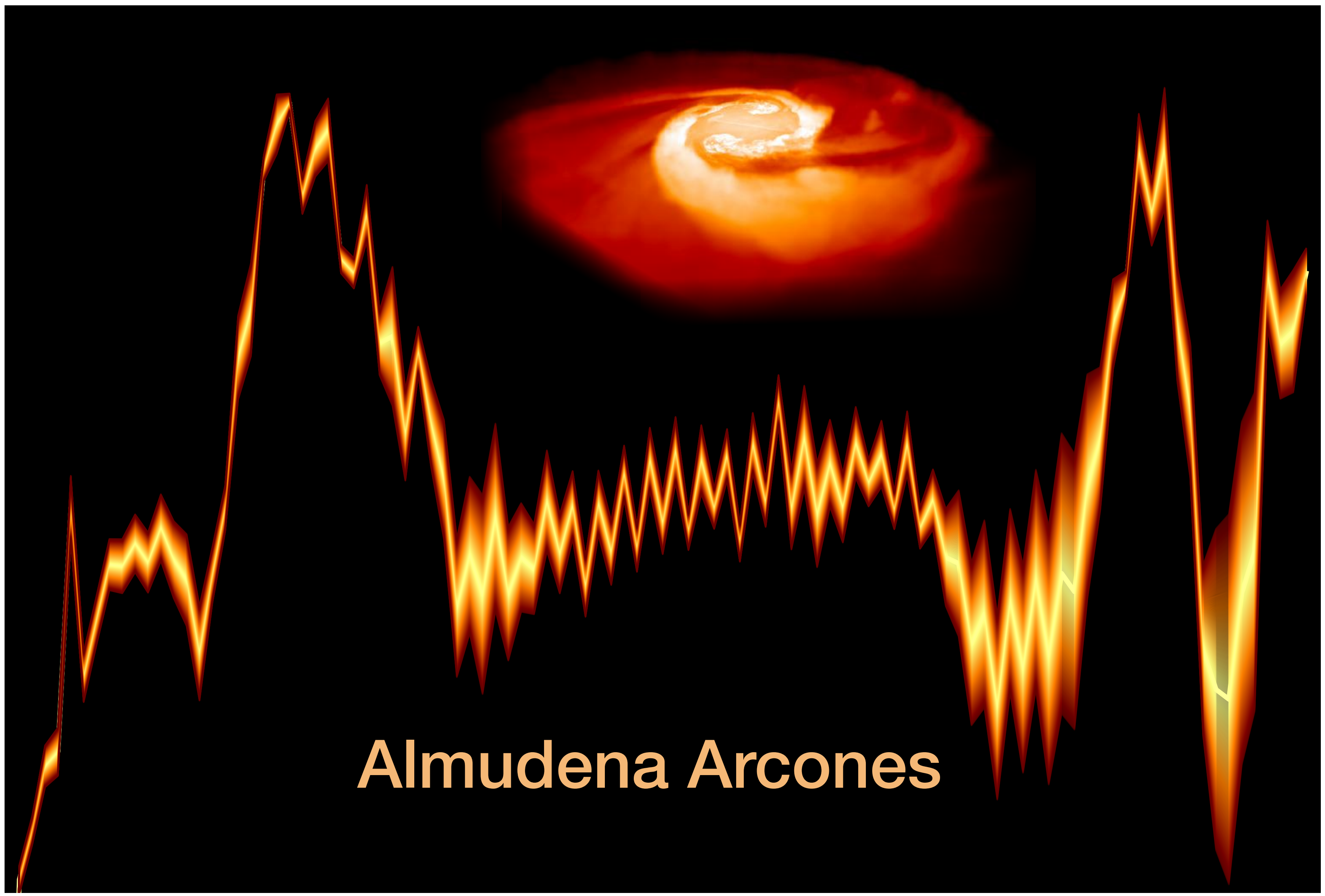
Are heavy r-process elements produced only in neutron-star mergers?

One year after gravitational wave detection GW170817



European Research Council
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TECHNISCHE UNIVERSITÄT DARMSTADT
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SFB 1245
Bundesministerium für Bildung und Forschung

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
119 Uun																	

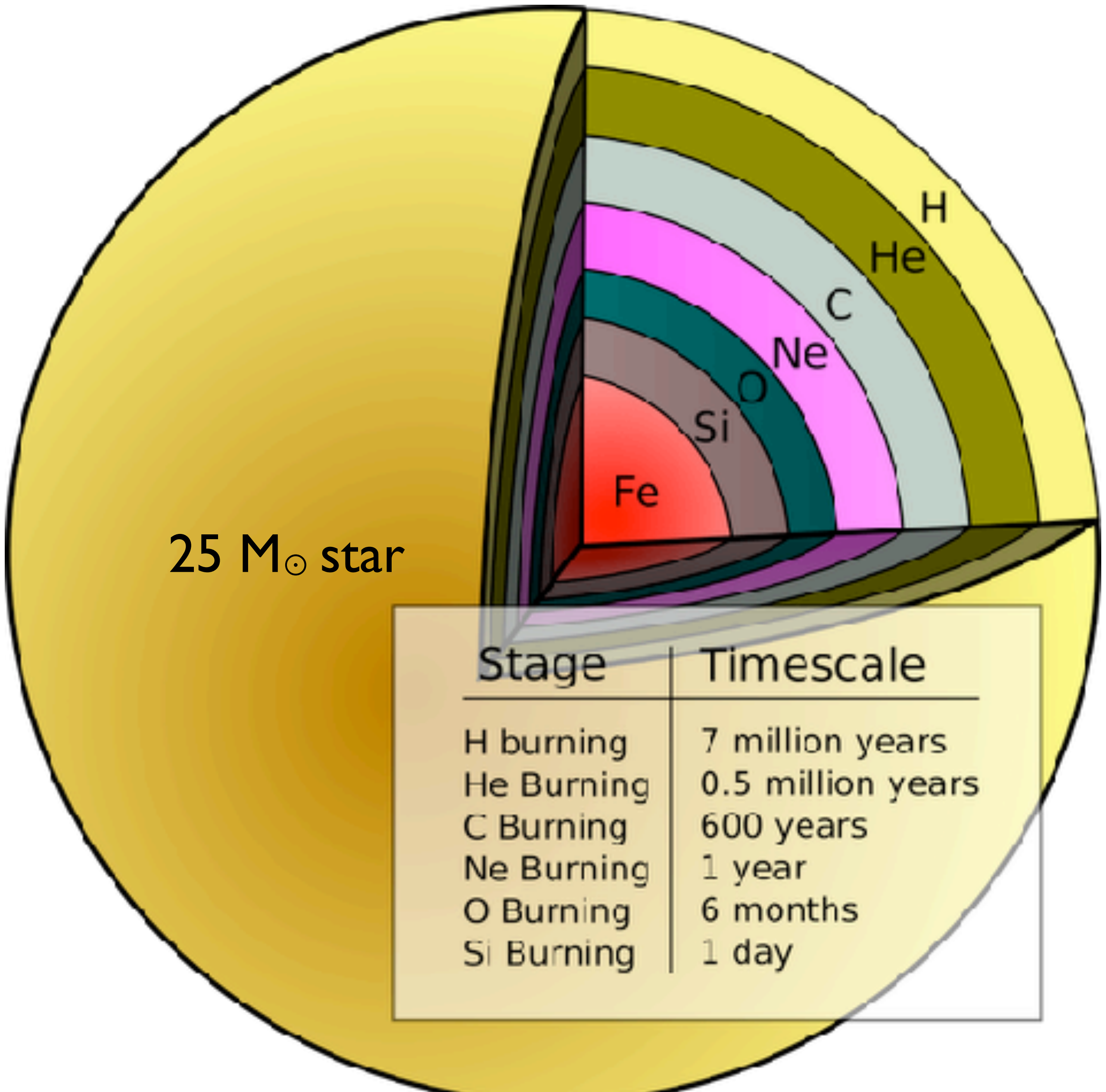
* Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

1
H

after Big Bang

2
He

Stars build elements up to iron group

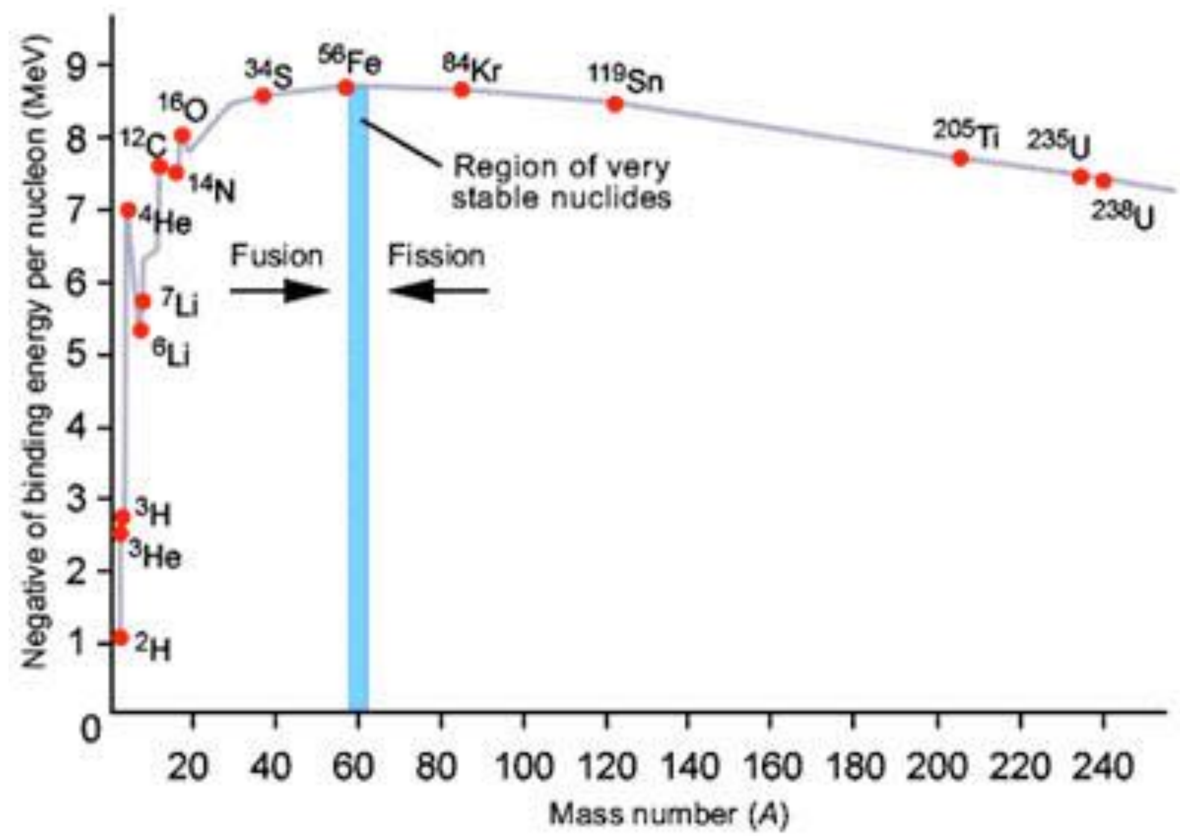


Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

Hydrostatic burning stages

Final stage: iron core

No more energy gain from fusion



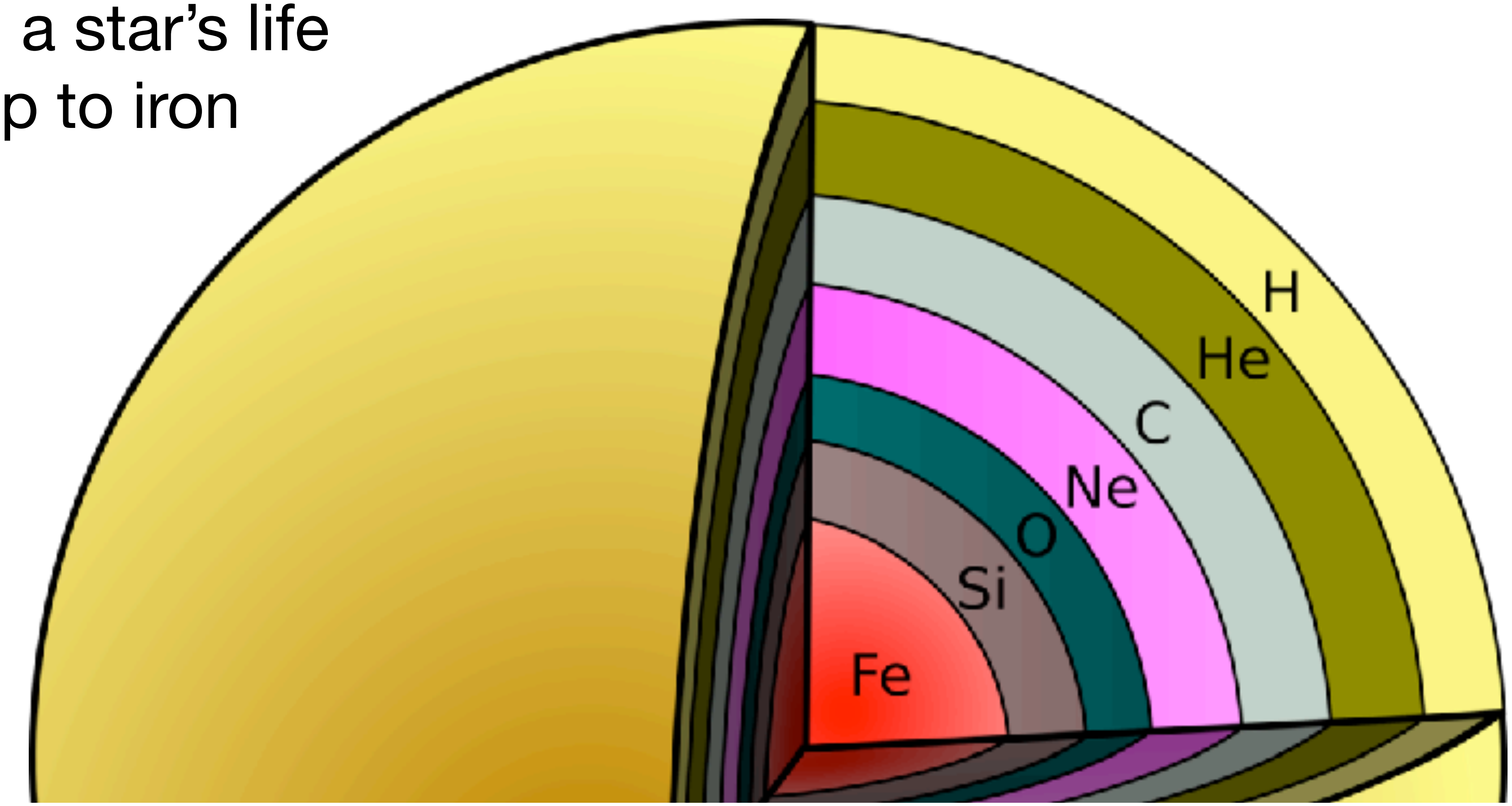
Massive stars: 8 $M_\odot < M \lesssim 70\ M_\odot$

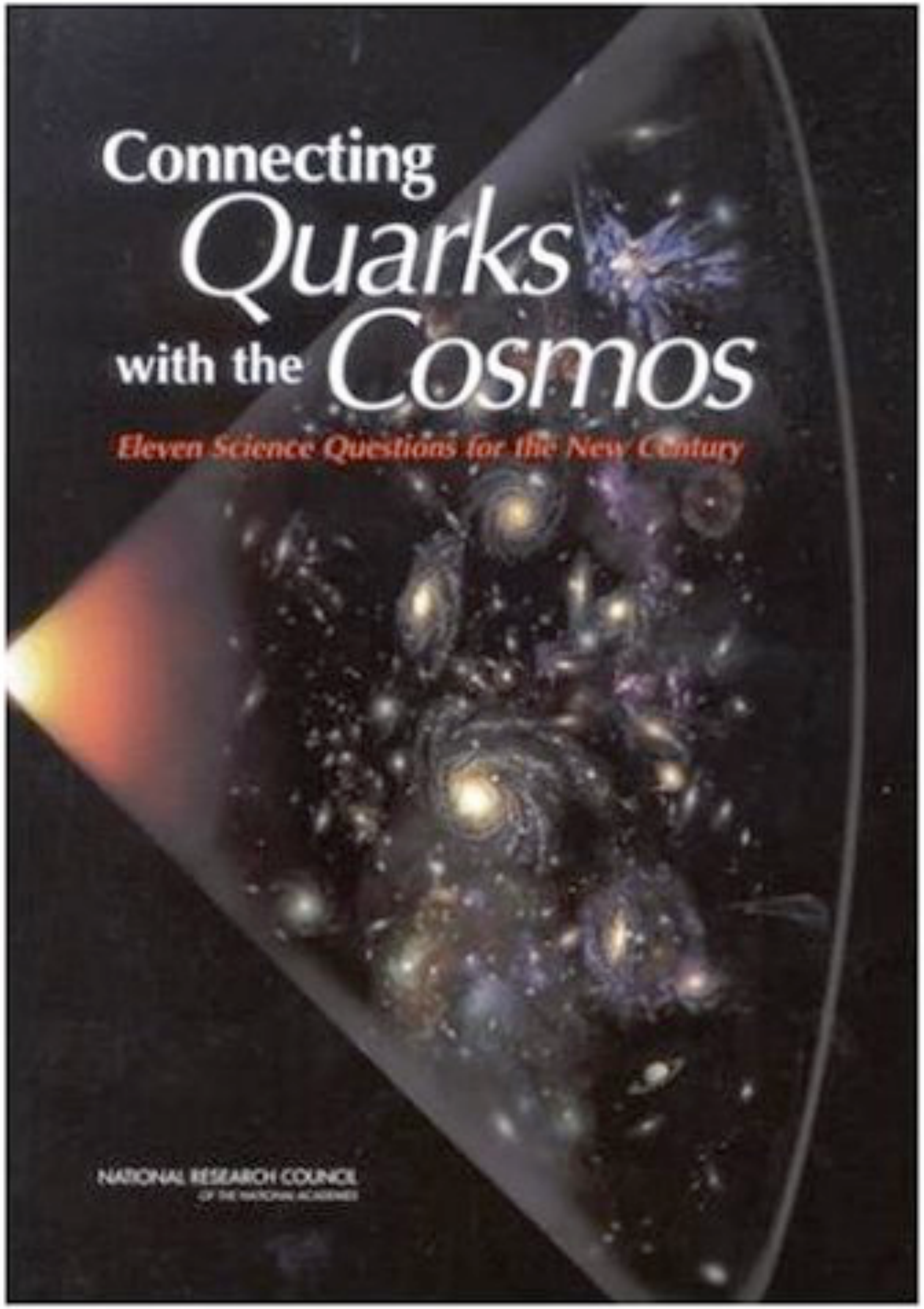
($M_\odot = 1.99 \times 10^{30}$ kg)

Nuclear fusion

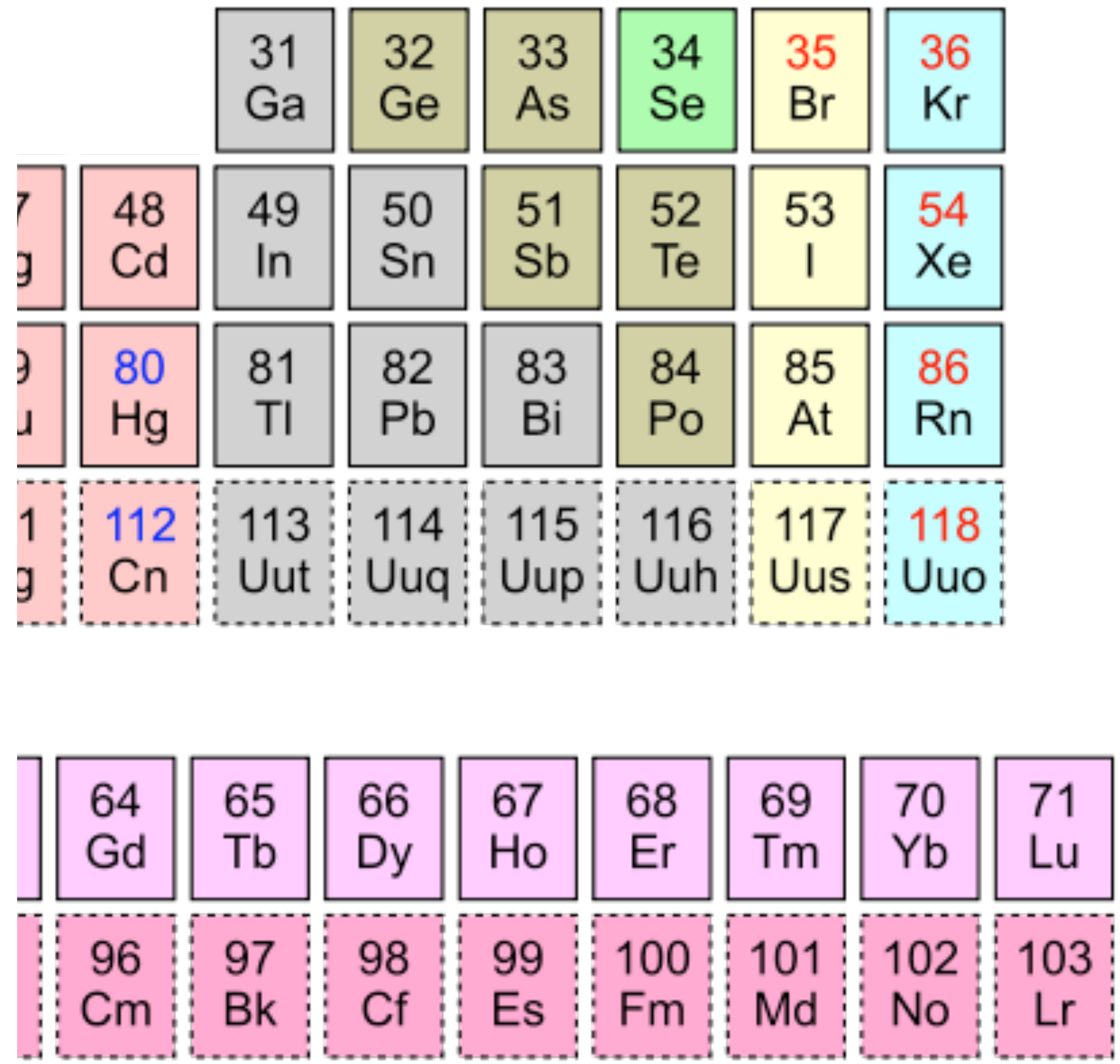
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn						

energy source during a star's life
produces elements up to iron



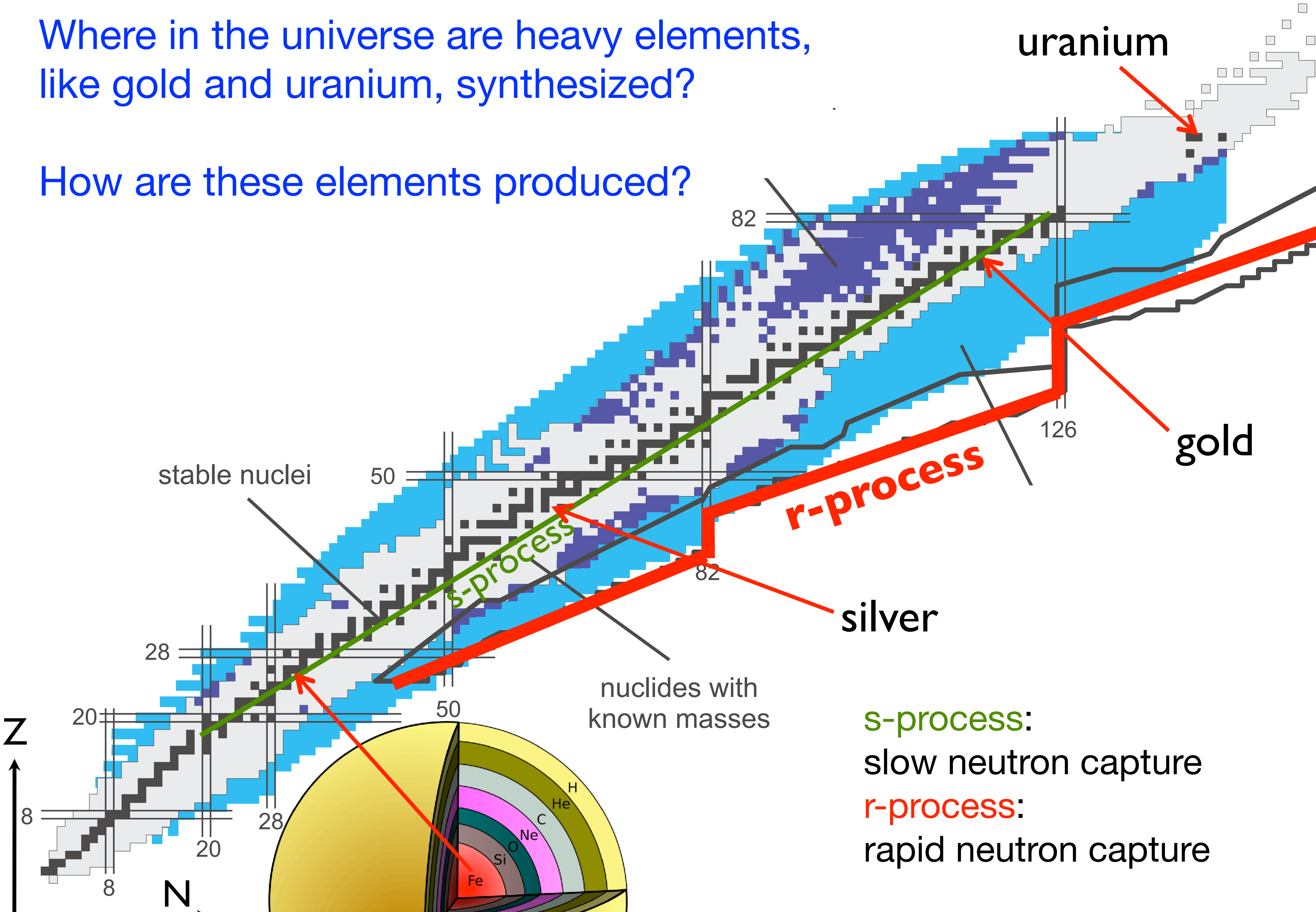


How were the elements from iron to uranium made?



Where in the universe are heavy elements, like gold and uranium, synthesized?

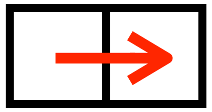
How are these elements produced?



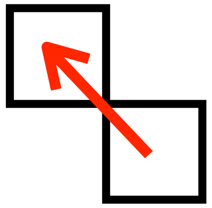
s-process:
slow neutron capture
r-process:
rapid neutron capture

s-process and r-process

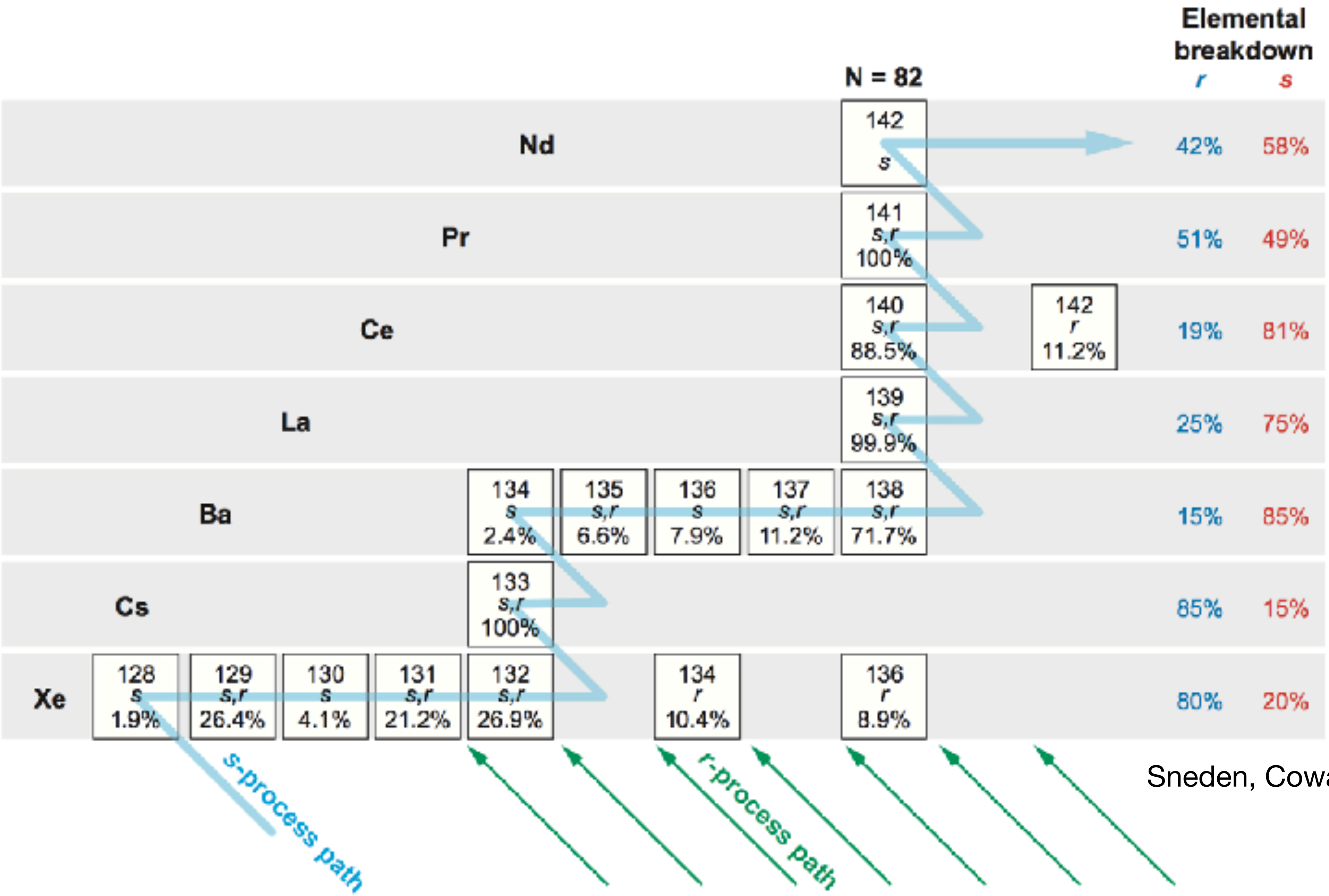
slow and rapid neutron capture compared to beta decay



neutron capture (n,γ): (Z,A) + n → (Z,A+1) + γ



beta decay: (Z,A) → (Z+1,A)

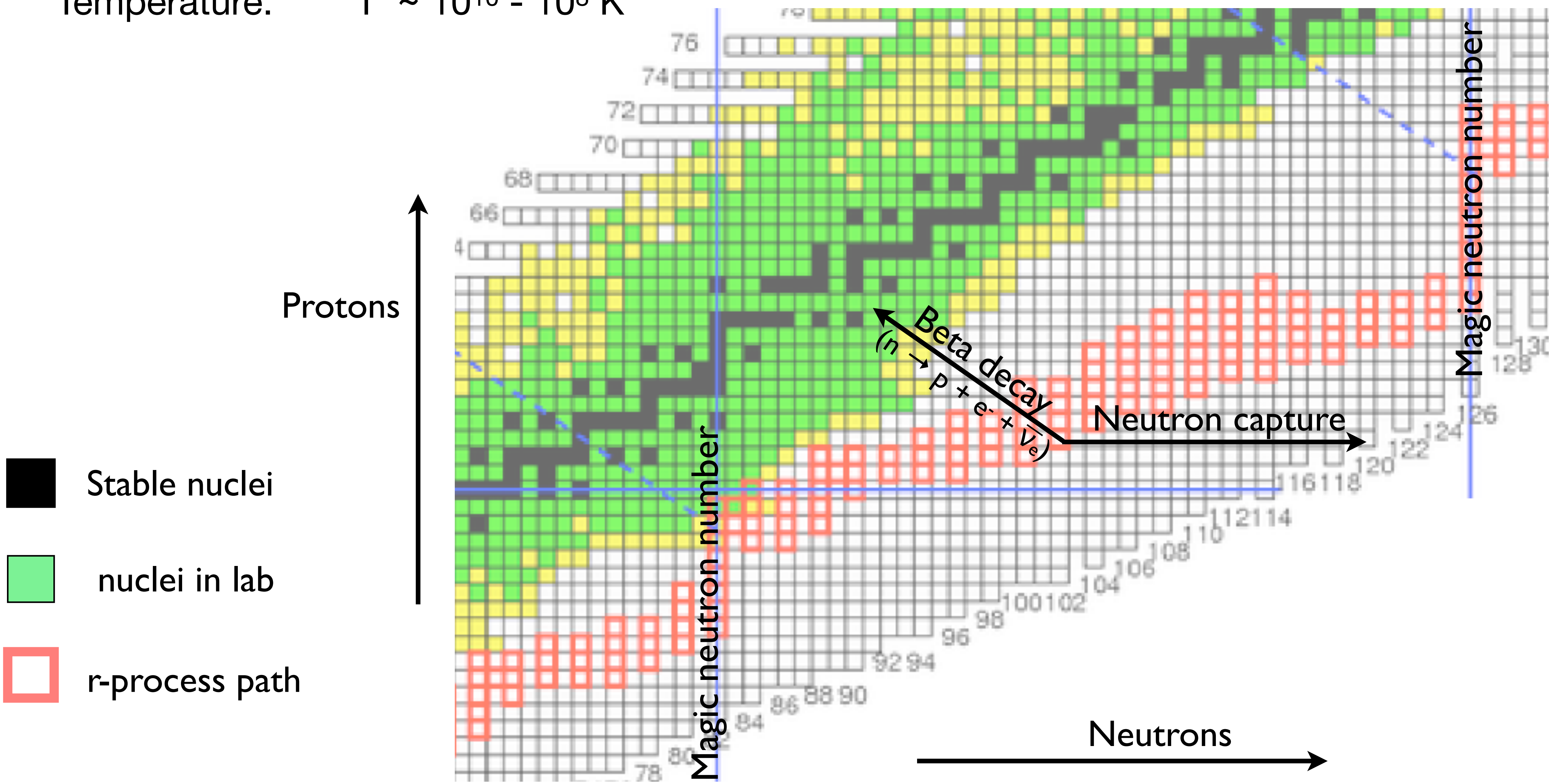


Sneden, Cowan, Gallino 2008

r-process

Rapid neutron capture compared to beta decay

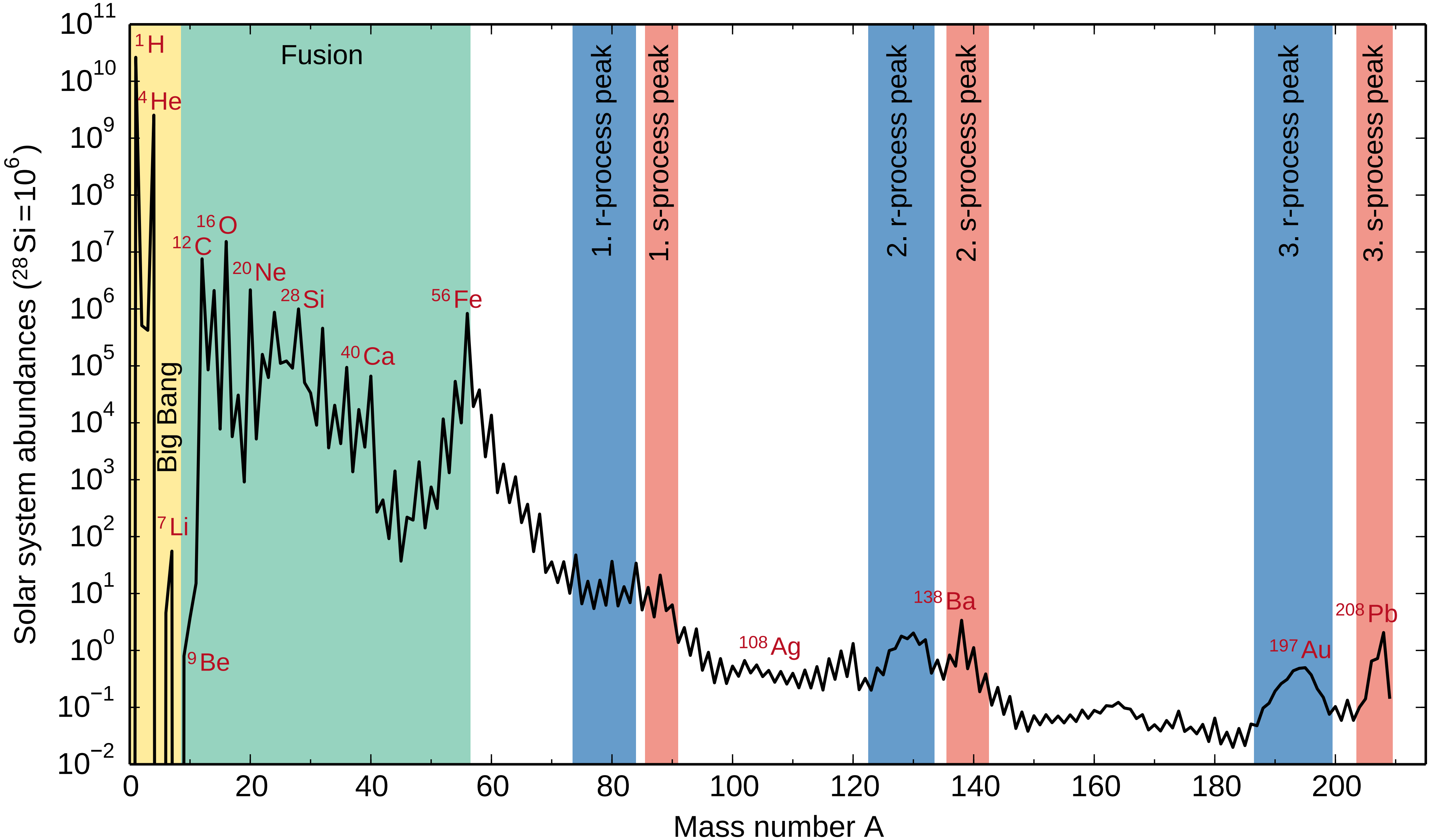
Neutron density: $N_n \sim 10^{27} - 10^{20}\ cm^{-3}$
Temperature: $T \sim 10^{10} - 10^{8}$ K

