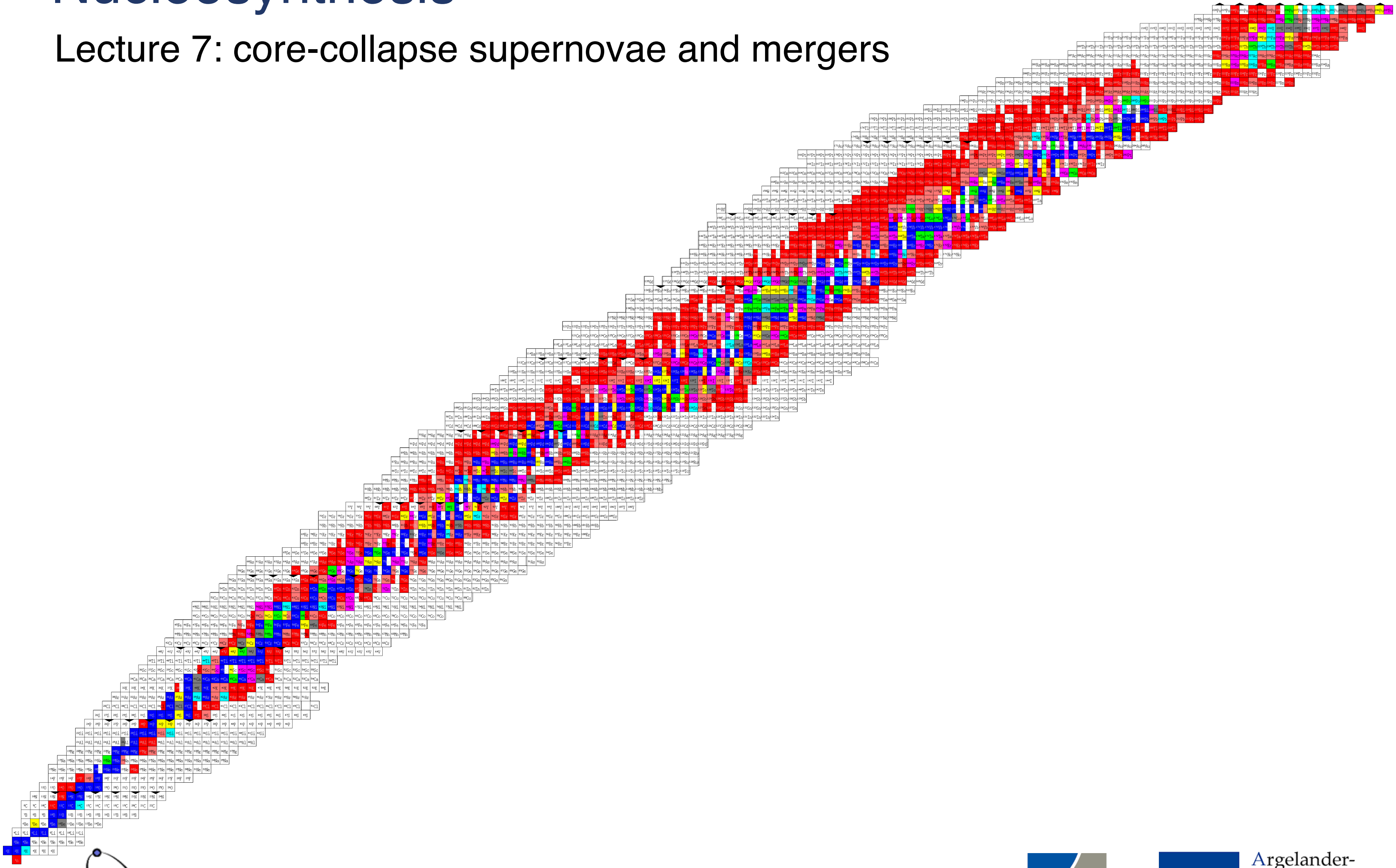
Nucleosynthesis

Lecture 7: core-collapse supernovae and mergers



Bonn-Cologne Graduate School
of Physics and Astronomy

UNIVERSITÄT BONN

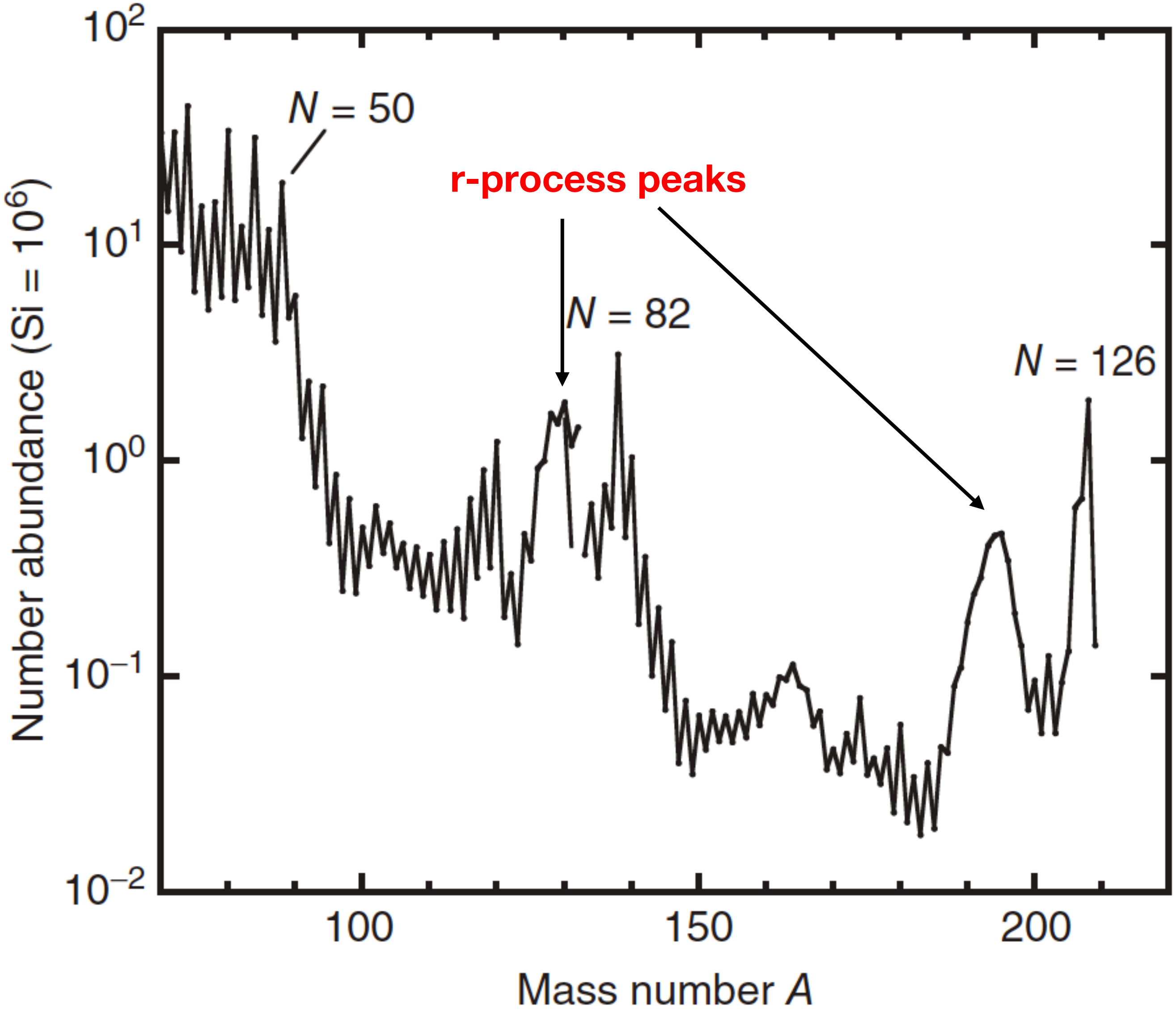
Argelander-
Institut
für
Astronomie

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

The quest for the origin of trans-iron elements



Credit: ILIADIS

Basic mechanism for nucleosynthesis beyond iron

60Zn 2.38 M ε: 100.00%	61Zn 89.1 S ε: 100.00%	62Zn 9.186 H ε: 100.00%	63Zn 38.47 M ε: 100.00%	64Zn ≥7.0E20 Y 49.17% 2ε	65Zn 243.93 D ε: 100.00%	66Zn STABLE 27.73%	67Zn STABLE 4.04%	68Zn STABLE 18.45%
59Cu 81.5 S ε: 100.00%	60Cu 23.7 M ε: 100.00%	61Cu 3.339 H ε: 100.00%	62Cu 9.673 M ε: 100.00%	63Cu STABLE 69.15%	64Cu 12.701 H ε: 61.50% β-: 38.50%	65Cu STABLE 30.85%	66Cu 5.120 M β-: 100.00%	67Cu 61.83 H β-: 100.00%
58Ni STABLE 68.077%	59Ni 7.6E+4 Y ε: 100.00%	60Ni STABLE 26.223%	61Ni STABLE 1.1399%	62Ni STABLE 3.6346%	63Ni 101.2 Y β-: 100.00%	64Ni STABLE 0.9255%	65Ni 2.5175 H β-: 100.00%	66Ni 54.6 H β-: 100.00%
57Co 271.74 D ε: 100.00%	58Co 70.86 D ε: 100.00%	59Co STABLE 100%	60Co 1925.28 D β-: 100.00%	61Co 1.649 H β-: 100.00%	62Co 1.50 M β-: 100.00%	63Co 27.4 S β-: 100.00%	64Co 0.30 S β-: 100.00%	65Co 1.16 S β-: 100.00%
56Fe STABLE 91.754%	57Fe STABLE 2.119%	58Fe STABLE 0.282%	59Fe 44.495 D β-: 100.00%	60Fe 2.62E+6 Y β-: 100.00%	61Fe 5.98 M β-: 100.00%	62Fe 68 S β-: 100.00%	63Fe 6.1 S β-: 100.00%	64Fe 2.0 S β-: 100.00%

Blackboard

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.
Away from the valley of stability this is not possible.
Elements are short-lived, therefore no measurements exist!!!

