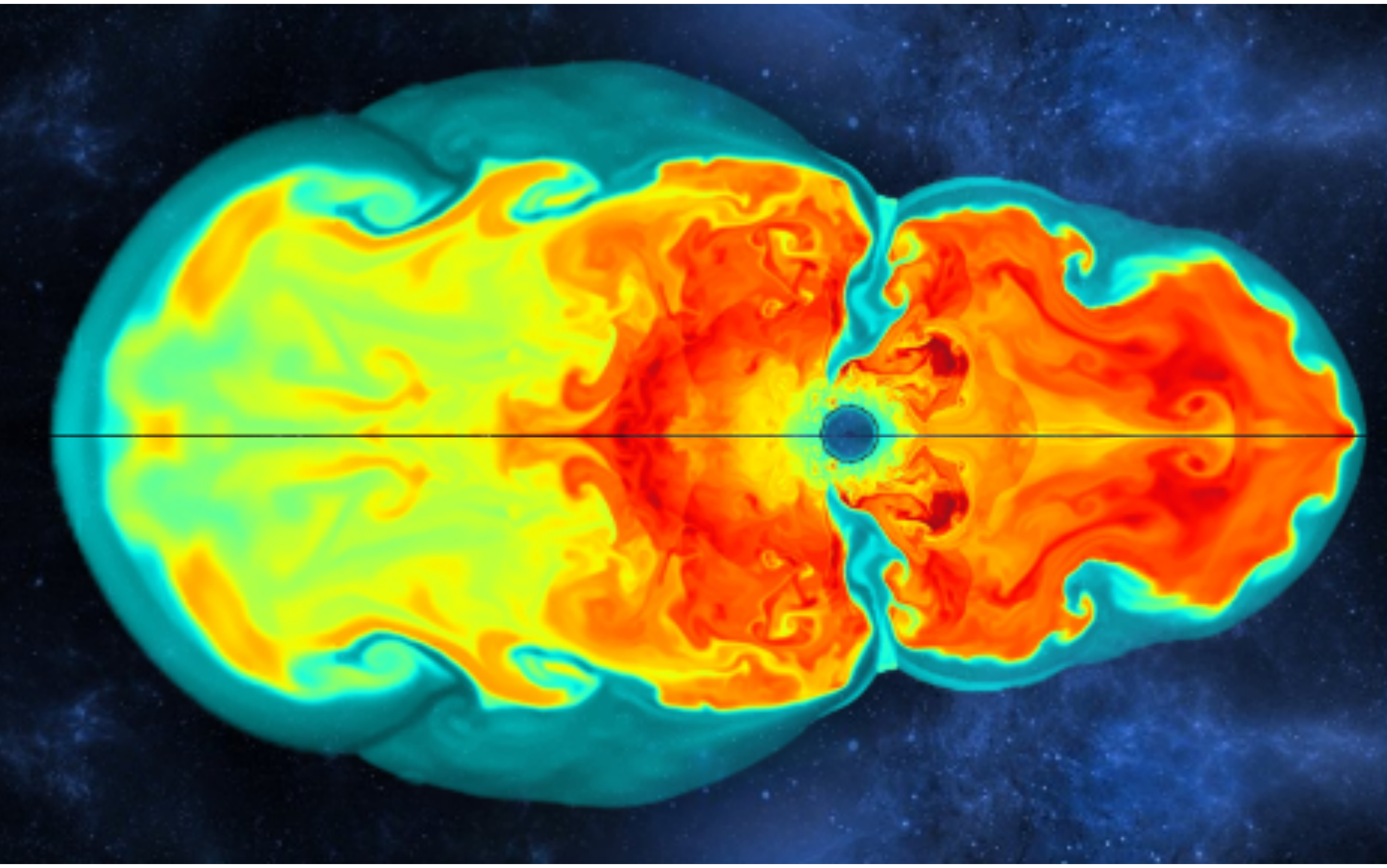
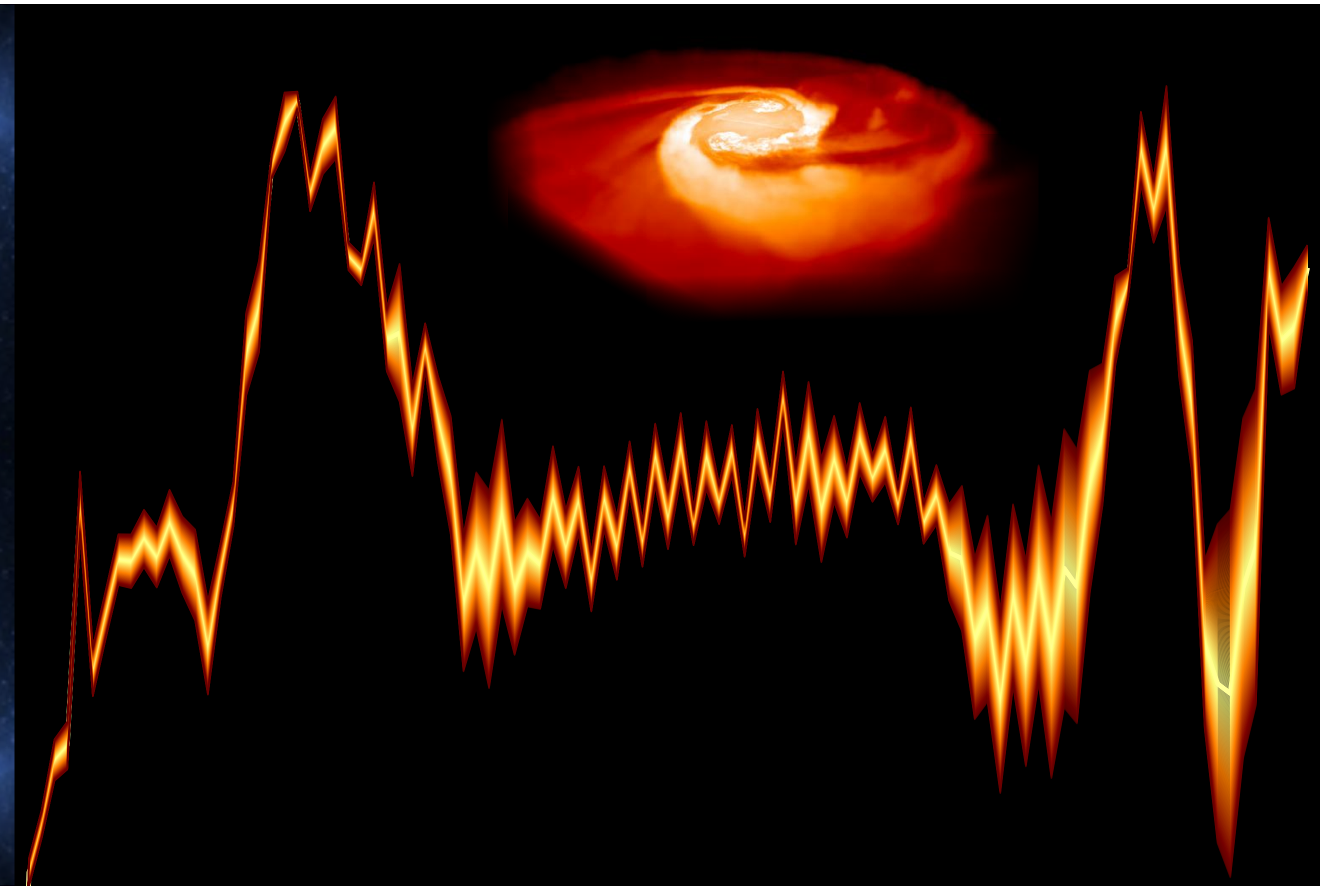
ASTROPARTICLE PHYSICS
IN GERMANY
Status and Perspectives
Mainz | 17–19 Sept 2018
JG|U PRISMA Astro.Teilchen.Physik

Creation of elements





Almudena Arcones

European Research Council
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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																	

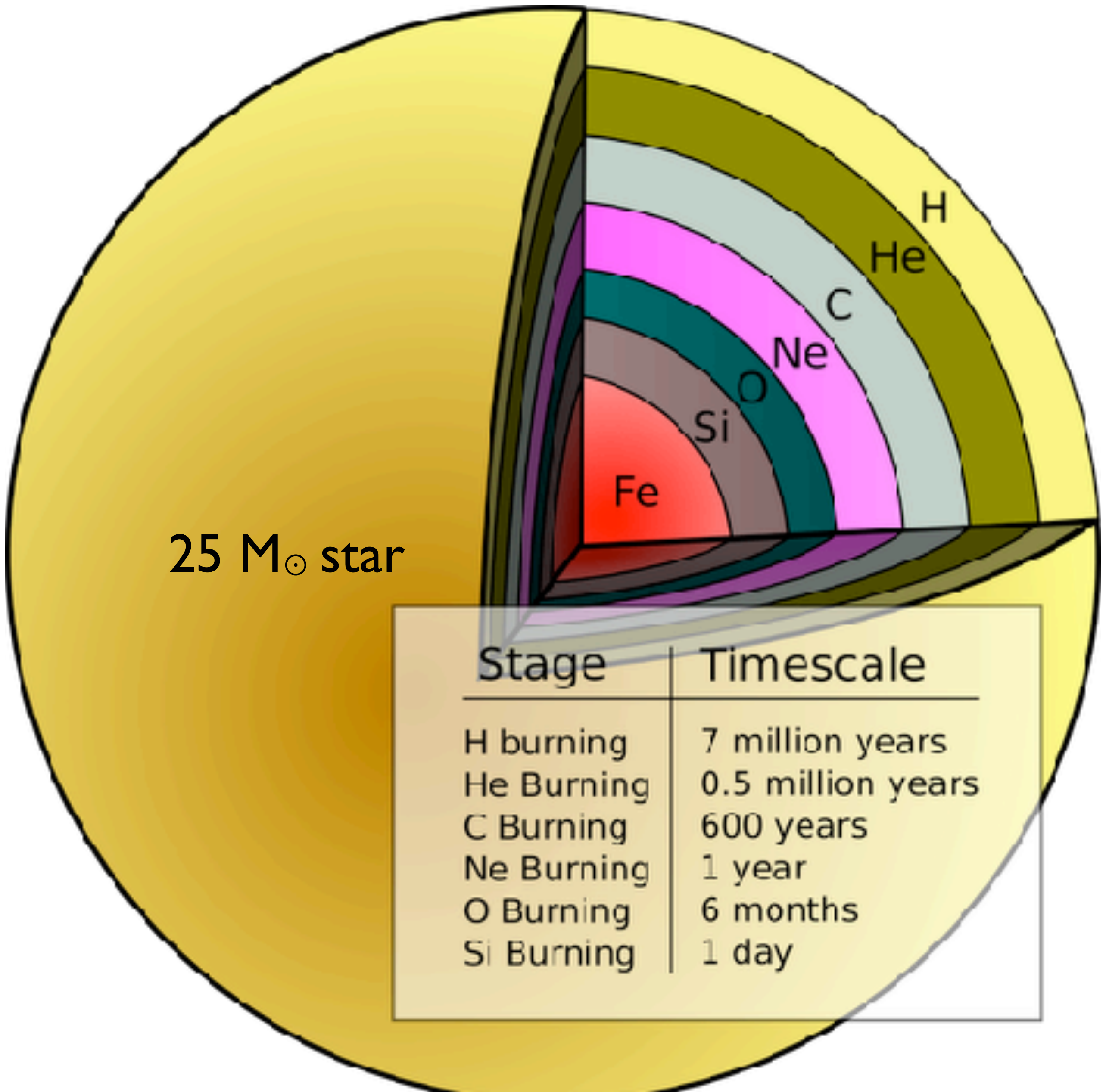
* Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

1
H

after Big Bang

2
He

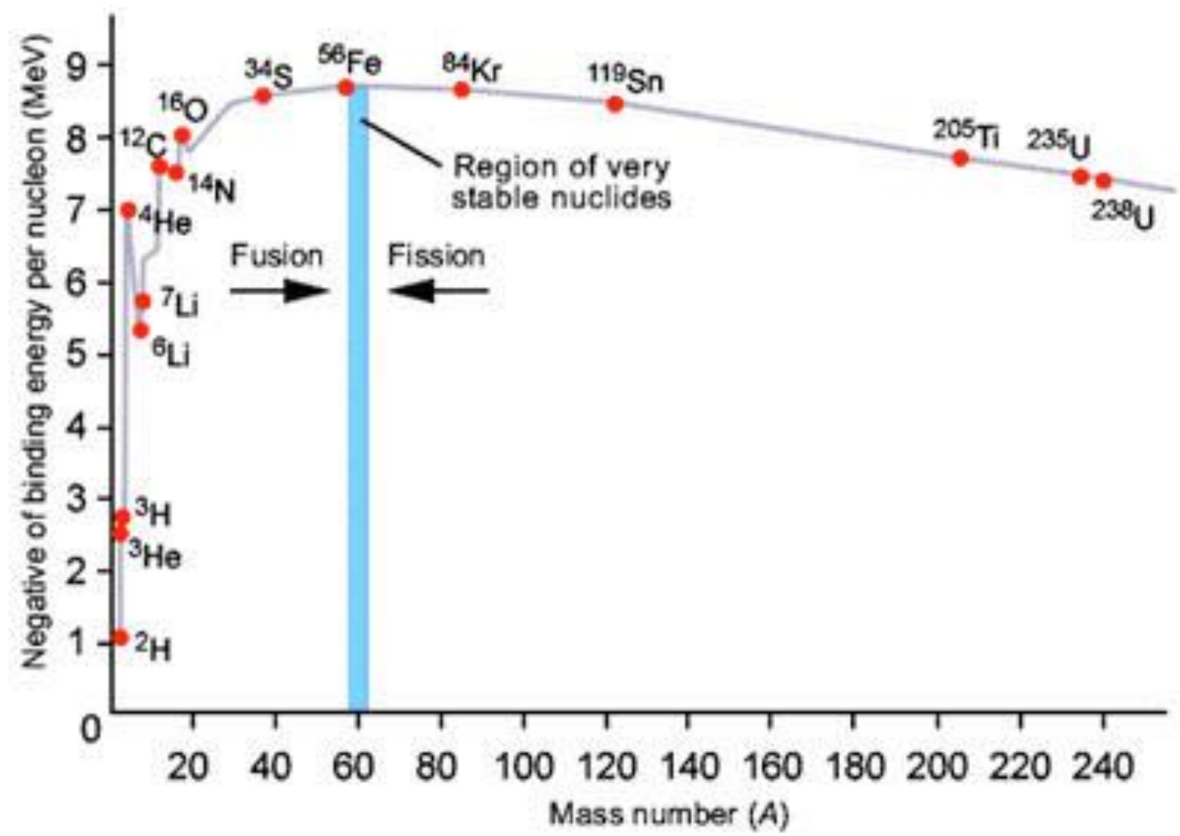
Stars build elements up to iron group



Hydrostatic burning stages

Final stage: iron core

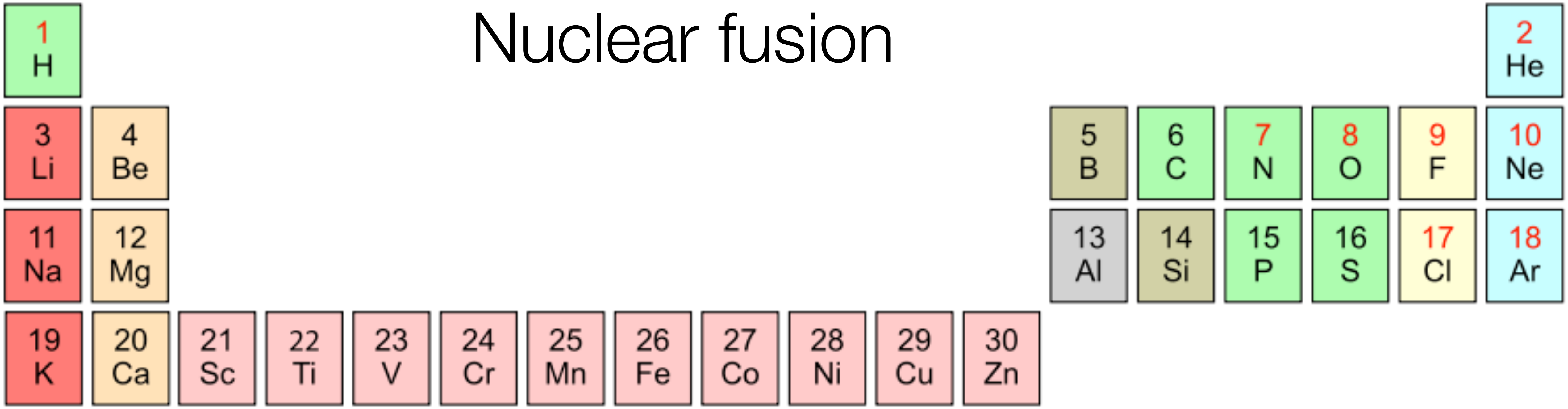
No more energy gain from fusion



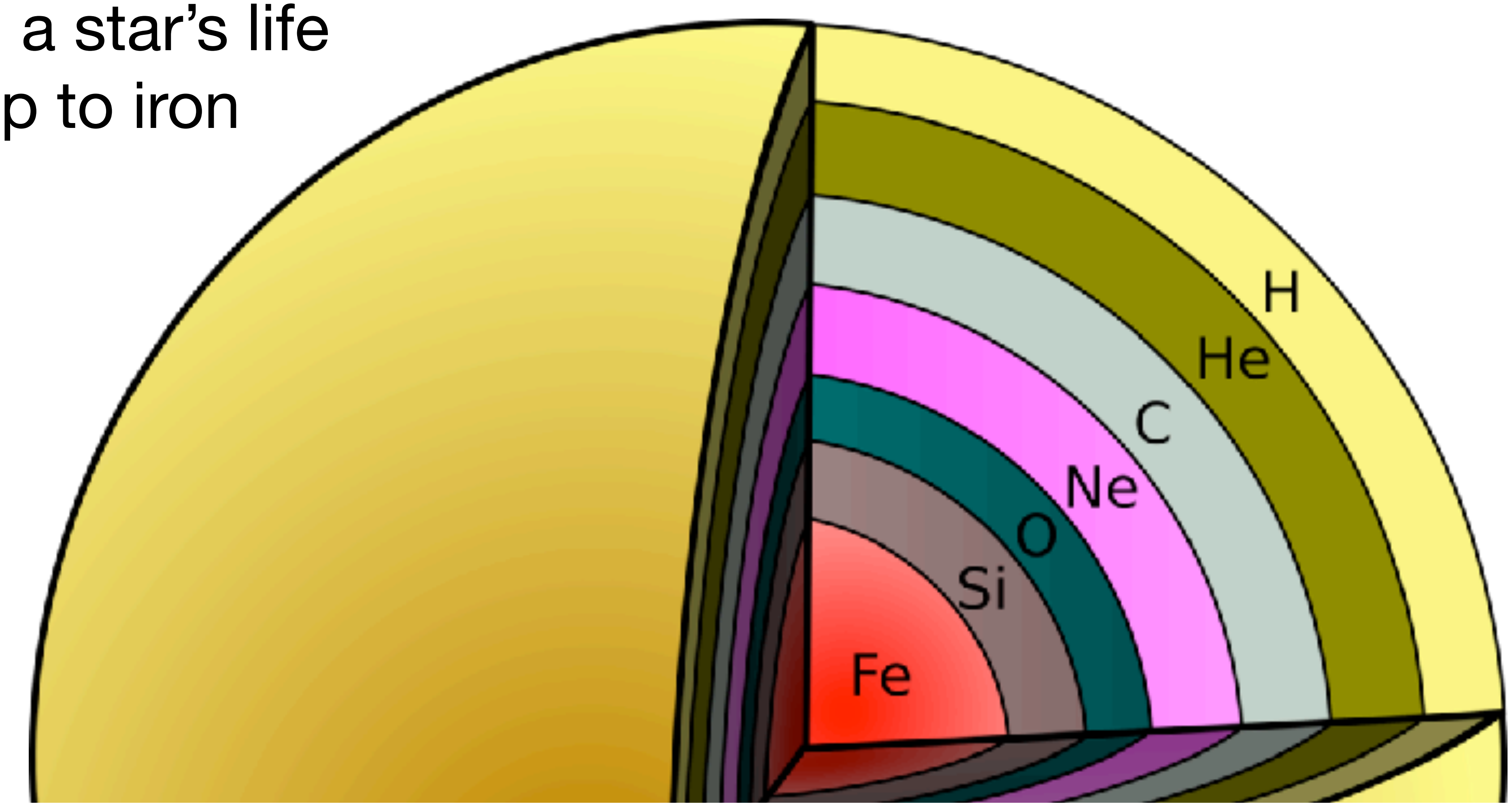
Massive stars: 8 $M_\odot < M \lesssim 70\ M_\odot$

