Impact of electron-captures on nuclei near N=50 on core-collapse supernovae

Rachel Titus

Nuclei in the Cosmos XV

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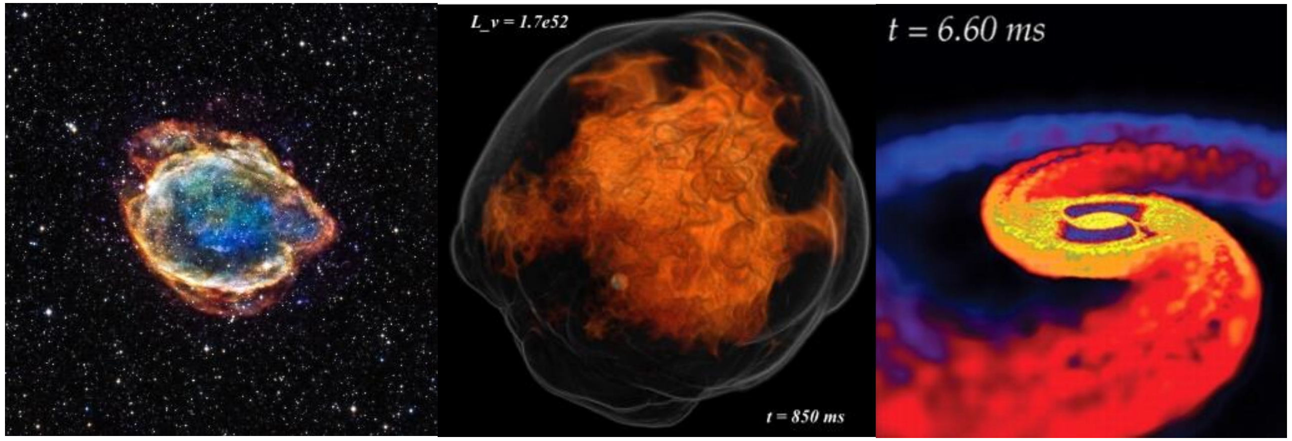
Outline

- Introduction
- Weak rate library
- Sensitivity study of N=50 region
- Experimental program
- Conclusions

Introduction

- Weak rates – important nuclear physics inputs to astrophysical simulations
  - Stellar nucleosynthesis
  - Core-collapse and thermonuclear supernovae
  - Neutron star mergers
  - Neutron star crust processes
  - …
- Electron capture rates are of particular interest

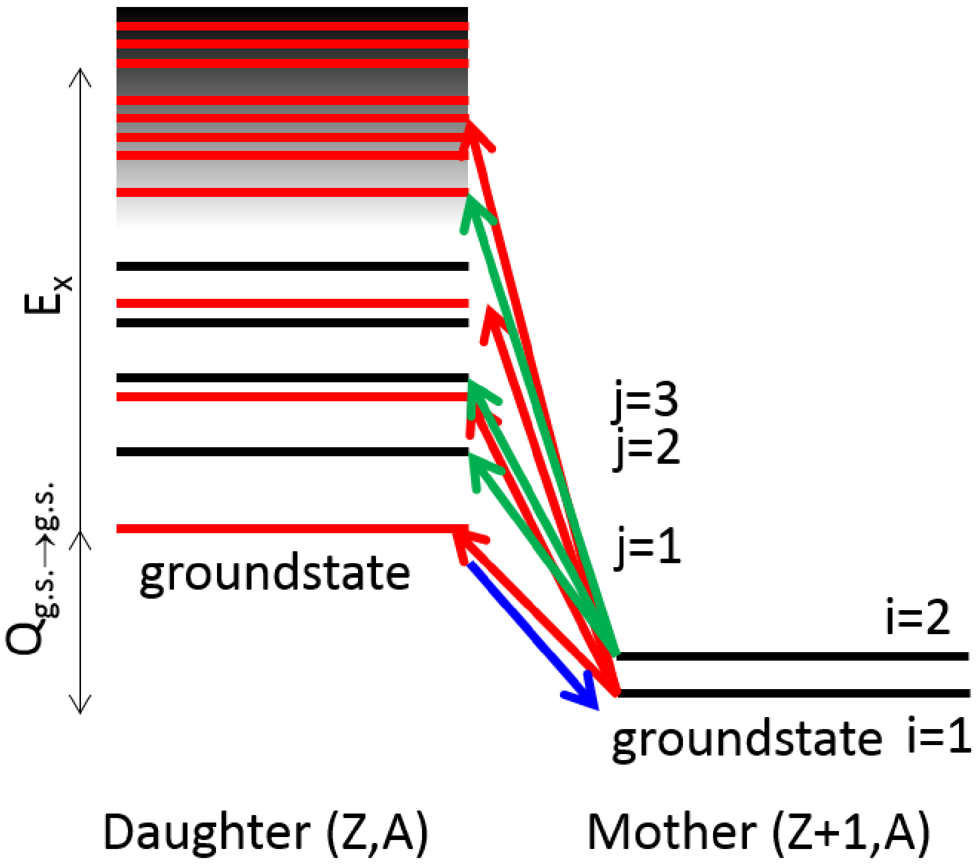


[1] Chandra X-ray Observatory (2014)
[2] S. M. Couch ApJ **775** 1 (2013)
[3] D. J. Price, S. Rosswog Science **312** 5774 (2008)

Introduction

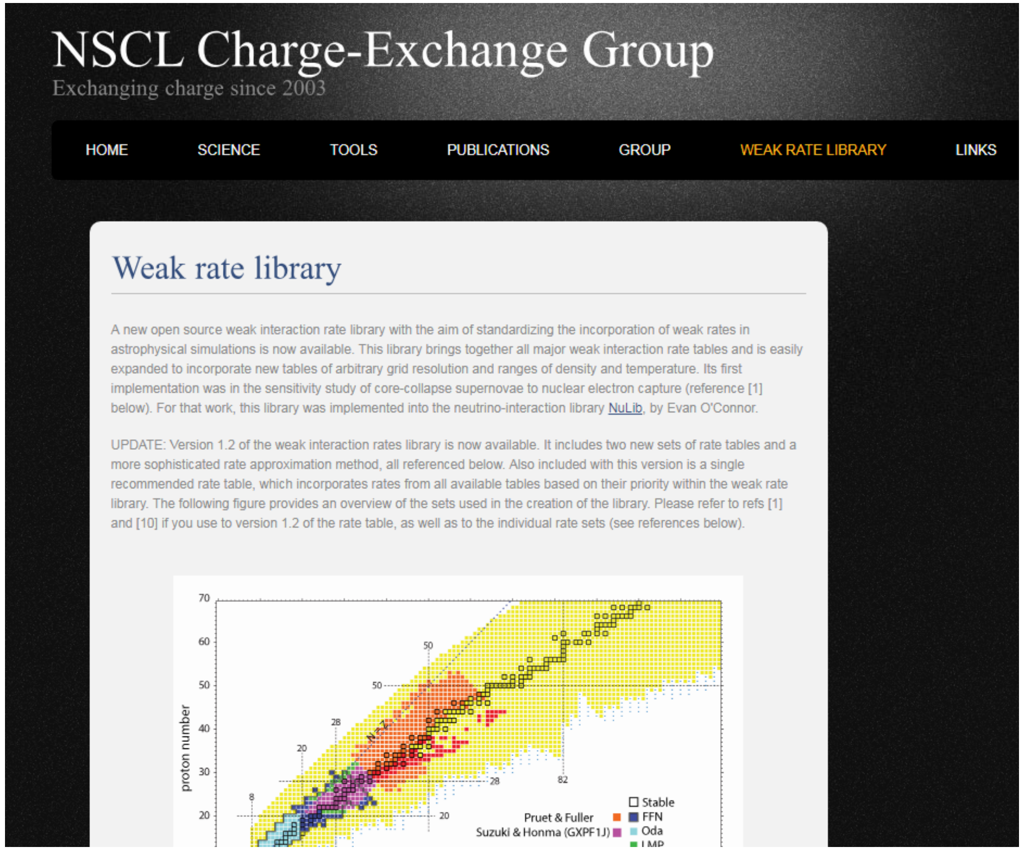
$$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) B(GT)_{ij}$$

