

Experimental Initiatives in Nuclear Astrophysics

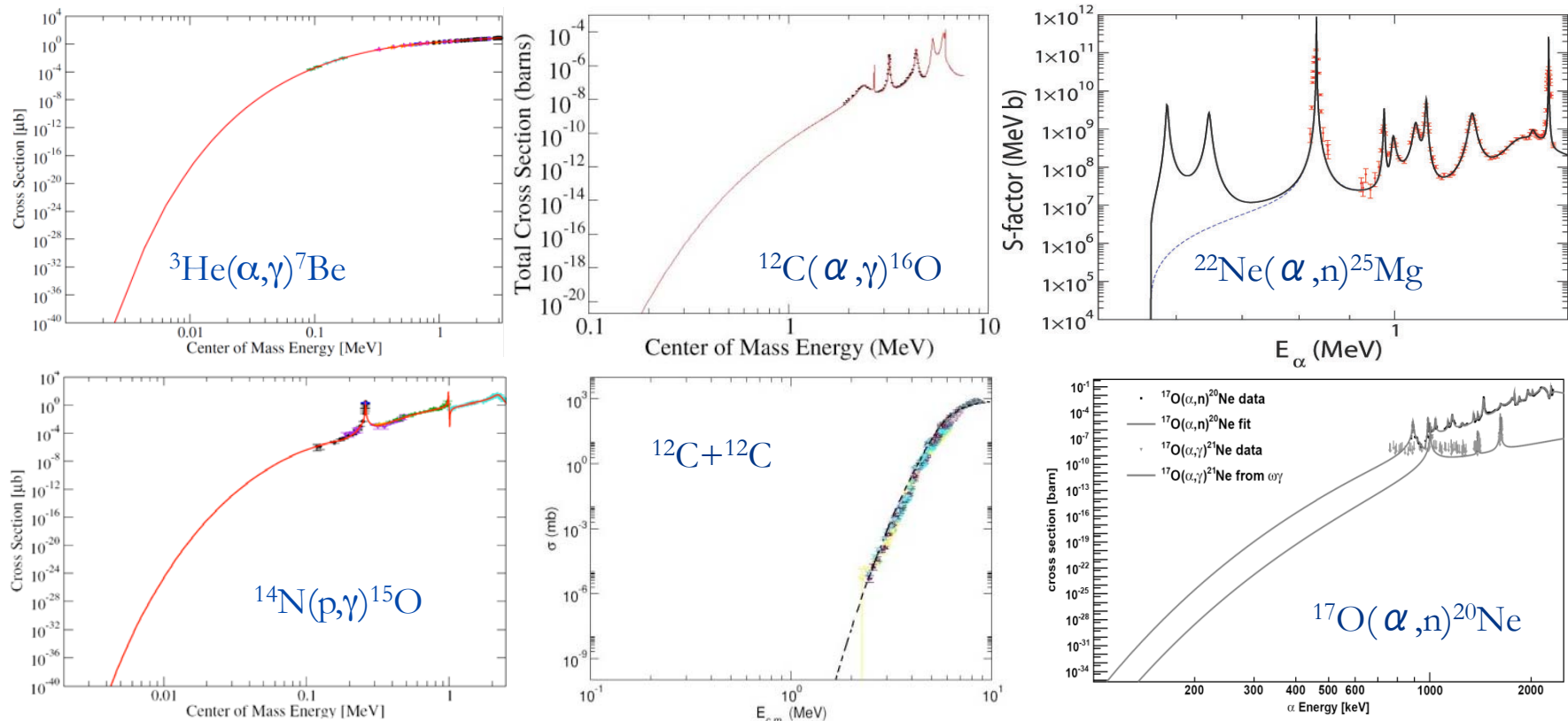
Carl Brune



- Astrophysics: H and He burning, S process
- Facilities: neutron and gamma beams, underground accelerators, ICF plasmas

Nuclear reaction rates

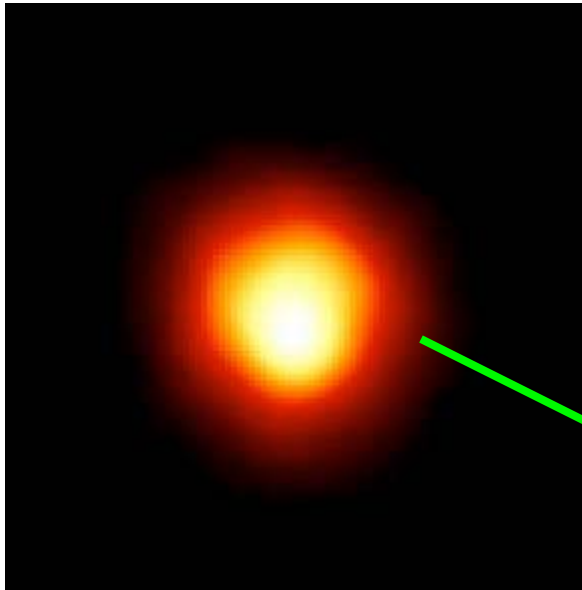
determine, energy production, isotopic abundance distribution, timescale of stellar events - **The art of the game is to identify the critical ones!**



Challenge is to model the experimental cross sections towards a reliable form to translate into reaction rates: Direct reaction models, R-matrix, statistical HF model are all part of the game!

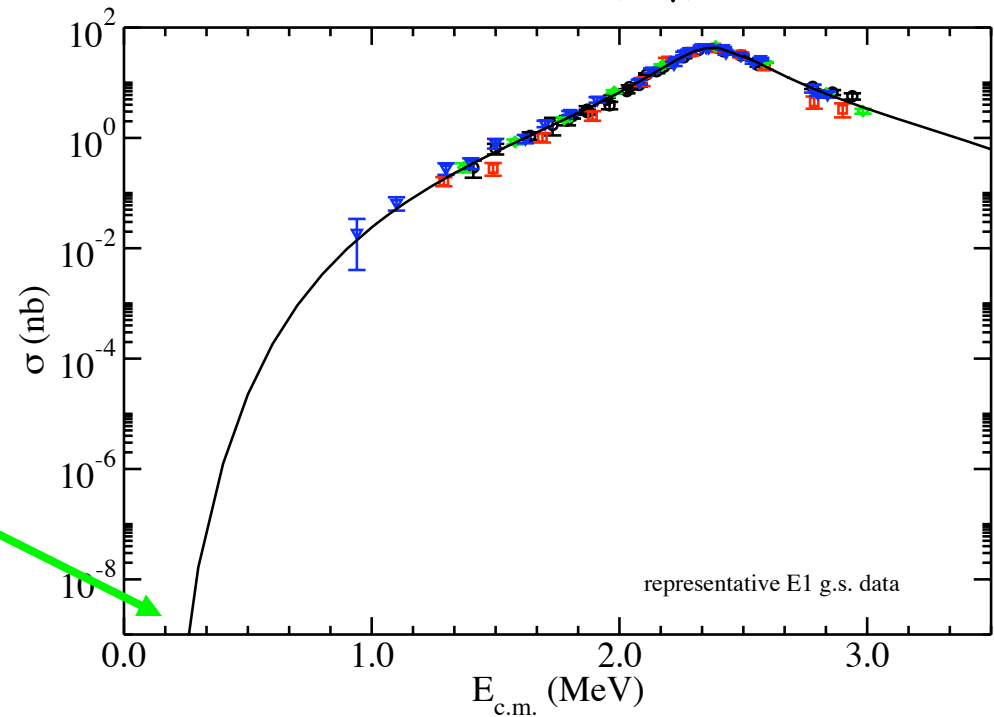
The Common Challenge:

Red Giant



$$T=(1-3)\times 10^8 \text{ K}$$

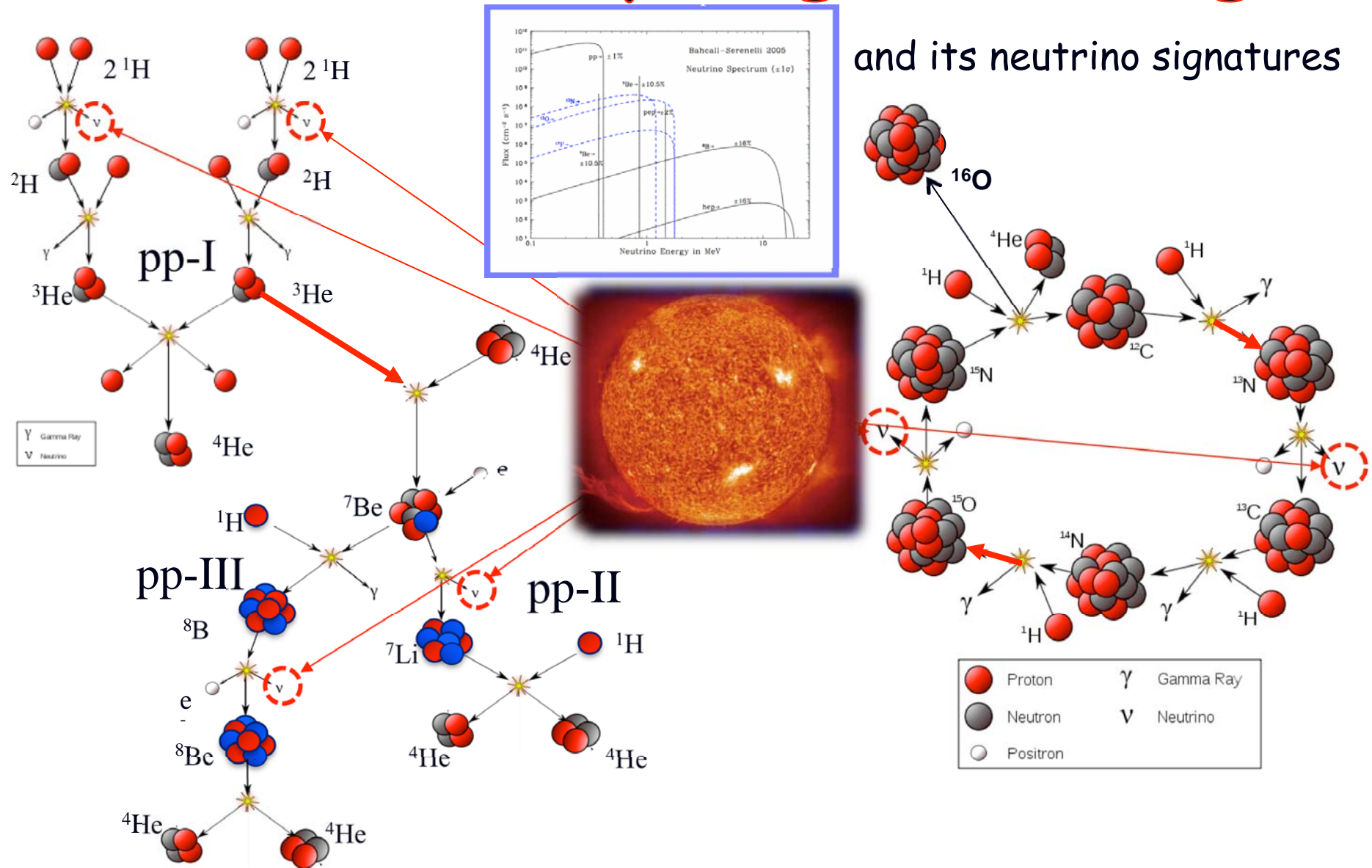
The Lab: $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$