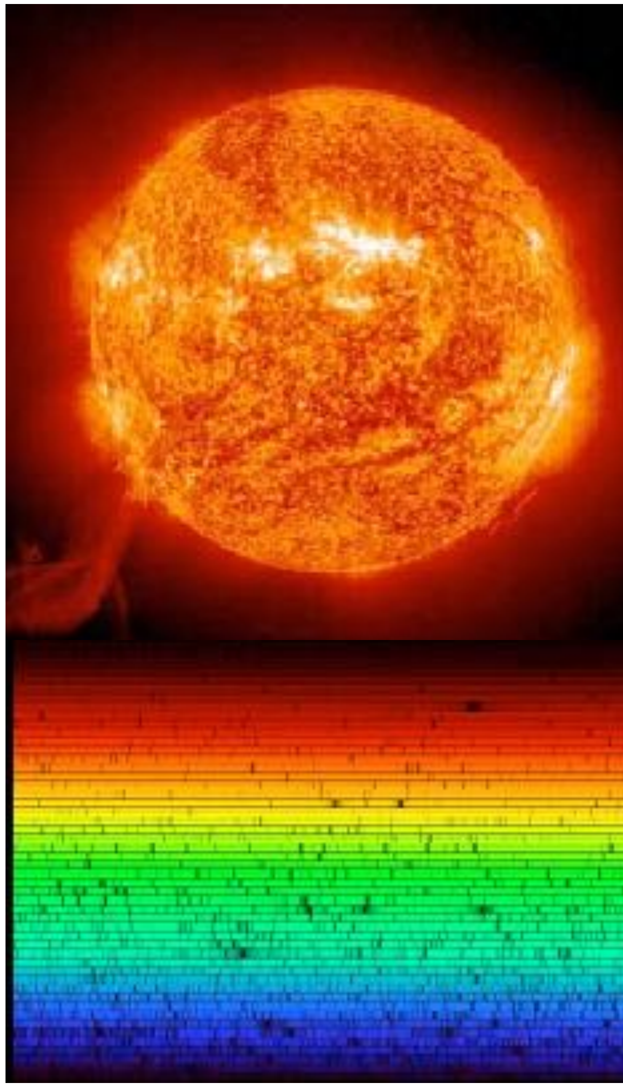


Solar system abundances

Solar photosphere and meteorites:
chemical signature of gas cloud where the Sun formed

Contribution of all nucleosynthesis processes

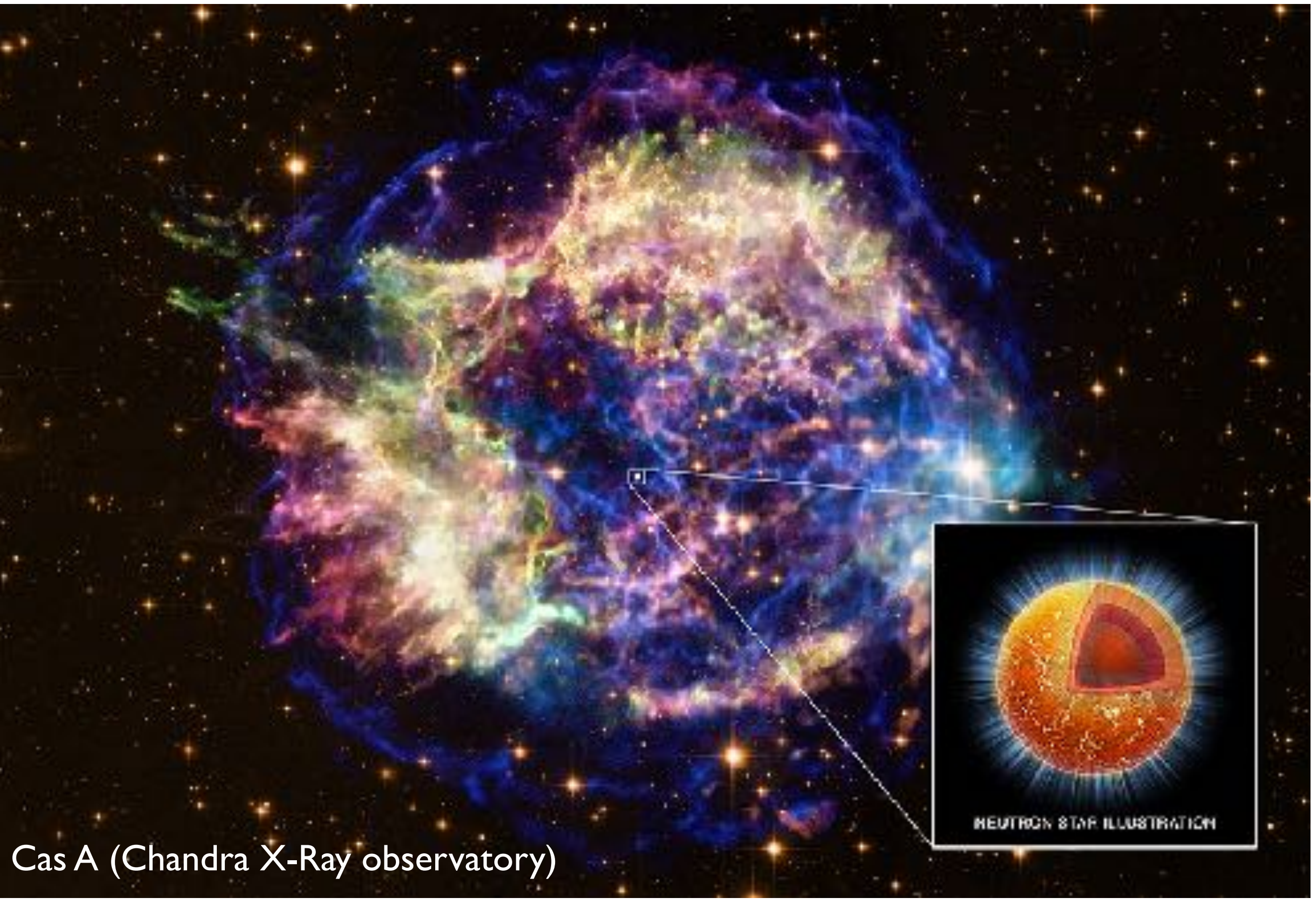




Where does the r-process occur?

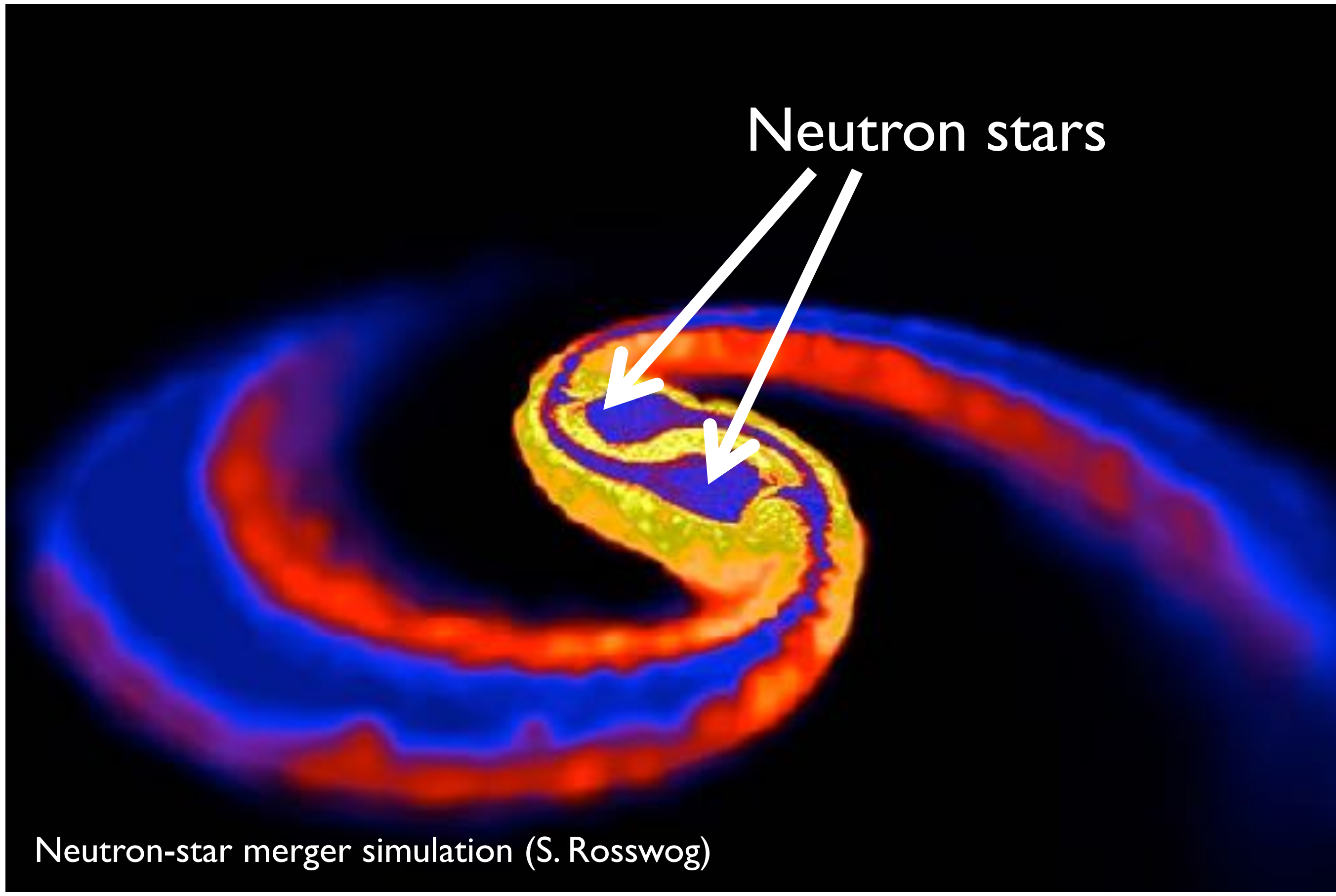
rapid process → explosions
high neutron densities → neutron stars

Core-collapse supernovae

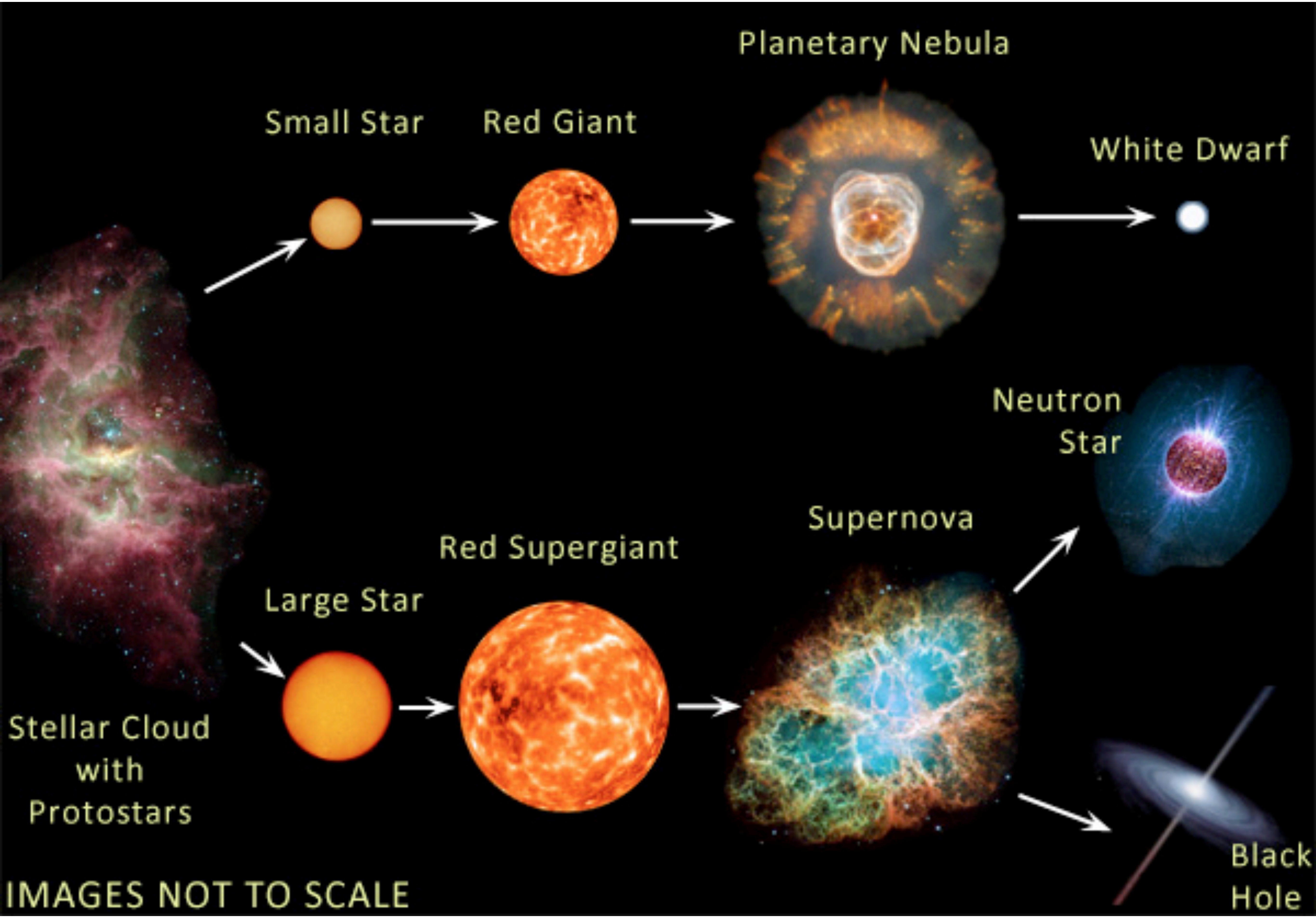


Cas A (Chandra X-Ray observatory)

Neutron star mergers



Neutron-star merger simulation (S. Rosswog)

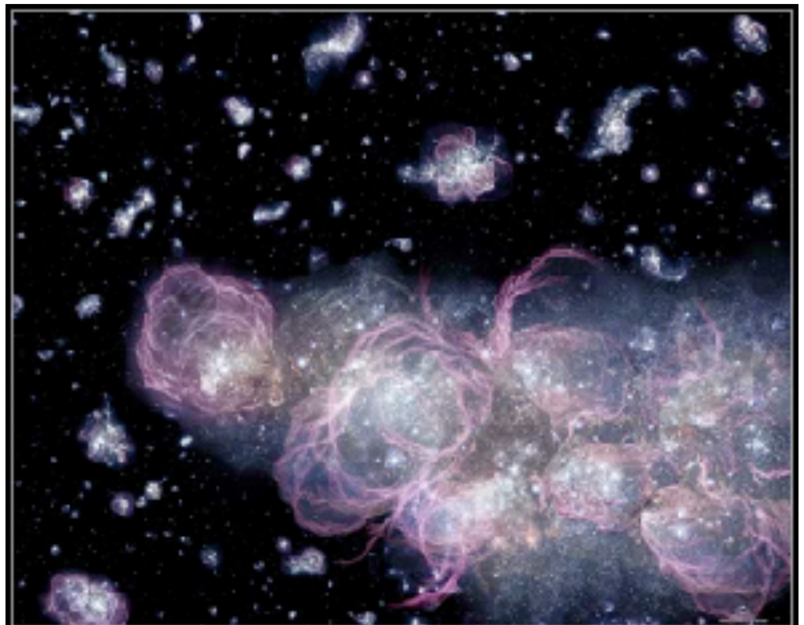


Planetary Nebula
Small Star
Red Giant
White Dwarf
Neutron Star
Supernova
Red Supergiant
Large Star
Stellar Cloud with Protostars
Black Hole
IMAGES NOT TO SCALE

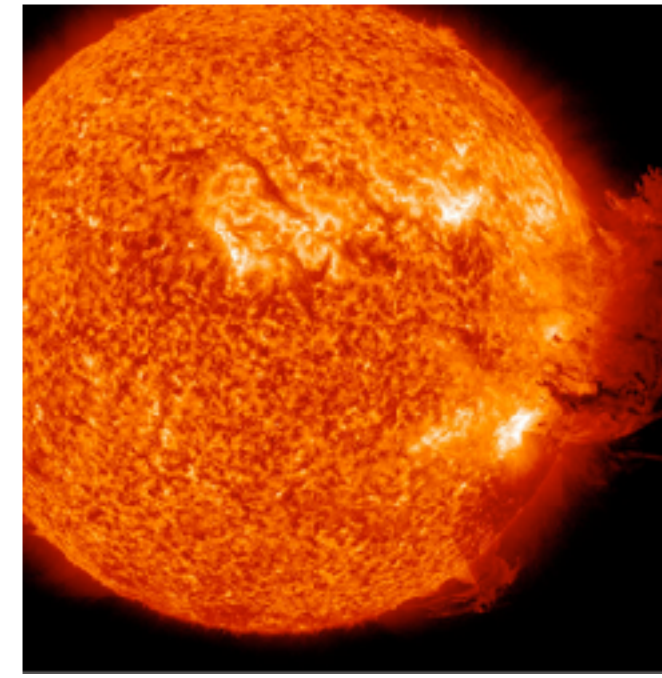
Galactic chemical evolution

First stars: H, He → Heavy elements ← New generation of stars

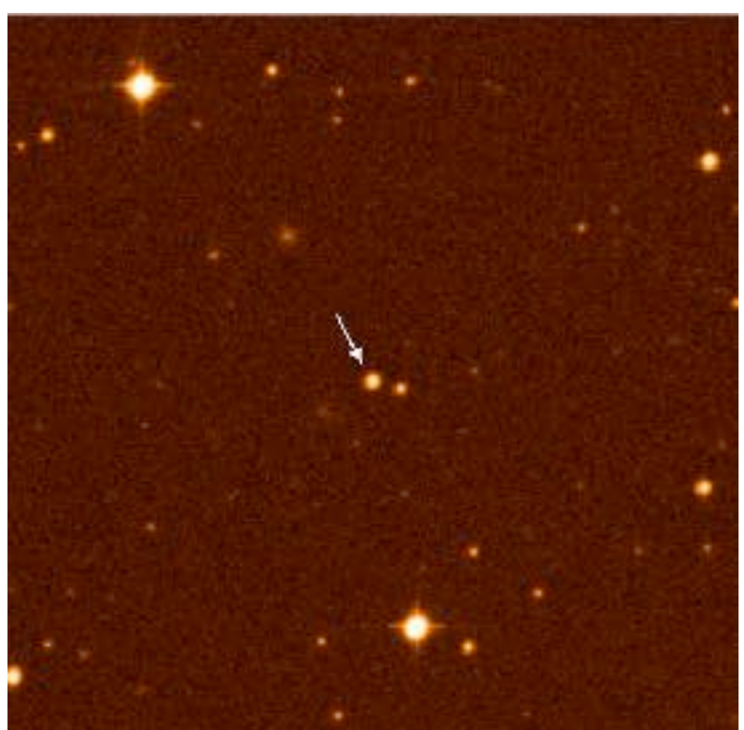
Heavy elements → Interstellar medium (ISM) → New generation of stars

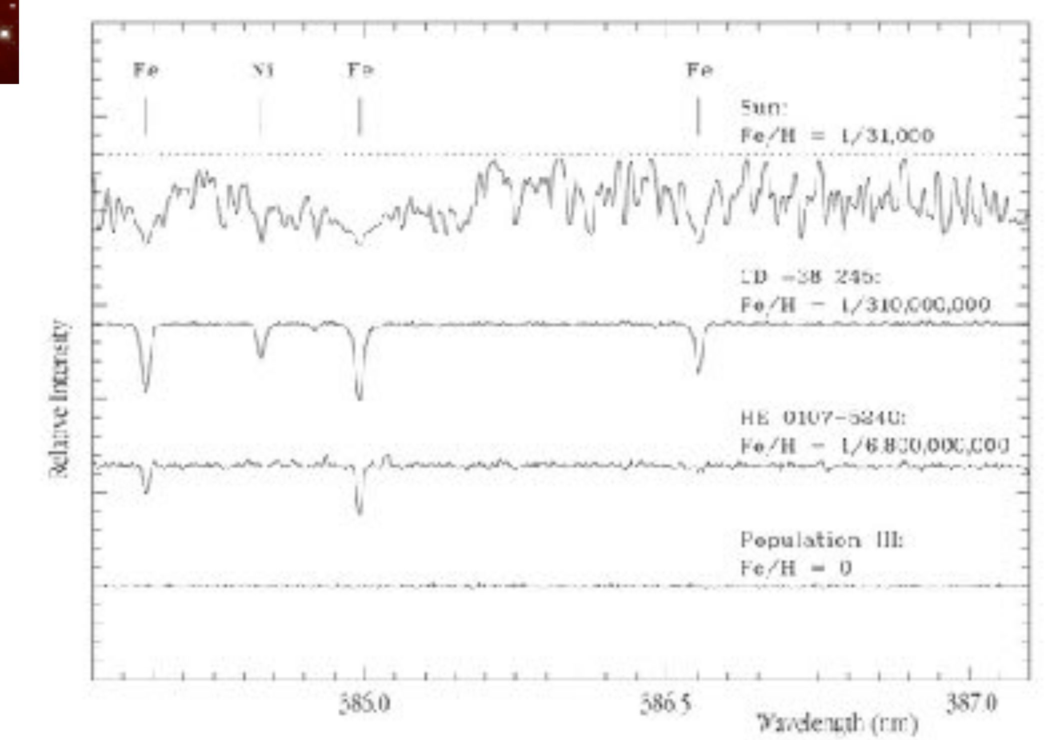


Artist's View of Star Formation in the Early Universe
Painting by Adolf Schaller • STScI-PRC02-02



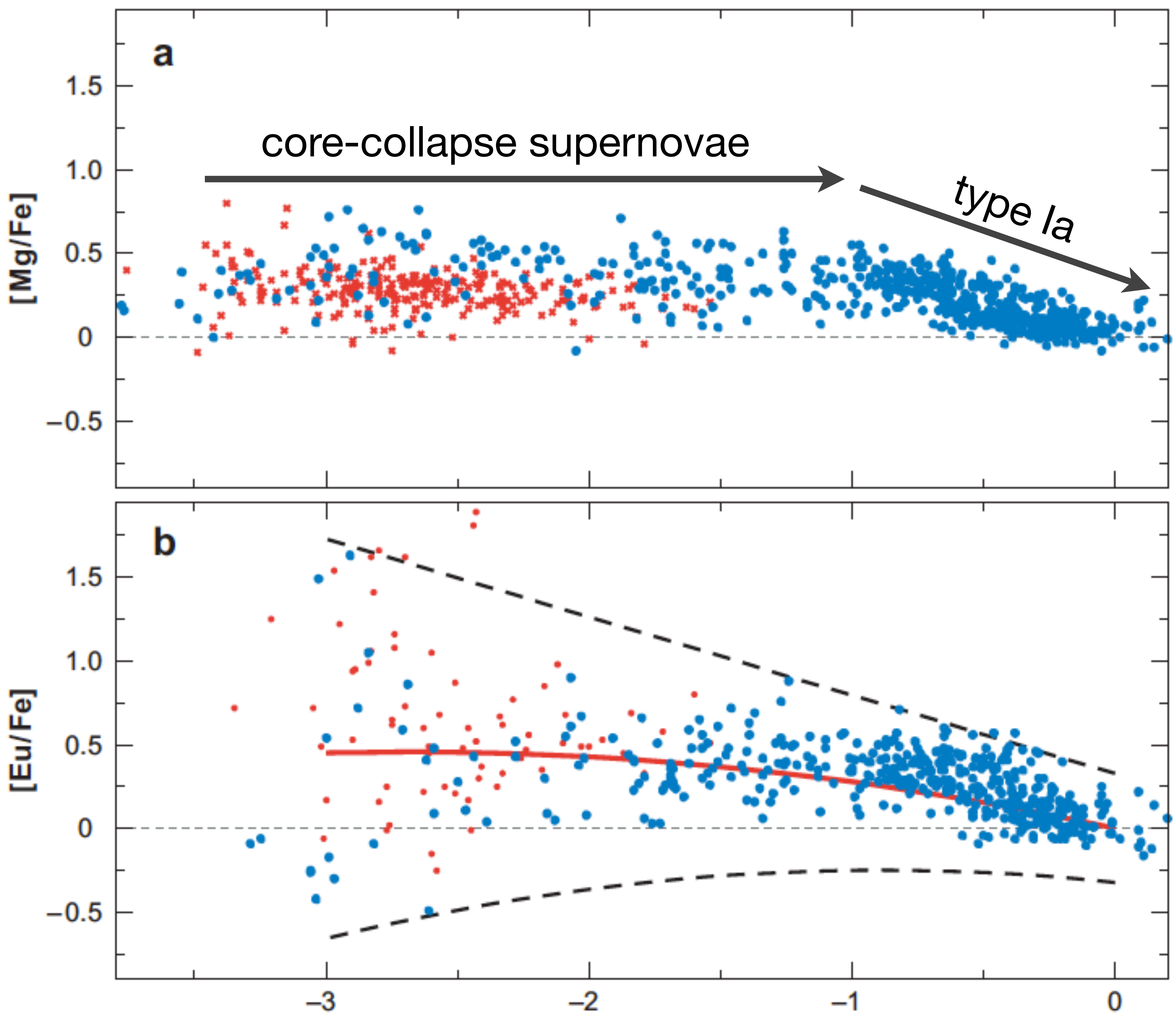
The very metal-deficient star
HE 0107-5240
(Hamburg-ESO survey)





Spectra of Stars with Different Metal Content

Trends with metallicity



Fe and Mg produced in same site: core-collapse supernovae

Significant scatter at low metallicities

r-process production rare in the early Galaxy

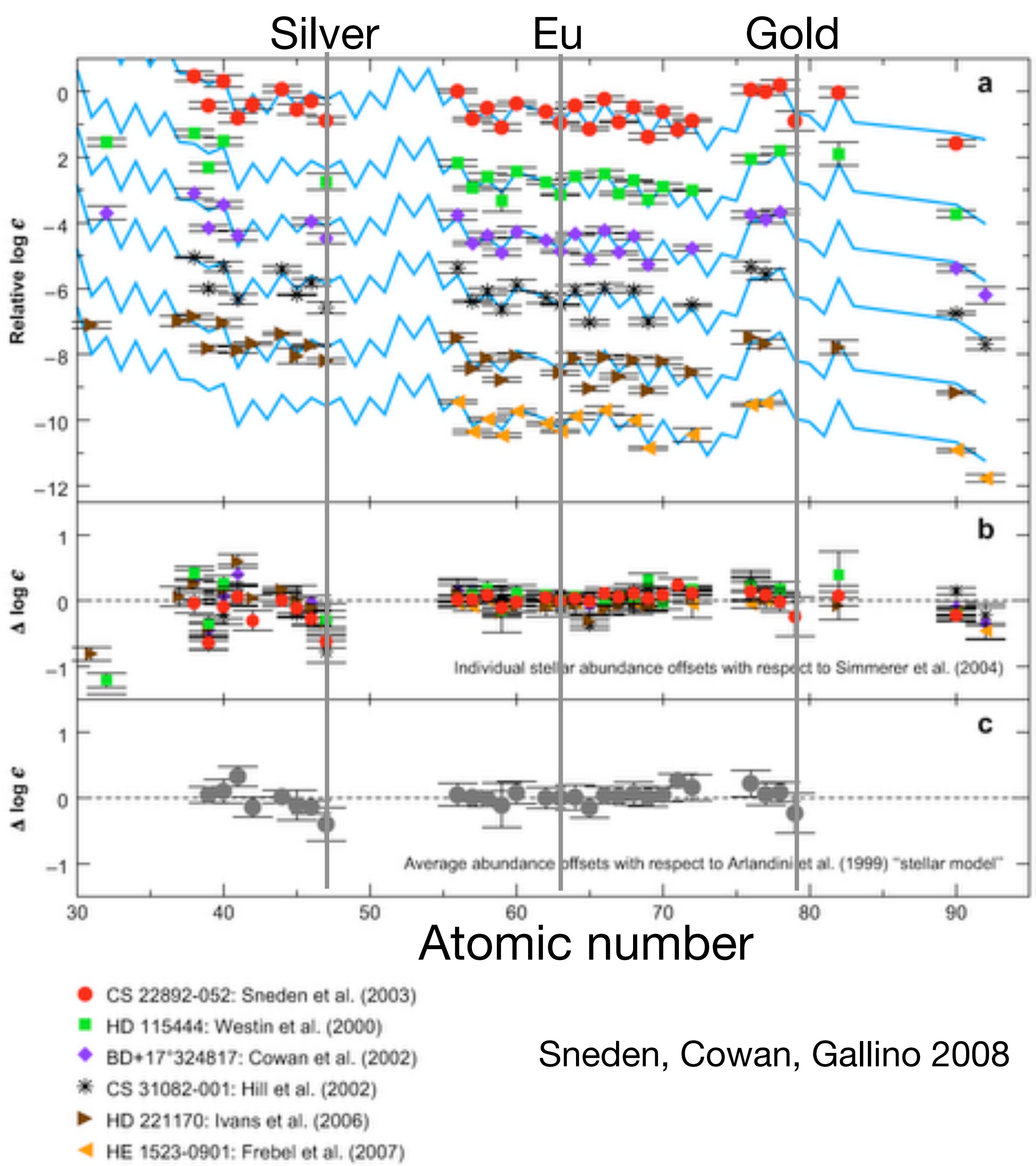
Mg and Fe production is not coupled to r-process production