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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

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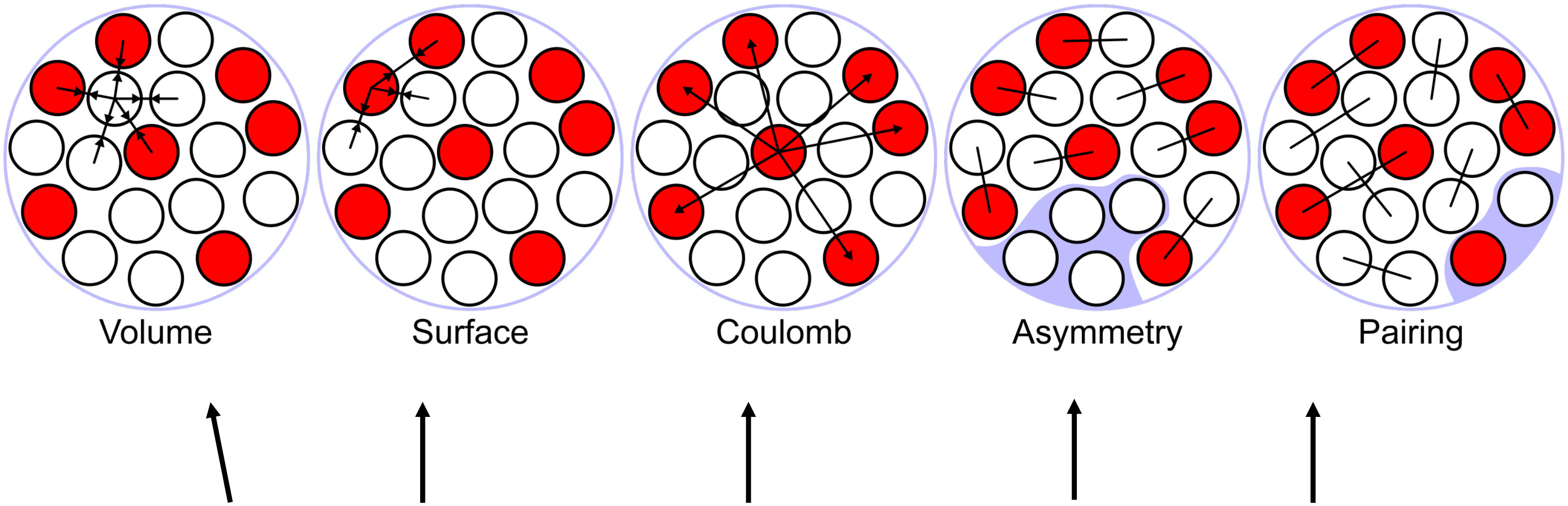
Nuclear physics interlude



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

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Nuclear physics interlude

Application 1

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

$$BE/A \simeq 8\,\mathrm{MeV}$$

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Nuclear physics interlude

Application 2

When does a nucleus become unstable to α-decay?

$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He $$

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

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

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Nuclear physics interlude

Application 3

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

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

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

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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?

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

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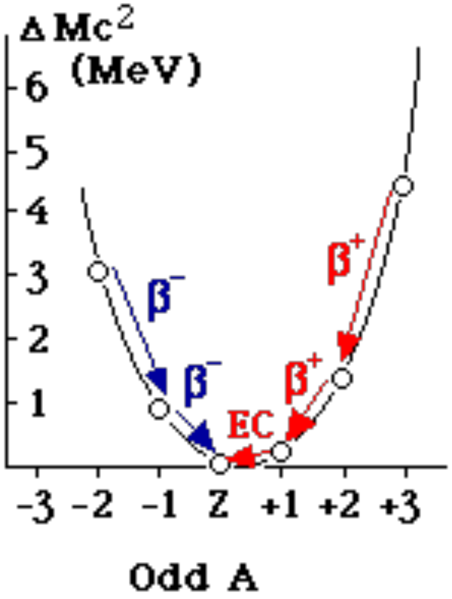
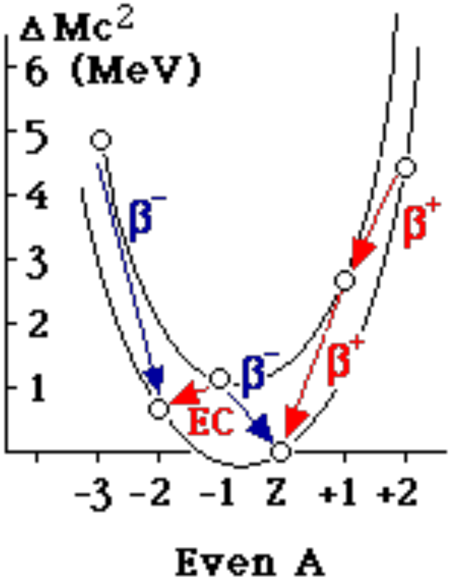
Nuclear physics interlude

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

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

For $\pm\delta$ two parabolas





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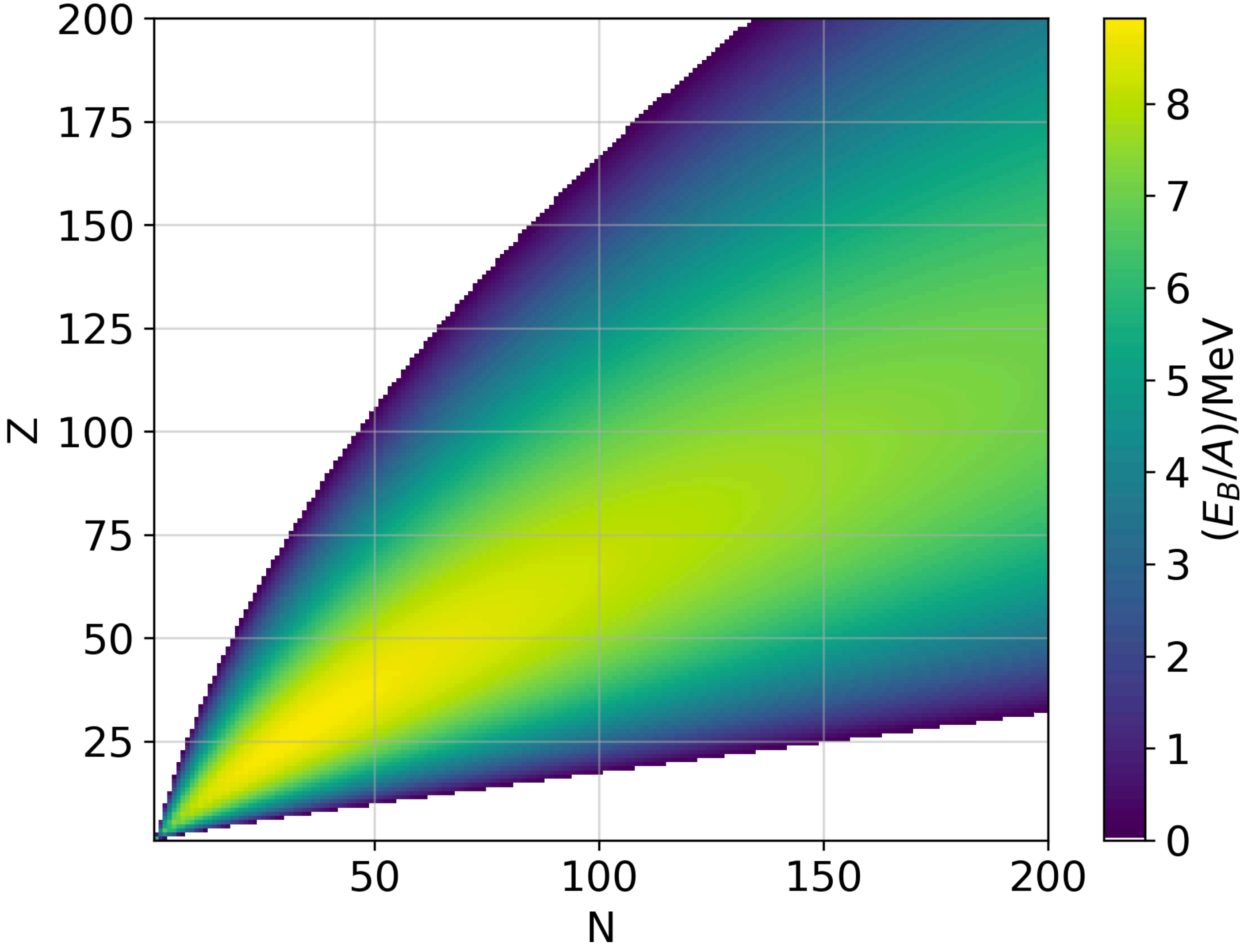
Nuclear physics interlude



