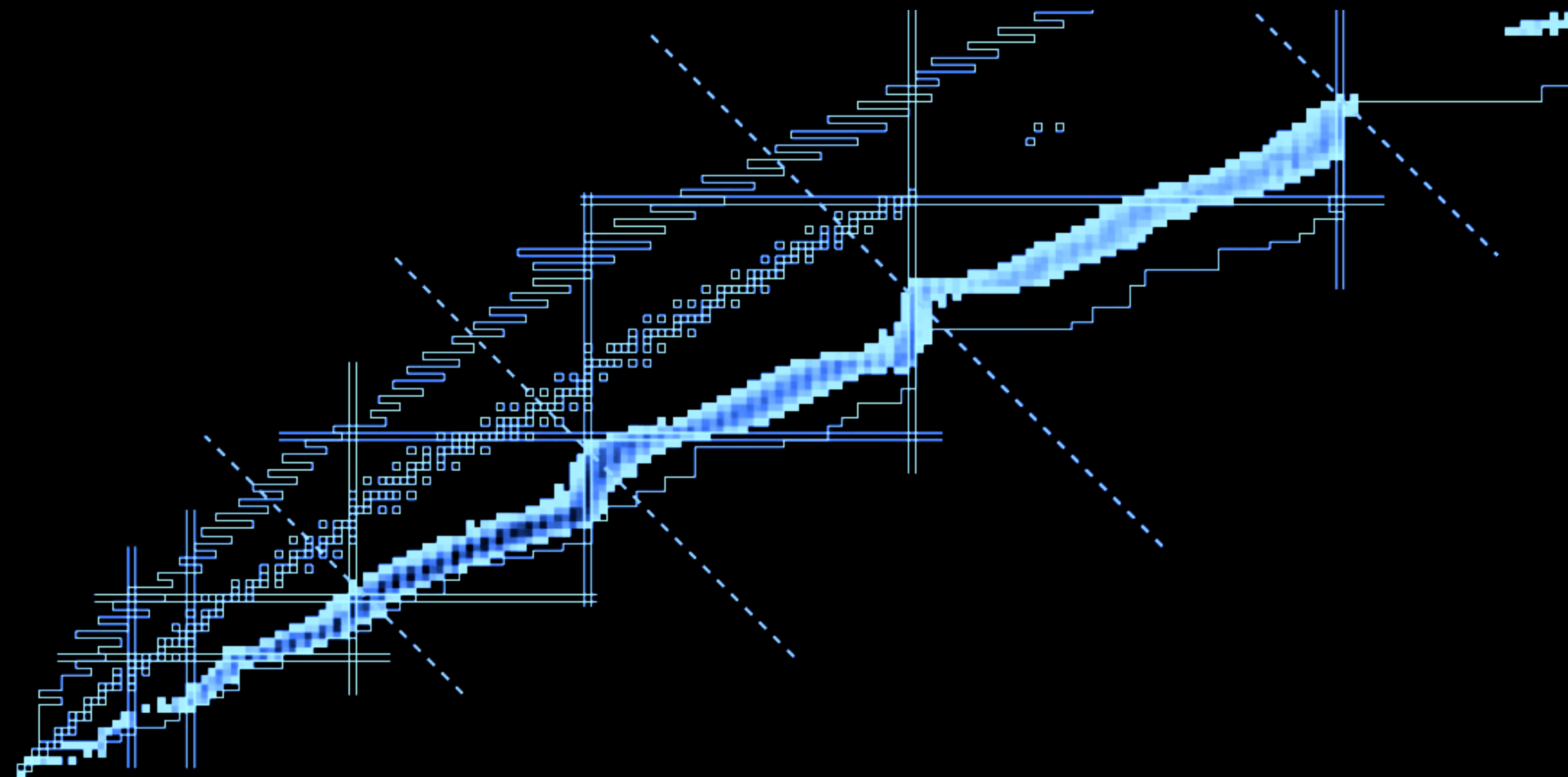
IMPACT OF NEUTRINO INTERACTIONS AND NUCLEAR UNCERTAINTIES ON THE R-PROCESS NUCLEOSYNTHESIS

GSI WORKSHOP 19.10.2022

INA KULLMANN - UNIVERSITÉ LIBRE DE BRUXELLES

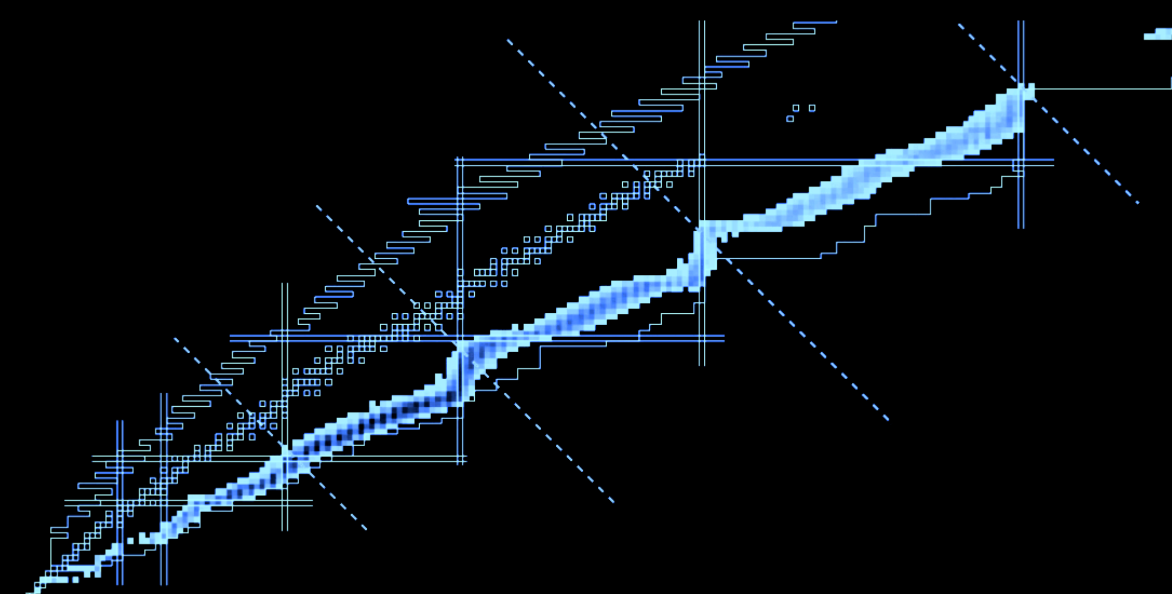
IN COLLABORATION WITH S. GORIELY, O.JUST A. BAUSWEIN, T. JANKA



COLLABORATION

- Nucleosynthesis work:
  Stephane Goriely & Ina Kullmann

- NS-NS merger hydrodynamical simulation:
  Oliver Just, Andreas Bauswein, Thomas Janka,
  Ricard Ardevol-Pulpillo



CONTENT

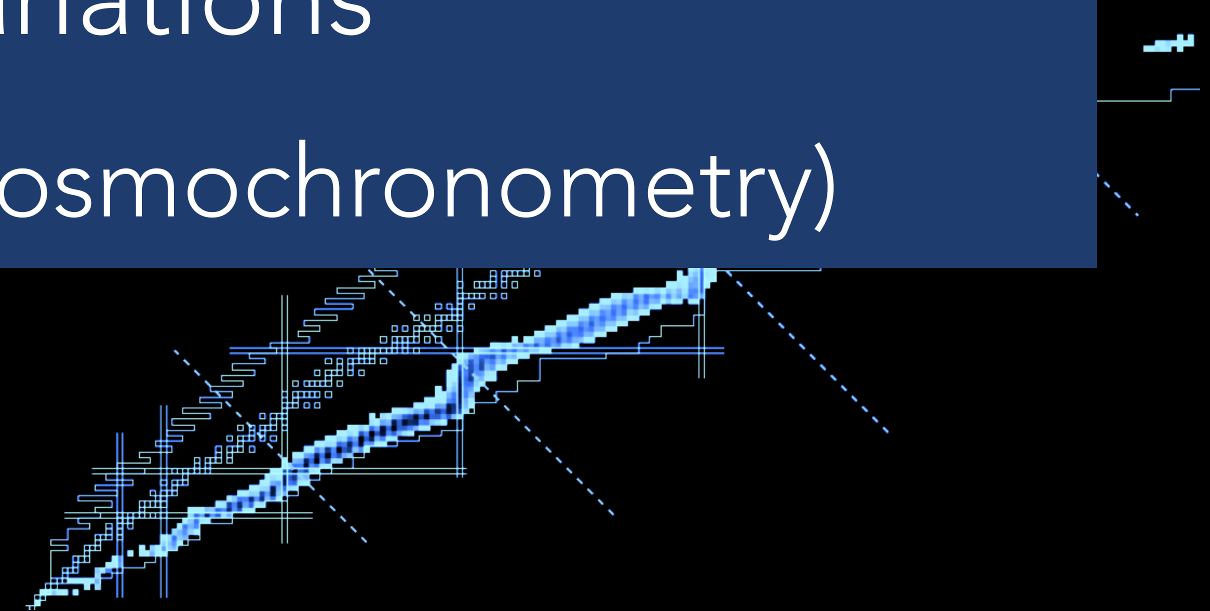
- **Introduction**

Kullmann et al. 2021, MNRAS, 510, 2804
Just et al. 2021, MNRAS, 510, 2820

- **Part 1: Dynamical ejecta including ν's**
  - conditions and composition
  - Impact on r-process nucleosynthesis
- **Part 2: Dynamical + BH-torus ejecta**

Kullmann et al. 2022 arXiv:2207.07421

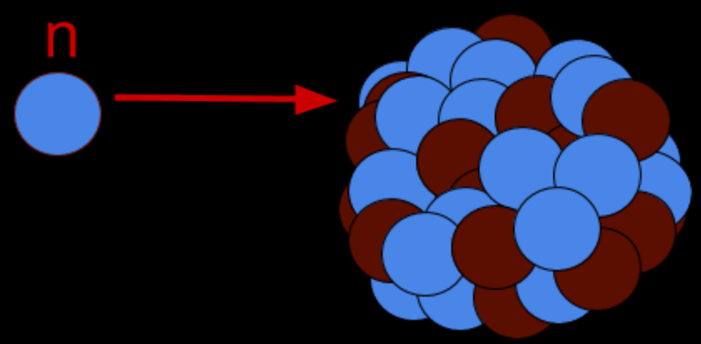
  - Nuclear physics input variations
  - Impact on r-process (& cosmochronometry)

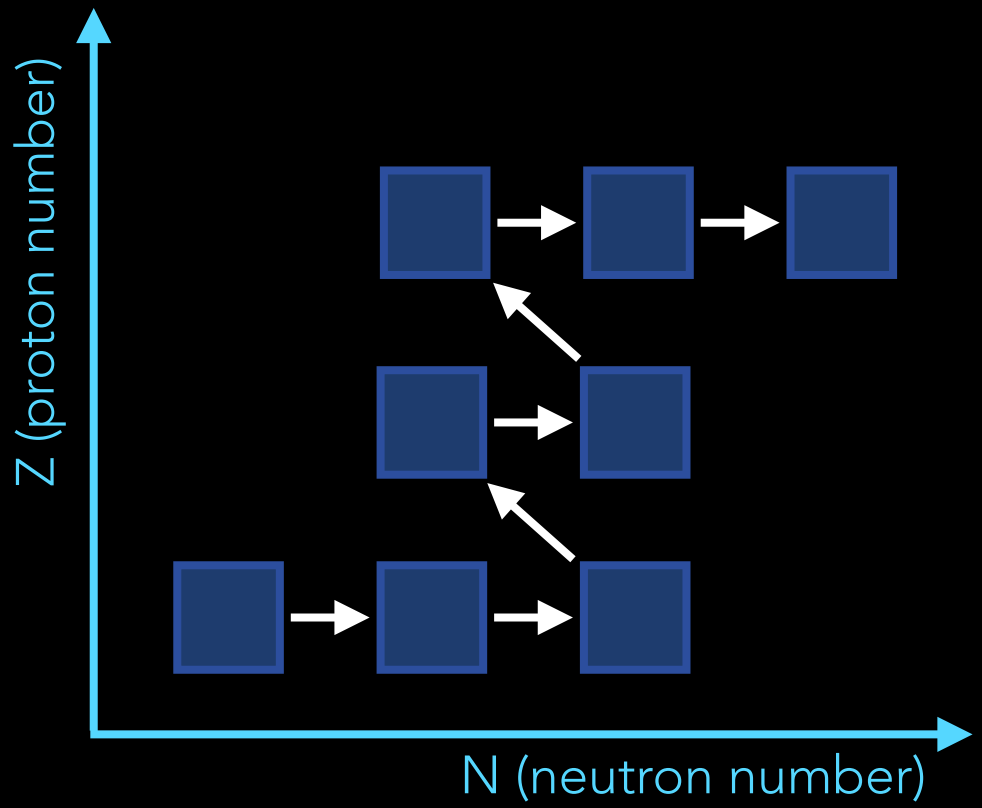


THE R-PROCESS

->RAPID NEUTRON CAPTURE PROCESS

- Synthesise ~50% of elements heavier than Iron
- Short timescales (~3s)
- Neutron rich environment
    - neutron-rich unstable & experimentally unknown nuclei





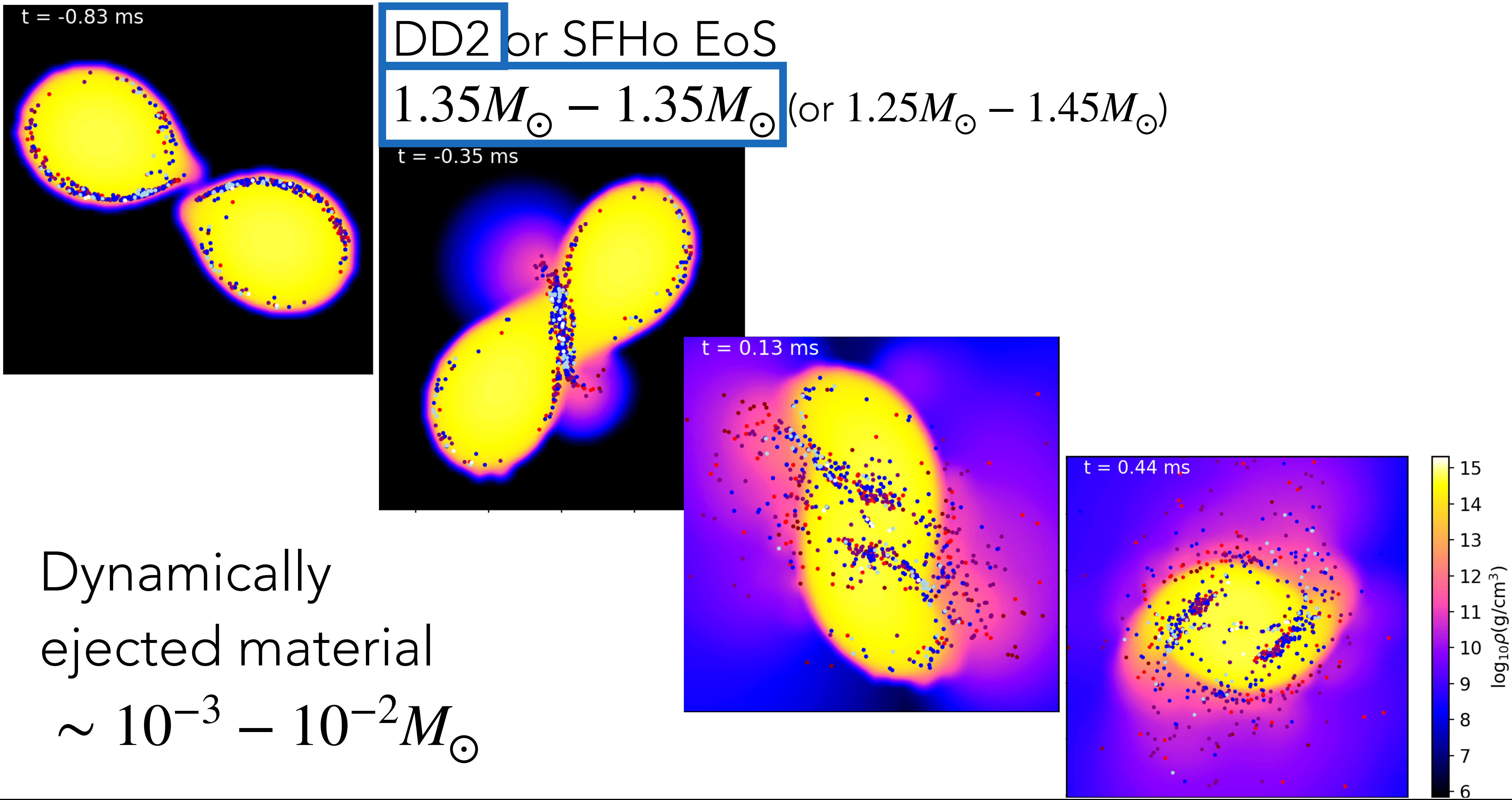
PART 1: DYNAMICAL EJECTA WITH NEUTRINO REACTIONS

Kullmann et al. 2021, MNRAS, 510, 2804
Just et al. 2021, MNRAS, 510, 2820

HYDRODYNAMICAL NS-NS MERGER SIMULATIONS (SPH)

DD2 or SFHo EoS

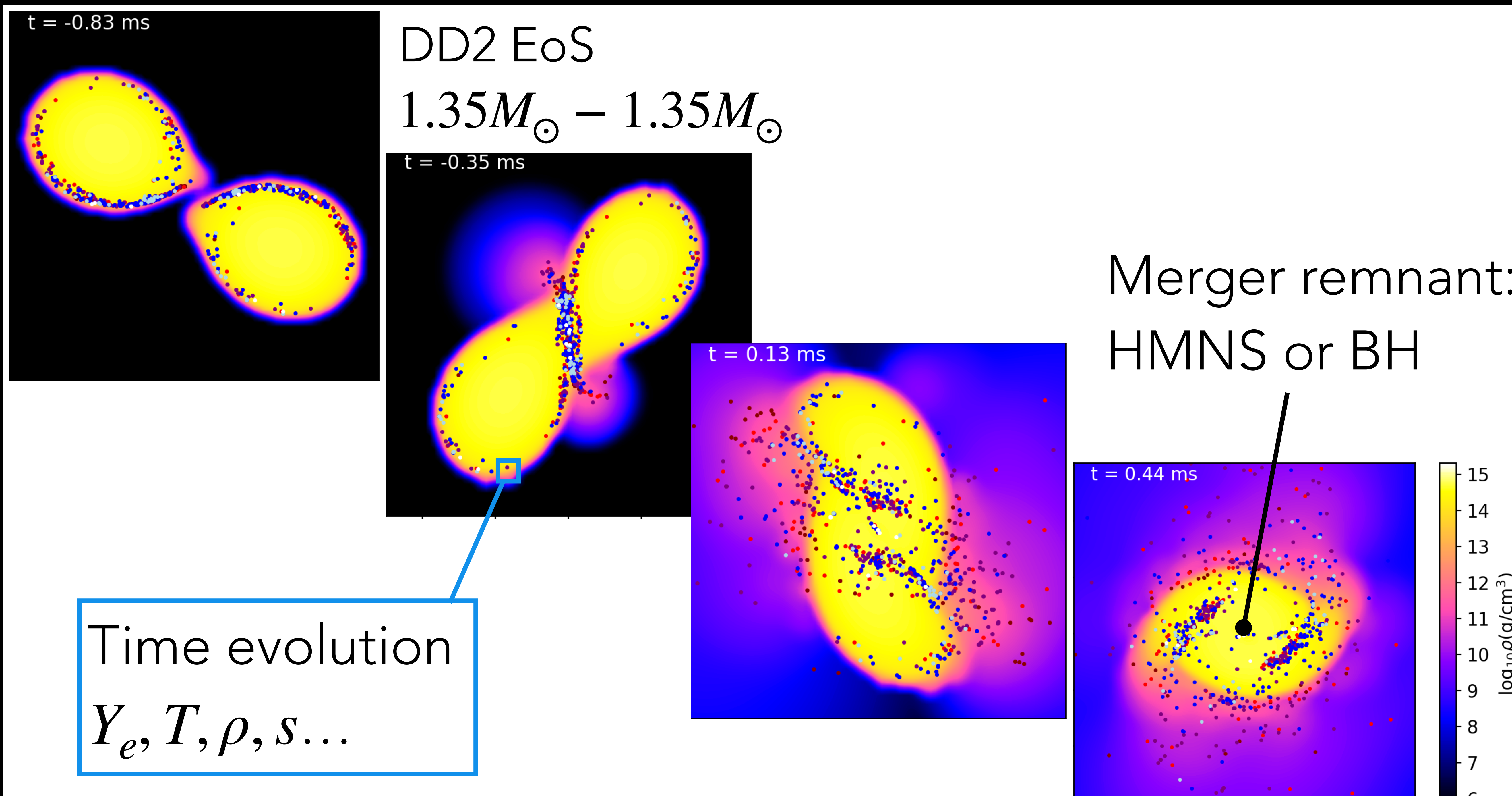
$1.35M_\odot - 1.35M_\odot$ (or $1.25M_\odot - 1.45M_\odot$)



