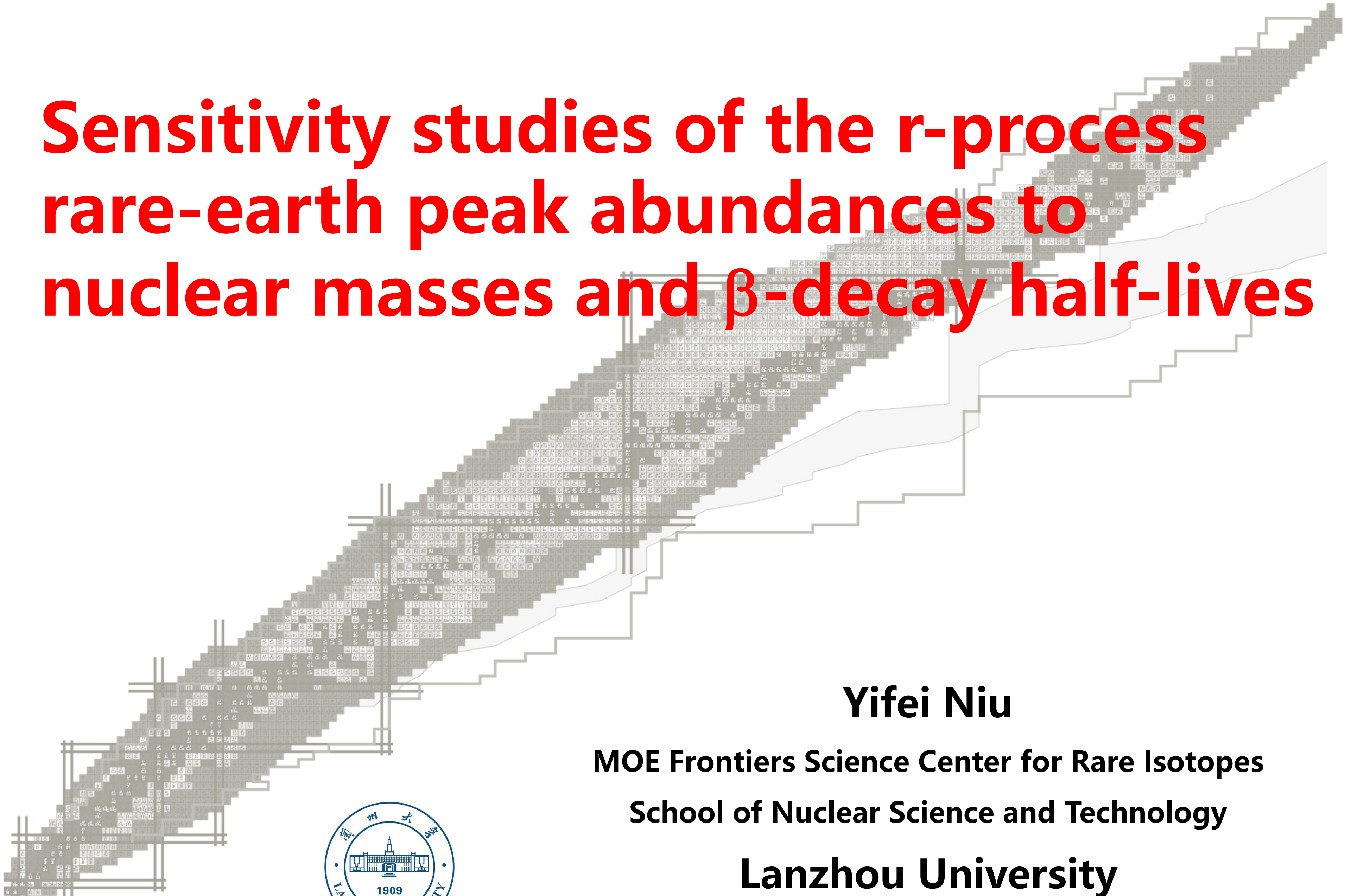
Sensitivity studies of the r-process rare-earth peak abundances to nuclear masses and β-decay half-lives



Yifei Niu

MOE Frontiers Science Center for Rare Isotopes

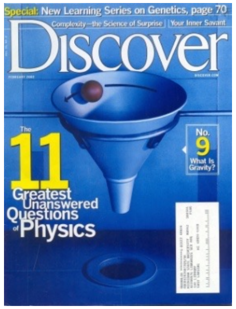
School of Nuclear Science and Technology

Lanzhou University

How Were the Heavy Elements Made?

How were the heavy elements from iron to uranium made?

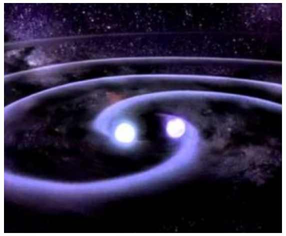
The 11 greatest unanswered questions of physics



- **Rapid neutron capture process (r-process)**

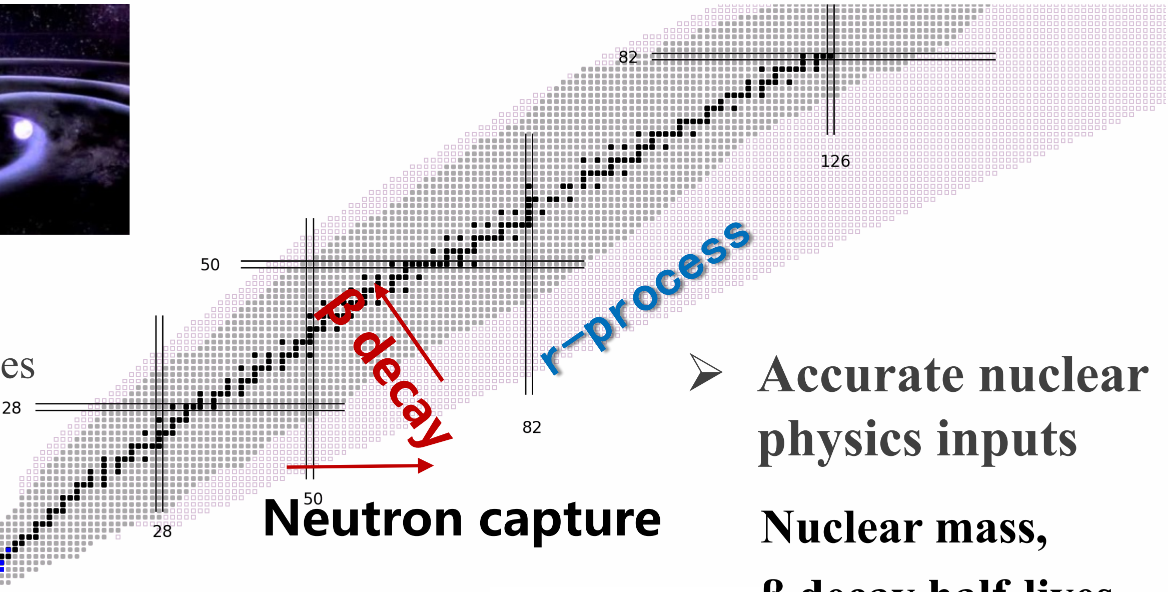
➢ **Where does r-process happen?**

Supernova Neutron star merger (NSM)



GW170817 NSM:
One of the main r-process sites

Nature **551**,64; 67; 75; 80 (2017)
Science **358**, 1559 (2017)
ApJL **848**, L17; L19 (2017)



➢ **Accurate nuclear physics inputs**

Nuclear mass,

β decay half-lives,

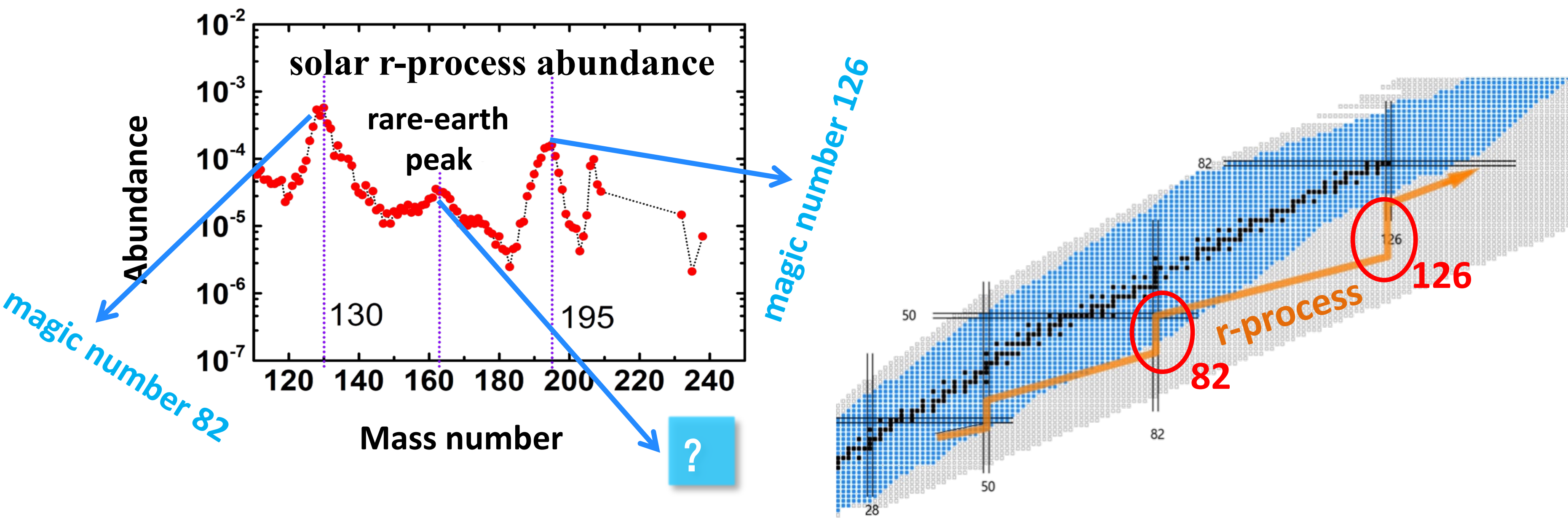
Neutron-capture rates,

…

The simulation of r-process plays an important role in determining the r-process site and interpreting the observed element abundance.

