β-decay of ^{133}In: a bridge between nuclear structure and the r-process

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on behalf of the VANDLE group at UTK
and the IDS collaboration at ISOLDE-CERN

THE UNIVERSITY OF TENNESSEE KNOXVILLE

14th Conference on the Intersections of Particle and Nuclear Physics
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Lake Buena Vista, Florida

- Physics motivation
- Experimental setup
- Results and discussion
- Theoretical calculations
- Summary and outlook

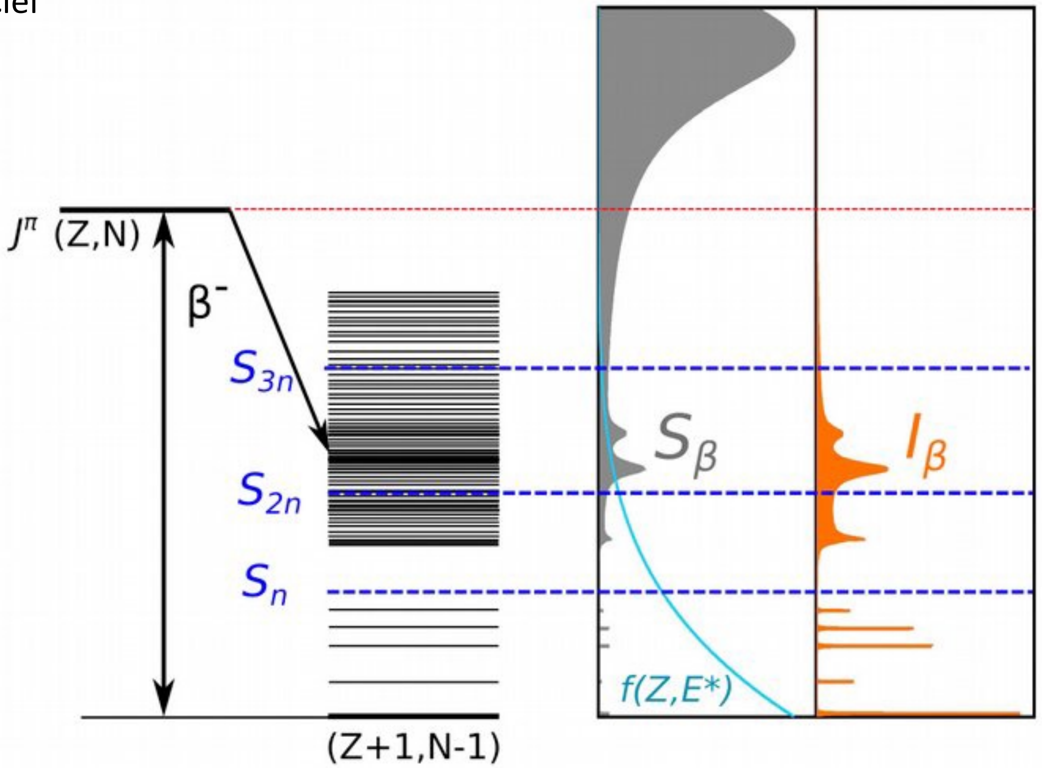
Beta decay, nuclear structure, and the r-process

$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i) \qquad S_\beta(E_i) = \left| \langle \psi_f | \hat{O}_\beta | \psi_{mother} \rangle \right|^2$$

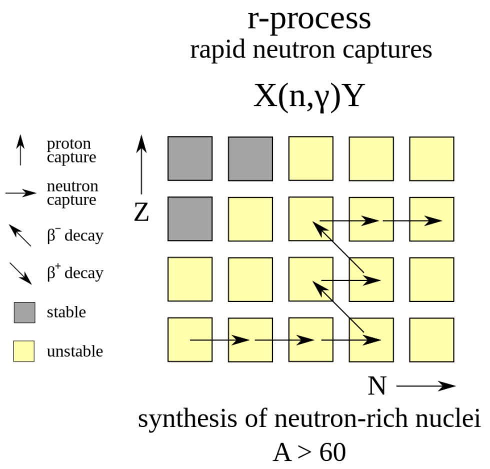
- S_β (β-decay strength) ← Wavefunction overlap between parent and daughter nuclei
- $f(Z, Q_\beta - E_i)$ ← phase-space factor (Fermi integral)

Why studying S_β is important?

- Nuclear structure in parent and daughter nuclei
- S_β → Gross nuclear β-decay properties ($T_{1/2}$, P_n, etc)
- Key inputs to understand nucleosynthesis (e.g., the r-process)



The role of nuclear physics in nucleosynthesis

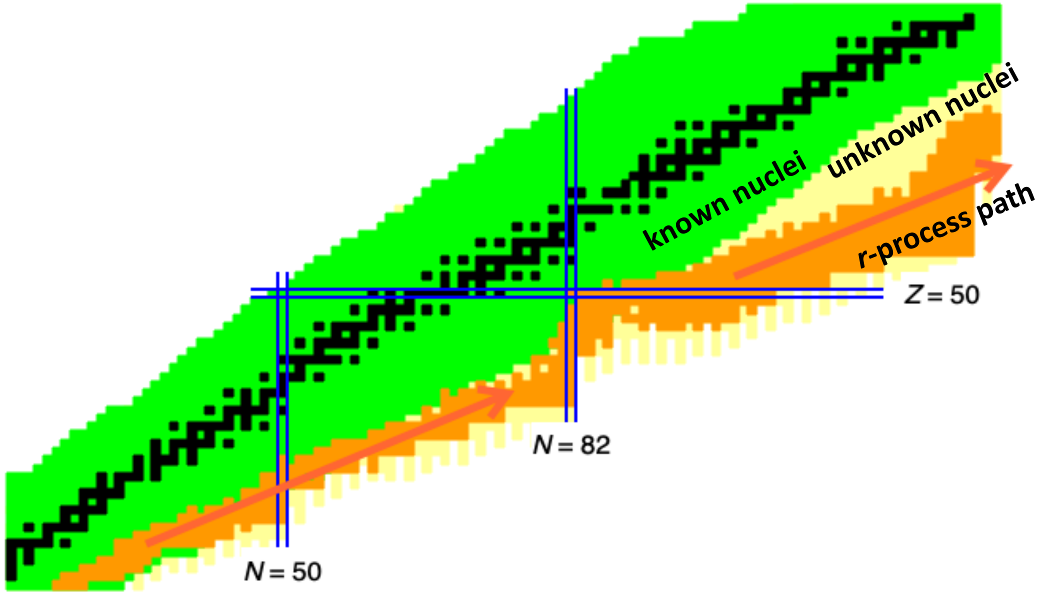


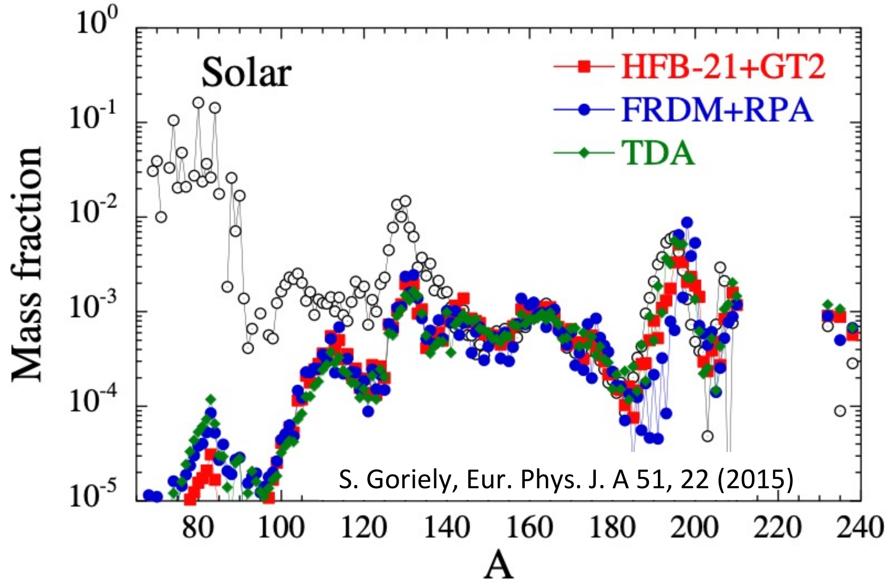
The r-process: rapid neutron capture + β decay

Requires the β-decay properties of a large number of neutron-rich nuclei (out of experimental reach)

Global models are employed to predict those unknown properties

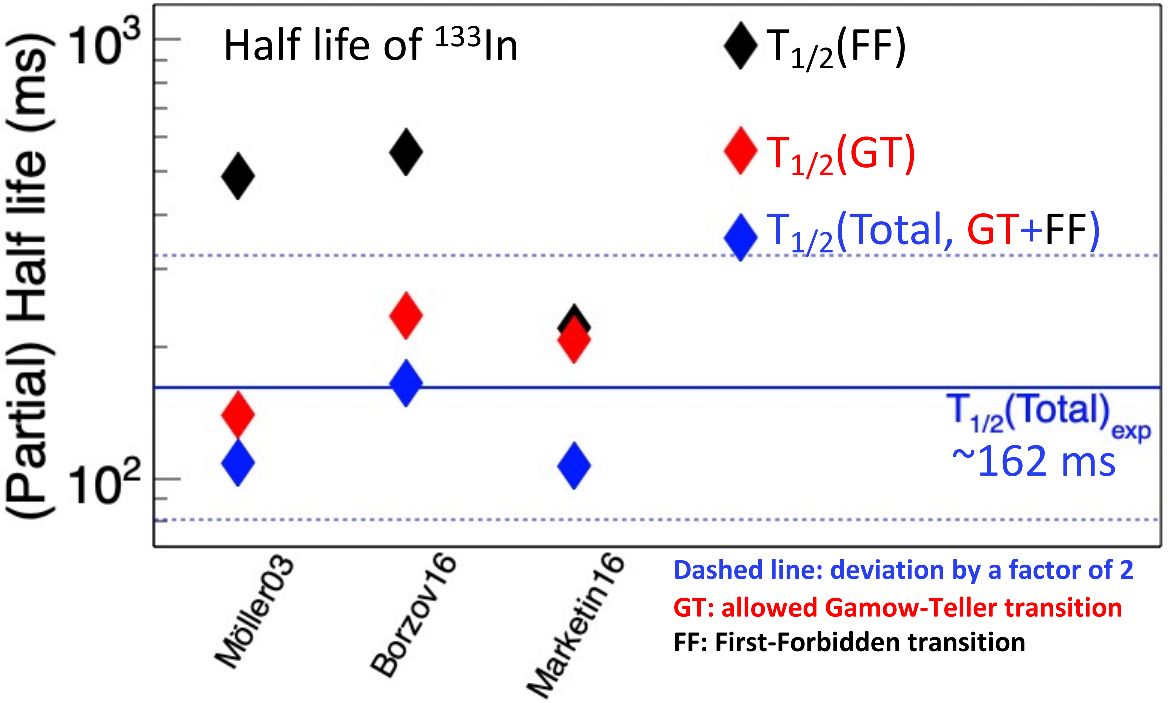
Their S_β needs to be verified by experimental measurement!





Experimental measurements resolve theoretical ambiguity

Similar $T_{1/2}$ may be predicted from **different** S_β distribution



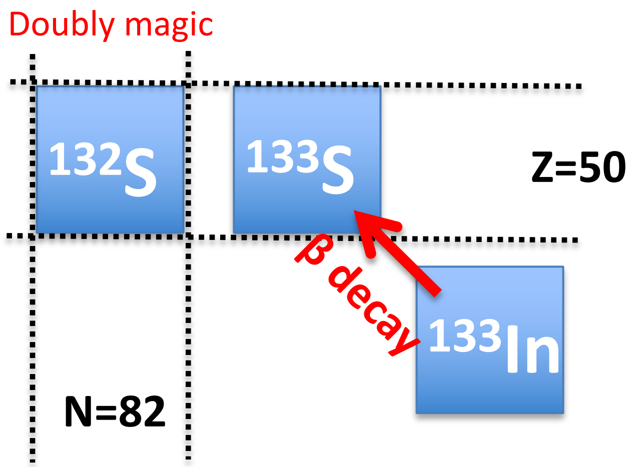
Dashed line: deviation by a factor of 2
GT: allowed Gamow-Teller transition
FF: First-Forbidden transition

- Moller03: P. Möller et al., Phys. Rev. C 67, 055802 (2003).
- Borzov16: I. Borzov, Physics of Atomic Nuclei 79, 910–923 (2016).
- Marketin16: T. Marketin et al., Phys. Rev. C 93, 025805 (2016).

