Introduction to Experimental Nuclear Astrophysics

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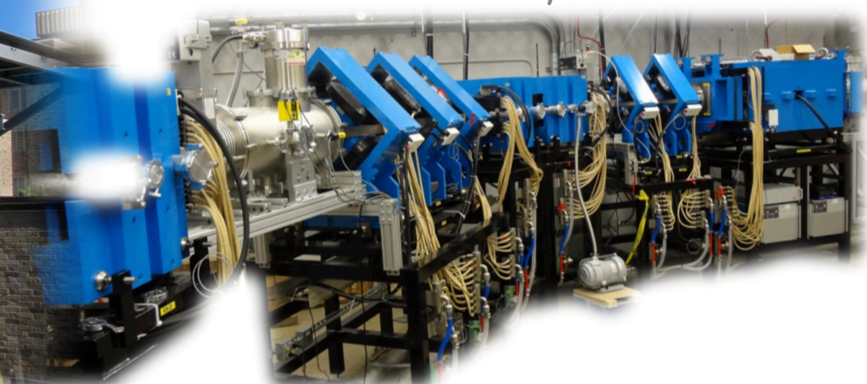
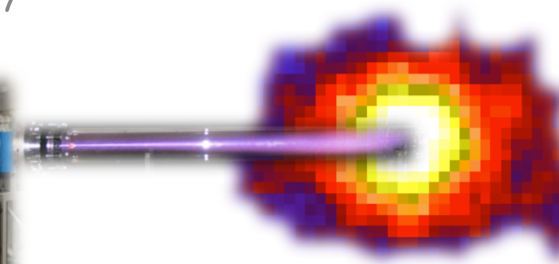
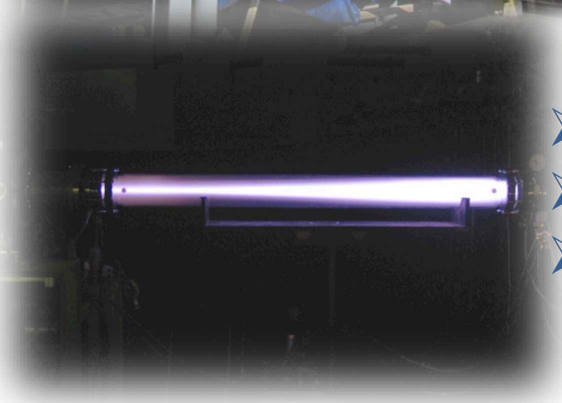
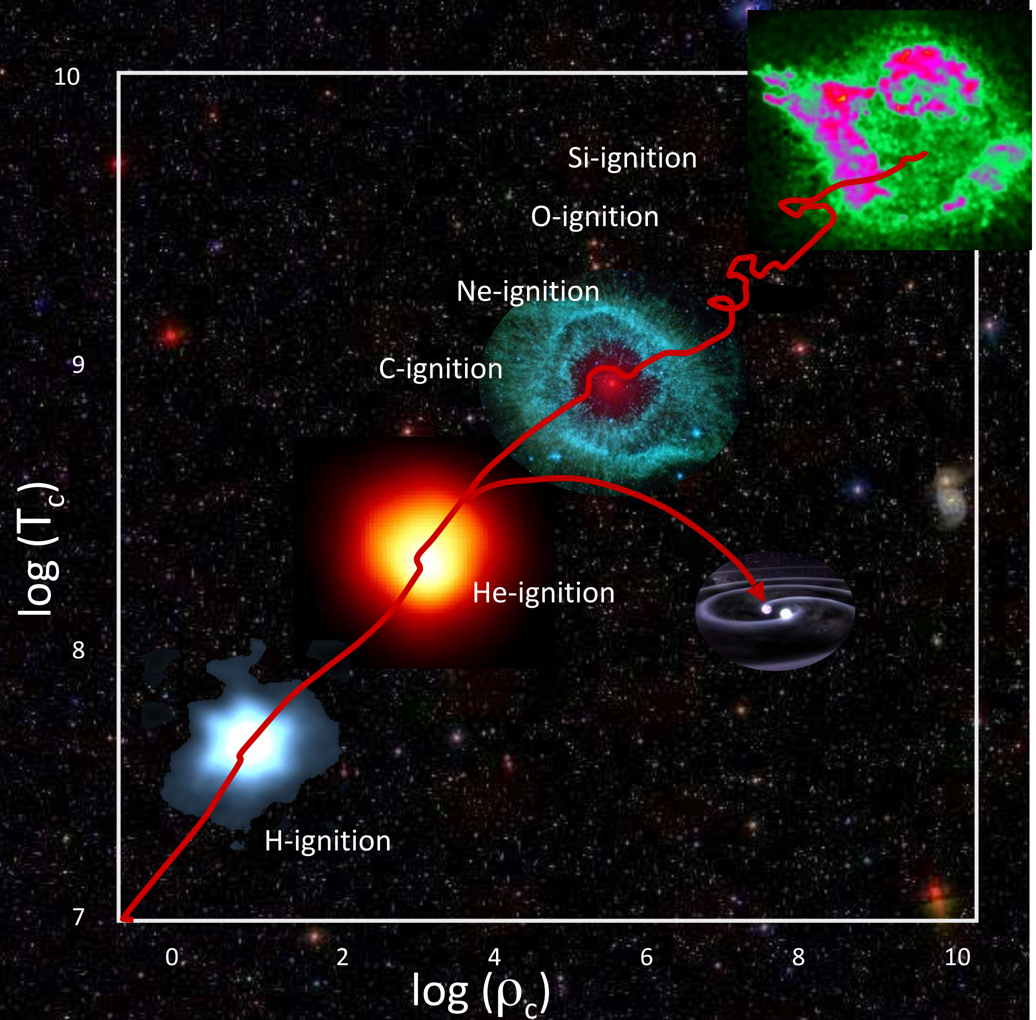






- The physics questions
- Stable beams and quiescent stellar burning
- Radioactive beams for stellar explosions

