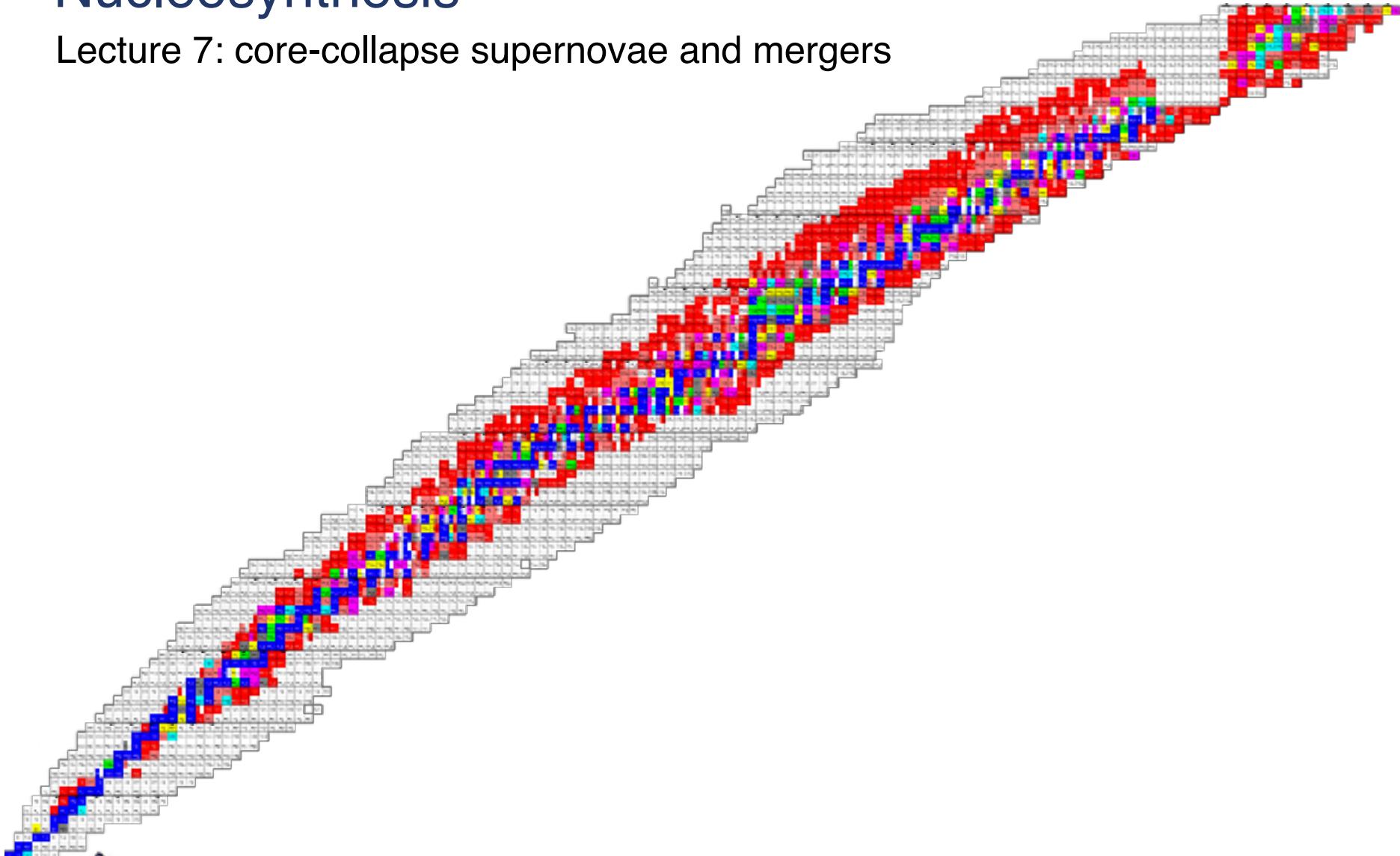


# Nucleosynthesis

Lecture 7: core-collapse supernovae and mergers



Bern-Cologne Graduate School  
of Physics and Astronomy

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Argelander-  
Institut  
für  
Astronomie

# Overview

- Lecture 1: Introduction & overview
- Lecture 2: Thermonuclear reactions
- Lecture 3: Big-bang nucleosynthesis
- Lecture 4: Thermonuclear reactions inside stars — I (H-burning)
- Lecture 5: Thermonuclear reactions inside stars — II (advanced burning)
- Lecture 6: Neutron-capture and supernovae — I
- [Lecture 7: Neutron-capture and supernovae — II](#)
- Lecture 8: Thermonuclear supernovae
- Lecture 9: Li, Be and B
- Lecture 10: Galactic chemical evolution and relation to astrobiology

Paper presentations I

June 21

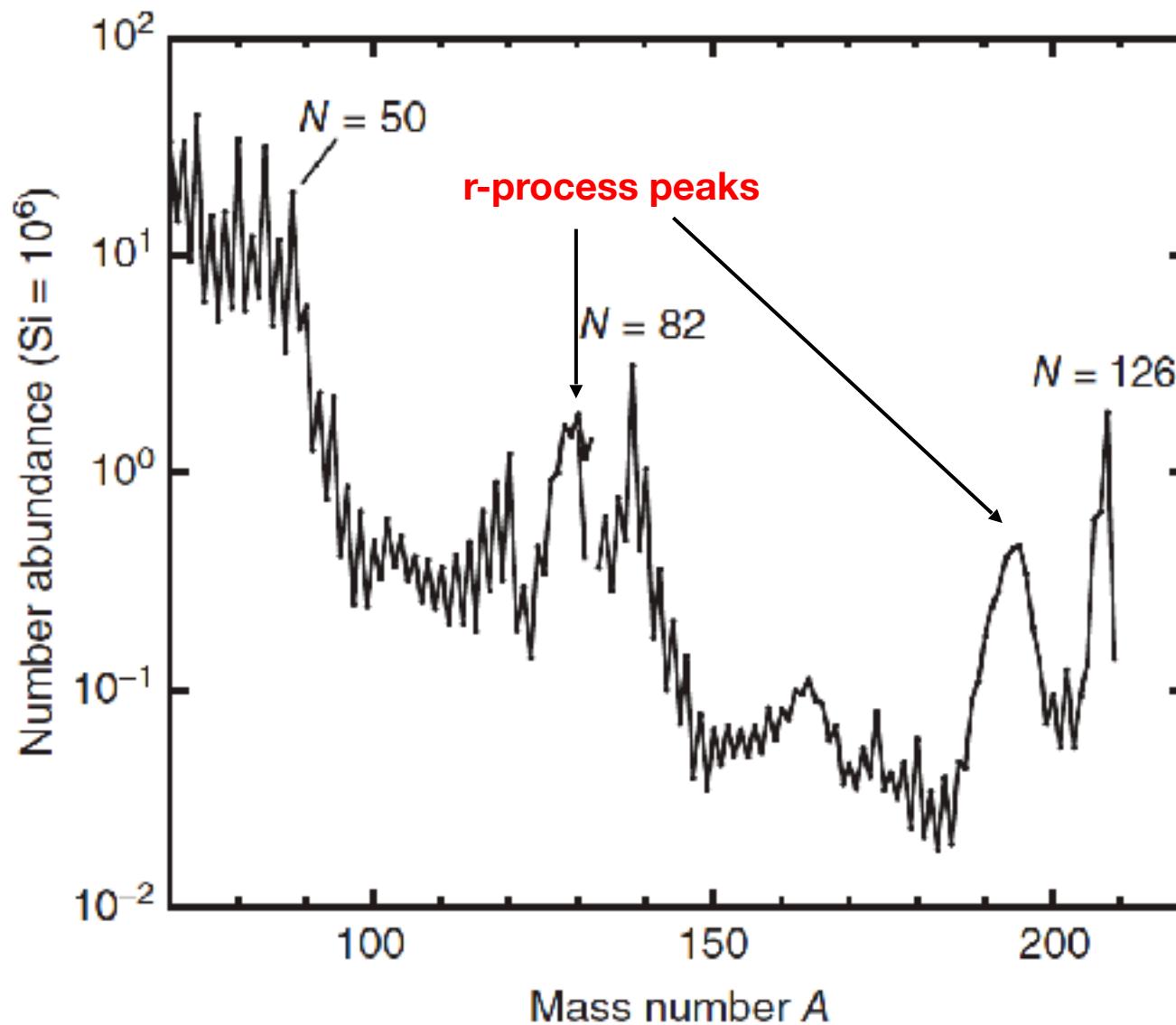
Paper presentations II

June 28

# Basic mechanism for nucleosynthesis beyond iron



## The quest for the origin of trans-iron elements



Credit: ILIADIS

## Nuclear physics interlude

**What determines if an isotope is stable or not?**

**Light nuclei:** lab measurements + shell model

**Heavy nuclei:** stable elements can be measured in the lab.

way from the valley of stability this is not possible.

Elements are short-lived, therefore no measurements exist!!!