Nuclear physics interlude

Quiz

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

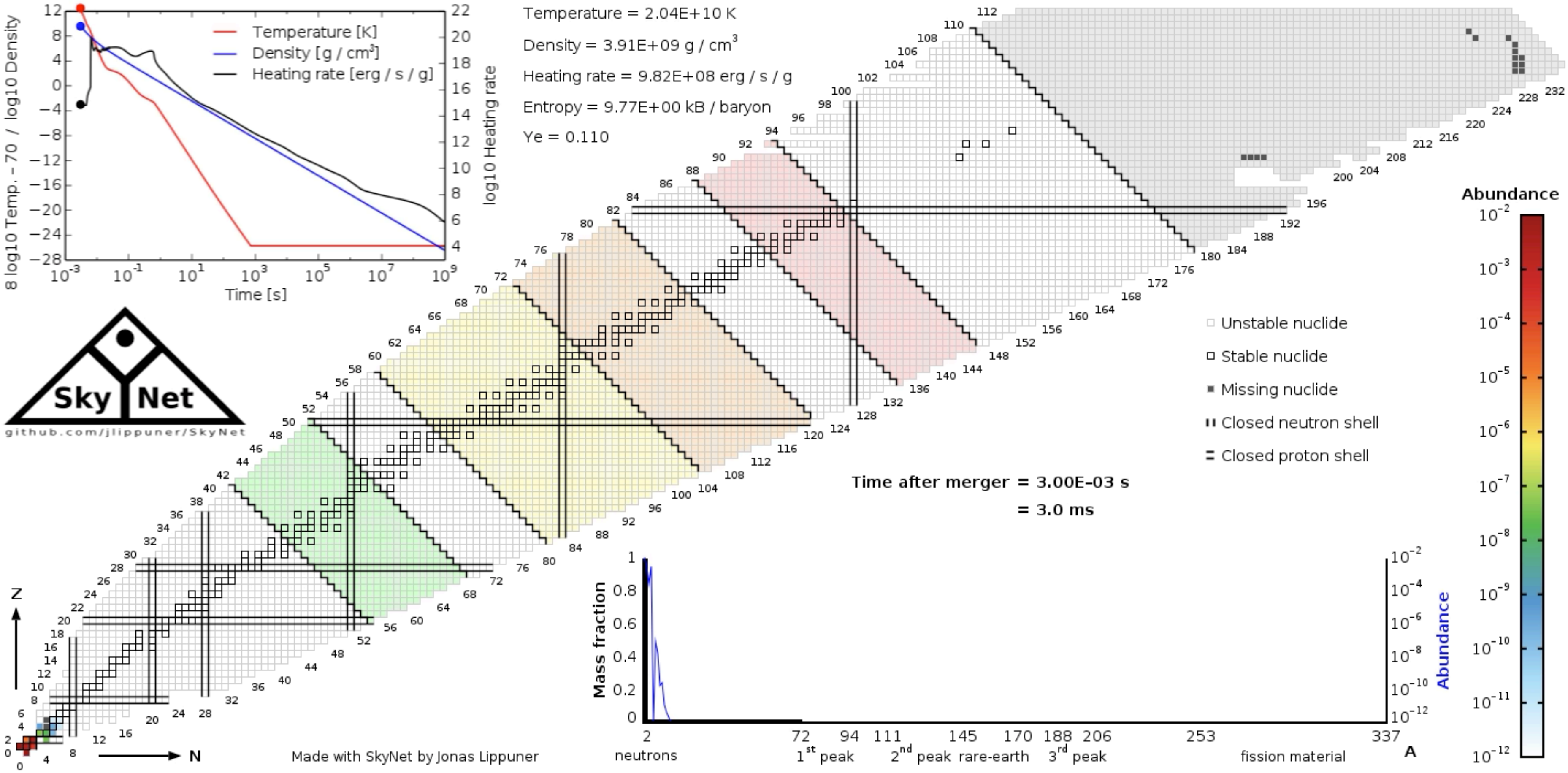
A. Nickel

B. Iron

C. Same

r-process

neutron capture timescales must be of order 10^{-4} s are required to avoid β-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.

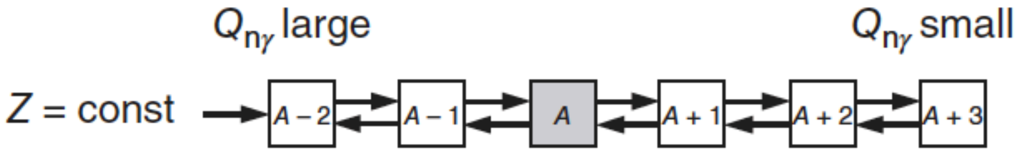
In the simulation, seeds quickly accumulate neutrons, but the neutron drip line is almost never reached. Why?

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”

r-process: a phenomenological model



$Q_{n\gamma}$ large

$Q_{n\gamma}$ small

Z = const

$A-2$

$A-1$

A

$A+1$

$A+2$

$A+3$

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

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

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

Blackboard

r-process: a phenomenological model

Constant T and Nn for a given duration τ

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

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

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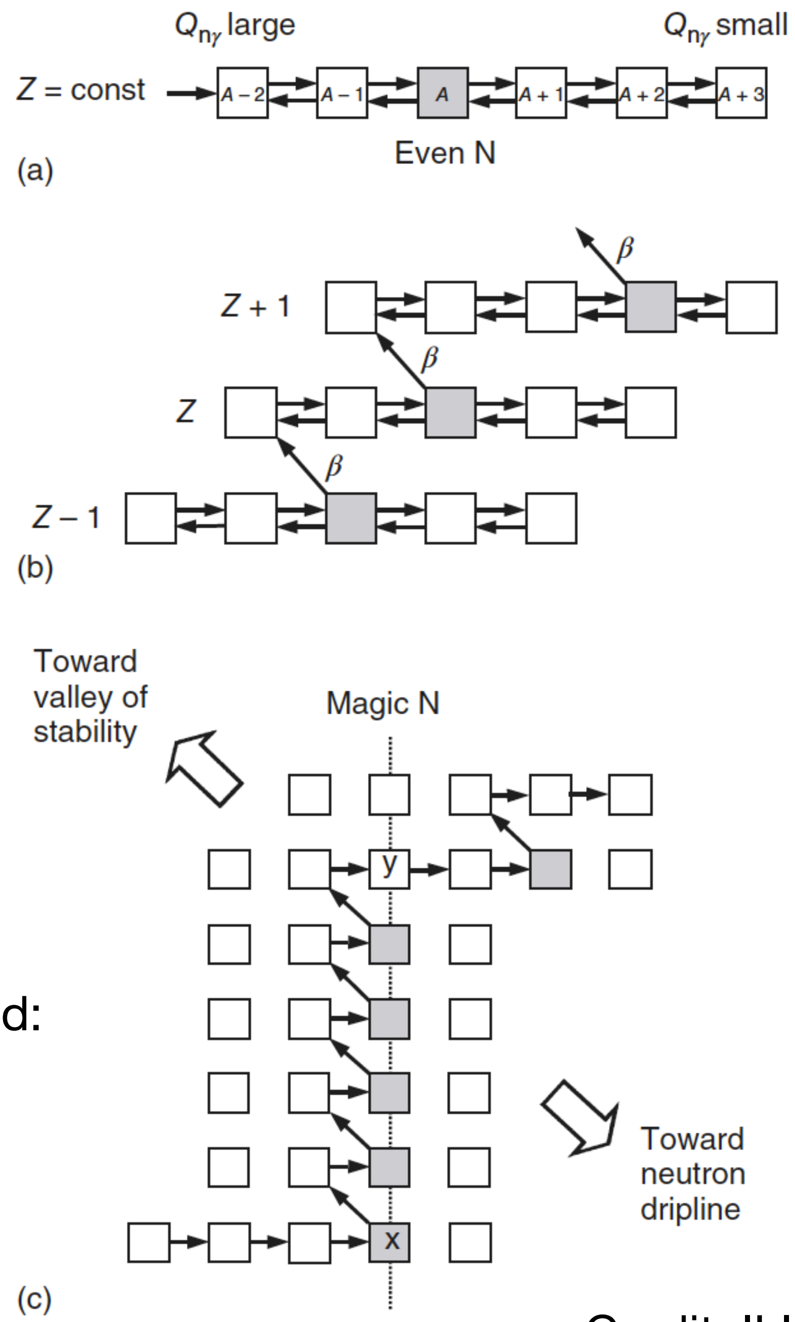
r-process: a phenomenological model