Dynamically ejected material $\sim 10^{-3} - 10^{-2} M_\odot$

HYDRODYNAMICAL NS-NS MERGER SIMULATIONS (SPH)

See Ardevol-Pulpillo et al. 2019, MNRAS, 485, 4754 = ILEAS

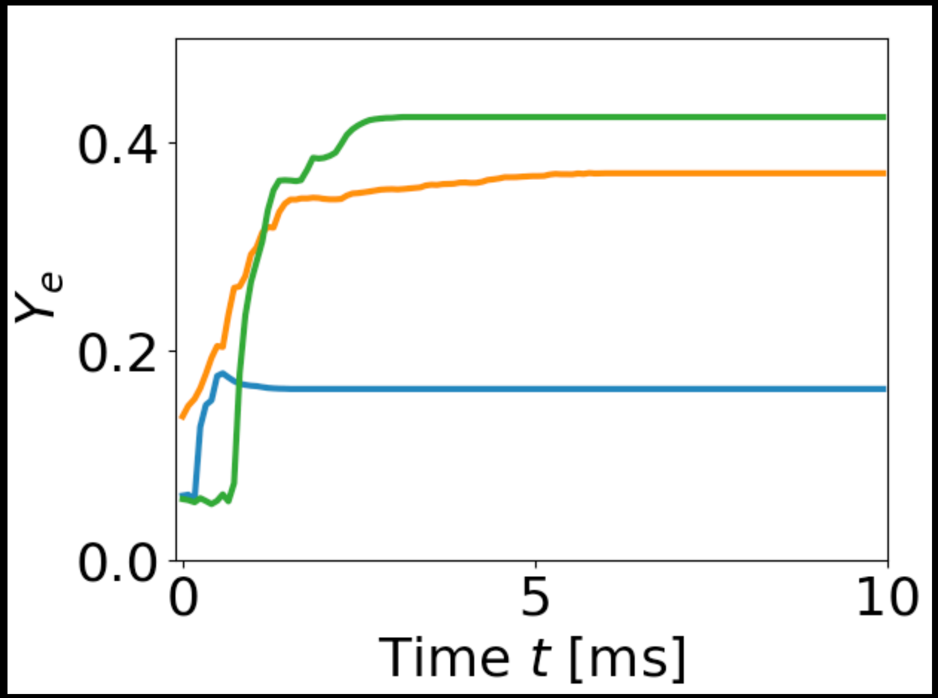


ADVANCED MODELING OF WEAK NUCLEONIC REACTIONS (ILEAS)

$$\nu_e + n \rightarrow p + e^-: \quad Y_e \uparrow$$

$$\bar{\nu}_e + p \rightarrow n + e^+: \quad Y_e \downarrow$$

t=5ms



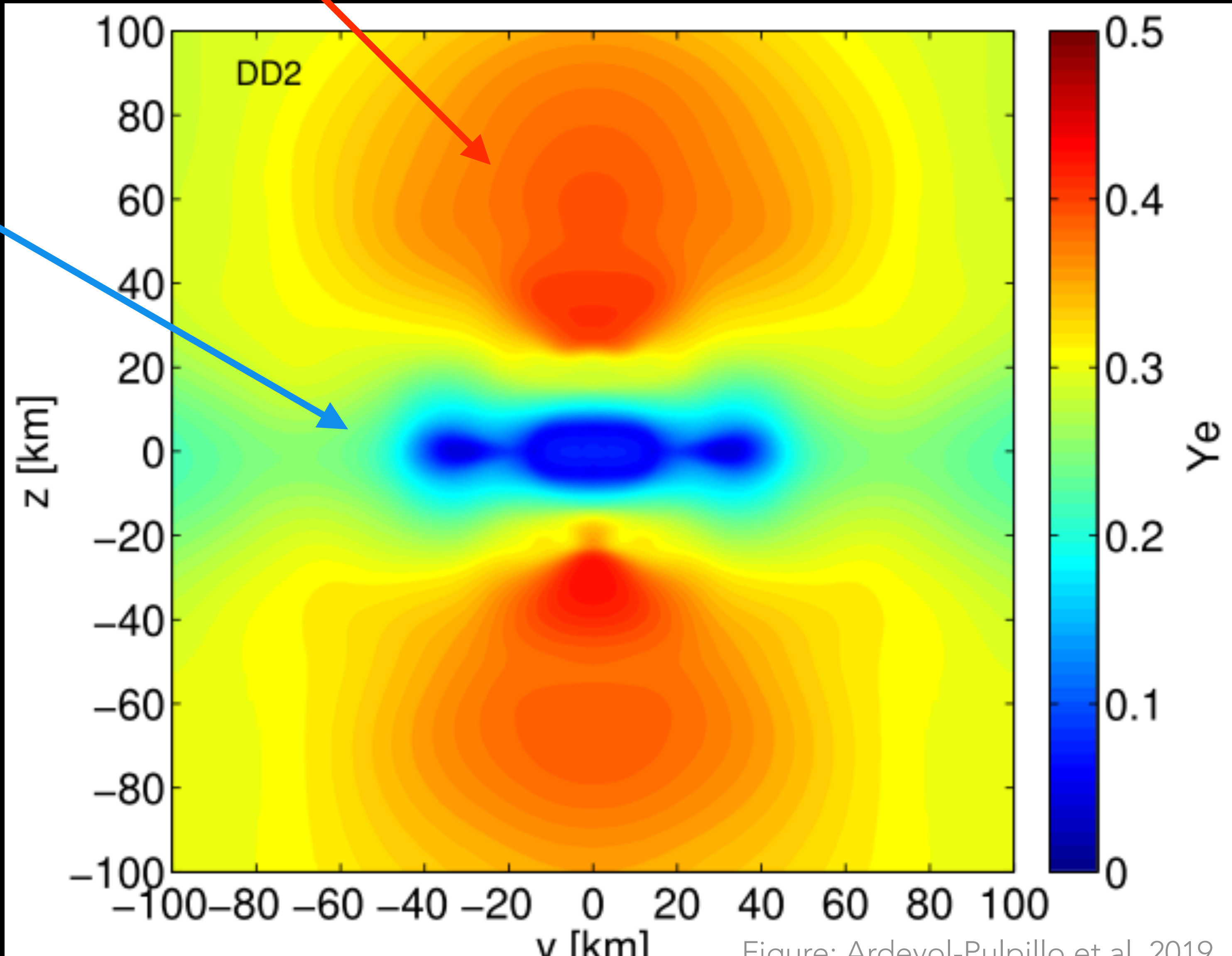


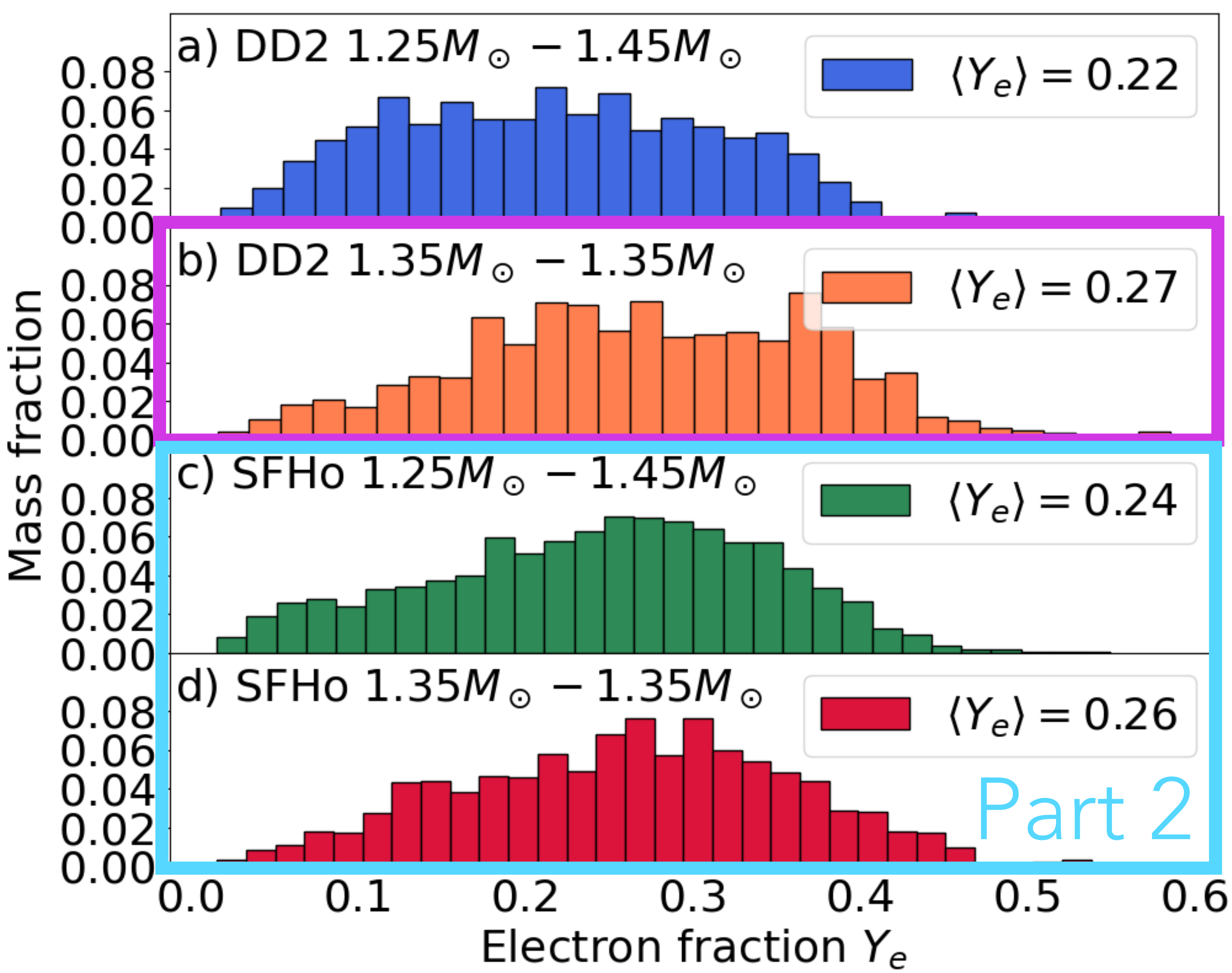
Figure: Ardevol-Pulpillo et al. 2019

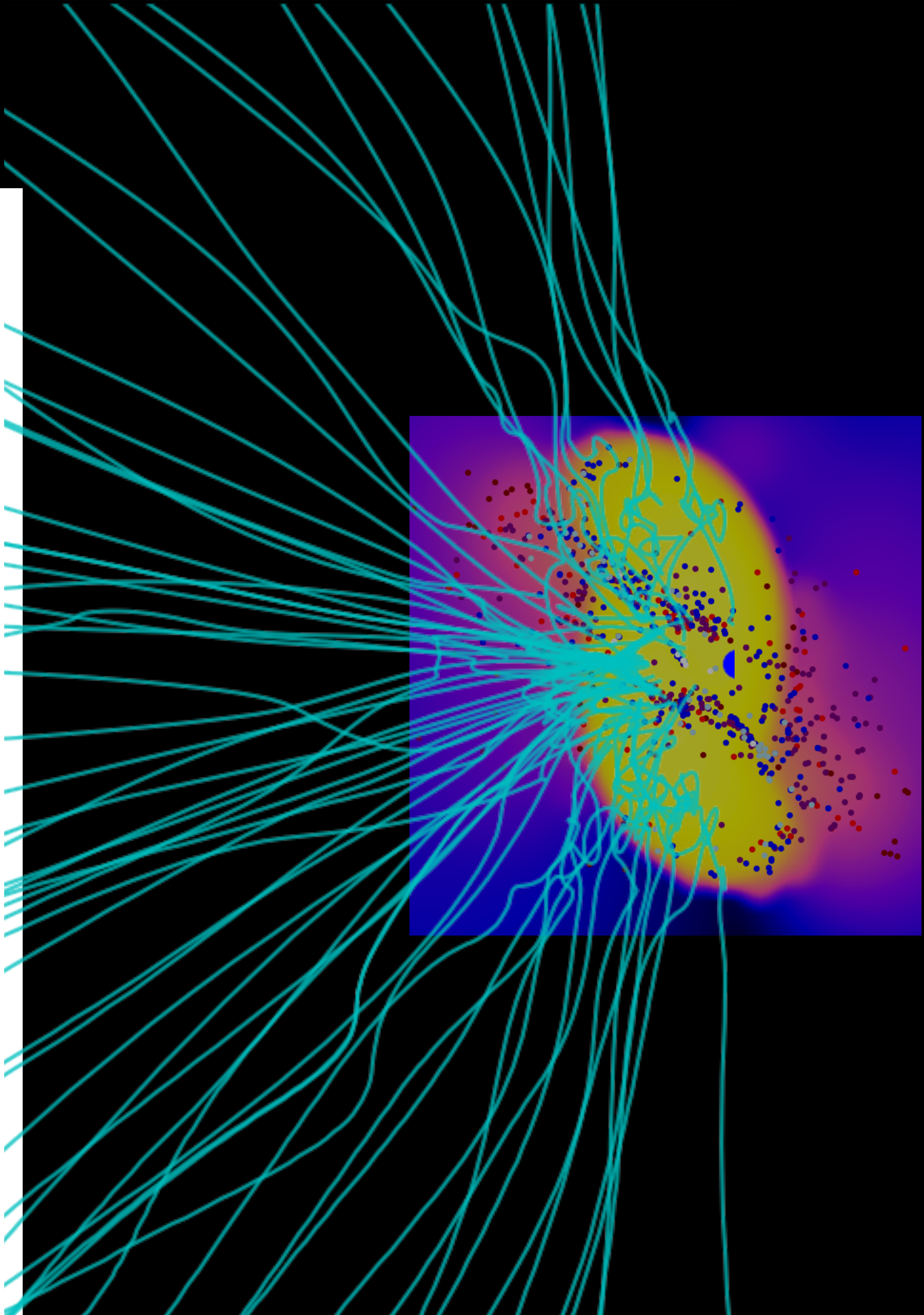
(See Ardevol-Pulpillo et al. 2019 for details)

COMPOSITION OF THE DYNAMICAL EJECTA

~800-4000 trajectories

Kullmann+2021





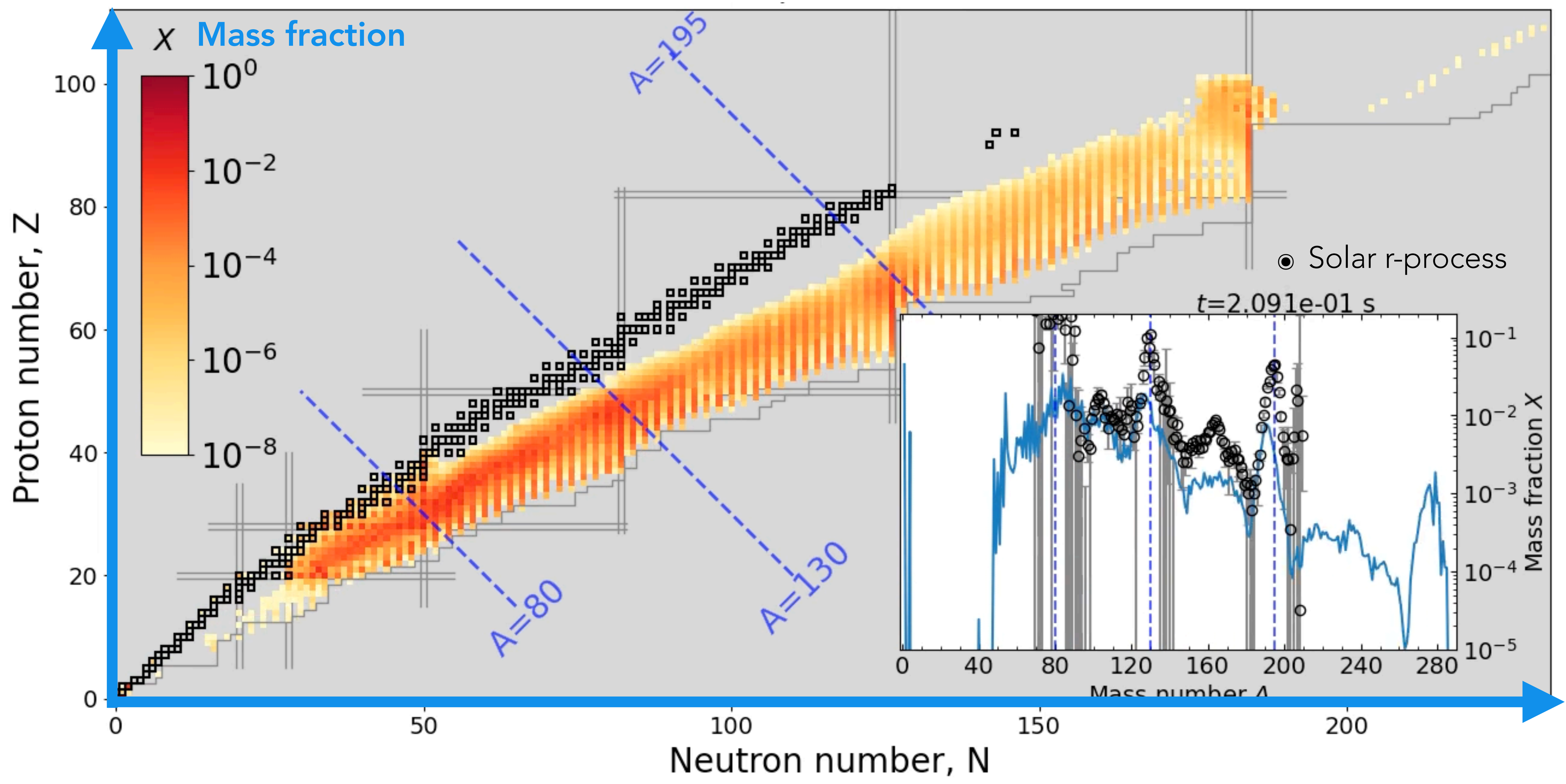
R-PROCESS CALCULATIONS

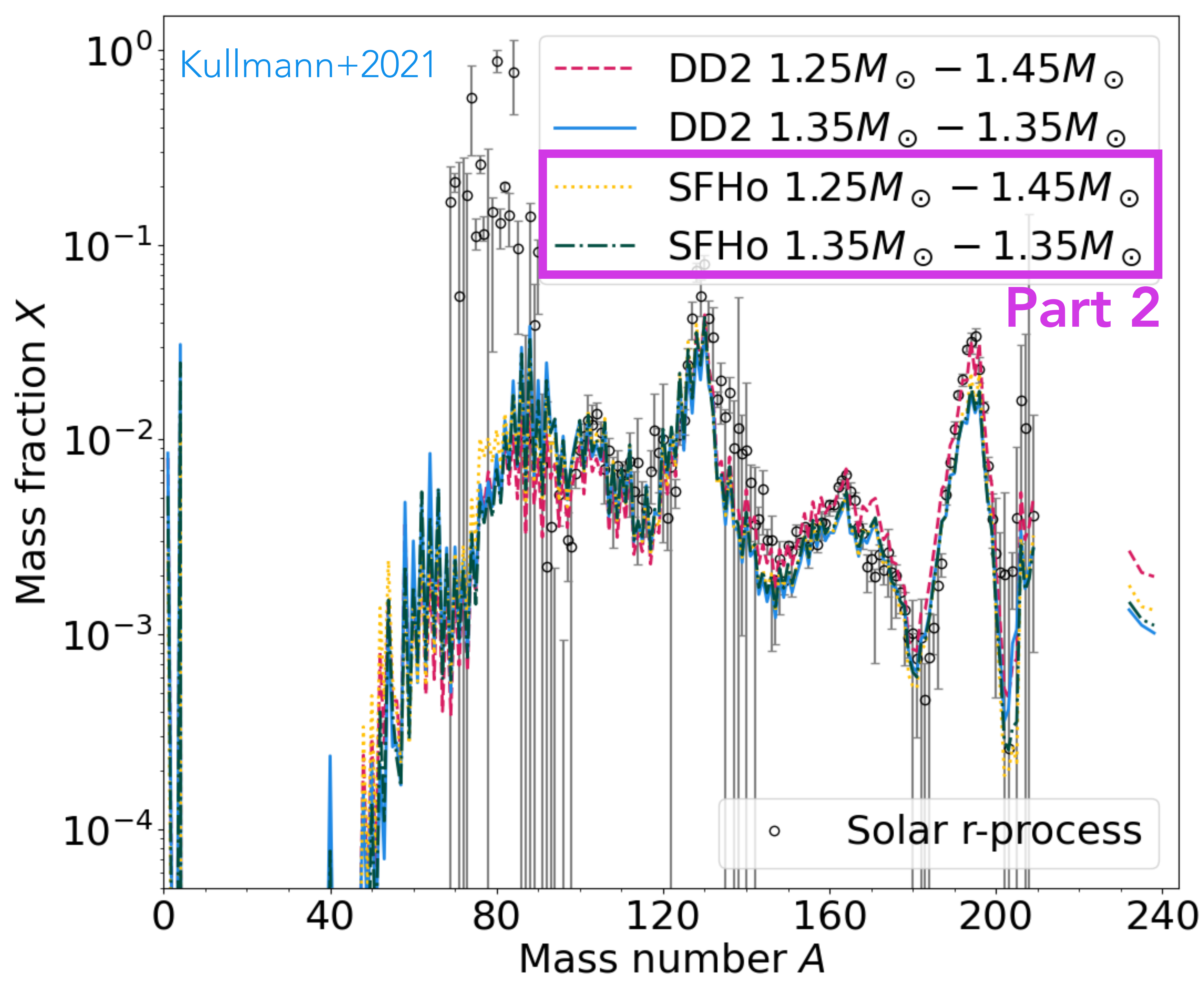
(animation)

