Nucleosynthesis in the ejecta of neutron star mergers and the role of nuclear masses.

Stylianos Nikas
University of Jyväskylä

stylianos.s.nikas@jyu.fi

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

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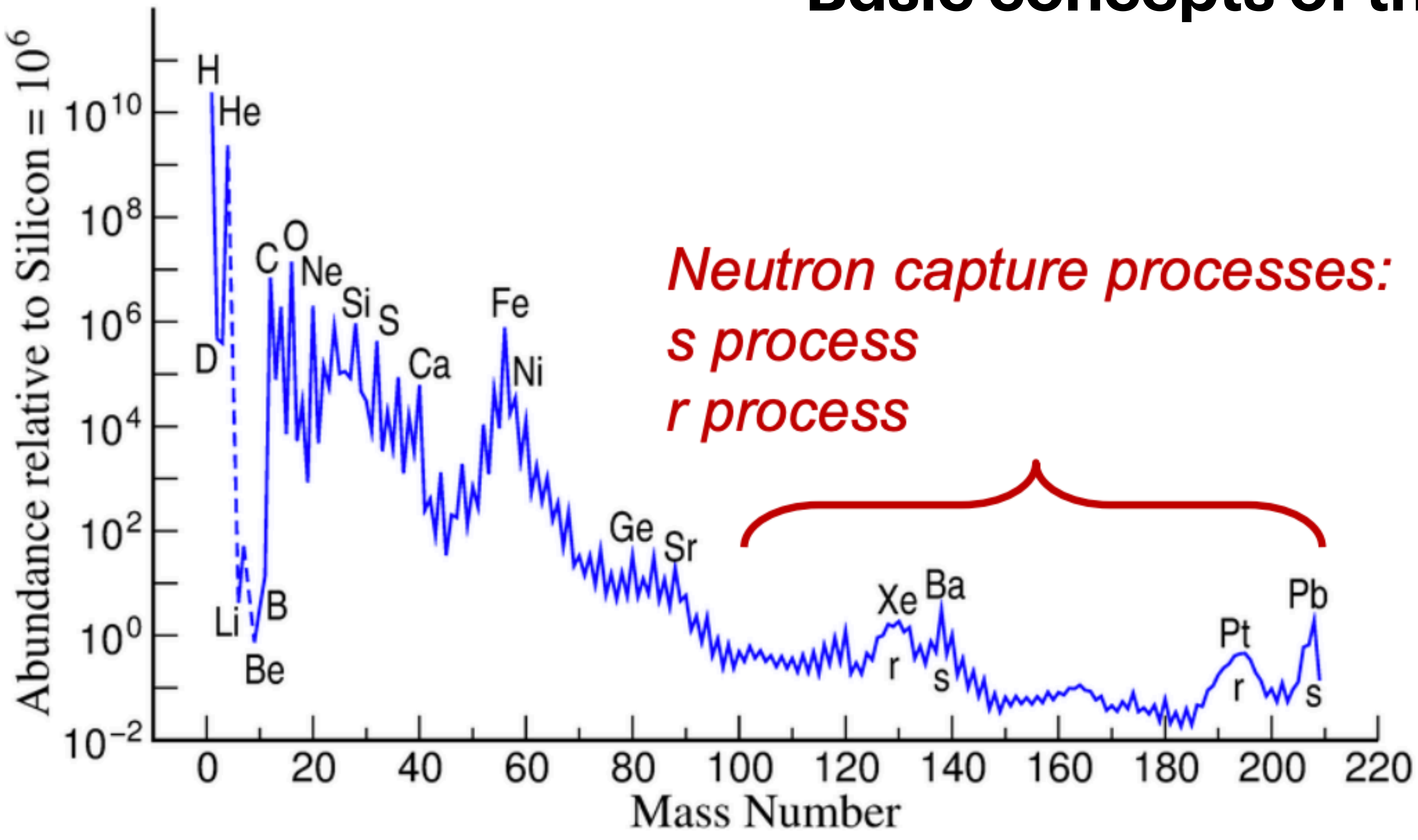
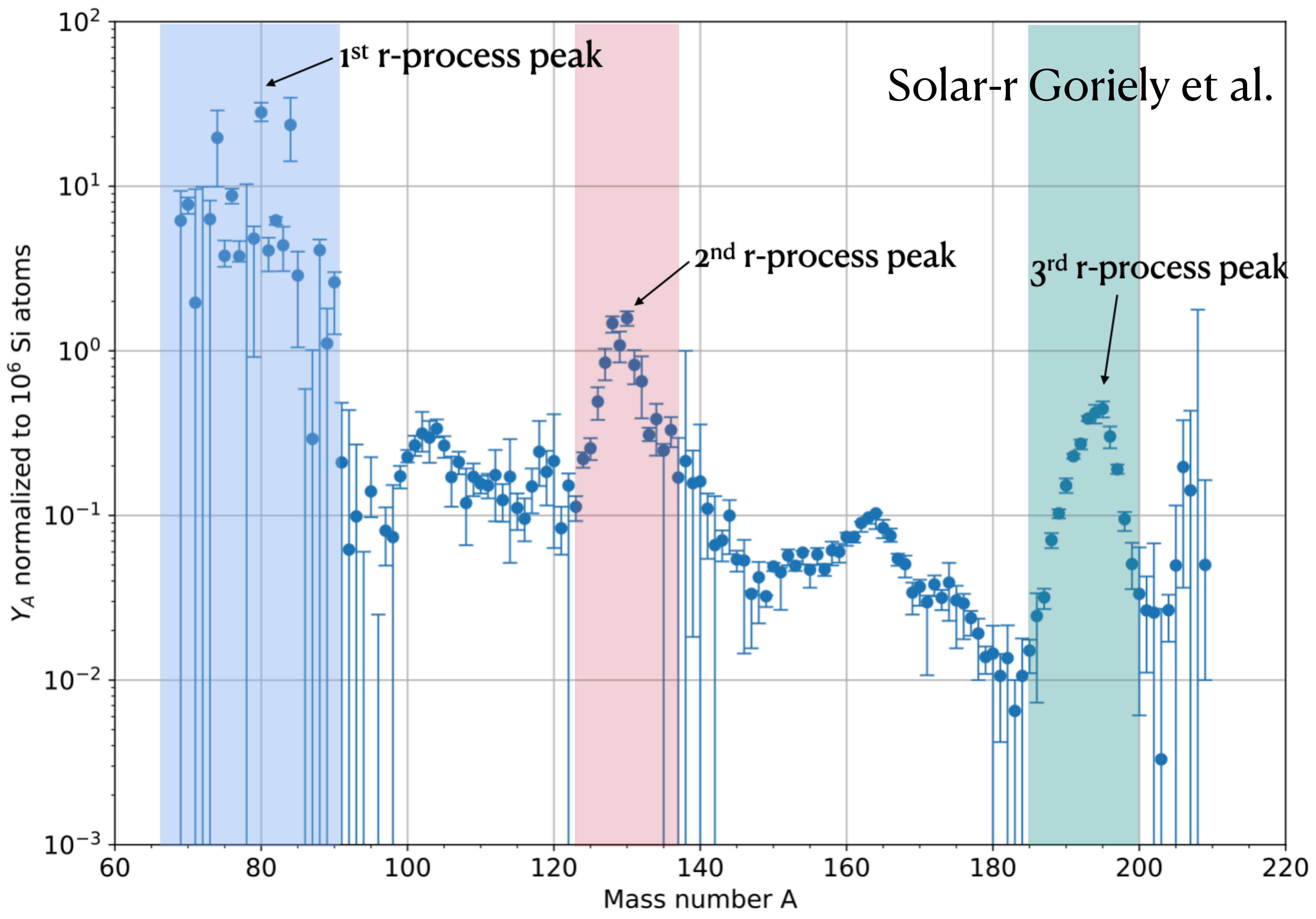
The r-process nucleosynthesis

Basic concepts of the r-process





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The r-process nucleosynthesis

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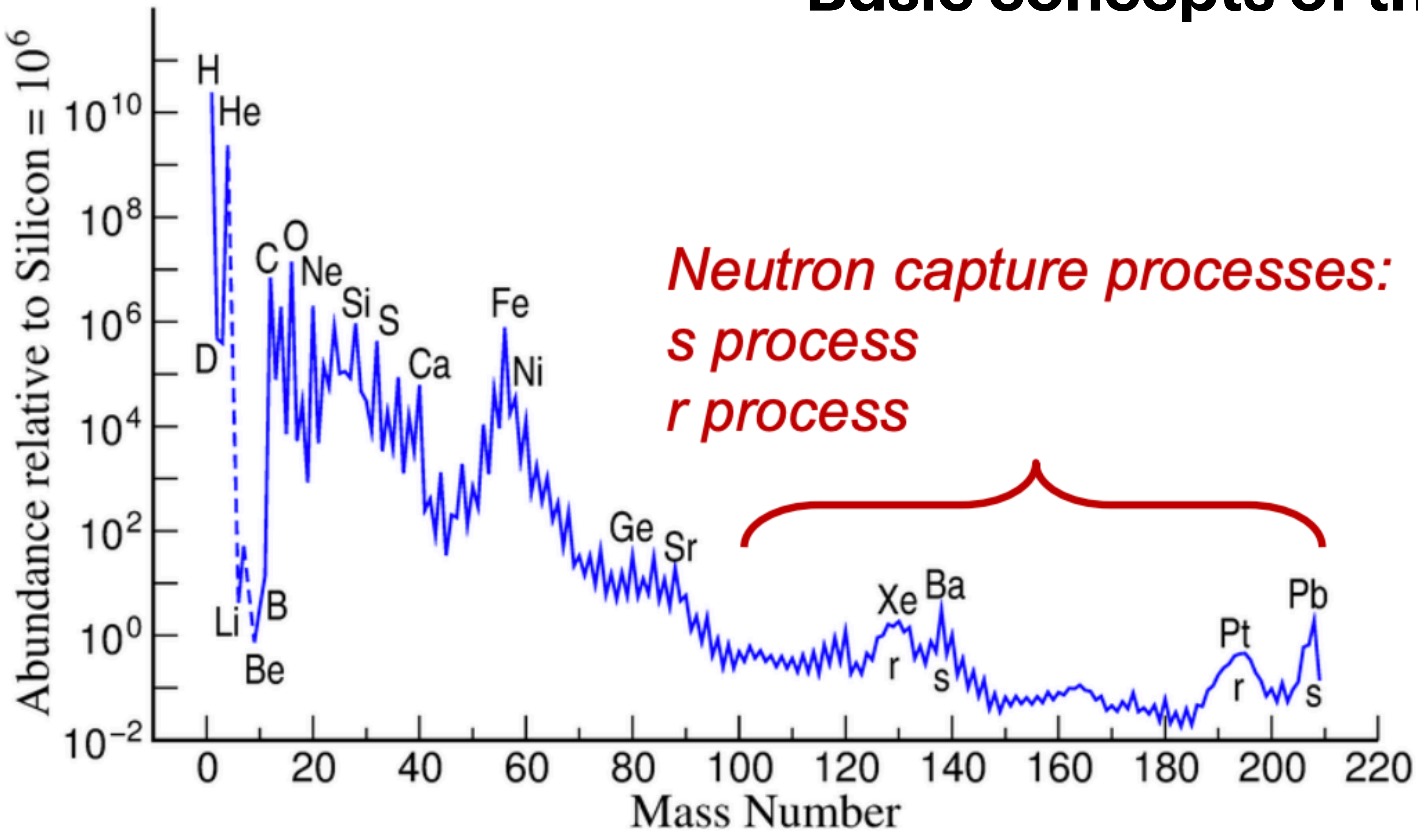

