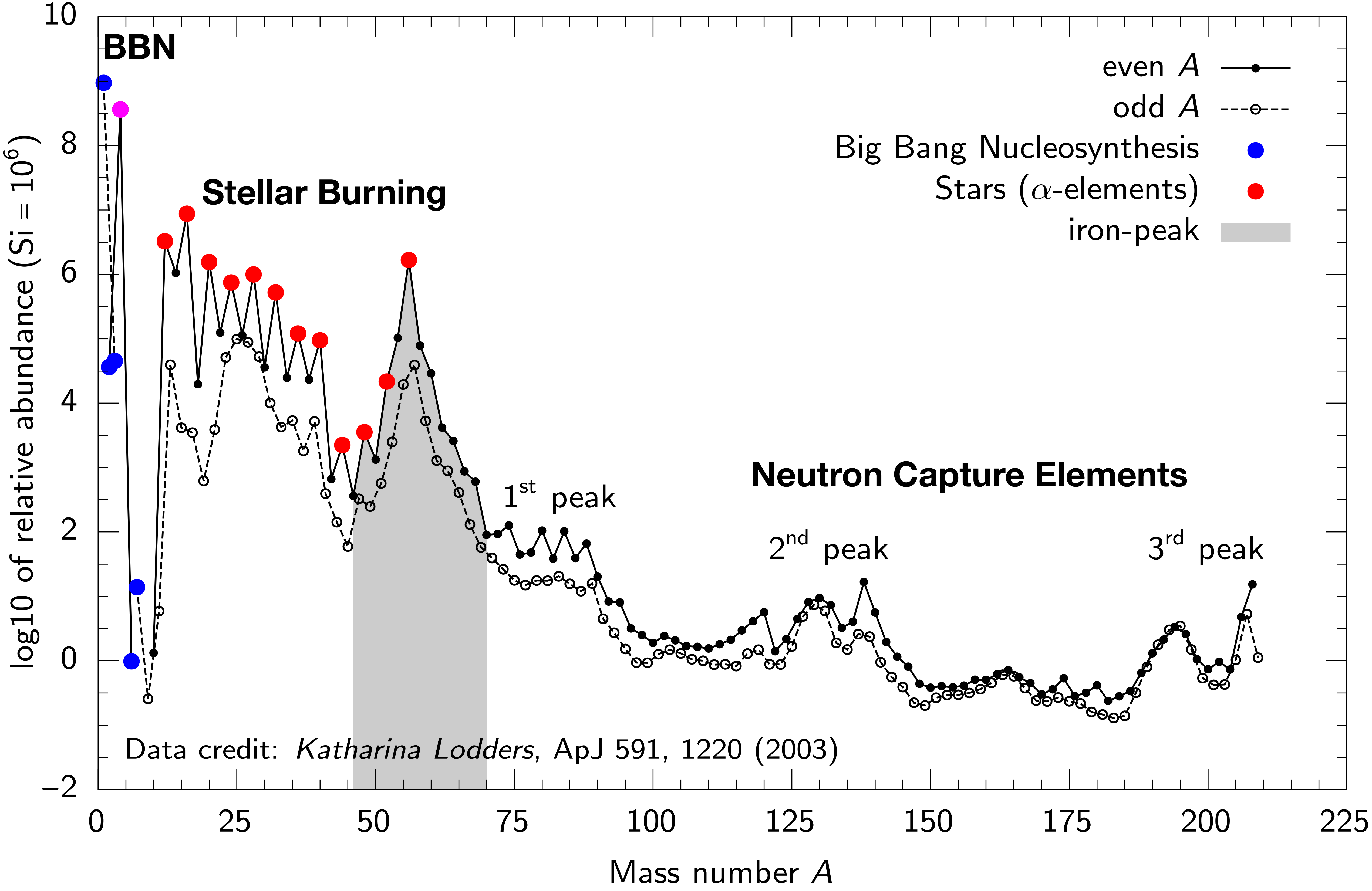
Astrophysics Theory

Luke Roberts, NSCL

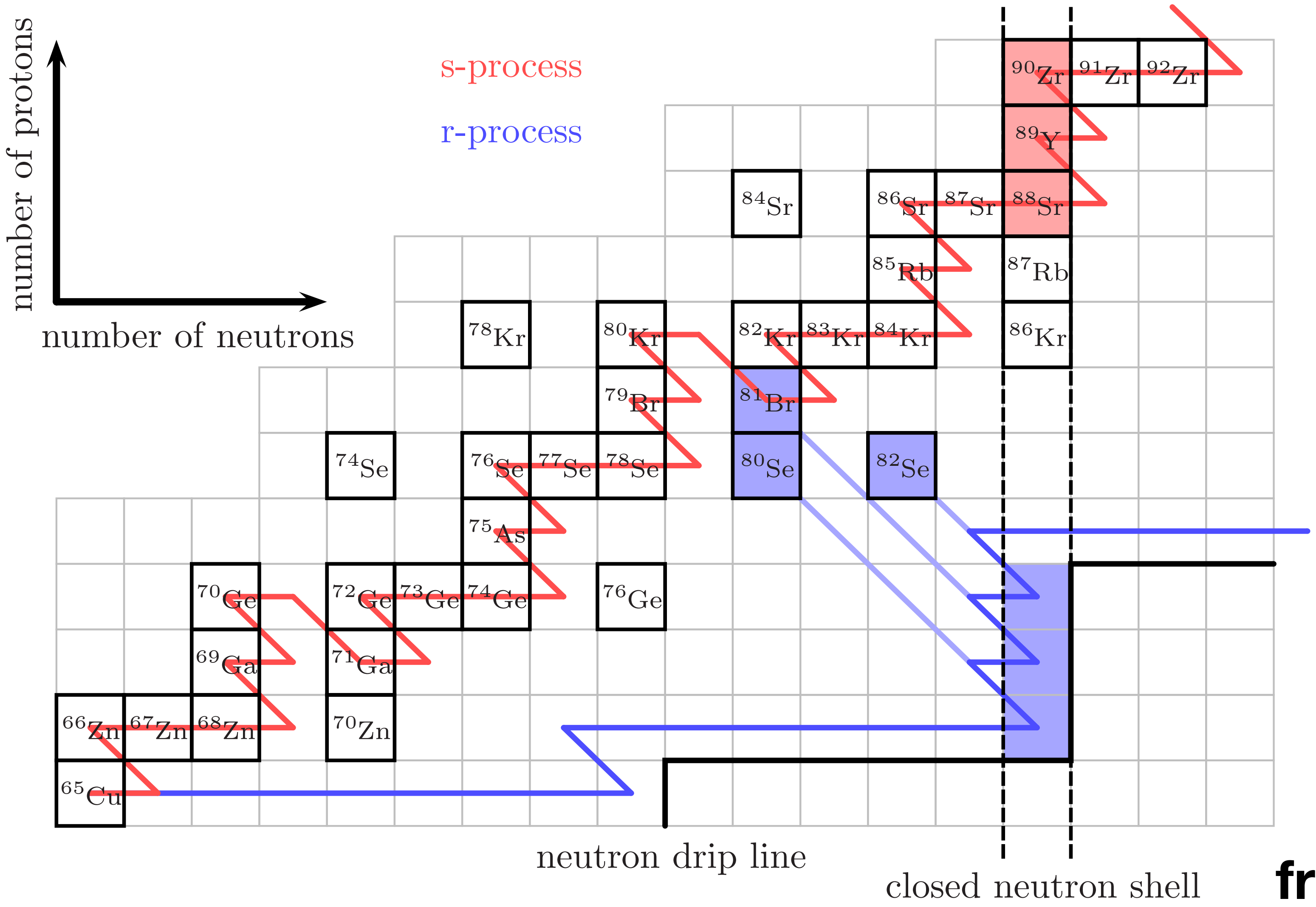
~~Astrophysics Theory~~
The r-Process and Astrophysical Sources of the r-Process

Luke Roberts, NSCL



Data credit: *Katharina Lodders*, ApJ 591, 1220 (2003)

Capturing Neutrons



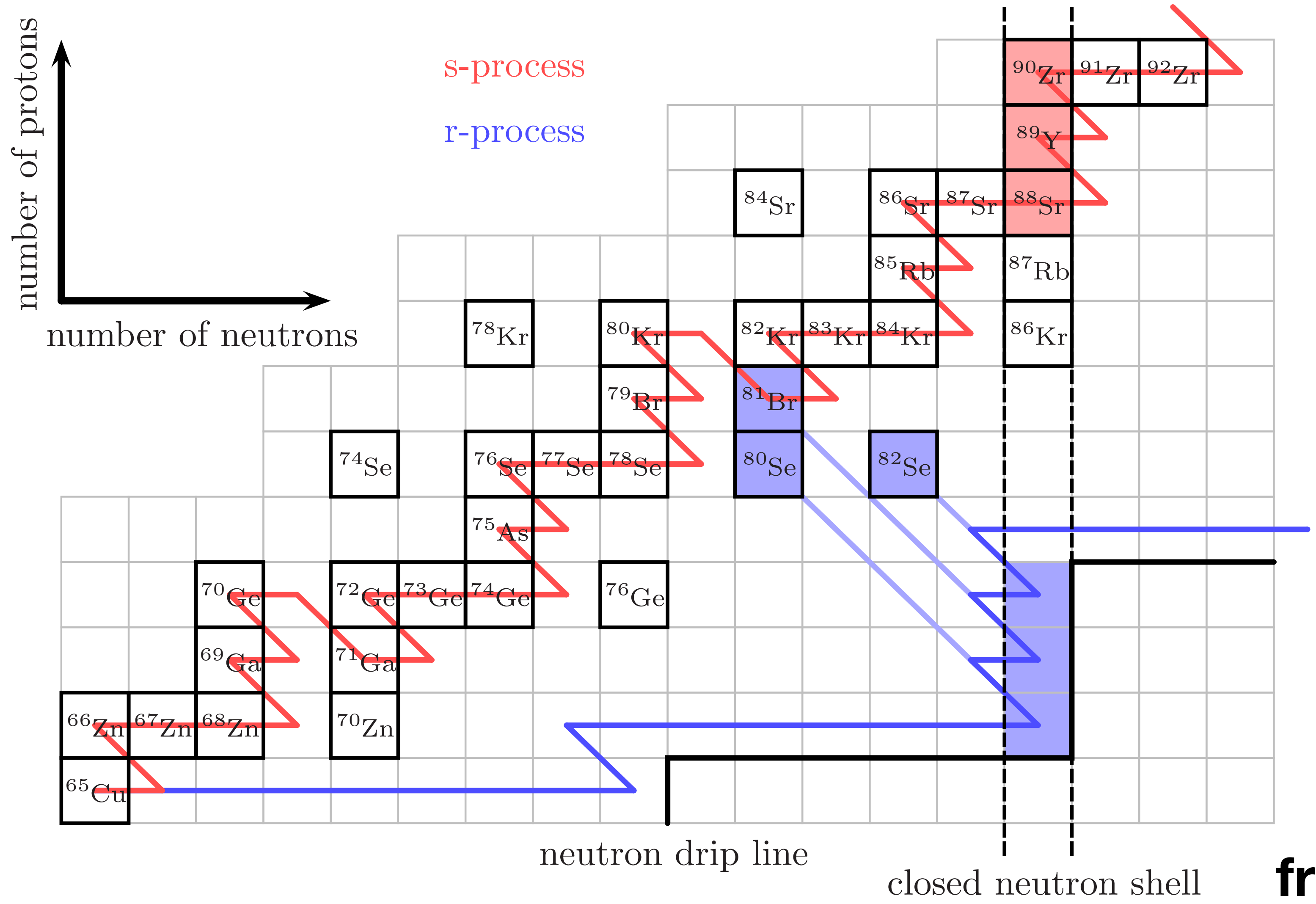
from J. Lippuner

Produce elements beyond iron by series of neutron captures followed by beta-decays:

$$(A, Z) + n \leftrightarrow (A+1, Z) + \gamma$$

$$(A, Z) \rightarrow (A, Z+1) + \bar{\nu}_e + e^-$$

Capturing Neutrons



from J. Lippuner

Two (maybe three) ways to do this:

r-process		**s-process**
$\tau_n \ll \tau_{\beta-}$	**or**	$\tau_n \gg \tau_{\beta-}$

(there is also evidence for a possible i-process)

Capturing Neutrons

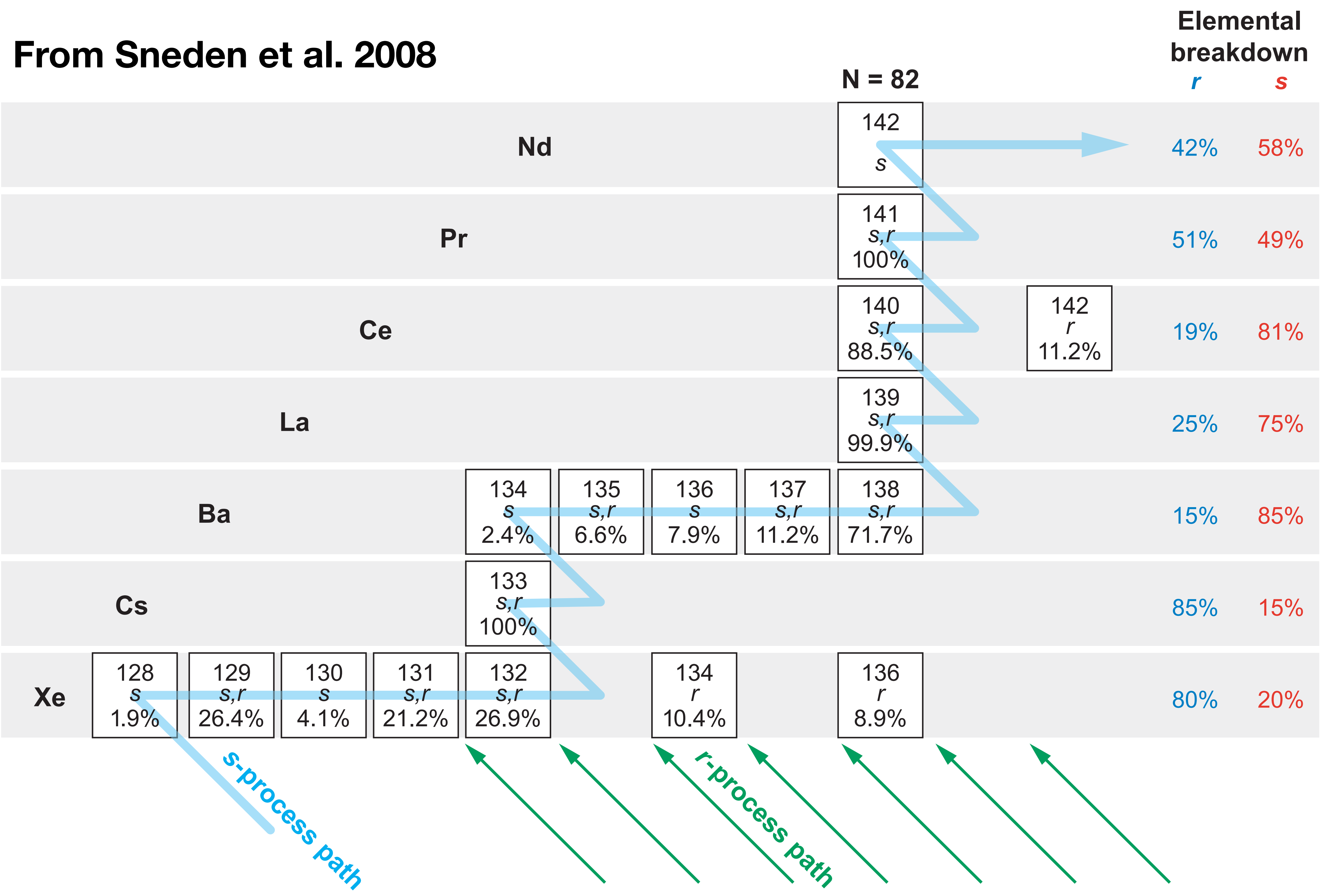
	s-process	**r-process**
mechanism	neutron capture, β^- decay	No Coulomb barrier!
τ_n	$10^2 - 10^5$ yr	$\ll \tau_{\beta-}$
$\tau_{\beta-}$	$\ll \tau_n$	$0.01 - 10$ s
site	AGB Stars inside massive stars	supernovae? NS-NS/BH mergers?
neutron source	$^{13}\mathrm{C} + {}^4\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \mathrm{n}$ $^{22}\mathrm{Ne} + {}^4\mathrm{He} \rightarrow {}^{25}\mathrm{Mg} + \mathrm{n}$	
path	valley of stability	neutron drip line
peaks*	$A = 88,\ 138,\ 208$ strontium, barium, lead	$A = 80,\ 130,\ 194$ selenium, xenon, platinum

* due to closed neutron shells at $N = 50,\ 82,\ 126$

from J. Lippuner

Separating s and r

From Sneden et al. 2008



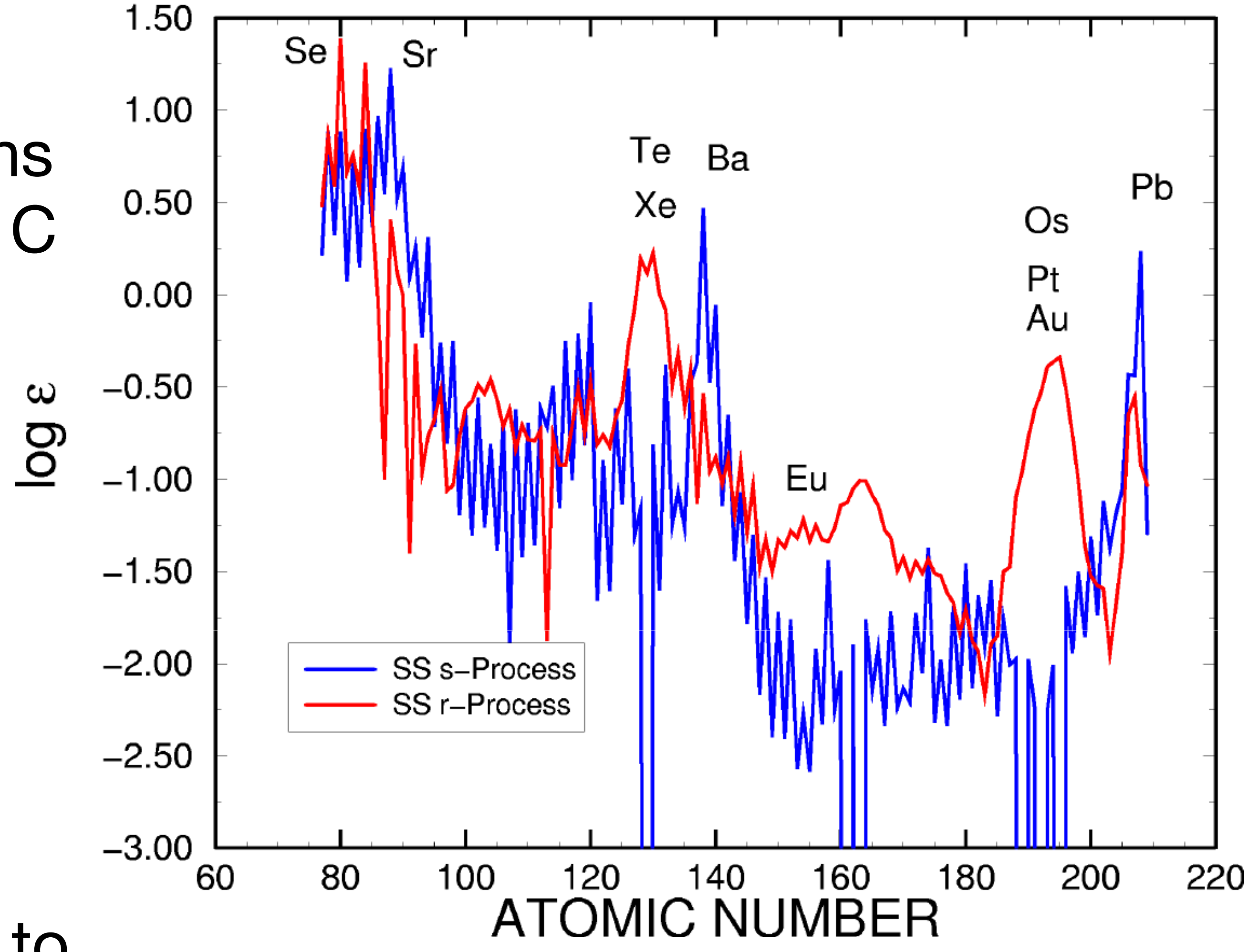
									N = 82		Elemental breakdown *r*	 *s*
Nd									142 *s*		42%	58%
Pr									141 *s,r* 100%		51%	49%
Ce									140 *s,r* 88.5%	142 *r* 11.2%	19%	81%
La									139 *s,r* 99.9%		25%	75%
Ba					134 *s* 2.4%	135 *s,r* 6.6%	136 *s* 7.9%	137 *s,r* 11.2%	138 *s,r* 71.7%		15%	85%
Cs					133 *s,r* 100%						85%	15%
Xe	128 *s* 1.9%	129 *s,r* 26.4%	130 *s* 4.1%	131 *s,r* 21.2%	132 *s,r* 26.9%		134 *r* 10.4%		136 *r* 8.9%		80%	20%

The s-process

- Secondary process, requires pre-existing seed nuclei to capture neutrons on
- Neutrons slowly produced by reactions in both AGB stars and during He and C burning in massive stars

