

Effect of β -decay on the *r*-process dynamics

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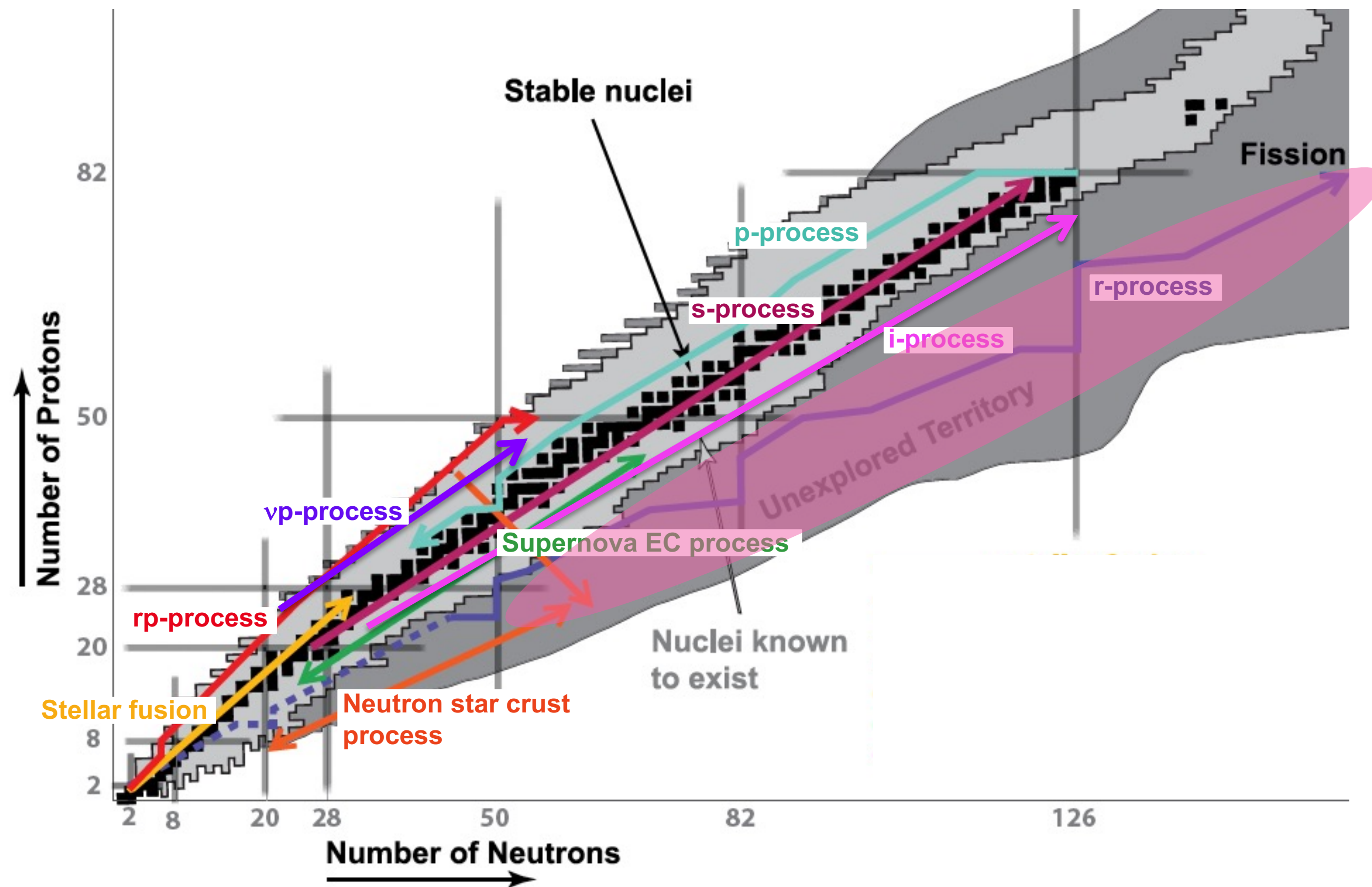
FRIB TA Topical Program

2025-09-18



Rapid neutron capture process (*r*-process)

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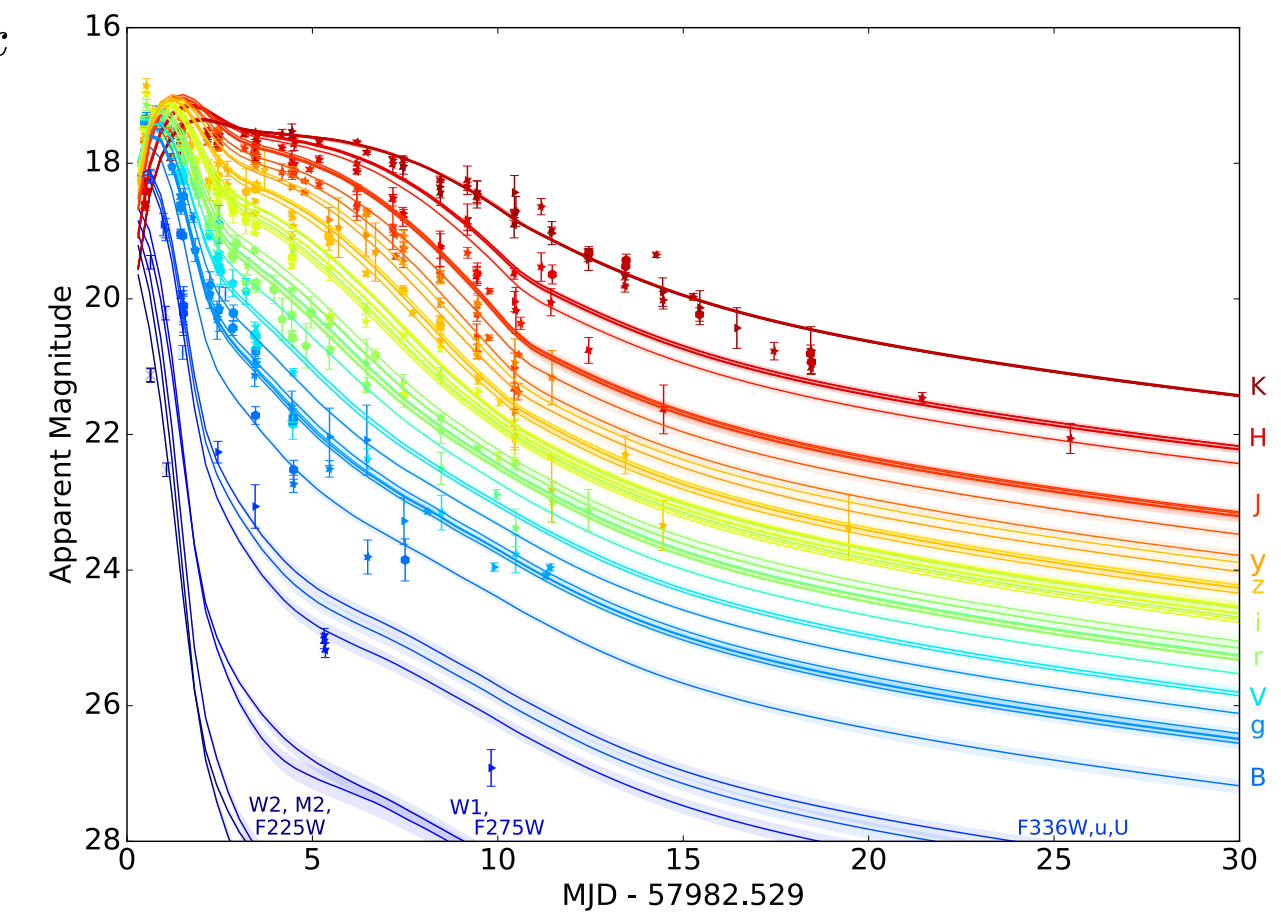
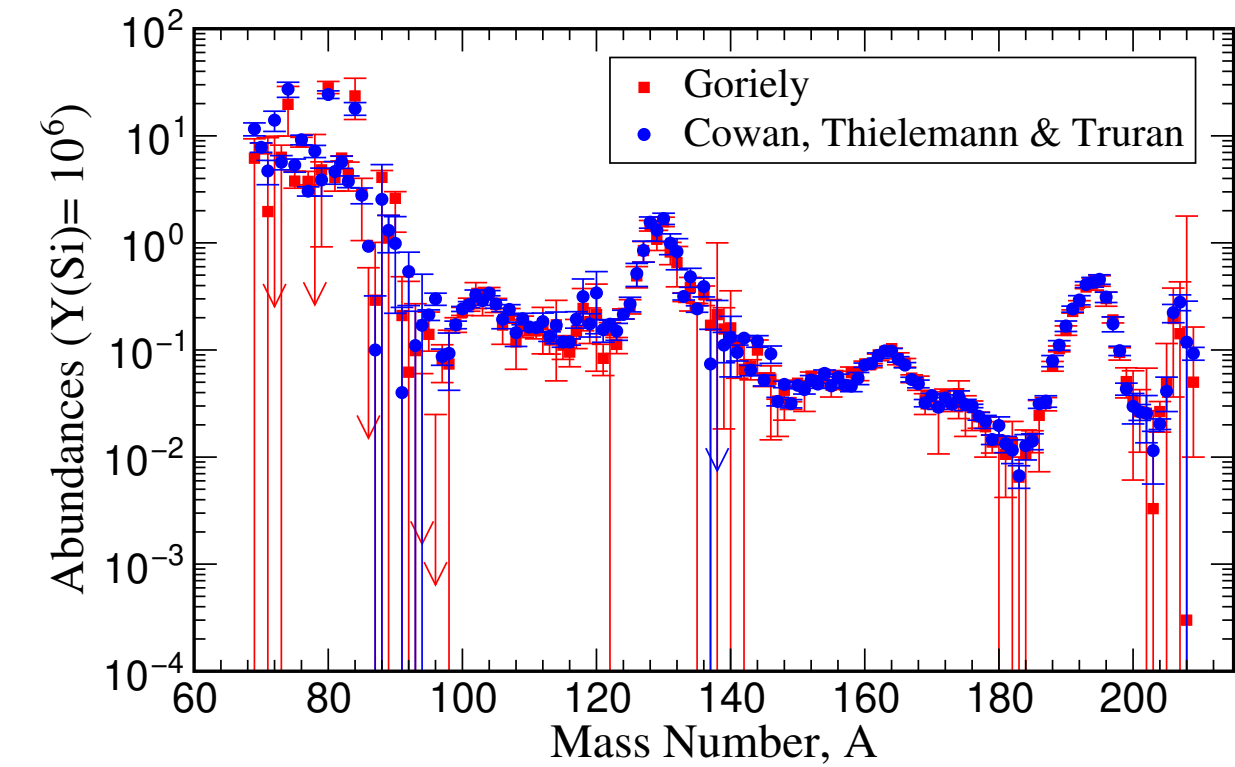
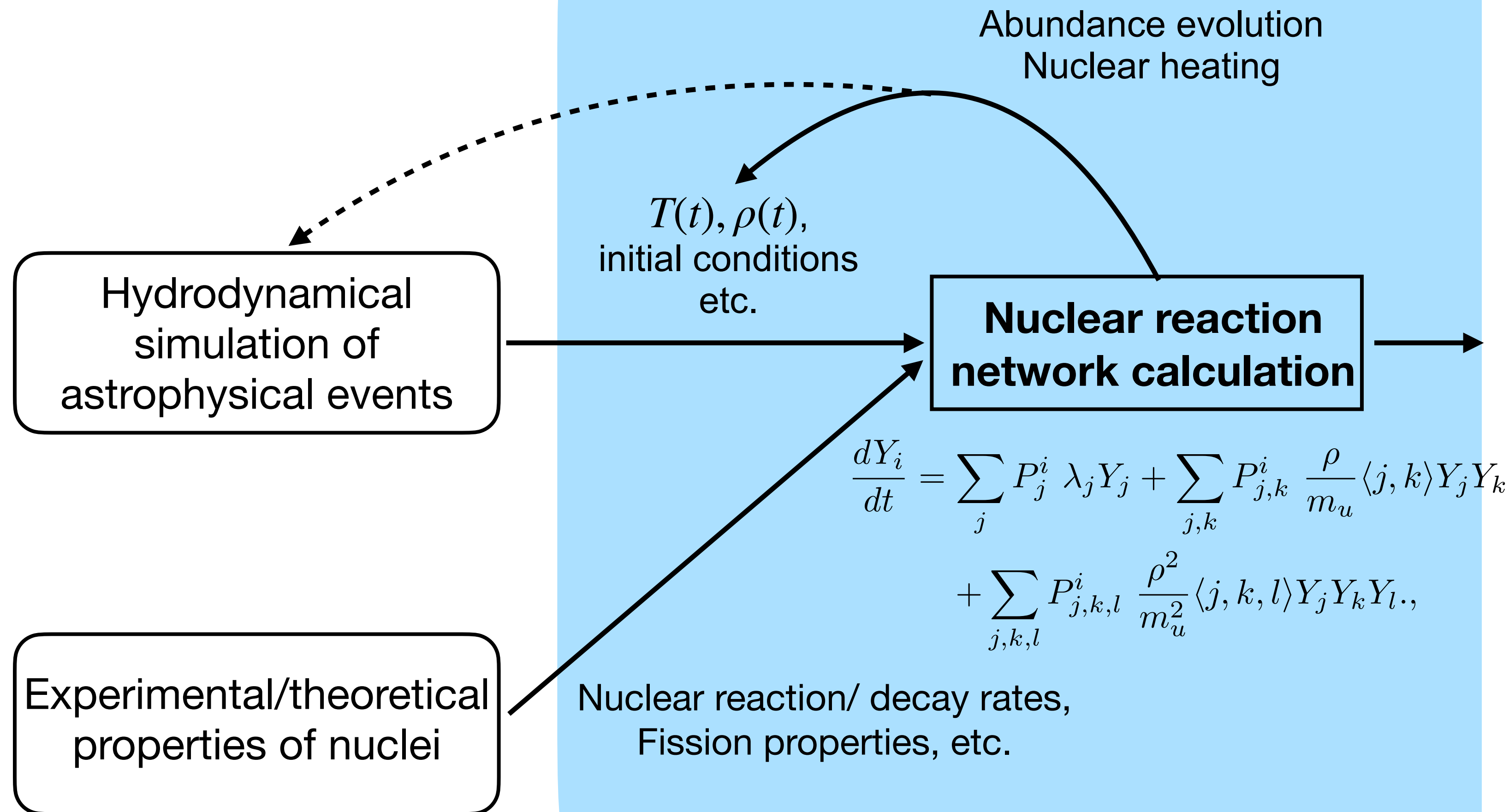


From Schatz et al. (2022), J. Phys. G: Nucl. Part. Phys. 49 110502

- Responsible for ~50% of the abundance of heavy elements
- High neutron density, temperature can reach > 10 GK
 - Compact binary mergers
 - Some types of core-collapse SNe
 - ?
- Required nuclear data
 - Nuclear masses
 - Neutron capture & photodissociation
 - β -decay & β -delayed neutron emission
 - Fission
 - ...
- **Contains neutron-rich nuclear physics**

r-process post-processing

Understand / reproduce
r-process observables



Propagation of nuclear physics uncertainty in nuclear reaction network calculations

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Nuclear mass model

Uncertainty in
phenomenological/microscopic
description of ground state



Reaction/decay rates

Mass uncertainty propagated to

- Neutron capture
- Photodissociation
- β -decay
- β -delayed neutron emission
- Fission rates & products

Systematic uncertainty in
the descriptions of reaction/decay



Nuclear reaction network calc.

Uncertainty in

- Treatment of heating
- Assumptions in astrophysical trajectory
- Unaccounted for reactions (e.g. neutrinos)

Underlying nuclear physics models / assumptions are not necessarily consistent.

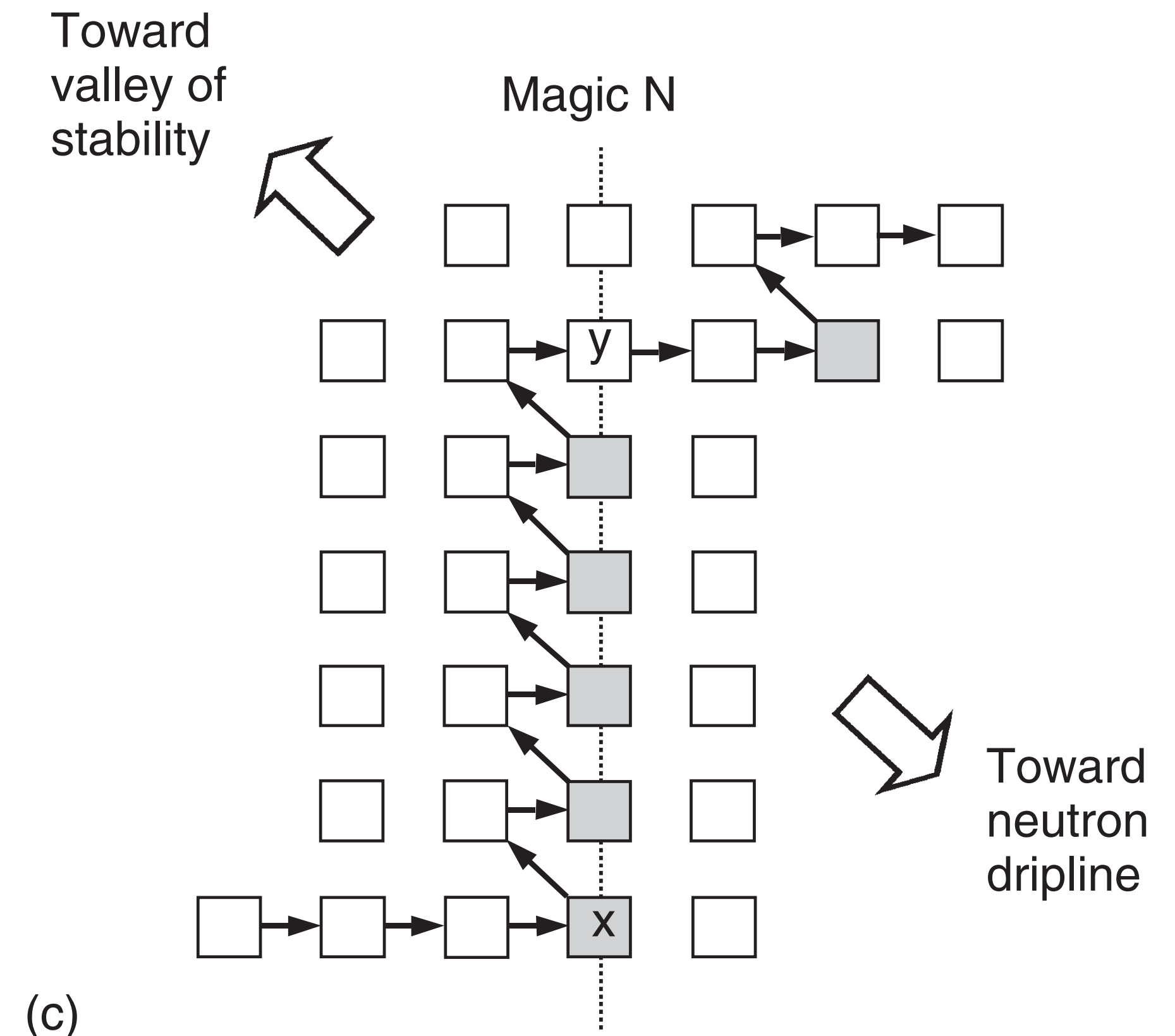
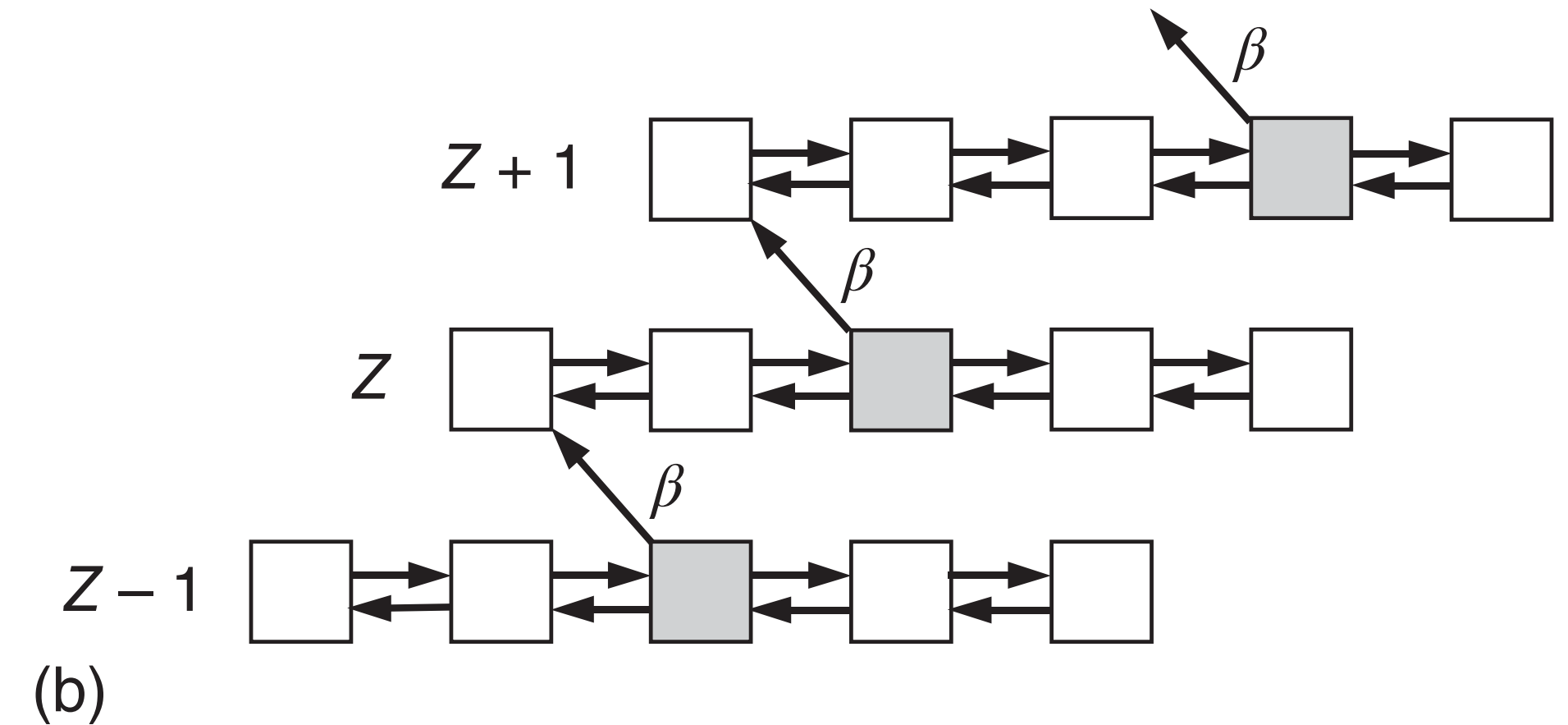
Role of β -decay in the r -process

- β -decays transfer material from Z to $Z+1$
 - Dictate the abundance pattern during $(n, \gamma) \leftrightarrow (\gamma, n)$

$$\frac{Y(Z, A+1)}{Y(Z, A)} = n_n \frac{G(Z, A+1)}{2G(Z, A)} \left[\frac{A+1}{A} \right]^{3/2} \times \left[\frac{2\pi\hbar^2}{m_u kT} \right]^{3/2} \exp\left(\frac{S_n(A+1)}{kT} \right)$$

- β -flow equilibrium:

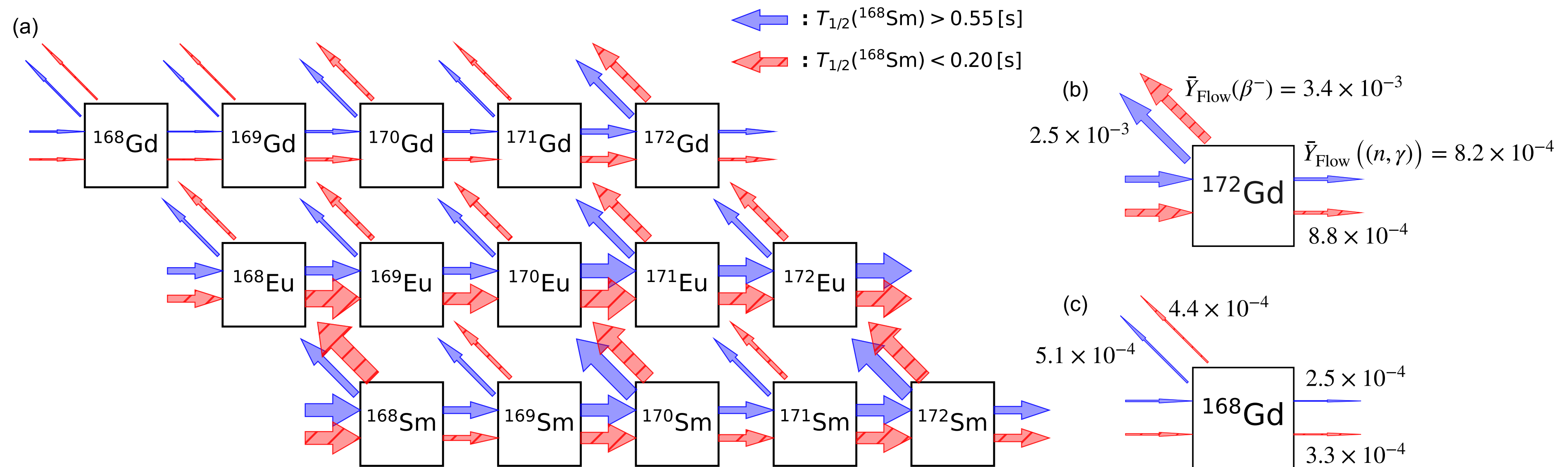
$$\begin{aligned} \sum_N \lambda_\beta(Z, N) Y(Z, N) &= Y(Z) \sum_N \lambda_\beta(Z, N) \frac{Y(Z, N)}{Y(Z)} \\ &= Y(Z) \lambda_\beta^{\text{eff}}(Z) = \text{const}, \end{aligned}$$



Role of β -decay in the r -process

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- β -decays transfer material from Z to $Z+1$
 - Dictate the abundance pattern during $(n, \gamma) \leftrightarrow (\gamma, n)$
 - Compete with neutron capture during the neutron freeze-out



G. Kiss, A. Vitéz-Sveicz, YS, et al. (2022) APJ, 936:107

Role of β -decay in the r -process

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Role of β -decay in the r -process

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- In less neutron-rich scenarios (e.g. weak r -process), β -decay may determine **how heavy the nucleosynthesis reaches**

Role of β -decay in the r -process

9

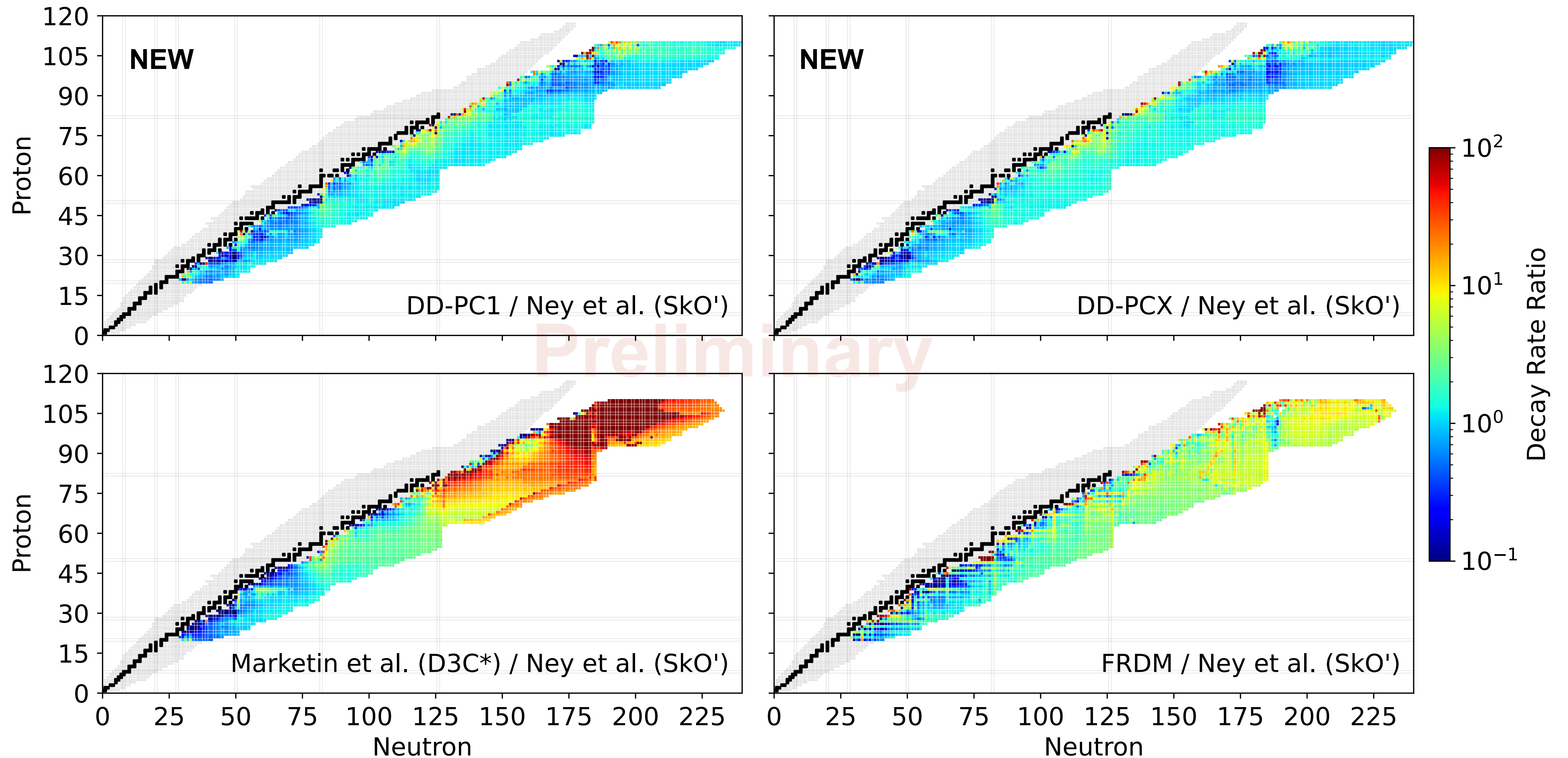
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- In less neutron-rich scenarios (e.g. weak r -process), β -decay may determine **how heavy the nucleosynthesis reaches**
- In neutron-rich conditions, β -decay affects the fission “flow”

Flow of reaction P :
$$F_P(t) \equiv \sum_{\text{all nuclei}} \lambda_P(t) \rho(t)^{N-1} \prod_{i=R_1, \dots, R_N} Y(Z_i, A_i, t),$$

Global theoretical β -decay data for *r*-process

- Typically include Gamow-Teller + first forbidden
- **Moller et al.:** FRDM2012 + QRPA rates
- **Marketin et al.:** Spherical proton-neutron relativistic QRPA (pnRQRPA)
- **Ney et al.:** Proton-neutron finite amplitude method (pnFAM) with a Skyrme functional with axial deformation
 - FAM avoids the construction of the huge QRPA matrix by solving the linear-response equation
- **NEW (Ravlić et al.):** Axially deformed pnRQRPA based on the linear-response approach
 - For more details of the framework, please see Ante Ravlić's talk on Friday

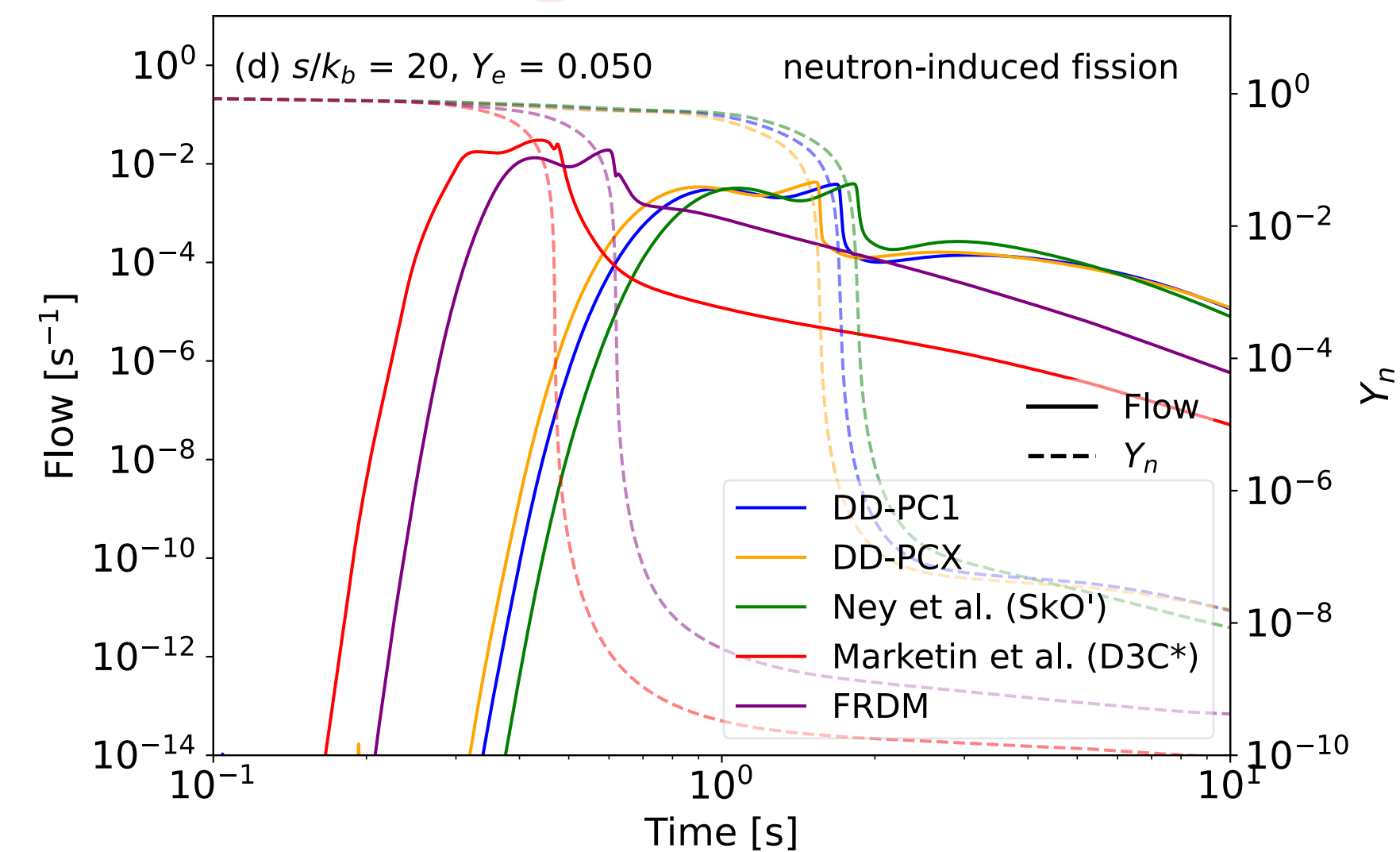
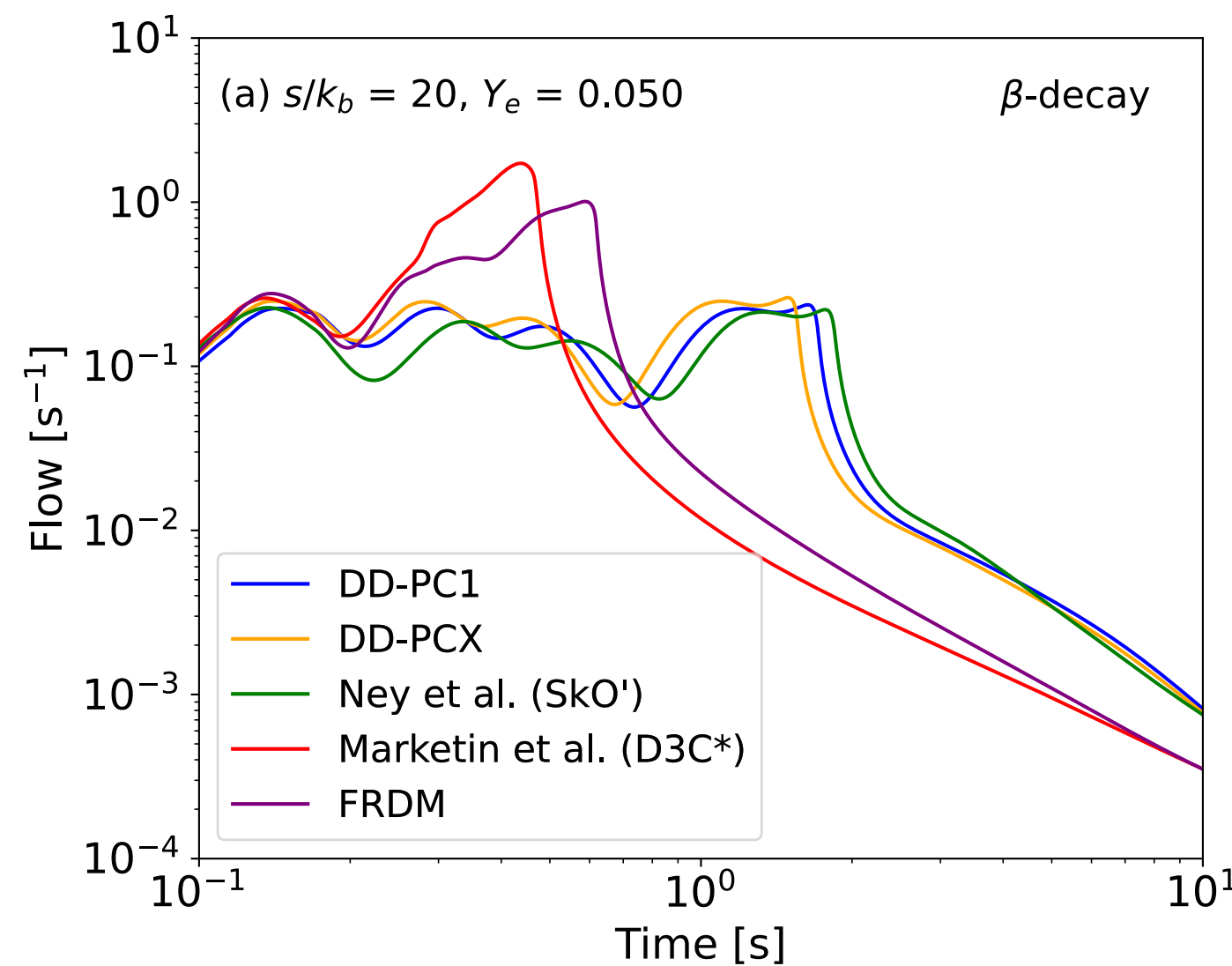
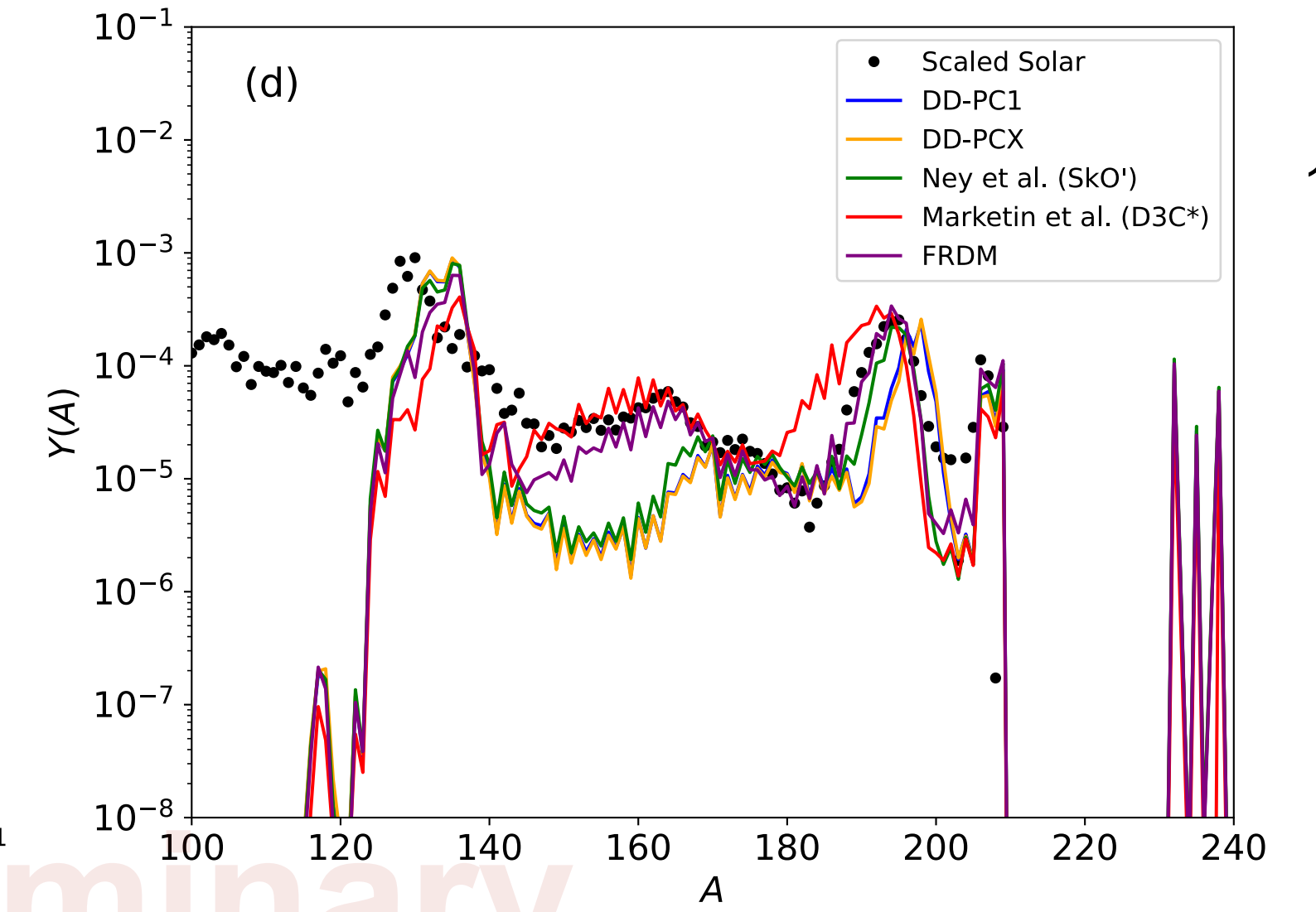
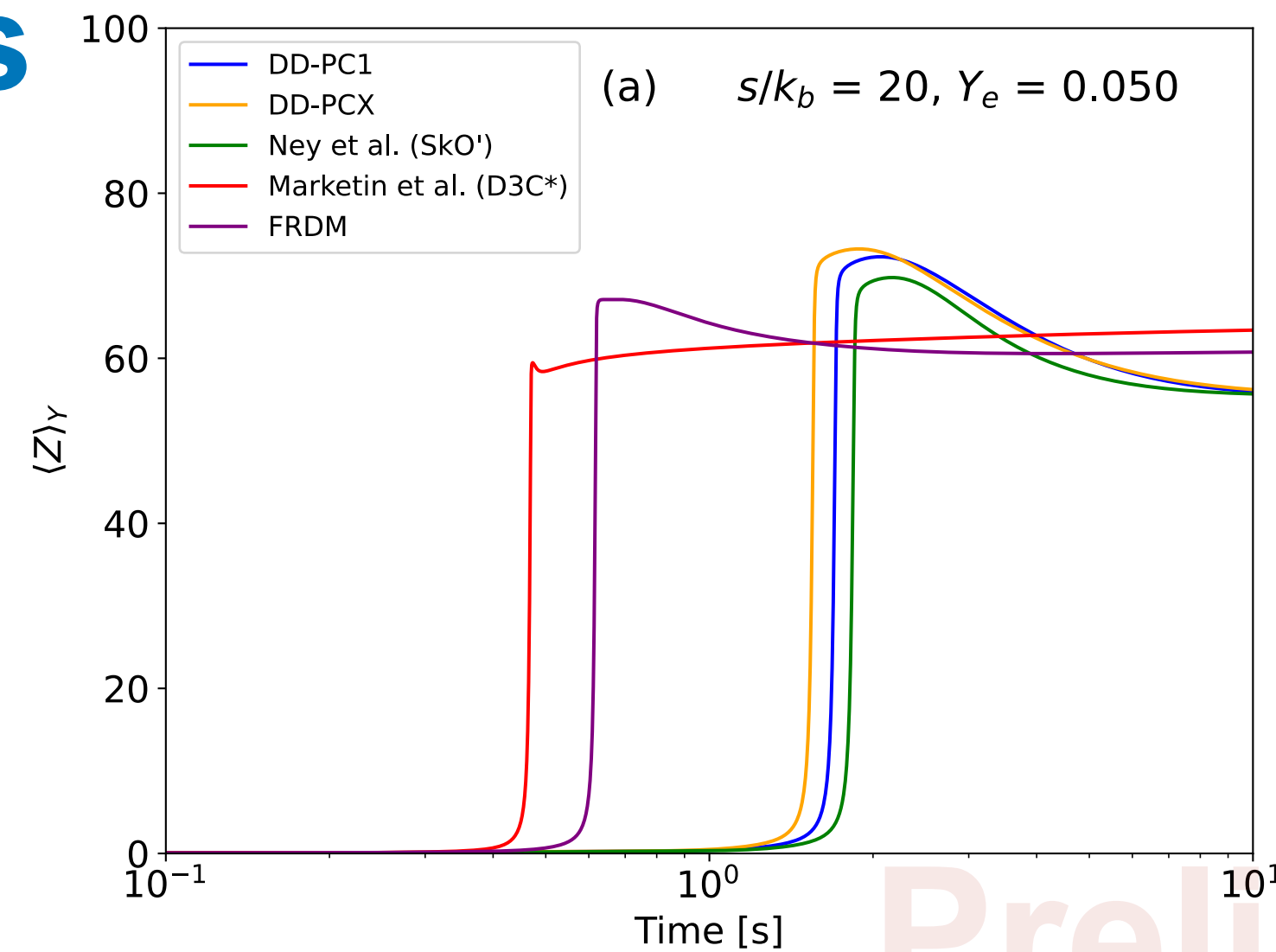
Global theoretical β -decay data for r -process



Ravlić, YS, Nazarewicz (in preparation)

