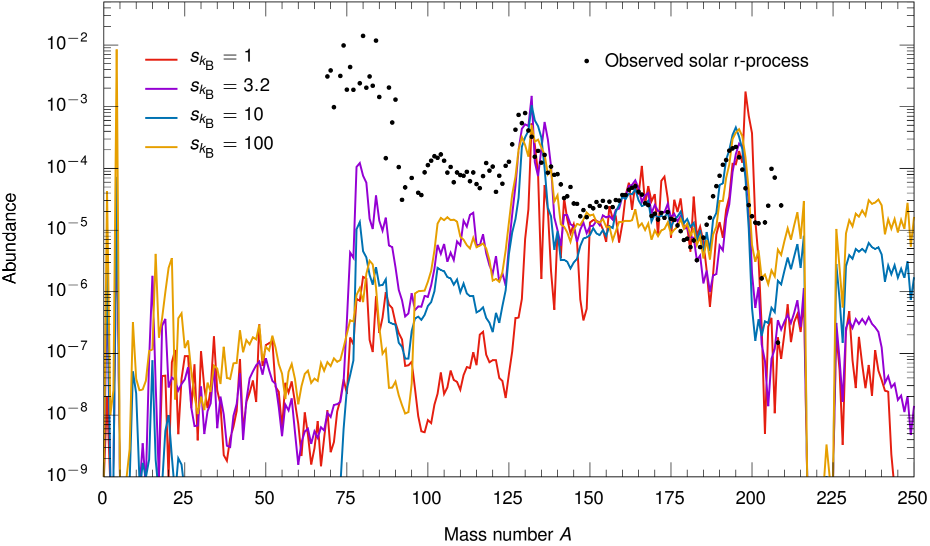


r-Process abundances vs. electron fraction



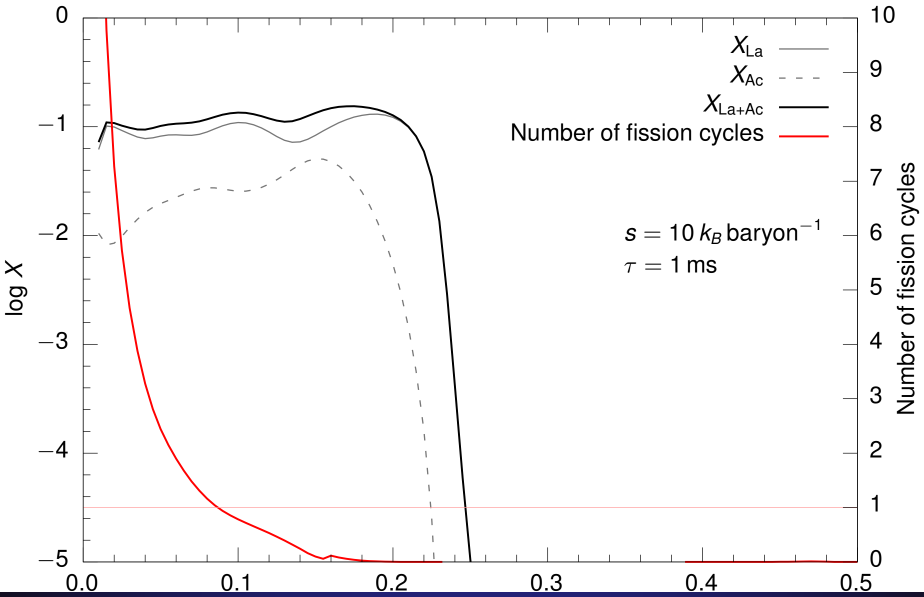
JL, Roberts 2015, ApJ 815, 82, arXiv:1508.03133

Final abundances vs. entropy

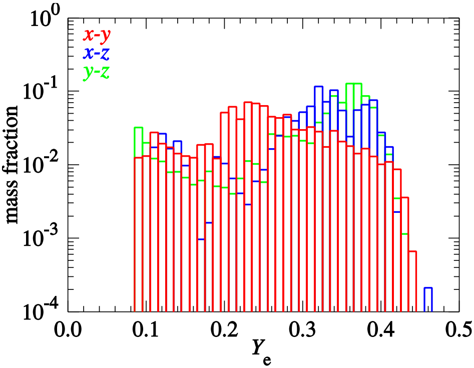


JL, Roberts 2015, ApJ 815, 82, arXiv:1508.03133

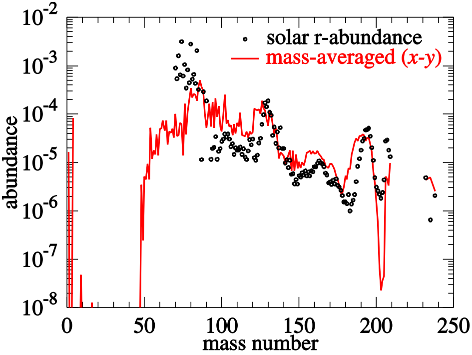
Impact of electron fraction



Full binary neutron star merger simulations



From Wanajo+14



From Wanajo+14

See also Goriely+15

Accretion disk outflow

Jonah Miller at LANL performed accretion disk simulation using GW170817 parameters

- Full GRMHD
- Monte Carlo neutrino transport
- Using νbhlight (see Miller+19a)

