Impacts of updated nuclear reaction rates on rp-process nucleosynthesis

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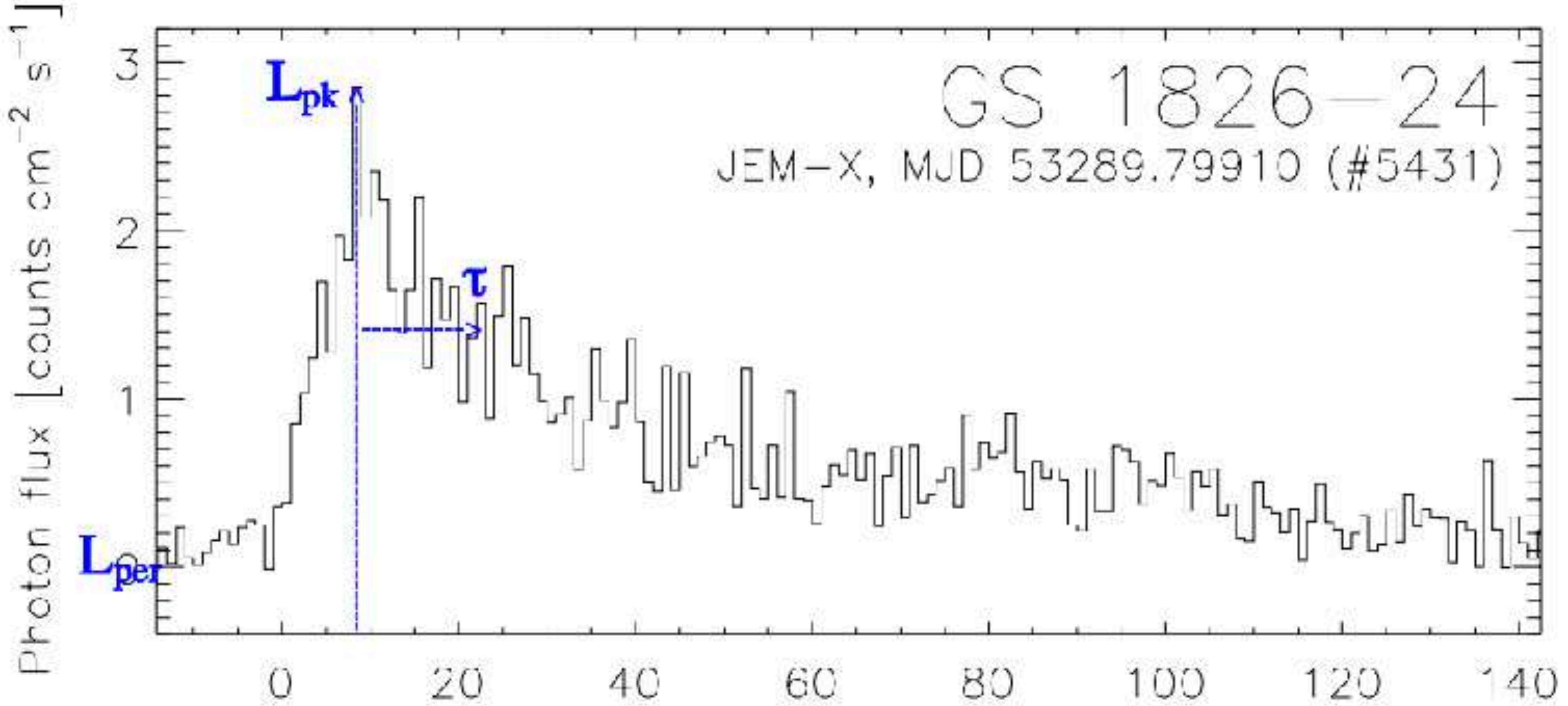
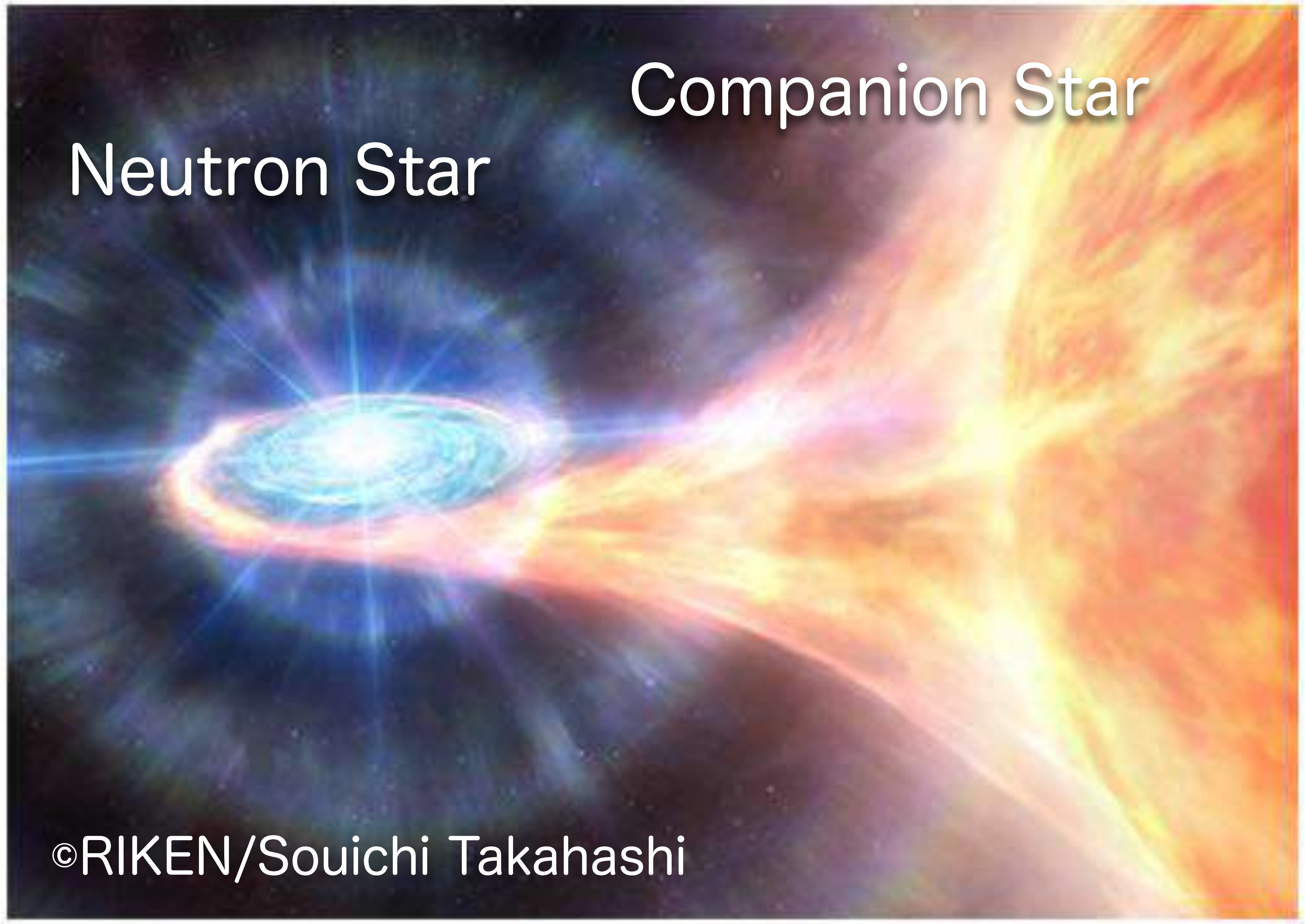
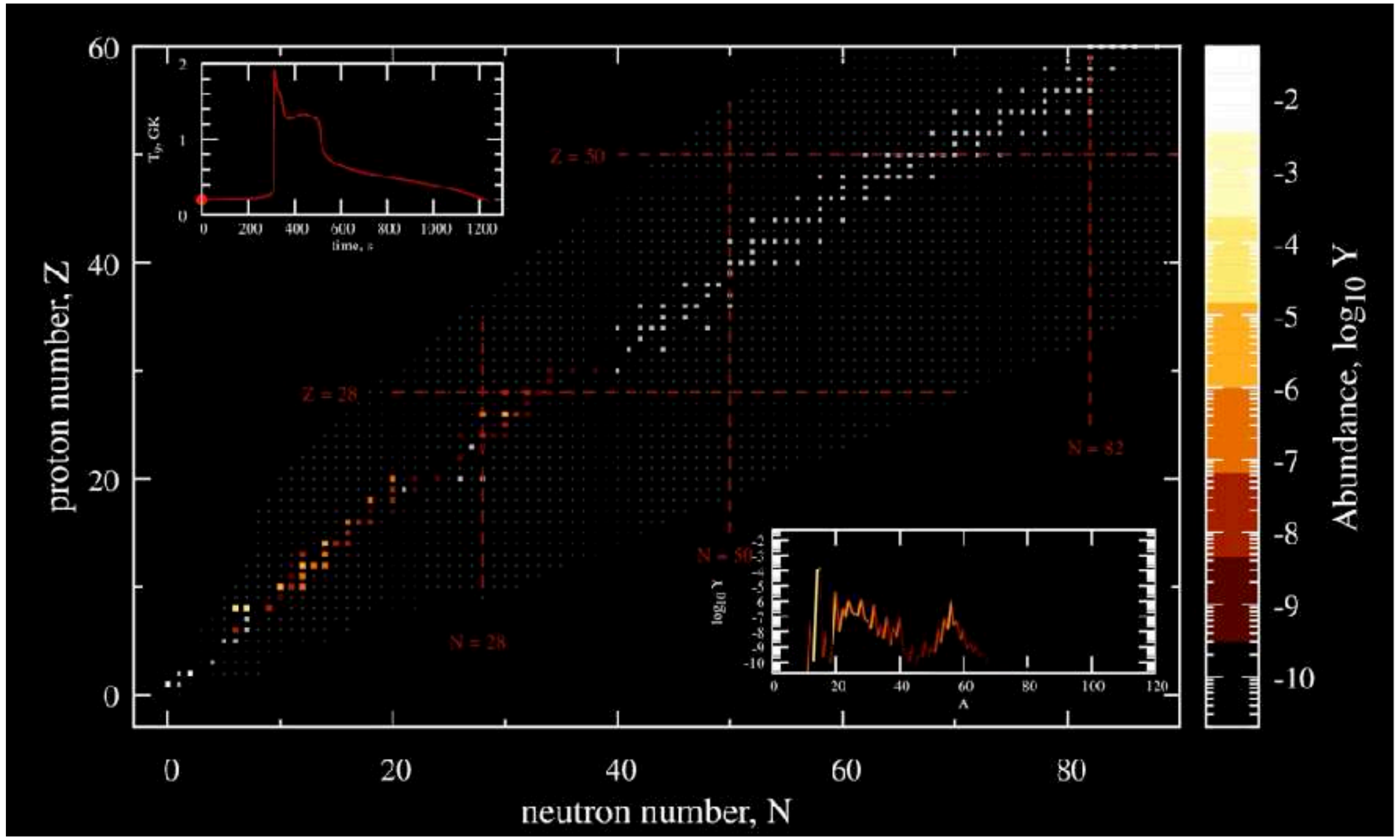
X-ray bursts (XRBs)

・Busts from mass X-ray binary systems
・nuclear explosion in the accreating laye
on the surface of the NS

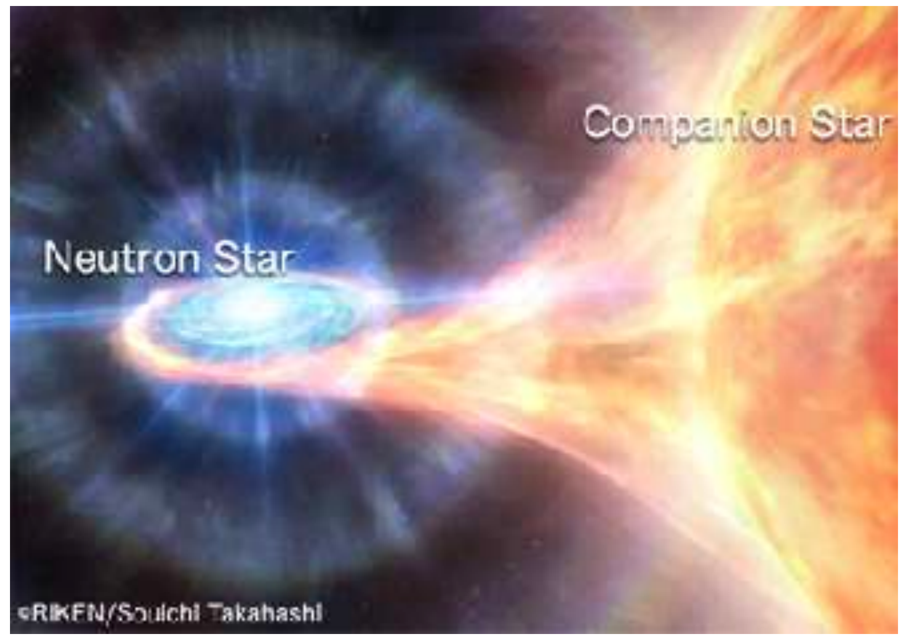


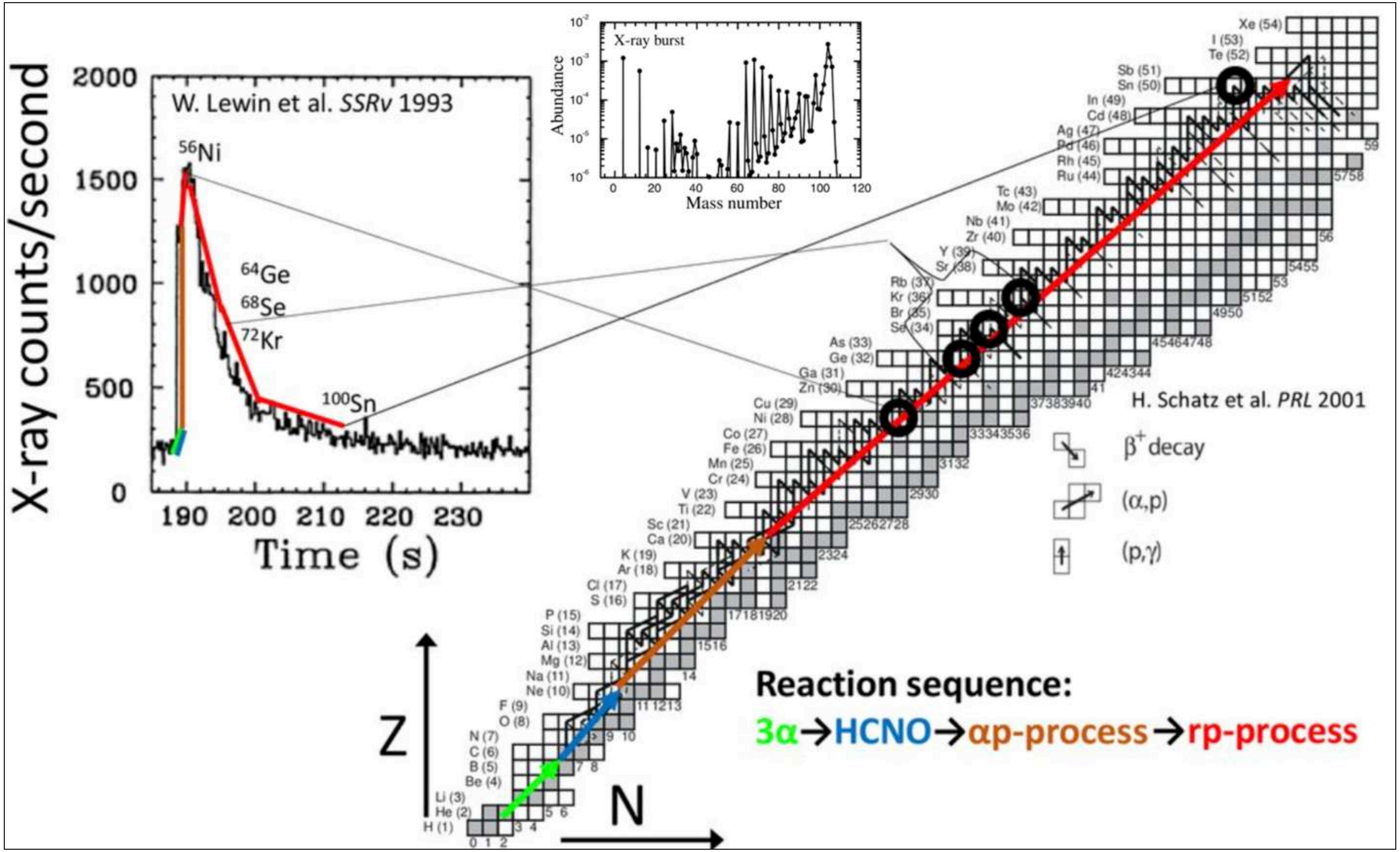




XRB and rp-process nucleosynthesis

X-ray bursts (XRB)