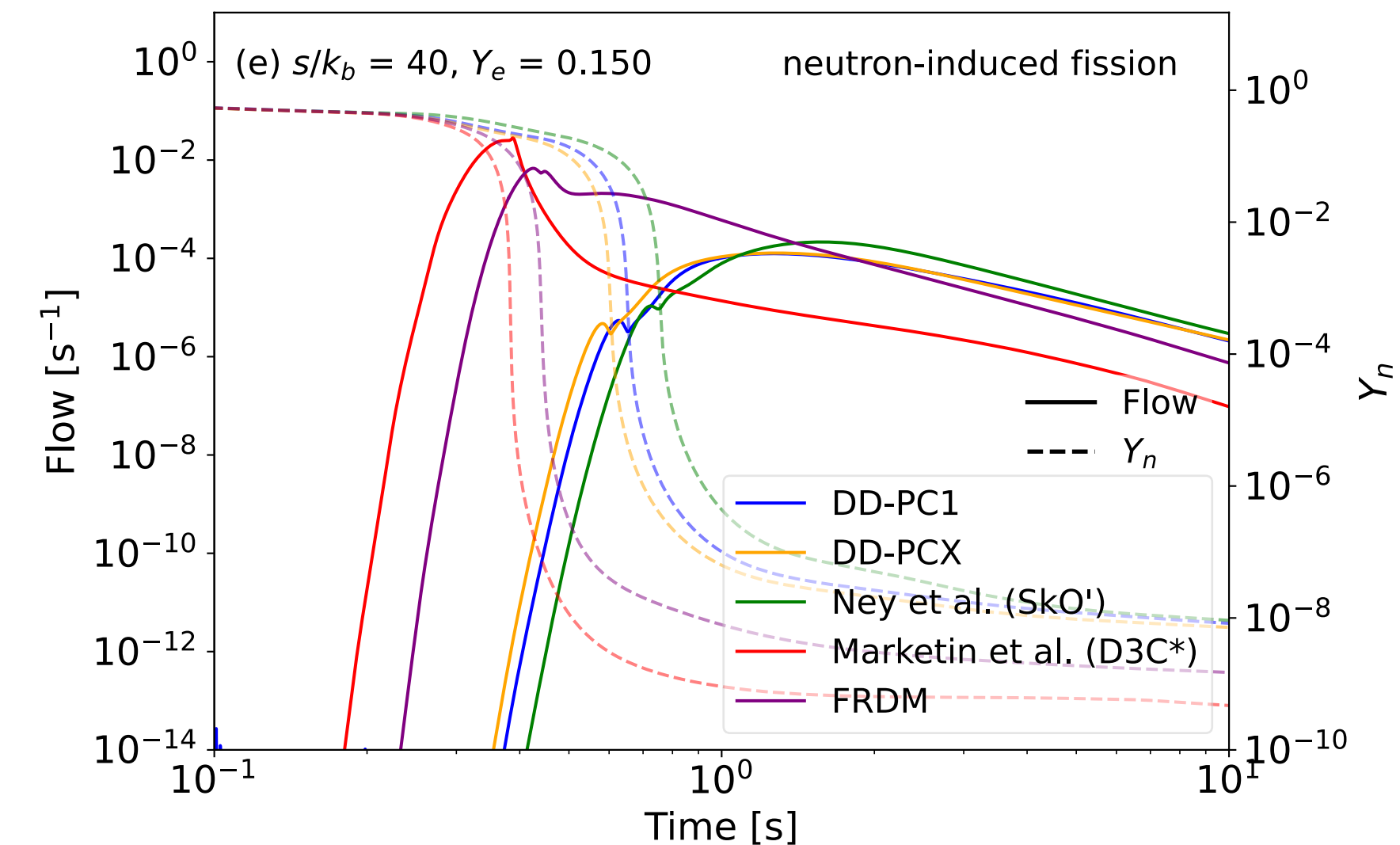
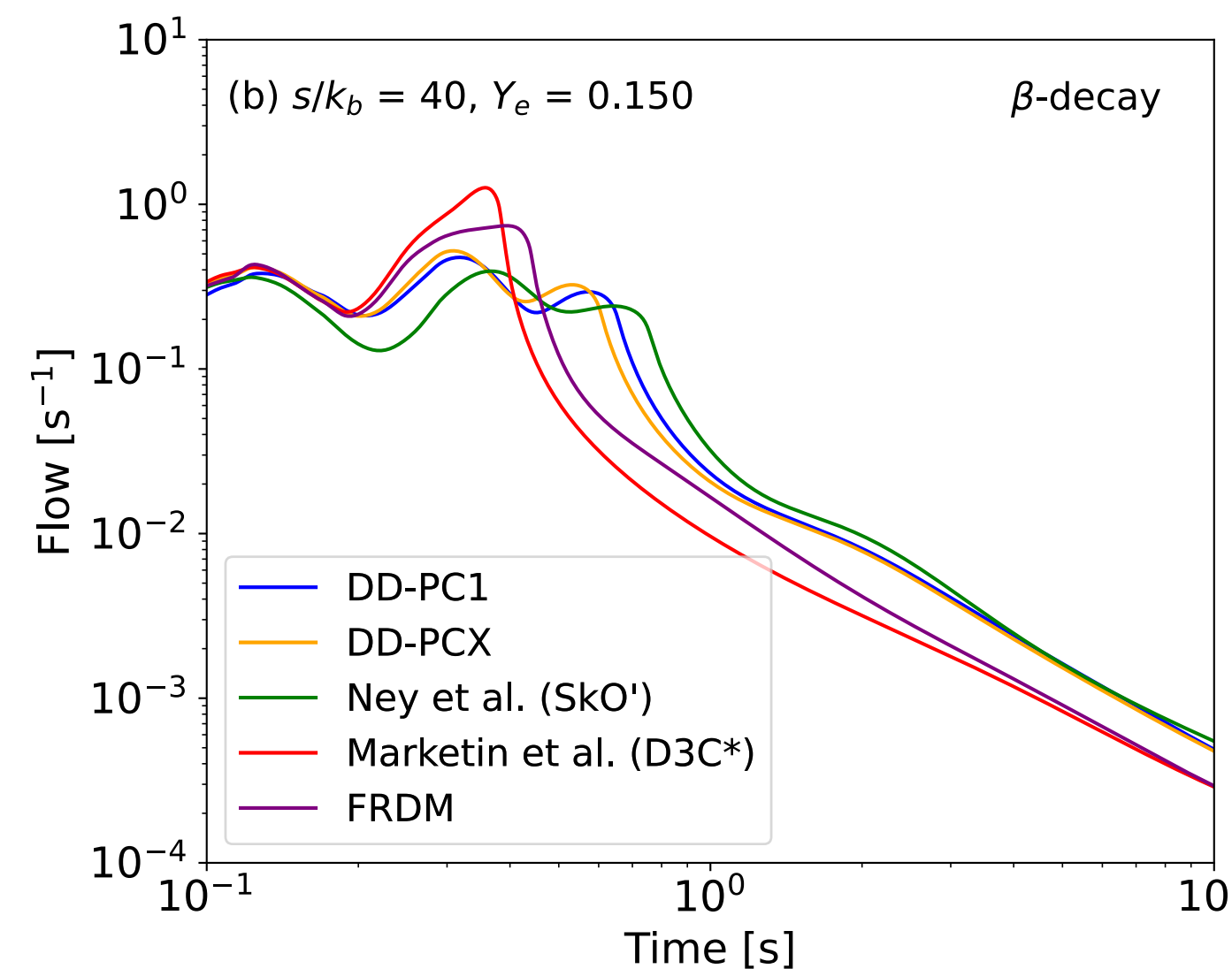
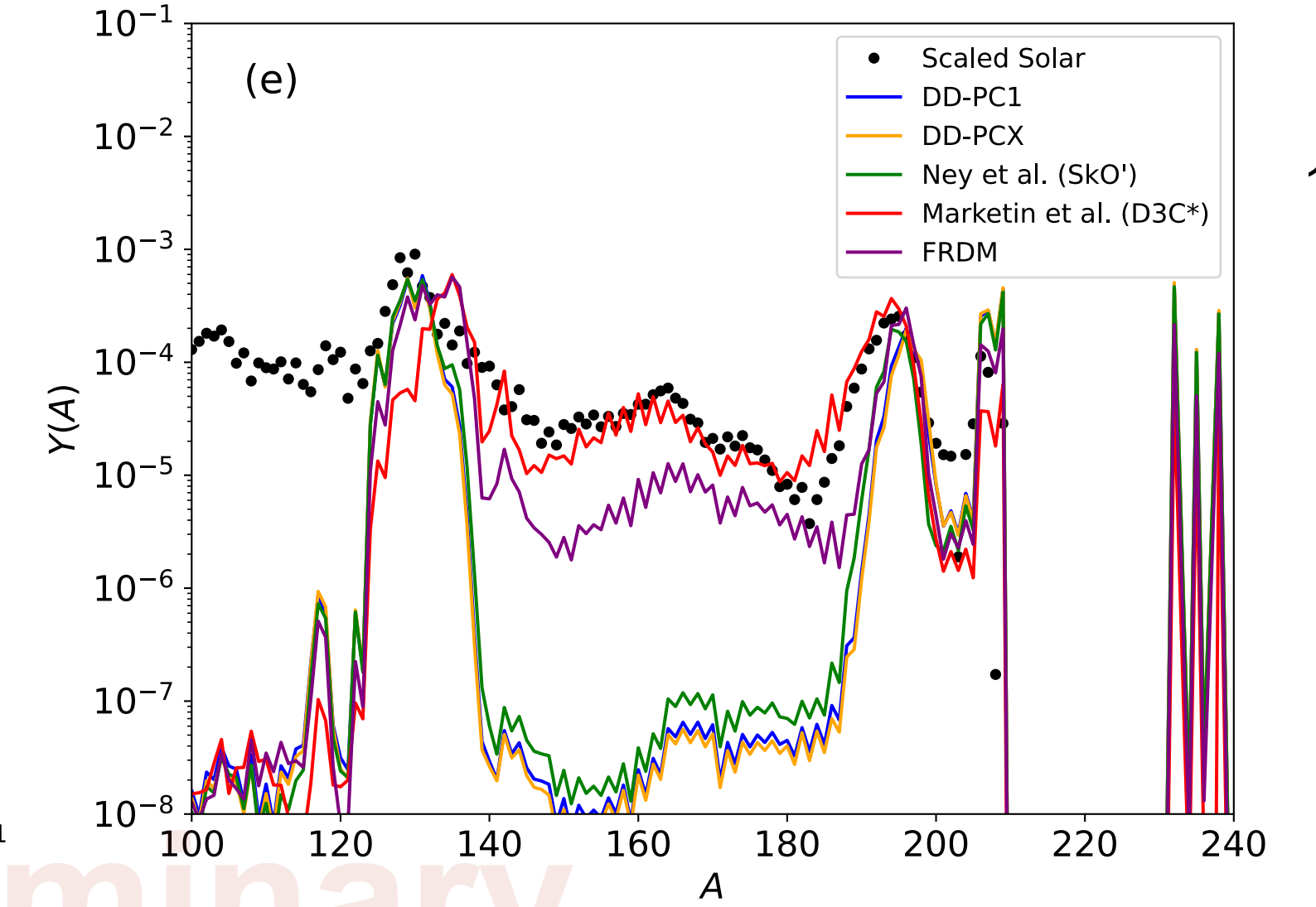
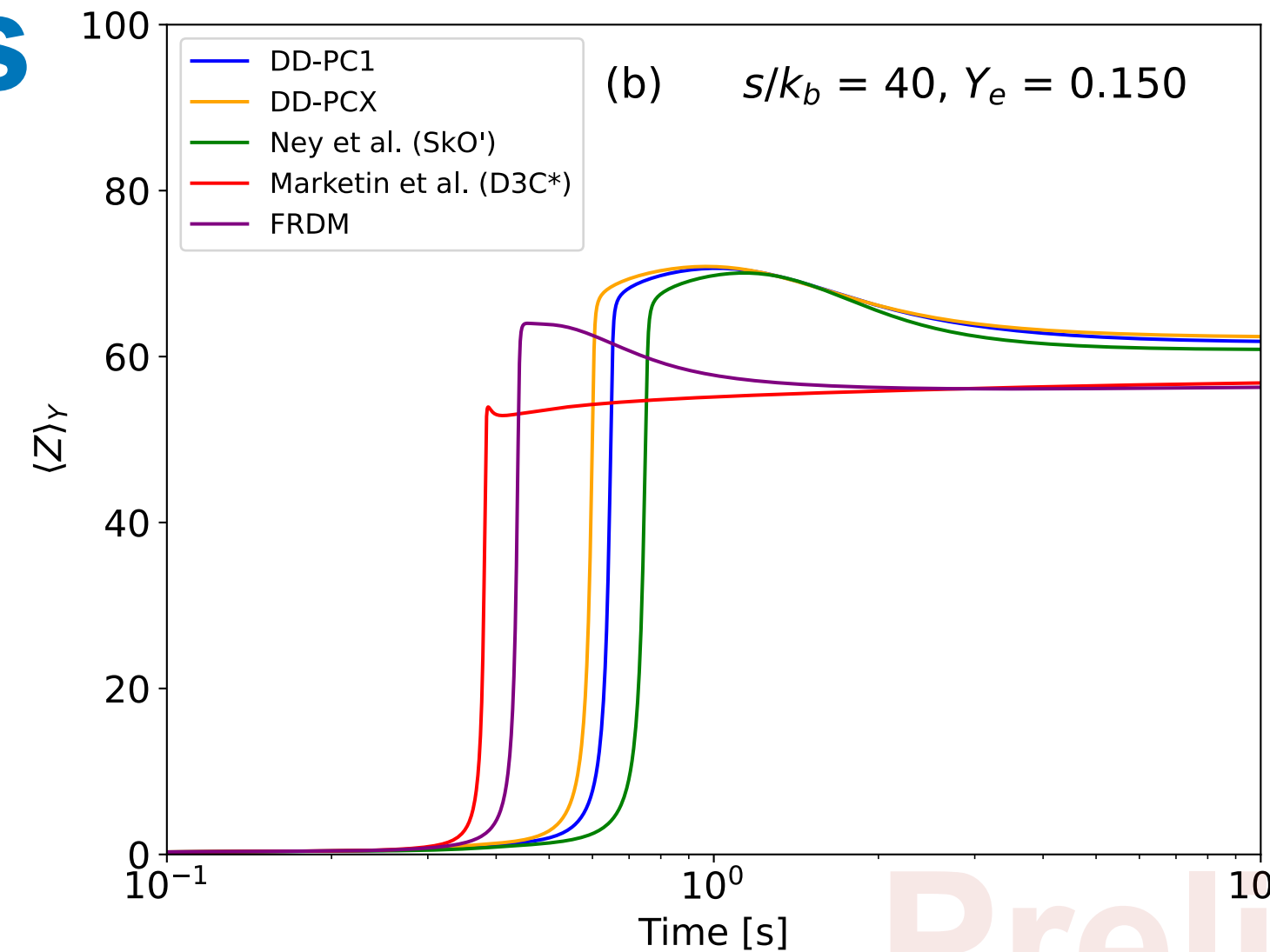
Effect of β -decay rates on r-process dynamics

- Parameterized trajectories
(Panov & Janka, A&A 494, 829-844(2009))
- Consistent results for β -decay rates based on axially deformed DFT + QRPA
- Effects are most significant in neutron-rich conditions
- r-process much slower with axially deformed DFT + QRPA rates