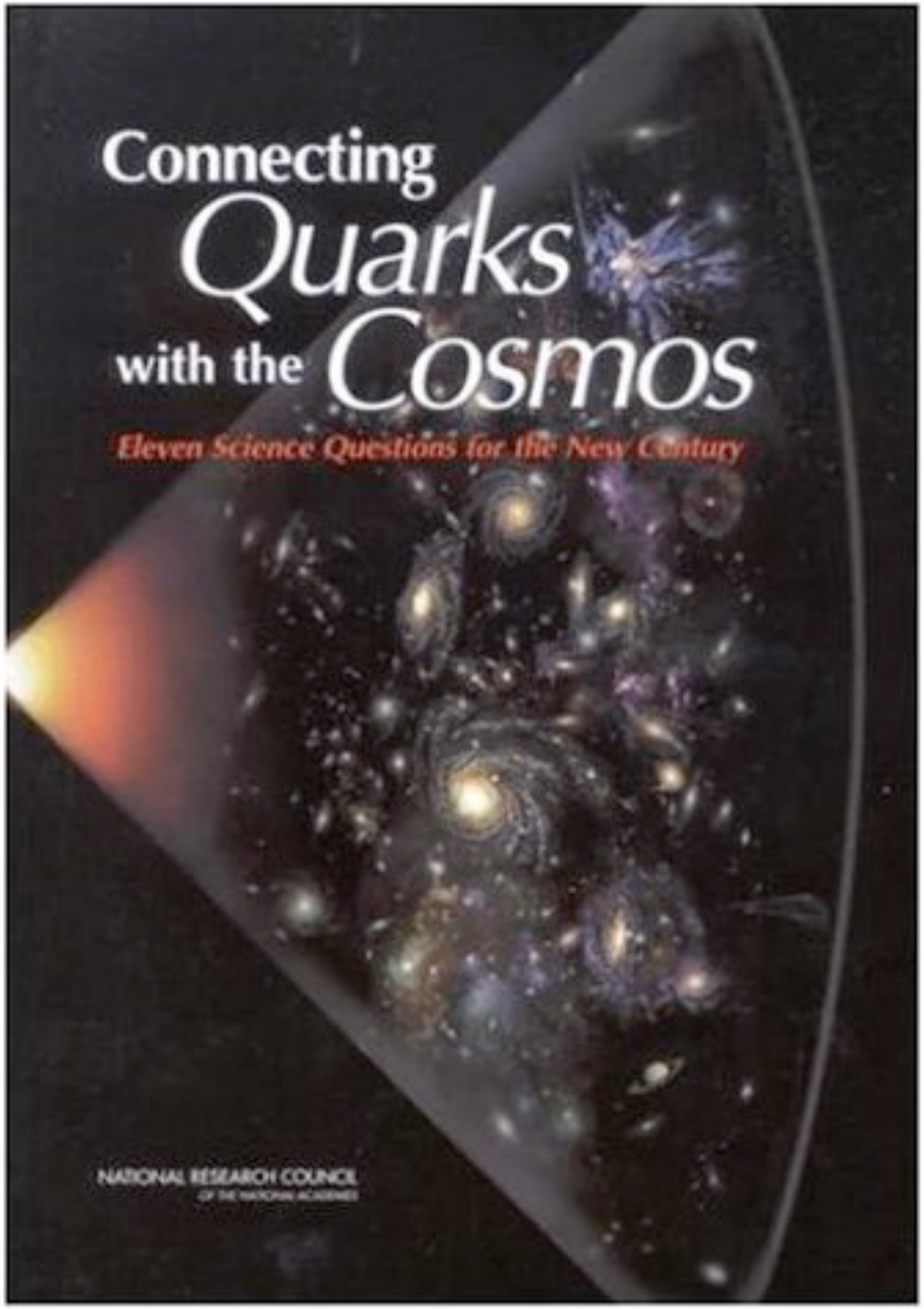
($M_\odot = 1.99 \times 10^{30}$ kg)

Nuclear fusion

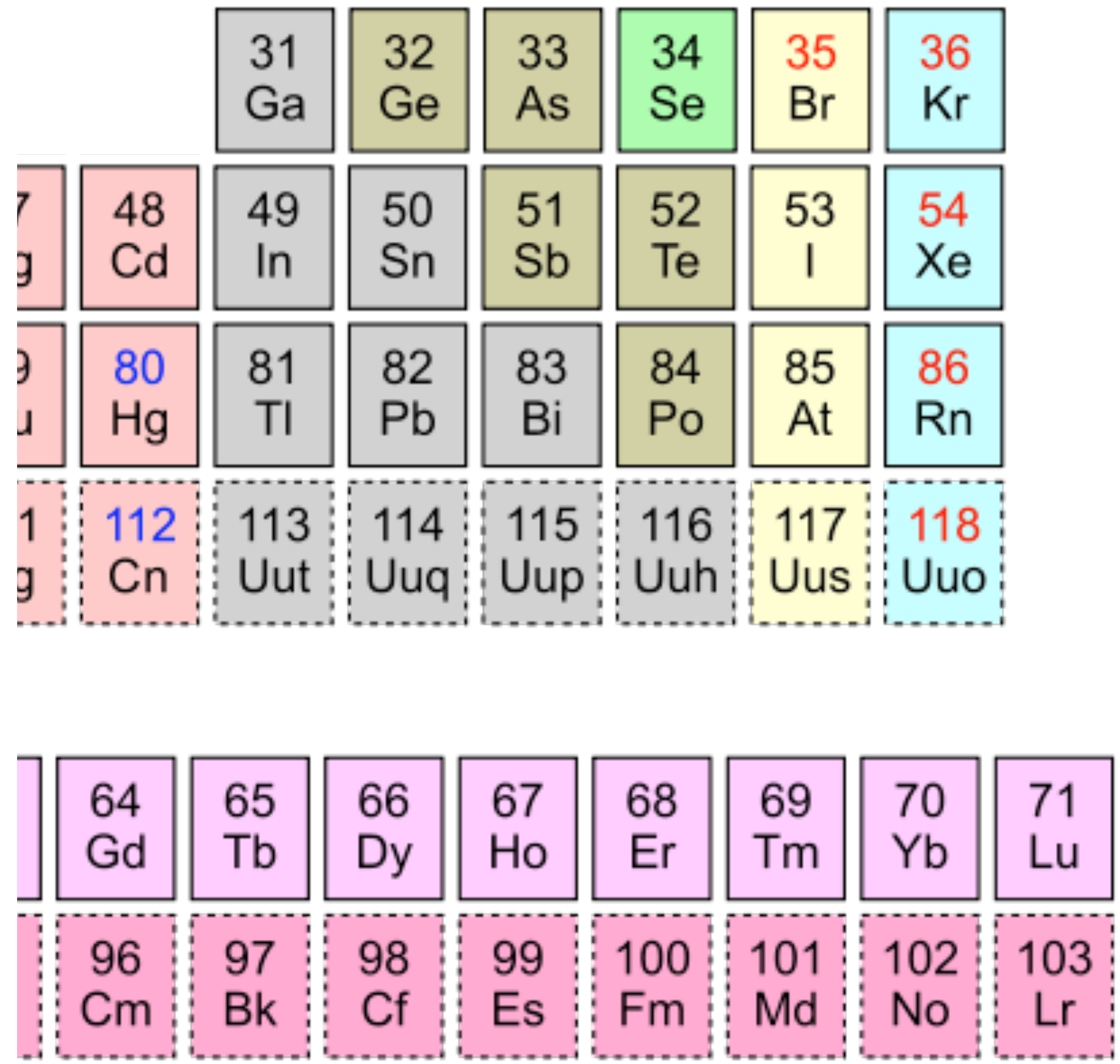


energy source during a star's life
produces elements up to iron





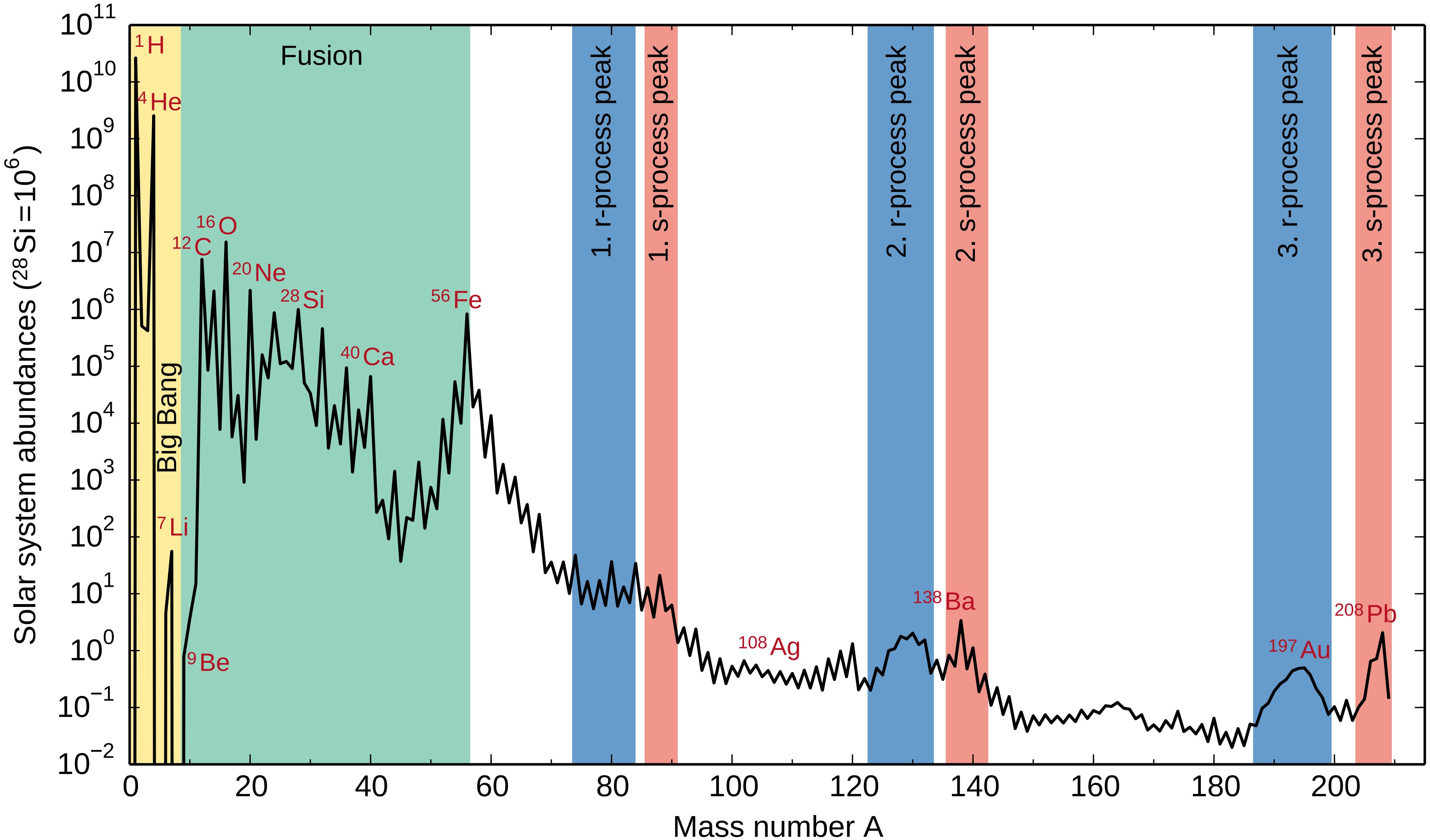
How were the elements from iron to uranium made?

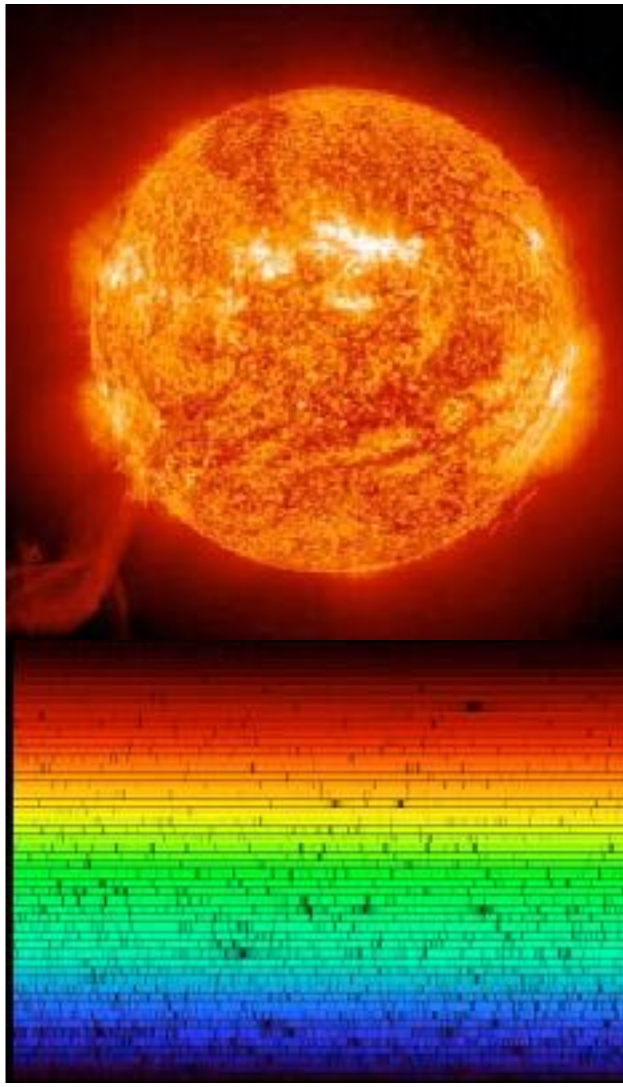


Solar system abundances

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

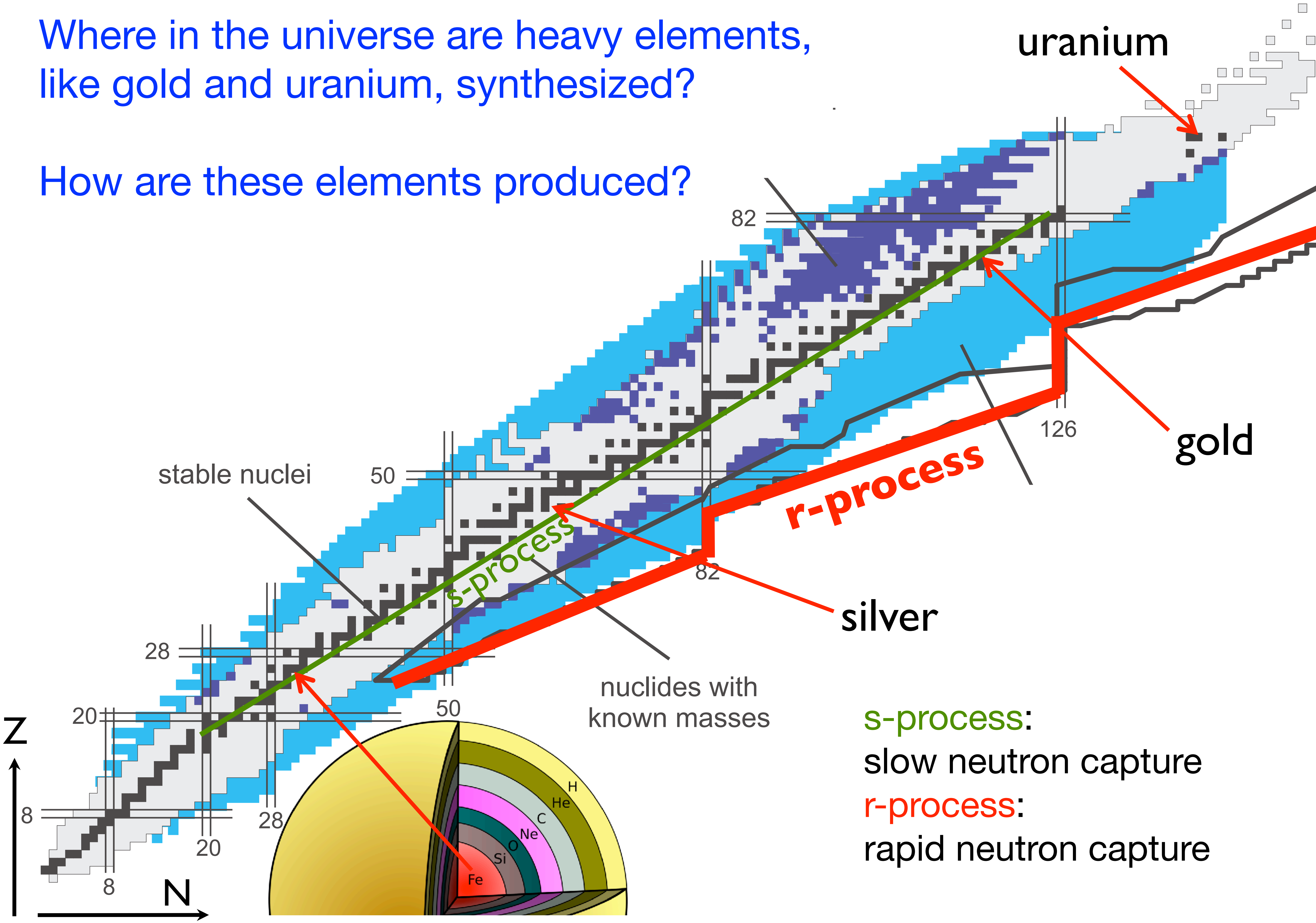
Contribution of all nucleosynthesis processes





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

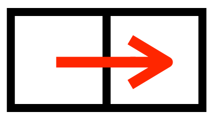
How are these elements produced?



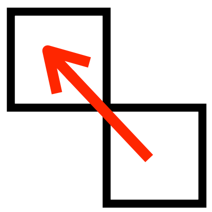
s-process:
slow neutron capture
r-process:
rapid neutron capture

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)

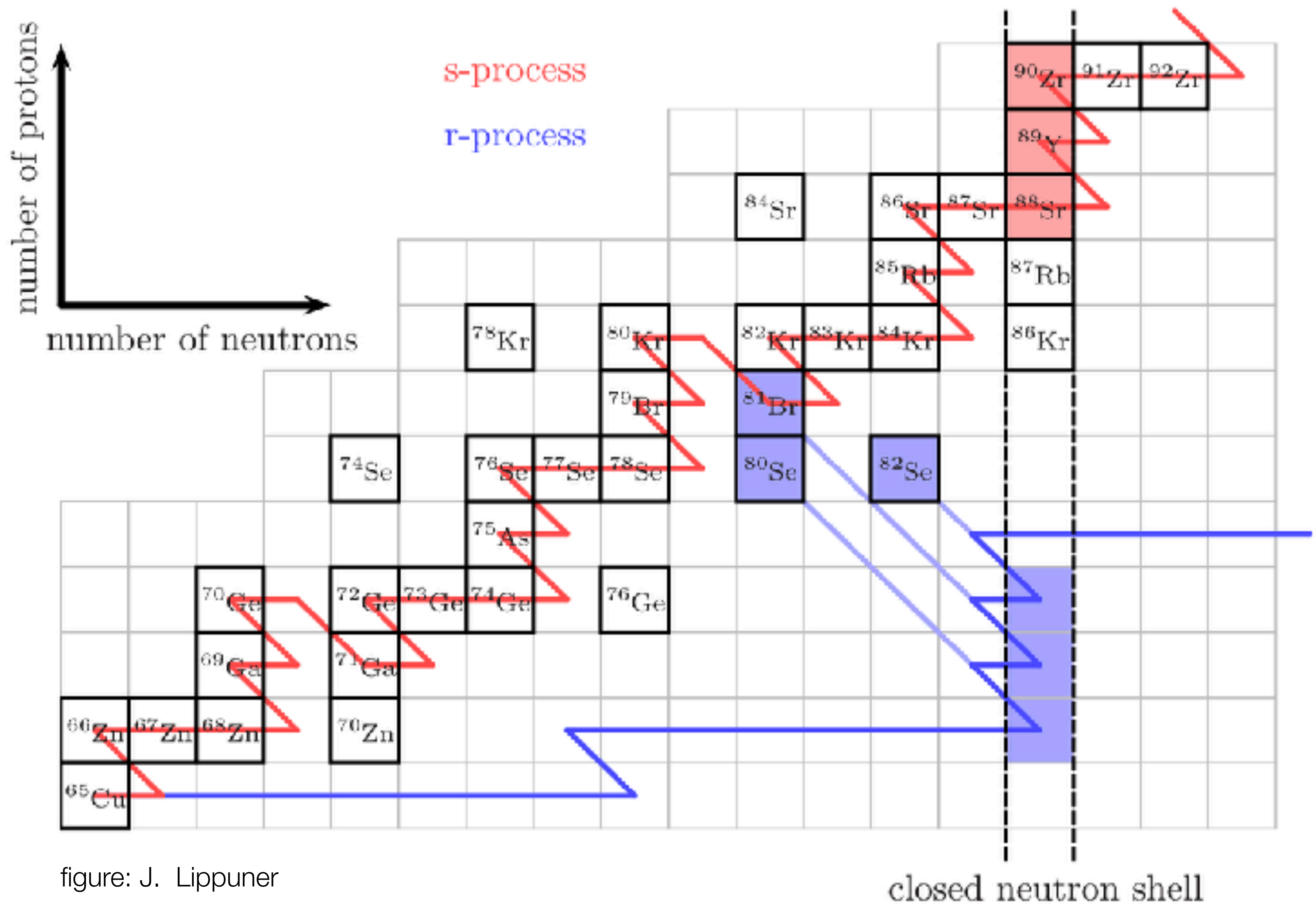
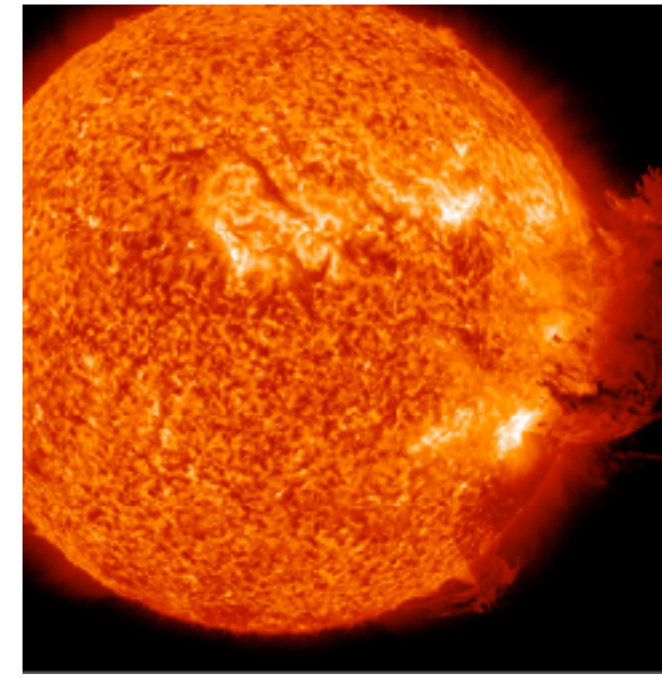