Kullmann+2021

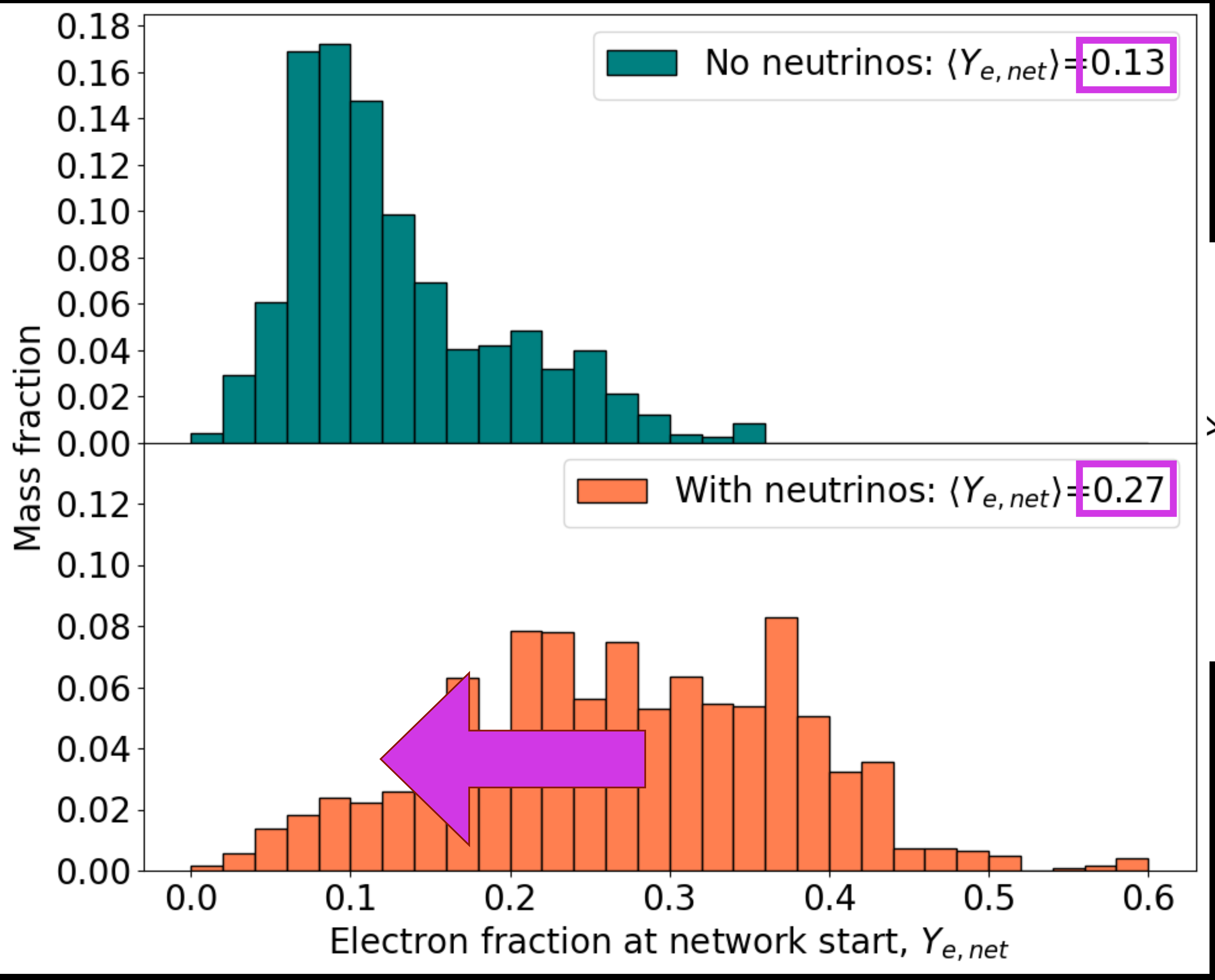
SFHo $1.35M_\odot - 1.35M_\odot$
(default nuclear physics input)

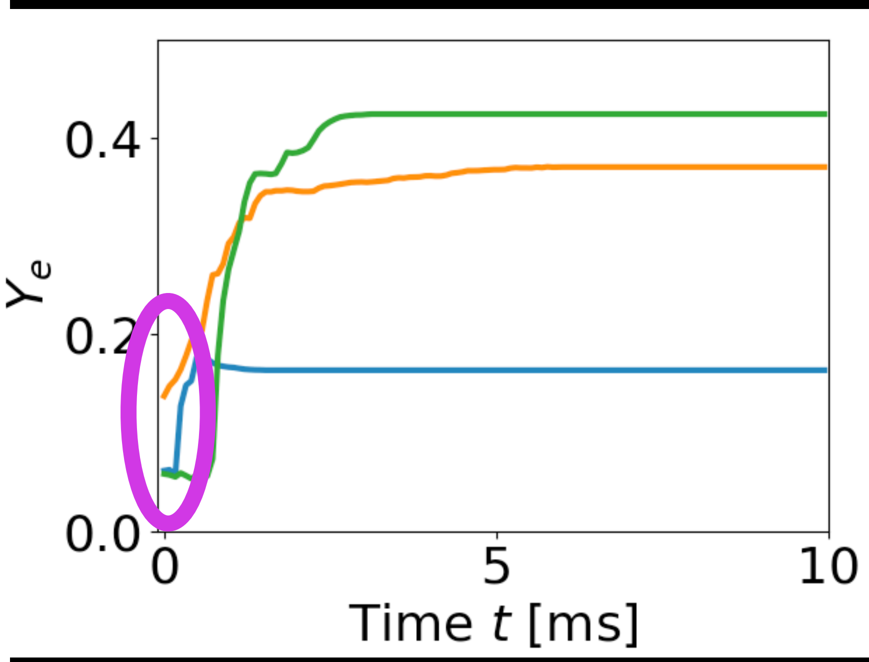
No fission recycling!




Kullmann+2021
DD2 $1.25M_\odot - 1.45M_\odot$
DD2 $1.35M_\odot - 1.35M_\odot$
SFHo $1.25M_\odot - 1.45M_\odot$
SFHo $1.35M_\odot - 1.35M_\odot$
Part 2
Solar r-process
Mass fraction X
Mass number A
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
40
80
120
160
200
240

IMPACT OF NEUTRINOS?





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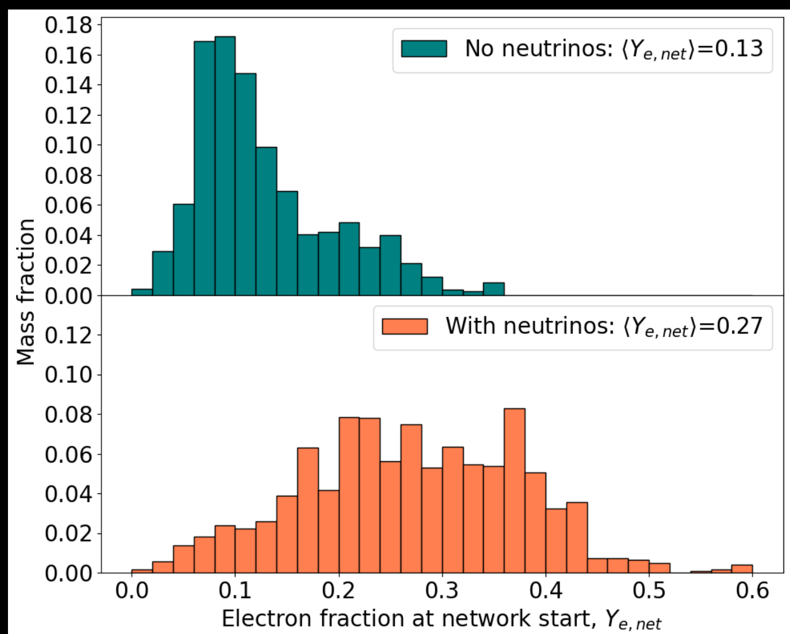
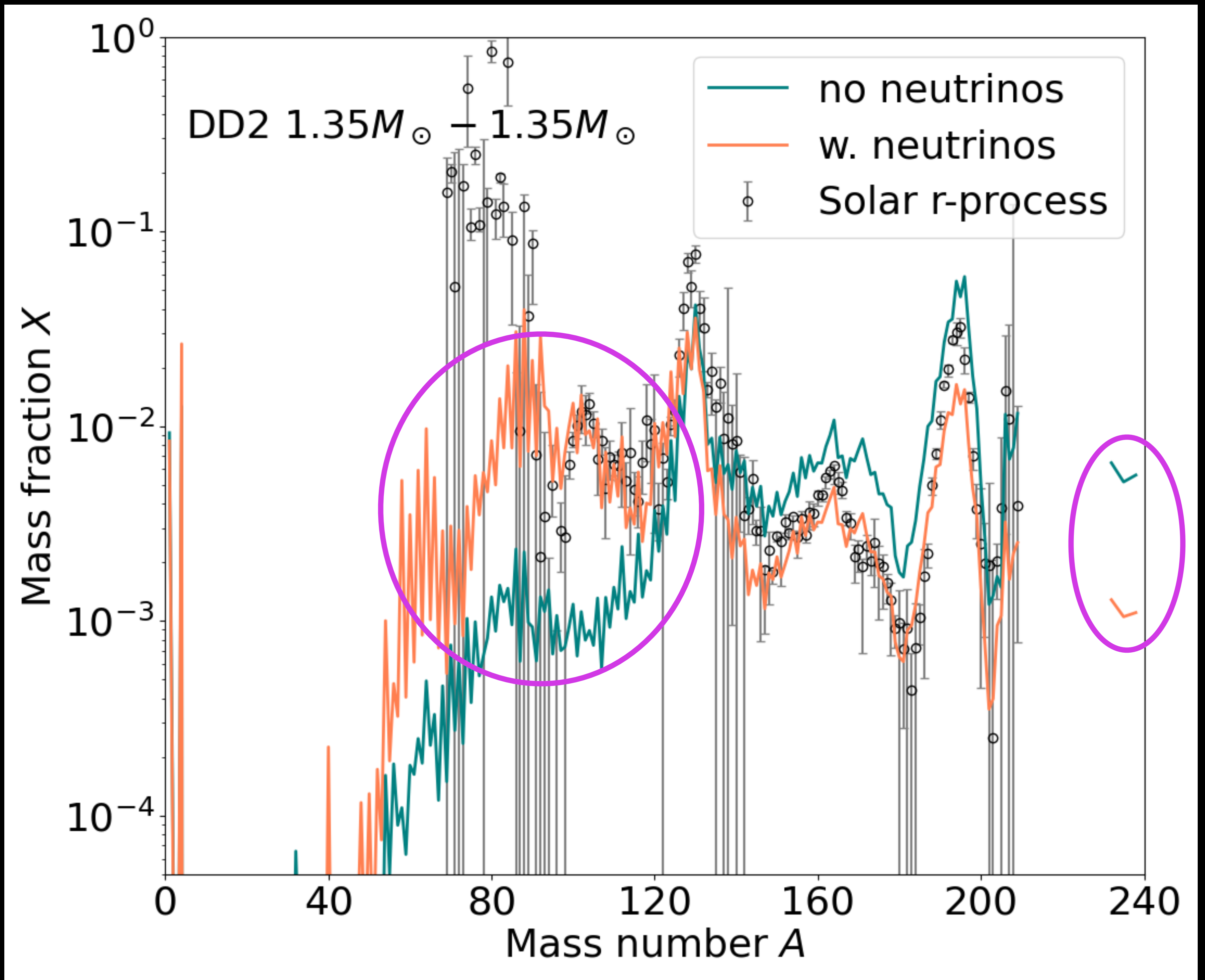
NUCLEOSYNTHESIS RESULTS

Kullmann+2021





HEATING RATE FROM RADIOACTIVE DECAY

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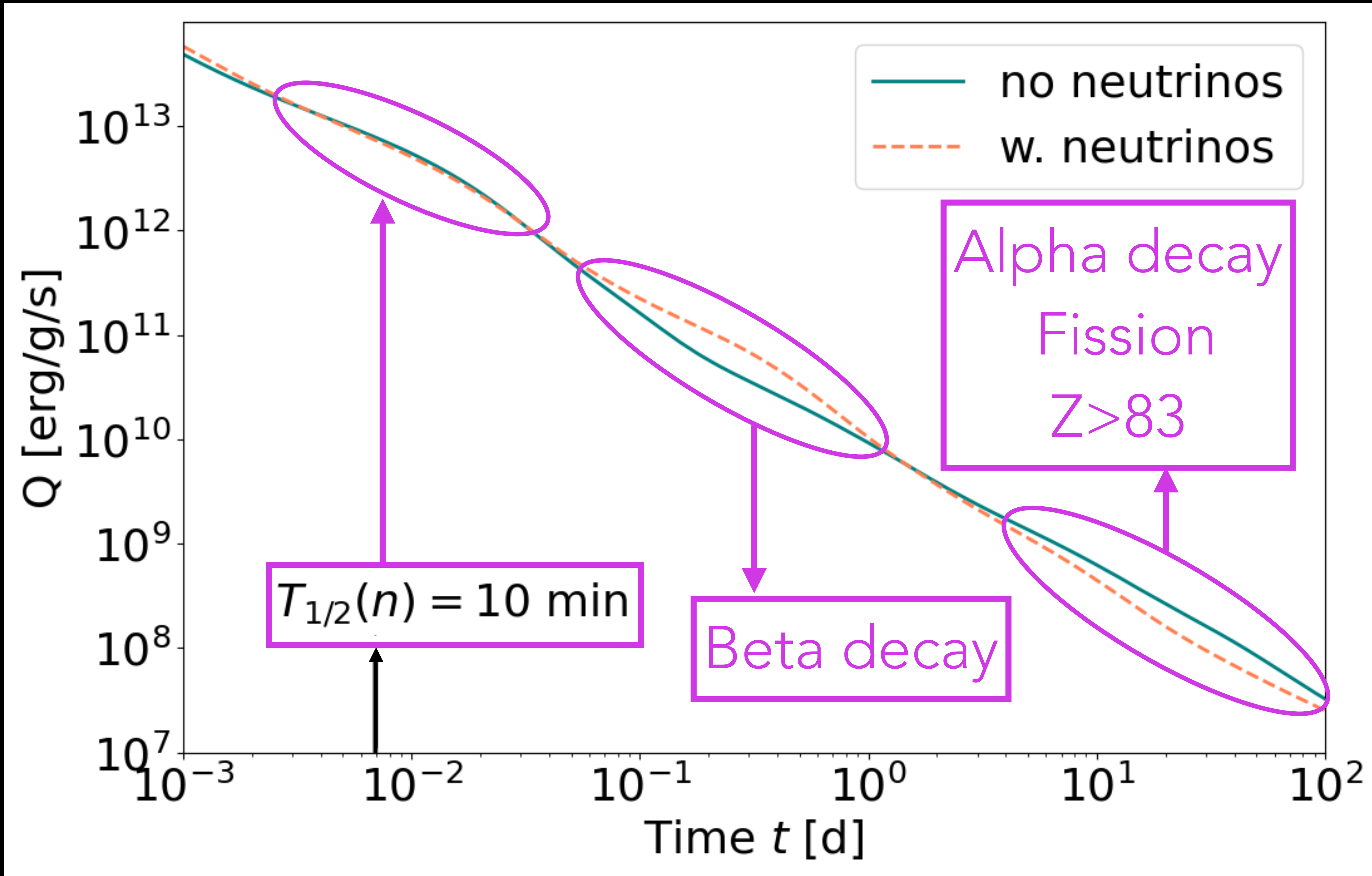
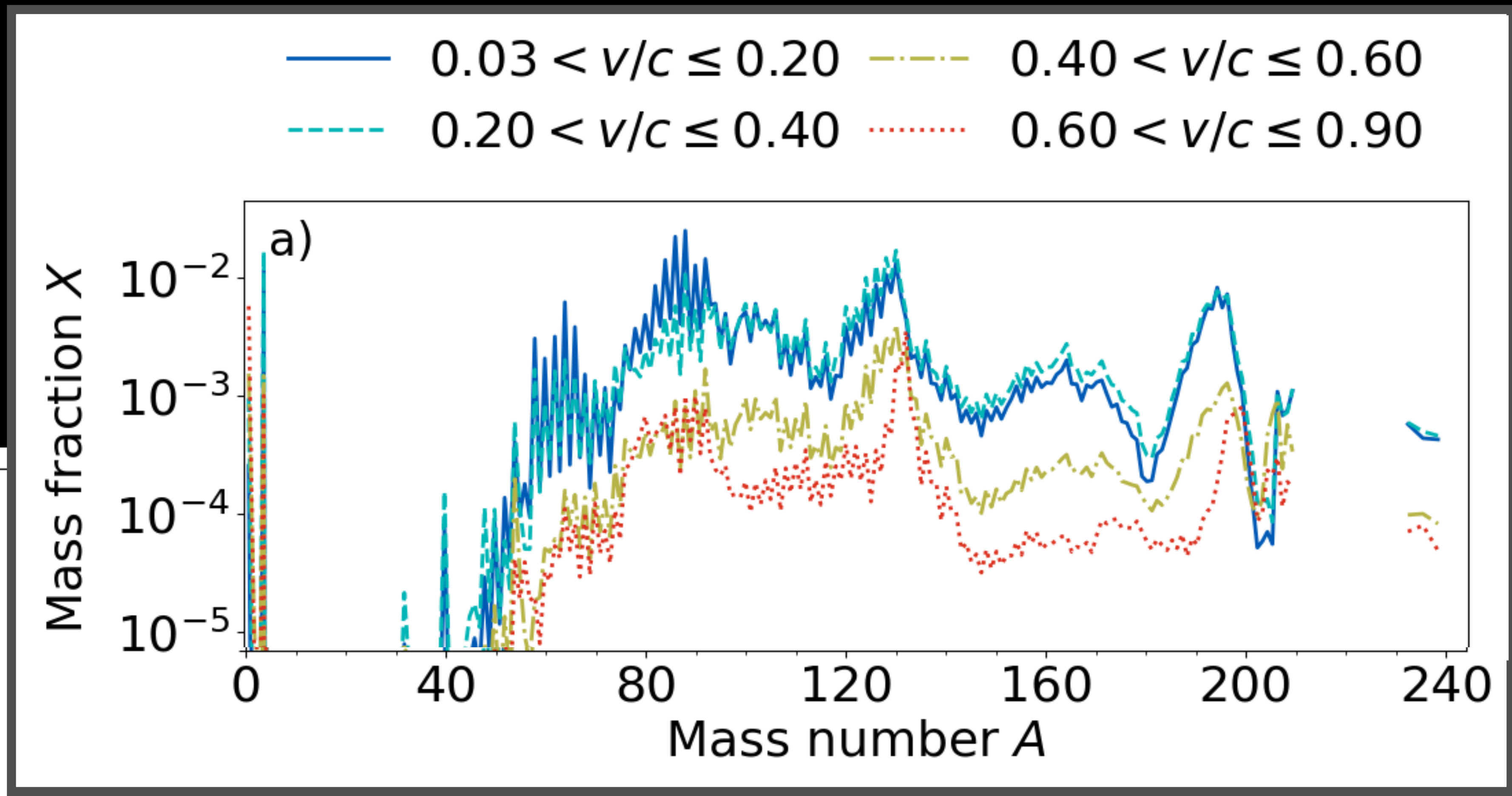
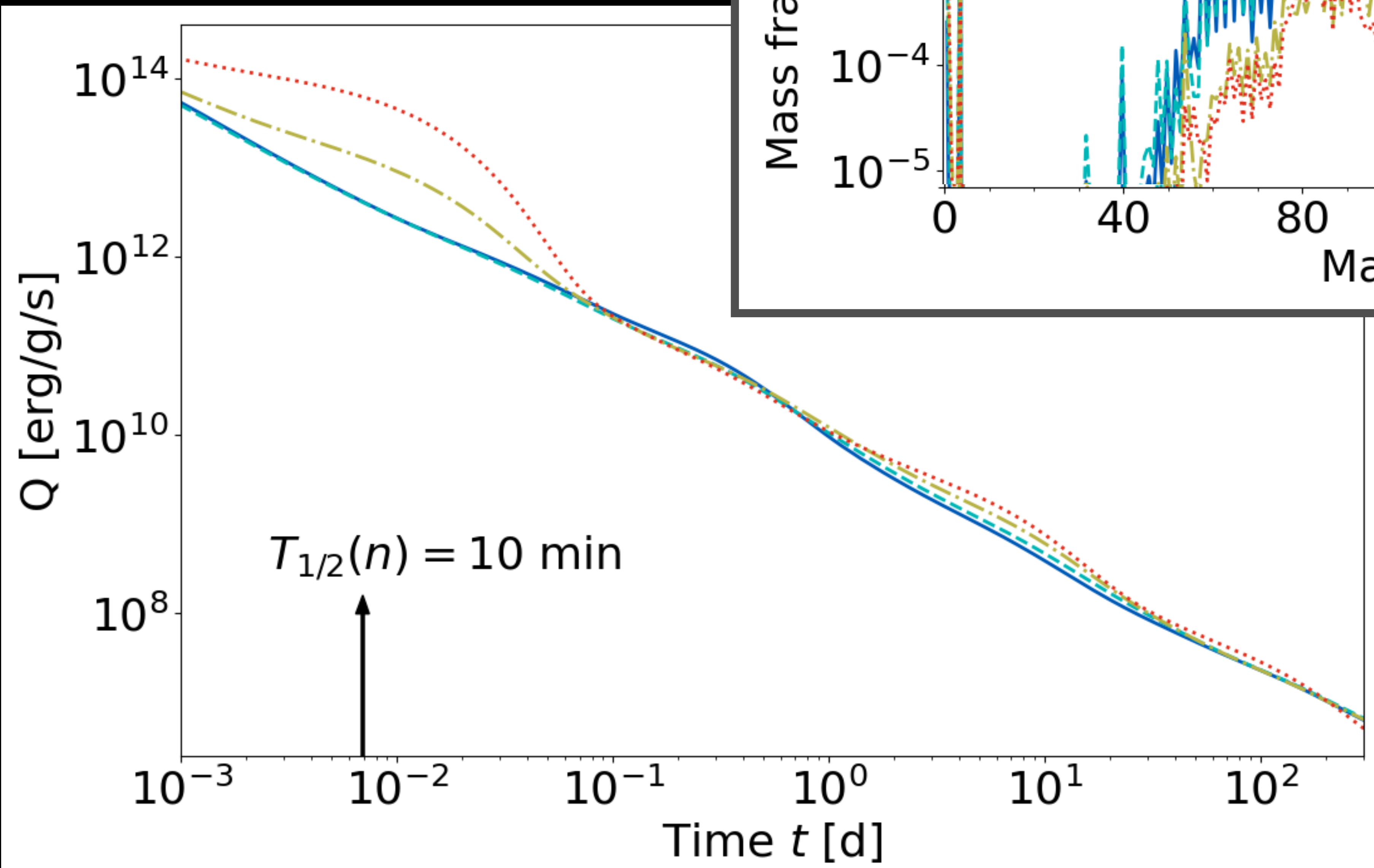