Sneden, Cowan, Gallino 2008

[Fe/H] **~time**

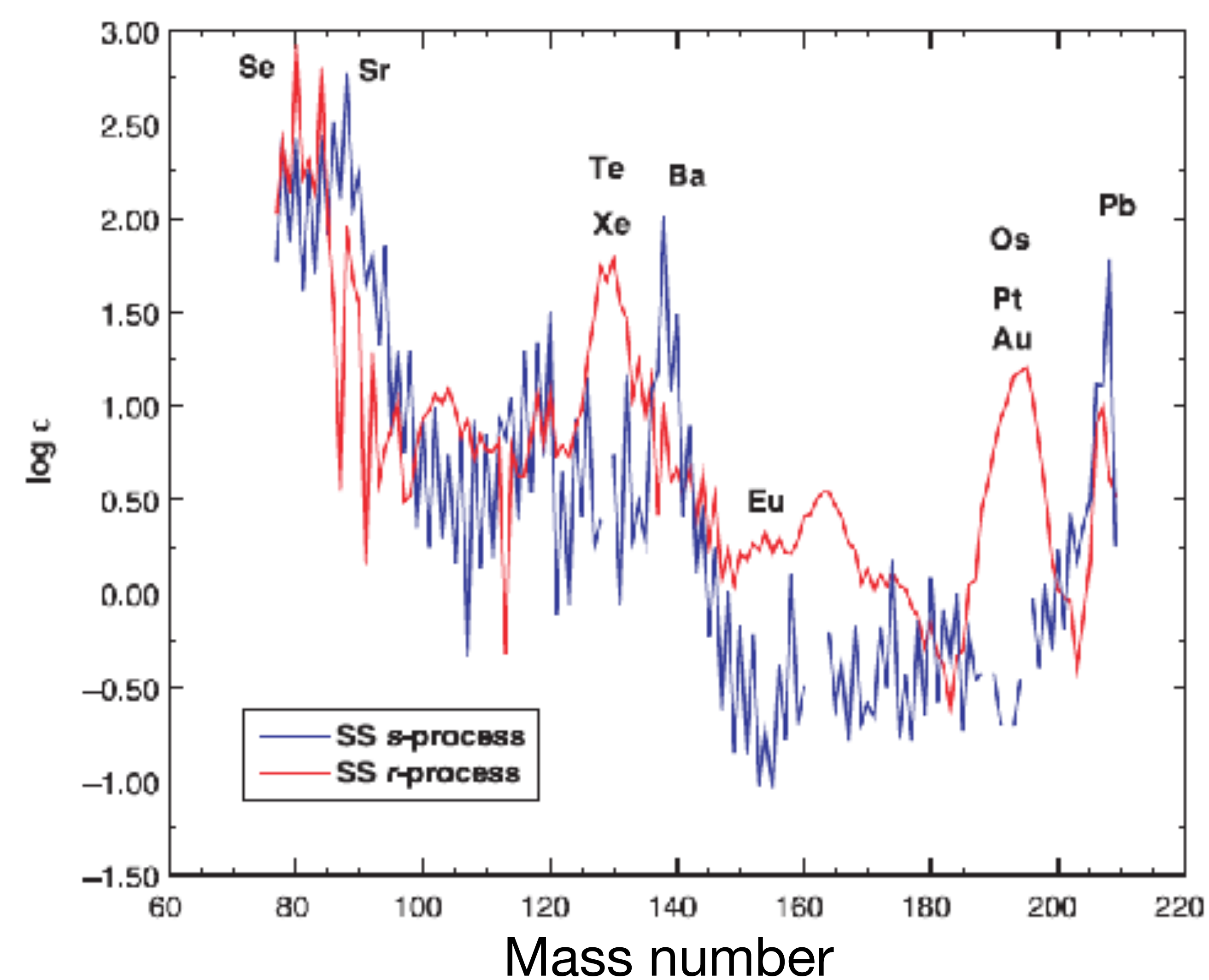
Fingerprint of the r-process

Oldest observed stars

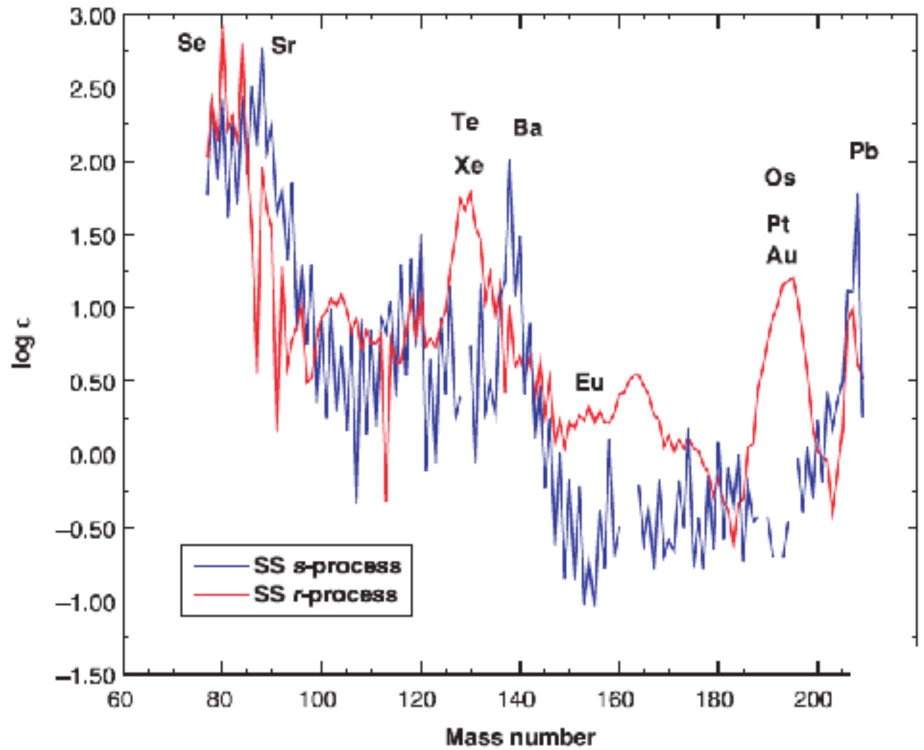


Sneden, Cowan, Gallino 2008

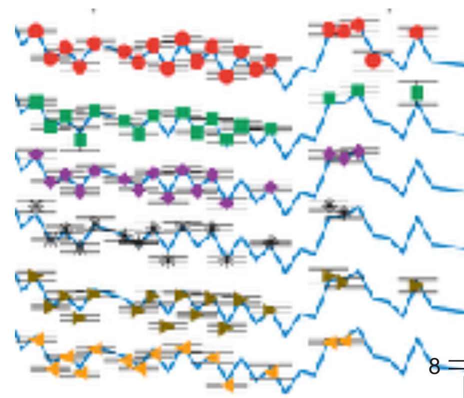
Solar system abundances

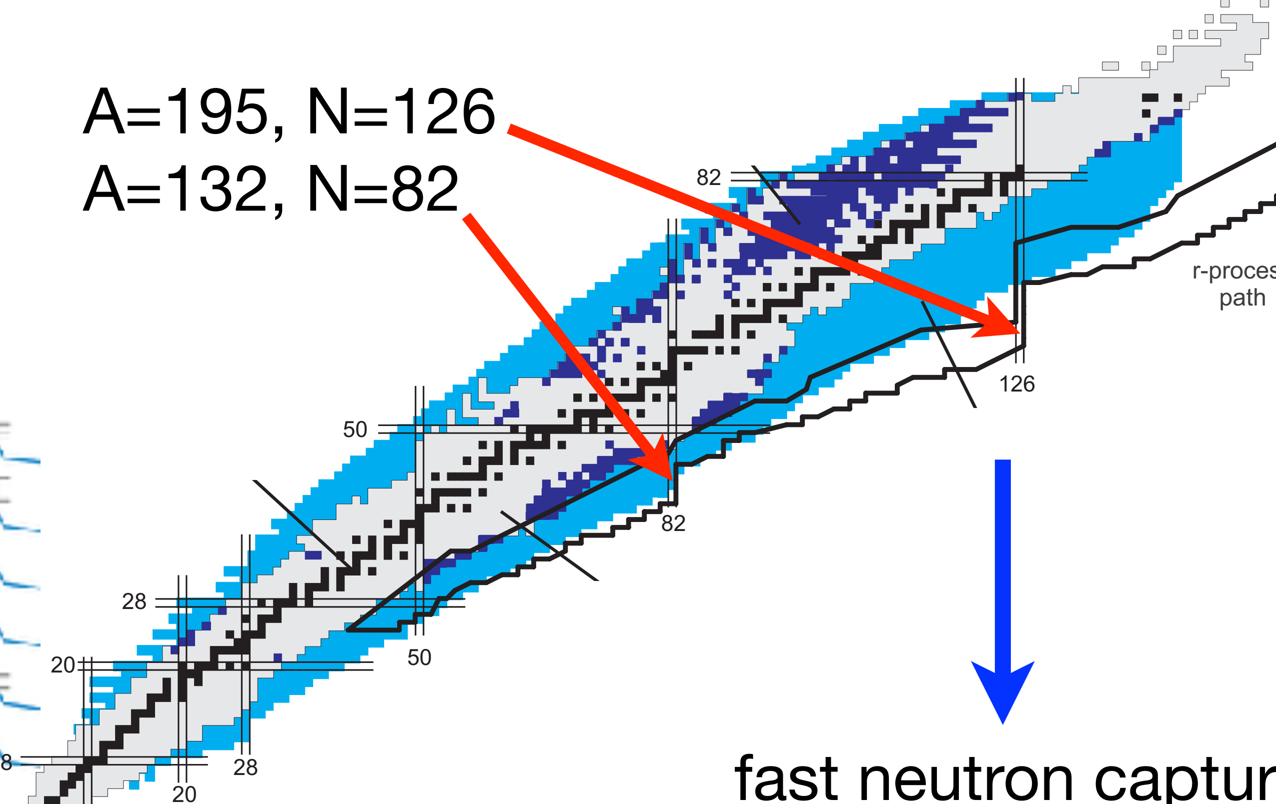


solar and UMP star abundances



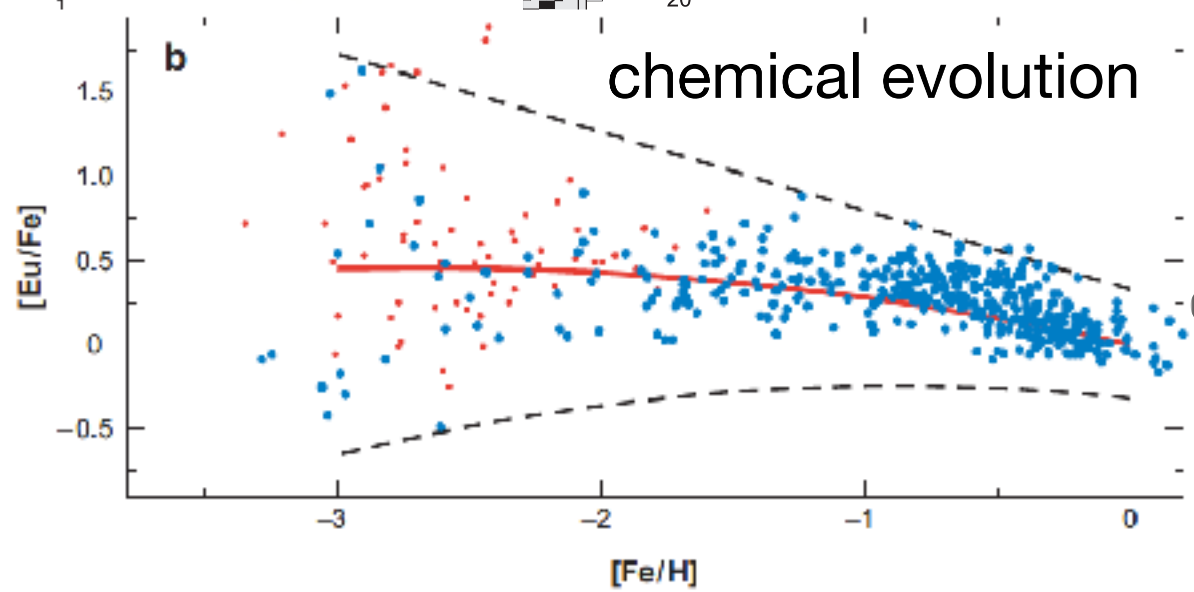
A=195, N=126
A=132, N=82



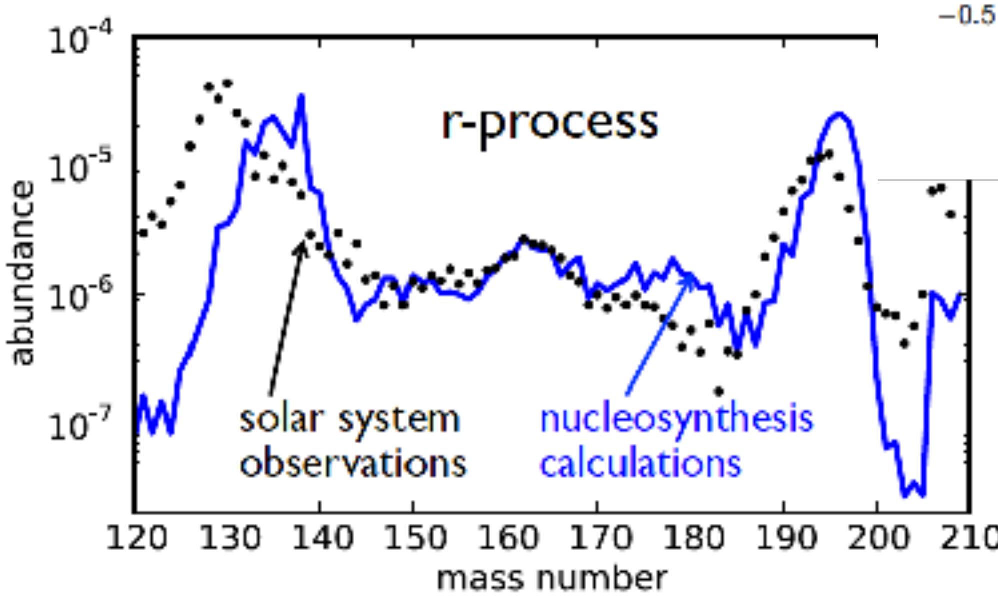


fast neutron capture
high neutron density

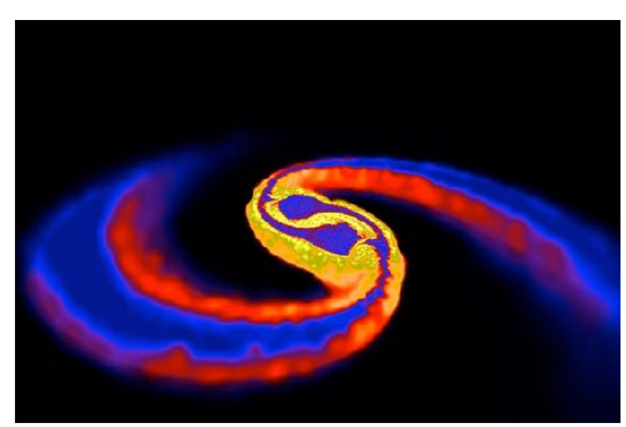
chemical evolution

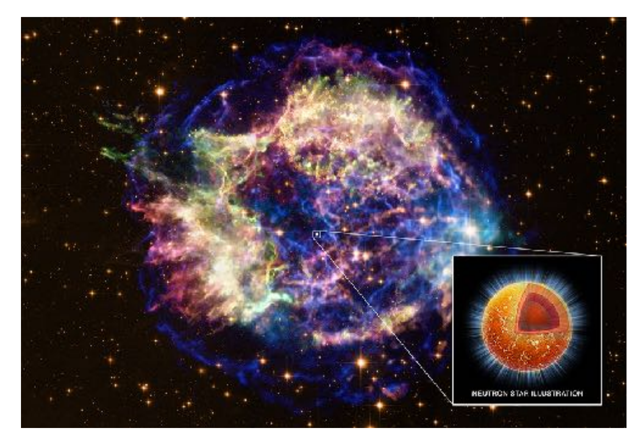


explosive environment
neutron rich



hydrodynamic simulations
high density EoS, neutrino transport





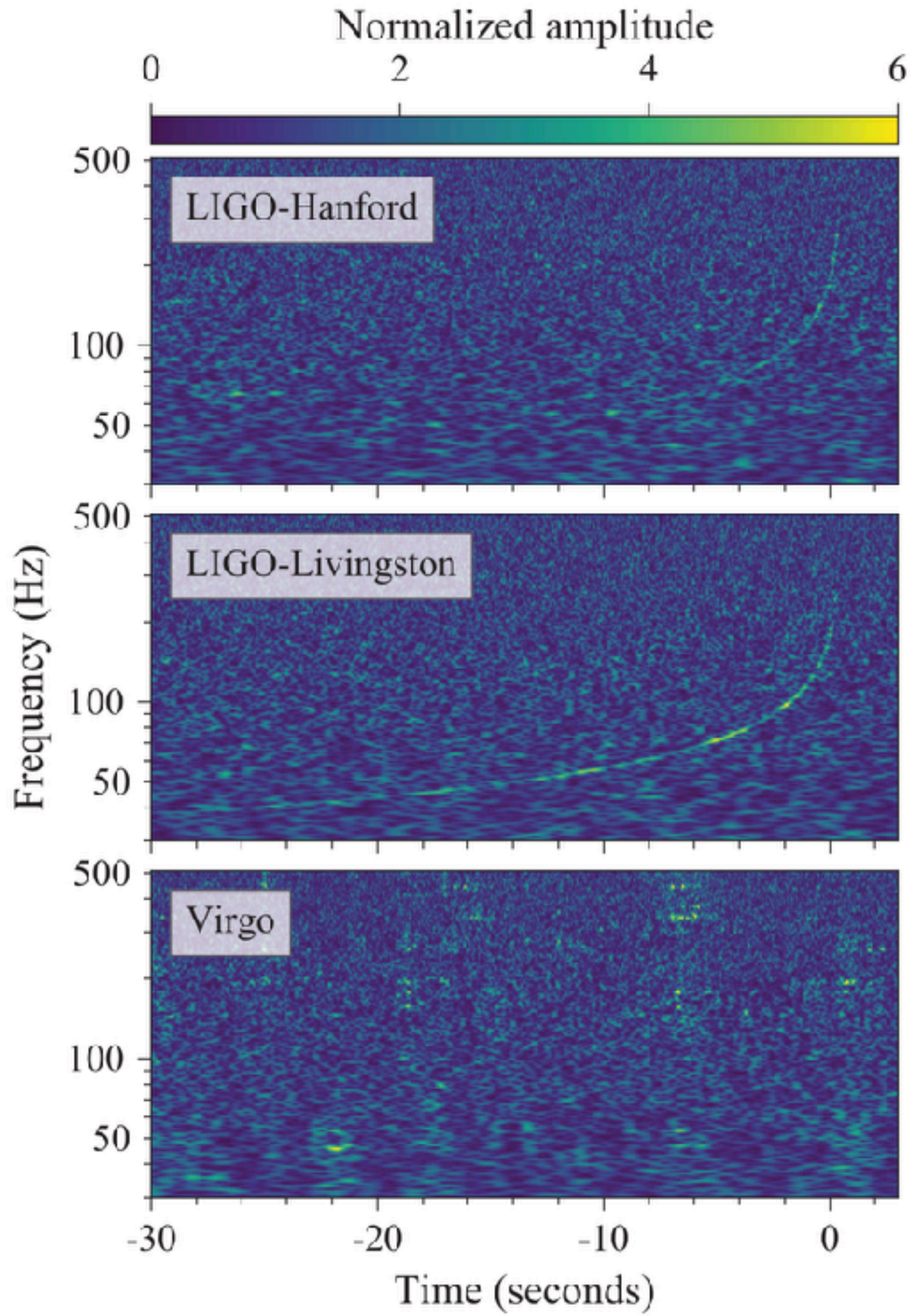
nucleosynthesis calculations
nuclear reaction network

GW170817

LIGO-LIVINGSTON OBSERVATORY

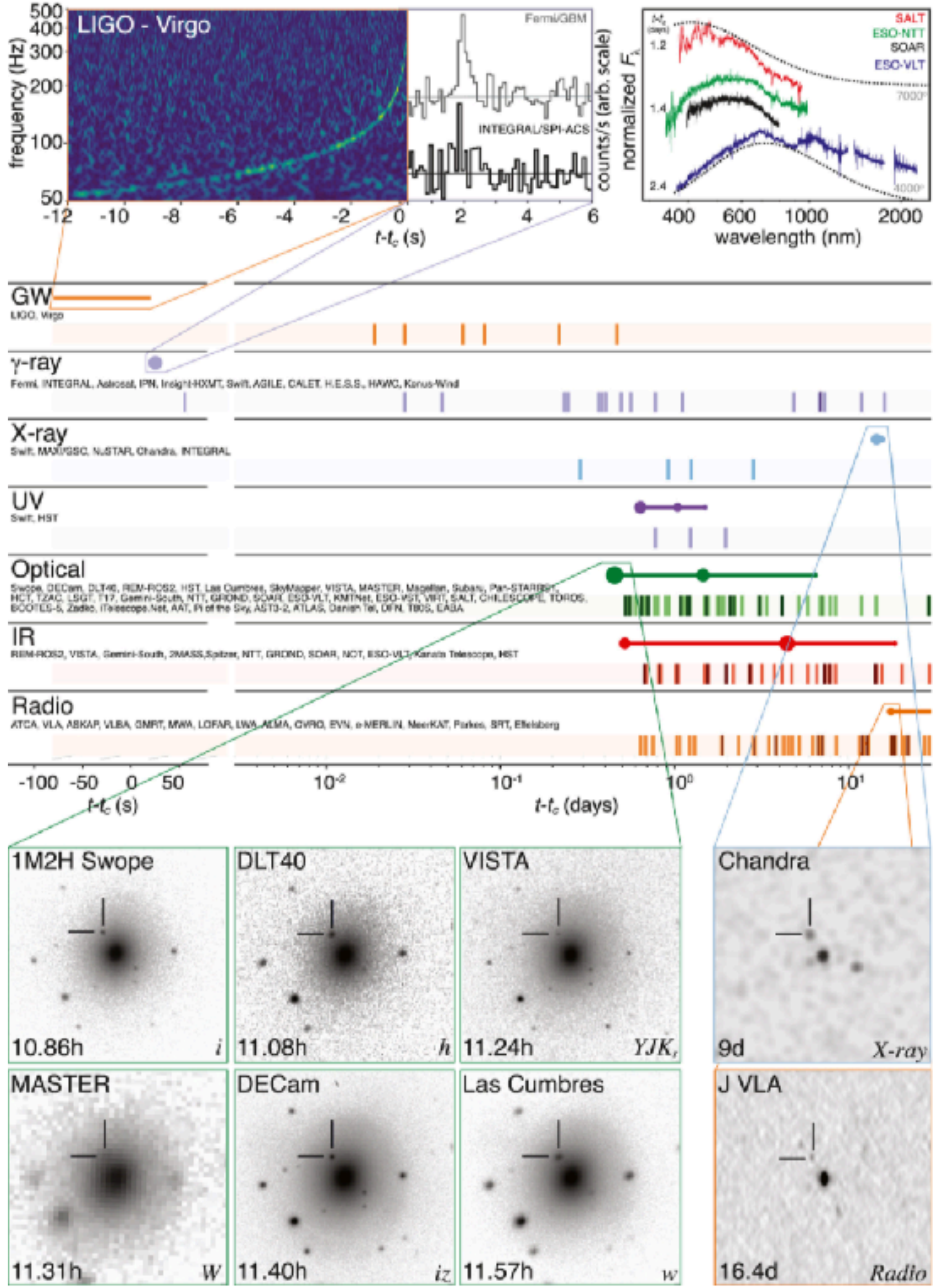
LIGO-HANFORD OBSERVATORY

VIRGO AT CASCINA, ITALY

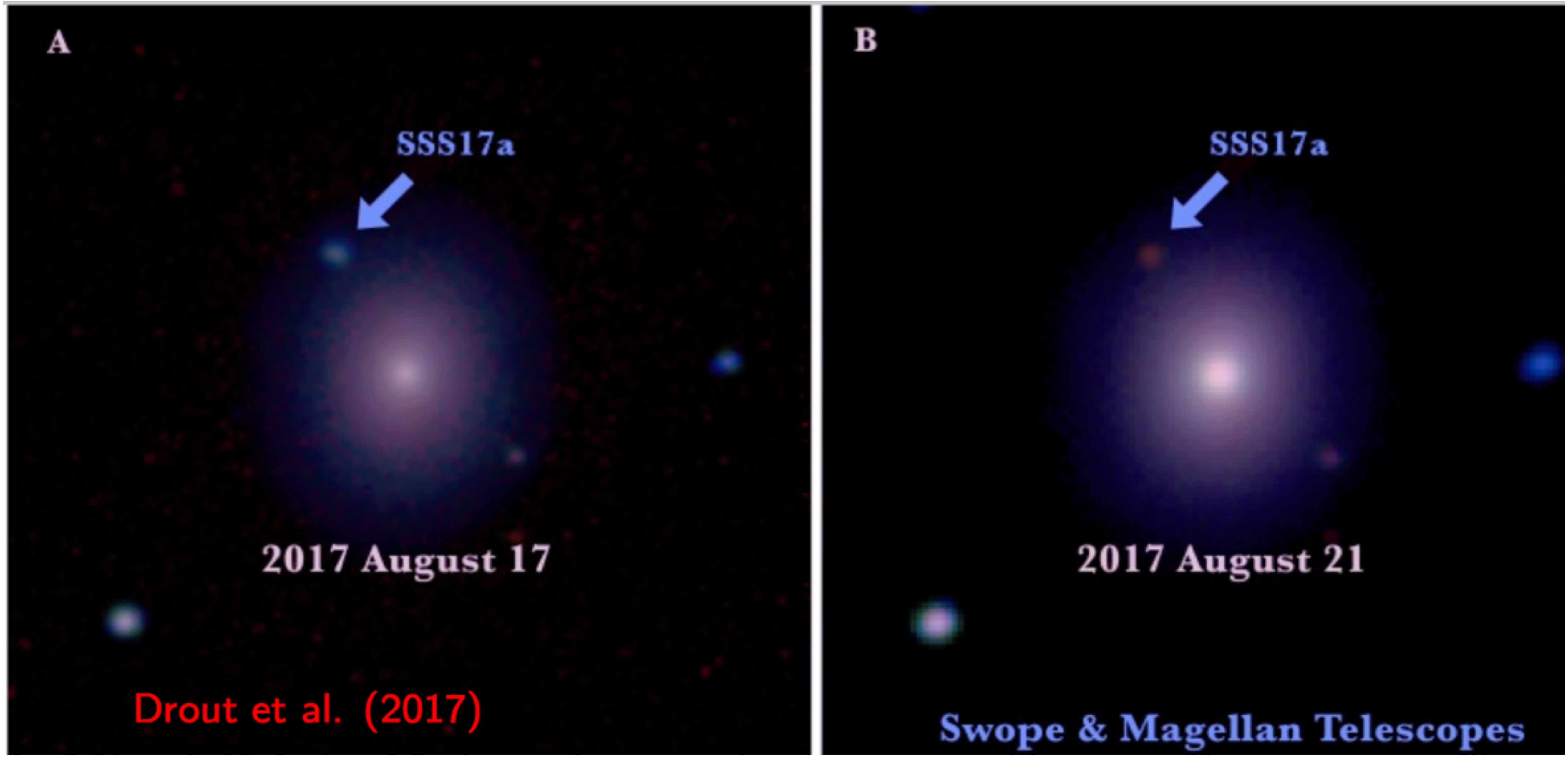


Normalized amplitude
0
2
4
6
500
100
50
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
-30
-20
-10
0
Time (seconds)

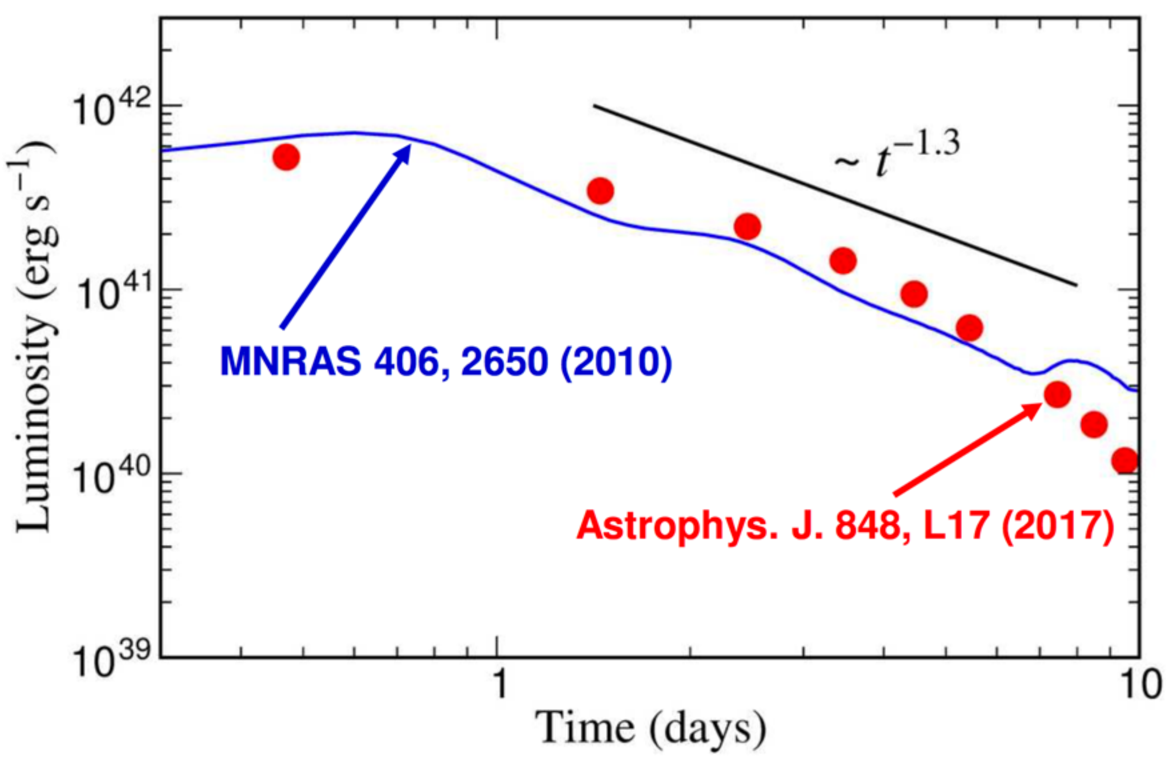
Multimessenger

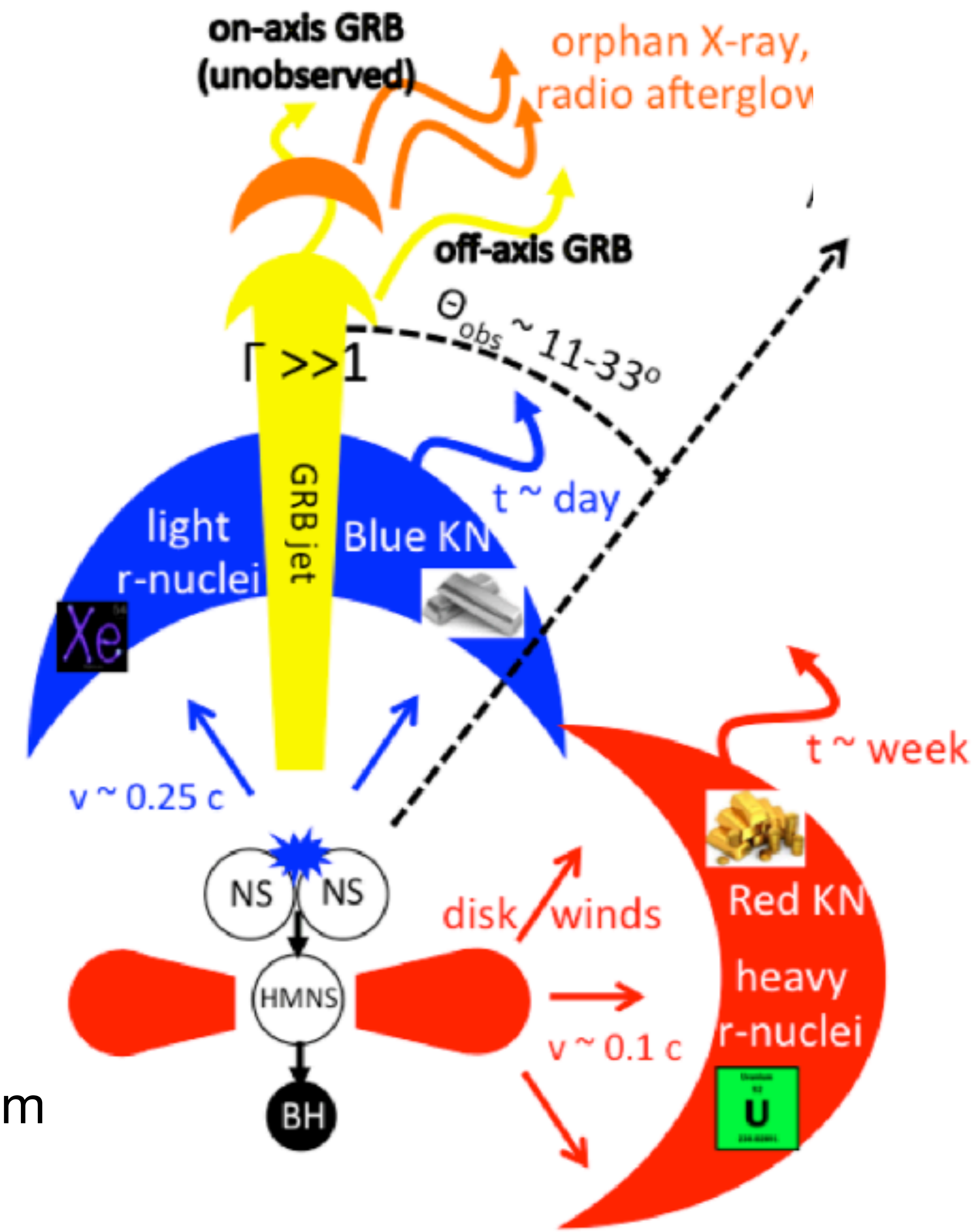


Kilonova


A
SSS17a
2017 August 17
Drout et al. (2017)
B
SSS17a
2017 August 21
Swope & Magellan Telescopes

