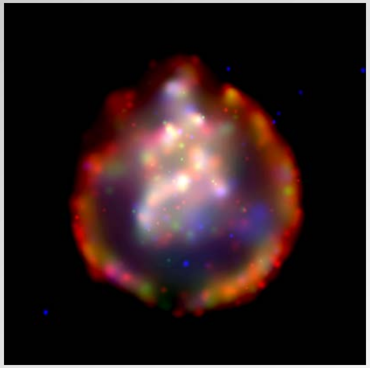    

Constraining weak interaction rates for astrophysics by using nuclear charge-exchange reactions

Remco G.T. Zegers

For the NSCL Charge-Exchange group and Collaborators

MICHIGAN STATE UNIVERSITY

Physics of Core-Collapse Supernova and Compact Star Formations

Waseda University, March 19-21, 2018

NSCL FRIB JINA-CEE GRETINA NSF U.S. DEPARTMENT OF ENERGY Office of Science

Contents

- Weak reaction rates in astrophysics (electron captures)
- Weak-rate library
- Charge-exchange reactions as a tool to extract Gamow-Teller strengths
- Experimental results and the testing of theoretical methods for estimating weak reaction rates
- Core-collapse supernovae – EC rate sensitivity studies
- EC rates on nuclei near N=50 above ^{78}Ni
- Development of the (d,^{2}He) reaction in inverse kinematics: a tool for constraining EC rates for unstable nuclei
- High-Rigidity Spectrometer for FRIB

EC rates in nuclear astrophysics

Graduate students
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Rachel Titus (^{86}Kr)
Jaclyn Schmitt
Alex Carls

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Bingshui Gao (^{93}Nb)

And…
Sam Austin
Daniel Bazin
Jorge Pereira
Shumpei Noji (^{45}Sc, ^{46}Ti)

Previous members who analyzed data shown in this presentation:
M. Scott, Y. Shimbara (^{56}Fe)
Masaki Sasano (^{56}Ni)
A.L. Cole
Kenjiro Miki (^{100}Mo)

…and our local and outside collaborators, in particular Alex Brown, the NSCL gamma group (Alexandra Gade, Dirk Weisshaar), H. Schatz, Ed Brown, Sean Couch, Sean Liddick, Artemis Spyrou, Andreas Stolz, Evan O'Connor (Stockholm U.), Yoshi Fujita, A Tamii (RCNP, Osaka U.), Muhsin Harakeh (KVI), Dieter Frekers (U. Muenster), Sanjib Gupta (IITR), Hide Sakai (RIKEN), Tomohiro Uesaka (RIBF), Elena Litvinova, Caroline Robin (WMU), Karlheinz Langanke (GSI), Gabriel Martínez-Pinedo (TU Darmstadt), Mika Mustonen (Yale) Lew Riley (Ursinus), B. Rubio (IFIC, Valencia) Gianluca Colò (Milano), Gretina collaboration, A1900 and CCF staff, and many others!

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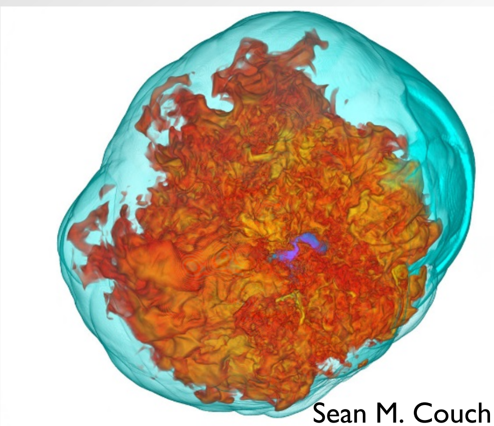
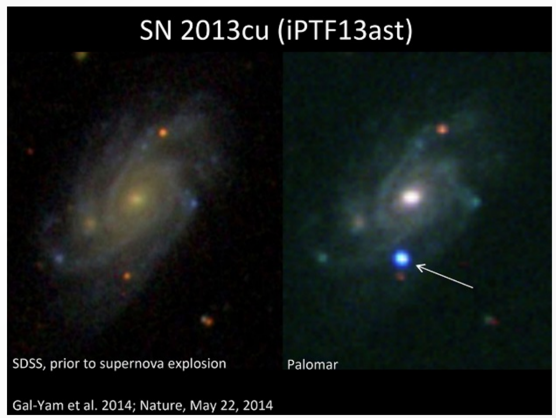
Weak rates in astrophysics

Weak reactions play strong roles in the evolution of a wide variety of nuclear astrophysical phenomena.

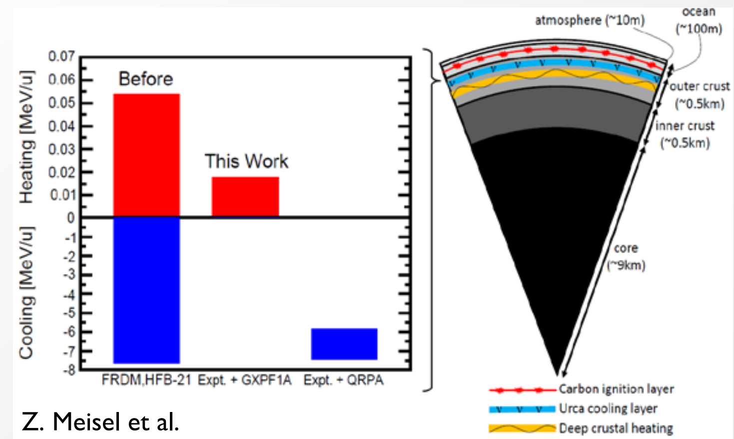
Core-collapse supernovae



Thermonuclear supernovae



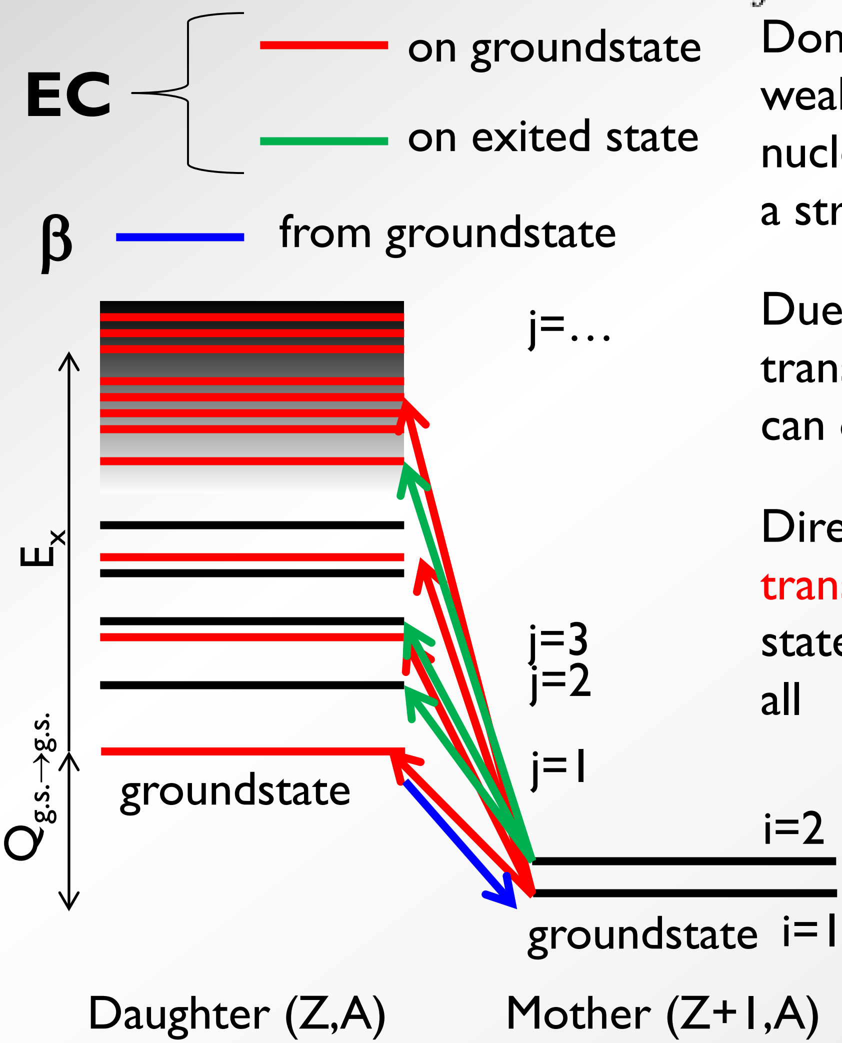
Cooling & heating in accreting neutron star crusts



Electron capture, β-decay, and neutrino interactions serve as input in simulations and largely rely on theoretical calculations in which density and temperature dependencies are taken into consideration. The theoretical models must be developed, constrained, and benchmarked.

electron capture rates on nuclei

$$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) \boxed{B(GT)_{ij}}$$



Dominated by allowed (Gamow-Teller ΔL=0, ΔS=1, ΔT=1) weak transitions between states in the initial and final nucleus. Each transitions is characterized by a Q-value and a strength, B(GT).

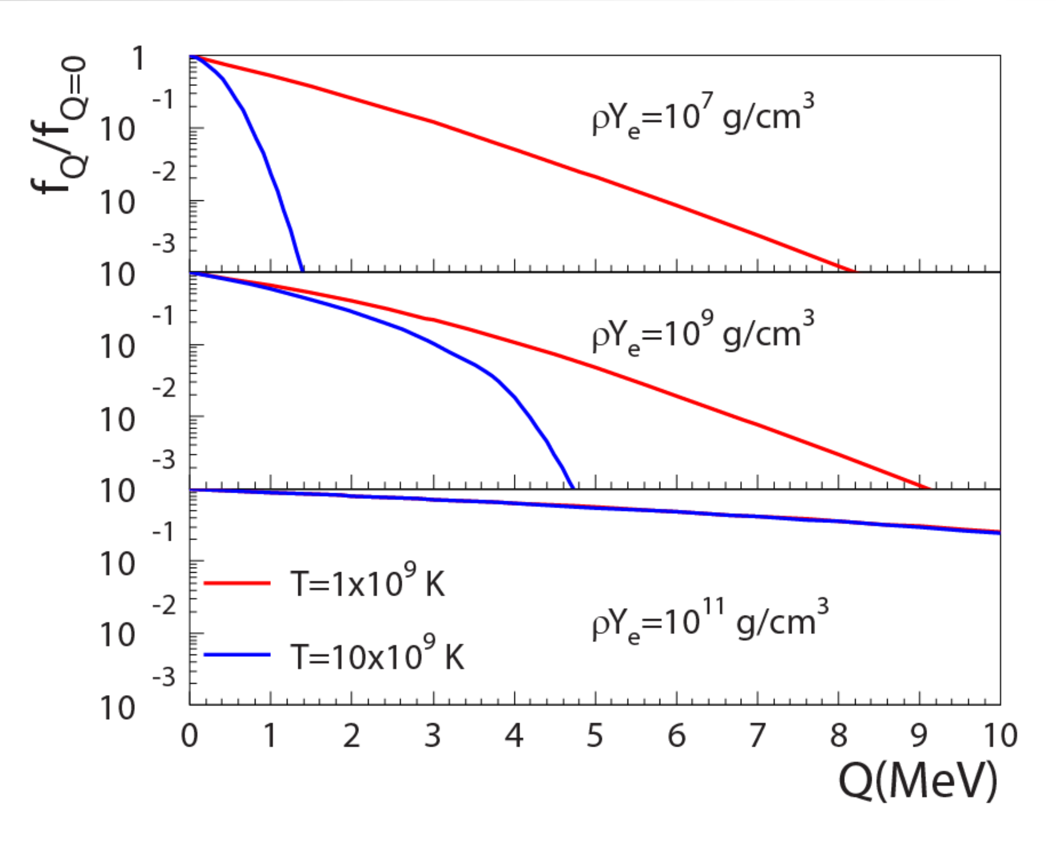
Due to finite temperature in stars, Gamow-Teller transitions from excited states in the mother nucleus can occur

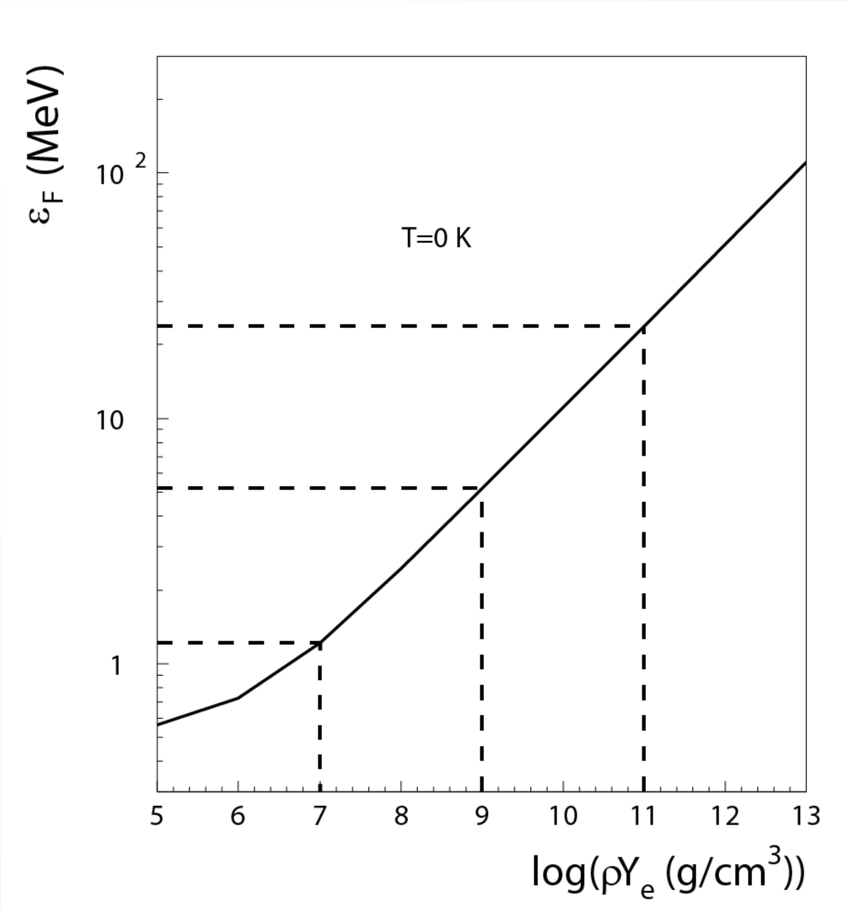
Direct empirical information on strength of transitions [B(GT)] is limited to low-lying excited states e.g. from the inverse (β-decay) transitions, if at all

EC rates on many (unstable) nuclei are important. Only fraction of transitions can be measured. Must rely on theoretical models benchmarked by experiments. (Quenching factor)

$$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) B(GT)_{ij}$$

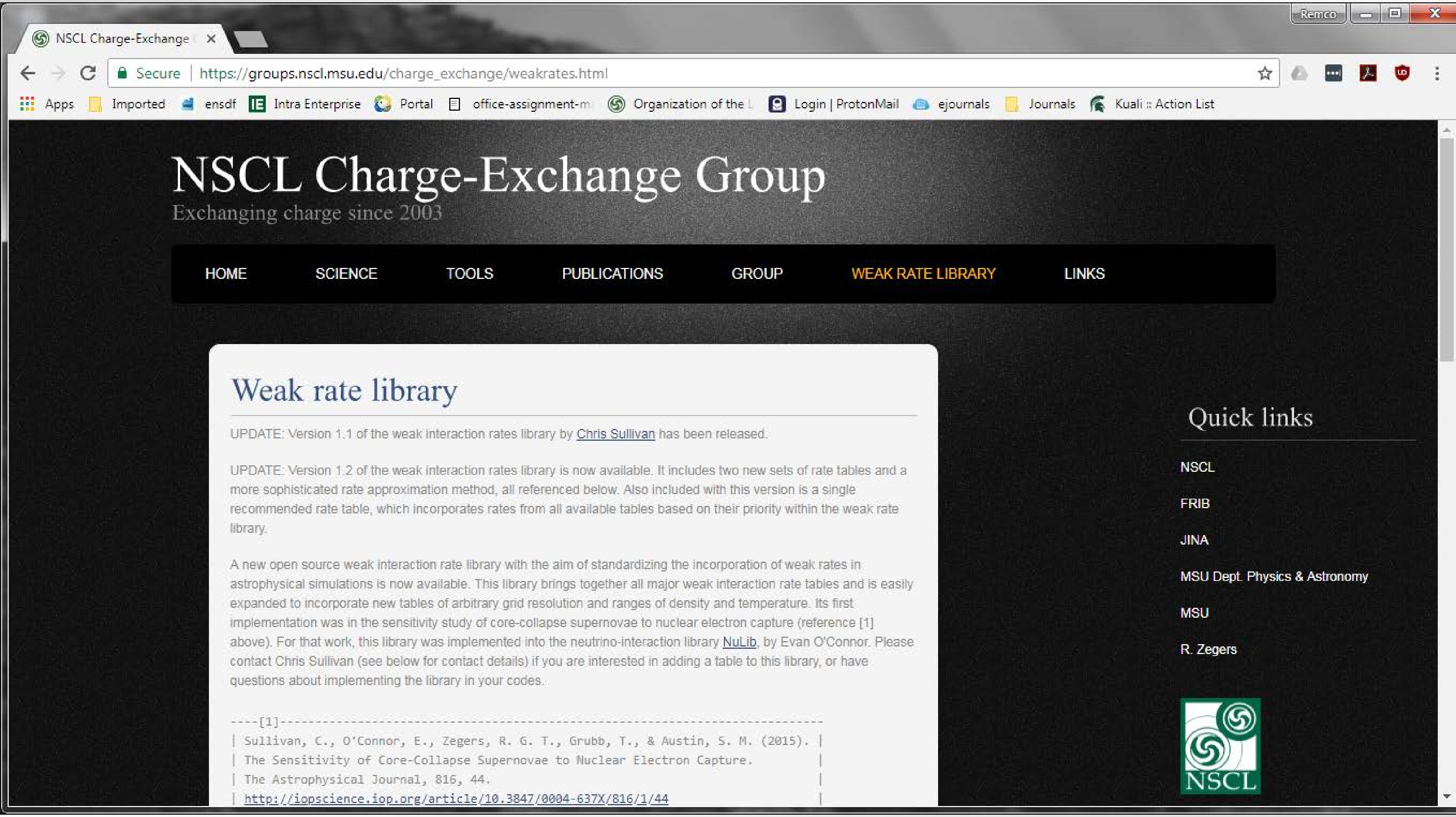
At low densities, only final states at low Q-value are important. Strong temperature dependence; high level of detail of distribution required





