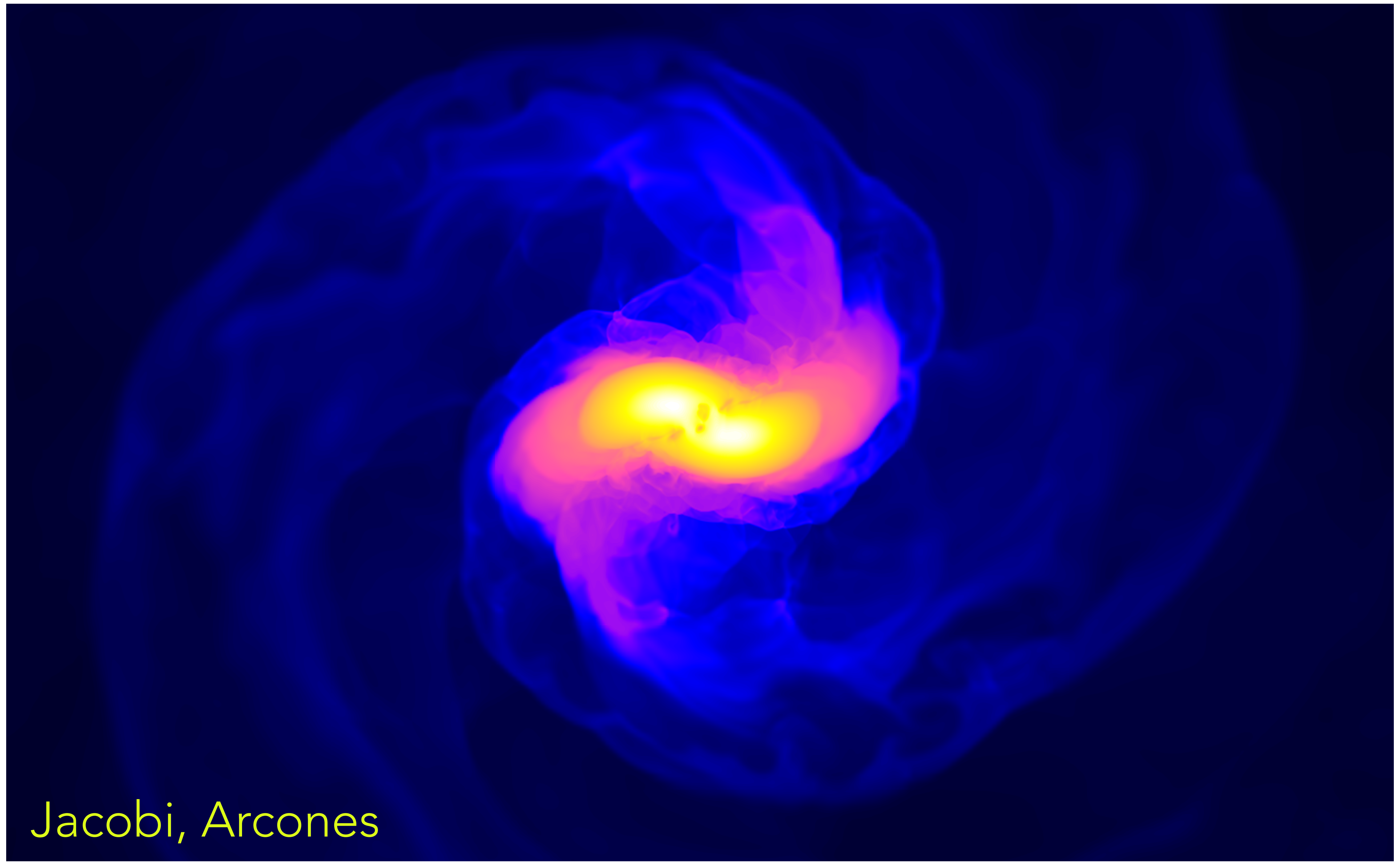
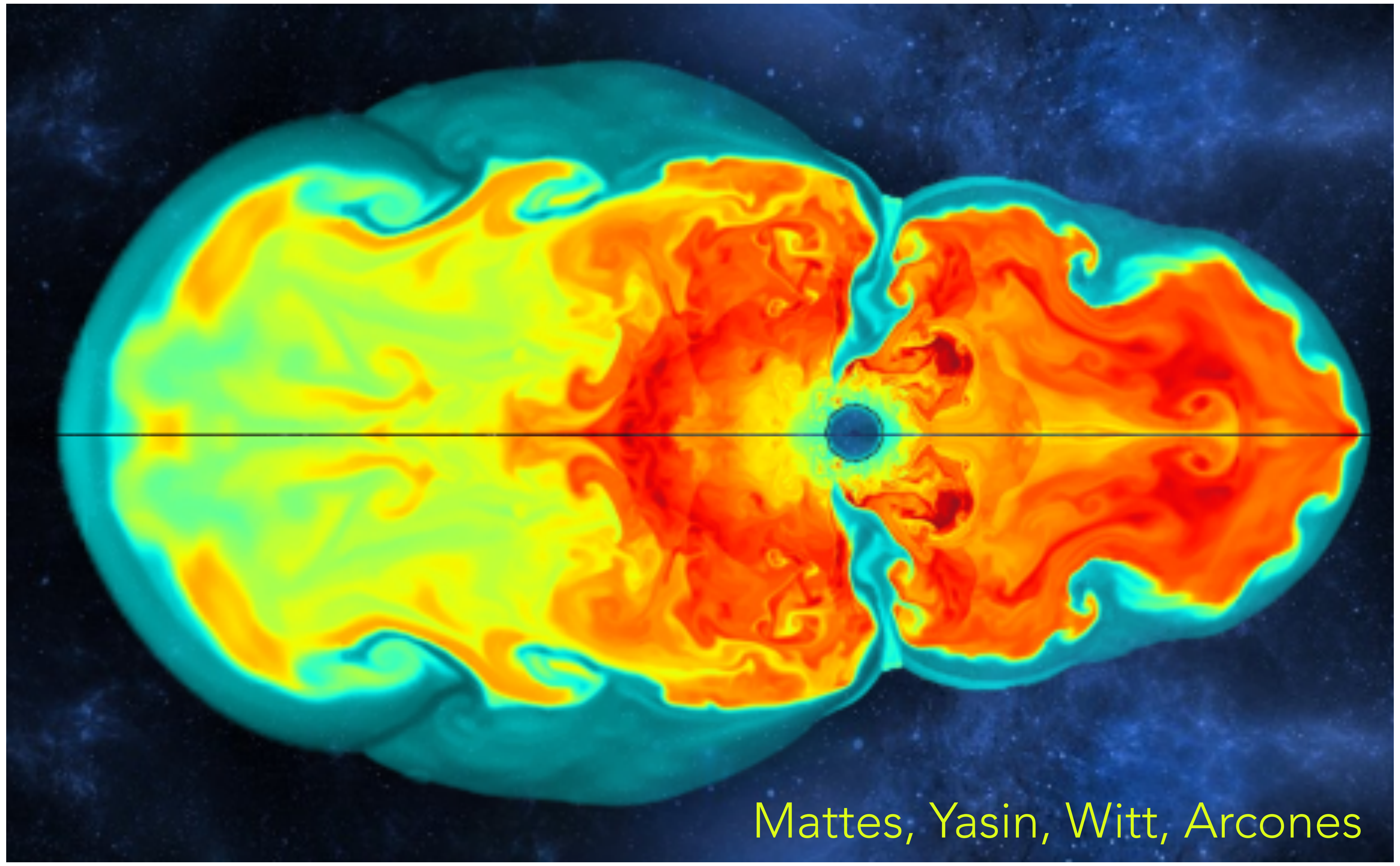
R-process in neutron star mergers and supernovae



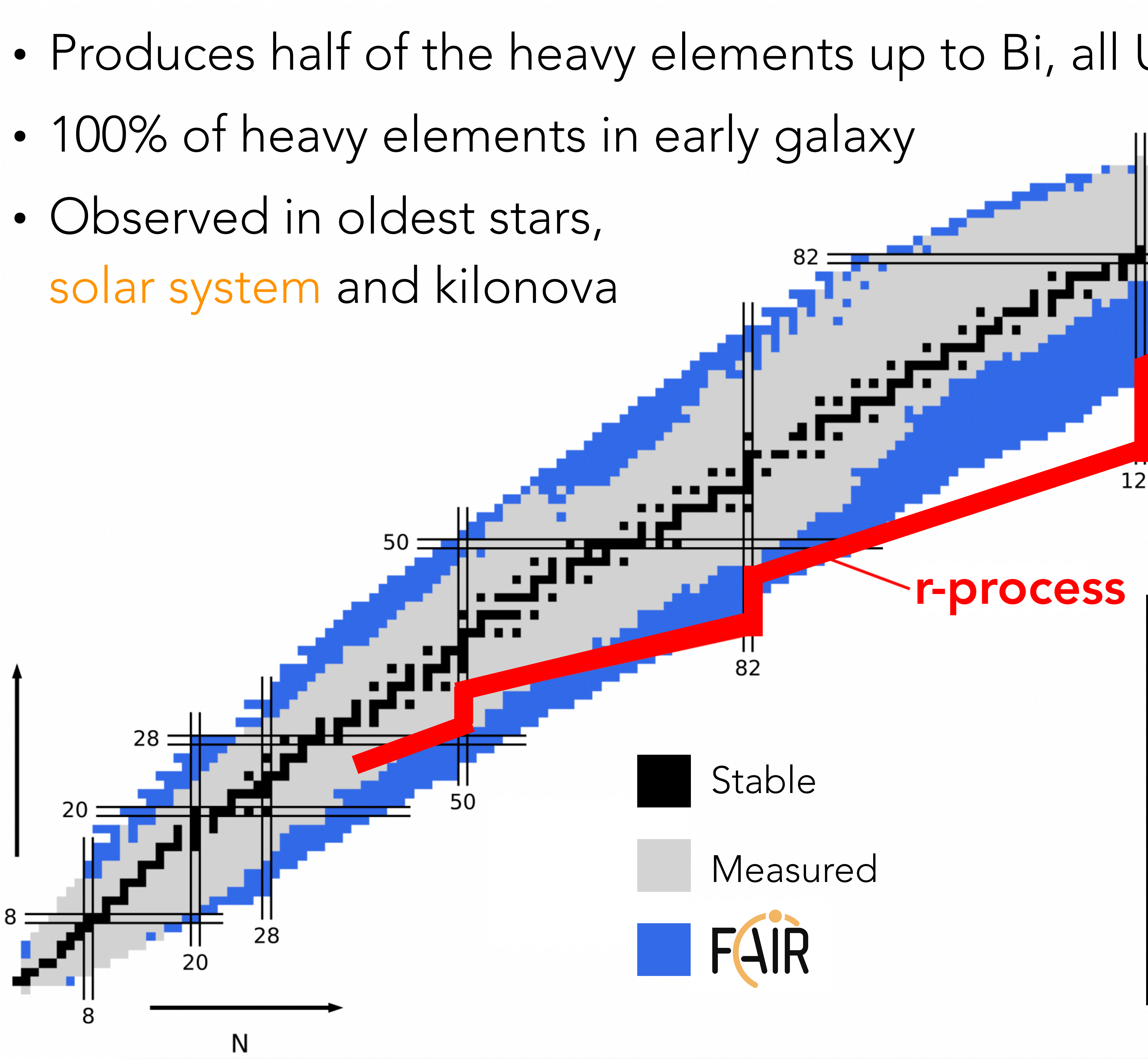


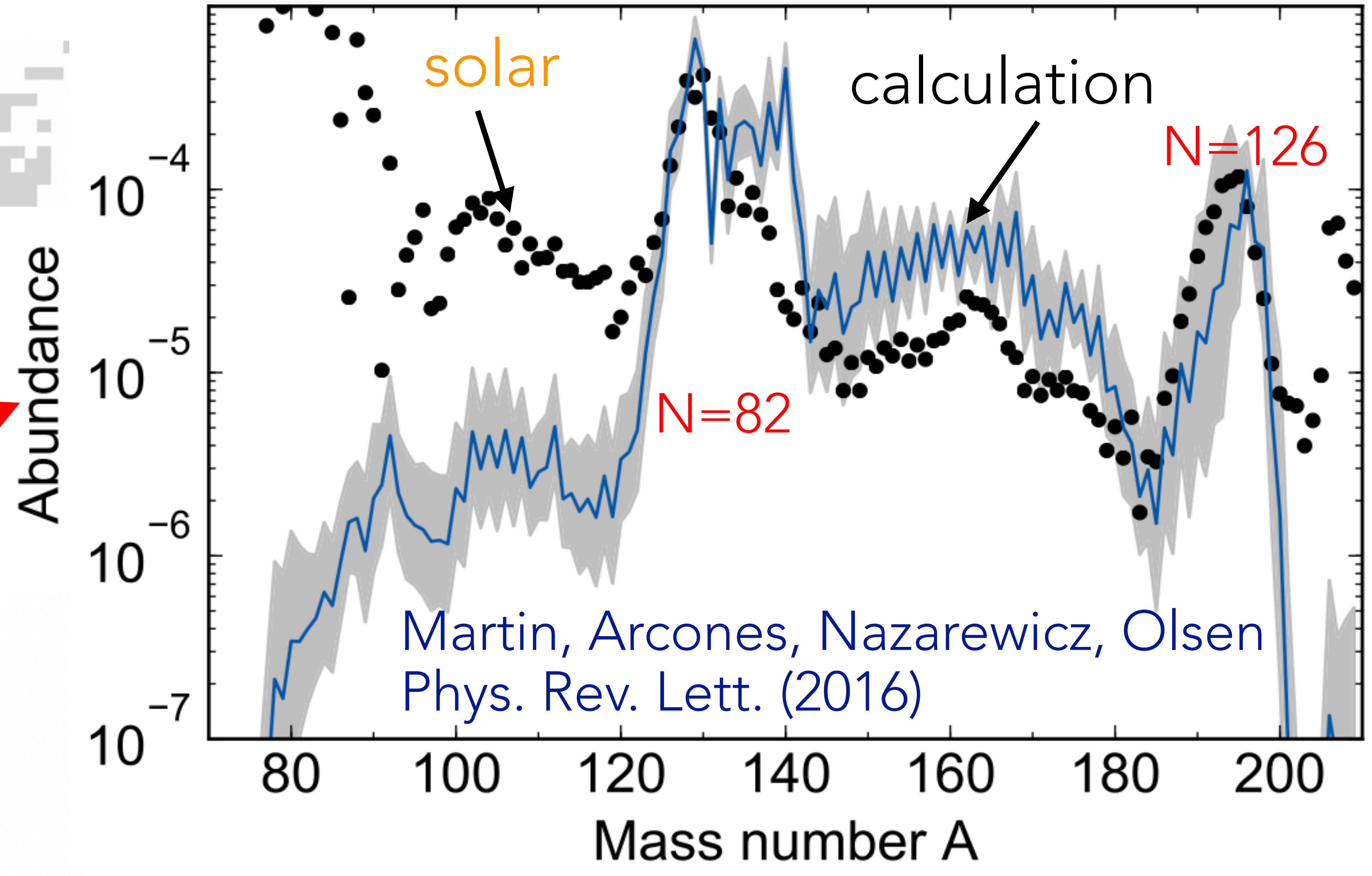
Almudena Arcones

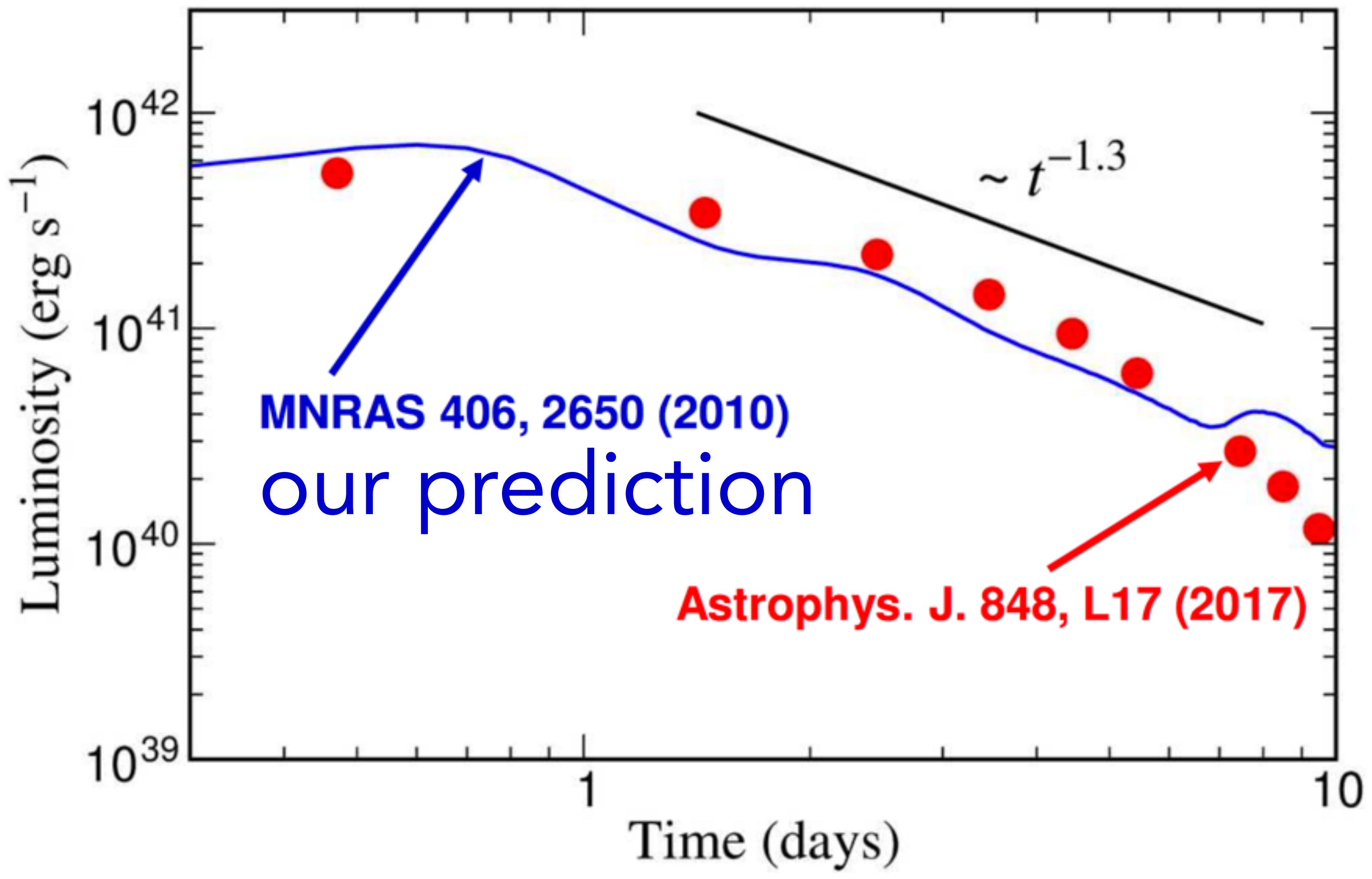
Max-Planck-Institut für Kernphysik Heidelberg
Technische Universität Darmstadt
GSI

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





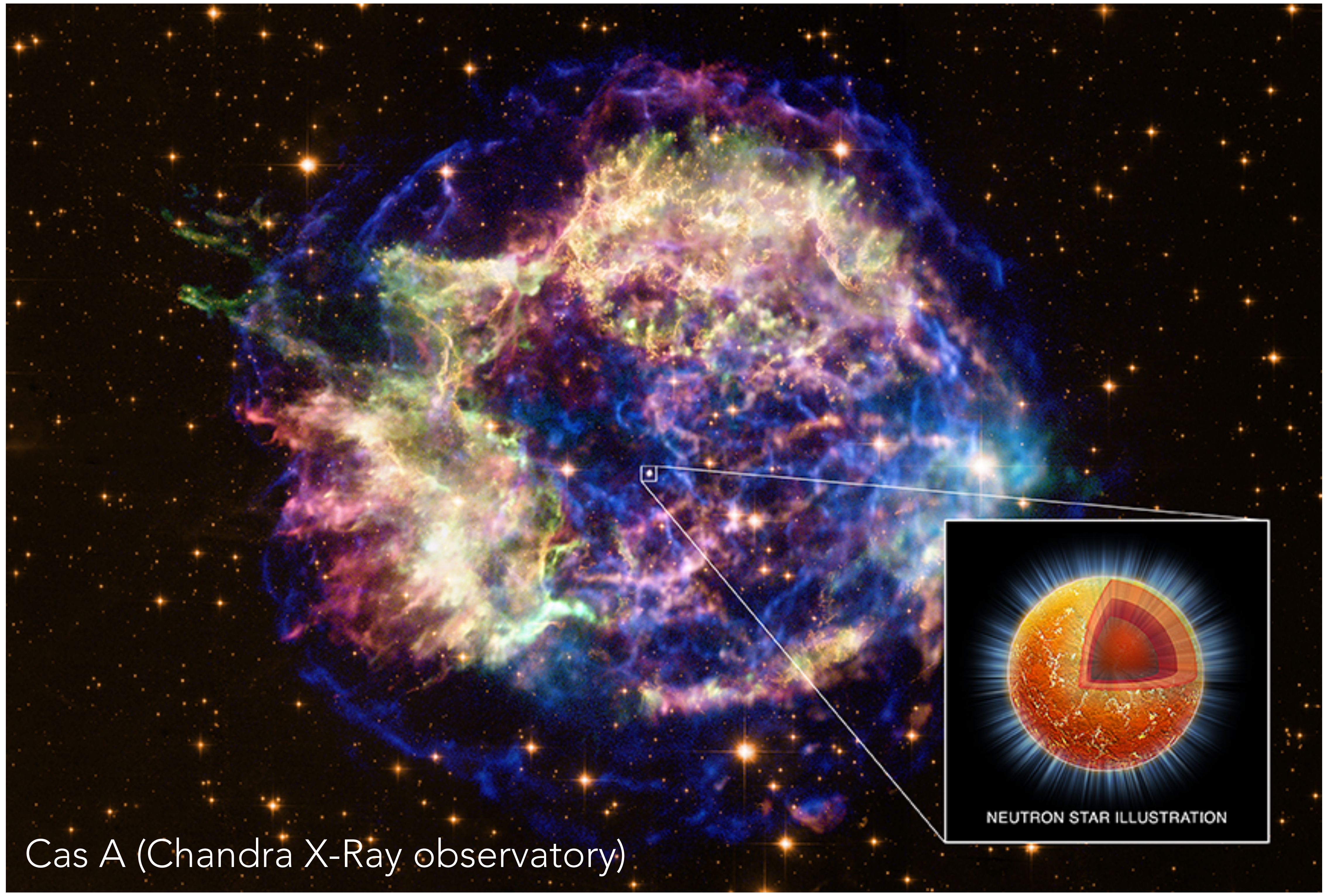


Origin of heavy elements?

