# Accelerating sensitivity studies for Type I X-ray burst with deep learning

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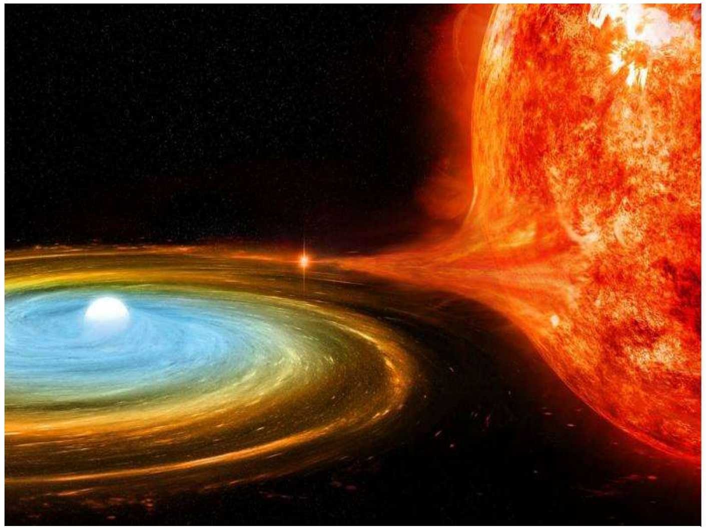
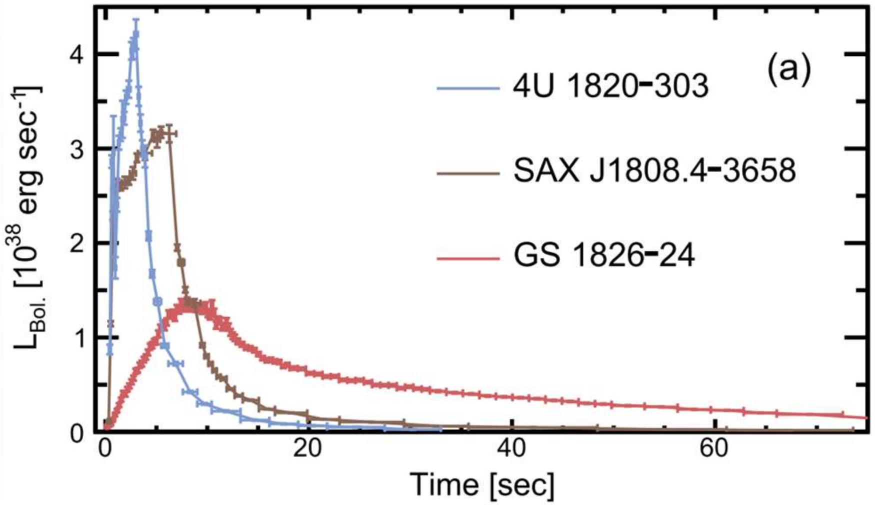
# Type I X-ray burst

- The X-ray Burst phenomenon is one of the most important astrophysical sites for probing rapid-proton capture process (rp-process).
- Many physical conditions were not constrained yet, including nuclear network.

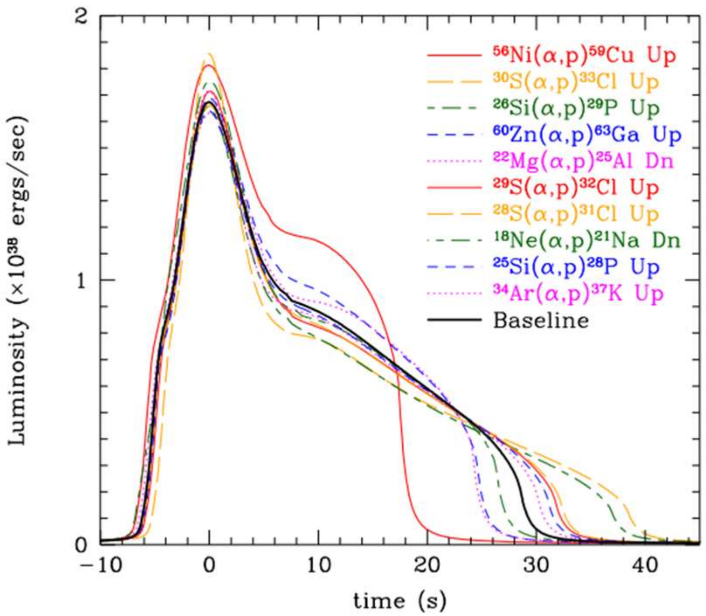





Z.Meisel et al., J.Phys.G:Nucl.Part.Phys. 45 093001 (2018)
D.K.Galloway, A.J.Goodwin and L.Keek, Publ.Astron.Soc.Aust. 34 E019 (2017)

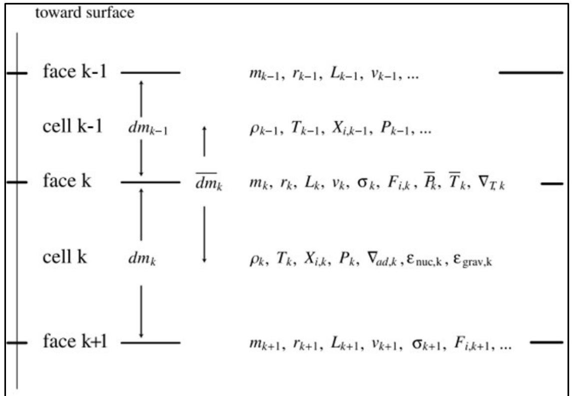
# Sensitivity study

- Identify **critical nuclear reactions** in thermonuclear runaways

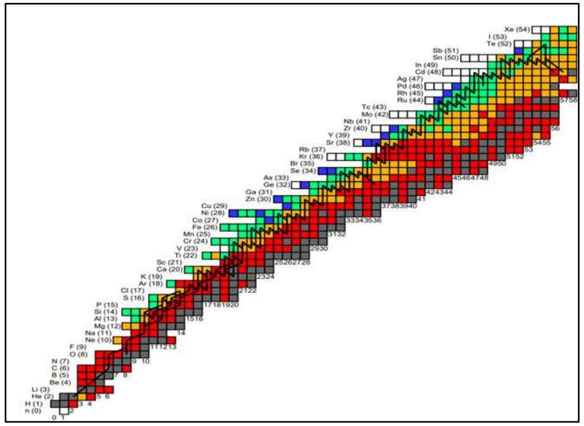



R.H.Cyburt *et al*., APJ 830, 55 (2016)