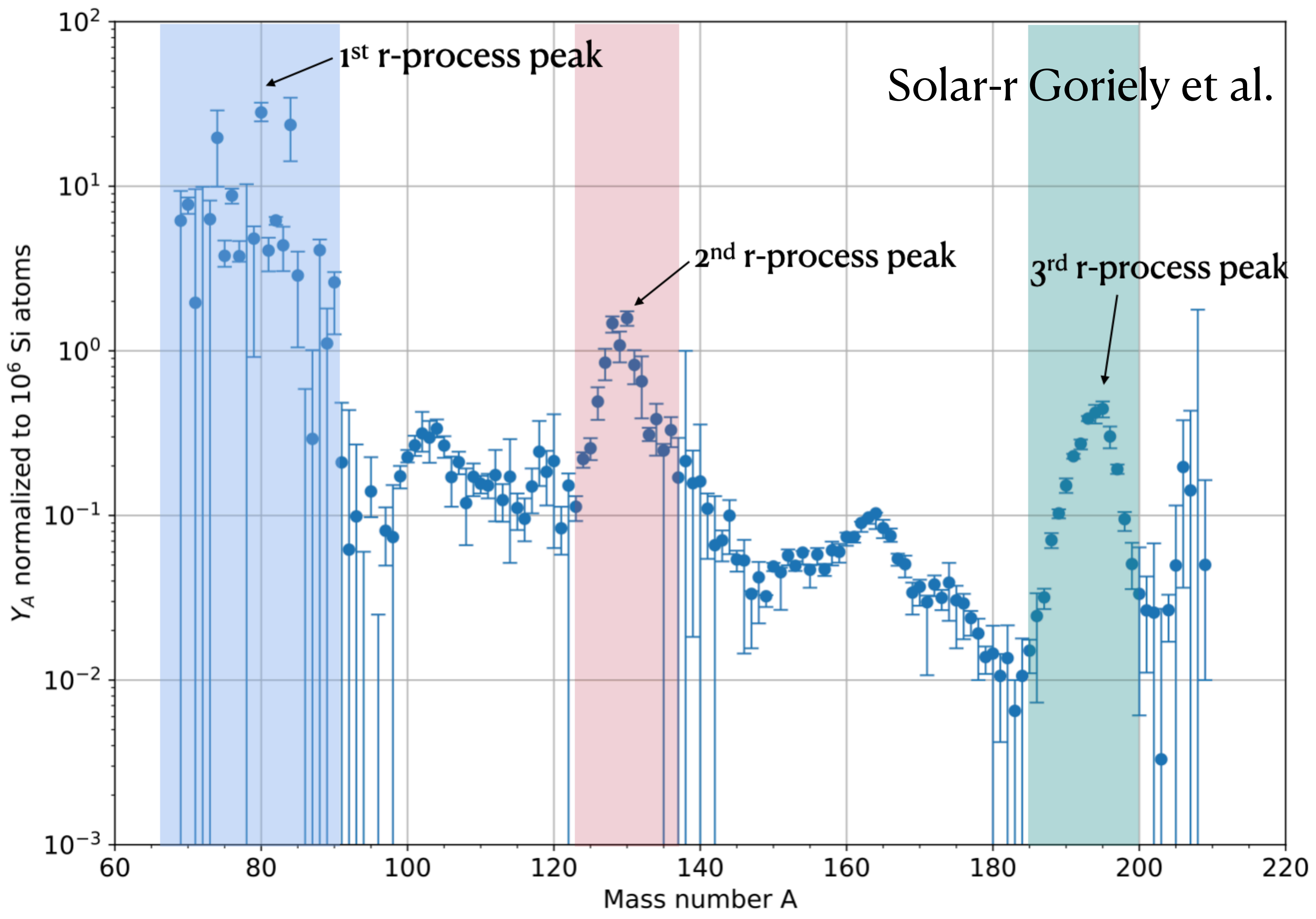

R-process is a primal process: provides enough neutrons and the seed nuclei

$A_{\text{final}} = A_{\text{initial}} + n_{\text{seed}}$

n_{seed} depends mainly on neutron richness ejecta

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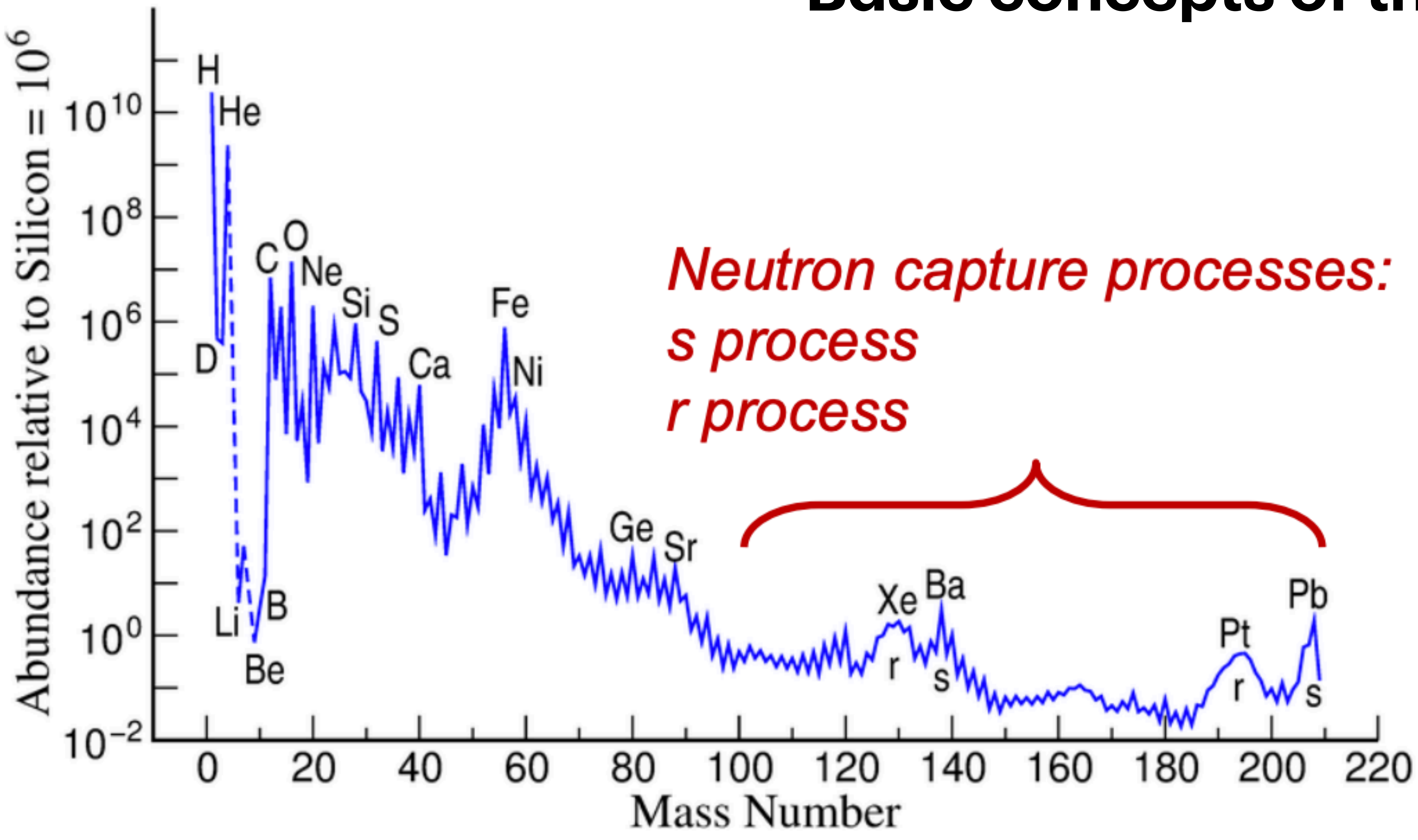
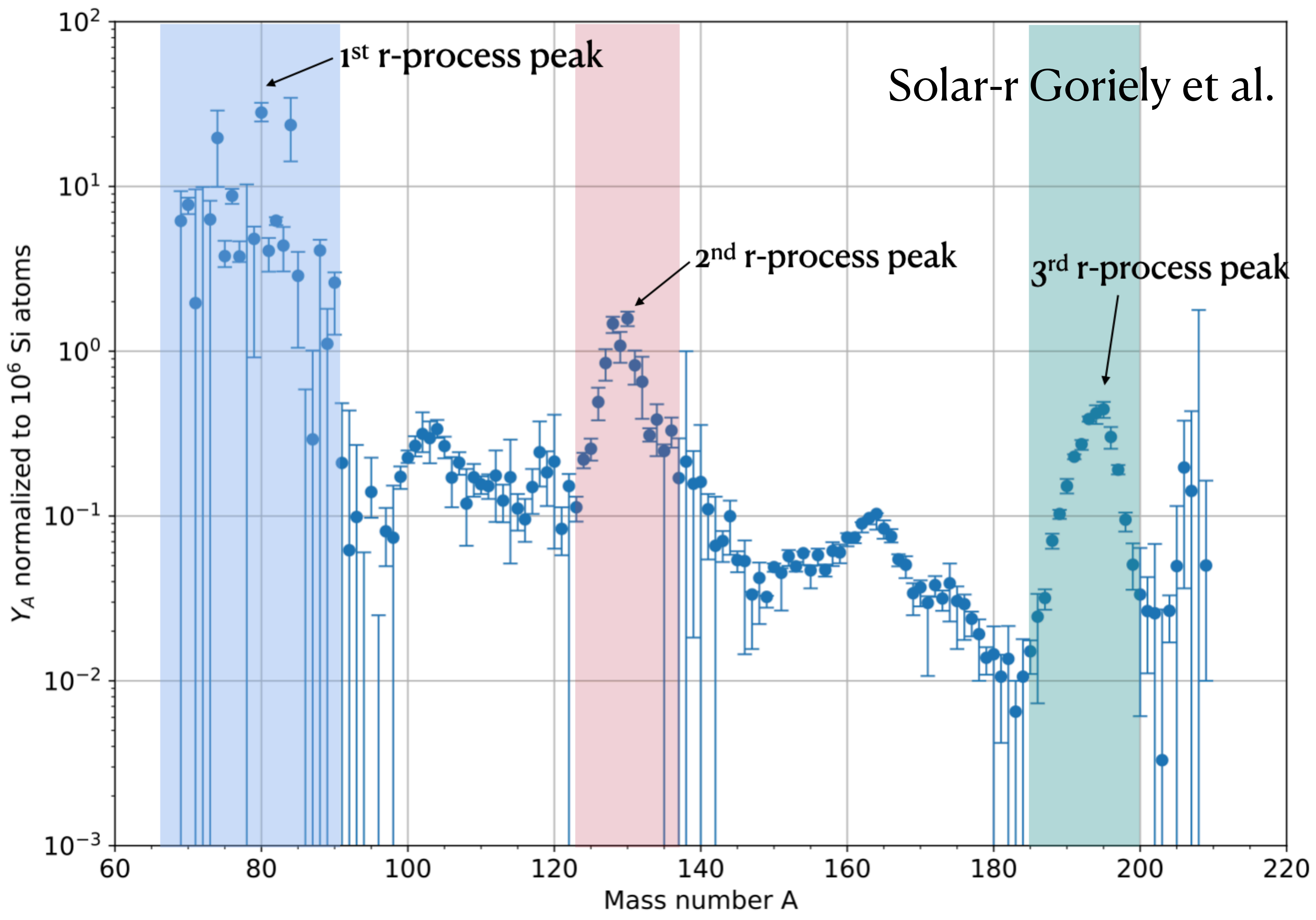




$Y_e>0.28$ $0.15<Y_e<0.28$ $Y_e<0.15$

R-process is a primal process: provides enough neutrons and the seed nuclei

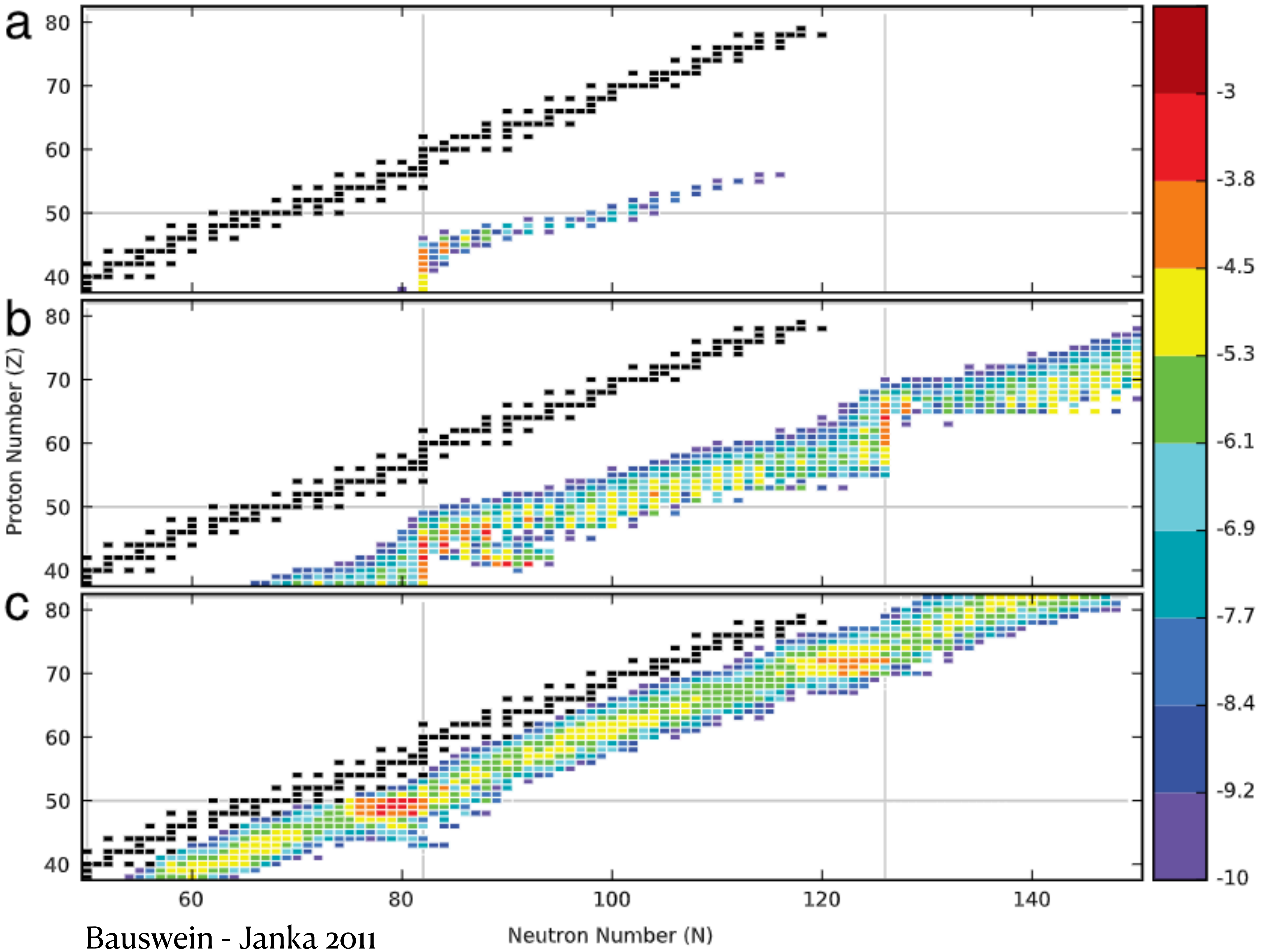
$$A_{\text{final}} = A_{\text{initial}} + n_{\text{seed}}$$

n_{seed} depends mainly on neutron richness ejecta -> Y_e

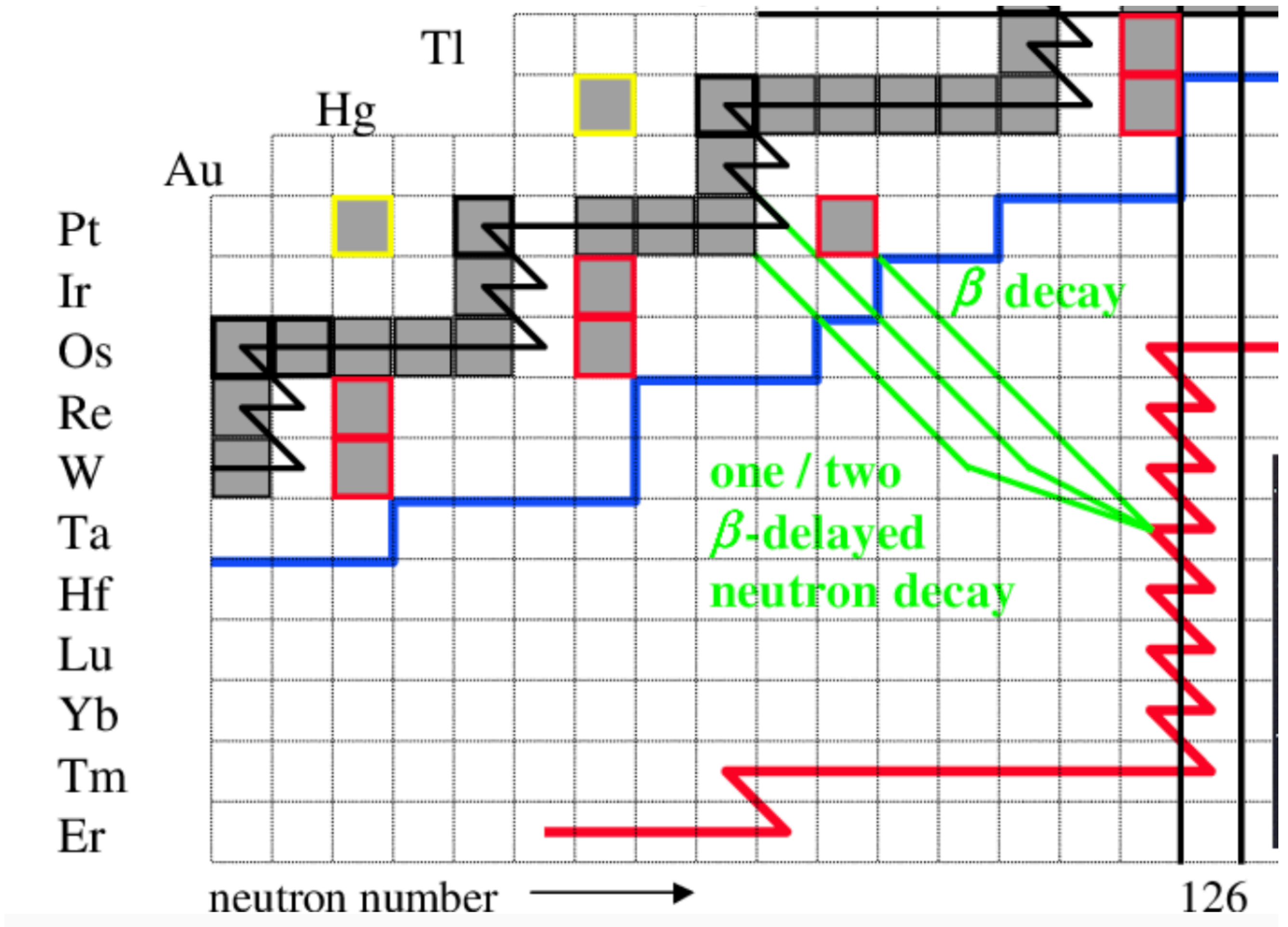
stylianos.s.nikas@jyu.fi

The r-process nucleosynthesis

Basics of the r-process



Bauswein - Janka 2011



D. Lunney 2006

The r-process modelling requires properties of exotic neutron-rich nuclei:

- **Nuclear masses**
- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

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WHY FOCUS ON MASSES?

