2–6 Nov., 2026@Beijin

Nuclear Reacton Network Hands-on: The rp-process in X-ray bursts

Nobuya Nishimura

ASC, Kogakuin U.

(CNS, U Tokyo & PRI, RIKEN)

KOGAKUIN UNIVERSITY | KUTE-TOKYO Kogakuin University of Technology & Engineering

東京大学 THE UNIVERSITY OF TOKYO

CNS RIKEN PRI 科研費 KAKENHI

“Nuclear reaction networks: X-ray bursts and the rp-process”

Hands-on Workshop Session by N. Nishimura

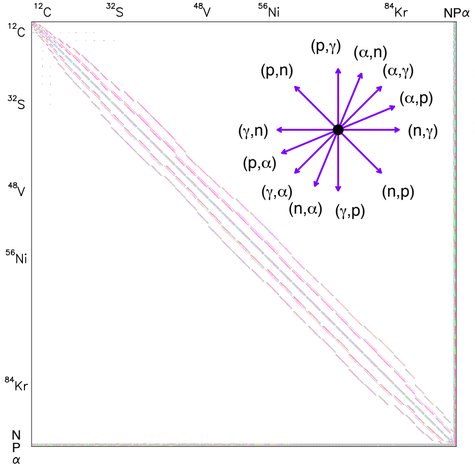
requirements for participants:

・Your PC with Unix-like systems (Linux, macOS, Windows w/ WSL2)

・Nuclear reaction network

Basics of nucleosynthesis calculations

$$\dot{y}_i = \frac{dy_i}{dt} = \sum_j N_{ij}\,\lambda_j\,y_j + \sum_{j,k} N_{ijk}\,\rho N_{\mathrm{Av}}\langle j,k\rangle\,y_j y_k + \cdots$$



487 Isotopes
5892 Rates
96.4% Sparse
Flows (#/sec):
5.14E+15
1.80E+12
6.28E+08
2.20E+05
7.68E+01
-3.72E+01
-1.07E+05
-3.05E+08
-8.71E+11
-2.49E+15
-7.13E+18

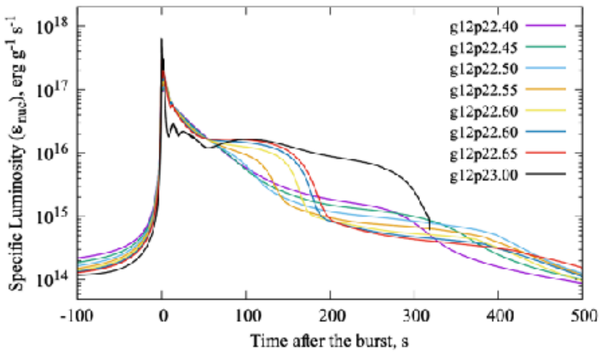
```
1
          n    p                                bet-n      7.82339e-01
-0.678638e+01 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
          n    p                                bet-r      7.82339e-01
-0.144863E+03-0.321159E+02 0.215255E+03-0.513257E+02
 0.537191E+00-0.594482E-02 0.666298E+02
          p    n                                bet+n     -7.82339e-01
 0.403762E+02-0.151751E+02 0.191430E+02-0.770289E+02
 0.125977E+02-0.232246E+01 0.237441E+02
          p    n                                bet+r     -7.82339e-01
-0.256638E+03-0.687362E+02 0.407138E+03-0.110813E+03
 0.130128E+01-0.158646E-01 0.129978E+03
          t  he3                                bet-      1.90000e-02
-0.201446e+02 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
        he3    t                                ec       -1.90000e-02
-0.324620e+02-0.213380e+00-0.821581e+00 0.111241e+02
-0.577338e+00 0.290471e-01-0.262705e+00
        he6  li6                                bet-      1.59700e+00
-0.153443e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
        li8  be8                                bet-      1.60039e+01
-0.192160e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
        li9  be9                                bet-      6.62200e+00
 0.135777e+01 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
```

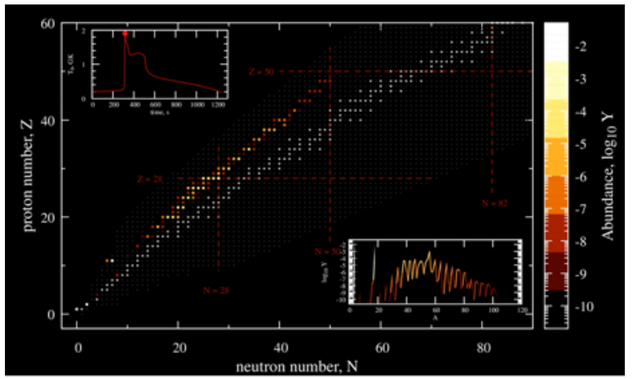
・X-ray Burst calculations

・Run one-zone X-ray burst model

・Vary astrophysical parameters and/or nuclear reaction rates

→ How do observables change?





Important Notes on Using the Workshop Code

- This code is not open source. Please use it only for your own learning and practice.
- Although this code is used in actual research, please do not publish or present results obtained with it in papers, at conferences, or elsewhere without consulting me (N. Nishimura) first.
- These restrictions are not intended to protect confidential information. They exist for two reasons:
    - The code does not meet the redistribution requirements of the physics and numerical libraries it uses.
    - The correctness of its behavior and results cannot be guaranteed if the code is modified by a third party.

If you would like to publish or present at conferences your results, please consult me in advance.