- small cross sections → high luminosity, low background
- extrapolation → need for theoretical guidance

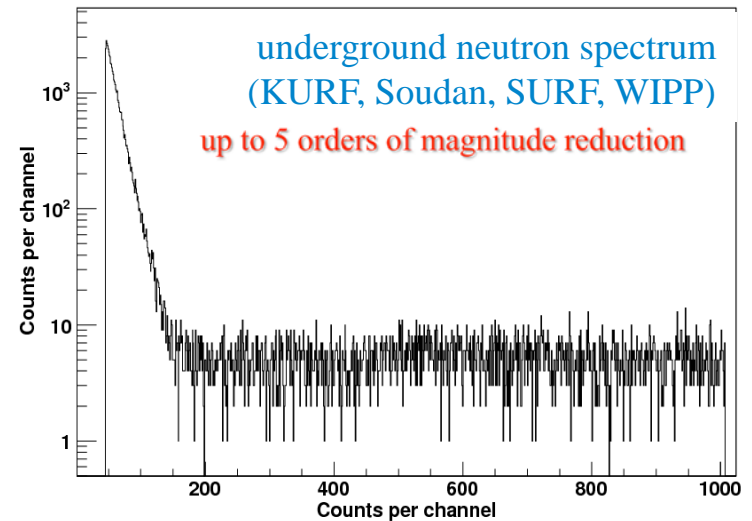
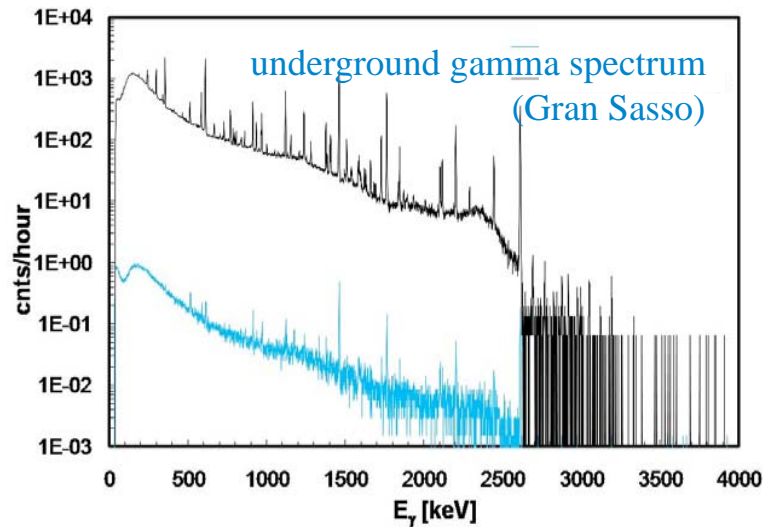
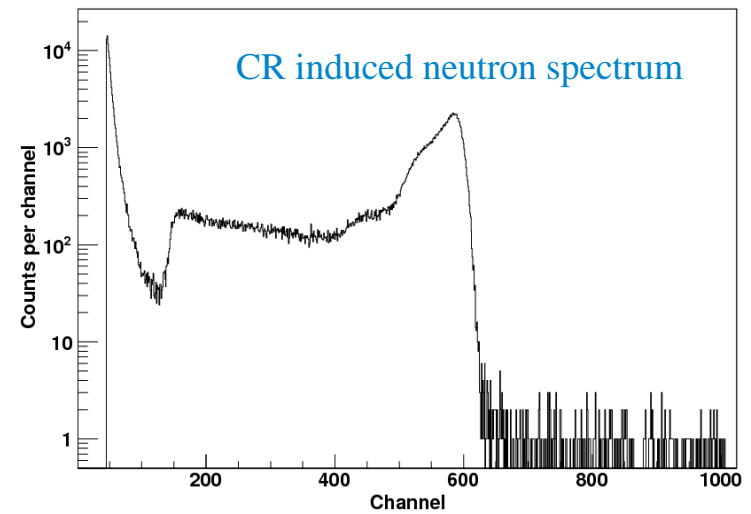
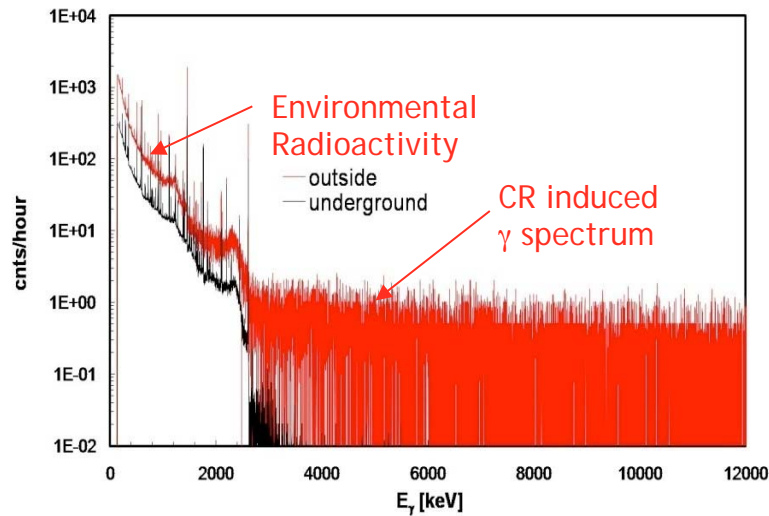
Modes of hydrogen burning

and its neutrino signatures



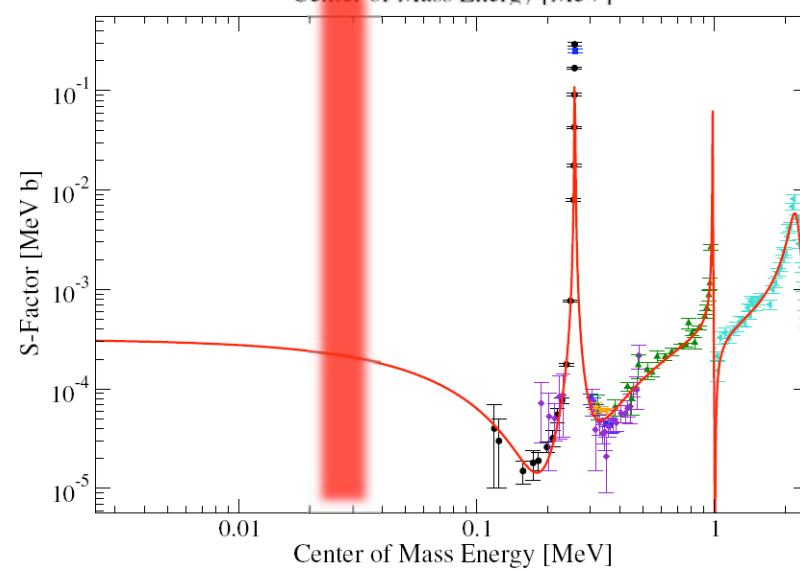
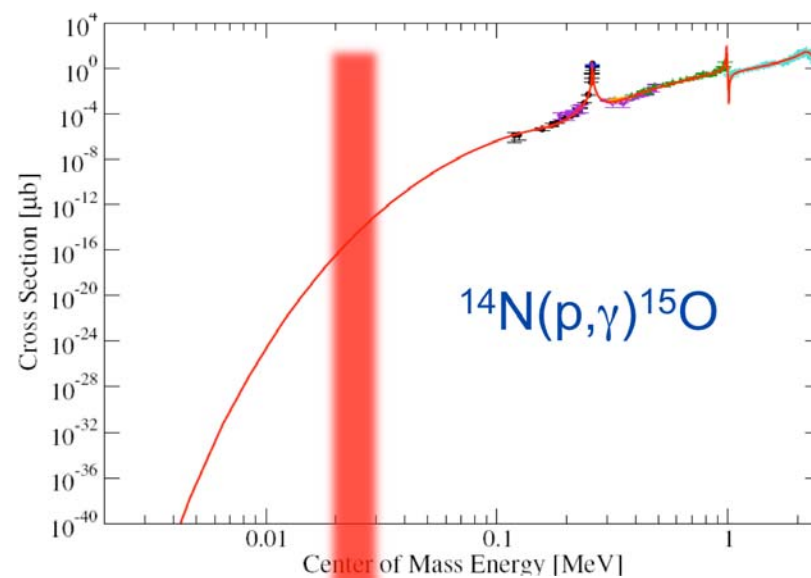
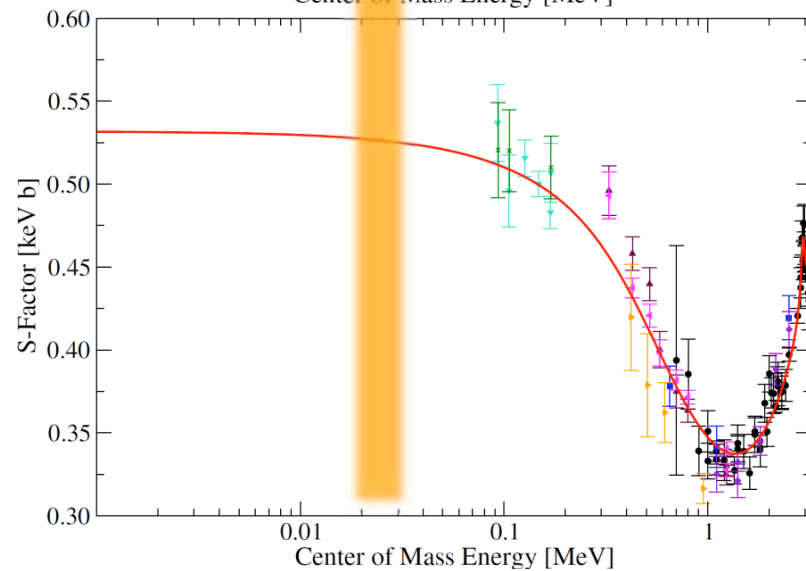
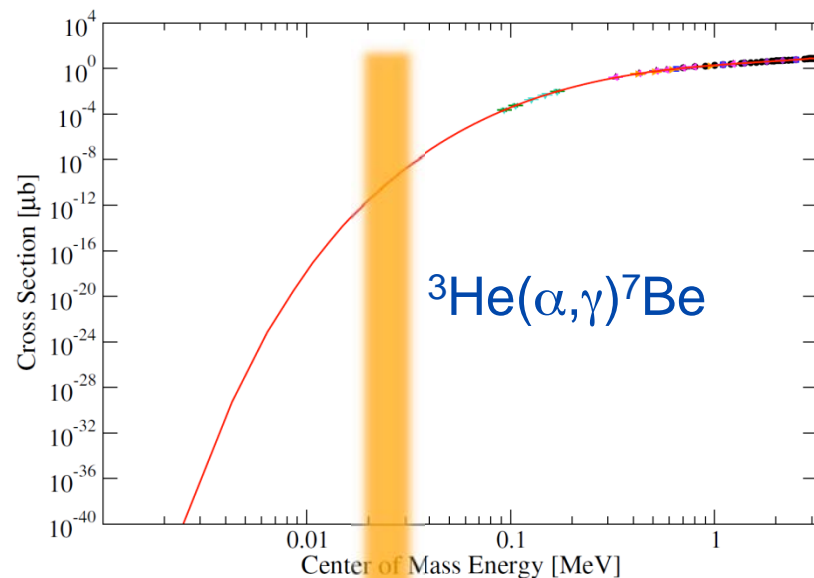