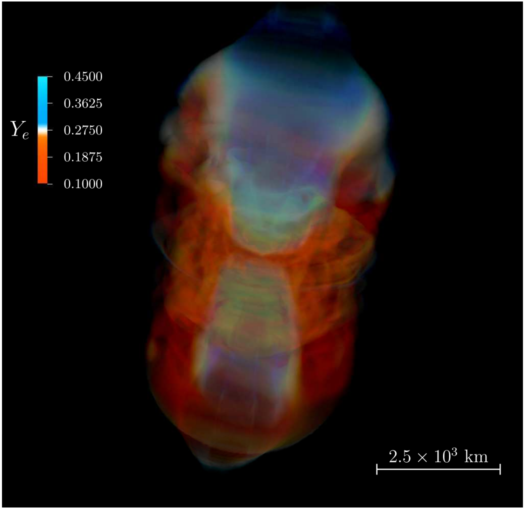


Figure from Miller+19b

Final abundances from accretion disk outflow

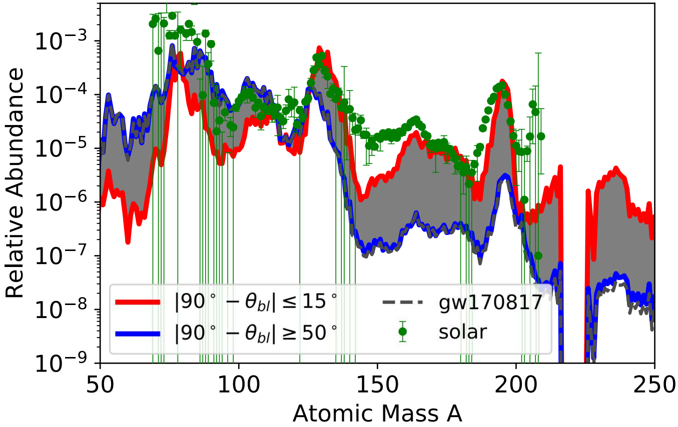


Figure from Miller+19b

Nucleosynthesis in HMNS disk outflow

- 3 $M_\odot$ central HMNS or BH, 0.03 $M_\odot$ accretion disk
- Variable HMNS lifetime, neutrino leakage, α viscosity

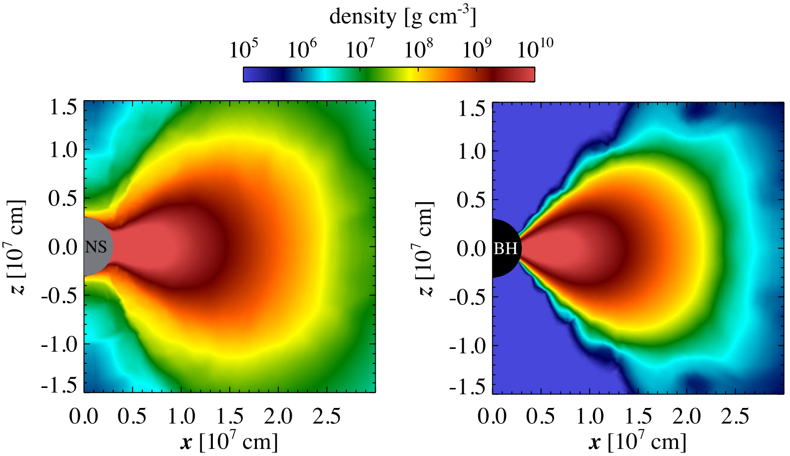
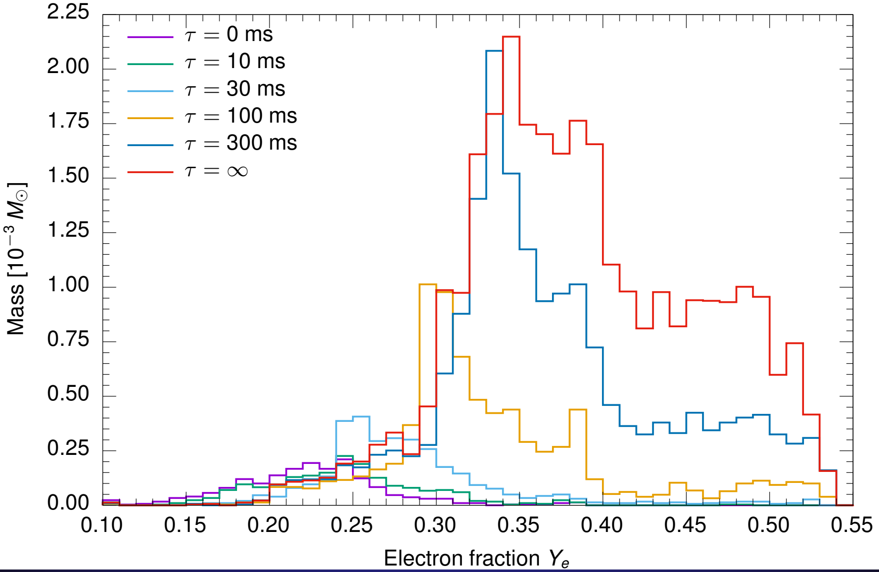
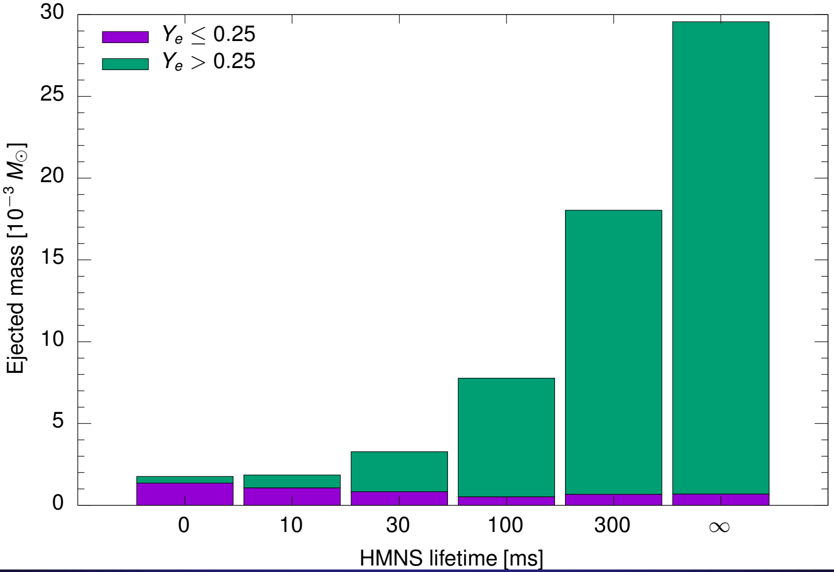


Figure from Metzger & Fernández (2014)

