Heavy element nucleosynthesis in astrophysical explosions

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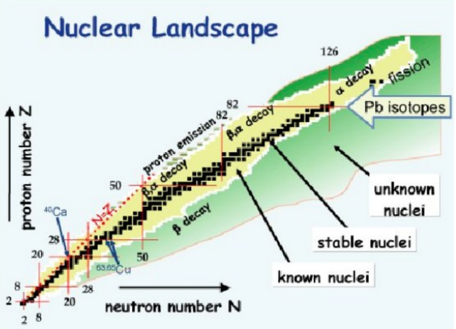
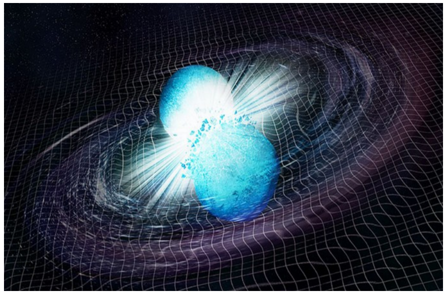
National Science and Technology Council

Outline

- Lecture 1: Introduction & basics of rapid-neutron (r-) process nucleosynthesis

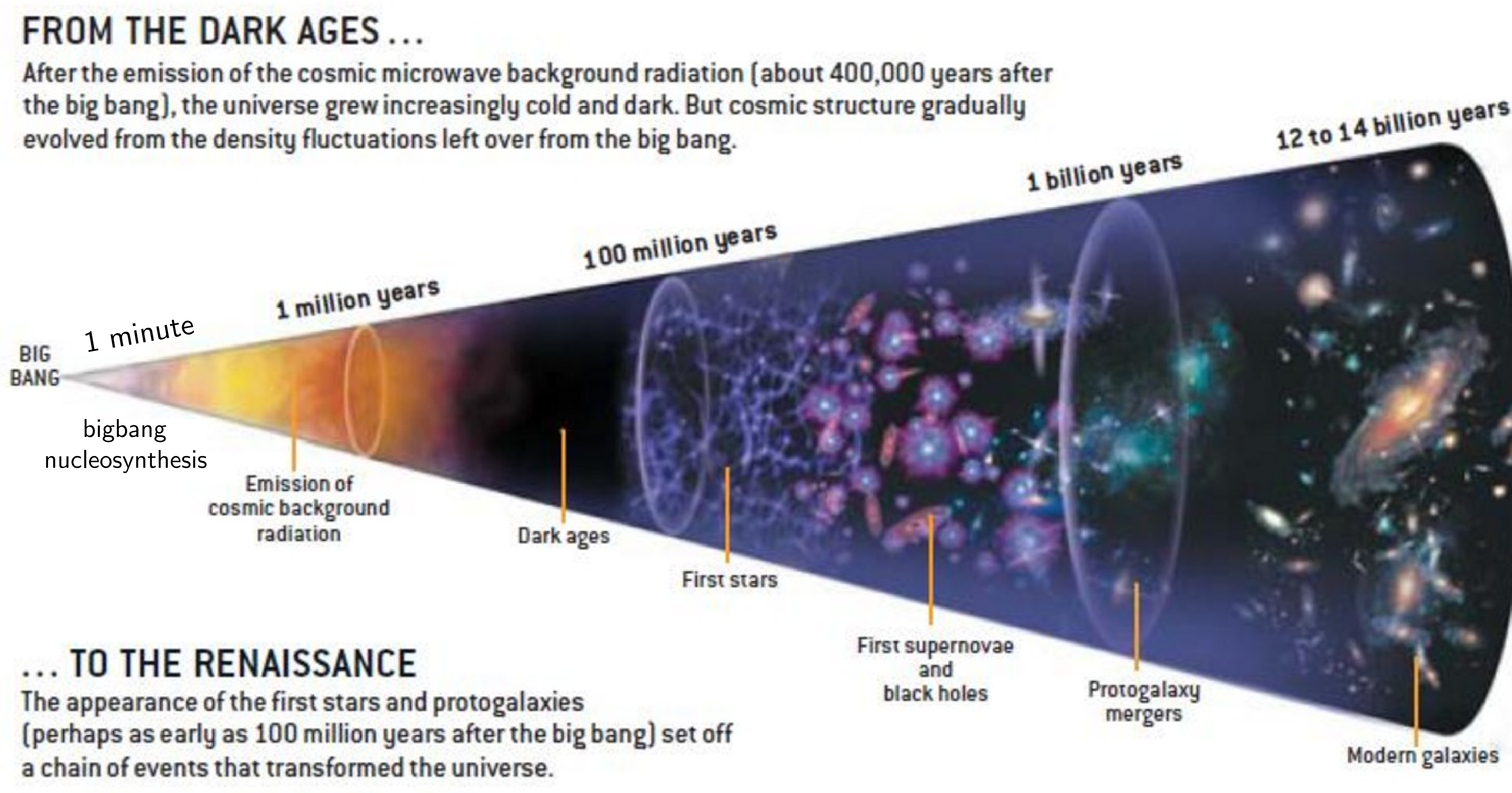


- Lecture 2: r-process in binary neutron star mergers & kilonova



- Lecture 3: heavy-element nucleosynthesis in supernovae

Cosmic evolution, galaxies, and stars



[adapted from Scientific American]

How does the Universe evolve to the present structure we see today?

ASTRONOMER'S PERIODIC TABLE

Hydrogen
1
H
1.0079

"X" ~ 71,5%

In the Universe today

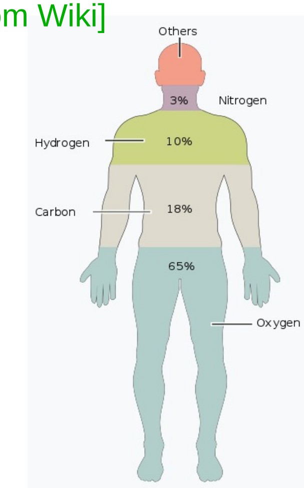
"Y" ~ 27%

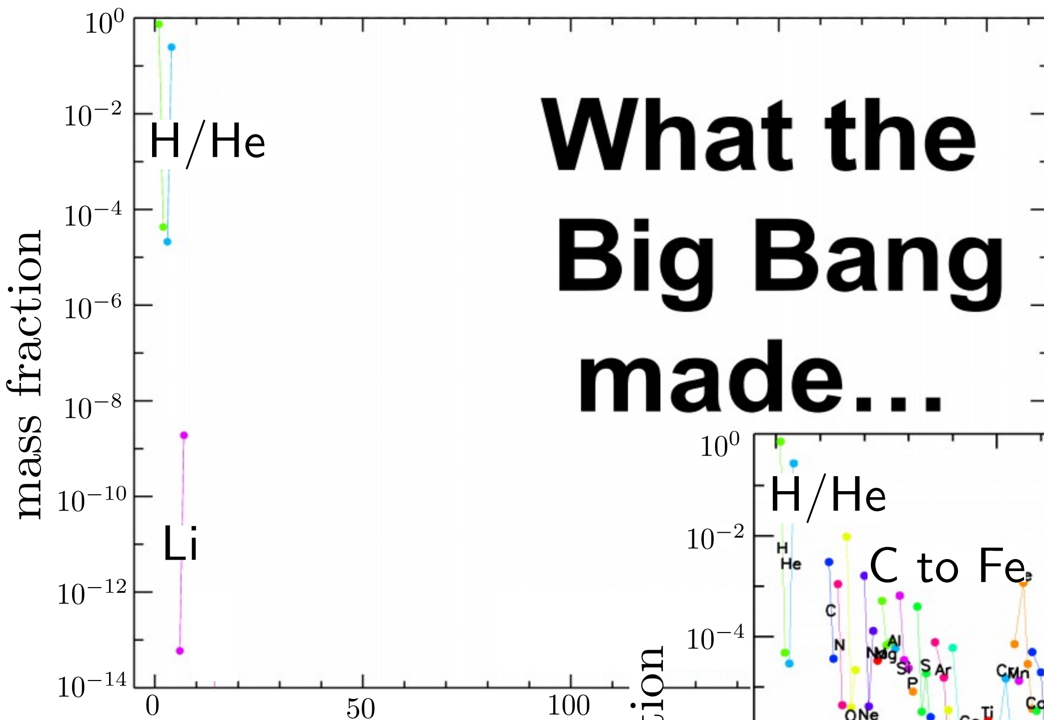
Helium
2
He
4.0026

All other elements combined

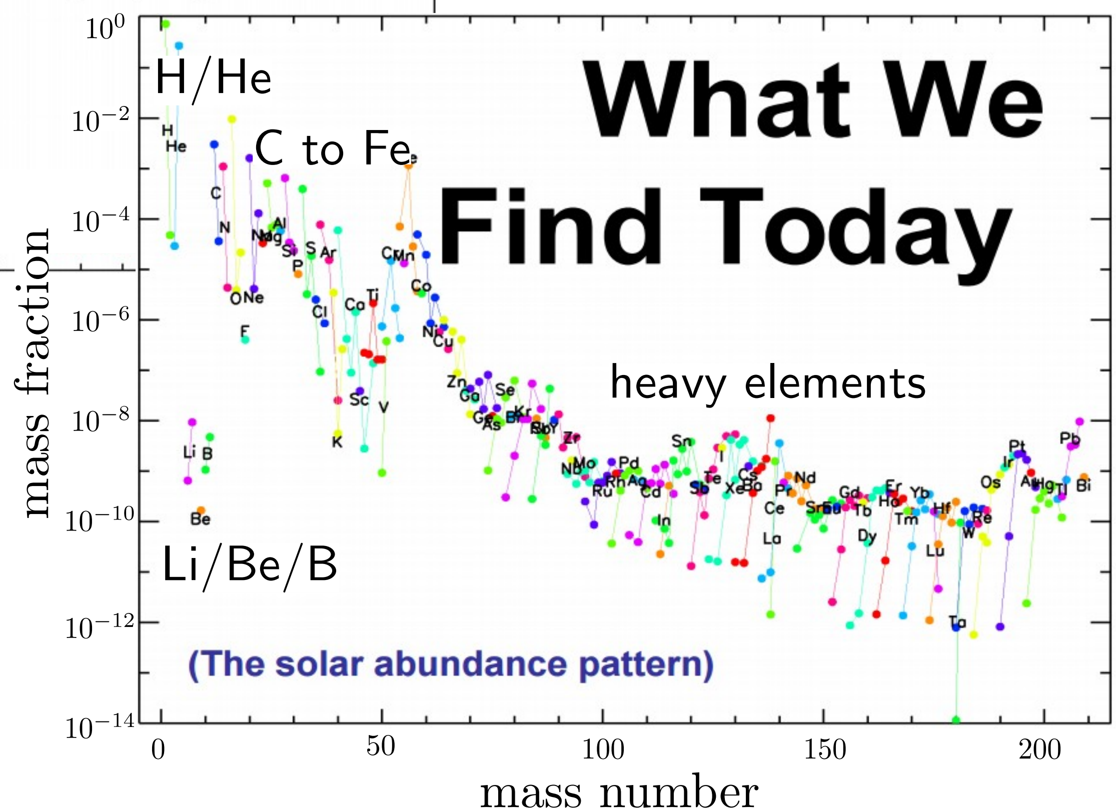
Metals "Z" ~ 1.4%

[Figure from A. Frebel's talk]



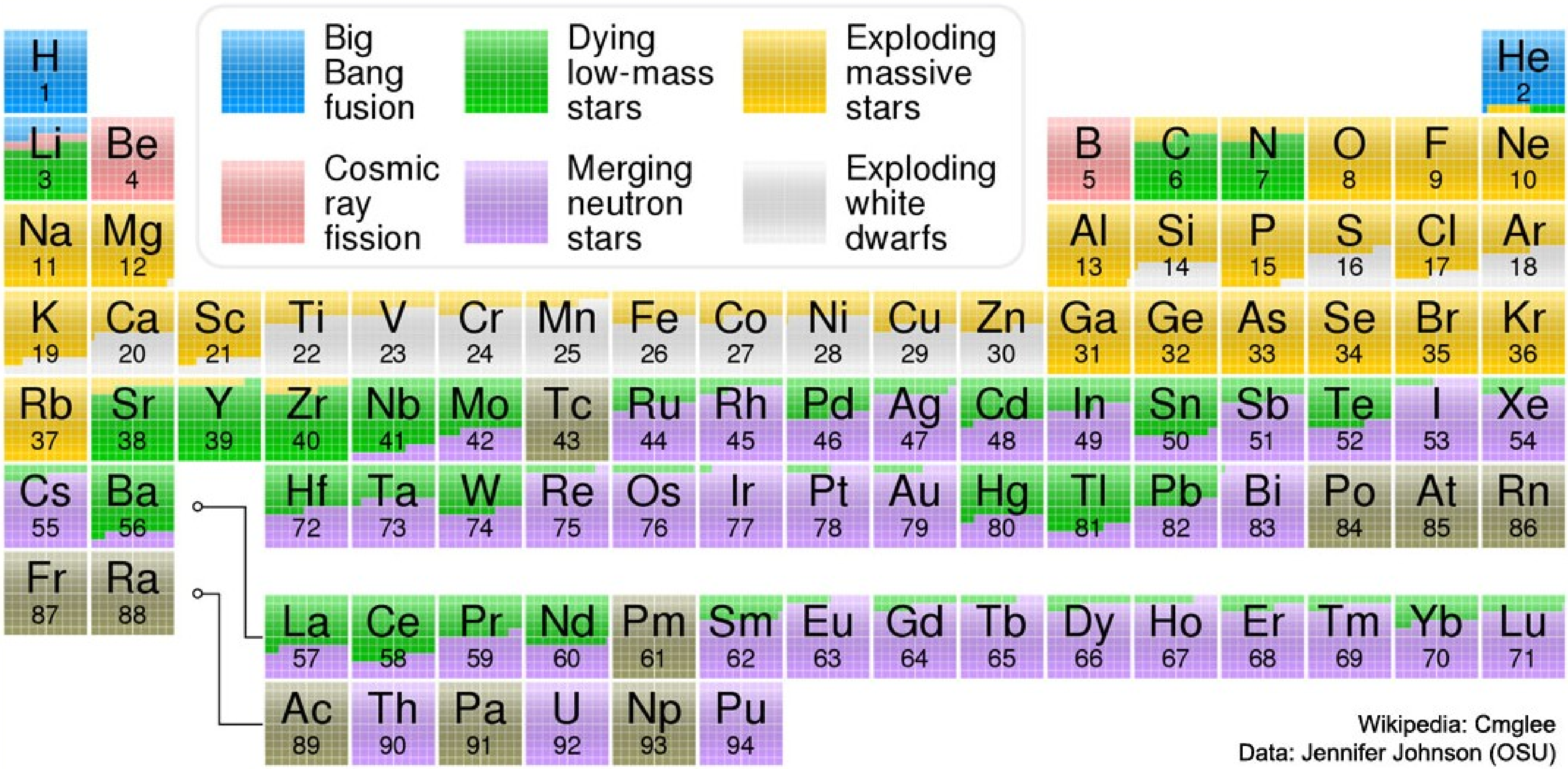


[from A. Heger]

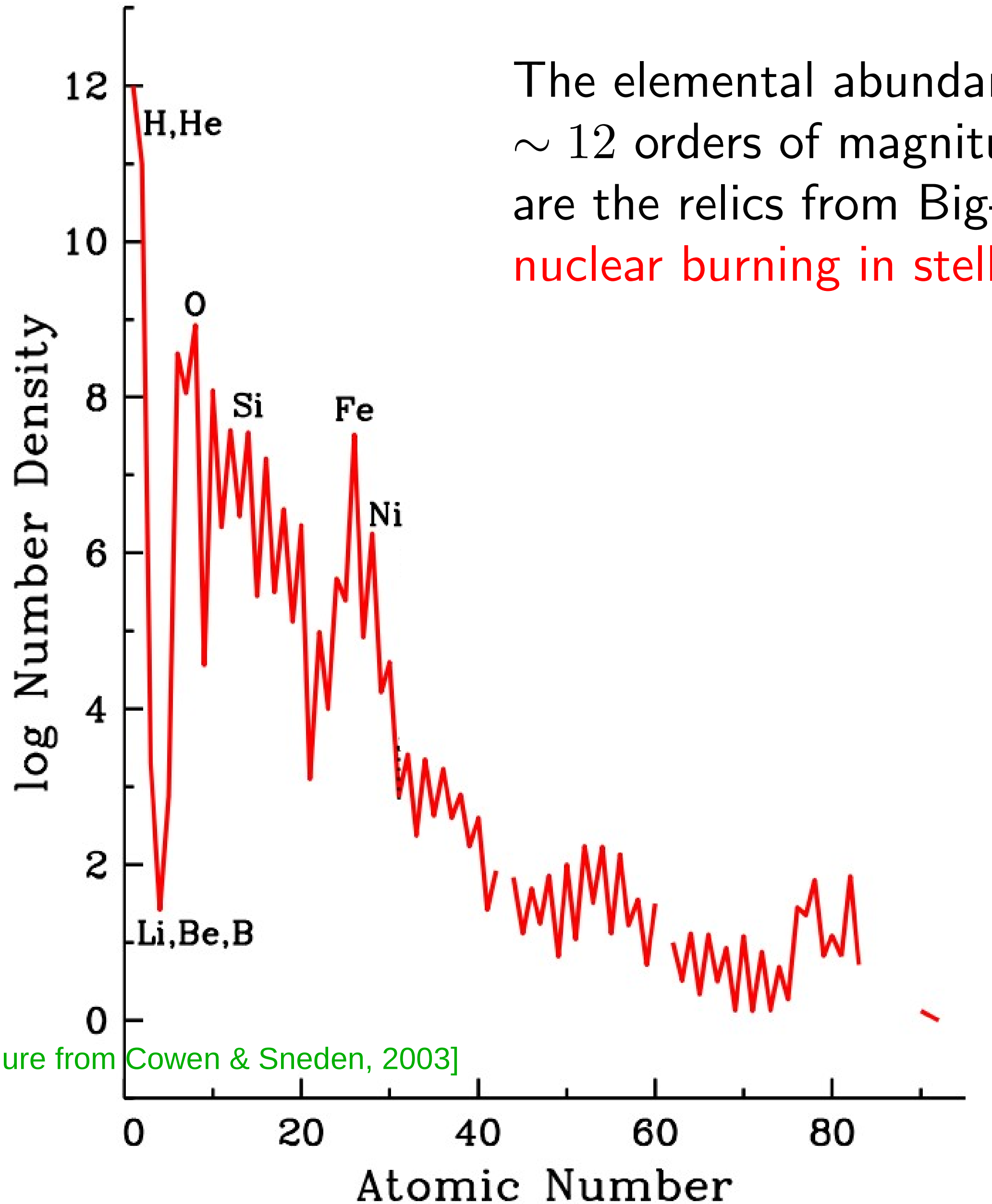


From where were the different atoms/isotopes made in the Universe?

Nuclear astrophysicist's Periodic Table



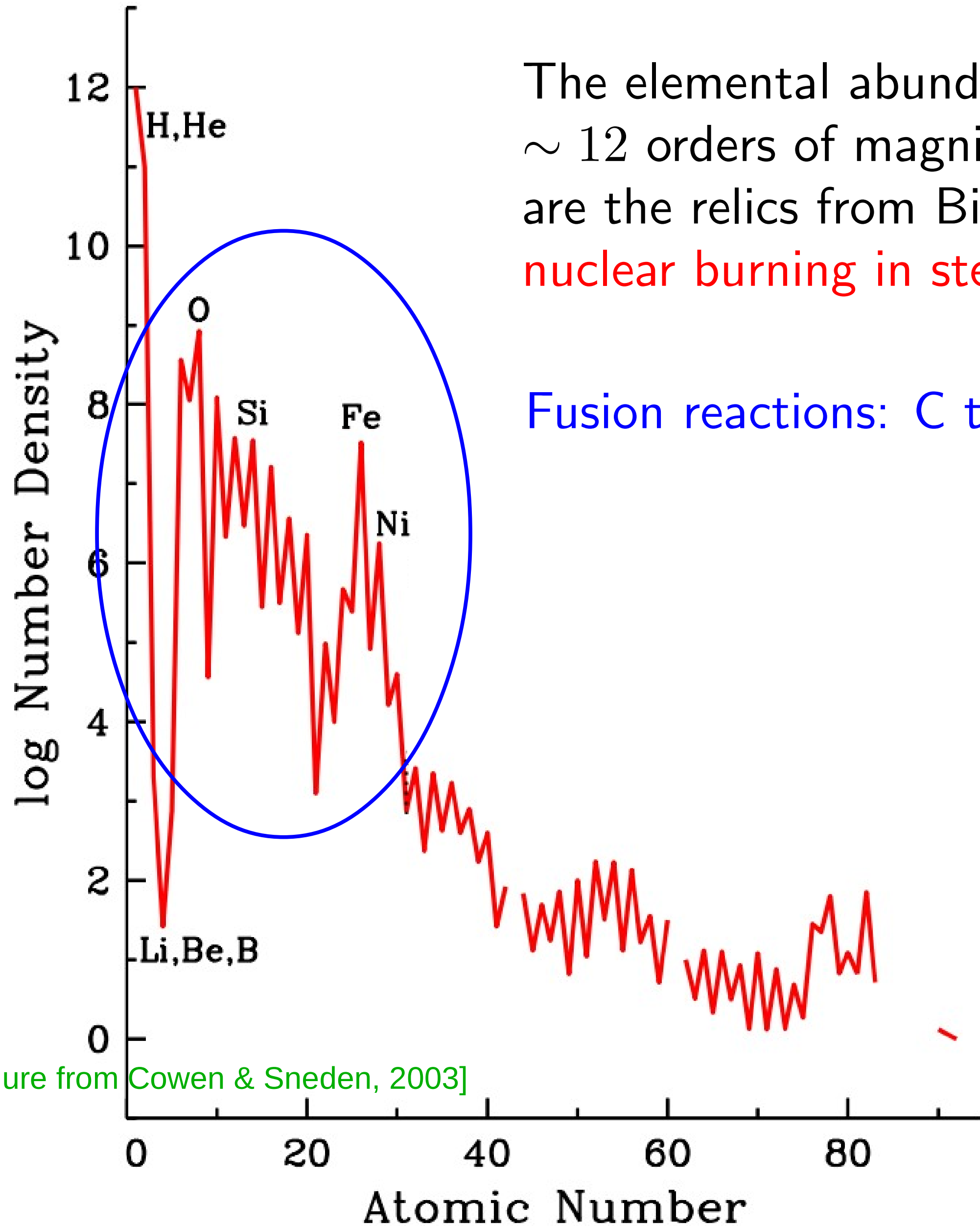
Elemental abundances in the solar system



[Figure from Cowen & Sneden, 2003]

The elemental abundances in the solar system spans ~ 12 orders of magnitudes. Only H, He, and maybe Li are the relics from Big-Bang, the rest are made by nuclear burning in stellar evolution or explosion

Elemental abundances in the solar system



[Figure from Cowen & Sneden, 2003]

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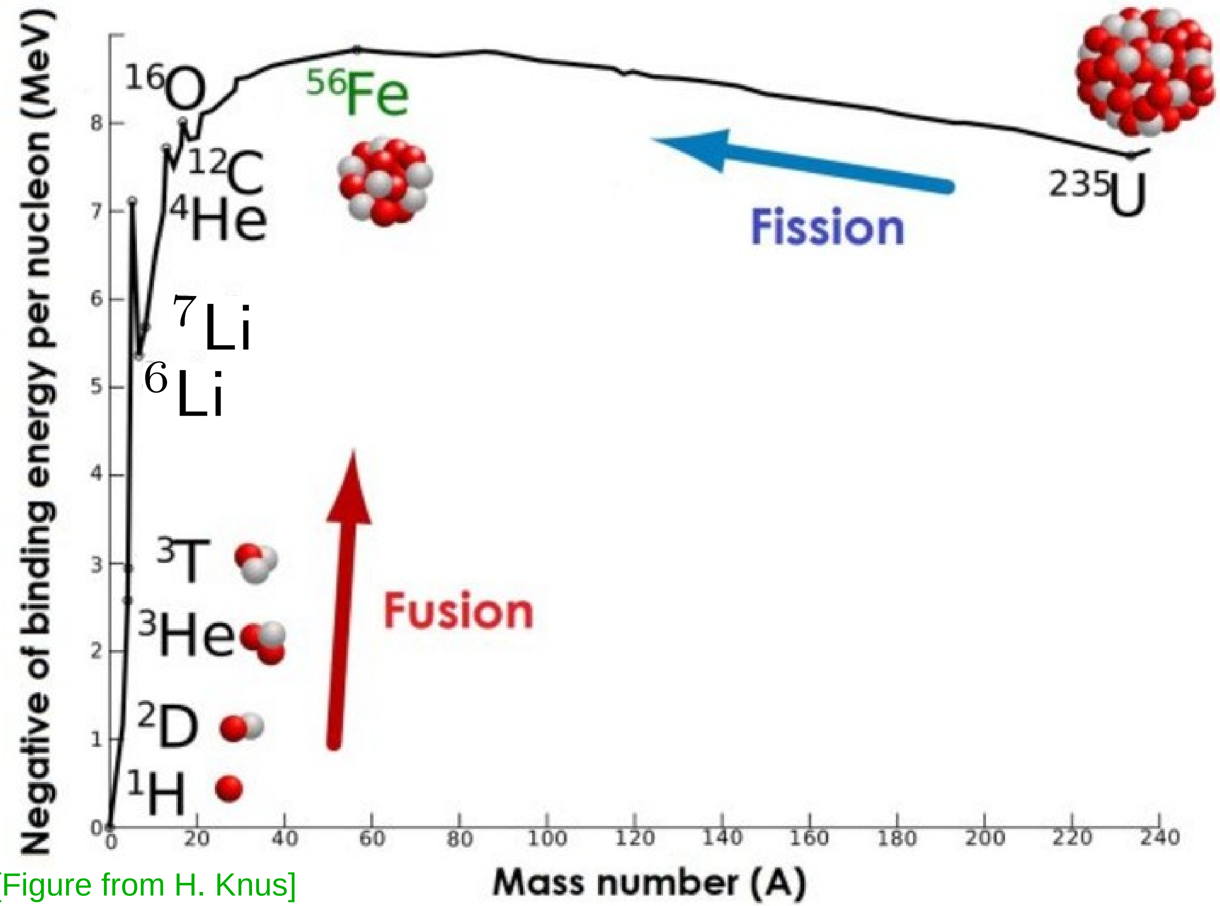
Fusion reactions: C to Fe and the neighborhood

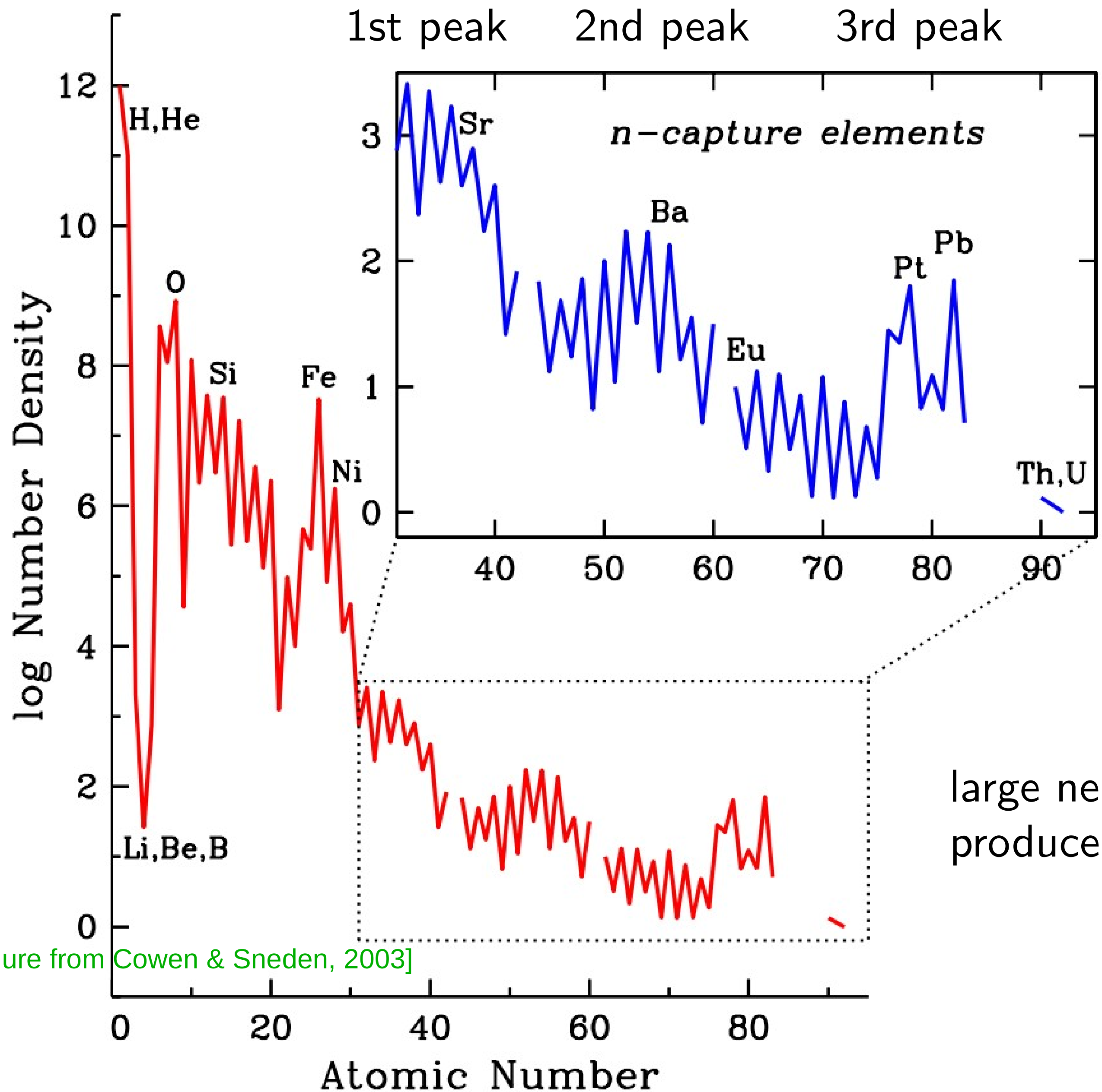


[Figure from H. Knus]

- fusion reactions from same nucleus stop at Fe

- fusion of a Fe (or heavy) nucleus and a light nucleus (e.g., p, n, ^{4}He...) still releases the nuclear binding energy

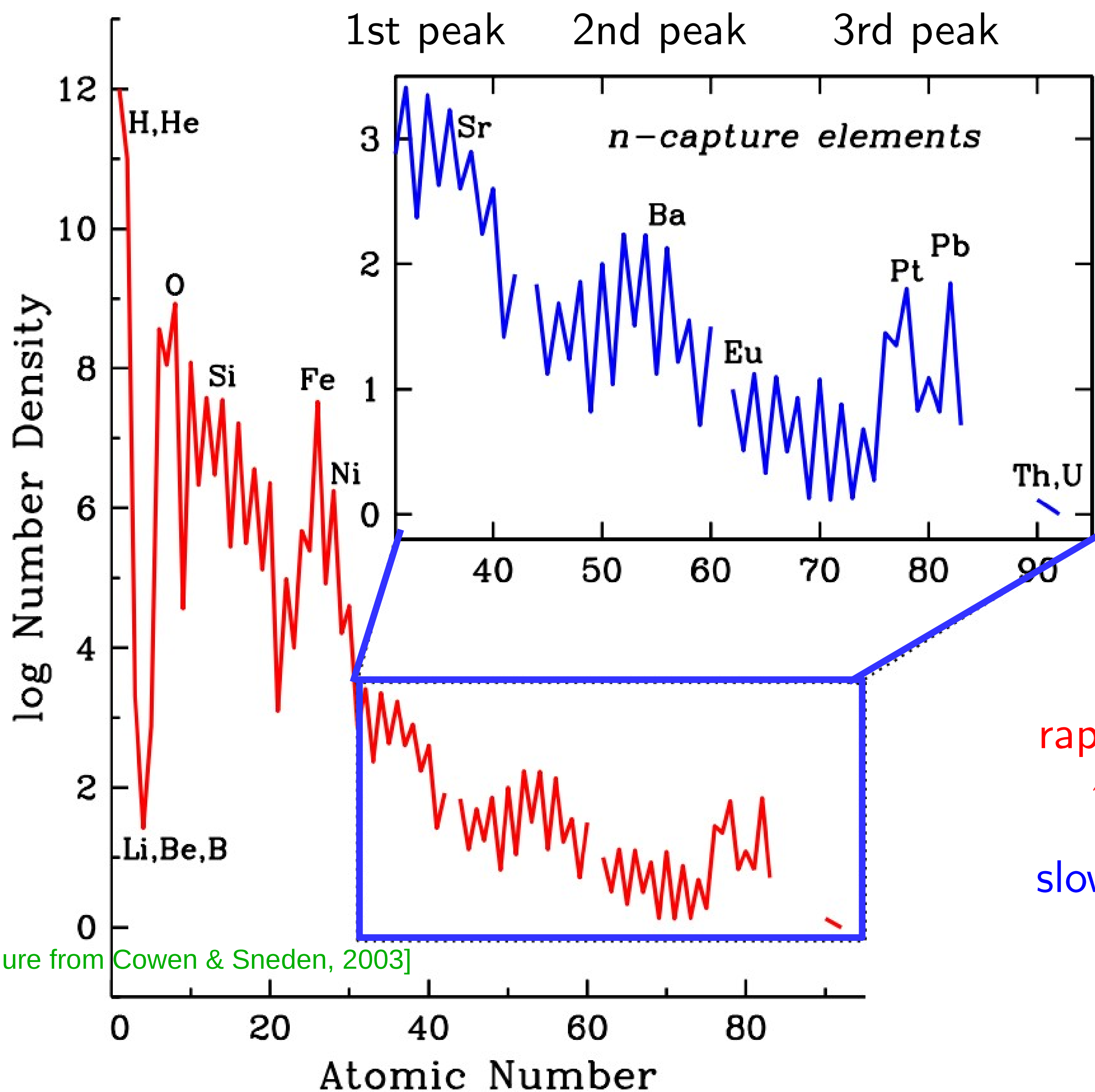
Elemental abundances in the solar system



[Figure from Cowen & Sneden, 2003]

large neutron density required to produce n-capture elements

Elemental abundances in the solar system



[Figure from Cowen & Sneden, 2003]

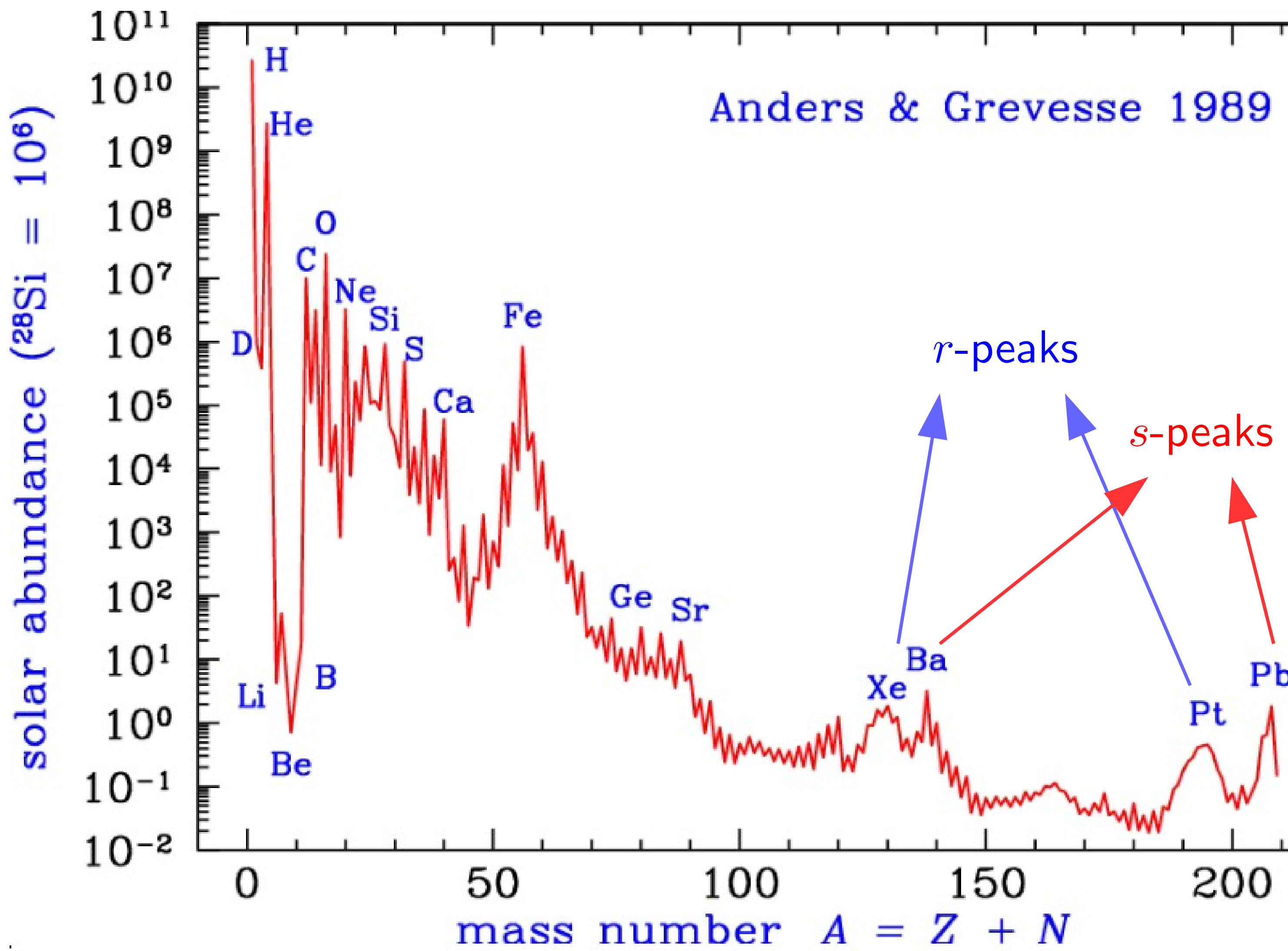
need strong or stable neutron sources in some astrophysical environments

rapid n-capture (r-) process:

$\tau_n \ll \tau_\beta$

slow n-capture (s-) process:

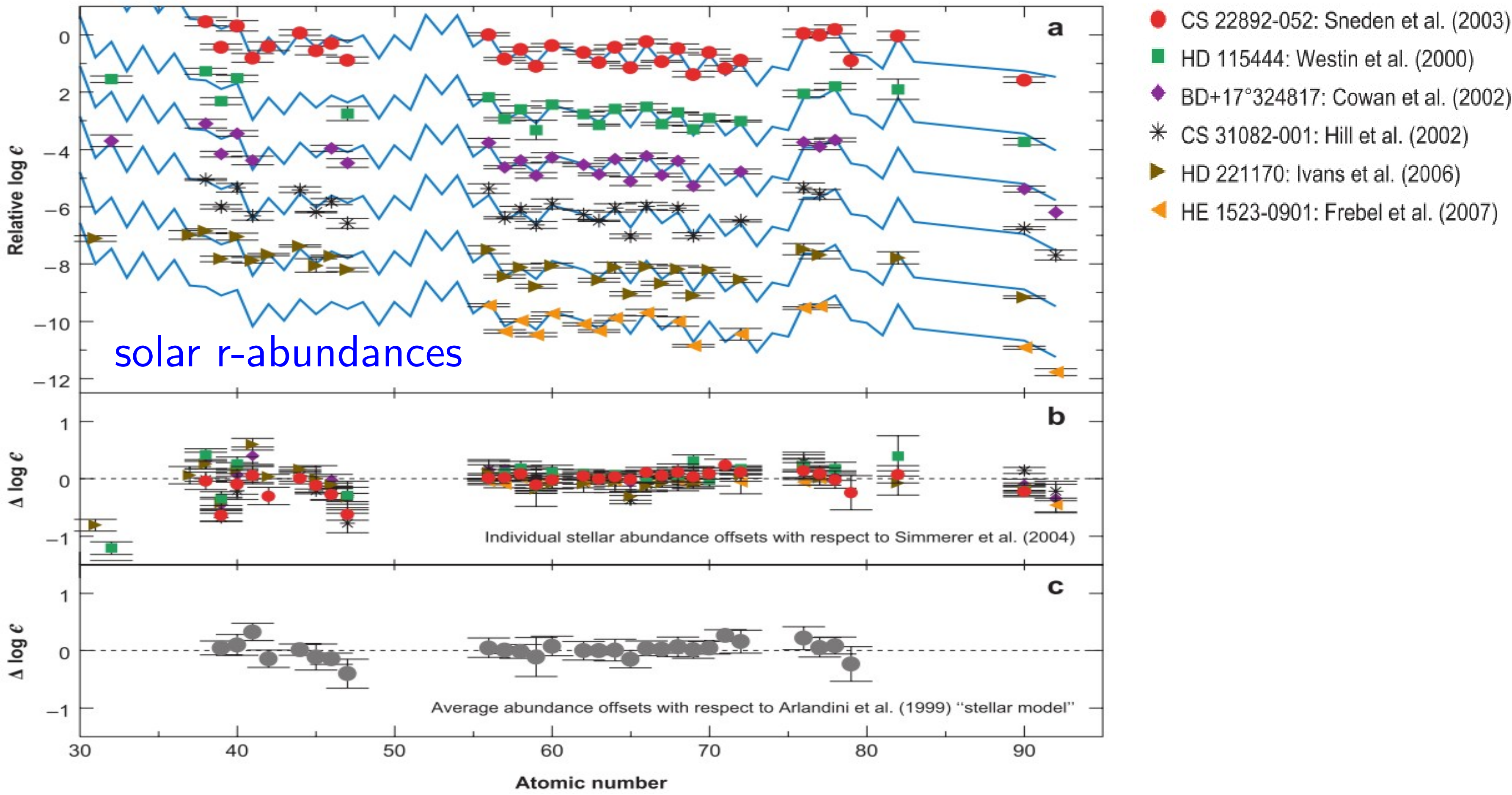
$\tau_n \gg \tau_\beta$


Anders & Grevesse 1989
solar abundance (^{28}Si = 10^6)
mass number $A = Z + N$
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
50
100
150
200
H
He
D
Li
Be
B
C
O
Ne
Si
S
Ca
Fe
Ge
Sr
Xe
Ba
Pt
Pb
r-peaks
s-peaks

r-process seen in metal-poor stars

the r-process pattern is also observed commonly on the surface of the metal-poor stars with [Fe/H]~ -3

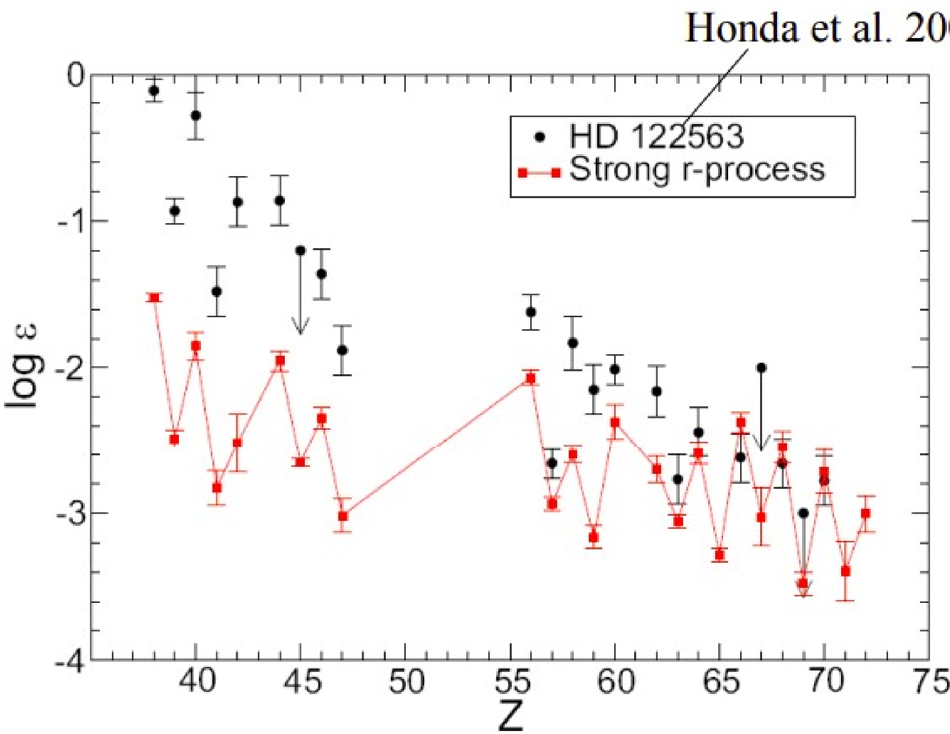
[Sneden et. al., ARA&A 46, 241 (2008)]

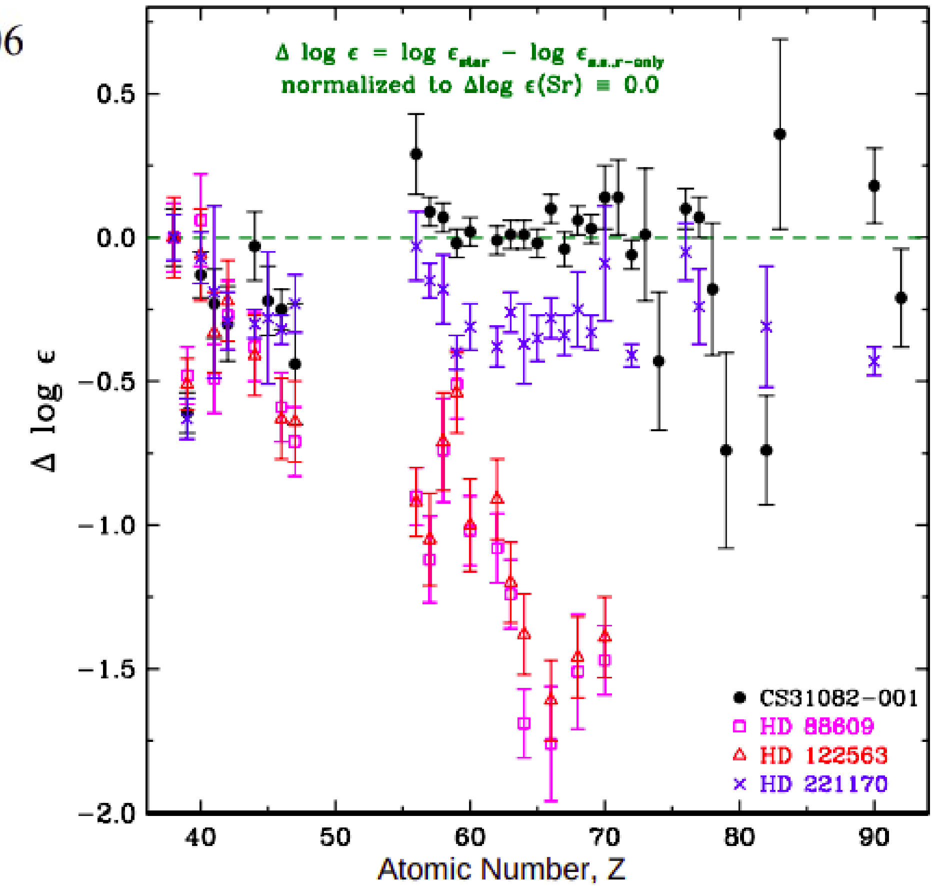


→ a ∼ primary and "universal" process that occurs in the cosmic evolution

r-process seen in metal-poor stars

a number of metal stars show “weaker” r-process pattern





[Cowan+ 2019]

$\rightarrow$ variation is needed

Burbidge, Burbidge, Fowler, Hoyle (B^2FH) pointed out already in 1957 that two n-capture processes are needed

slow n-capture process:

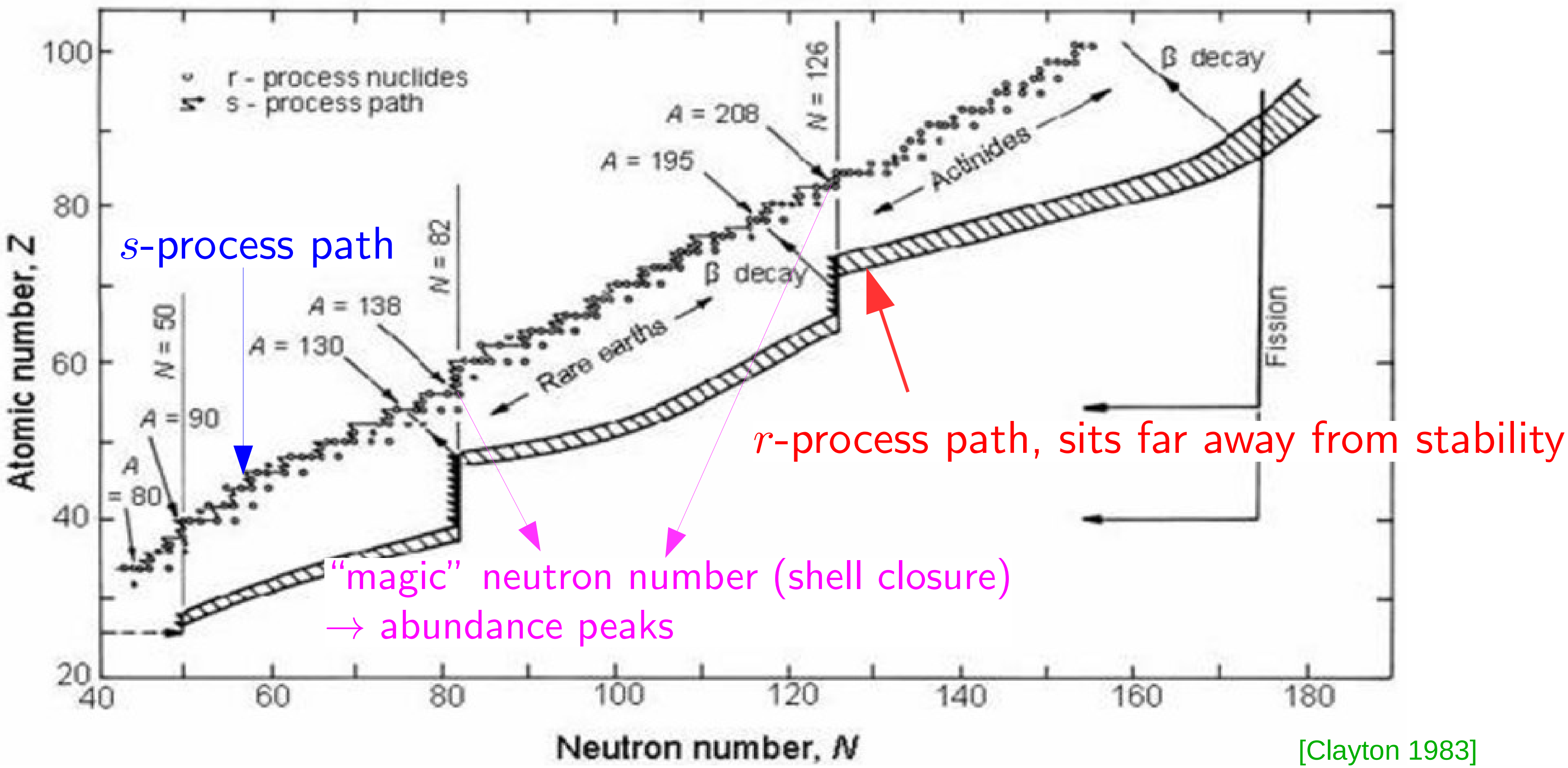
$\tau_n \gg \tau_\beta$

$\rightarrow$ stellar burning (AGB stars)

rapid n-capture process:

$\tau_n \ll \tau_\beta$

$\rightarrow$ large neutron density!