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

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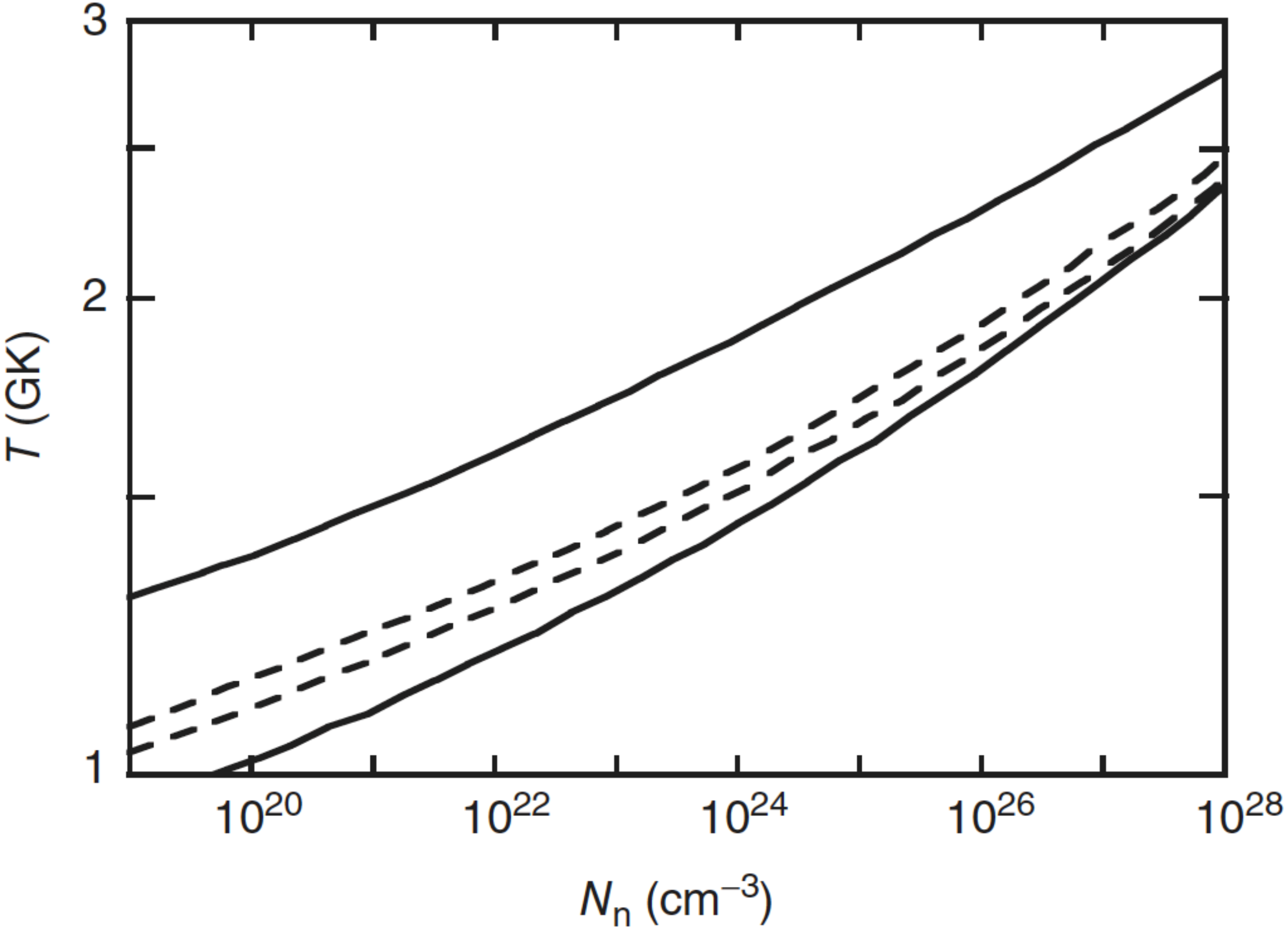
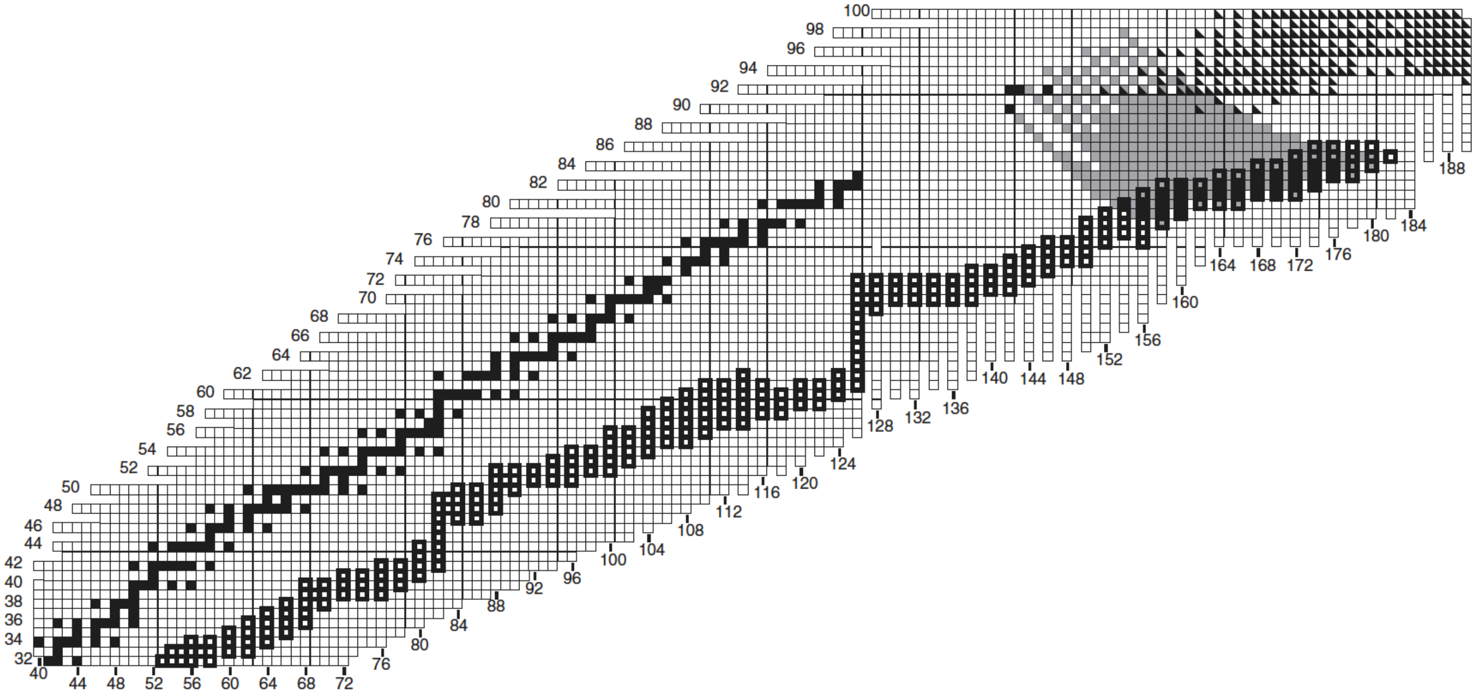
Credit: ILIADIS

r-process: a phenomenological model



Credit: ILIADIS

r-process: a phenomenological model

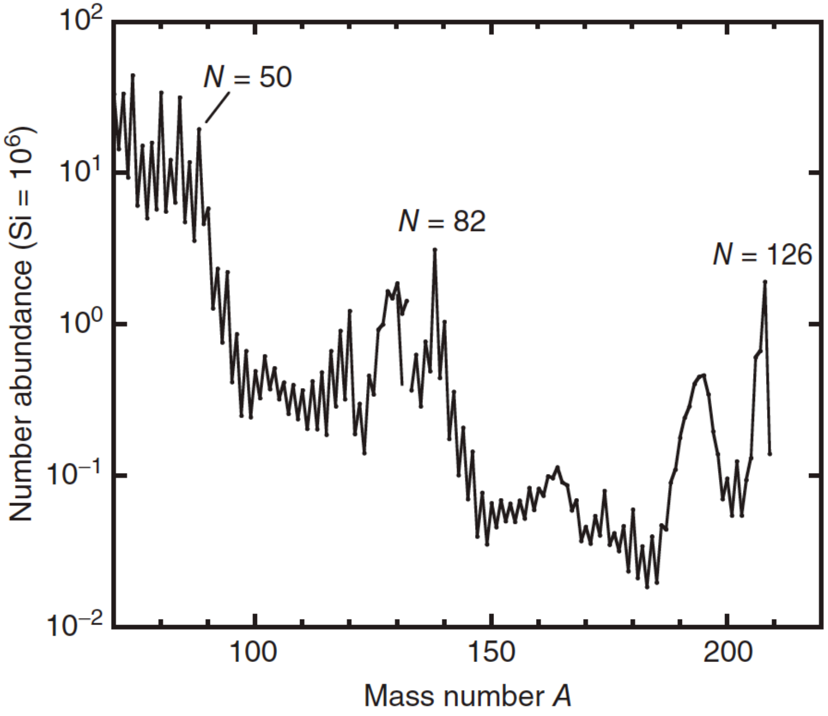


At high A, the process stops due to fission: the fragments provide extra seed nuclei at different Z

Credit: ILIADIS

r-process: a phenomenological model

In this simple model, the triplet T, Nn, τ 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