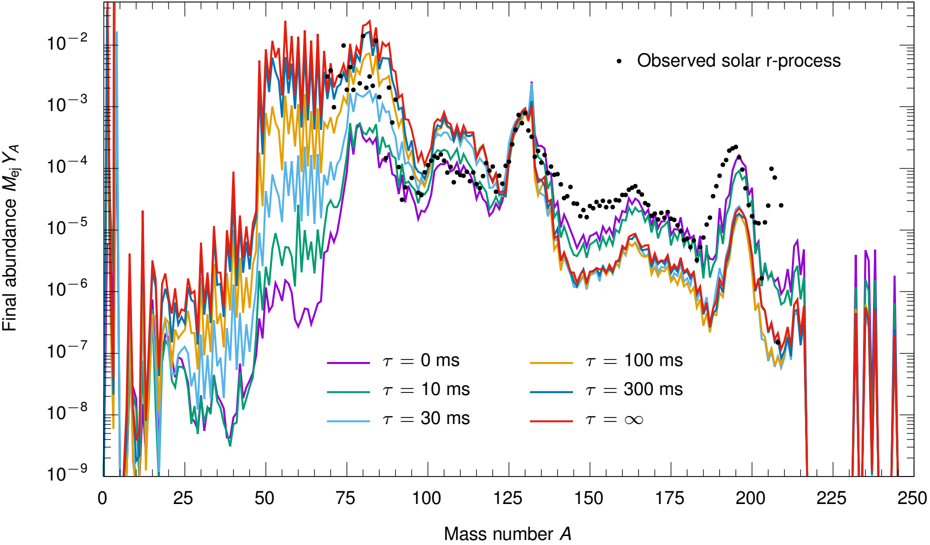
Electron fraction distribution



Ejected mass



Final abundances



JL, Fernández, Roberts, et al. 2017, MNRAS 472, 904, arXiv:1703.06216

Black hole–neutron star merger

Roberts, JL, Duez, et al. 2017, *MNRAS* 464, 3907, arXiv:1601.07942

1. Full GR simulation of BH–NS
   Francois Foucart (UNH), *Foucart et al.*, Phys. Rev. D 90, 024026 (2014)
2. Evolve ejecta in SPH code
   Matt Duez (WSU)
3. Nucleosynthesis with varying neutrino luminosity
   JL and Luke Roberts (MSU)

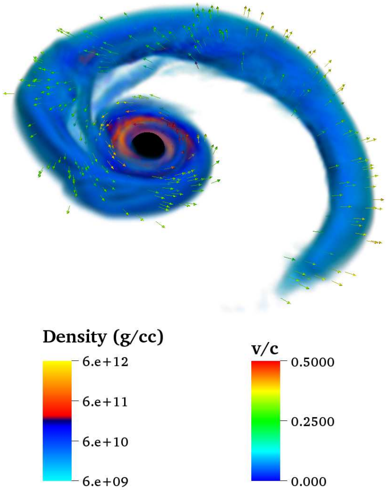
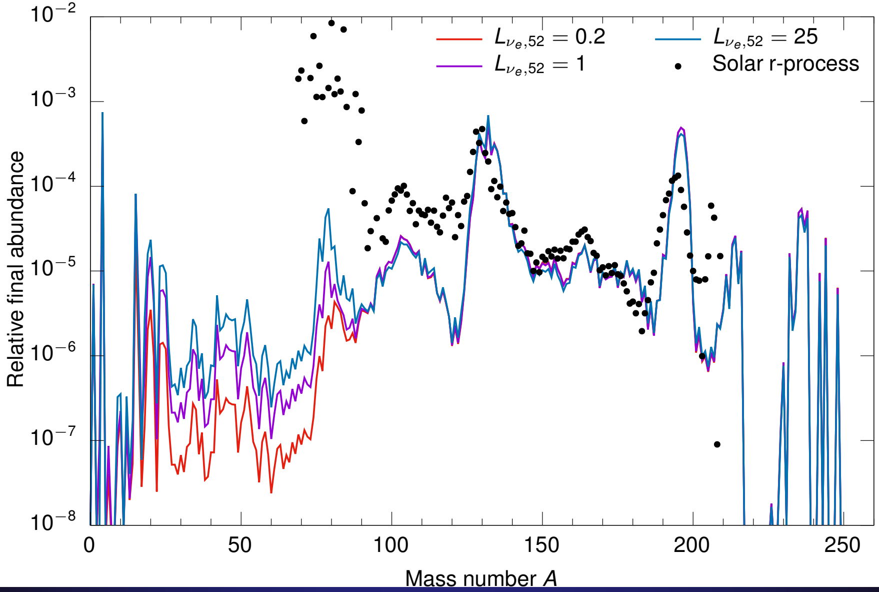
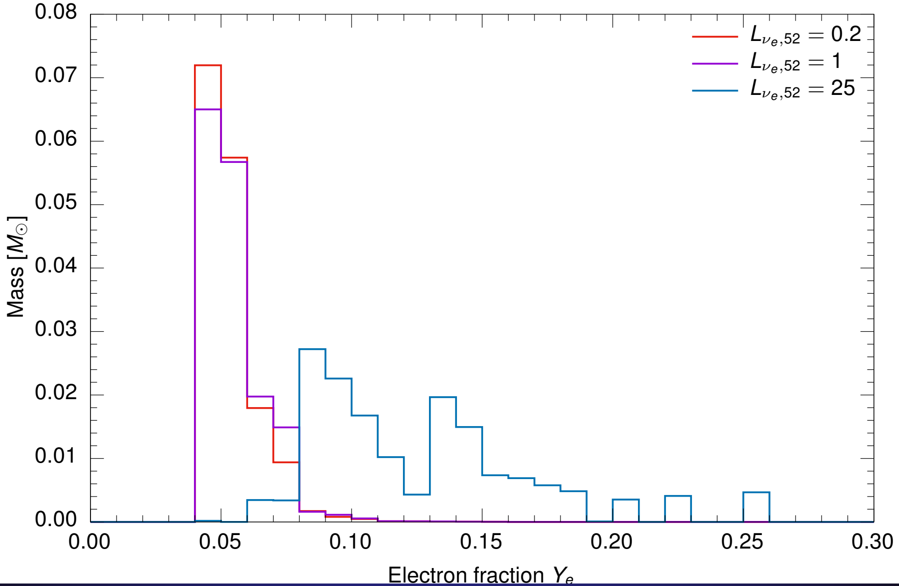