At high densities, the full GT distribution is important, less detail required

Weak rate library

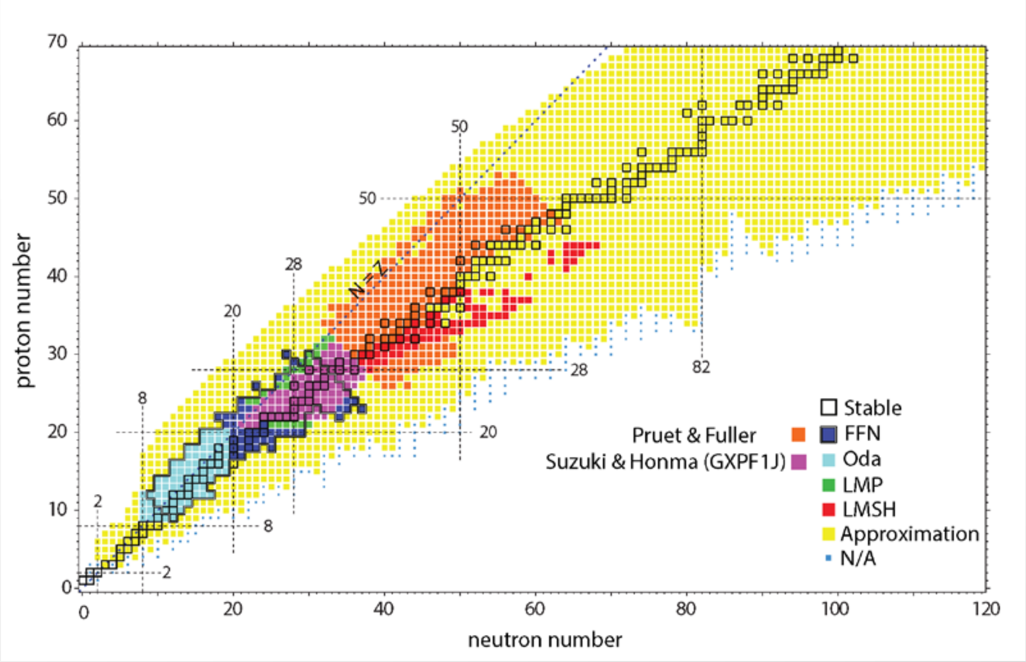


New weak rate library

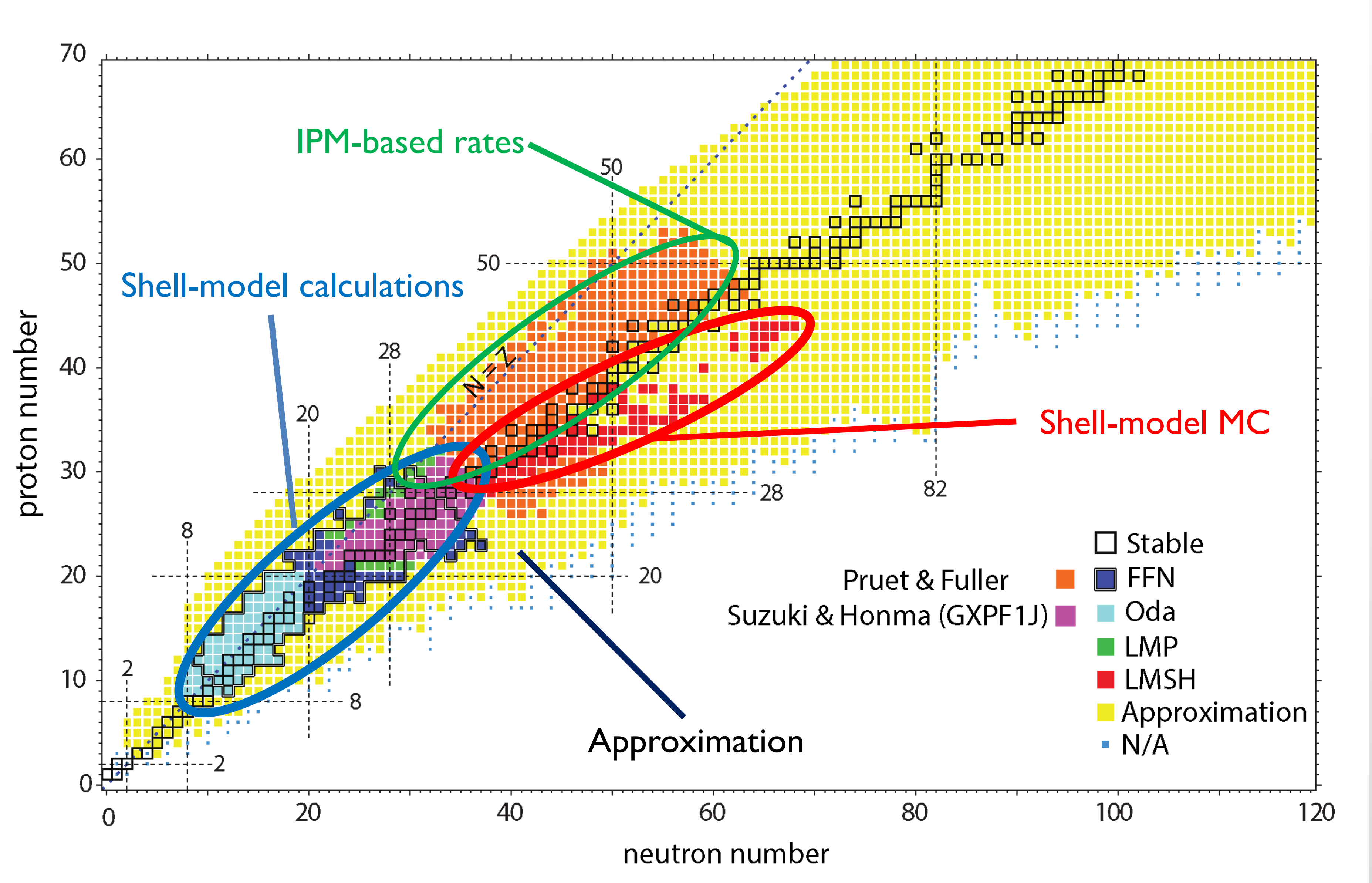
C. Sullivan et al., Ap. J., 816, 44 (2015) https://github.com/csullivan/weakrates

Updated: R. Titus et al. , J. Phys. G: Nucl. Part. Phys **45**, 014004 (2017)

- Open source library aims to standardize the incorporation of weak rates in astrophysical simulations
- Library is implemented into neutrino-interaction library NuLib (http://www.nulib.org/; E. O'Connor)
- Plain electron-capture rate table available on http://groups.nscl.msu.edu/charge_exchange/weakrates.html



Weak rate library: EC rates

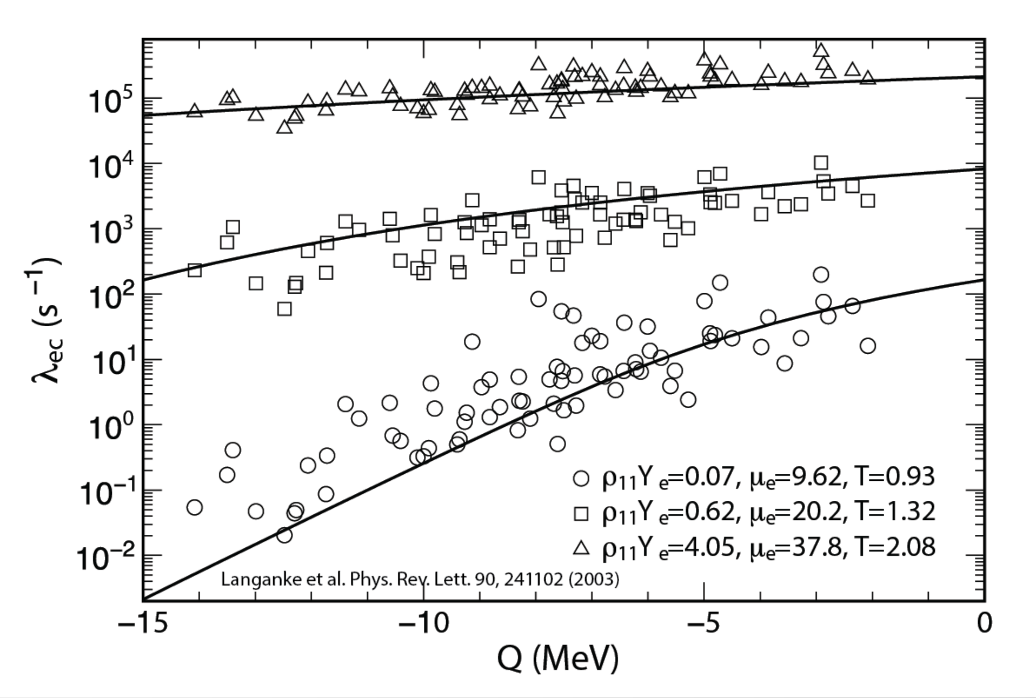


Approximation of weak rates of (medium) heavy nuclei

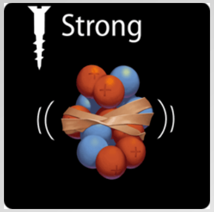
- Rate approximated based on a fit to shell-model calculations for lighter nuclei. A single transition strength (B=4.6) and excitation energy (ΔE=2.5 MeV) were chosen for all nuclei (Langanke and Martinez-Pinedo, PRL 90 241102 (2003)).
- Updated parameterization now included in weak-rate library – considers odd-even and isospin effects (A. Raduta et al. PRC 95, 025805 (2017)).

$$\lambda_{\mathrm{EC}} = \frac{\ln 2 \cdot B}{K}\left(\frac{T}{m_e c^2}\right)^5 \left[F_4(\eta) - 2\chi F_3(\eta) + \chi^2 F_2(\eta)\right]$$

$$\chi = (Q - \Delta E)/T,\ \eta = \chi + \mu_e/T$$

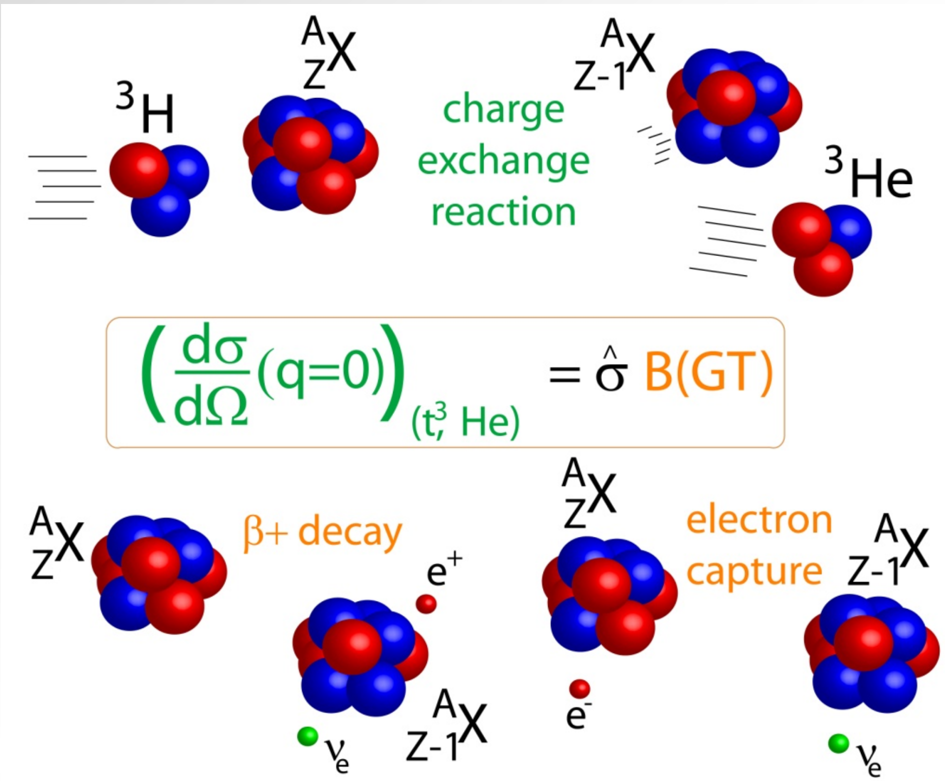


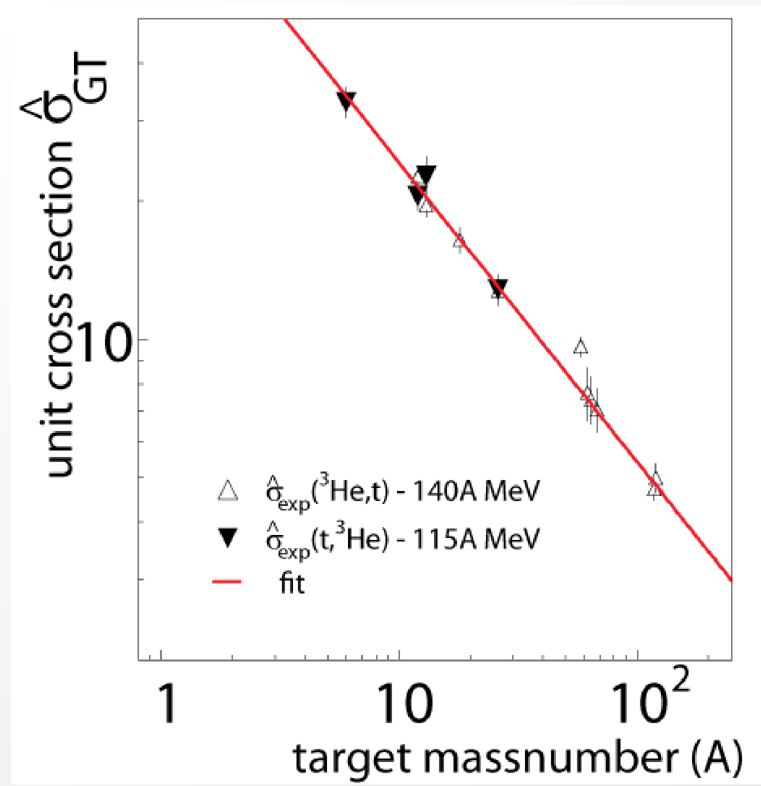
Charge-exchange reactions & β/EC-decay



$$\left(\frac{d\sigma}{d\Omega}\right)_{q=0} = \hat{\sigma} B(GT)$$

Perform experiments ~ 100 AMeV or above





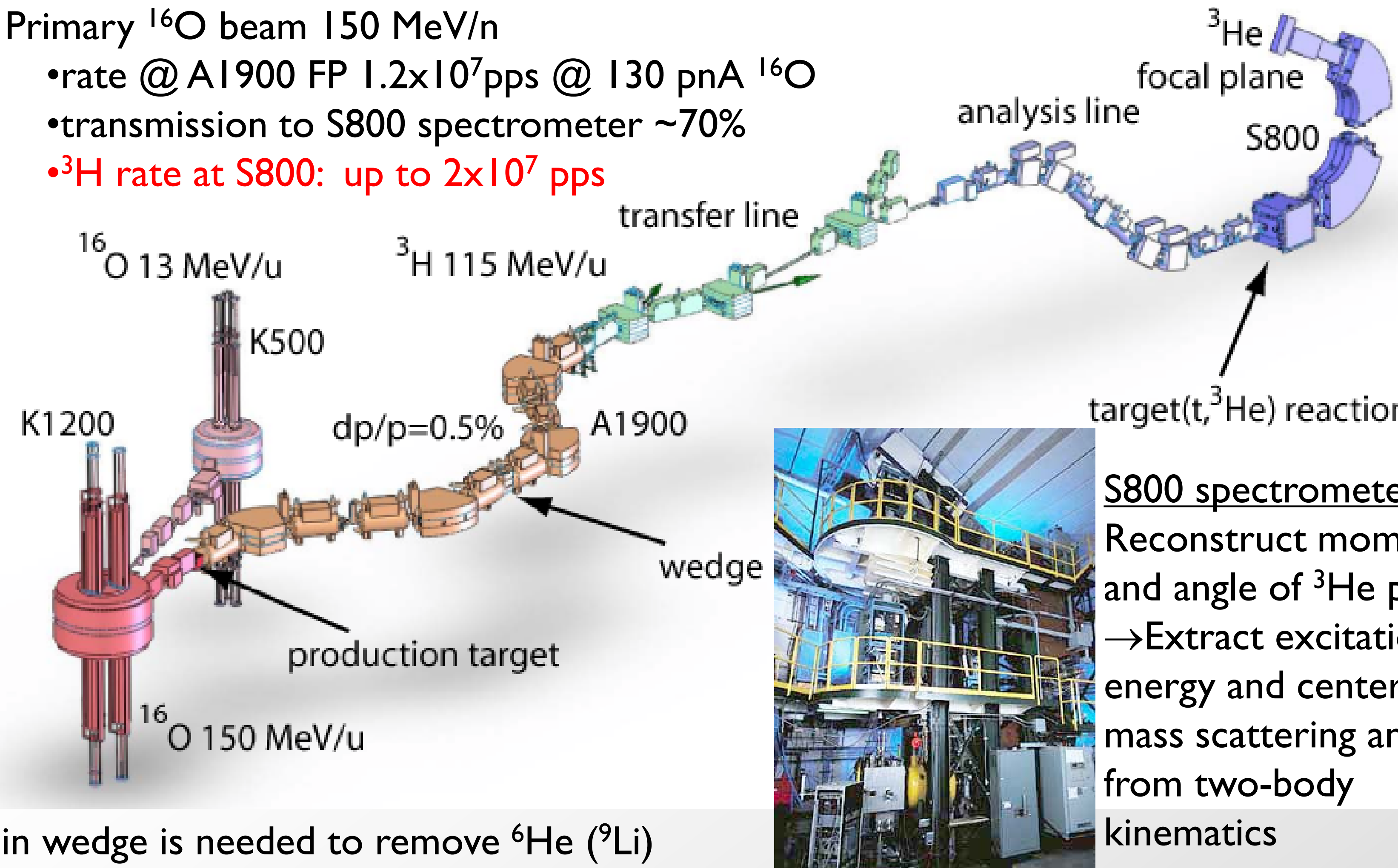
$$\frac{K}{ft} = \left(\frac{g_A}{g_v}\right)^2 B(GT)$$

The unit cross section is calibrated against transitions for which β-decay data are available

Producing a triton beam for (t,^{3}He) experiments

Primary ^{16}O beam 150 MeV/n

- rate @ A1900 FP 1.2×10^{7}pps @ 130 pnA ^{16}O
- transmission to S800 spectrometer ~70%
- ^{3}H rate at S800: up to 2×10^{7} pps

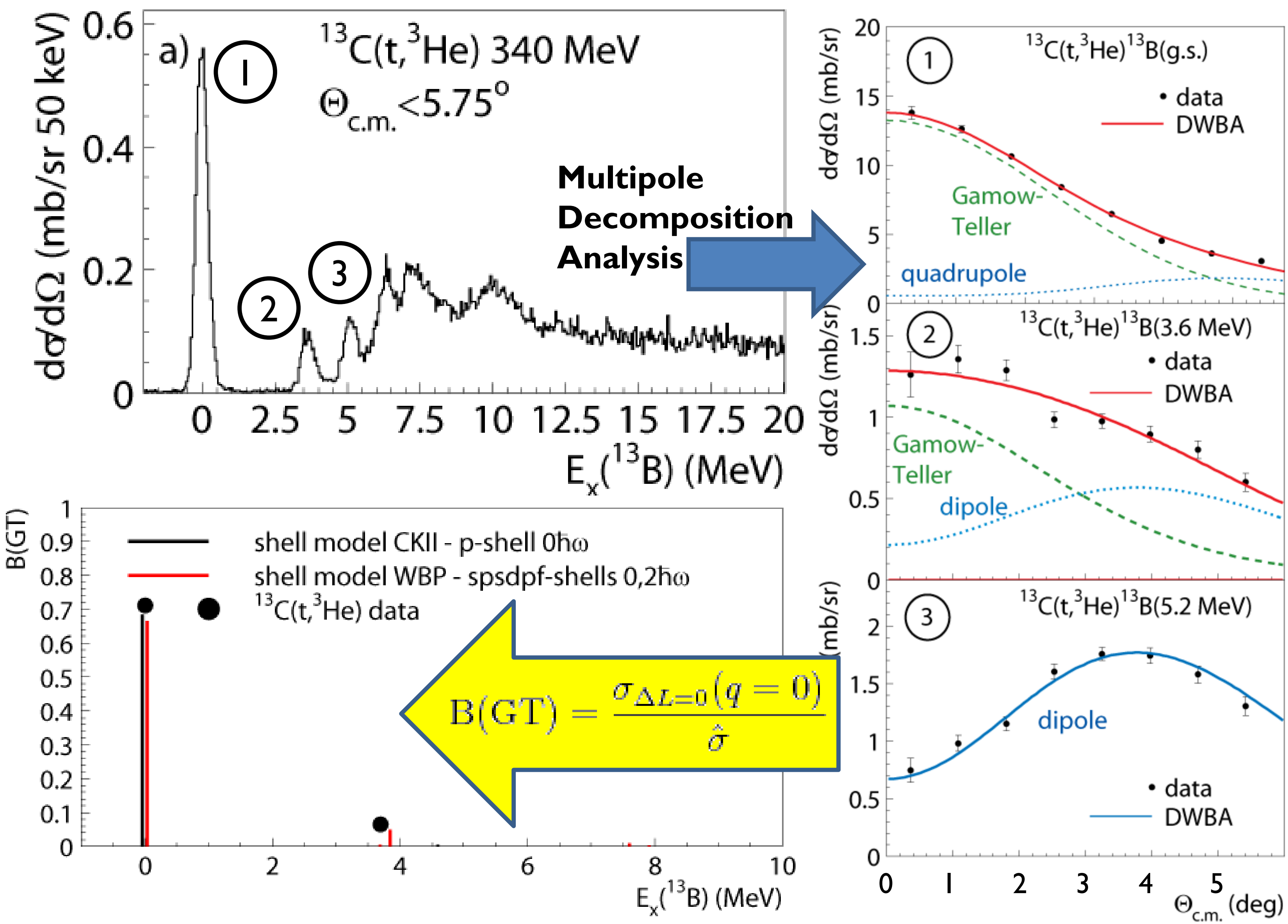


<u>S800 spectrometer</u>
Reconstruct momentum and angle of ^{3}He particle
→Extract excitation-energy and center-of-mass scattering angle from two-body kinematics

Thin wedge is needed to remove ^{6}He (^{9}Li)
Background channel ^{6}He->^{3}He + 3n

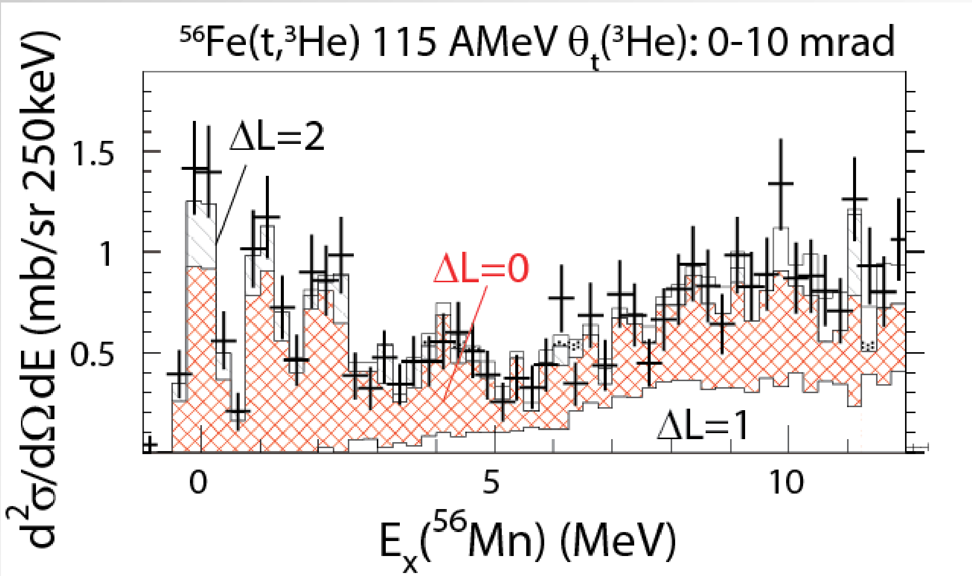
G.W. Hitt Nucl. Instr. and Meth. A 566 (2006), 264.

