Nucleosynthesis in core-collapse supernovae

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Technische Universität Darmstadt

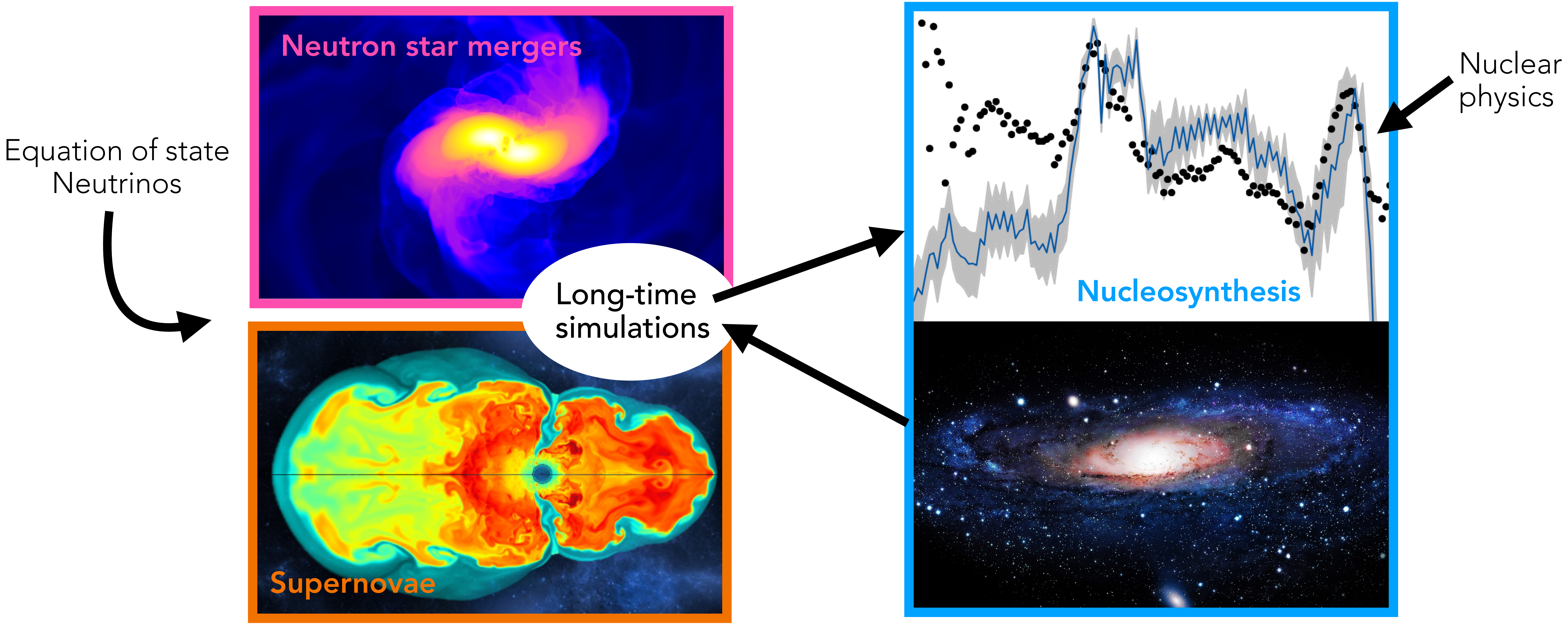
GSI

ELEMENTS

SFB 1245

DFG

Connecting astrophysics and nuclear physics



Nucleosynthesis network

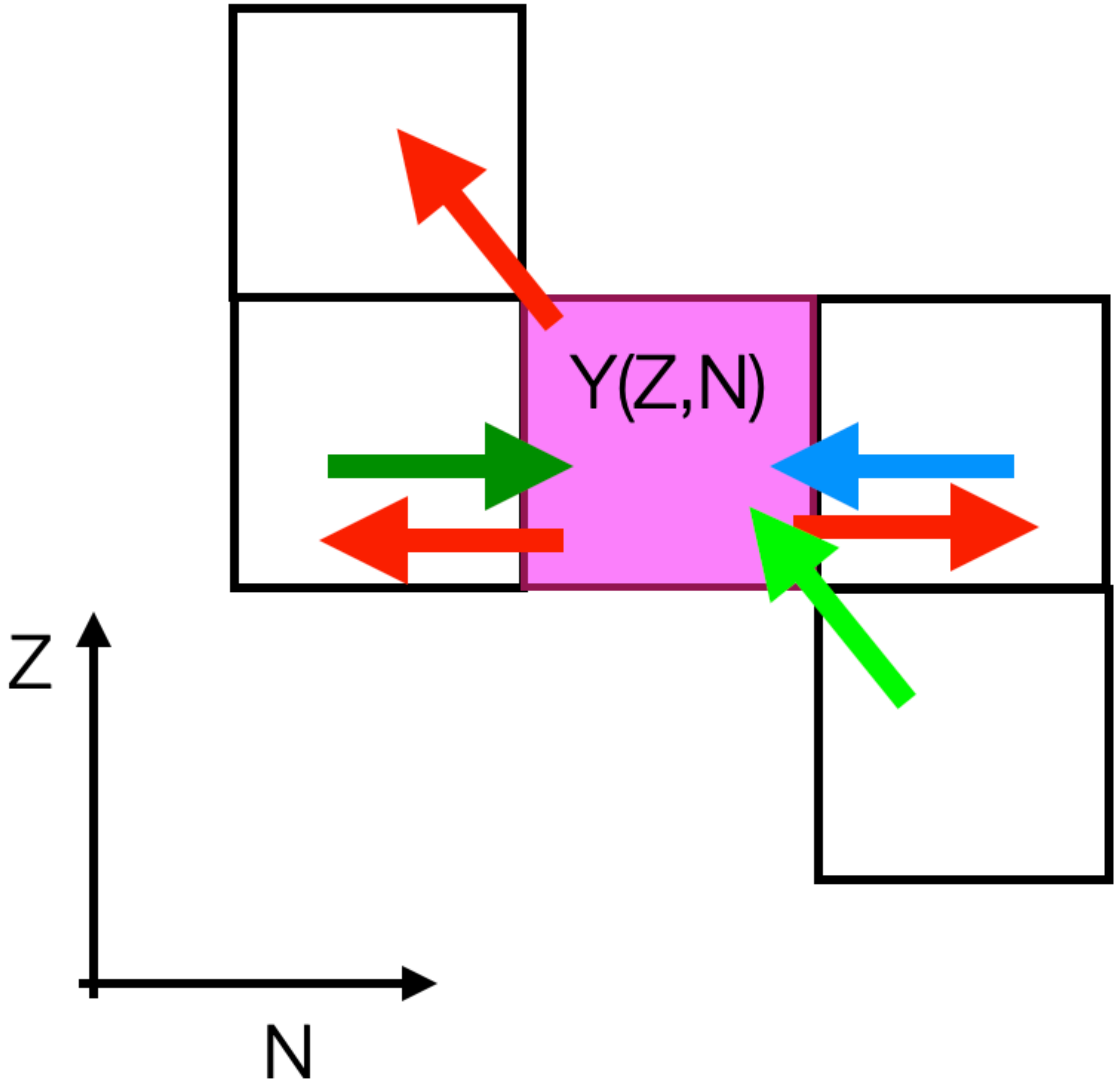
WinNet

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

$$\frac{dY}{dt} = \dot{Y}(Z,N) =$$

$$\lambda_{(n,\gamma)}Y(Z,N-1) + \lambda_{(\gamma,n)}Y(Z,N+1) + \lambda_{\beta}Y(Z-1,N-1)$$

$$-(\lambda_{(n,\gamma)} + \lambda_{(\gamma,n)} + \lambda_{\beta})Y(Z,N)$$



Nuclear physics:
masses, beta decays, reaction rates,
fission (barriers and yield distribution)

Astrophysics:
density and temperature evolution: $\rho(t), T(t)$
initial composition (at high T: NSE $\Rightarrow Y(Z,N) = f(\rho, T, Y_e)$)

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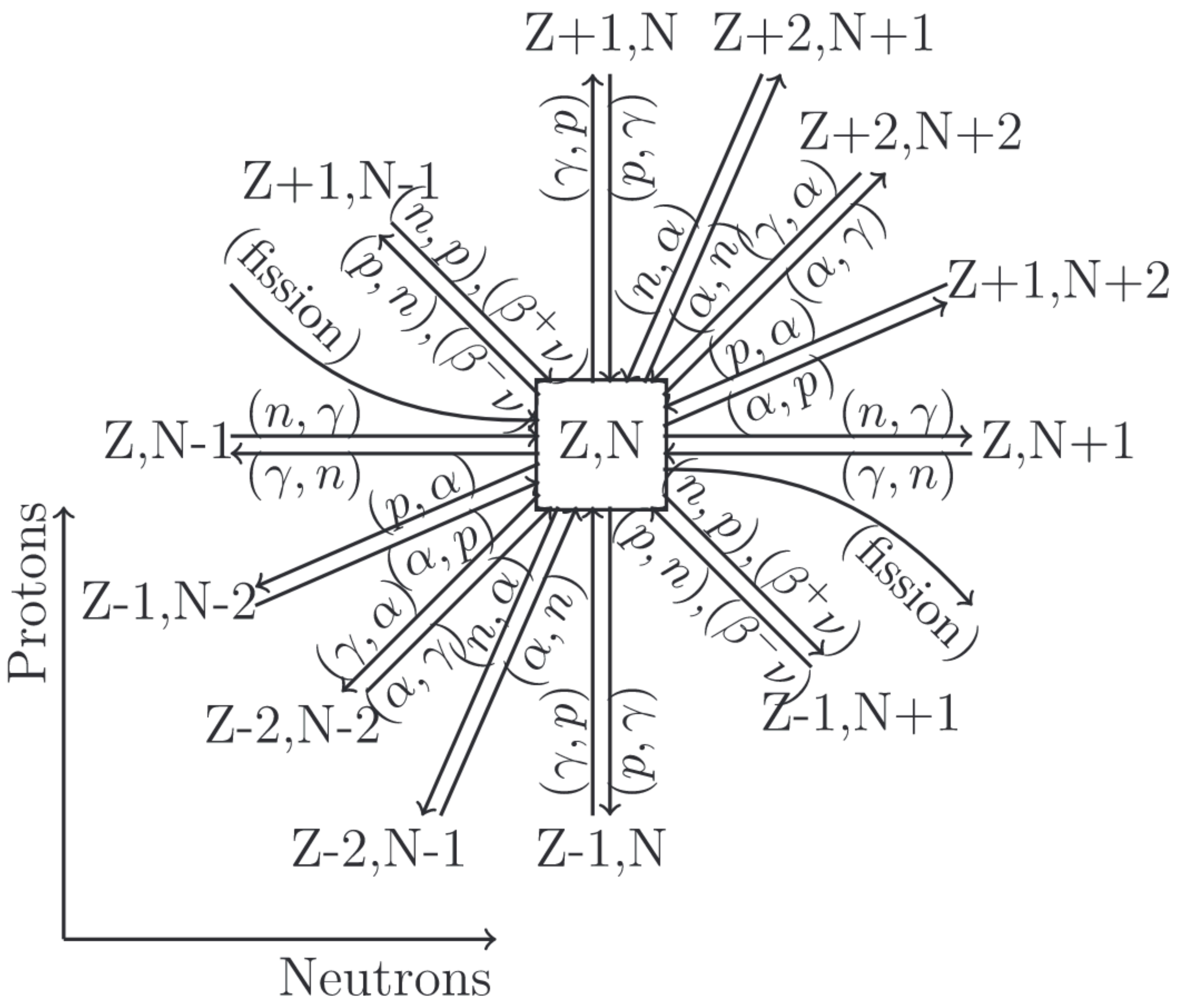

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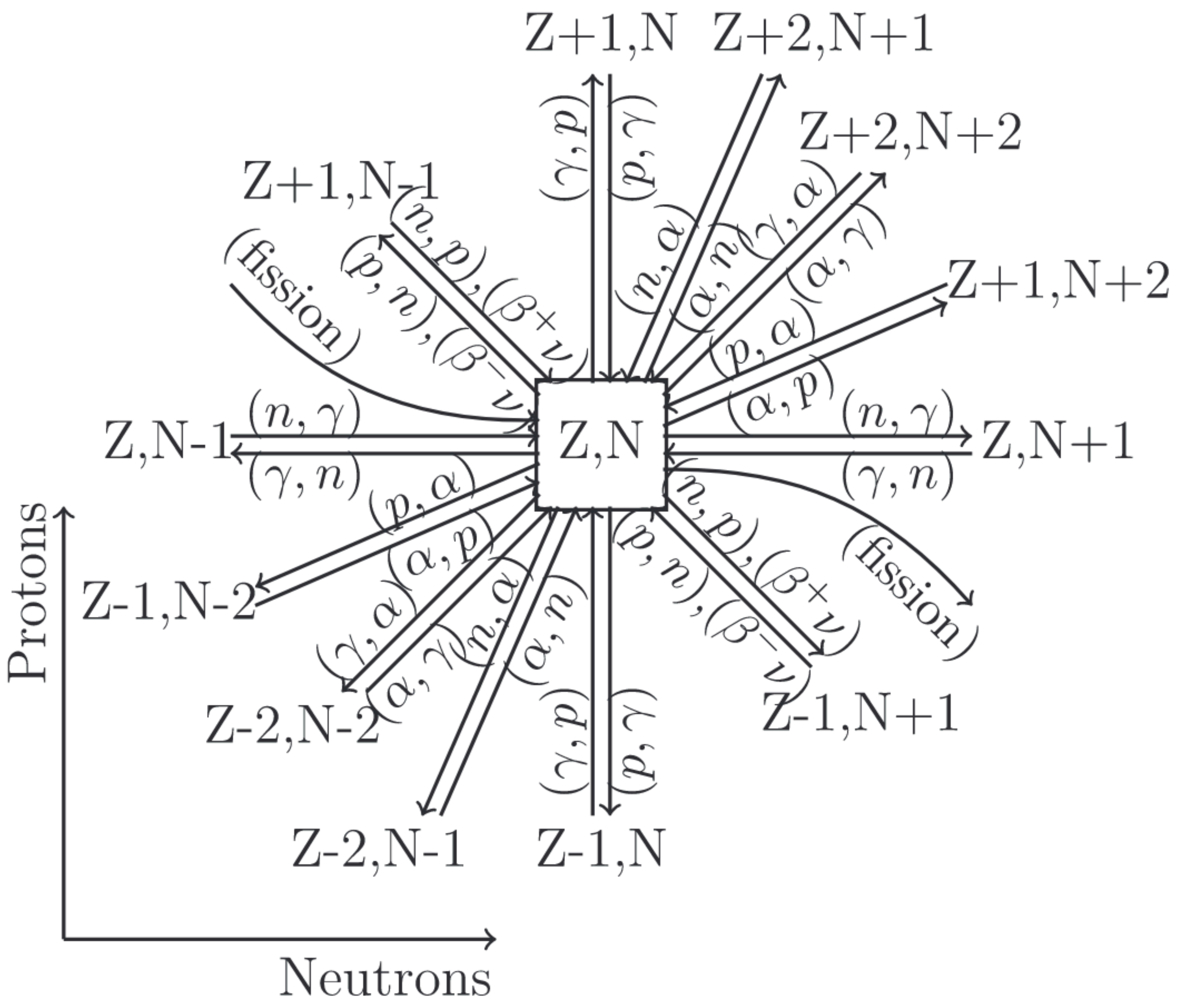

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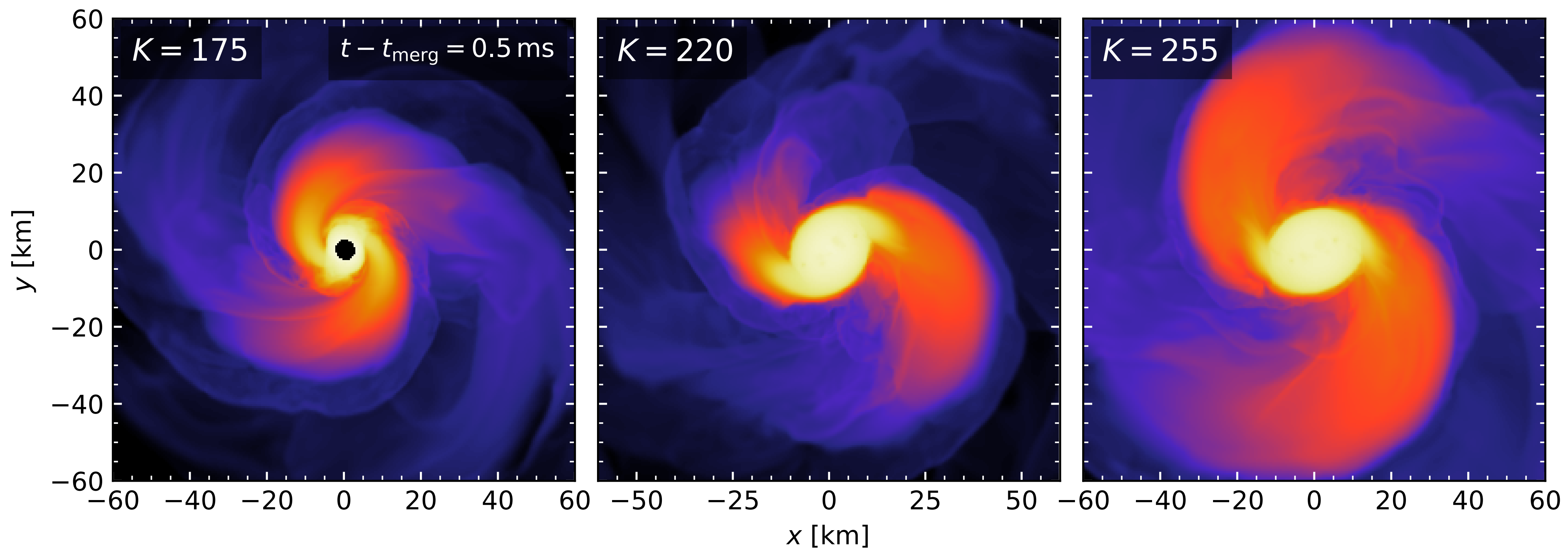
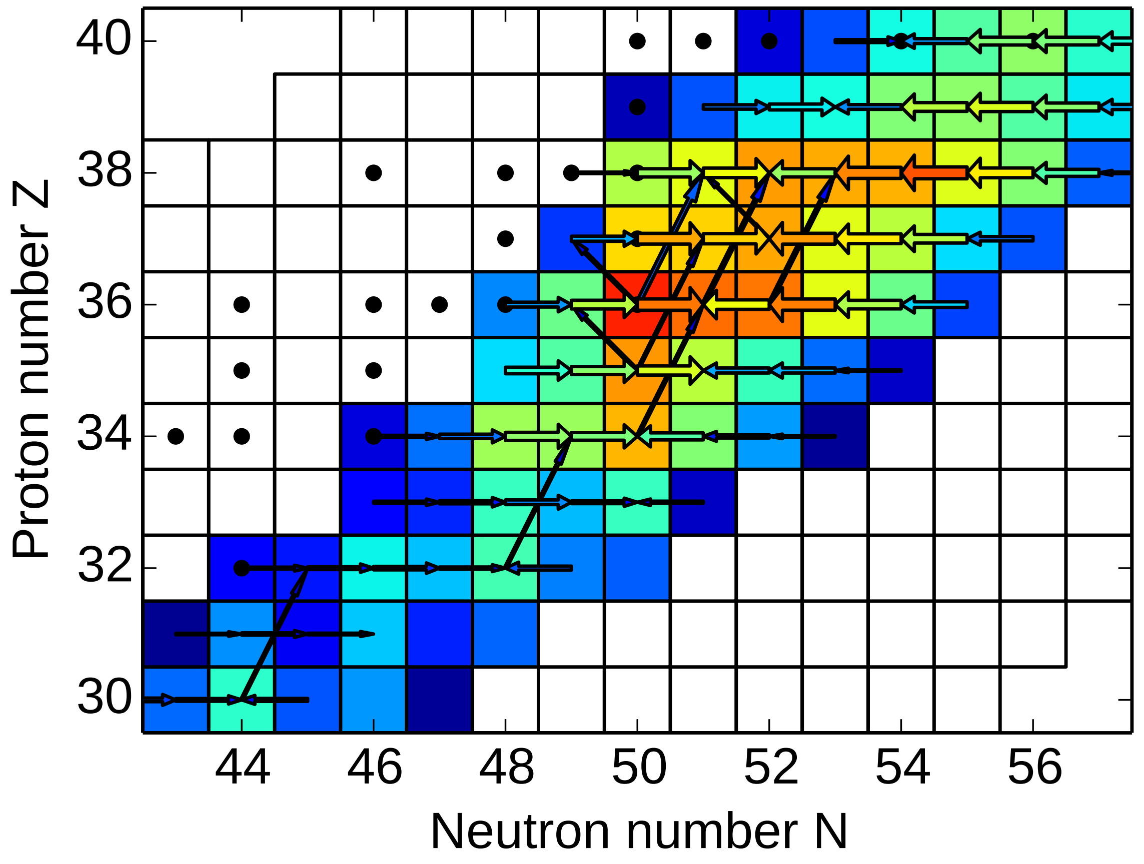
Jan Kuske Poster
[arXiv:2506.00092]

nuclear - astro connections

Neutron star mergers
EoS -> simulations -> r-process -> kilonova

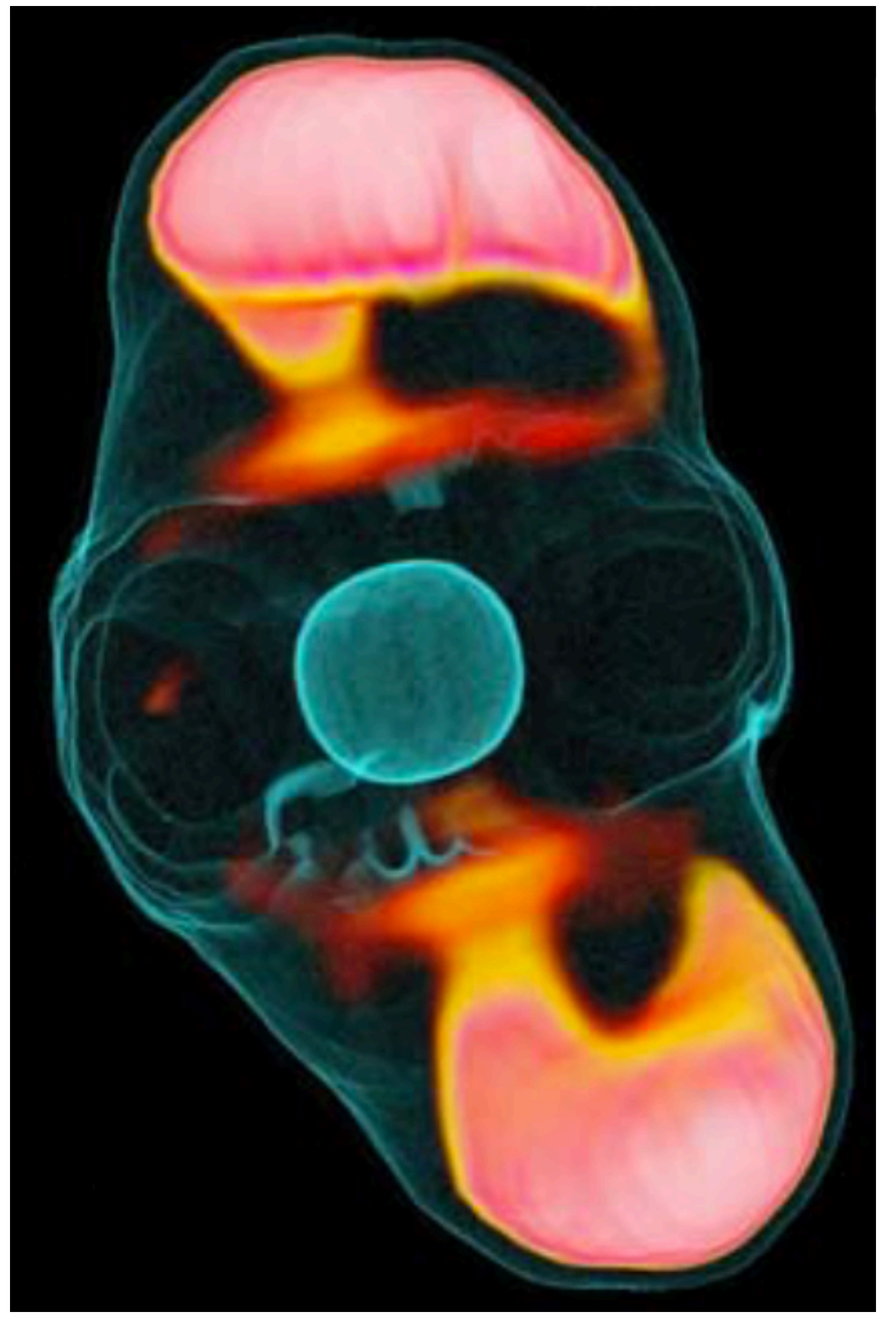
Jacobi et al., MNRAS 2024, Ricigliano et al., MNRAS 2024



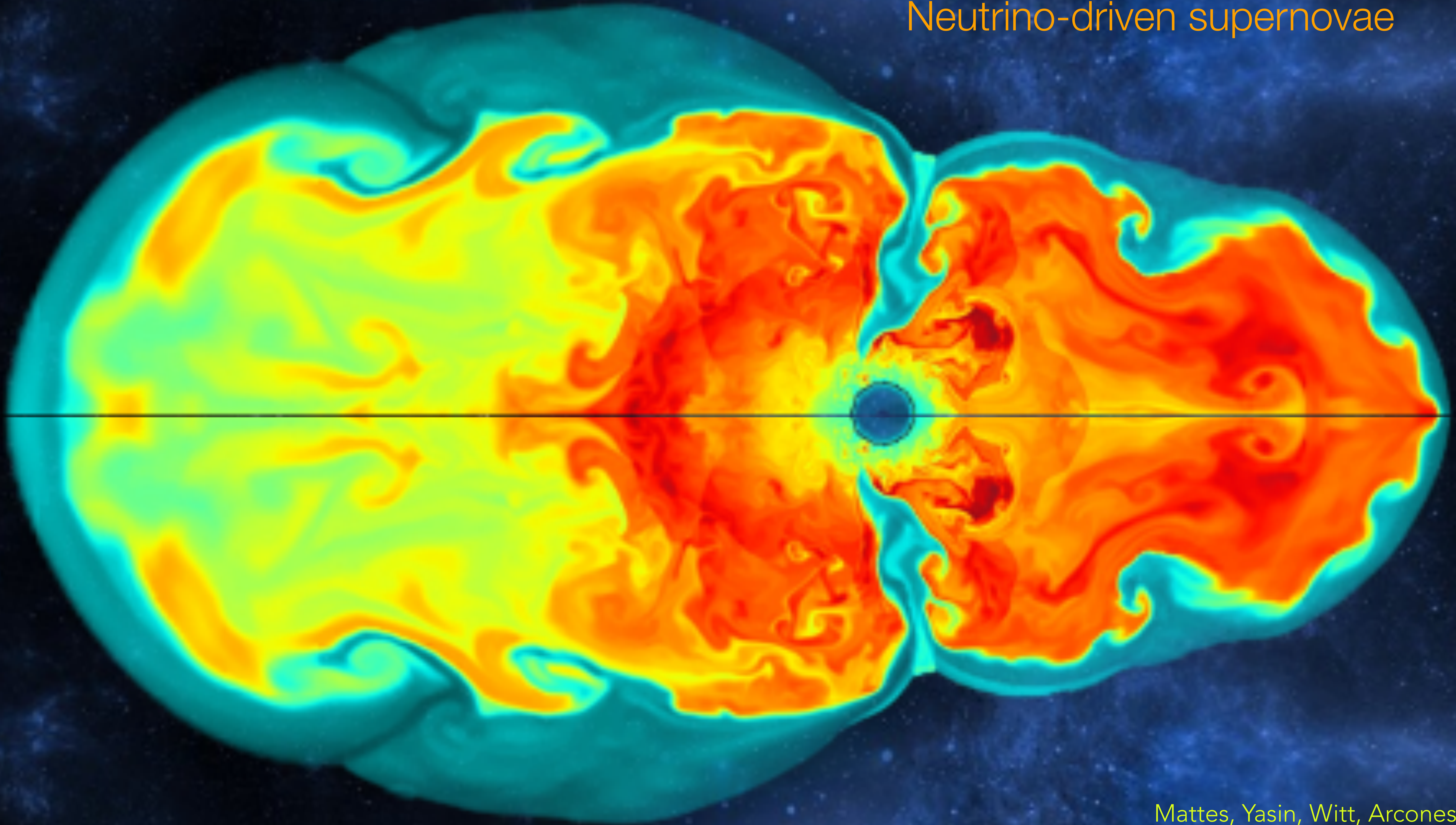


Core-collapse supernovae:
Weak r-process and (α, n) reactions

Magneto-rotational supernovae: r-process?



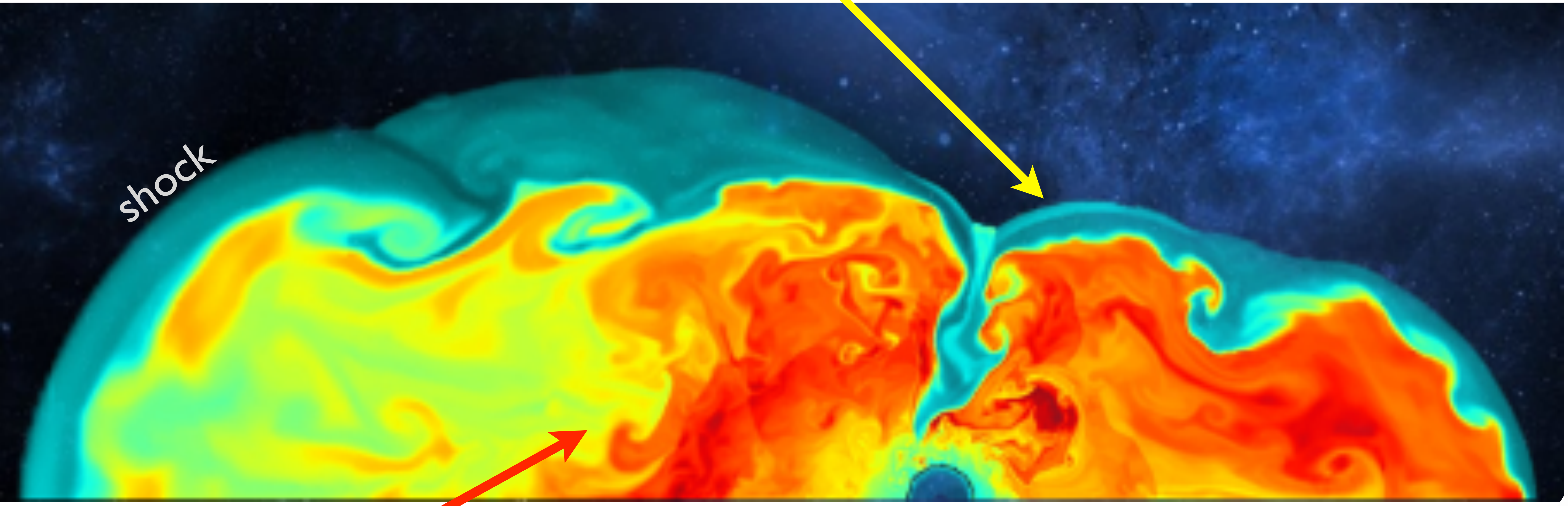
Neutrino-driven supernovae



Mattes, Yasin, Witt, Arcones

Supernova nucleosynthesis

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

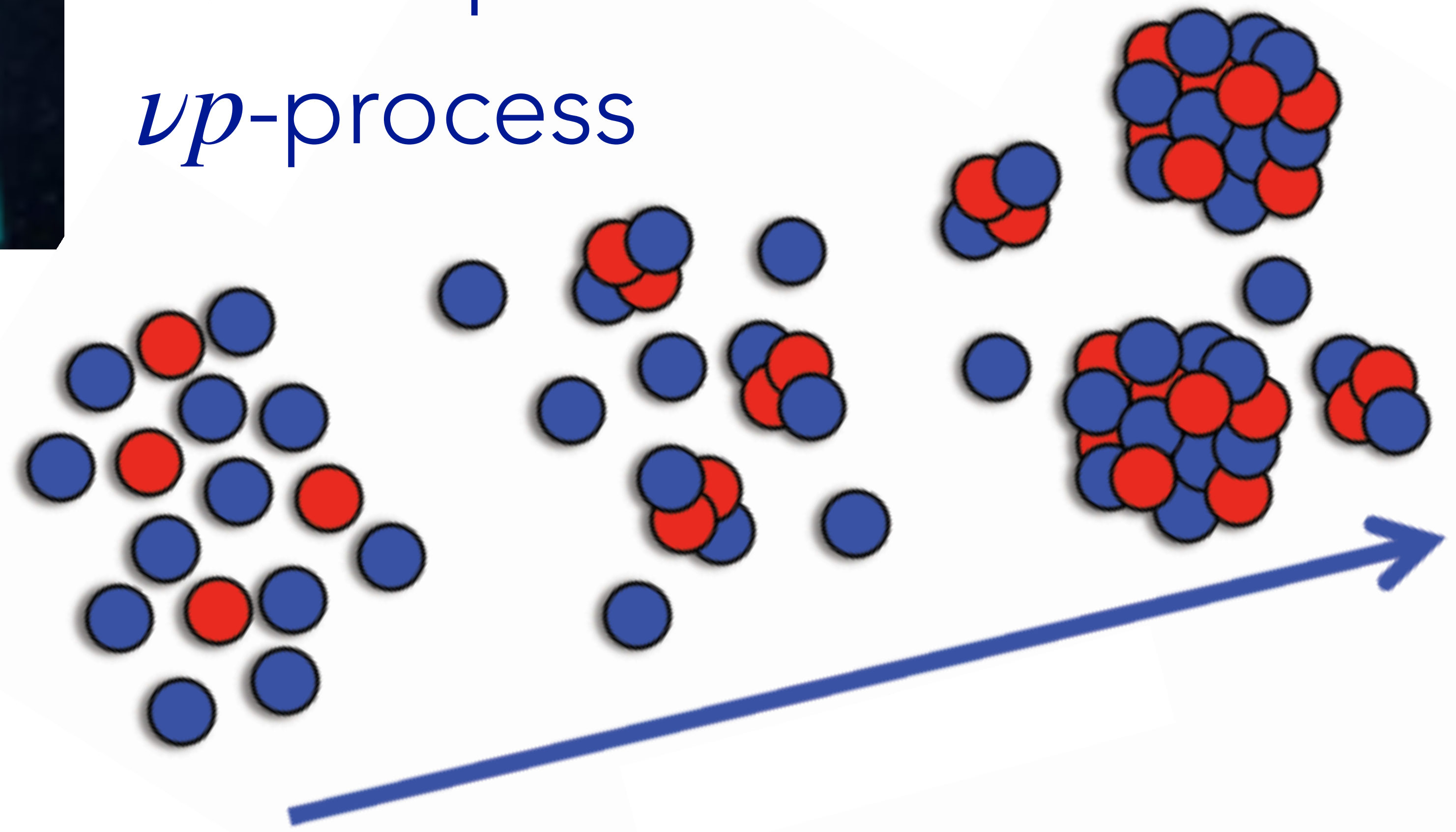


neutrino-driven ejecta

Nuclear statistical equilibrium (NSE)

charged particle reactions
α-process

r-process
weak r-process
νp-process



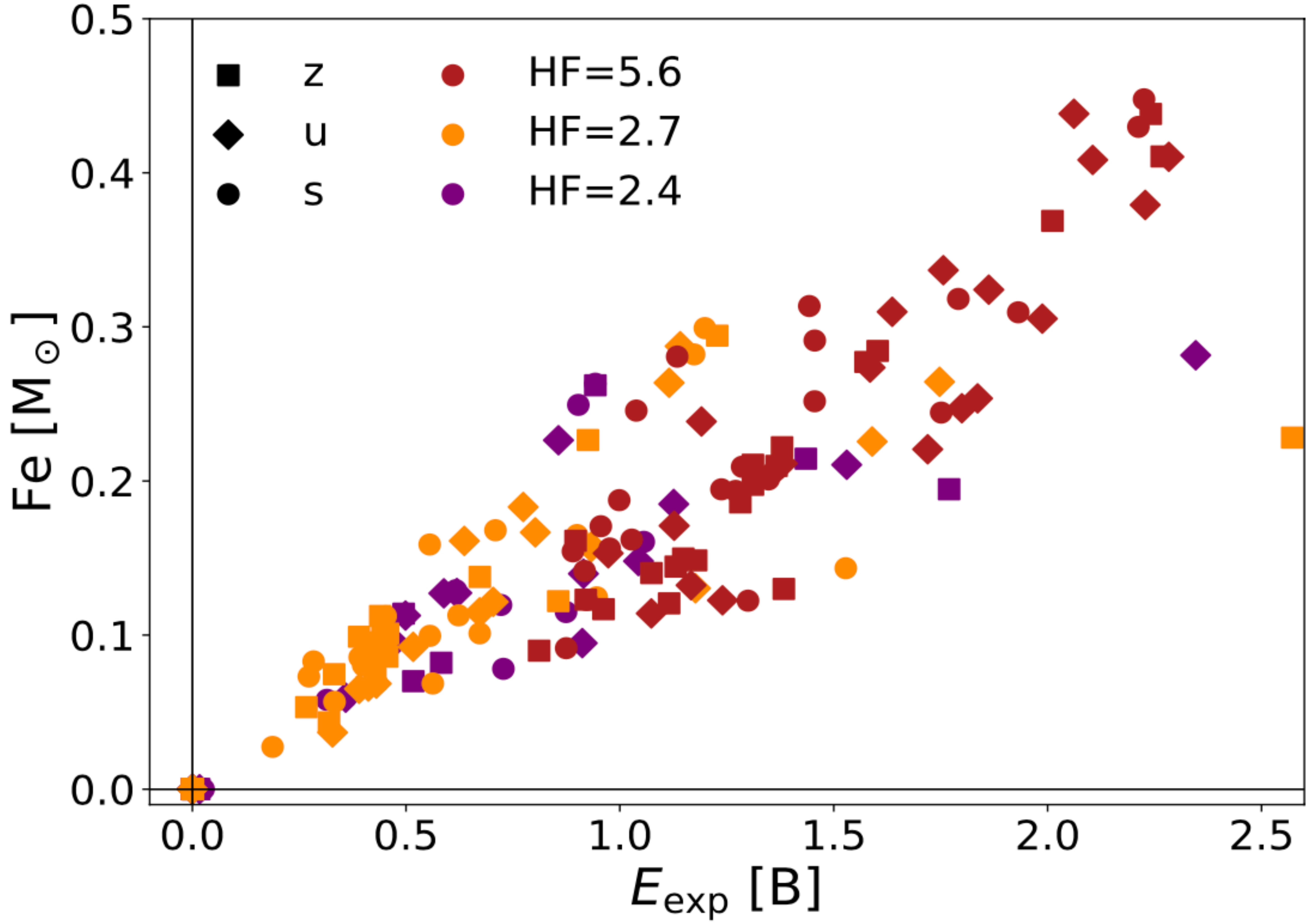
Core-collapse supernova yields for galactic chemical evolution (GCE)