Background Reduction

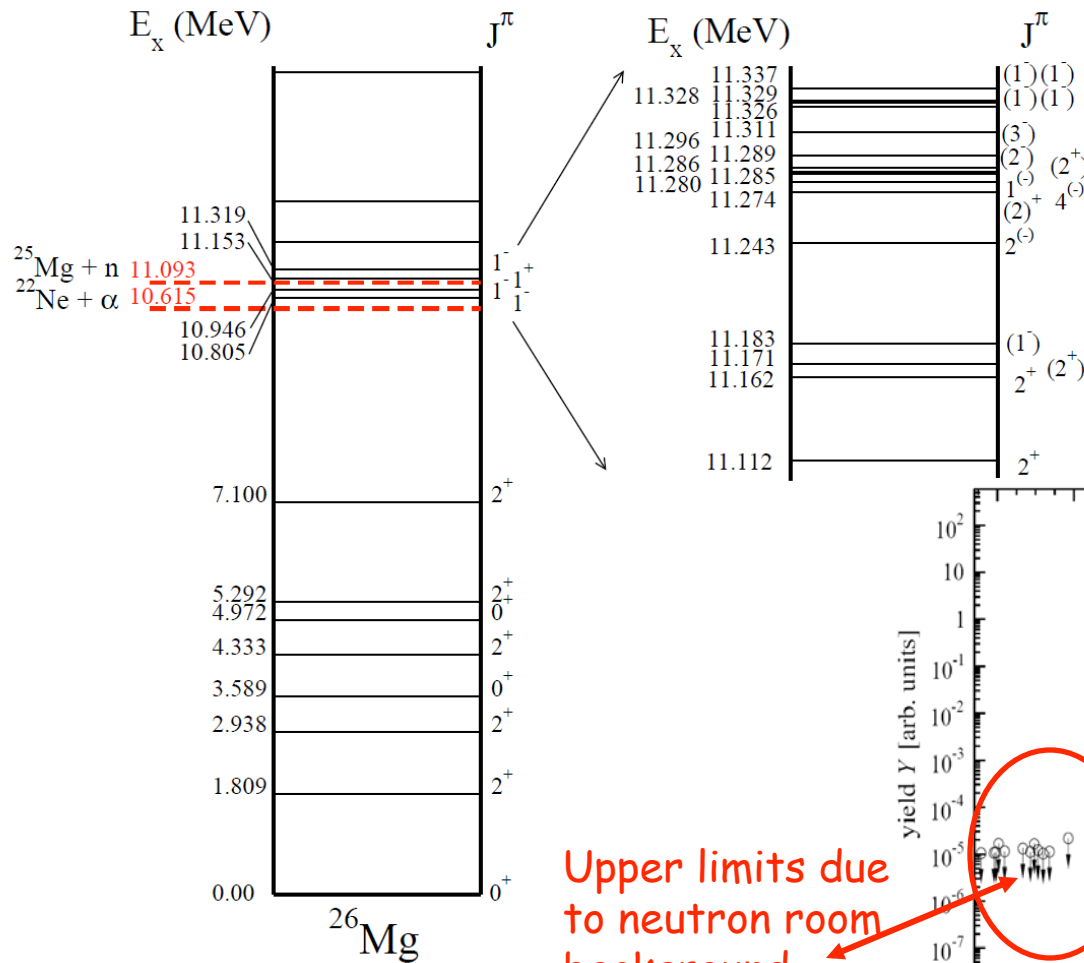


High luminosity, low background experiments

The two most critical Rates



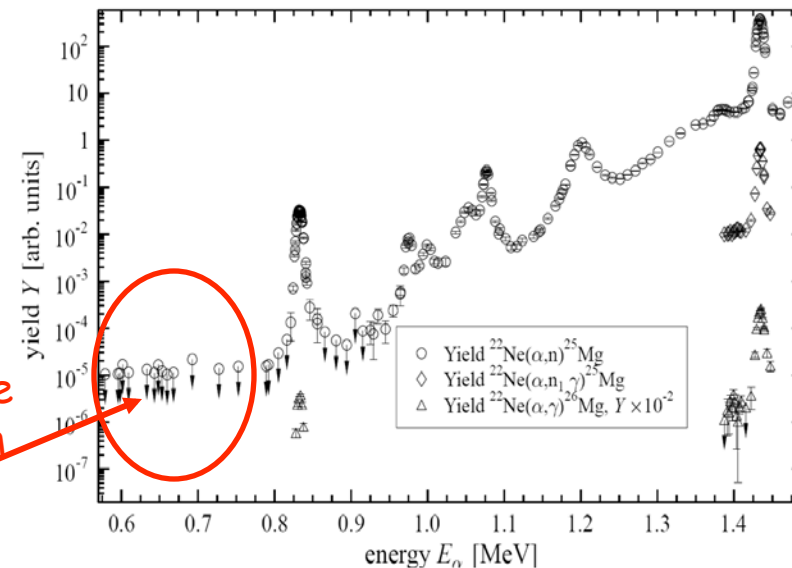
$^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ as stellar neutron source



➤ Negative Q-value requires higher energies

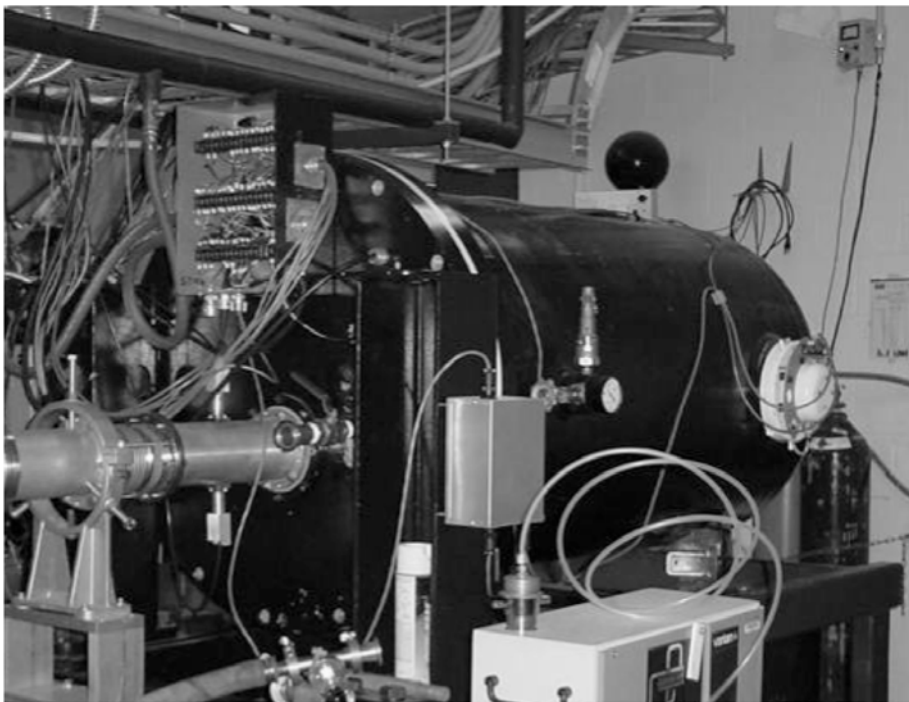
➤ Uncertainty in low energy cross section