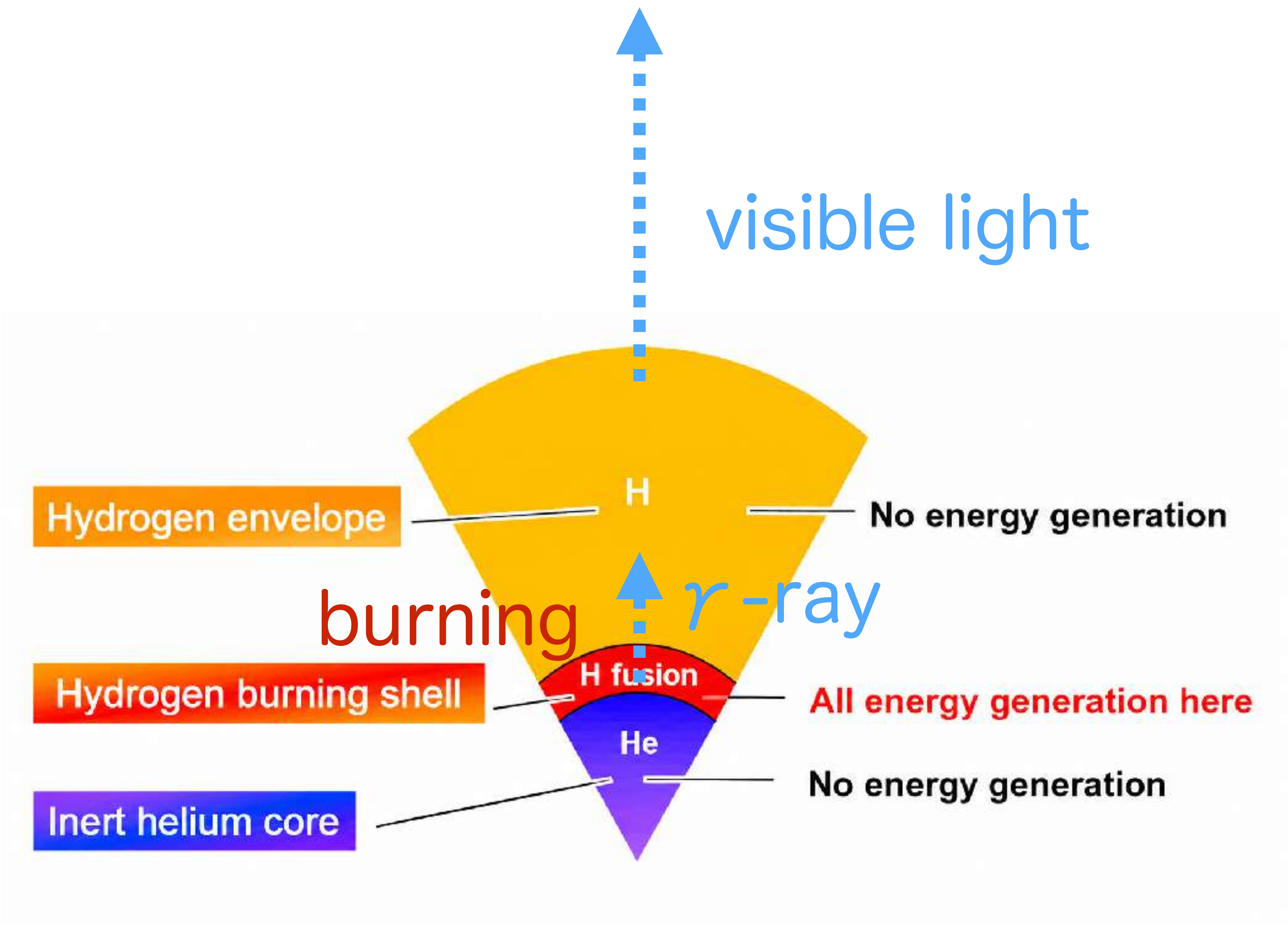




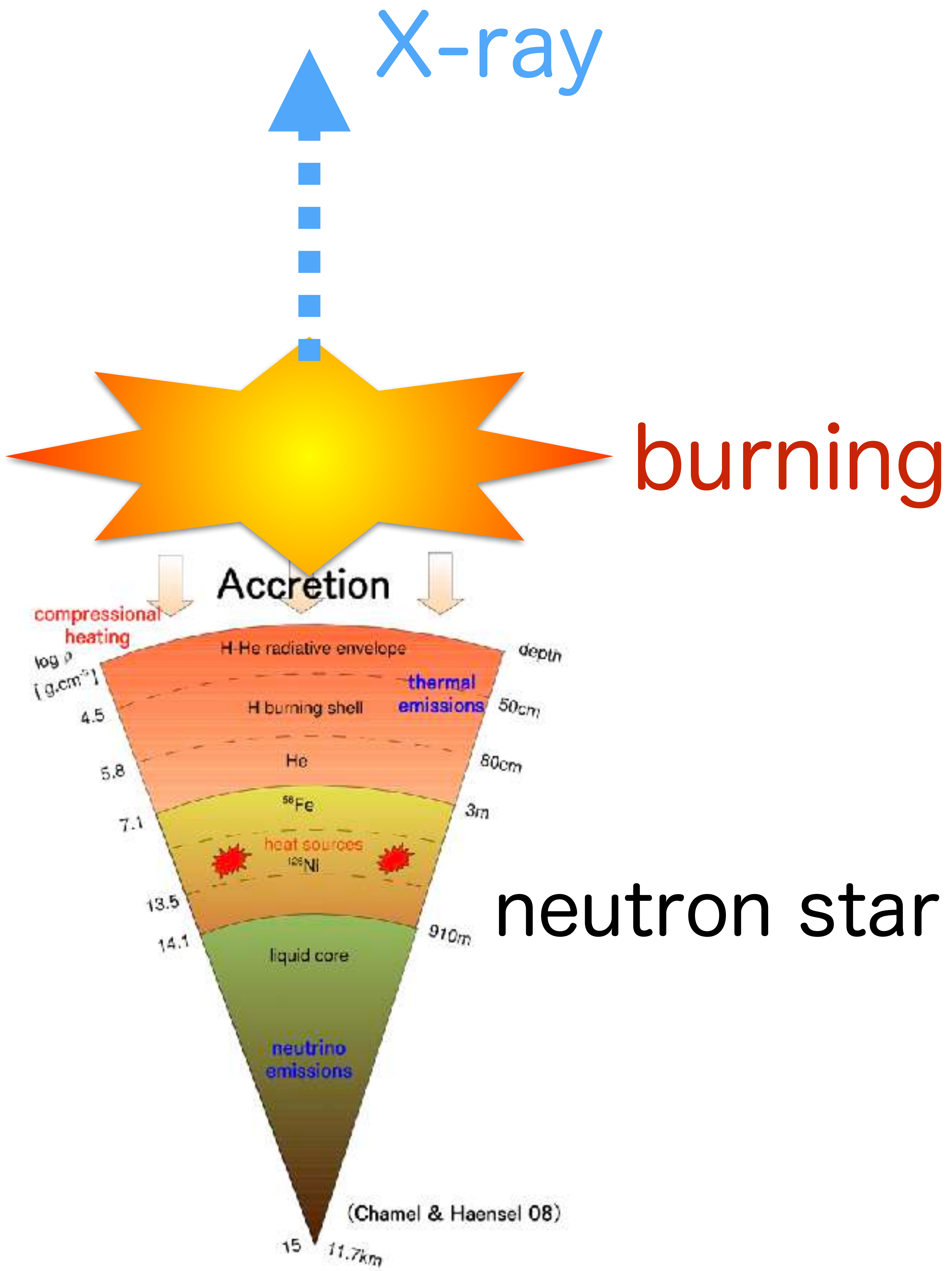
Meisel+(2018)

Stars vs accreting NS

regular stars

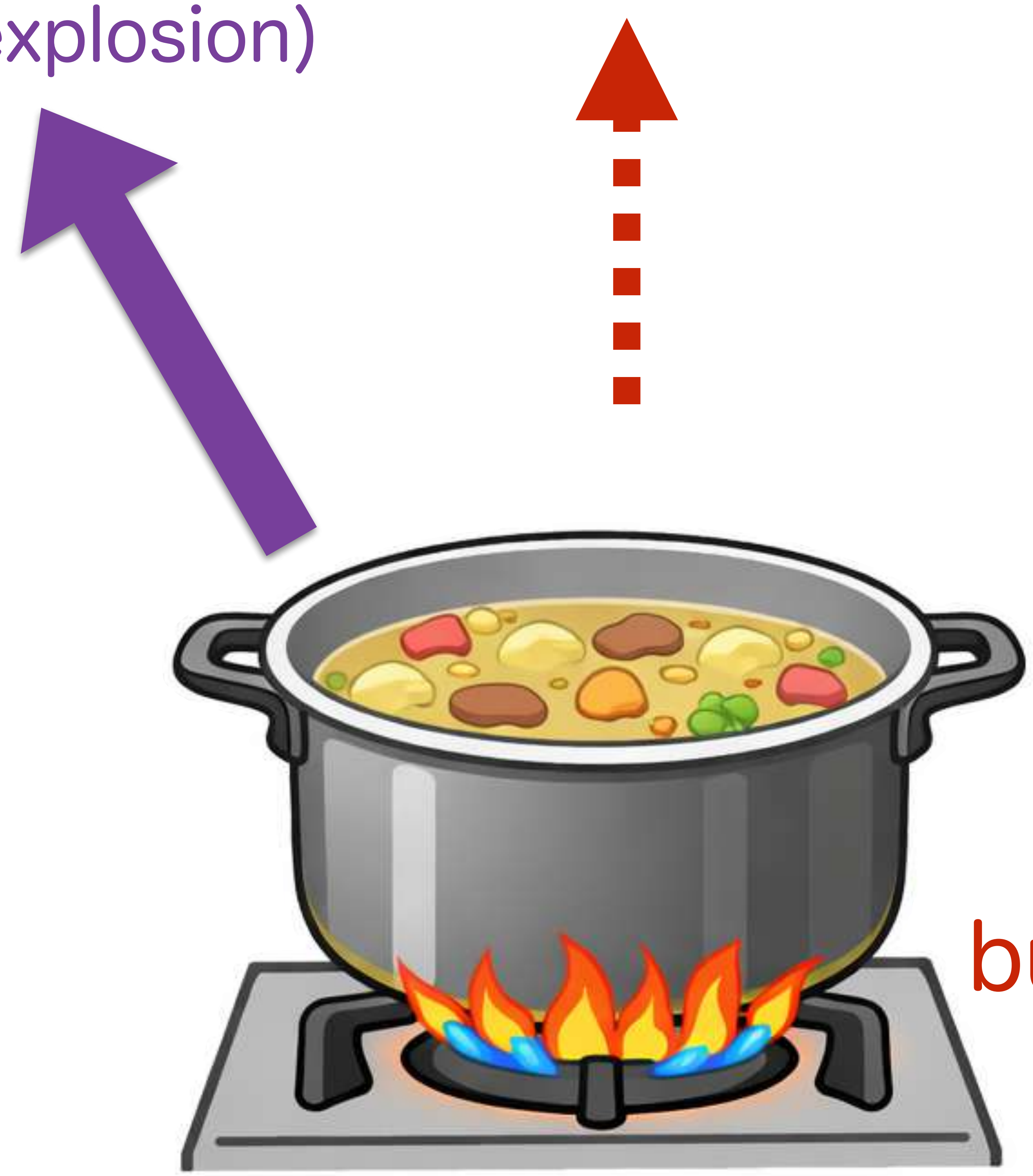


X-ray burst (on NS)



Stars vs accreting NS

regular stars



X-ray burst (on NS)

illustration by ChatGPT

Talk plan

1. Impacts of the 26Si(α,p)29P rate

- impacts of rate uncertainty on the light curve and nucleosynthesis
- expected impacts by a new measurement at CRIB

2. Impacts of new theory rates

- new rate calculations by SMARAGD (updated of NON-SMOKER)

3. (Temperature-resolved rate sensitivity)

- Impacts of triple-α and $^{12}C(a,g)^{16}O$ on ^{56}Ni production in PISN

Impacts of the $^{28}Si(\alpha,p)^{29}P$ rate

in collaboration with CNS (U Tokyo) group

・Hayakawa+NN+, in prep. → main experiment paper

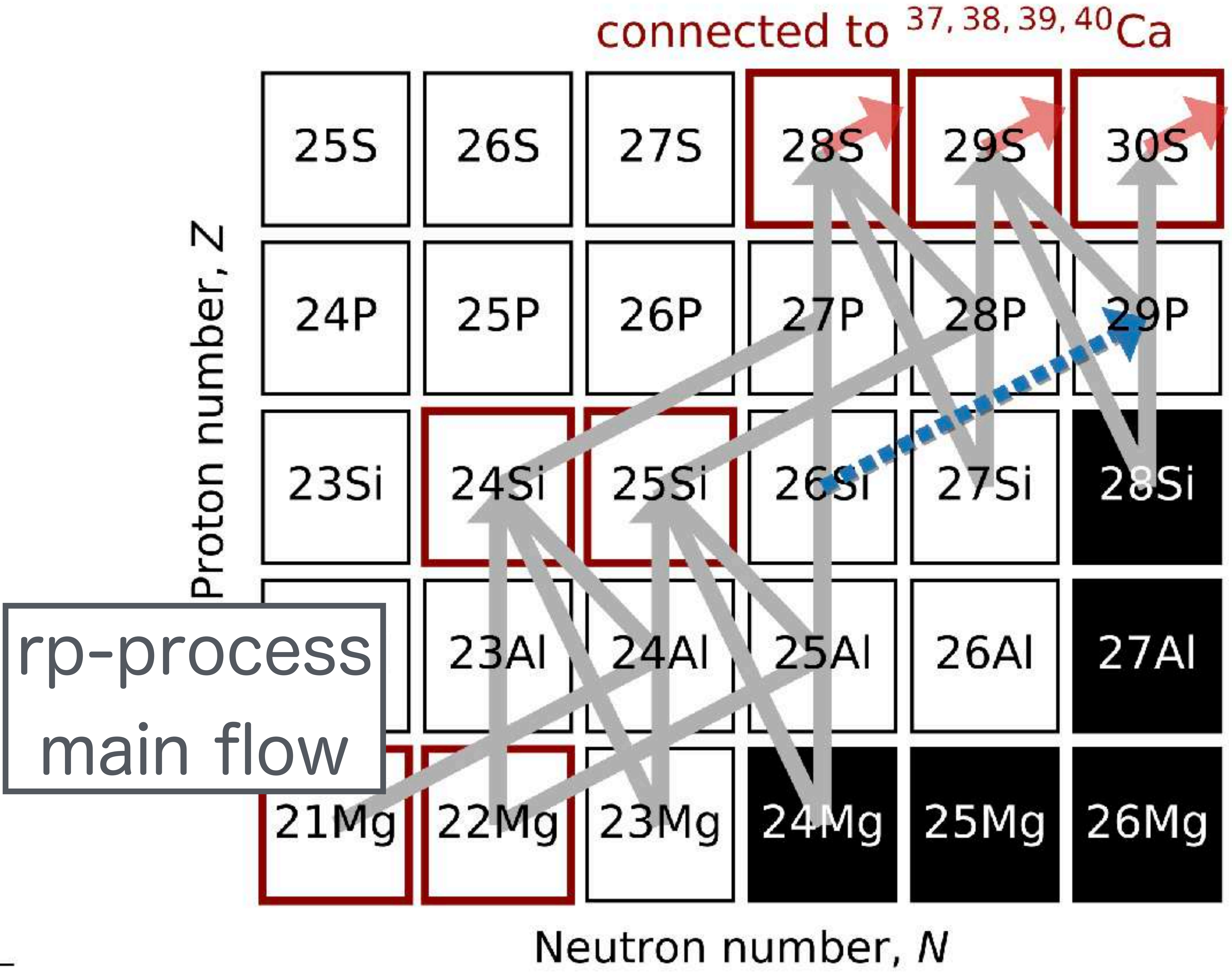
・NN, Dohi+, in prep.

