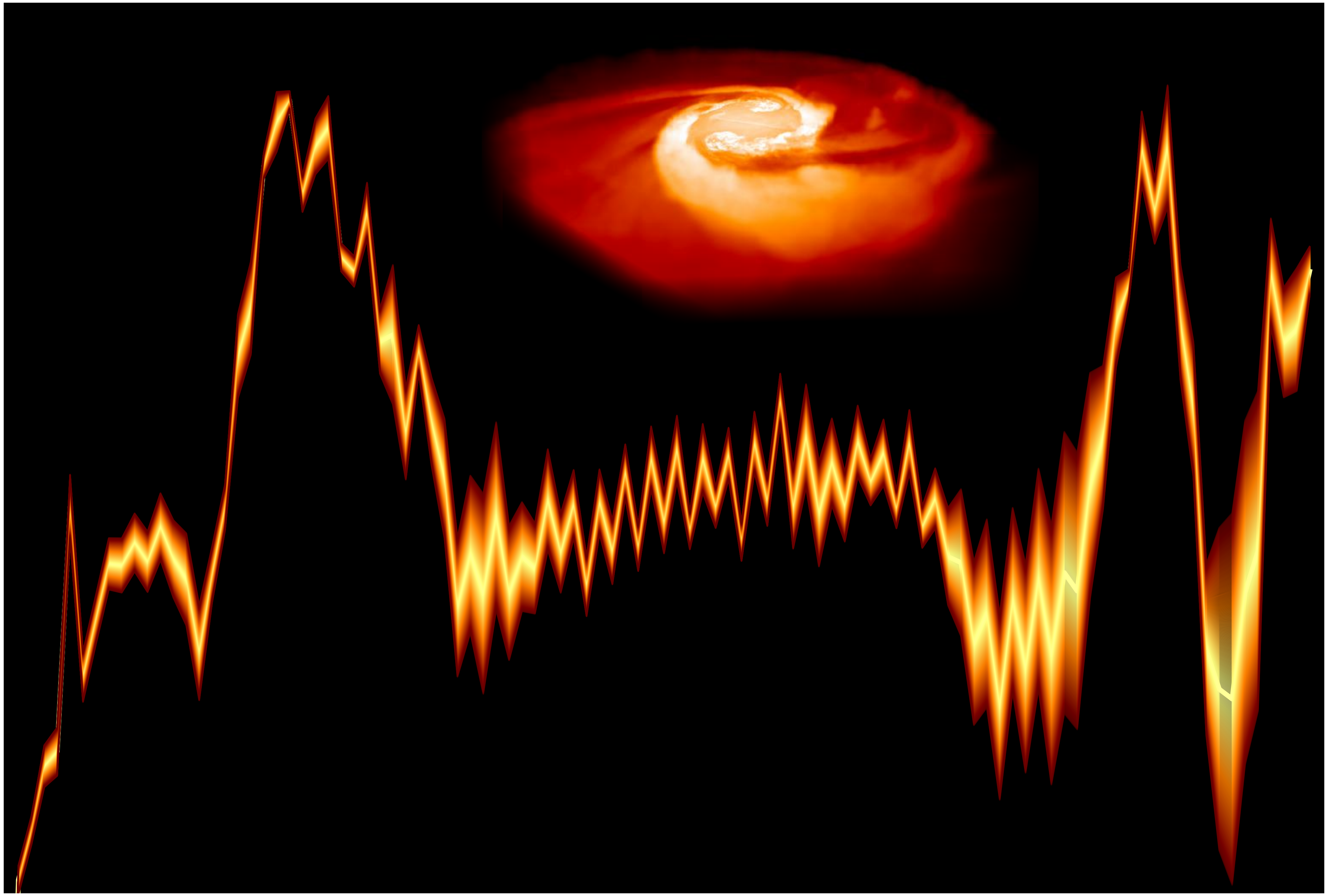
The Science of Third-Generation Gravitational-Wave Detectors

Berlin-Brandenburg Academy of Sciences and Humanities, 22-23 October 2019

Nucleosynthesis in GW transients



Almudena Arcones

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und Forschung

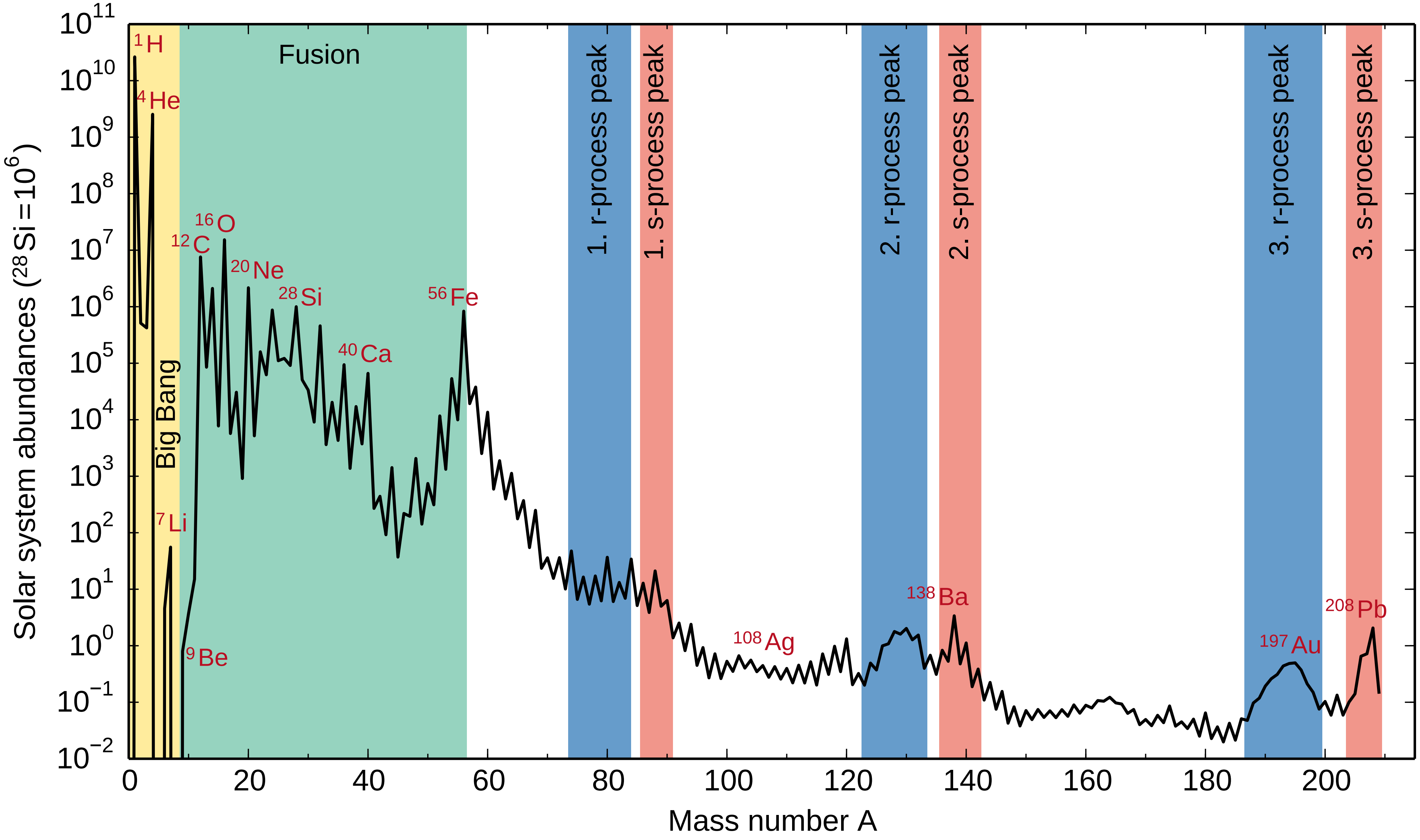
SFB 1245

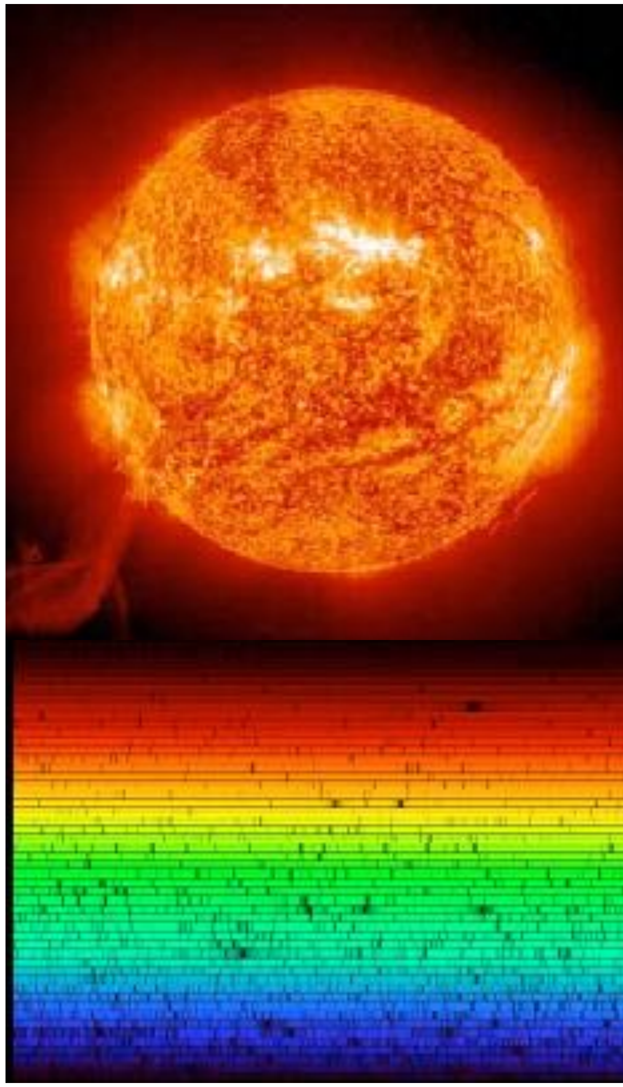
DFG

Solar system abundances

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

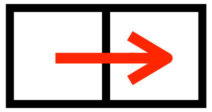
Contribution of all nucleosynthesis processes



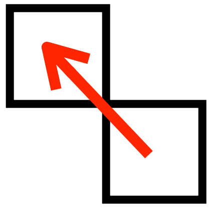


s-process and r-process

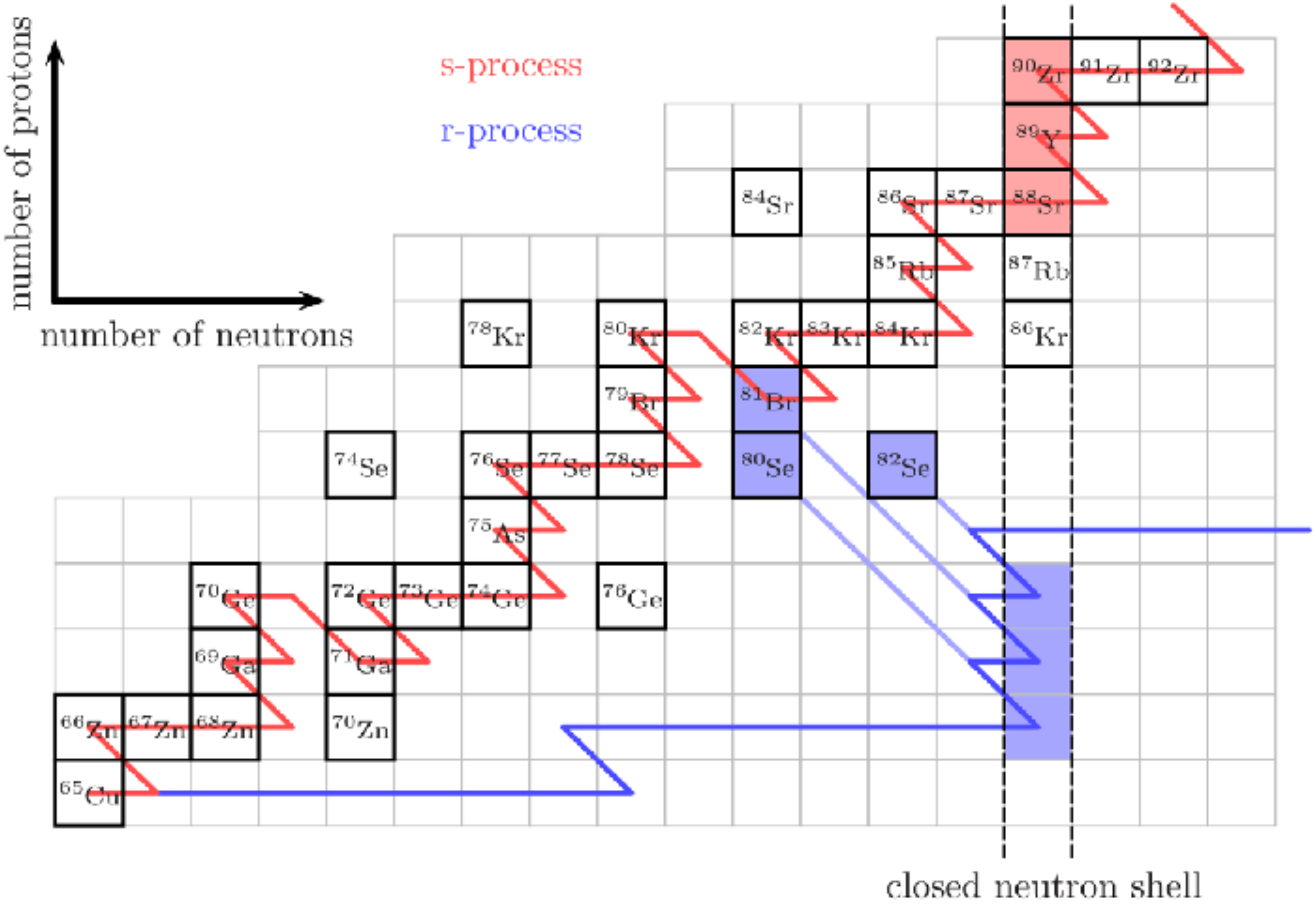
slow and rapid neutron capture compared to beta decay



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

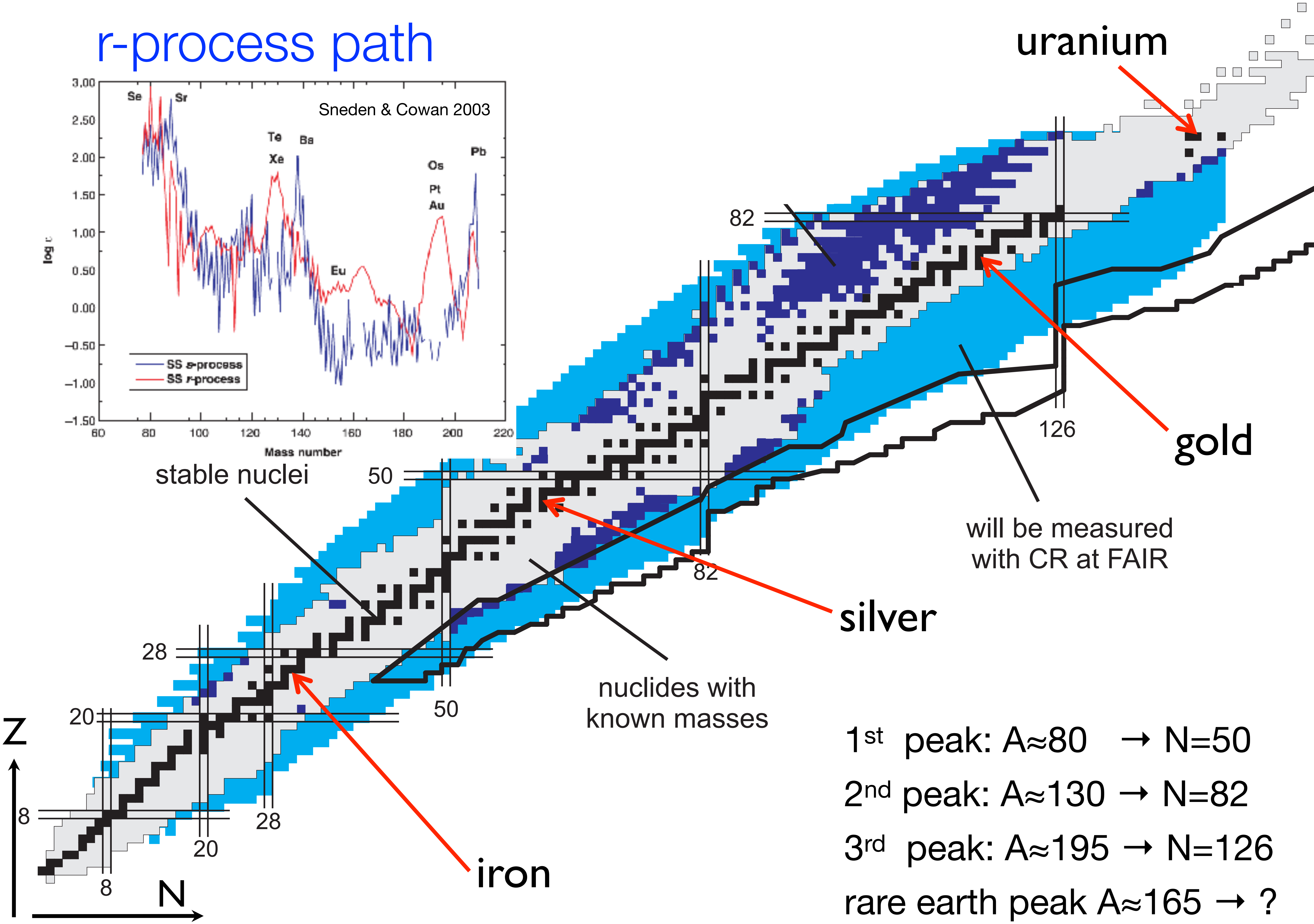


beta decay: (Z,A) → (Z+1,A)



Horowitz et al. J. Phys. G 2019

r-process path



1st peak: A≈80 → N=50

2nd peak: A≈130 → N=82

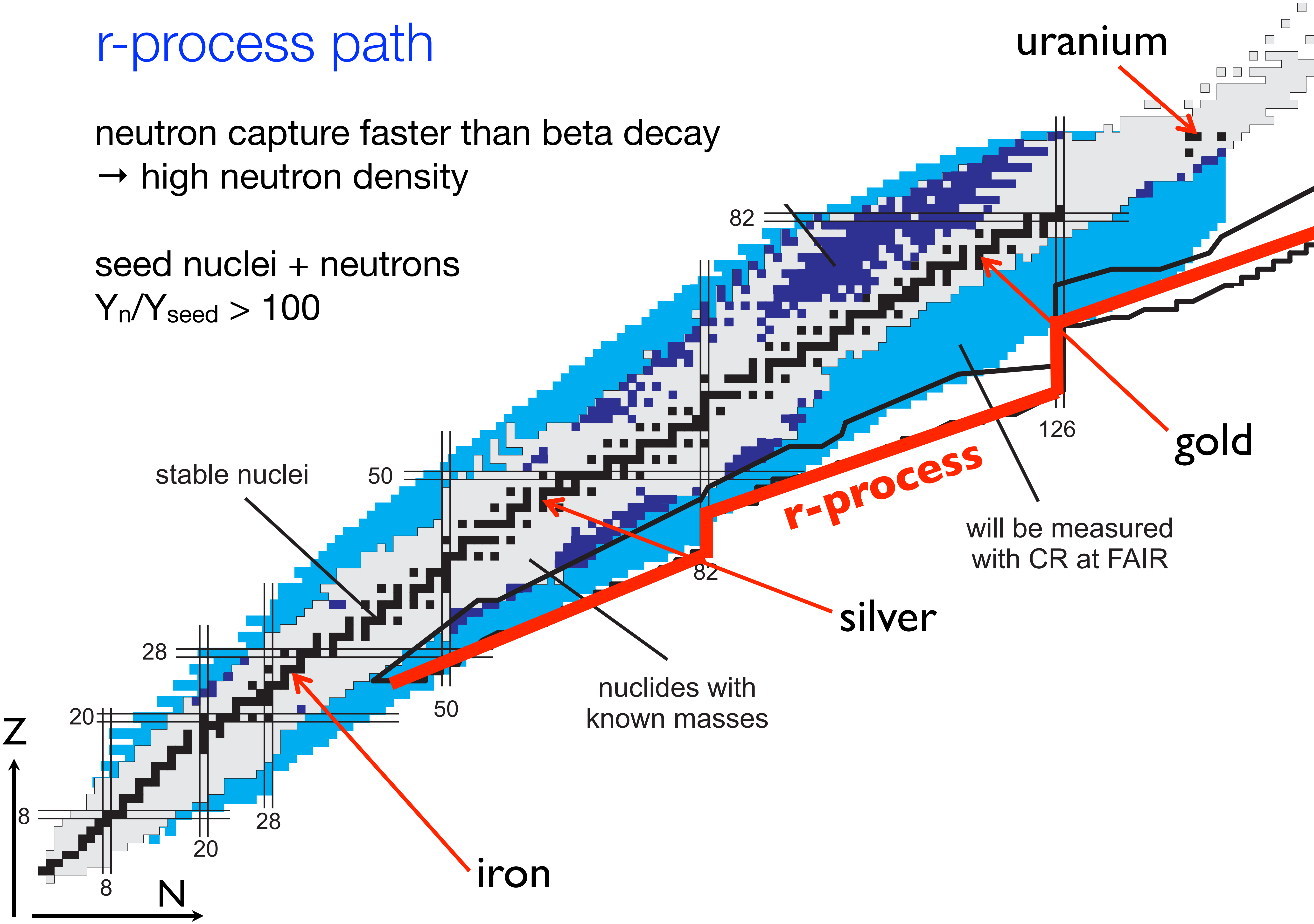
3rd peak: A≈195 → N=126

rare earth peak A≈165 → ?