The mystery of rare-earth peak formation

The mystery of r-process rare-earth peak formation



- Abundance peaks at A=130 and 195: magic nuclei with long β-decay half-lives and small neutron-capture cross sections
- **The rare-earth peak is located between two closed neutron shells, and its formation mechanism is still a controversial topic.**

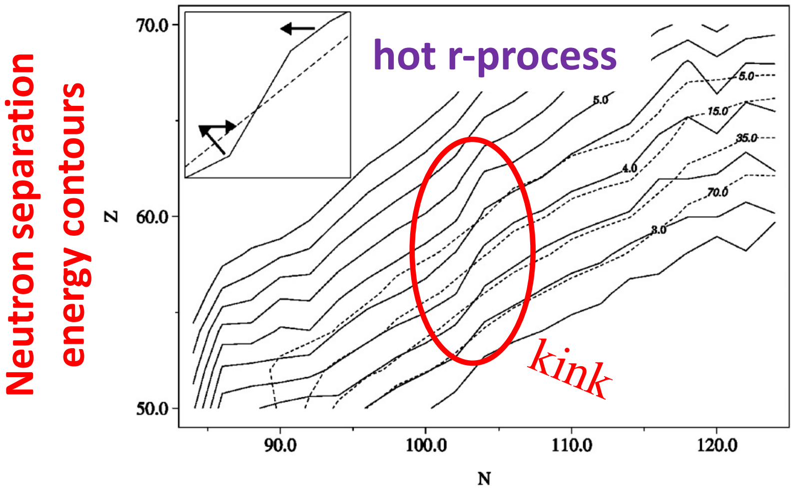
R. Surman et al., PRL, 79 1809-1812 (1997)
M. R. Mumpower et al., PRC, 85 045801 (2012)

The mystery of rare-earth peak formation

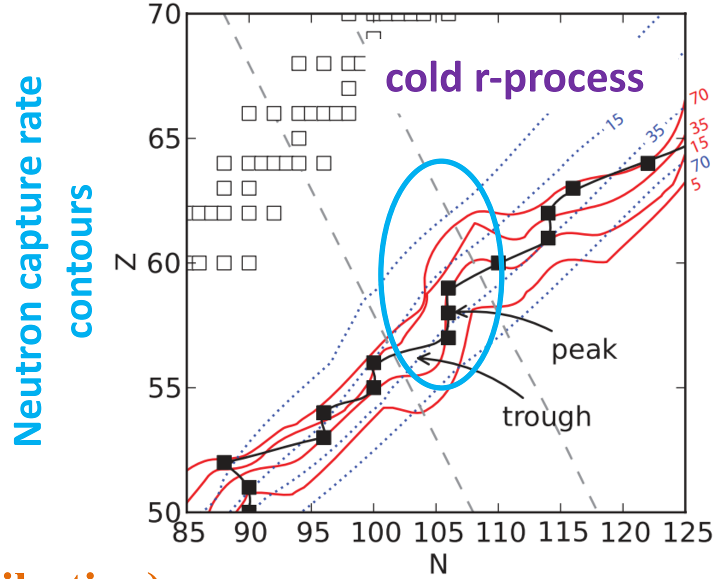
Possible formation mechanism of rare-earth peak

M. R. Mumpower et al., PRC, 85 045801 (2012)

- **Dynamical formation mechanism (mass, neutron-capture, β decay)**

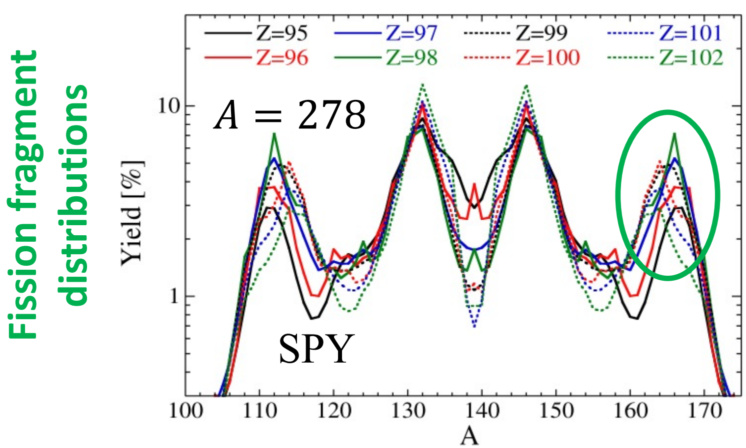


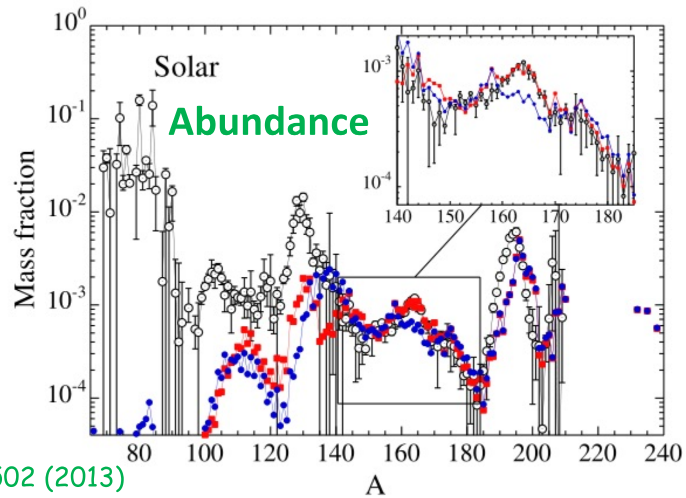
R. Surman et al., PRL, 79 1809-1812 (1997)



- **Fission mechanism (fission fragment distribution)**

extreme neutron-rich scenario





S. Goriely, et al., PRL, 111:242502 (2013)

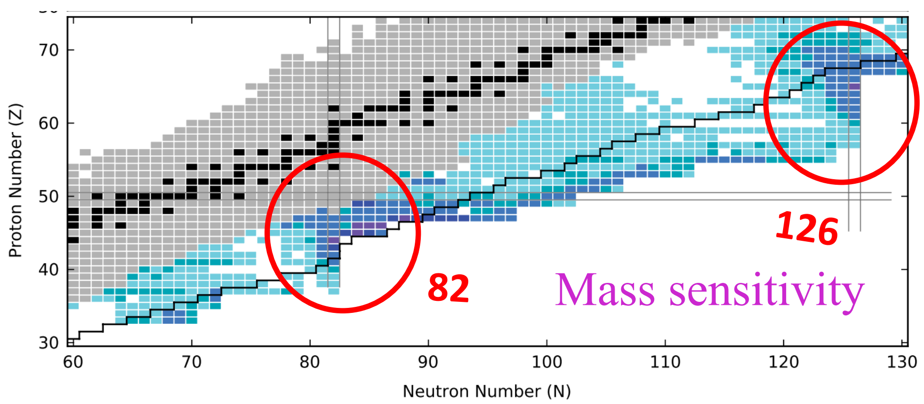
Early sensitivity studies

Sensitivity studies

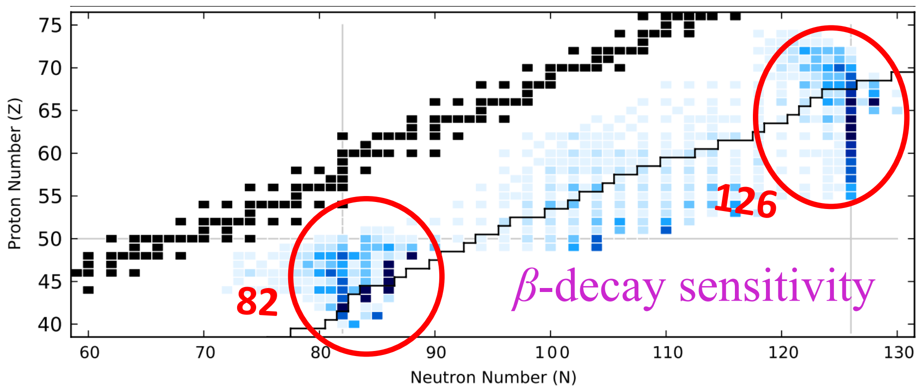
Sensitivity measure: $F = 100 \sum_{A} |X(A) - X_{\text{baseline}}(A)|$

