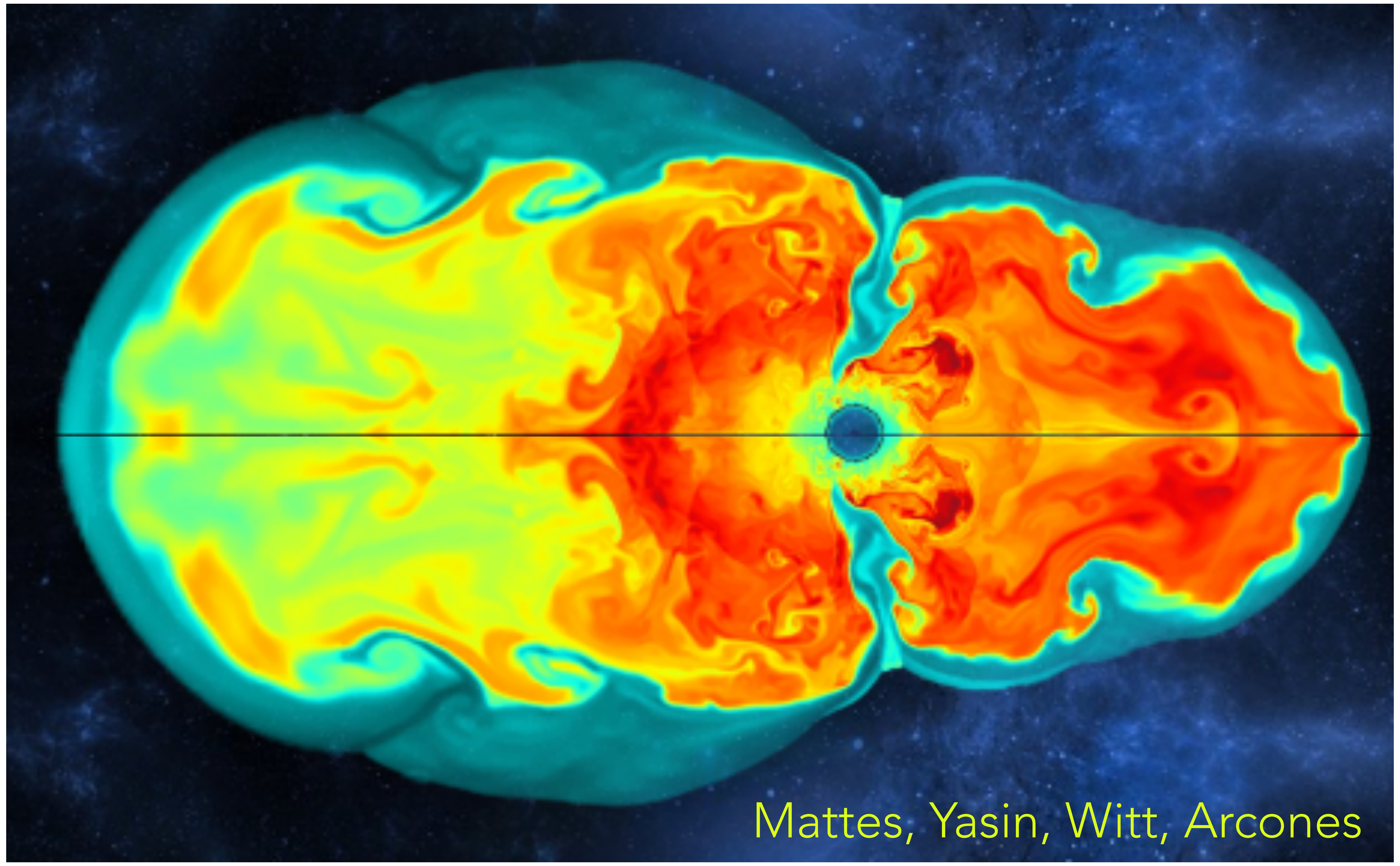
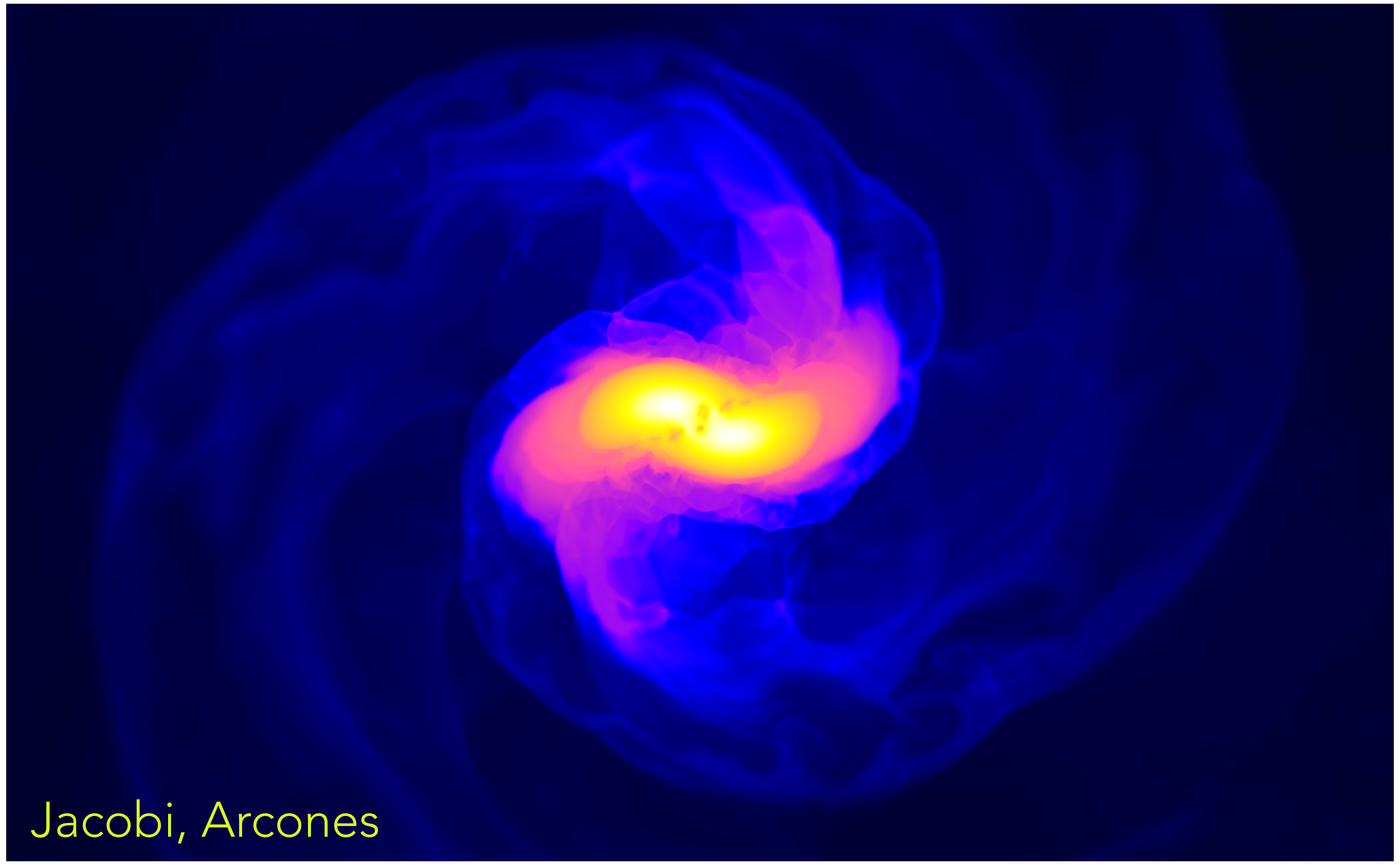
60th International Winter Meeting on Nuclear Physics
Bormio, 22 - 26 January 2024

Core-collapse supernovae and neutron star mergers





Almudena Arcones

European Research Council
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GSI

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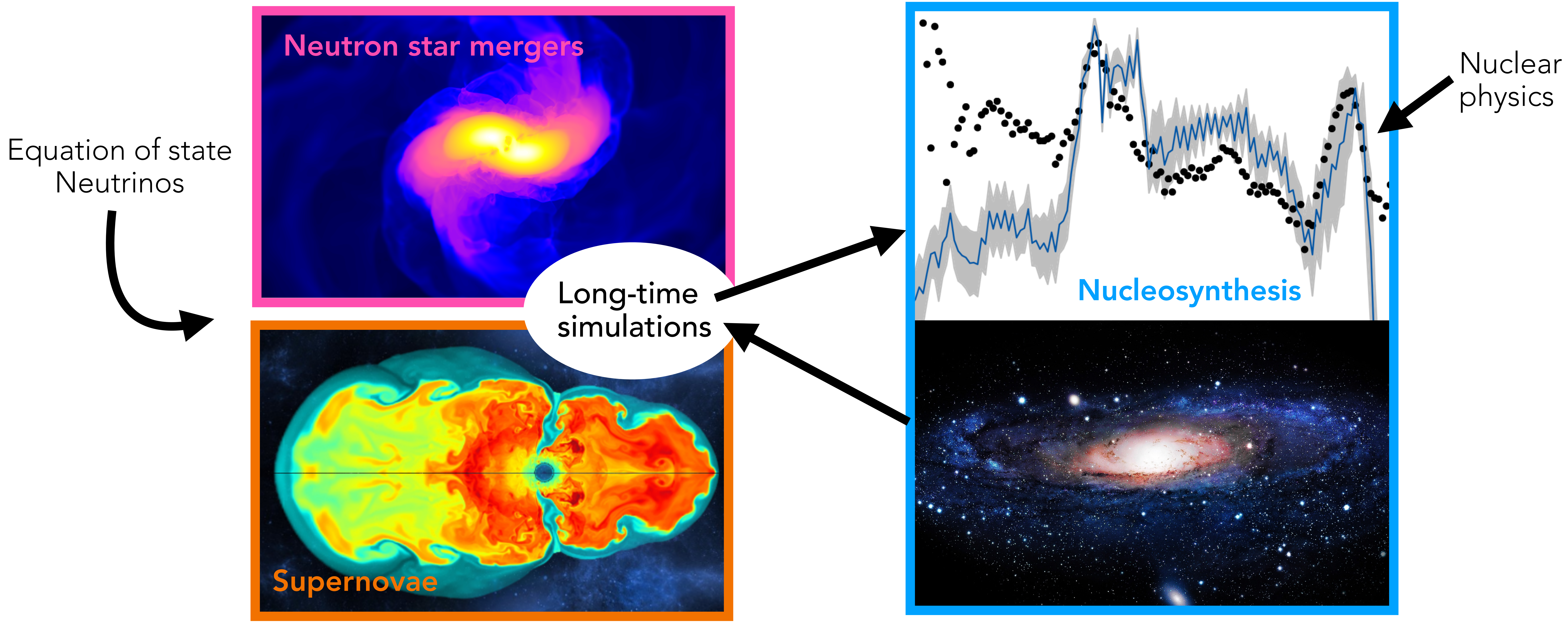
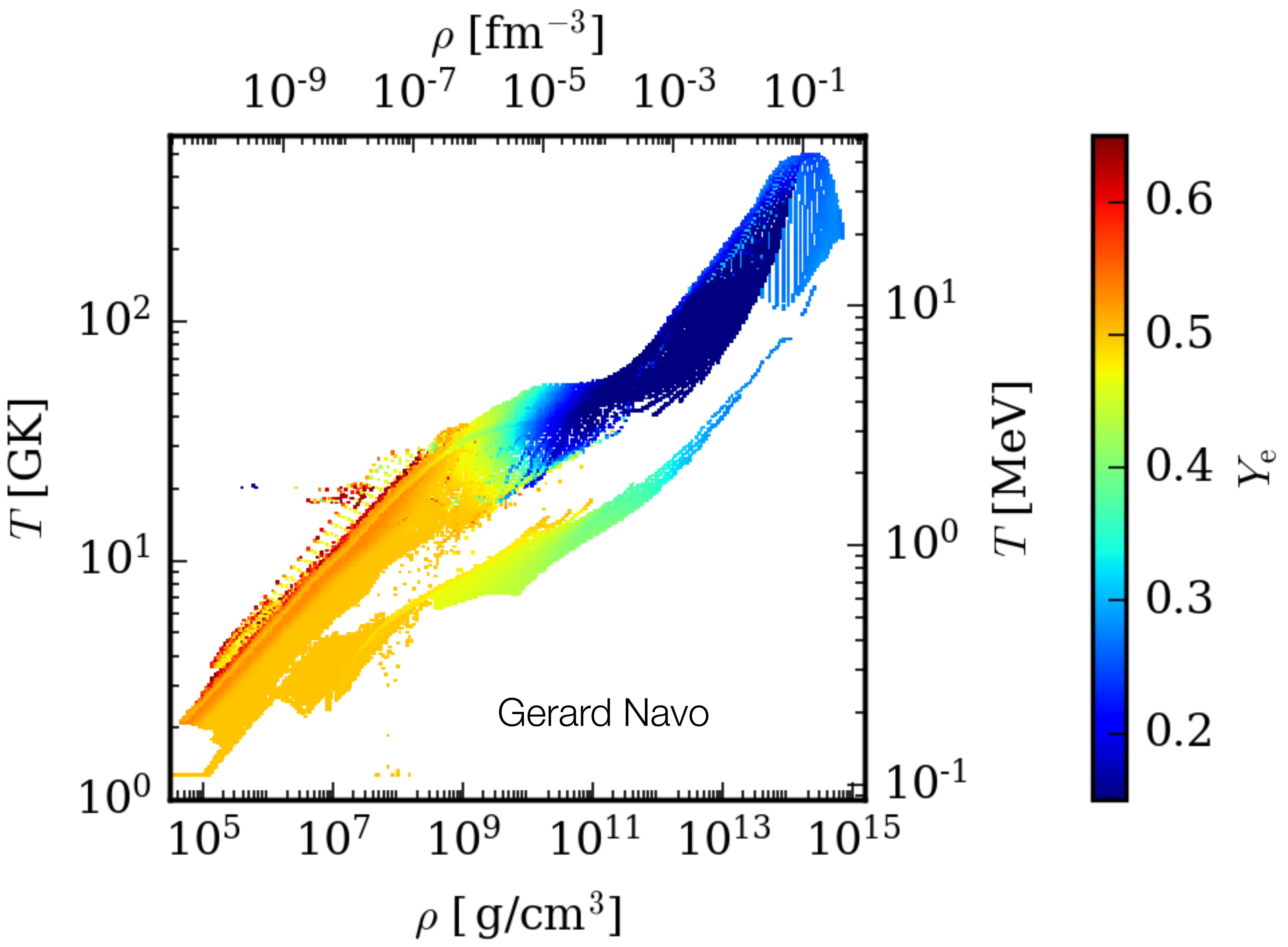
Cosmic laboratories for nuclear physics