HIGH-VELOCITY COMPONENT





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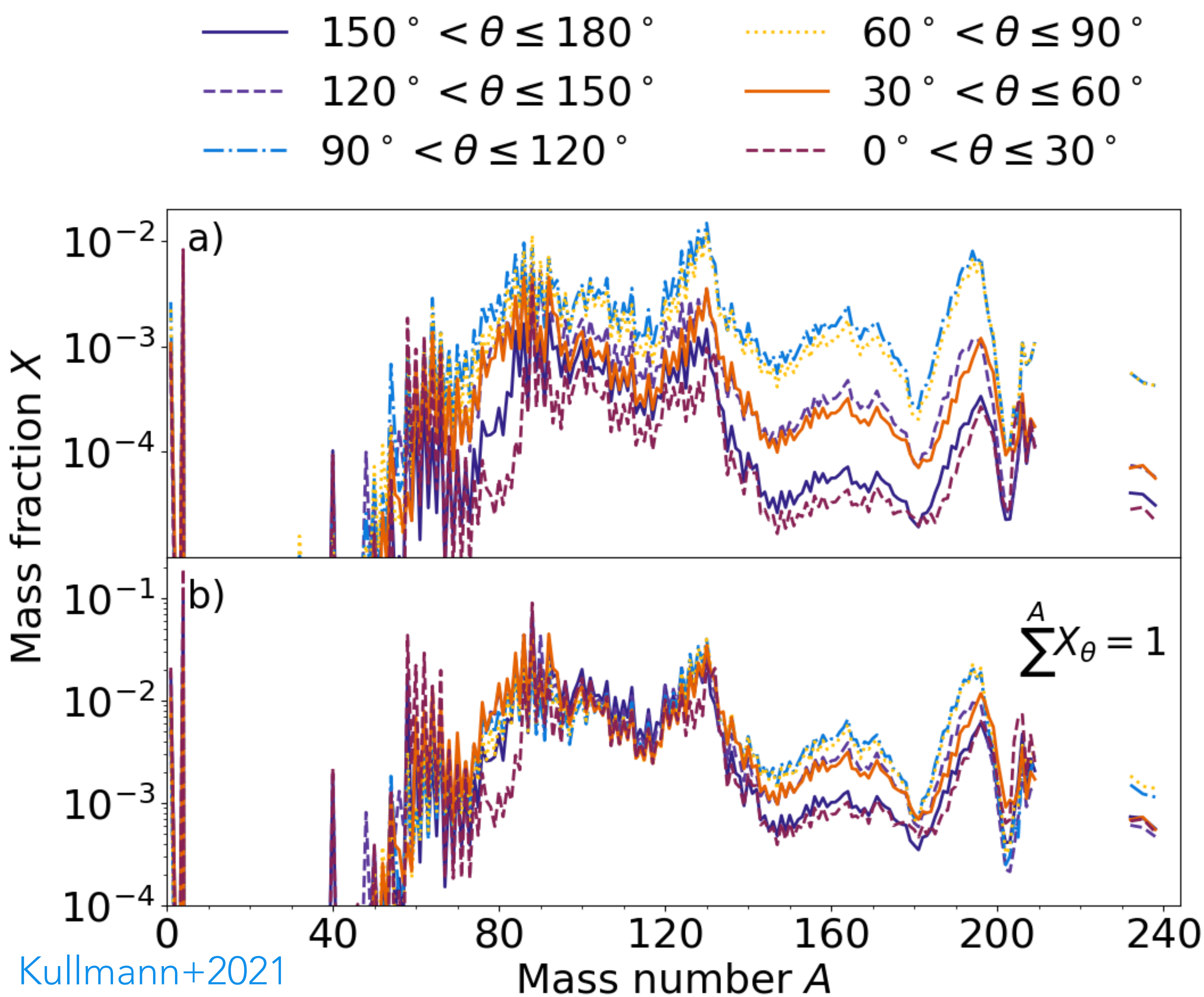
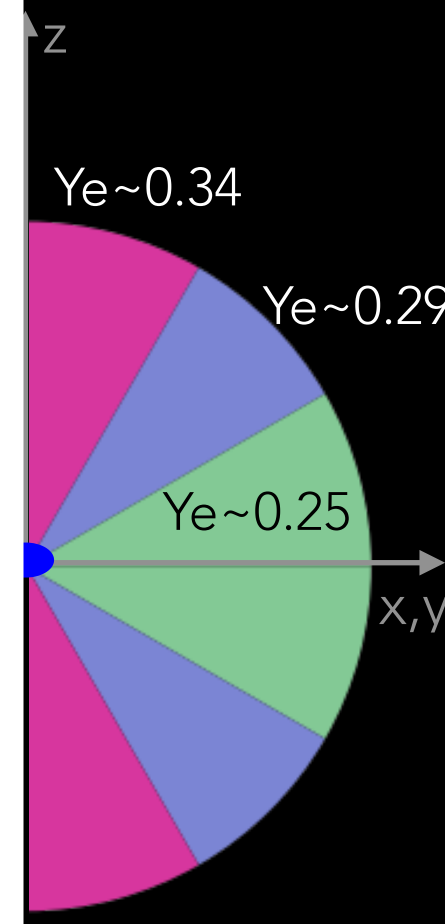
ANGULAR DISTRIBUTION



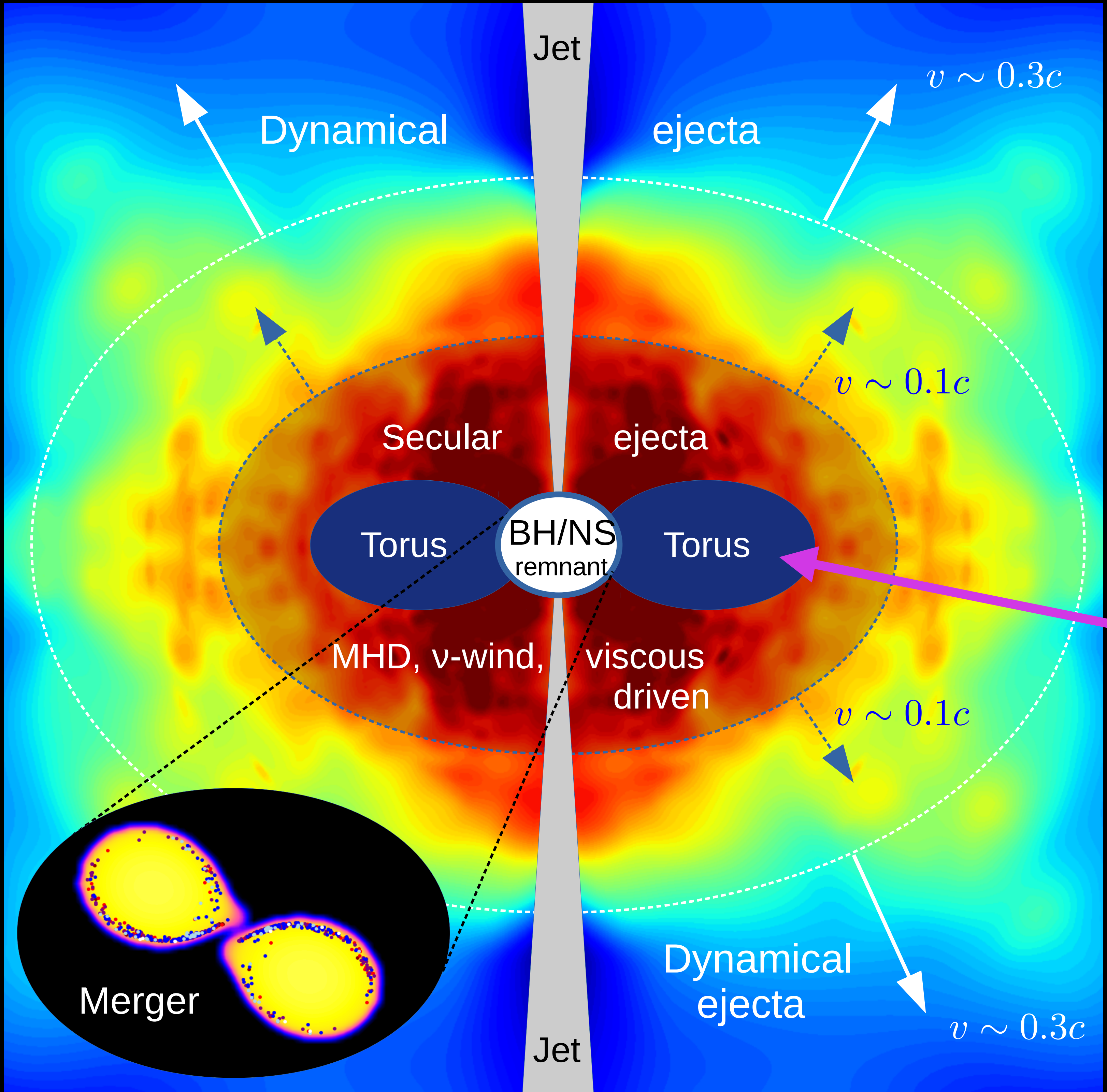
Kullmann+2021



PART 2: TOTAL EJECTA & NUCLEAR UNCERTAINTIES

Kullmann et al. 2022 arXiv:2207.07421

HYDRODYNAMICAL NS-NS MERGER SIMULATIONS



Dynamical ejecta

(ILEAS 2019)

+ BH-Torus

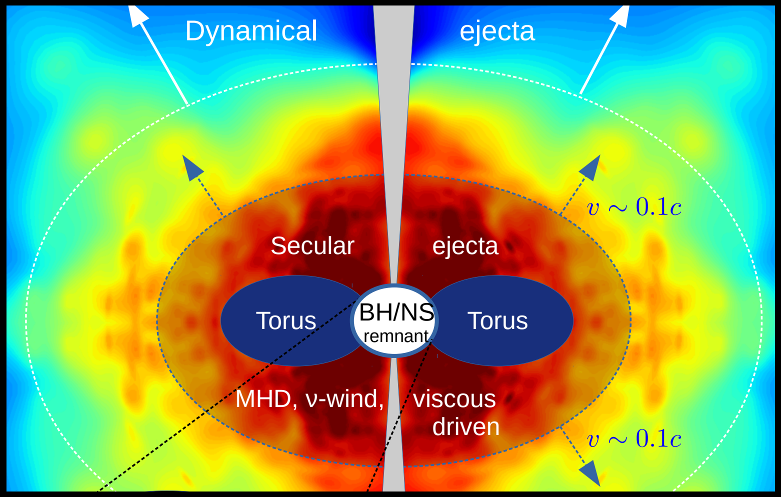
(Just et al. 2015)

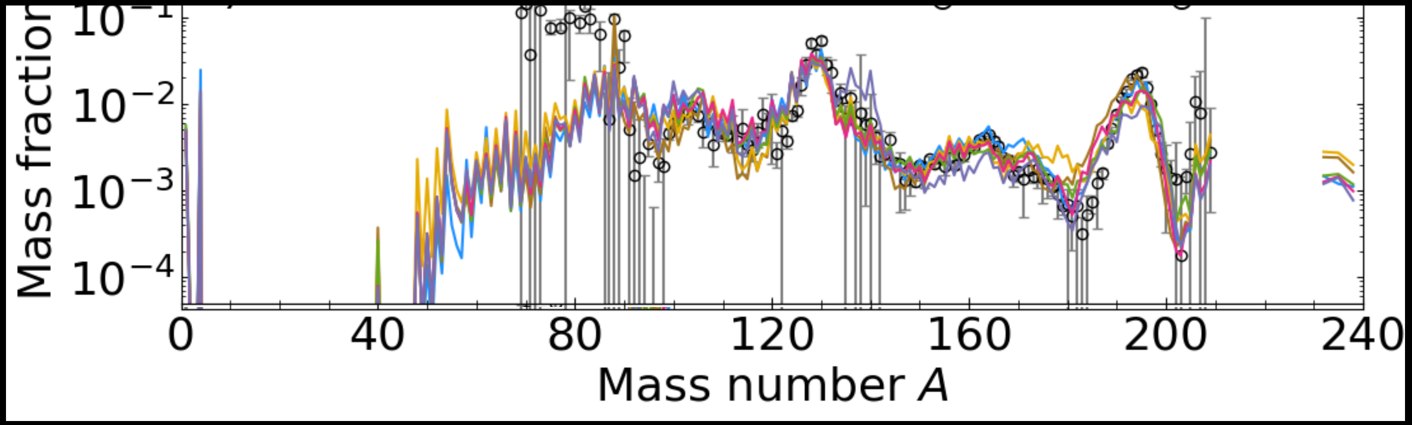
Generally higher Ye

Illustration: O. Just & A. Bauswein

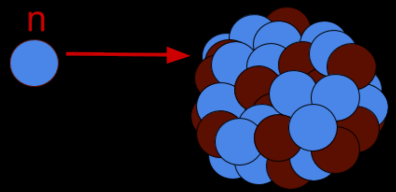
NUCLEAR INPUT VARIATIONS

2x SFHo Dynamical (ILEAS)
+ 2x BH-Torus (Just'15)

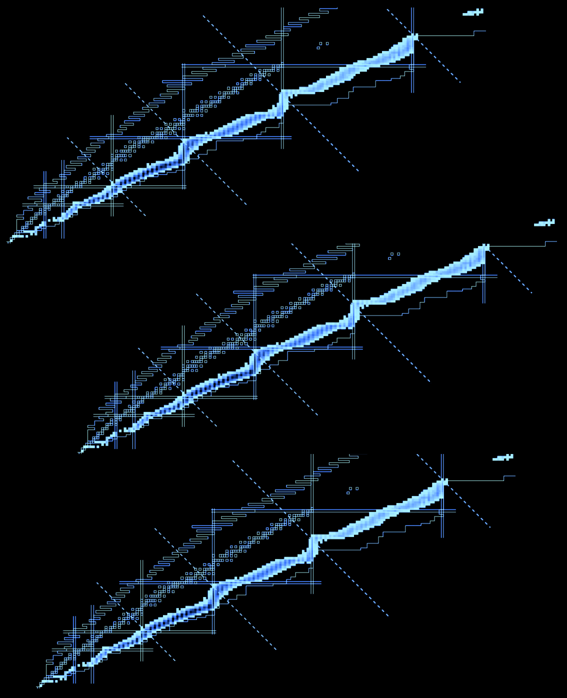




nuclear input



r-process network calculations

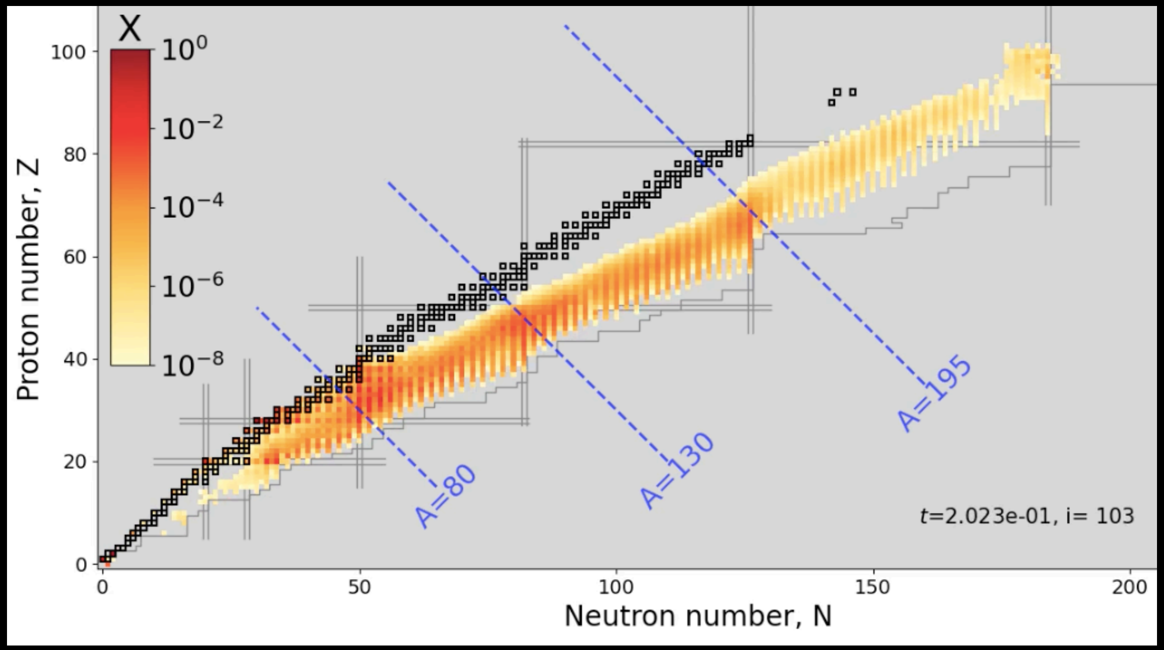


NUCLEAR PHYSICS INPUT

Kullmann et al. 2022 arXiv:2207.07421

Only use global models that reproduce "accurately" experimental data

Varied:



✳ 6 mass models (rms<0.8 MeV)

✳ 4 models for the β-decay rates

✳ 2 models for (n, γ) rates: CN or CN+DC

✳ 2 versions of the fission properties (barriers and fragment distr.)