## Nuclear physics interlude

### Liquid drop model

Semi-empirical model to understand binding energies and other nuclear properties  
Modern versions of the LDM work extremely well for large nuclei

Assumption:

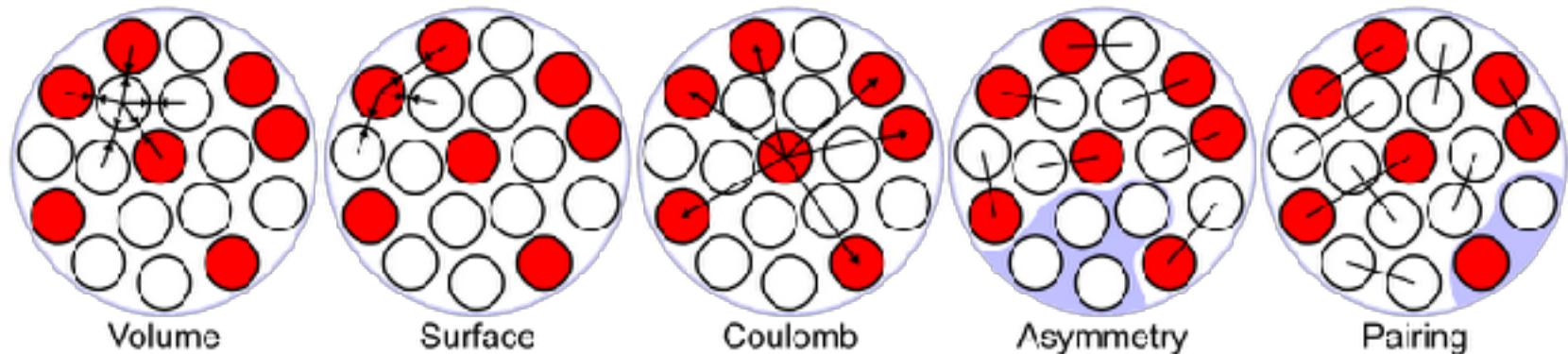
Nuclear force can be modelled after molecular forces in a liquid drop

Motivation:

Constant nuclear density



## Nuclear physics interlude



$$BE(Z, N) = aA - bA^{2/3} - c \frac{Z(Z-1)}{A^{1/3}} - d \frac{(N-Z)^2}{A} \pm \delta(A, Z) + S(A, Z)$$

## Nuclear physics interlude

### Application 1

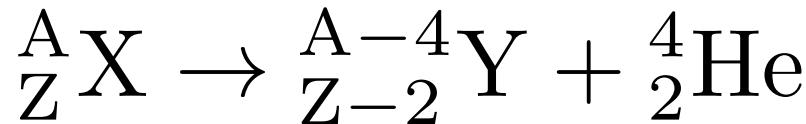
What is the binding energy of a typical neutron or proton in a heavy nucleus?

$$BE/A \simeq 8 \text{ MeV}$$

## Nuclear physics interlude

### Application 2

When does a nucleus become unstable to  $\alpha$ -decay?



$$\begin{aligned} Q_a &= \text{BE}(A - 4, Z - 2) + \text{BE}(\alpha) - \text{BE}(A, Z) = 0 \\ &= [\text{BE}(A - 4, Z - 2) - \text{BE}(A, Z - 2)] \\ &\quad + \text{BE}(\alpha) + [\text{BE}(A, Z - 2) - \text{BE}(A, Z)] \\ &= 28.296 - 4 \frac{\partial \text{BE}}{\partial A}{}_Z - 2 \frac{\partial \text{BE}}{\partial Z}{}_A \end{aligned}$$

$$Q_a = -36.68 + 44.9A^{-1/3} + 1.02A^{2/3} \text{ MeV} = 0 \Rightarrow A \simeq 146$$

# Nuclear physics interlude

## Application 3

What is the condition that determines the location of the neutron (proton) drip line?

$$Q_n = 0 \Rightarrow BE(A + 1, Z) - BE(A, Z) = 0 \Rightarrow \frac{\partial BE}{\partial A} \Big|_Z = 0$$

More generally, a necessary condition for nuclear stability is that for a collection of  $A$  nucleons there exists no other combination that weights less (more tightly bound)

One needs to be careful with this definition since the decay timescales can be well in excess of the lifetime of the Universe.

A more practical definition: An isotope is stable if it has a measurable abundance or if no decay has been observed in the lab

## Nuclear physics interlude

### Application 4

What is the optimal neutron to proton ratio? In other words, what is the optimal number of protons  $Z$  for a given  $A$ ?

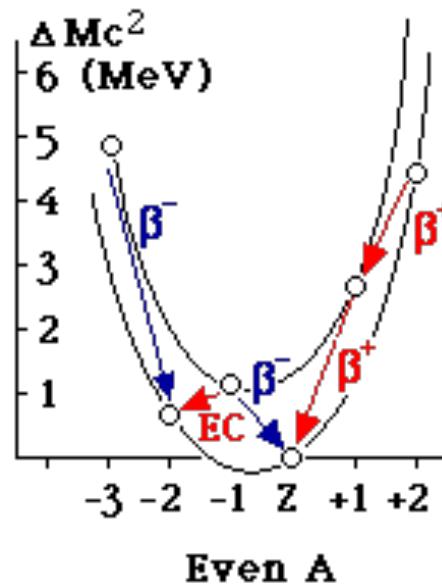
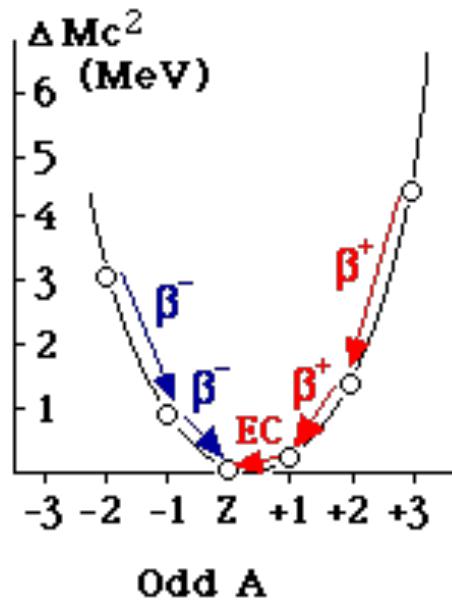
$$\frac{\partial BE(A, Z)}{\partial Z} \Big|_A = 0 \Rightarrow Z_{\text{opt}} = \frac{2cA}{dA^{2/3} + 4c}$$

## Nuclear physics interlude

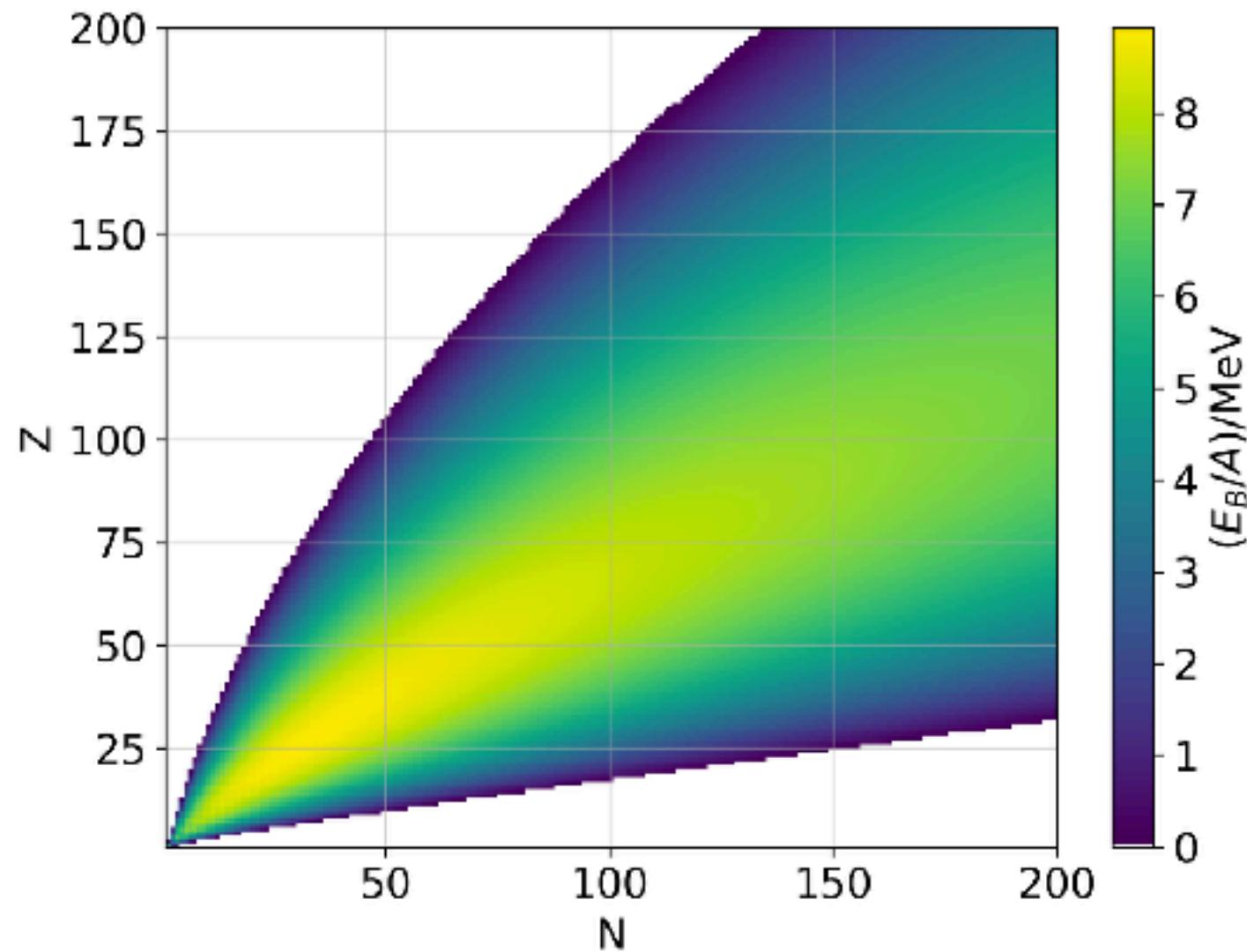
Consequence: Difference in binding energy for nuclei with the same A but arbitrary Z is a parabola