It takes too long time and expenses to calculate **hydrodynamics simulation** with a **large size of nuclear network**

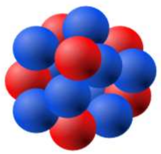



B.Paxon *et al*., APJS 192, 3 (2011)



# Current challenges

- Simulation with **hydrodynamic calculations** & **large nuclear network** takes too long time.
- Only single reaction variations have been tested.

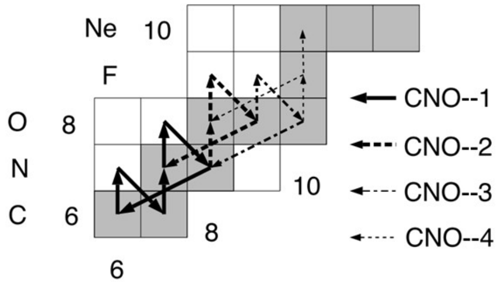


$\Gamma_p$
$\Gamma_\alpha$
$\Gamma_\gamma$
$B_\lambda$
…

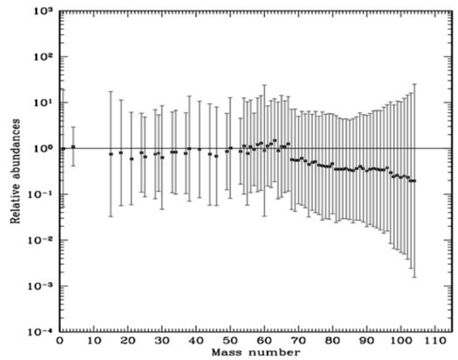
$^{14}O(\alpha,p)^{17}F$

$^{14}O(\alpha,\gamma)^{18}Ne$

Effect of a nuclear property uncertainty on nucler network




Collective impact of a cycle




Uncertainty propagation

M. Wiescher, J. Gorres and H.Schatz, J.Phys. G: Nucl. Part. Phys 25, R133 (1999)
A. Parikh *et al.*, APJS 178, 110 (2008)

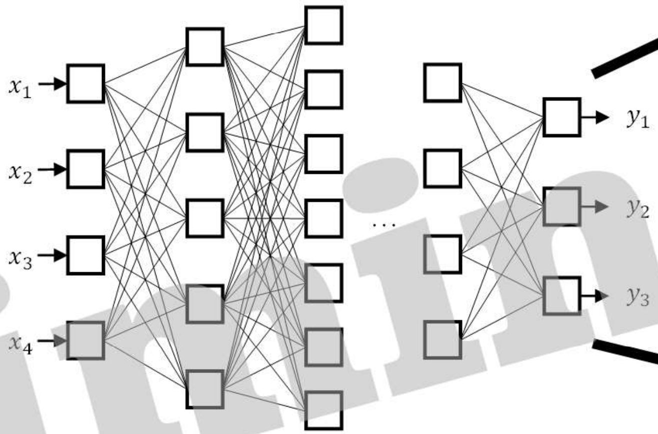
**Input Data:**
**Reaction rate factors**

Total 726 reactions

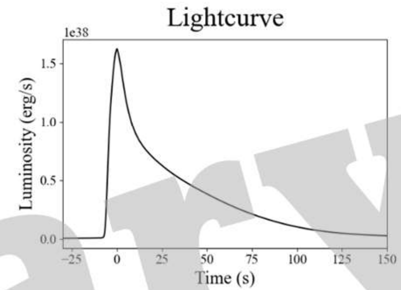
| reaction | factor |
|---|---|
| $^{15}O(\alpha, \gamma)^{19}Ne$ | x 1.051 |
| $^{14}O(\alpha, p)^{17}F$ | x 0.802 |
| . . . | . . . |
| $^{56}Ni(\alpha, p)^{59}Cu$ | x 23.08 |
| $^{60}Zn(\alpha, p)^{63}Ga$ | x 41.76 |
| $^{63}Ga(p, \gamma)^{64}Ge$ | x 0.002 |