figure: J. Lippuner

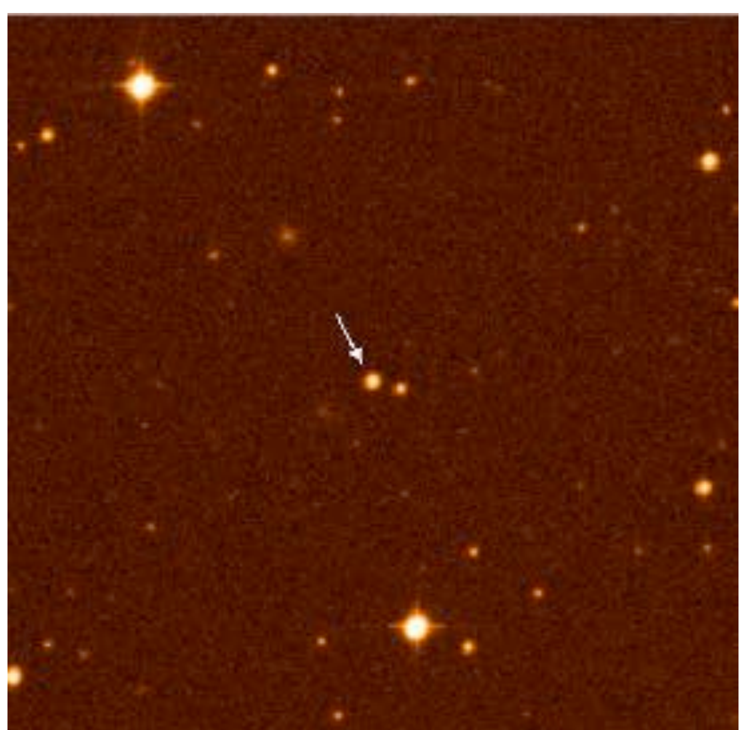
Galactic chemical evolution

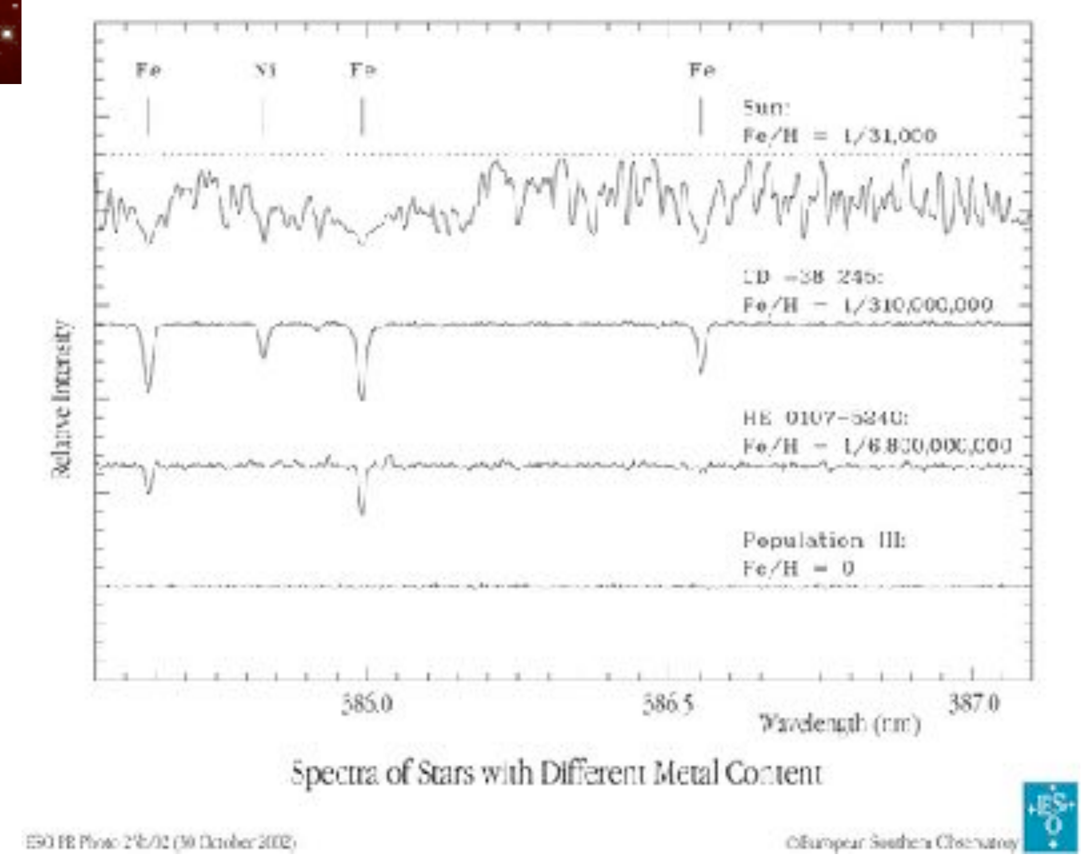
First stars: H, He → Heavy elements ← New generation of stars

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



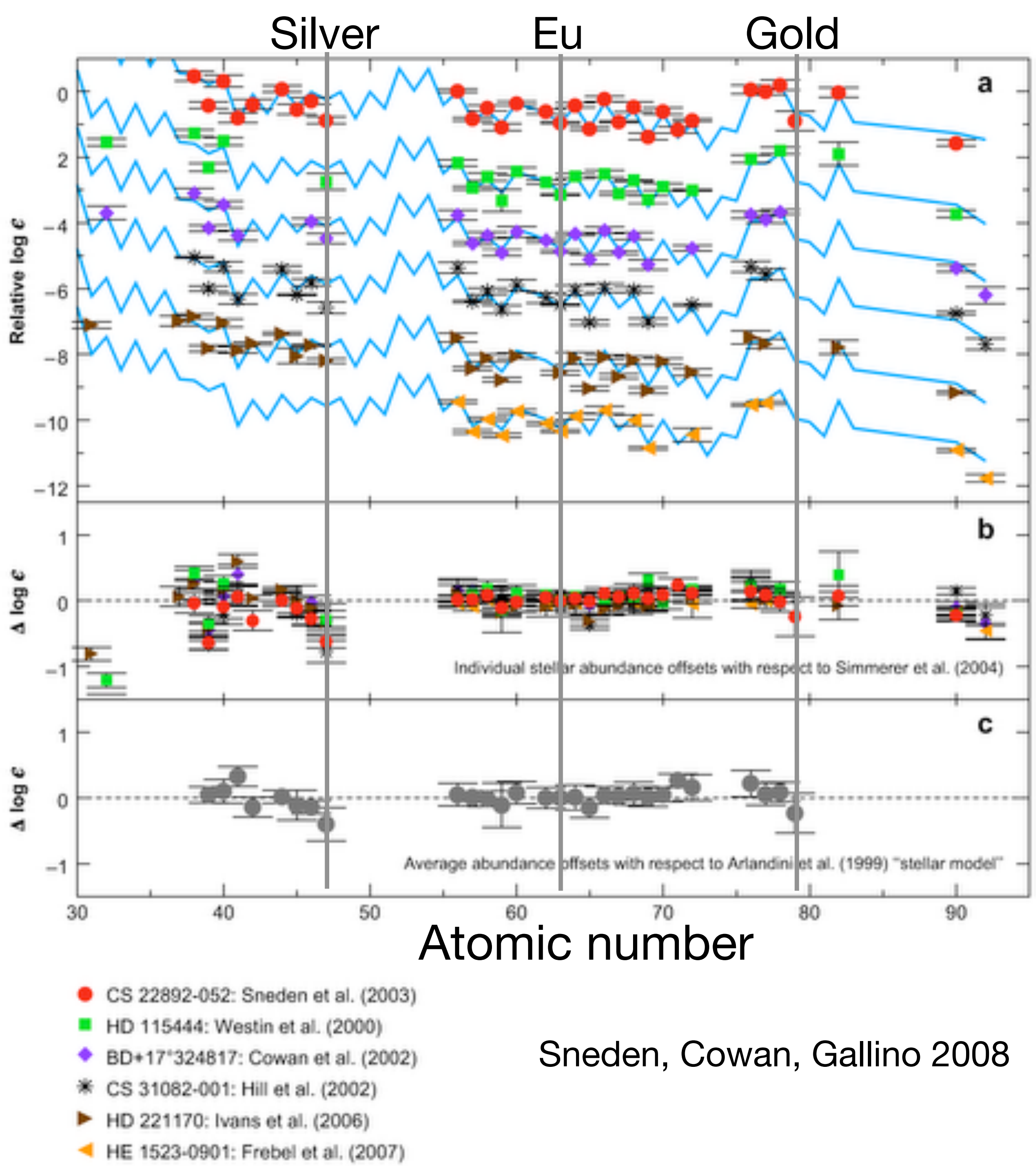
The very metal-deficient star
HE 0107-5240
(Hamburg-ESO survey)





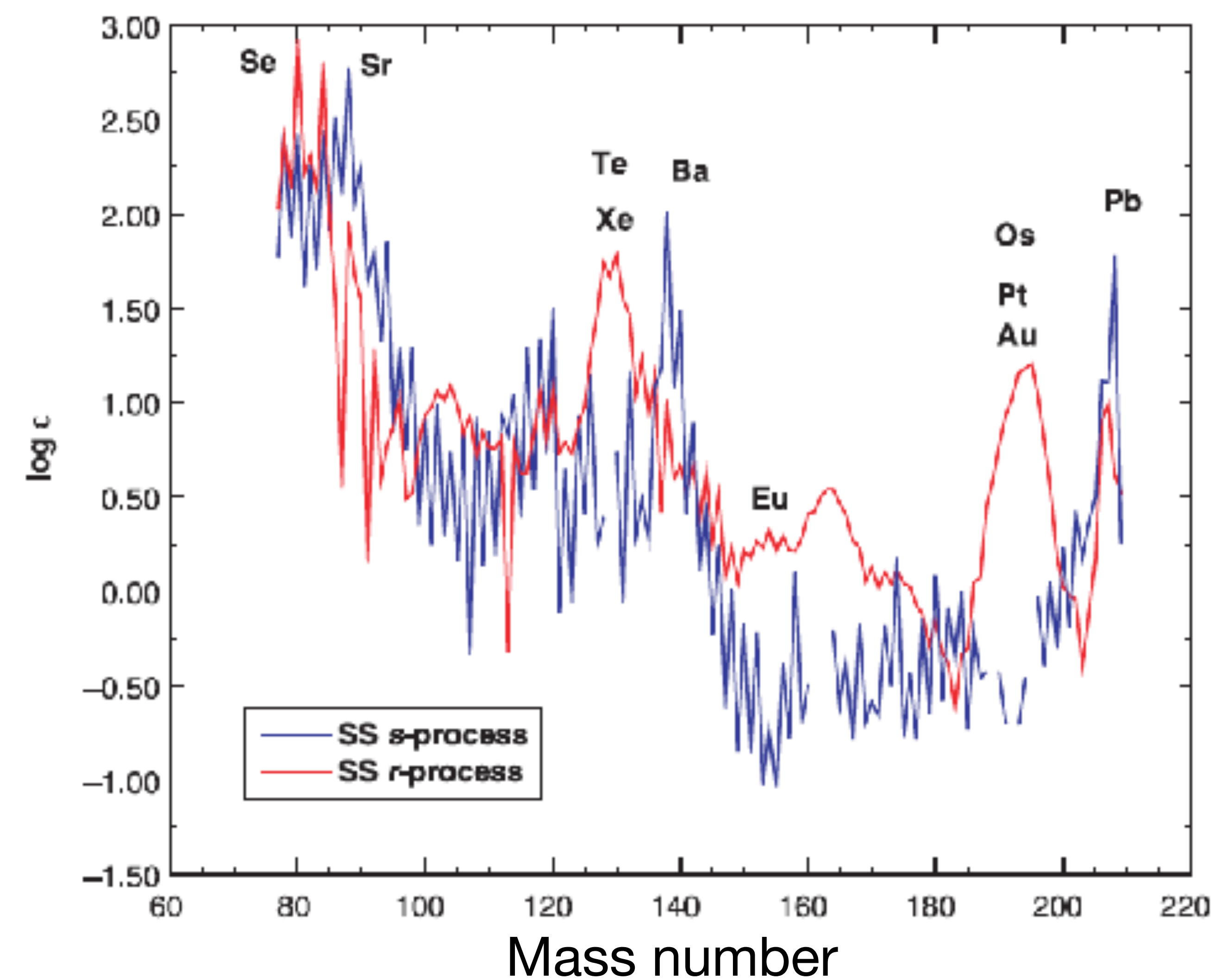
Fingerprint of the r-process

Oldest observed stars



Sneden, Cowan, Gallino 2008

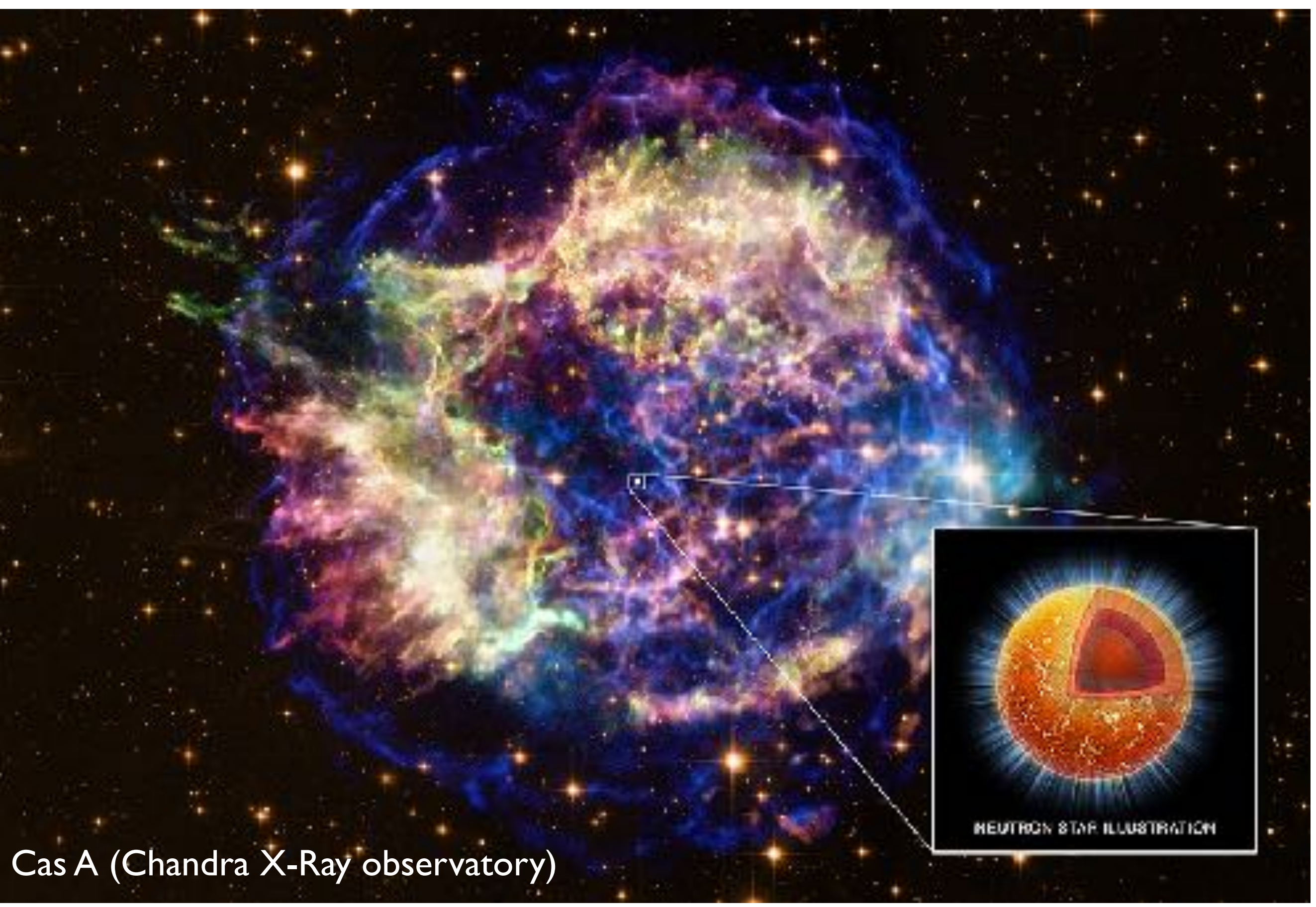
Solar system abundances



Where does the r-process occur?

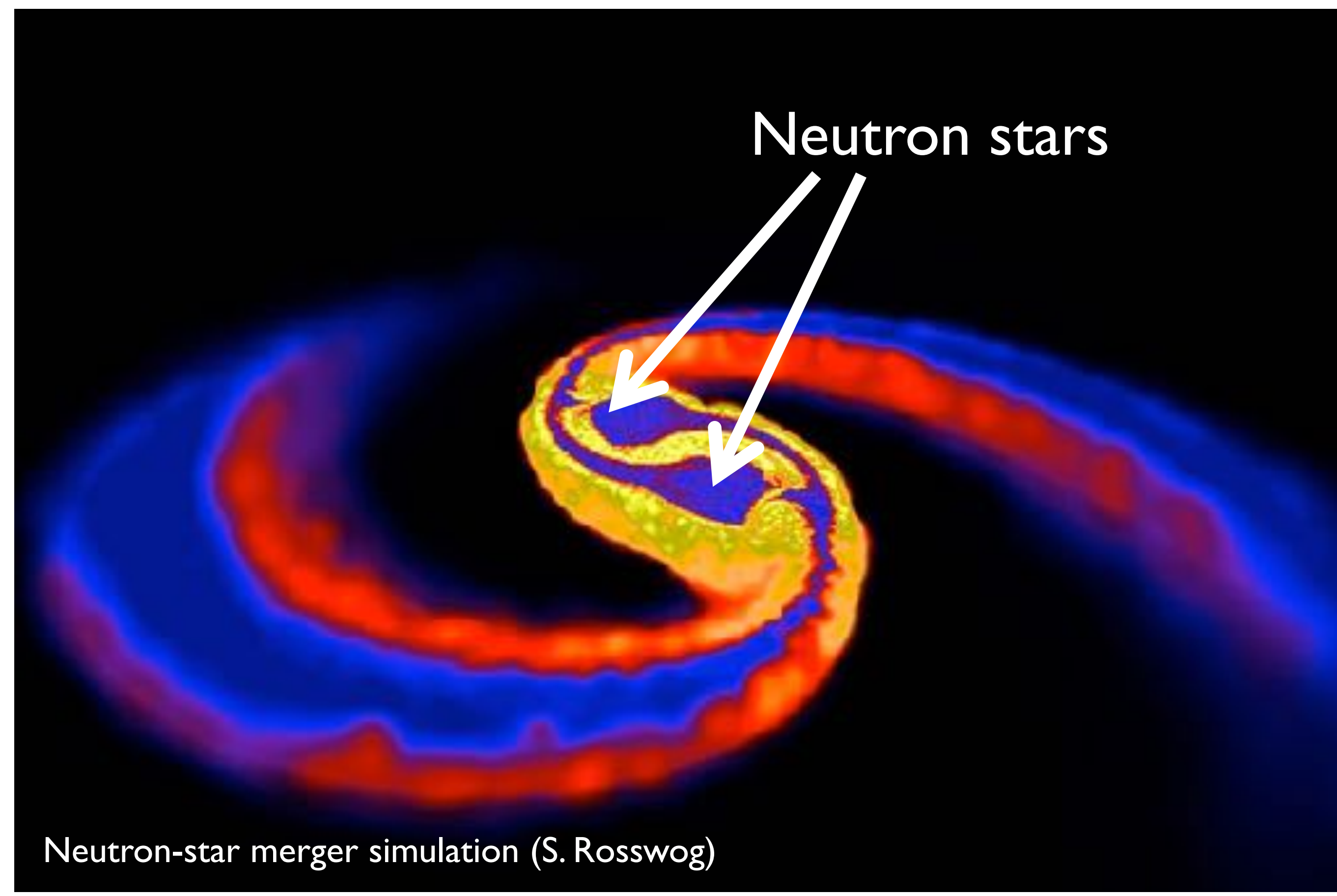
rapid process → explosions
high neutron densities → neutron stars