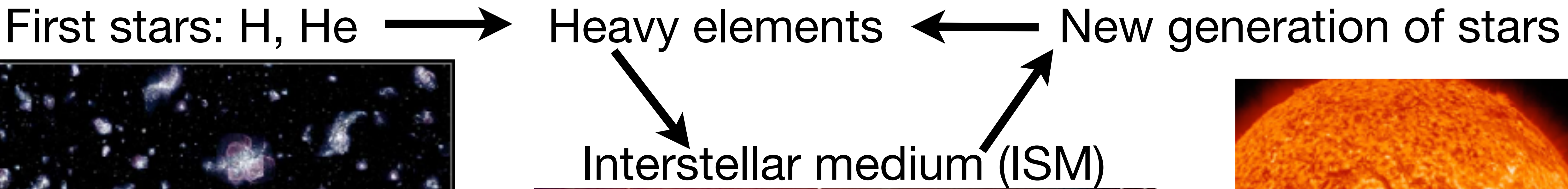
r-process path

neutron capture faster than beta decay
→ high neutron density

seed nuclei + neutrons
$Y_n/Y_{seed} > 100$



Galactic chemical evolution

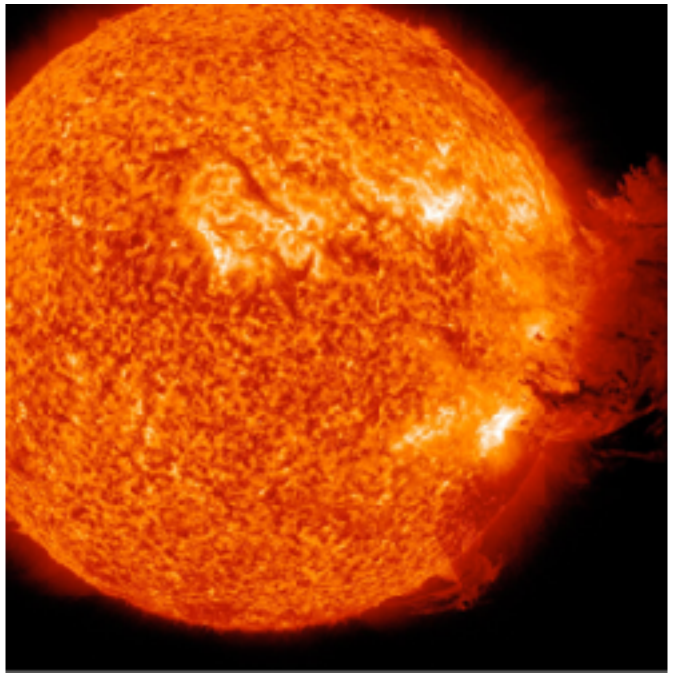


First stars: H, He → Heavy elements ← New generation of stars

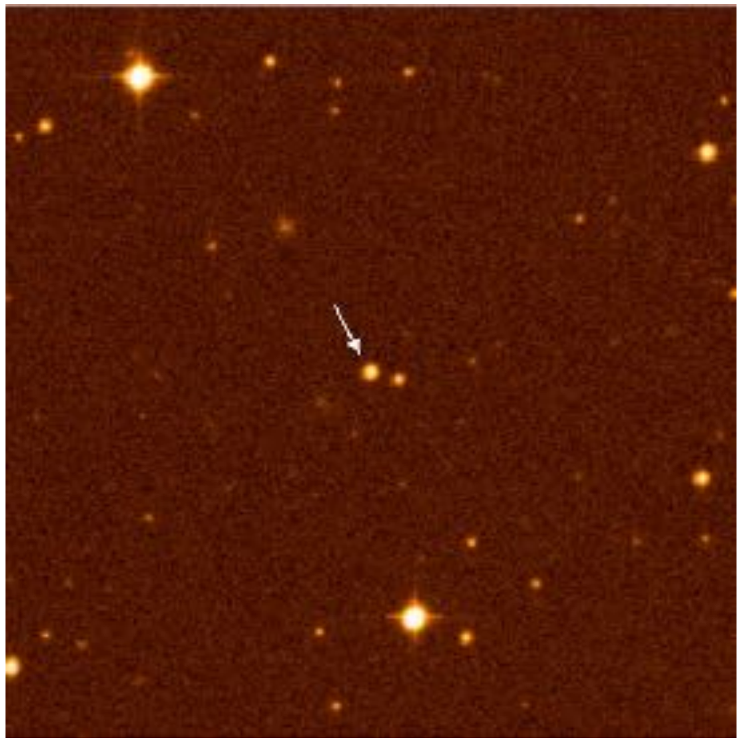
Heavy elements → Interstellar medium (ISM) → New generation of stars

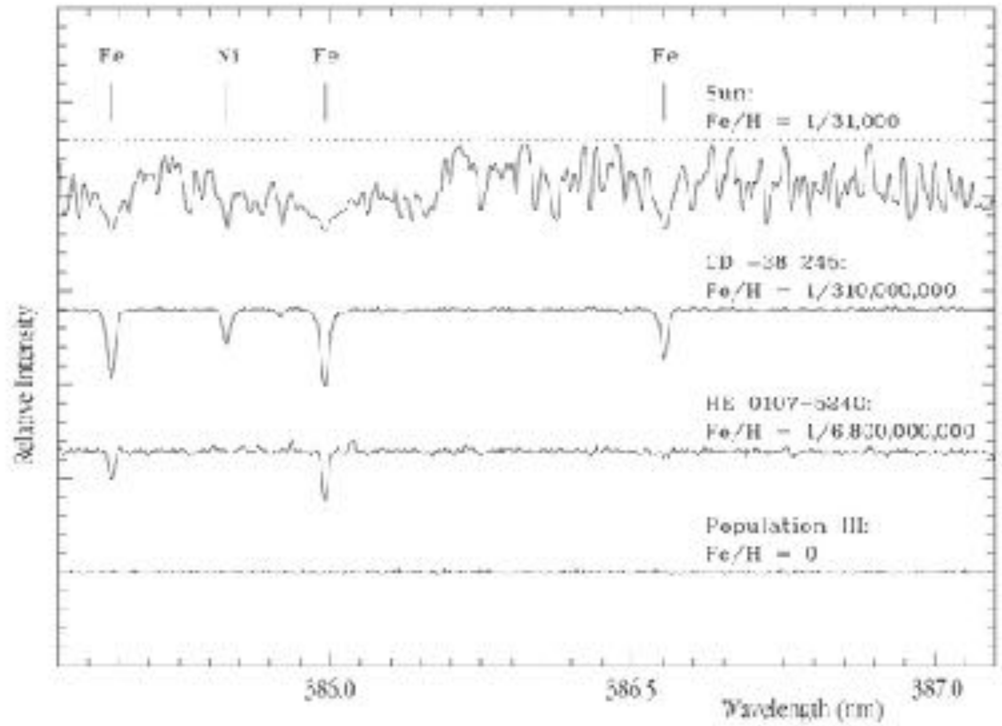
Artist's View of Star Formation in the Early Universe

Painting by Adolf Schaller • STScI-PRC02-02



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



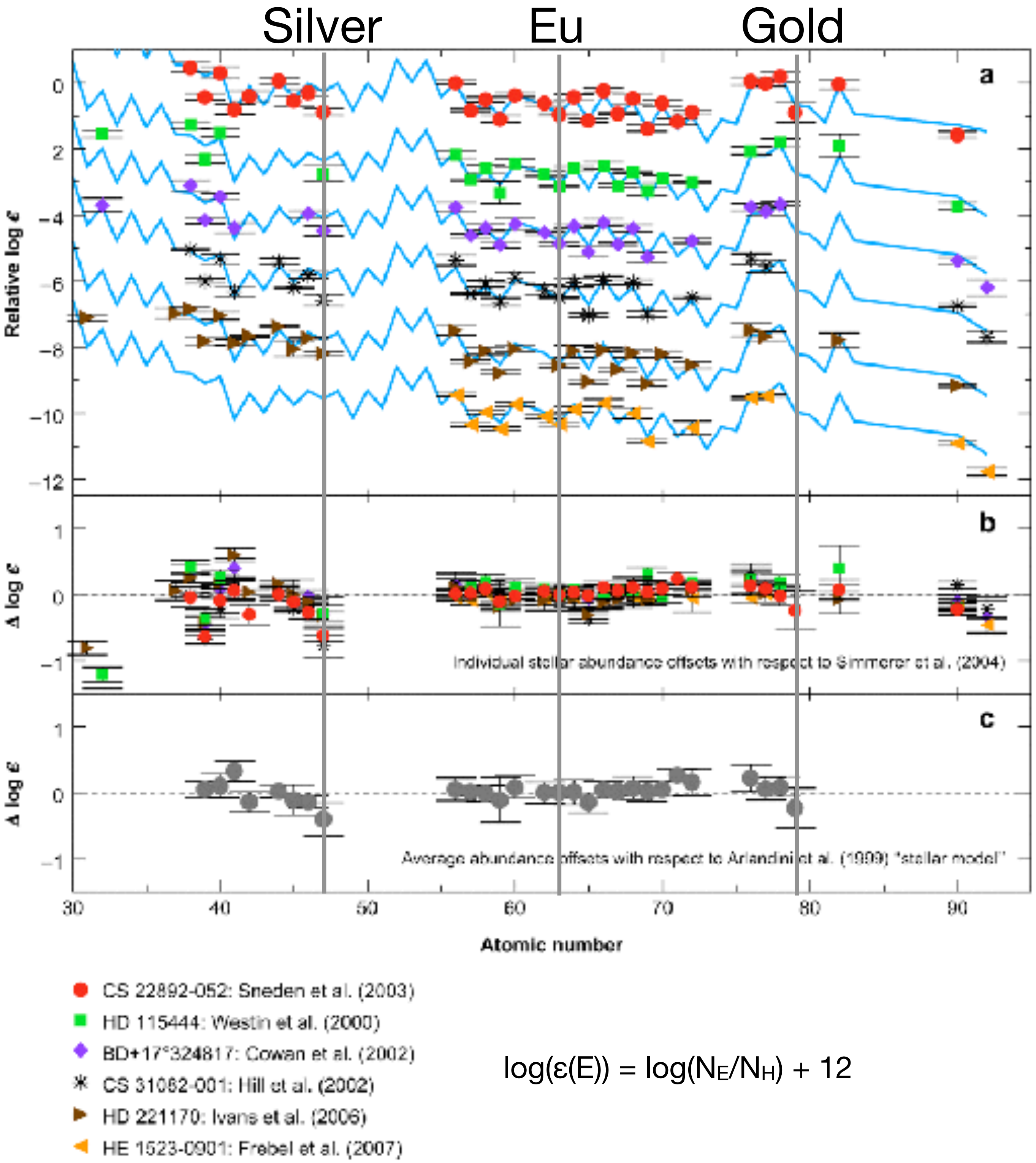


Spectra of Stars with Different Metal Content

ESO PR Photo 29b/02 (30 October 2002)

©European Southern Observatory

r-process in ultra metal-poor stars



$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$

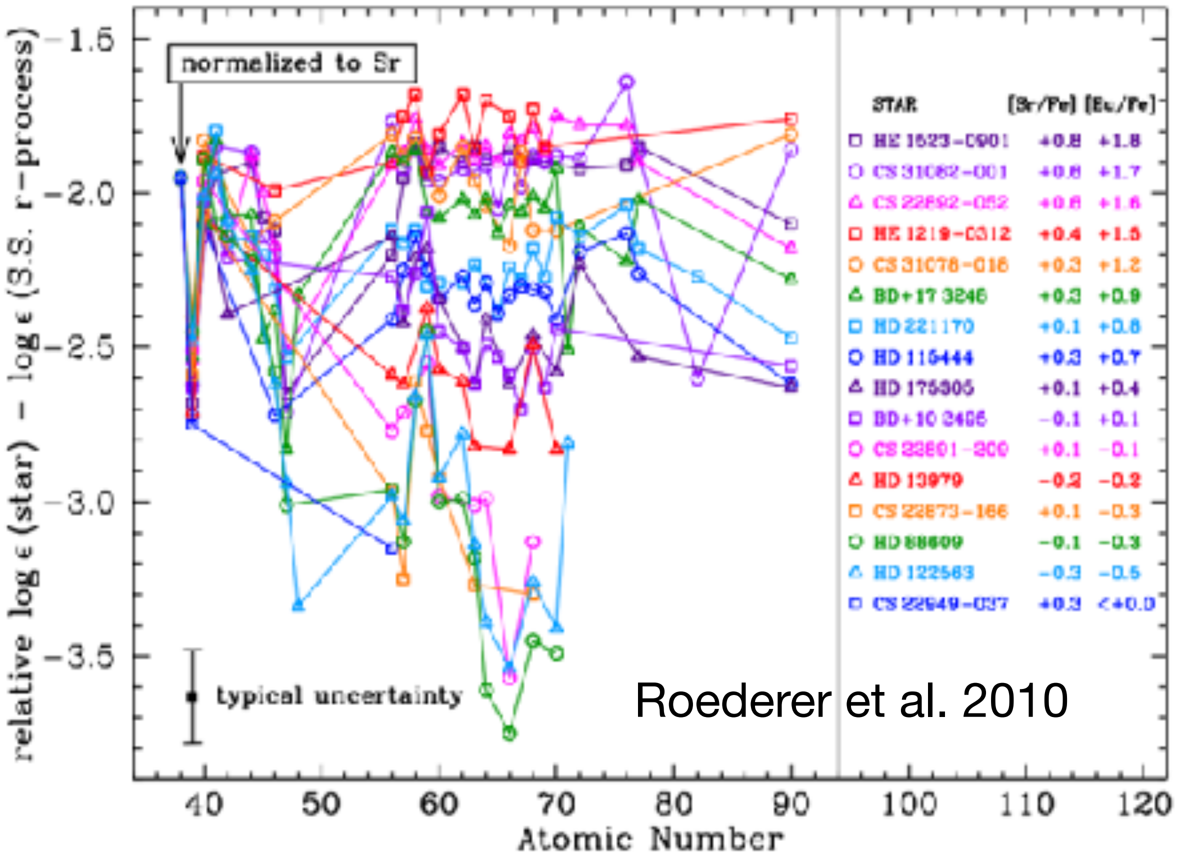
Sneden, Cowan, Gallino 2008

Abundances of r-process elements:

- ultra metal-poor stars and
- r-process solar system: N_{solar} - N_s

Robust r-process for 56<Z<83

Scatter for lighter heavy elements, Z~40

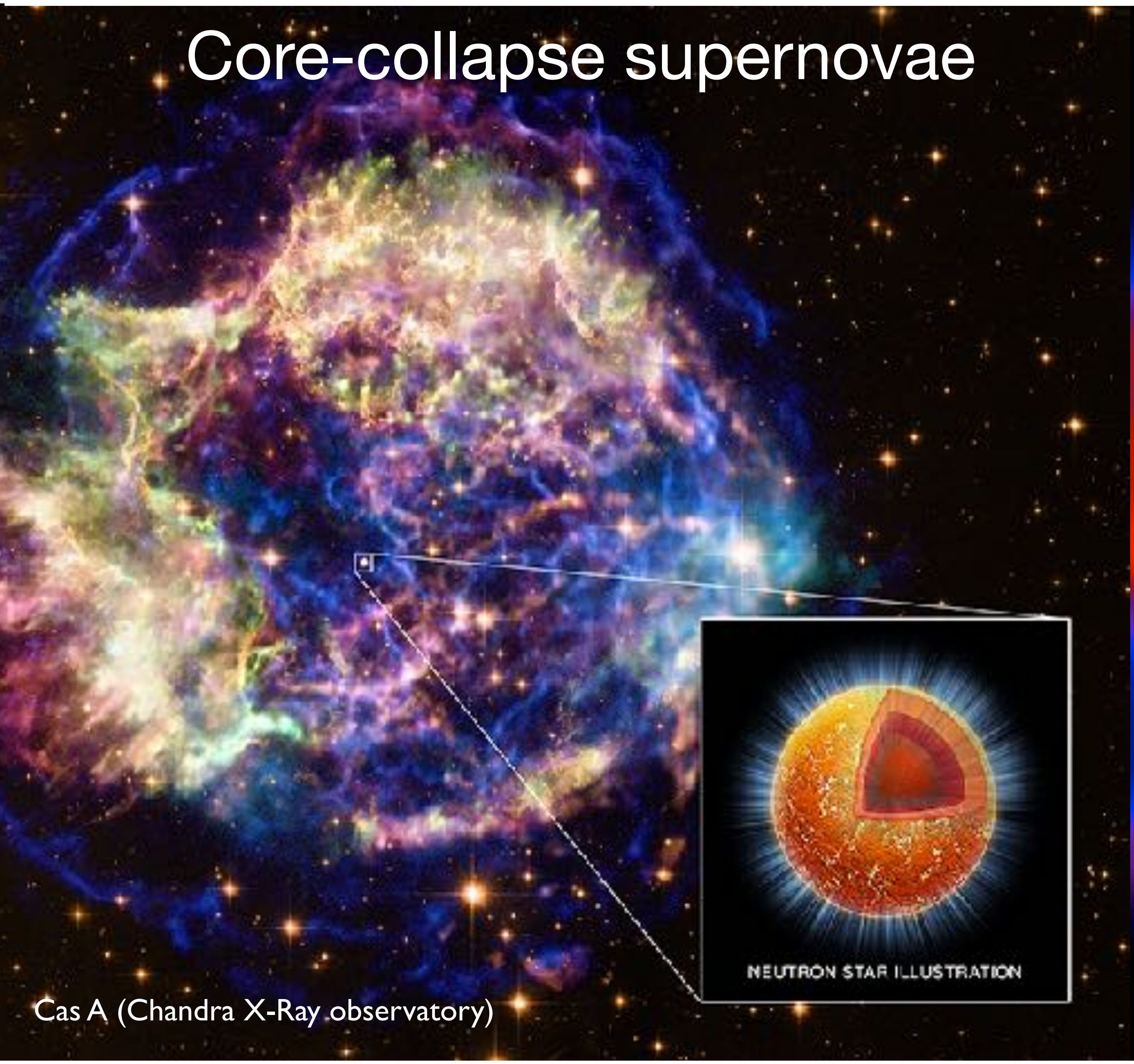


Roederer et al. 2010

Where does the r-process occur?