- Electron-capture rates on nuclei
  - Depend on stellar temperature and density
  - Include transitions from excited states due to finite temperature in stars (green)
- Dominated by Gamow-Teller transitions
  - Characterized by a Q-value and a strength, B(GT)
  - Only a fraction, if any, of the transitions can be measured directly – low-lying excited states
  - Rely on theoretical models for additional transitions
- Charge-exchange experiments
  - No limitations due to the Q-value window, compared to β-decay



Weak rate library

- Initially published in 2016; continually updated with new rate tables
- Electron capture rates from a variety of sources
  - Theoretical calculations
    - Shell model, Monte Carlo shell model, independent particle model
    - Approximation
  - Experimental data
    - Charge-exchange experiments
- Good coverage of the chart of nuclides for the valley of stability and low-mass nuclei
- Available as part of NuLib or as plain ASCII tables
- First application of the library is in the sensitivity study of core-collapse supernovae



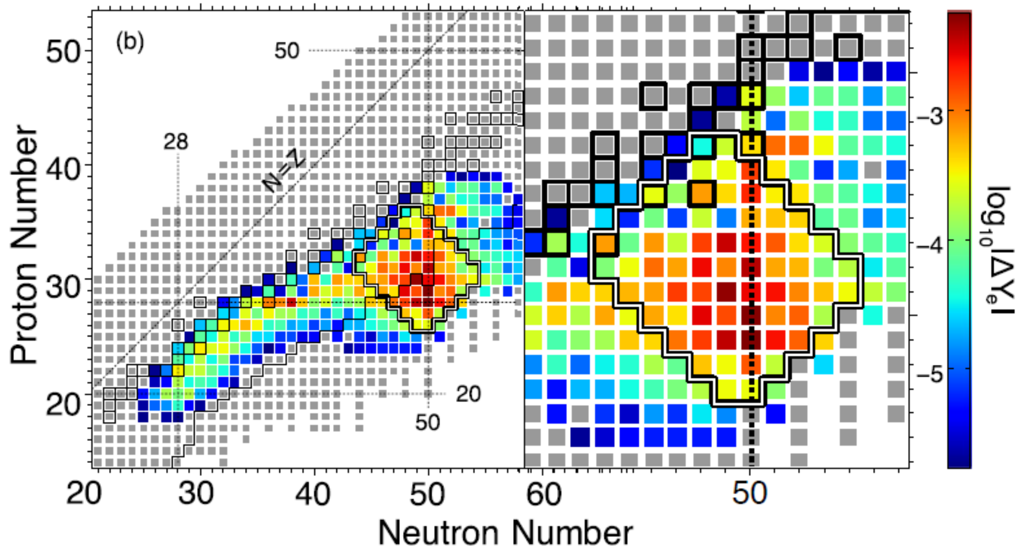
[1] https://groups.nscl.msu.edu/charge_exchange/weakrates.html
[2] C. Sullivan *et al*. ApJ **816** 44 (2016)
[3] E. O'Connor. Astrophys. J. Suppl. Ser. **219** 24 (2015)
[4] R. Titus *et al*. J. Phys. G **45** 014044 (2017)

Sensitivity study

- High-impact region of electron-capture rates, centered on the N=50 shell closure, cause the largest change in electron fraction
- Goal: to determine the effect of nuclei in this high-sensitivity region on the late stages of core-collapse
- Method: scale electron capture rates by different factors to determine the magnitude of such a change on parameters from the simulation
  - Scaling factors based on the systematic uncertainty in the rates in this region

High-sensitivity region: 74 nuclei

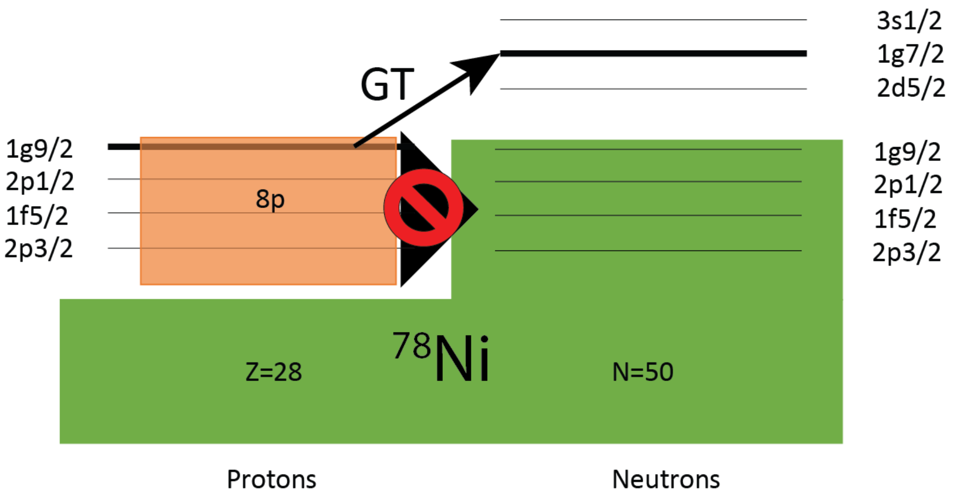
- Iron-75 to krypton-85,
- Gallium-75 to zinc-84