Upper limits due to neutron room background

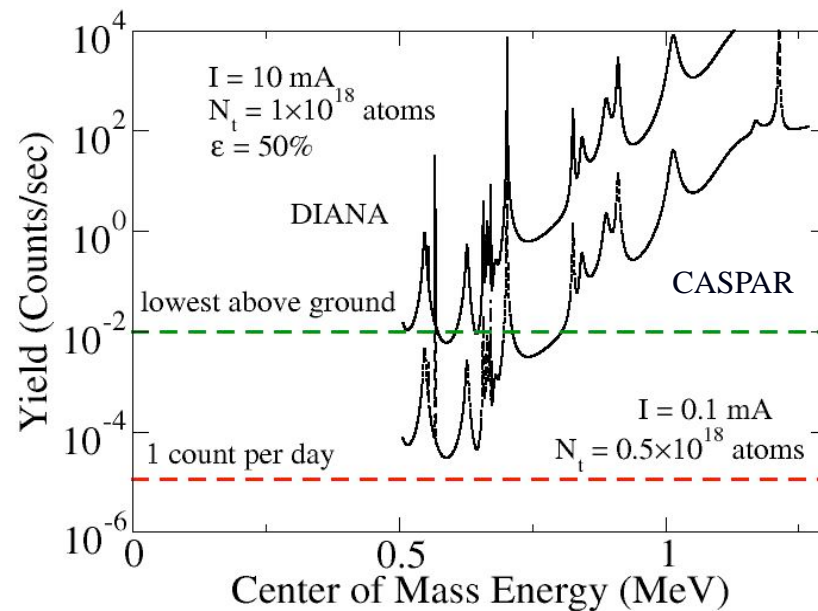
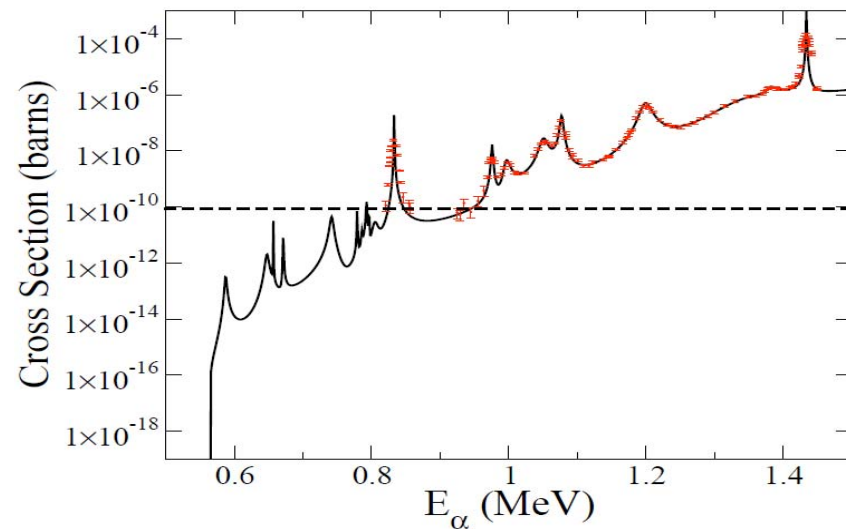


CASPAR (Compact Accelerator for Performing Astrophysical Research)

1MV Van de Graff 200 μ A α beam

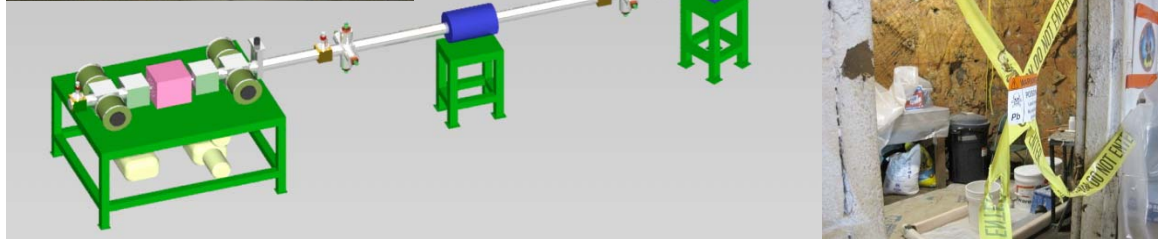


Location is being prepared and accelerator being rebuilt and tested, gas target system is being built from existent components!

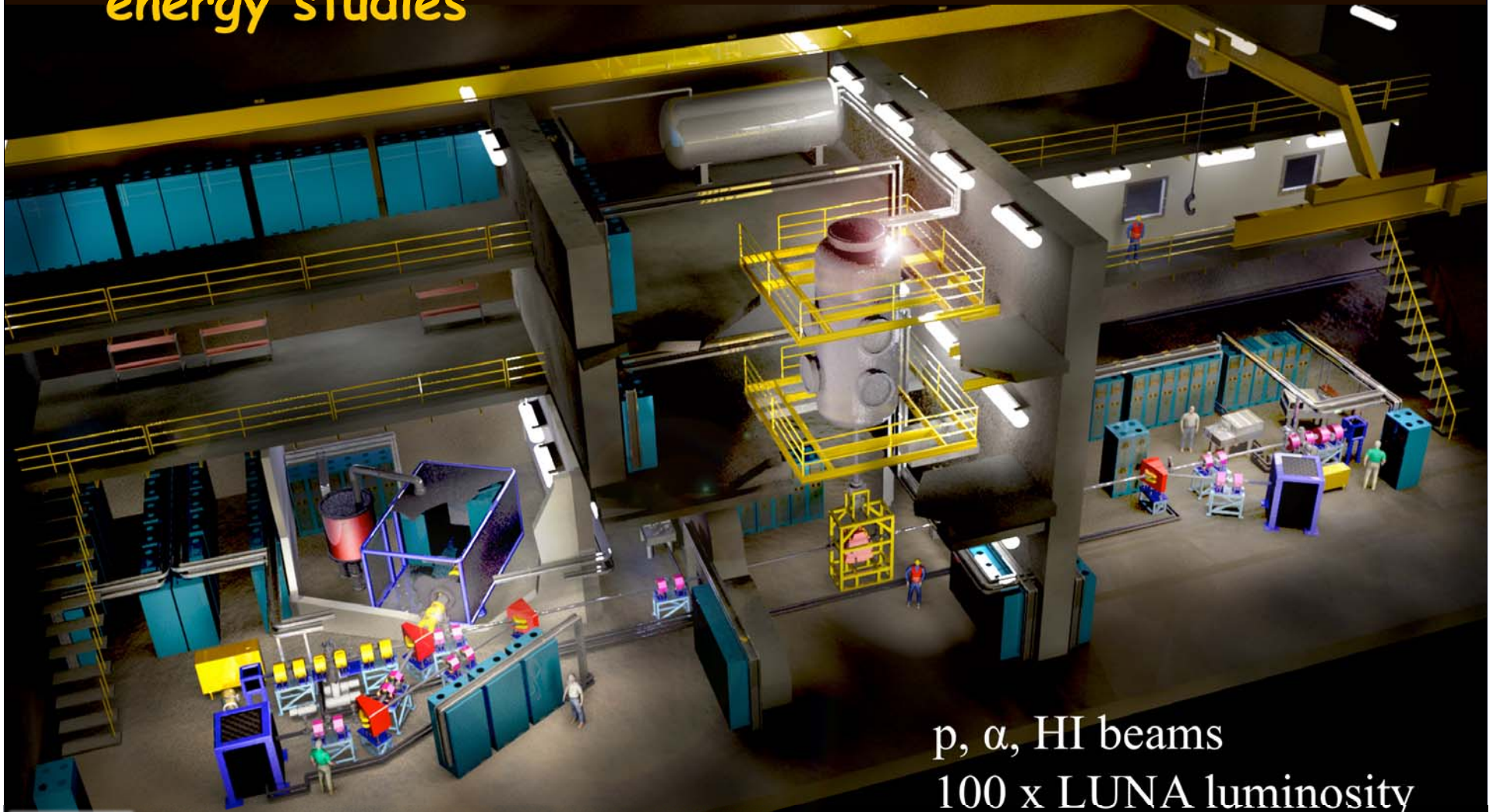


The Caspar Plan

Location is being prepared and accelerator being rebuilt and tested, gas target system is being built from existent components!



For the longer term:
Underground accelerator project DIANA for low
energy studies

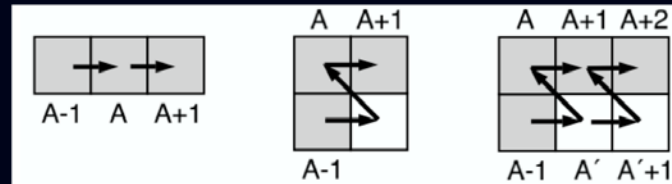
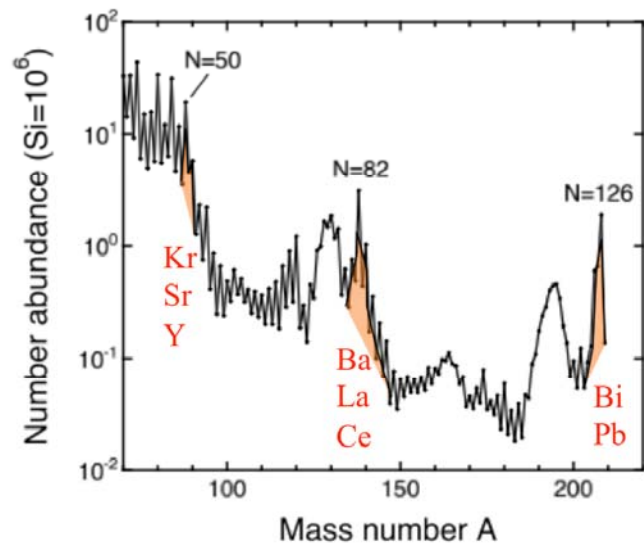