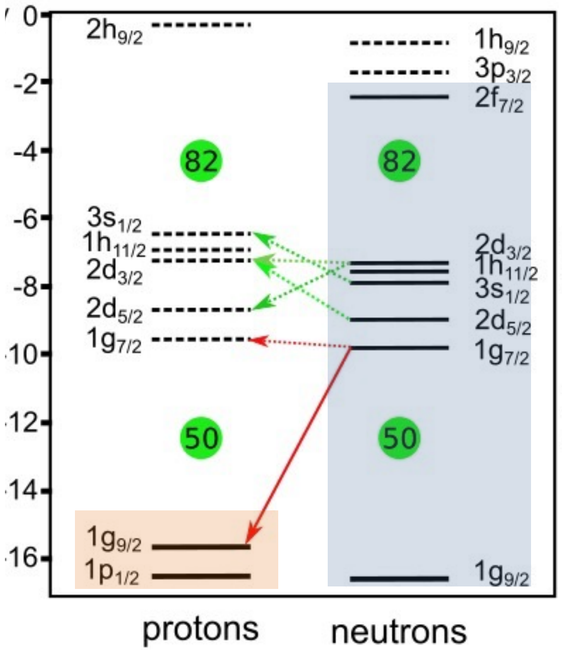
Measuring beta-strength function in the r-process nuclei
→ Strong constrain on nuclear theories

^{133}In (Z=49 and N=84) is special:

- ^{133}In → ^{133}Sn* → ^{132}Sn+*n*: system with simple structure
- Large neutron-proton asymmetry → a variety of decay channels that are available in the r-process nuclei
- A perfect beta-decay demonstrator in the southeast of ^{132}Sn

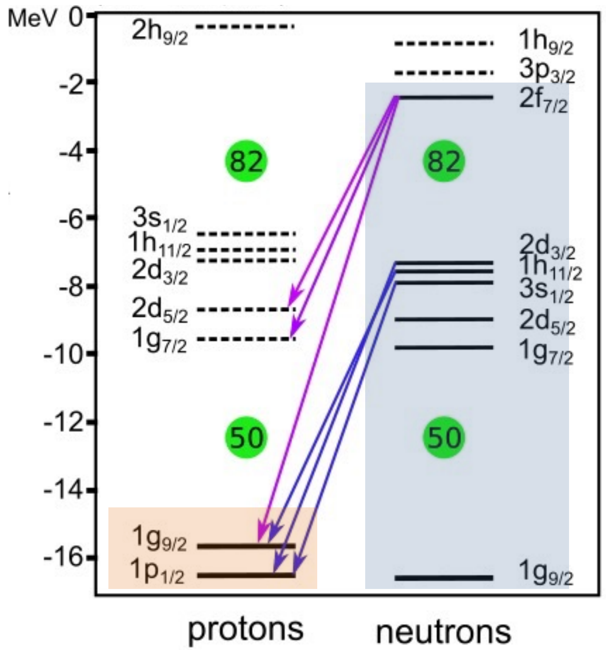


Strong β-decay channels in the southeast of ^{132}Sn (Z<50, N>82)



GT transitions

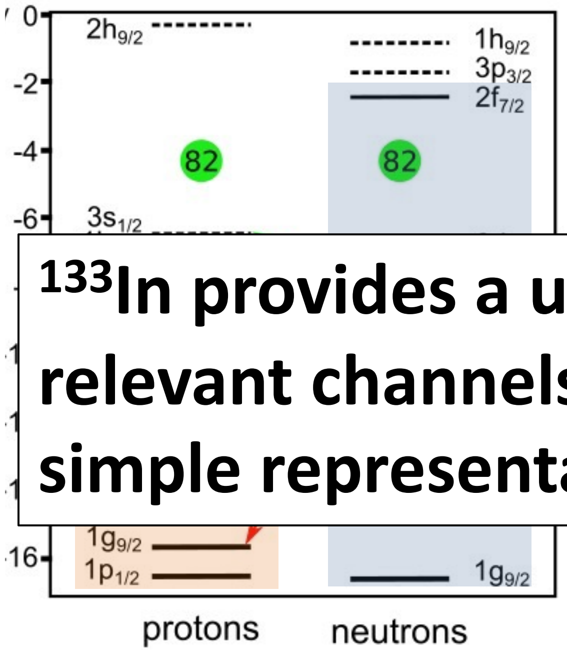
- A strong GT transition $\nu g_{7/2} \rightarrow \pi g_{9/2}$
- No other GT transitions equally competitive
- Dominates the β decay of the whole area

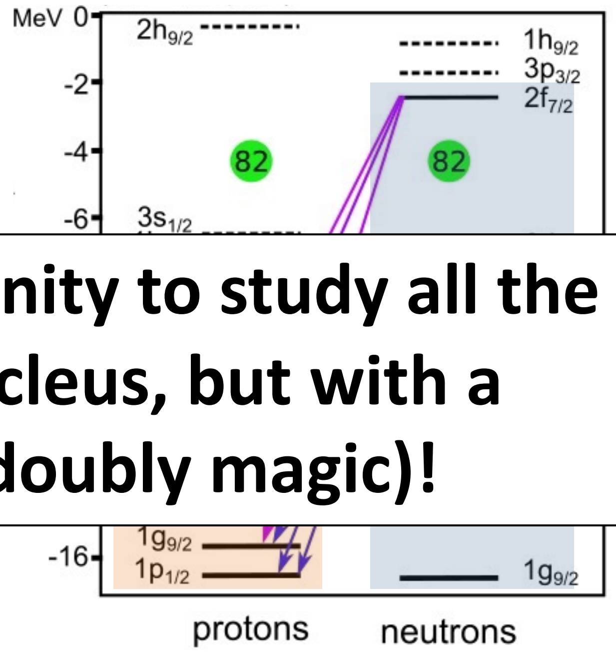


FF transitions

- Smaller transition matrix than the GT transition
- Large transition energy (phase-space factor) due to the asymmetric neutron-to-proton ratio
- Competing with the GT transition, shorten the half life

Strong β-decay channels in the southeast of ^{132}Sn (Z<50, N>82)





^{133}In provides a unique opportunity to study all the relevant channels in a single nucleus, but with a simple representation (^{132}Sn is doubly magic)!

GT transitions

- A strong GT transition $\nu g_{7/2} \rightarrow \pi g_{9/2}$
- No other GT transitions equally competitive
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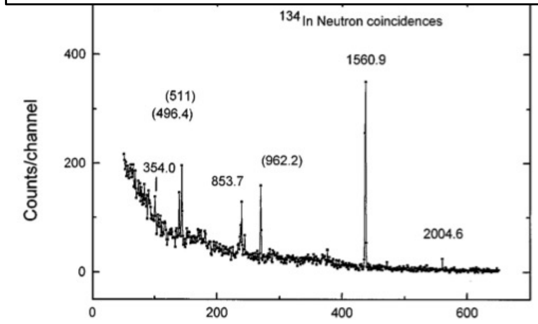
FF transitions

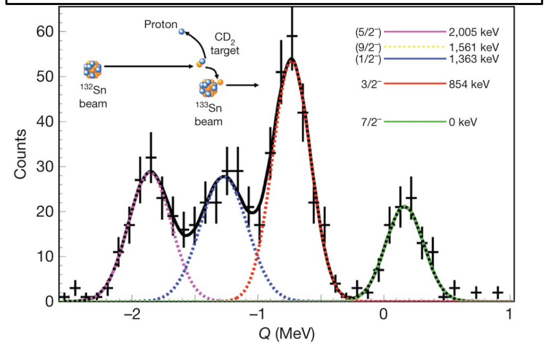
- Smaller transition matrix than the GT transition
- Large transition energy (phase-space factor) due to the asymmetric neutron-to-proton ratio
- Competing with the GT transition, shorten the half life

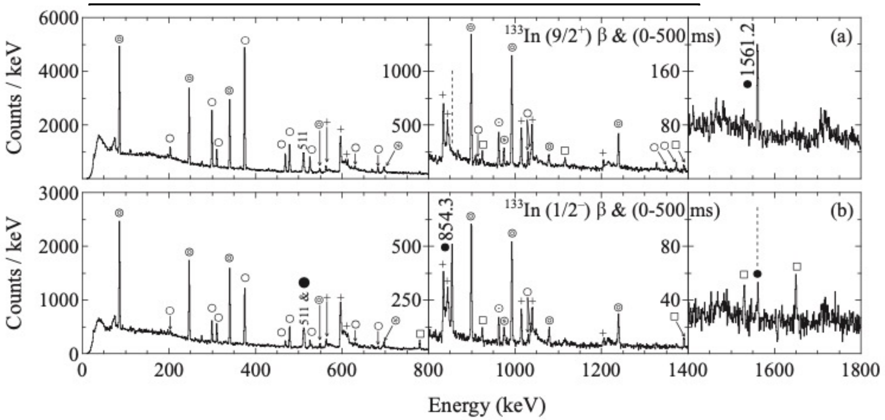
The main decay channel in ^{133}In has not been observed…

P. Hoff *et al.*, Phys. Rev. Lett. **77**, 1020 (1996).

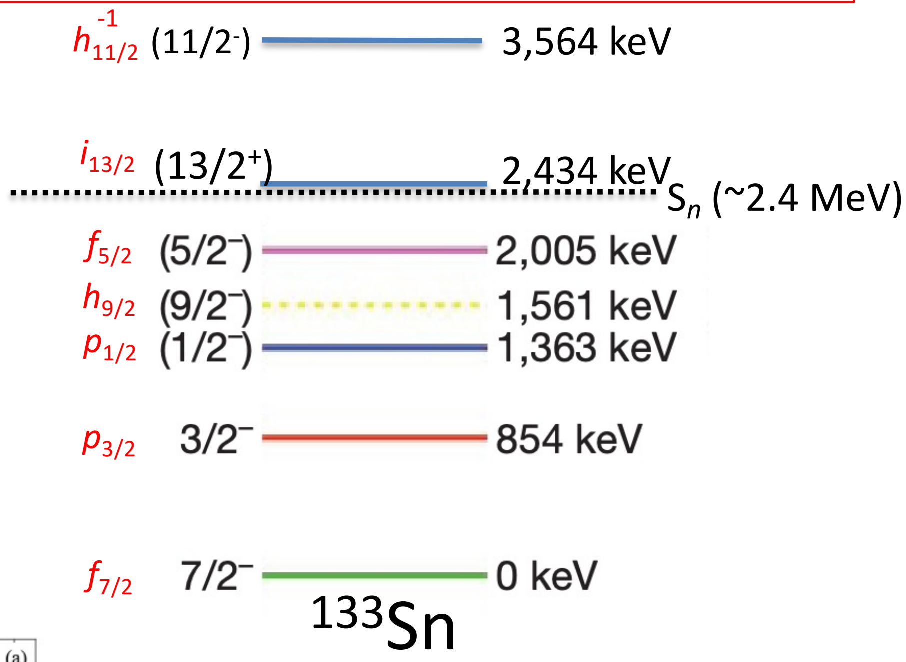


K.L. Jones *et al.*, Nature **465**, 454 (2010).

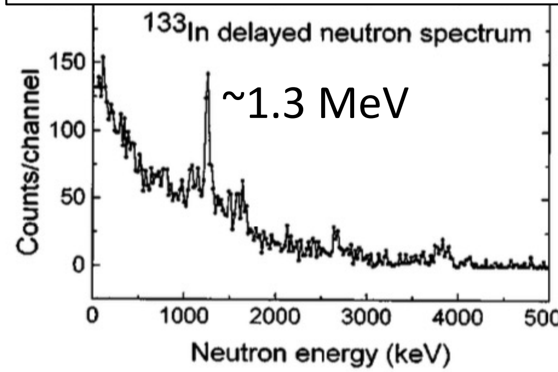




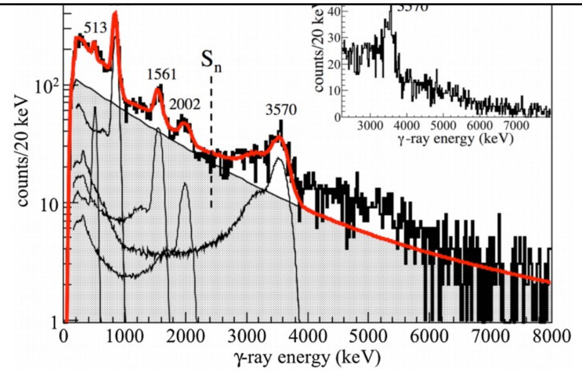
~90% β decay of ^{133}In is followed by neutron emission
Strong strength (unknown) above S_n



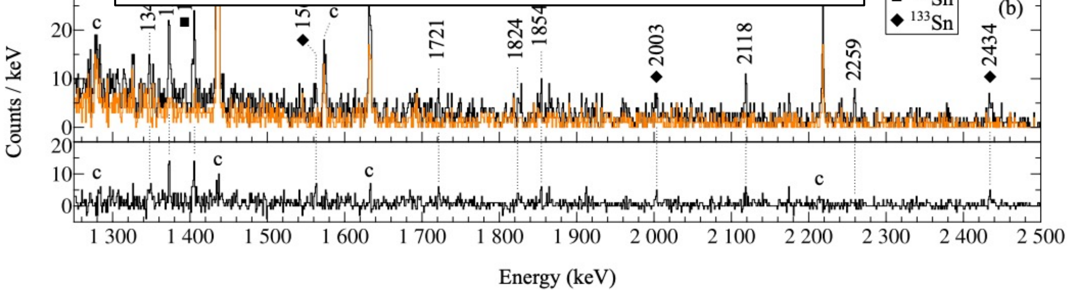
P. Hoff *et al.*, Phys. Rev. Lett. **77**, 1020 (1996).



V. Vaquero *et al.*, Phys. Rev. Lett. 118, 202502 (2017)



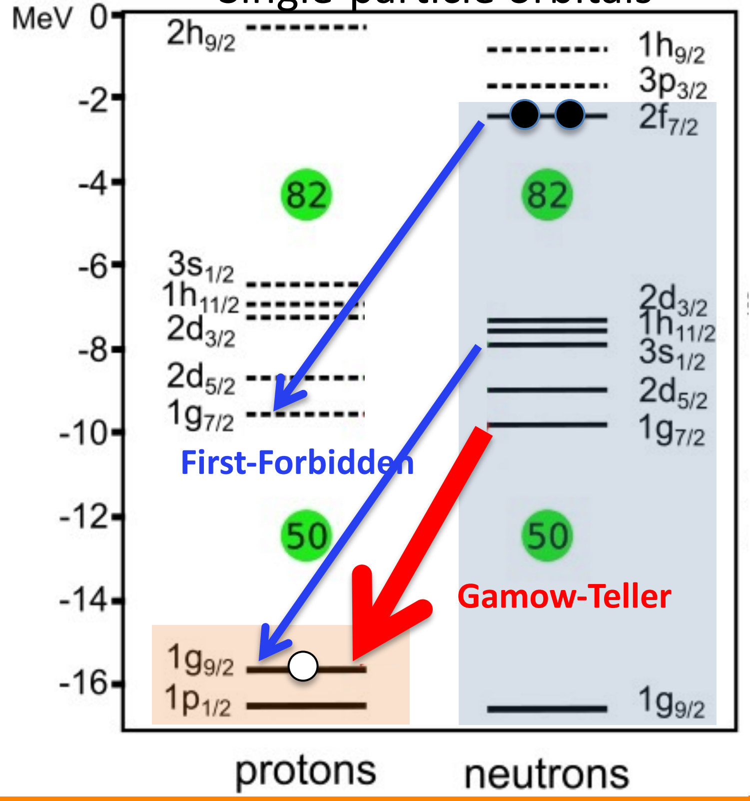
M. Piersa-Silkowska *et al.*, Phys. Rev. C. 104, 044328 (2021)



We aimed for the simple decay from ^{133}In

GT: A **strong** transition with **large** matrix element
FF: many **weak** transitions with **small** matrix elements but **large** phase-space factor
The GT and FF channels in ^{133}In are universal in this region