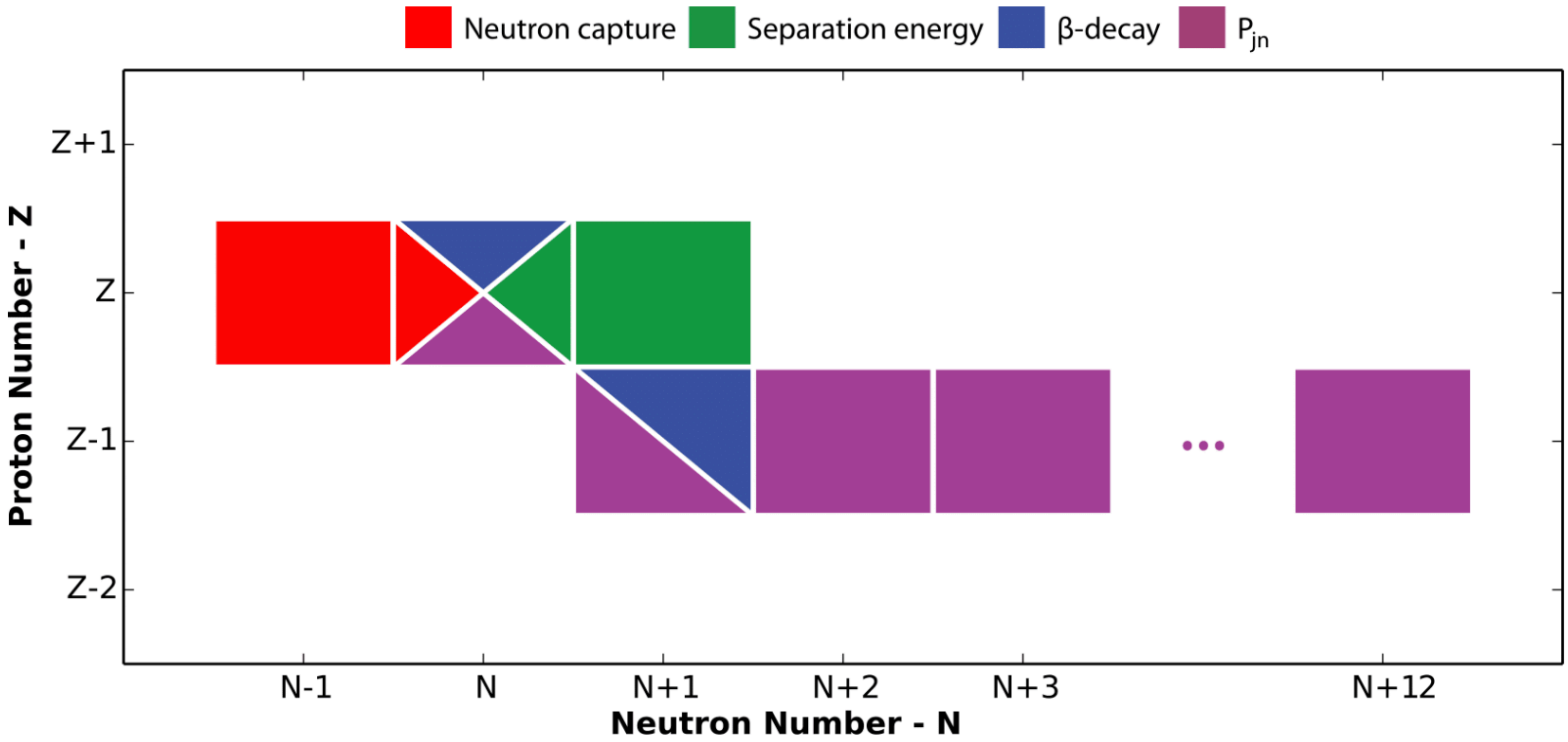


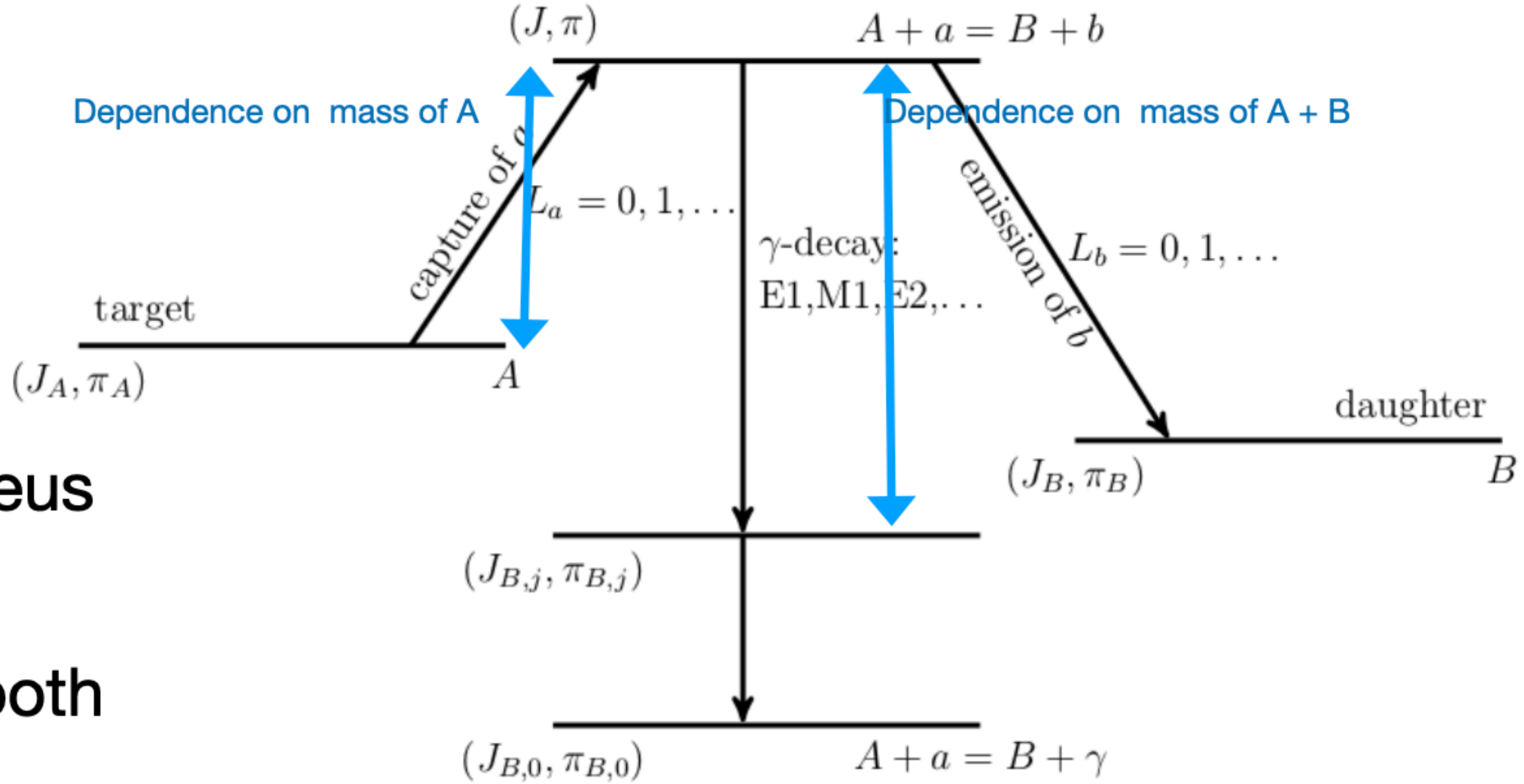
Fig. M. Mumpower

stylianos.s.nikas@jyu.fi

How nuclear masses affect an r-process calculation

Impact on the determination of (n,γ) reaction rate

$$\sigma^{\mu}_{n,\gamma} \propto \sum_{J^\pi} (2J+1) \frac{T^{\mu}_{n}(J^\pi) T_{\gamma}(J^\pi)}{T_{tot}(J^\pi)}$$



In the case of an (n,γ) reaction

- The energy of the compound nucleus depend on nuclear mass of A
- The energy of the γ-ray depends both on nuclear mass of A and B

stylianos.s.nikas@jyu.fi
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

How nuclear masses affect an r-process calculation

Impact on the determination of (γ,n) reaction rate

The inverse rate (γ,n) reaction rate can be derived from:

$$\lambda_\gamma = \left(\frac{m_u kT}{2\pi\hbar^2}\right)^{3/2} \frac{G_a G_b}{G_c} \left(\frac{A_a A_b}{A_c}\right)^{3/2} \exp(-Q/kT) \frac{\langle a, b \rangle}{1 + \delta_{ab}}.$$

whenever the population of states in parent and daughter nucleus follows a thermal distribution.

stylianos.s.nikas@jyu.fi

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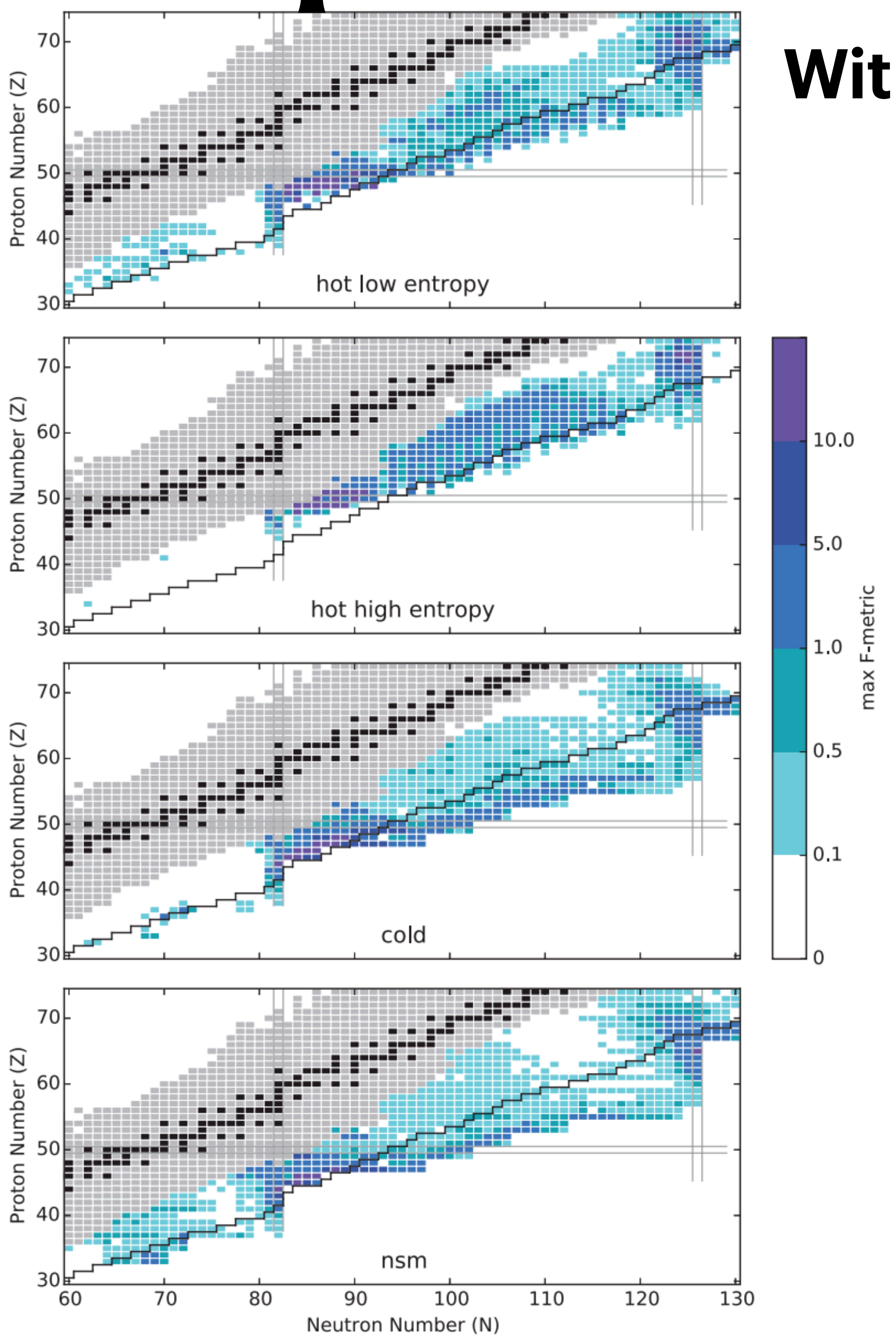
whenever the population of states in parent and daughter nucleus follows a thermal distribution.