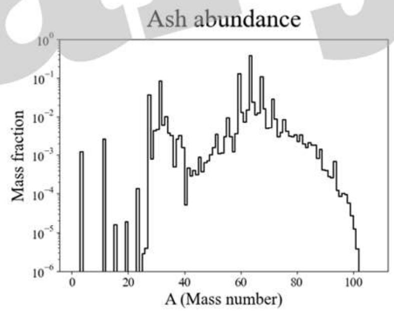
From 1 to 120,
Randomly sampled factors

**Deep Neural Network**




**Output Data:**
**XRBs properties**



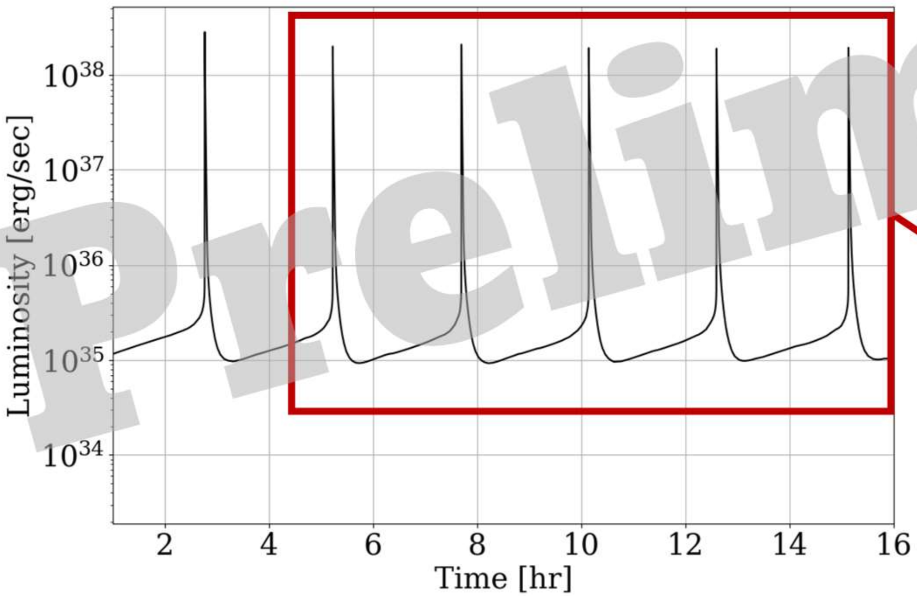


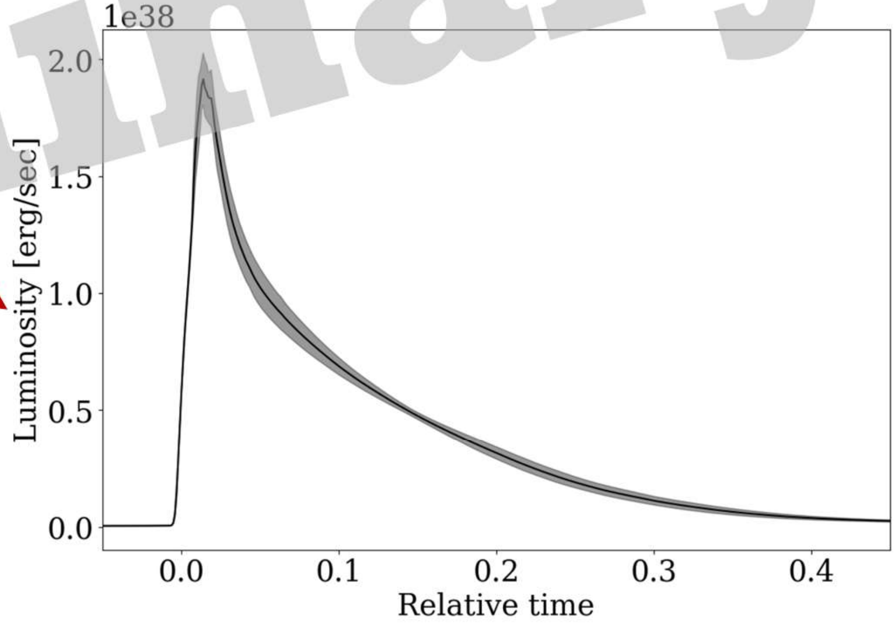

- By training $\sim\mathcal{O}(3)$ datasets, computational expense for generating light curves varying $_{726}C_2$=263,175 pairs (or any combinations!) of nuclear reaction rates gets affordable.
- Reduced running time can help to **explore the effects of multiple reaction variations on nuclear network**.

# Training data: light curve

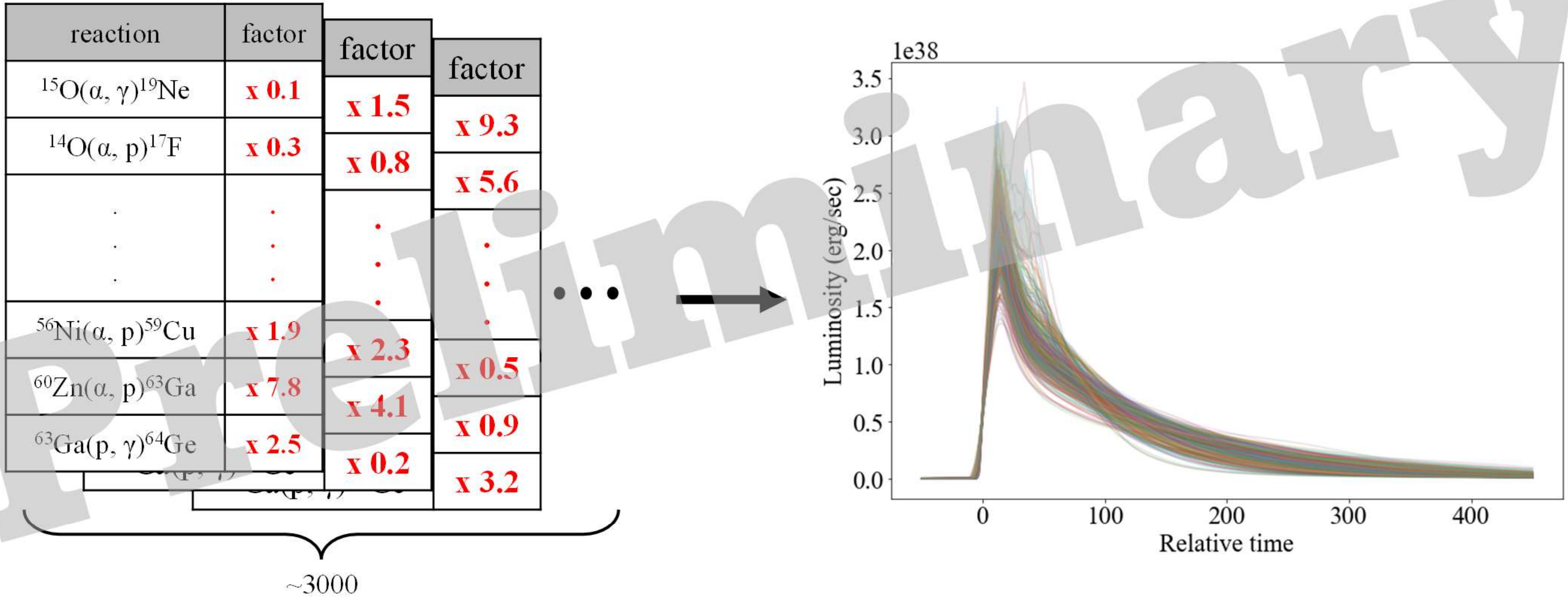
- **MESA** (Modules for Experiments in Stellar Astrophysics) is a 1D multi-zone simulation code.
- Physical parameters best reproduced light curve features of GS 1826-24 were taken.