Core-collapse supernovae



Cas A (Chandra X-Ray observatory)

Neutron star mergers



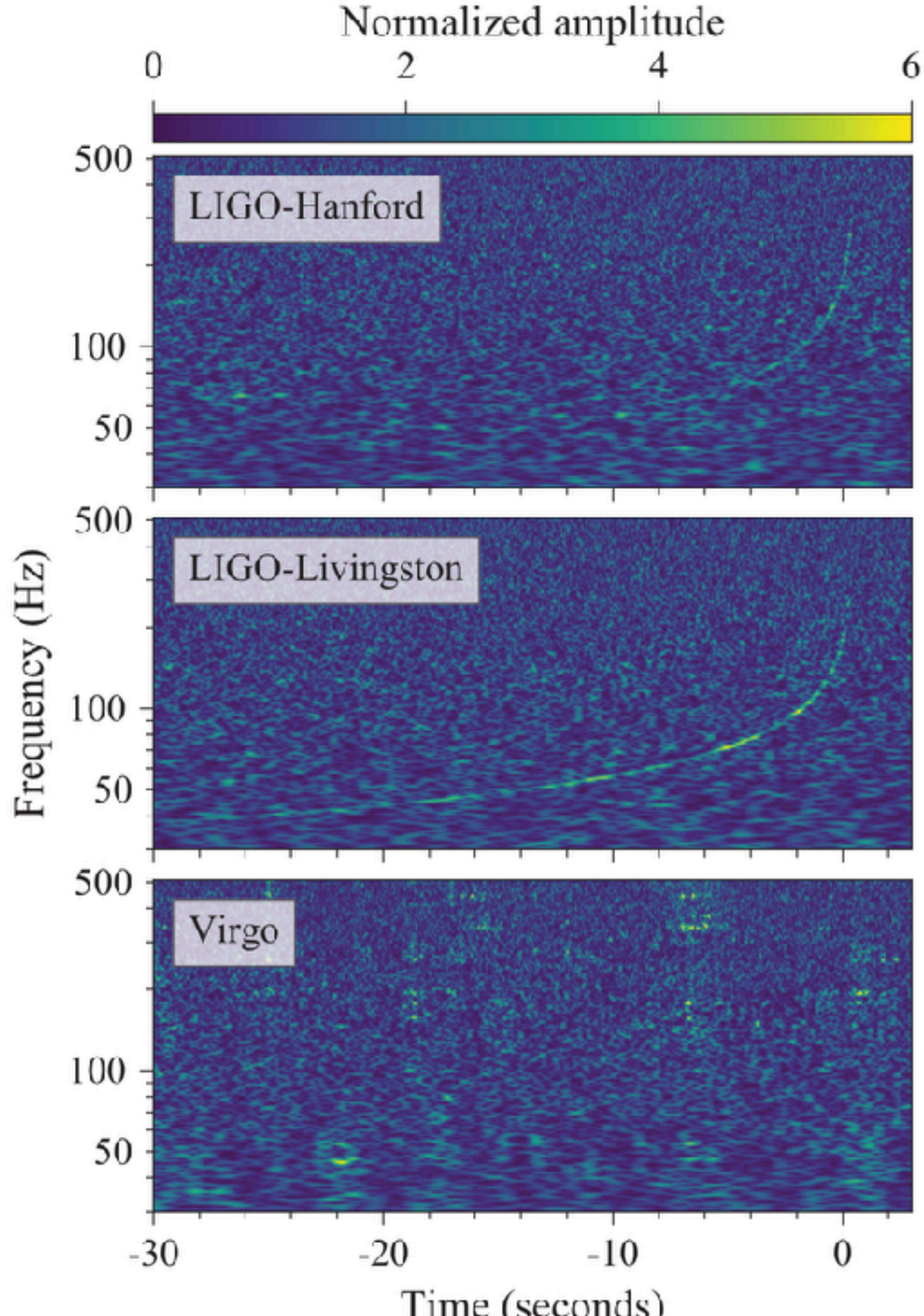
Neutron-star merger simulation (S. Rosswog)

