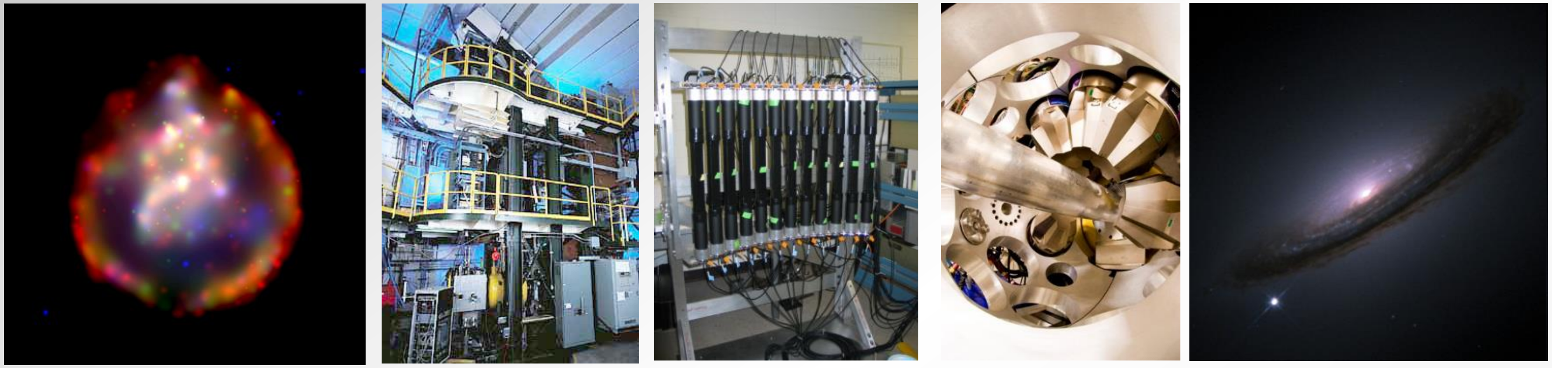


High-Resolution Spectroscopy in charge-exchange reactions with rare-isotope beams

Applications to weak-reaction rates for astrophysics

Remco G.T. Zegers

For the NSCL Charge-Exchange group and Collaborators

U.S. DEPARTMENT OF ENERGY
Office of Science

MICHIGAN STATE UNIVERSITY

NSF

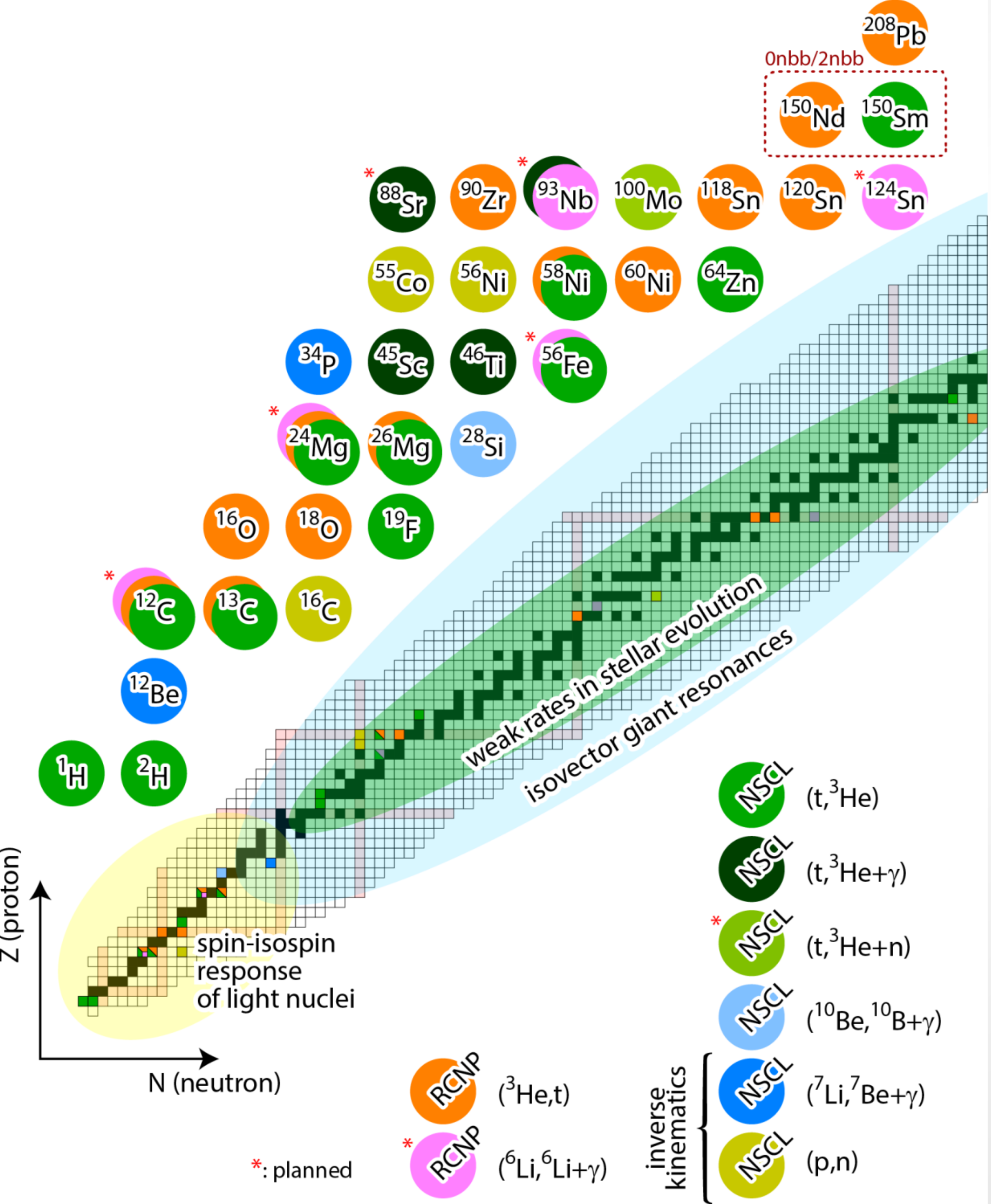
GRETINA

FRIB

NSCL

JINA-CEE

NSCL charge-exchange group program

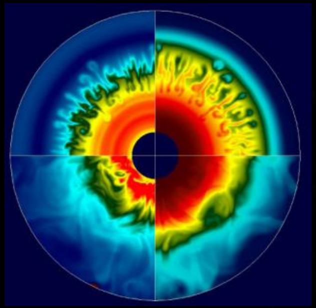


Charge-exchange experiments with different probes for a variety of objectives:

- Astrophysics – weak reaction rates
- (Neutrinoless) Double beta decay
- Shell evolution in light systems
- Giant resonances and the macroscopic properties of nuclear matter
- Novel probes for isolating particular multipole responses
- Studies of the charge-exchange reaction mechanism

Core-Collapse Supernovae: a multi-physics problem

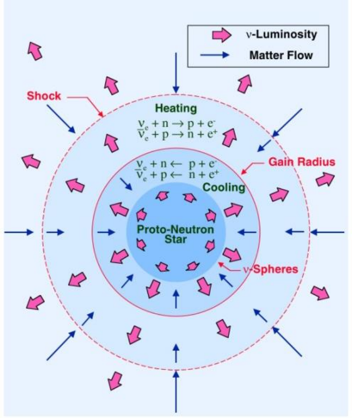
Hydrodynamics – Convection, Turbulence



Müller, E. and Janka, H.-T.
A&A 317, 140–163, (1997)

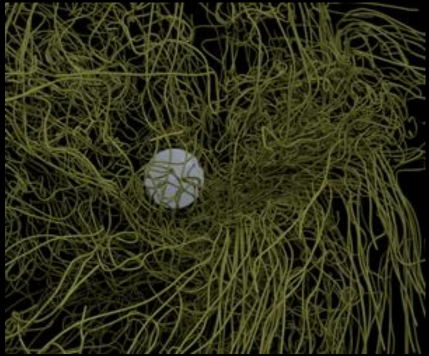
Fryer, C. L., & Warren, M. S. 2002, ApJ, 574, L65

Multi-Dimensional Effects - Asymmetries



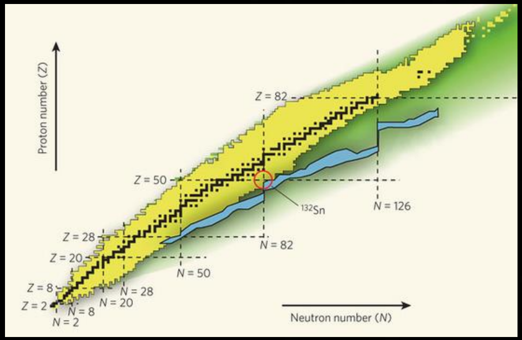
Neutrino physics (transport/ oscillations / interactions)

Magnetic fields



Pugmire et al., ORNL

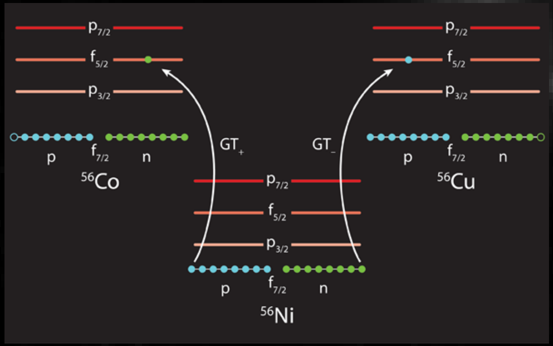
r-process



P. Cottle Nature 465, 430–431 (2010)

electron captures

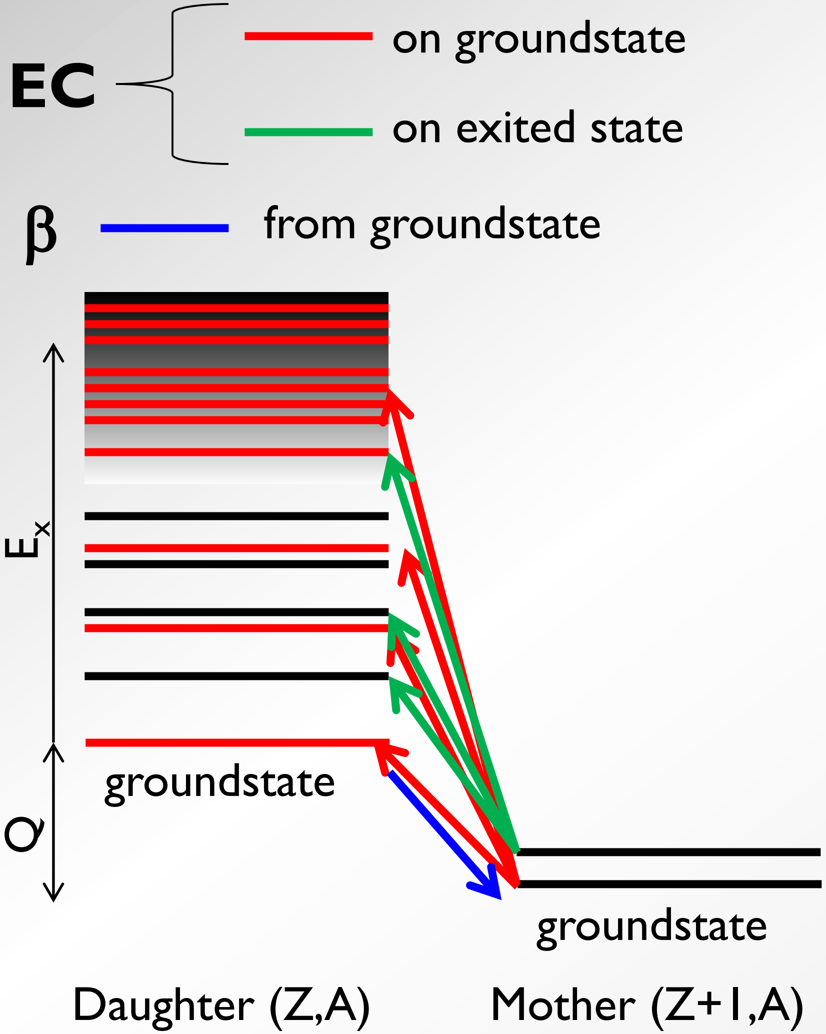
K. Langanke, Physics 4, 91 (2011)



> "Despite experimental and theoretical progress, lack of knowledge of relevant or accurate weak-interaction data still constitutes a major obstacle in the simulation of some astrophysical scenarios today."