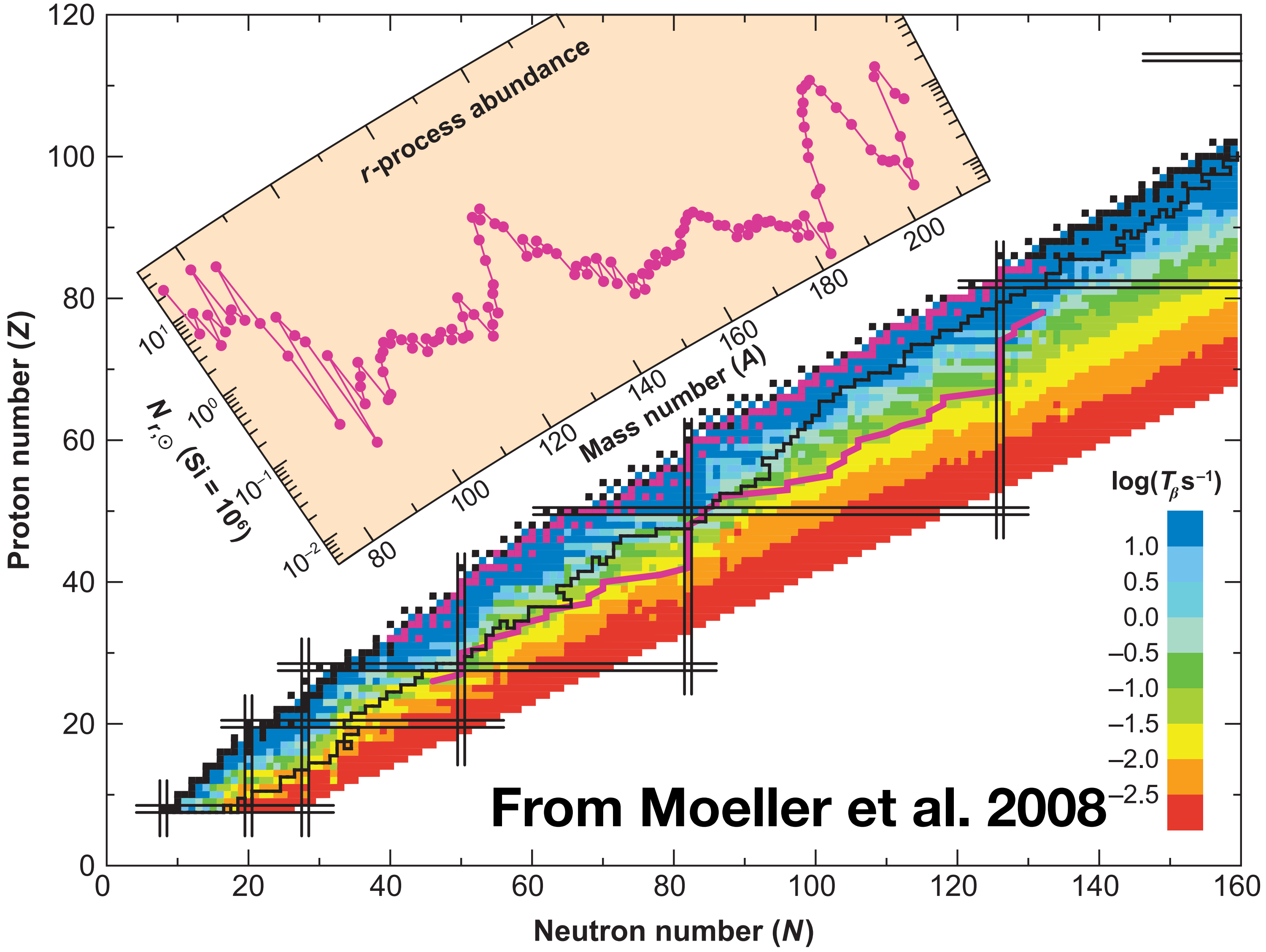
$$^{13}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \mathrm{n}$$
$$^{22}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{25}\mathrm{Mg} + \mathrm{n}$$

- Flow is mainly sensitive to neutron capture cross sections
- With accurate cross sections, can determine the s-process contribution to the solar abundances



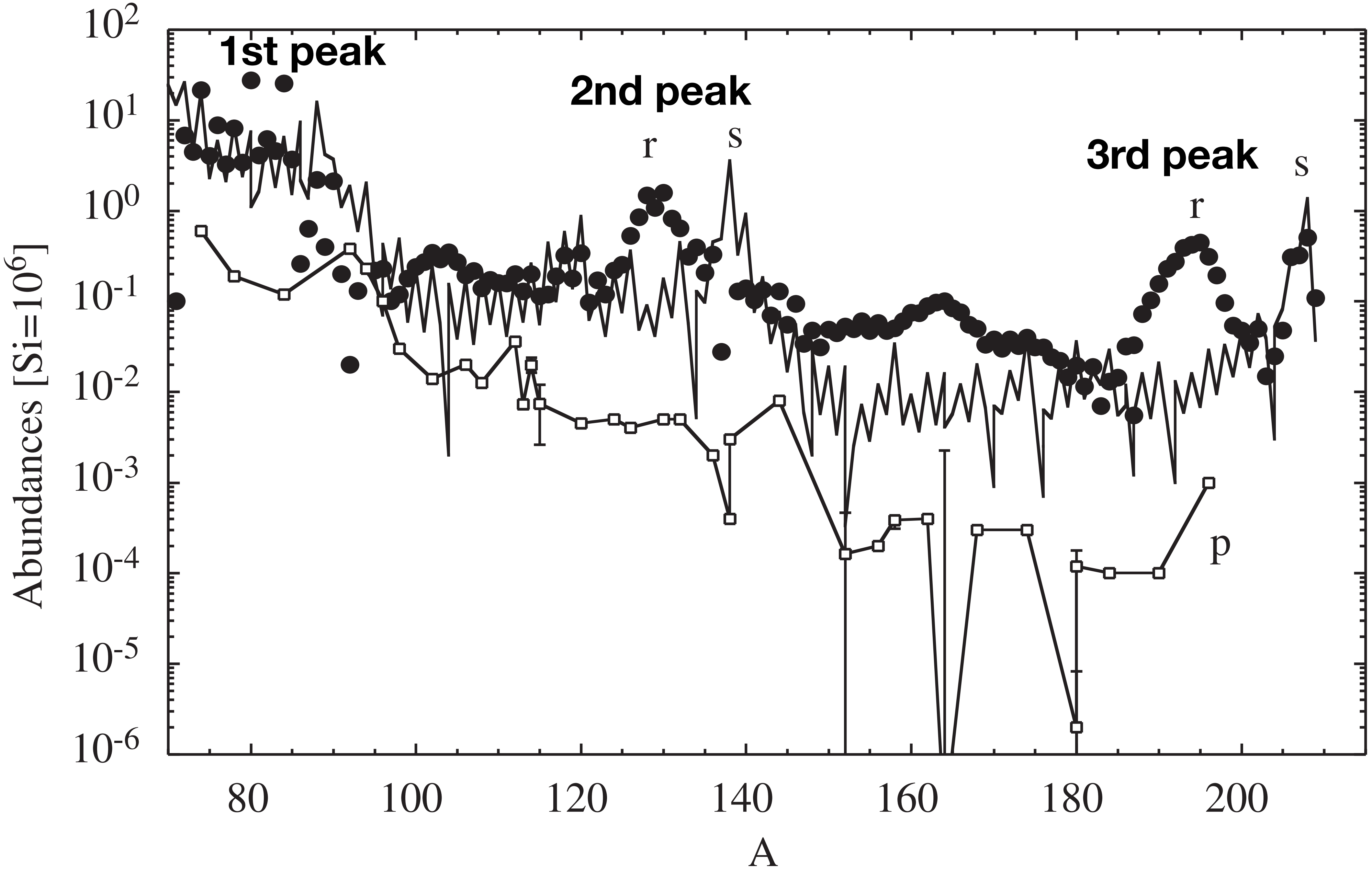
Solar r-process residuals

- Material builds up at neutron closed shells during neutron capture flow
- When neutrons are exhausted, material stays at the same mass number and decays back to stability
- Mass at which flow intersects closed shells is where peaks end up in the r-process distribution
- Different positions of peaks from s-process since intersection points are different, lower mass for r-process



From Moeller et al. 2008

Solar r-process residuals

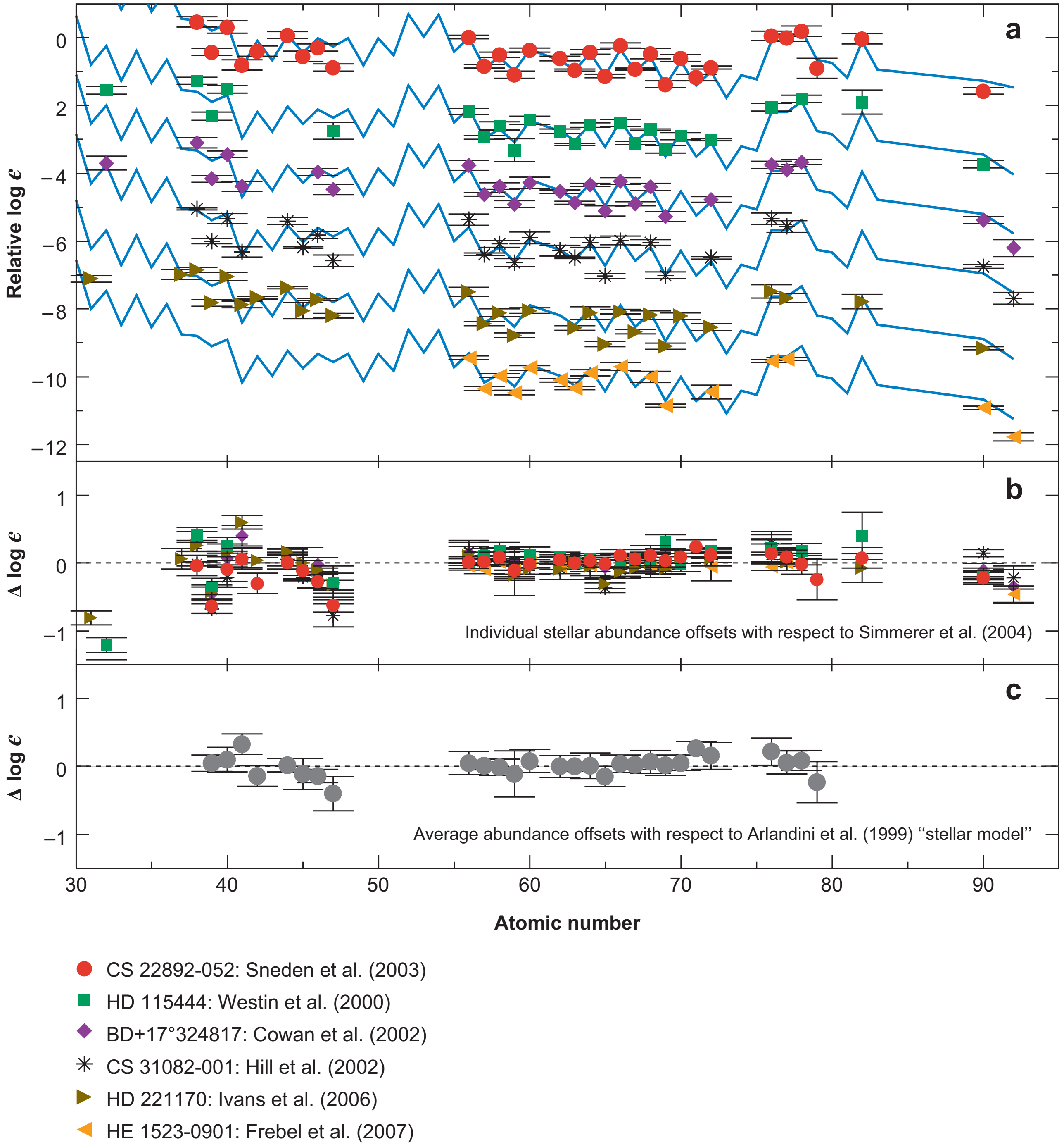


r-process in the galaxy

- Can also find low metallicity halo stars with significant enhancement of neutron capture nuclei

- In many stars, the pattern of second and third peak nuclei is very similar to the pattern of r-process residuals, suggesting they only have r-process enrichment

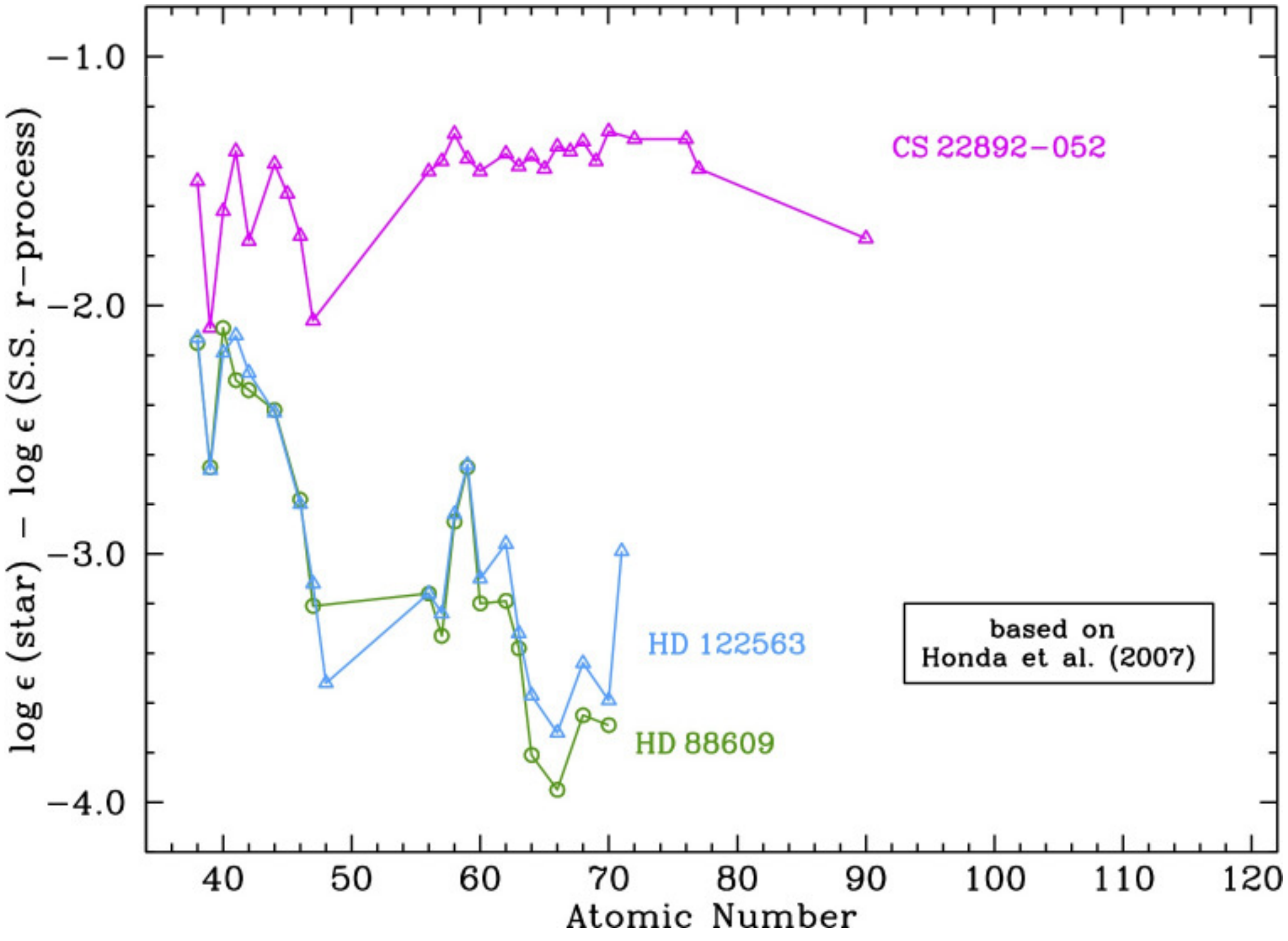
- There is more variation in the first peak r-process abundances among low metallicity halo stars



r-process in the galaxy

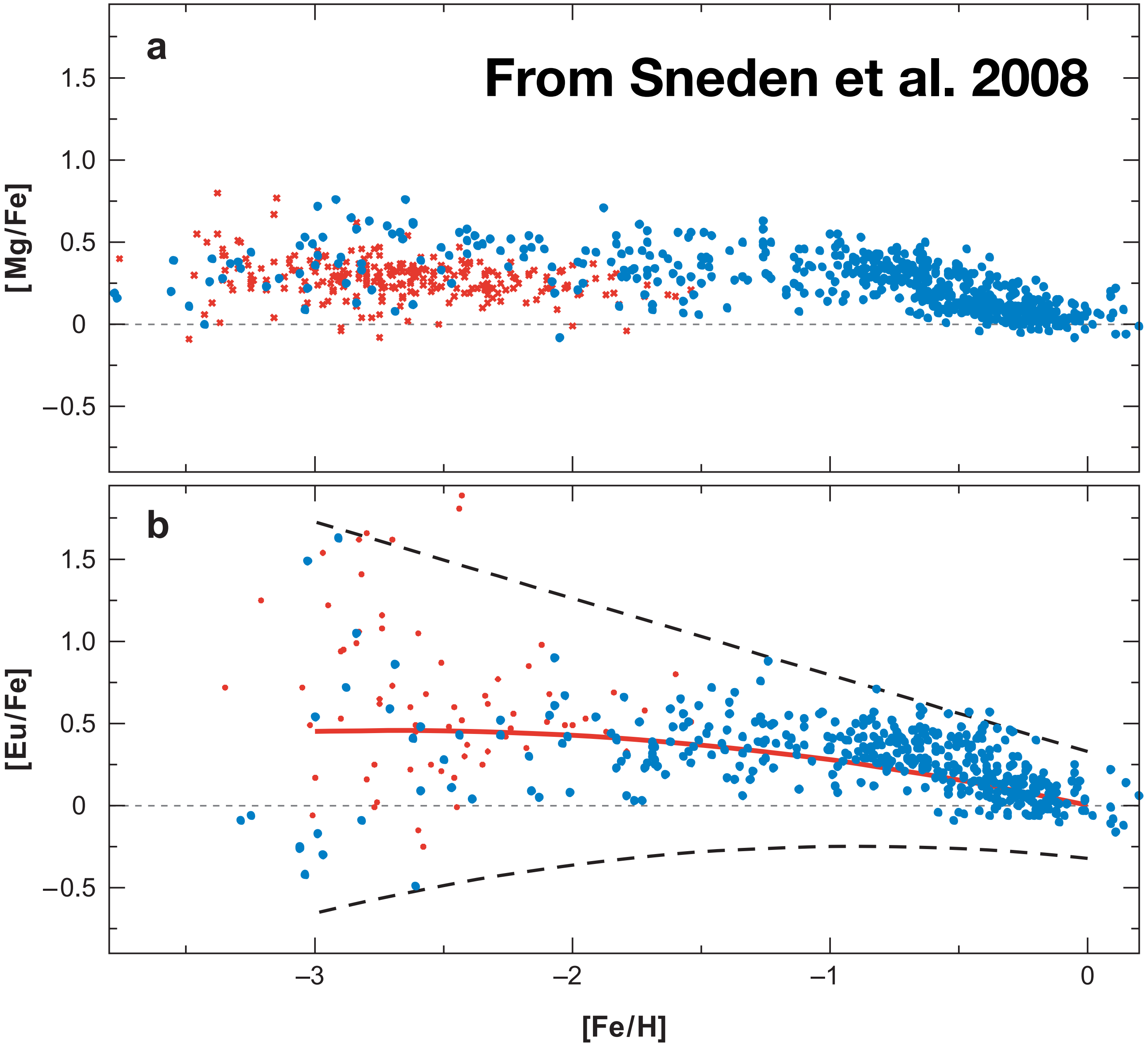
- Also can find some low-metallicity halo stars that are enriched in neutron capture elements that have an abundance pattern that is significantly different than the solar r-process abundance pattern

- Suggests there might need to be two r-process sites:
  - main r-process (up to third peak)
  - weak r-process (dominated by Sr, Y, Zr)



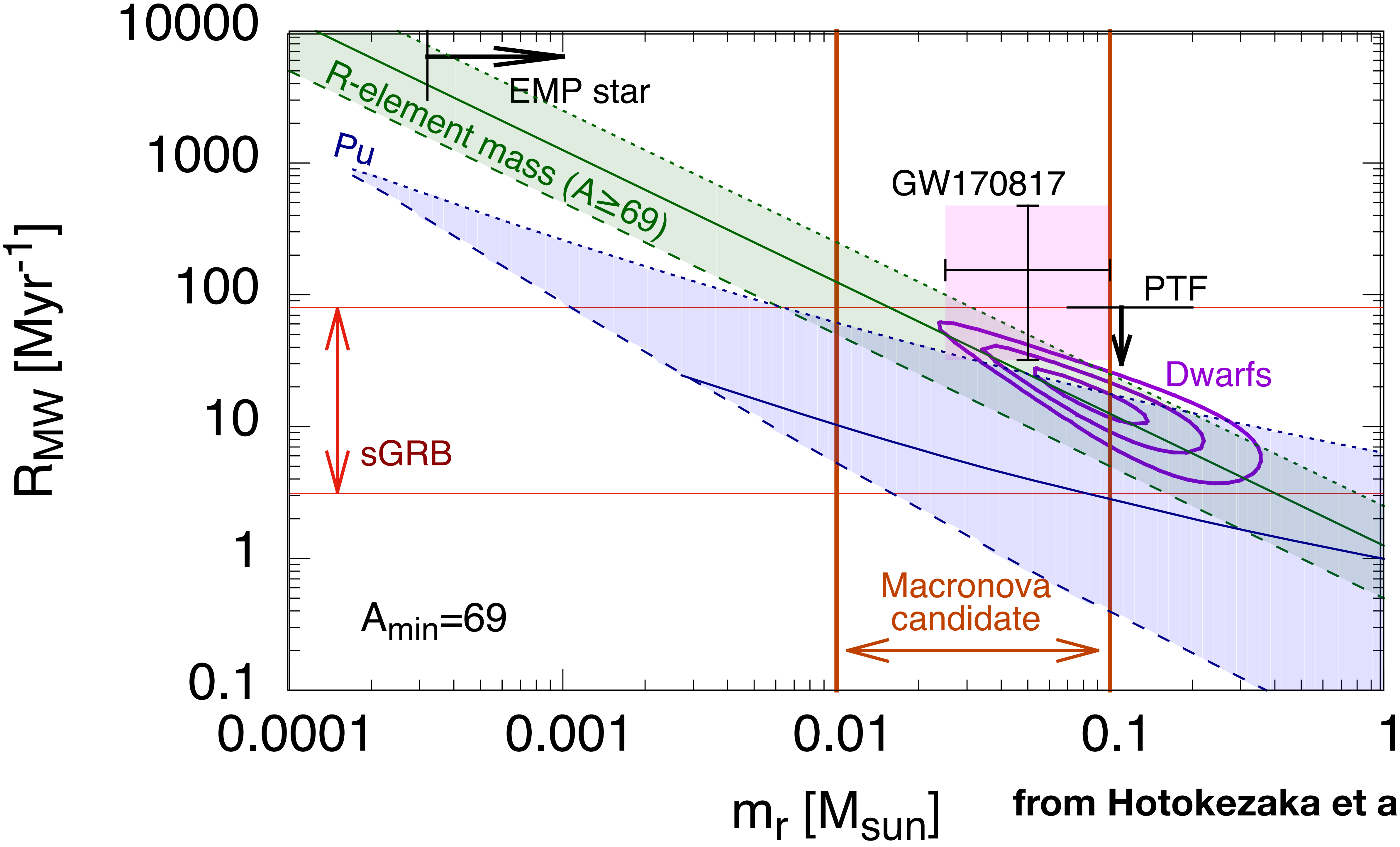
r-process in the galaxy

- r-process enhancement present at very low metallicity, similar to the beginning of enrichment of the ISM by supernovae
- Suggests that r-process must be a primary process
- Maybe an argument in favor of being associated with supernovae