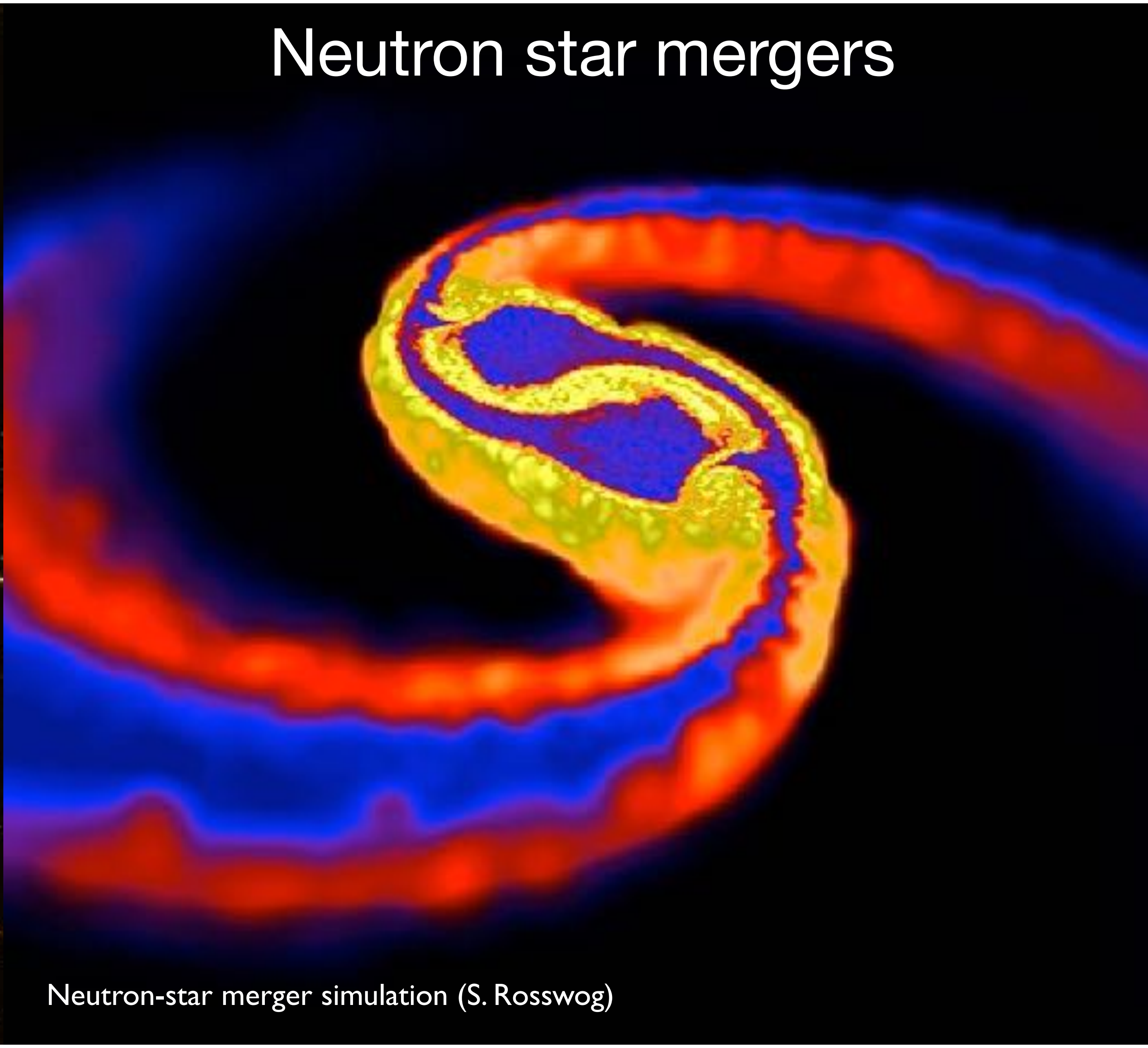
rapid process → explosions
high neutron densities → neutron stars

Core-collapse supernovae



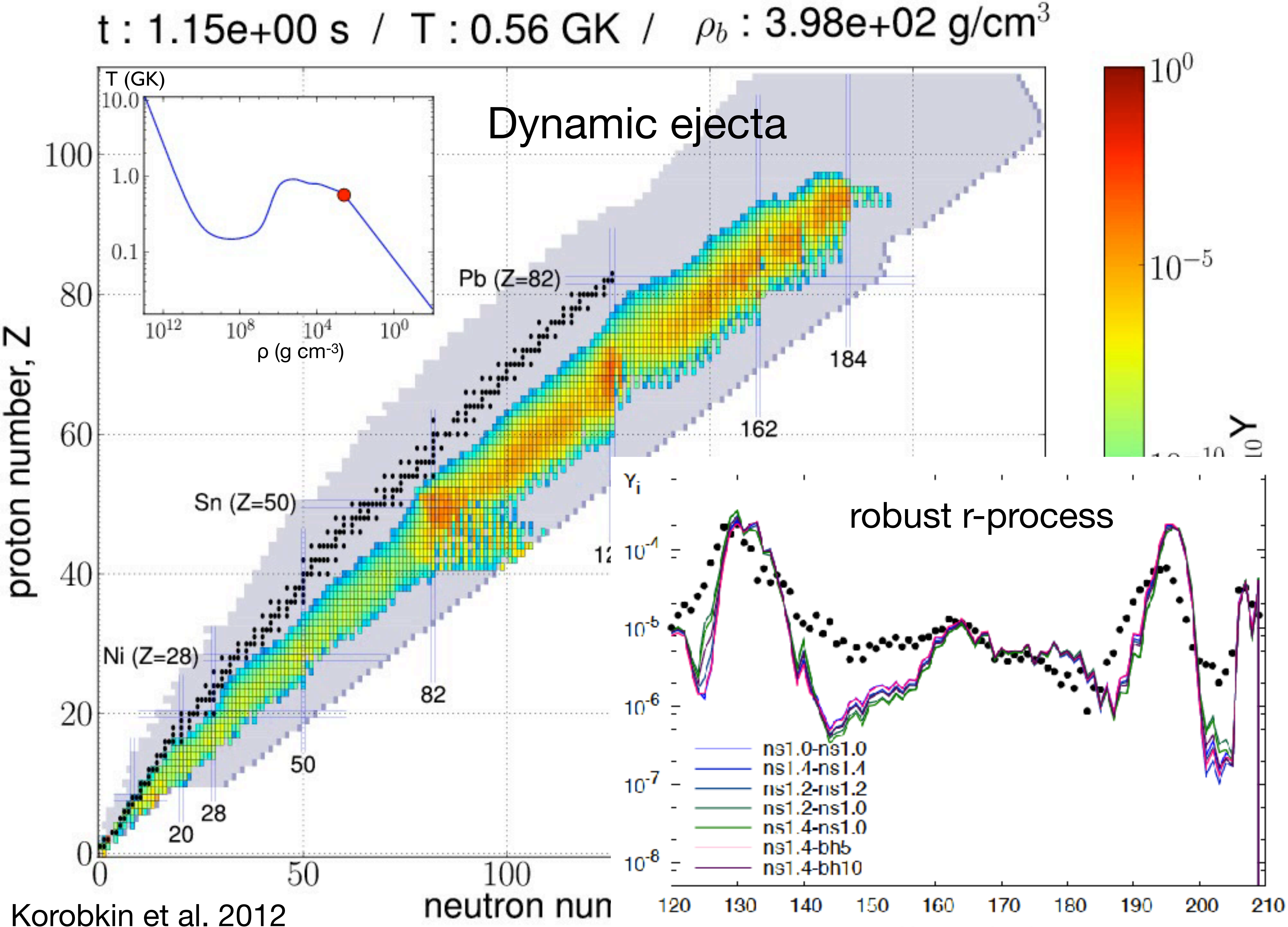
Cas A (Chandra X-Ray observatory)

Neutron star mergers



Neutron-star merger simulation (S. Rosswog)

Neutron star mergers



Dynamic ejecta

robust r-process

Korobkin et al. 2012

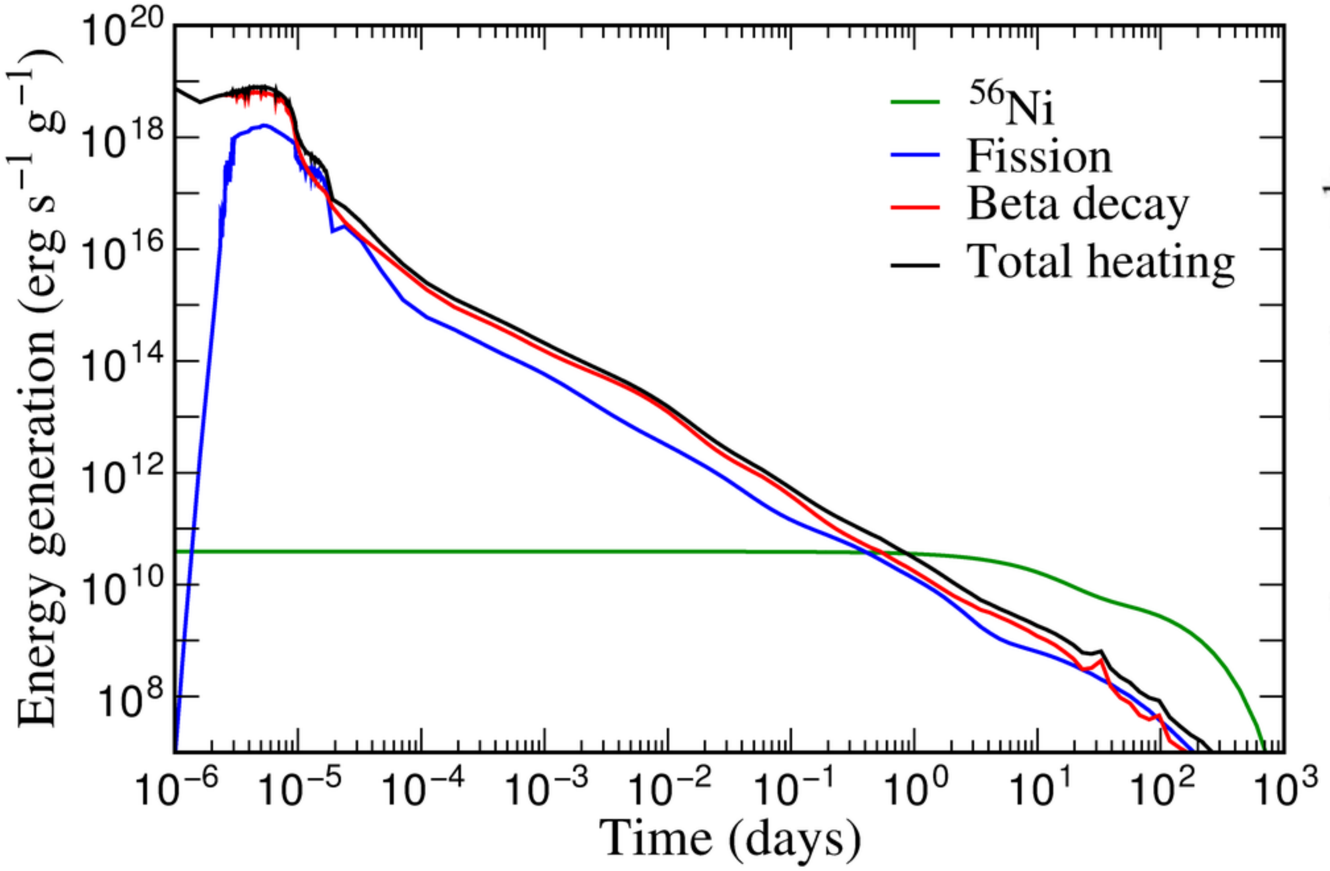
R-process fingerprint: Kilonova

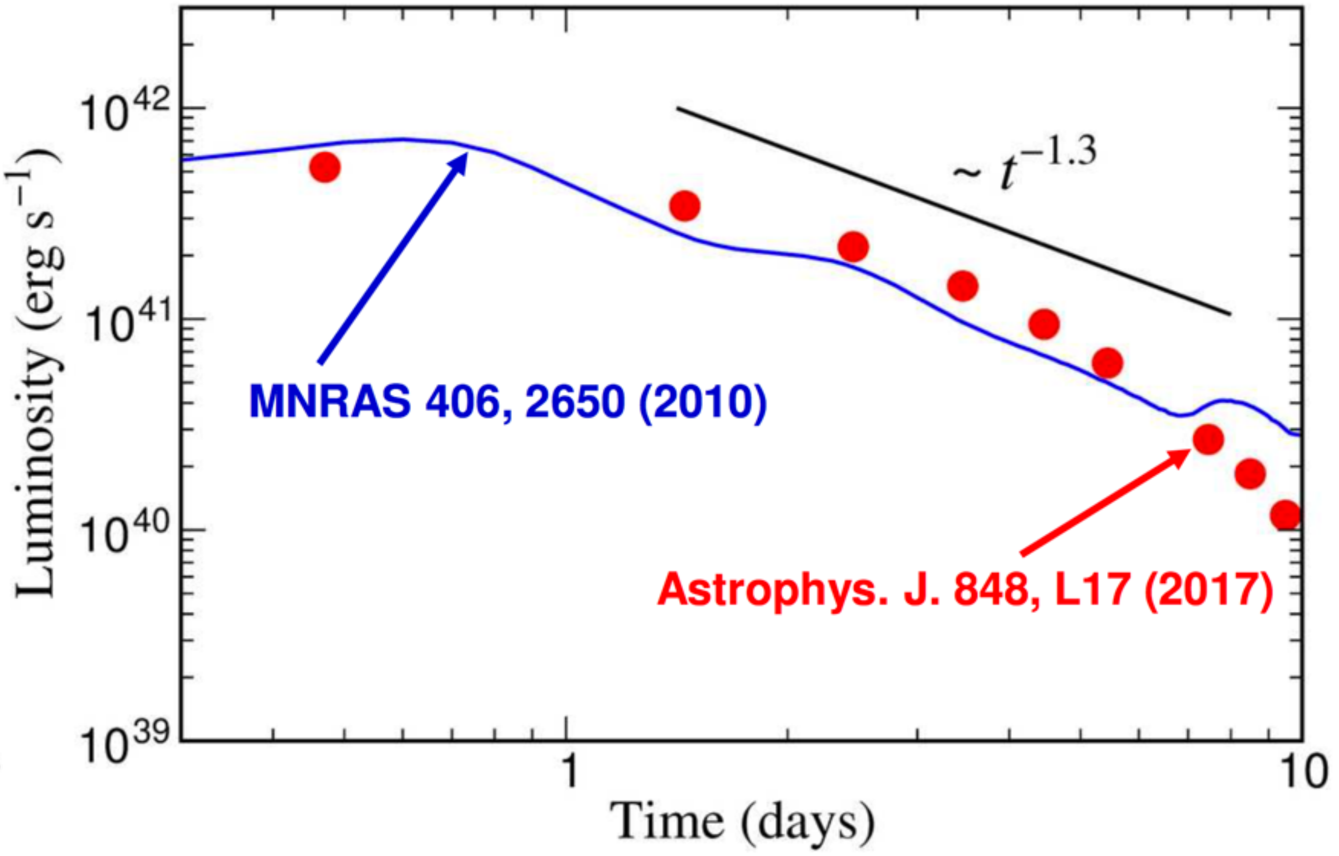
Radioactive decay of neutron-rich nuclei —> transient with kilo-nova luminosity

Li & Paczynski (1998)

Electromagnetic counter part to gravitational waves —> observed after GW170817

Metzger, Martinez-Pinedo, Darbha, Quataert, Arcones, Kasen et al. (2010)

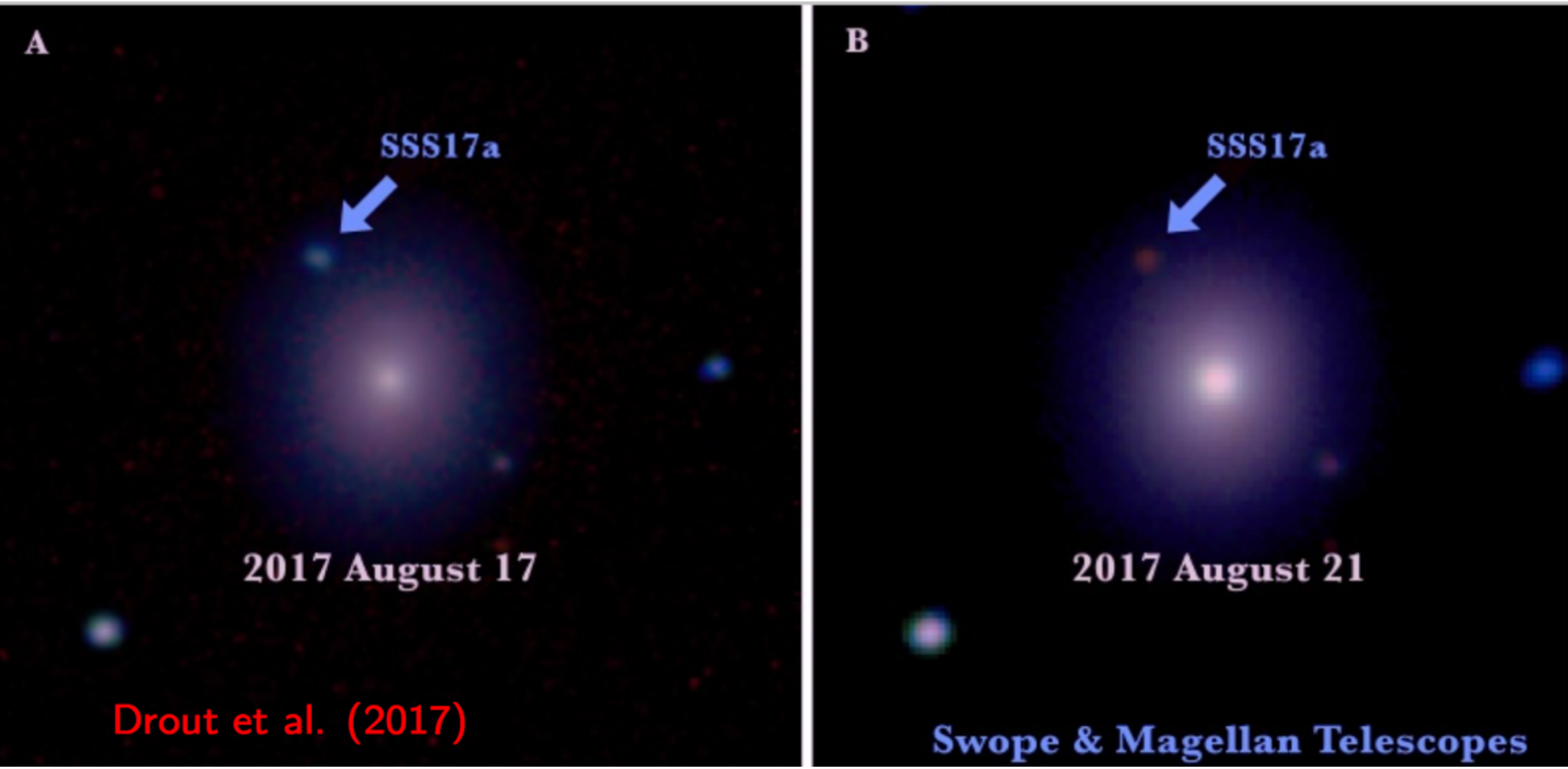




MNRAS 406, 2650 (2010)

Astrophys. J. 848, L17 (2017)

Kilonova

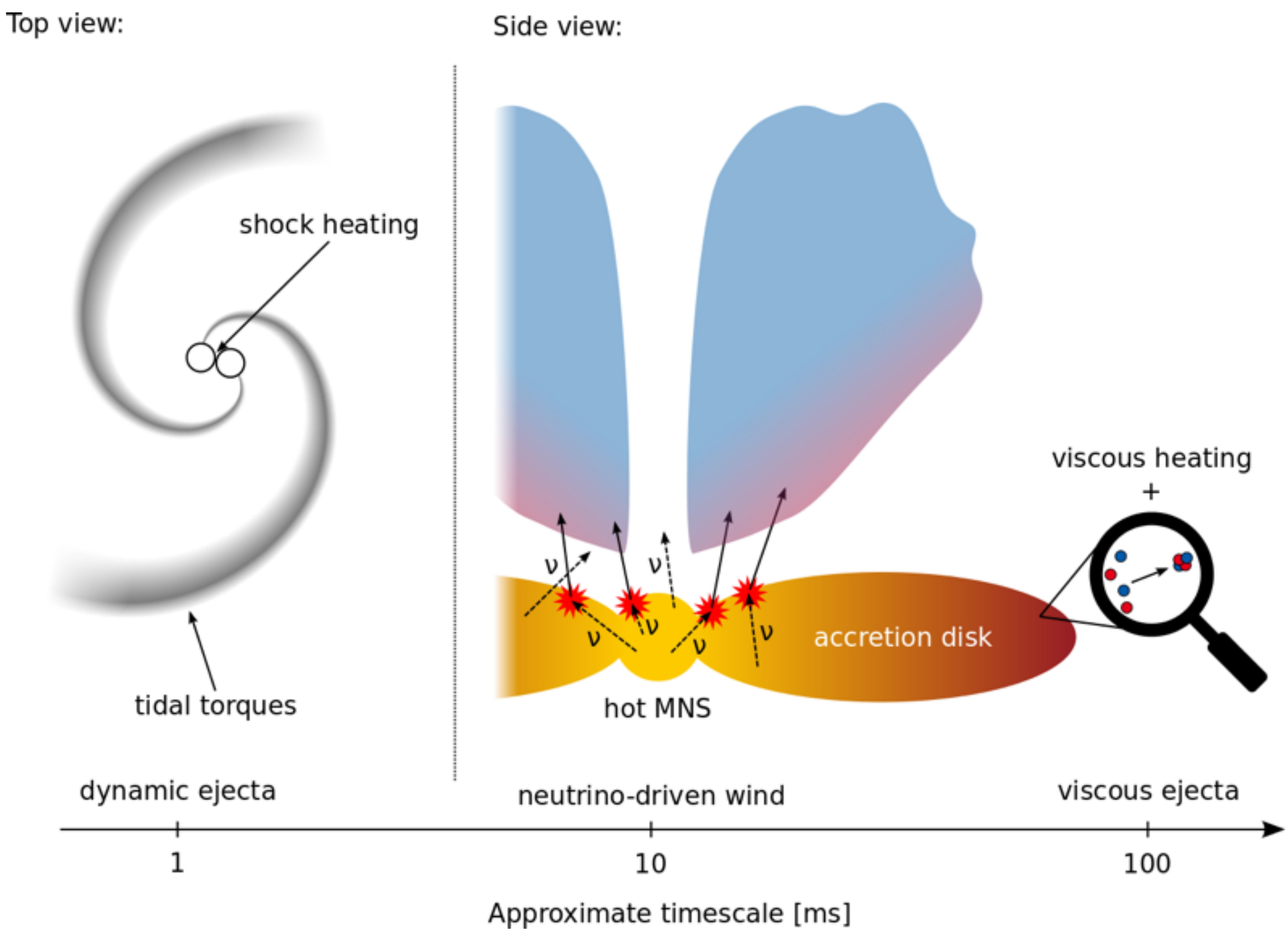


Drout et al. (2017)

