Improving neutron capture rate predictions using Apollo + HELIOS

Experiment development :

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Nuclear reaction model and mass:

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Supernova modeling :

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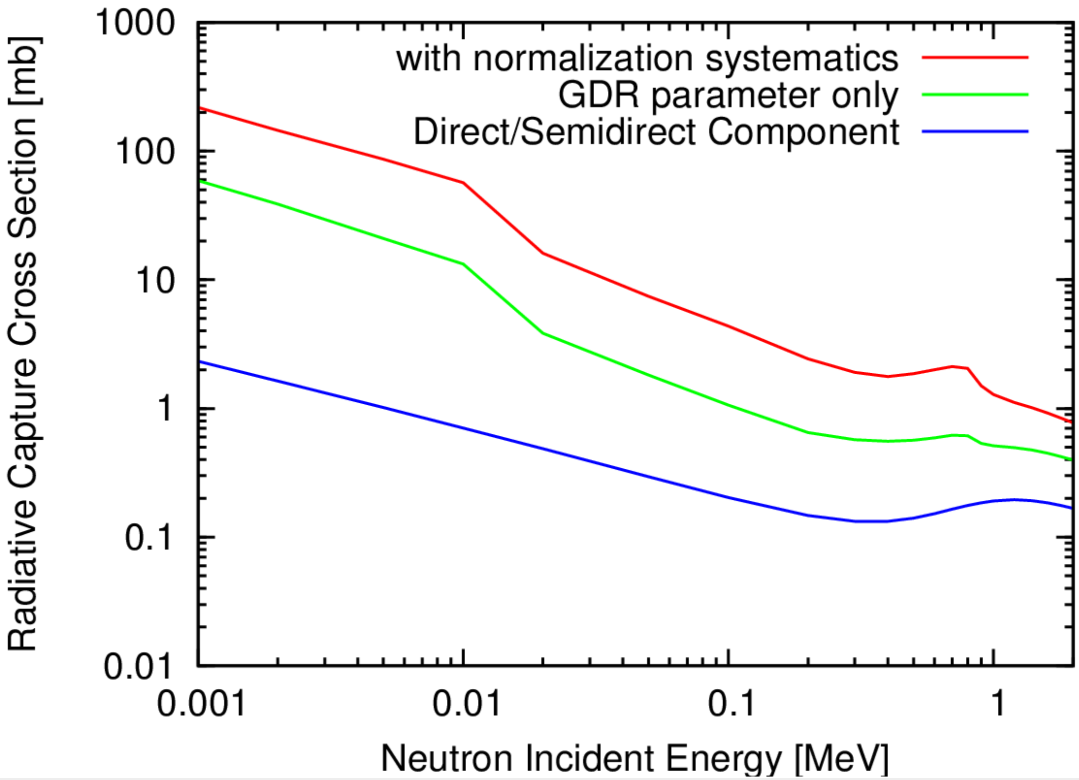
Neutron Capture Challenges for the *r* Process

- There is not an accepted model or site for the *r* process
  - ❖ Which nuclei are involved?
- Regardless of the model, several 1000 reaction rates are needed
  - ❖ While experiment can guide the rates, they cannot all be measured
- Reaction rates far from stability are needed
  - ❖ Depending on the model, nuclei 5-20 neutrons from stability will play a role
- Neutron energies of interest remain below 500 keV
- The Good News: moderate precision required
  - ❖ 20-50% would be great