Rapid neutron capture process

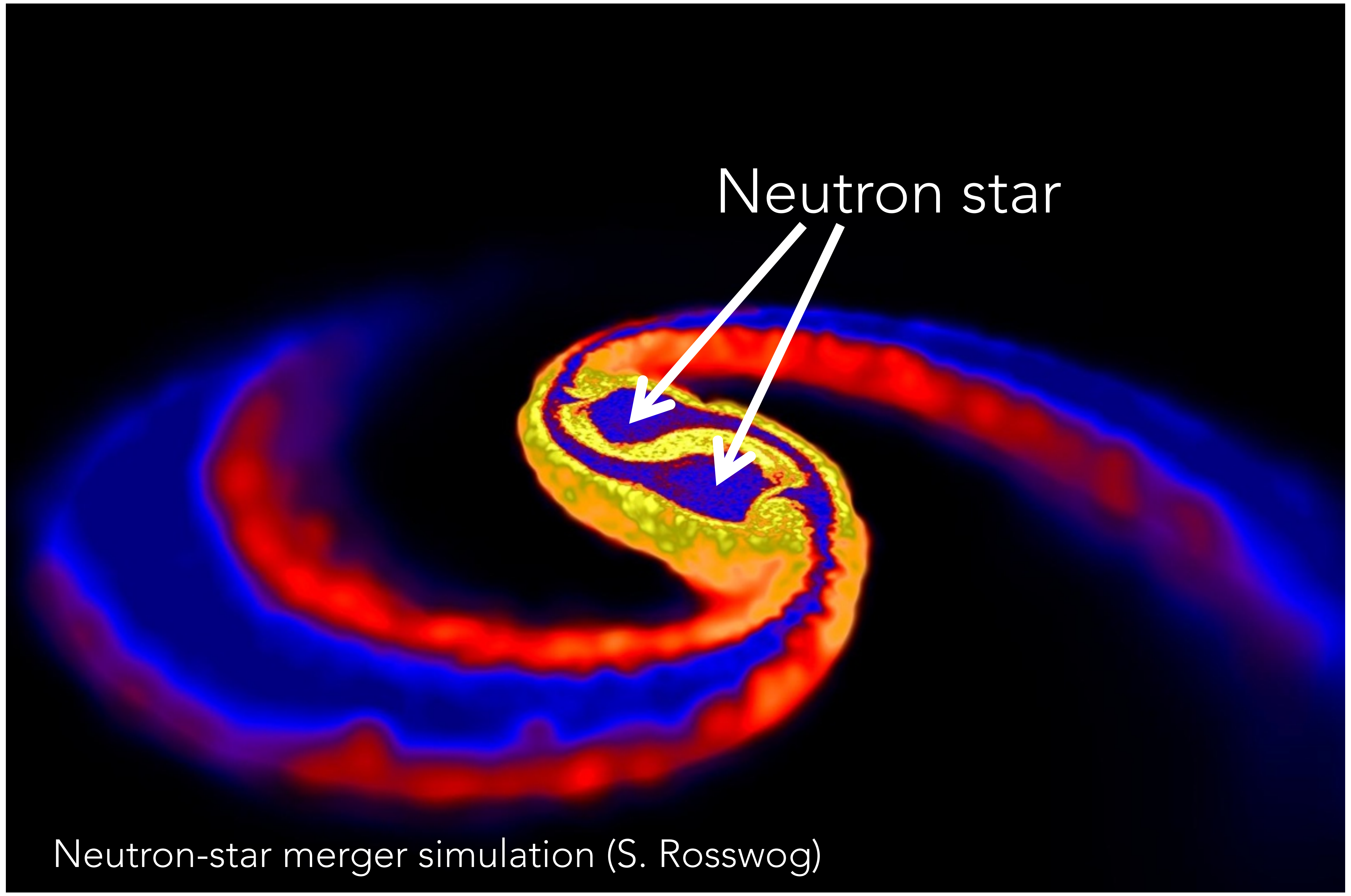
Explosive and high neutron densities

Rare Supernovae



Cas A (Chandra X-Ray observatory)

Neutron star mergers



Neutron-star merger simulation (S. Rosswog)

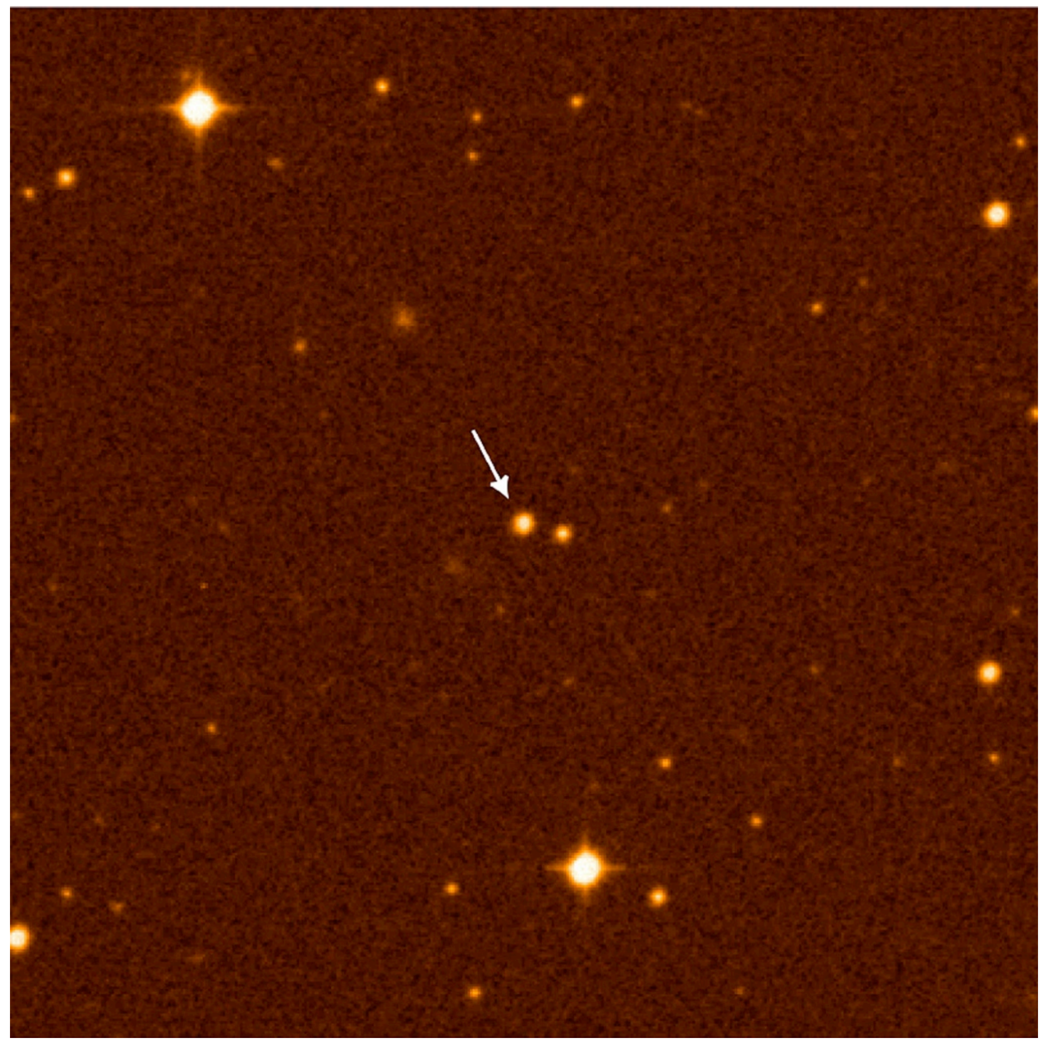
Galactic Chemical Evolution (GCE)

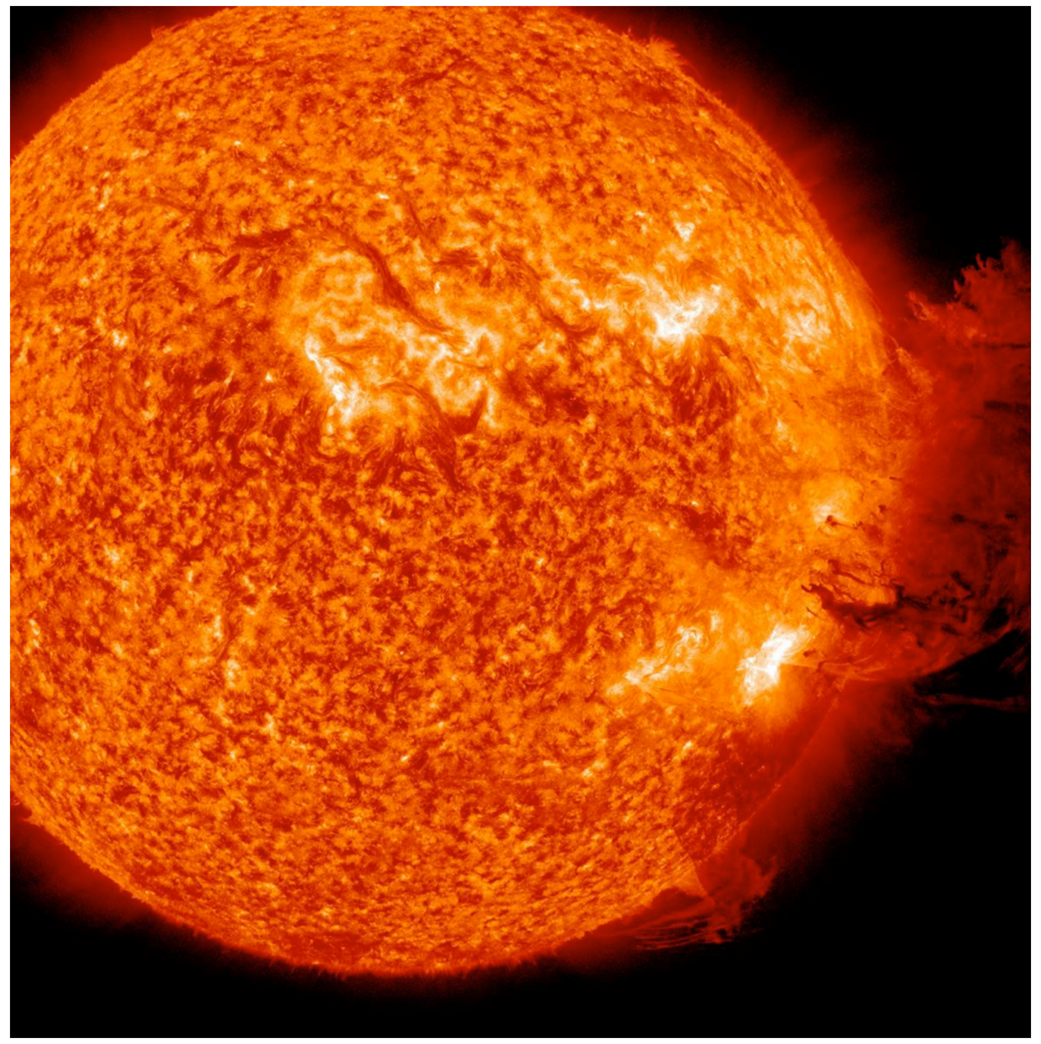
First stars: H, He → Heavy elements → Interstellar medium (ISM)

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

New generation of stars

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



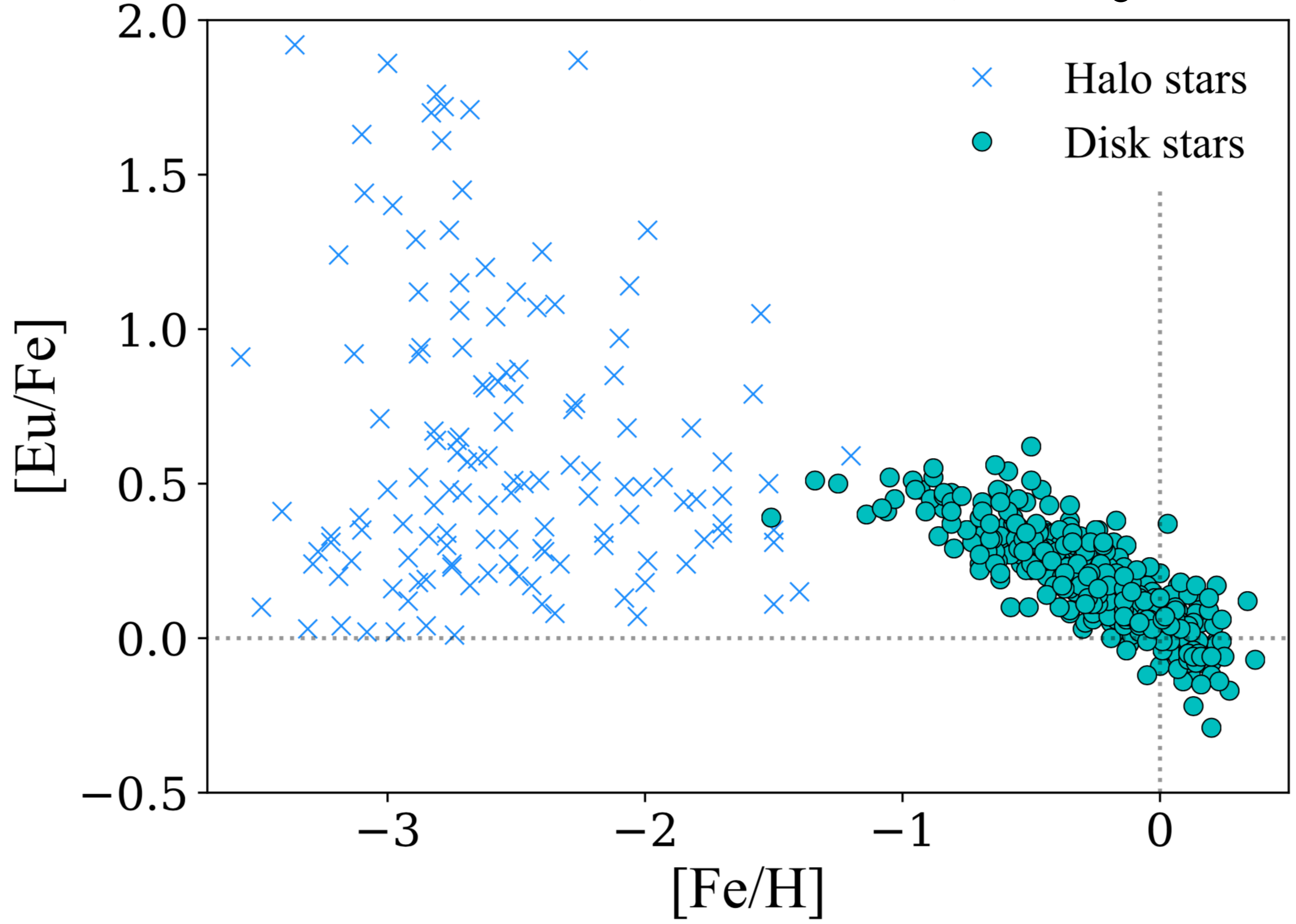


Observations and galactic chemical evolution

Evolution with time (or metallicity) -> Galactic Chemical Evolution (GCE)

-> r-process sites: mergers vs. supernovae

$$[A/B] = \log_{10}(Y_A/Y_B)_* - \log_{10}(Y_A/Y_B)_\odot$$



Matteucci et al. MNRAS (2014), Côté et al. ApJ (2019), Molero et al. MNRAS (2021)

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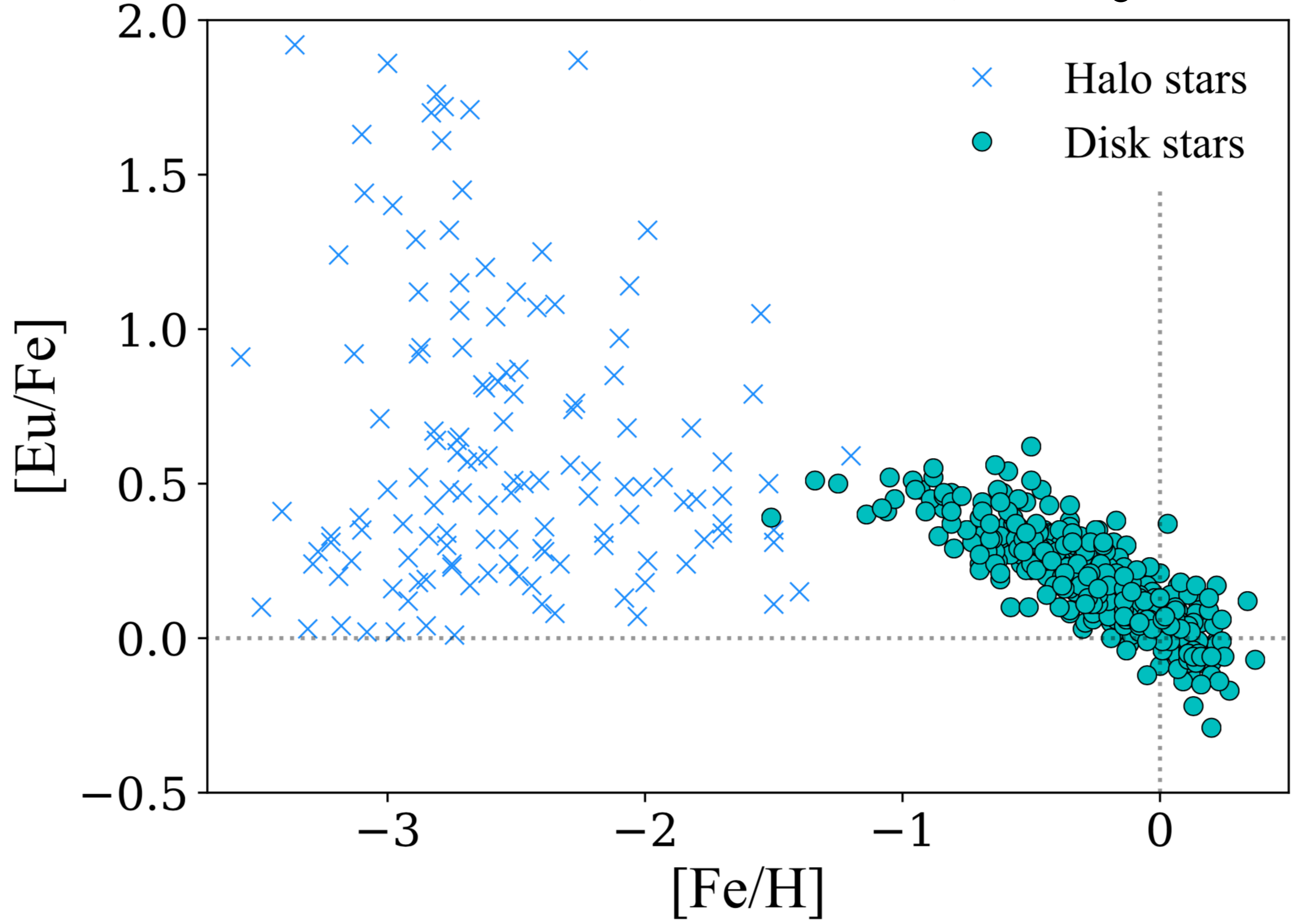
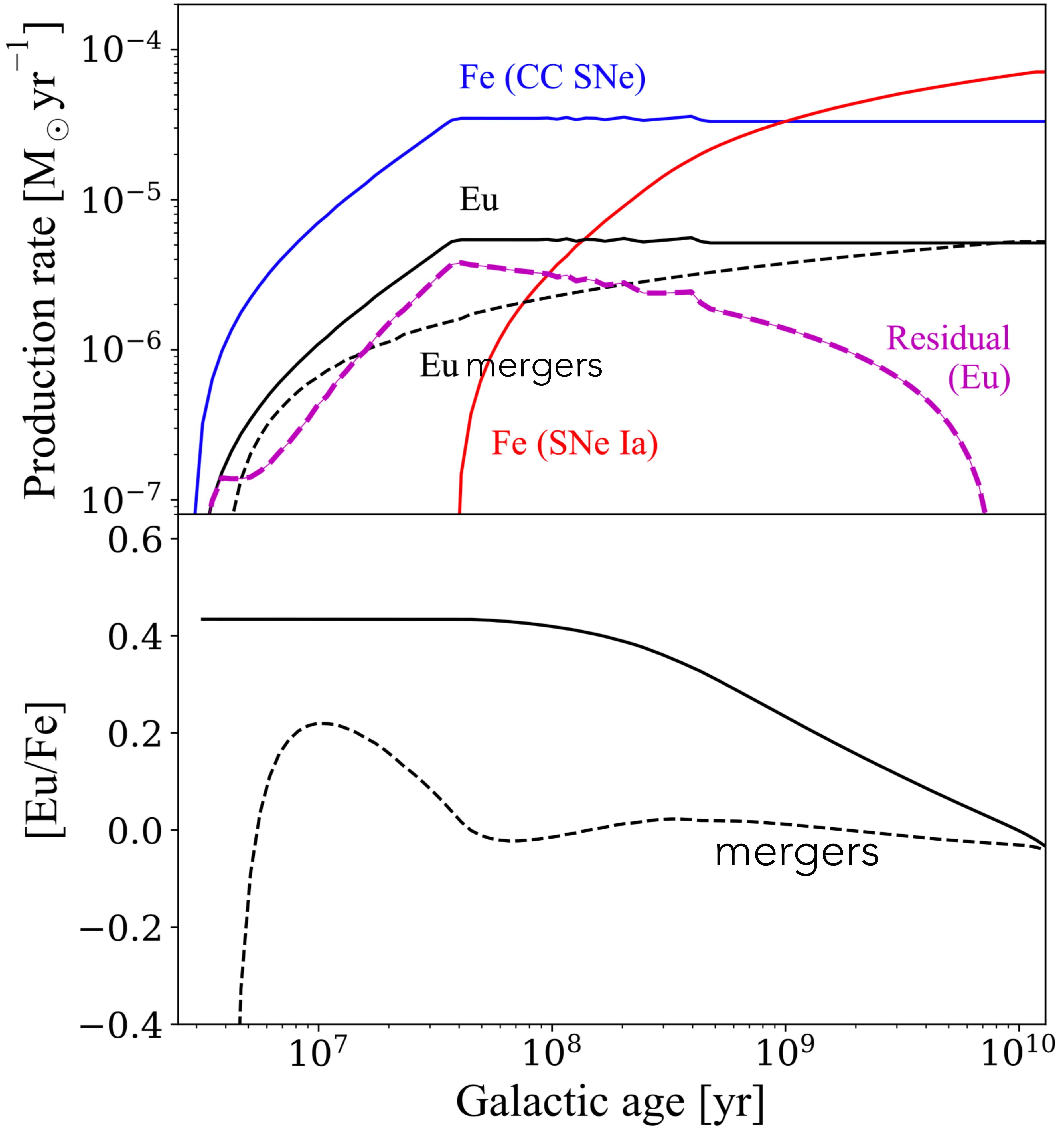


Côté et al. ApJ (2019)



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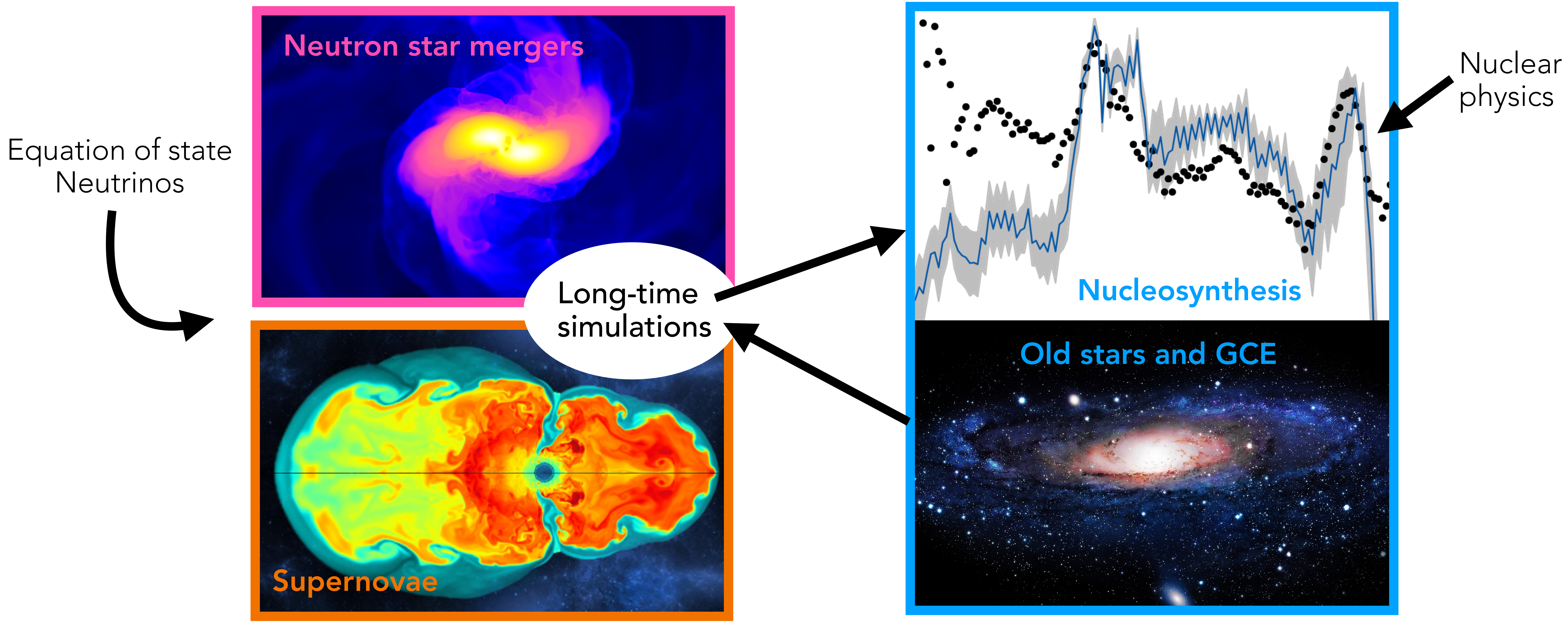
R-process: from simulations to observations