Silver kilonova

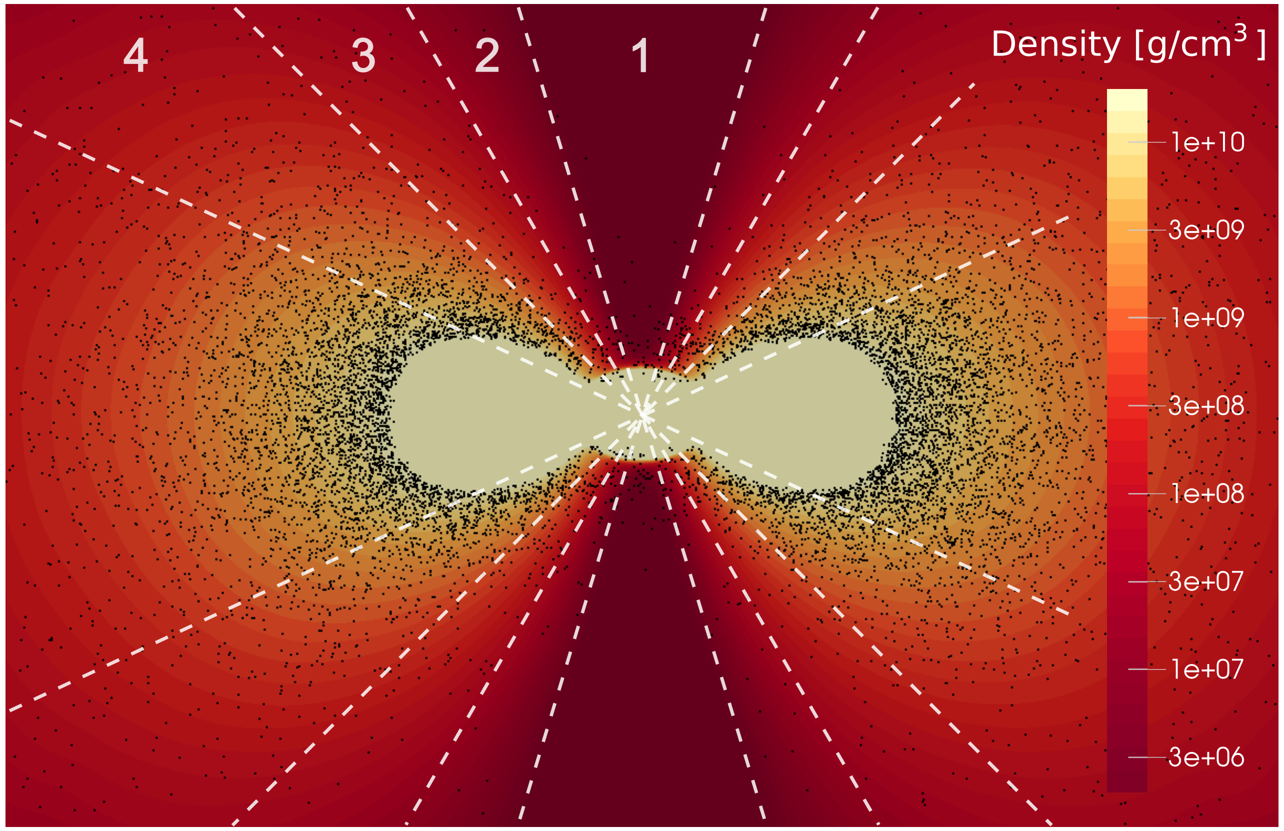
Gold kilonova

Neutron star merger ejecta



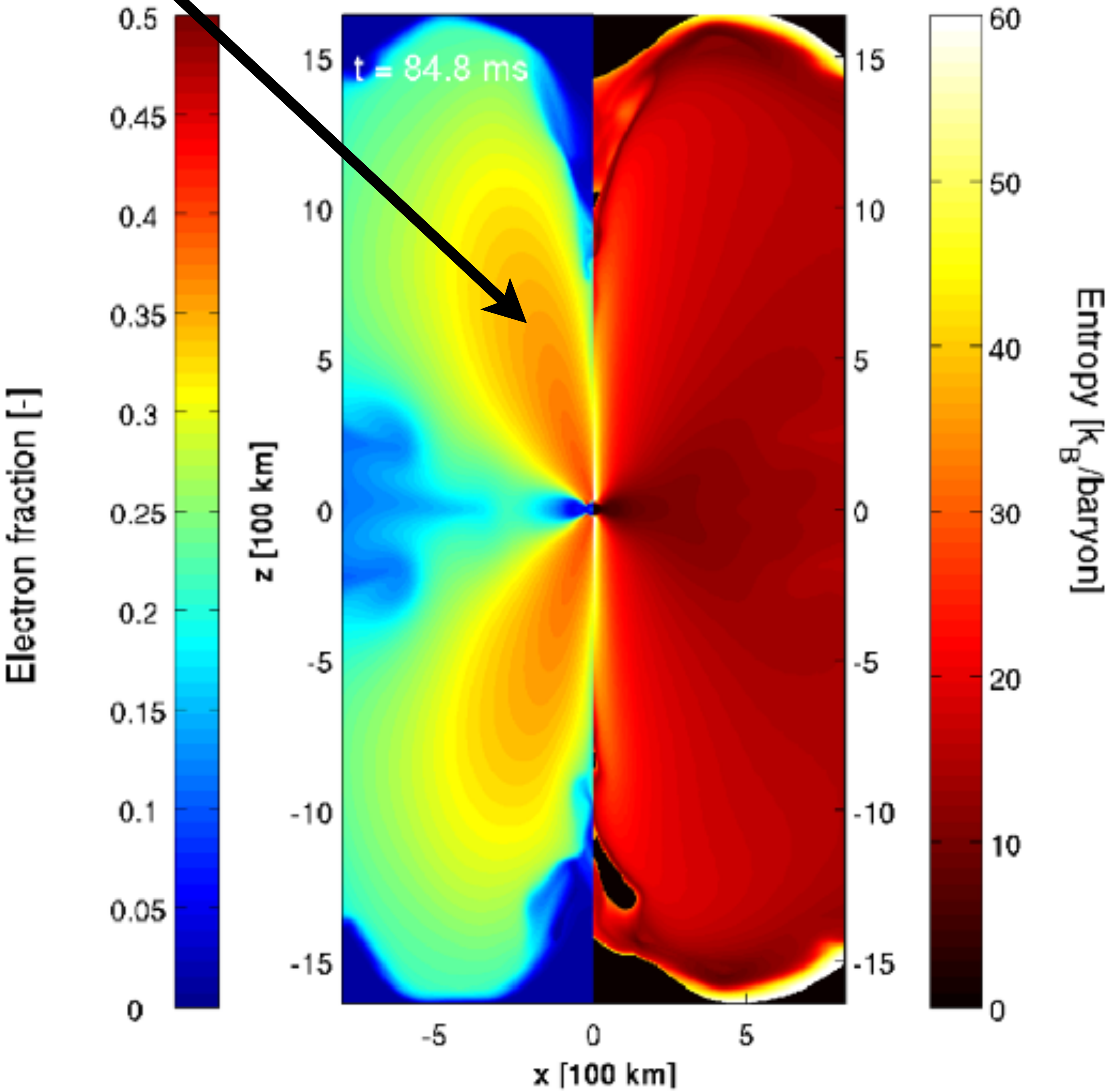
Neutron star mergers: neutrino-driven wind

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



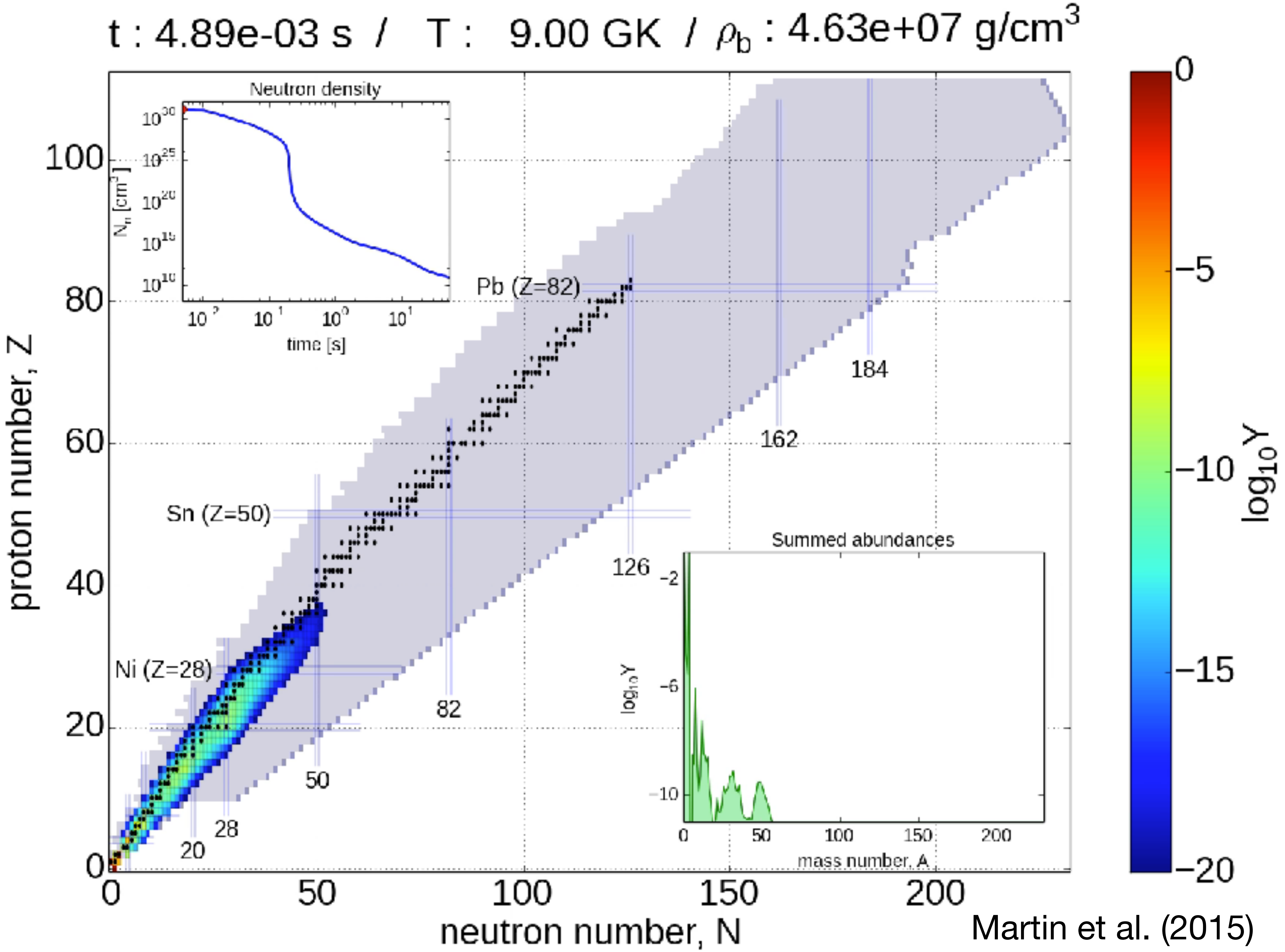
Martin et al. (2015)

Perego et al. (2014)



see also
Fernandez & Metzger 2013, Metzger & Fernandez 2014,
Just et al. 2014, Sekiguchi et al. 2016

Neutron star mergers: neutrino-driven wind

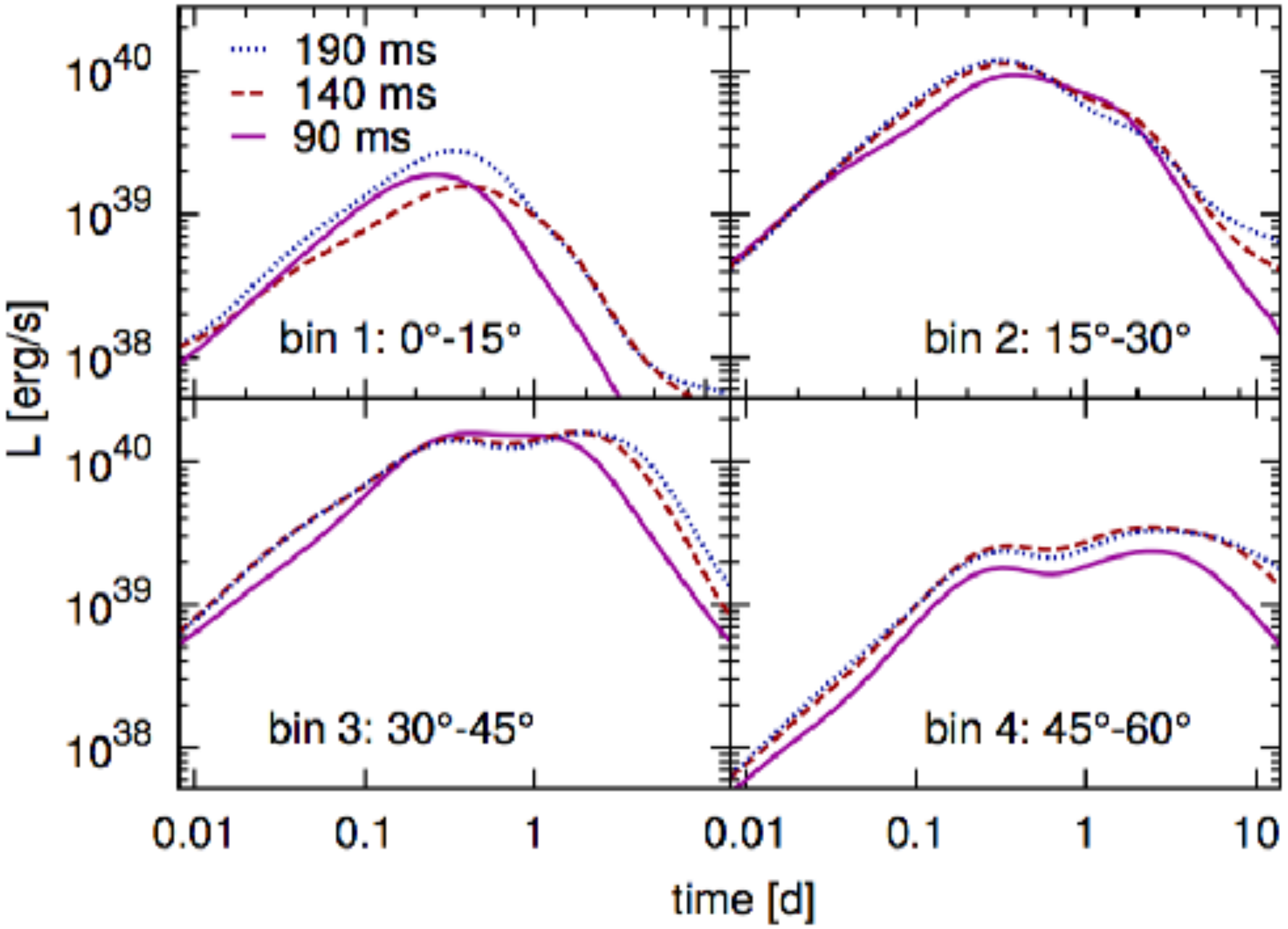


Martin et al. (2015)

Time and angle dependency

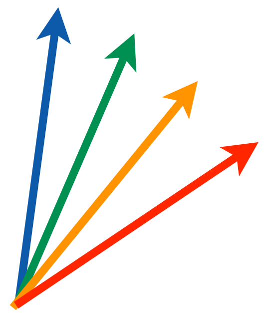
Black hole formation determines time for wind nucleosynthesis
(Fernandez & Metzger 2013, Kasen et al. 2015)

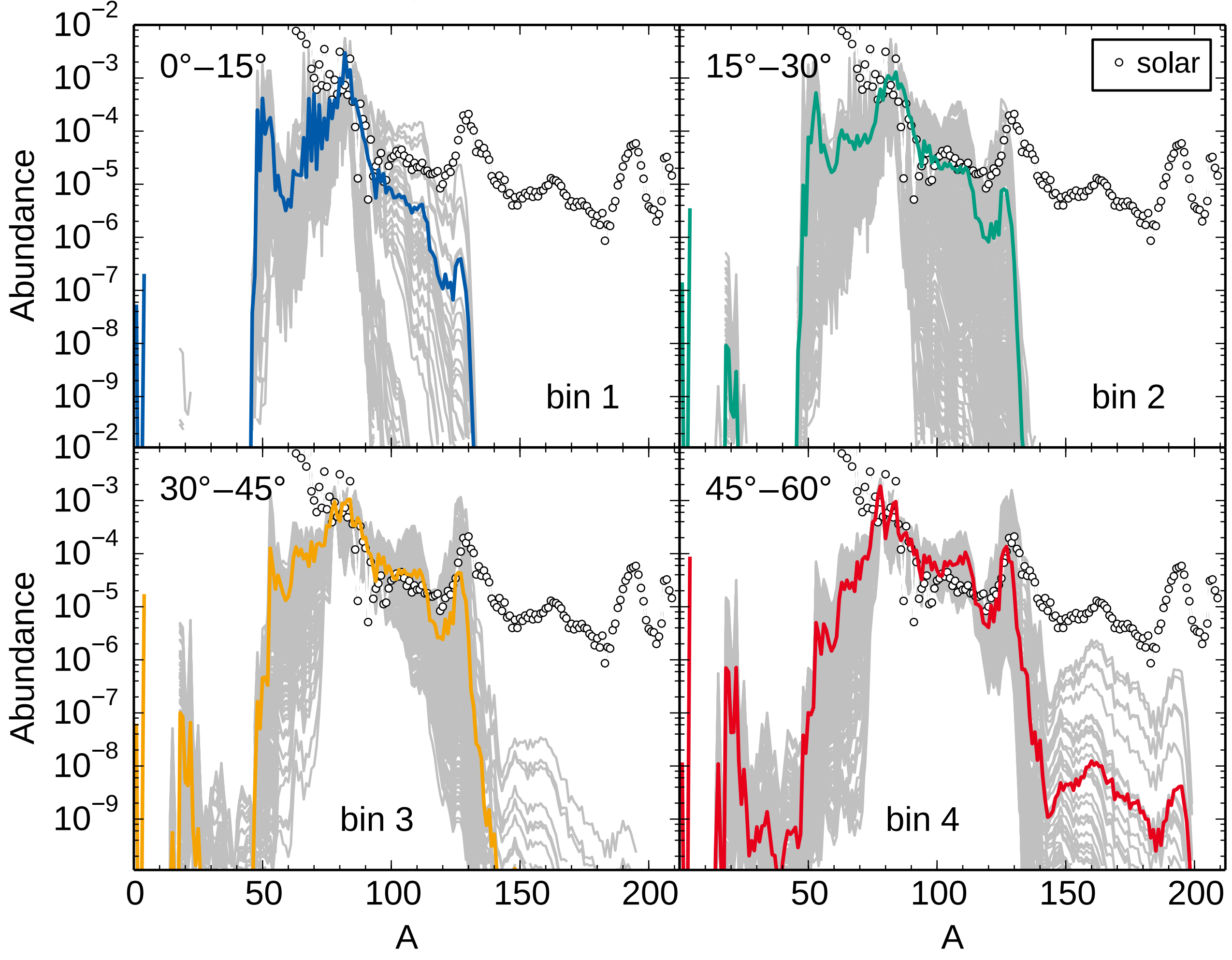
Early times: low Y_e: heavy elements
Late times: Y_e ~0.35: lighter heavy elements