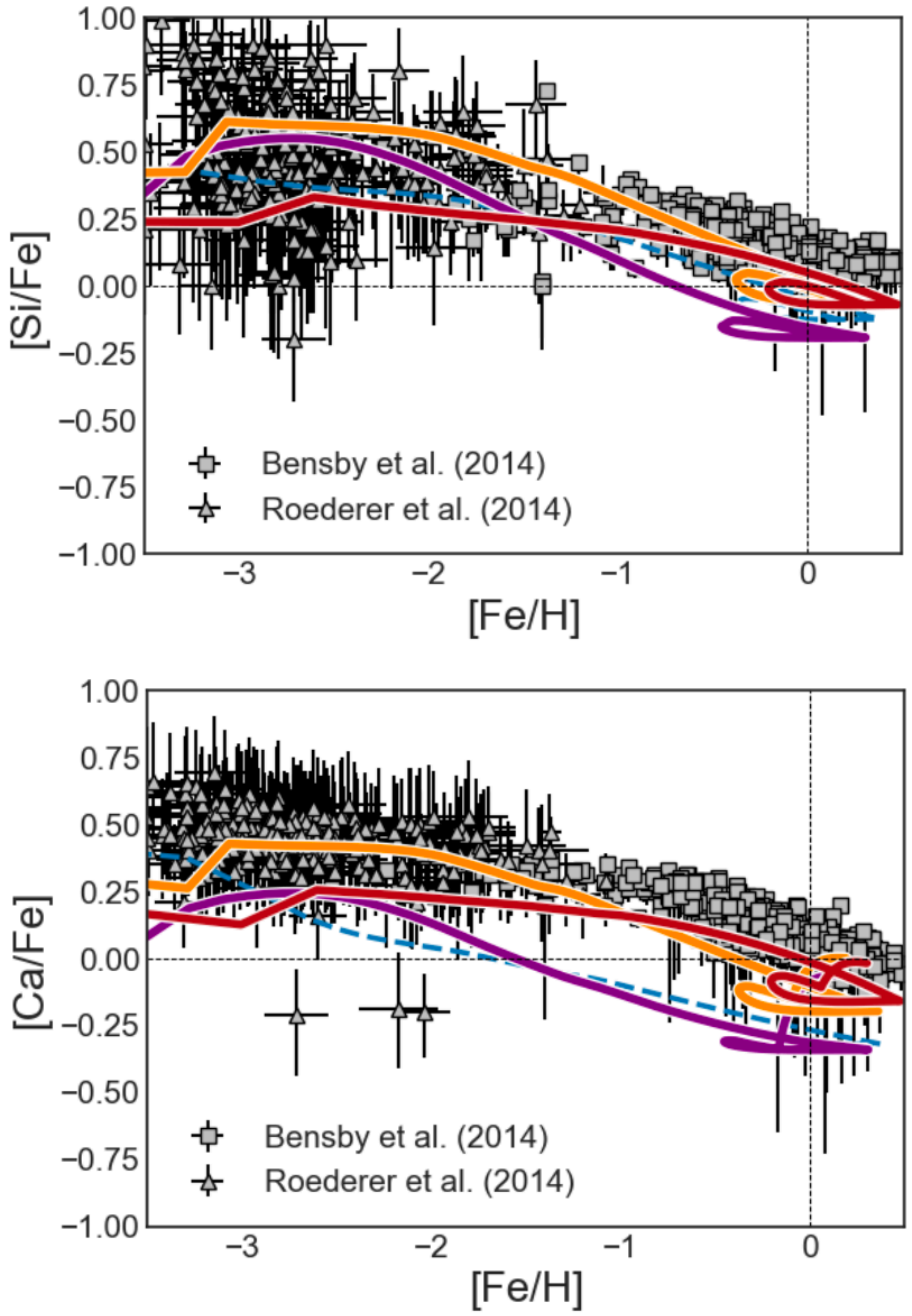
Reduced alpha-network within simulations (Navó et al. 2023)

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

⟶propagate uncertainties from supernova models to GCE

Jost, Molero et al. (2024)





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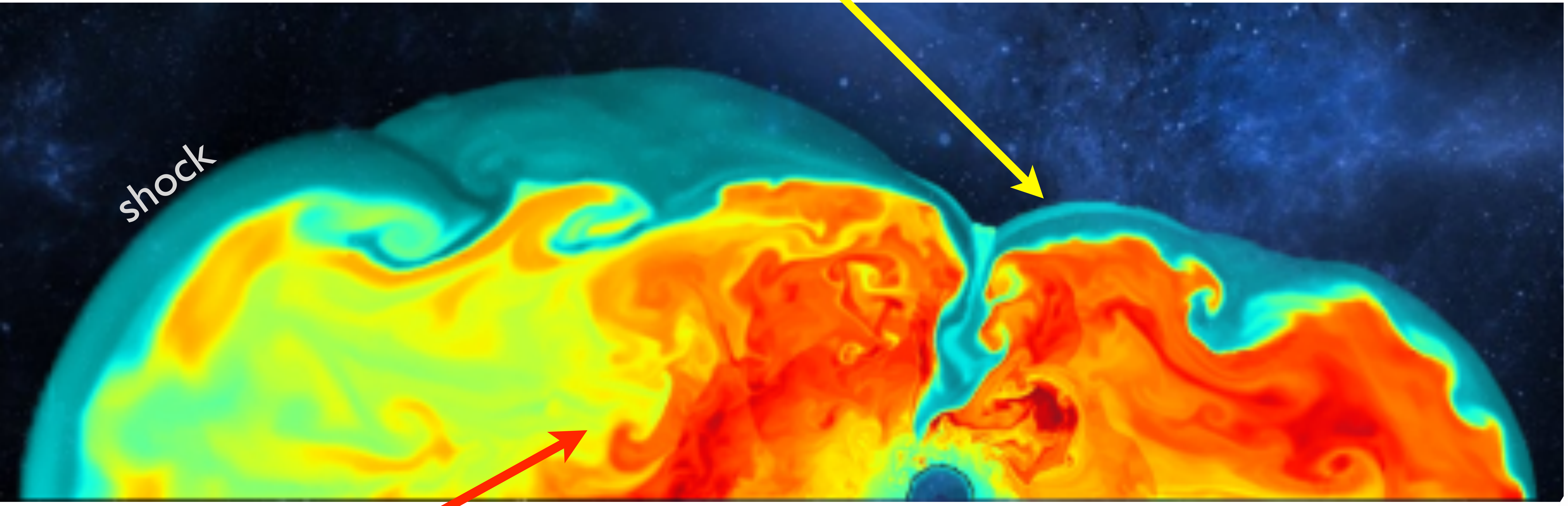

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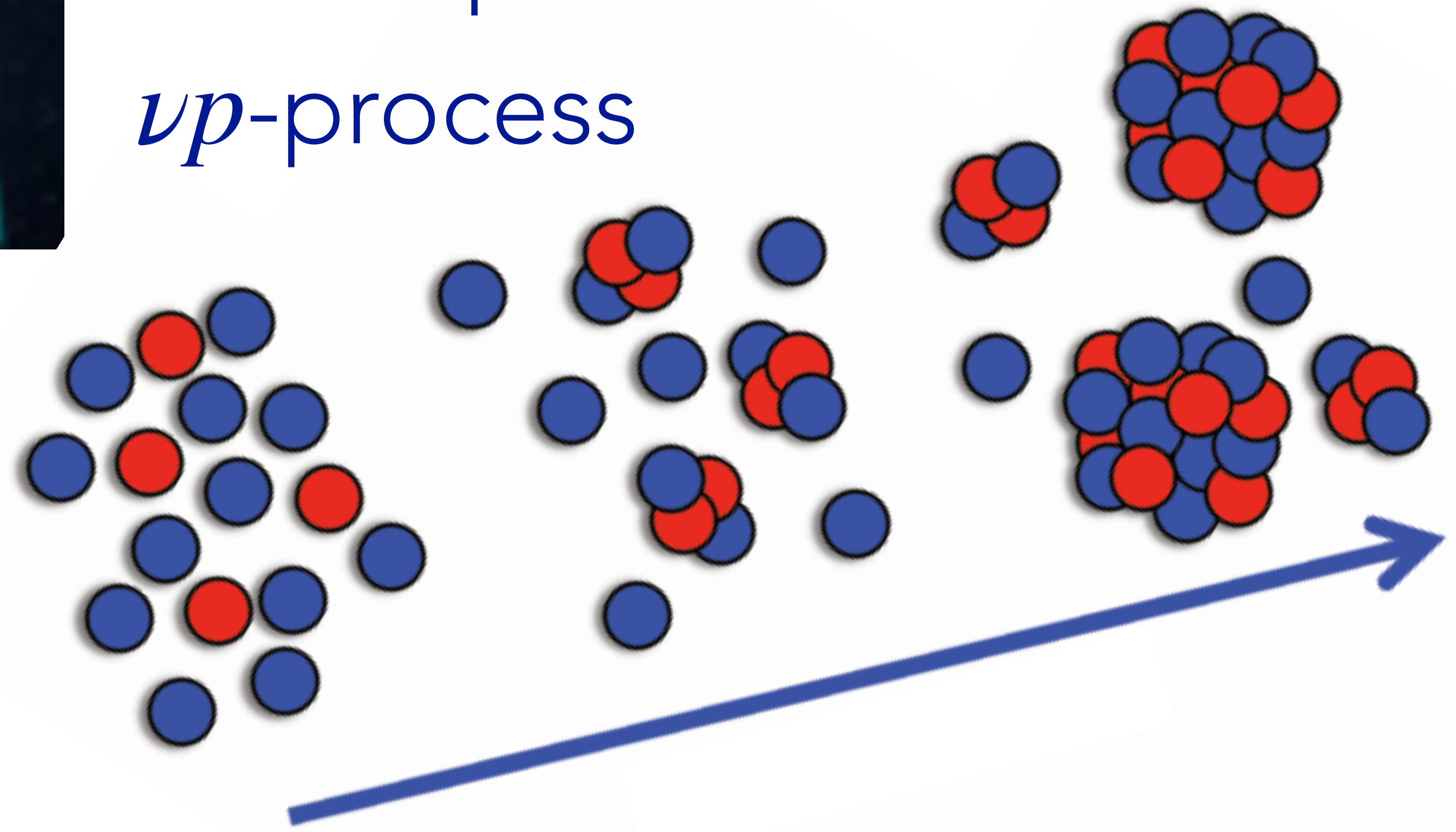

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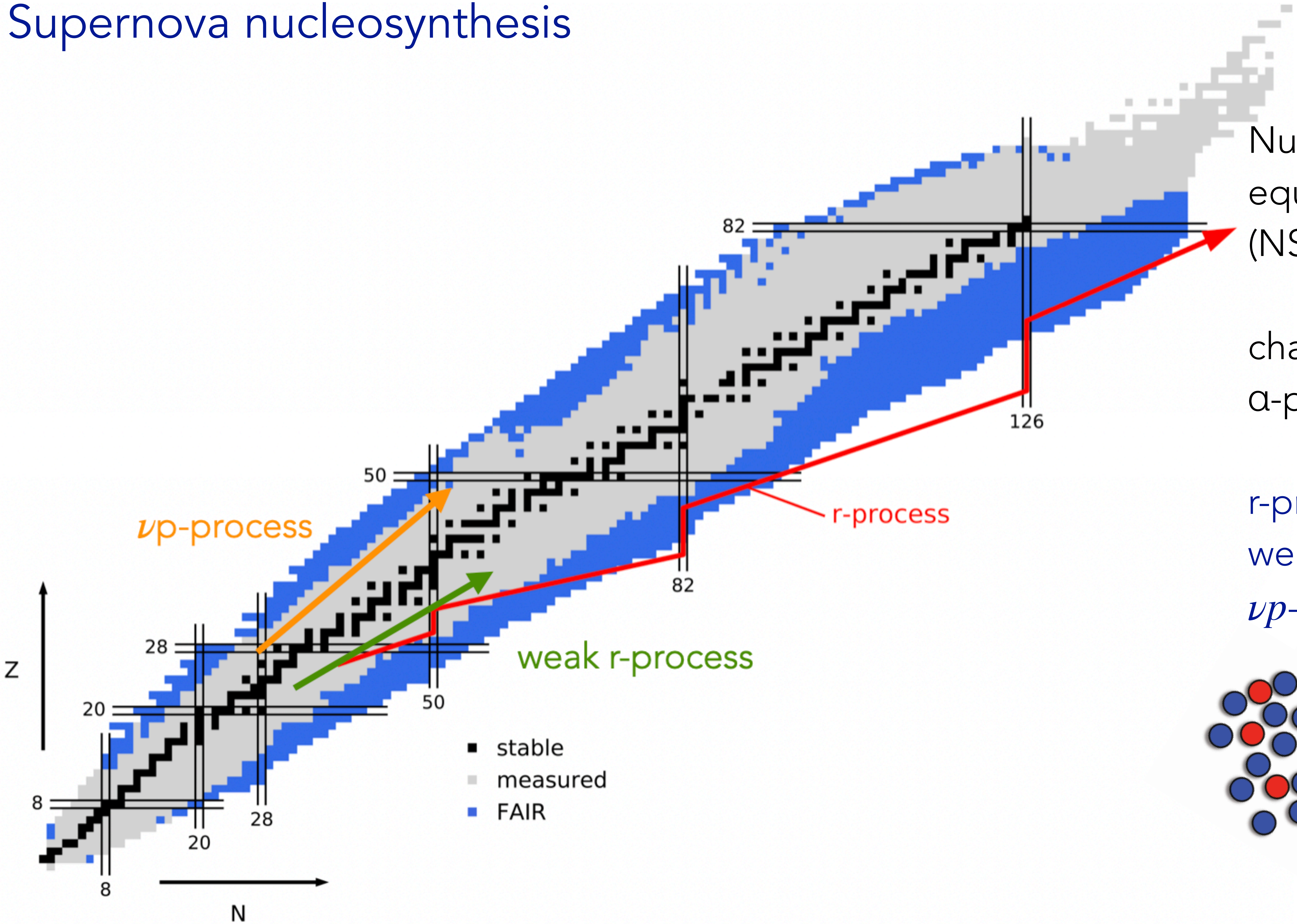

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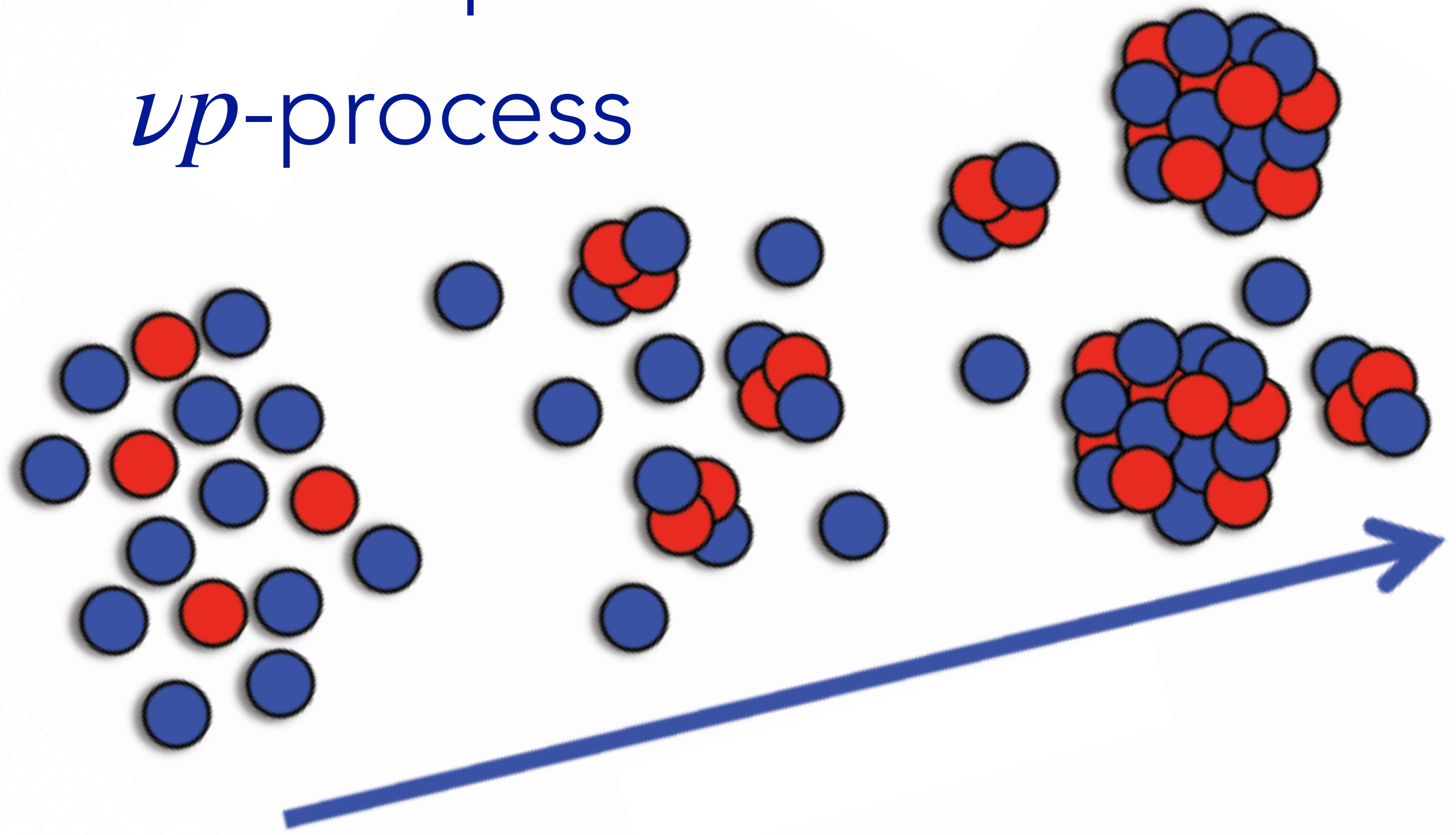


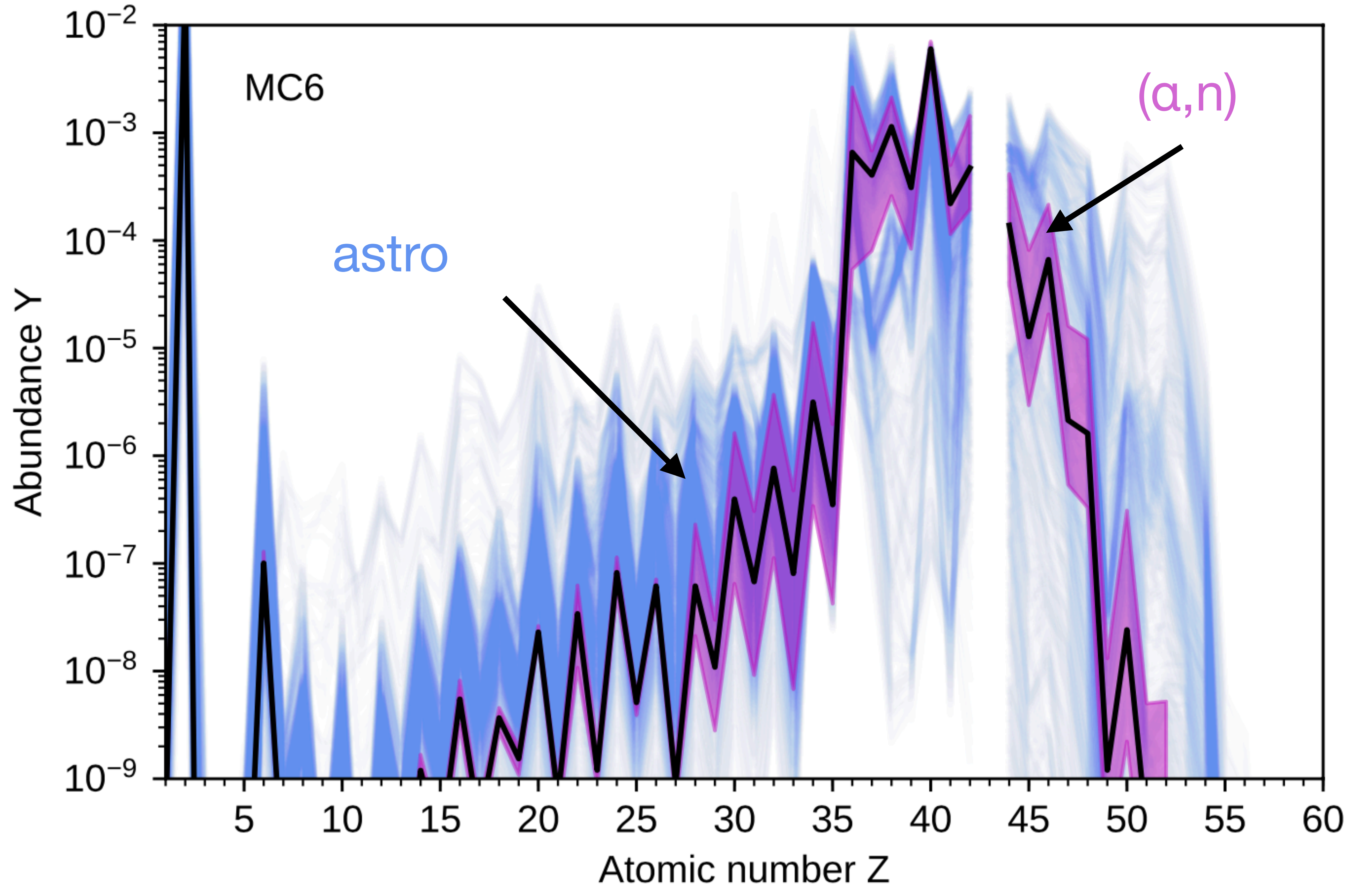
Core-collapse supernova: weak r-process

Neutrino-driven supernovae: elements up to Ag

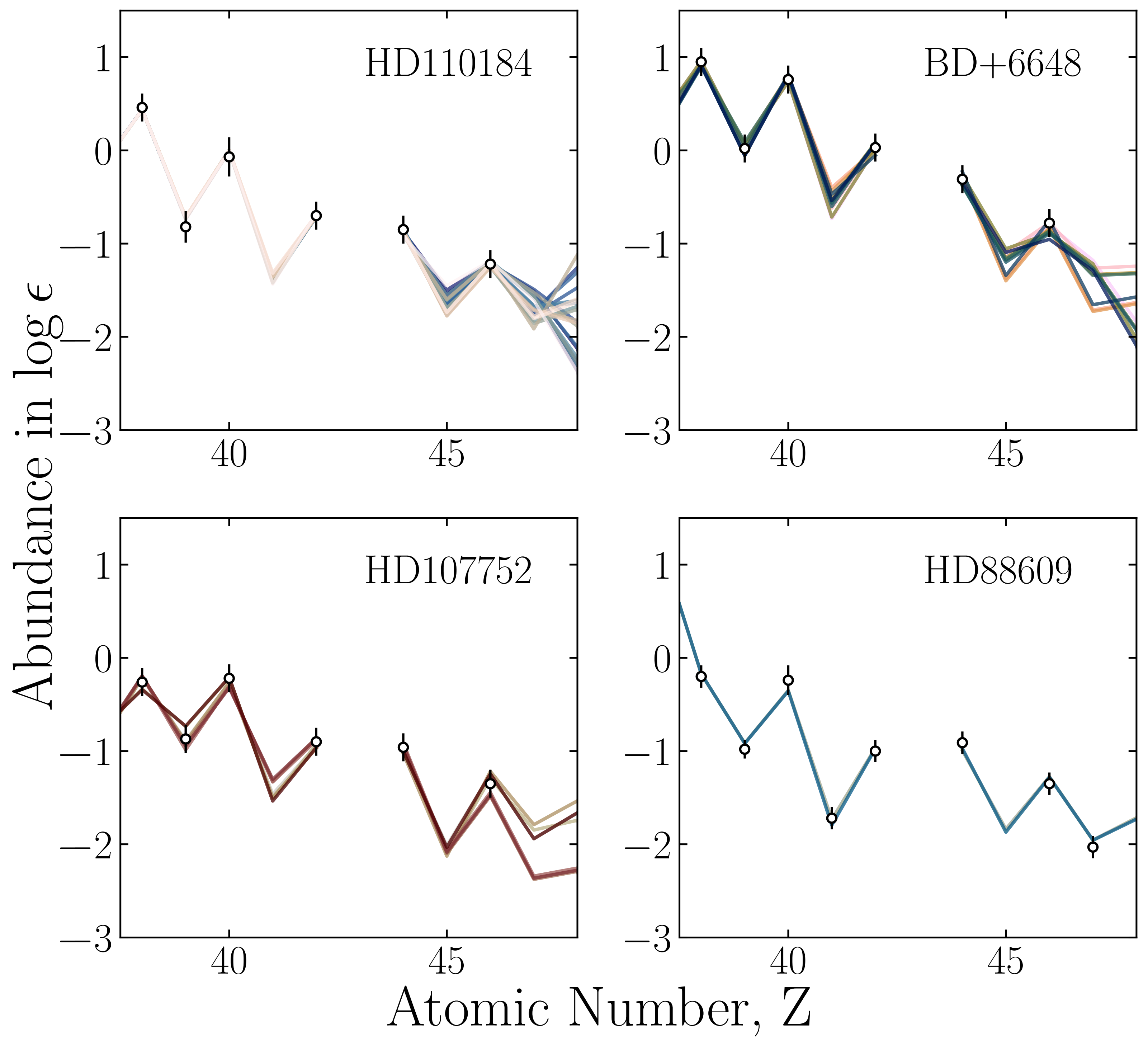
Combine astrophysics and nuclear physics uncertainties

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)



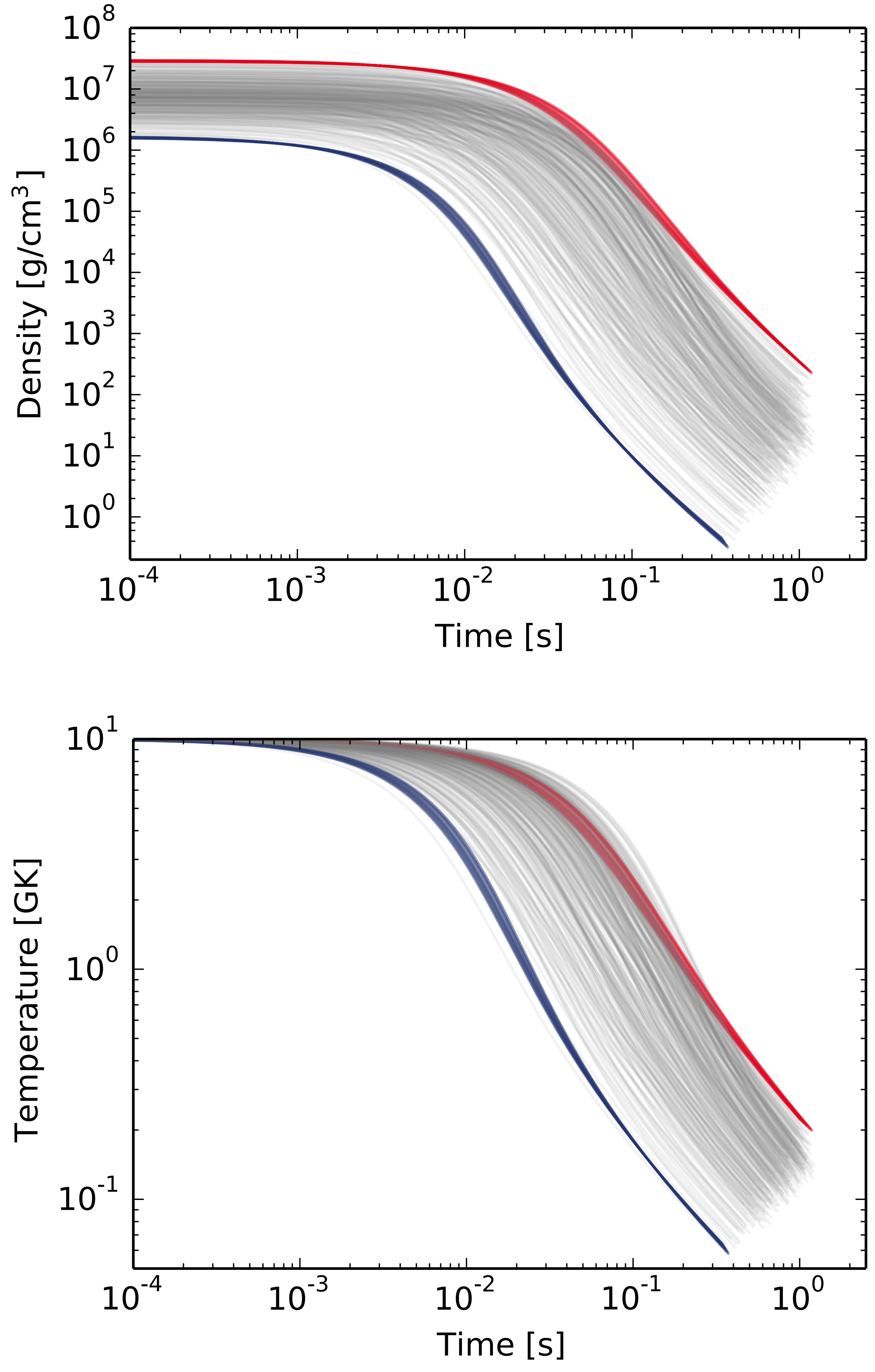
Psaltis et al. ApJ (2022), Psaltis et al. ApJ (2024)



Astrophysics uncertainties/variability

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

Steady-state model: all possible conditions and nucleosynthesis pattern in neutrino-driven ejecta