Multipole decomposition

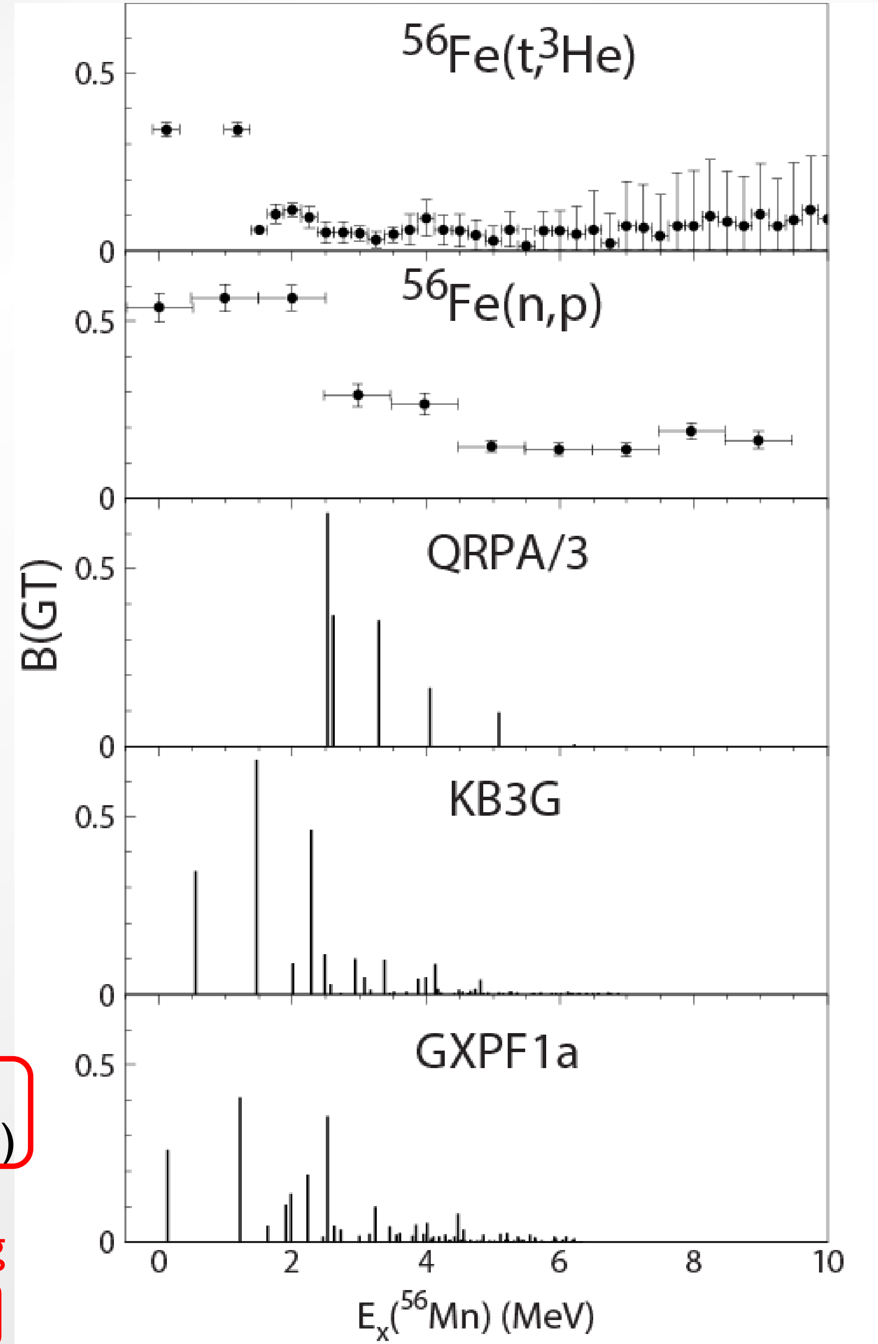


C. Guess et al., Phys. Rev. C 80, 024305 (2009)

$^{56}Fe(t,^3He)$



Result from multipole decompositions analysis



Experiment

$^{56}Fe(t,^3He)$ - M. Scott et al., PRC 90, 025801 (2014)

$^{56}Fe(n,p)$ - S. El-Kateb et al., PRC 49, 3128 (1994)

$^{56}Fe(d,^2He)$ – D. Frekers et al. – in analysis

Theory – Shell model

KB3G - A. Poves et al., NPA694, 157 (2001)

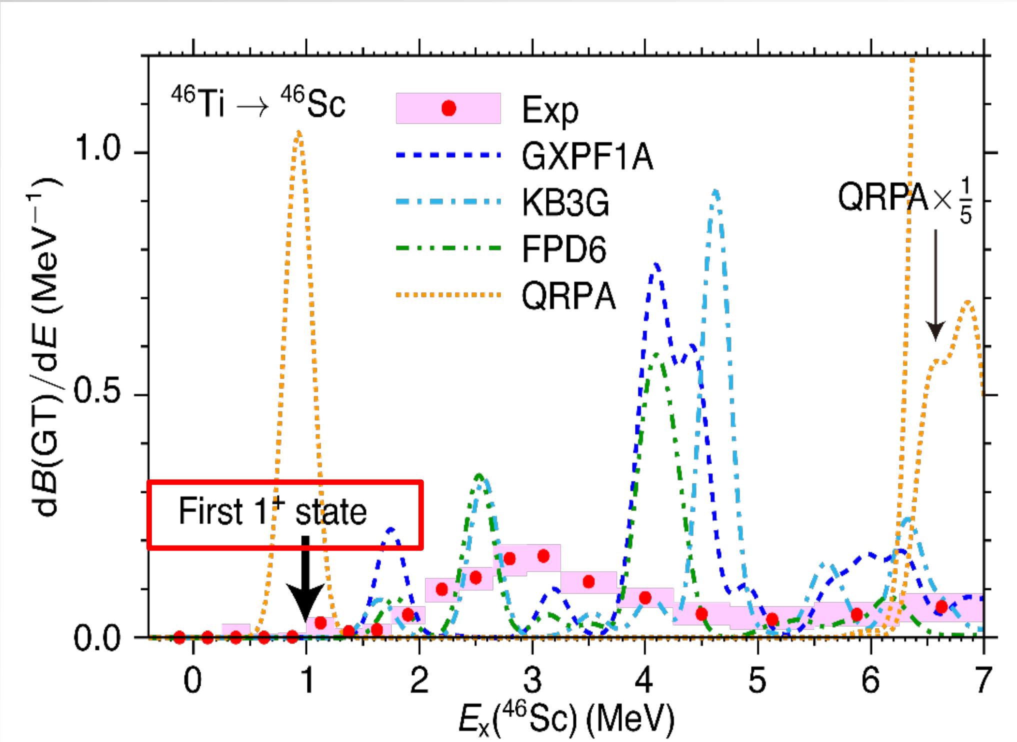
GXPF1a - M. Honma et al. PRC 65, 061301(R) (2002)

Used in astrophysical modelling

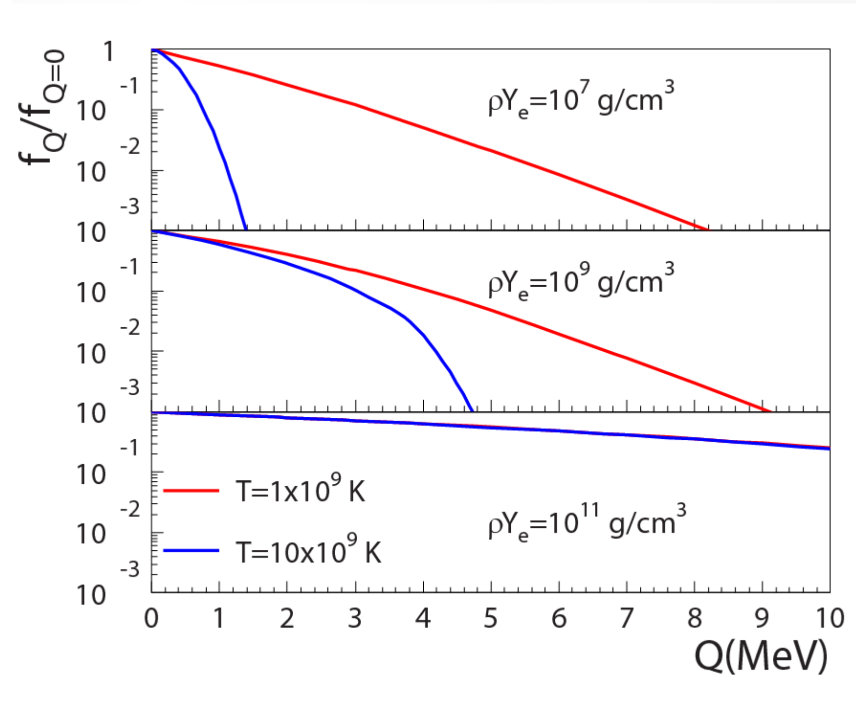
Theory – QRPA

P. Moller and J. Randrup, NPA514, 1 (1990); S. Gupta

$^{46}Ti(t,^{3}He)$



Contribution of excited states (at Q>0) to electron-capture rate

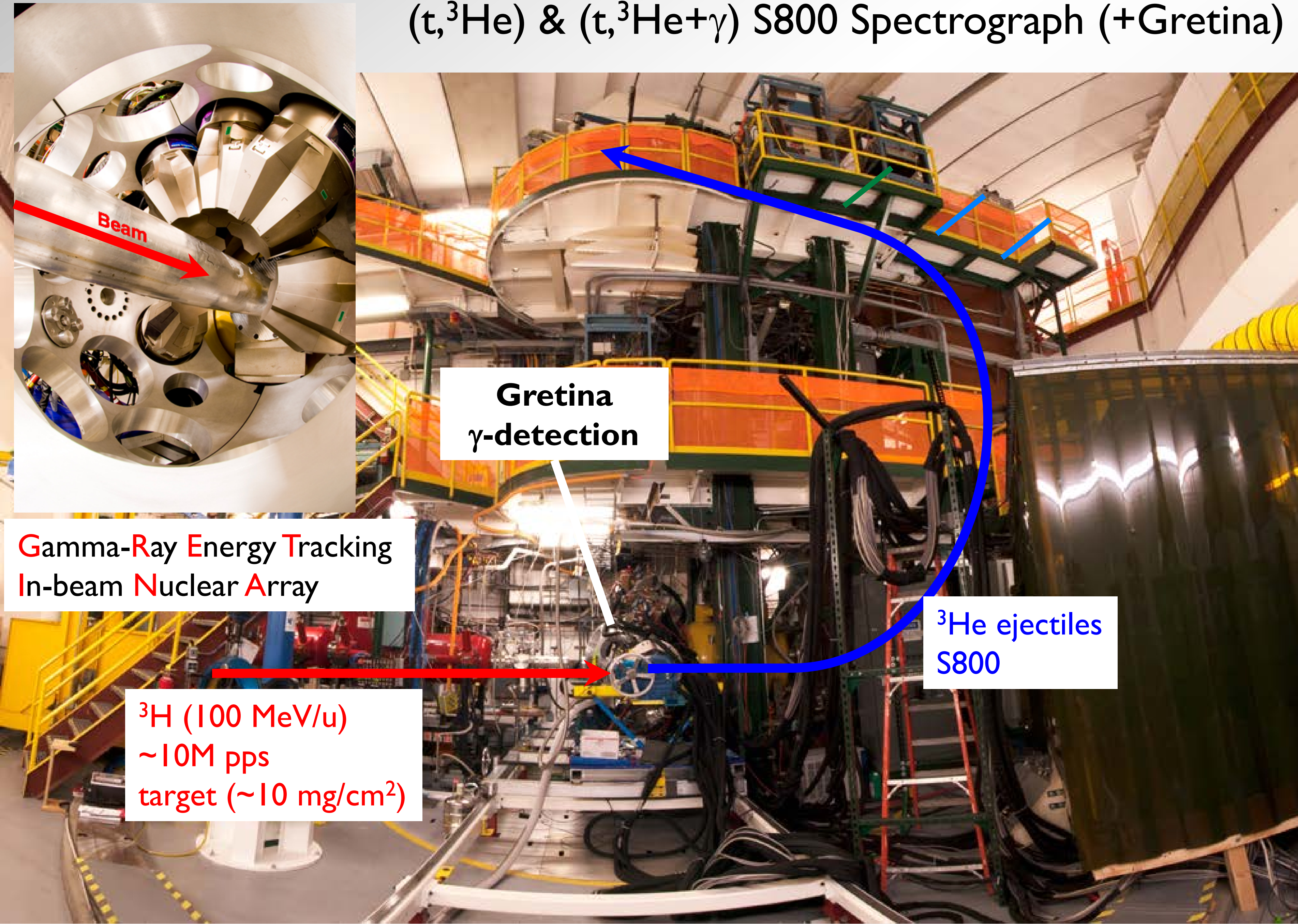


Large differences between theory and data are observed for ^{46}Ti

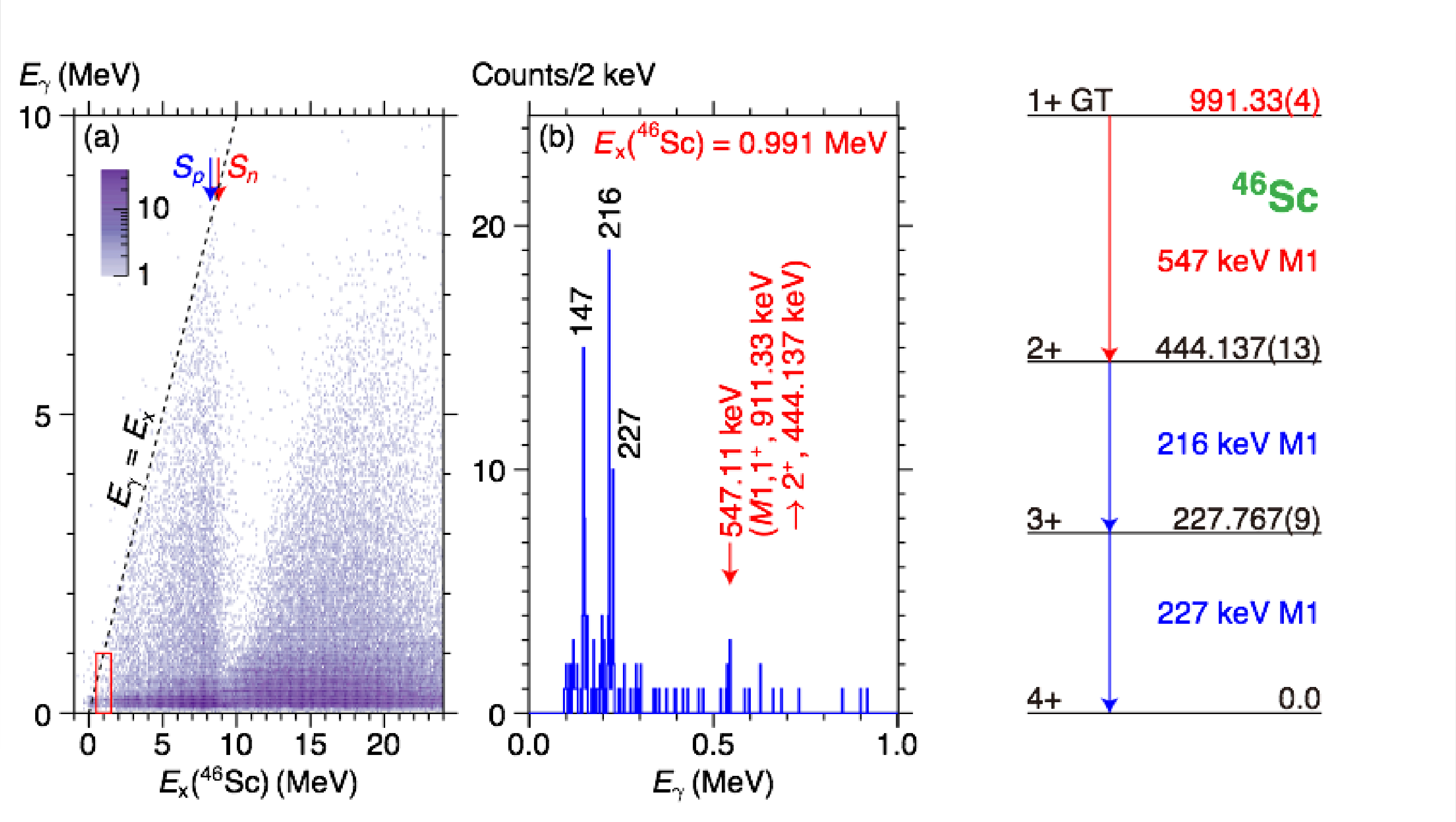
How to identify important, but weak low-lying states?

S. Noji et al., Phys. Rev. C **92**, 024312 (2015), Phys. Rev. Lett. **112**, 252501 (2014)

(t,^{3}He) & (t,^{3}He+γ) S800 Spectrograph (+Gretina)



Low-lying GT strength: $^{46}Ti(t,^{3}He+\gamma)$

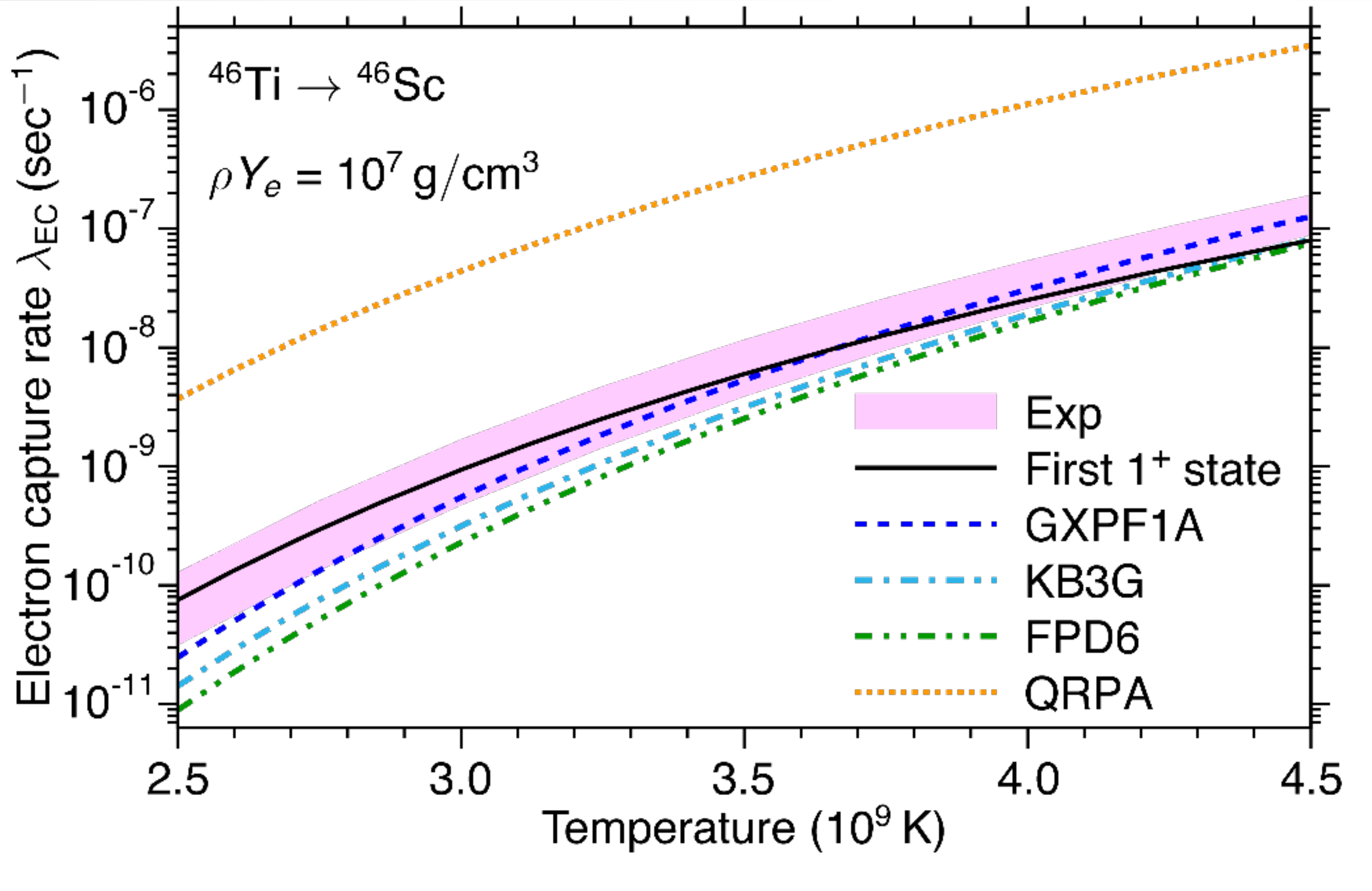


For ^{46}Ti: weak low-lying GT transition is observed in γ-coincident data:

$B(GT)_{0.991}=0.009 \pm 0.005(exp) \pm 0.003\ (sys)$

Not Separable in singles data.