There is an exponential dependence on the Q values

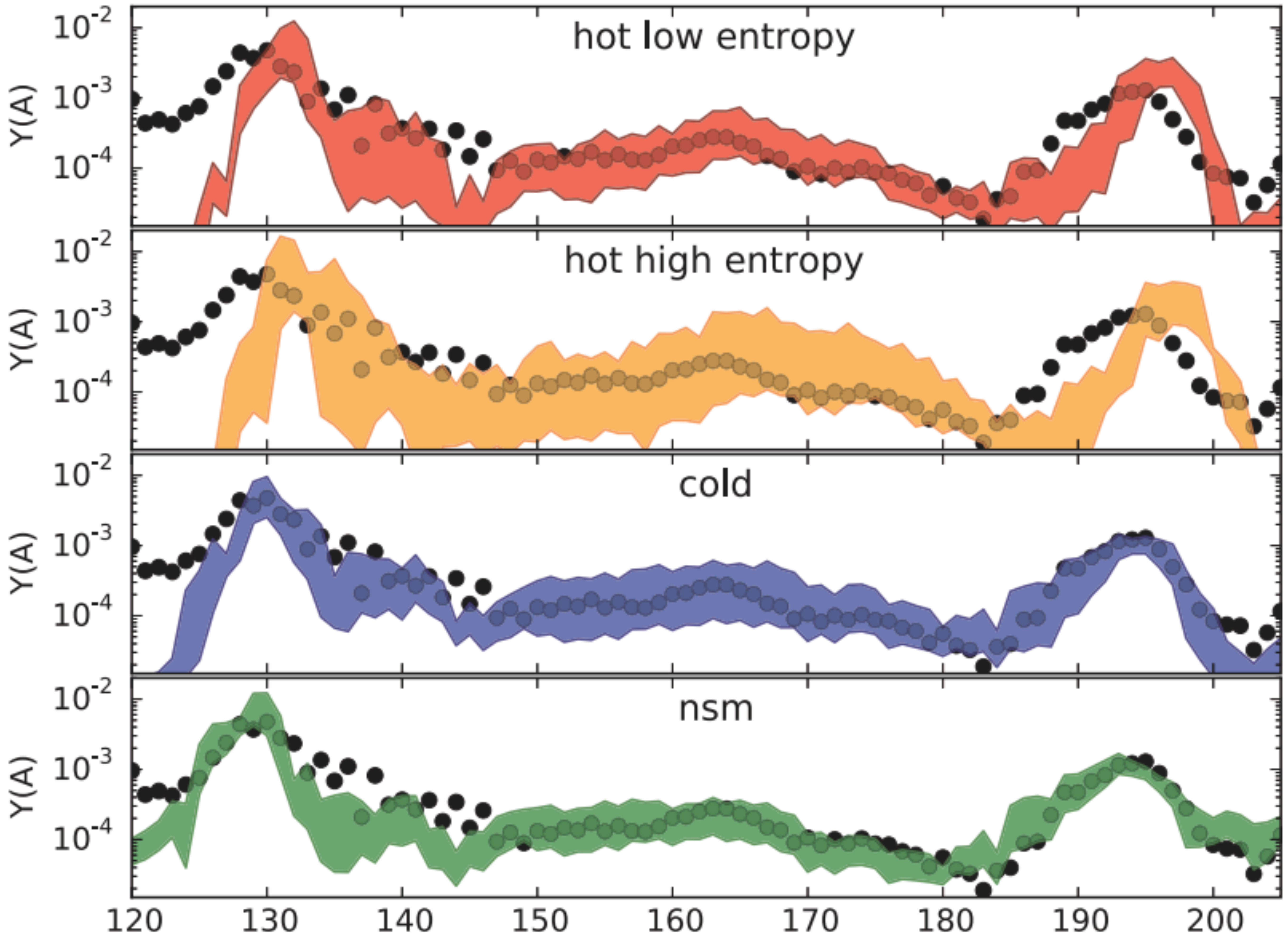
stylianos.s.nikas@jyu.fi

Impact of mass uncertainties to the r-process



Without precision mass measurements

M. R. Mumpower 2014



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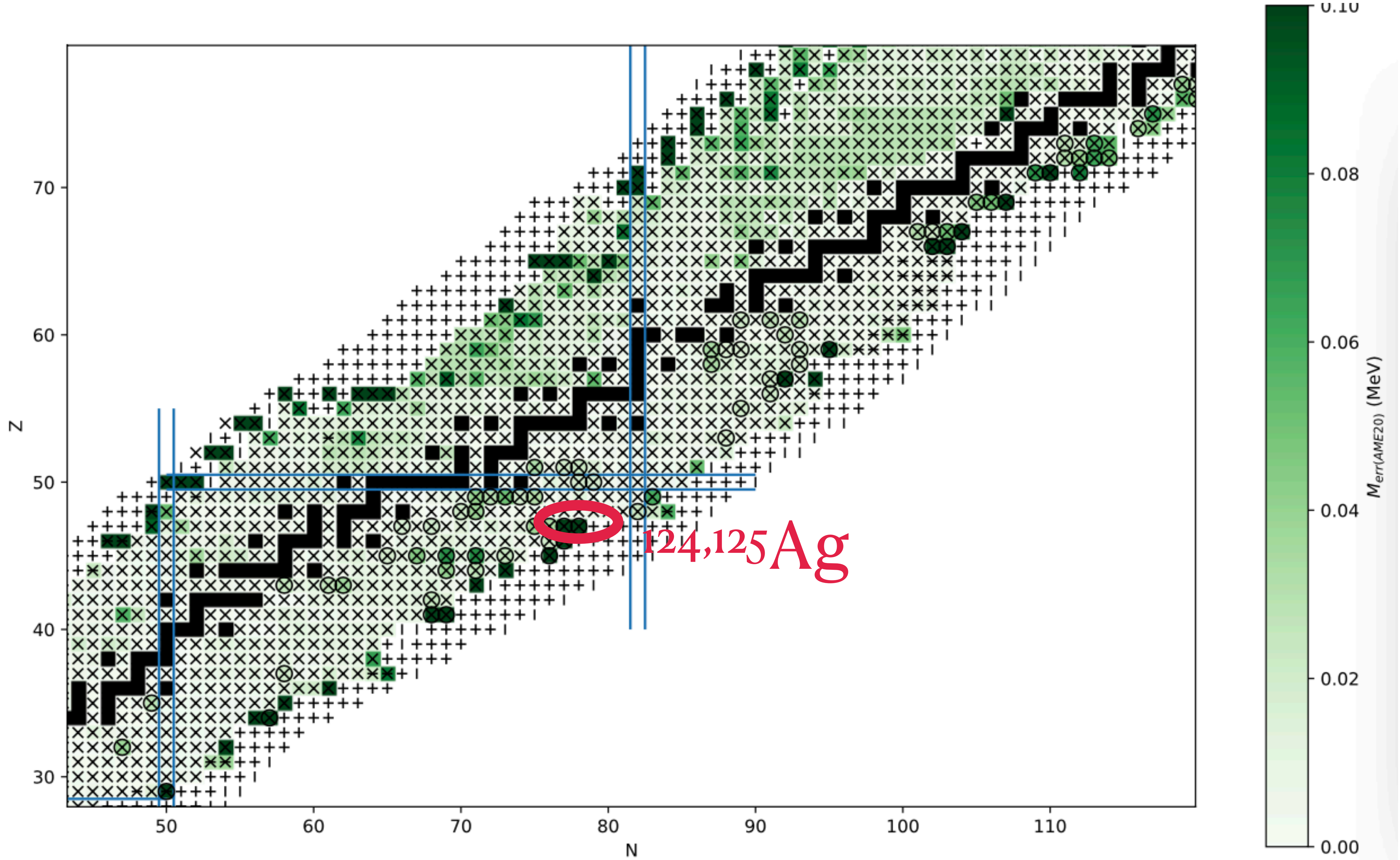
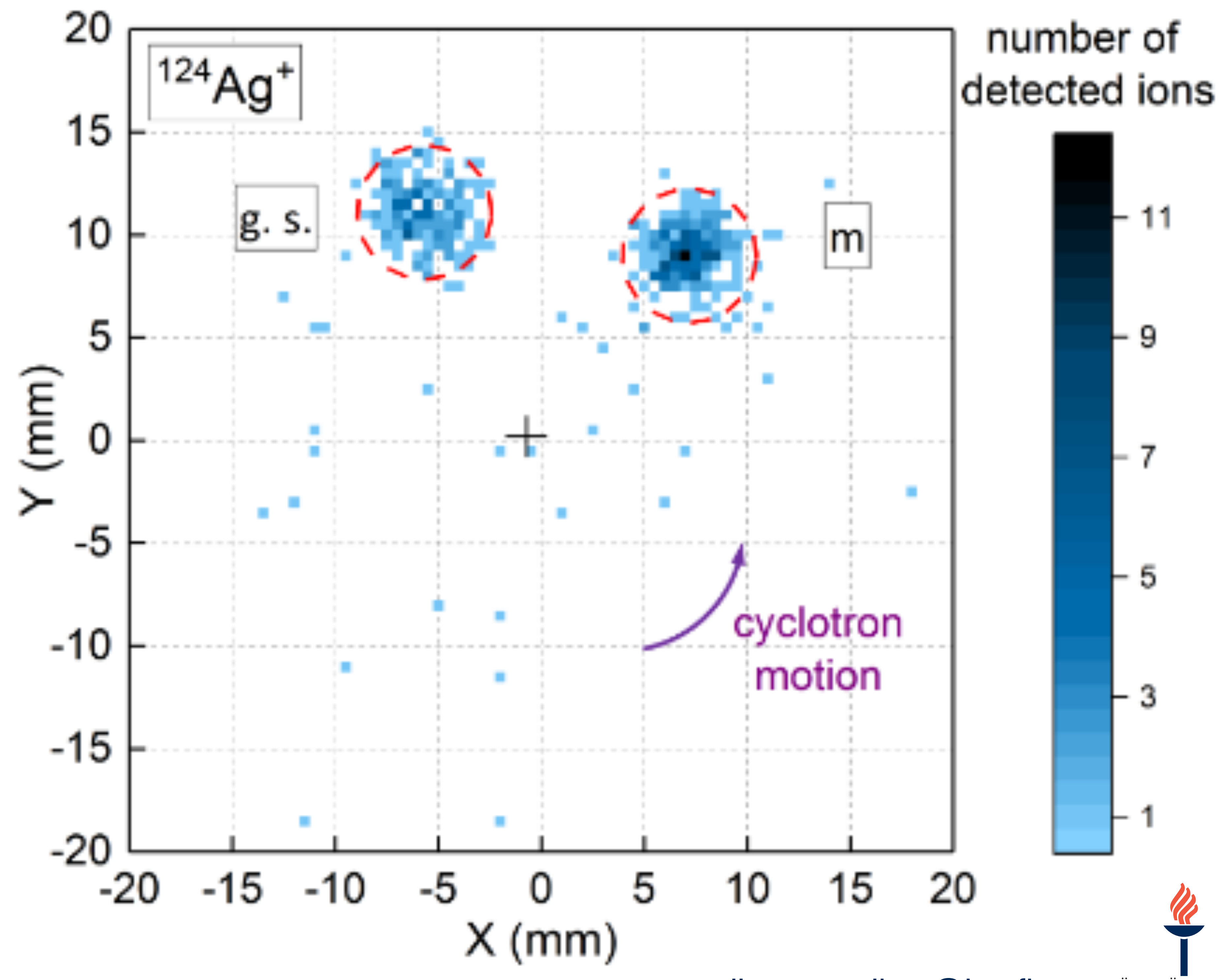
Nuclear masses

Current state of known nuclear masses

Experimentally known masses can have uncertainties of more than 100 keV

There can be cases where the isomeric state and ground state determination was not clear





stylianos.s.nikas@jyu.fi

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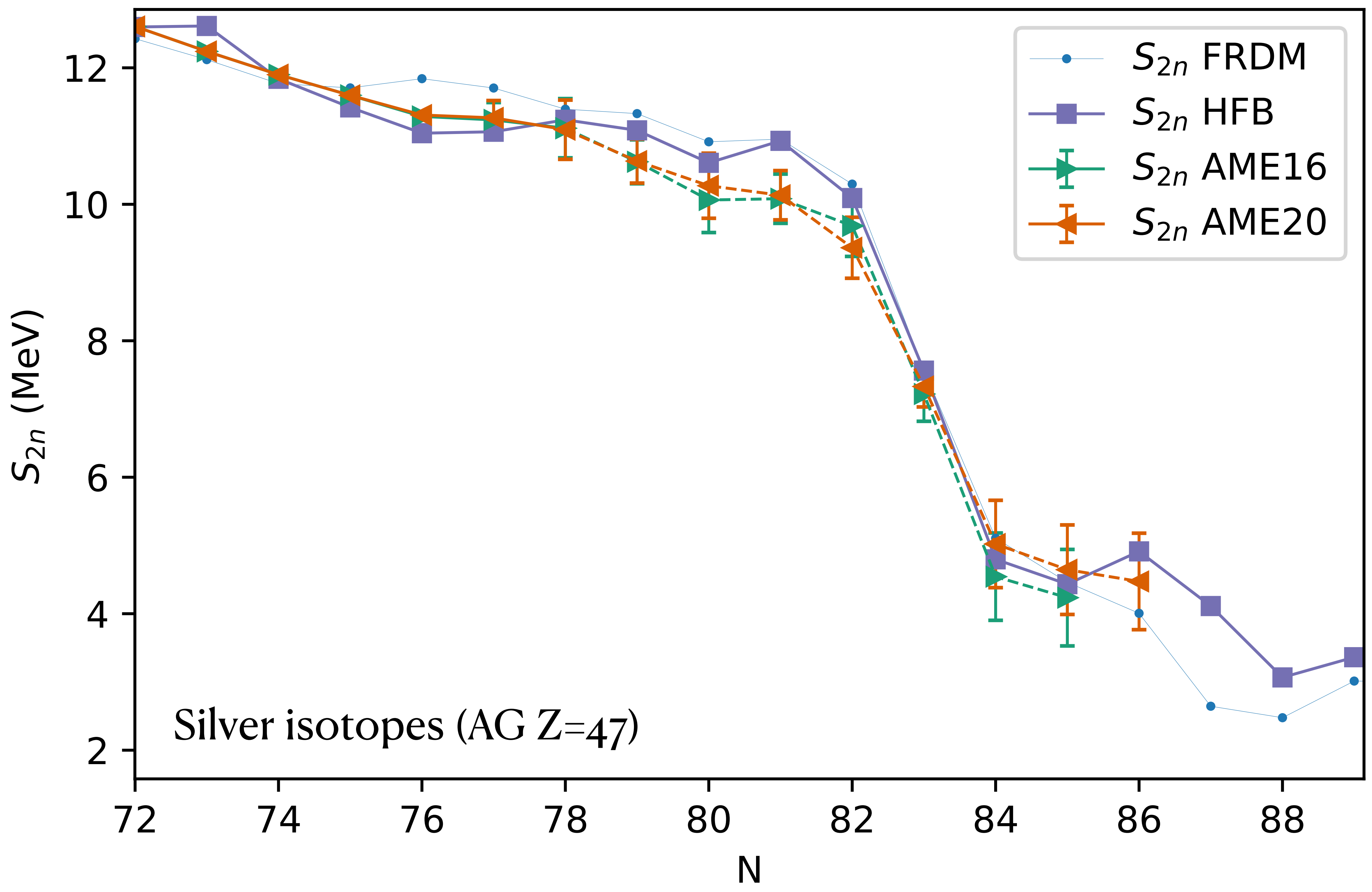
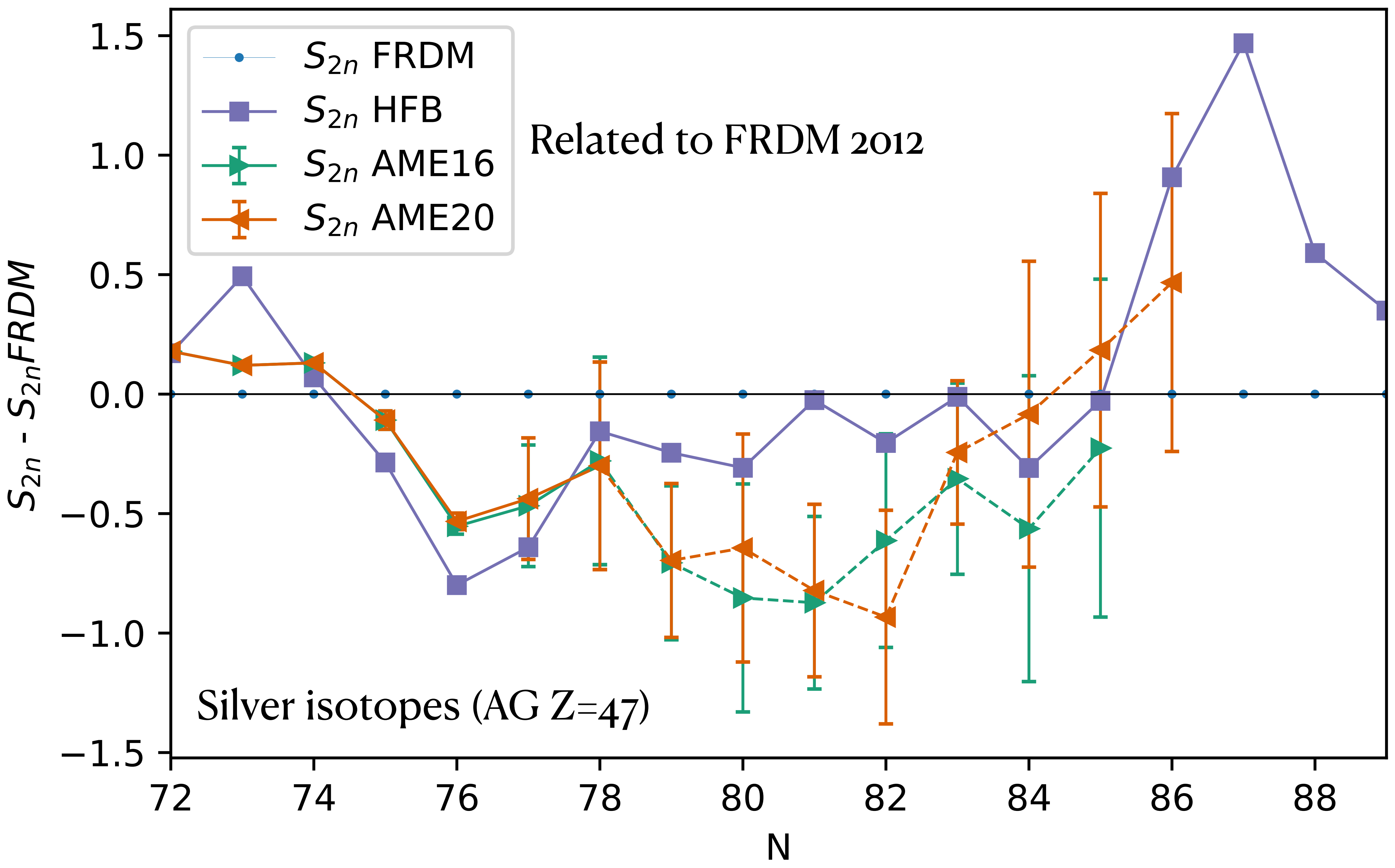
Nuclear masses