Martin et al. (2015)

angle dependency

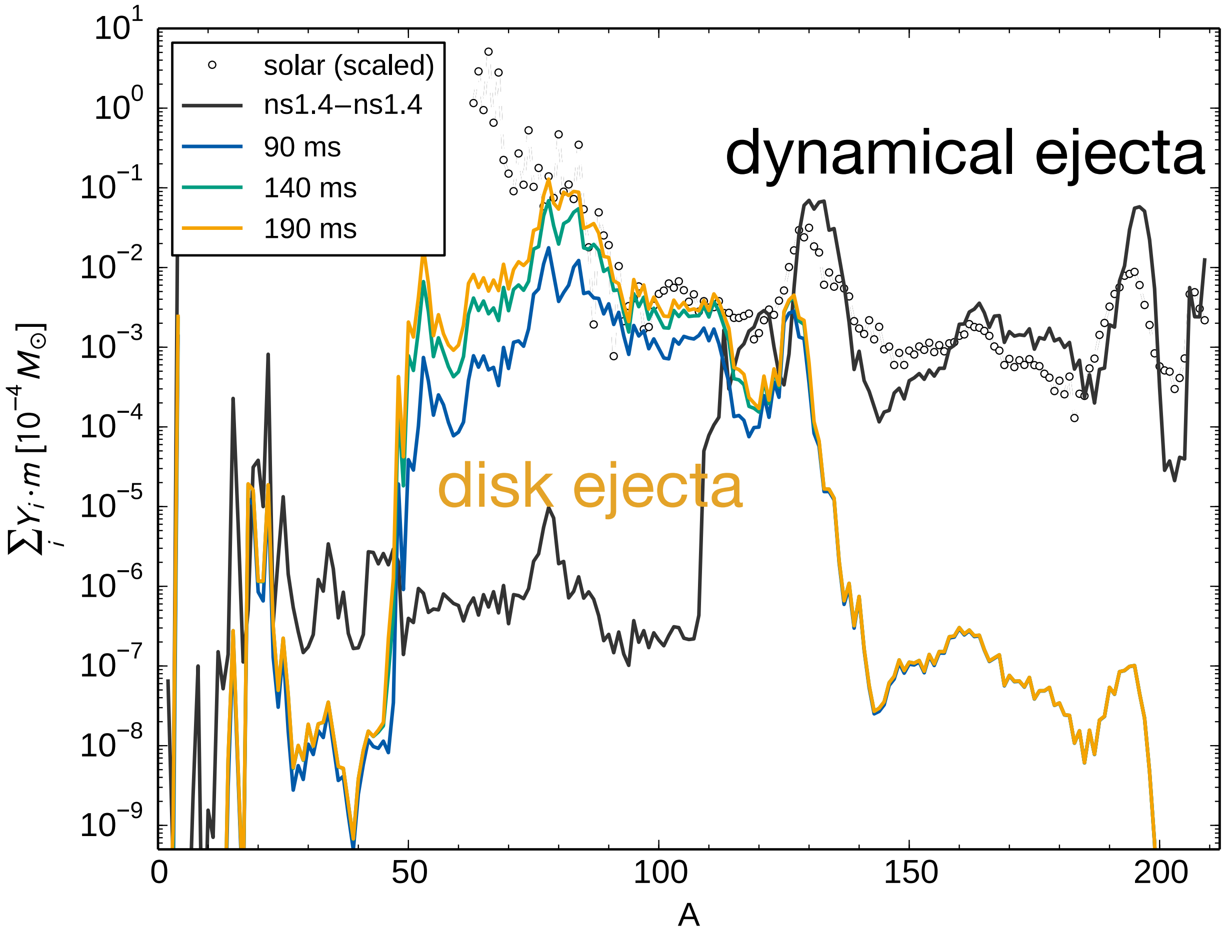




Wind and dynamic ejecta

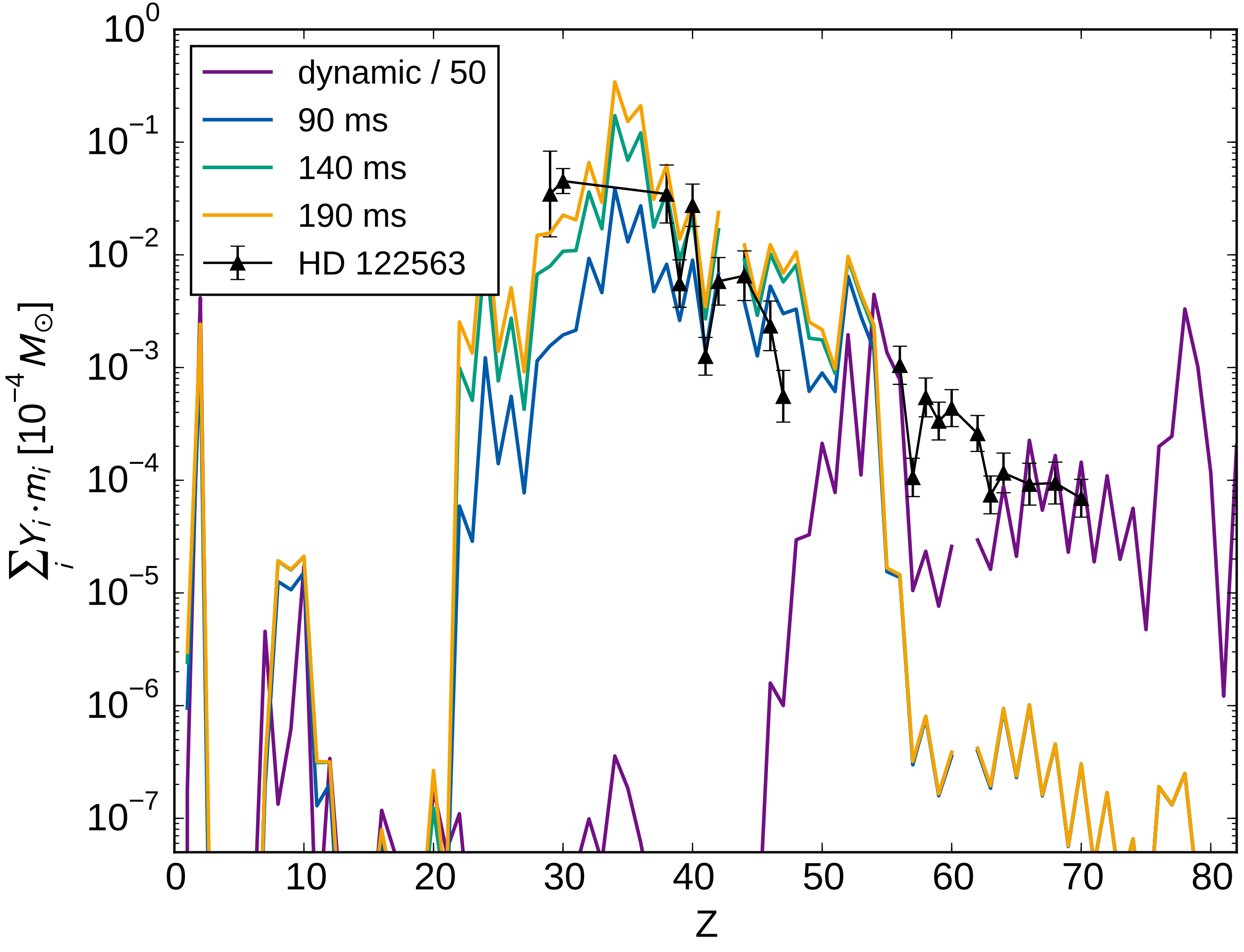
Wind ejecta complement dynamic ejecta

Complete mixing: solar system abundances and UMP stars



Martin et al. (2015)

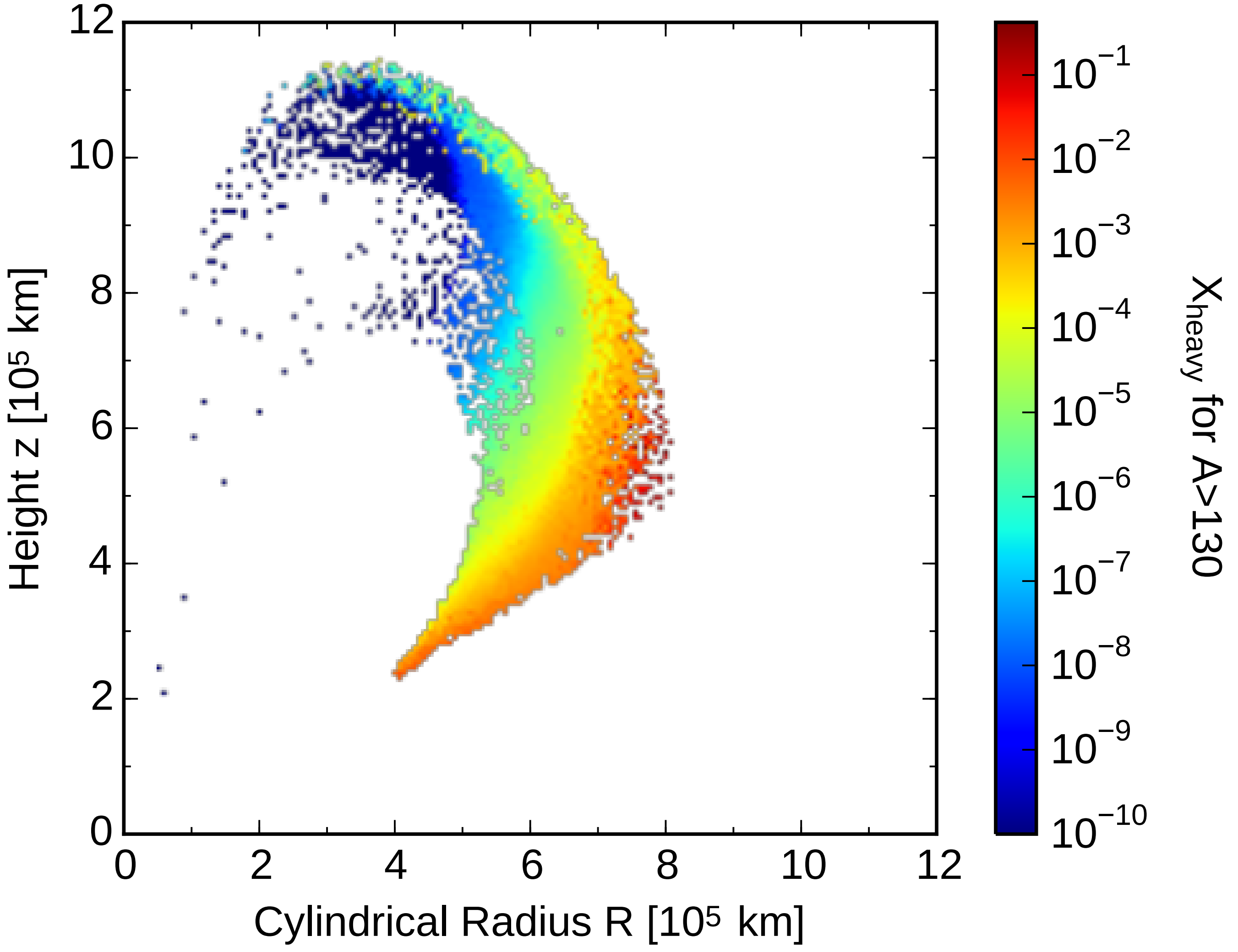
Partial mixing: Honda-like star?



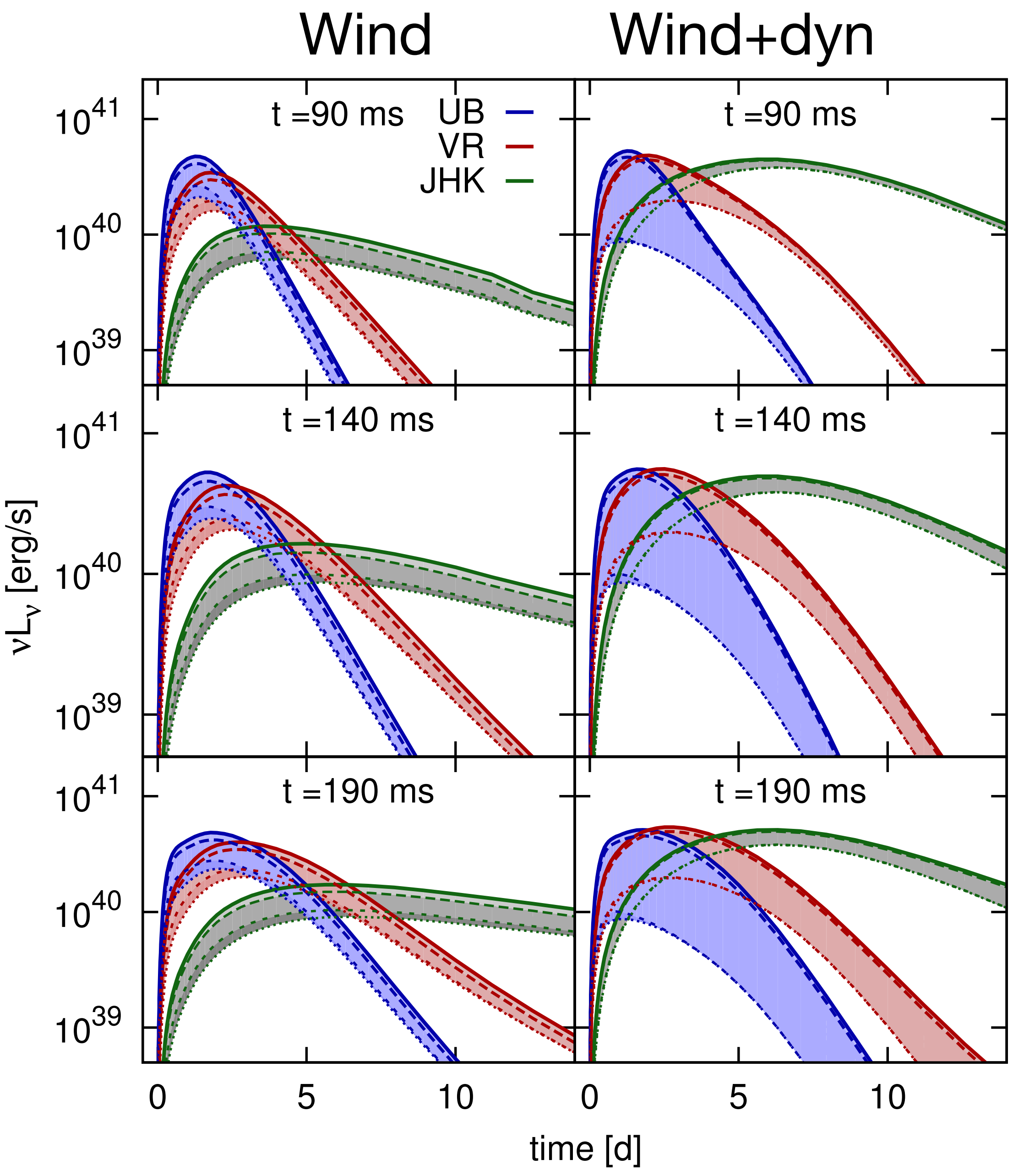
Two components: Hansen et al. 2014

Wind kilonova

Less or no heavy r-process depending on angle → lower opacities
- Wind kilonova peaks on blue after ~4 hours
- Dynamic ejecta kilonova peaks on IR after 4-5 days



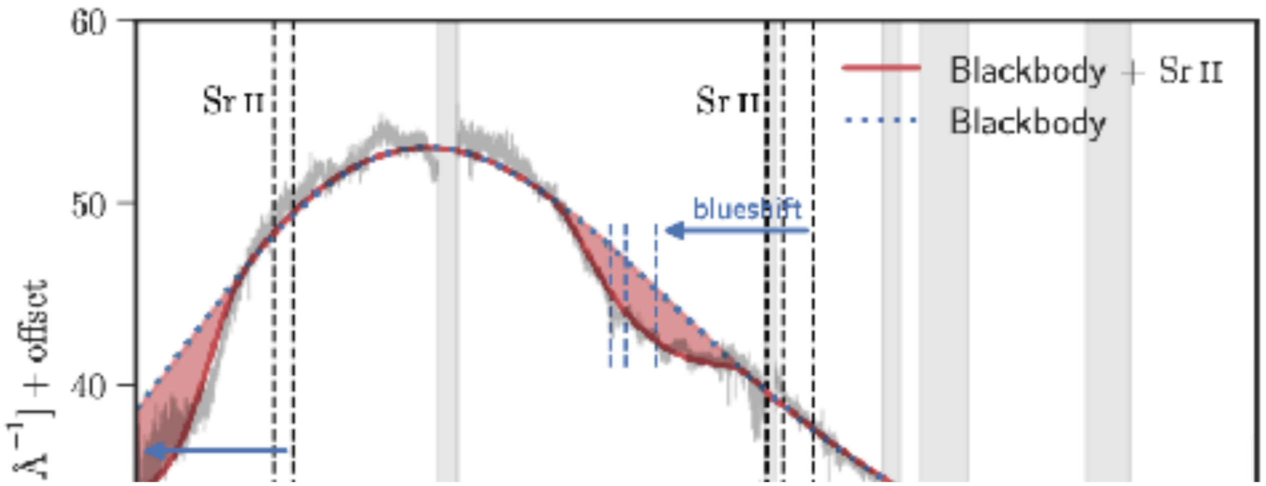
Martin et al. (2015)



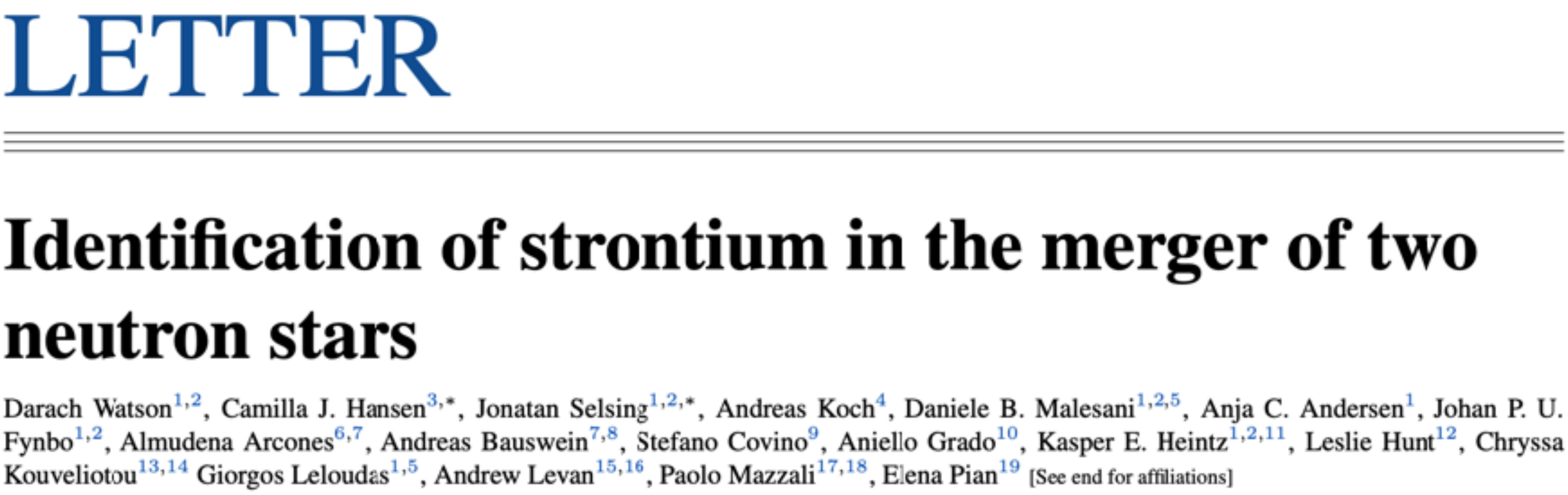
Three times for ns collapse: t=90, 140 and 190 ms

First direct detection of r-process element

Ground-based observations of AT2017gfo (GW170817)



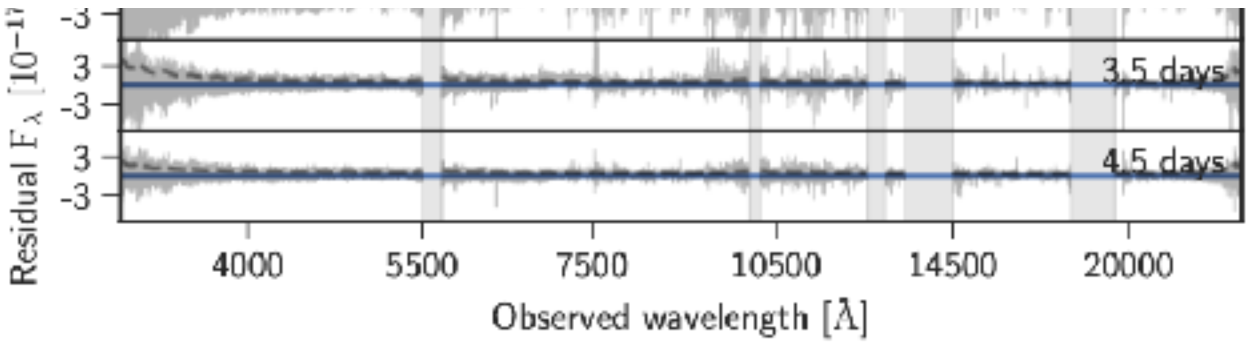
$$M_{\rm Sr} \approx 5 \cdot 10^{-5} M_{\odot}$$