Contents

1. **Introduction**
   - nuclear reaction network
   - X-ray bursts
2. **Setups**
   - one-zone X-ray burst code (including a nuclear reaction network)
   - preparation of execution environment and test run
   - how to plot results
3. **Run example case**
   - plot results

Nuclear reaction network

- Ordinary differential eqs. for the change of $y_i(t)$ (the number fraction i th nucleus)
- The time variation $\dot{y}_i \sim \Delta y/\Delta t$ (finite difference) causes thermonuclear reaction (decay) rates
- In the astrophysical environments (fluids), the abundances are also changed by advection. But, the timescale of nuclear reactions can be small. (Lagrangian description is convenient.)

basic equations

thermonuclear reaction rate & astrophysics (temperature and density)

$$\dot{y}_i = \frac{dy_i}{dt} = \sum_j N_{ij} \lambda_j y_j + \sum_{j,k} N_{ijk} \rho N_{\rm Av} \langle j,k \rangle y_j y_k + \sum_{j,k,l} N_{ijkl} \rho^2 N_{\rm Av}{}^2 \langle j,k,l \rangle y_j + \cdots$$

1 body (decay)

β-decay, e^+/e^- capture
(and fission)

2-body reaction
(incl. $2 \to 2$)

main nuclear reactions
n-induced decay

3-body reaction
(3→1, 3→2)

triple-α, (α,α,n)

Stiff equations sytem

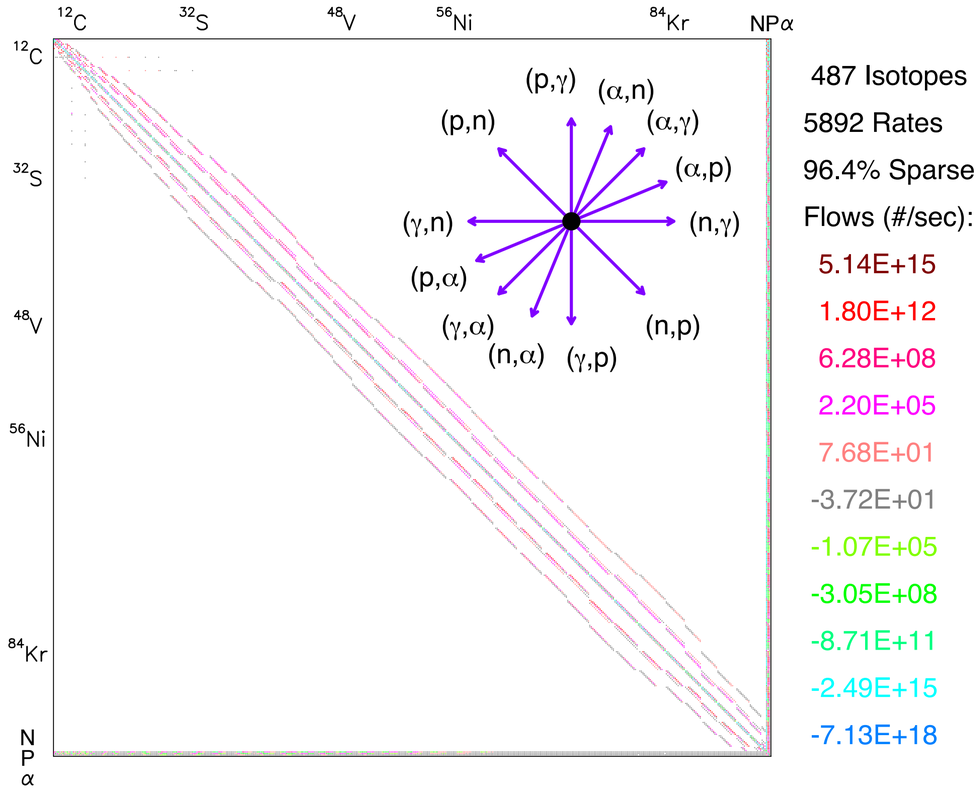
- The time evolution (integration) is based on an implicit scheme rather than an explicit scheme, as few very fast reactions can become a bottleneck.
- Jacobian becomes sparse → “stiff” equations

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + \cdots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + \cdots + a_{2n}x_n = b_2 \\ a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + \cdots + a_{3n}x_n = b_3 \\ \cdots \\ a_{n1}x_1 + a_{n2}x_2 + a_{n3}x_3 + \cdots + a_{nn}x_n = b_n \end{cases}$$

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\ \vdots & & \ddots & & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ \vdots \\ b_n \end{pmatrix}$$

sparse matrix

nearby nucleus made by n/p/a captures and decay



http://cococubed.asu.edu

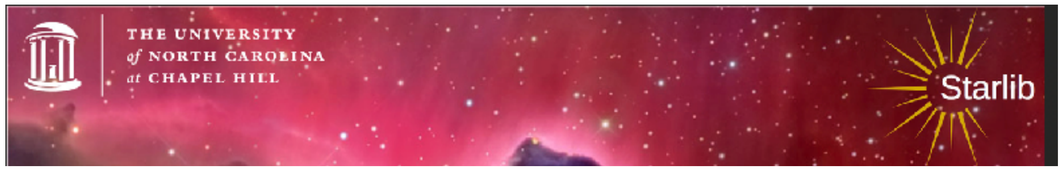
Astrophysical reaction data base

・Reaction rates (Maxwel-averaged) are given as a function of temperature T.

  ・Screening effects can sometimes be significant, given as a electron density

・Thermonuclear reactions are, in principle, not described by simple analytic functions, but they exhibit somewhat smooth characteristics. This smoothness can be expressed using a combination of a few fitting functions.

  ・numerical table? (e.g, Bruslib, Starlib) or function fitting? (e.g., Reaclib)



https://starlib.github.io/Rate-Library/



https://reaclib.jinaweb.org/

・Detailed data covering the target temperature range would be ideal, but function fittings have some advantages, especially when considering the physical relationships.

  ・Function fittings can reduce the amount of data

    (but, it is generally not an issue for modern computers…)

  ・high accuracy in maintaining the balance between forward and reverse rates (in equilibrium).