Model predictions away from stability

Changes between 0.5-1.5 MeV between models and experiment & extrapolations + large error bars (0.2-0.5 MeV)





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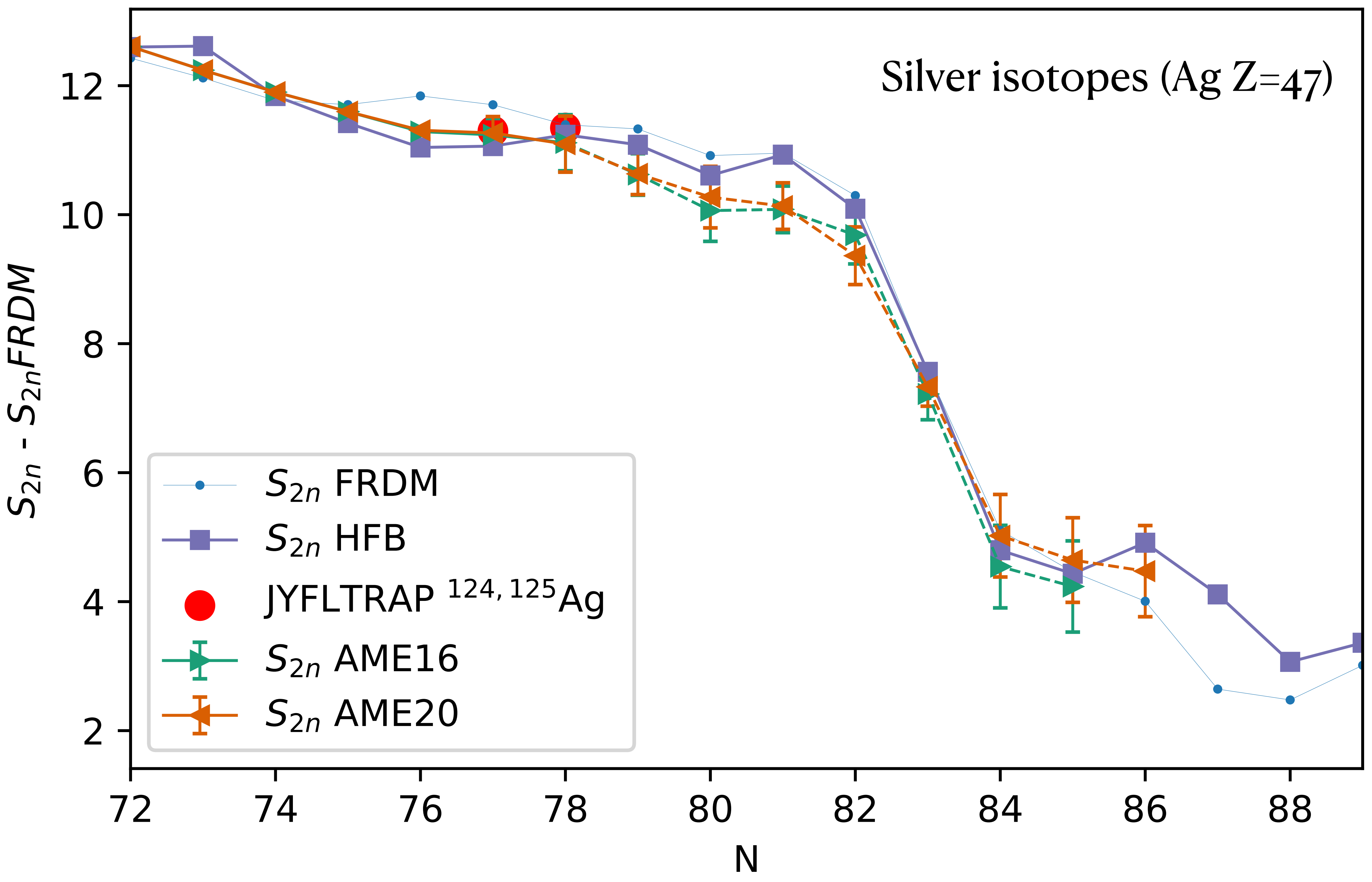
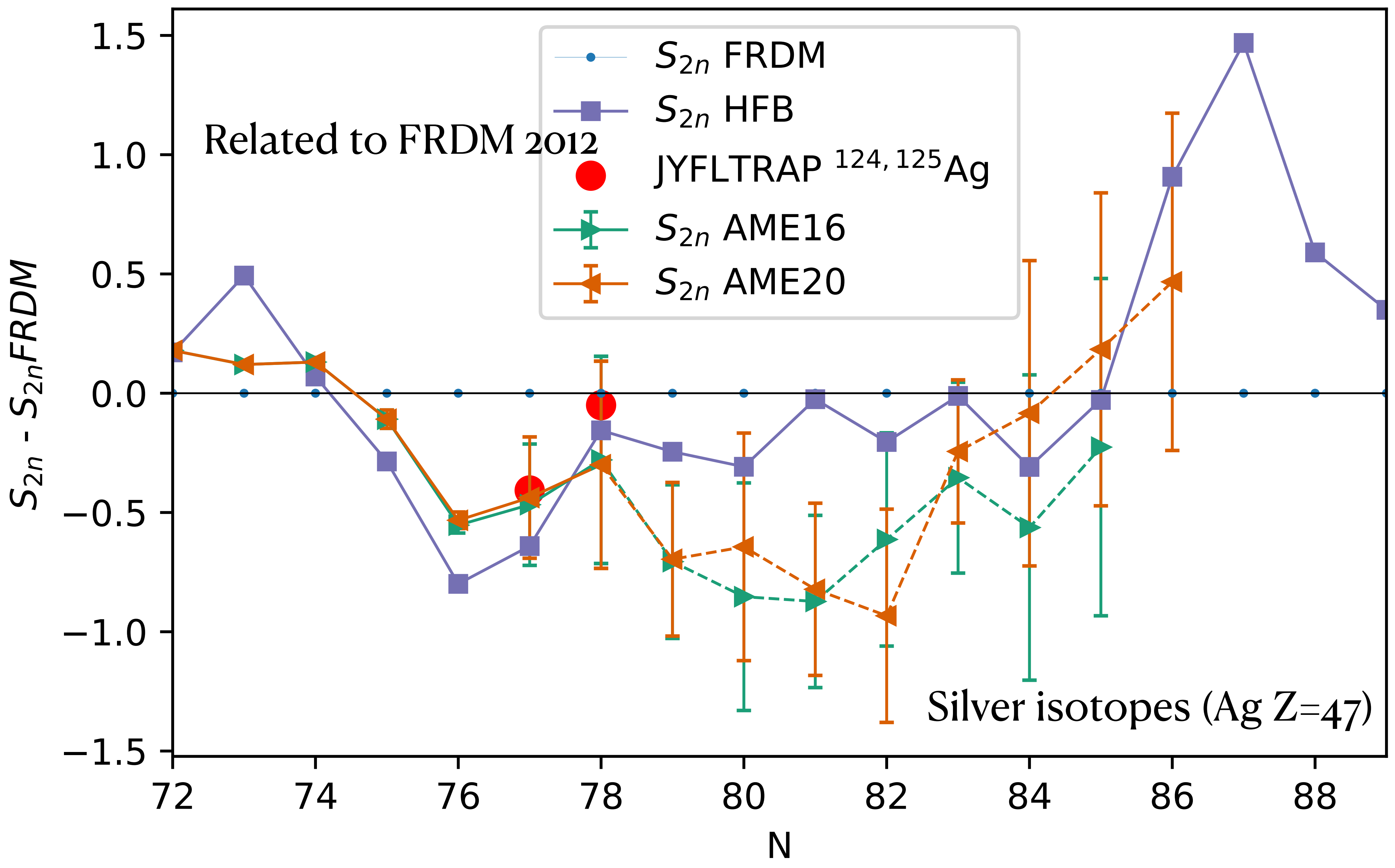
Nuclear masses

Model predictions away from stability

Changes between 0.5-1.5 MeV between models and experiment & extrapolations + large error bars (0.2-0.5 MeV)