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Credit: ILIADIS

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

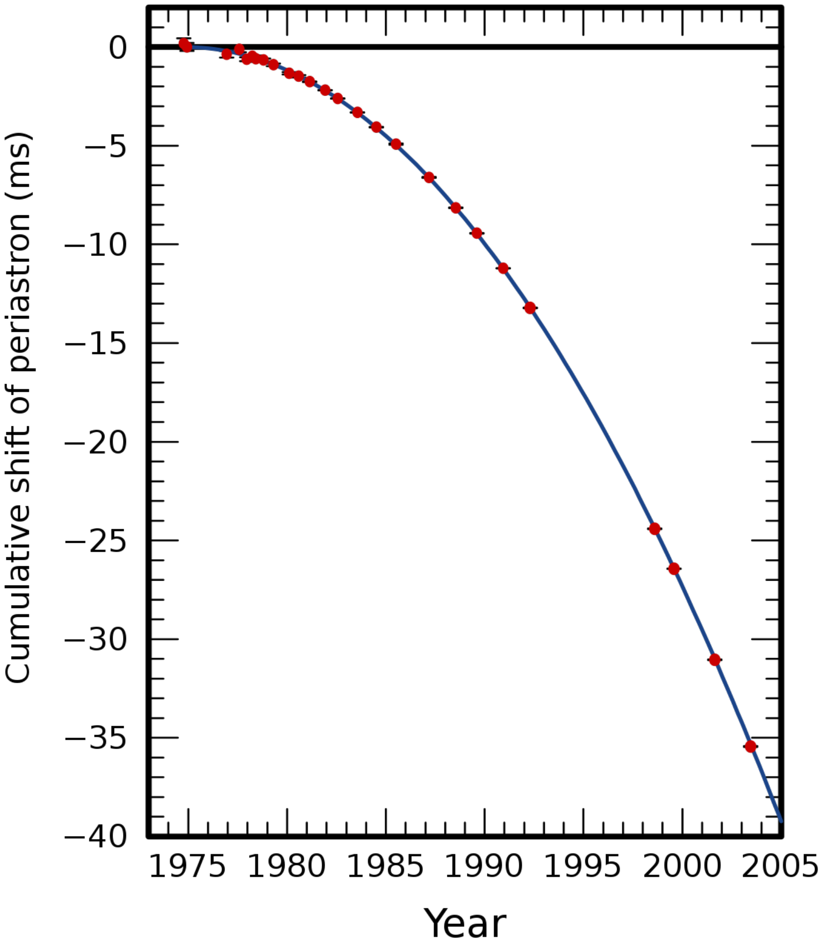
neutron star mergers

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

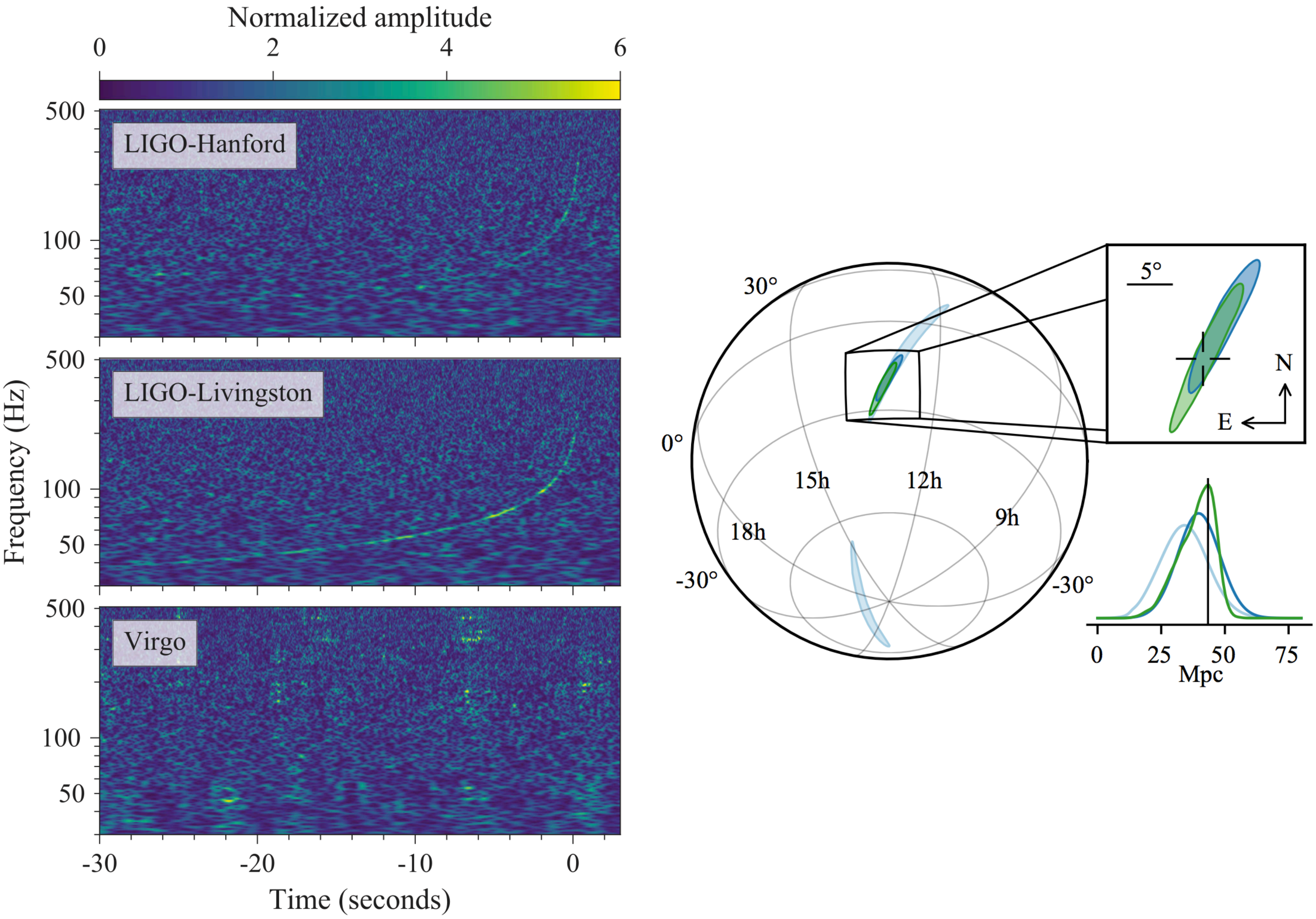
Orbital decay due to emission of gravitational waves detected after a few years

first observation of GWs!!!

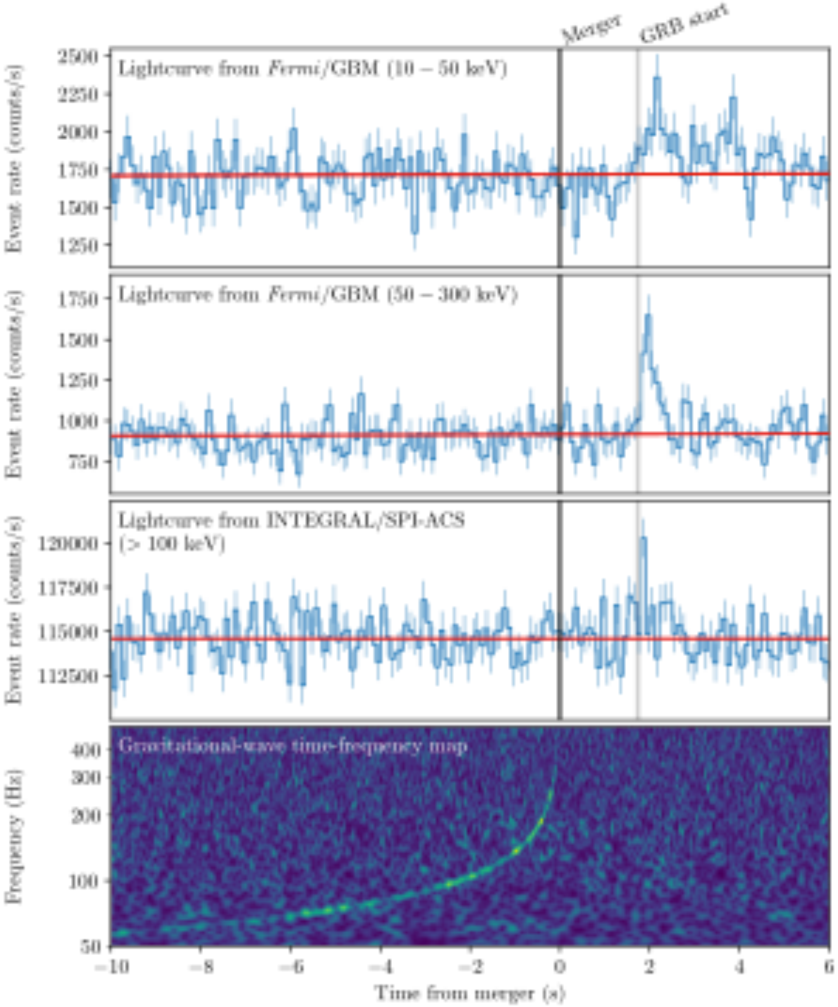
the two stars will merge in 300 Myr

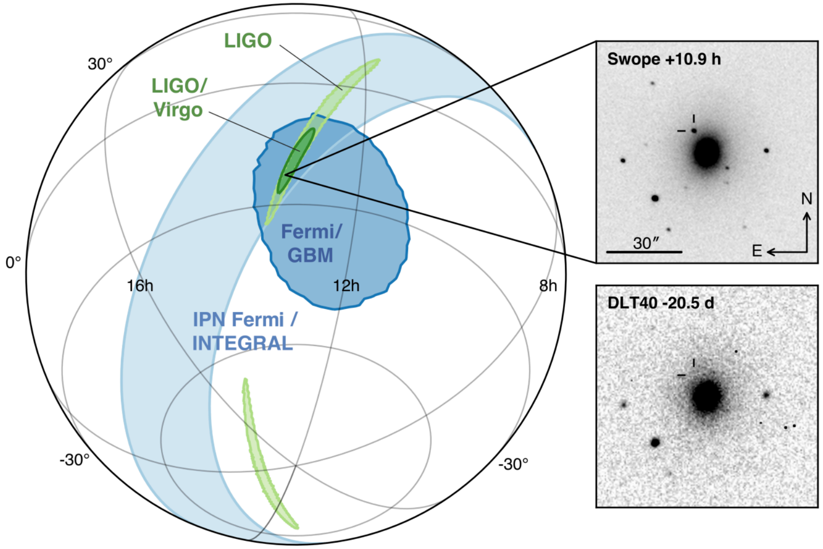


GW 170817

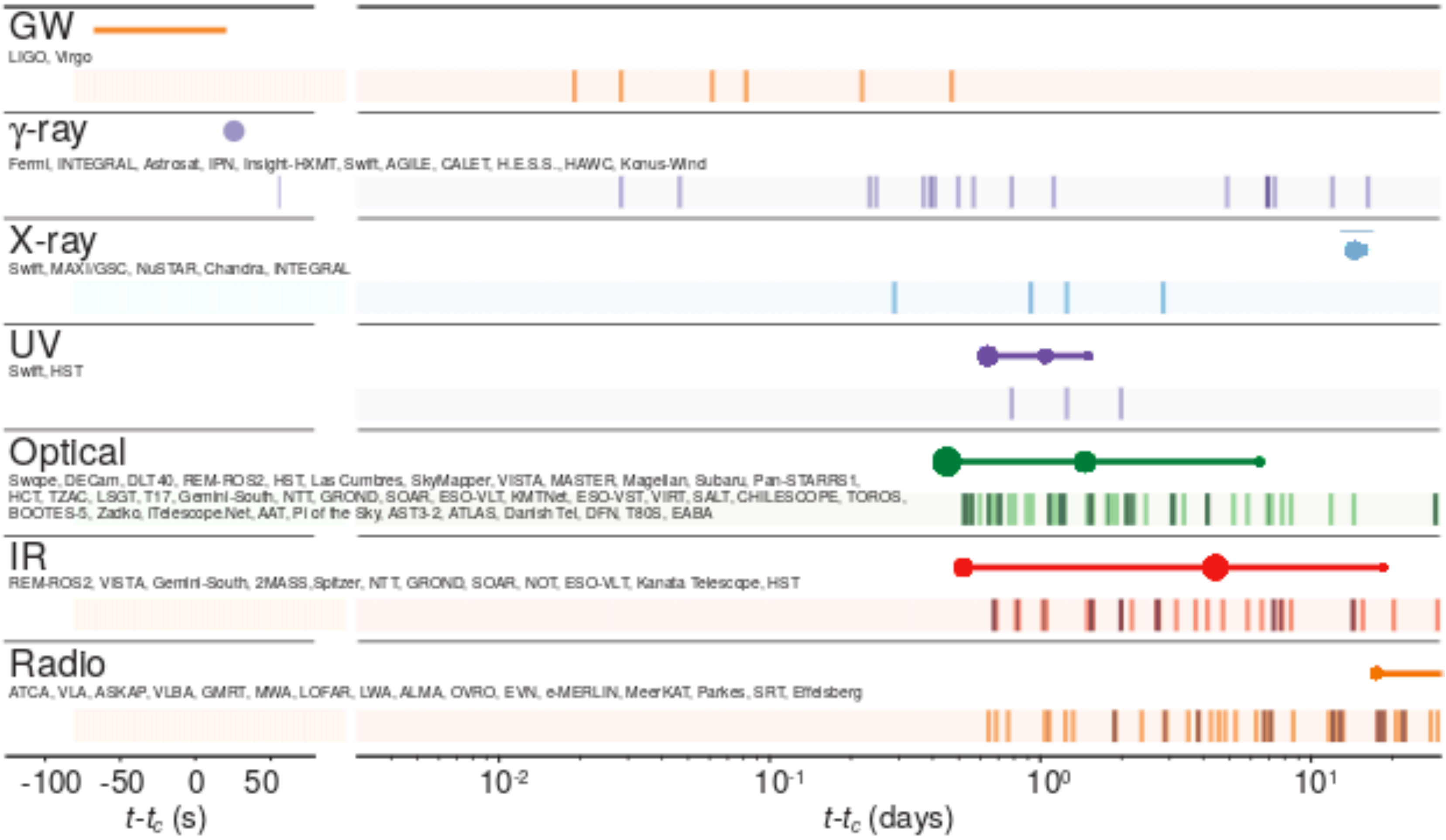

Normalized amplitude
0
2
4
6
500
100
50
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
-30
-20
-10
0
Time (seconds)
30°
0°
-30°
-30°
15h
12h
9h
18h
5°
N
E
0
25
50
75
Mpc