Galactic r-process budget

Supernova rate is up here



from Hotokezaka et al. (2017)

r-process conditions

Some Nomenclature

Abundance: $$Y_i = \frac{n_i}{n_b}$$

Number of nuclei of species *i* per baryon in a fluid

Mass fraction: $$X_i = \frac{A_i n_i}{n_b}$$

Fraction of baryons locked in nuclei of species *i*

$$\Rightarrow \quad \sum_i X_i = 1$$

Electron fraction: $$Y_e = \frac{n_{e^-} - n_{e^+}}{n_b}$$

Net number of electrons per baryon

Charge Neutrality $$\Rightarrow \quad Y_e = \sum_i Z_i Y_i$$

Initial Conditions for the r-process

- In most r-process scenarios, material starts at high density and high temperature

- Therefore, nuclear statistical equilibrium (NSE) holds, where forward and reverse strong reactions are balanced

$$\mu_{(A,Z)} = (A-Z)\mu_n + Z\mu_p$$

Nuclei can be treated as Boltzmann particles:

$$\mu_{(A,Z)} = m_{(A,Z)} + T\ln\left[\frac{n_b Y_{(A,Z)}}{G_{(A,Z)}(T)}\left(\frac{2\pi\hbar^2 c^2}{m_{(A,Z)}T}\right)^{3/2}\right]$$

Initial Conditions for the r-process

$$\mu_{(A,Z)} = (A-Z)\mu_n + Z\mu_p$$

$$\Rightarrow \qquad Y_{(A,Z)} \approx \frac{G_{(A,Z)} A^{3/2}}{2^A} \left(\frac{n_b}{n_Q}\right)^{A-1} Y_n^N Y_p^Z \exp[BE_{(A,Z)}/T]$$

where

$$BE_{(A,Z)} = (A-Z)m_n + Zm_p - m_{(A,Z)}$$

and

$$n_Q = \left(\frac{m_n T}{2\pi\hbar^2 c^2}\right)^{3/2}$$

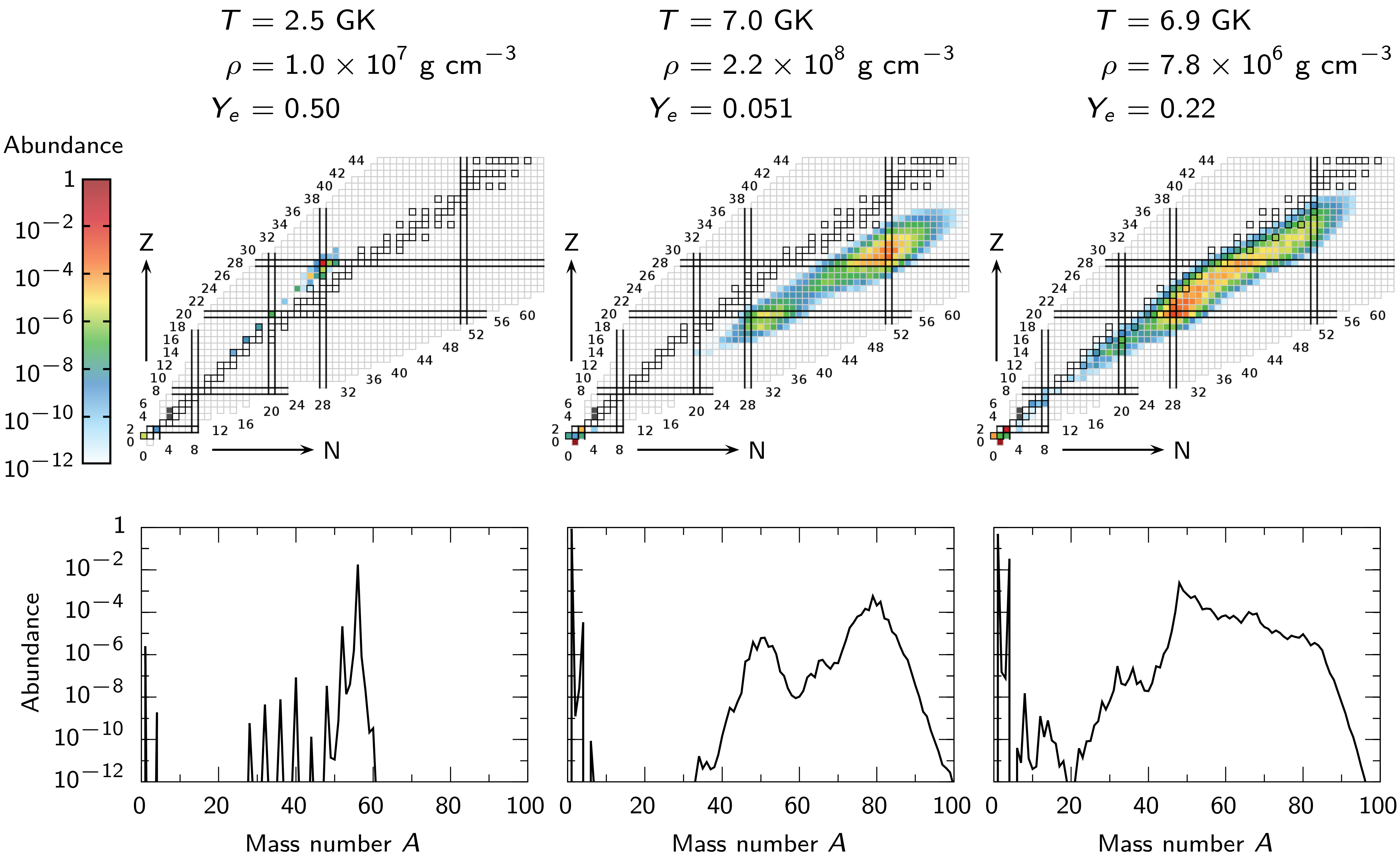
Baryon number conservation and charge neutrality give:

$$Y_e = \sum_i Z_i Y_i \qquad\qquad 1 = \sum_i A_i Y_i$$

So that

$$\boxed{Y_{(A,Z)} = Y_{(A,Z)}(n_b, Y_e, T)}$$

NSE



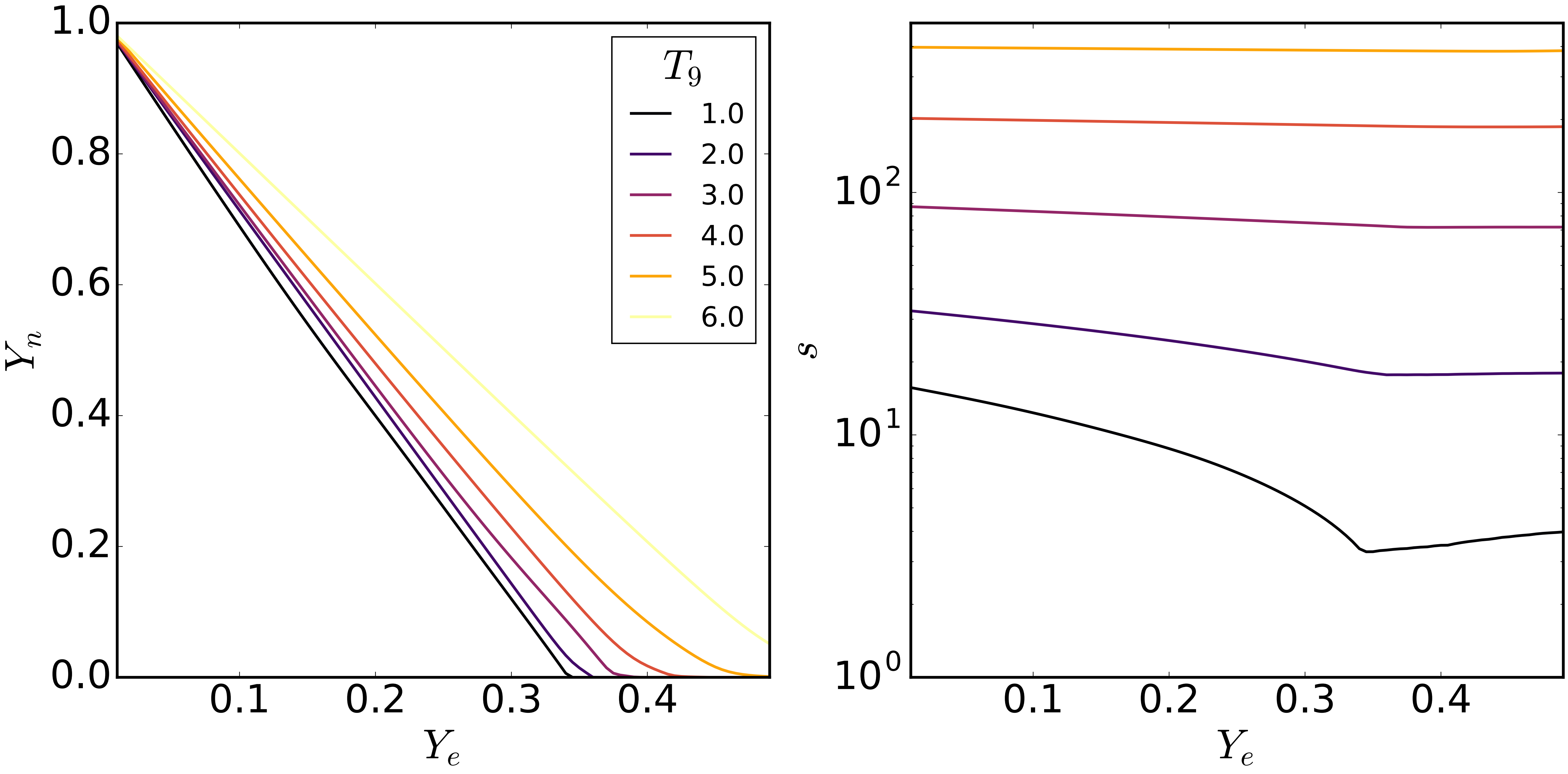
$T = 2.5$ GK
$\rho = 1.0 \times 10^7$ g cm^{-3}
$Y_e = 0.50$

$T = 7.0$ GK
$\rho = 2.2 \times 10^8$ g cm^{-3}
$Y_e = 0.051$

$T = 6.9$ GK
$\rho = 7.8 \times 10^6$ g cm^{-3}
$Y_e = 0.22$

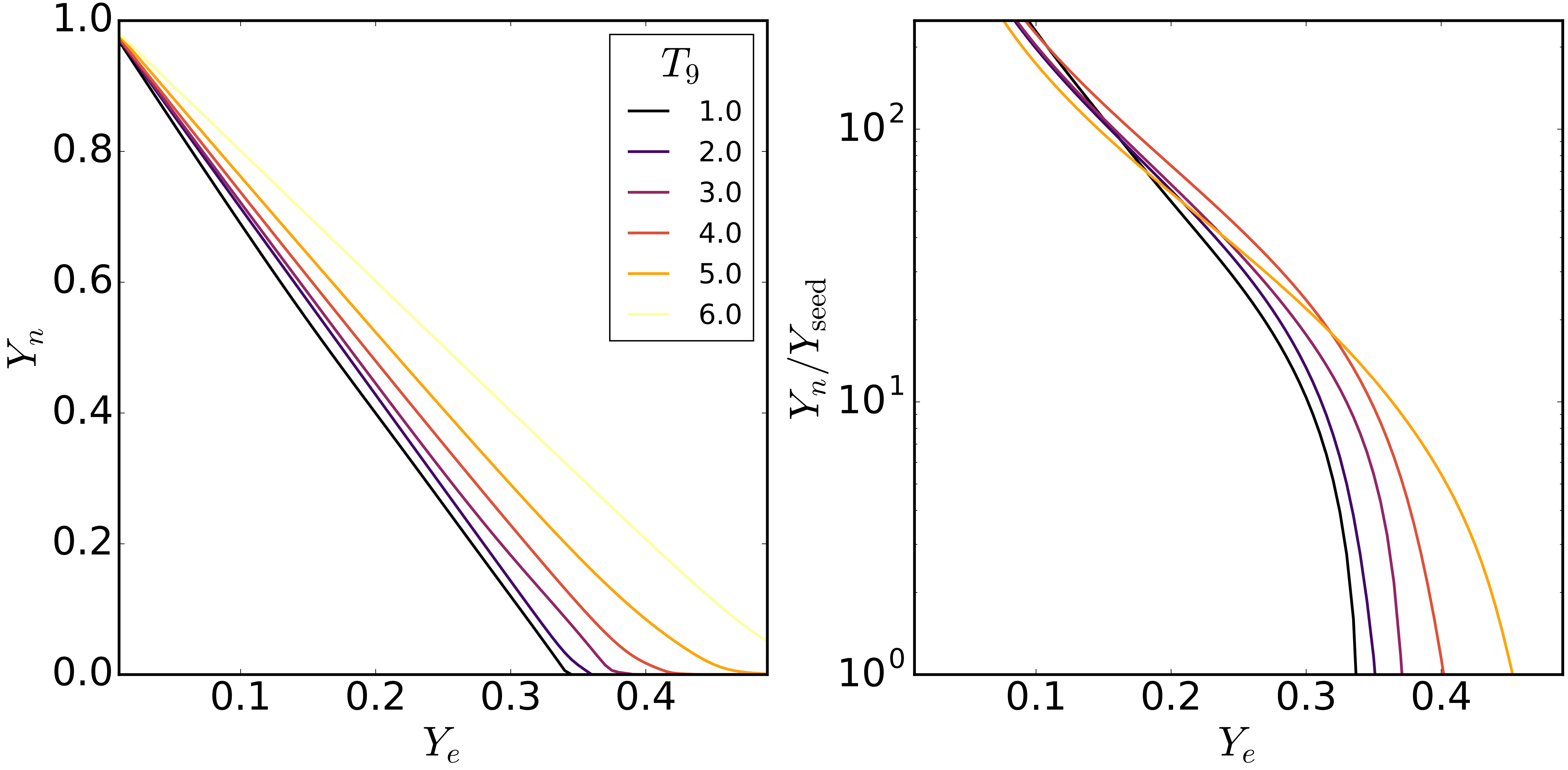
from J. Lippuner

NSE Neutron Fractions



Lower Y_e, higher s result in larger numbers of free neutrons in NSE

Neutron-to-Seed Ratio



The initial neutron-to-seed ratio is a useful metric for wether or not a complete r-process will occur

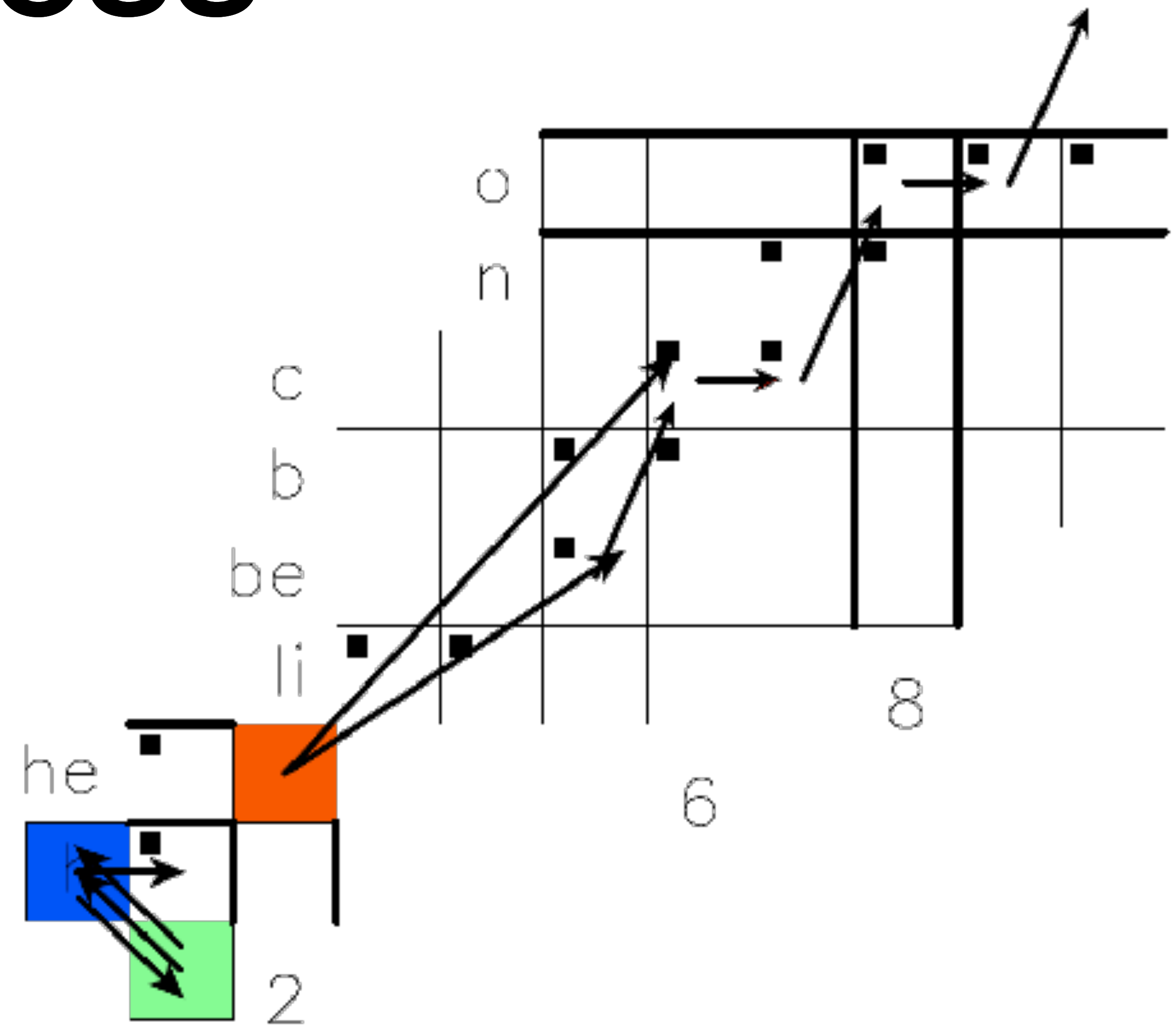
Initial Conditions for the r-process

- In high-entropy material, seeds may not form during NSE
- Instead left with alpha particles and neutrons
- Make seed nuclei via

$$3\alpha \rightarrow {}^{12}C \rightarrow ...$$

or

$$2\alpha + n \rightarrow {}^{9}Be$$
$${}^{9}Be + \alpha \rightarrow n + {}^{12}C \rightarrow ...$$



$$\frac{dY_{\mathrm{seed}}}{dt} \propto \rho^3 Y_\alpha^3 Y_n \rightarrow \frac{N_n}{N_{\mathrm{seed}}} \propto \frac{s^3}{Y_e^3 \tau_d}$$

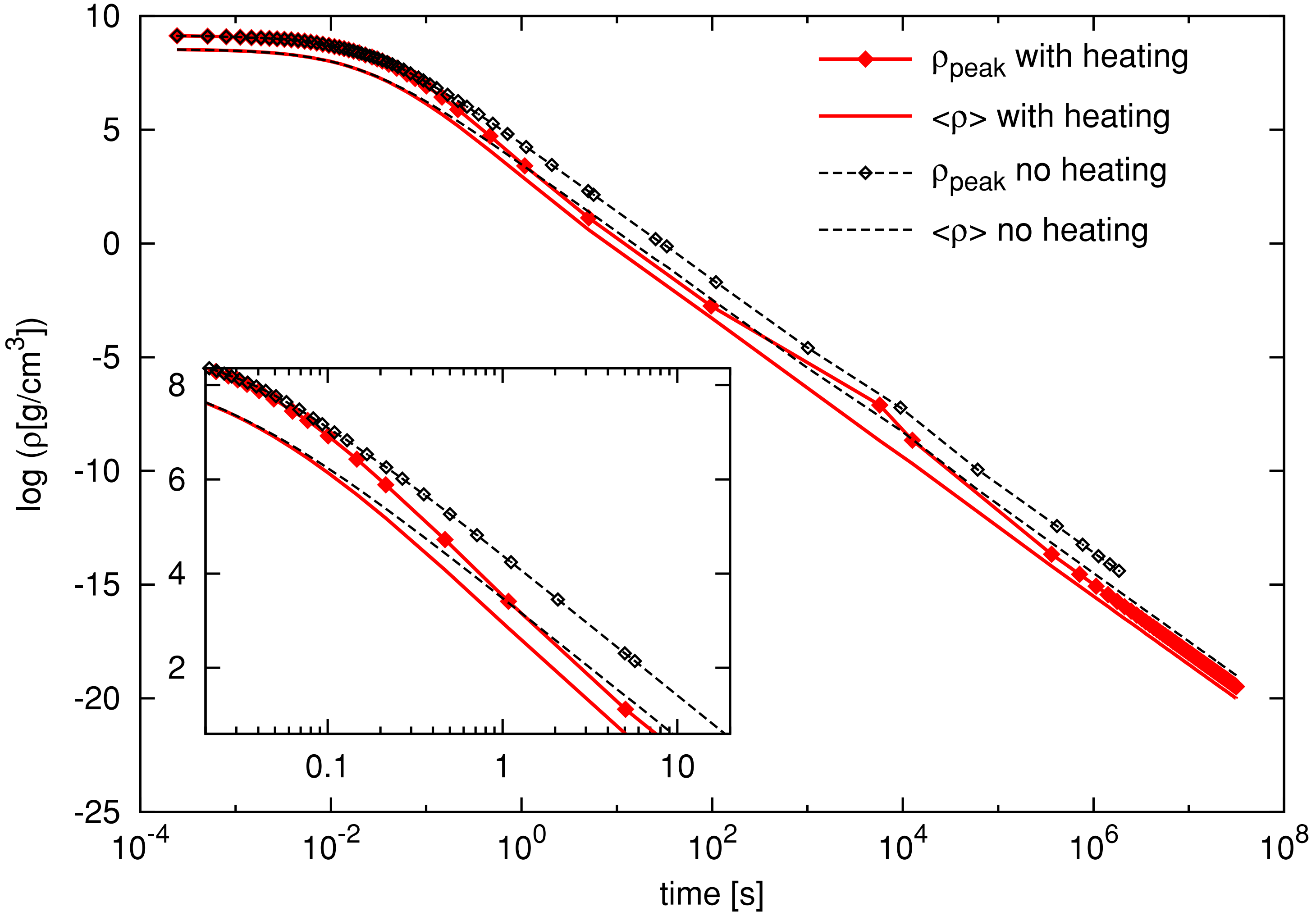
Nucleosynthesis is much more sensitive to the dynamics, but can make r-process nuclei for much higher Y_e