Kilonova

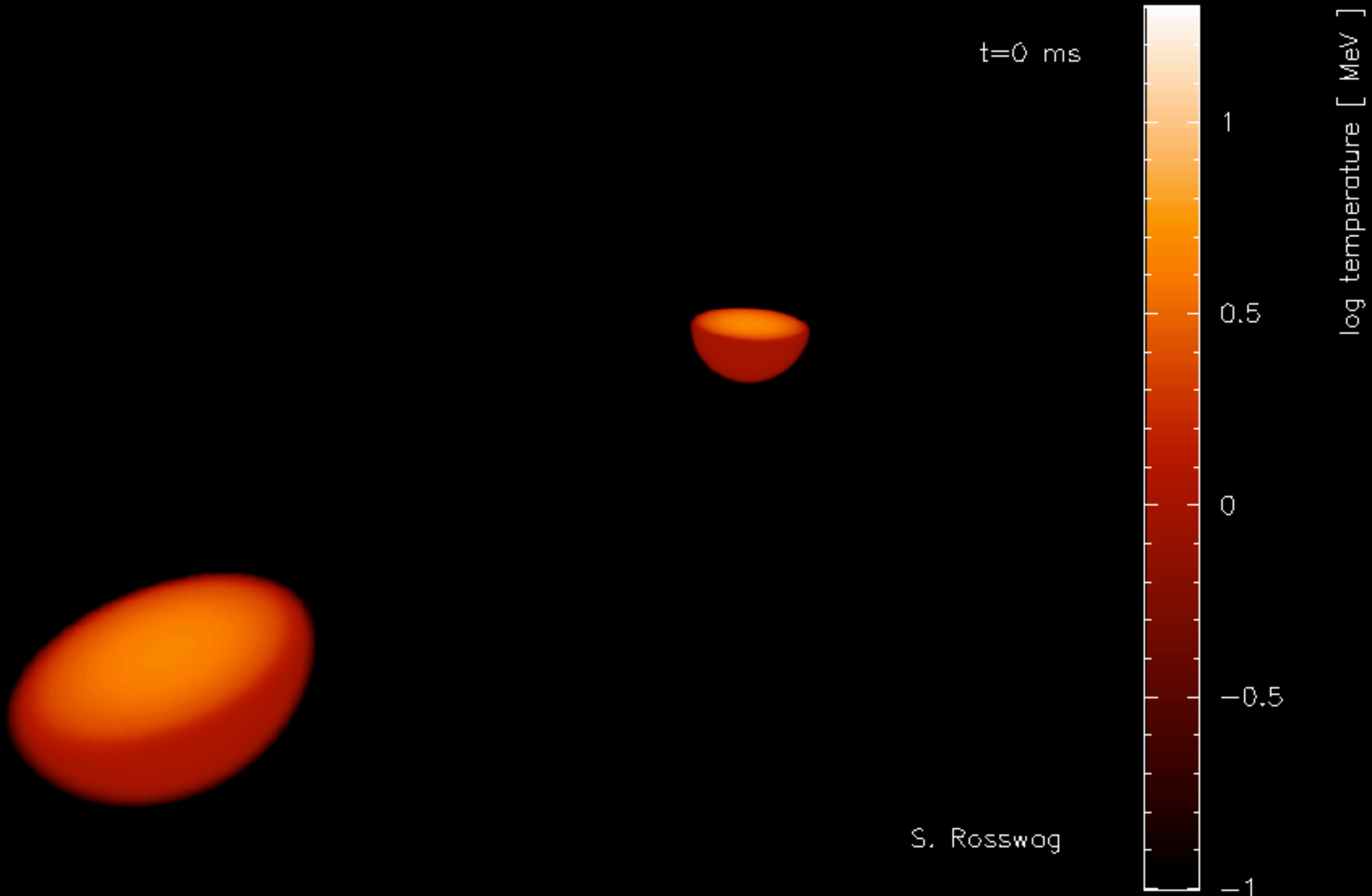




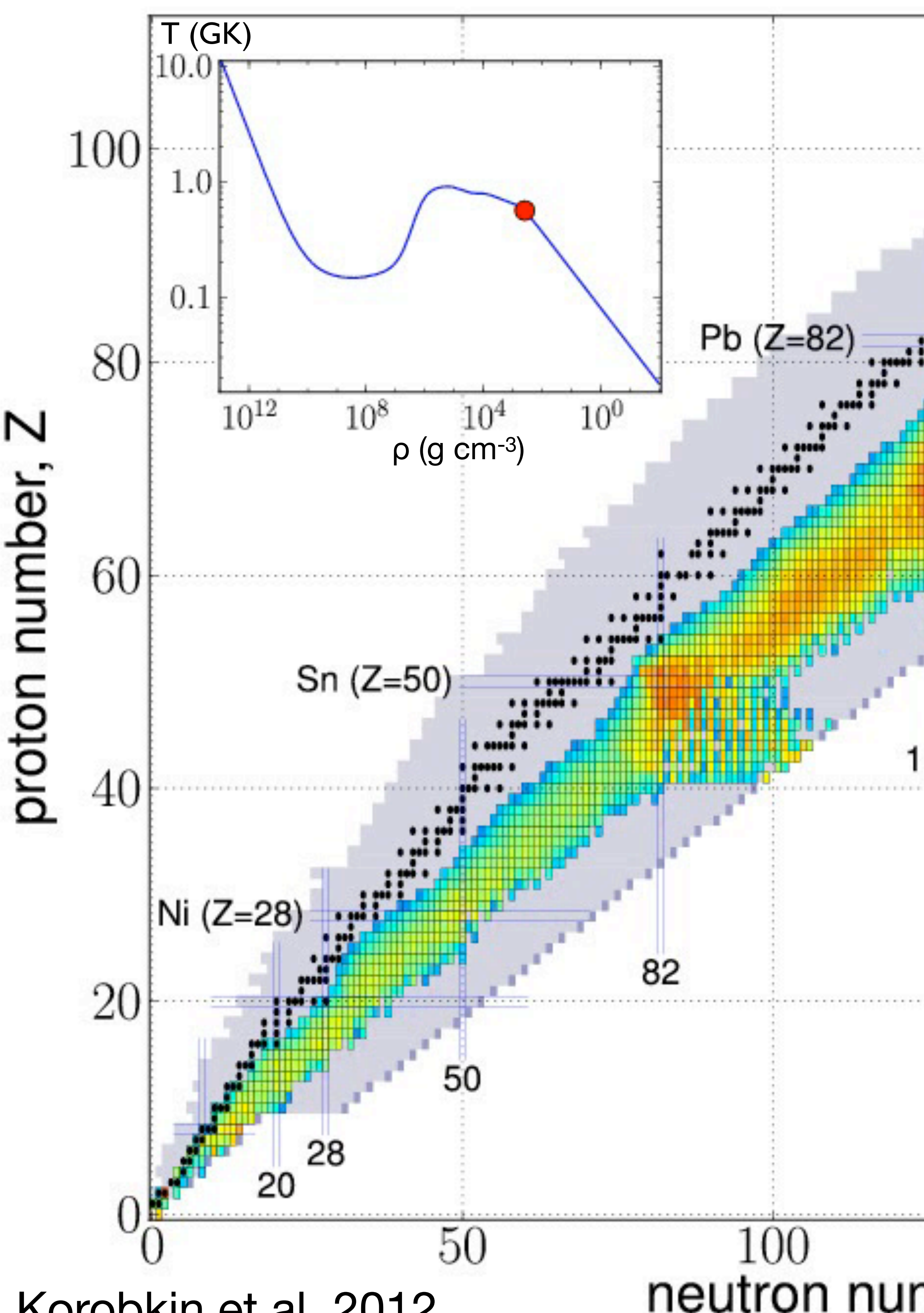
R-process in neutron star mergers confirmed by kilonova (radioactive decay of n-rich nuclei) after gravitational wave detection from GW170817

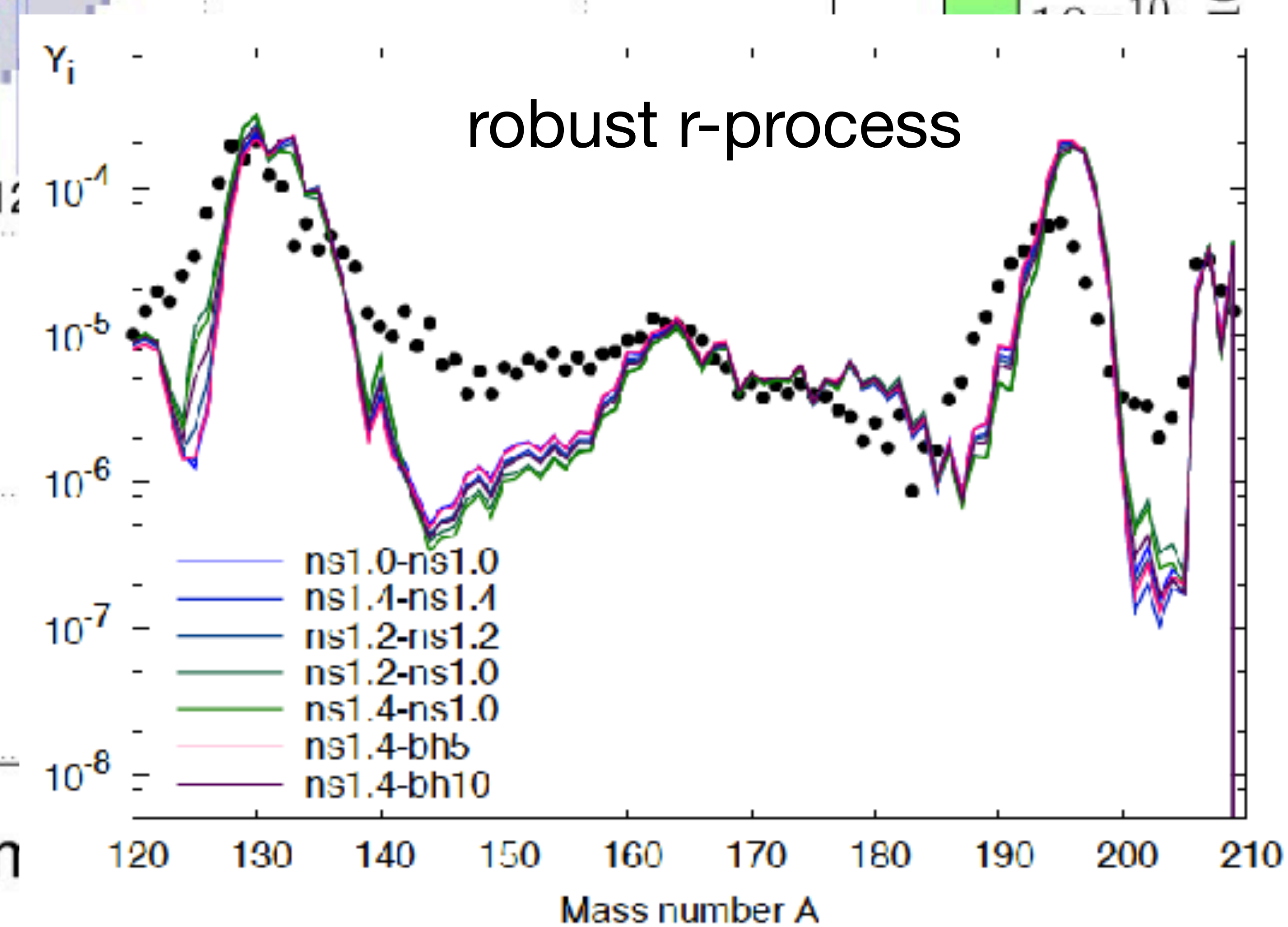
Li & Paczynski (1998)

Neutron star mergers



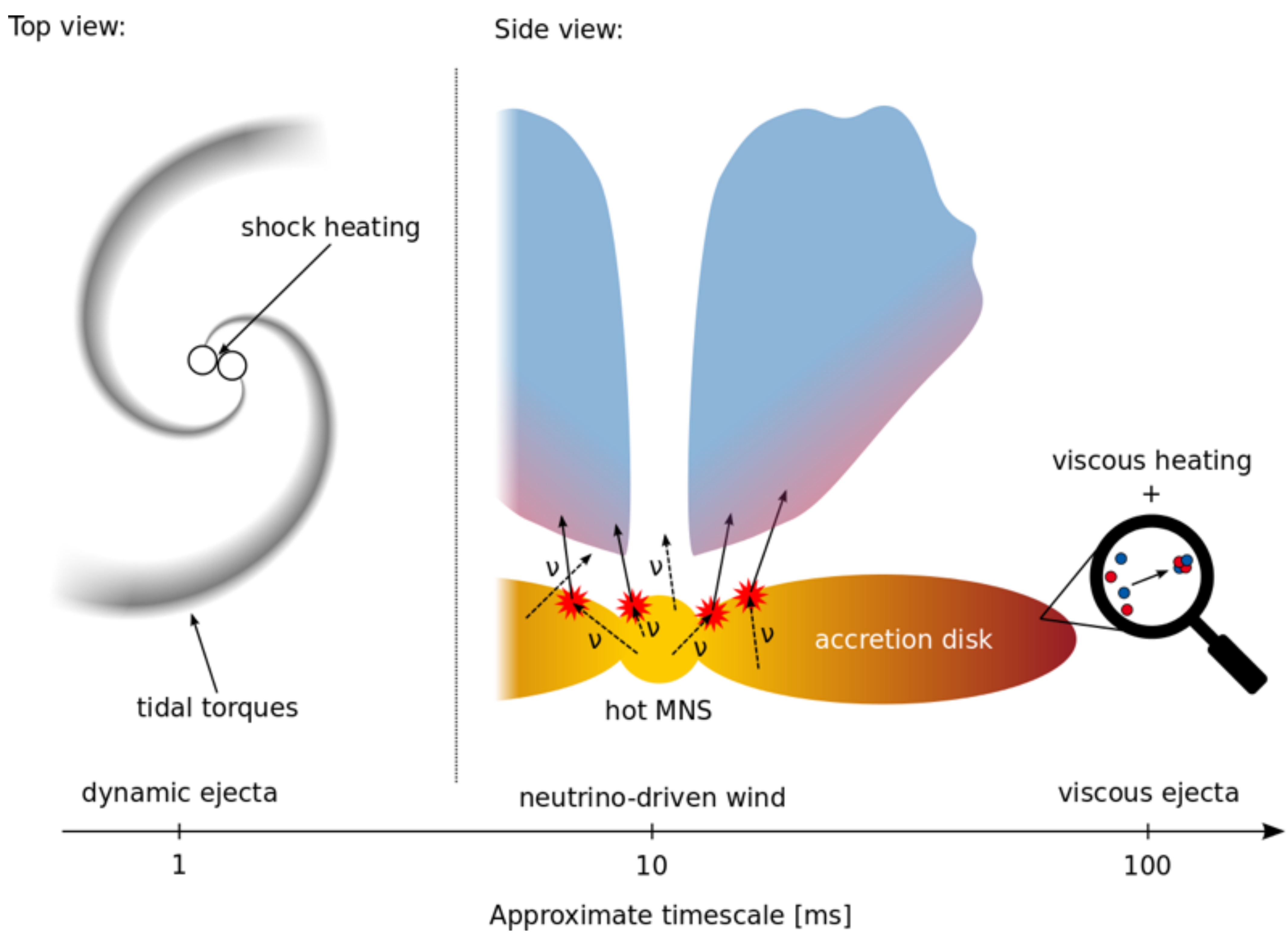
t : 1.15e+00 s / T : 0.56 GK / ρ_b : 3.98e+02 g/cm^3





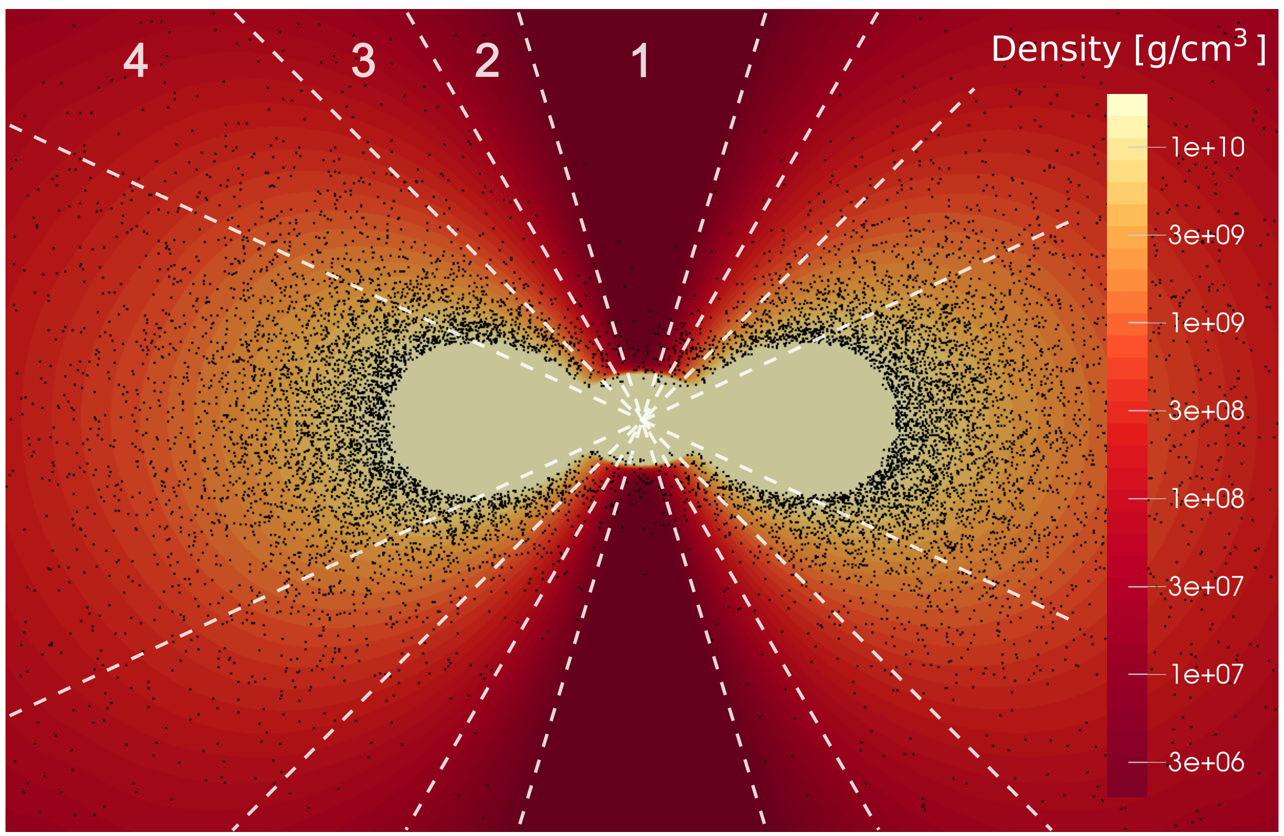
Korobkin et al. 2012

Ejecta and nucleosynthesis



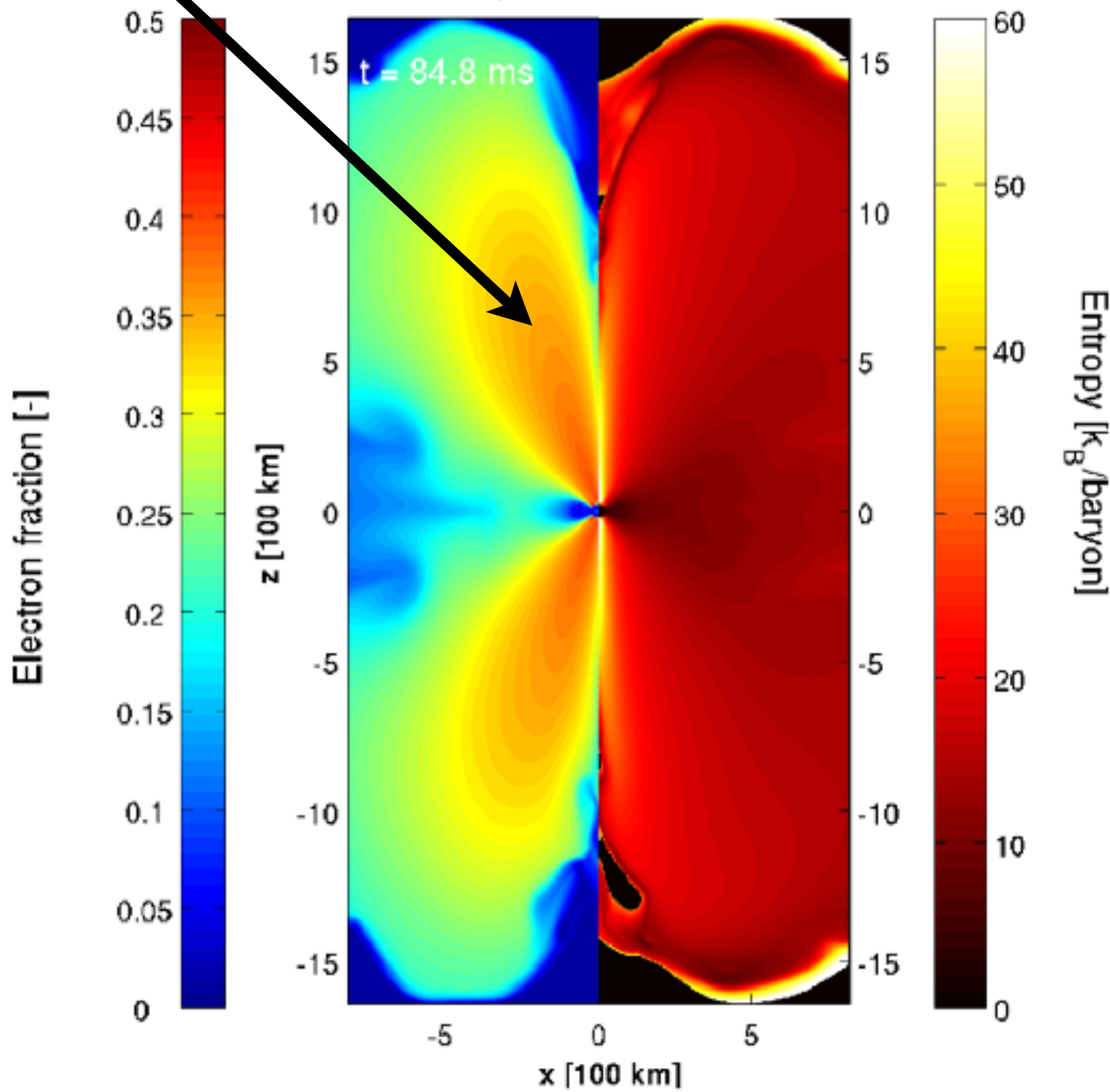
Neutron star mergers: neutrino-driven wind

3D simulations after merger
disk and neutrino-wind evolution
neutrino emission and absorption
Nucleosynthesis: 17 000 tracers



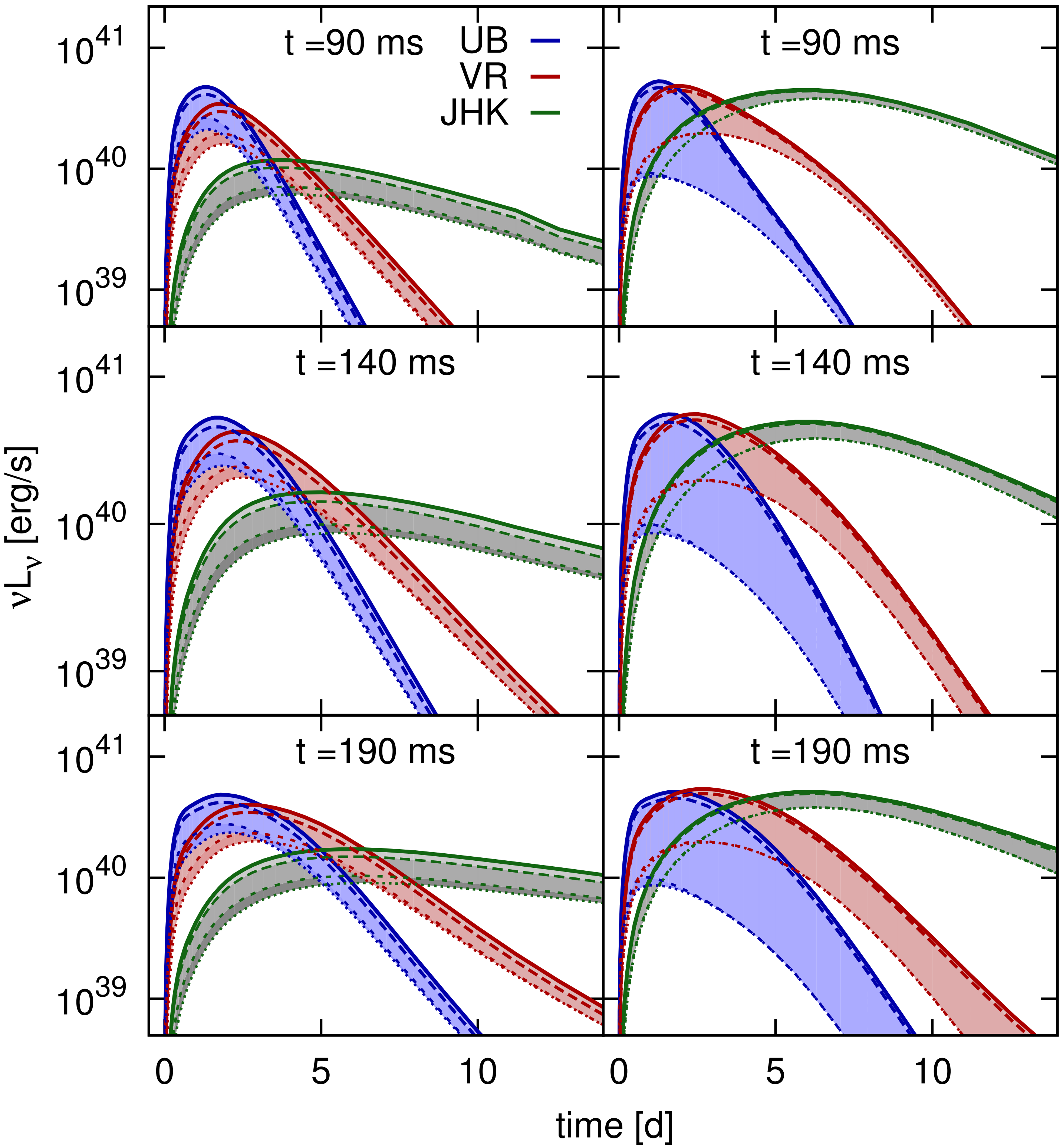
Martin et al. (2015)

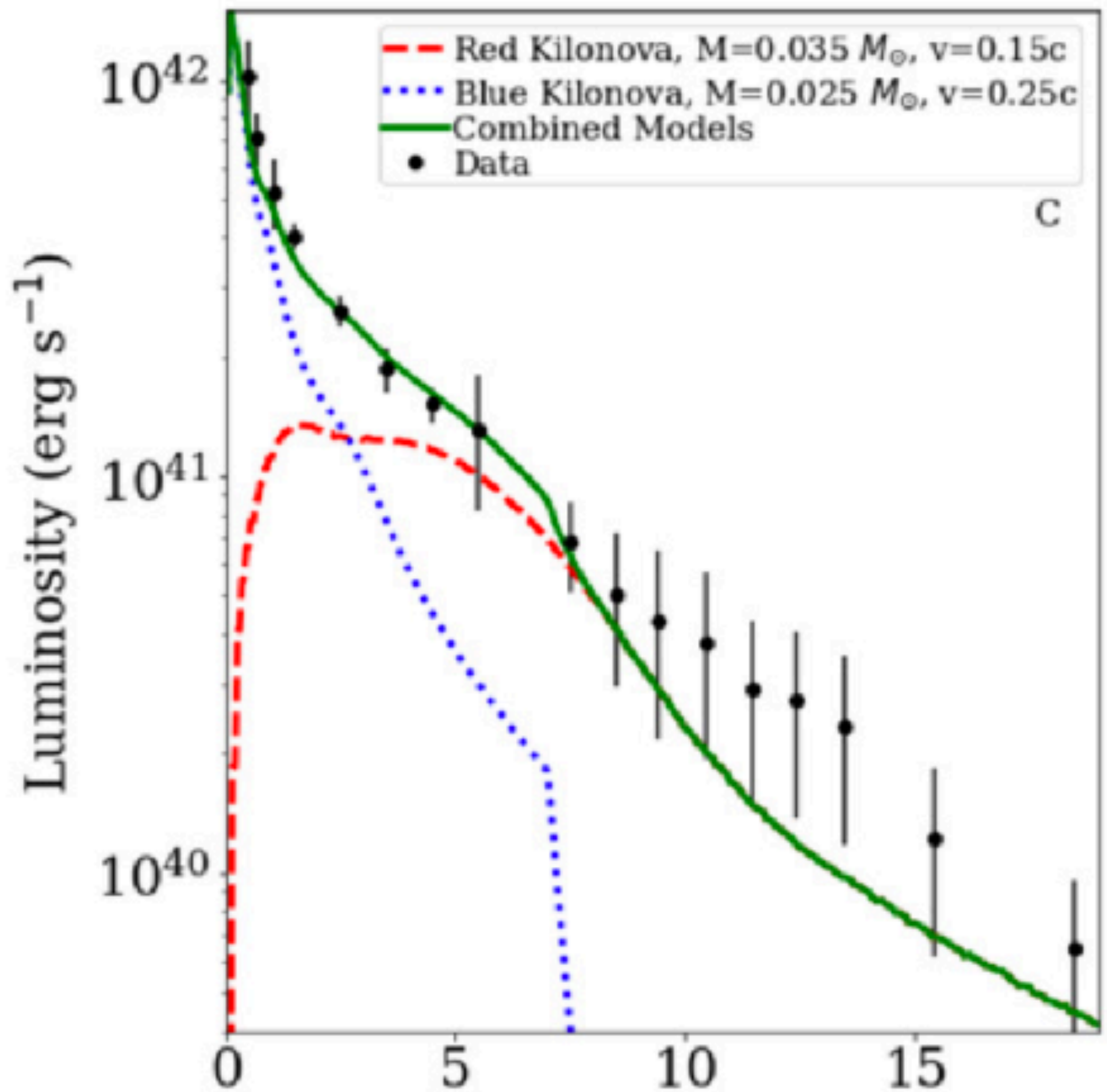
Perego et al. (2014)



see also
Fernandez & Metzger 2013, Metzger & Fernandez 2014,
Just et al. 2014, Sekiguchi et al.

Kilonova



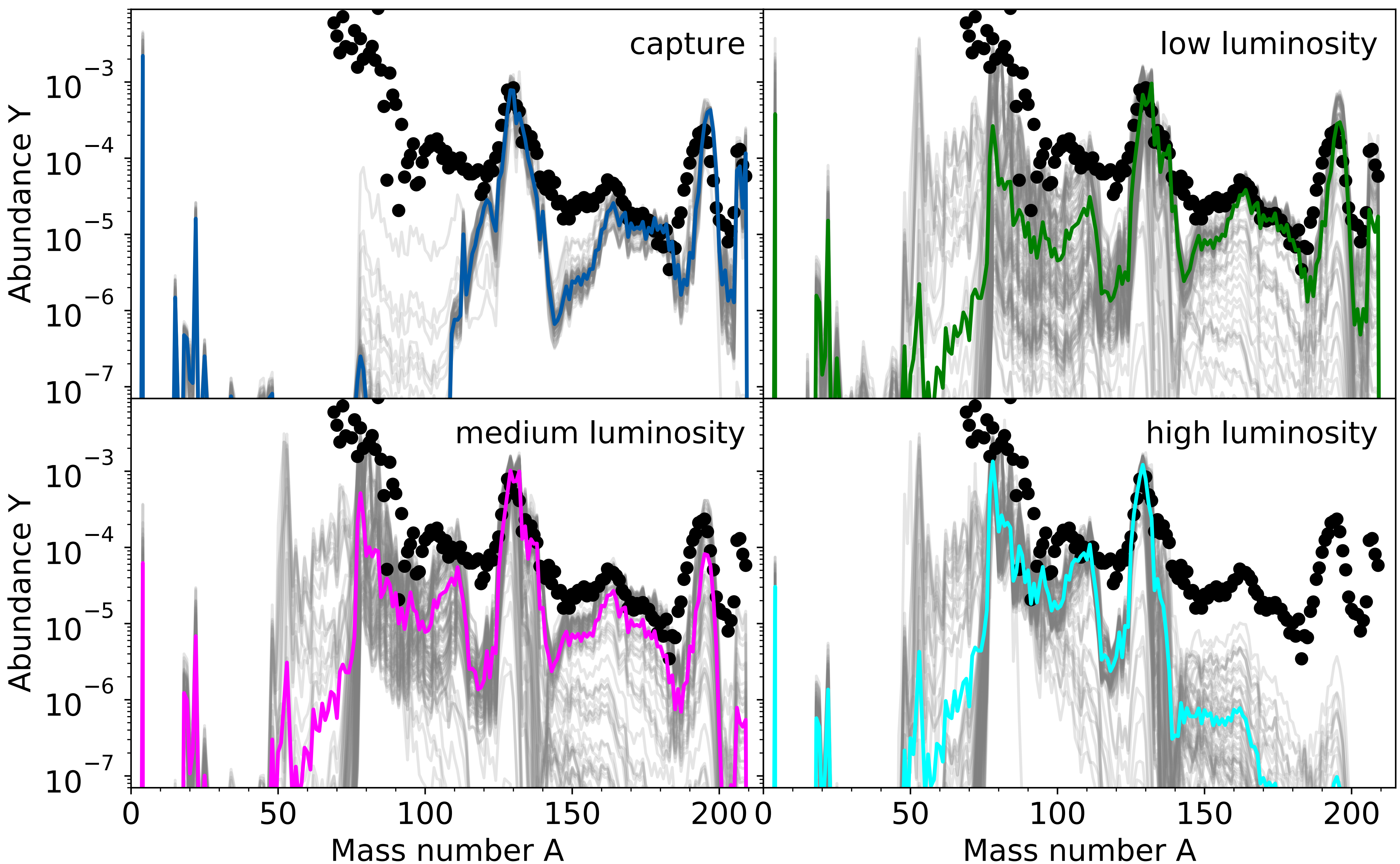


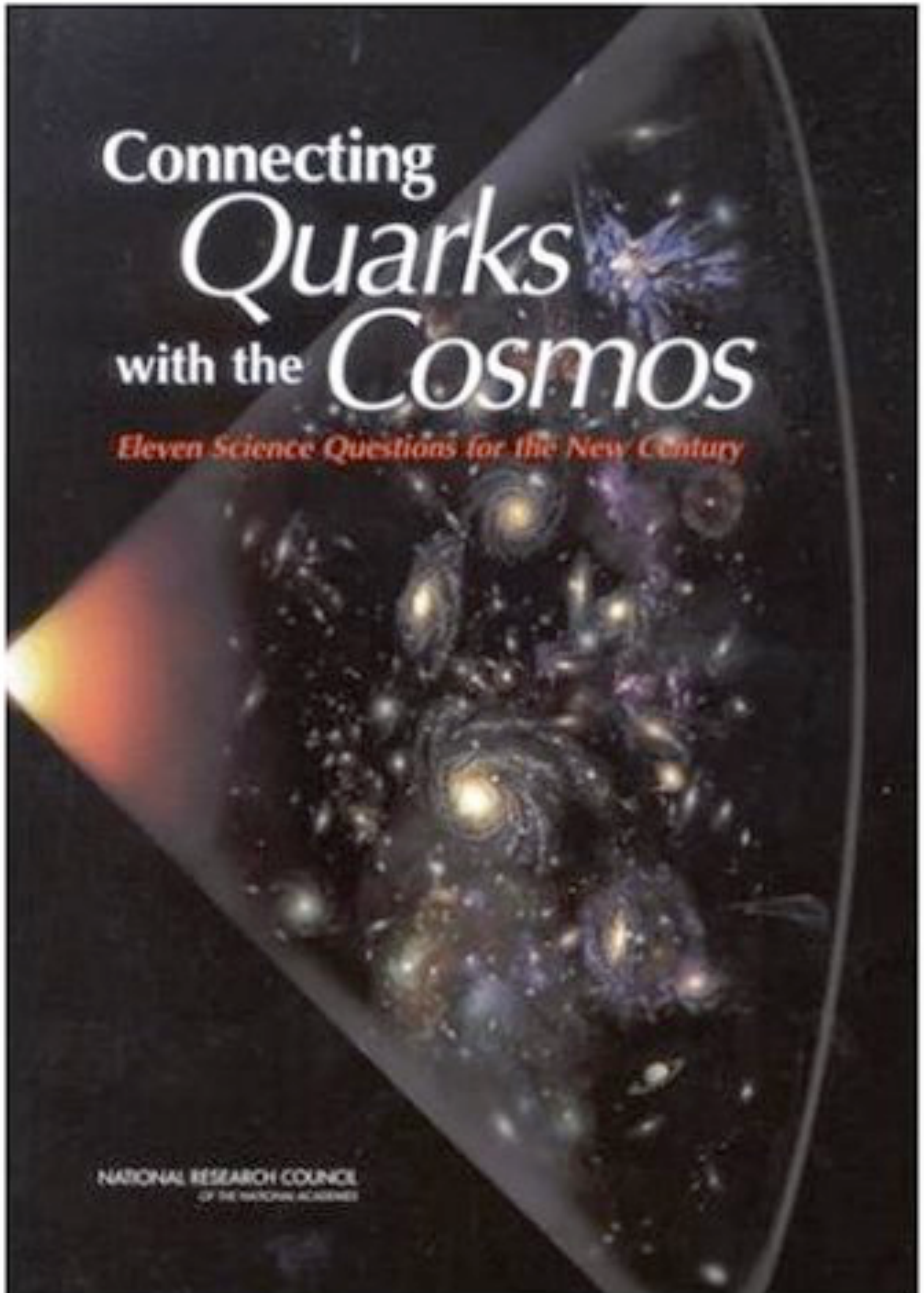
GW170817

Martin et al. (2015)