GW 170817


Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Lightcurve from Fermi/GBM (50 – 300 keV)
Lightcurve from INTEGRAL/SPI-ACS (> 100 keV)
Gravitational-wave time-frequency map
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)
2500
2250
2000
1750
1500
1250
1000
750
120000
117500
115000
112500
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6


LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
30°
0°
-30°
-30°
16h
12h
8h
Swope +10.9 h
N
E
30″
DLT40 -20.5 d

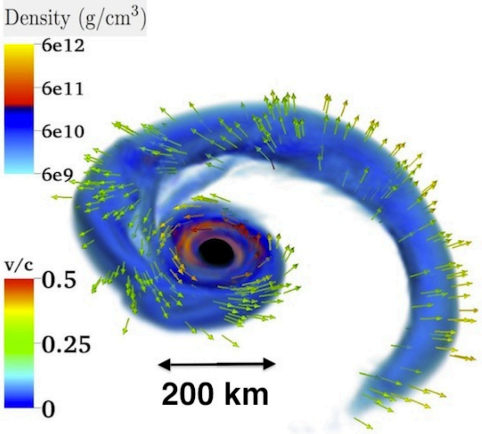
GW 170817


GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, ITelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS, Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-t_c (s)
10^-2
10^-1
10^0
10^1
t-t_c (days)

neutron star mergers

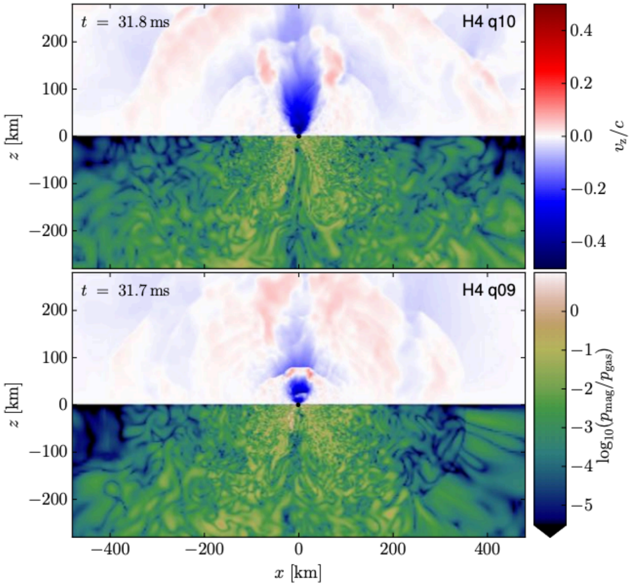
Potential sources of ejecta in neutron star mergers

tidal ejecta

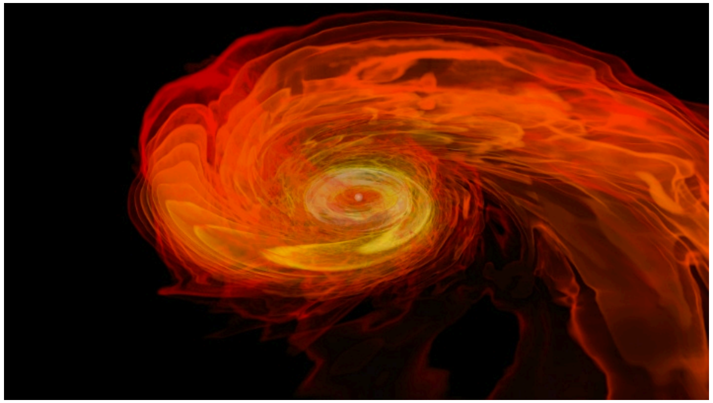


collision heated ejecta

ν- and B-driven winds



post-merger accretion disk



neutron star mergers

tidal ejecta: v~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~0.2c, hot, v-emission (T=10 MeV, $Y_e > 0.25$, $M_{ej} < 10^{-3}$)

fast blue transient

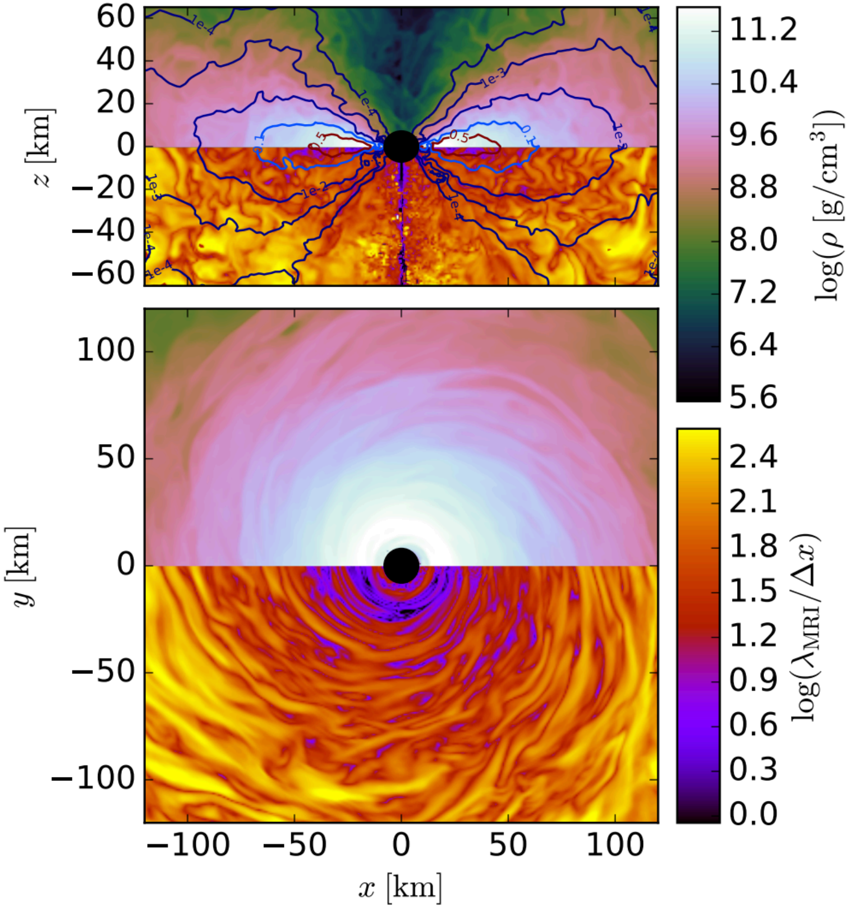
v- and B-driven winds: reabsorption of neutrinos and B-field amplification drives a strong wind with T~10 MeV, $Y_e > 0.25$ and v<0.1c …in NS-NS mergers only

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)

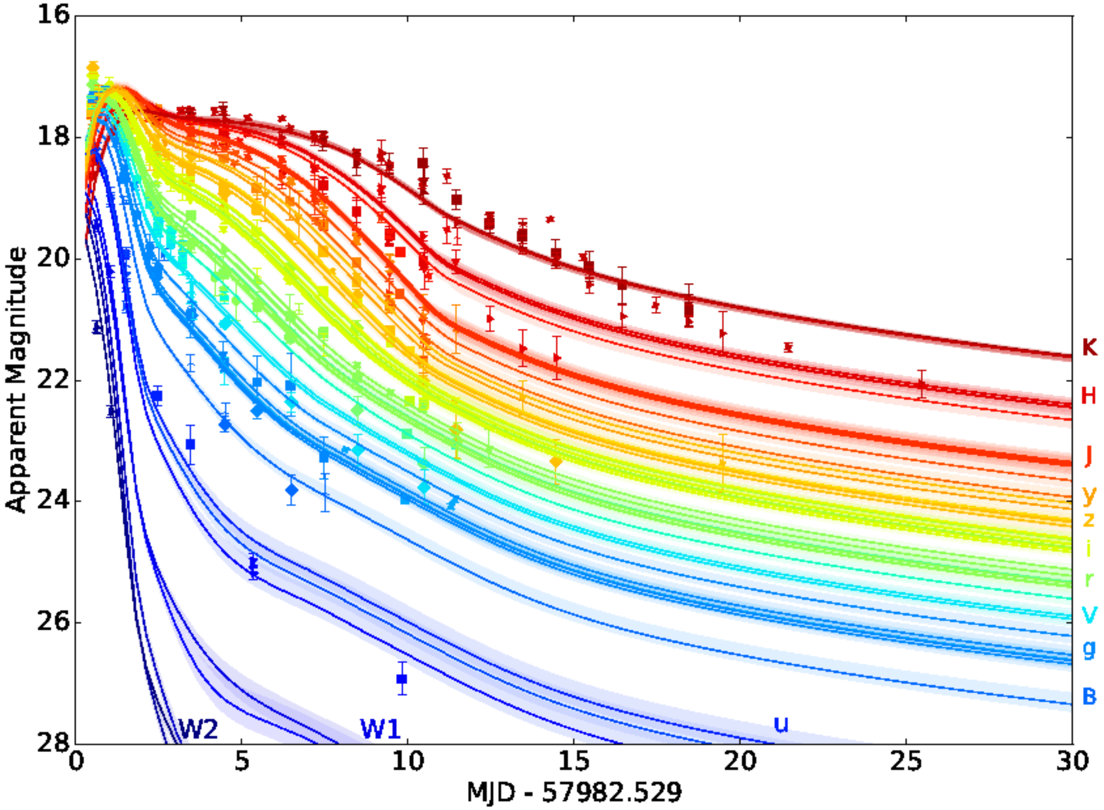
Neutron-rich outflows,
Y<0.25, v<0.1c, Mej < 0.1 M_{sol}
give rise to a slow red transient