Electron-capture rates in pre-supernovae star



This low-lying transition is important for estimating an accurate electron-capture rate in pre-supernovae stars.

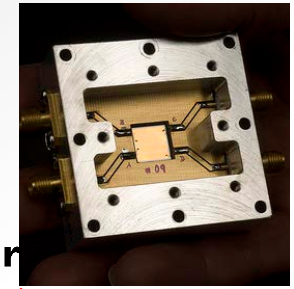
(p,n) in inverse kinematics

S800 spectrometer

Heavy residue collection

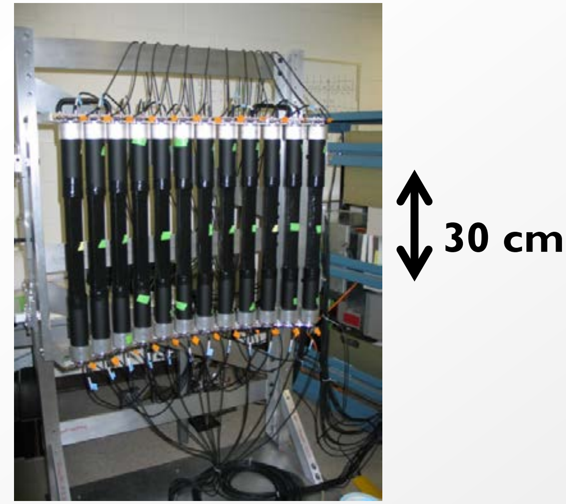
Bρ< 4 Tm /130° bend

Particle identification



Diamond detector

Beam particle timing



Low Energy Neutron Detector Array (LENDA)

neutron detection

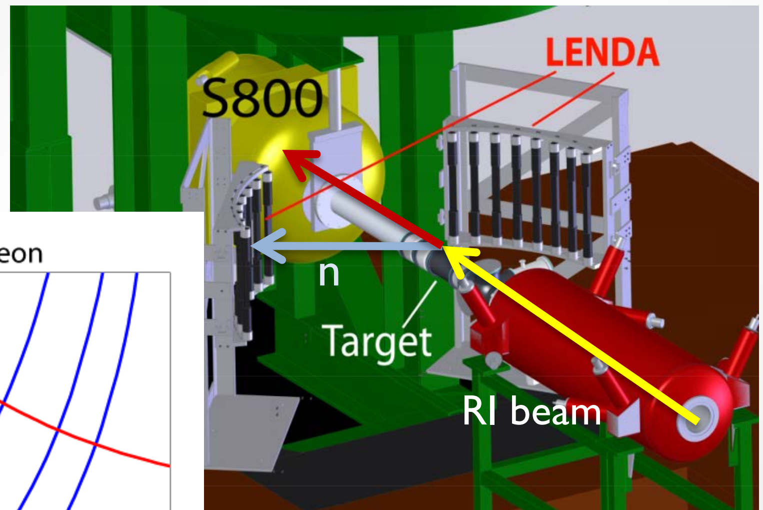
Plastic scintillator

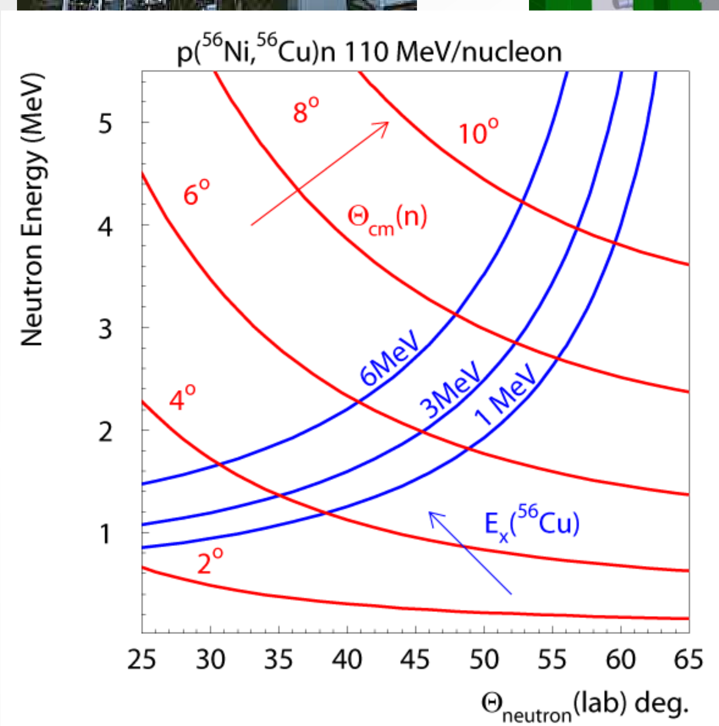
24 bars 2.5x4.5x30cm

150 keV < E_n < 10 MeV

ΔE_n ~ 5% $\Delta\theta_n$ < 2°

efficiency 15-40%





Liquid Hydrogen target

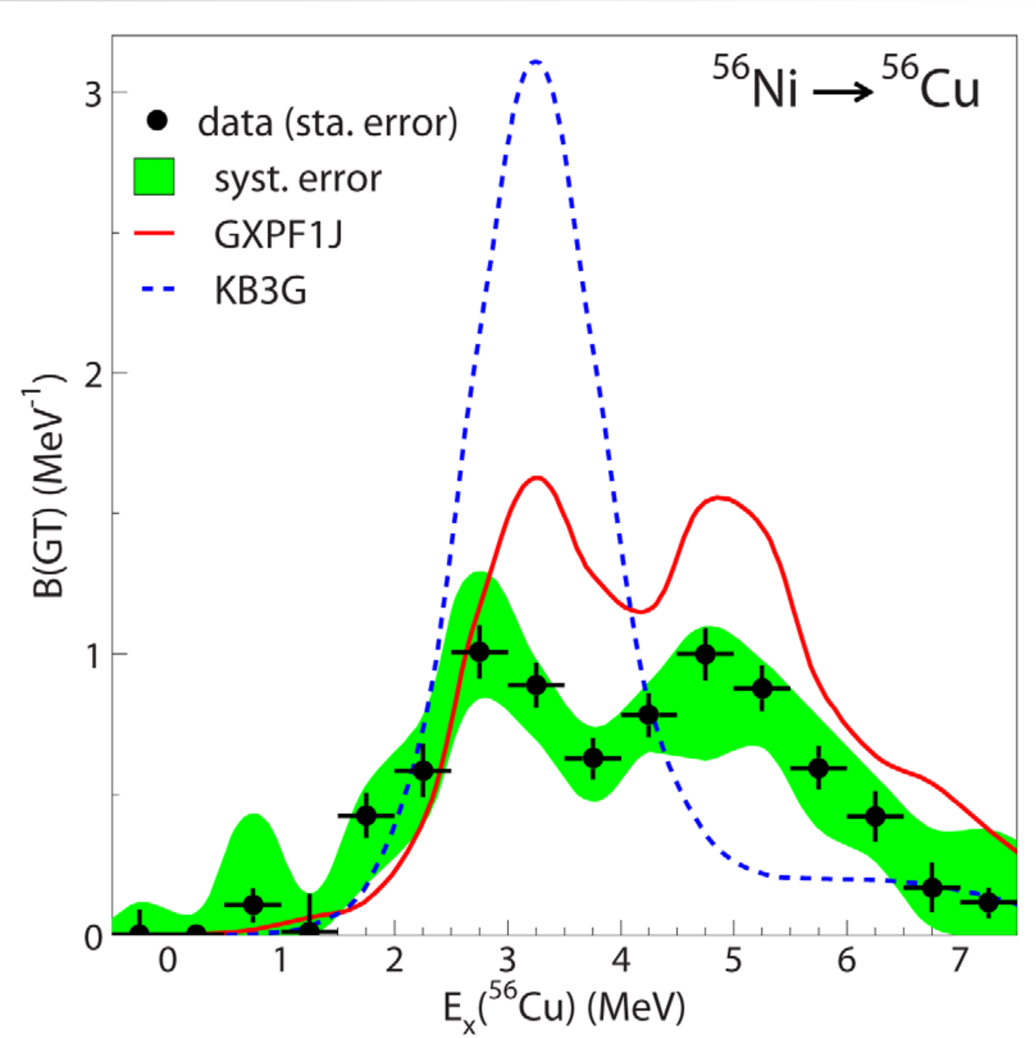
"proton" target

65 mg/cm² (~7 mm)

~3.5 cm diameter

T=20 K ~1 atm

Experiment on key nuclei can reveal and clarify specific differences between theoretical models

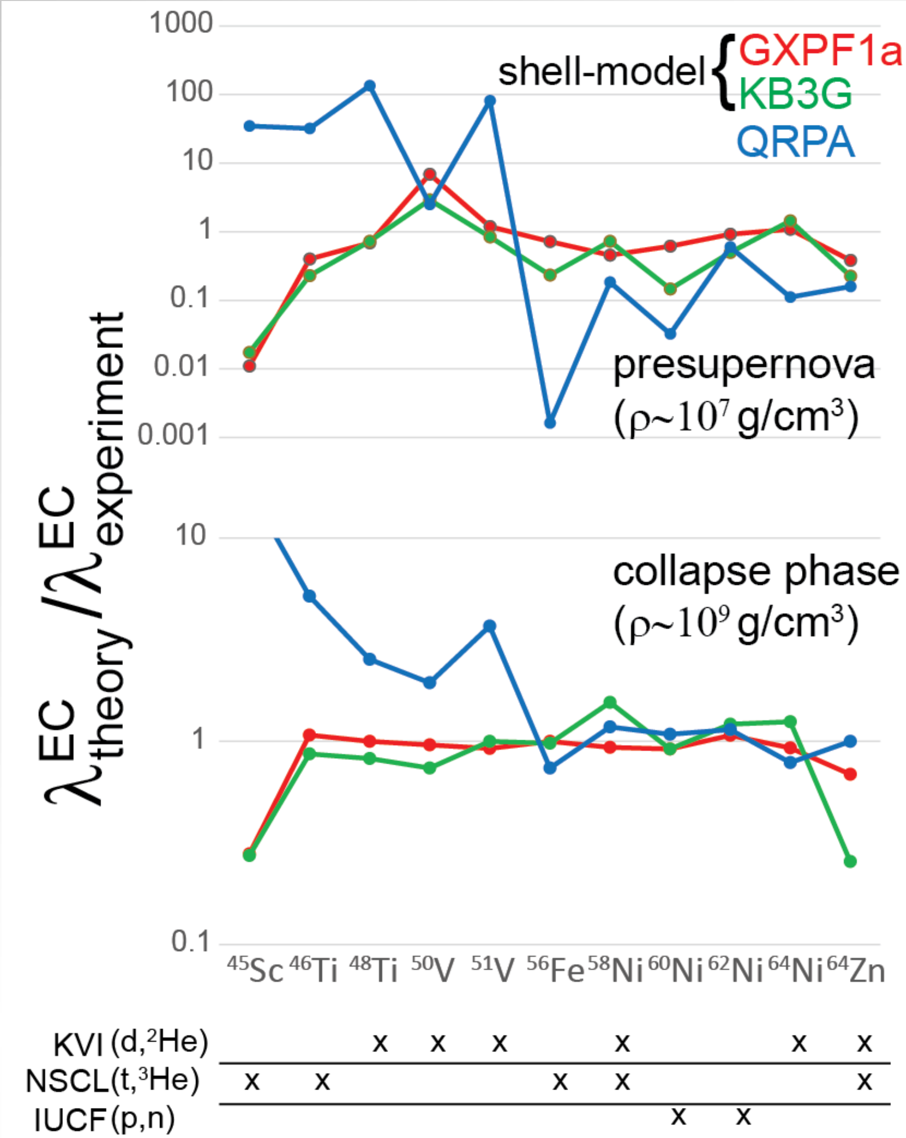


^{56}Ni(p,n) in inverse kinematics provided key input for understanding the difference between leading shell-model calculations

Experiment provided information on important nucleus for astrophysics

M. Sasano et al., Phys. Rev. C **86**, 034324 (2012), Phys. Rev. Lett. **107**, 202501 (2011)

Systematic EC rate comparisons



A.L. Cole et al., PRC 86, 015809 (2012)

Systemic comparison of EC rates calculated from theory and derived from data provide framework for error estimation of theoretical rates

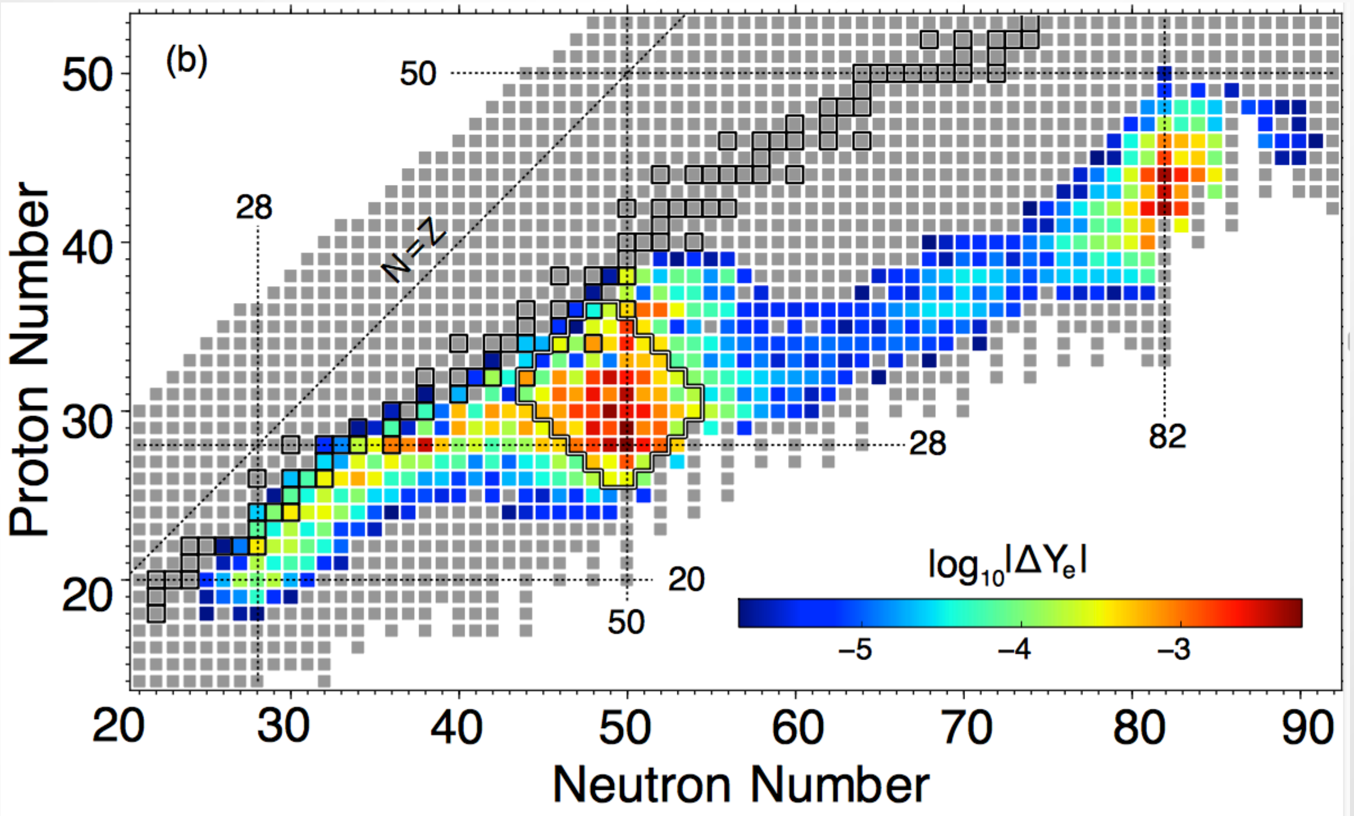
Systematic studies provide a way to benchmark and improve theoretical calculations

Experimental results from different facilities and probes are combined to perform comprehensive comparisons

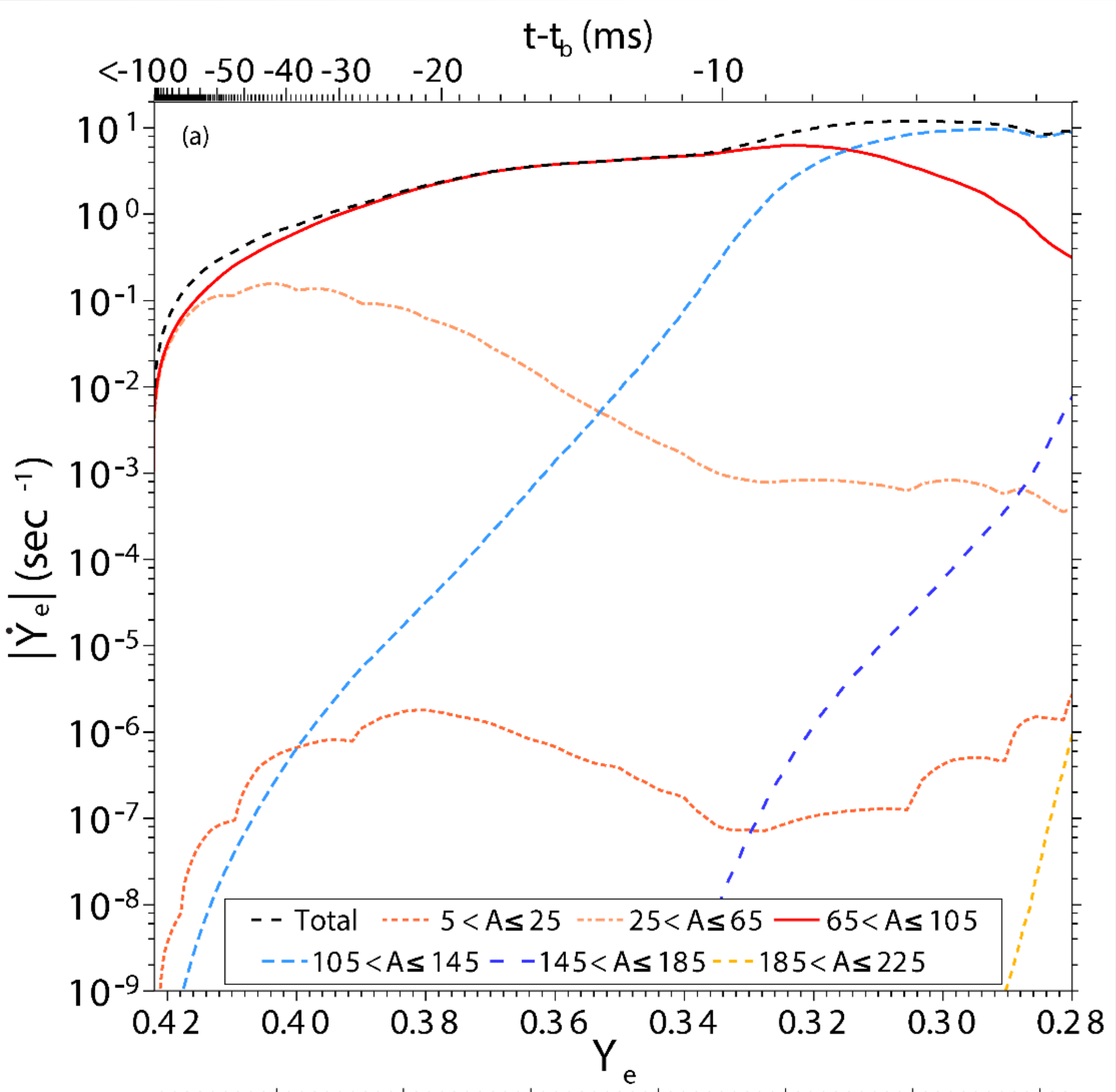
Sensitivity Study of Core Collapse Supernovae

C. Sullivan et al., Ap. J., 816, 44 (2015)

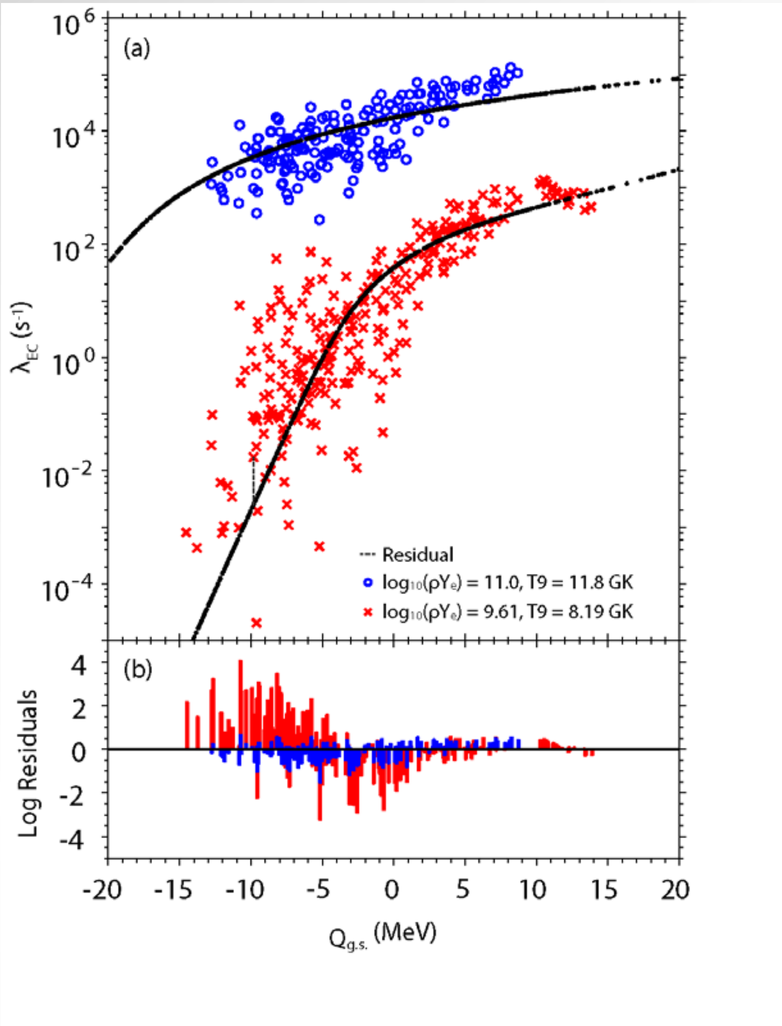
- GR1D simulation with modern weak rate estimates up to 100 ms after bounce
- Calculations guide experimental and theoretical efforts, building on previous work focused on EC rates by e.g. Martínez-Pinedo, Langanke, Hix, Heger…
- Which nuclei contribute most to deleptonization of central zone?