Nuclear Burning in Stars



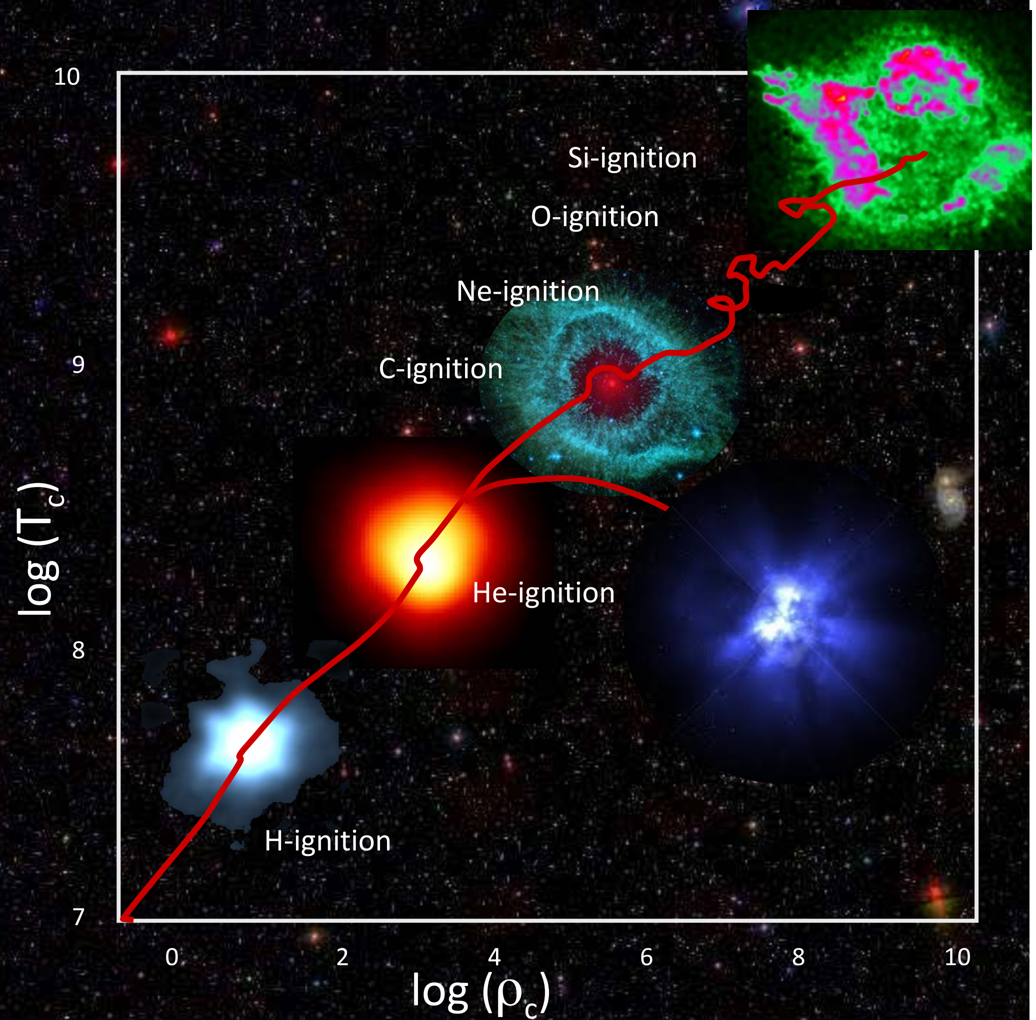
is characterized by low energy reaction sequences at different temperature and density conditions:

- pp-chains,
- CNO cycles
- triple alpha process
- s-process
- Carbon/Oxygen fusion

producing energy for maintaining stability, and provide seed for subsequent explosion in novae, supernovae, and X-ray bursts!

- Hot CNO cycles,
- rp-process
- αp-process
- νp-process

Nuclear Burning in Stars



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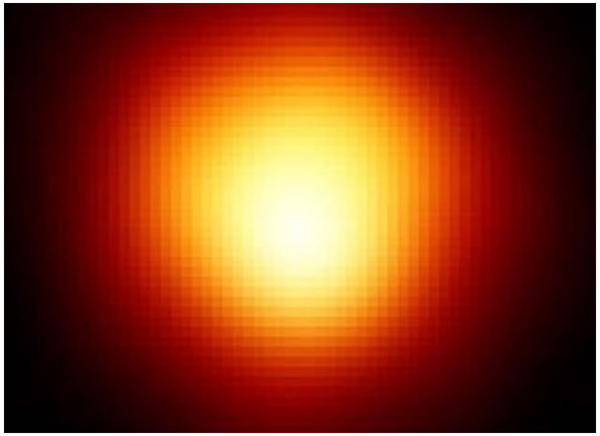
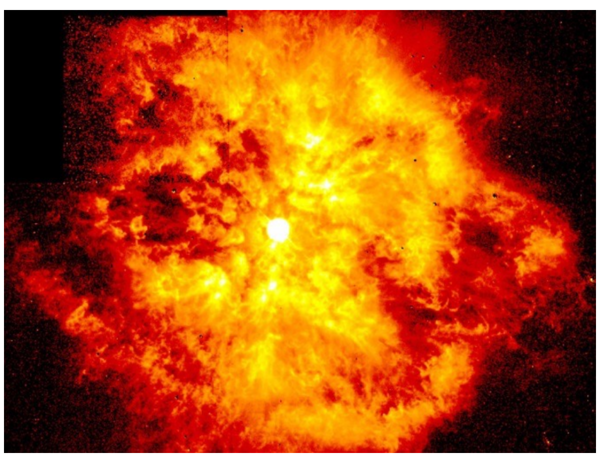




The physics goals of stellar reaction studies

- Solar neutrino production
- The lifetime of stars
- Stellar neutron sources and s-process
- Late burning phases
- The ignition of type Ia supernovae
- Explosive processes, rp/αp-process, p-process
- r-process and r-nuclei decay mechanisms

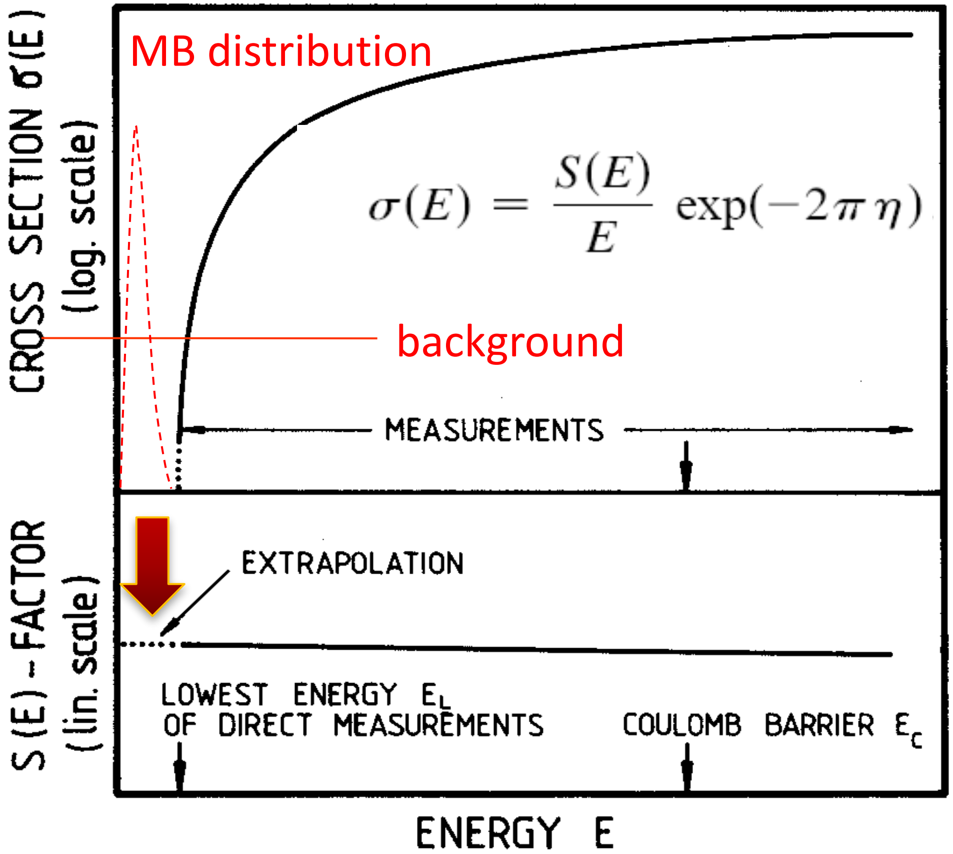
Measurements:

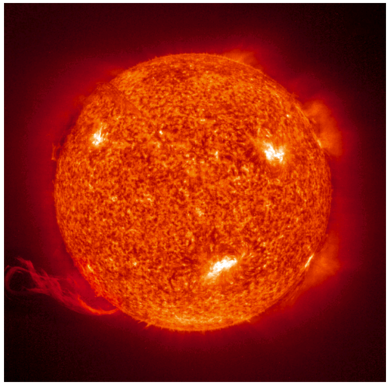
- Direct measurements with background suppression techniques
  (coincidence rejection, underground, inverse kinematics)
- Indirect methods
  (Transfer reactions, Trojan horse method)

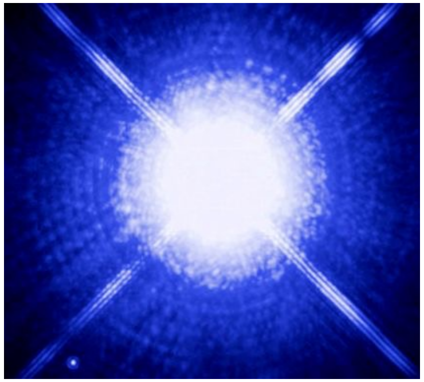
Theory:

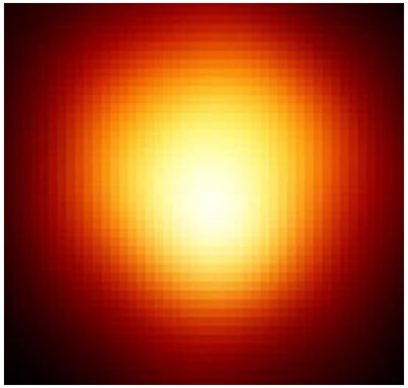
- Reaction theory
  (R-matrix, HF-theory, reaction models, plasma effects)

The challenge of charged particle reactions



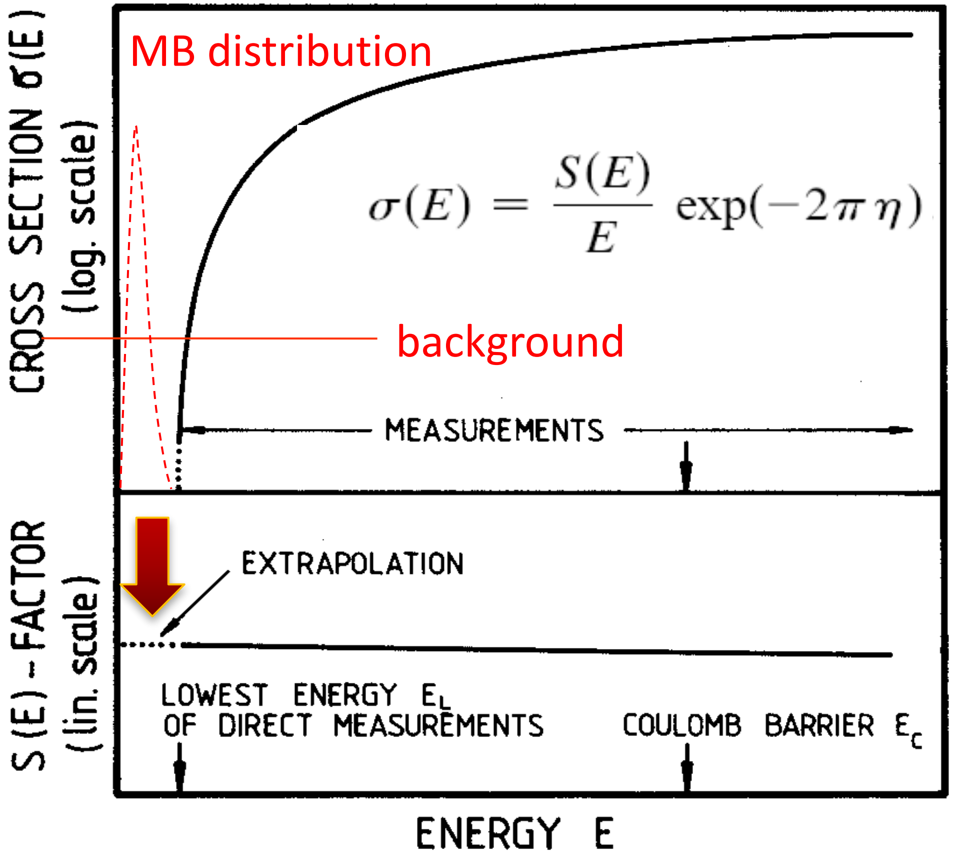


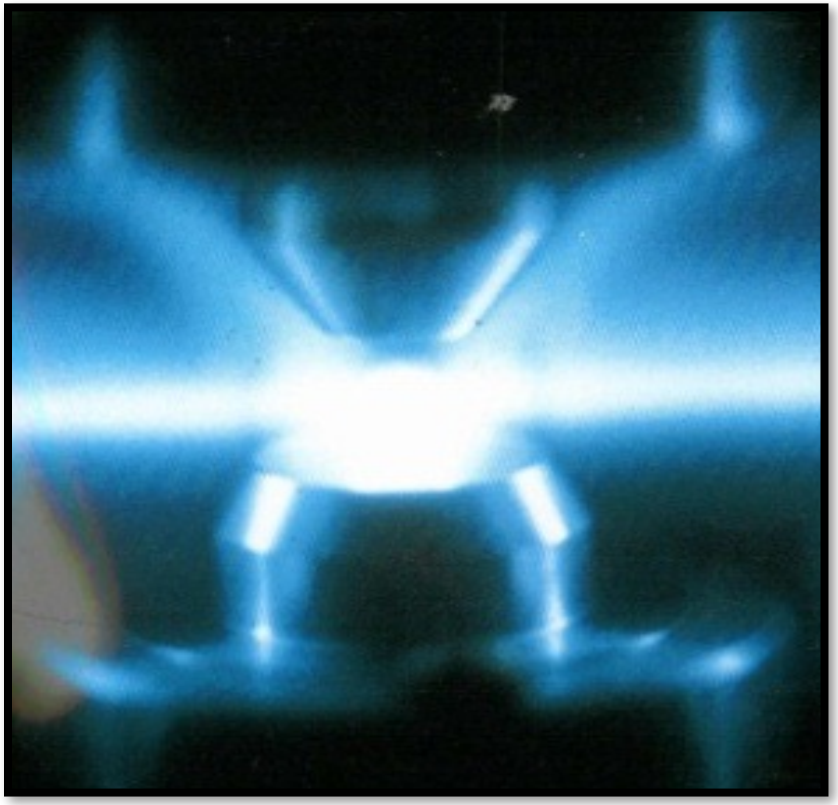




$$N_A\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\cdot\mu}}\cdot(kT)^{-3/2}\cdot\int_0^\infty E\,\sigma(E)\exp\left(-\frac{E}{kT}\right)dE$$