✳ (2 NLD & 2 γSF)

NUCLEAR MASSES

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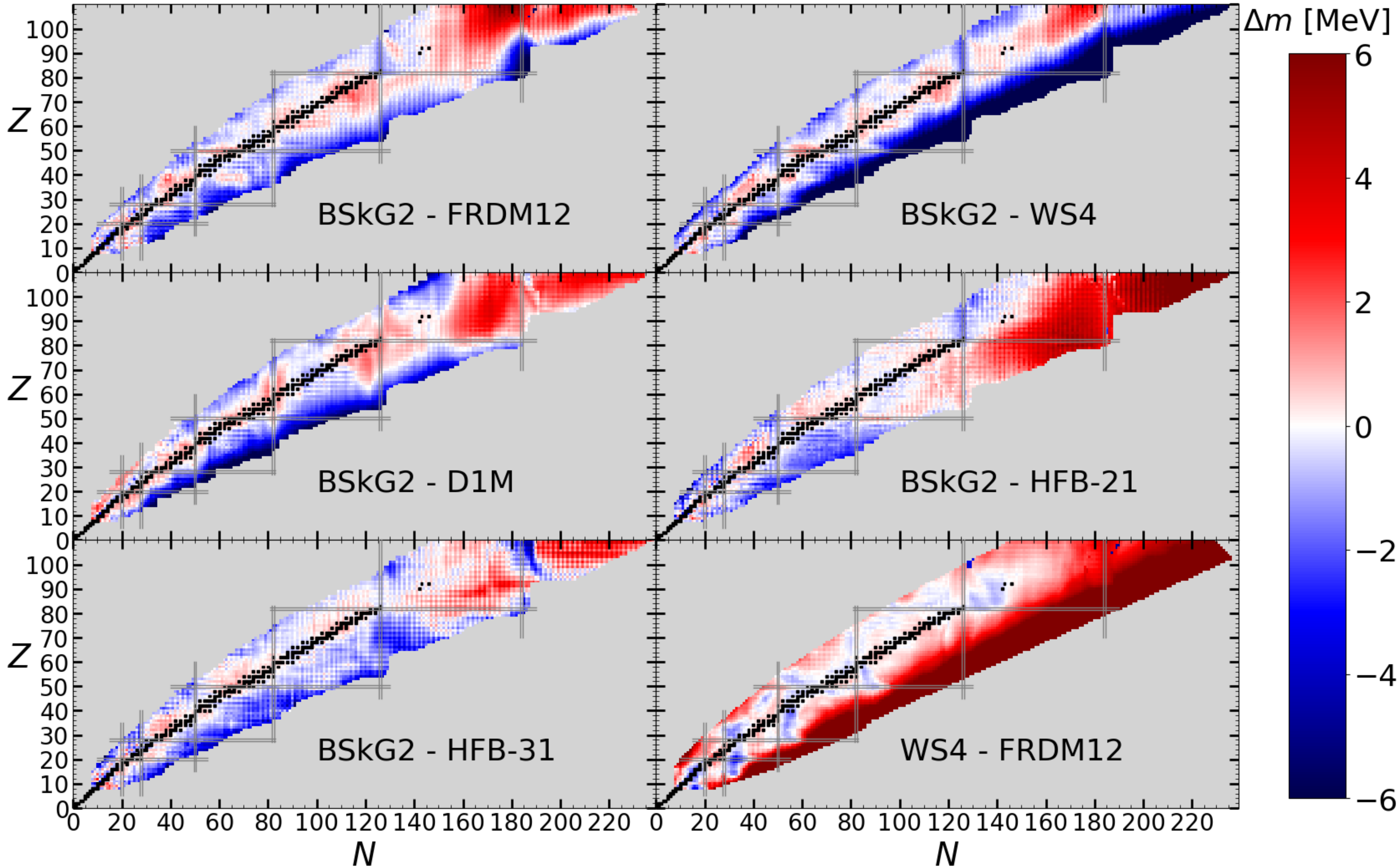

β- DECAY RATES

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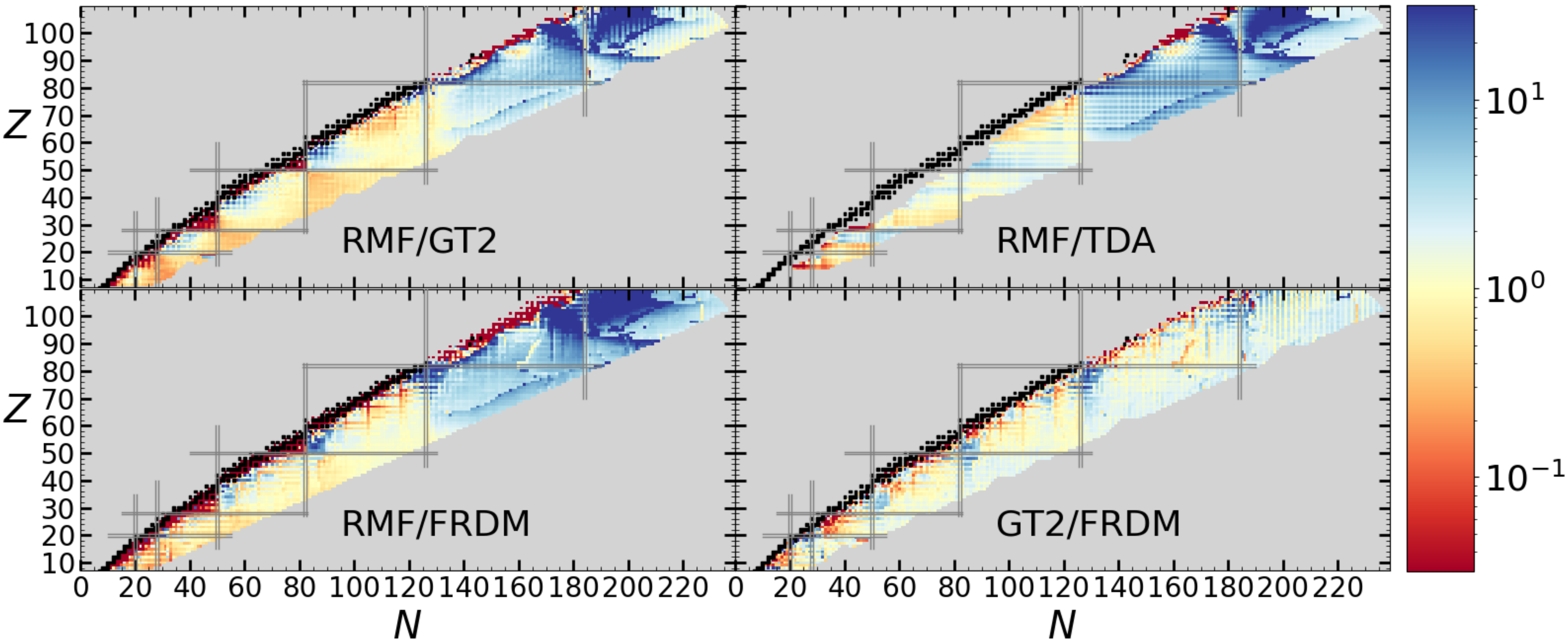

GT2= Tachibana et al. 1990

FRDM+QRPA= Möller et al. 2003

TDA= Klapdor et al. 1984

RMF+QRPA= Marketin et al. 2016

CALCULATING (n, γ) RATES

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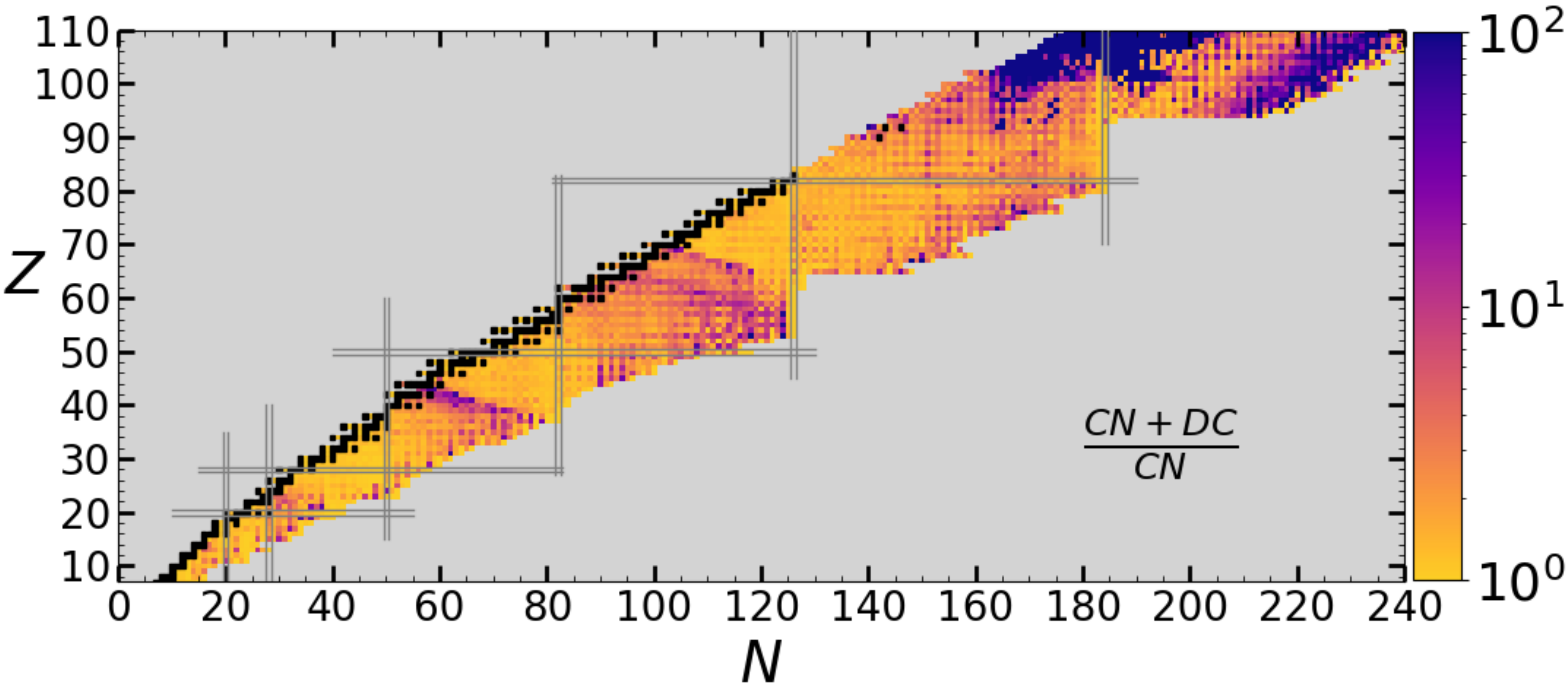

DC: direct capture

CN: compound nucleus

FISSION BARRIERS
(WHEN DO NUCLEI FISSION?)

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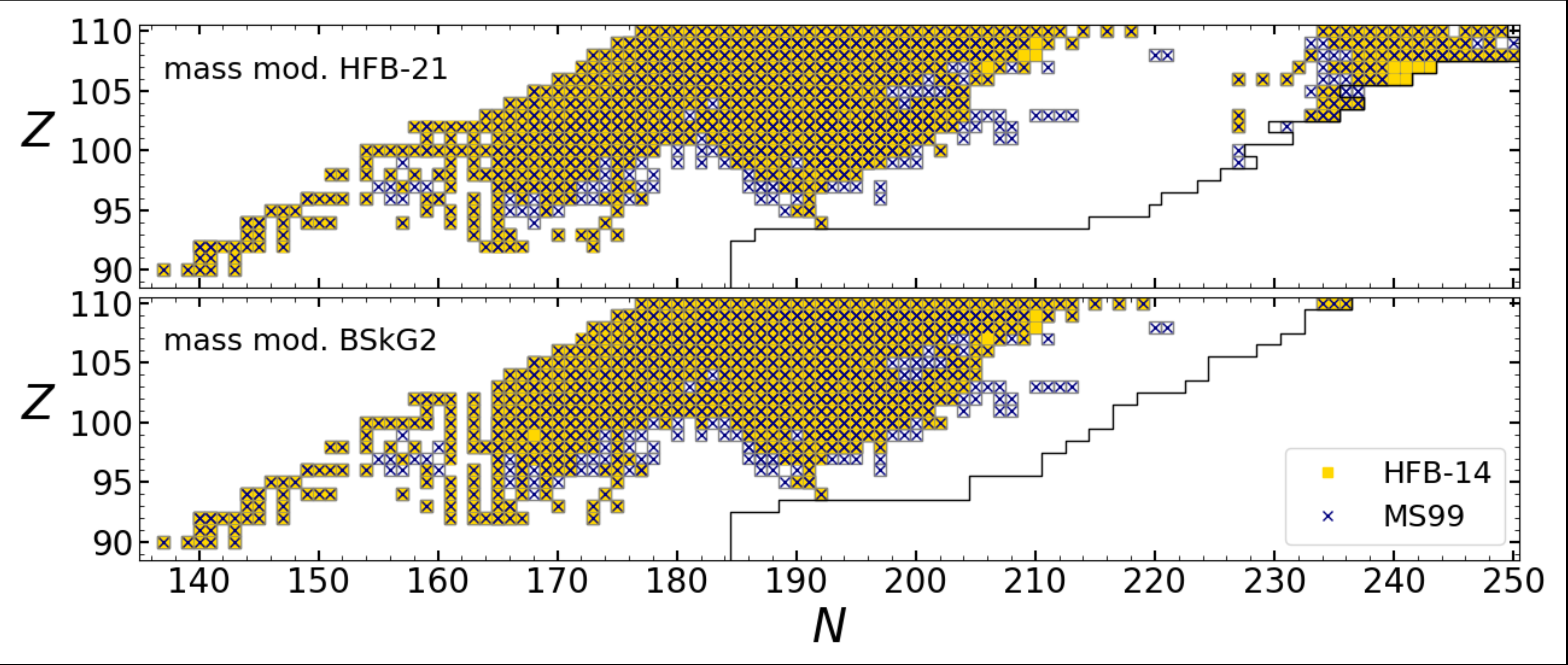
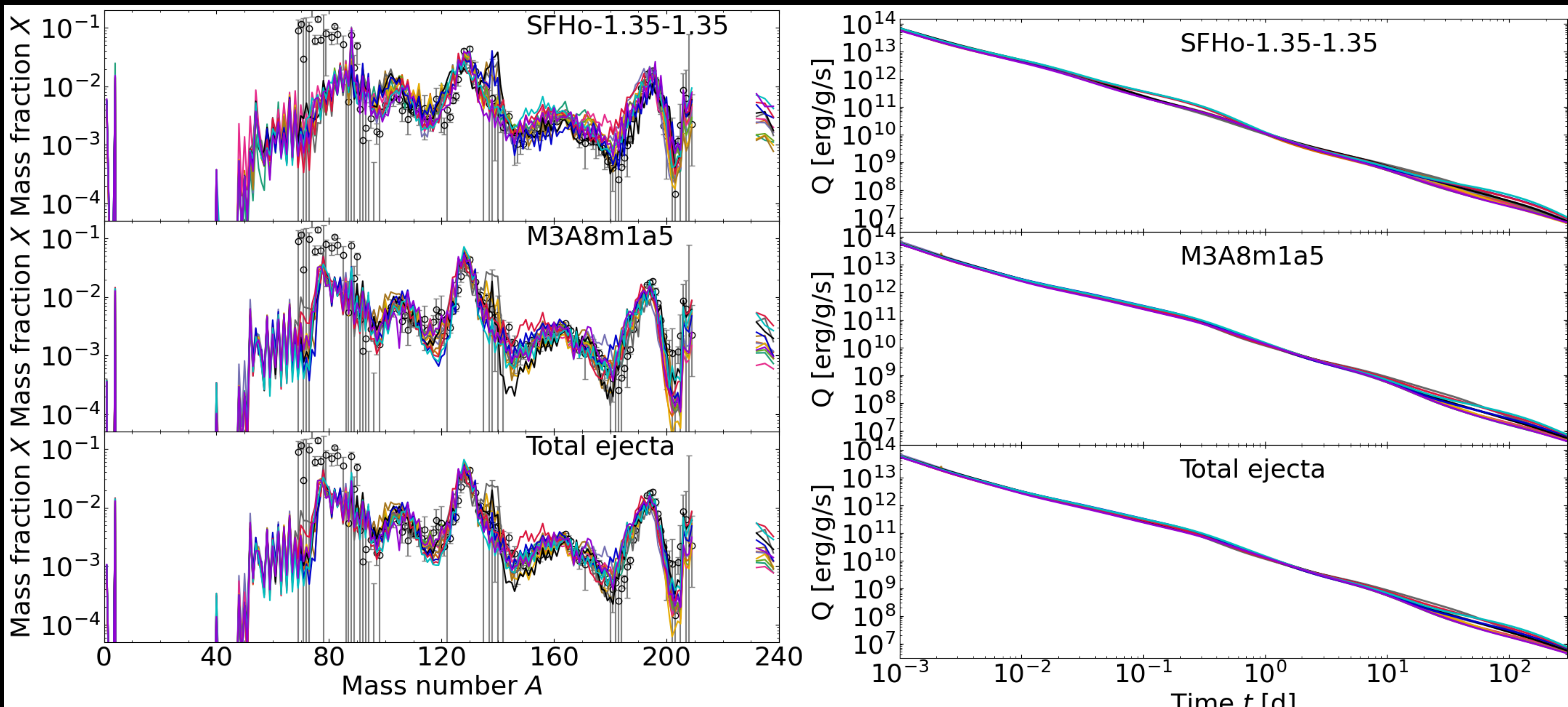
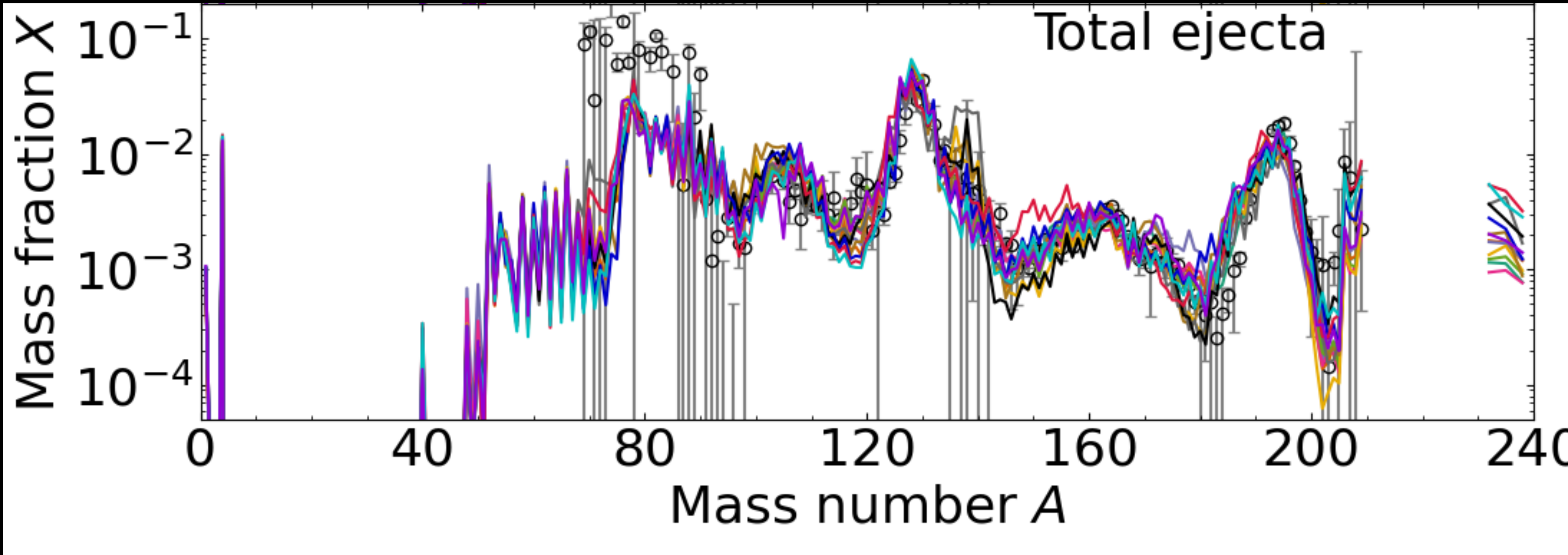


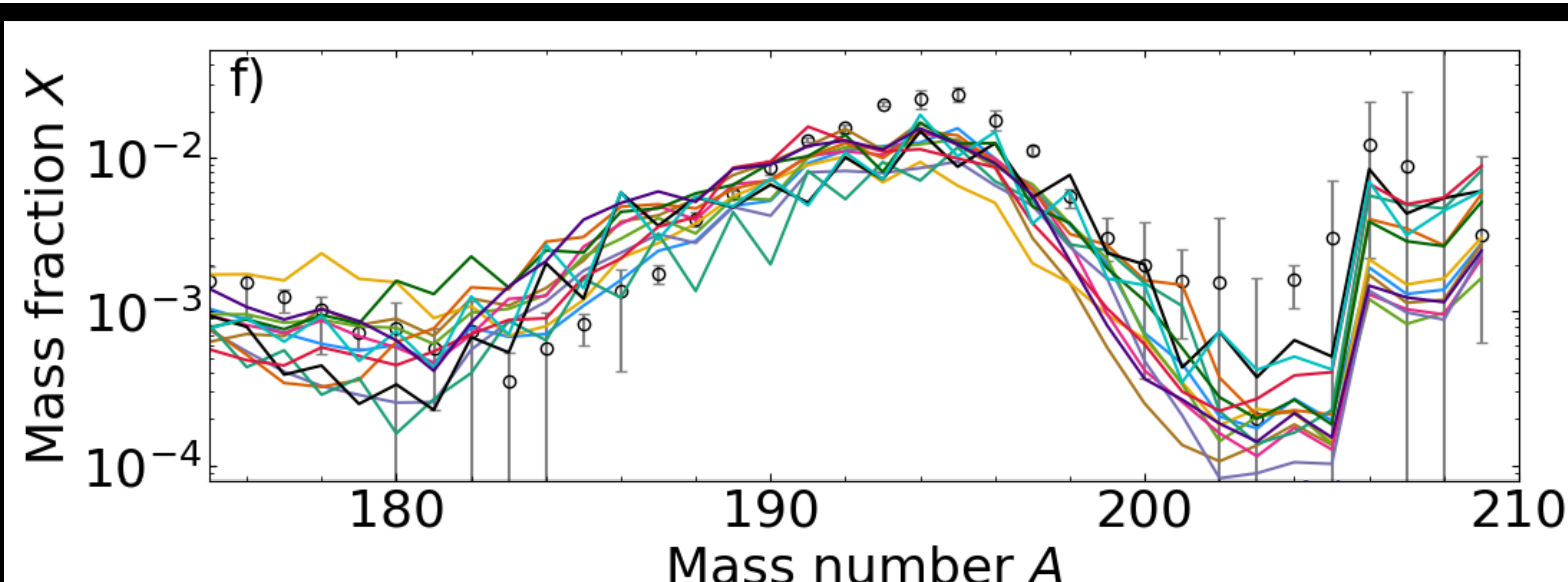
(and fragment distributions)