Siegel & Metzger, PRL 2017

GW 170817 kilonova

What was observed



Fast blue transient

$M_{ej} = 10^{-2}$ Msun
$v_{ej} = 0.2\text{-}0.3c$
$Y_e > 0.25$
$X_{La} < 10^{-4}$

Slow red transient

$M_{ej} = 5\text{x}10^{-2}$ Msun
$v_{ej} = 0.1c$
$Y_e < 0.25$
$X_{La} \sim 0.01$

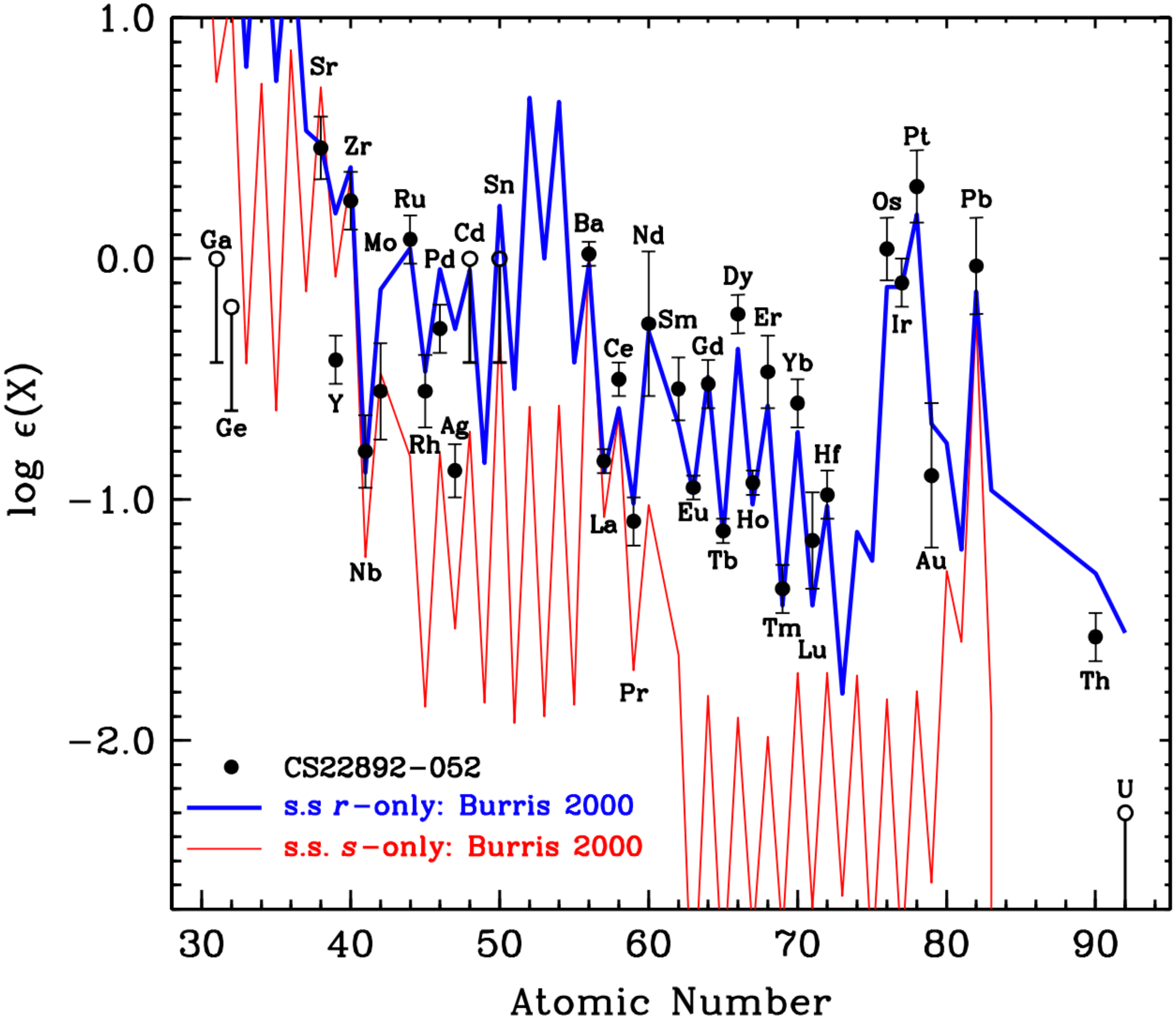
collision ejecta + disk: can explain the production of all r-process elements (mainly the disk component!)

See Drout et al. 2017 and references therein

challenges for DNS mergers

Sneden's star: Fe/H = -3.1

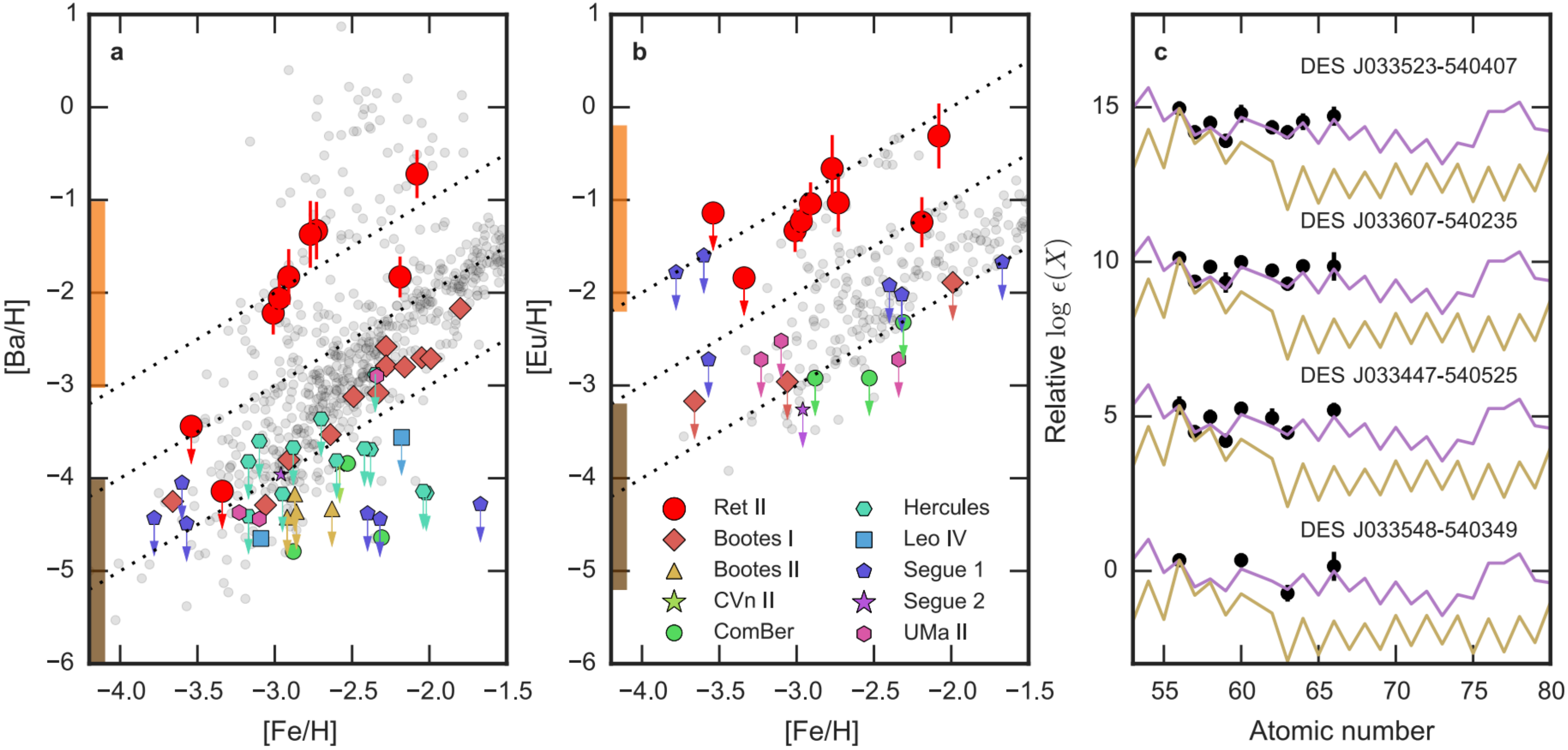
r-process elements are present in extremely old stars