The challenge of charged particle reactions





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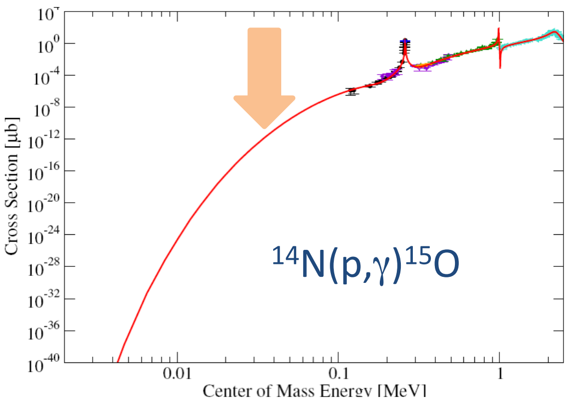
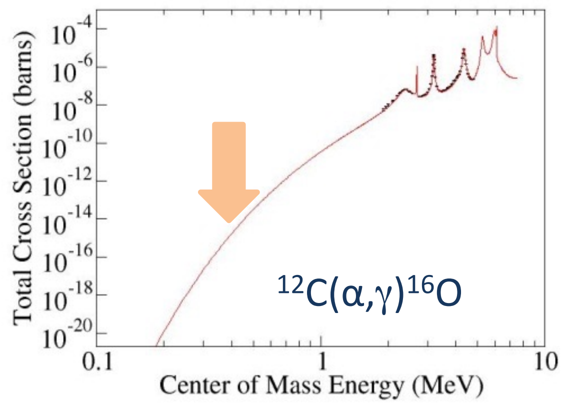
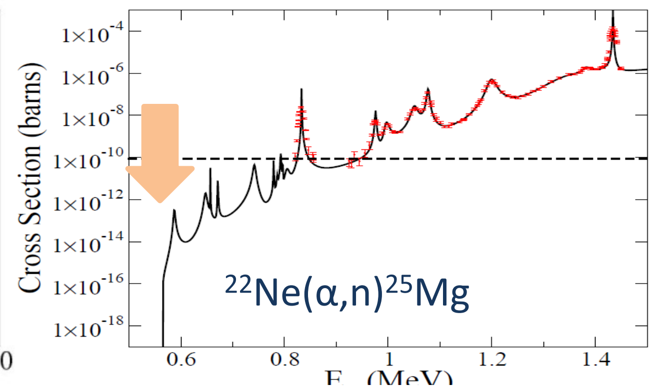
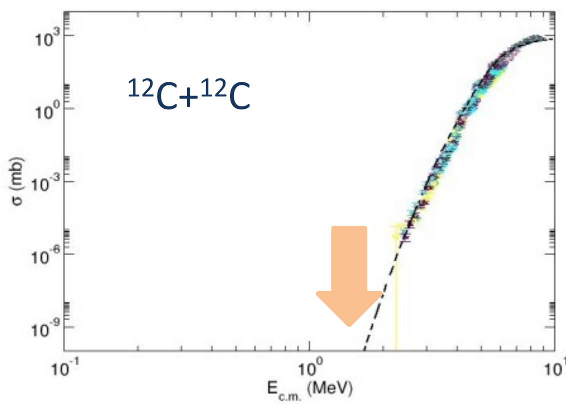
Nuclear reaction rates

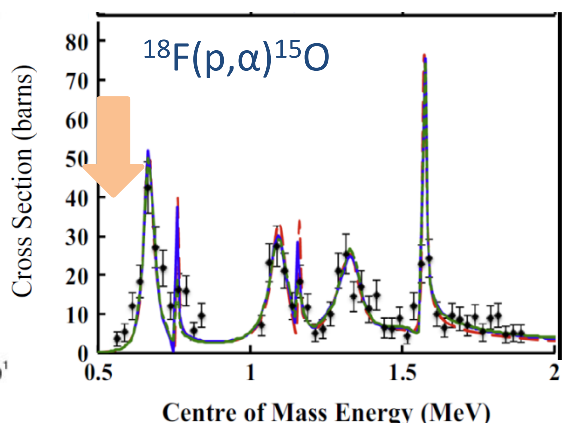
determine, energy production, isotopic abundance distribution, timescale of stellar events – **The art of the game is to identify the critical ones!**