p, α , HI beams
100 x LUNA luminosity



High luminosity, low background experiments

Astrophysical s-Process: General

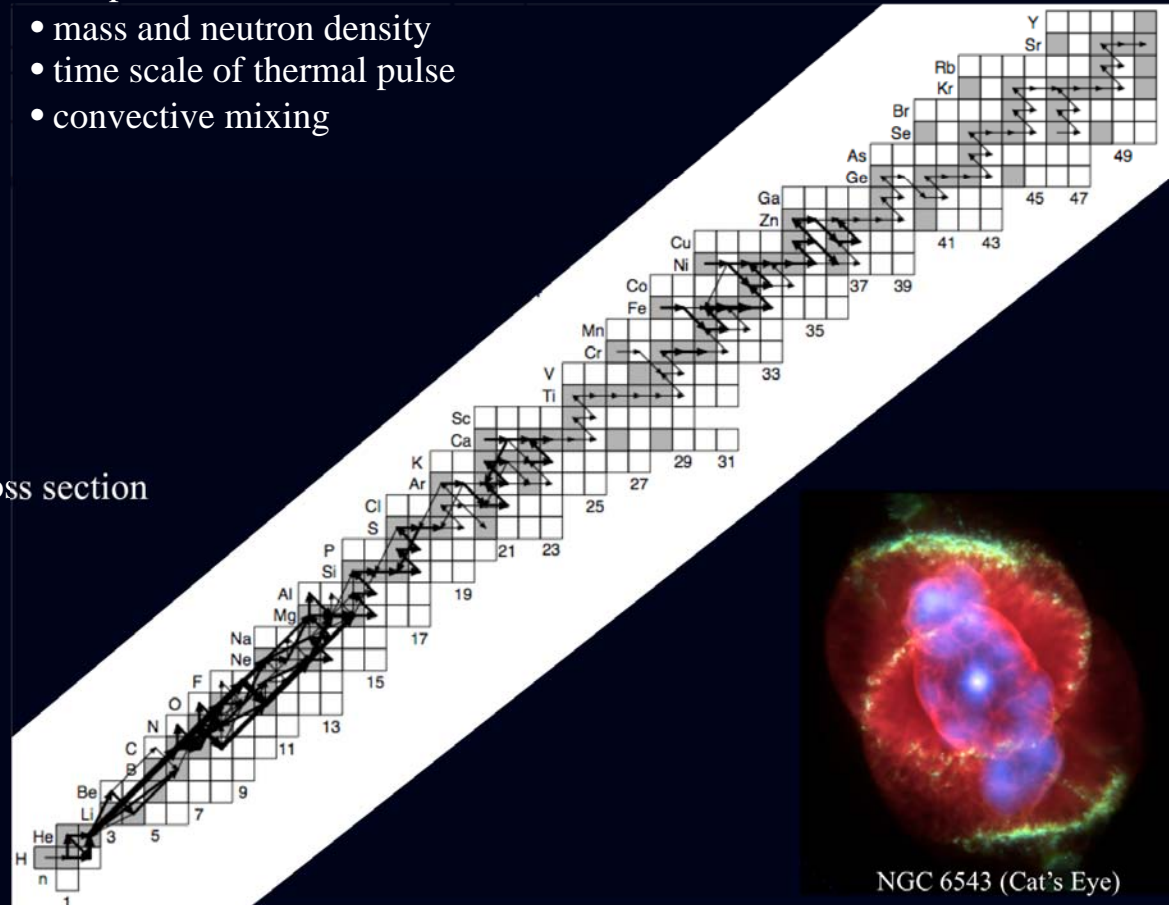


Betelgeuse (α Orionis)

Branchings important for determining:

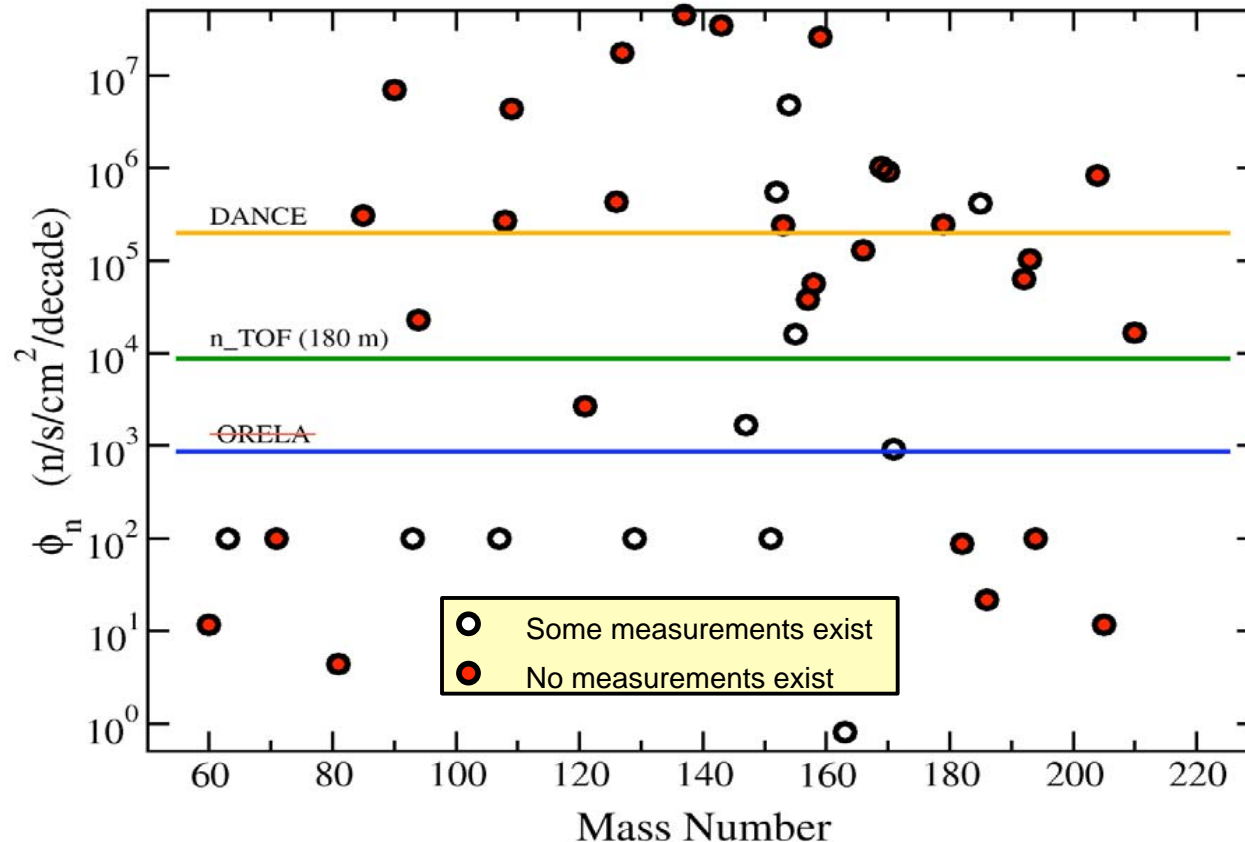
- temperature
- mass and neutron density
- time scale of thermal pulse
- convective mixing

- $\lambda_{\beta} \gg \lambda_{n\gamma}$
- $\tau_{n\gamma} \approx 10$ years
- $N_n \approx 10^8$ neutrons/cm³
- abundance depends on neutron capture cross section
[peaks at neutron magic numbers]
- neutron sources:
 $^{13}\text{C}(\alpha, n)$
 $^{22}\text{Ne}(\alpha, n)$



NGC 6543 (Cat's Eye)

LANSCCE and DANCE enable neutron capture measurements on s-process branch points



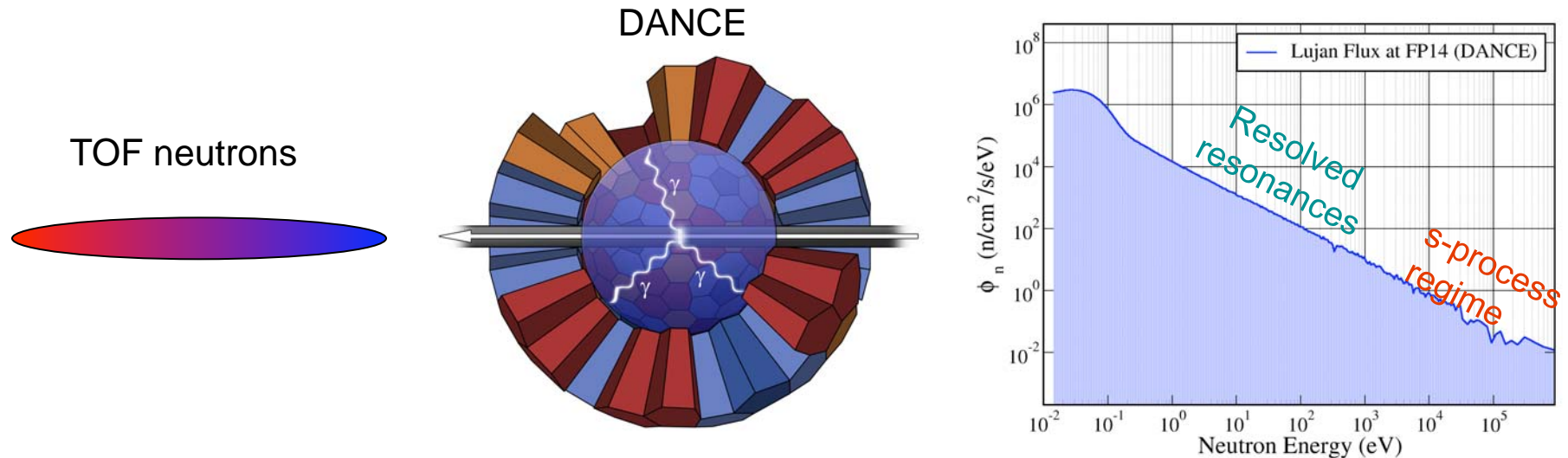
Each branch-point illustrates how the s-process operates in stars of different **mass**, **age** and **metallicity**

Only with measurements on many isotopes will we understand the **temperature** and **densities** in the many different s-process scenarios

Increased neutron intensities and radioisotope production schemes are making samples available for which have not been possible to study in the past

A. Couture and R. Reifarth, "Direct Measurements of Neutron Capture on Radioactive Isotopes", At. Data and Nucl. Data Tables, **93** (2007) 803.

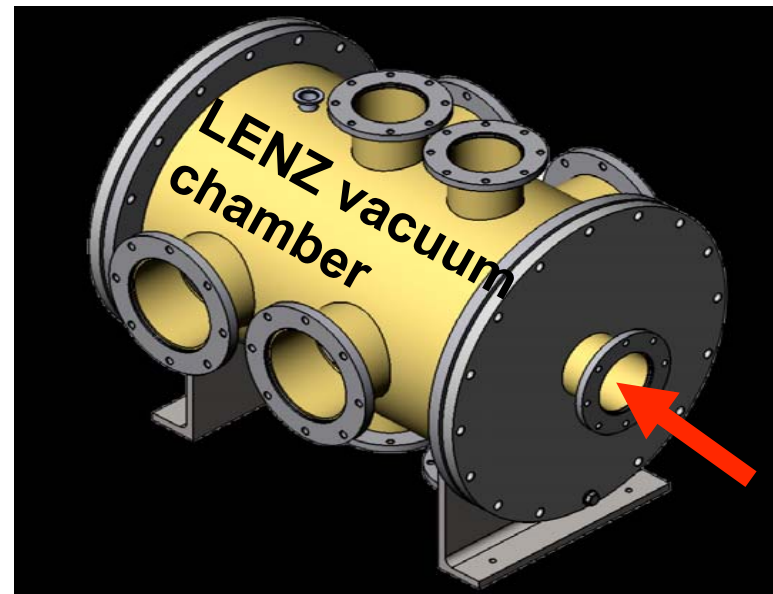
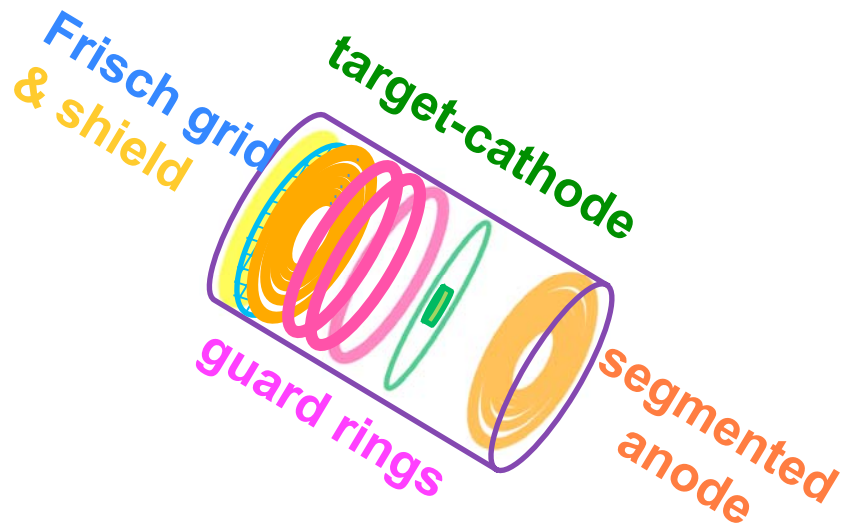
Direct cross section measurements and nuclear structure studies inform astrophysical environments