K. Langanke and G. Martinez-Pinedo, RMP 75, 819 (2003).

electron captures



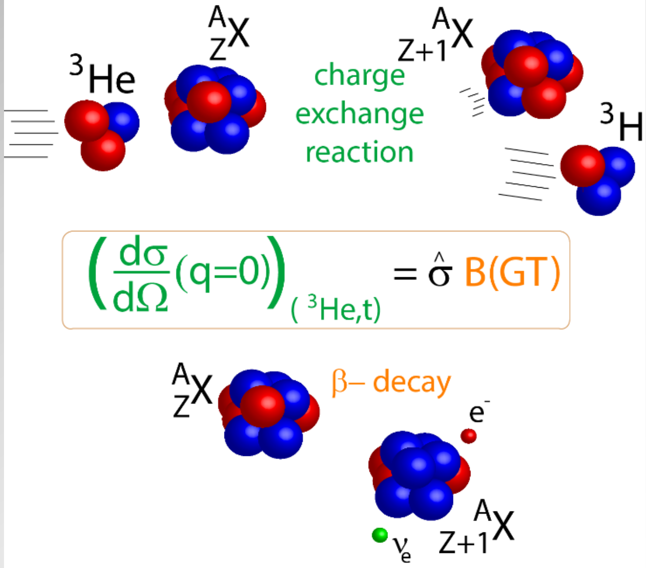
Dominated by allowed (Gamow-Teller) weak transitions between states in the initial and final nucleus:

- No transfer of orbital angular momentum **(ΔL=0)**
- Transfer of spin **(ΔS=1)**
- Transfer of isospin **(ΔT=1)**

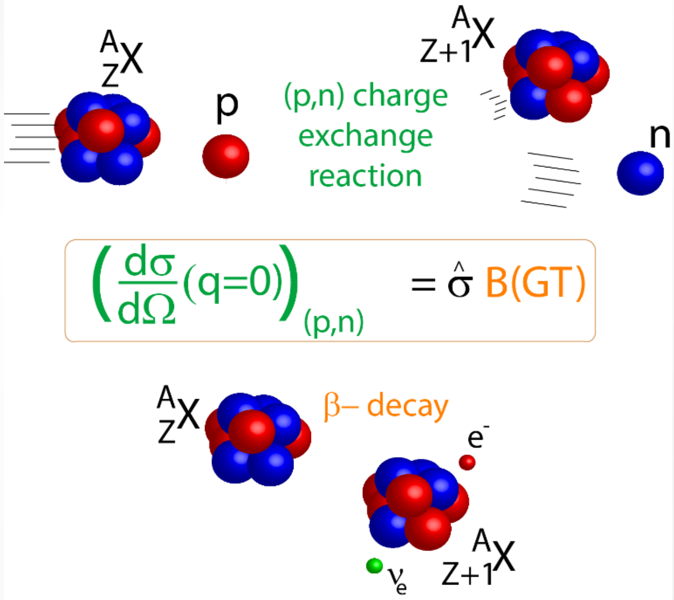
Due to finite temperature in stars, Gamow-Teller transitions from excited states in the mother nucleus can occur

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

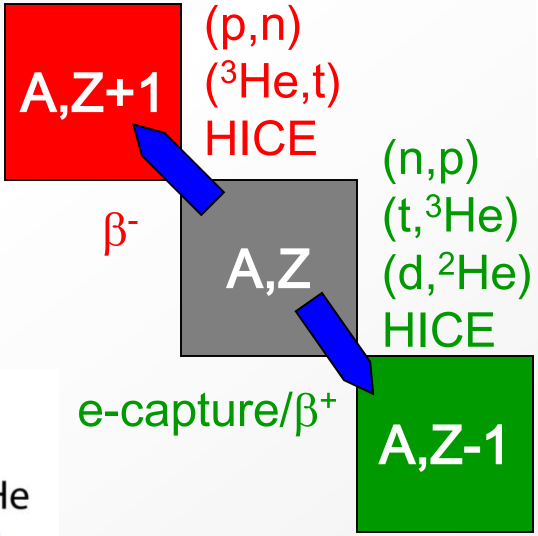
In astrophysical environments, typically EC on many nuclei play a role – we need accurate theories to estimate the relevant rates, benchmarked by experiments



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



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



A,Z+1

(p,n)
(^{3}He,t)
HICE

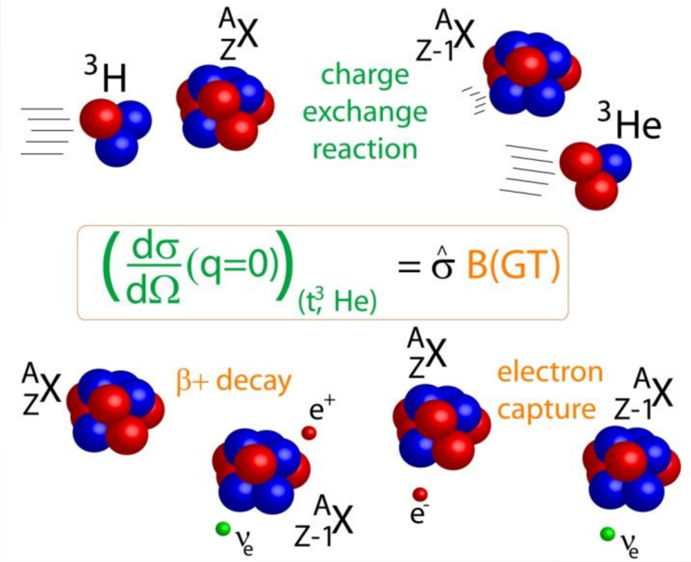
β^-

A,Z

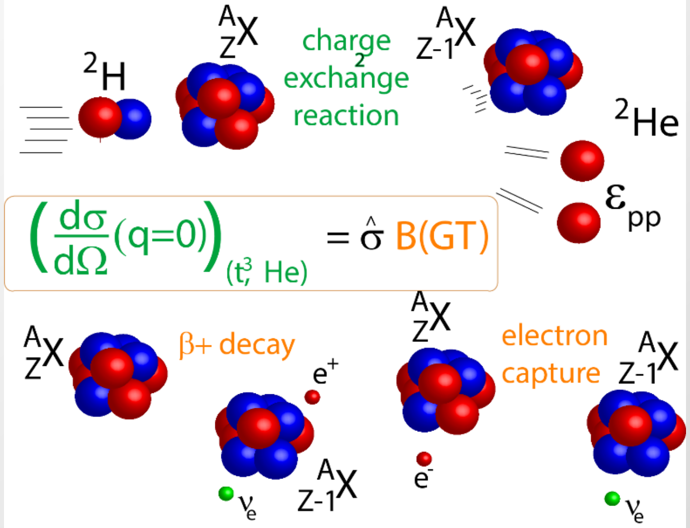
(n,p)
(t,^{3}He)
(d,^{2}He)
HICE

e-capture/β^+

A,Z-1

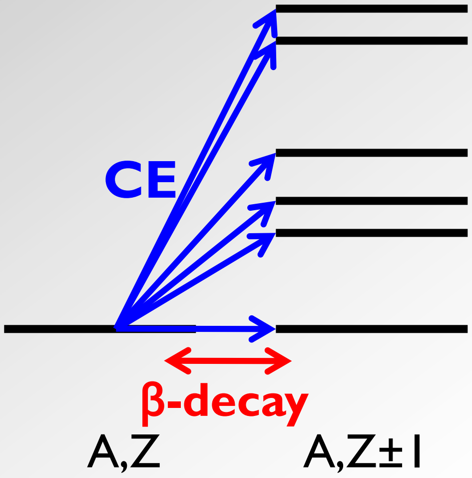


$$\left(\frac{d\sigma}{d\Omega}(q=0)\right)_{(t,^{3}He)} = \hat{\sigma}\,B(GT)$$



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

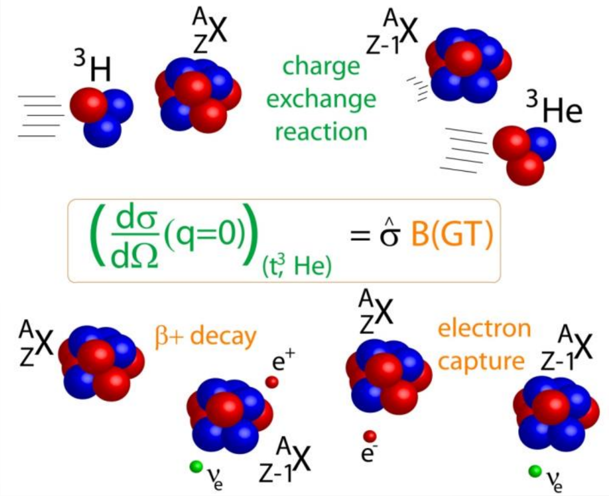
calibrating the proportionality

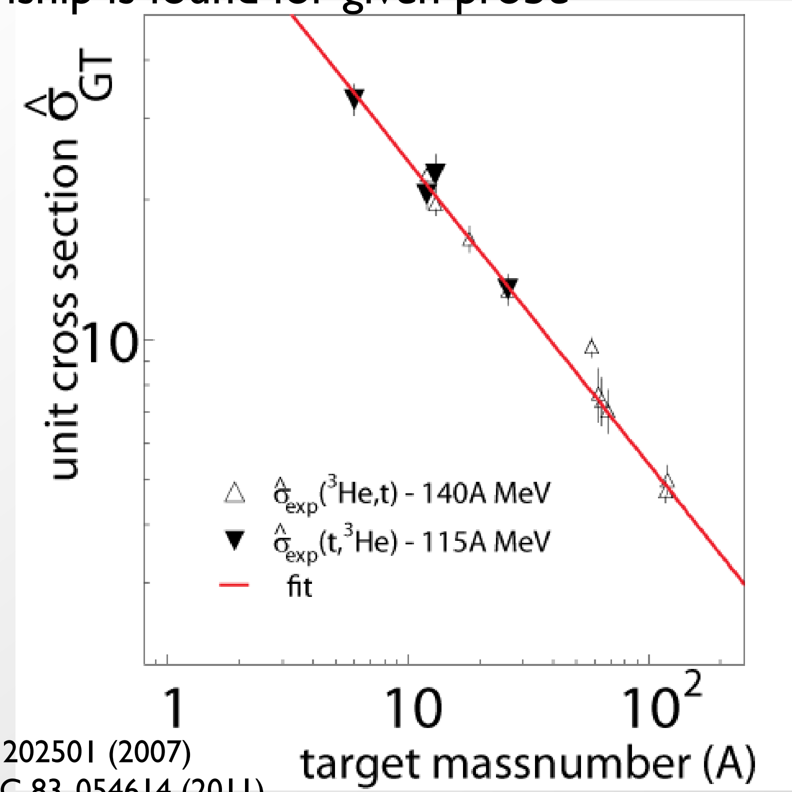


The unit cross section is conveniently calibrated using transitions for which the Gamow-Teller strength is known from β-decay.