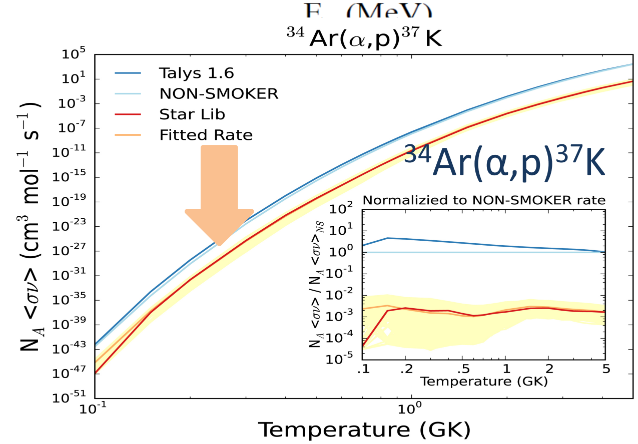






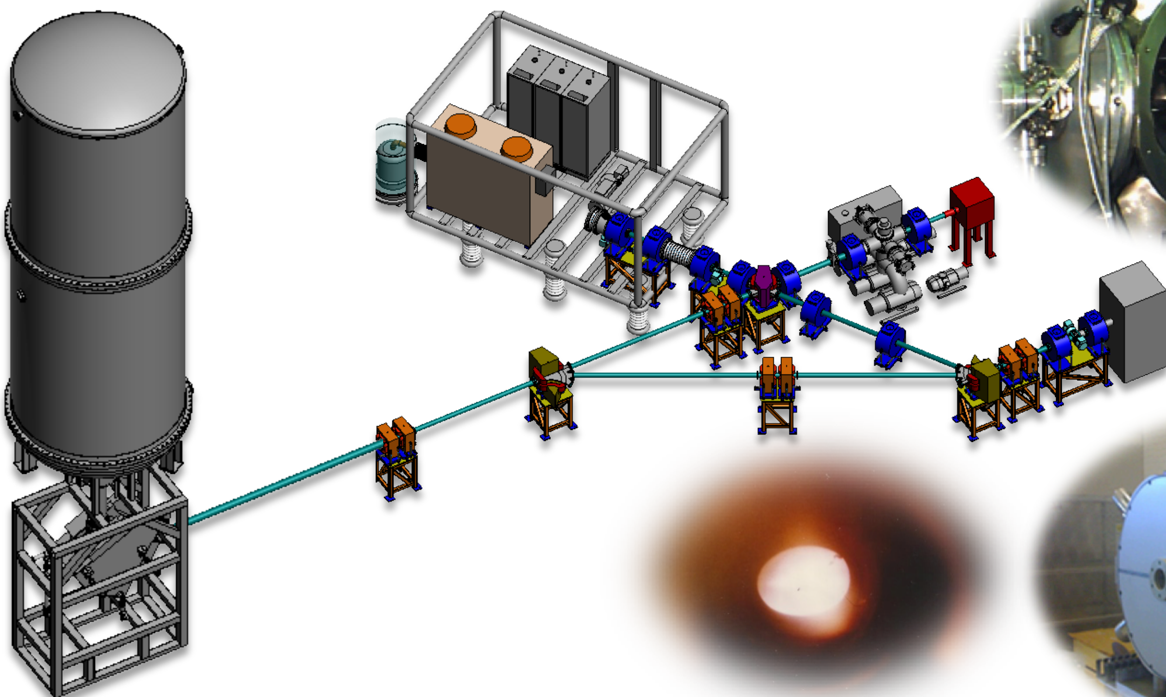


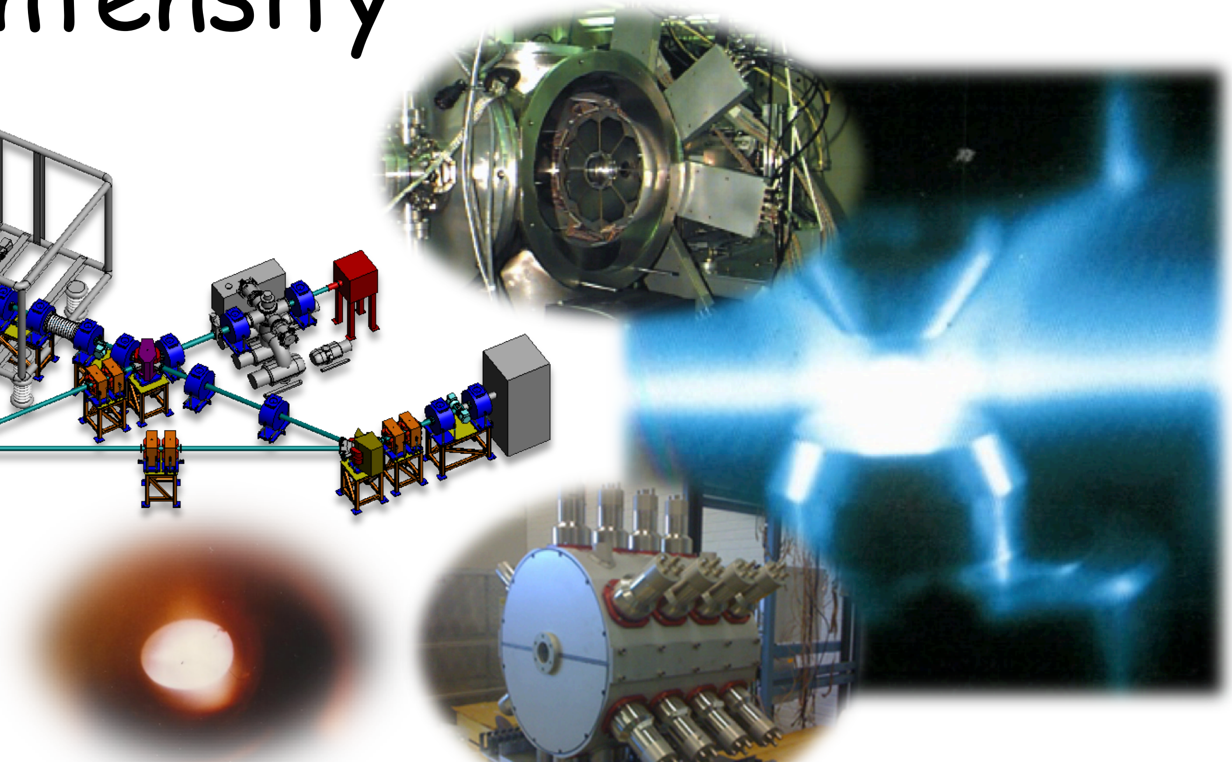




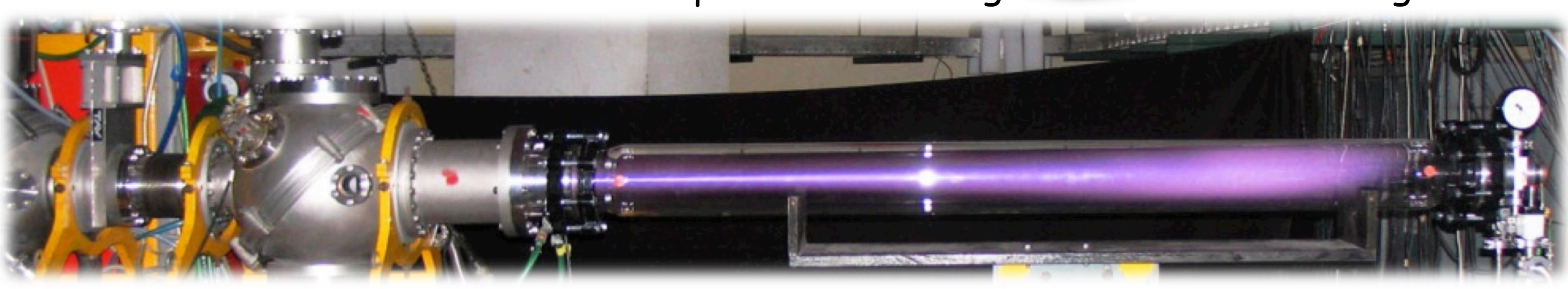
Challenge is to model the experimental cross sections towards a reliable form to translate into reaction rates: Direct reaction models, R-matrix, statistical HF model are all part of the game!