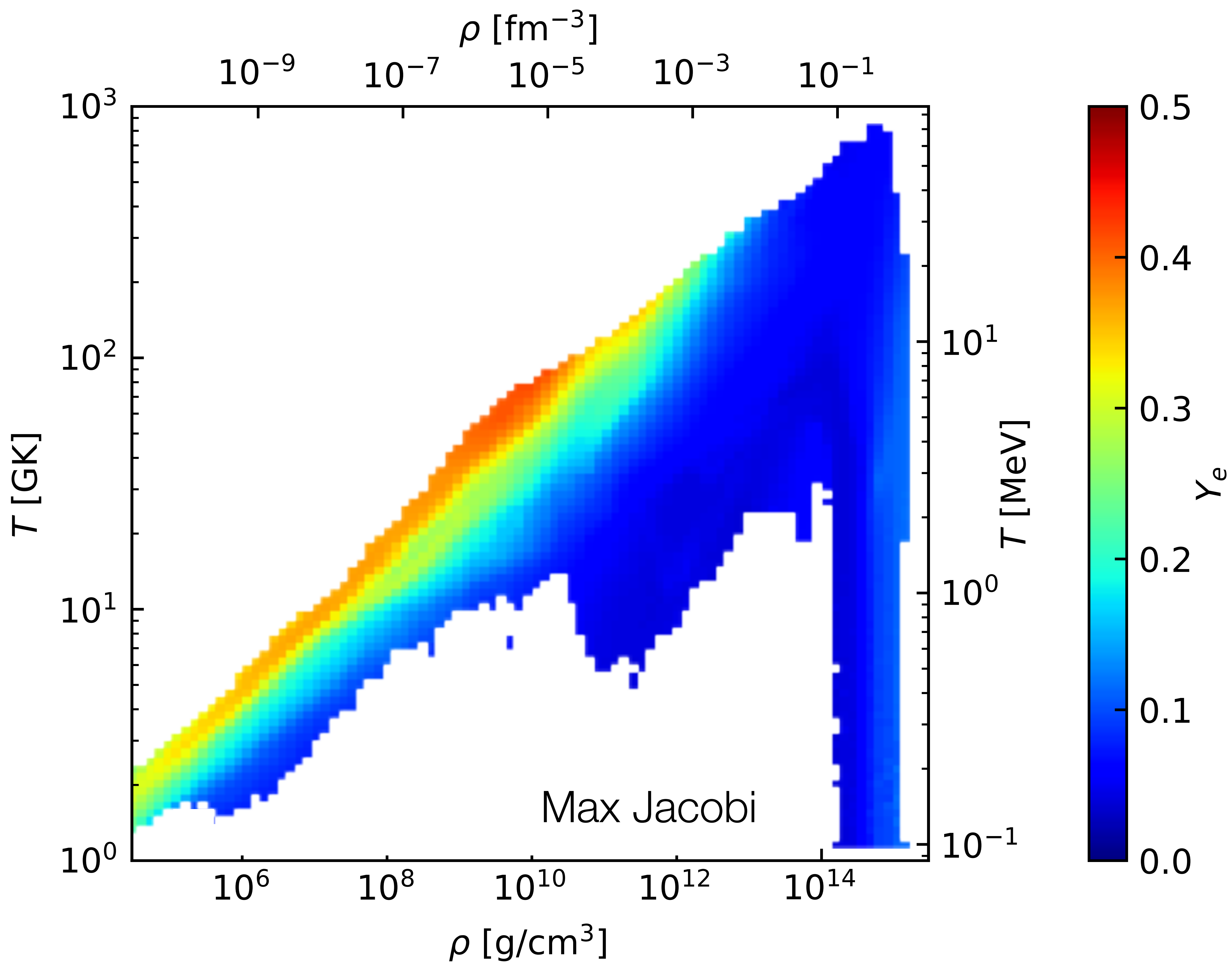


Extreme conditions

Core-collapse supernovae

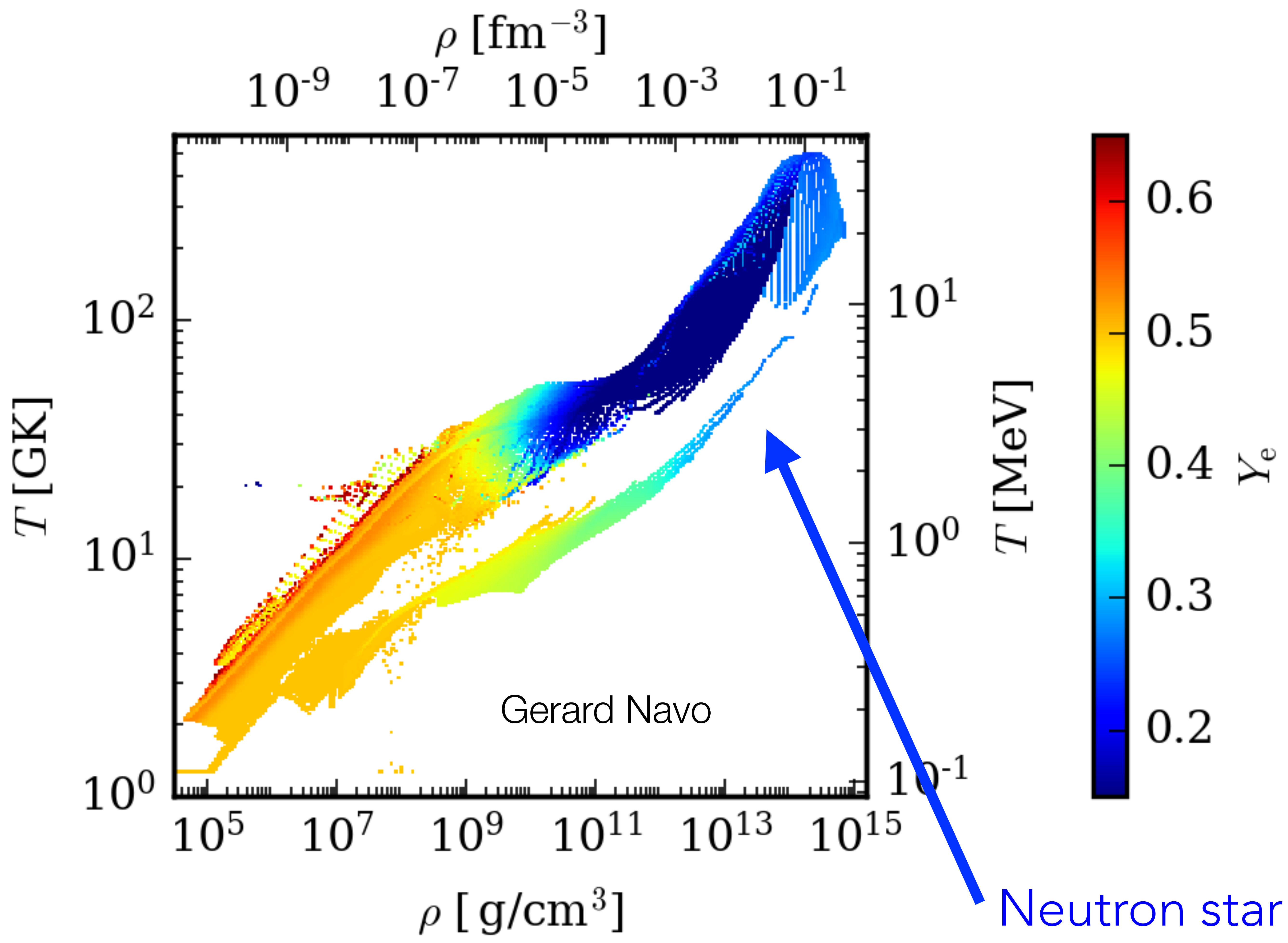


Neutron star mergers

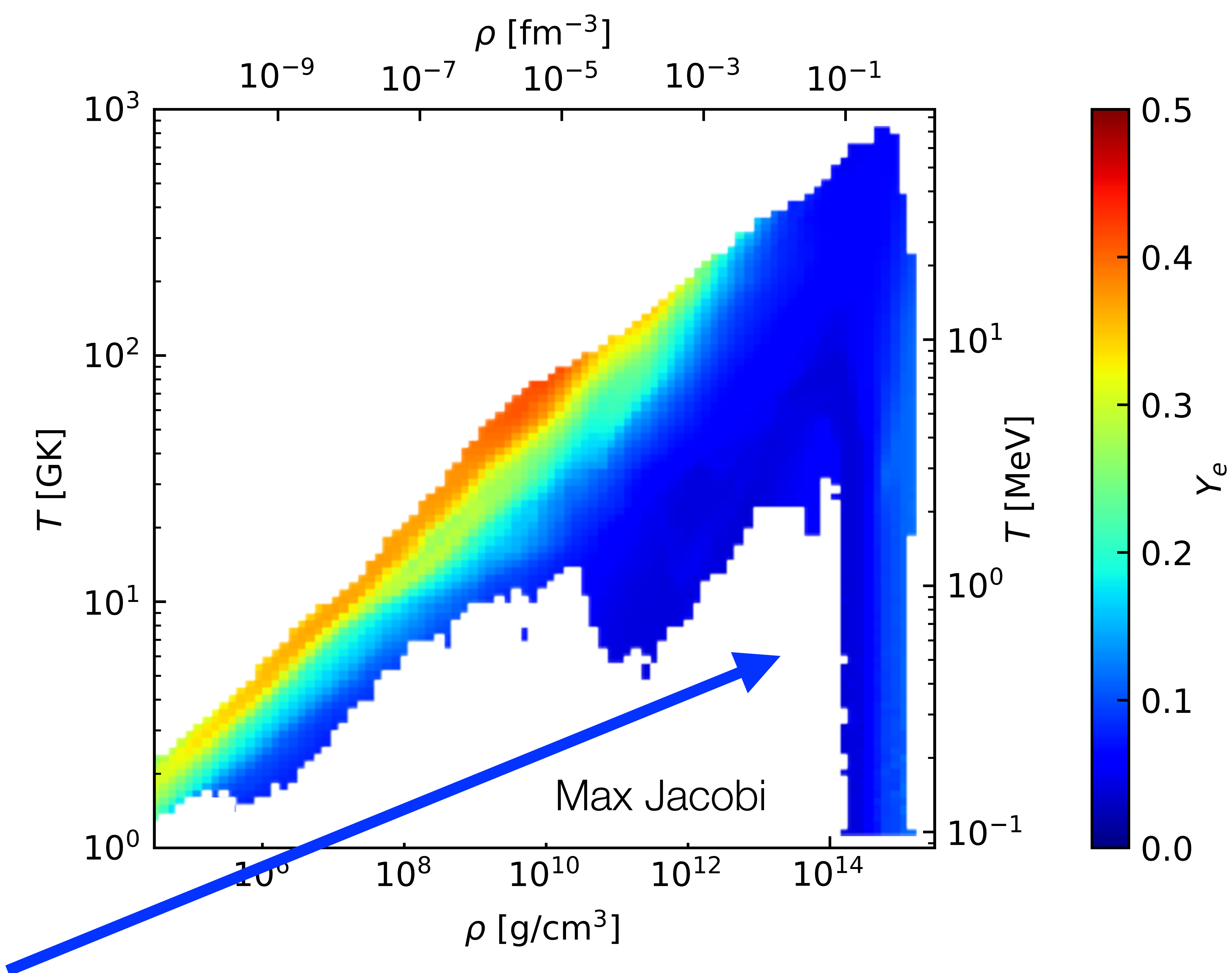


Extreme conditions

Core-collapse supernovae



Neutron star mergers

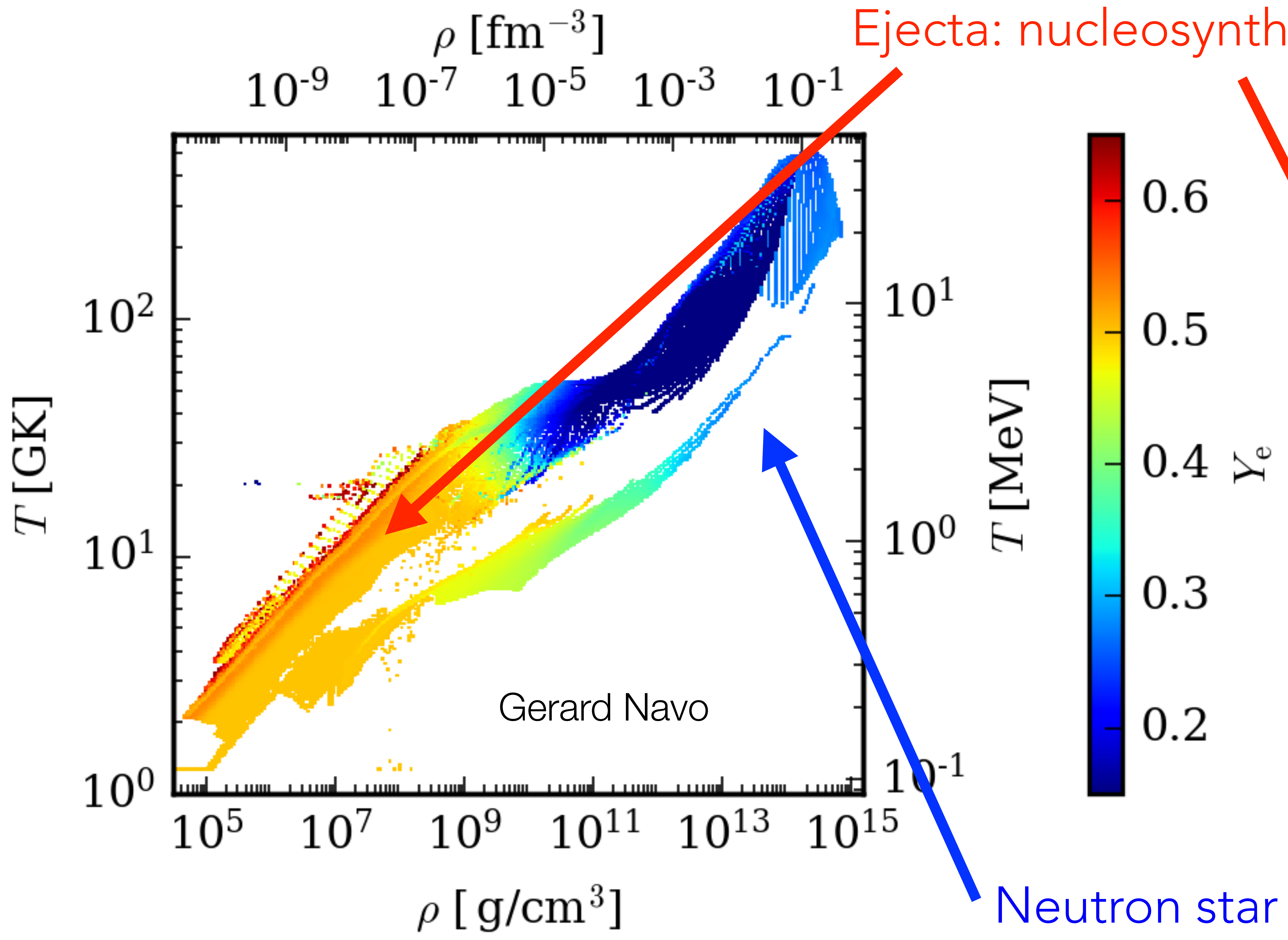


Neutron star

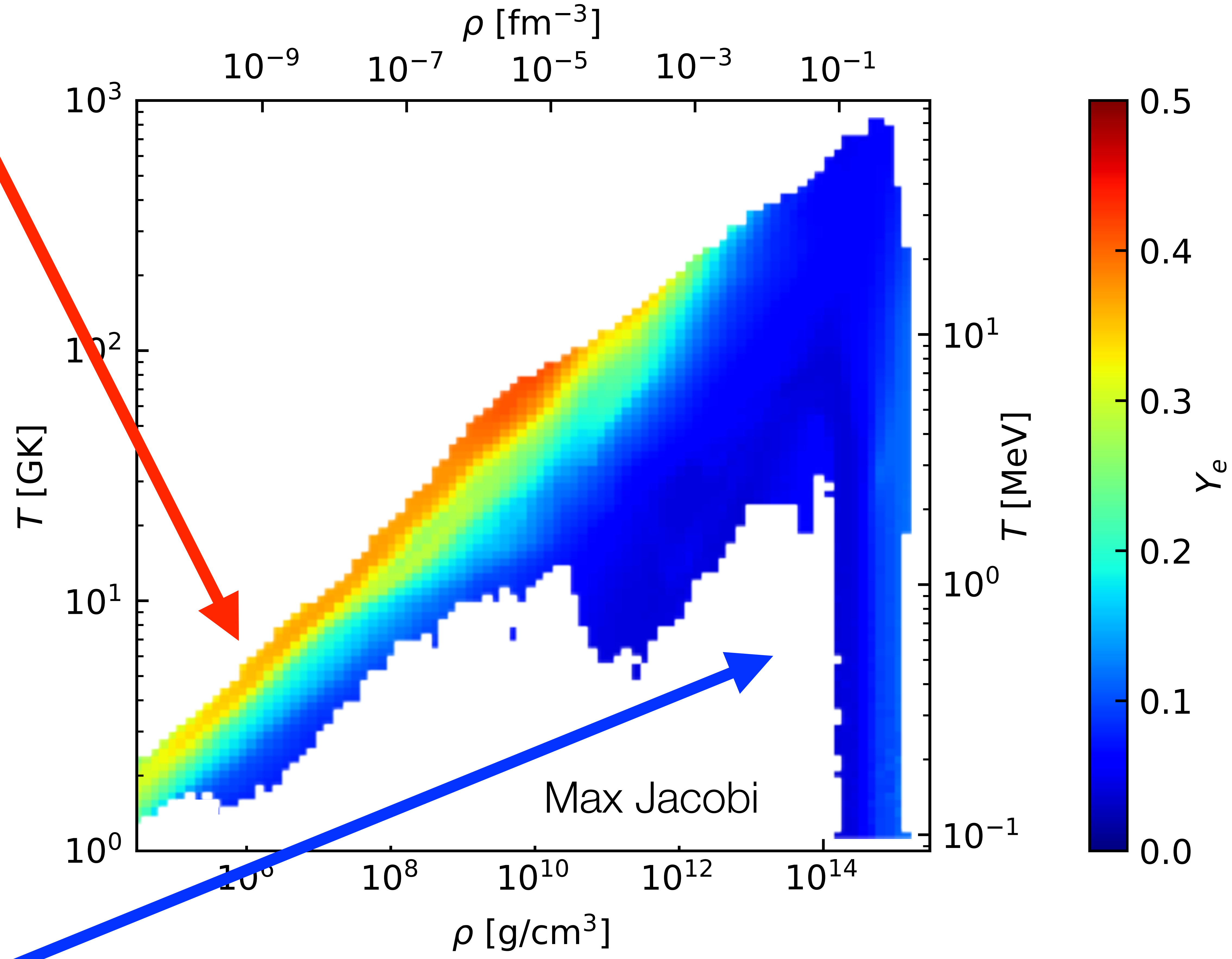
Extreme conditions

Core-collapse supernovae

Neutron star mergers

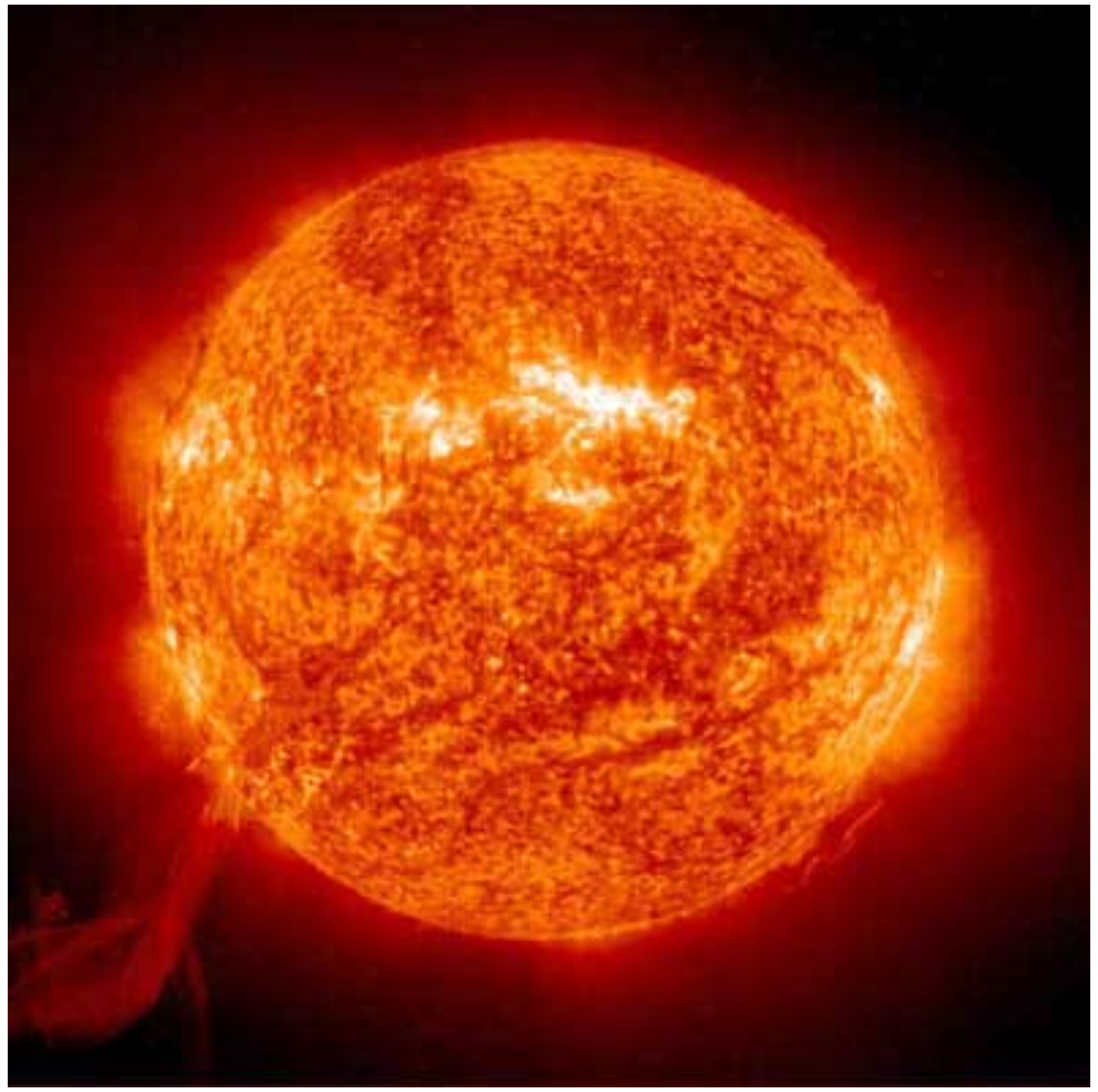


Ejecta: nucleosynthesis

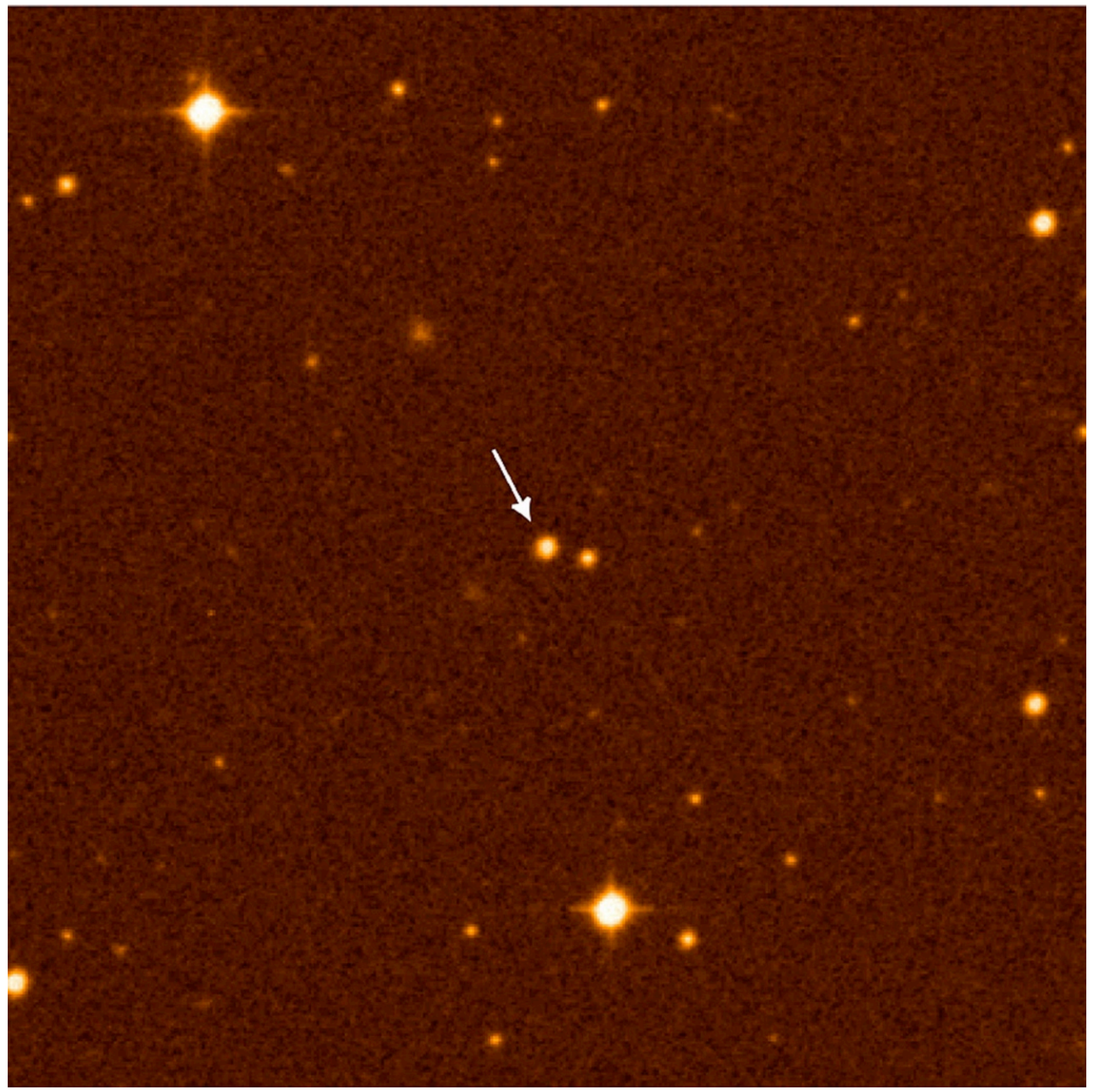


Neutron star

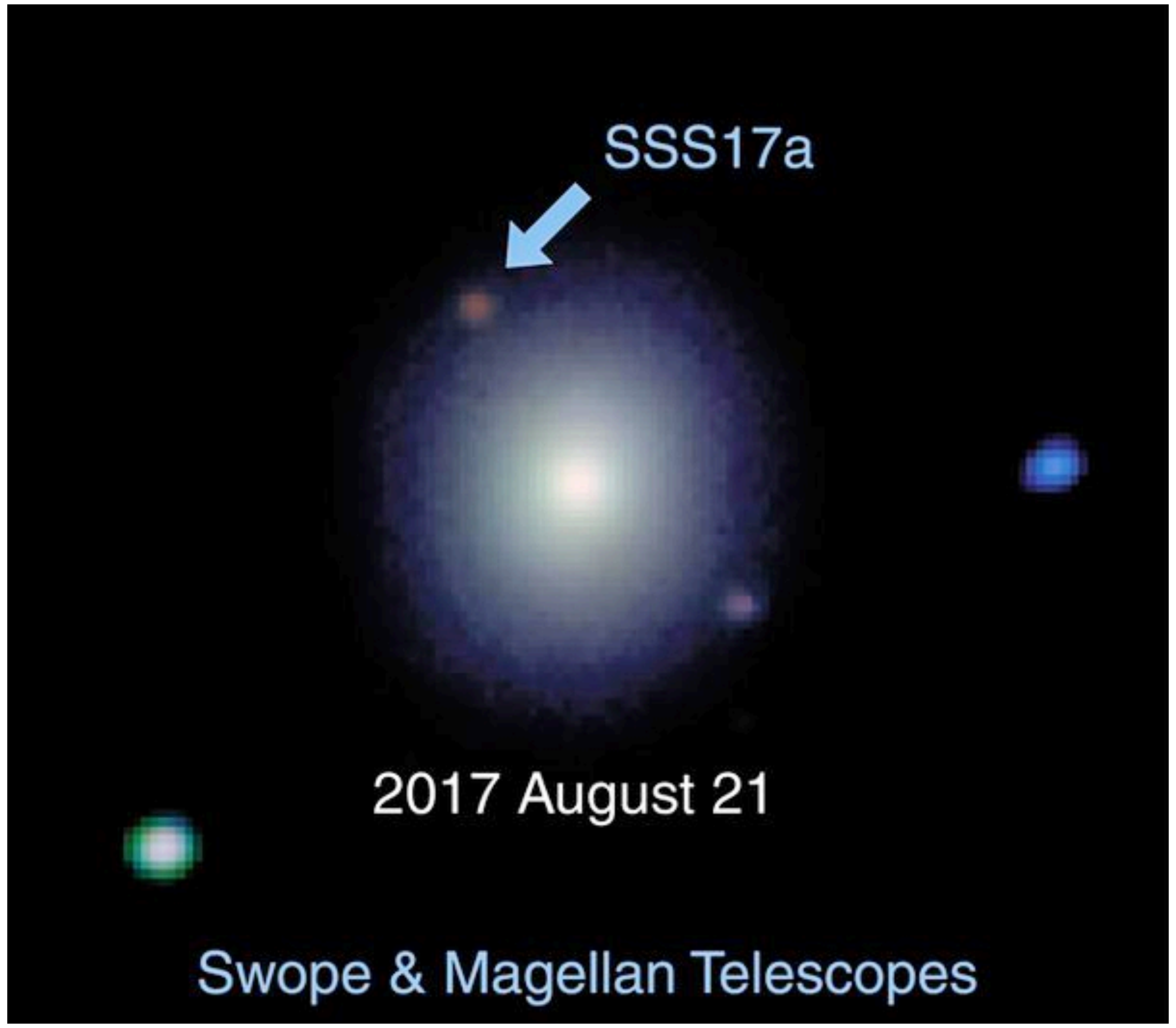
Observable: heavy elements produced by the r-process



Solar system

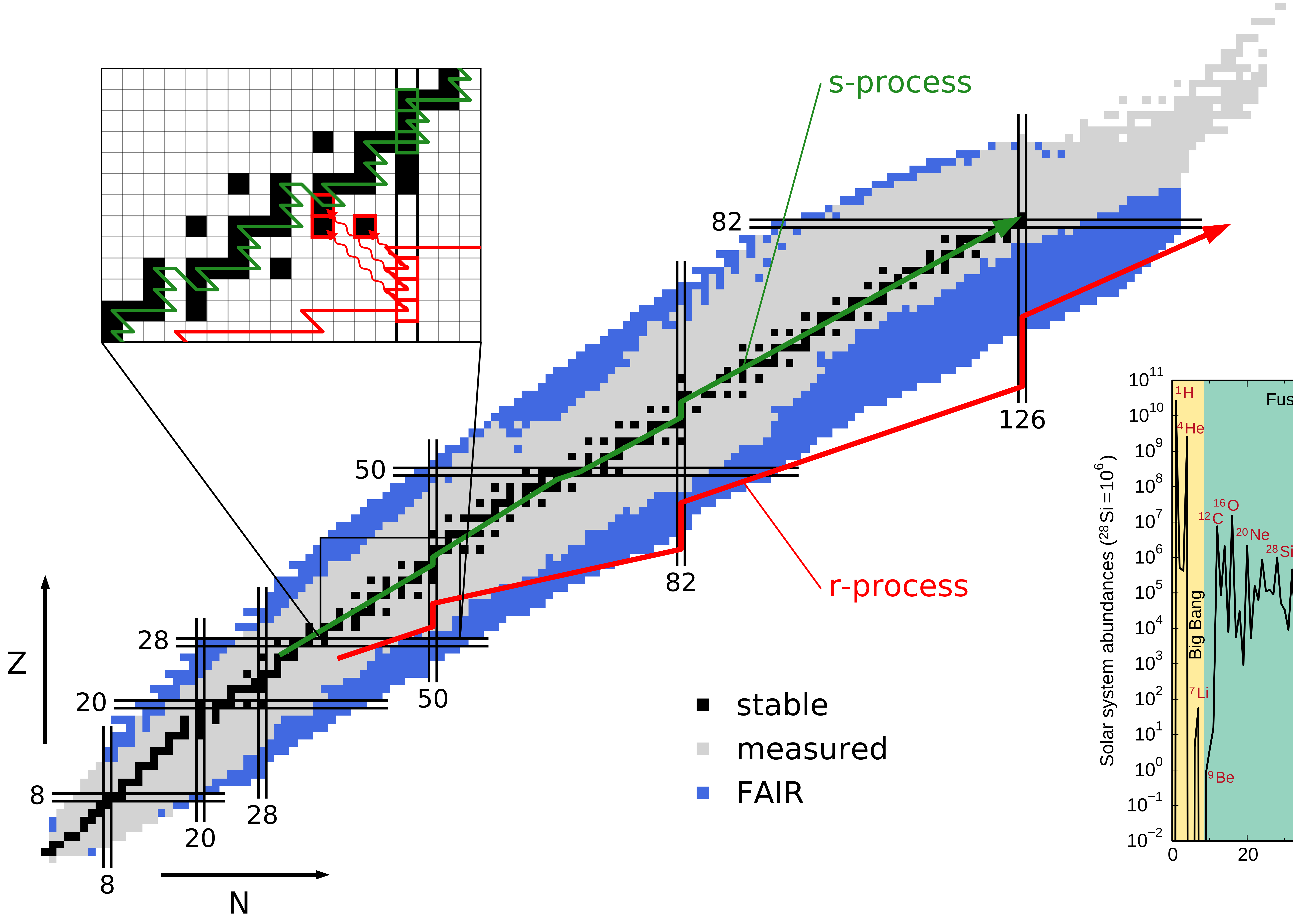


Oldest stars

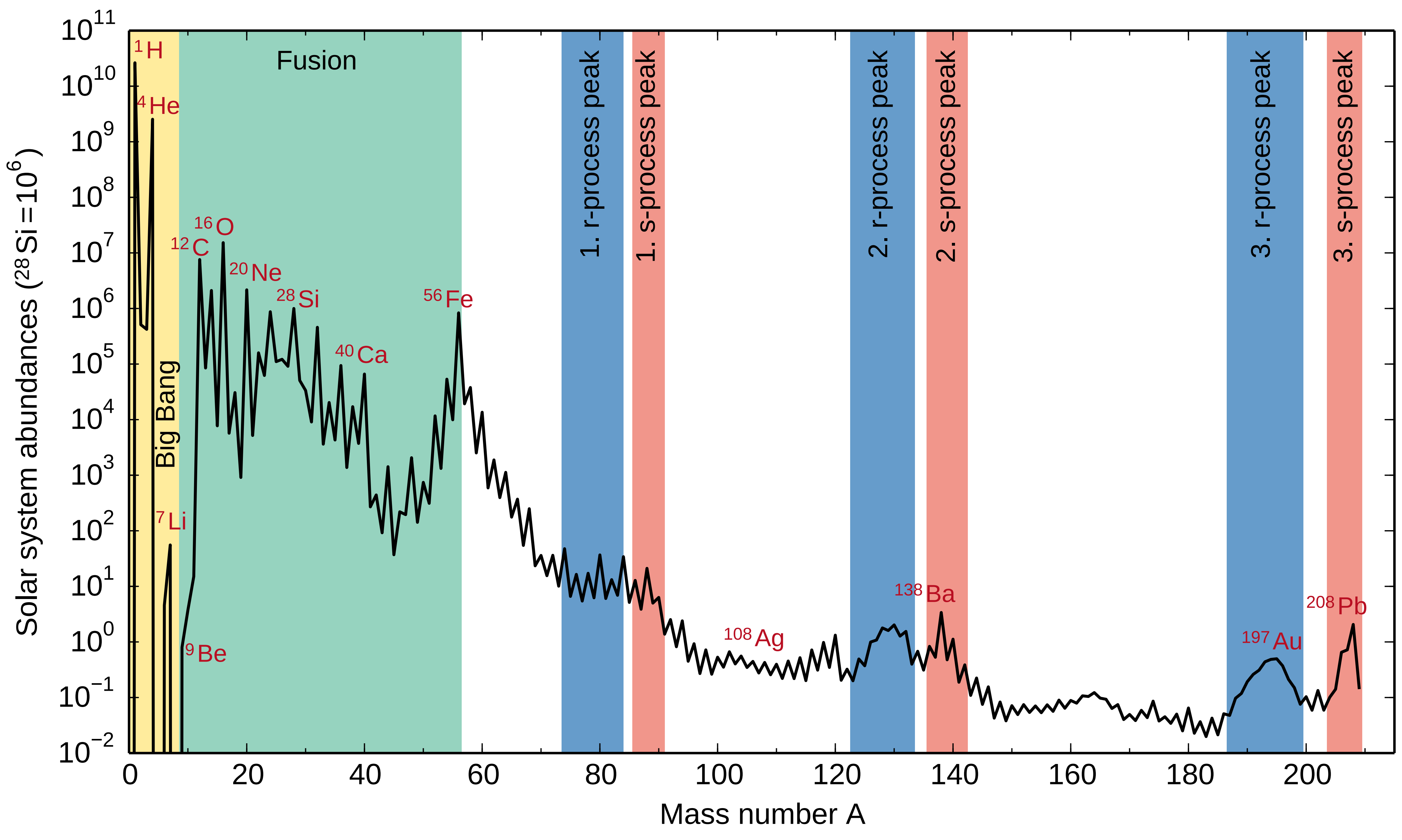


Kilonova

Neutron capture processes

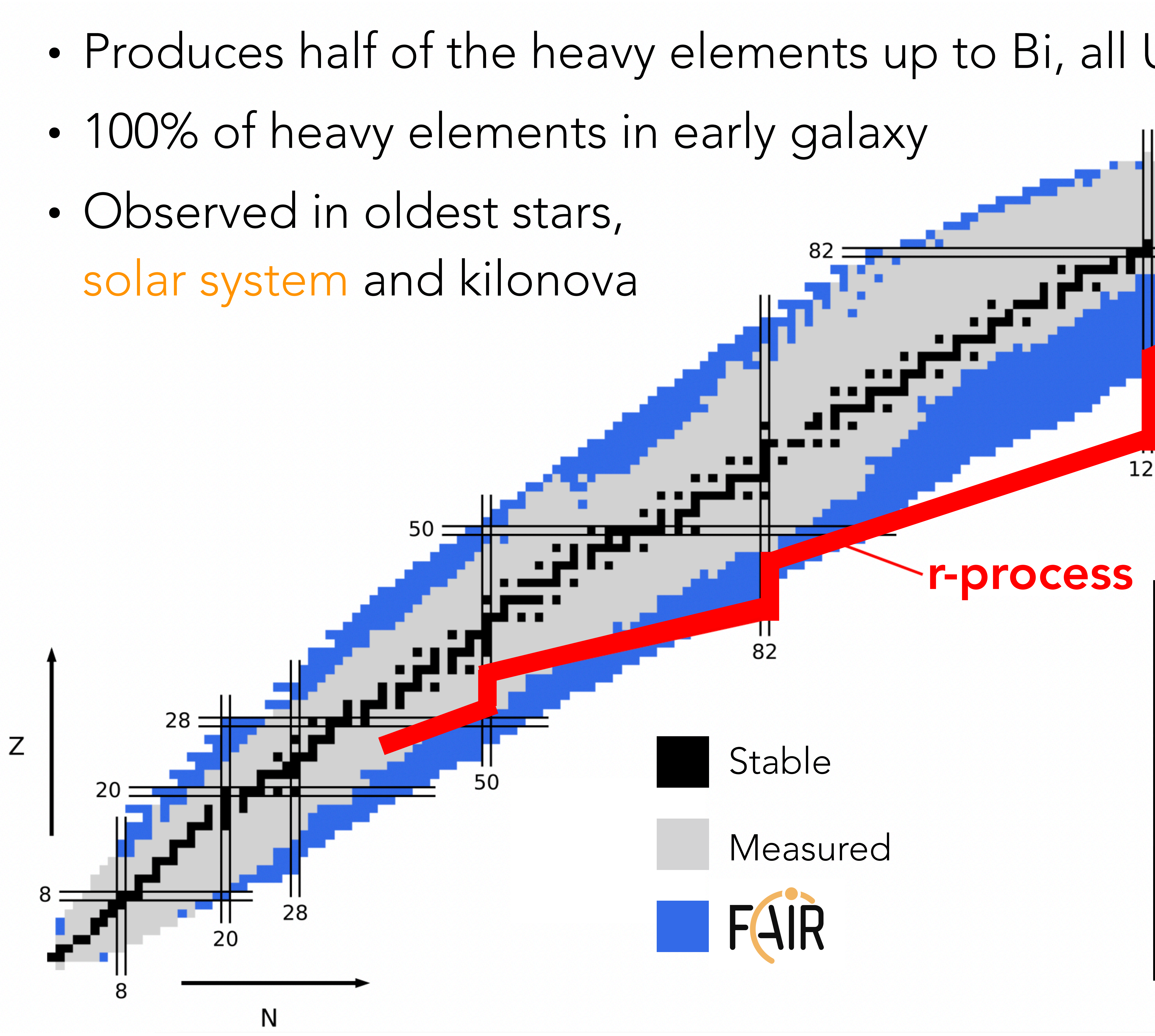


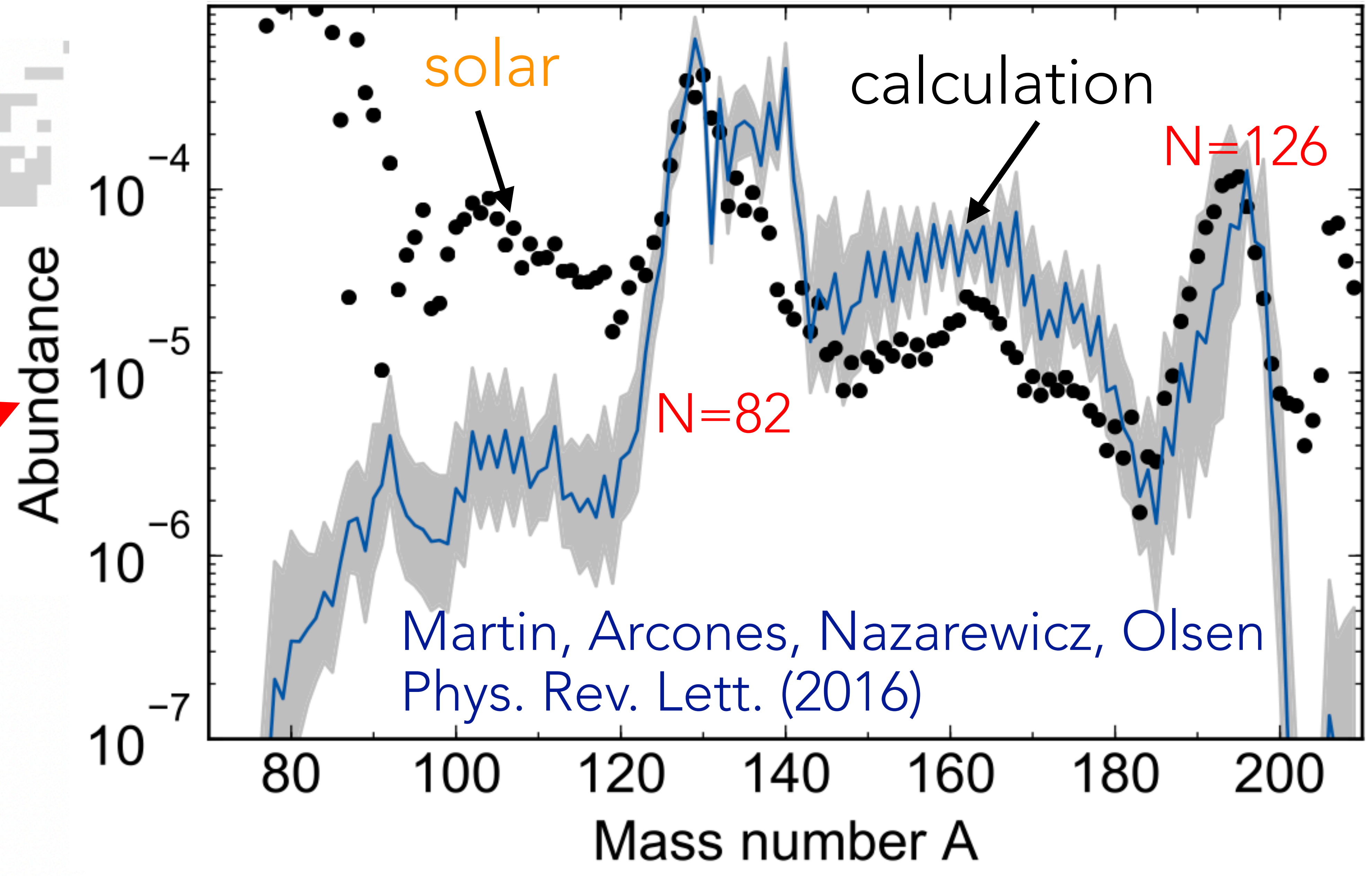
Heavy elements produced by neutron capture processes: s-process and r-process

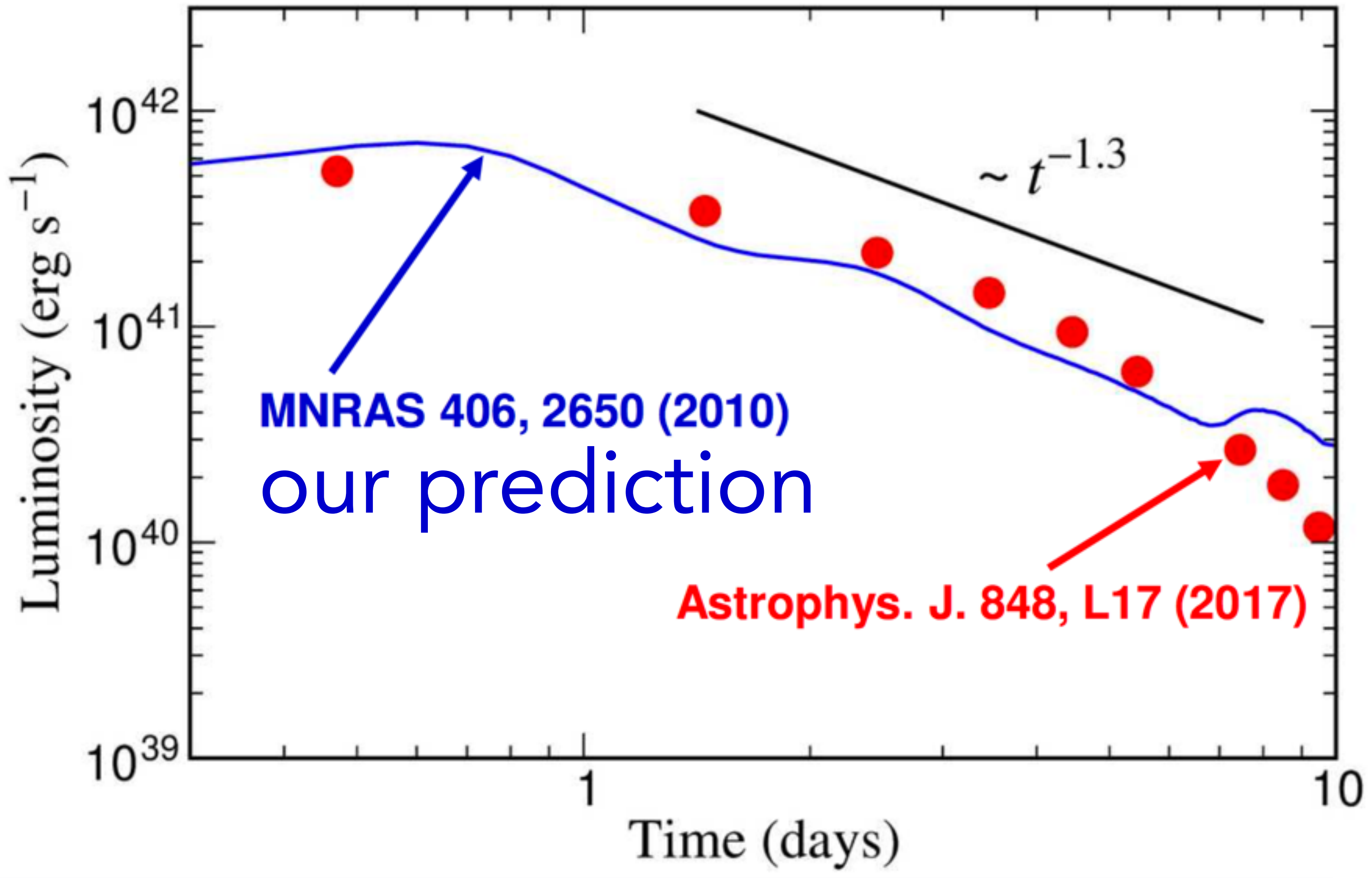


Rapid neutron capture process

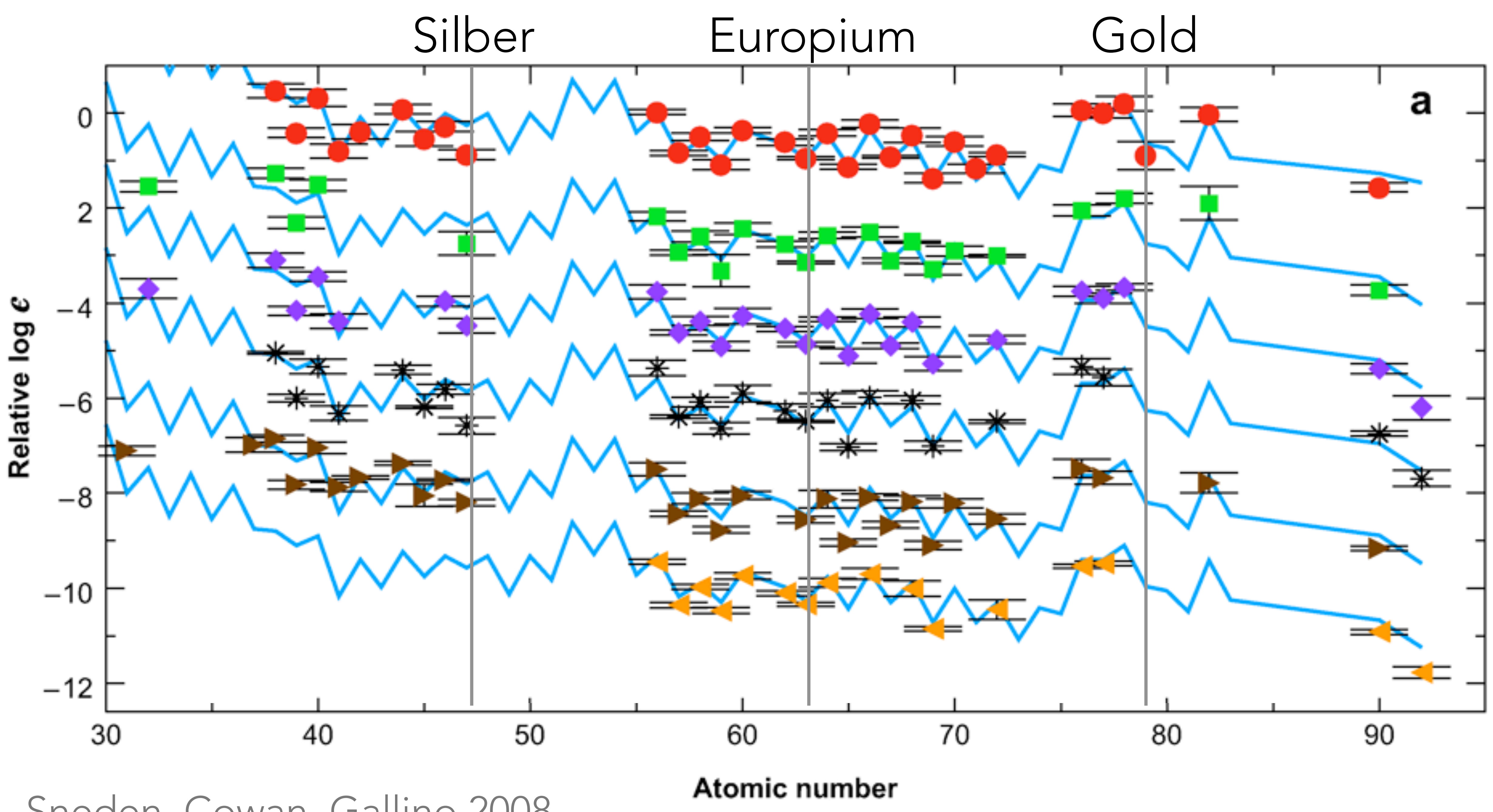
- Produces half of the heavy elements up to Bi, all U and Th
- 100% of heavy elements in early galaxy
- Observed in oldest stars, solar system and kilonova



