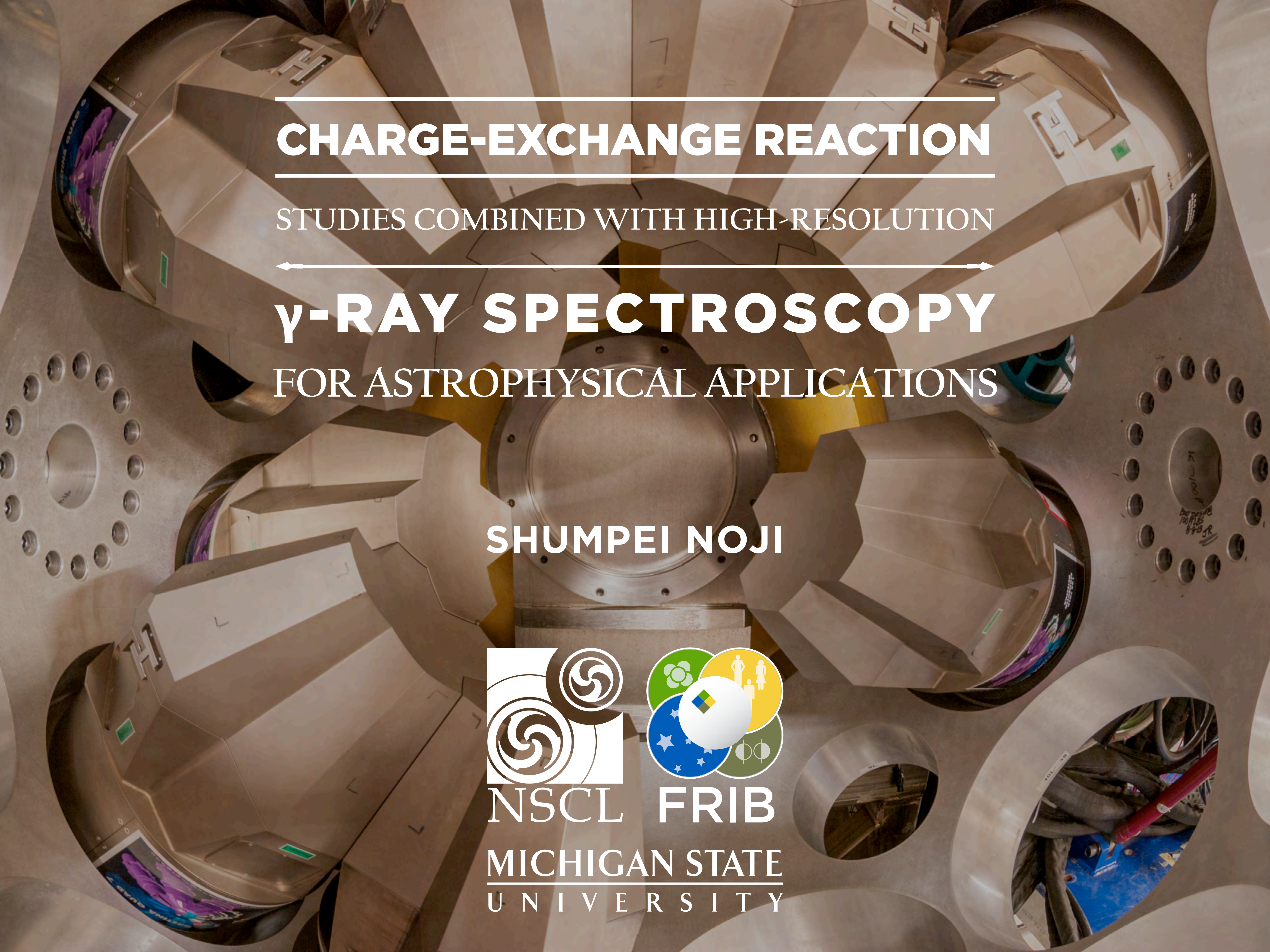


CHARGE-EXCHANGE REACTION

STUDIES COMBINED WITH HIGH-RESOLUTION

γ-RAY SPECTROSCOPY

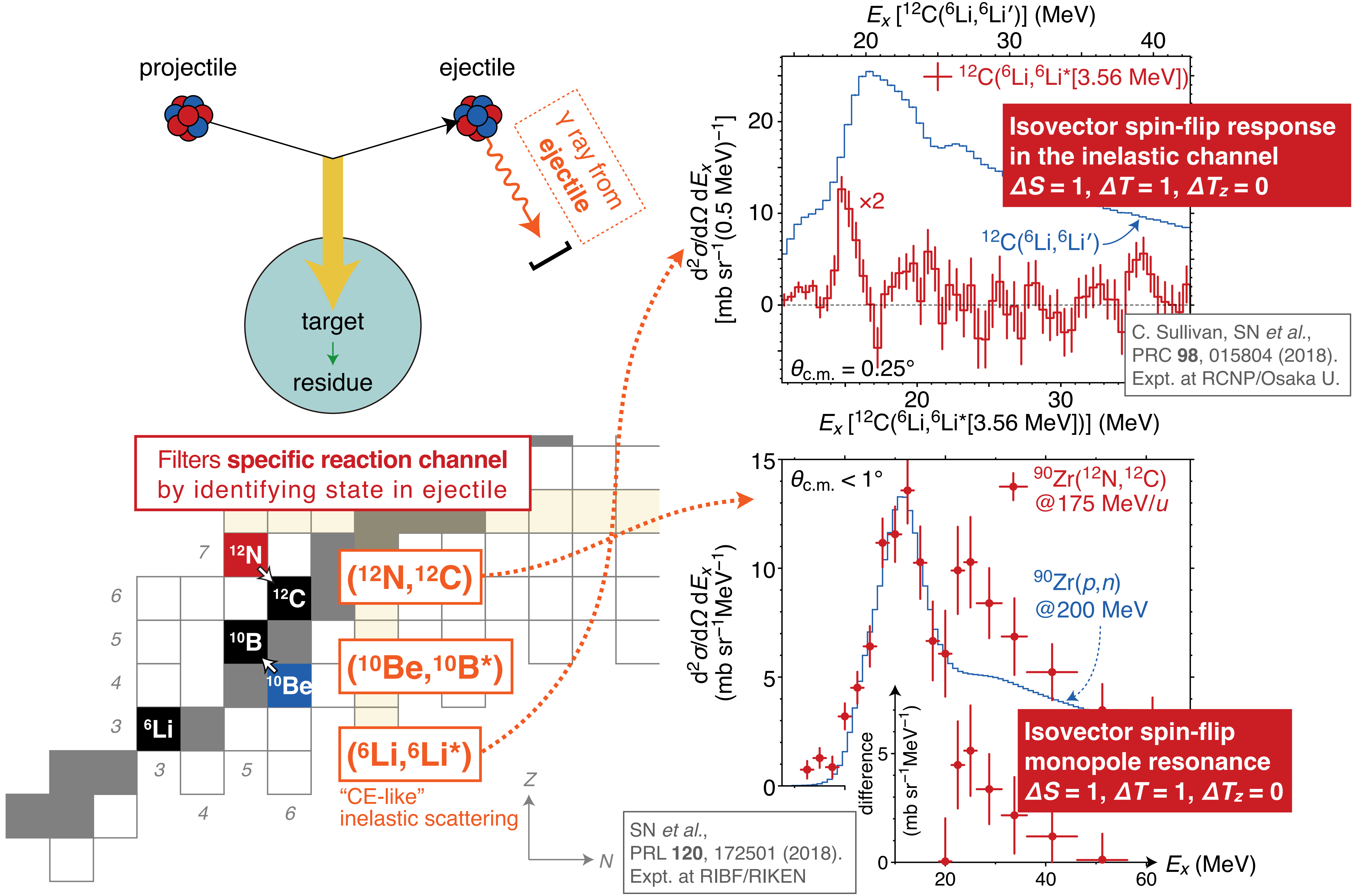
FOR ASTROPHYSICAL APPLICATIONS

SHUMPEI NOJI

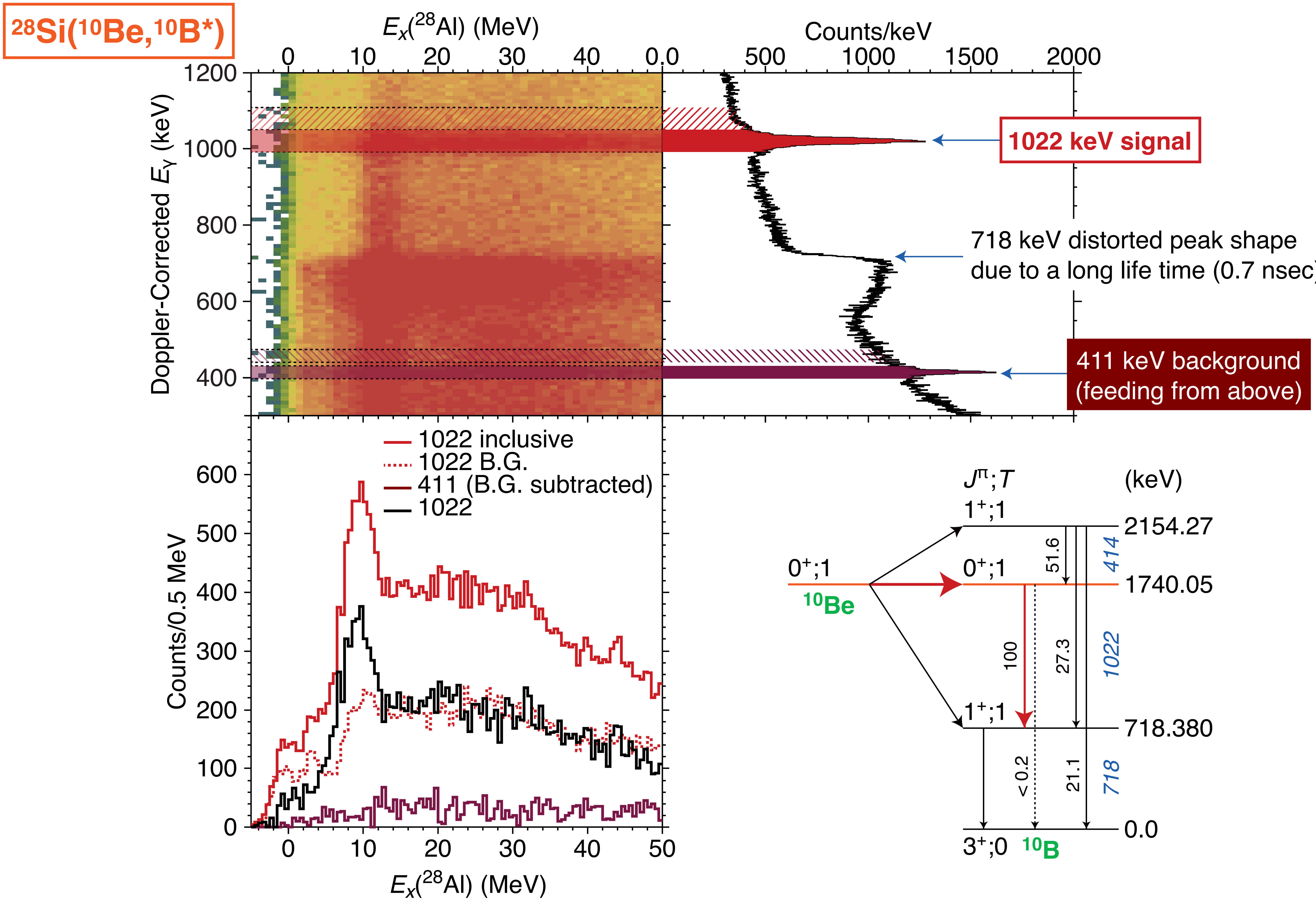
NSCL FRIB

MICHIGAN STATE UNIVERSITY

Charge-Exchange-Reaction Probes Combined with γ-Ray Coincidences Offer Unique Spectroscopic Opportunities