- High intensity time-of-flight neutrons + high segmentation calorimetry enable cross section, resonance, and decay studies
- DAQ upgrades are underway to improve the resolution and flexibility of DANCE (auxiliary detectors)

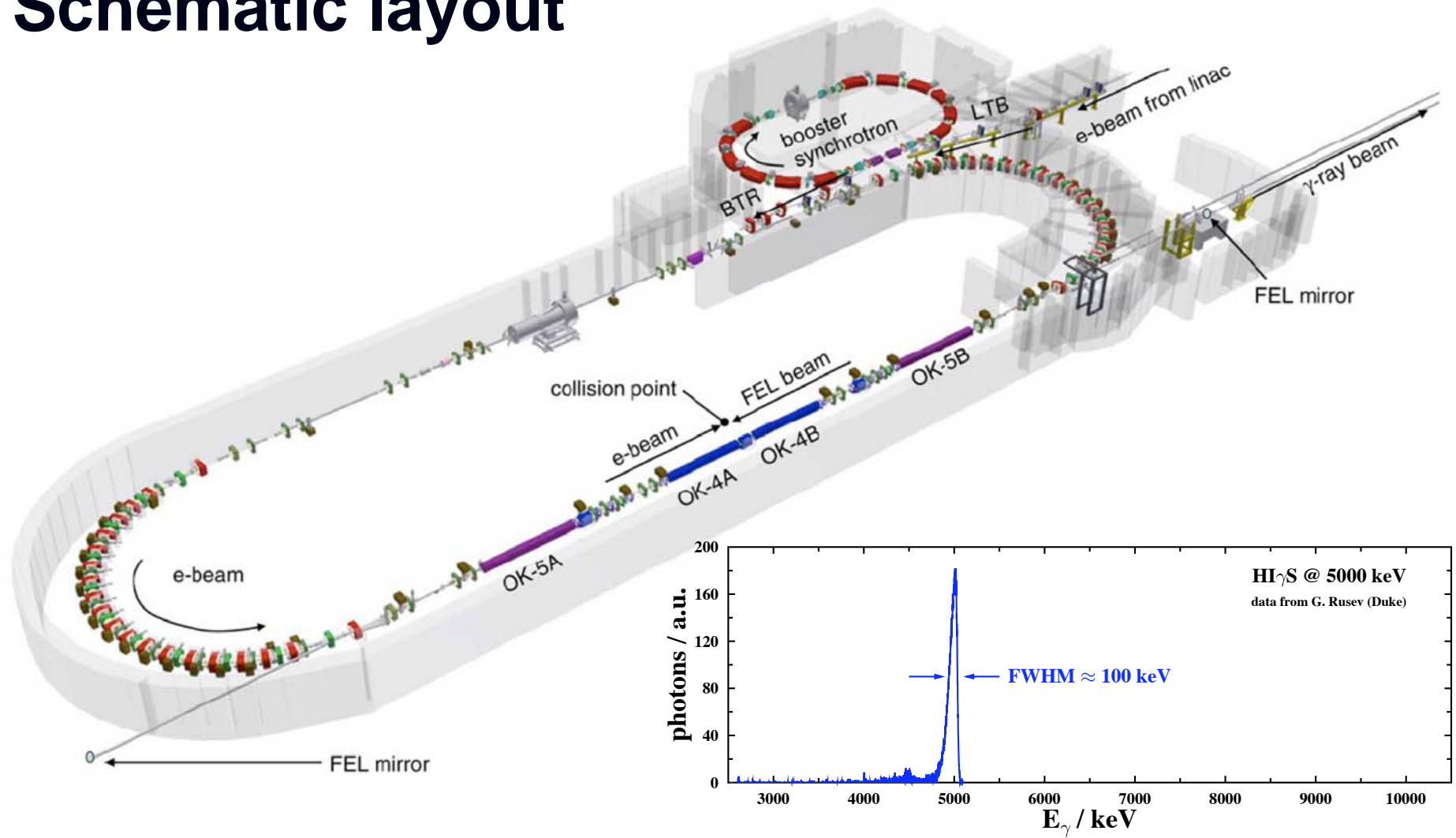
Neutron-induced charged particle reaction instrument (LENZ) is being developed at LANSCE

- For nuclear astrophysics, low-energy (n,a) and (n,p) reactions ($E_n \sim$ thermal to 2 MeV) will be studied using a twin Frisch-gridded ionization chamber (shown in the left figure) with digitizers, providing a large solid angle and low detection threshold
- For level density information in reaction models and (n,p) and (n,a) cross sections on structural materials in reactor design, high-energy ($E_n < 30$ MeV) measurement will couple this ionization chamber with segmented silicon strip detectors

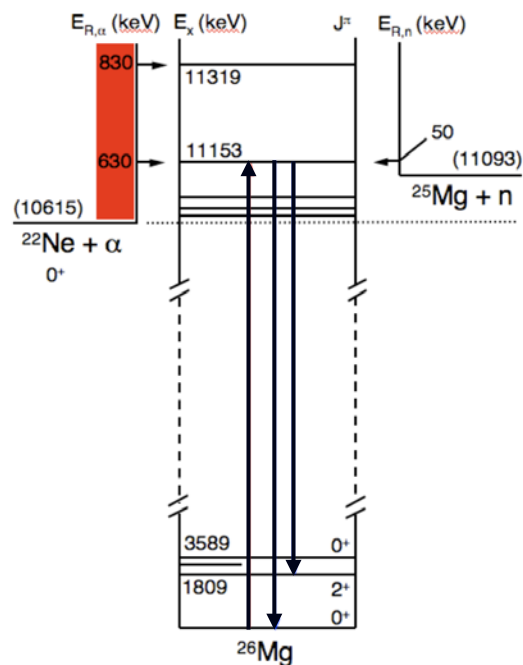


The High Intensity γ -ray source HI γ S at TUNL

Schematic layout



Astrophysical s-Process: $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ Neutron Source



$^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$, $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$

$^{26}\text{Mg}(\gamma, \gamma')^{26}\text{Mg}$

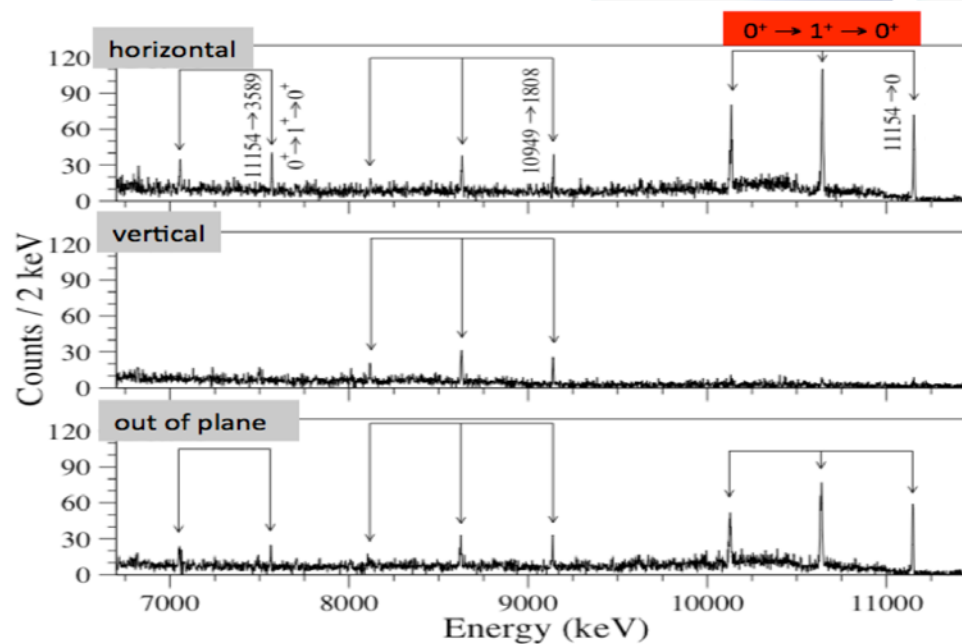
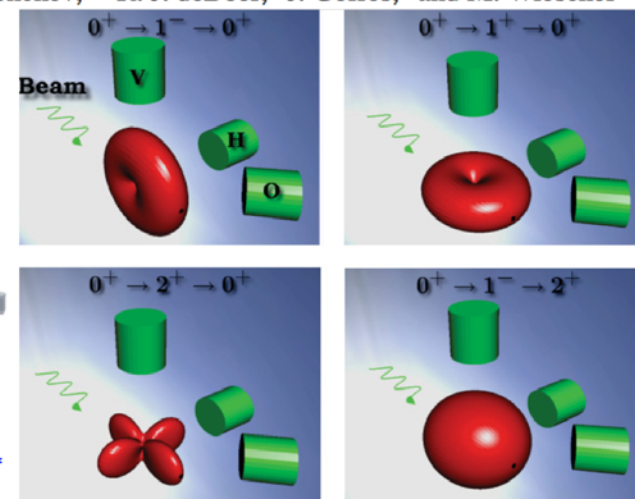
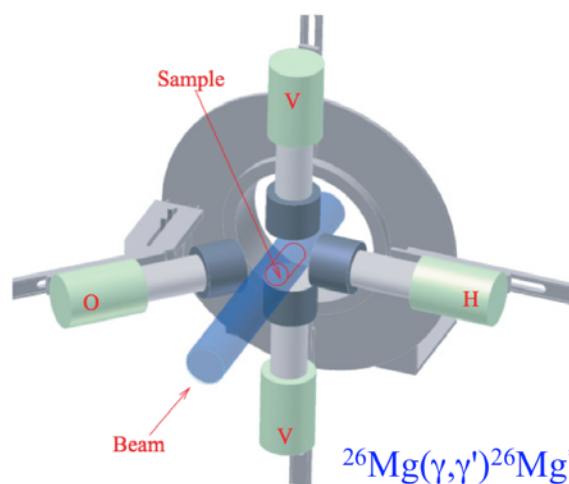
at $E_\gamma = 10$ MeV:

- $10^7/\text{s}$
- $\Delta E_\gamma = 200$ keV

PHYSICAL REVIEW C **80**, 055803 (2009)

Photoexcitation of astrophysically important states in ^{26}Mg

R. Longland,^{1,3} C. Iliadis,^{1,3} G. Rusev,^{2,3} A. P. Tonchev,^{2,3} R. J. deBoer,⁴ J. Görres,⁴ and M. Wiescher⁴



1+
[unnatural
parity!]