  ・nuclear reactions satisfy the detailed balance (forward reaction ↔ reverse reaction)

REACLIB library

analytic fitting by seven parameters a_i $(i = 1,2,3,4,5,6)$: can be more than 2

$$N_A\langle\sigma v\rangle^* = \exp\left[a_0 + a_1 T_9^{-1} + a_2 T_9^{-1/3} + a_3 T_9^{1/3} + a_4 T_9 + a_5 T_9^{5/3} + a_6 \ln T_9\right] = \exp\left[a_0 + \sum_{i=1}^{5} a_i T_9^{\frac{2i-5}{3}} + a_6 \ln T_9\right]$$

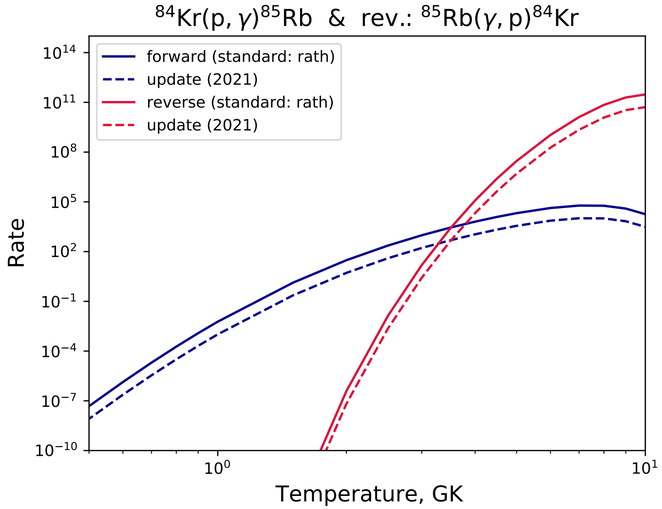
example

```
1


        n    p                                   bet-n     7.82339e-01
-0.678638e+01 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
        n    p                                   bet-r     7.82339e-01
-0.144863E+03-0.321159E+02 0.215255E+03-0.513257E+02
 0.537191E+00-0.594482E-02 0.666298E+02
        p    n                                   bet+n    -7.82339e-01
 0.403762E+02-0.151751E+02 0.191430E+02-0.770289E+02
 0.125977E+02-0.232246E+01 0.237441E+02
        p    n                                   bet+r    -7.82339e-01
-0.256638E+03-0.687362E+02 0.407138E+03-0.110813E+03
 0.130128E+01-0.158646E-01 0.129978E+03
        t  he3                                   bet-      1.90000e-02
-0.201446e+02 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
      he3    t                                     ec     -1.90000e-02
-0.324620e+02-0.213380e+00-0.821581e+00 0.111241e+02
-0.577338e+00 0.290471e-01-0.262705e+00
      he6  li6                                   bet-      1.59700e+00
-0.153443e+00 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
      li8  be8                                   bet-      1.60039e+01
-0.192160e+00 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
      li9  be9                                   bet-      6.62200e+00
 0.135777e+01 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
```

reaction types

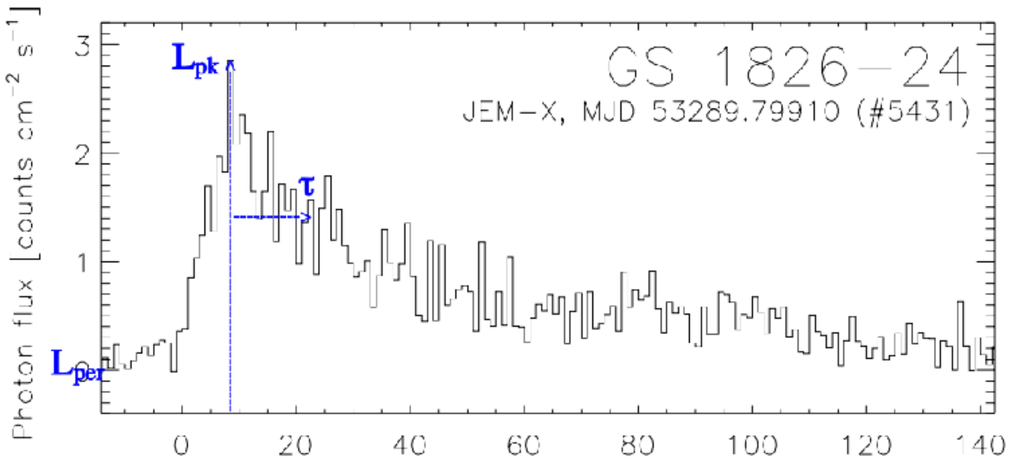
type	ver1			ver2		
1	1	→	2	1	→	2
2	1	→	2 + 3	1	→	2 + 3
3	1	→	2 + 3 + 4	1	→	2 + 3 + 4
4	1 + 2	→	3	1 + 2	→	3
5	1 + 2	→	3 + 4	1 + 2	→	3 + 4
6	1 + 2	→	3 + 4 + 5	1 + 2	→	3 + 4 + 5
7	1 + 2	→	3 + 4 + 5 + 6	1 + 2	→	3 + 4 + 5 + 6
8*	1 + 2 + 3	→	4 (+ 5)	1 + 2 + 3	→	4
9		—		1 + 2 + 3	→	4 + 5
10		—		1 + 2 + 3	→	4 + 5 + 6
11		—		1	→	2 + 3 + 4 + 5