challenges from NS merger r-process

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

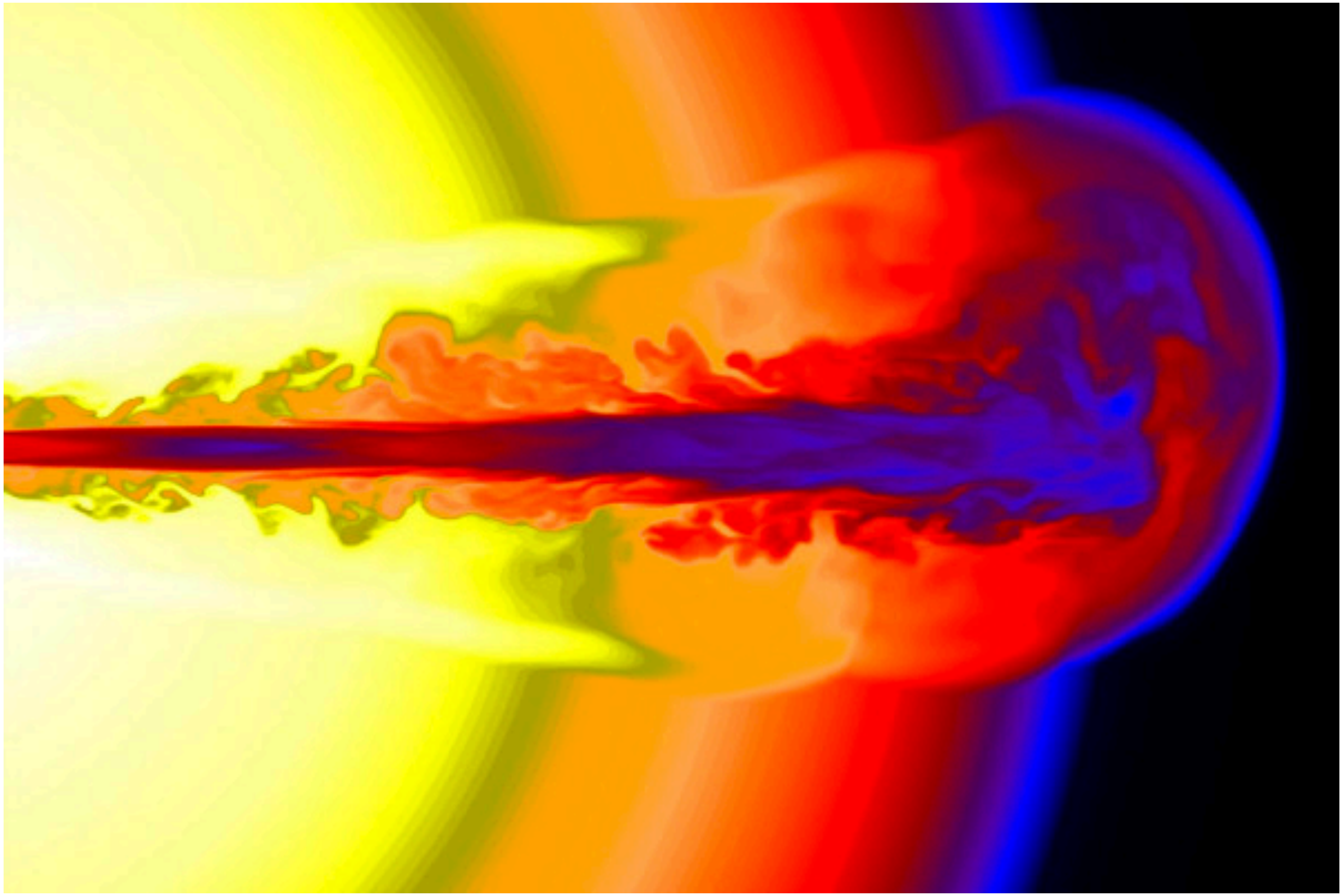
Reticulum II ($v_{esc} < 10$ km/s)



Ji et al. 2015

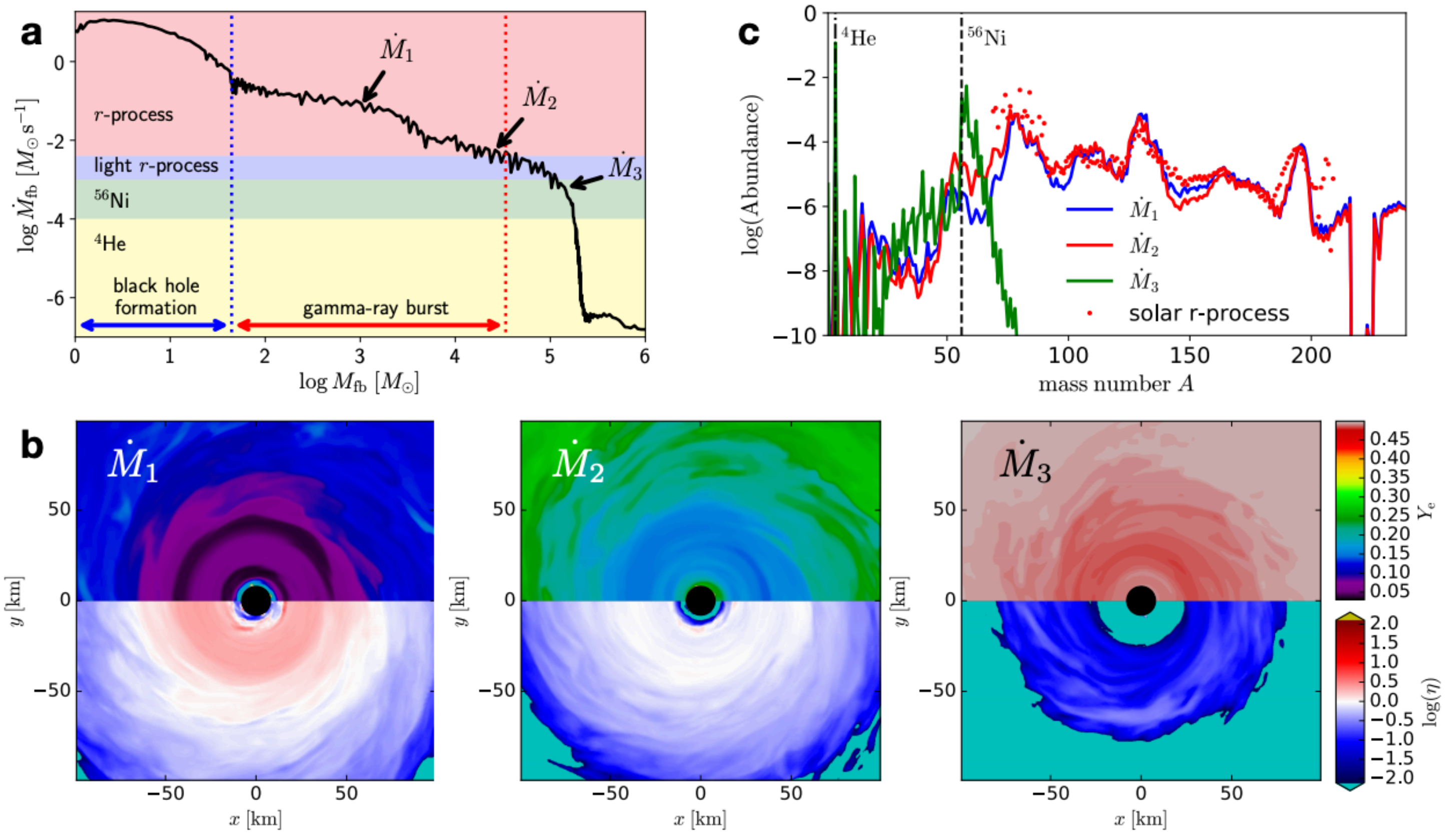
challenges from NS merger r-process

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



collapsars/hypernovae

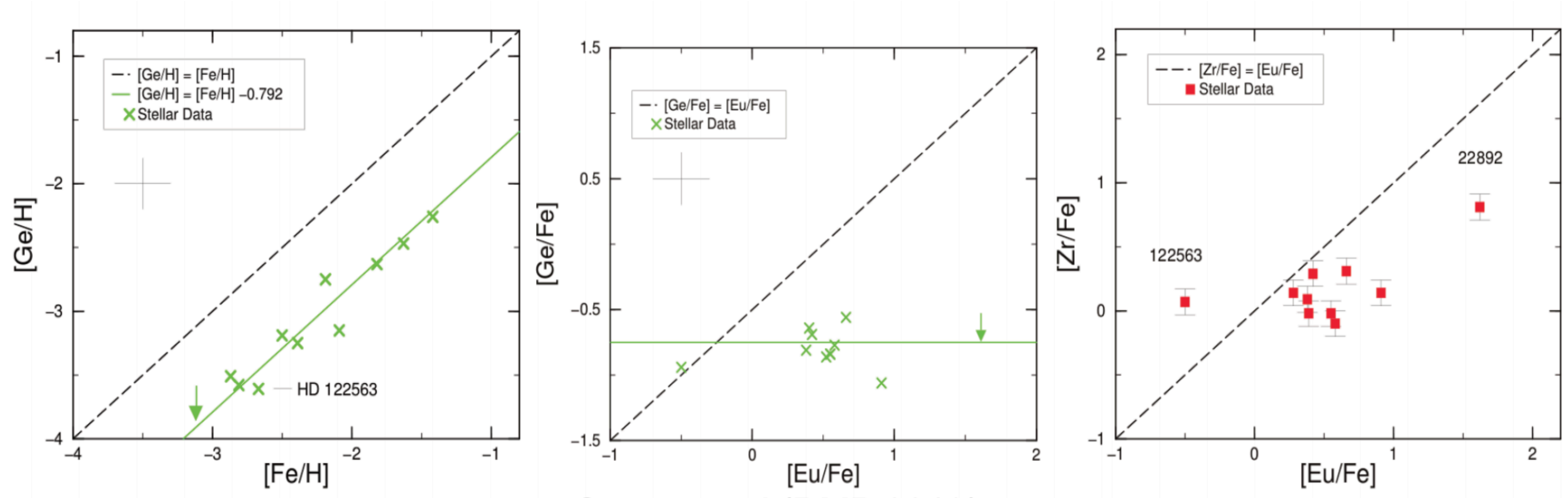
Massive star collapses and the core forms a black hole
The inner part has ~0 specific J and is accreted directly,
the outer core forms an accretion disk around the black hole and a jet that pierces through the outer layers
Similar nucleosynthesis to DNS, but NO delay in respect to star formation



Siegel, Barnes, Metzger (2019)

summary

Multiple sites?



Cowan et al (RMP 2019)

At early times all Fe comes from massive stars. In the above, Ge correlates strongly with Fe and thus probably has the same origin

Eu however does not!

Zr is intermediate

Up next: What are supernovae good for?