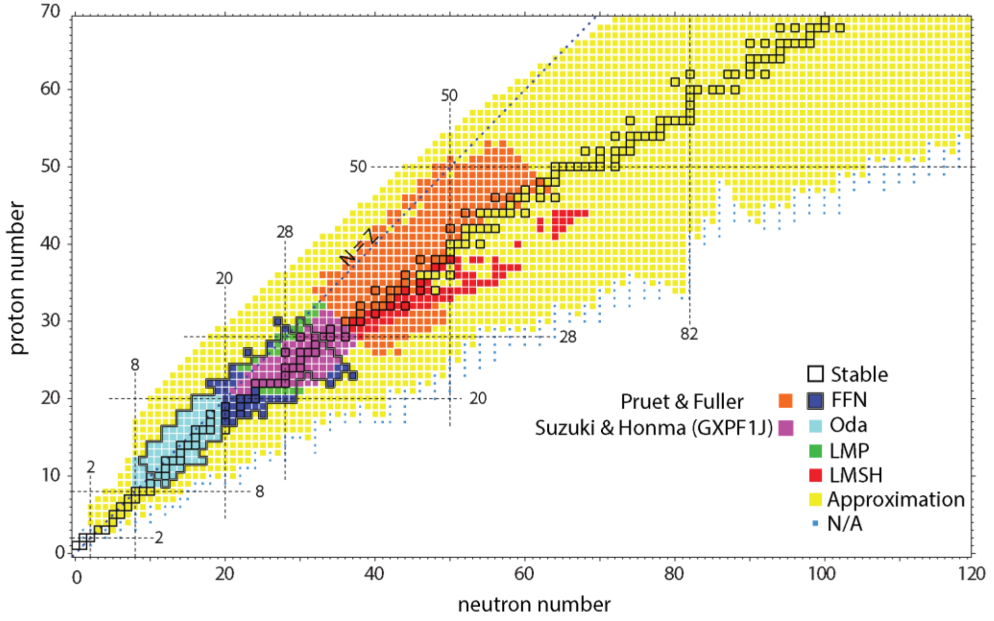
[1] C. Sullivan *et al*. ApJ **816** 44 (2016)
[2] E. O'Connor Astrophys. J. Suppl. Ser. **219** 24 (2015)
[3] E. O'Connor, C. D. Ott Class. Quantum Grav. **27** 114103 (2010)

Weak rate library

- For nuclei without calculated electron capture rates, an approximate method is used
- Single B(GT) and excitation energy
  - Based on fits to middle-mass, mid-shell, stable nuclei (LMP table)



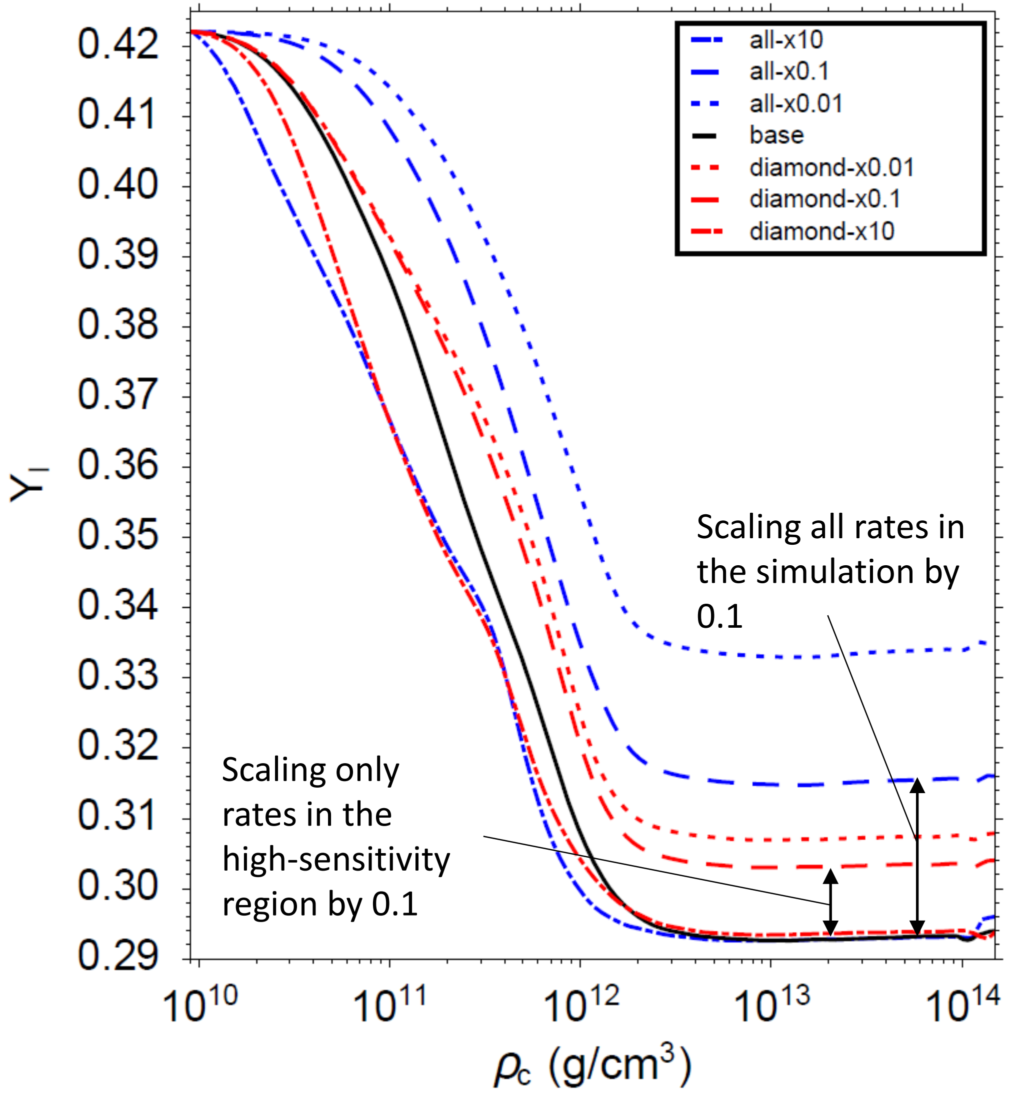
[1] K. Langanke *et al*. Phys. Rev. Lett. **90** 241102 (2003)
[2] R. Titus *et al*. J. Phys. G **45** 014044 (2017)



- Often extrapolating to high-mass nuclei, highly unstable nuclei, and those nuclei lying on a shell closure
  - Does not account for Pauli blocking
  - Overestimate electron-capture rates by an order of magnitude or more

Sensitivity study

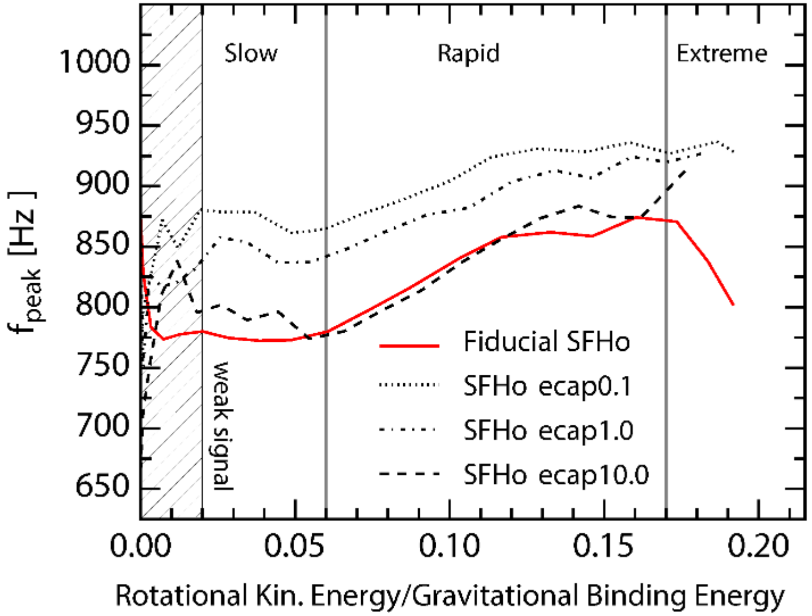
- Scaling factors x10, x0.1, x0.01
  - Scale rates of all nuclei participating in the simulation (blue lines)
  - Scale rates of 74 nuclei in the high-sensitivity region (red lines)
- Lepton fraction as a function of core density (=time)
  - Electron capture rates affect the speed of the deleptonization of the core
  - Lower EC rates yield a higher lepton fraction
- Nuclei in the high-sensitivity region account for 50% of the difference in the final lepton fraction