Single-particle orbitals

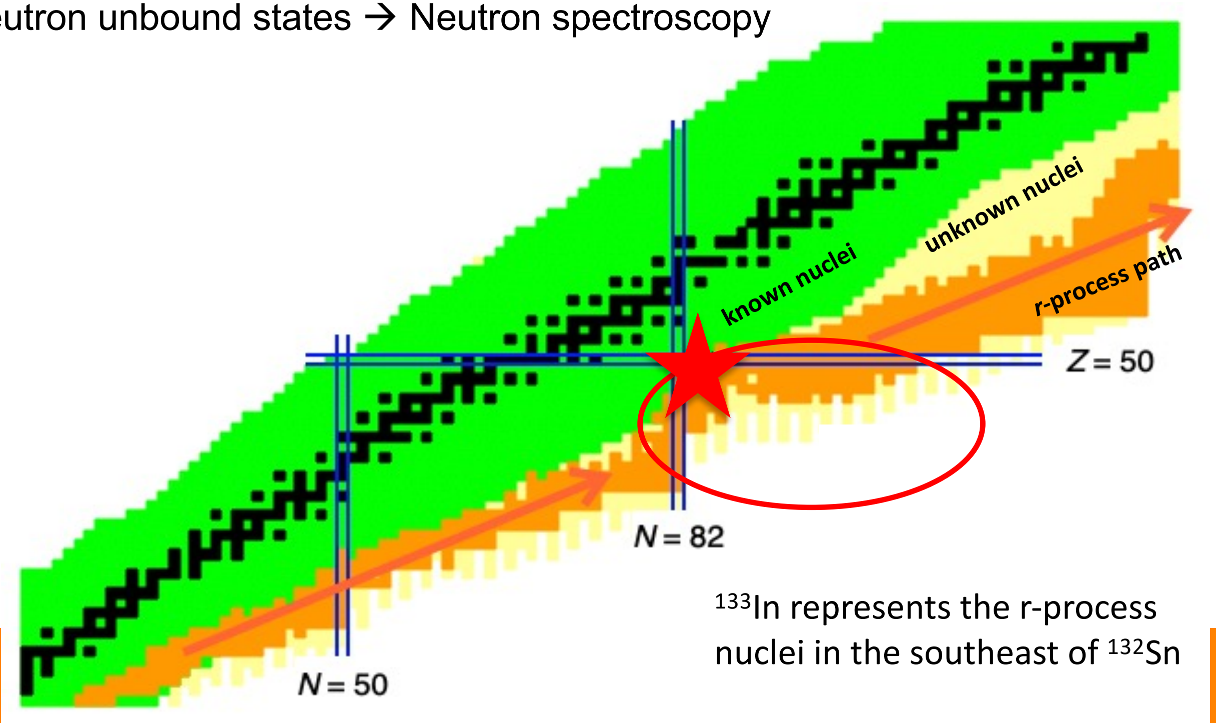


Following the β decay of ^{133}In, we want to

- Determine the excitation energy of the GT state ($\nu g_{7/2}$) in ^{133}Sn and the $B_{GT}(\nu g_{7/2} \rightarrow \pi g_{9/2})$ matrix element.
- Address other neutron-hole orbitals inside the N=82 core, and the FF decay strength to the corresponding states in ^{133}Sn.

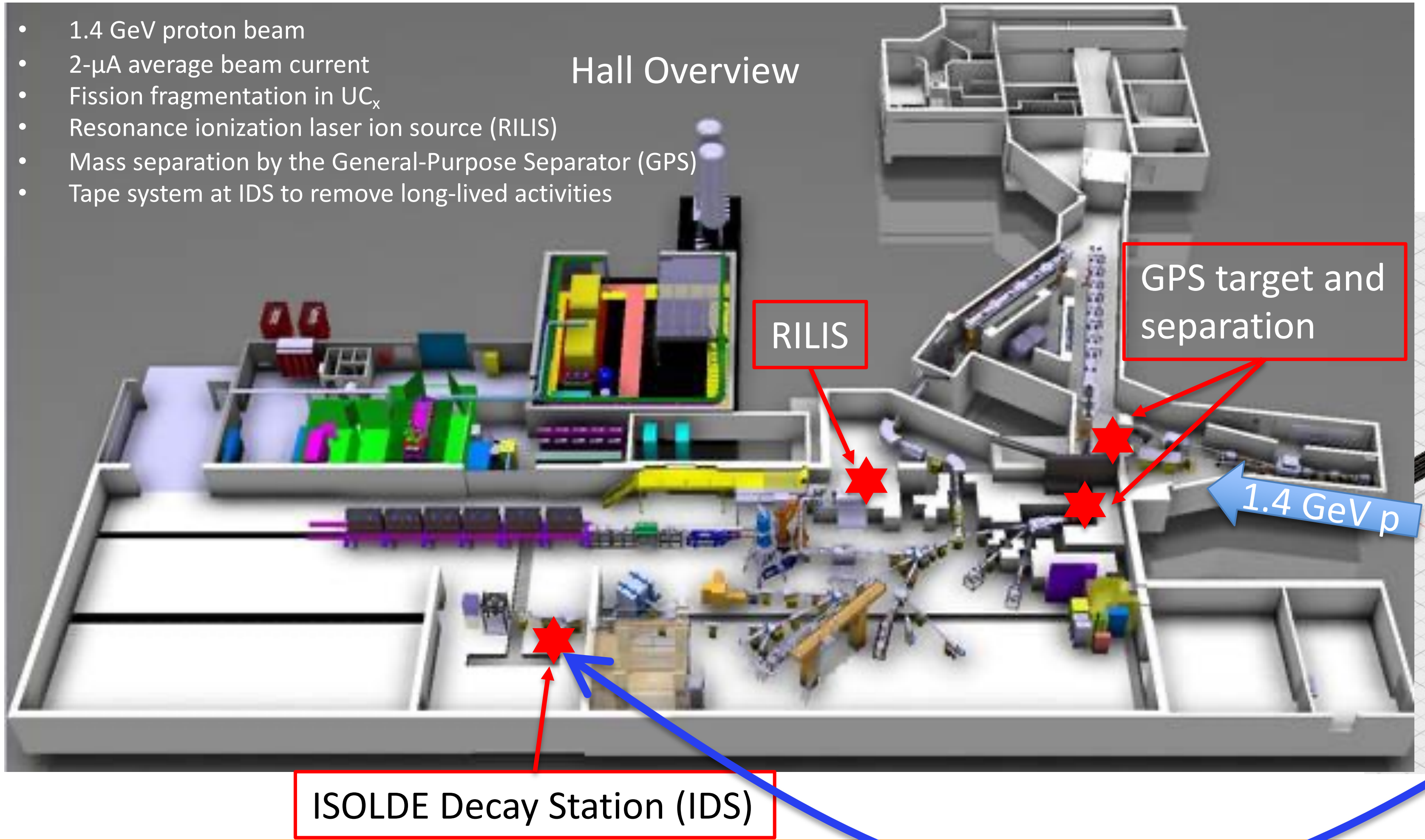
→ Establish the first complete β-decay strength distribution in an r-process nucleus

Neutron unbound states → Neutron spectroscopy

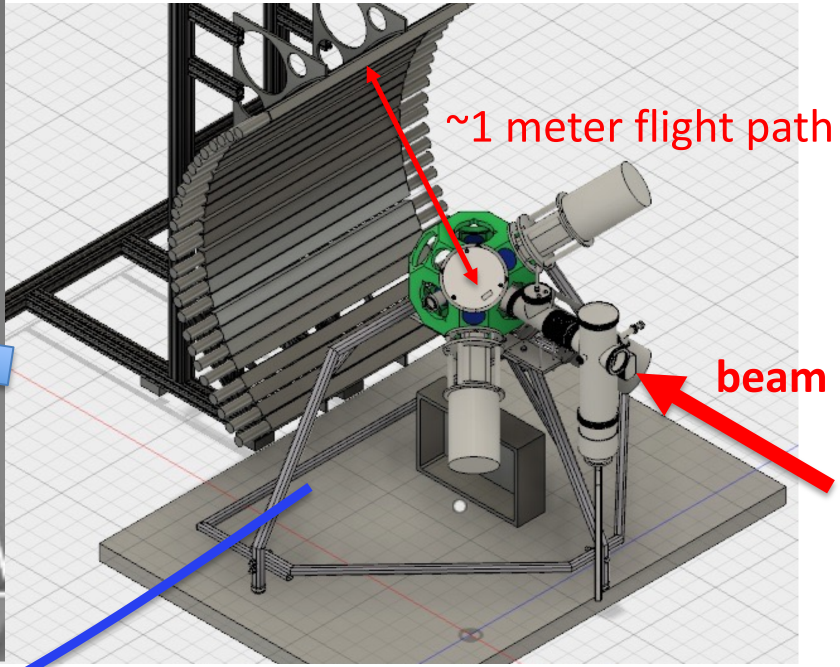


^{133}In represents the r-process nuclei in the southeast of ^{132}Sn

Experimental at ISOLDE (IS632, PI: Miguel Madurga and Robert Grzywacz)

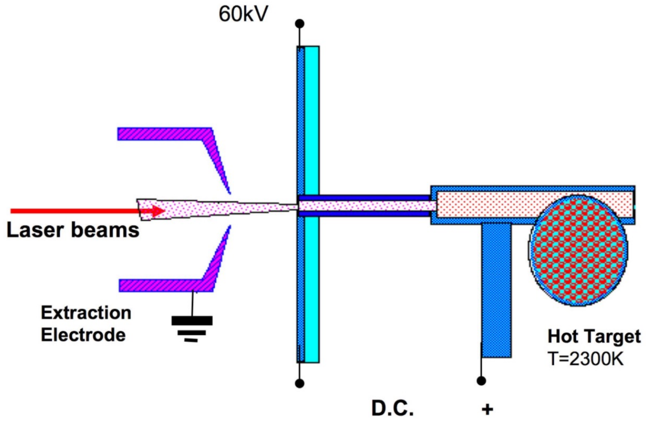


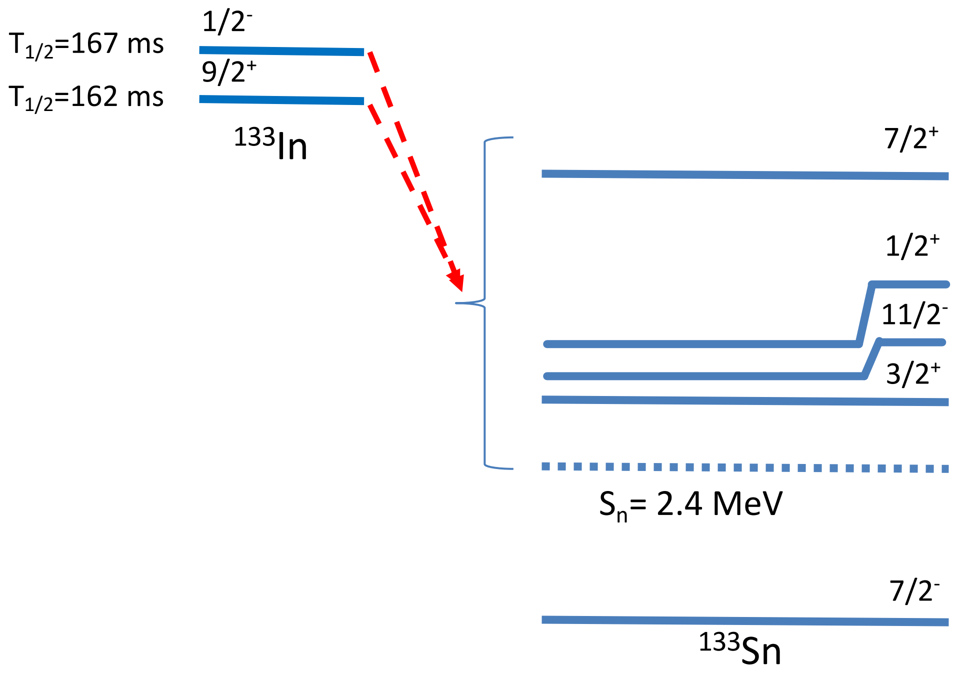
At ISOLDE Decay Station (IDS)
Tape system to remove long-lived activities
Two β detectors (front and back) with 80% efficiency
4 HPGe clovers + 26 Neutron detectors (INDiE*)
2% γ and 10% neutron efficiency at 1 MeV

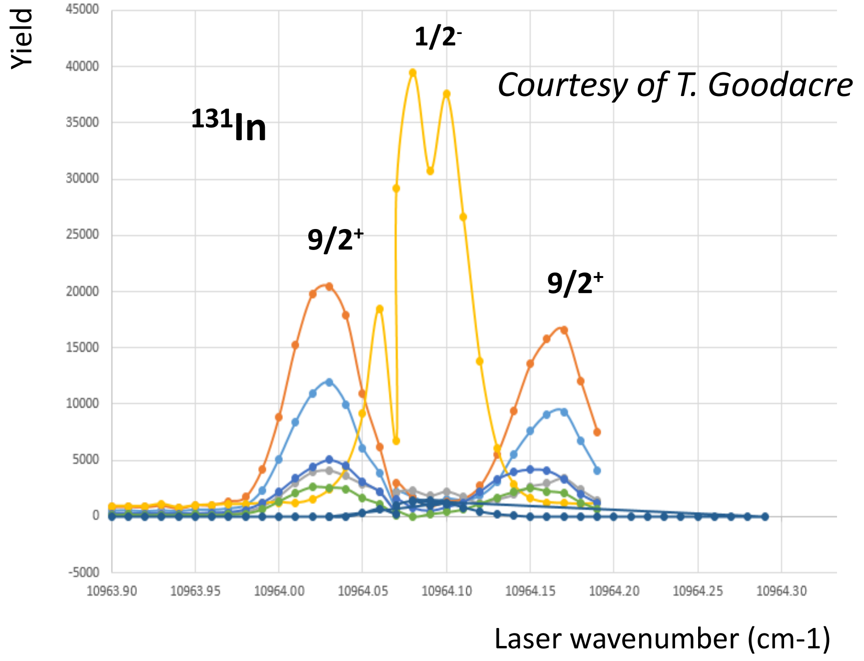


Isomer selection with RILIS at ISOLDE

- ^{133}In in the ground state ($9/2^+$) or isomer ($1/2^-$) can be separated!
- Beta-decay selection rules + laser ionization → spin-parity assignment (tentative)