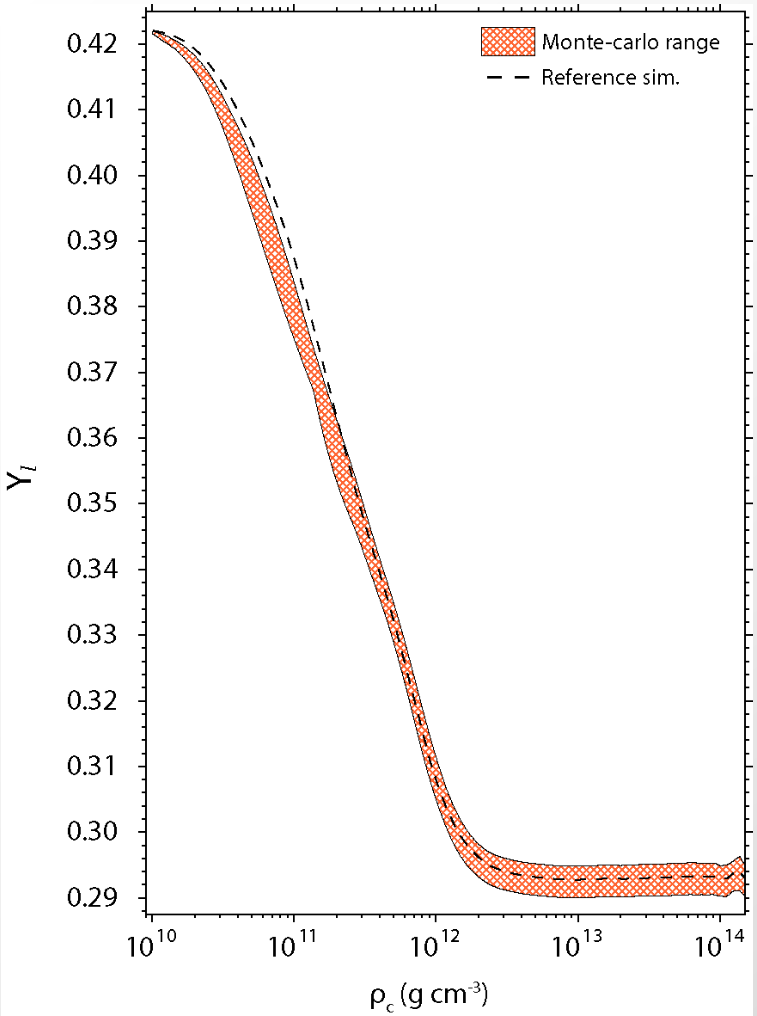
Which groups of nuclei play important roles during what phase of late evolution of CCSN?



Do variations around approximated EC rates affect the late evolution?



No!



Sensitivity study of key parameters of CCSN

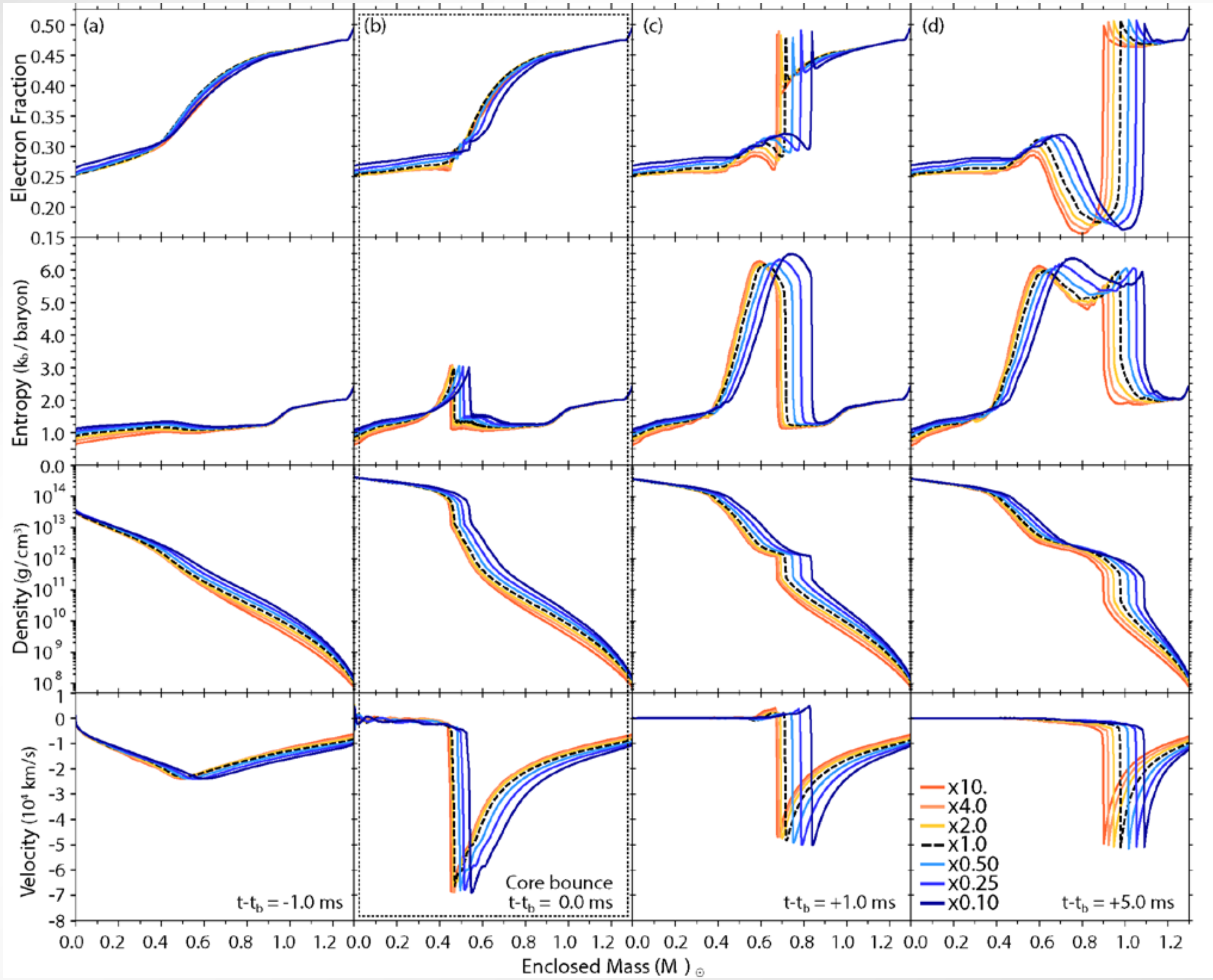
By varying the EC rate within uncertainties of theoretical rates models determined by benchmarking against experiments, the sensitivity of the core-collapse simulations to input weak rates can be compared with other uncertainties, such as in progenitor and equation-of-state models

Electron fraction

Entropy

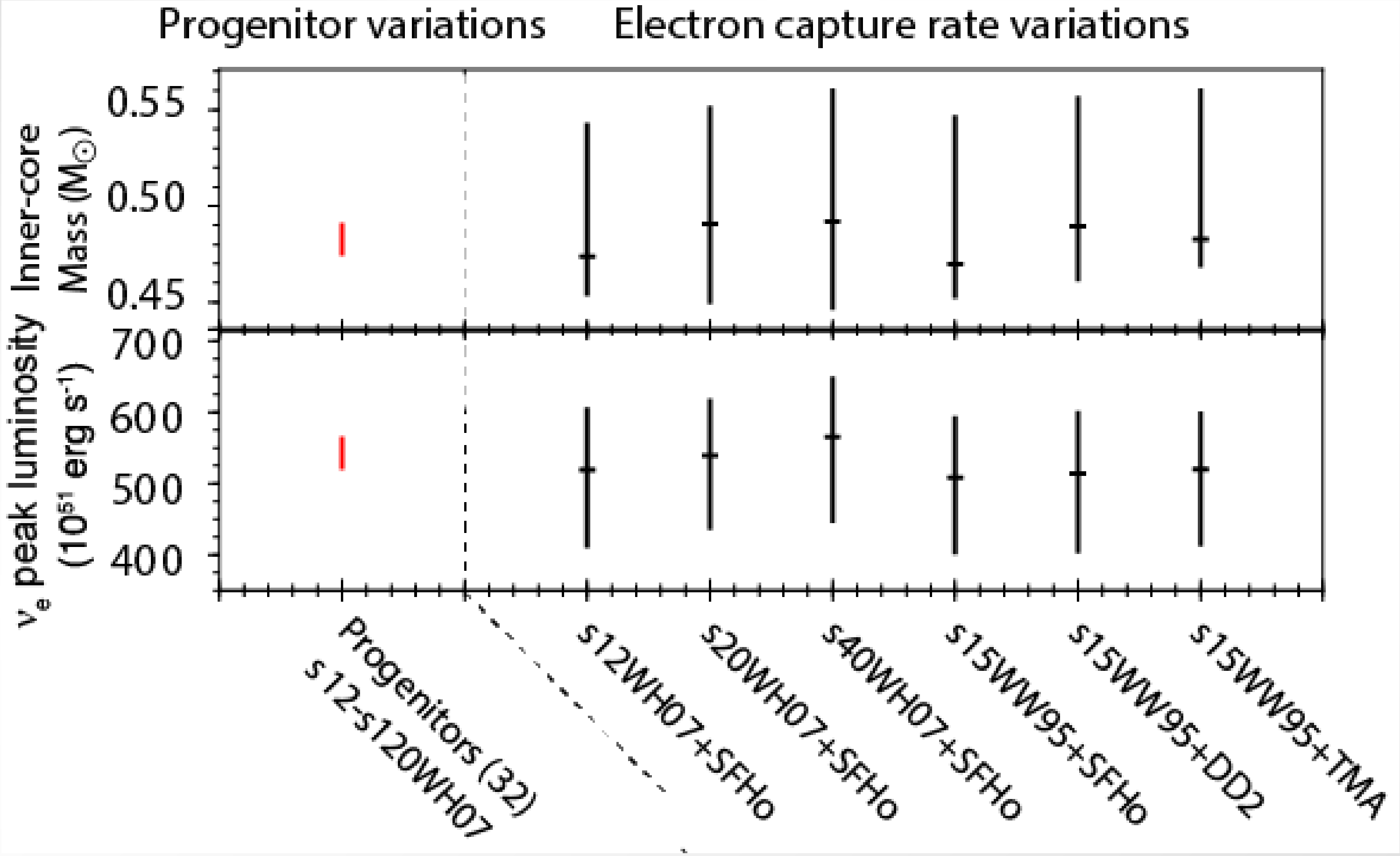
Density

Velocity

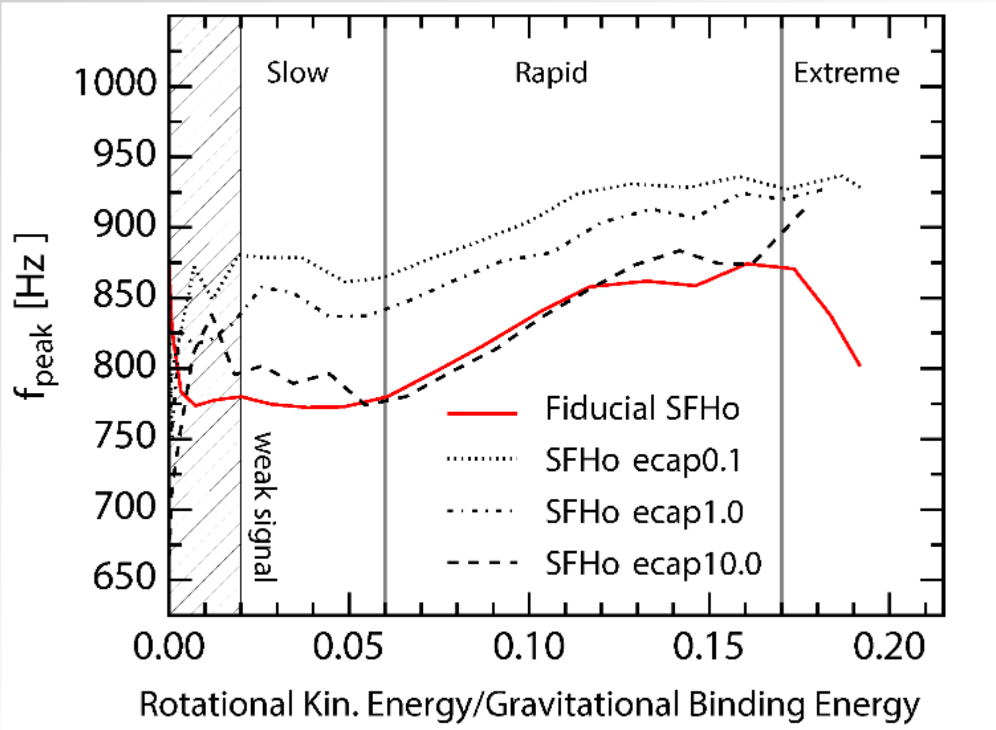


collapse phase just after the onset of neutrino trapping | Core bounce | Core bounce+1ms | Core bounce+5ms

How strongly do systematic uncertainties in EC rates affect the late evolution compared to uncertainties in the EoS and the progenitor model?

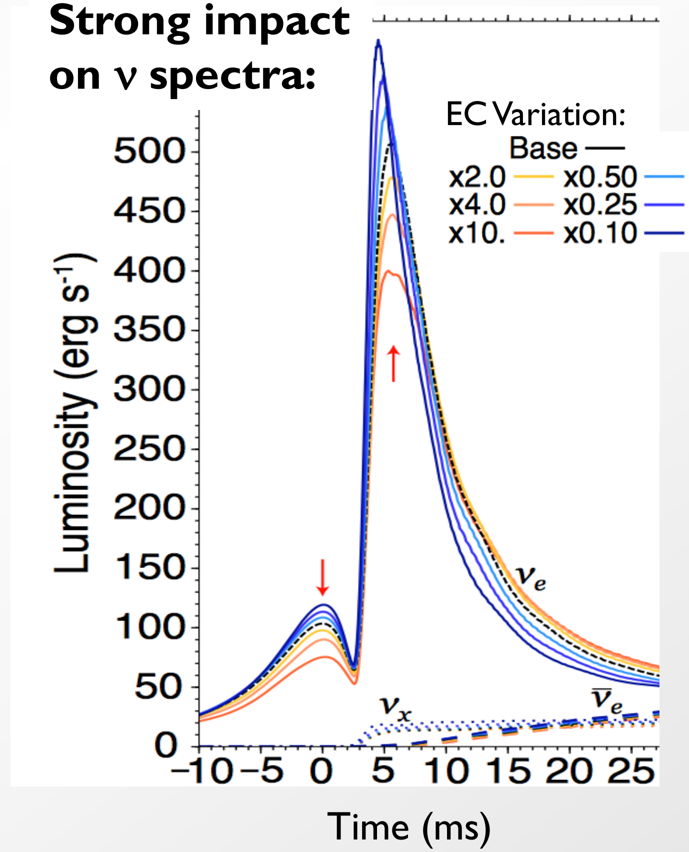


Library is already used in GR1D (1D), CoCoNuT (2D), FLASH (3D) core-collapse simulation codes



S. Richters et al., Phys. Rev. D 95, 063019 (2017)
Using the CoCoNut (2D) code

Strong impact on ν spectra:



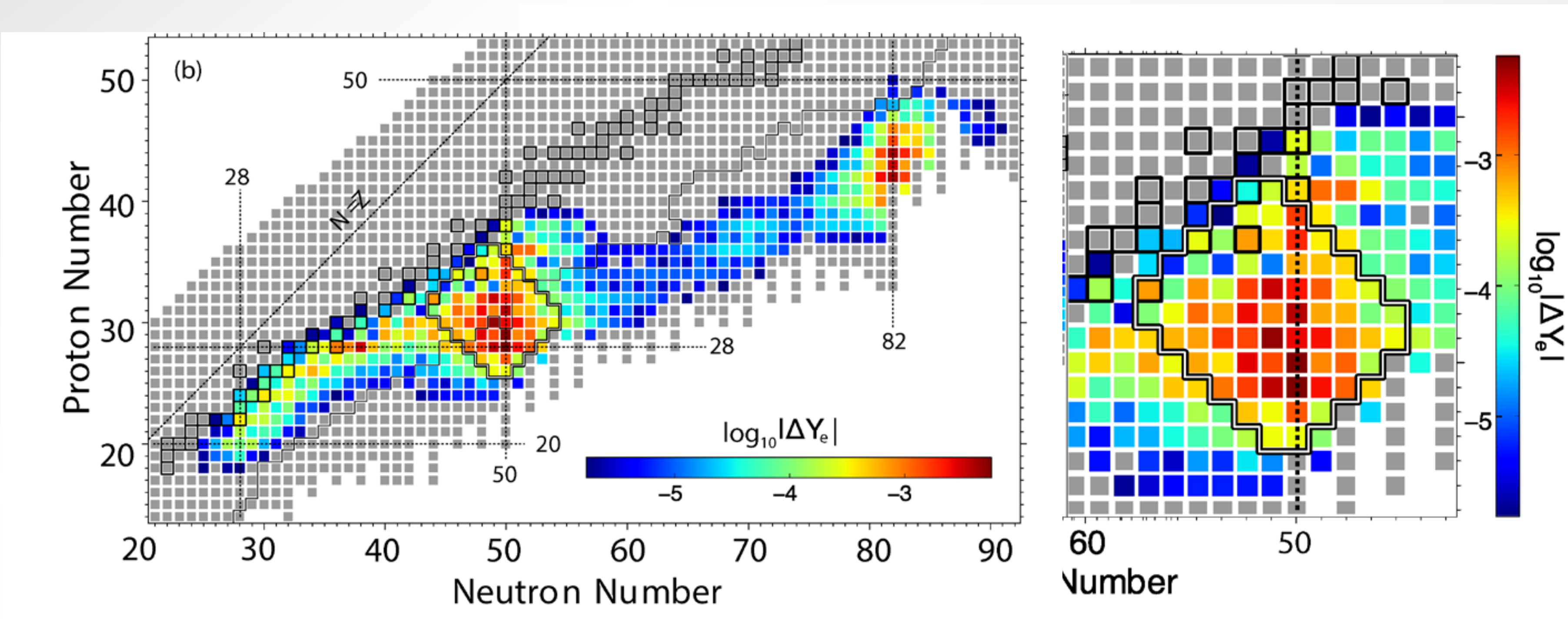
C. Sullivan et al.,

Uncertainties in frequency of gravitational waves from CCSNe due to uncertainties in EC rates is comparable to the uncertainties in EoS