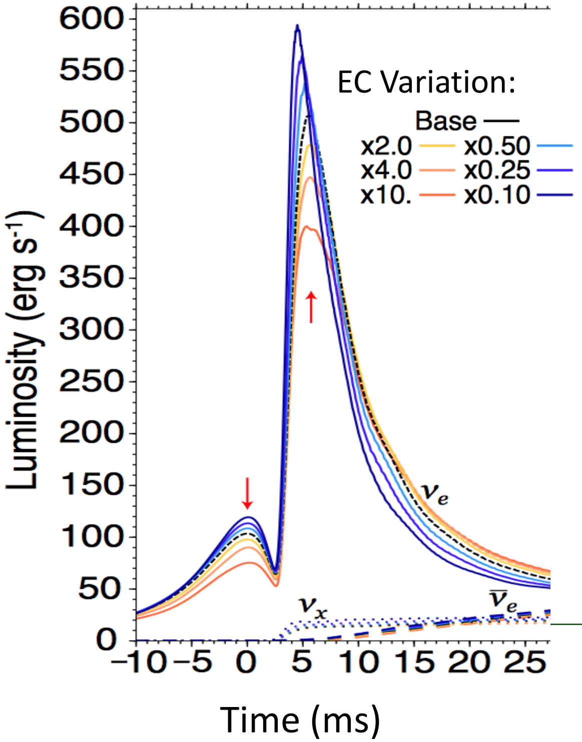


[1] R. Titus *et al*. J. Phys. G **45** 014044 (2017)

Sensitivity study

- Conclusion: electron capture rates for 74 nuclei in the high-sensitivity region have a high impact on the dynamical evolution of the core-collapse supernova simulation
  - Lepton fraction, electron fraction, entropy, density, in-fall velocity, neutrino luminosity
  - Using an inaccurate rate approximation can have a noticeable effect on the simulation
  - Calculating/measuring these rates accurately is imperative to understanding the late stages of core collapse
- Further experimental analysis of this region is required
  - Validate and benchmark current theoretical models
  - Guide future theoretical development





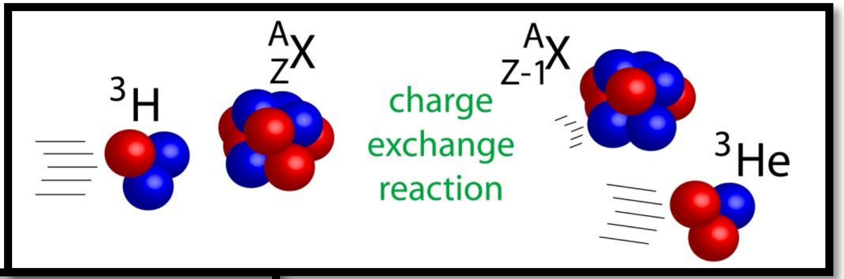
[1] R. Titus *et al*. J. Phys. G **45** 014044 (2017)
[2] C. Sullivan *et al*. ApJ **816** 44 (2016)
[3] S. Richters *et al.* Phys. Rev. D **95** 063019 (2017)

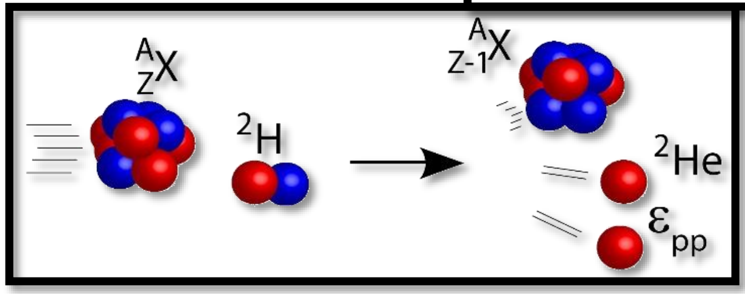
Experimental program

$$\left(\frac{d\sigma}{d\Omega}(q=0)\right)_{(t,^3He)} = \hat{\sigma}\, B(GT)$$

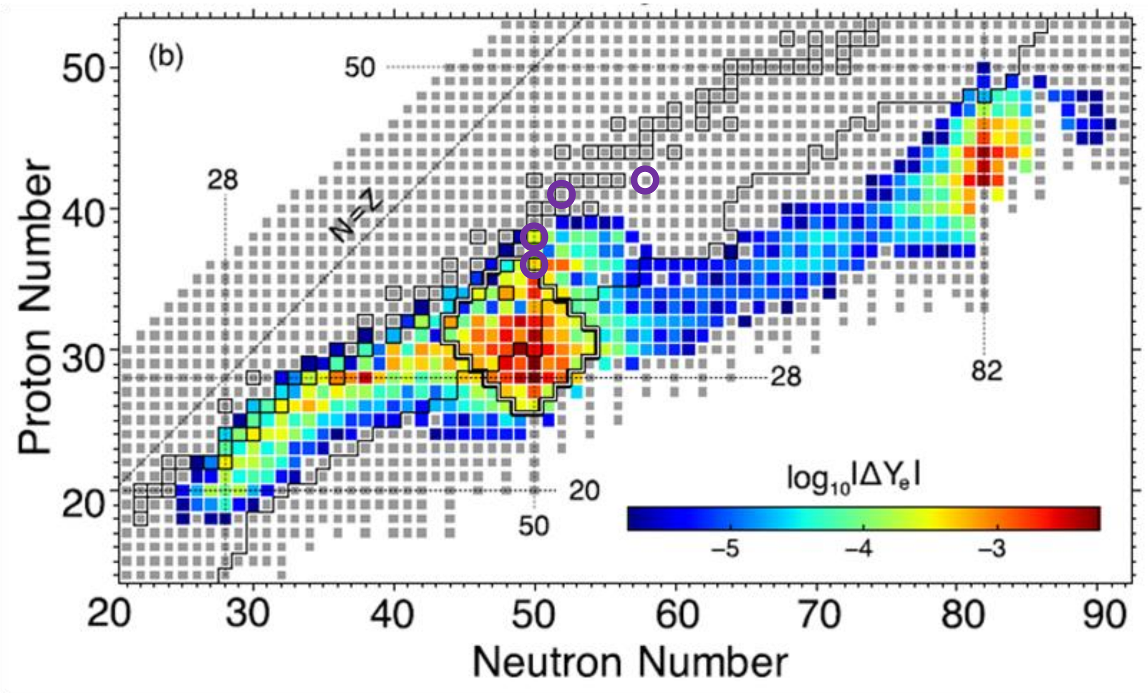
- Charge exchange reactions are effective for extracting Gamow-Teller strength
  - Probes: $(t,{}^3He)$, (n,p), $(d,{}^2He)$
- $(t,{}^3He)$ experiments performed at the National Superconducting Cyclotron Laboratory
  - ^{86}Kr (R. Titus), ^{88}Sr (J. Zamora)
  - ^{93}Nb (B. Gao), ^{100}Mo (K. Miki)