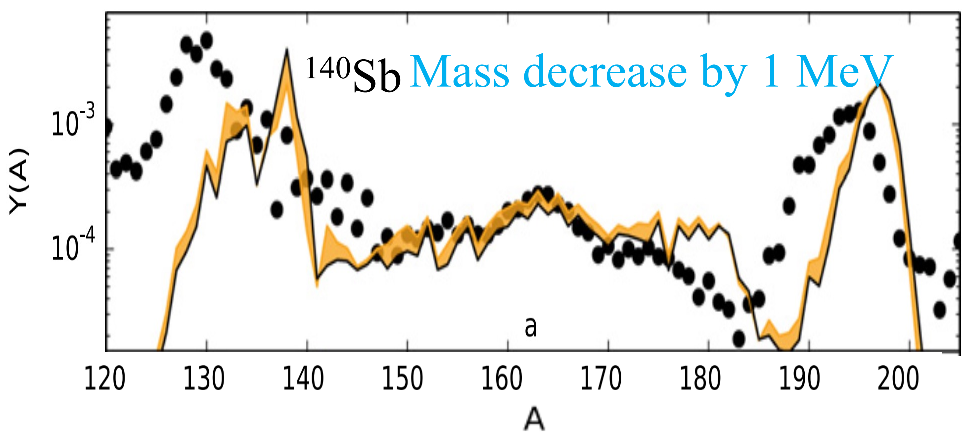
- Identify the **key nuclei** that have strong impact on the r-process abundances.
- **Early sensitivity studies** (Focus more on global effects on the abundance distributions):

M. R. Mumpower, et al., PPNP, 86 86-126 (2016)

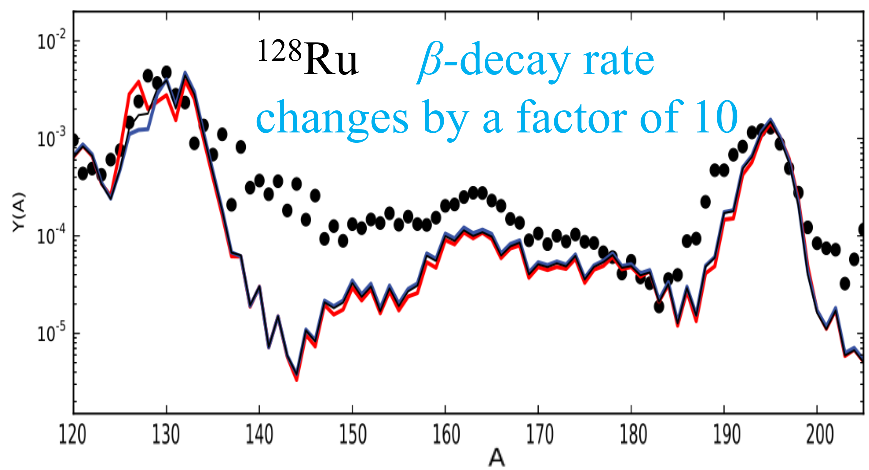


M. R. Mumpower, et al., AIP Adv. 4 041009 (2014)





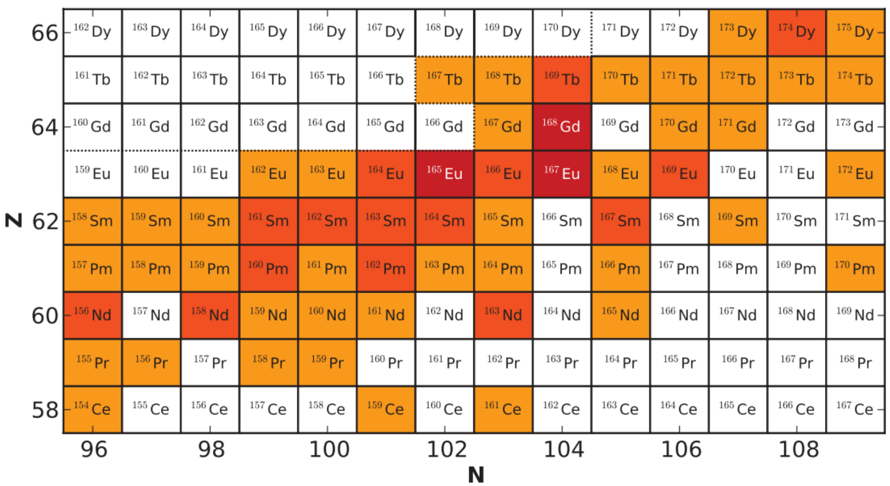
M. R. Mumpower, et al., JPG, 42 034027 (2015)



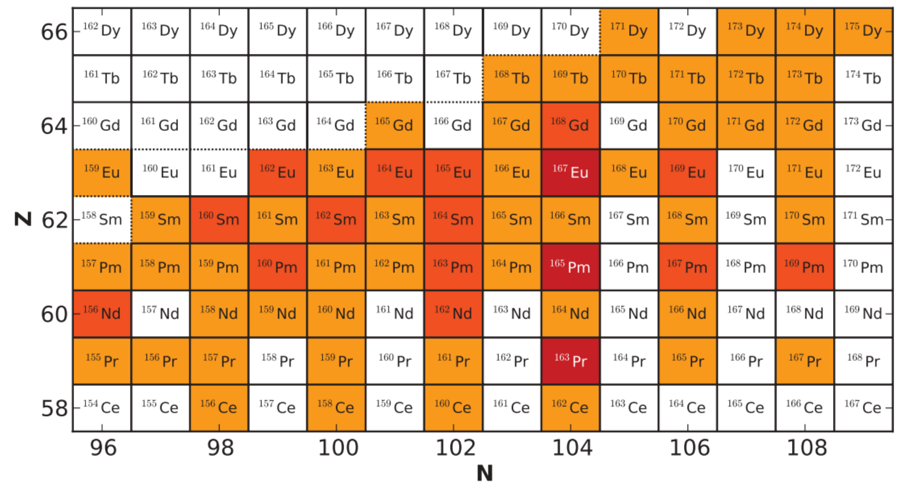
Sensitivity study for rare-earth peak

- **Rare-earth peak region:** **the sensitivity study of r-process abundances to neutron capture rates**

M. R. Mumpower, et al., PRC, 86:035803 (2012)



(a)



(b)

Rare-earth peak region:

- **Mass sensitivity study？**
- ***β*-decay sensitivity study？**

Our work:

We will perform sensitivity studies focused on the rare-earth peak by varying nuclear mass and *β*-decay rate of every single nucleus.

- We aim to **identify the most influential nuclei** and show their **effects on the rare-earth peak abundance pattern**.
- The most influential nuclei are recommended to be the targets of future researches.

Nuclear physics inputs and astrophysical scenarios

➢ Dynamical r-process model

http://sourceforge.net/p/nucnet-tools

Nuclear network *NucNet* (Bradley S. Meyer) involves more than 6000 isotopes up to No (Z=102) .

➢ Nuclear physics inputs:

- ✓ **Nuclear mass**: FRDM-1995.
- ✓ **Neutron capture rates**: JINA REACLIB database / calculated with TALYS as nuclear mass changes.
- ✓ ***β*-decay rates**: JINA REACLIB database
- ✓ **Fission**: consider three fission channels (SF, NF, *β*DF)

  Fission yields: determined by GEF2021 model / symmetric fission treatment

➢ Astrophysical scenarios :

Parameterized trajectory where the density evolves as a function of time :

$$\rho(t) = \rho_1 e^{-t/\tau} + \rho_2 \left(\frac{\Delta}{\Delta + t}\right)^n \qquad T_0\text{=10 GK}$$

- ✓ **hot1:** hot wind r-process→ fewer fissioning nuclei, fission is negligible (S =150 k_B, τ=20 ms, n=2, Y_e =0.3)
- ✓ **hot2:** hot wind r-process→ a large number of fission events occur, with GEF model (S=233 k_B, τ=35 ms, n=2, Y_e=0.1)
- ✓ **cold:** cold wind r-process→ a large number of fission events occur, with GEF model (S =150 k_B, τ=20 ms, n=6, Y_e =0.2)

An additional set of simulations in the cold scenario :

- ✓ **cold-sym:** same as cold scenario but use a simple symmetric fission treatment

Sensitivity calculations

Mass sensitivity calculations:

Varying nuclear mass Δ*M*=±1 MeV of every single nucleus in the region of interest for the rare-earth peak formation (414 nuclei).

Mass sensitivity measure *F*:

$$F = 100 \sum_{A=150}^{178} \frac{\left|Y_{+1}(A) - Y_{origin}(A)\right| + \left|Y_{-1}(A) - Y_{origin}(A)\right|}{Y_{origin}(A)}$$

$Y_{origin}(A)$ →baseline abundance

$Y_{+1}(A)$, $Y_{-1}(A)$ → abundance with $\Delta\text{M} = \pm 1$ MeV

β-decay sensitivity calculations:

Increasing and decreasing *β*-decay rate by a factor of 10 for each nucleus in the region of interest for the rare-earth peak formation.