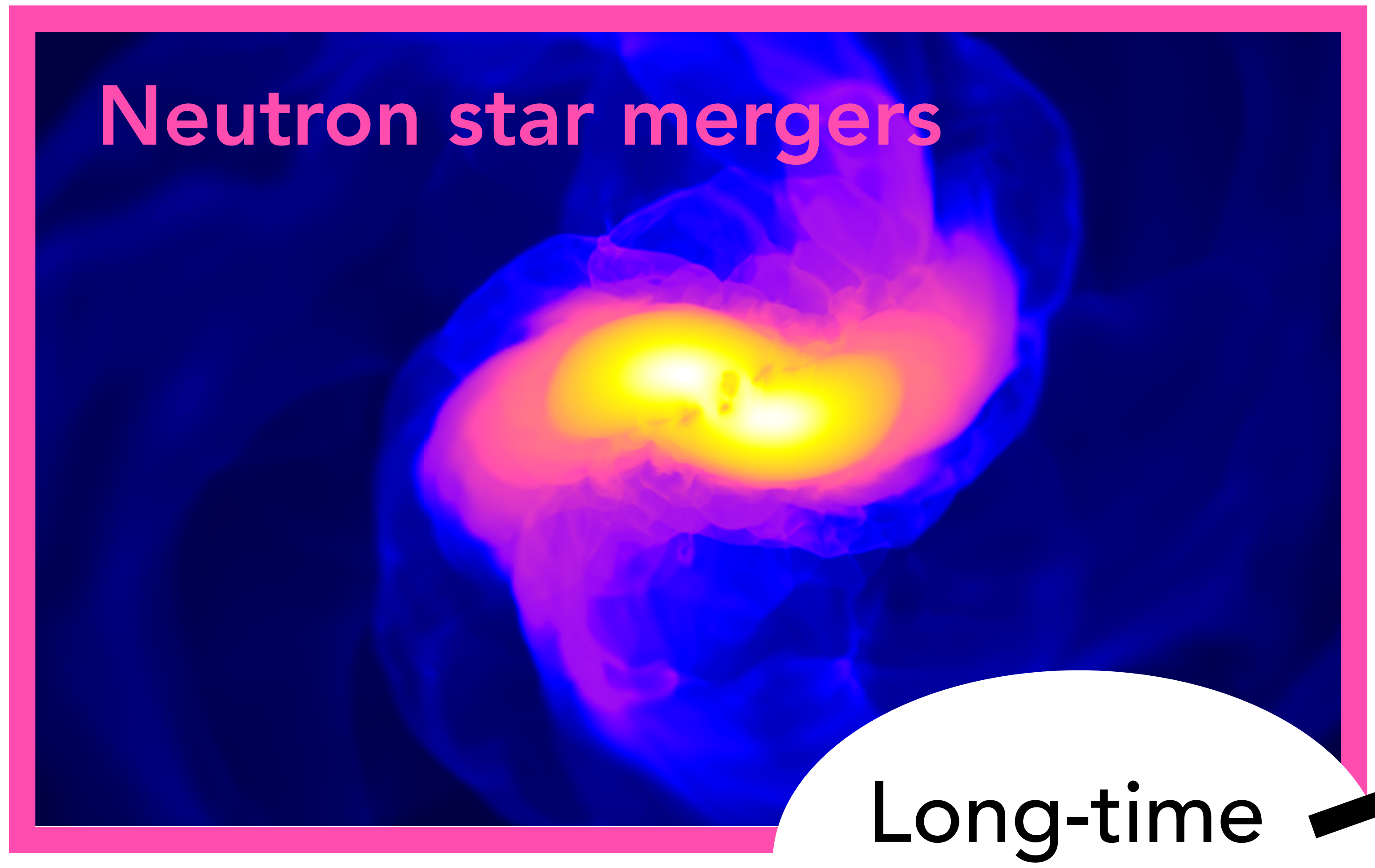


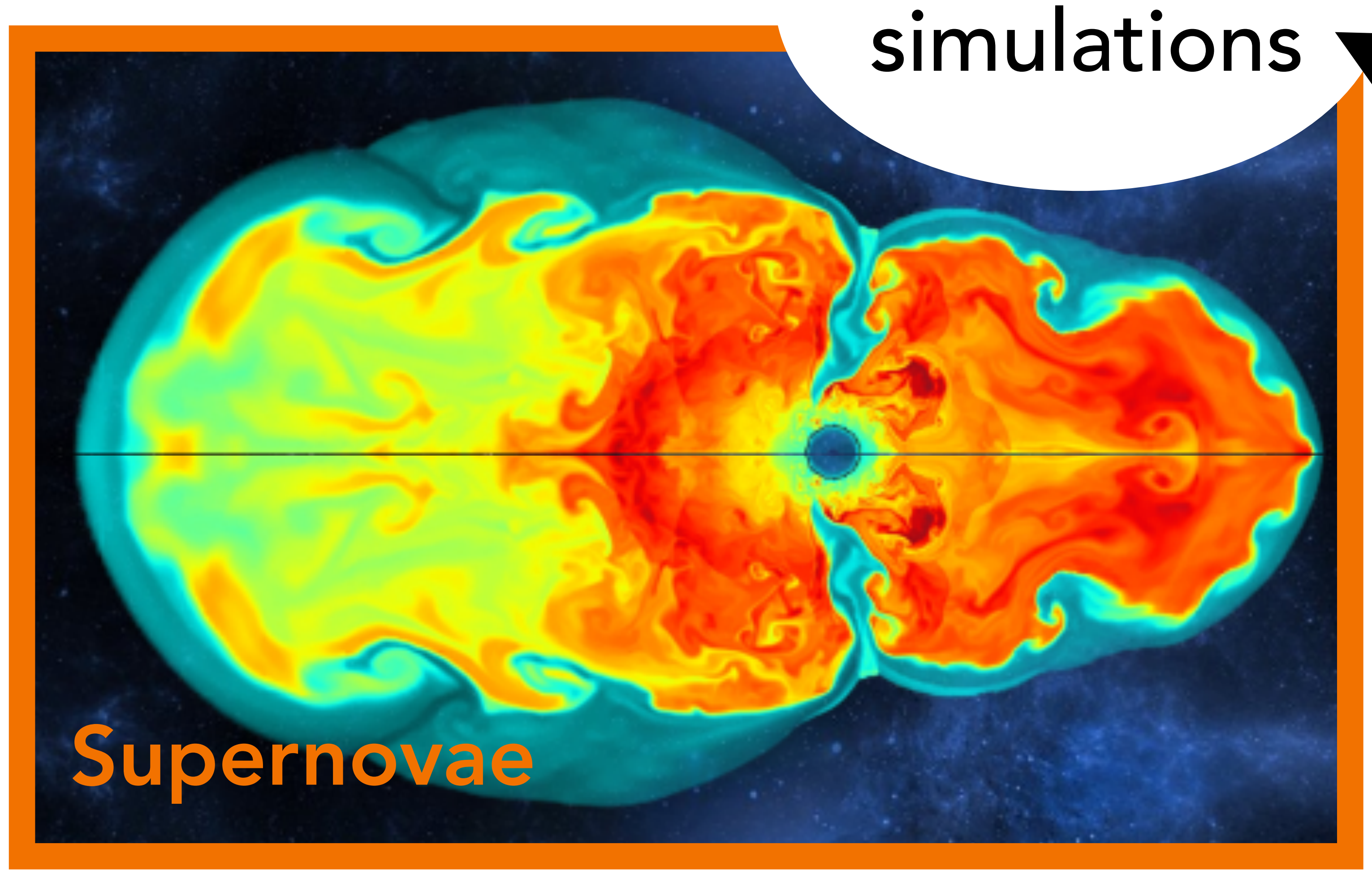
R-process: from simulations to observations

WinNet

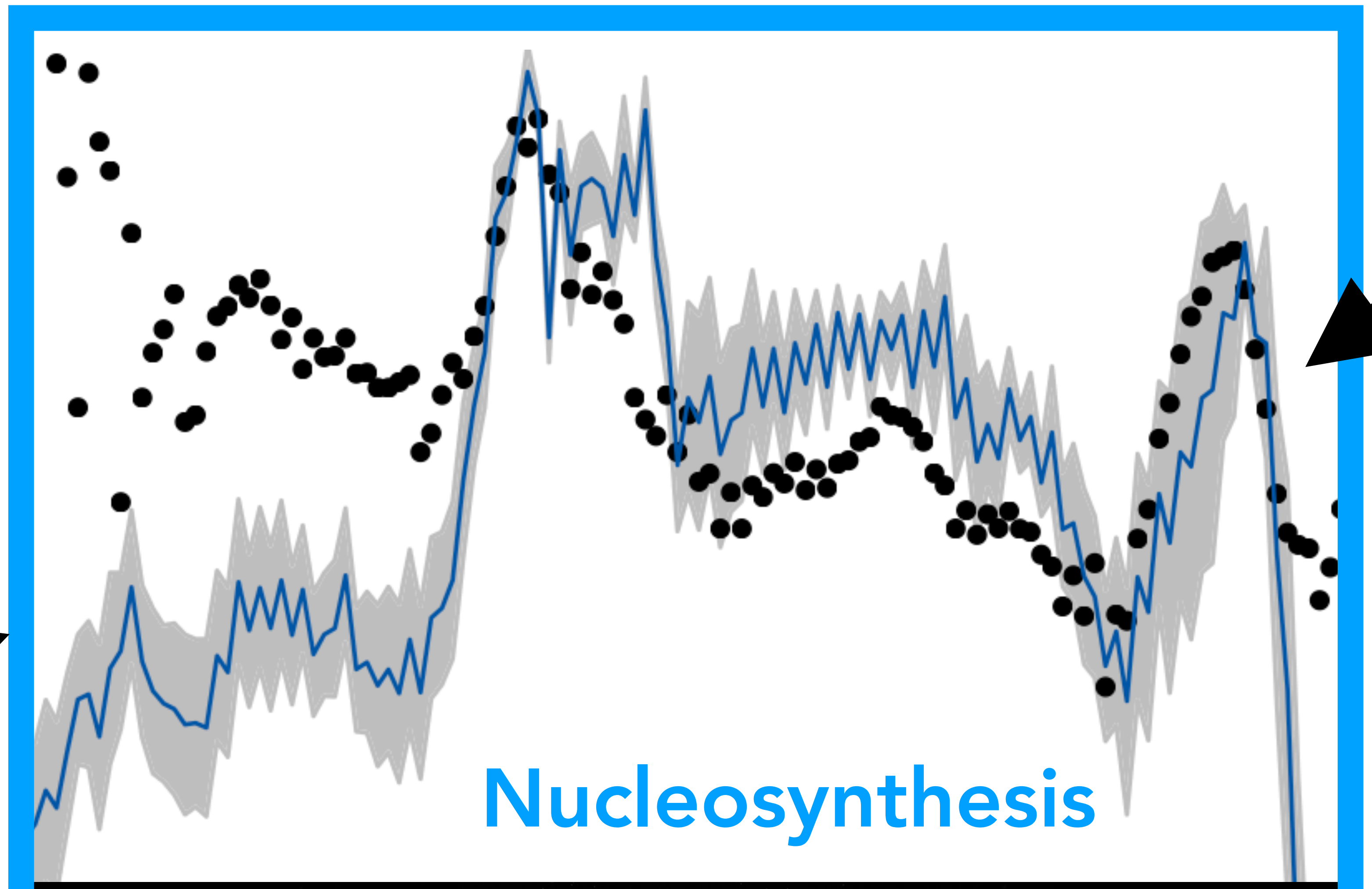
https://github.com/nuc-astro Reichert et al. 2023

Equation of state
Neutrinos





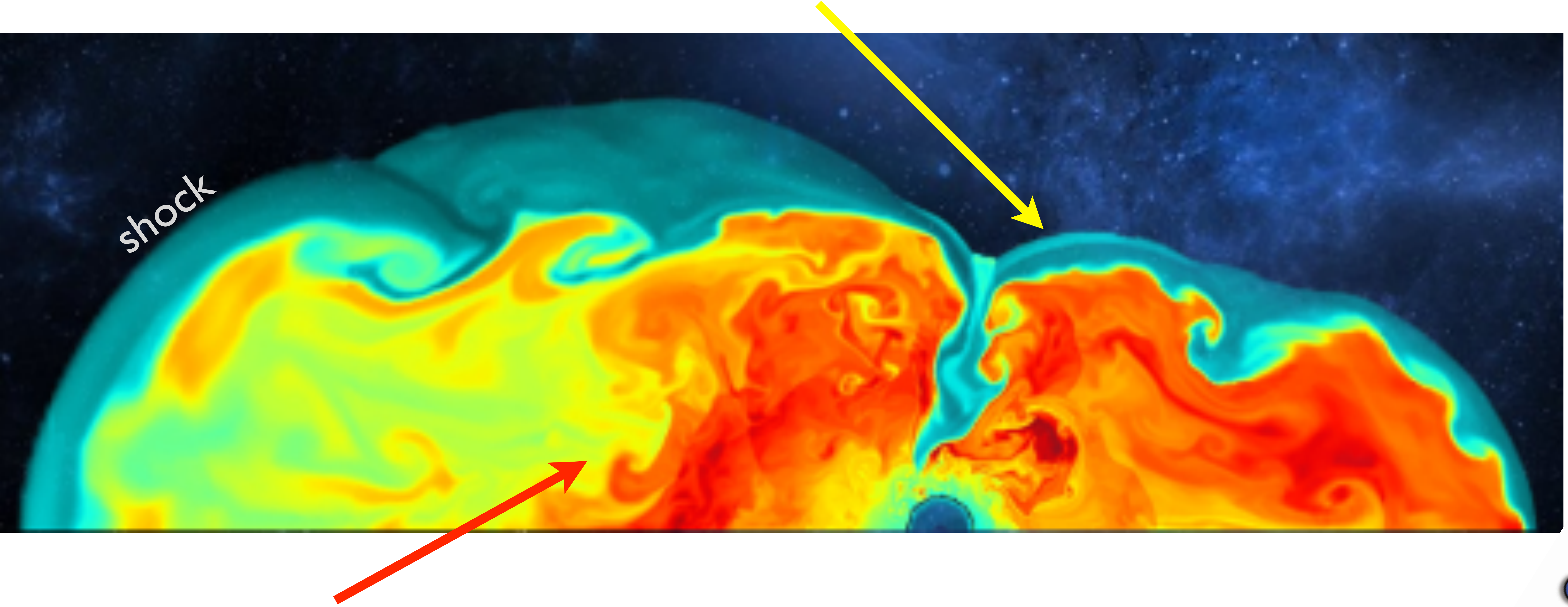
Long-time simulations



Nuclear physics

Supernova nucleosynthesis

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

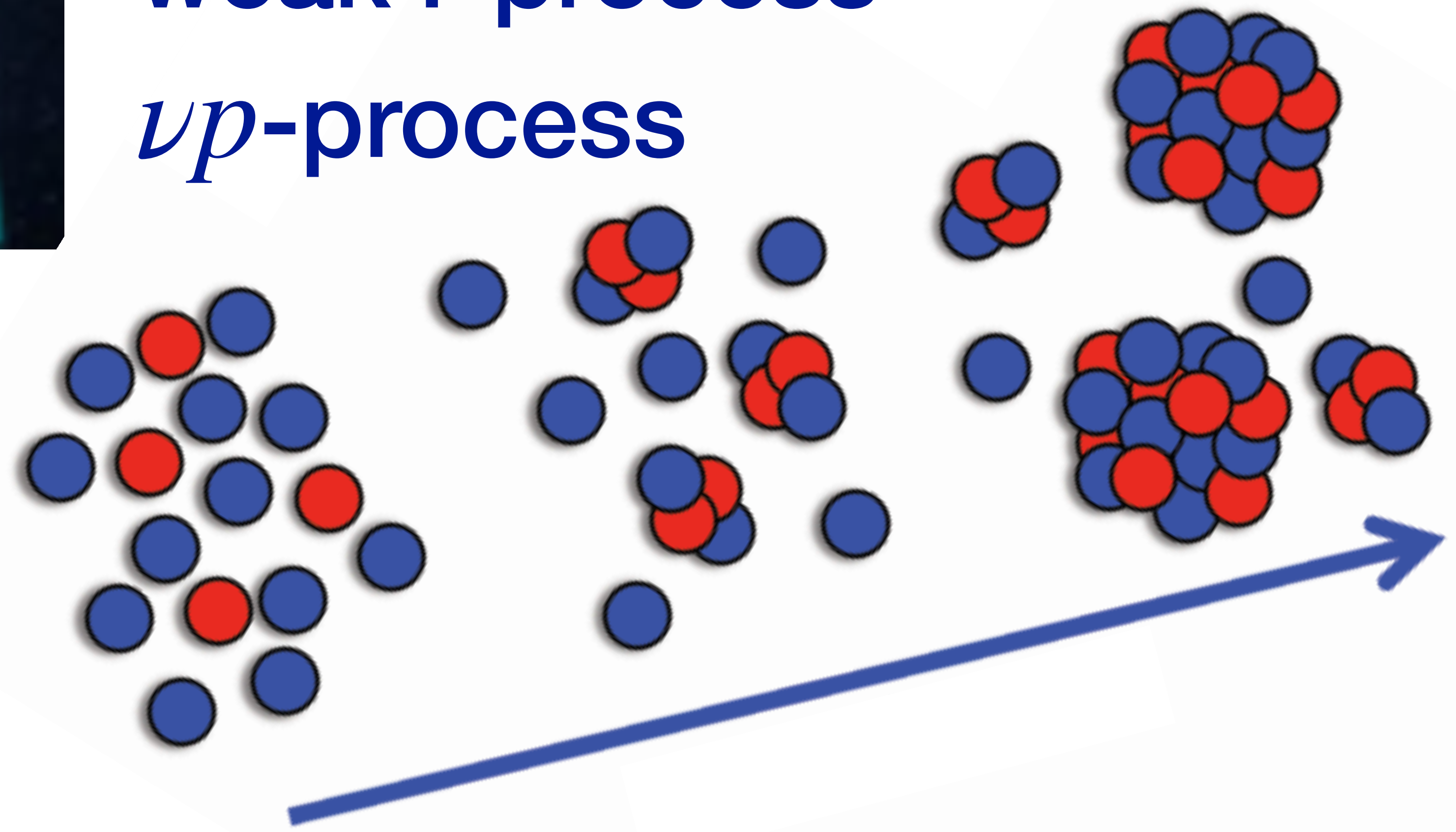


neutrino-driven ejecta

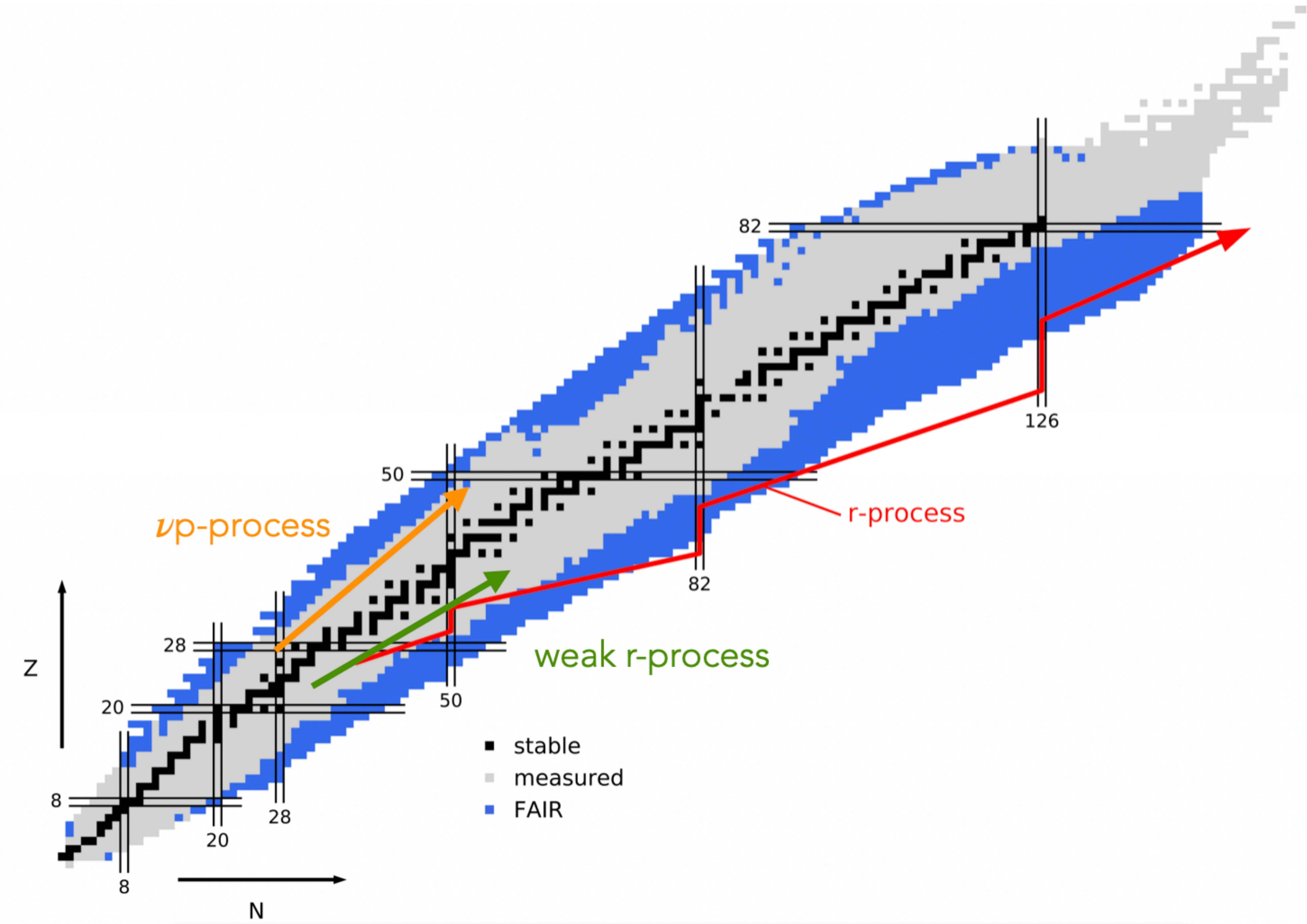
Nuclear statistical equilibrium (NSE)