Accurate Determination of γ-Ray Energies with High Efficiency by GRETINA Allowed for Unambiguous Extraction of Spin-non-flip, Isospin-flip Transitions



Excitation-Energy Spectrum was Decomposed into Different Multipoles; Monopole & Dipole Strengths were Successfully Identified

- Multipole Decomposition Analysis

$\sigma^{\mathrm{exp}}(\theta_{\mathrm{c.m.}}, E_x)$

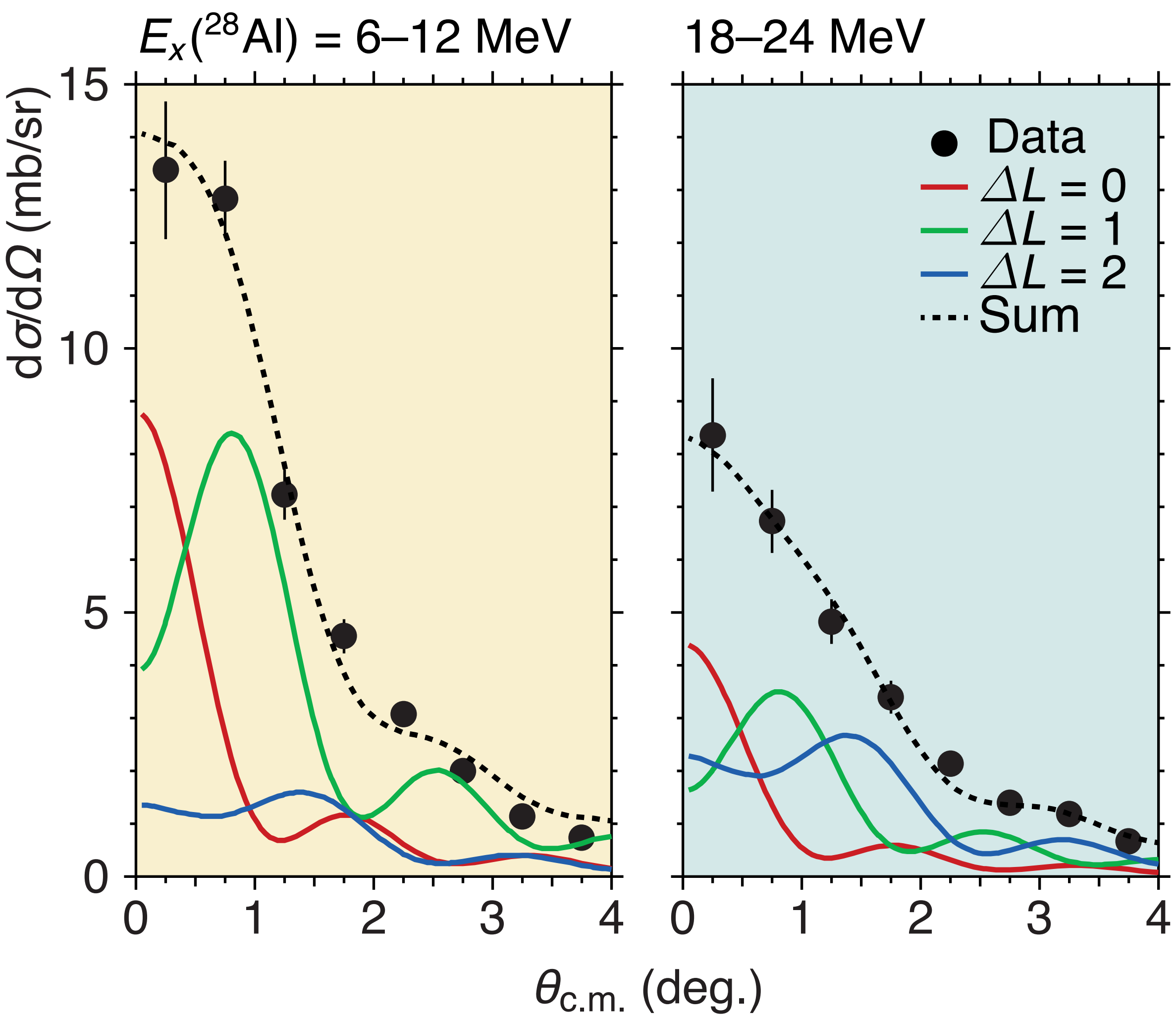
↑ fit

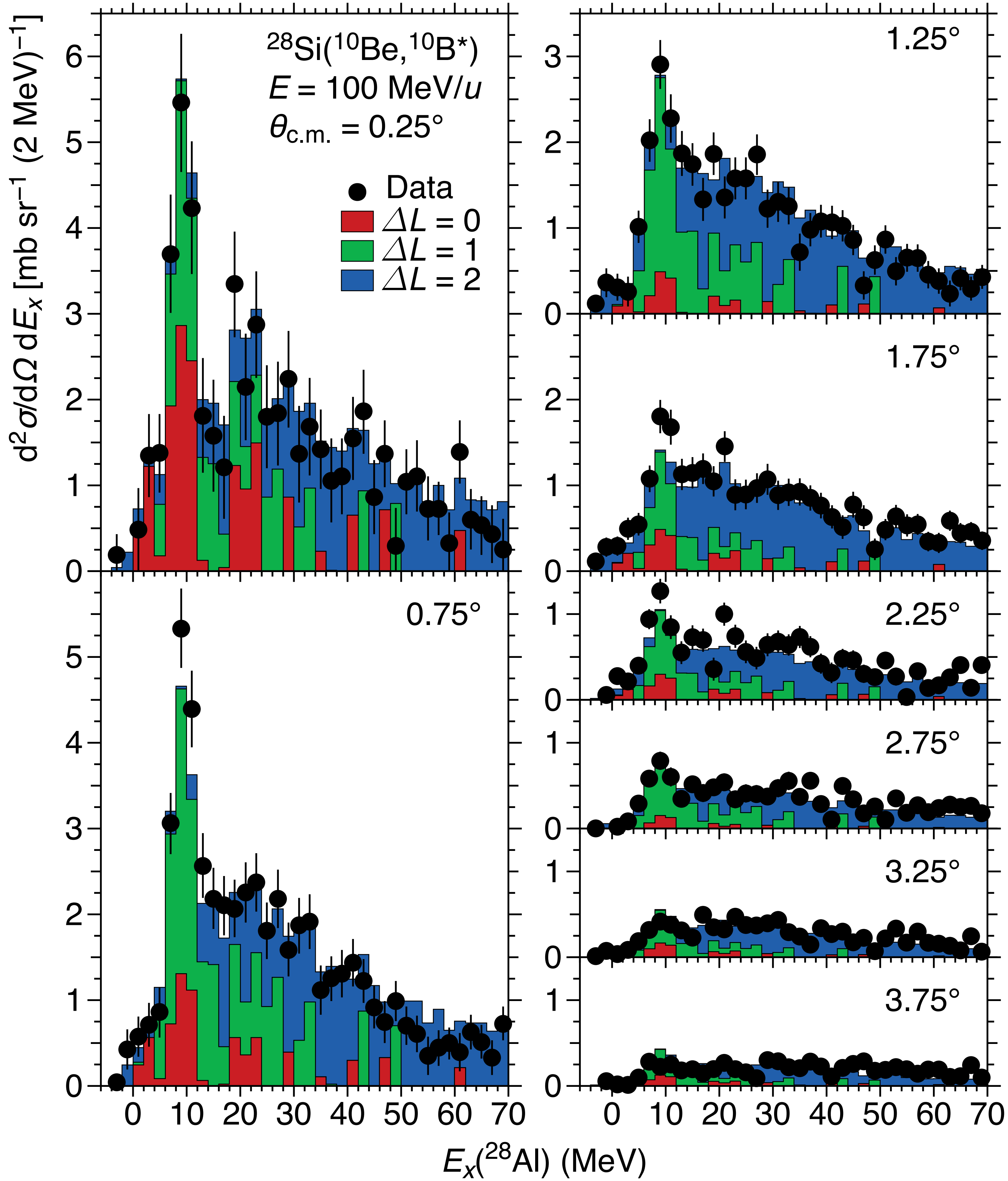
fit coeffs.

$$\sigma^{\mathrm{DWBA}}(\theta_{\mathrm{c.m.}}, E_x) = \sum_{J^\pi} \boxed{a_{J^\pi}(E_x)}\, \sigma^{\mathrm{DWBA}}_{J^\pi}(\theta_{\mathrm{c.m.}}, E_x)$$