Stable beam experiments with high beam intensity





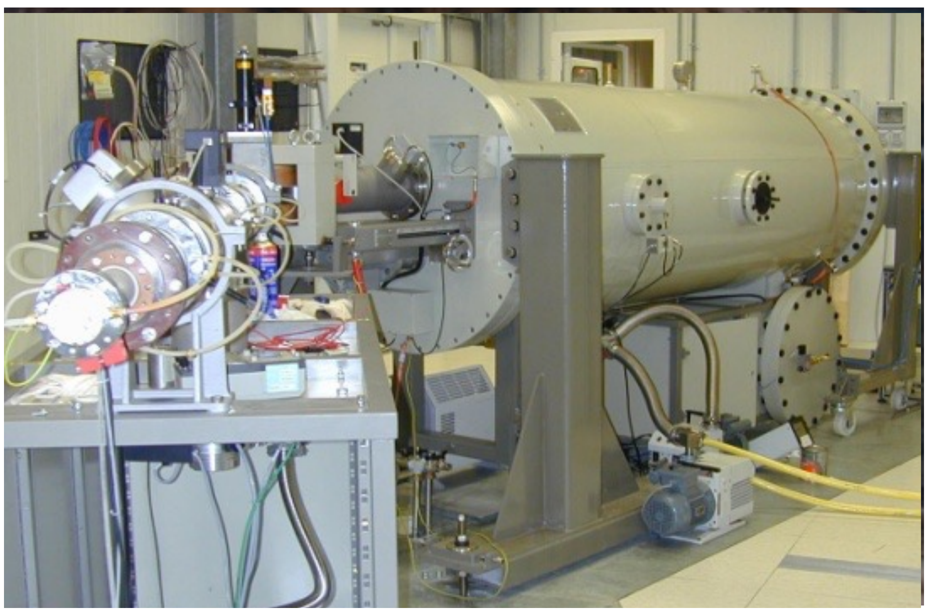
Yield measurements with particle and/or gamma detector arrangements

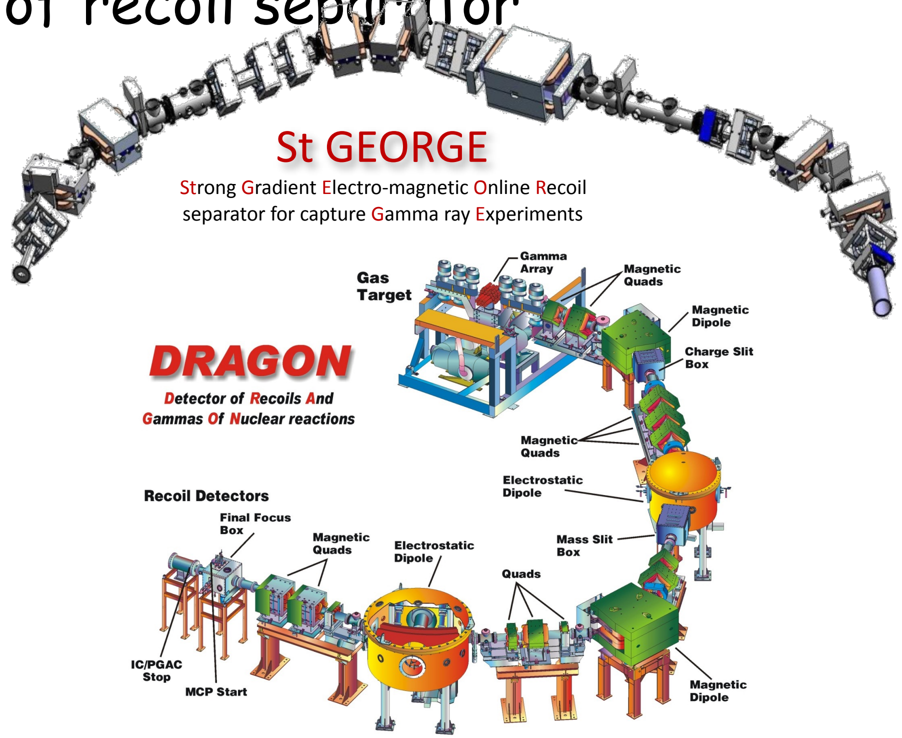


Forward or inverse kinematics

Light ion on heavy target with measurement of light reaction products, limited by solid angle and detection efficiency.

Heavy ion on light target with measurement of heavy ion recoil yield, limited by initial beam intensity and acceptance of recoil separator





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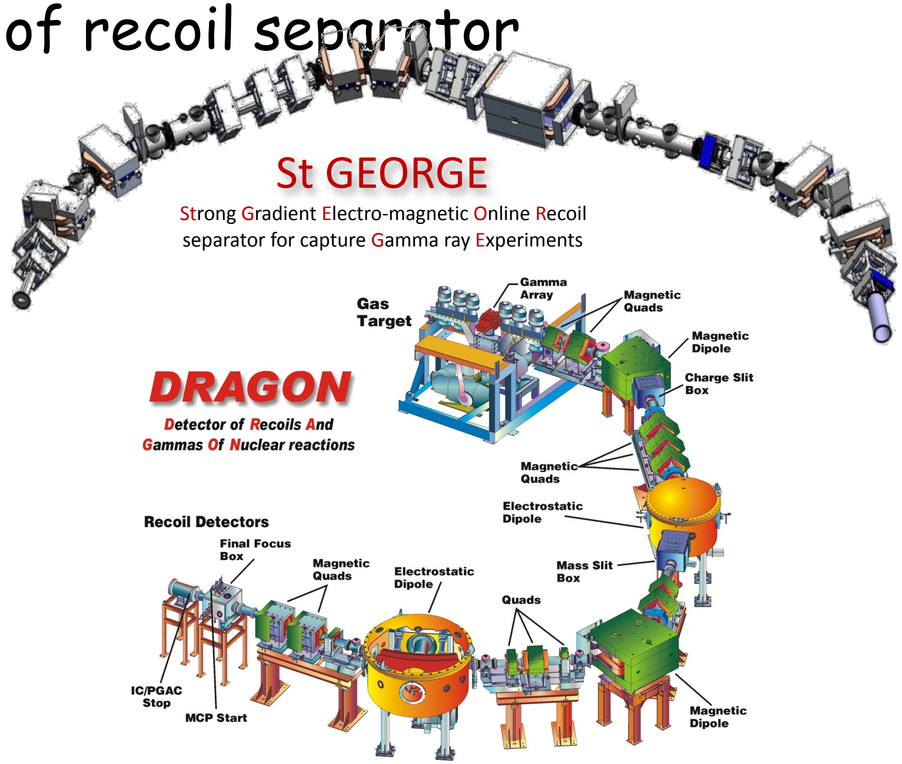
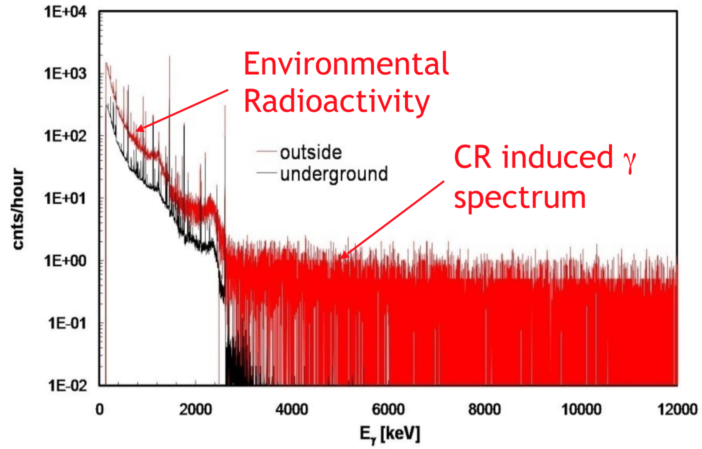
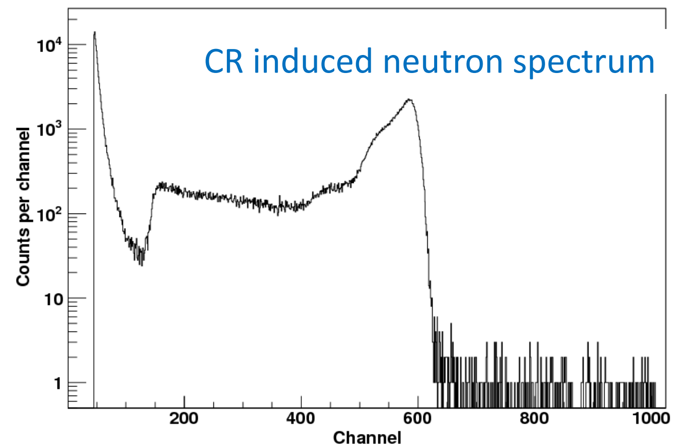
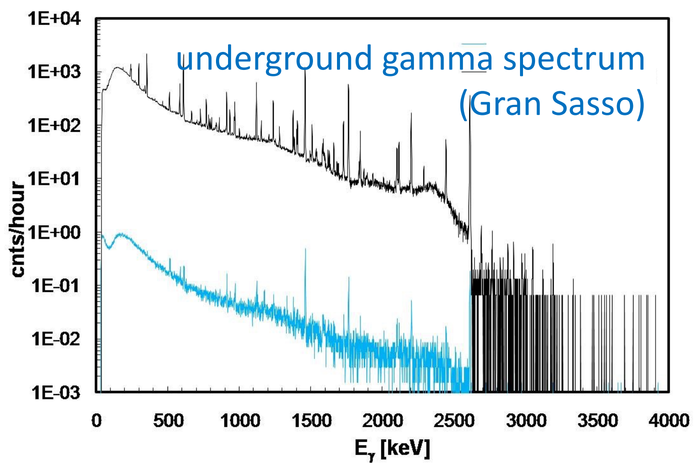