charged particle reactions
α-process

r-process
weak r-process
νp-process



Supernova nucleosynthesis



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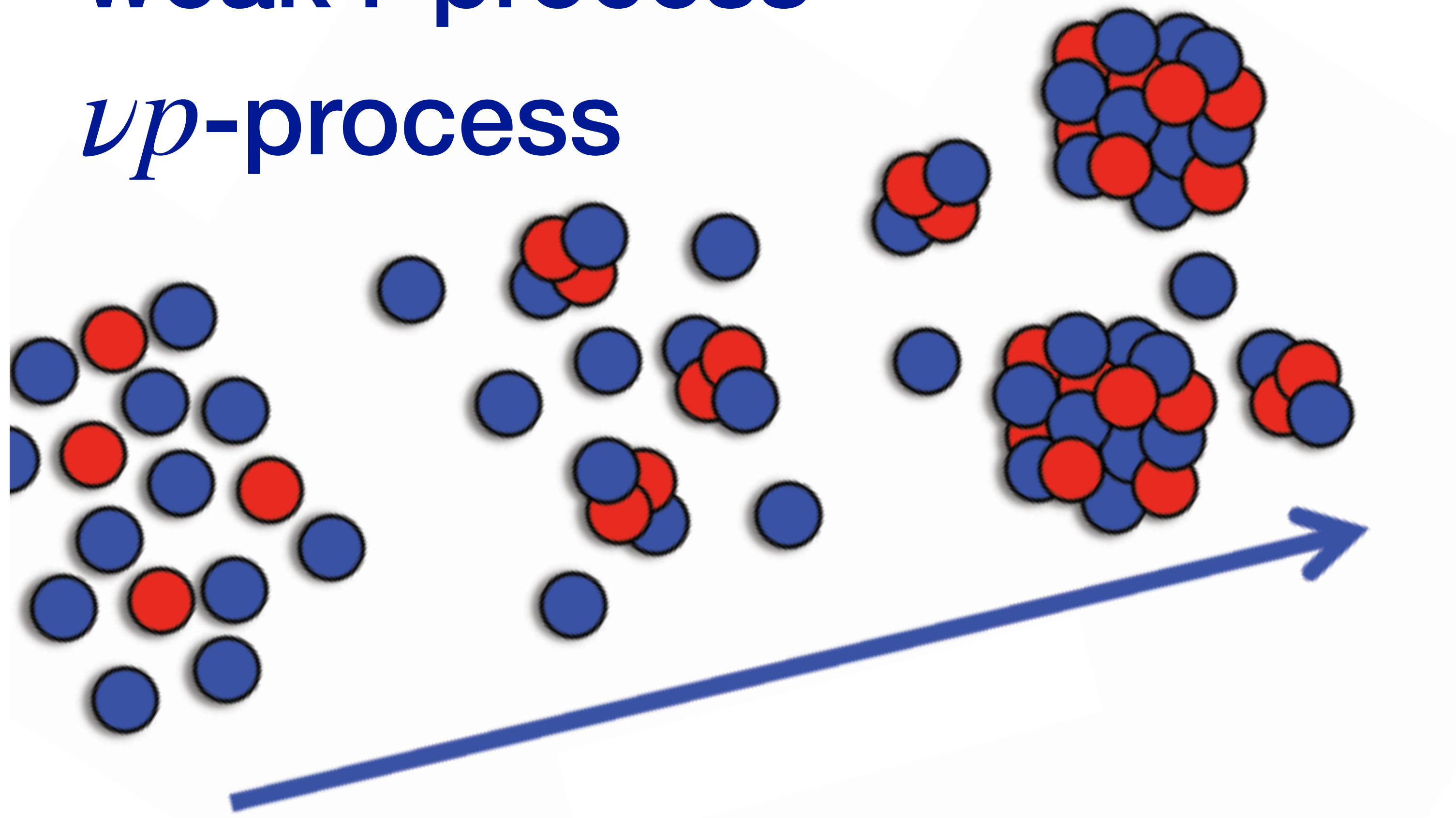
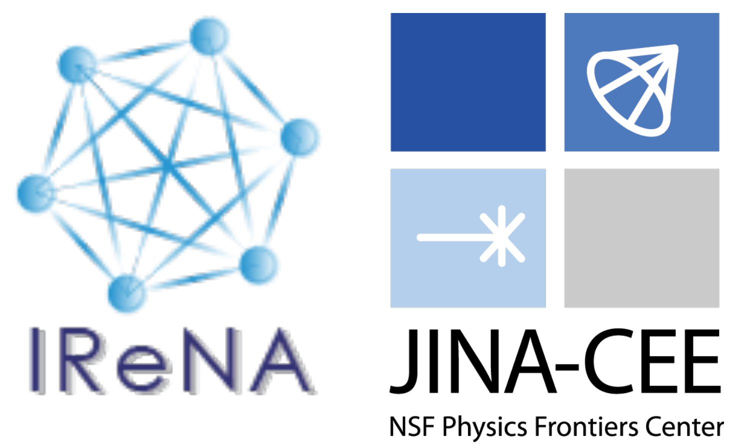
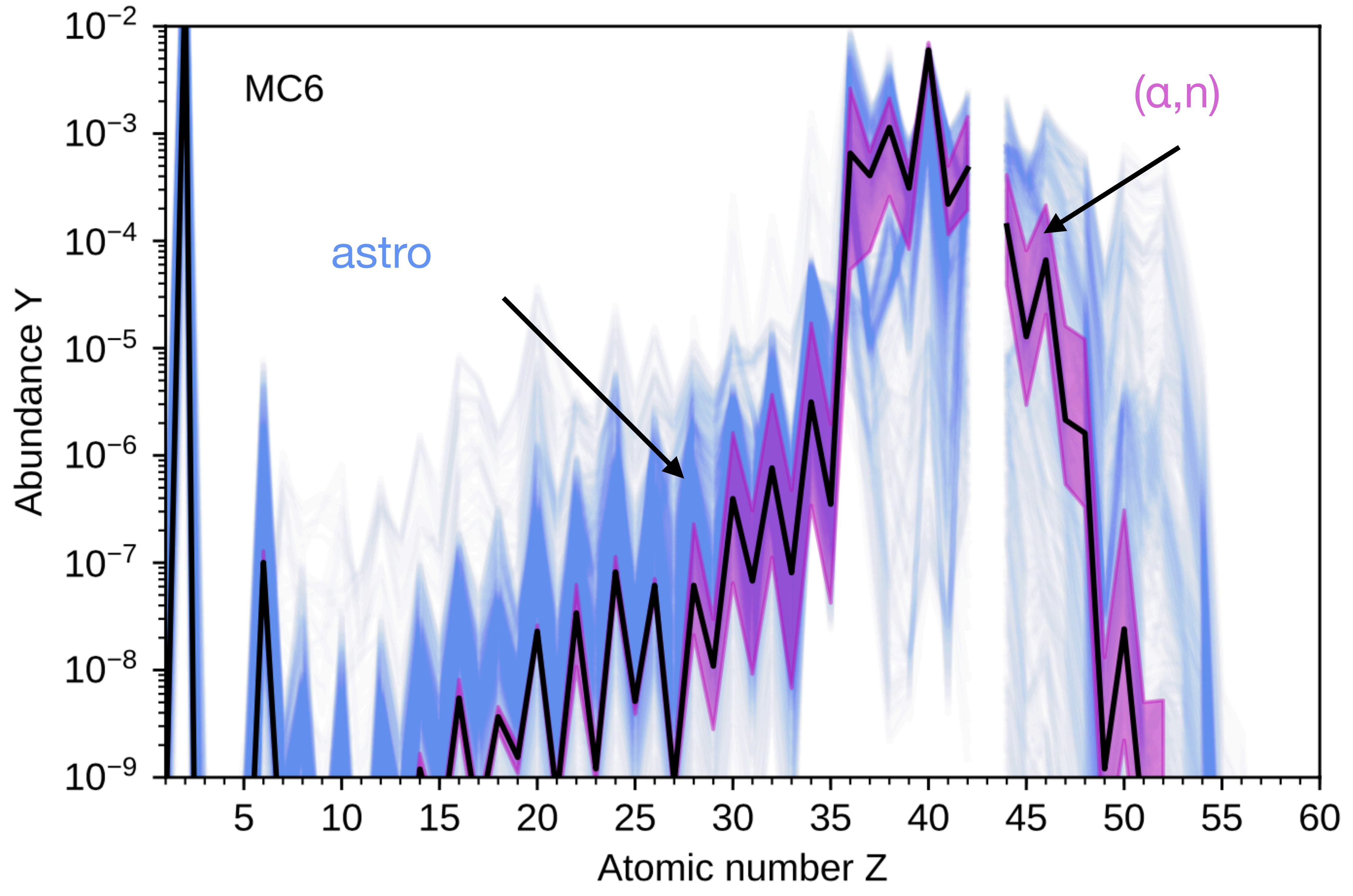


Core-collapse supernova: weak r-process

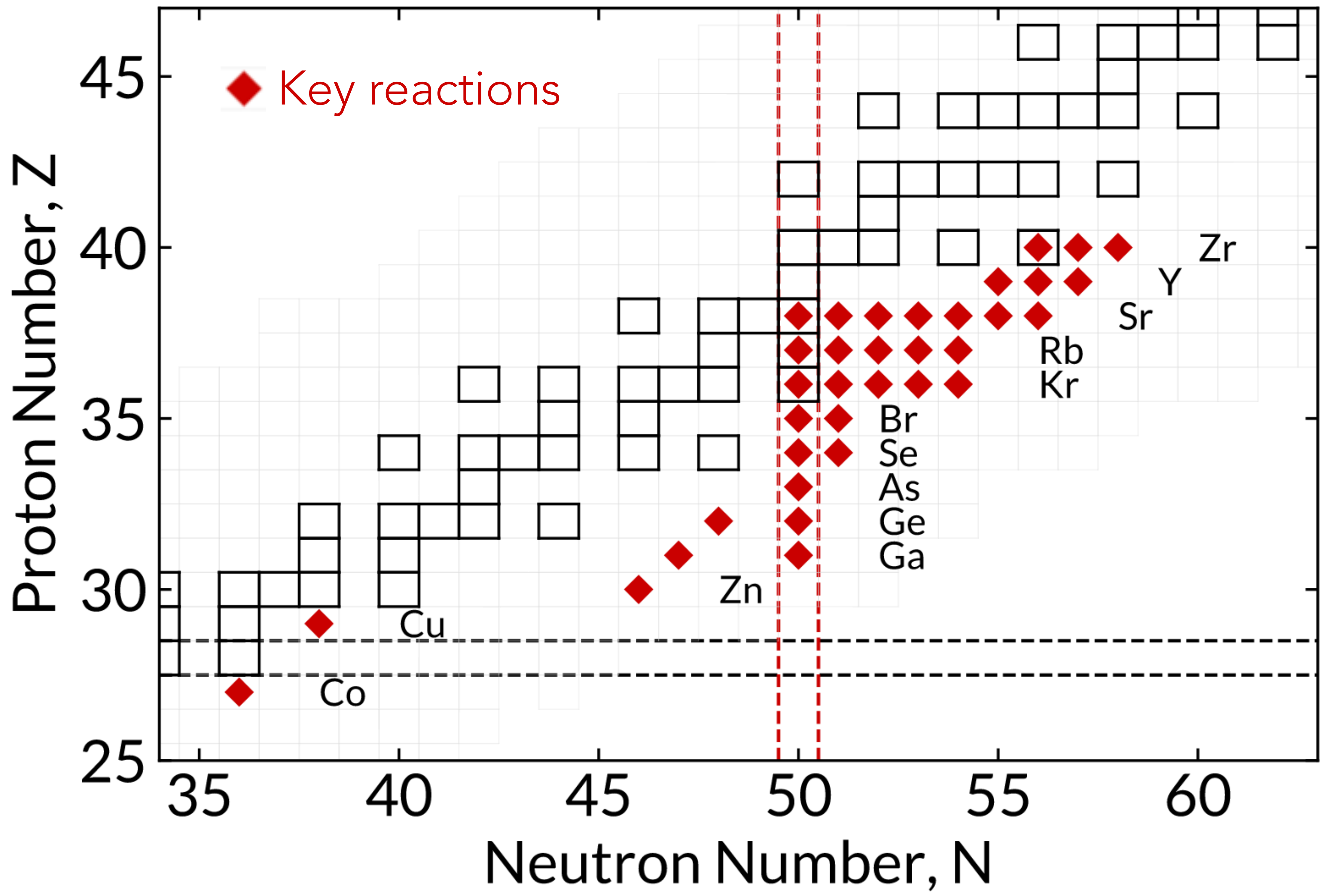
Neutrino-driven supernovae: elements up to Ag
Combine astrophysics and nuclear physics uncertainties
Motivation and support for experiments at NSCL, ANL, TRIUMF, ATOMKI



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



Psaltis et al. ApJ (2022), Psaltis et al. ApJ (2024)

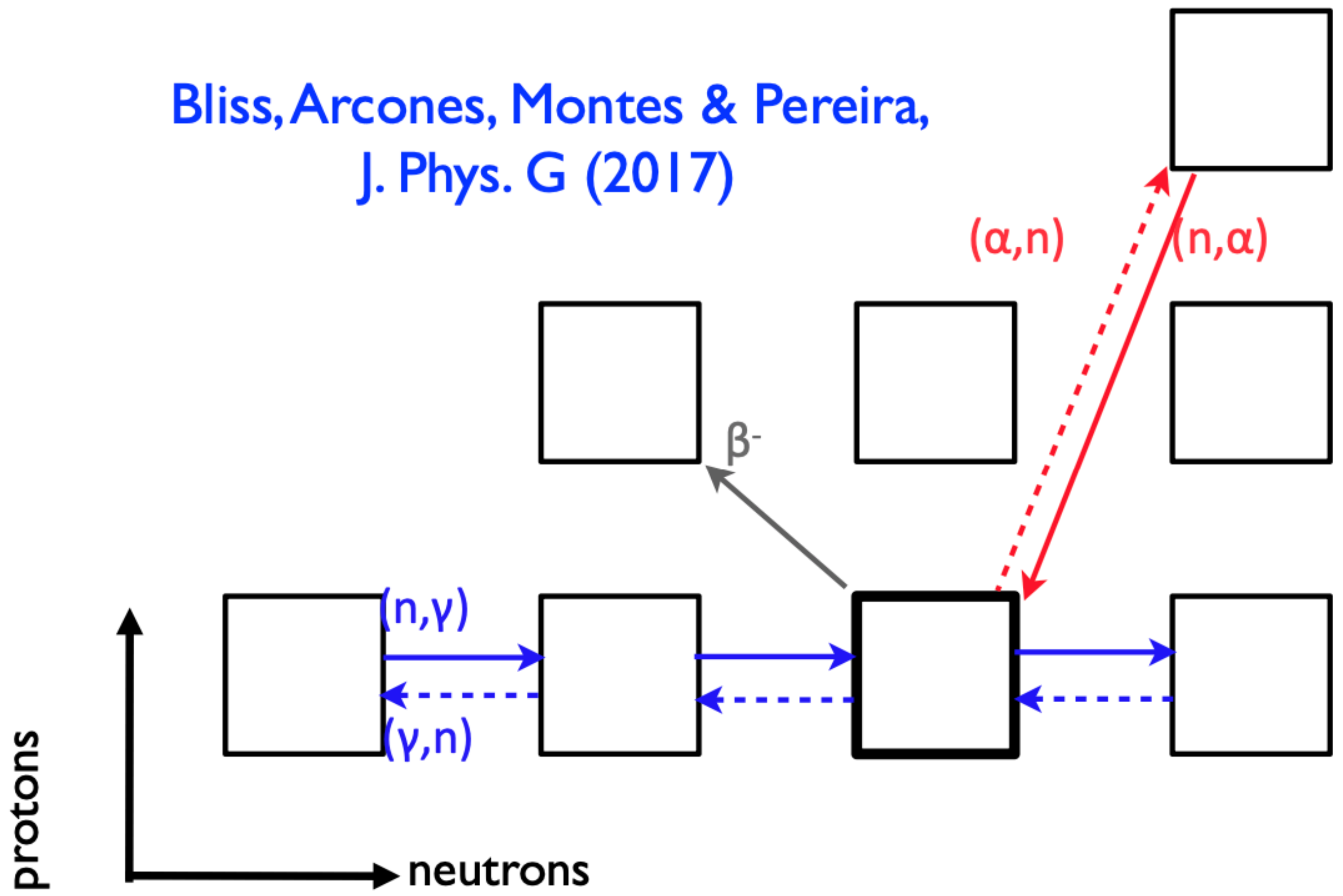


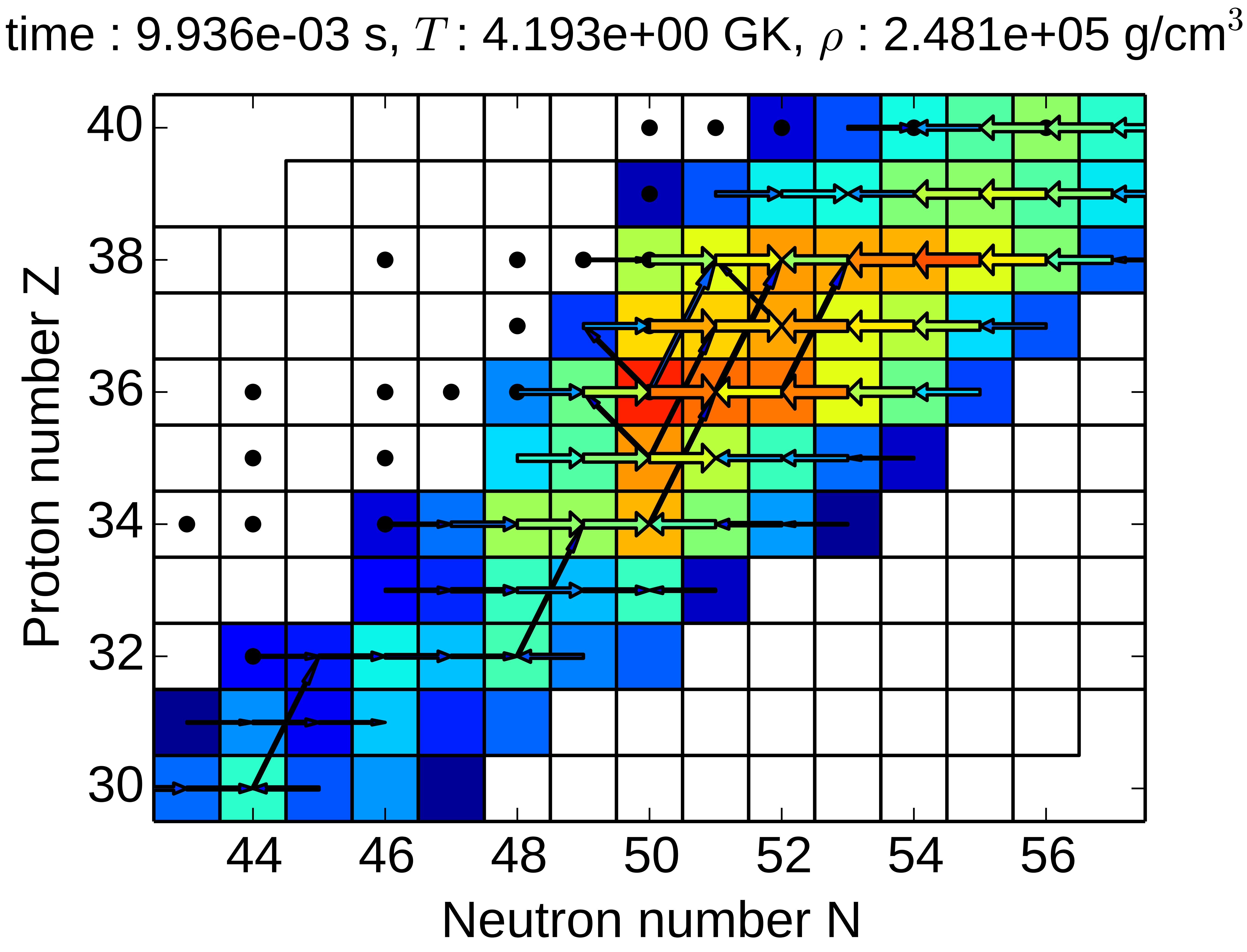
Nuclear physics uncertainty

Path close to stability:

- masses and beta decays known
- beta decays slow
- (α,n) reactions move matter to higher Z

Bliss, Arcones, Montes & Pereira,
J. Phys. G (2017)

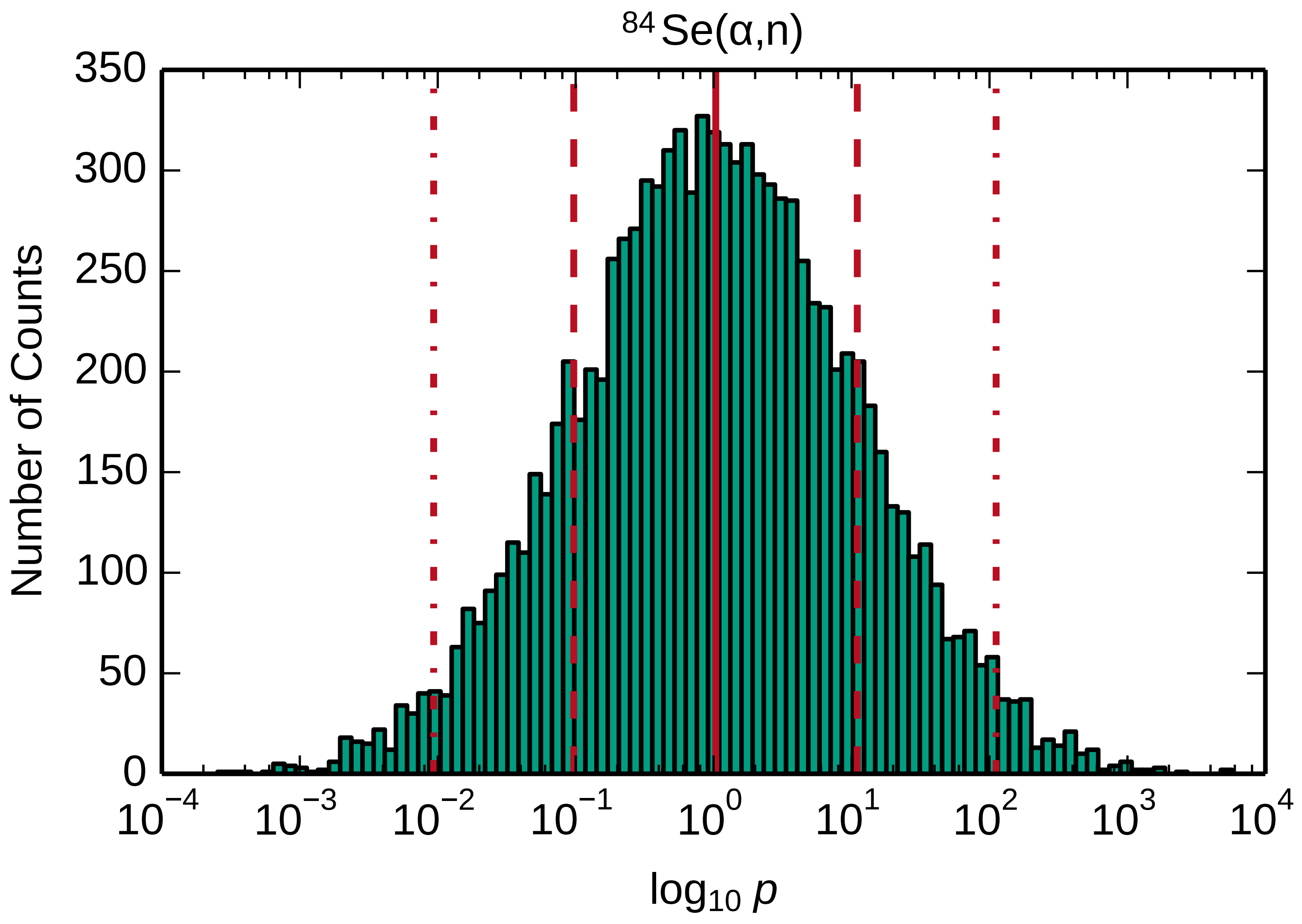




Sensitivity study

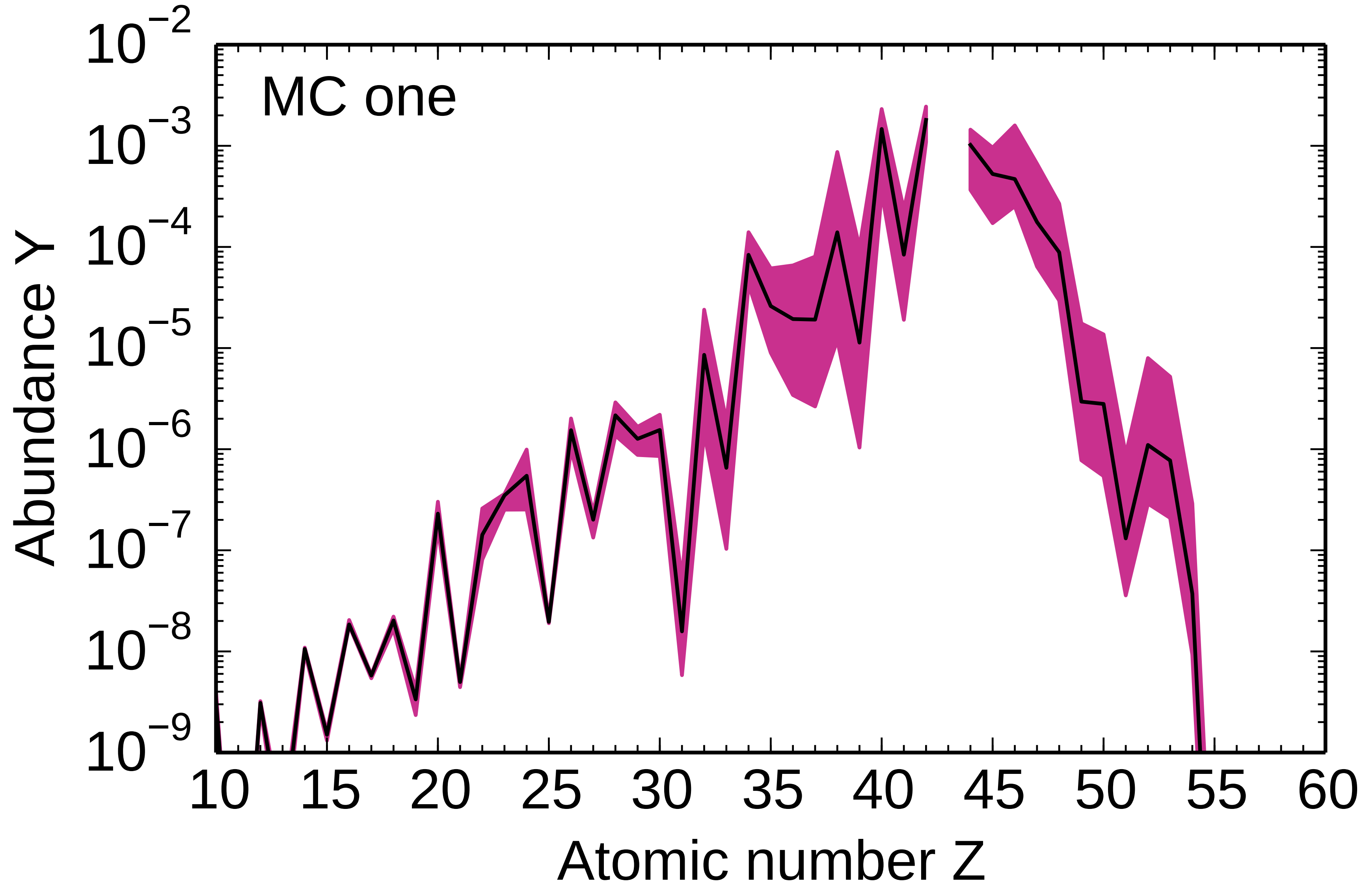
Independently vary each (α,n) reaction rate between Fe and Rh by a random factor