Calculating the r-process

- Time dependent thermodynamic conditions from simulations (if post-processing)
- By the time r-process starts, homologous expansion has set in with:

$$v \propto r$$

$$\Rightarrow \qquad \rho = \rho_0 \left(\frac{t}{t_0} \right)^{-3}$$



from Rosswog et al. (2014)

Calculating the r-process

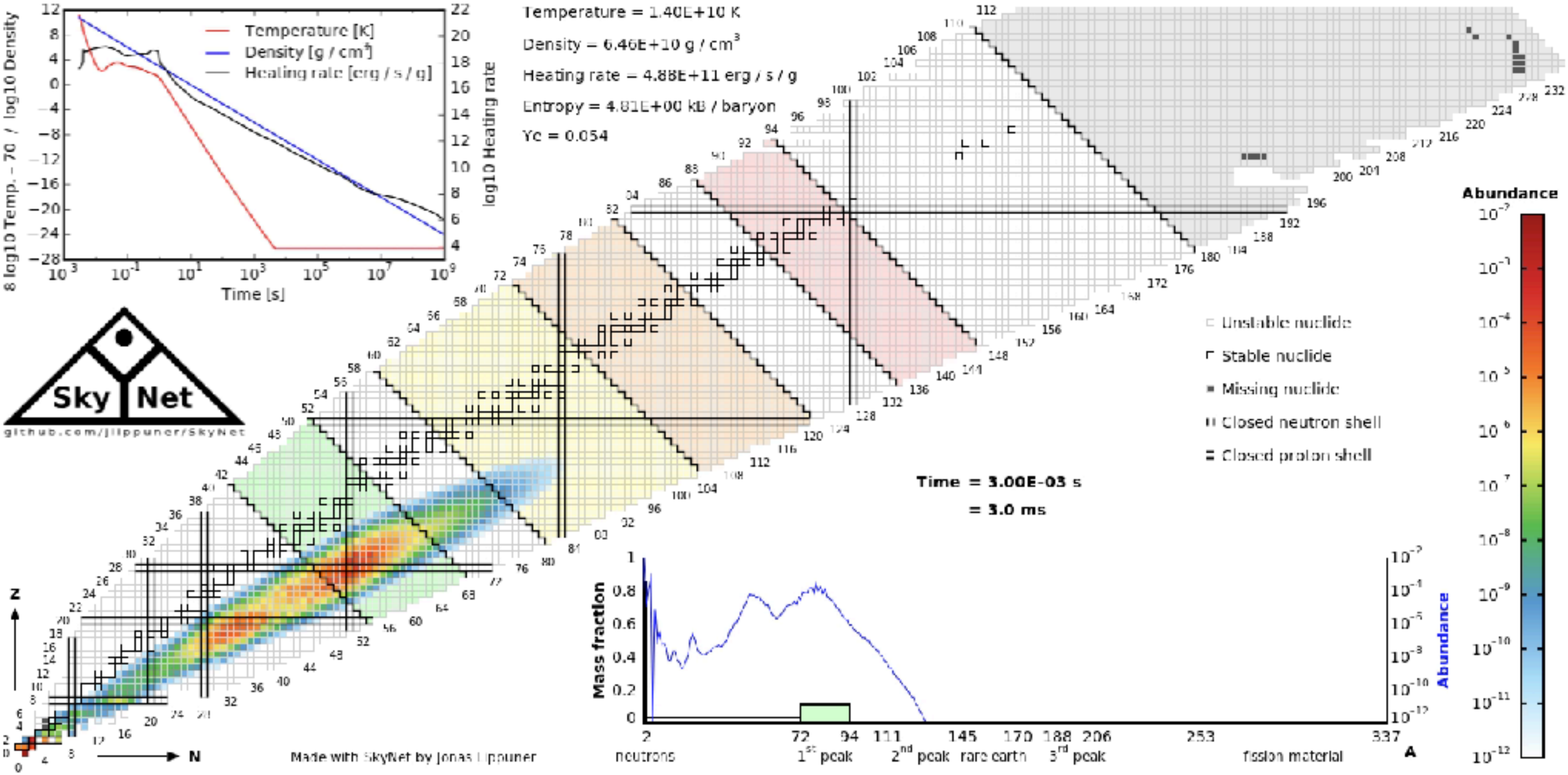
- Large, coupled system of stiff ODEs
- Need to employ implicit methods
- Input nuclear data:
  - masses
  - partition functions
  - beta-decay rates
  - neutron capture rates
  - fission rates
  - …
- Initial composition

$$\begin{aligned}\dot{Y}_{(A,Z)} \quad = \quad & n_b\langle\sigma v\rangle_{n+(A-1,Z)}Y_nY_{(A-1,Z)} - \lambda_{\gamma(A,Z)}Y_{(A,Z)} \\ & -n_b\langle\sigma v\rangle_{n+(A,Z)}Y_nY_{(A,Z)} + \lambda_{\gamma(A+1,Z)}Y_{(A+1,Z)} \\ & +\lambda_{\beta^-(A,Z-1)}Y_{(A,Z-1)} - \lambda_{\beta^-(A,Z)}Y_{(A,Z)}\end{aligned}$$

+ fission + electron capture + …

Velocity averaged cross-section:

$$\langle\sigma_\alpha v_{\mathrm{rel}}\rangle = \int_{[1]}\frac{f_1}{n_1}\int_{[2]}\frac{f_2}{n_2}v_{\mathrm{rel}}\sigma_\alpha$$


Temperature = 1.40E+10 K
Density = 6.46E+10 g / cm^3
Heating rate = 4.88E+11 erg / s / g
Entropy = 4.81E+00 kB / baryon
Ye = 0.054
Temperature [K]
Density [g / cm^3]
Heating rate [erg / s / g]
8 log10 Temp. − 70 / log10 Density
log10 Heating rate
Time [s]
Sky Net
github.com/jlippuner/SkyNet
Unstable nuclide
Stable nuclide
Missing nuclide
Closed neutron shell
Closed proton shell
Time = 3.00E-03 s
= 3.0 ms
Abundance
Z
N
Made with SkyNet by Jonas Lippuner
Mass fraction
Abundance
A
neutrons
1st peak
2nd peak
rare earth
3rd peak
fission material
2
72
94
111
145
170
188
206
253
337

Self-heating

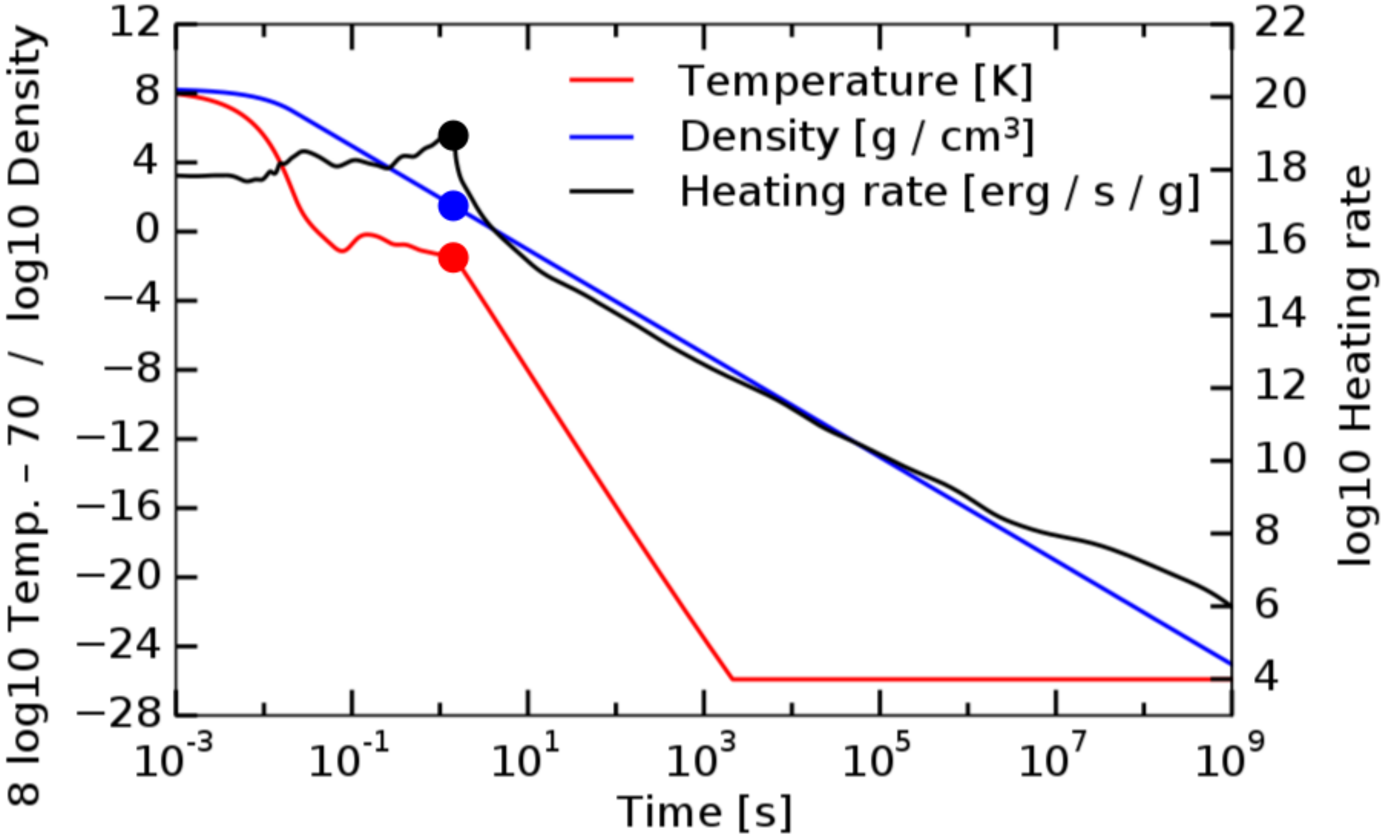
- Neutron captures and beta decays release rest-mass energy

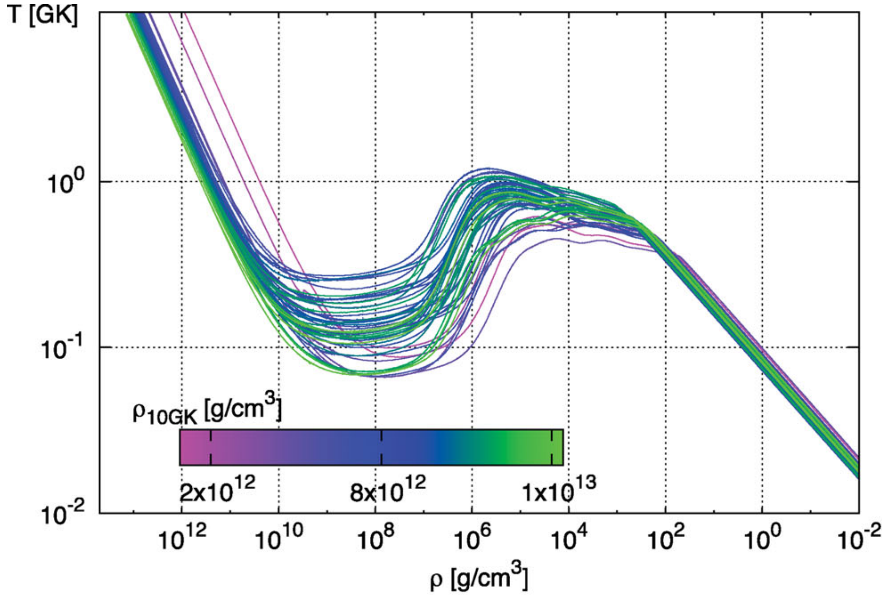
$$d\epsilon = dq_{\text{ext}} - PdV = Tds - PdV + \sum_i \mu_i dY_i + \mu_e dY_e$$

$$\Rightarrow \quad ds = dq_{\text{ext}}/T + \sum_i \frac{\mu_i}{T} dY_i + \frac{\mu_e}{T} dY_e$$

- Increases the entropy of the fluid and keeps the temperature of the expanding gas near constant

- This can substantially impact the path of the r-process





Parameterizing r-process conditions

Because equilibrium conditions hold initially, the properties fluid elements are described reasonably well by three parameters:

Electron Fraction at 5 GK:	Y_e	Most important, sets the number of (free) neutrons
Entropy per baryon:	S	important, helps set the number of free neutrons and determines density during r-process
Dynamical timescale:	$\tau_d = \left(\frac{n_b}{\dot{n}_b}\right)_{T\approx 1\,\mathrm{GK}}$	Impacts when reactions fall out of NSE, also impacts non-equilibrium seed formation for high entropy ejecta

Run r-process Calculations Yourself

Sky Net

github.com/jlippuner/SkyNet

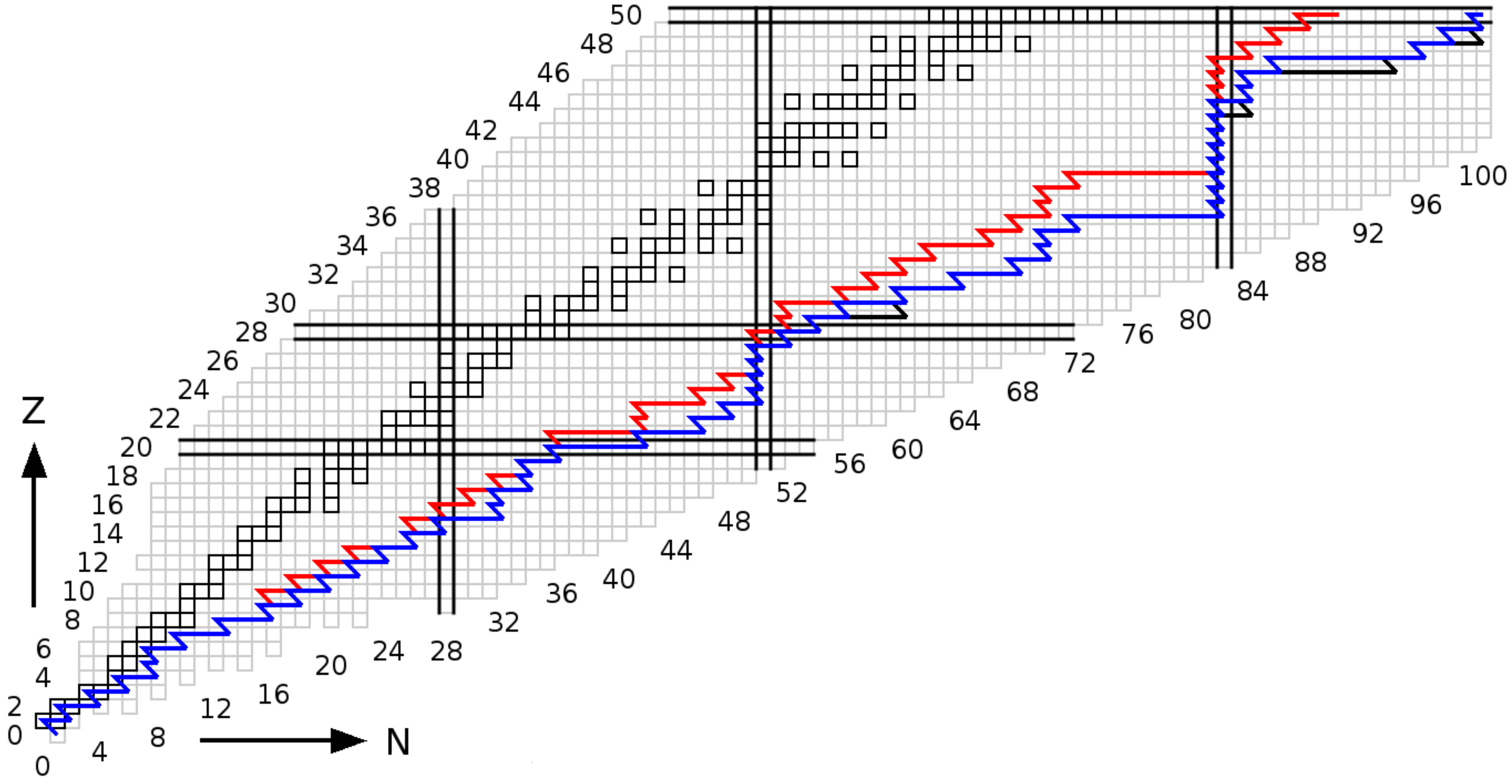
- General-purpose nuclear reaction network
- $\sim$8000 isotopes, $\sim$140,000 nuclear reactions
- Evolves temperature and entropy based on nuclear reactions
- Input: $\rho(t)$, initial composition, initial entropy or temperature
- Open source

The r-Process and Astrophysical Sources of the r-Process

Luke Roberts, NSCL

r-process path depends on conditions

- Higher temperature implies path lies closer to stability
- Path particularly sensitive to mass differences
- Neutron separation energies small just beyond neutron closed shells, forces the path to stay along closed shells until closer to stability



r-process paths predicted by the waiting point approximation for two different outflows

r-process path depends on conditions

- Higher temperature implies path lies closer to stability
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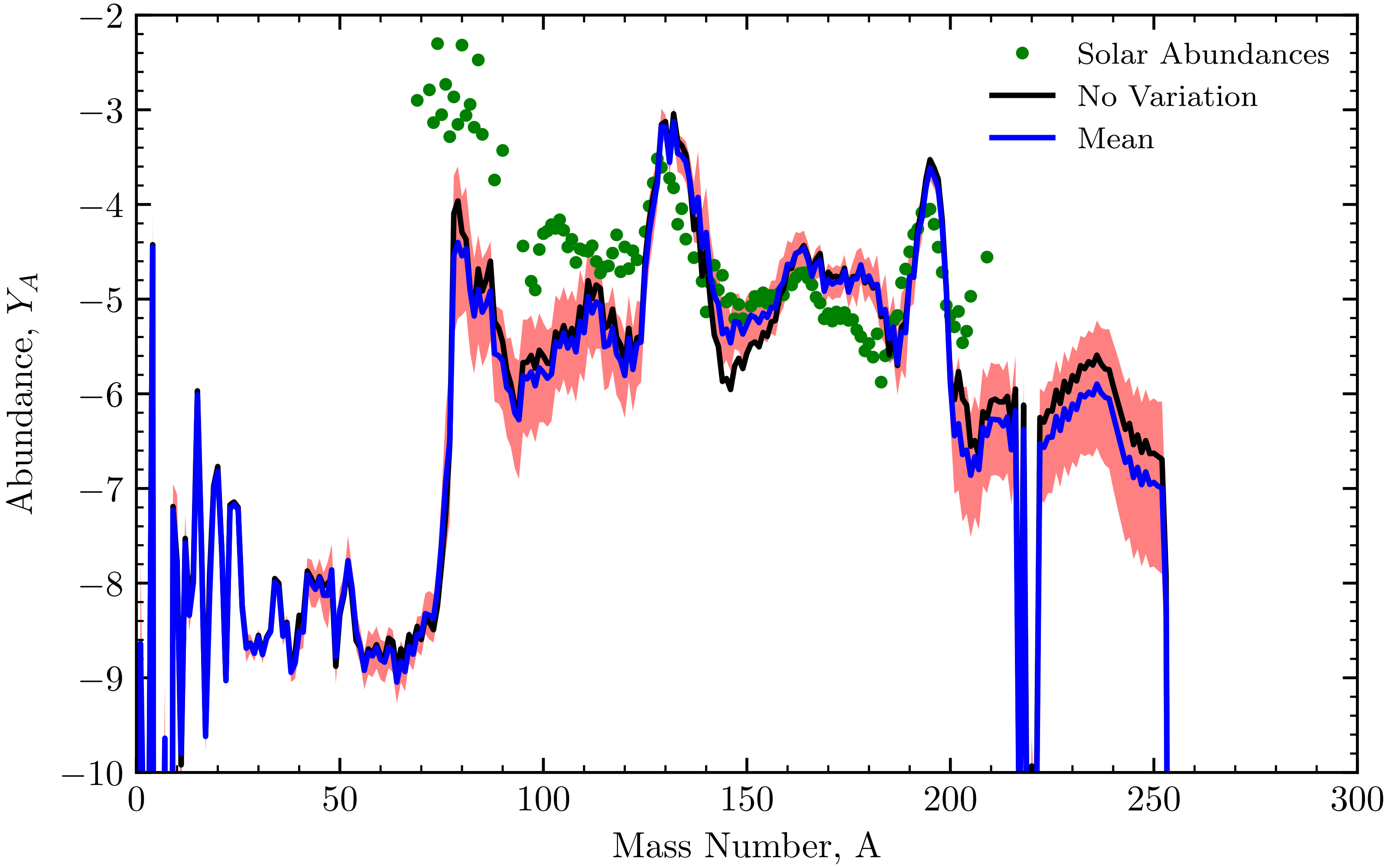
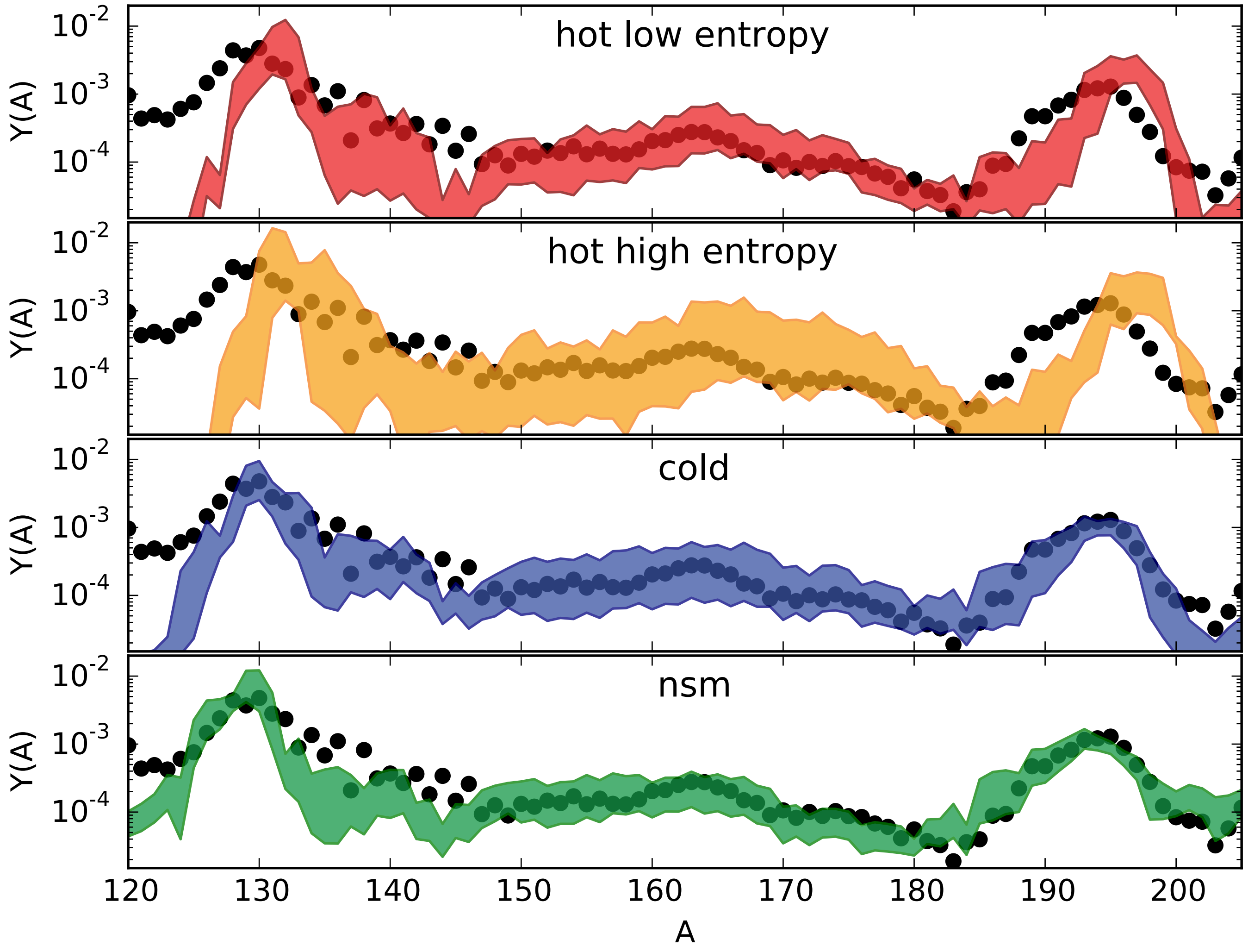