  Z.Meisel, *et al.*, APJ 860, 147 (2018)



- Default reaction rates are adopted from **JINA REACLIB** Cyburt, *et al.*, APJS 189 (2010) 240
- Every 726 (α, p), (p, γ), and (α, γ) reactions were increased or decreased by random factors.



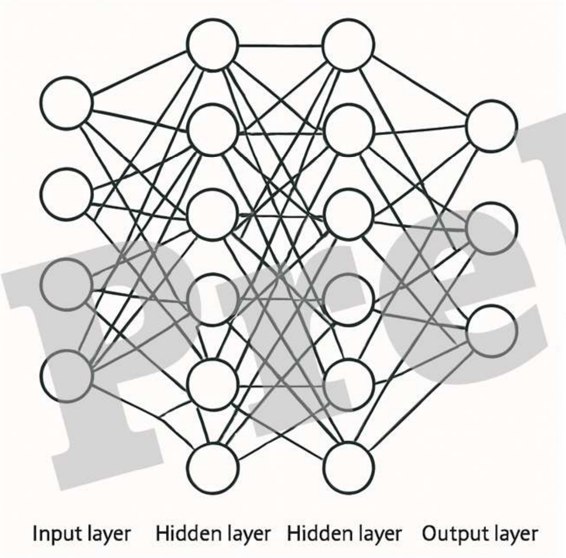



- The light curve data sets were generated with given varied reaction rates.

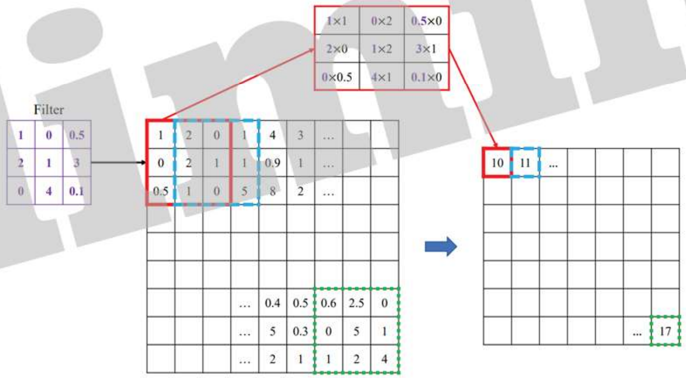
C.H.Kim *[dissetation]. SKKU; 2024.*
*V. Ashish et al., NIPS, 30 (2017)*

# Deep Neural Network

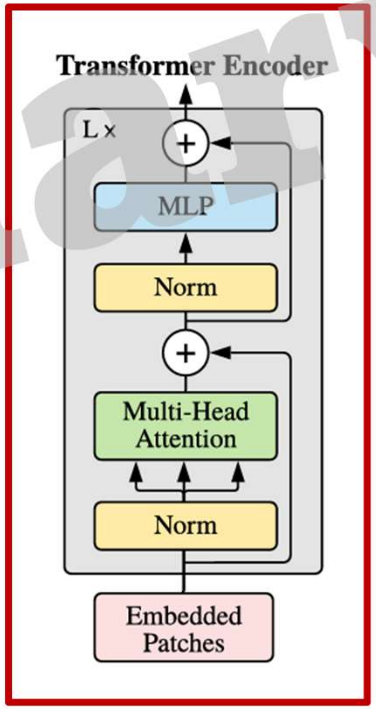
- Various type of DNN structures.




Linear net




ConvNet



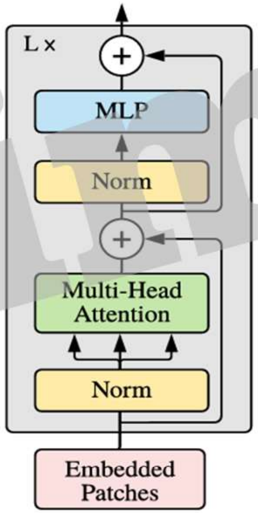

Vision Transformer

# Data pre-processing & Training

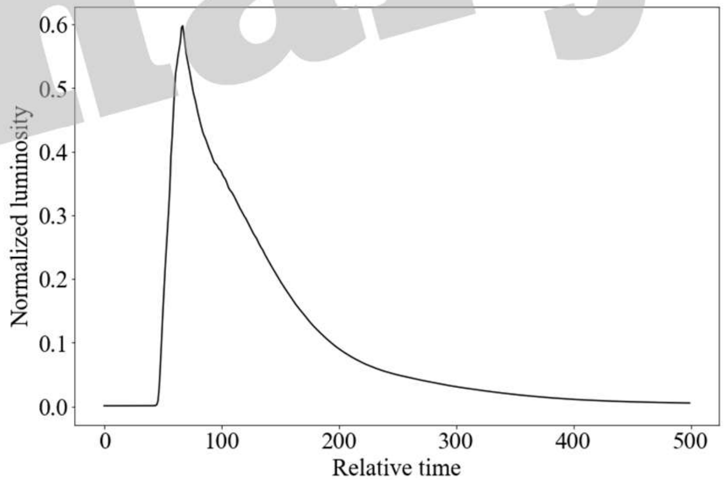
- Input(=Features) and Output(=Labels) are pre-processed.
- By modifying the hyper-parameters, appropriate DNN is built up.

| reaction | factor |
|---|---|
| $^{15}O(\alpha, \gamma)^{19}Ne$ | **x 0.1** |
| $^{14}O(\alpha, p)^{17}F$ | **x 0.3** |
| ⋮ | ⋮ |
| $^{56}Ni(\alpha, p)^{59}Cu$ | **x 1.9** |
| $^{60}Zn(\alpha, p)^{63}Ga$ | **x 7.8** |
| $^{63}Ga(p, \gamma)^{64}Ge$ | **x 2.5** |