$$\Delta BE(\delta = 0) = \text{const.} (Z - Z_{\text{opt}})^2$$

For  $\pm\delta$  two parabolas



## Nuclear physics interlude



## Nuclear physics interlude

### Quiz

**Consider Nickel and Iron: which one has the highest binding energy?**

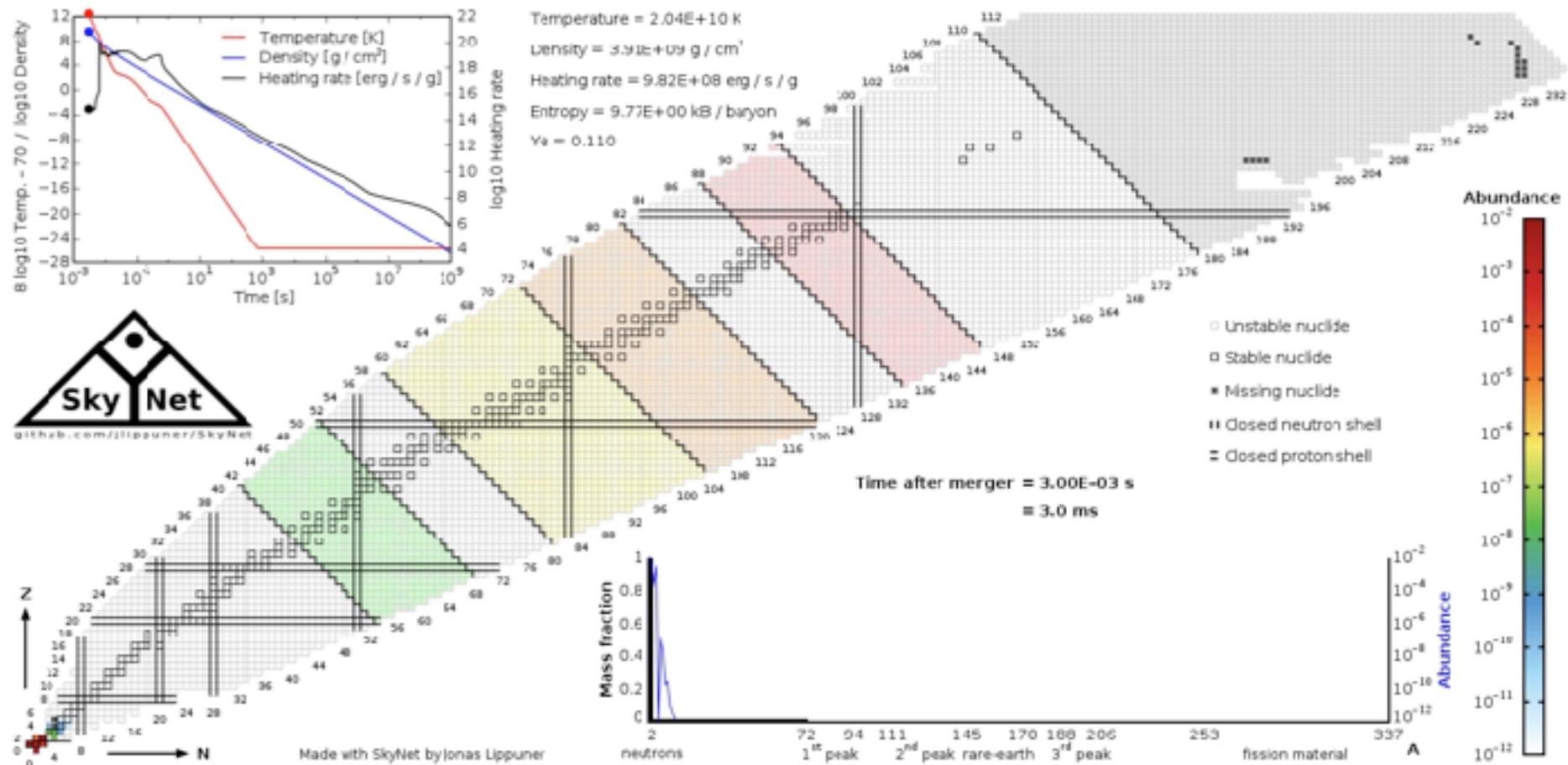
A. Nickel

B. Iron

C. Same

# r-process

neutron capture timescales must be of order  $10^{-4}$  s are required to avoid  $\beta$ -decays completely



Credit: Jonas Lippuner

## r-process: a phenomenological model

r-process calculations are extremely complex compared to s-process. Nevertheless we can construct a simple phenomenological model to gain some insight into the astrophysical conditions, etc.

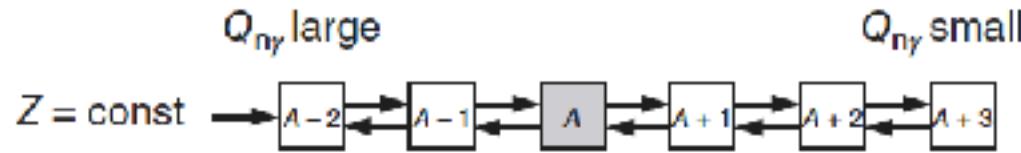
In the simulation, seeds quickly accumulate neutrons, but the neutron drip line is almost never reached. Why?

This would be the case for zero temperature. However, because the temperature is large, photo-disintegration reactions play an important role

$$(n, \gamma) \leftrightarrow (\gamma, n)$$

Because of that the flow “stops” at lower neutron numbers . At these waiting points, beta reactions occur and the flow migrates to higher Z  
Our first task would be to determine the locations of “waiting point nuclei”

## Basic mechanism for nucleosynthesis beyond iron



$$\frac{\delta N(Z, A)}{\delta t} = -N_n N(Z, A) \langle \sigma v \rangle_{ZA} + N(Z, A + 1) \lambda_\gamma(Z, A + 1)$$

At high enough temperatures, the forward/backward reactions are in equilibrium

$$\frac{N(Z, A + 1)}{N(Z, A)} = N_n \left( \frac{\hbar^2}{2\pi m_A kT} \right)^{3/2} \frac{2J_{Z,A+1} + 1}{2J_{Z,A} + 1} \frac{G_{Z,A+1}}{G_Z} e^{Q_n/kT}$$

## Basic mechanism for nucleosynthesis beyond iron

Constant T and Nn for a given duration  $\tau$

$$\frac{N(Z, A+1)}{N(Z, A)} = N_n \left( \frac{\hbar^2}{2\pi m_A kT} \right)^{3/2} \frac{2J_{Z,A+1} + 1}{2J_{Z,A} + 1} \frac{G_{Z,A+1}}{G_Z} e^{Q_n/kT}$$

The above, together with the condition  $\frac{N(Z, A+1)}{N(Z, A)} = 1$ , determine Qn

For example, for  $T=1.3$  GK,  $N=10^{22}$  cm $^{-3}$ ,  $Q_{ng} = 3$  MeV

Abundance is built around the isotopes for which  $Q=3$  MeV

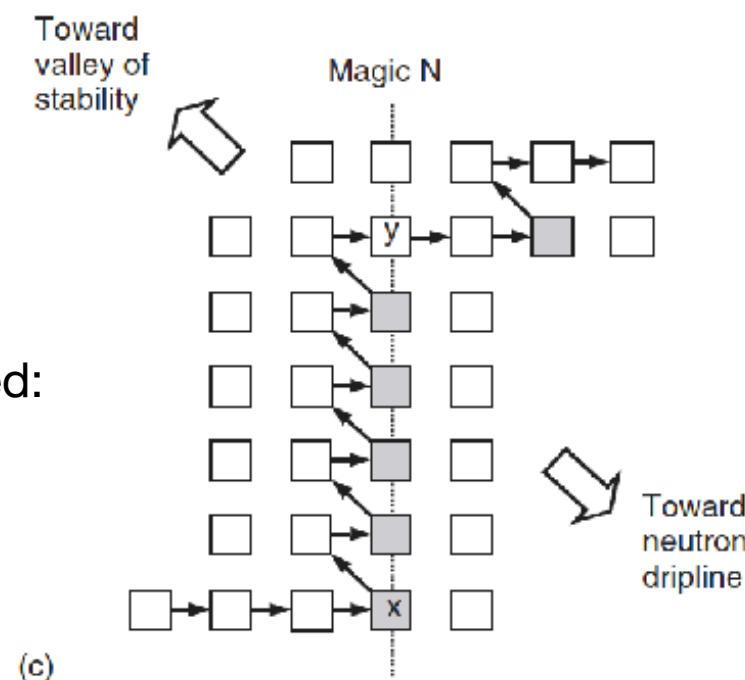
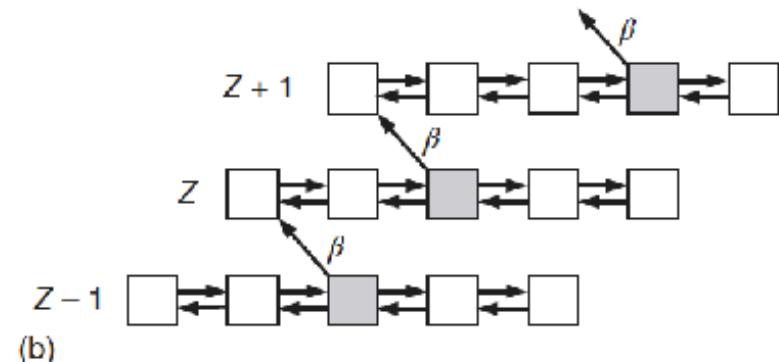
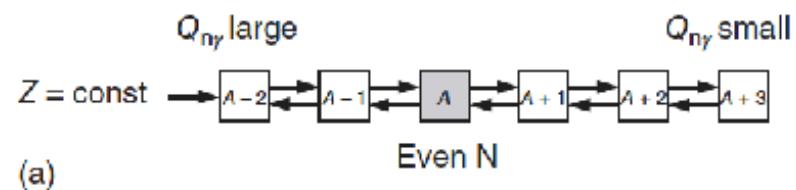
# r-process: a phenomenological model