LETTER

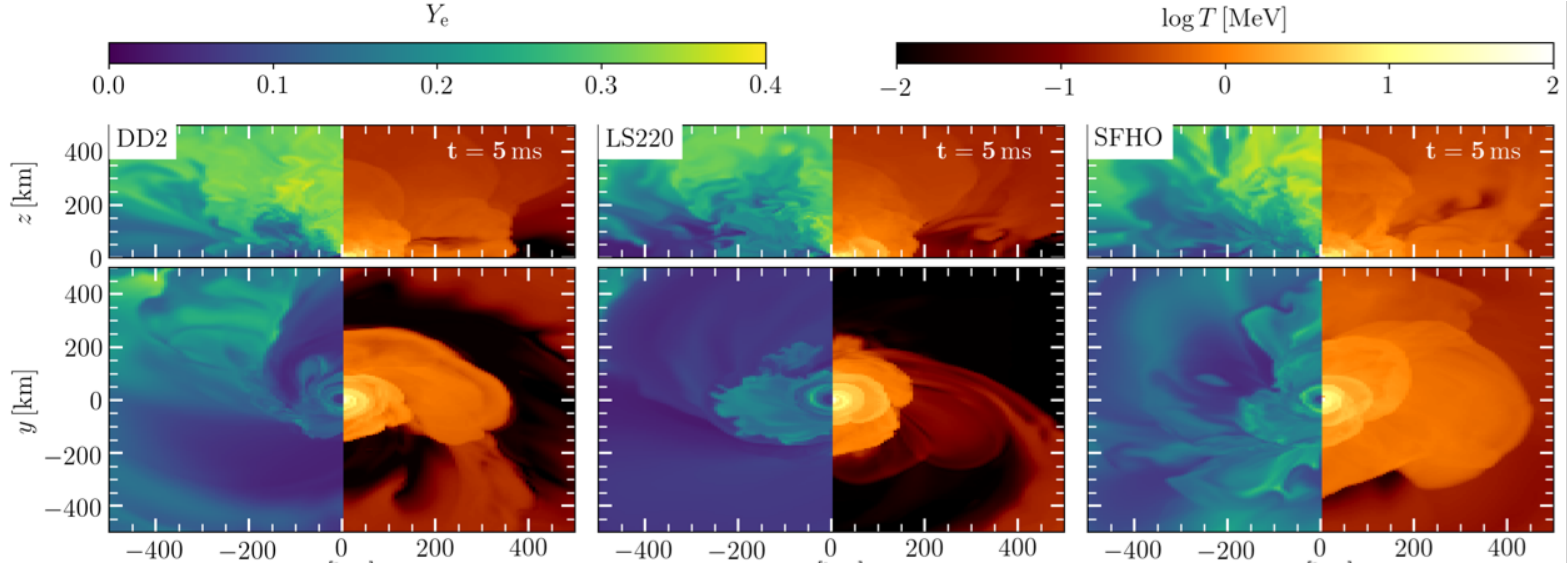
Identification of strontium in the merger of two neutron stars

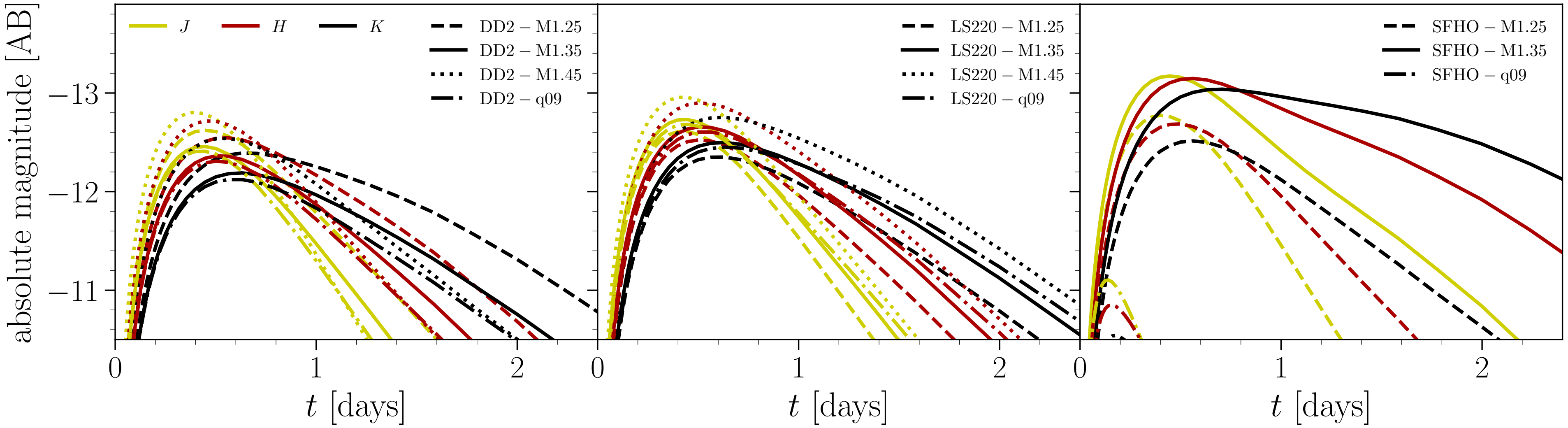
Darach Watson[1,2], Camilla J. Hansen[3,*], Jonatan Selsing[1,2,*], Andreas Koch[4], Daniele B. Malesani[1,2,5], Anja C. Andersen[1], Johan P. U. Fynbo[1,2], Almudena Arcones[6,7], Andreas Bauswein[7,8], Stefano Covino[9], Aniello Grado[10], Kasper E. Heintz[1,2,11], Leslie Hunt[12], Chryssa Kouveliotou[13,14] Giorgos Leloudas[1,5], Andrew Levan[15,16], Paolo Mazzali[17,18], Elena Pian[19] [See end for affiliations]



Equation of state and neutrinos

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





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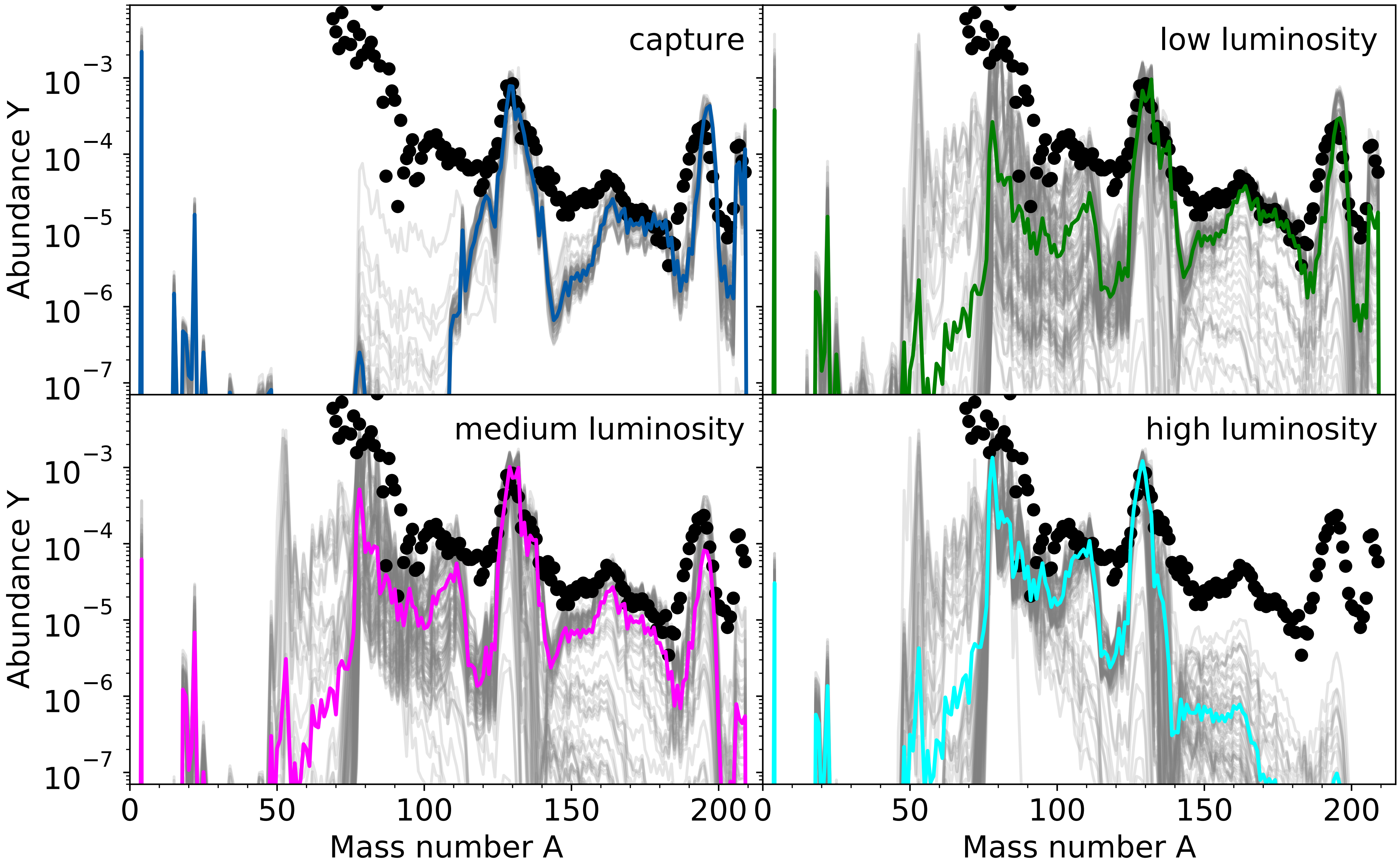
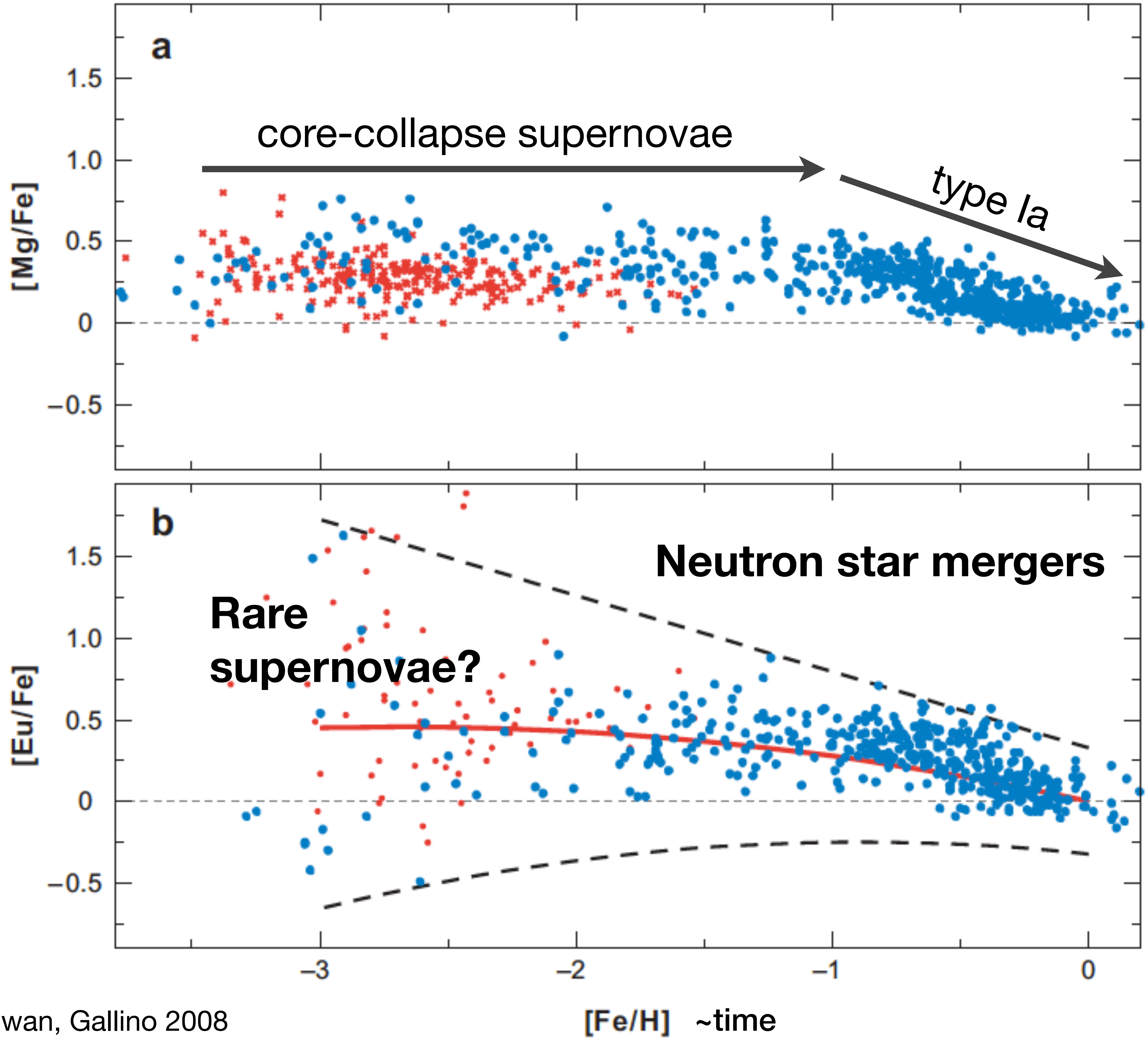
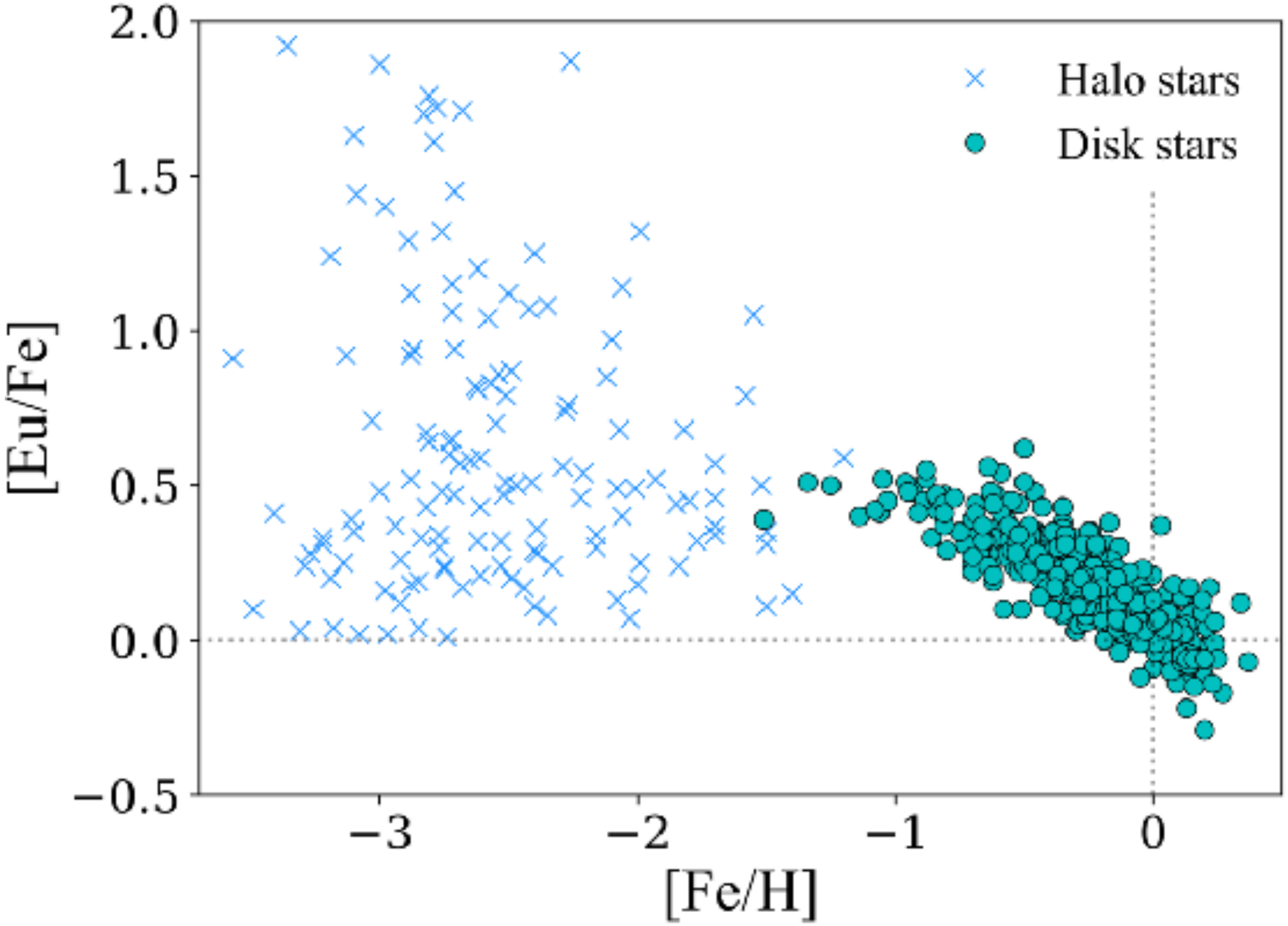