The unit cross section depends on beam energy, charge exchange probe and target mass number: empirically, a simple mass-dependent relationship is found for given probe

Once calibrated, Gamow-Teller strengths can be extracted model-independently.



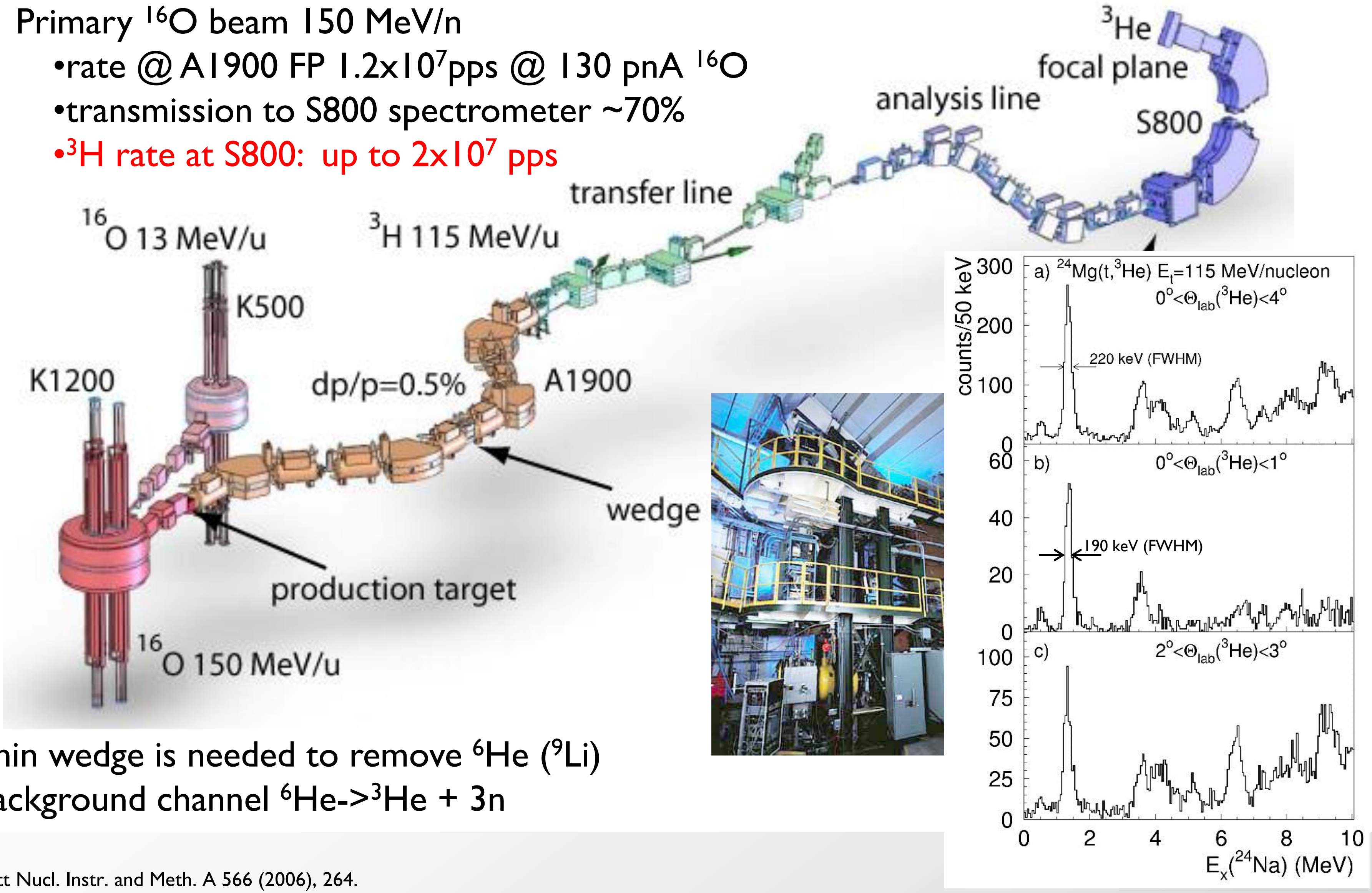


R.Z. et al., Phys. Rev. Lett. 99, 202501 (2007)
G. Perdikakis et al., Phys. Rev. C 83, 054614 (2011)

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

Primary ^{16}O beam 150 MeV/n

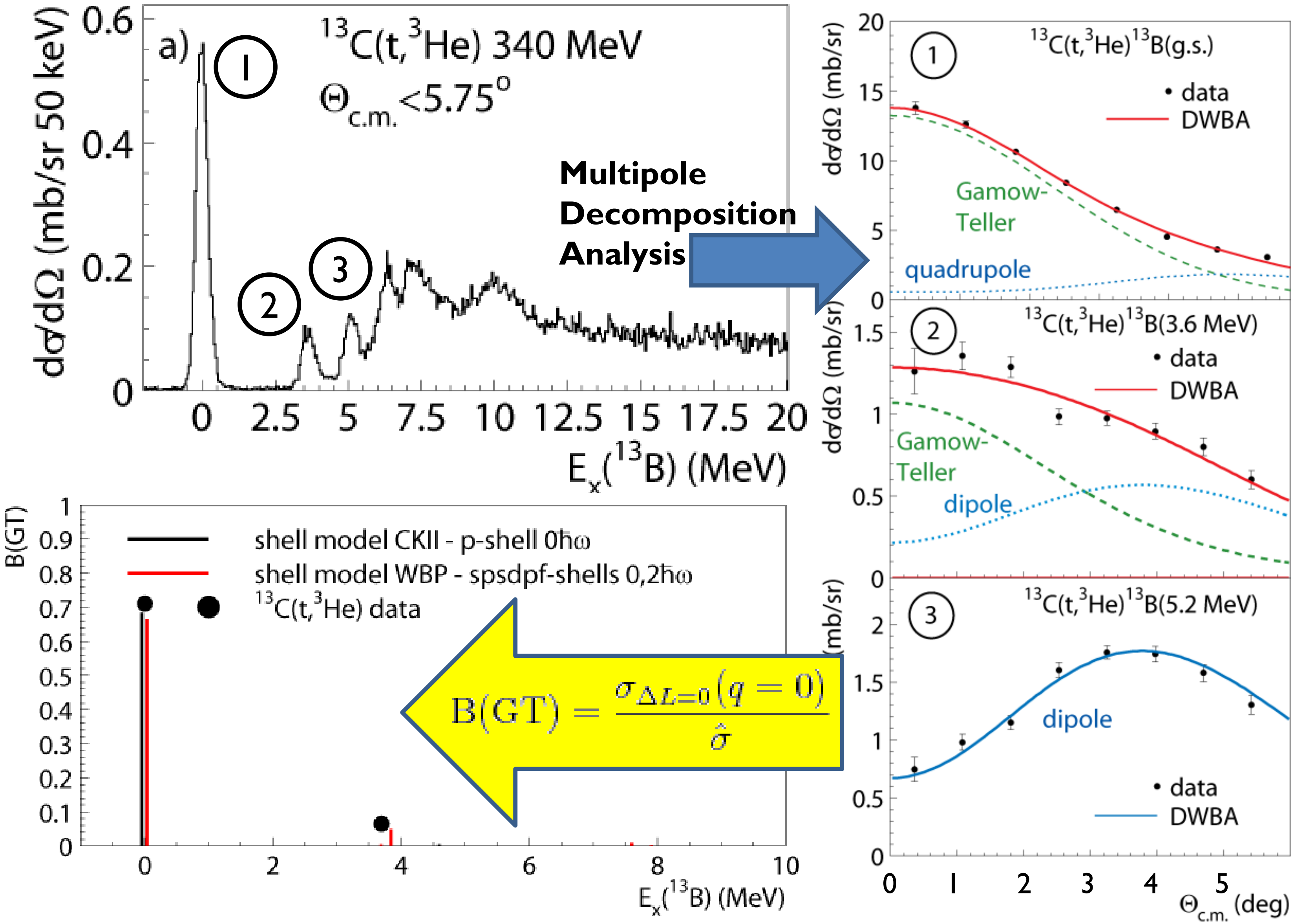
- rate @ A1900 FP 1.2×10^7pps @ 130 pnA ^{16}O
- transmission to S800 spectrometer ~70%
- ^{3}H rate at S800: up to 2×10^7 pps



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



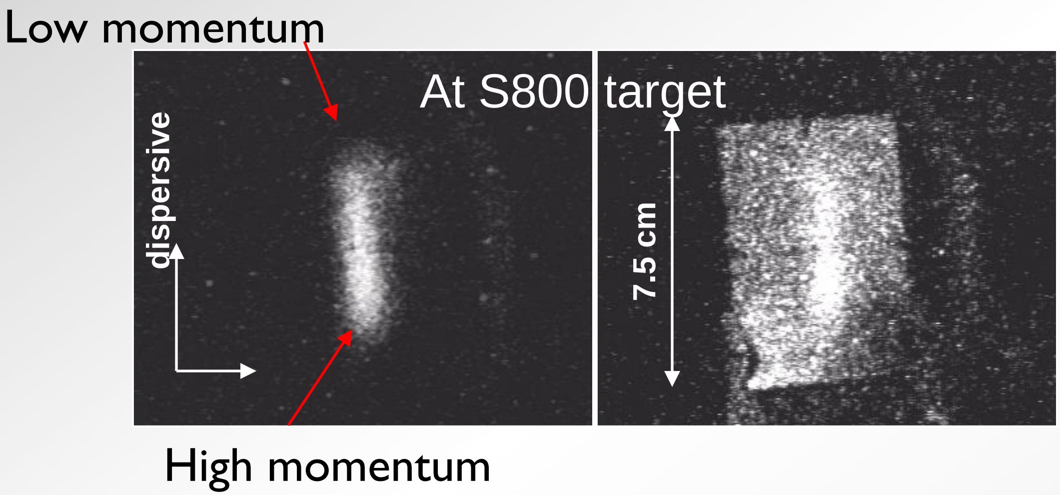
Multipole Decomposition Analysis

$$\mathrm{B(GT)} = \frac{\sigma_{\Delta L=0}(q=0)}{\hat{\sigma}}$$

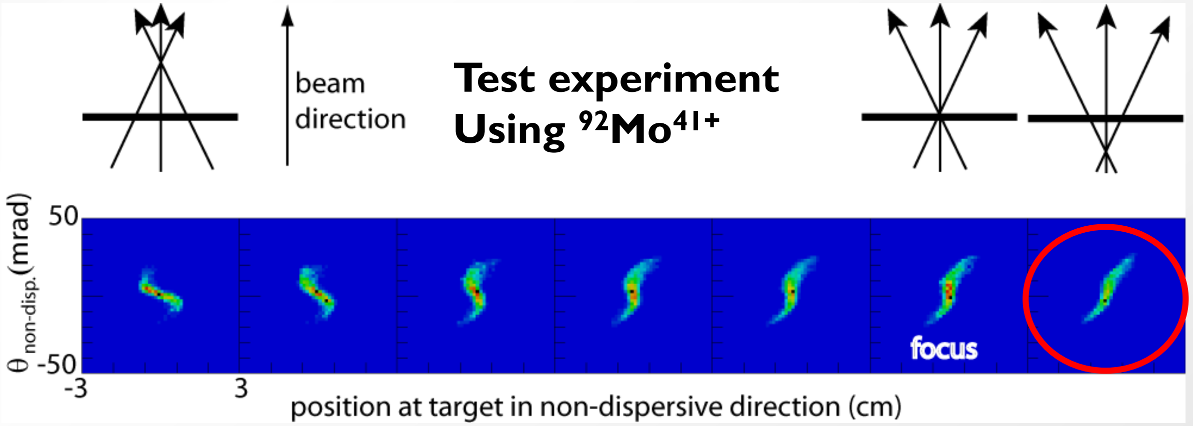
C. Guess et al., Phys. Rev. C 80, 024305 (2009)

(t,^{3}He) at the S800 spectrometer

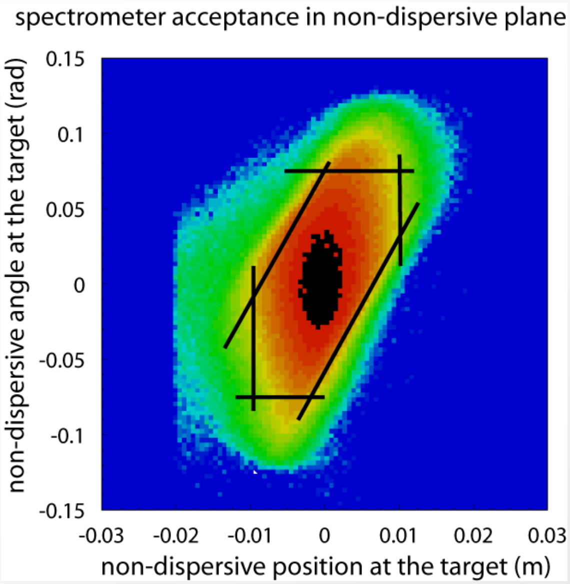
- dispersion matching: ~3 MeV $\Delta E_{triton} \Rightarrow \sigma_E(t,^3He) \sim 250$ keV
- raytracing with 5th order map ~1° angular resolution



Non-dispersive defocusing of the beam to increase angular resolution Improves angular resolution to ~0.5°.