Astrophysical s-Process: Branchings

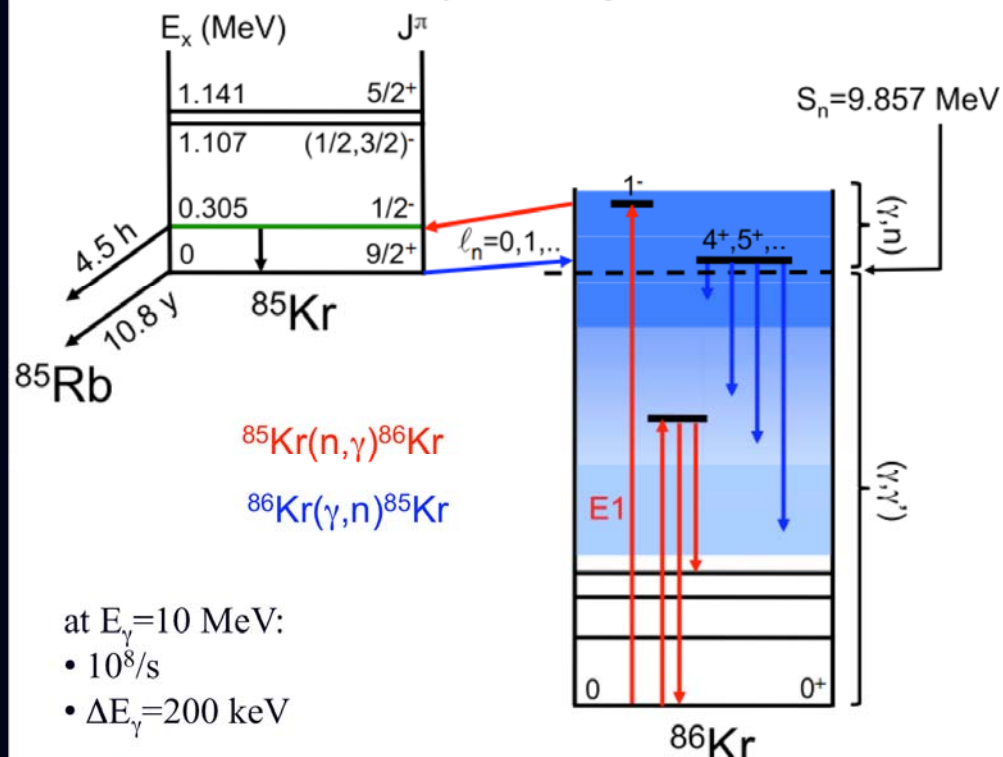
PRL 111, 112501 (2013)

PHYSICAL REVIEW LETTERS

week ending
13 SEPTEMBER 2013

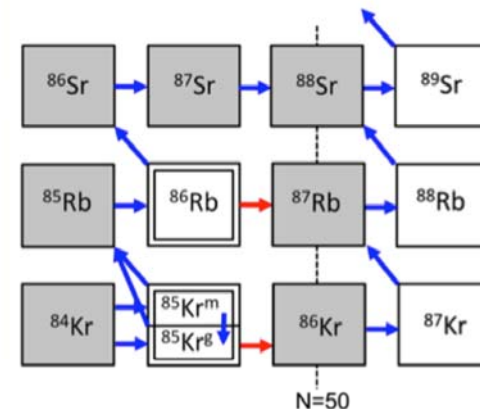
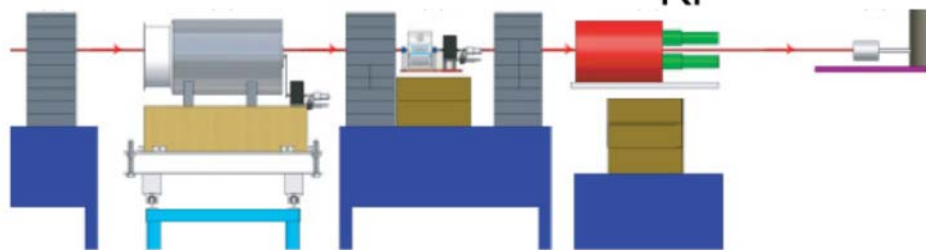
Cross-Section Measurements of the $^{86}\text{Kr}(\gamma, n)$ Reaction to Probe the s-Process Branching at ^{85}Kr

R. Raut,^{1,2,*} A. P. Tonchev,^{1,2,†} G. Rusev,^{1,2,‡} W. Tornow,^{1,2} C. Iliadis,^{3,2} M. Lugaro,⁴ J. Buntain,⁴ S. Goriely,⁵
J. H. Kelley,^{2,6} R. Schwengner,⁷ A. Banu,⁸ and N. Tsoneva^{9,10}



at $E_\gamma = 10$ MeV:

- $10^8/\text{s}$
- $\Delta E_\gamma = 200$ keV

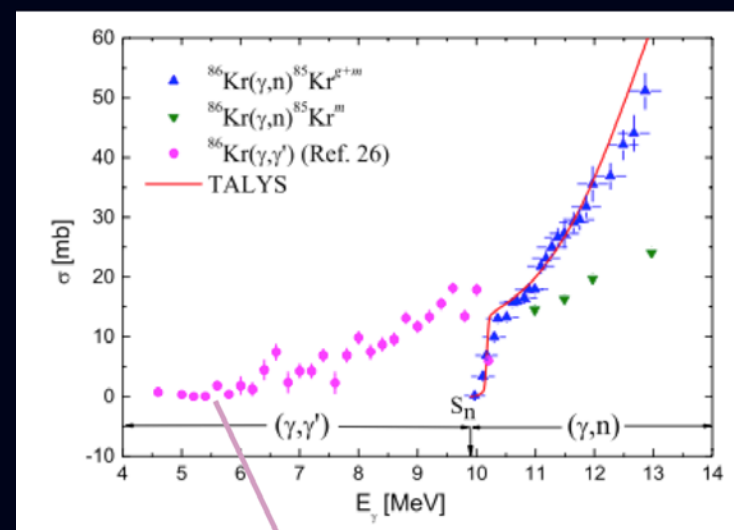


Photon transmission coefficient

$$T_\gamma \sim \int_0^{E^*} \rho T_{E1}(E^* - \epsilon) d\epsilon$$

Photon strength function

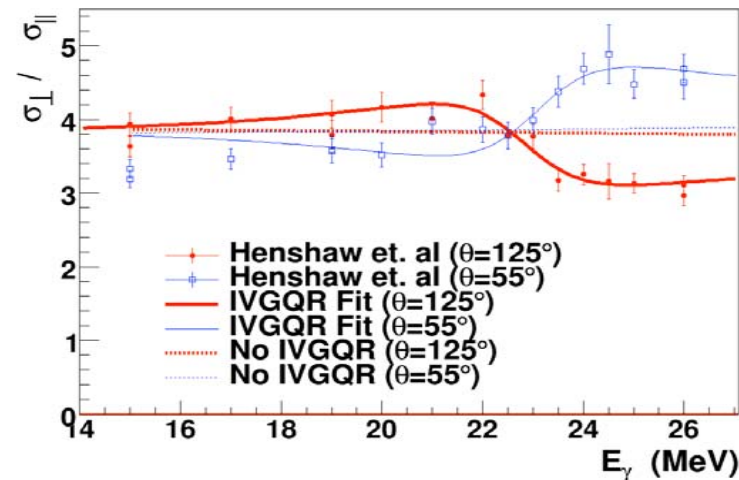
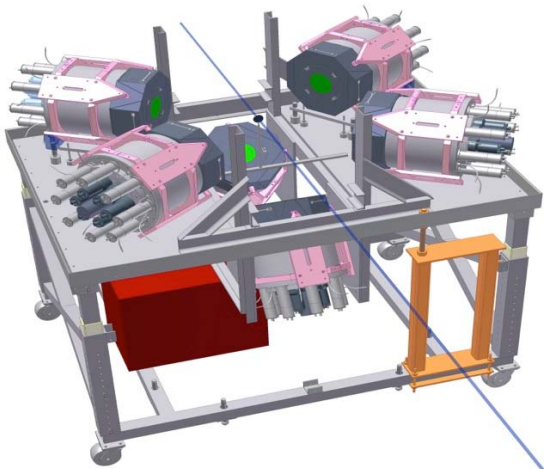
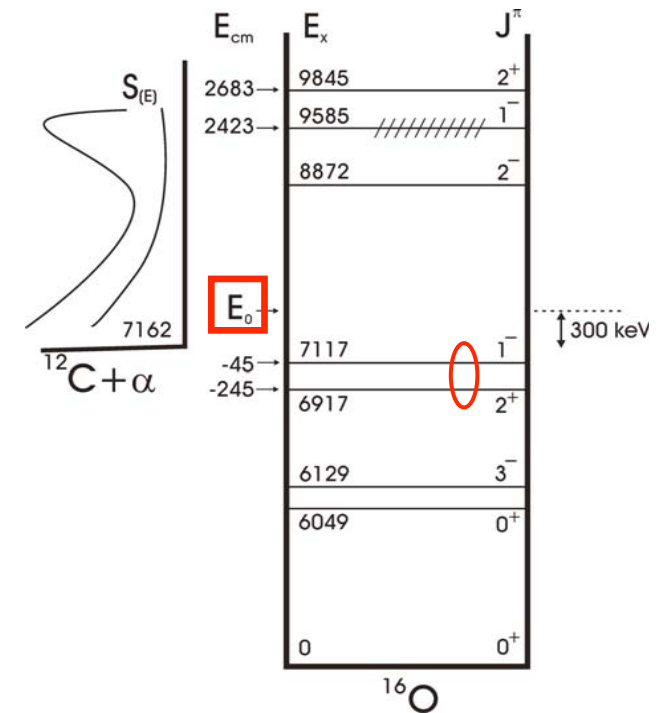
$$\langle \sigma_a \rangle = \pi^2 \lambda^2 \omega \langle \langle \Gamma_0 \rangle / D \rangle_{I_e}$$