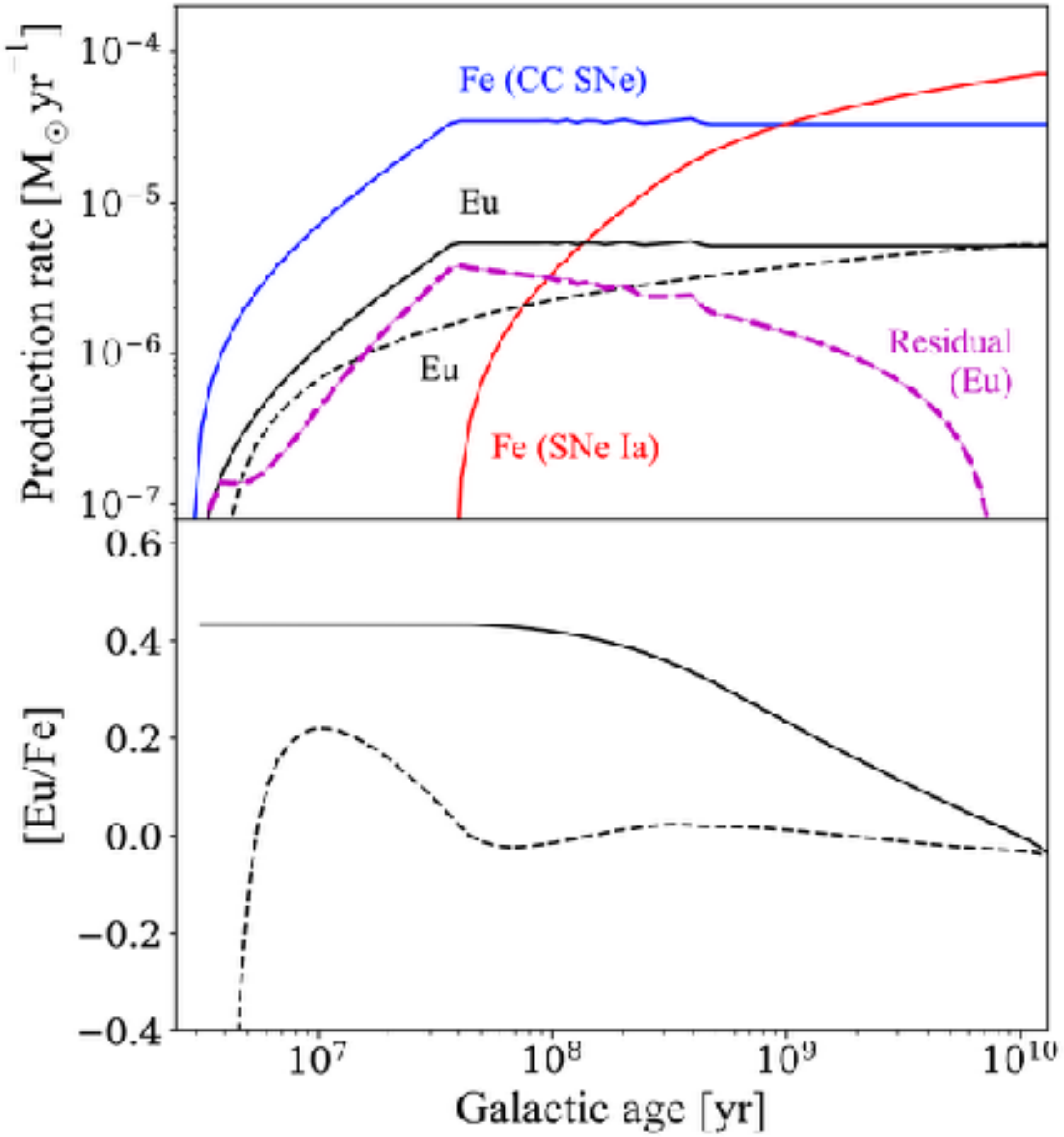
Trends with metallicity



Sneden, Cowan, Gallino 2008

Galactic chemical evolution



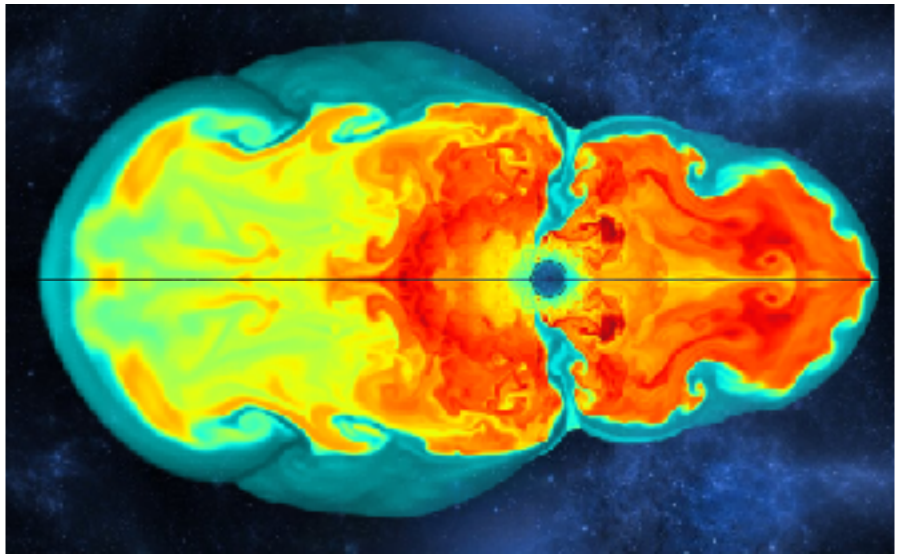


Scatter at low metallicities: rare event, Eu ejected early

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

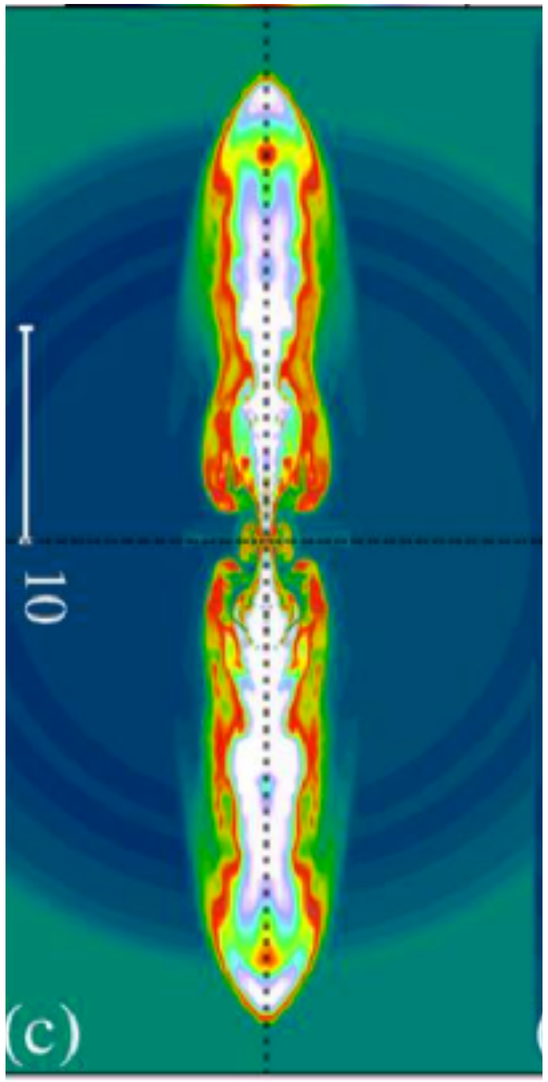
Côté et al. 2019

Core-collapse supernovae



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

Bliss et al. 2018: astro uncertainties



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

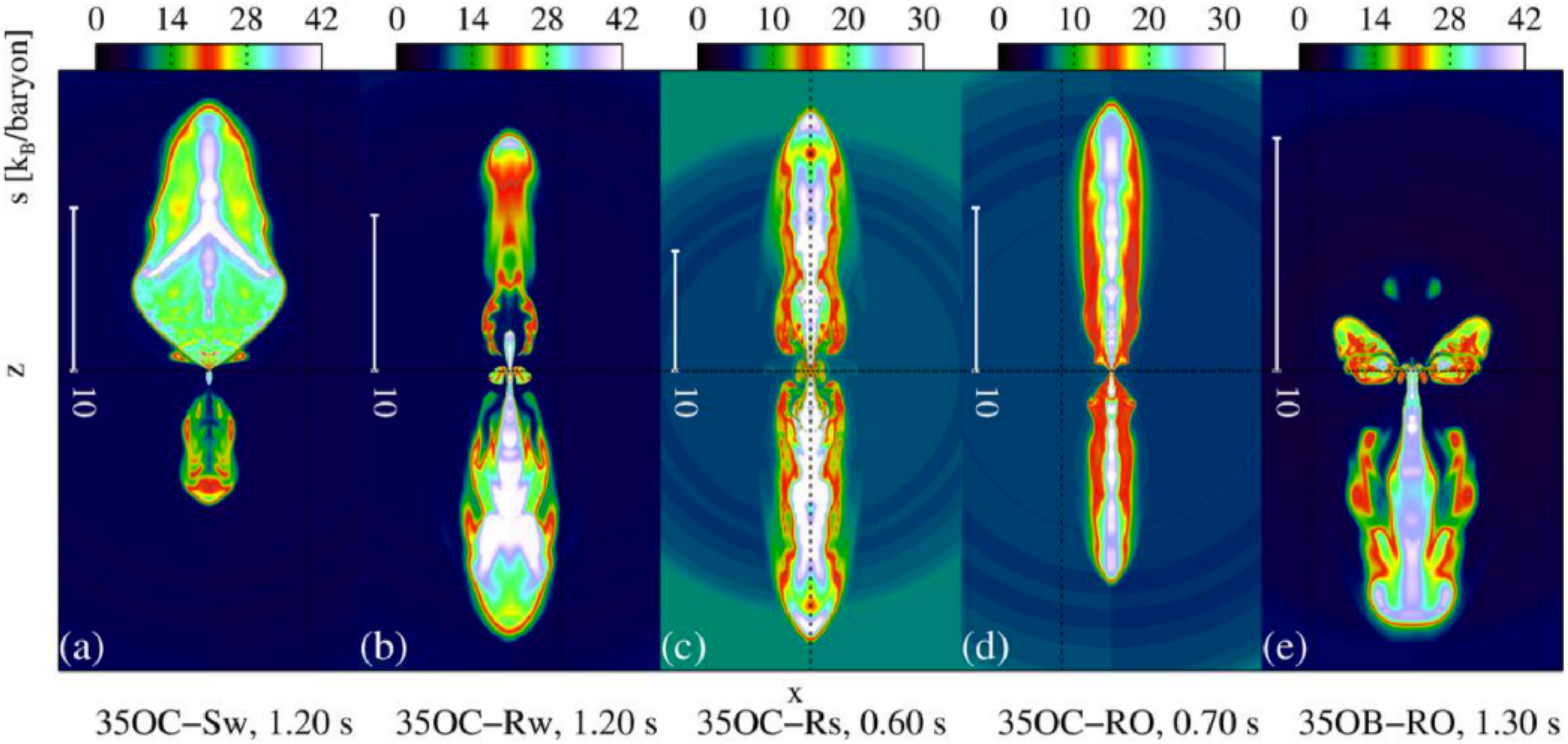
2D and 3D + parametric neutrino treatment :

- jet-like explosion: heavy r-process
- magnetic field vs. neutrinos: weak r-process

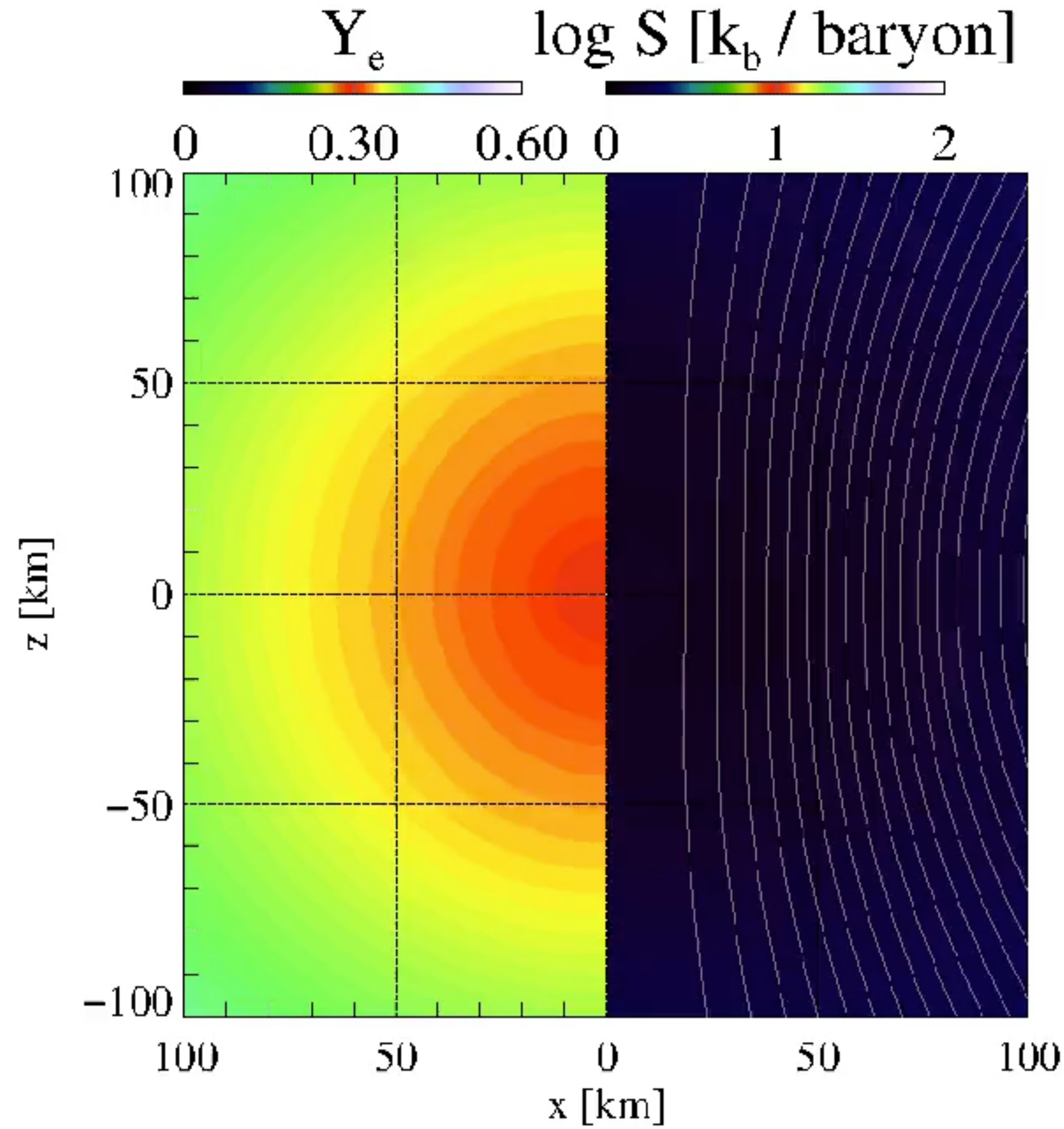
Nishimura et al. 2015, 2017, Winteler et al. 2012, Mösta et al. 2018

Magneto-rotational supernovae: r-process

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



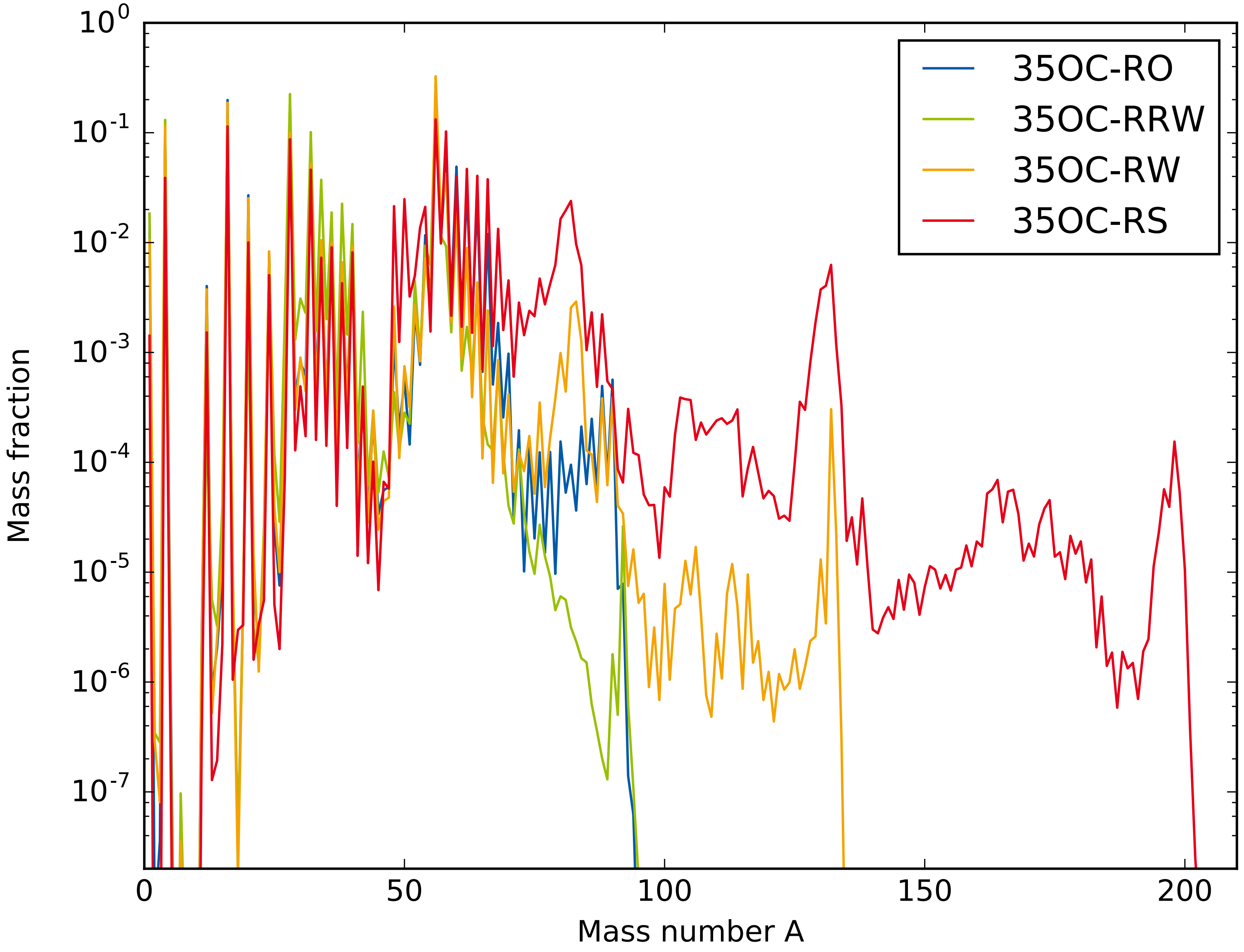
Obergaulinger & Aloy (2017)



Martin Obergaulinger

t = 0.4000 s

Impact of rotation and magnetic field

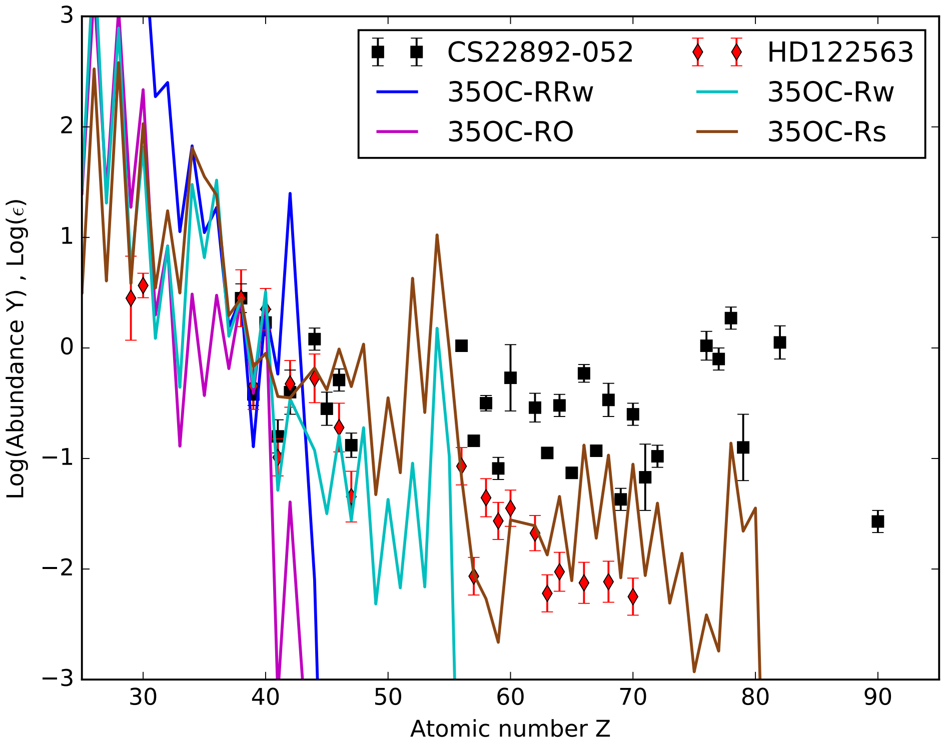


RO: progenitor

RRW: weak mag. field
strong rot.

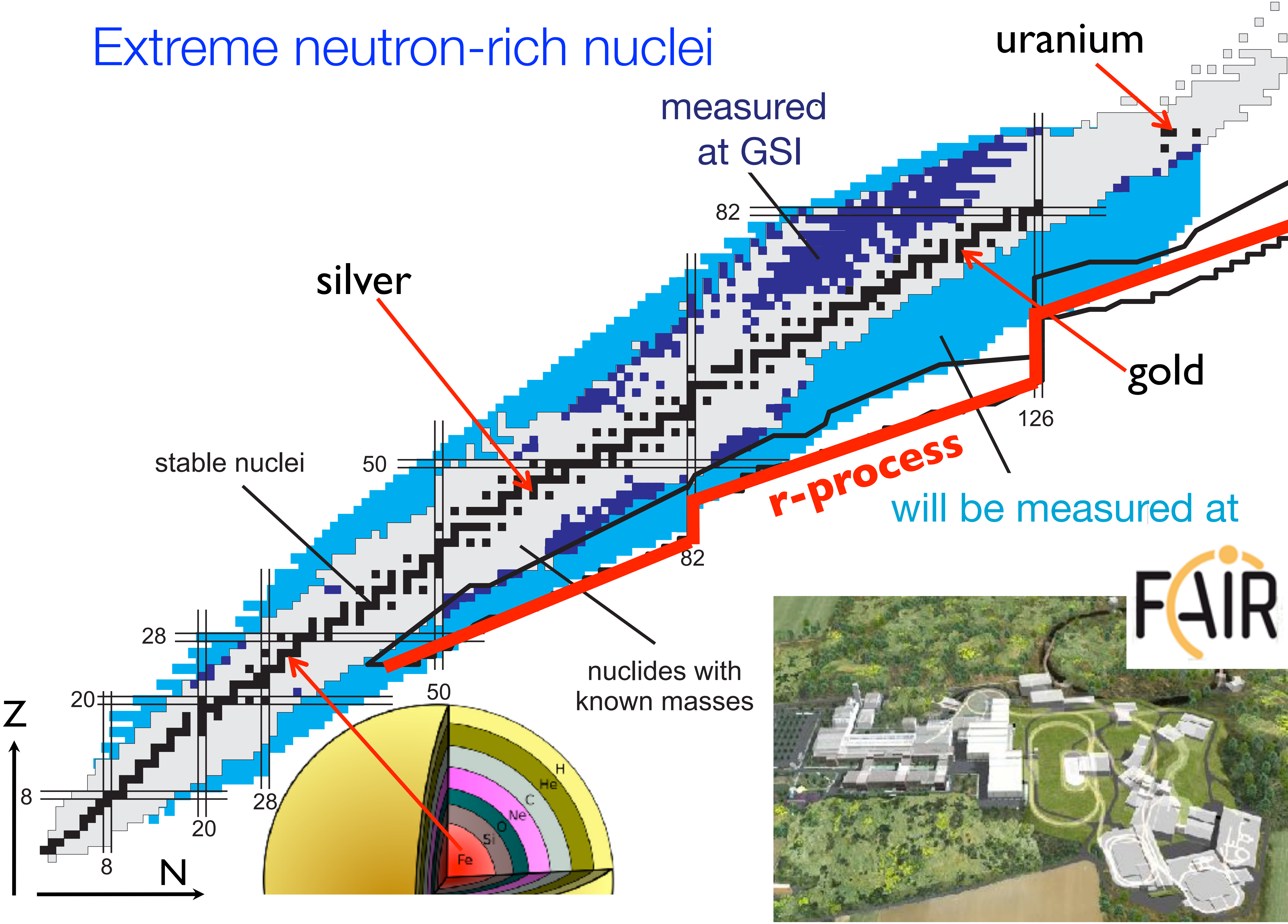
RW: weak mag. field

RS: strong mag. Field



Reichert, Obergaulinger, Aloy, Arcones (in prep)