neutron flux increase moves waiting points closer to the drip line

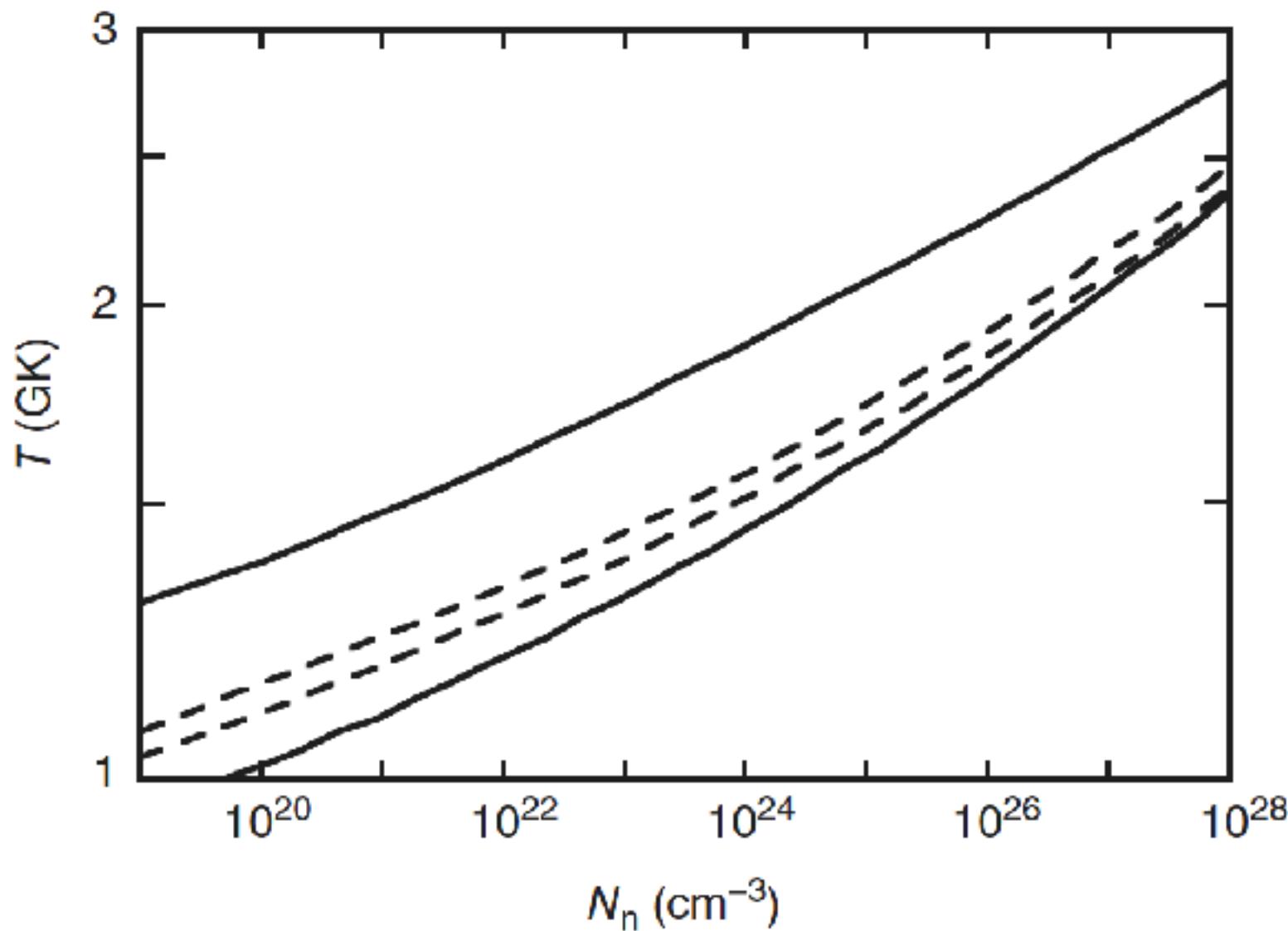
temperature increase, moves chain near the stability line

Temperature cannot be too high:  
destruction of heavy nuclei+migration  
to the stability valley

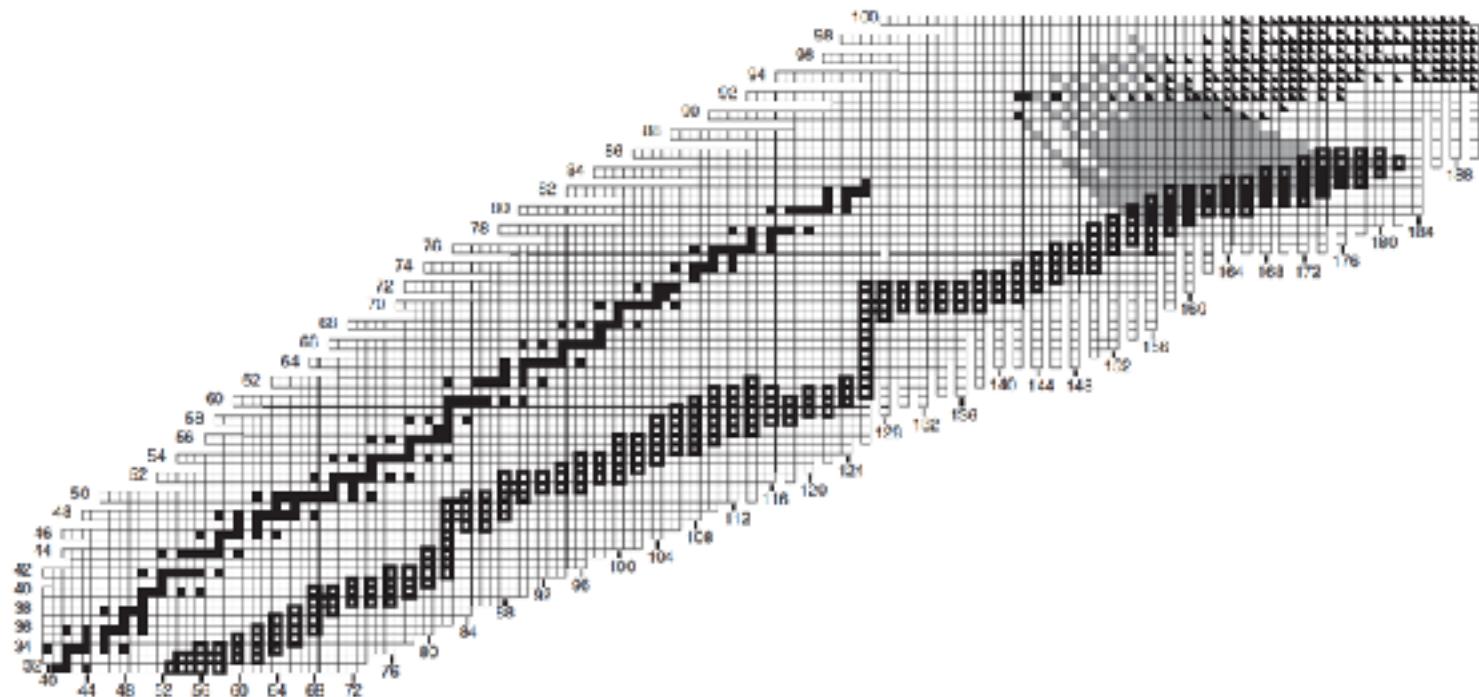
Neutron flux and temperature are correlated:  
one can compensate for the other



## r-process: a phenomenological model



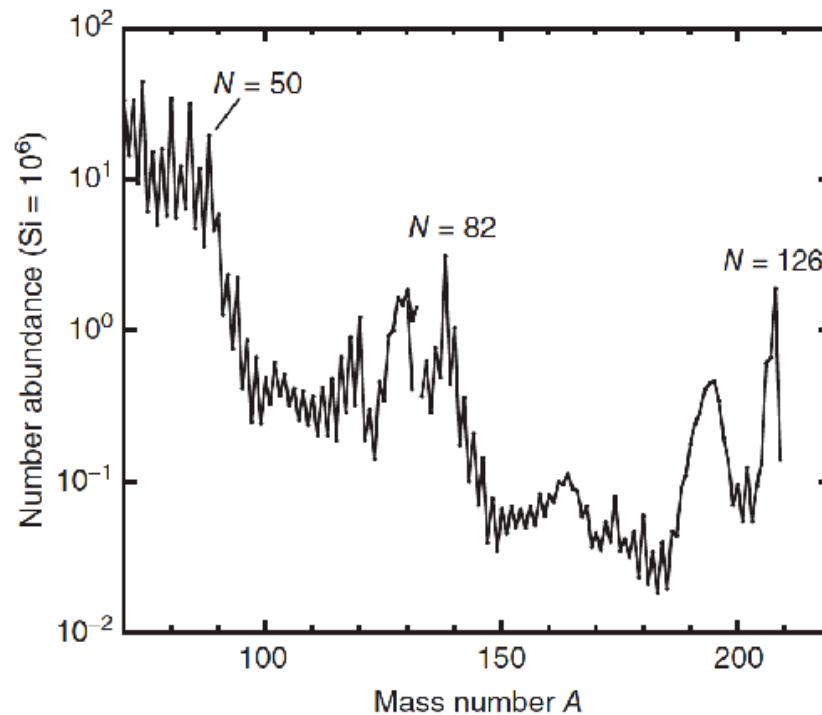
## r-process: a phenomenological model



At high A, the process stops due to fission: the fragments provide extra seed nuclei at different Z

## r-process: a phenomenological model

In this simple model, the triplet T, Nn,  $\tau$  determines everything, thus these parameters can be tuned to match the observer r-element abundances



No unique set of values can explained the observations: motivation for multiple components

## The quest for r-process sites

The observed abundances require high neutron fluxes, high temperatures and short durations —> explosive events!

The exact conditions remain a mystery for more than 60 years

Core-collapse supernovae are the most well-studied candidates for r-process nucleosynthesis