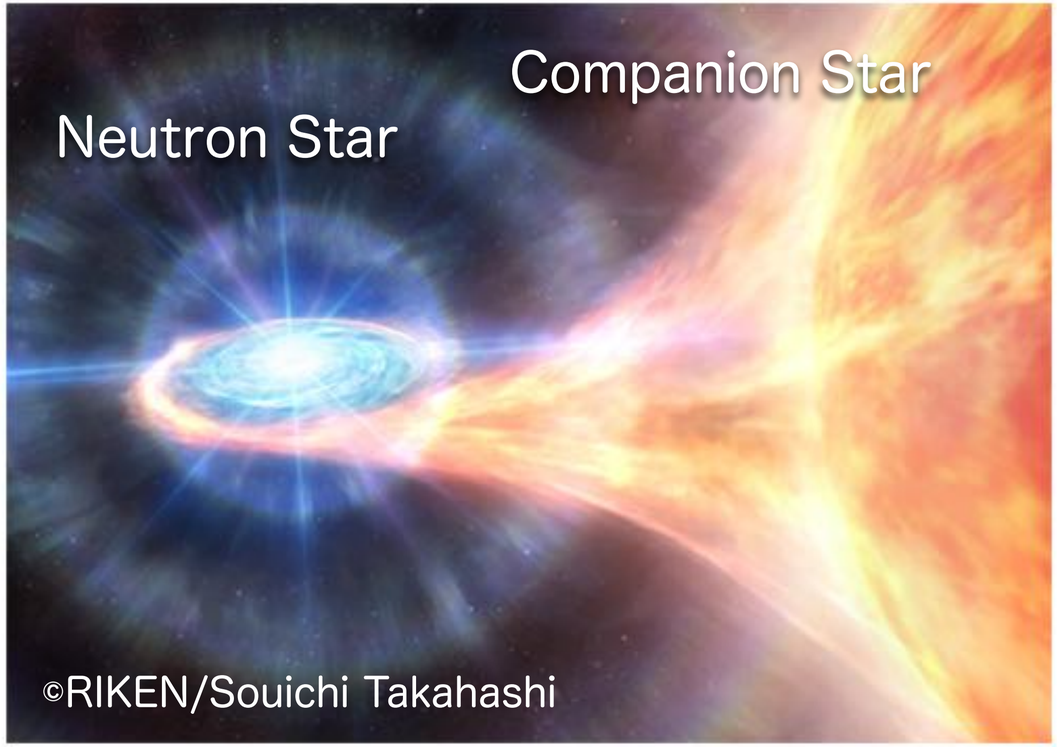


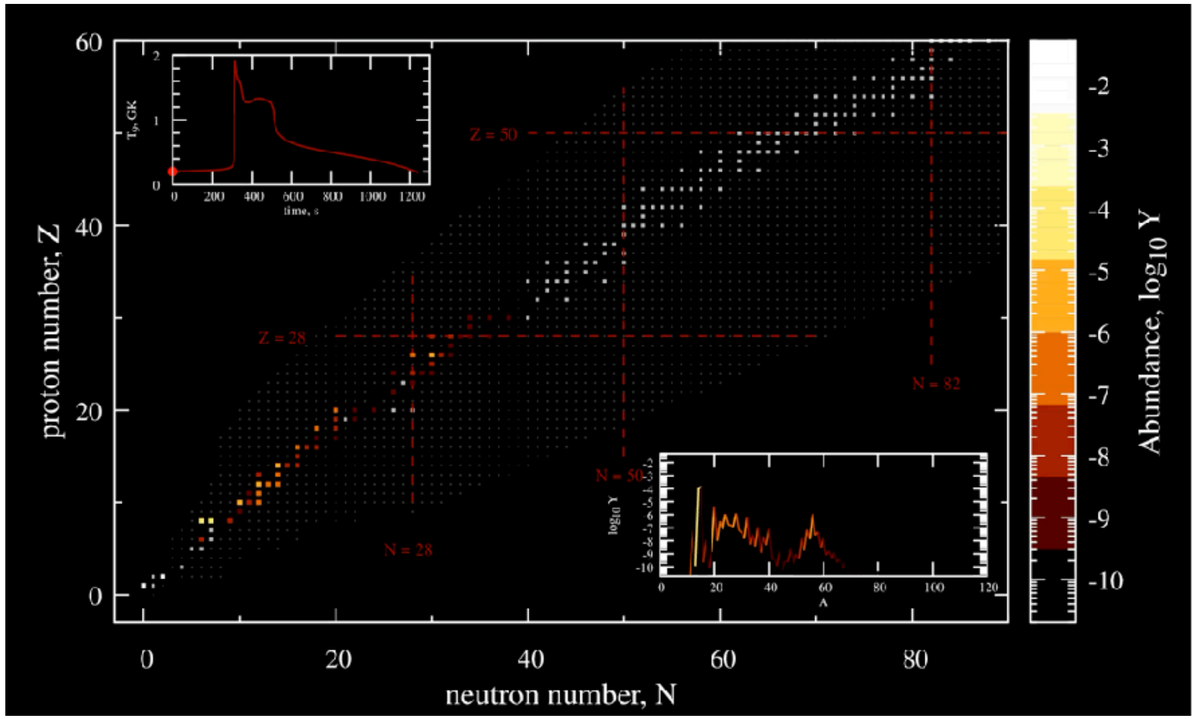
analysis for
Lotay+NN+ PRL (2021)

X-ray bursts (XRBs)