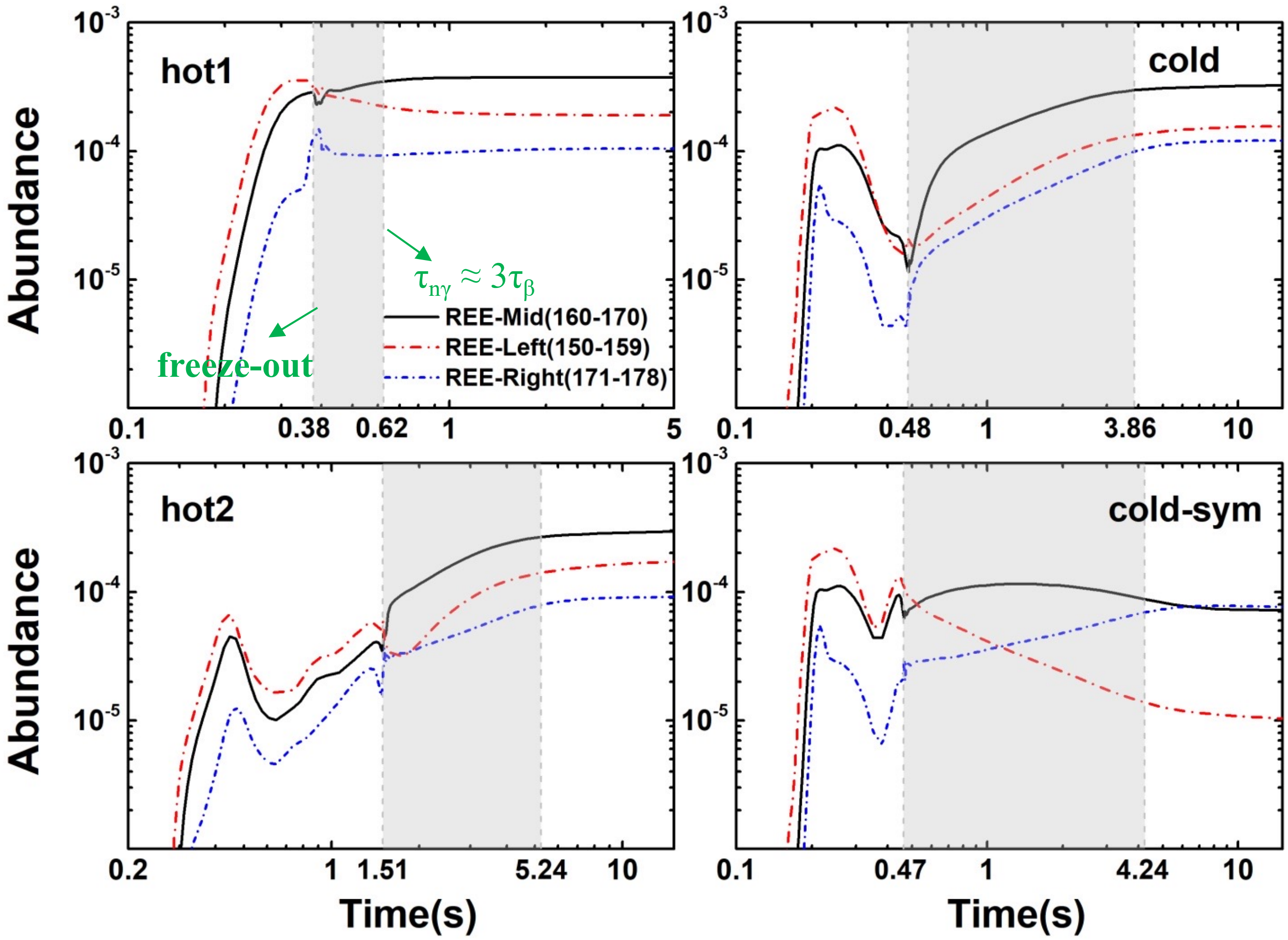
***β*-decay sensitivity measure:**

$$F = 100 \sum_{A=150}^{178} \frac{\left|Y_{\beta\times10}(A) - Y_{origin}(A)\right| + \left|Y_{\beta/10}(A) - Y_{origin}(A)\right|}{Y_{origin}(A)}$$

$Y_{origin}(A)$ → baseline abundance

$Y_{\beta\times10}(A)$, $Y_{\beta/10}(A)$ → abundances with increase and decrease in *β*-decay rate by a factor of 10

Time interval of rare-earth peak formation



(n,γ) , β decay timescale:

$$\frac{1}{\tau_\beta} = \frac{\sum_{Z,A} \lambda_\beta(Z,A) Y(Z,A)}{\sum_{Z,A} Y(Z,A)}$$

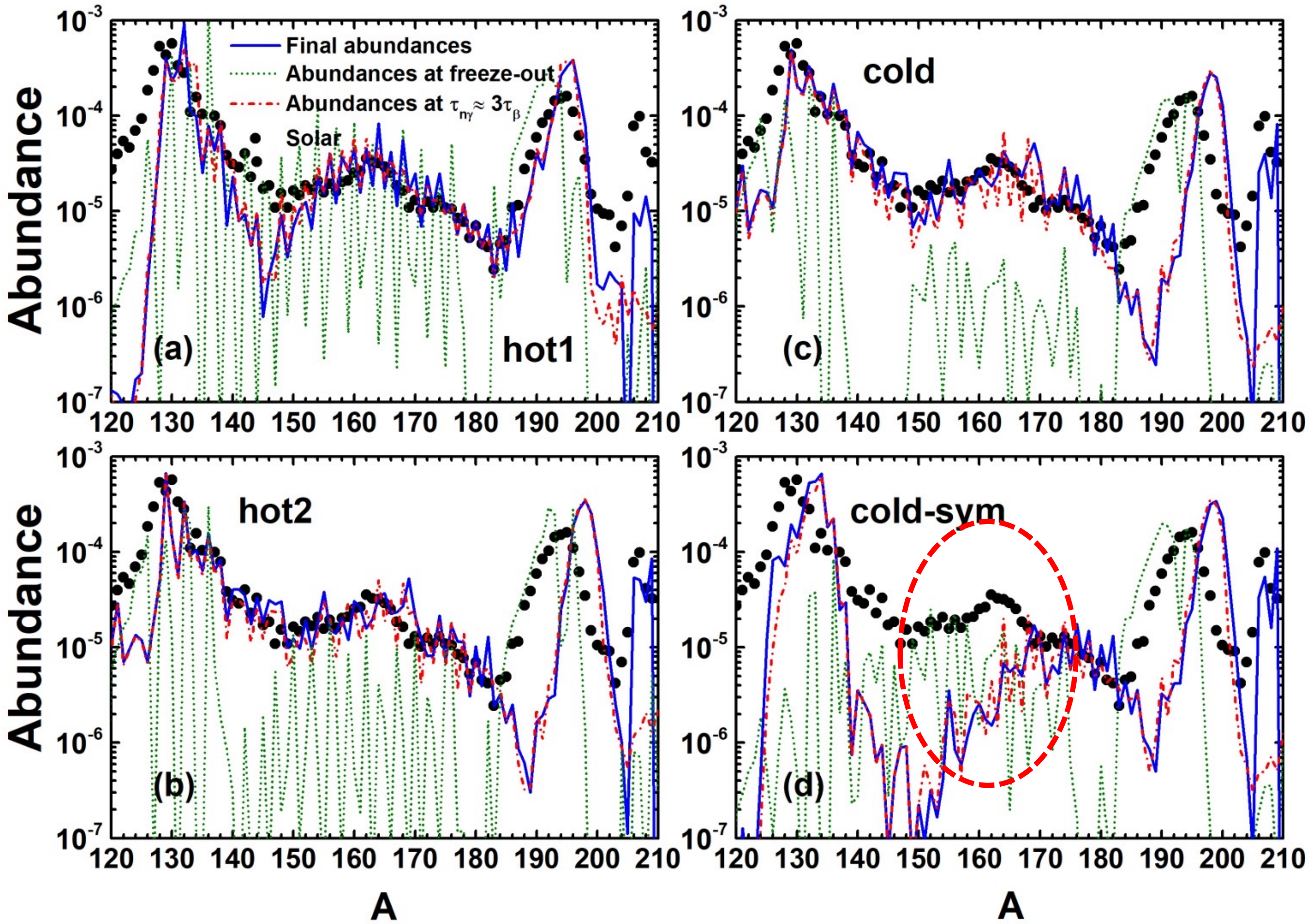
$$\frac{1}{\tau_{n\gamma}} = \frac{\sum_{Z,A} N_n \langle \sigma v \rangle_{(Z,A)} Y(Z,A)}{\sum_{Z,A} Y(Z,A)}$$

- After r-process freeze-out, the abundance in the region A = 160 - 170 becomes the largest ➔ Onset of peak formation.
- After $\tau_{n\gamma} \approx 3\tau_\beta$, the abundance in the three mass regions tends to be constant ➔ Completion of peak formation

The shaded area represents the time interval of rare-earth peak formation, from the time of r-process freeze-out (R = 1) to the point where the timescale $\tau_{n\gamma} \approx 3\tau_\beta$.