<https://youtu.be/1vLzRwJ2lHQ>

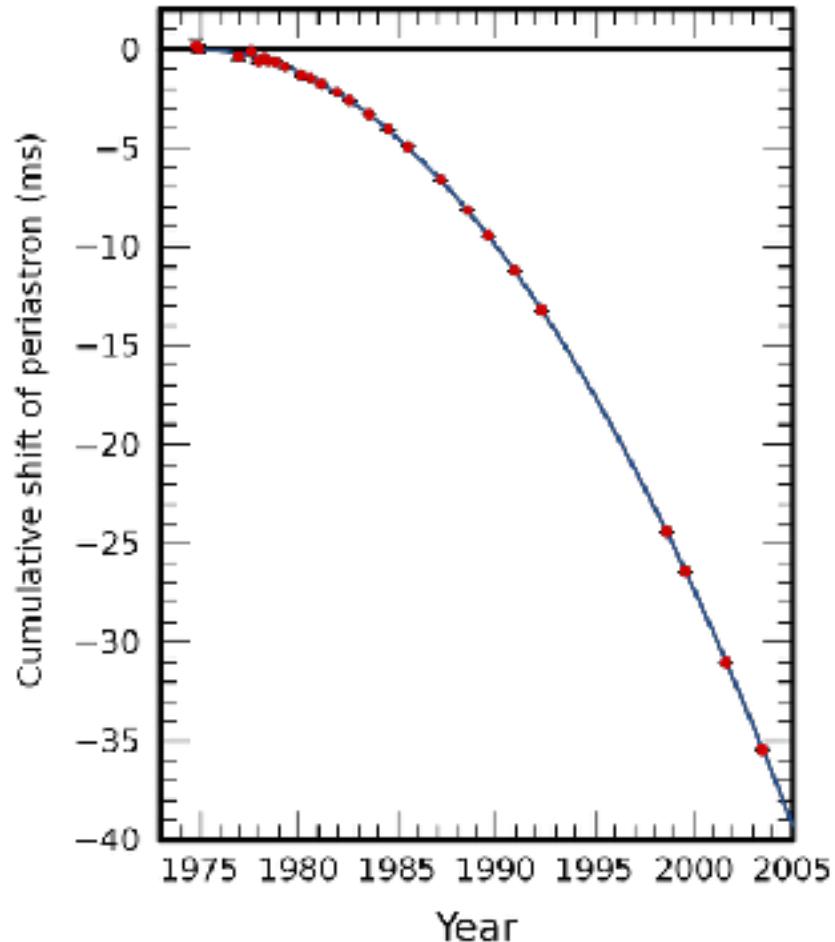
## neutron star mergers

First double neutron star discovered in 1974 by J. Taylor and R. Hulse

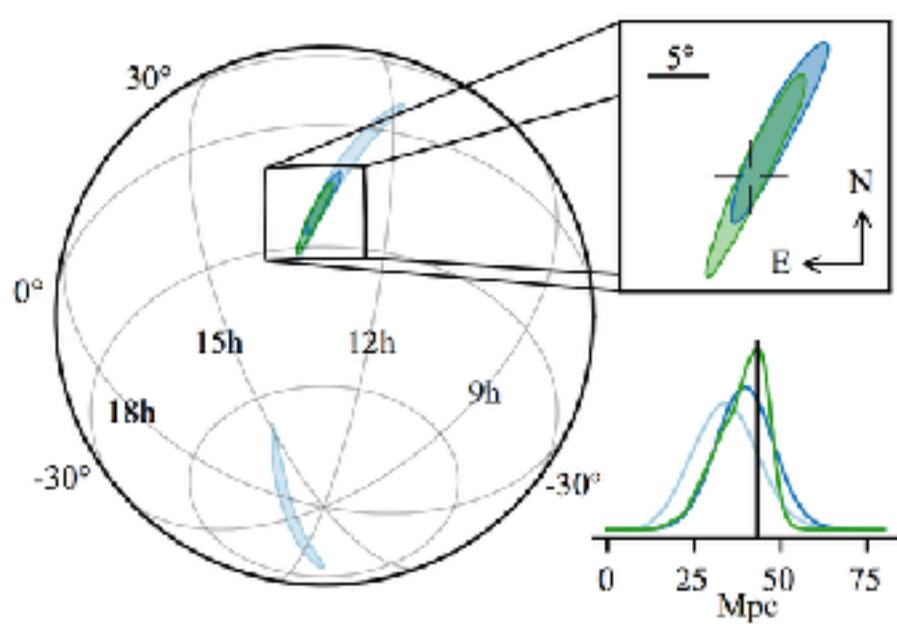
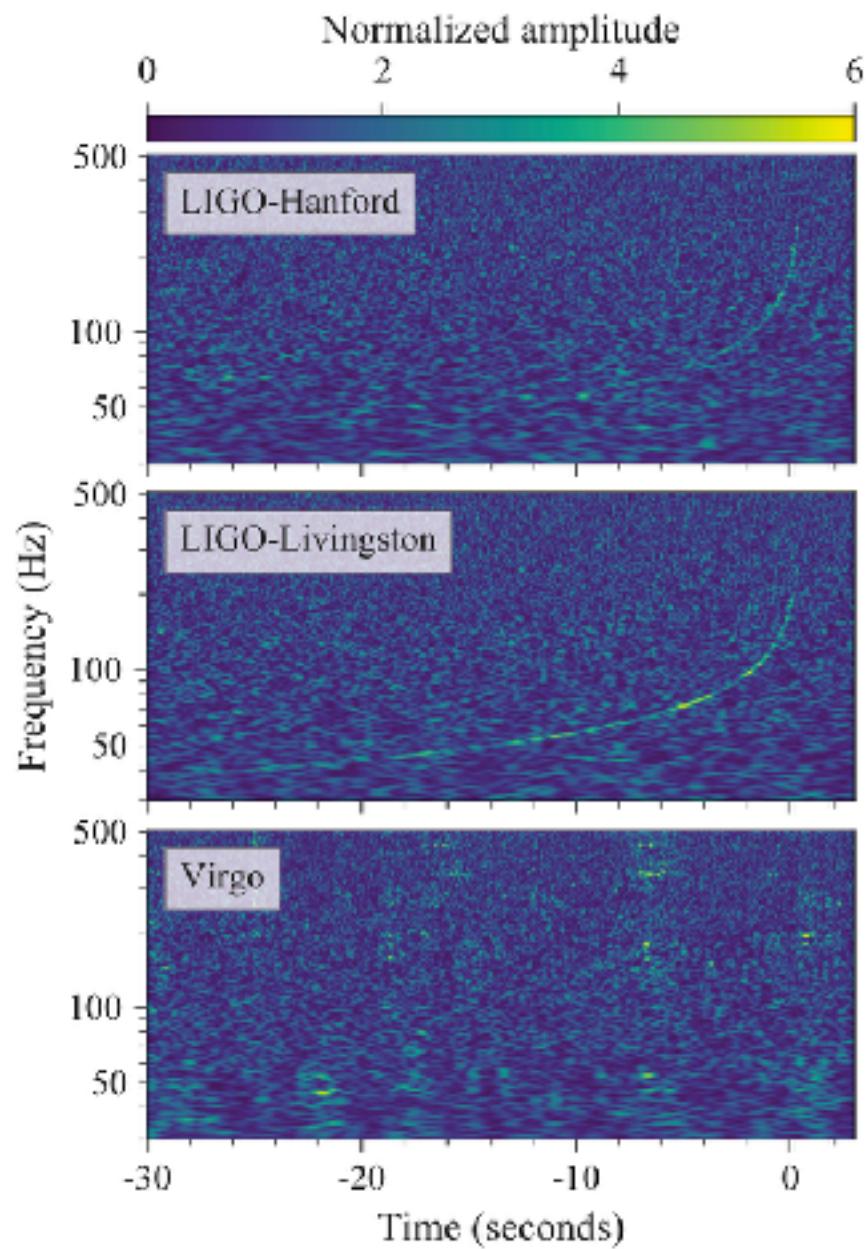
Orbital decay due to emission of gravitational waves detected after a few years

first observation of GWs!!!

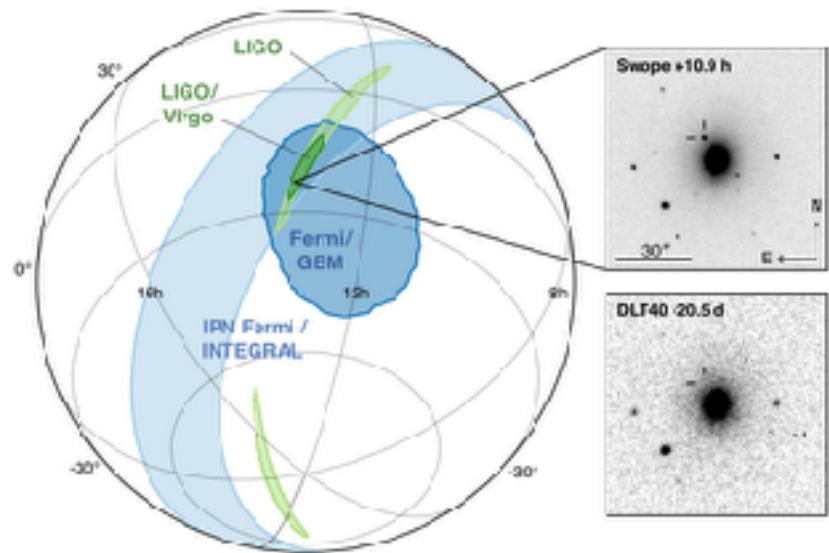
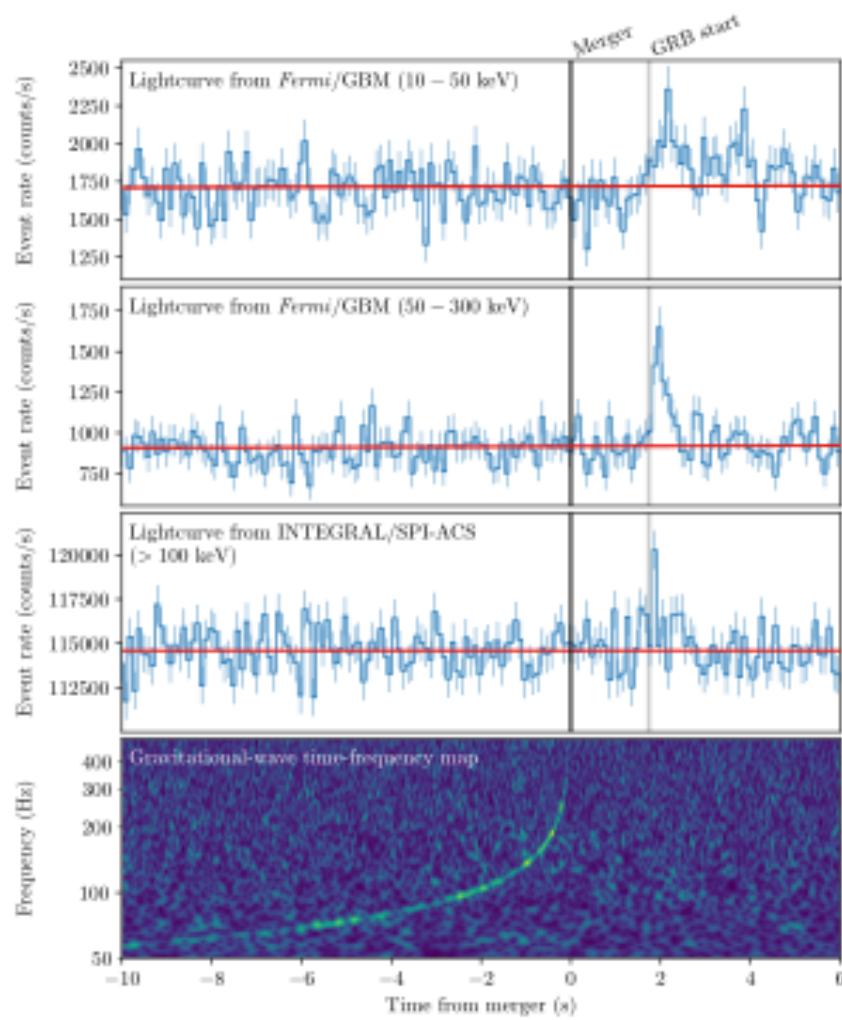
the two stars will merge in 300 Myr