Figure credit: F. Foucart

BHNS: Final abundances vs. neutrino luminosity



BHNS: Electron fraction distribution



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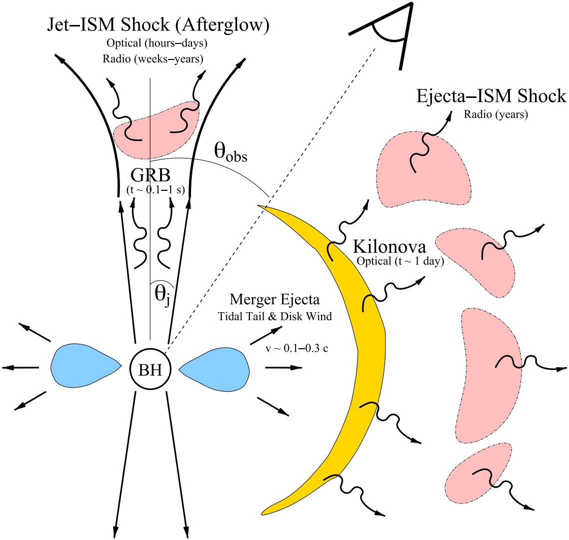
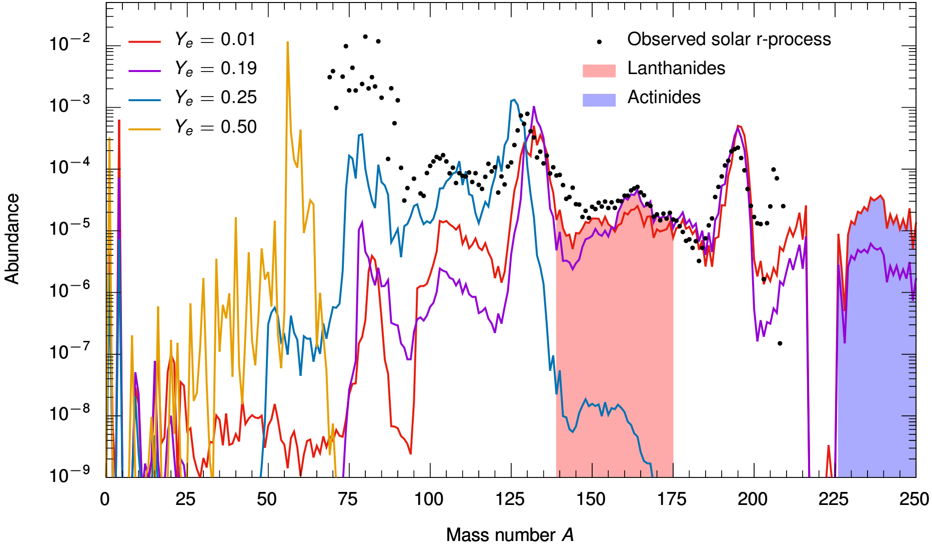
Observational signature of r-process: Kilonova



Metzger & Berger, 2012, ApJ 746, 48

Impact of lanthanides



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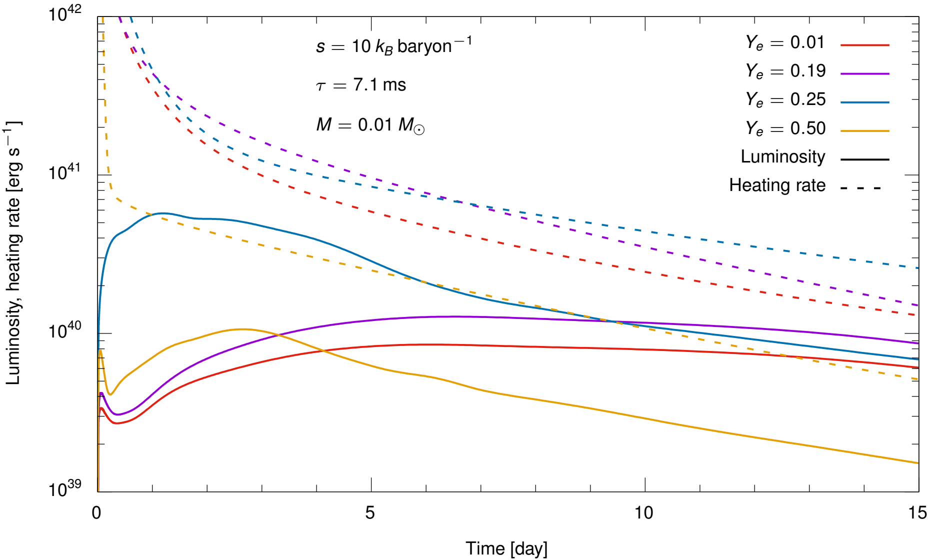
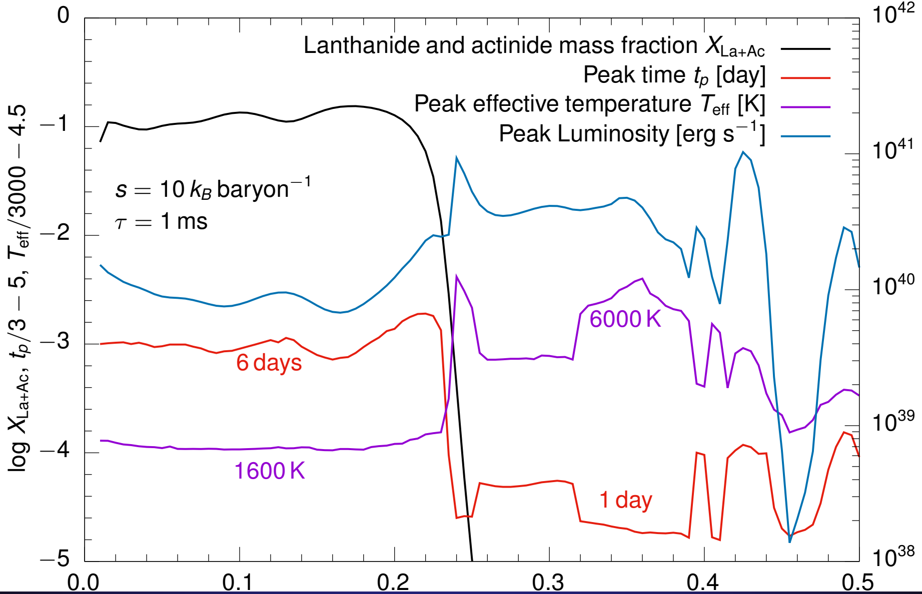
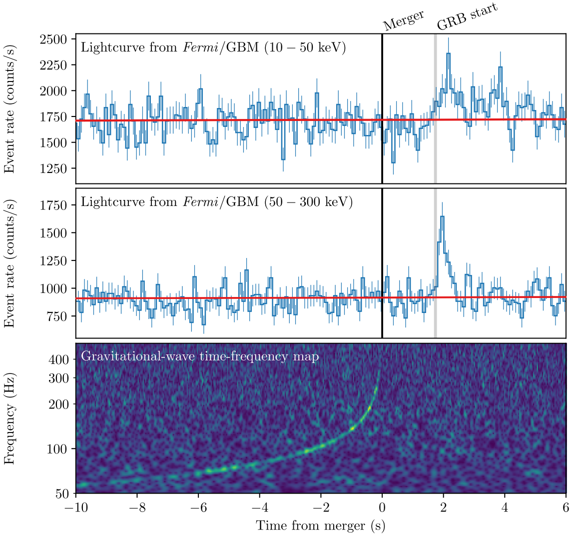