$(t,{}^3He)$





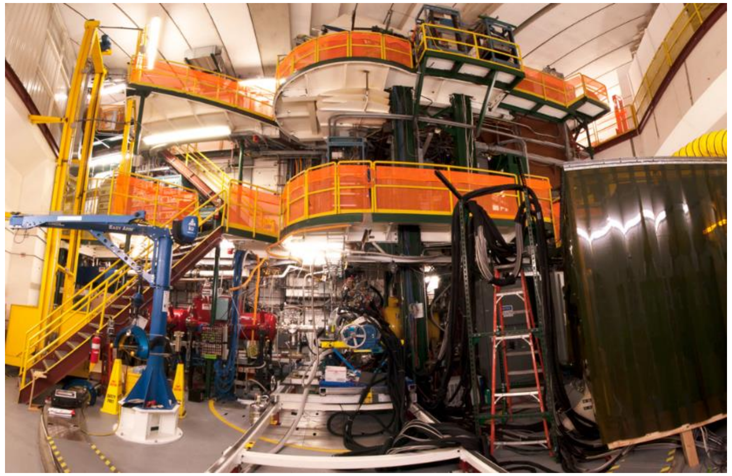
$(d,{}^2He)$



[1] R. Titus *et al*. J. Phys. G **45** 014044 (2017)
[2] K. Miki *et al.* Phys. Lett. B **769** 339 (2017)

Experimental program

- ^{88}Sr(t,^{3}He+γ) experimental results
  - Very little Gamow-Teller strength measured (L=0 in red)
  - Calculated electron-capture rates smaller than the approximate method by 2 orders of magnitude
  - Indicate strong overestimation of EC rates in the current simulation
- Tentatively, similar results from the ^{86}Kr analysis



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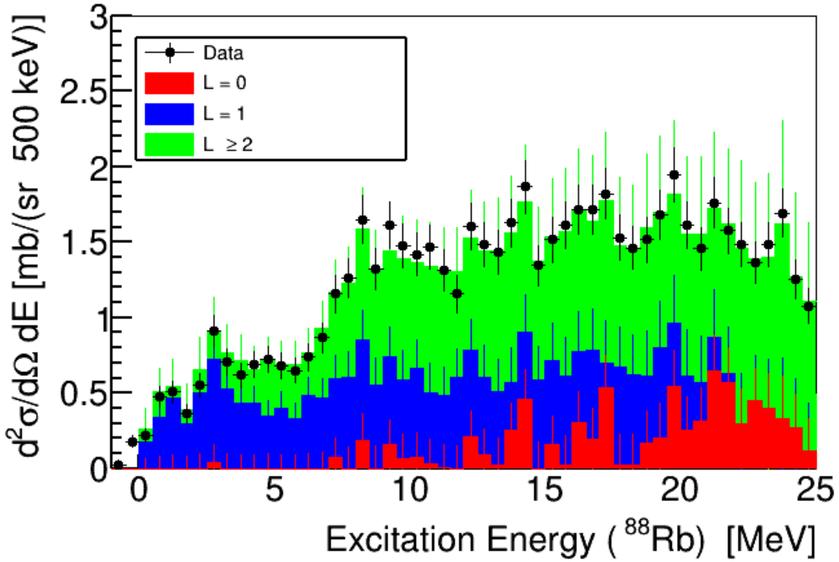
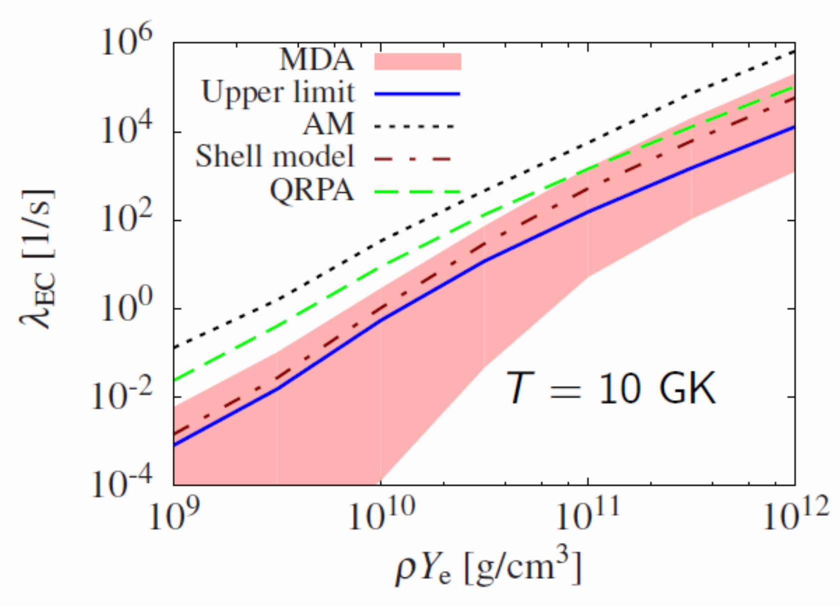
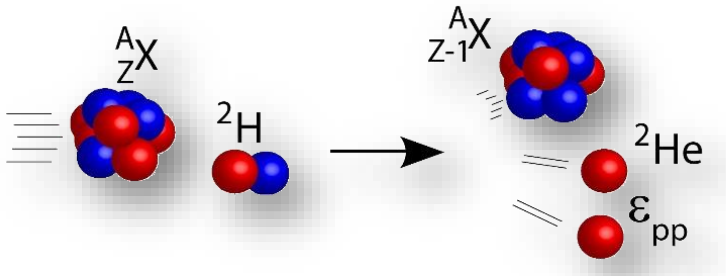