Test experiment
Using $^{92}Mo^{41+}$



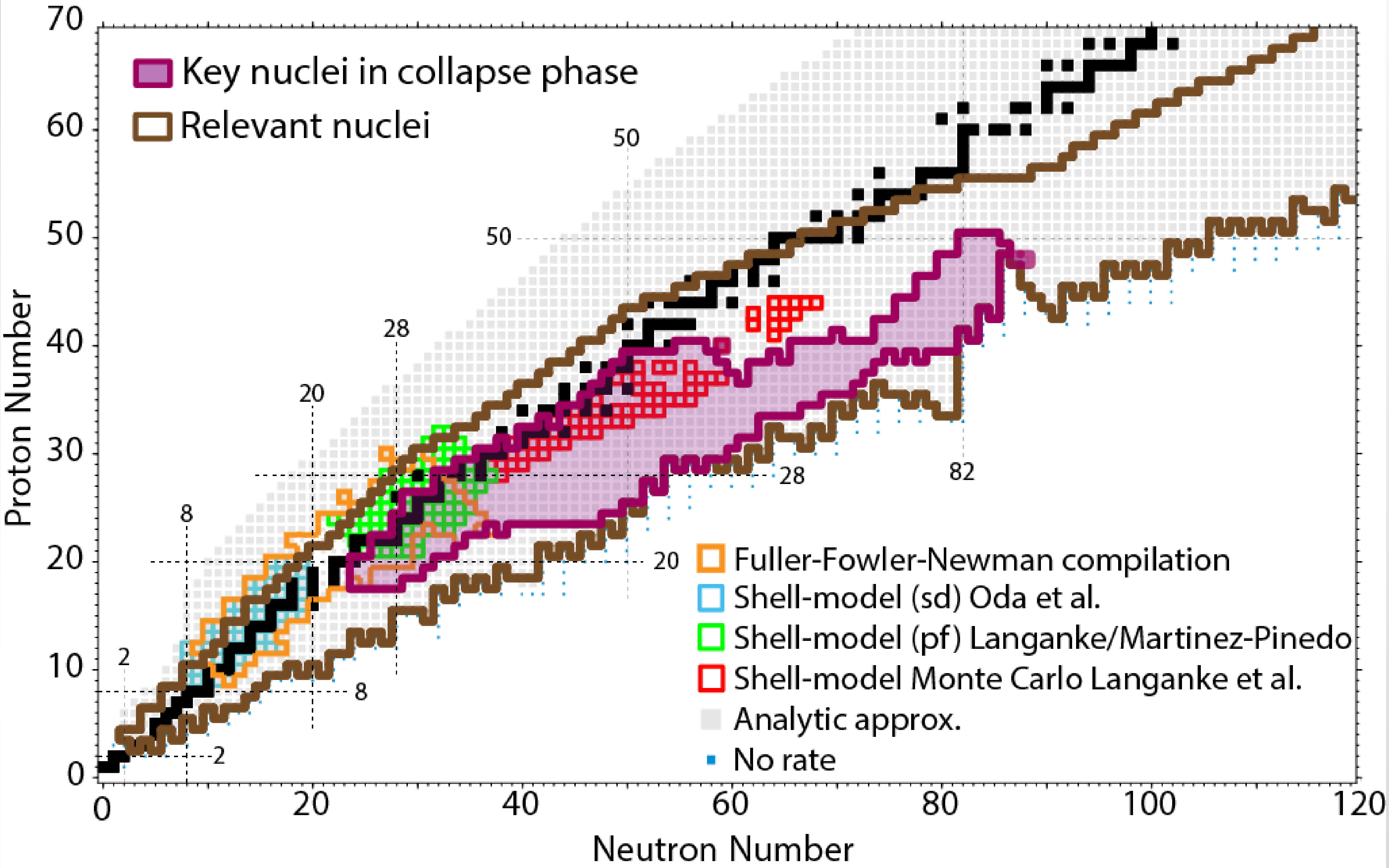
Acceptance is a complex function of:

- $X_{non\text{-}dispersive}$
- $\theta_{non\text{-}dispersive}$
- $X_{focal\ plane}$
- $\theta_{dispersive}$

Monte-Carlo Simulations needed

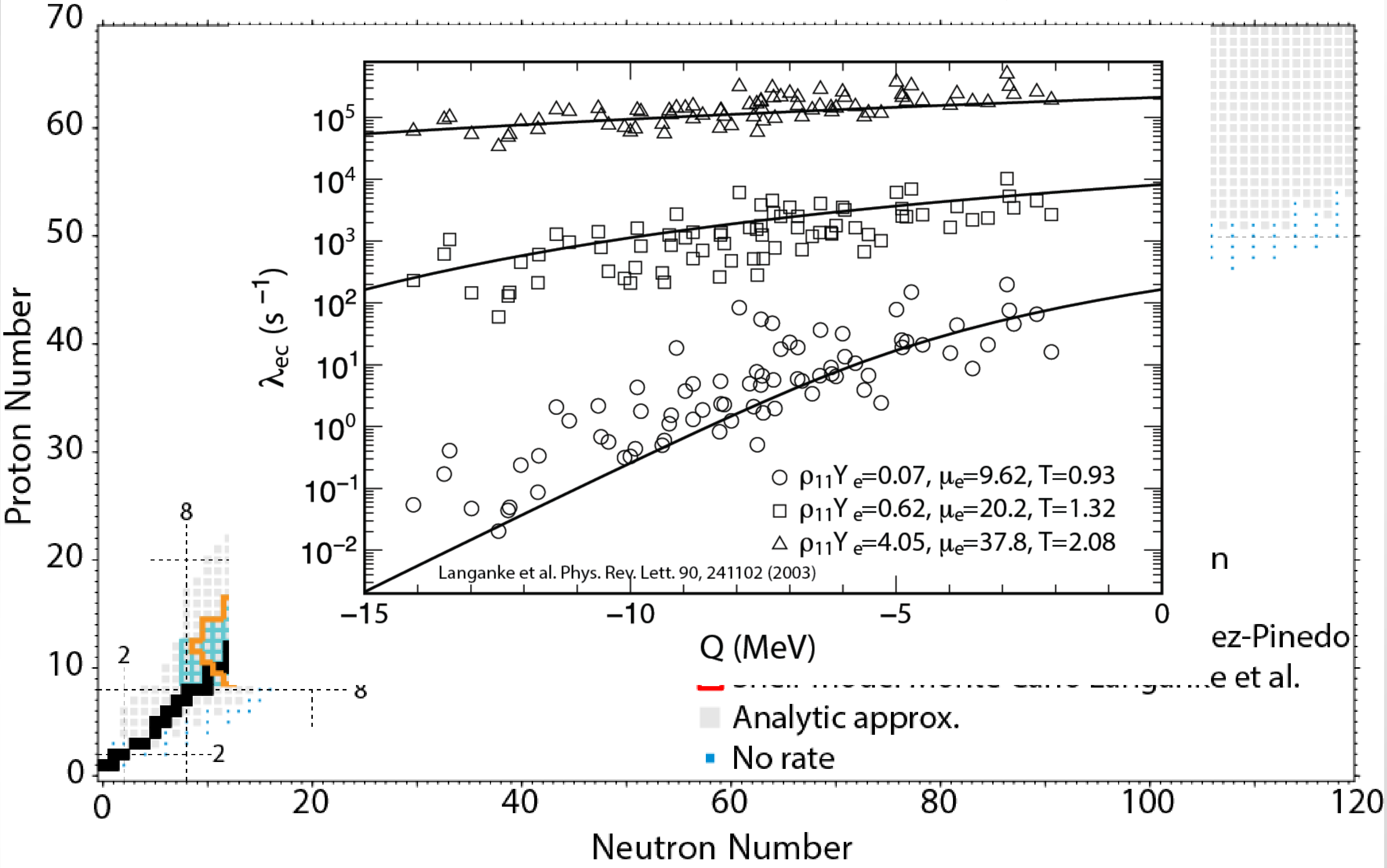
Theoretical weak reaction rates

weak rate library: Sullivan et al. arXiv:1508.07348, Ap. J. to be published

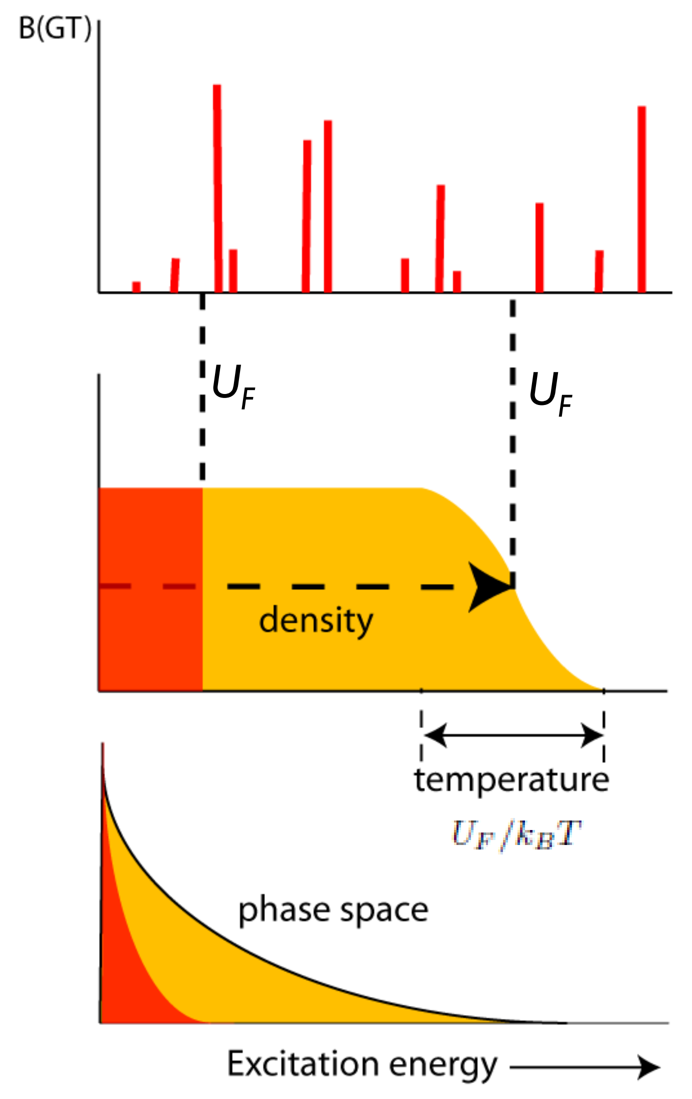


Theoretical weak reaction rates

weak rate library: Sullivan et al. arXiv:1508.07348, Ap. J. to be published


Langanke et al. Phys. Rev. Lett. 90, 241102 (2003)