Rare-earth peak formation

The abundance distributions at different times

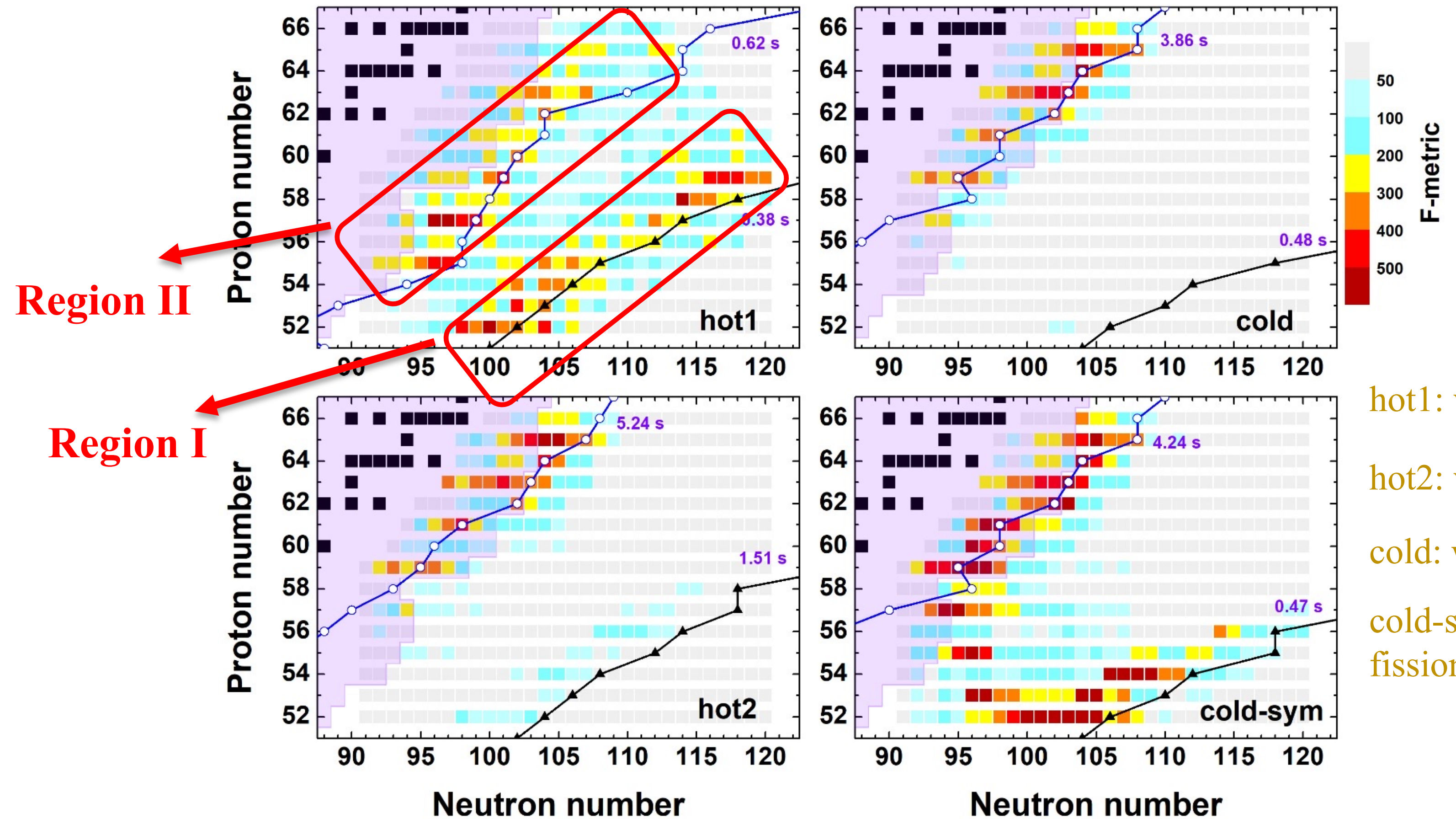


- For hot1, hot2 and cold scenarios, the rare-earth peak can be reproduced well.

- For *cold-sym*, the rare-earth peak cannot be reproduced correctly, indicating the unreasonable distribution of fission fragments. ➞ **Fission fragments play an important role in shaping rare-earth peak abundances.**

Sensitivity of rare-earth peak abundance to nuclear mass

Sensitivity measures *F* between ±1 MeV mass variations in four different scenarios



hot1: without fission

hot2: with fission-GEF

cold: with fission-GEF

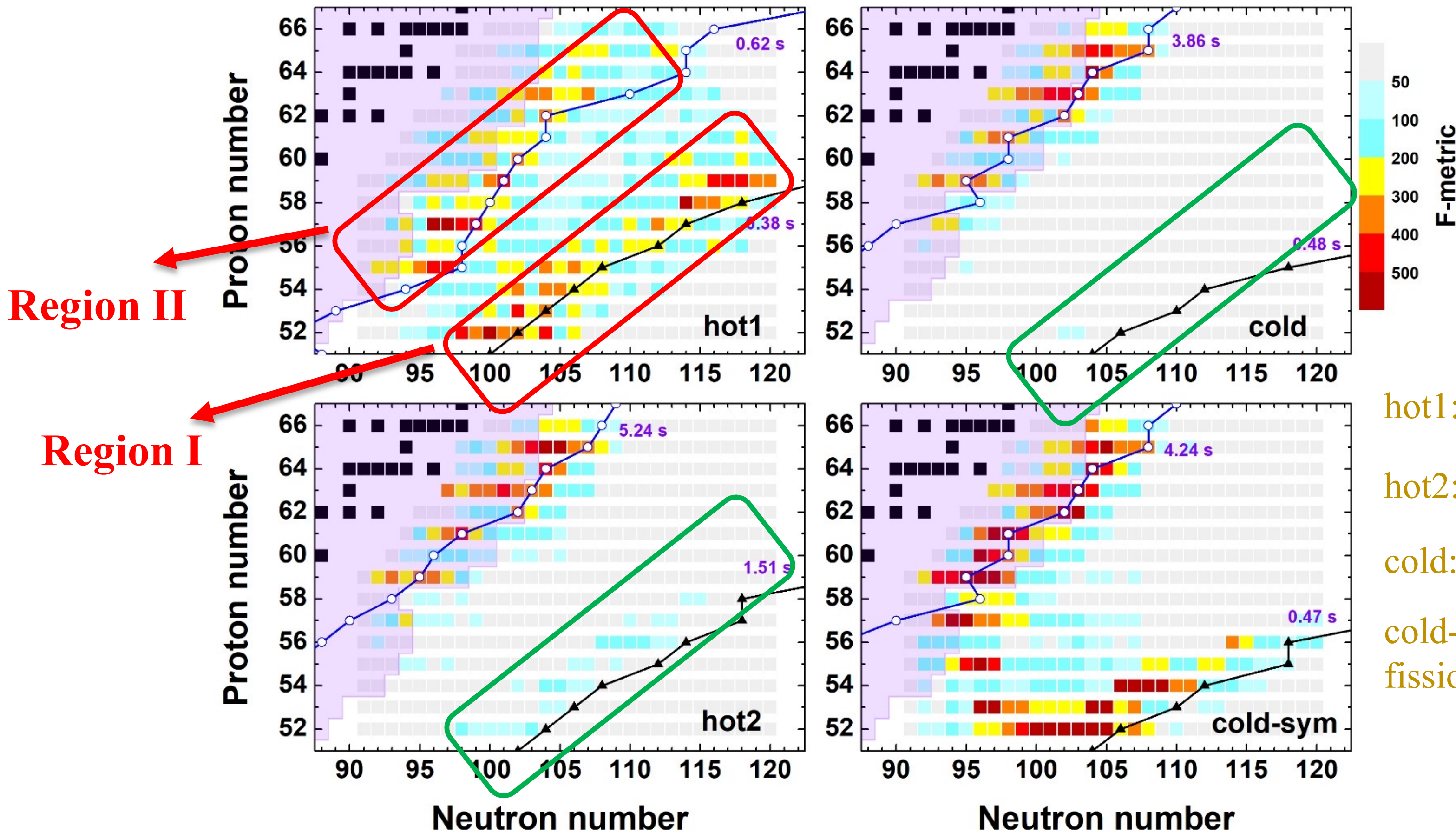
cold-sym: symmetric fission (unreasonable)

Region I : 20-30 neutrons away from stability (lie along r-process freeze-out path) ➞ onset of peak formation

Region II : 7-15 neutrons away from stability (lie along r-process path at the point $\tau_{n\gamma} \approx 3\tau_{\beta}$) ➞ completion of peak formation

Sensitivity of rare-earth peak abundance to nuclear mass

Sensitivity measures *F* between ±1 MeV mass variations in four different scenarios



hot1: without fission

hot2: with fission-GEF

cold: with fission-GEF

cold-sym: symmetric fission (unreasonable)

- For *hot2* and *cold*, the sensitivities for nuclei in region I are masked by fission deposition.

Sensitivity of rare-earth peak abundance to nuclear mass

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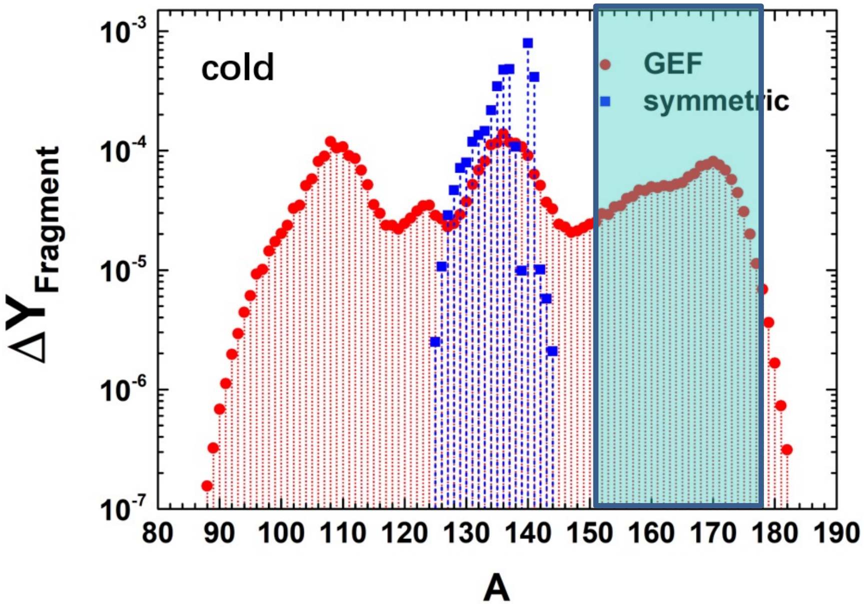
■ The contribution of fission fragments to abundances



$\Delta Y_{Fragment}$ represents the increase in the abundance of nuclei with a given mass number due to fission.