[Clayton 1983]

requirement for r-process (i)

For a typical r-process, the β-decay lifte time of a nucleus is $\tau_\beta \sim 10$ ms

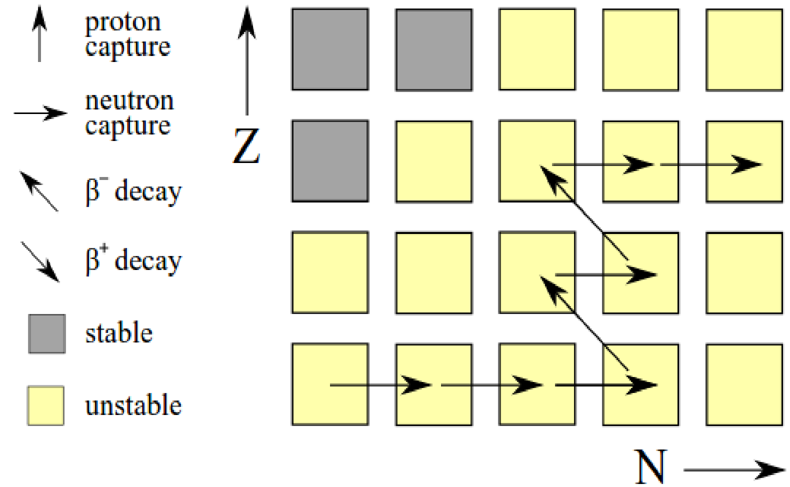
$$\rightarrow \lambda_\beta \sim \tau_\beta^{-1} \sim 10^{-2}\ \mathrm{s}^{-1}$$

the typical neutron capture rate,
$\lambda_n = n_n \times \langle \sigma_{(n,\gamma)} v \rangle_T$

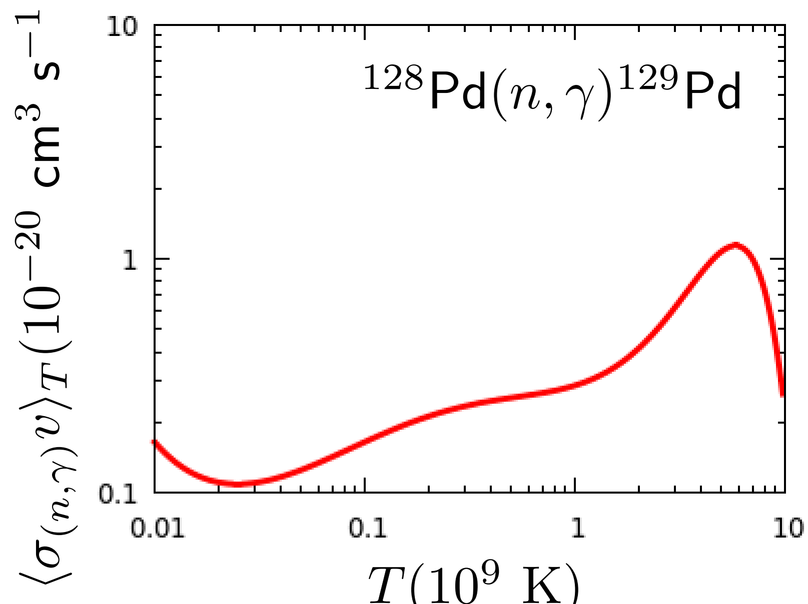
At $T \lesssim 10^9$ K,
$\langle \sigma_{(n,\gamma)} v \rangle_T \sim 10^{-20}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

$\rightarrow n_n \gg 10^{18}\ \mathrm{cm}^{-3}$ for $\lambda_n \gg \lambda_\beta$

[from Wiki]



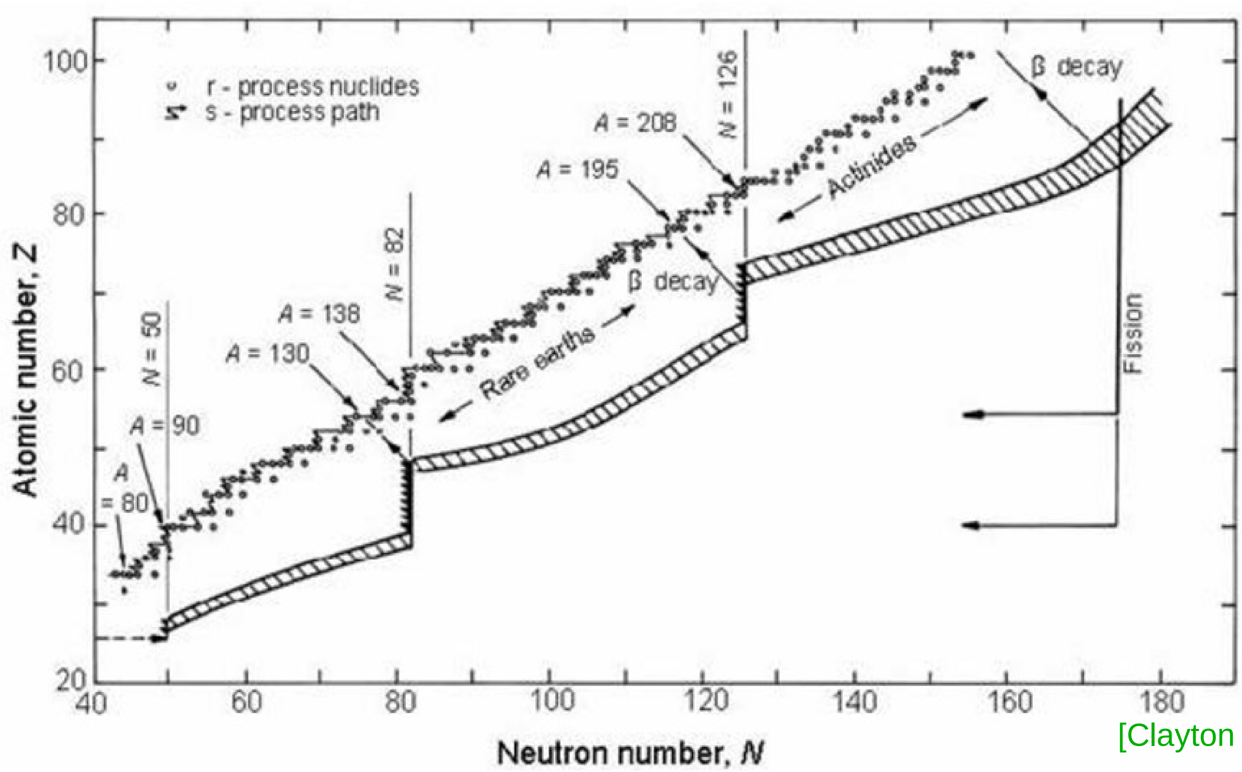
synthesis of neutron-rich nuclei
A > 60



requirement for r-process (ii)

large neutron number density relative to that of seed nuclei, i.e., large neutron-to-seed ratio, $R_{n/s} \equiv n_n/n_{\mathrm{seed}}$

$$\langle A_{\mathrm{heavy}} \rangle \approx \langle A_{\mathrm{seed}} \rangle + R_{n/s} \quad \text{when no fission occurs}$$



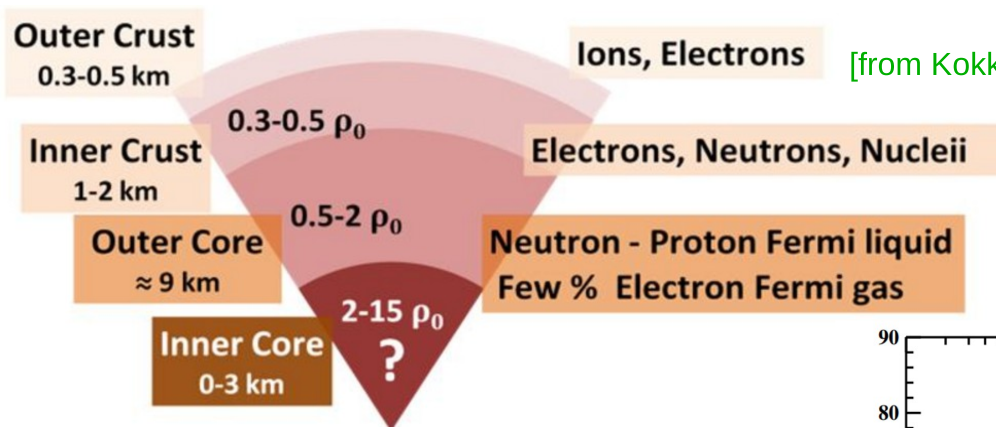
[Clayton 1983]

requirement for r-process (iii)

The environment needs to contain the seed nuclei

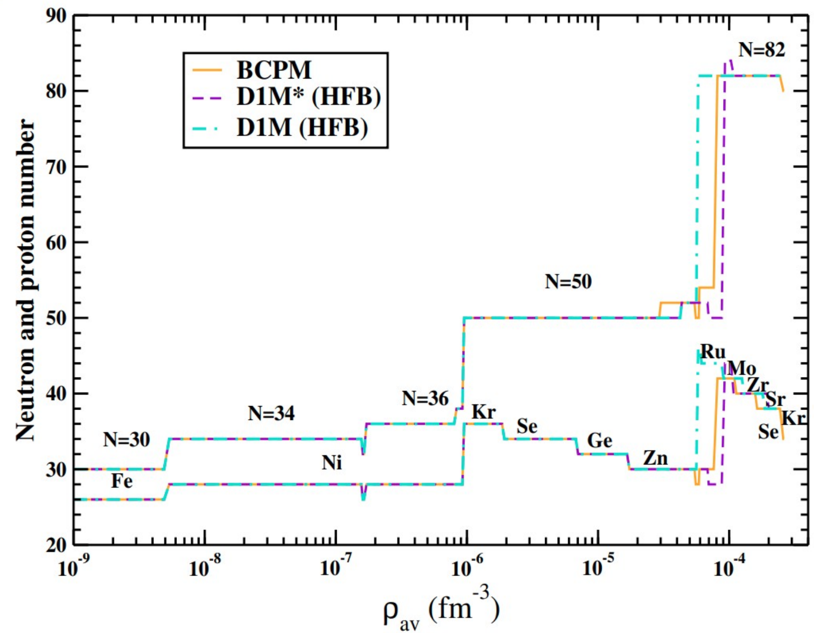
$\rightarrow$ depends on the temperature & density condition (evolution)

(i) pre-existing nuclei. e.g., decompressed matter from neutron star crusts



[from Kokkotas]

[Vinas+2021]



$$Y_e \equiv n_e/n_{\rm baryon} \approx 0.05$$

$$\rightarrow R_{\rm n/s} \sim 500 - 1000$$

$$(R_{n/s} \propto Y_e^{-1})$$

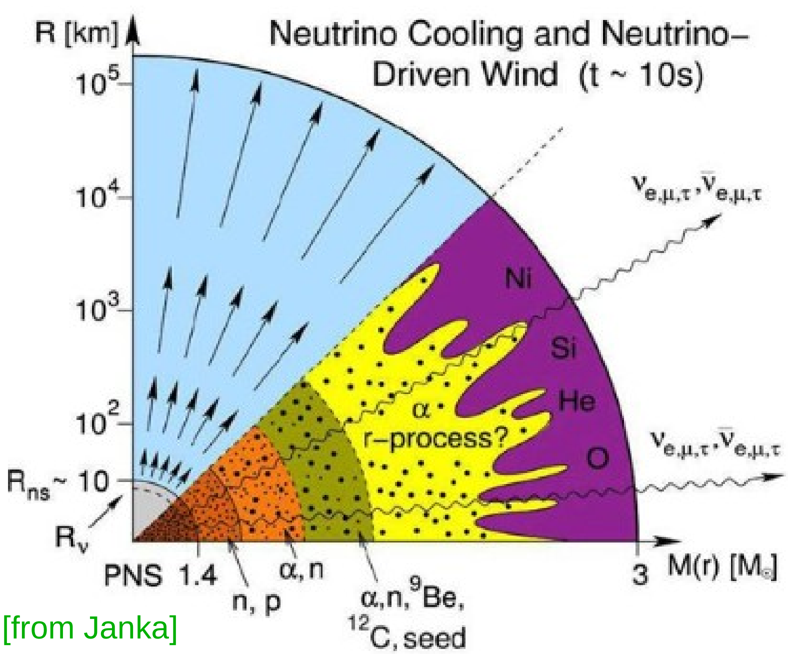
requirement for r-process (iii)

The environment needs to contain the seed nuclei

$\rightarrow$ depends on the temperature & density condition (evolution)

(ii) seed nuclei formation in expanding material with initially high temperature

e.g., shocked heated ejecta,
neutrino-driven ejecta,
viscosity-heated ejecta,...



[from Janka]

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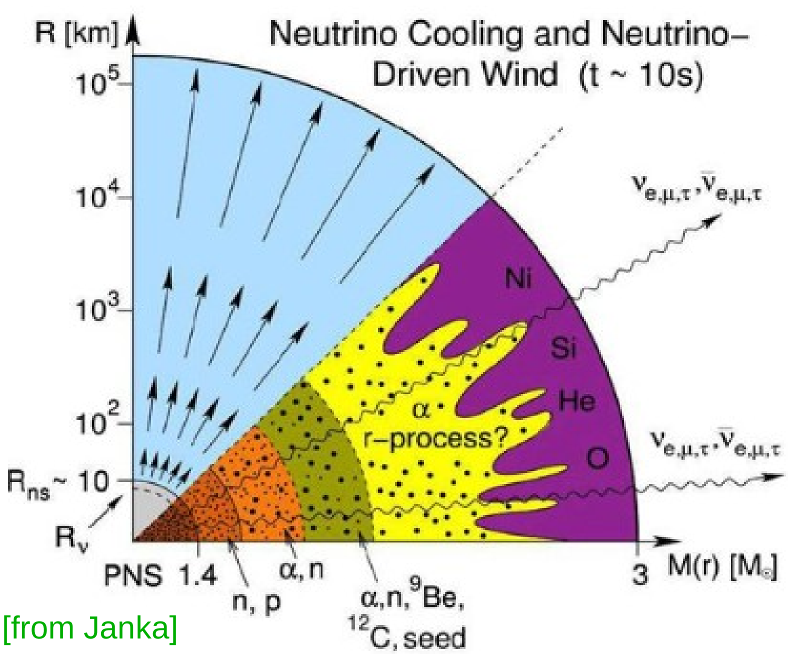
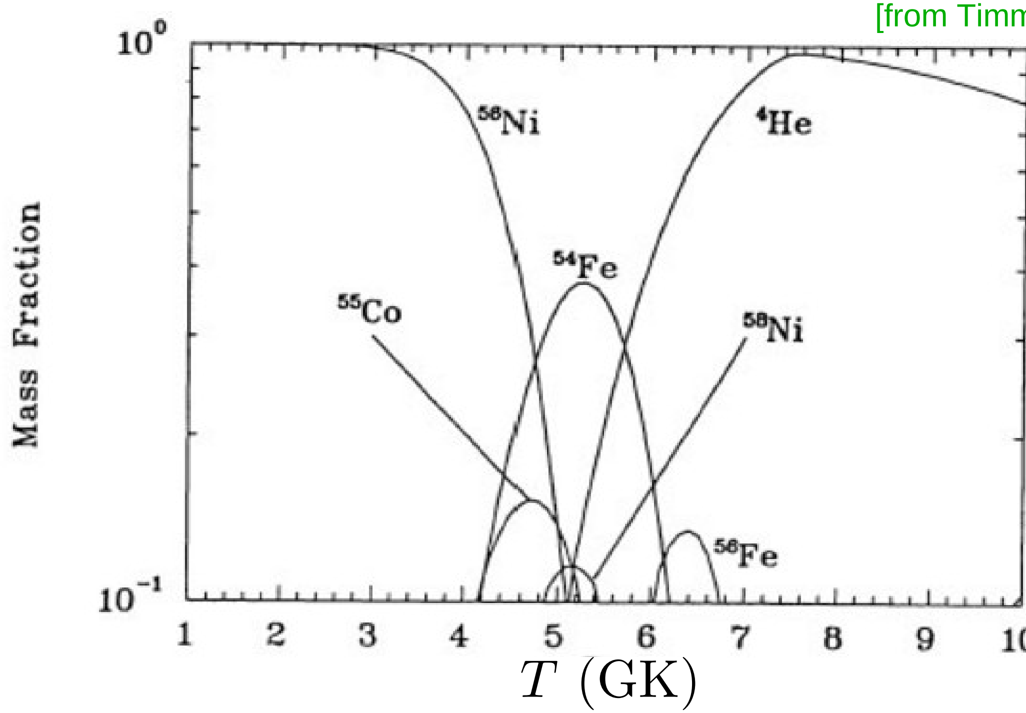


[from Janka]

[from Timmes]



Composition under nuclear statistical equilibium (NSE)

$$\mu(N, Z) \leftrightarrow N\mu_n + Z\mu_p$$

requirement for r-process (iii)

The environment needs to contain the seed nuclei

$\rightarrow$ depends on the temperature & density condition (evolution)

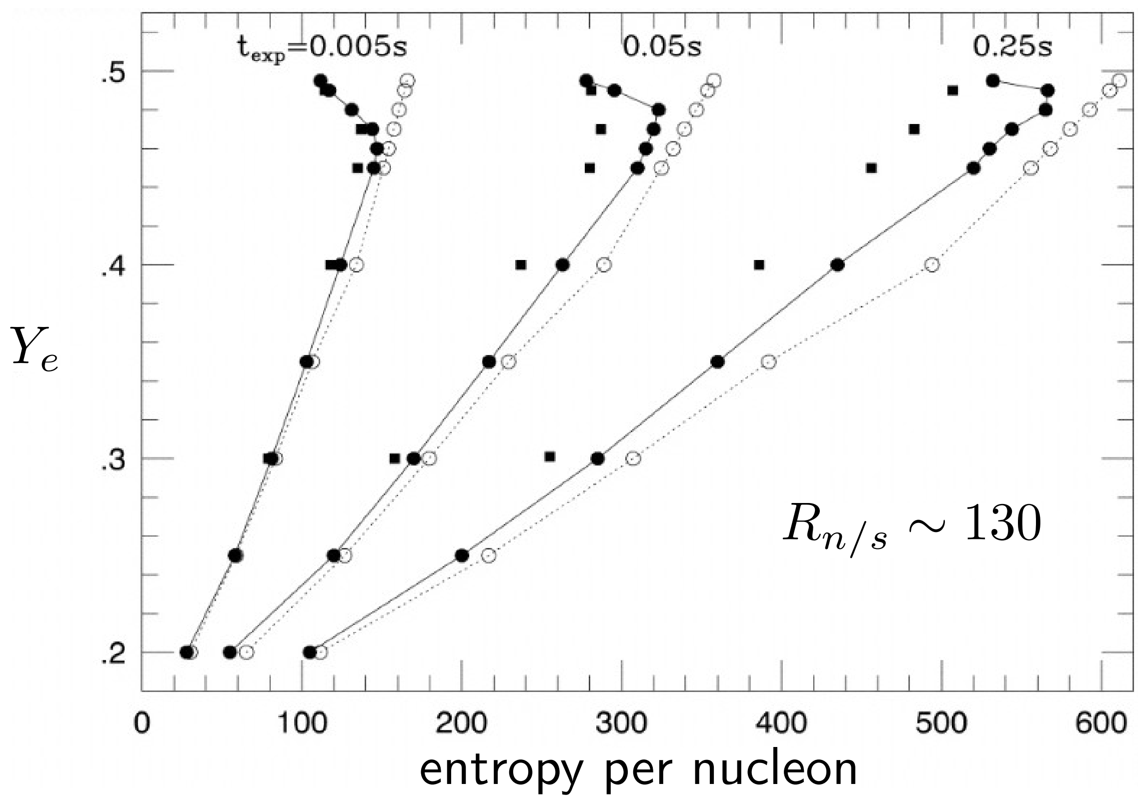
(ii) seed nuclei formation in expanding material with initially high temperature

three important quantities affecting $R_{n/s}$:

- electron number fraction per baryon, $Y_e \equiv n_e/n_b$
- entropy per baryon s
- expansion timescale, $\tau_{\rm exp} = d(\ln\rho)/dt$

lower Y_e, higher entropy, faster expansion
$\leftrightarrow$ higher $R_{n/s}$

[from Qian]



Initially, $Y_n^0 = 1 - Y_e$, $Y_p^0 = Y_e$

Assuming all protons are locked in seed nuclei, right before n-captures

$$R_{n/s} = \frac{Y_n}{Y_{\rm seed}} = \frac{Y_n^0 - N_{\rm seed}(Y_p^0/Z_{\rm seed})}{(Y_p^0/Z_{\rm seed})}$$

$$\langle A\rangle_{\rm final} \approx A_{\rm seed} + R_{n/s}$$

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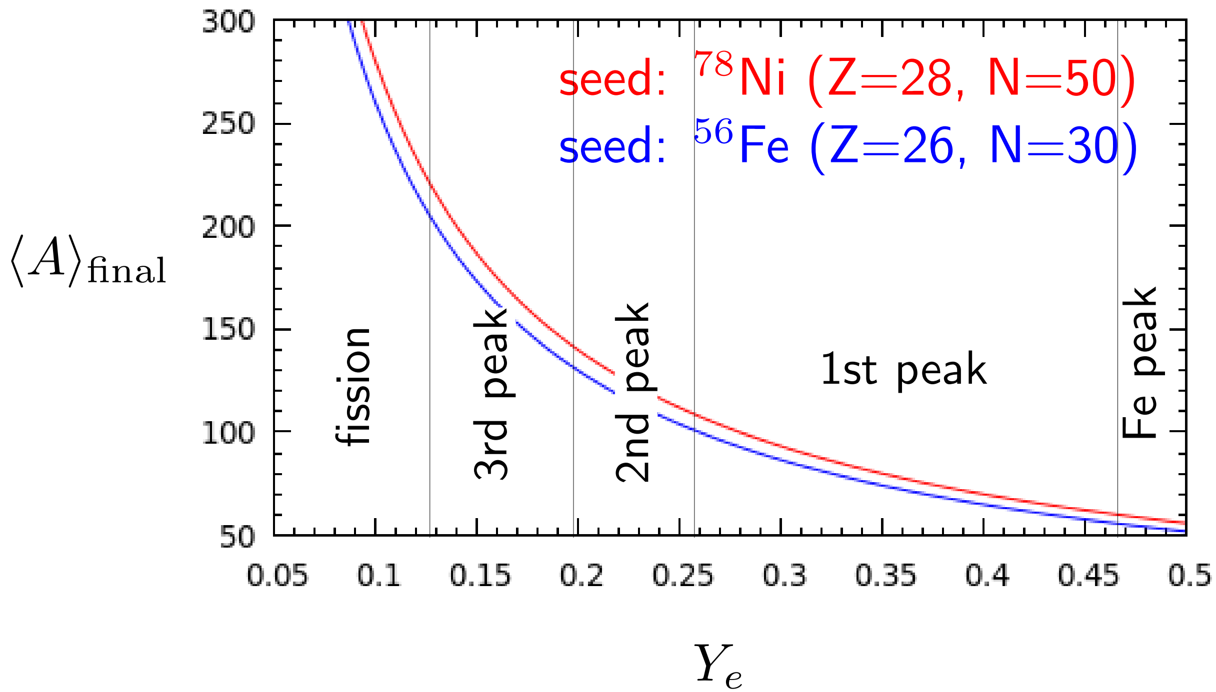

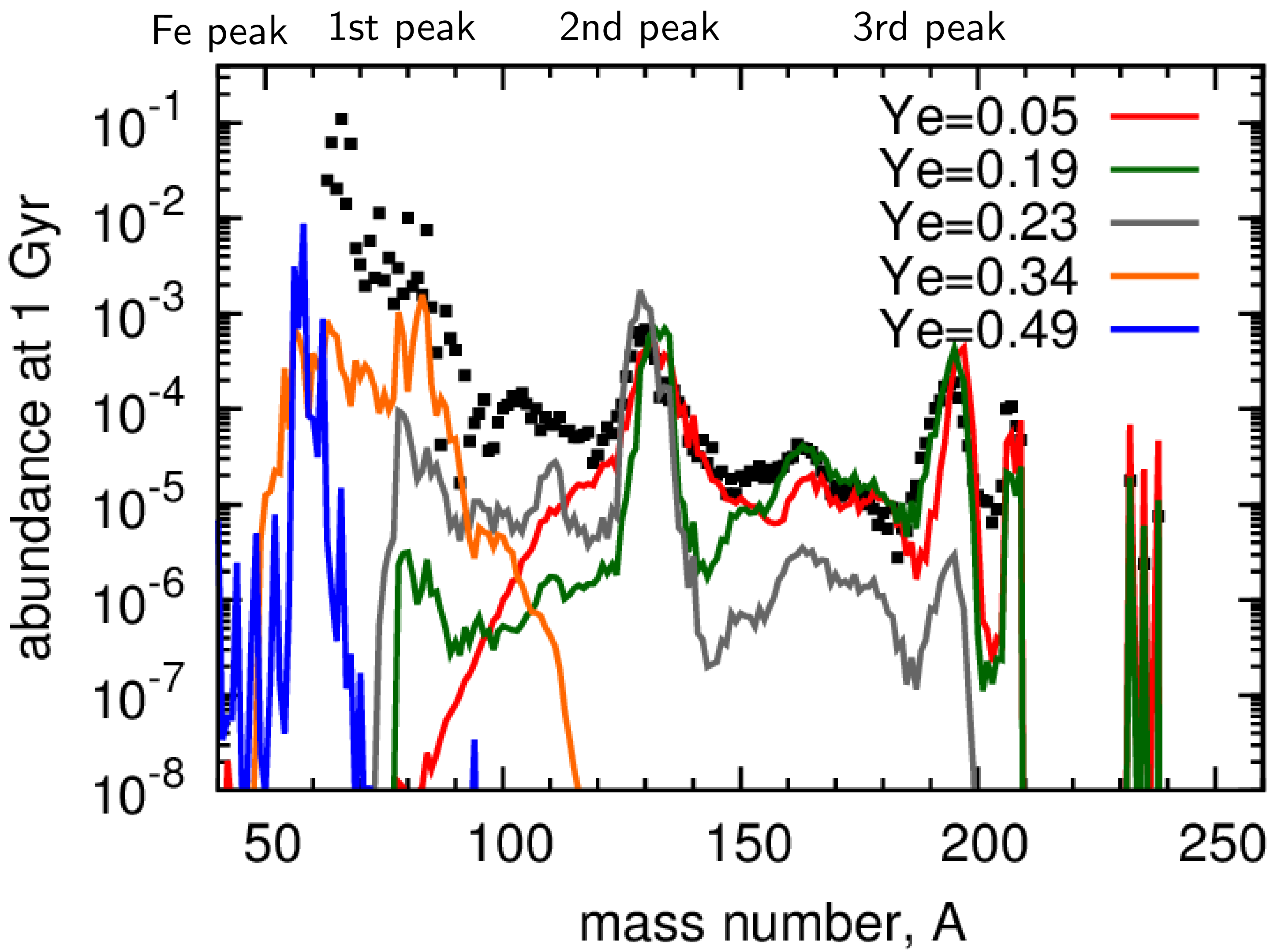

Fe peak
1st peak
2nd peak
3rd peak
Ye=0.05
Ye=0.19
Ye=0.23
Ye=0.34
Ye=0.49
abundance at 1 Gyr
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
50
100
150
200
250
mass number, A

Nuclear reaction network

$$\dot{Y}_i = \underbrace{\sum_j \mathcal{N}^i_j \lambda_j Y_j}_{} + \underbrace{\sum_{j,k} \mathcal{N}^i_{j,k} \rho N_A \langle j,k \rangle Y_j Y_k}_{} + \underbrace{\sum_{j,k,l} \mathcal{N}^i_{j,k,l} \rho^2 N_A^2 \langle j,k,l \rangle Y_j Y_k Y_l}_{}.$$

one-body reaction: decay, photo-disintegration, spon. & β-delayed fission...

two-body reaction: neutron captures, neutron-induced fission...

three-body reaction: $\alpha\alpha n$, αnn...

Solving $\sim$ few thousand of stiff ordinary differential equations with $\sim 10^5$-10^6 reaction rates (minutes to hours for a single core computation)

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Solving $\sim$ few thousand of stiff ordinary differential equations with $\sim 10^5$-10^6 reaction rates (minutes to hours for a single core computation)

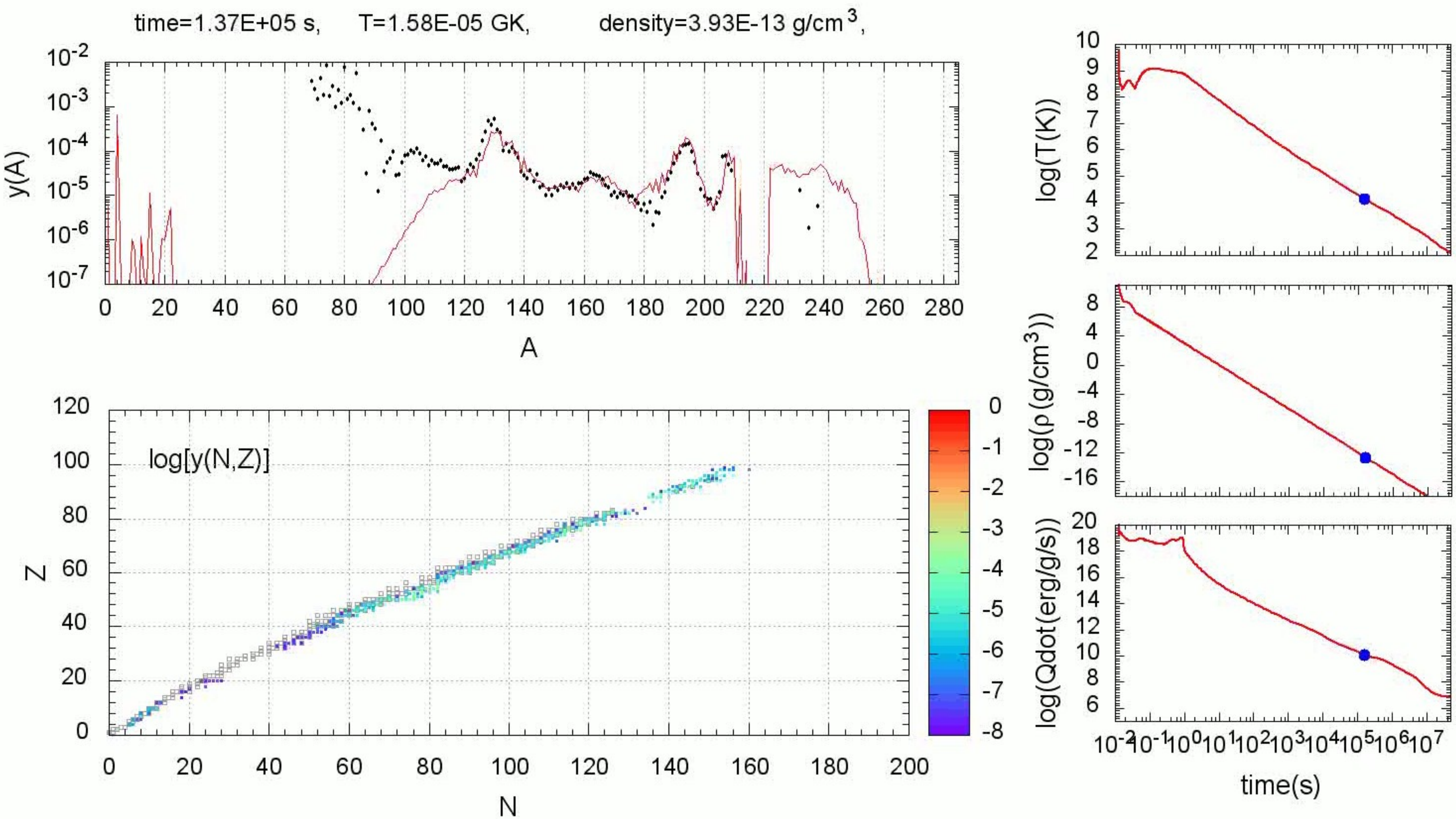
The initial composition usually determined by NSE for given $\rho(0)$, $T(0)$, $Y_e(0)$. Closed equations with the supply of $\rho(t)$.

temperature evolution coupled to nuclear reactions through entropy change due to nuclear energy release, assuming $pdV = 0$

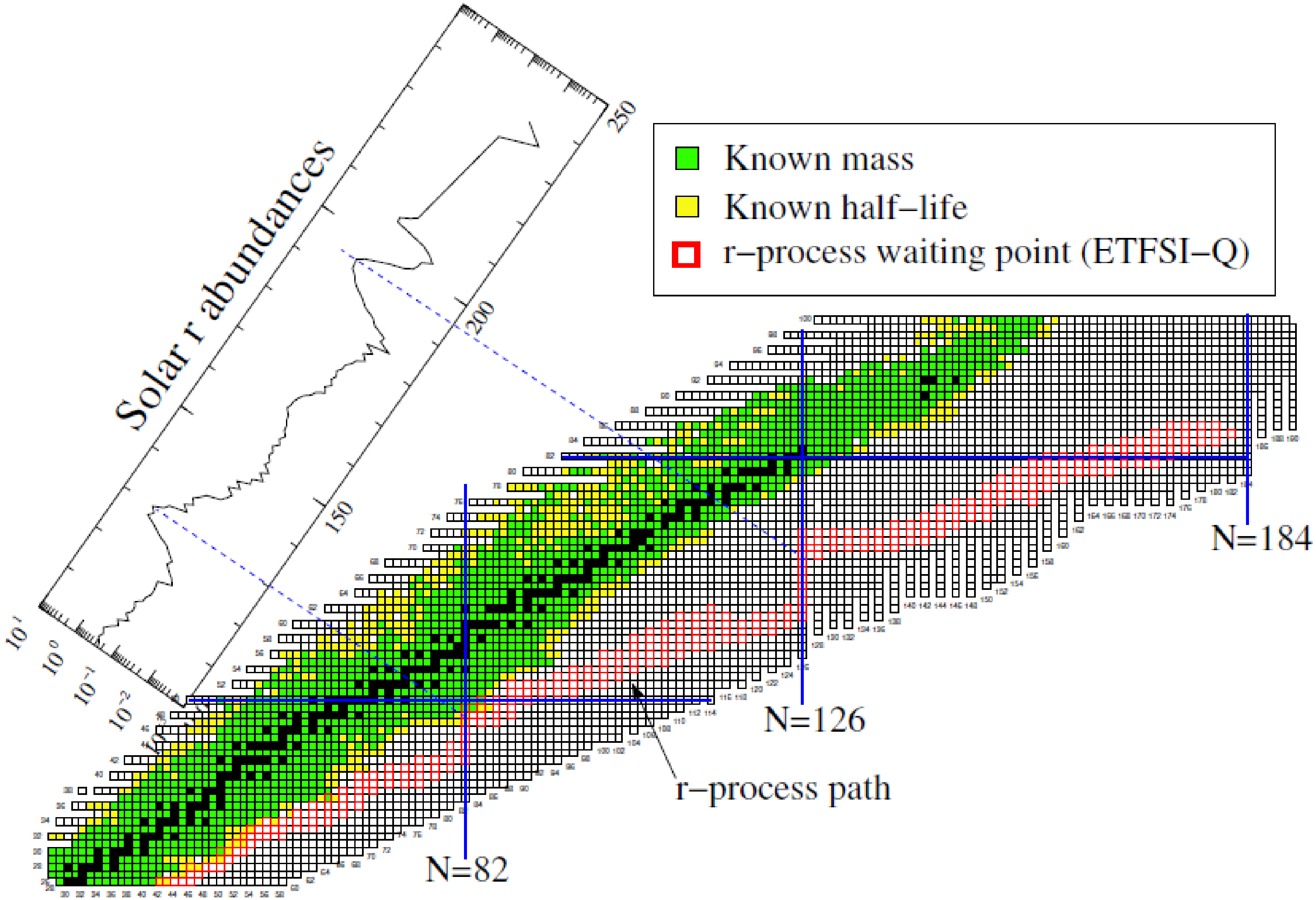
$$\frac{ds}{dt} = -\frac{1}{k_B T} \sum_i \left(m_i c^2 + \mu_i\right) \frac{dY_i}{dt}$$

r-process nucleosynthesis

an r-process calculation with $R_{n/s} \sim 500$, decompressed material from NS crust



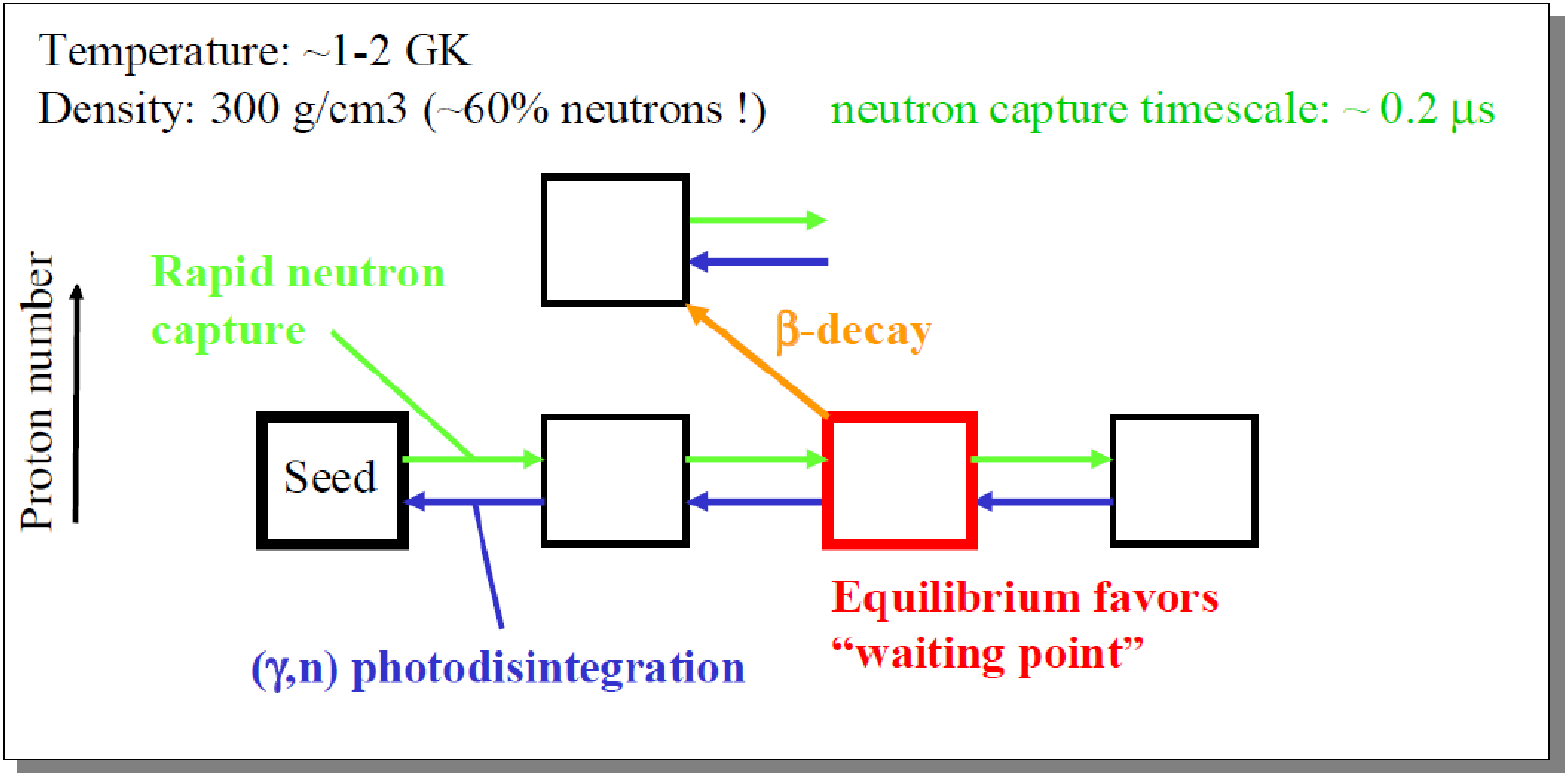
astrophysical conditions determine how far the r-process goes,
nuclear physics determines the abundance distribution



[from Martinez-Pinedo]

largely rely on theoretical nuclear physics inputs...

What nuclear physics inputs are important?