Equation of state and neutrinos

GR simulations: different EoS (Bovard et al. 2017)
impact of neutrinos (Martin et al. 2018)





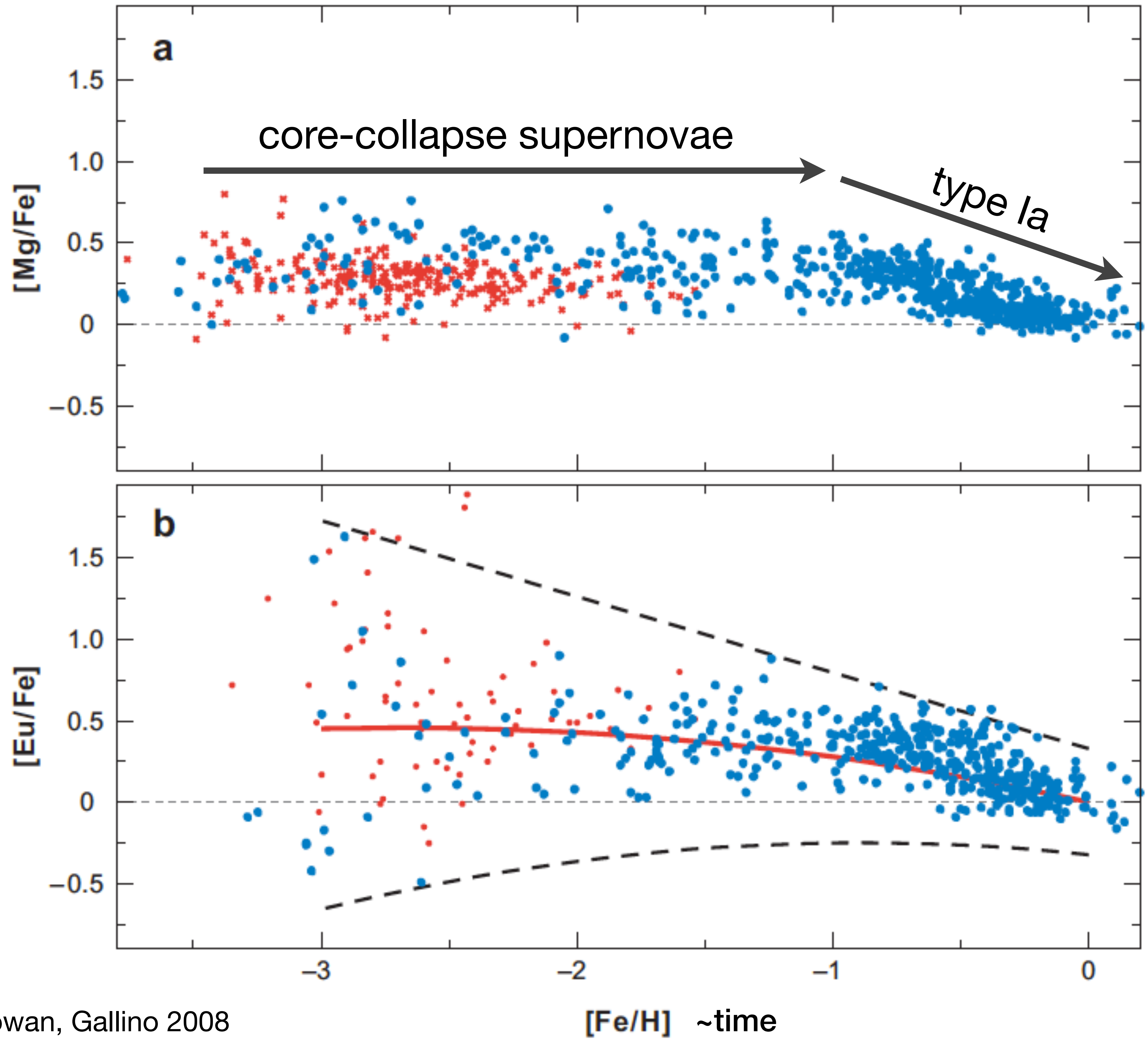
How were the elements
from iron to uranium made?

R-process in neutron star mergers

Are we done? No

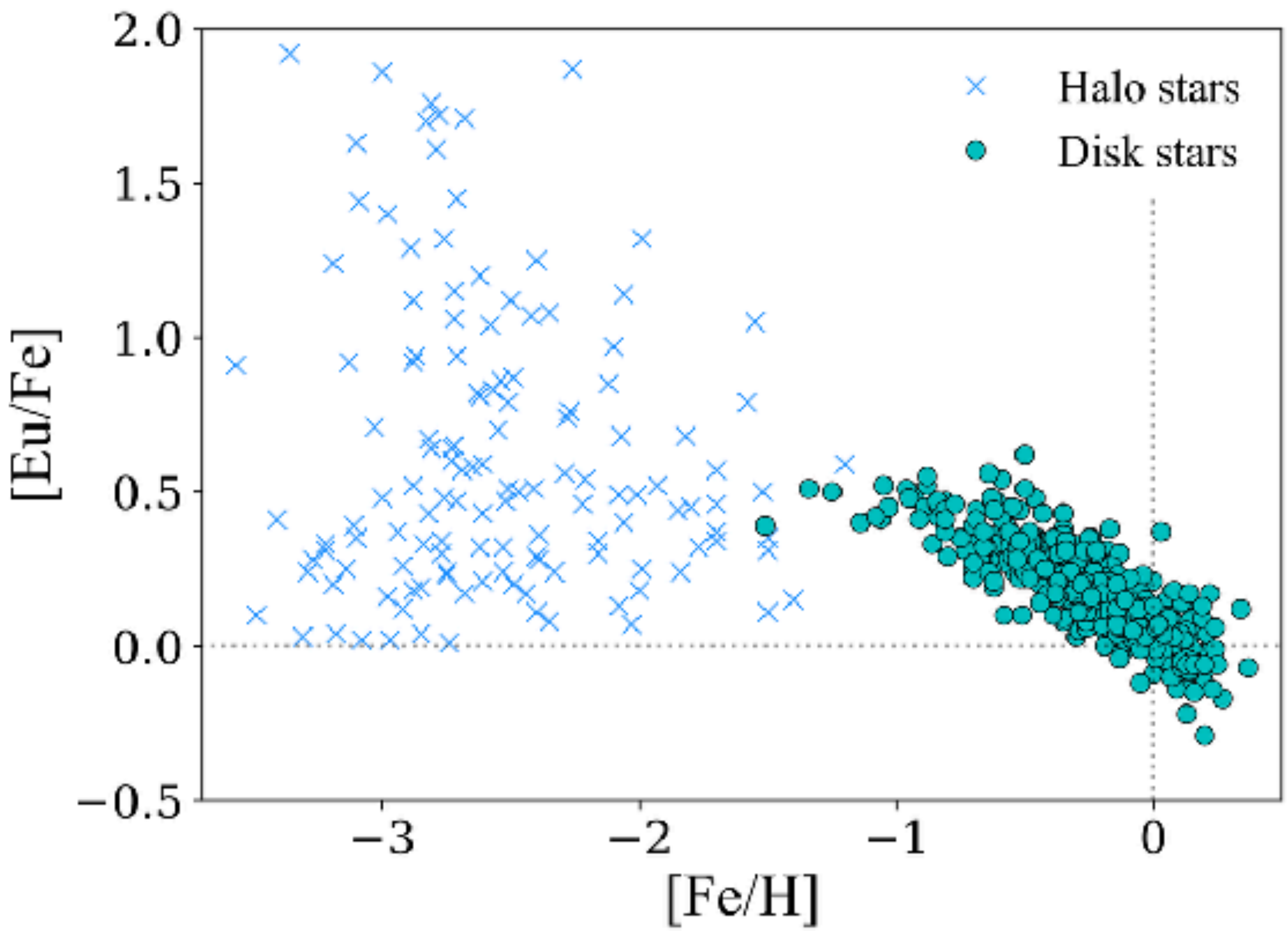
- GCE points to more contributions
- Nuclear physics of extreme neutron-rich nuclei

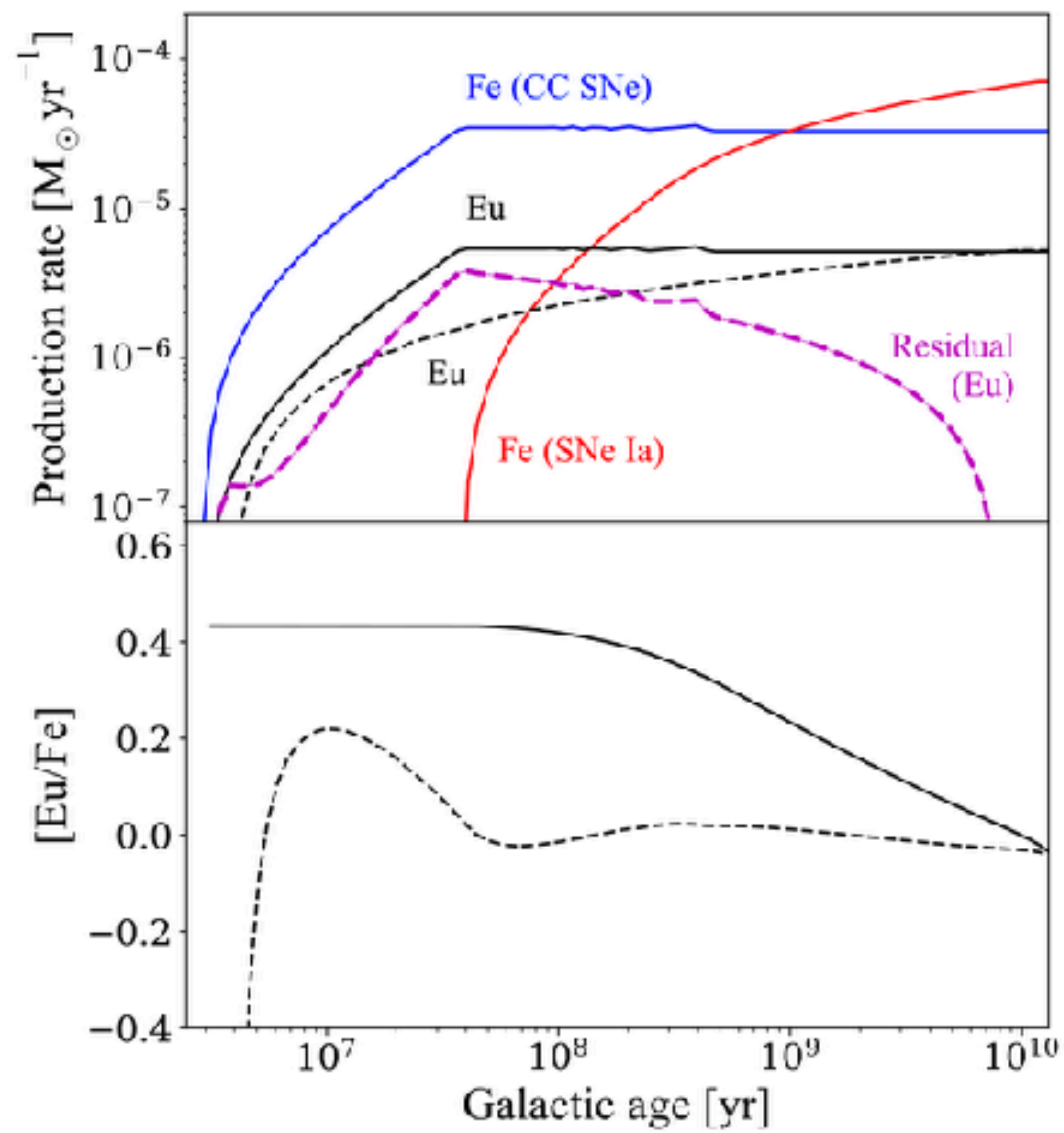
Trends with metallicity



Sneden, Cowan, Gallino 2008

Galactic chemical evolution



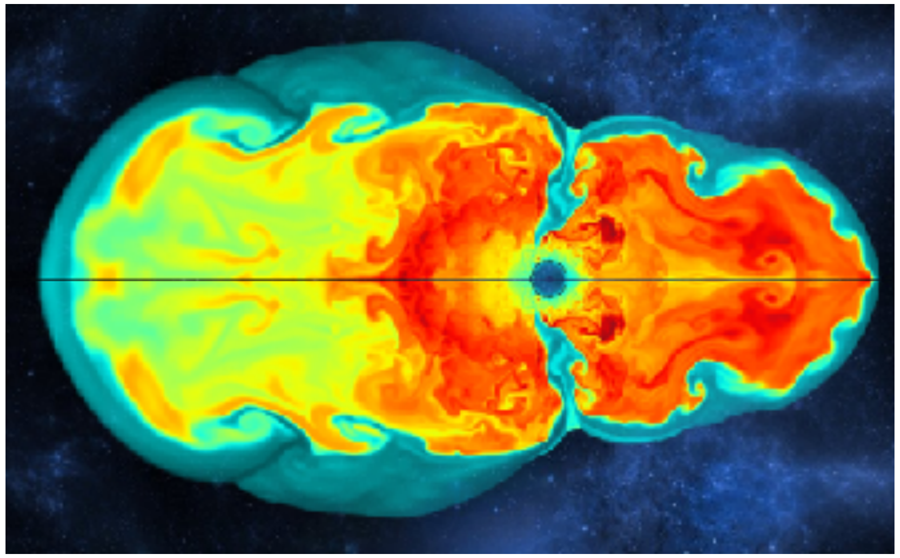


Scatter at low metallicities: rare event, Eu ejected early

Eu/Fe drops around [Fe/H]~-1: most of Eu should be ejected before sn Ia

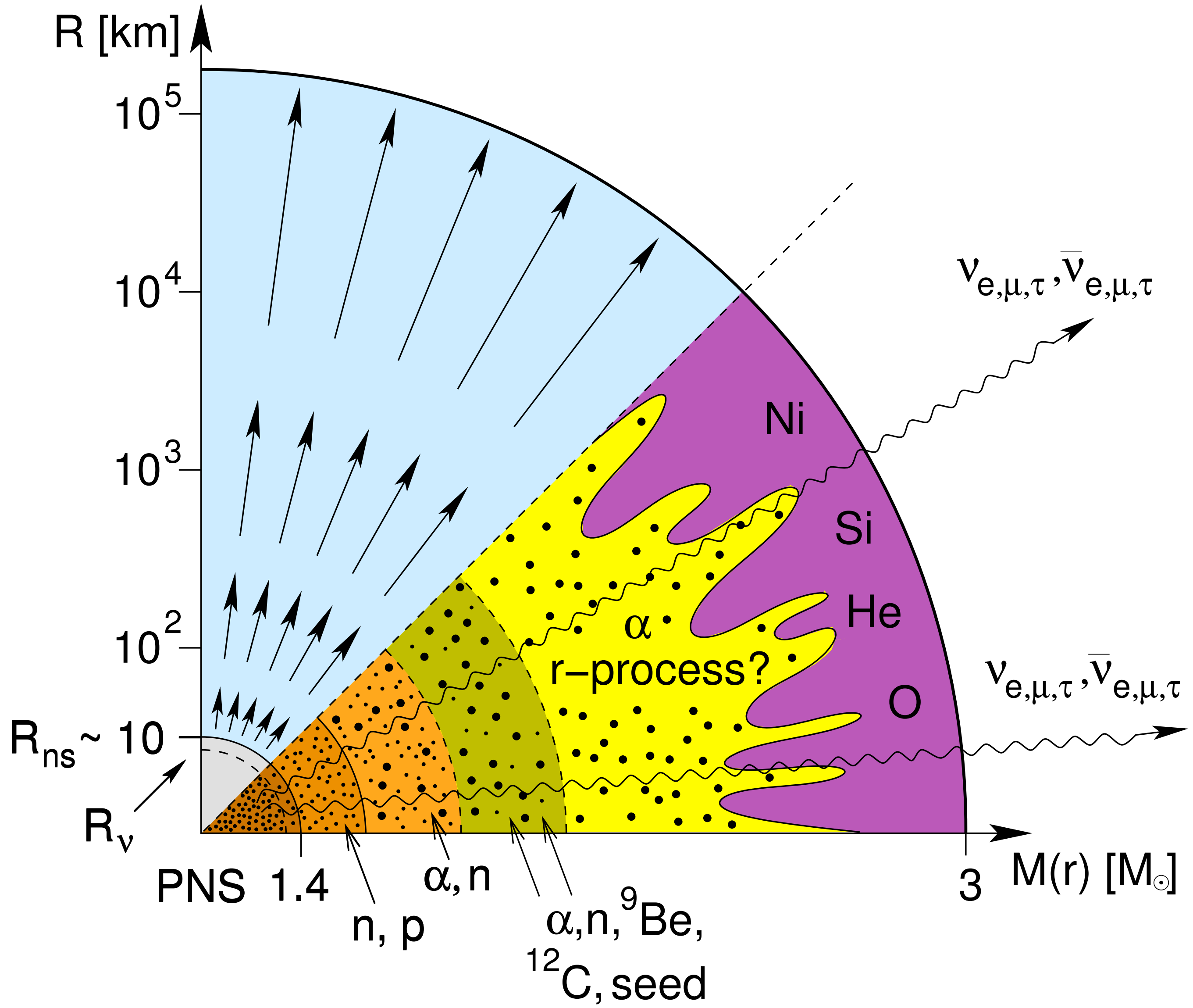
Côté et al. 2018 (to be submitted)

Core-collapse supernovae

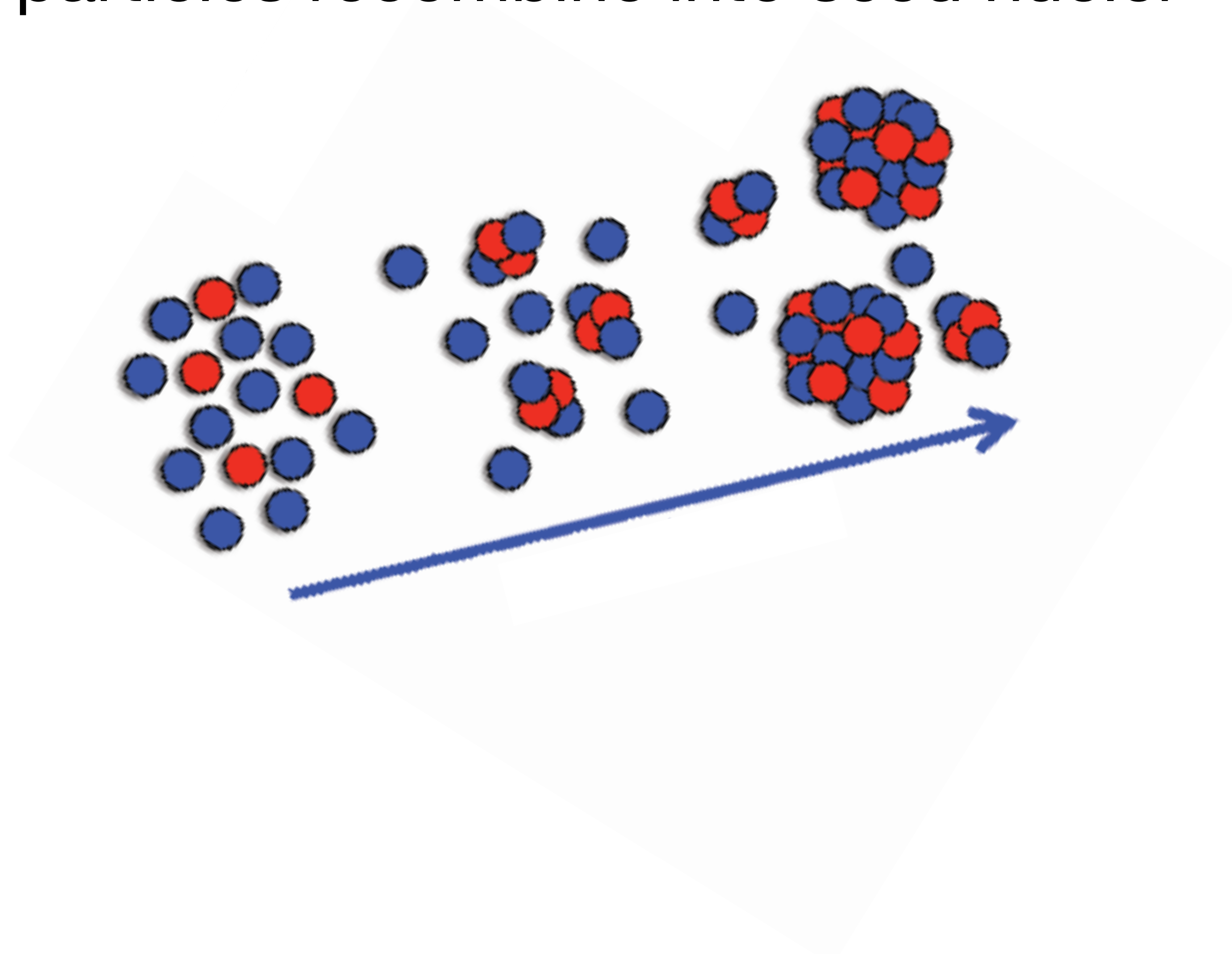


Standard **neutrino-driven supernova**:
Weak r-process and νp-process
Elements up to ~Ag

Neutrino-driven winds



neutrons and protons form α-particles
α-particles recombine into seed nuclei



NSE → charged particle reactions / α-process → r-process

T = 10 - 8 GK 8 - 2 GK

weak r-process
νp-process

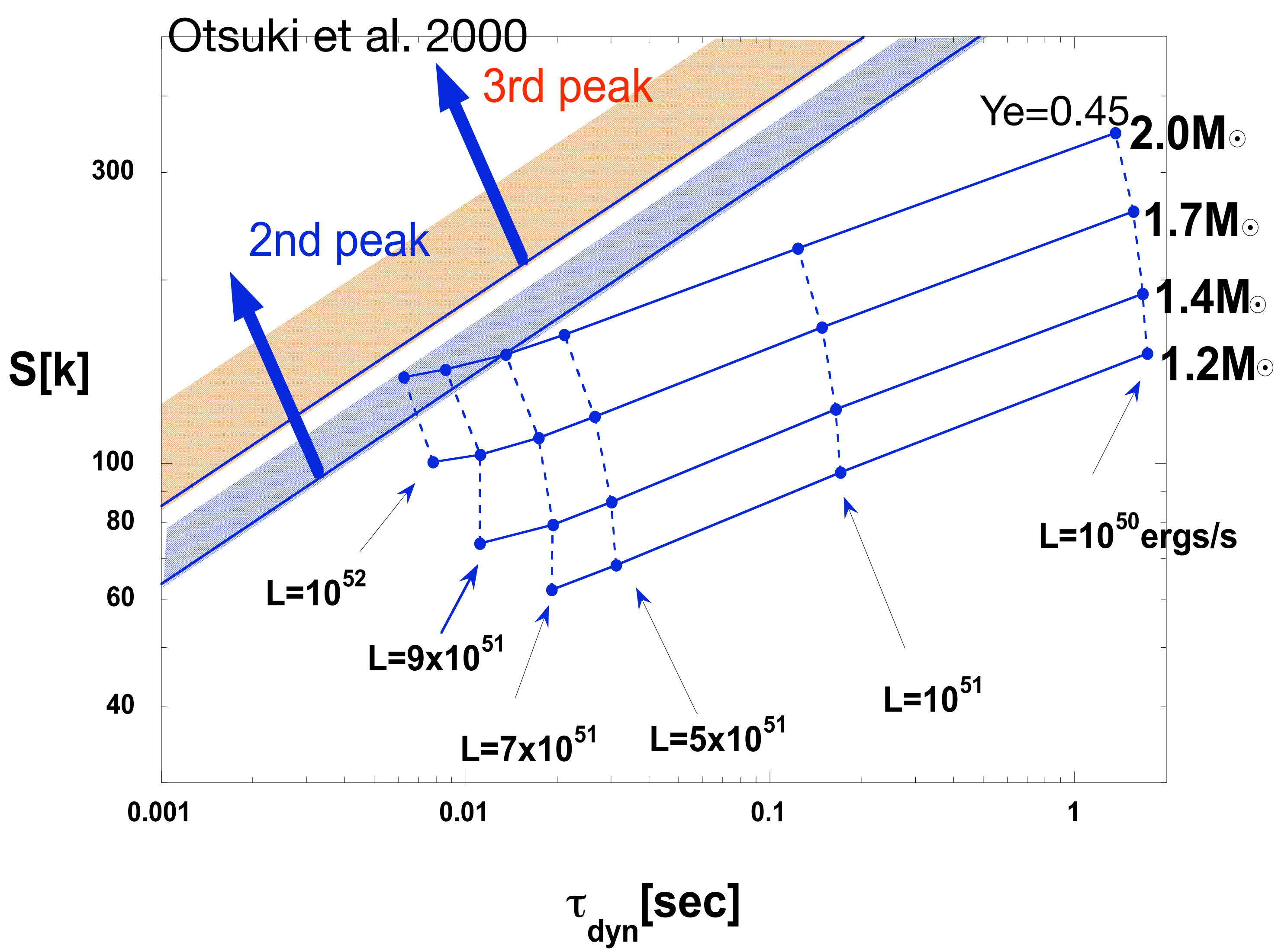
T < 3 GK

for a review see Arcones & Thielemann (2013)

Neutrino-driven wind parameters

r-process ⇒ high neutron-to-seed ratio (Y_n/Y_{seed}~100)

- Short expansion time scale: inhibit α-process and formation of seed nuclei
- High entropy: photons dissociate seed nuclei into nucleons
- Electron fraction: Y_e<0.5



Arcones & Thielemann (2013)

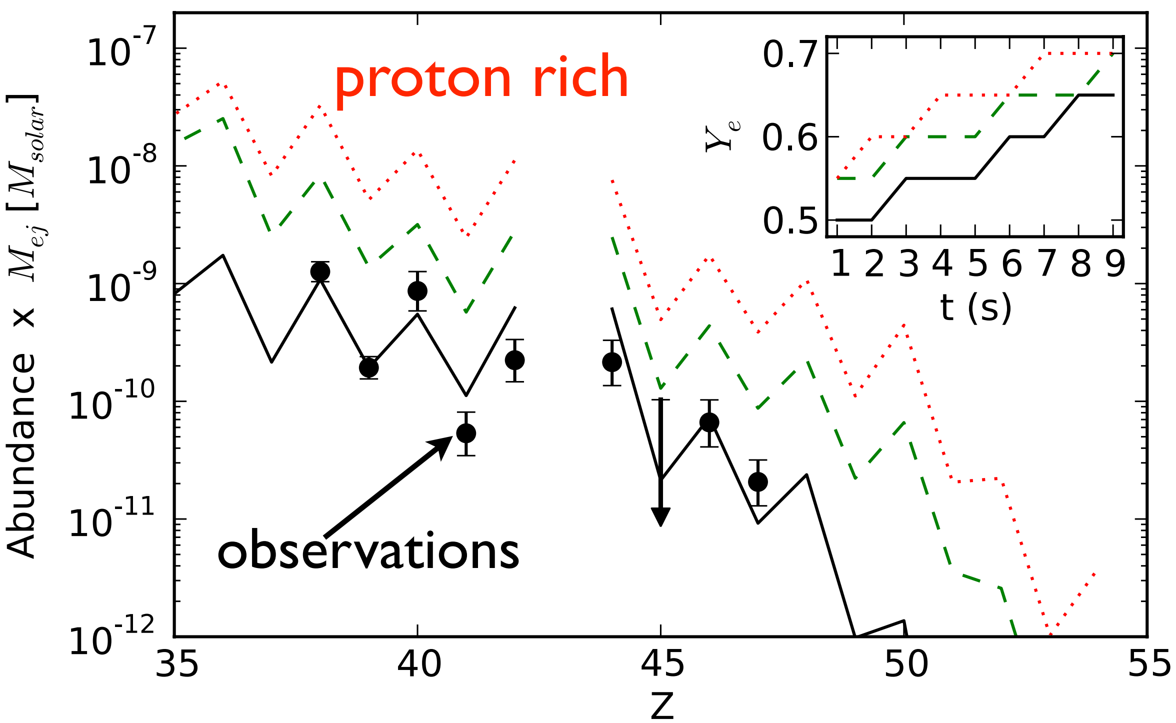
Conditions are not realized in hydrodynamic simulations
(Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011, ...)

S_{wind} = 50 - 120 k_B/nuc
τ = few ms
Y_e ≈ 0.4 - 0.6?

Additional ingredients:
wind termination, extra energy source, rotation and magnetic fields, neutrino oscillations

Lighter heavy elements in neutrino-driven winds

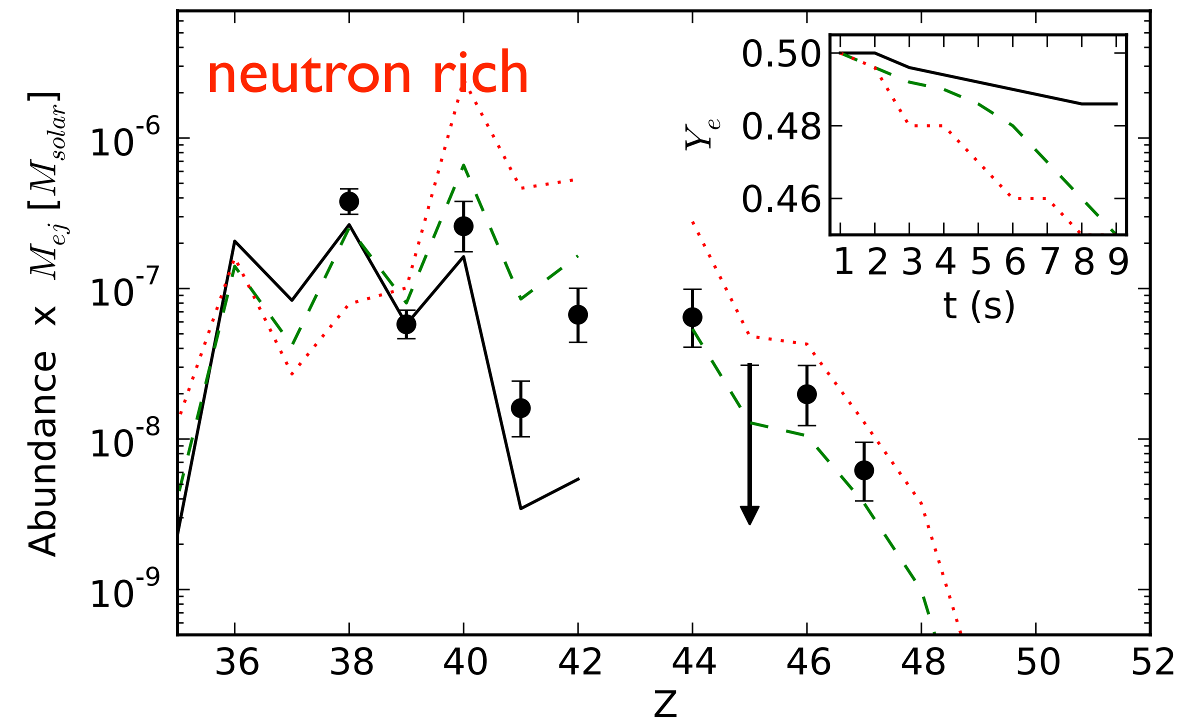
vp-process



Observation pattern reproduced!