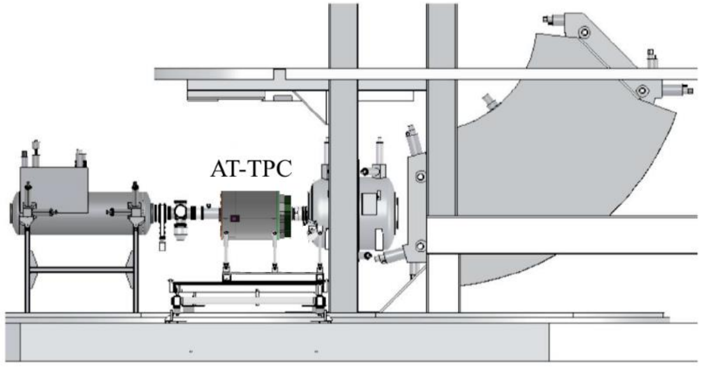


Figures generated by J. Zamora

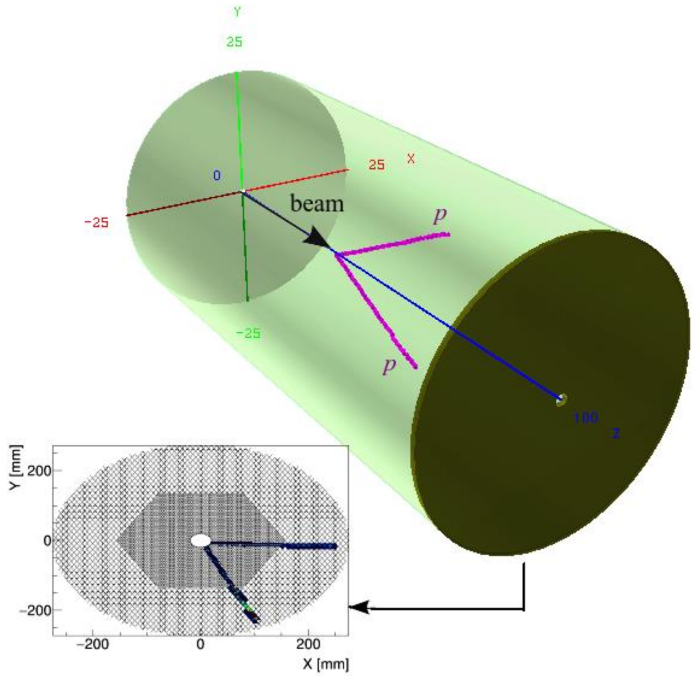
Experimental program

- Many of the nuclei of interest for nuclear astrophysics are unstable
- (d,^{2}He) charge-exchange reaction in inverse kinematics: probe for electron-capture rates on unstable isotopes
  - Active Target Time Projection Chamber (AT-TPC) in conjunction with the S800 magnetic spectrometer
  - Measure Gamow-Teller strength for nuclei pertinent to astrophysics





AT-TPC and the S800 at the NSCL



Conclusions

- Electron-capture rates are used as inputs in simulations of many astrophysical phenomena
- Electron-captures on nuclei near the N=50 shell closure have a large effect on the behavior of core-collapse supernova simulations
  - Nuclei predominately have their EC rates approximated
  - Likely overestimating rates and introducing large uncertainties into the simulation
- Necessary to obtain accurate rates for nuclei in the high-sensitivity region
  - Development of new theoretical models and rate sets
  - Charge-exchange experiments to benchmark current theories
- Good nuclear physics inputs yield more accurate representation of core-collapse supernovae and other phenomena

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- Experimental Collaboration
  - R. G. T. Zegers
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  - S. Lipschutz
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  - S. Noji
  - J. Pereira
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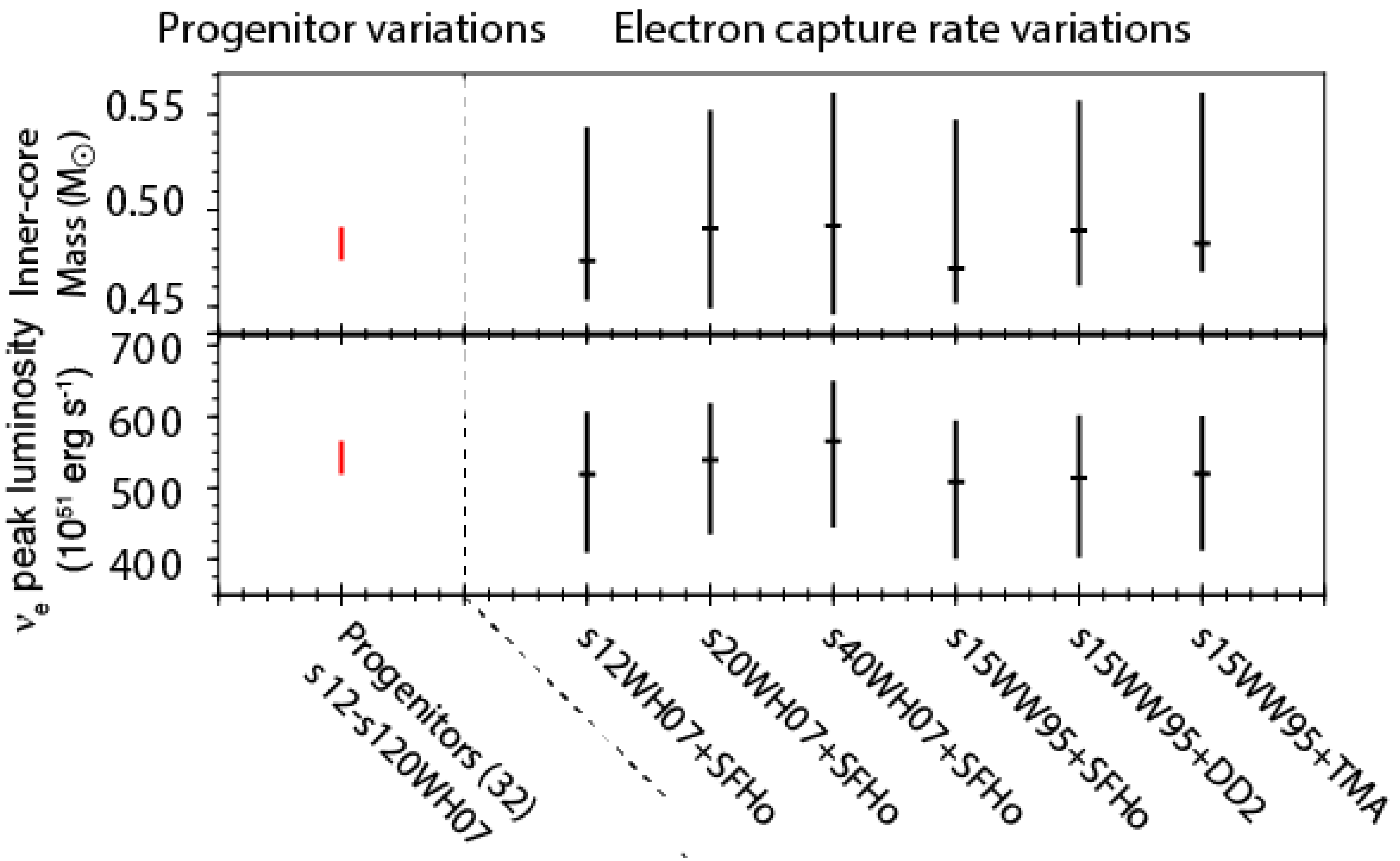
  - D. Weisshaar
  - B. Elman
  - B. Longfellow
  - E. Lunderberg
  - J. Belarge
  - P. Bender
  - T. Mijatovic