Underlying global nuclear properties off stability are poorly known

$^{142}Cs(n,\gamma)^{143}Cs$



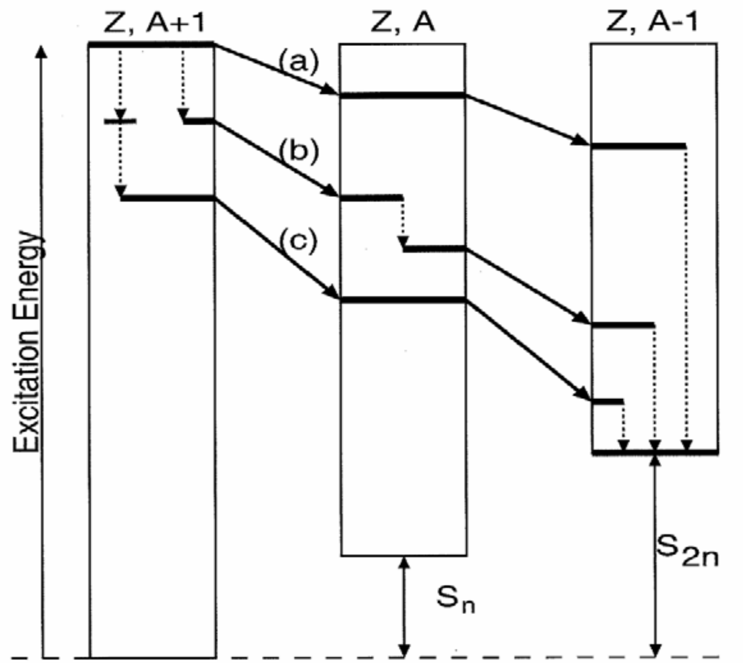
Calculated cross sections using a Hauser – Feshbach code (CoH, Kawano) demonstrate the strong dependence on the nuclear inputs

Prediction of (n,γ) cross sections using Monte Carlo Method

- To predict unknown nuclear reaction cross sections in continuum, the Monte Carlo method using statistical Hauser-Feshbach formalism has been developed by LANL theory group. (Kawano et al.)
- Direct Capture calculations for radiative cross sections are implemented using the Skyrme-Hartree-Fock-BCS approach for bound state wave functions (Bonneau et al. 2007).
- Simulate the emission processes by the MC method and record all the history of emitted particles and gamma rays, so that not only the cross sections are obtained but also the intermediate steps can be reconstructed.

This method allows to compare the experimental outputs directly with theoretical predictions, so will improve the predictive capability for the region where we still have to extrapolate.

Monte Carlo Method in Statistical Hauser-Feshbach formalism



(Kawano et al. J. Nucl. Sci. Technol. 2006)

Possible exit channels after forming a compound nucleus

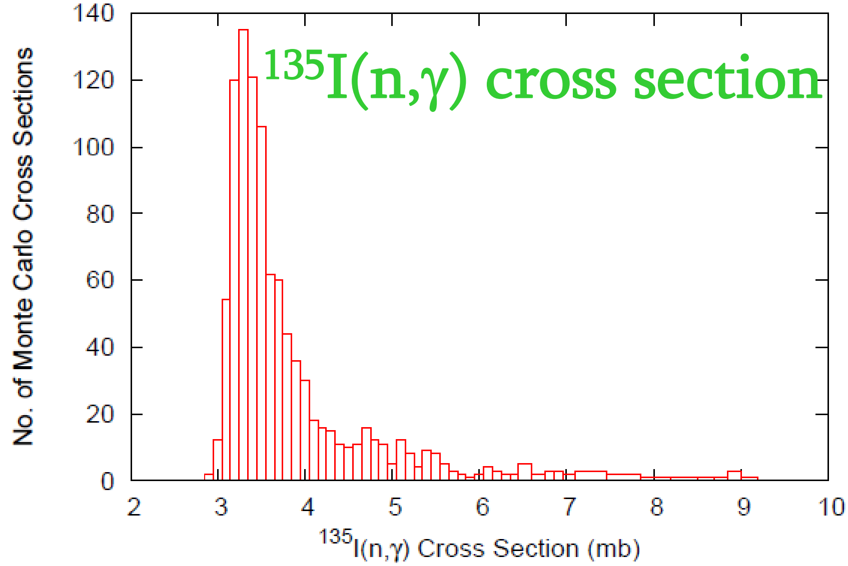
→ (a) n,n,γ
(b) γ,n,γ,n,γ
(c) γ,γ,n,n,γ
…