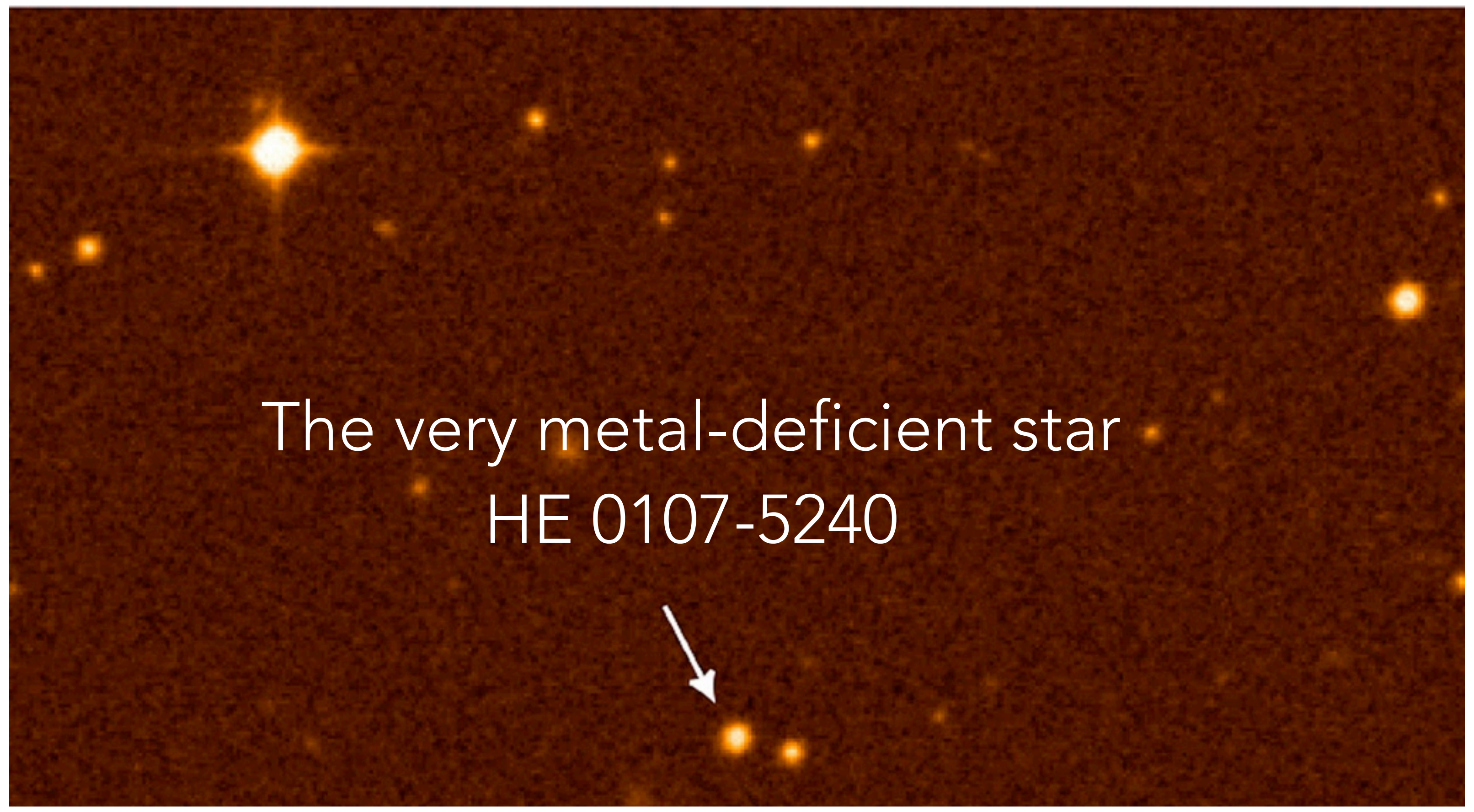




Oldest stars



Sneden, Cowan, Gallino 2008

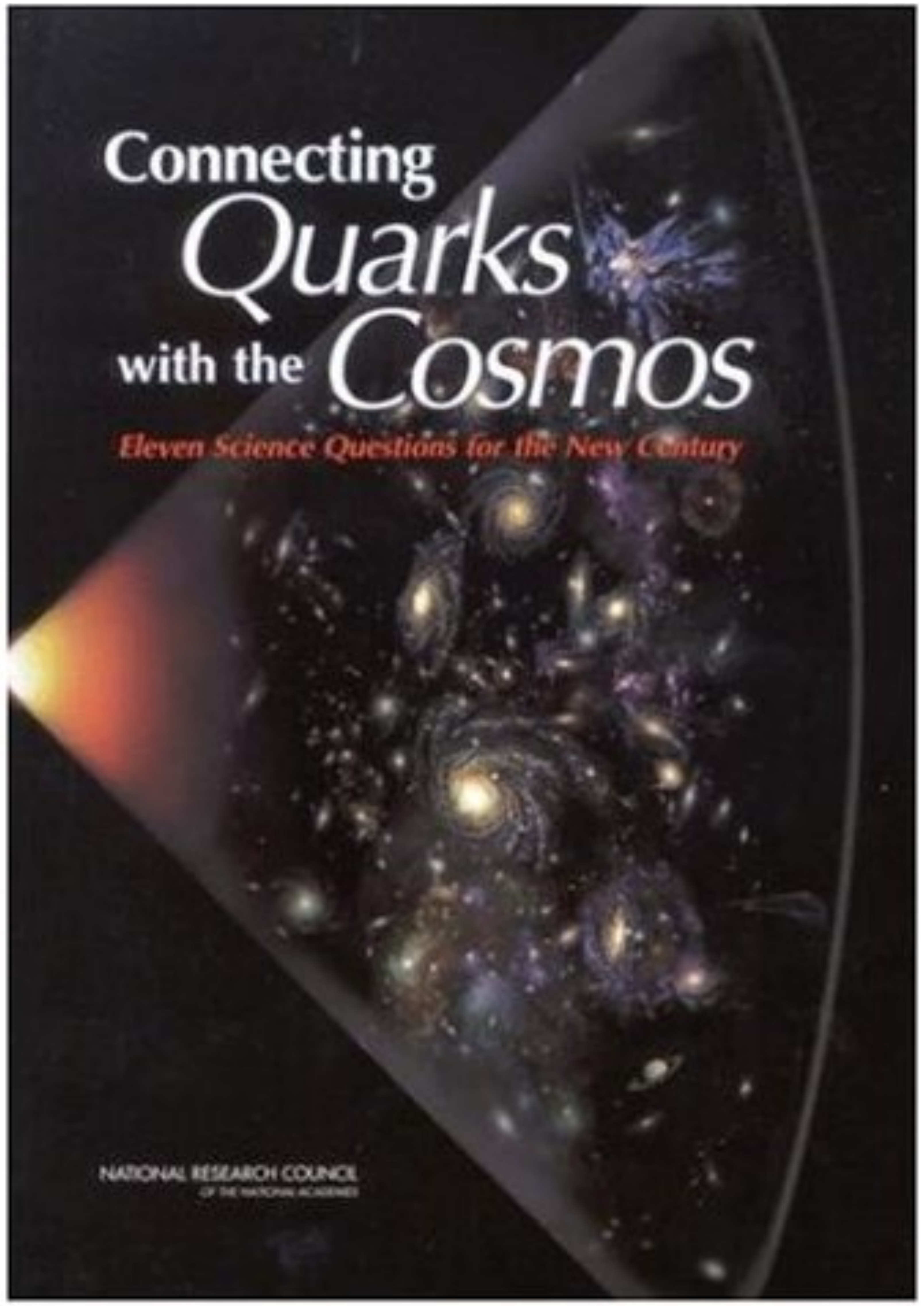


r-process in oldest stars and in Solar system same relative abundances:

Robust r-process

R-process from observations

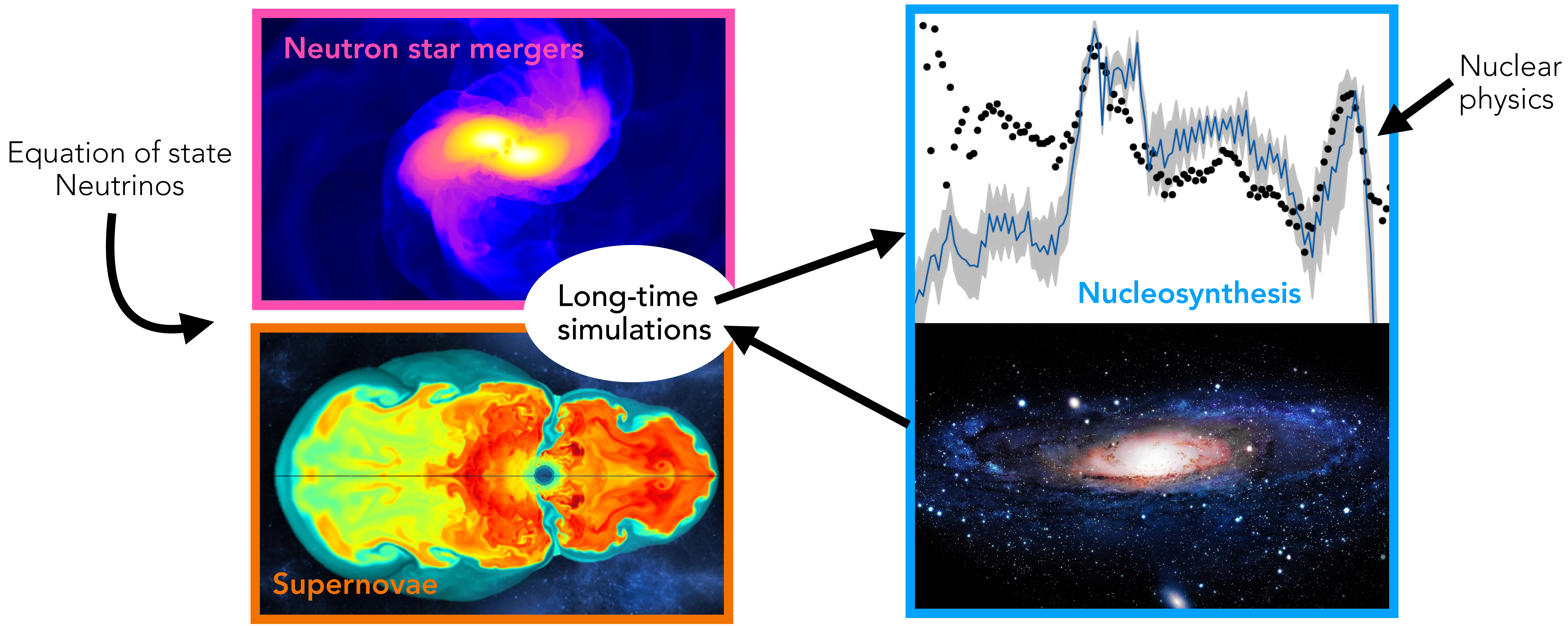
- Solar system: residual r-process
  r-process peaks and path → fast neutron capture
- Astrophysical environment: explosive and high neutron density
- Old stars: robust process from 2nd to 3rd peak
  contribution from other process(es) below 2nd peak
- Chemical evolution: r-process rare and early



How were the elements from iron to uranium made in the universe?

Several r-processes and several sites

R-process: from simulations to observations



R-process: from simulations to observations

WinNet

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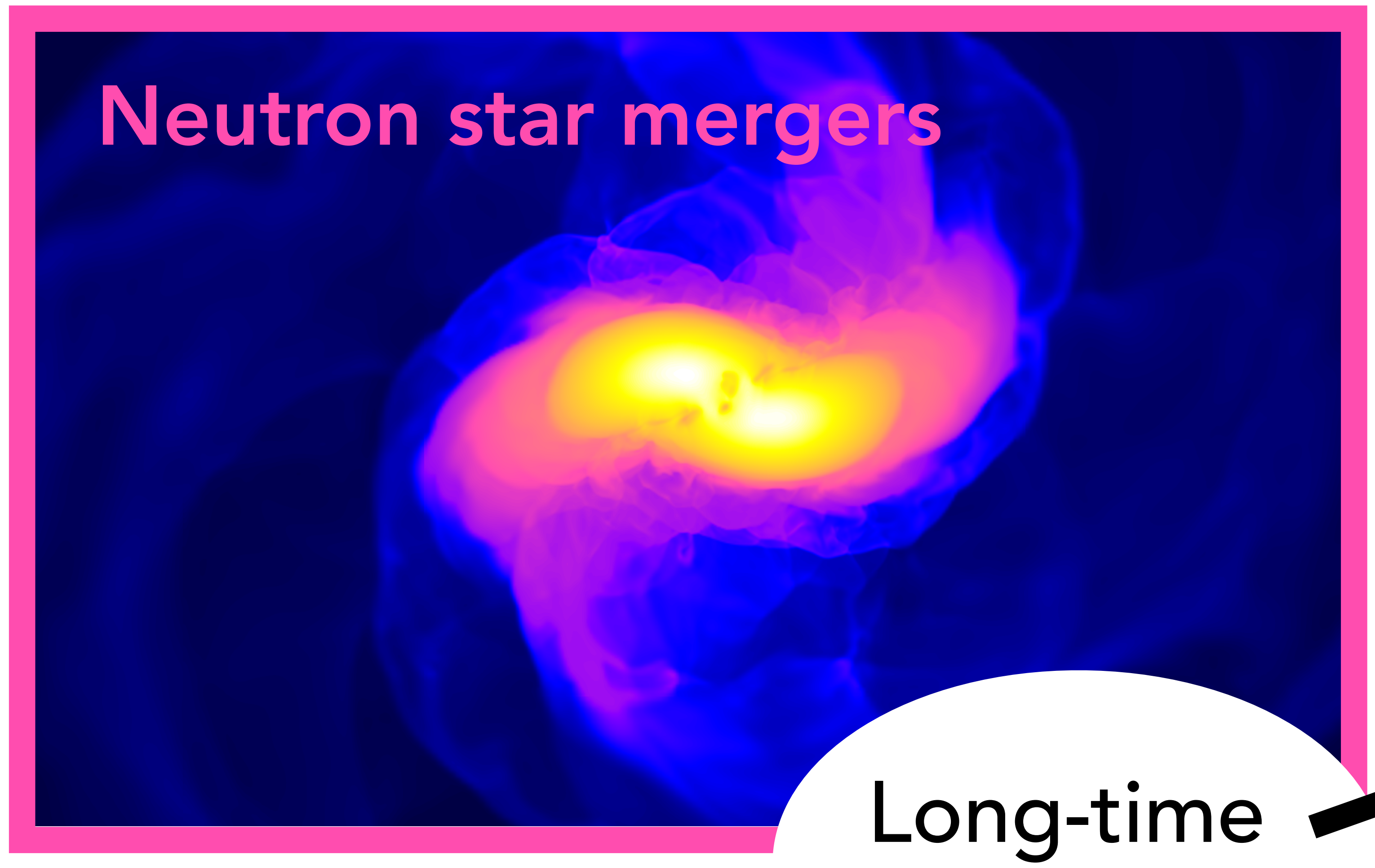
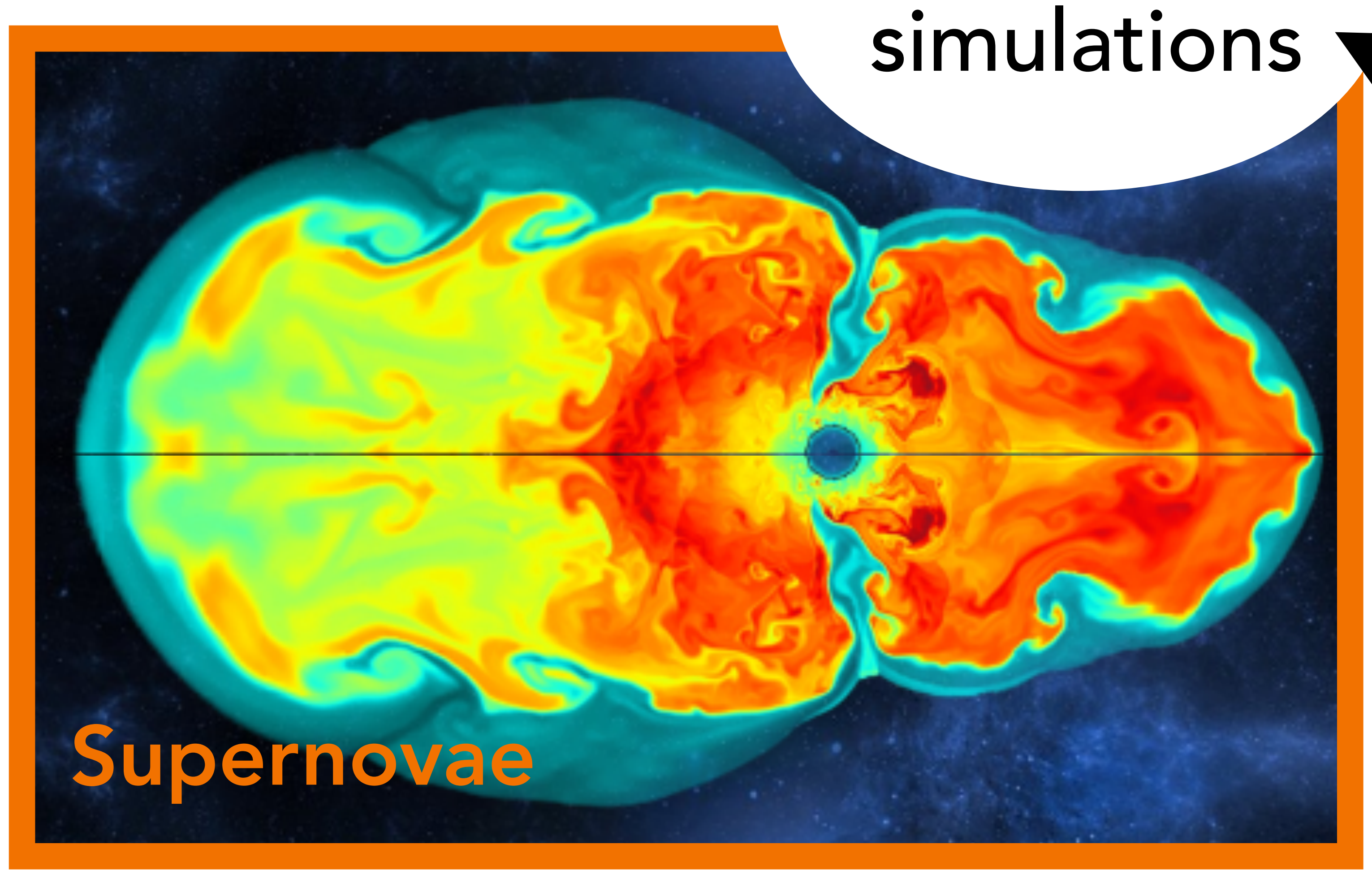
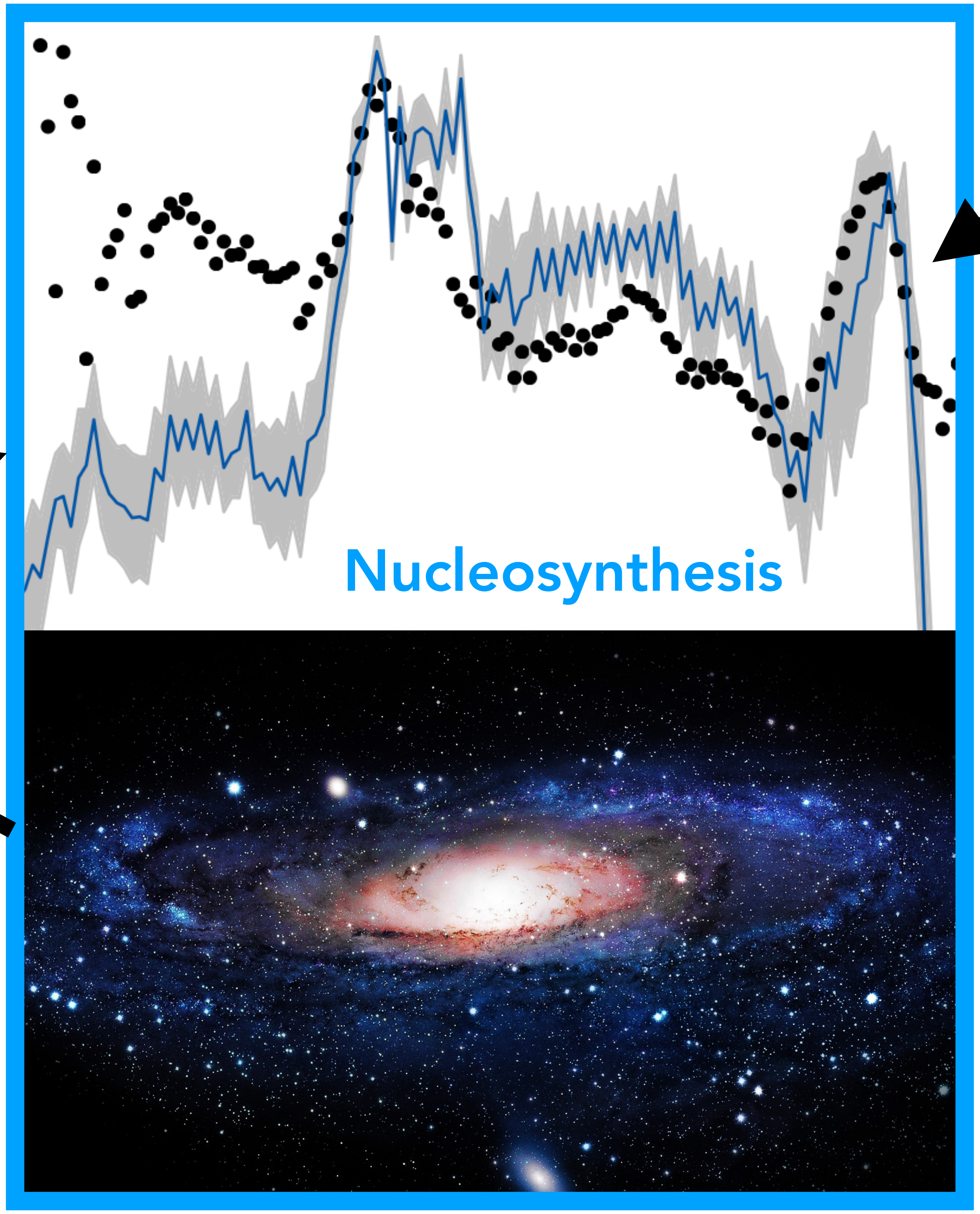
https://github.com/nuc-astro ApJS (2023)