Extras

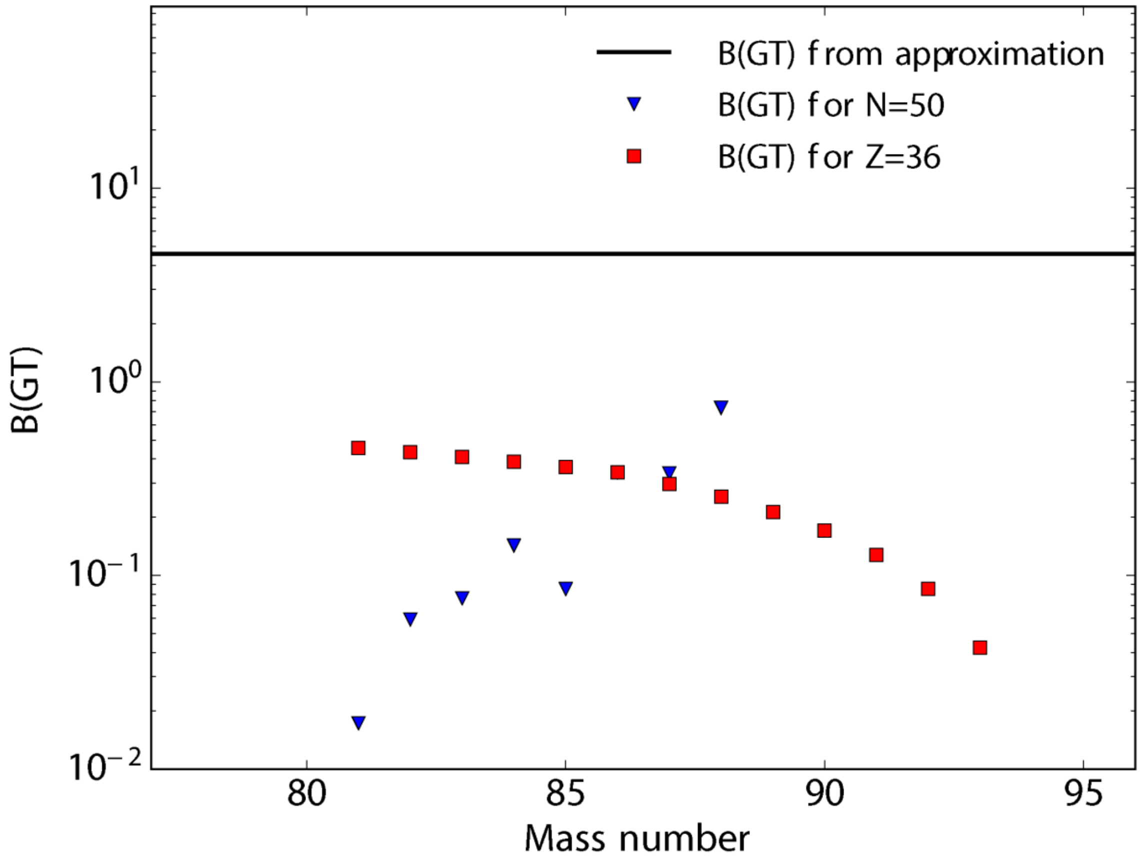
- Rate tables
  - **FFN** – G. M. Fuller, W. A. Fowler and M. J. Newman, *Astrophys. J.* **252** 715 (1982)
  - **ODA** – T. Oda, M. Hino, K. Muto, M. Takahara and K. Sato, *At. Data Nucl. Data Tables* **56** 231 (1994)
  - **LMP** – K. Langanke and G. Martínez-Pinedo, *At. Data Nucl. Data Tables* **79** 146 (2001)

    K. Langanke and G. Martínez-Pinedo, *Rev. Mod. Phys.* **75** 819 (2003)
  - **LMSH** – W. R. Hix, O. E. B. Messer, A. Mezzacappa, M Liebendörfer, J. Sampaio, K. Langanke, D. J. Dean and G. Martínez-Pinedo, *Phys. Rev. Lett.* **91** 201102 (2003)

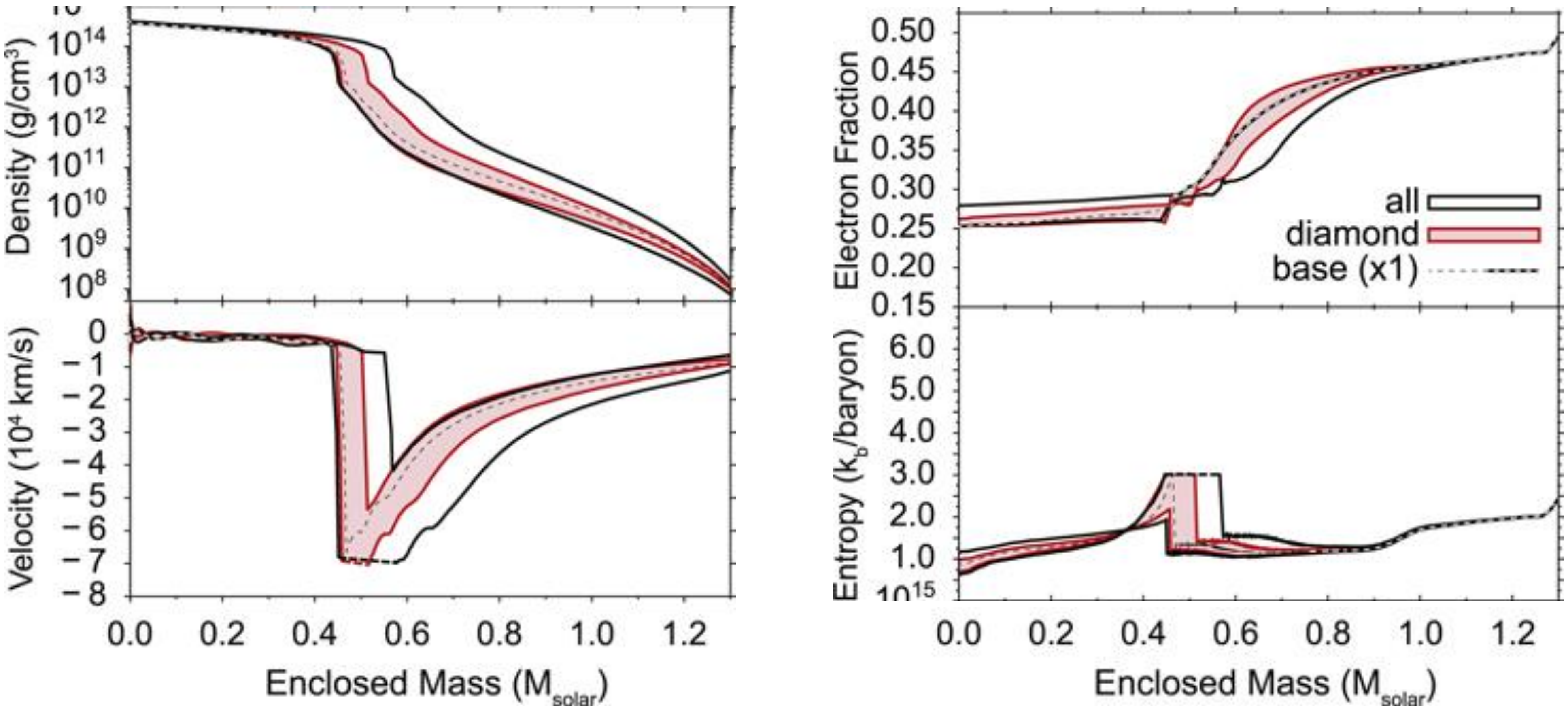
    K. Langanke, E. Kolbe and D. J. Dean, *Phys. Rev.* C **63** 032801 (2001)
  - **Pruet & Fuller** – J. Pruet and G. M. Fuller, *Astrophys. J. Suppl. Ser.* **149** 189 (2003)
  - **Suzuki & Honma** – T. Suzuki, H. Toki and K. Nomoto, *Astrophys. J.* **817** 163 (2016)
  - **Approximation (updated)** – Ad. R. Raduta, *Phys. Rev. C* **95** 025805 (2017)