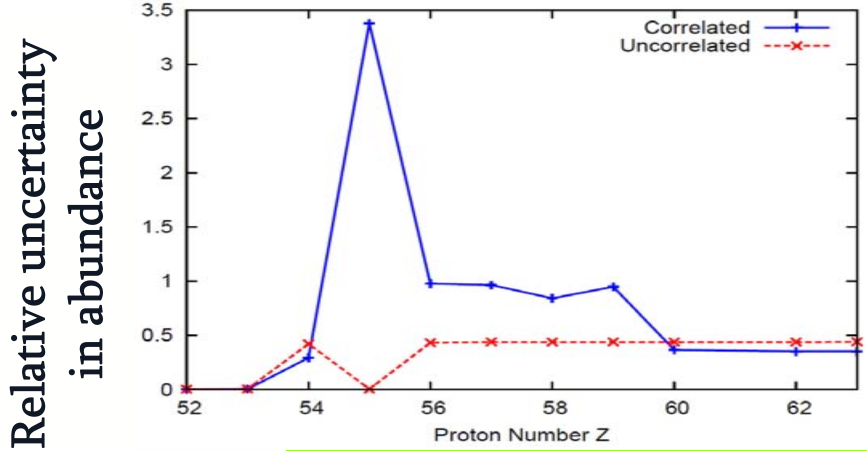
Probability is estimated using HF formalism using :
-Optical Model potential for charged-particles and neutrons
-level density parameters
-γ-ray strength function
-discrete level properties for all residual nuclei

Detailed comparisons (*e.g.* average γ-ray multiplicity, cascade) will help to predict the photon strength functions.

Implement realistic rate uncertainties in nuclear network

- Bertolli and Kawano have developed Monte Carlo technique for predicting realistic nuclear uncertainties for reaction rates based on existing data
- Correlated sensitivity studies for neutron capture in astrophysical environment
- These uncertainties have been folded into the nucleosynthesis code (NuGid), propagating the effects all the way through to yields for r-process nucleosynthesis





Courtesy M. Bertolli

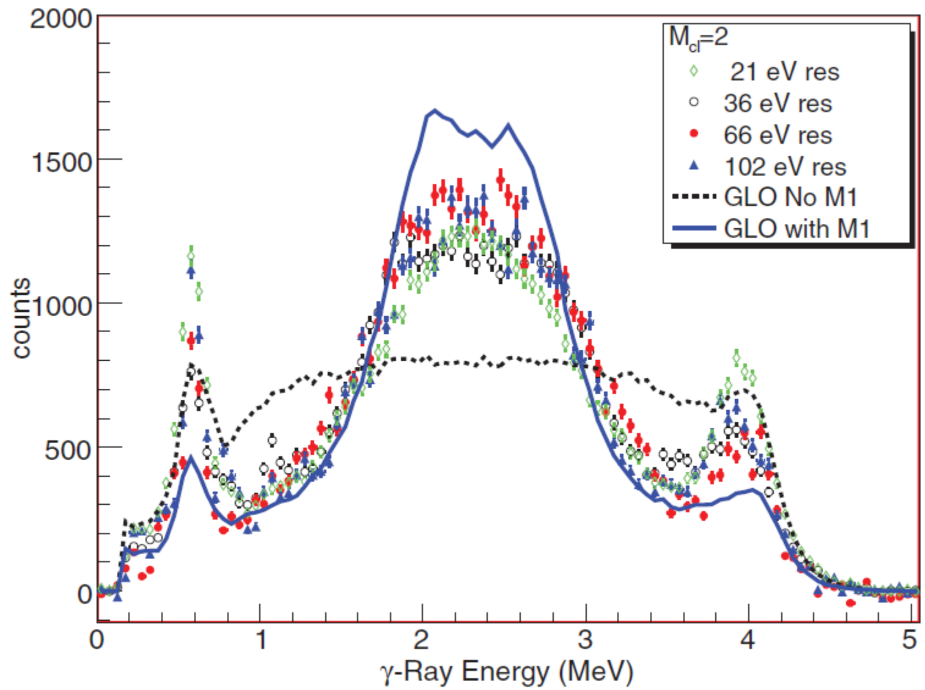
How to tie this γ-ray data with Monte-Carlo Hauser-Feshbach calculation?