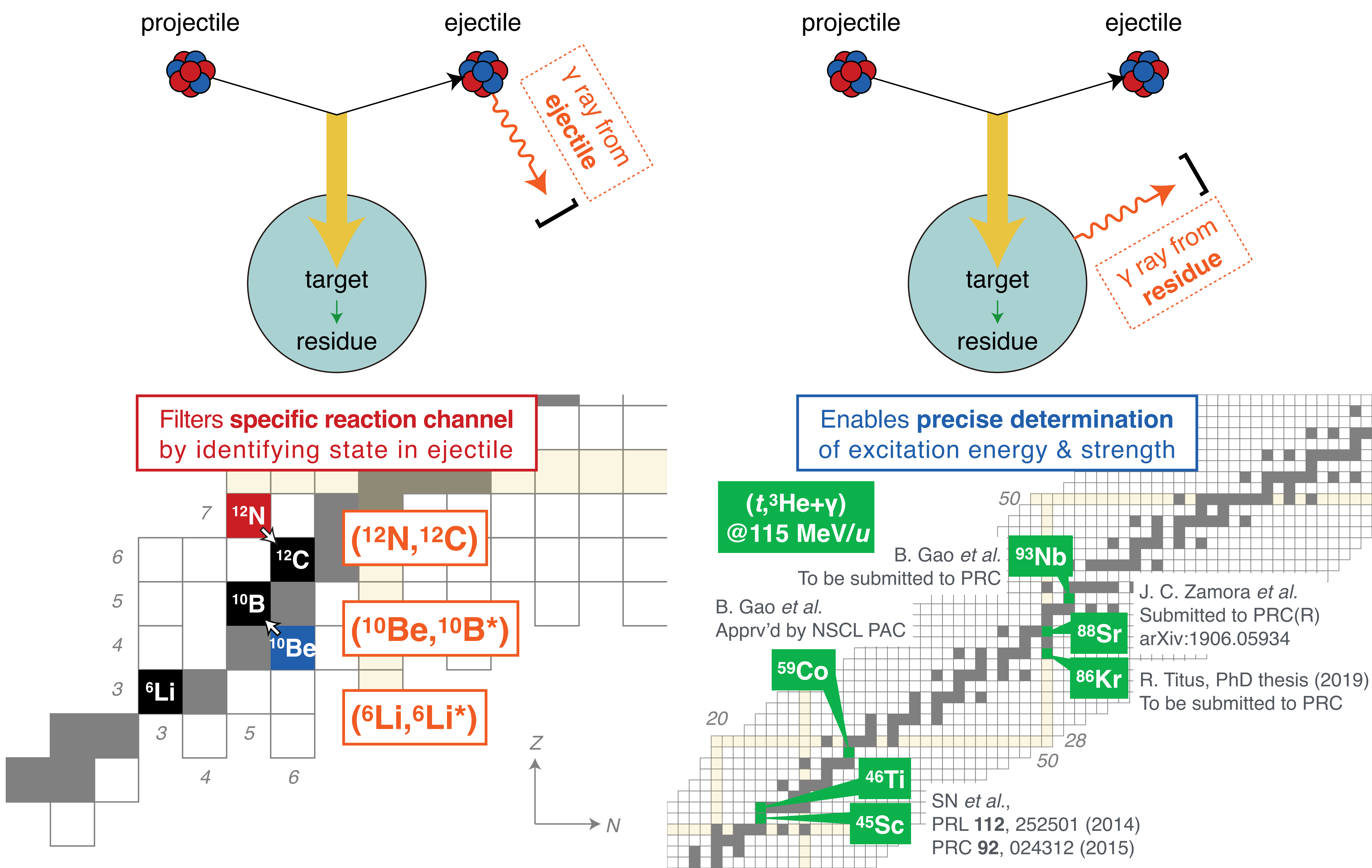
DWBA calculations with FOLD/DWHI
microscopic form factor for projectile & target

(smeared to emulate angular resolution)



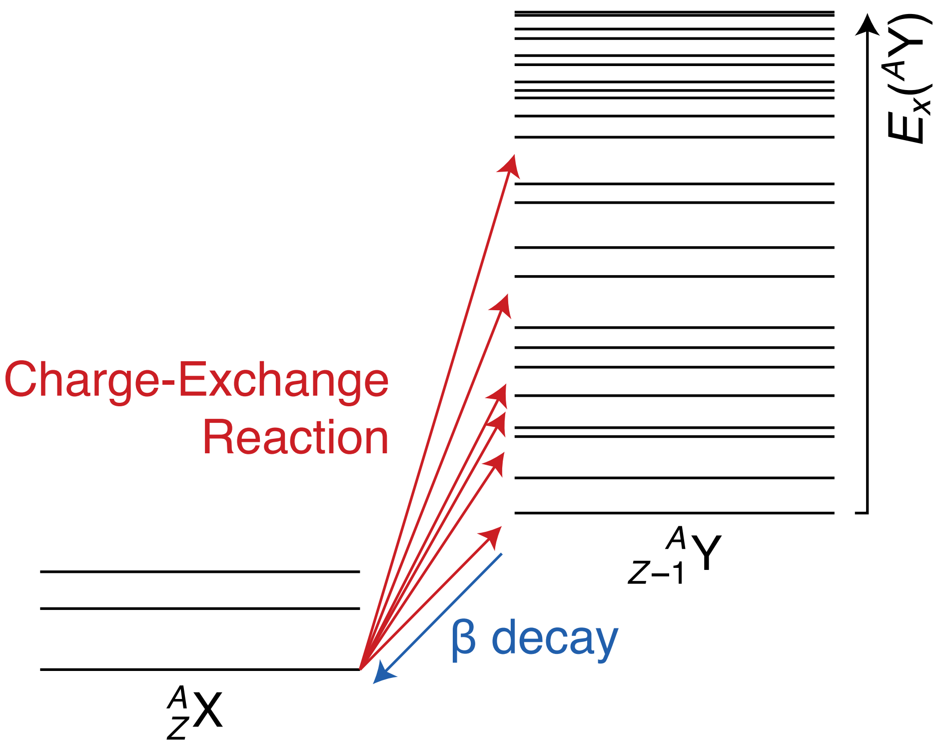


γ Coincidences Provide More Detailed Information on Excited Residue than is Possible by Charged-Particle Analysis Alone



CCSNe are Attractive Sites for Improving our Understanding of the Universe, for which Nuclear-Physics Processes Play a Major Role

- Accurate & detailed description of NP processes is important for understanding CCSNe
  - Contribute to nucleosynthesis
  - Stimulate galactic chemical evolution
  - Birthplaces of neutron stars & black holes
  - Predicted emission sites of gravitational waves

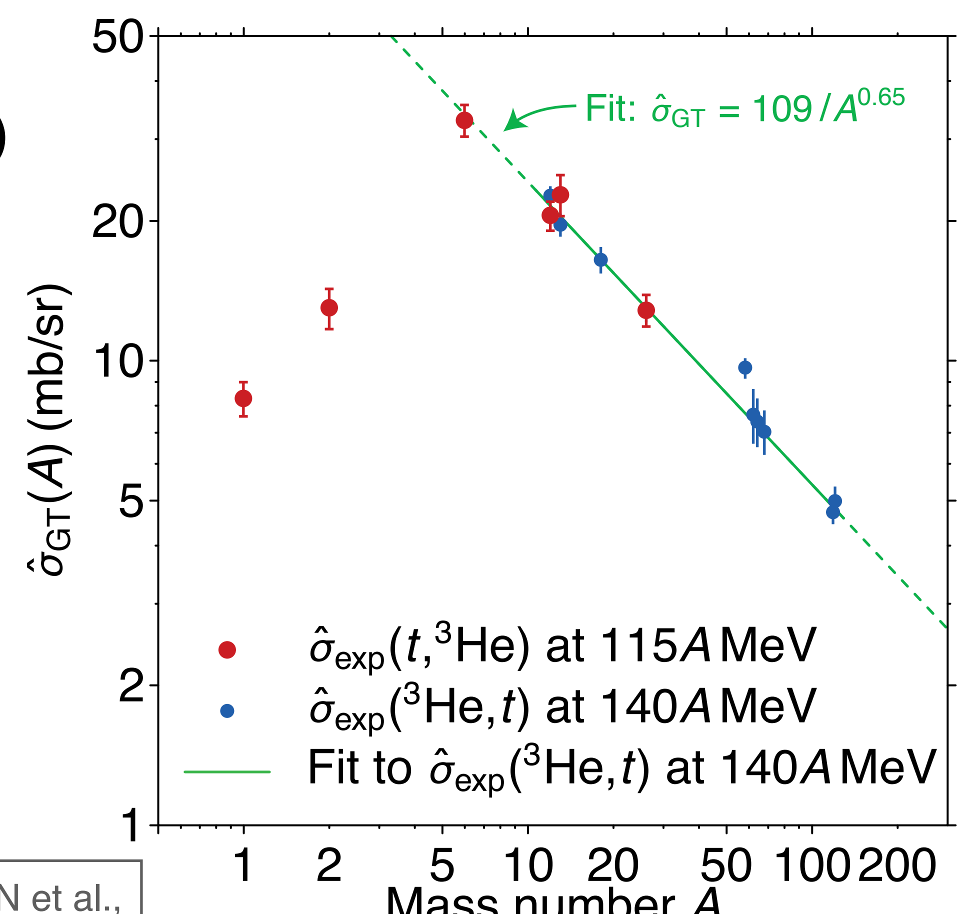


- For understanding evolution of CCSNe stellar electron captures are a key
  - Neutronize stellar core, decrease electron abundance
  - Reduce electron degeneracy pressure (which supports stars)
  - Lead to supernova explosion

- Electron captures are dominated by β+ Gamow-Teller transitions
  - Accessible *via* charge-exchange reactions
    - » Unlike β decays, no *Q*-value restrictions
  - Well-established, empirical proportionality between CE cross section & GT transition strengths [*B*(GT)]

$\sigma_{\Delta L=0}(0°) \approx \hat{\sigma}_{GT} B(GT)$

GT unit cross section



G. Perdikakis, SN et al., PRC 83, 054614 (2011).

Electron-Capture Rates are Derived from GT Transition-Strength Distributions where their Detailed Low-Lying Structures can be Important