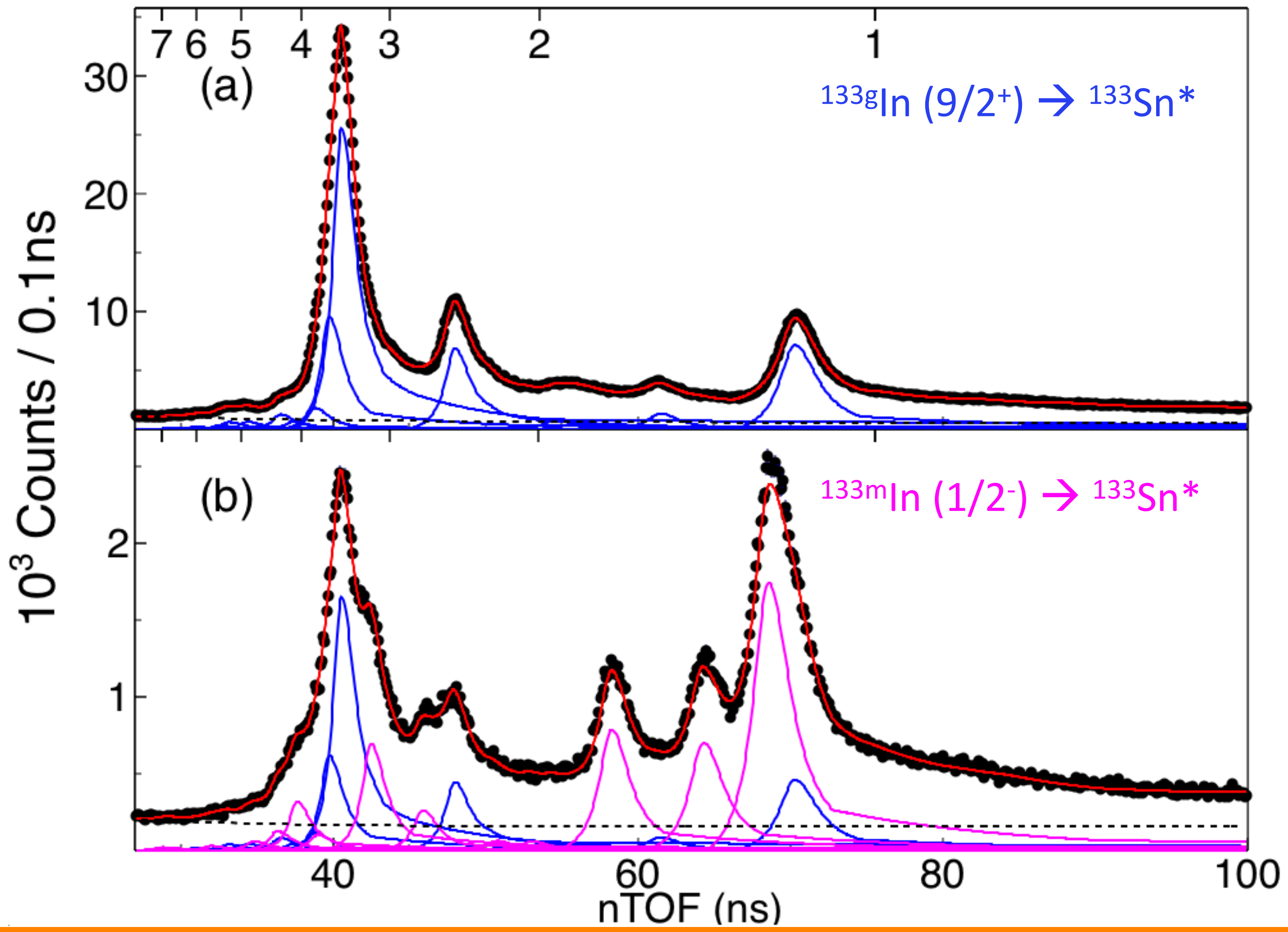






First neutron spectroscopy with isomer selection using RILIS

Neutron TOF following the ^{133}In decay

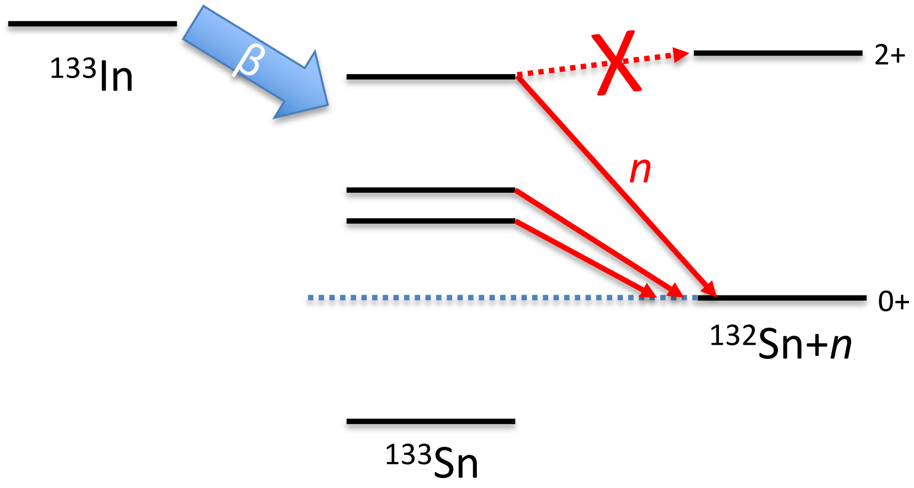


Simplicity:

- No neutron-gamma or neutron-neutron cascade in the strong neutron peaks → A single transition directly feeding the g.s. of ^{132}Sn (because E_{2+} > 4 MeV).

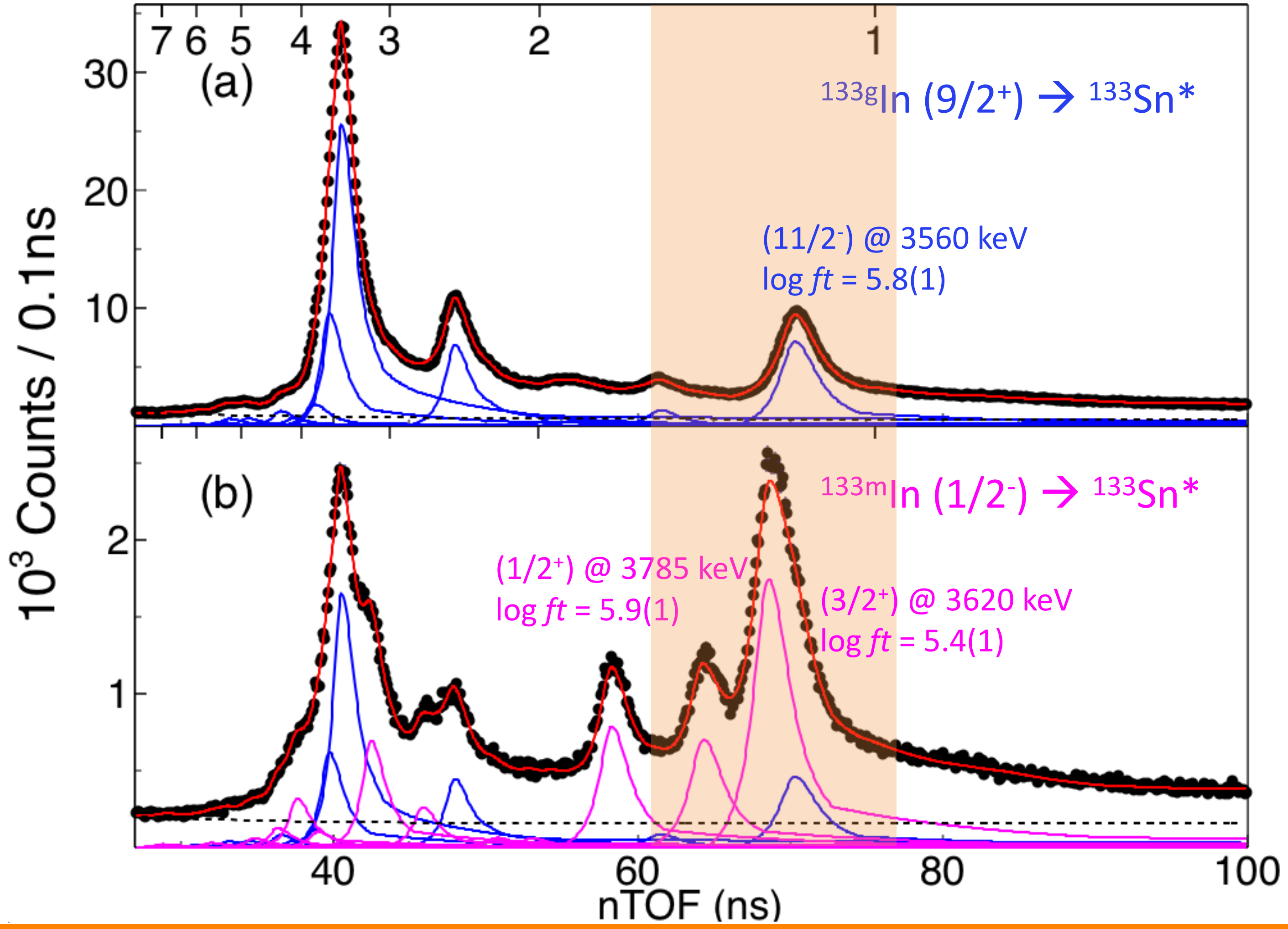
From fitting analysis:

- Neutron kinetic energy → Excitation energy of the state (Ex)
- Peak intensity → β-decay strength to the state (I_β)