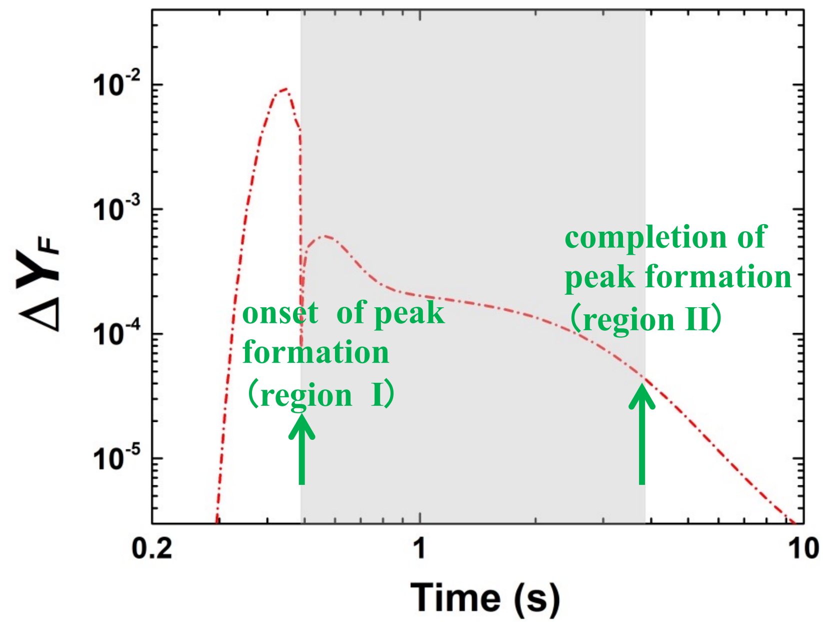
Integrated fission flow: $f_i^{(n)} = \int (dY_{f,i}{}^{(n)}/dt)dt$

The contribution of fission fragments to abundances:

$$\Delta Y_{Fragment}(A) = \sum_n \sum_i f_i^{(n)} \times w_i(A)$$

fission yield

■ Evolution of the contribution of fission fragments to rare-earth peak abundance over time

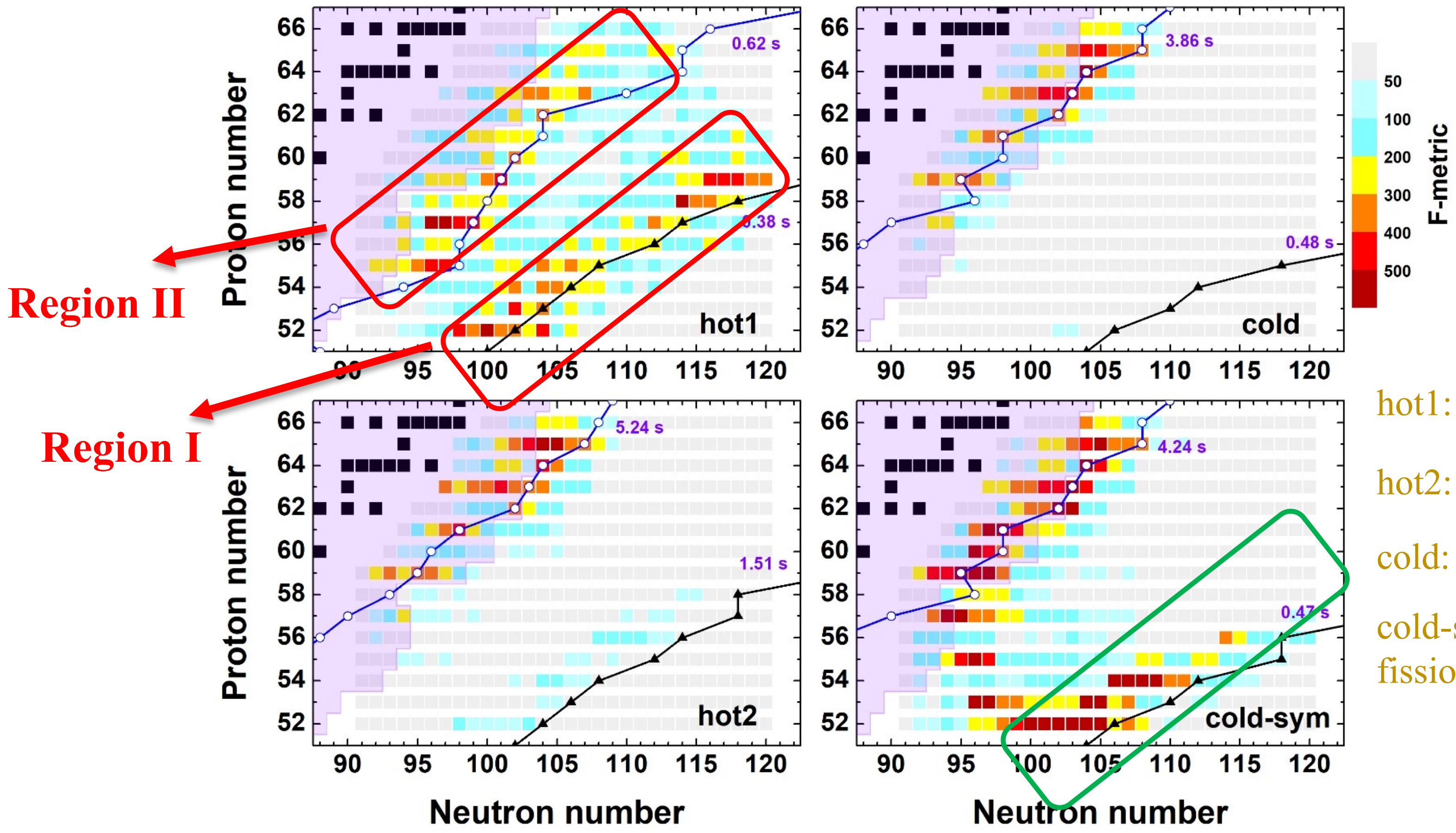


- Fission deposition erases the sensitivities to masses along the early r-process path (region I). However, the contribution of fission fragments decreases over time during the decay back to stability →

The sensitivities are not easily concealed by fission deposition for nuclei in region II.

Sensitivity of rare-earth peak abundance to nuclear mass

Sensitivity measures *F* between ±1 MeV mass variations in four different scenarios



hot1: without fission

hot2: with fission-GEF

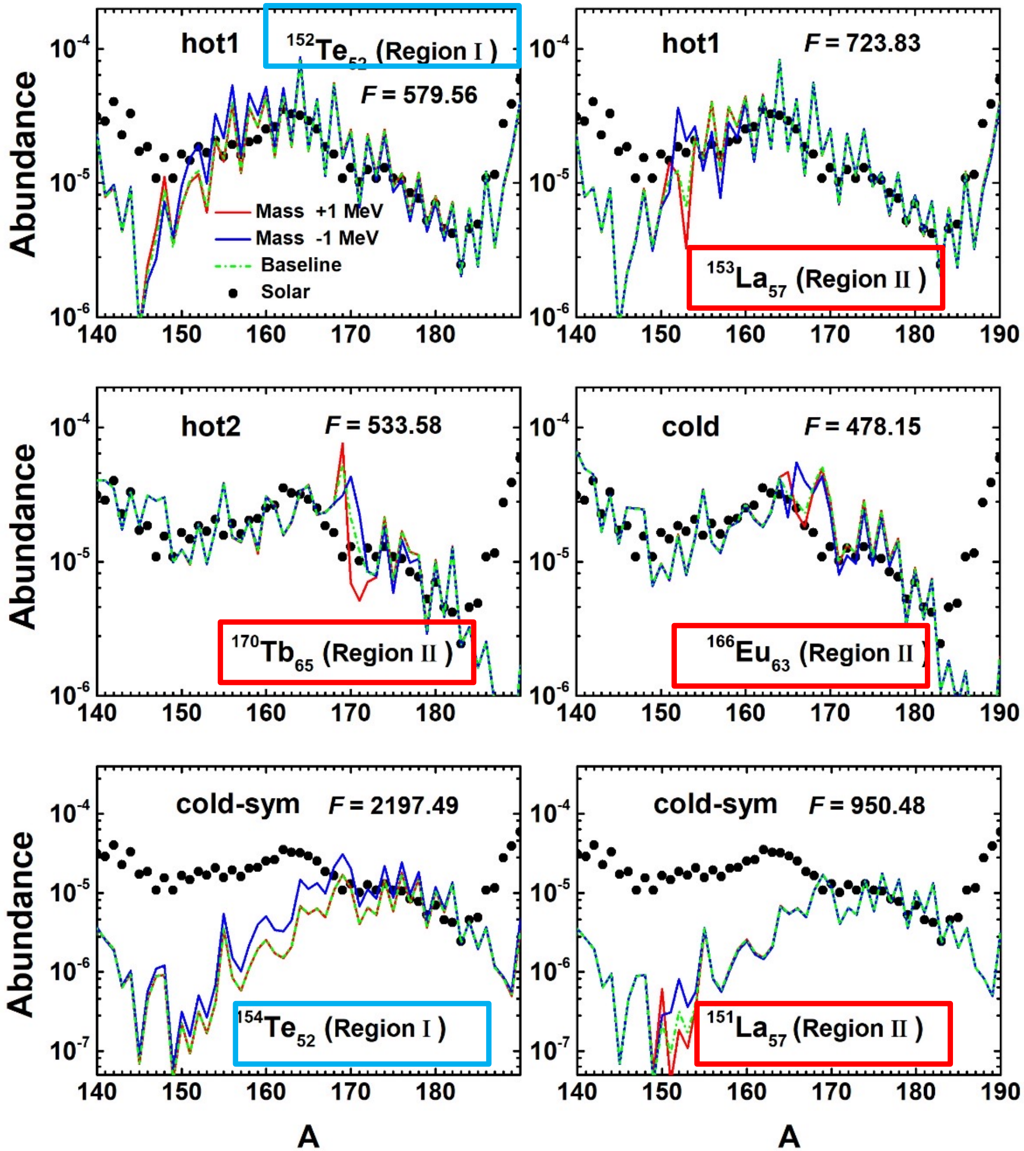
cold: with fission-GEF

cold-sym: symmetric fission (unreasonable)

- For *cold-sym*, the sensitivity in region I is increased again because the fission fragments do not directly contribute to the rare-earth mass region.