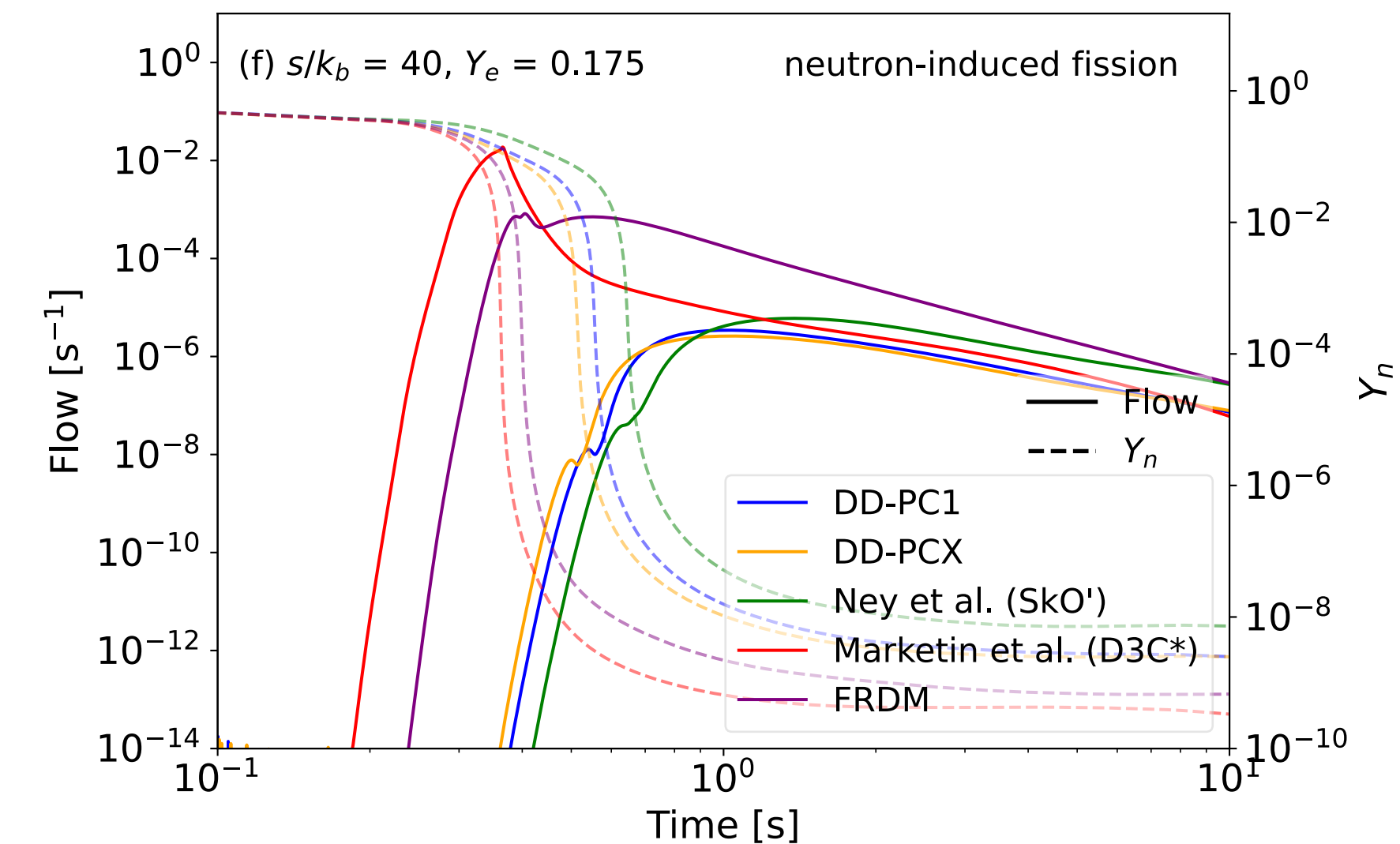
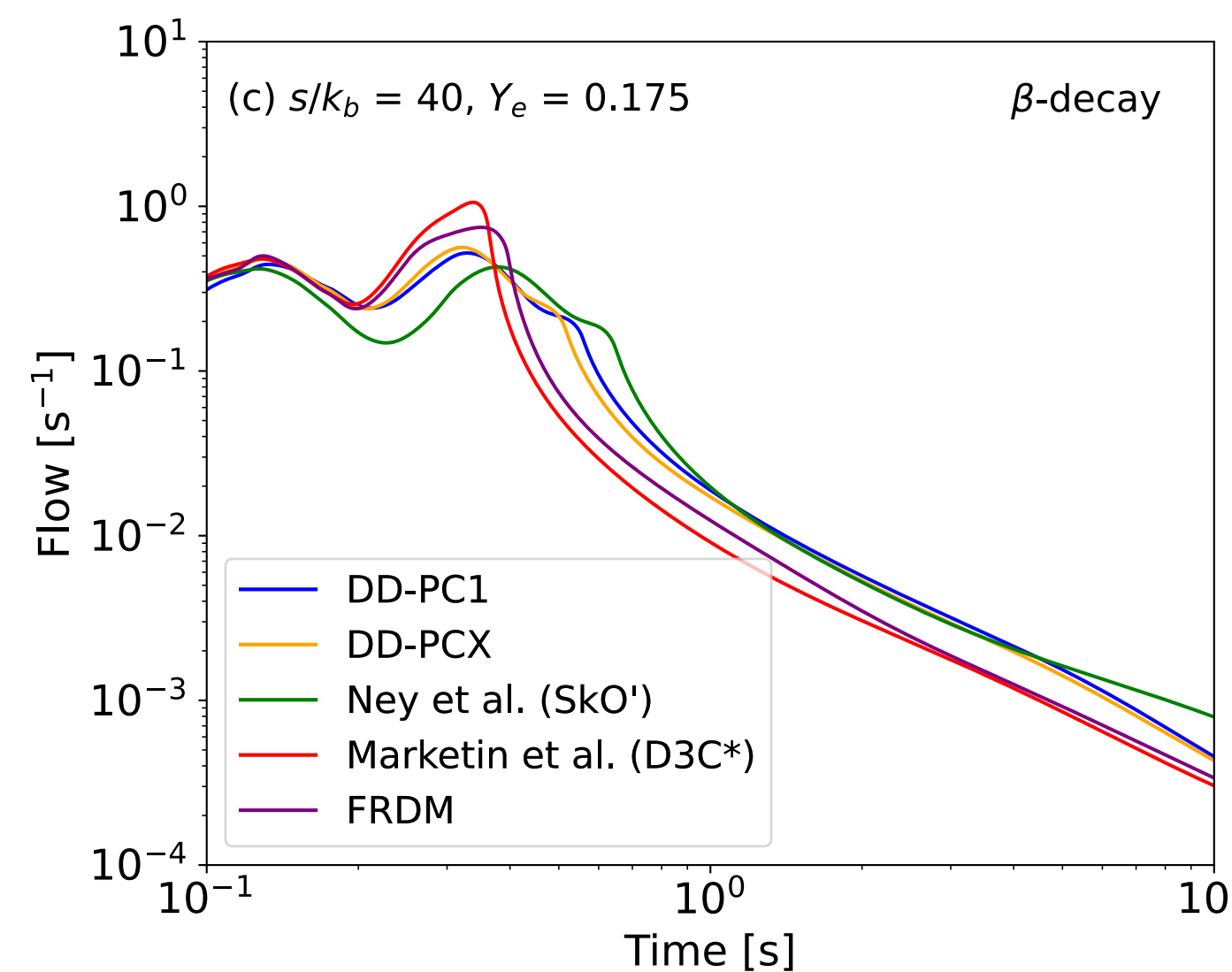
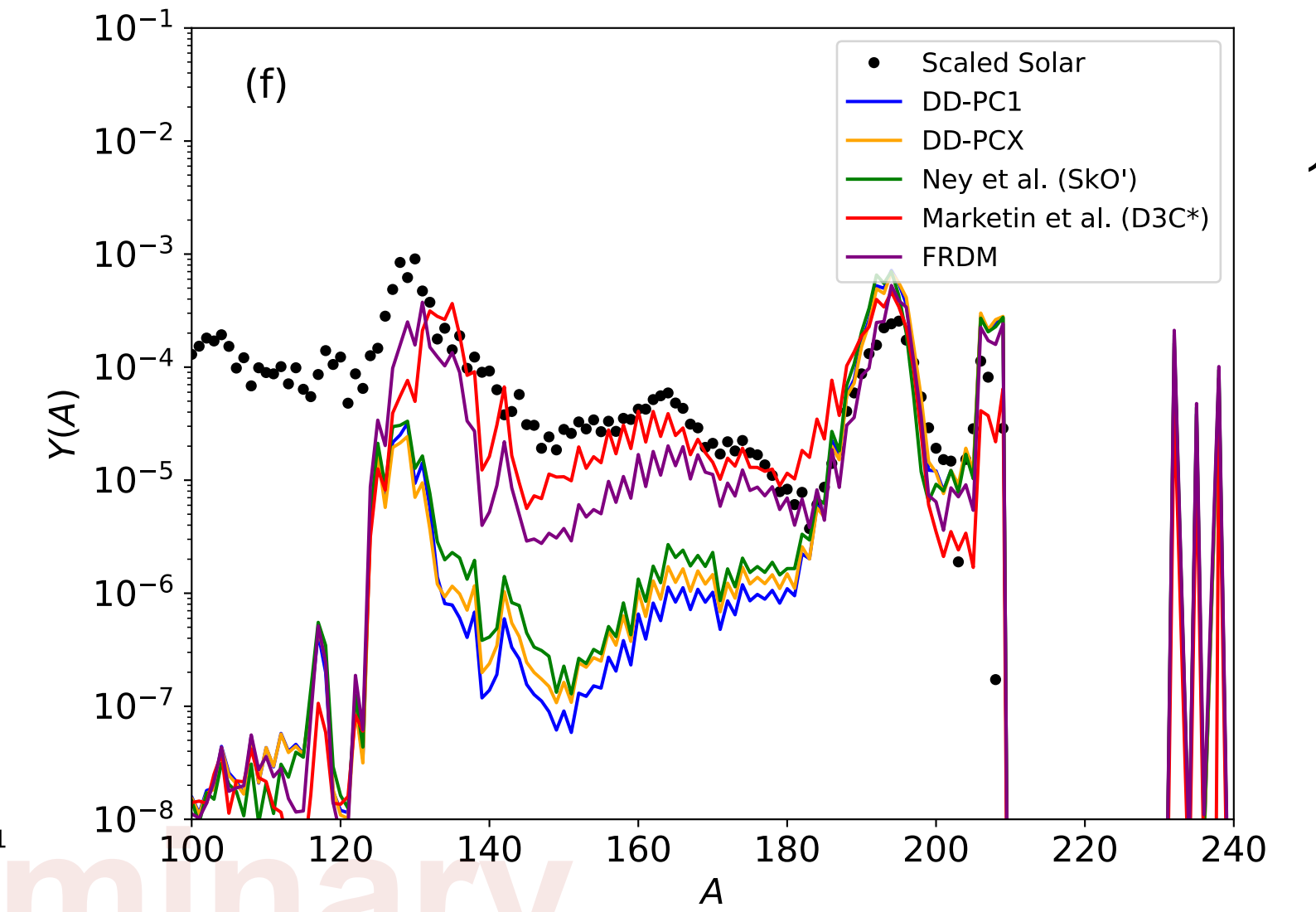
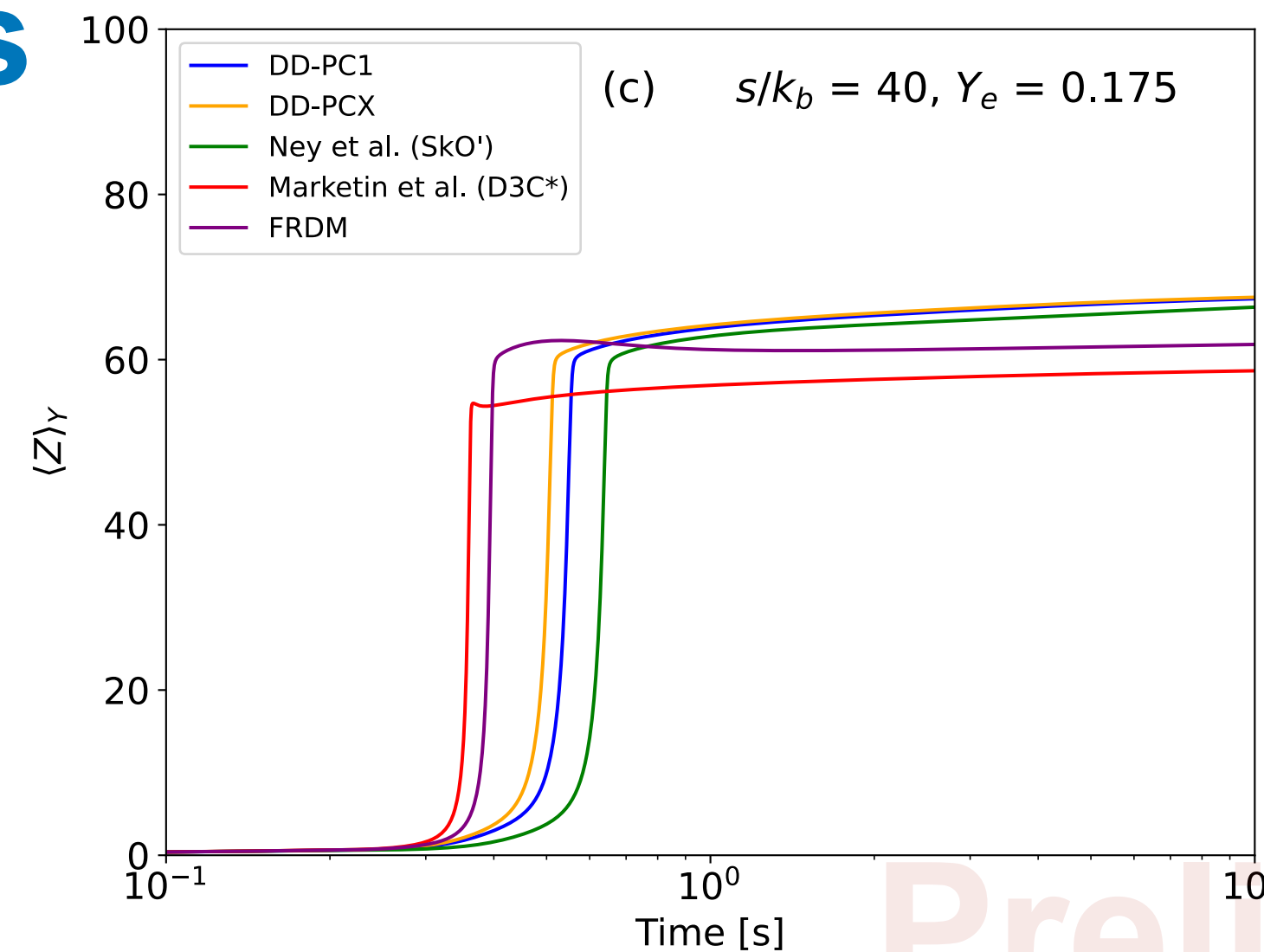
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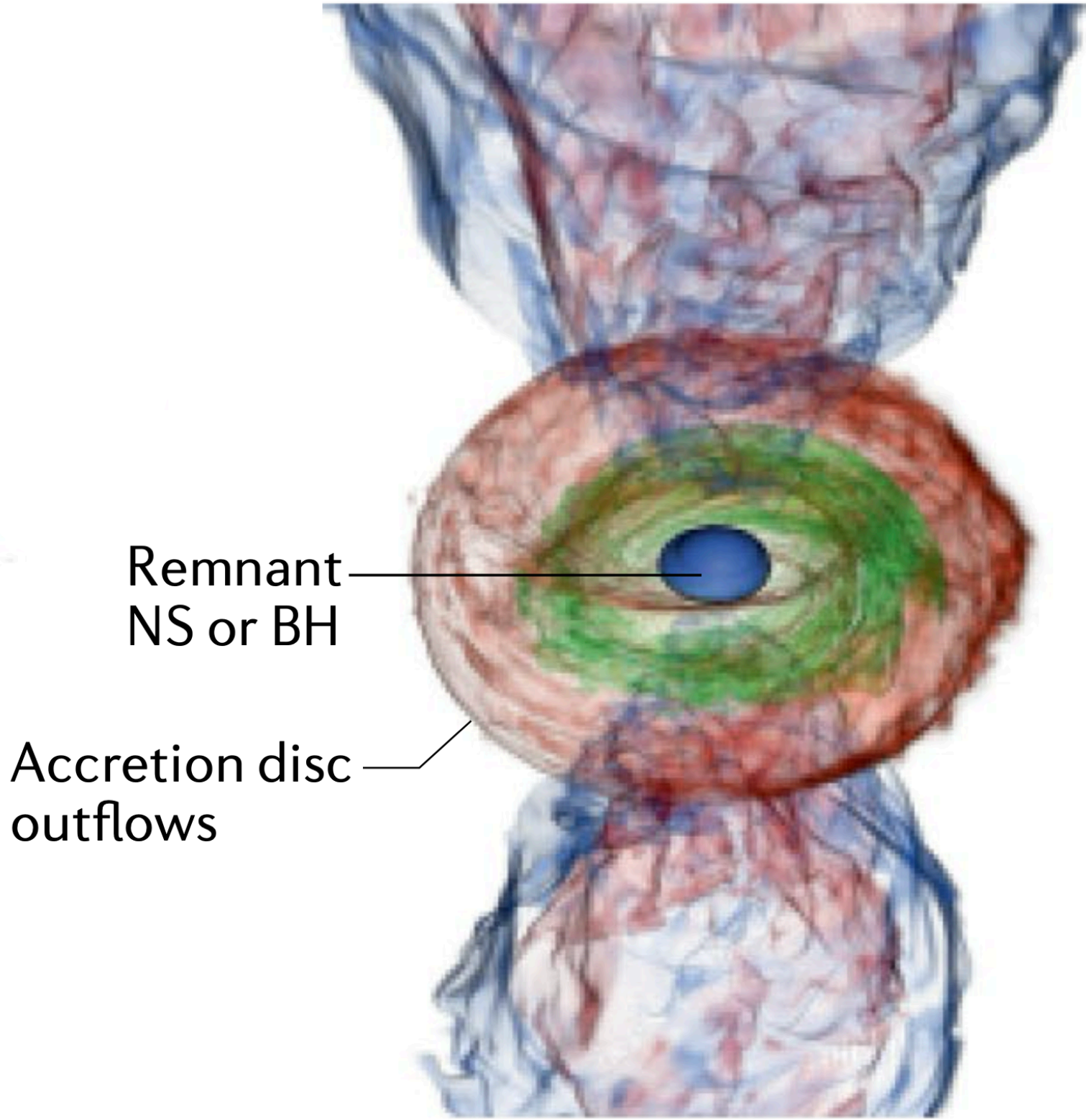
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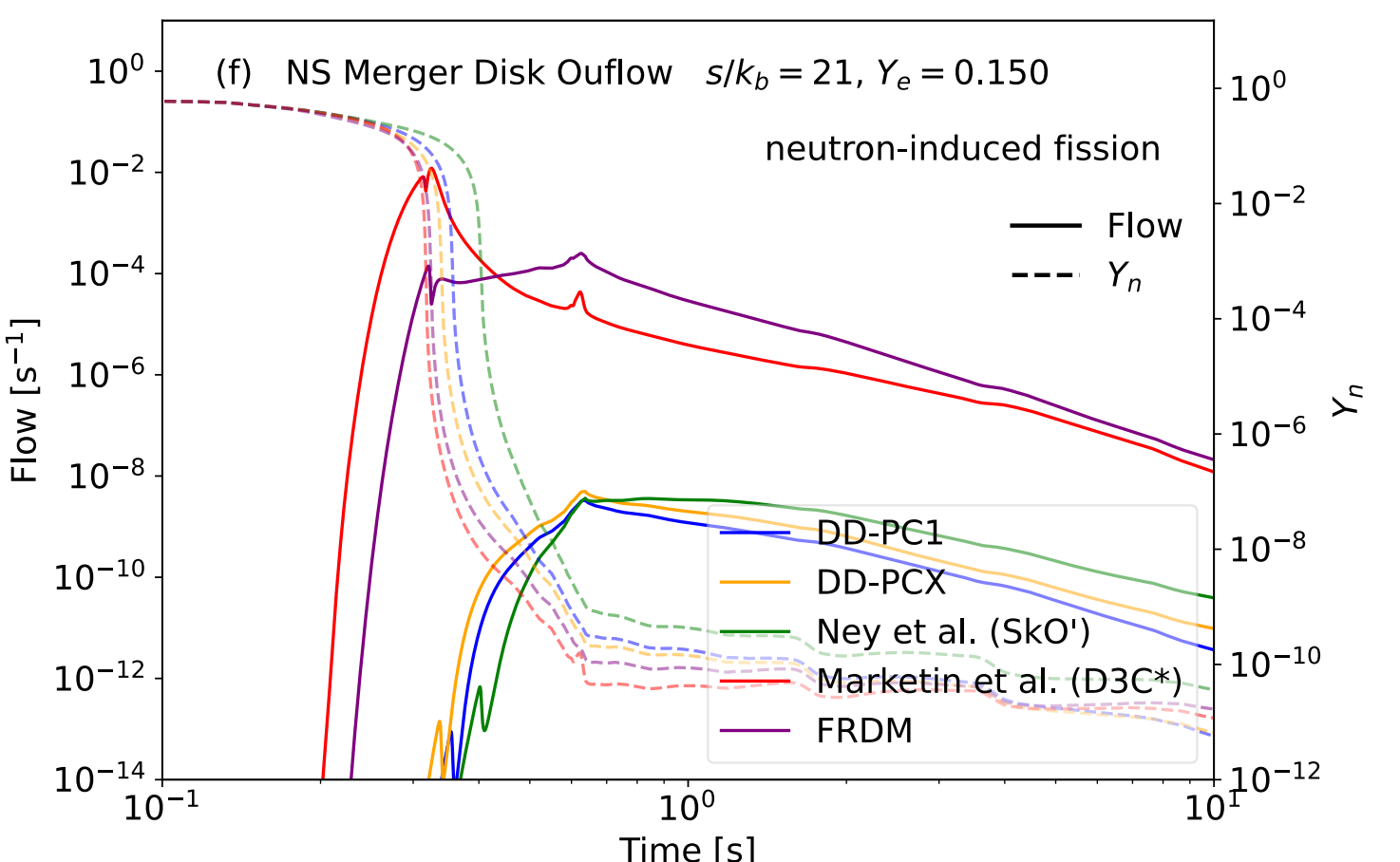
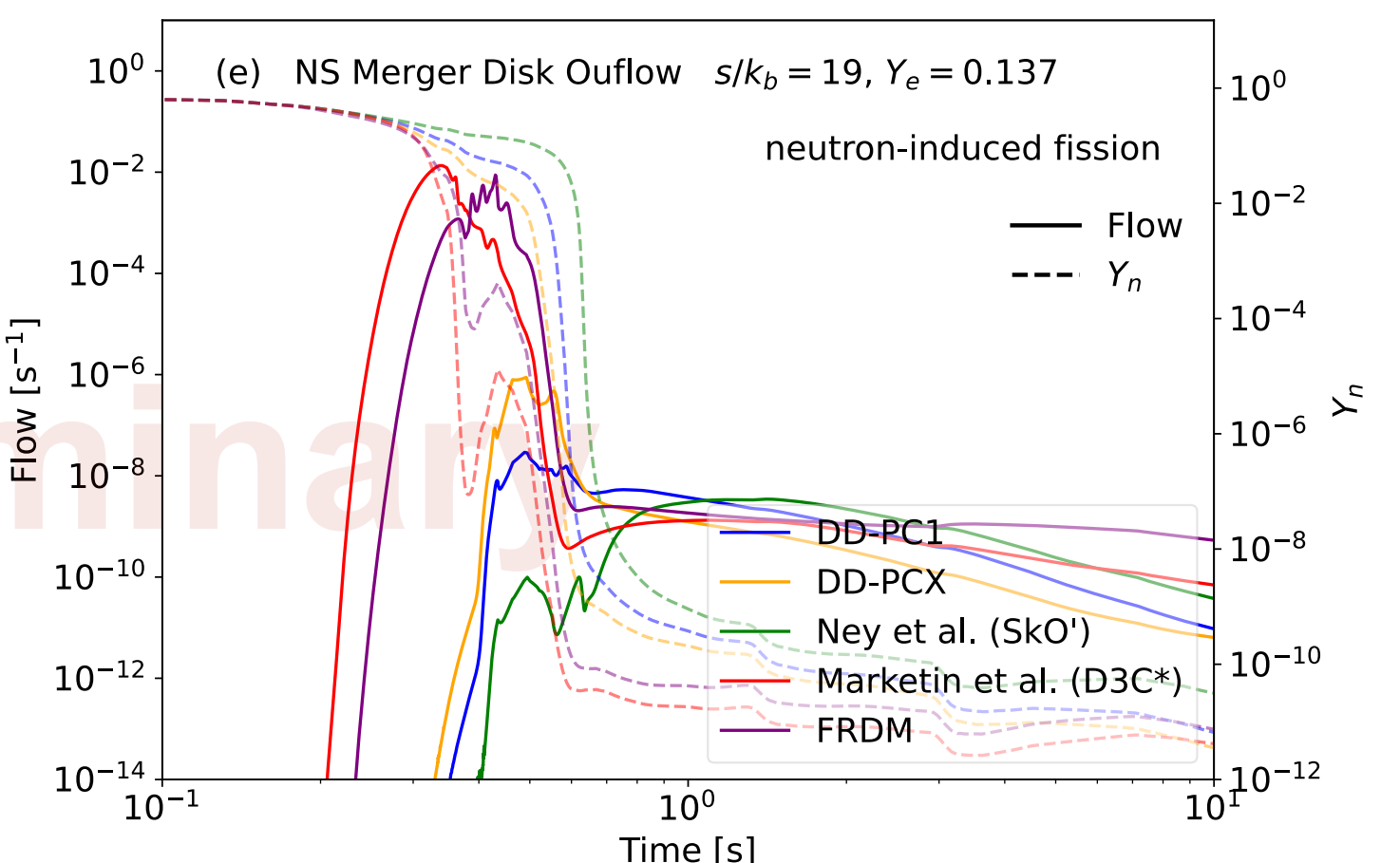
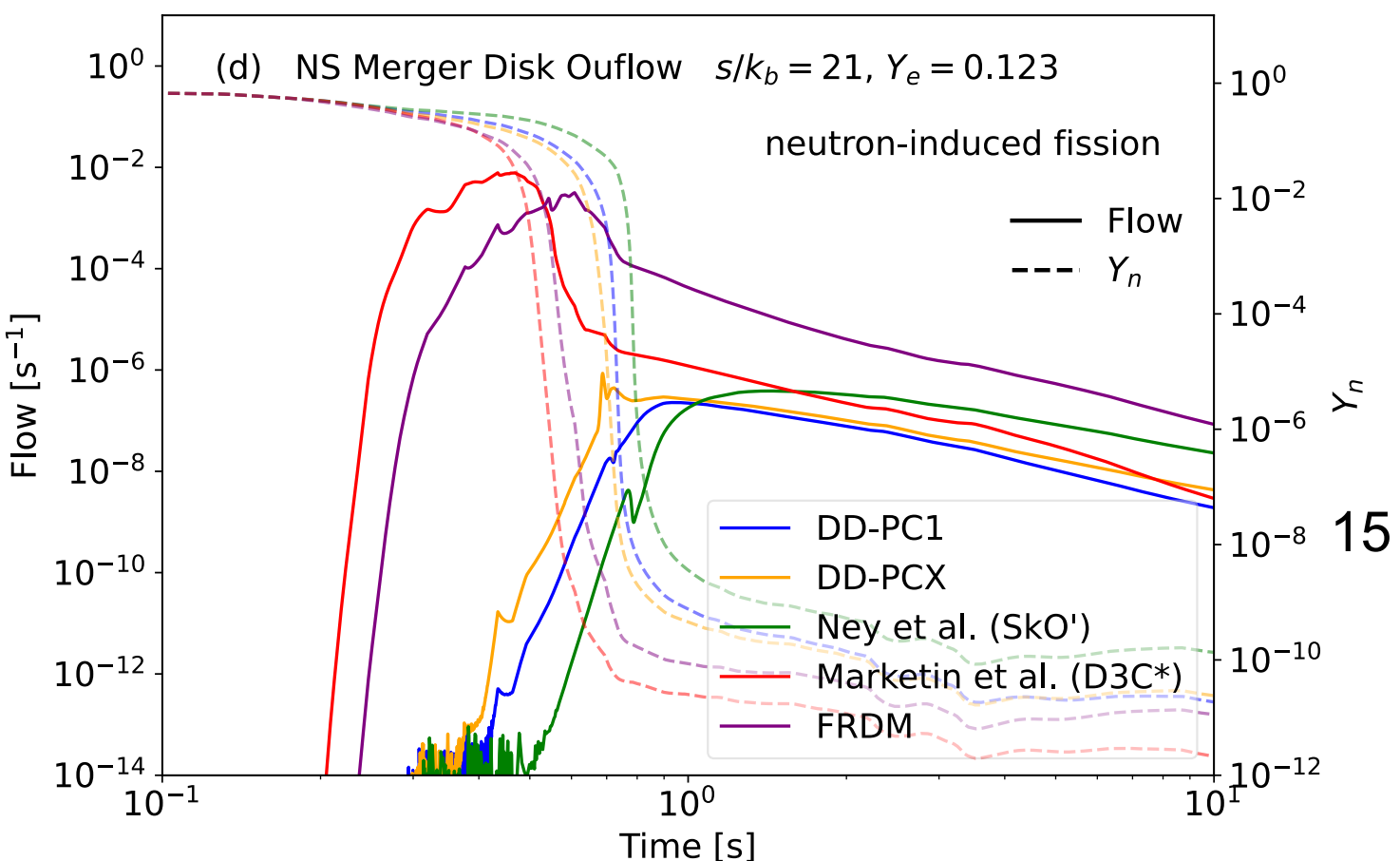
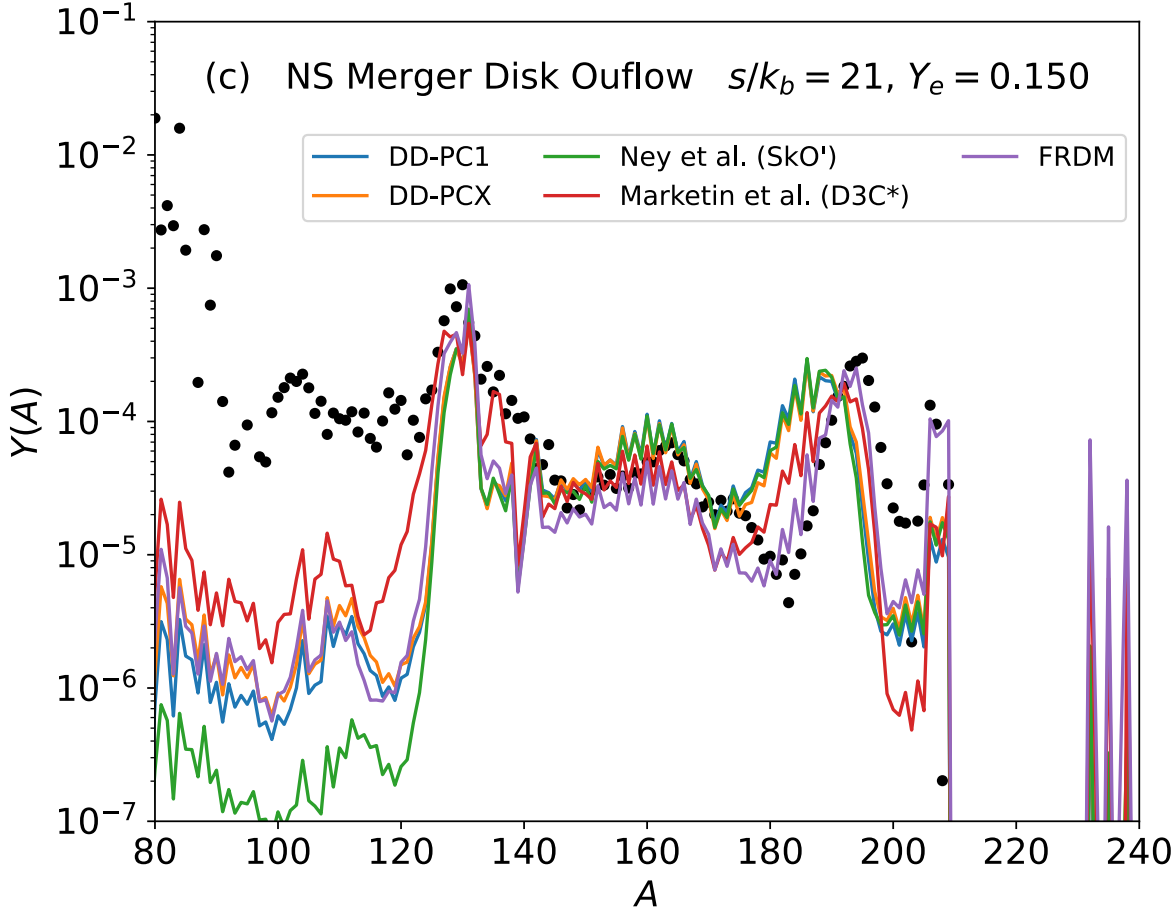
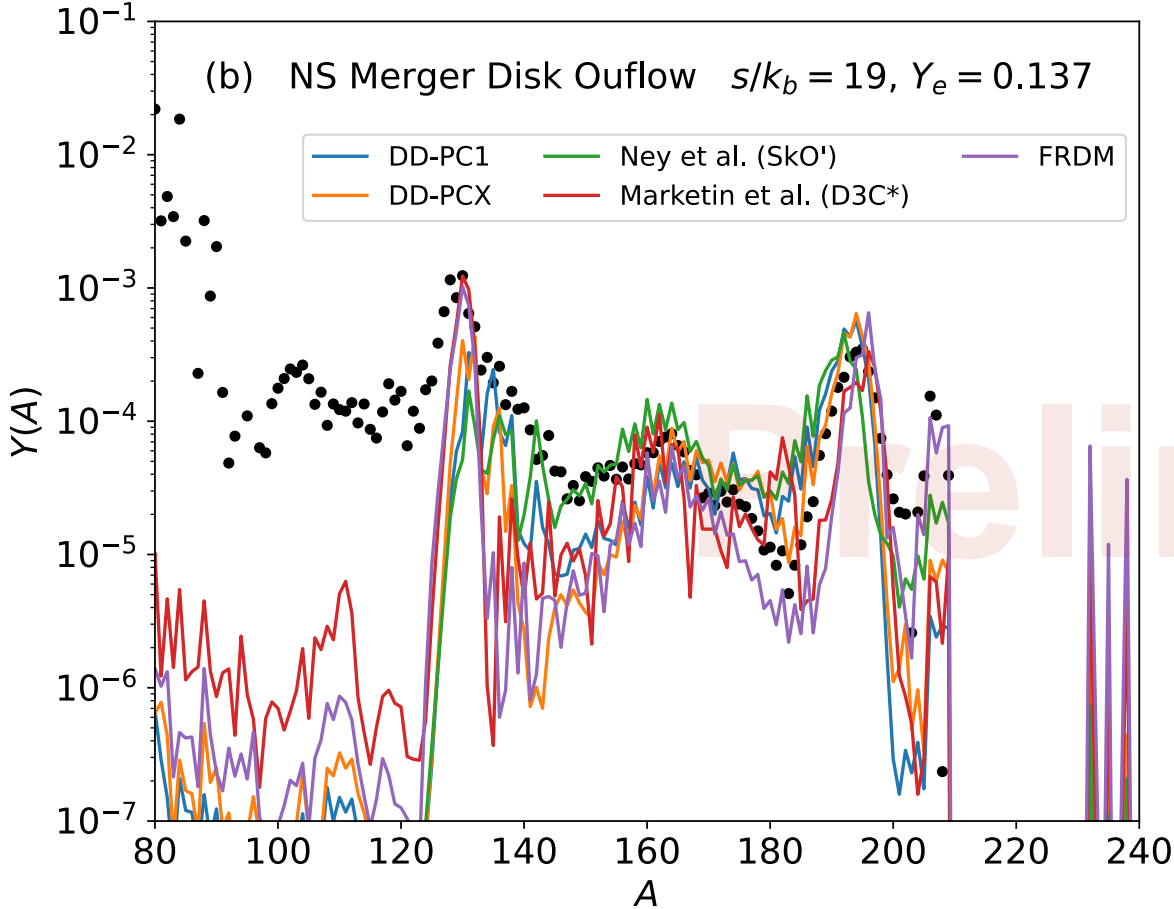
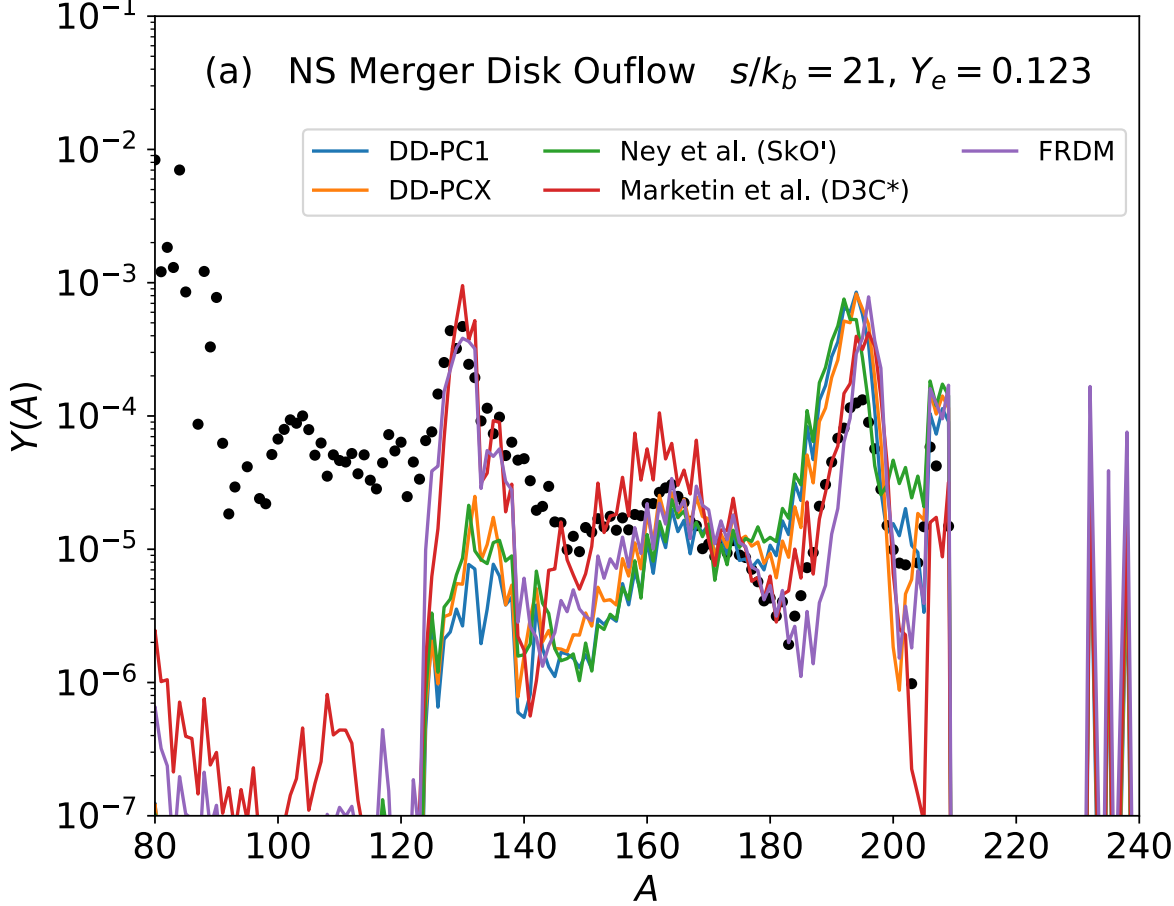
Effect of β -decay rates on r-process dynamics