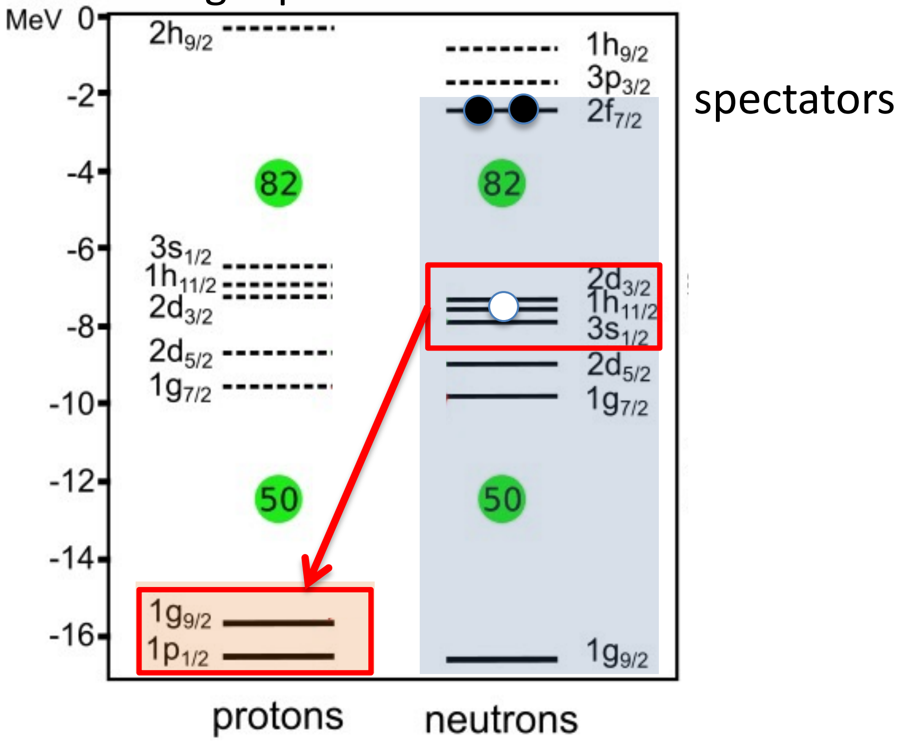


Simple interpretation from the single-particle picture

Neutron TOF following the ^{133}In decay



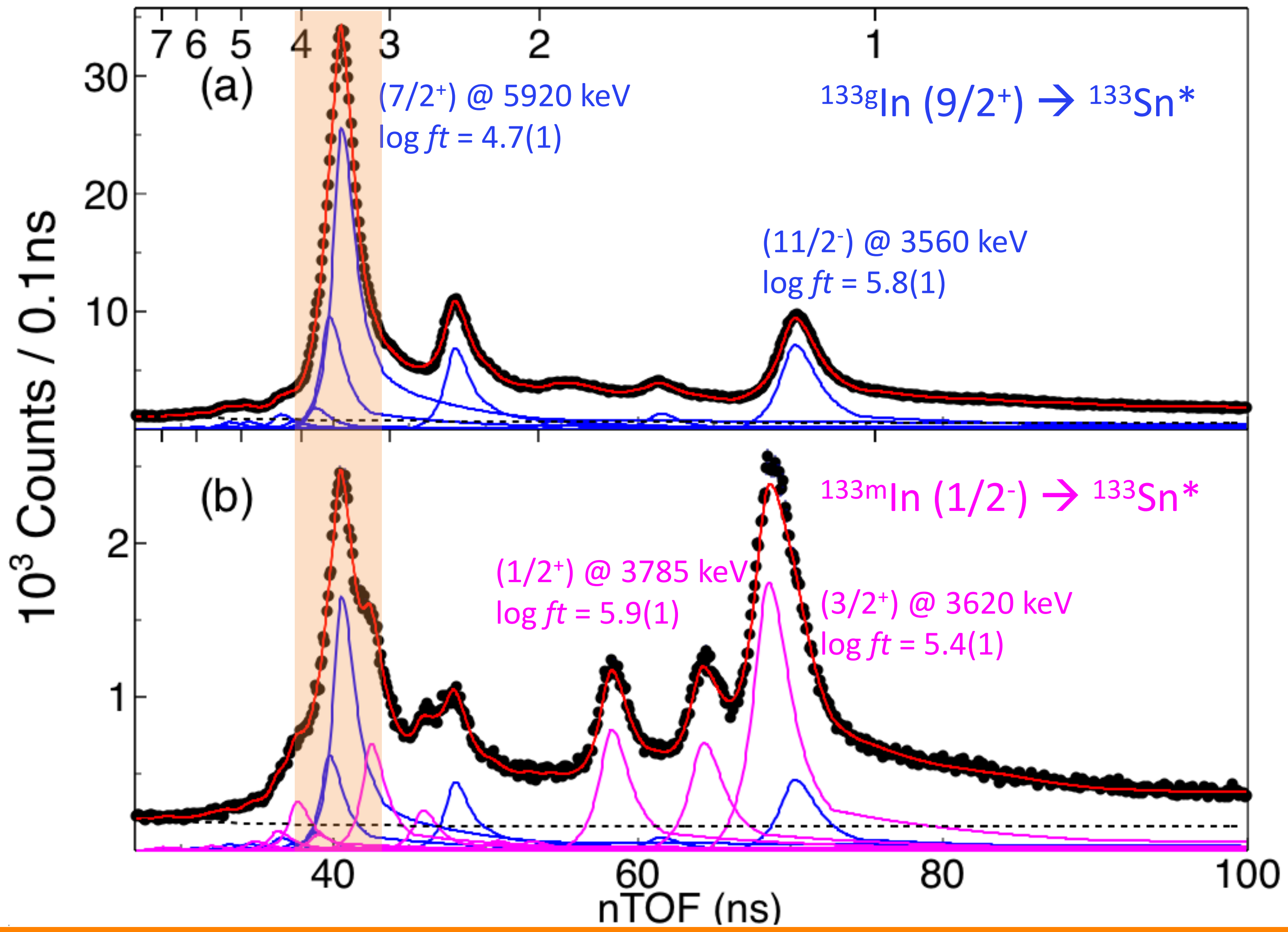
Single-particle orbitals



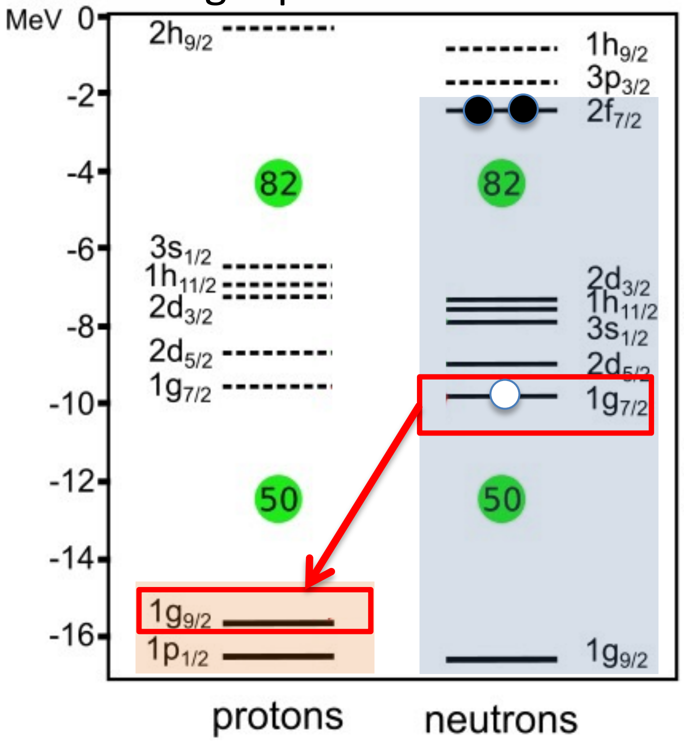
Neutrons from $h_{11/2}$, $d_{3/2}$ or $s_{1/2}$ (N<82)
→ proton on $g_{9/2}$ or $p_{1/2}$ (Z<50) → ν2p1h
FF transitions at E_{ex}~3.5 MeV

Simple interpretation from the single-particle picture

Neutron TOF following the ^{133}In decay



Single-particle orbitals



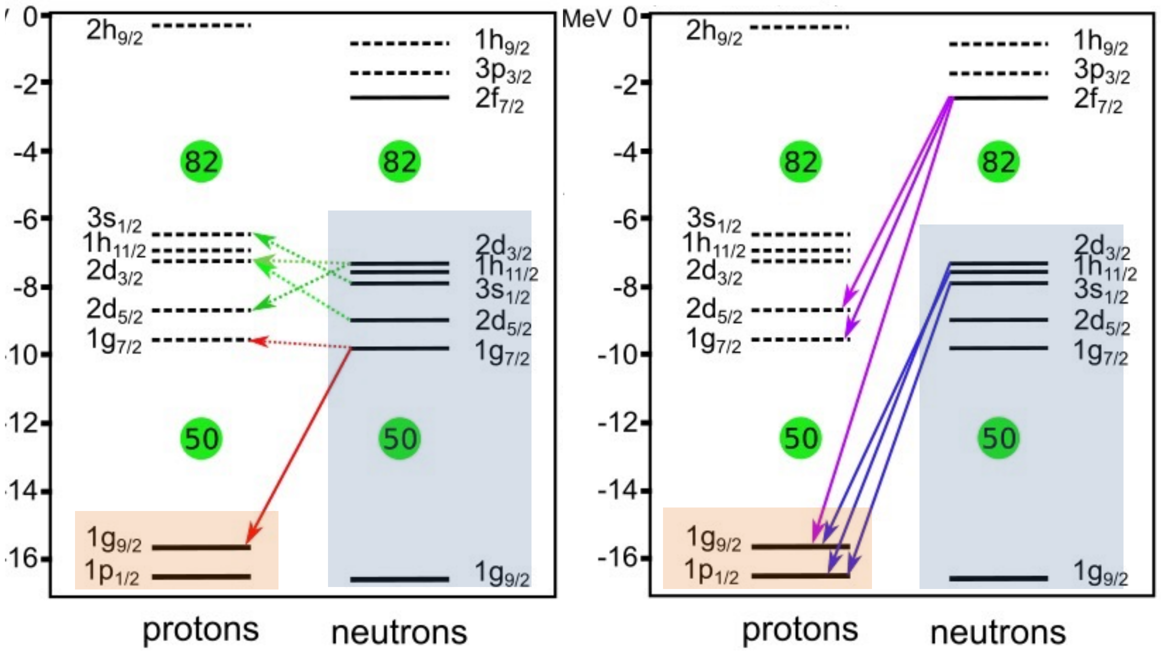
spectators

Neutrons from $g_{7/2}$ (N<82)

→ proton on $g_{9/2}$ (Z<50) → ν2p1h

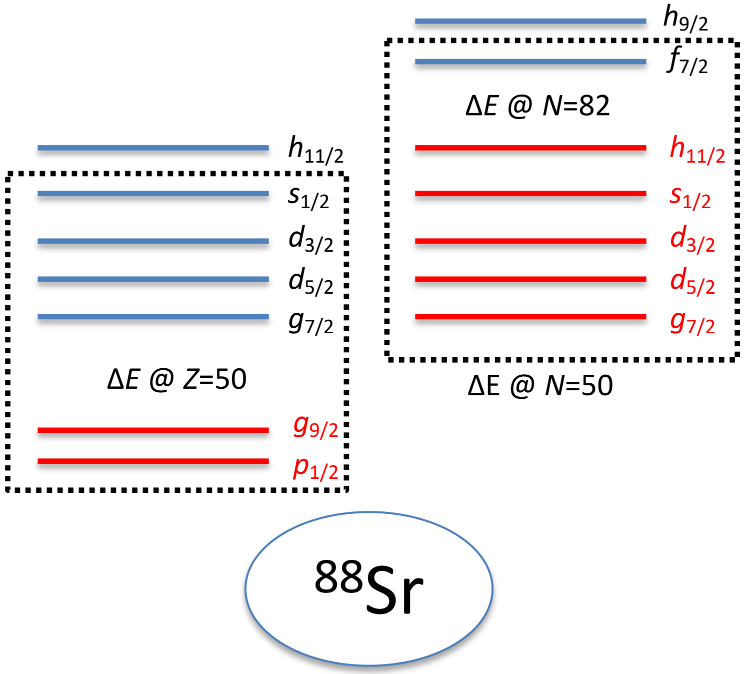
GT transition at E_{ex}~6.0 MeV

Large-scale shell-model (LSSM) calculation on ^{133}In→^{133}Sn



We need to include particle-hole excitation across ^{132}Sn!

Large model space + realistic *NN* potential



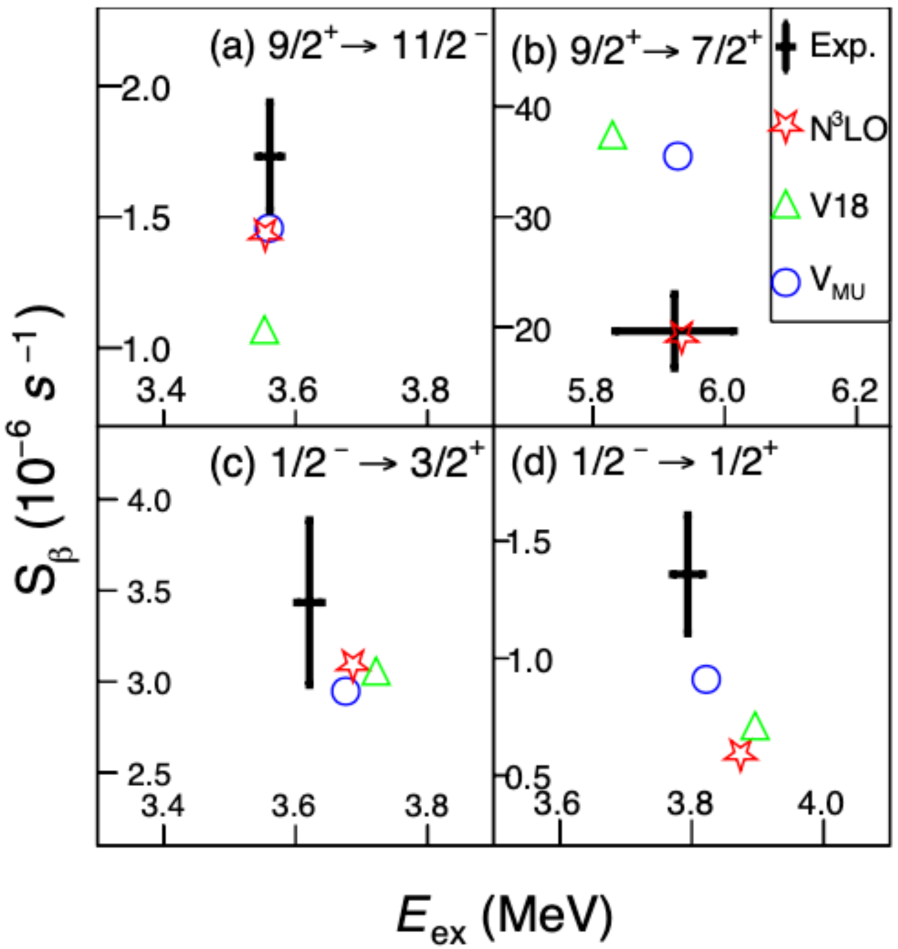
- ^{88}Sr core with 12 single-particle orbits
- Single-particle energies from experimental data
- Two-body-matrix-element from (a) N^3LO (MBPT) [1], (b) Argonne V18 (MBPT) [2], and (c) V_{MU} (private communication with Prof. C.X. Yuan) [3]

[1] D. Entem et al., Phys. Rev. C 68, 041001 (2003).
[2] R. B. Wiringa et al., Phys. Rev. C 51, 38–51 (1995).
[3] T. Otsuka et al., Phys. Rev. Lett. 104, 012501 (2010).

MBPT = Many-body perturbation theory. M.Hjorth-Jensen et al, Physics Reports 261, 125–270 (1995)

Comparison: Experiment vs. LSSM

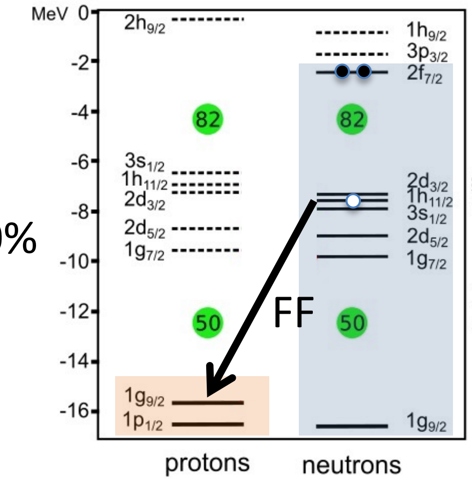
- Four transitions → neutron 2p1h states
- $S_\beta = 1/ft$ (same for GT and FF transitions)
- GT and FF transition matrix elements are calculated using SM wave functions (KSH
- FF quenching factors from Ref. [1]
- GT quenching factor q=0.6 [2].



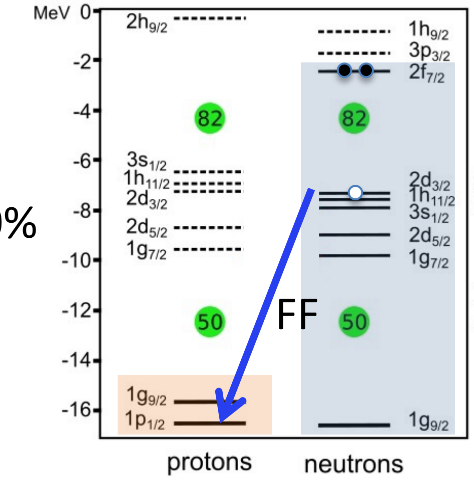
[1] Q. Zhi *et al*., Phys. Rev. C. **87**, 025803 (2013).
[2] E. Caurier et al., Phys. Lett. B 711, 62 (2012).