RESULTS (ALL VARIATIONS)



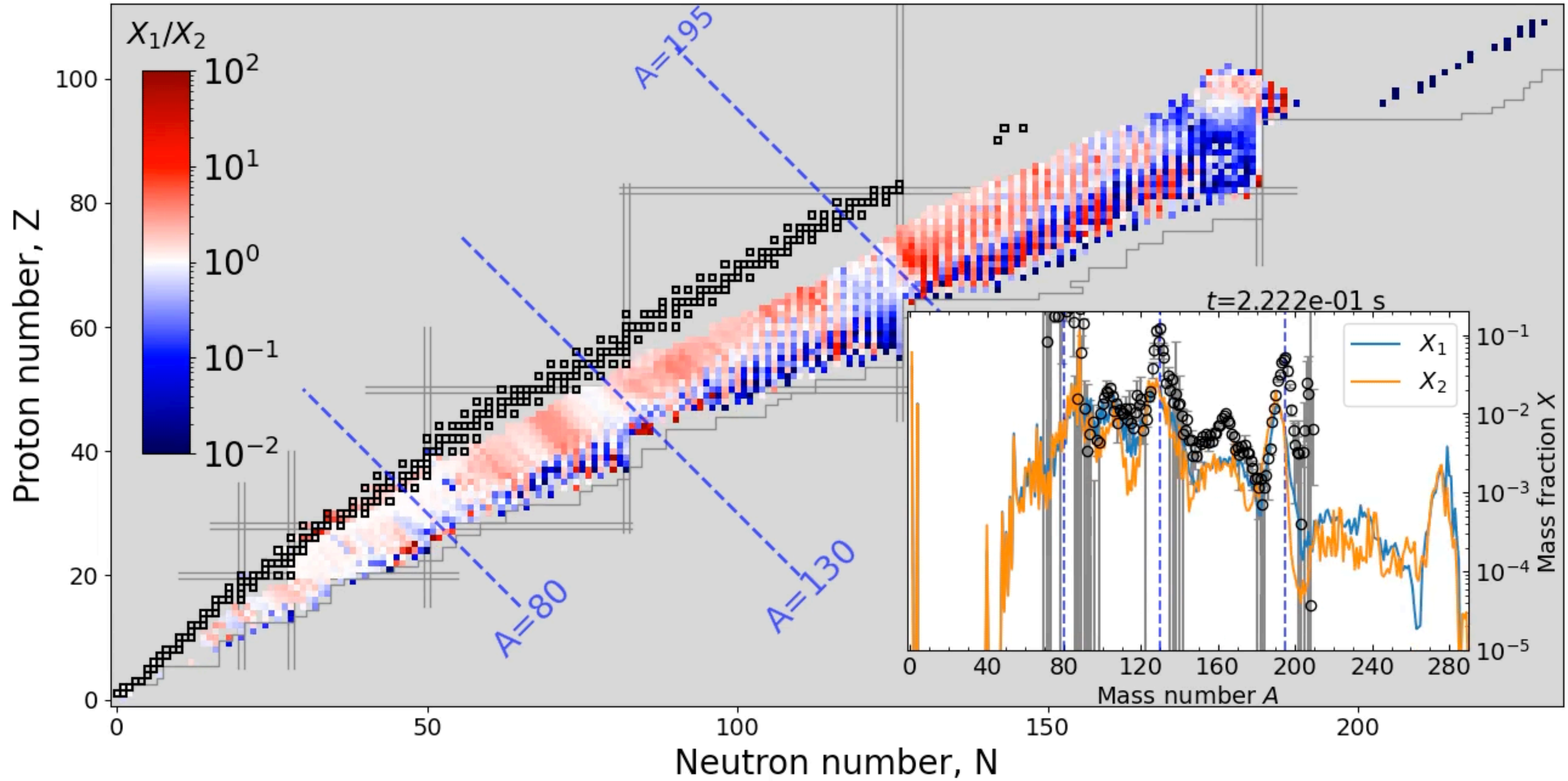
See Kullmann+2022 for details!


Total ejecta
Mass fraction X
10−1
10−2
10−3
10−4
0
40
80
120
160
200
240
Mass number A

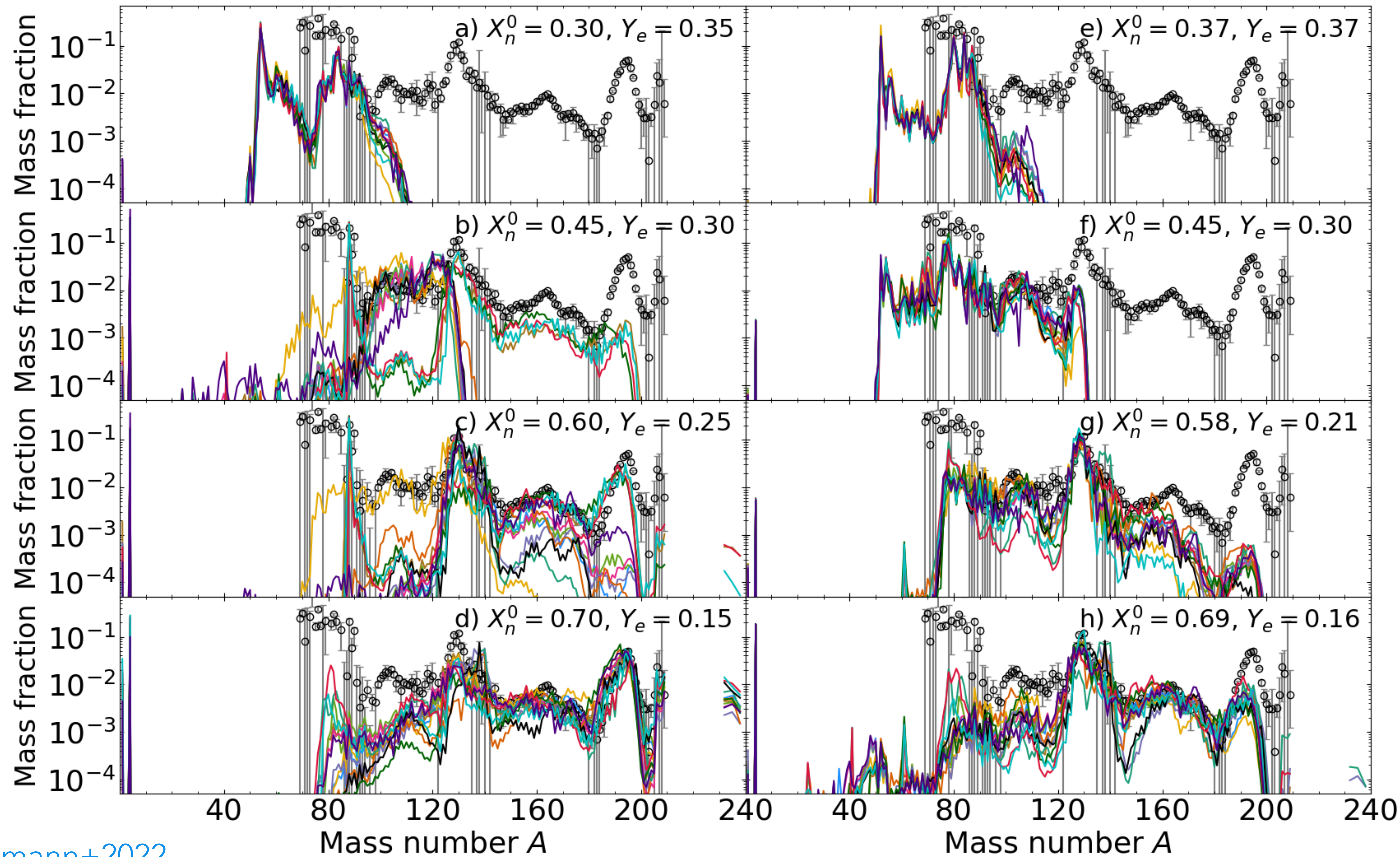

f)
Mass fraction X
10−2
10−3
10−4
180
190
200
210
Mass number A

R-PROCESS ANIMATION

Mass models BSkG2 (X_1) v.s. FRDM12 (X_2)



WHEN USING SINGLE TRAJECTORIES…



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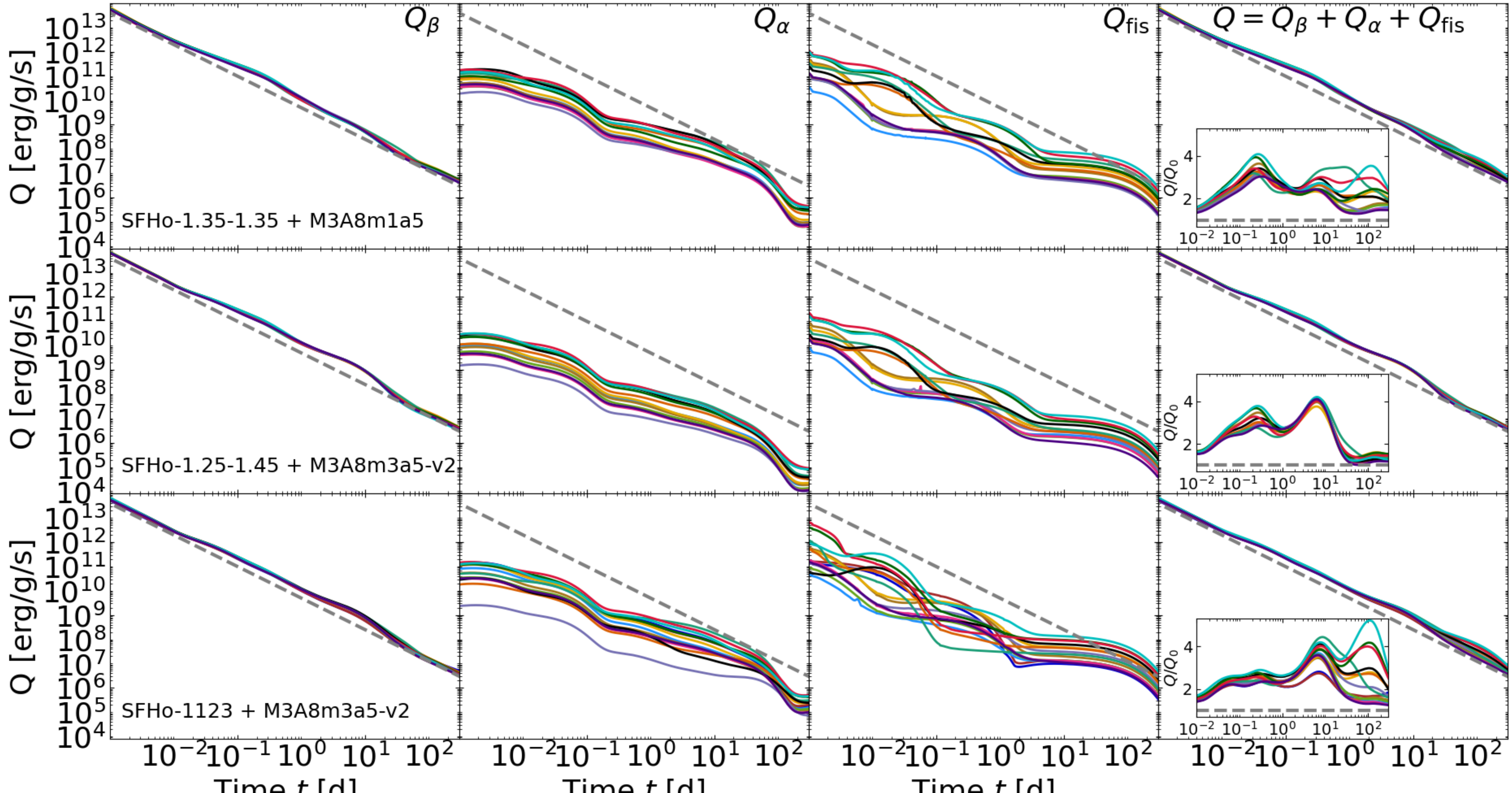
HEATING RATES (BEFORE THERMALIZATION)



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COSMOCHRONOMETRY

Kullmann+2022

$$\log\left(\frac{\mathrm{Th}}{\mathrm{U}}\right)_{\mathrm{obs}} = \log\left(\frac{\mathrm{Th}}{\mathrm{U}}\right)_{\mathrm{r}} + \log\left(\mathrm{e}\left(\frac{1}{\tau(\mathrm{U})} - \frac{1}{\tau(\mathrm{Th})}\right)\right) * t^{*}_{\mathrm{U,Th}}$$

U^{238} and Th^{232} of $\tau(\mathrm{U}) = 6.45\mathrm{Gyr}$ and $\tau(\mathrm{Th}) = 20.27\mathrm{Gyr}$,

	SFHo-125-145	SFHo-135-135	SFHo-1123	M3A8m1a5	M3A8m3a5-v2	SFHo-1.35-1.35 + M3A8m1a5	SFHo-1.25-1.45 + M3A8m3a5-v2	SFHo-11 + M3A8m3
$(\mathrm{Th/U})_{\mathrm{mean}}$	1.57	1.58	1.55	1.52	1.71	1.54	1.68	1.54
$\sigma_{(\mathrm{Th/U})}$	0.29	0.26	0.31	0.43	0.43	0.32	0.38	0.31
CS22892-052	11.78	11.72	11.96	12.33	11.10	12.01	11.22	11.97
CS29497-004	18.54	18.47	[illegible]	19.09	17.85	18.77	17.98	18.72
CS31082-001	16.36	16.29	[illegible]	16.91	[illegible]	16.59	15.80	16.54
HE1523-0901	14.61	14.55	[illegible]	15.16	13.93	14.85	14.06	14.80
J0954+5246	13.74	13.68	[illegible]	14.29	13.06	13.98	13.18	13.93
J2038-0023	15.49	15.42	15.66	16.04	14.80	15.72	14.93	15.67
σ_{t^*}	1.70	1.53	1.80	2.65	2.29	1.93	2.10	1.80
$t^*_{\mathrm{mean}} - t^*_{\mathrm{min}}$	3.03	2.83	3.43	4.28	4.00	2.96	3.35	3.44
$t^*_{\mathrm{max}} - t^*_{\mathrm{mean}}$	2.39	2.32	2.19	4.39	3.51	2.97	3.19	2.19

CONCLUSIONS NUCLEAR UNCERTAINTIES STUDY

r-process abundance:

- span a factor ~20 (for A>90), but global shape preserved
- actinide production varies by a factor of 5-7
- the position, shape and width of the r-process peaks vary with nuclear model

Heating rate

- insensitive for t<0.1d, large differences in fission contribution at late time (t>10 d)

Cosmochronometric ages:

- Nuclear physics input give rise to an uncertainty of ~2 Gyr

Thank you for the attention!

Questions?

BACKUP

SUMMARY & CONCLUSIONS

Part 1:

- Impact abundances, heating rate
- angular and velocity dependence
- high velocity component