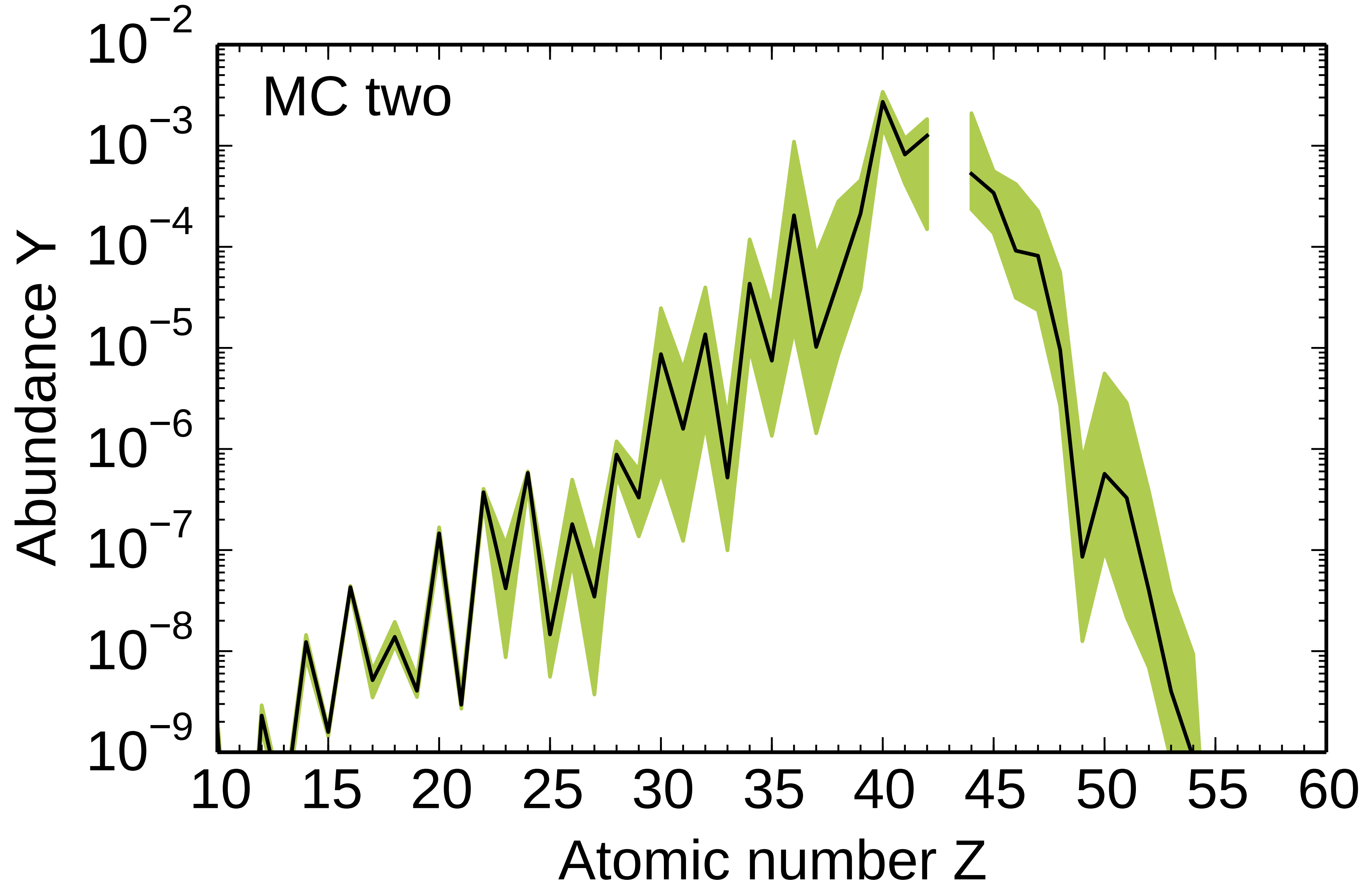
Include theoretical and experimental uncertainties
→ log-normal distributed rates (μ = 0, σ = 2.3)



36 representative trajectories
10 000 Monte Carlo runs

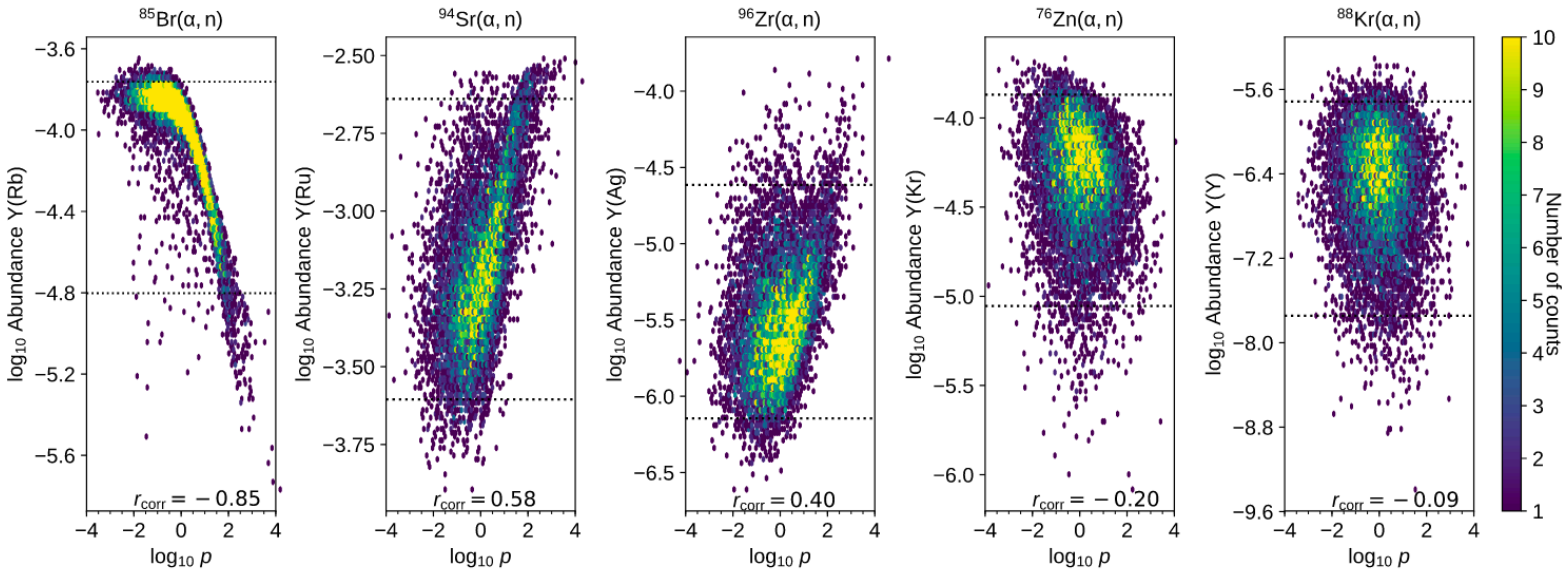
Bliss et al., PRC (2020)





Sensitivity study: key reactions

Bliss et al., PRC (2020)



Spearman rank order correlation

$$\rho_{\rm corr} = \frac{\sum_{i=1}^{n}\left(R(p_i) - \overline{R(p)}\right)\left(R(y_i) - \overline{R(y)}\right)}{\sqrt{\sum_{i=1}^{n}\left(R(p_i) - \overline{R(p)}\right)^2}\sqrt{\sum_{i=1}^{n}\left(R(y_i) - \overline{R(y)}\right)^2}}$$

→ Monotonic changes

→ $-1 \leq \rho_{corr} \leq +1$

Sensitivity study: key reactions

Bliss et al., PRC (2020)

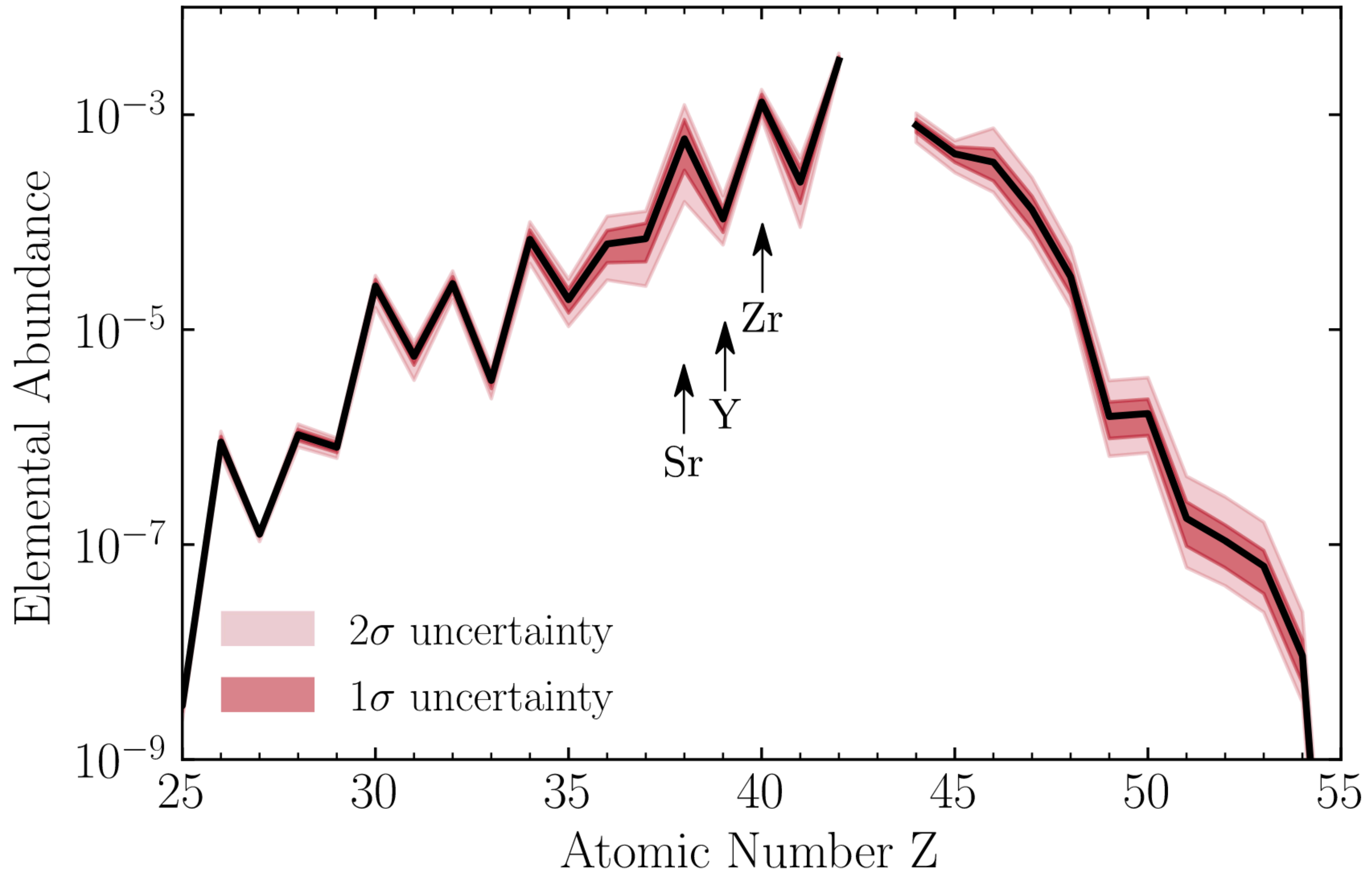
Key reactions ⇒ large correlation + significant impact on abundance for several astro conditions

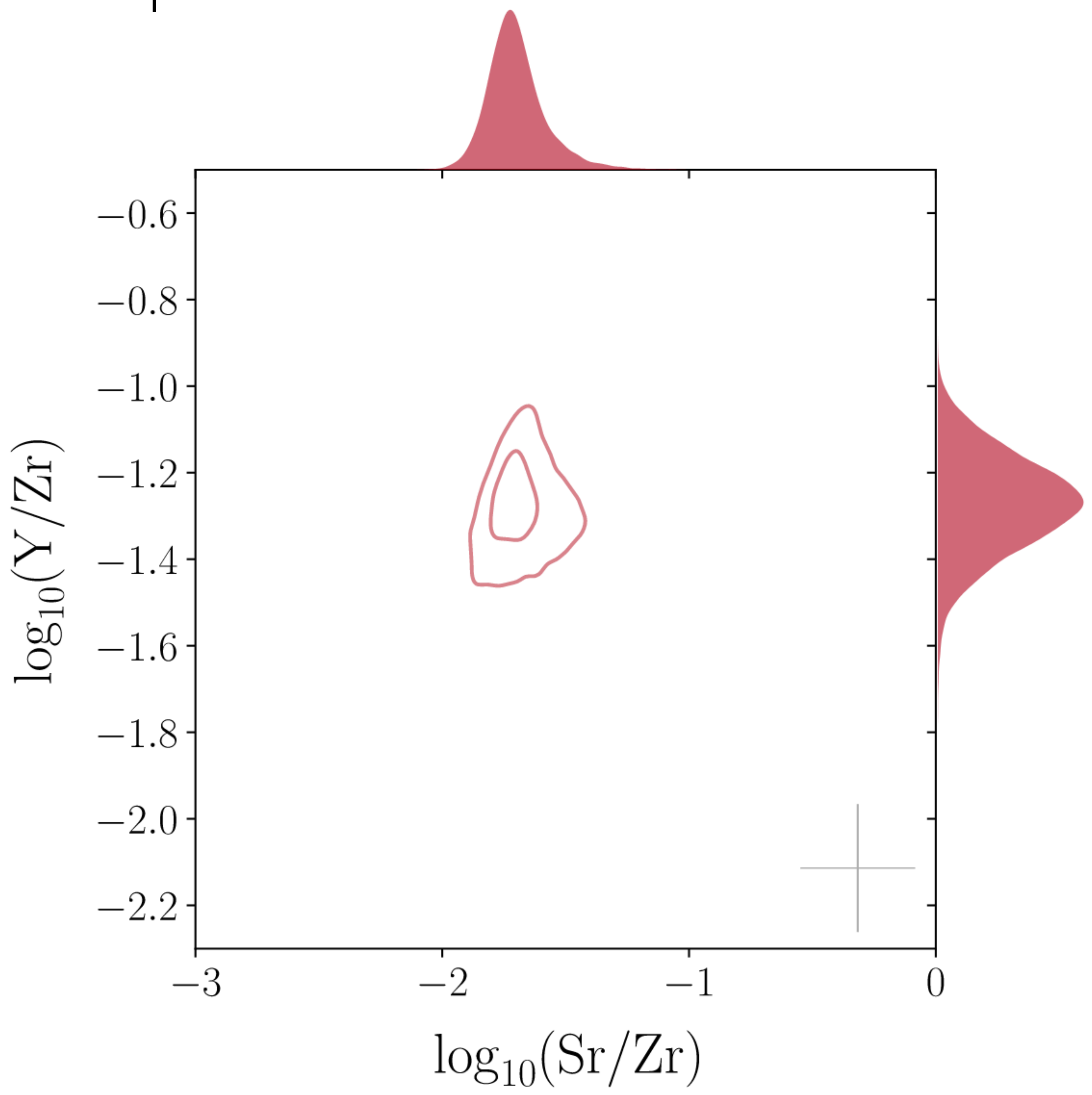
Reaction	Z	MC tracers
^{59}Fe$(\alpha,n)^{62}$Ni	39 – 42, 45	34, 36
^{68}Fe$(\alpha,n)^{71}$Ni	36, 37	3
^{63}Co$(\alpha,n)^{66}$Cu	39–42, 45	20, 34, 36
^{71}Co$(\alpha,n)^{74}$Cu	36, 37	3
^{74}Ni$(\alpha,n)^{77}$Zn	36–42	2, 3, 17, 18, 32
^{76}Ni$(\alpha,n)^{79}$Zn	36–42	2, 3, 18, 32
^{67}Cu$(\alpha,n)^{70}$Ga	47	35
^{77}Cu$(\alpha,n)^{80}$Ga	37	3
^{72}Zn$(\alpha,n)^{75}$Ge	39–42	36
^{76}Zn$(\alpha,n)^{79}$Ge	36, 37–42	2, 3, 17, 18, 32
^{78}Zn$(\alpha,n)^{81}$Ge	36, 37–42	2, 3, 17, 18, 32
^{79}Zn$(\alpha,n)^{82}$Ge	36, 37–42	2, 3, 18, 32
^{80}Zn$(\alpha,n)^{83}$Ge	36, 37, 39–42	2, 3, 18, 32
^{81}Ga$(\alpha,n)^{84}$As	36, 38, 39, 41	17, 32
^{78}Ge$(\alpha,n)^{81}$Se	39–42	36
^{80}Ge$(\alpha,n)^{83}$Se	36–39, 42	28, 33, 36
^{82}Ge$(\alpha,n)^{85}$Se	36–39, 41	11, 17, 19, 27, 28, 33
^{83}As$(\alpha,n)^{86}$Br	36, 37, 41	11, 26, 27, 28, 33
^{84}Se$(\alpha,n)^{87}$Kr	36–42, 44, 45	2, 6, 7, 8, 9, 10, 11, 18, 19, 20, 22, 23, 24, 26, 27, 28, 29, 30, 31, 33, 34, 36
^{85}Se$(\alpha,n)^{88}$Kr	36–42, 44, 45	2, 6, 7, 8, 9, 10, 11, 18, 19, 22, 23, 24, 26, 27, 28, 29, 30, 31
^{85}Br$(\alpha,n)^{88}$Rb	37–39	6, 7, 8, 9, 10, 22, 23, 24, 26, 28, 29, 30, 31
^{87}Br$(\alpha,n)^{90}$Rb	37, 39	6, 9, 10, 29, 31
^{88}Br$(\alpha,n)^{91}$Rb	39	26
^{86}Kr$(\alpha,n)^{89}$Sr	38–42, 44, 45, 47	4, 5, 7, 8, 13, 14, 15, 16, 20, 24, 25, 33, 34, 35

Comparison to observations

Psaltis et al., ApJ (2022)

Abundance with uncertainties for several astro conditions ⟶ compare abundance ratios





Based on optical potentials from Mohr et al., ADNDT (2021)