Production of p-nuclei

weak r-process



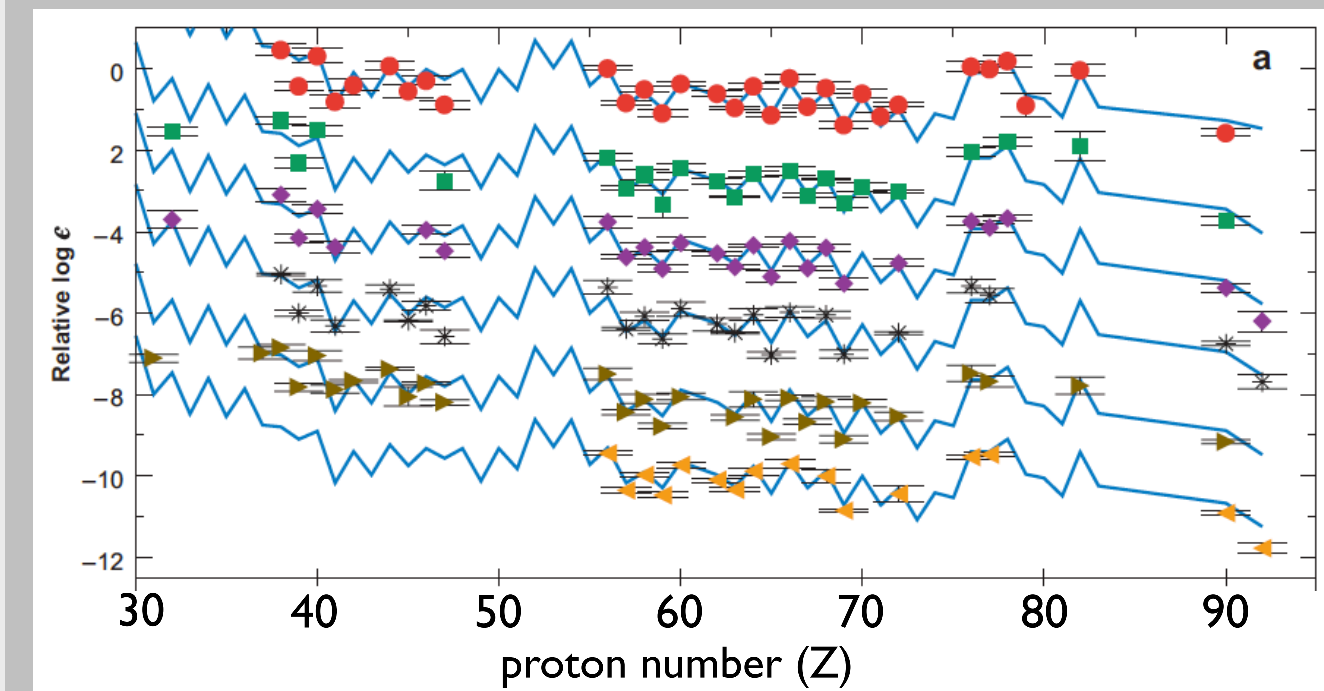
Overproduction at A=90, magic neutron number N=50 (Hoffman et al. 1996) suggests: only a fraction of neutron-rich ejecta

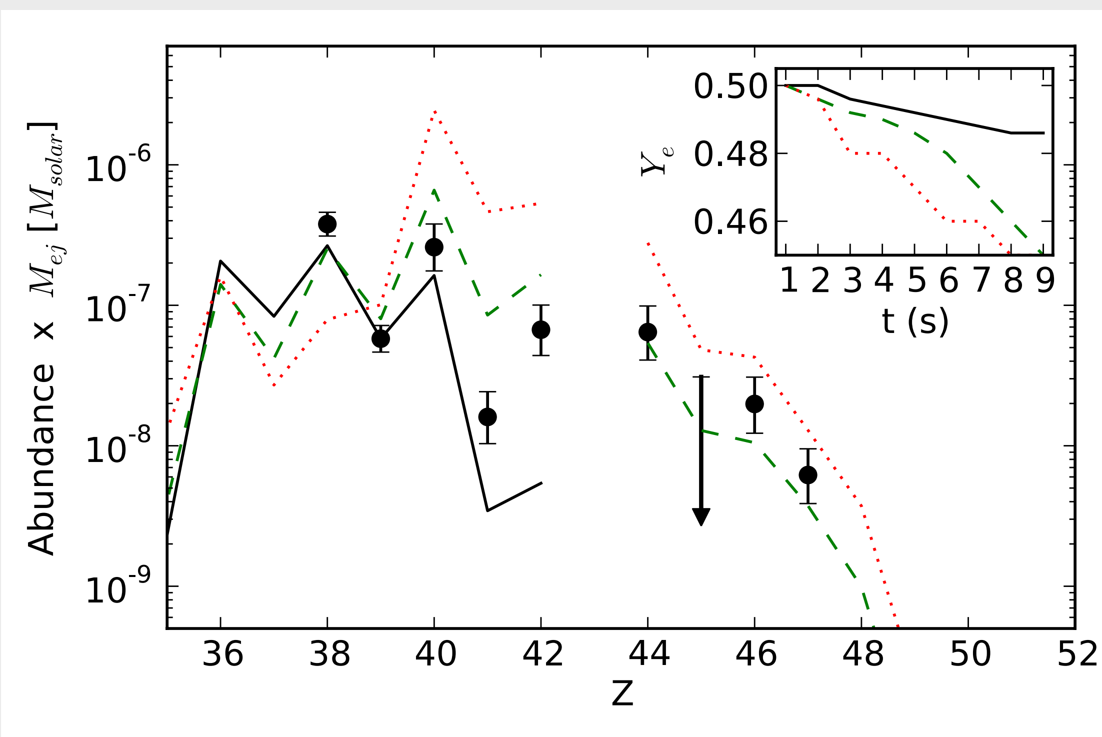
(Arcones & Montes, 2011)

Origin of elements from Sr to Ag

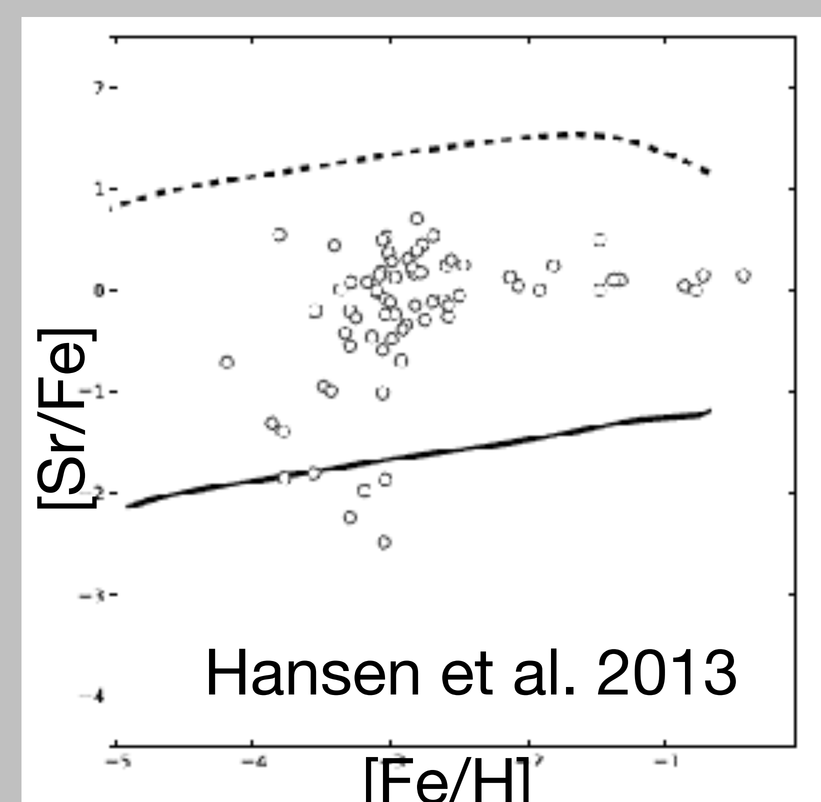
Astrophysical site

Observations





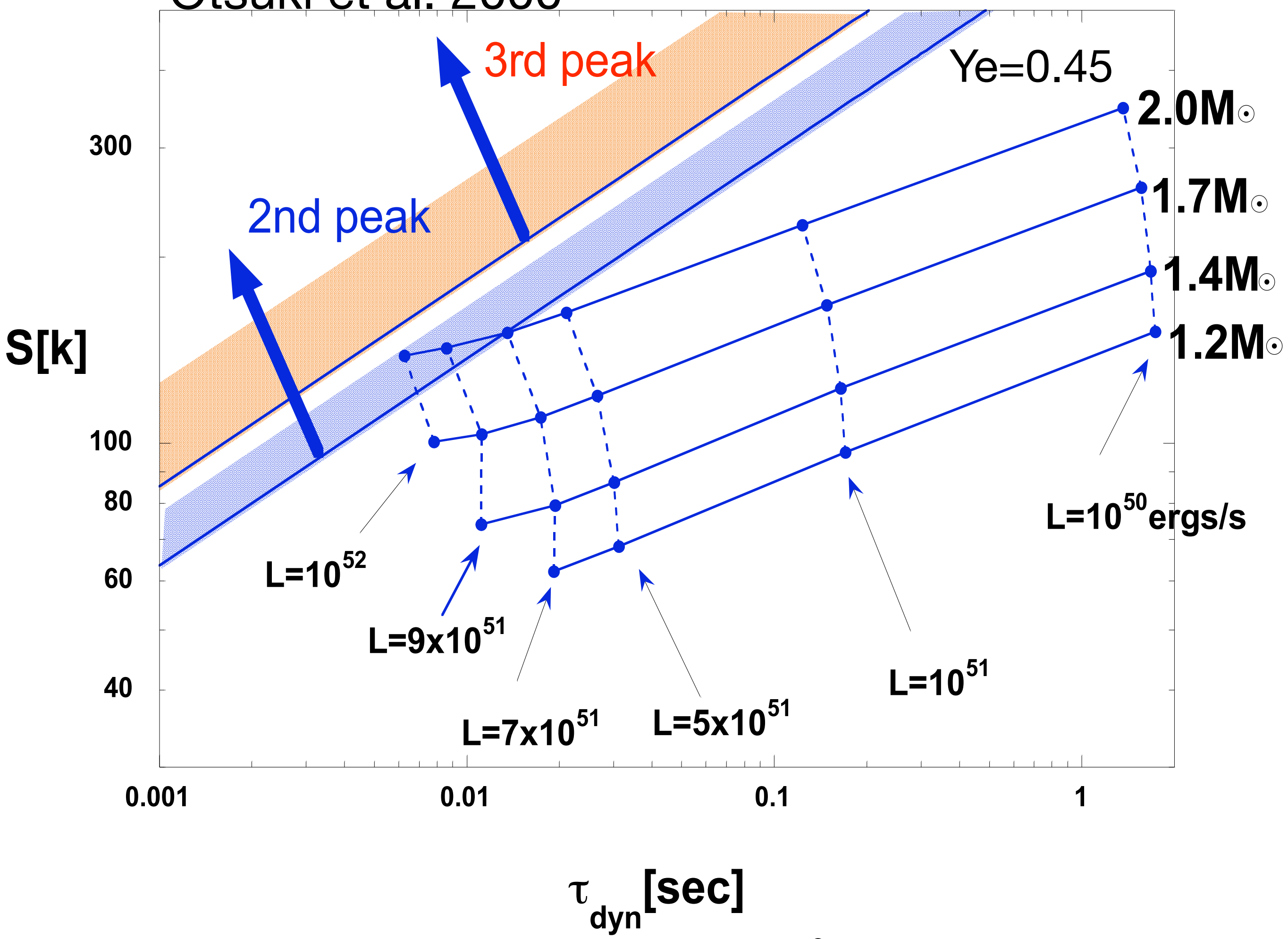
Nucleosynthesis:
identify key reactions



Chemical evolution

Impact of astrophysical uncertainties

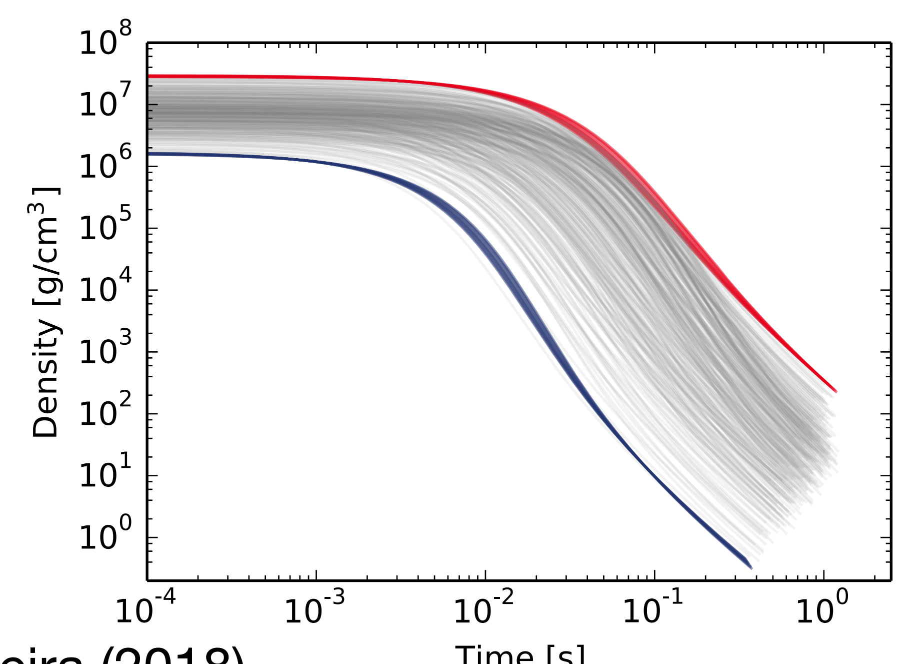
Otsuki et al. 2000

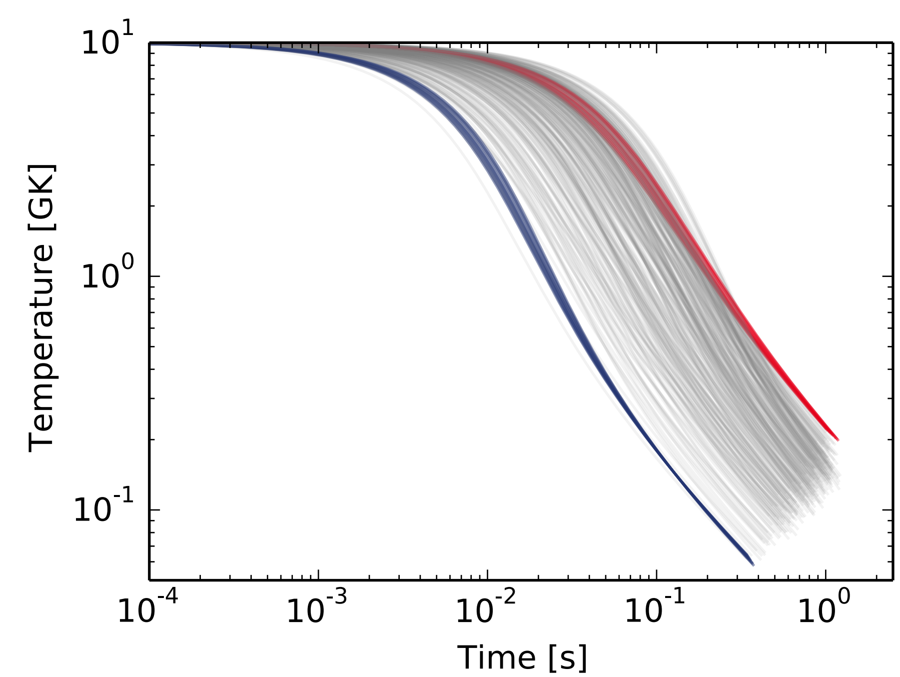


Steady-state model to explore possible nucleosynthesis patterns in neutrino-driven ejecta

Nucleosynthesis ~3000 trajectories

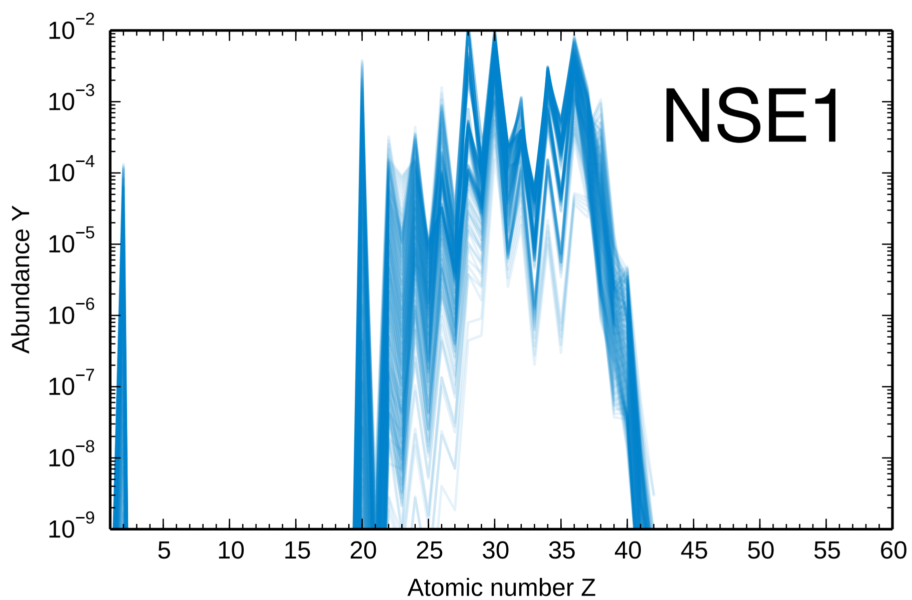
Input parameters:
M_{ns}, R_{ns}, Y_e

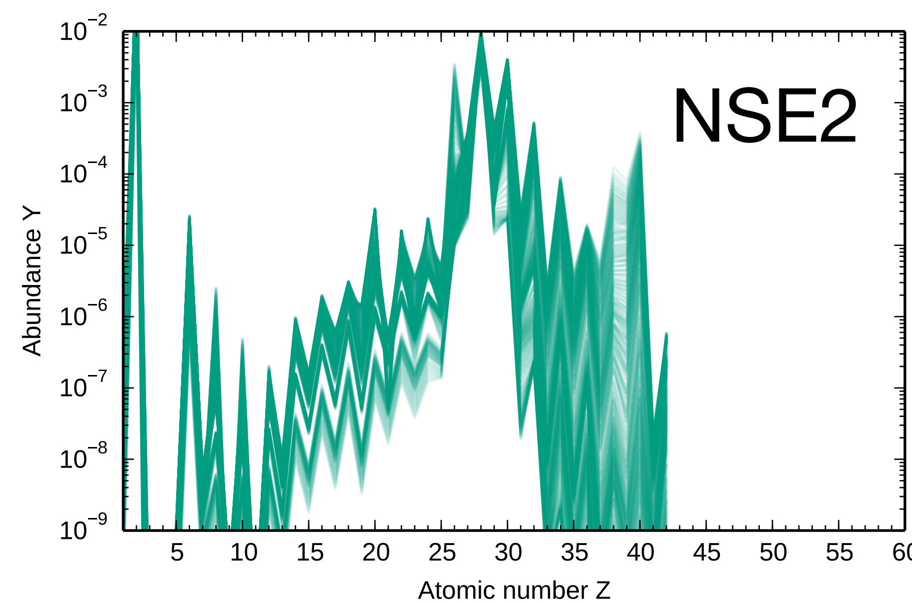




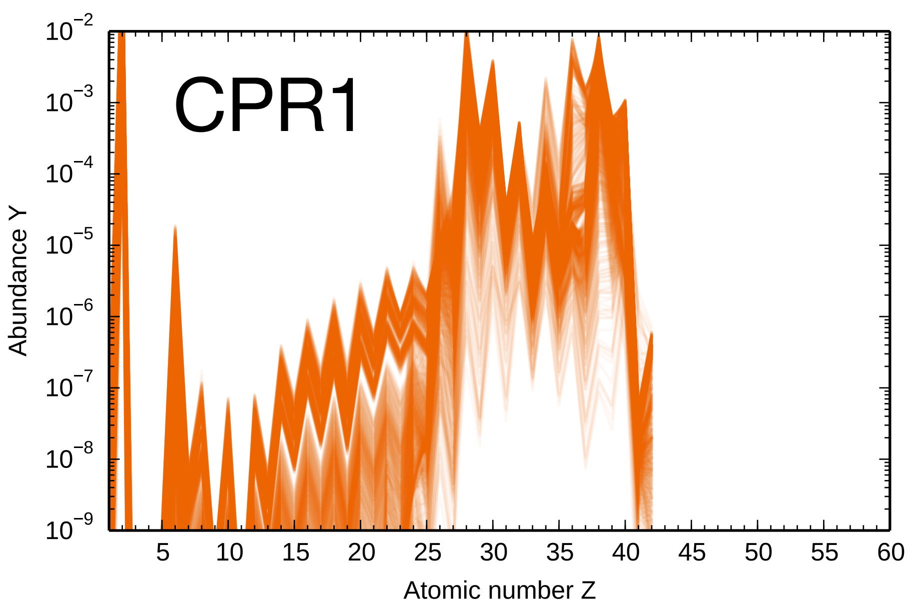
Bliss, Witt, Arcones, Montes, Pereira (2018)

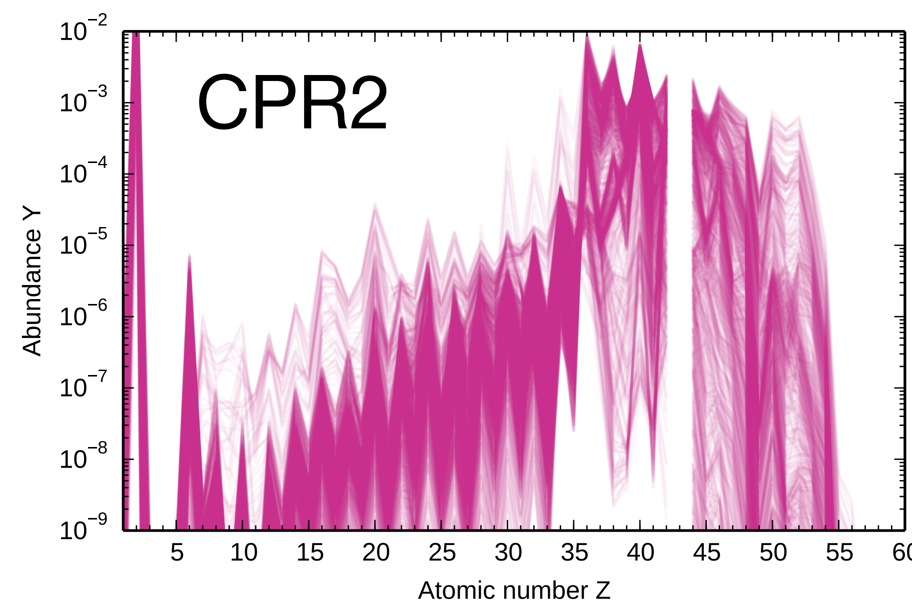
Characteristic nucleosynthesis patterns





binding energies
partition functions



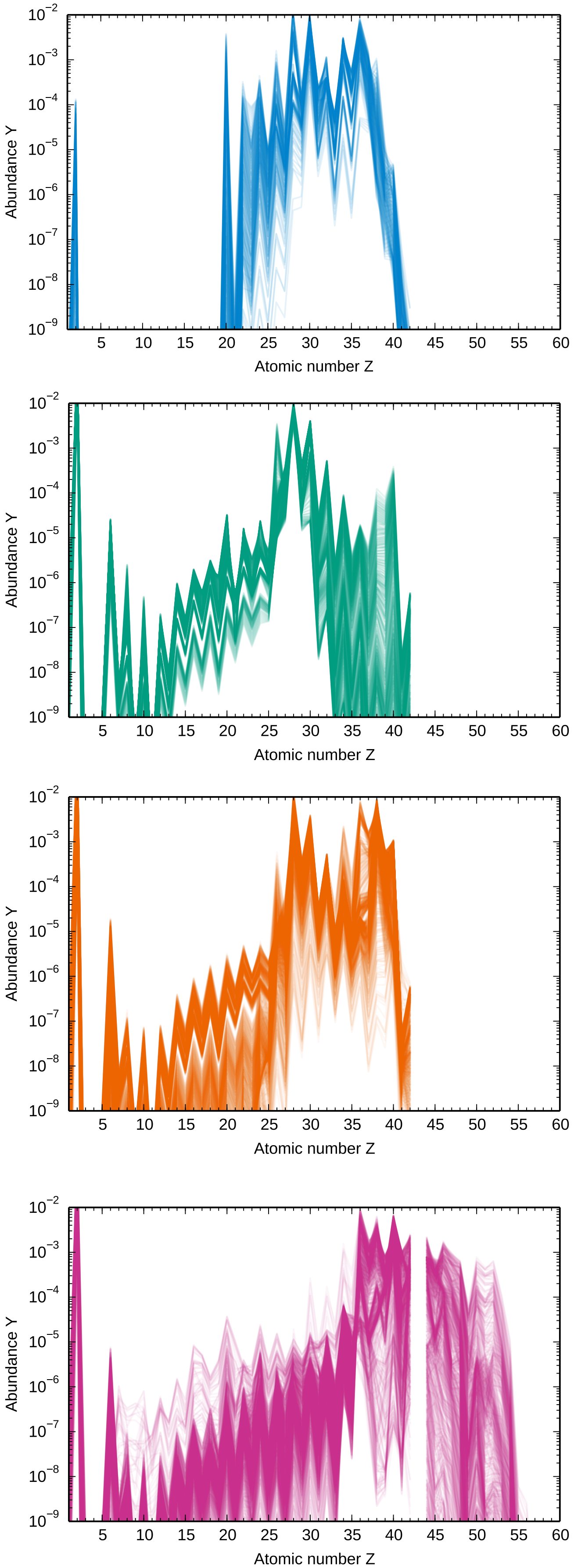


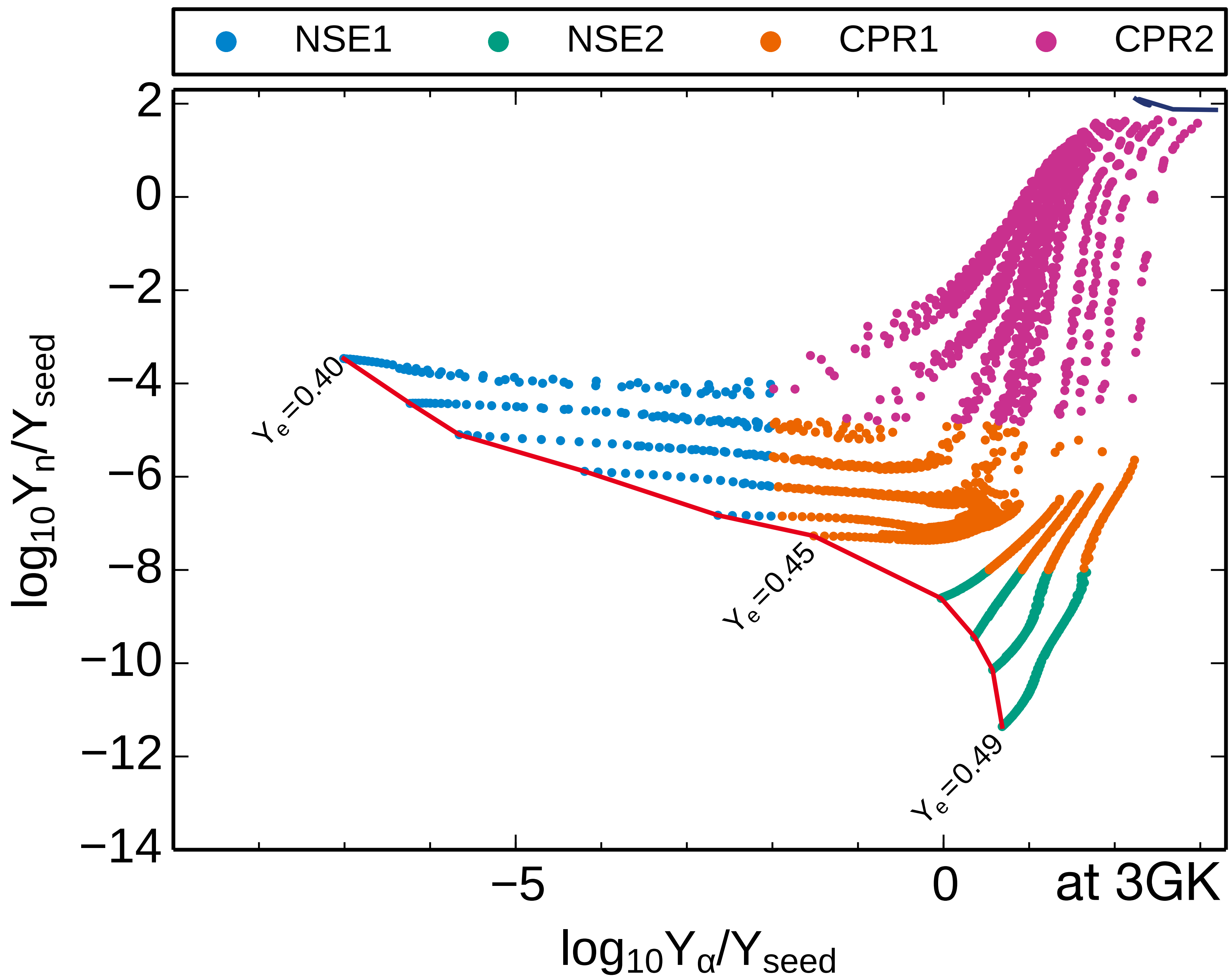
Q-values of (α,n) reactions

Individual reactions

Bliss, Witt, Arcones, Montes, Pereira (2018)

Classification of nucleosynthesis patterns



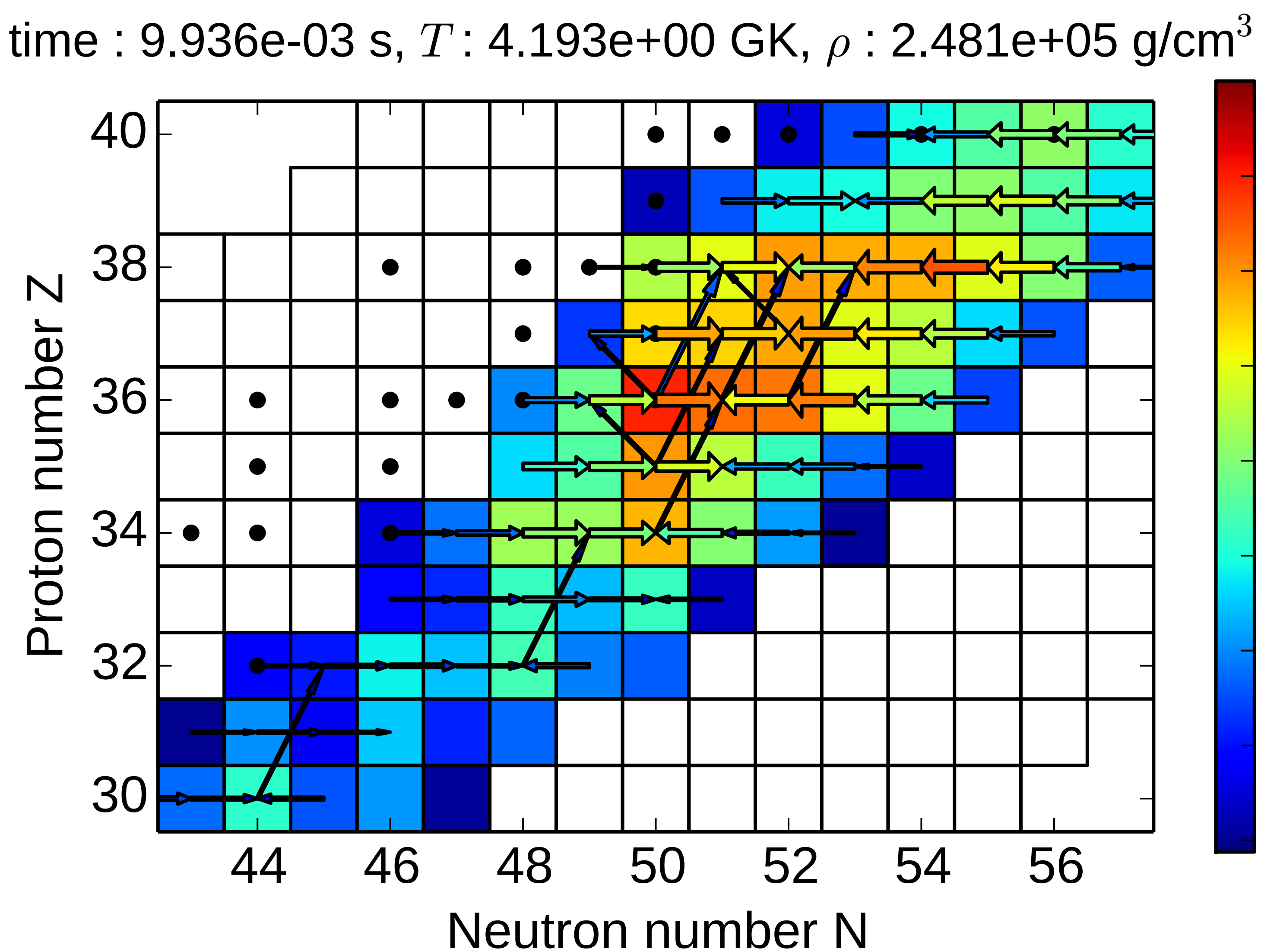


Bliss, Witt, Arcones, Montes, Pereira (2018)

- Estimate nucleosynthesis based on Y_n, Y_{alpha}, Y_{seed}
- Provide representative trajectories to explore impact of nuclear physics input (nuc-astro.eu)

Reactions in neutrino-driven supernova ejecta

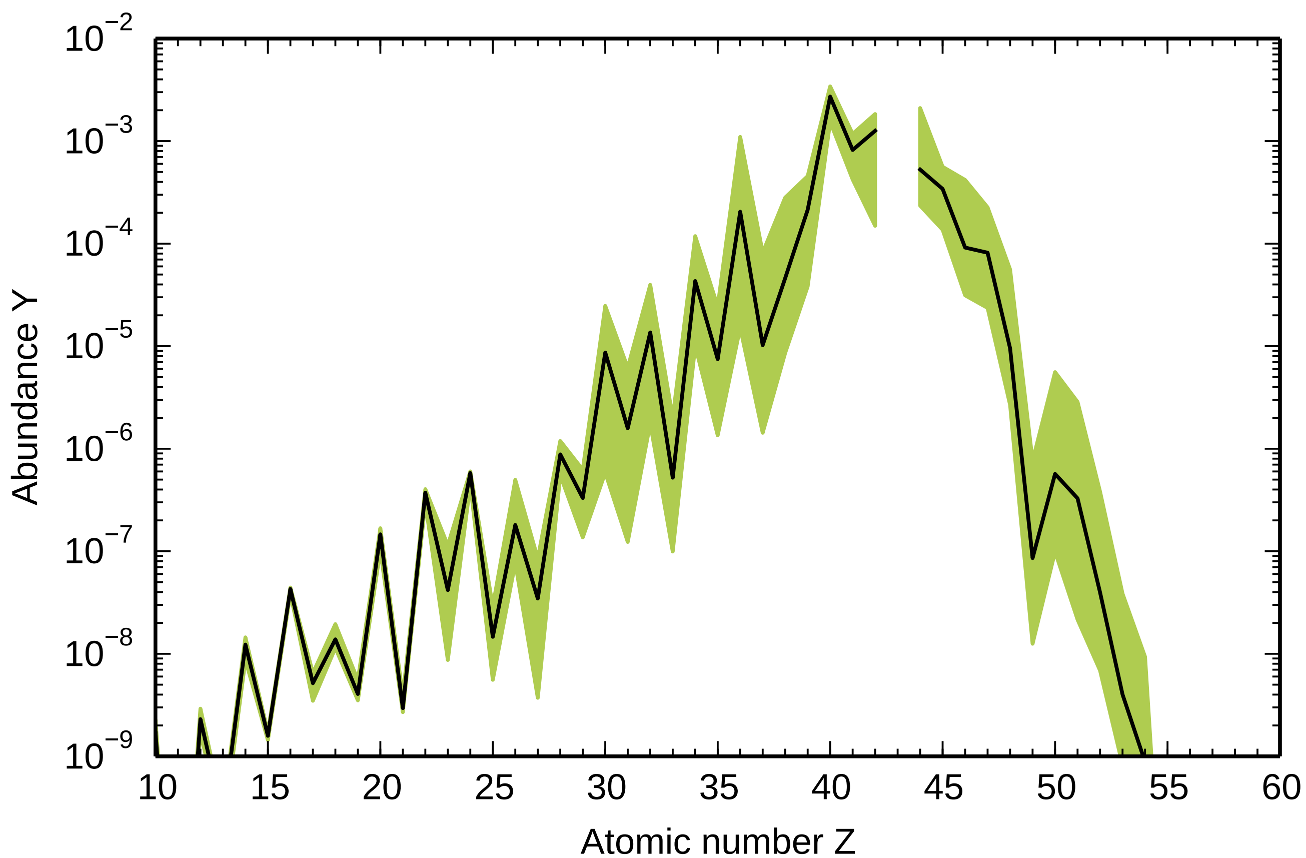
- Important reactions: α-, n-, p-capture reactions, β-decays
- $\tau_{expansion} << \tau_{\beta}$ → (α,n) are key reactions
- α-process (Hoffman & Woosley 1992)
- Absence of relevant experiments
  → theoretical reaction rates based on Hauser-Feshbach model