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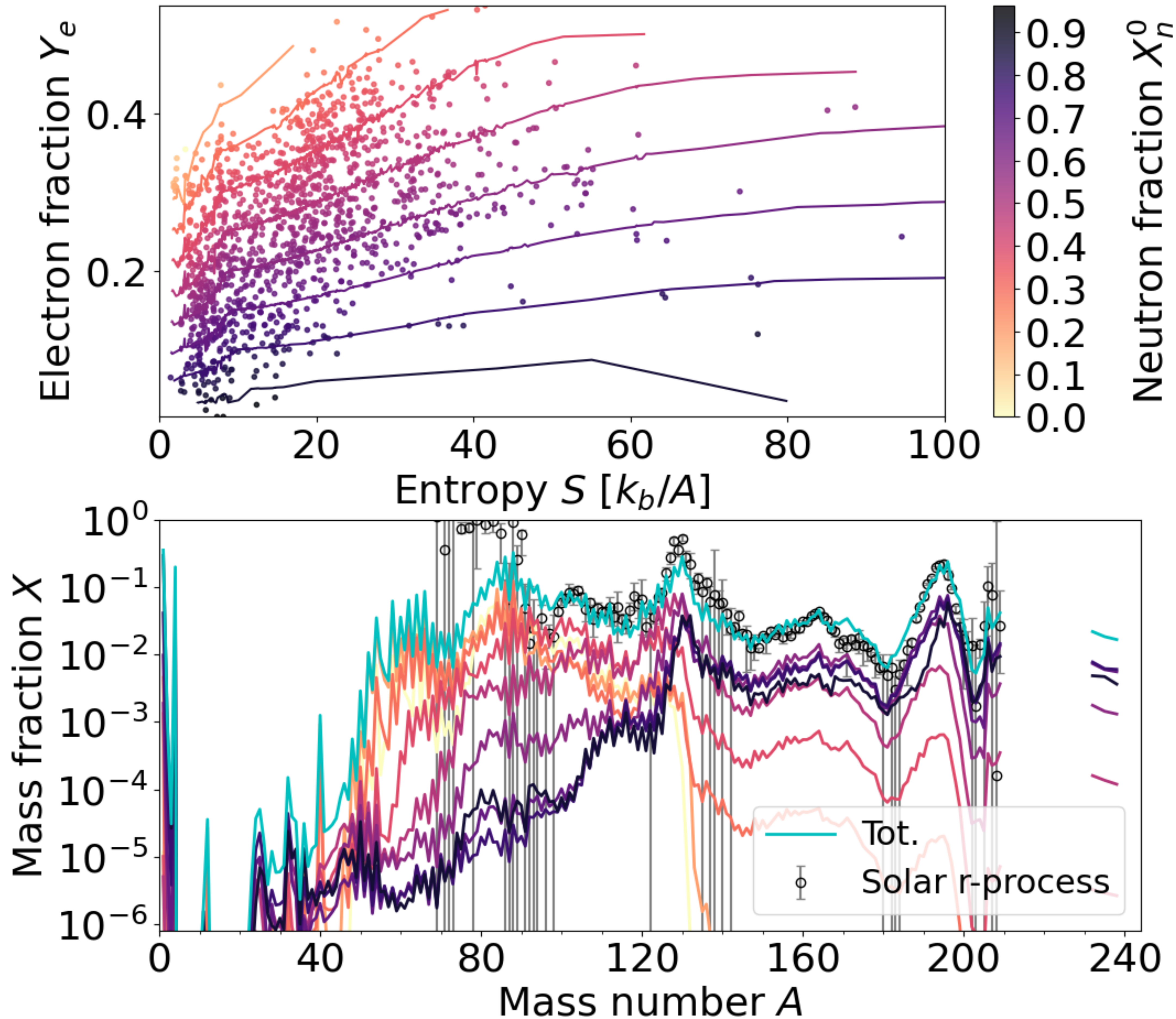
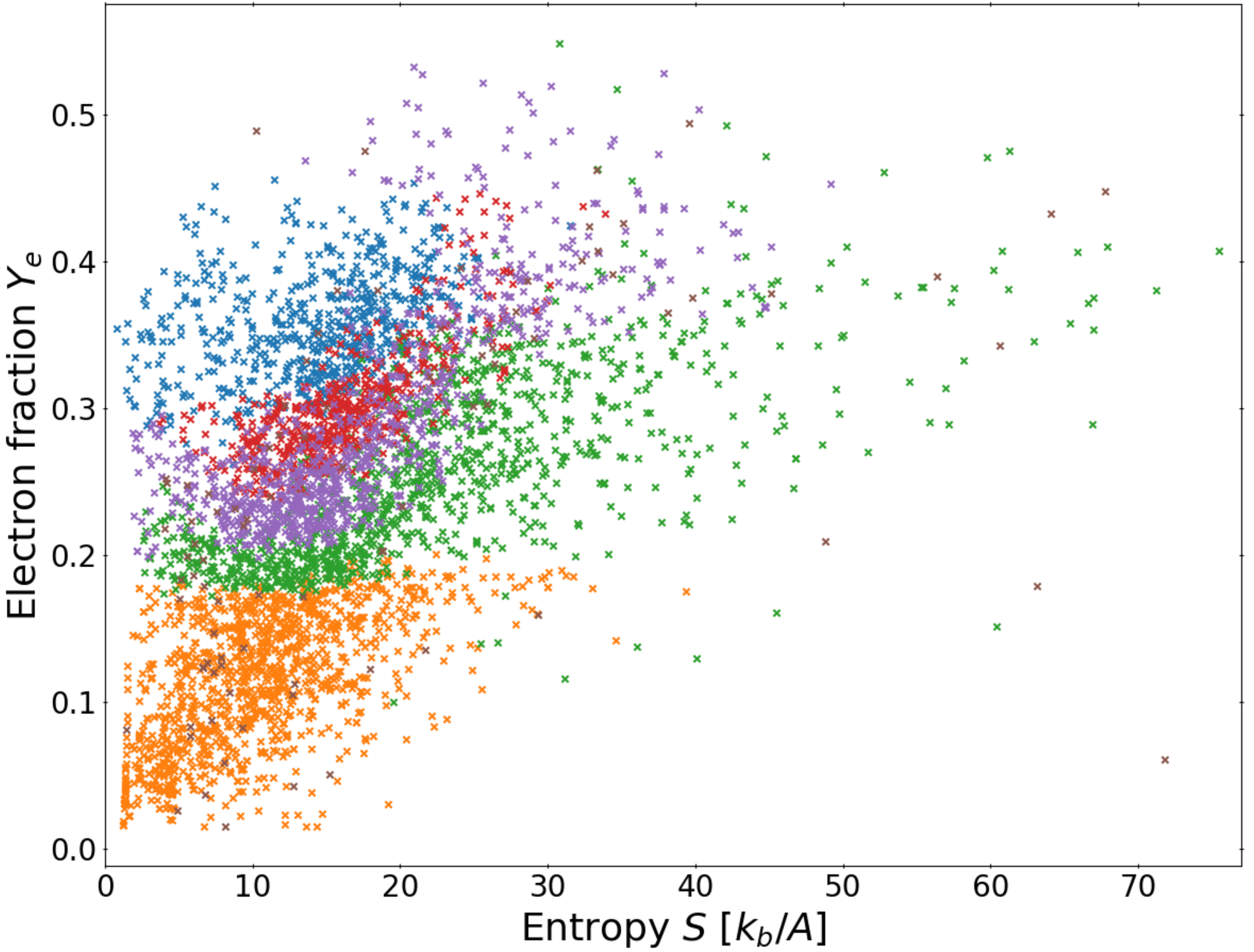
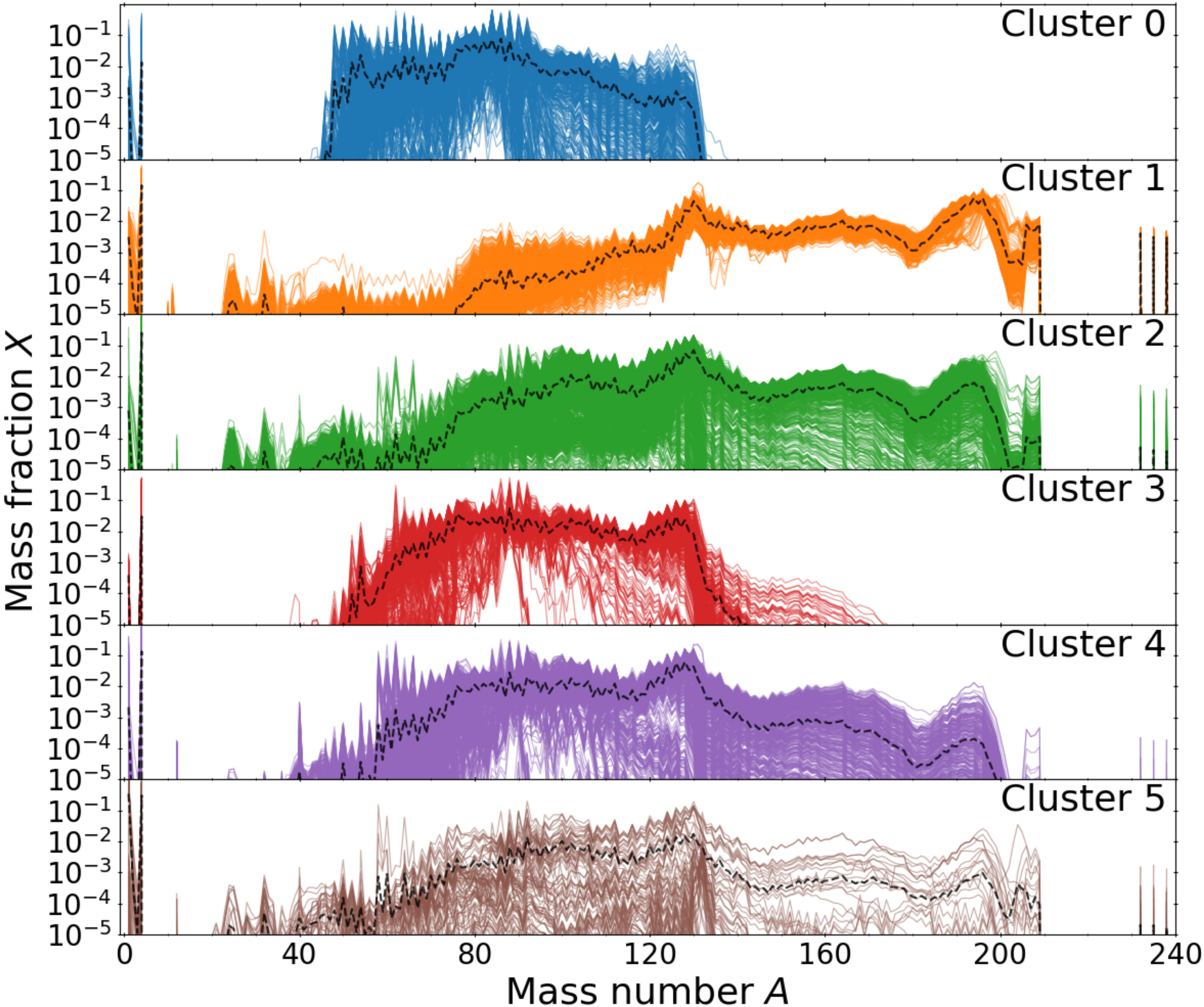
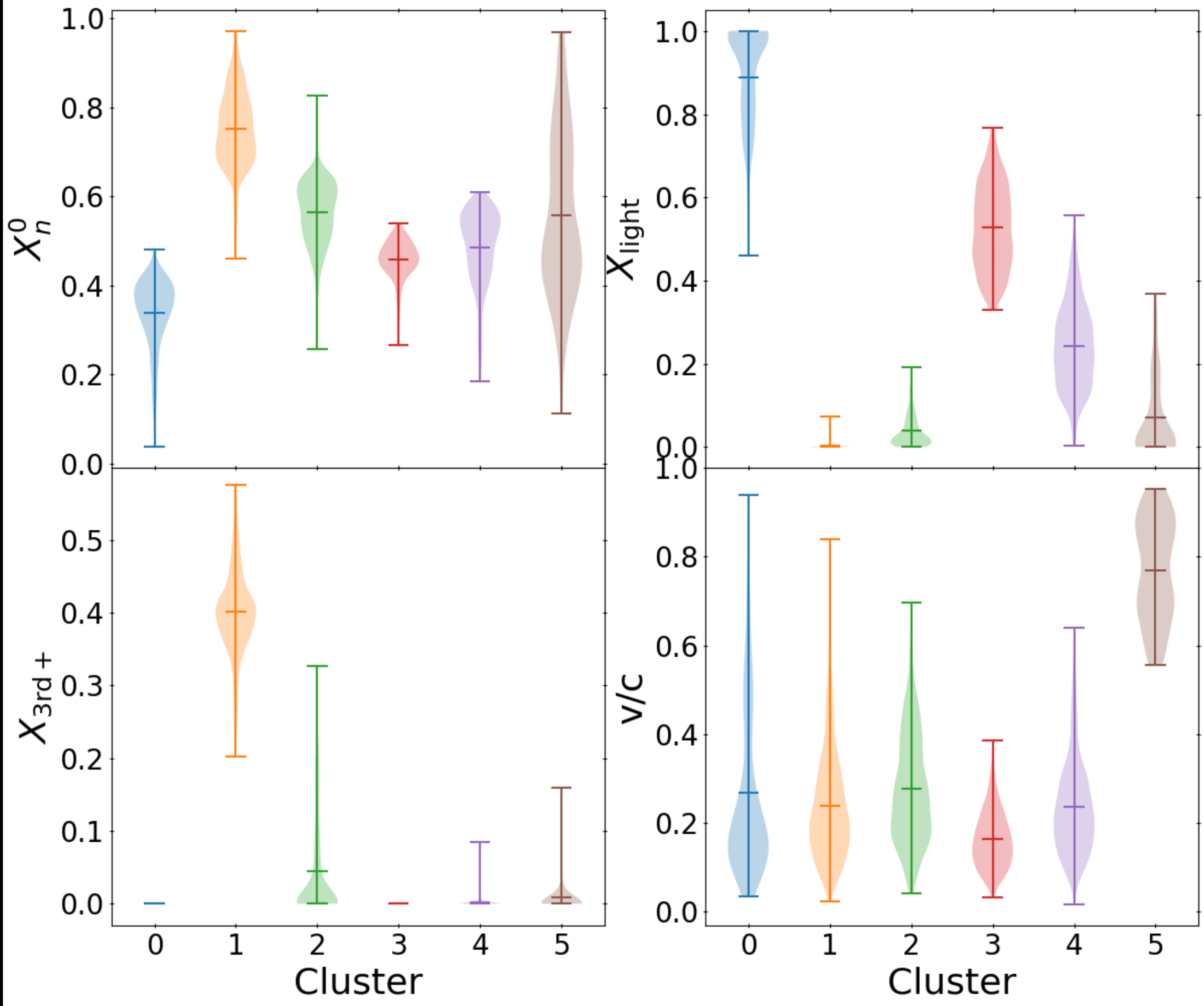

Electron fraction Y_e
0.4
0.2
0
20
40
60
80
100
Entropy S [k_b/A]
Neutron fraction X_n^0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Mass fraction X
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
40
80
120
160
200
240
Mass number A
Tot.
Solar r-process



Electron fraction Y_e
0.0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
40
50
60
70
Entropy S $[k_b/A]$

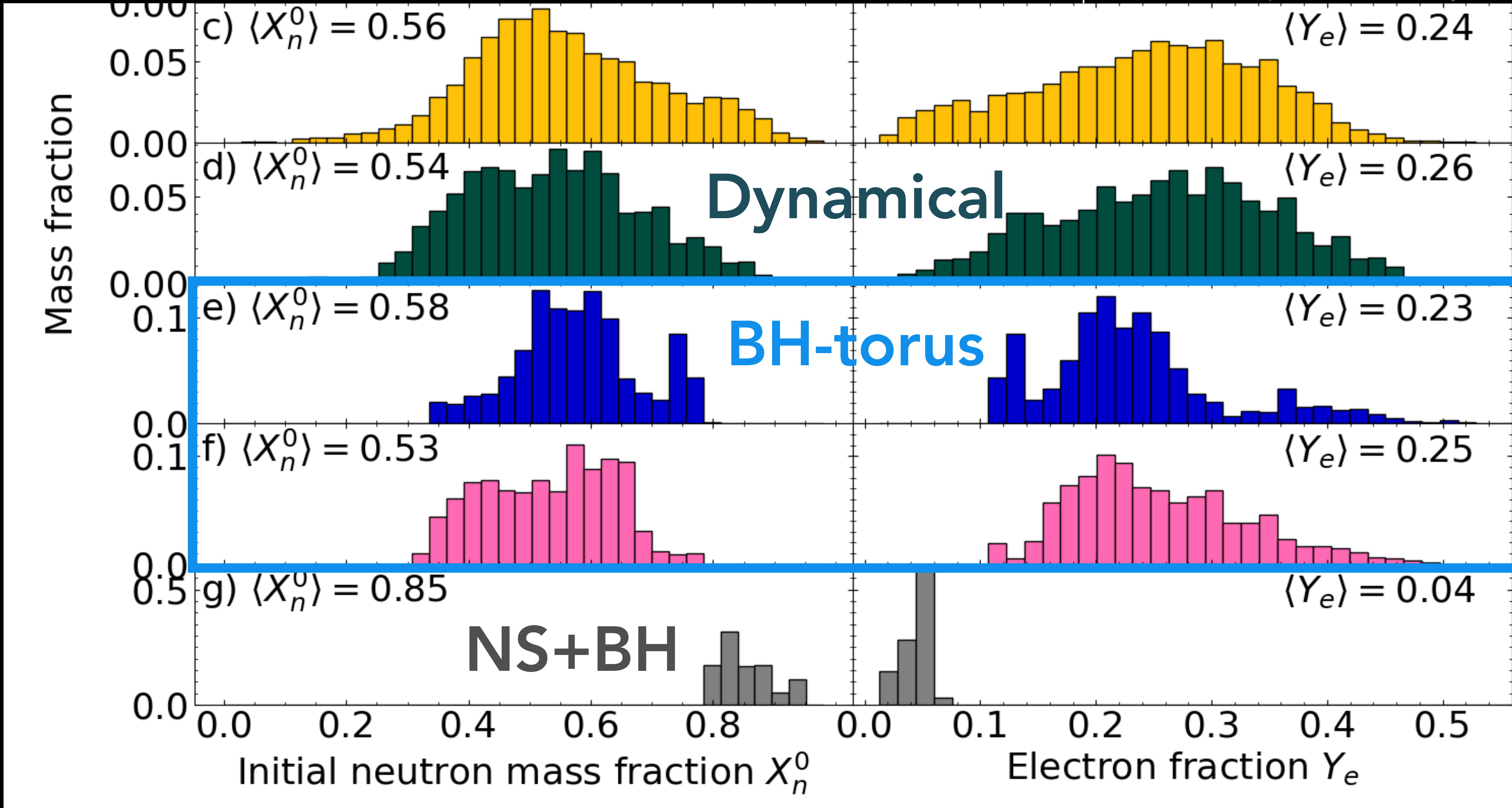


Cluster 0
Cluster 1
Cluster 2
Cluster 3
Cluster 4
Cluster 5
Mass fraction X
Mass number A
0
40
80
120
160
200
240
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

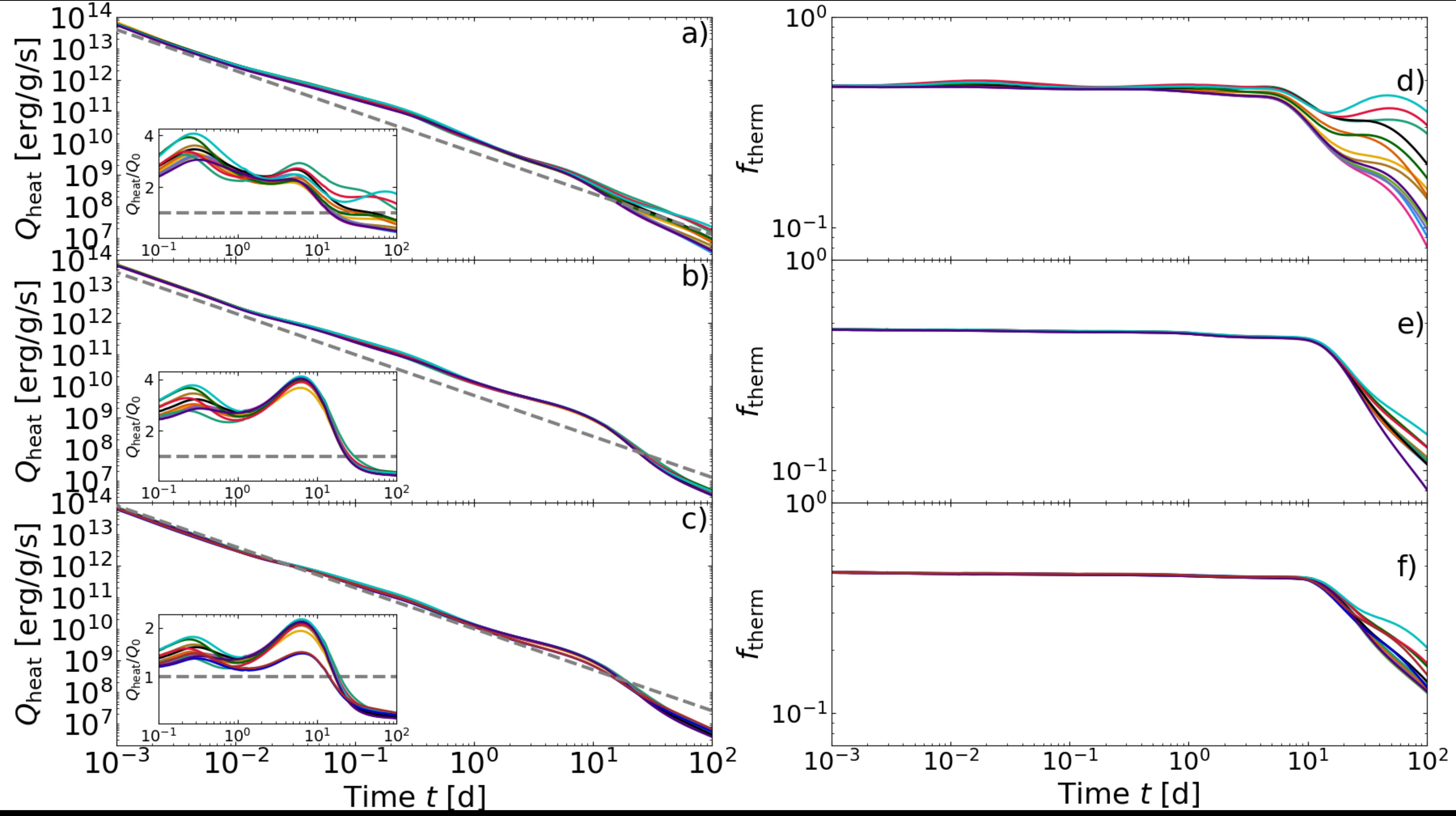


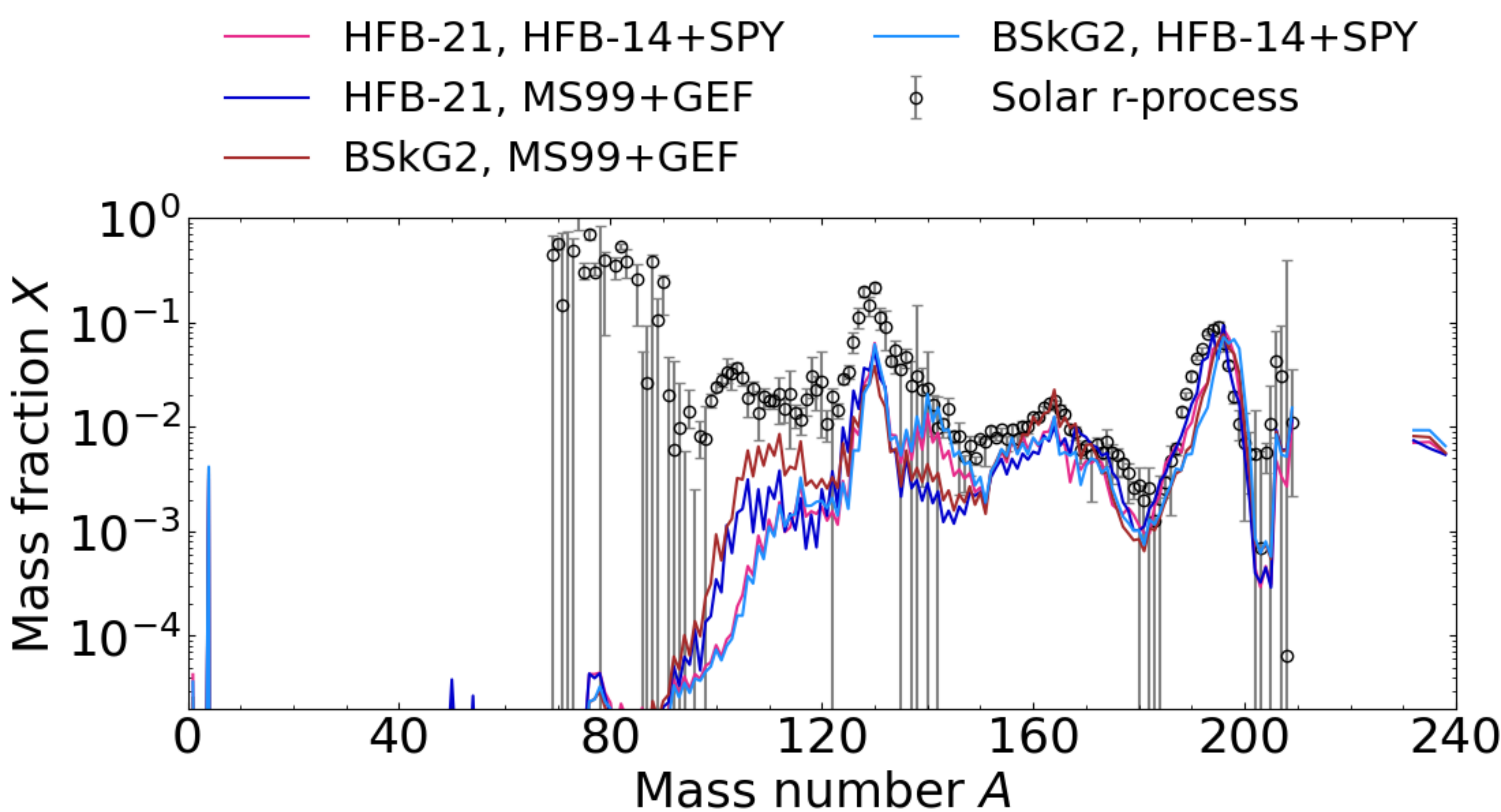
1.0
0.8
0.6
0.4
0.2
0.0
X_n^0
X_{light}
0.5
0.4
0.3
0.2
0.1
0.0
$X_{3\text{rd}+}$
v/c
0 1 2 3 4 5
Cluster
0 1 2 3 4 5
Cluster