Rate factor




ViT model

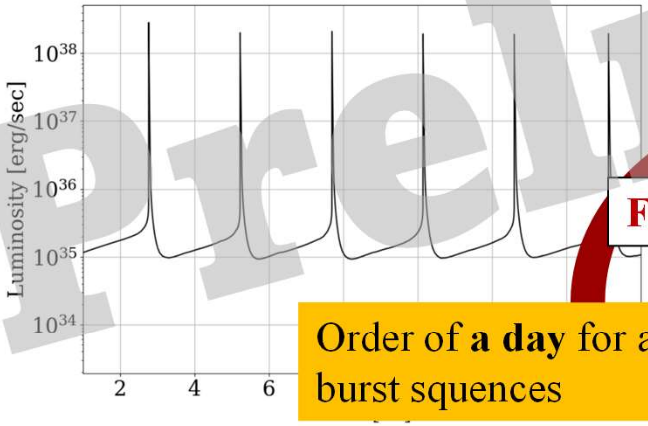



Light curve

# Performance test

- Lightcurve generation takes about 4-ms with the GPU below.
  - Tesla V100 32GB SXM2
- Compare MESA calculation time with CPU.

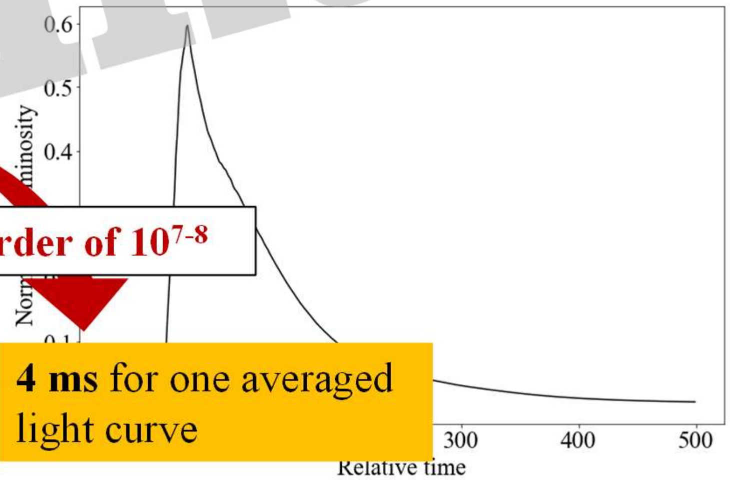





Order of **a day** for a burst squences

Intel Xeon Platinum 8360Y
(2.6GHz, 36Cores)