Excitation energy and resolution



At different astrophysical densities and temperatures, different ranges in excitation energy contribute to the weak reaction rates

Fermi energy:

$$U_F(T=0) = 0.511\left[\left(1.018(\rho_6 Y_e)^{\frac{2}{3}}+1\right)-1\right]$$

Degeneracy:

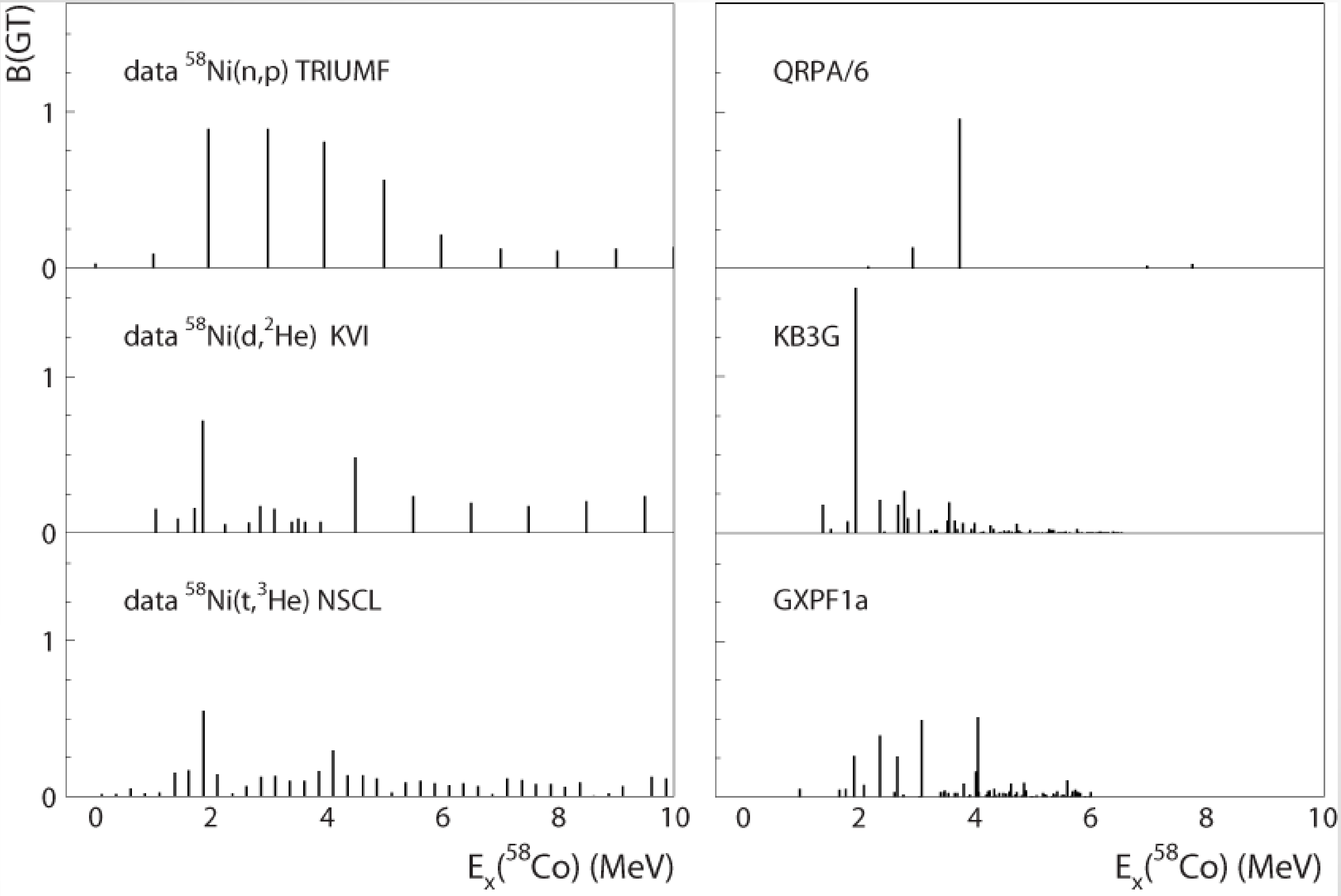
$$U_F/k_BT$$

Low density: e-captures on low-lying states
High density: e-captures up to high E_x

Low temperature: Fermi surface cut off sharply
High temperature: Fermi surface smeared out

At low densities/temperature, accurate knowledge of low-lying states is critical, even if transitions are week