[from Burcher]

quasi-equilibrium flow is usually reached during the r-process

nuclear masses

$(n,\gamma) \leftrightarrow (\gamma,n)$ equilibrium: $\mu(Z,A+1) \leftrightarrow \mu_n + \mu(Z,A)$

$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} \left(\frac{A+1}{A}\right)^{3/2} \frac{G(Z,A+1)}{2G(Z,A)} \exp\left[\frac{S_n(Z,A+1)}{kT}\right]$$

$$\boxed{S_n \equiv m_{(Z,A)} + m_n - m_{(Z,A+1)}}$$

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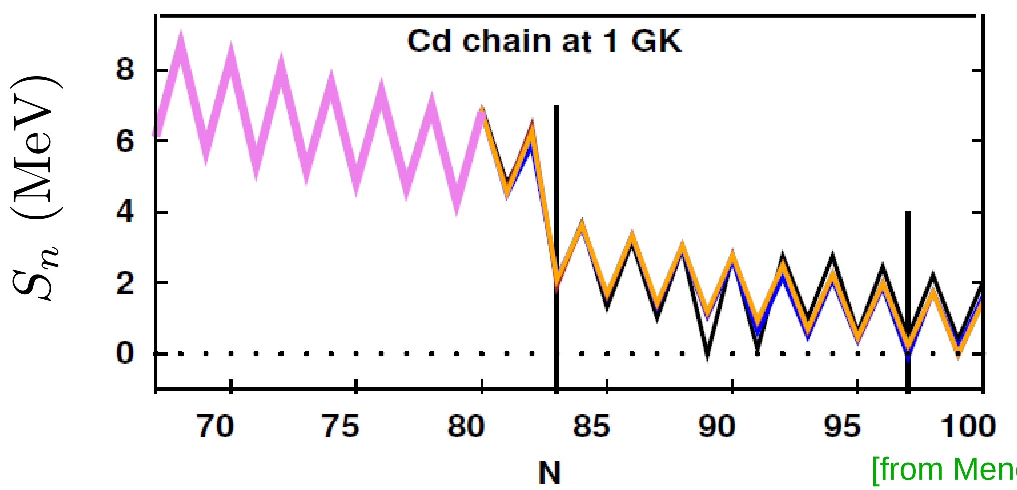
$$\boxed{S_n \equiv m_{(Z,A)} + m_n - m_{(Z,A+1)}}$$

along an isotopic chain (constant Z), the nucleus with neutron separation energy $S_n = S_n^0$ has the largest abundance.

$$\boxed{S_n^0(\mathrm{MeV}) = \frac{T_9}{5.04}\left(34.075 - \log n_n + \frac{3}{2}\log T_9\right)}$$



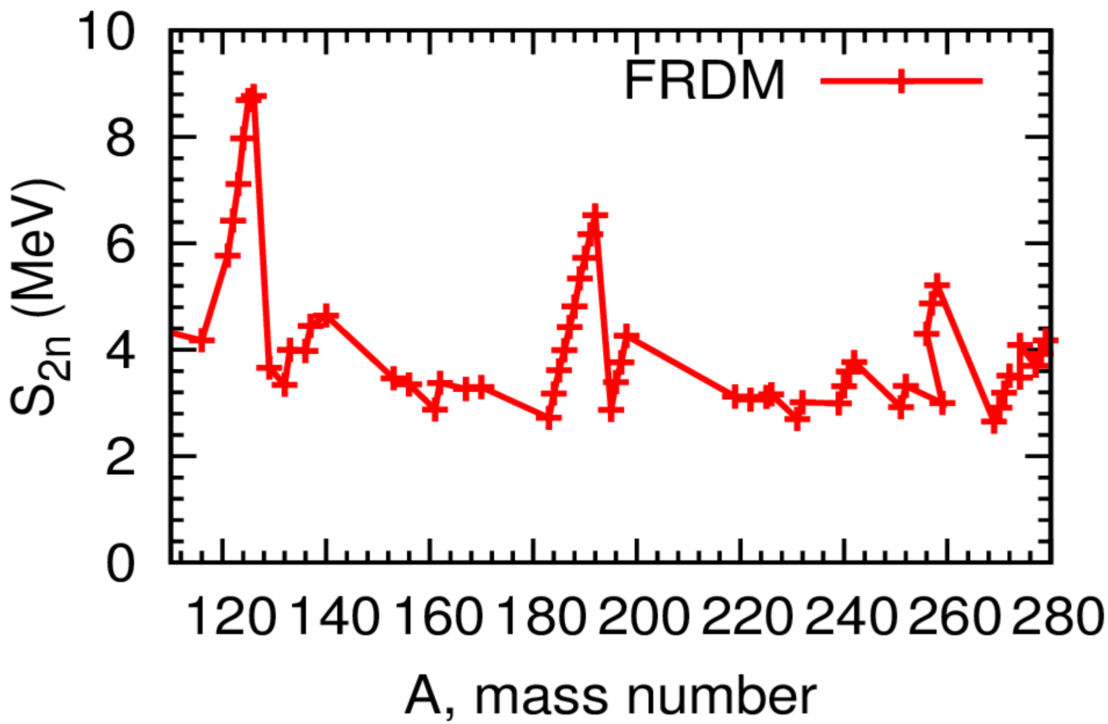
[from Mendoza-Temis]

nuclear masses

$$\boxed{S_n^0(\mathrm{MeV}) = \frac{T_9}{5.04}\left(34.075 - \log n_n + \frac{3}{2}\log T_9\right)}$$

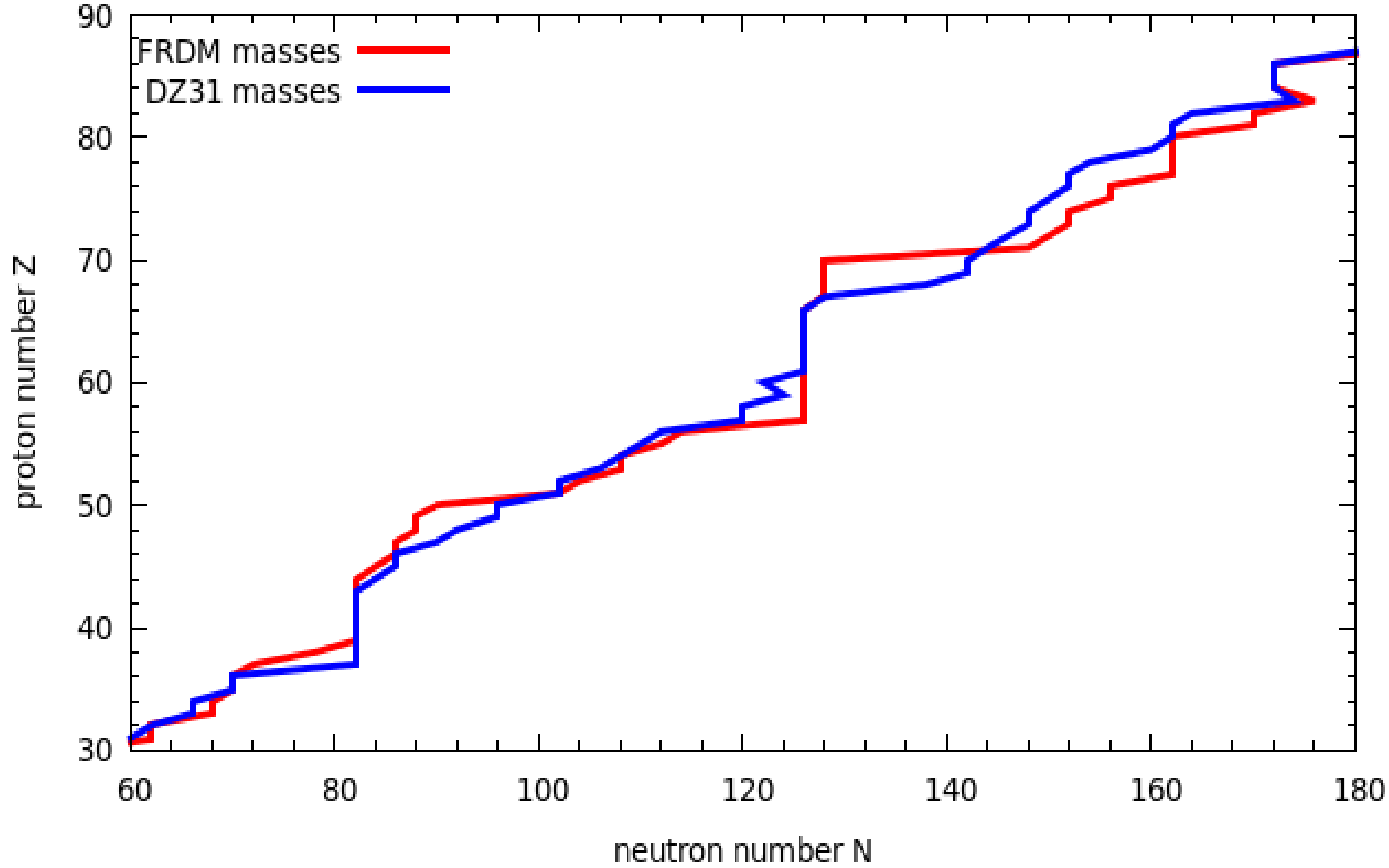
For a typical r-process condition:

$T \approx 0.75$ GK $\quad n_n \approx 3 \times 10^{24}\ \mathrm{cm}^{-3} \quad S_n^0 \approx 1.4\ \mathrm{MeV}$



nuclear masses

nuclear mass prediction determine the r-process path



beta decay rates

given the large supply of neutrons, the steady β flow is often reached

$$Y(Z)\langle\lambda_\beta(Z)\rangle = Y(Z+1)\langle\lambda_\beta(Z+1)\rangle$$

$\rightarrow$ nuclei with longer β-decay halflives are more abundant

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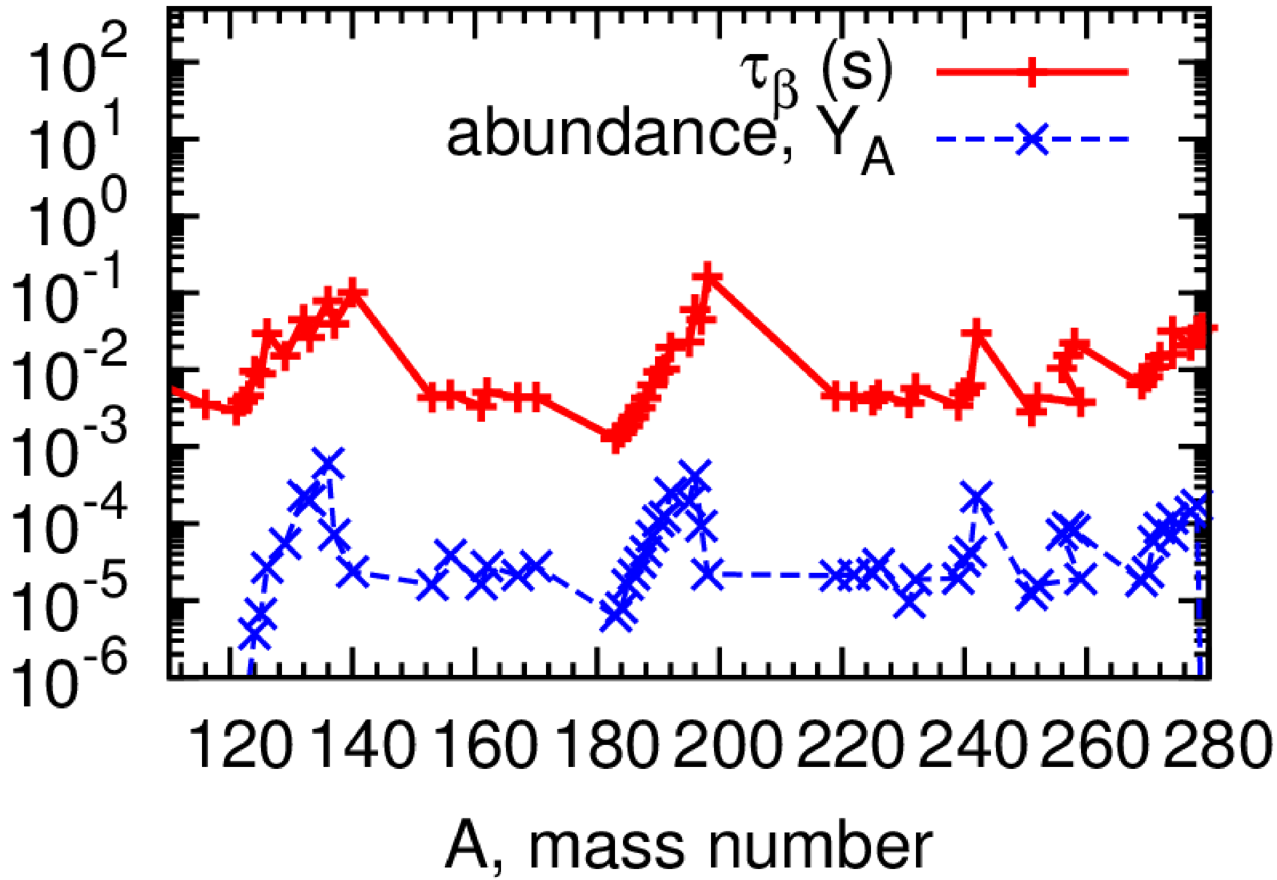

$T \approx 0.75$ GK

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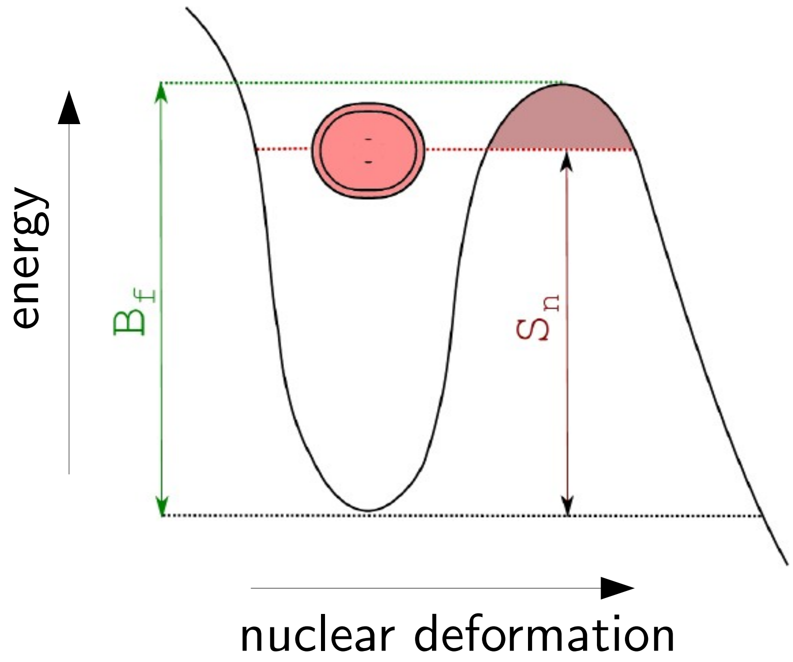
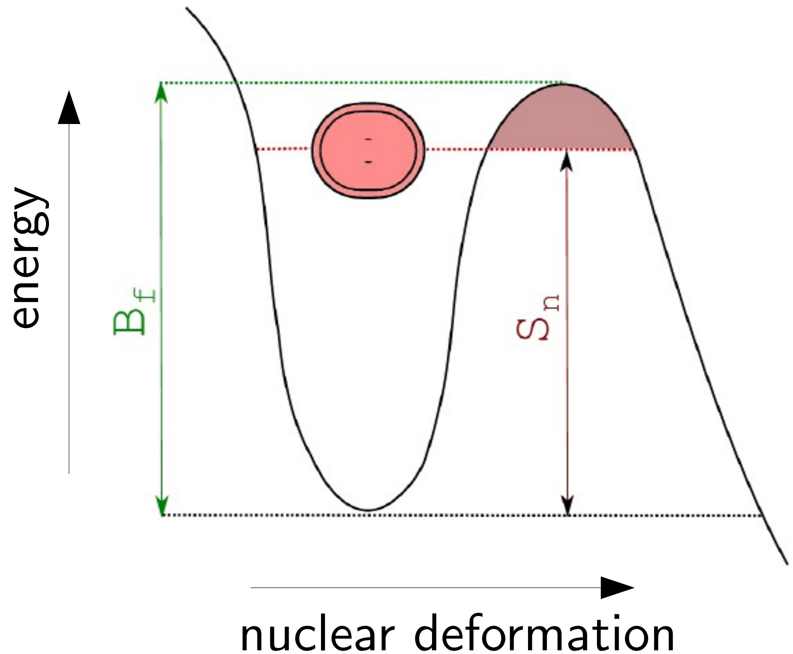
fission rates and fragment distributions



during the r-process, fission induced by the neutron-capture of a nucleus can proceed very fast and close the r-process path, when $S_n \sim B_f$, where B_f is the fission potential barrier

$\rightarrow$ fission barrier height prediction determines where the r-process ends

fission rates and fragment distributions



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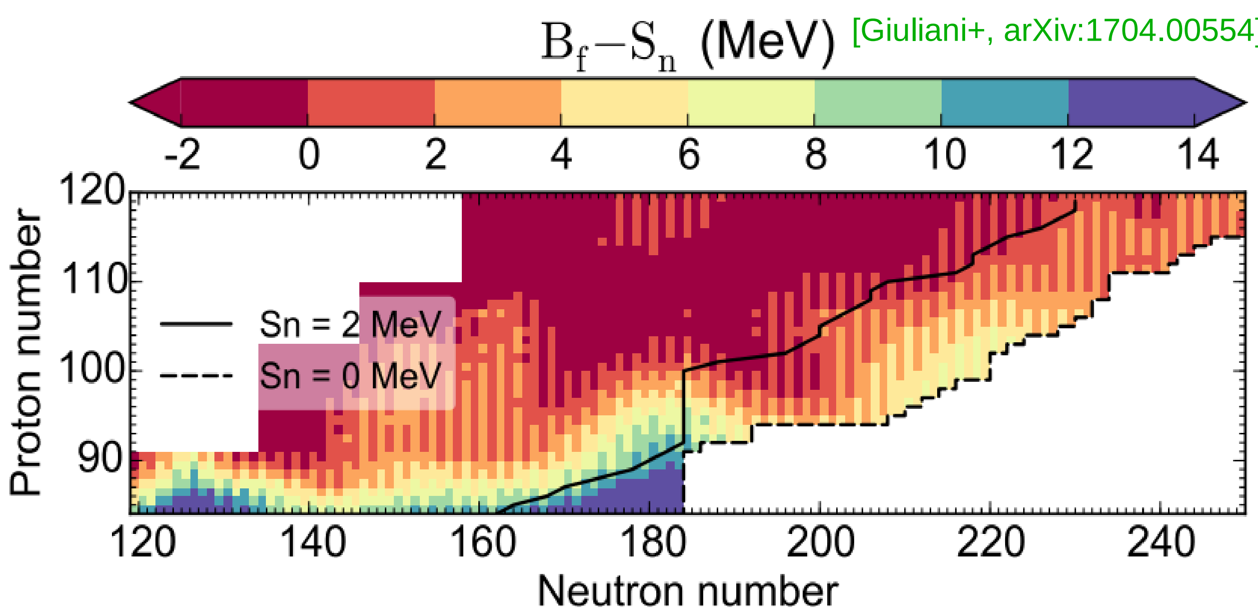
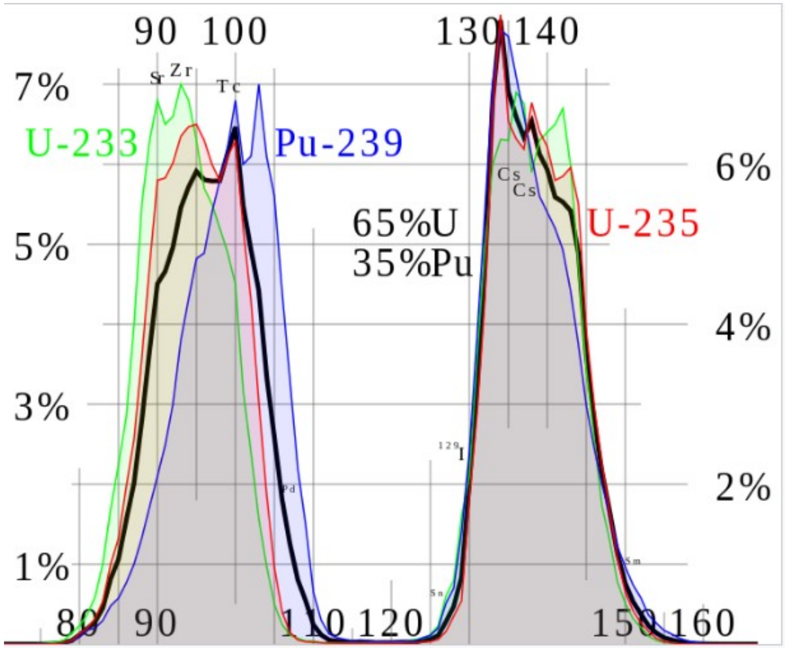
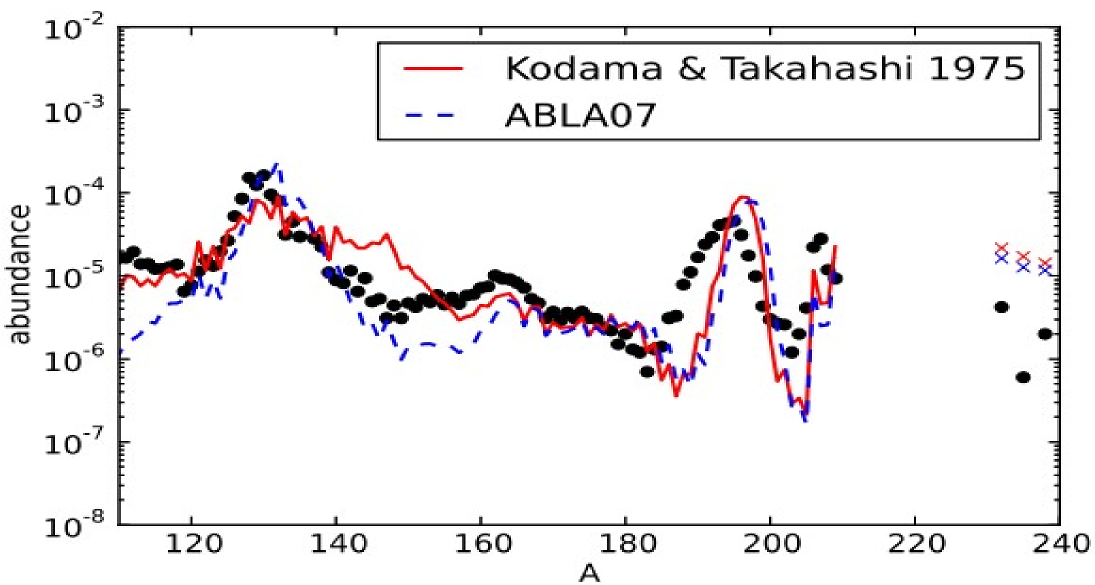


fission rates and fragment distributions

[from Wiki]



How do the fission daughter nuclei distribute from the fissioning neutron-rich mother-nucleus shapes the final abundances



[Eichler+ 2015]

Extract nuclear physics property from solar abundance?

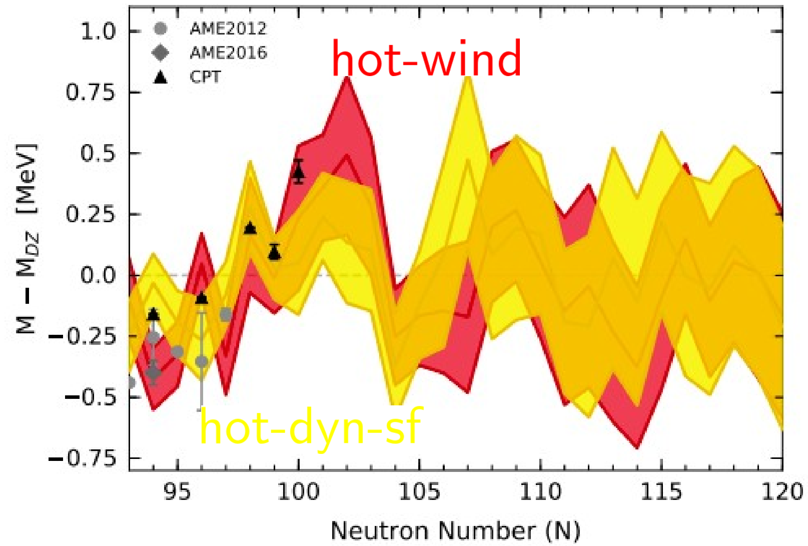
Vassh+2022 try to "optimize" the mass surface for regions relevant to the rare-earth peak

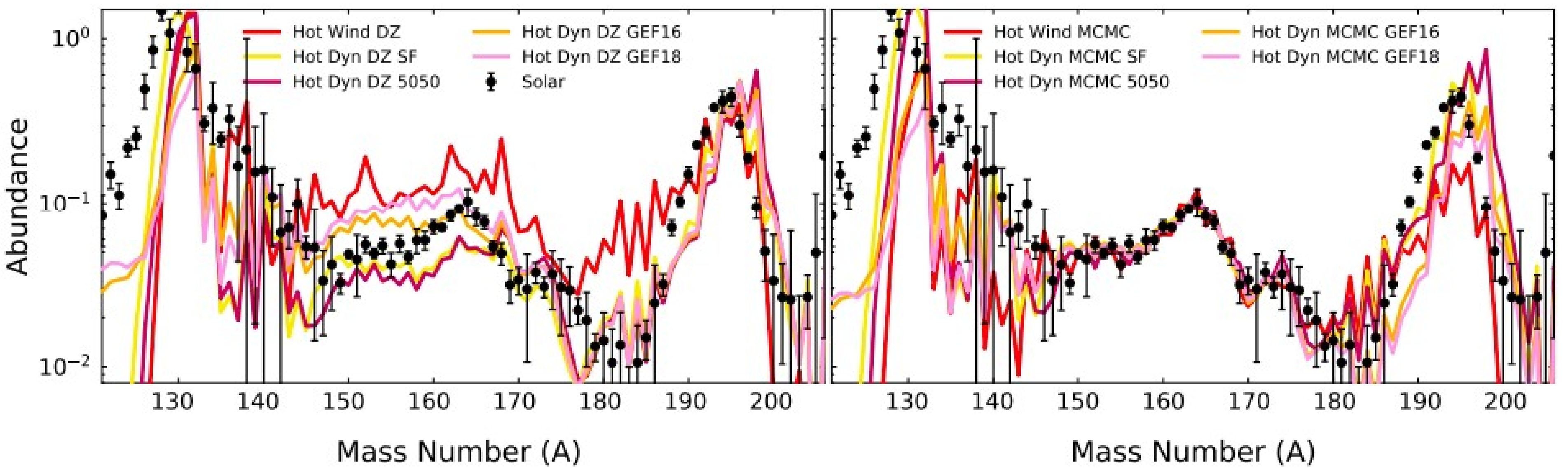
$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

by considering specific expansion condition

[Vassh+2202.09437]

for $Z = 60$





Summary (I)

- Observations in nature (the Solar system and others) and the understanding of nuclear physics together demend that the rapid neutron-capture process must happen in the history of the Universe.
- The global condition of the r-process is largely determined by astrophysics – how to dispel material that is very neutron rich?
- The detail understanding of how the r-process operates rely on the advance of the nuclear physics in the neutron-rich side

Summary (I)

- Observations in nature (the Solar system and others) and the understanding of nuclear physics together demend that the rapid neutron-capture process must happen in the history of the Universe.
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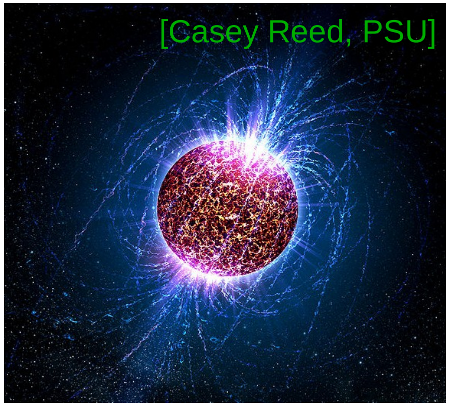
- The detail understanding of how the r-process operates rely on the advance of the nuclear physics in the neutron-rich side

– How do neutron star mergers provide such conditions?

– How do we know that r-process does happen in neutron star mergers?

The r-process and neutron stars



$M \sim 1.4 M_\odot$
$R \sim 10$ km
$\rho \gtrsim 10^{14}$ g cm^{-3}
$\gtrsim 95\%$ "neutrons"

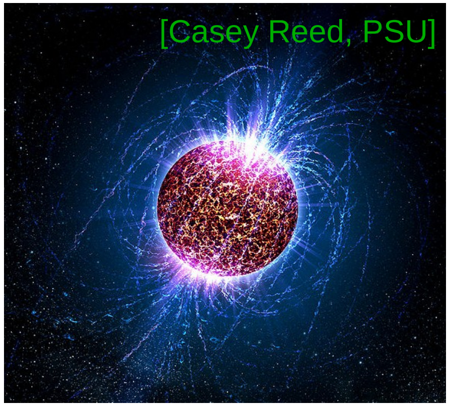
Ideal condition for rapid neutron captures can be obtained,
If one can "unbind" (part of) a neutron star:

– high density with large amount of neutrons

– compact object $\leftrightarrow$ short dynamic timescale

$$[\tau_{\rm dyn} \sim \sqrt{R^3/(GM)}]$$

The r-process and neutron stars



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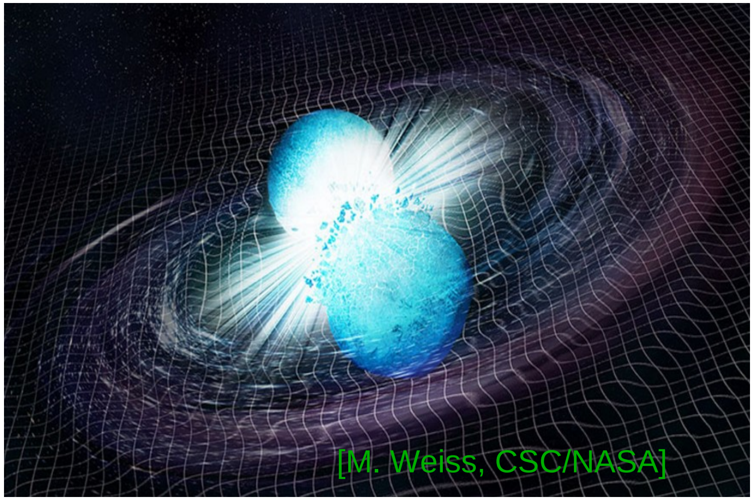
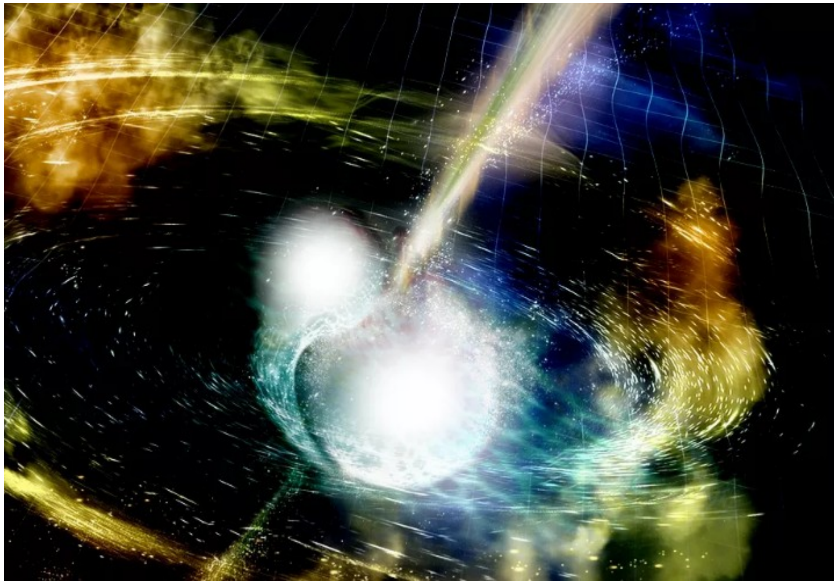
It's not easy to unbind things from a neutron star. Opportunities are:

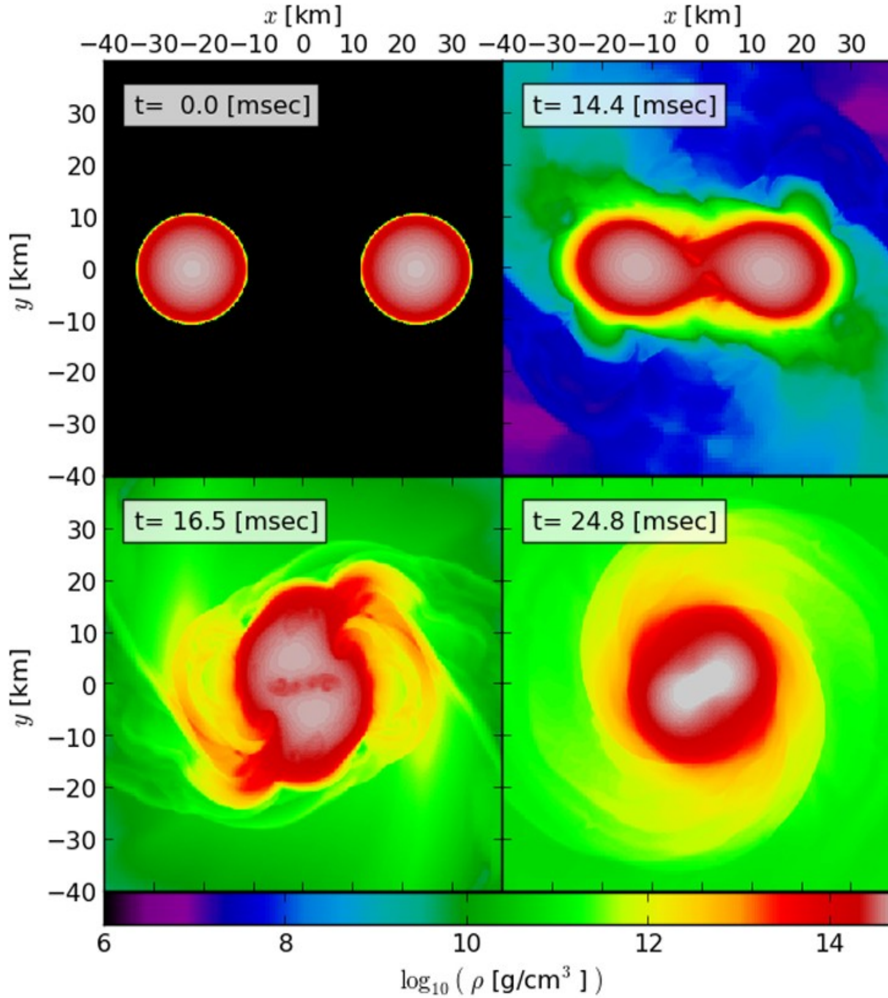
(i) a neutron star was born
(death of massive star)
$\rightarrow$ core-collapse supernovae

(ii) a neutron star dies
$\rightarrow$ neutron star mergers



Binary neutron star mergers





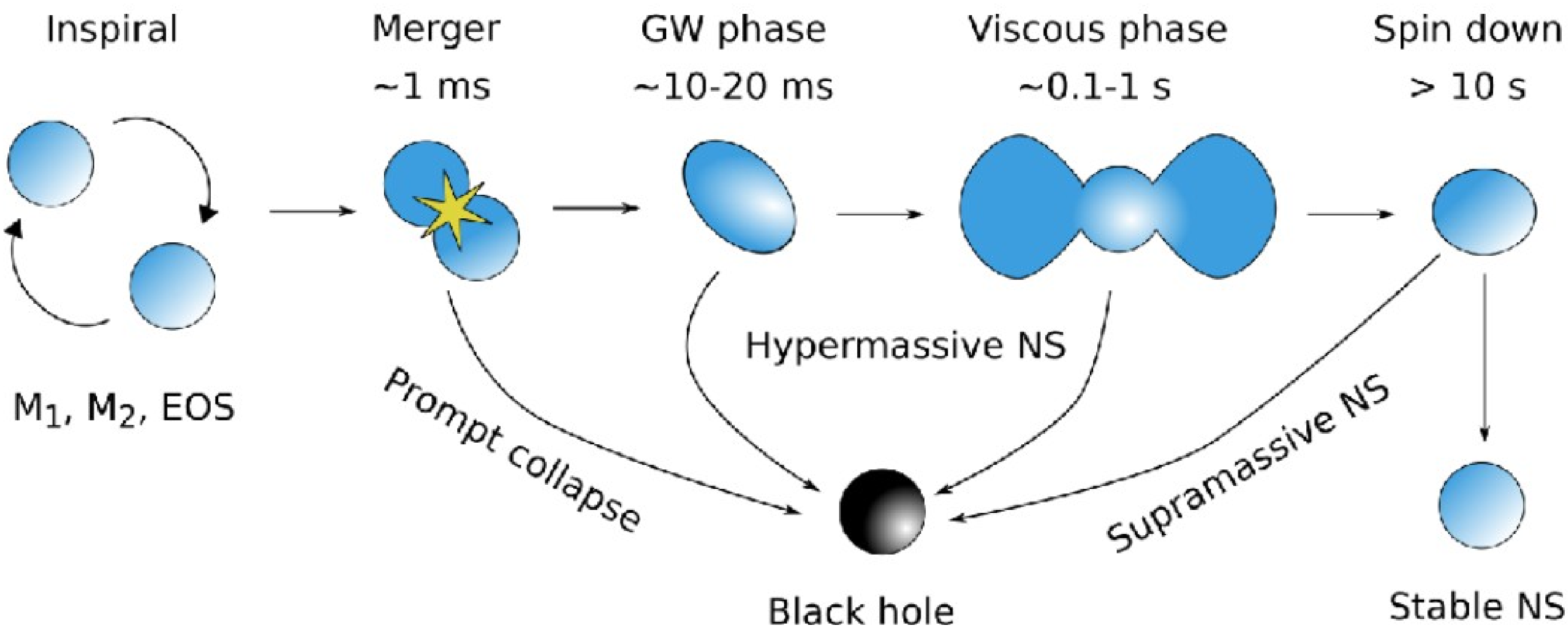
[From L. Rezzolla]

GW170817 confimrs that:

- gravitational wave sources
- origin of short γ-ray bursts
- origin of heavy elements (the r-process)$\rightarrow$ kilonovae

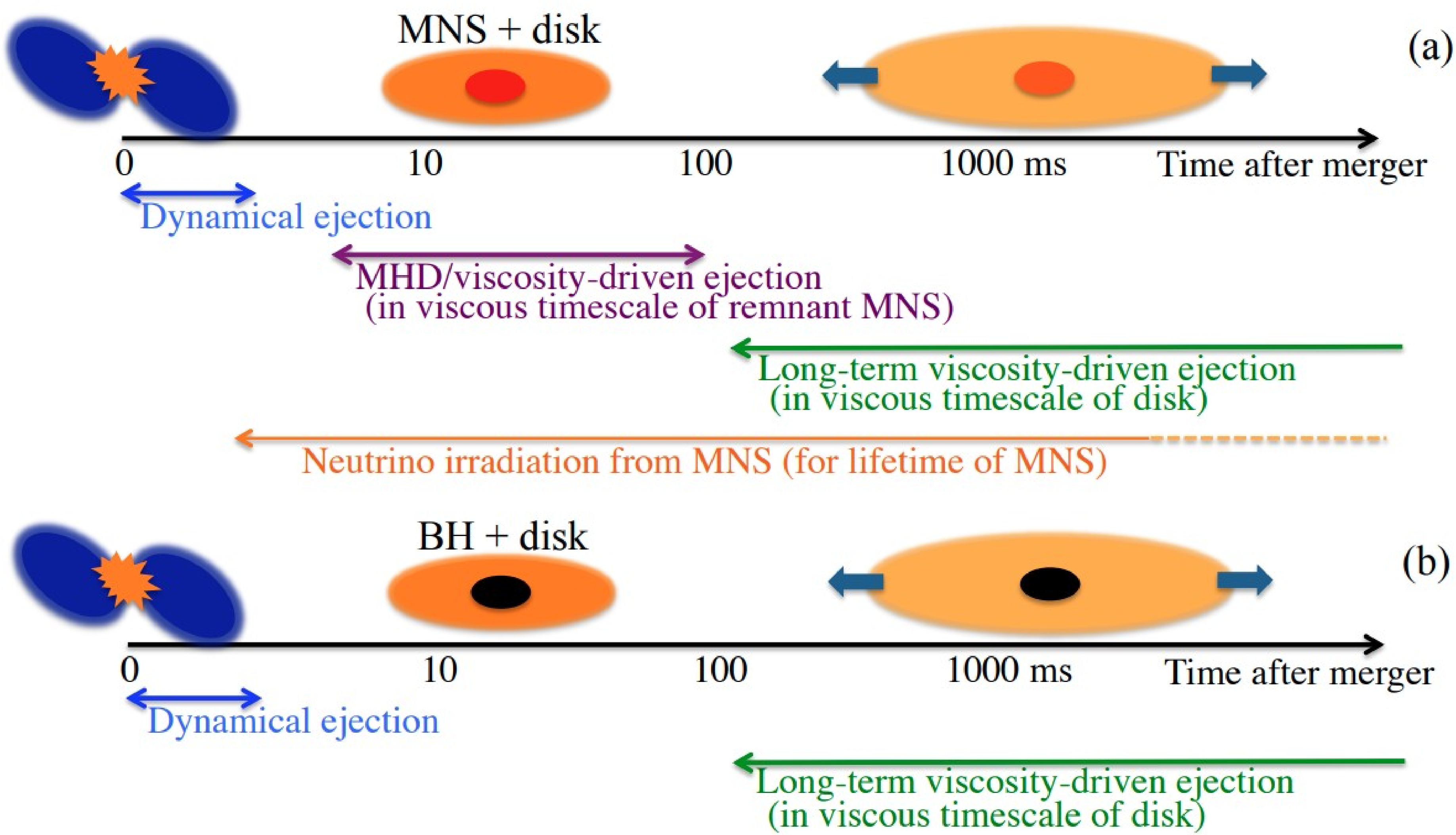
So far the only detected event with EM counterpart

NS merger: roadmap



mass ejectaion can happen in all the phases

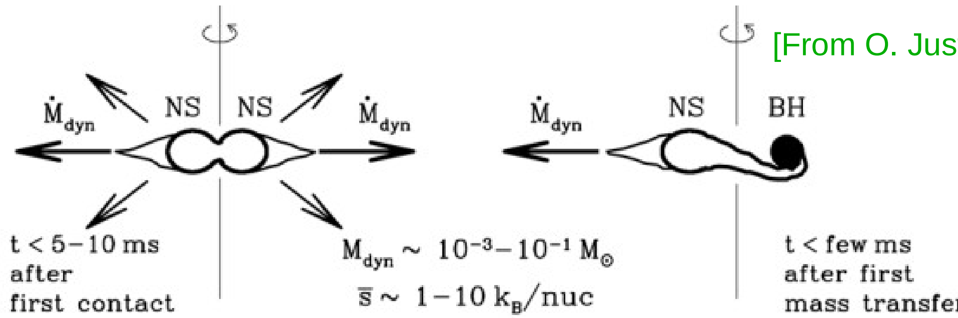
[From D. Radice]



[Shibata & Hotokezaka 1908.02350]

Dynamical ejecta

[Rosswog+, Janka+, Shibata+, Radice+, Rezzolla+,...]



(i) tidally stripped:

- decompressed from neutron star crusts
- low $Y_e \sim 0.05$, initially cold (low entropy)
- mostly close to the equatorial plane
- $10^{-4} - 10^{-3} M_\odot$, depending on the binary masses, spins, and EoS

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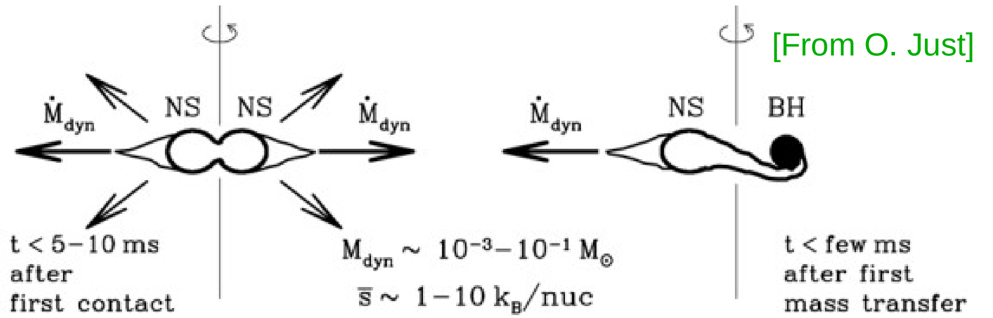

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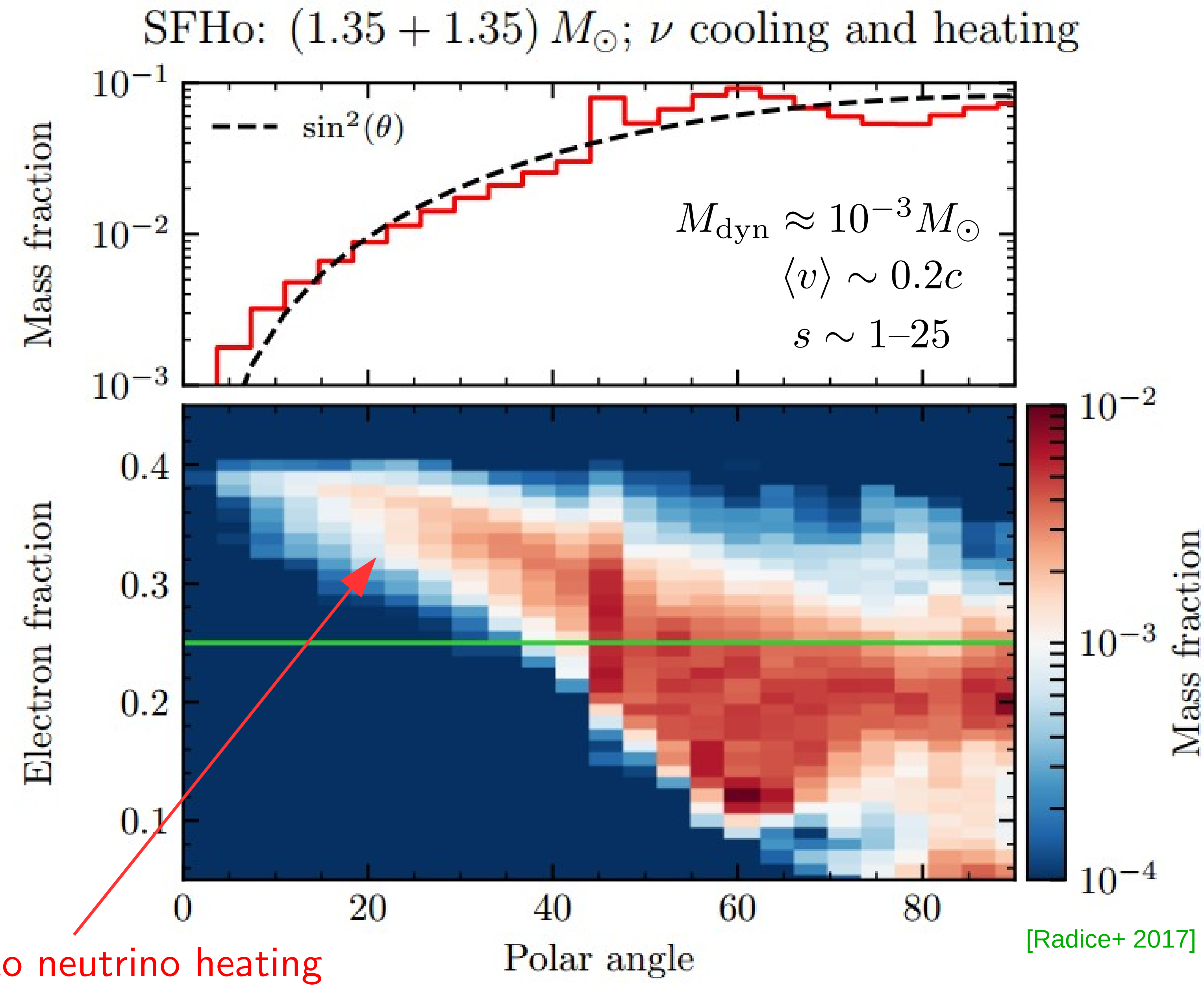
(ii) shock-heated:

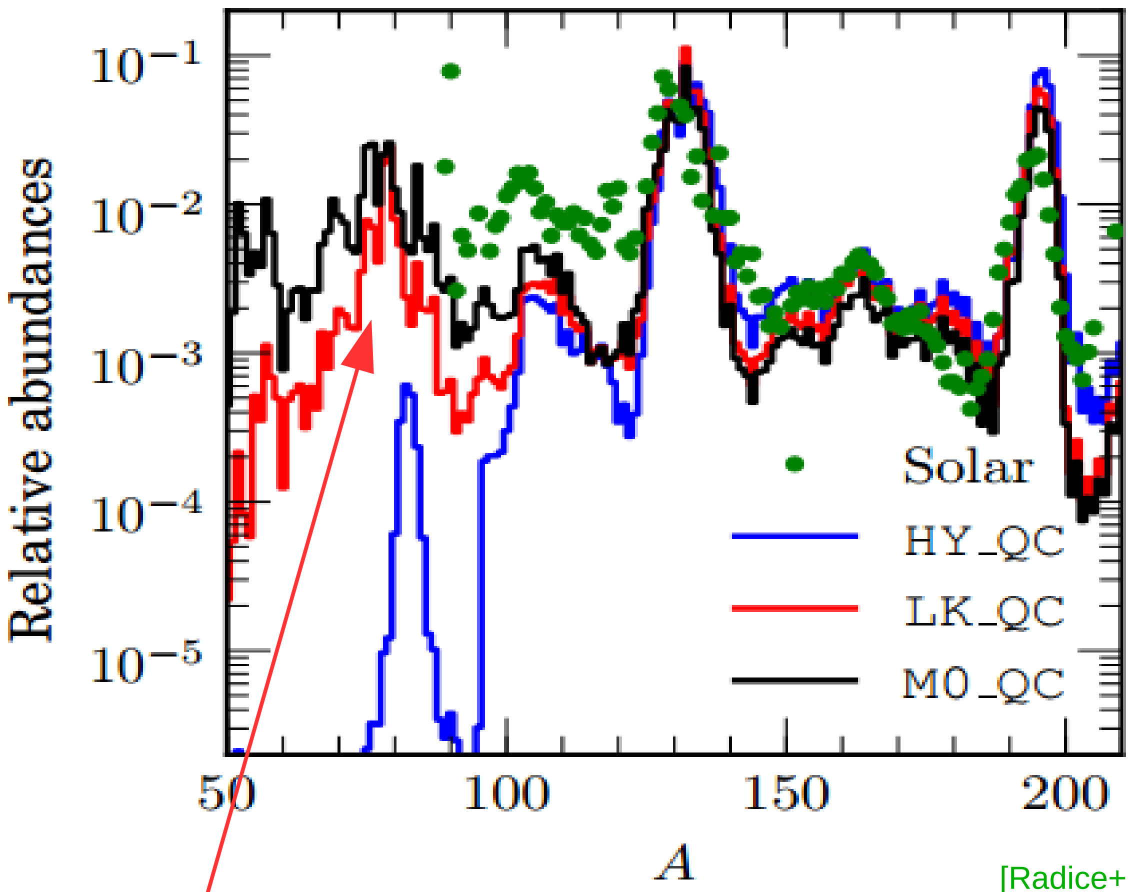
- "sqeezed" out from the contact interface of two NSs
- shock $\rightarrow$ high temperature
  $\rightarrow$ weak interactions change Y_e (broad distribution from $\sim 0.1 - 0.5$)
- close to isotropic
- $10^{-3} - 10^{-2} M_\odot$, depending on the binary masses, spins, and EoS