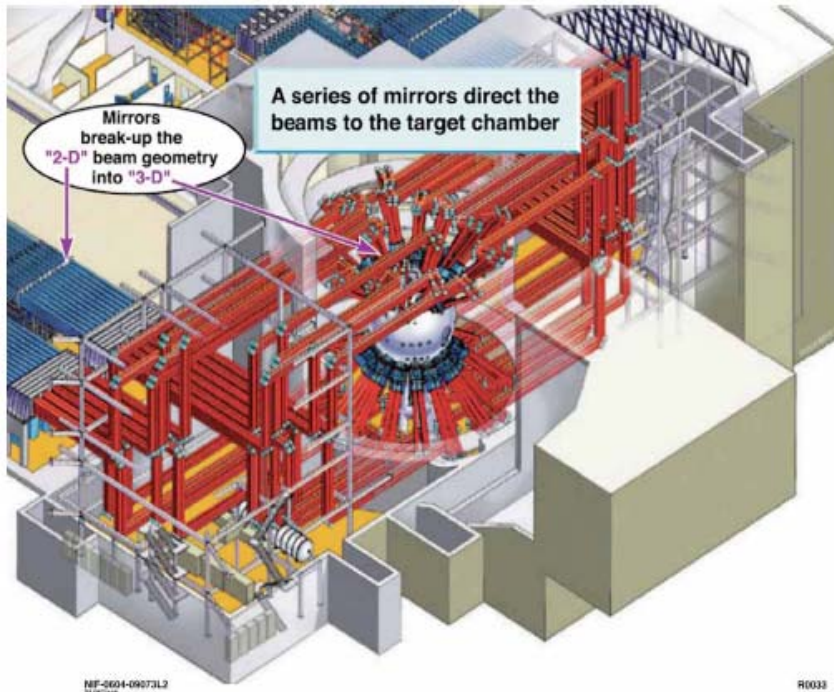
Schwengner et al., PRC 87, 024306 (2013)

Other Nuclear Astrophysics with HIGS

- $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ via $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ and Optical TPC
 - near the threshold
 - at higher energies ($E_x > 10 \text{ MeV}$)
- Isovector Giant Quadrupole Resonances in Heavy Nuclei [S. Henshaw et al., PRL 107, 222501 (2011)] → neutron star equation of state
- P-Process



NIF-National Ignition Facility @ LLNL

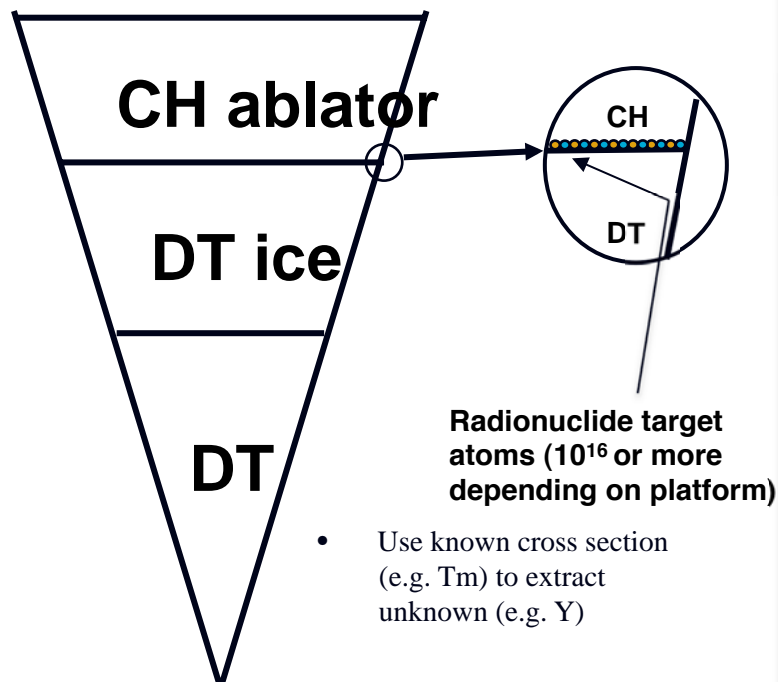


NIF Laser System: 192 laser beams produce 1.8 MJ, IR-UV $\rightarrow 3\omega=352\text{nm}$, 2+ ns, 5×10^{14} Watt in 1mm^2 spot)

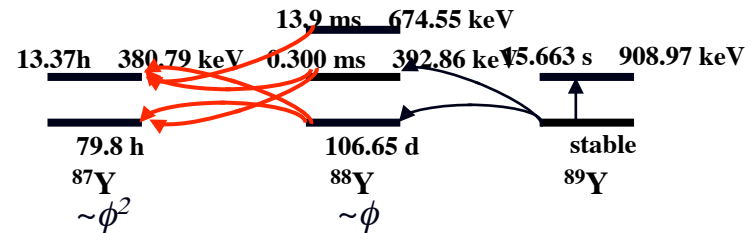
- Direct measurement of thermonuclear reaction rates in plasma conditions
- Reactions on excited states
- Electron screening

Experimental Concept – We will add radioactive tracers to Symcap capsules to study production and cross sections of excited state and second-order capture species

- Goal: Measure capture and excited state cross sections relevant to WCI and GS programs
- Experiment: Add 1016 atoms of radioactive tracers to DT Symcap
- Evaluate collection of capsule material and cross section determination
- Required diagnostics: SRC



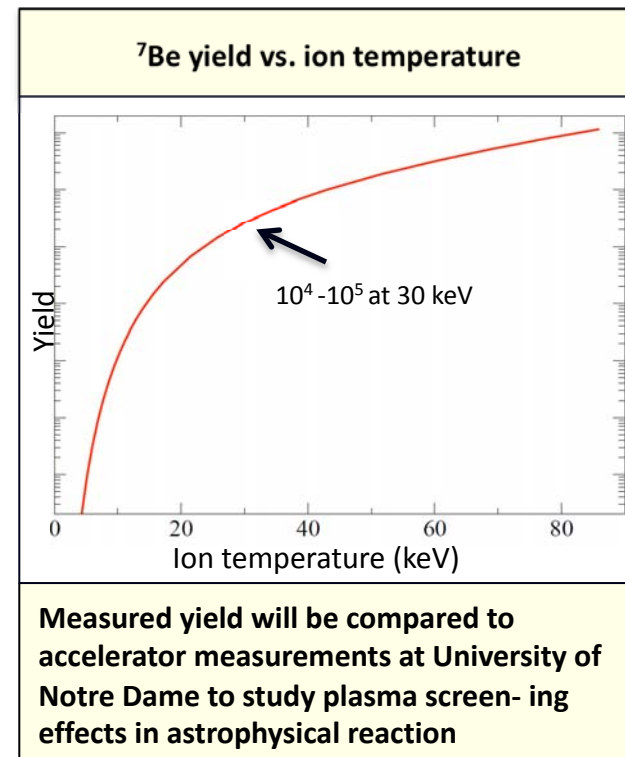
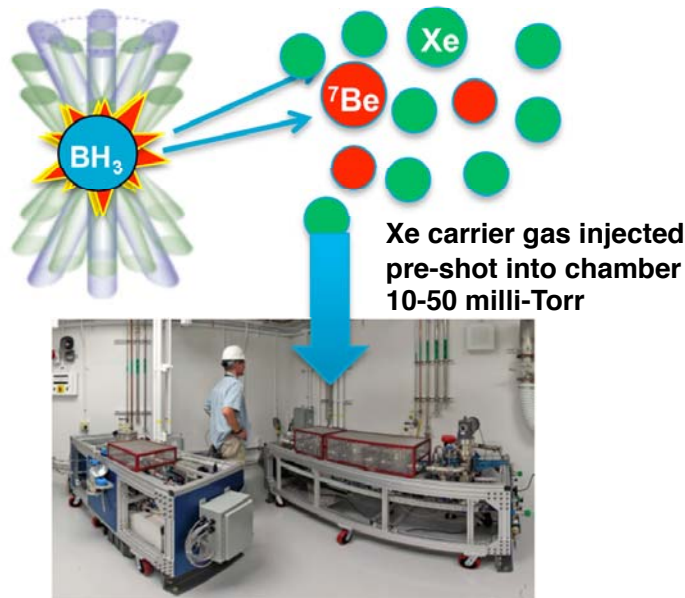
Measure cross sections (n,γ and $n,2n$) for radioactive species



- Run two similar capsules, one loaded with ^{89}Y and the other with ^{88}Y (radioactive)
- Extract unknown cross sections from excited states from the difference

Experimental Concept – We will use BH₃ filled targets to study the astrophysical ¹⁰B(p,a) ⁷Be reaction and explore physics of plasma screening

- Measure reactivity of ¹⁰B(p,a) in plasma
- Run ¹⁰B(p,a) reaction in plasma and
- collect radioactive debris with RAGS
- Novel collection concept needs tested
- Laser Energy range < 1 MJ
- Complementary experiment measures same reaction on B in/on the hohlraum (non-plasma)



To Summarize

- There are several outstanding questions in H burning, He burning, and the S process.
- Novel approaches using a wide range of facilities are being utilized to address these challenges.
- I would like to thank several colleagues for supplying slides or other information: Michael Wiescher, Aaron Couture, Calvin Howell, Art Champagne, Christian Iliadis, Jac Caggiano, and Lee Bernstein.