**Faster than before by order of $10^{7\text{-}8}$**



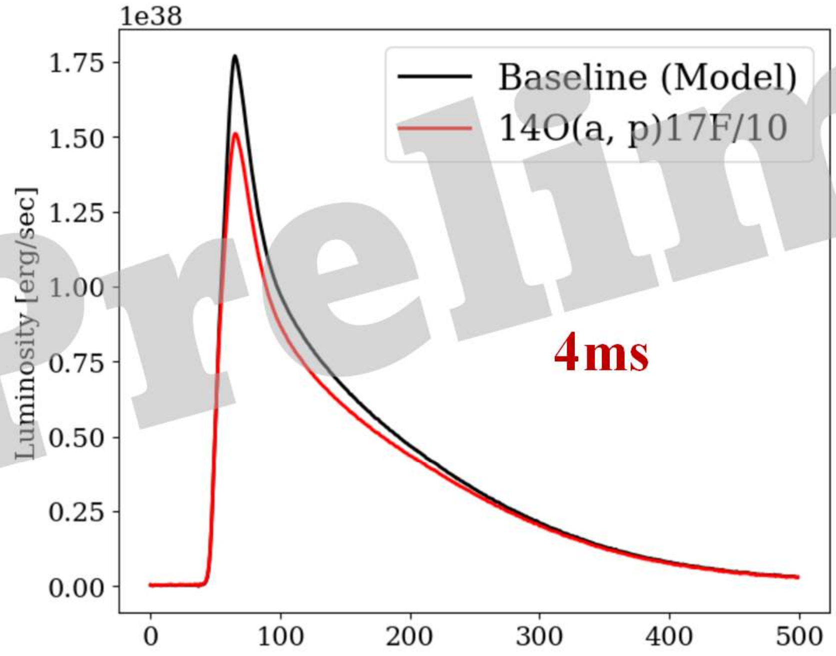

**4 ms** for one averaged light curve

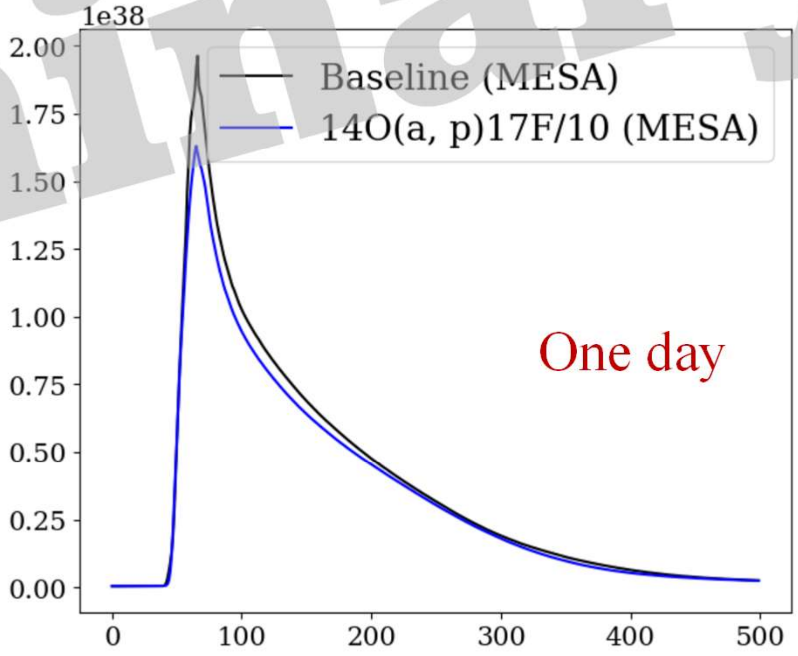
Tesla V100 32GB SXM2

# Preliminary results of sensitivity study

# Single reaction variation

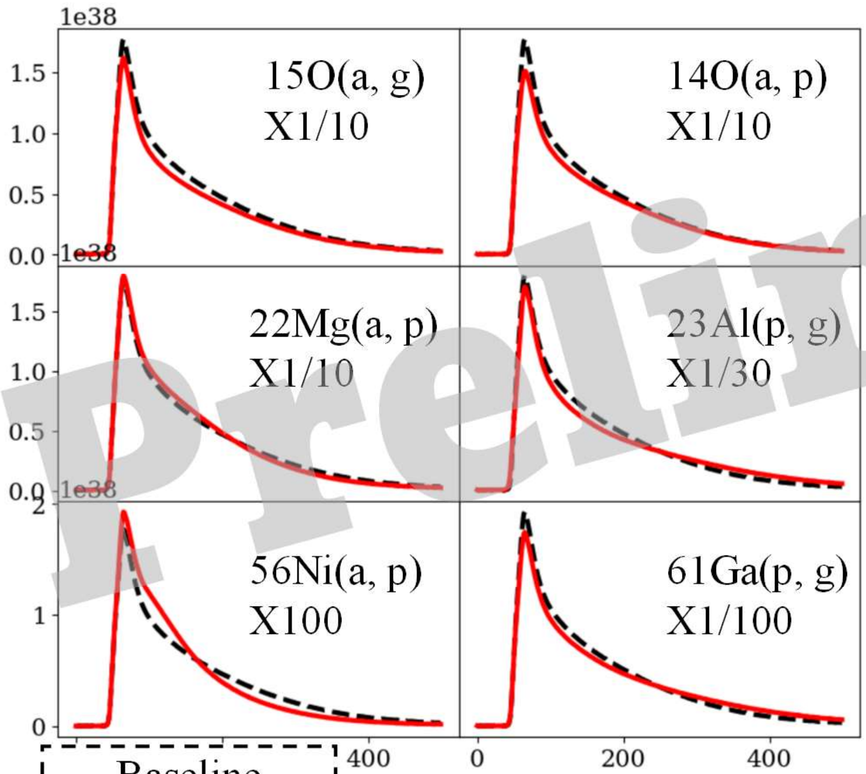
- Change every 726 (α, p), (p, γ), and (α, γ) rate factor individually.
- The model prediction is quite similar with MESA calculation.



# Comparison with previous study

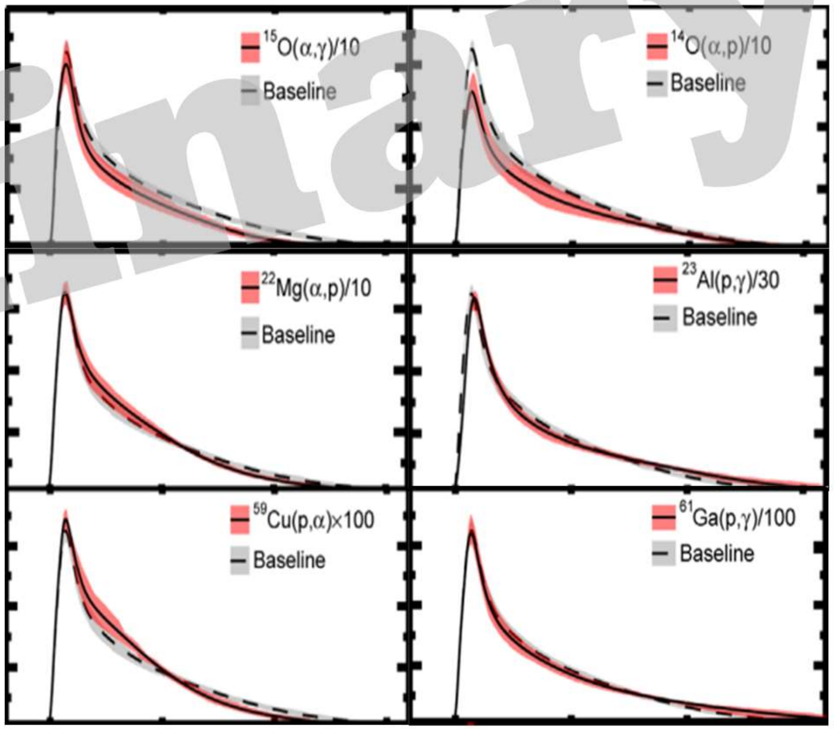
Model prediction




Baseline

Rate variation

MESA (from previous study)




Z. Meisel *et al.*, APJ (2019)

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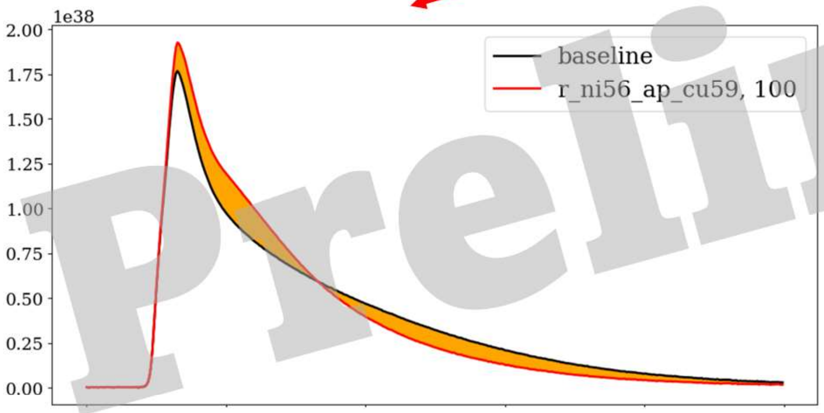
# New sensitive reaction list