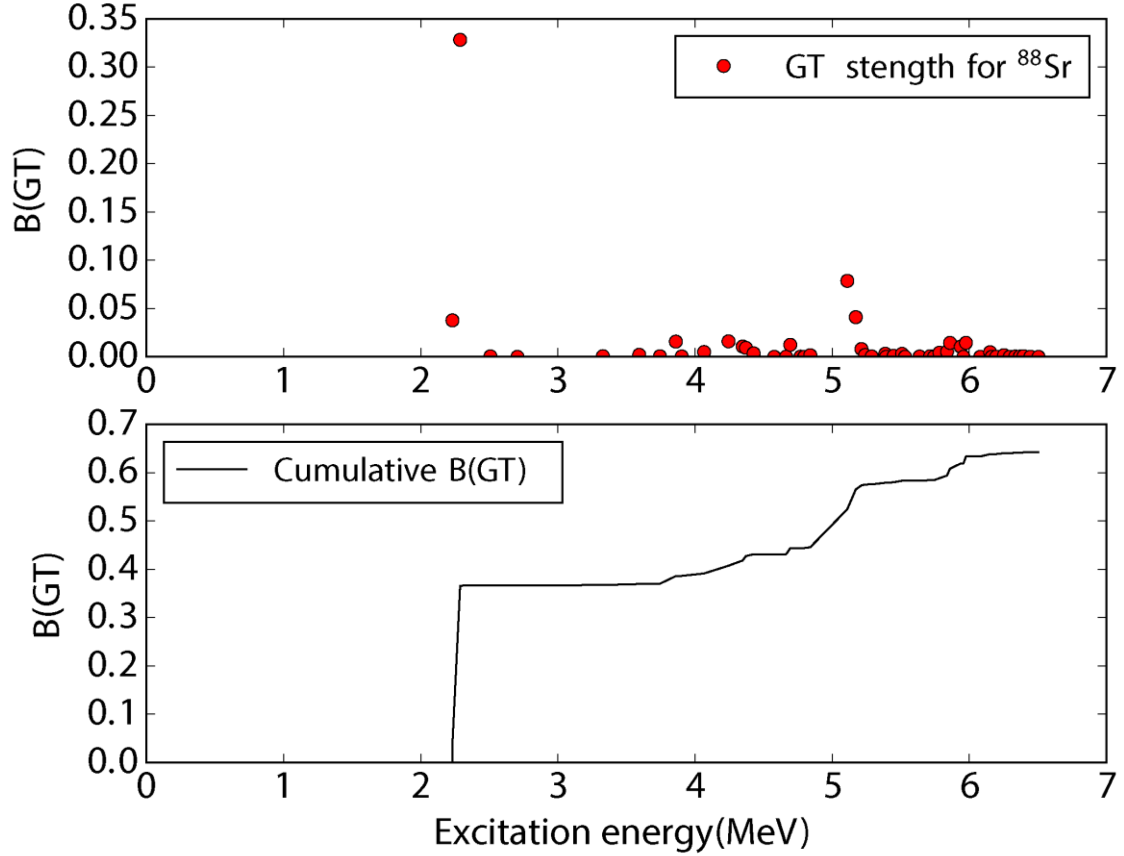


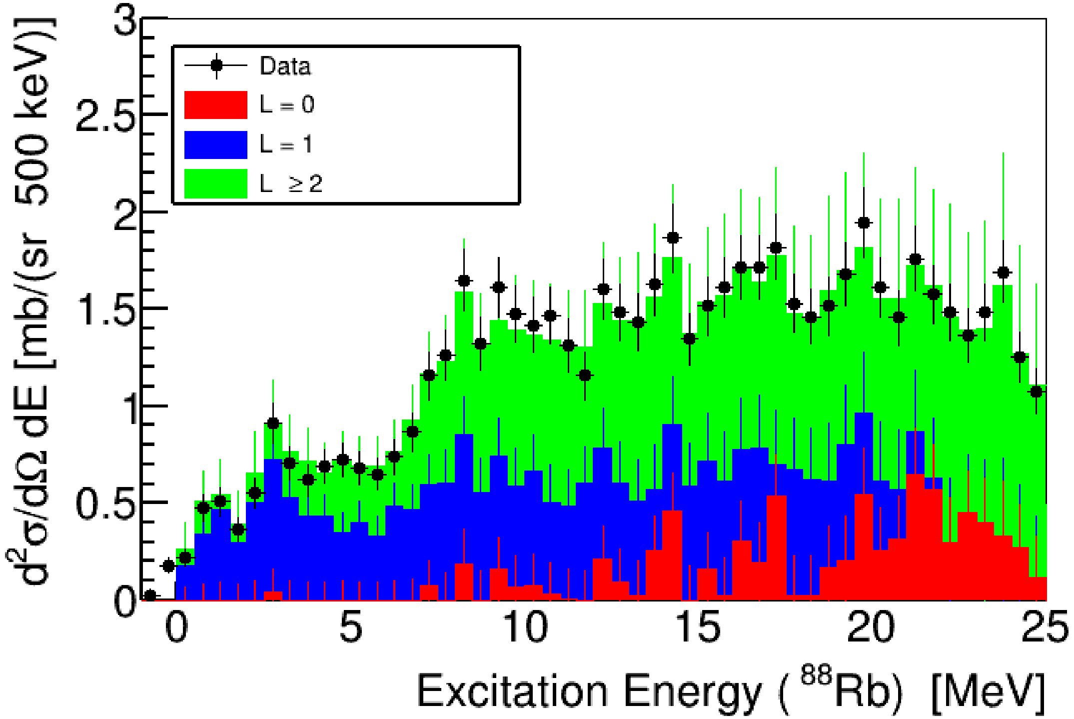
Progenitor variations
Electron capture rate variations
Inner-core Mass ($M_\odot$)
0.55
0.50
0.45
ν_e peak luminosity (10^{51} erg s^{-1})
700
600
500
400
Progenitors (32)
s12-s120WH07
s12WH07+SFHo
s20WH07+SFHo
s40WH07+SFHo
s15WW95+SFHo
s15WW95+DD2
s15WW95+TMA



Red = krypton isotopes
Blue = N=50 nuclei
Black = B(GT) for the approximation, 4.6


Density (g/cm^3)
Velocity (10^4 km/s)
Enclosed Mass (M_solar)
Electron Fraction
Entropy (k_b/baryon)
all
diamond
base (x1)





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