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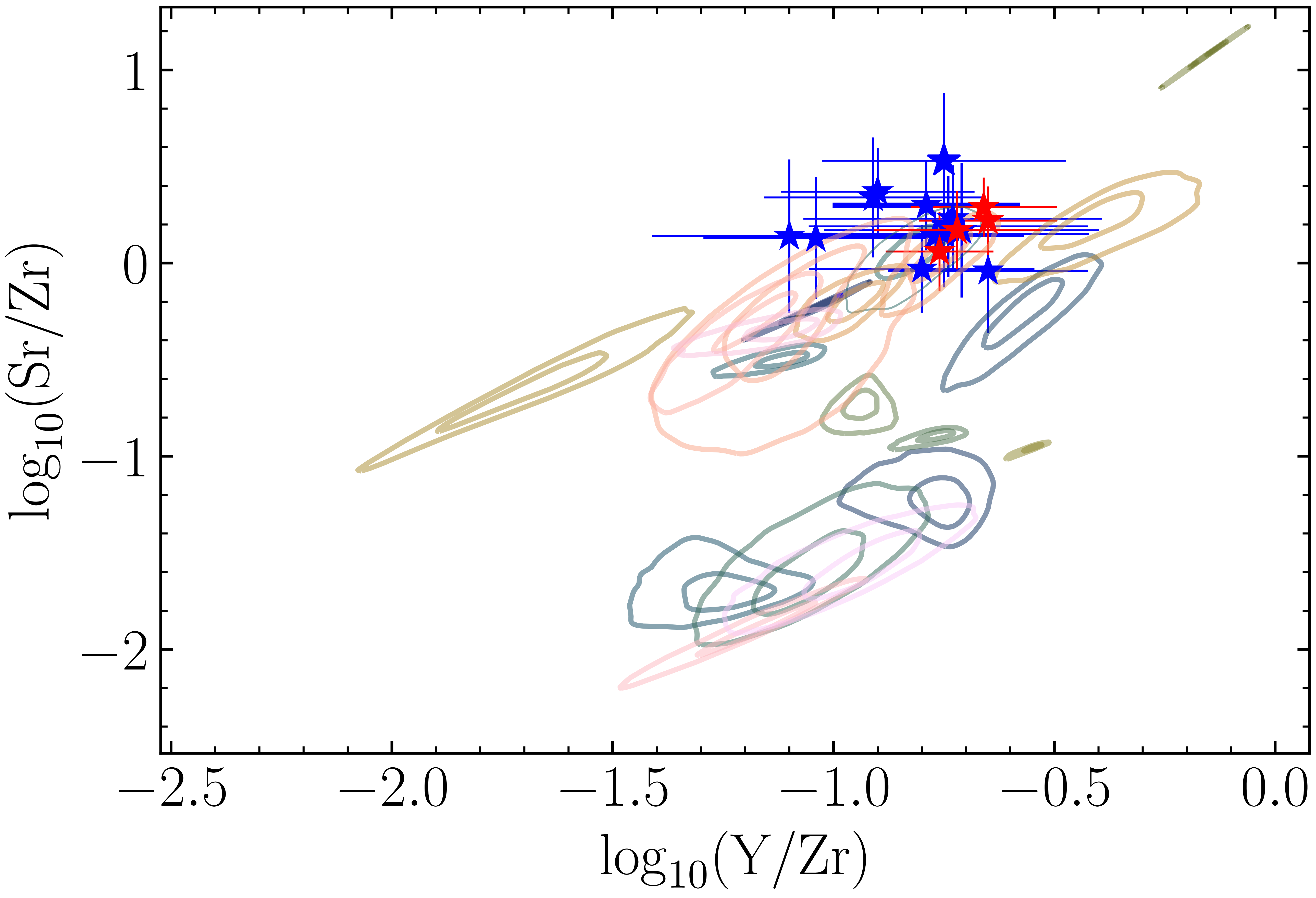
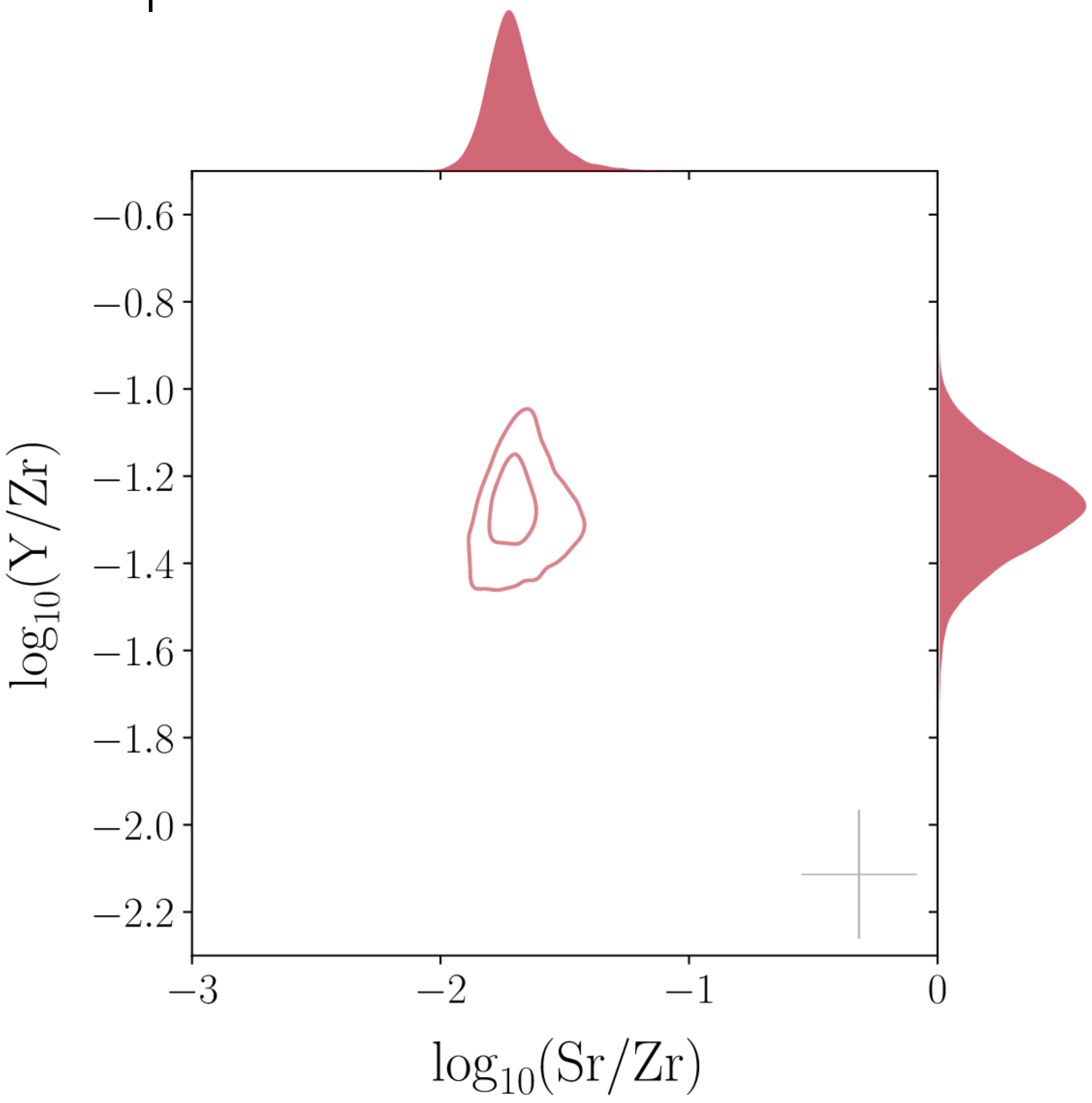




Based on optical potentials from Mohr et al., ADNDT (2021)

What has been measured so far?

- $^{86}Kr(\alpha, n)$, $^{96}Zr(\alpha, n)$ and $^{100}Mo(\alpha, n)$ at ATOMKI

  G.G. Kiss et al., Astrophys. J **908**, 202 (2021) • T.N. Szegedi et al., Phys. Rev. C **104**, 035804 (2021)

- $^{75}Ga(\alpha, n)$, $^{85,86}Kr(\alpha, xn)$, $^{85}Br(\alpha, xn)$ at NSCL/FRIB (HabaNERO/SECAR)

  F. Montes, J. Pereira et al.

- $^{86}Kr(\alpha, xn)$, $^{87}Rb(\alpha, xn)$, $^{88}Sr(\alpha, xn)$, $^{100}Mo(\alpha, xn)$ at Argonne (MUSIC)

  M. L. Avila, C. Fougères et al.

  W. J. Ong et al., Phys. Rev. C **105**, 055803 (2022)

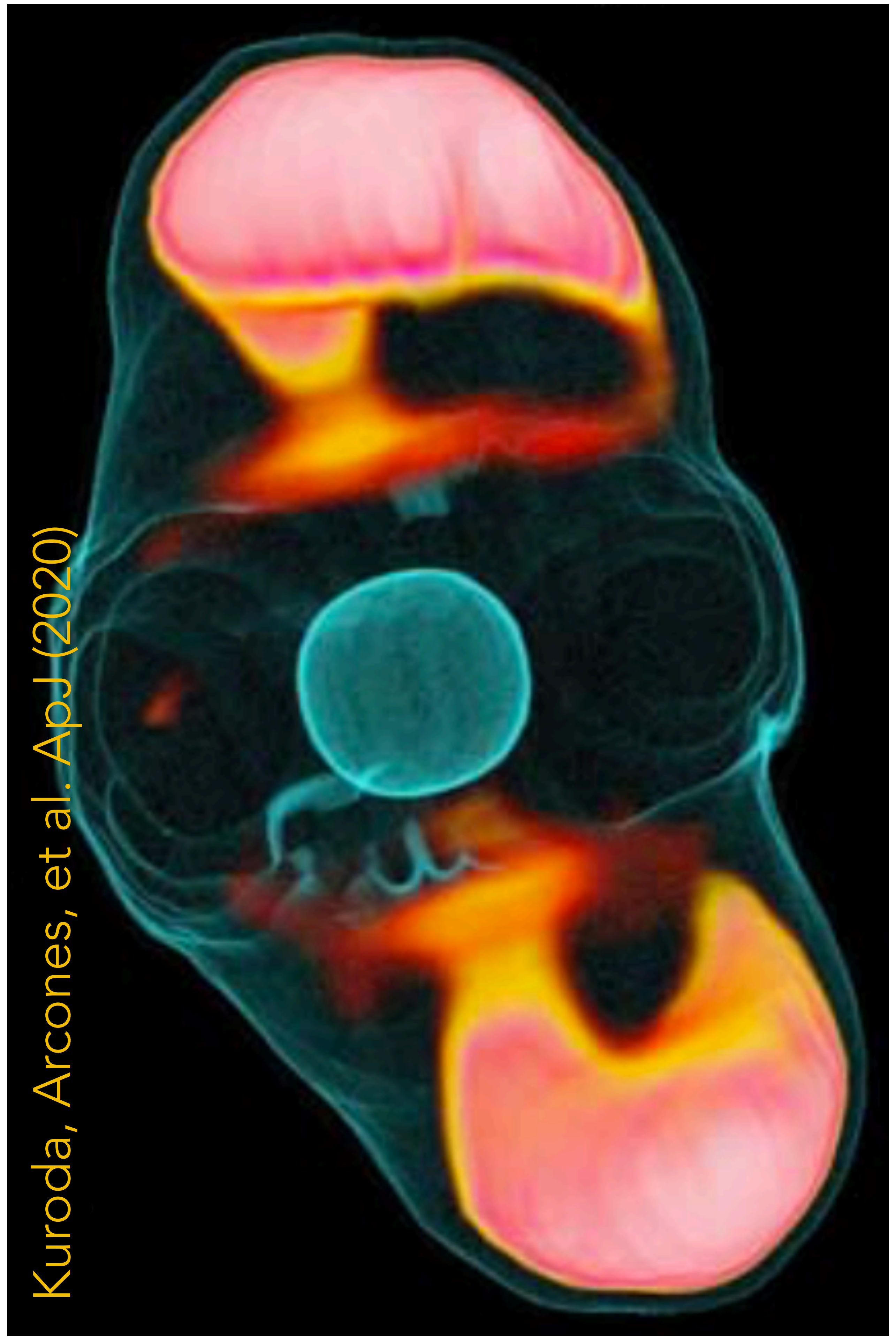
- $^{86}Kr(\alpha, n)$ and $^{94}Sr(\alpha, n)$ at TRIUMF (EMMA)

  C. Aa. Diget, A. M. Laird, M. Williams et al.

  C. Angus *et al.*, EPJ Web of Conferences, NPA-X (2023)

r-process in supernovae?

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


Kuroda, Arcones, et al. ApJ (2020)

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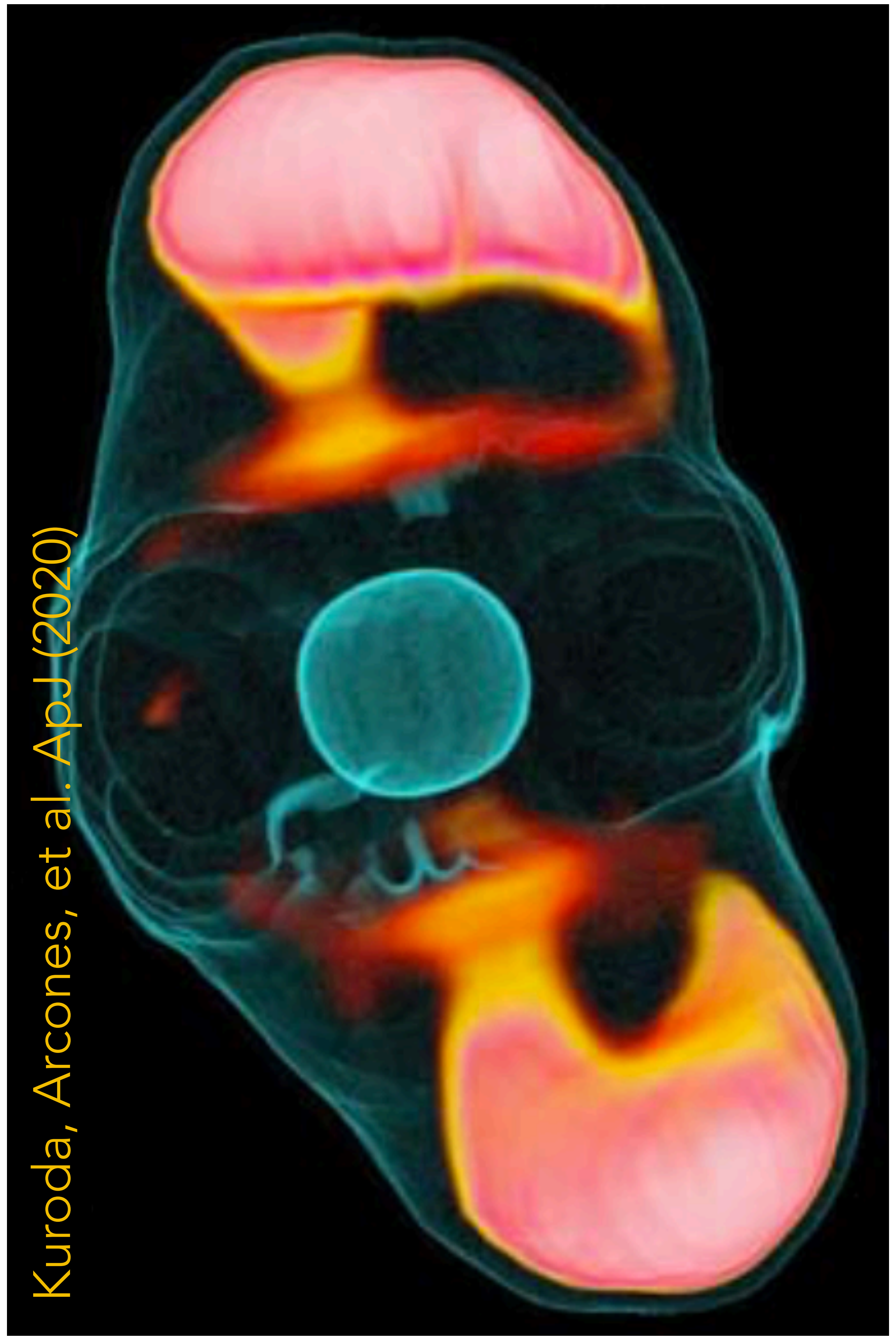

Neutron-rich matter ejected by magnetic field (Cameron 2003, Nishimura et al. 2006)

2D and 3D + parametric neutrino treatment

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

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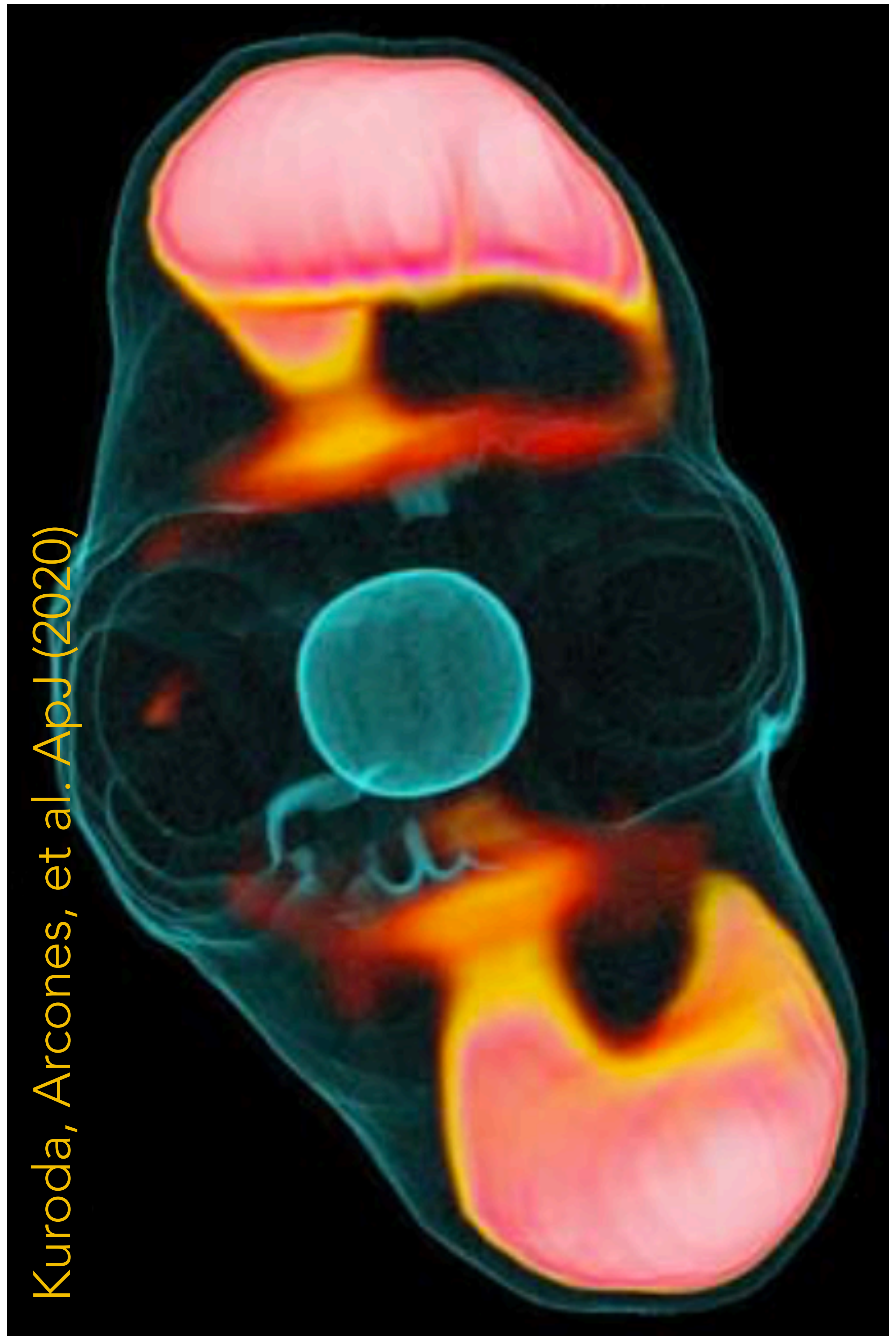

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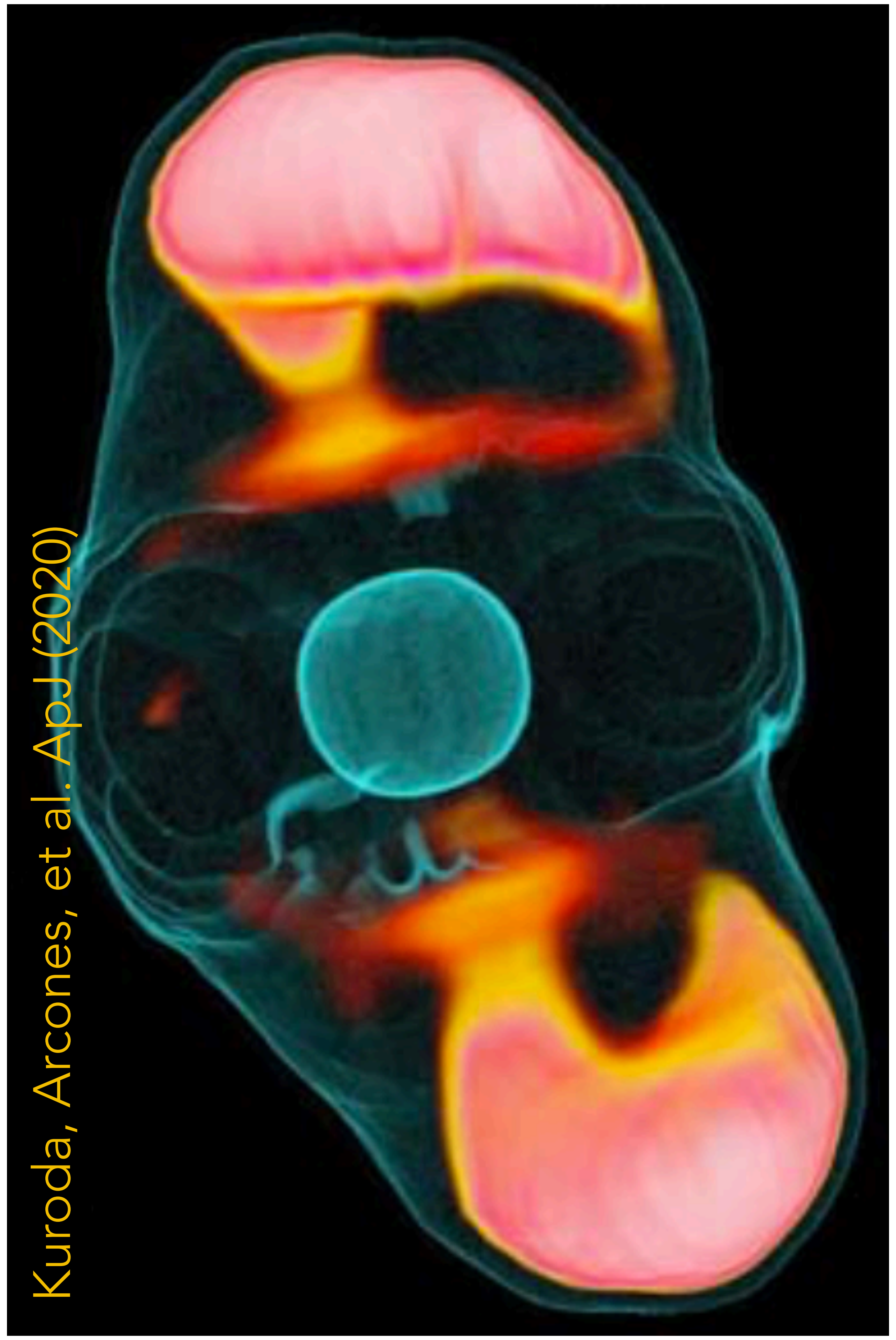

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Open questions

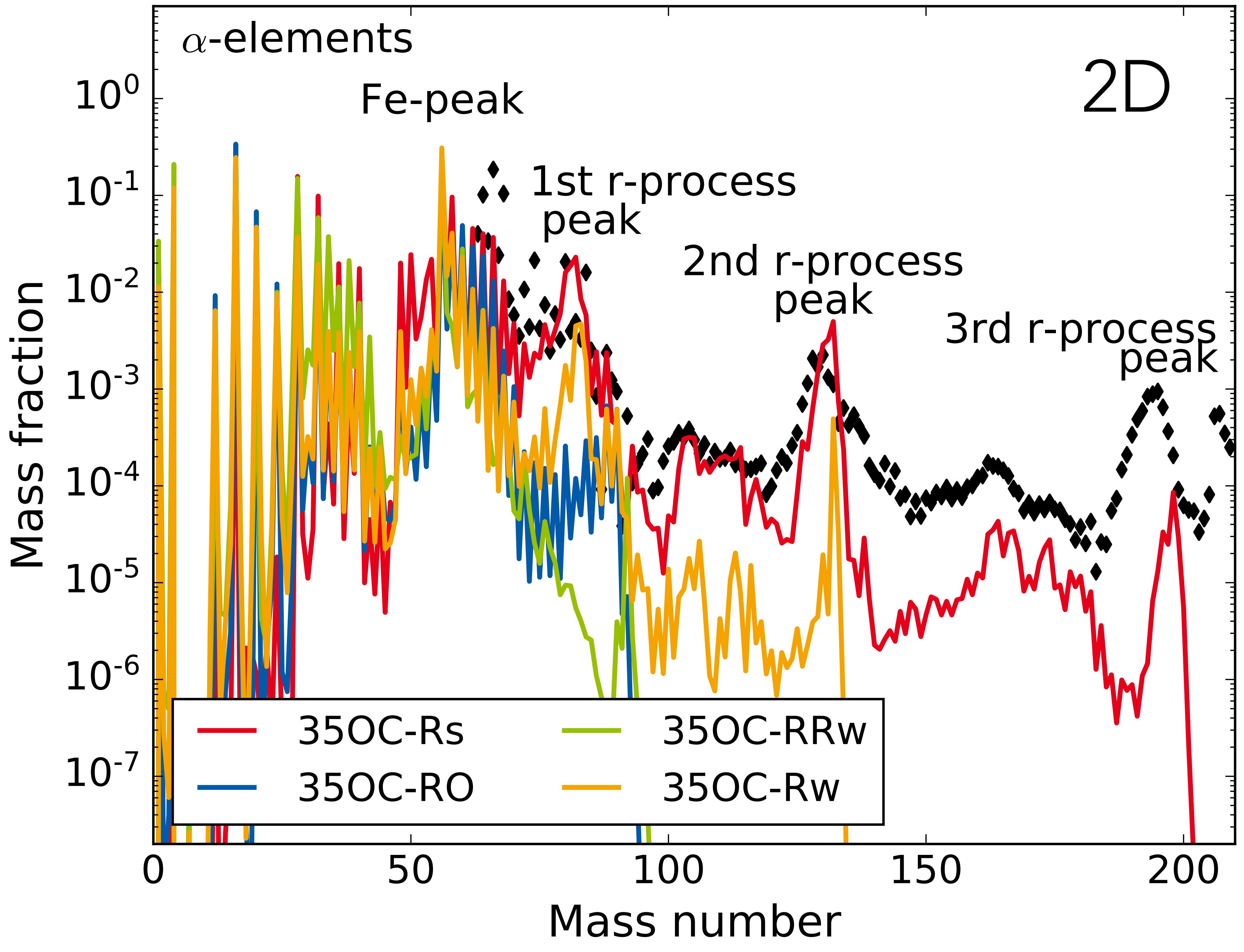
- Long-time evolution:
  Magnetar (neutron star) vs. Collapsar (black hole): **r-process possible?**
- Impact of magnetic field strength and morphology on nucleosynthesis