- Define "different factor" to quantify impact of a reaction variation.
- Different factor $\equiv \int |\langle L_{base} \rangle - \langle L_{varied} \rangle| dt$ Cyburt, et al., APJ 830, 55 (2016)

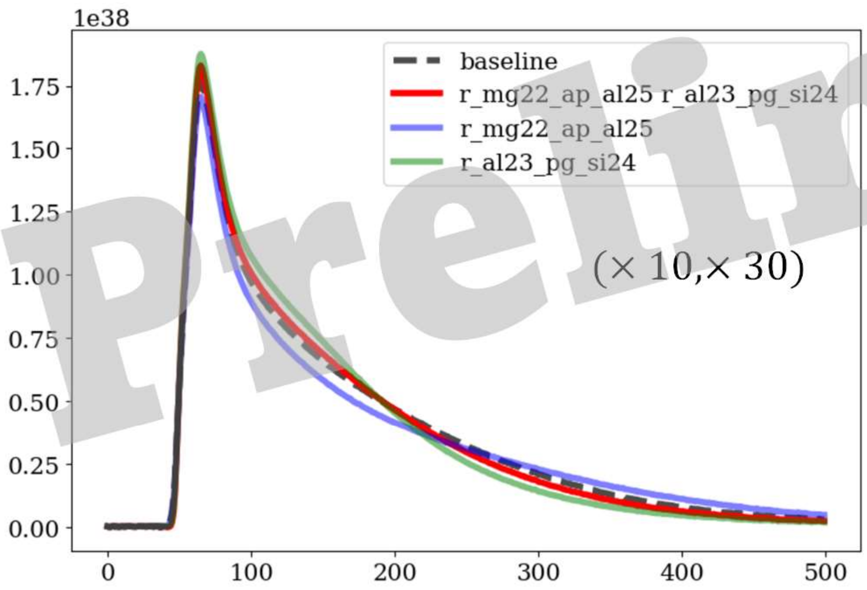


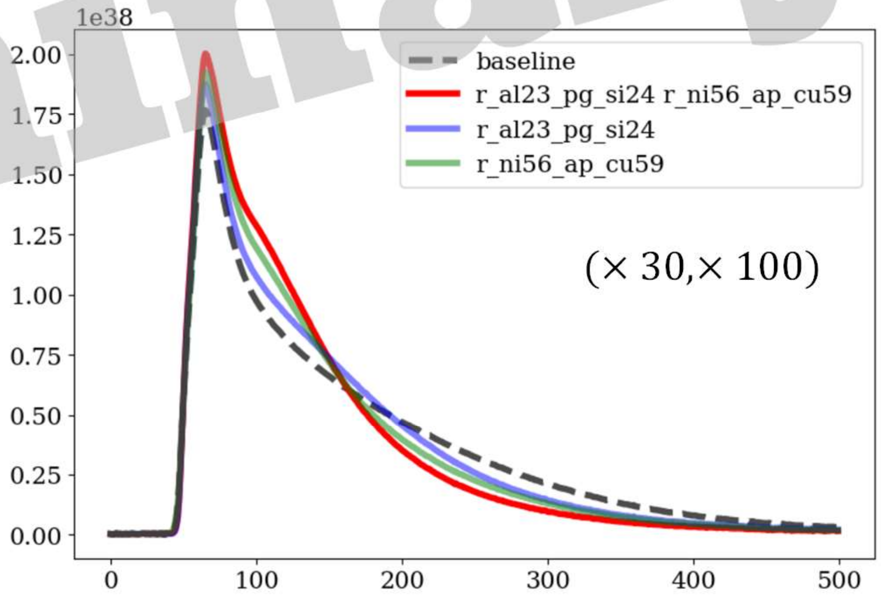

| Reaction | Up/down | Diff_factor |
|---|---|---|
| $^{35}K(p,\gamma)^{36}Ca$ | Up | 1.75E+38 |
| $^{31}P(p,\gamma)^{32}S$ | Down | 1.19E+38 |
| $^{23}Na(p,\gamma)^{24}Mg$ | Down | 3.02E+38 |
| $^{20}Ne(\alpha,p)^{23}Na$ | Up | 4.06E+38 |
| $^{12}C(\alpha,p)^{15}N$ | Down | 1.49E+38 |

# Double variations

- Every possible combinations, total **1,000,000 pairs** were investigated in just **a few hours.**
- Overall, their effect on the lightcurve baseline was linearly added up.