GW170817

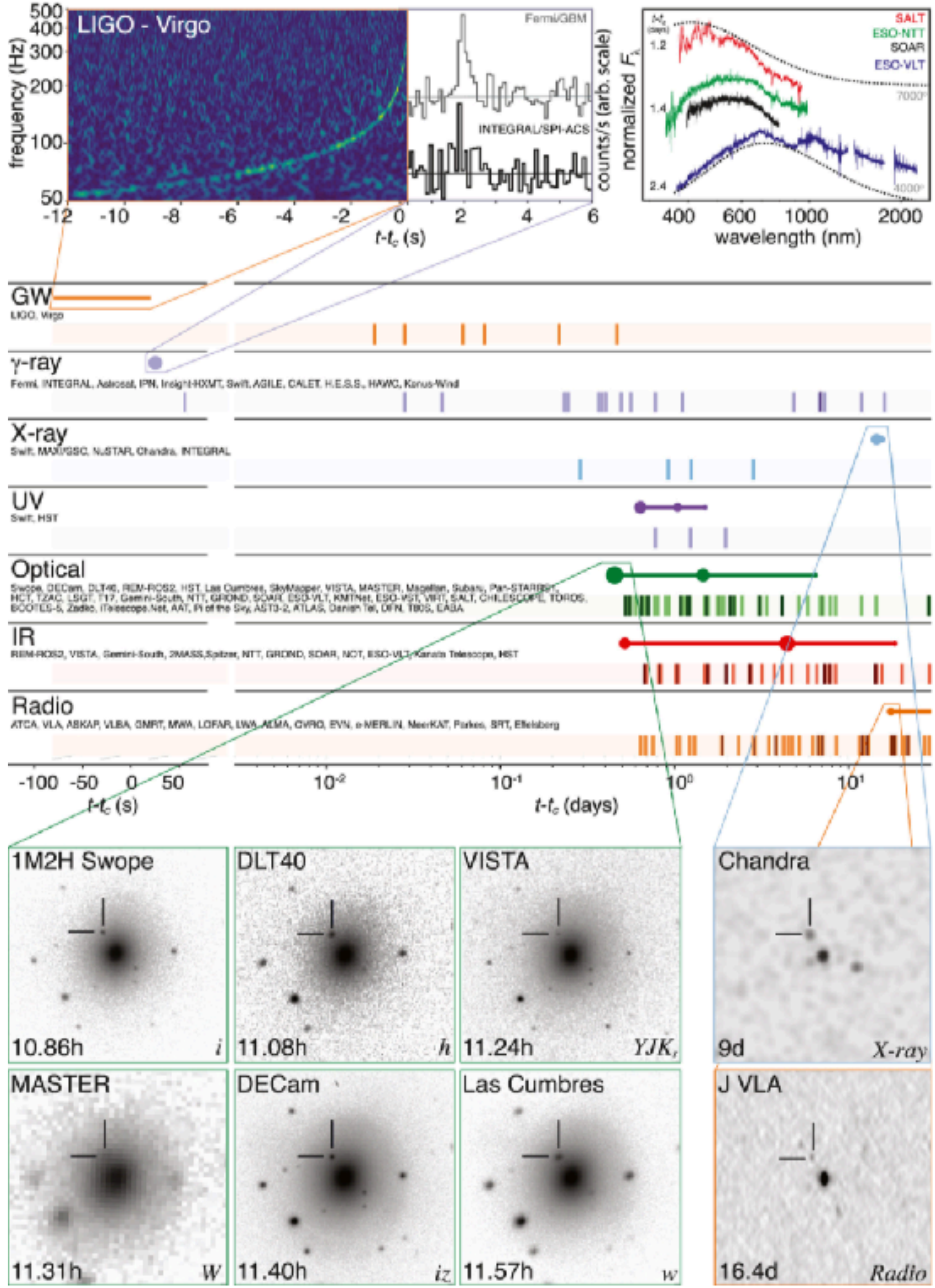

LIGO-LIVINGSTON OBSERVATORY


LIGO-HANFORD OBSERVATORY

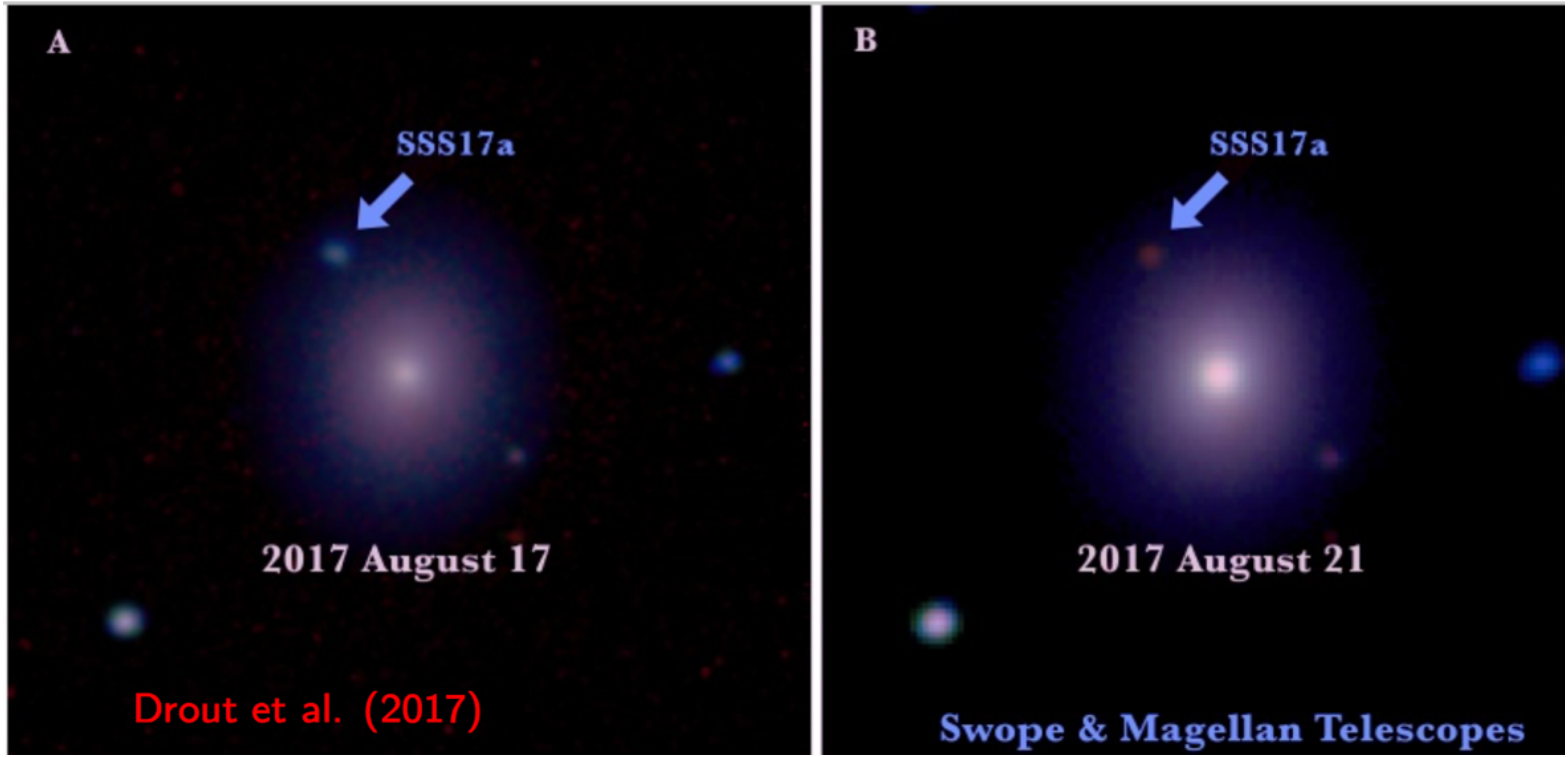

VIRGO AT CASCINA, ITALY


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

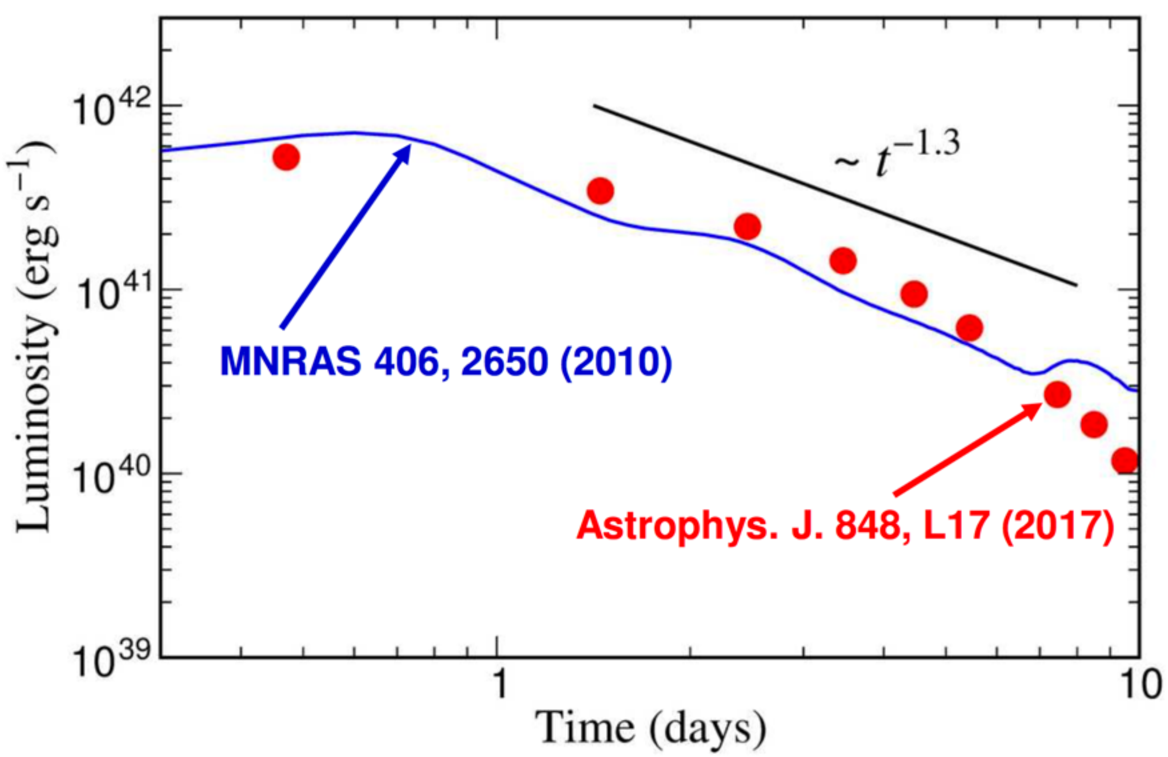
Multimessenger

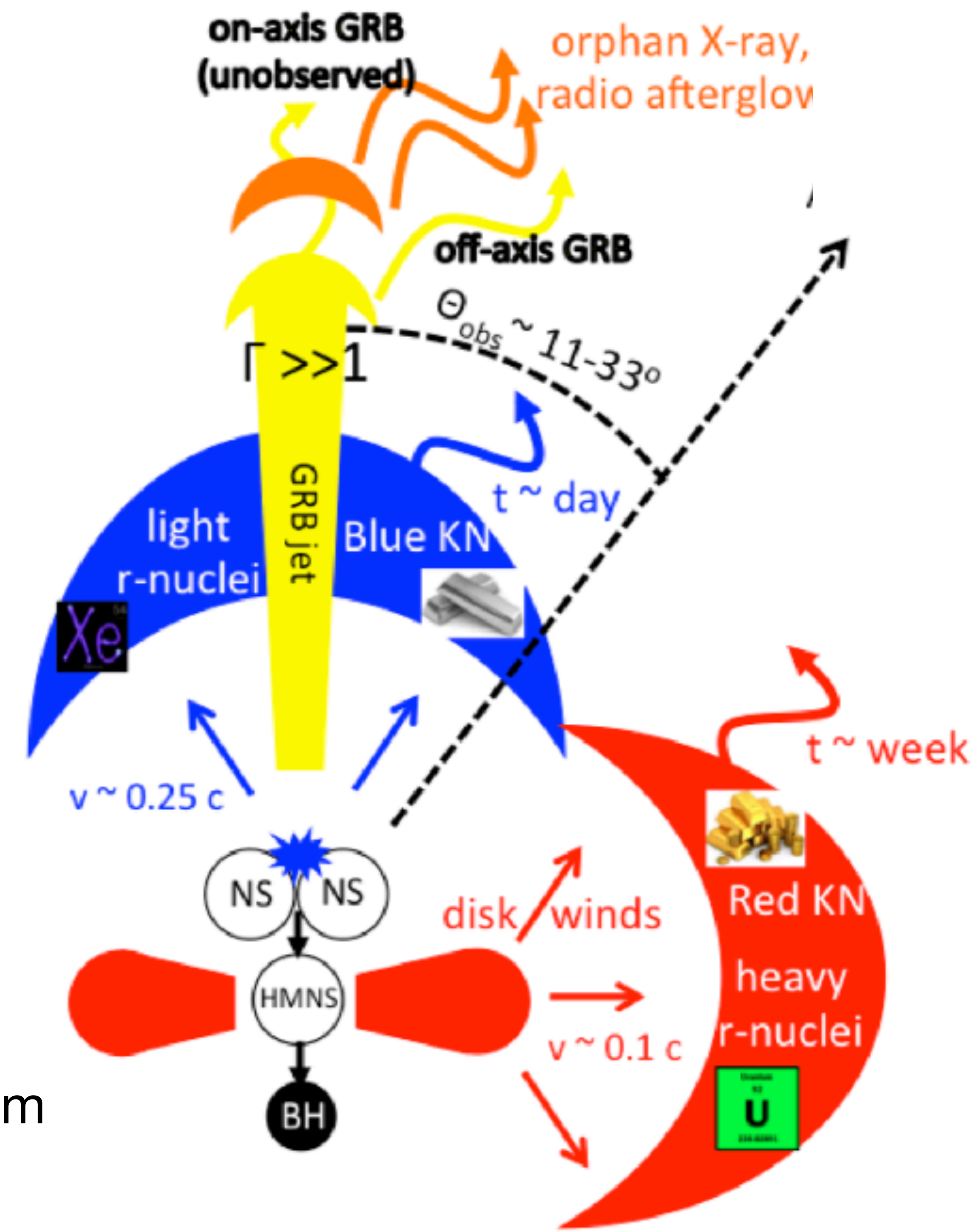


Kilonova


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

Kilonova

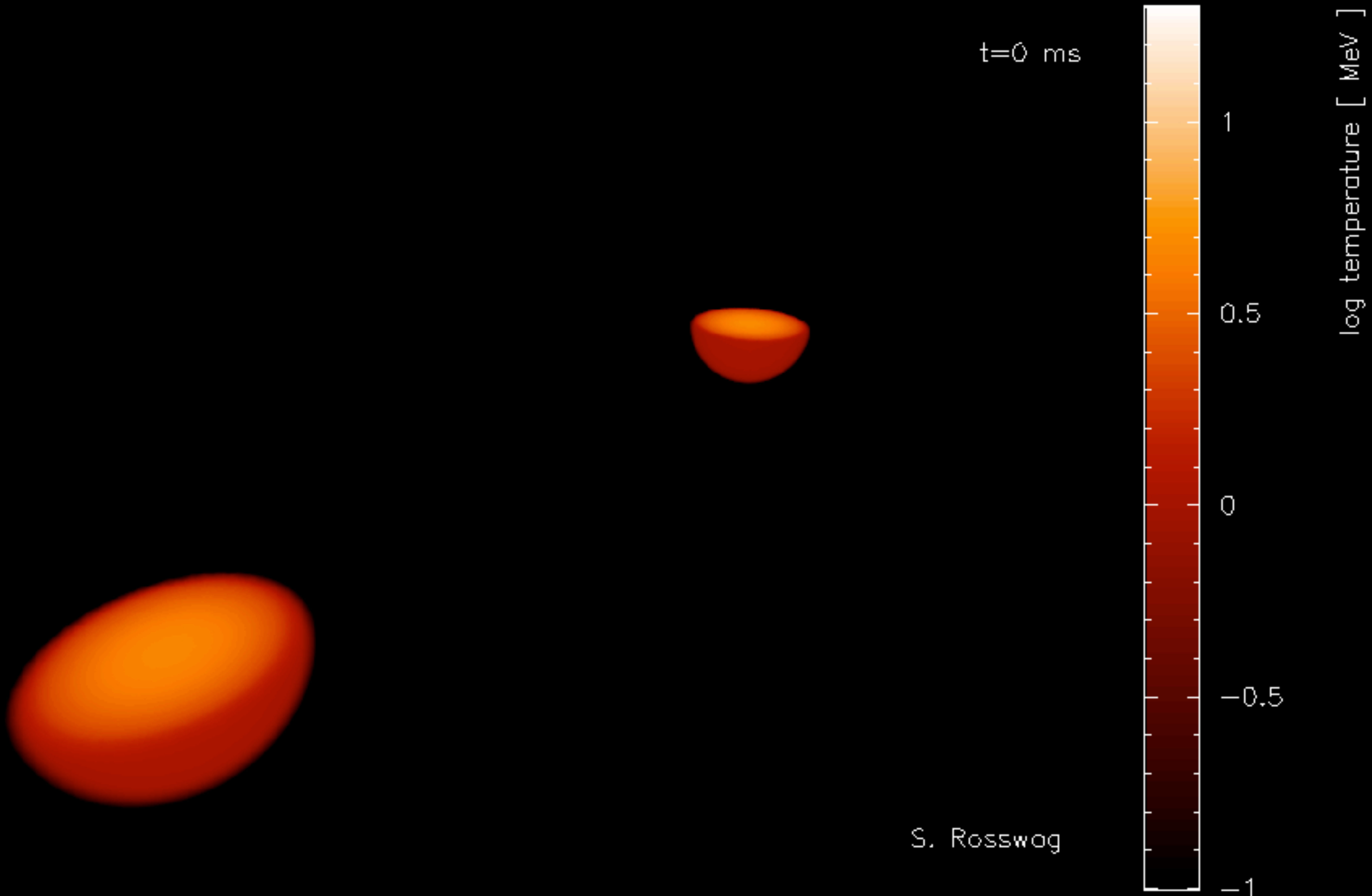


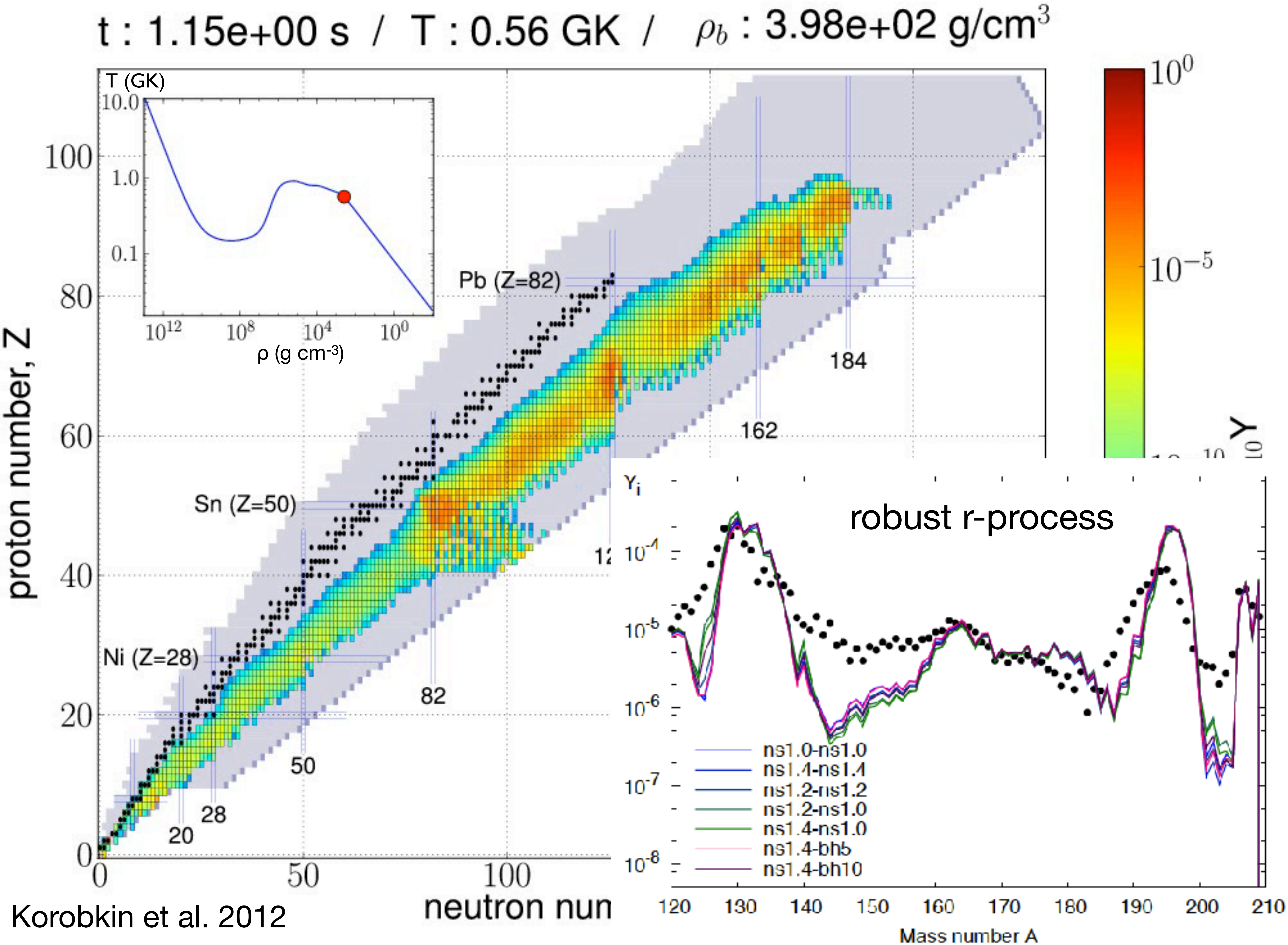


R-process in neutron star mergers confirmed by kilonova
(radioactive decay of n-rich nuclei)
after gravitational wave detection from GW170817

Li & Paczynski (1998)

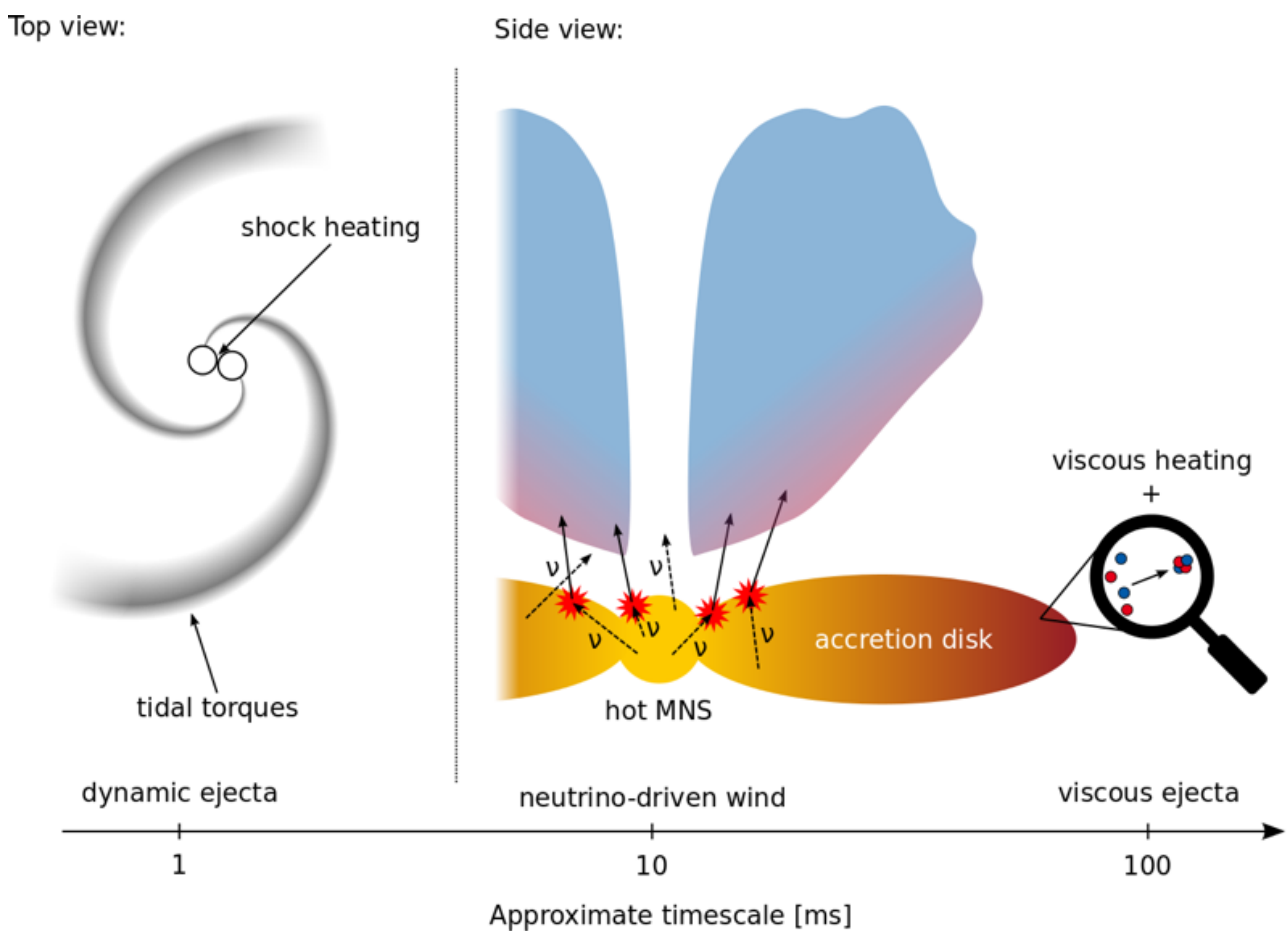
Neutron star mergers





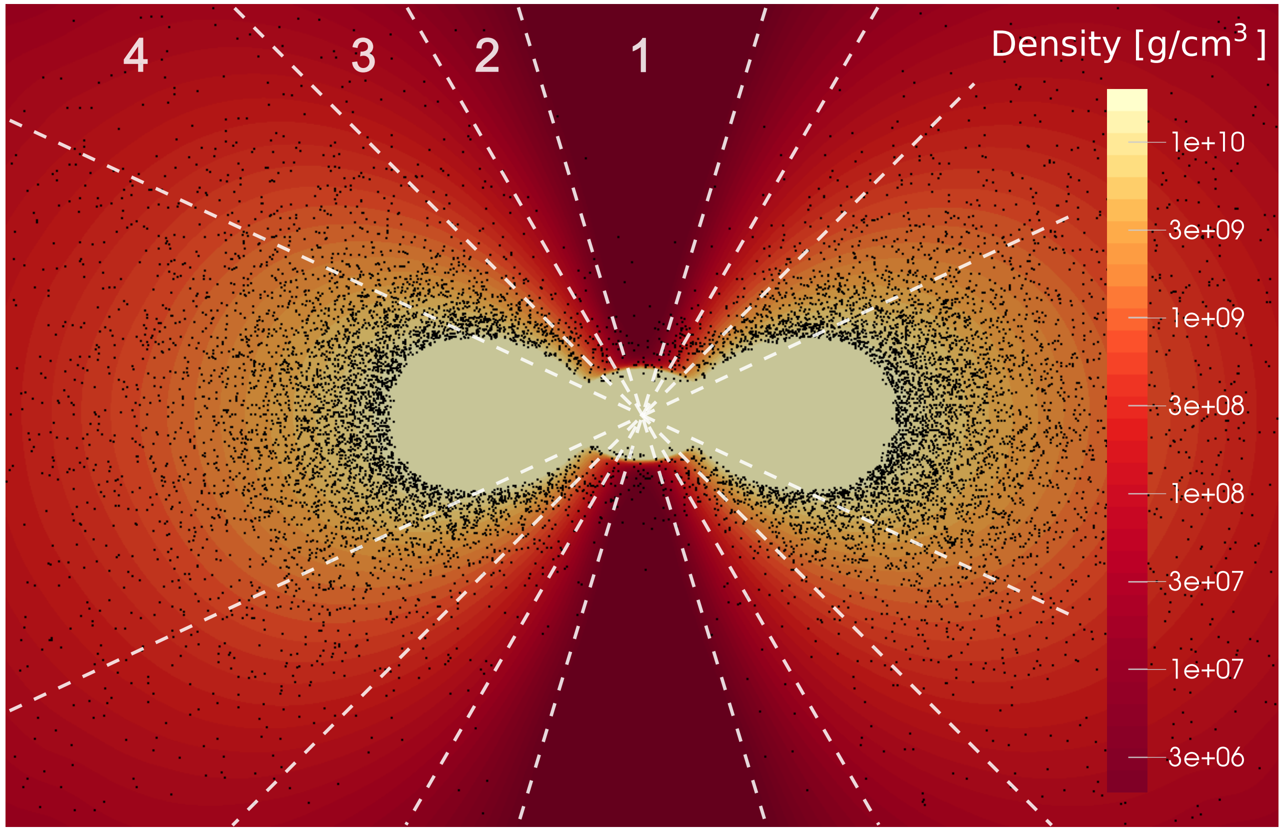
Korobkin et al. 2012

Ejecta and nucleosynthesis



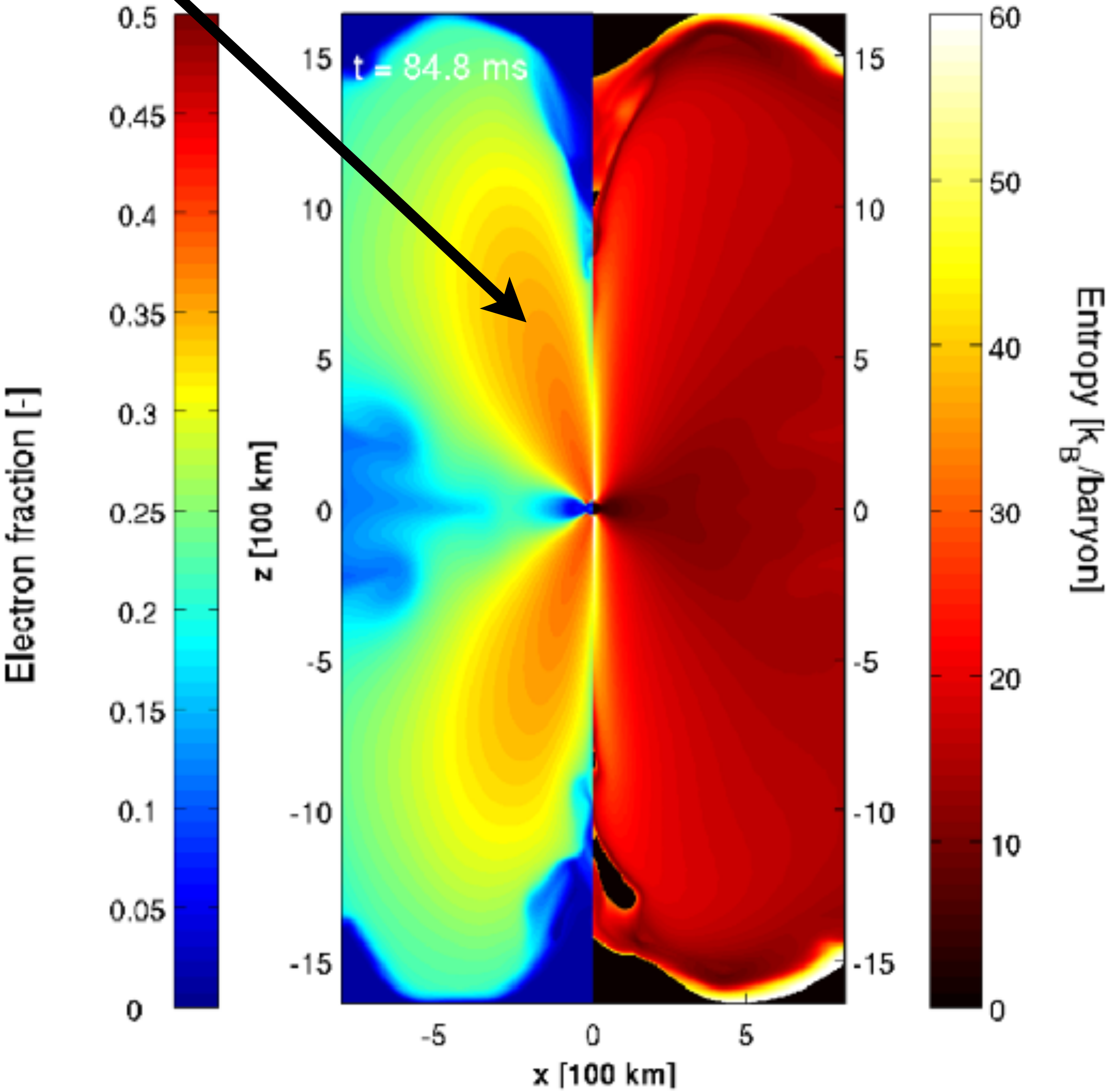
Neutron star mergers: neutrino-driven wind

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



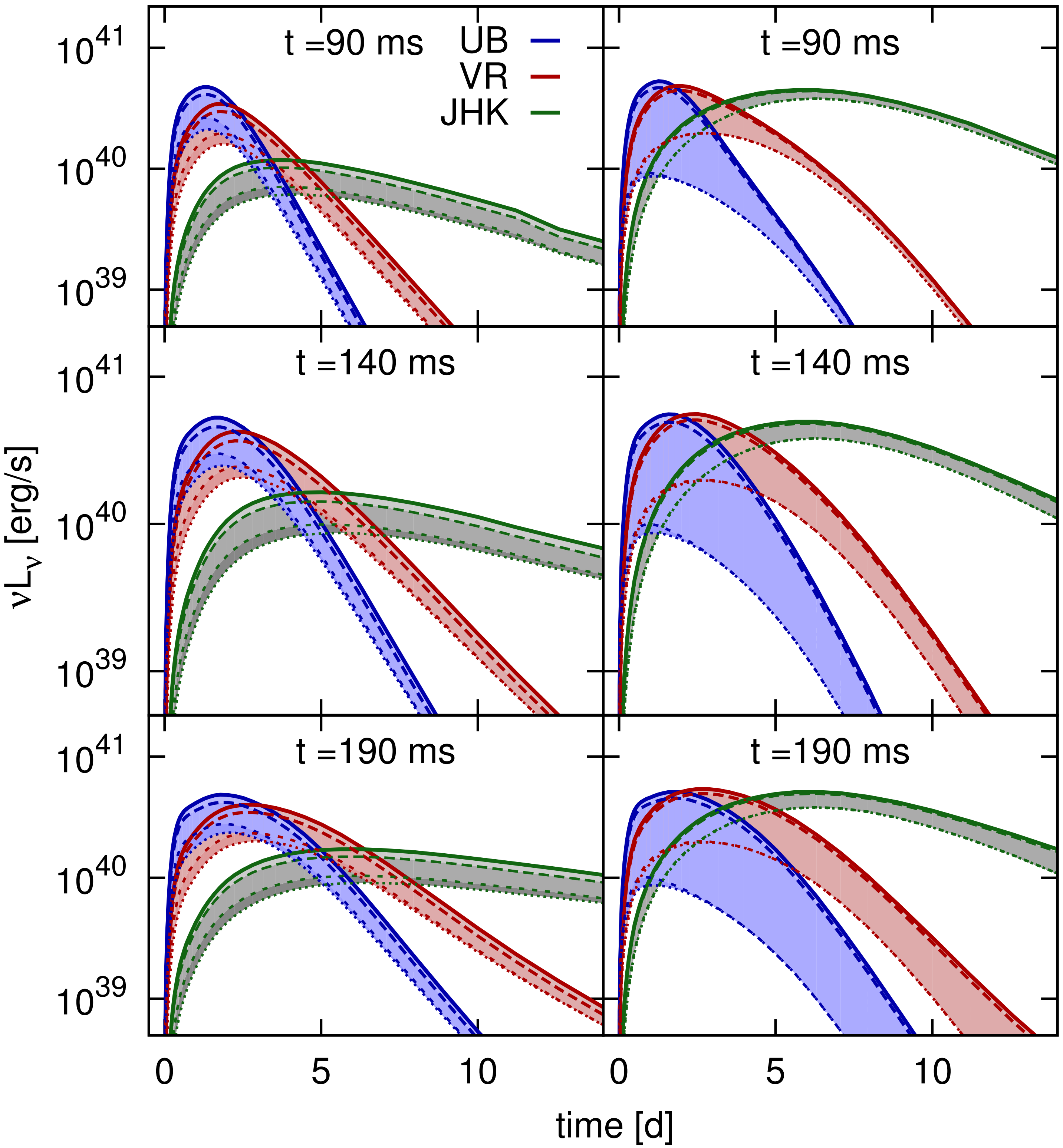
Martin et al. (2015)

Perego et al. (2014)

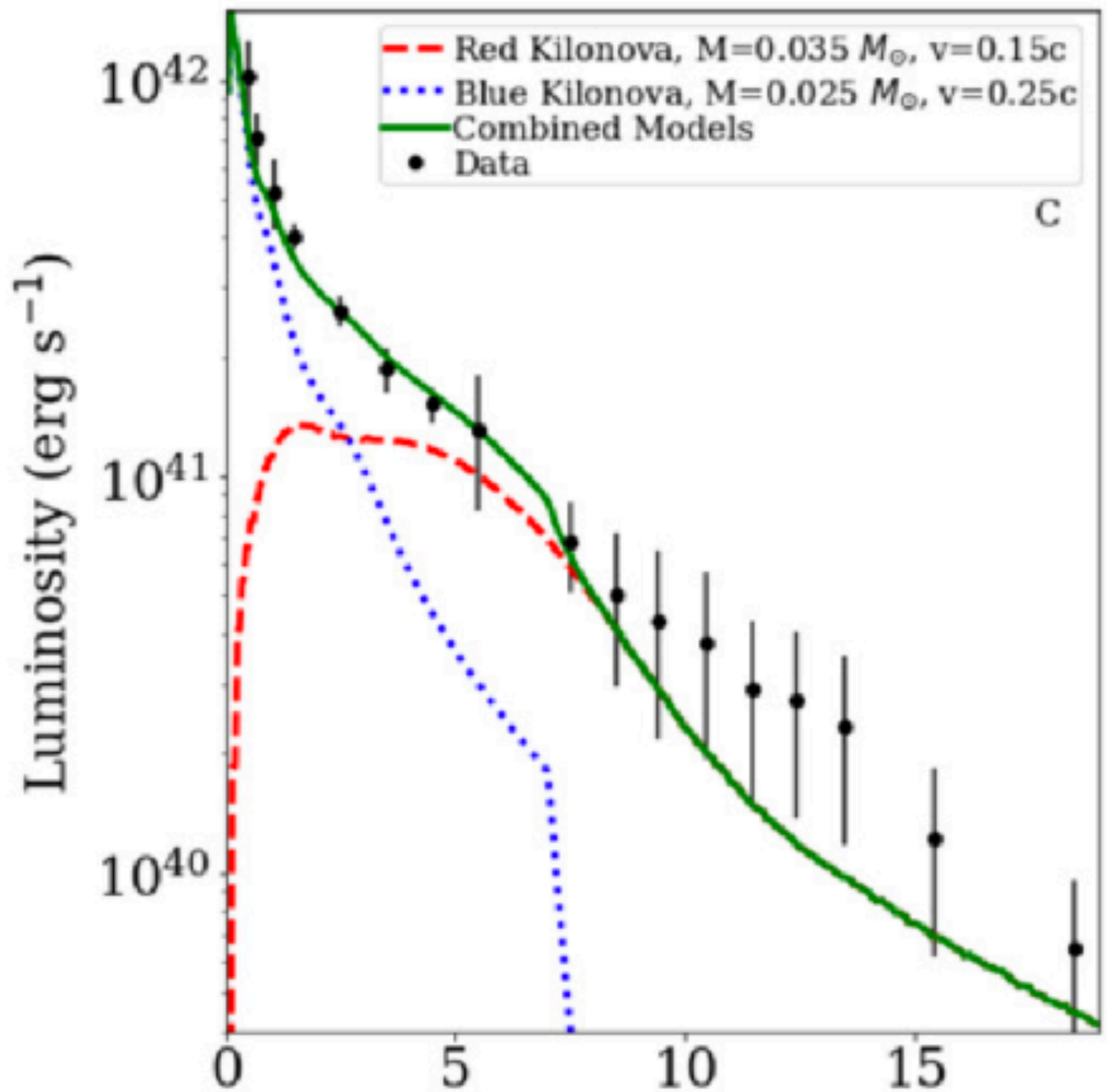


see also
Fernandez & Metzger 2013, Metzger & Fernandez 2014,
Just et al. 2014, Sekiguchi et al.