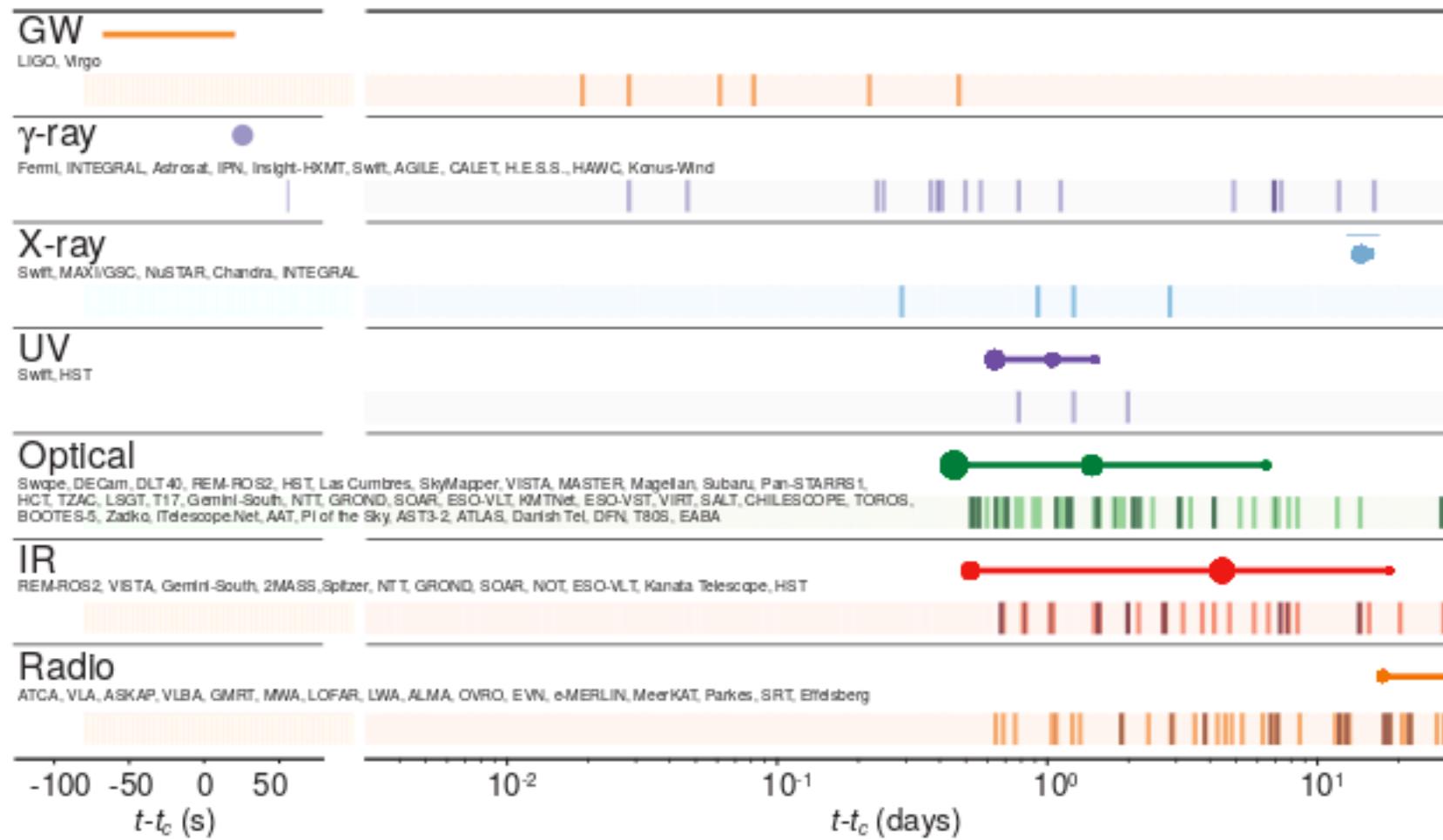
# GW 170817



# GW 170817



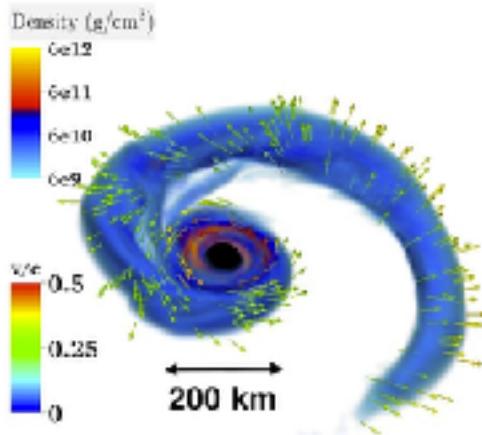
# GW 170817



# neutron star mergers

## Potential sources of ejecta in neutron star mergers

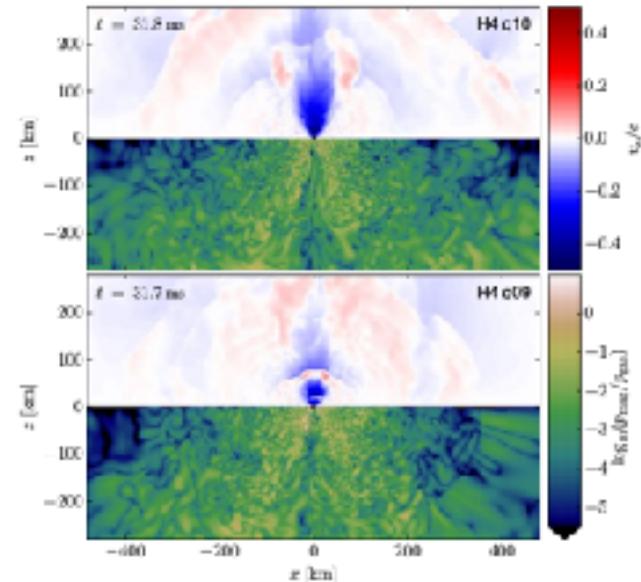
tidal ejecta



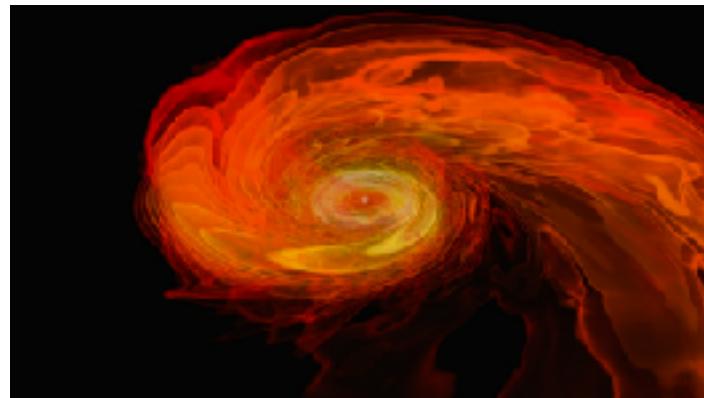
collision heated ejecta



v- and B-driven winds



post-merger accretion disk



## neutron star mergers

**tidal ejecta:**  $v \sim 0.2c$ , cold, neutron-rich material ( $T=0$  K,  $Y_e < 0.1$ ,  $M_{ej} < 10^{-3}$ )  
fast red transient (high opacity due to lanthanides)

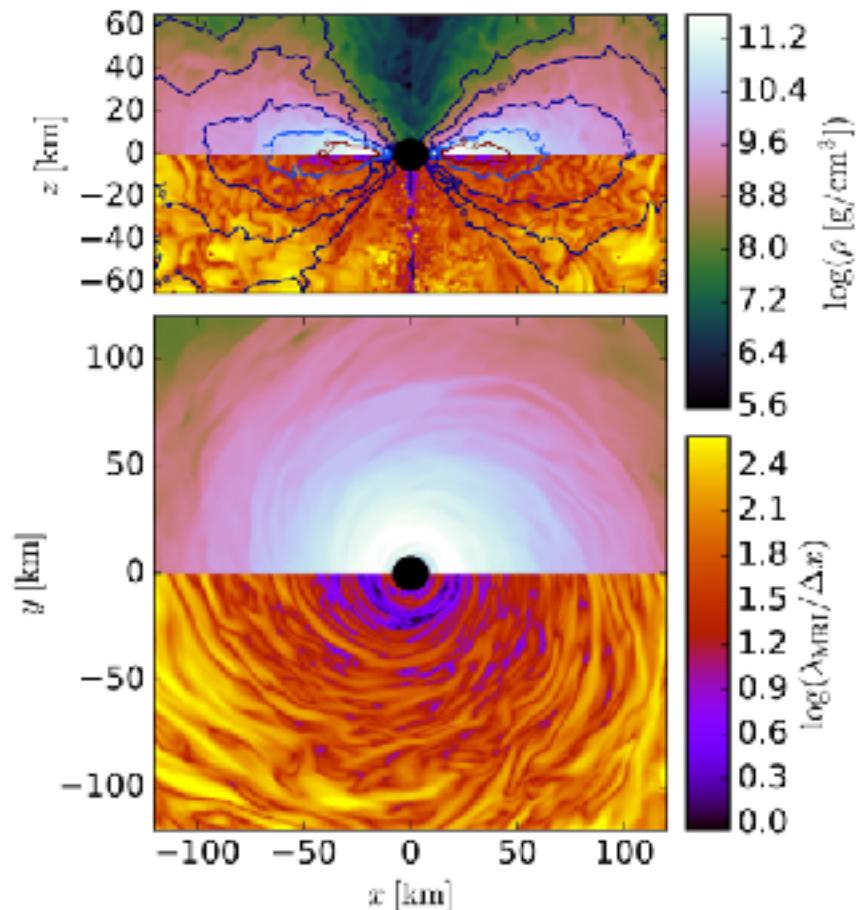
**collision-heated ejecta:**  $v \sim 0.2c$ , hot,  $\nu$ -emission ( $T=10$  MeV,  $Y_e > 0.25$ ,  $M_{ej} < 10^{-3}$ )  
fast blue transient