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

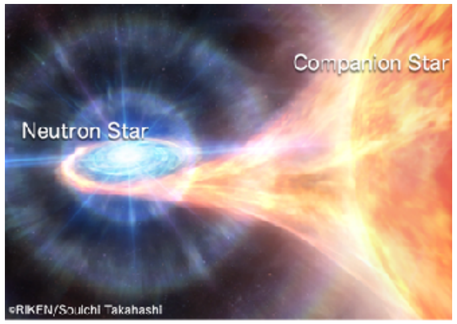


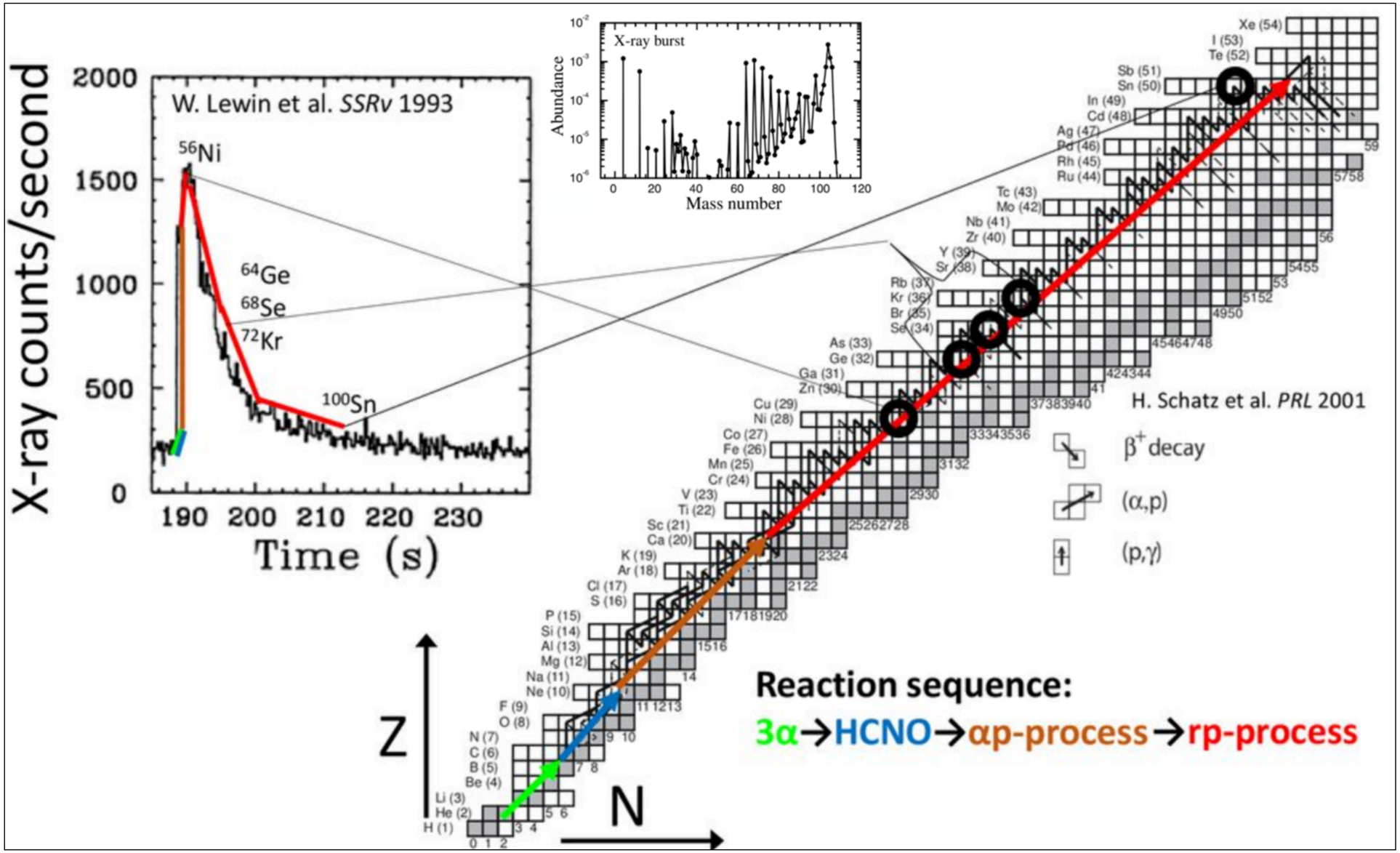




XRB and rp-process nucleosynthesis

X-ray bursts (XRB)