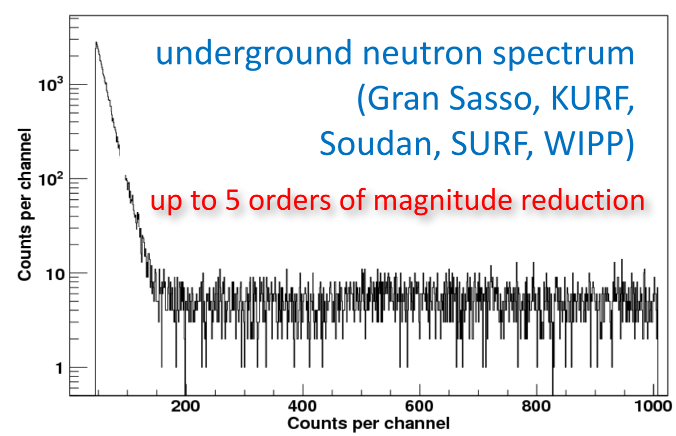
Underground Accelerator Location

Main advantage reduction of CR induced background







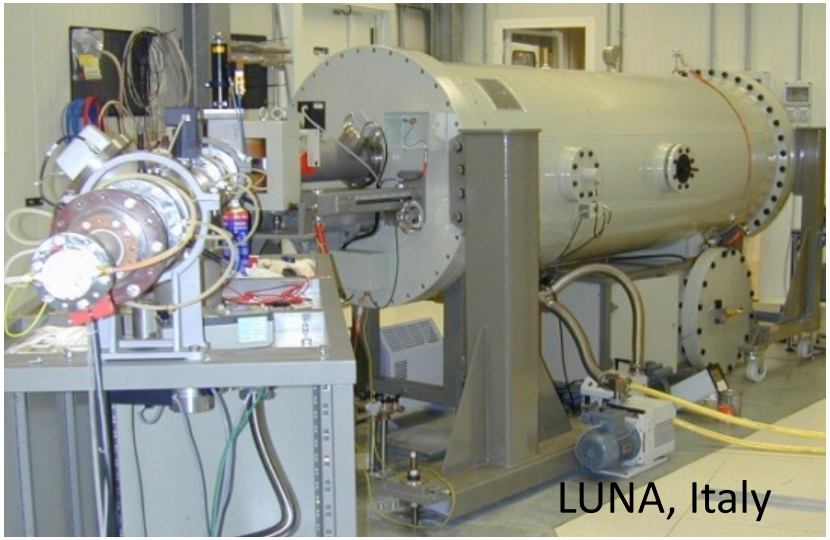


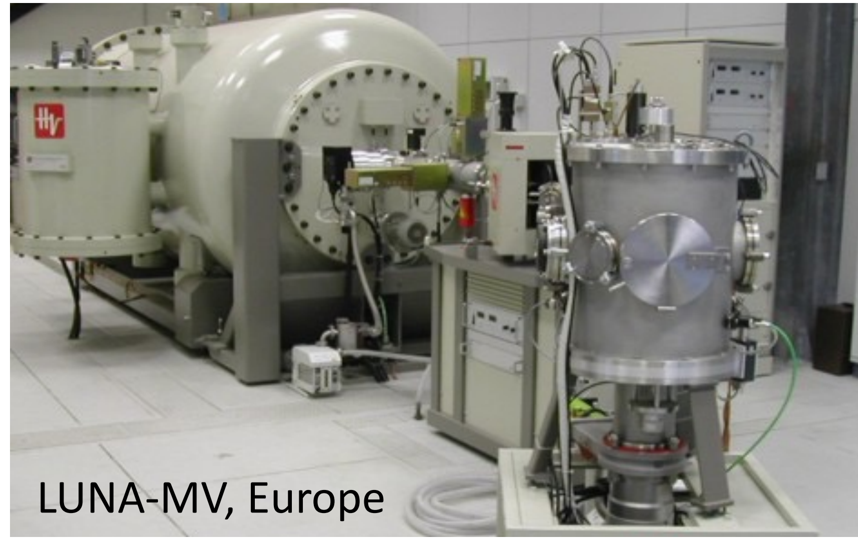
High luminosity, low background experiments