- NS merger disk outflow (Metzger & Fernández, MNRAS 441, 3444(2014))

Accretion disc ejecta (~0.1–1 s)



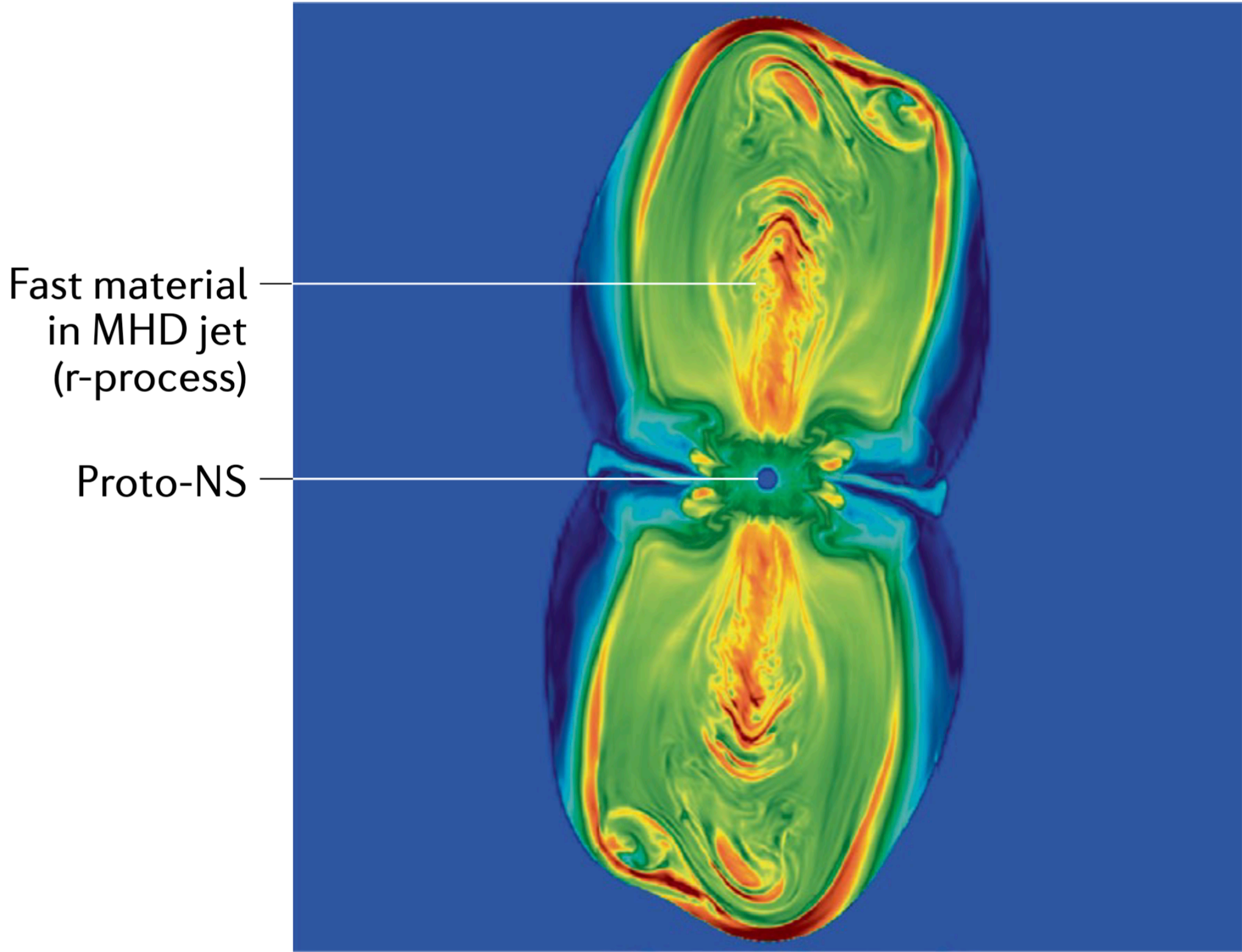
Siegel, Nature Reviews Physics 4, 306–318 (2022)



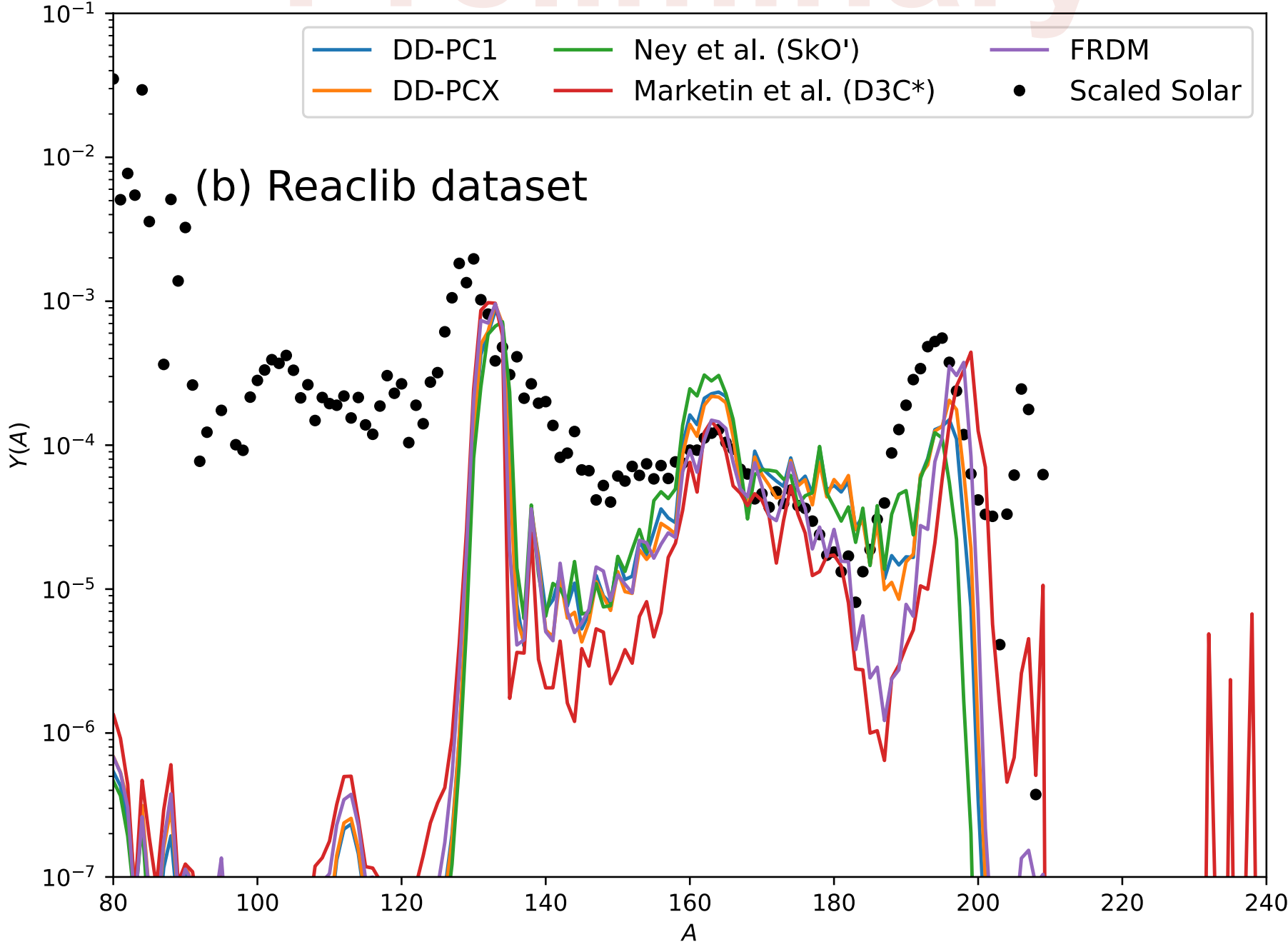
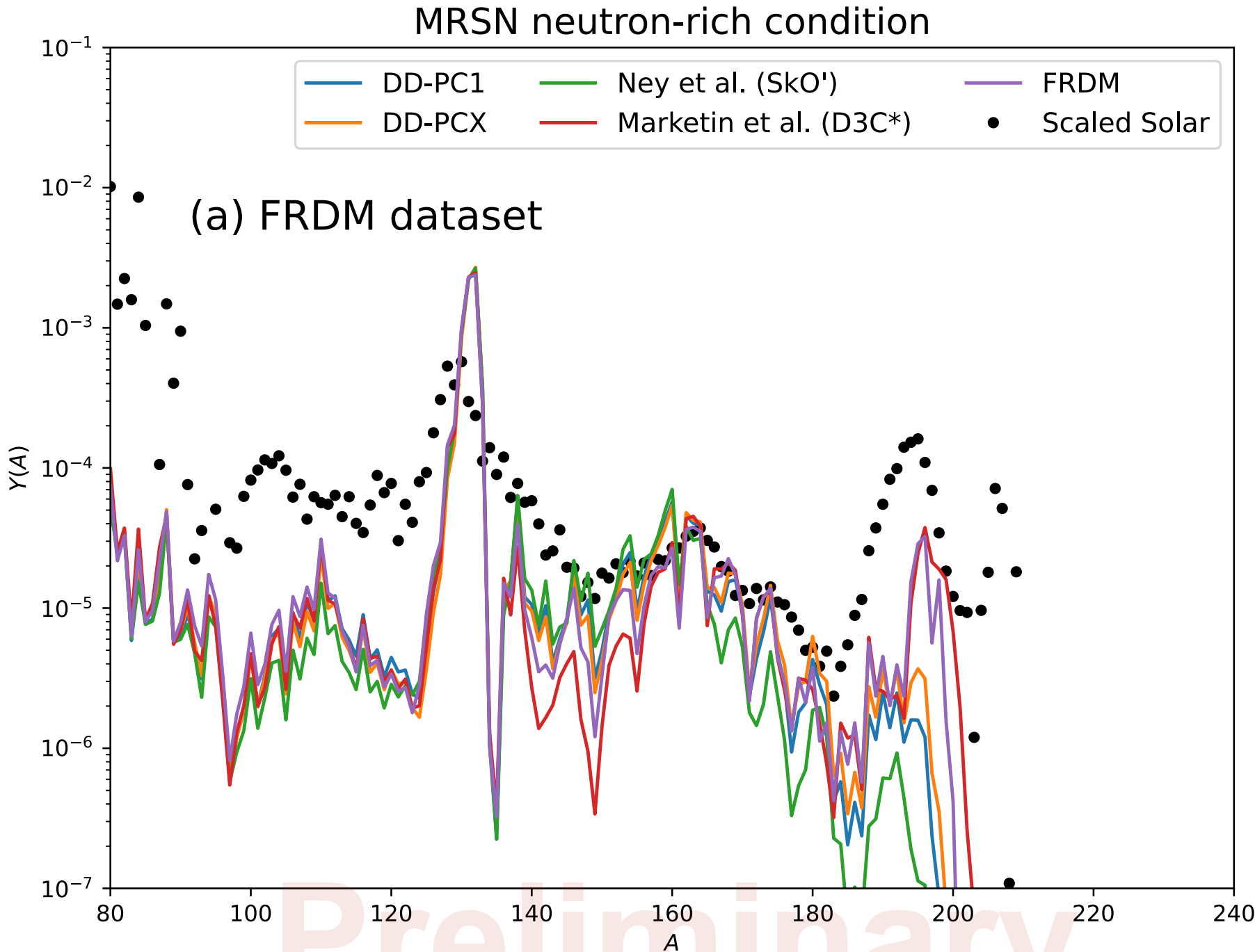
Ravlić, YS, Nazarewicz (in preparation)

Effect of β -decay rates on r-process dynamics

- Magnetorotational supernovae
(Reichert et al., MNRAS 501, 5733 (2021))



Siegel, Nature Reviews Physics 4, 306–318 (2022)



Ravlić, YS, Nazarewicz (in preparation)

Summary: Effect of β -decay on r -process dynamics

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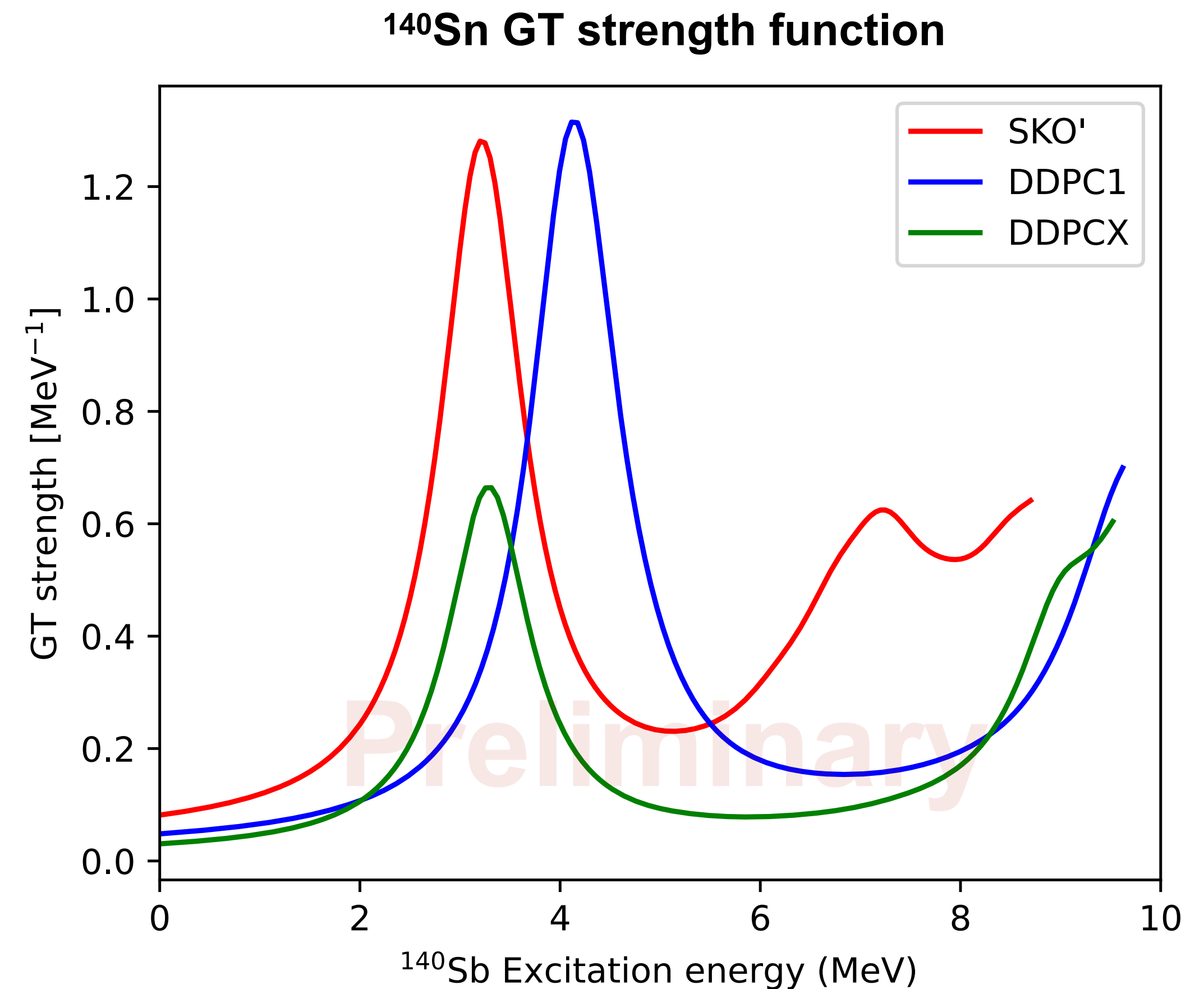
- New axially deformed relativistic calculations agree well with the non-relativistic calculation
- Newer calculations point to reduced flows of neutron-induced fission
- In less neutron-rich conditions e.g. MRSNe, production of the third r -process peak ($A \sim 196$) is affected
- Working towards more complete nuclear data based on axially deformed DFT
- Future direction of global β -decay calculations:
higher-order correlations, non-Skyrme functionals...?

Nuclear data for *r*-process and theoretical frameworks

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β -delayed neutron emission

- Recent calculations
 - FRDM + QRPA + Hauser-Feshbach (HF).
 - Spherical pnRQRPA + HF
- Extension to FAM calculations
 - ➡ Obtain β -strength functions with FAM
 - ➡ Spin-dependent population of the daughter nucleus
 - ➡ Statistical de-excitation with Hauser-Feshbach calculations



SKO' : pnFAM (code provided by the UNC group)
DDPC-1 & -X : pnRQRPA by Ante Ravlić (FRIB)

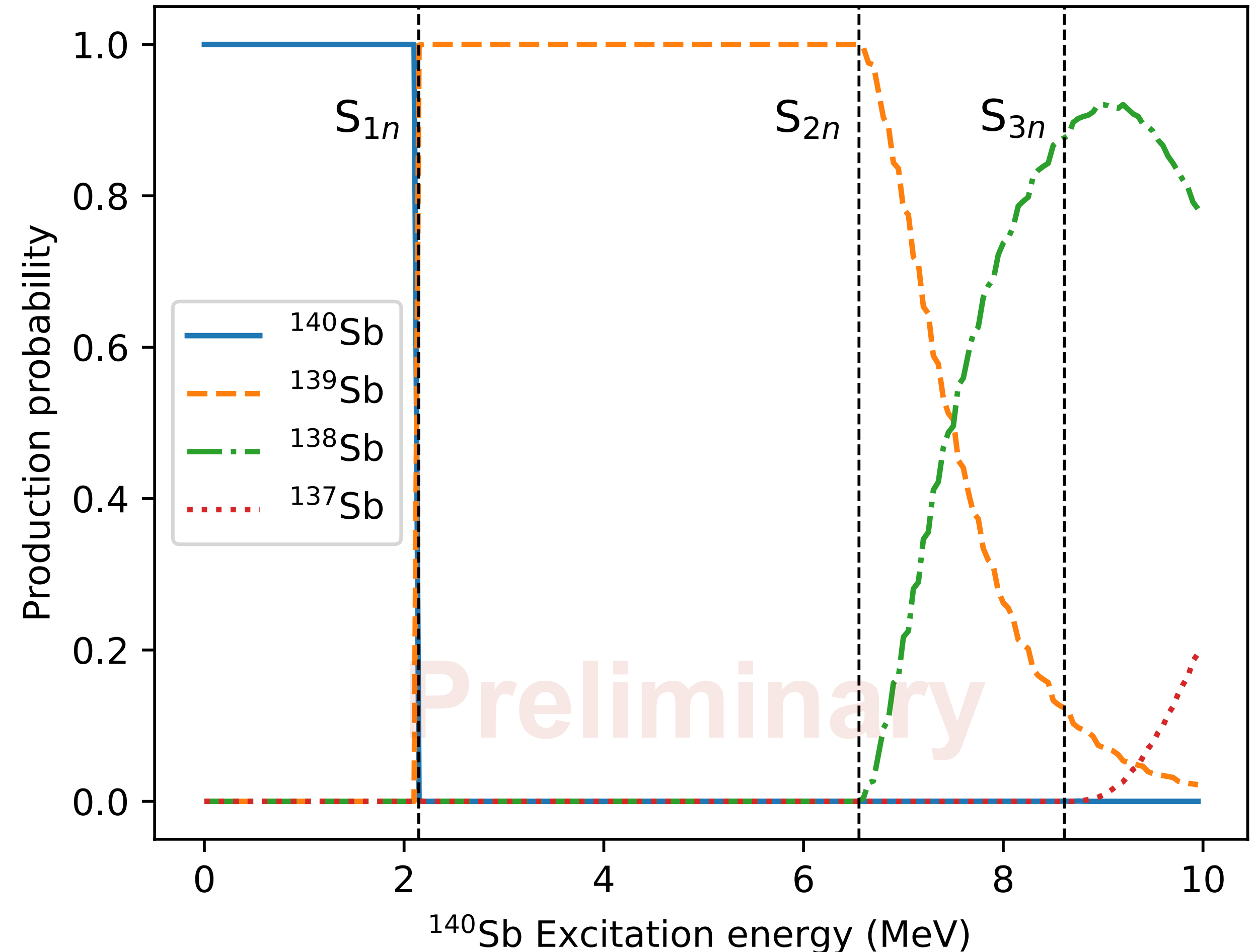
Nuclear data for *r*-process and theoretical frameworks

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β -delayed neutron emission

- For the modelling of multiple neutron emissions and γ - n competition, HF calculations are necessary.
- HF calculations require:
 - S_{xn} values (mass model)
 - γ -SF (E1, M1, ...)
Skyrme + FAM:
Li, et al. Phys. Rev. C **110**, 034317 (2024)
 - Level density,
 - Optical potential

β -delayed neutron emission probabilities (TALYS)