Based on Otsuki et al. 2000: study of 3 000 trajectories

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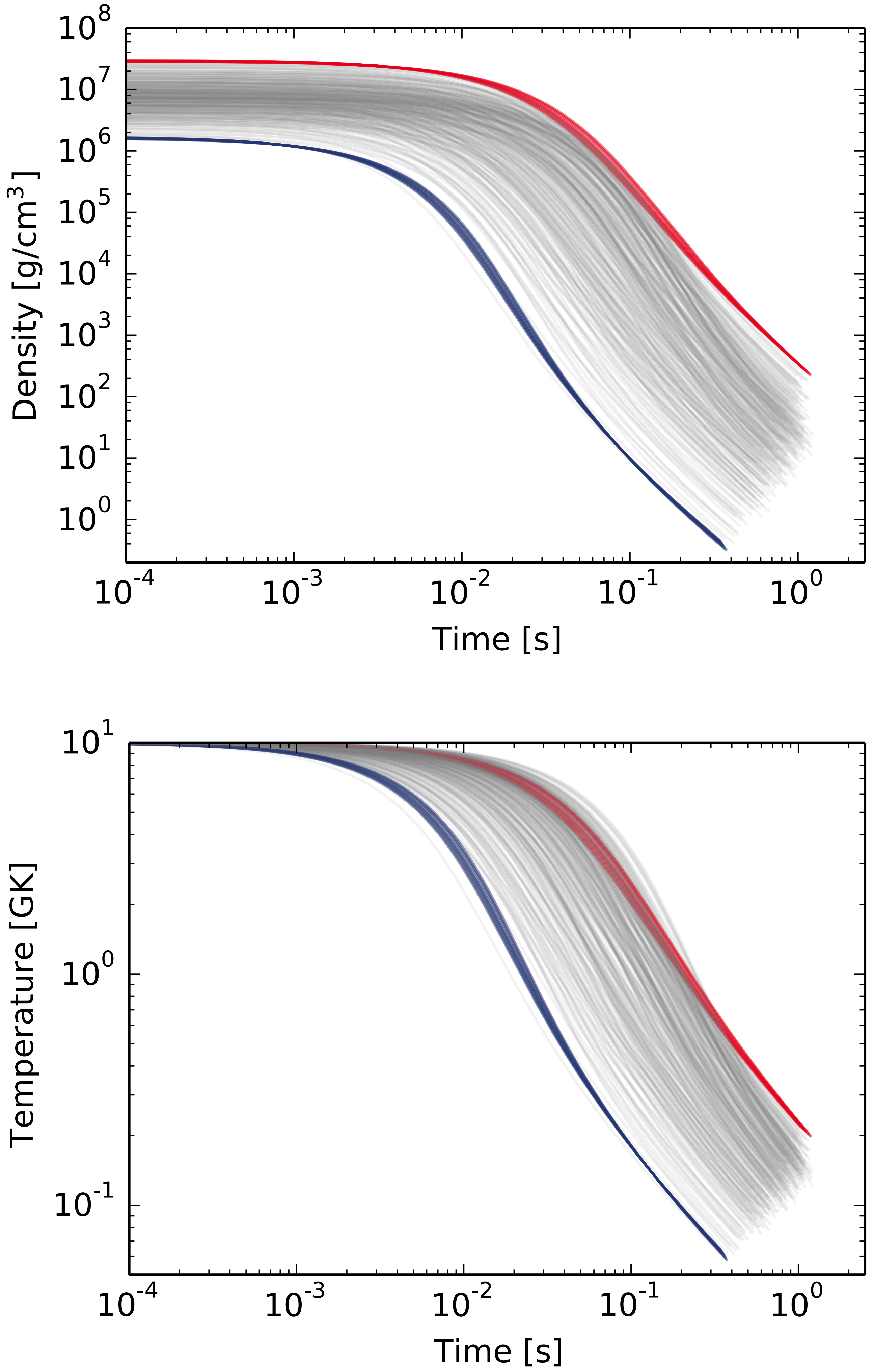
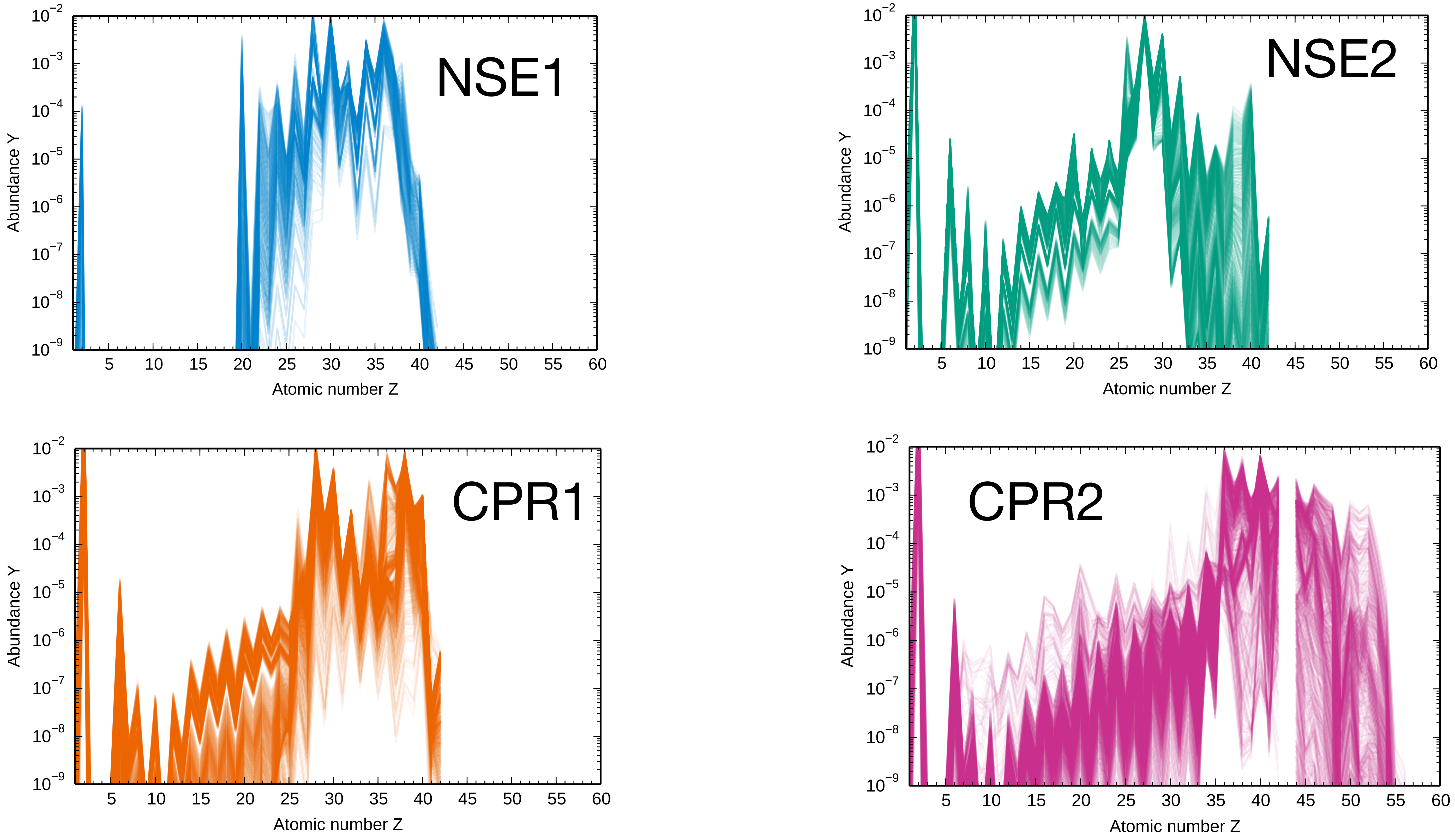


Based on Otsuki et al. 2000: study of 3 000 trajectories

Four characteristic patterns



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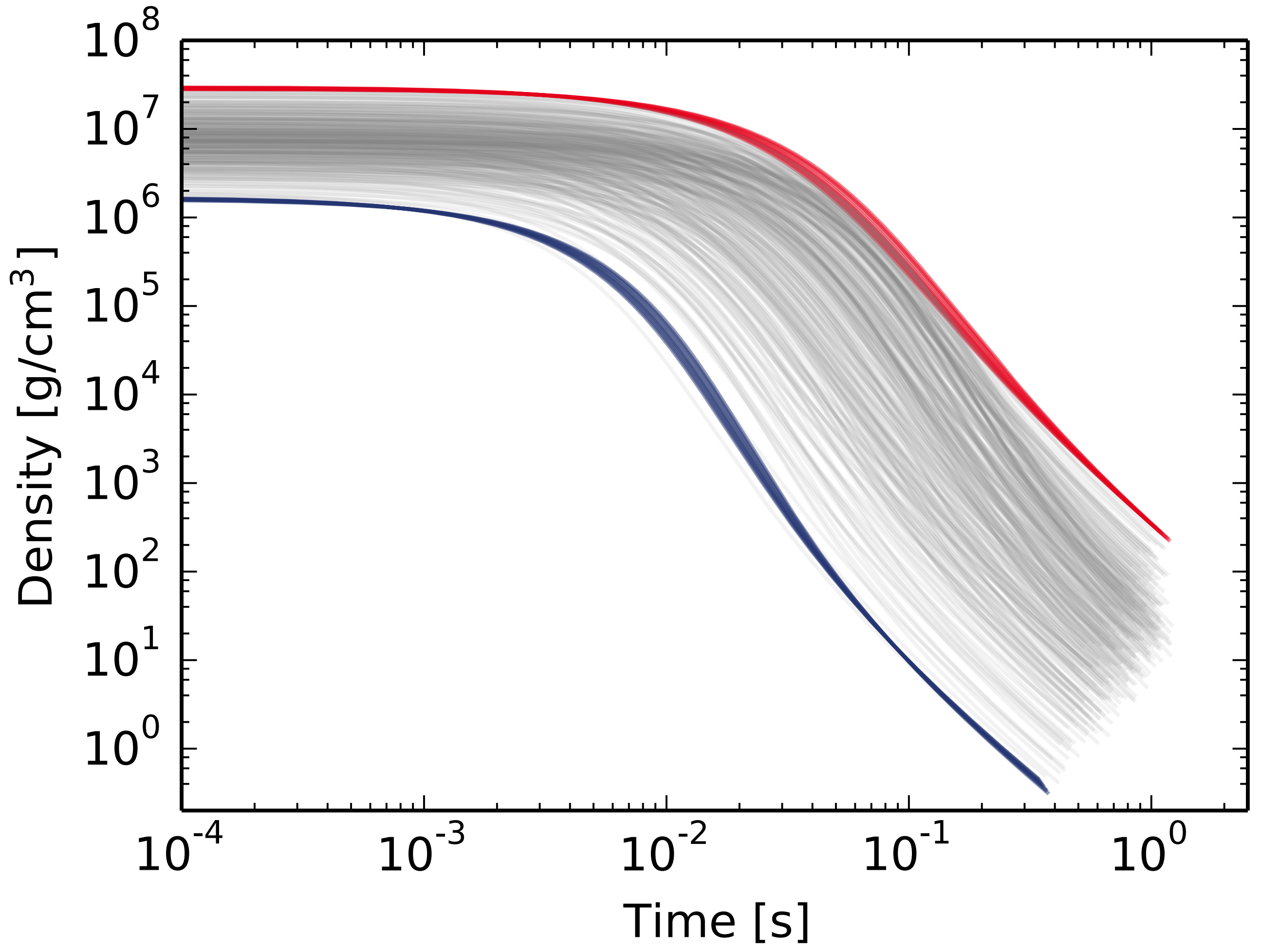

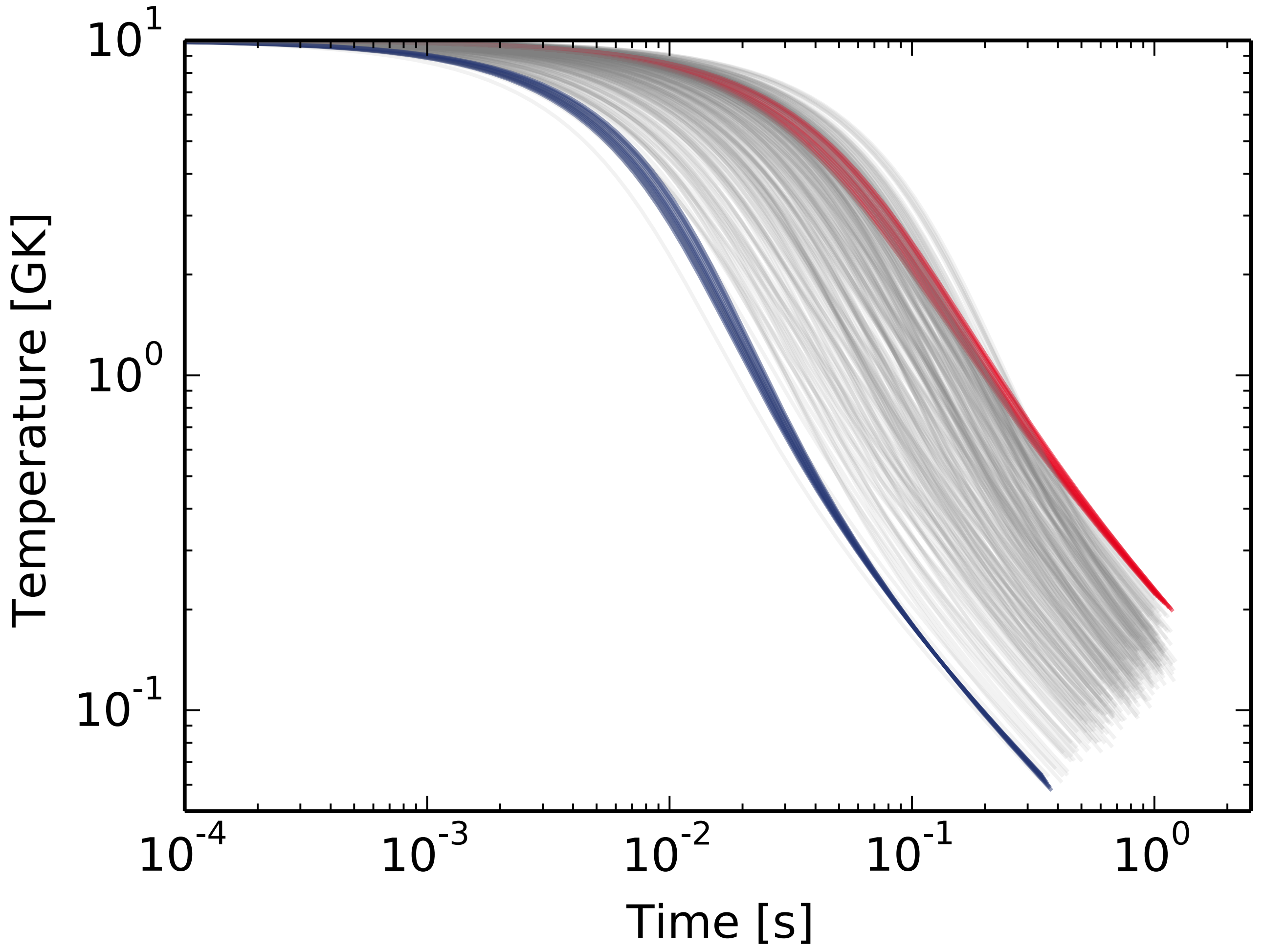

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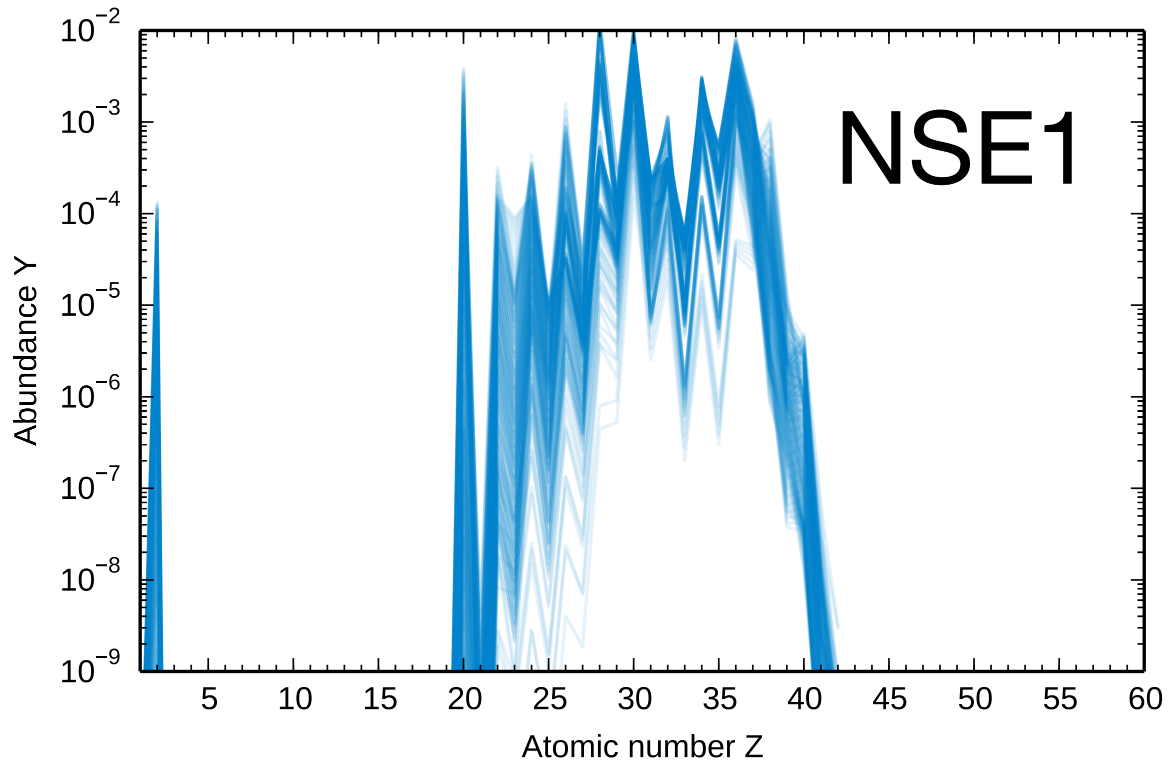
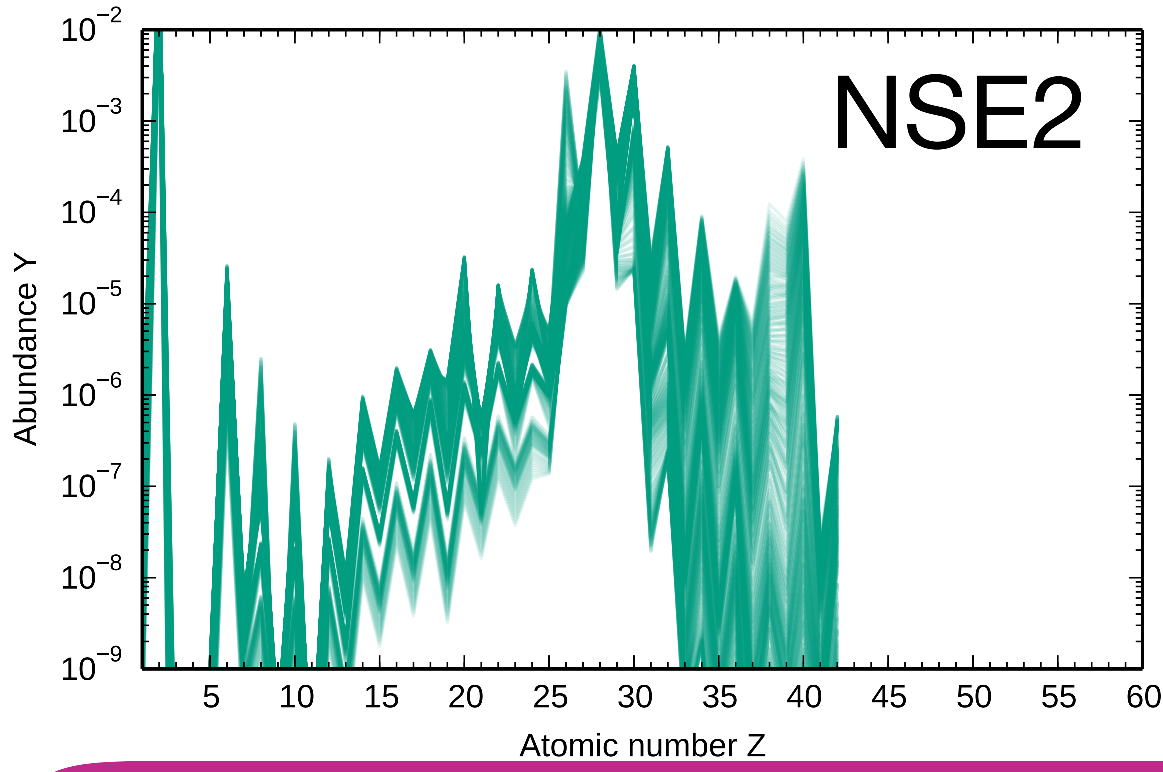
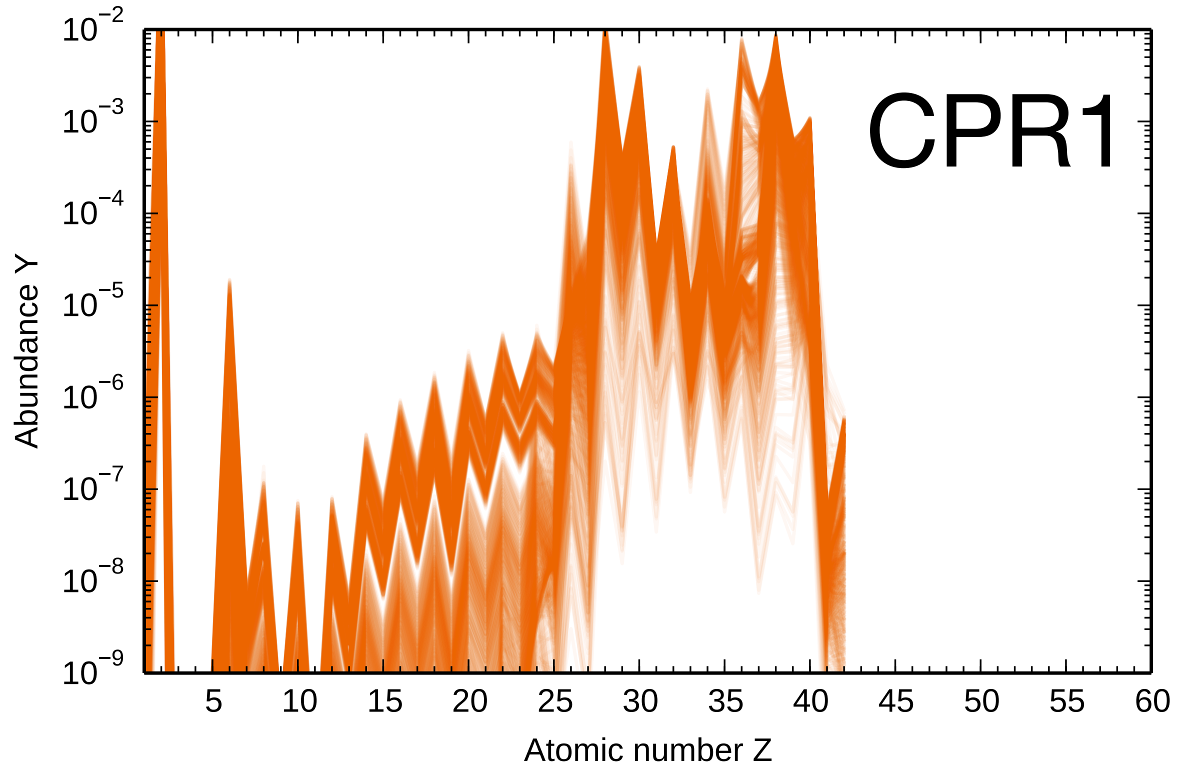
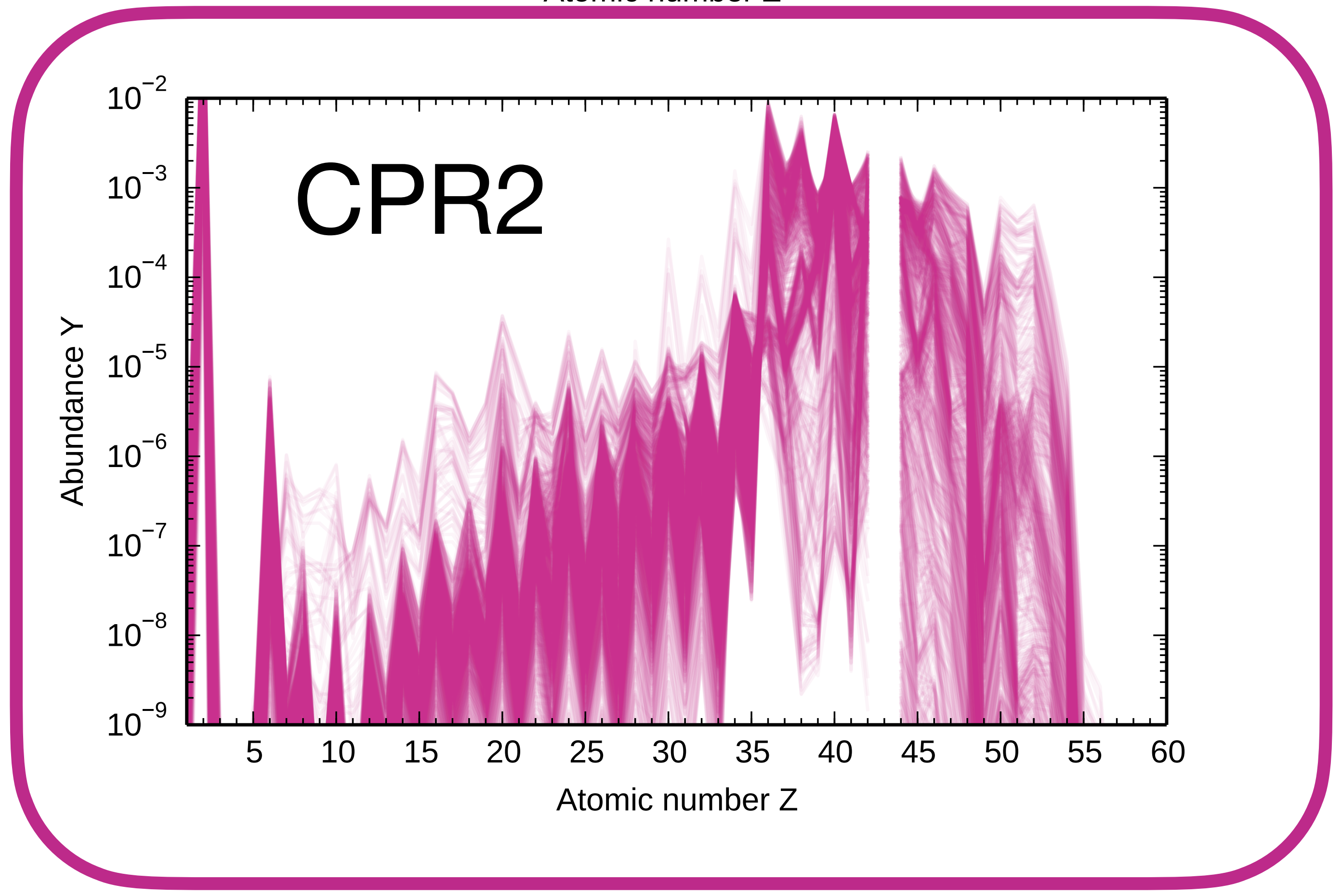




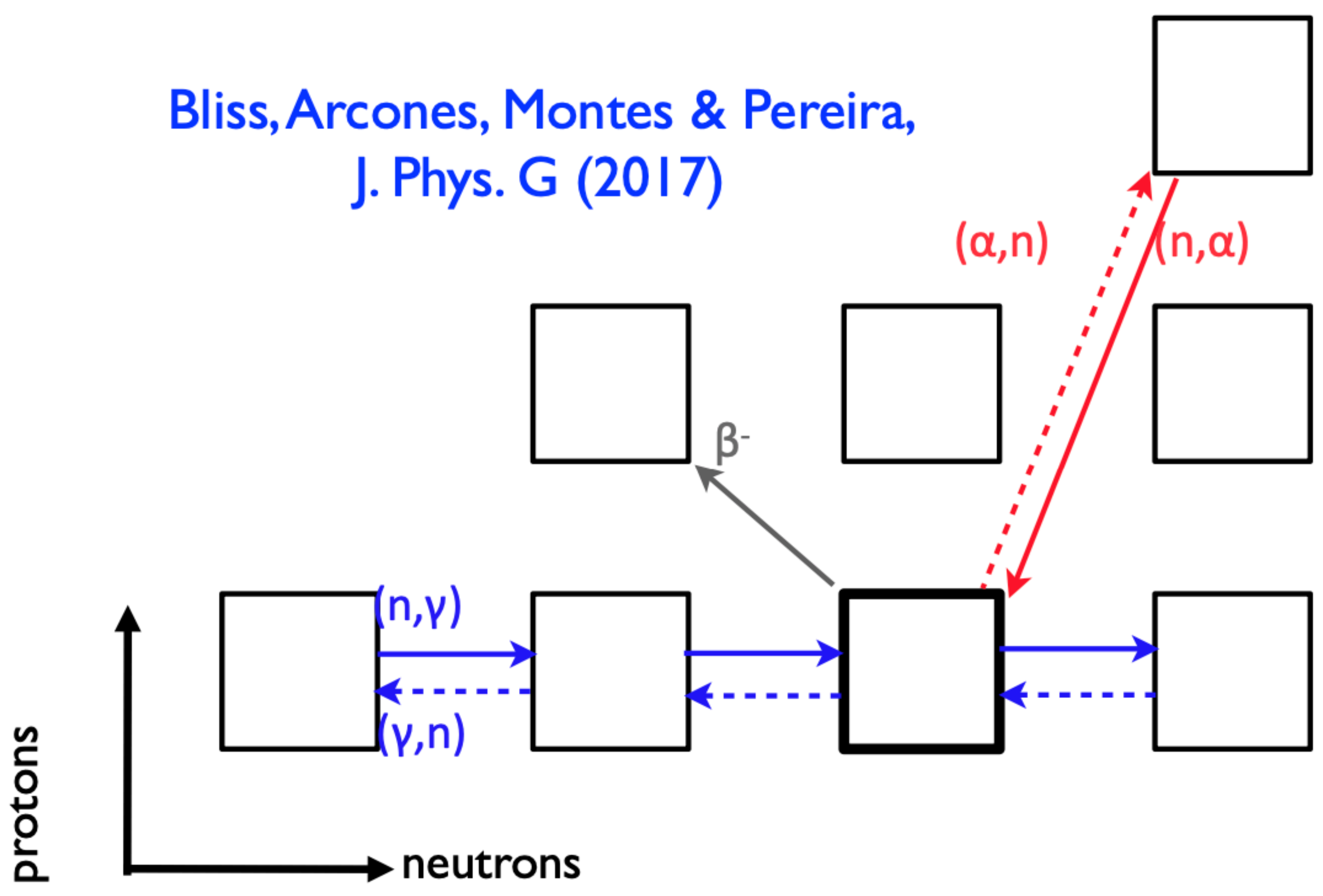


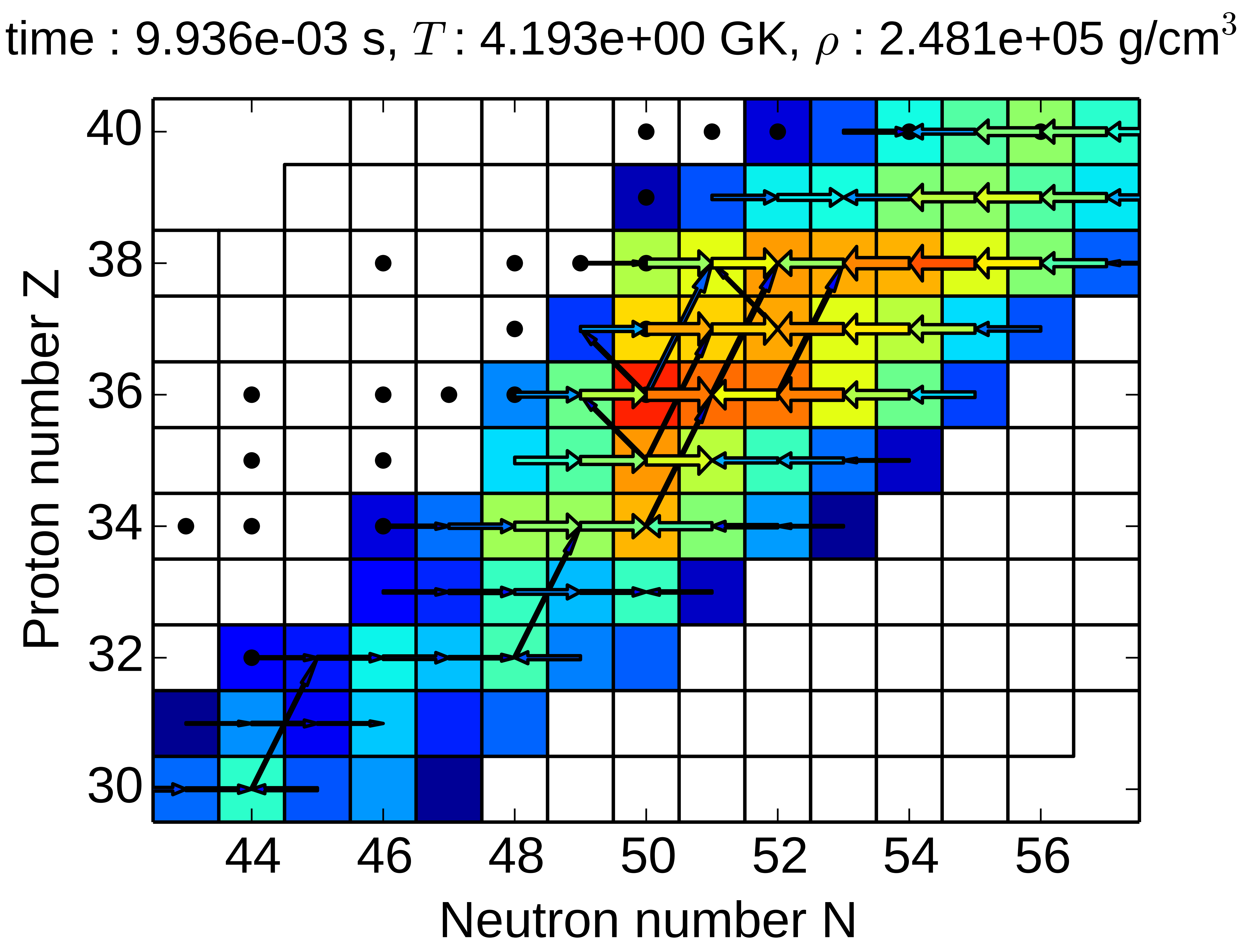


Nuclear physics uncertainty

Path close to stability:

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



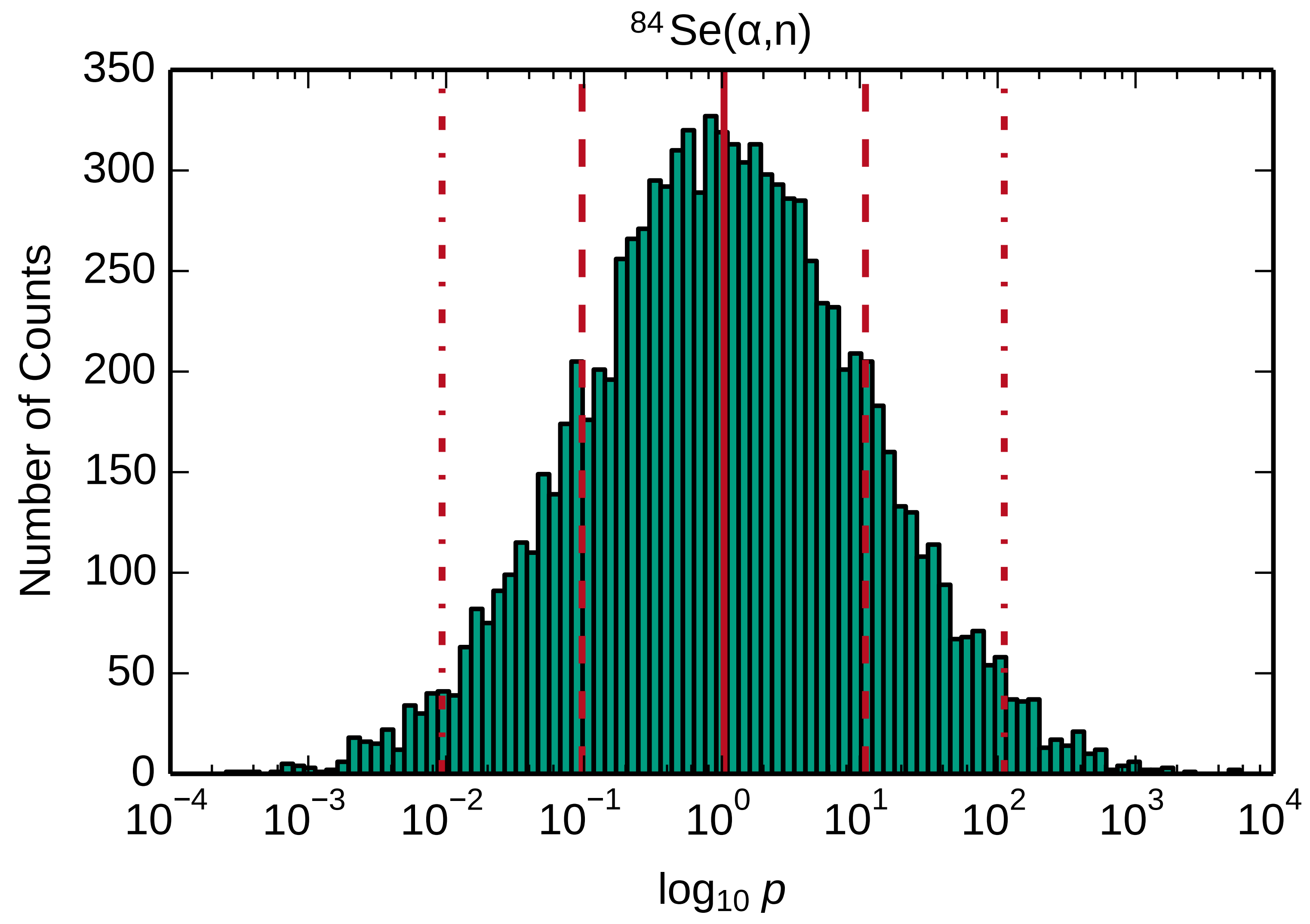


Sensitivity study

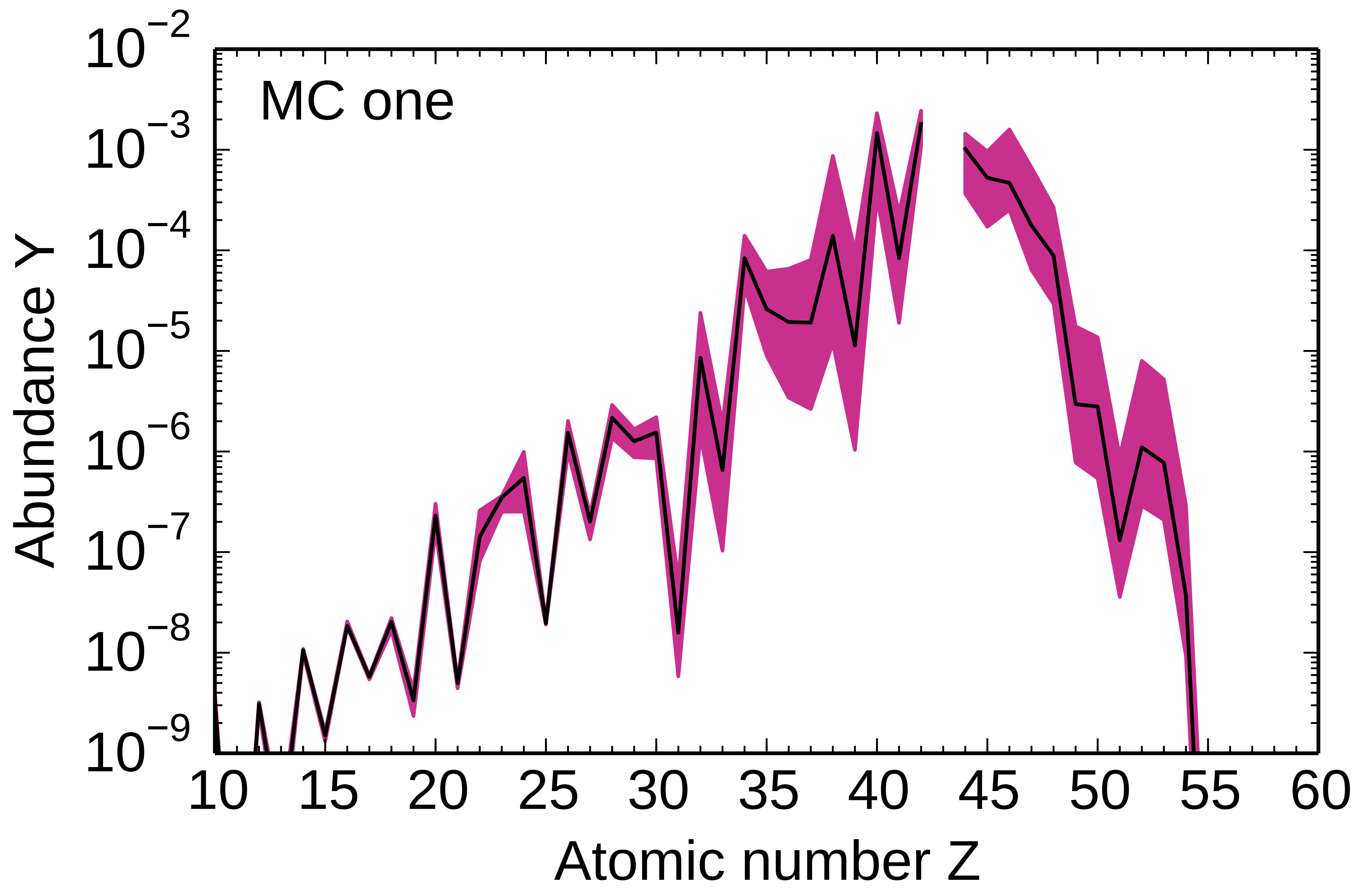
Bliss et al., PRC (2020)

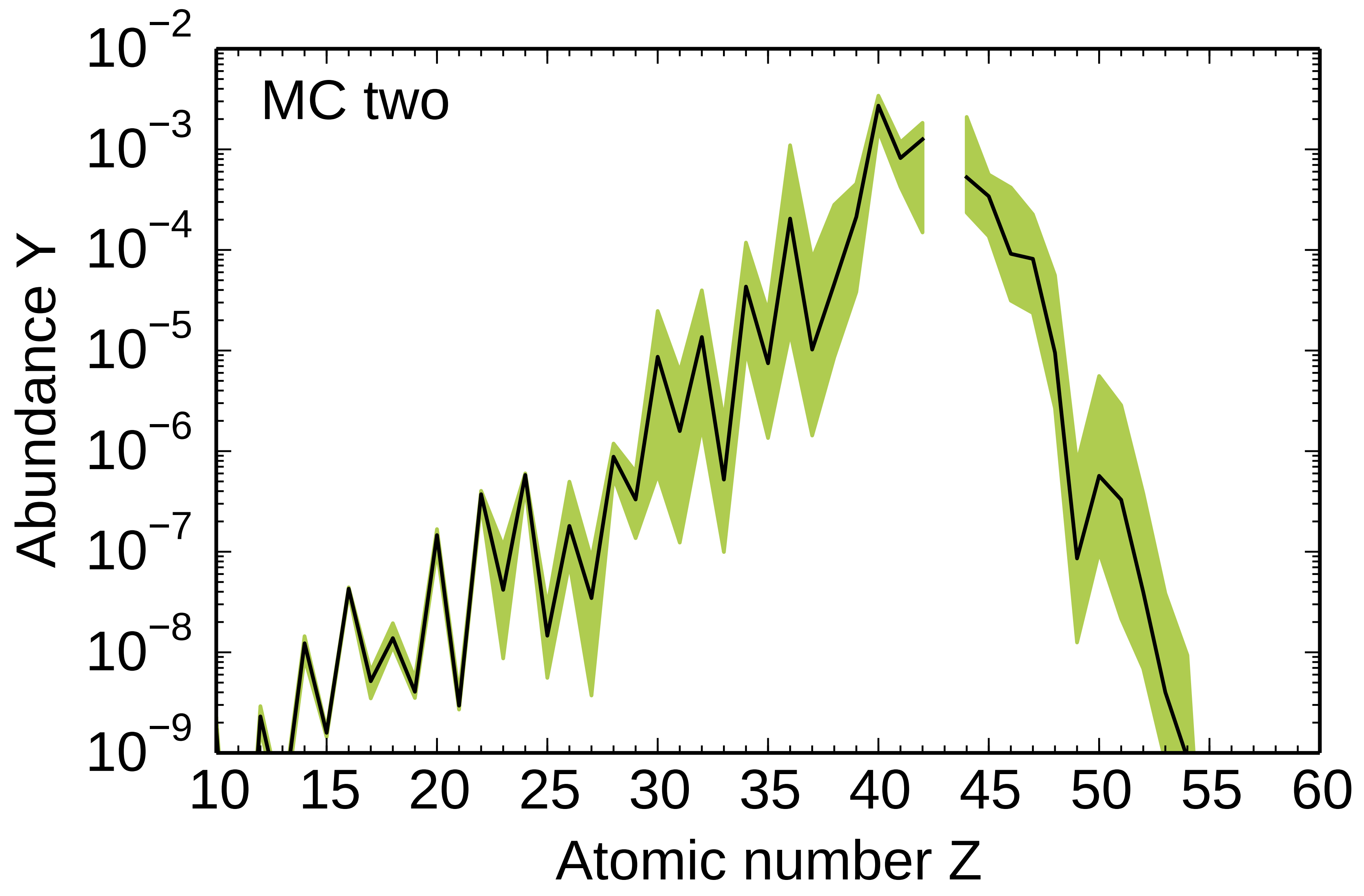
Independently vary each (α,n) reaction rate between Fe and Rh by a random factor

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



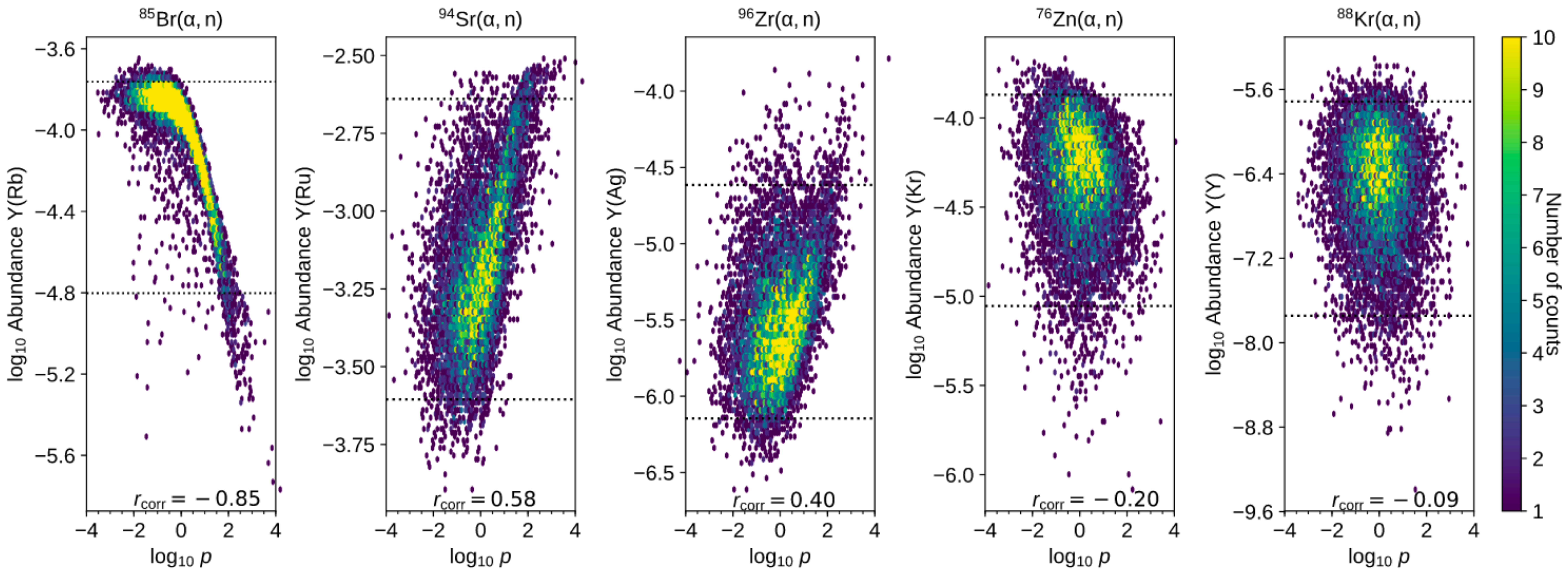
36 representative trajectories of group CPR2,
10 000 Monte Carlo runs





Sensitivity study: key reactions

Bliss et al., PRC (2020)



Spearman rank order correlation

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

→ Monotonic changes

→ $-1 \leq \rho_{\mathrm{corr}} \leq +1$

Sensitivity study: key reactions

Bliss et al., PRC (2020)

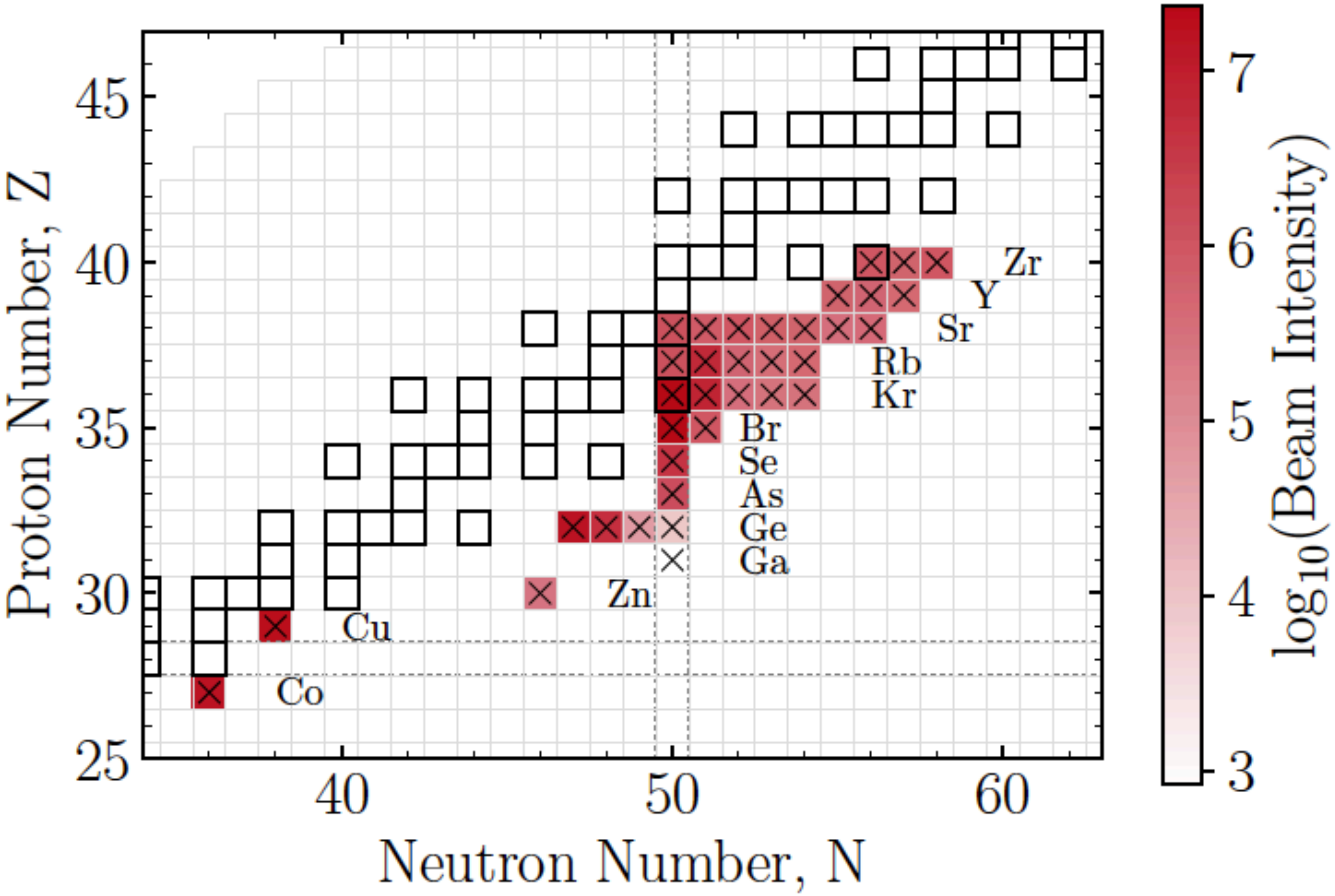
Key reactions ⇒ large correlation + significant impact on abundance for several astro conditions

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

Identify key reactions

Key reactions ⇒ large correlation + significant impact on abundance ratios

Psaltis et al., ApJ (2022)



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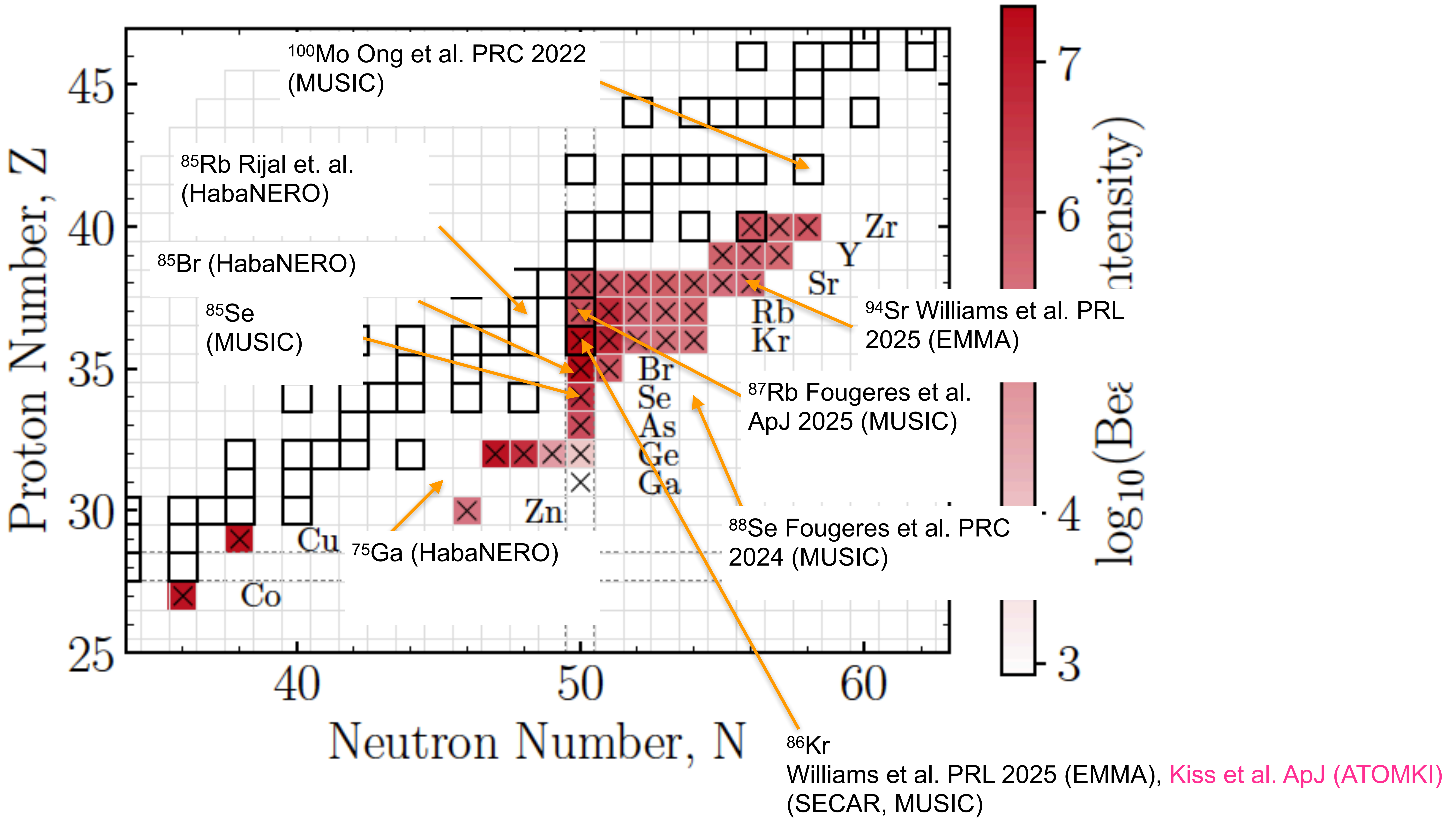
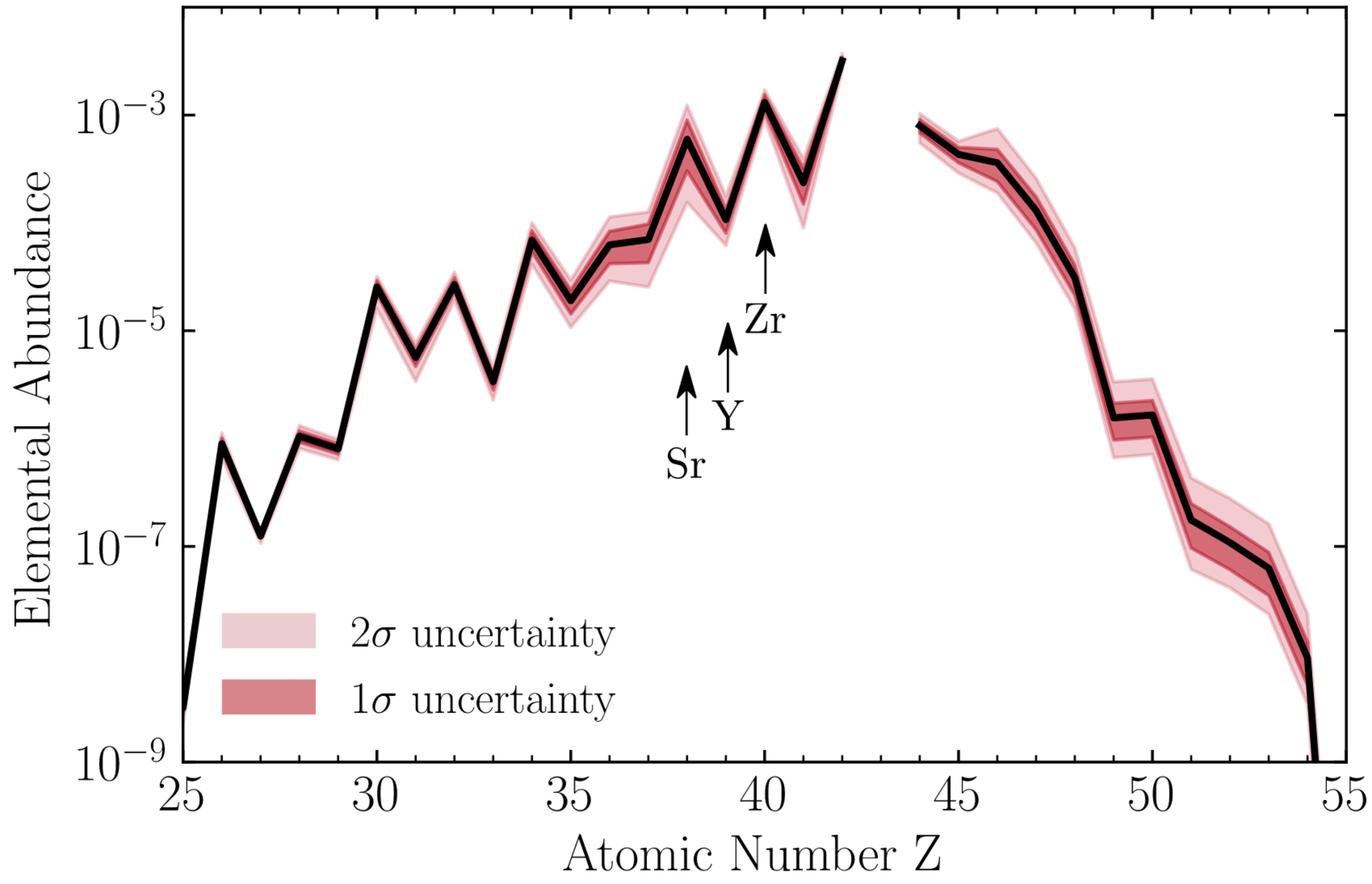
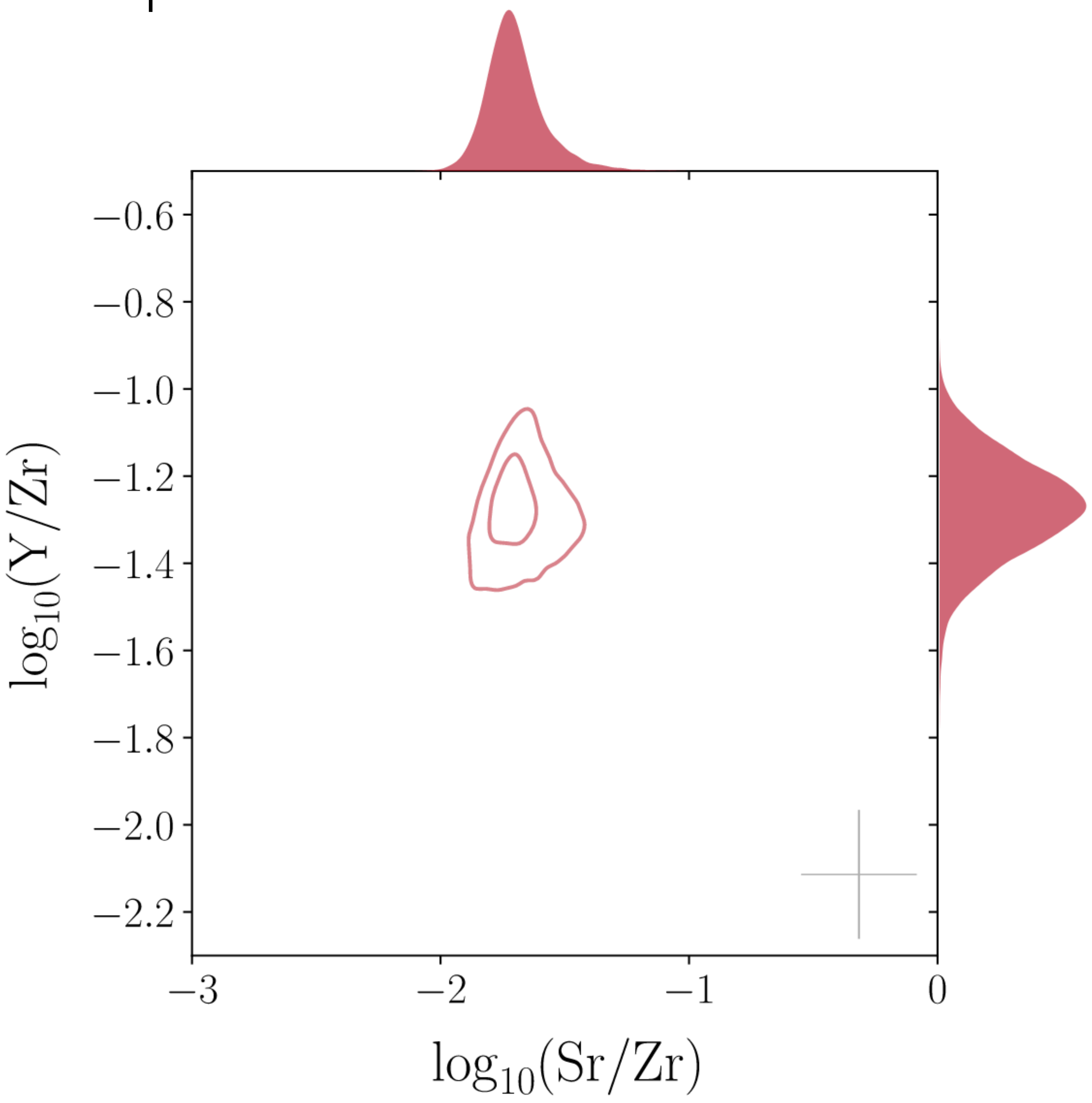


Comparison to observations

Psaltis et al., ApJ (2022)

Abundance with uncertainties for several astro conditions ⟶ compare abundance ratios





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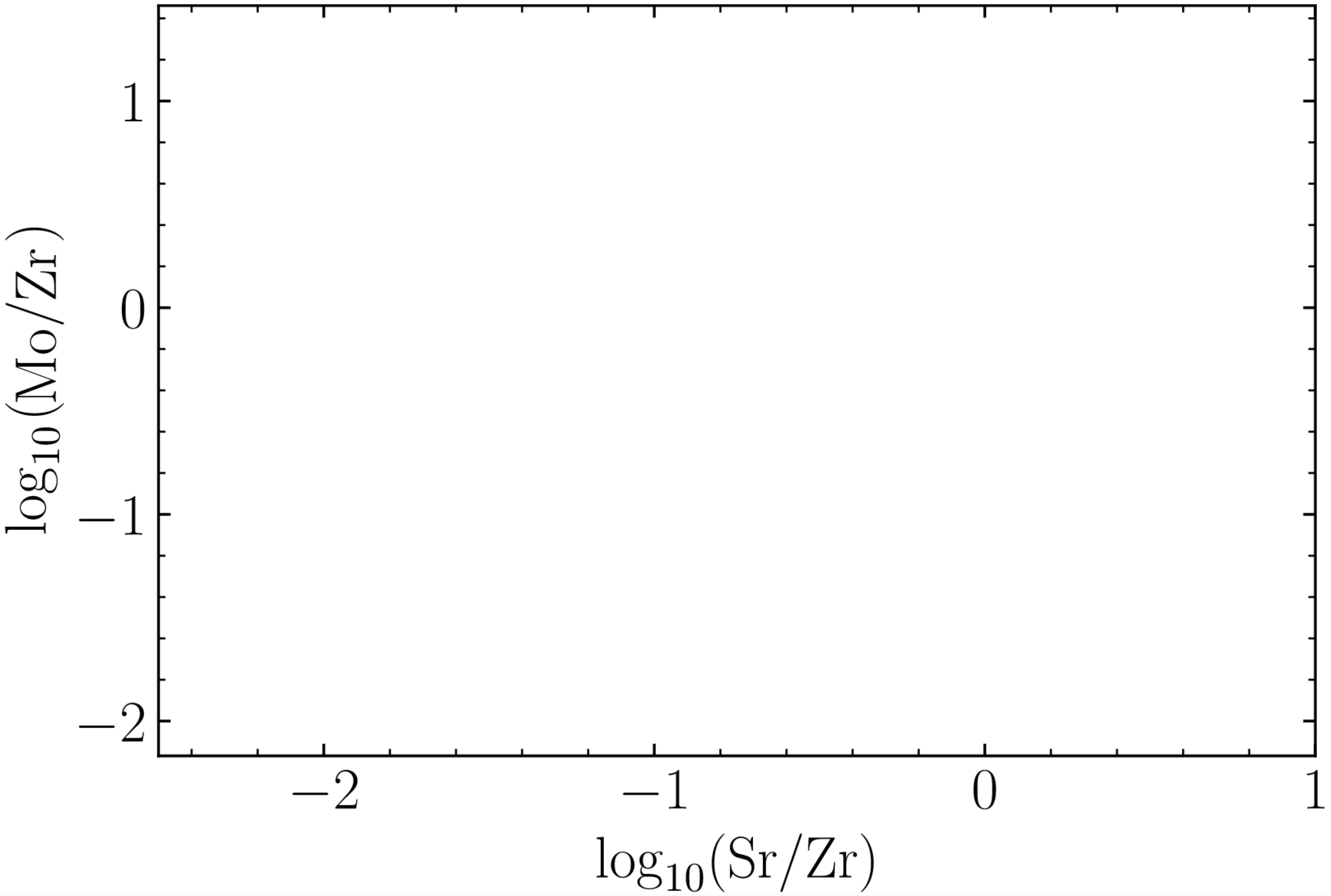

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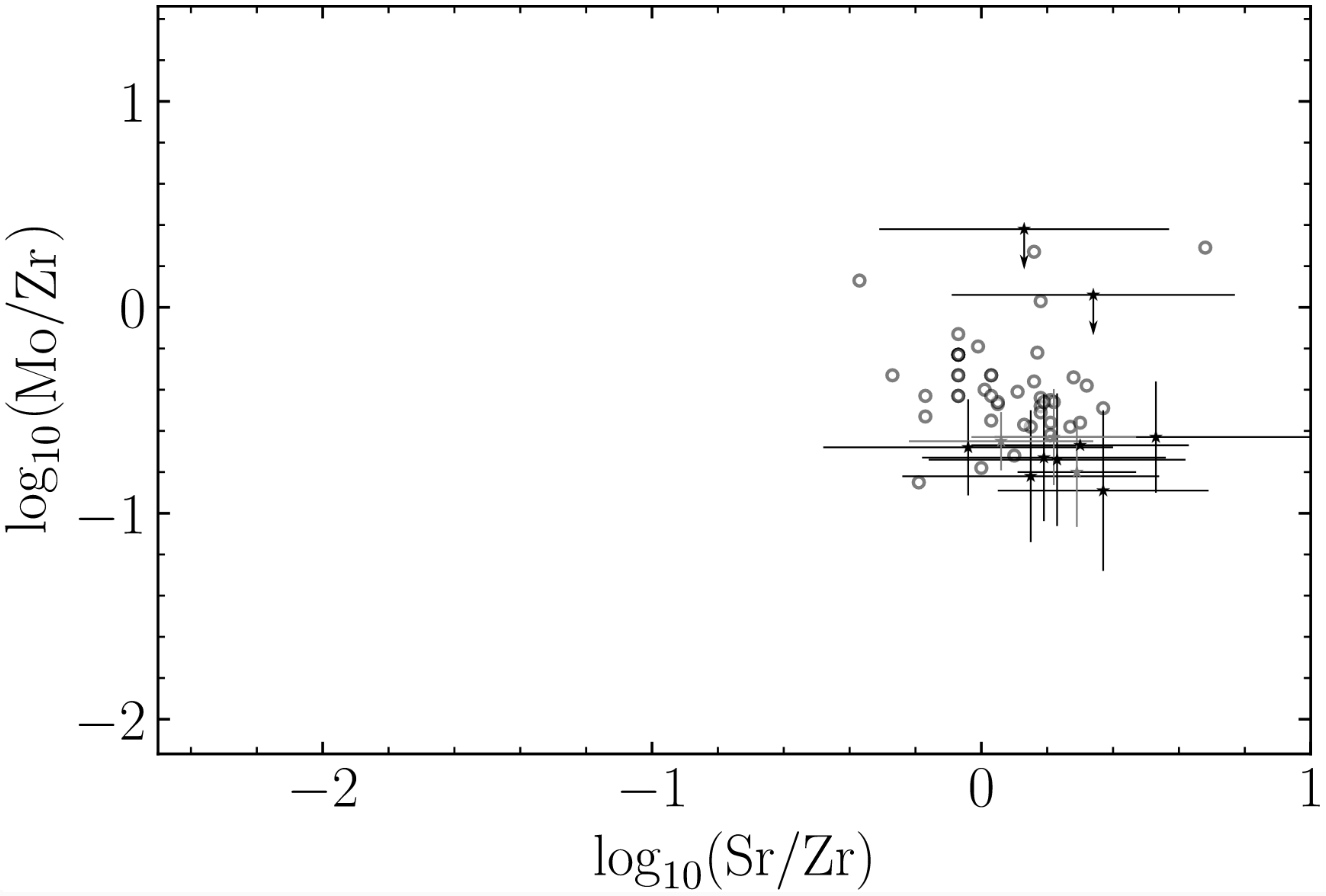