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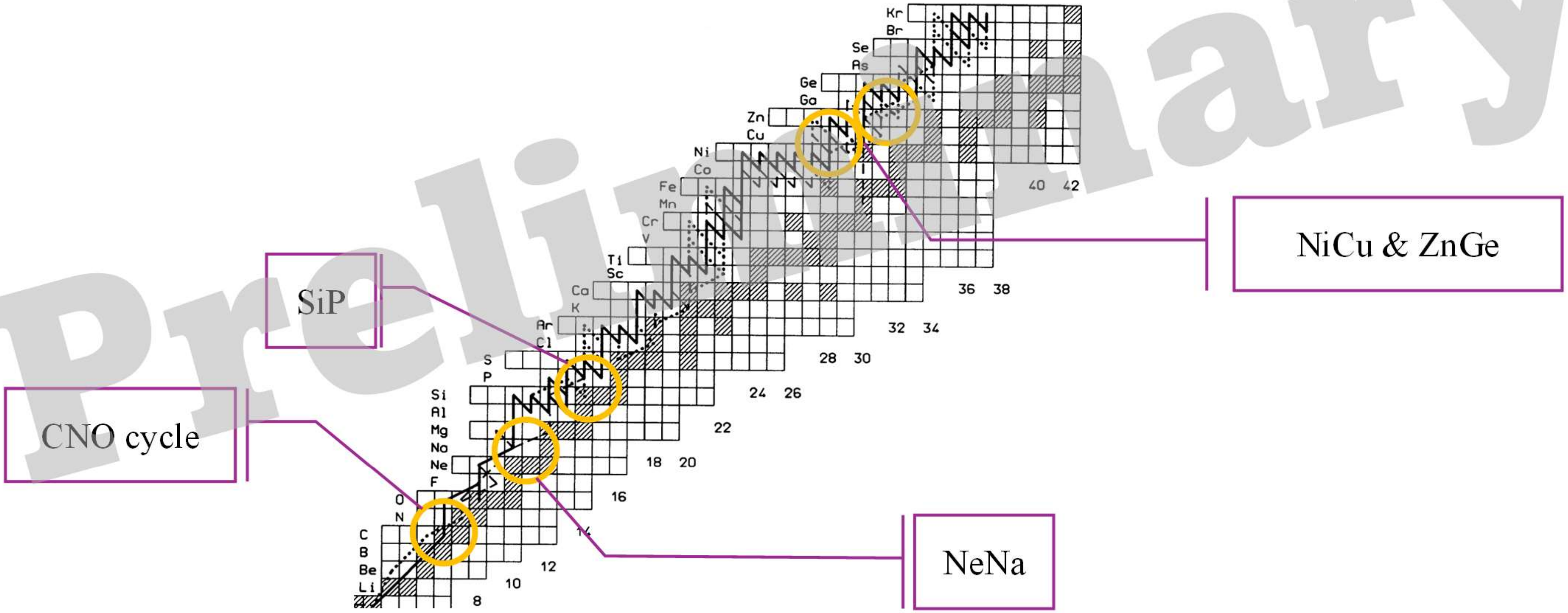
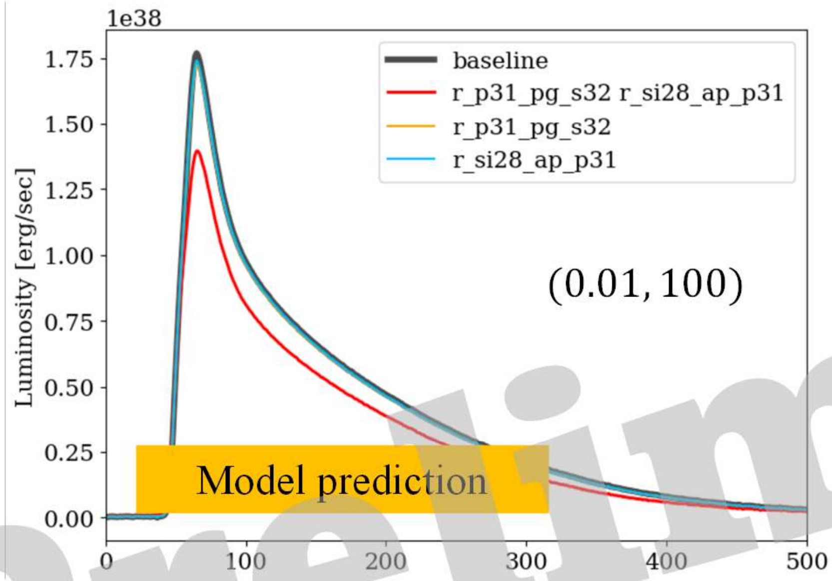
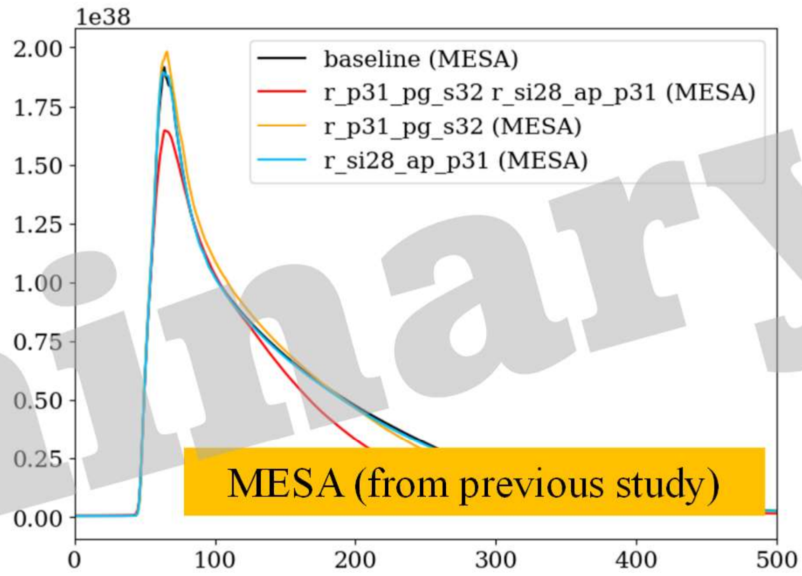
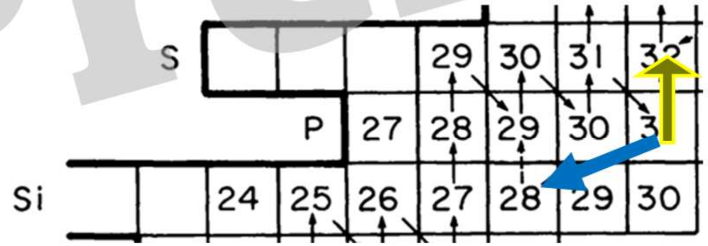
- Some special cases indicating **correlation** are found.
- Usually, relevant to cycle in nuclear network (NeNa, ZnGe, NiCu, CNO…).



• Effect of SiP cycle strength




The reaction flows are trapped in SiP cycle.
→ Energy generation is interrupted.
→ Luminosity decreased.

C.Iliadis, et al., Nucl.Phys.A 559, 83 (1993)

# Summary

- We are developing **X-ray burst emulators** by **deep learning.**
- Dataset was generated using MESA, hydrodynamic simulation code.
- Light curve emulator has been developed and shows good performance.
- Sensitivity study with the emulator identified **new pairs of sensitive reactions**.
- Future works
  - MC uncertainty propagation
  - Training models for recurrence time or abundance study
  - Effect of triple, quadraple… or multiple reaction rate variation
  - Effect of nuclear mass model