Benchmarking the library & guiding the theory

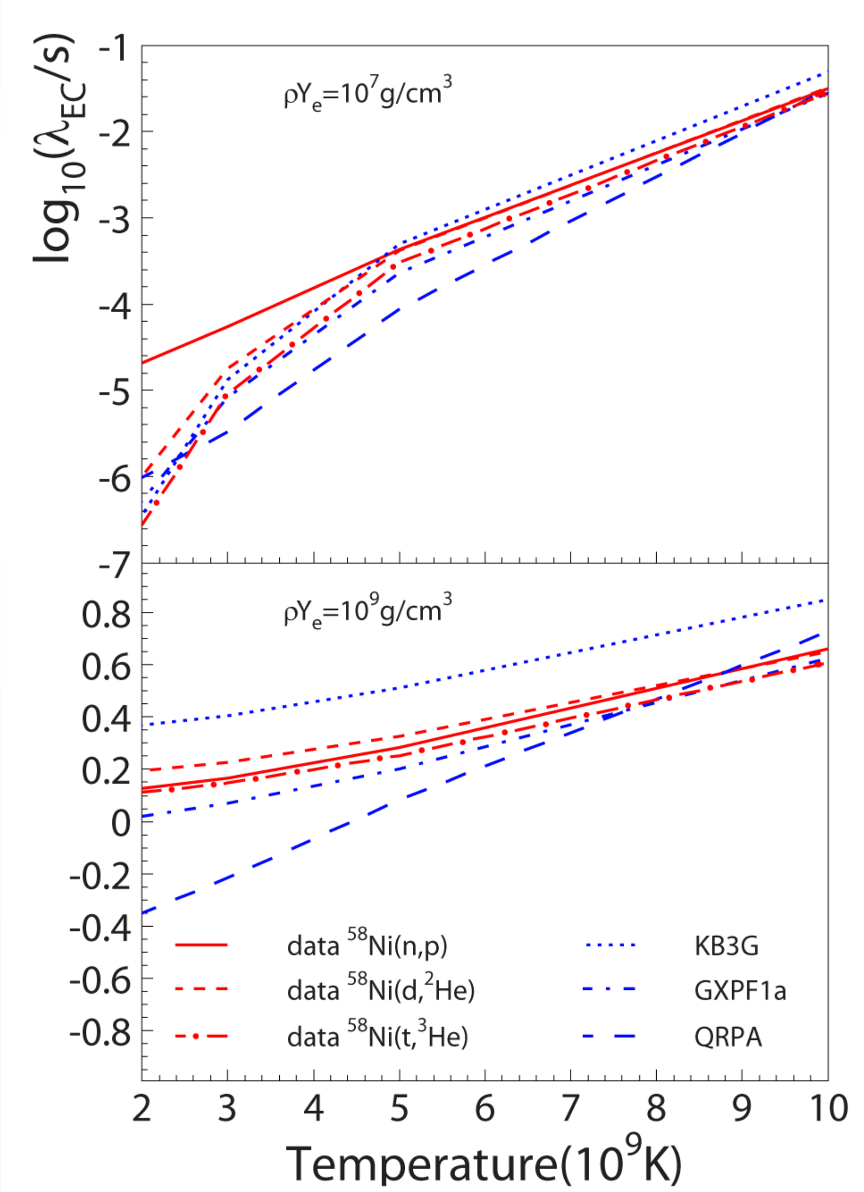


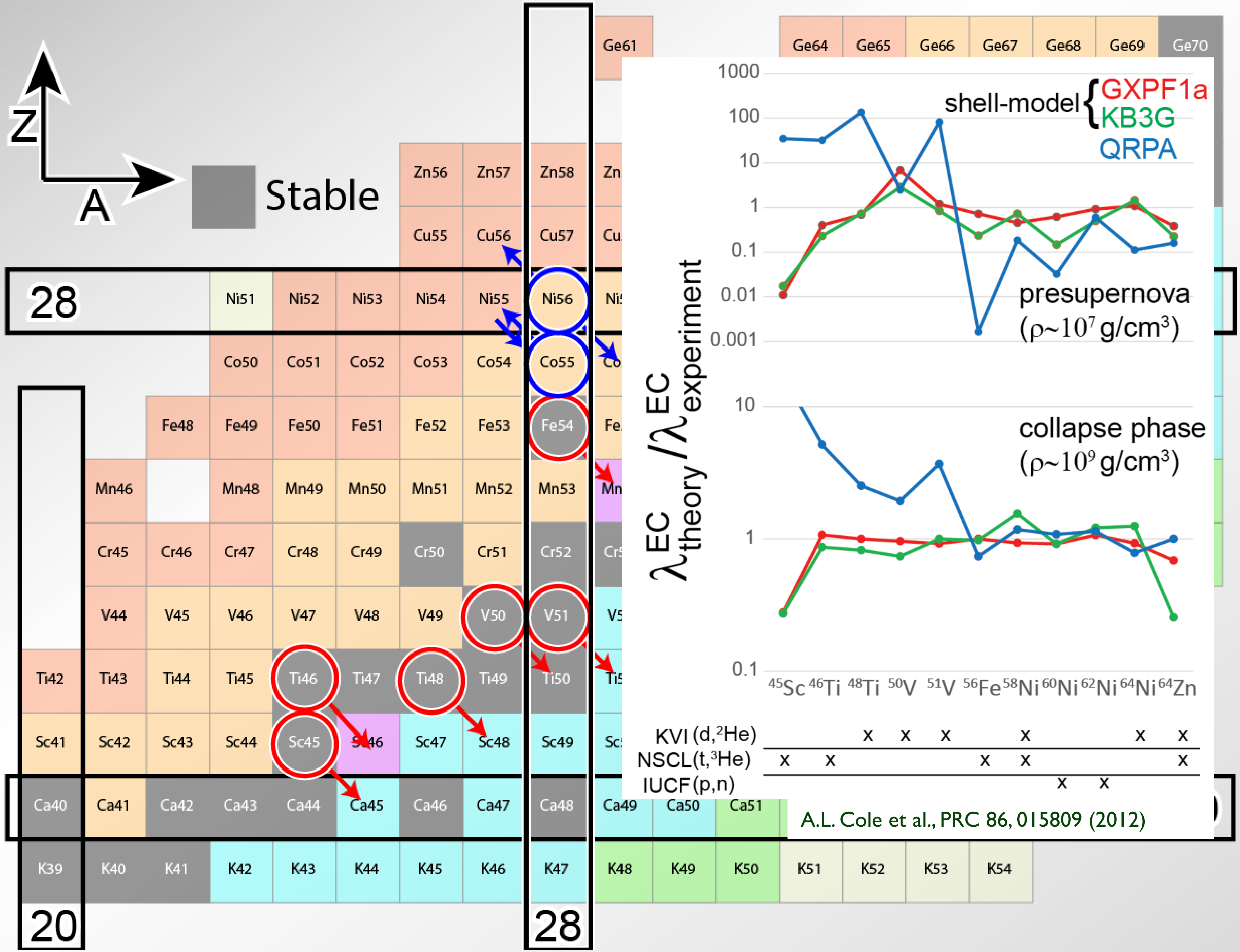
Electron-capture rates

Phase-space

$$\lambda = \sum_i \sum_f \ln 2 \frac{f_{ij}(T,\rho)}{ft_{ij}}$$

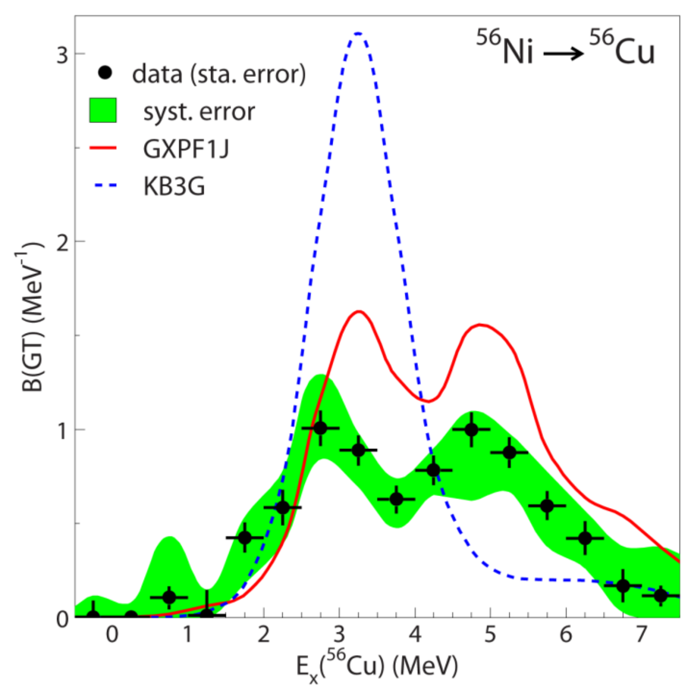
Transition strength





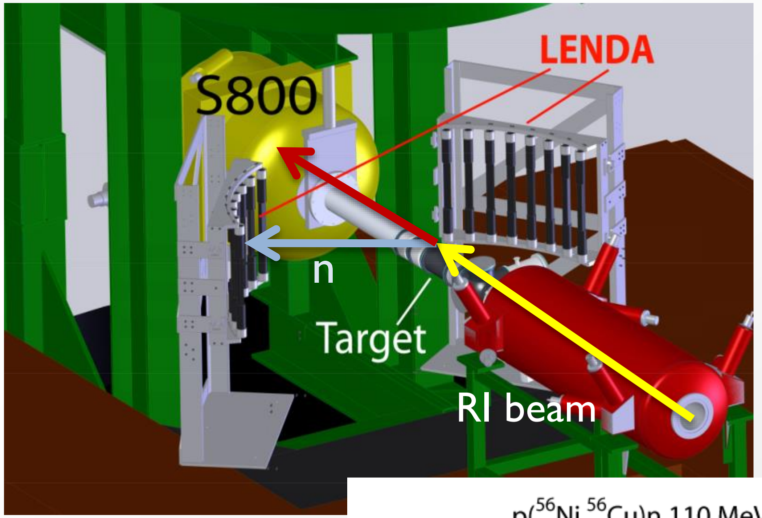
A.L. Cole et al., PRC 86, 015809 (2012)

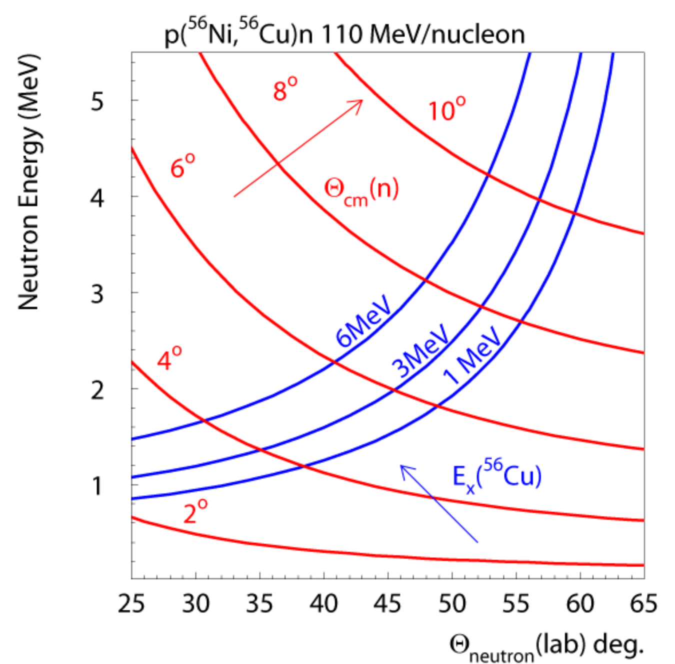
^{56}Ni-understanding the model differences development of (p,n) in inverse kinematics



See talk by M. Sasano

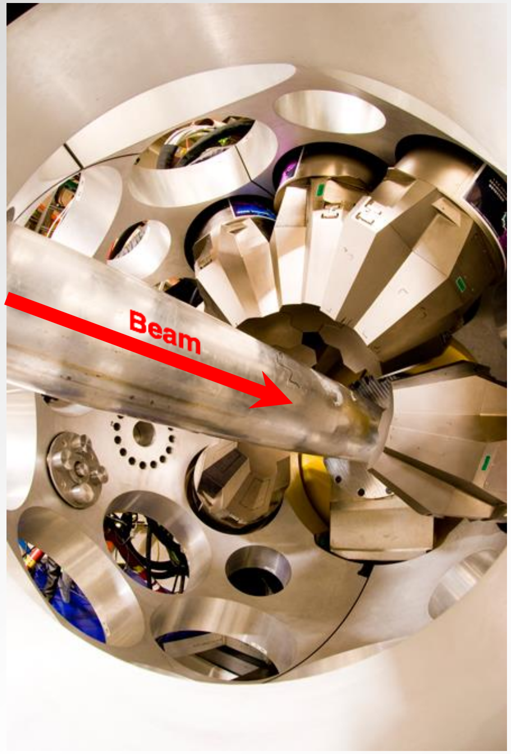
S800 spectrometer
Low-Energy Neutron Detector
LH$_2$ target



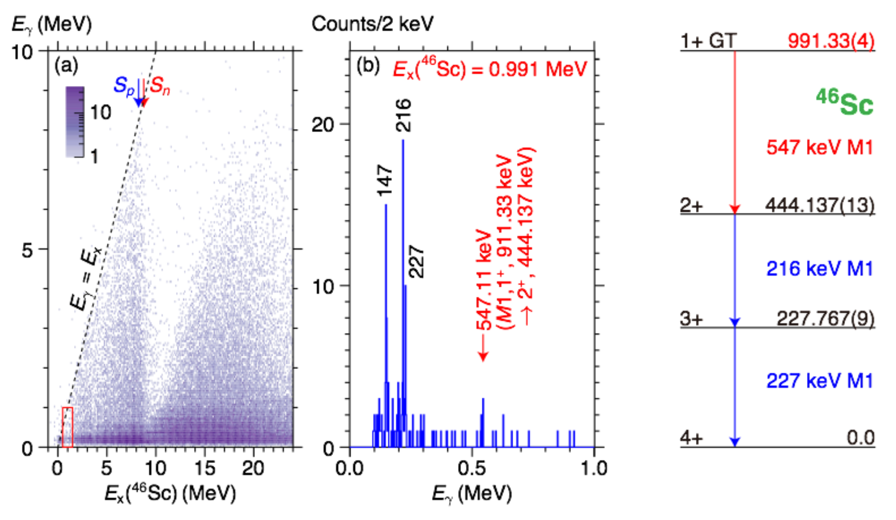


Searches for very weak transitions

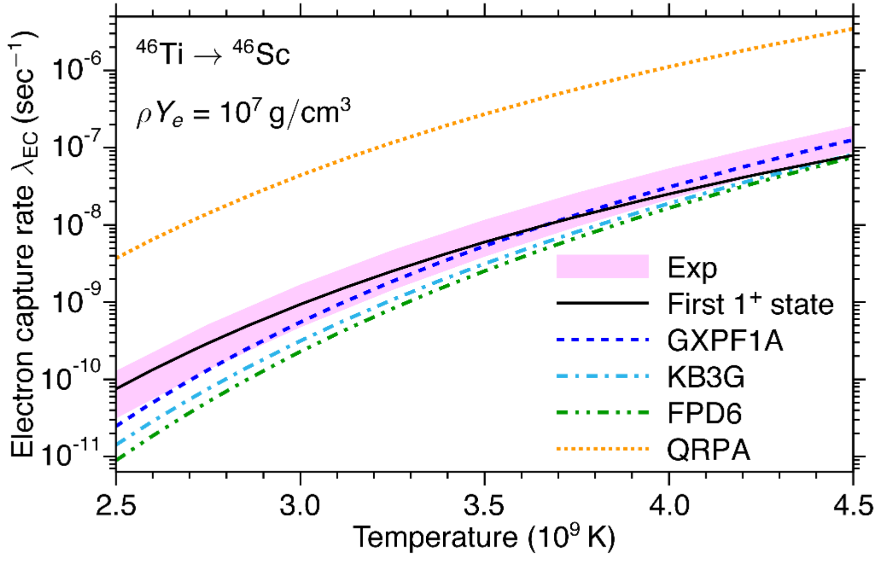
Development of (t,^{3}He+γ) reaction using S800+GRETINA



See talk by S. Noji



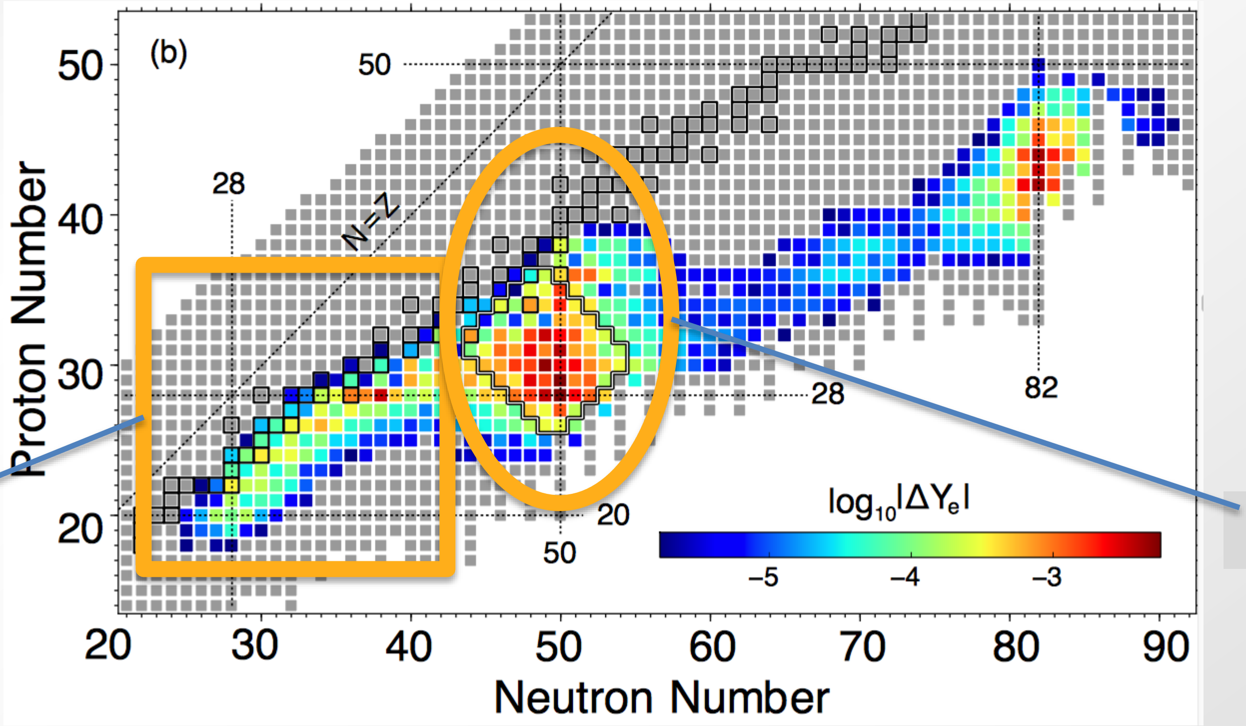
For ^{46}Ti: $B(GT)_{0.991} = 0.009 \pm 0.005(\mathrm{exp}) \pm 0.003\ (\mathrm{sys})$