A key reaction: $^{26}Si(a,p)^{29}P$

Key reactions (Cyburt+2016)

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{56}Ni(\alpha, p)^{59}Cu$	U	12.5	1
2	$^{59}Cu(p, \gamma)^{60}Zn$	D	12.1	1
3	$^{15}O(\alpha, \gamma)^{19}Ne$	D	7.9	1
4	$^{30}S(\alpha, p)^{33}Cl$	U	7.8	1
5	$^{26}Si(\alpha, p)^{29}P$	U	5.3	1
6	$^{61}Ga(p, \gamma)^{62}Ge$	D	5.0	1
7	$^{23}Al(p, \gamma)^{24}Si$	U	4.8	1
8	$^{27}P(p, \gamma)^{28}S$	D	4.4	1
9	$^{63}Ga(p, \gamma)^{64}Ge$	D	3.8	1
10	$^{60}Zn(\alpha, p)^{63}Ga$	U	3.6	1
11	$^{22}Mg(\alpha, p)^{25}Al$	D	3.5	1
12	$^{56}Ni(p, \gamma)^{57}Cu$	D	3.4	1
13	$^{29}S(\alpha, p)^{32}Cl$	U	2.8	1
14	$^{28}S(\alpha, p)^{31}Cl$	U	2.7	1
15	$^{31}Cl(p, \gamma)^{32}Ar$	U	2.7	1
16	$^{35}K(p, \gamma)^{36}Ca$	U	2.5	2
17	$^{18}Ne(\alpha, p)^{21}Na$	D	2.3	2
18	$^{25}Si(\alpha, p)^{28}P$	U	1.9	2
19	$^{57}Cu(p, \gamma)^{58}Zn$	D	1.7	2
20	$^{34}Ar(\alpha, p)^{37}K$	U	1.6	3
21	$^{24}Si(\alpha, p)^{27}P$	U	1.4	3
22	$^{22}Mg(p, \gamma)^{23}Al$	D	1.1	3
23	$^{65}As(p, \gamma)^{66}Se$	U	1.0	3
24	$^{14}O(\alpha, p)^{17}F$	U	1.0	3
25	$^{40}Sc(p, \gamma)^{41}Ti$	D	0.9	3
26	$^{34}Ar(p, \gamma)^{35}K$	D	0.8	3
27	$^{47}Mn(p, \gamma)^{48}Fe$	D	0.8	3
28	$^{39}Ca(p, \gamma)^{40}Sc$	D	0.8	3

Not on the main flow,
but may act as a sub-branch



One-zone XRB models

One-zone X-ray burst model

(Sugimoto & Fujimoto 1978, Fujimoto+1981)

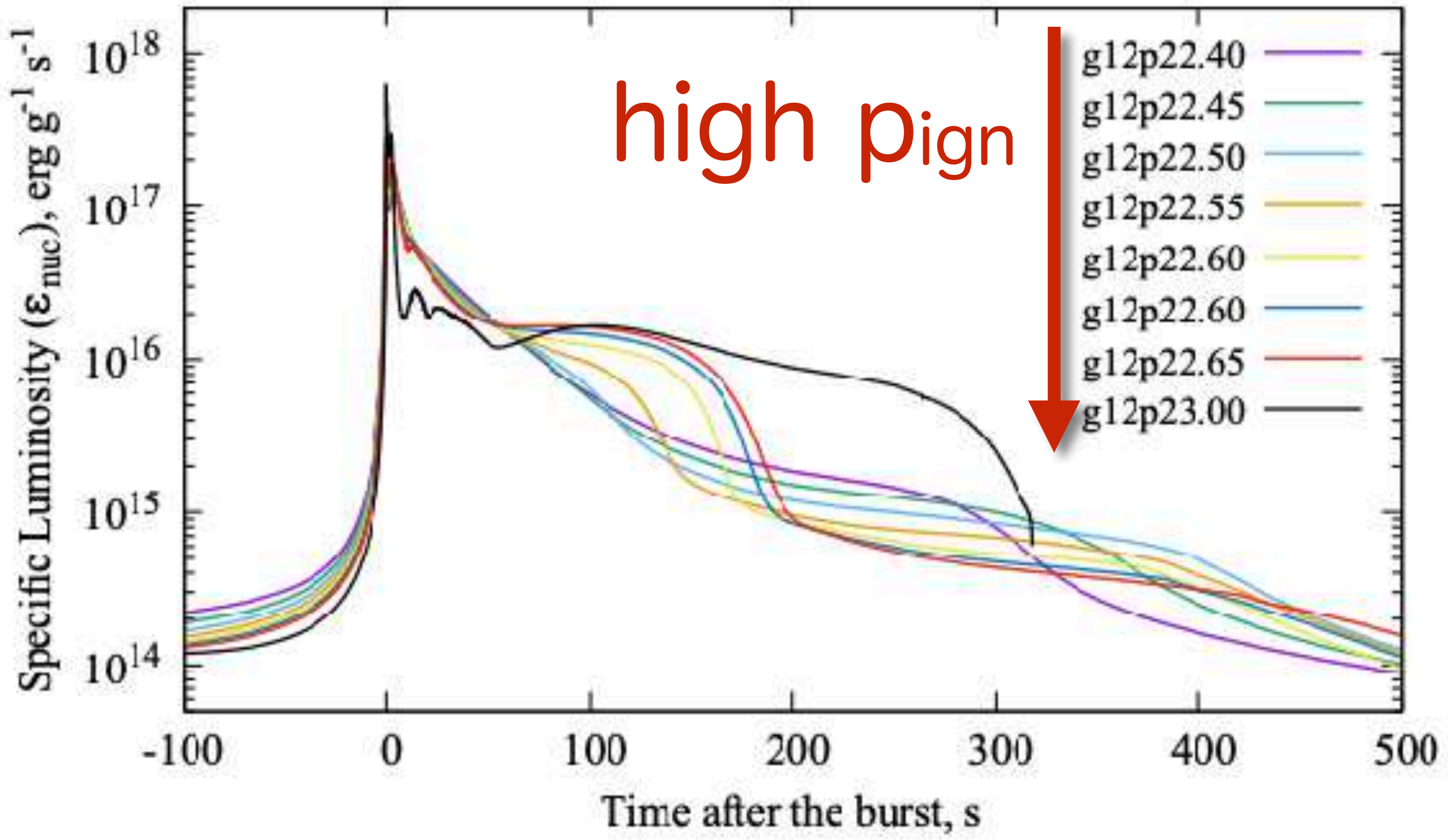
- surface gravity: g_s 1.318×10^{14}, 2.399×10^{14} cm/s^2
- ignition pressure: p_{ign} $2.5 \times 10^{22} \sim 1.6 \times 10^{23}$ dyn/cm^2

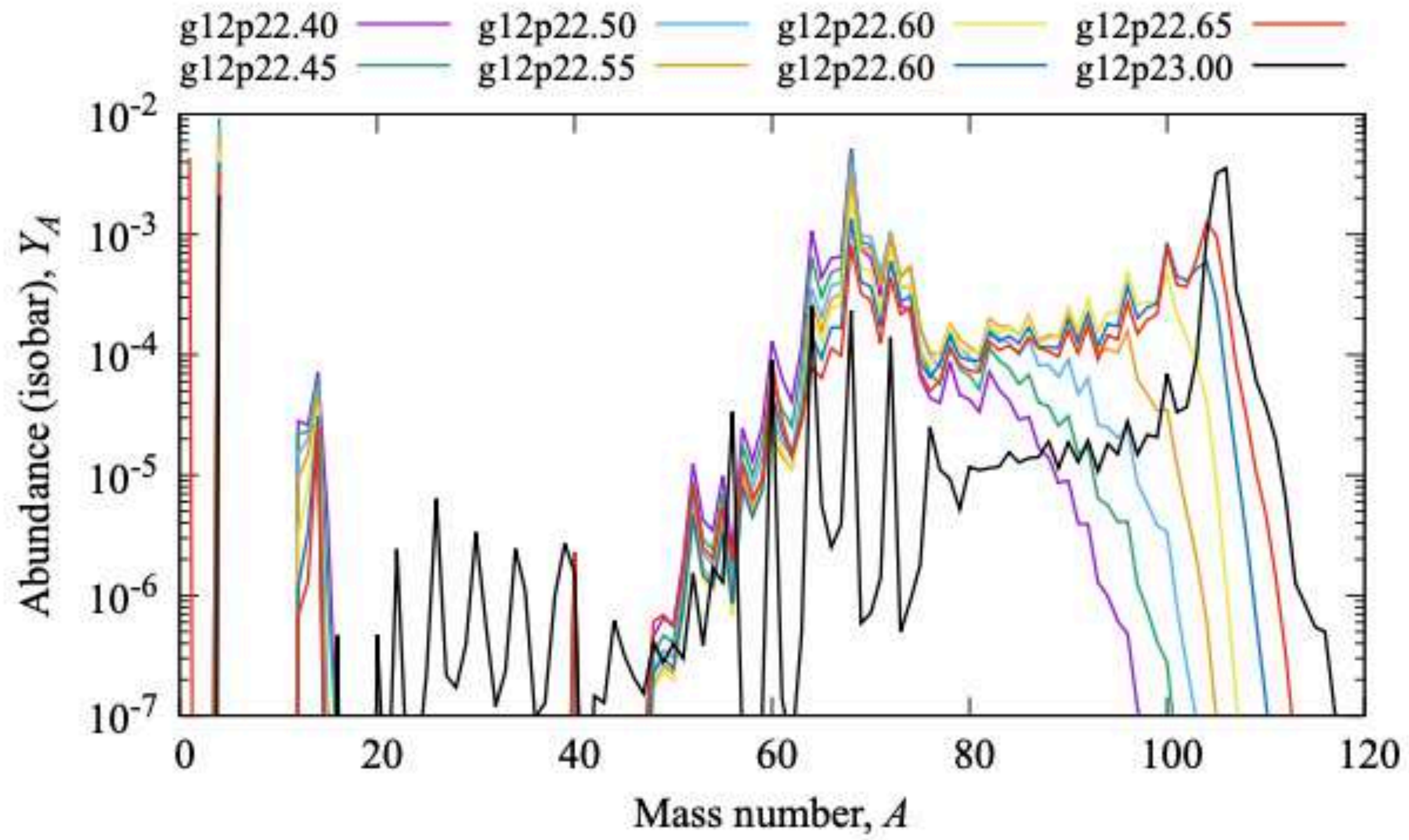
$g_{suf} = 14.12$	model #	01	02	03	04	05	06	07	08
	name	g12p22.40	g12p22.45	g12p22.50	g12p22.55	g12p22.60	g12p22.65	g12p22.70	g12p23.00
	P_{ing}	22.40	22.45	22.50	22.55	22.60	22.65	22.70	23.00
	T_{ing} (GK)	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
$g_{suf} = 14.38$	model #	09	10	11	12	13	14	15	16
	name	g38p22.70	g38p22.75	g38p22.80	g38p22.85	g38p22.90	g38p22.95	g38p23.00	g38p23.20
	P_{ing}	22.70	22.75	22.80	22.85	22.90	22.95	23.00	23.20
	T_{ing} (GK)	0.25	0.1	0.1	0.1	0.1	0.1	0.1	0.1

$g_s = 1.318 \times 10^{14}$ cm/s^2

typical NS:

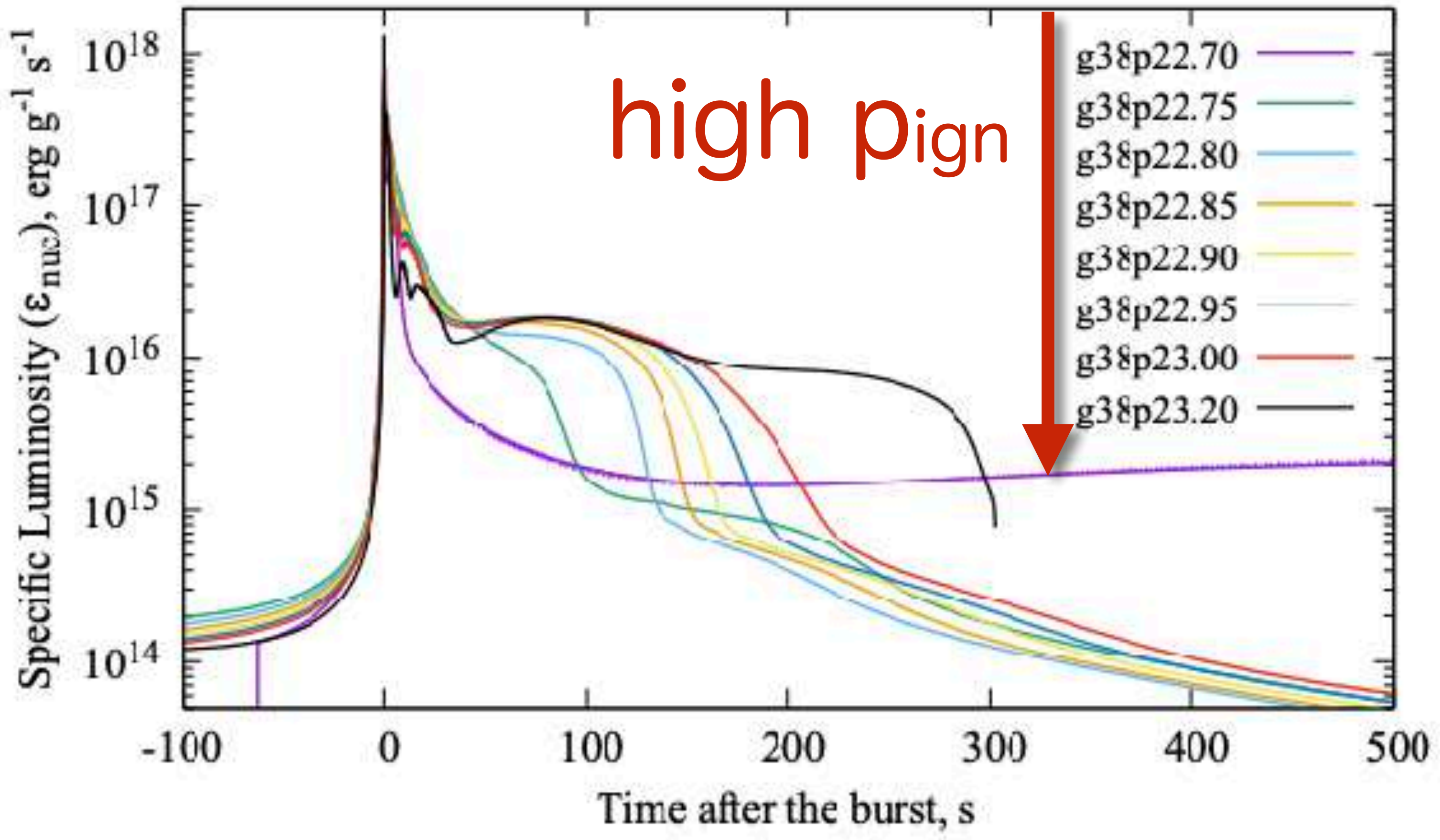
1.4 $M_\odot$, 10 km

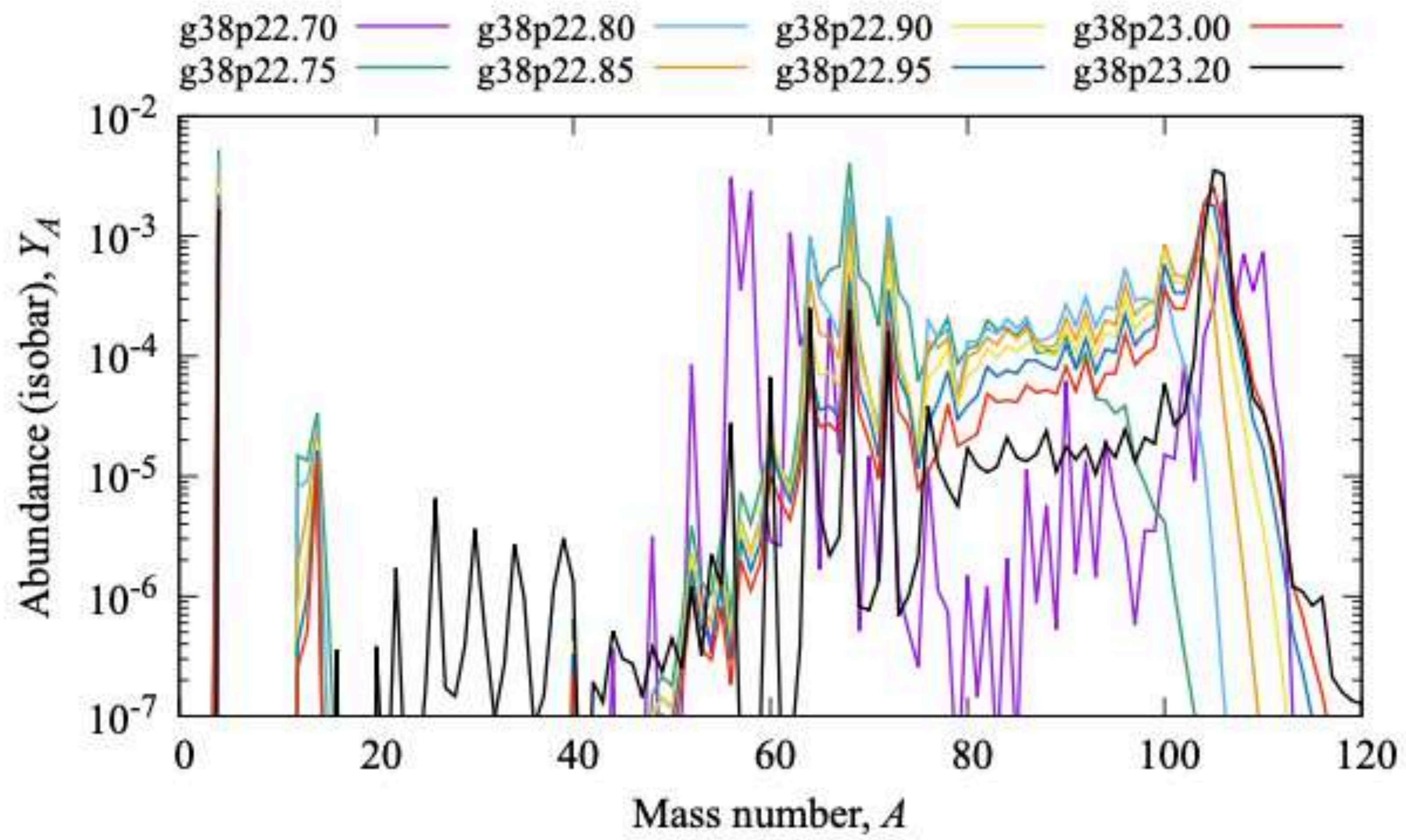




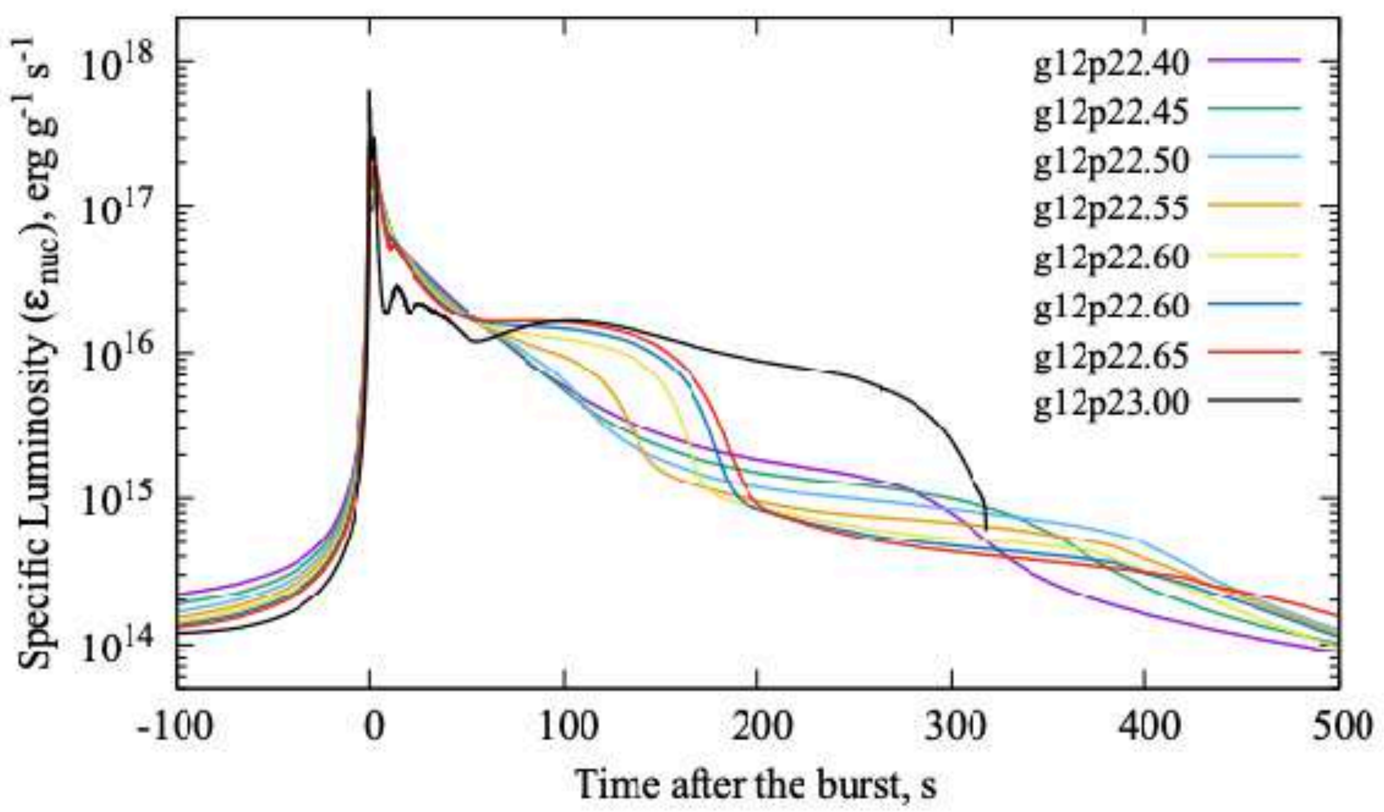
$g_s = 2.399 \times 10^{14}$ cm/s^2

stronger g_s



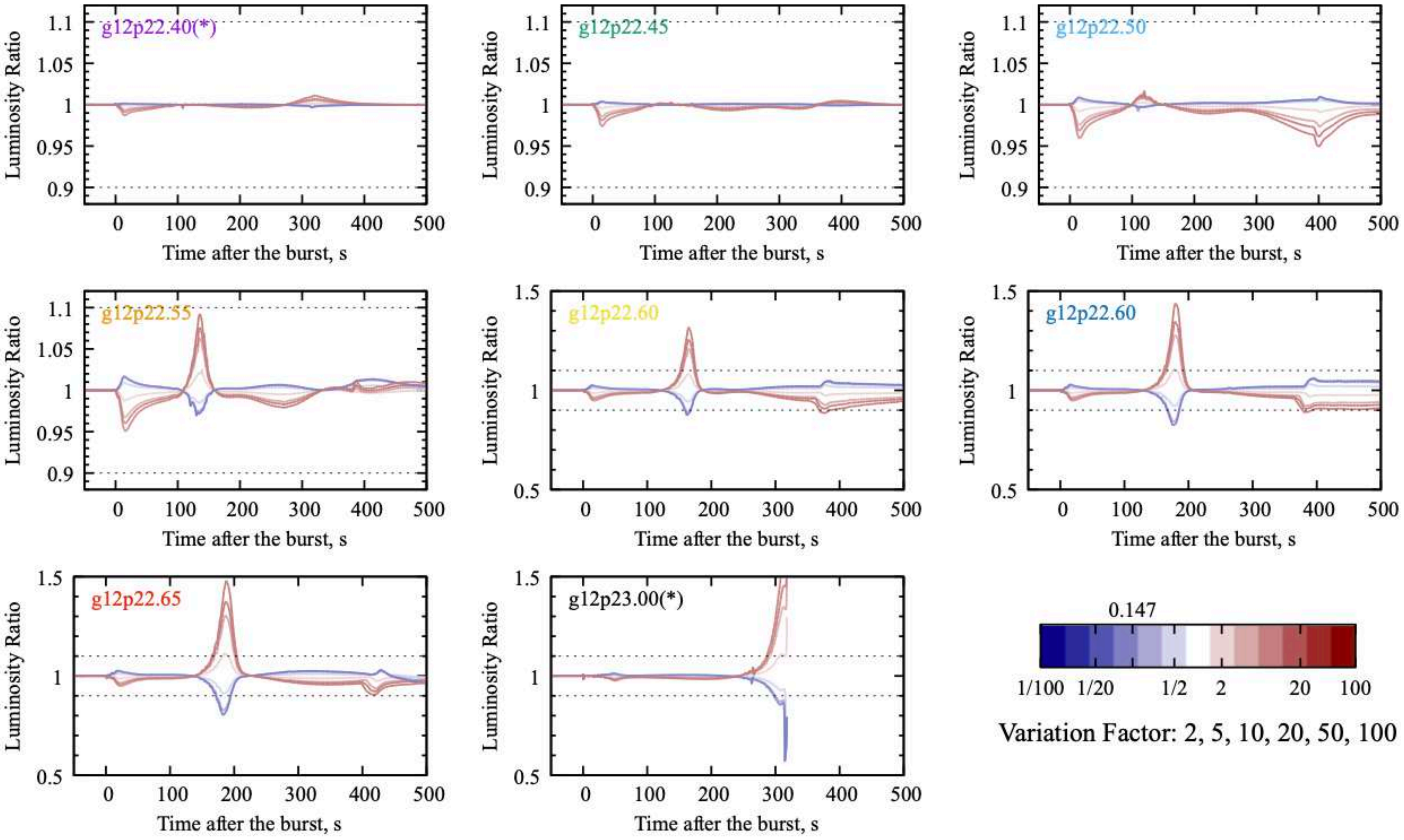


Impacts on light curves

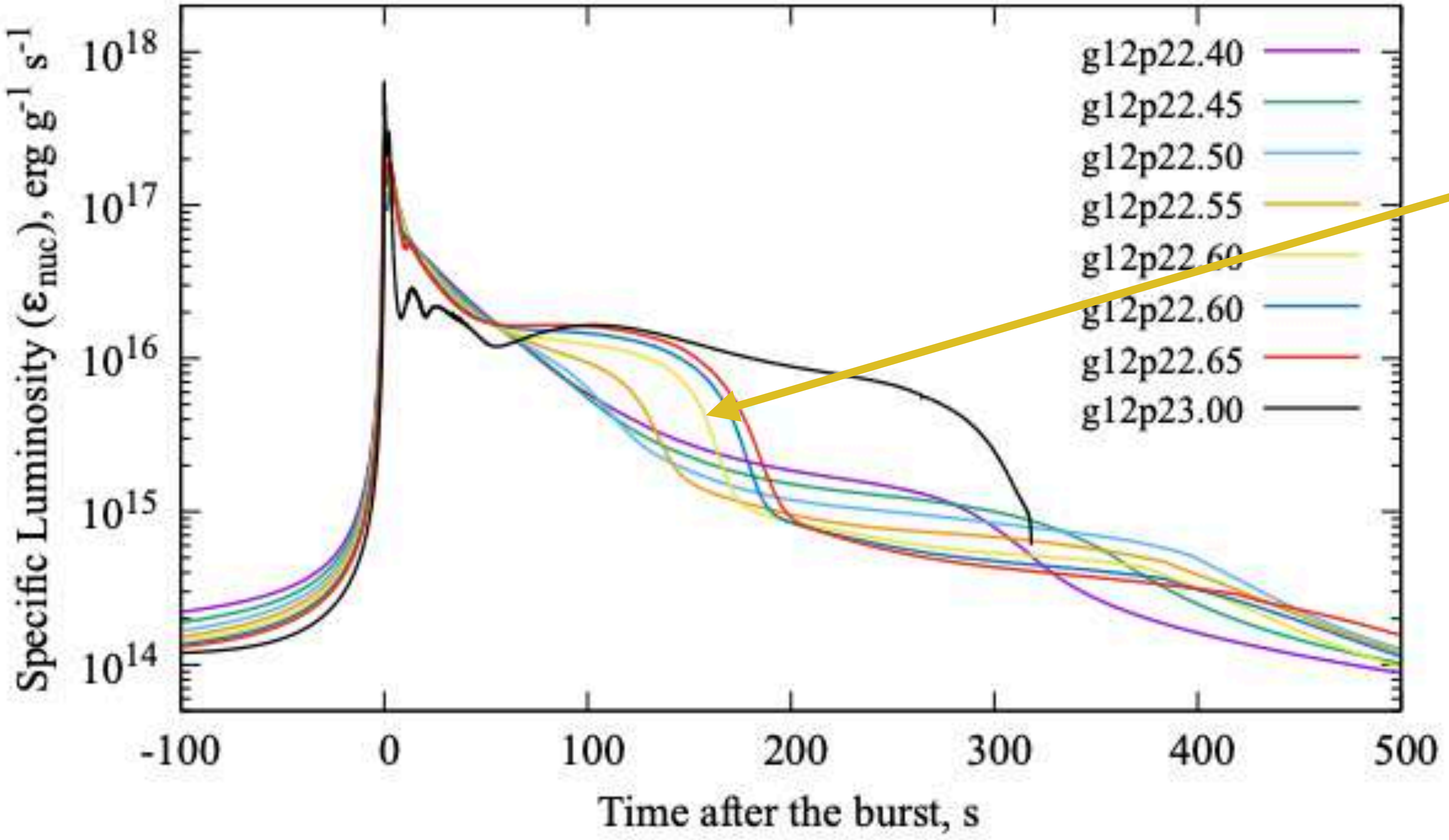


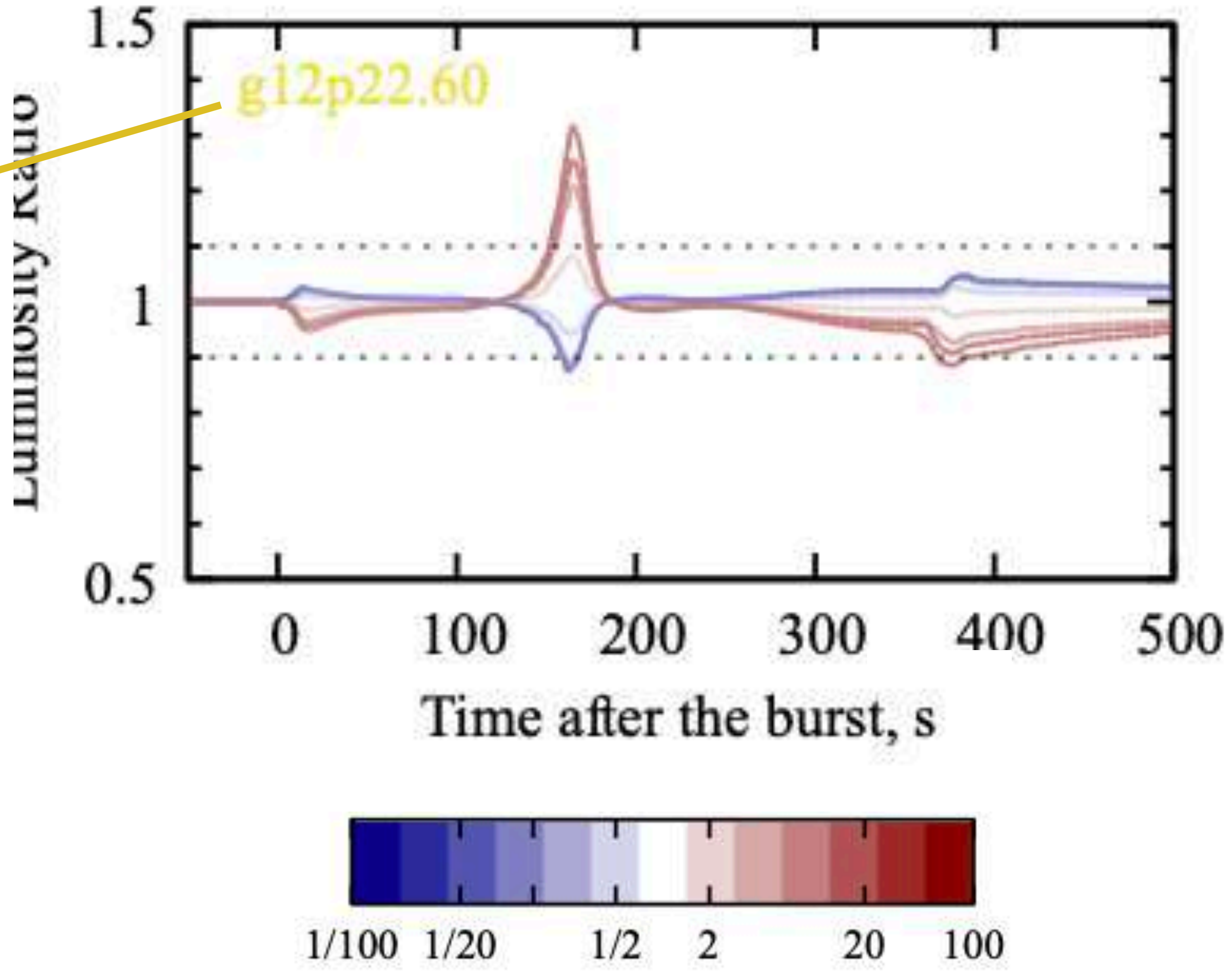
typical NS:

1.4 $M_{\odot}$, 10 km



Impacts on light curves





Variation Factor: 2, 5, 10, 20, 50, 100

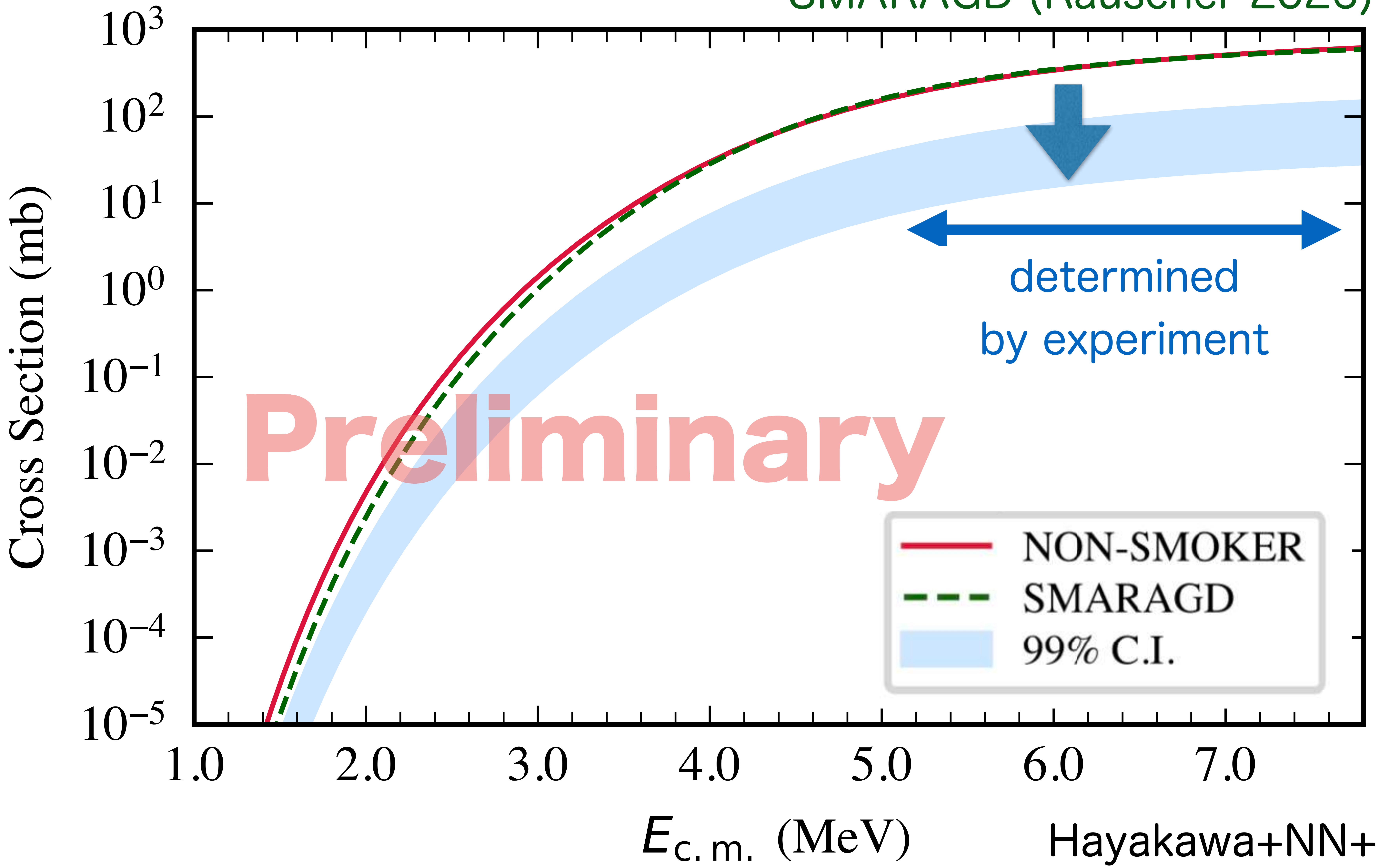
typical NS:

1.4 $M_{\odot}$, 10 km

Impacts on the nucleosynthesis products

siginificantly lower than Statistical calculations → weak impacts on XRB light curves

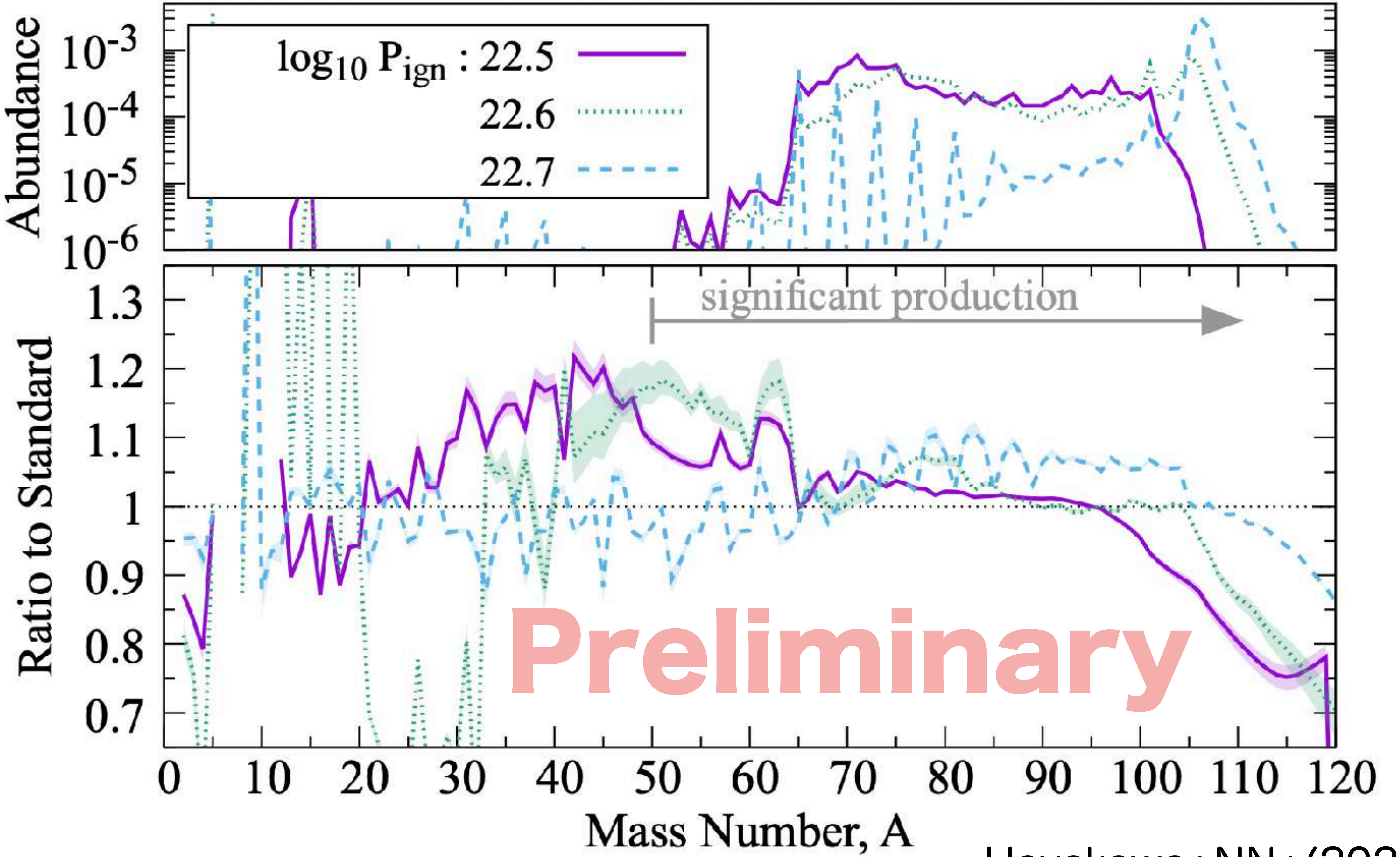
SMARAGD (Rauscher 2026)



Hayakawa+NN+(2026), in prep.

Impacts on the nucleosynthesis products

ratio with a uncertainty band (experimental)



Hayakawa+NN+(2026), in prep.

Impacts of new theory rates

references

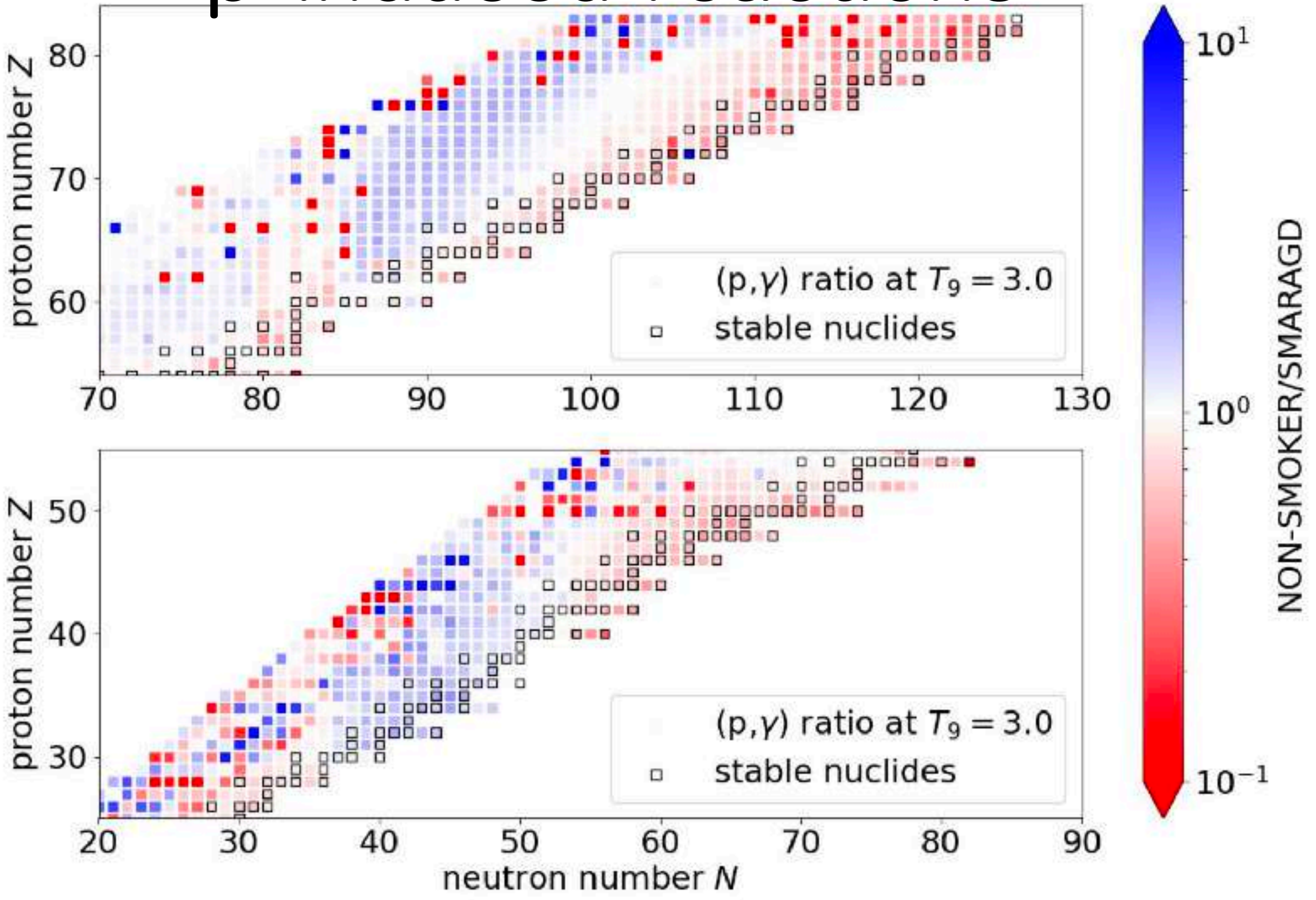
- Rauscher EPJ A, 62 (2026) → SMARAGD
- NN, Dohi, Rauscher+, in prep.

Impacts of new theory rates

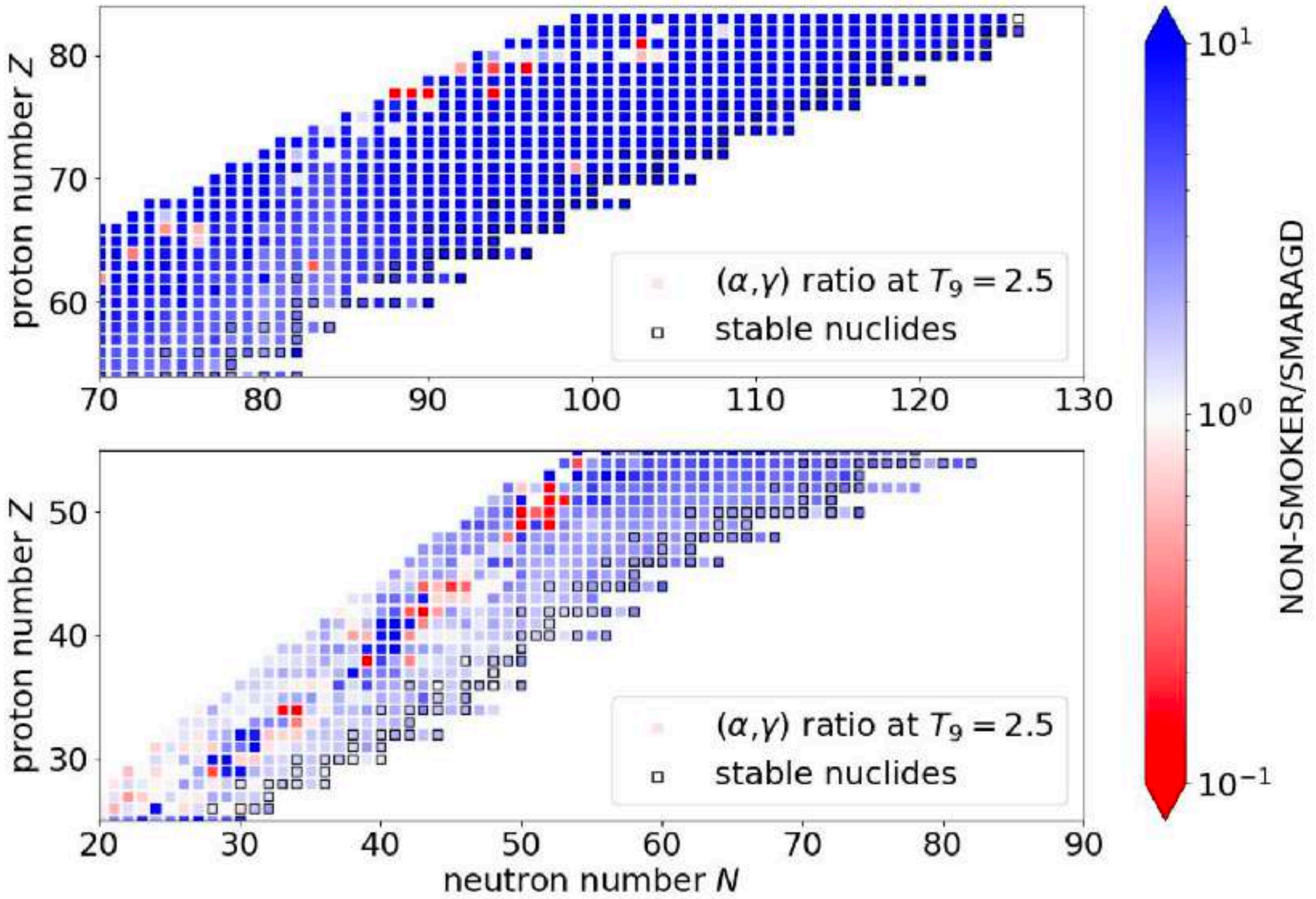
- ・new theoretical rates by SMARAGD (statisitcal model); Rauscher (2026)
  - ・latest physics inputs & physics model (e.g., direct capture)
  - ・better agreement with experiments than previous calaultions (NON-SMOKER
- ・a major update on widely used Reaclib (astrophysical reaction rates) since 1990’s