Equation of state
Neutrinos



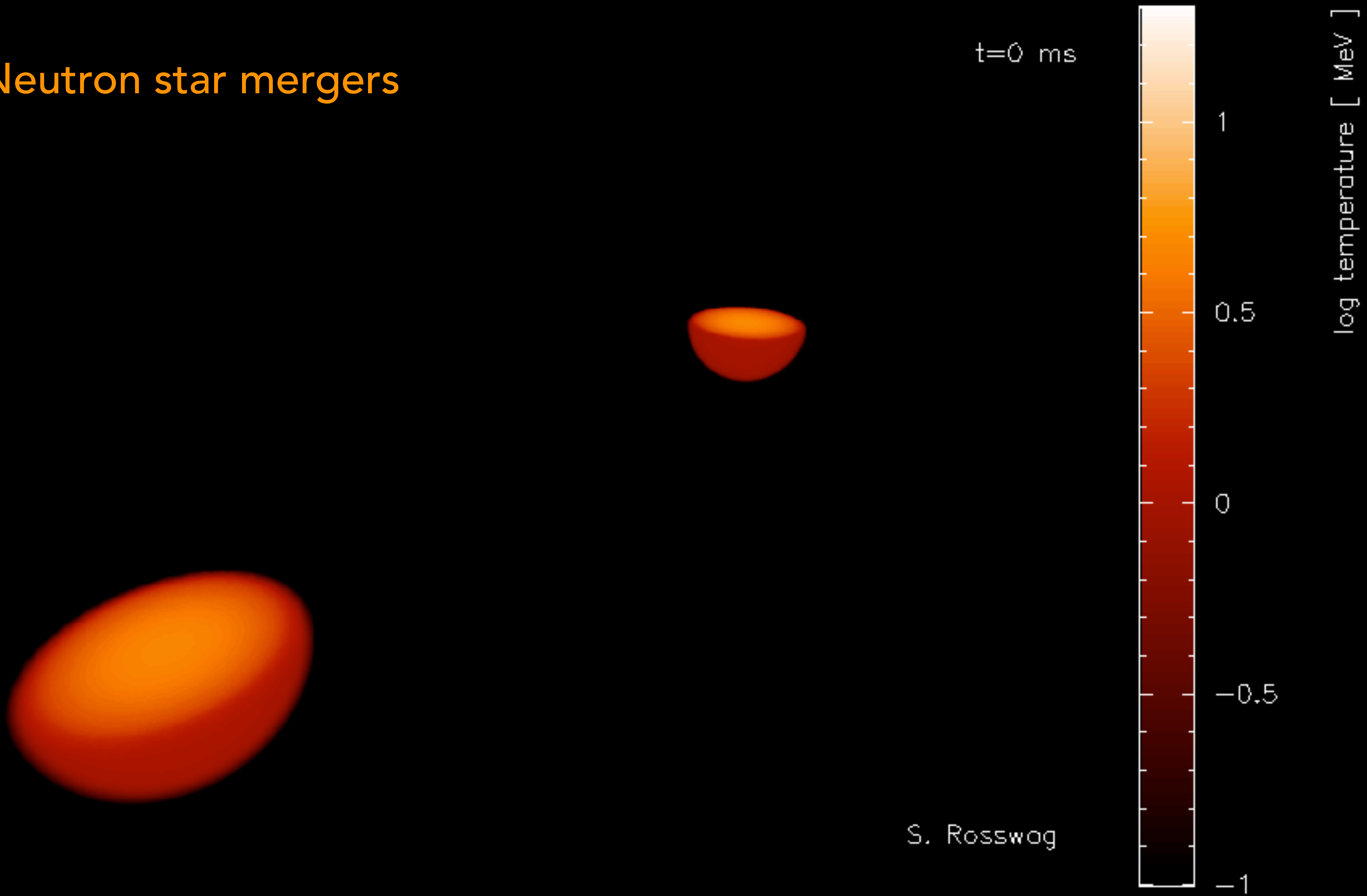


Long-time simulations

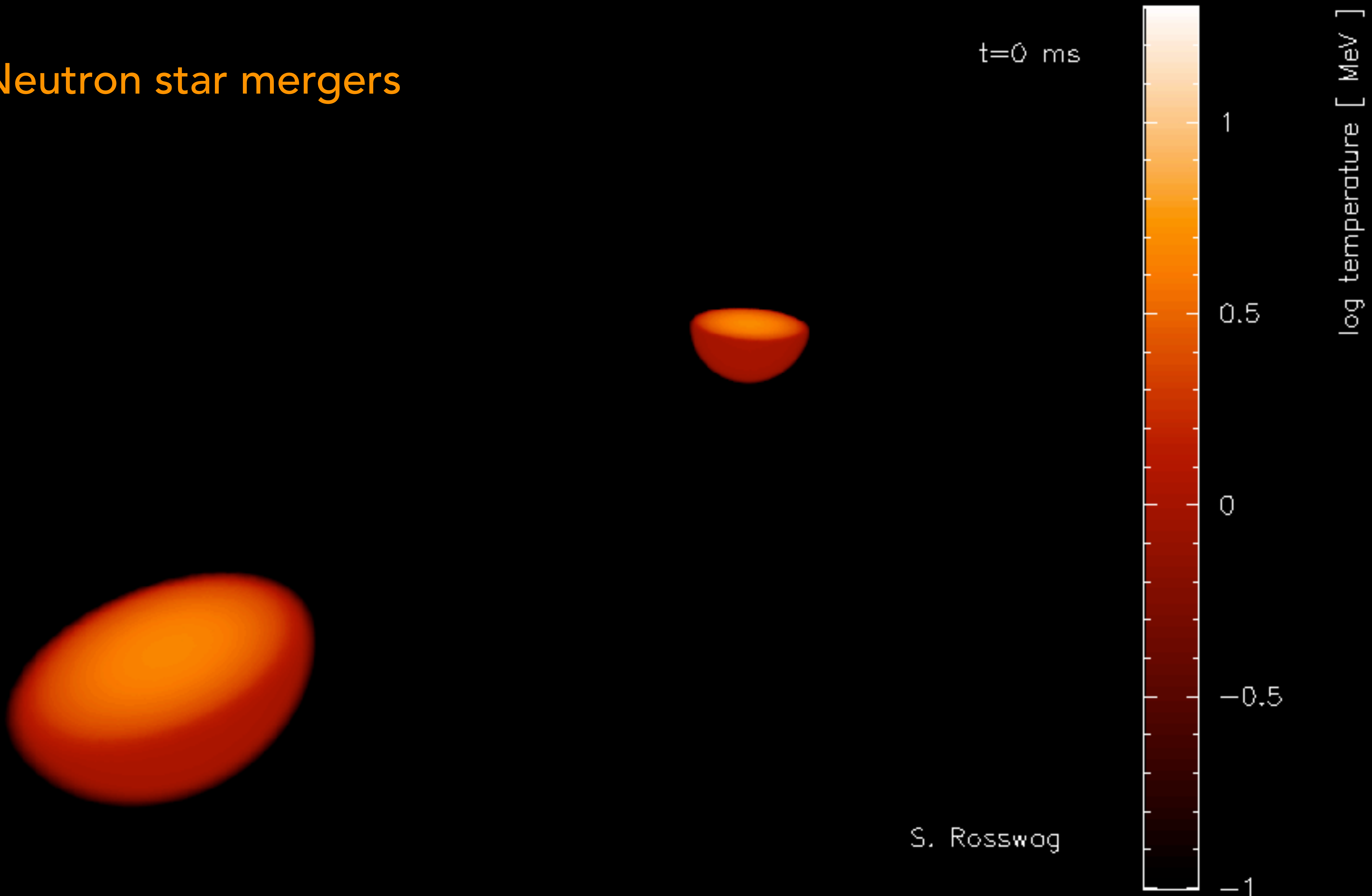


Nuclear physics

Neutron star mergers



Neutron star mergers



Neutron star merger: GW170817

LIGO-LIVINGSTON OBSERVATORY

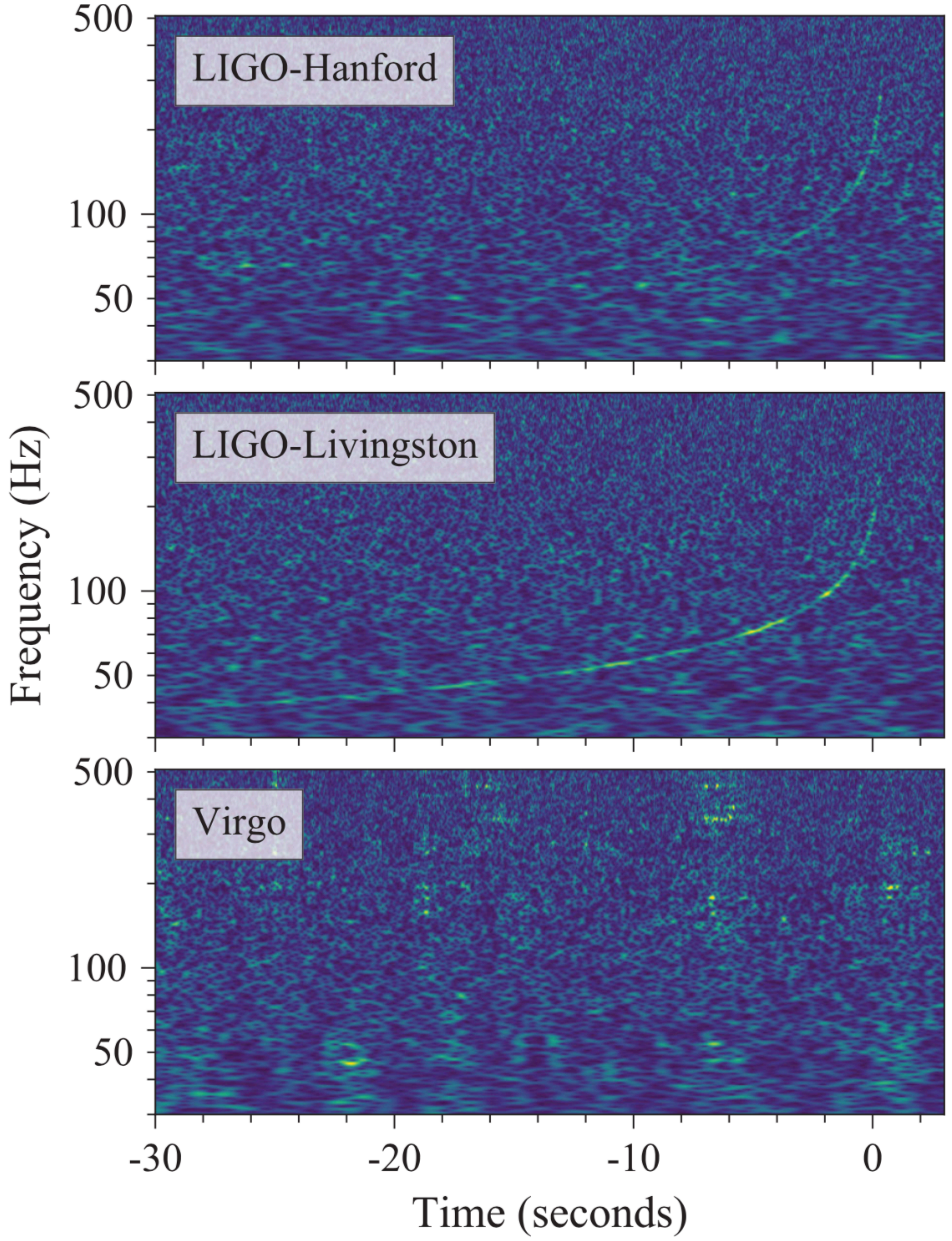
LIGO-HANFORD OBSERVATORY

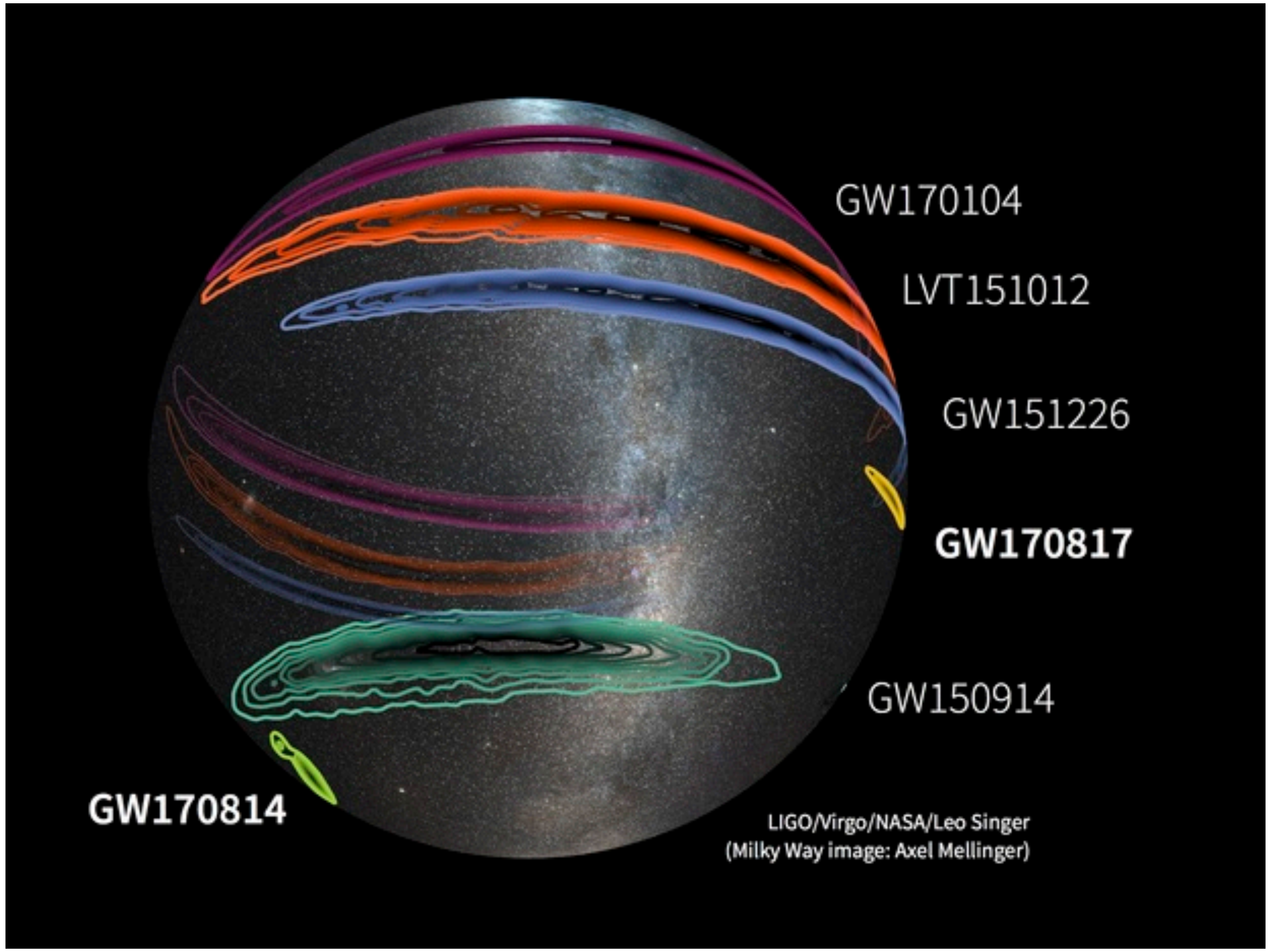
Credit: LIGO Hanford

VIRGO AT CASCINA, ITALY

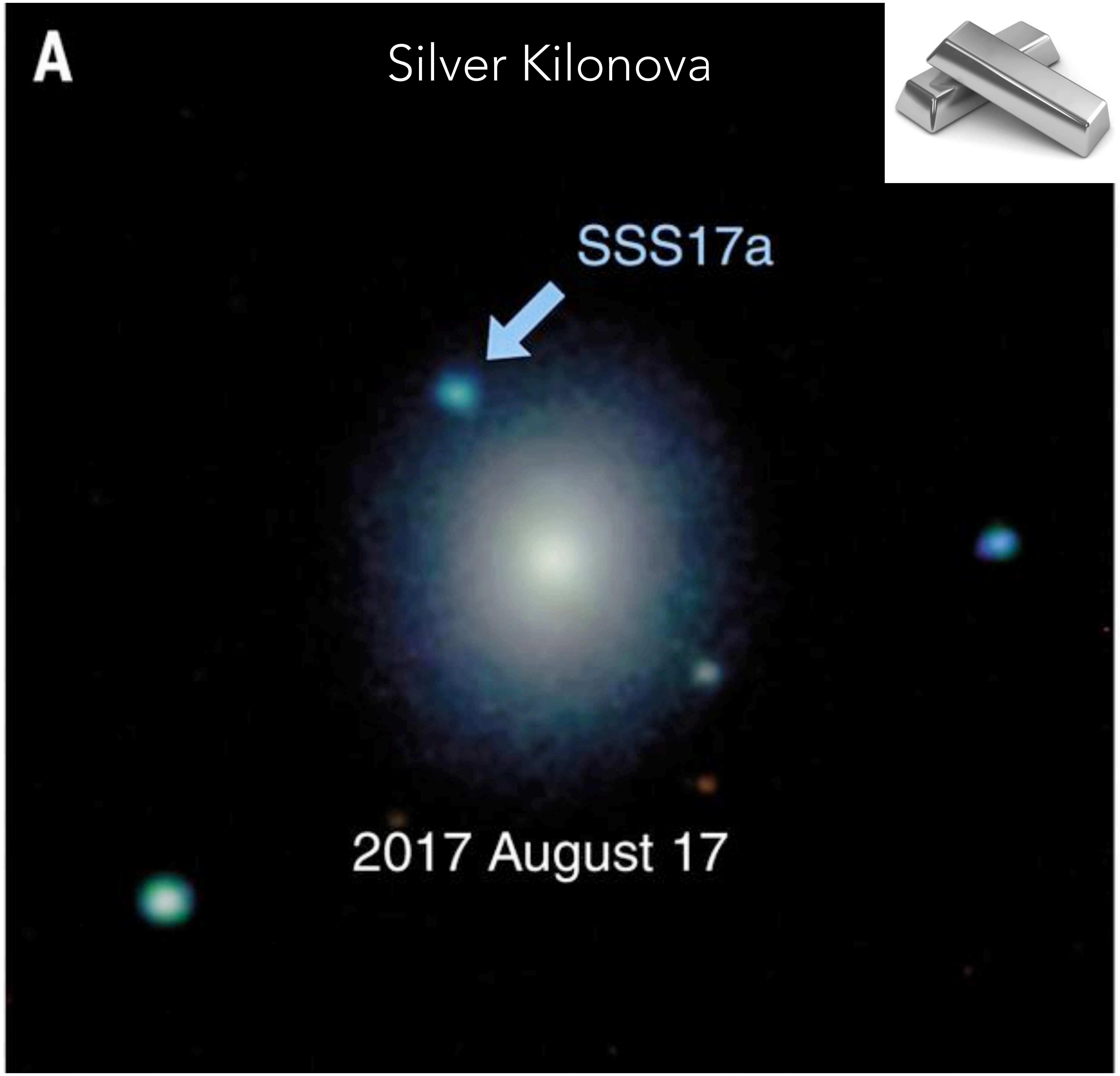
Credit: Virgo

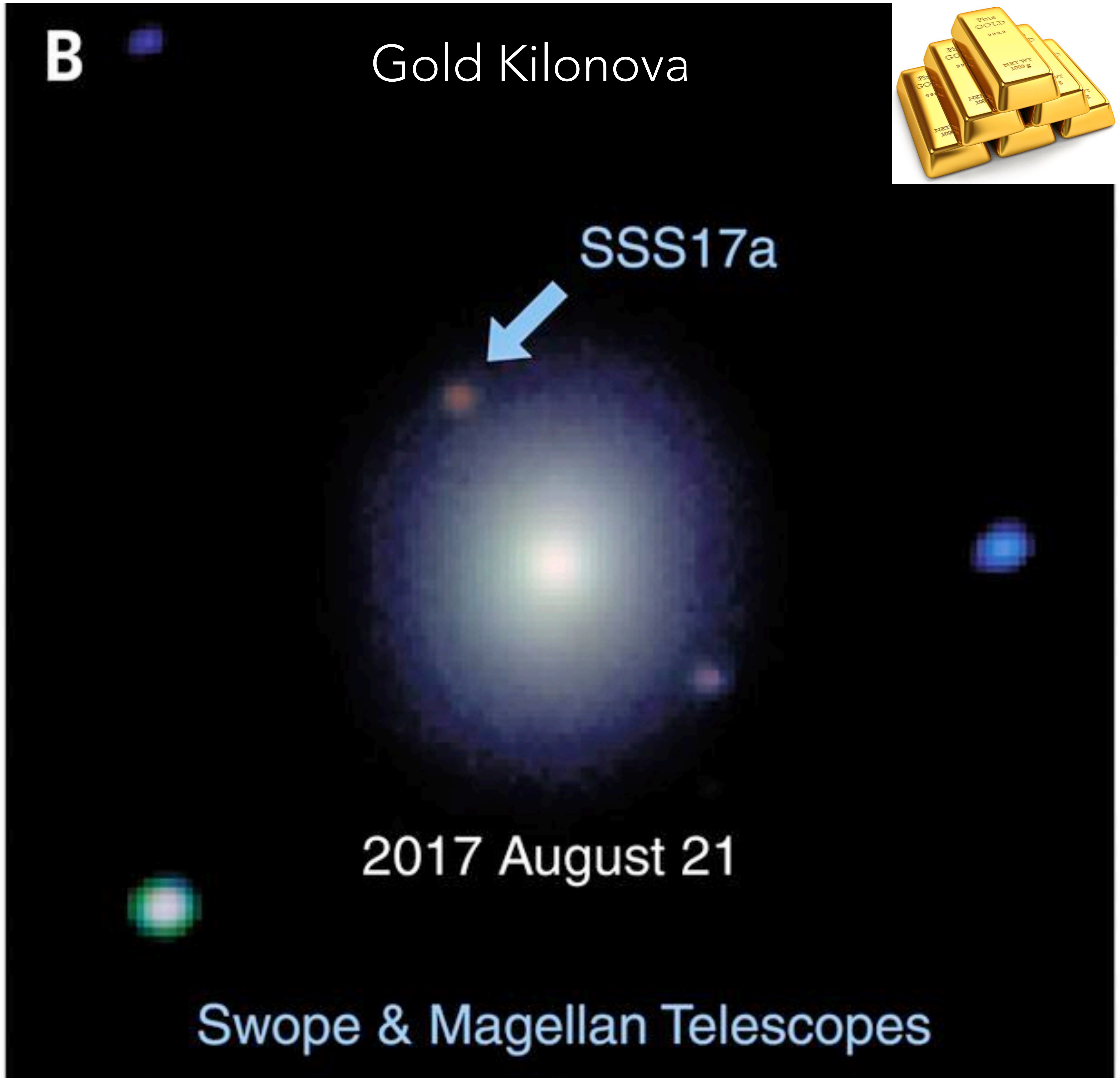
17. August 2017 Virgo-LIGO-collaboration discovered a neutron star merger



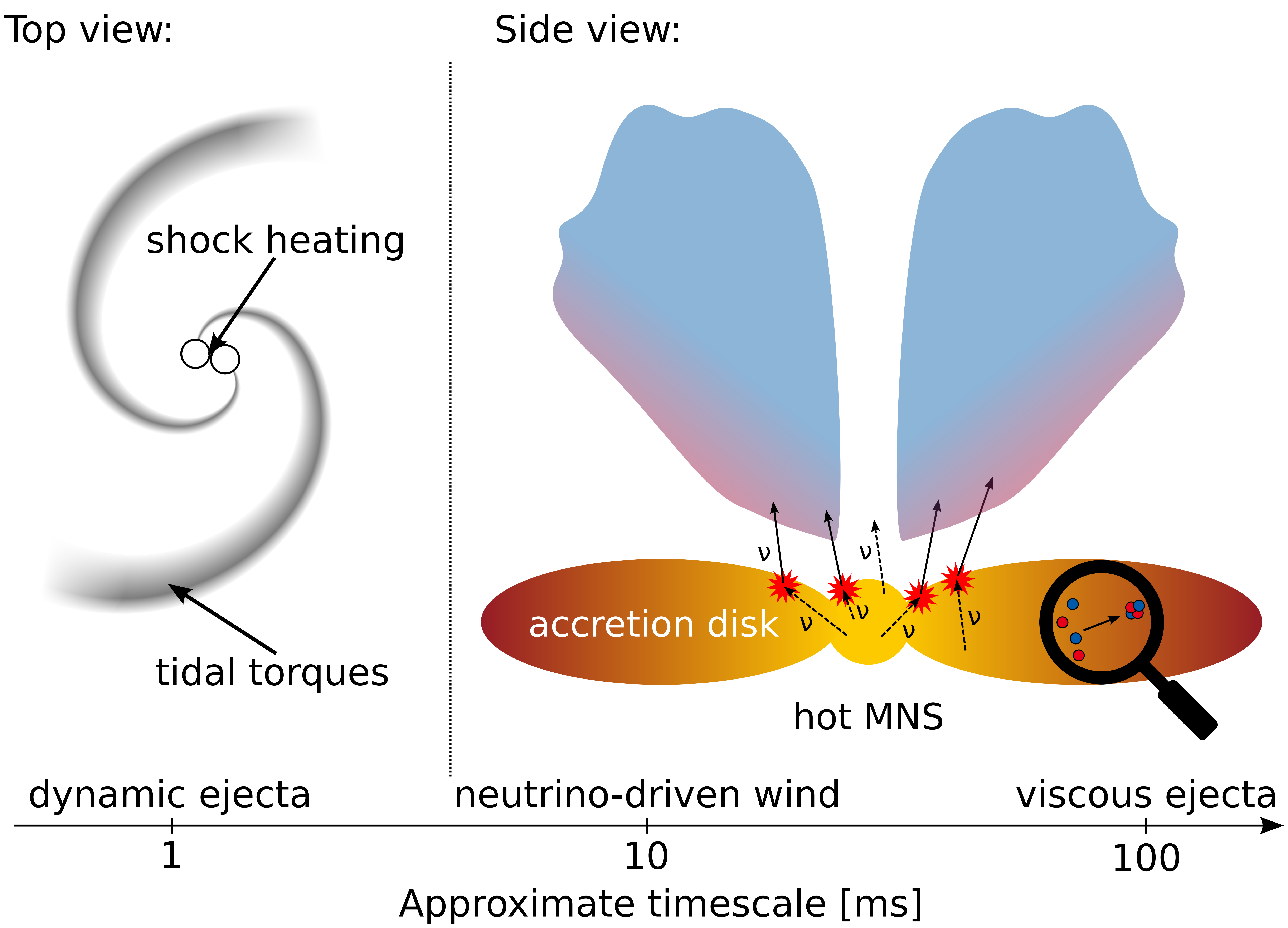


Kilonova


A
Silver Kilonova
SSS17a
2017 August 17

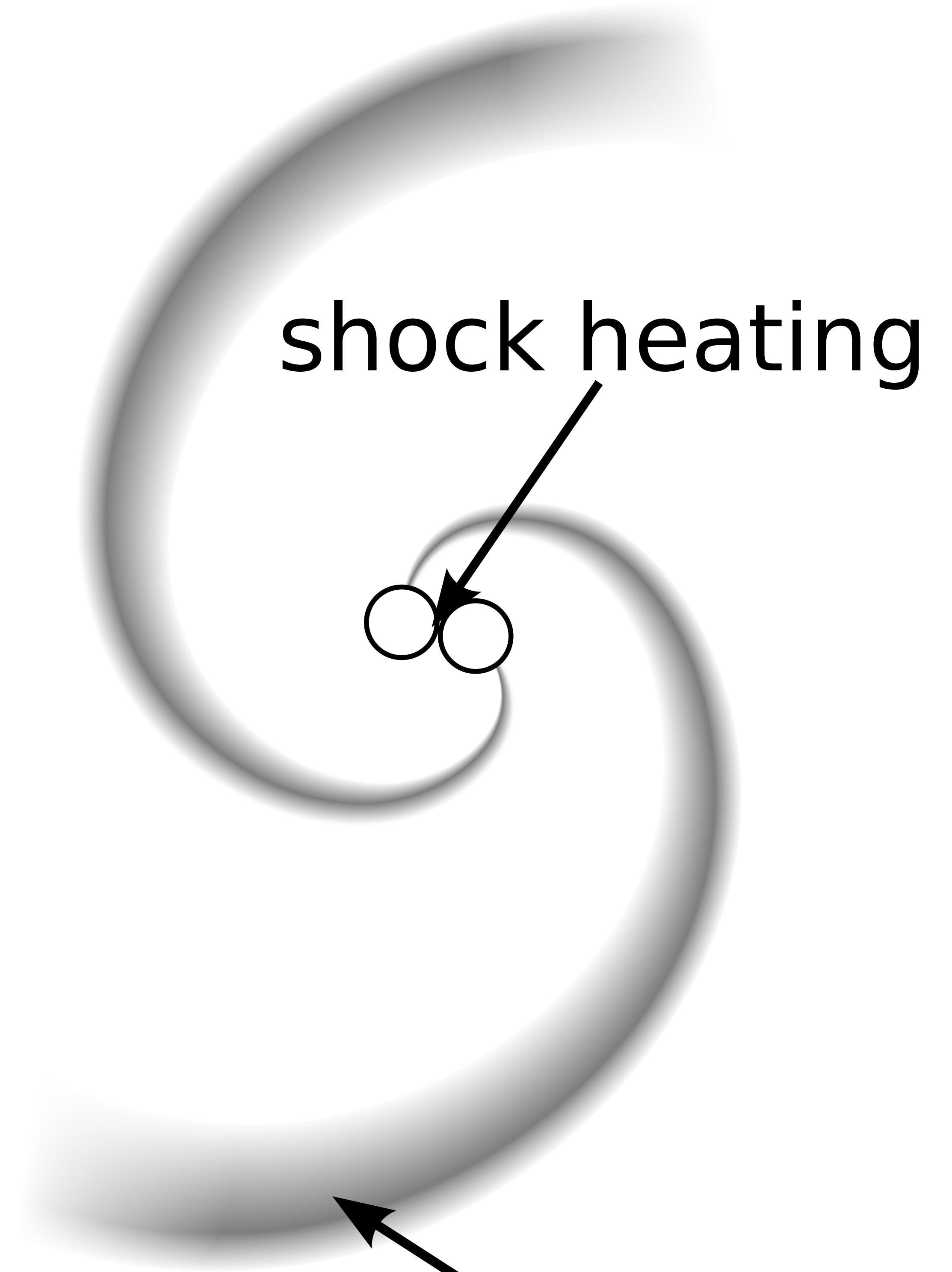

B
Gold Kilonova
SSS17a
2017 August 21
Swope & Magellan Telescopes

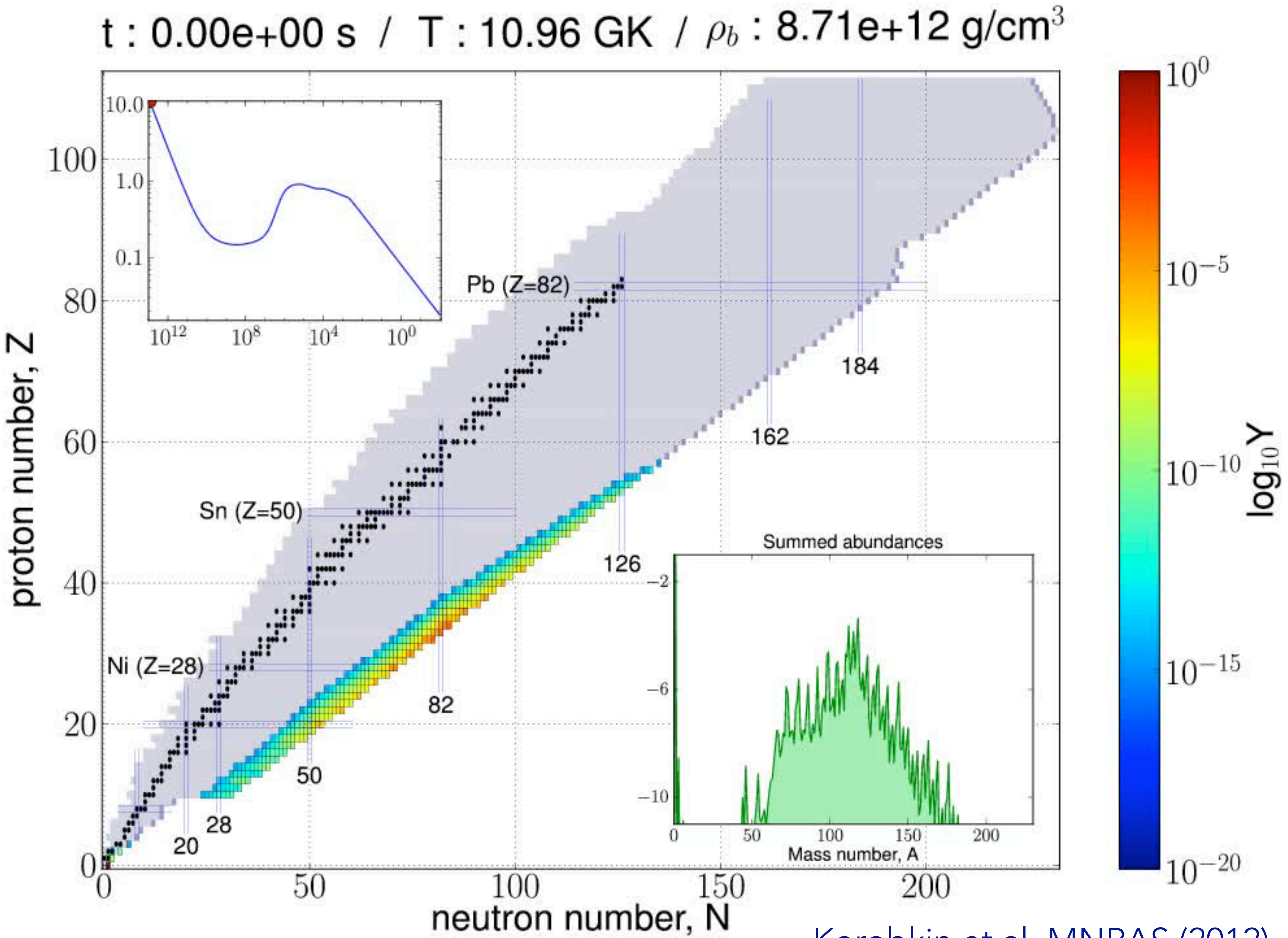
Dynamical and disk ejecta



Dynamical ejecta

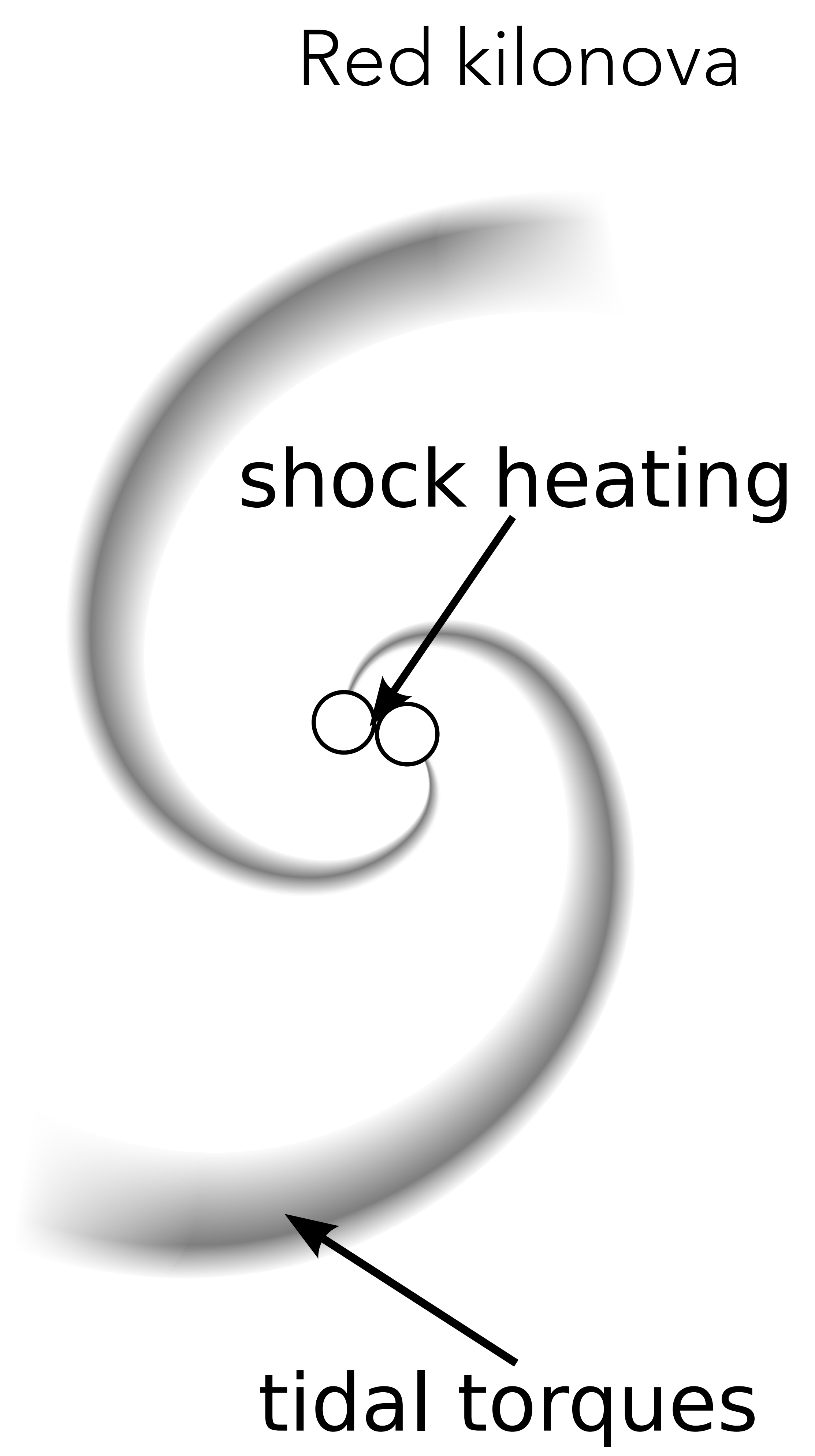
Red kilonova

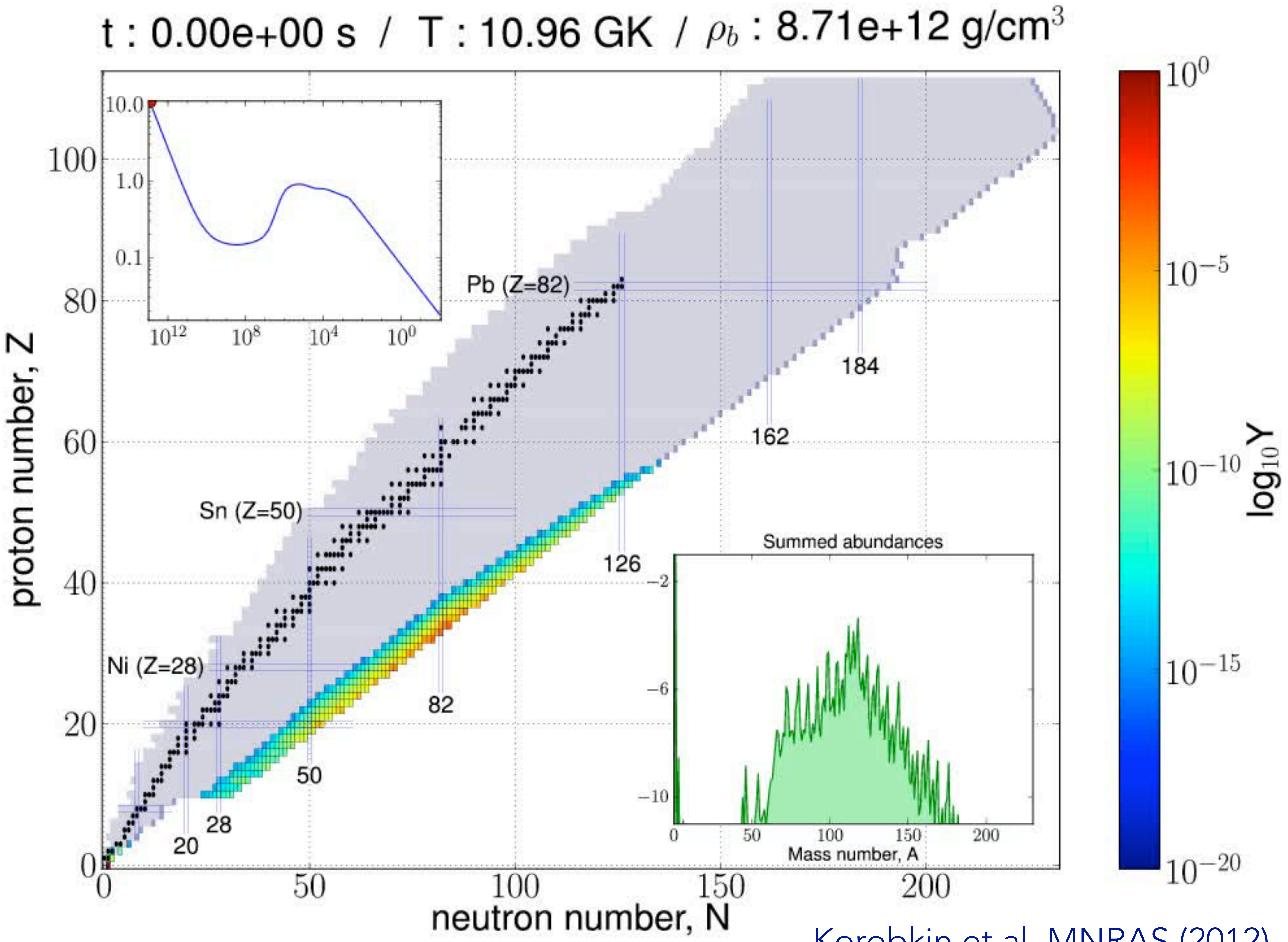




Korobkin et al. MNRAS (2012)