[Radice+ 2017]

due to neutrino heating

$\rightarrow$ needs improved ν-transport treatment (including flavor oscillations)



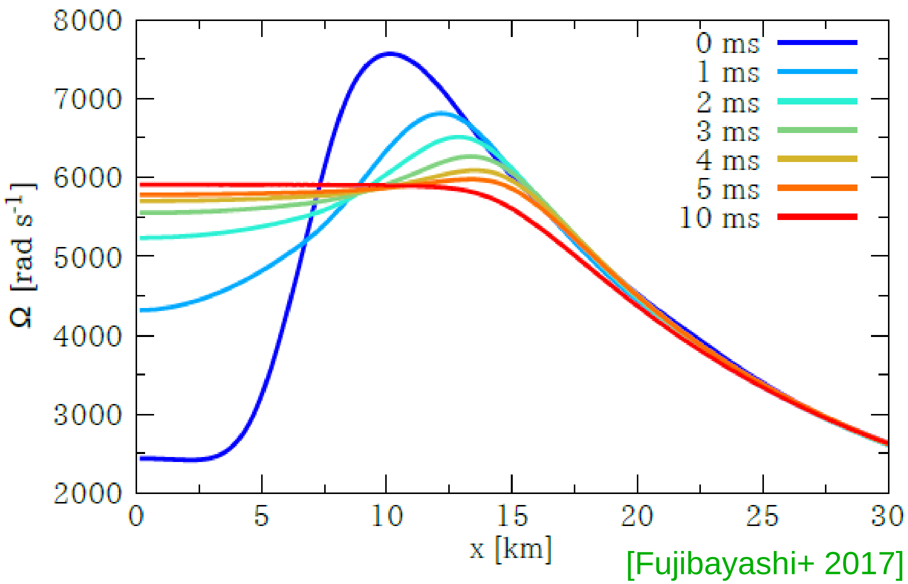
[Radice+ 2016]

due to neutrino heating

Early viscous ejecta from HMNS

- viscosity inside the hyper-massive neutron star can efficiently remove the differential rotation

- shockwave can be generated during this process and unbound some of the surrounding material when propagating outward



[Fujibayashi+ 2017]

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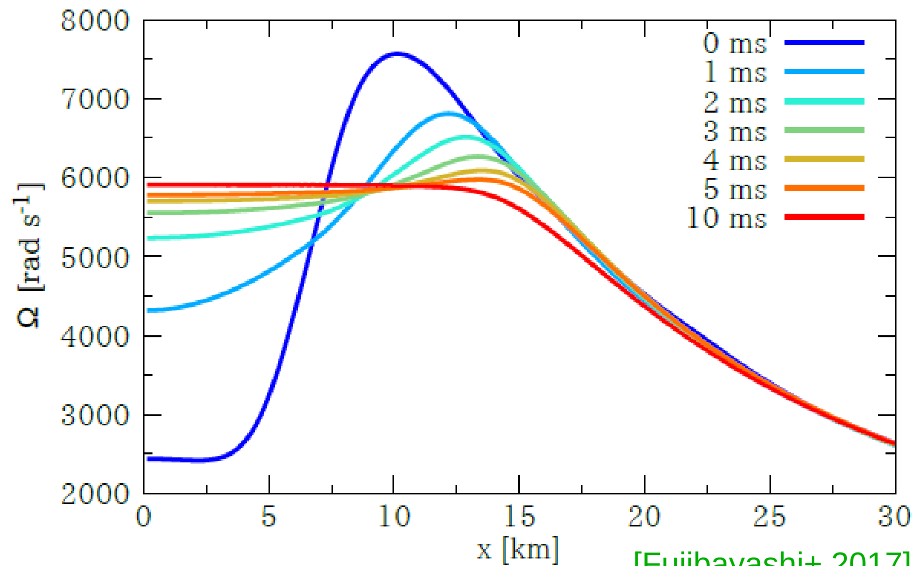
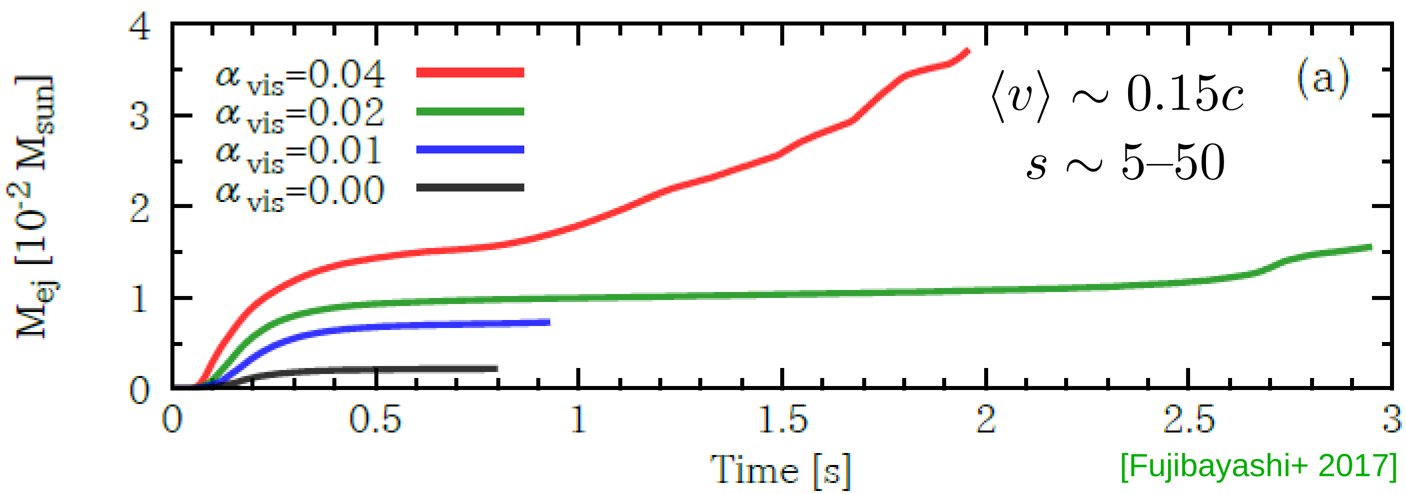
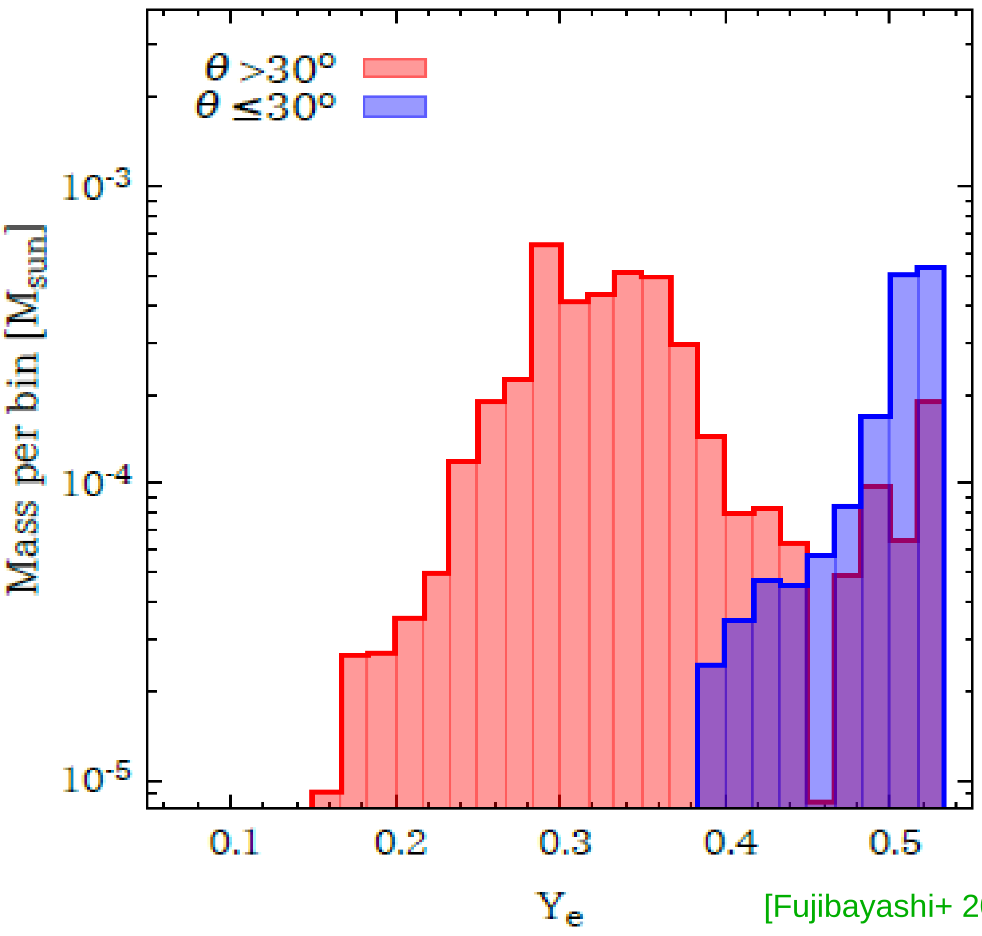


[Fujibayashi+ 2017]



[Fujibayashi+ 2017]

amount of ejecta depends on the assumed viscosity parameter

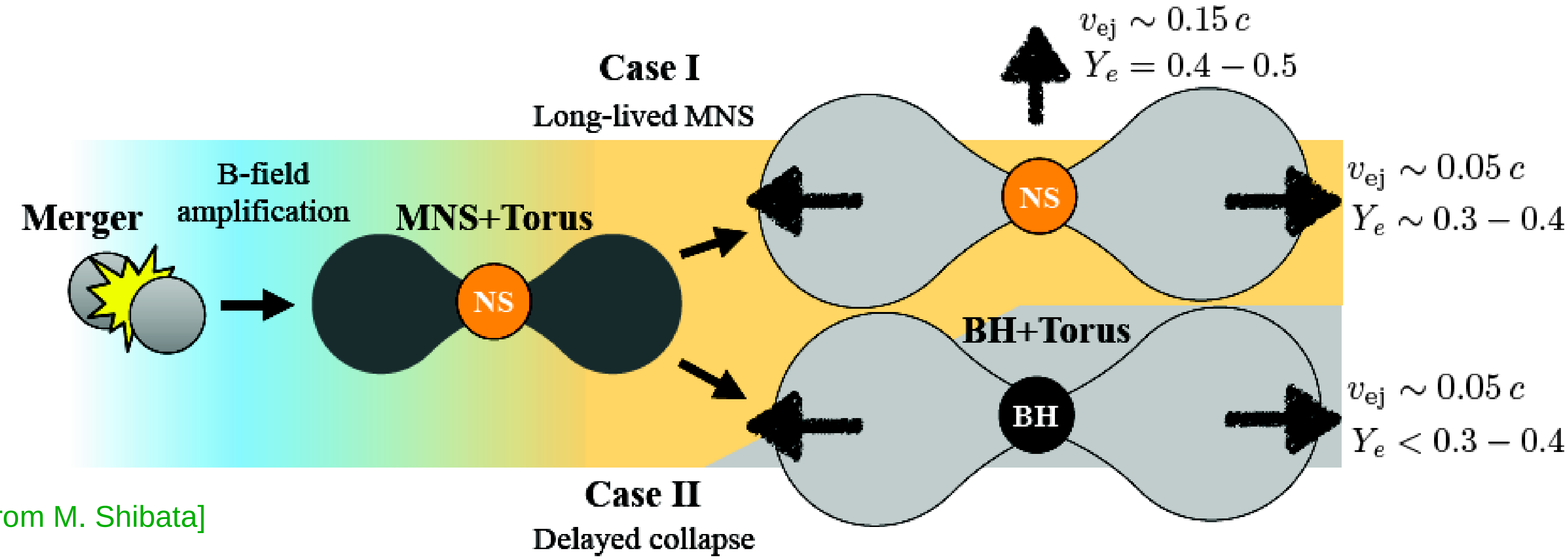


[Fujibayashi+ 2017]

composition largely re-shaped by $e^{\pm}$ captures and neutrinos absorption

Late viscous ejecta from accretion disk

[Fernandez+, Just+, Siegel+, Shibata+,...]

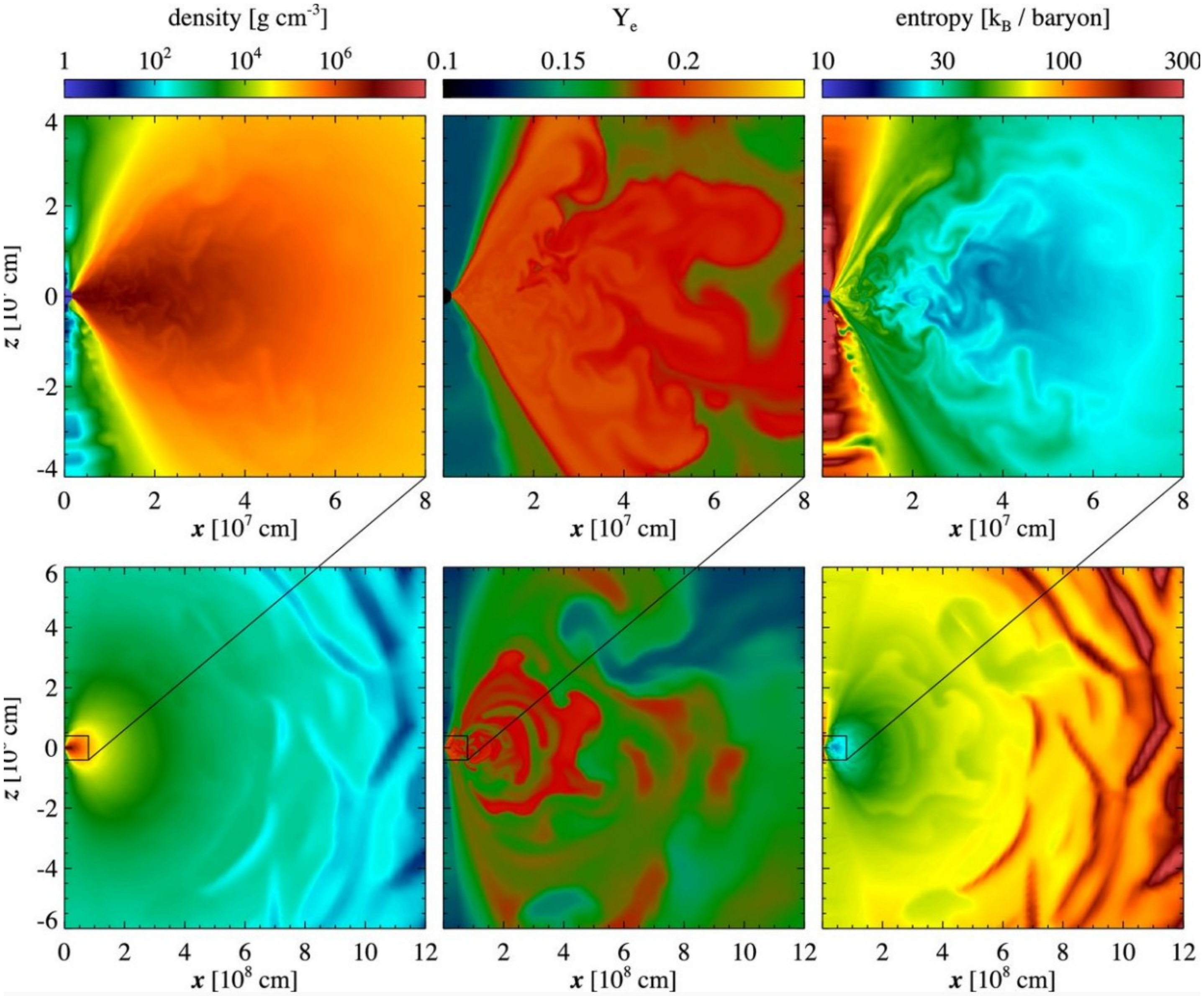


[From M. Shibata]

long-term evolution of the MNS/BH + accretion disk can ejecta more material

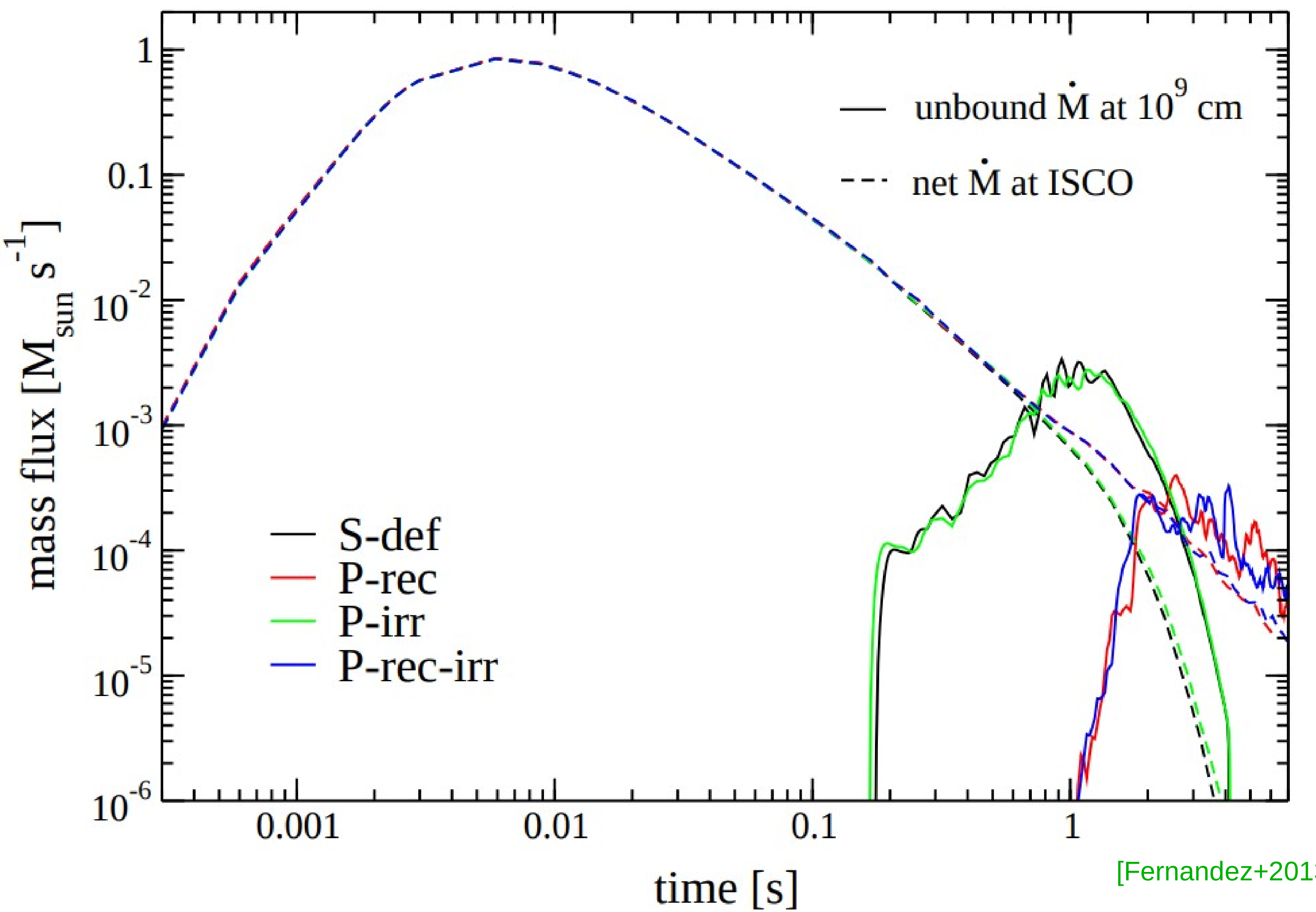
neutrino cooling becomes inefficient
$\rightarrow$ disk gets heated by viscosity
$\rightarrow$ it inflates and partly become unbound (aided by nuclear recombination energy)

Late viscous ejecta from accretion disk



[Fernandez+2013]

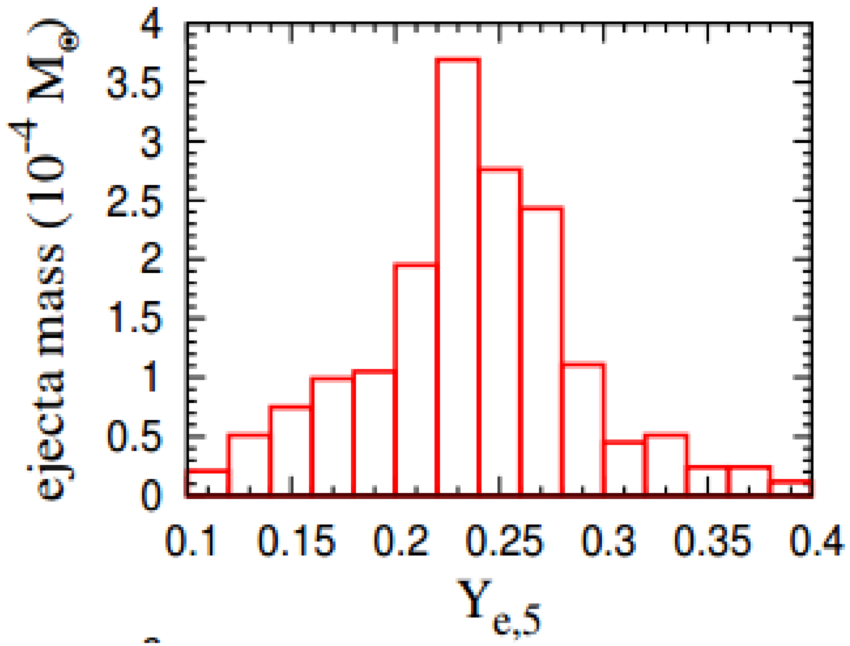
Late viscous ejecta from accretion disk

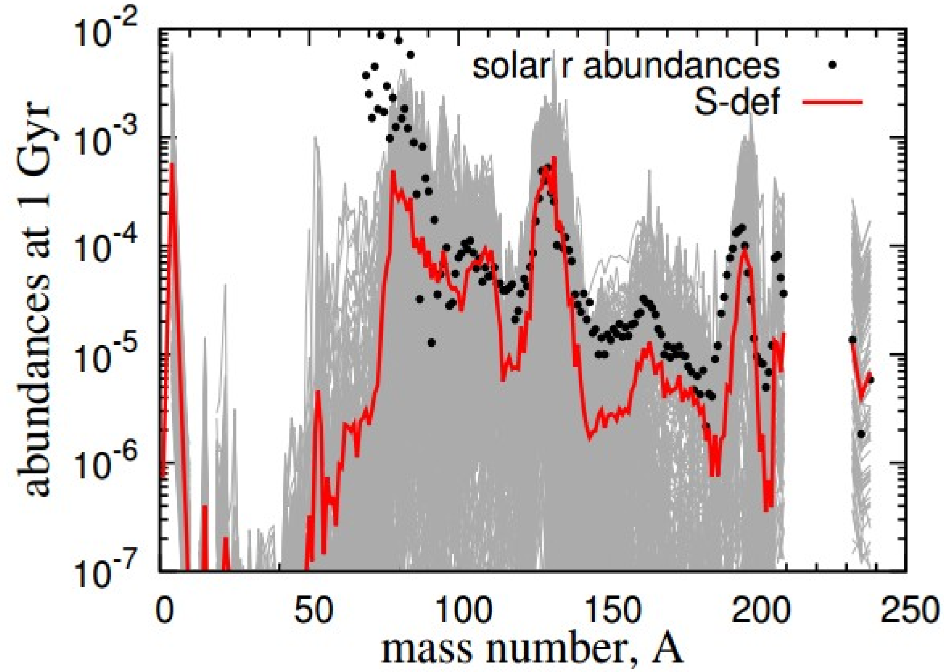


[Fernandez+2013]

BH–disk case

$\langle v \rangle \sim 0.05 - 0.1c \qquad s \sim 5\text{–}50$





[MRW+ 2016]

- results mildly sensitive to the initial condition of the disk mass, entropy, size
- recent 3D MHD BH-disk simulations give outcome similar to relatively large viscosity case $\alpha \gtrsim 0.02$ [Siegel+ 2017, Fernandez+2018, Fahlman+2022,...]

With a short-lived HMNS

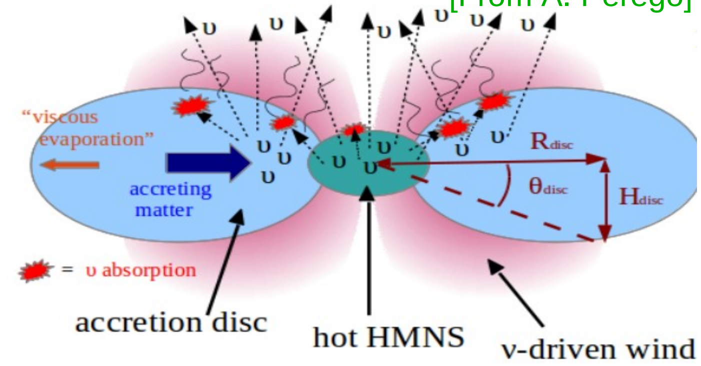
HMNS has lifetime $\sim \mathcal{O}(10-100)$ ms

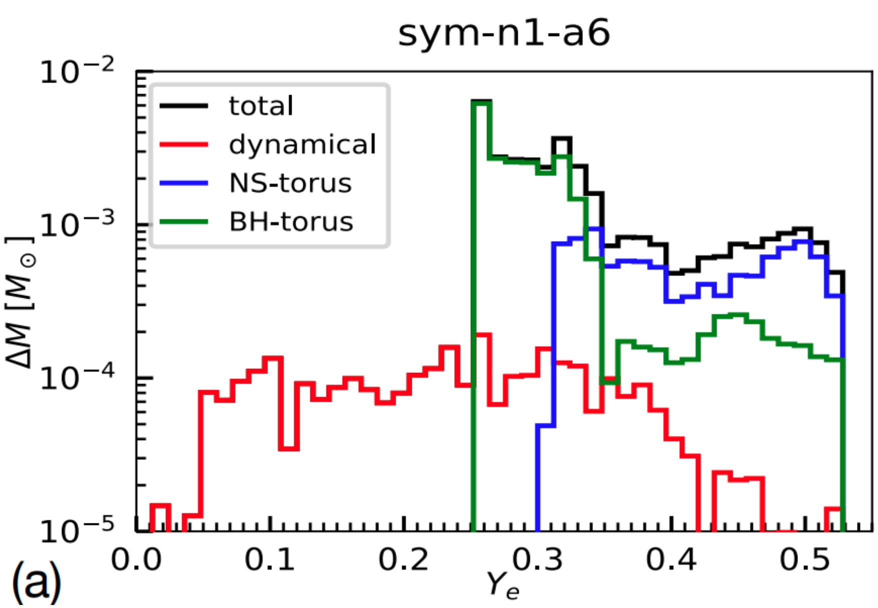
$\rightarrow$ strong neutrino emission before BH formation

$\rightarrow$ larger $Y_e \gtrsim 0.3$ for NS–disk wind

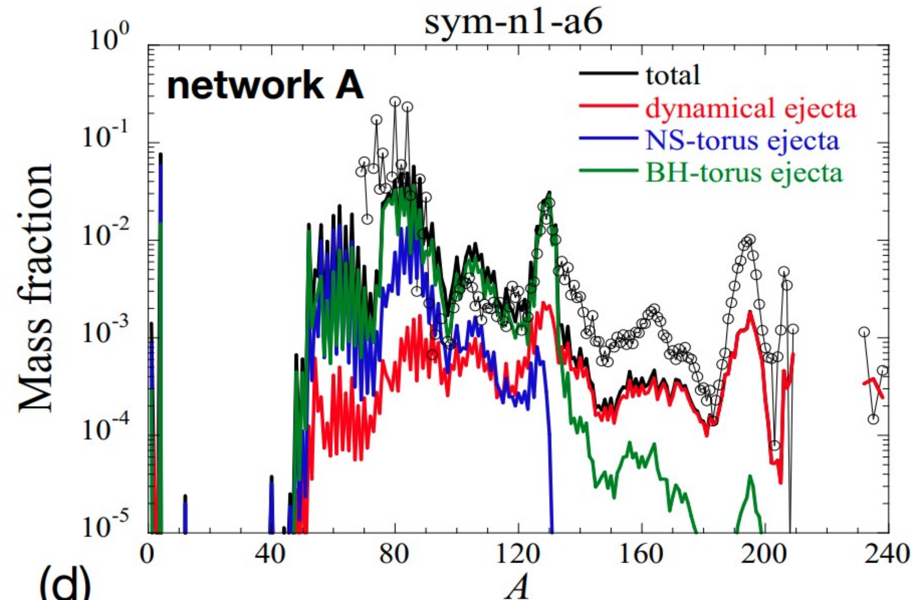
$\rightarrow$ also higher $Y_e \gtrsim 0.25$ for the subsequent BH-disk wind

[From A. Perego]





(a)



(d)

[Just+ 2302.10928]

Summary (II)

- Theory predicts various different mass ejection mechanism from the mergers. Exact property of the ejecta depends on the binary progenitor system.
- Neutrinos from the remnant hyper-massive neutron stars are needed to create material with $Y_e > 0.3$ in polar direction

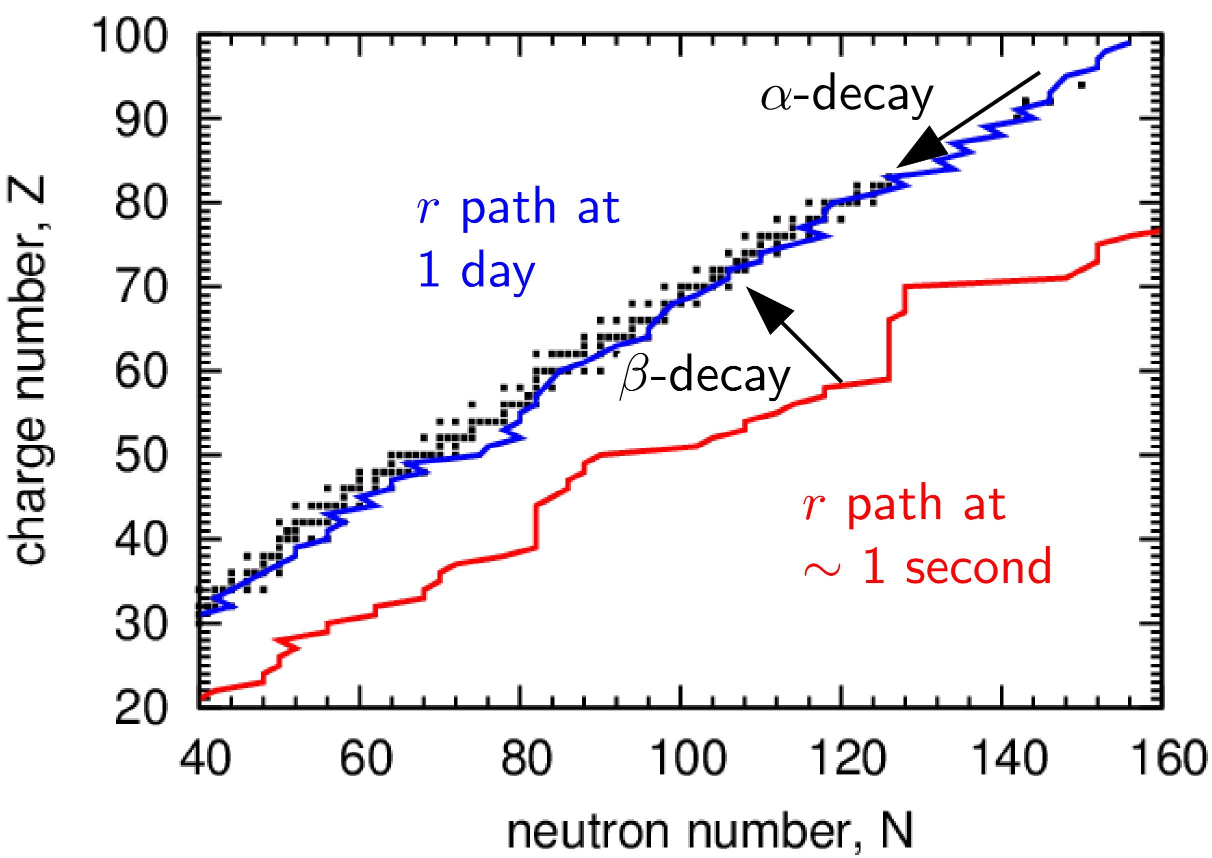
Type of binary	Remnant	$M_{\mathrm{ej,dyn}}$	$M_{\mathrm{ej,vis}}$	$Y_{e,\mathrm{dyn}}$	$Y_{e,\mathrm{vis}}$	$\langle v_{\mathrm{ej,dyn}} \rangle$
Low-m BNS	SMNS	$O(10^{-3})$	$O(10^{-2})$	0.05–0.5	0.3–0.5	0.15
Mid-m BNS (stiff EOS)	HMNS	$O(10^{-3})$	$O(10^{-2})$	0.05–0.5	0.2–0.5	0.15
Mid-m BNS (soft EOS)	HMNS	$\sim 10^{-2}$	$O(10^{-2})$	0.05–0.5	0.2–0.5	0.20
High-m BNS ($q \sim 1$)	BH	$< 10^{-3}$	$< 10^{-3}$	—	—	—
High-m BNS ($q \ll 1$)	BH	$O(10^{-3})$	$\lesssim 10^{-2}$	0.05–0.1	0.05–0.3	0.30
BH-NS	BH	0–0.1	0–0.1	0.05–0.1	0.05–0.3	0.30

[Adapted from Shibata+2018]

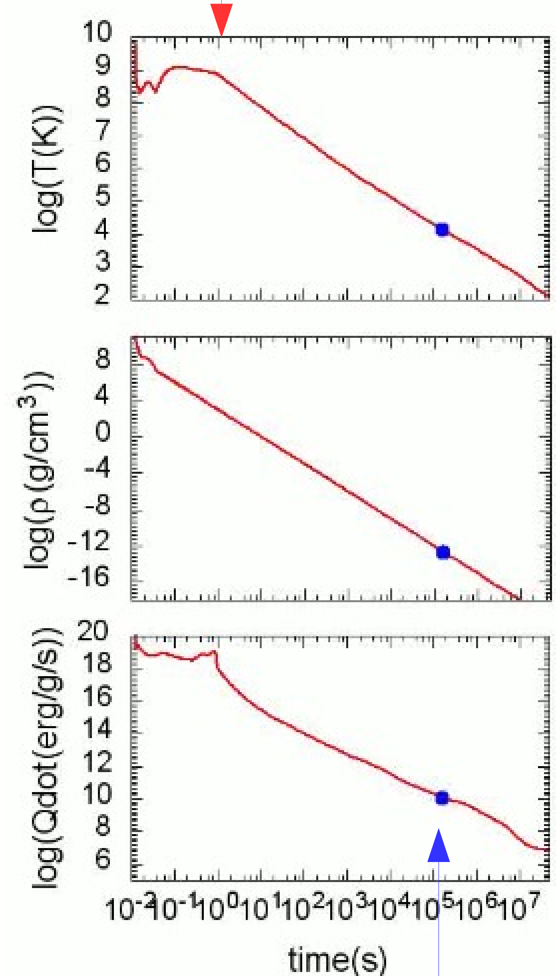
– How do they power the kilonova emission?

Kilonova 101

The radioactive nuclei continue to decay back to the valley of stability and keep injecting energy into the expanding material



r-process ends here



we see kilonova here

Kilonova 101

When density is large, photons cannot escape the system, these injected energy gets entirely converted into the internal and kinetic energy of the system.

The observation of the EM signals becomes possible when most of the thermal photons can escape.

Kilonova 101

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The observation of the EM signals becomes possible when most of the thermal photons can escape.

diffusion time scale:

$$\tau_{\rm diff} \sim \frac{R^2}{c \cdot l}$$

ejecta expansion time scale:

$$\tau_{\rm exp} \sim \frac{R}{v_{\rm ej}}$$

R: typical radius of the ejecta $\sim v_{\rm ej} t$

l: photon mean-free-path$\sim (\kappa\rho)^{-1}$

κ: photon opacity

ρ: mean mass density $\sim M_{\rm ej}(\pi R^3)^{-1}$

$$\rightarrow t_{\rm peak} \sim \left(\frac{\kappa M_{\rm ej}}{\pi c v_{\rm ej}}\right)^{1/2} \sim 3.8 \text{ day} \left[\left(\frac{\kappa}{10 {\rm cm}^2/{\rm g}}\right)\left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)\left(\frac{0.1c}{v_{\rm ej}}\right)\right]^{1/2}$$

κ: opacity, $M_{\rm ej}$, $v_{\rm ej}$: mass and velocity of the ejecta

Kilonova 101

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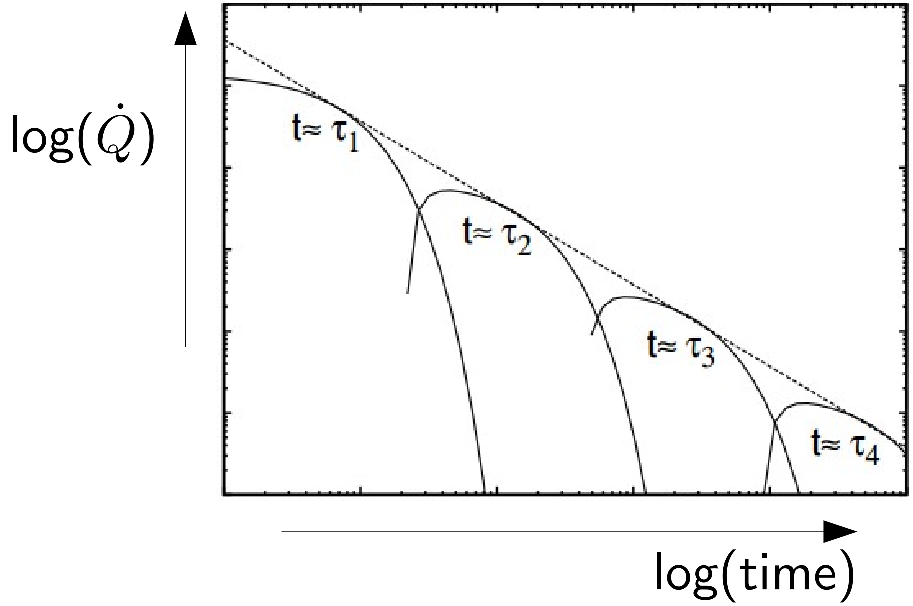
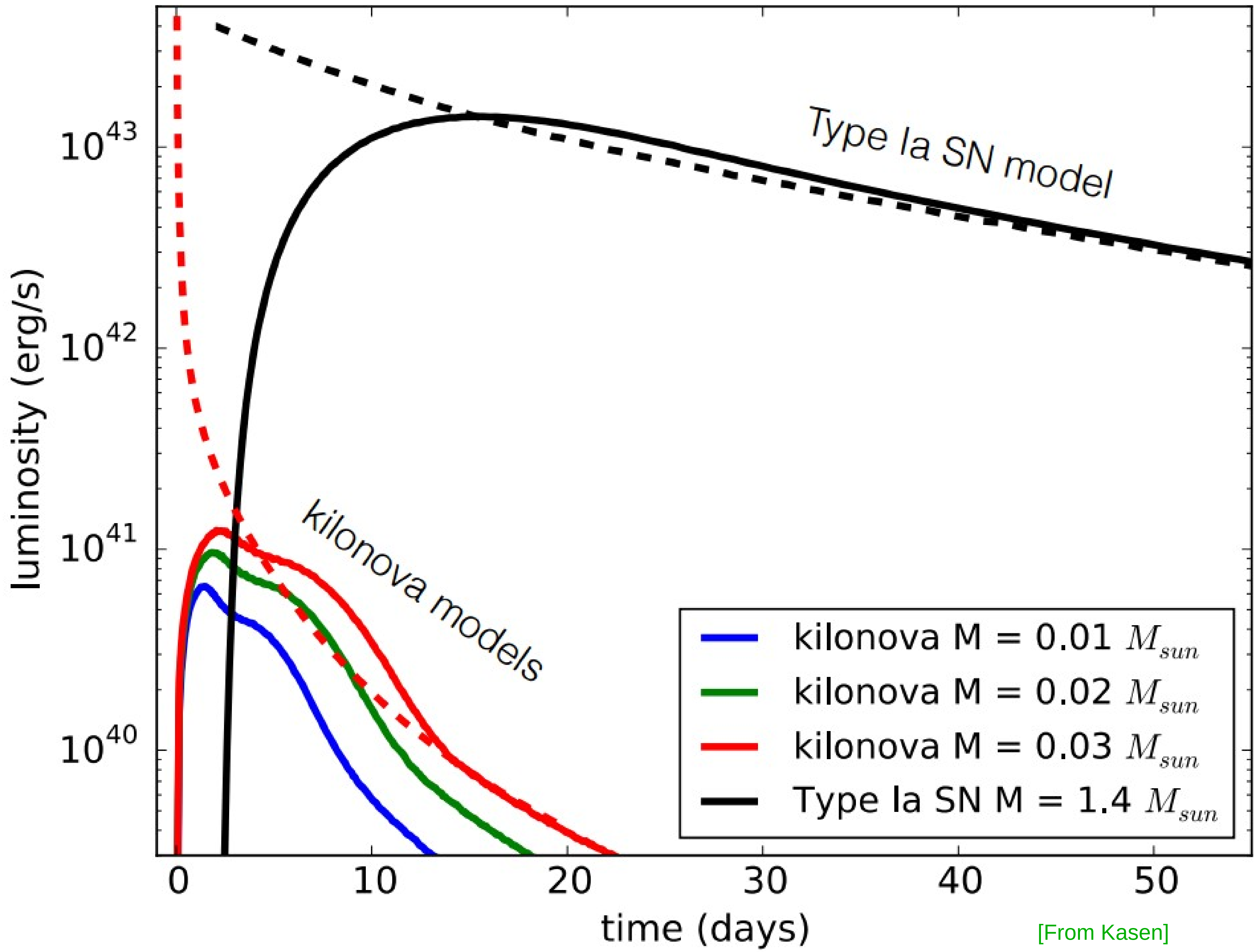
$$\rightarrow L(t_{\rm peak}) \sim \dot{\varepsilon}(t_{\rm peak}) \sim M\dot{Q}(t_{\rm peak}) \sim 2.0 \times 10^{41} {\rm erg/s} \times \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right) \times \left(\frac{t_{\rm peak}}{1 {\rm day}}\right)^{-1.3}$$

[Arnett's law]

$\dot{Q}$ is the radioactivity energy release rate $\approx 10^{10} \times (t/1{\rm day})^{-1.3}$ erg/s

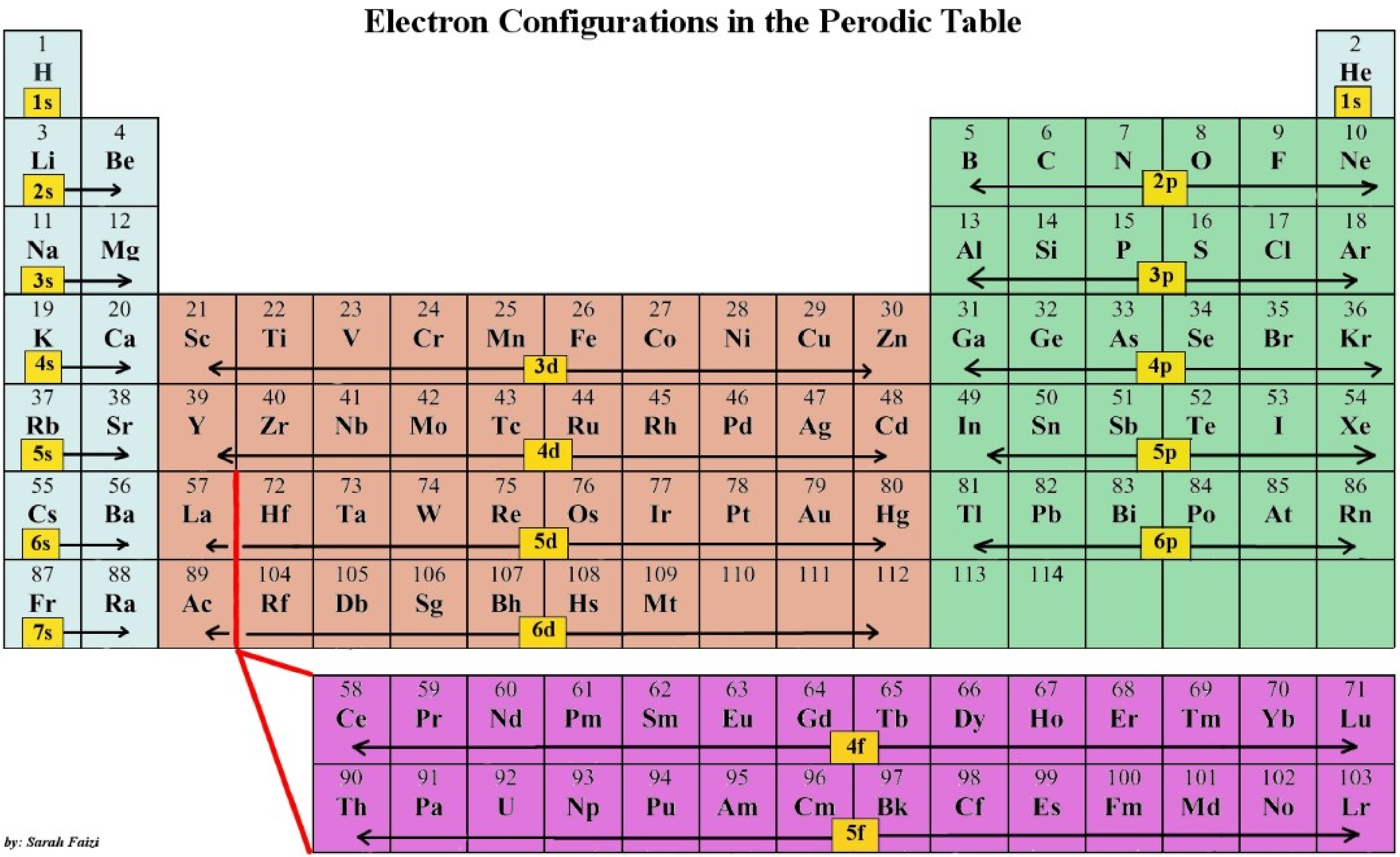




Type Ia SN model
kilonova models
kilonova M = 0.01 M_{sun}
kilonova M = 0.02 M_{sun}
kilonova M = 0.03 M_{sun}
Type Ia SN M = 1.4 M_{sun}
luminosity (erg/s)
10^{43}
10^{42}
10^{41}
10^{40}
0
10
20
30
40
50
time (days)