The effect of nuclear mass on the final abundances

- **The effect of mass variations on the final rare-earth peak abundances for selected nuclei in different scenarios.**

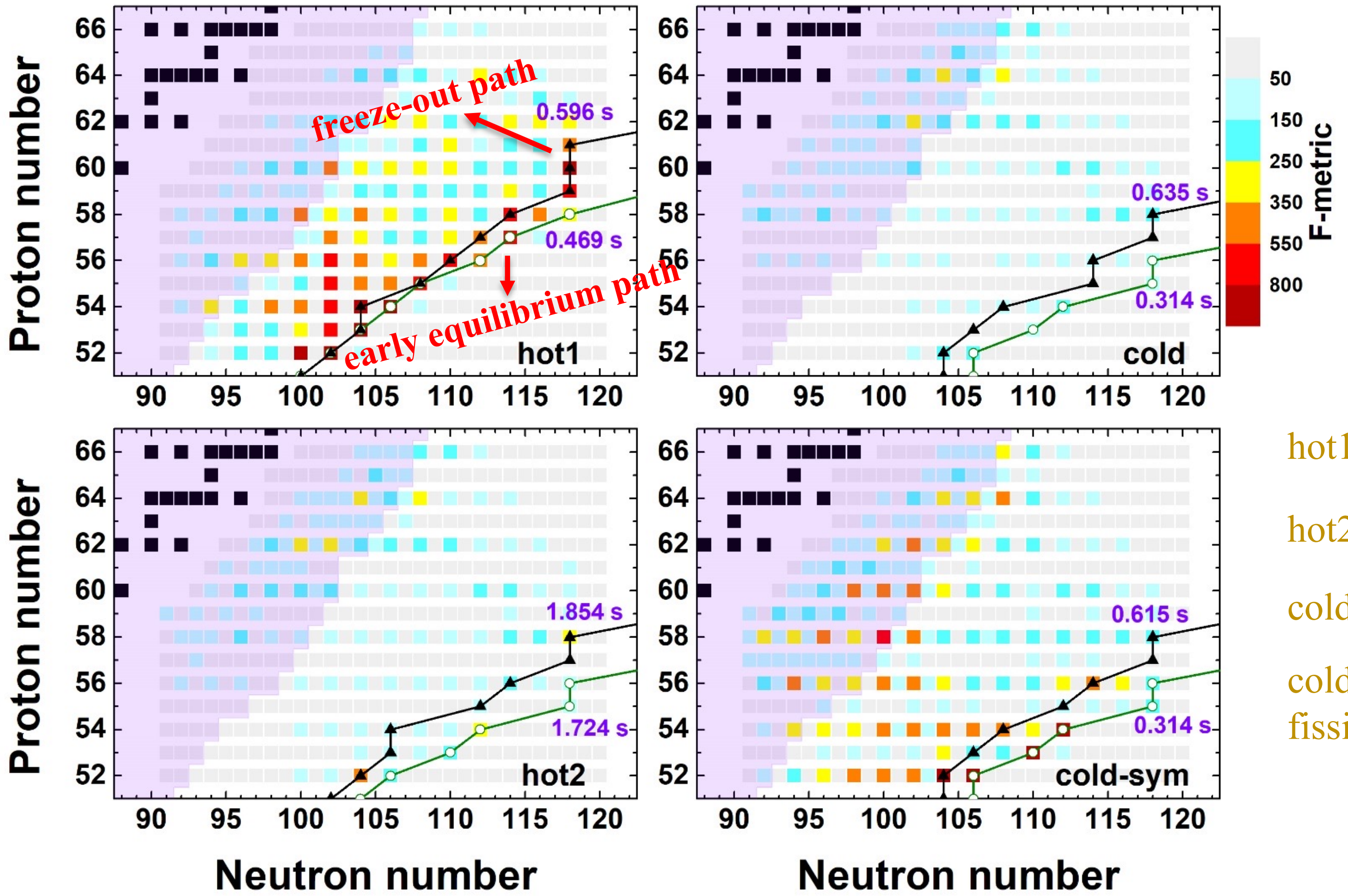


- **Mass variation in region II:** affects the local structure of the rare-earth peak abundance distribution curve.

- **Mass variation in region I** (further away from stability line): affects a larger mass range (several mass number range) in rare-earth peak abundance distribution than the case of region II.

Sensitivity of rare-earth peak abundance to β decay

Sensitivity measures *F* for β-decay sensitivity studies in four different scenarios



hot1: without fission

hot2: with fission-GEF

cold: with fission-GEF

cold-sym: symmetric fission (unreasonable)

- The most impactful nuclei include even-neutron-number (N) nuclei on the early r-process equilibrium path or r-process freeze-out path and nuclei with N = 100,102, and 104.
- Fission deposition significantly reduces the sensitivity of the rare-earth peak abundances to β-decay rate variation.

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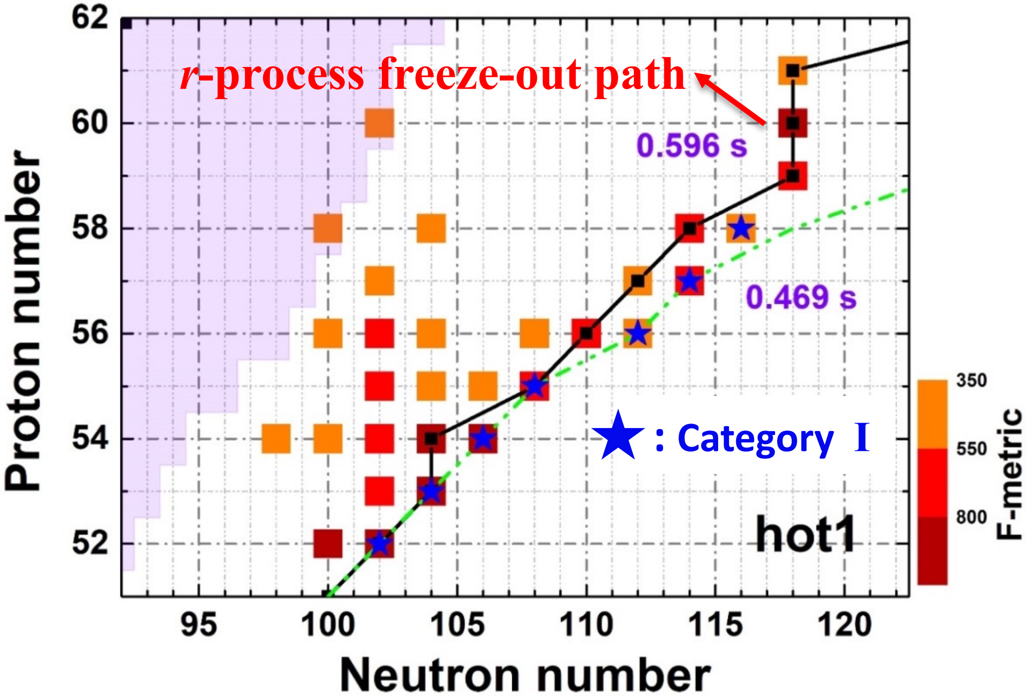
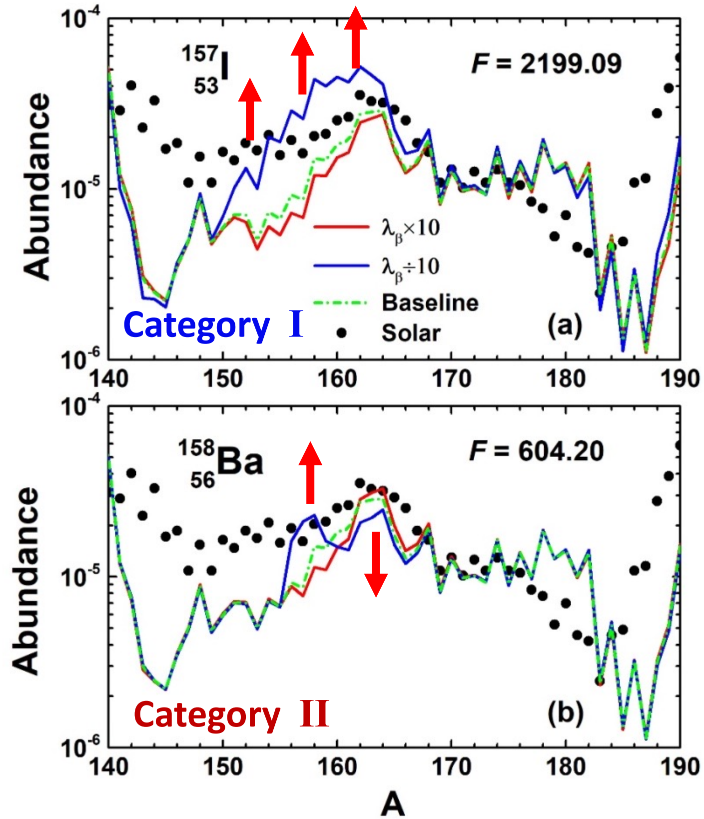
The different effects of *β*-decay rate on the final rare-earth peak abundances.