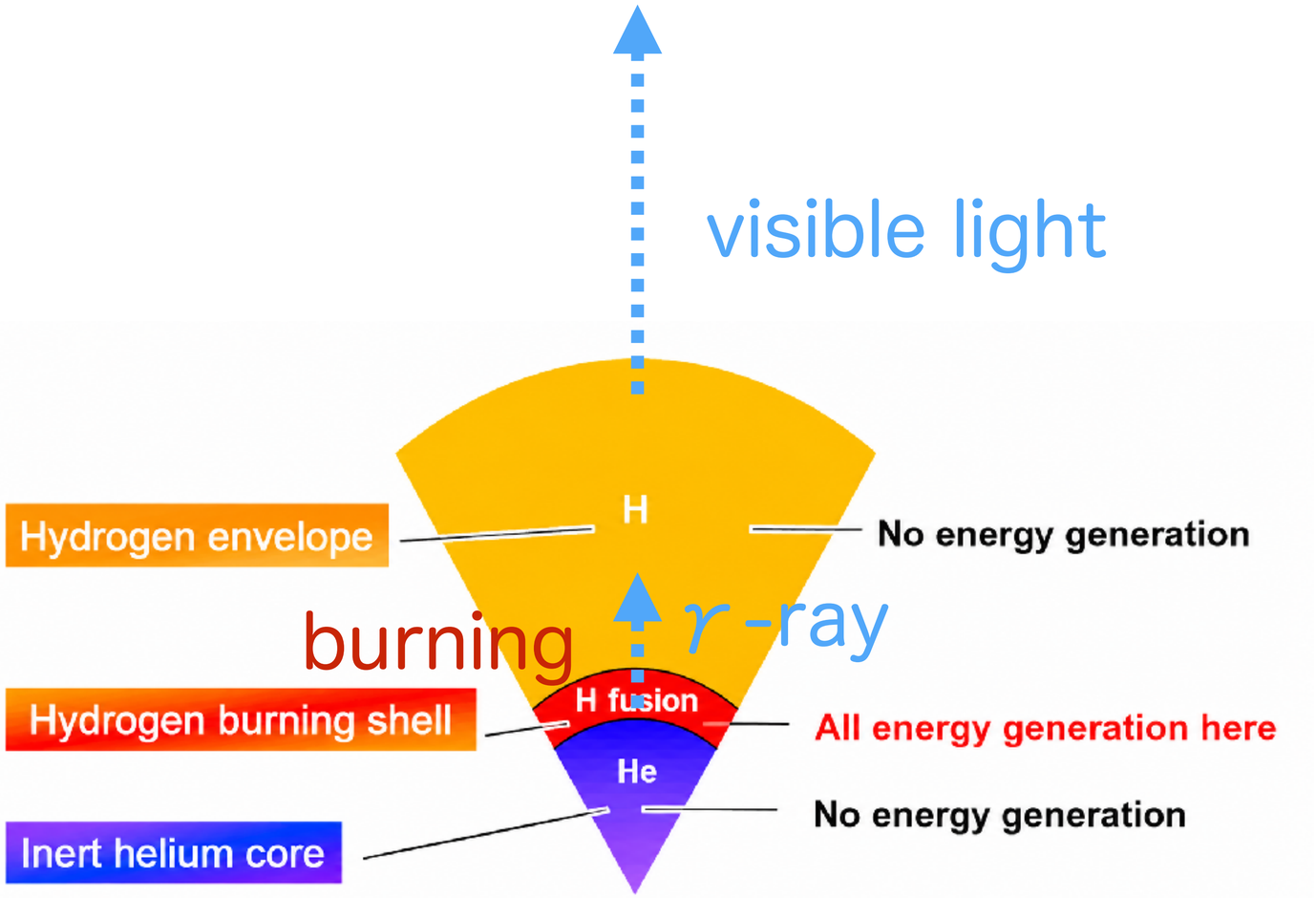




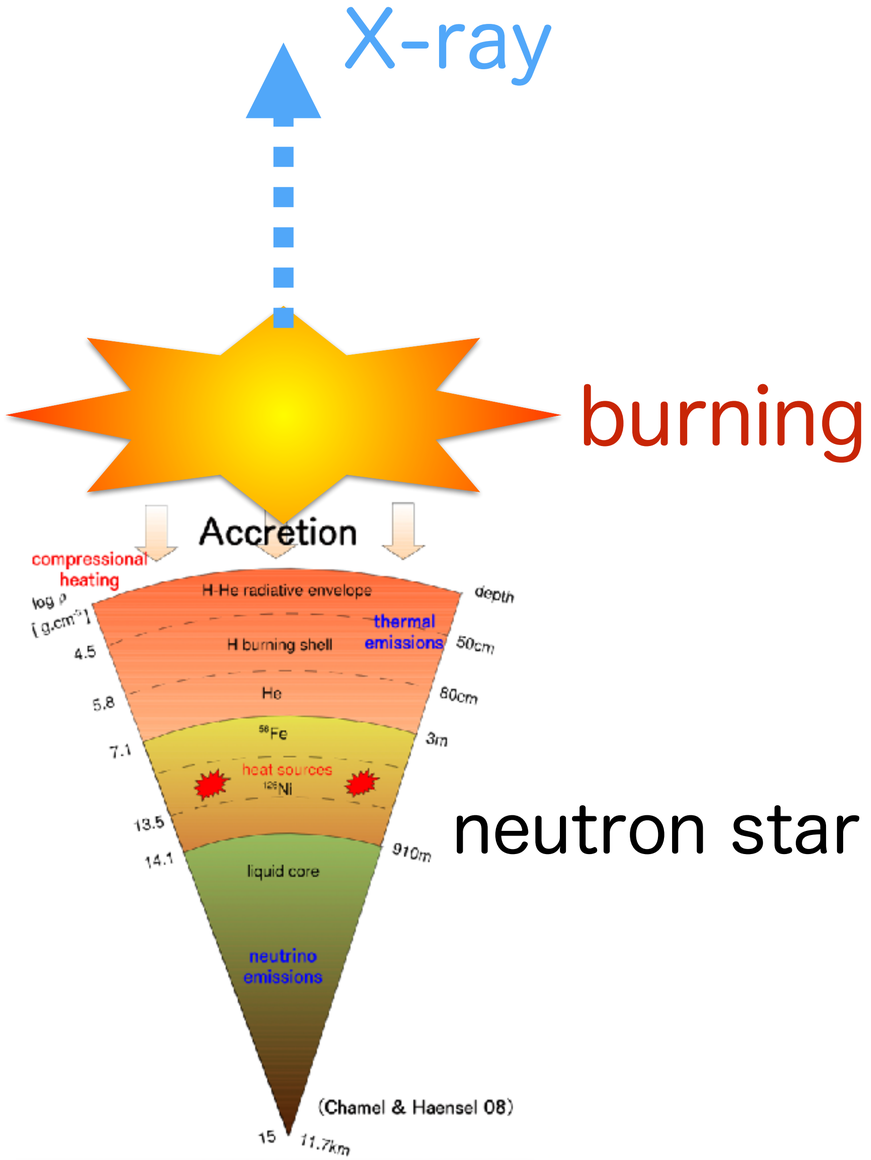
Meisel+(2018)

Stars vs accreting NS

regular stars



X-ray burst (on NS)