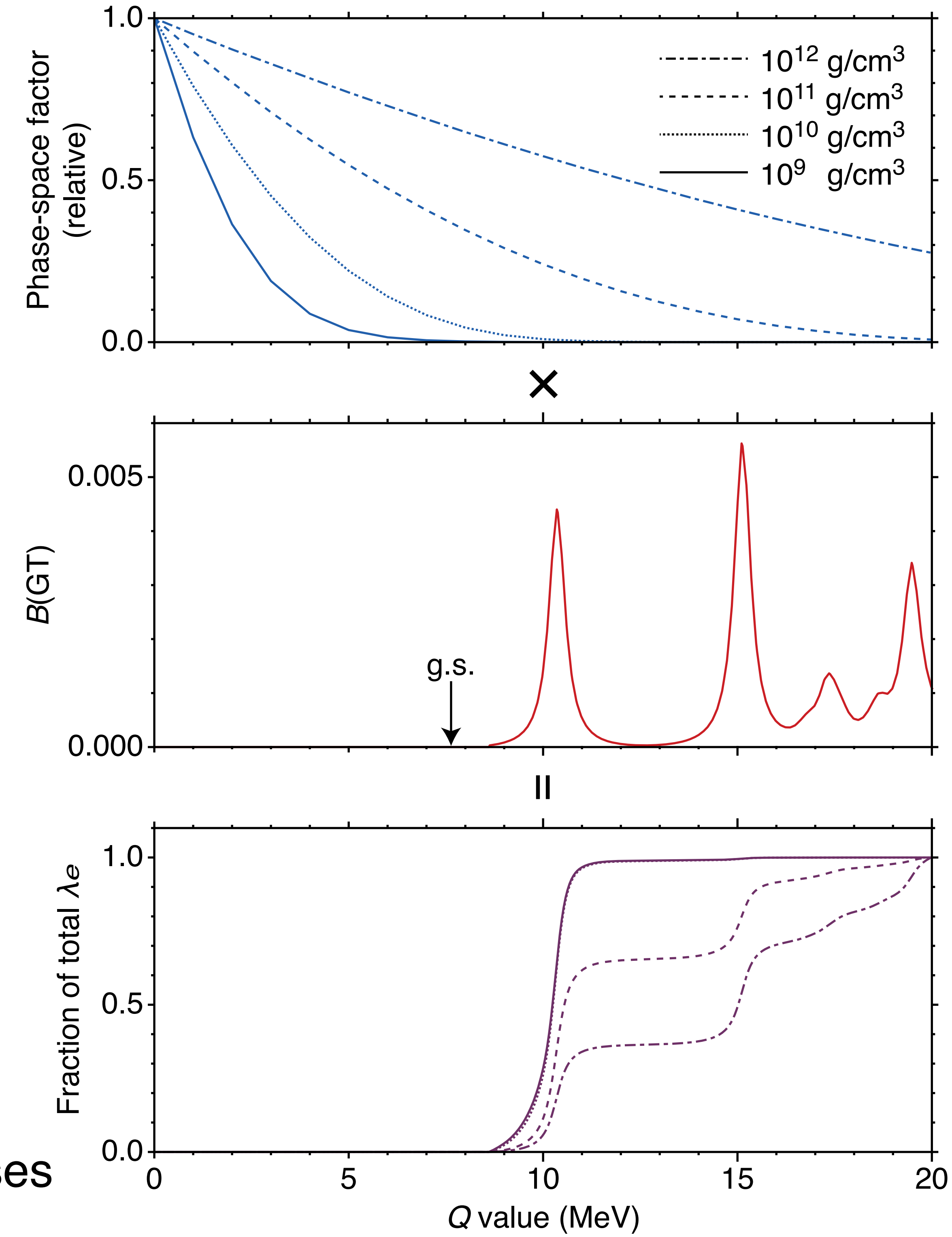
- Electron-capture rate is the sum of B(GT) for all the possible transitions weighted by the phase-space factors

$$\lambda_{EC}(T,\rho) = \text{const.} \sum_{i,j} \boxed{f_{ij}(T,\rho)}\ \boxed{B_{ij}(\mathrm{GT})}$$

Gamow-Teller transition strength

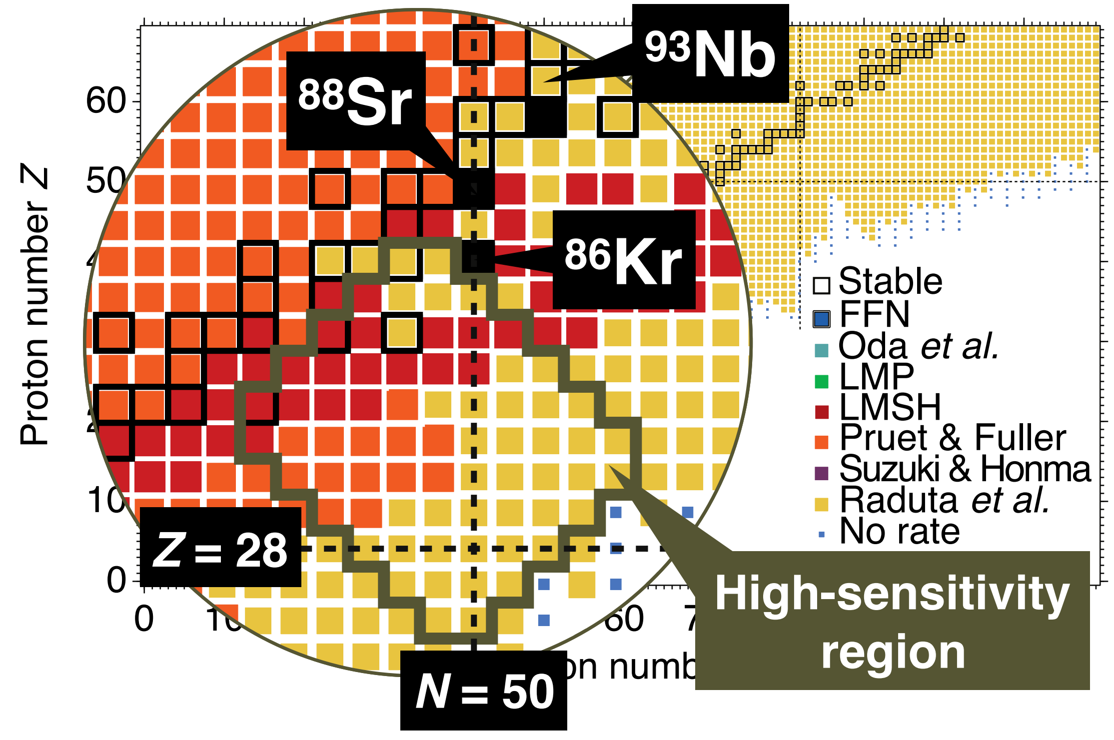
  - Phase-space factor
    - » Decreases as E_x becomes higher
    - » Decreases as temperature (T) & density (ρ) go up
  - B(GT) to low-lying states & their sum can become important at relevant T & ρ for core collapse

- Experiments target crucial nuclei
  - Many nuclei contribute, majority are unstable
    - » Infeasible to measure B(GT) for even a sizable fraction of all the cases
  - ECs can take place from excited states of mother
    - » Impossible to measure such a transition in the laboratory
  - Provide experimental information on most crucial cases
    - » Benchmark & constrain theoretical models so theory can reproduce/predict experimental B(GT)

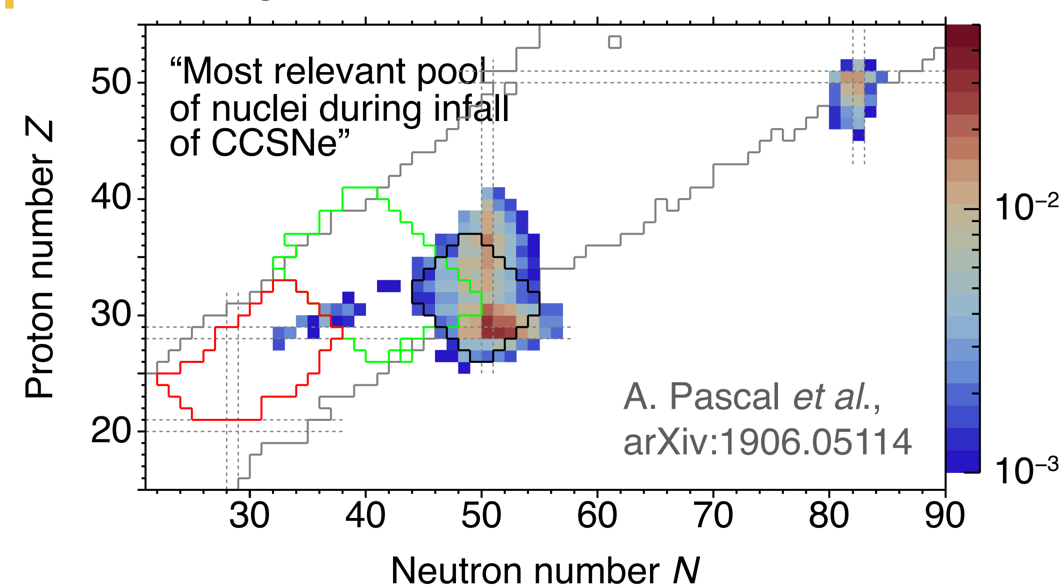


Sensitivity Studies have Identified Nuclei of High Impact on CCSNe, for which Microscopic Calculations were not Available

- Weak-Rate Library has been compiled
  - EC rates from multiple sources (theory & experiment) included in a comprehensive library [1]
- High-sensitivity region has been located
  - ~70 nuclei (out of 8,000+) around $N = 50$ play an important role in CCSNe [2,3]
    - » Supported by recent studies by A. Pascal *et al.*
- Few microscopic calculations had existed for high-sensitivity nuclei
  - Most relied on a simplistic **single-state approximation**
    - » Represented by single transition with common B(GT) (= 4.6) at an excitation energy
    - » Not accounting for Pauli blocking
      - Overestimating EC rates by an order of magnitude or more
- (t,^{3}He+γ) reaction on ^{86}Kr, ^{88}Sr, ^{93}Nb
  - (t,^{3}He) analysis
    - » B(GT) for wide E_x (≤ 25 MeV) & high energy resolution (≤ 500 keV)
  - γ-ray coincidences with HPGe
    - » More detailed information on transitions to low-lying states