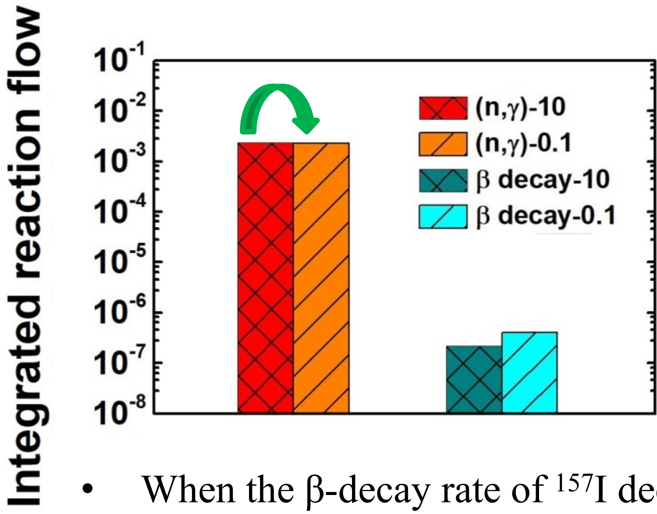


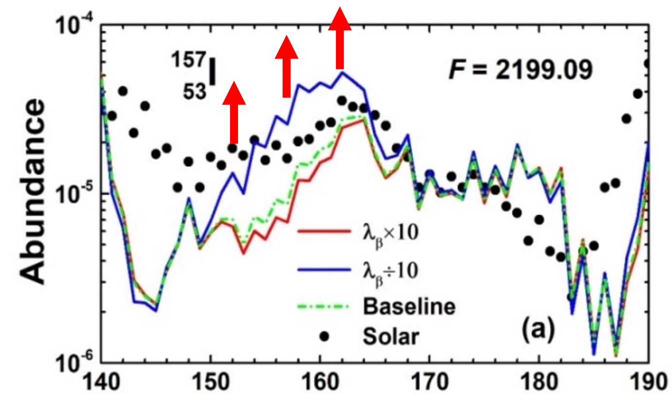
When the *β*-decay rate decreases:

- For nuclei **on the right side of the freeze-out path**: abundance increases in the range of more than10 mass numbers **→ Category I**
- For nuclei **on the left side of the freeze-out path** : abundance increases at mass number *A* of this nucleus and decreases at higher mass numbers **→ Category II**

Effects of β-decay on reaction flow

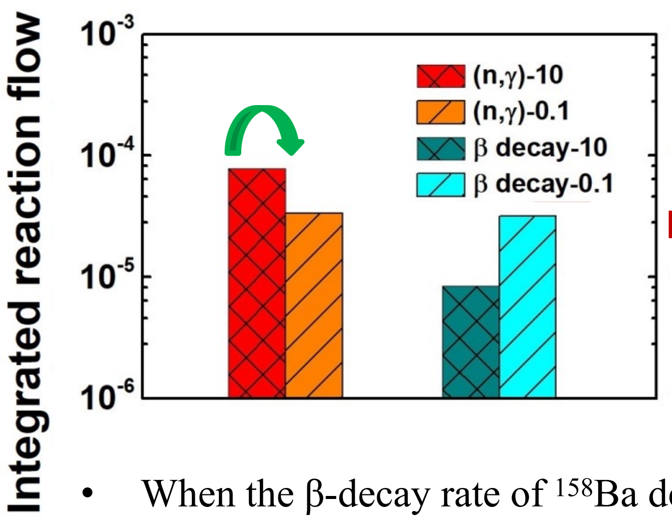
- ^{157}I (Category I) β-decay rate changes → Integrated reaction flow of daughter nuclei ^{157}Xe:

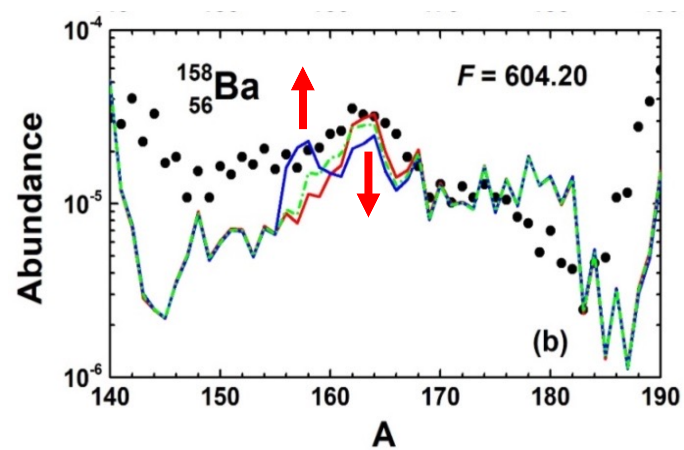




- When the β-decay rate of ^{157}I decreases, the neutron capture flow of the β-decay daughter nucleus ^{157}Xe remains almost unchanged.

- ^{158}Ba (Category II) β-decay rate changes → Integrated reaction flow of daughter nuclei ^{158}La :





- When the β-decay rate of ^{158}Ba decreases, the neutron capture flow of the β-decay daughter nucleus ^{158}La decreases obviously.

Effects of β-decay on reaction flow

When the β-decay rate decreases:

- **For nuclei on the right side of the r-process freeze-out path, e.g. ^{157}I (Category I):**

  The number of neutrons in the environment is still very large when the nuclear flow reaches this nucleus ➡

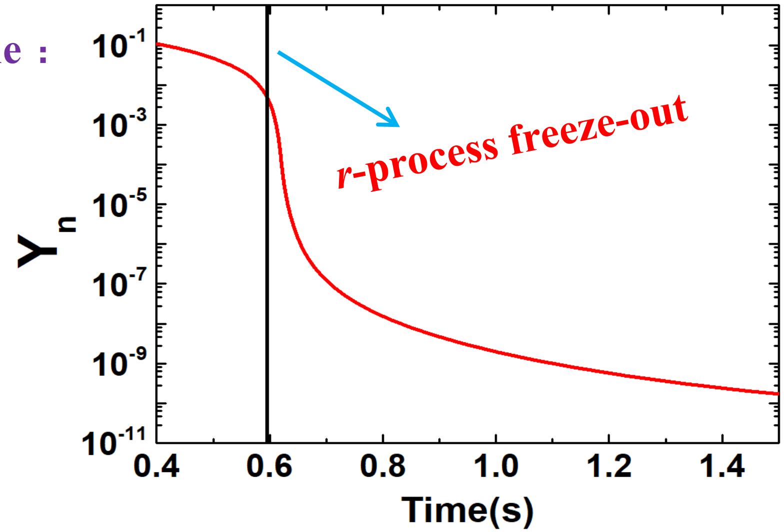
  Neutron capture of β-decay daughter nuclei does not decrease much

- **For nuclei on the left side of the freeze-out path , e.g. ^{158}Ba (Category II):**

  The neutron abundance decreases significantly with time after freeze-out ➡

  Later population of daughter nuclei results in neutron captures inactive due to the low neutron number in the environment at later time.

Evolution of neutron abundance over time：



Recommended nuclei for experiments

Nuclear mass

Z	A	Element	Sensitivity F
55	150	Cs	350.8407
57	153	La	723.8286
57	154	La	672.9493
59	159	Pr	388.5283
60	162	Nd	311.8340
62	166	Sm	361.5929
63	166	Eu	478.1464
63	167	Eu	374.1917
64	168	Gd	516.6238
65	169	Tb	516.5123

β decay half-life

Z	A	Element	Sensitivity F
54	152	Xe	388.8900
56	156	Ba	501.2561
56	158	Ba	604.1971
57	159	La	356.6990
58	160	Ce	339.1698
58	162	Ce	384.2443
60	164	Nd	295.1975
60	166	Nd	261.9961
62	168	Sm	261.8911
62	170	Sm	328.3856

- These nuclei are close to the current experimental capability and have high sensitivity measures

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Summary

✓ **The sensitivities of the r-process rare-earth peak abundances to nuclear masses and β-decay rates have been studied in different astrophysical scenarios.**

- The most influential nuclei for rare-earth peak abundance have been identified, and they are recommended as targets for future research.
- The fission deposition can significantly reduce the sensitivities of the r-process rare-earth peak abundances to nuclear mass and β-decay rate variations.
- The effects of mass and β-decay rate variations on the final rare-earth peak abundance patterns have been studied.

Outlook:

- In different astrophysical scenarios, the relative contributions of dynamical formation mechanism and fission formation mechanism of rare-earth peak ?

Acknowledgement

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Collaborators:

LZU: Y. W. Hao   Anhui Uni.: Z. M. Niu

- ✓ Y. W. Hao, Y. F. Niu, and Z. M. Niu, PLB 844, 138092 (2023)
- ✓ Y. W. Hao, Y. F. Niu, and Z. M. Niu, PRC 108, L062802 (2023)

Thank you!