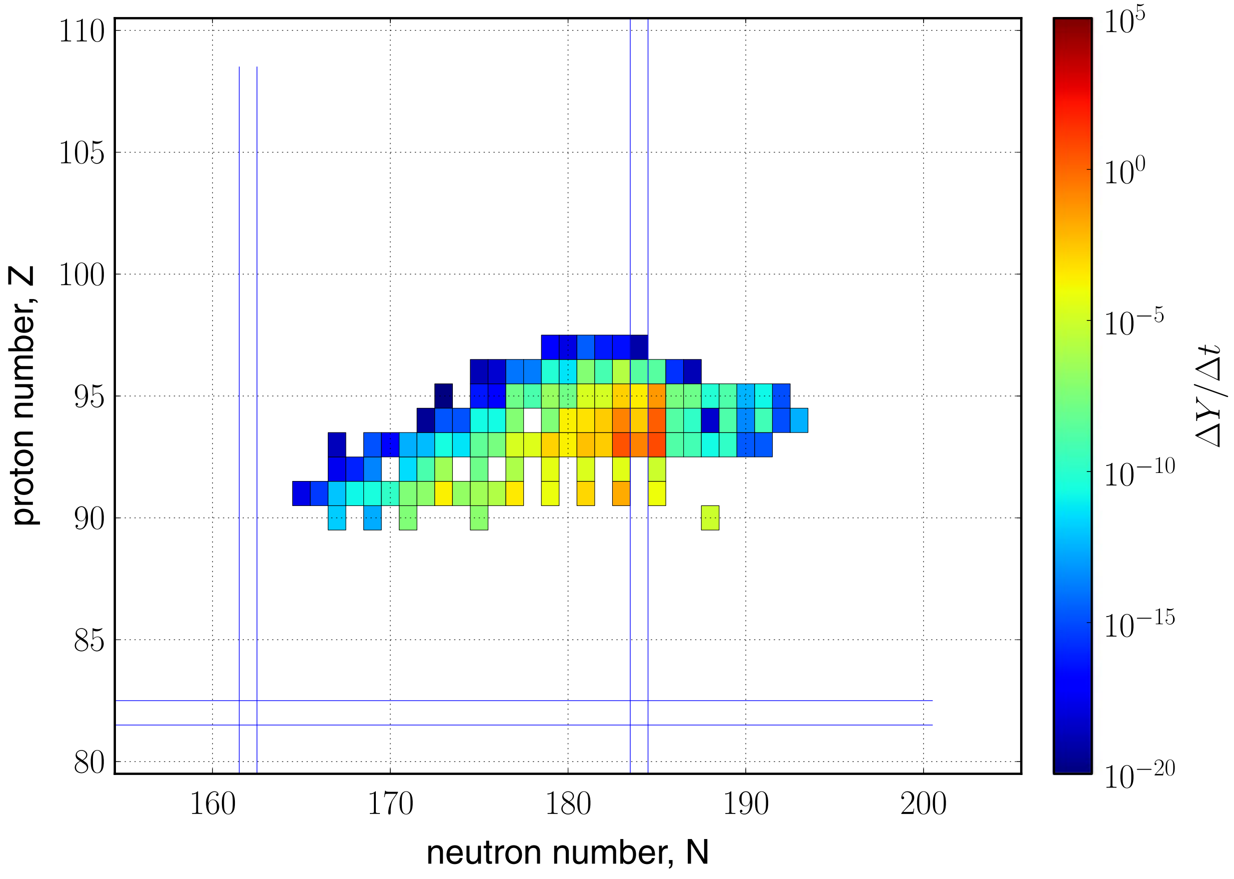
Sensitivity to input nuclear physics

- Propagating mass uncertainties through all inputs to the reaction network
  - neutron captures
  - photo-dissociation
  - beta-decays

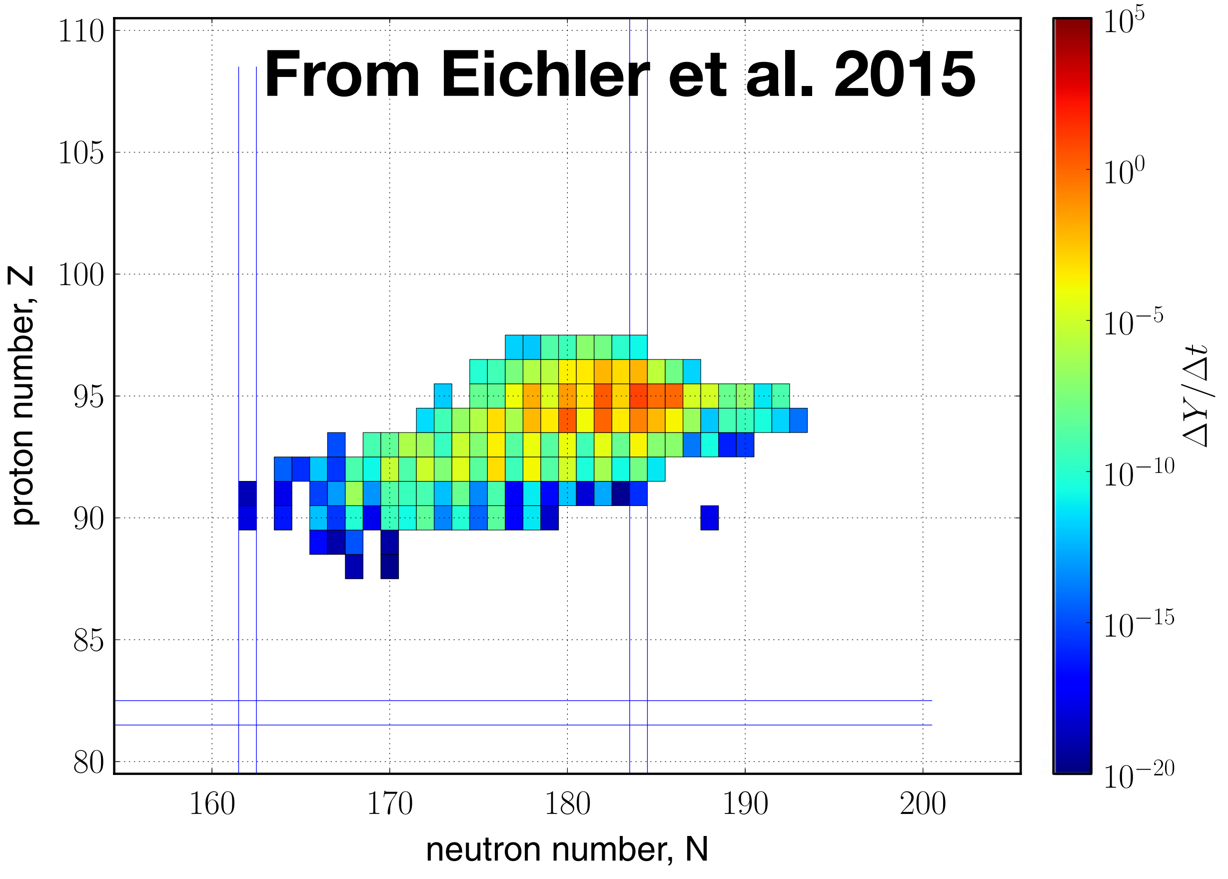


Mumpower et al. (2015)

Fission: The end of the r-process



(a) β-delayed fission


From Eichler et al. 2015

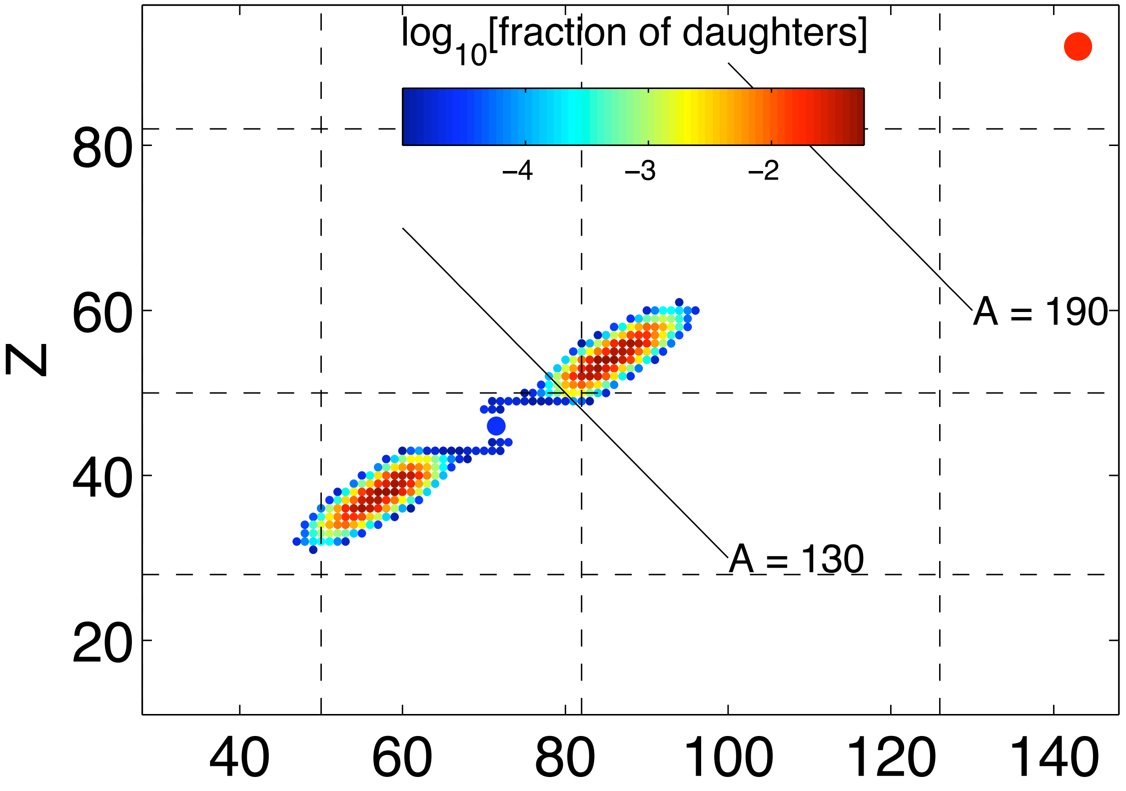
(b) neutron-induced fission

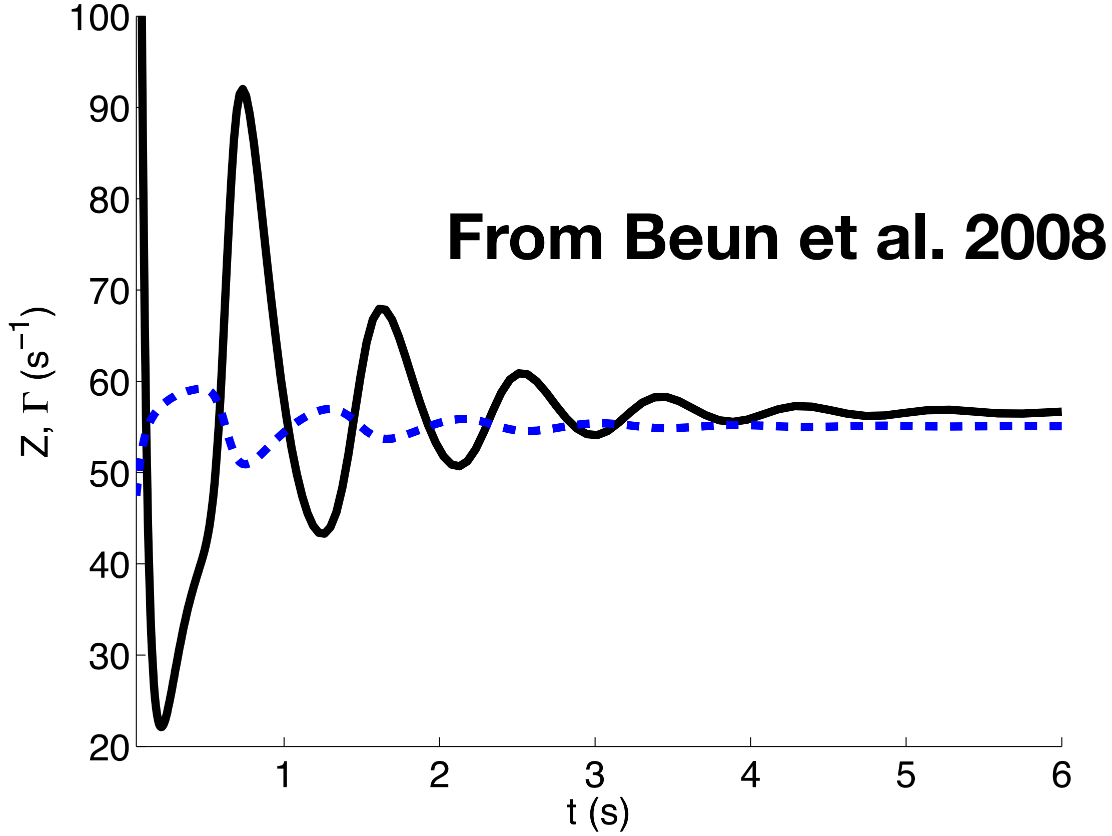
- Once material reaches nuclei susceptible to either neutron induced or beta-delayed fission, the r-process reaches its maximum extent

- Material is pushed back down to lower mass

Fission Cycling

- Fission takes single seed, turns it into two back near the first peak
- If the initial neutron-to-seed ratio is high, material can cycle through this process a number of times
- Distribution of daughter nuclei important to final pattern



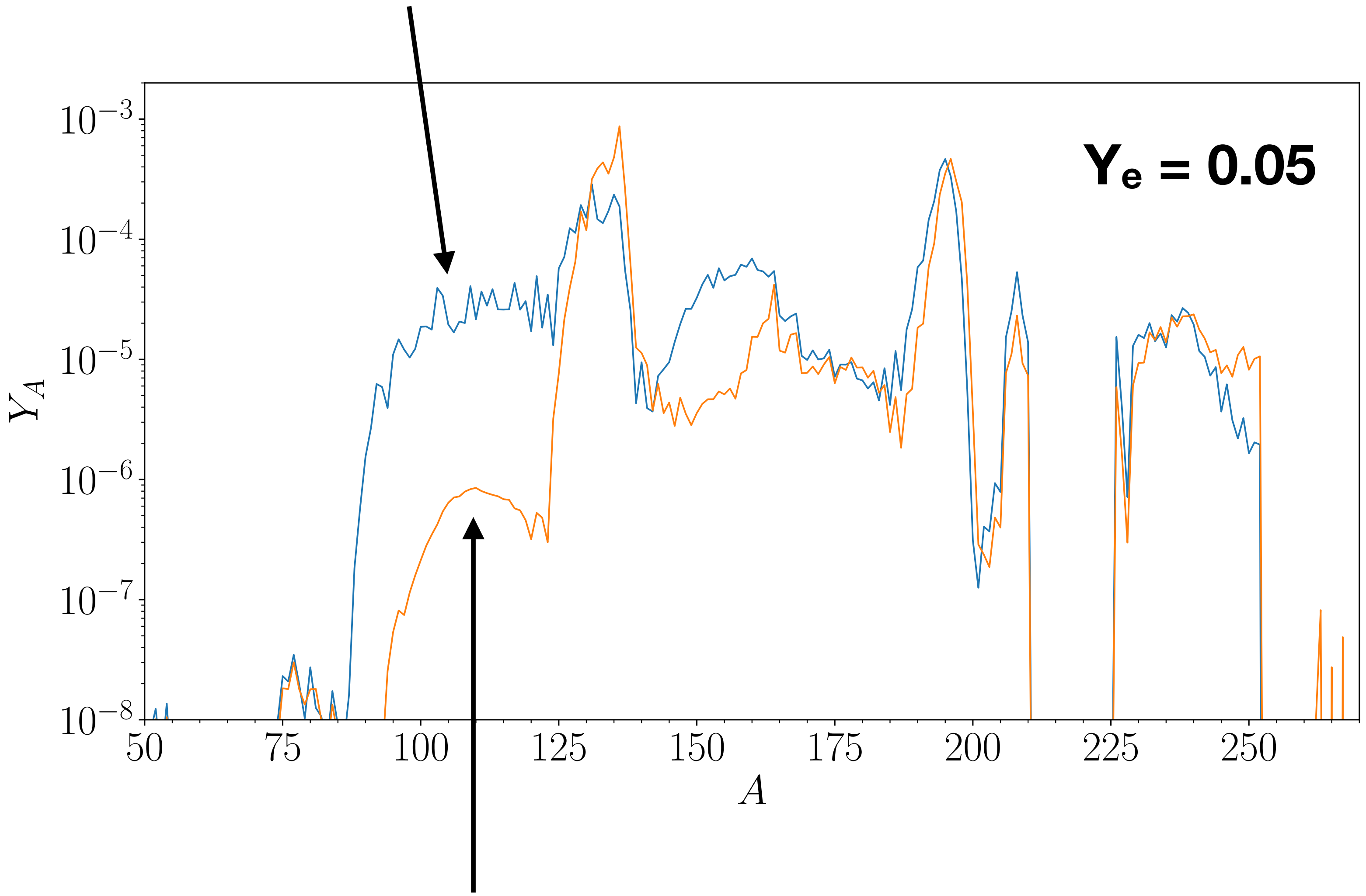


From Beun et al. 2008

Late-time Fission

- Fission after neutron exhaustion, either by beta-delayed fission or spontaneous fission can substantially impact the abundance pattern at low mass