Light curves vs. electron fraction



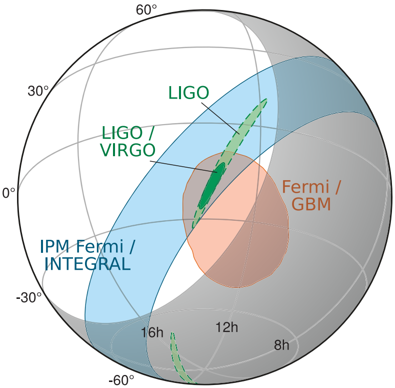
First neutron star merger observation: GW170817



LIGO et al. 2017, ApJL 848, L13

GW170817: Hunt for electromagnetic counterpart

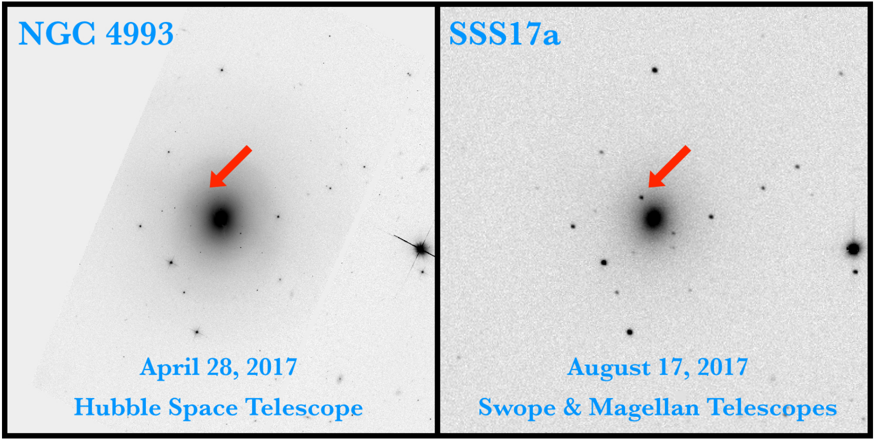
- LIGO/VIRGO localization: 31 deg^2
  $\sim$ 150 full moons
- Distance estimate: 40 ± 8 Mpc
- 49 galaxies in that volume
- Check all galaxies starting with most massive first



Kasliwal et al., 2017, Science 358, 1559

GW170817: Counterpart discovered in NGC 4993

- Discovered 10.9 hours after merger
- Host galaxy: NGC 4993, elliptical galaxy, constellation Hydra, 40 Mpc $\sim$ 130 Mly

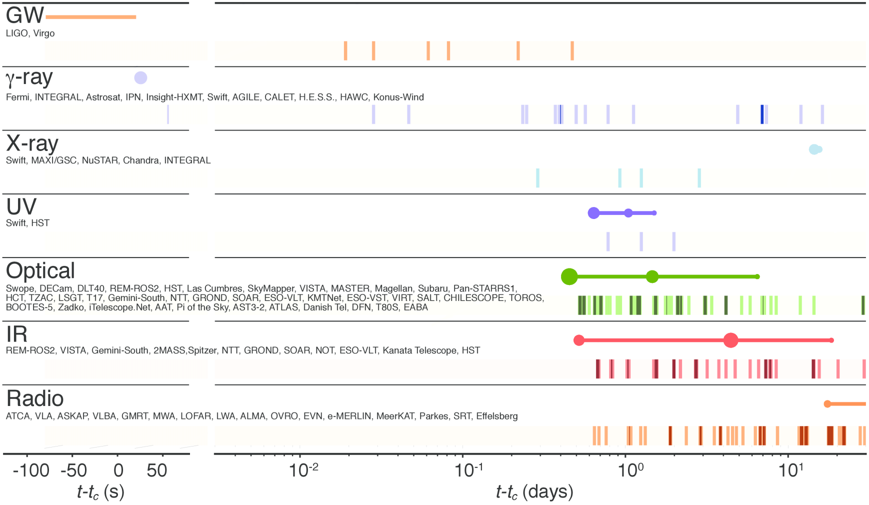


Credit: 1M2H Team / UC Santa Cruz & Carnegie Observatories / Ryan Foley

GW170817: Rapid color evolution

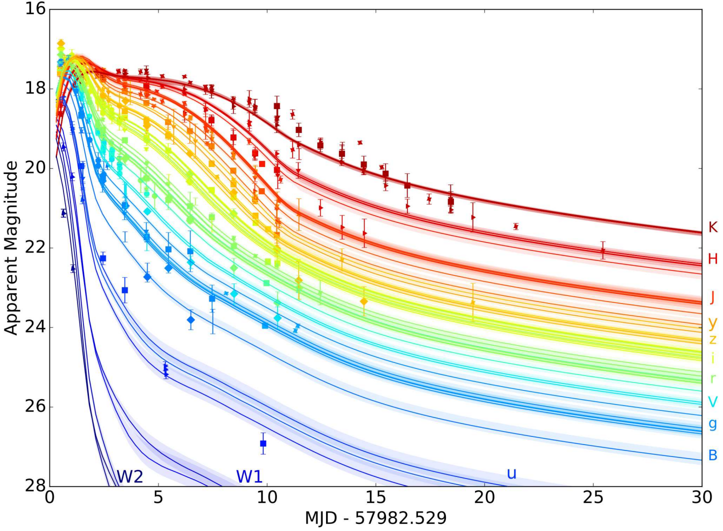
Credit: ESO / N.R. Tanvir, A.J. Levan and the VIN-ROUGE collaboration