Dynamical ejecta

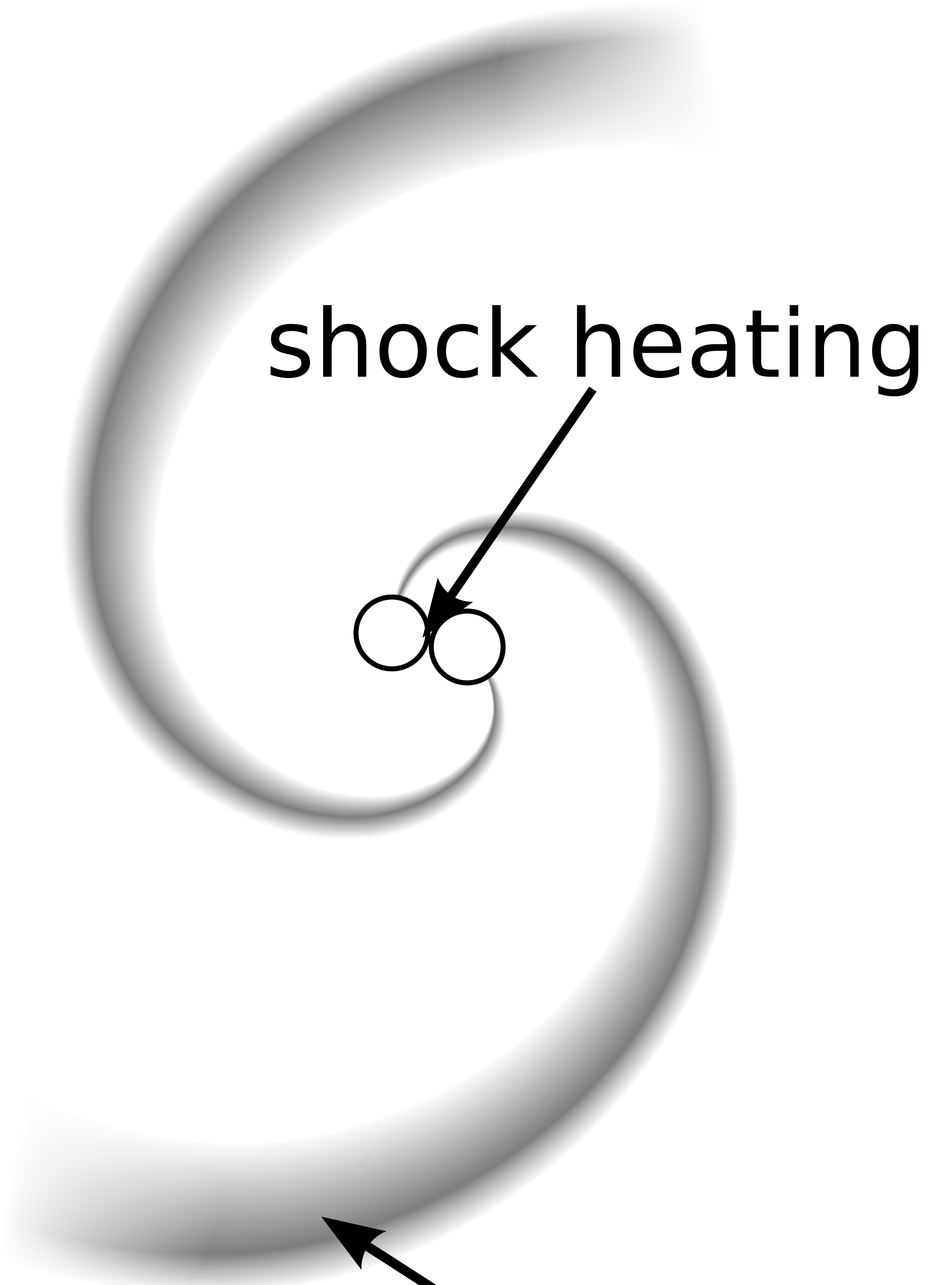


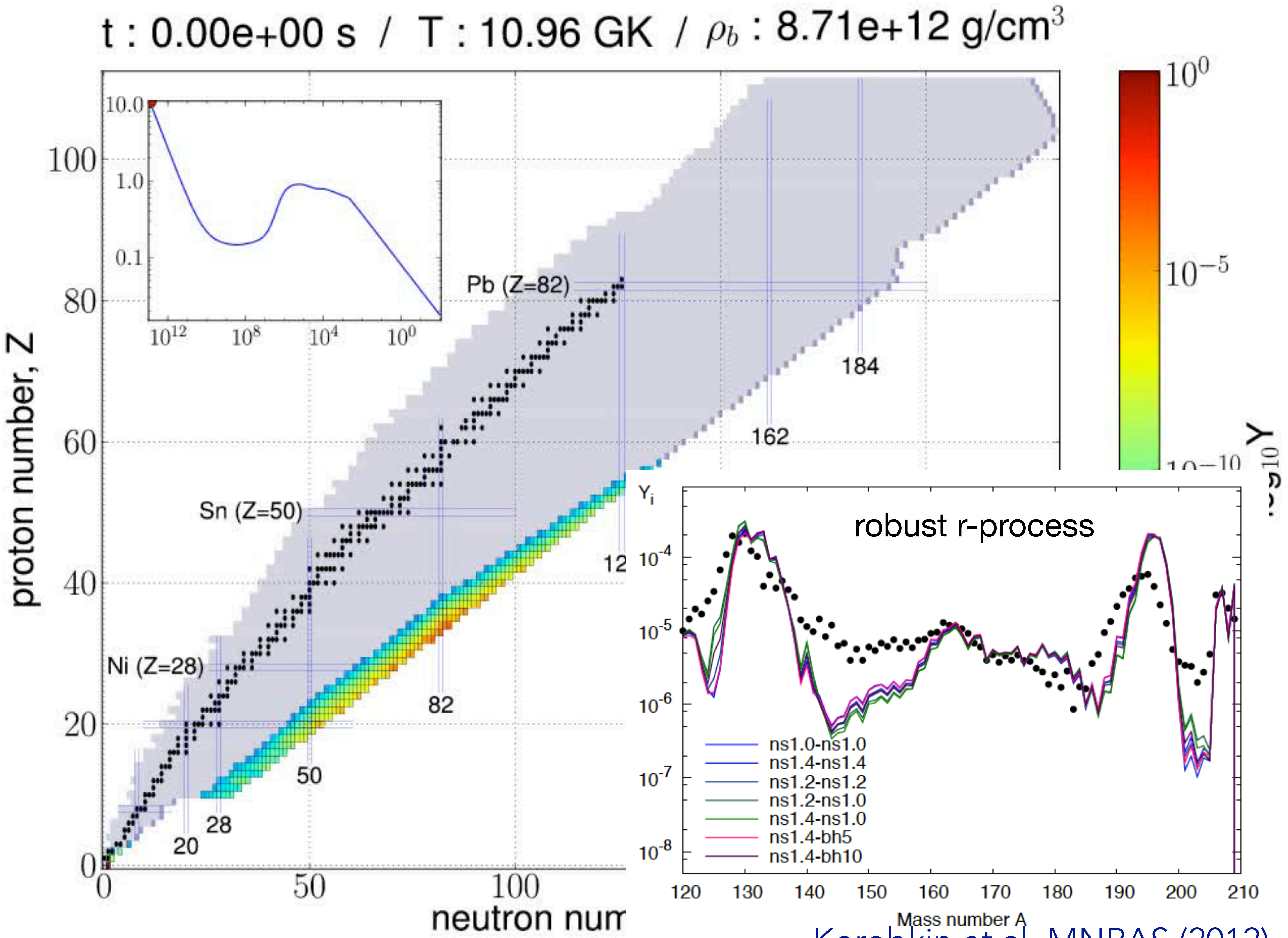


Korobkin et al. MNRAS (2012)

Dynamical ejecta

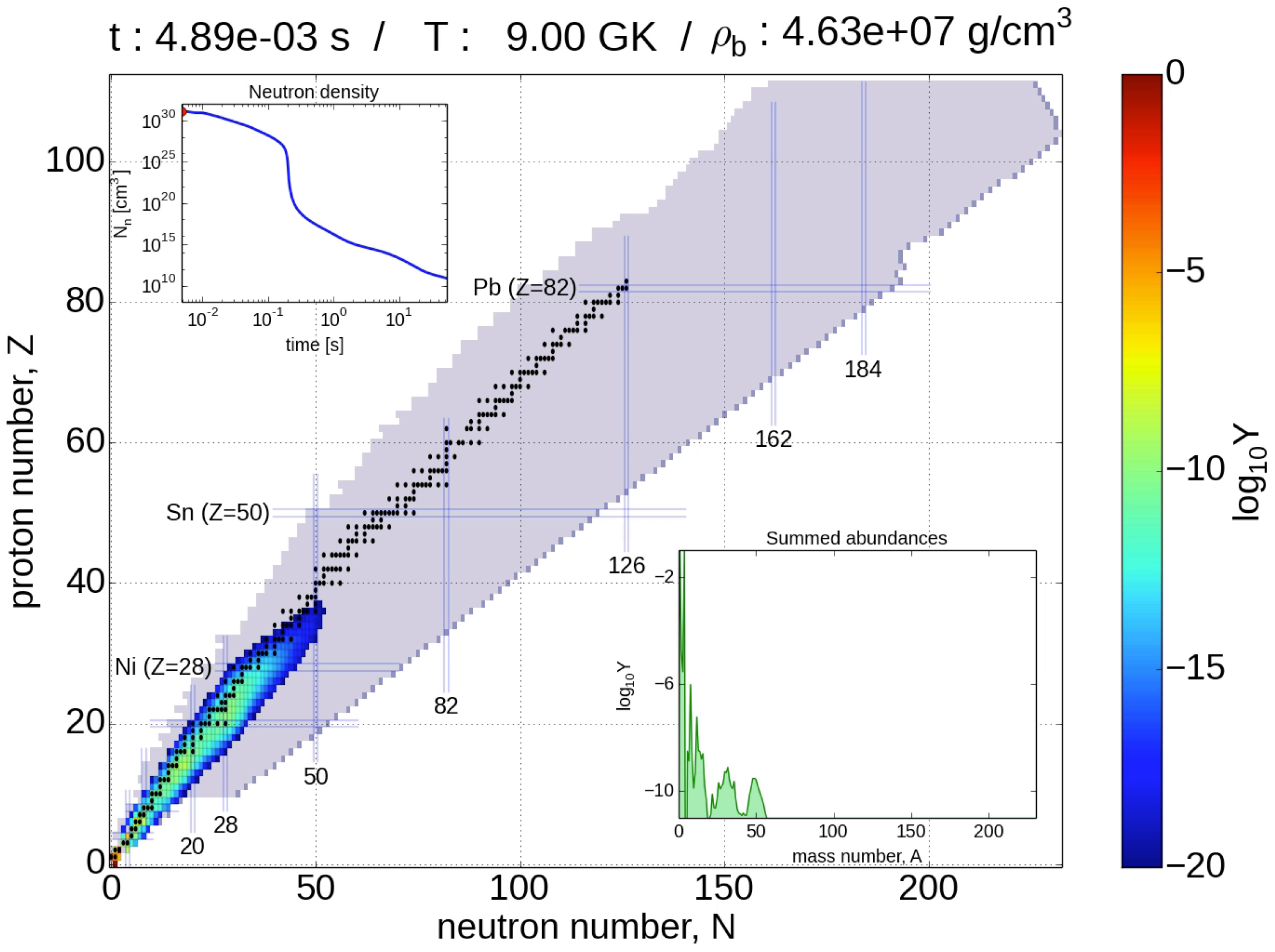
Red kilonova



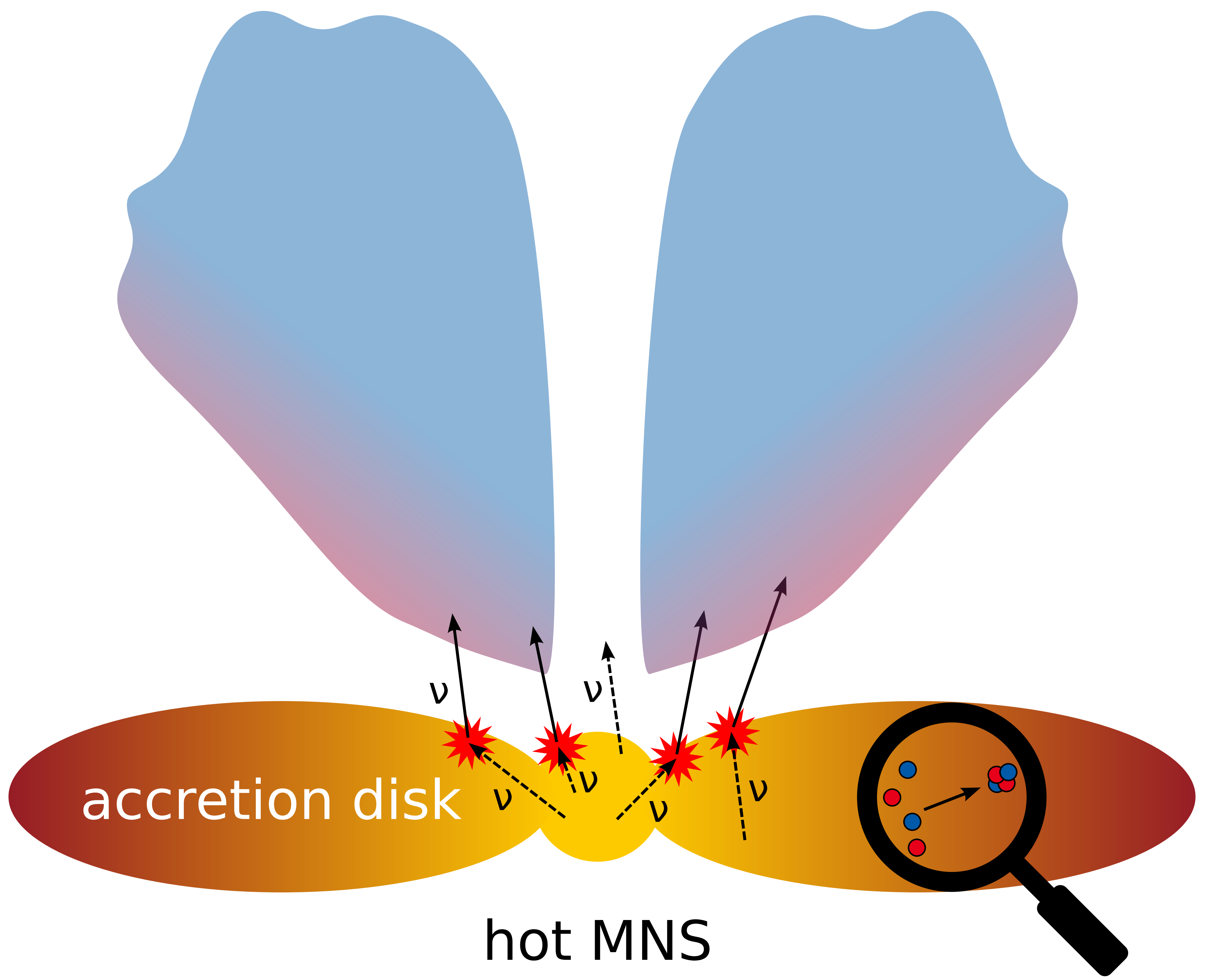


Korobkin et al. MNRAS (2012)

Accretion disk ejecta

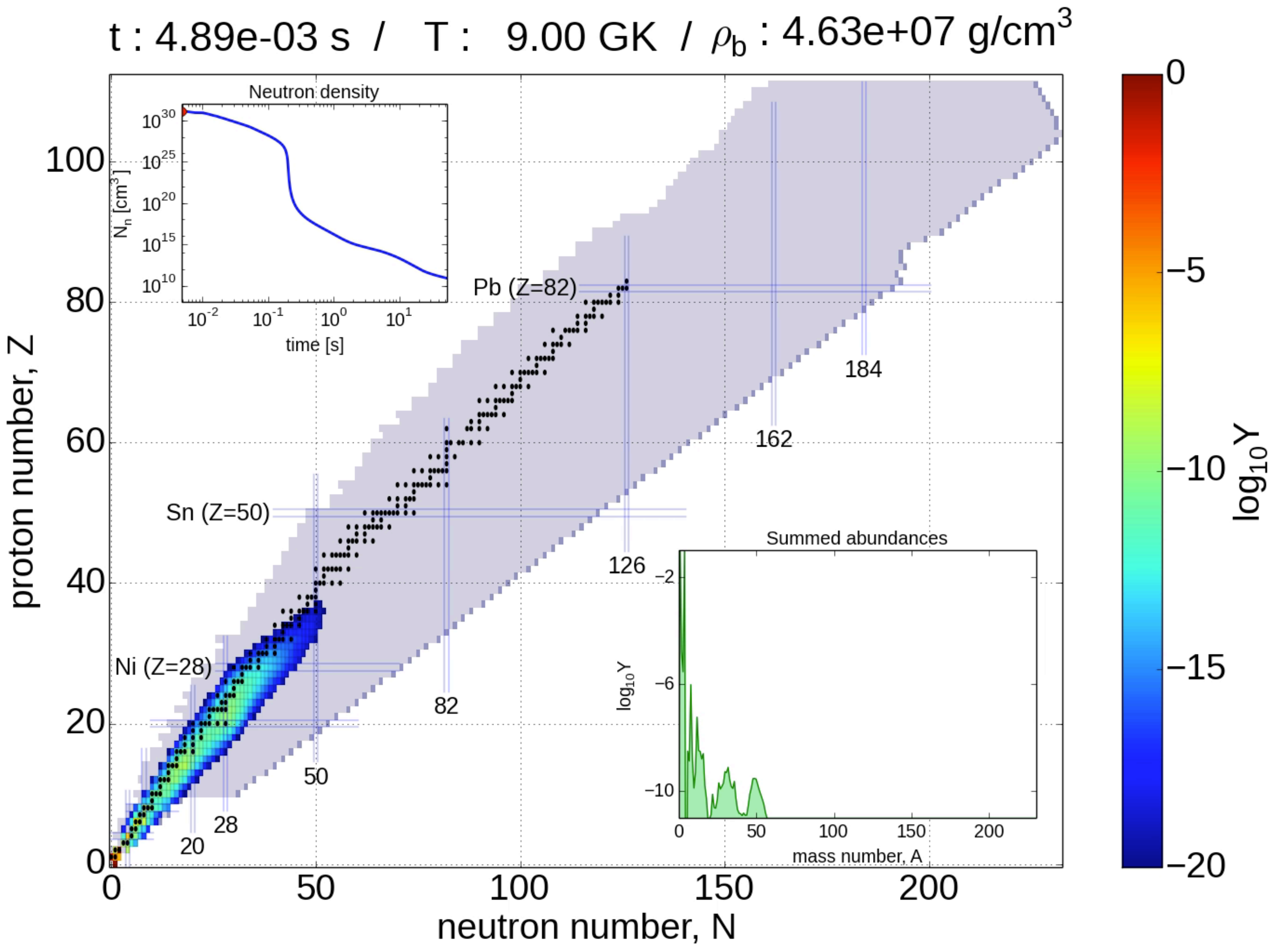


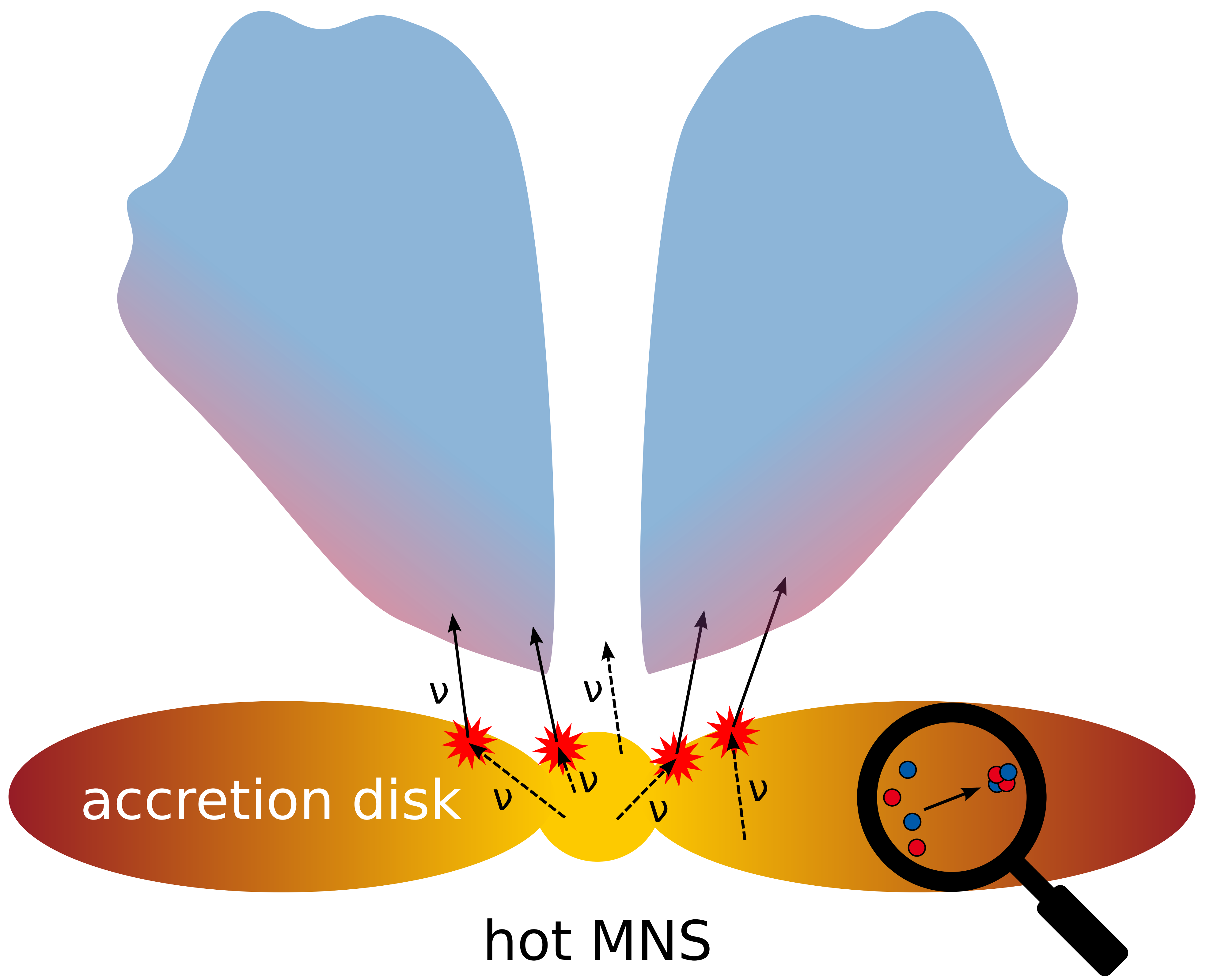
Martin et al. ApJ (2015), Perego et al. MNRAS (2014)



Blue kilonova

Accretion disk ejecta





Blue kilonova

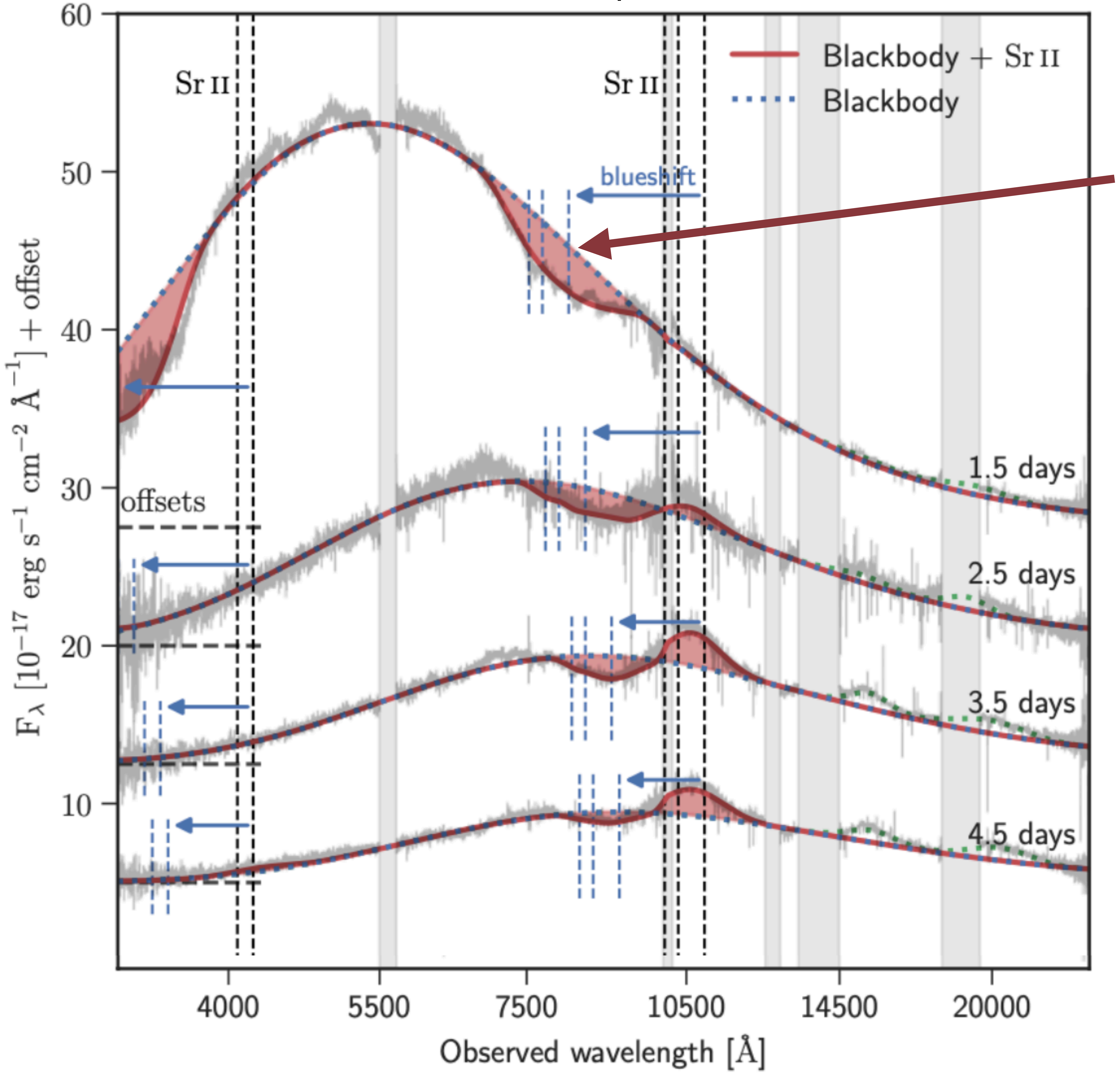
Martin et al. ApJ (2015), Perego et al. MNRAS (2014)

Blue kilonova and Strontium (Z=38)