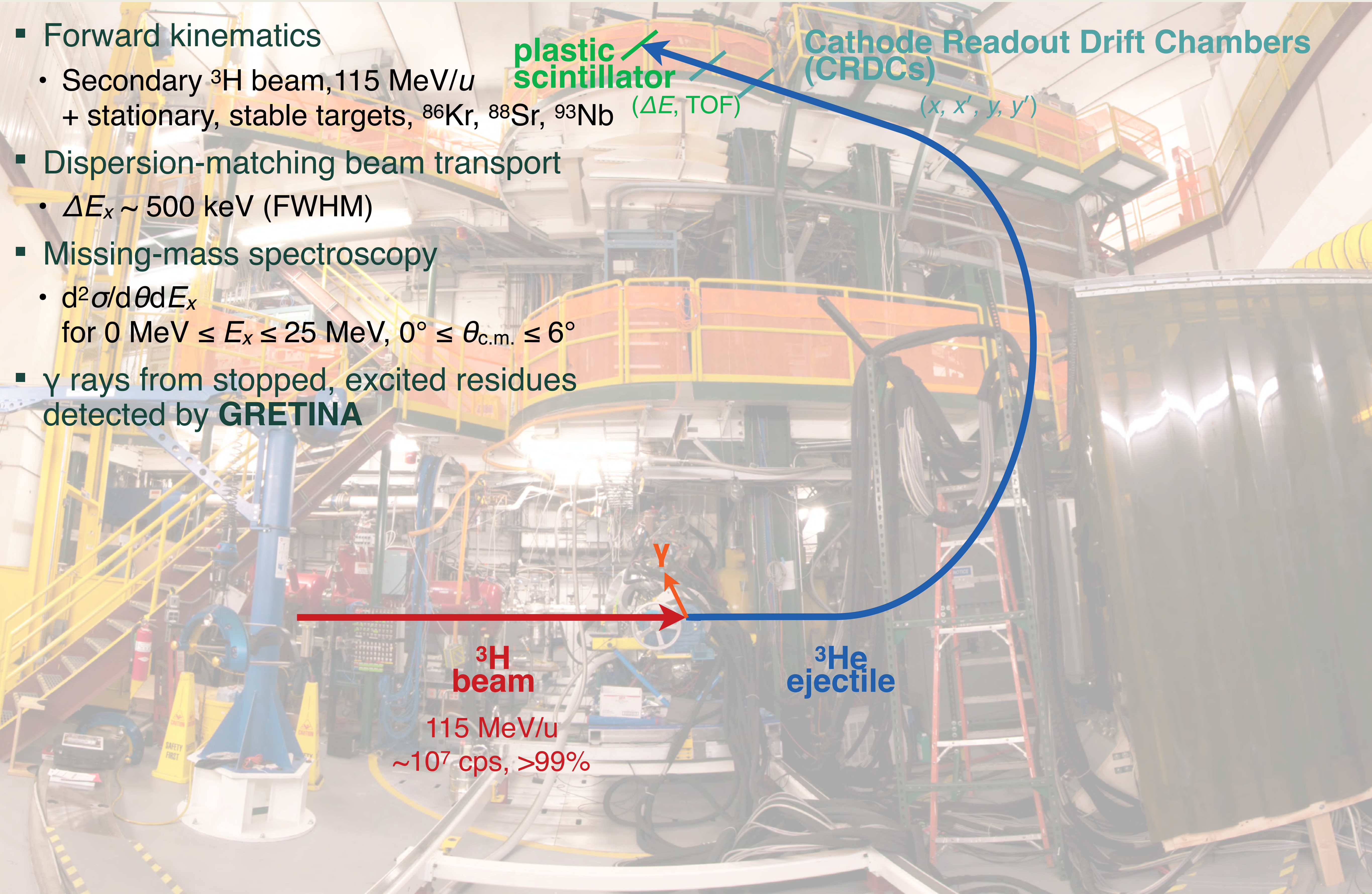
“Time-integrated relative deleptonization rate”



[1] https://groups.nscl.msu.edu/charge_exchange/weakrates.html
[2] C. Sullivan *et al.*, ApJ **816**, 44 (2016).
[3] R. Titus *et al.*, J. Phys. G **45**, 014044 (2017).

(t,^{3}He+γ) Measurements at 115 MeV/u were Performed at NSCL/MSU with the S800 Spectrograph & GRETINA

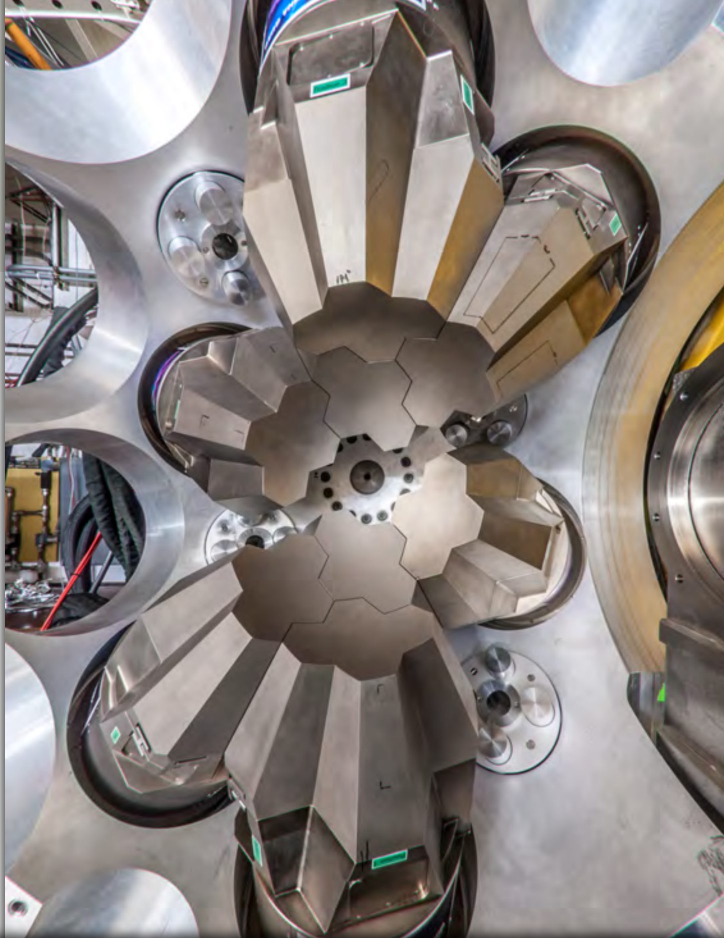
- Forward kinematics
  - Secondary ^{3}H beam,115 MeV/u + stationary, stable targets, ^{86}Kr, ^{88}Sr, ^{93}Nb
- Dispersion-matching beam transport
  - $\Delta E_x \sim$ 500 keV (FWHM)
- Missing-mass spectroscopy
  - $d^2\sigma/d\theta dE_x$ for 0 MeV $\leq E_x \leq$ 25 MeV, 0° $\leq \theta_{c.m.} \leq$ 6°
- γ rays from stopped, excited residues detected by **GRETINA**

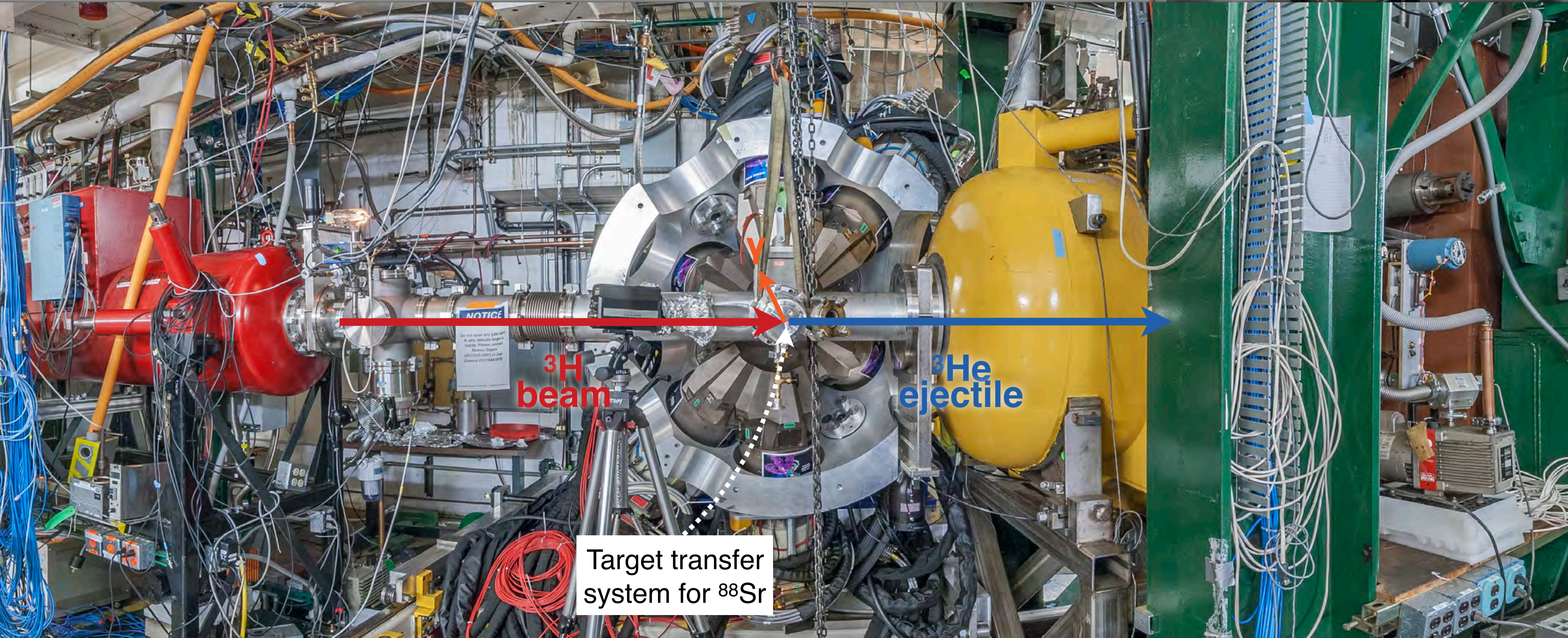


GRETINA's Efficiency & Resolution were Crucial for this Experimental Technique

- Eight GRETINA modules were mounted on one hemisphere
  - Accommodating the special reaction targets
    - ^{88}Sr (highly reactive in air; with a target transfer system; 19.6 mg/cm^2)
    - ^{86}Kr (gas; gas handing system; 295 K, 1210 Torr; 20 mg/cm^2)
  - Solid-angle coverage: ~1π sr; photopeak efficiency: ~4% at 2 MeV
  - No Doppler reconstruction — measured γ rays from residues at rest