GW170817: Huge observing campaign



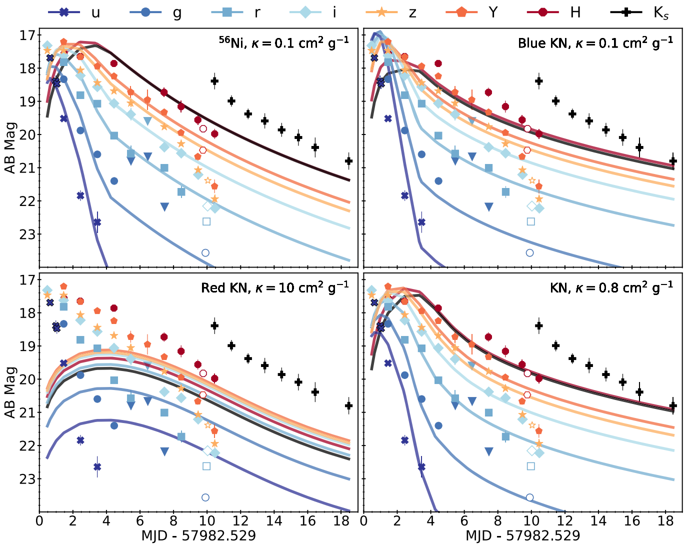
LIGO et al., 2017, ApJL 848, L12

GW170817: Combined light curve



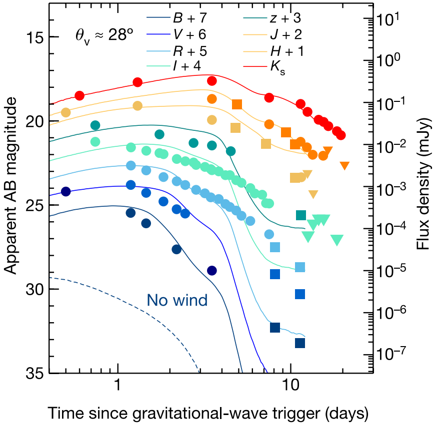
Villar et al., 2017, ApJL 851, L21

GW170817: One-component kilonova models fail

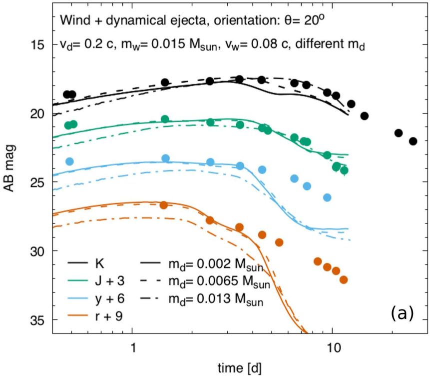


Cowperthwaite et al., 2017, ApJL 848, L17

GW170817: Two-component models do better

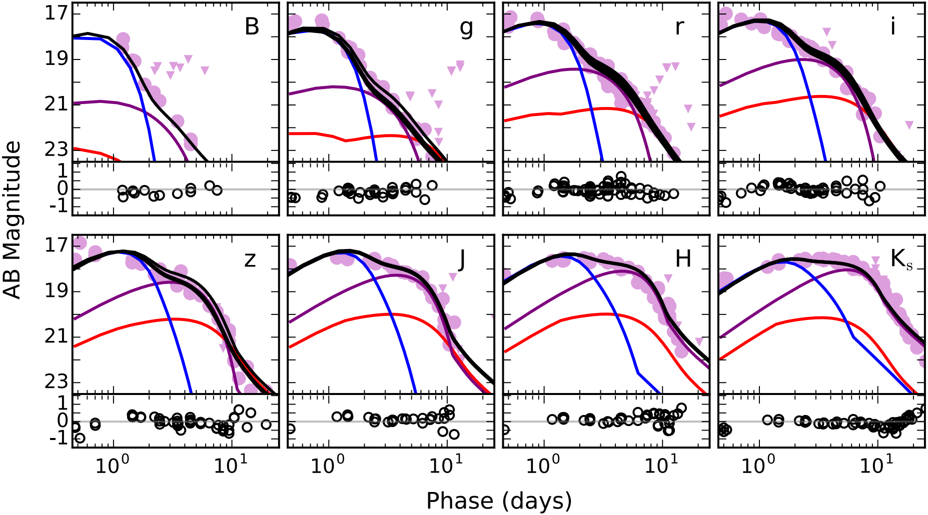


Troja et al., 2017, Nature 551, 71



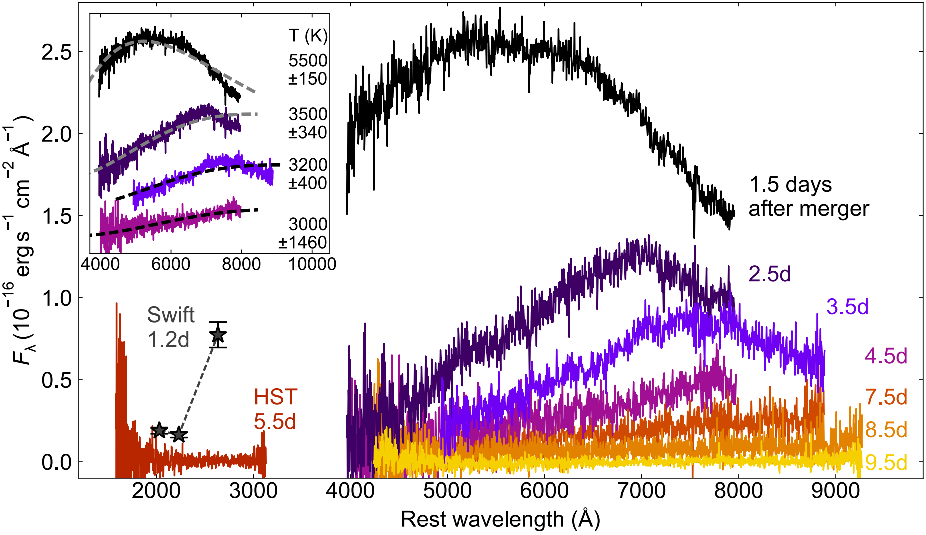
Tanvir et al., 2017, ApJL 848, L27

GW170817: Three-component model needed?