neutron star

Stars vs accreting NS

regular stars

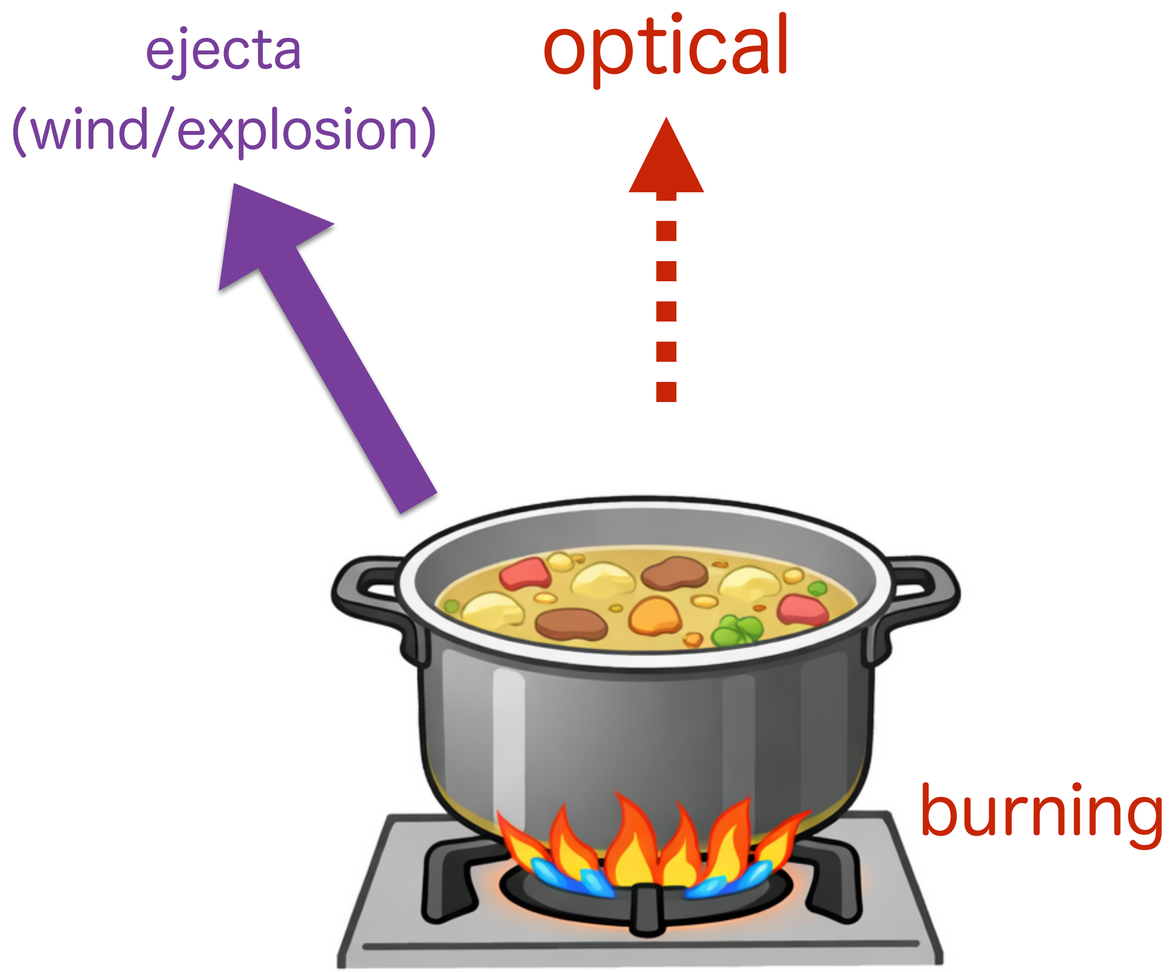


illustration by ChatGPT

Stars vs accreting NS

regular stars

ejecta
(wind/explosion)

optical



burning

X-ray burst (on NS)

X-ray



burning

NS cooling

illustration by ChatGPT

One-zone XRB models

One-zone X-ray burst model

(Sugimoto & Fujimoto 1978, Fujimoto+1981)

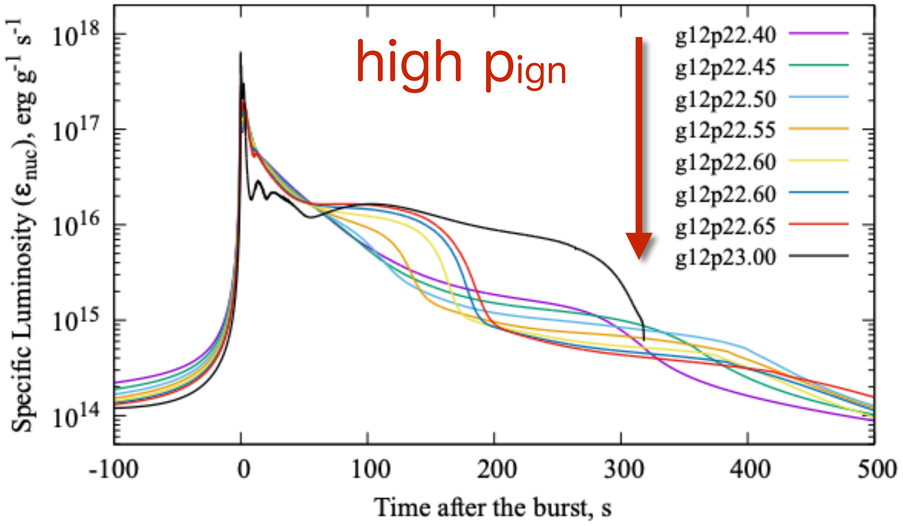
- surface gravity: $g_{\rm s} = 1.318 \times 10^{14},\ 2.399 \times 10^{14}\ {\rm cm/s^2}$
- ignition pressure: $p_{\rm ign} = 2.5 \times 10^{22} \sim 1.6 \times 10^{23}\ {\rm dyn/cm^2}$
- iginition temperature: $T_{\rm ign} \sim 0.1 - 0.2\ {\rm GK}$