Comparison to NON-SMOKER

p-induced reactions



α-induced reactions

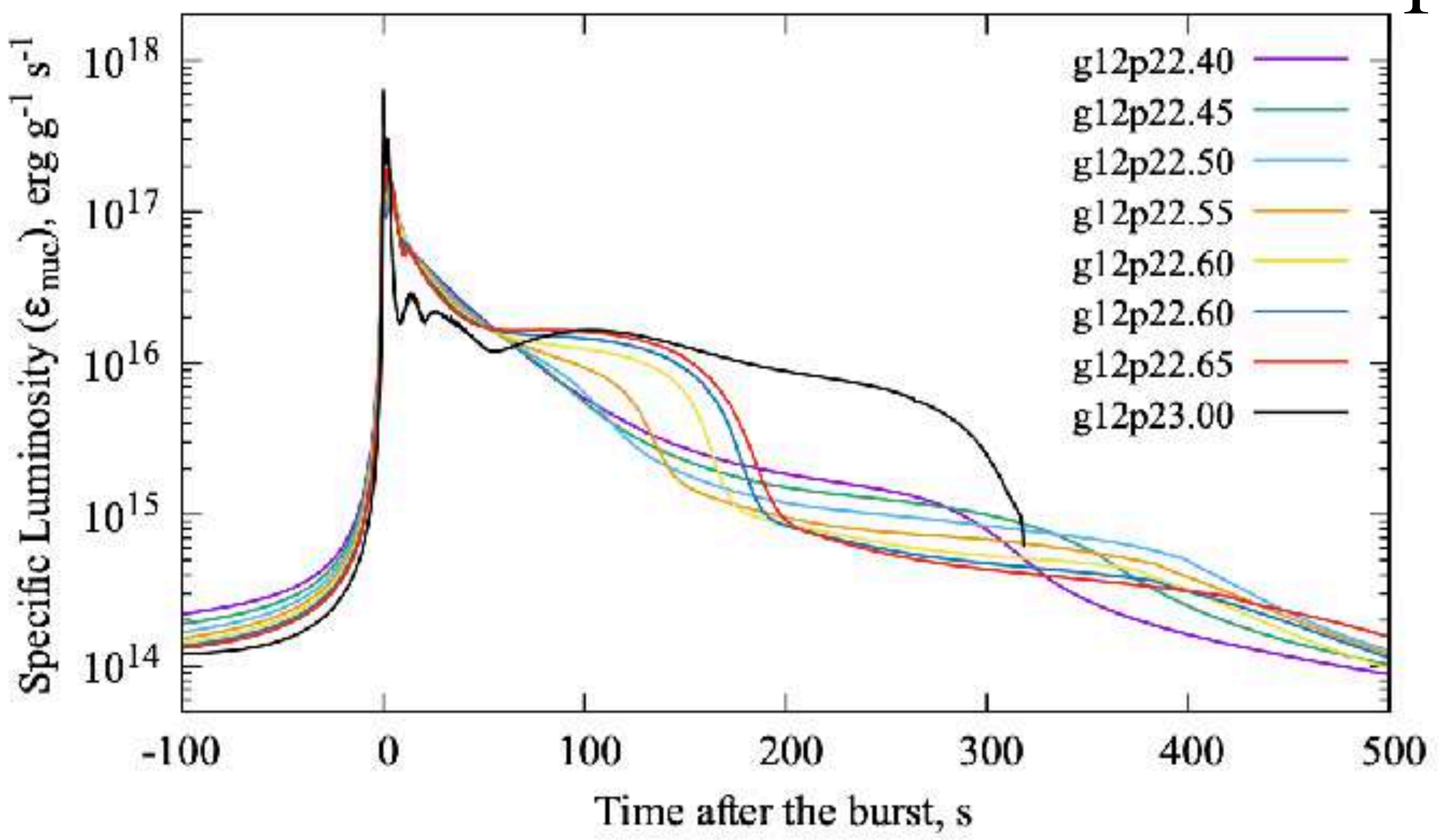


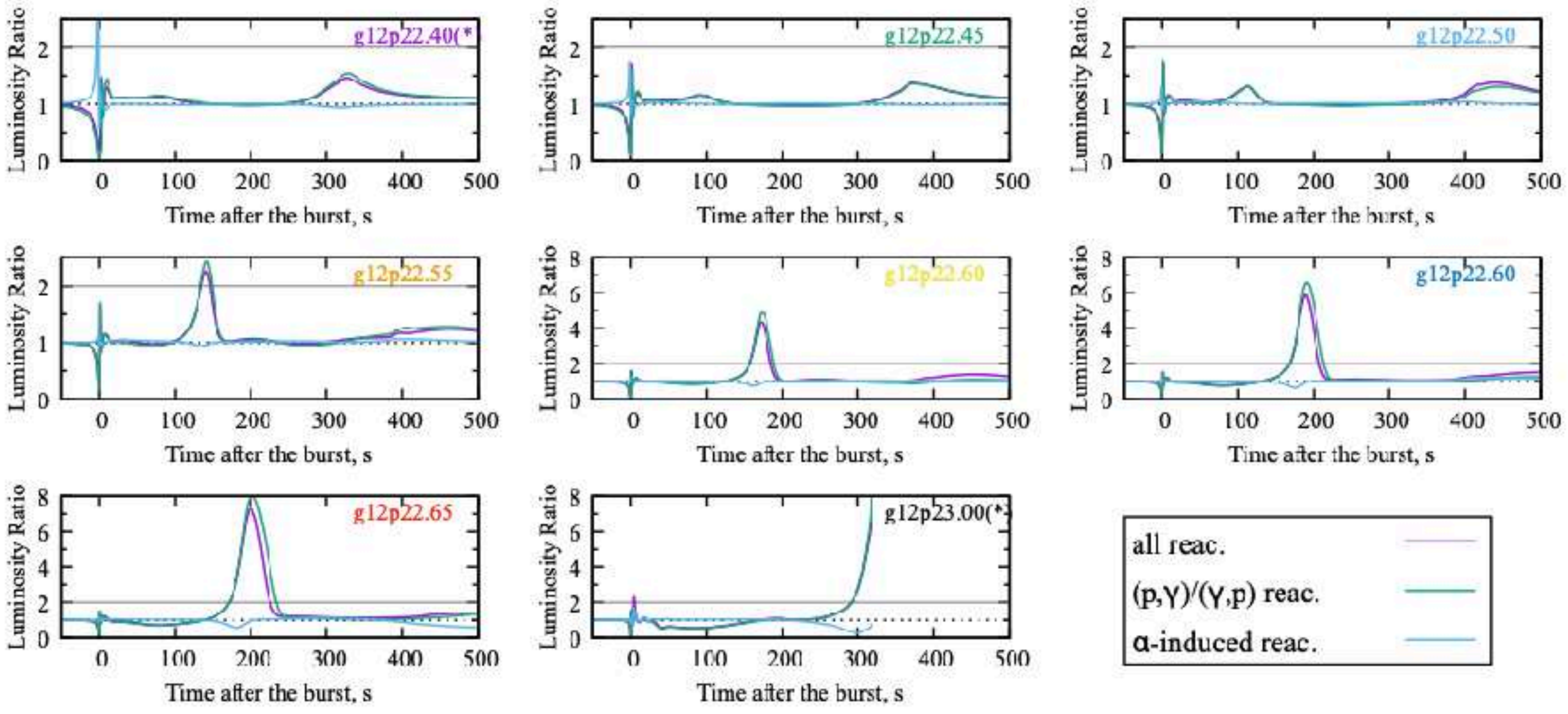
vs SMARAGD (Rauscher 2026)

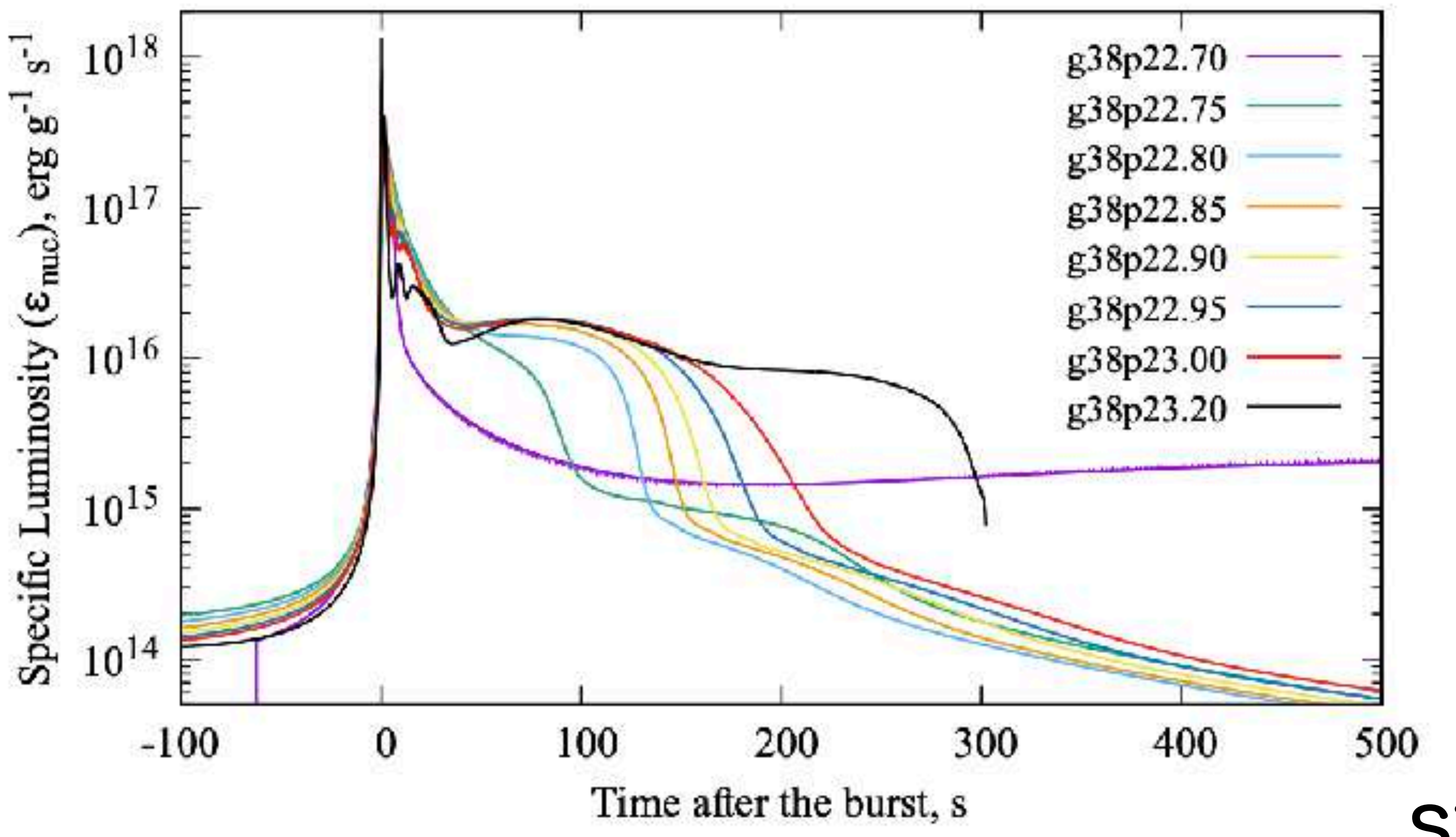
typical NS:

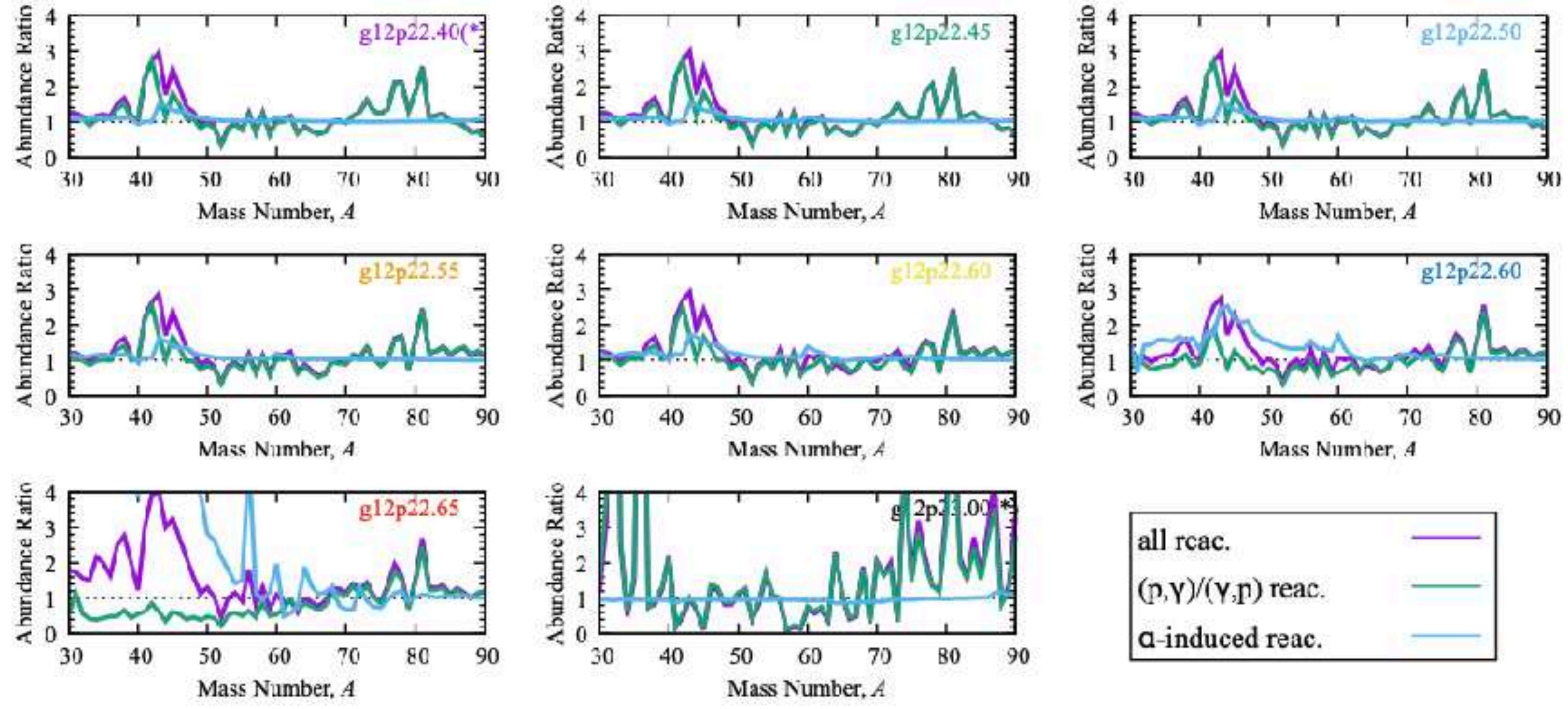
1.4 $M_\odot$, 10 km

comparison to NON-SMOKER



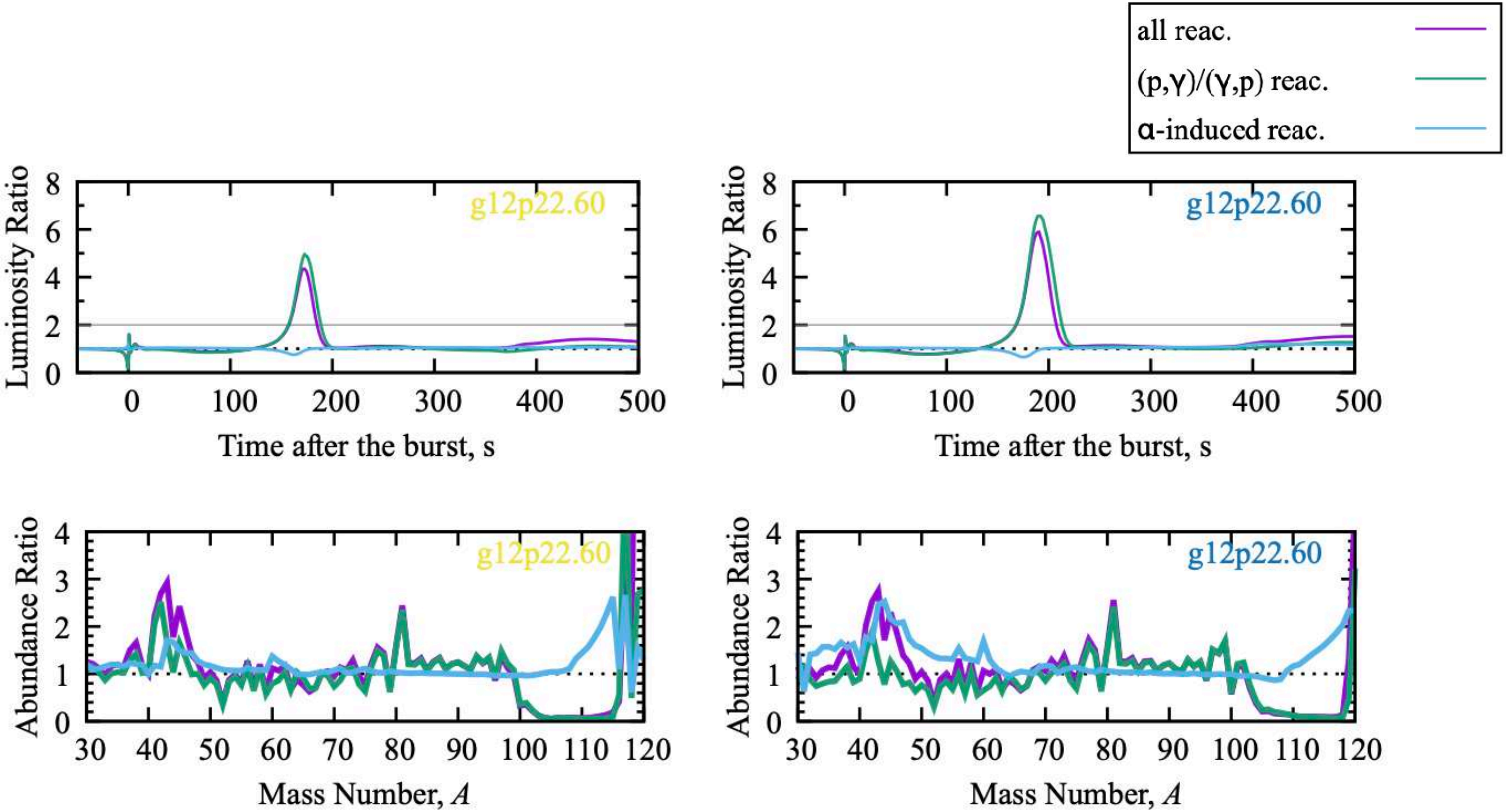




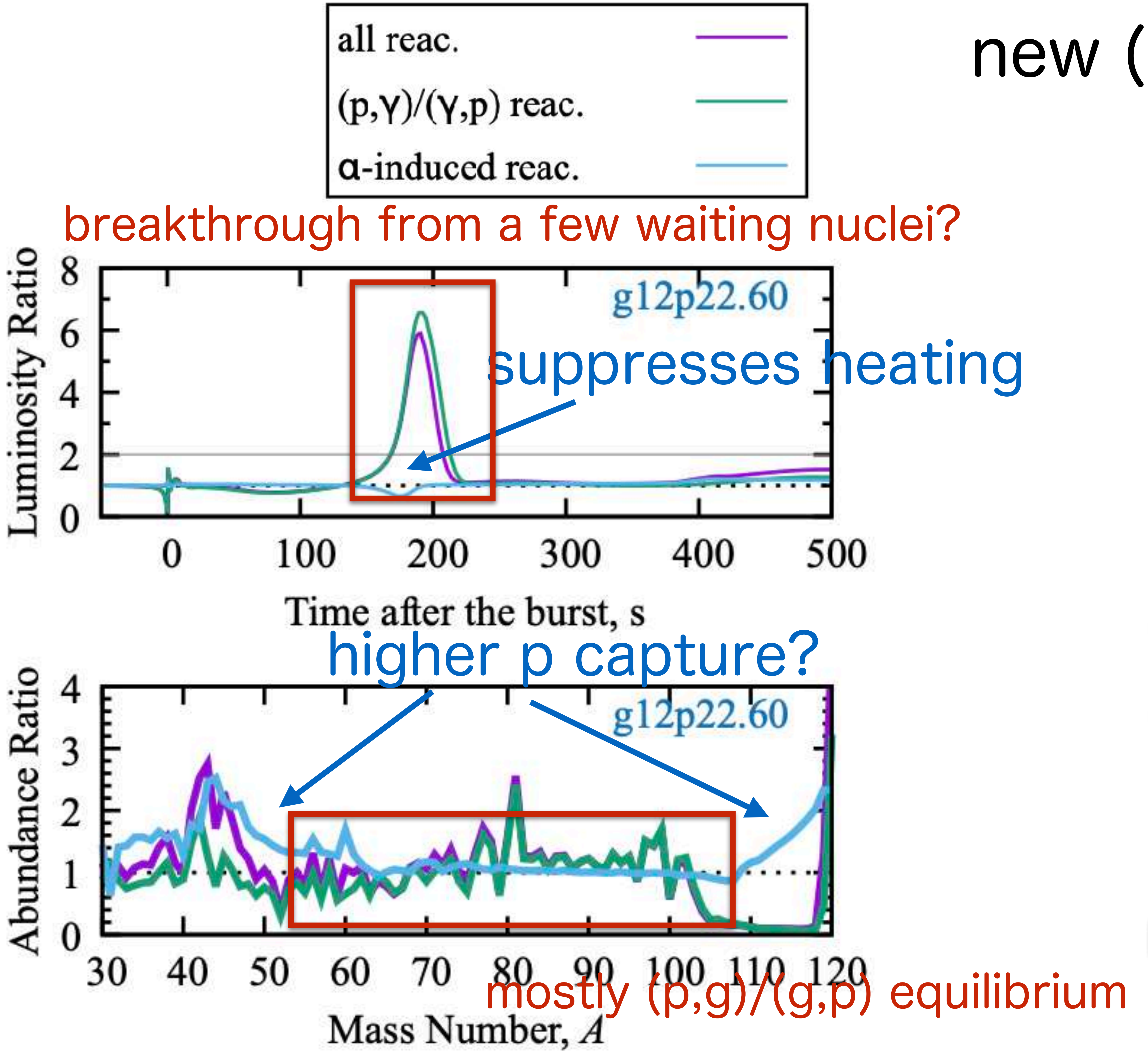


stronger g_s

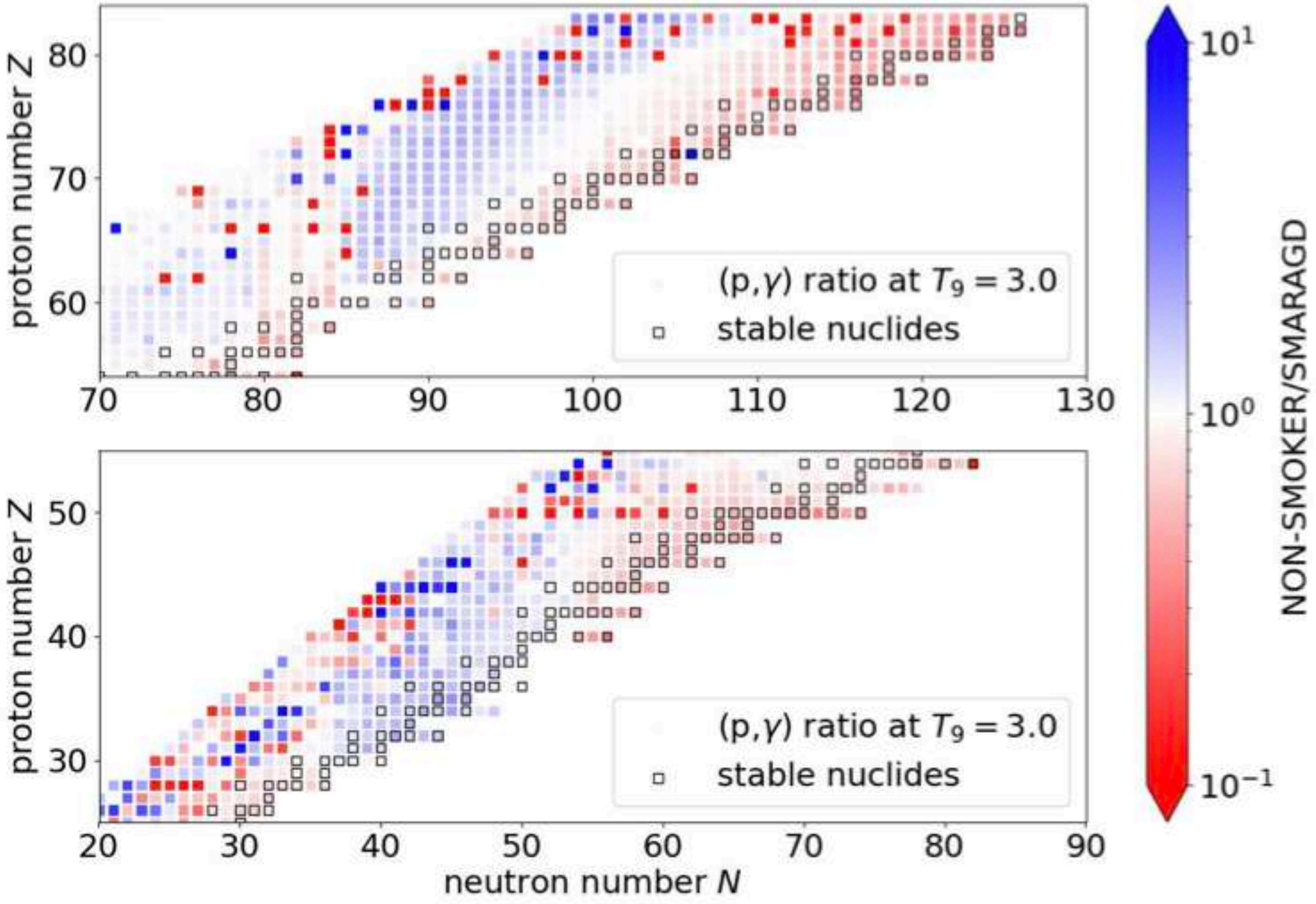
Effects of new rates (preliminary)



Effects of new rates (preliminary)

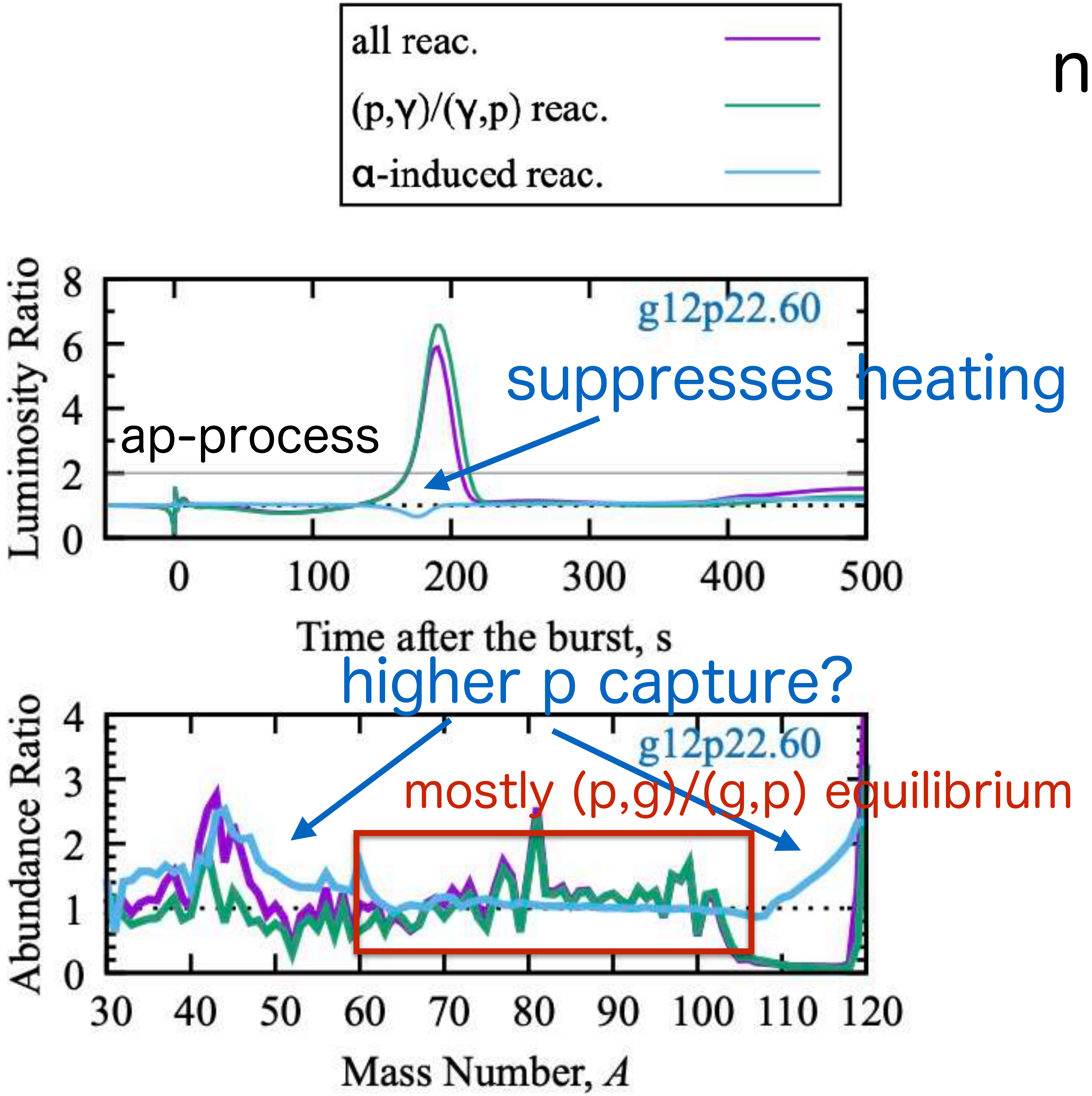


new (p,g) rates show difference
(but not simple)



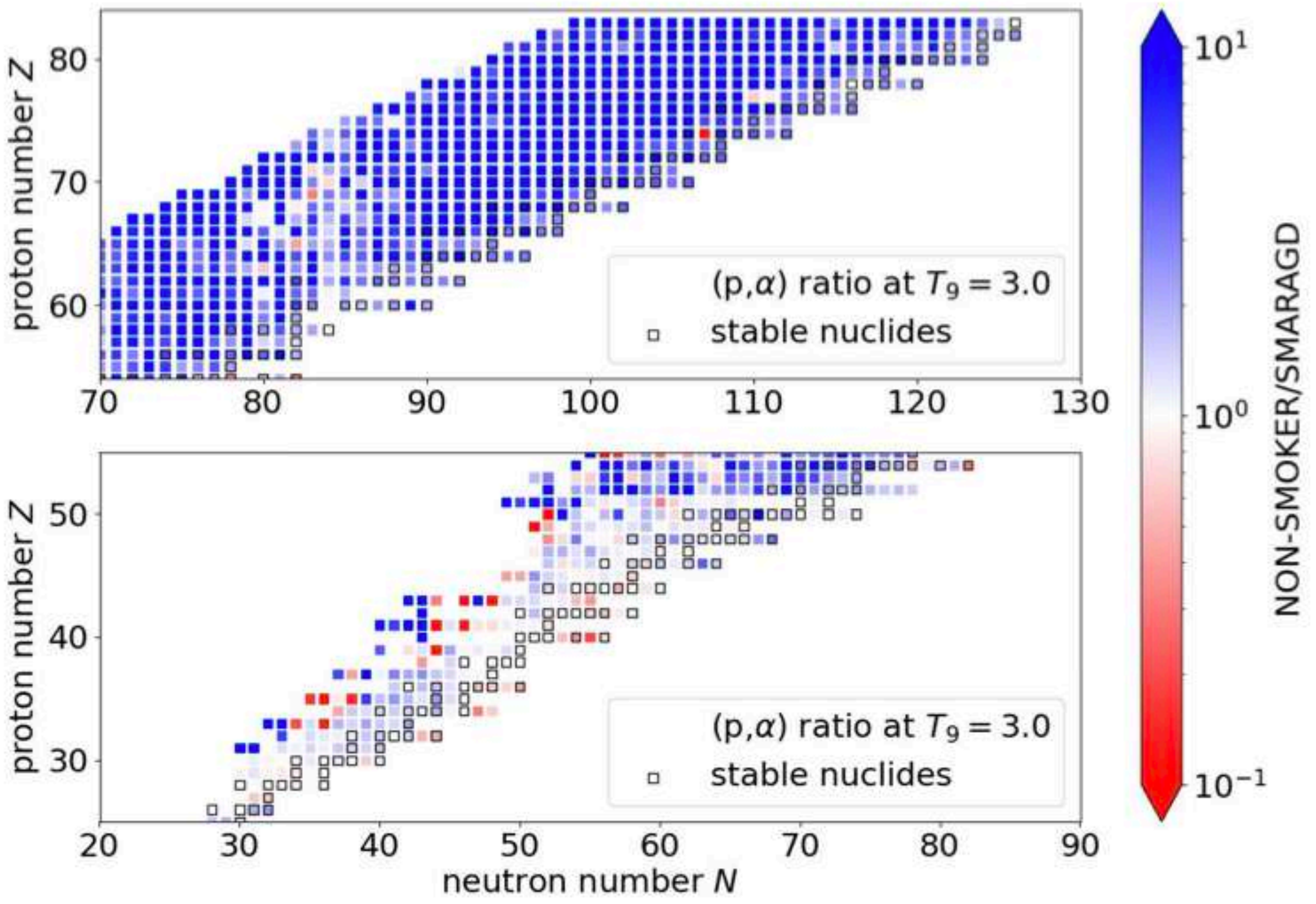
focus more on individual reaction rates

Effects of new rates (preliminary)



new rates show weaker (p,a)

→ larger Y_p



→ focus more on individual reaction rates

Temperature-resolved rate sensitivity

see Poster #04 by H. Kawashimo

<u>based on</u>

・Kawashimo, NN & Suwa (2026), arXiv:2605.27264

Reaction/decay rate uncertainty?

nuclear physics to nucleosynthesis

experiment — theory

Nuclear property → Reaction model → Cross section, Rate →

nucleosynthesis

also diversity — (less uncertain) — observation

Astrophysical model → Reaction network → Abundances

uncertianty factor (const.)