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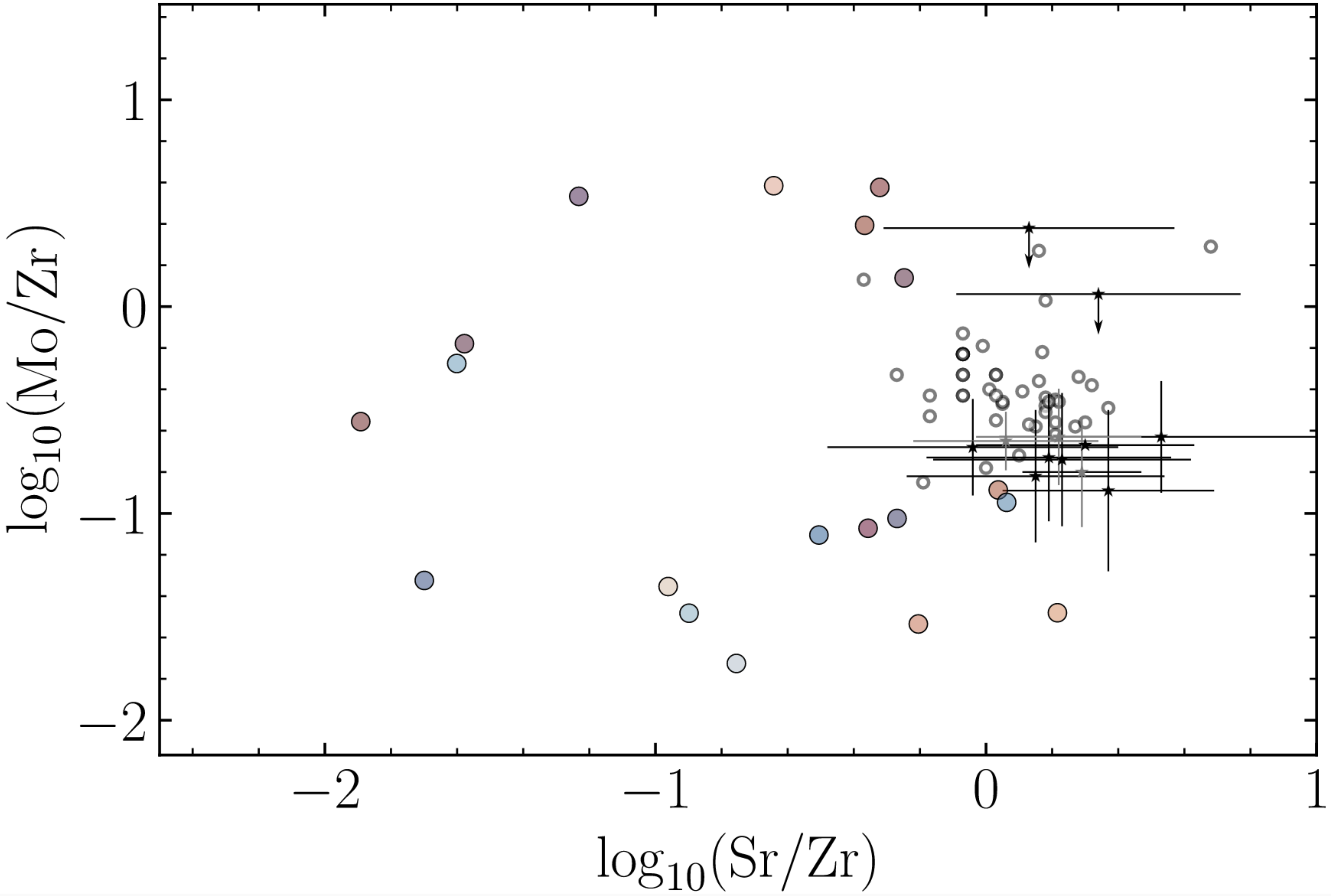

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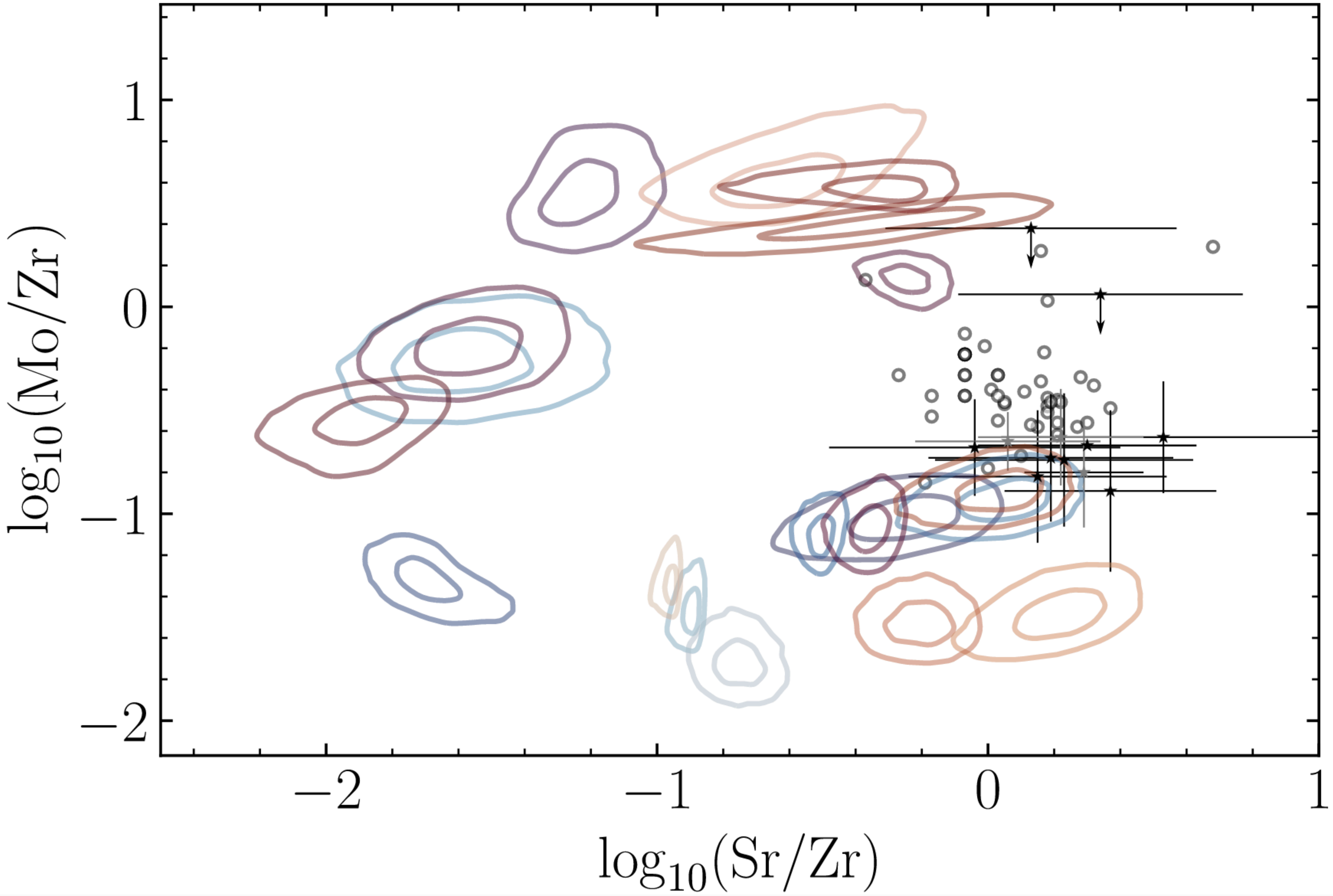
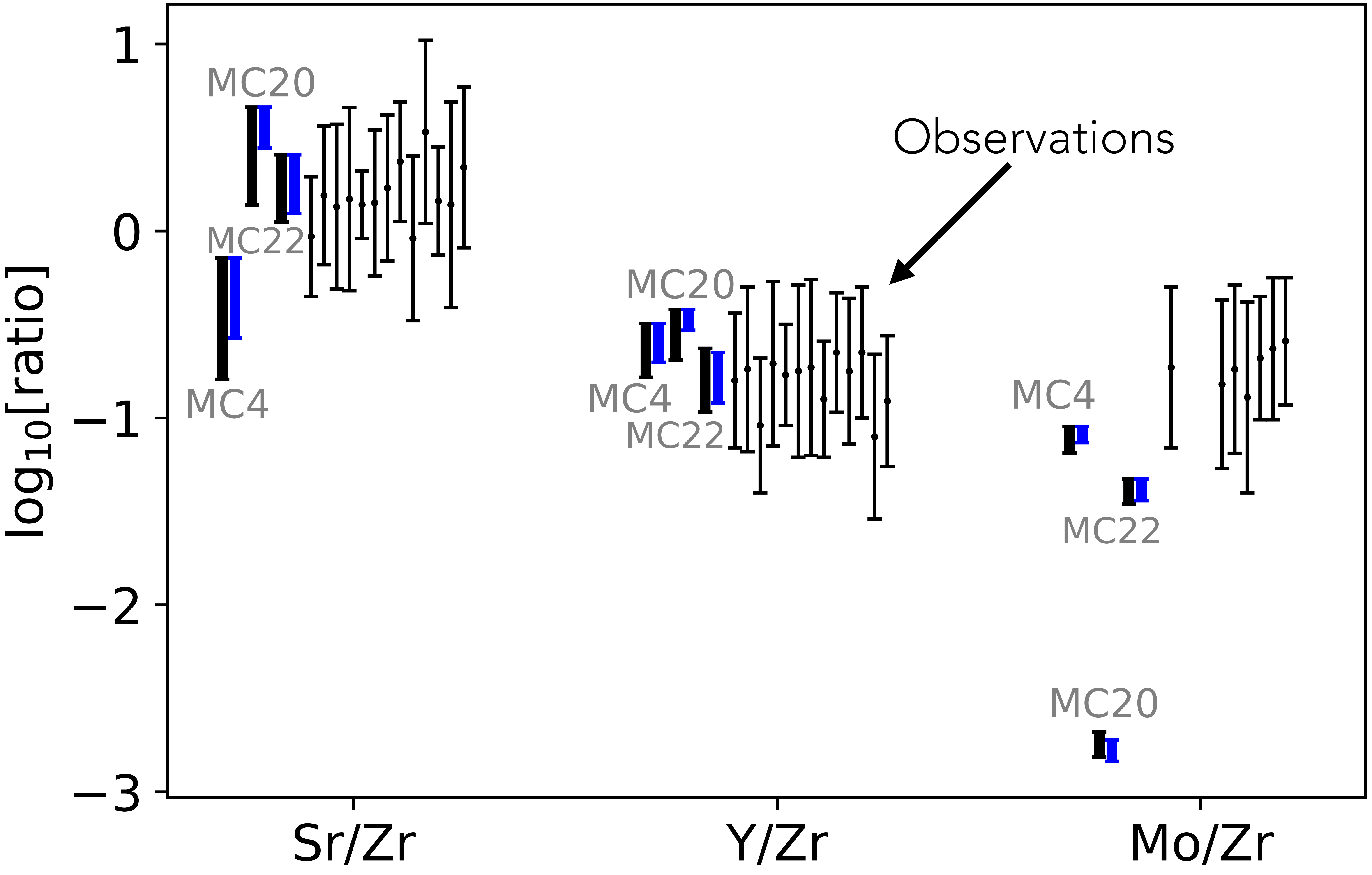


Comparison to observations

Kiss et al., ApJ (2025)

ATOMKI experiment for $^{86}Kr\ (\alpha,n)^{89}Sr$ ⟶ one reaction enough to reduce nuclear uncertainty



All (α,n) same uncertainty

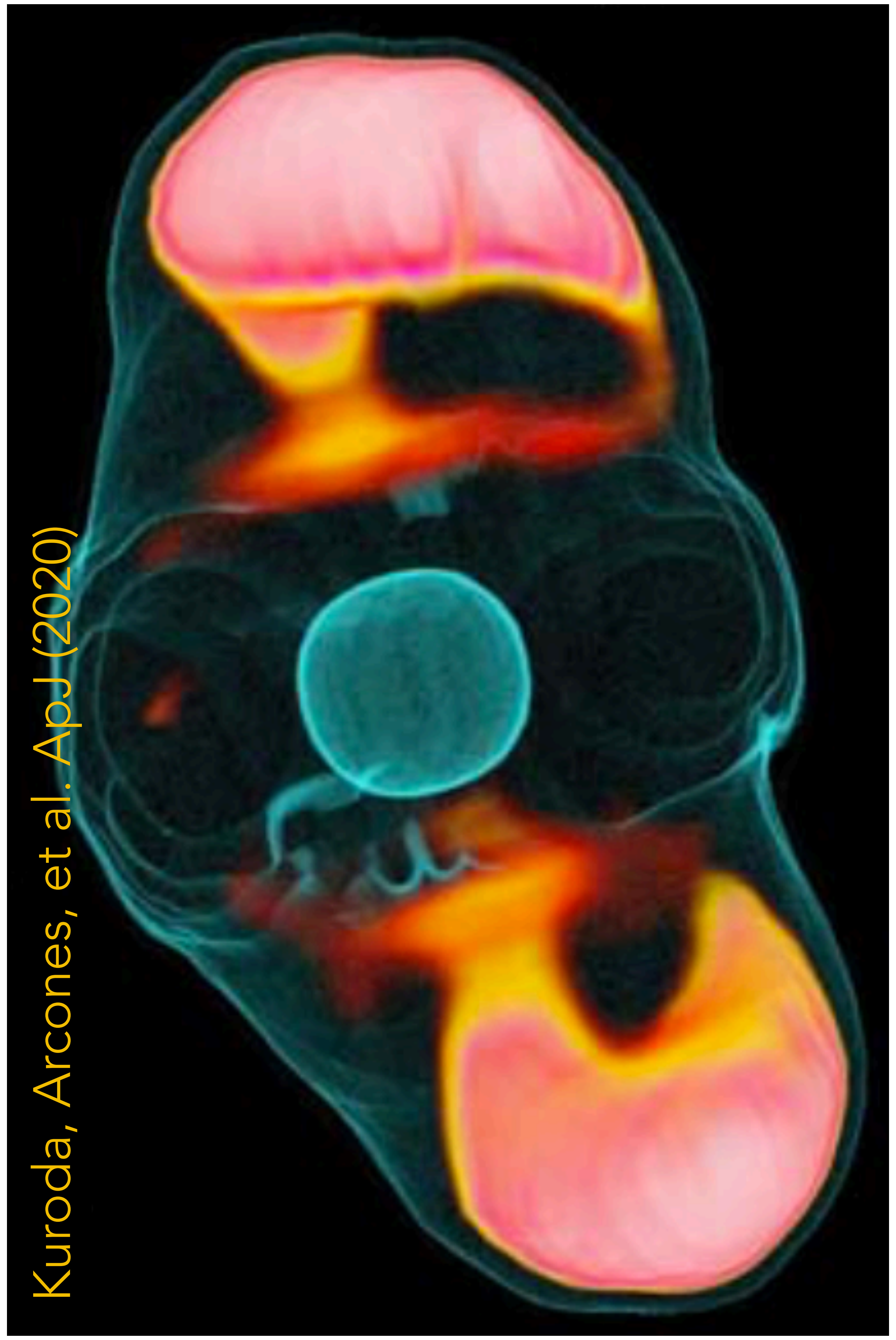
Uncertainty of $^{86}Kr\ (\alpha,n)^{89}Sr$ reduced by new experiment

Magneto-rotational supernovae

Kuroda, Arcones

r-process in supernovae?

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



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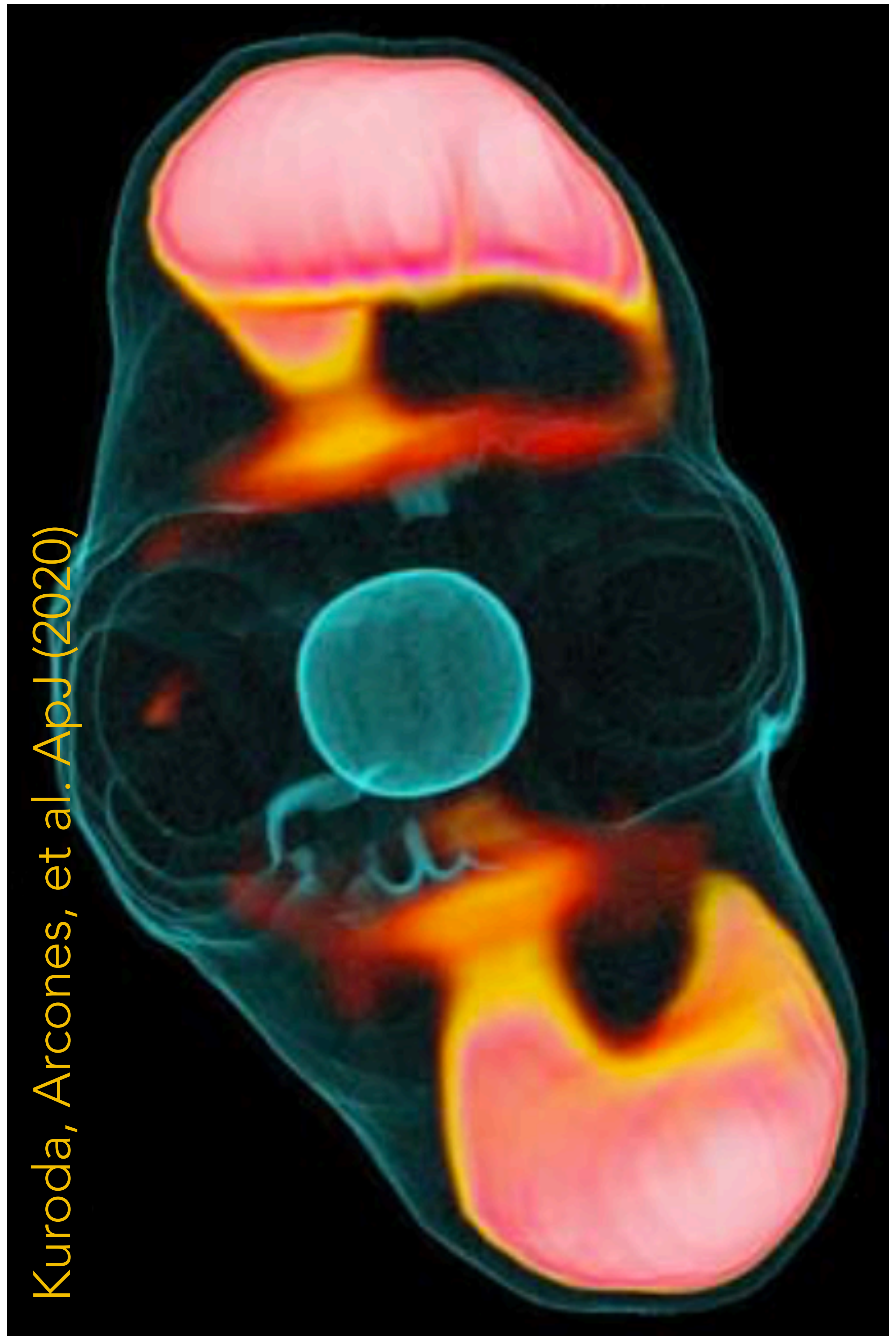

Neutron-rich matter ejected by magnetic field (Cameron 2003, Nishimura et al. 2006)

2D and 3D + parametric neutrino treatment

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

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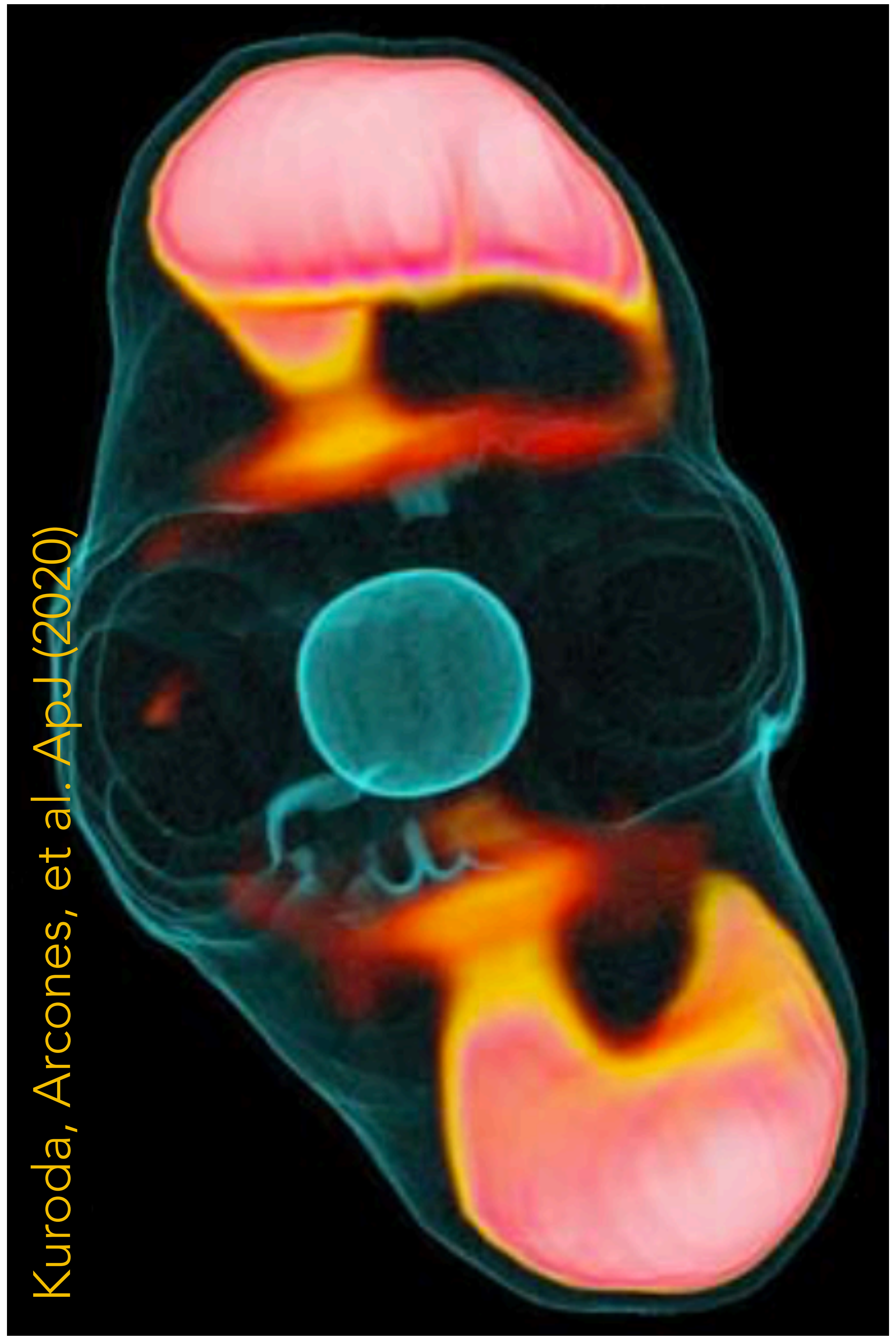

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First simulations of explosions with magnetic fields and detailed neutrino transport (Obergaulinger & Aloy 2017, Kuroda et al. 2020), and their nucleosynthesis (Reichert et al. ApJ 2021, Reichert et al. MNRAS 2023)

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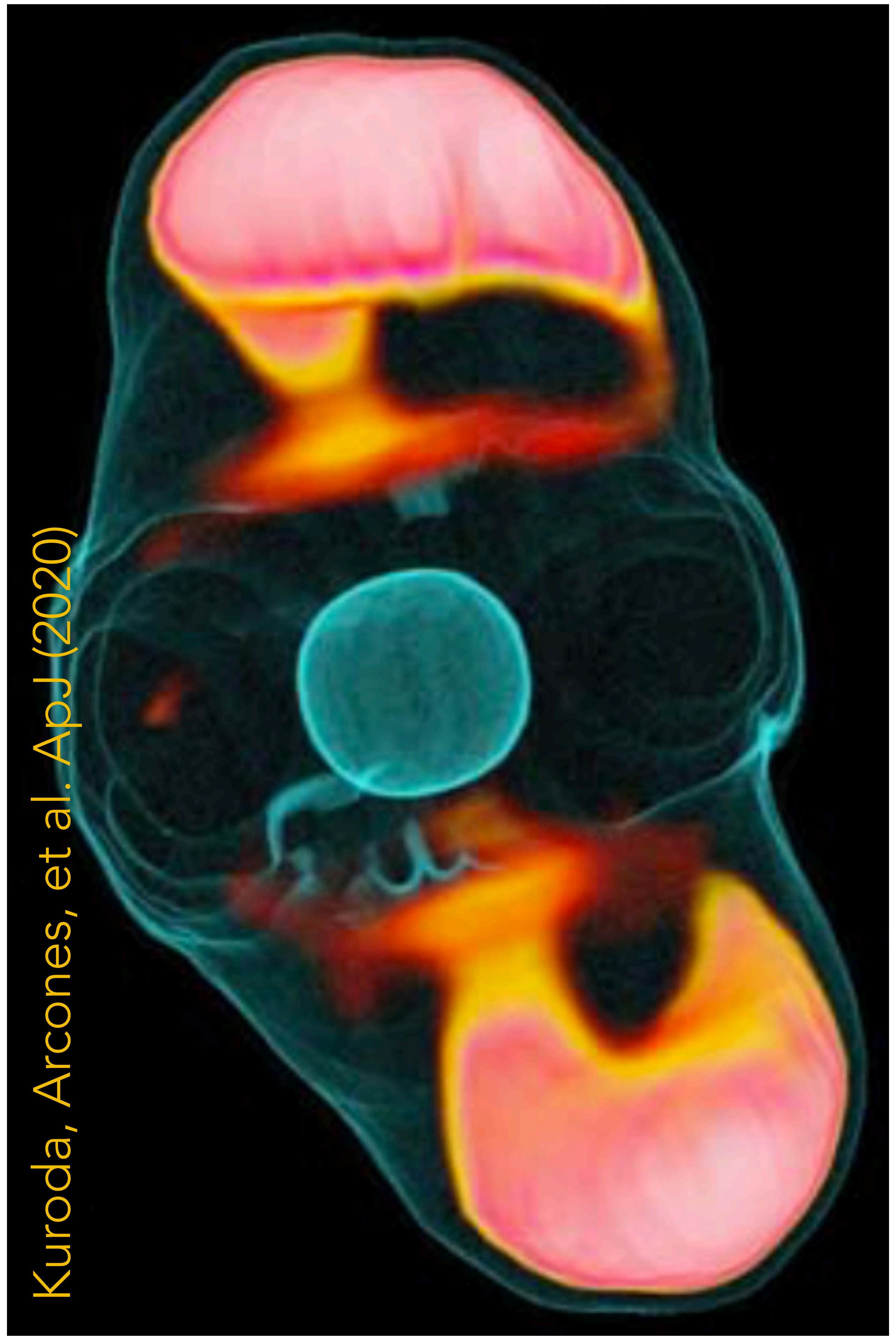

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2D and 3D + parametric neutrino treatment
Winteler et al. 2012, Nishimura et al. 2015, 2017, Mösta et al. 2018

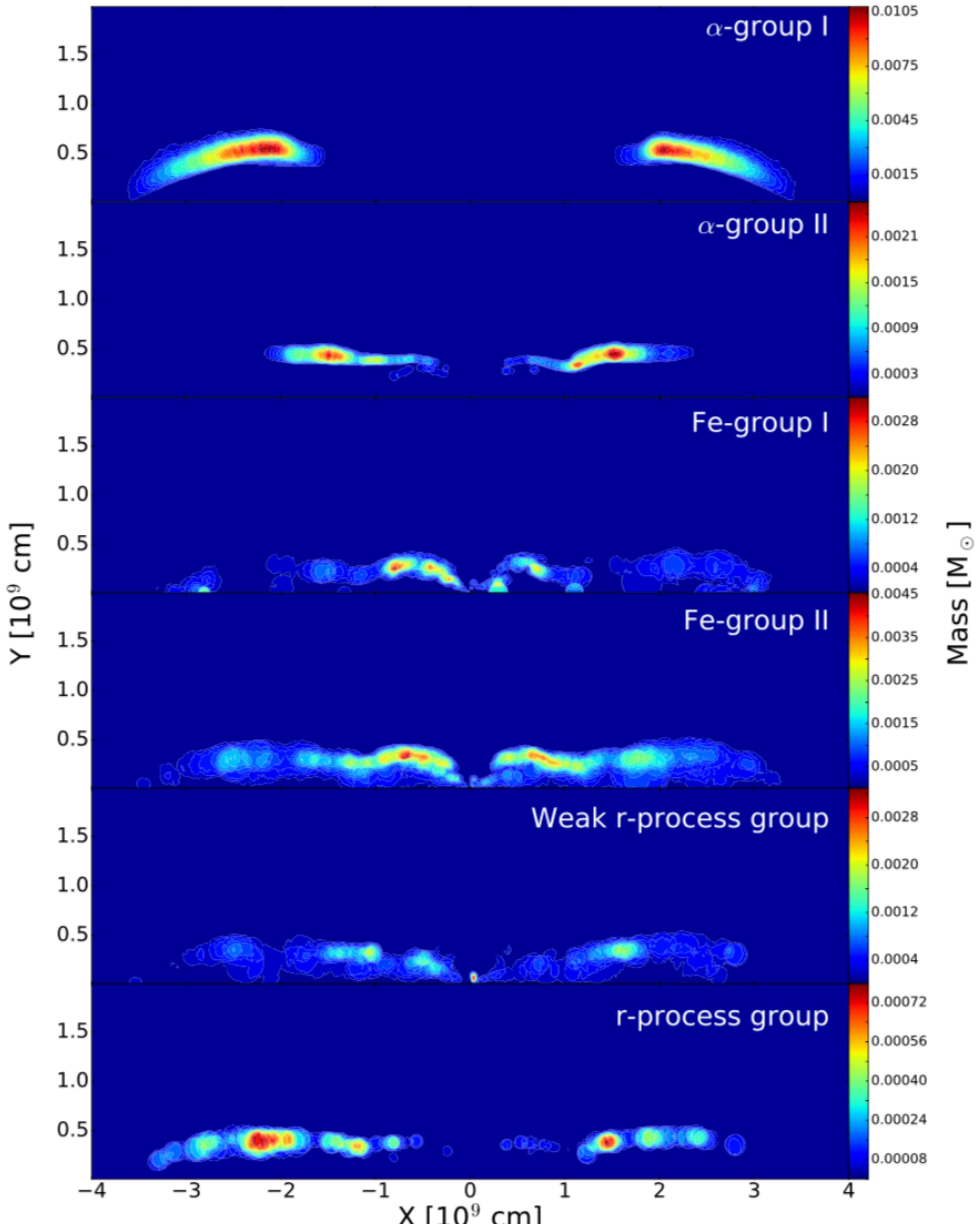
First simulations of explosions with magnetic fields and detailed neutrino transport (Obergaulinger & Aloy 2017, Kuroda et al. 2020), and their nucleosynthesis (Reichert et al. ApJ 2021, Reichert et al. MNRAS 2023)

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. MNRAS (2024)

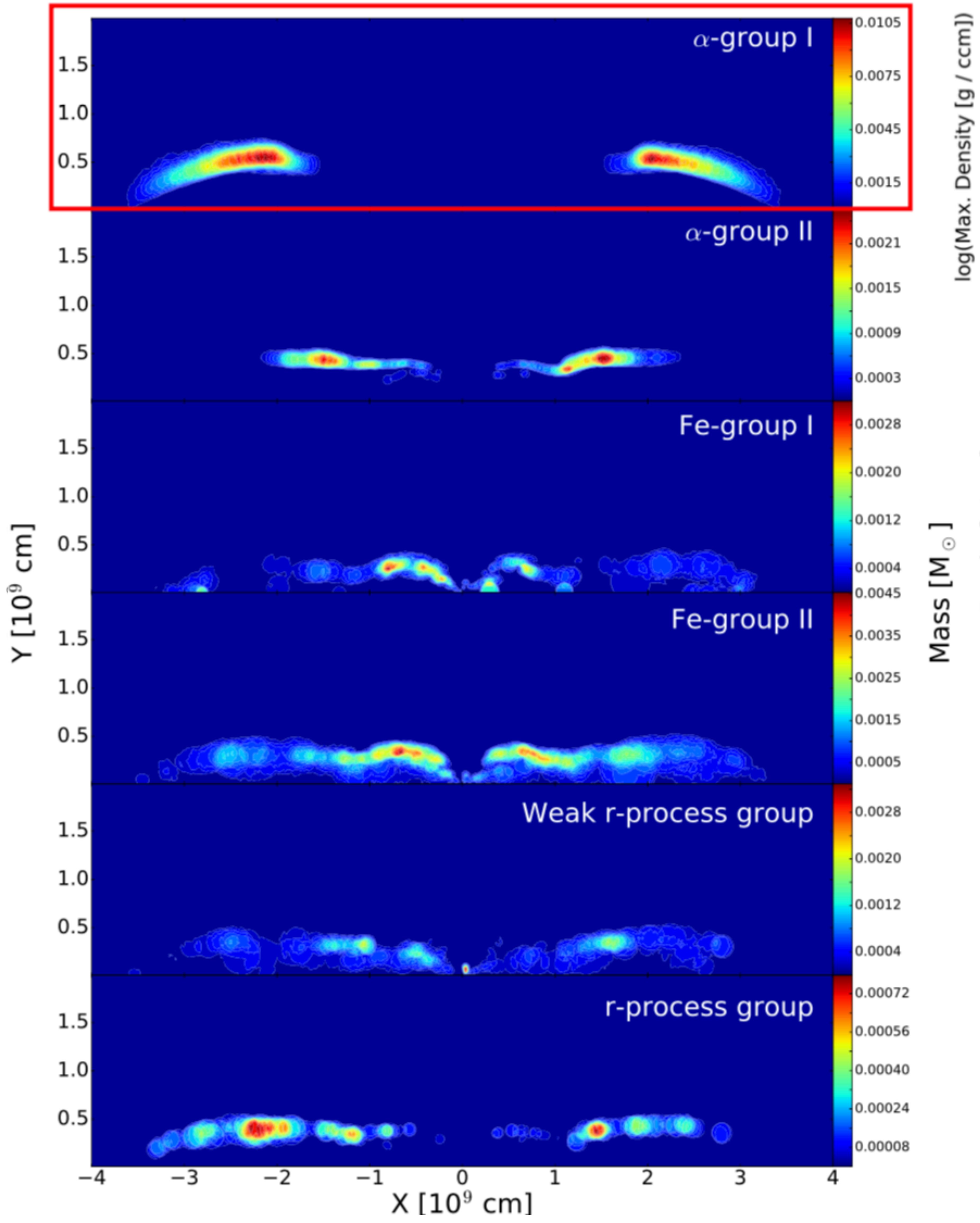
Reichert et al. ApJ (2021)