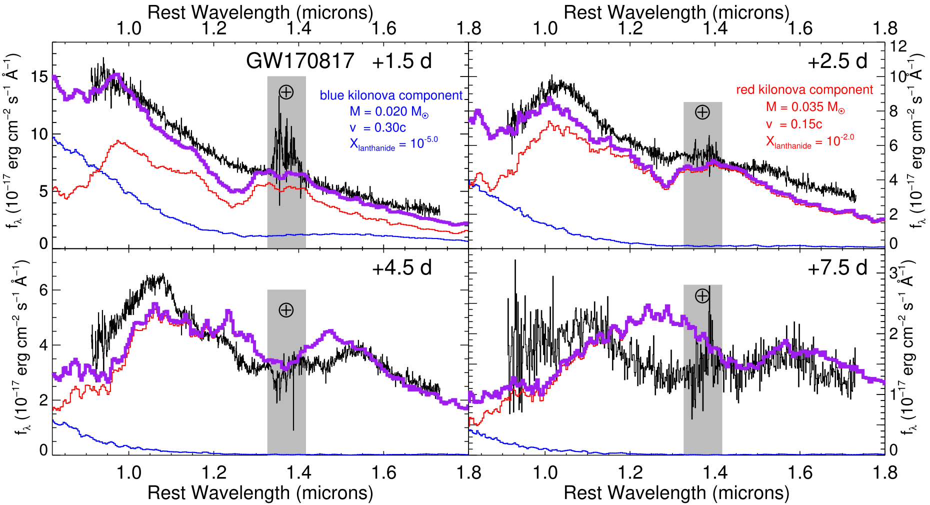
Villar et al., 2017, ApJL 851, L21

GW170817: Featureless optical spectrum



Nicholl et al., 2017, ApJL 848, L18

GW170817: Infrared spectrum



Chornock et al., 2017, ApJL 848, L19

GW170817: What we learned

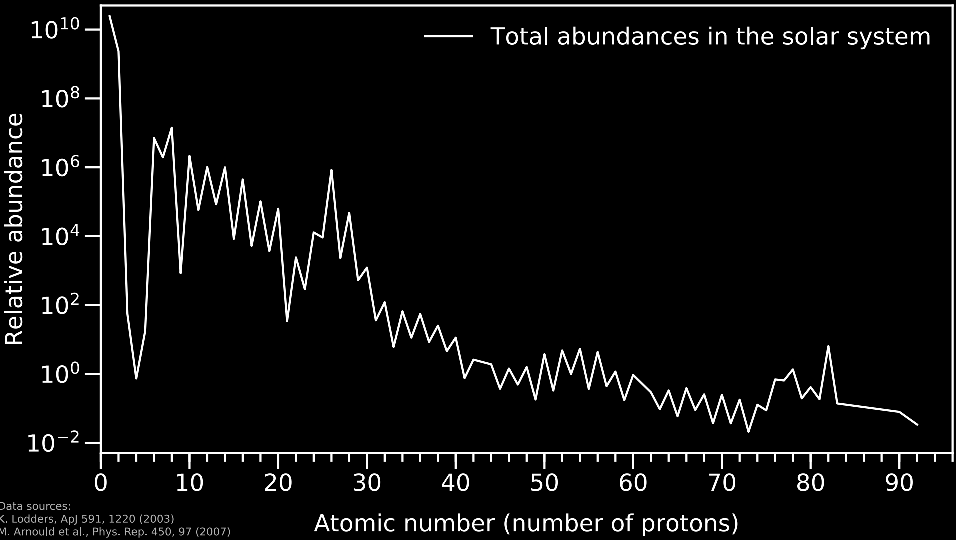
- Confirmed neutron star mergers make short GRBs (but this was a weird GRB)
- Total ejecta mass larger than expected: $\sim 5 \times 10^{-2}\, M_\odot$
- Neutron star mergers can easily make all r-process material in the galaxy
- Blue (lanthanide-free) component larger than expected, maybe large disk wind or blue dynamical component
- Lanthanide-rich component is evidence for full r-process, tens of Earth masses of gold and platinum
- "Purple" kilonova component with $X_{\mathrm{La}} \sim 10^{-3} - 10^{-2}$, $\kappa \sim 3\ \mathrm{cm}^2\ \mathrm{g}^{-1}$?
- Gravity propagates at the speed of light, rules out many alternative theories of gravity besides Einstein's General Relativity

Summary

- s- and r-process create heavy elements beyond the iron peak
- r-process happens in dynamical and disk ejecta in a neutron star merger
- SkyNet is free and open source state of the art nuclear reaction network
  - Feature-rich
  - Checked against other existing reaction networks
- Dynamical ejecta (NS-NS and BH-NS) is generally neutron-rich enough for full r-process
- Disk outflow may have neutron-rich and neutron-poor components
- GW170817: First LIGO detection of neutron star merger accompanied by GRB and kilonova
  - Kilonova followed pretty well what we expected
  - Yet more work is needed to understand light curve in detail, purple component?

Extra slides

Solar system abundances



Data sources:
K. Lodders, ApJ 591, 1220 (2003)
M. Arnould et al., Phys. Rep. 450, 97 (2007)

First (wrong) attempt: $\alpha\beta\gamma$

PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
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AND
H. BETHE
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AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty} (10^6/t^2)dt \cong 5\times10^4, \qquad (2)$$

which gives us $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5\times10^5$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value

Birth of modern theory of nucleosynthesis: B^2FH

REVIEWS OF

MODERN PHYSICS

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Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

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"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

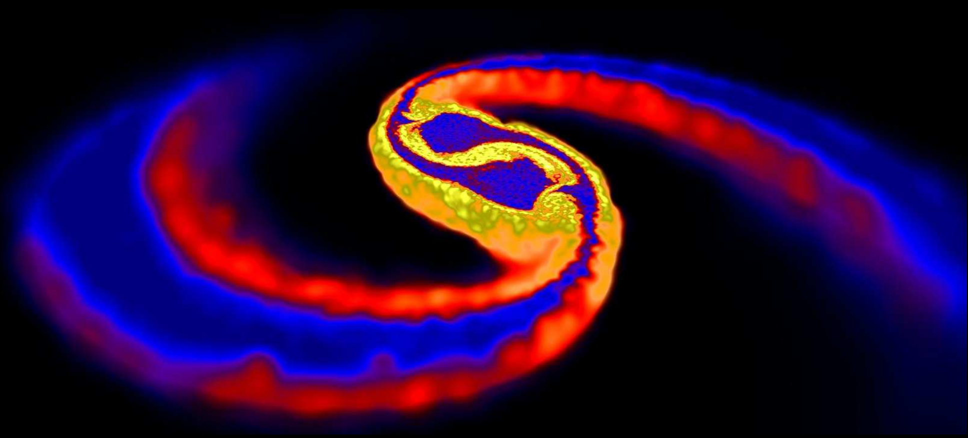
but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