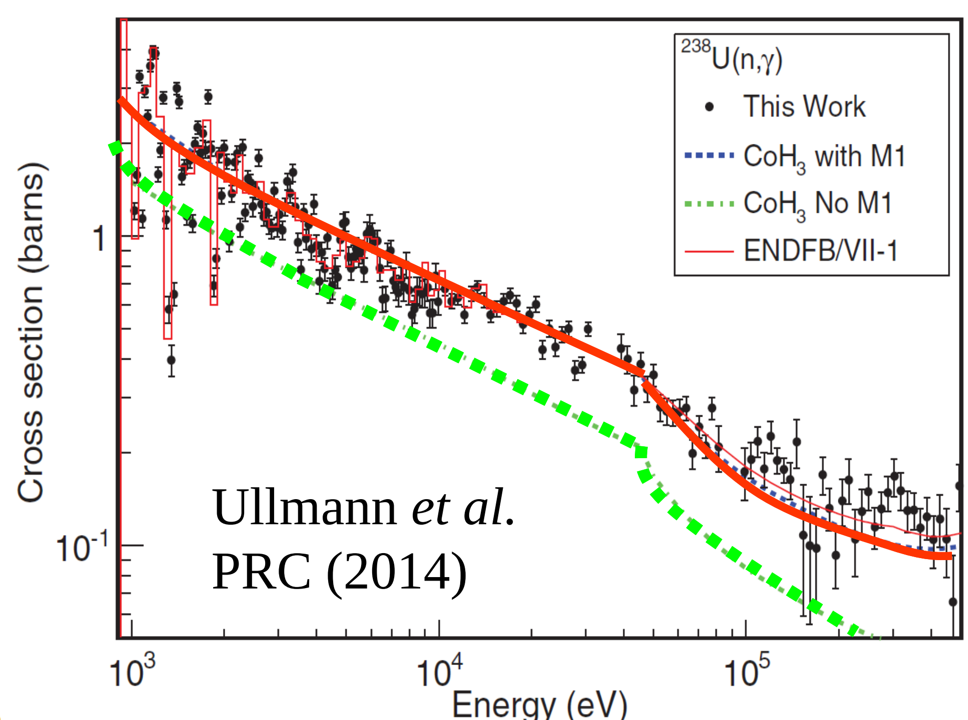
Nuclear properties are deduced using Monte-Carlo Hauser-Feshbach code (MCHF) with DANCE ^{238}U(n,γ) data at LANSCE

2-step γ-ray cascade shows better fit with M1 strength

Better nuclear input feeds

Calculated MCHF cross section is improved





Apollo + HELIOS on unstable beams

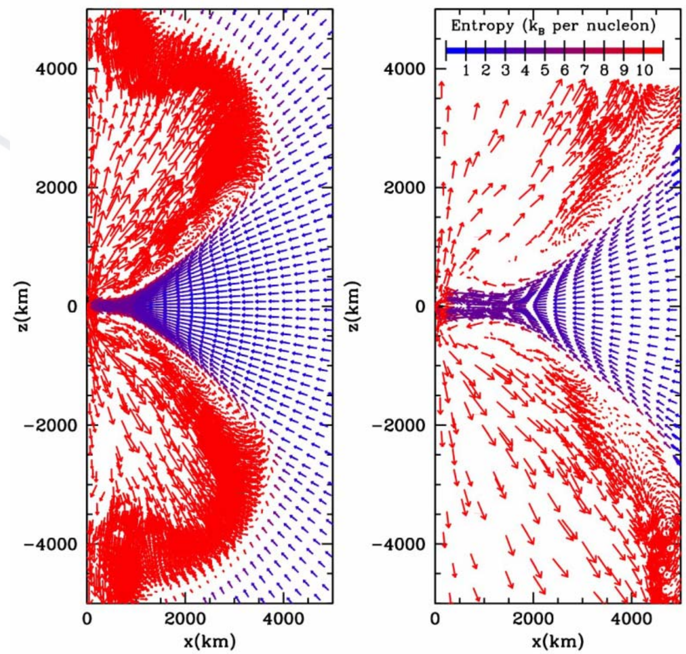
- Use Apollo + HELIOS to improve nuclear input parameters
- Use (d,p) reactions on CARIBU beams for measuring γ-ray cascades, multiplicities, etc.
- Compare the observables with GEANT + HFMC
- Deduce photon strength functions
- Feed these new nuclear inputs to calculate reaction rates