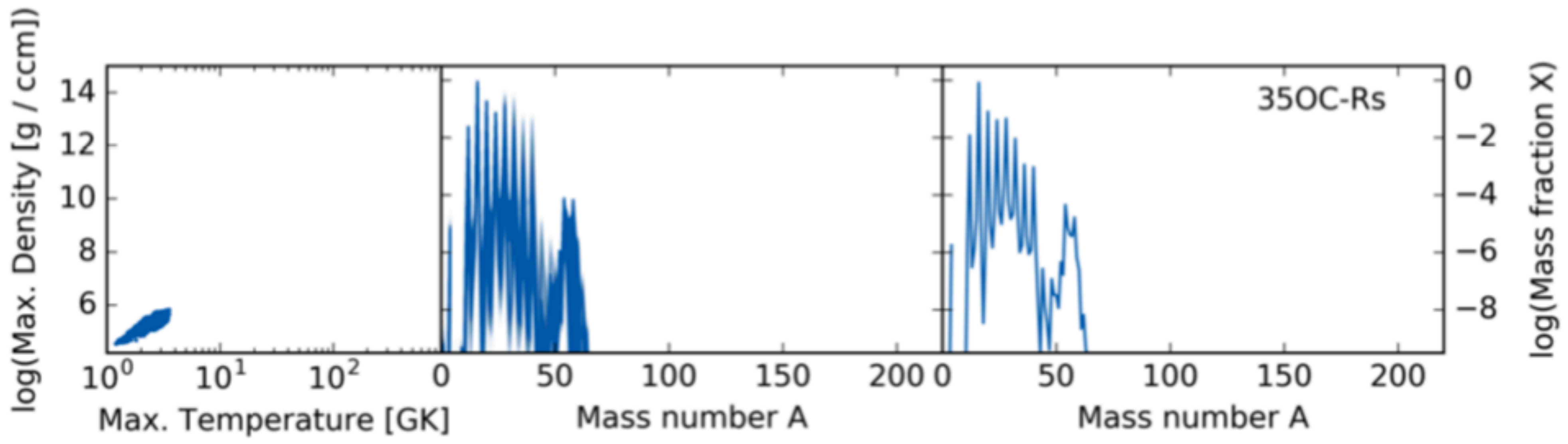
Nucleosynthesis in magneto-rotational supernovae

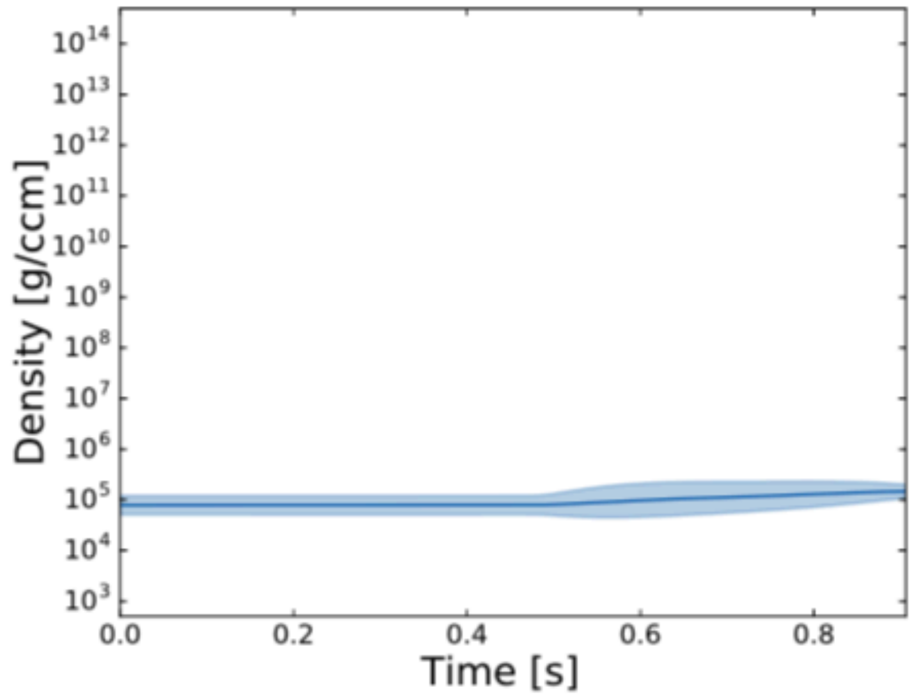


Reichert et al. ApJ (2021)

Nucleosynthesis in magneto-rotational supernovae



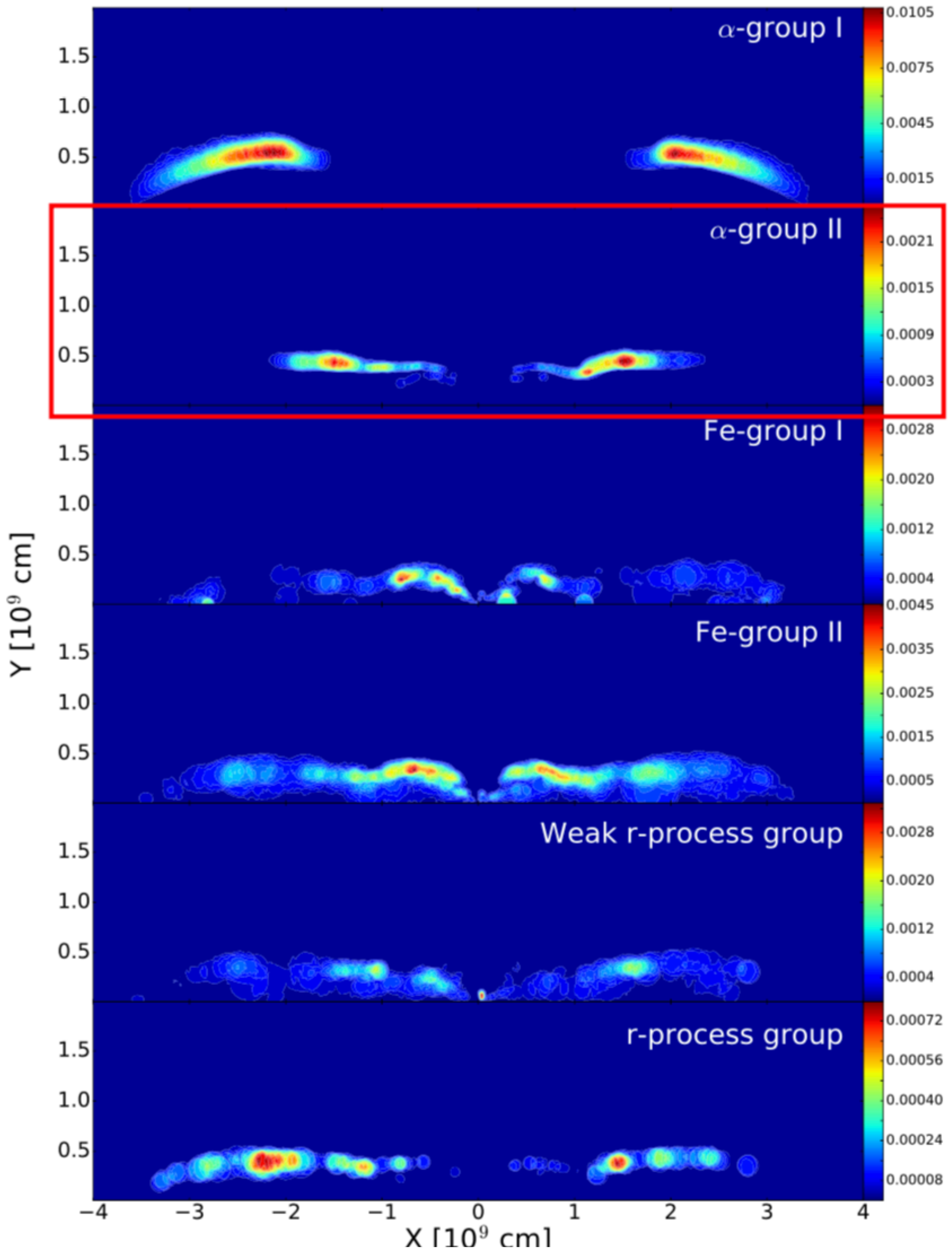


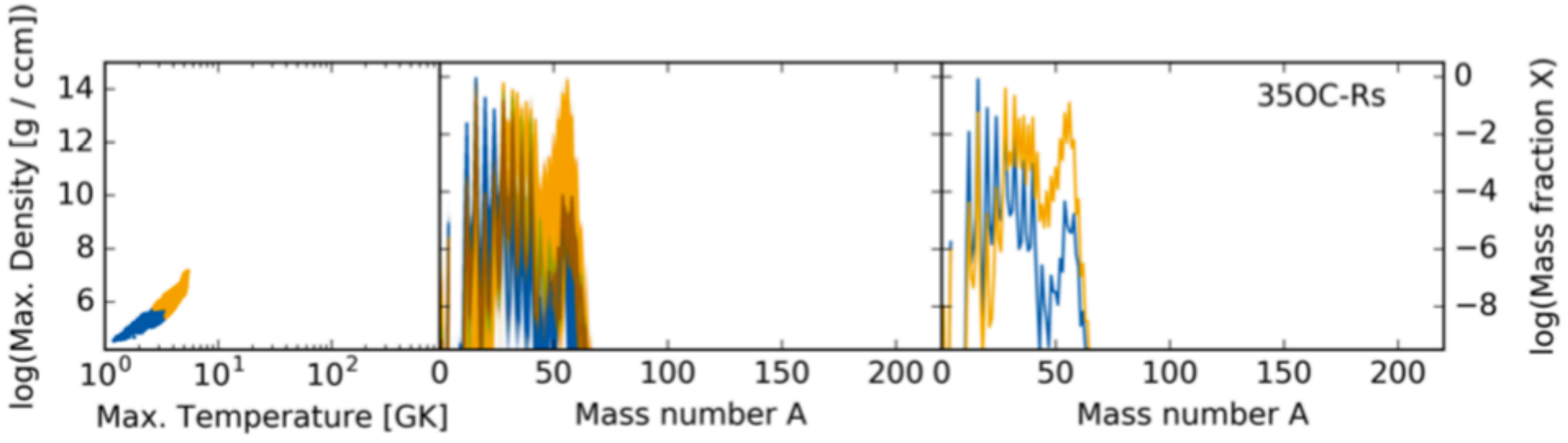


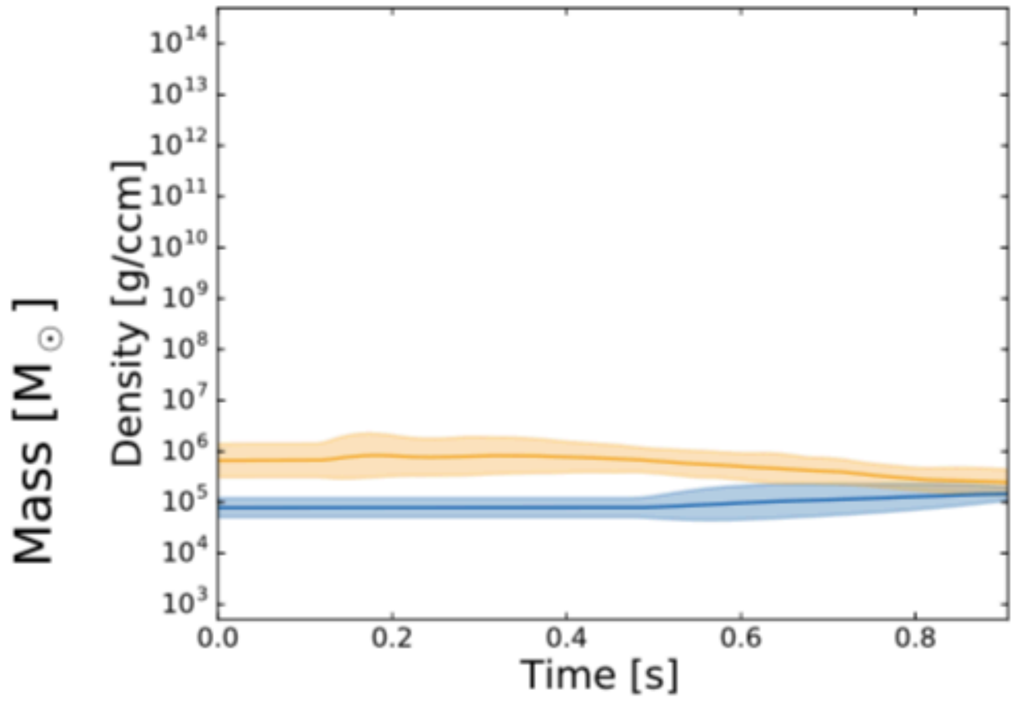
- Progenitor composition
- $T_{\rm max} \lesssim 3\,{\rm GK}$
- $\rho_{\rm max} \lesssim 10^6\,{\rm g\,/ccm}$

Reichert et al. ApJ (2021)

Nucleosynthesis in magneto-rotational supernovae



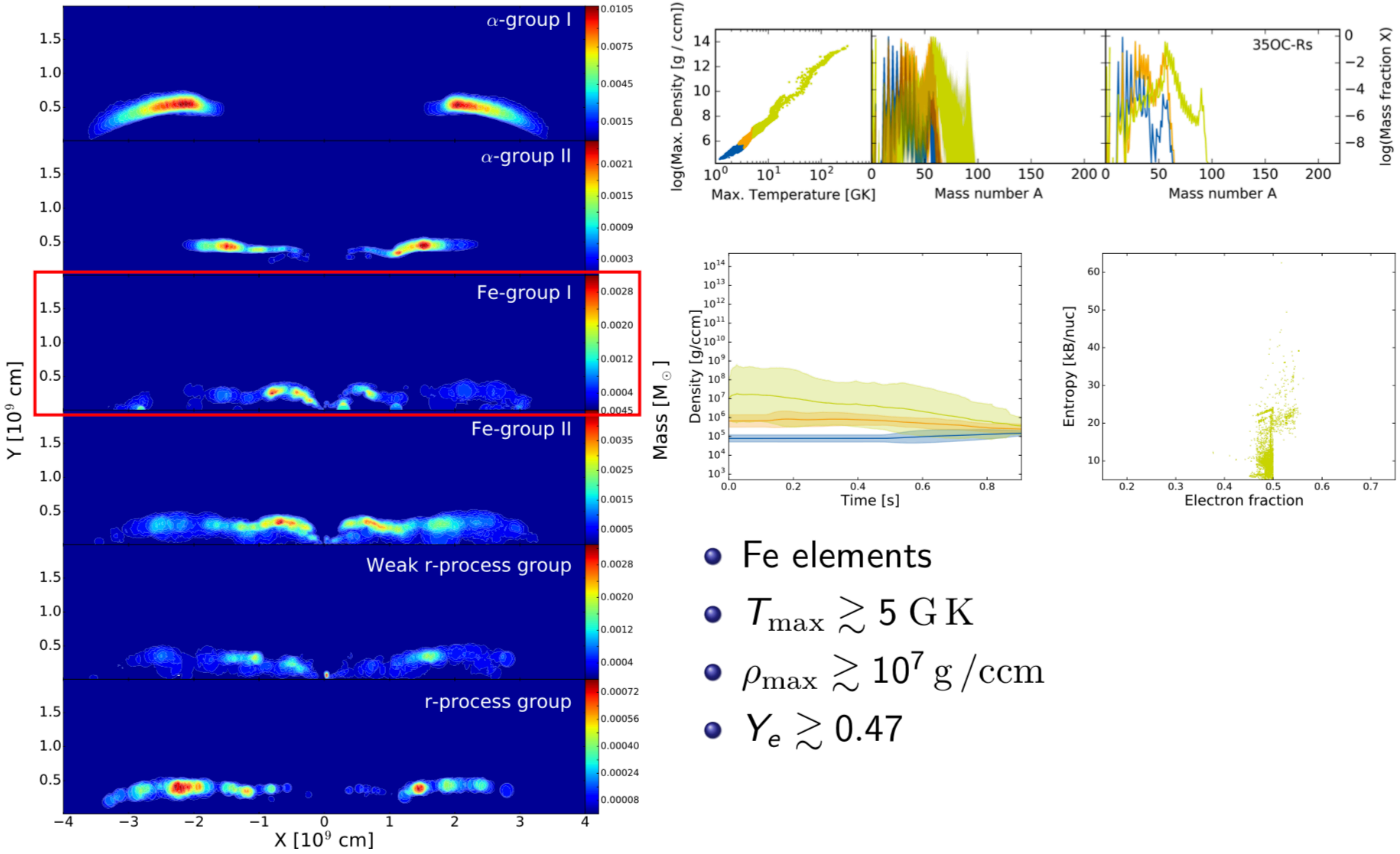




- α+Fe elements
- $T_{\rm max} \lesssim 5\,{\rm GK}$
- $\rho_{\rm max} \lesssim 10^7\,{\rm g/ccm}$

Reichert et al. ApJ (2021)

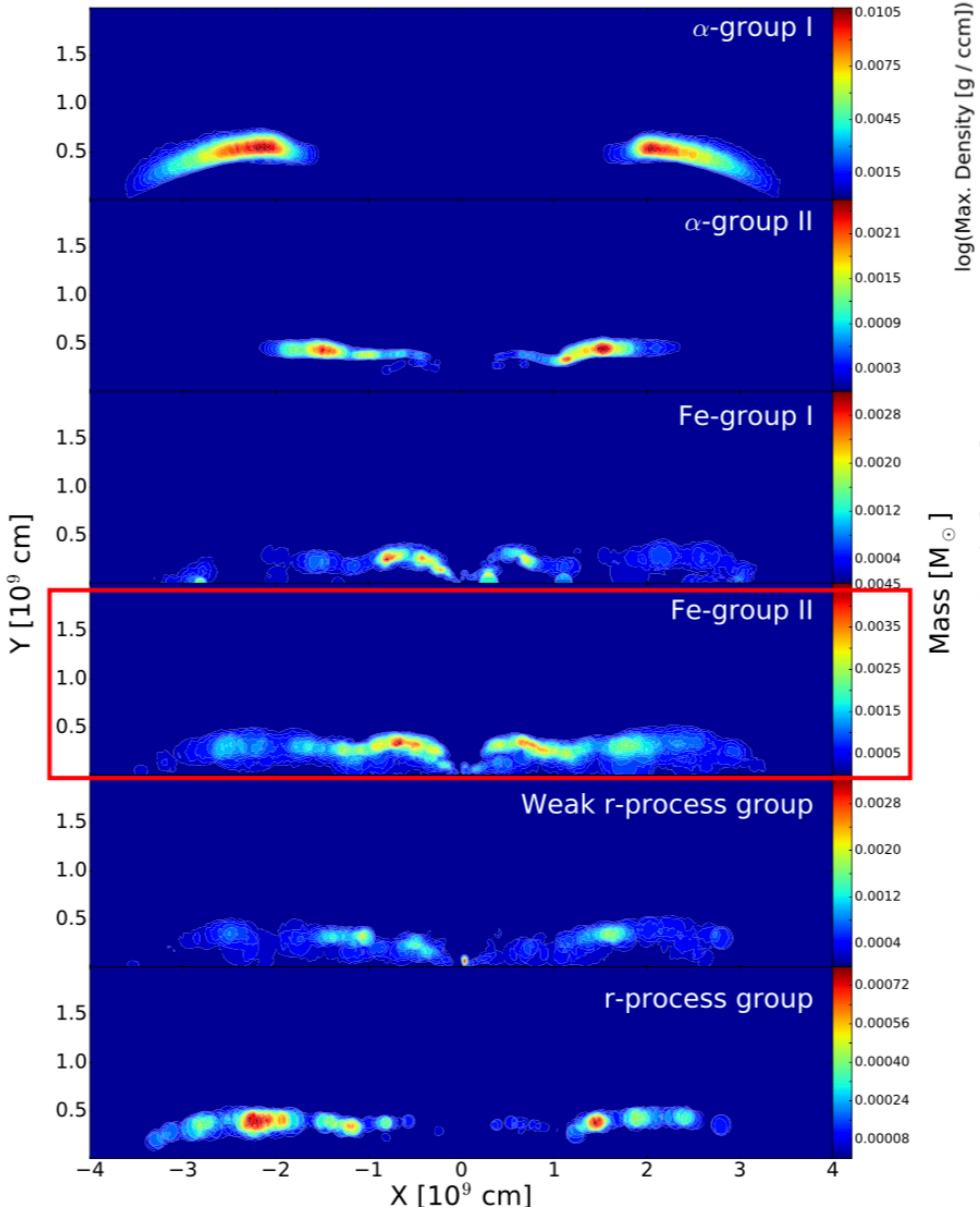
Nucleosynthesis in magneto-rotational supernovae

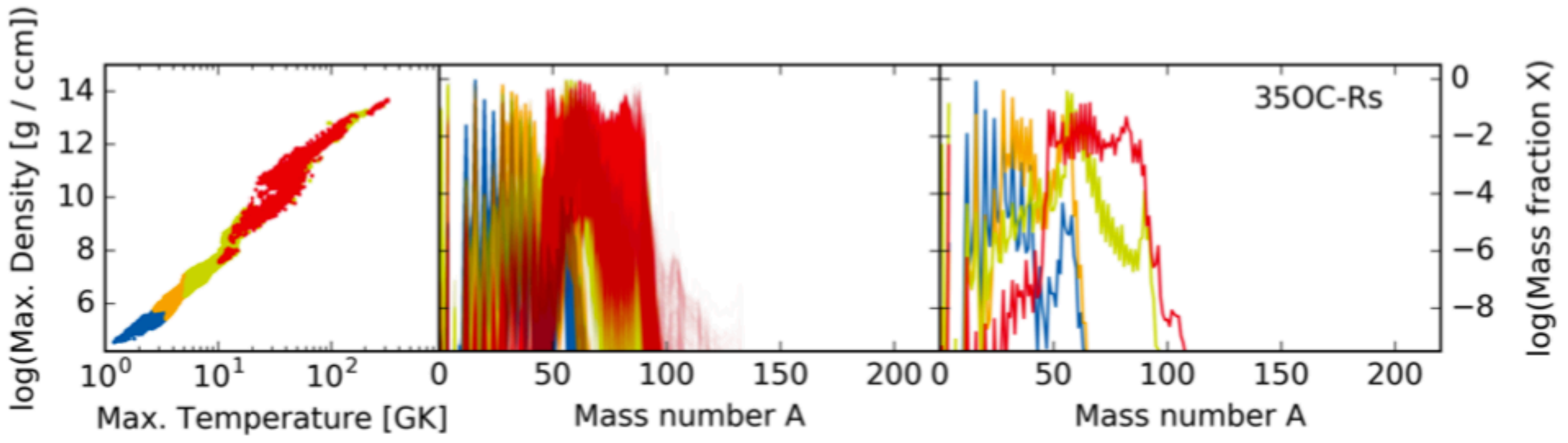


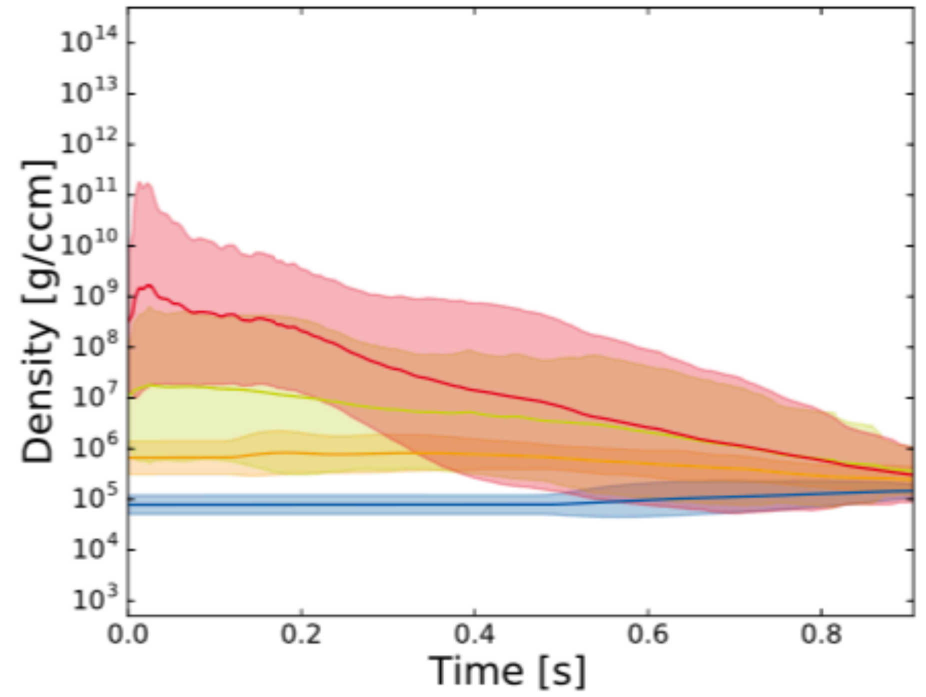
- Fe elements
- $T_{\max} \gtrsim 5\,\mathrm{GK}$
- $\rho_{\max} \gtrsim 10^7\,\mathrm{g/ccm}$
- $Y_e \gtrsim 0.47$

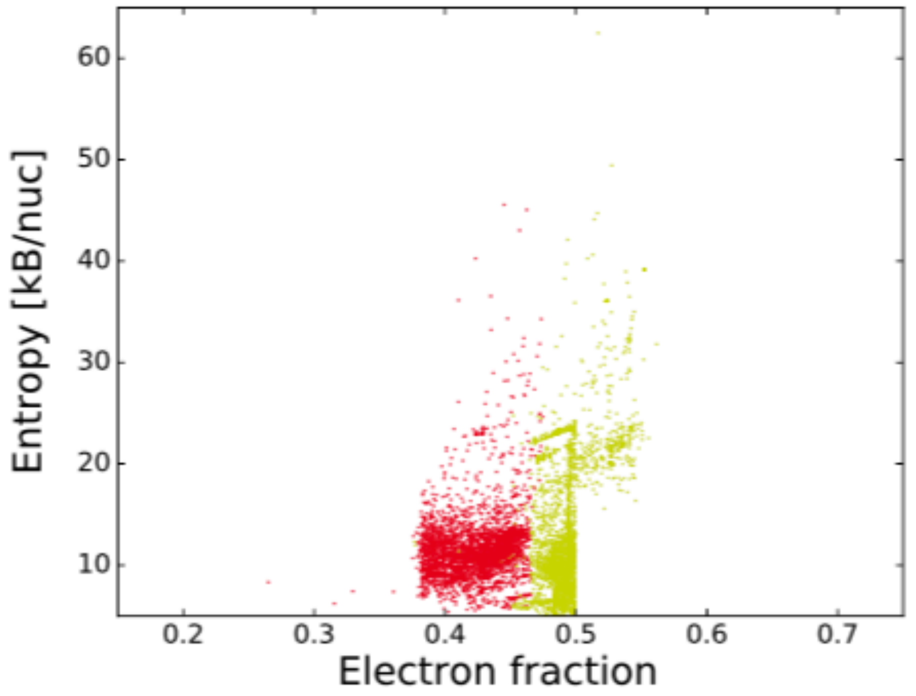
Reichert et al. ApJ (2021)

Nucleosynthesis in magneto-rotational supernovae





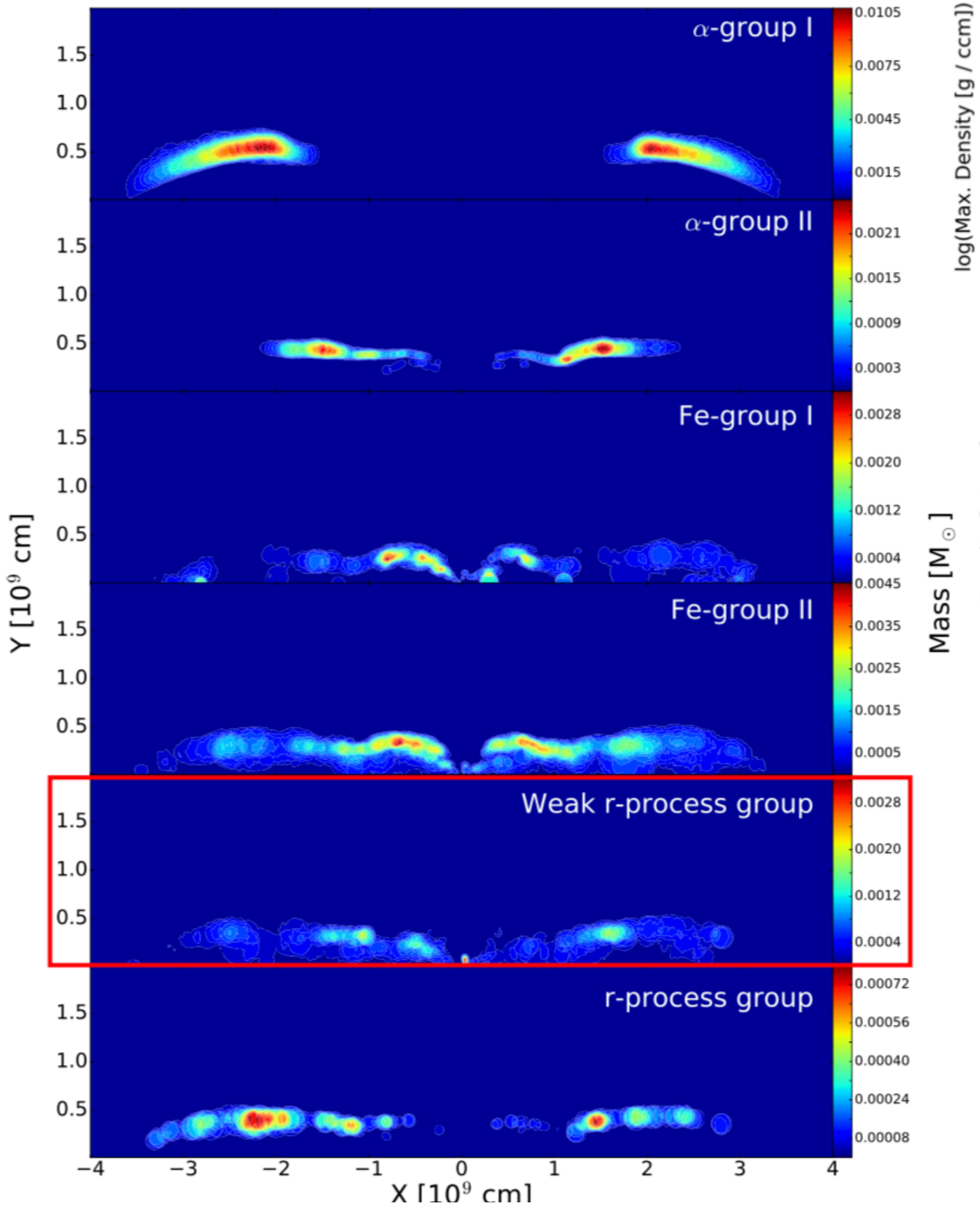


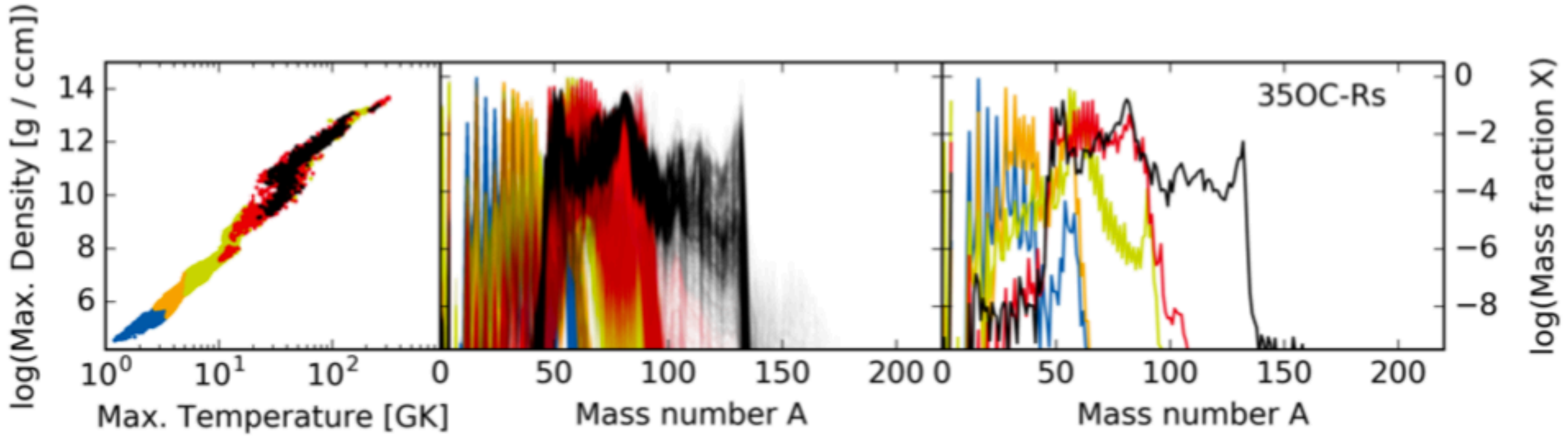


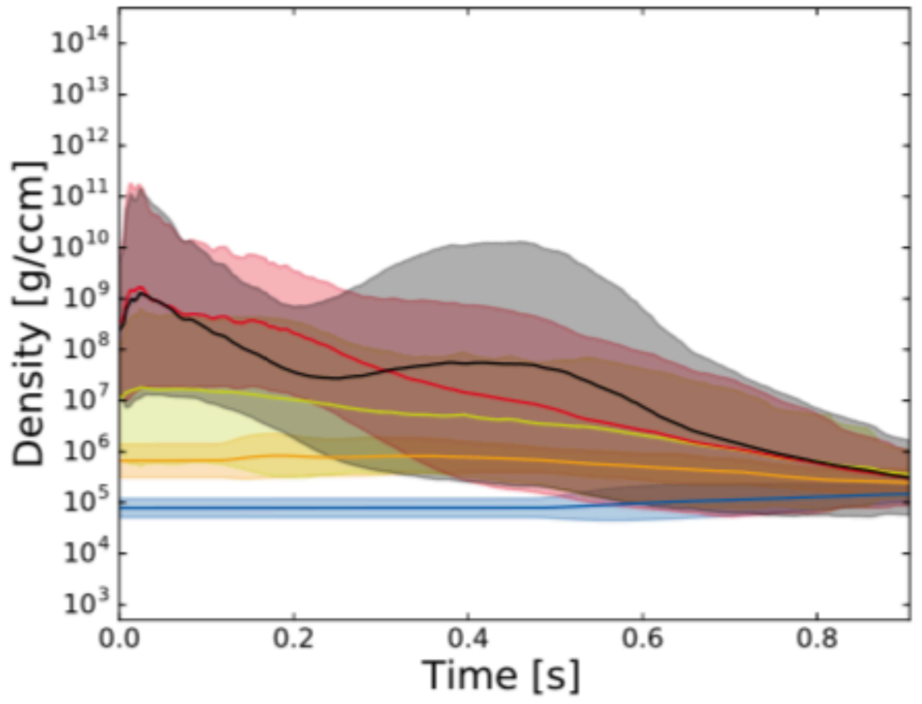
- 1st r-process peak
- $T_{\max} \gtrsim 10\,\mathrm{GK}$
- $\rho_{\max} \gtrsim 10^7\,\mathrm{g/ccm}$
- $0.38 \lesssim Y_e \lesssim 0.47$