TABLE OF CONTENTS

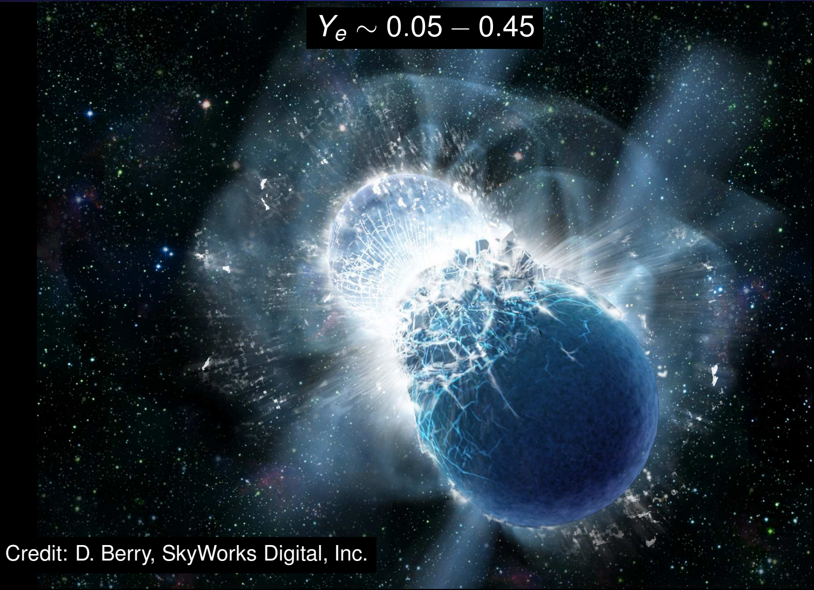
NS–NS ejecta sources: Tidal tails

$Y_e \sim 0.05 - 0.45$

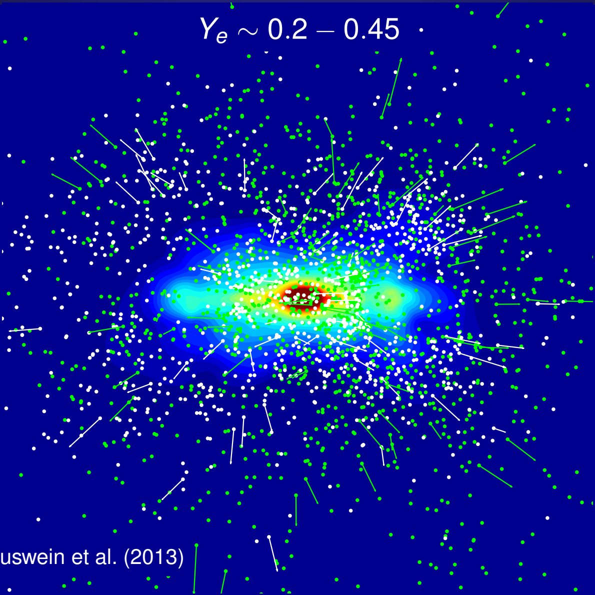


Credit: D. J. Price et al. (2006)

NS–NS ejecta sources: Collision interface



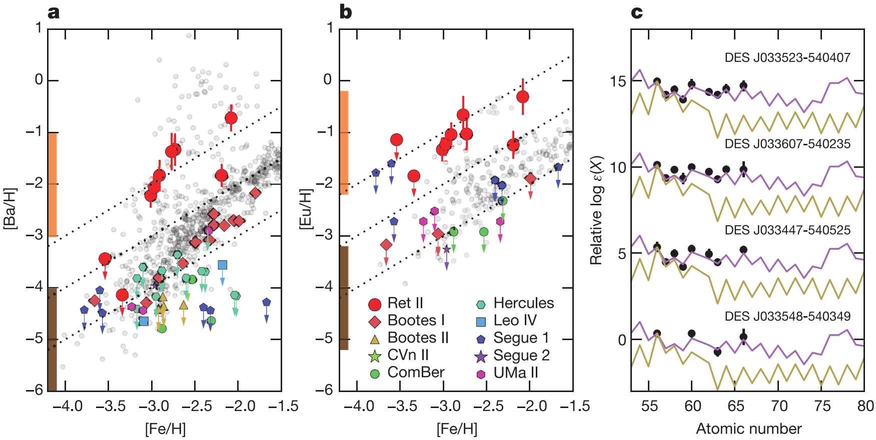
NS–NS ejecta sources: Disk outflow



Credit: A. Bauswein et al. (2013)

Recent evidence for rare r-process

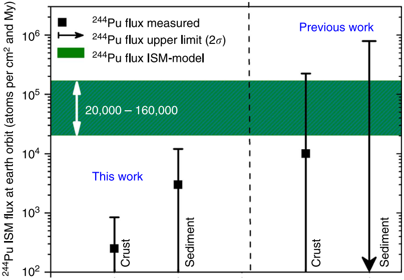
- Reticulum II: 1 in 10 highly r-process enhanced ultra-faint dwarf galaxy
- Recently discovered second UFD with r-process star: Tucana III
  Hansen et al., 2017, ApJ 838, 1



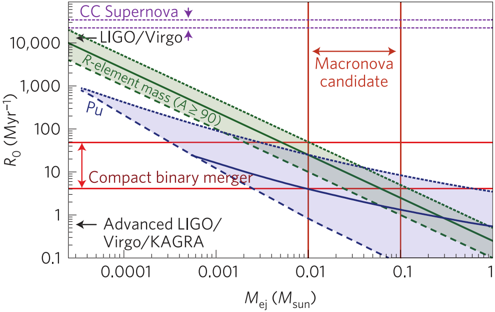
Ji et al., 2016, Nature 531, 610

Recent evidence for rare r-process

- ^{244}Pu is actinide (r-process only) with $\tau_{1/2} \sim 80$ Myr ($< \tau_{\rm mix} \sim 300$ Myr)
- Interstellar material is swept up and deposited in deep-sea crust
- Measure abundance of ^{244}Pu in 25 Myr old deep-sea crust $\rightarrow$ ^{244}Pu abundance in ISM



From Wallner+15



From Hotokezaka+15