Kilonova



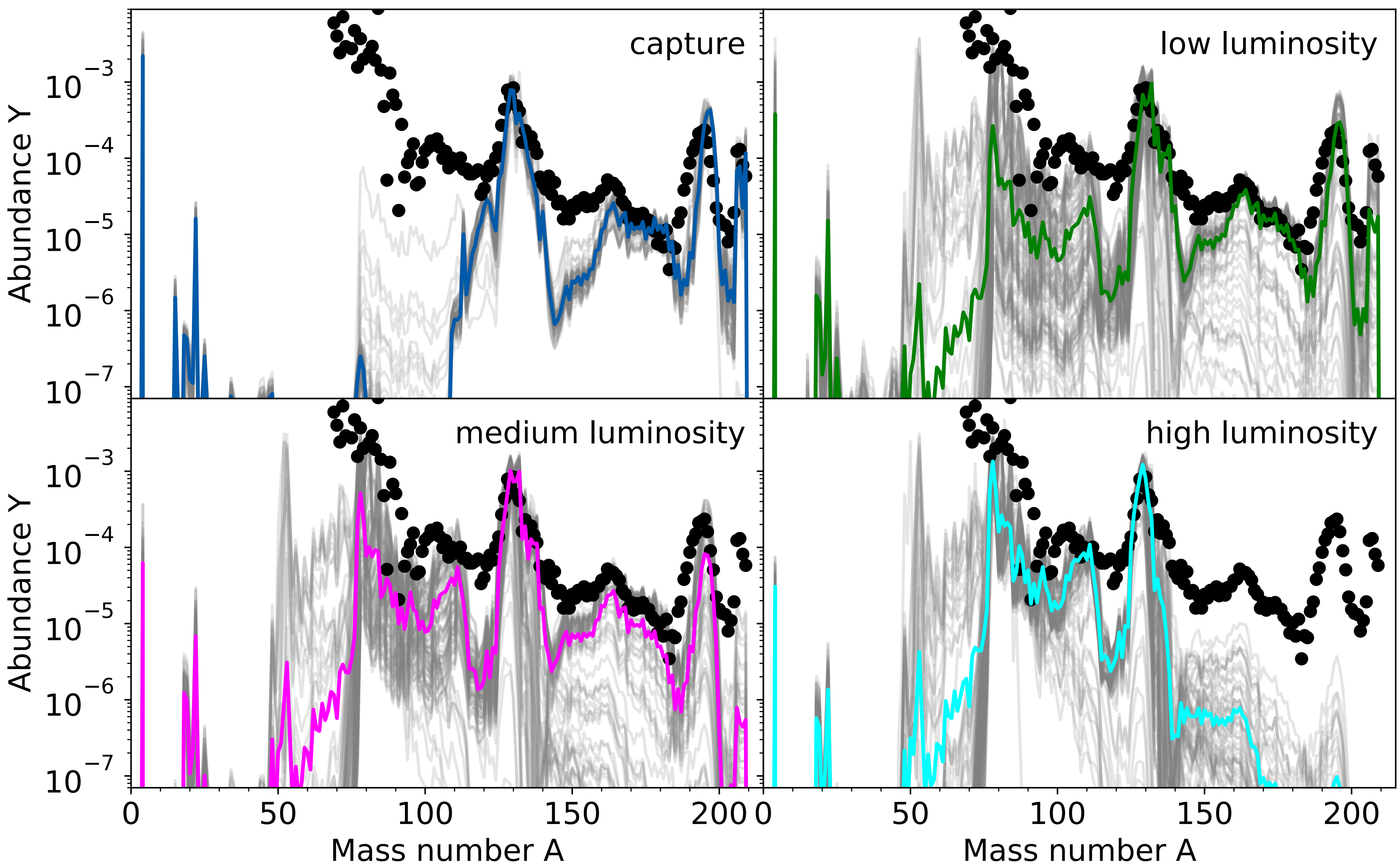
Martin et al. (2015)

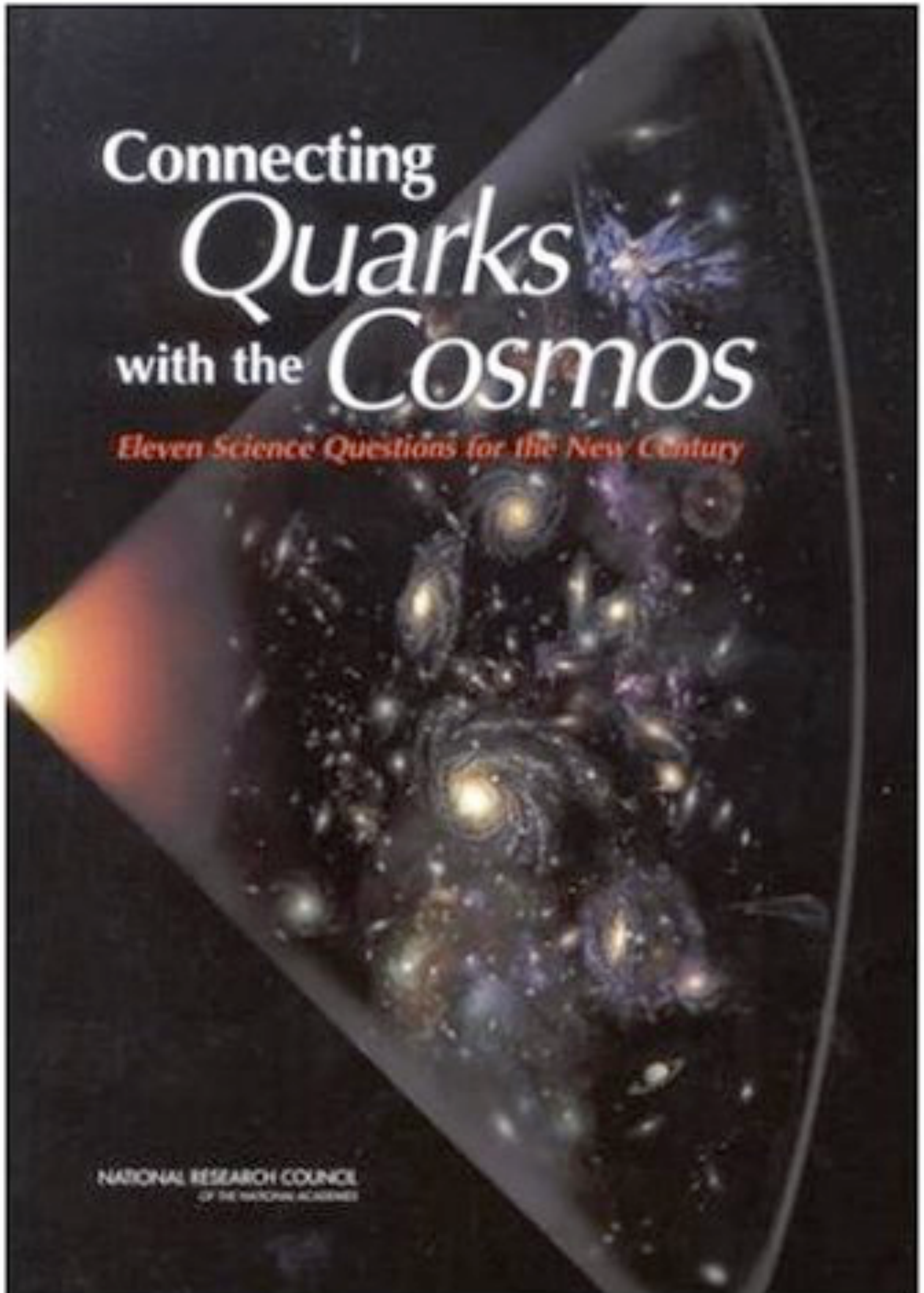


GW170817

Equation of state and neutrinos

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





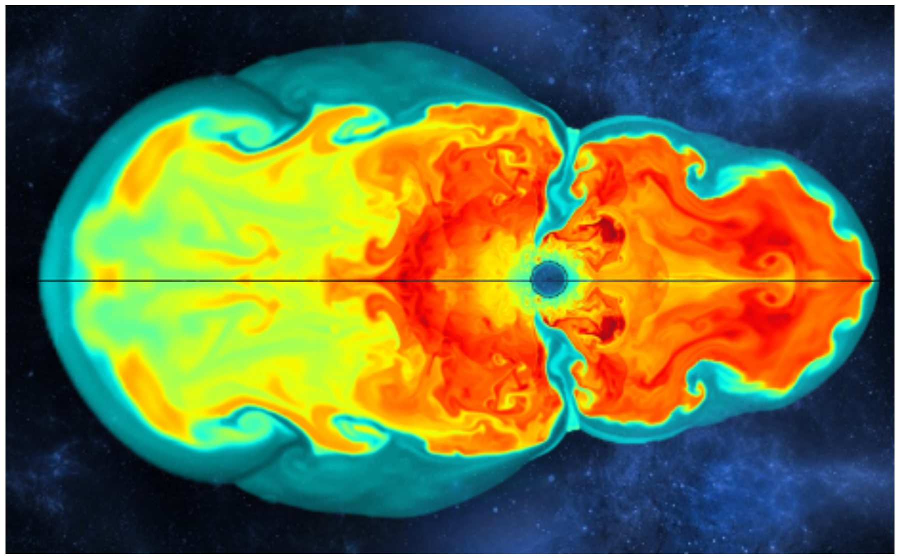
How were the elements
from iron to uranium made?

R-process in neutron star mergers

Are we done? No

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

Core-collapse supernovae

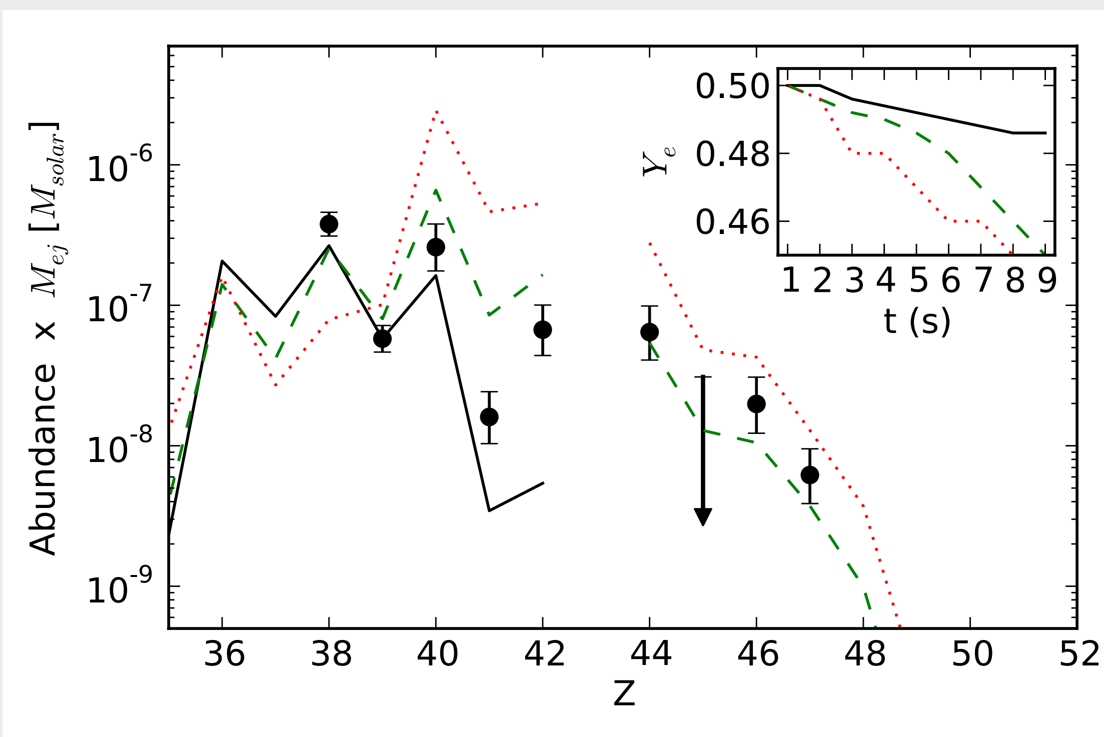


Standard **neutrino-driven supernova**:
Weak r-process and νp-process
Elements up to ~Ag