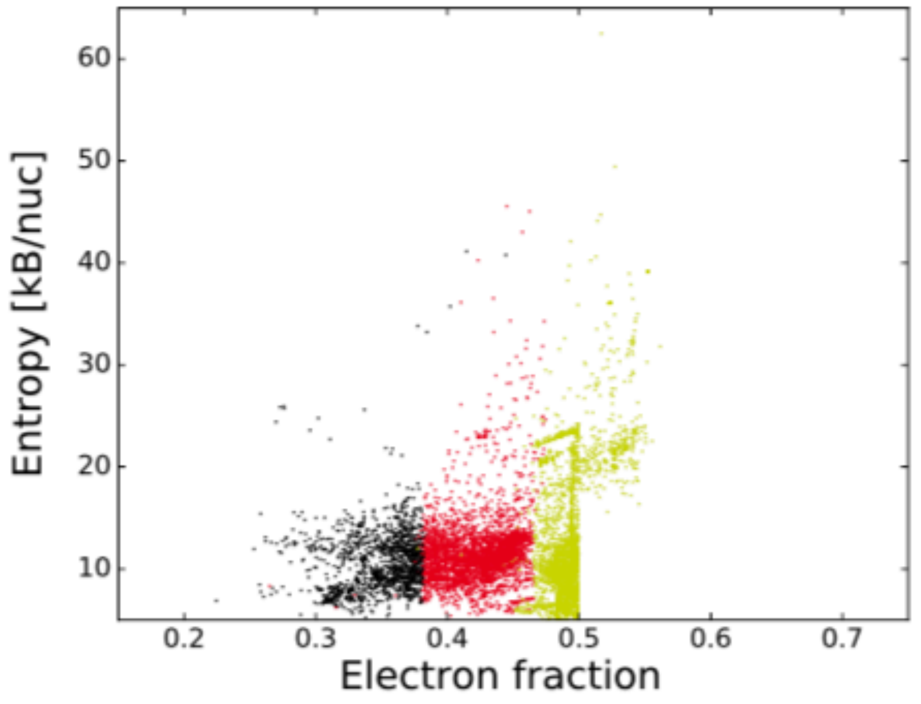
Reichert et al. ApJ (2021)

Nucleosynthesis in magneto-rotational supernovae





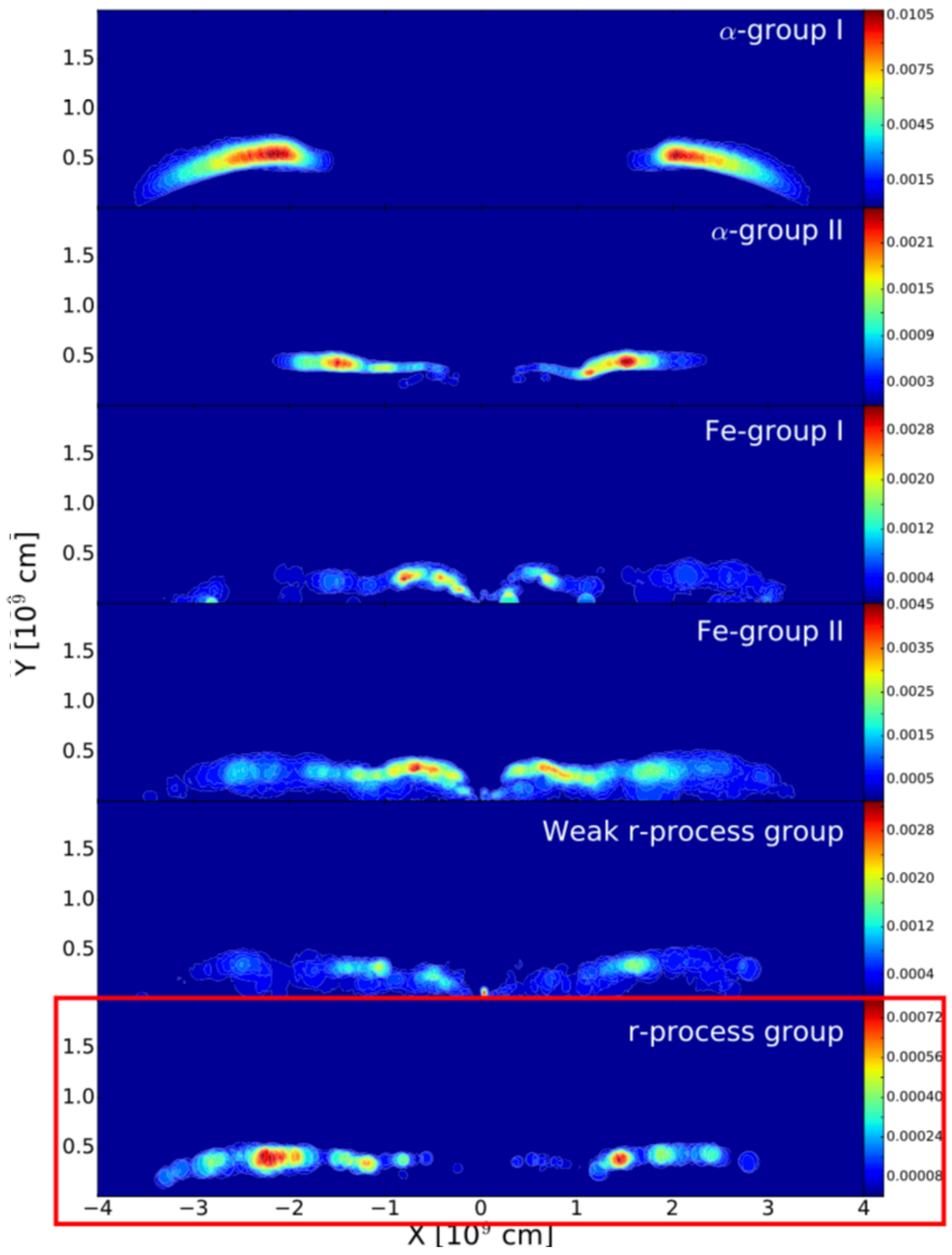


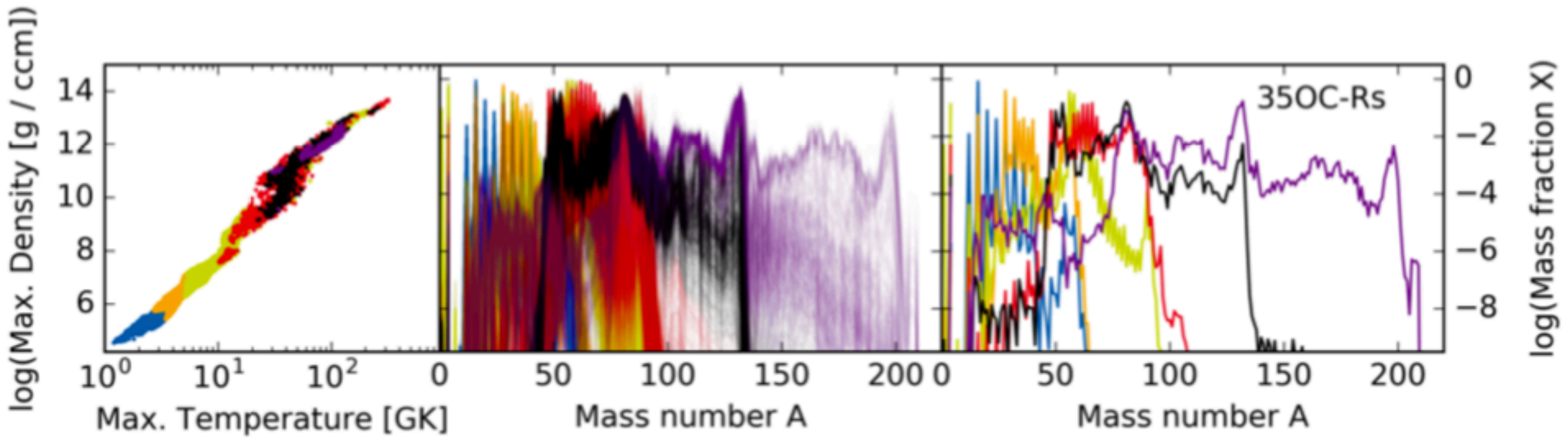


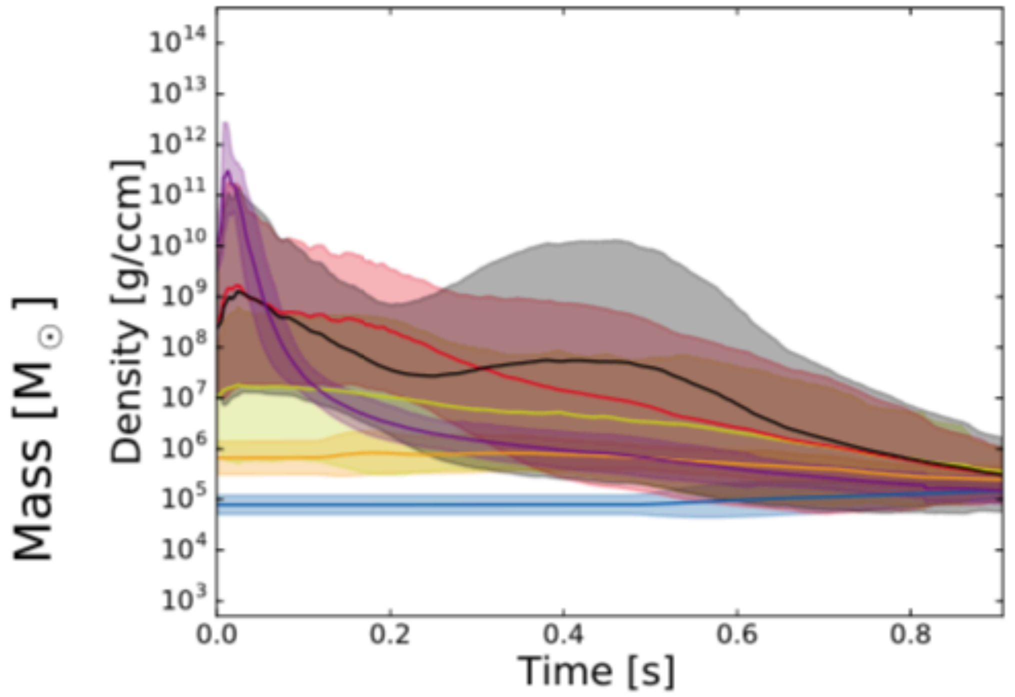
- 2nd r-process peak
- $T_{\max} \gtrsim 20\,\mathrm{GK}$
- $\rho_{\max} \gtrsim 10^9\,\mathrm{g/ccm}$
- $0.25 \lesssim Y_e \lesssim 0.38$

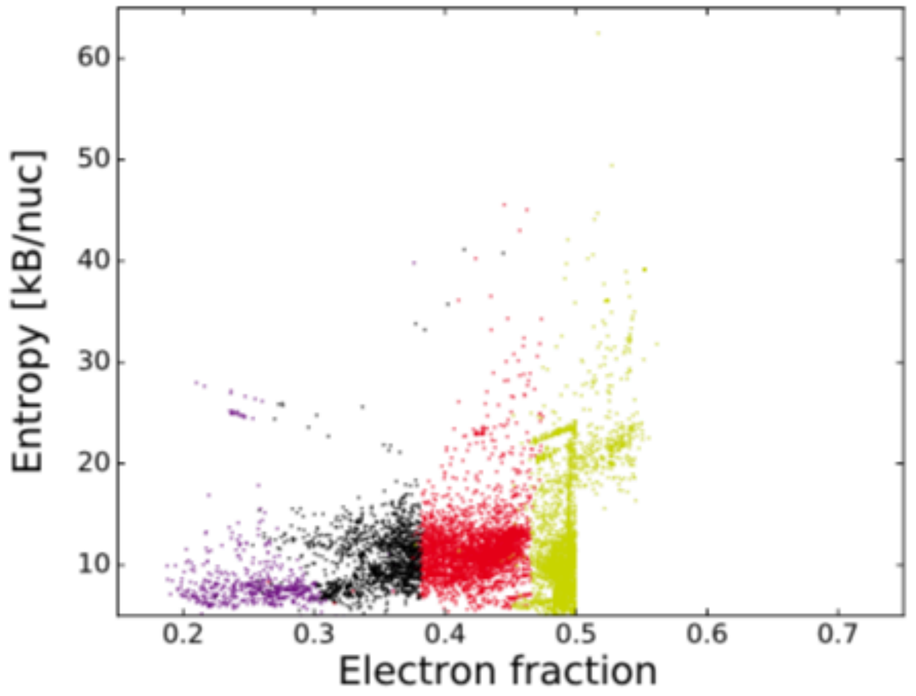
Reichert et al. ApJ (2021)

Nucleosynthesis in magneto-rotational supernovae







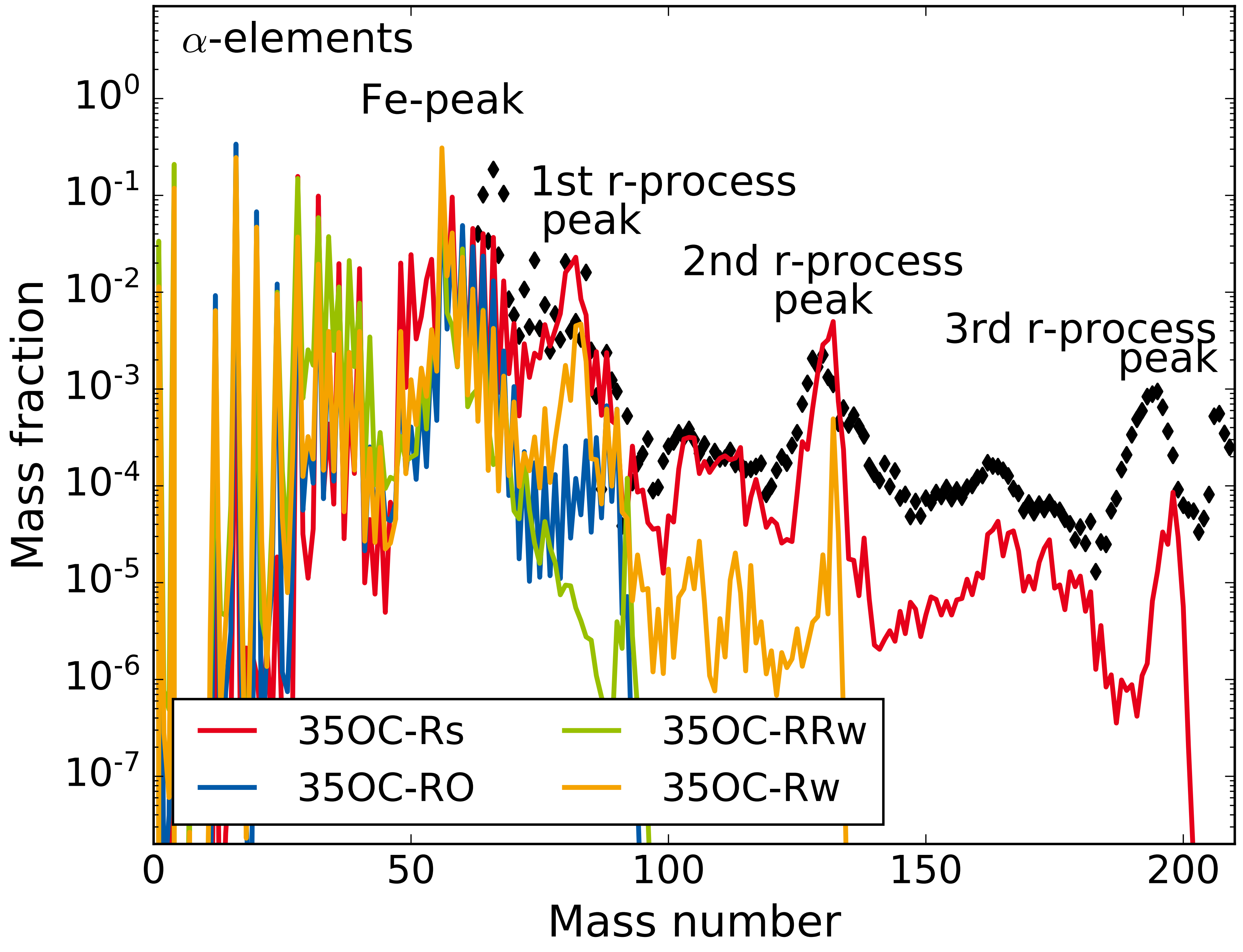


- 3rd r-process peak
- $T_{\max} \gtrsim 30\,\mathrm{GK}$
- $\rho_{\max} \gtrsim 10^{11}\,\mathrm{g/ccm}$
- $Y_e \lesssim 0.25$
- Steep gradients

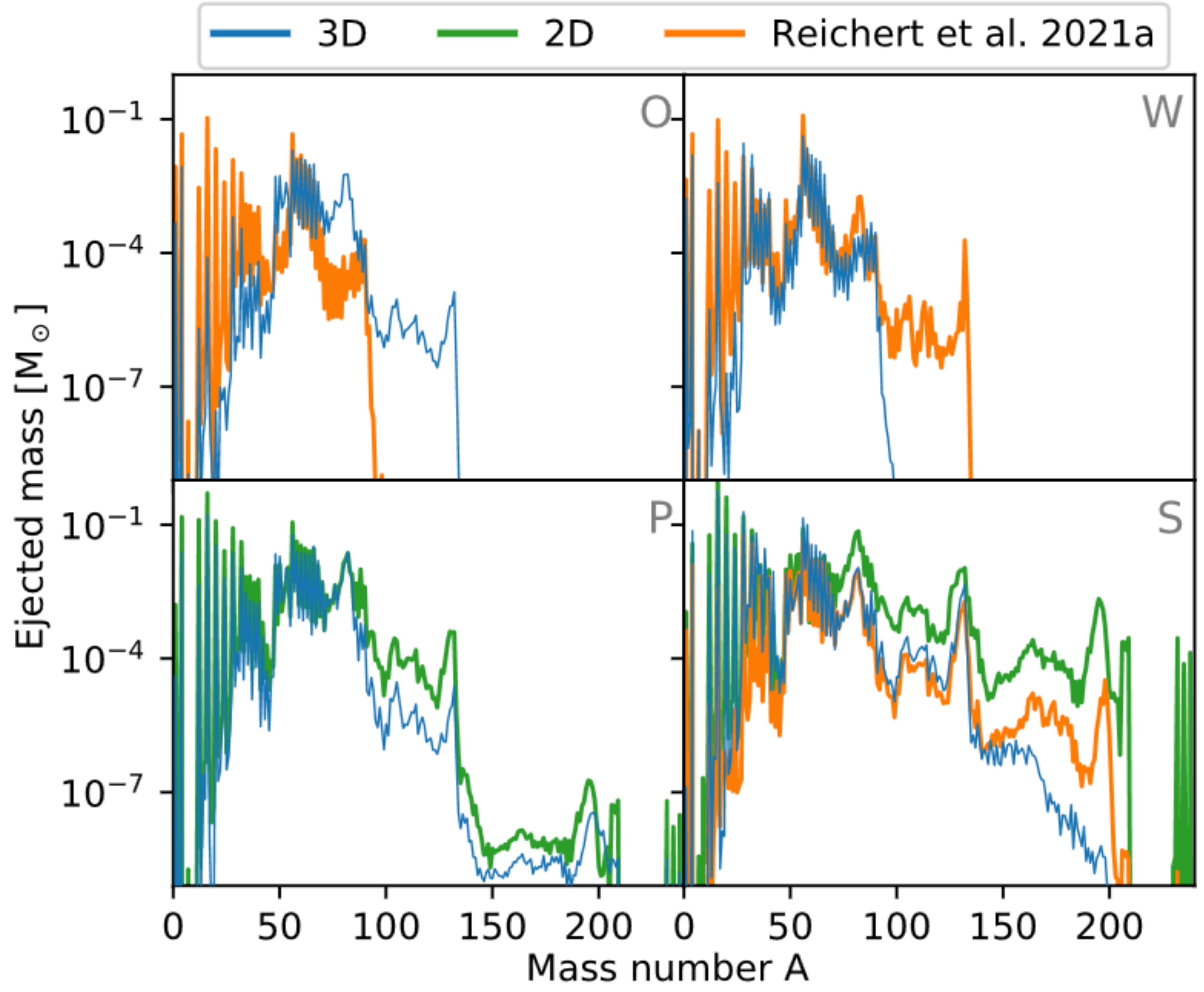
Nucleosynthesis in magneto-rotational supernovae

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

Impact of magnetic field strength and configuration Reichert et al. MNRAS (2023)



Reichert et al. ApJ (2021)



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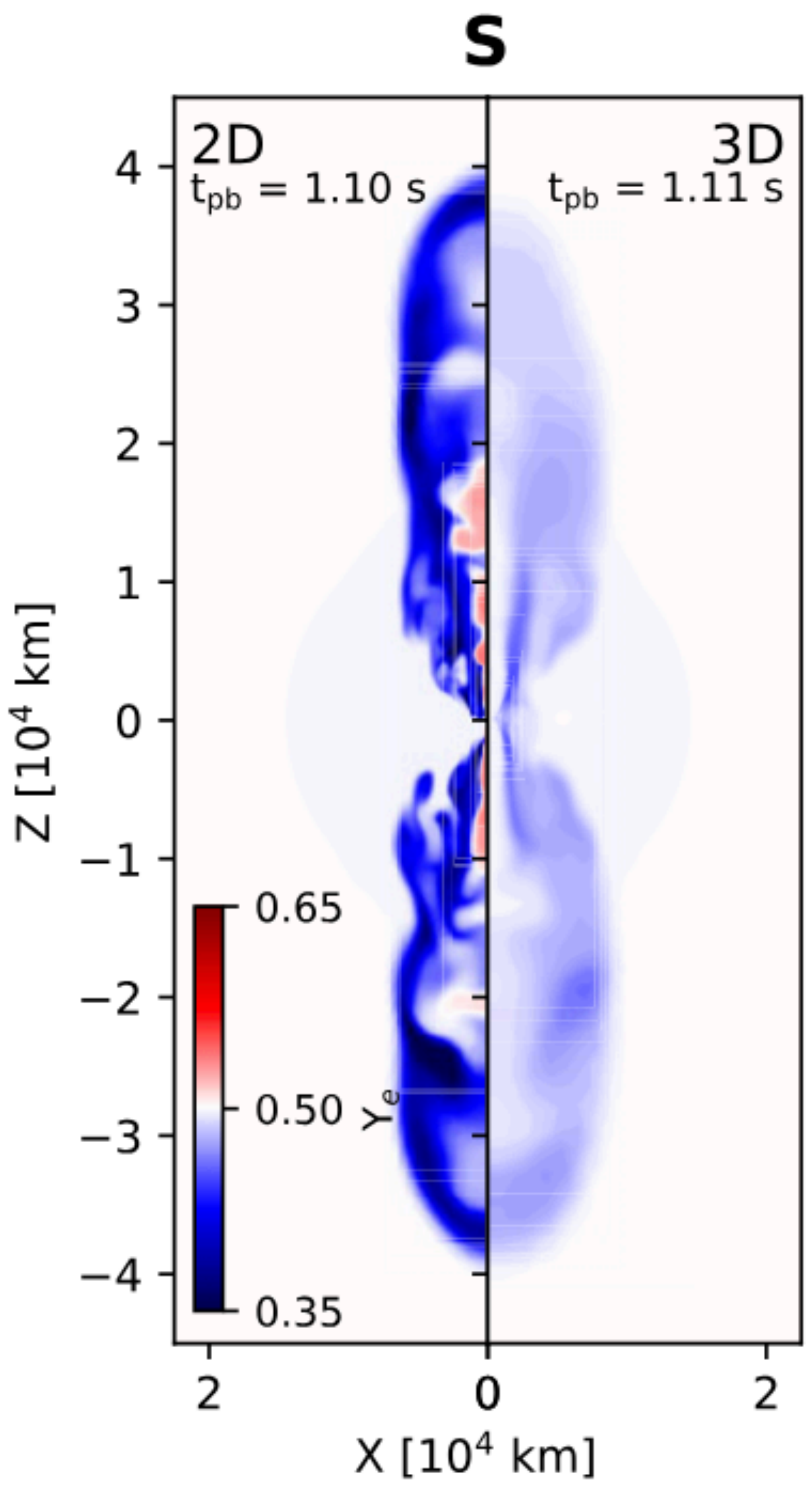
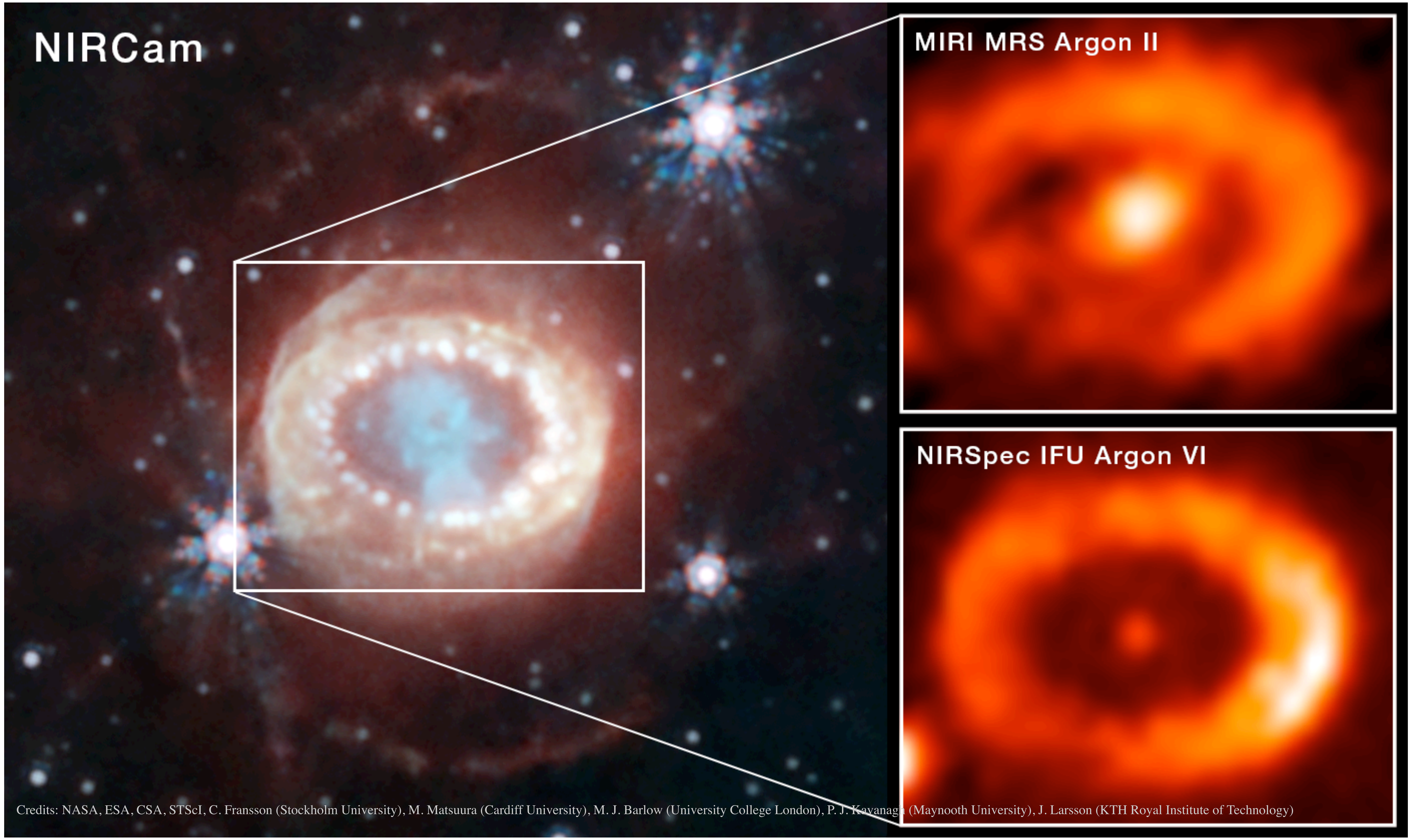


Obergaulinger & Aloy 2017
Obergaulinger et al. 2020

R-process in supernovae?

Ricigliano, Hotokezaka, Arcones, submitted: arxiv:2502.15896

Nebula phase: Can we observe emission lines from freshly synthesized r-process elements?

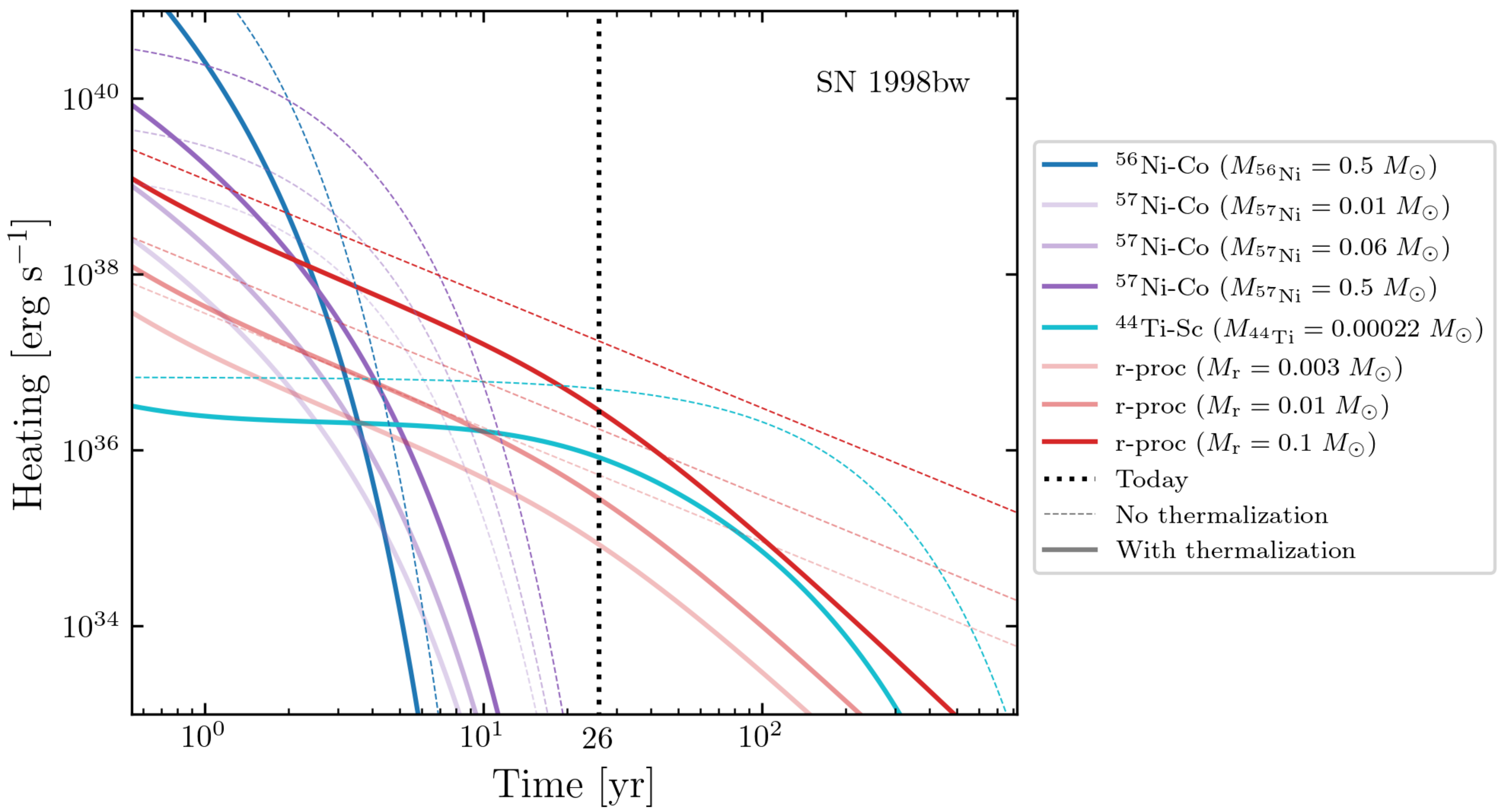


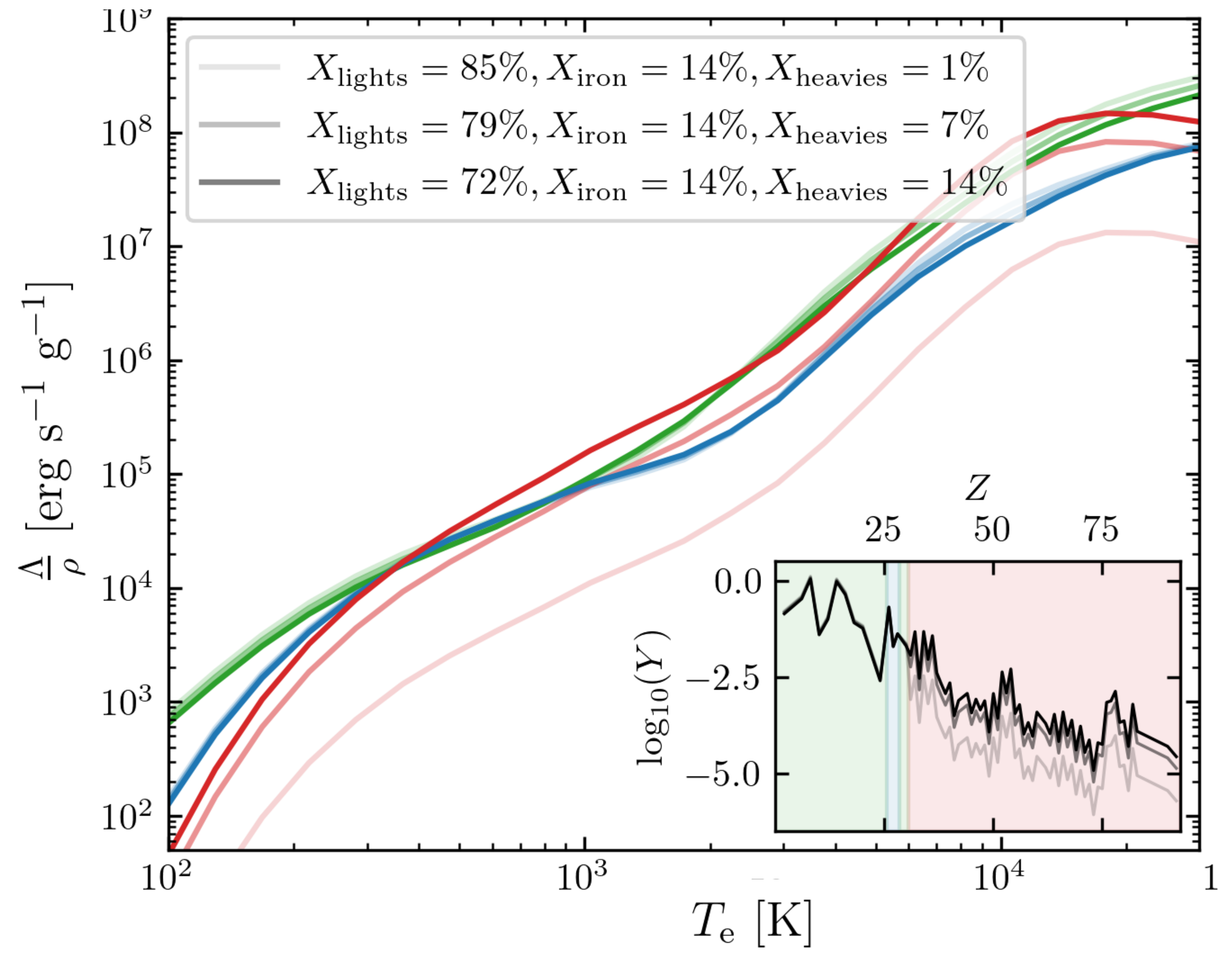
SN 1987A

R-process in supernovae?