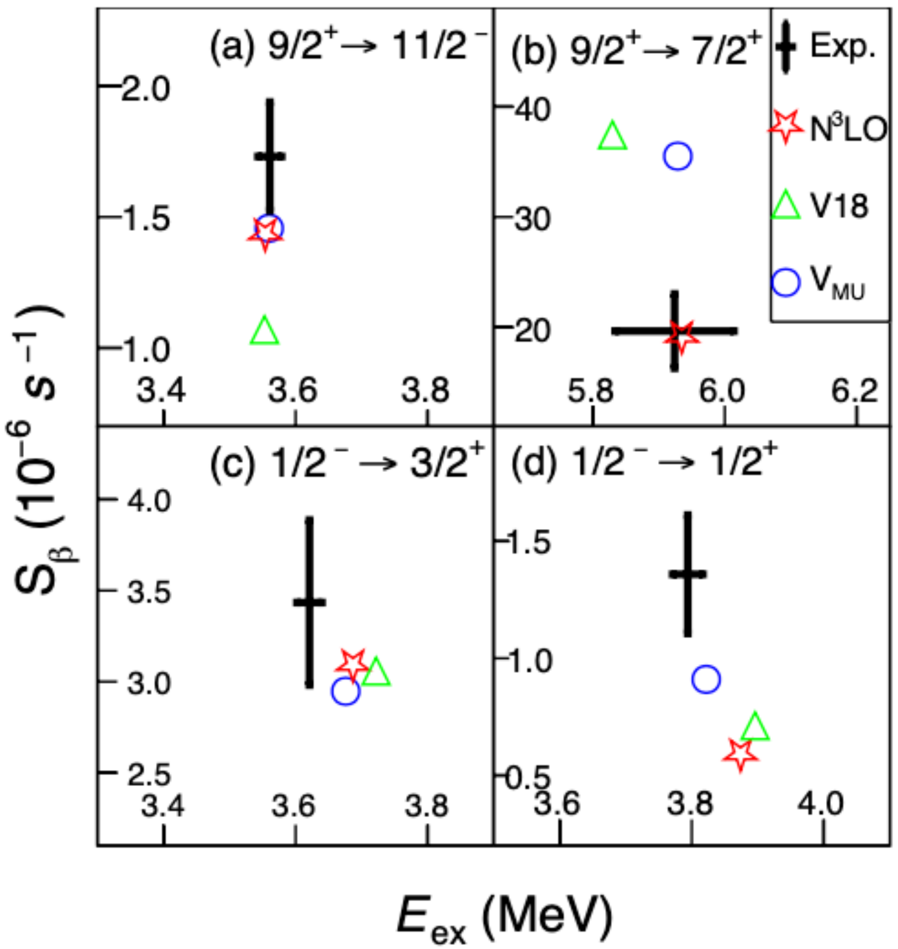
Comparison: Experiment vs. LSSM

>80%

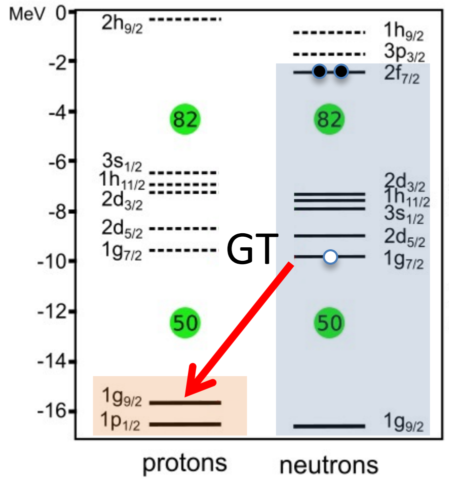


>80%

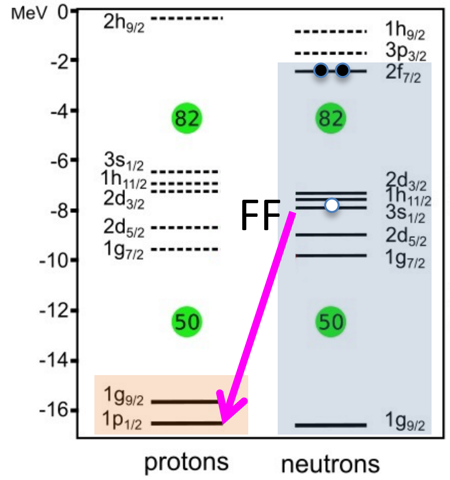




~45%

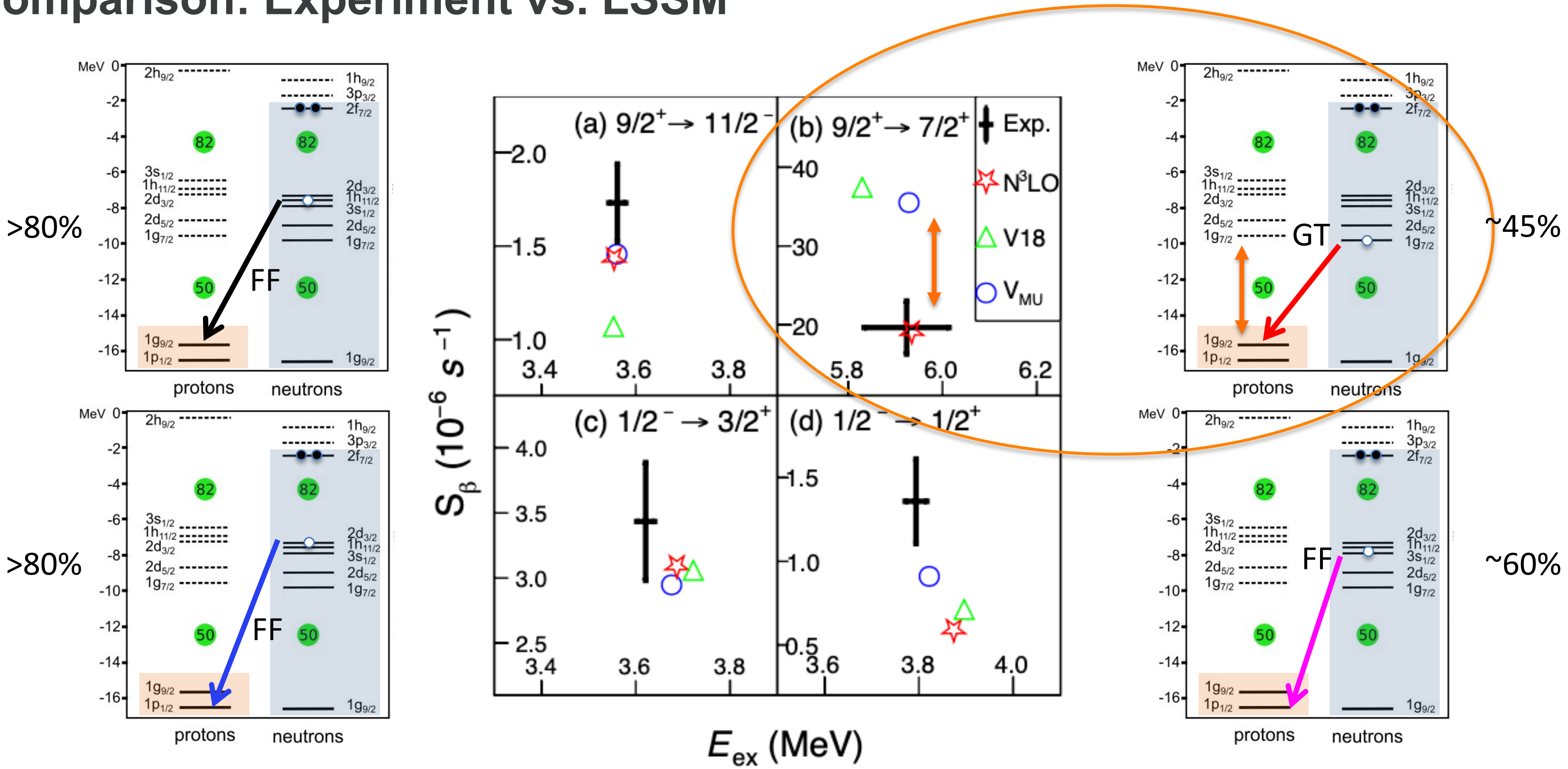


~60%



The simple single-particle picture is supported by LSSM

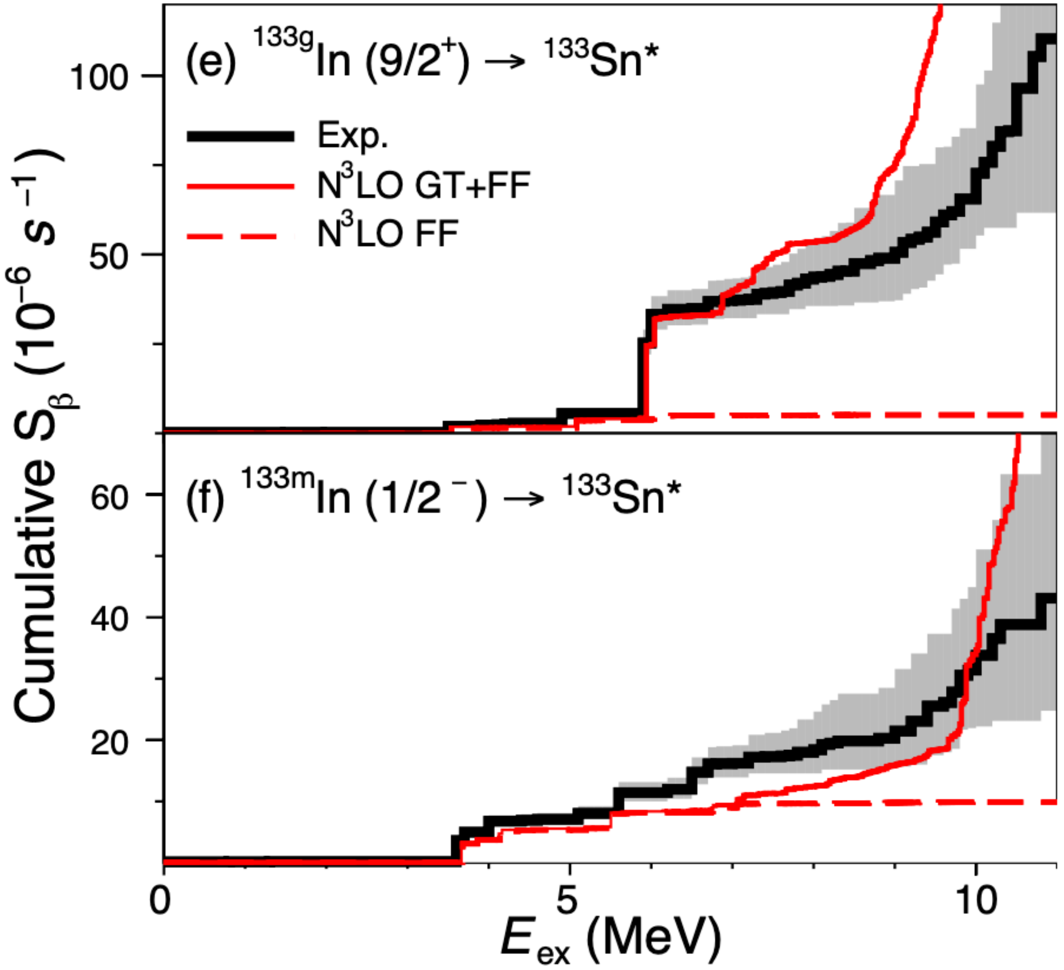
Comparison: Experiment vs. LSSM



The GT strength is sensitive to the amount of proton excitation (across Z=50)!

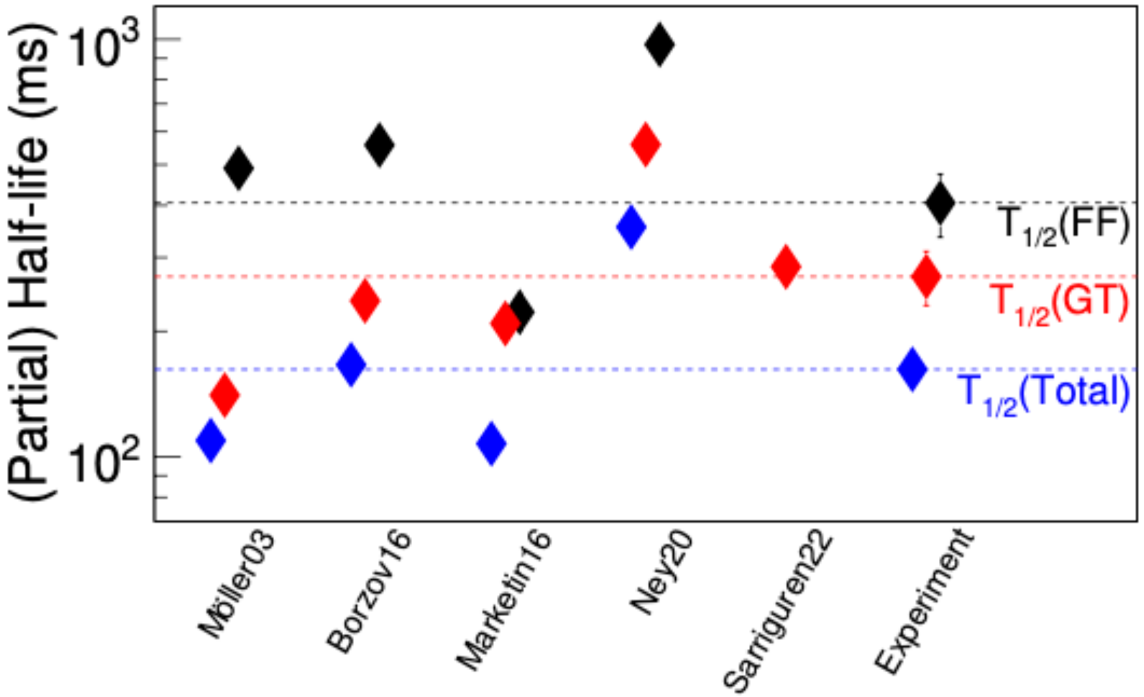
Comparison: Experiment vs. LSSM

- Good agreement up to Ex =9 MeV
- FF below 6 MeV and GT above 6 MeV
- The discrepancy at >9 MeV might be due to the model truncation
- Good shell-model initiator for the β decay in the southeast of ^{132}Sn (important for the r-process)
- Future development is demanded



Feedback to the global calculations

Ground-state decay of ^{133}In ($I^{\pi}=9/2^{+}$)



Exp data

Because the $7/2^{+}$ state (the lowest GT state) in ^{133}Sn is observed at 5.92 MeV:

- FF partial half life: sum of β feedings up to 5.9 MeV
- GT partial half life: sum of β feedings beyond 5.9 MeV

List of models:

- Moller03: P. Möller et al., Phys. Rev. C 67, 055802 (2003).
- Borzov16: I. Borzov, Physics of Atomic Nuclei 79, 910 (2016).
- Marketin16: T. Marketin et al., Phys. Rev. C 93, 025805 (2016).
- Ney20: E. Ney, J. Engel et al., Phys. Rev. C 102, 034326 (2020).
- Sarriguren22: P. Sarriguren private communication (2022).

Different types of QRPA calculations that differ in their degree of self consistency, the density functional used, or the method of calculation

Even for this (simple) nucleus, predicting the partial half lives of (or the competition between) GT and FF channels is not trivial!