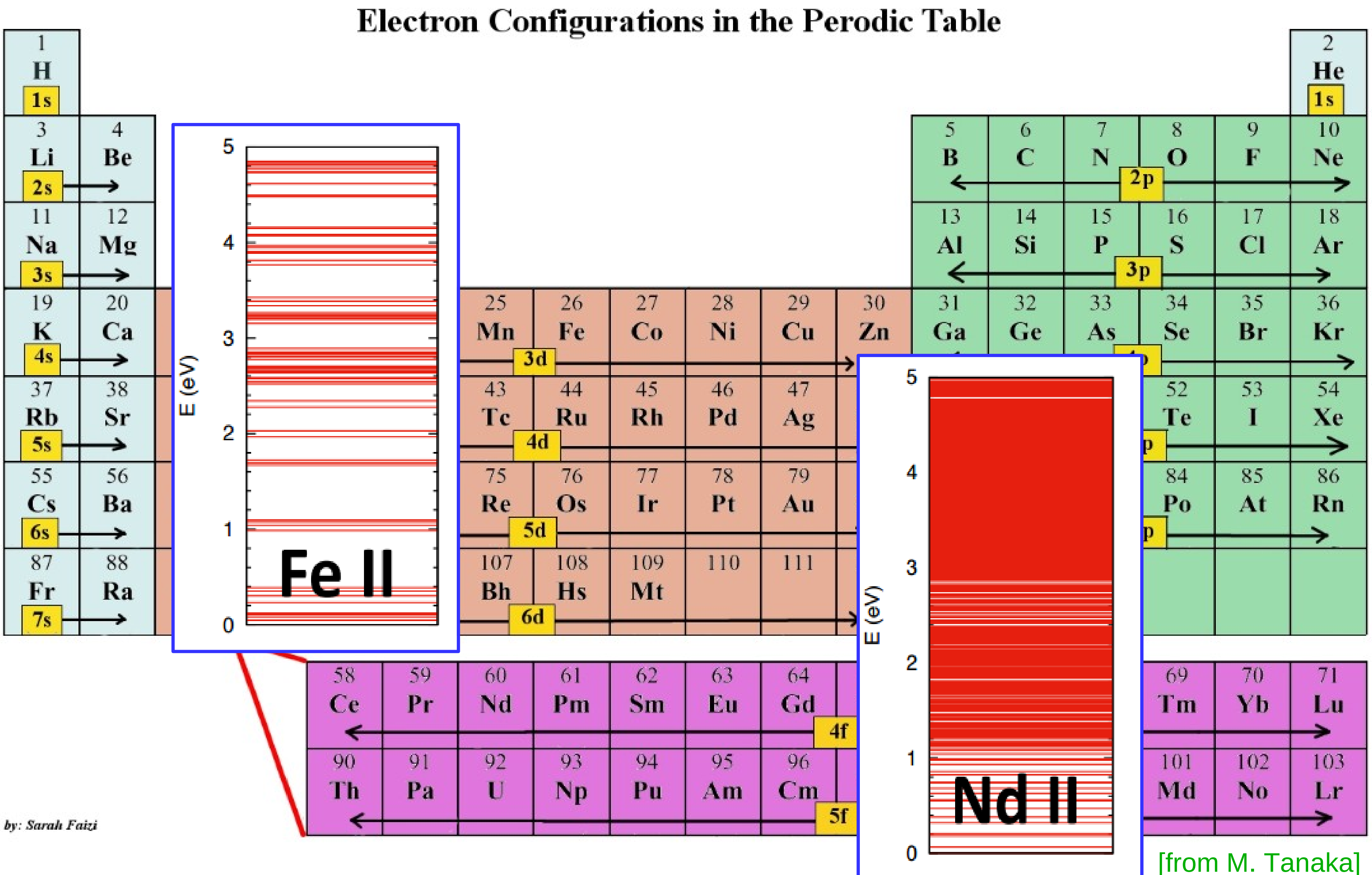
[From Kasen]

Opacity & Lanthanides



lanthanides and actinides contain elements with valence f-shell electrons
$\rightarrow$ richer level structure

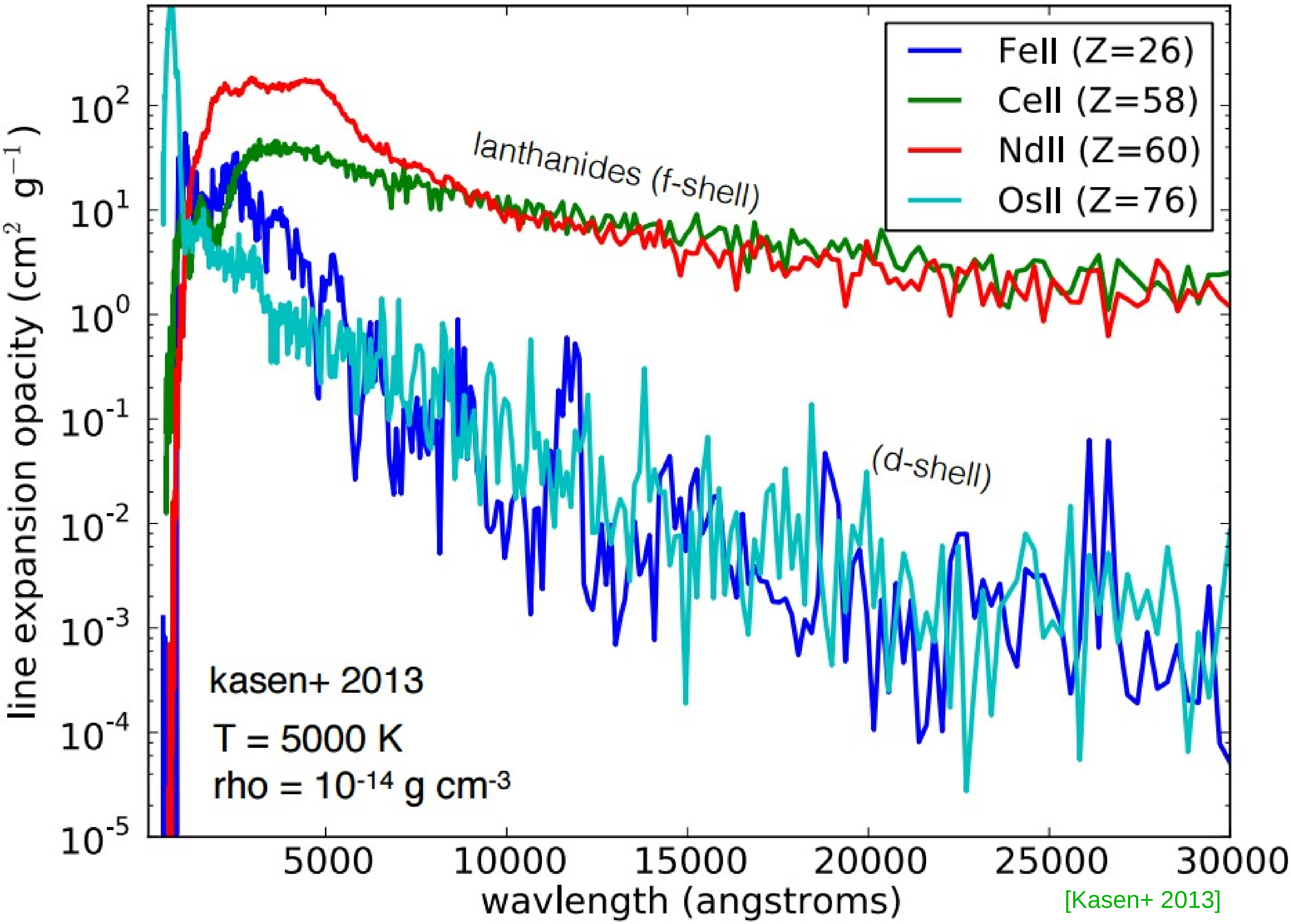
Opacity & Lanthanides



[from M. Tanaka]

lanthanides and actinides contain elements with valence f-shell electrons
$\rightarrow$ richer level structure

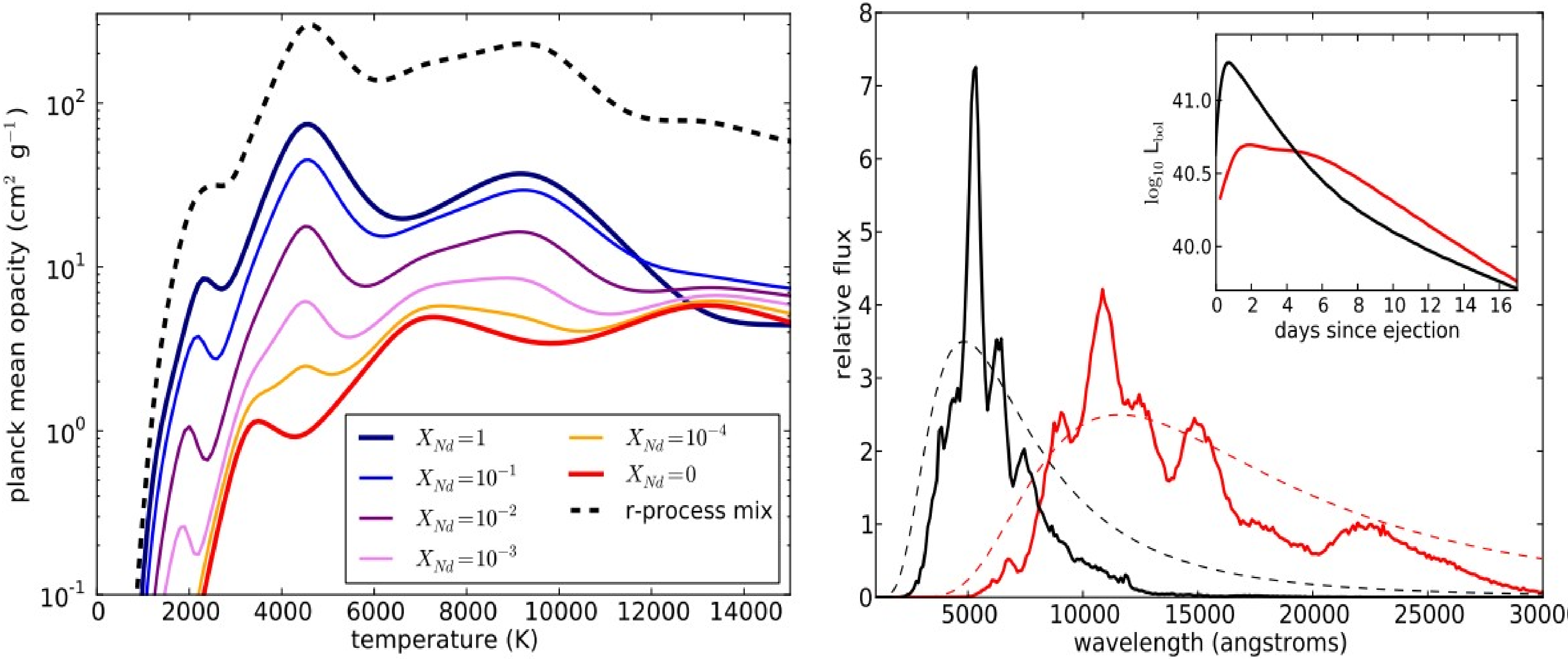
kilonova opacity from atomic structure modeling



[Kasen+ 2013]

Opacity & Lanthanides

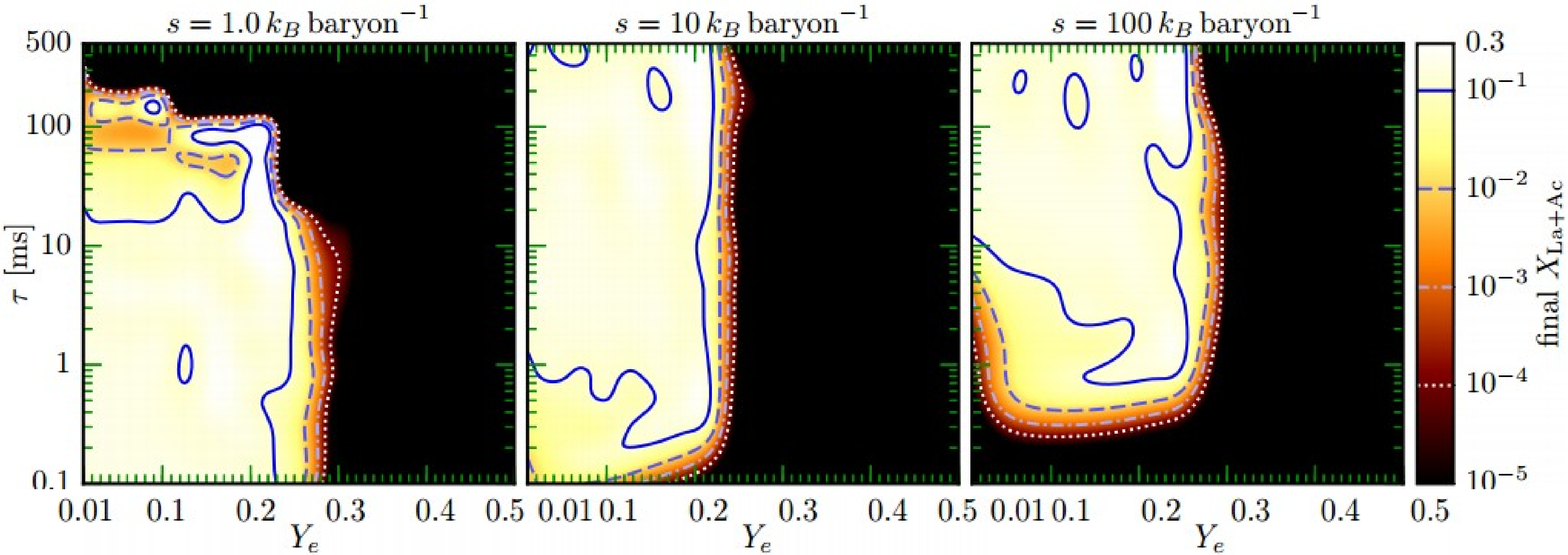
[Kasen+ 2013]



– the opacity with and without Lanthanides can differ by a factor of $\gtrsim 10$

Lanthanides turn-off

[Lippuner+ 2016]

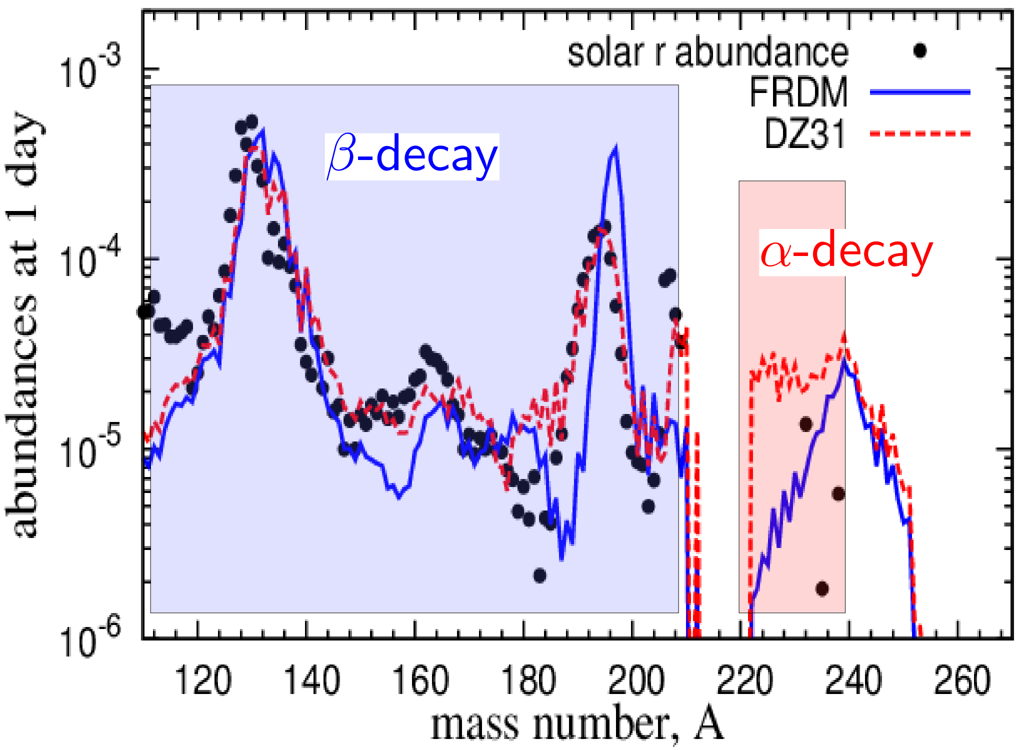


Litltle material with $Y_e \lesssim 0.25 \rightarrow$ lanthanide-poor, peaked early, blue-ish

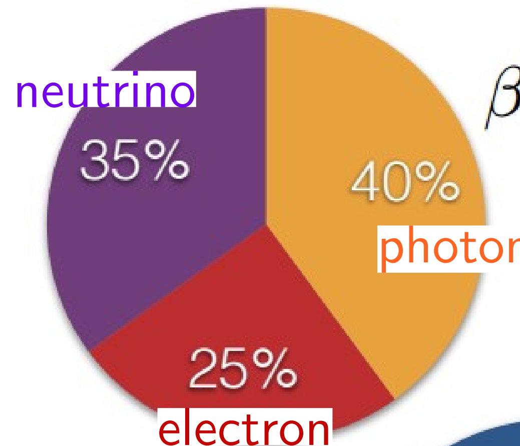
Large amount of material with $Y_e \lesssim 0.25 \rightarrow$ lanthanide rich, peaked late, red-ish

Particle thermalization

The radioactive decay energy only gets deposited into the medium when the decay products can be thermalized



Mendoza-Temis+ 2015, Barnes+ 2016



β-decay

$Q_\beta \sim 1$ MeV

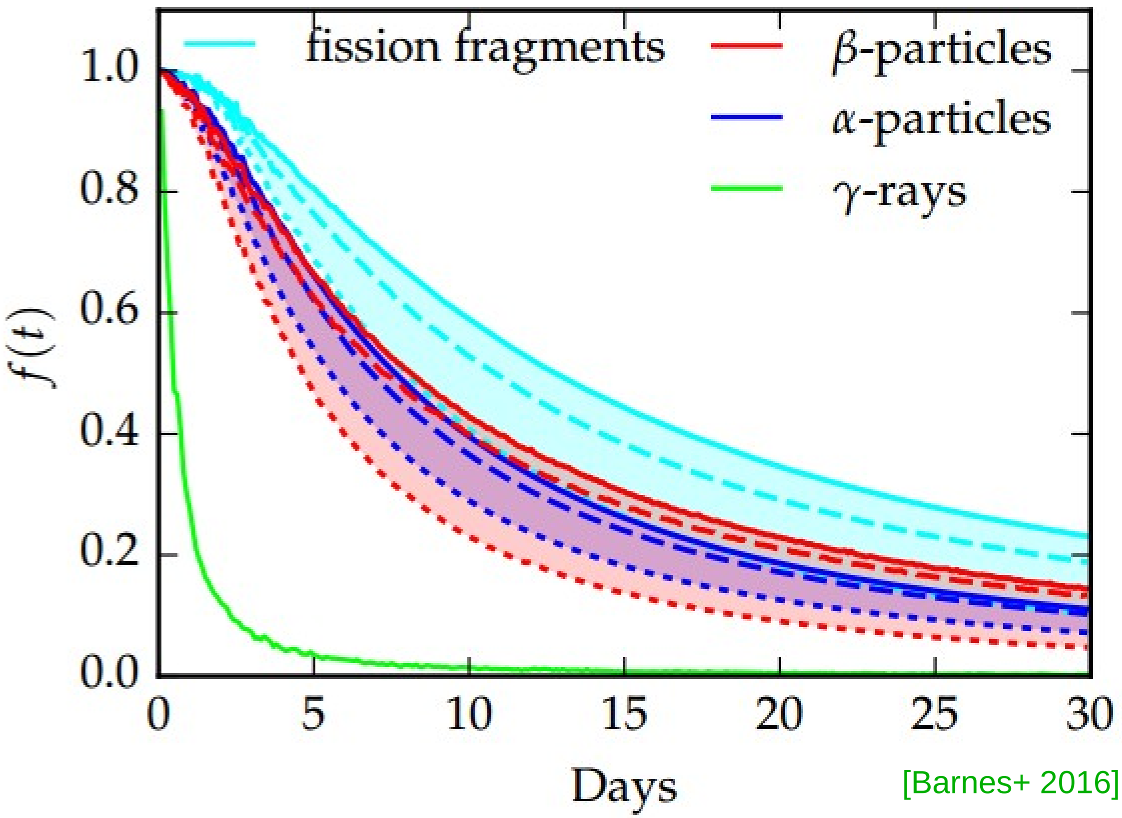
α -decay

$Q_\alpha \sim 6$ MeV

Particle thermalization

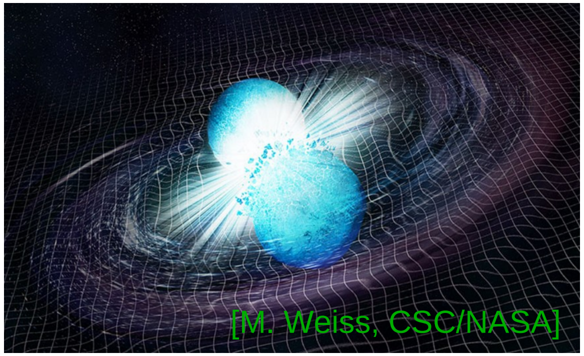
γ : photoionization and Compton scattering

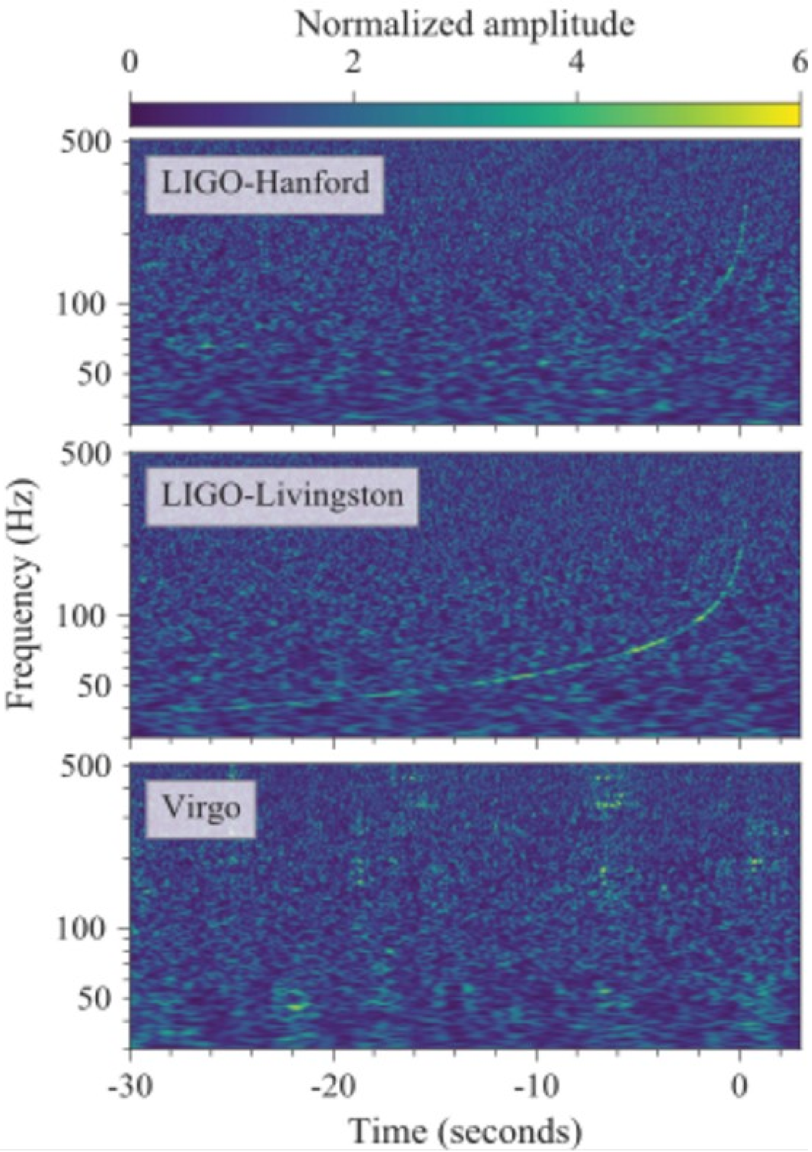
e^{-} & α: ionization & excitation



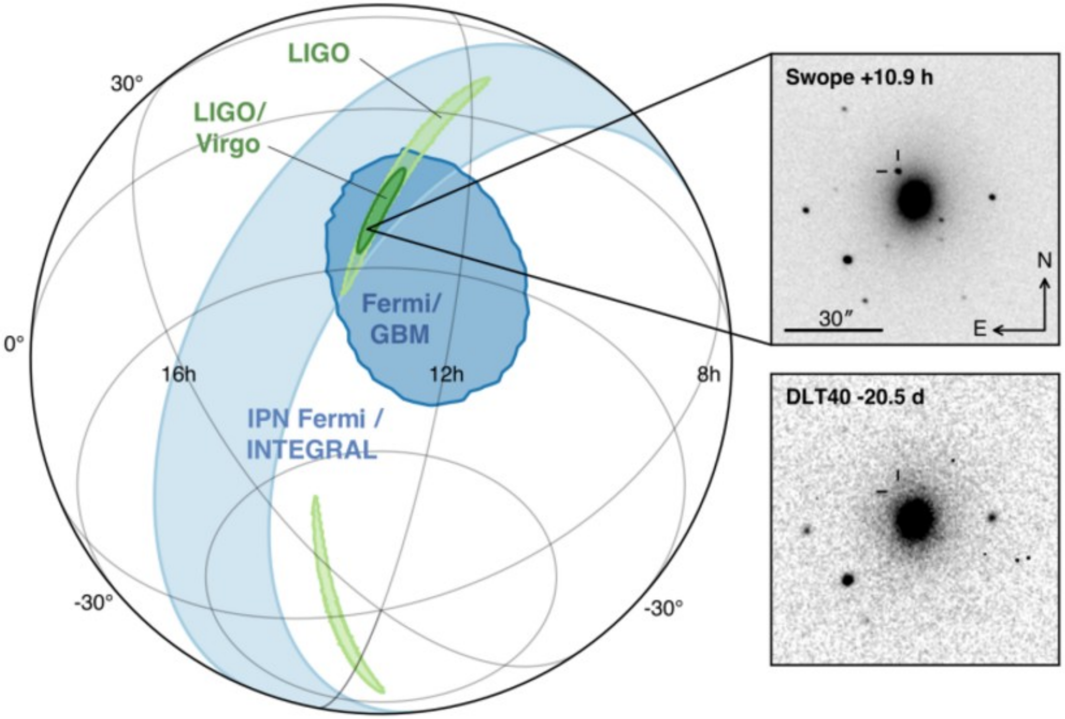
[Barnes+ 2016]

Multi-messenger observations of GW170817

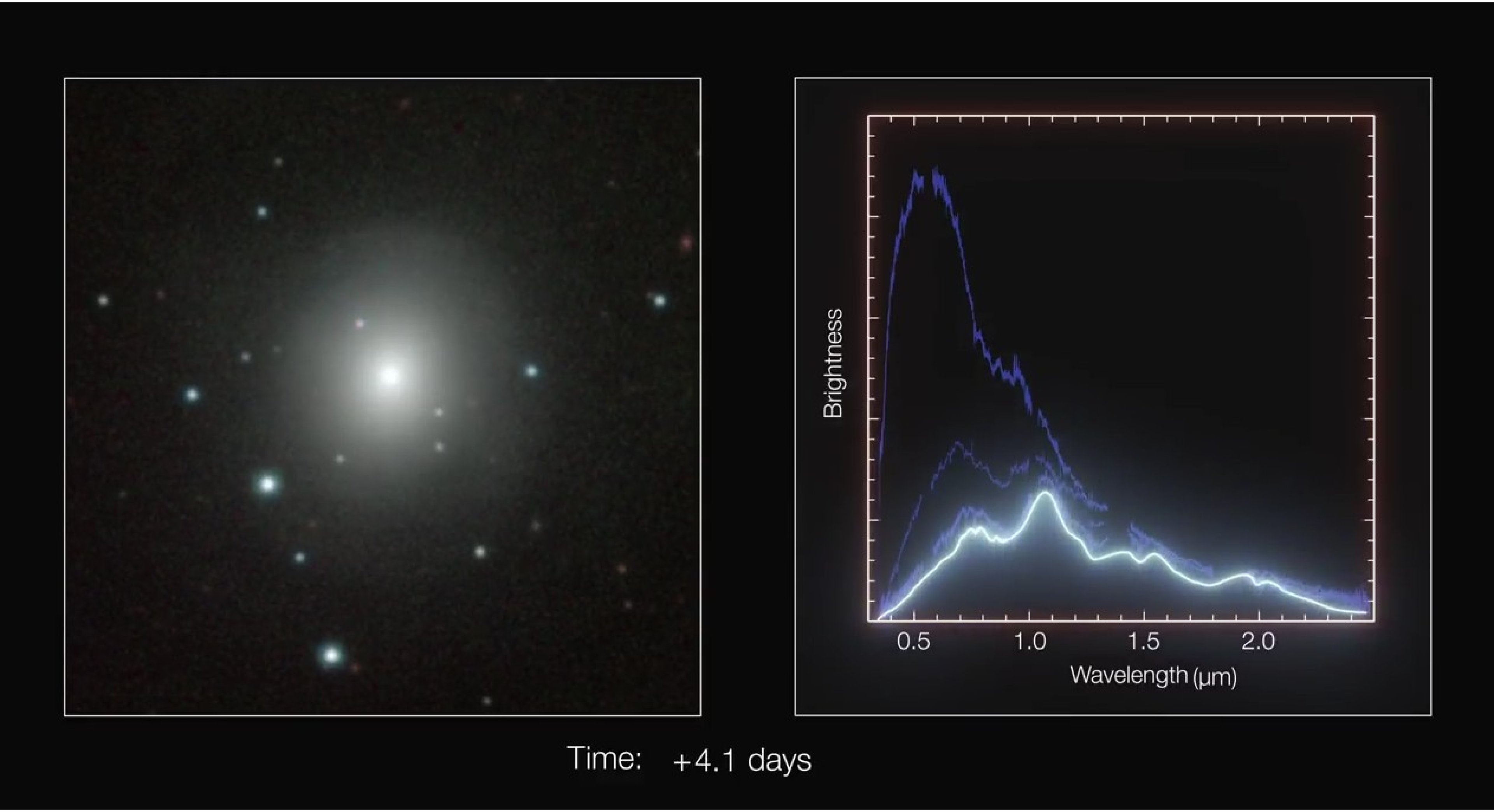




[from LIGO/Virgo]



Kilonova from GW170817: AT2017gfo



Cataclysmic Collision Artist's illustration of two merging ne
narrow beams show the bursts of gamma rays that are sh
depicted. The clouds glow with visible

Astronomers Confirm Origin of Universe's Heaviest Elements in Neutron Star Mergers

Oct 17, 2017 by News Staff / Source

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Origin of Universe's heavy elements, ranging from gold to uranium, has finally been confirmed, after a gravitational wave source was seen and heard for the first time ever by an international collaboration of astronomers and astrophysicists.

Home / Physics / General Physics

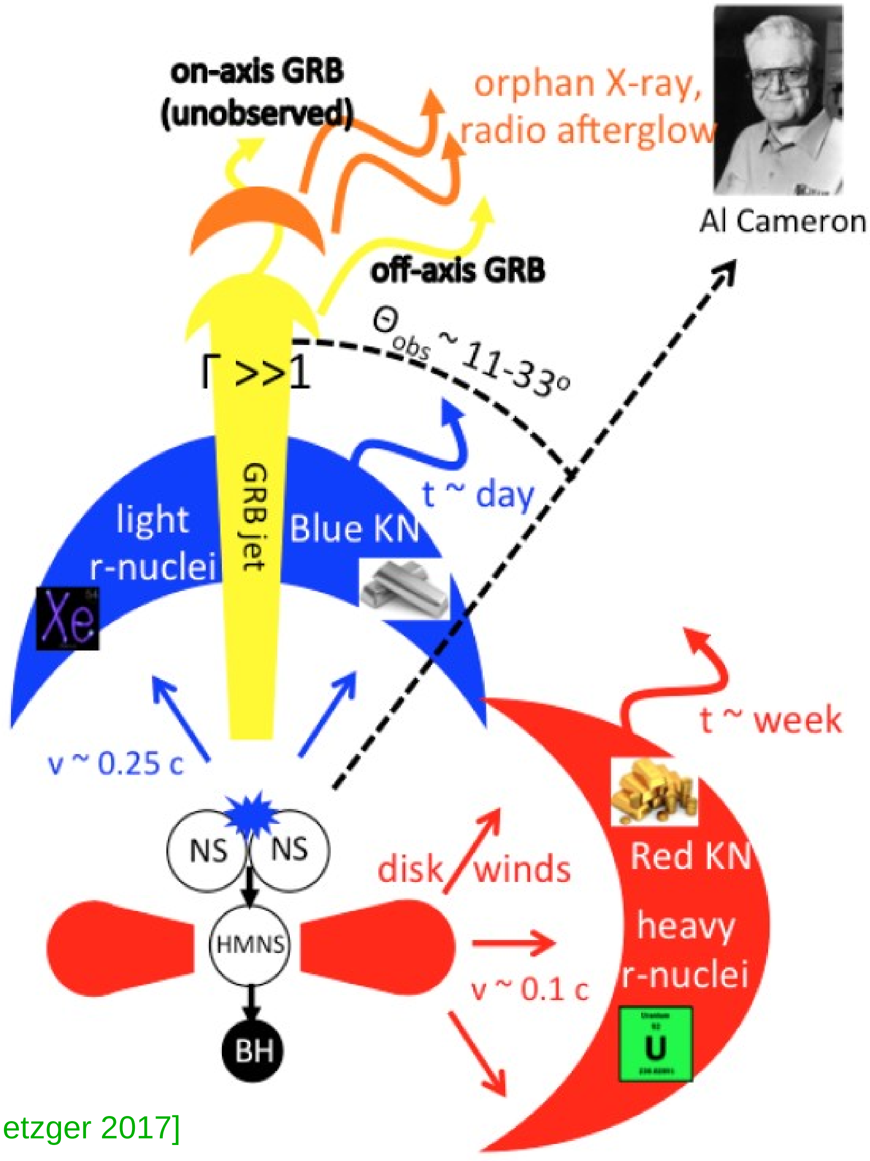
OCTOBER 16, 2017

Astronomers strike cosmic gold, confirm origin of precious metals in neutron star mergers

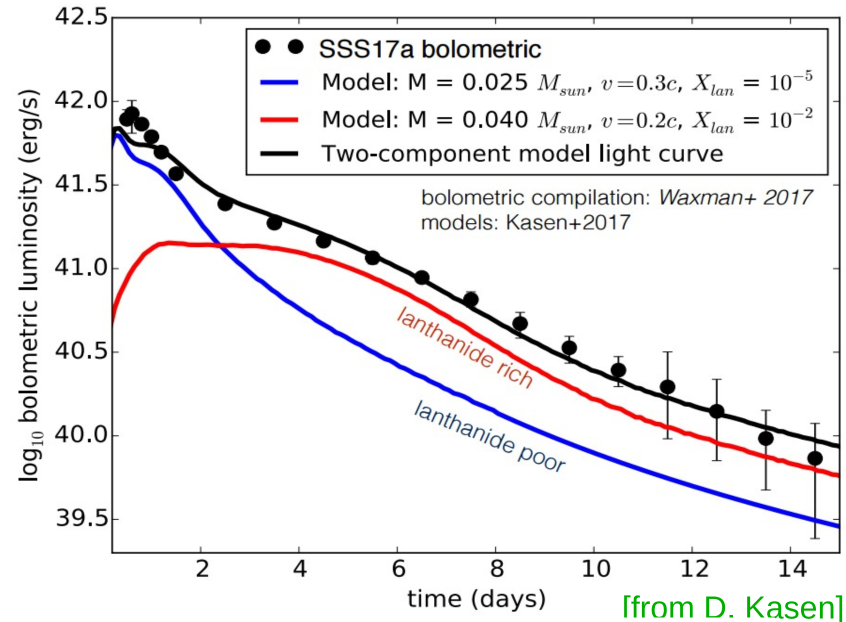
by University of California - Berkeley

Earlier intepretration of AT2017gfo

Most popular: two components: Kasen+2017, Tanaka+2017, Metzger+2017,...



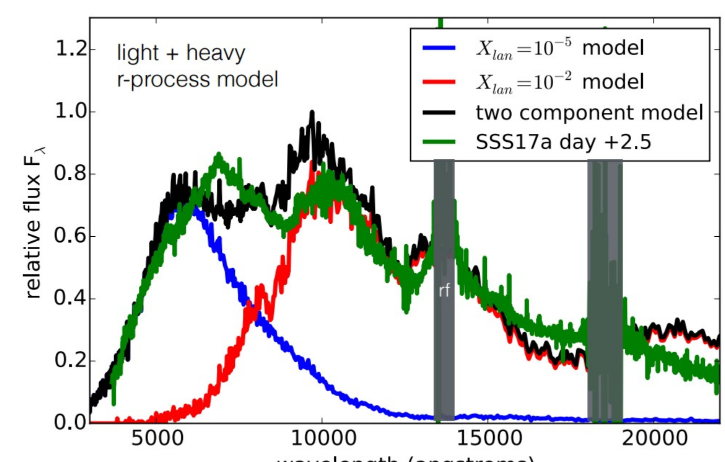
[Metzger 2017]



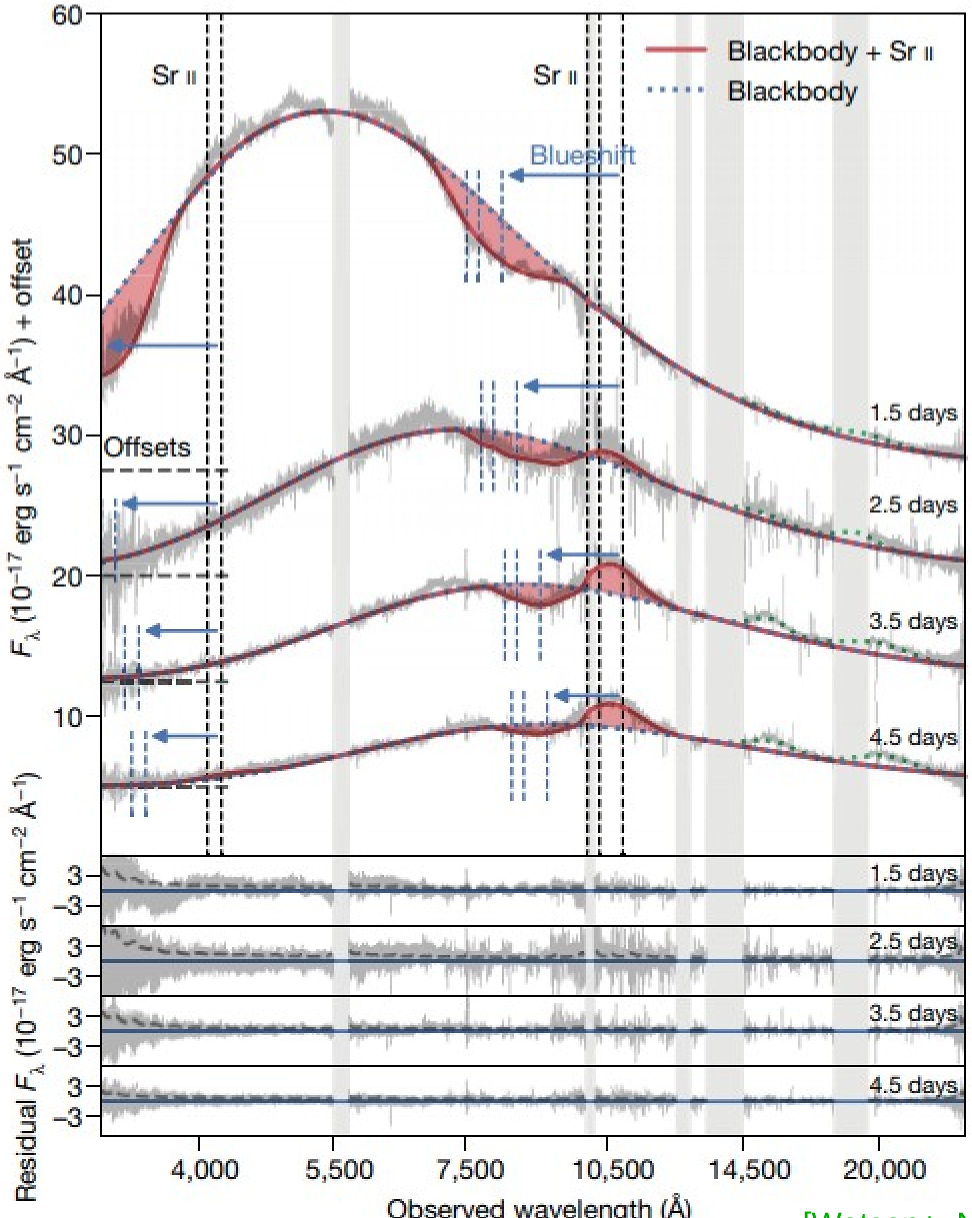
[from D. Kasen]

kilonova SSS17a spectrum @ day 2.5

data Pian+2017 x-shooter, models Kasen+2017



Identification of specific elements in GW170817?



$> 10^{-5}\ M_\odot$ of Sr?

$(Z = 38,\ A = 88)$

(see also Domoto+2103.15284
Gillanders+2202.01786
Perego+2209.08988
Tarumi+2302.13061)

Recently Domoto+2302.10928 suggests potential absorption feature of La and Ce.
Also, Hotokezaka+2307.00988 claims hints of Te emission line in the nebulae phase

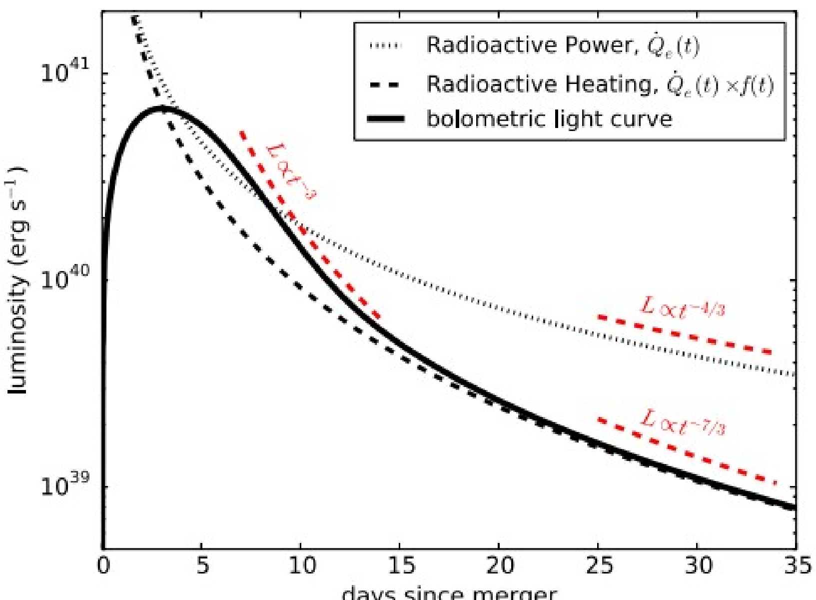
[Watson+, Nature 574 (2019) 497]

Impact of nuclear physics inputs on kilonova heating

Only until recently, we realize that this can be one major uncertainty in modeling the kilonova lightcurves

peak and post-peak light: $L_{\mathrm{bolometric}}(t) \sim \dot{Q}(t)$

$\rightarrow$ small amount of nuclei that can release relatively large amount of energy may dominate the kilonova lightcurve



[Kasen & Barnes 2018]

- fissioning nuclei (e.g., ^{254}Cf)
  [Zhu+2018, MRW+2019, Giuliani+2020]
- α-decay chains (e.g., ^{222}Rn, $^{223-225}$Ra)
  [Barnes+2016, Rosswog+2016, MRW+2019]
- β-decay chains (e.g., ^{66}Ni, ^{72}Zn)
  [Wanajo+2019, MRW+2019]

Californium-254 and kilonova

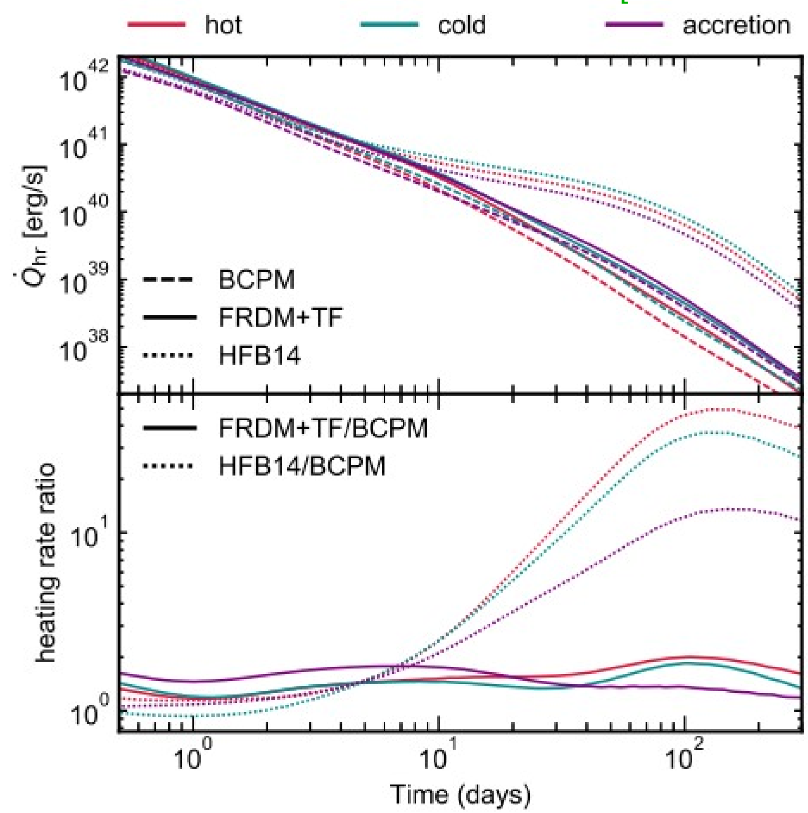
[Zhu+2018, MRW+2019, Giuliani+2020]

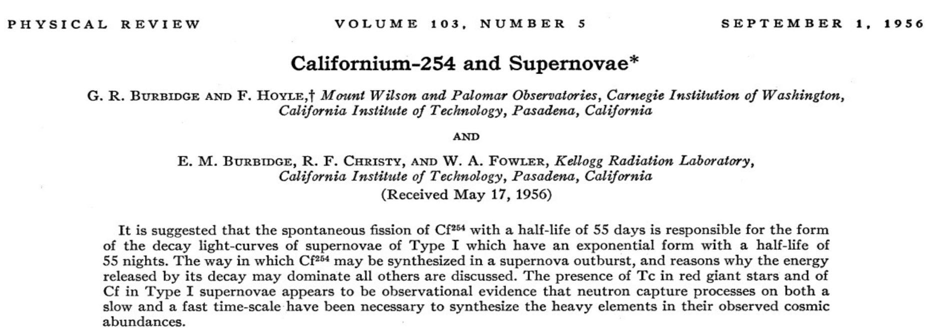
^{254}Cf is the only known nuclei that can fission spontaneously relevant for kilonova, with $\tau_{1/2} \simeq 60.5$ d and $\Delta E \simeq 180$ MeV per decay

A small abundance of $\gtrsim 10^{-6}$ can produce late-time heating that overpowers energy from other nuclear decays

The yield is sensitive to how one models fission. More precisely, the branching of fission channels along the $A = 254$ isobar

[Giuliani+2020]





PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

Californium-254 and Supernovae*

G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

AND

E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

It is suggested that the spontaneous fission of Cf^{254} with a half-life of 55 days is responsible for the form of the decay light-curves of supernovae of Type I which have an exponential form with a half-life of 55 nights. The way in which Cf^{254} may be synthesized in a supernova outburst, and reasons why the energy released by its decay may dominate all others are discussed. The presence of Tc in red giant stars and of Cf in Type I supernovae appears to be observational evidence that neutron capture processes on both a slow and a fast time-scale have been necessary to synthesize the heavy elements in their observed cosmic abundances.