EC rates strongly affect neutrino peak luminosity

The importance of nuclei near N~50 above ^{78}Ni and below ^{90}Zr

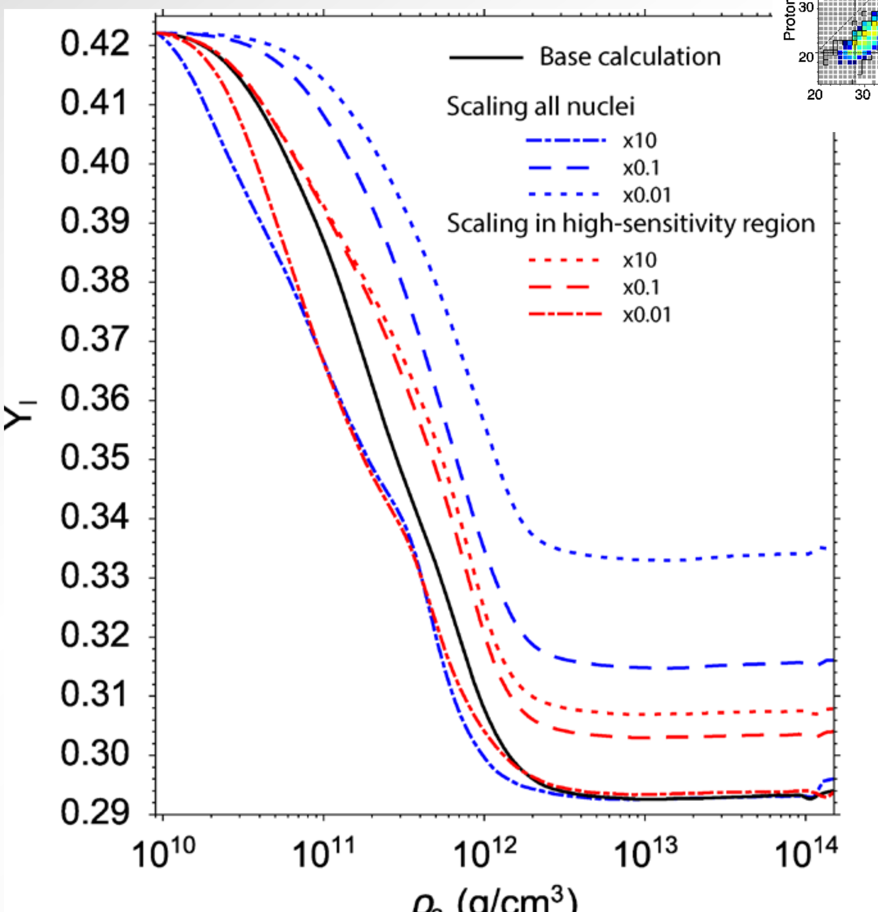
- Nuclei contribute very strongly to the change in Y_e during late evolution
- Provides opportunity to investigate a relative small group of nuclei
- Very little experimental data available: beta/EC-decay Q-value forbidden
- Charge-exchange reactions are the only way to provide insight

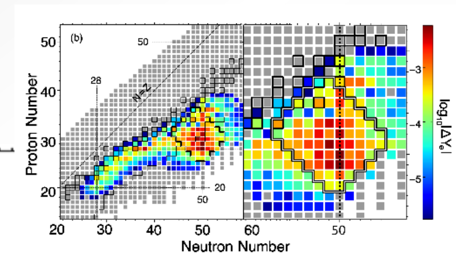


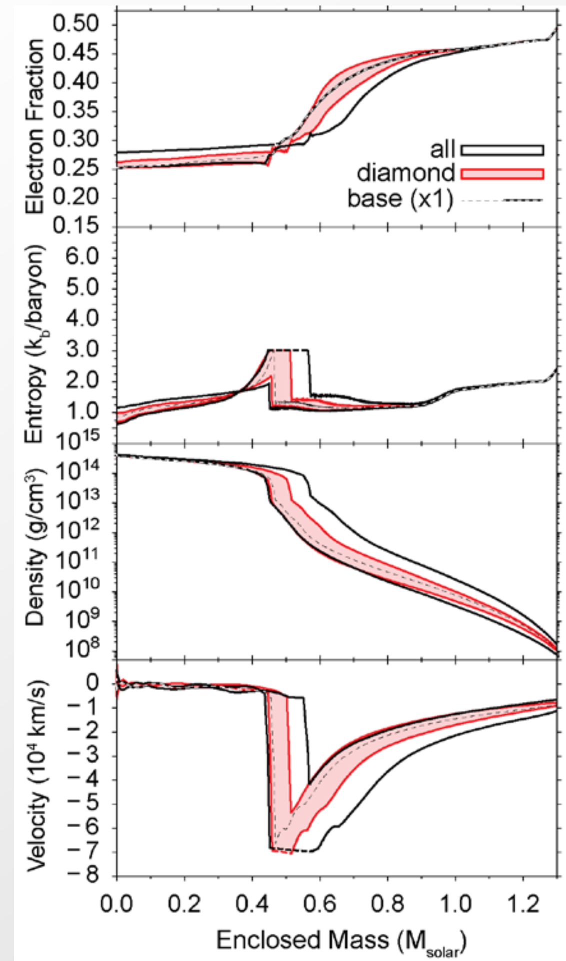
Sensitivity study of diamond region near N~50

R. Titus et al. , J. Phys. G: Nucl. Part. Phys 45, 014004 (2017)

- Systematic uncertainties in EC rates for a small group (~75) nuclei contribute about 50% of the total uncertainty due to poorly constrained EC rates

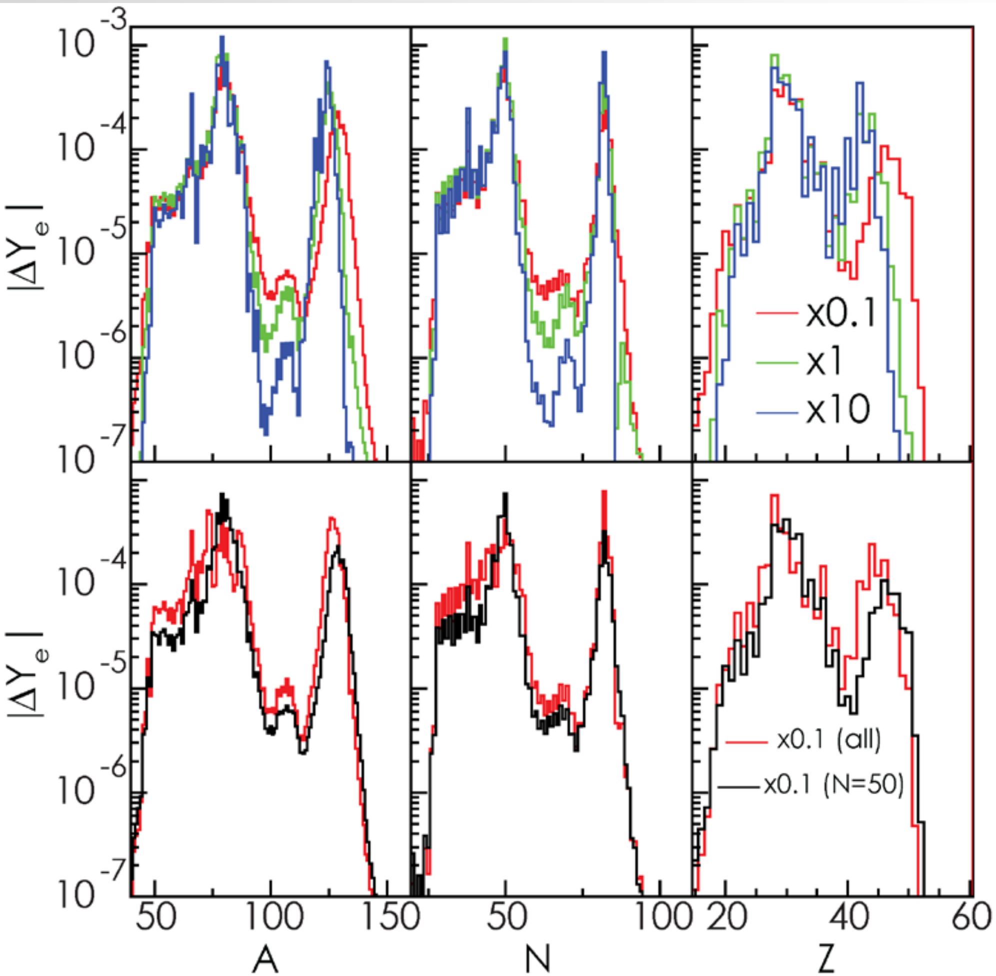






Systematic uncertainties in EC rates affect the nuclei produced in the late stages

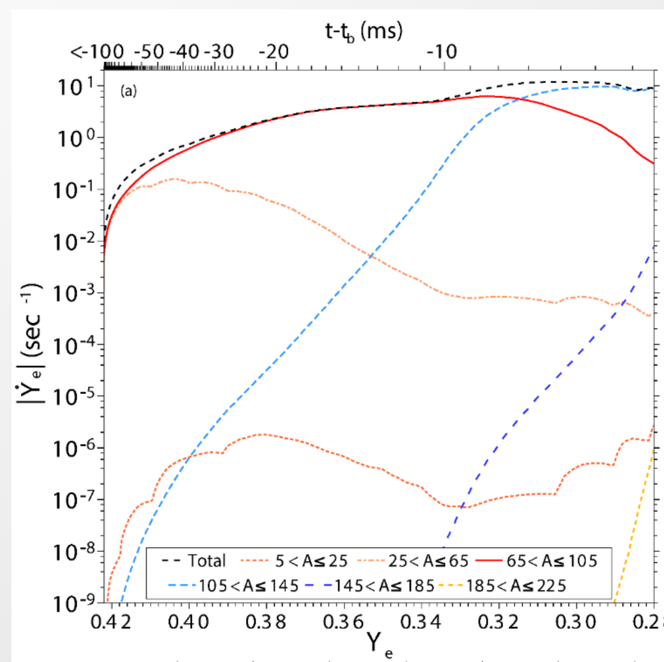
EC rates in diamond region changed only



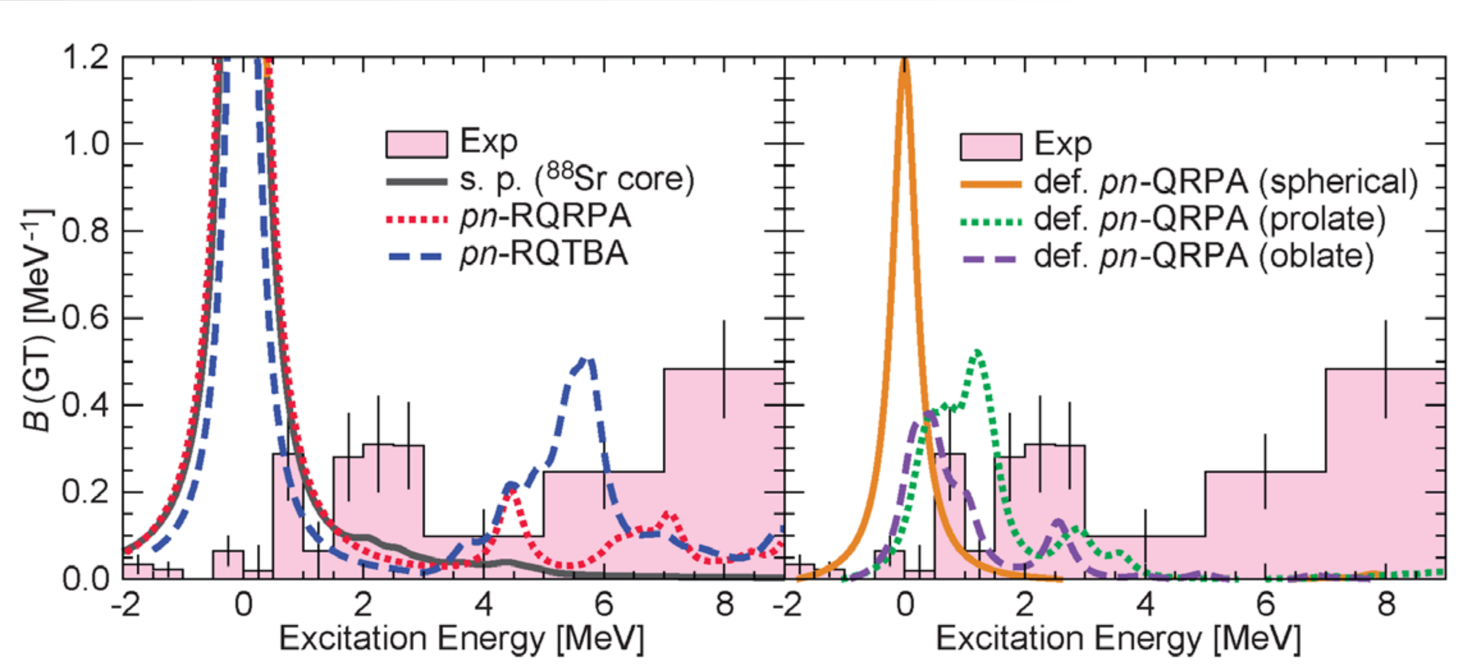
Comparison of systematic variations of EC rates for all nuclei and those in diamond region only

Reduction in EC rates results in lower production of proton-rich nuclei

Variations in the diamond region near N~50 are key as they contribute to the change in Y_e relatively early in the late evolution.



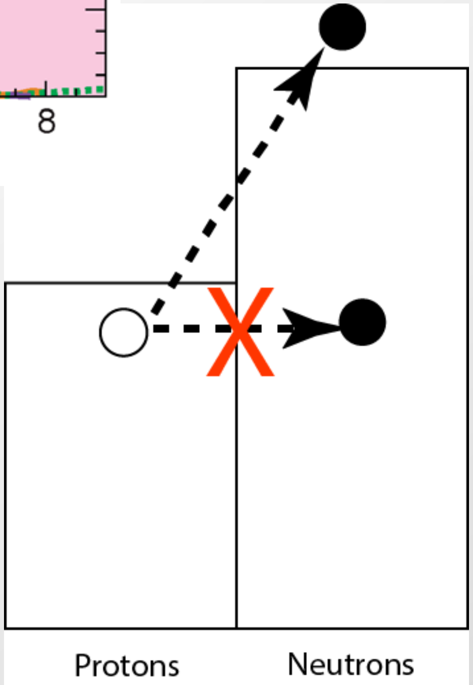
^{100}Mo(t,^{3}He): Pauli blocking and deformation



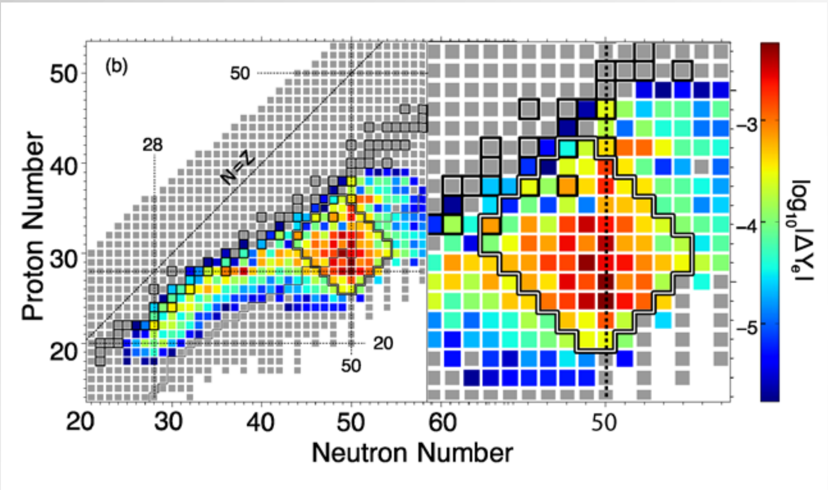
K. Miki et al., Phys. Lett. B 769, 339 (2017)

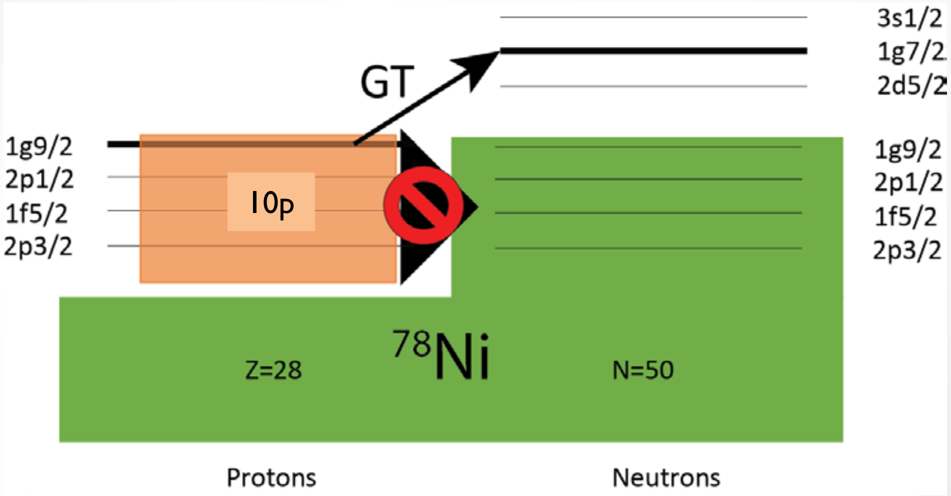
In heavier neutron-rich systems, Pauli blocking effects become very strong and GT strengths are strongly reduced

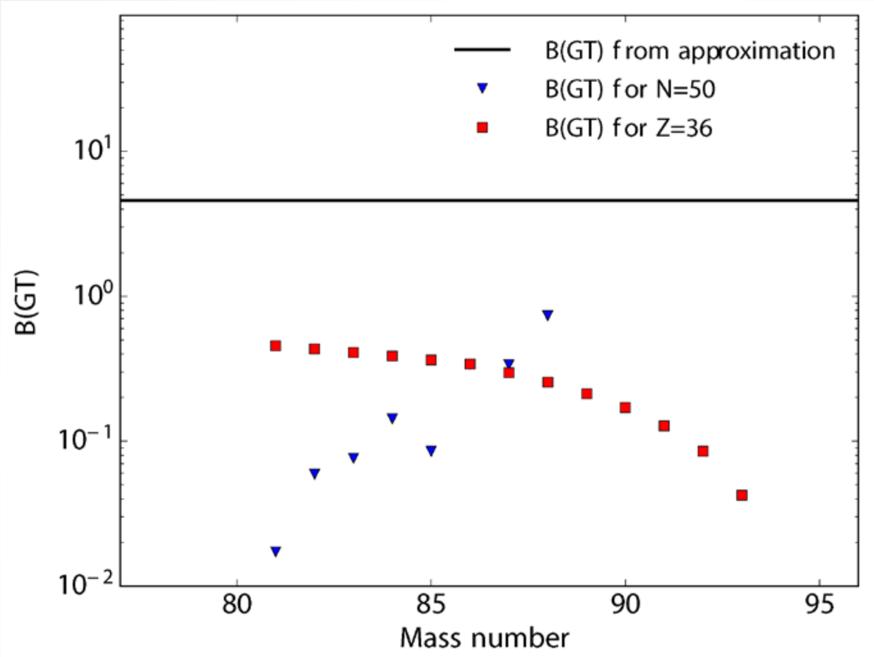
Analysis complicated by strong presence of isovector spin giant monopole resonance in spectrum