**$\nu$ - and B-driven winds:** reabsorption of neutrinos and B-field amplification drives  
a strong wind with  $T \sim 10$  MeV,  $Y_e > 0.25$  and  $v < 0.1c$  ...in NS-NS mergers only  
slow blue transient

# neutron star mergers

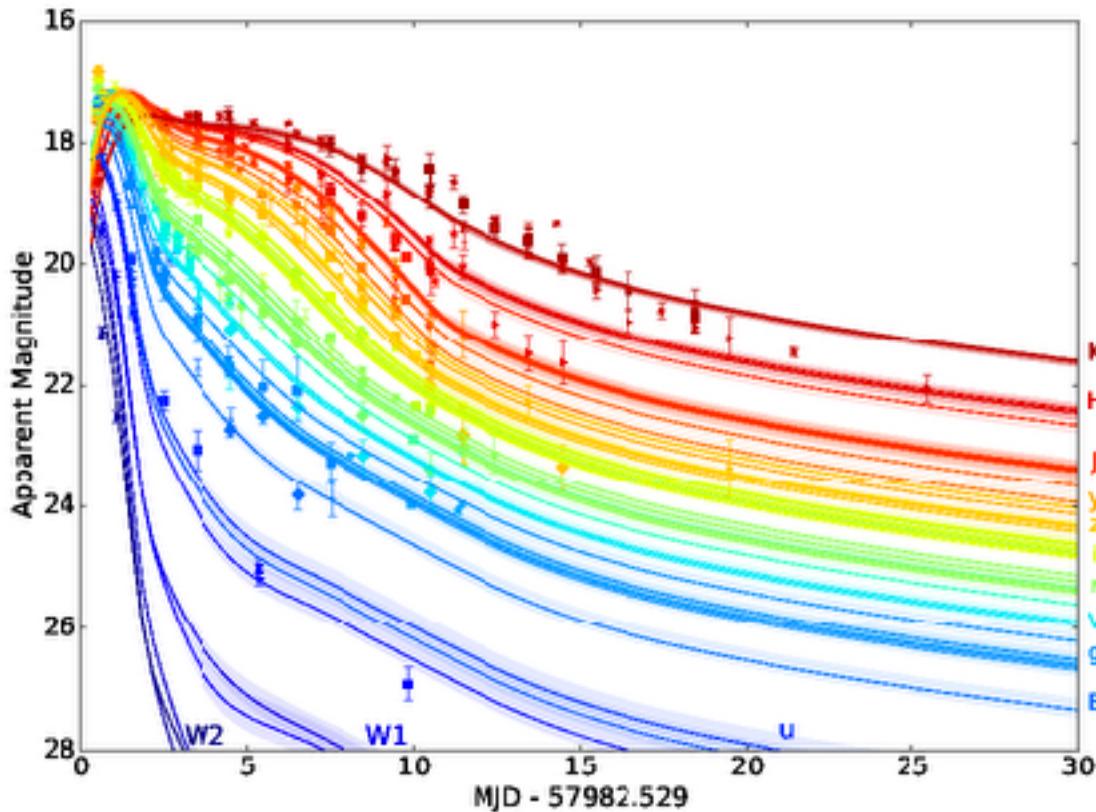
**post-merger accretion disk:** neutron-rich mater ejected from a hot corona and further heated due to nuclear burning (similar to SNe)

Neutron-rich outflows,  
 $Y < 0.25$ ,  $v < 0.1c$ ,  $M_{ej} < 0.1 M_{\odot}$   
give rise to a slow red transient



# GW 170817 kilonova

What was observed



**Fast blue transient**

$$M_{ej} = 10^{-2} \text{ Msun}$$

$$v_{ej} = 0.2\text{-}0.3c$$

$$Y_e > 0.25$$

$$X_{La} < 10^{-4}$$

**Slow red transient**

$$M_{ej} = 5 \times 10^{-2} \text{ Msun}$$

$$v_{ej} = 0.1c$$

$$Y_e < 0.25$$

$$X_{La} \sim 0.01$$

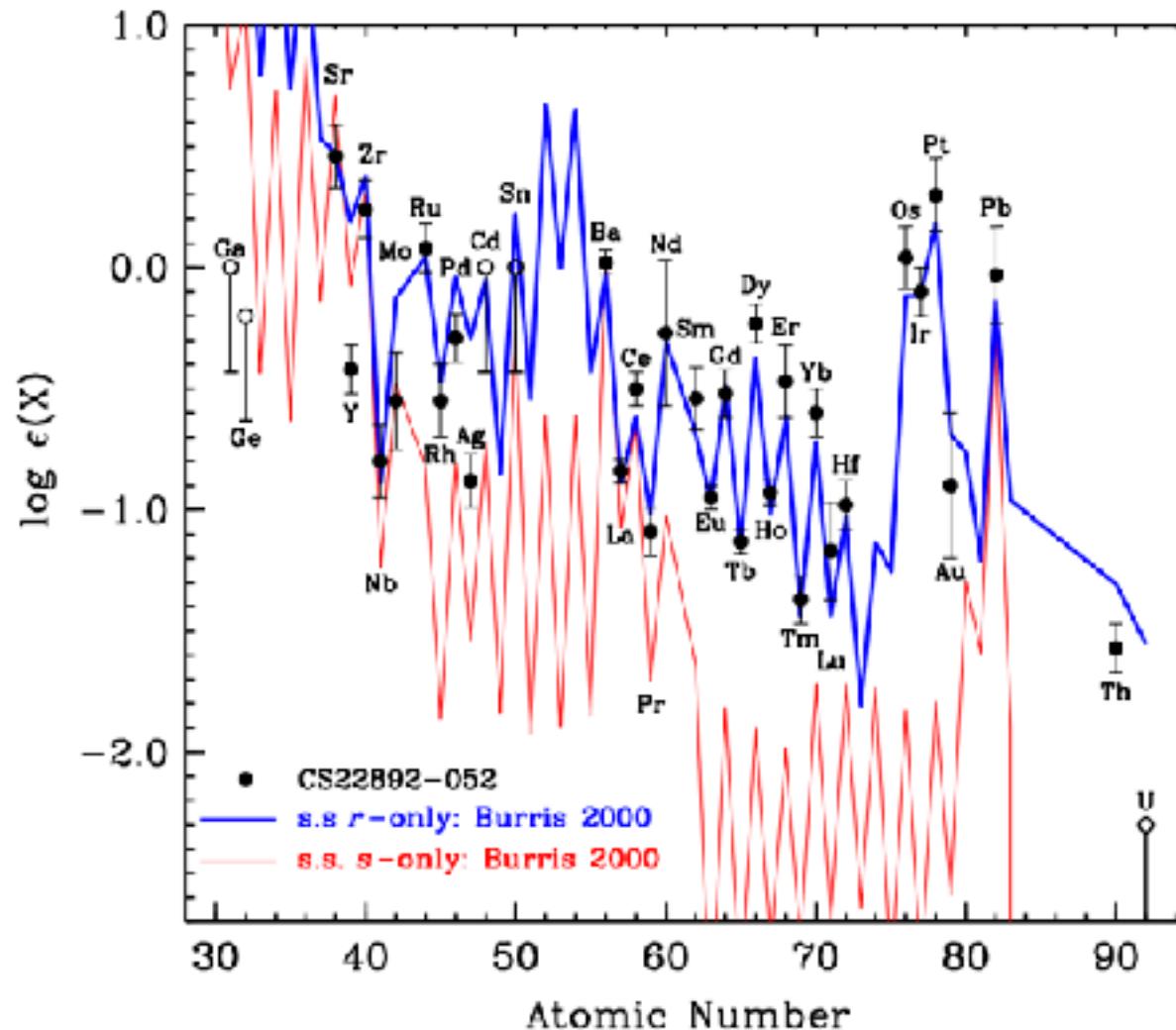
**collision ejecta + disk: can explain the production of all r-process elements  
(mainly the disk component!)**

See Drout et al. 2017 and references therein

## challenges for DNS mergers

Sneden's star: Fe/H = -3.1

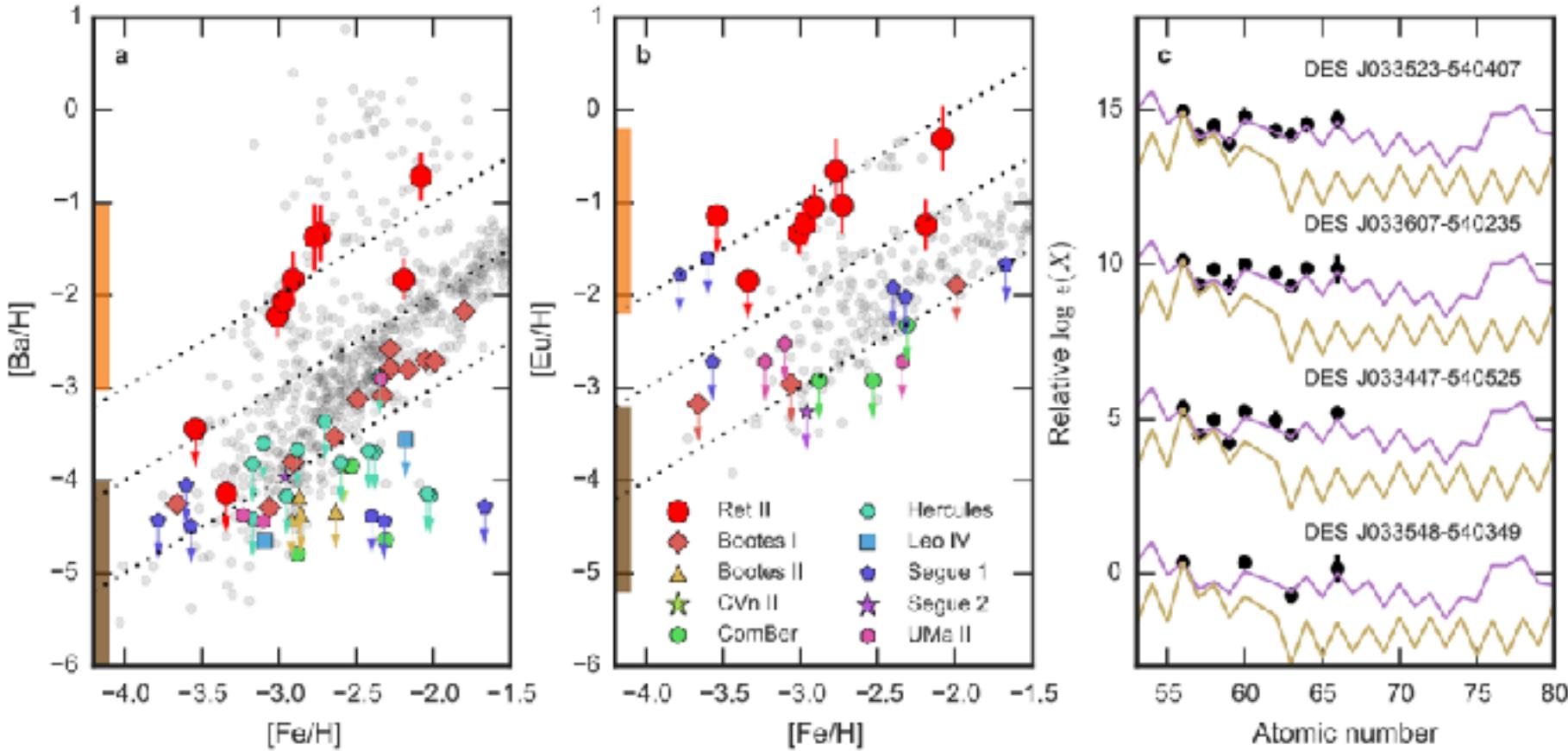
r-process elements are present in extremely old stars