First direct detection of r-process

Very Large Telescope (VLT), Chile

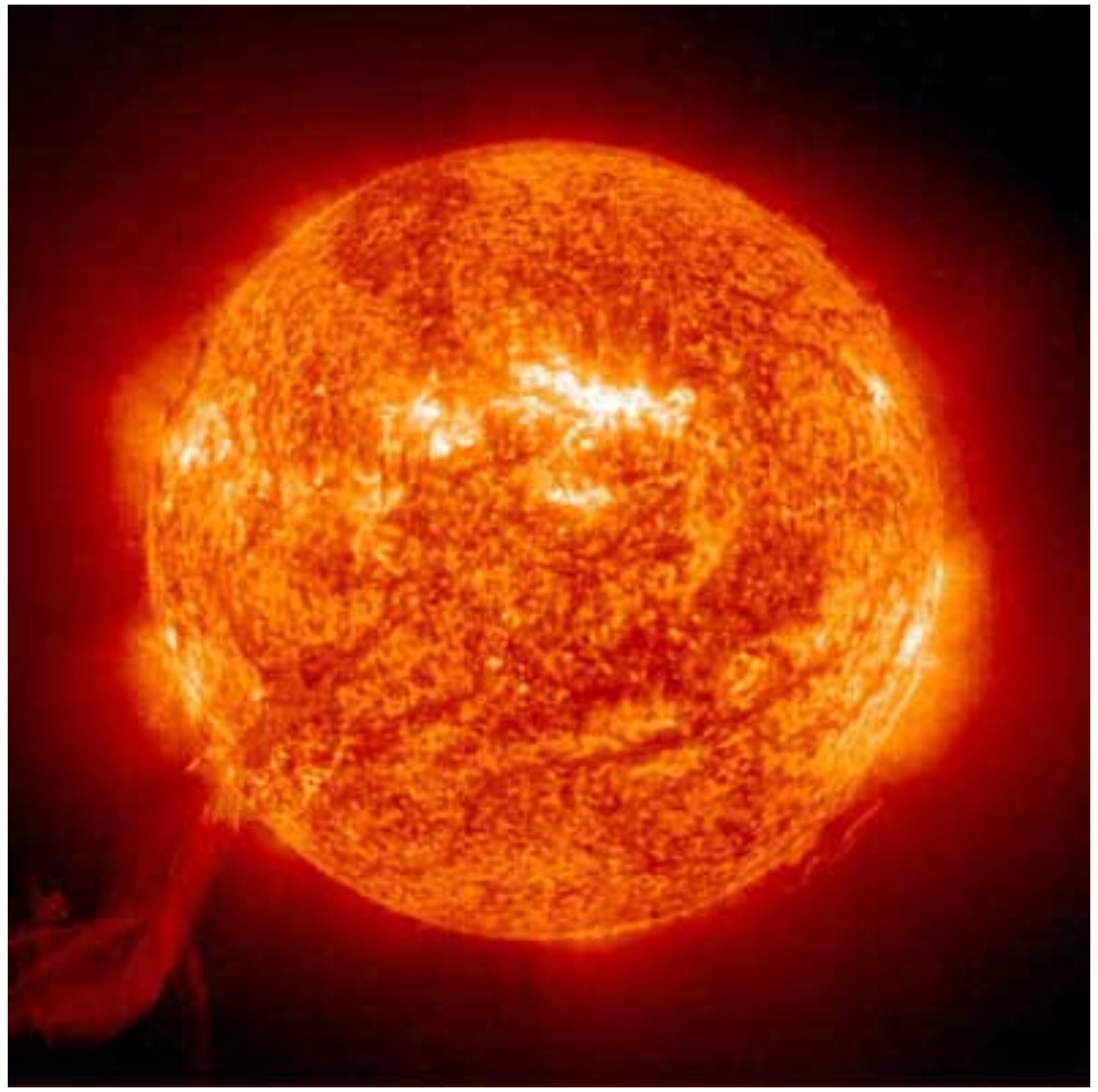
kilonova spectrum



Sr freshly synthesized

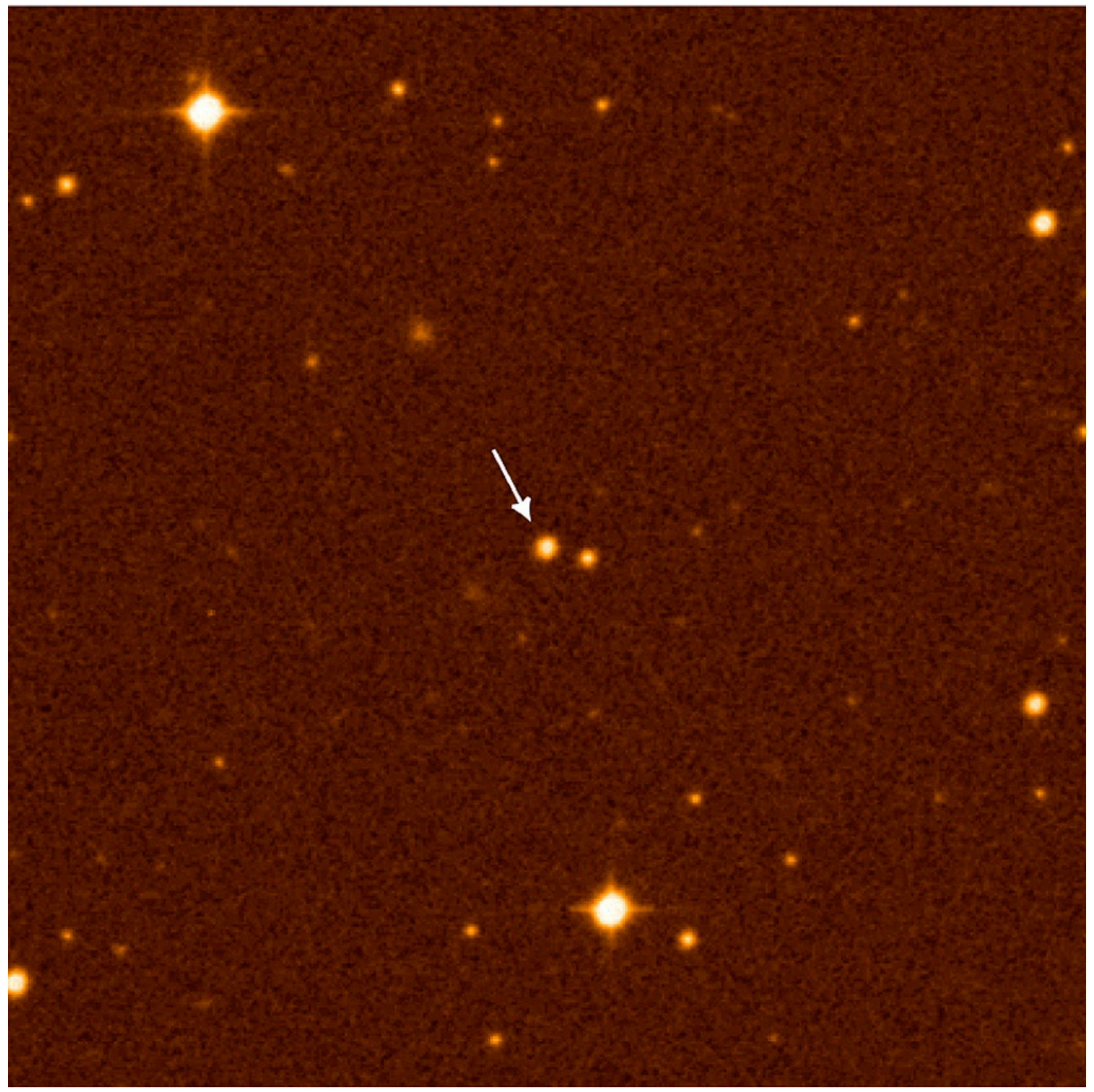
Watson et al. Nature (2019)

Observable: heavy elements produced by the r-process



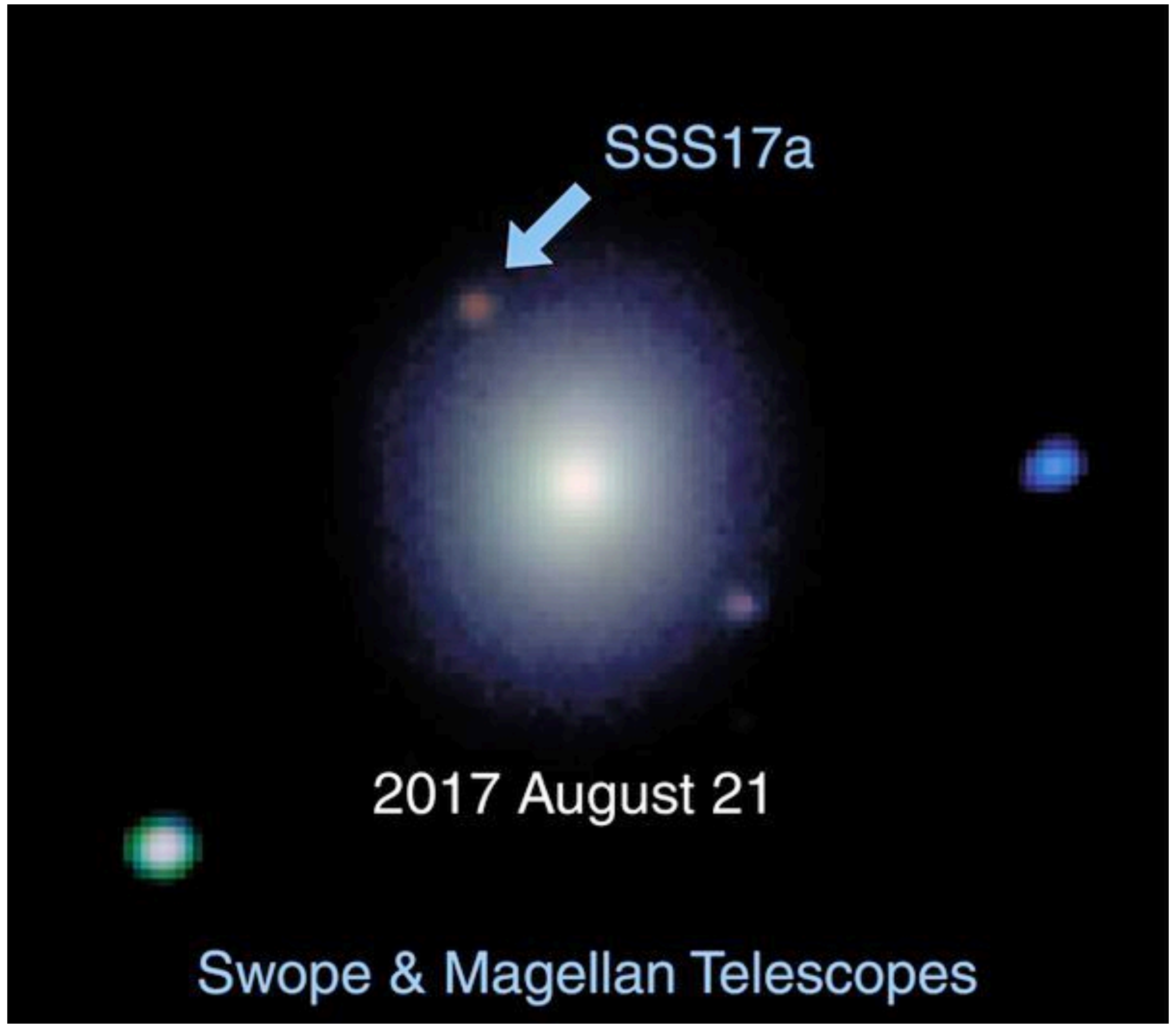
Solar system

?



Oldest stars

?

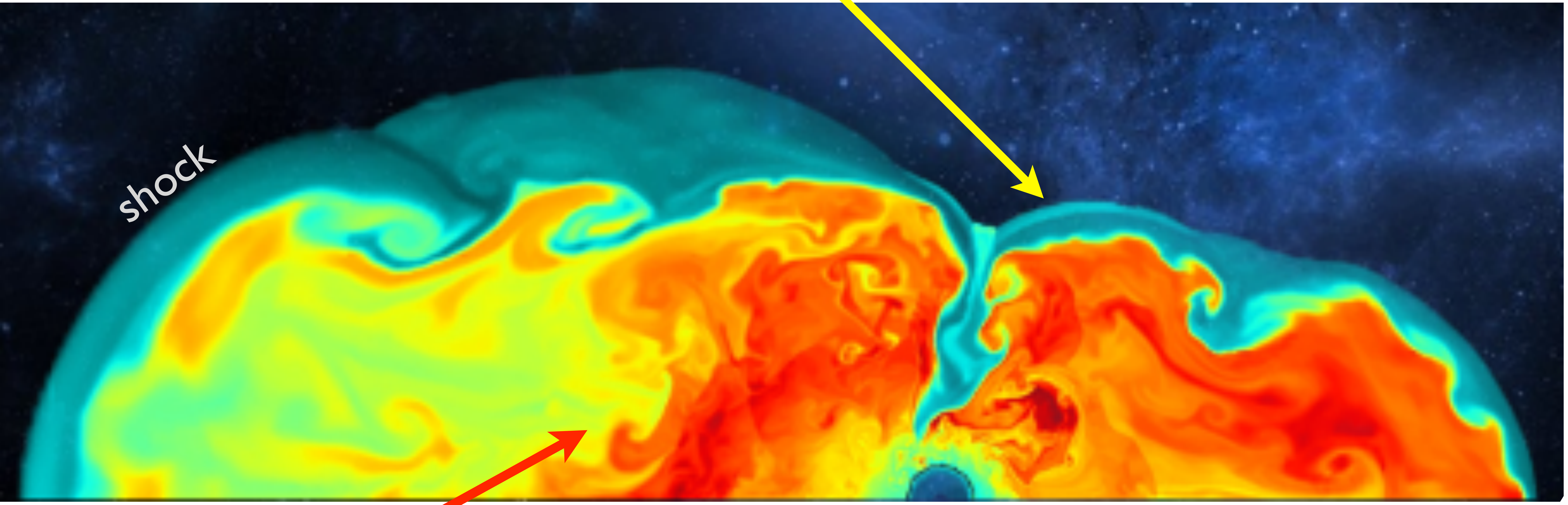


Kilonova

✓

Supernova nucleosynthesis

Explosive nucleosynthesis: O, Mg, Si, S, Ca, Ti, Fe
shock wave heats falling matter

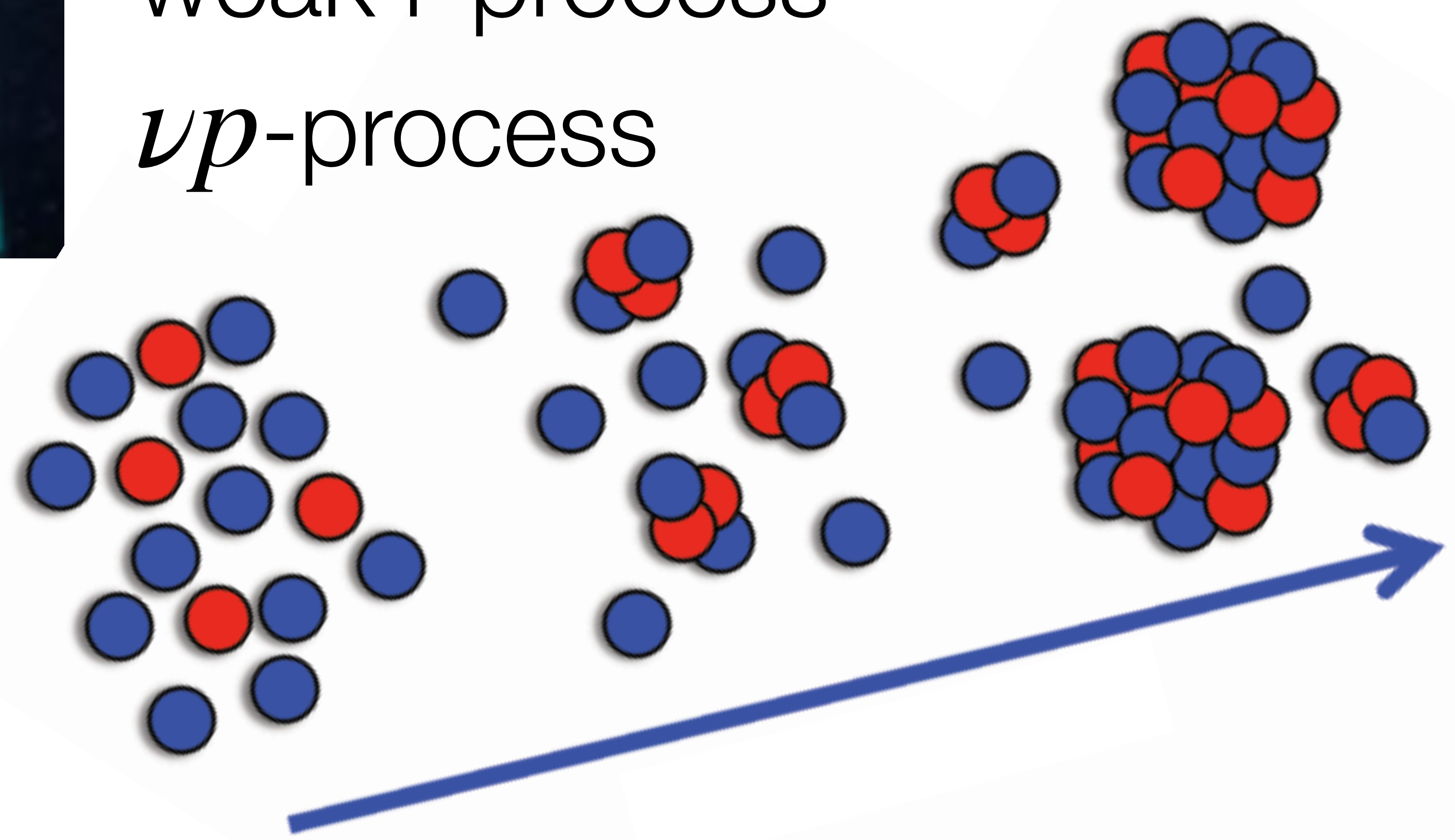


neutrino-driven ejecta

Nuclear statistical equilibrium (NSE)

charged particle reactions
α-process

r-process
weak r-process
νp-process



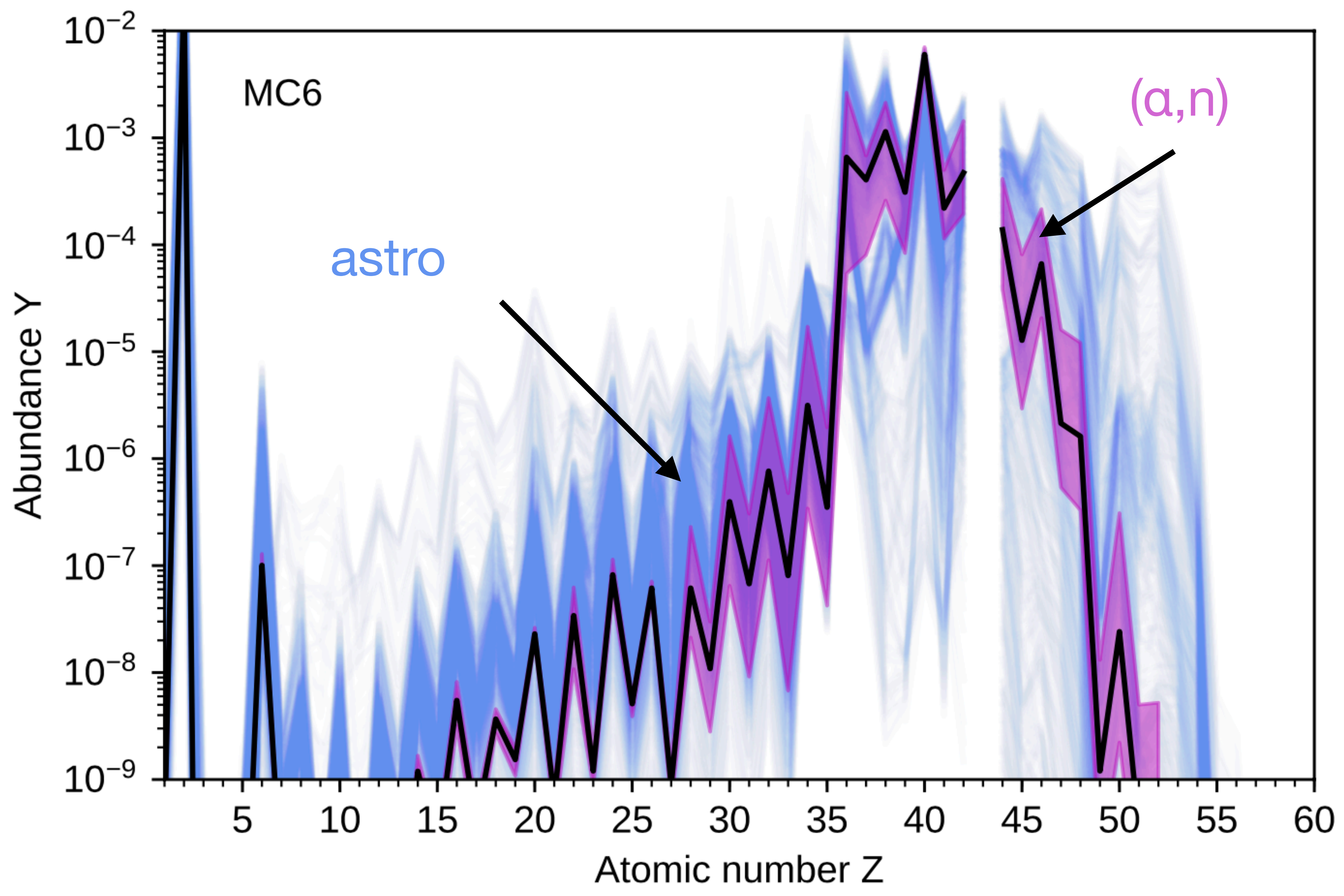
Core-collapse supernova: weak r-process

Neutrino-driven supernovae: elements up to Ag

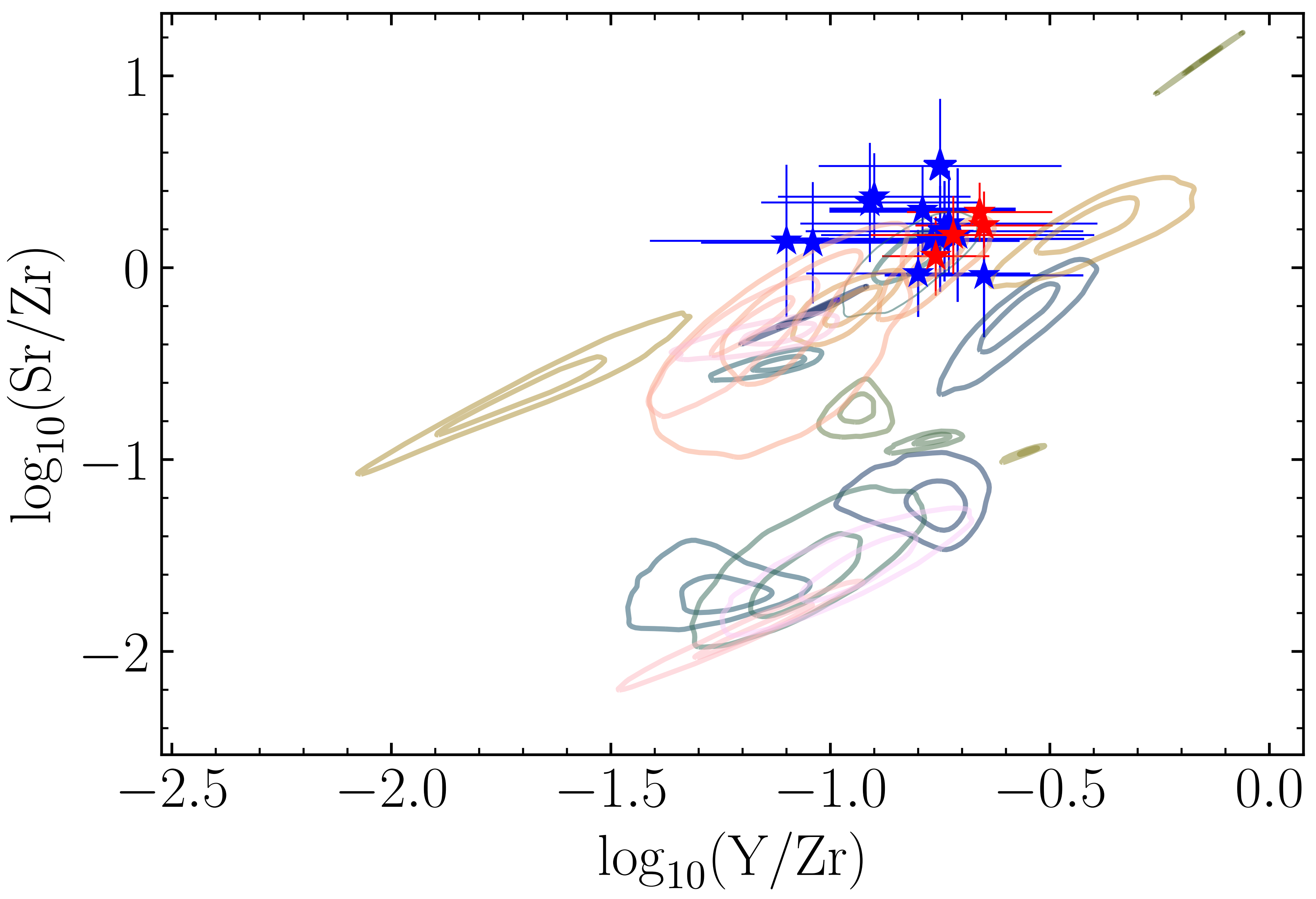
Combine astrophysics and nuclear physics uncertainties

Motivation and support for experiments at NSCL, ANL, TRIUMF, ATOMKI

Bliss et al. JPG (2017), Bliss et al. ApJ (2018), Bliss et al. PRC (2020)

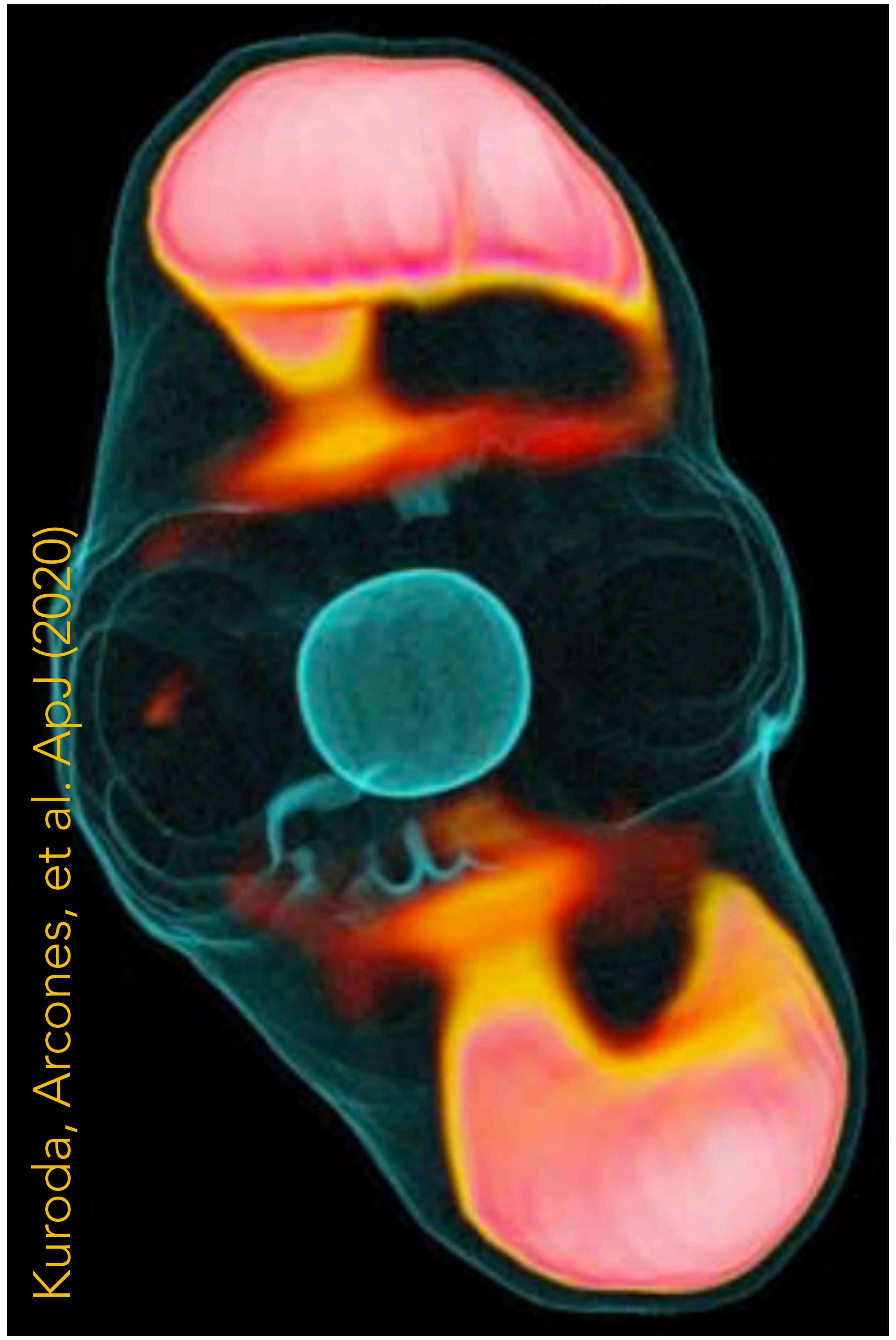


Psaltis et al. ApJ (2022)



r-process in supernovae?

- Neutrino-driven supernovae: elements up to Ag
- Magneto-rotational supernovae: elements up to U and Th?