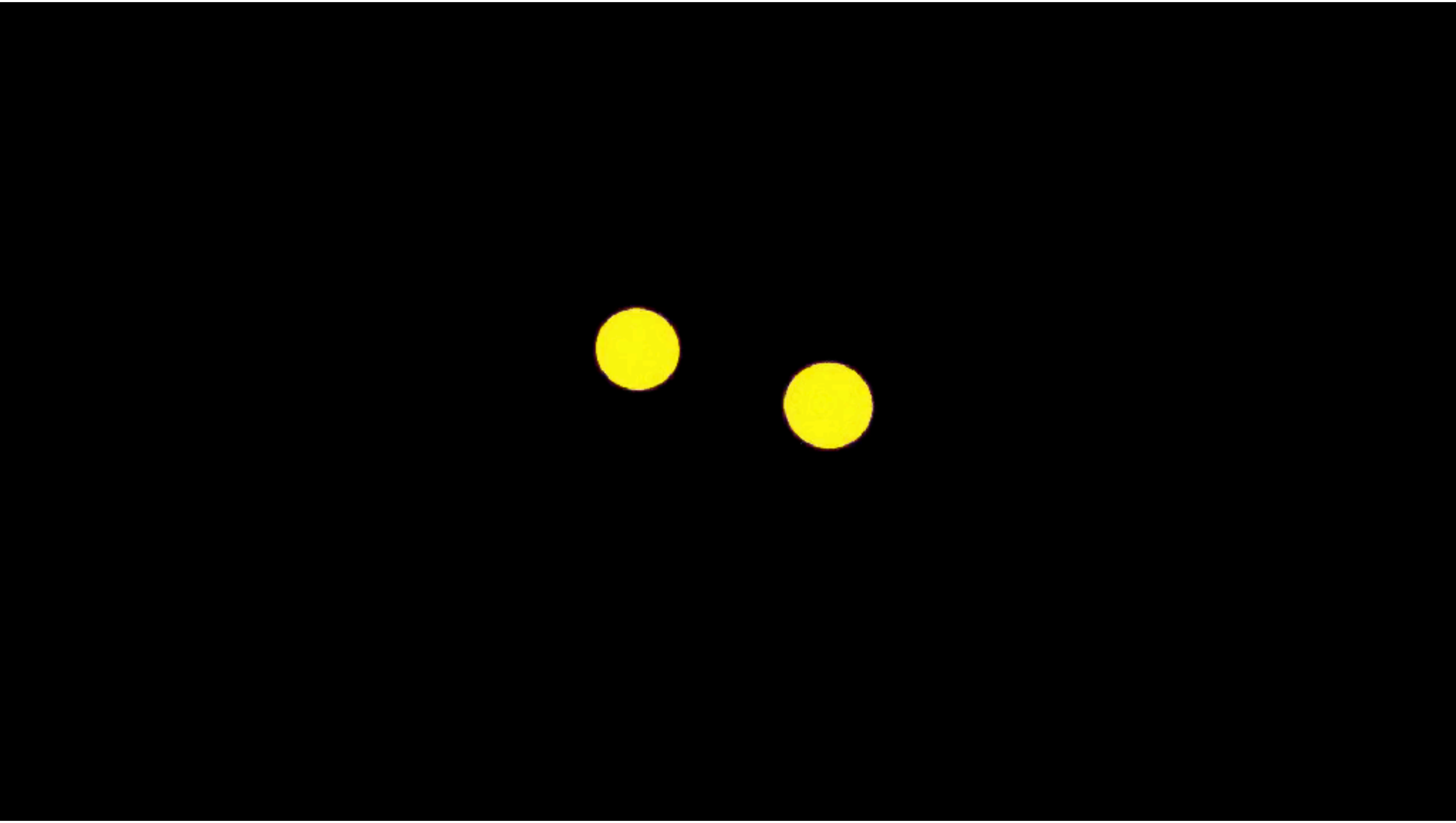
- Fission fragment distributions are not erased by subsequent neutron capture



Beta-delayed fission

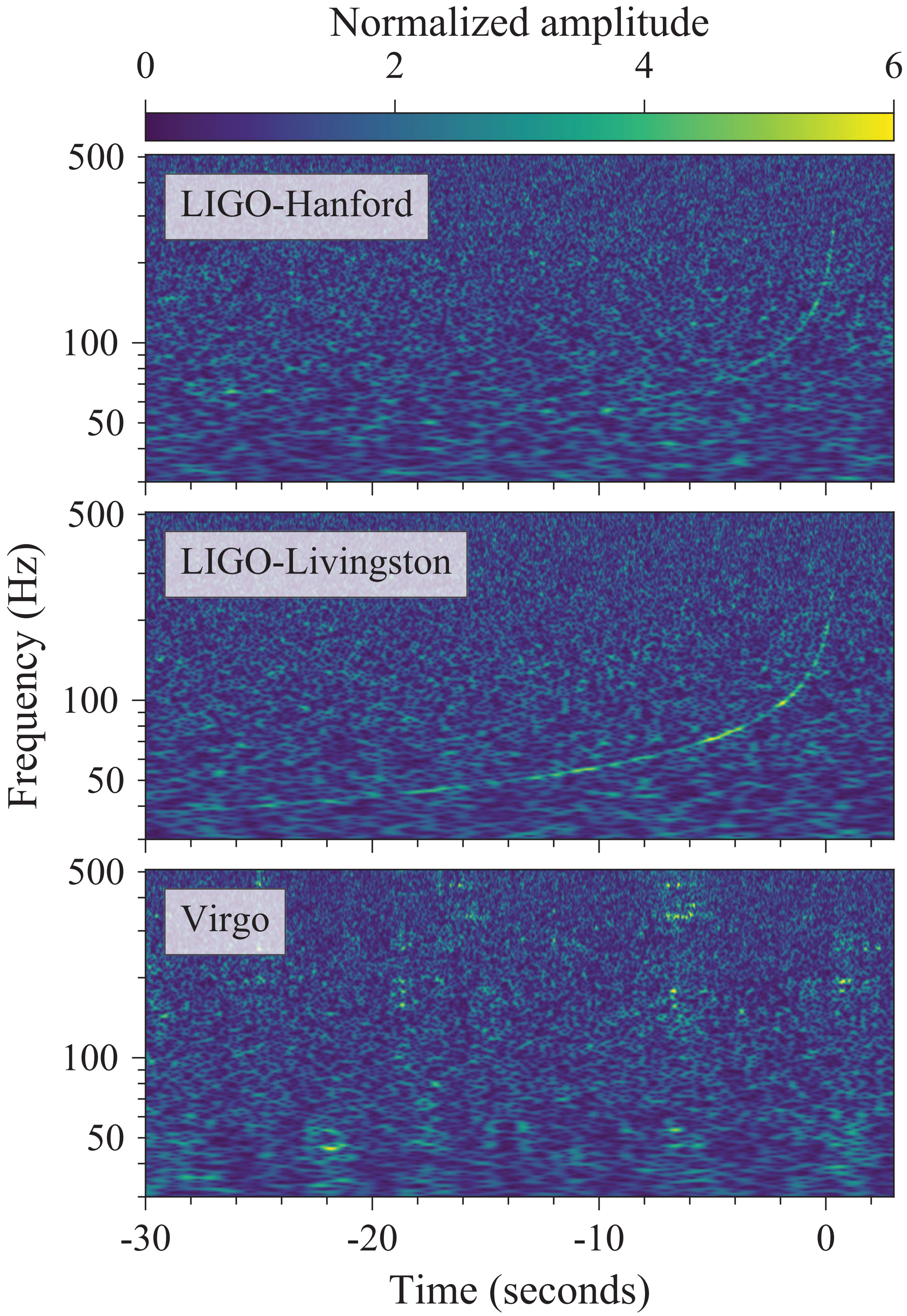
No beta-delayed fission

What is the astrophysical source of the r-process?

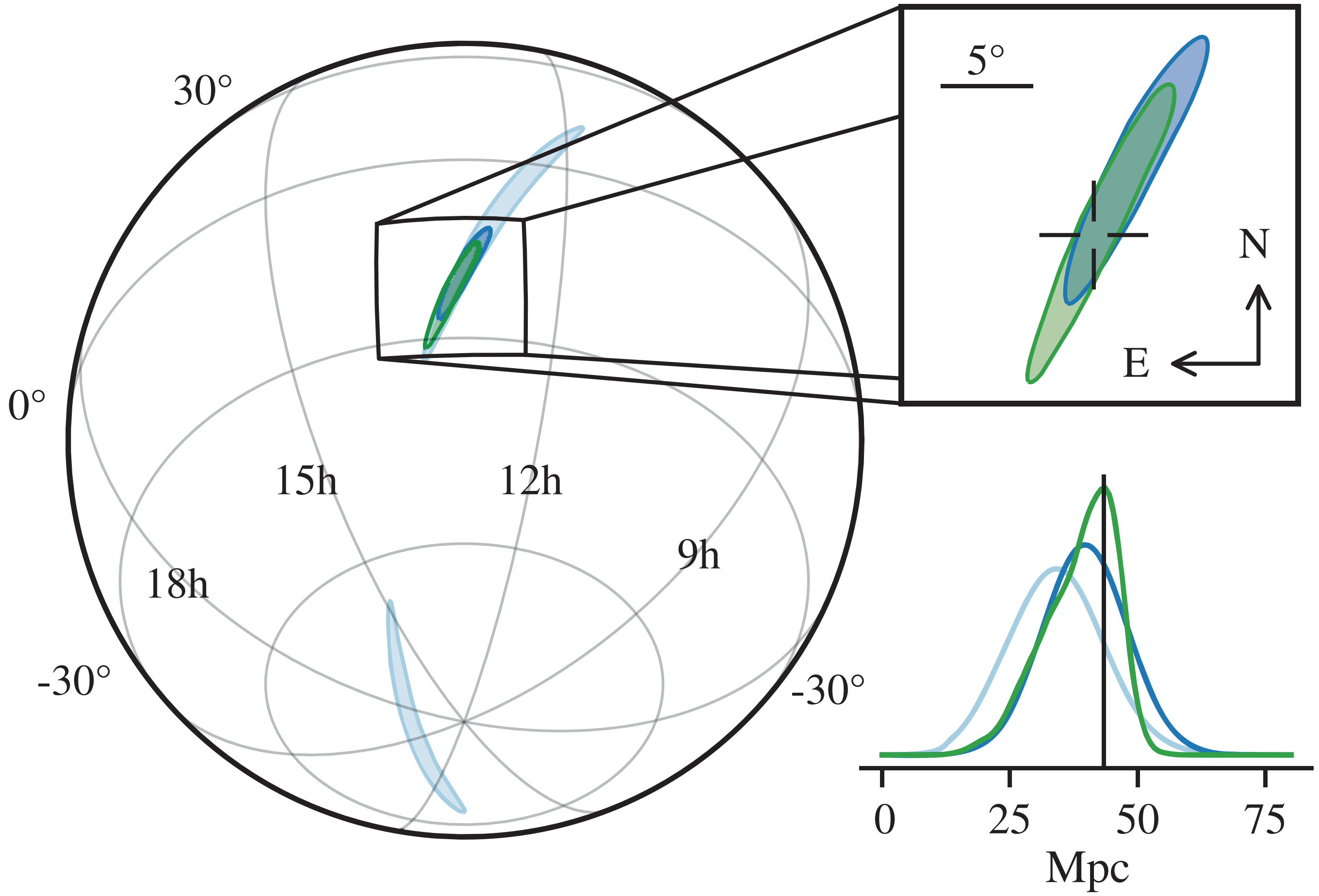


From D. Radice

GW170817

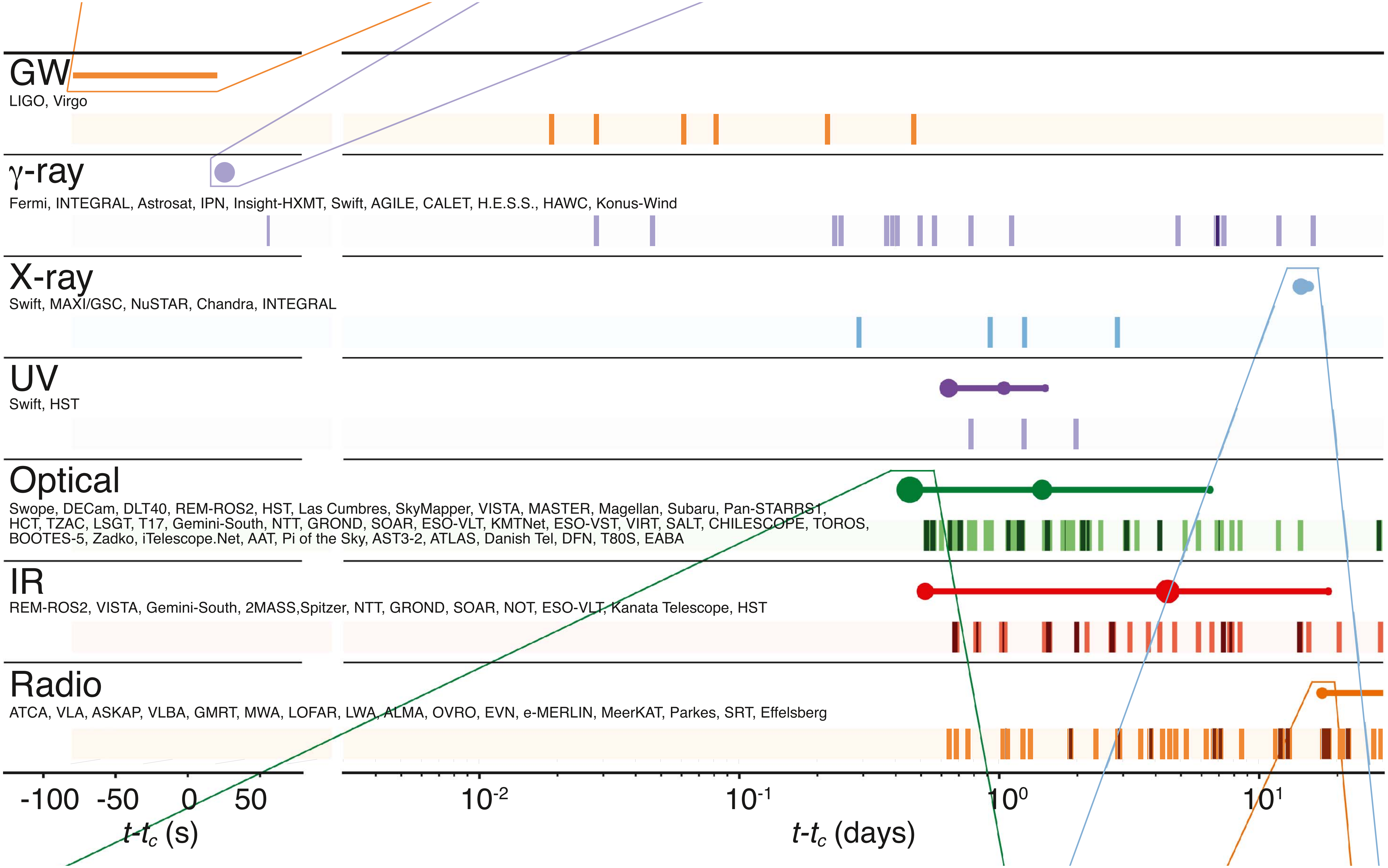


GW Detections



Sky Localization

GW170817 + EM


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)

EoS Constraints from In-Spiral

Induced quadrupole moment

Quadrupolar tidal field

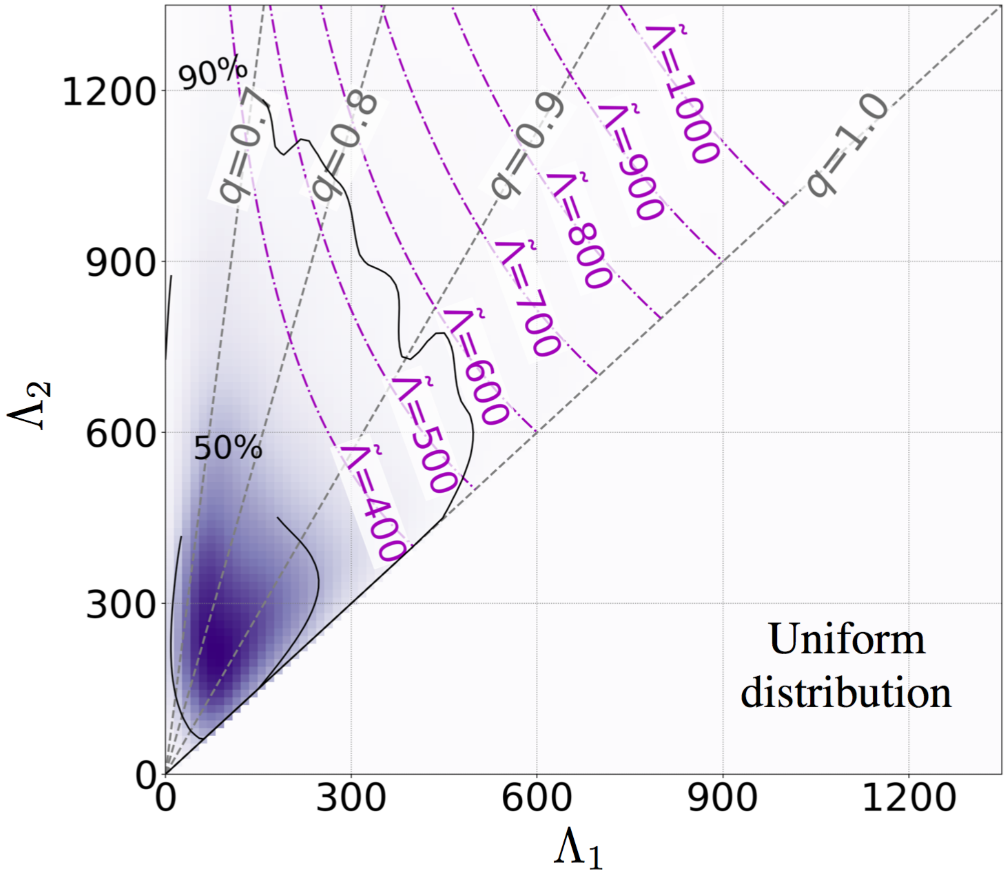
$$Q_{ij} = -\Lambda \mathcal{E}_{ij}$$

Tidal deformability of a NS

- Tidal fields excite NS deformations and remove orbital energy in addition to GW losses

- Introduces a *measurable* correction to the phase evolution of the GWs, but at 5PN order

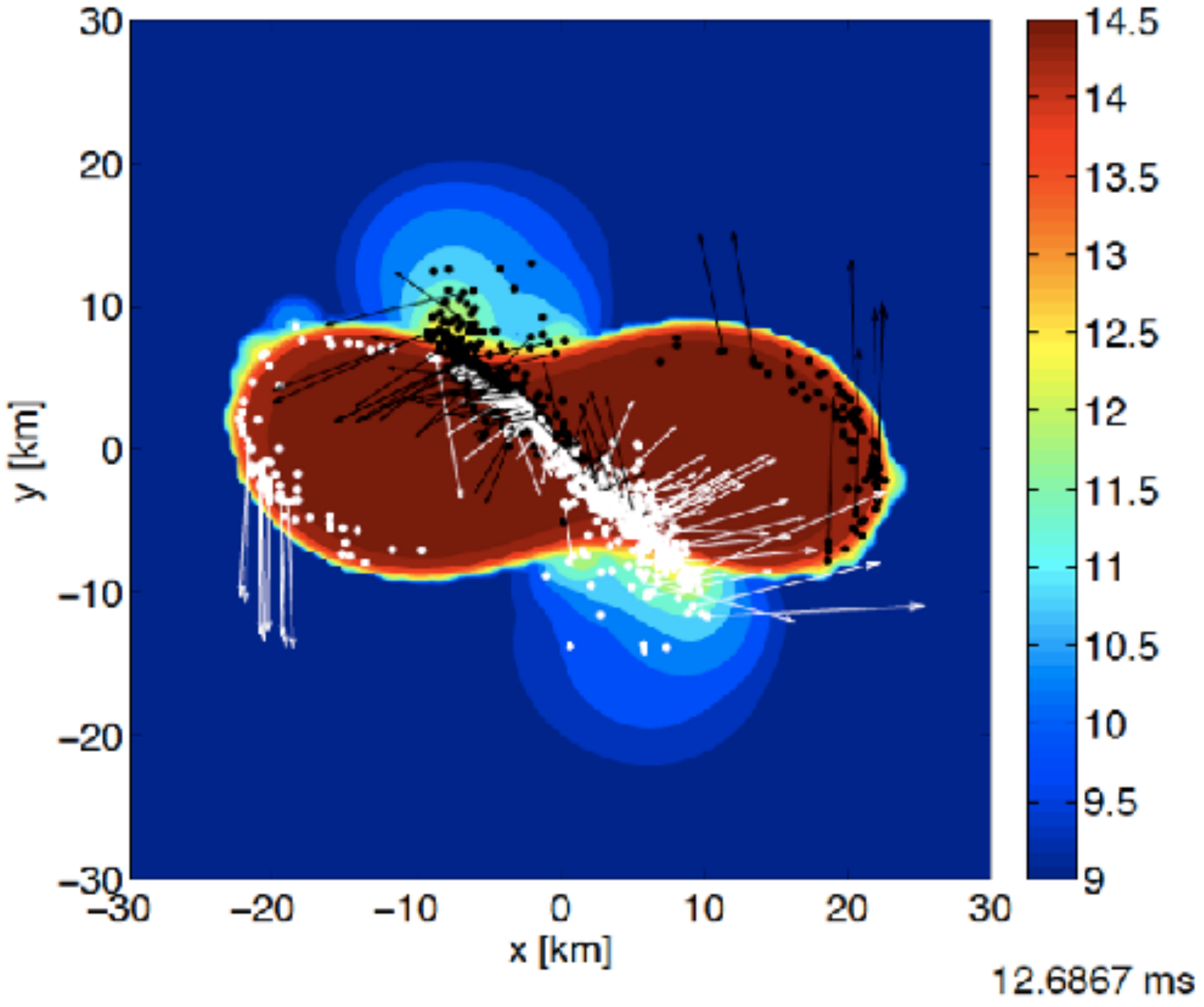
$$\delta\Psi = -\frac{9}{16}\frac{v^5}{\mu M^4}\left[\left(11\frac{m_2}{m_1}+\frac{M}{m_1}\right)\lambda_1 + 1 \leftrightarrow 2\right]$$