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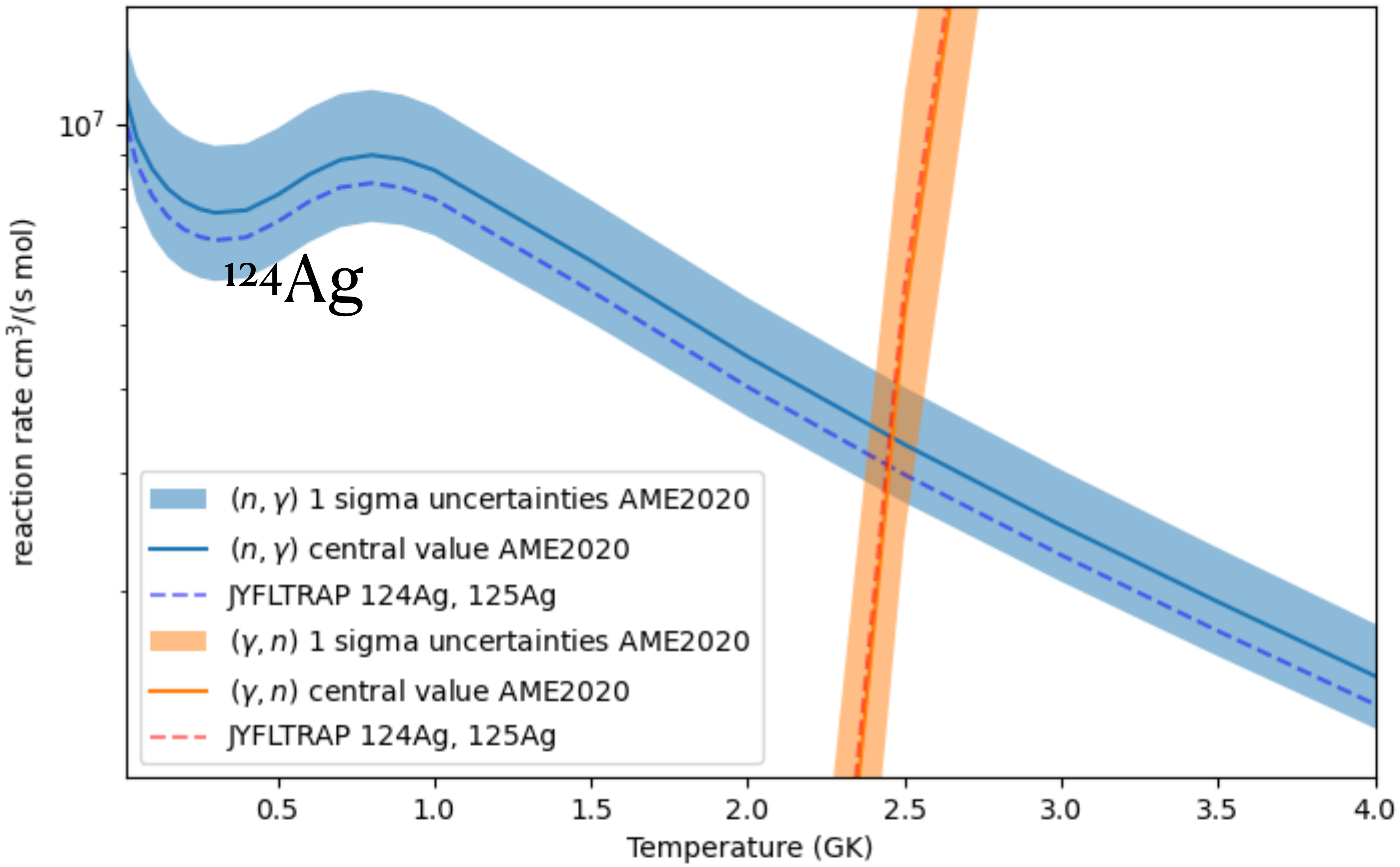
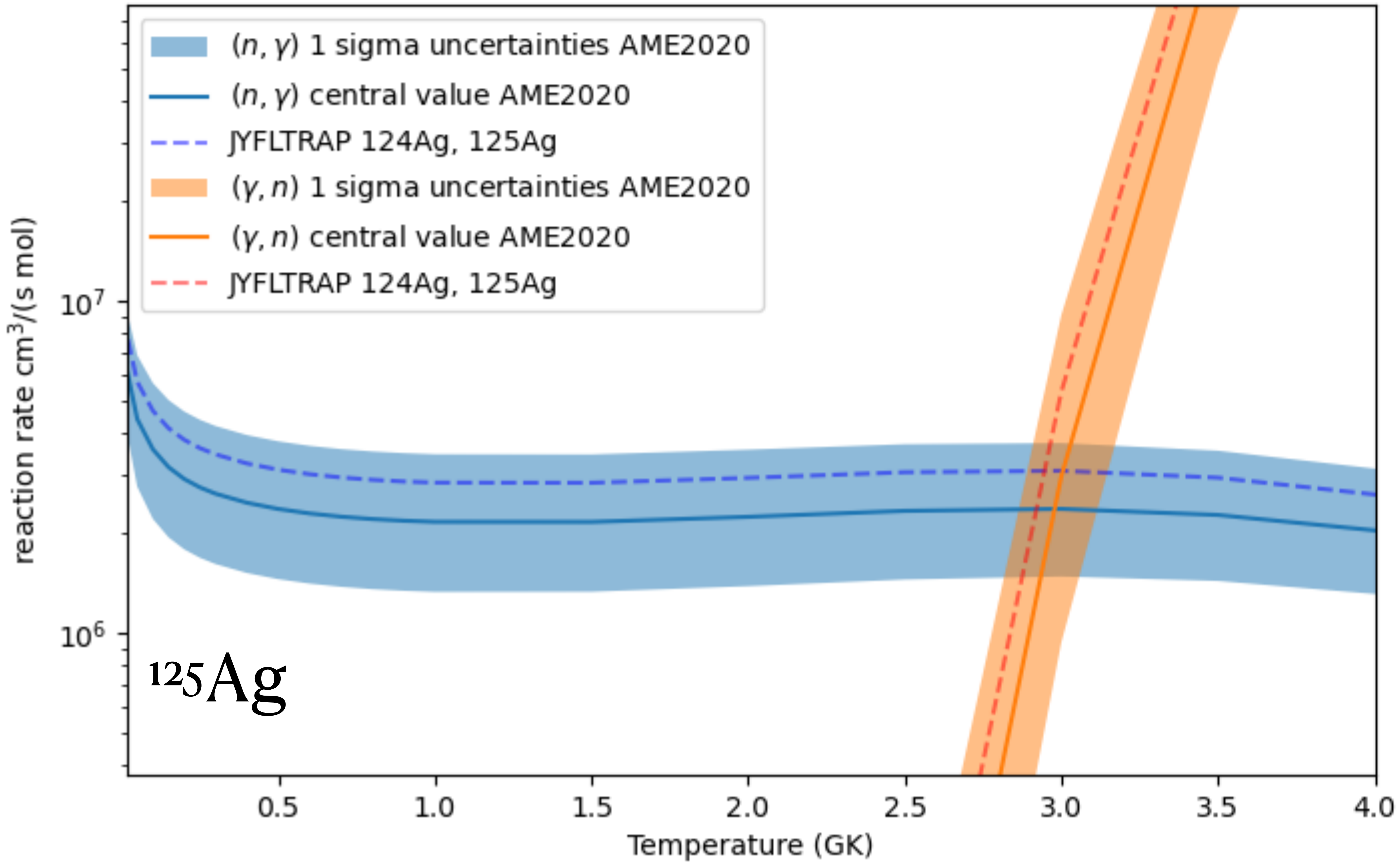
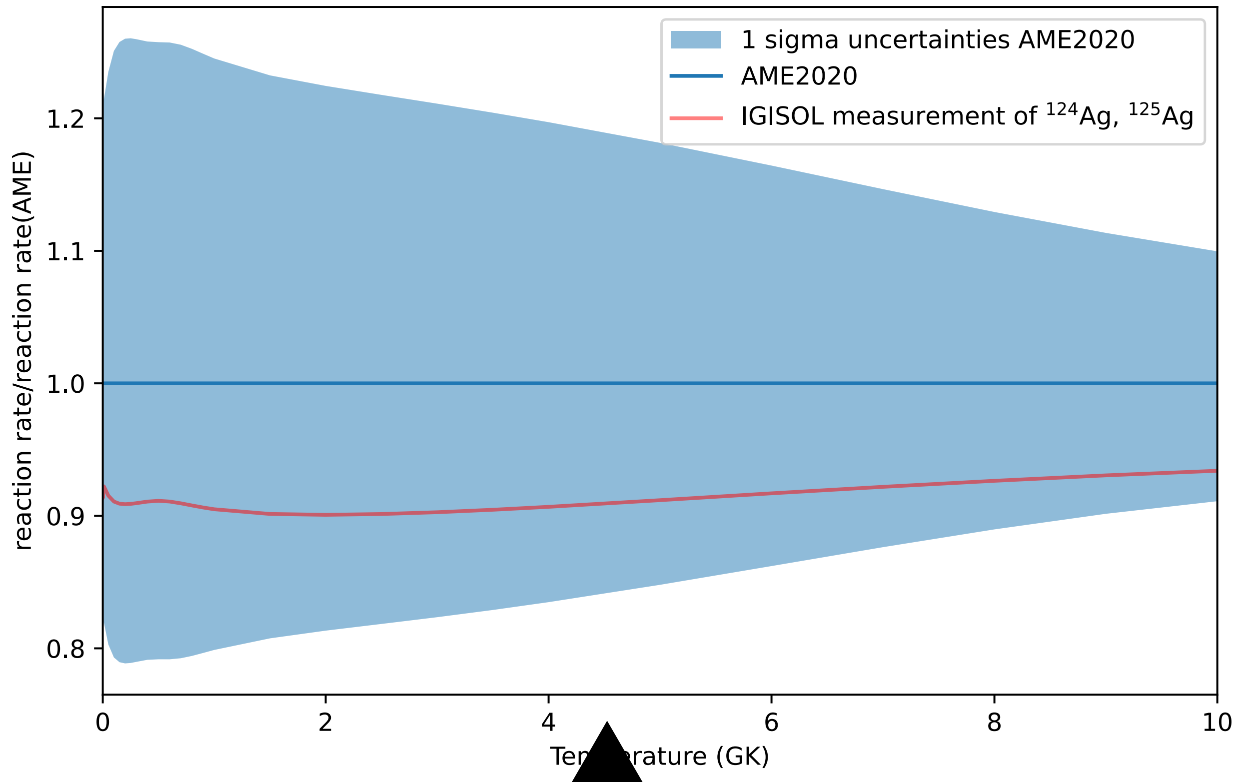
Impact in the calculation of reaction rates



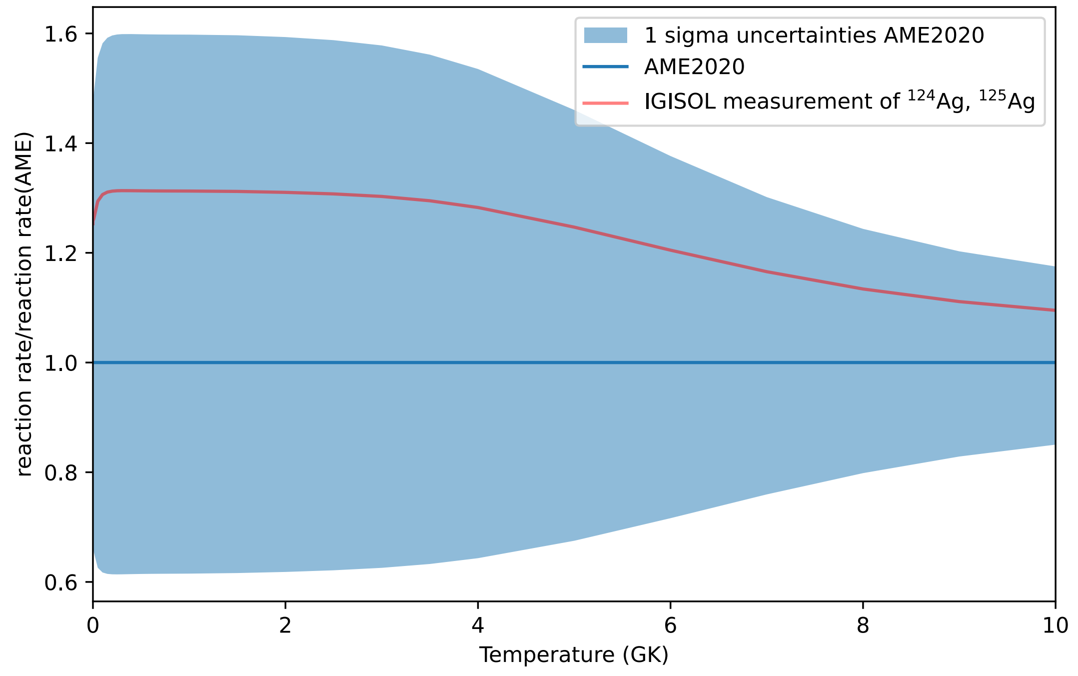


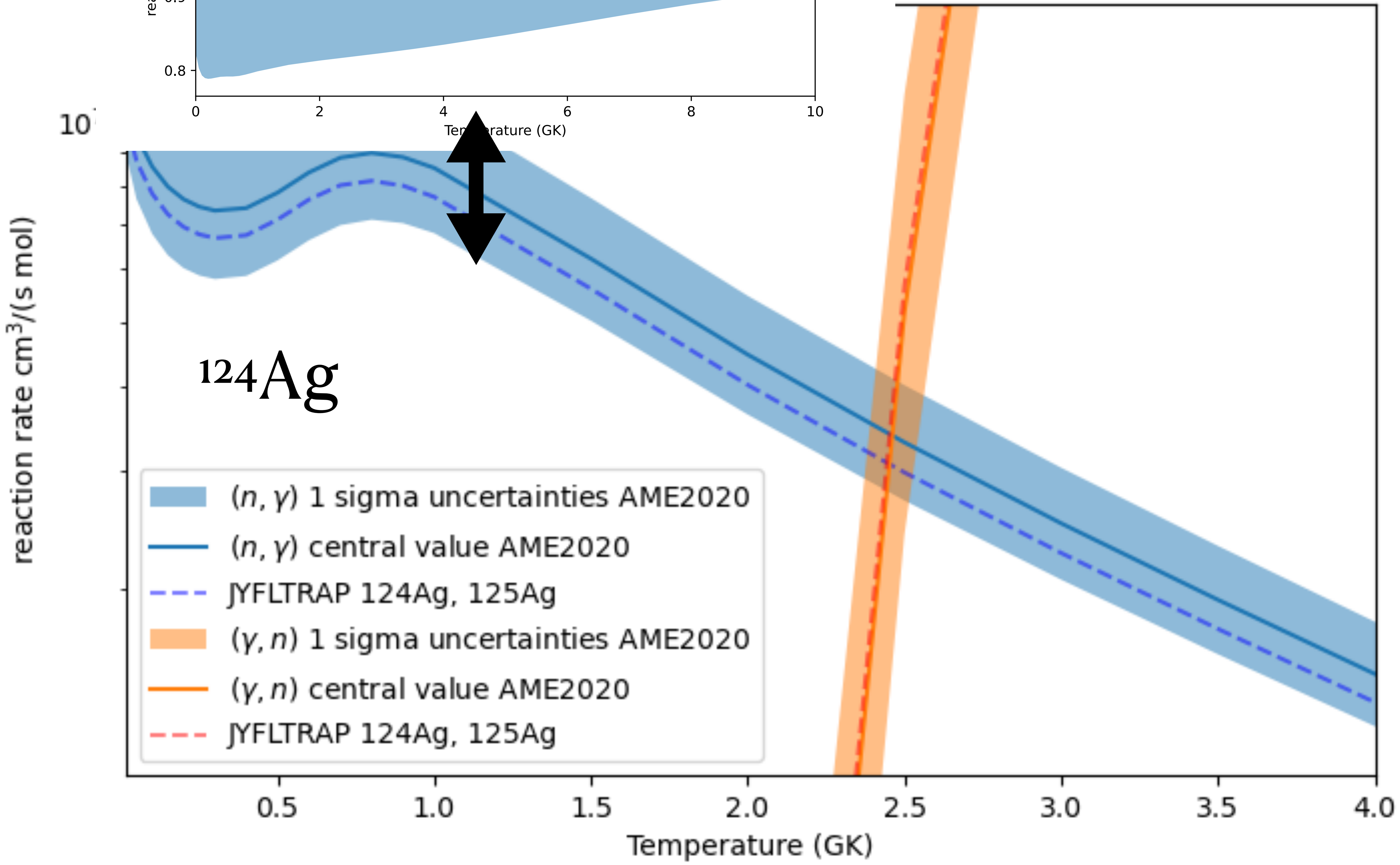
stylianos.s.nikas@jyu.fi

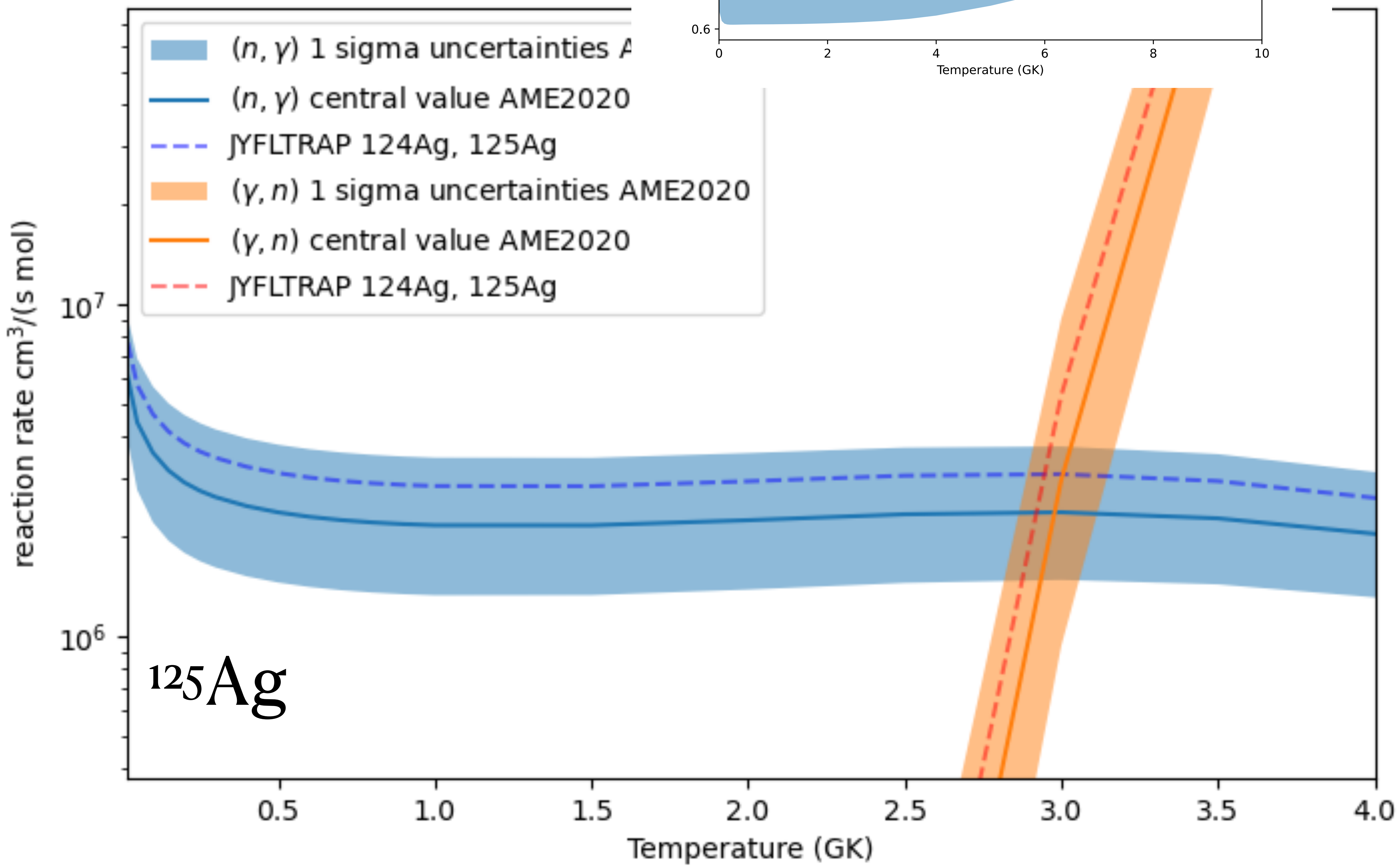
Impact in the calculation of reaction rates