Neutron-rich matter ejected by magnetic field (Cameron 2003, Nishimura et al. 2006)
2D and 3D + parametric neutrino treatment
Winteler et al. 2012, Nishimura et al. 2015, 2017, Mösta et al. 2018

First 3D simulations of explosions with magnetic fields and detailed neutrino transport, and their nucleosynthesis

Reichert et al. ApJ (2021), Reichert et al. MNRAS (2023)

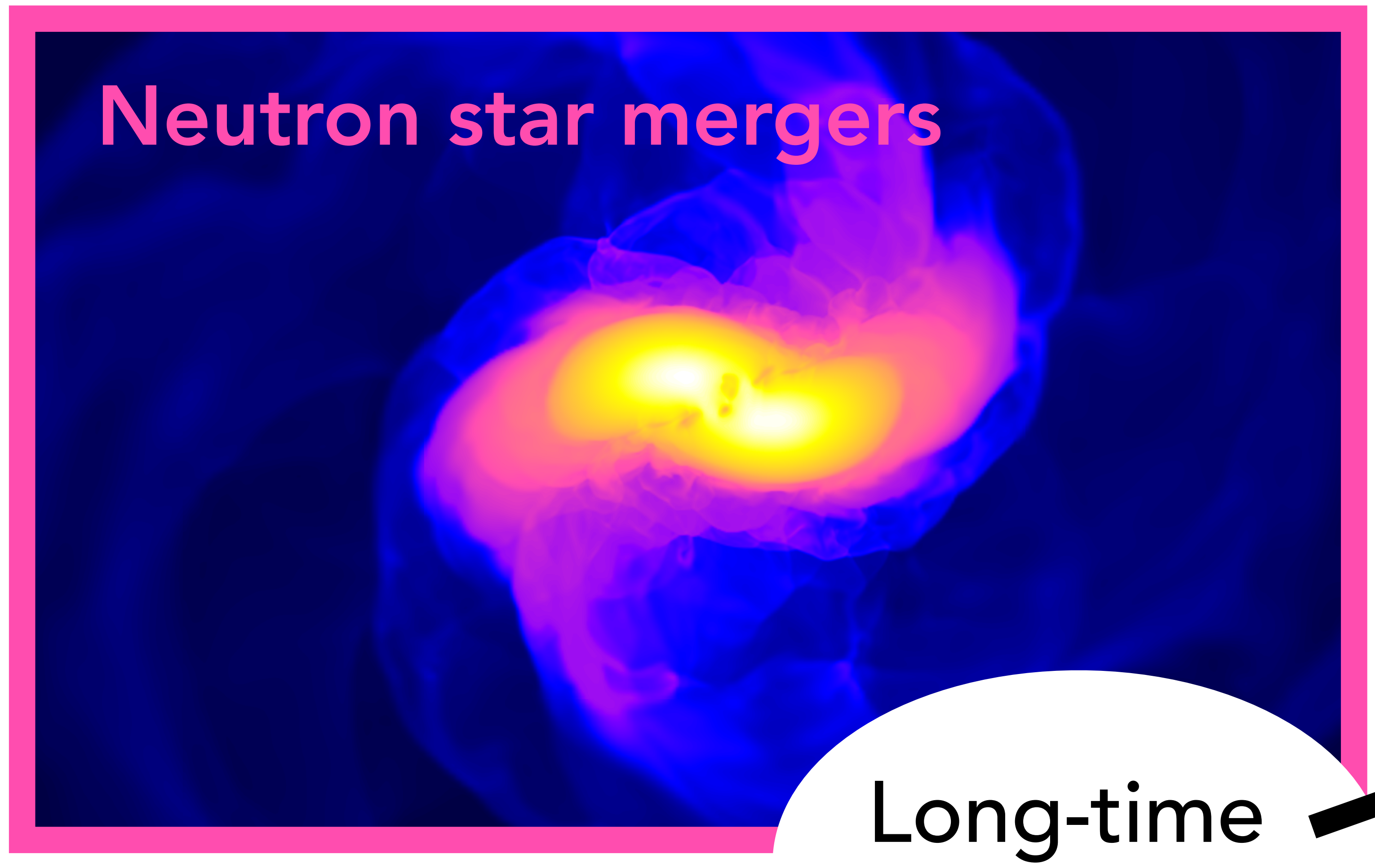
Open questions

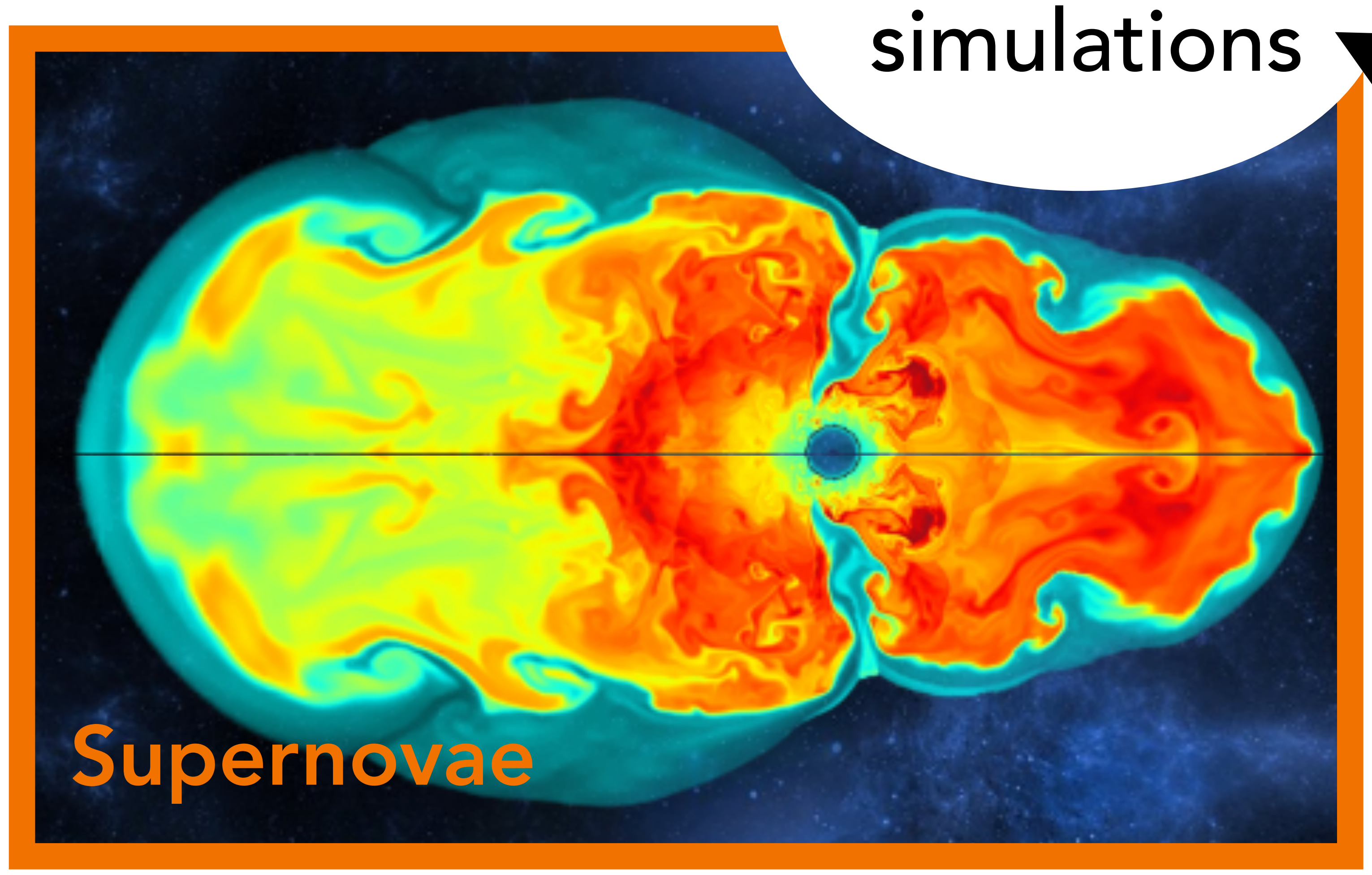
- Long-time evolution:
  Magnetar (neutron star) vs. Collapsar (black hole): **r-process possible?**
- Impact of magnetic field strength and morphology on nucleosynthesis

Reichert et al. (to be submitted)

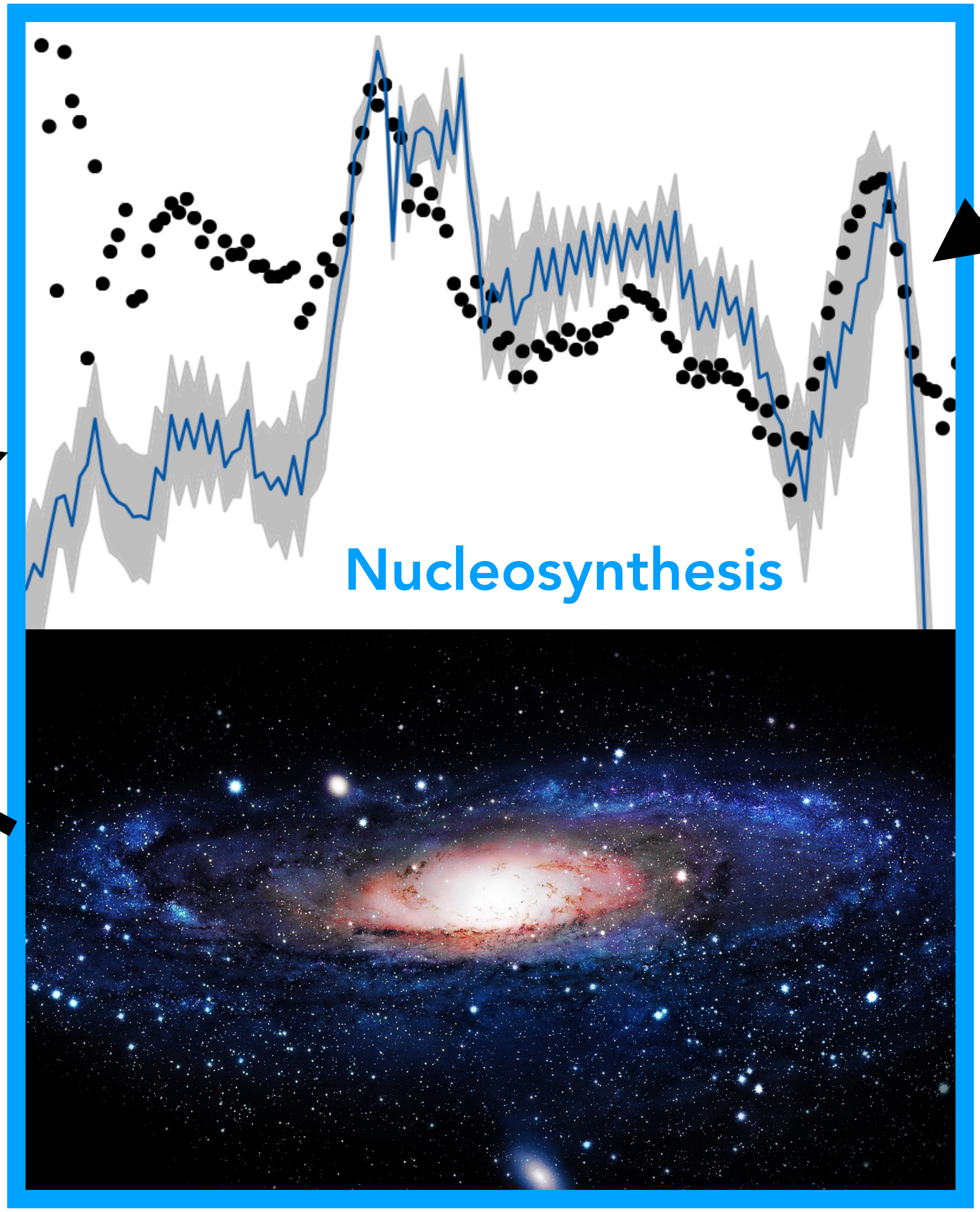
R-process: from simulations to observations

Equation of state
Neutrinos





Long-time simulations

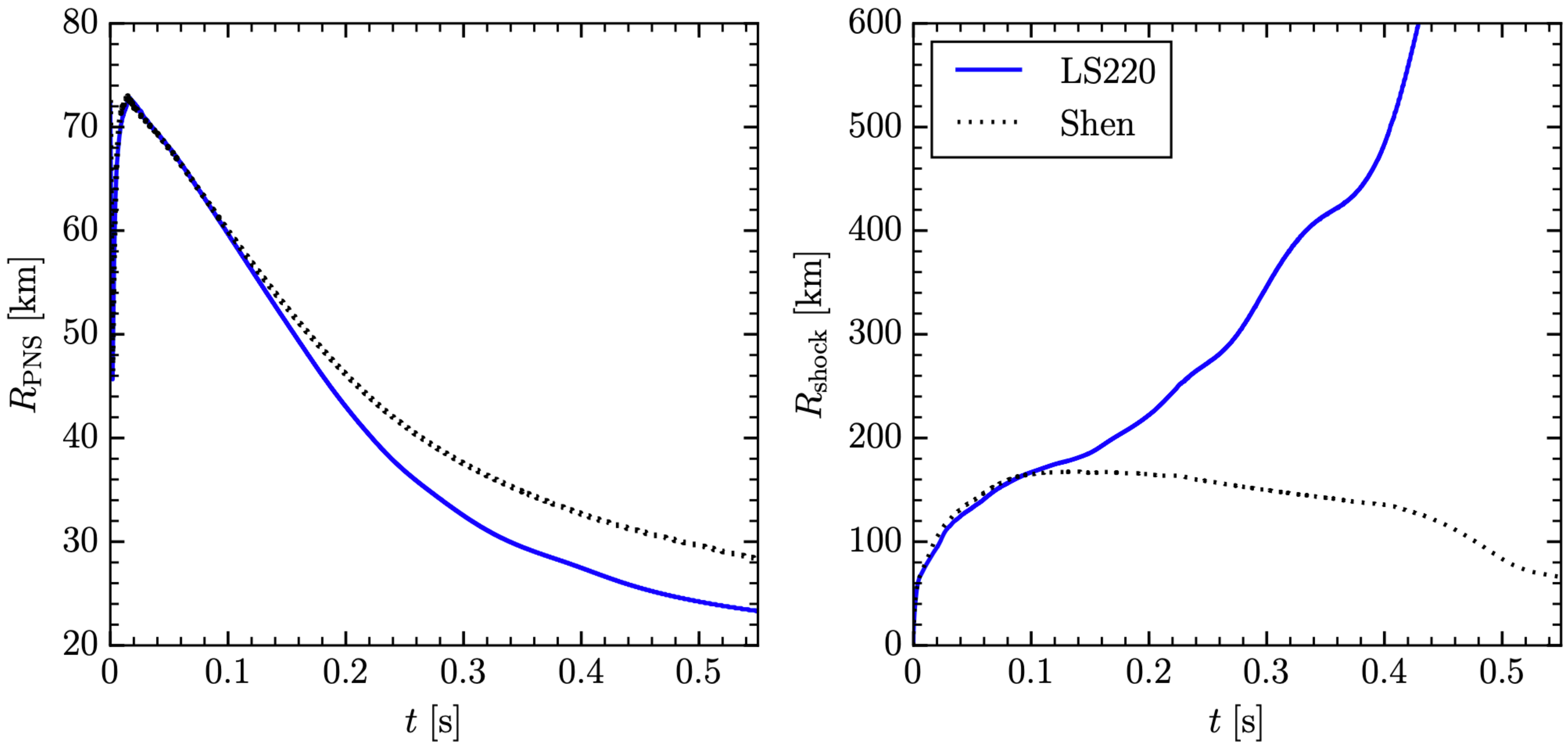


Nuclear physics

Equation of state in core-collapse supernovae

First systematic study of nuclear matter properties

1D simulations, FLASH + M1 + increased neutrino heating

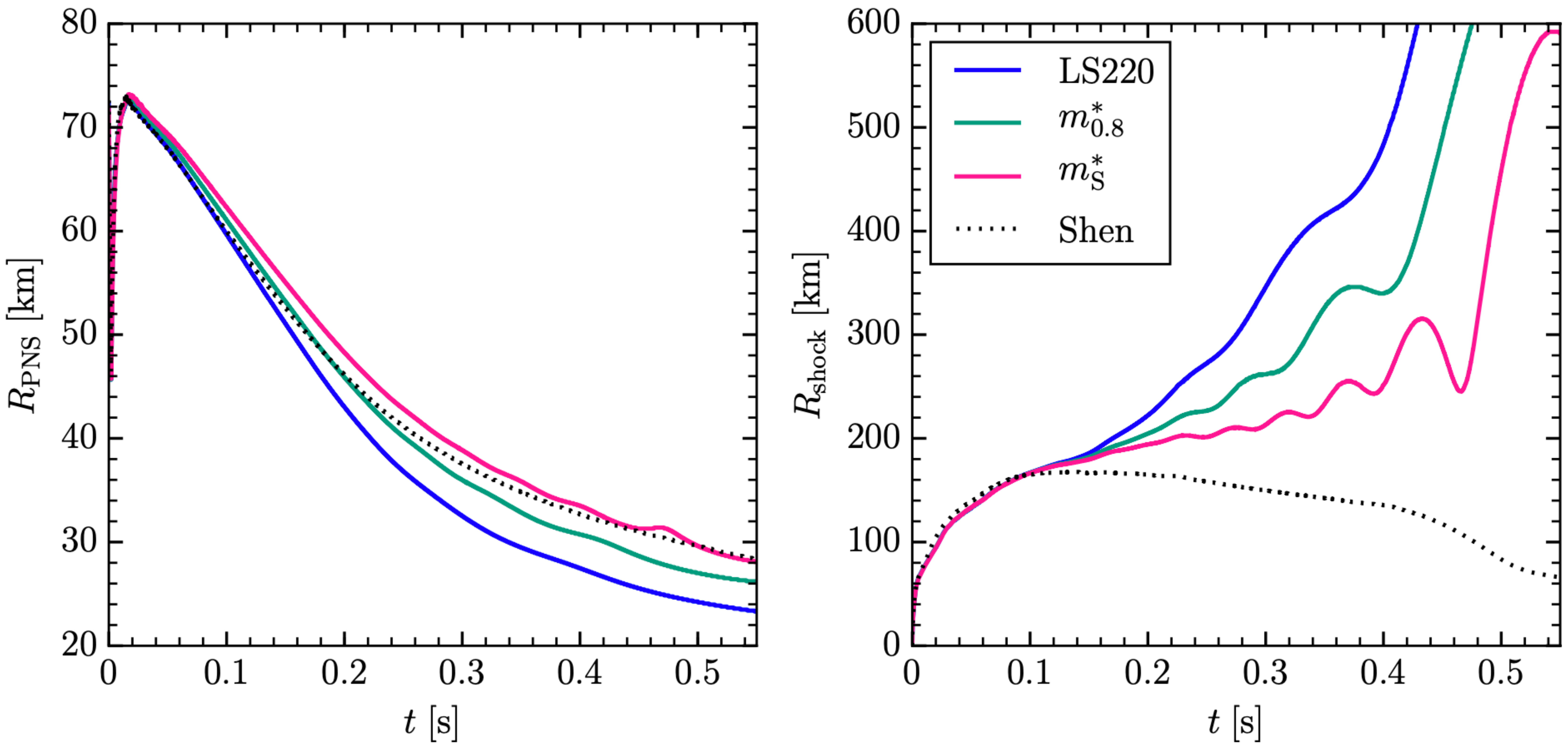


Yasin, Schäfer (now Huth), Arcones, Schwenk, PRL (2020)

Equation of state in core-collapse supernovae

First systematic study of nuclear matter properties

1D simulations, FLASH + M1 + increased neutrino heating



Effective mass:

PNS contraction

Yasin, Schäfer (now Huth), Arcones, Schwenk, PRL (2020)

Equation of state in core-collapse supernovae

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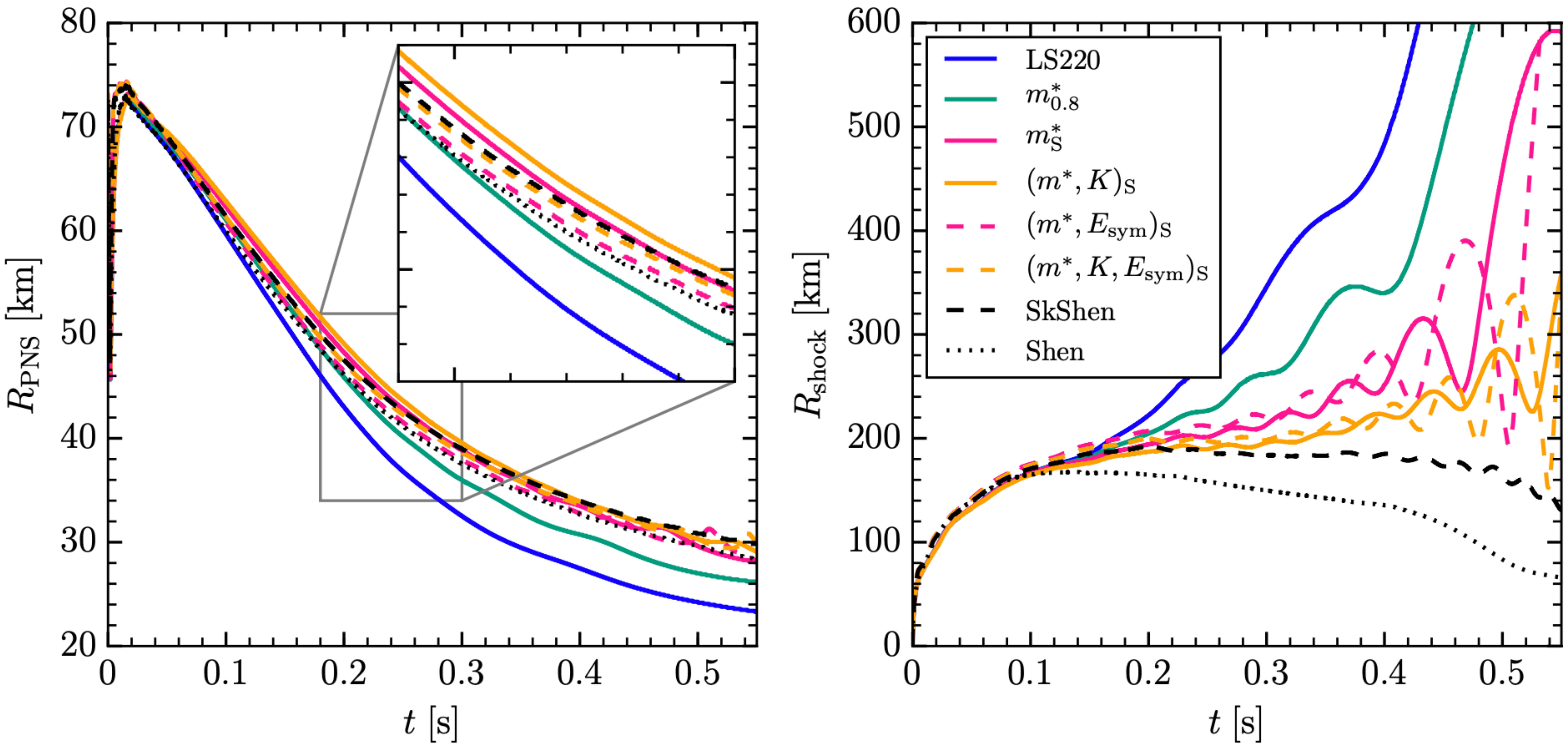


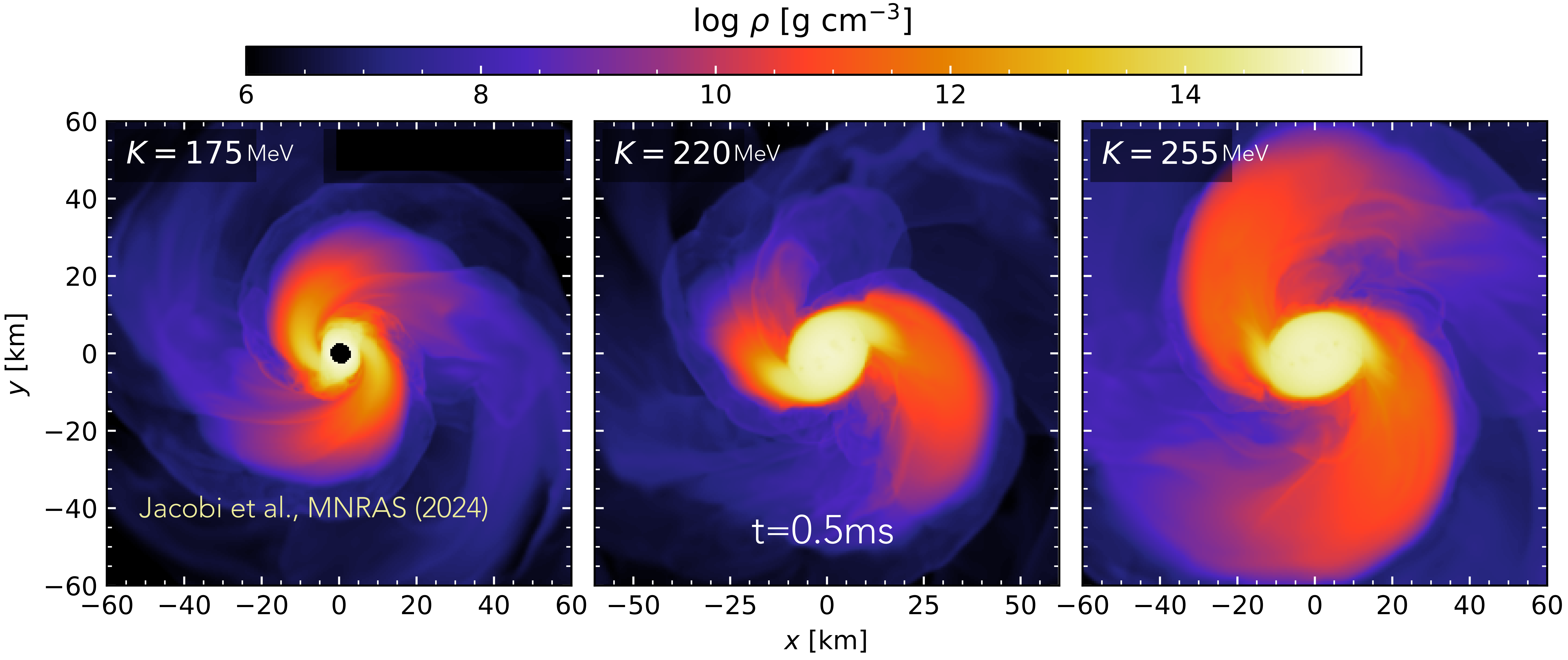
Effective mass:

PNS contraction

Yasin, Schäfer (now Huth), Arcones, Schwenk, PRL (2020)

Equation of state in neutron star mergers

Systematic variations of key properties



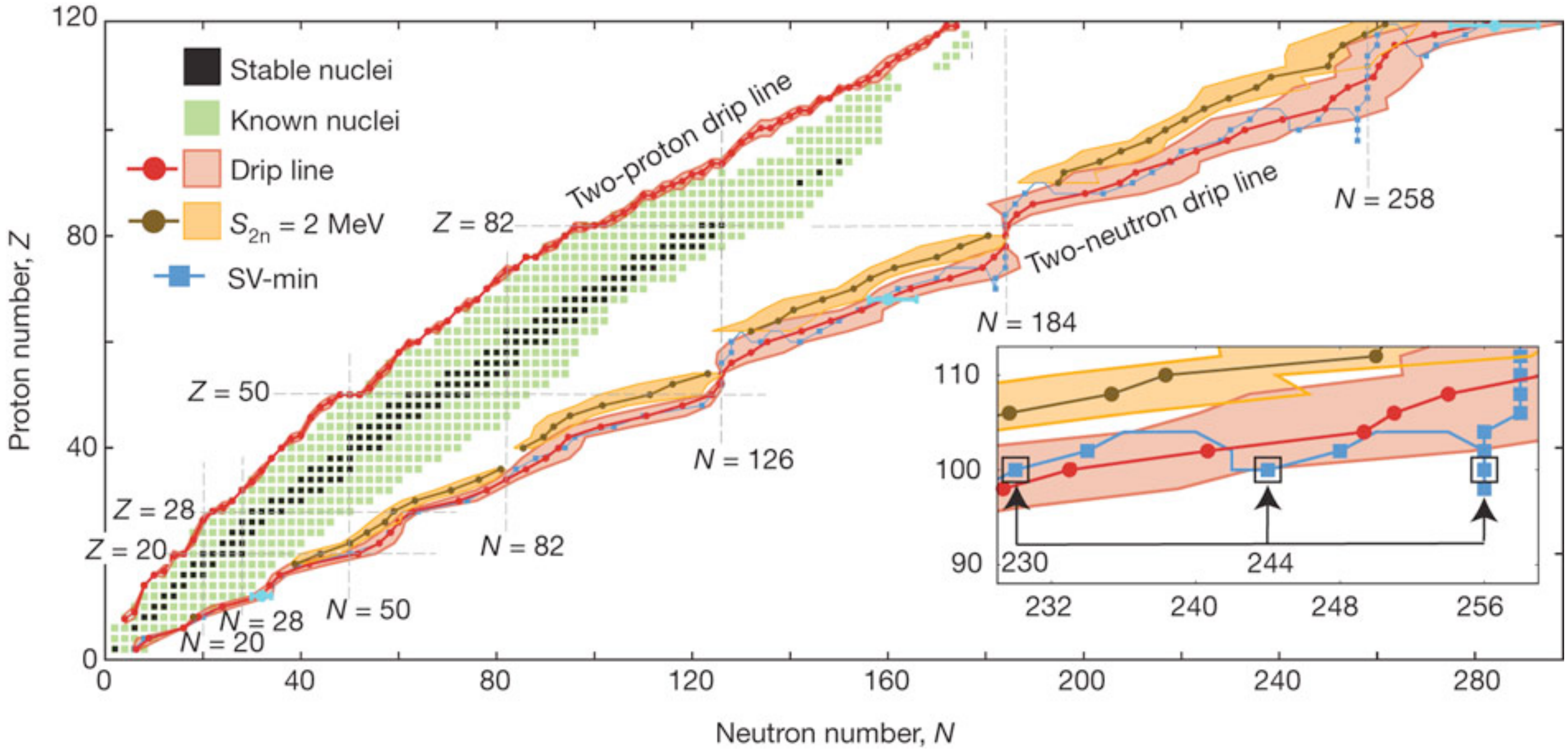
Impact on:

dynamics, gravitational waves, mass ejected (Jacobi et al., MNRAS 2024)

nucleosynthesis and kilonova (Ricigliano et al., in prep.)

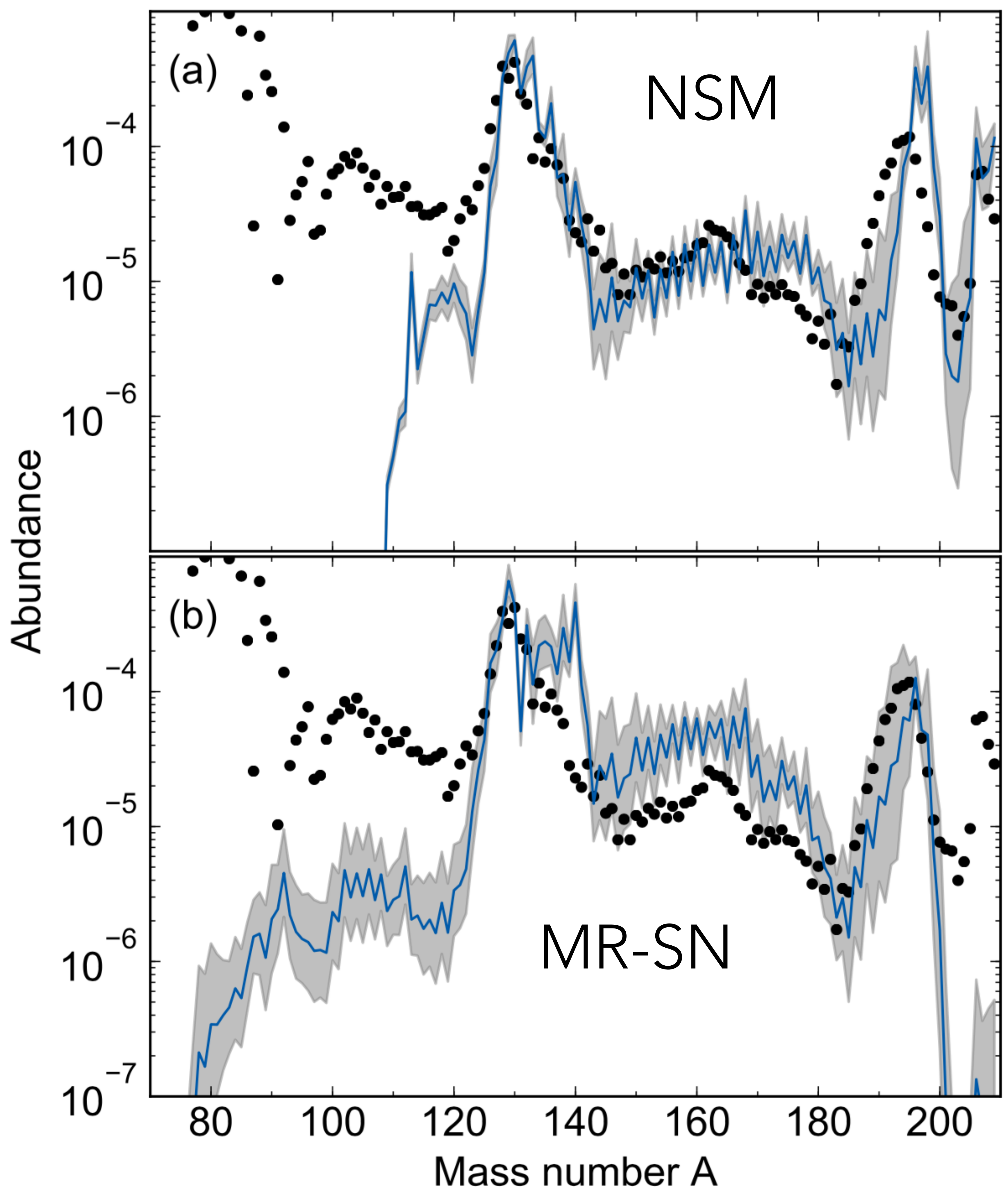
Nuclear physics input

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., Nature 2012)
- two realistic astrophysical scenarios: MR-SN + NSM

First systematic uncertainty band for r-process abundances

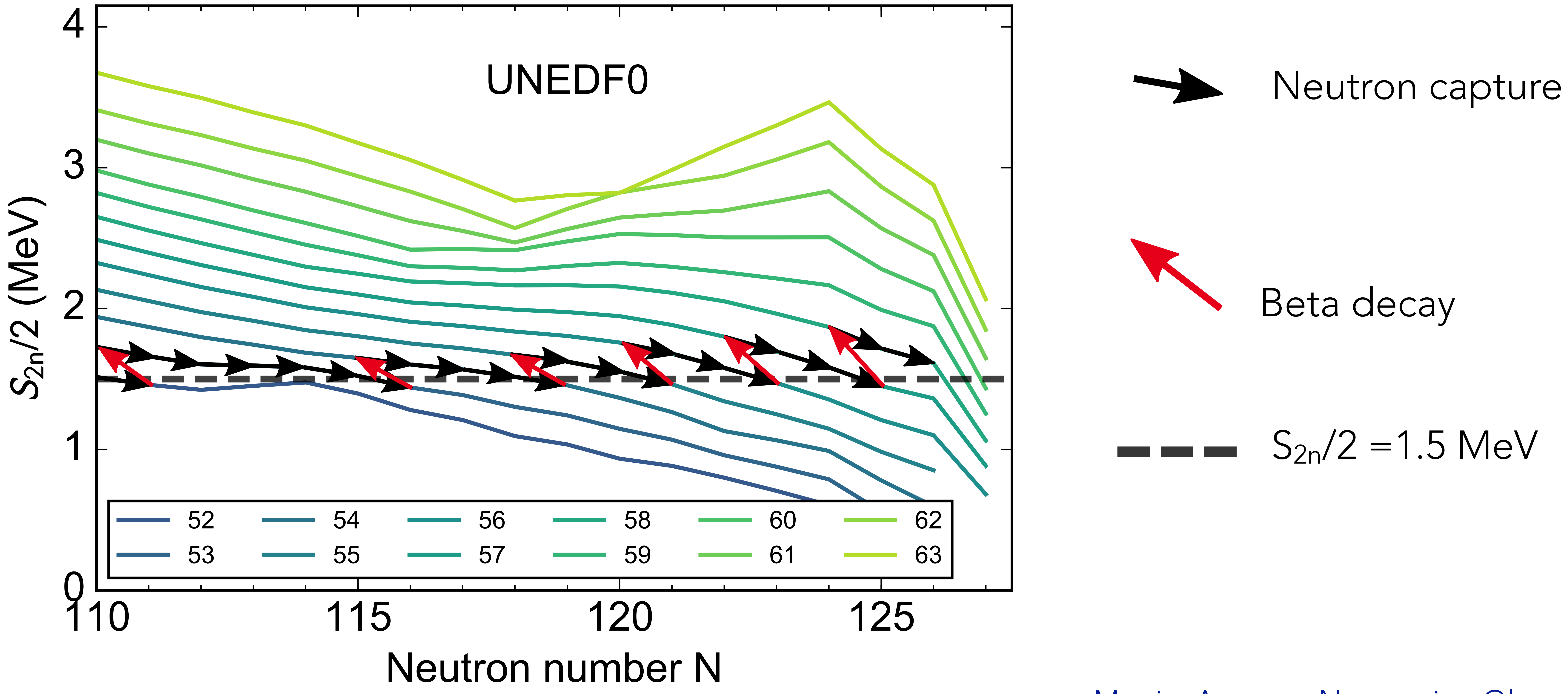
Uncertainty band depends on mass number,
in contrast to homogeneous band for all mass numbers
Mumpower et al. 2015

Can we link masses to r-process abundances?