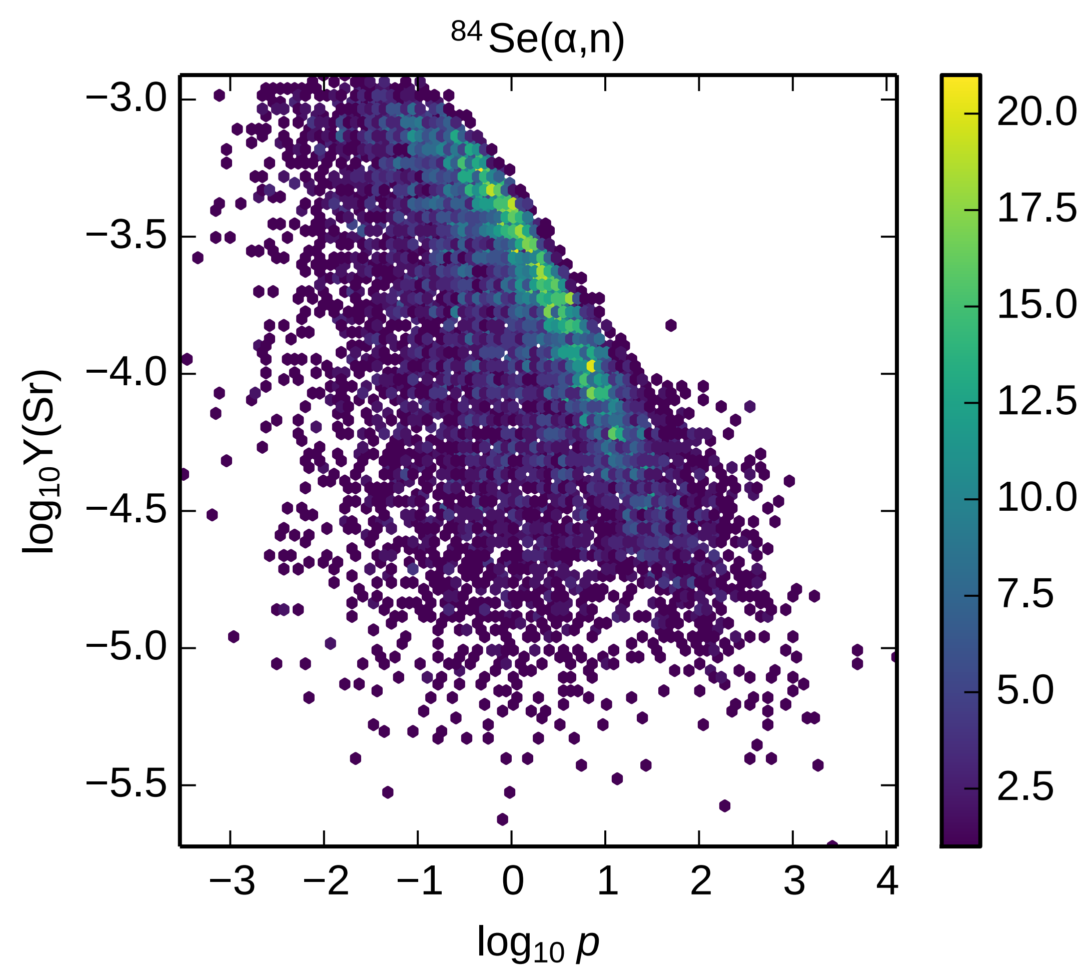


J. Bliss, A. Arcones,
F. Montes, and J. Pereira (2017)

(α,n) reactions: sensitivity study

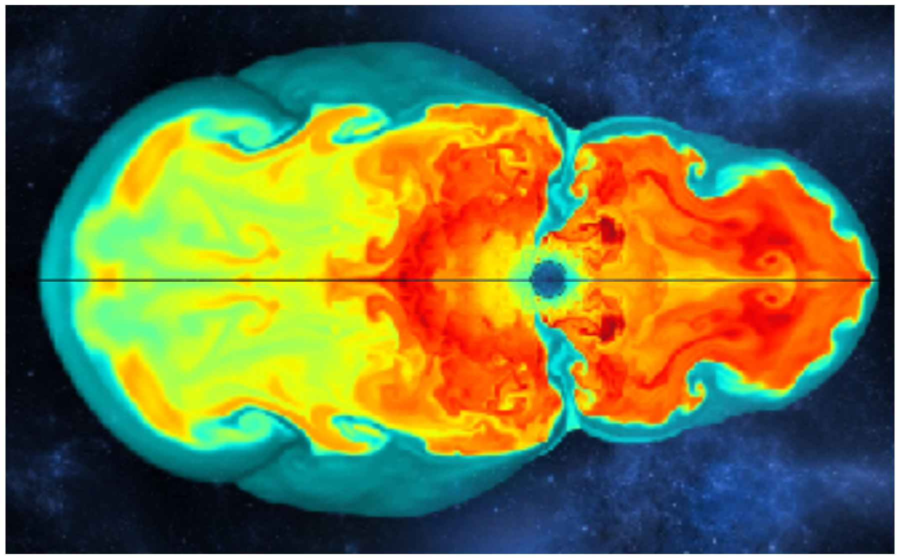
- Independently vary each (α,n) rate between Fe and Rh by a random factor
- Identification of key reactions → large correlation and abundance change
- ^{82}Ge, ^{84,85}Se, ^{85}Br(α,n) strongly affect abundance of Z=36–39
- Measurement of key (α,n) reactions to reduce nuclear physics uncertainties:
  → ^{75}Ga(α,n) and ^{85}Br(α,n) at ReA3 (NSCL/MSU)
  → need more experiments



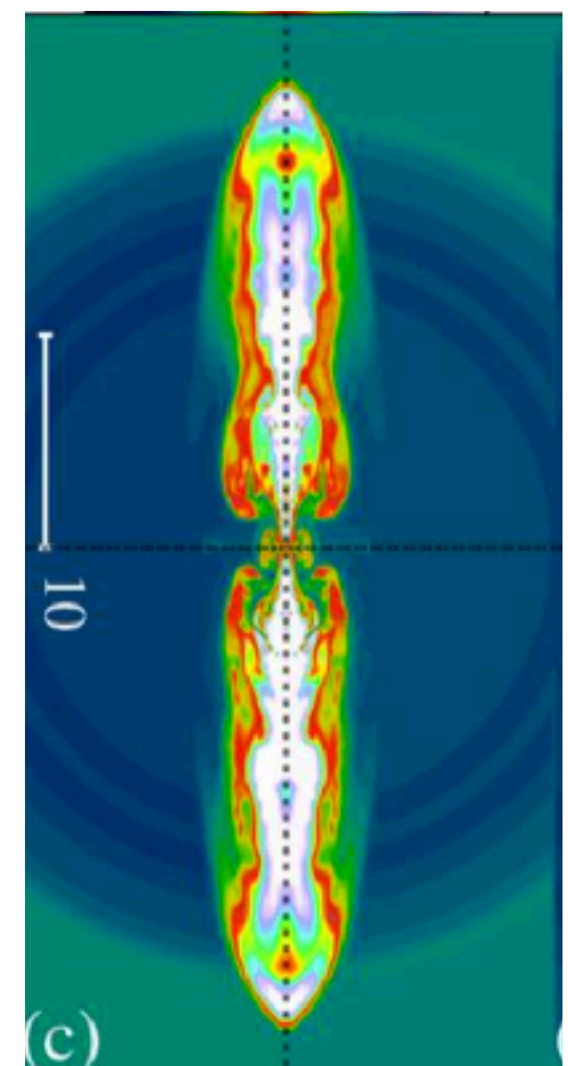


J. Bliss, A. Arcones, F. Montes, and J. Pereira in preparation

Core-collapse supernovae



Standard **neutrino-driven supernova**:
Weak r-process and vp-process
Elements up to ~Ag



Magneto-rotational supernovae
Neutron-rich matter ejected by strong magnetic field
(Cameron 2003, Nishimura et al. 2006)

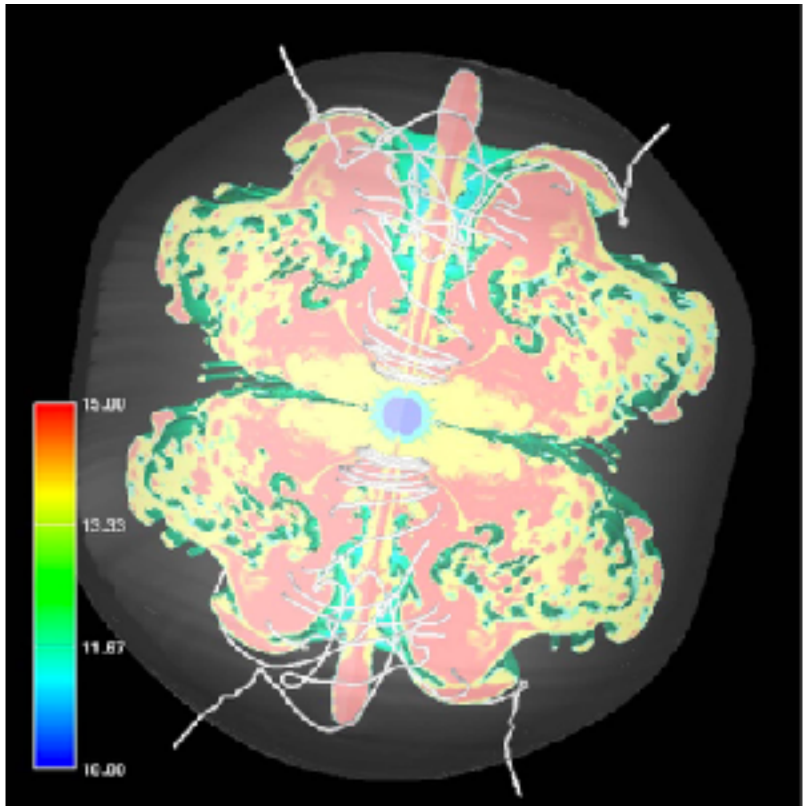
2D and 3D + parametric neutrino treatment :
- jet-like explosion: heavy r-process
- magnetic field vs. neutrinos: weak r-process

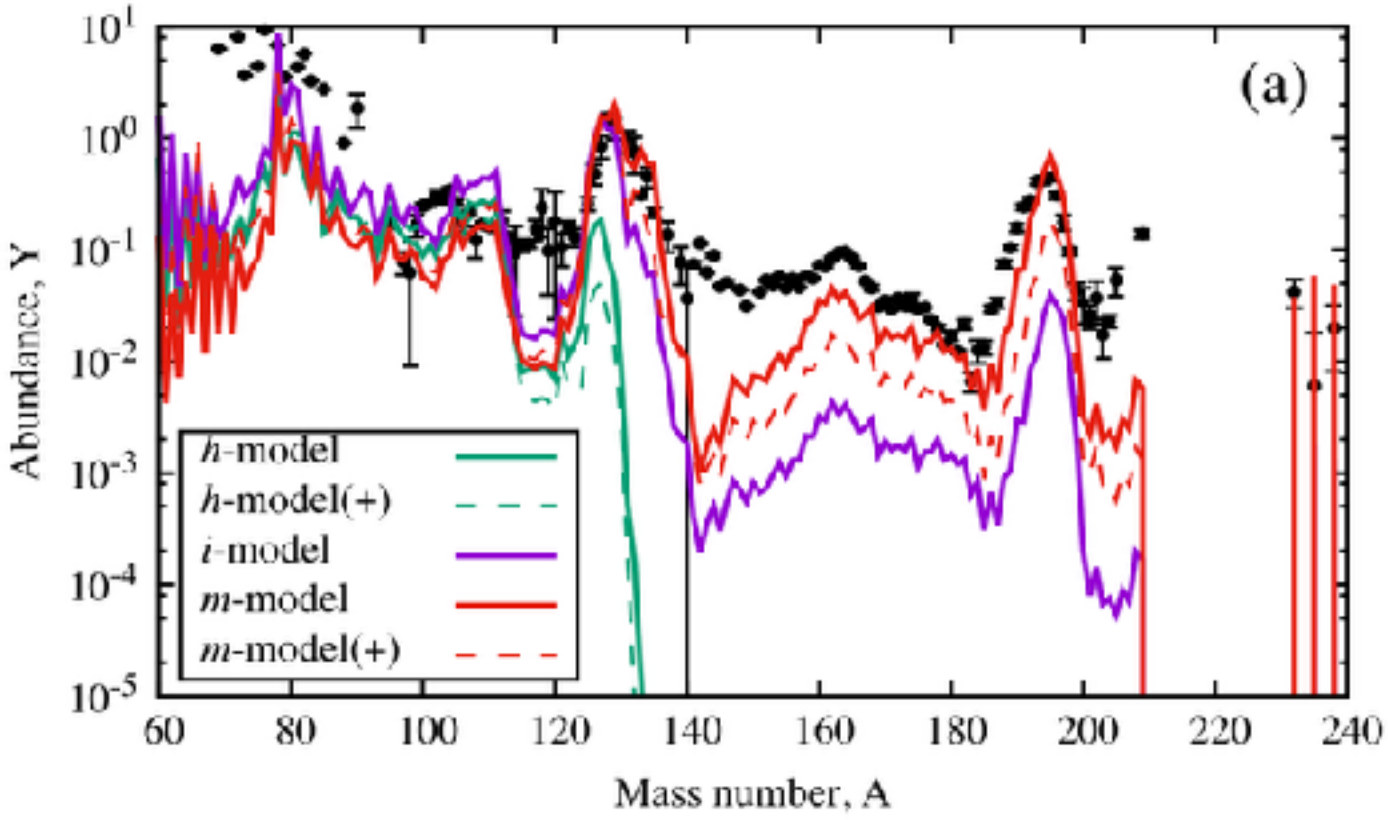
Nishimura et al. 2015, 2017, Winteler et al. 2012, Mösta et al. 2018

Magneto-rotational supernovae: r-process

Neutron-rich matter ejected by strong magnetic field
(Cameron 2003, Nishimura et al. 2006)

2D, parametric neutrino treatment (Nishimura et al. 2015, 2017)
magnetic field vs. neutrinos

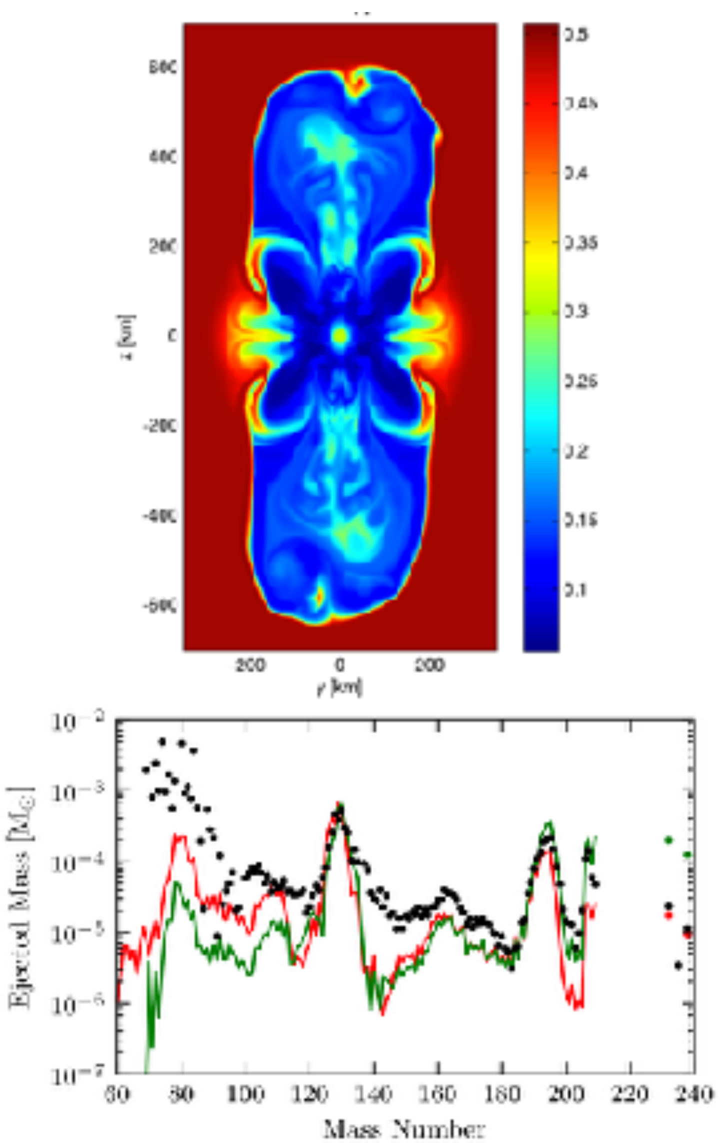




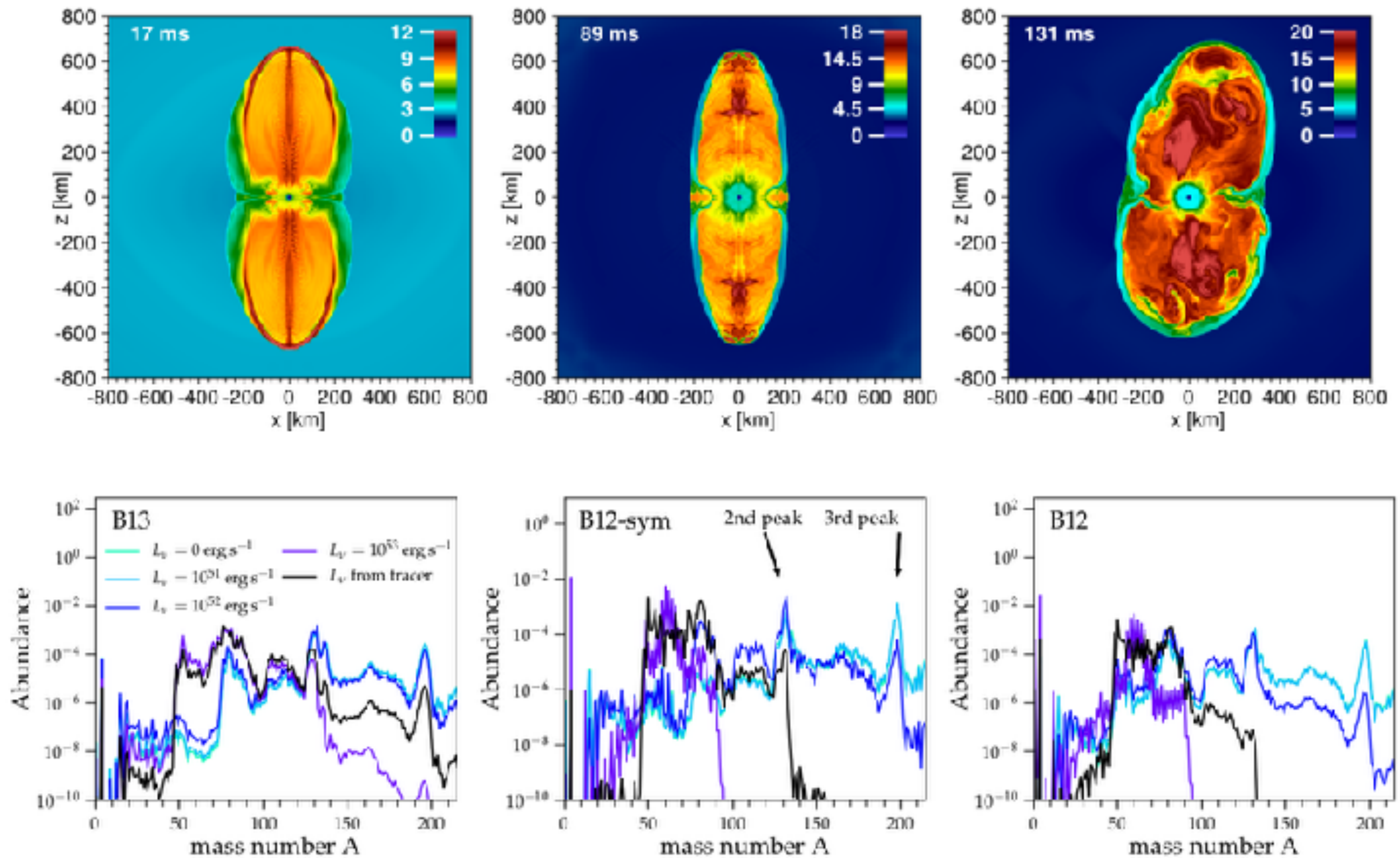
Magneto-rotational supernovae: r-process

3D, leakage (Winteler et al. 2012, Mösta et al. 2017)

- jet-like explosion, heavy r-process:
  strong magnetic field (10^{13}G) or symmetry (~2D), 10^{12}G
- Weak r-process: 3D, 10^{12}G



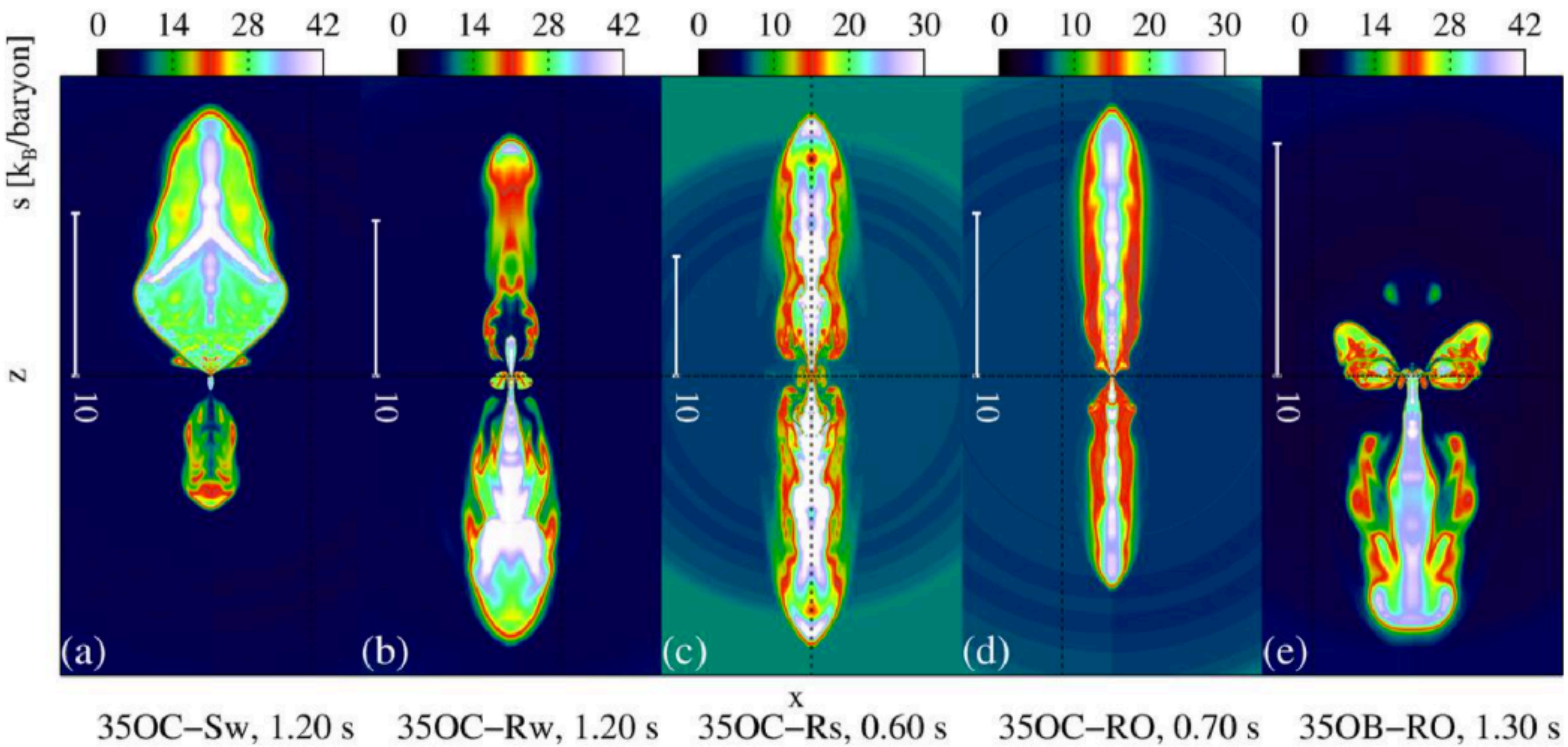
Winteler et al. 2012



Mösta et al. 2017

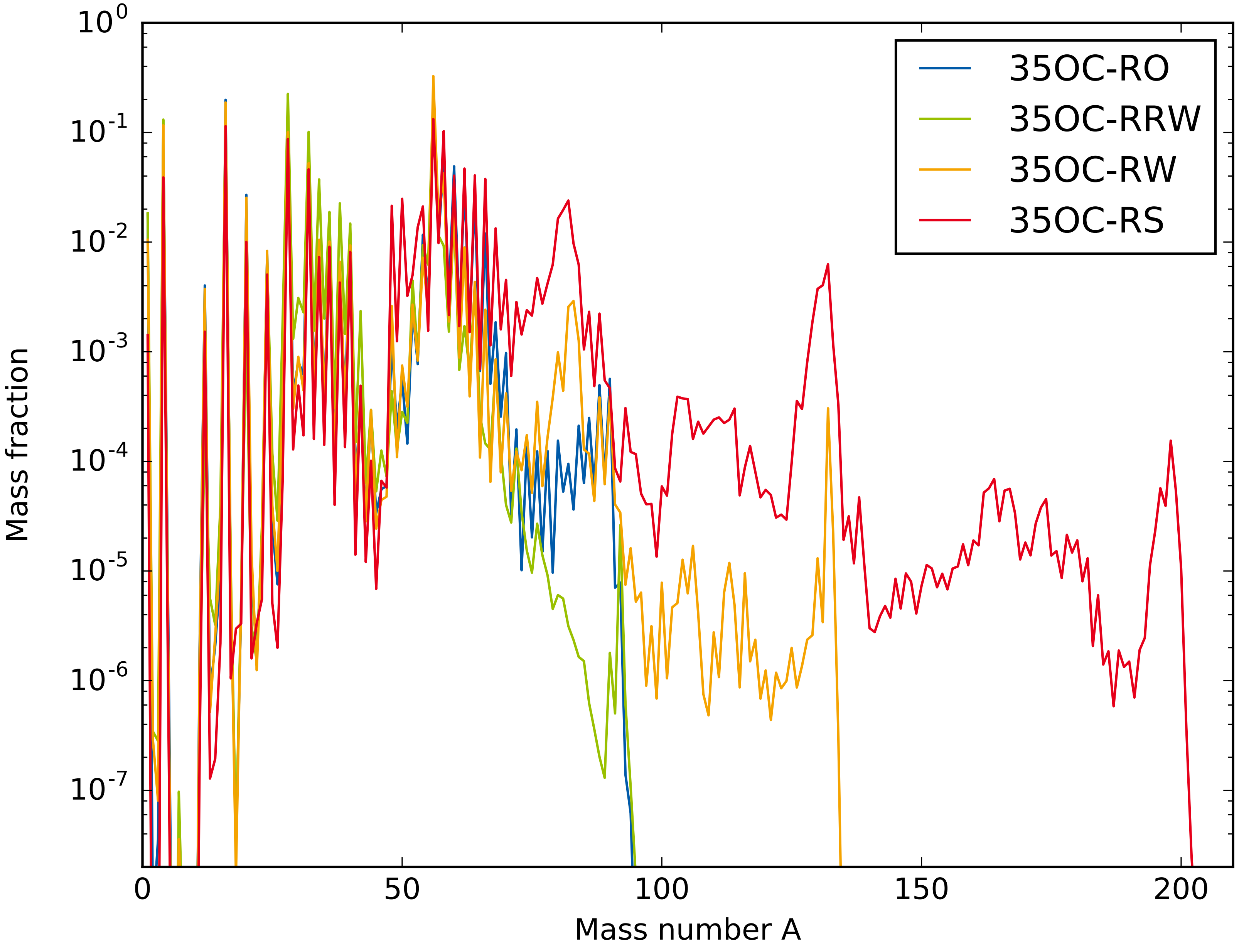
Magneto-rotational supernovae: r-process

Neutrinos and late evolution are important
Martin Obergaulinger: 2D, M1, ~1-2s
Progenitor: 35 M_{sun}



Obergaulinger & Aloy (2017)

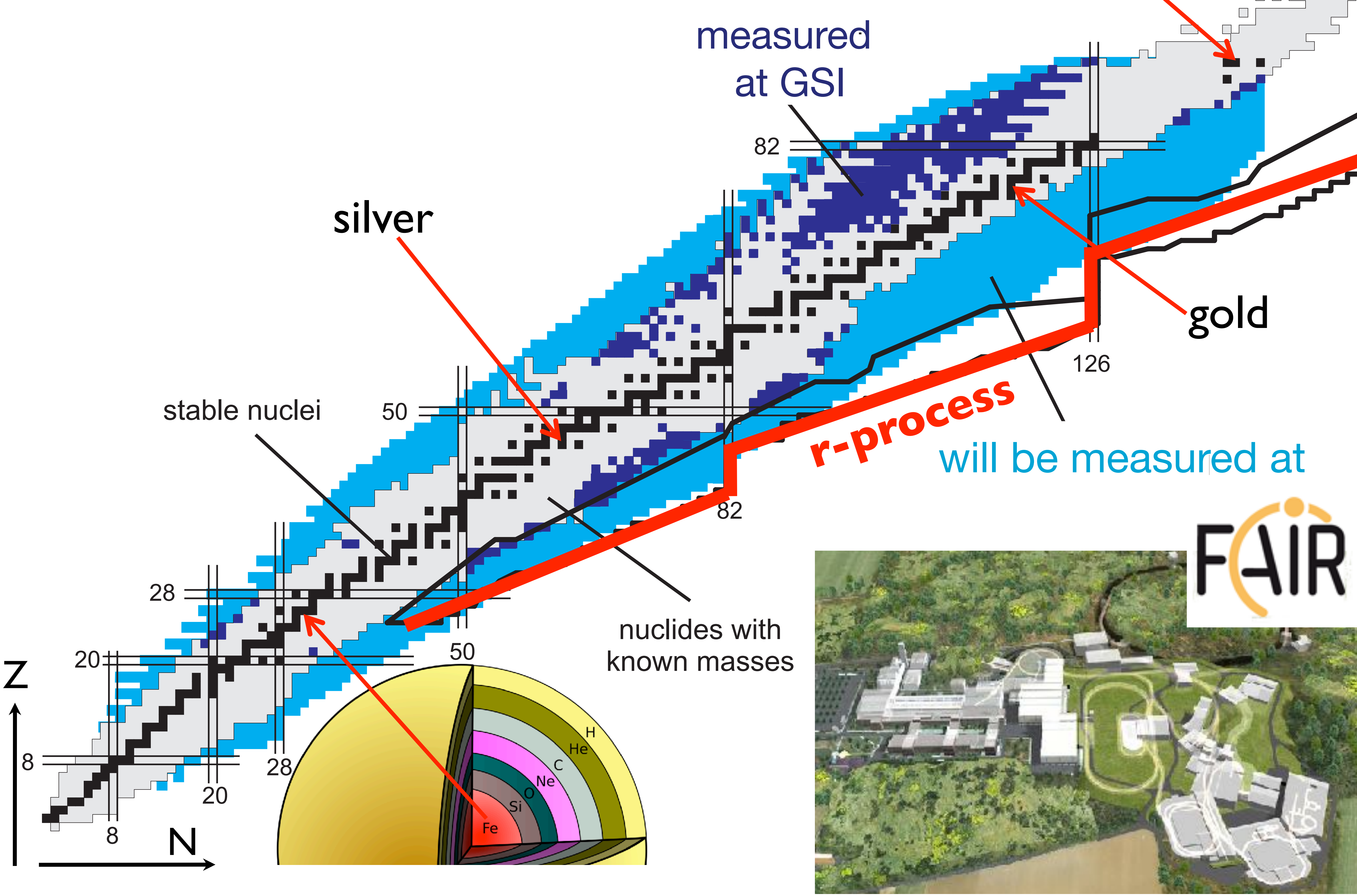
Impact of rotation and magnetic field



RO: progenitor
RRW: weak mag. field
strong rot.
RW: weak mag. field
RS: strong mag. field