Summary and conclusion

- In experiment:
  - Decay of ^{133g}In (9/2+) and ^{133m}In (1/2-) were studied at IDS with INDiE + RILIS
  - Observed all the major decay channels (GT+FF) from ^{133}In via isolated neutron resonances in ^{133}Sn
  - Link the observation to the single-particle transitions near ^{132}Sn

- In theory:
  - Calculate the ^{133}In→^{133}Sn decay with LSSM + effective *NN* potentials
  - Well reproduced the FF decay strength at lower Ex energy.
  - The GT strength at ~ 6MeV is sensitive to the amount of proton excitation across Z=50

- Feedback to global calculations:
  - Different global models (for r-process simulation) predictions a wide range of the GT+FF competition

- Our measurement established the β-decay strength distribution of extremely neutron-rich nuclei

→ An anchor-point measurement for the state-of-the-art models in the southeast of ^{132}Sn

Collaboration of IS632

Z. Y. Xu,[1] M. Madurga,[1] R. Grzywacz,[1,2] T. T. King,[1] A. Algora,[3] A. N. Andreyev,[4] J. Benito,[5] T. Berry,[6] M. J. G. Borge,[7] C. Costache,[8] A. Fijalkowska,[9,10] A. Gottardo,[11] L. Fraile,[5] C. Halverson,[1] J. Heideman,[1] A. Illana,[12] Ł. Janiak,[10] T. Kurtukian-Nieto,[13] A. Korgul,[10] R. Lozeva,[14] R. Licâ,[15,8] C. Mazzocchi,[10] C. Mihai,[8] A.I. Morales,[3] M. Piersa,[10] P. Sarriguren,[7] M. Singh,[1] C. Sotty,[8] M. Stepaniuk,[10] O. Tengblad,[7] A. Turturica,[8] V. Vedia,[5] S. Viñals,[7] R. Yokoyama,[1] and C. X. Yuan[16]

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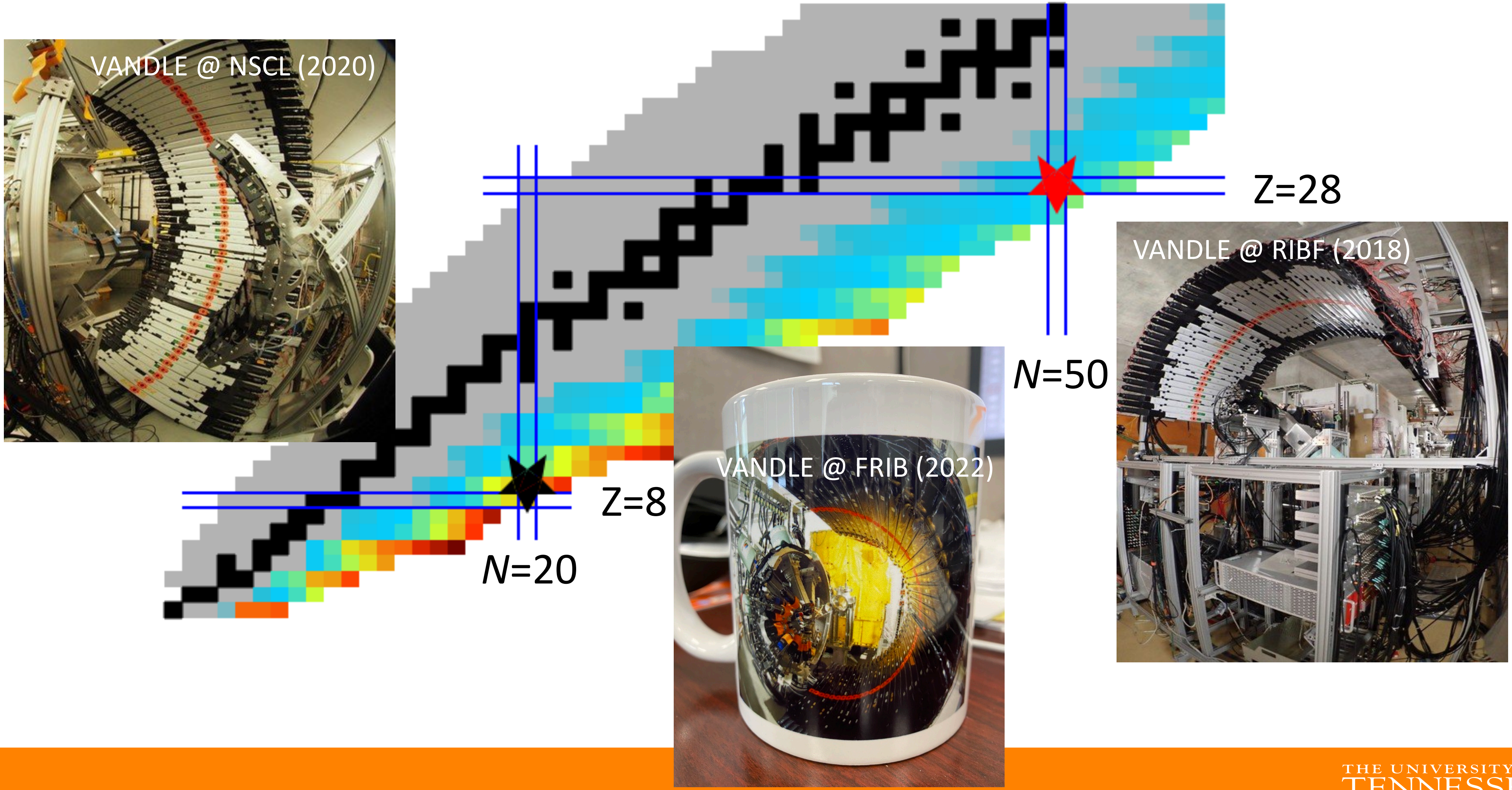
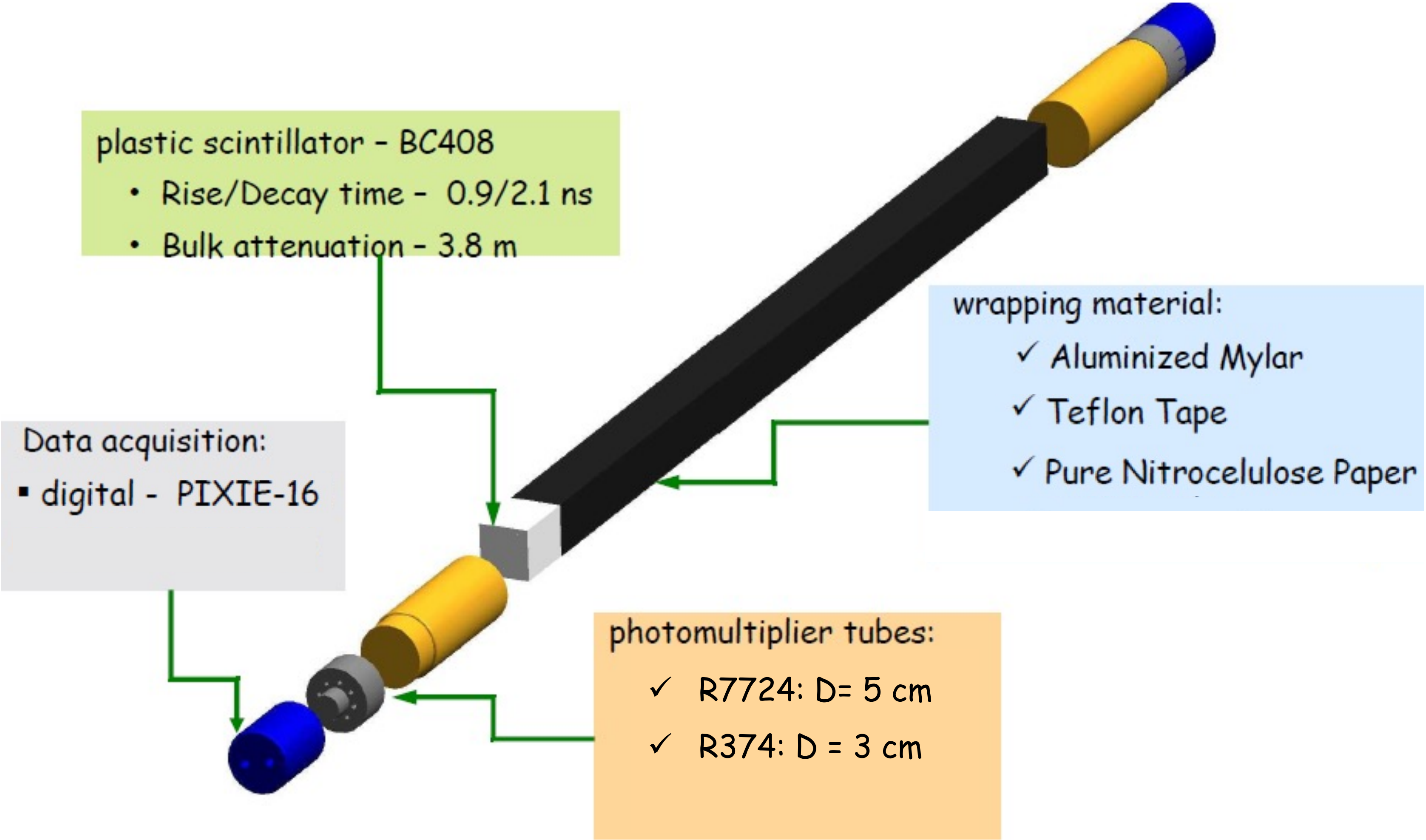
Recent activities of VANDLE