Up to a factor of 5 uncertainty in the reaction rates, due to the mass uncertainties of ^{124,125}Ag. 10-20% difference between central values.
Main advantage of the new measurements is the drastic reduction of the error bars







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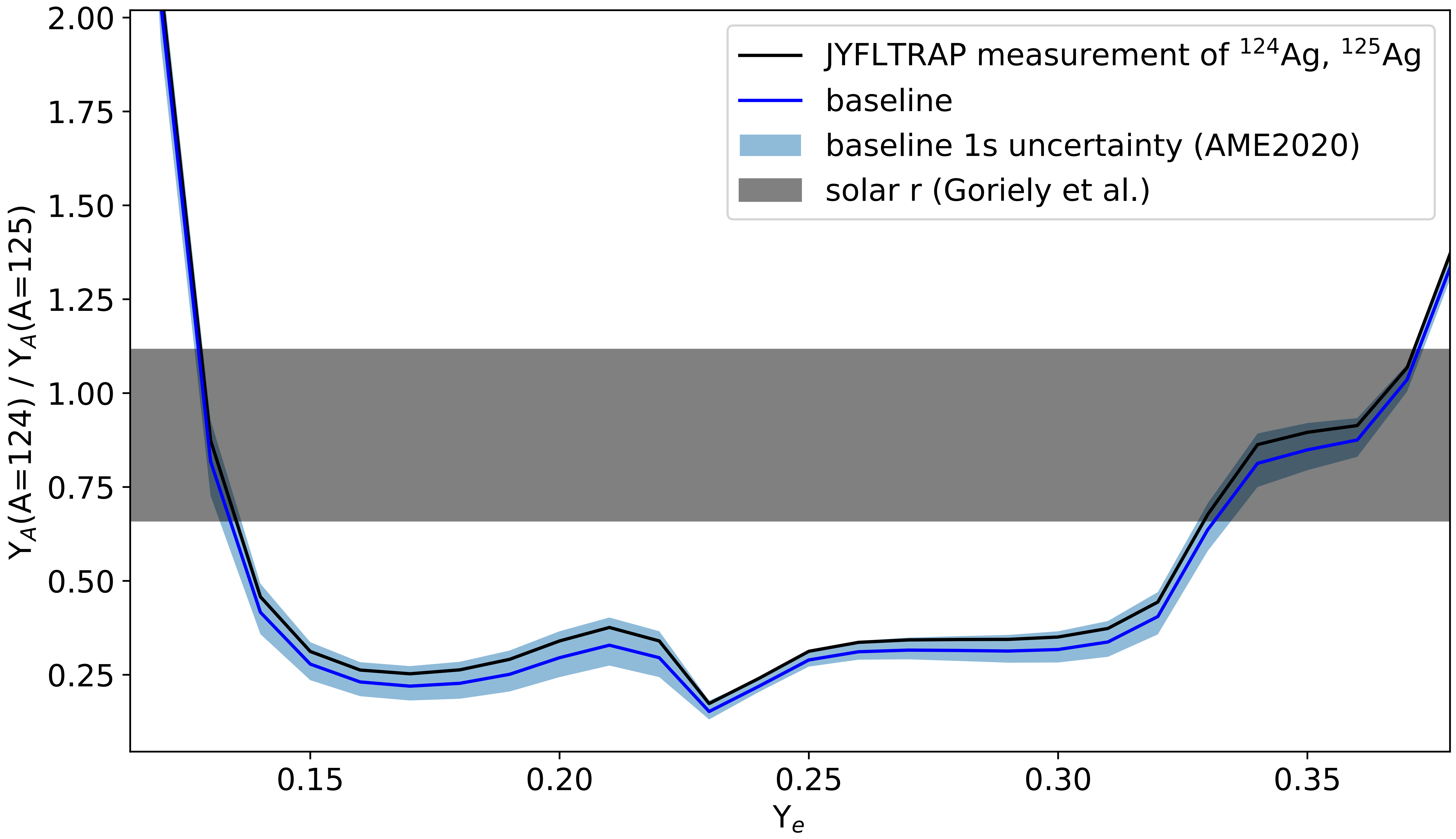
Impact on the calculated abundance pattern

- The error bars are drastically reduced (not visible in this plot) due to the low uncertainty of the new mass measurements



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Impact on the calculated abundance pattern

PHYSICAL REVIEW LETTERS 128, 152701 (2022)

First Application of Mass Measurements with the Rare-RI Ring Reveals the Solar *r*-Process Abundance Trend at $A = 122$ and $A = 123$

H. F. Li,[1,2,3,4] S. Naimi,[3,*] T. M. Sprouse,[5] M. R. Mumpower,[5] Y. Abe,[3] Y. Yamaguchi,[3] D. Nagae,[3,†] F. Suzaki,[3,‡] M. Wakasugi,[3] H. Arakawa,[6] W. B. Dou,[6] D. Hamakawa,[6] S. Hosoi,[6] Y. Inada,[6] D. Kajiki,[6] T. Kobayashi,[6] M. Sakaue,[6] Y. Yokoda,[6] T. Yamaguchi,[6] R. Kagesawa,[7] D. Kamioka,[7] T. Moriguchi,[7] M. Mukai,[7,§] A. Ozawa,[7] S. Ota,[8,∥] N. Kitamura,[8] S. Masuoka,[8] S. Michimasa,[8] H. Baba,[3] N. Fukuda,[3] Y. Shimizu,[3] H. Suzuki,[3] H. Takeda,[3] D. S. Ahn,[3,9] M. Wang,[1] C. Y. Fu,[1] Q. Wang,[1] S. Suzuki,[1] Z. Ge,[1,¶] Yu. A. Litvinov,[10] G. Lorusso,[11,12] P. M. Walker,[12] Zs. Podolyak,[12] and T. Uesaka[3]

[1]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*
[2]*Lanzhou University, Lanzhou 730000, People's Republic of China*
[3]*Riken Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan*
[4]*University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[5]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[6]*Department of Physics, Saitama University, Saitama 338-8570, Japan*
[7]*Institute of Physics, University of Tsukuba, Ibaraki 305-8571, Japan*
[8]*Center for Nuclear Study, University of Tokyo, Wako, Saitama 351-0198, Japan*
[9]*Center for Exotic Nuclear Studies, Institute for Basic Science (IBS), Daejeon 34126, Republic of Korea*
[10]*GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany*
[11]*National Physical Laboratory, Teddington, TW11 0LW, United Kingdom*
[12]*Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*

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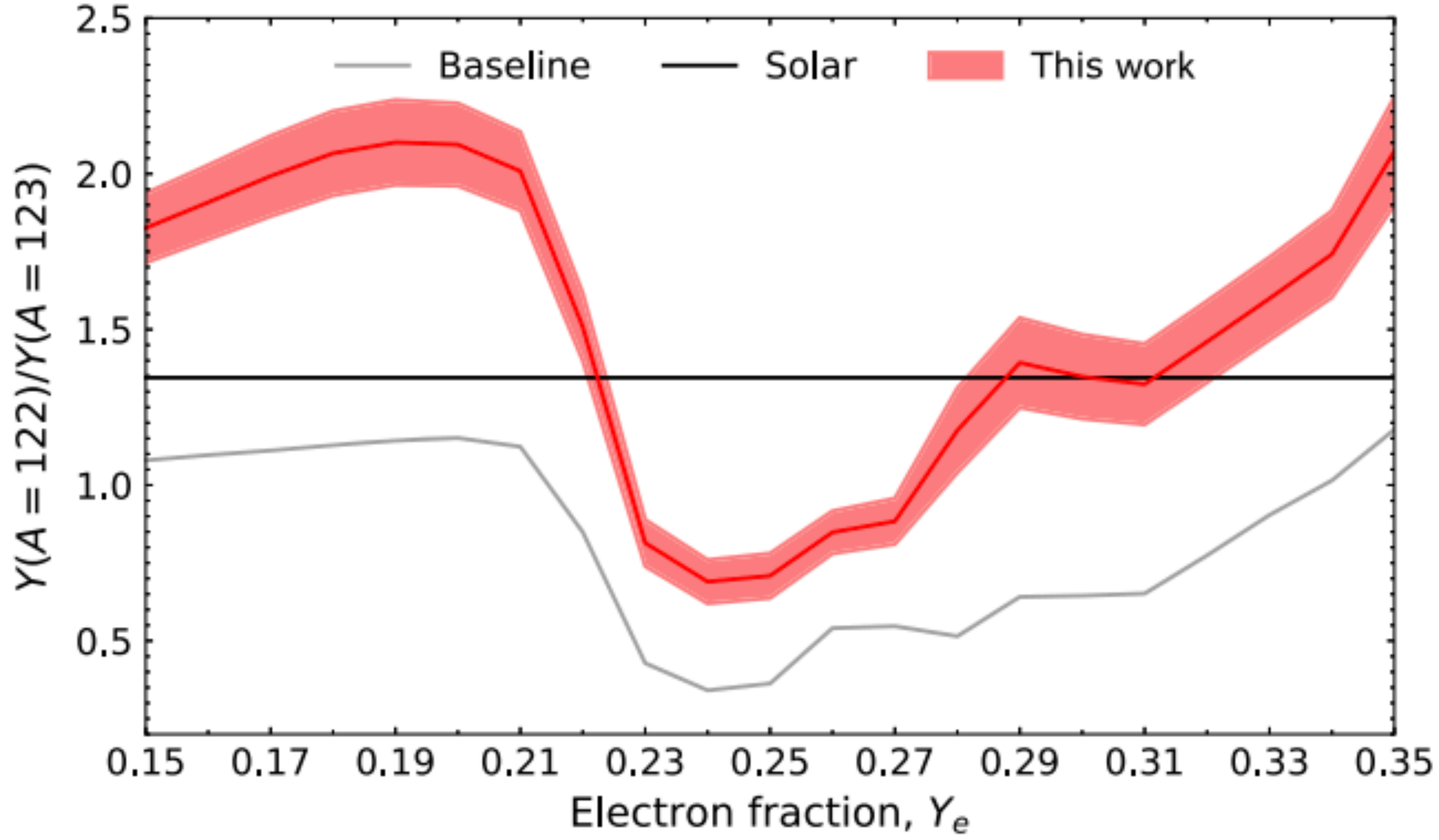

^{124}Ag was used as a reference isotope for the measurements of the masses of ^{126}In, ^{125}Cd and ^{123}Pd

These can now be redetermined with a better precision.

AME2020 mass and uncertainty of ^{124}Ag (KeV)

124 Ag -66229.951 251.503 124

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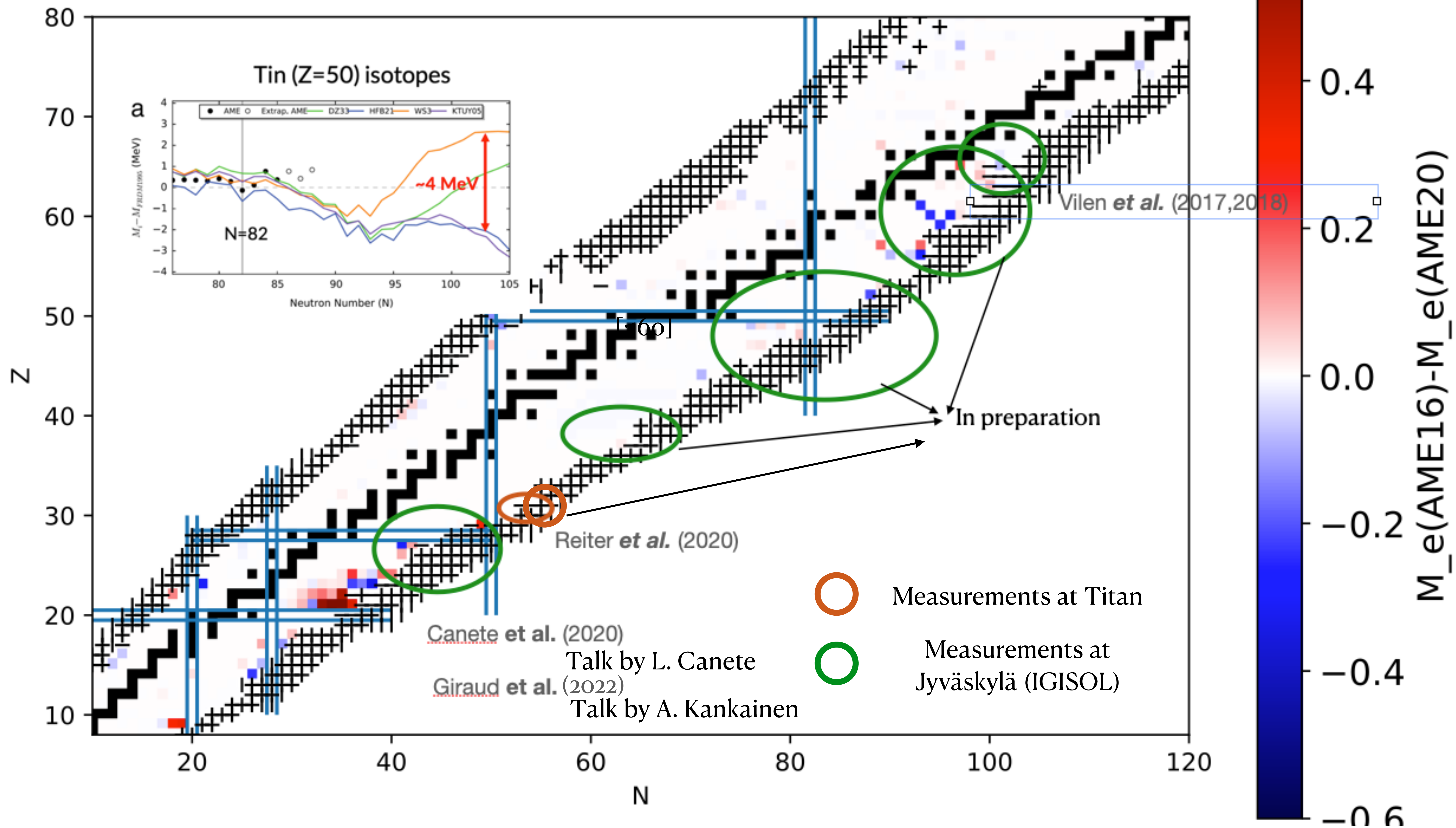
The grand picture