T-dependent uncertainty (systematics)

T-dependent uncertainty (nuclear strucure e.g., resonance)

simple rate variation

T-dependent variation

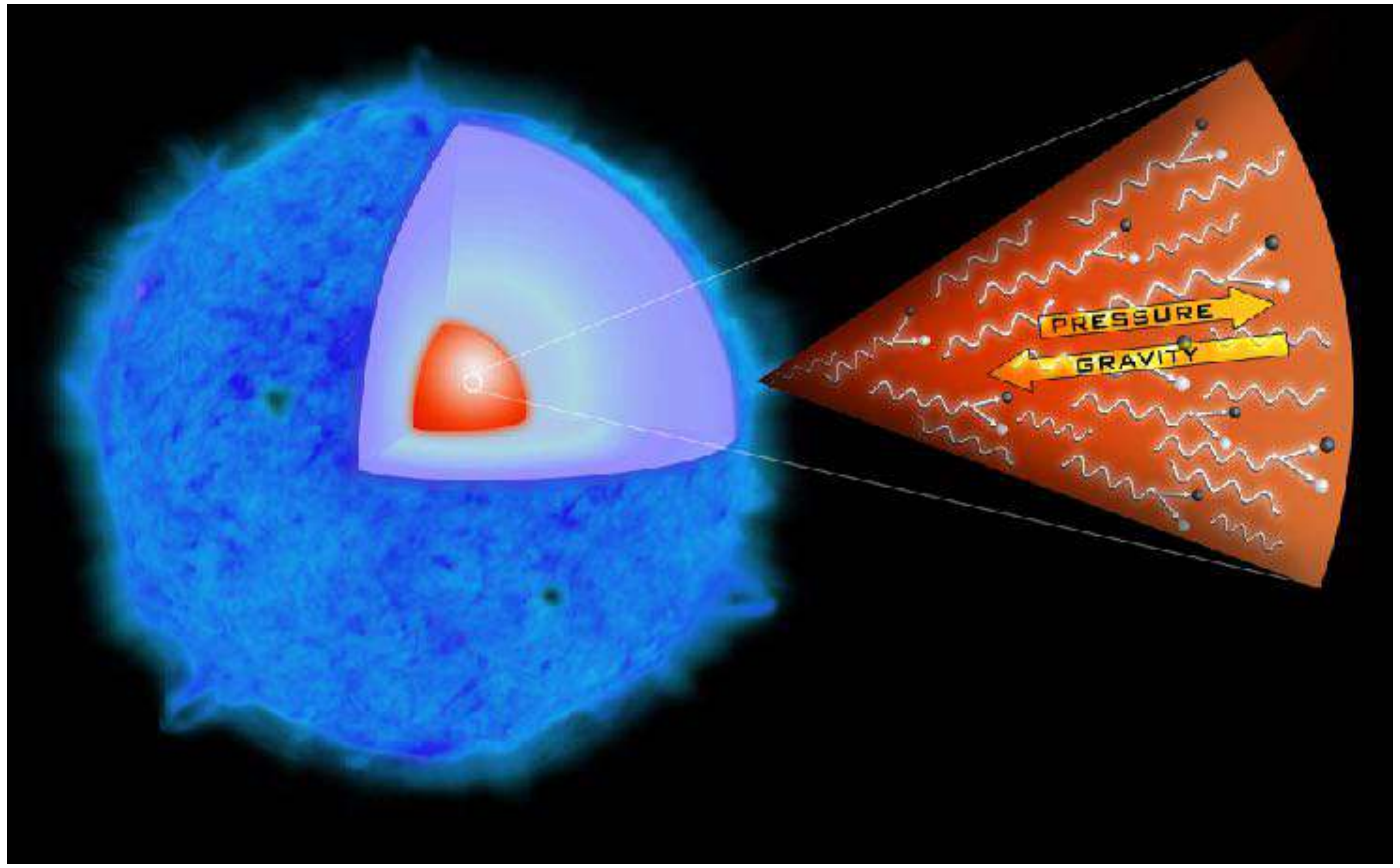
T-resolved rate sensitivity

realistic

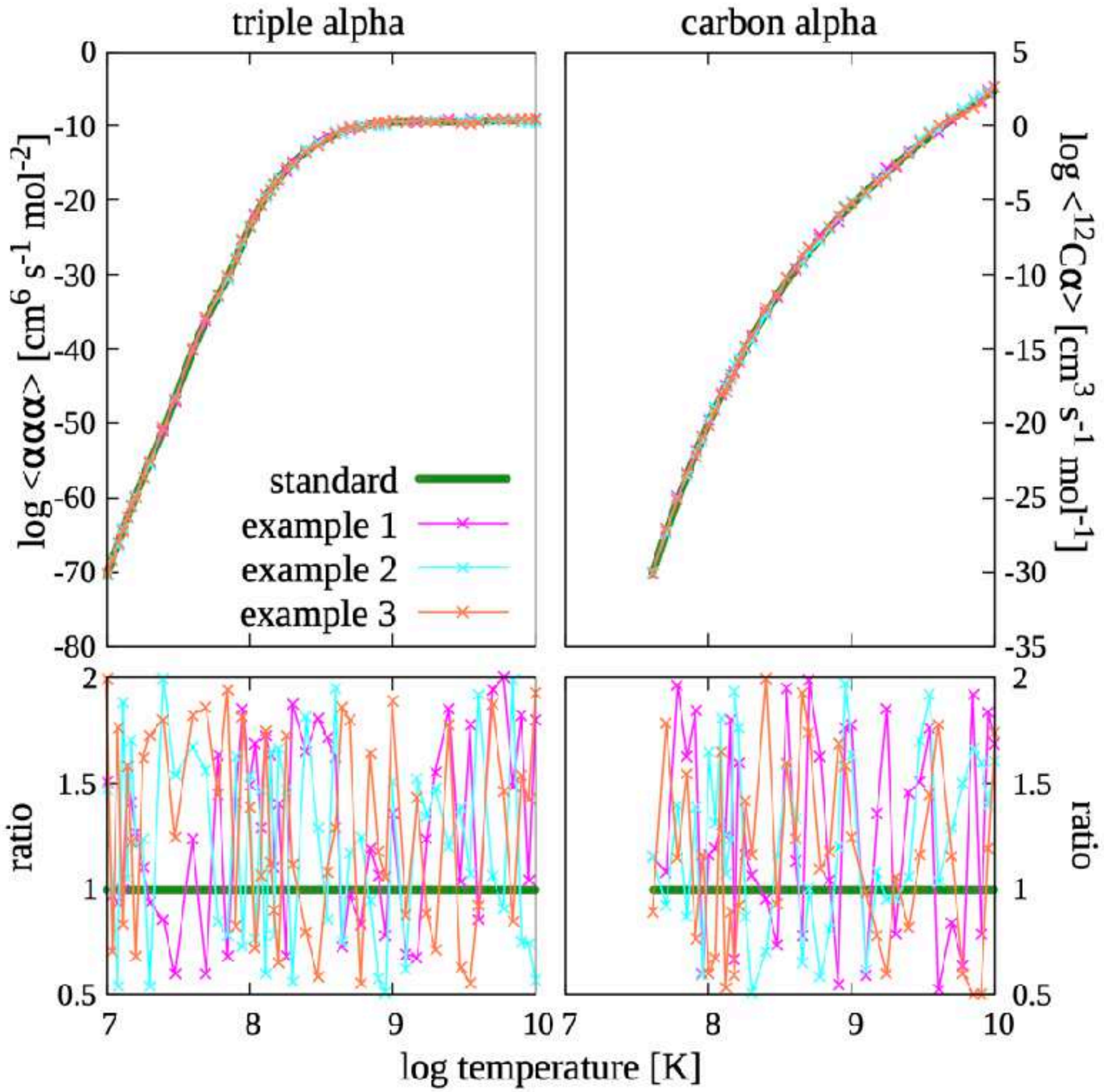
“Temperature resolved” sensitivity

Pair-instability Supernovae

- Explosion of very massive stars ($> 100\ M_{\odot}$)
- triggered by e^-—e^+ pair creation from high-energy gamma-ray
- occures after He burning in a massive C/O core
- complete disruption of the star with production of a large amount of ^{56}Ni



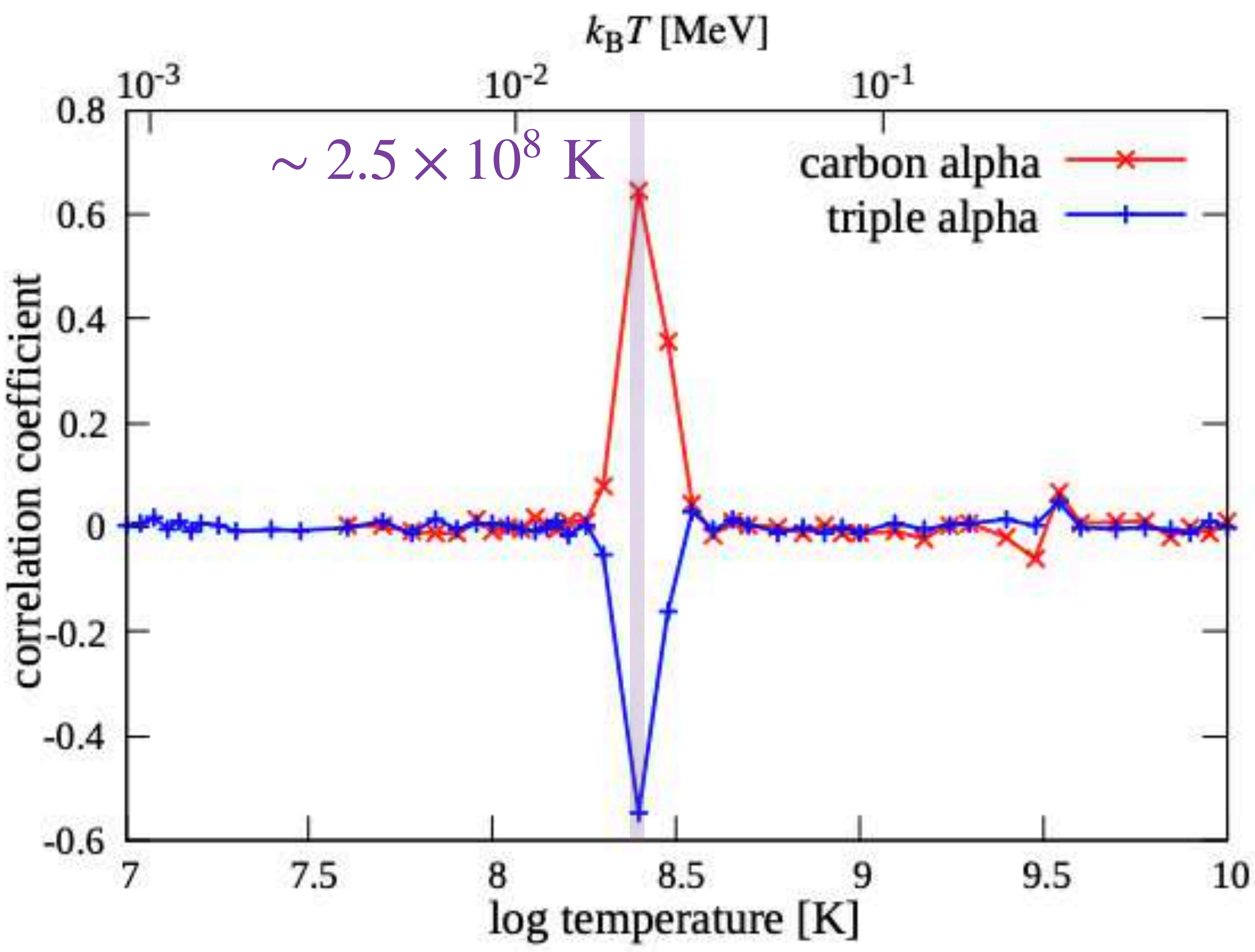
key rates in He burning



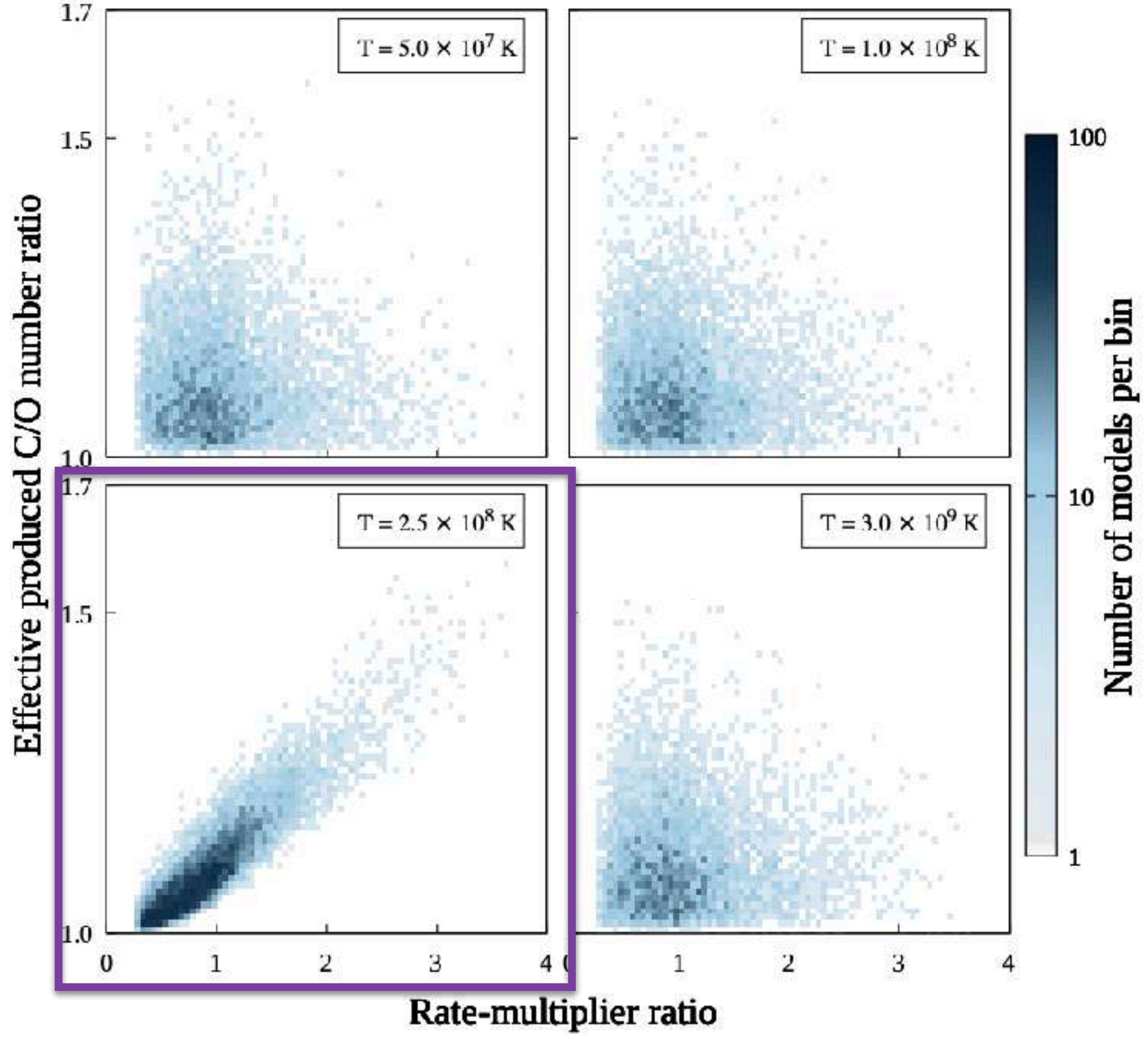
Key T in ^{56}Ni production PISNe

- $100\ M_\odot$ very massive star (H-envelope stripped)
- Evolution and explosion are calculated by the MESA code
- Correlation (rate variation vs ^{56}Ni): Peason's coefficient

higher impact T: triple-α & ^{12}C(a,g)^{16}O



C/O vs. rate factor ratio



Summary

1. Impacts of the 26Si(α,p)29P rate

・A key reaction in XRB nucleosynthesis (recently measured by CRIB)

・Impact study based on one-zone XRB models

  ・a higher rate suppresses the XRB peak and increases decline phase

  ・a lower rate shows opposite trend, but much smaller impacts on XRBs

・New CRIB experiment (a lower rate) may solve this puzzle with high accuracy

2. Impacts of new theory rates

・update reaction rates by the statisical model calculation

・Impacts on light curves: suppress early growth and gradually enhance later phase

・caused by faster p-induced reactions below N=Z=50 (then slower in beyond it) ?

3. (Temperature-resolved rate sensitivity)

・Impacts of triple-α and 12C(a,g)16O on 56Ni production in PISN

→ application to X-ray burst nucleosynthesis (rp-process)?