Reichert et al. MNRAS (2024)

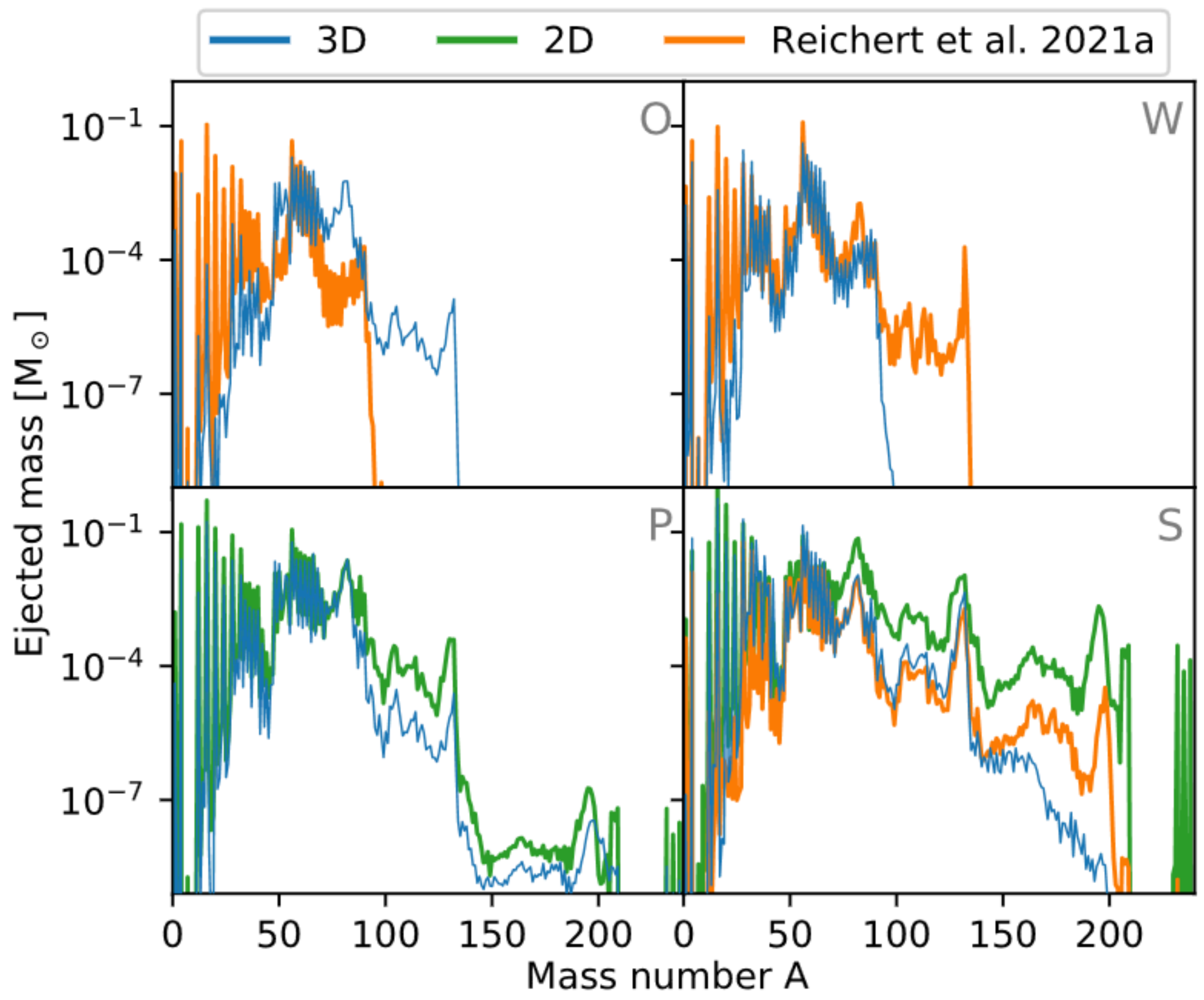
Nucleosynthesis in magneto-rotational supernovae

Nucleosynthesis based on 2D and 3D simulations with detailed neutrino transport

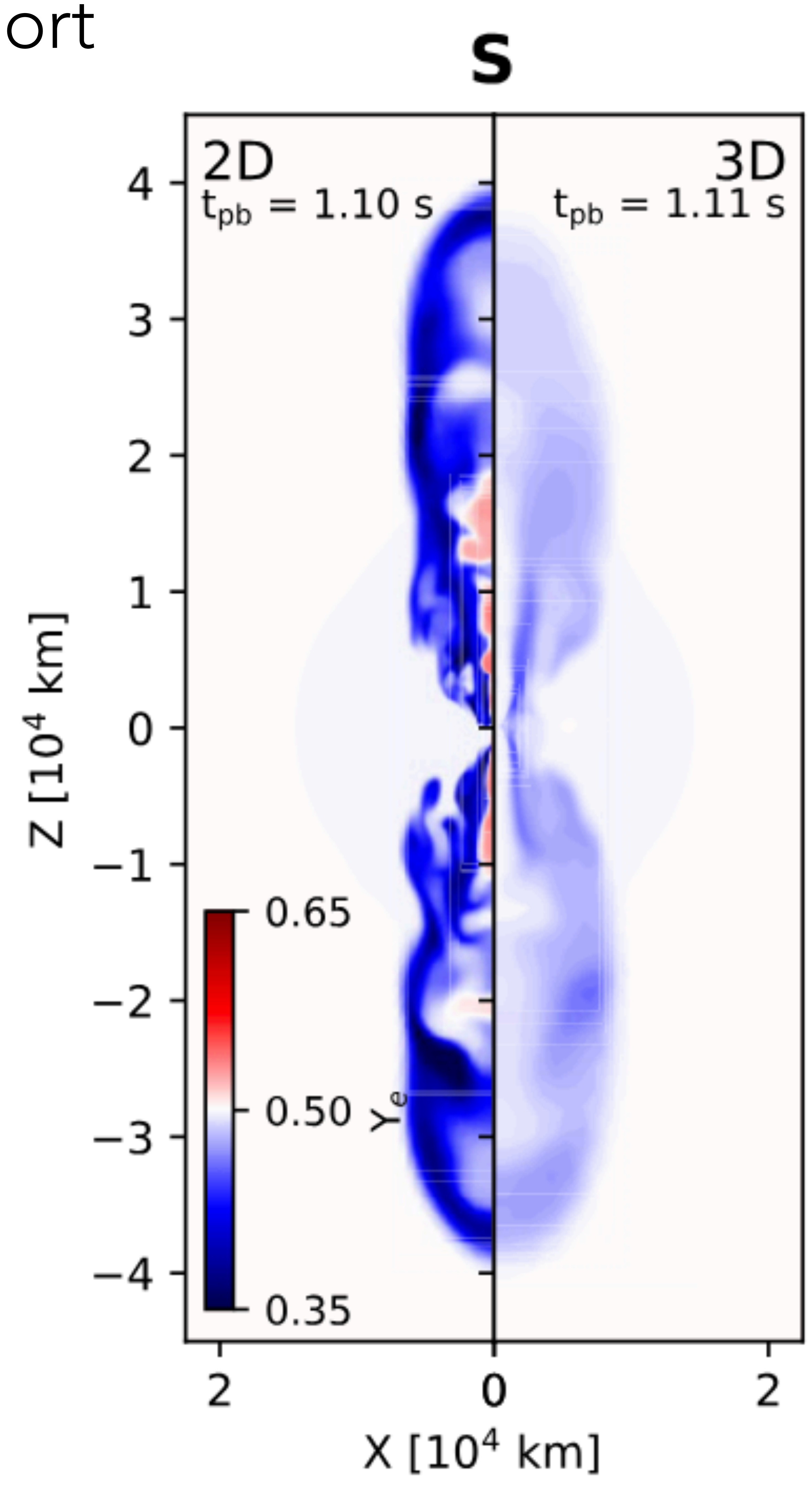
Impact of magnetic field strength and configuration (Reichert et al. 2024)



Reichert et al. ApJ (2021)

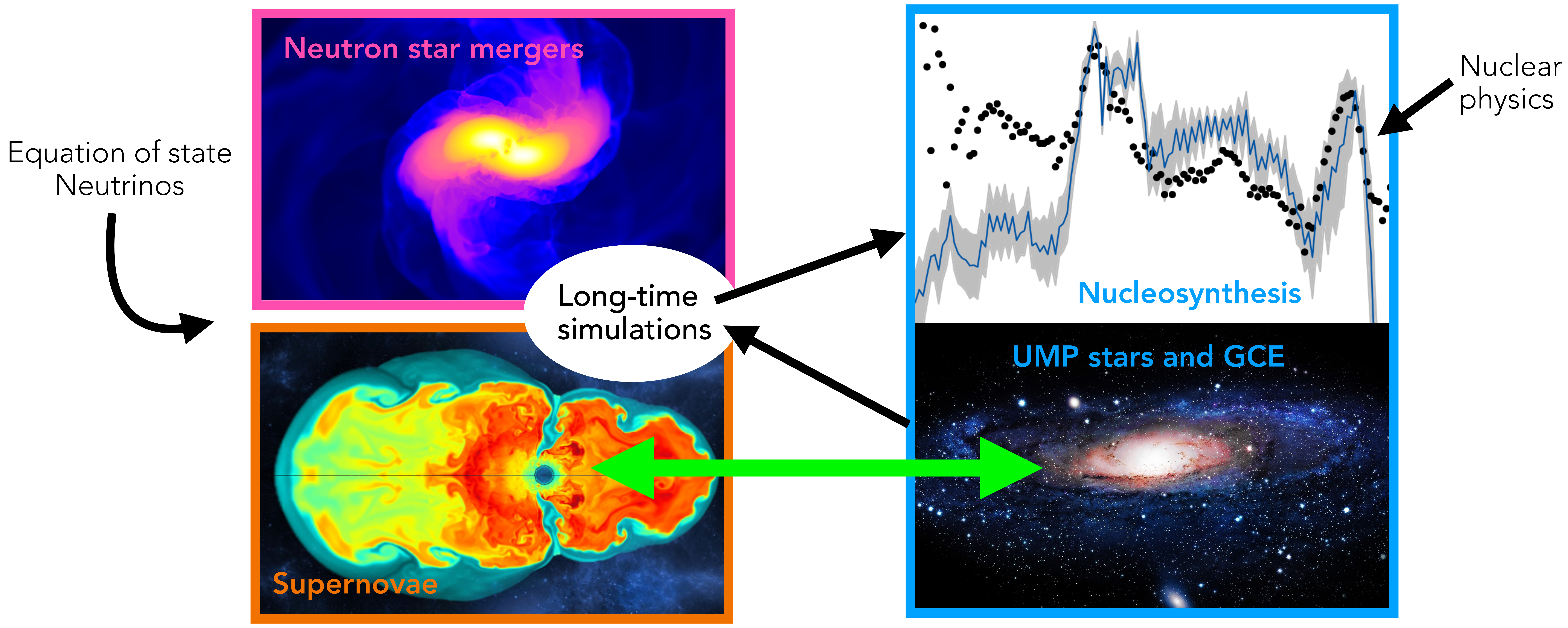


Reichert et al. MNRAS (2023)



Obergaulinger et al. 2020

R-process: from simulations to observations

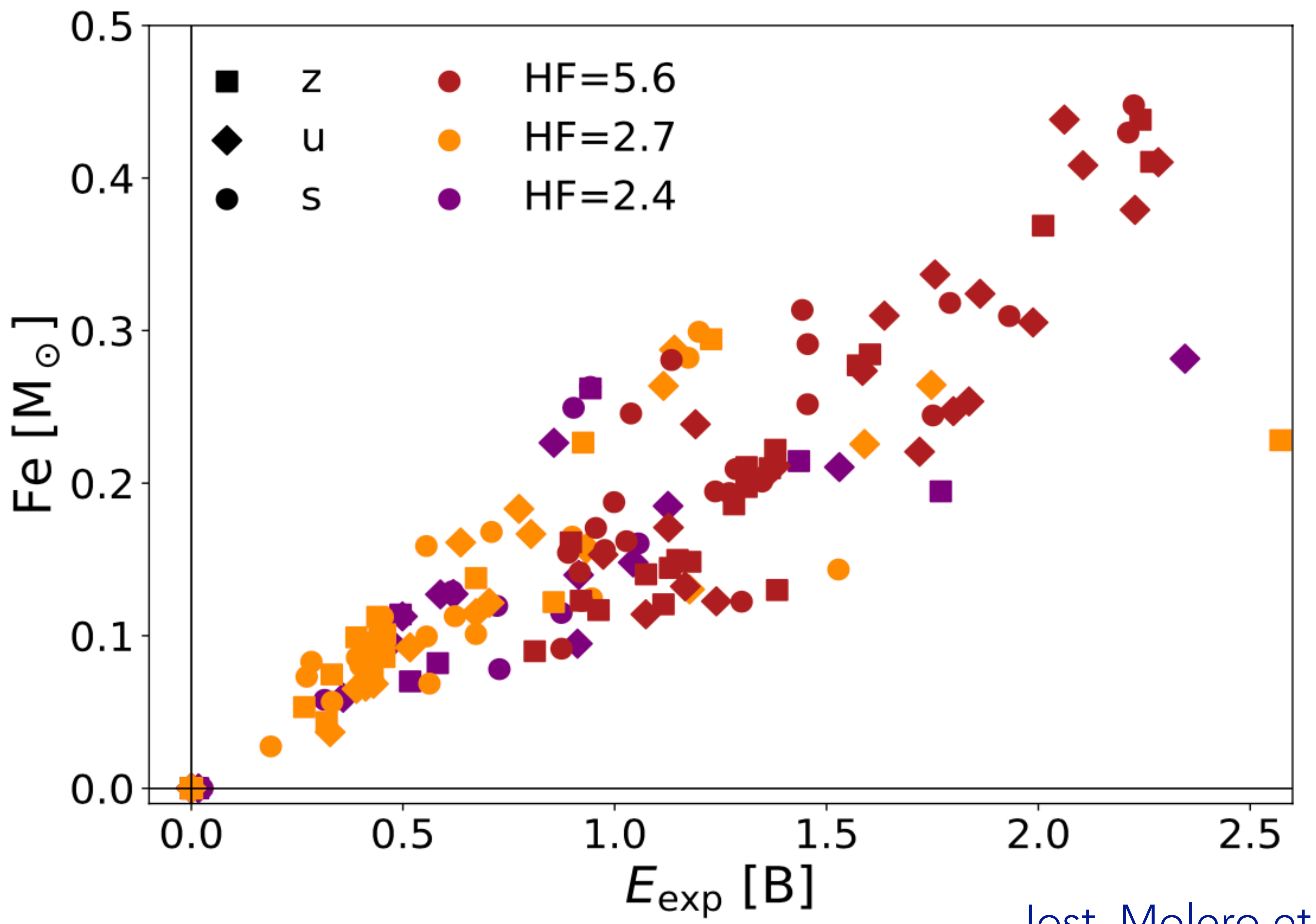


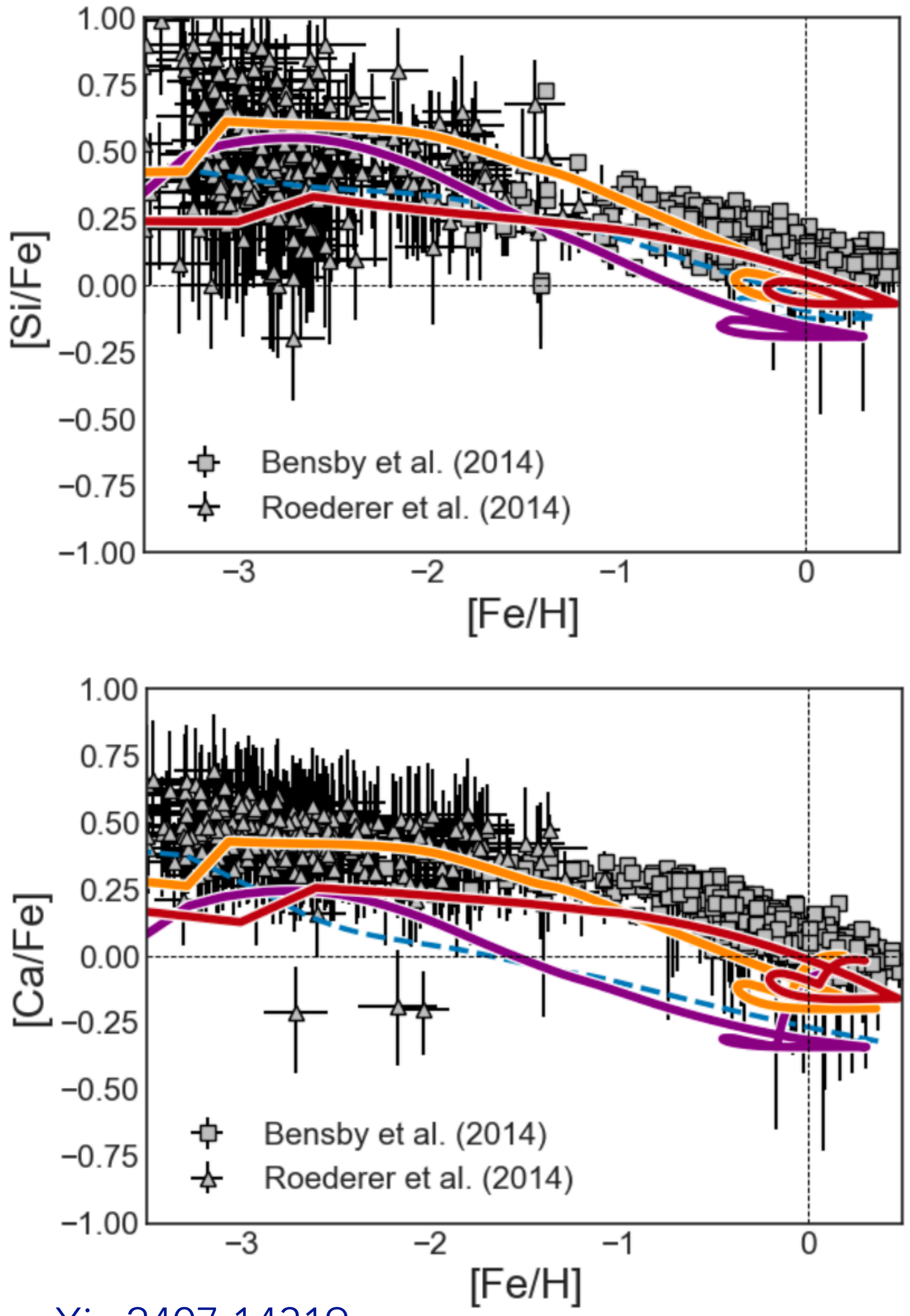
Core-collapse supernova yields for galactic chemical evolution (GCE)

Reduced alpha-network within simulations (Navó et al. 2023)

189 simulations,1D + accurate neutrino transport + neutrino heating

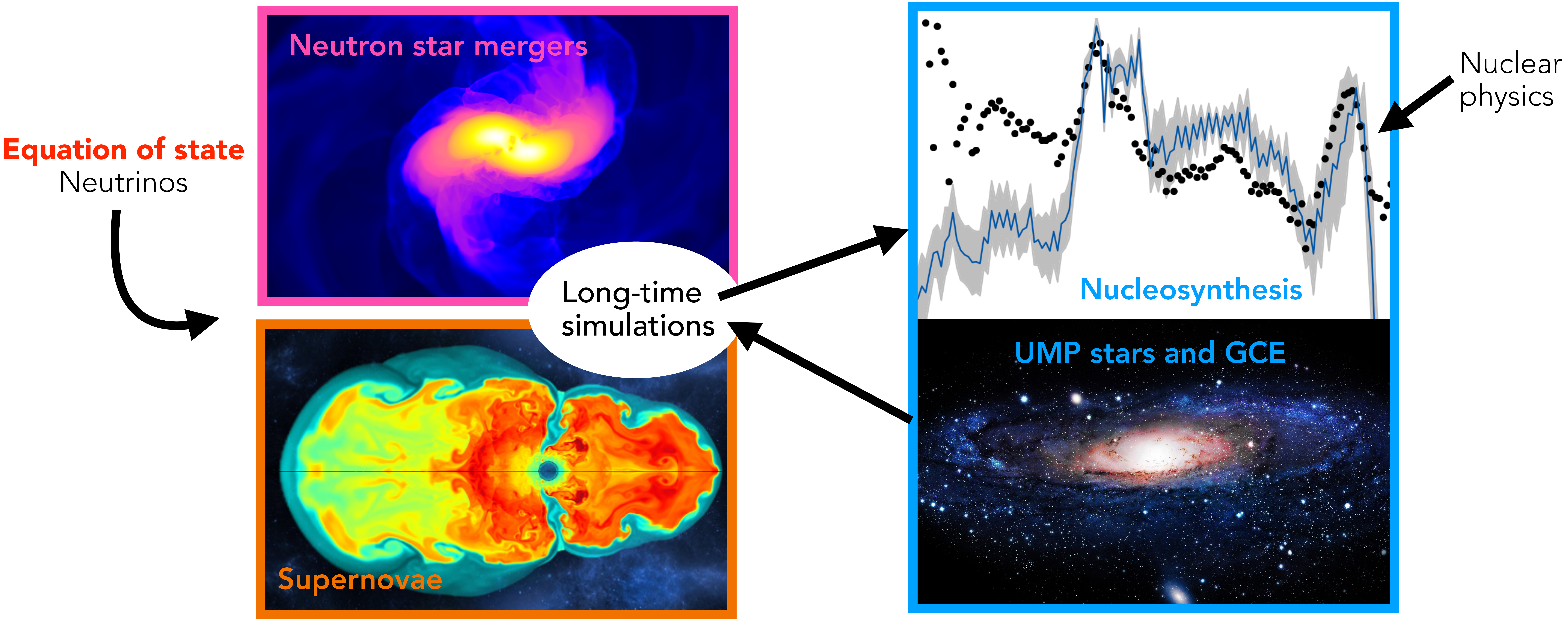
⟶propagate uncertainties from supernova models to GCE





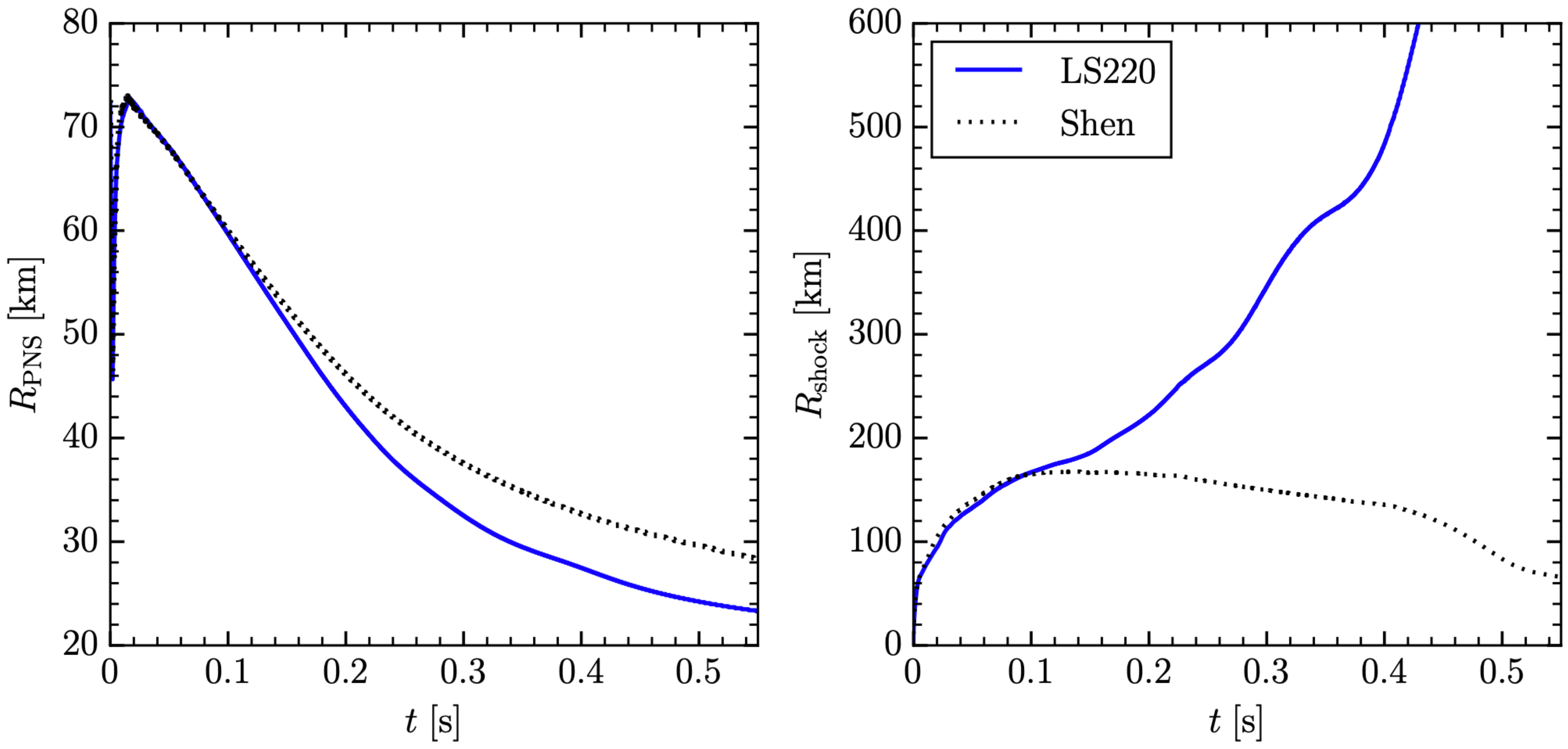
Jost, Molero et al. submitted, arXiv:2407:14319