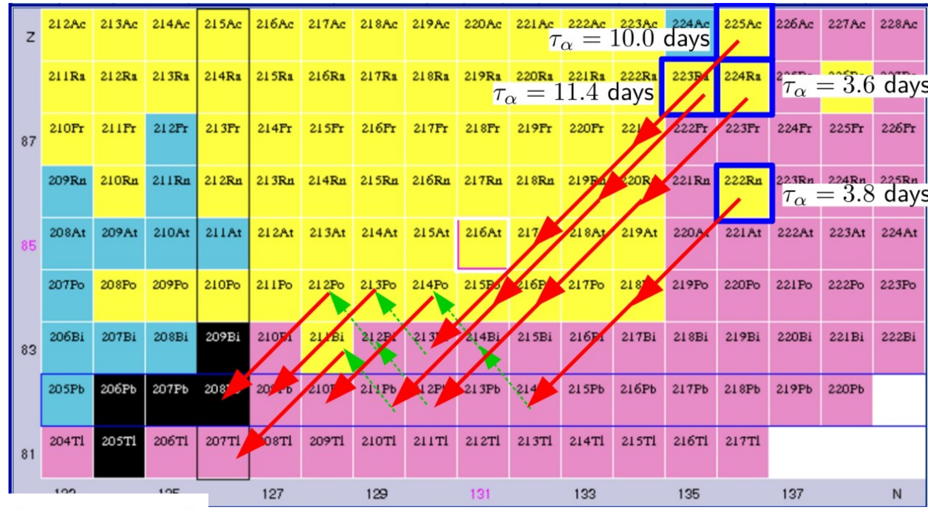
Burbidge+ tried to link ^{254}Cf to Type Ia supernovae back in 1956. Can this eventually be observed with kilonovae?

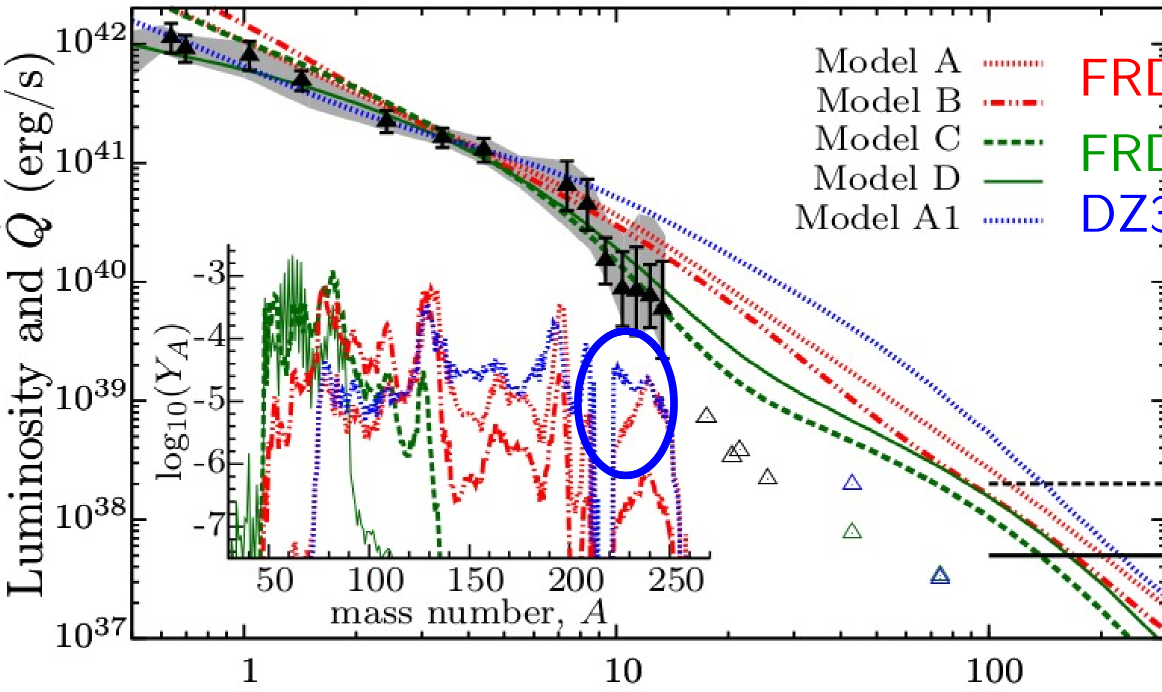
Alpha-decay actinides and kilonova

[Barnes+2016, Rosswog+2016, MRW+2019]

The α decay chains from ^{223}Ra and $^{223-225}$Rn, each of which has lifetimes of ~ 4 or 10 days, can also result in execessive heating at late time

$\Delta E_\alpha^{\rm eff} \sim 30$ MeV per decay chain





FRDM, low Y_e

FRDM, high Y_e

DZ31, low Y_e

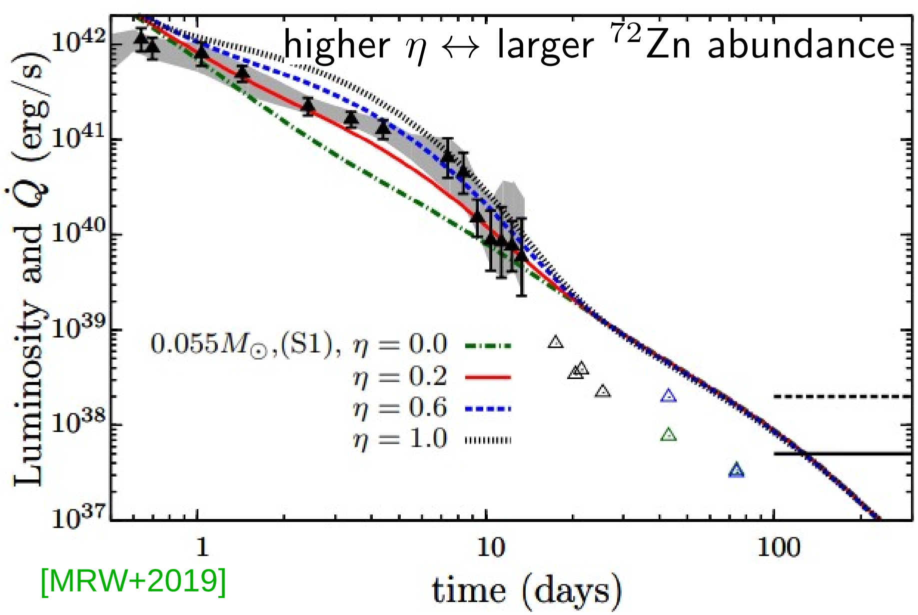
amount of these actinides can be sensitive to mass models or β rates

[MRW+2019]

Lighter elements powered kilonovae?

A couple β-decay sequences involve a longer-lived nucleus followed by a shorter-lived one:

- ${}^{66}\mathrm{Ni} \longrightarrow {}^{66}\mathrm{Cu} \longrightarrow {}^{66}\mathrm{Zn}$
- ${}^{72}\mathrm{Zn} \longrightarrow {}^{72}\mathrm{Ga} \longrightarrow {}^{72}\mathrm{Ge}$



[MRW+2019]

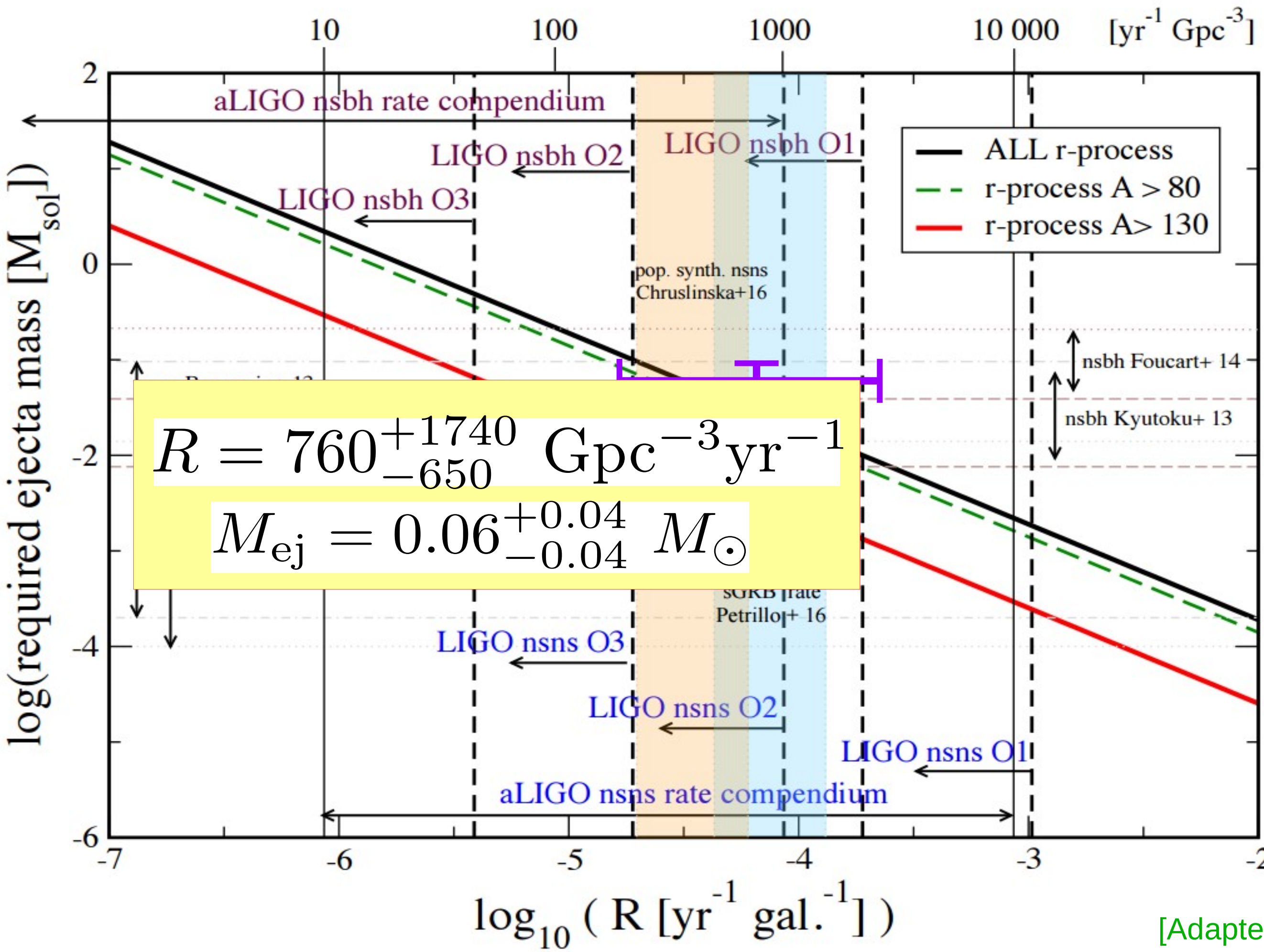
If merger ejecta contains lots of high $Y_e \gtrsim 0.3$ material, lightcurve may be dominated by these light nuclei at a few days

(see also Wanajo 2019)

NS mergers as the dominating source of the r-process?

Assuming the entire Galactic r-process elements are made in the same way:

$M_{r,\mathrm{tot}} \sim \tau_{\mathrm{MW}} \times R \times M_{\mathrm{ej}}$



$$R = 760^{+1740}_{-650}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

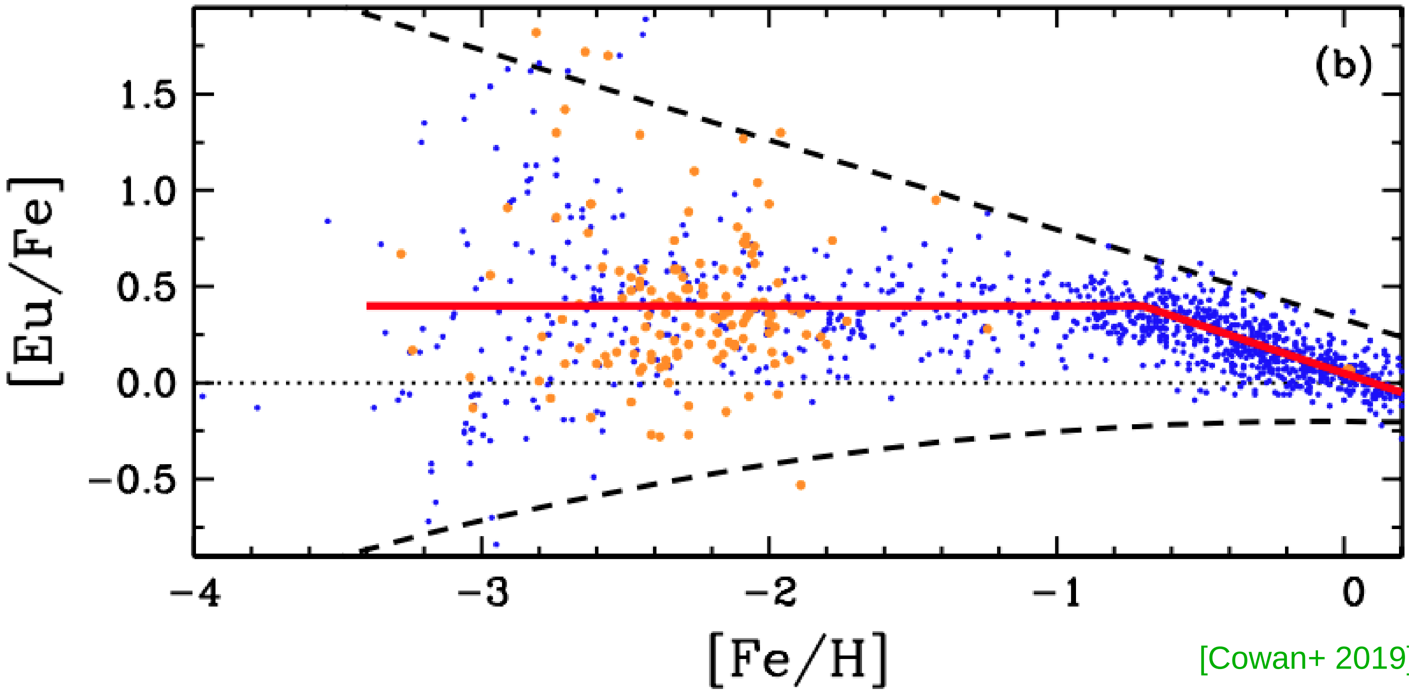
$$M_{\mathrm{ej}} = 0.06^{+0.04}_{-0.04}\ M_\odot$$

[Adapted from Rosswog+2017]

Do we need r-process sites beyond mergers?

$$[A/B] \equiv \log_{10}\left(\frac{n_A^*/n_B^*}{n_A^\odot/n_B^\odot}\right)$$

Observation of Eu abundance for stars with different metalicity



[Cowan+ 2019]

– r-process enrichment at low metalicity ([Fe/H]$\lesssim -3$)

$\rightarrow$ massive stars association?

– large scatters at low metalicity

$\rightarrow$ events less frequent than core-collapse supernovae?

A consistent model to trace the (chemical) evolution of the Milky Way is desired

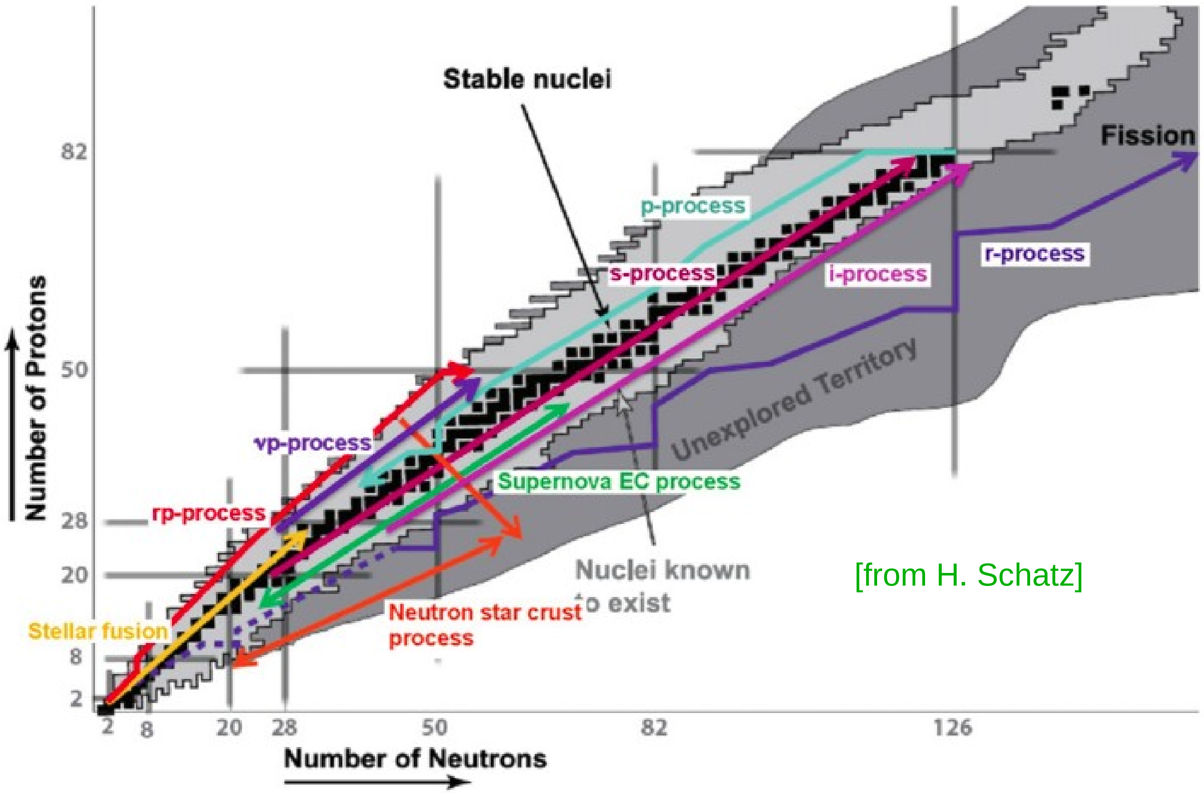
Summary (III)

- The r-process heating can power the observed kilonova emission. Early-time heating is dominated by β-decay of many r-process nuclei, while the late-time heating may be influenced by fission or α-decay of a few trans-lead nuclei.
- Existence of non-negligible amount of lanthanides makes red-ish kilonova that provides the evidence of the r-process in GW170817. Investigation for signatures due specific elements were made and hints were found.
- GW170817 overall strongly supports that BNS mergers being the dominant sources of the r-process. Whether we need additional sources to explain the r-process enrichment in early galaxies is still under debate.

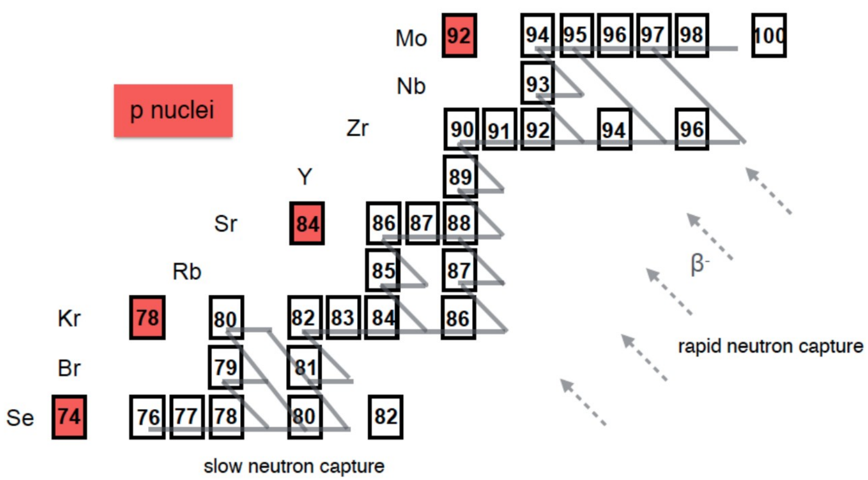
– Other processes for other heavy elements?

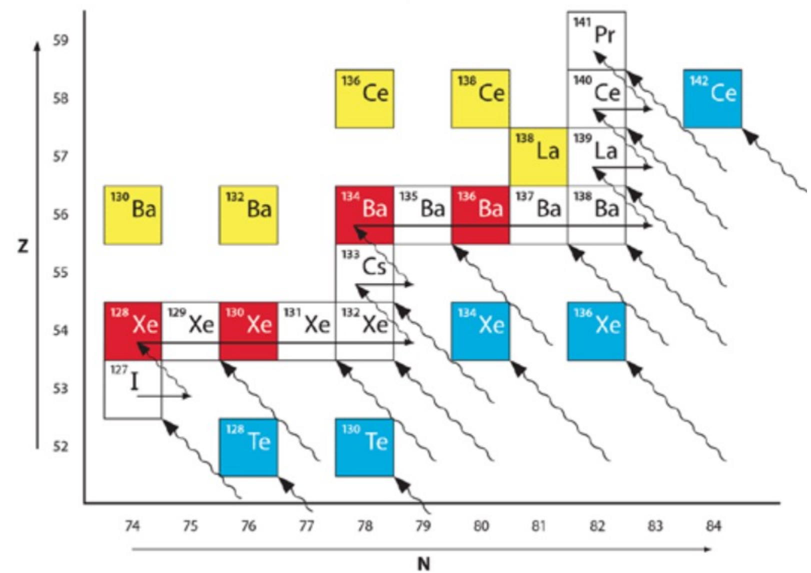
certain nuclei need processes other than s- and r-process

$\rightarrow$ supernovae?



[from H. Schatz]

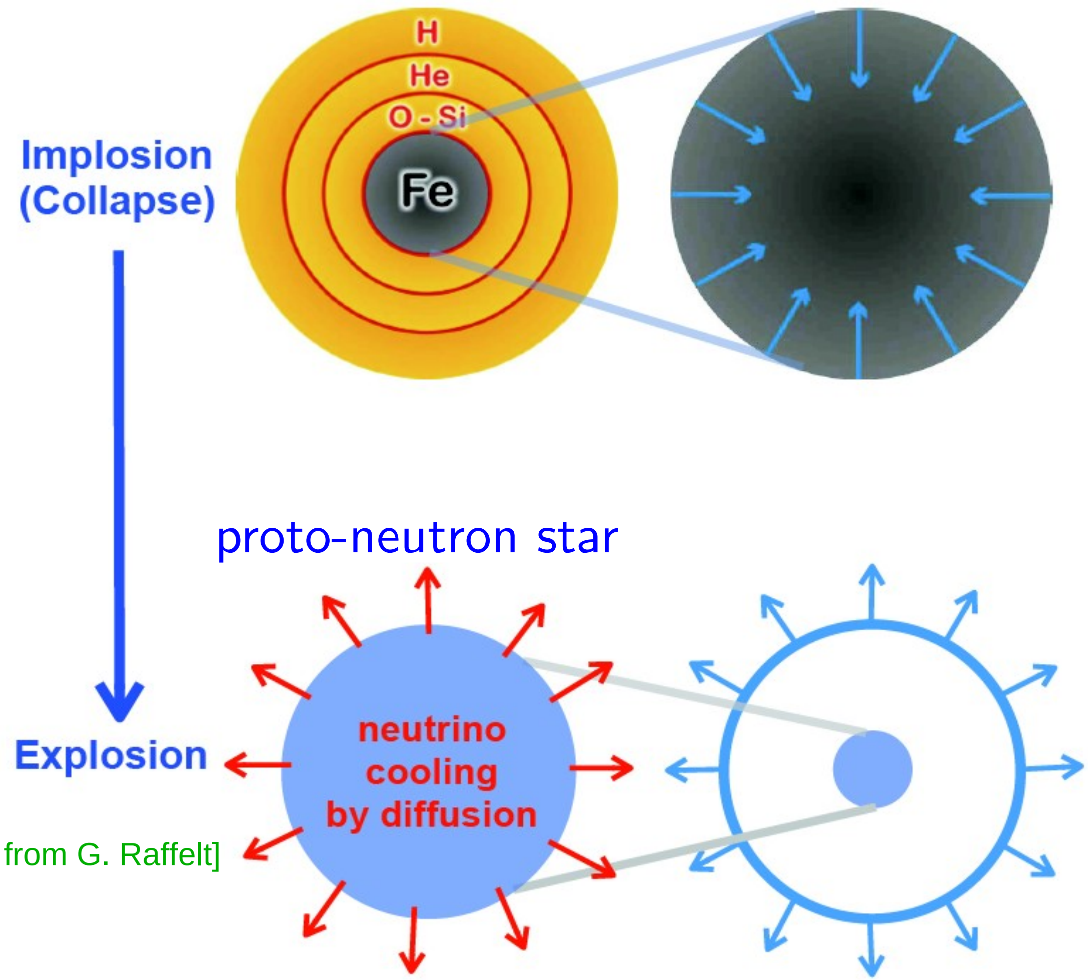




[From Lederer]

Core-collapse supernovae

progenitor star



[Figure from G. Raffelt]

$M_{\rm Fe,core} \approx 1.4 M_\odot$

$R_{\rm Fe,core} \approx 3000$ km

$\rho_c \approx 10^9$ g cm^{-3}

$T_c \approx 10^{10}$ K~ 1 MeV

$M_{\rm PNS} \approx 1.4 M_\odot$

$R_{\rm PNS} \approx 15$–50 km

$\rho_c \approx 3 \times 10^{14}$ g cm^{-3}

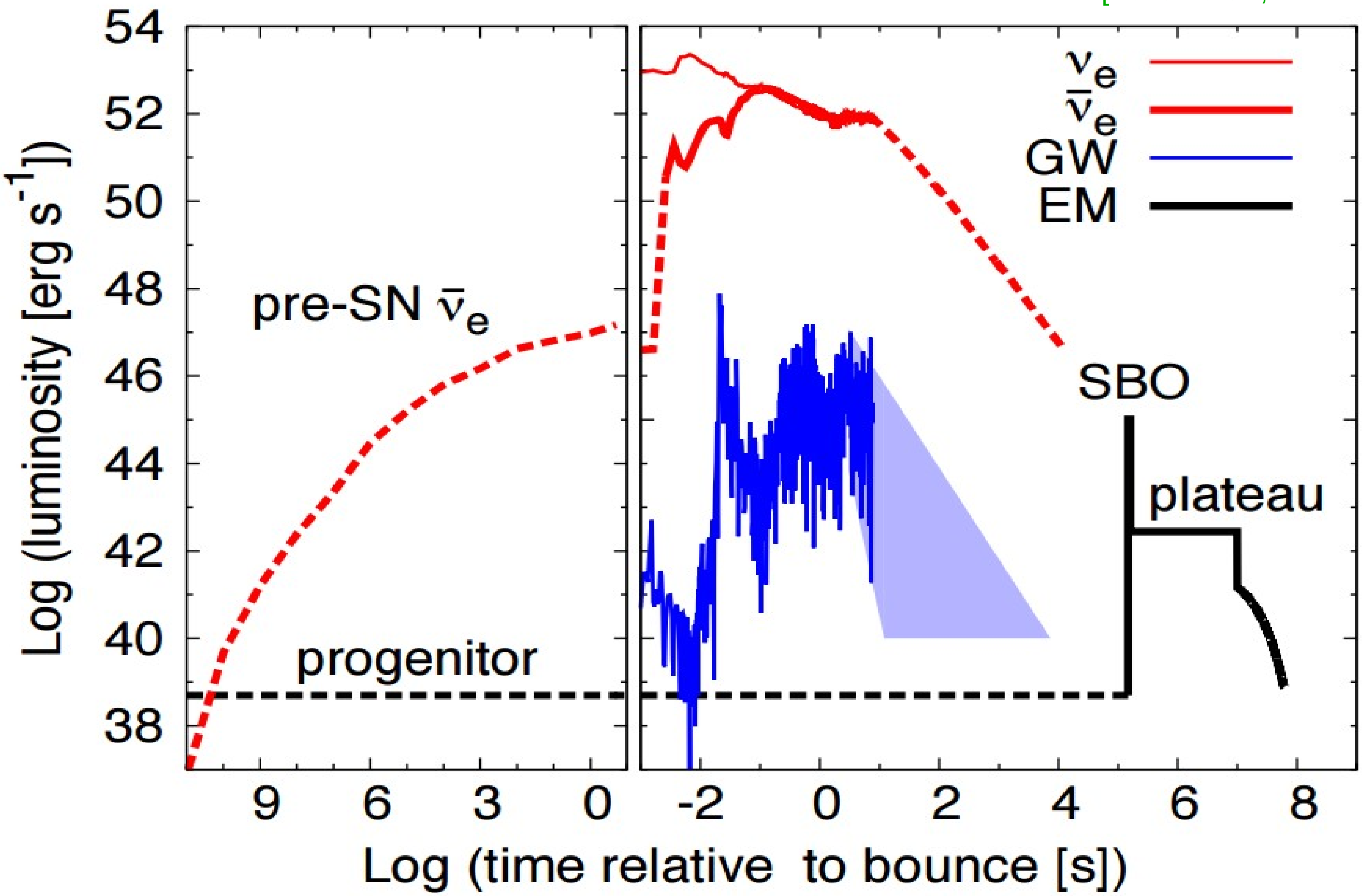
$T_c \approx 30$ MeV

$E_{\rm grav} \sim \frac{G M_{\rm PNS}^2}{R_{\rm PNS}} \sim 10^{53}$ erg, nearly all being converted to neutrinos

Multi-messengers from core-collapse supernovae

energy release:
$E_\gamma \sim 10^{49}$ erg, $E_{GW} \sim 10^{46}$ erg, $E_{\mathrm{kinetic}} \sim 10^{51}$ erg, $E_\nu \sim 10^{53}$ erg.

[Nakamura+, MNRAS 461, 3 (2016)]



(c.f. $L_\odot \approx 4 \times 10^{33} \mathrm{erg\ s^{-1}}$)

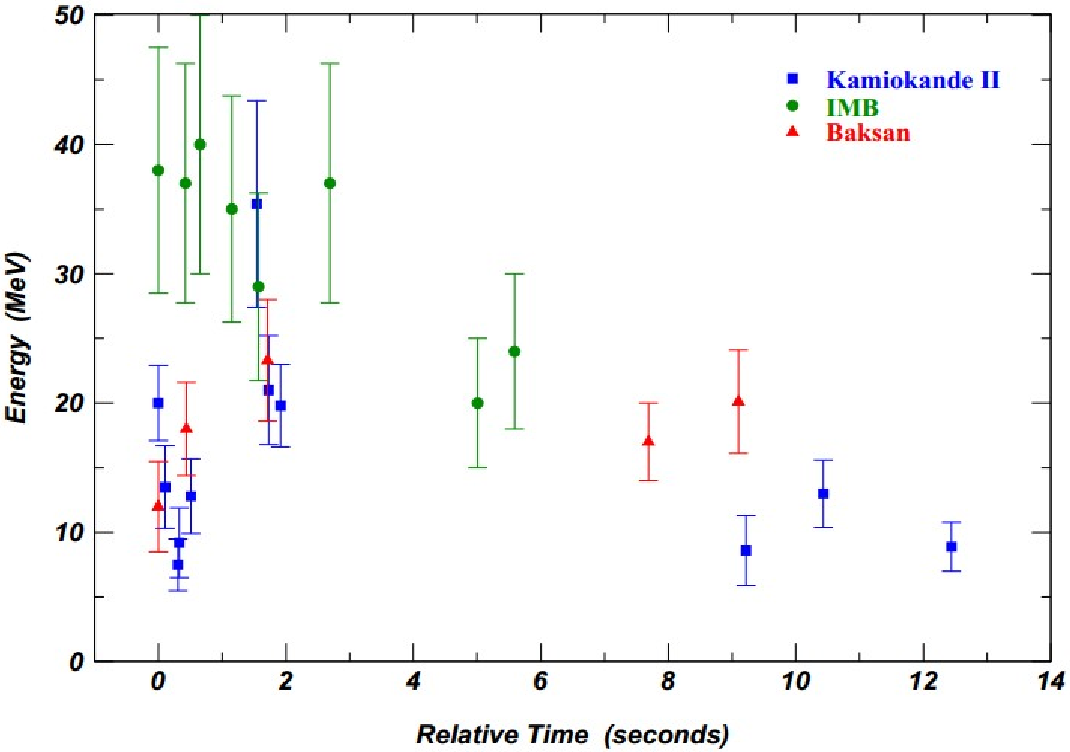
Neutrinos from SN 1987A

~ 20 SN $\bar{\nu}_e$ detected from SN1987a in ~ 10 seconds,

$L_{\bar{\nu}_e} \sim 10^{52}$ erg, $\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV

The Tarantula Nebula and supernova 1987a in the LMC (~50 kpc)

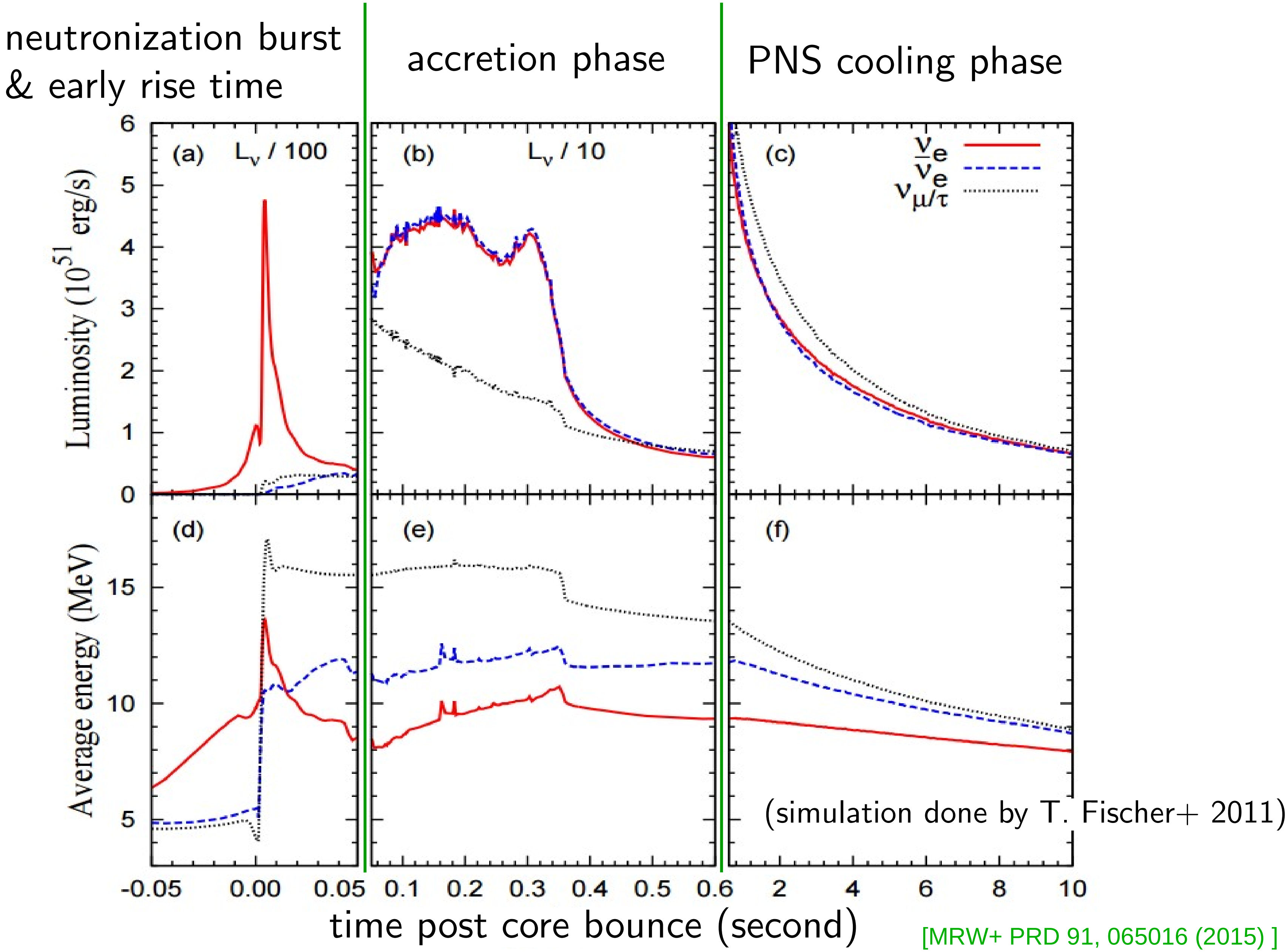
(From AAO website)



[J. Heise PhD Thesis (2002)]

We may see thousands of neutrino events in ALL FLAVORS when the next Galactic SN goes off!

General feature of supernova neutrino emission



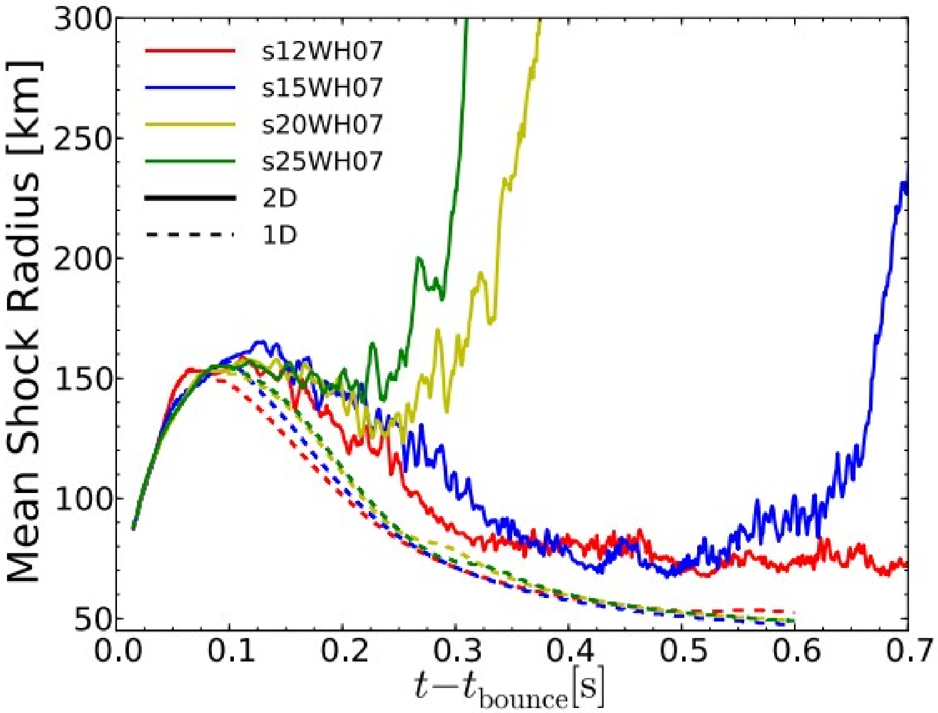
[MRW+ PRD 91, 065016 (2015)]

Accretion phase: turning the implosion to explosion

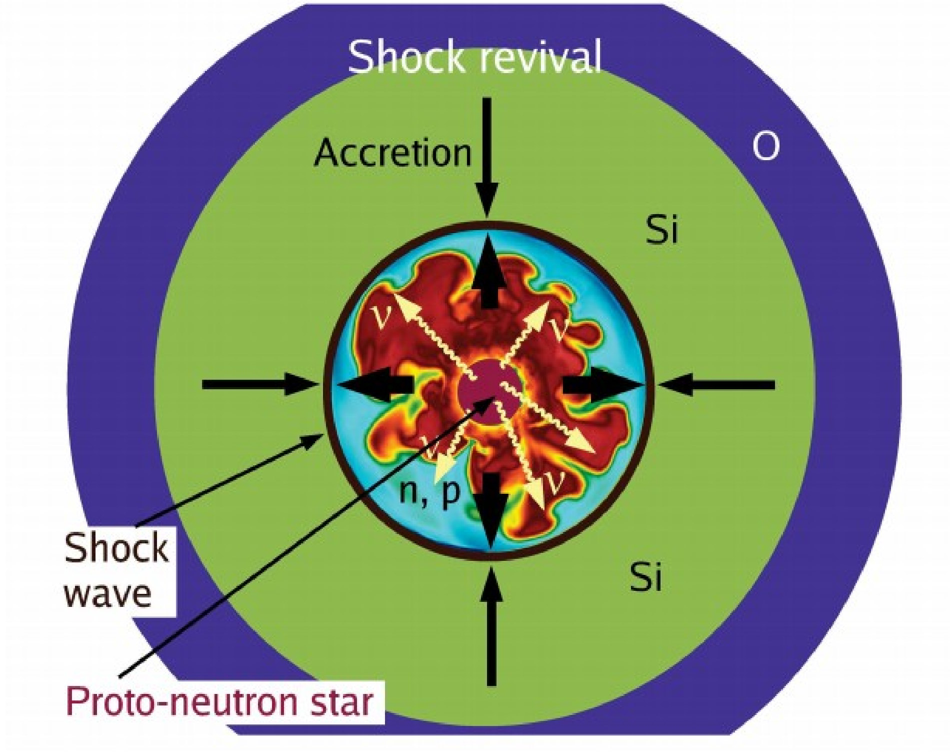
– The shock wave loses its energy and stalls by disintegrating irons into nucleons

– Neutrinos radiating from the PNS can deposit a few percent of the energy to re-start the shock, aided by small scale convections and/or large scale shock oscillations

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



[E. O'connor, S. Couch, ApJ 854, 63 (2018)]



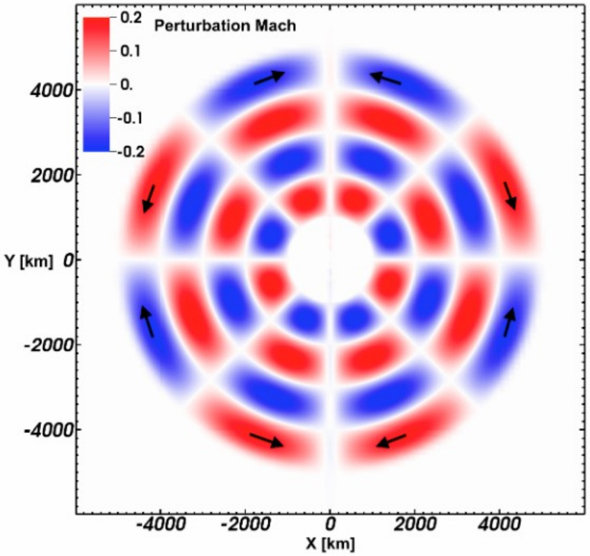
[Janka+, PTEP 01A309, 2012]

Fore-front issues in supernova theory

State-of-the-art multi-D simulations have not yet reached consistent outcome in terms of the explosions. Several factors or issues still need to be improved or resolved.

Numerical/astrophysical side:

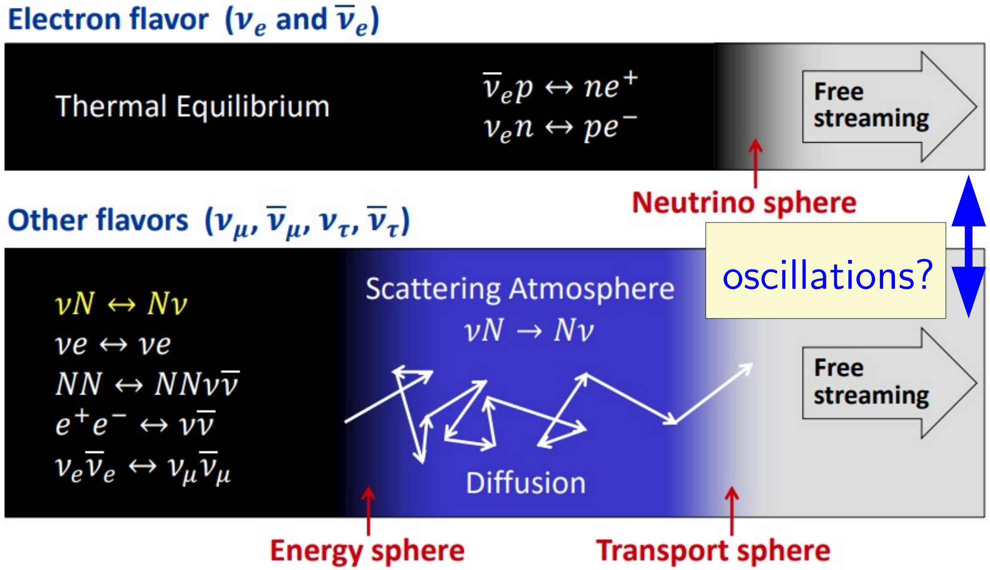
- numerical convergence in full 7D
- pre-supernova progenitor model
  [e.g., Couch+, Mueller+, Burrows+...]
- proto-neutron star composition
  [e.g., Bollig+ 2017, Fore+ 2019]



[Couch+ 2012]

Microphysics side:

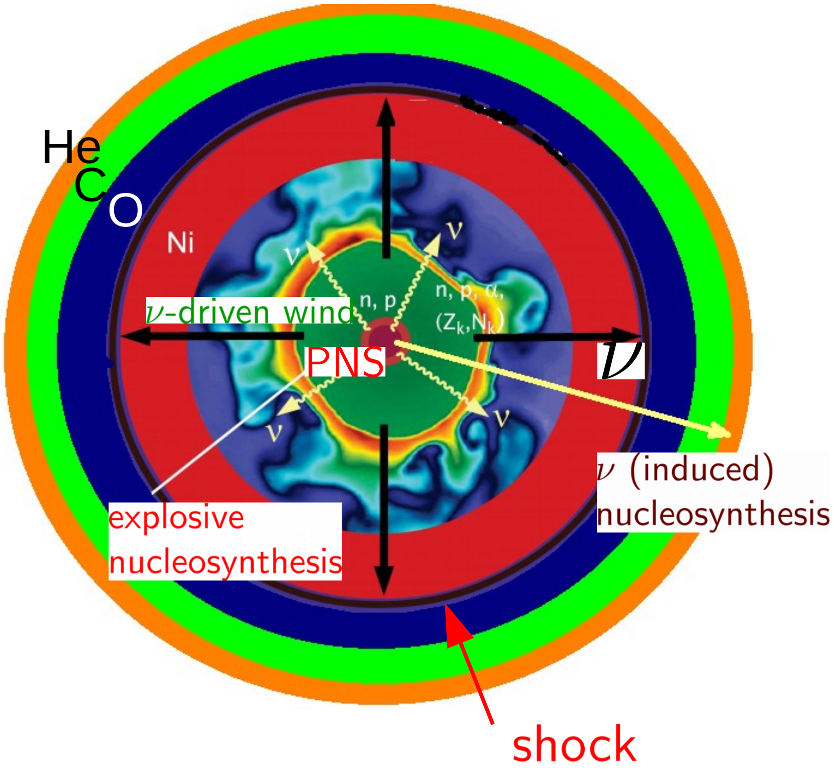
- neutrino nuclear matter interaction
  [Horowitz+, Reddy+, Roberts+, Martinez-Pinedo+,...]
- neutrino flavor oscillations
  [Raffelt+, Mirizzi+, Tamborra+, Duan+, Volpe+,...]