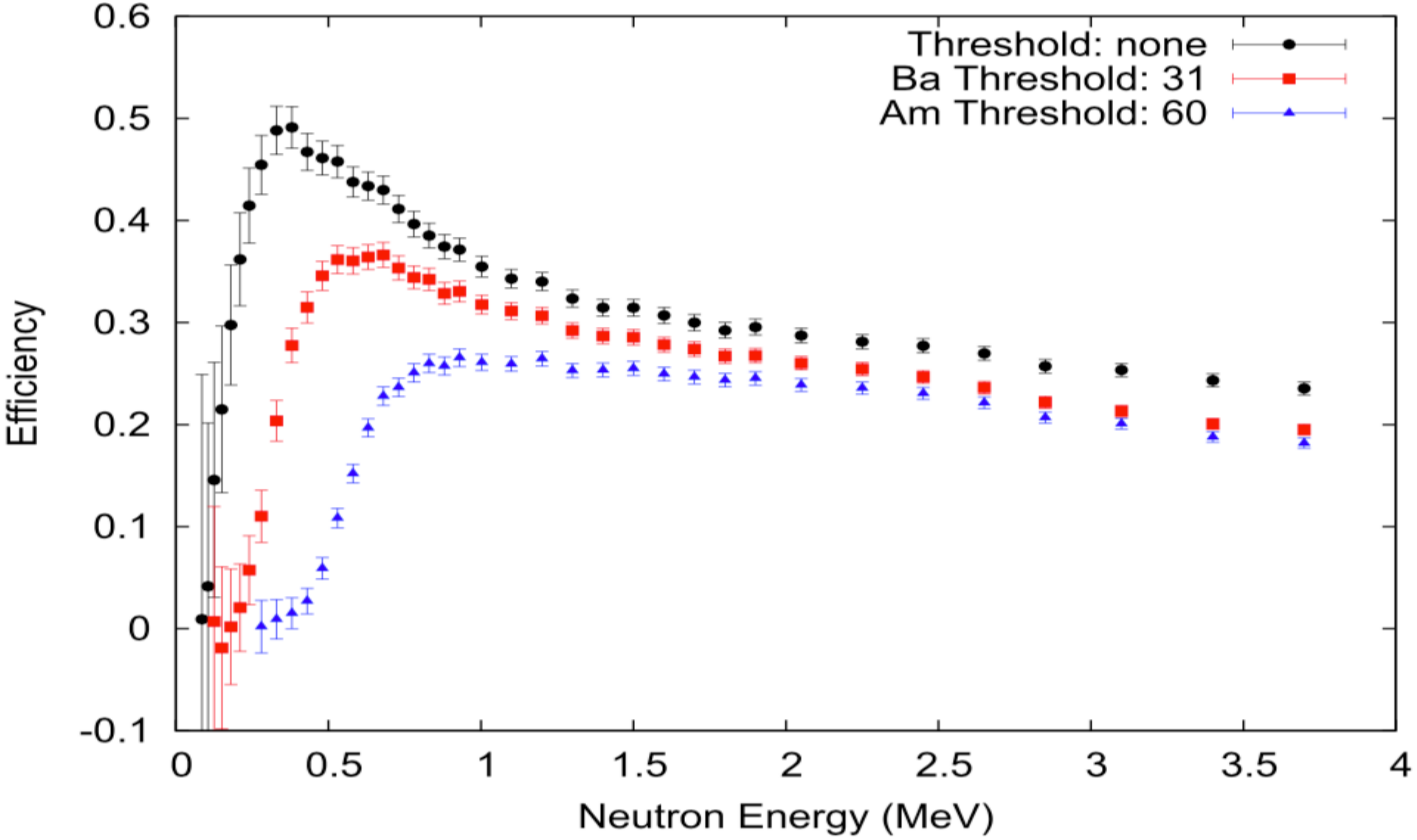


Backup slides

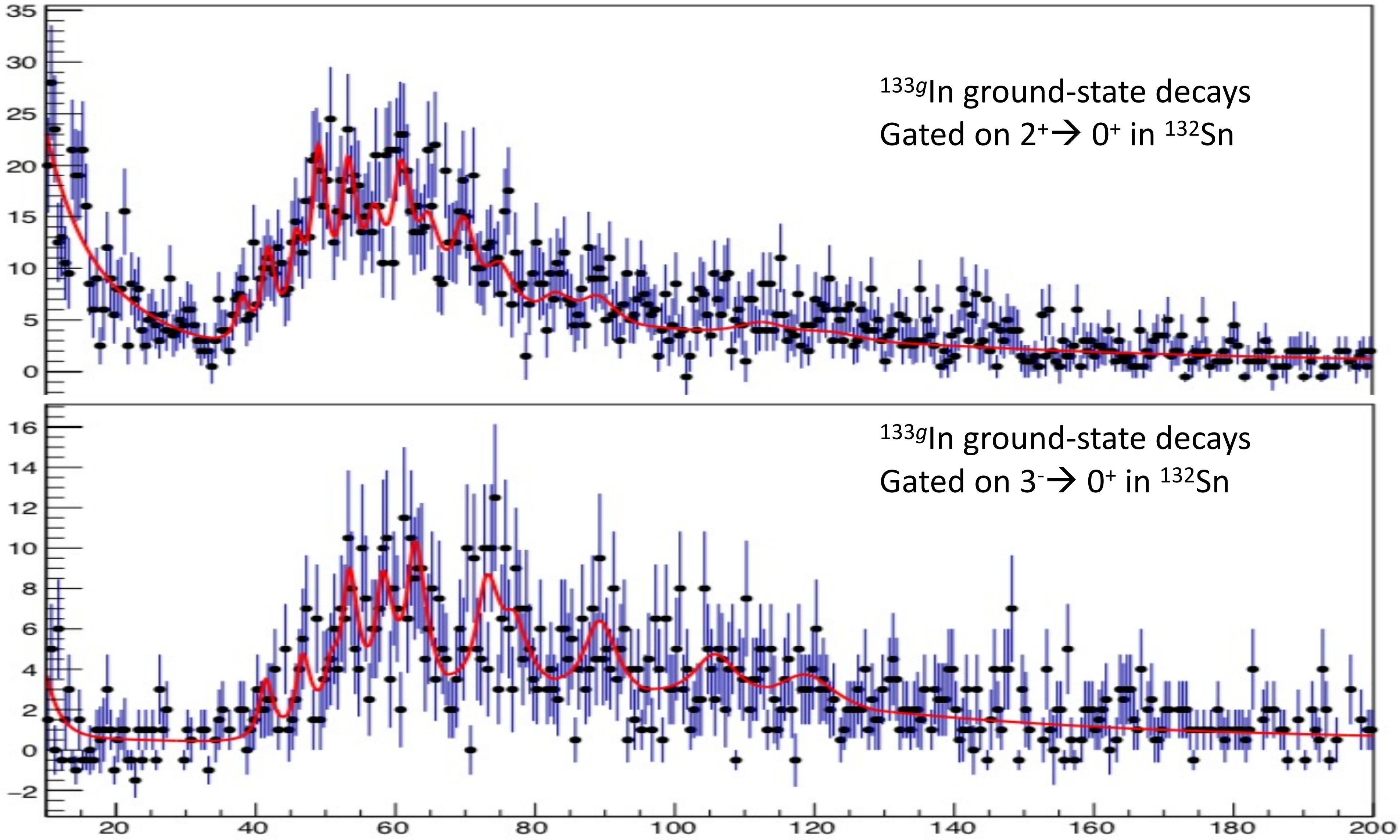
Detector components



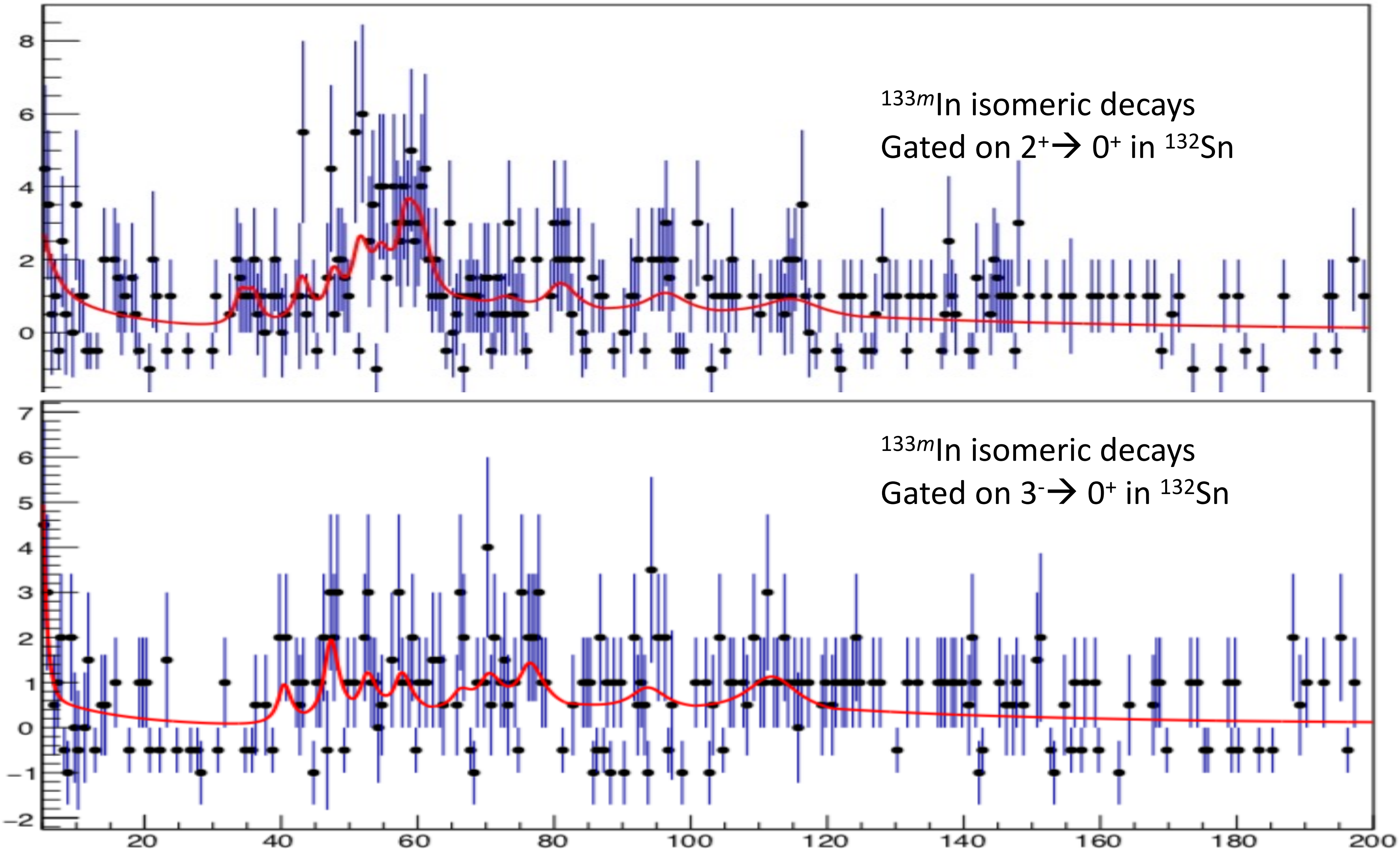
Neutron efficiency curve



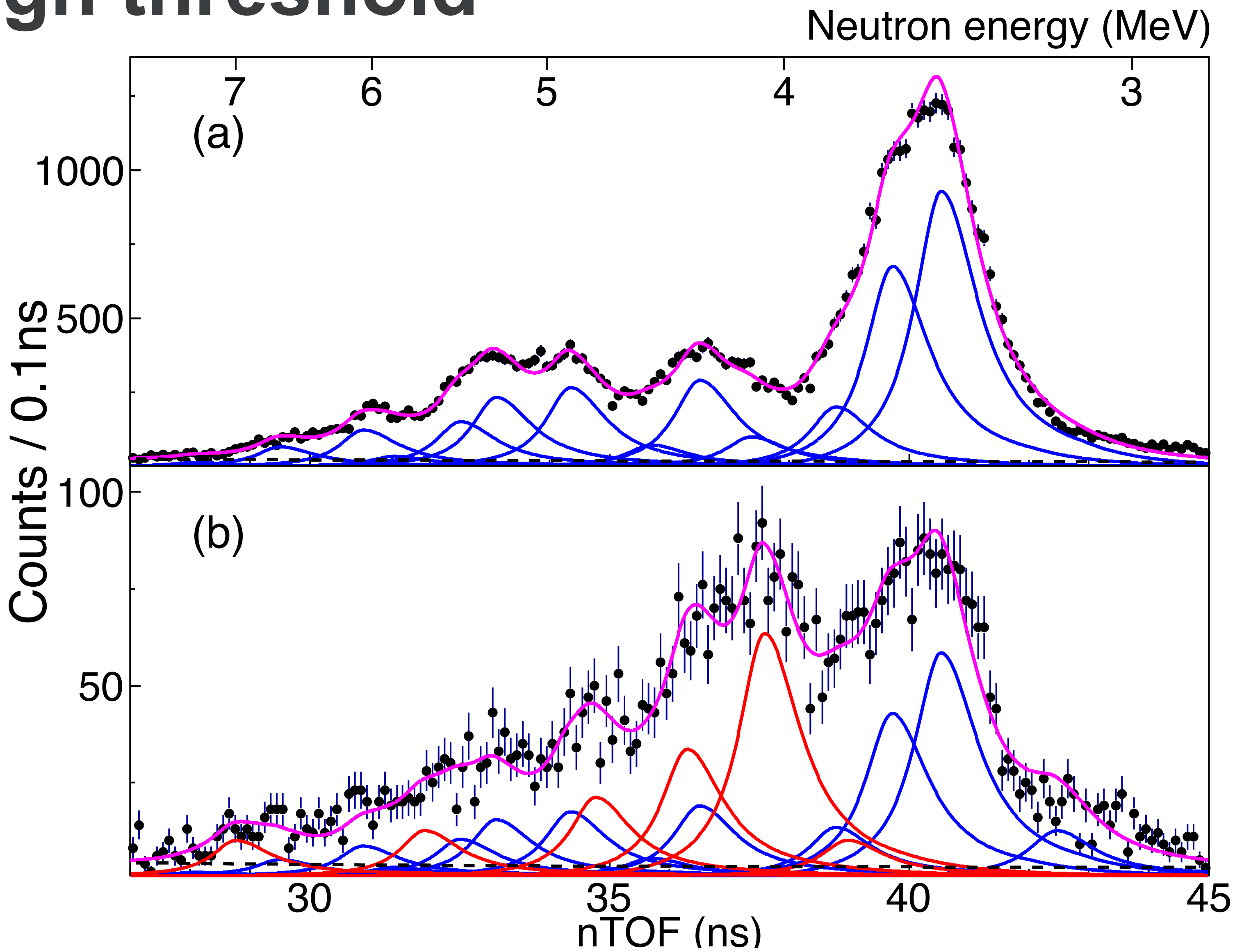
Gamma-ray gated ToF$_n$ spectrum



Gamma-ray gated ToF$_n$ spectrum

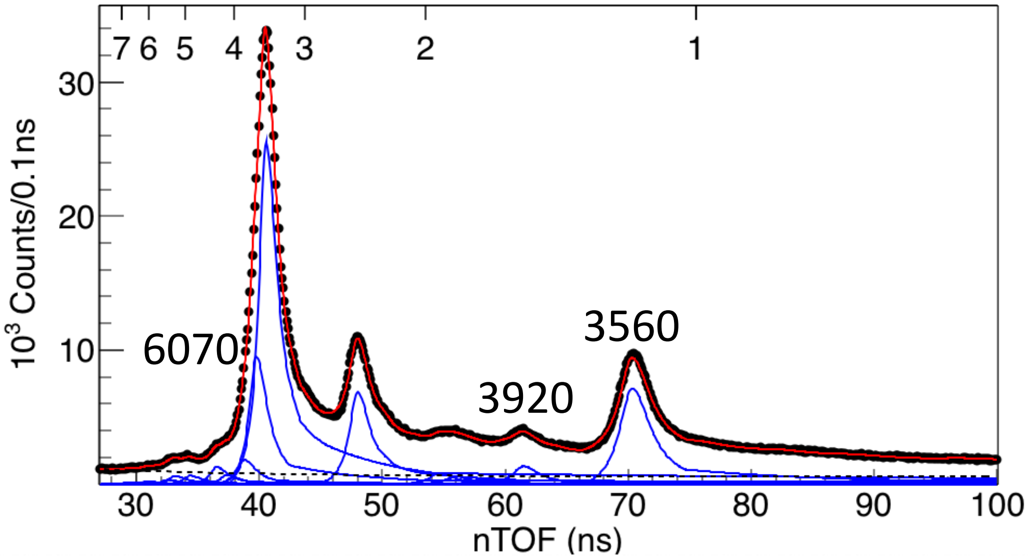


ToF with high threshold

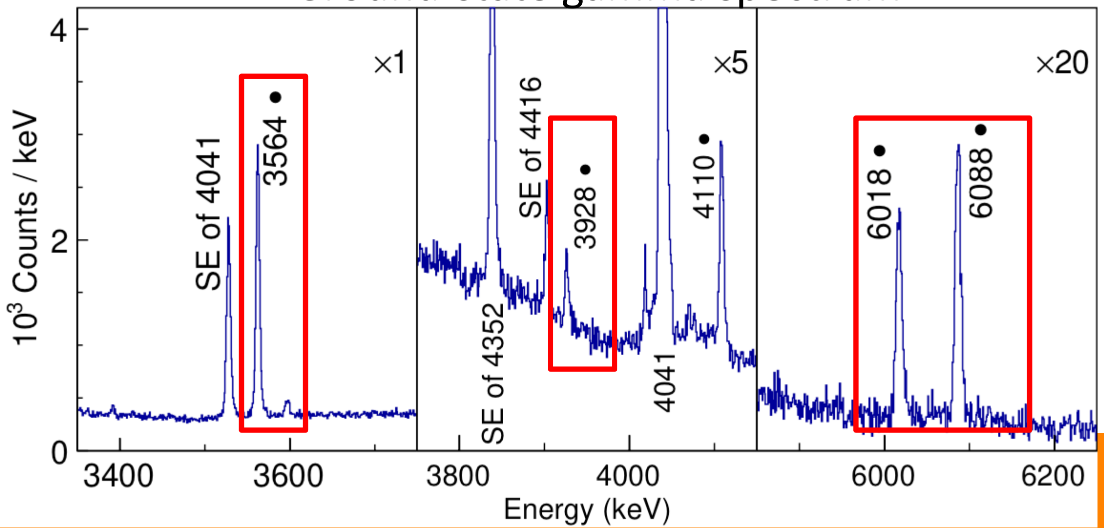


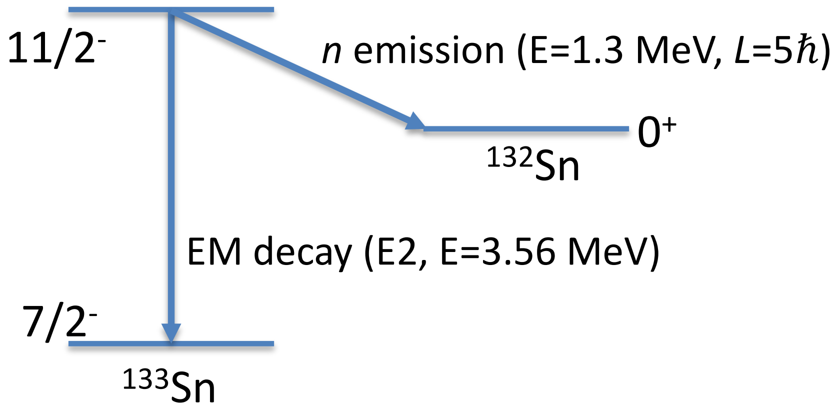
Neutron-gamma competition

Ground-state neutron spectrum



Ground-state gamma spectrum





- A few candidates of neutron unbound states that undergo both gamma decay and neutron emission.
- Both neutron and gamma decays from the 3560-keV state have already been observed [1-3].
- The ratio of partial decay width can be extracted
- Will use statistical model (Kawano et al.,) to understand the competition quantitatively

[1] P. Hoff et al., Phys. Rev. Lett. 77, 1020 (1996).
[2] V. Vaquero et al., Phys. Rev. Lett. 118, 202502 (2017).
[3] M. Piersa et al., Phys. Rev. C 99, 024304 (2019).