# challenges from NS merger r-process

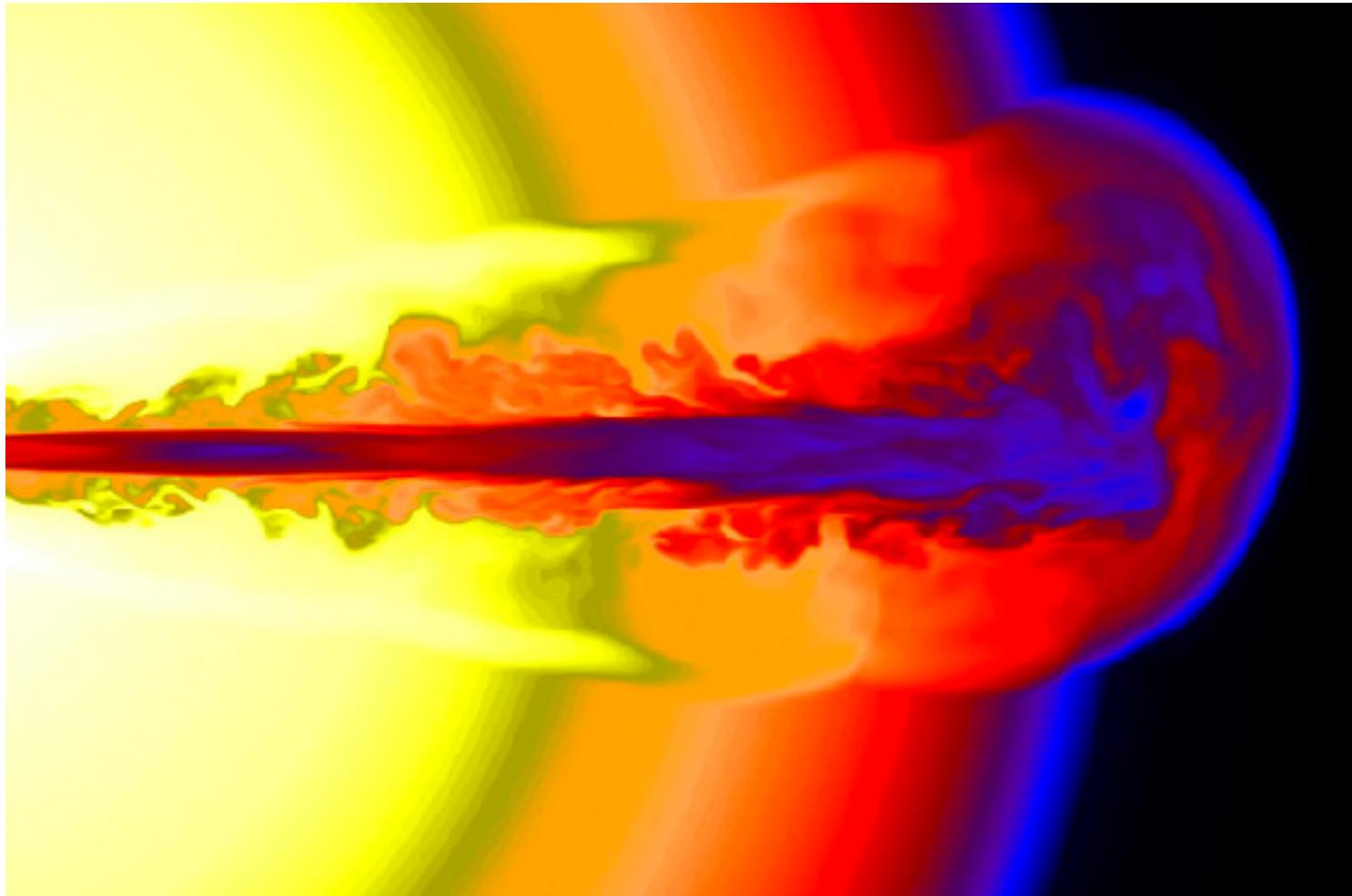
r-process elements are present in old stars that live in small galaxies!

Reticulum II ( $v_{\text{esc}} < 10 \text{ km/s}$ )



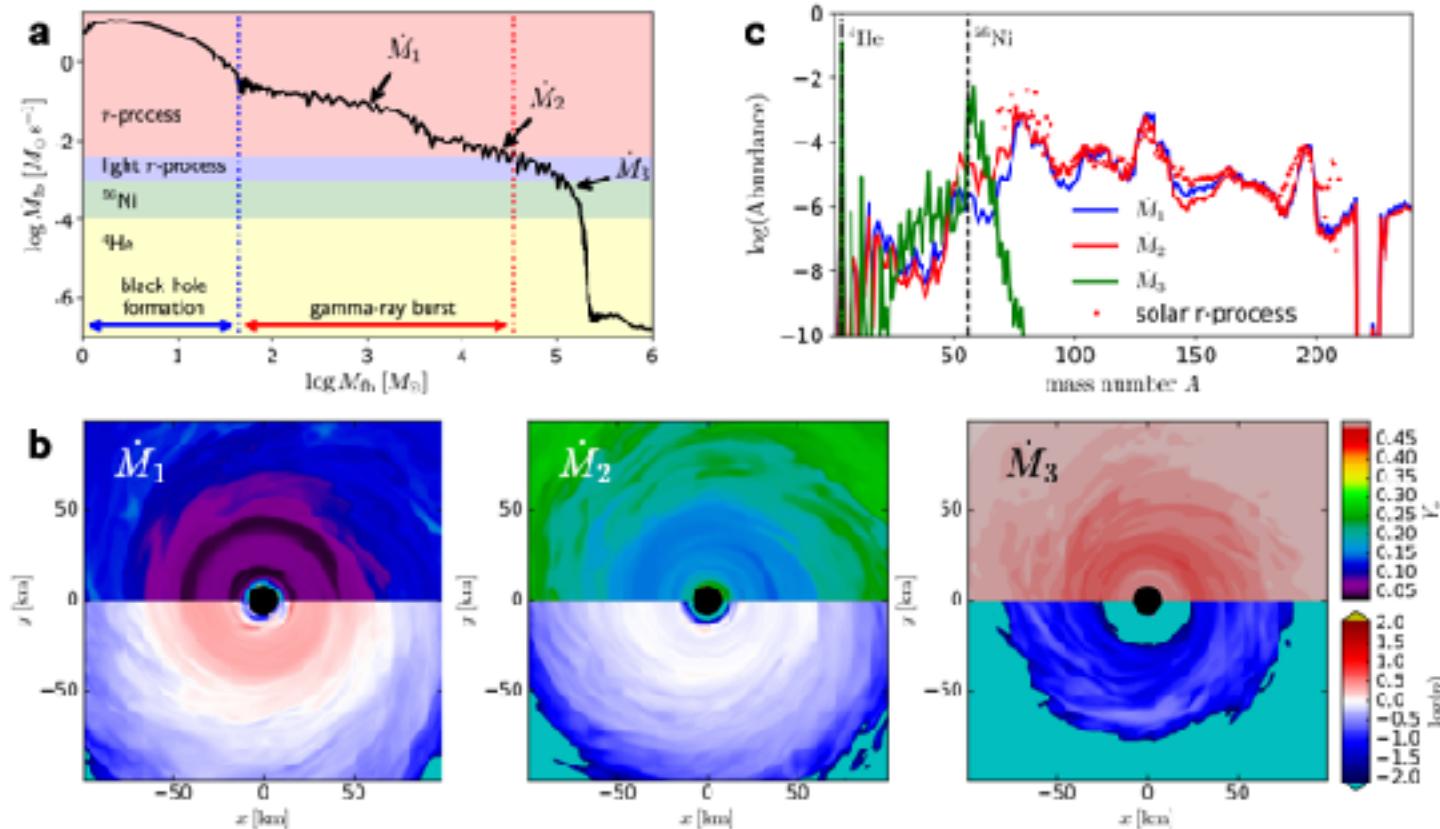
## challenges from NS merger r-process

If only there could be a neutron-rich disk around a black hole WITHOUT a neutron star merger....



# collapsars/hypernovae

Massive star collapses and the core forms a black hole  
The inner part has  $\sim 0$  specific J and is accreted directly,  
the outer core forms an accretion disk around the black hole and a jet that pierces  
through the outer layers  
Similar nucleosynthesis to DNS, but NO delay in respect to star formation



**Up next: What are supernovae good for?**