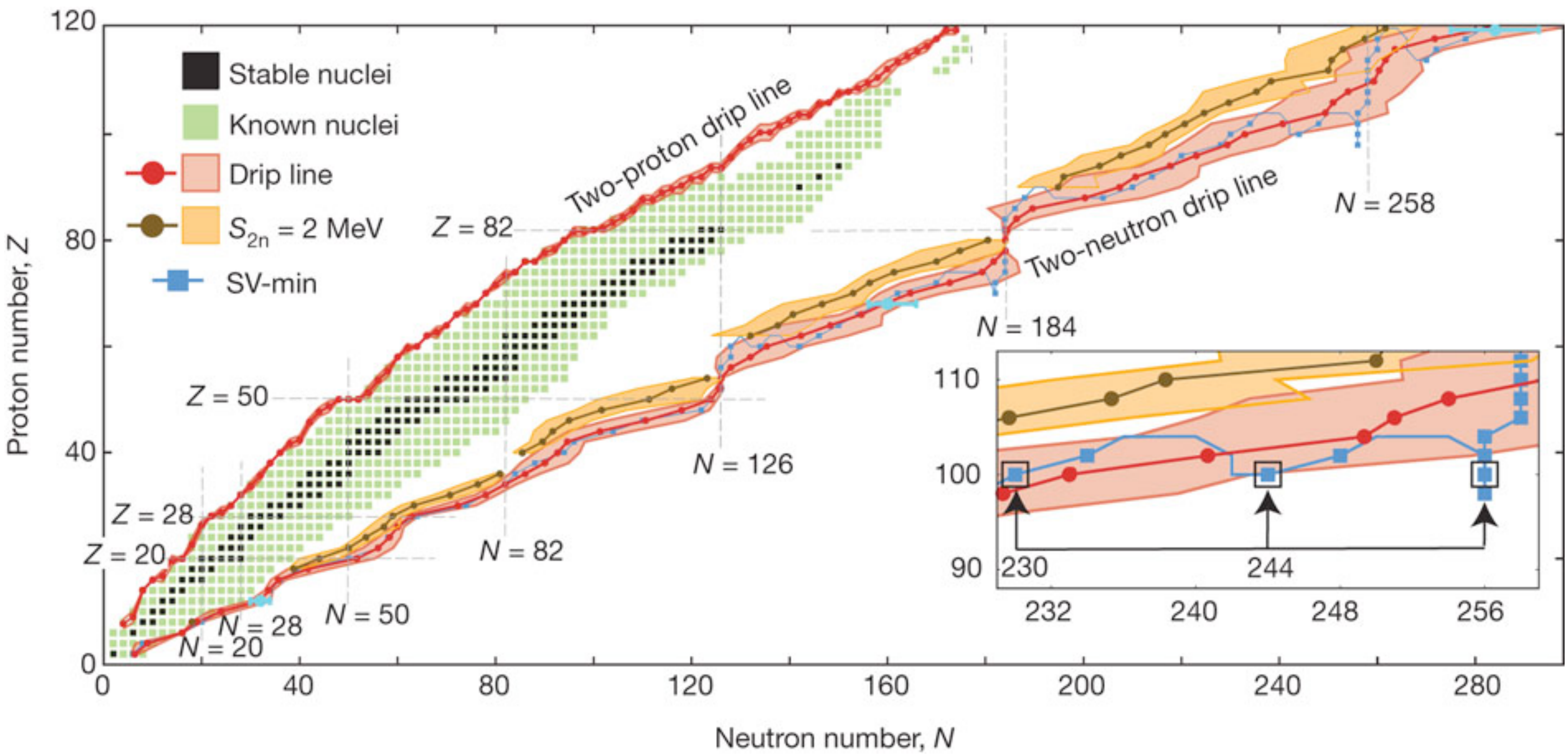
Reichert, Obergaulinger, Aloy, Arcones (in prep)

Extreme neutron-rich nuclei



Nuclear physics input

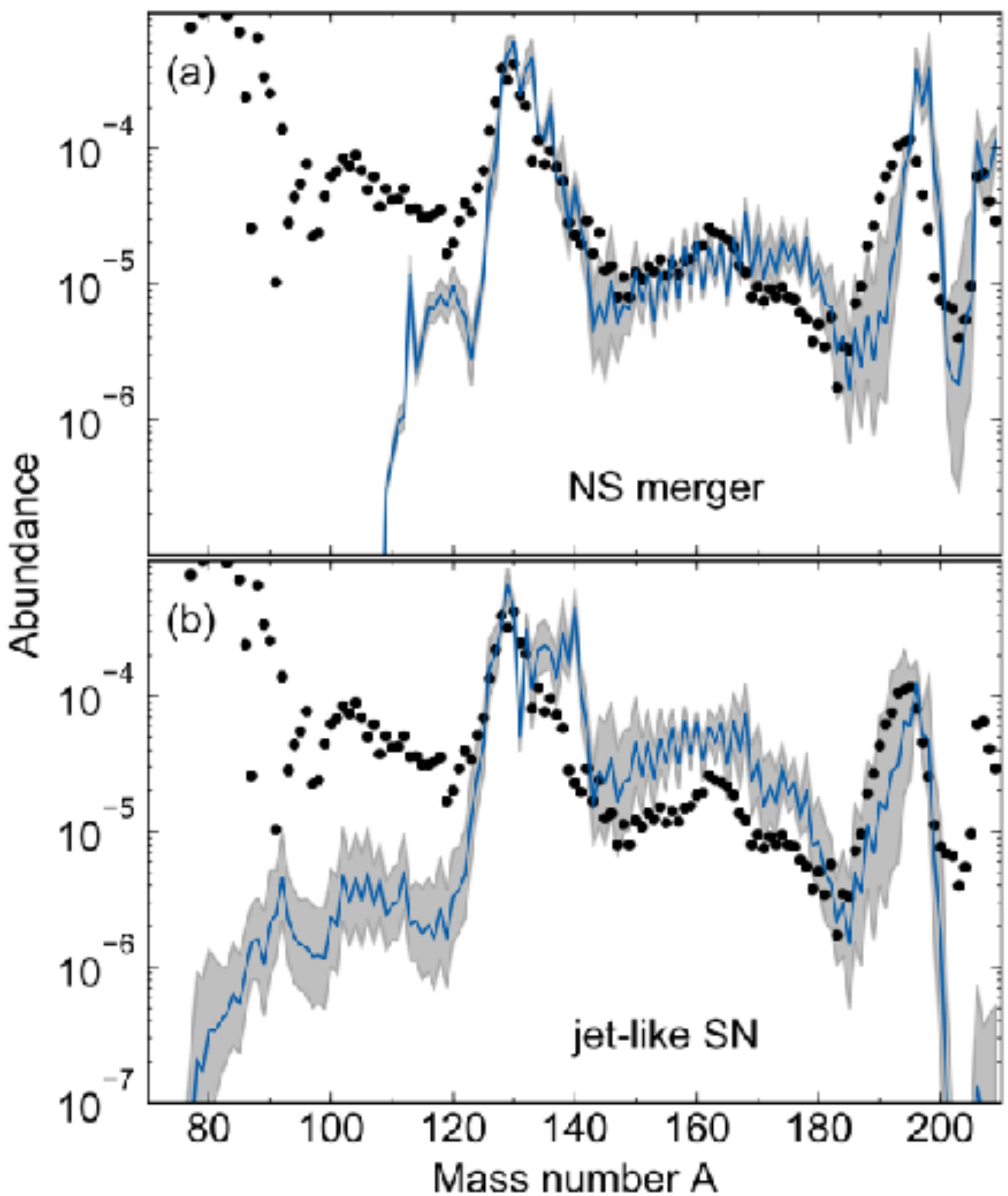
nuclear masses, beta decay, reaction rates (neutron capture), fission



Erler et al. (2012)

Nuclear masses

Abundances based on density functional theory
- six sets of different parametrisation (Erler et al. 2012)
- two realistic astrophysical scenarios: jet-like sn and neutron star mergers



Martin, Arcones, Nazarewicz, Olsen (2016)

First systematic uncertainty band
for r-process abundances

Uncertainty band depends on A,
in contrast to homogeneous band for all A
e.g., Mumpower et al. 2015

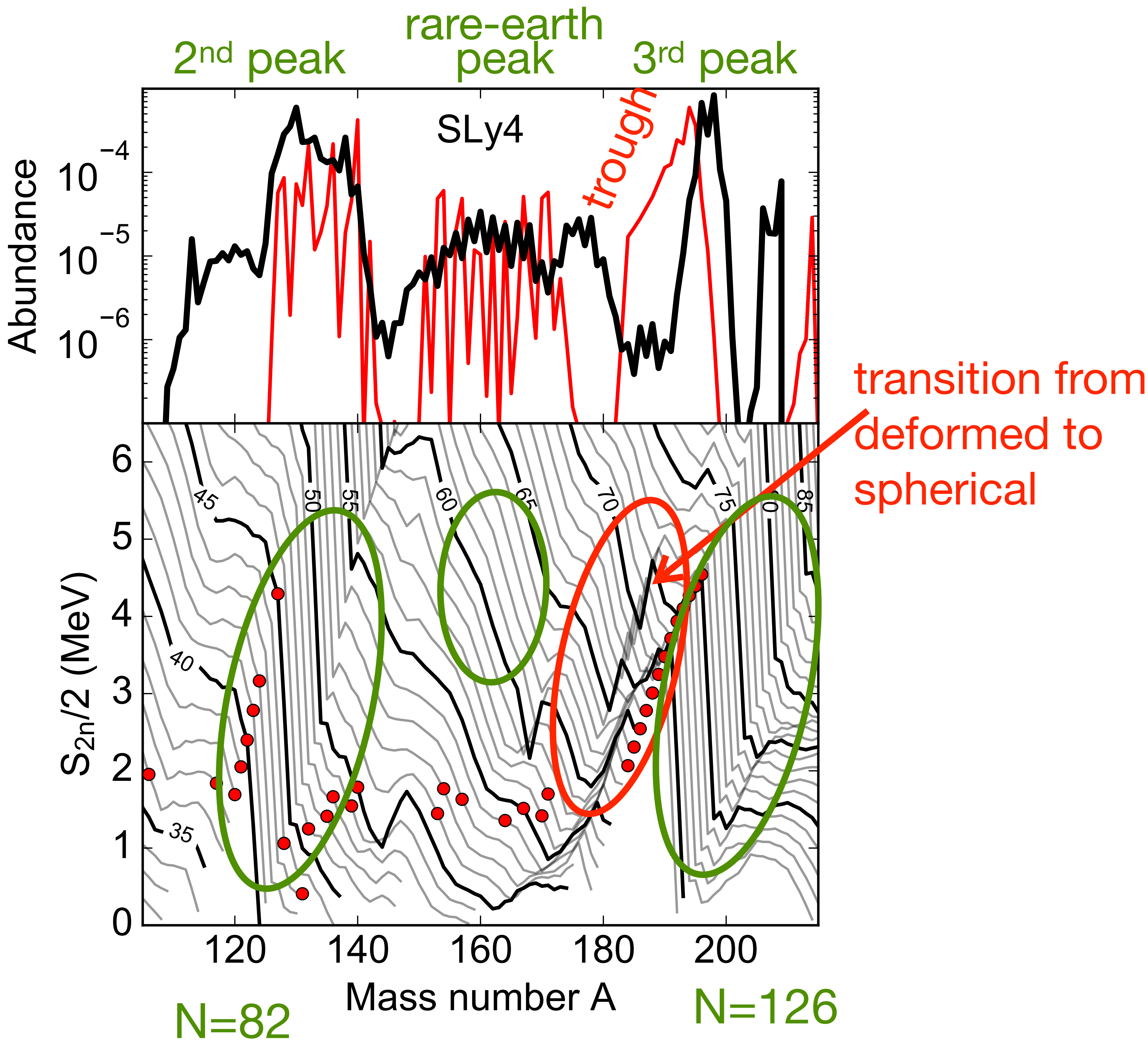
Can we link masses to r-process abundances?

Two neutron separation energy: abundances

Abundances

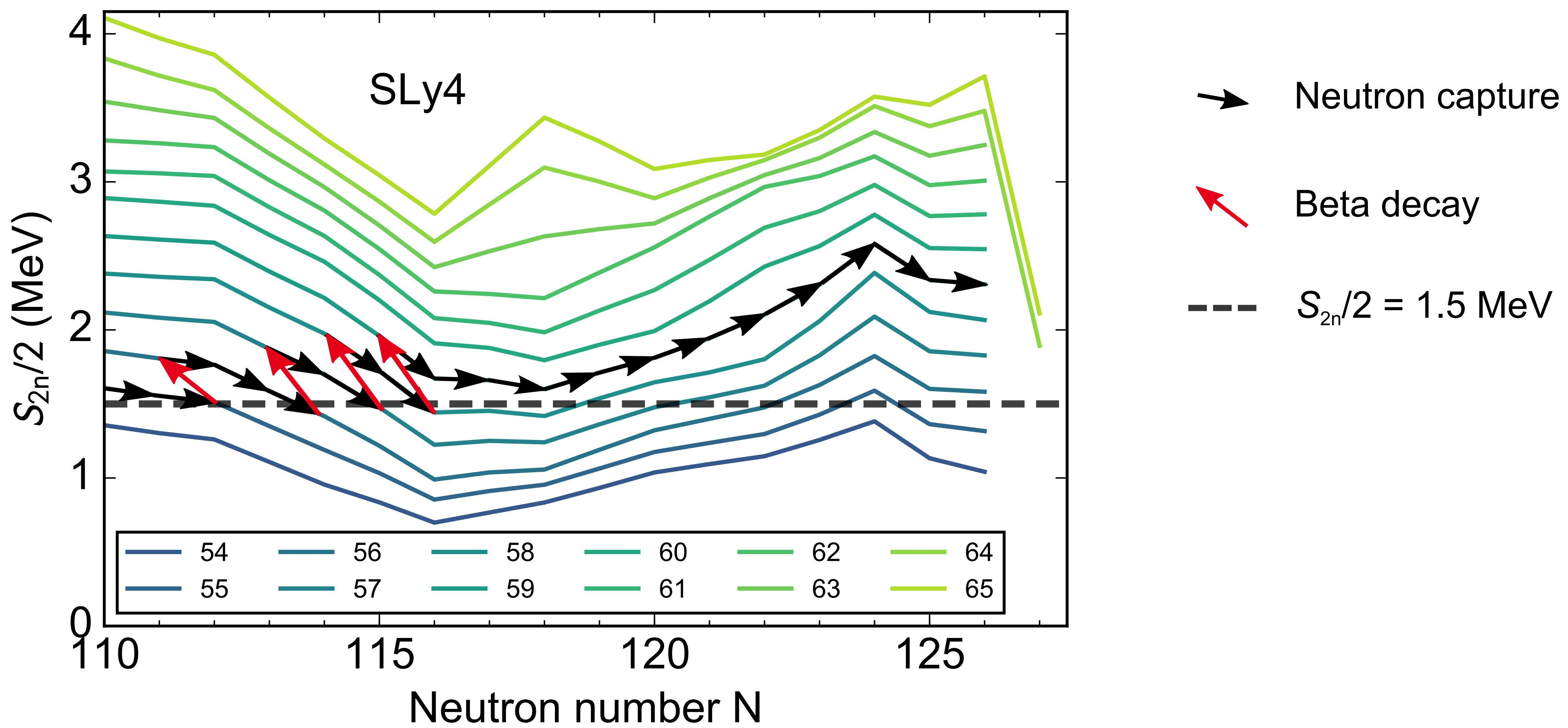
S_{2n}

Nuclear properties



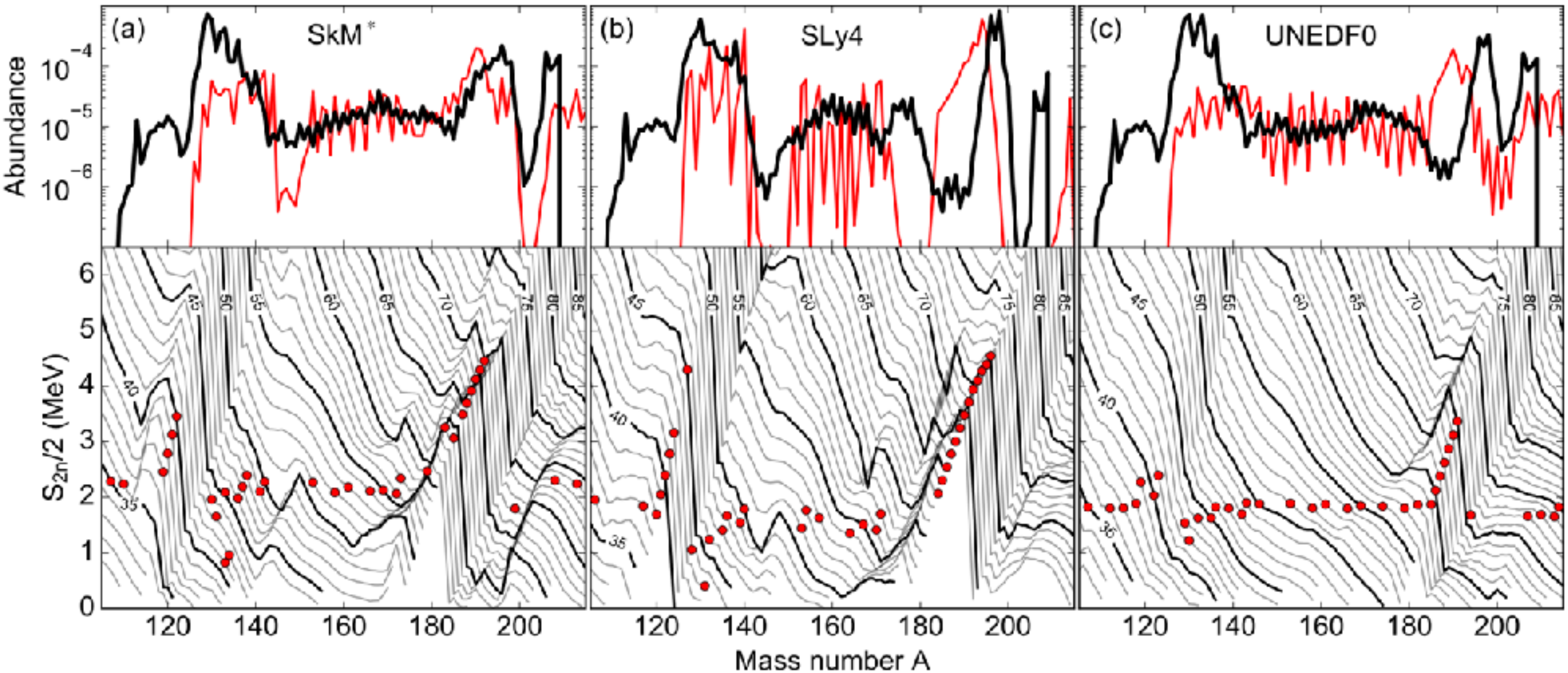
Two neutron separation energy

Nucleosynthesis path at constant S_n: (n,γ)-(γ,n) equilibrium



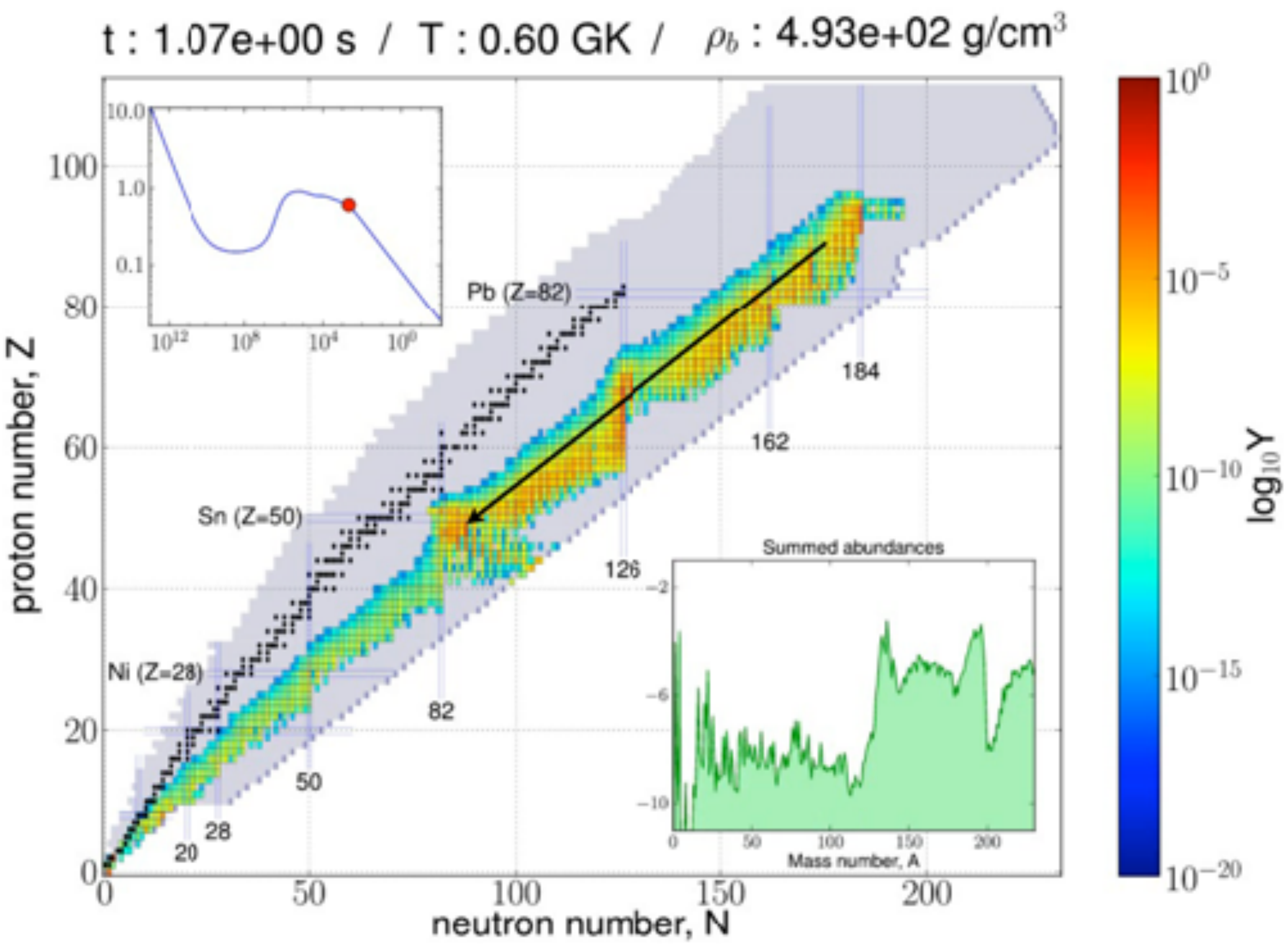
Martin, Arcones, Nazarewicz, Olsen (2016)

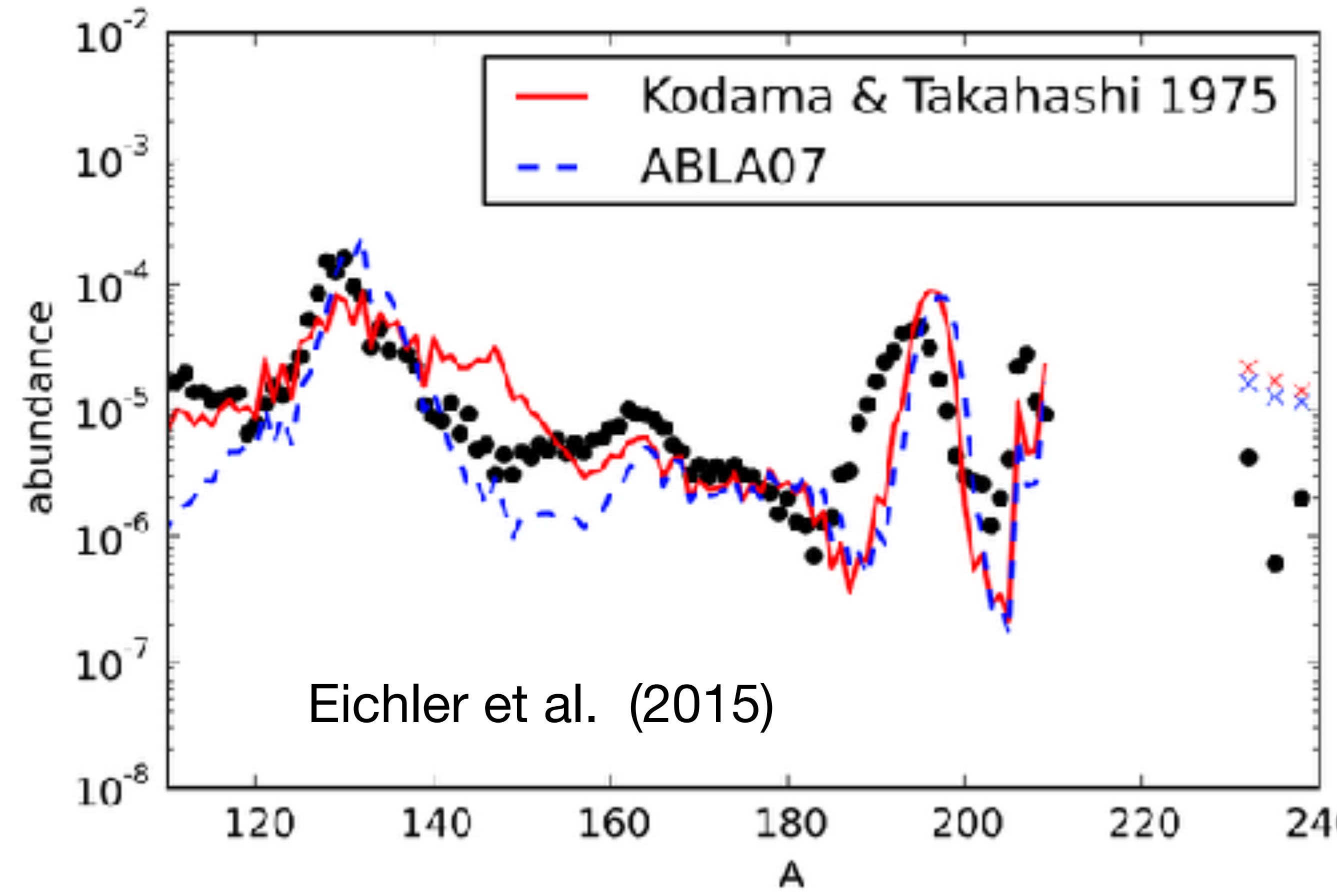
Two neutron separation energy: abundances



Martin, Arcones, Nazarewicz, Olsen (2016)

Fission: barriers and yield distributions

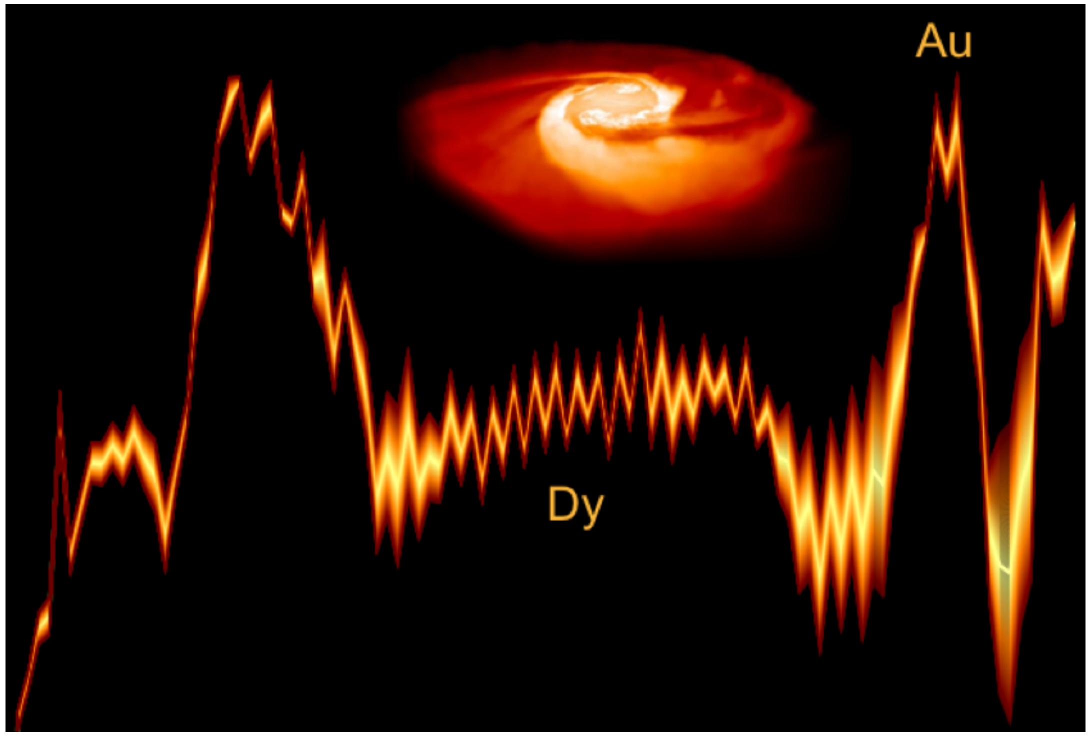


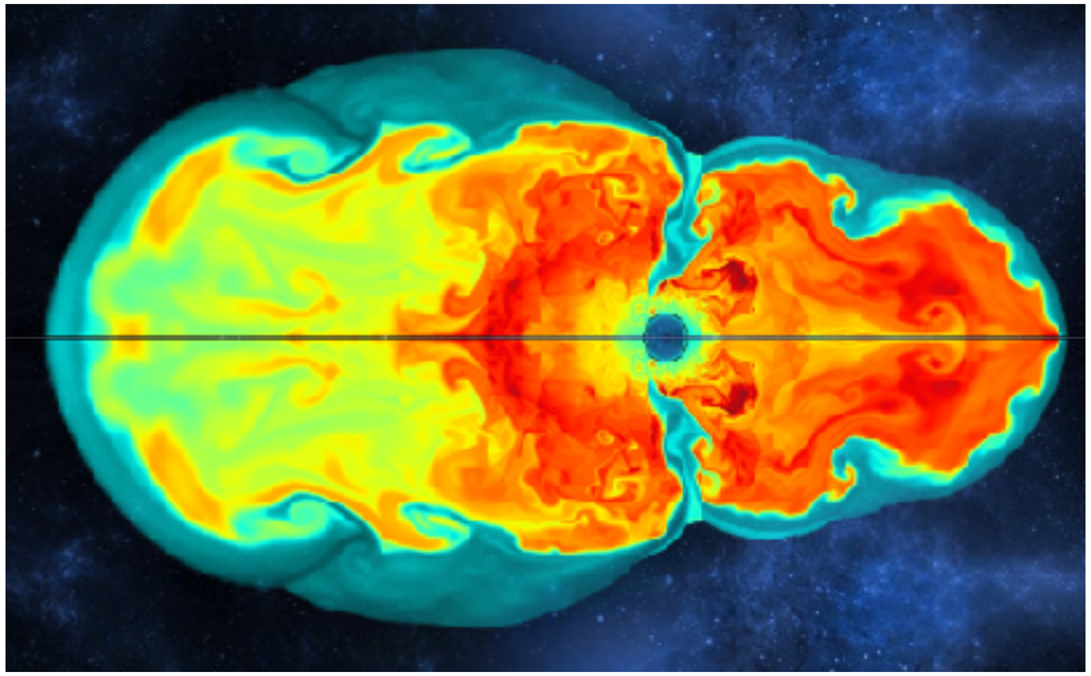


Neutron star mergers: r-process with two fission descriptions

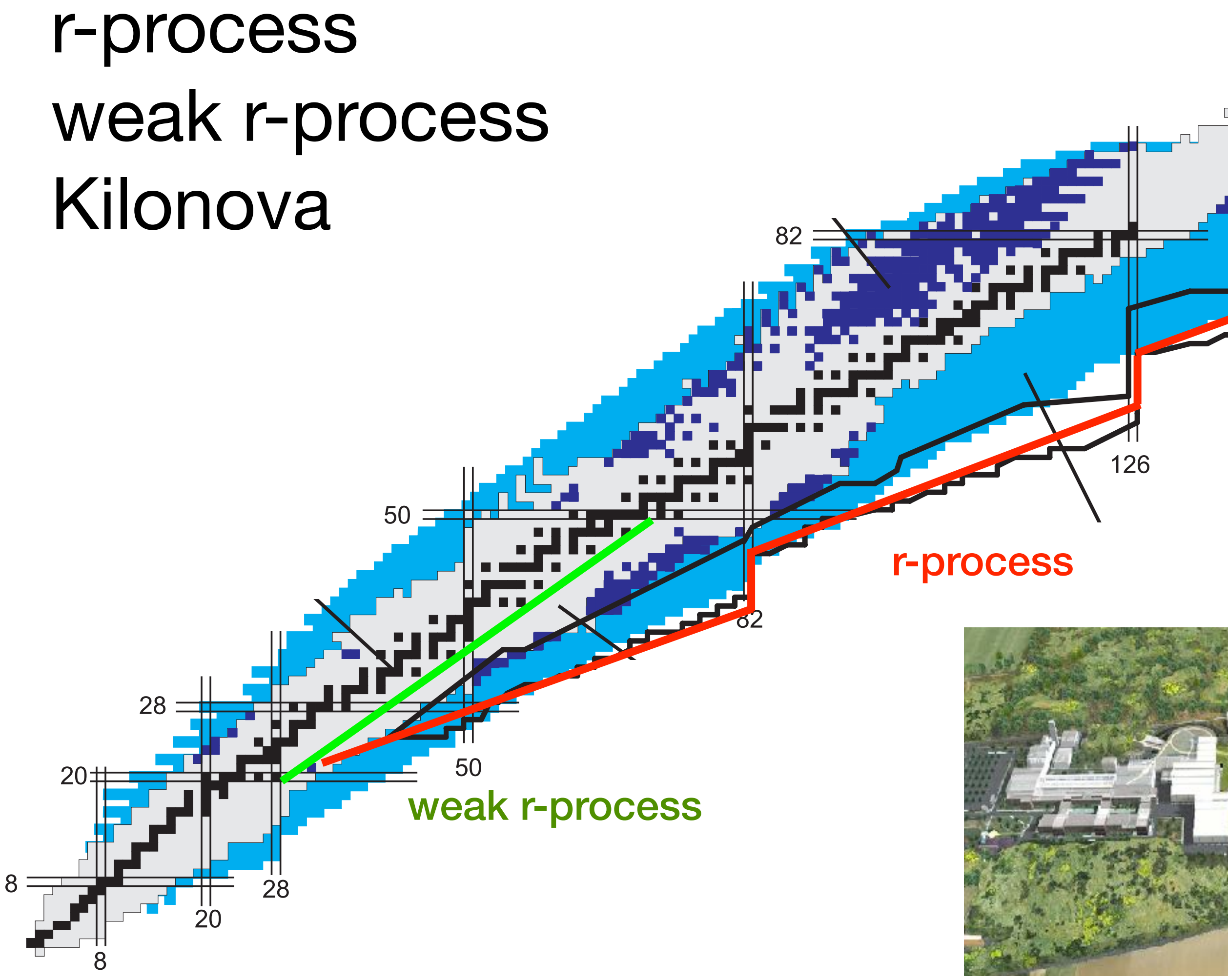
2nd peak (A~130): fission yield distribution
3rd peak (A~195): mass model, neutron captures

Conclusions





Neutron star mergers:
r-process
weak r-process
Kilonova



Core-collapse supernovae:
wind: up to ~Ag
Magneto-rot.: r-process