$$\Lambda_{1,2} = \frac{2}{3}k_2\left(\frac{R_{1,2}c^2}{Gm_{1,2}}\right)^5$$

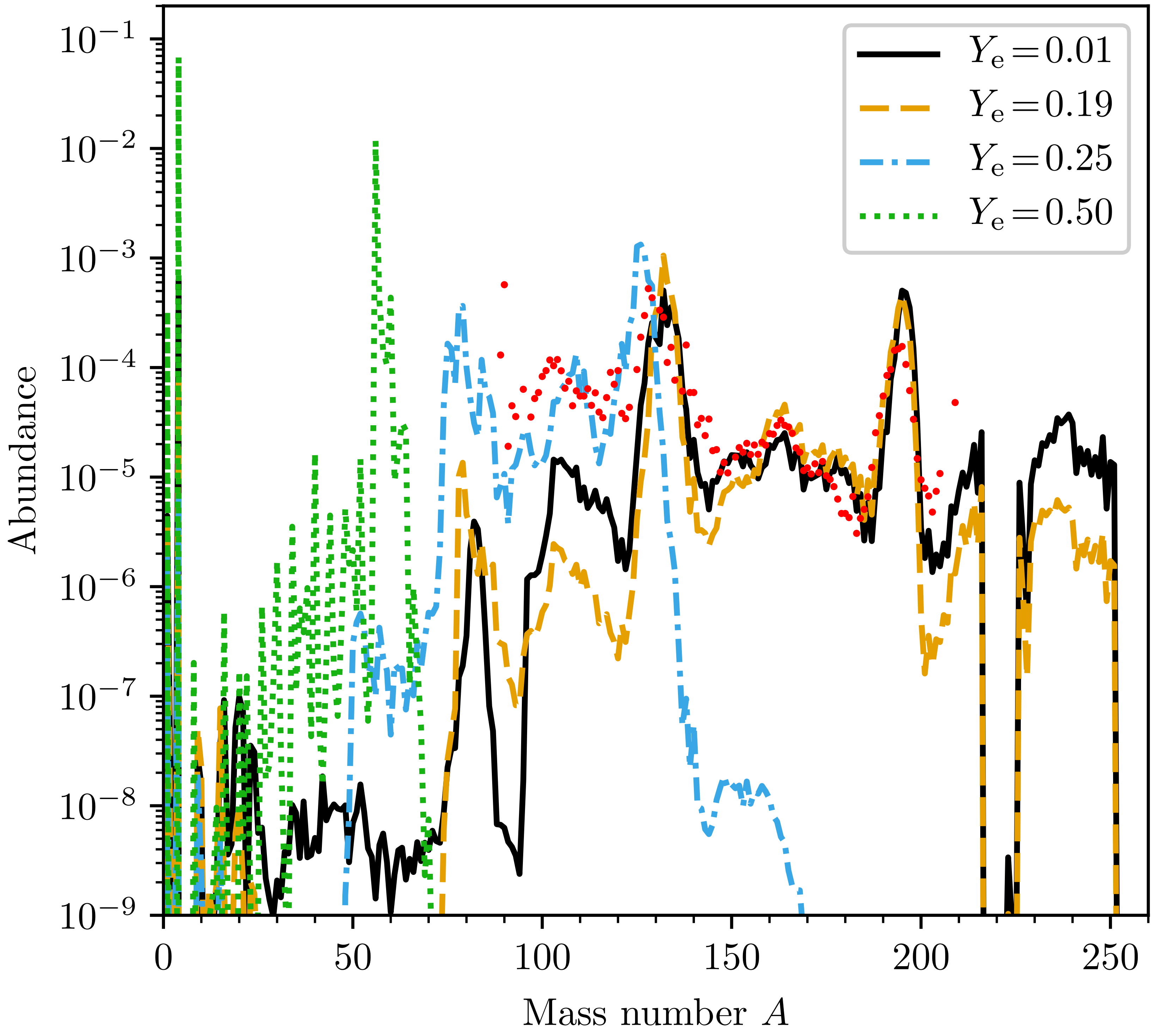
Mass Ejection from NS Mergers

1. Dynamical Ejecta
    - Tidal ejecta
    - Shock heated ejecta
2. Disk ejecta



Bauswein et al. ’13

Nucleosynthesis Depends on Y_e

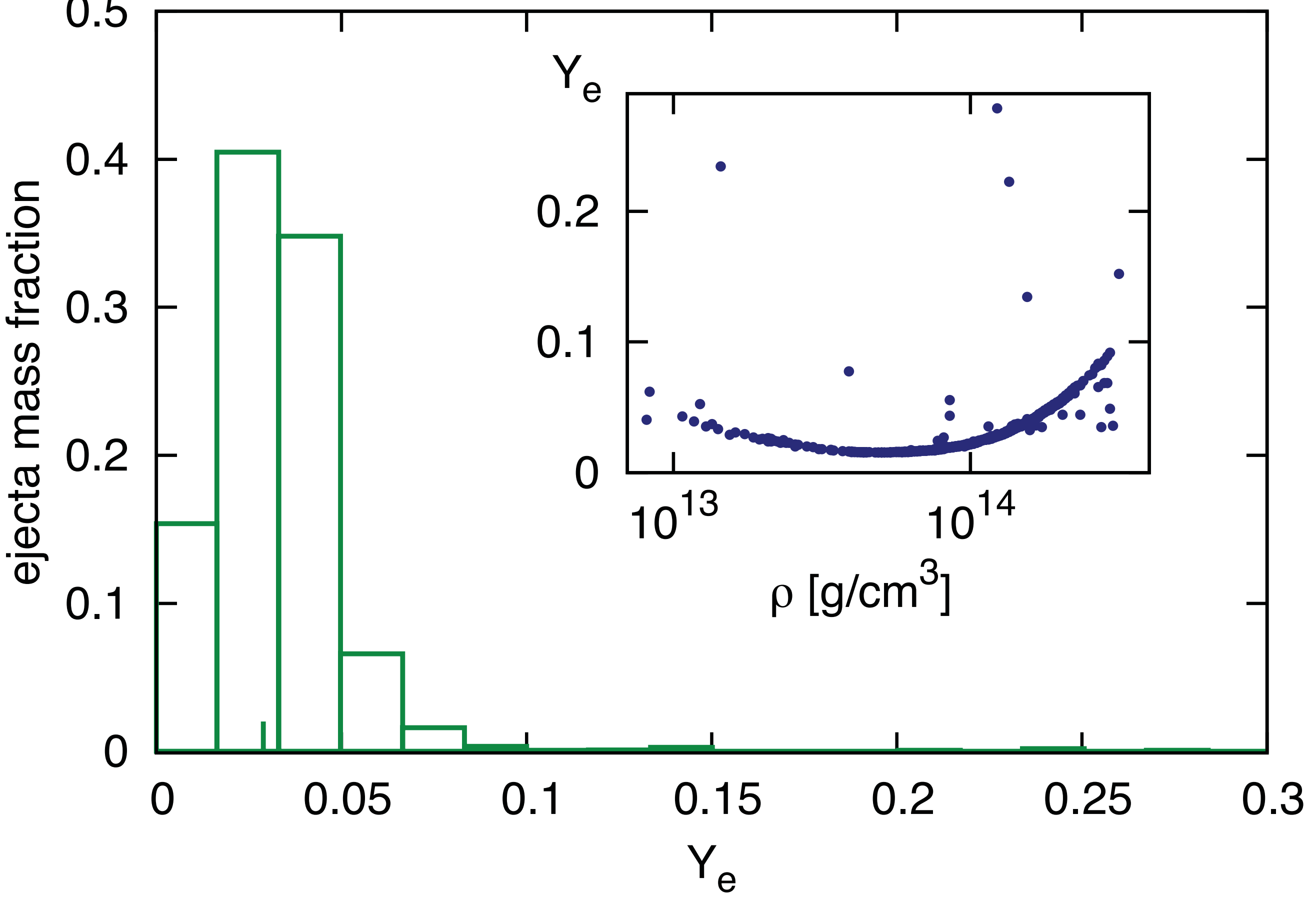


How does Y_e get set?

Tidal Ejecta

- Material squeezed through the outer Lagrange points during merger
- Material is not shocked and likely undergoes few weak reactions
- Electron fraction distribution essentially that of the progenitor NS

from Korobkin et al. (2012)



Electron fraction set by beta equilibrium of cold NS:

$$\mu_{e^-} + \mu_p = \mu_n$$

Predicts Y_e<0.1 for most of the material

Changing Y_e for the r-process

$$\begin{aligned} e^- + p &\leftrightarrow \nu_e + n \\ e^+ + n &\leftrightarrow \bar{\nu}_e + p \end{aligned}$$

Evolution of the electron fraction is governed by

$$\frac{dY_e}{dt} = (\lambda_{\nu_e} + \lambda_{e^+})Y_n - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})Y_p + \ldots$$

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$$Y_e(t) \approx Y_{e,0}\exp(-t/\tau_w) + [1 - \exp(-t/\tau_w)]Y_{e,eq}$$

where

$$\tau_w = [\lambda_{e^-} + \lambda_{e+} + \lambda_{\nu_e} + \lambda_{\bar{\nu}_e}]^{-1}$$

$$Y_{e,eq} = \frac{\lambda_{\nu_e} + \lambda_{e+}}{\lambda_{\nu_e} + \lambda_{e+} + \lambda_{\bar{\nu}_e} + \lambda_{e-}}$$

Changing Y_e with electrons

- Under degenerate conditions, electron capture dominates and expect small Y_e

- Increase temperature, lift degeneracy, produce pairs (as long as T > m_e), positron and electron capture rates are similar and $Y_{e,eq}$~0.5

For relativistic electrons:

$$\mu_e \gg T$$

$$\lambda_{e^-} \approx 8 \times 10^{-3}\,\mathrm{s}^{-1} \left(\frac{\mu_e}{m_e}\right)^5$$

$$\lambda_{e^+} \approx 2 \times 10^{-2}\,\mathrm{s}^{-1} \left(\frac{T}{m_e}\right)^5 \exp(-\mu_e/T)$$

or

$$\mu_e \ll T$$

$$\lambda_{e^\pm} \approx 2 \times 10^{-2}\,\mathrm{s}^{-1} \left(\frac{T}{m_e}\right)^5$$

Setting Y_e by neutrinos

Evolution of the electron fraction is governed by

$$\frac{dY_e}{dt} = (\lambda_{\nu_e} + \lambda_{e^+})Y_n - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})Y_p + \ldots$$

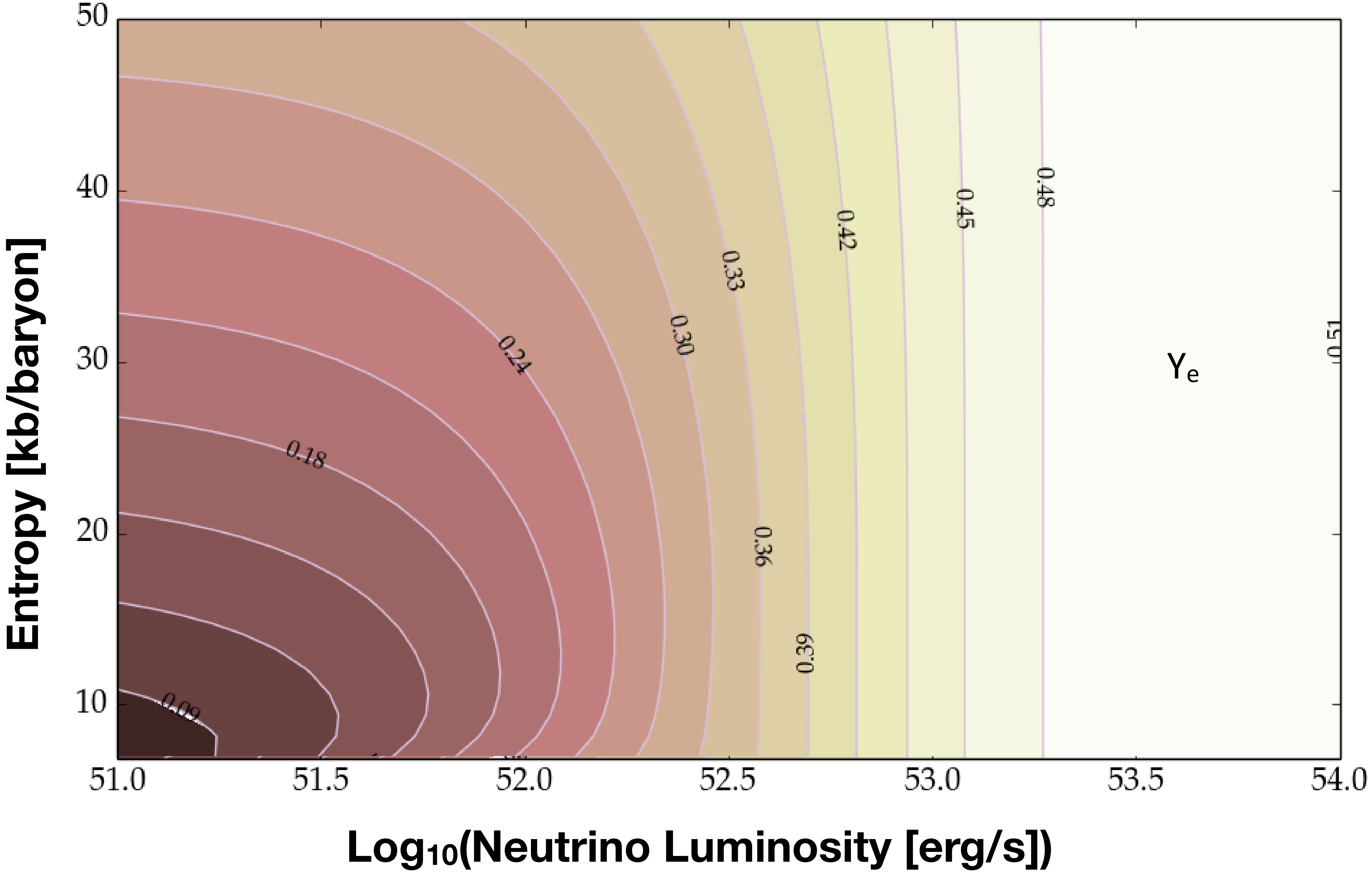
$$Y_e(t) \approx Y_{e,0}\exp(-t/\tau_w) + [1 - \exp(-t/\tau_w)]Y_{e,eq}$$

When we have:

$$\lambda_\nu \gg \lambda_{e^+,e^-}$$

$$\Rightarrow \qquad Y_{e,eq} \approx \frac{\lambda_{\nu_e}}{\lambda_{\nu_e} + \lambda_{\bar{\nu}_e}}$$

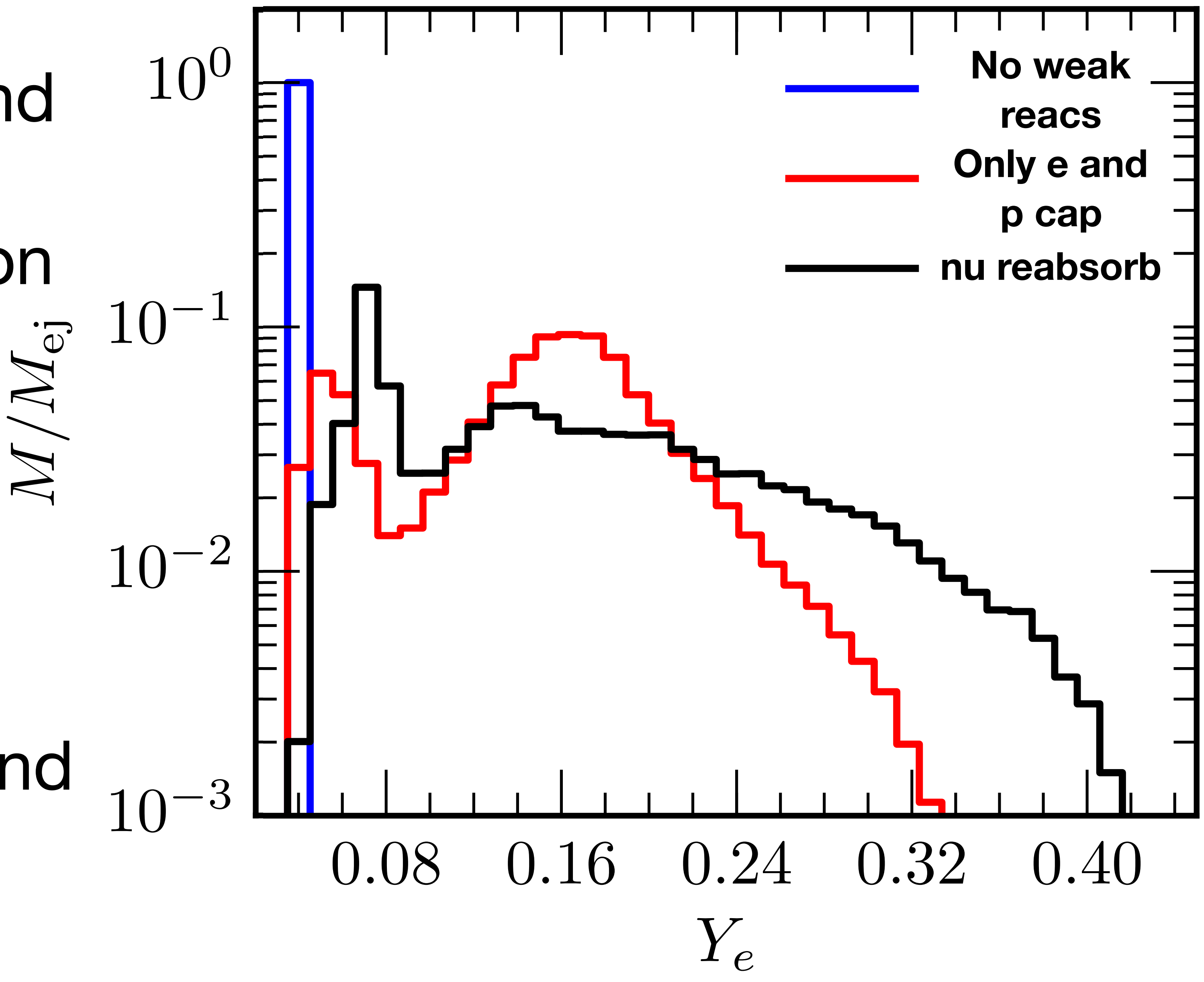
Weak Interactions in NS Mergers



Assuming similar electron neutrino and anti-neutrino properties

Weak Interactions in the Dynamical Ejecta

- Shock heating lifts electron degeneracy and allows for pair capture, increasing Y_e by positron capture
- Additionally, neutrino capture alters Y_e
- Neutrino luminosities and average energies fairly similar

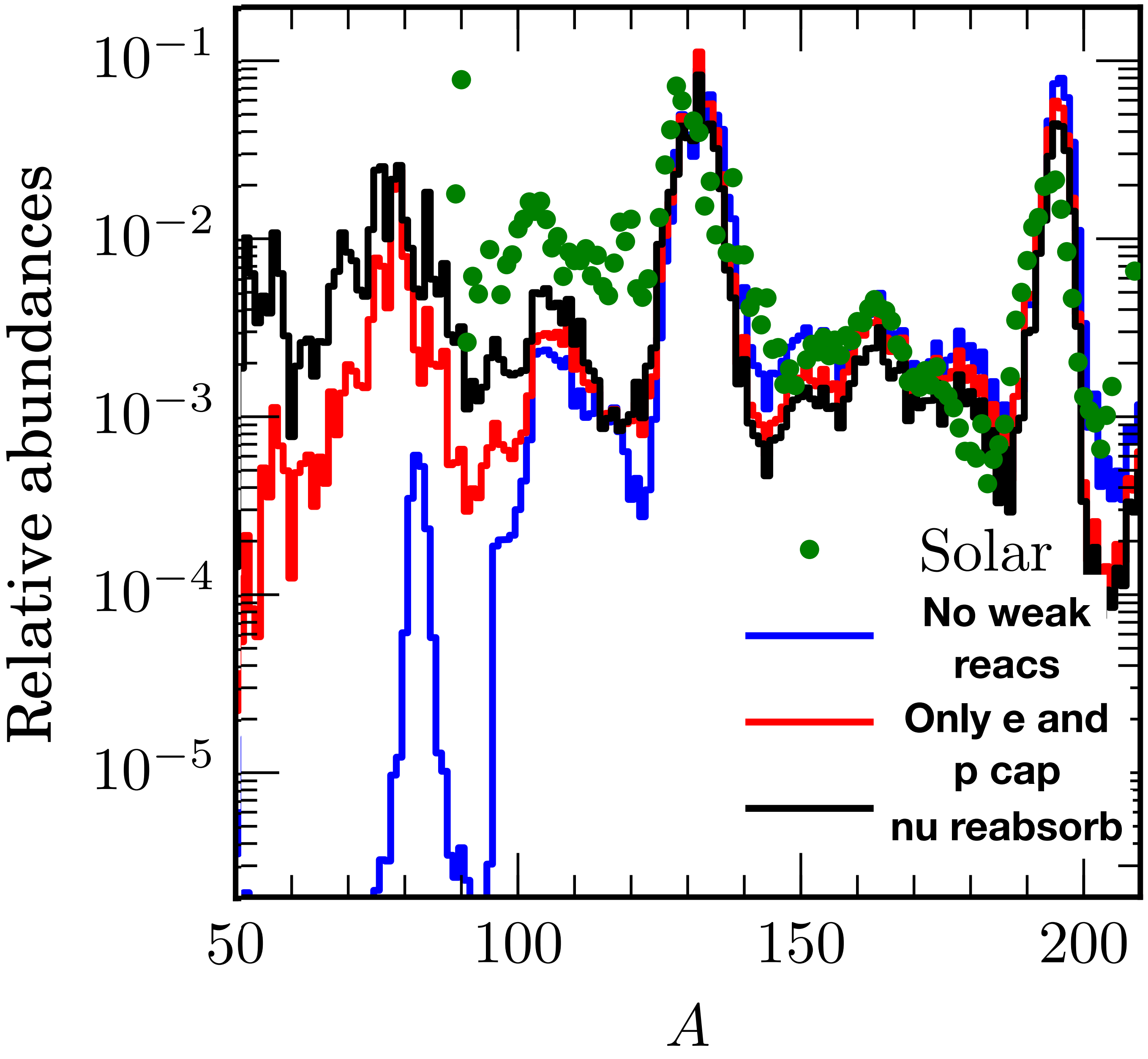


from Radice et al.