[Janka 1702.08713, Raffelt 2012]

Nucleosynthesis in supernovae

[Modified from Janka+, PTEP 01A309, 2012]



Major different nucleosynthesis sites:

- explosive nucleosynthesis

  post-shock high-tempterature in shocked inner envelopes

- ν (induced) nucleosynthesis

  seed nuclei in outer shells influenced by neutrinos

- ν-driven wind

  innermost ejecta launched from the surface of the proto-neutron star

Solving the nucleosynthesis yields in each of these sites require dynamic calculation of a nuclear reaction network (supplied with the evolution of hydrodynamic variables)

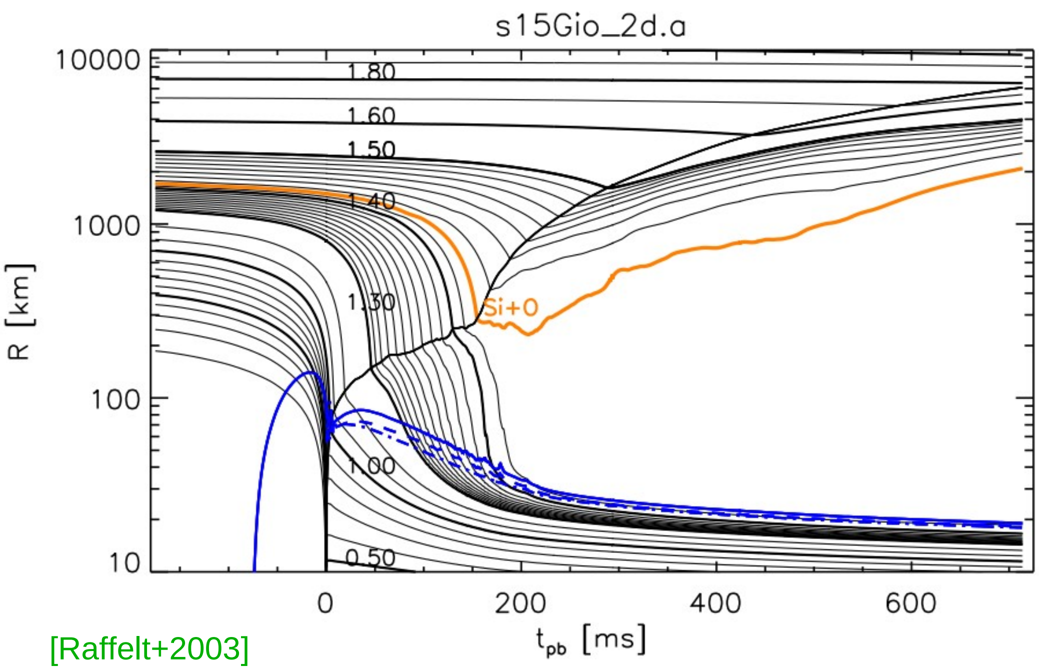
Shock heating and nucleosynthesis

The SN shock not only expel the overlying envelop, but also heat up some regions enough to reshape the composition of nuclear species

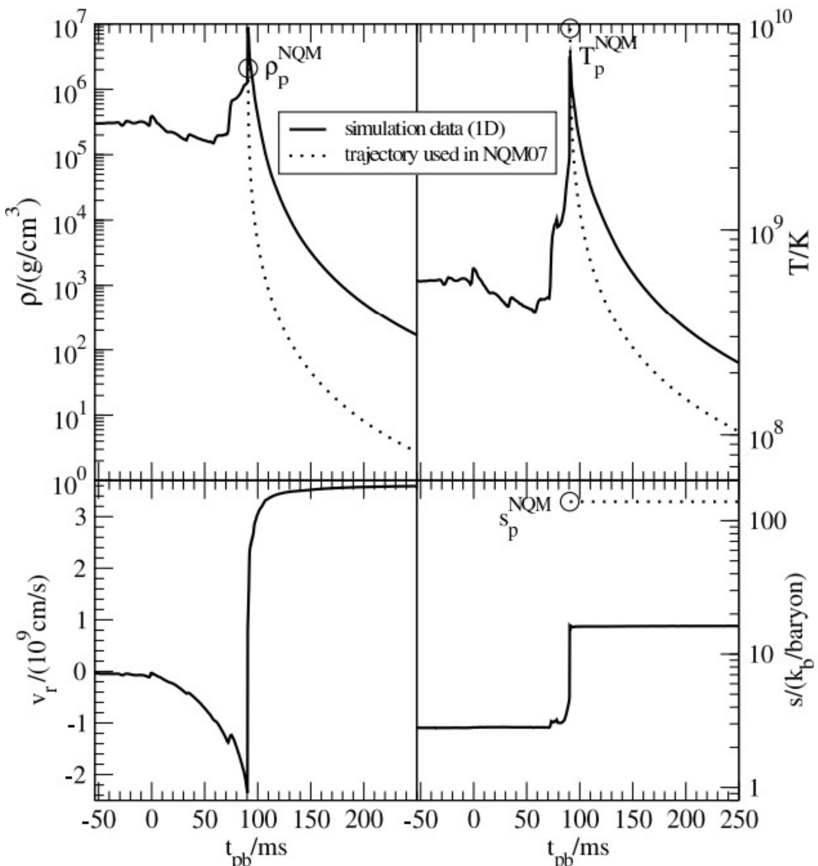
The post-shock peak temperature (T_s) for a mass shell goes roughtly

$$E_{\rm expl} \sim \frac{4\pi}{3} r^3 \cdot a \cdot T_s^4$$

[Janka+ 2007]



[Raffelt+2003]



Shock heating and nucleosynthesis

The SN shock not only expel the overlying envelop, but also heat up some regions enough to reshape the composition of nuclear species

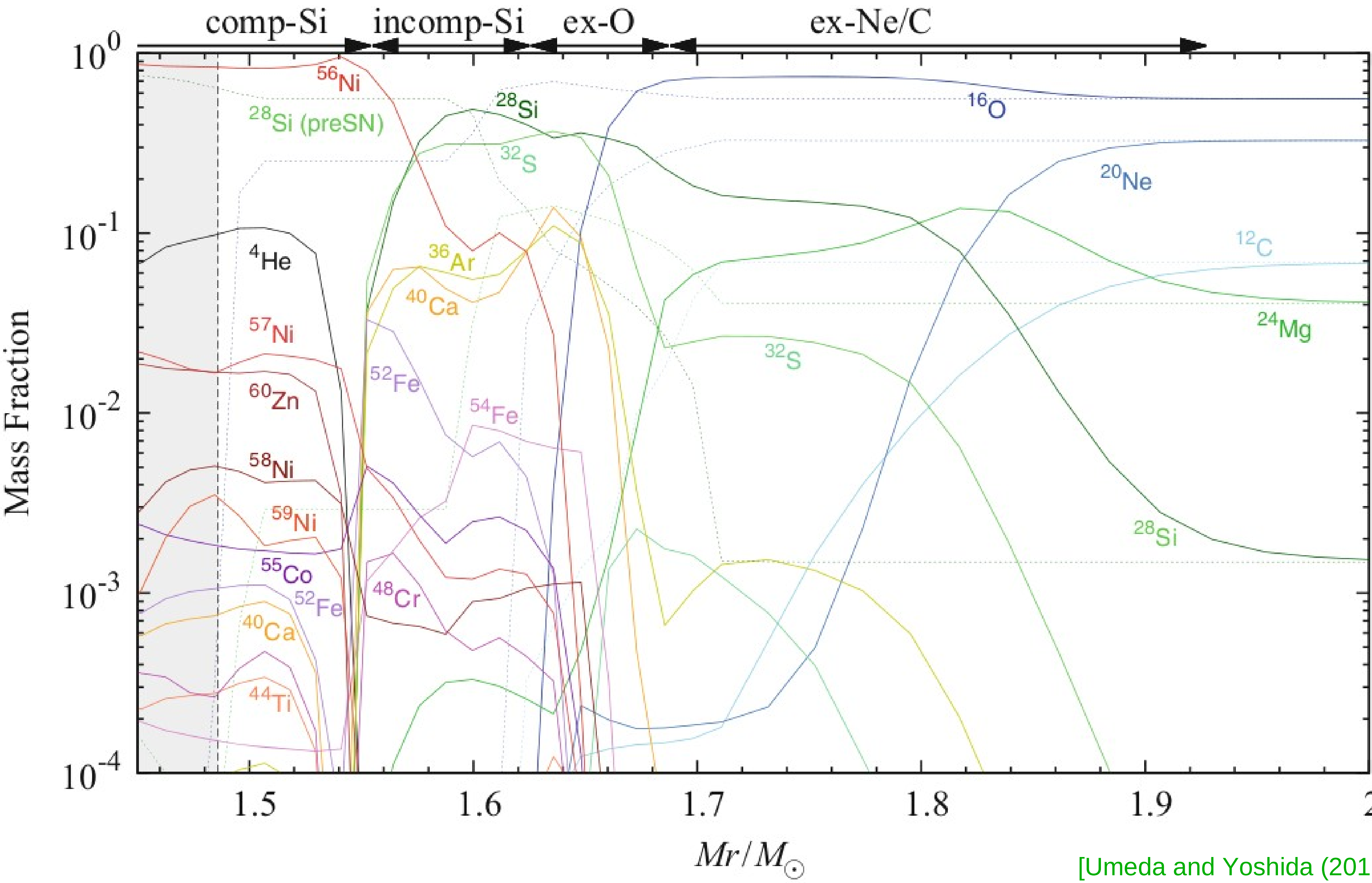
The post-shock peak temperature (T_s) for a mass shell goes roughtly

$$E_{\rm expl} \sim \frac{4\pi}{3} r^3 \cdot a \cdot T_s^4$$

Inner mass shells get heated up more, thus allows production of heavier nuclei

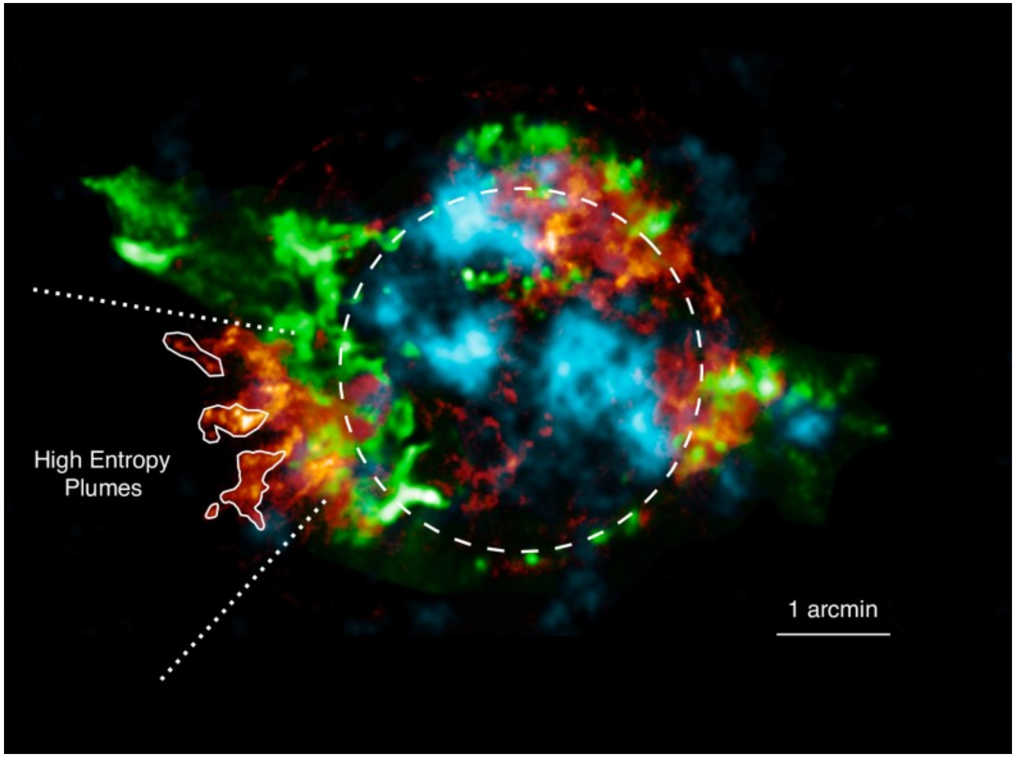
- $T_s \gtrsim 5$ GK, complete Si burning $\to$ mainly ^{56}Ni
- $4 \lesssim T_s \lesssim 5$ GK, incomplete Si burning $\to$ Ni, Si, S, other iron group nuclei
- $3 \lesssim T_s \lesssim 4$ GK, O burning $\to$ Si, S, Ar, Ca,...
- $2 \lesssim T_s \lesssim 3$ GK, Ne/O burning $\to$ Si, S, Mg, Al, γ-process (p-nuclei),...
- $T_s \lesssim 2$ GK, temperature too low for explosive nucleosynthesis

A 15 $M_\odot$ progenitor (zero metalicity):



[Umeda and Yoshida (2017)]

Cassiopeia A (Cas A) at ~ 3.4 kpc away, a very young remnant from SN explosion at late 17th century has been providing interesting information for explosive nucleosynthesis yields



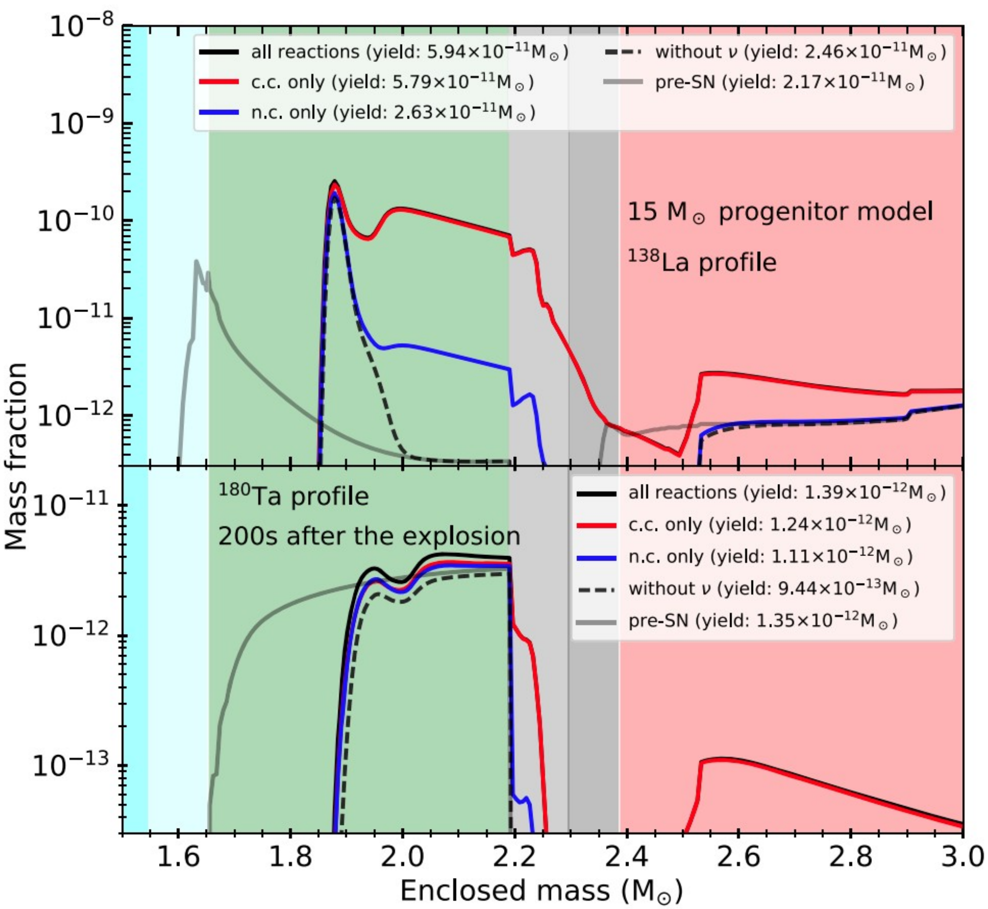
– the spatial distribution of the synthesized elements indicates that the explosion was highly asymmetric

– hints of neutrino-driven explosion from the Ti/Fe and Cr/Fe yields?

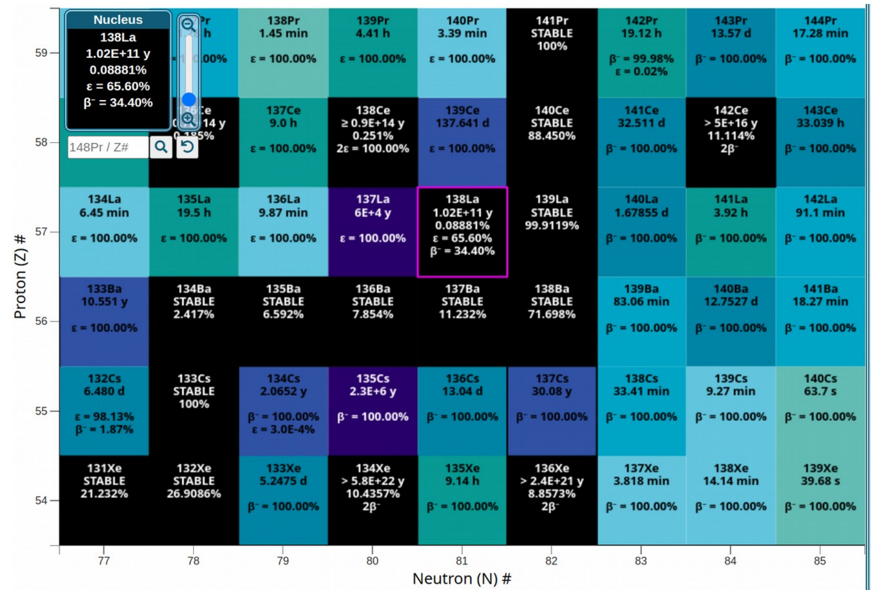
[Sato+ 2021]

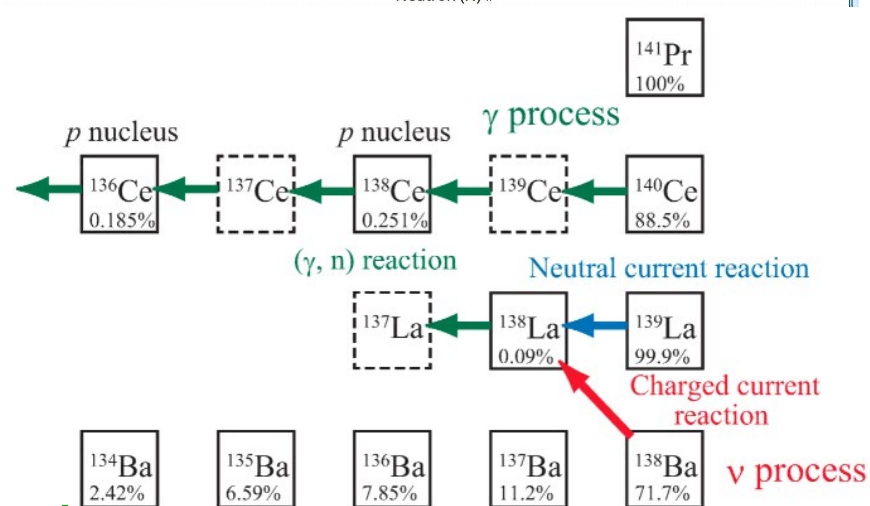
Neutrino nucleosynthesis

Neutrinos can interact with pre-existing nuclei in stellar envelope and produce certain isotopes not able to be made by other processes



[Sieverding+ 2018]





[Hayakwa+ 2017]

The exact yields depend on the prediction of neutrino energy spectra

[a] $T_{\nu_e} = 2.8$ MeV, $T_{\bar{\nu}_e} = T_{\nu_{\mu,\tau}} = 4.0$ MeV.
[b] $T_{\nu_e} = 4.0$ MeV, $T_{\bar{\nu}_e} = 5.0$ MeV, $T_{\nu_{\mu,\tau}} = 6.0$ MeV.

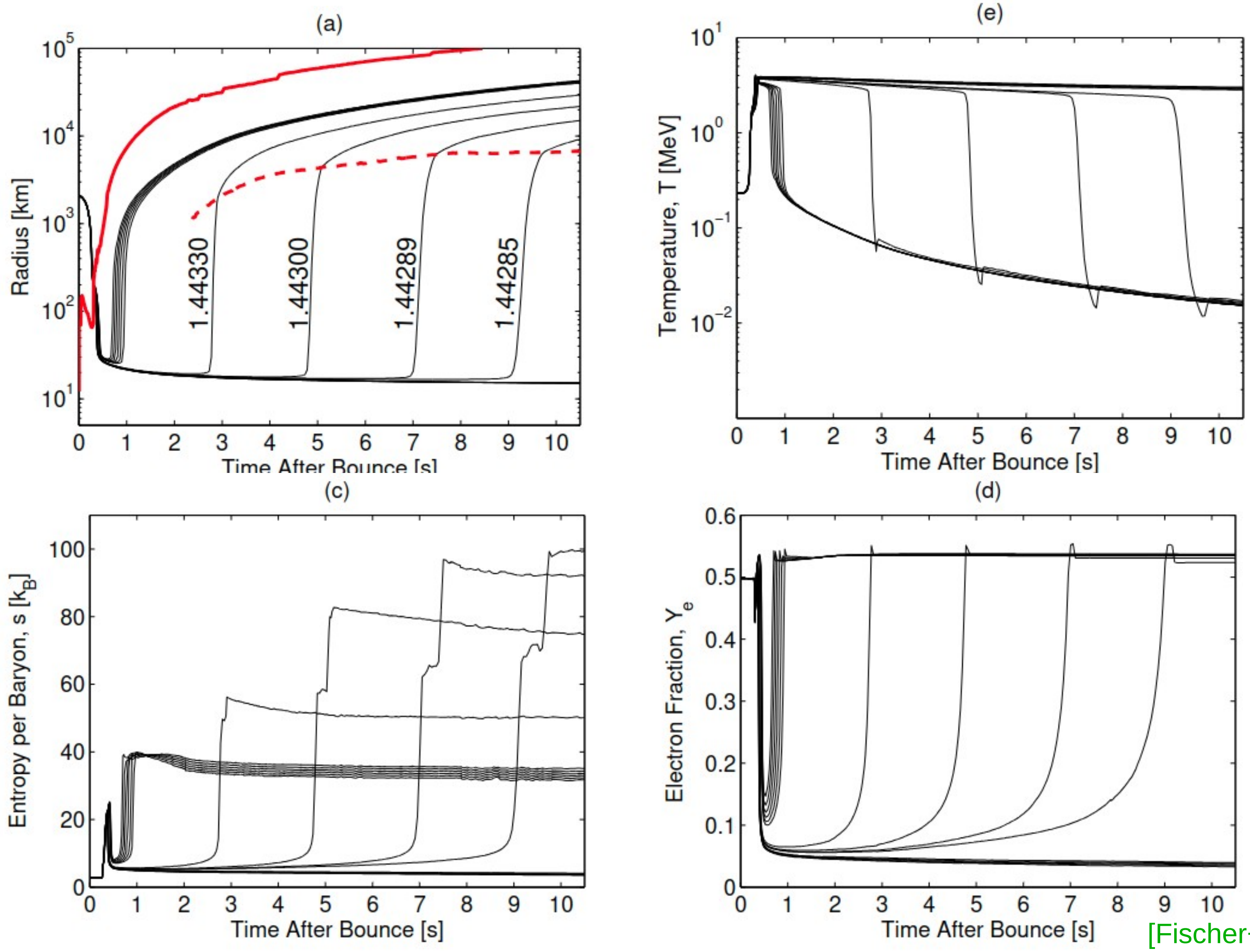
[Sieverding+ 2018]

Nucleus	No ν	Low Energies[a]		
		With ν	Only Charged Current	Only Neutral Current
^{7}Li	0.002	0.04	0.01	0.03
^{11}B	0.01	0.31	0.17	0.21
^{15}N	0.06	0.09	0.08	0.08
^{19}F	0.13	0.18	0.14	0.16
^{138}La	0.16	0.46	0.44	0.18
^{180}Ta[c]	0.20	0.49	0.48	0.24

Nucleus	No ν	High Energies[b]		
		With ν	Only Charged Current	Only Neutral Current
^{7}Li	0.002	0.58	0.05	0.57
^{11}B	0.01	1.57	0.58	1.31
^{15}N	0.06	0.16	0.10	0.15
^{19}F	0.13	0.29	0.17	0.26
^{138}La	0.16	0.77	0.73	0.22
^{180}Ta[c]	0.20	0.84	0.80	0.33

Neutrino-driven wind

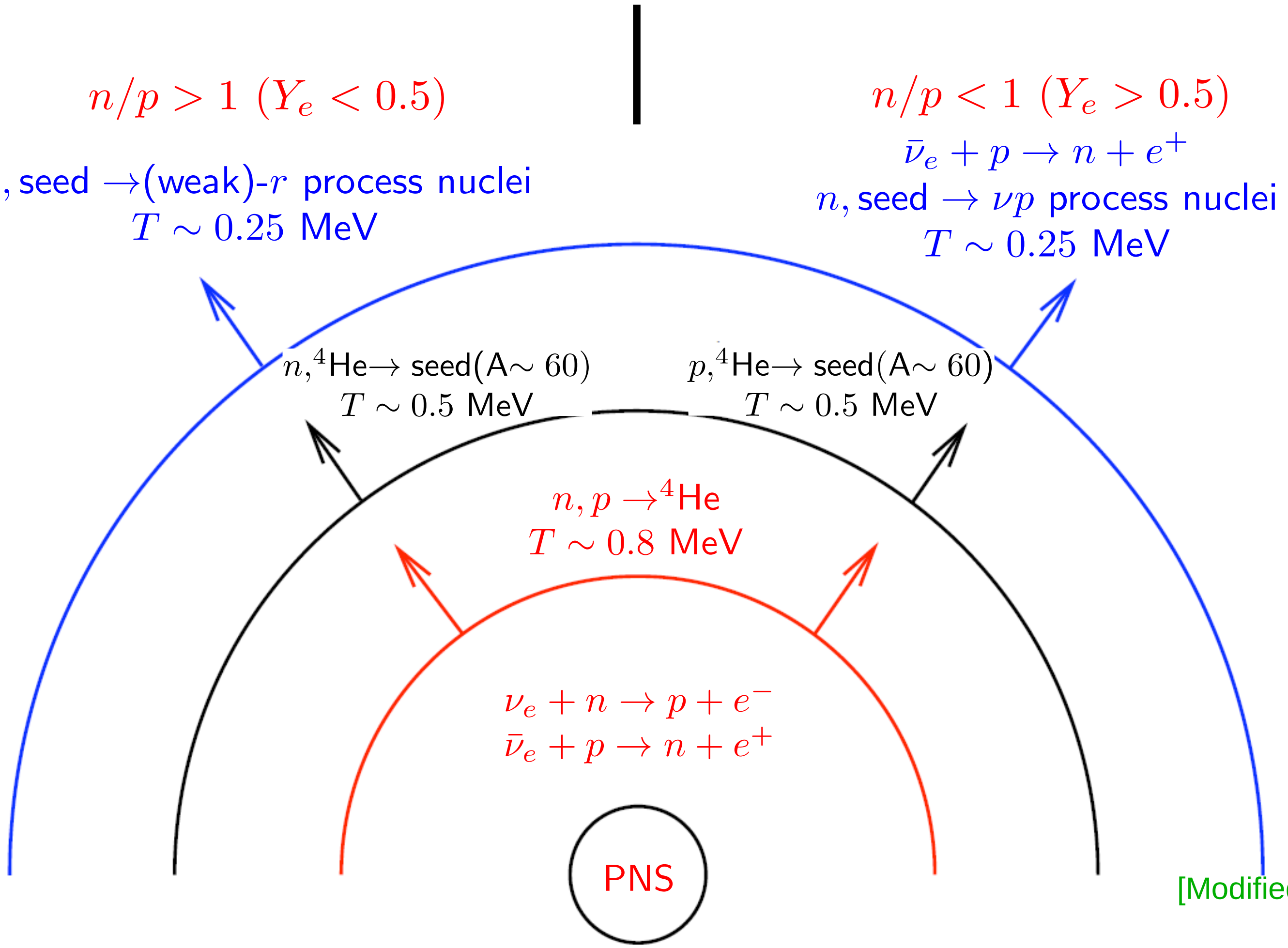
Neutrinos diffusing out from the cooling PNS can blow off the PNS atmosphere – just like the stellar wind driven by photons



[Fischer+2010]

Neutrino-driven wind

Neutrinos diffusing out from the cooling PNS can blow off the PNS atmosphere – just like the stellar wind driven by photons



[Modified from Y.-Z. Qian]

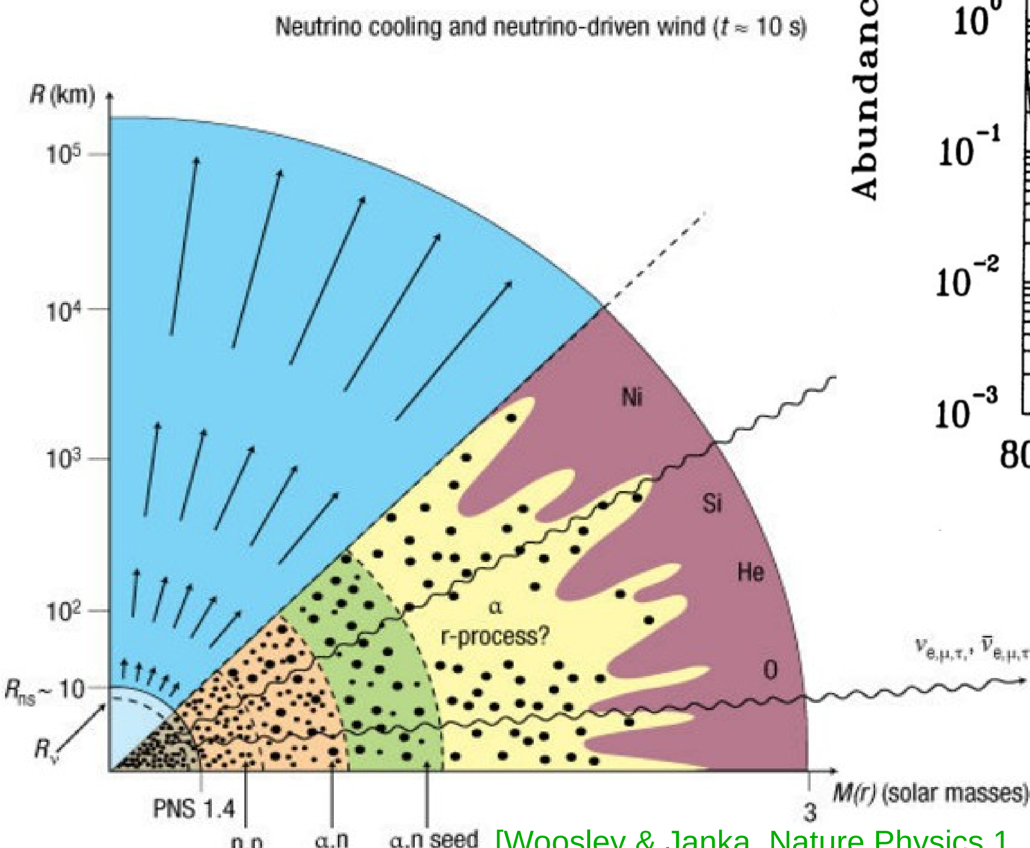
$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle \gtrsim 4(m_n - m_p)$ $\rightarrow$ neutron-rich ejecta, (weak) r process

$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle \lesssim 4(m_n - m_p)$ $\rightarrow$ proton-rich ejecta, νp process

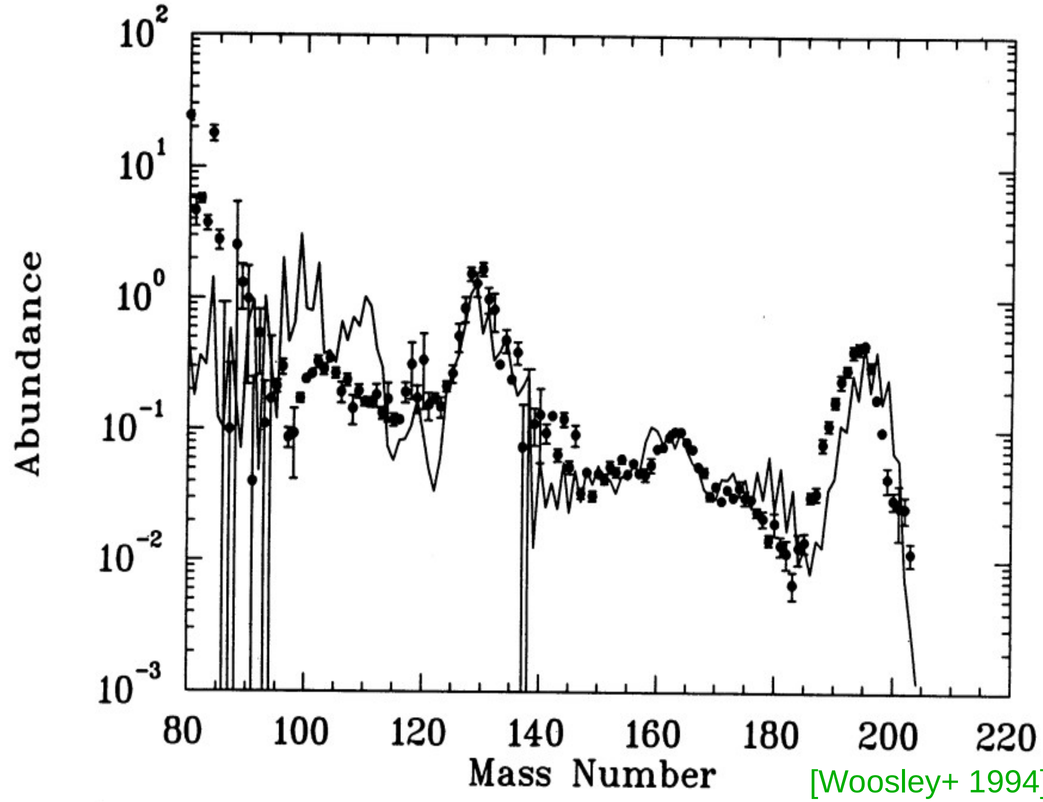
r-process in neutrino-driven wind?

$$R_{n/s} \propto \frac{s^3}{\tau_{\rm dyn} Y_e^3}$$

– earlier work of Woosley+ 1994 derived high entropy ($s \gtrsim 400$), and low $Y_e \lesssim 0.4$ condition favorable for r-process



[Woosley & Janka, Nature Physics 1, 147 (2005)]



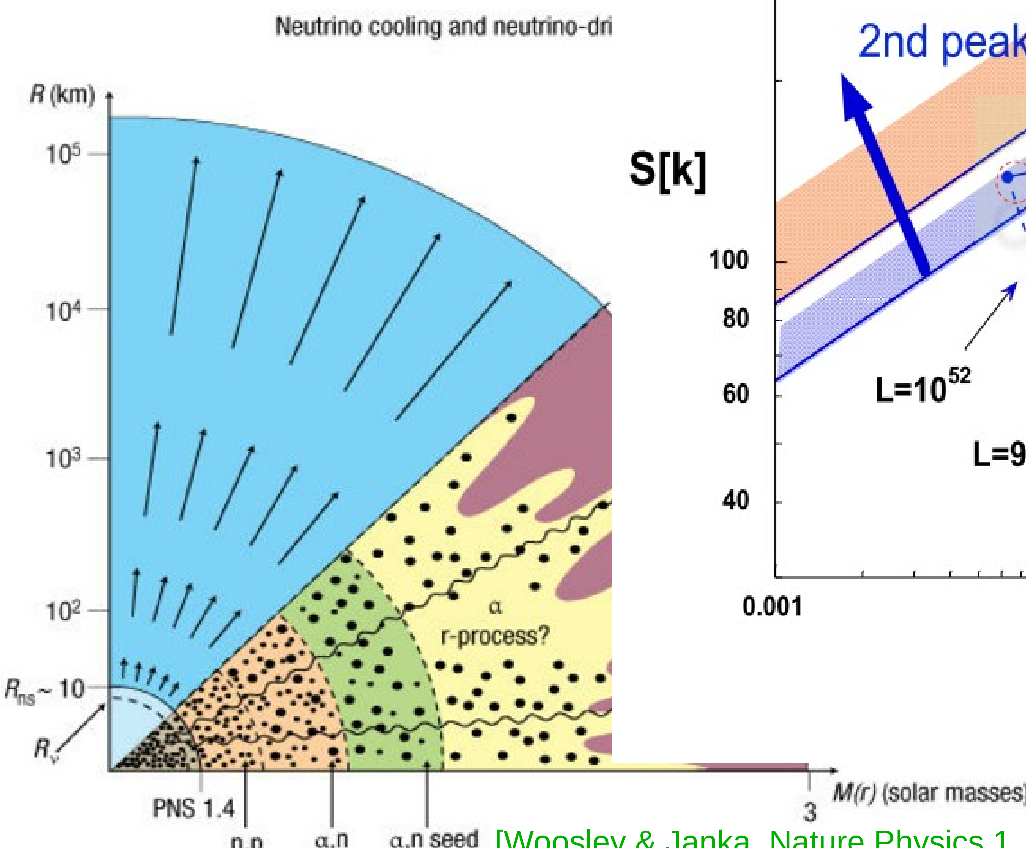
[Woosley+ 1994]

r-process in neutrino-driven wind?

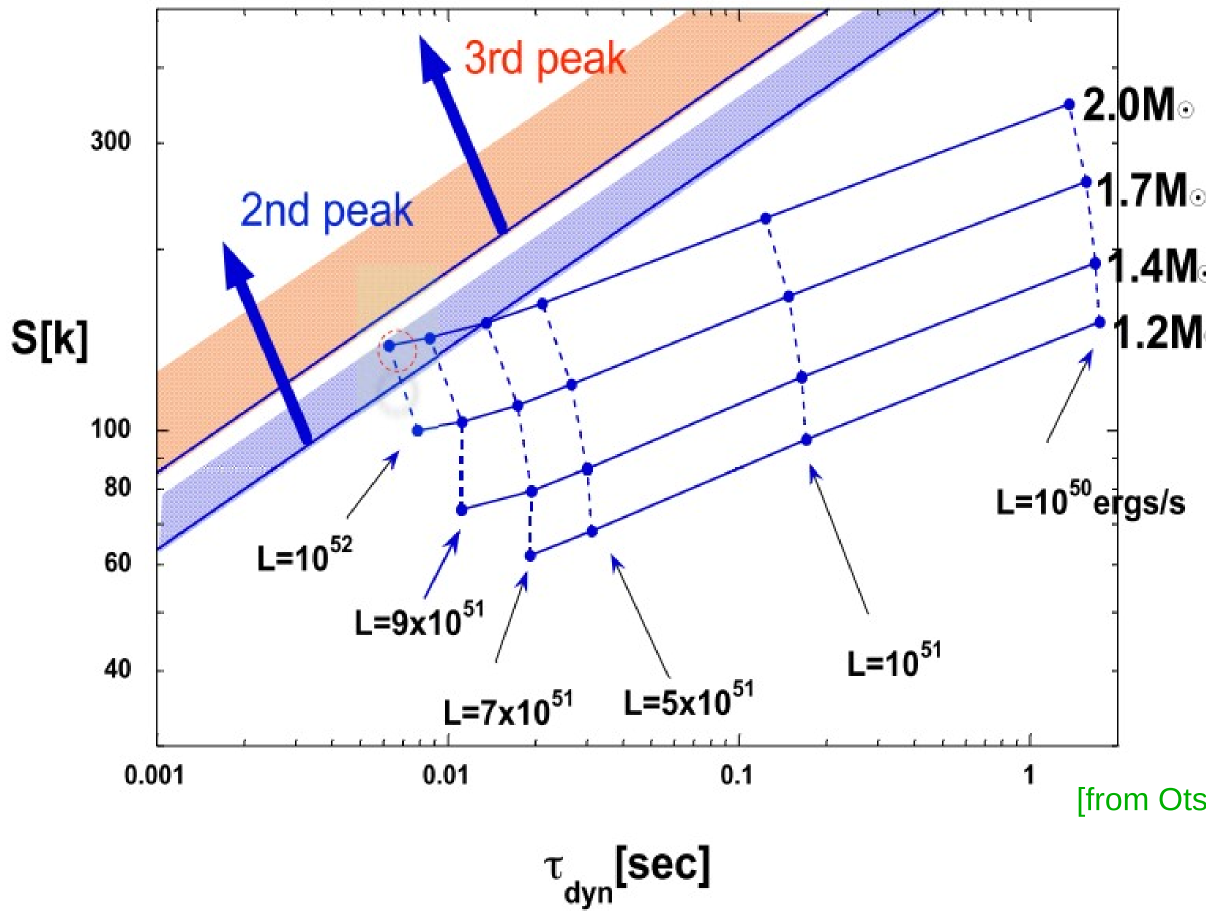
$$R_{n/s} \propto \frac{s^3}{\tau_{\rm dyn} Y_e^3}$$

– earlier work of Woosley+ 1994 derived high entropy ($s \gtrsim 400$), and low $Y_e \lesssim 0.4$ condition favorable for r-process

– not reproduced by steady-state wind models [Qian+ 1996, Thompson+ 2001, Otsuki+ 2000]



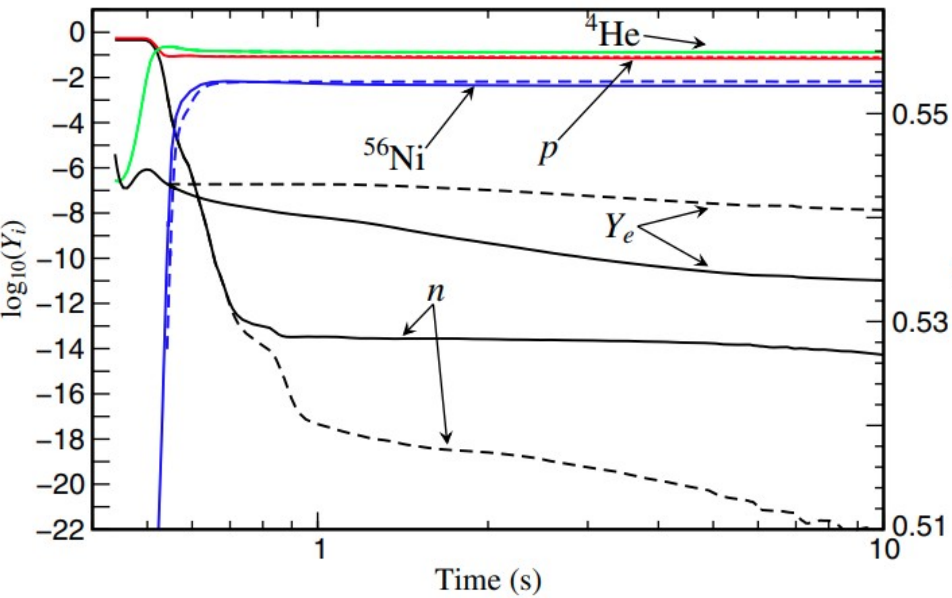
[Woosley & Janka, Nature Physics 1, 147 (2005)]

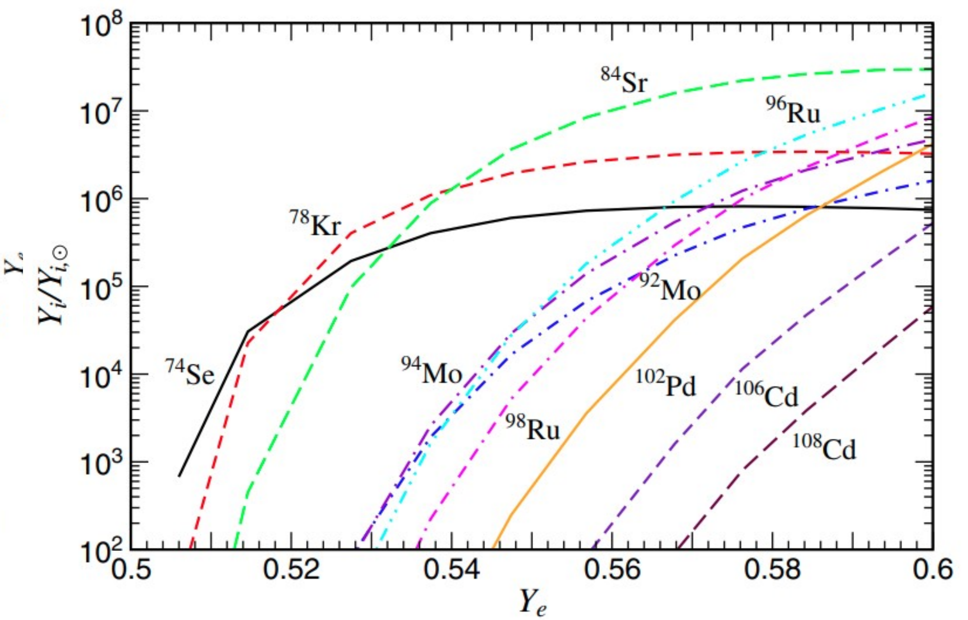


[from Otsuki]

νp-process in neutrino-driven wind?

The reaction of $\bar{\nu}_e + p \to n + e^+$ in proton-rich wind at $r \lesssim 10^3$ km where the neutrino fluxes are still large enough can lead to (n,p) reaction to overcome "bottleneck" (slow) proton capture reaction on e.g., ^{64}Ge to produce heavier p-rich nuclei

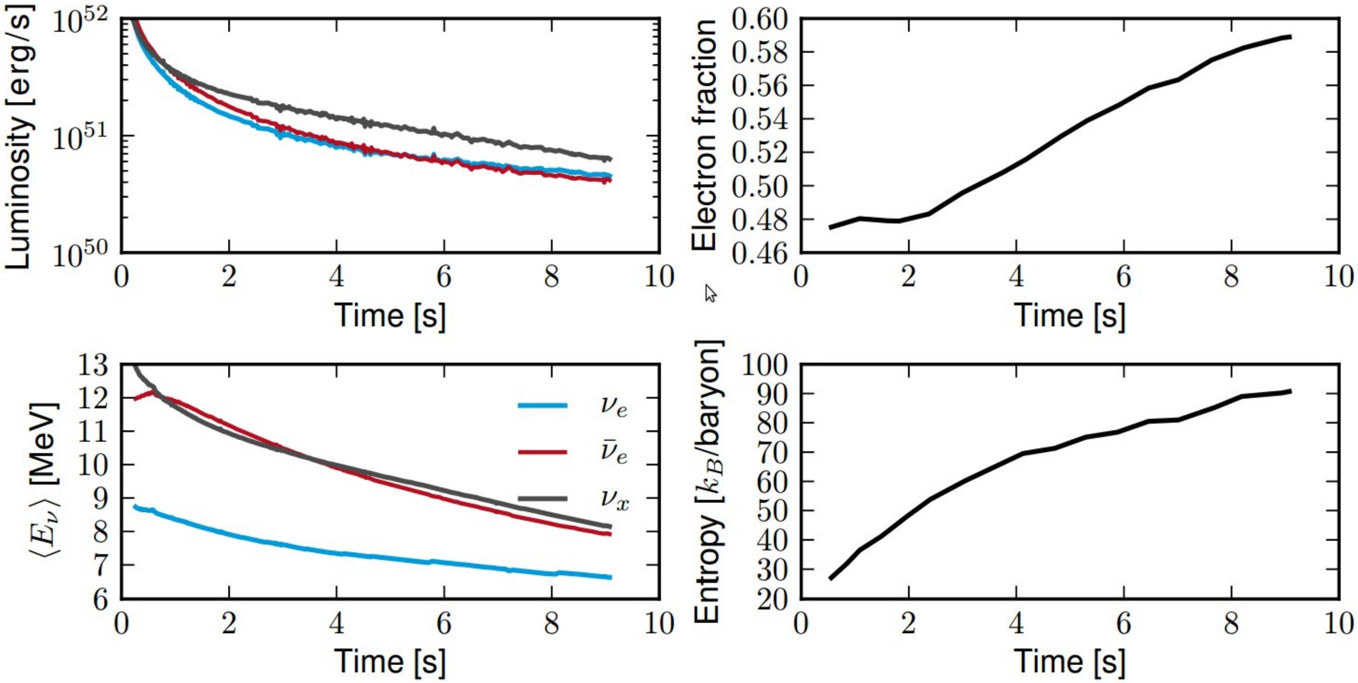




[Froehlich+2005]

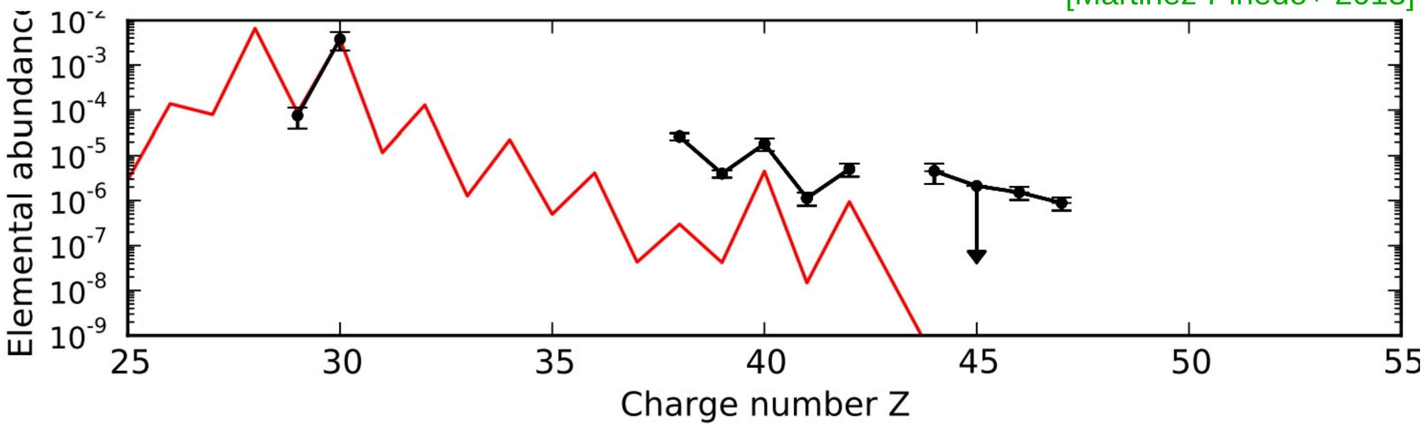
νp-process in neutrino-driven wind?