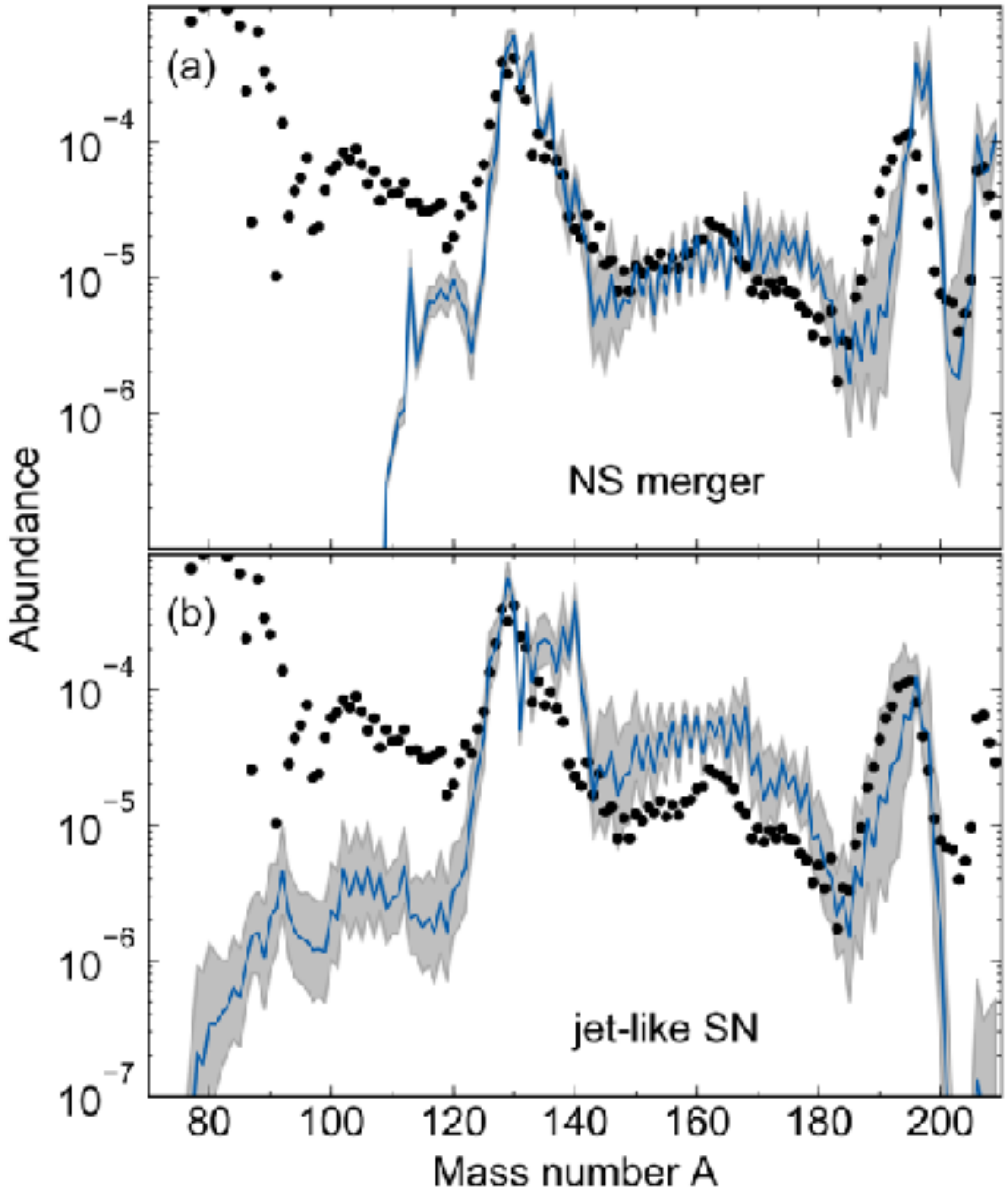
Extreme neutron-rich nuclei



Nuclear 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



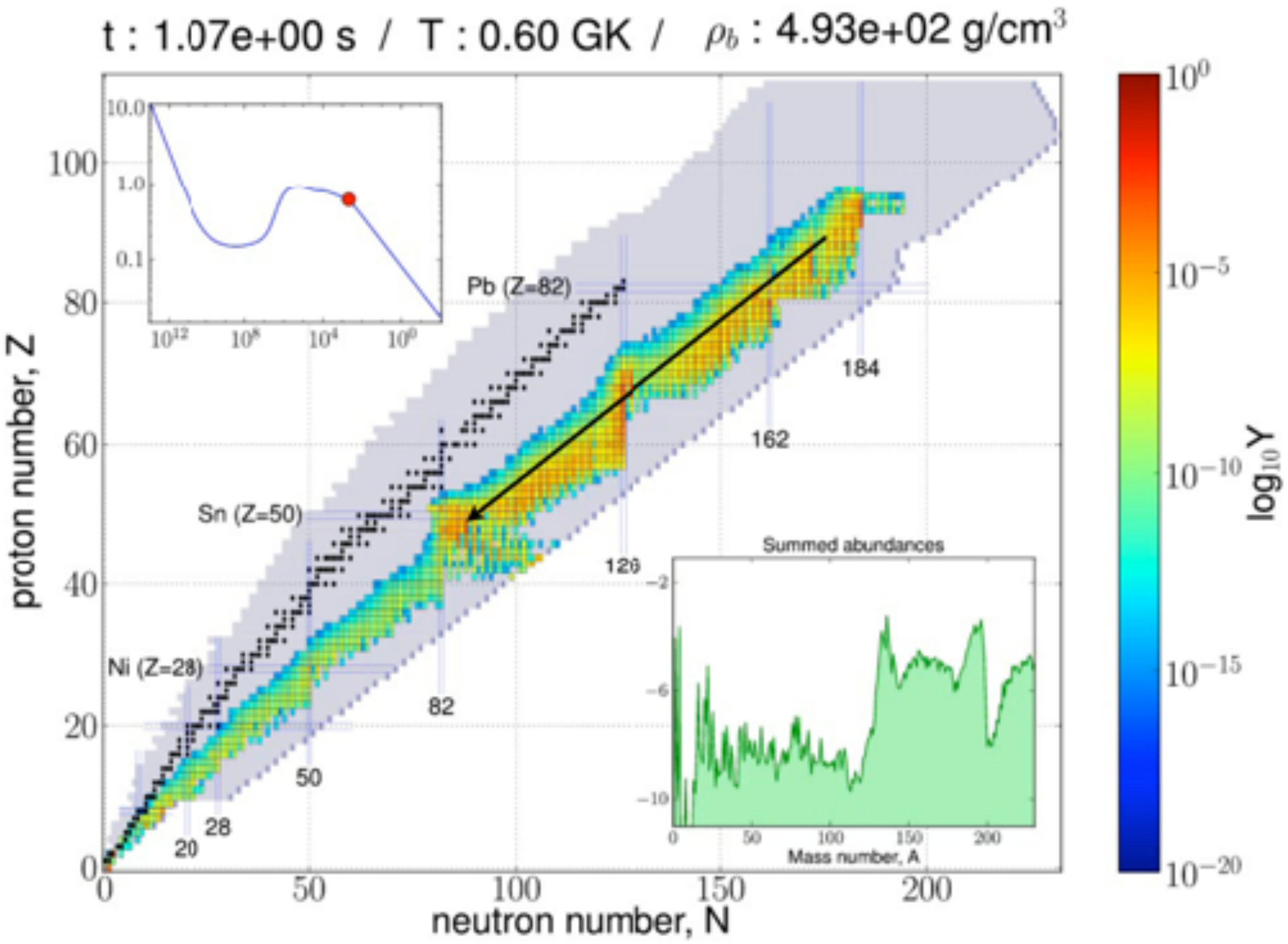
Martin, Arcones, Nazarewicz, Olsen (2016)

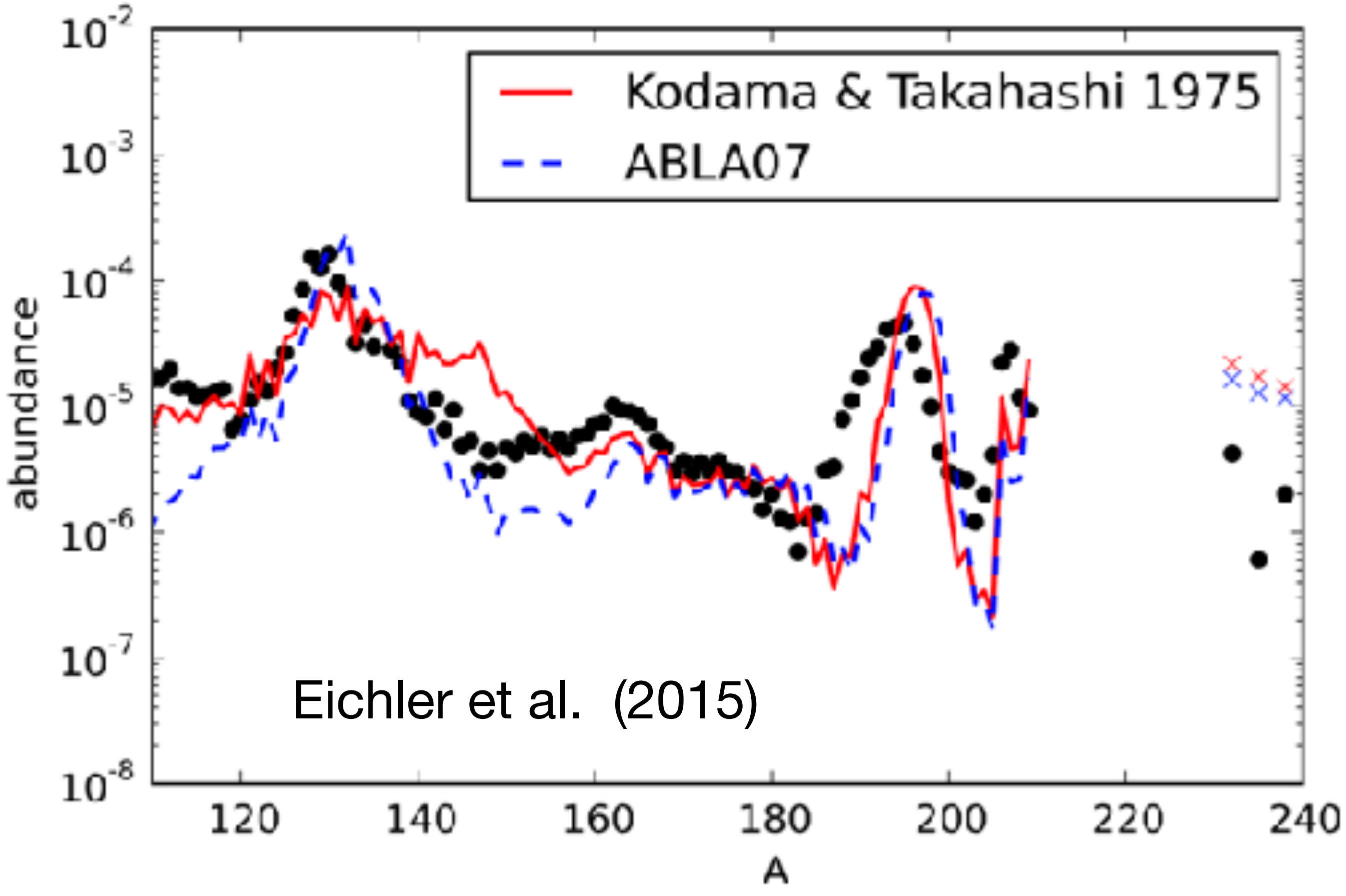
First systematic uncertainty band
for r-process abundances

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?

Fission: barriers and yield distributions



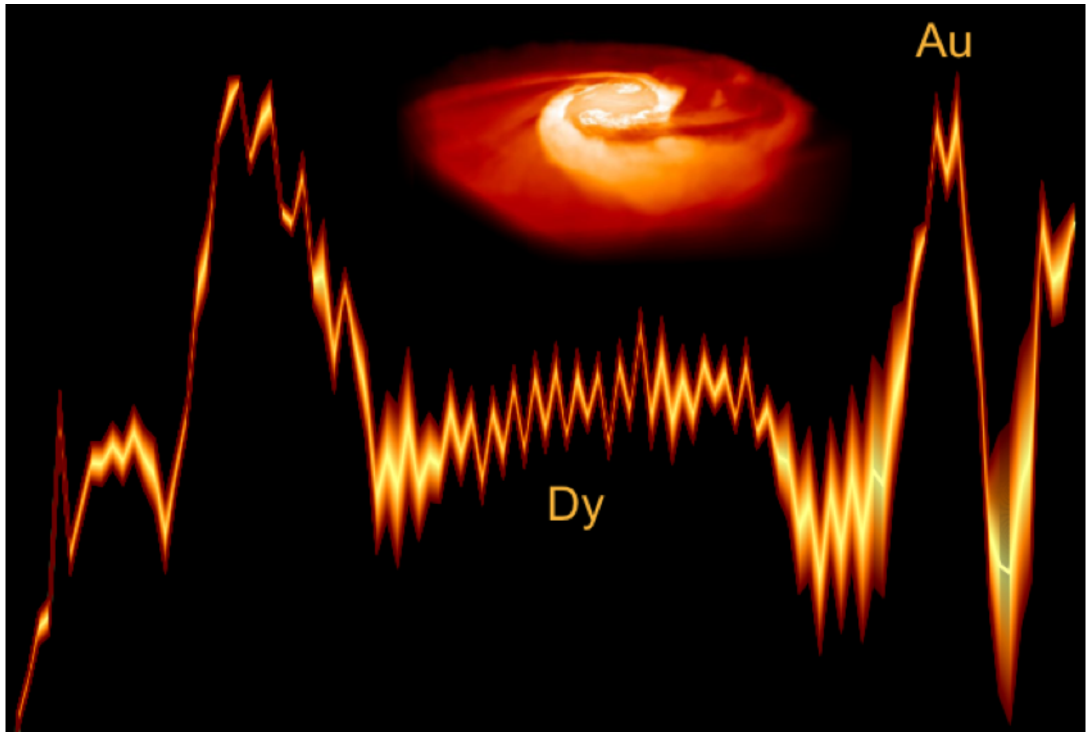


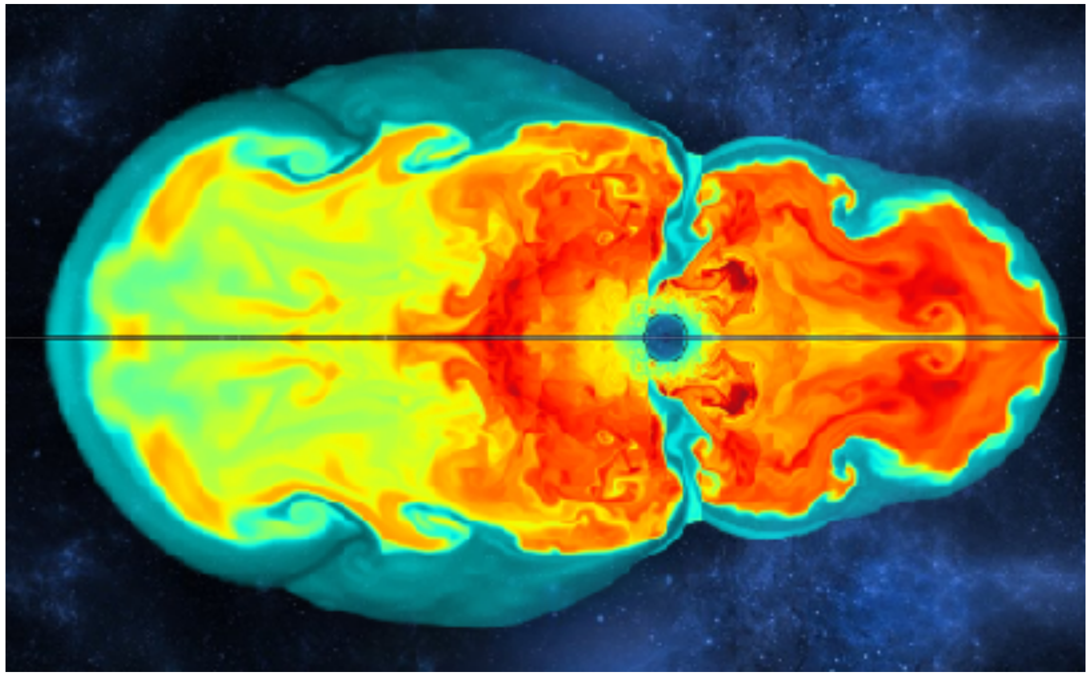
Eichler et al. (2015)

Neutron star mergers: r-process with two fission descriptions

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

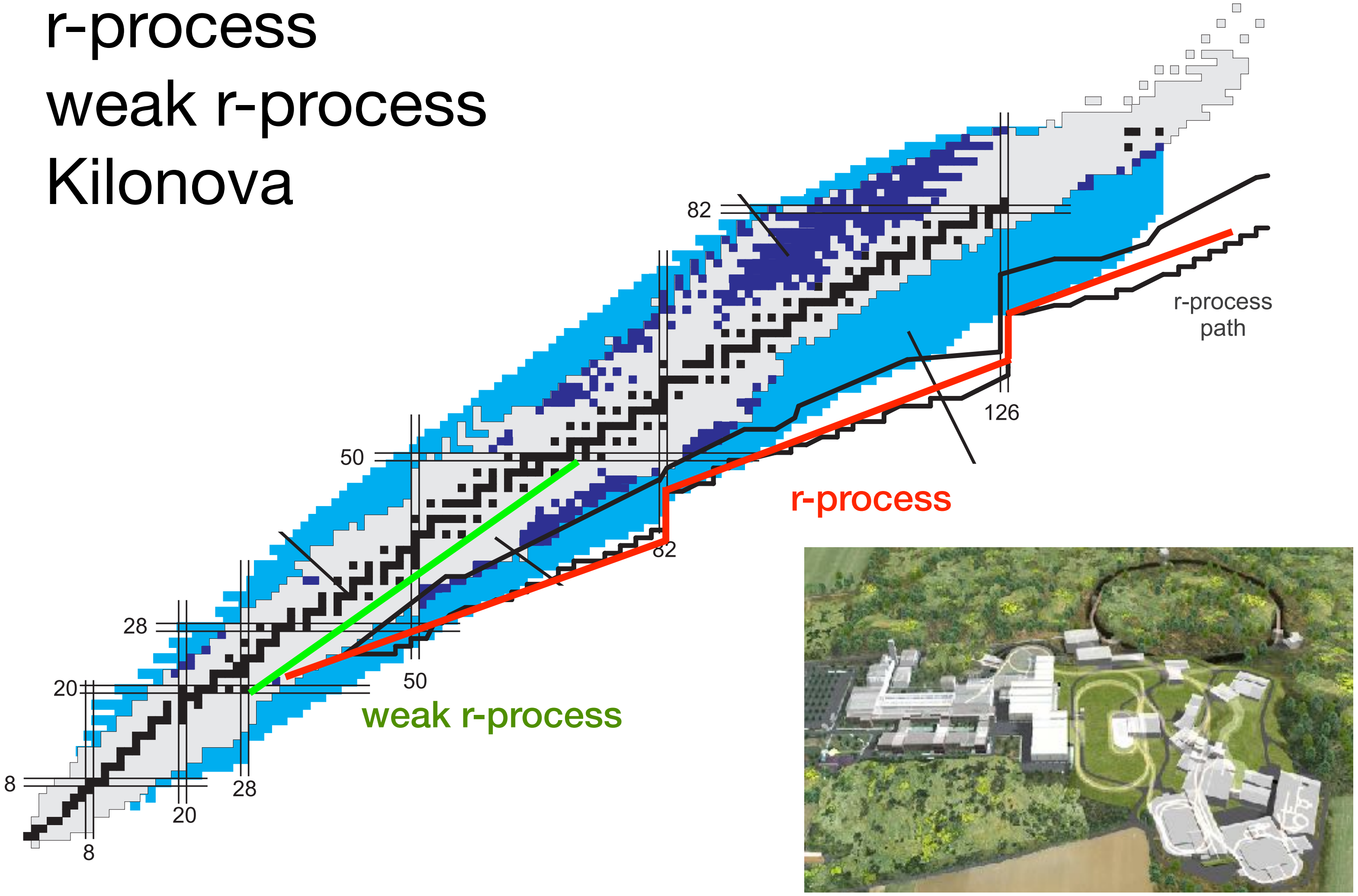
Conclusions





Neutron star mergers:

r-process
weak r-process
Kilonova



Core-collapse supernovae:

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

FAIR

New era

Heavy elements synthesized in
neutron star mergers and core-collapse supernovae

Multimessenger astronomy: EM+GW+neutrinos

Improved astrophysical simulations + detailed microphysics (supercomputers)

New experimental frontier: extreme-neutron rich nuclei
(FAIR, FRIB, RIKEN, TRIUMF,…)

Observations of oldest stars (E-ELT, ESPRESSO,…)

Neutron star mergers and core-collapse supernovae
laboratories for physics at the extremes