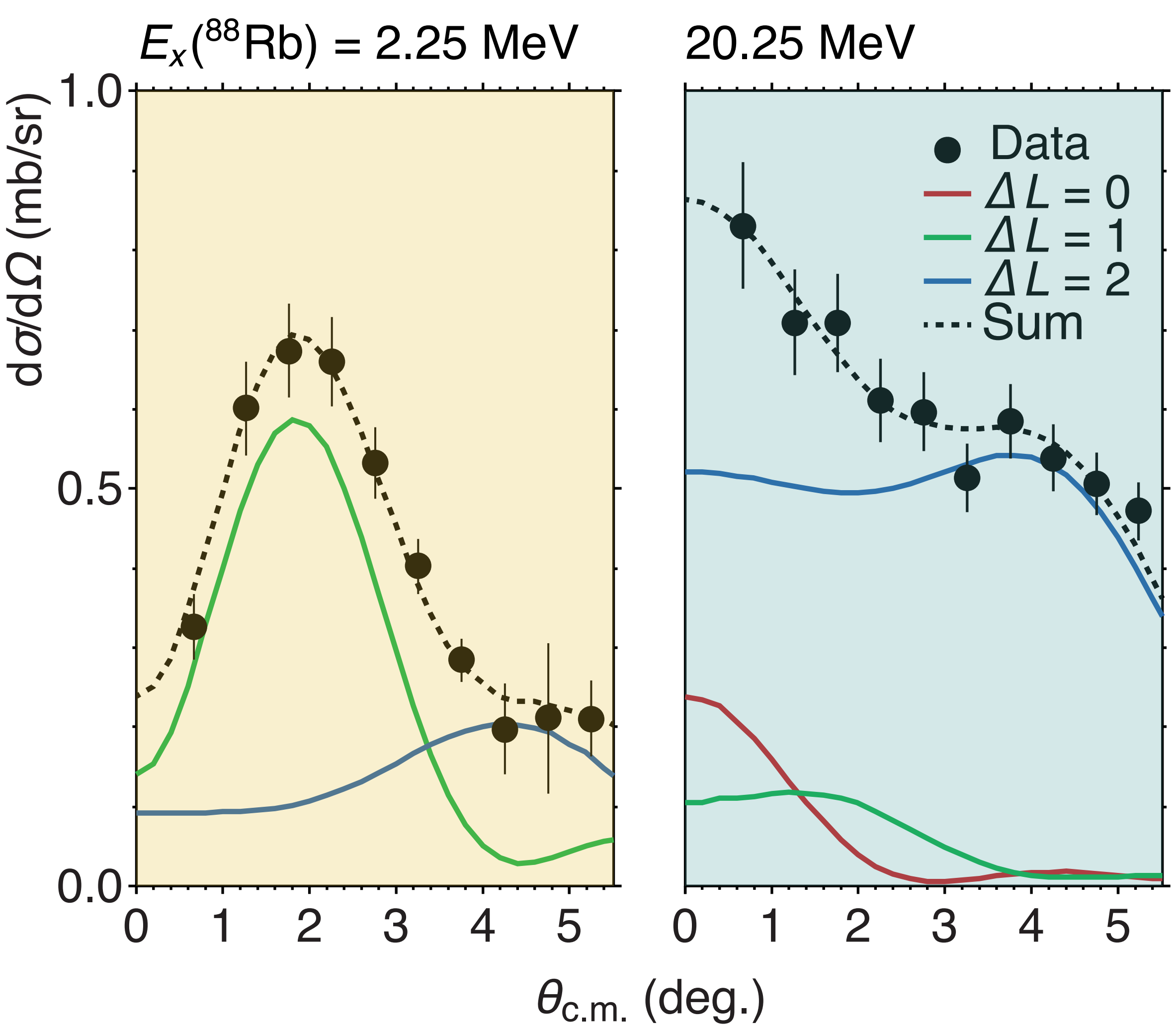
[1] S. Paschalis *et al.*, NIMA **709** (2013) 44.
[2] D. Weisshaar *et al.*, NIMA **847** (2017) 187.

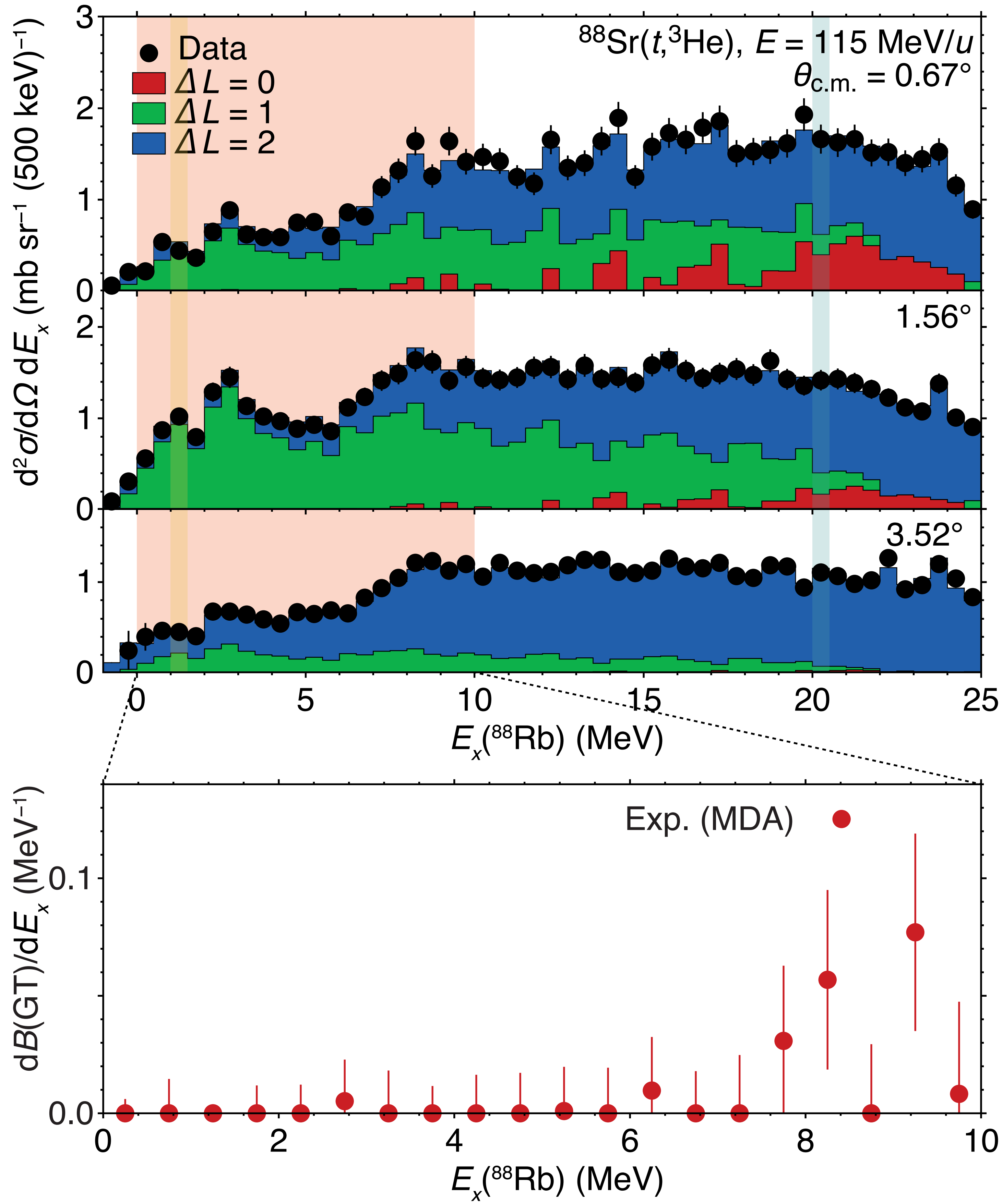




Excitation-Energy Spectrum was Decomposed into Different Multipoles; GT Strength Obtained from Extracted Monopole Component was Small

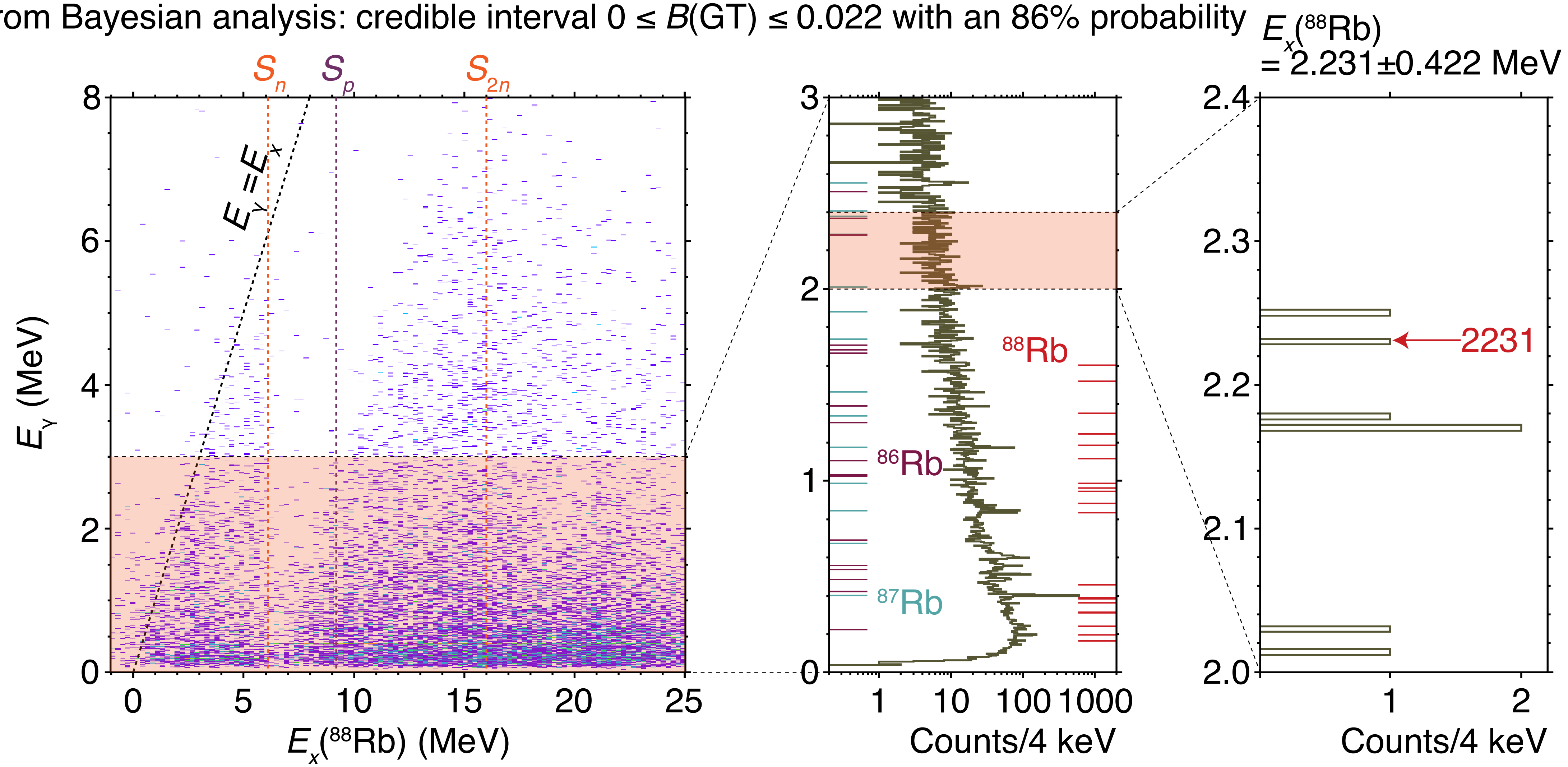
- Multipole Decomposition Analysis
  - $\Sigma\, B(\mathrm{GT}) = 0.10 \pm 0.05$ for $E_x \leq 10$ MeV
  - Significantly smaller than ^{90}Zr → ^{90}Y, for $E_x \leq 10$ MeV
    - » $\Sigma\, B(\mathrm{GT}) = 0.7 \pm 0.1$ (stat.) $\pm\, 0.1$ (sys.)
      - π0g9/2 occupation: 0.7 for ^{88}Sr; 1.0 for ^{90}Zr