Nuclear data for *r*-process and theoretical frameworks

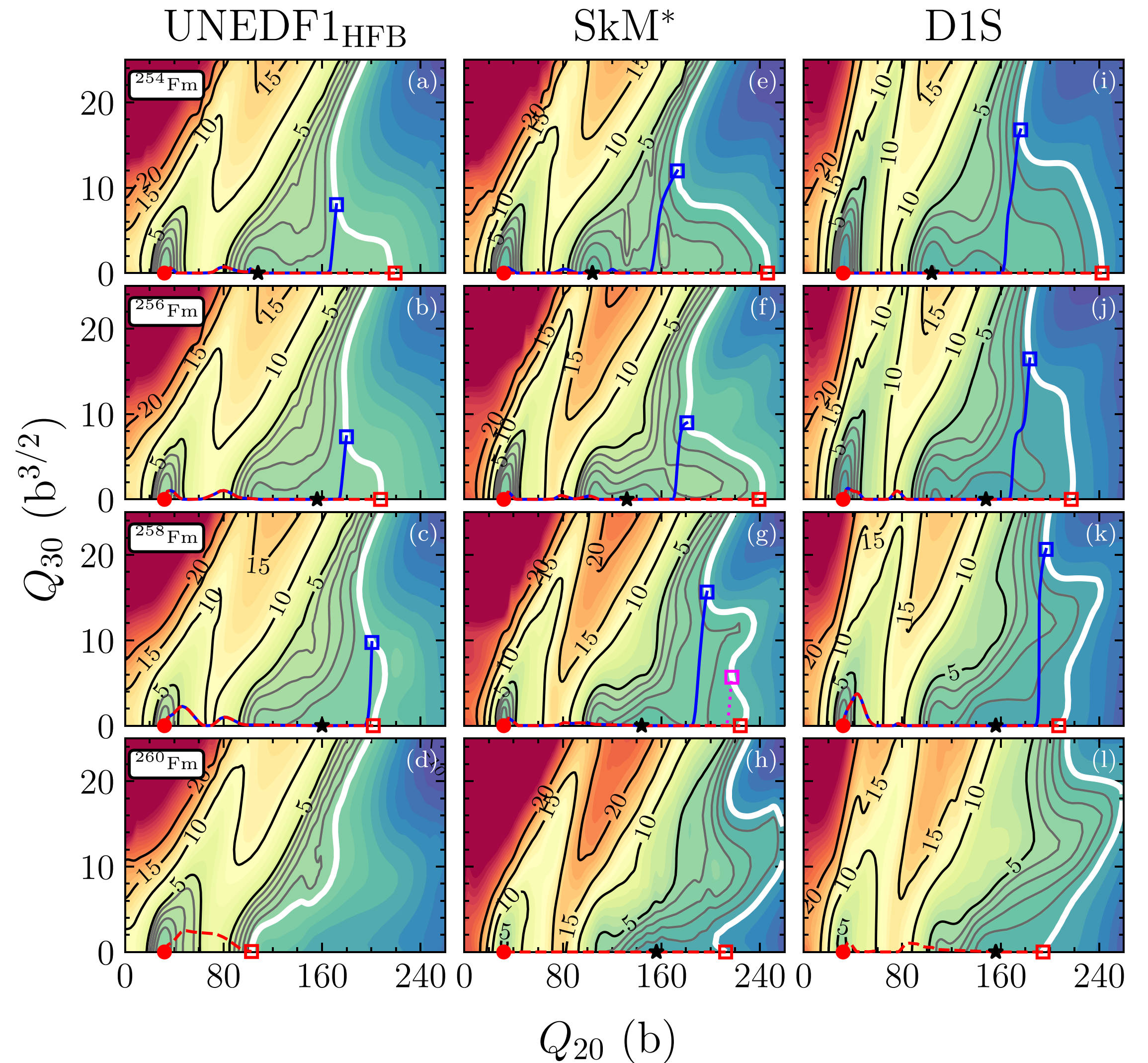
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Neutron capture

- Hauser-Feshbach calculations
 - γ -SF, level density, optical potential

Fission properties

- PES and fission yield calculations with Skyrme-HFB
- Global calculations are led by
 - Daniel Lay (FRIB/MSU, now at Argonne),
 - Eric Flynn (FRIB/MSU)
- Combine with HF for *n*-induced / β -delayed fission



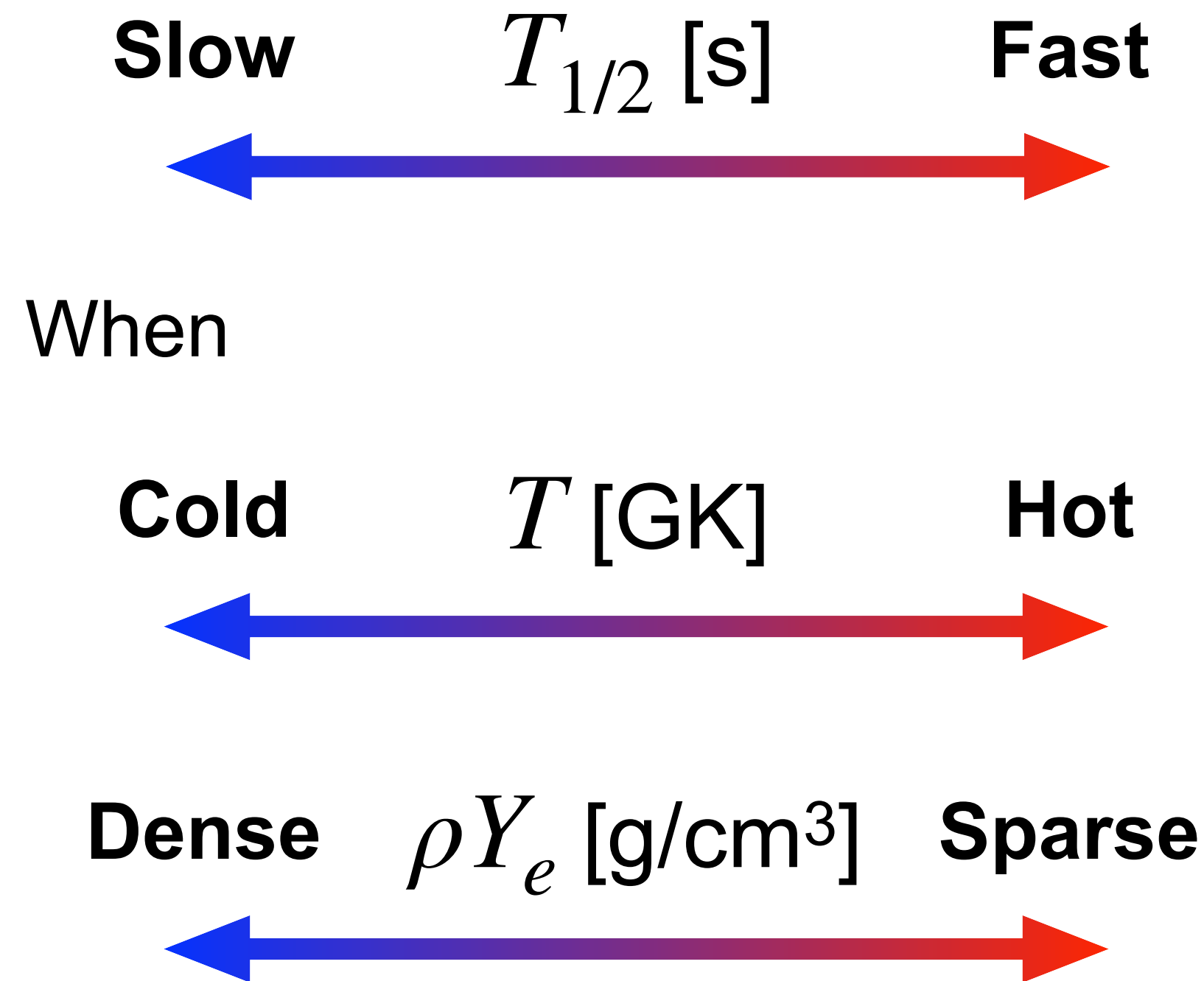
D. Lay, E. Flynn, et al., Phys. Rev. C 109, 044306 (2024)

Finite-temperature effect on β -decay rates

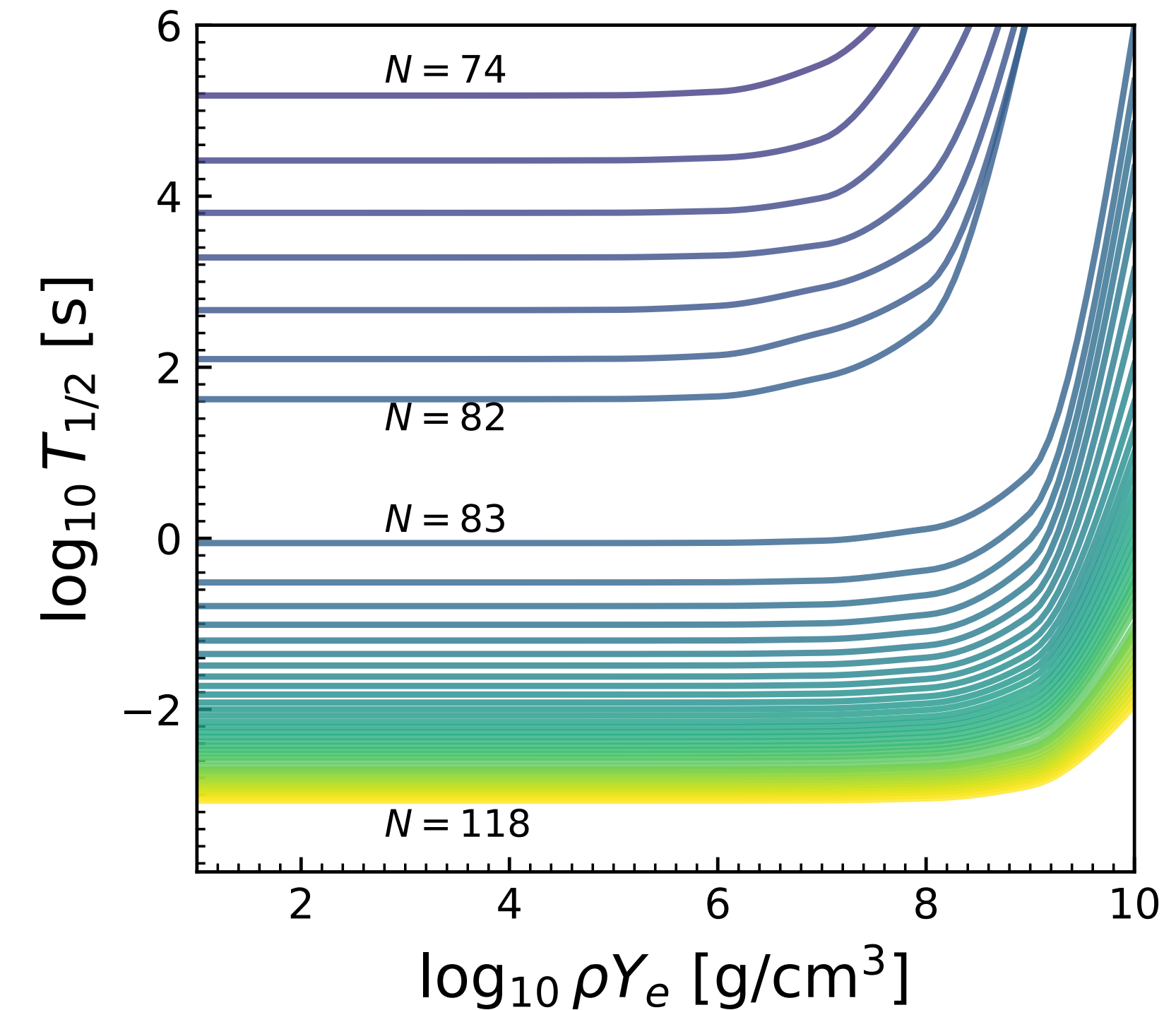
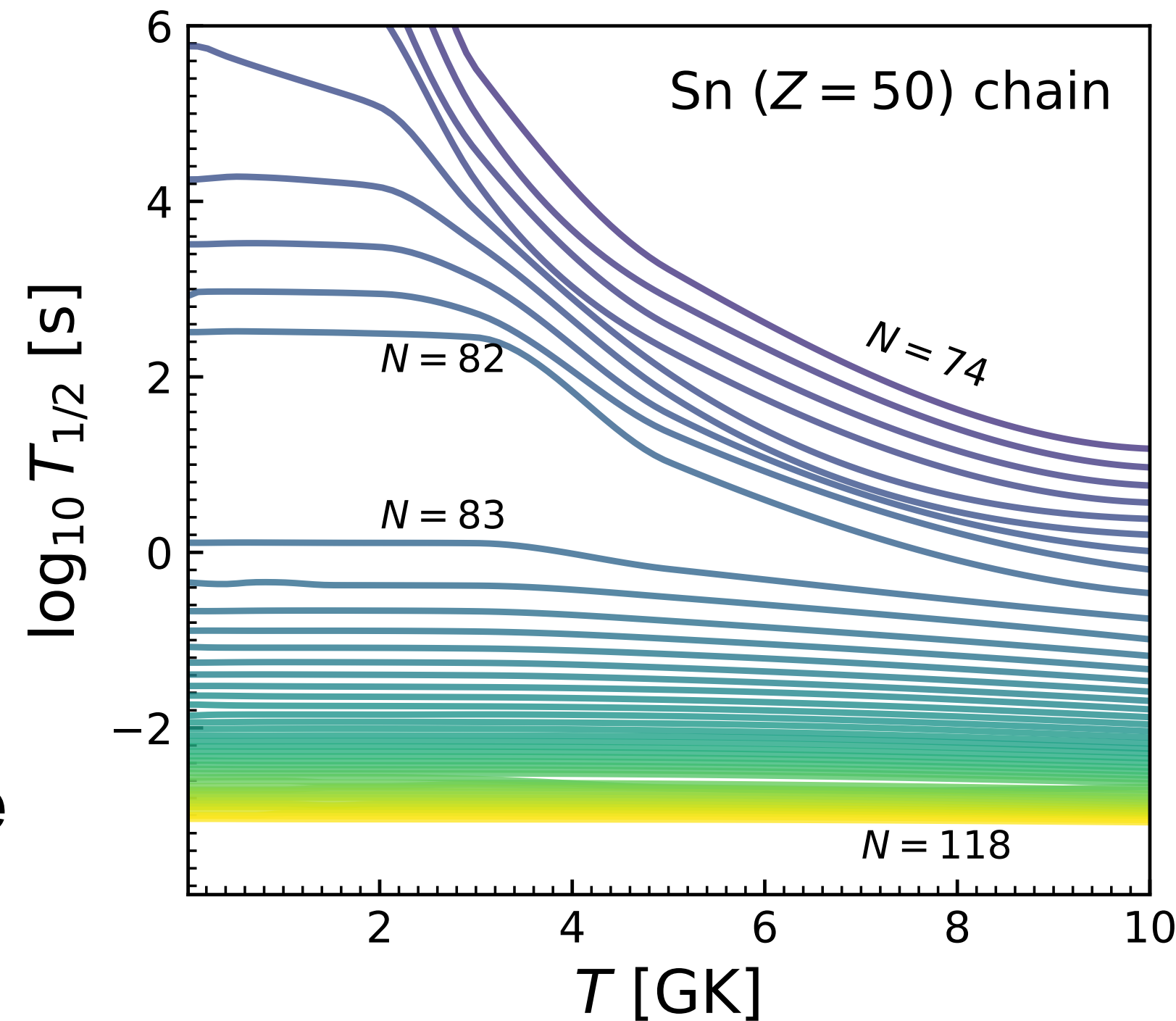
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- Hot environment ($T > 1$ GK) has various effects on the properties of nuclei
Systematic study: Ravlić et al. PRC, **104**, 054318 (2021) and PRC **109**, 014318 (2024)

- β -decay:



Finite-temperature effect on β -decay half-lives
calculated with FT-pnRQRPA (Ravlić et al.)



- May have an impact in the early stage of the r -process, when it is hot and near stability

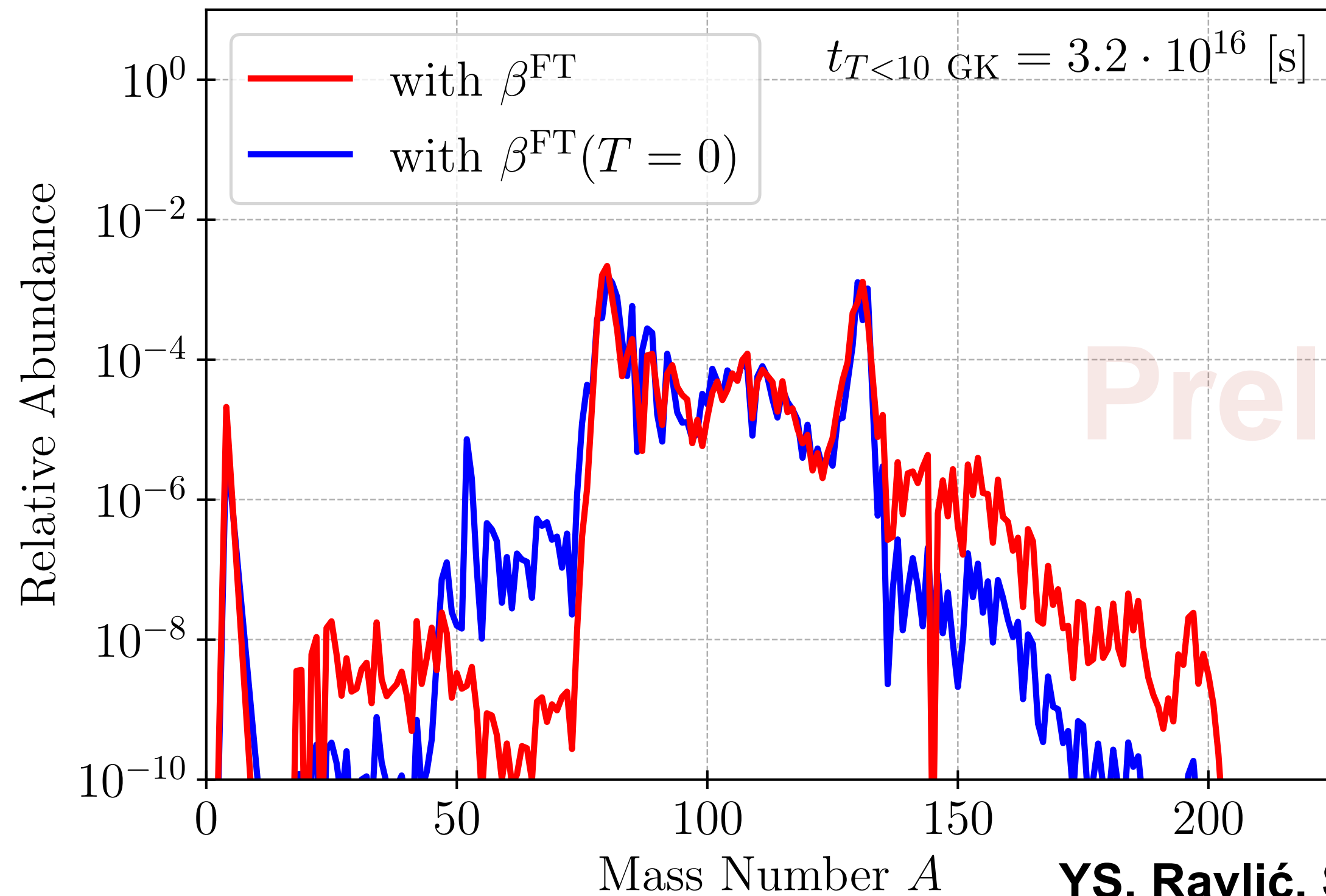
YS, Ravlić, Surman (in preparation)

Effect in weak r -process conditions

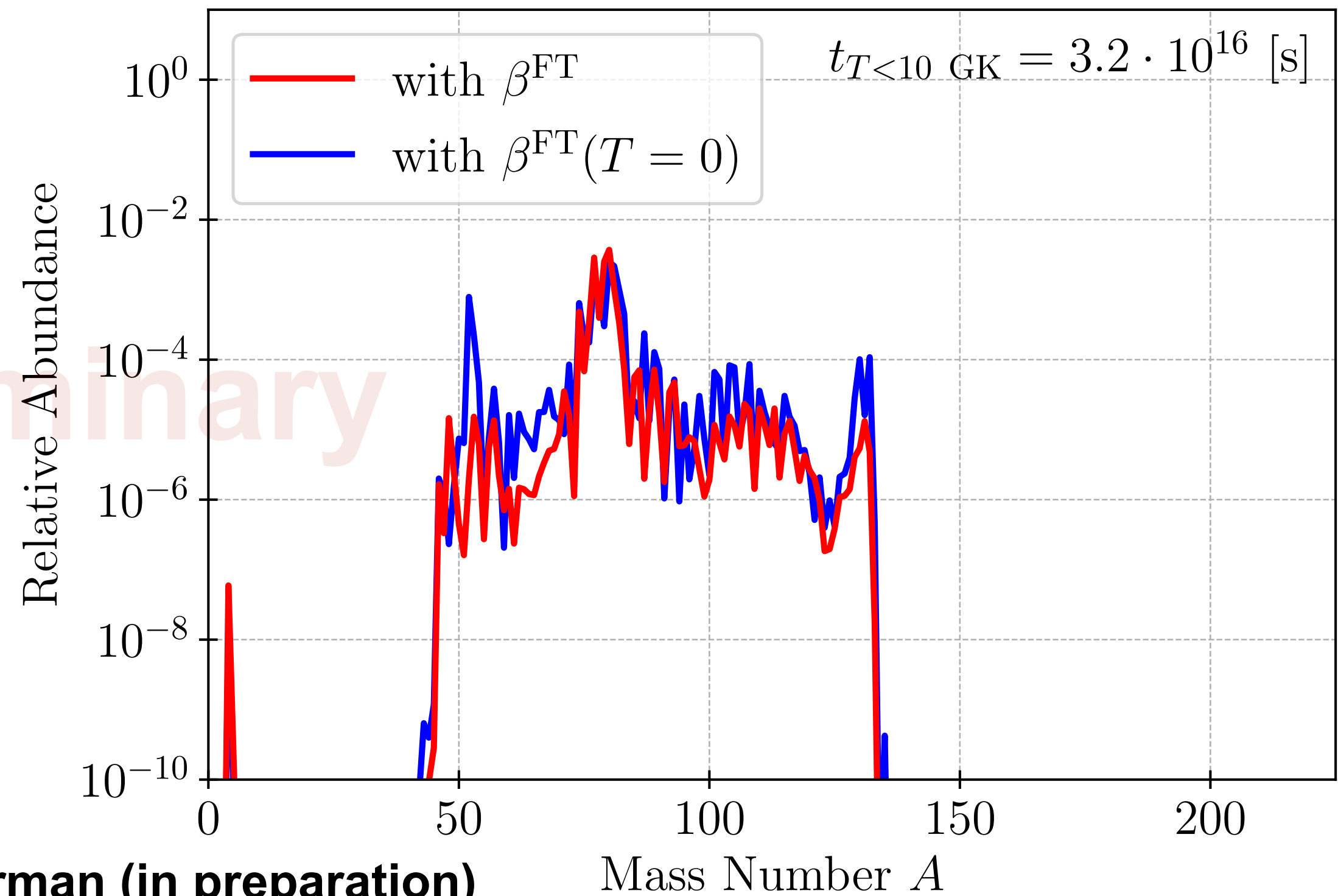
- Astrophysical conditions:
 - ✱ Magneto-rotational supernovae: Reichert et al. MNRAS 501, 5733 (2021)
 - ✱ HMNS disk outflow: Metzger & Fernández MNRAS 441, 3444 (2014)
- T - ρY_e - dependent β -decay rates for $20 \leq Z \leq 60$ isotopes