Weak Interactions in the Dynamical Ejecta

- Nevertheless, still produce quite a bit of material with $Y_e < 0.25$ so second and third peak still produced

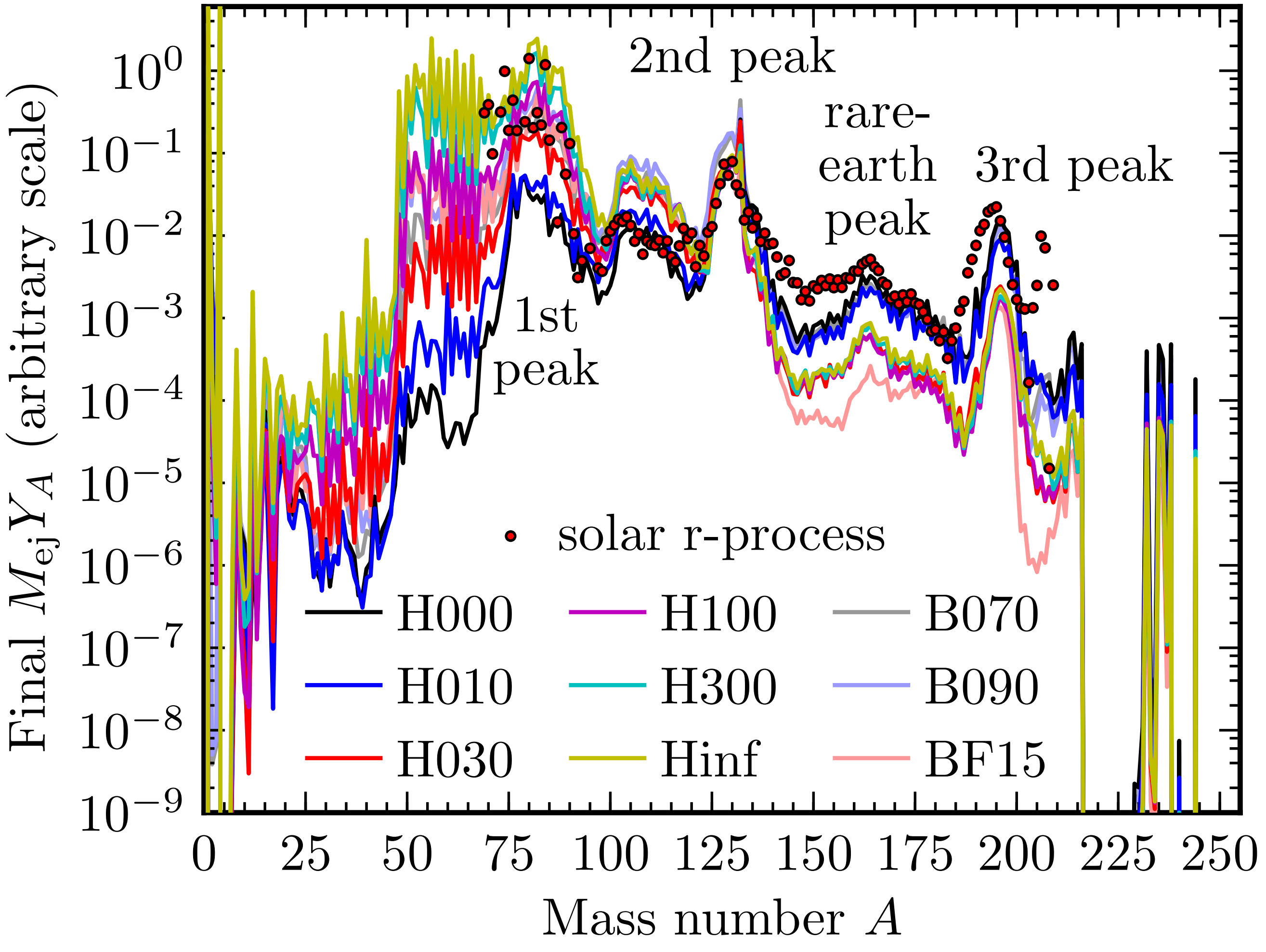
- Weak interactions have a significant impact on the amount of first peak production



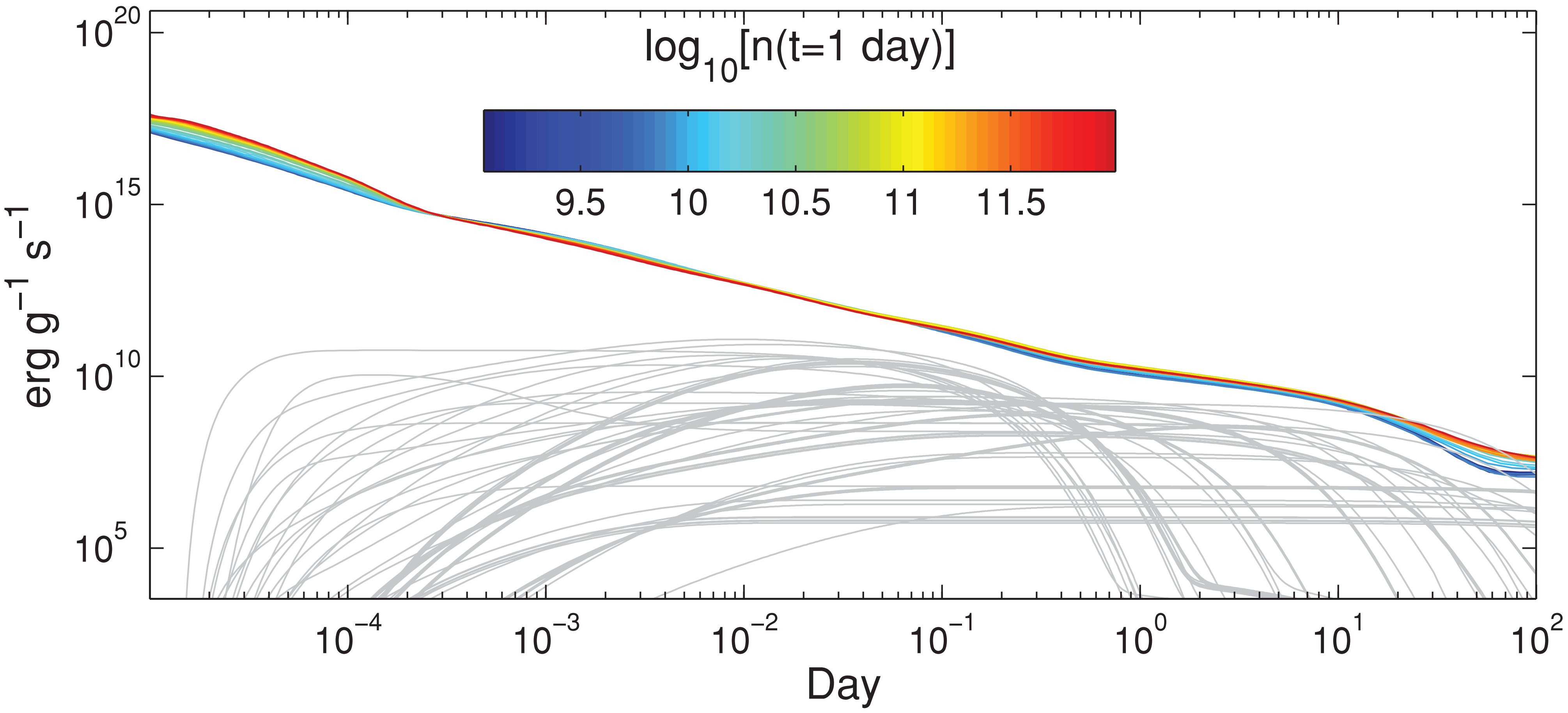
from Radice et al. (2016)

Disk Ejecta

- Material in the remnant disk also experiences a large number of weak interactions
- Broad range of Y_e
- Produce 1st, 2nd, and 3rd peak



Decay to Stability



- Beta decays, alpha decays, and fission back towards stability
- Decays move to longer and longer timescales as one gets closer to stability since beta-decay Q values decrease closer to stability
- These decays release energy into the fluid, relevant to kilonovae (see Brian’s lecture)

Kilonovae (see Li & Paczynski 1998)

Radioactivity powered transients

$$\tau = \underset{\text{opacity}}{\kappa} \; \underset{\text{density}}{\rho} \; \underset{\text{radius}}{R} = \kappa \frac{3 M_{ej}}{4\pi v_{ej}^2 t^2}$$

- Diffusive process, so timescale for escape given by random walk
  - Net displacement: $\vec{d} = \sum_{i=1}^{N} \vec{l}_i$ ← distances traveled between N-scatters

$$\Rightarrow |\vec{d}|^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} \vec{l}_i \cdot \vec{l}_j = \sum_{i=1}^{N} \vec{l}_i \cdot \vec{l}_i$$

← for scattering in random directions

$$= N \lambda_{mfp}^2$$

- Path length traveled $L = N \lambda_{mfp}$

$$\Rightarrow t_{diff} = \frac{L}{c} = \frac{R^2}{c \lambda_{mfp}} = \frac{R \tau}{c}$$

$$= \frac{3 \kappa M_{ej}}{4\pi v_{ej} c \, t}$$

$$t_{diff} \simeq 7.3 \text{ days} \left(\frac{\kappa}{1 \text{ cm}^2 \text{ g}^{-1}}\right) \left(\frac{M_{ej}}{0.01 M_\odot}\right) \left(\frac{v_{ej}}{0.1 c}\right)^{-1} \left(\frac{t}{1 \text{ day}}\right)^{-1}$$

- Peak timescale given by $t_{diff} = t$

$$\Rightarrow \quad t_{peak} = \left(\frac{3\kappa M_{ej}}{4\pi v_{ej} c}\right)^{1/2}$$

$$= 2.7\,\mathrm{day}\left(\frac{\kappa}{1\,\mathrm{cm^2\,g^{-1}}}\right)^{1/2}\left(\frac{M_{ej}}{0.01\,M_\odot}\right)^{1/2}\left(\frac{v_{ej}}{0.1\,c}\right)^{-1/2}$$

- Peak luminosity
  - Adiabatic losses remove energy injected before t_{peak}: $\dfrac{dE}{dt} = -L - P\dfrac{dV}{dt} + M_{ej}\,\dot{q}_{nuc}(t)$
  - This implies approximately $L_{peak} = M_{ej}\,\dot{q}_{nuc}(t_{peak})$

    $\dot{q}(t_{peak}) \sim 10^{10}$ erg/g/s $\Rightarrow L_{peak} \sim 10^{41}$ erg/s $\left(\dfrac{M_{ej}}{0.01\,M_\odot}\right)$

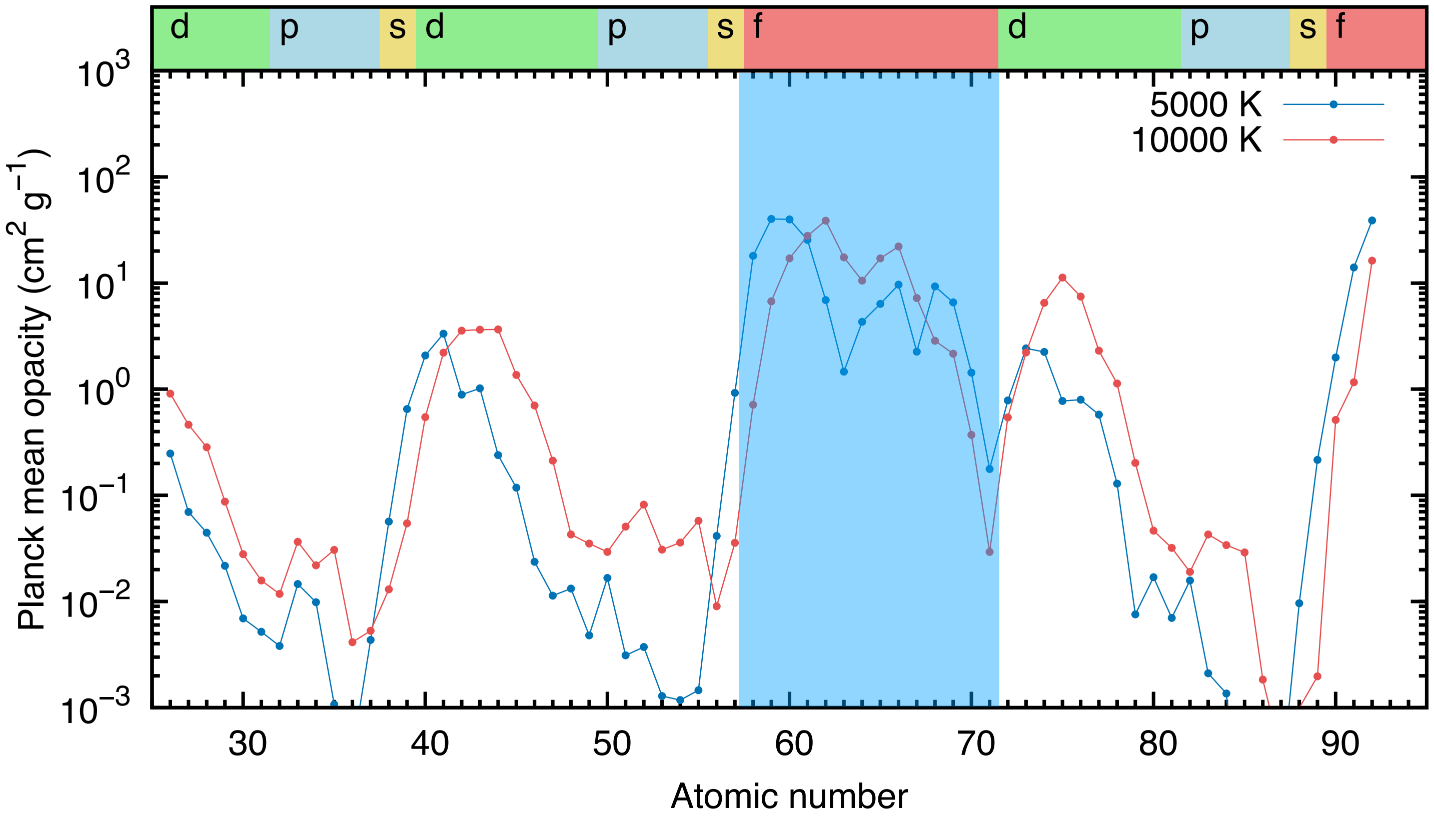
- Peak temperature

$$L = 4\pi R^2 \sigma T^4 \quad \Rightarrow \quad T = \left(\frac{M_{ej}\,\dot{q}_{nuc}(t_{peak})}{4\pi\sigma v_{ej}^2 t_{peak}^2}\right)^{1/4}$$

$$T \approx 10^4\,\mathrm{K}\left(\frac{\kappa}{1\,\mathrm{cm^2\,g^{-1}}}\right)^{-1/4}\left(\frac{v_{ej}}{0.1\,c}\right)^{-1/4}\left(\frac{\dot{q}_{nuc}(t_{peak})}{10^{10}\,\mathrm{erg/g/s}}\right)^{1/4}$$

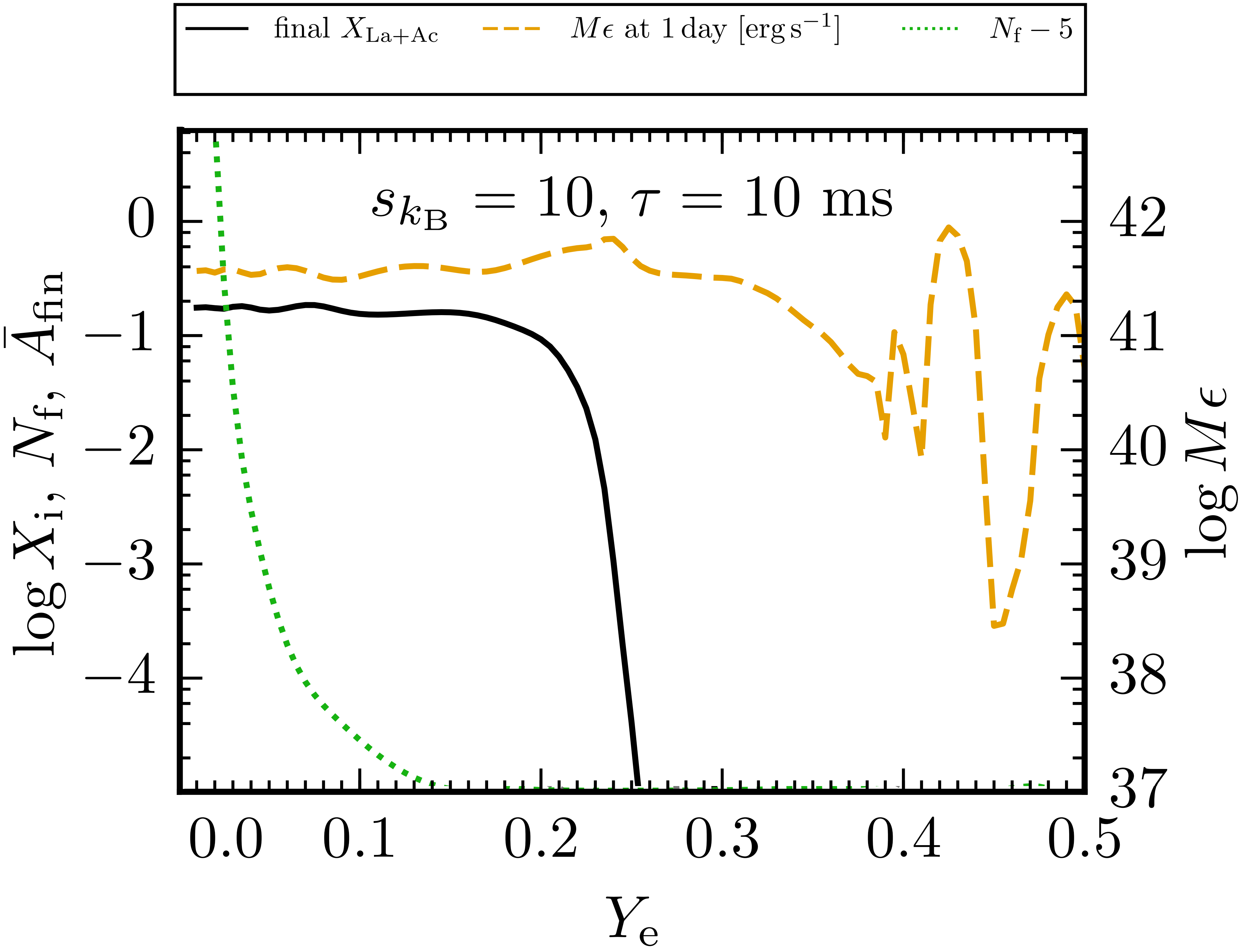
Opacity Dependence on the Composition

- Lanthanides and Actinides provide a larger opacity than iron peak elements
- Makes kilonova redder and longer
- Gives indication that heavy r-process elements might have been produced

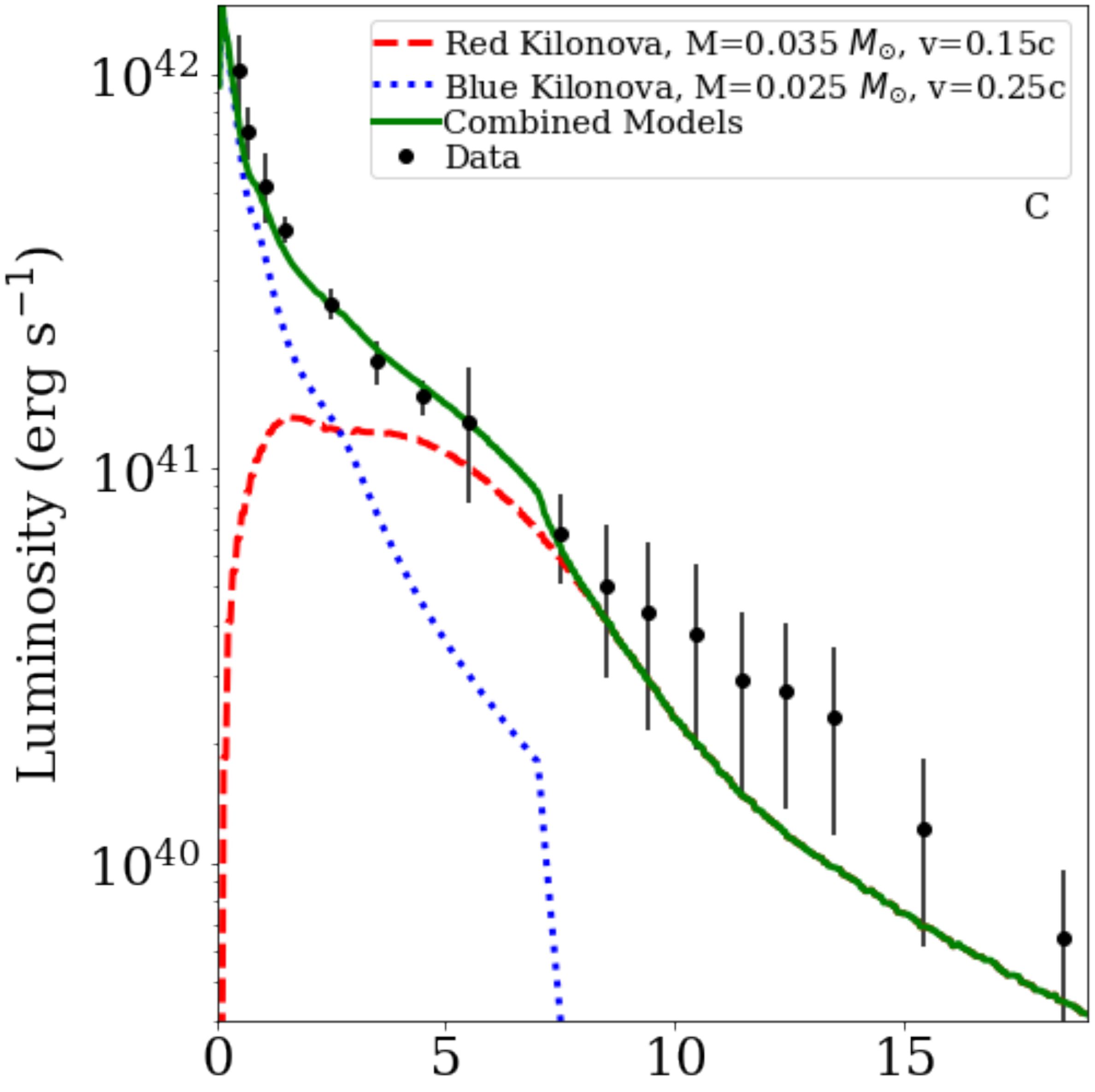


from Tanaka et al. (2019)

Dependence of Nucleosynthesis on Initial Conditions



Kilonova Models and Observations



transient AT 2017gfo