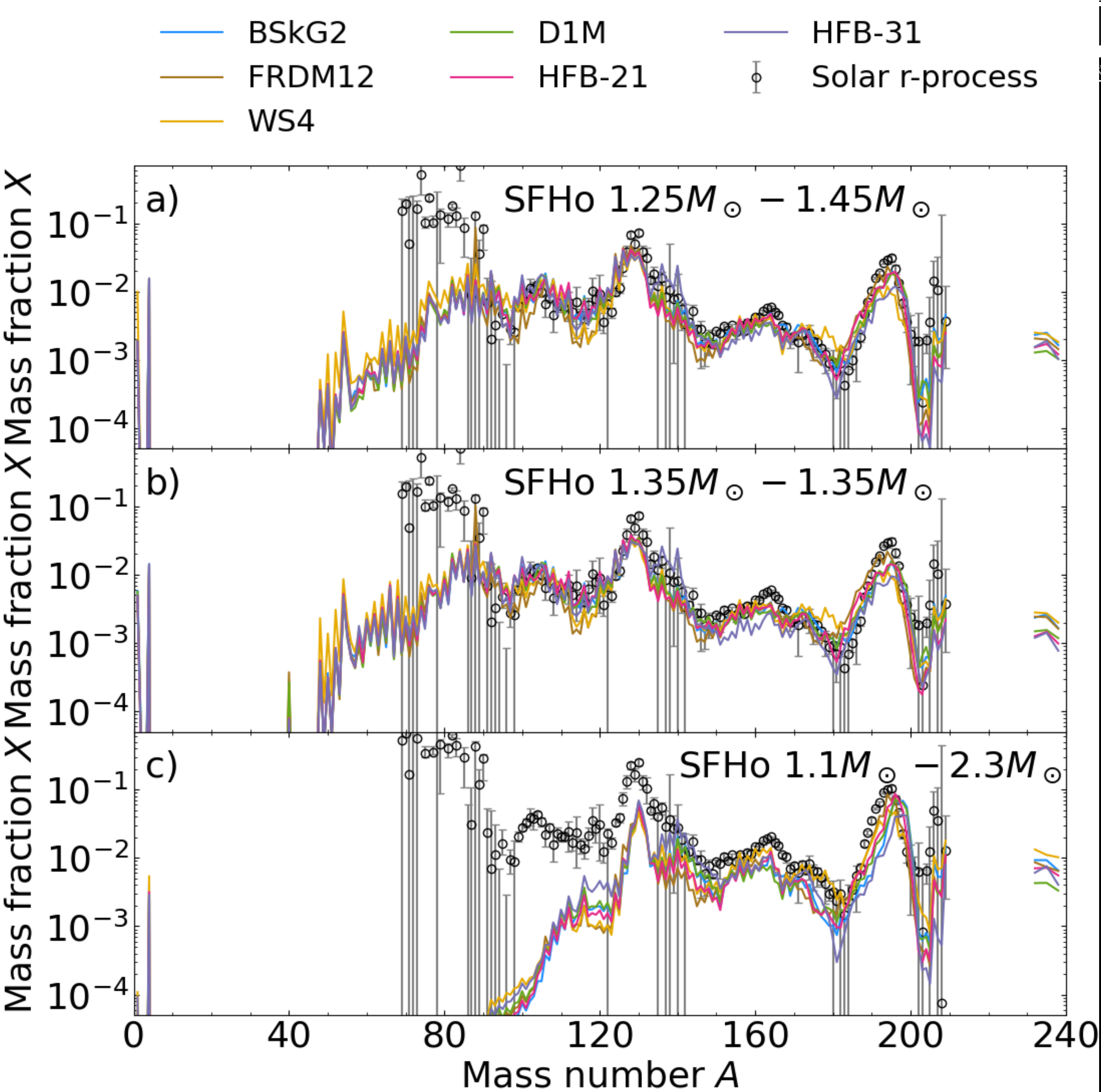
Kullmann+2022

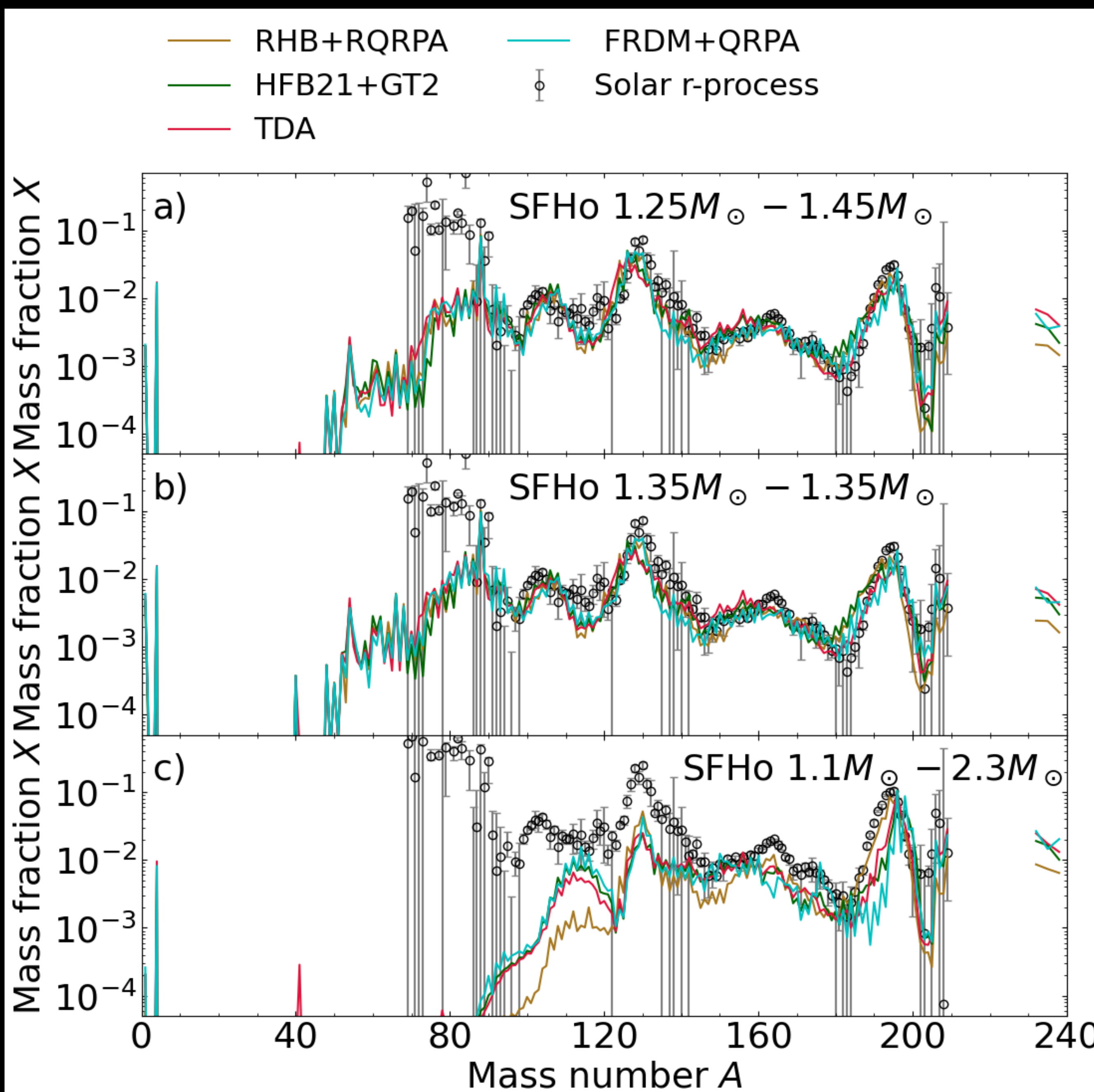


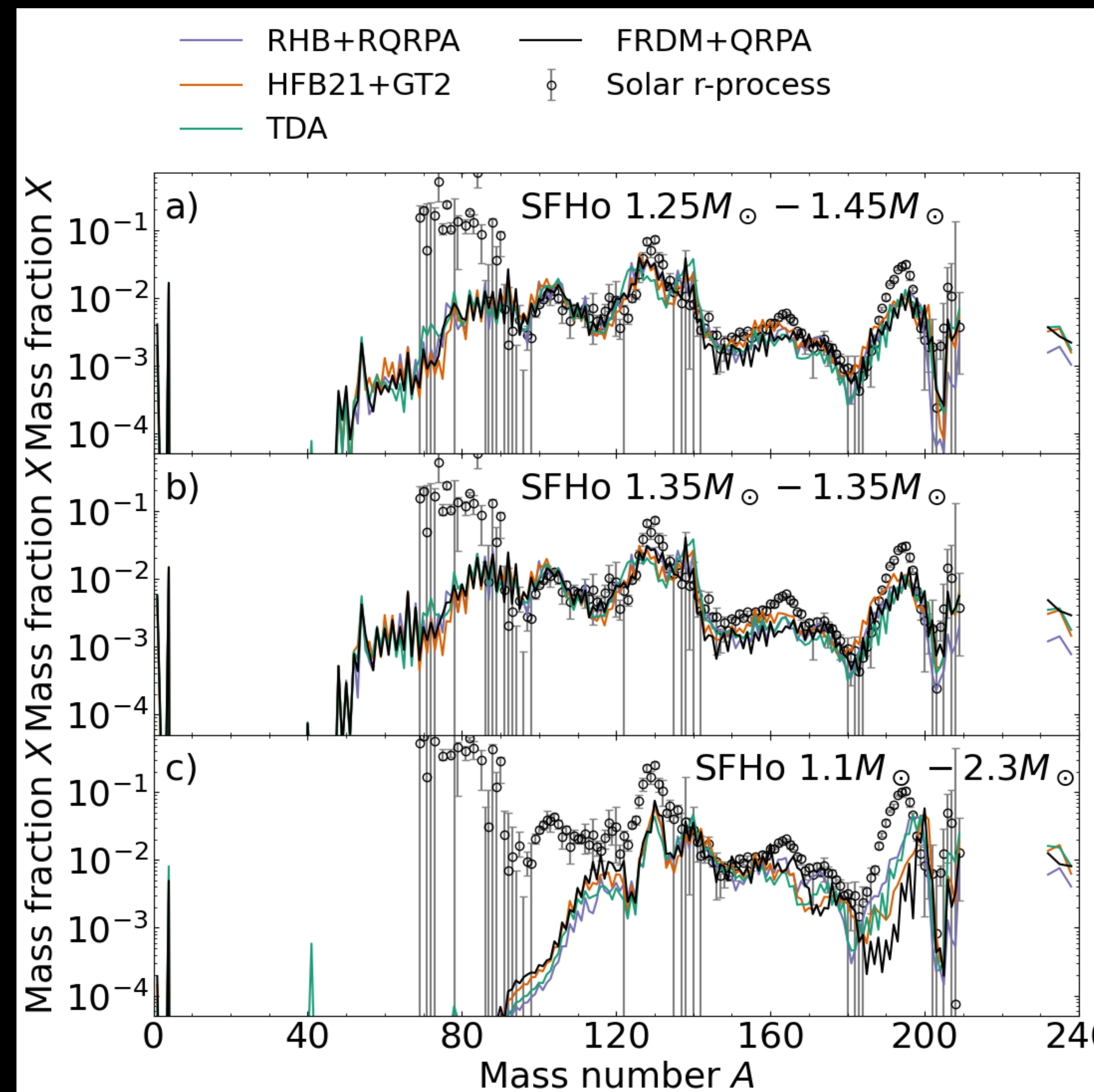
	Model name	q	$\langle Y_e \rangle$	$\langle X_n^0 \rangle$	M_{ej} $[10^{-3}\ M_\odot]$	N_{tot}	M_{BH} $[M_\odot]$	A_{BH}	M_{torus} $[M_\odot]$
c)	sfho-125-145	0.86	0.24	0.56	8.7	4398	2.40	0.80	0.17
d)	sfho-135-135	1.00	0.26	0.54	3.3	1263	2.45	0.83	0.09
g)	sfho-11-23	0.48	0.04	0.85	40.4	13175	3.09	0.82	0.26
e)	M3A8m1a5	-	0.23	0.58	24.7	4150	3.00	0.80	0.10
f)	M3A8m3a5-v2	-	0.24	0.56	70.1	2116	3.00	0.80	0.30

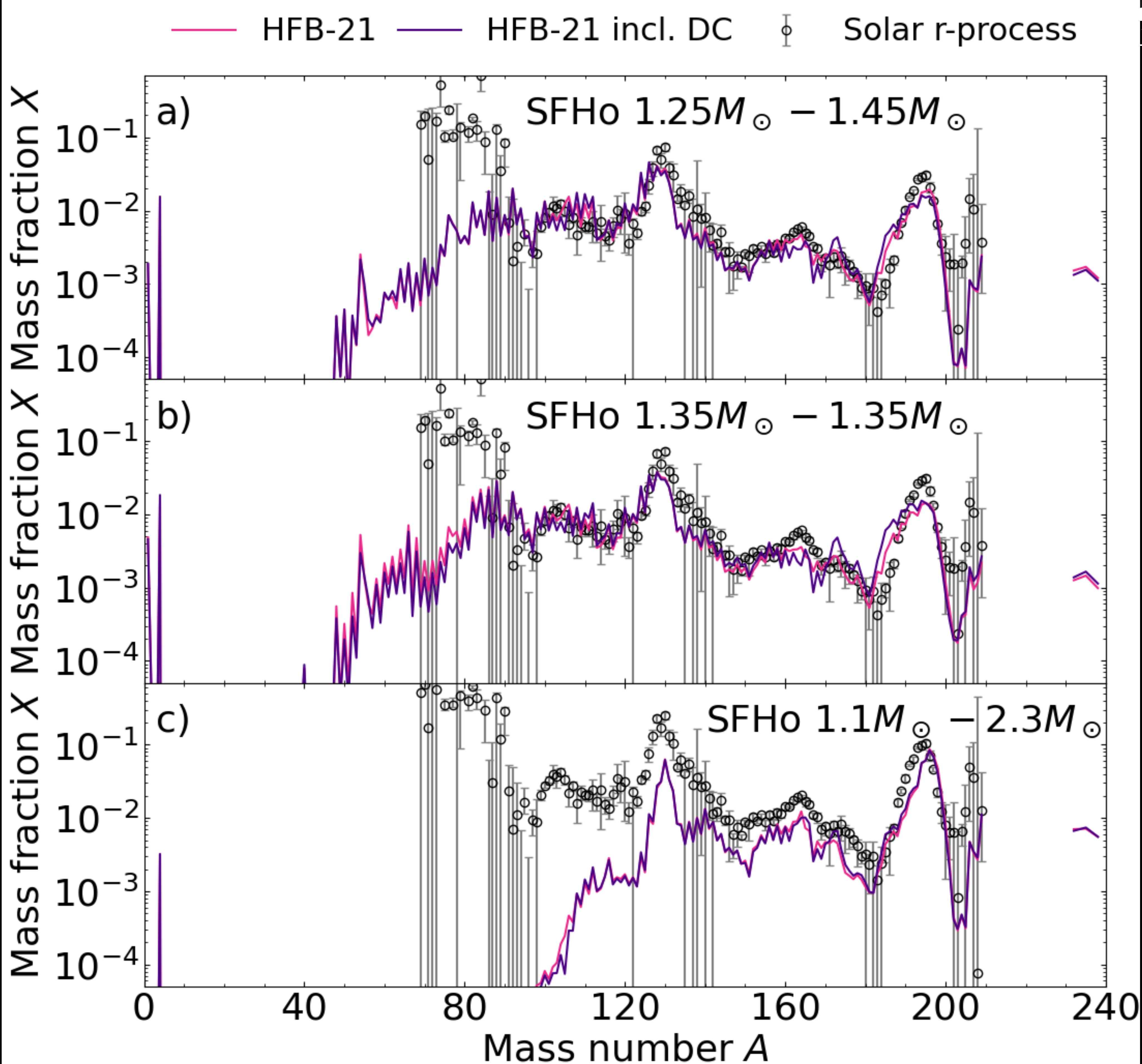

a)
b)
c)
d)
e)
f)
Q_heat [erg/g/s]
f_therm
Q_heat/Q_0
Time t [d]


HFB-21, HFB-14+SPY
BSkG2, HFB-14+SPY
HFB-21, MS99+GEF
Solar r-process
BSkG2, MS99+GEF
Mass fraction X
10^0
10^-1
10^-2
10^-3
10^-4
0
40
80
120
160
200
240
Mass number A

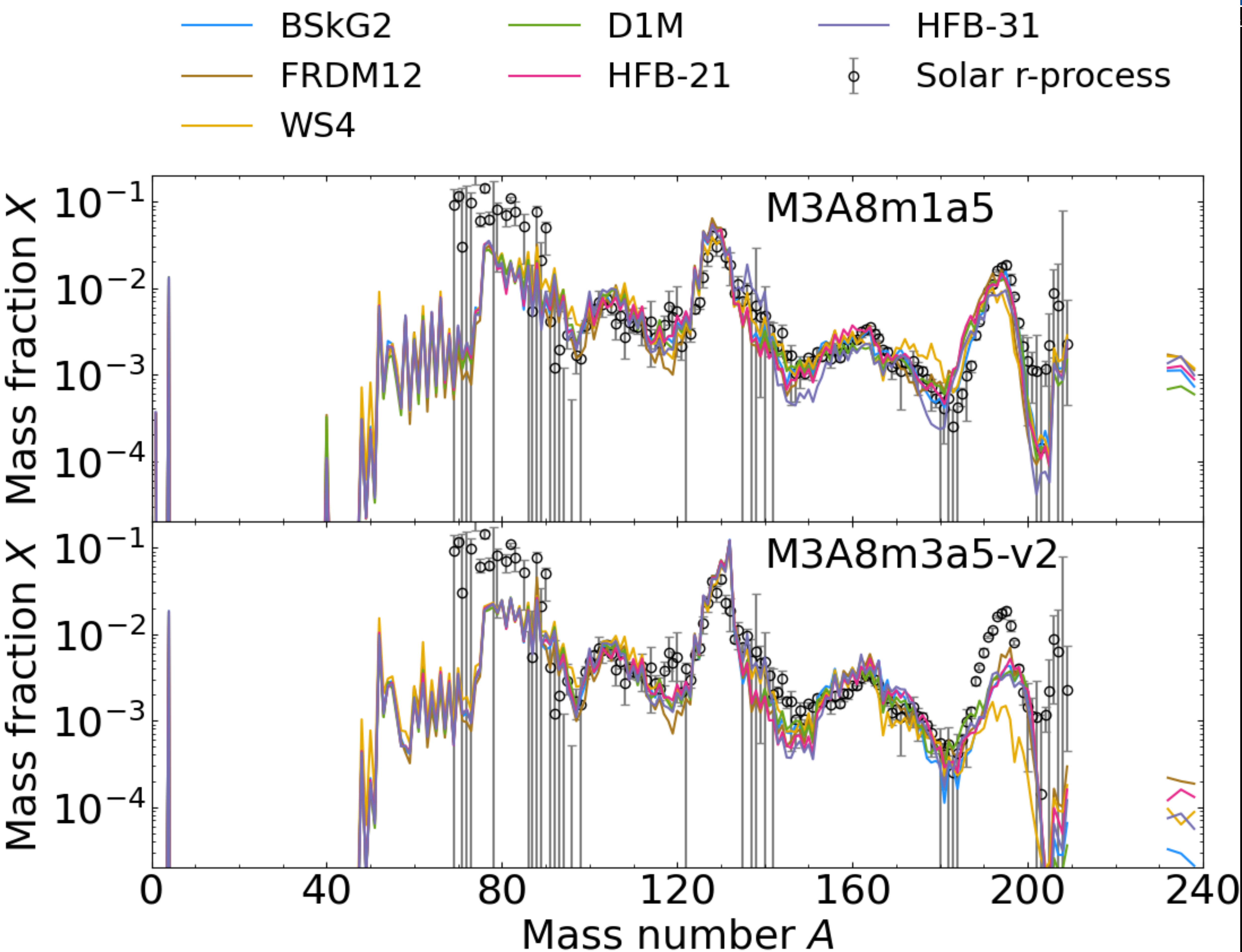

BSkG2
D1M
HFB-31
FRDM12
HFB-21
Solar r-process
WS4
a) SFHo $1.25M_\odot - 1.45M_\odot$
b) SFHo $1.35M_\odot - 1.35M_\odot$
c) SFHo $1.1M_\odot - 2.3M_\odot$
Mass fraction X
Mass number A
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
40
80
120
160
200
240


RHB+RQRPA
FRDM+QRPA
HFB21+GT2
Solar r-process
TDA
a) SFHo 1.25M⊙ − 1.45M⊙
b) SFHo 1.35M⊙ − 1.35M⊙
c) SFHo 1.1M⊙ − 2.3M⊙
Mass fraction X
Mass number A


RHB+RQRPA
FRDM+QRPA
HFB21+GT2
Solar r-process
TDA
a) SFHo 1.25M⊙ − 1.45M⊙
b) SFHo 1.35M⊙ − 1.35M⊙
c) SFHo 1.1M⊙ − 2.3M⊙
Mass fraction X
Mass number A



HFB-21
HFB-21 incl. DC
Solar r-process
a)
SFHo $1.25M_\odot - 1.45M_\odot$
b)
SFHo $1.35M_\odot - 1.35M_\odot$
c)
SFHo $1.1M_\odot - 2.3M_\odot$
Mass fraction X
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
40
80
120
160
200
240
Mass number A



BSkG2
D1M
HFB-31
FRDM12
HFB-21
Solar r-process
WS4
M3A8m1a5
M3A8m3a5-v2
Mass fraction X
Mass number A
0
40
80
120
160
200
240