Analysis of γ Rays Provide Stricter Constraint on GT Strength for Low-Lying States in ^{88}Rb

- E_x (S800) vs E_γ (GRETINA)
  - Distinct $E_\gamma = E_x$ line → Background nearly non-existent, clean gate based on E_x
  - Particle-decay channels open at separation energies (S_n & S_p)
    - γ-ray transitions from states in ^{88}Rb, as well as ^{87}Rb and ^{86}Rb observed
    - Non observation from ^{87}Kr: Proton-emission probability from ^{88}Rb very small
- γ decays from GT states (E_x gated $E\gamma$ spectrum)
  - No significant signals observed from low-lying 1^+ states in ^{88}Rb reachable by GT transitions from ^{88}Sr
  - Only one count could be attributed to known 1^+ state in ^{88}Rb at 2.231 MeV
    - From Bayesian analysis: credible interval $0 \leq B(\mathrm{GT}) \leq 0.022$ with an 86% probability

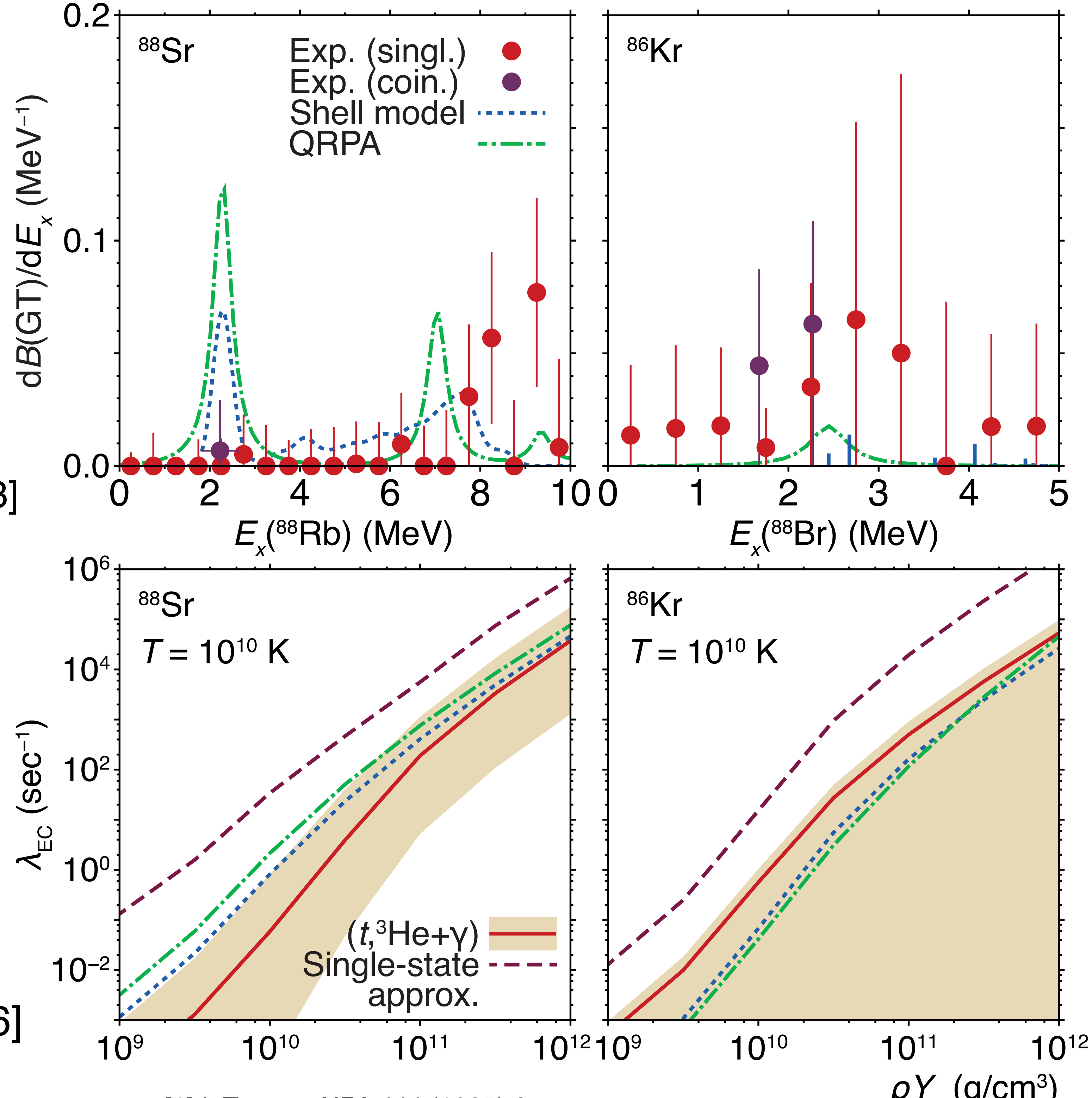


Shell-Model & QRPA Calculations are Consistent with Experiment; Single-State Approximation Overestimates Strength by 2 Orders of Magnitude

- Shell model
  - ^{78}Ni core
    + π particles $0f_{5/2}$, $1p_{3/2}$, $1p_{1/2}$, $0g_{9/2}$
    + ν holes $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $0h_{11/2}$
  - NuShellX; TBME from jj44pna & CD-Bonn
  - Consequences of model-space truncation taken into account [1]
- QRPA
  - Performed using the axially-deformed Skyrme Finite Amplitude Method (FAM) [2,3]
  - Extended to odd-*A*, equal-filing approx. [4]
- Theory is consistent w/ experiment in summed *B*(GT)

Σ *B*(GT)	Exp	SM	QRPA
^{88}Sr ($E_x \leq 10$ MeV)	0.1±0.05	0.12	0.14
^{86}Kr ($E_x \leq 5$ MeV)	$0.108^{+0.063}_{-0.108}$	0.035	0.024

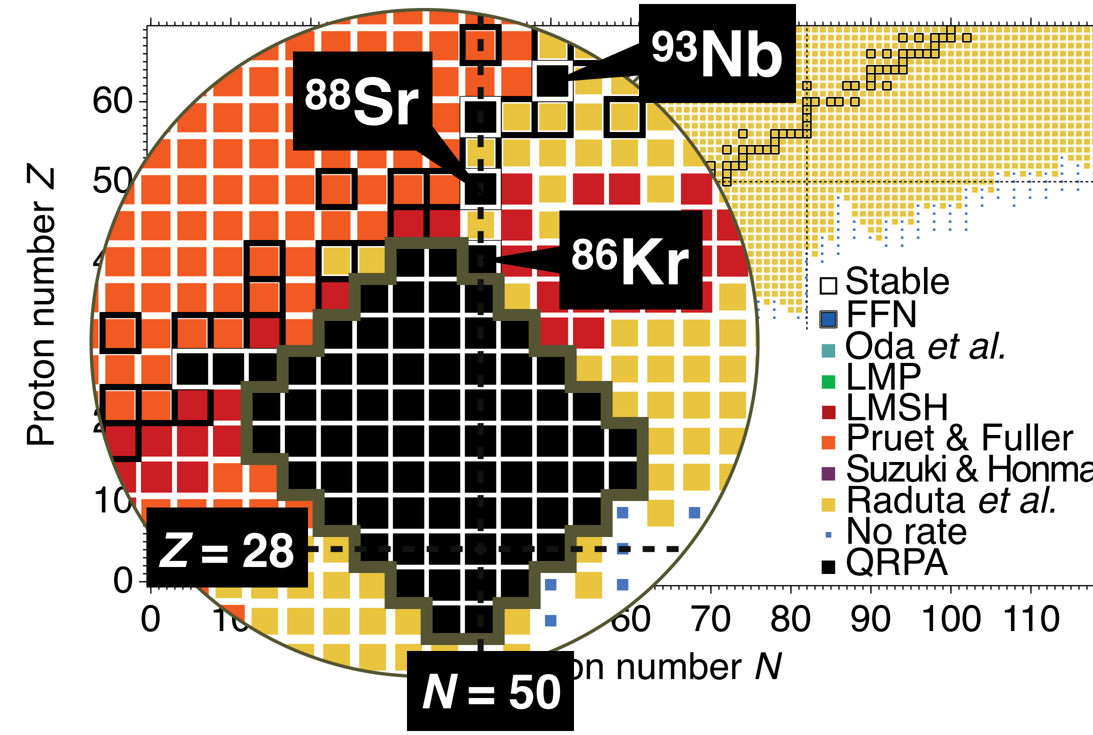
- Single-state approximation [*B*(GT) = 4.6] overestimating by a factor of ~100
- EC rates closer at higher densities, (rates are primarily determined by Σ *B*(GT), & less sensitive to detailed structure)