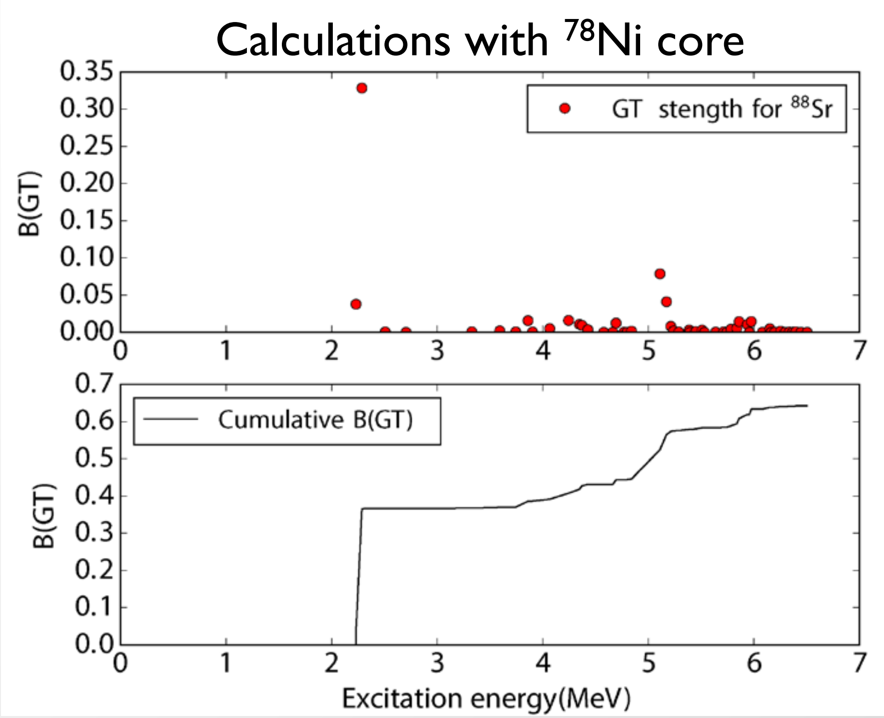


GT+ strengths along N=50

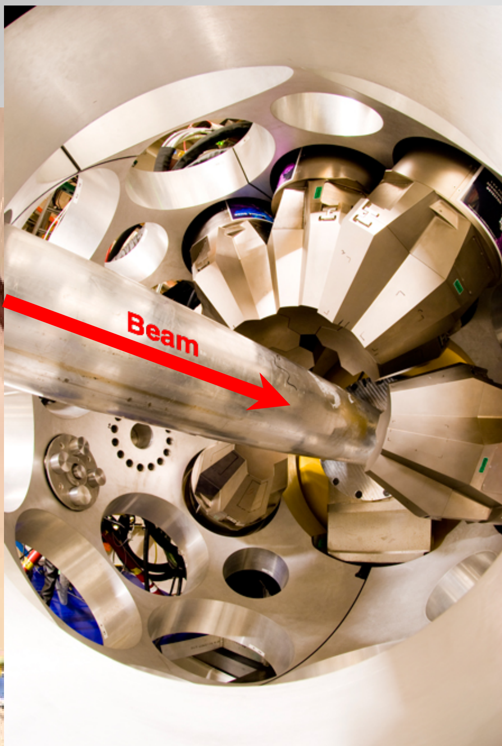




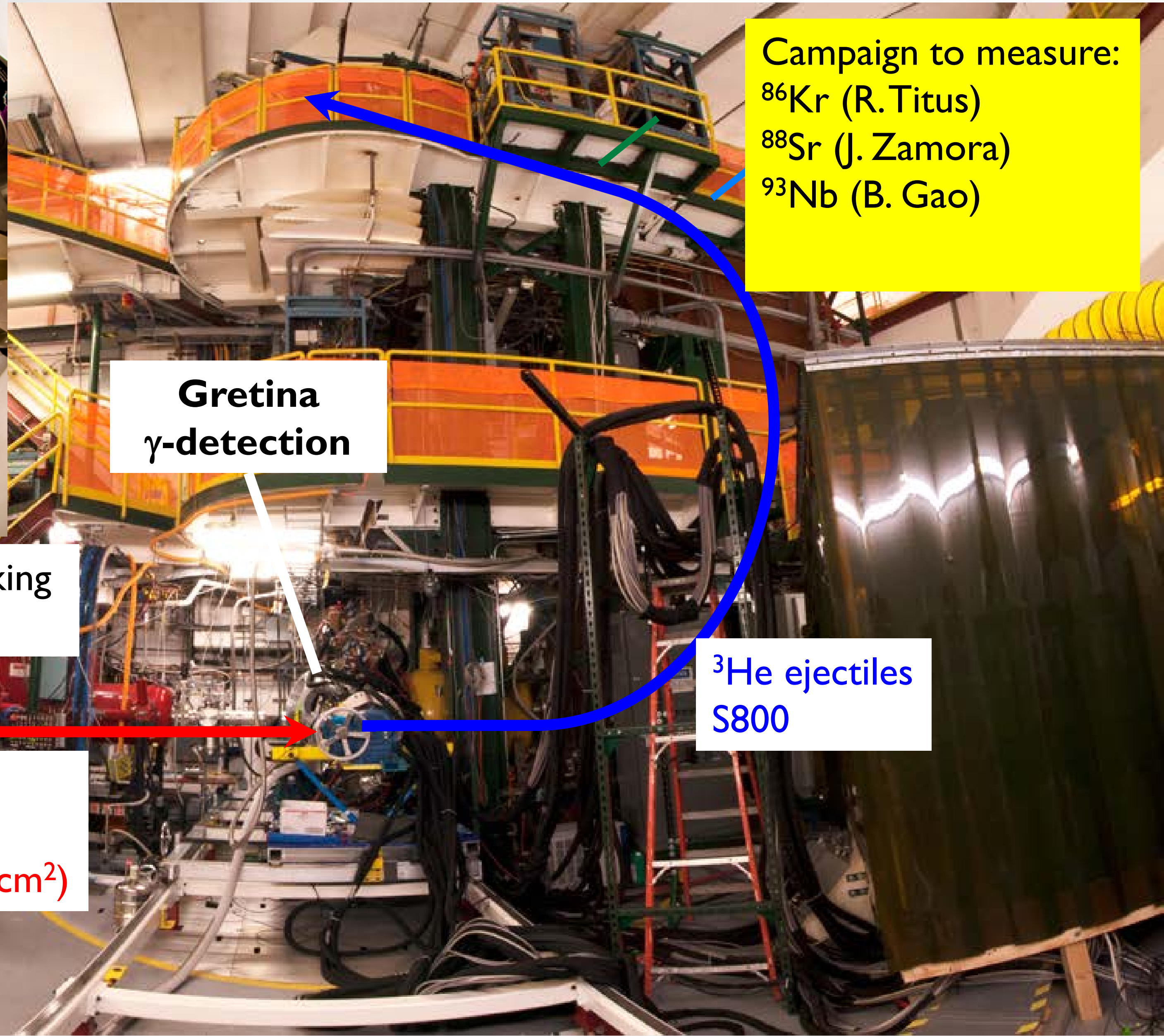




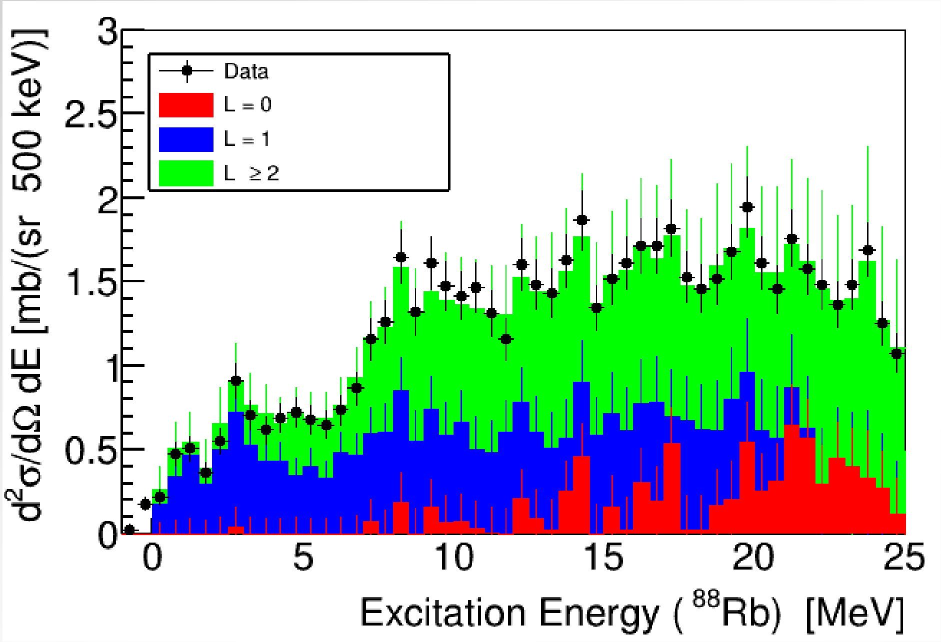
(t,^{3}He) & (t,^{3}He+γ) S800 Spectrograph (+Gretina)



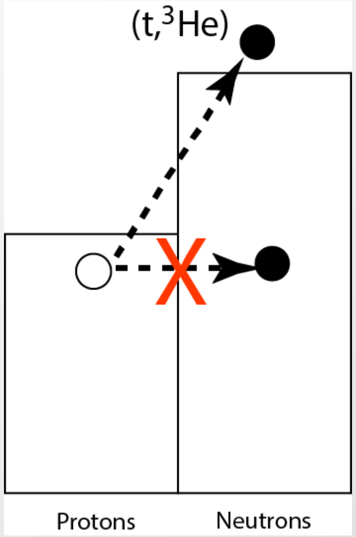
Gamma-Ray Energy Tracking
In-beam Nuclear Array



$^{88}Sr(t,{}^{3}He+\gamma)$ – preliminary



- GT strength below 7 MeV extracted from MDA is very small
- Pauli blocking stronger than anticipated and/or strong core polarization leads to reduction of strength
- Opportunity to use ^{88}Sr as a shell-model core for estimating GT strengths and EC rates?



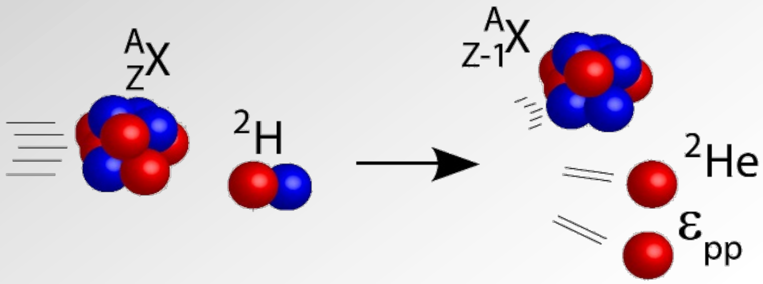
- No γ rays observed associated with the decay of known low-lying GT states in ^{88}Rb. Strong upper limit on low-lying GT strength

Analysis: Juan Zamora

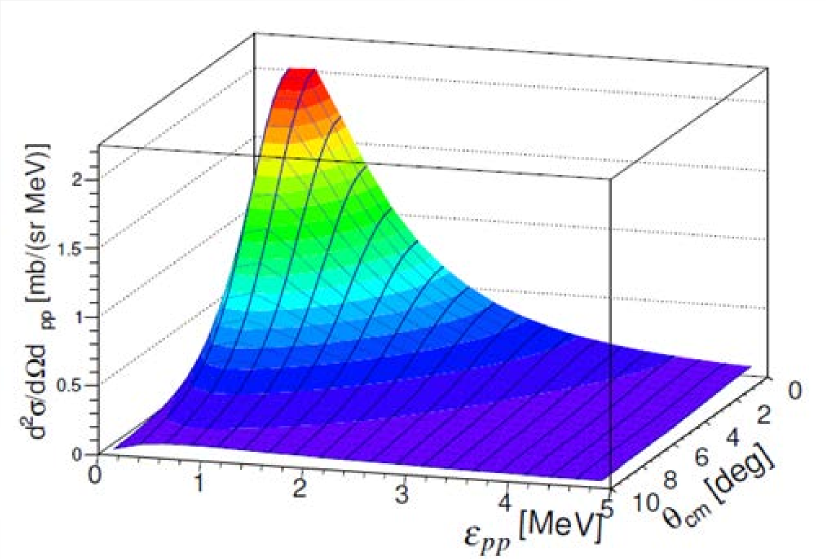
Charge-exchange reactions in inverse kinematics on rare isotopes in the EC (n,p) reaction?

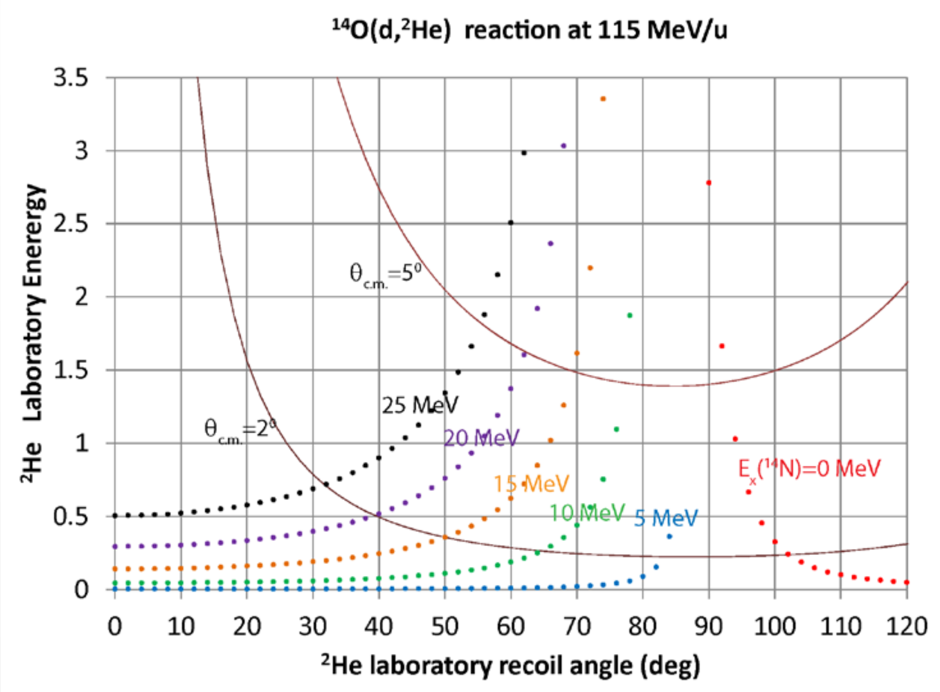
- Many of the nuclei for which EC rates are important for astrophysics are unstable and neutron-rich: need experimental tool!
- (^{7}Li,^{7}Be) reaction in inverse kinematics has been successfully developed, but only applicable for low excitation energies and light nuclei [RZ et al., PRL 104, 212504 (2010); R. Meharchand et al., PRL 108, 122501 (2012)]
- In collaboration with the AT-TPC collaboration, the CE group is developing the (d,^{2}He) reaction as a new tool for inverse kinematics experiments.
- (d,^{2}He) reaction has been used extensively and successfully in forward kinematics at KVI, RIKEN, and Texas A&M.

(d,^{2}He) in inverse kinematics



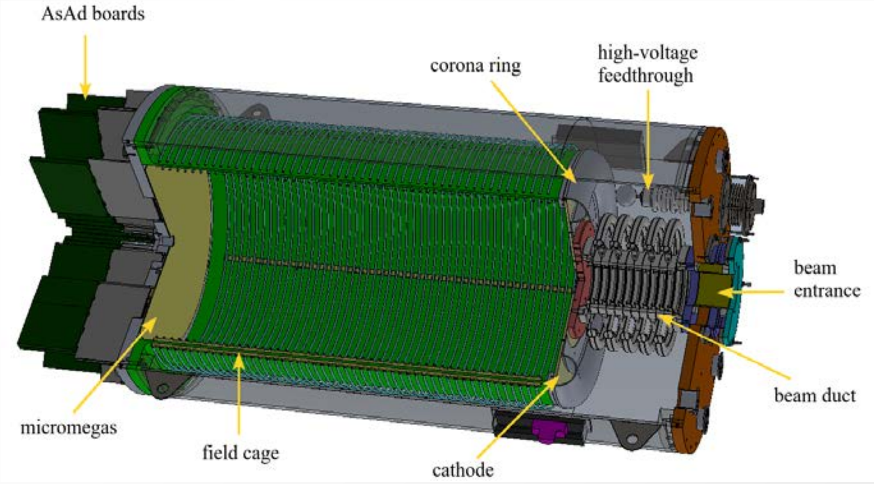
- ^{2}He is an unbound 2-p system
- If the relative energy between the two protons is small (ε_{pp}<1 MeV), ΔS=1 is ensured and a pure spin-transfer probe is created
- In inverse kinematics, the two protons have very low energy if the momentum transfer is small: difficult to measure

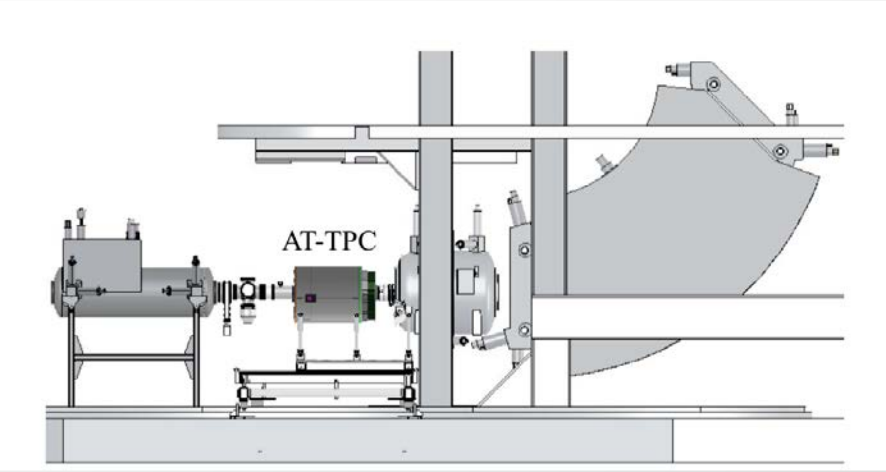




Measurement of the (d,^{2}He) reaction in inverse kinematics by using the Active-Target Time-Projection Chamber (AT-TPC)

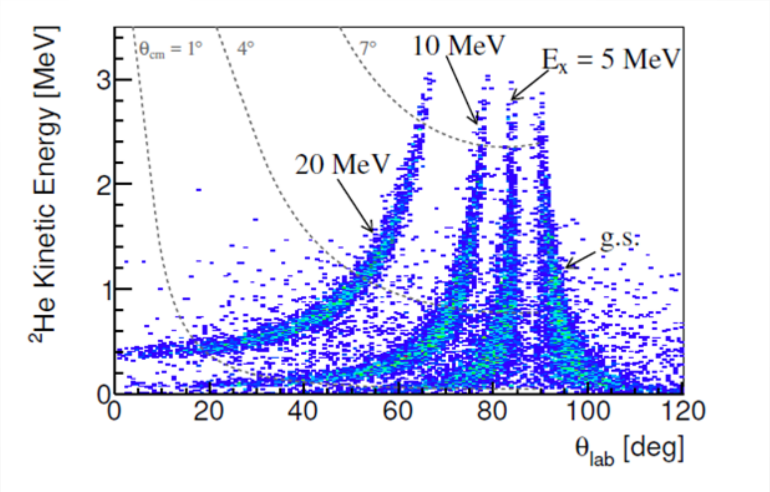
- AT-TPC with D_2 gas – serves as target and tracking medium
- AT-TPC has been used successfully with low-energy reaccelerated beams, but will for (d,^{2}He) in inverse kinematics be placed in front of the S800 spectrometer, which serves to collect and identify reaction residues
- Trigger: measurement of 2 proton tracks (stopped in AT-TPC) and residue in S800
- First experiment: proposed ^{14}O(d,^{2}He) – relatively easy case to establish method

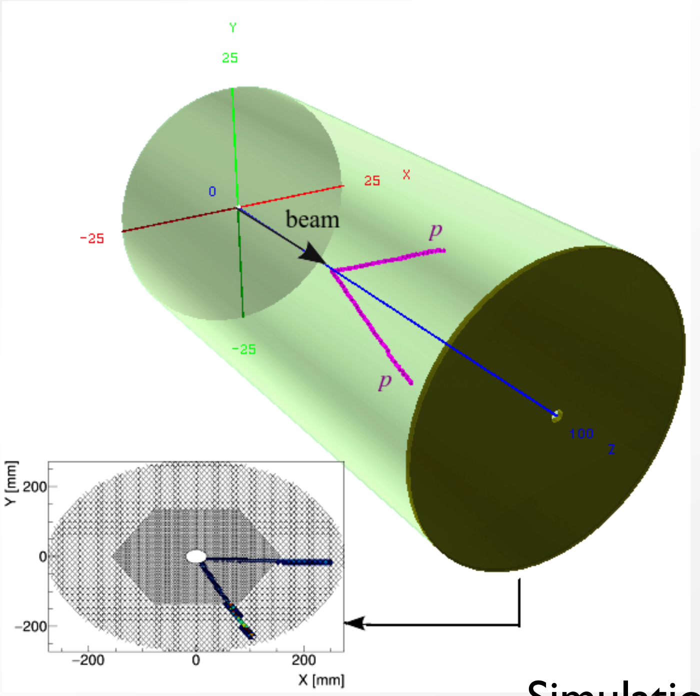




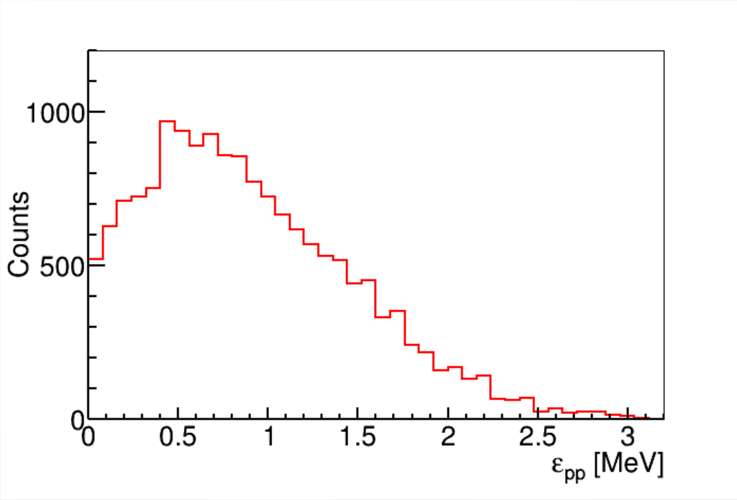
(d,^{2}He) in inverse kinematics: simulations