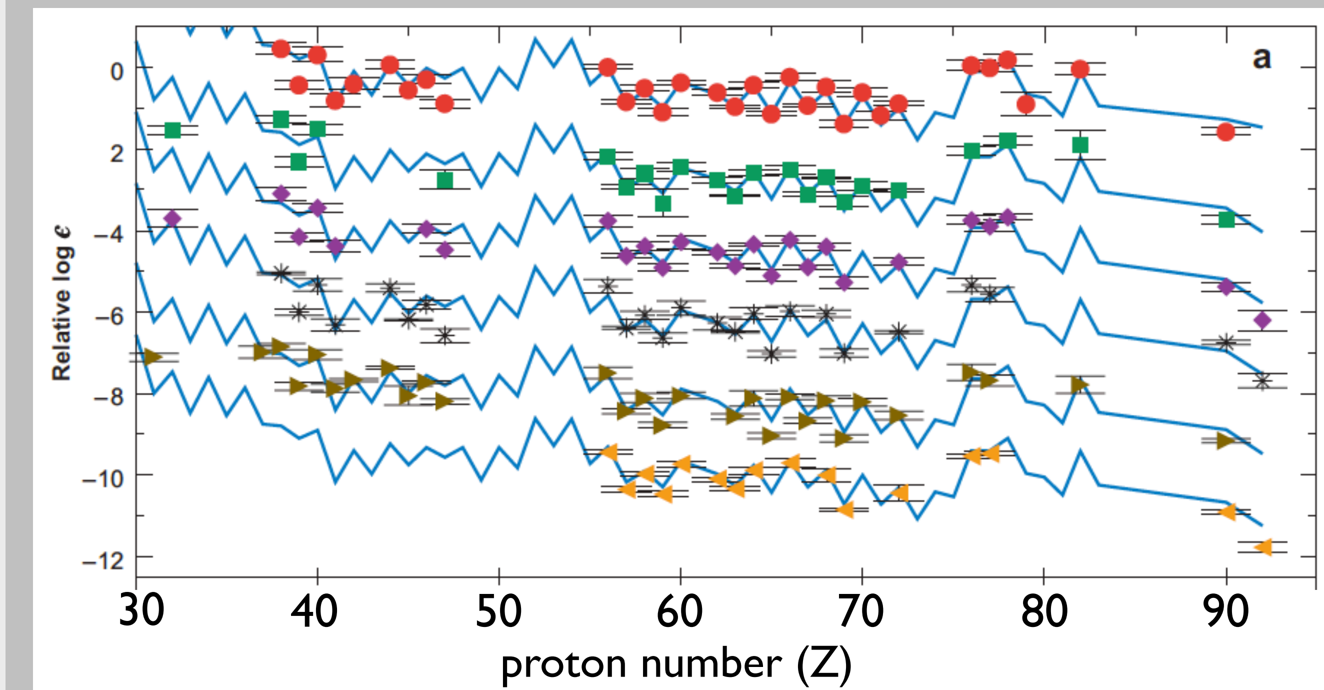
Origin of elements from Sr to Ag

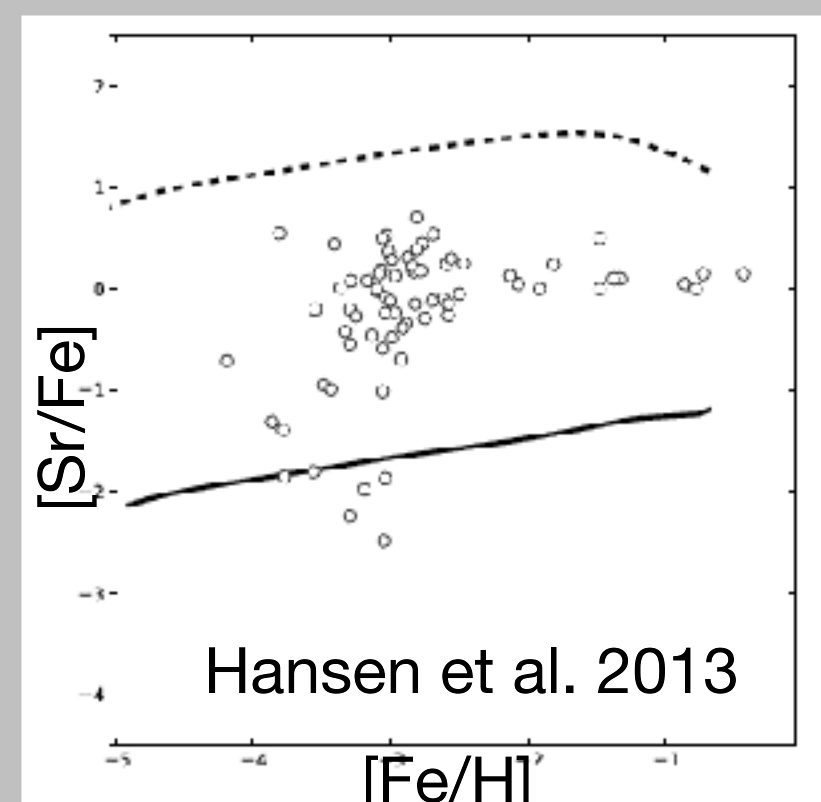
Astrophysical site

Observations



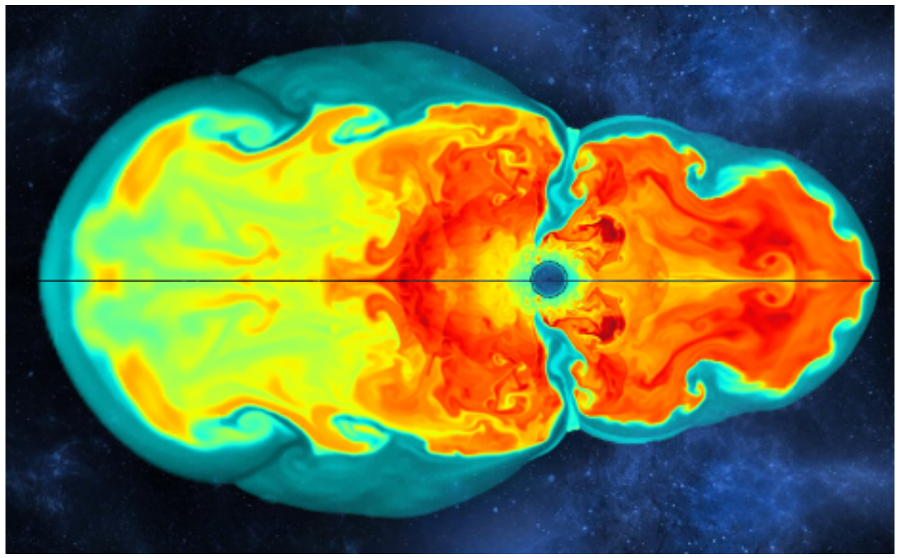
Nucleosynthesis:
identify key reactions





Chemical evolution

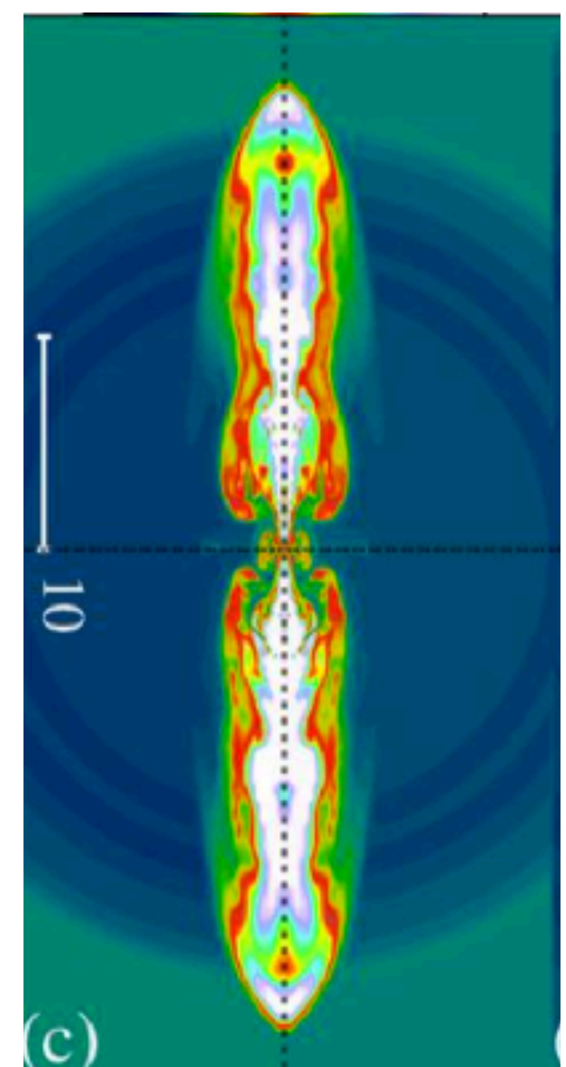
Core-collapse supernovae



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

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

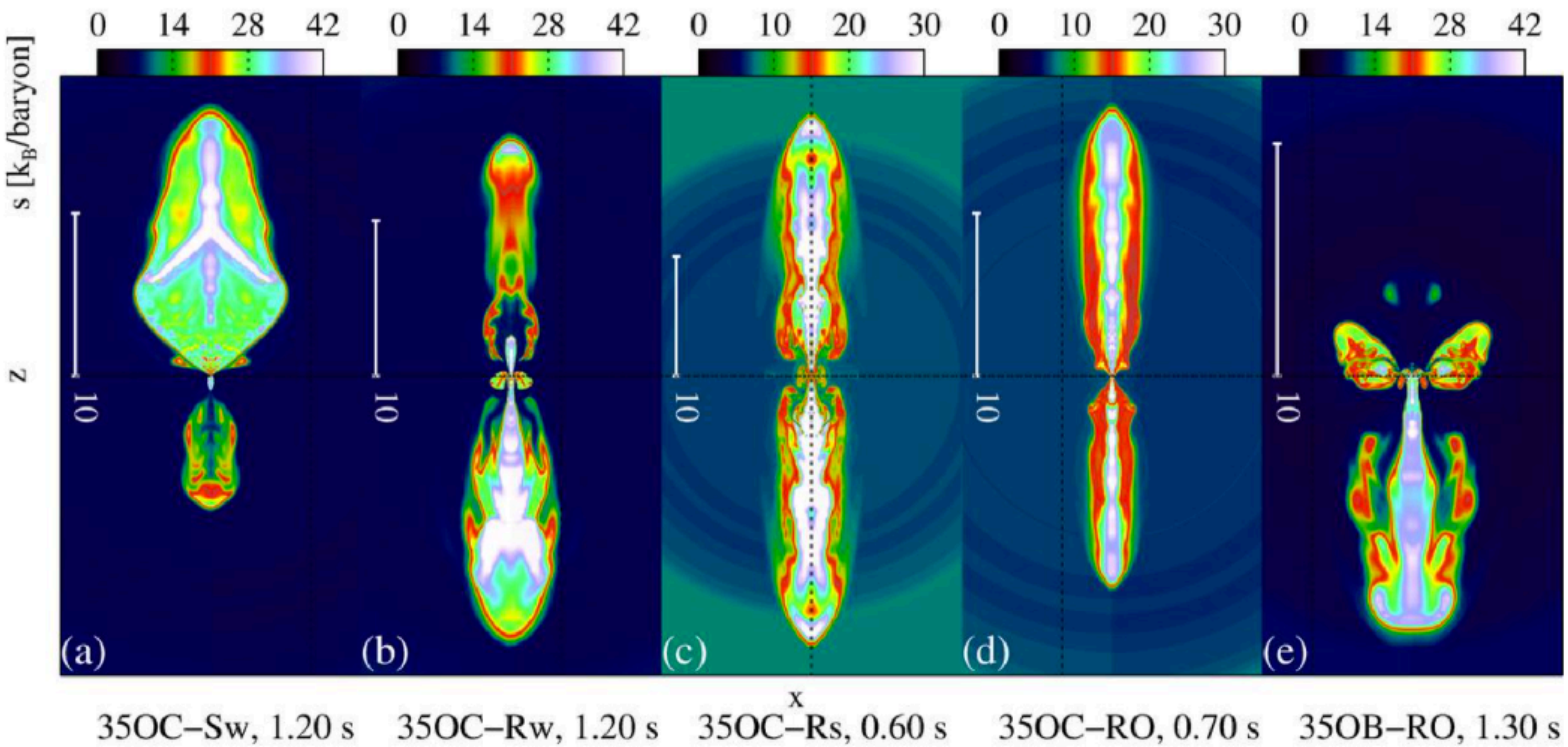
2D and 3D + parametric neutrino treatment :
- jet-like explosion: heavy r-process
- magnetic field vs. neutrinos: weak r-process



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

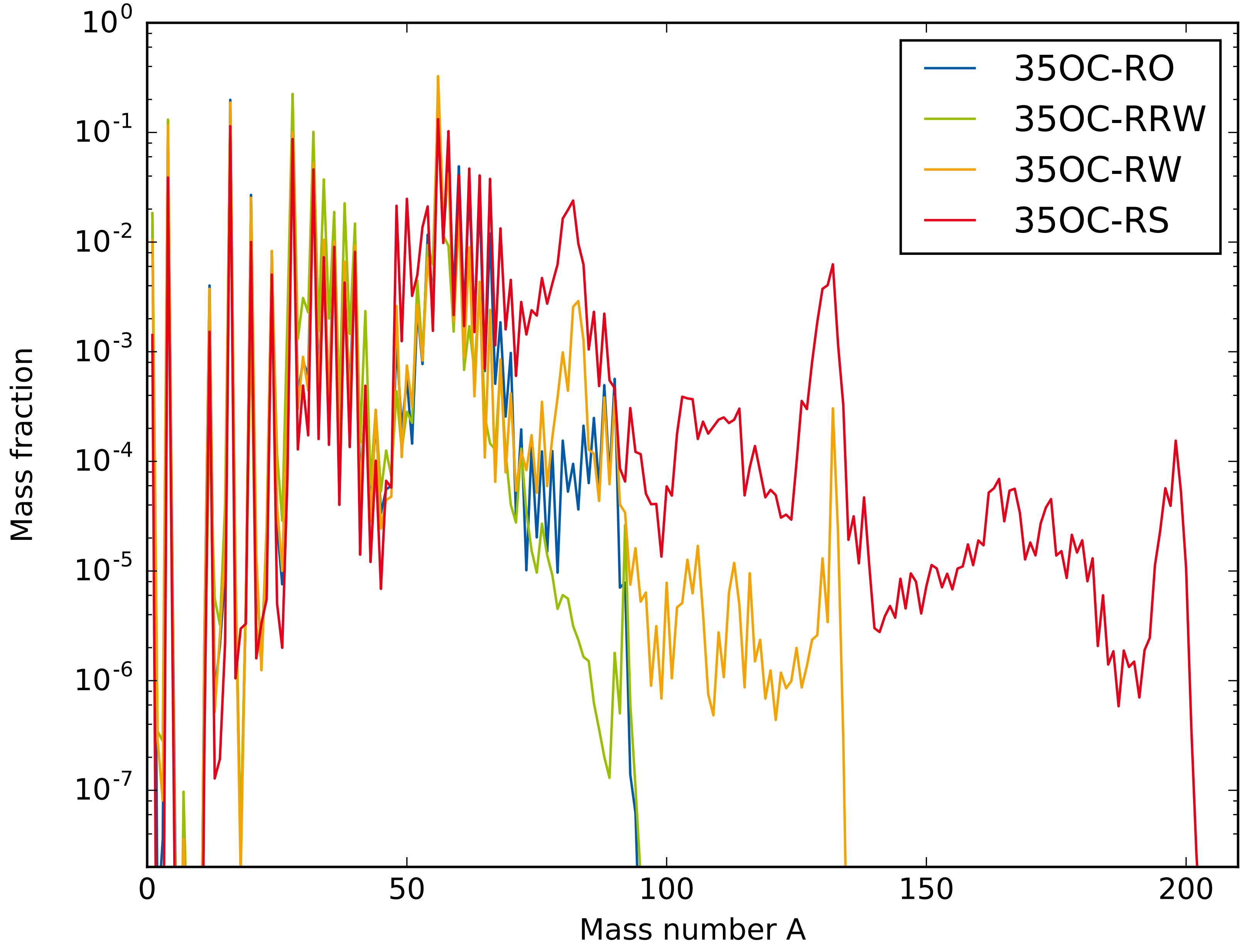
Magneto-rotational supernovae: r-process

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

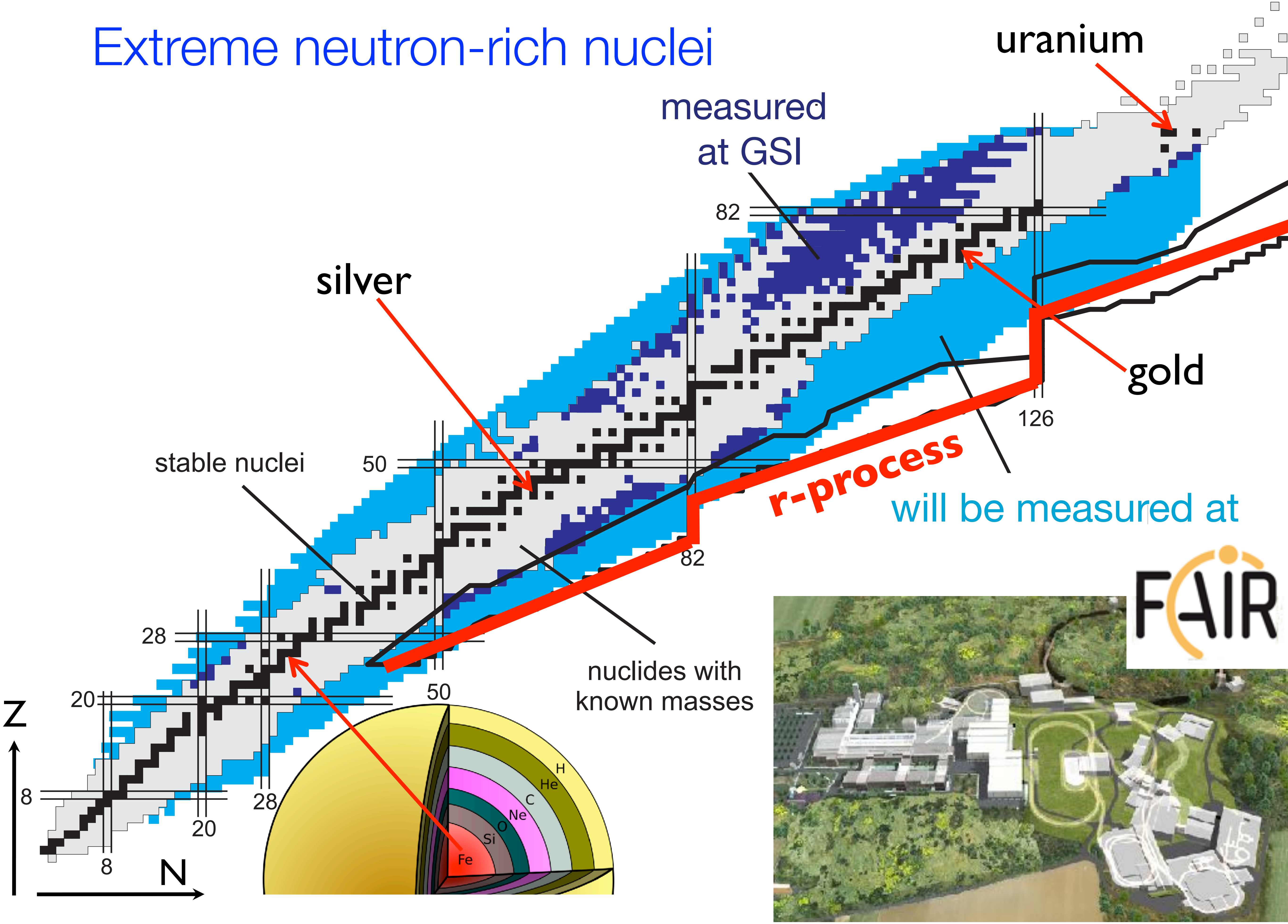
RRW: weak mag. field
strong rot.

RW: weak mag. field

RS: strong mag. field

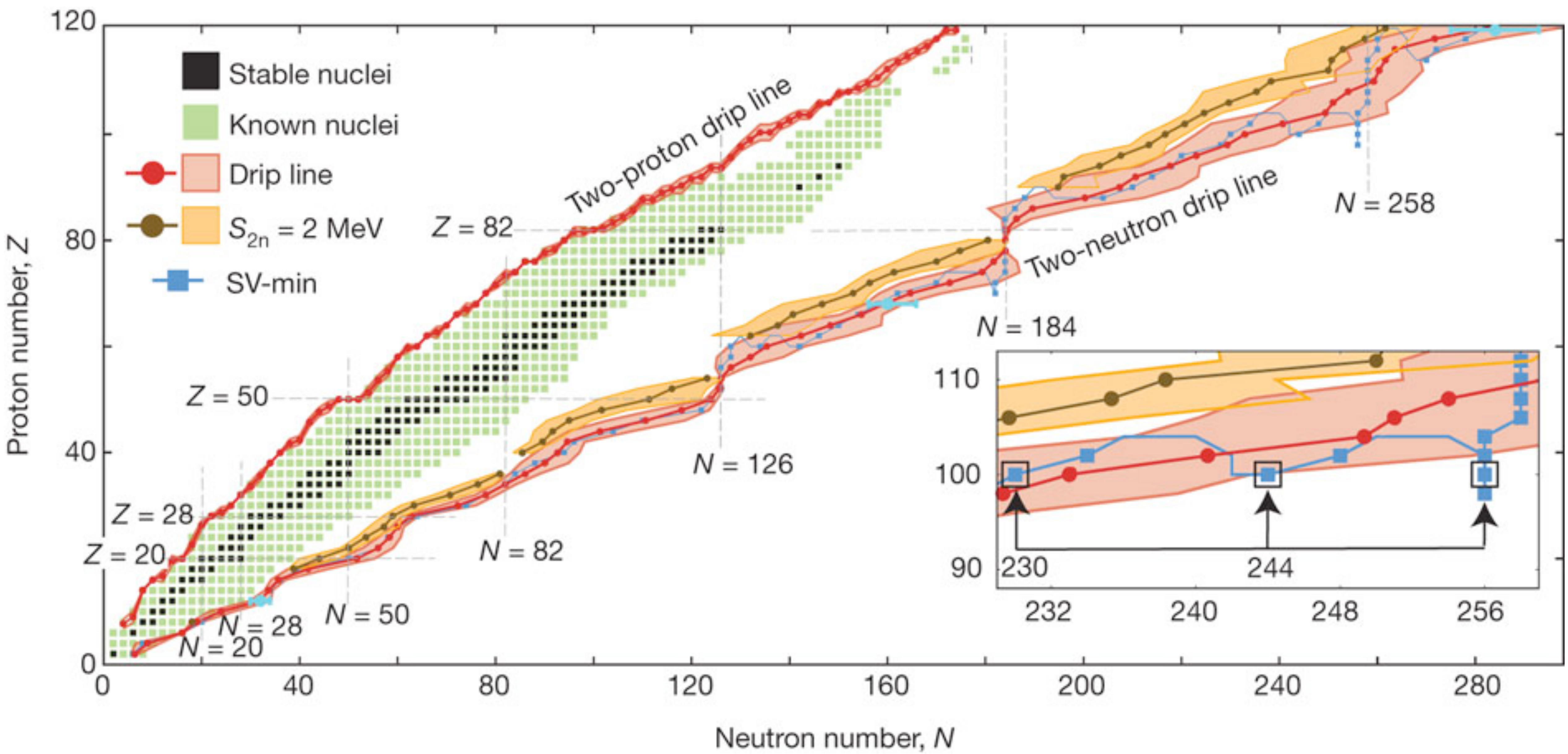
Reichert, Obergaulinger, Aloy, Arcones (in prep)

Extreme neutron-rich nuclei



Nuclear physics input

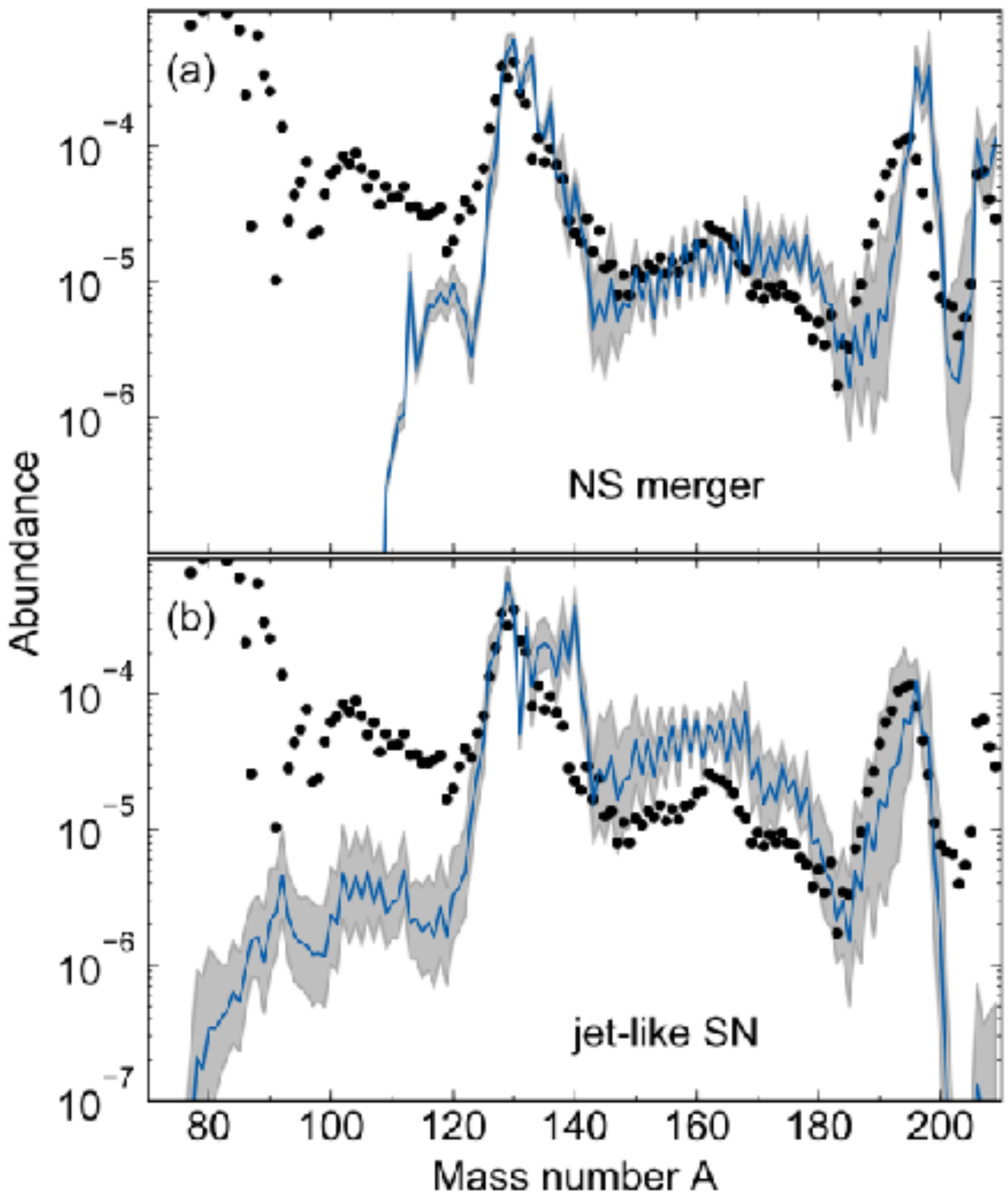
nuclear masses, beta decay, reaction rates (neutron capture), fission