R-process: from simulations to observations



Equation of state in core-collapse supernovae

First systematic study of nuclear matter properties
1D simulations, FLASH + M1 + increased neutrino heating



Yasin et al., PRL (2020)

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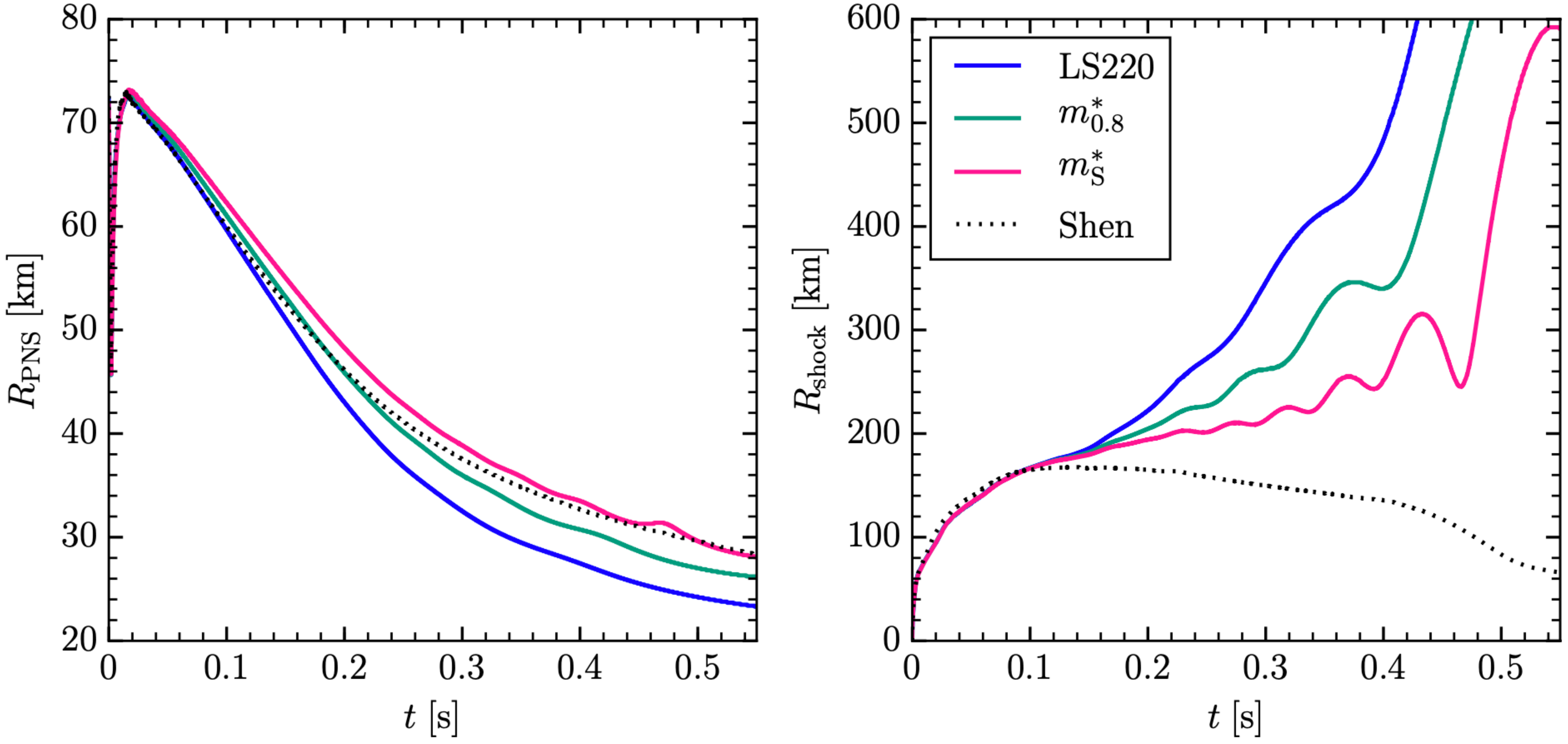

Yasin et al., PRL (2020)

Effective mass:
PNS contraction

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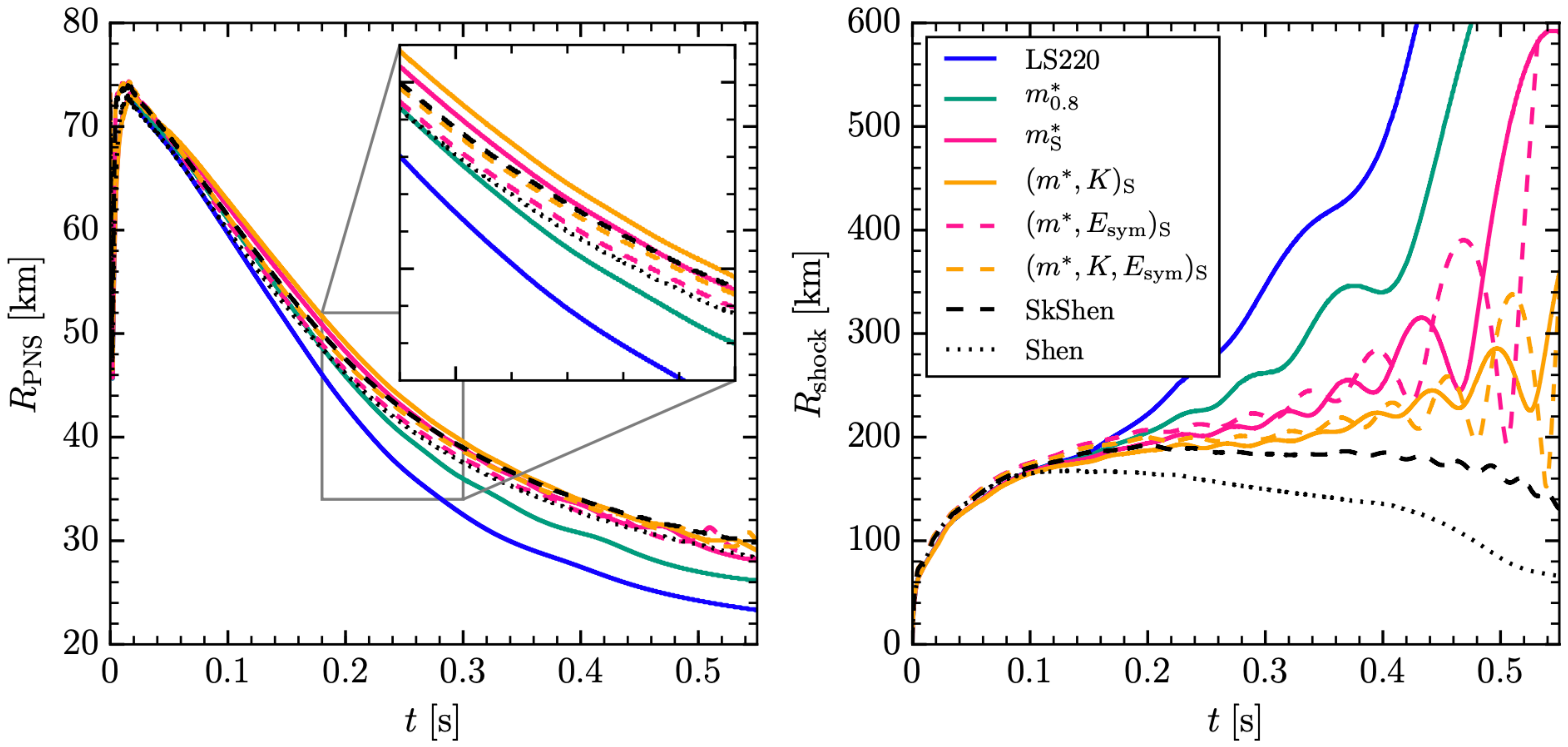


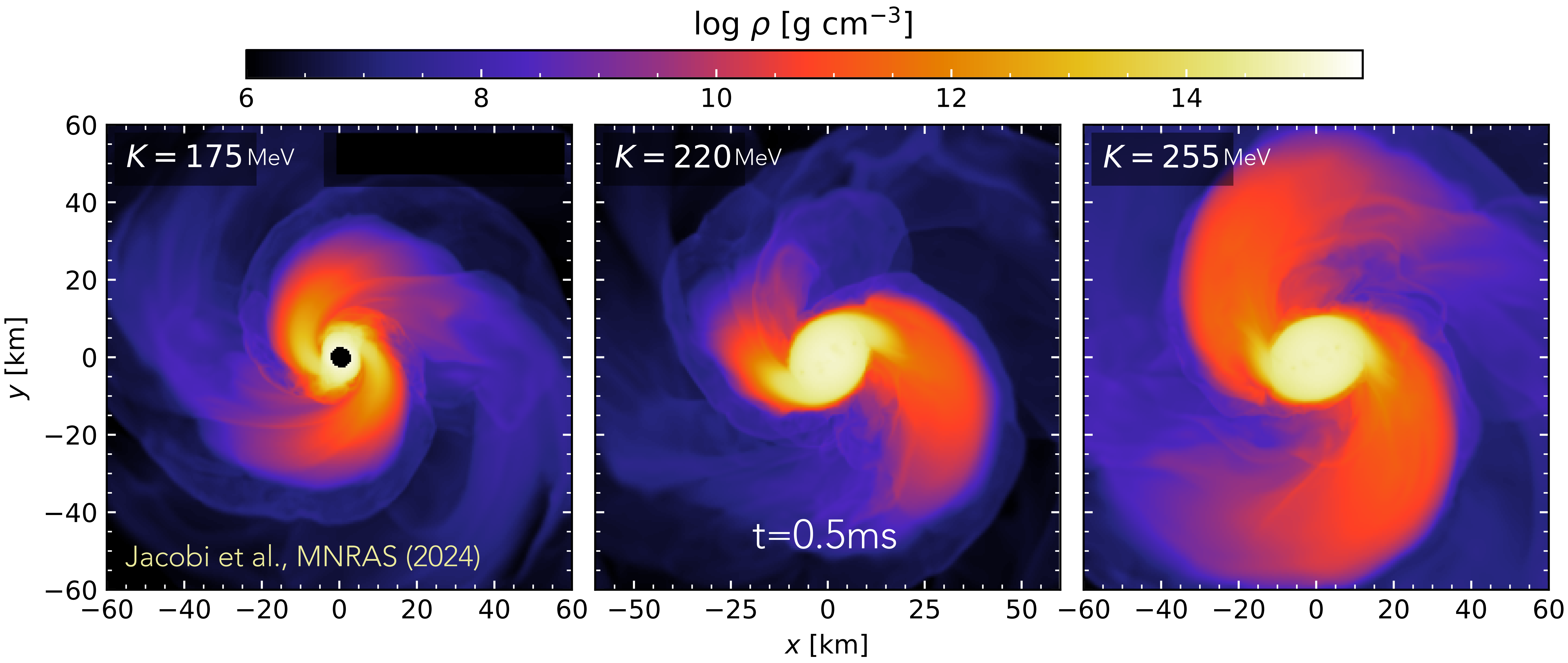
Effective mass:
PNS contraction

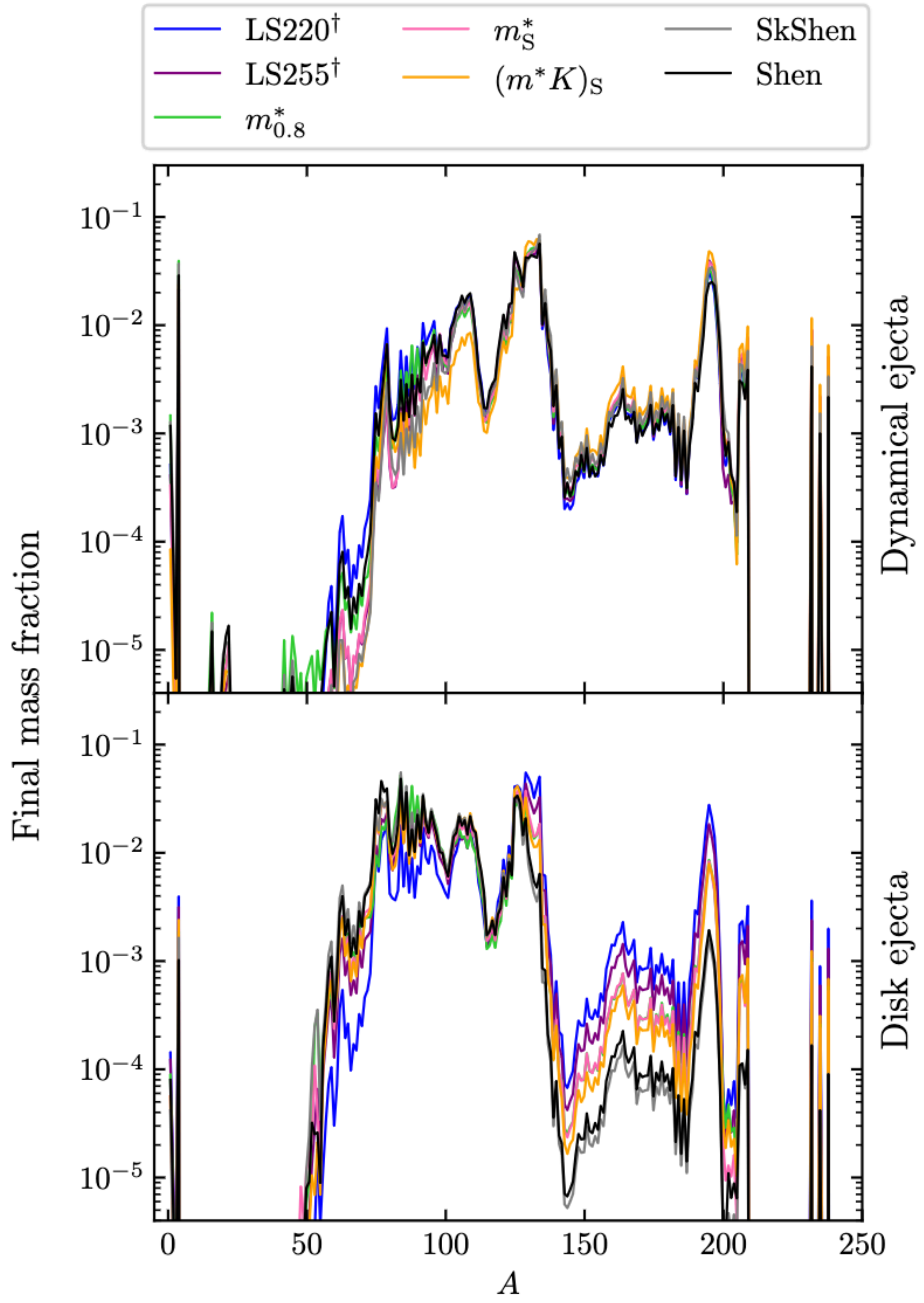
Yasin et al., PRL (2020)

Equation of state in neutron star mergers

Systematic variations of key nuclear matter properties

following Bovard et al. PRC, 2017





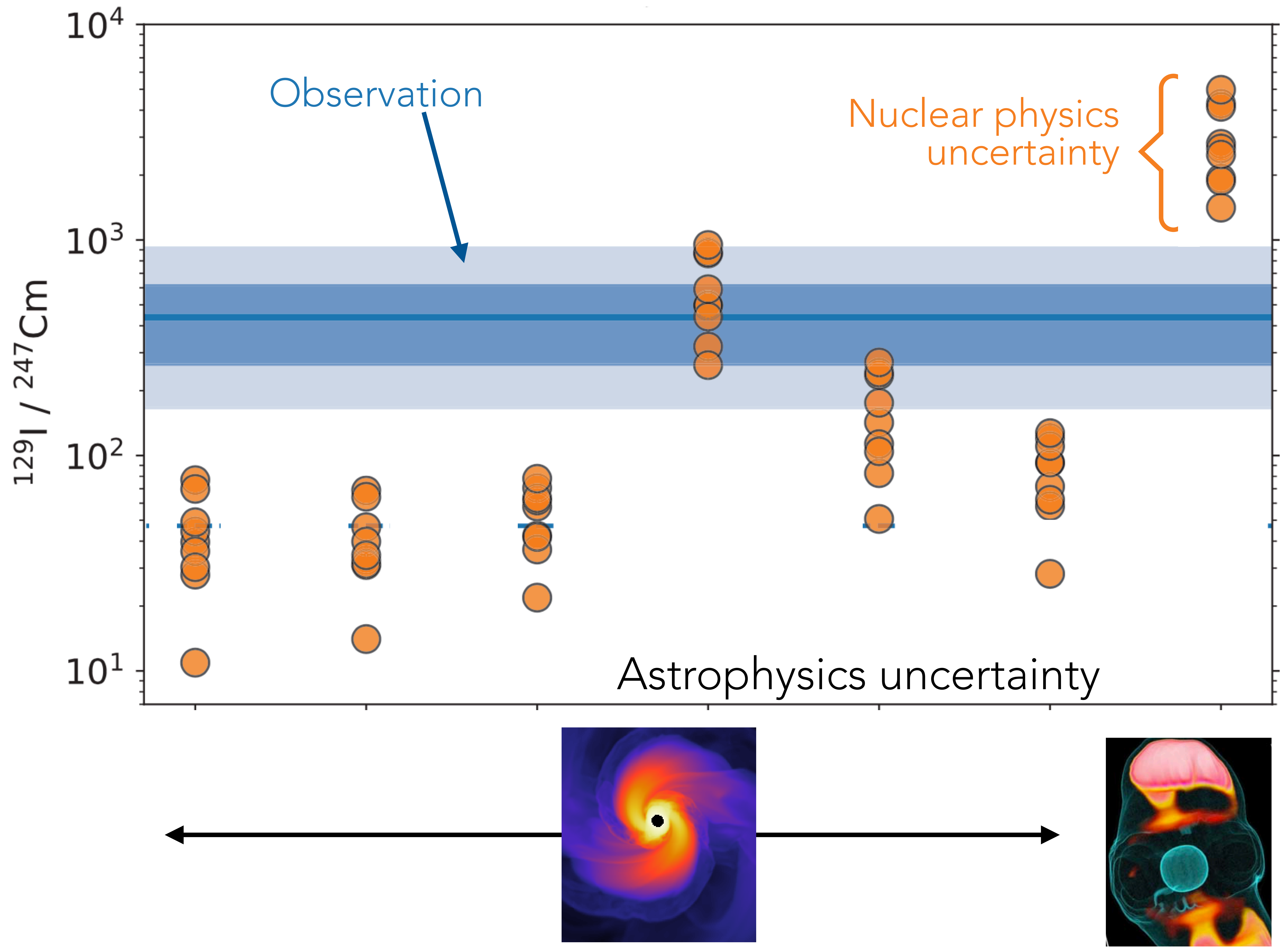
Impact on:

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

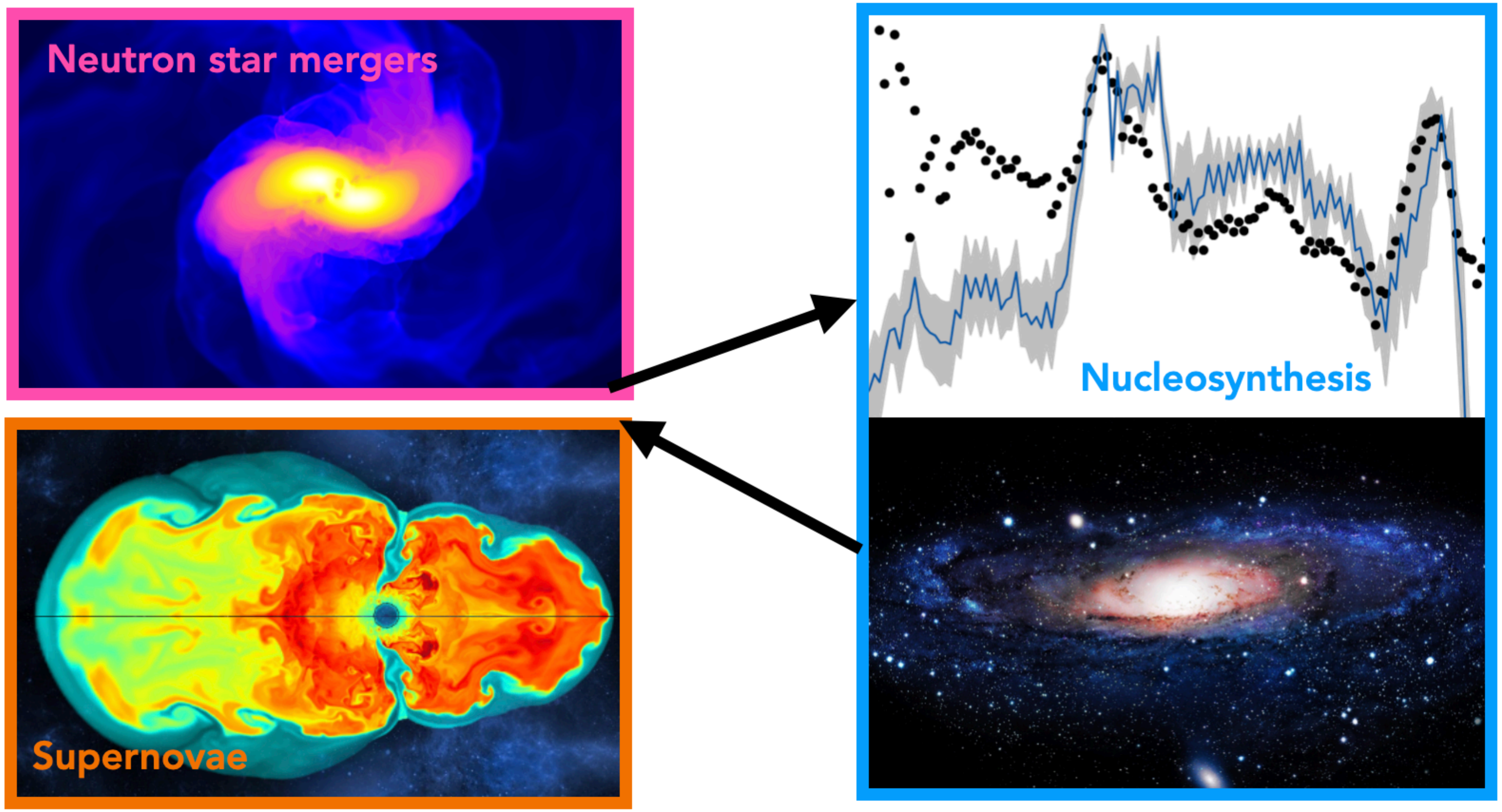
nucleosynthesis and kilonova (Ricigliano et al., MNRAS 2024)

R-process: from simulations to observations

Côtè et al. Science (2021)



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



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