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MRSN weak r example

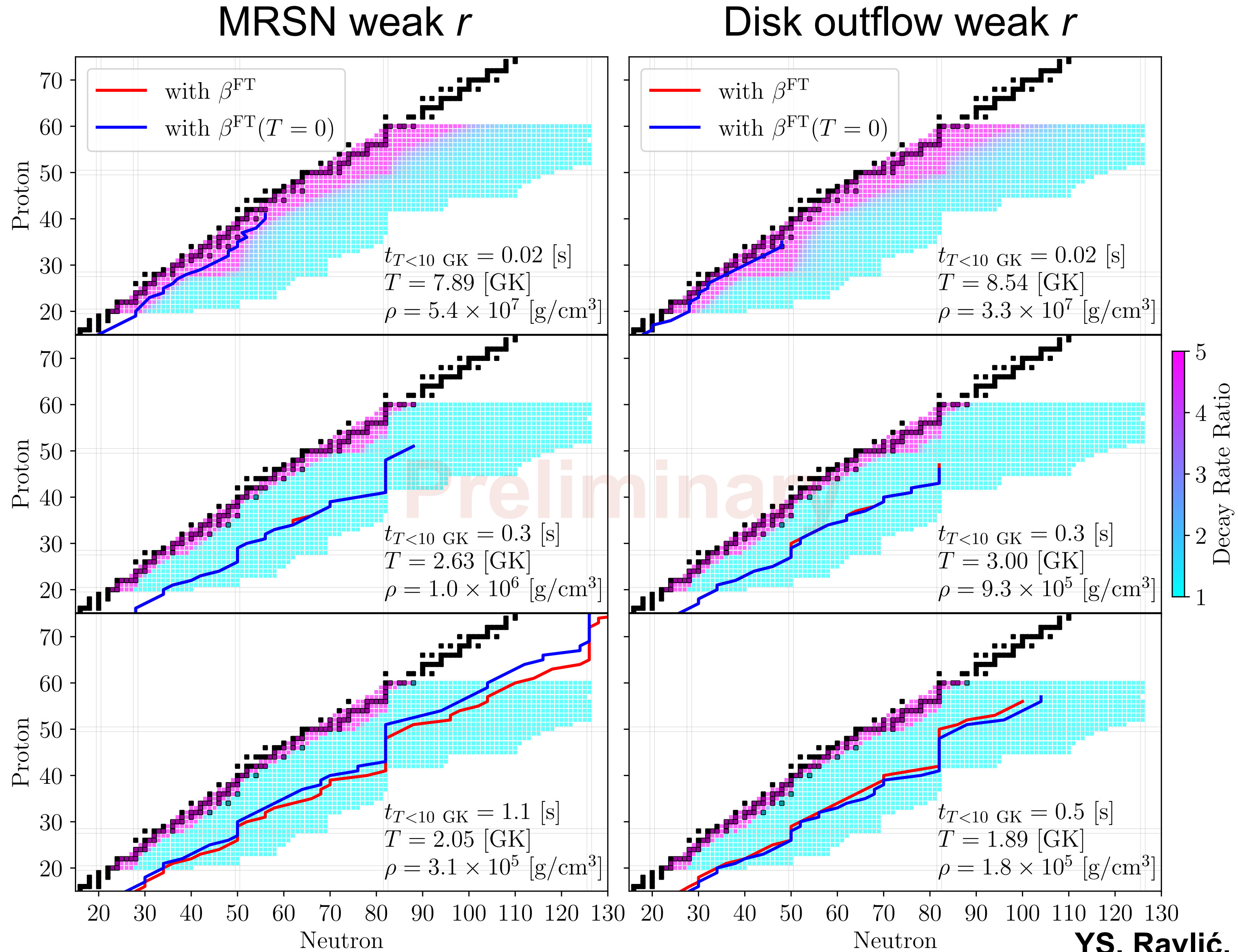


Disk outflow weak r example



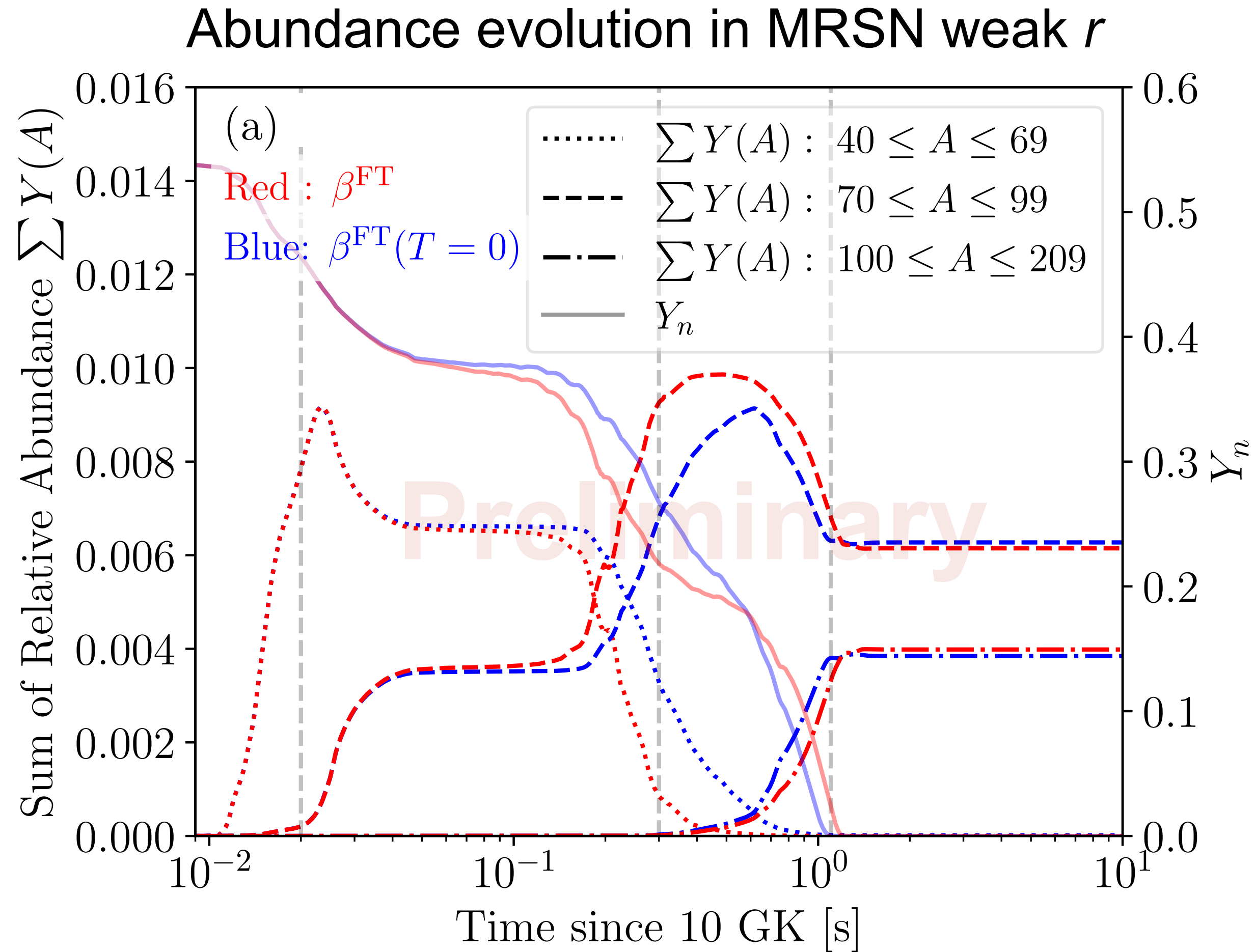
Effect in weak r -process conditions

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Effect in weak *r*-process conditions

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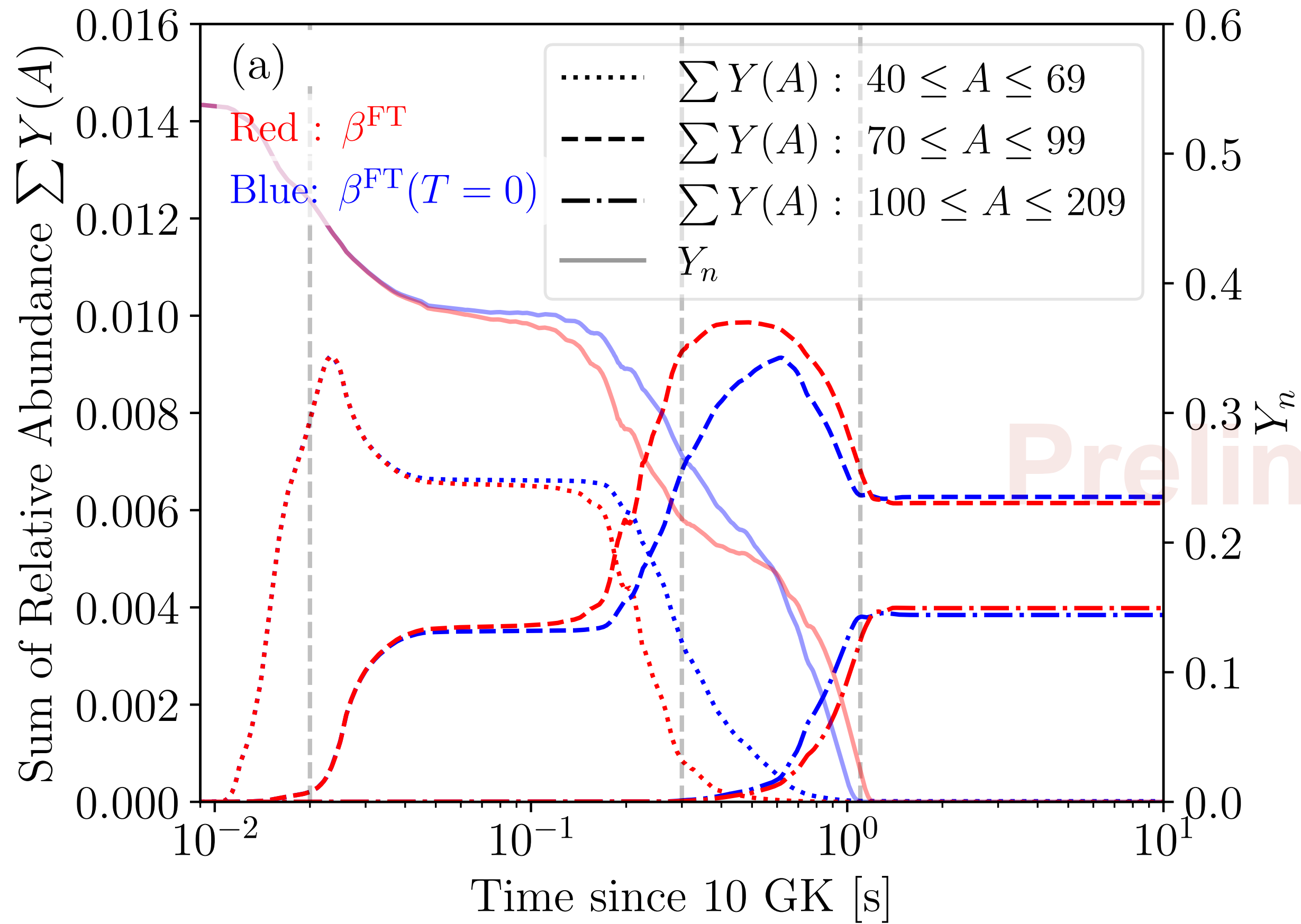
YS, Ravlić, Surman (in preparation)

- Faster β -decay rates enhance $A \sim 80$ peak
- Faster β -decay rates also enhance the consumption of free neutrons
- Depending on the availability of free neutrons after $A \sim 80$ peak reaches a maximum, production of heavier elements may be either enhanced or suppressed.

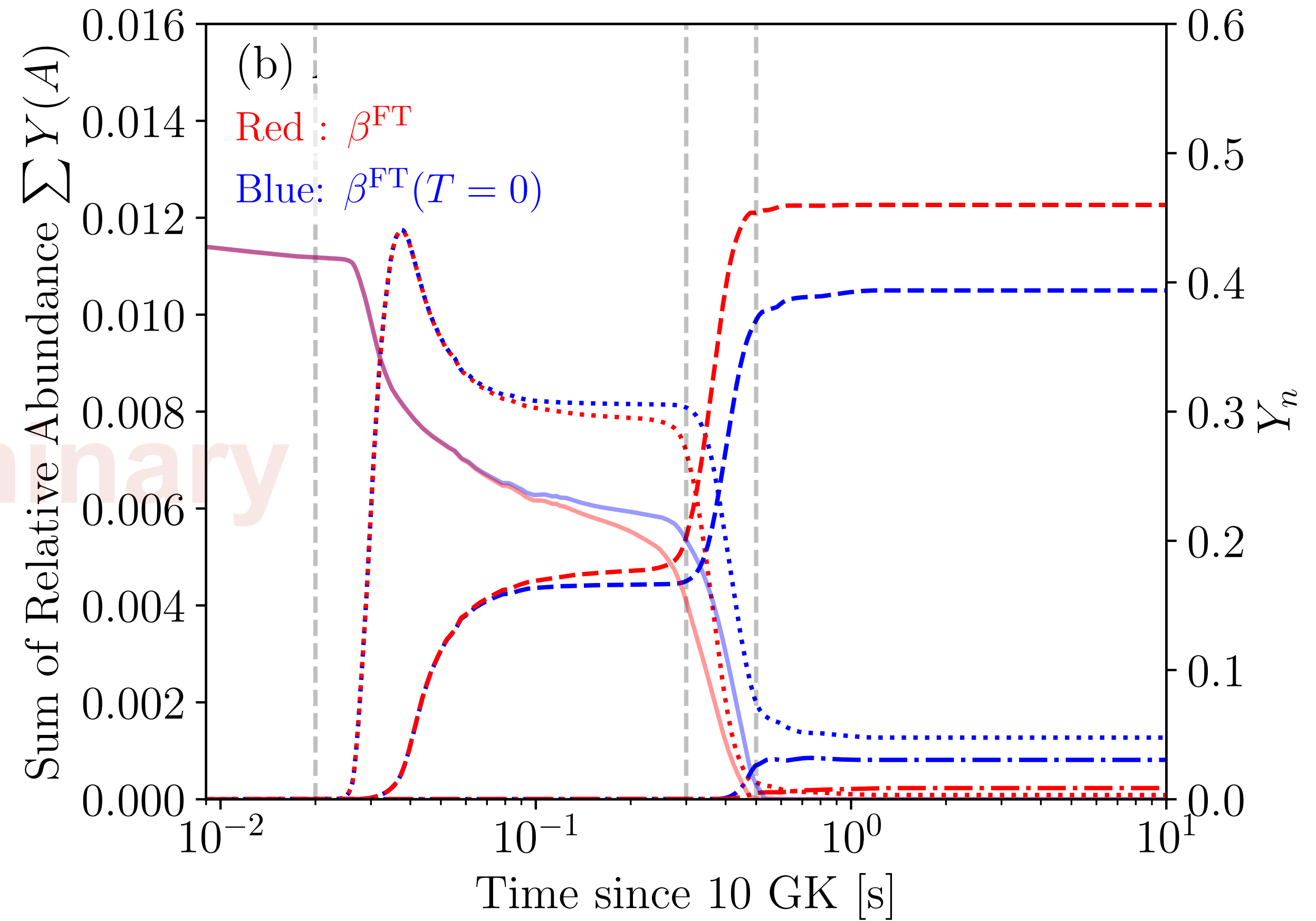
Effect in weak r-process conditions

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Abundance evolution in MRSN weak r



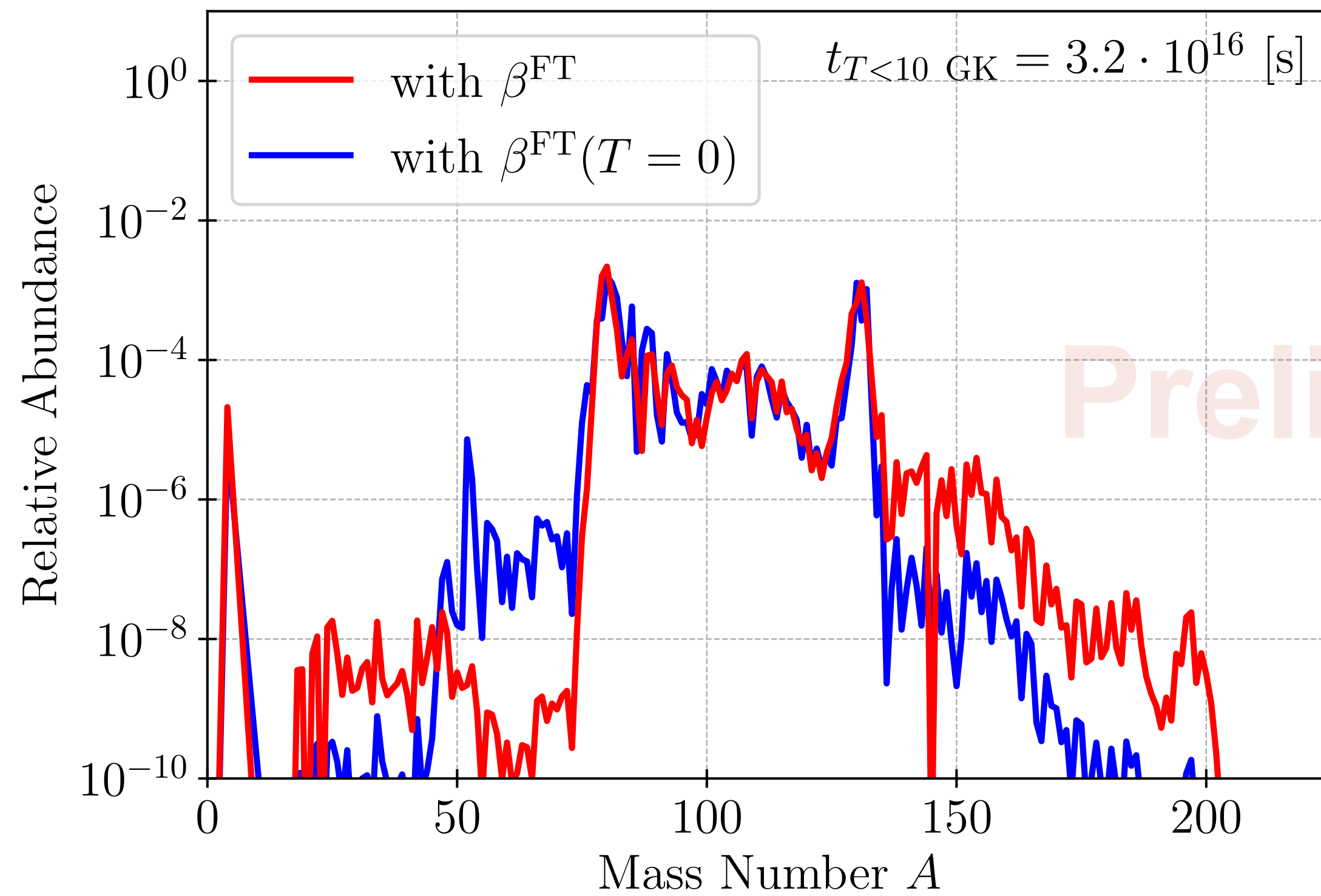
Disk outflow weak r



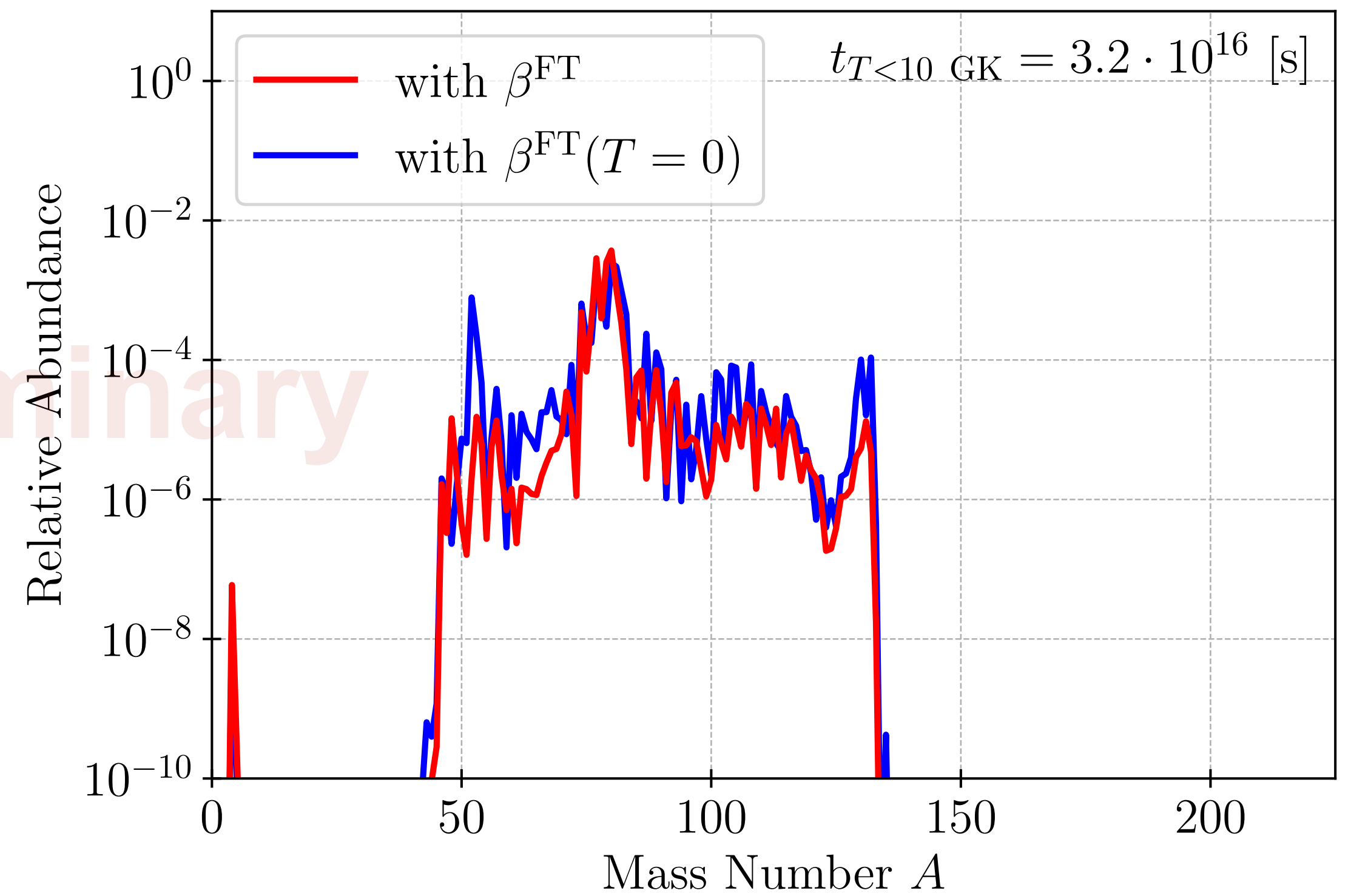
Effect in weak r-process conditions

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Final abundance for MRSN weak r