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

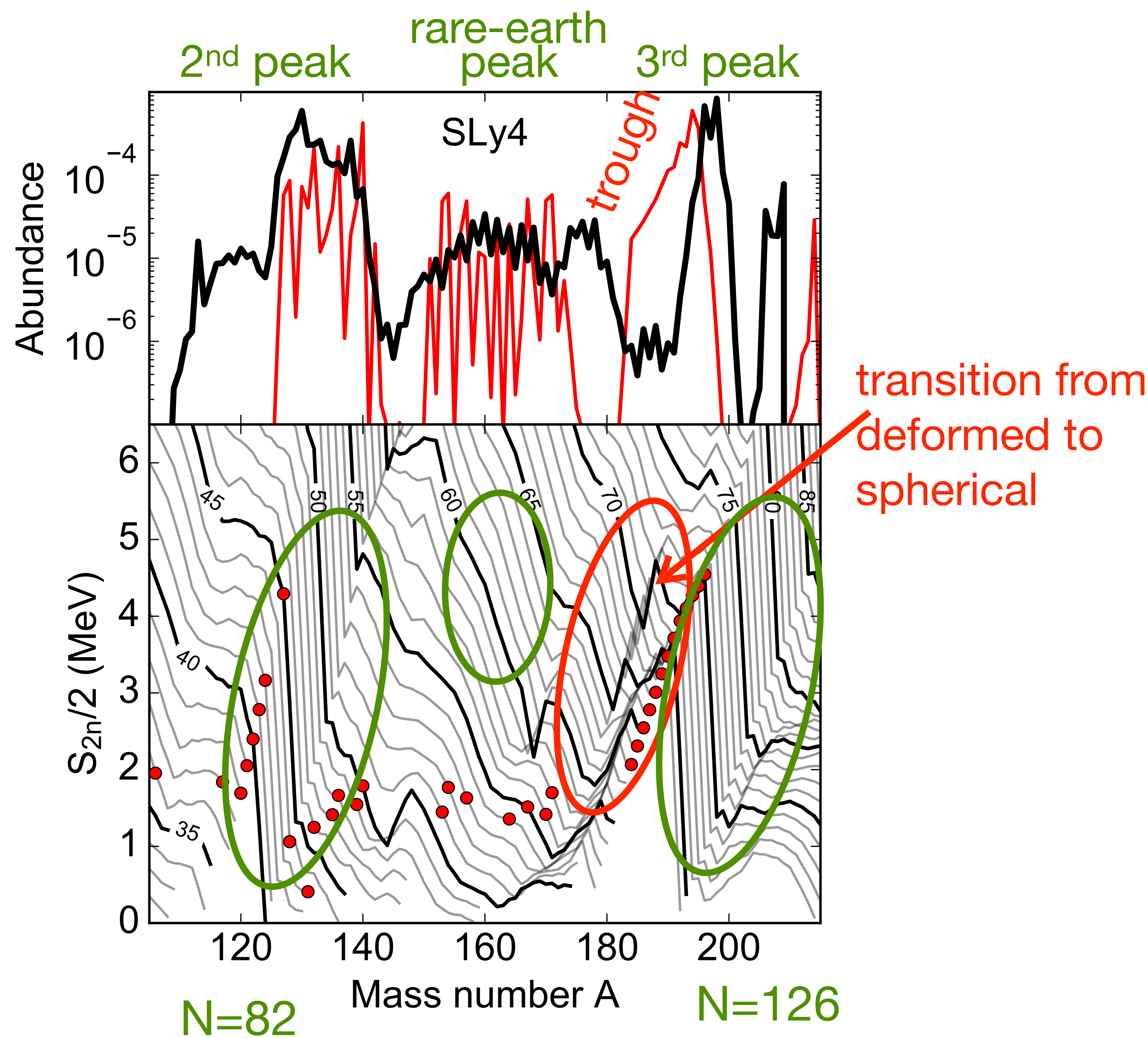
Can we link masses to r-process abundances?

Two neutron separation energy: abundances

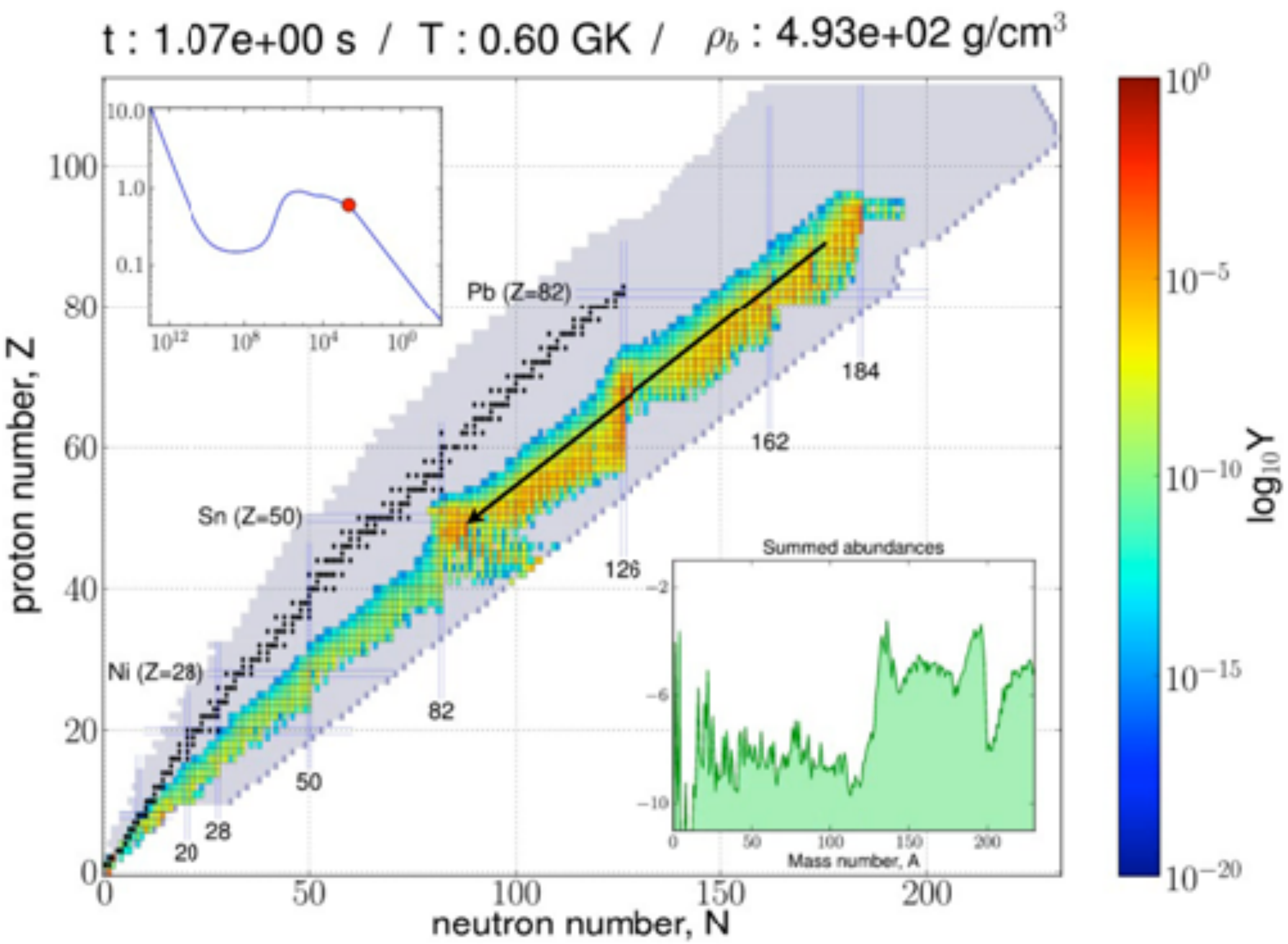
Abundances

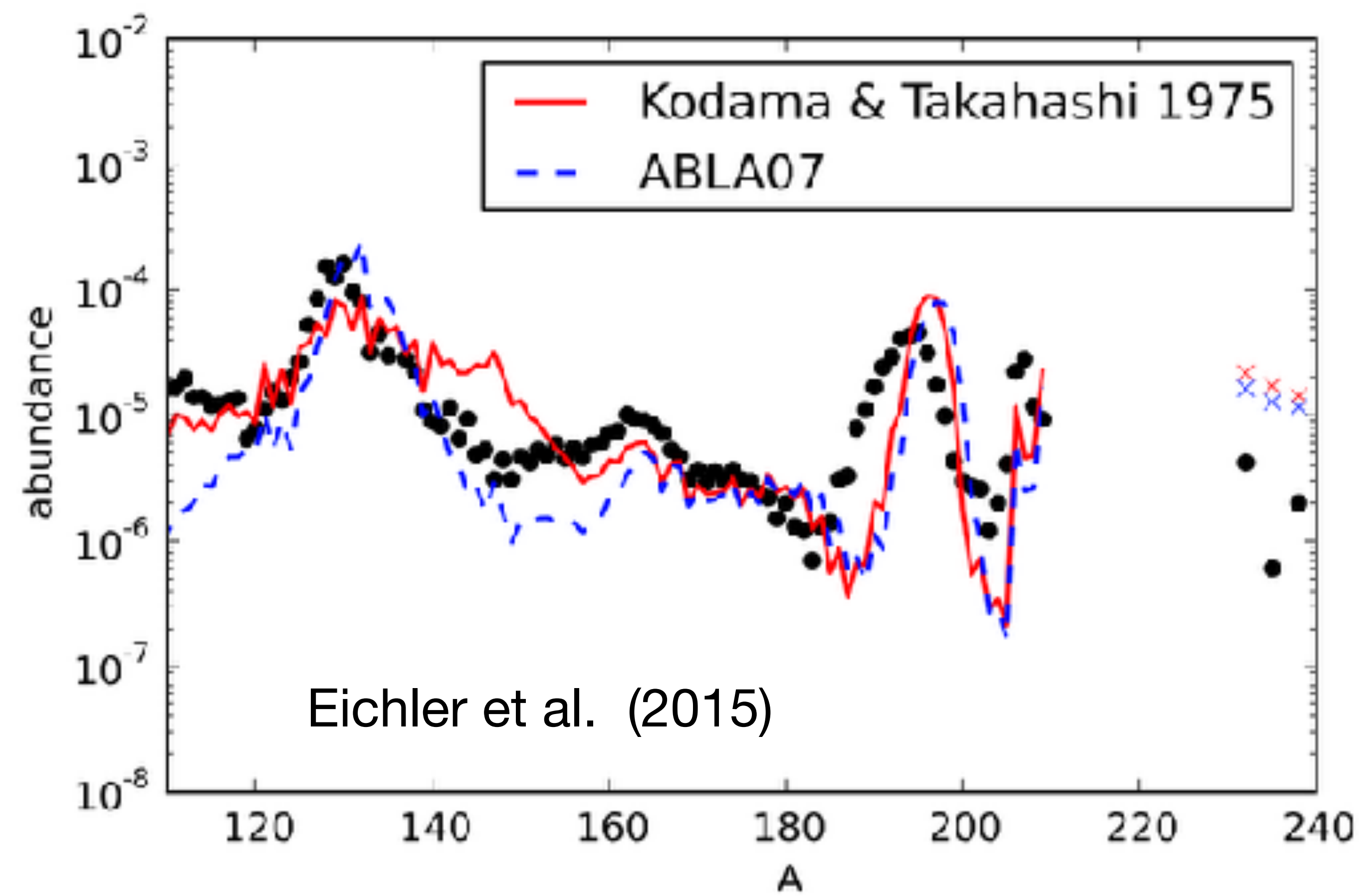
S_{2n}

Nuclear properties



Fission: barriers and yield distributions

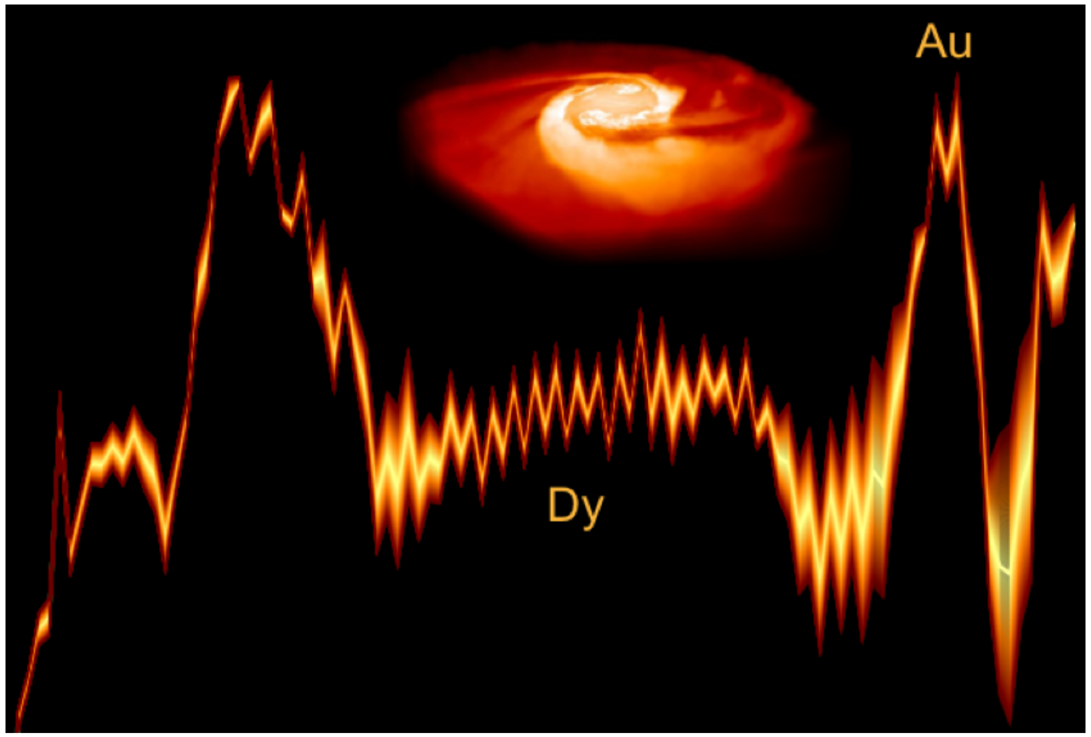




Neutron star mergers: r-process with two fission descriptions

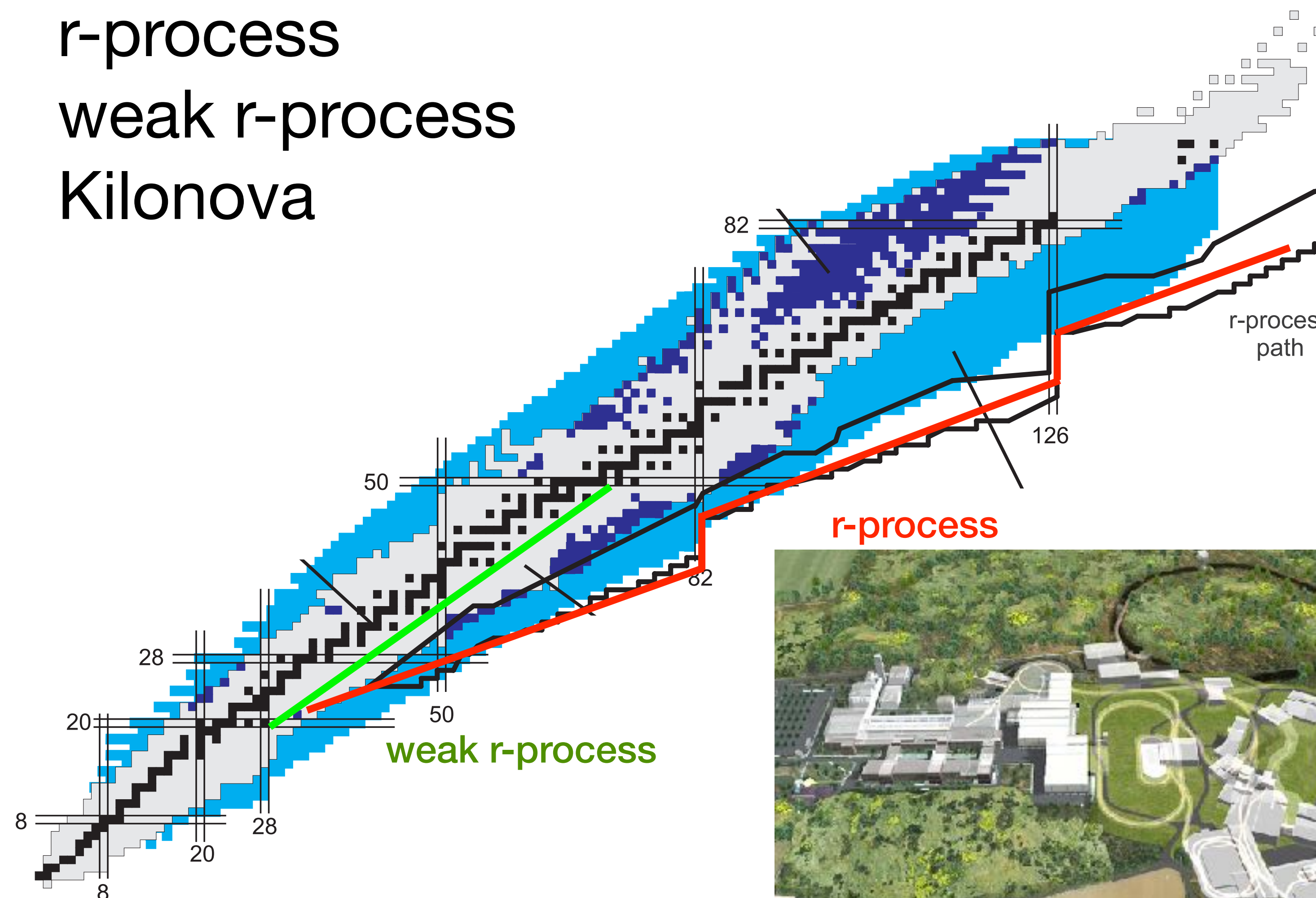
2nd peak (A~130): fission yield distribution
3rd peak (A~195): mass model, neutron captures

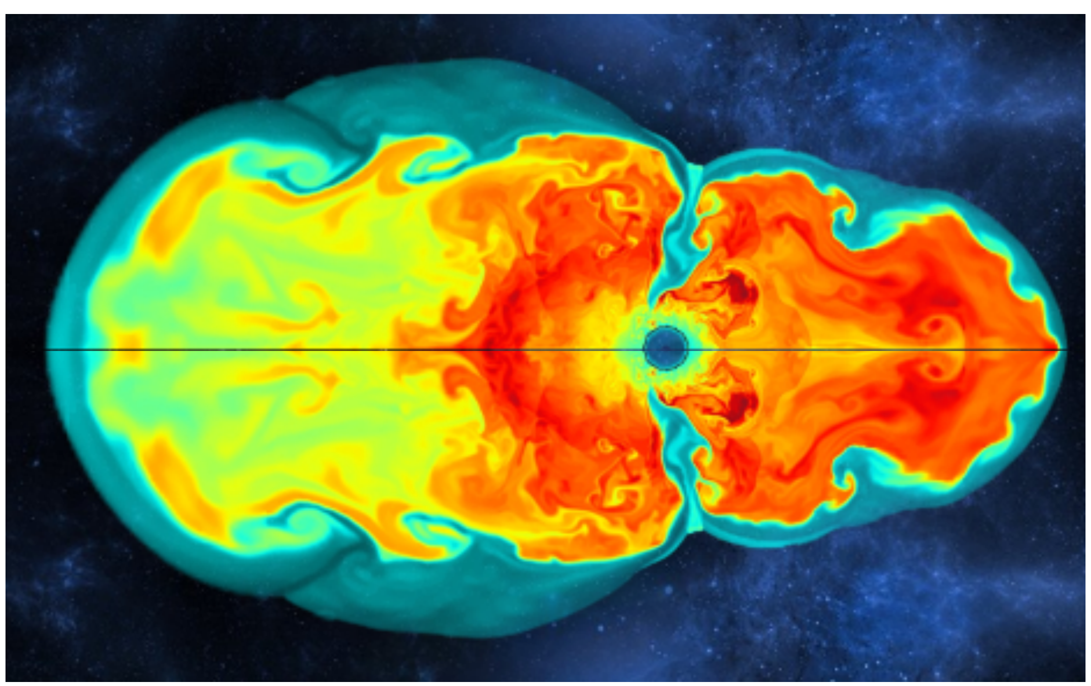
Conclusions



Neutron star mergers:

r-process
weak r-process
Kilonova





Core-collapse supernovae:

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