- GEANT4 simulations indicate feasibility of method
- E_x resolution ~1 MeV
- GT strength up to high E_x can be extracted





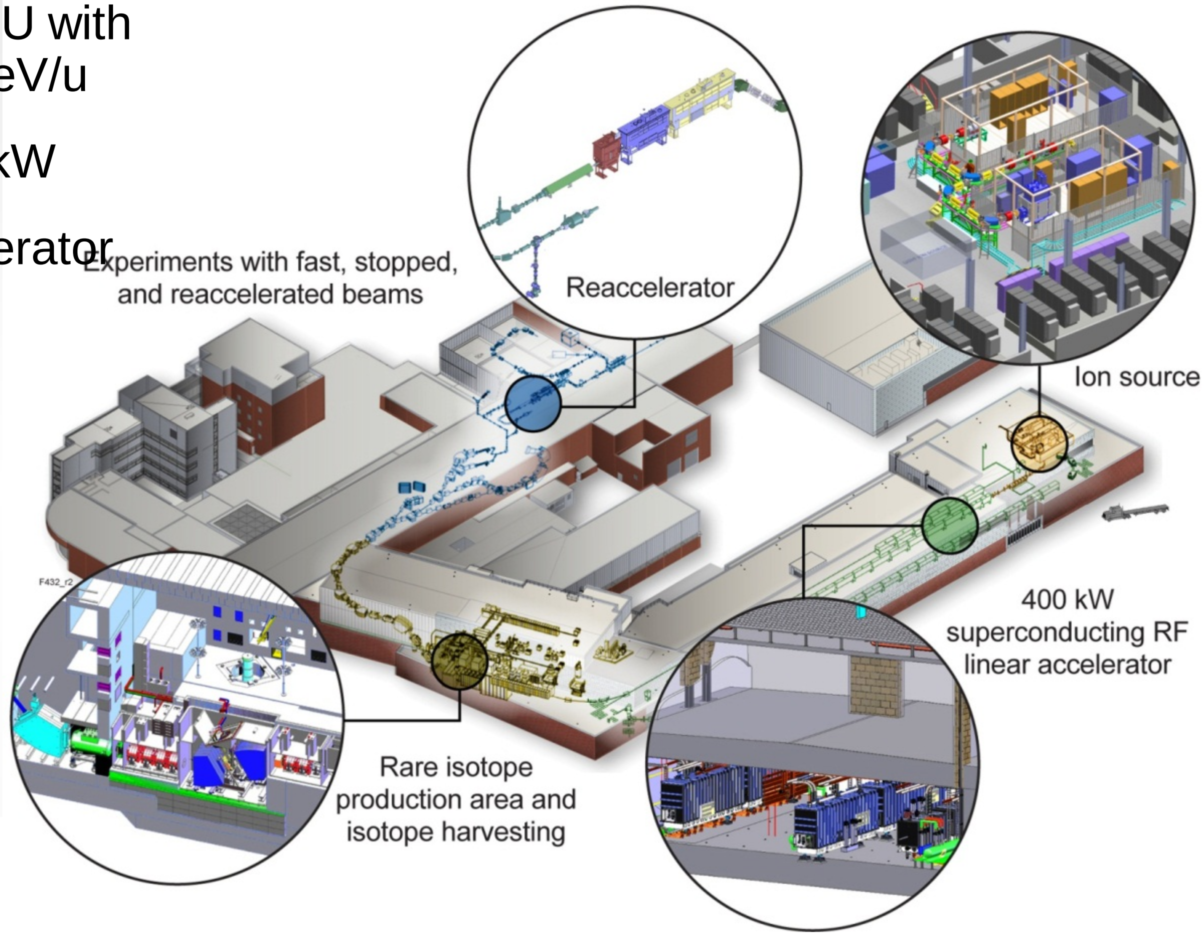
Simulated reconstruction of (d,^{2}He) kinematics

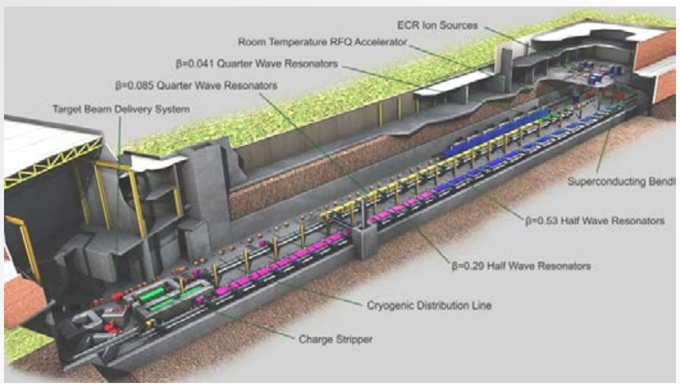


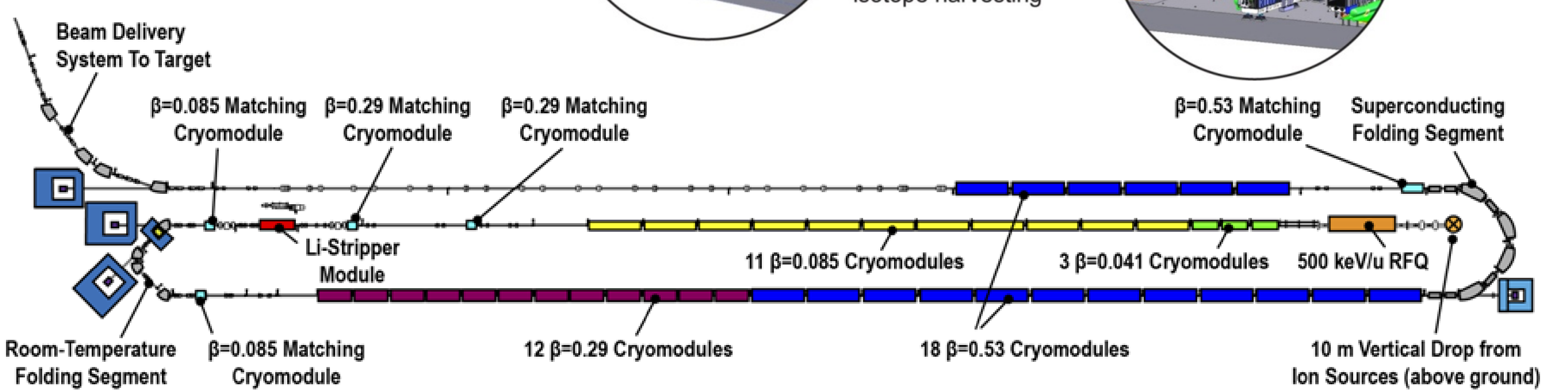
Simulations: J. Zamora

FRIB SRF Driver Linear Accelerator

- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide beam power up to 400kW
- Highest power heavy ion accelerator in the world
- Operations commence ~2021

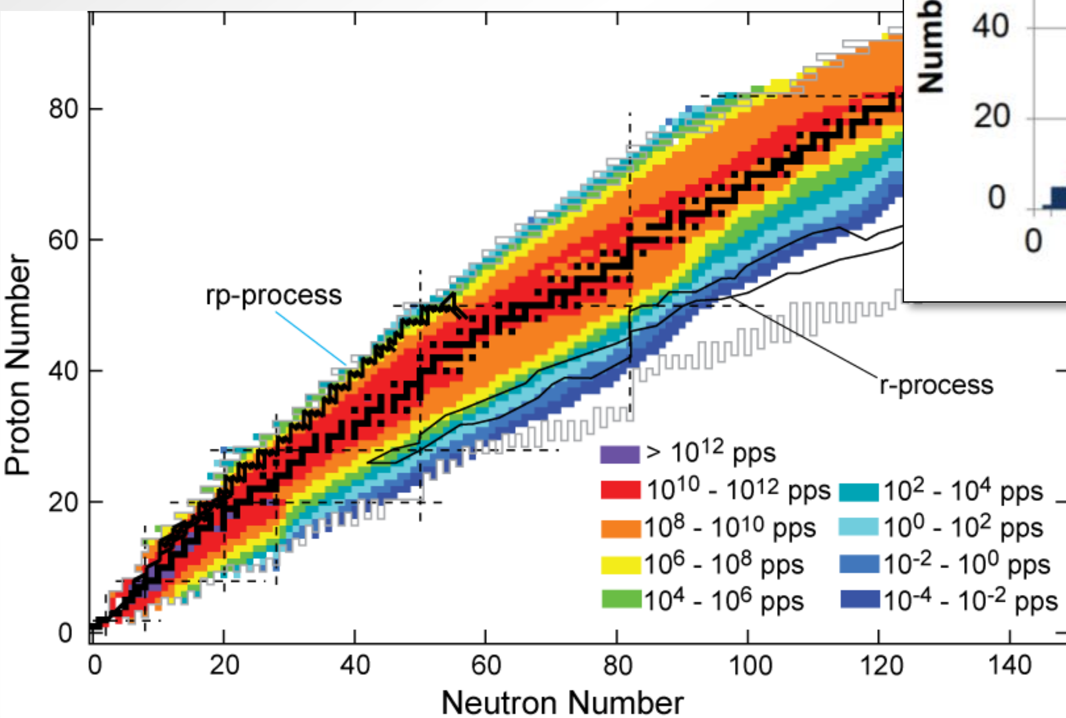


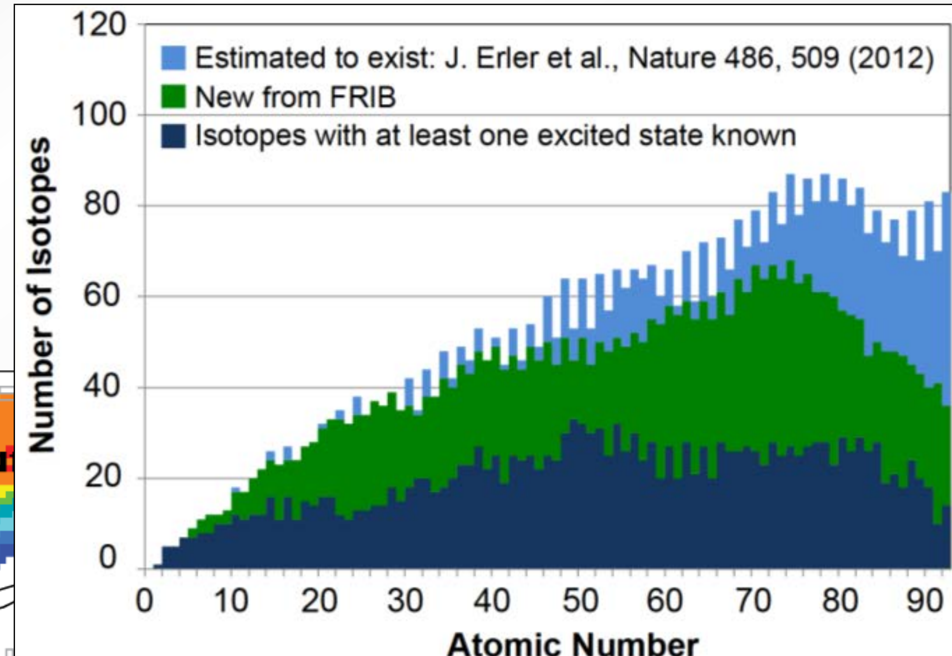




Isotope production at FRIB

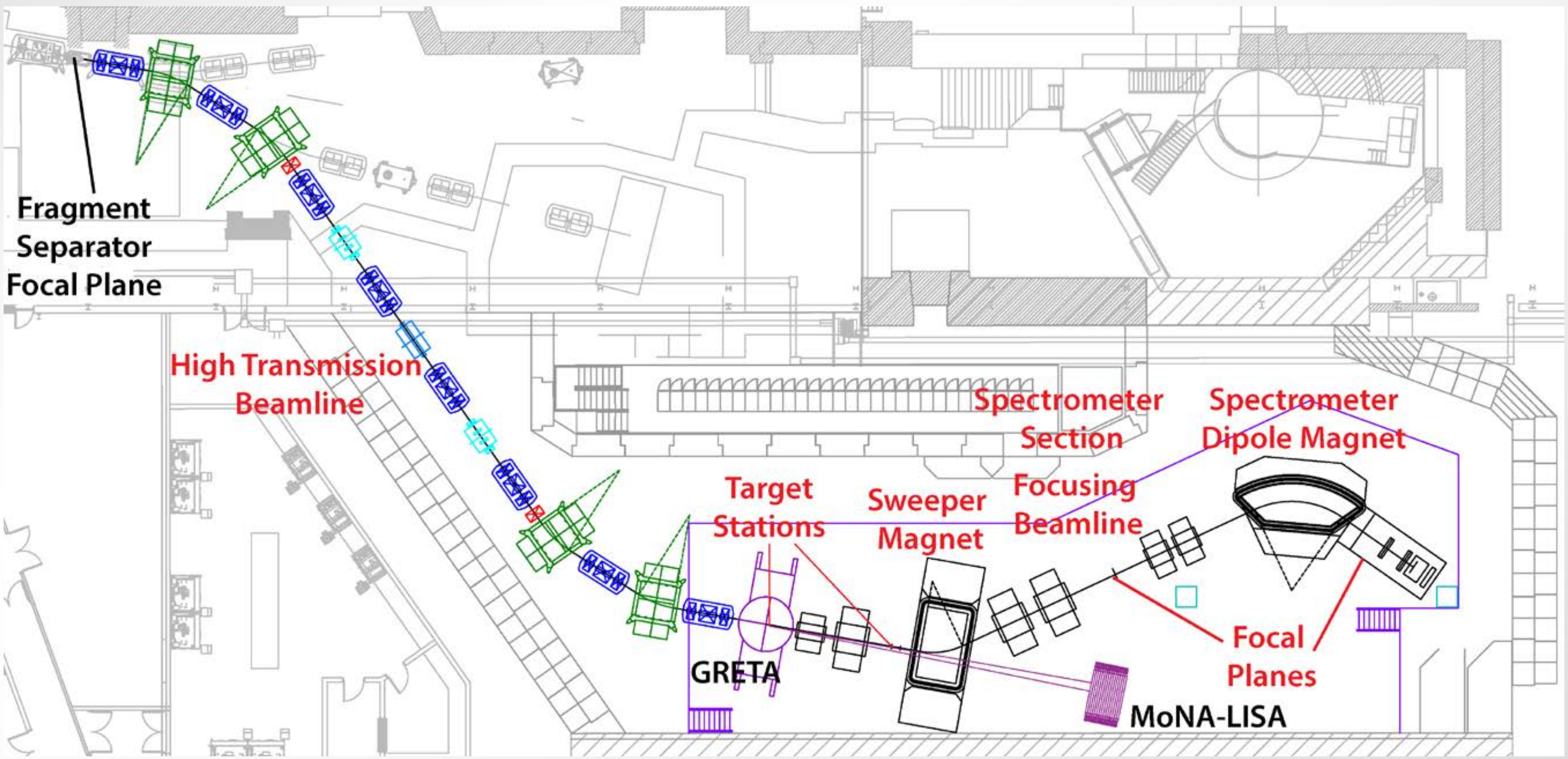
Production of in-flight rare isotope beams with 400 kW beam power using light to heavy ions up to ^{238}U with energy ≥ 200 MeV/u





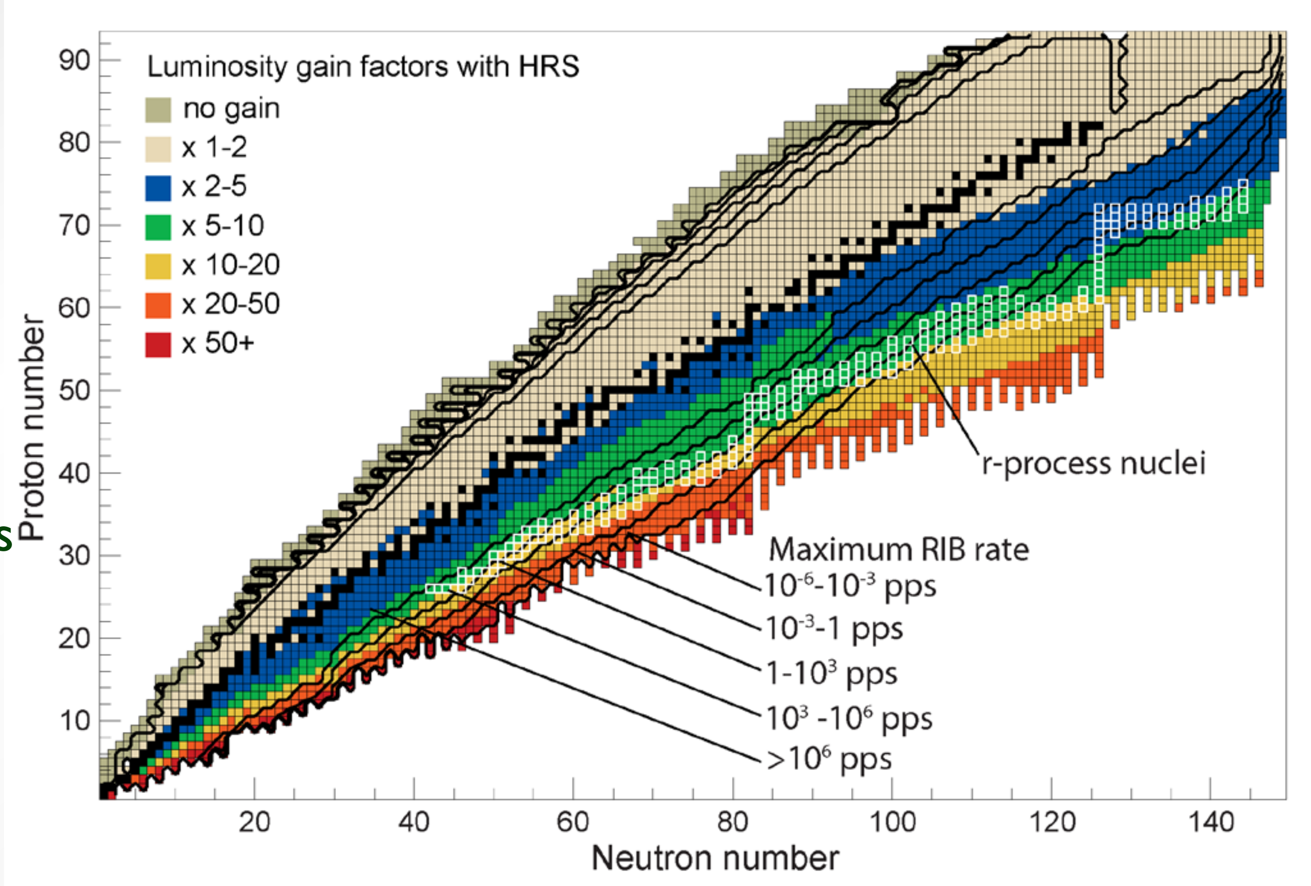
High-Rigidity Spectrometer at FRIB

- For a broad program with fast rare-isotope beams at FRIB, including charge-exchange, mass-measurement, and EoS studies
- Offer increases in luminosity by factors 2-100 compared to using existing spectrometers, with the highest gains for the most neutron-rich isotopes
- Construction of high-bay started



HRS@FRIB

- For over 90% of neutron-rich isotopes gain factors of 2-100 are achieved; on average about 10
- For the most asymmetric neutron-rich systems, gain factors are larger than 50
- For nuclei in the path of the astrophysical r-process gain factors are 5-20
- On the proton-rich side gain factors are 1-2, with an average of 1.5



Conclusions & Outlook

- NSCL CE group pursues a broad program aimed at constraining and improving weak reaction rates for nuclear astrophysics, in close collaboration with nuclear astrophysicists and theorists
- Development of new experimental tools for studying EC rates in rare isotopes in progress: $(d,{}^{2}He)$ reaction in inverse kinematics
- Additional programs also provide input of interest of astrophysics:
  - Isovector giant resonances with novel reaction tools: EoS (NSCL)
  - CE reactions on light unstable ions: shell evolution & quenching of GT strength (NSCL)
  - $({}^{6}Li,{}^{6}Li^{*}[3.56\ MeV])$ reaction as a new tool for constraining inelastic neutrino scattering cross sections (RCNP)
- Development of a new High Rigidity Spectrometer for FRIB with many applications for astrophysics, including very neutron-rich systems