EC Sensitivity studies – core-collapse supernovae

C. Sullivan et al., arxiv:1508.07348 – Ap. J.

- NSCL created weak rate library (as part of NuLIB) for astrophysical simulations - Collaboration between NSCL charge-exchange group and E. O'Connor (NCSU)
- Library allows for electron-capture sensitivity studies: first applied for core-collapse supernovae using the GR1D code – further uses in simulations of thermonuclear supernovae and neutron-star crusts foreseen
- Work on β^- rates and ν-scattering rates should be included

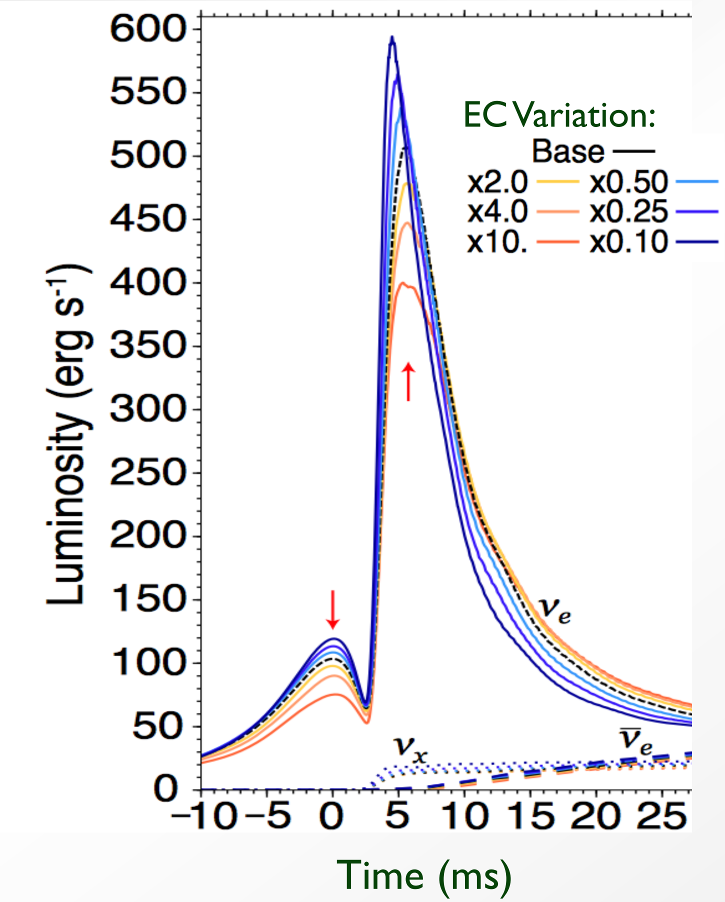


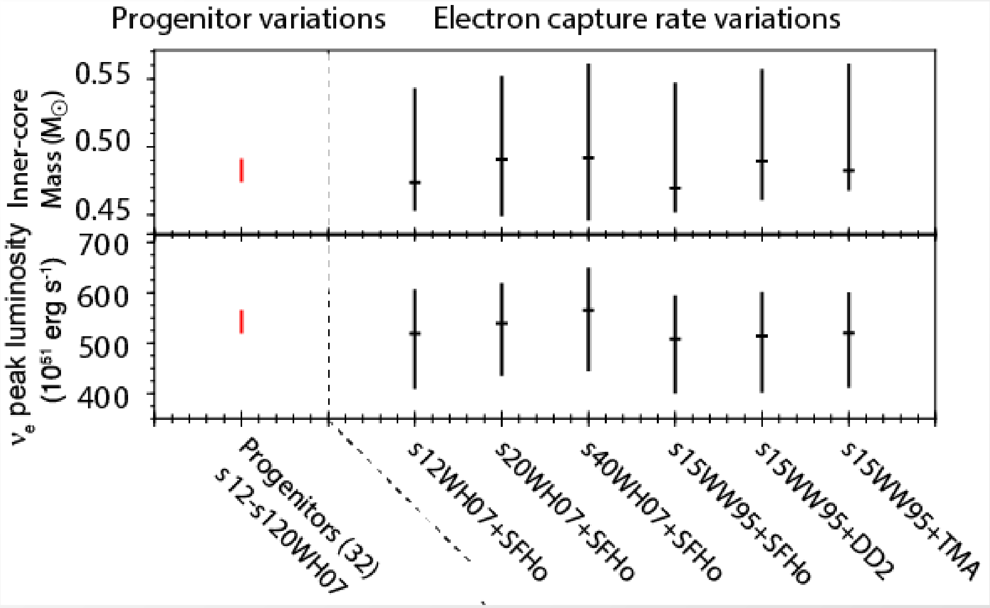
Past focus

Future Thrust

GR1D simulations of core-collapse supernovae

GR1D simulations and sensitivity studies: uncertainties in EC rates have 20% effects on key properties of core-collapse supernovae

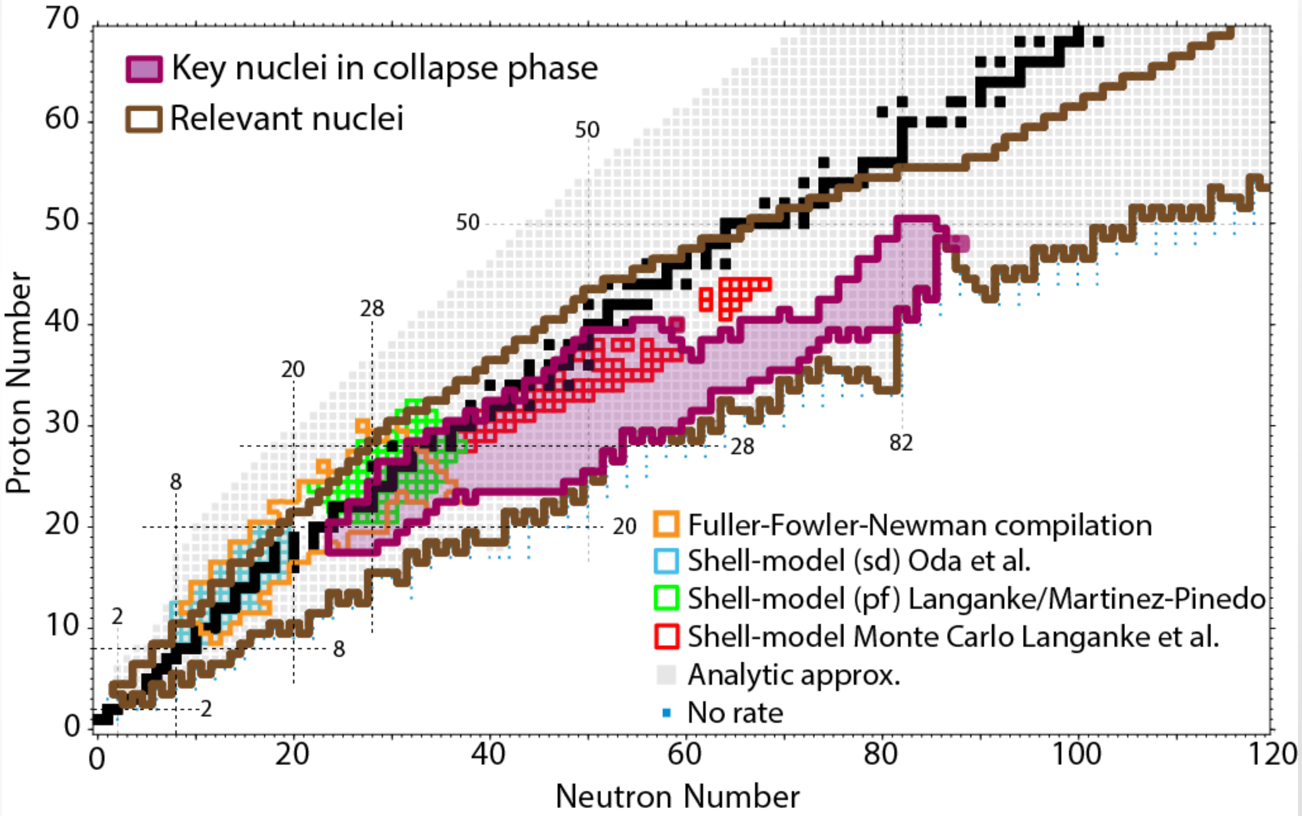




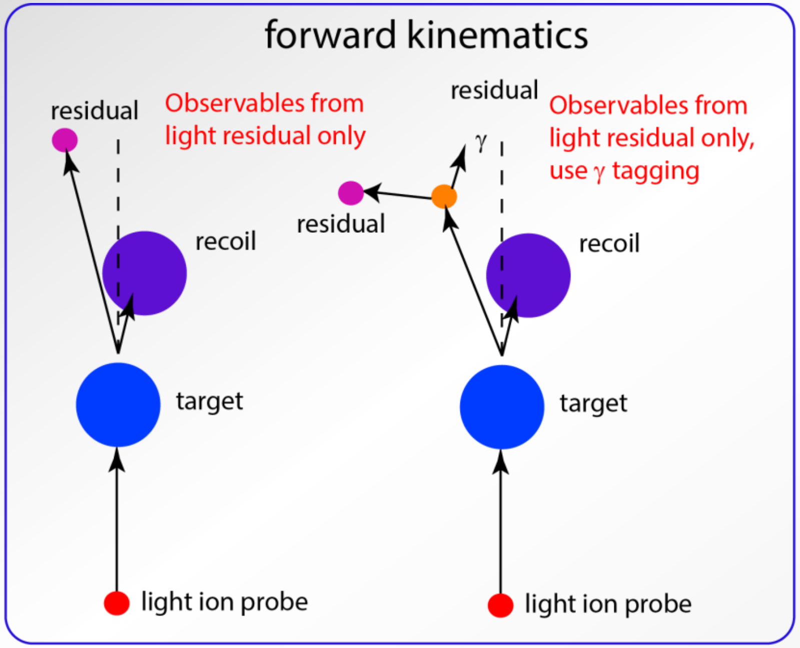
Theoretical weak reaction rates

weak rate library: Sullivan et al. arXiv:1508.07348, Ap. J. to be published

- Additional studies will be pursued
  - 2D simulations of CCSN using GR1D output as input to FLASH
  - Thermonuclear supernovae
- Additional input to library sought - also need constraints on β^- strengths