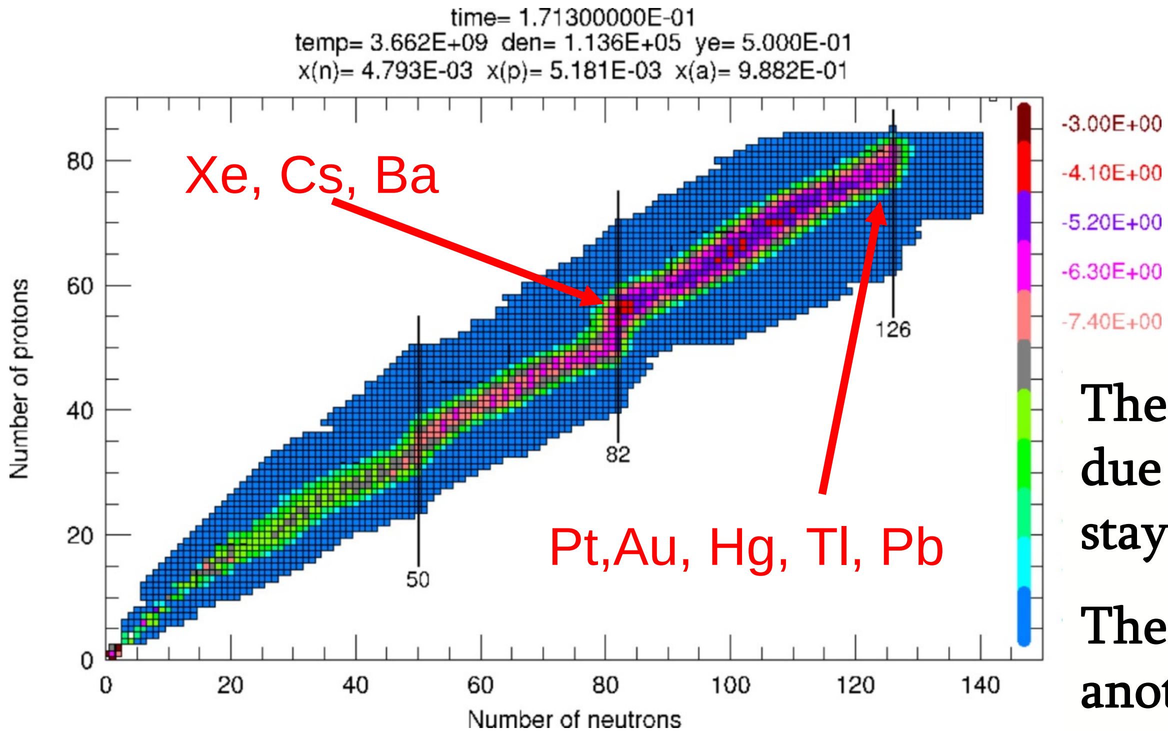
Facility upgrades & experimental instrumentation at ATLAS

1. Intensity & purity improvement from CARIBU beams
2. Flexible recoil detection with HELIOS

Supernova hydrodynamics and nucleosynthesis

2D Hydro Simulation of Supernova Fallback model shows the data need for Xe, Cs, Ba, Pt, Au, etc.





The first bottleneck is at N=82, but due to the proton abundance, it stays near stable isotopes.

The second bottleneck at N=126 is another place to explore!

Fryer, Herwig, Hungerford, and Timmes, *Ap. J.* (2006)

Courtesy A. Couture