Martin, Arcones, Nazarewicz, Olsen, PRL (2016)

Two neutron separation energy

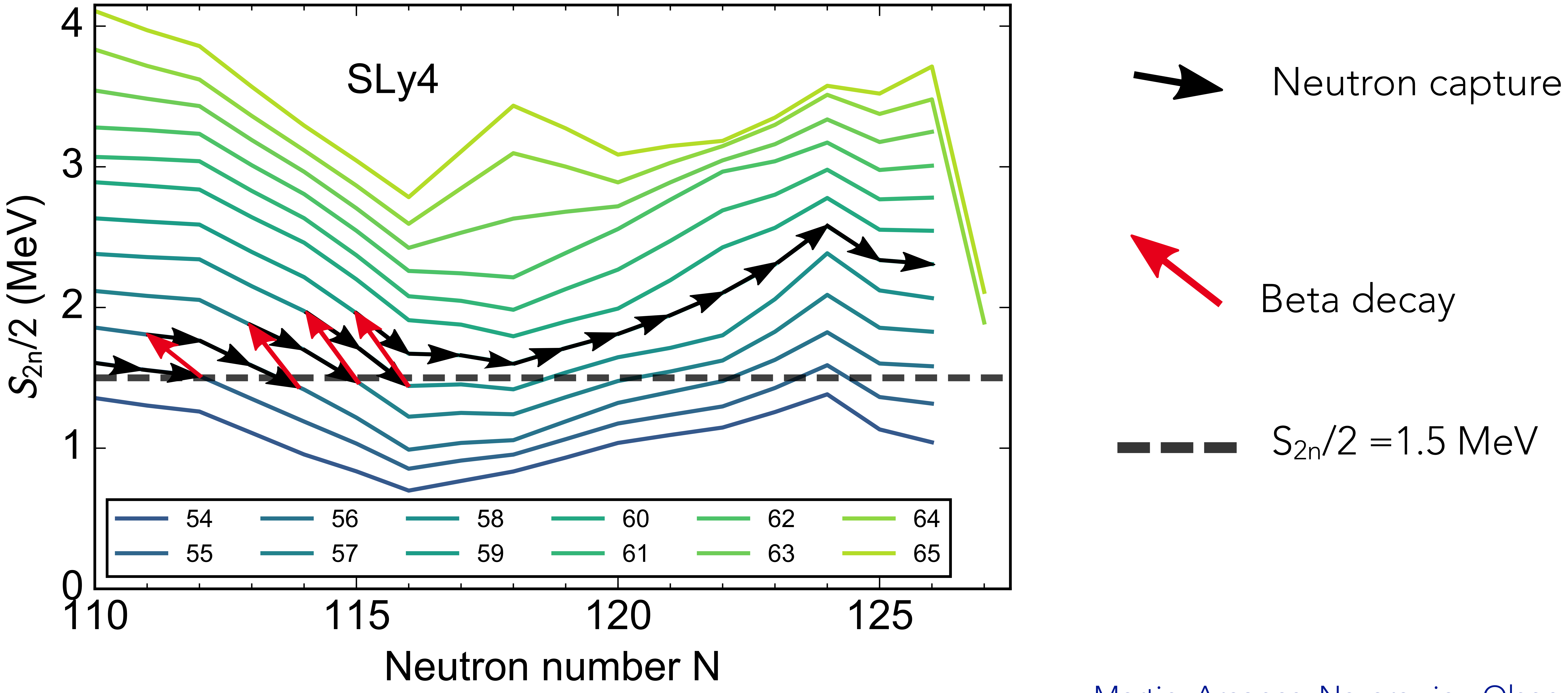
Nucleosynthesis path at constant S_n: (n,γ)-(γ,n) equilibrium



Martin, Arcones, Nazarewicz, Olsen, PRL (2016)

Two neutron separation energy

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



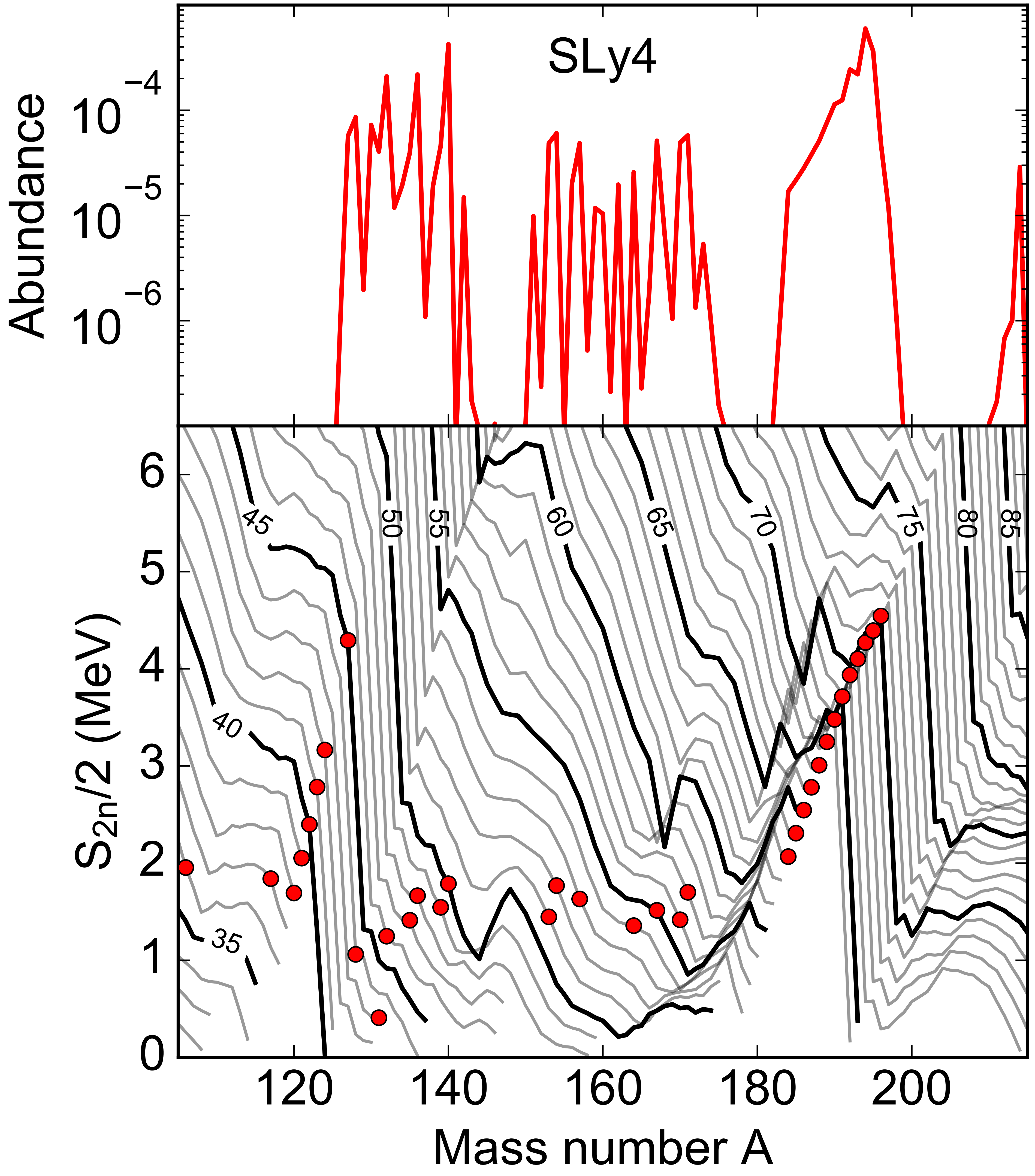
Martin, Arcones, Nazarewicz, Olsen, PRL (2016)

Two neutron separation energy -> abundances

Abundances

S_{2n}

Nuclear properties



Two neutron separation energy -> abundances

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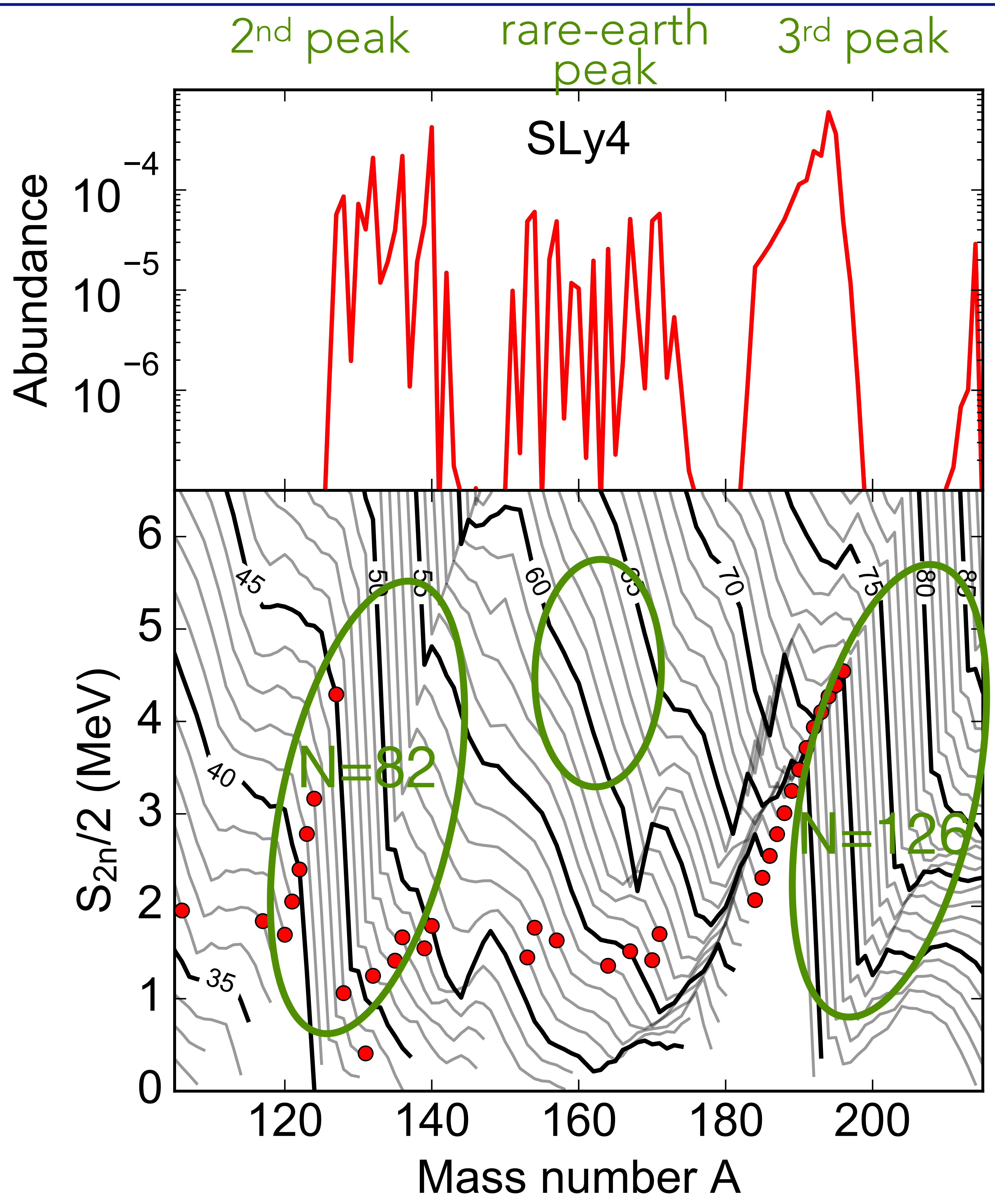

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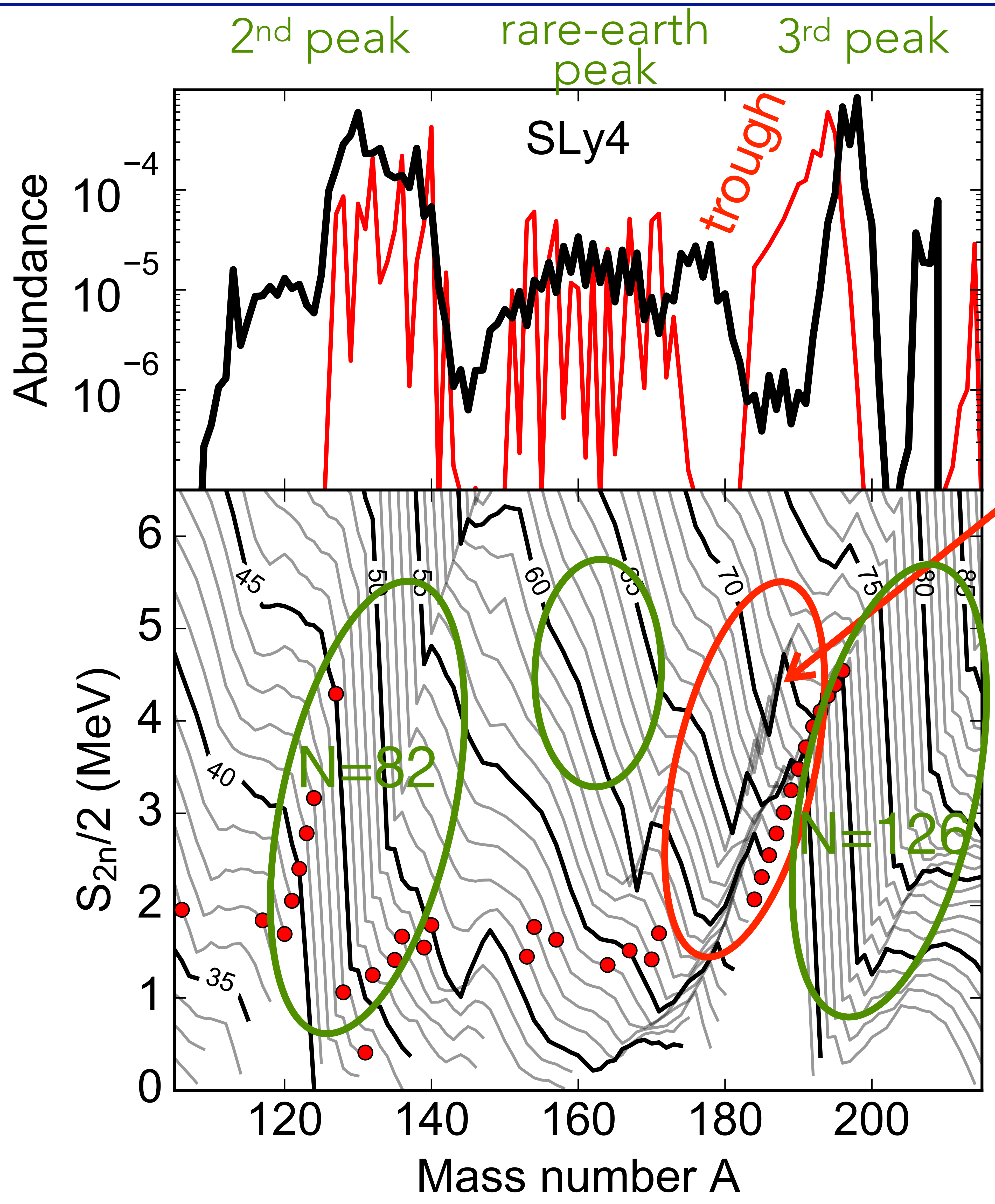
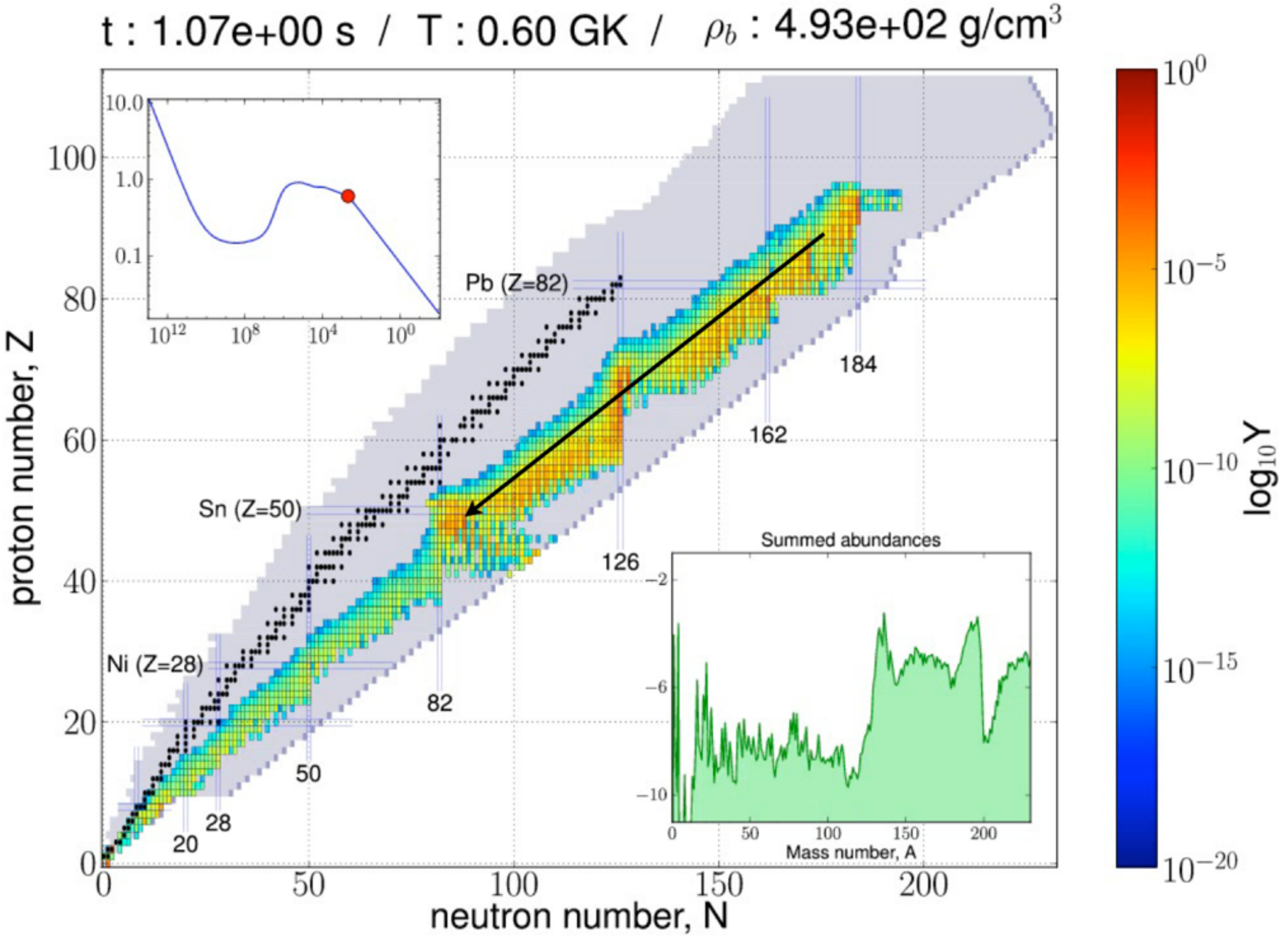
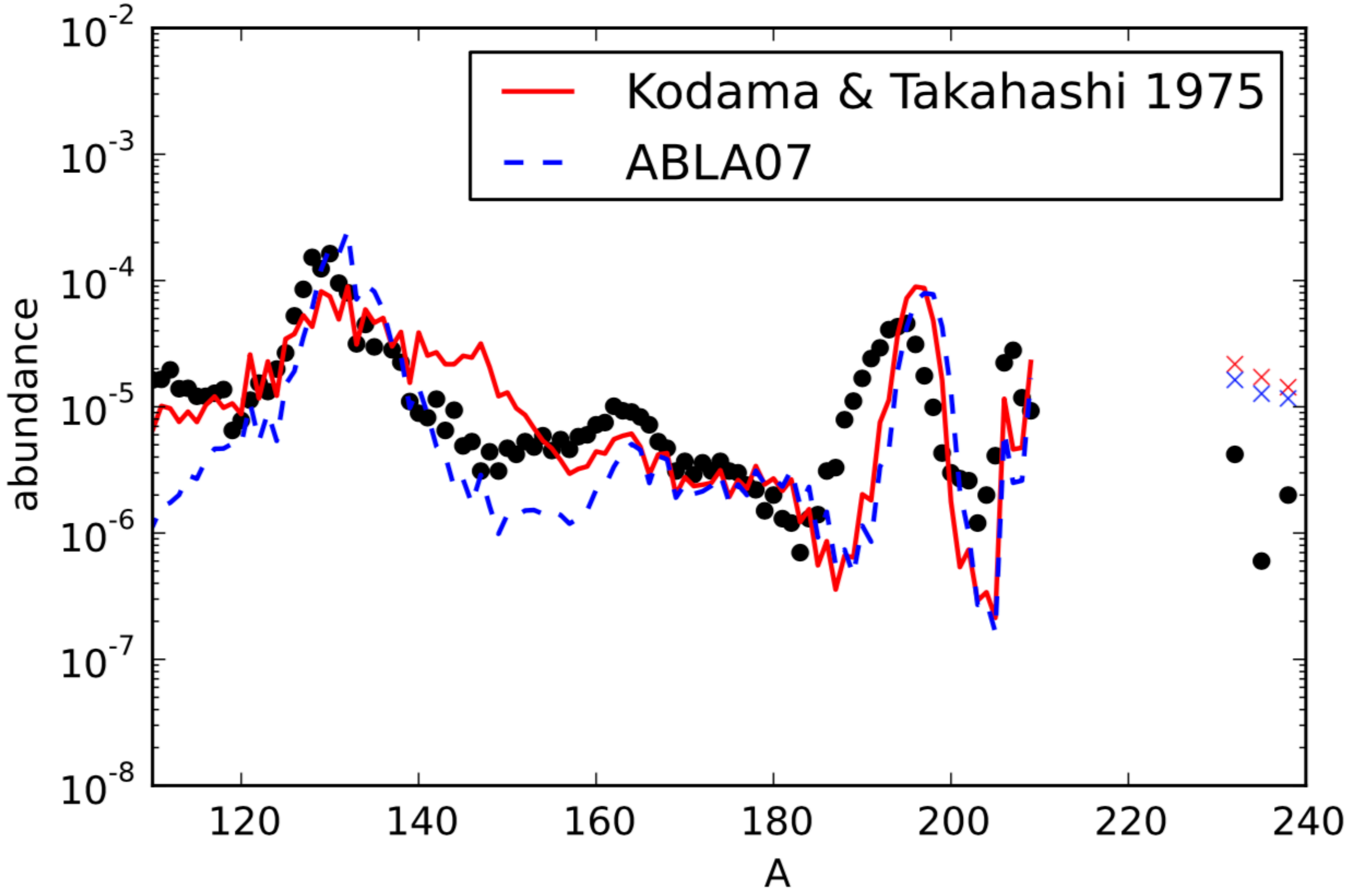


transition from deformed to spherical

Neutron captures are critical during decay to stability!

Fission: barriers and yield distributions





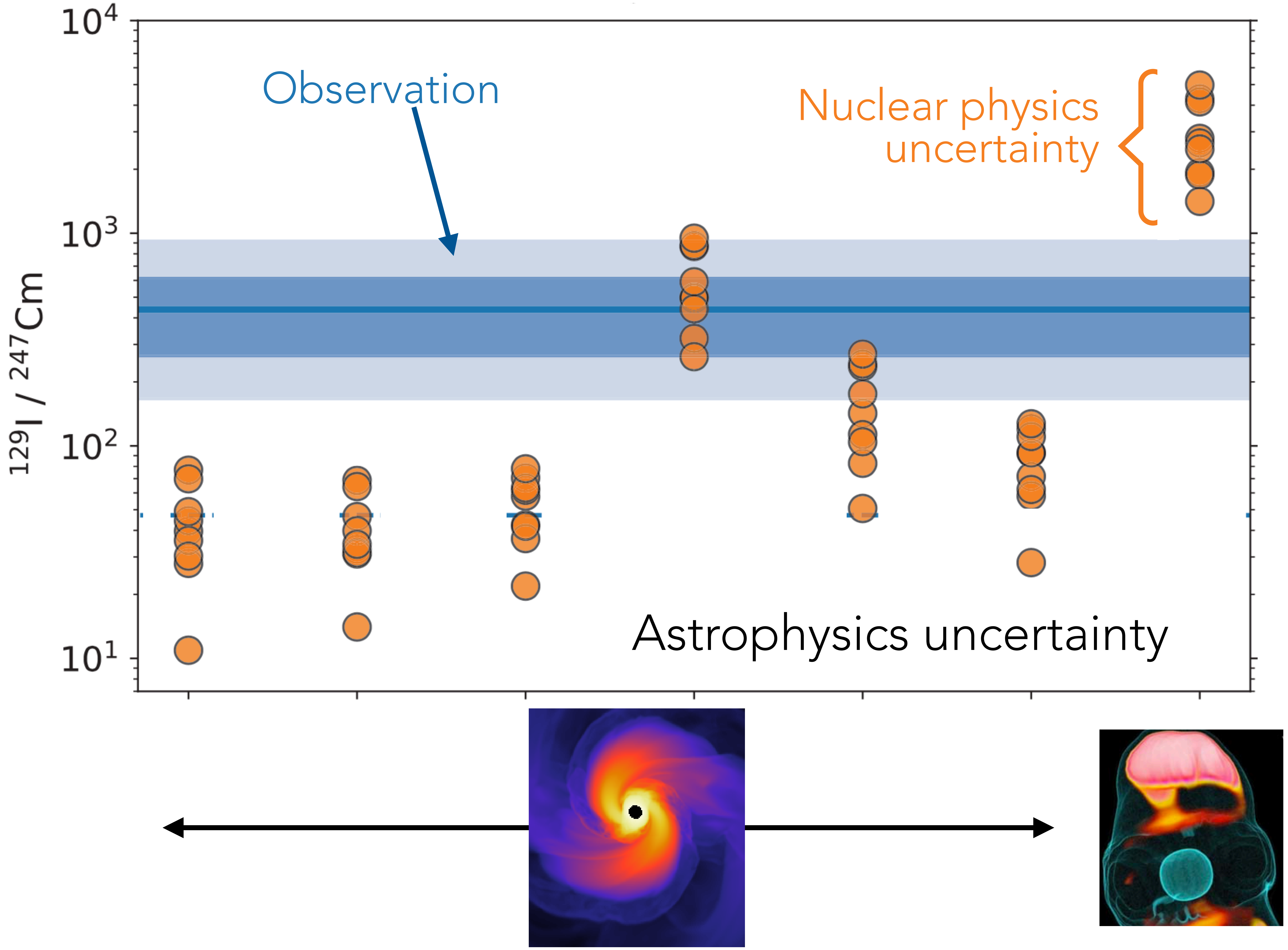
2nd peak (A~130): fission yield distribution

3rd peak (A~195): mass model, neutron captures

Eichler et al. ApJ (2015), Eichler et al. ApJ (2019)

Nucleosynthesis: connecting simulations to observations

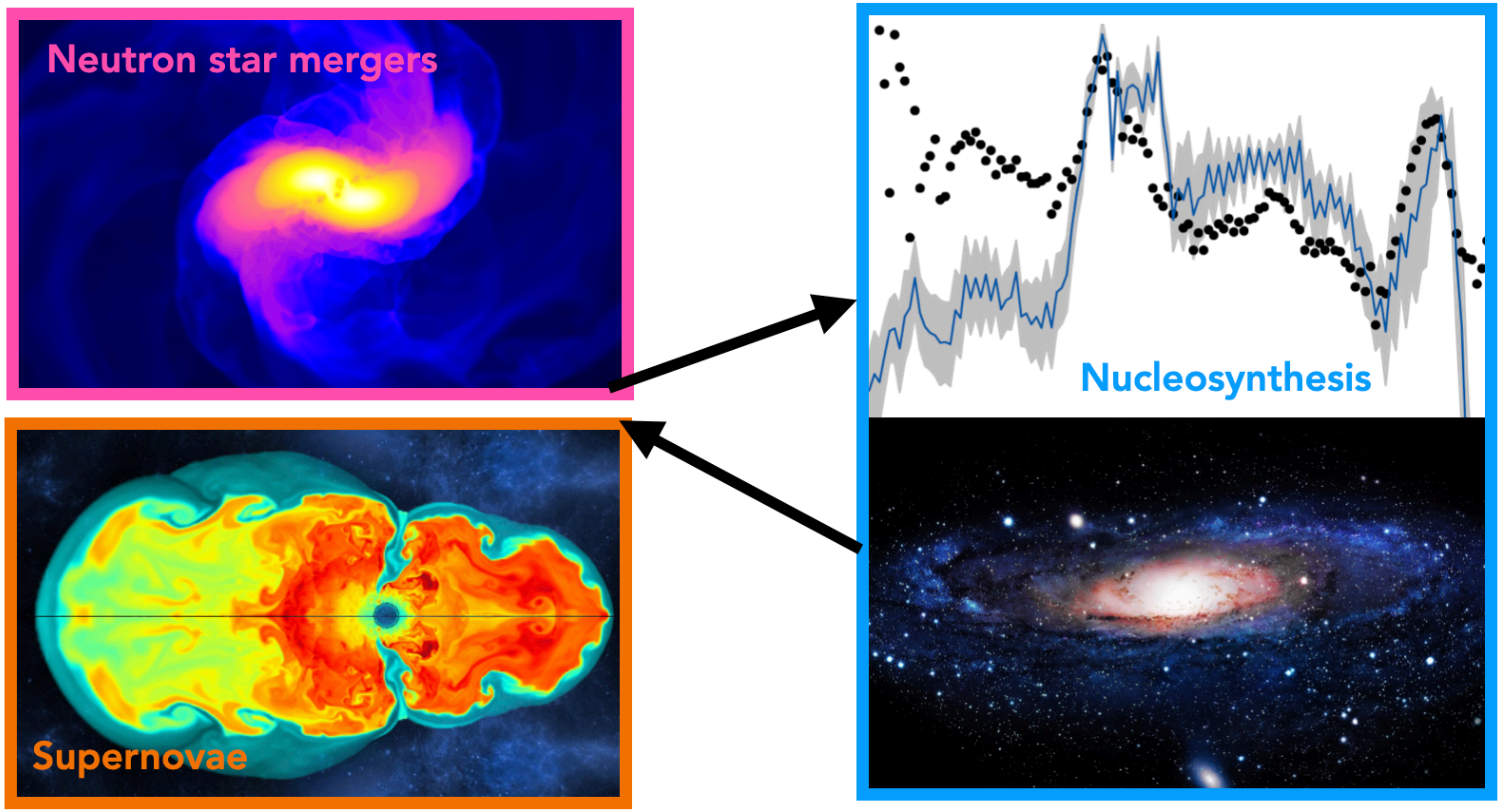
Côtè et al. Science (2021)



Exciting time

- **Multimessenger astronomy**: electromagnetic + gravitational waves + neutrinos
- Advanced **astrophysical simulations** + detailed **physics** (supercomputers)
- **New experimental frontier**: extreme-neutron rich nuclei at FAIR, FRIB, RIKEN, ISOLDE, TRIUMF,…
- Increased number observations of **oldest stars**: large telescopes and new spectrographs

Mergers and supernovae as cosmic laboratories establish the origin and history of heavy elements in the universe



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