(p,n) (n,p)
(d,^{2}He)
(^{3}He,t) (t,^{3}He)
HICEX
π-CEX

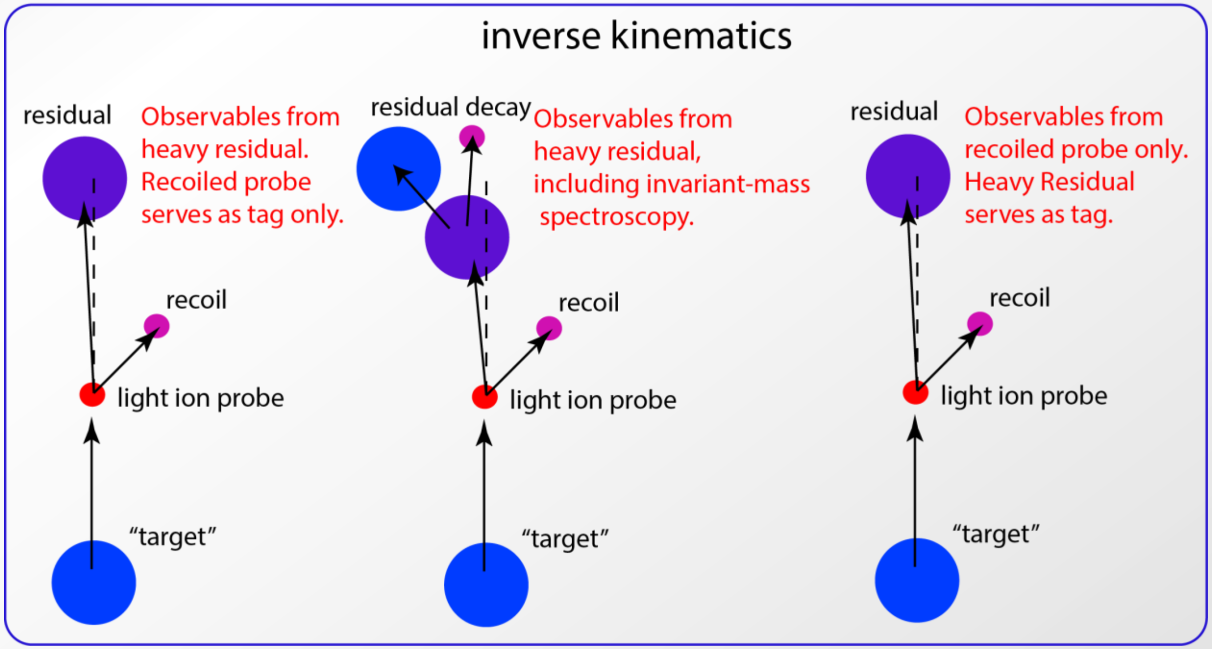


Observables from light residual only

Observables from light residual only, use γ tagging

(^{7}Li,^{7}Be+γ)
(^{10}C,^{10}B+γ)
(^{10}Be,^{10}B+γ)
(^{12}N,^{12}C+γ)
etc…

(^{7}Li,^{7}Be+γ): Successfully applied for light ions, will require invariant mass spectroscopy for heavy ions



Observables from heavy residual. Recoiled probe serves as tag only.

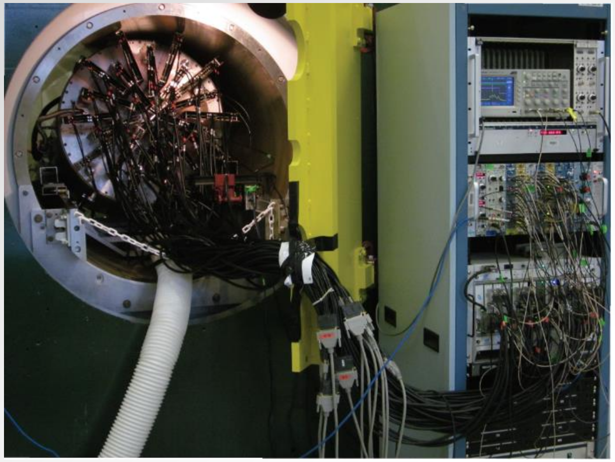
Observables from heavy residual, including invariant-mass spectroscopy.

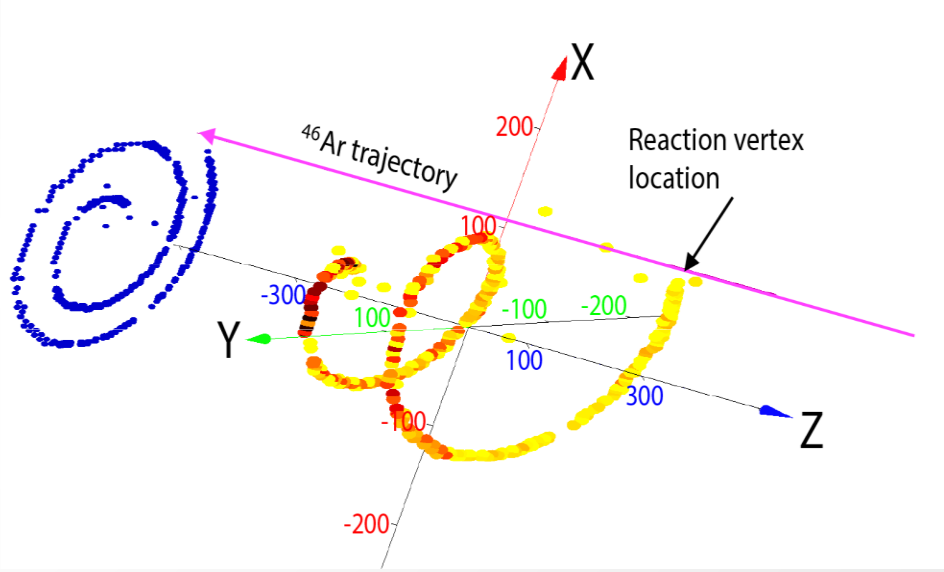
Observables from recoiled probe only. Heavy Residual serves as tag.

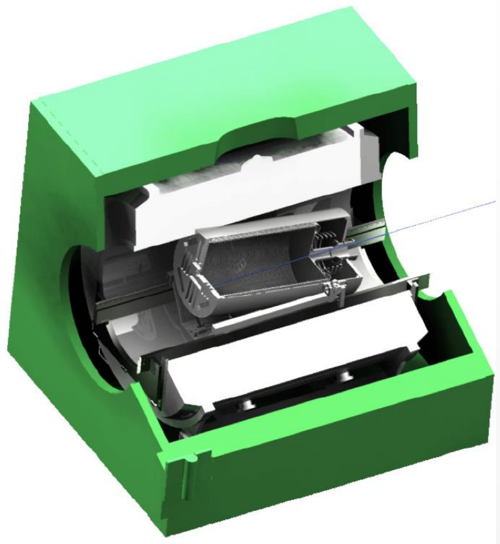
(p,n) – OK!
(d,^{2}He)?

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

Use Active Target Time Projection Chamber at S800

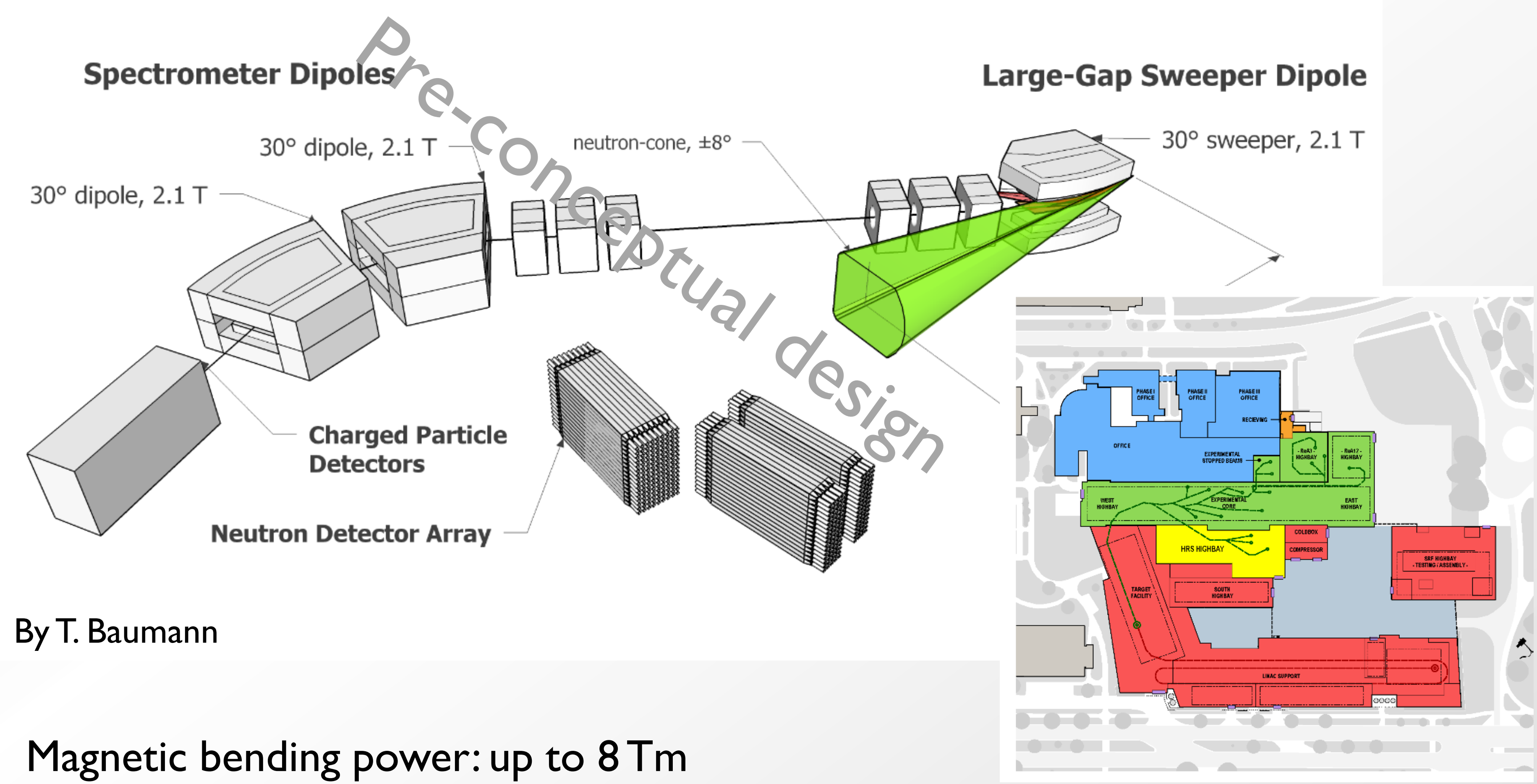






From recent ^{46}Ar+p resonant scattering experiment AT-TPC was used reaccelerated beam of ^{46}Ar isotopes

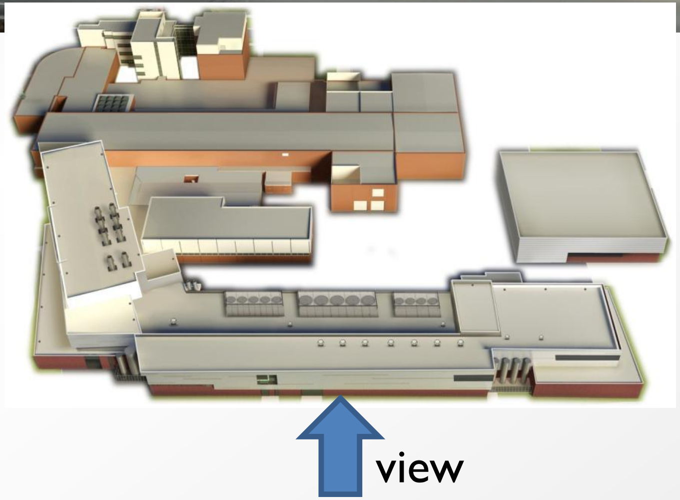
A High-Rigidity Spectrometer for FRIB



By T. Baumann

Magnetic bending power: up to 8 Tm
Large momentum (10% dp/p) and angular acceptances (80x80 mrad)
Particle identification capabilities extending to heavy masses (~200)
Momentum resolution 1 in 5000; intermediate image after sweeper
Invariant mass spectroscopy: ±6° opening in sweeper dipole for neutrons

Facility for Rare Isotope Beams (FRIB)



October 2015