Disk outflow weak r

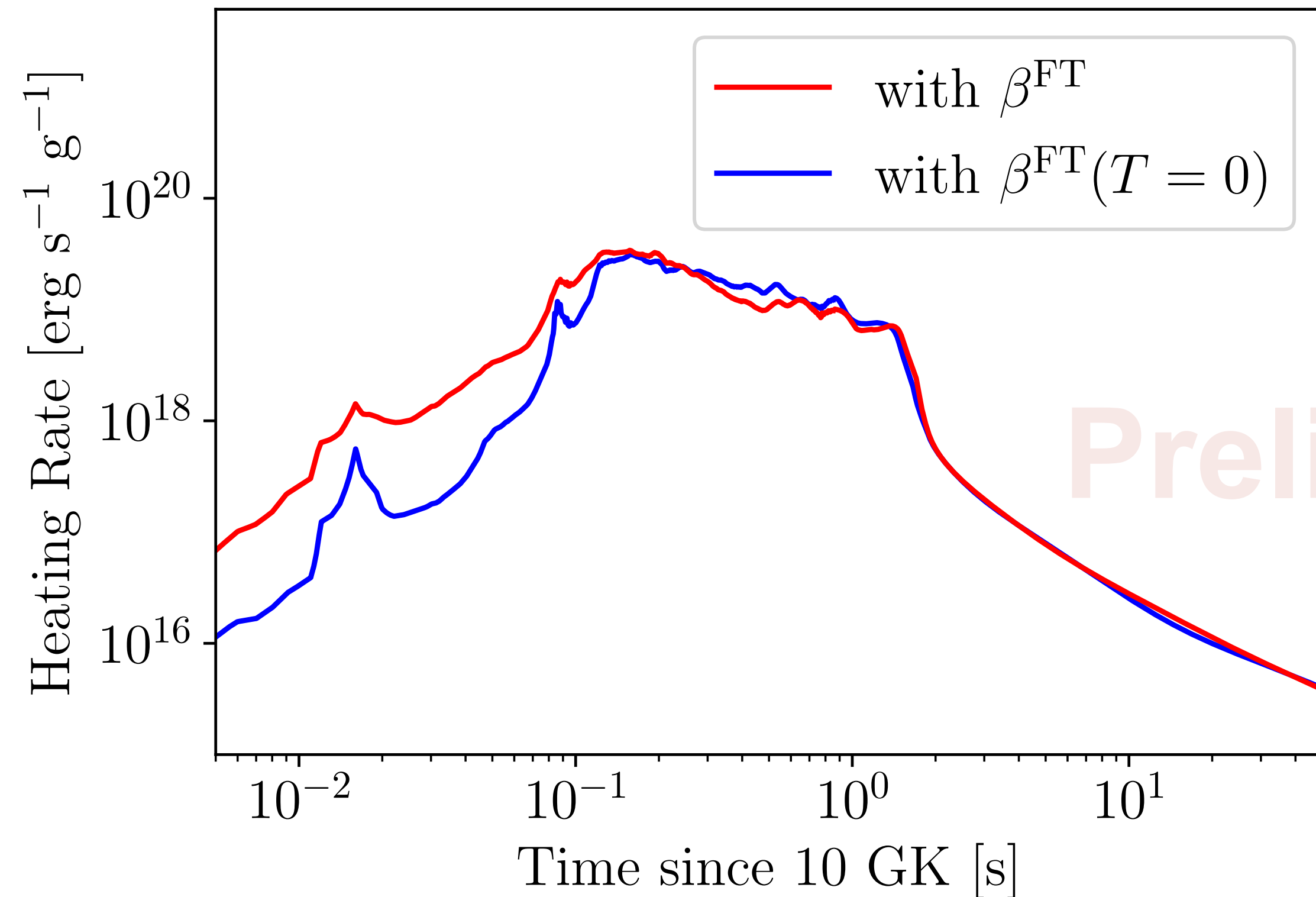


Effect on energy release

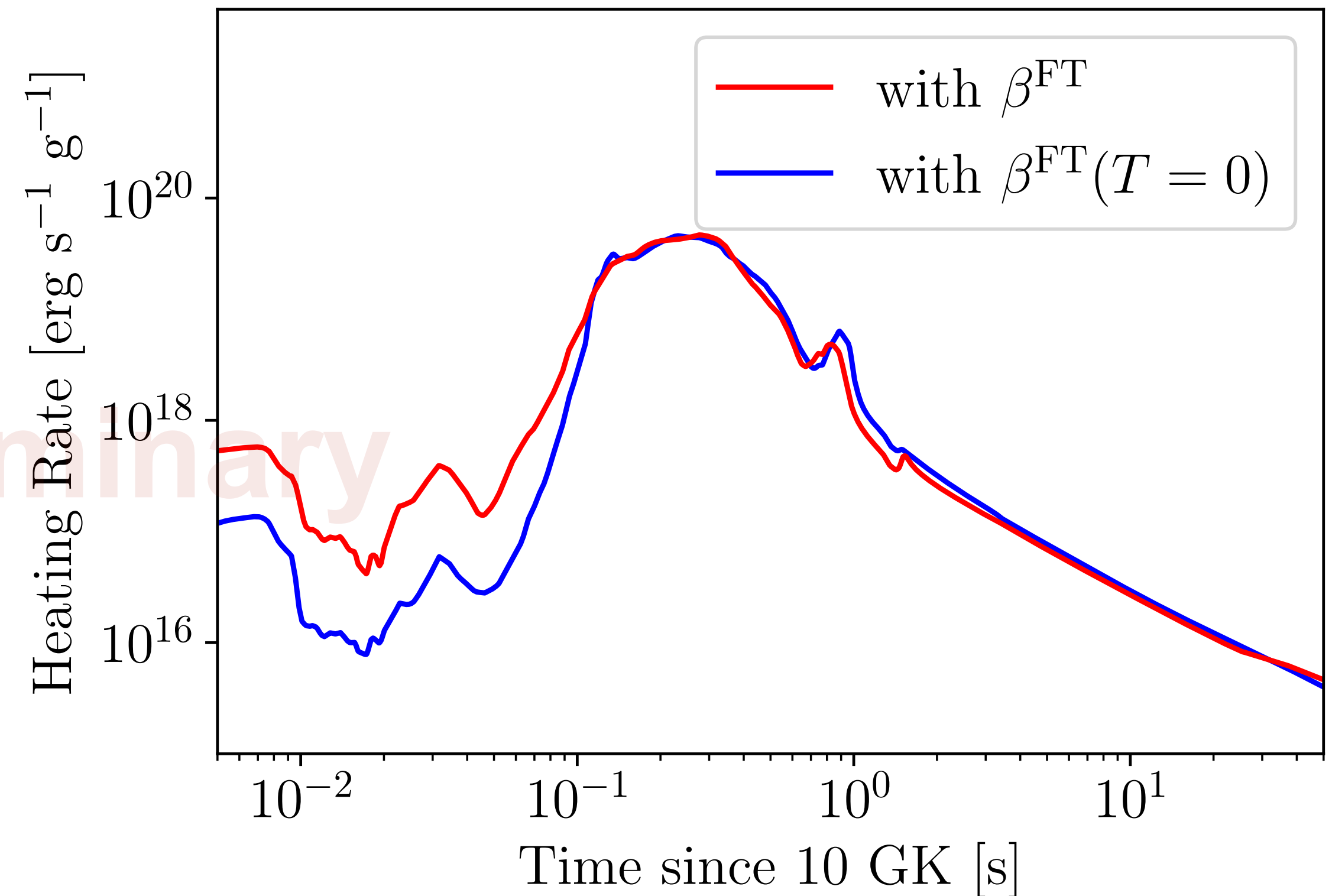
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- Faster β -decay rates at the beginning increase the heating rate
 - Inclusion of nuclear reheating may further enhance the effect.
- Related talk: Wednesday, Session APR-R11, Pranav Nalamwar (Notre Dame)

Energy release rate for MRSN weak r



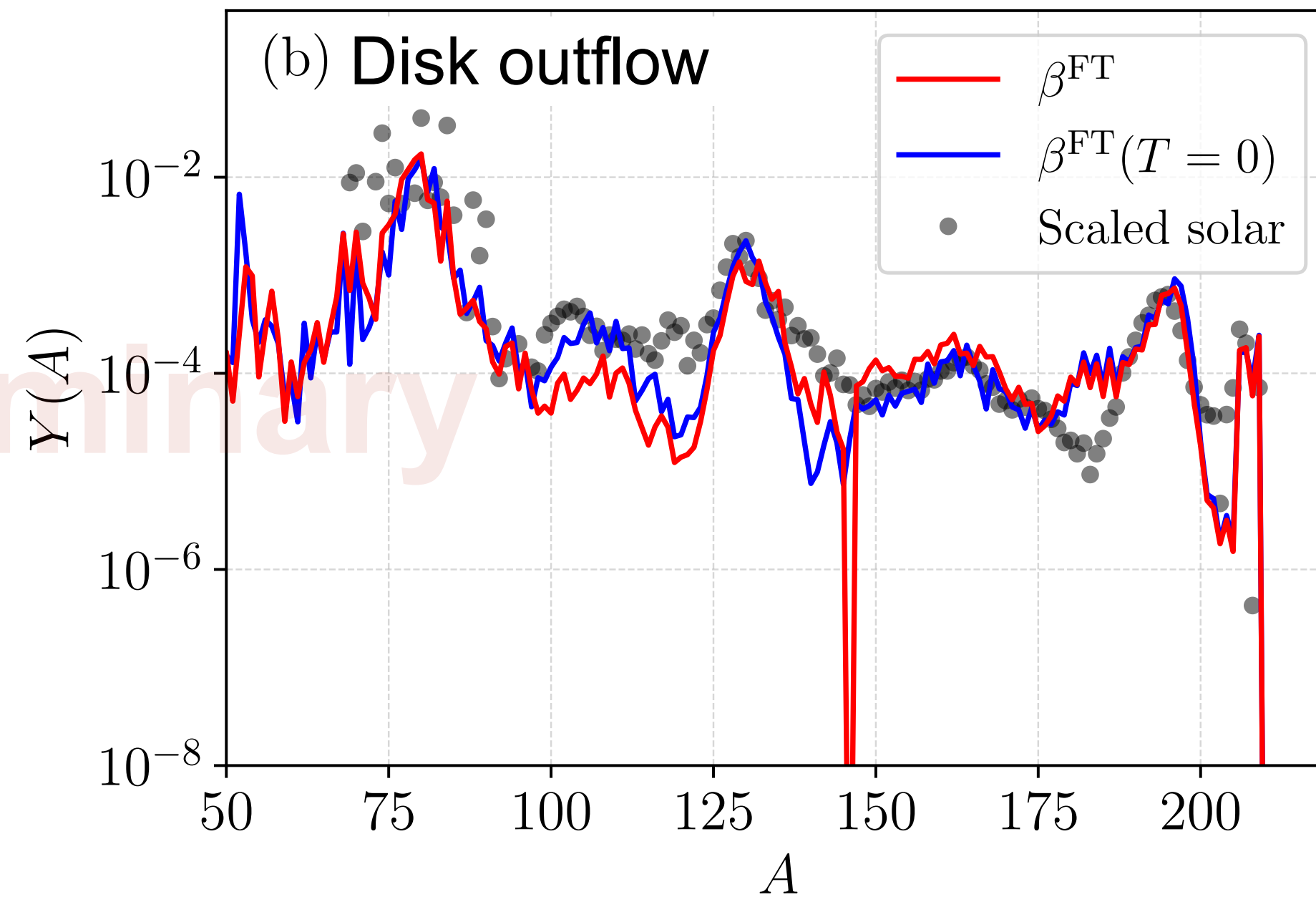
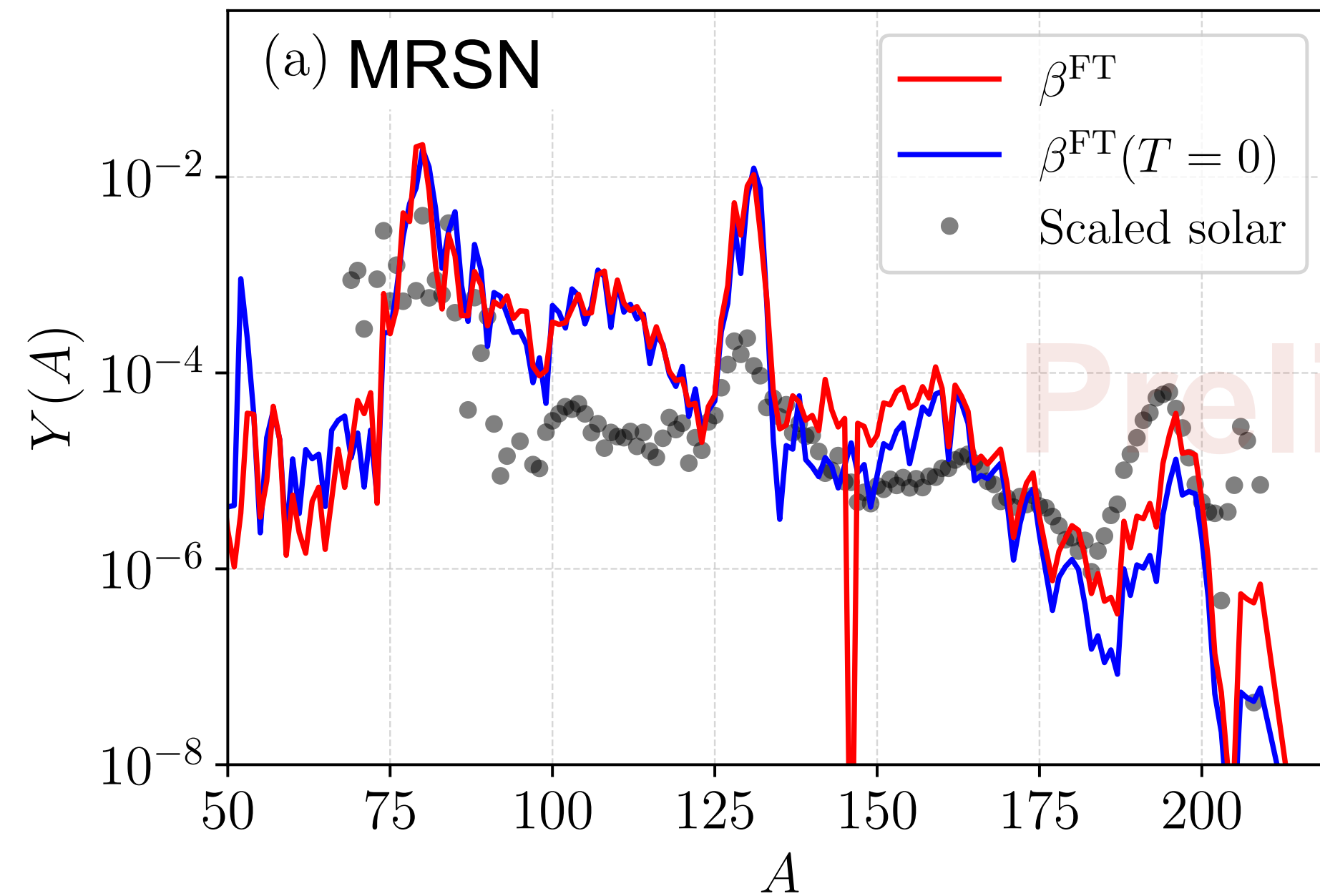
Disk outflow weak r



Finite Temperature β -decay: Summary and outlook

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- Finite-temperature β -decay rates of nuclei $20 \leq Z \leq 60$ included in the r -process
- Increased β -decay rates in a hot environment (initial phase of the r -process) have implications for the r -process nucleosynthesis.
- In addition to $(n, \gamma) \leftrightarrow (\gamma, n)$ and freeze-out phases, β -decay may play a role in the early phase.



Summary and outlook

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- New axially deformed relativistic calculations consistent with non-relativistic calculations.
- β -decay rates significantly affect the (neutron-induced) fission flows and formation of $A \sim 196$ peak.
 - Effect on observables e.g. abundances in metal-poor stars, kilonovae (Kelsey's talk)
- Finite temperature β -decay may play a role in the early phase of the r -process.
- Future direction: consistent and uncertainty-quantified nuclear data based on many-body theories

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- Rebecca Surman

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- Matt Mumpower

FRIB, Michigan State University

- Ante Ravlić
- Witek Nazarewicz
- Kyle Godbey

NP3M Collaboration



Propagation of nuclear physics uncertainty in nuclear reaction network calculations

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Nuclear mass model

Uncertainty in
phenomenological/microscopic
description of ground state



Reaction/decay rates

Mass uncertainty propagated to

- Neutron capture
- Photodissociation
- β -decay
- β -delayed neutron emission
- Fission rates & products

Systematic uncertainty in
the descriptions of reaction/decay



Nuclear reaction network calc.

Uncertainty in

- Treatment of heating
- Assumptions in astrophysical trajectory
- Unaccounted for reactions (e.g. neutrinos)

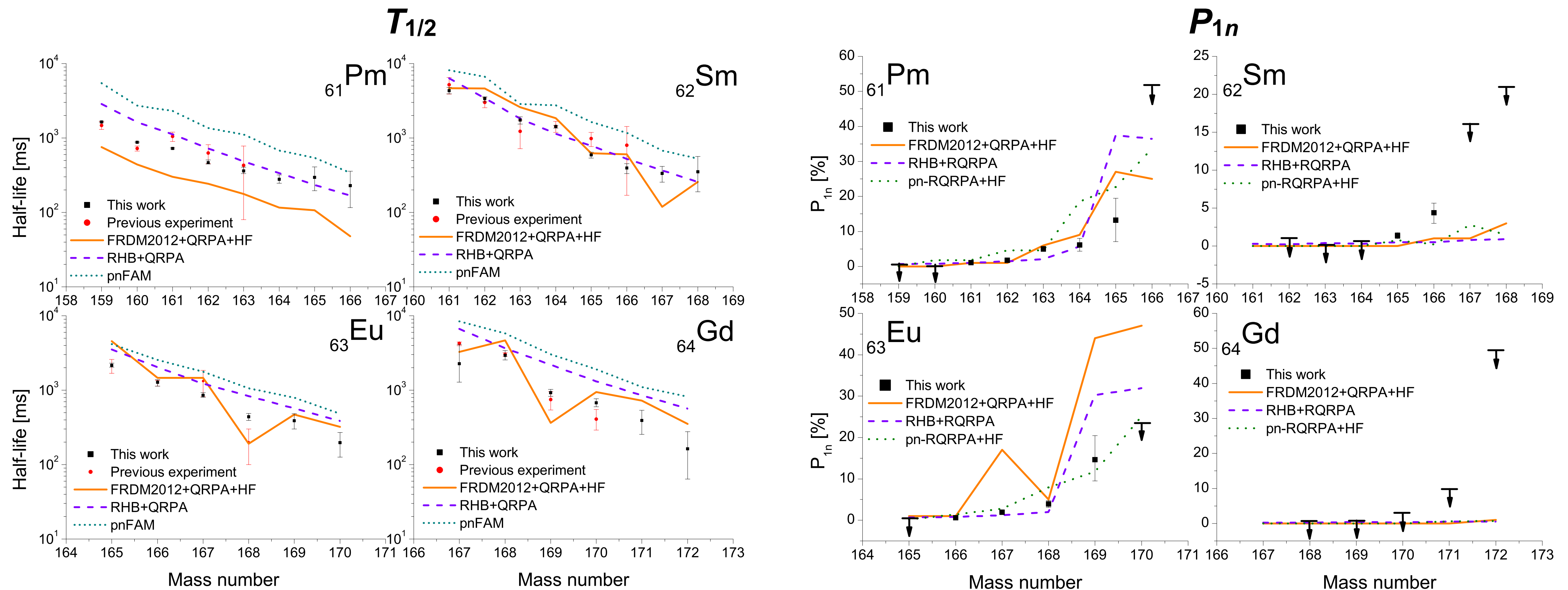
Underlying nuclear physics models / assumptions are not necessarily consistent.

BRIKEN experimental data

P_{1n} and $T_{1/2}$ of $^{159-166}\text{Pm}$, $^{161-168}\text{Sm}$, $^{165-170}\text{Eu}$, and $^{167-172}\text{Gd}$

measured with the BRIKEN detector system (28 isotopes, **9 new** $T_{1/2}$ and **28 new** P_{1n})

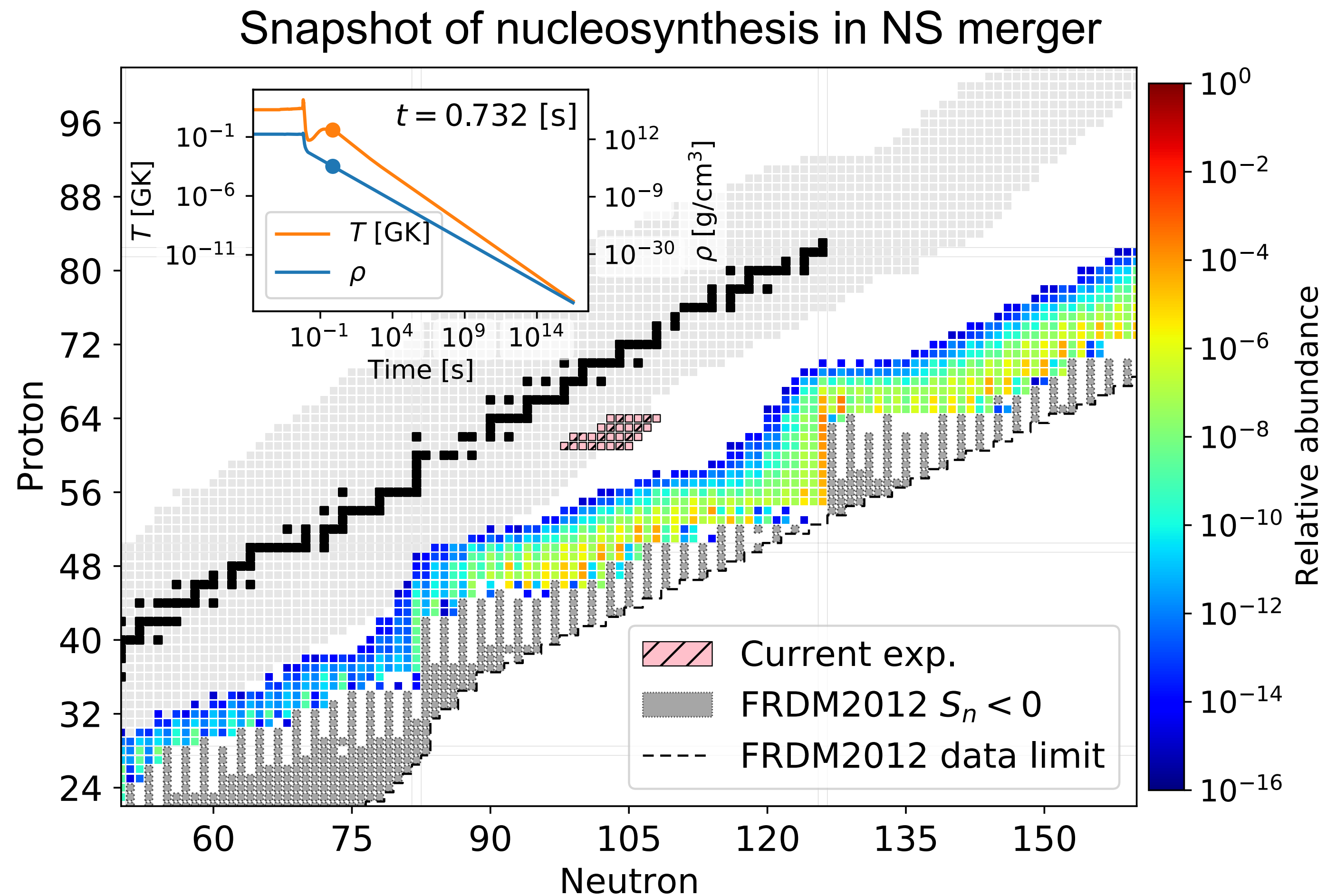
New experimental data from BRIKEN



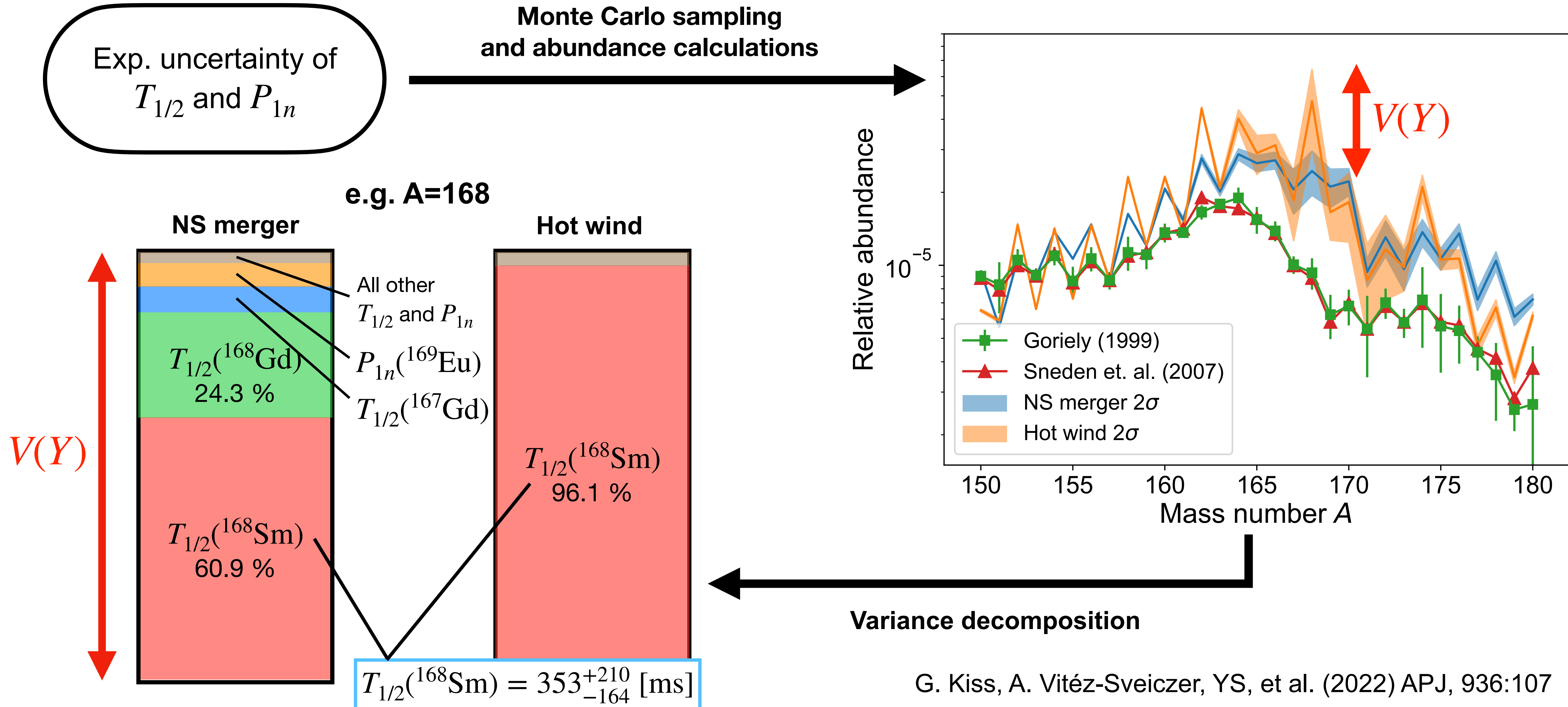
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Variance-based sensitivity analysis



Variance-based sensitivity analysis