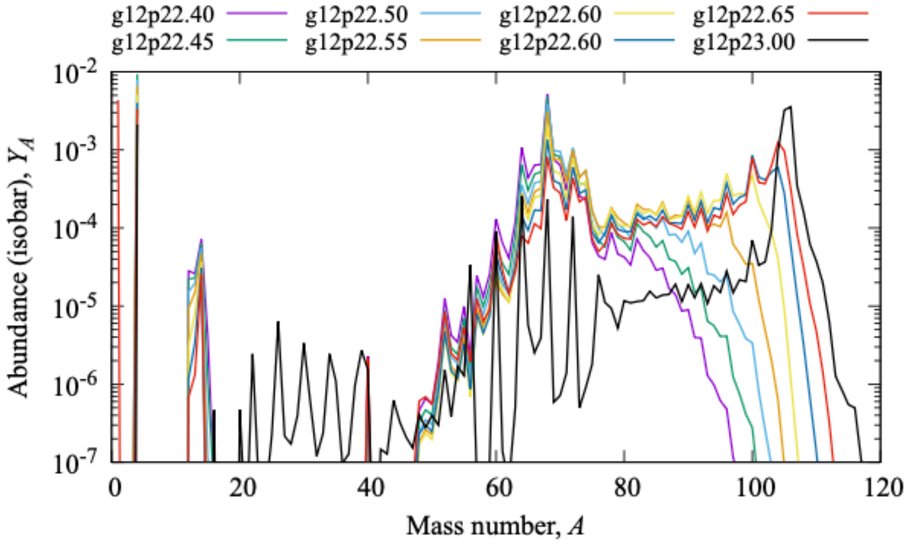
$g_{\rm suf} = 14.12$	model #	01	02	03	04	05	06	07	08
	name	g12p22.40	g12p22.45	g12p22.50	g12p22.55	g12p22.60	g12p22.65	g12p22.70	g12p23.00
	$P_{\rm ing}$	22.40	22.45	22.50	22.55	22.60	22.65	22.70	23.00
	$T_{\rm ing}$ (GK)	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
$g_{\rm suf} = 14.38$	model #	09	10	11	12	13	14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

One-zone XRB models

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

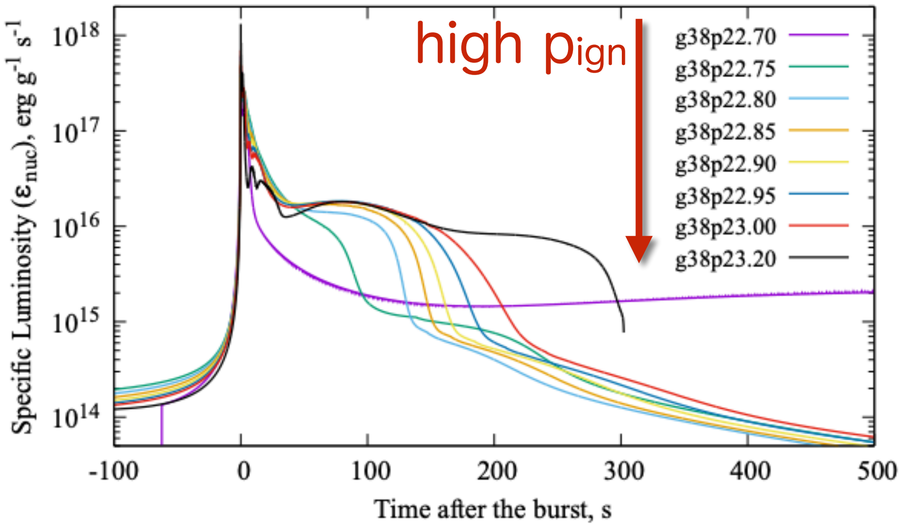
typical NS: 1.4 $M_\odot$, 10 km

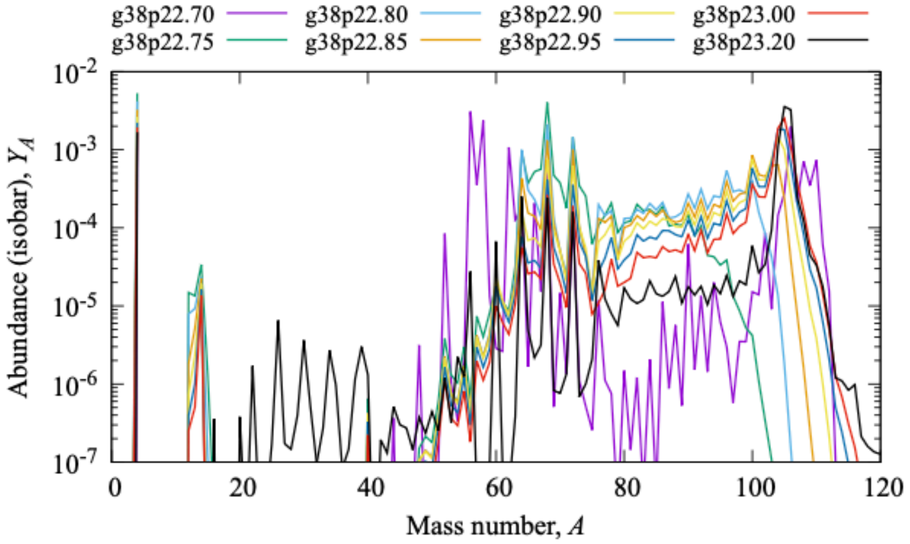




$g_s = 2.399 \times 10^{14}$ cm/s^2

stronger g_s





Codes and tools

Please donload from the following links.

- Main codes: https://nnobuya.github.io/tmp/xrb_1zone_oece.zip
  → unzip pass: oece@2026
- execution data: https://nnobuya.github.io/tmp/work_oece.zip

Code setup

1. build matrix_solver library　please “make clean” if files exist

```
MacBook-Pro-91:xrb_1zone_oece nobuya$ cd matrix_solver/
MacBook-Pro-91:matrix_solver nobuya$ make
mkdir -p build/blas
gfortran -03 -c blas/caxpy.f -o build/blas/caxpy.o
mkdir -p build/blas
```

2. build the main code: flsh.out

```
MacBook-Pro-91:matrix_solver nobuya$ cd ../src/
MacBook-Pro-91:src nobuya$ make
gfortran -03 ./opac/opacparam.f90 ./nse/mod_const.f90 ./r
ffn.f90   -c  opac/opacparam.f90
```

Run environment

1. Check exec_all.in

exec_all.in

```
initial=true
#initial=false

mdl_st=3
mdl_en=3

# max
#mdl_st=1
#mdl_en=16


exe_path=$HOME/code/xrb_1zone_oece/src/flsh.out
```

preparation

model numbers

path to flsh.out