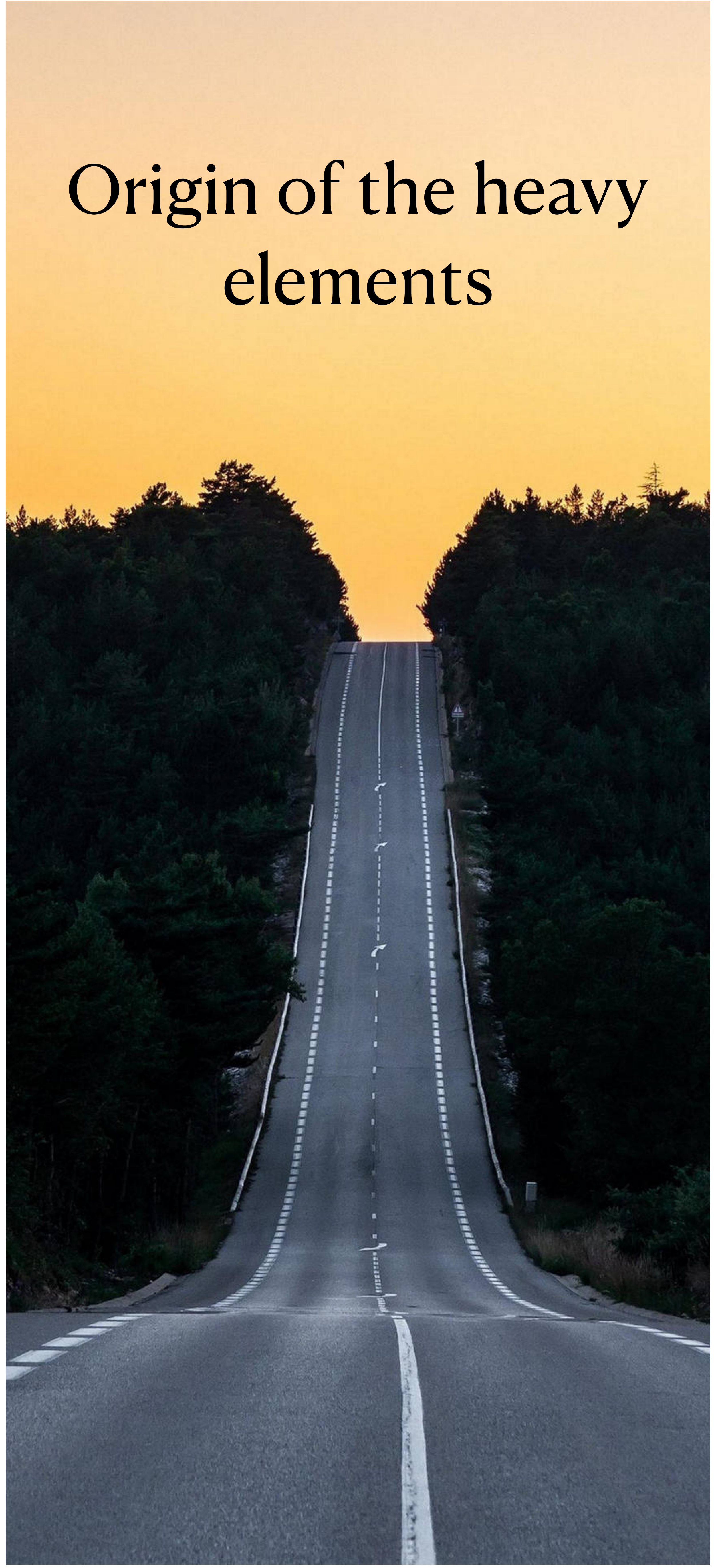
Stylianos Nikas - JYU, Nuclear Physics in Astrophysics X Tuesday 6 September 2022, CERN Geneva
stylianos.s.nikas@jyu.fi
JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ

Summary

- Precision mass measurements are essential to model neutron capture reaction rates for nuclear reaction networks.
- Even previously measured masses may have large uncertainties (>100KeV).
- The measurements of $^{124,125}Ag$ drastically reduce the error bars present in AME2020.
- We can use the new measurement of the reference isotope of ^{124}Ag to redetermine the measurements of the masses of ^{126}In, ^{125}Cd and ^{123}Pd with better accuracy.
- We explored the impact of the new measurement to the calculation of reaction rates finding up to 20% change relative to AME2020 and drastic reduction of the reaction rate uncertainty.
- We studied sensitivity of the r-process abundances to the new masses finding changes to the abundance pattern up to 10%

stylianos.s.nikas@jyu.fi

Origin of the heavy elements



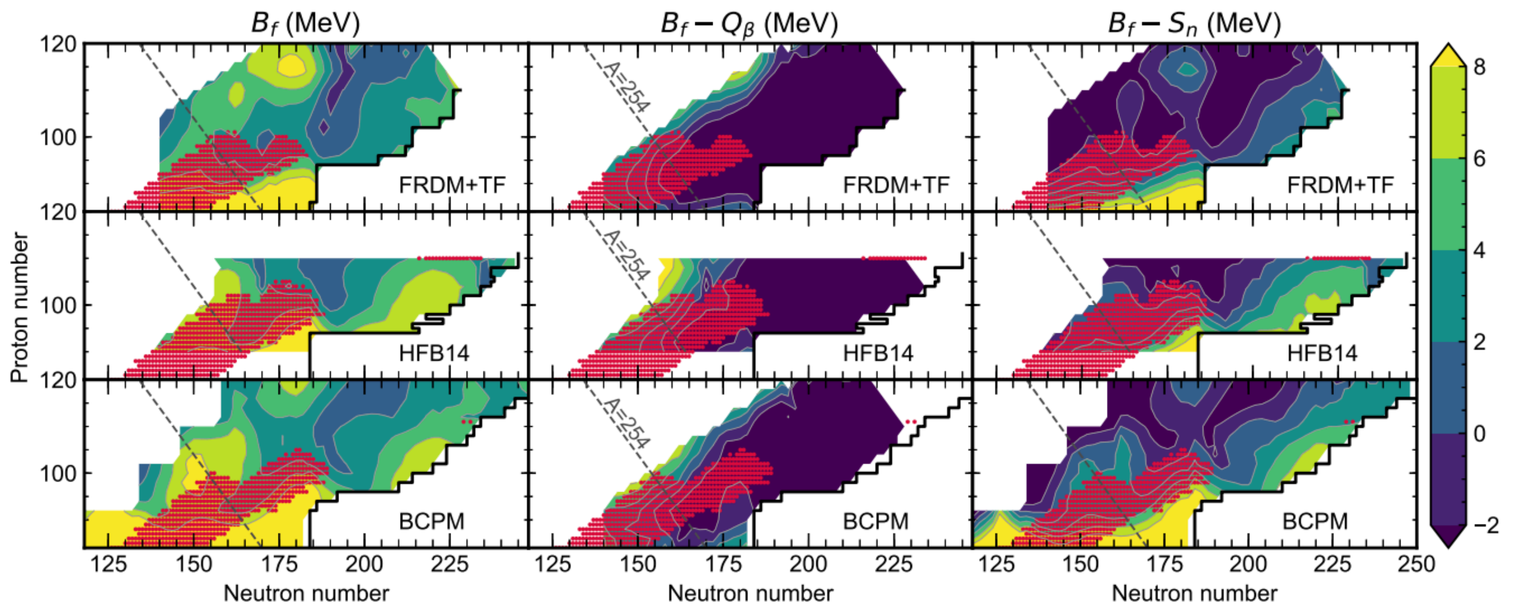
What else is needed

Observables/kilonova

Talk by Gabriel Martínez-Pinedo, Brian Metzger

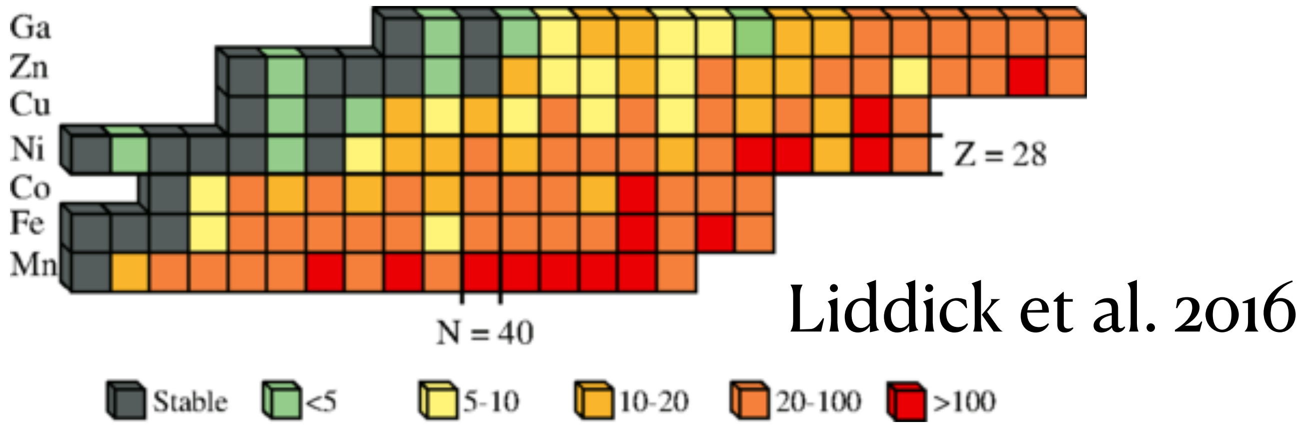
Fission yields, and fission barriers

Giuliani et al. 2020



Neutron capture rates

Talk by Artemis Spyrou, Dennis Muecher



Liddick et al. 2016

Isomeric states

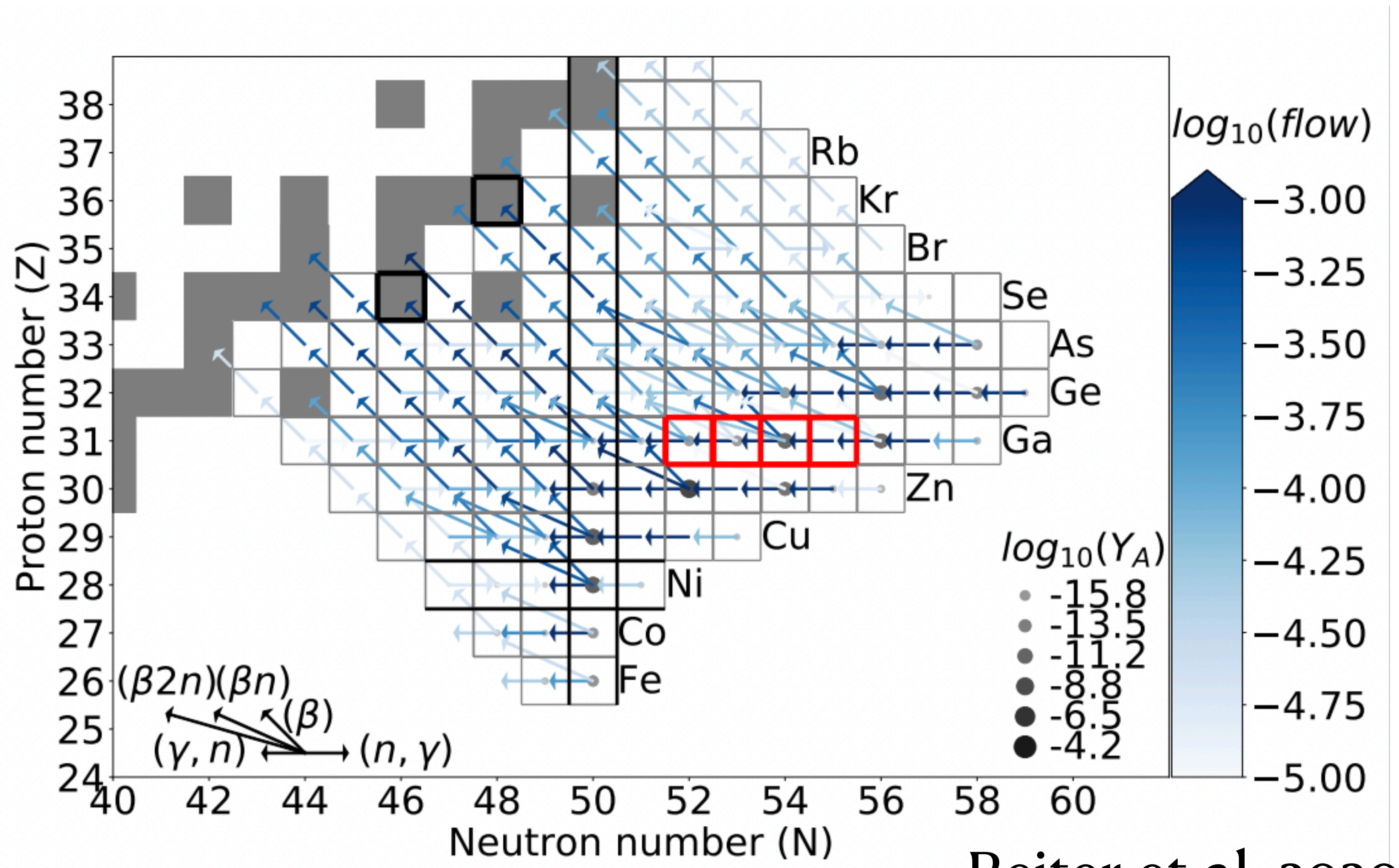
Nuclear masses

Talk byAnu Kankainen

beta delayed neutron emission

beta decay rates

Talk by Alvaro Tolosa Delgado



Reiter et al. 2020

Thank you for your attention

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Gabriel Martínez-Pinedo

University of Edinburgh

Moritz Pascal Reiter

TRIUMF

Andrew Jacobs

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

TECHNISCHE UNIVERSITÄT DARMSTADT

GSI

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stylianos.s.nikas@jyu.fi