Recent 1D PNS cooling simulation ($11.2\ M_\odot$ progenitor):



Nucleosynthesis yields:

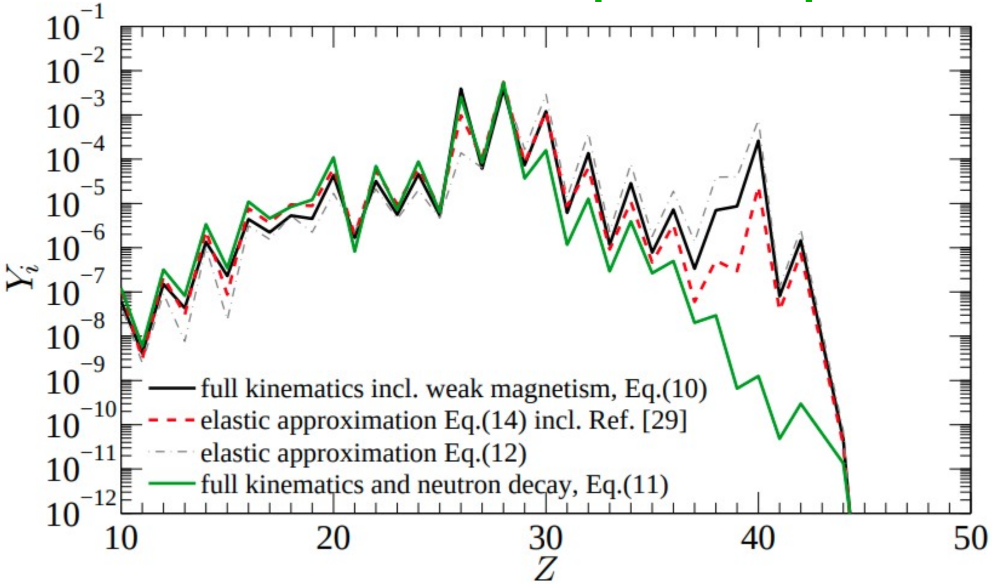
[Martinez-Pinedo+ 2013]



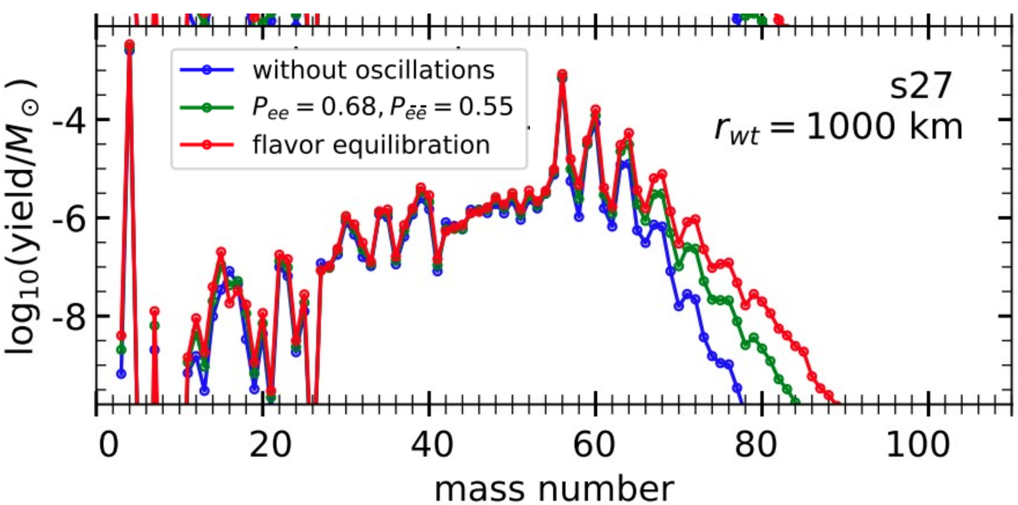
νp-process in neutrino-driven wind?

– with improved modeling of neutrino nuclear matter interaction

[Fischer+ 2018]



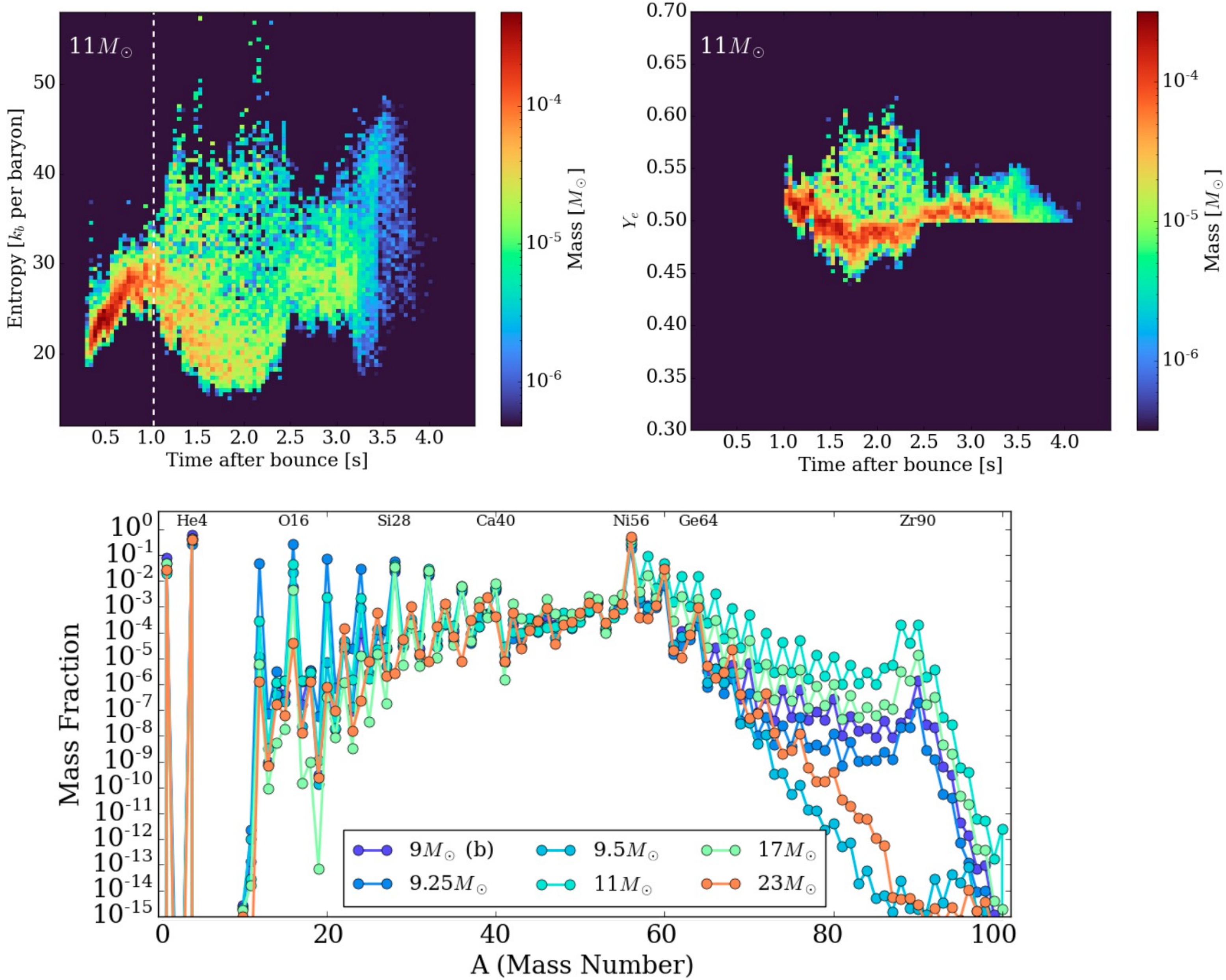
– assuming neutrino energy spectra are largely affected by flavor oscillations



[Xiong+ 2020]

Neutrino-driven wind in multi-D SN simulations

[Wang & Burrows 2023]



[Fischer+ 2308.03962]

Neutrinos and nucleosynthesis of elements

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Abstract

Neutrinos are known to play important roles in many astrophysical scenarios from the early period of the big bang to current stellar evolution being a unique messenger of the fusion reactions occurring in the center of our sun. In particular, neutrinos are crucial in determining the dynamics and the composition evolution in explosive events such as core-collapse supernovae and the merger of two neutron stars. In this paper, we review the current understanding of supernovae and binary neutron star mergers by focusing on the role of neutrinos therein. Several recent improvements on the theoretical modeling of neutrino interaction rates in nuclear matter as well as their impact on the heavy element nucleosynthesis in the supernova neutrino-driven wind are discussed, including the neutrino-nucleon opacity at the mean field level taking into account the relativistic kinematics of nucleons, the effect due to the nucleon-nucleon correlation, and the nucleon-nucleon bremsstrahlung. We also review the framework used to compute the neutrino-nucleus interactions and the up-to-date yield prediction for isotopes from neutrino nucleosynthesis occurring in the outer envelope of the supernova progenitor star during the explosion. Here improved predictions of energy spectra of supernova neutrinos of all flavors have had significant impact on the nucleosynthesis yields. Rapid progresses in modeling the flavor oscillations of neutrinos in these environments, including several novel mechanisms for collective neutrino oscillations and their potential impacts on various nucleosynthesis processes are summarized.

Keywords: Core-collapse supernova, neutron star merger, neutrino, nucleosynthesis

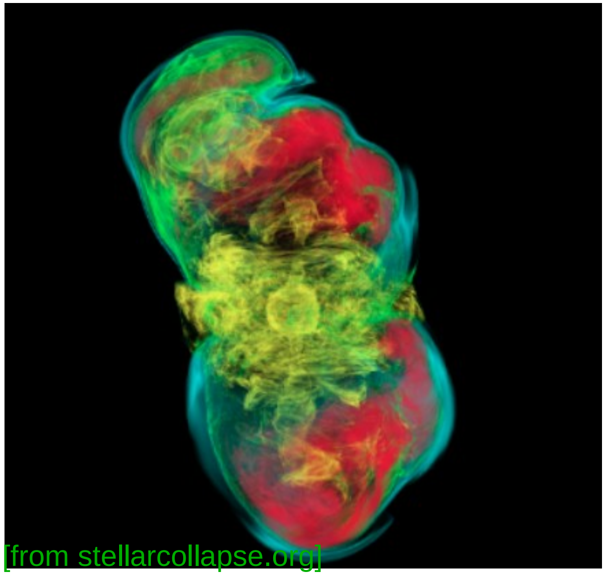
Alternative sites for supernova r-process?

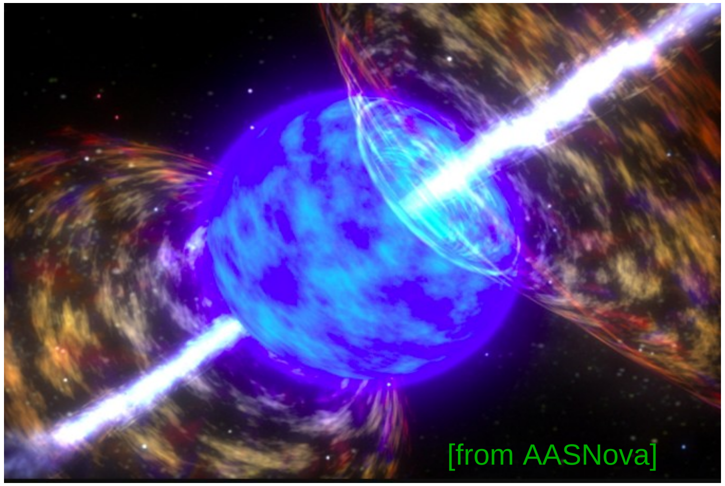
The "typical" core-collapse supernovae do not seem to make strong r-process.
What are other possibilities?

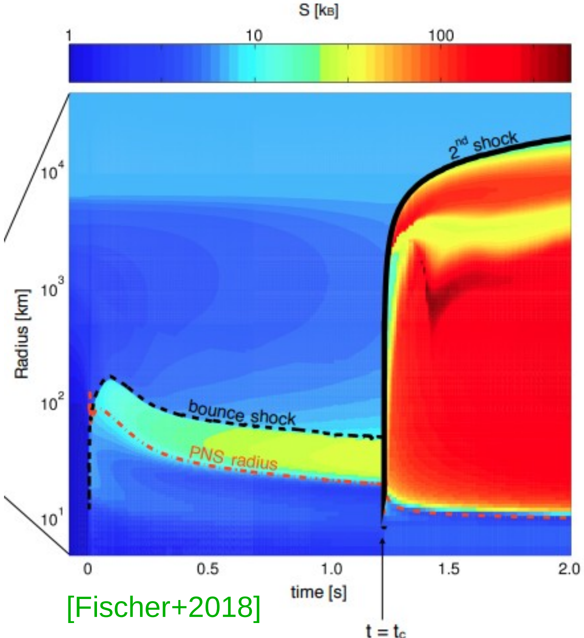
– faster expansion to reduce neutrino exposure (which raise Y_e)?

– higher entropy in the wind?

- magneto-rotational supernovae [Winteler+ 2012, Moesta+ 2014,...]
- collapsars [Siegel+2018, ...]
- hadron-quark phase transition supernovae [Takahara+ 1988, Sagert+ 2009, Fischer+ 2018,...]


[from stellarcollapse.org]

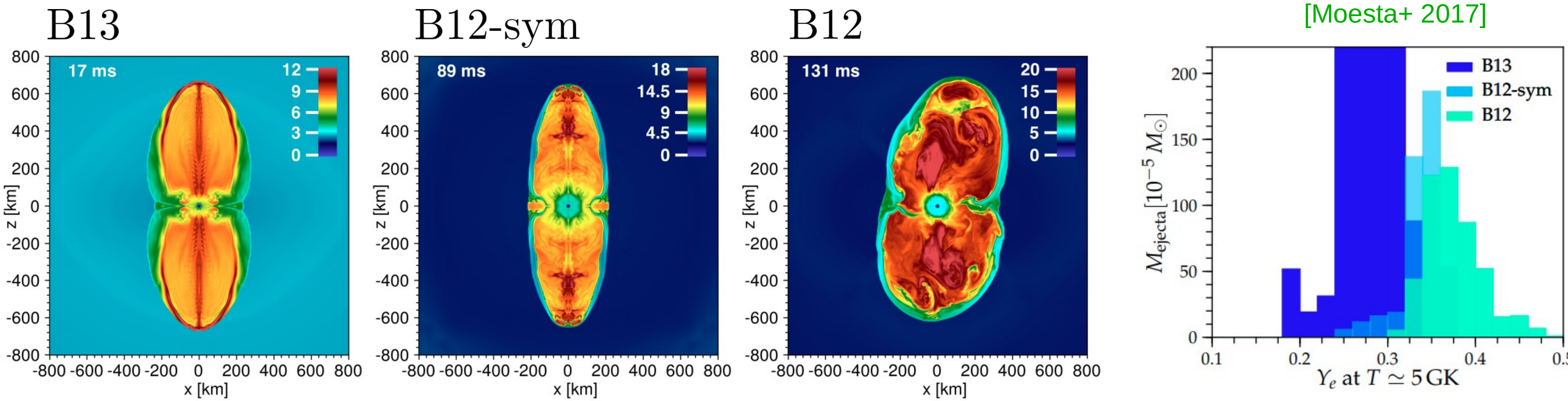

[from AASNova]

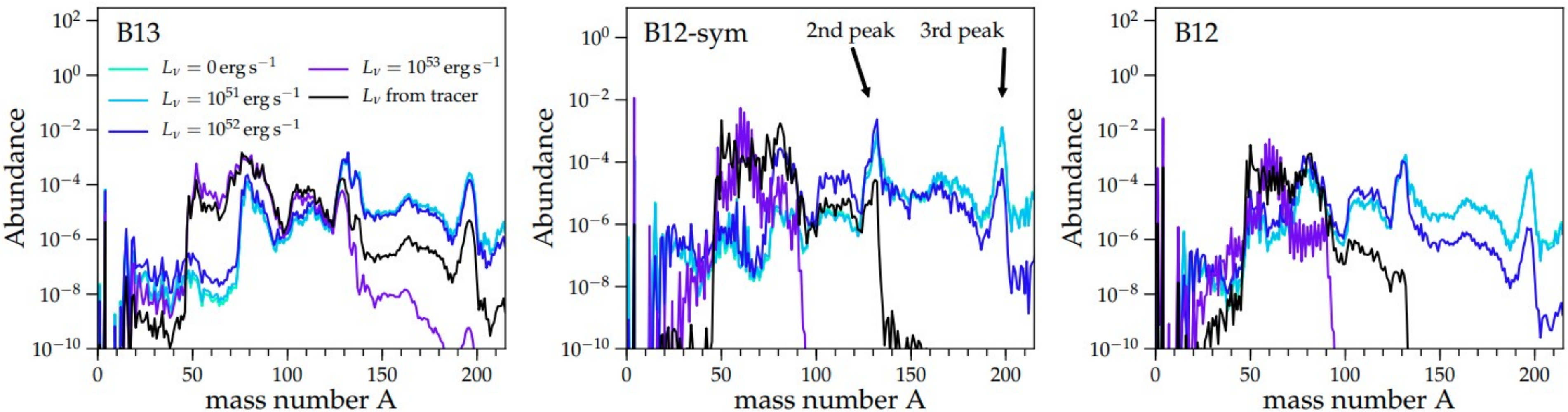


[Fischer+2018]

r-process yields in magnetorotational SNe

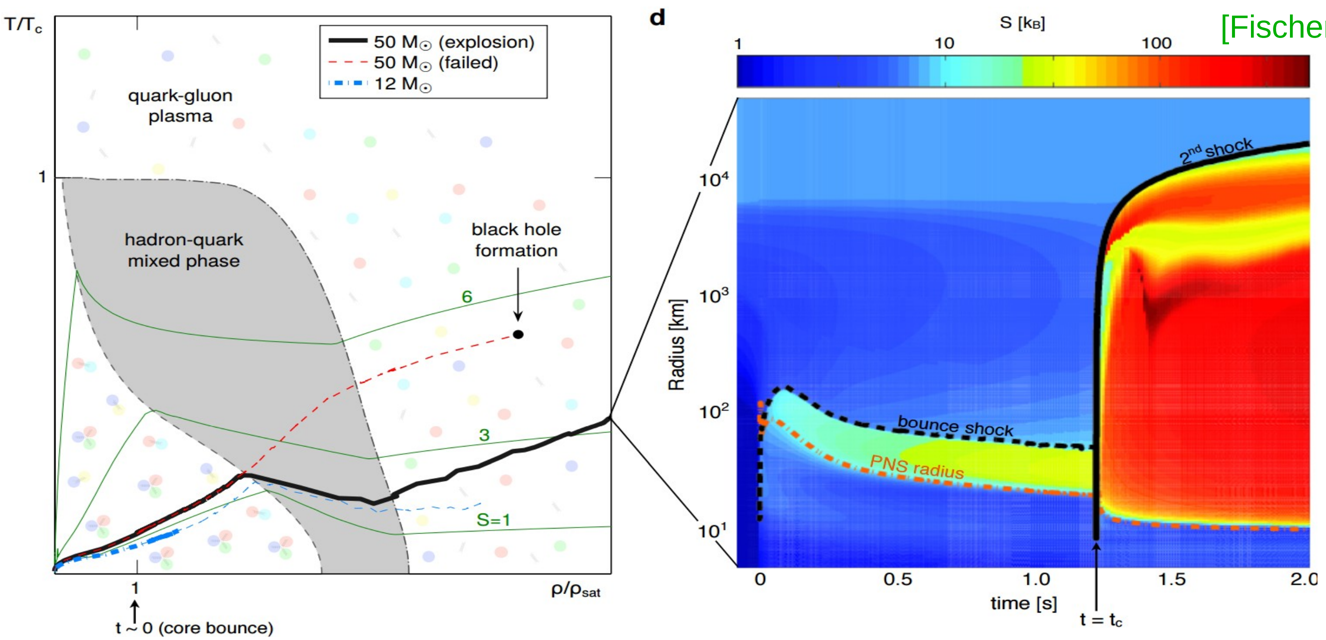
[Moesta+ 2017]





r-process above 2nd peak only obtained for very jet-like explosion achieved with very strong pre-collapse magnetic field or with quenched neutrino luminosity

r-process yields in phase-transition SNe

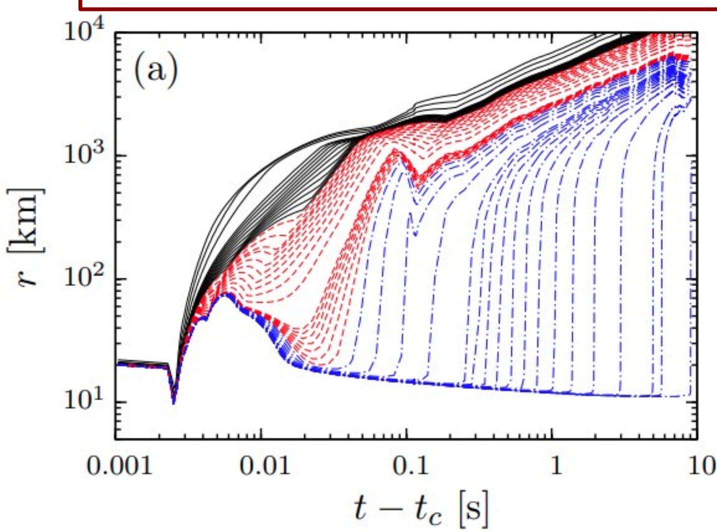


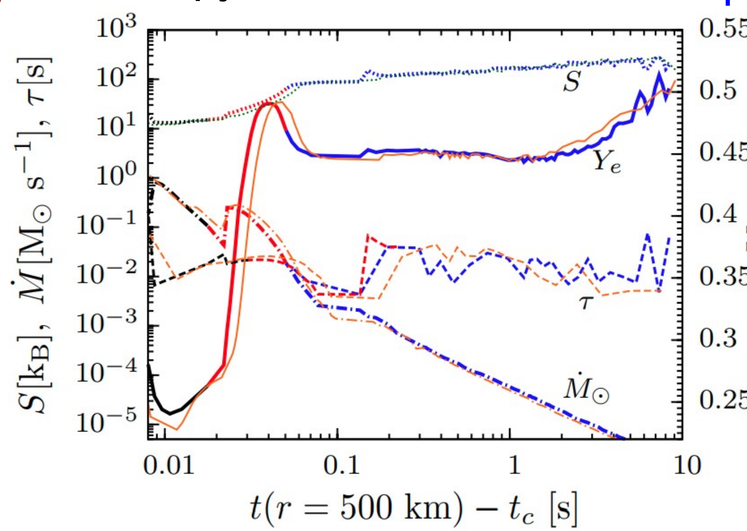
[Fischer+2018]

explosion achieved by shock from 2nd collapse due to phase transition

ejecta: direct, intermediate, and ν-driven

low Y_e & entropy → high Y_e & entropy



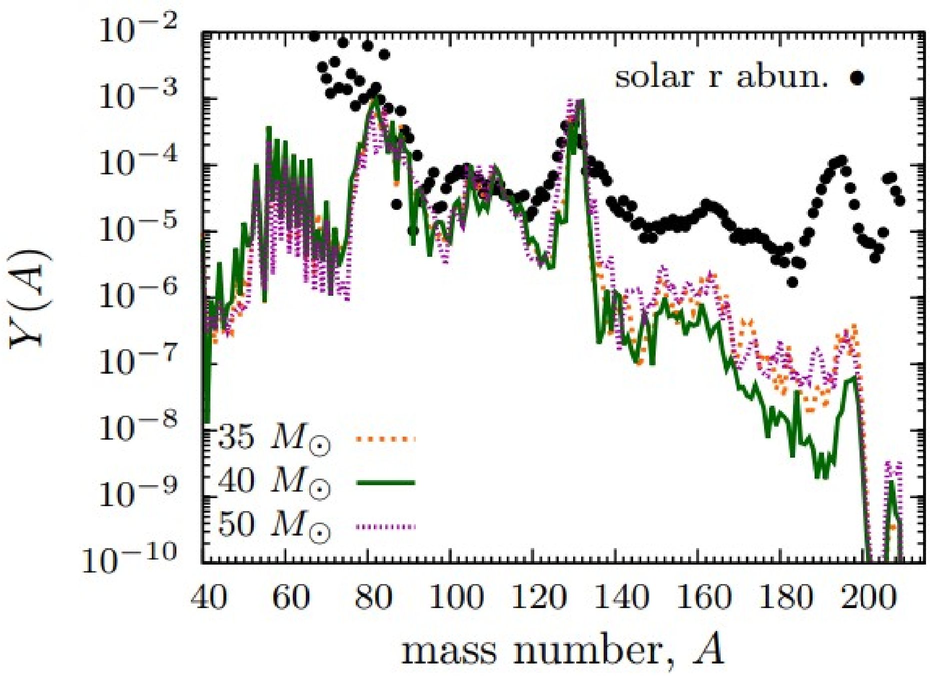


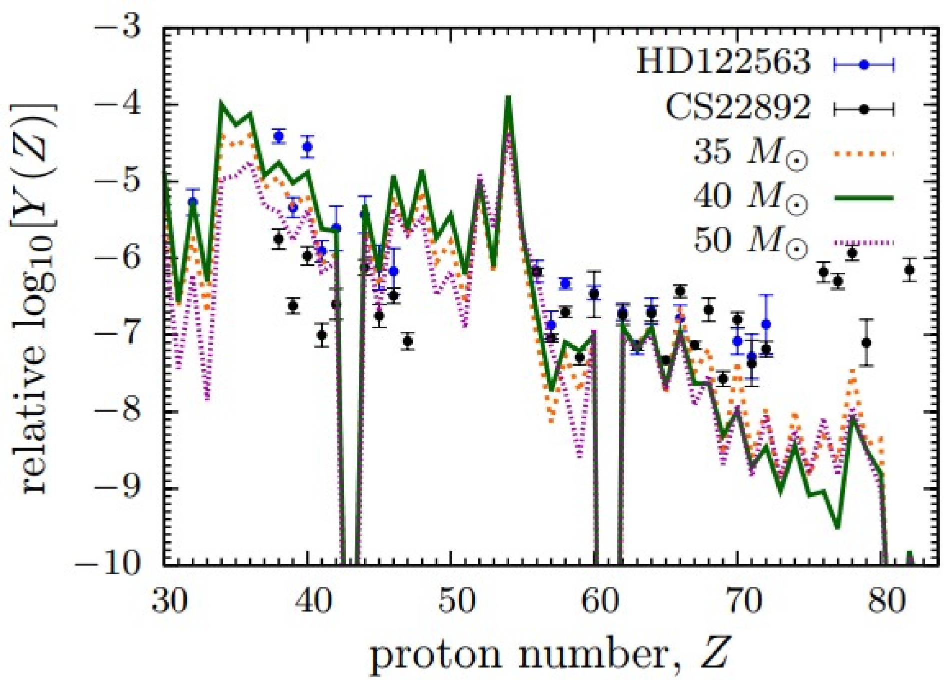
[Fischer, MRW, Wehmeyer+ 2020]

Integrated nucleosynthesis yields

Table 3. Ejecta Properties of the Supernova Explosion Models.

$M^{\rm a}_{\rm prog}$ ($M_\odot$)	$M^{\rm b}_{\rm inner\ ejecta}$ ($10^{-2}\ M_\odot$)	$M^{\rm c}_{\rm direct}$ ($10^{-2}\ M_\odot$)	$M^{\rm d}_{\rm intermediate}$ ($10^{-3}\ M_\odot$)	$M^{\rm e}_{\rm NDW}$ ($10^{-3}\ M_\odot$)	$M^{*}_{\rm Fe}$ ($10^{-2}\ M_\odot$)	$M^{*}_{\rm Sr}$ ($10^{-4}\ M_\odot$)	$M^{*}_{\rm Eu}$ ($10^{-6}\ M_\odot$)	$M^{*,\times}_{^{244}\rm Pu}$ ($10^{-10}\ M_\odot$)	$M^{**}_{^{60}\rm Fe}$ ($10^{-5}\ M_\odot$)
$35^\dagger$	1.44	1.03	3.72	0.33	7.15	6.50	7.86	2.09	12.2
$40^\dagger$	1.33	0.97	3.19	0.43	7.62	6.15	2.26	2.64	3.2
$50^\ddagger$	1.80	1.45	3.06	0.46	3.73	8.22	11.03	22.59	0.5

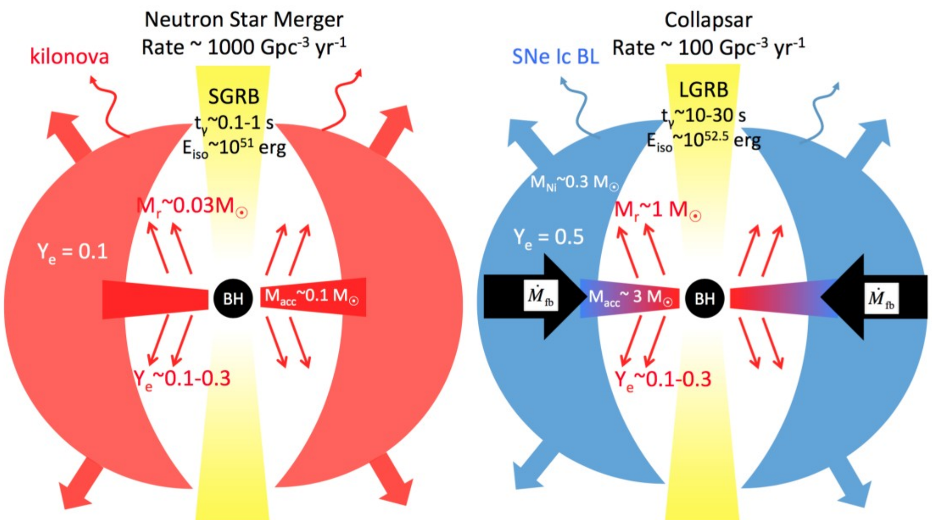




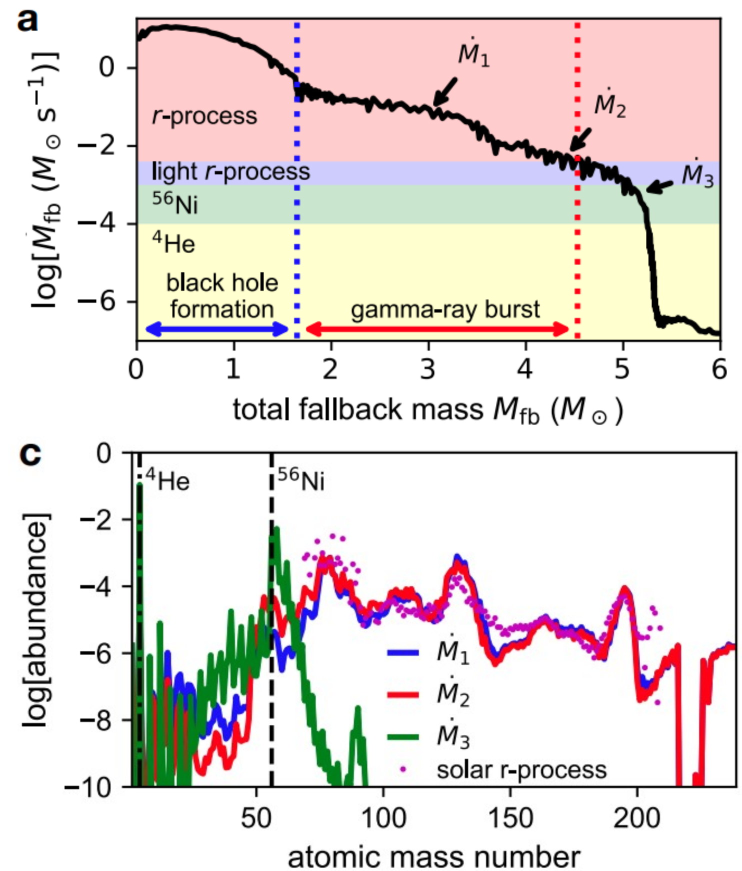
[Fischer, MRW, Wehmeyer+ 2020]

r-process in collapsar outflow?

Siegel+ suggested that the accretion disk of collapsars can result in neutron-rich outflow in a way similar to the BH-disk system from BNSMs



[Siegel, Barnes, Metzger 2018]



However, other studies that adopt certain rotating progenitor models or more advanced neutrino transport do not find strong r-process

[Miller+, Just+, Fujibayashi+, Zenati+]

Impact of r-process neutrinos on high-energy neutrinos?

r-process naturally produce $\bar{\nu}_e$ via β-decay

$\rightarrow \sim 10^{56}\ \bar{\nu}_e$ of $E_L \sim 5 - 10$ MeV for $\sim 1\ M_\odot$ r-process material

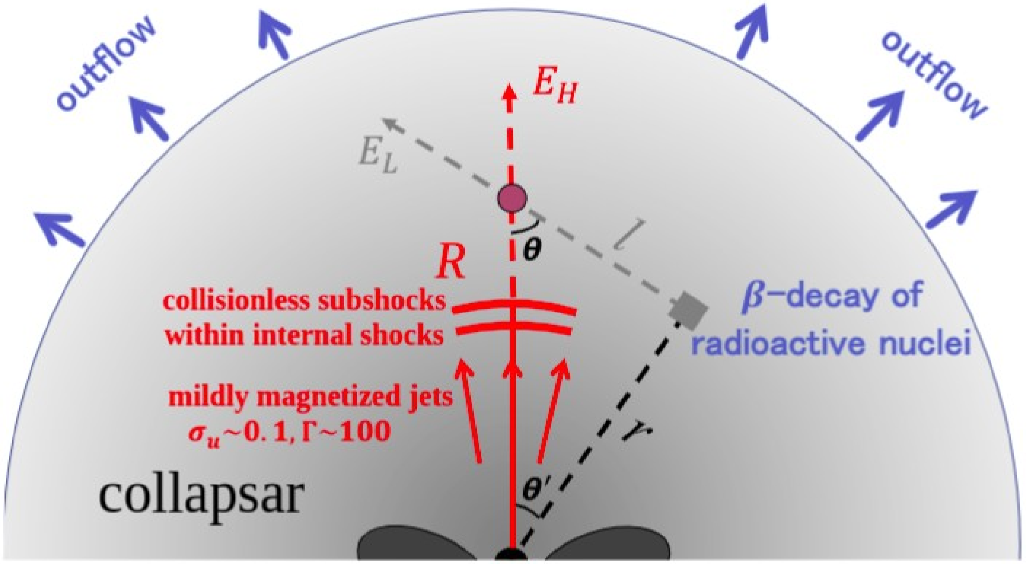
These r-process decay neutrinos can oscillate to different flavors and annhiliate with high-energy neutrinos of $E_H \sim 100 - 1000$ TeV via Z-resonance

$$\text{At } R \sim 10^{10}\ \text{cm}, \quad n_{\bar{\nu},\mathrm{LE}} \sim 10^{23}\ \mathrm{cm}^{-3} \left(\frac{\dot{M}}{0.02 M_\odot/\mathrm{s}}\right) \left(\frac{0.05c}{v_{\mathrm{ej}}}\right) \left(\frac{10^{10}\ \mathrm{cm}}{R}\right)^2$$

With $\sigma_{\mathrm{res}} \sim 10^{-31}$ cm^2

$\rightarrow \sigma_{\mathrm{res}} n_{\bar{\nu},\mathrm{LE}} R \gg \mathcal{O}(1)$

efficient annhiliation

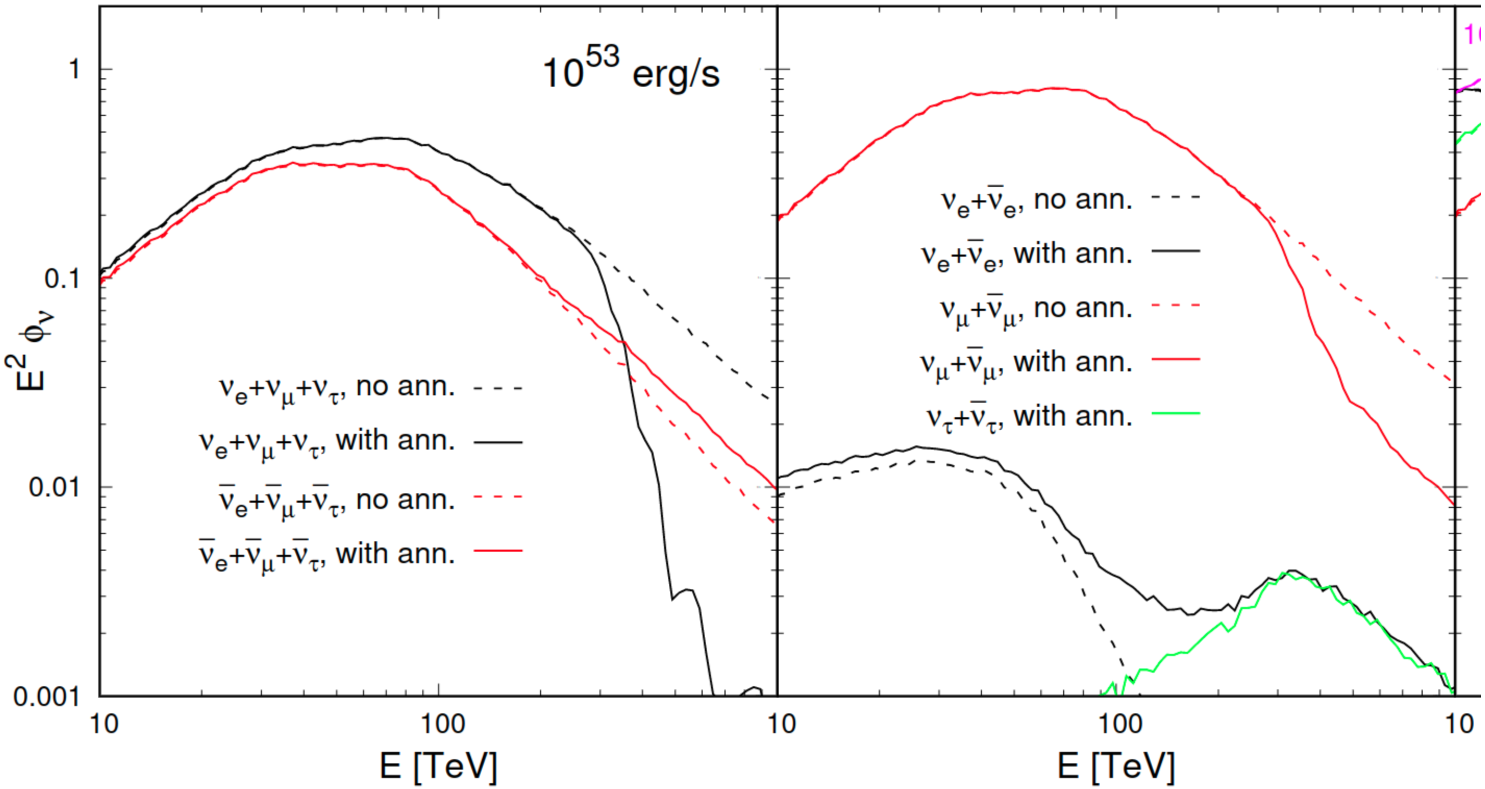


[G. Guo, Y.-Q. Qian, MRW, 2212.08266]

Effect of neutrino pair annhiliation

$L_{\rm iso} = 10^{53}$erg, $\Gamma_r = 2\Gamma_s \sim 450$, $\epsilon_{B,u} = B_u^2/(8\pi\rho_u c^2) = 0.05$, $R \sim \times 10^{10}$cm:

[G. Guo, Y.-Q. Qian, MRW, 2212.08266]

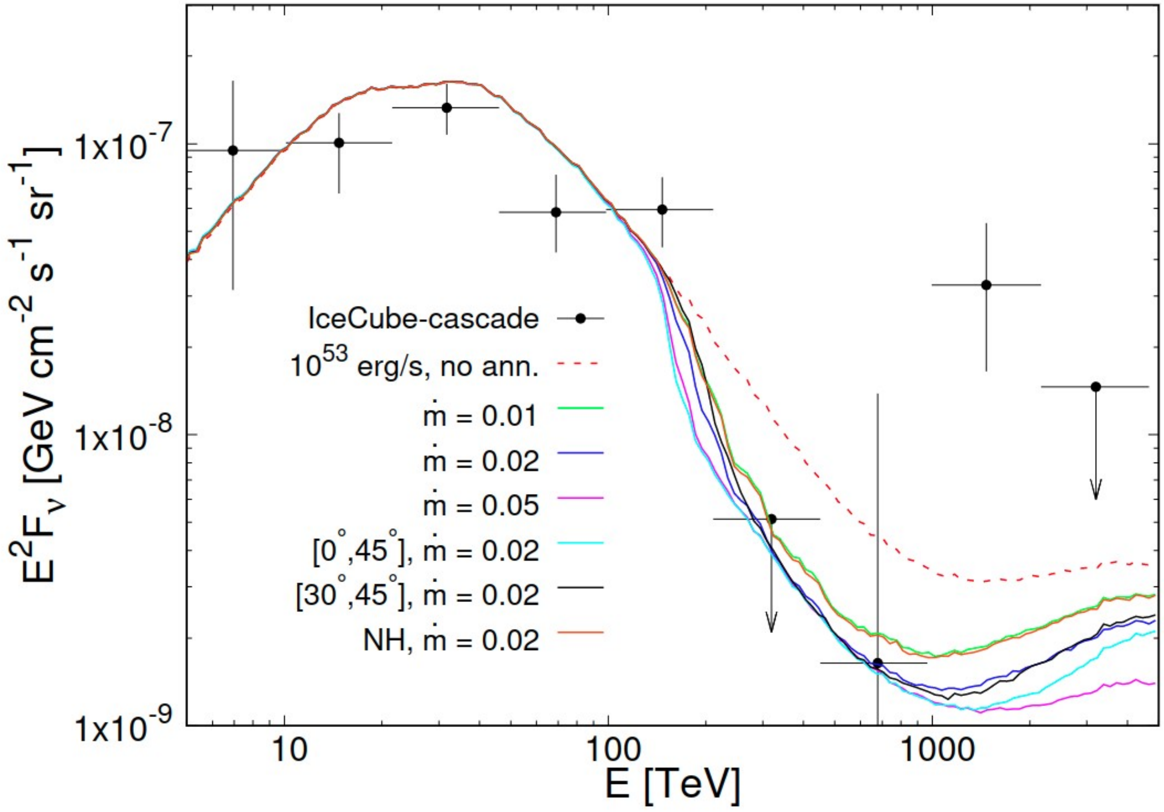


- μ flavor neutrinos dominate due to efficient cooling of $\mu^\pm$
- strong cutoff of ν above ~ 300 TeV due to efficient annhilation
- similar results hold for different values of $L_{\rm iso}$ and $\epsilon_{B,u}$

Diffuse flux v.s. IceCube detection

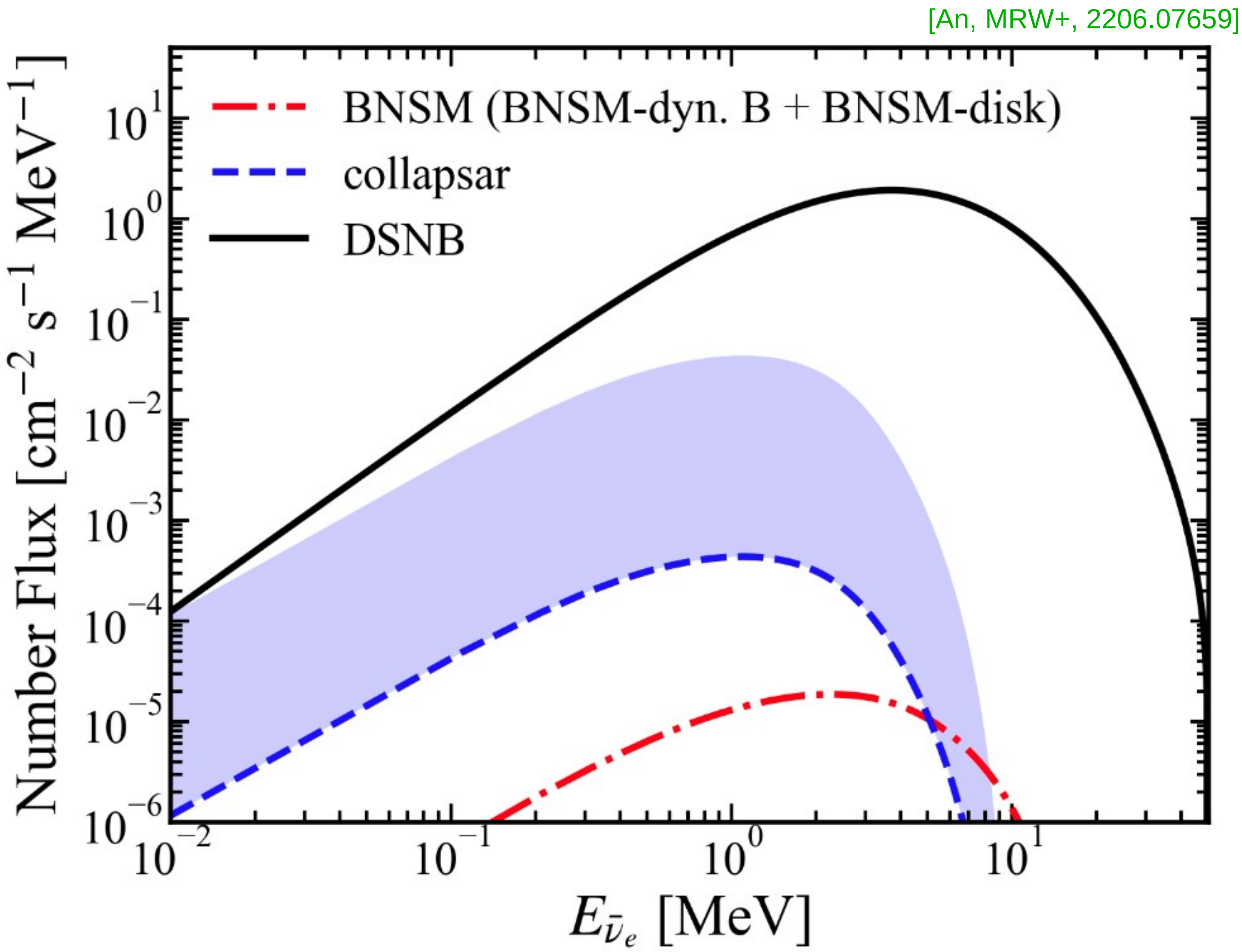
Assuming that such sources are ~ 10 times more frequent than the bright GRB, the resulting diffuse flux may be compatible to what detected at IceCube

[G. Guo, Y.-Q. Qian, MRW, 2212.08266]



May be further tested with imporved statistics on diffuse flux, precise flavor measurements, or from nearby (~ 100 Mpc) point-source event

Diffuse r-process neutrino background (DrNB)?



Won't be significant background for DSNB at relevant energy of $\sim \mathcal{O}(10)$ MeV, but may (at best) become comparable at sub-MeV

Summary (IV)

- The r-process in typical core-collapse supernovae are unlikely to happen. Alternative sites (magneto-rotational SN, phase-transition SN, collapsars) have been proposed but remain largely uncertain.
- Current SN models predicts that lighter heavy-elements (A~ 90) can be synthesized in the neutrino-driven wind via freeze-out process and potentially with some νp process. Improved SN modeling including neutrino interaction and flavor oscillations are needed to pin down the exact yields.
- Certain rare nuclei that cannot be made by s-, r-, or $p-$ processes can be produced by neutrino-process in the stellar envelope. The yields also depend on the precise prediction of supernova neutrino energy spectra.