Nebula phase: Can we observe emission lines from freshly synthesized r-process elements?

Nebula model: heating and cooling also from r-process

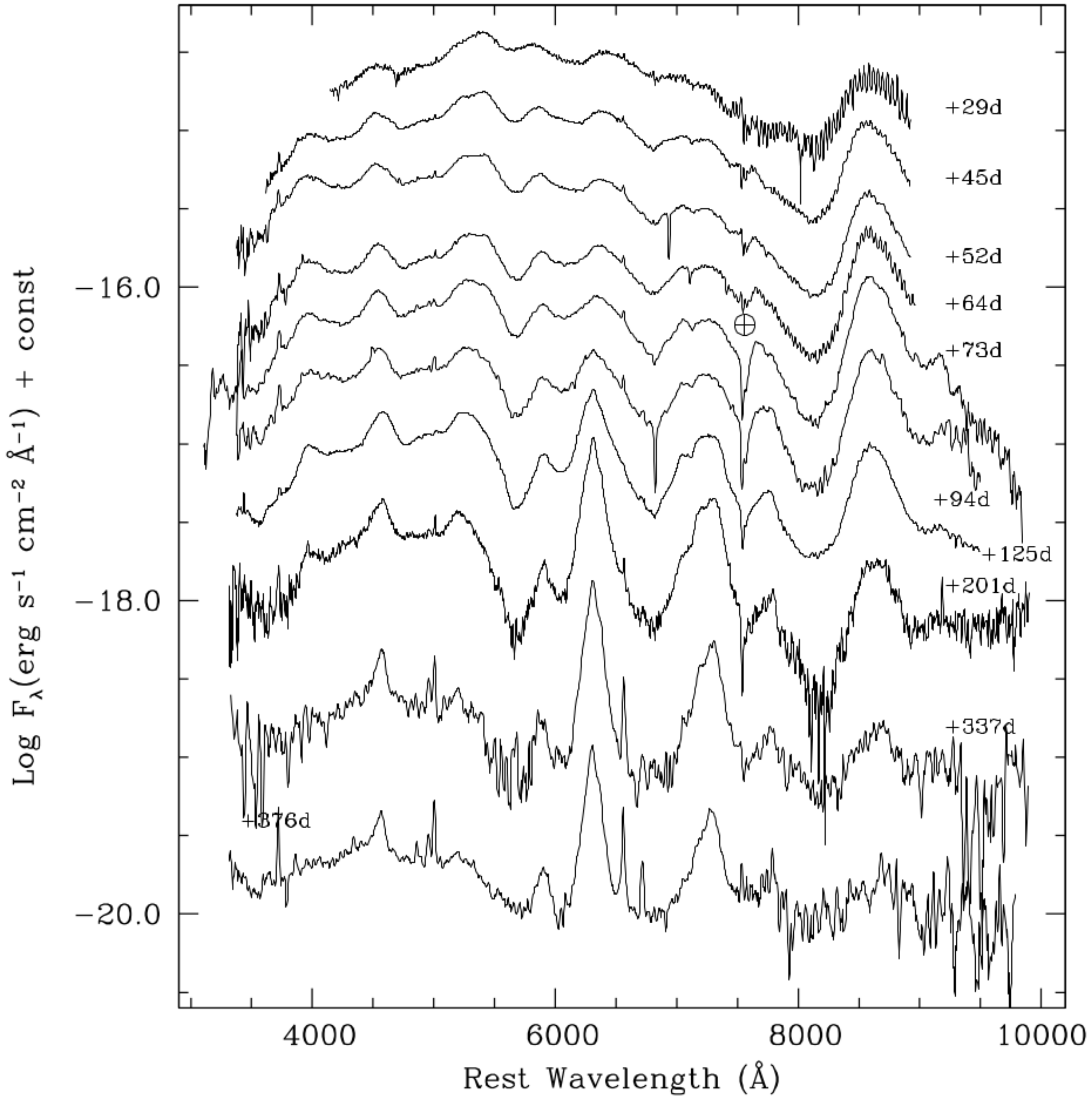




Ricigliano, Hotokezaka, Arcones, submitted: arxiv:2502.15896

R-process emission lines

SN 1998bw associated to GRB 980425



Short rise time,
narrow light peak,
huge luminosity,
broad spectral lines

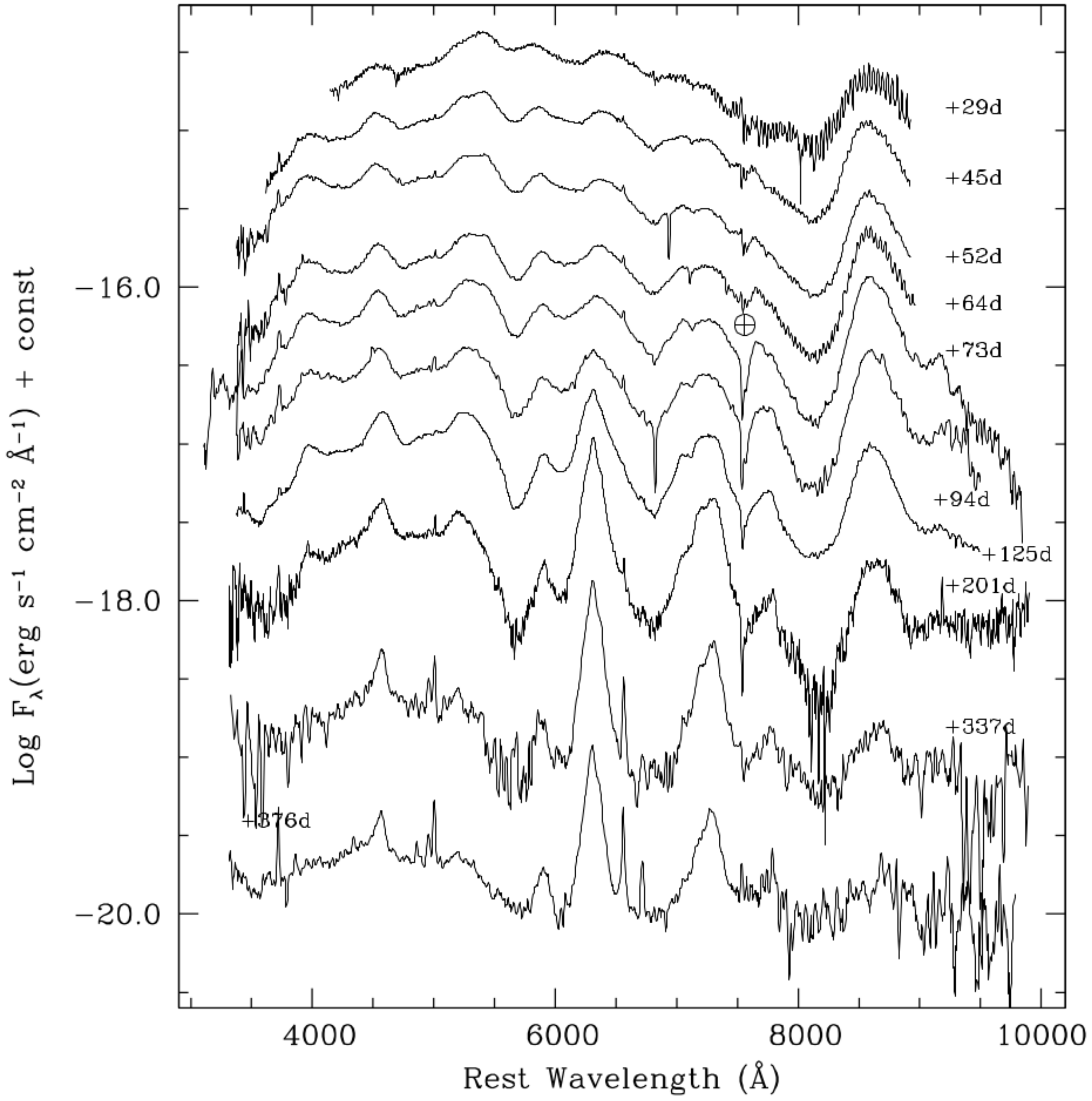
Decrease of
continuum

Still high luminosity,
narrow spectral lines,
low ionization

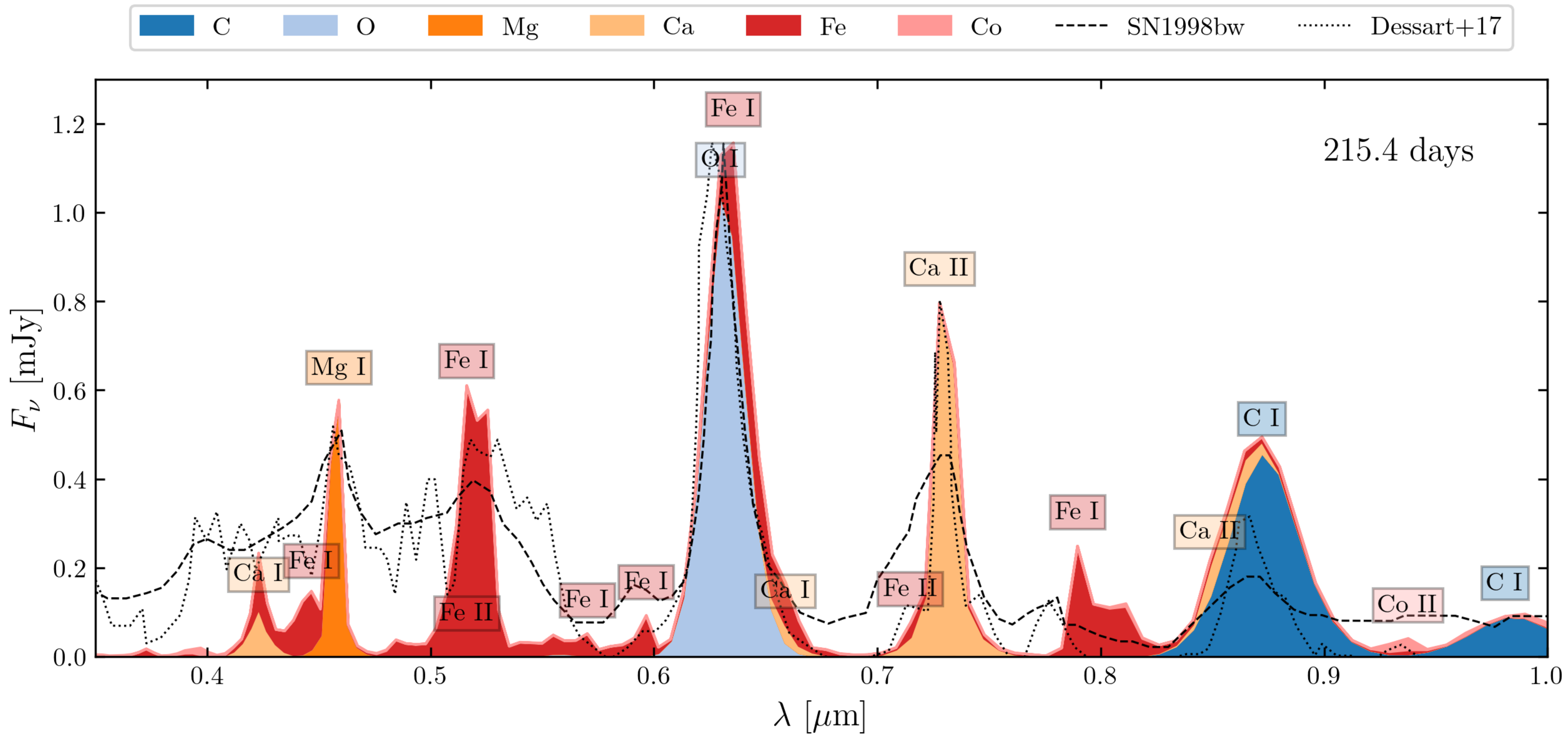
Patat et al. 2001

R-process emission lines

SN 1998bw associated to GRB 980425



Patat et al. 2001

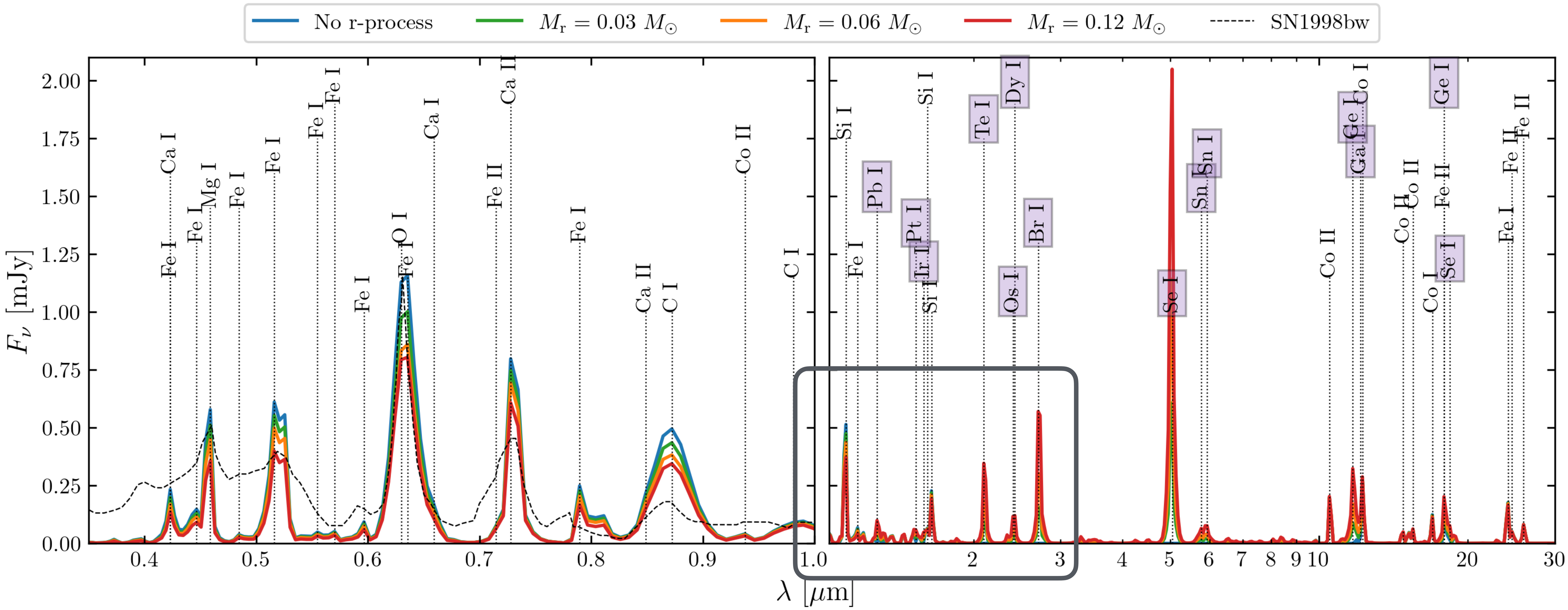


Main features roughly reproduced

Expected flux levels

Ricigliano, Hotokezaka, Arcones, submitted: arxiv:2502.15896

Heavy elements in spectrum



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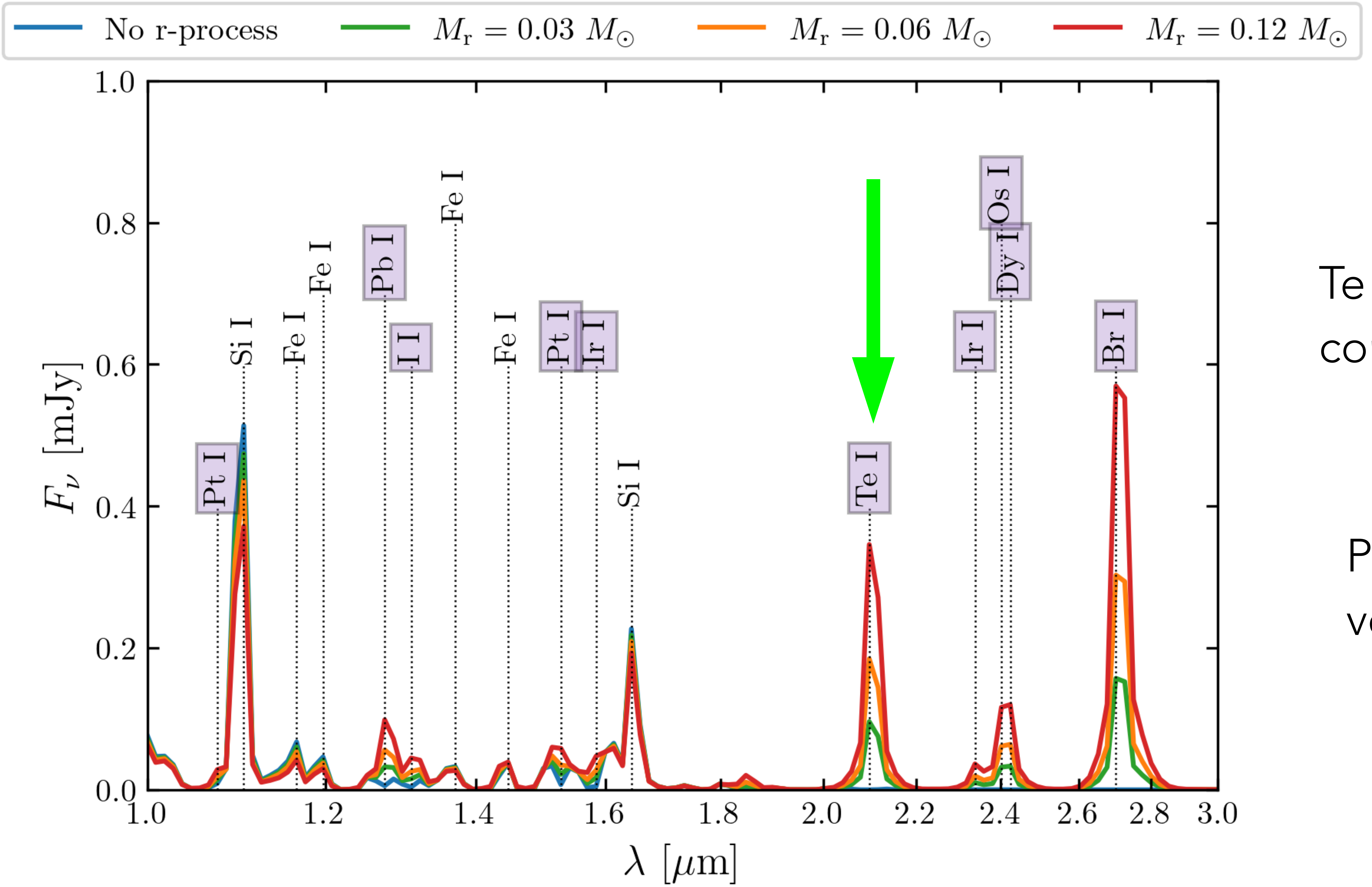


Te I at $2.10\ \mu\mathrm{m}\ (5p^4 3P_1\ -\ 5p^4 3P_2)$ comparable to Si I features

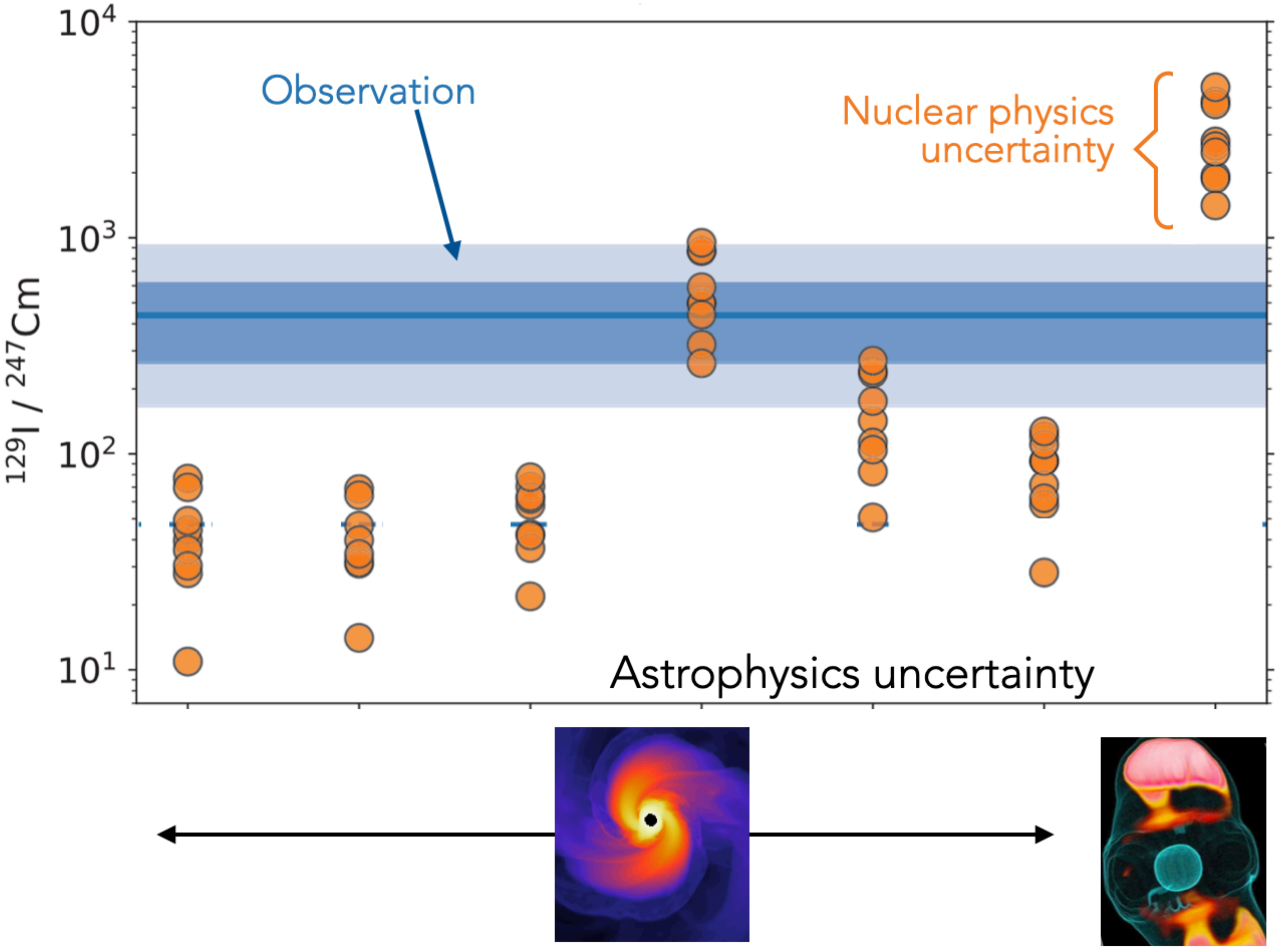
↓

Presence (absence) easily verifiable with JWST

Ricigliano, Hotokezaka, Arcones, submitted: arxiv:2502.15896

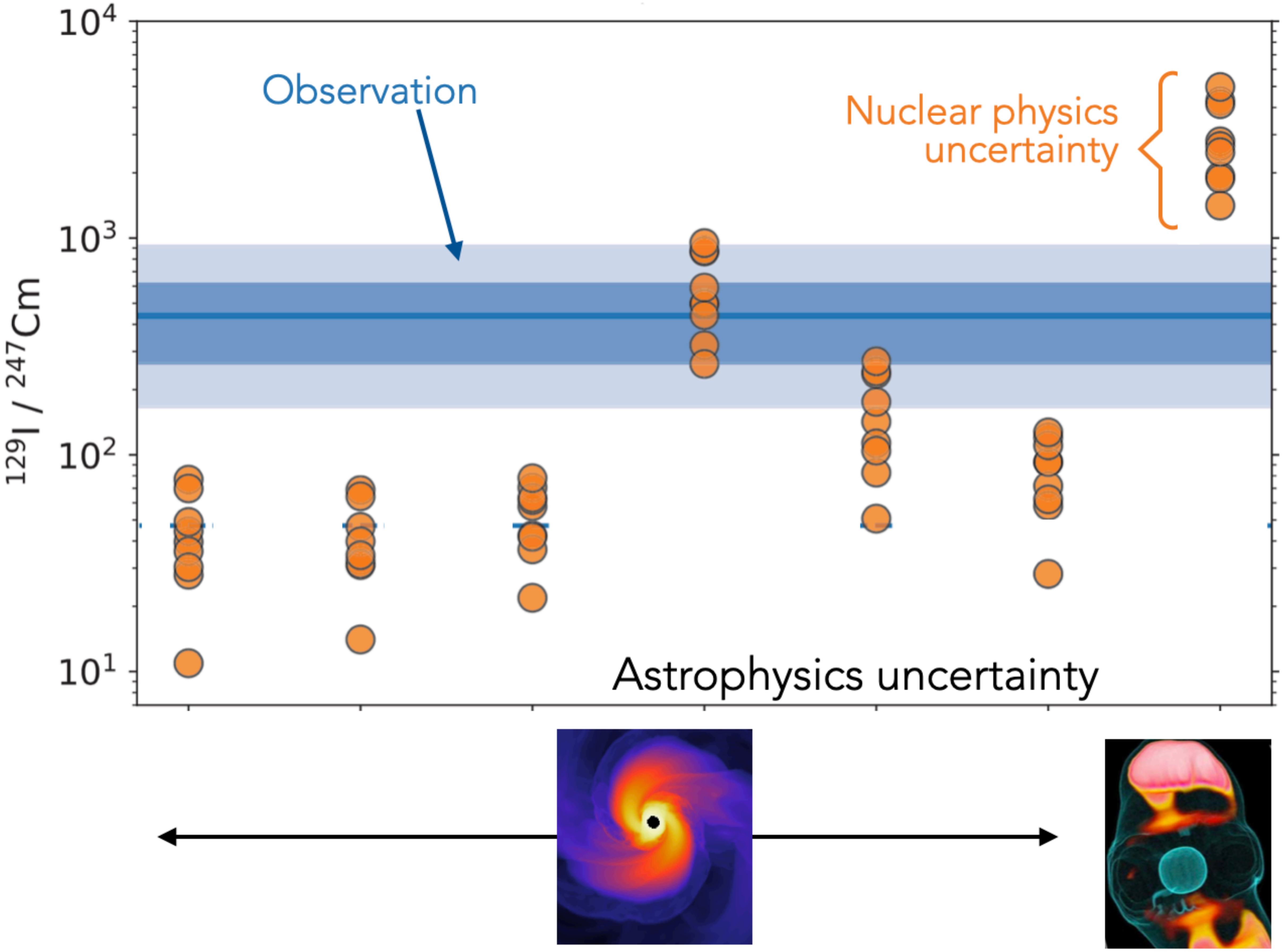
Connecting astrophysics and nuclear physics

Côtè et al. Science (2021)



Connecting astrophysics and nuclear physics

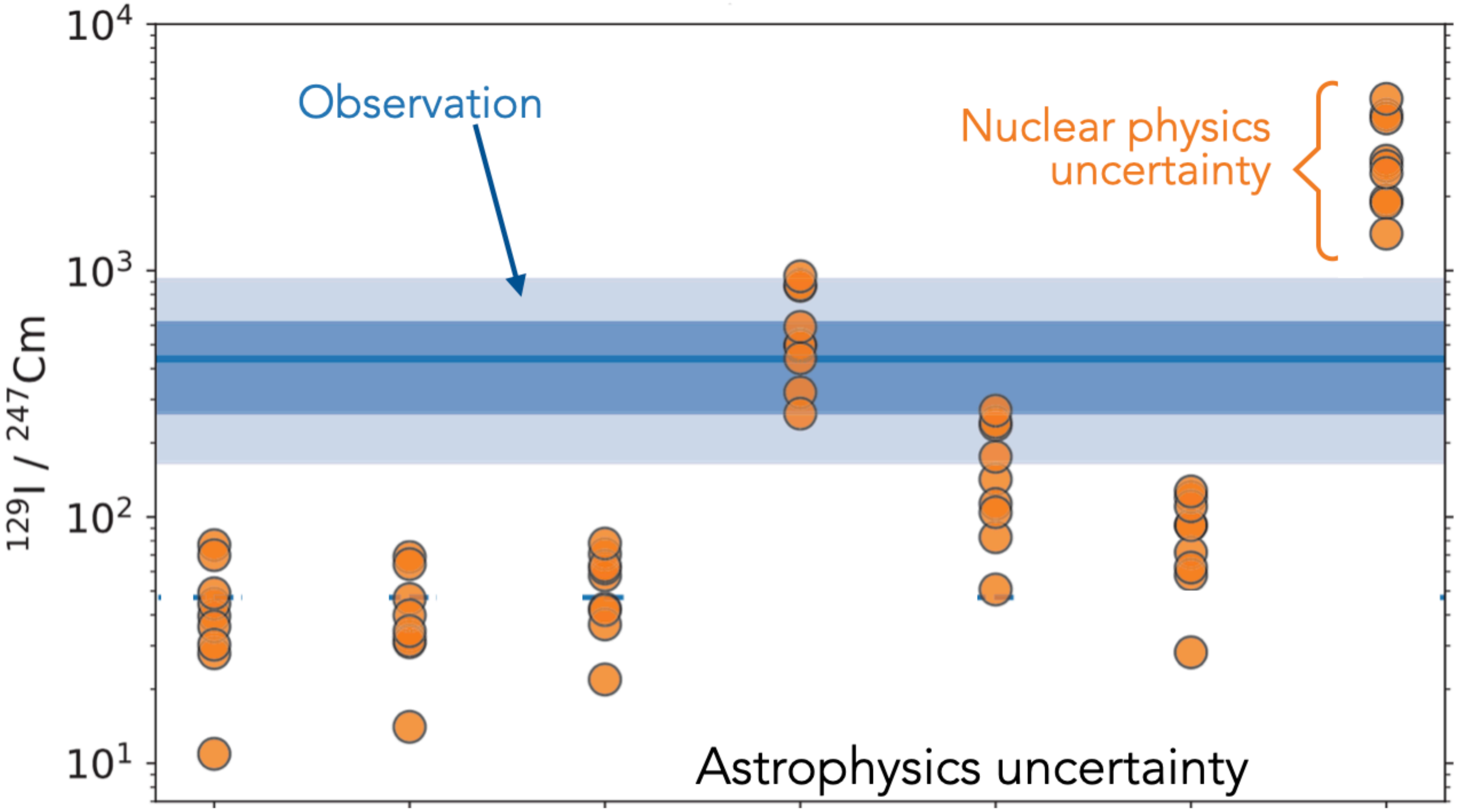
Côtè et al. Science (2021)

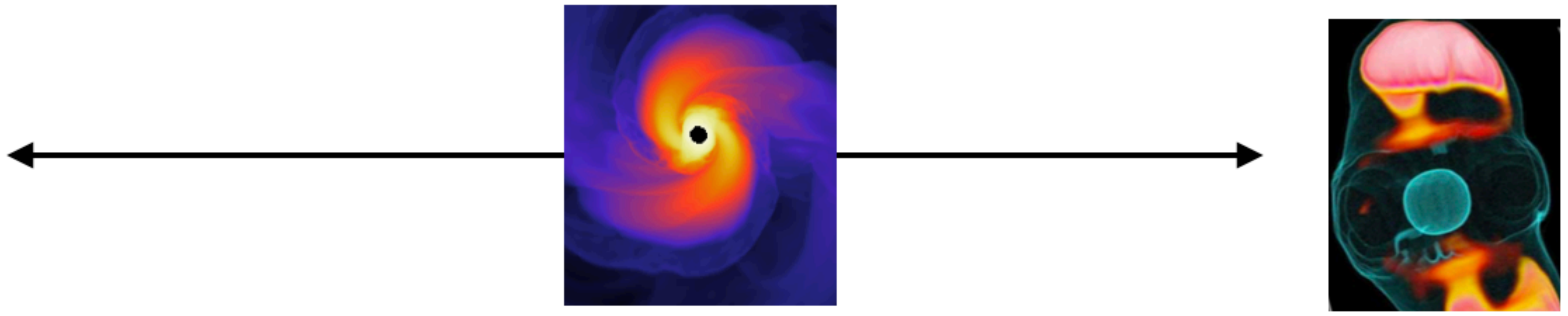


- **Multimessenger astronomy**: electromagnetic + gravitational waves + neutrinos
- Advanced **astrophysical simulations** + detailed **physics** (supercomputers)
- **New experimental frontier**: extreme-neutron rich nuclei at FAIR, FRIB, RIKEN, ISOLDE, TRIUMF,…
- Increased number observations of **oldest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

Connecting astrophysics and nuclear physics

Côtè et al. Science (2021)





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Origin and history of heavy elements in the Universe