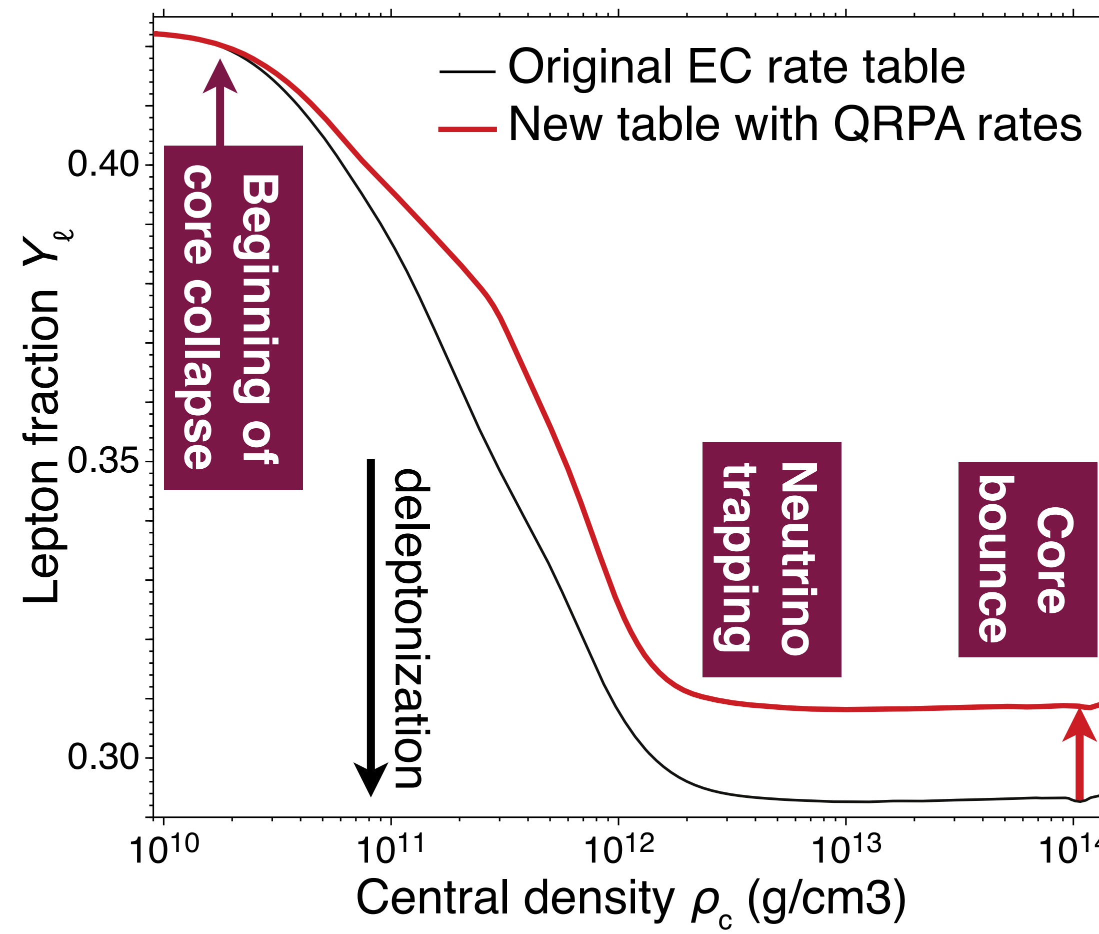


[1] I. Towner, NPA 444 (1985) 2.
[2] P. Avogadro & T. Nakatsukasa, PRC 84, 014314 (2011).
[3] M. T. Mustonen et al., PRC 90, 024308 (2014).
[4] T. Shafer et al., PRC 94, 055802 (2016).

EC Rates Based on QRPA are Included in Weak-Rate Library for the Use in Astrophysical Simulations

- New rate table for astrophysical simulations has been developed
  - EC rates calculated on the basis of QRPA framework are included for nuclei in the high-sensitivity region
- CCSN simulations performed with new rates
  - Neutrino-transport code NuLib
    + General-relativistic, spherically-symmetric hydrodynamics code GR1D
  - Late-stage evolution of the collapsing star
  - Significant reduction (~14%) in deleptonization with the new rates
- Potential multi-messenger signals useful for better understanding/modeling CCSNe will be affected
  - Neutrino emission
  - Gravitational-wave emittance





Summary & Conclusions

- Electron captures on nuclei near $N = 50$
  have a large impact on the behavior of core-collapse supernovæ

- Few microscopic calculations had existed for this region
  for astrophysical simulations

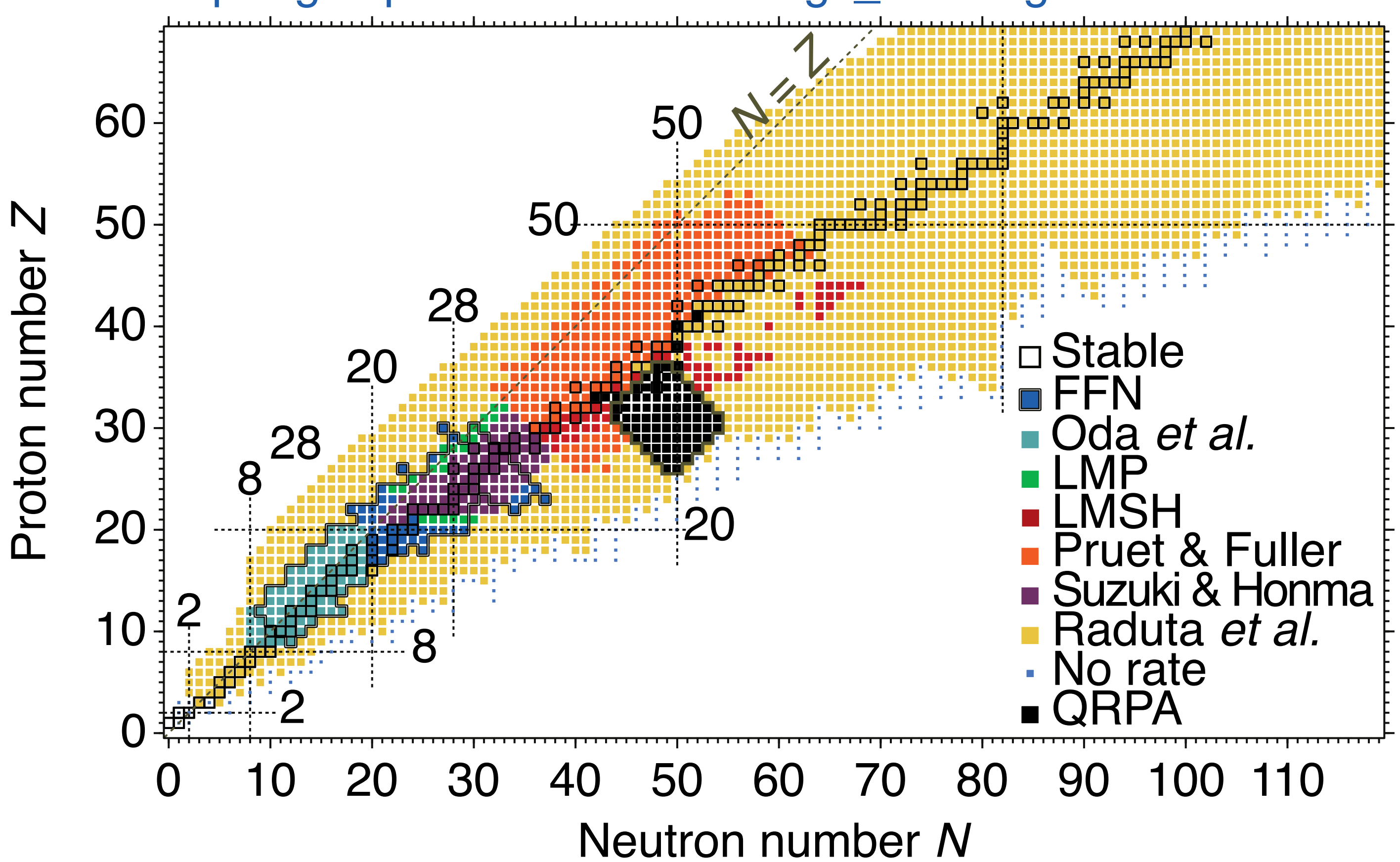
- Gamow-Teller transition strengths [B(GT)] of ^{88}Sr & ^{86}Kr (also of ^{93}Nb) were extracted
  via (t,^{3}He+γ) measurements

- γ-ray coincidences were pivotal
  in determining low-lying strengths

- Shell-model & QRPA calculations
  were found capable of reproducing
  experimental B(GT)

- Weak-Rate Library now includes
  new EC rates based on QRPA,
  and is ready for the use
  in astrophysical simulations

https://groups.nscl.msu.edu/charge_exchange/weakrates.html



Acknowledgements

- NSCL Charge-Exchange Group
  - R. G. T. Zegers, **J. C. Zamora*** (^{88}Sr), **B. Gao*** (^{93}Nb), **C. Sullivan#** (Weak-Rate Library), **R. Titus** (^{86}Kr), S. Lipschutz#, J. Schmitt, A. Carls, M. DeNudt, C. Maher, C. Hulquist, D. Bazin, J. Pereira, Sam M. Austin

* Postdoc until 2018
\# Graduated in 2018

arXiv:1906.05934 [nucl-ex]

Experimental Constraint on Stellar Electron-Capture Rates from the ^{88}Sr$(t,{}^{3}\mathrm{He}+\gamma)^{88}$Rb reaction at 115 MeV/u

J. C. Zamora,[1,2] R.G.T. Zegers,[1,2,3] Sam M. Austin,[1,2] D. Bazin,[1] B. A. Brown,[1,2,3] P.C. Bender,[1] H.L. Crawford,[4] J. Engel,[5] A. Falduto,[6,2] A. Gade,[1,2,3] P. Gastis,[6,2] B. Gao,[1,2] T. Ginter,[1] C. J. Guess,[7] S. Lipschutz,[1,2,3] B. Longfellow,[1,3] A.O. Macchiavelli,[4] K. Miki,[8] E. Ney,[5] S. Noji,[1,2] J. Pereira,[1,2] J. Schmitt,[1,2,3] C. Sullivan,[1,2,3] R. Titus,[1,2,3] and D. Weisshaar[1]

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[2]*Joint Institute for Nuclear Astrophysics: CEE, Michigan State University, East Lansing, MI 48824, USA*
[3]*Departament of Phys...*
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Gamow-Teller transitions to ^{93}Zr via the ^{93}Nb(t,^{3}He+γ) re... its application to the stellar electron-capture rates at N...

B. Gao,[1,2] R.G.T. Zegers,[3,4,5] J. C. Zamora,[6,4] Sam A. Austin,[3,4] D. ... Bender,[3] A. Falduto,[7,4] A. Gade,[3,4,5] P. Gastis,[7,4] C. J. Guess,[8] S. Lip... S. Noji,[3,4] J. Pereira,[3,4] J. Schmitt,[3,4,5] C. Sullivan,[3,4,5] R. Titus,...

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...ant roles in core-collapse superno... ...on theoretical calculations which... ...easurement of the Gamow-Teller... ...$(t,{}^{3}\mathrm{He}+\gamma)$ charge-exchange re... ...strength distributions were extr... ...mpared with shell-model and qu... ...l features of the experimental... ...the detailed distributions. C... ...agree very well with those based... ...larger discrepancies were foun... ...he parameterized approximation...

Constraints for stellar electron-capture rates on ^{86}Kr via the ^{86}Kr$(t,{}^{3}\mathrm{He}+\gamma)$ reaction and the implications for core-collapse supernovae

R. Titus,[1,2,3] E. Ney,[4] R.G.T. Zegers,[1,2,3,*] Sam M. Austin,[1,2] D. Bazin,[1,3] J. Belarge,[1] P.C. Bender,[5] B. A. Brown,[1,2,3] C. M. Campbell,[6] B. Elman,[1,3] J. Engel,[4] A. Gade,[1,2,3] B. Gao,[7] E. Kwan,[1] S. Lipschutz,[1,2,3] B. Longfellow,[1,3] E. Lunderberg,[1,3] T. Mijatović,[1] S. Noji,[1,2] J. Pereira,[1,2] J. Schmitt,[1,2,3] C. Sullivan,[1,2,3] D. Weisshaar,[1] and J. C. Zamora[8]

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