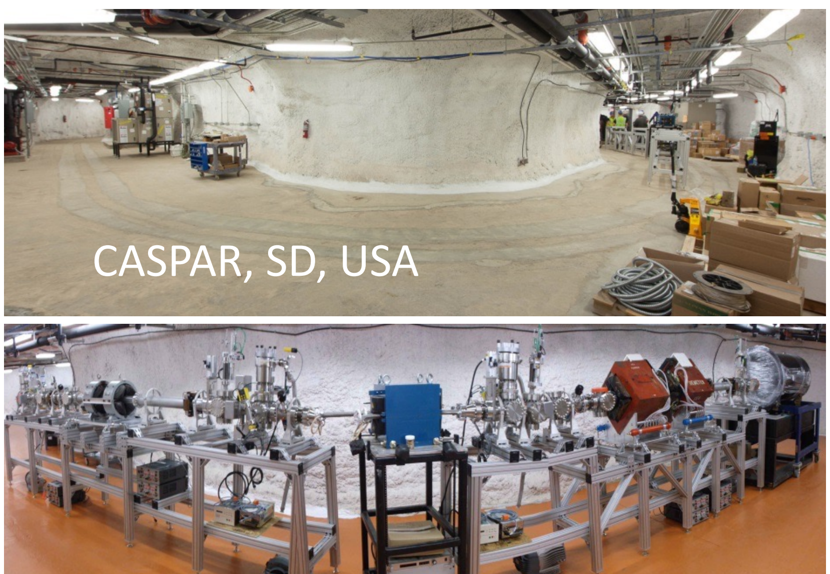
Underground accelerator project DIANA for low energy studies

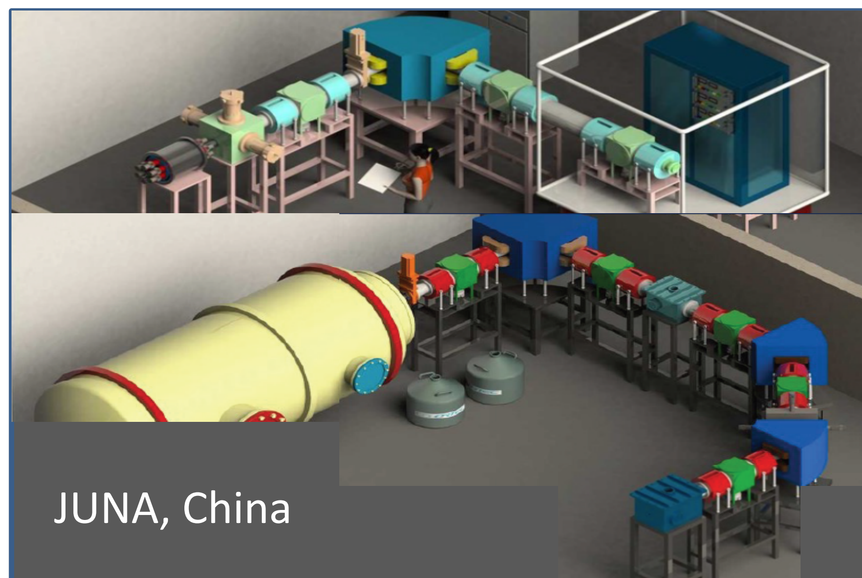
High luminosity, low background experiments

LUNA(-MV), CASPAR, JUNA

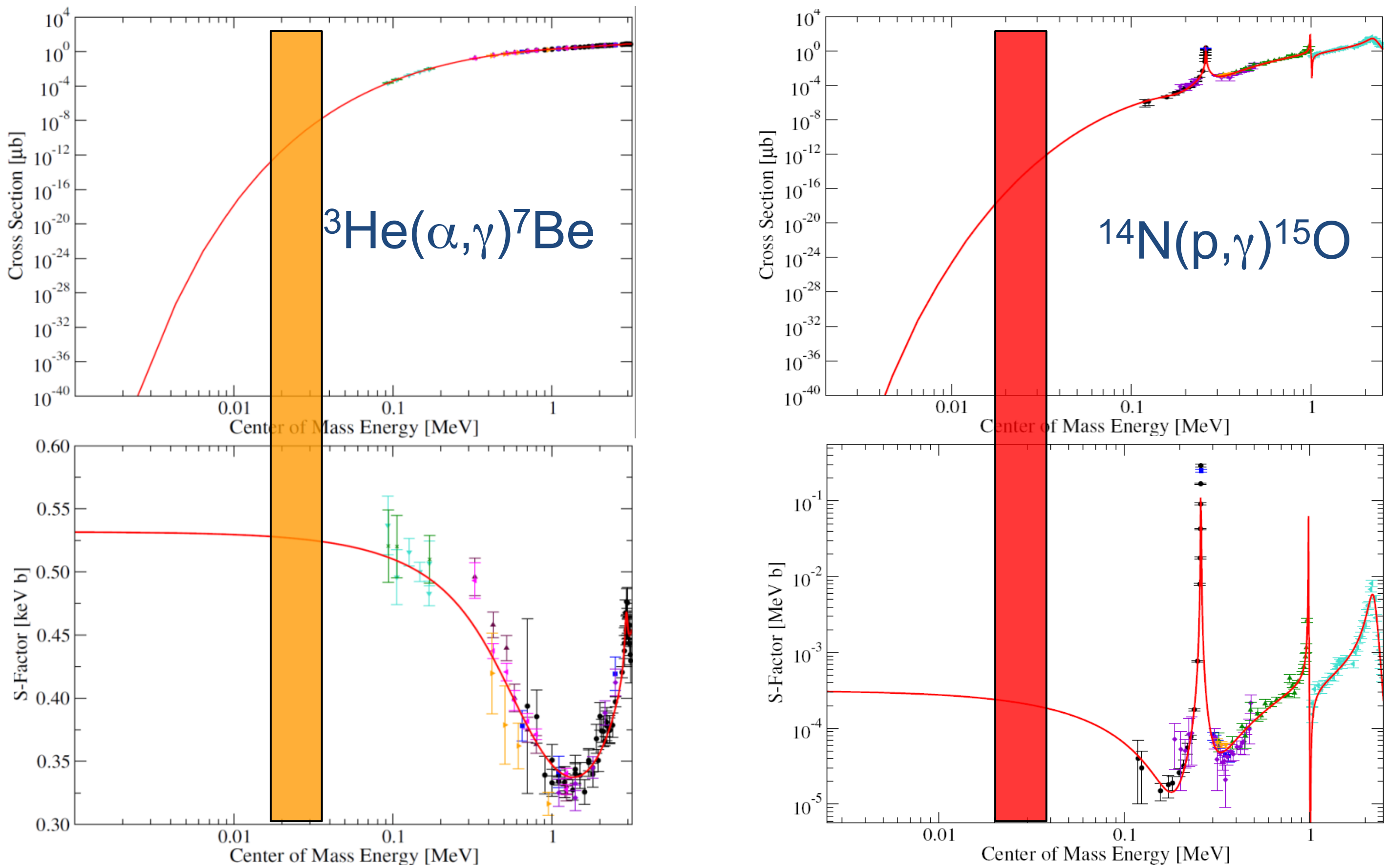








Achievements in hydrogen burning



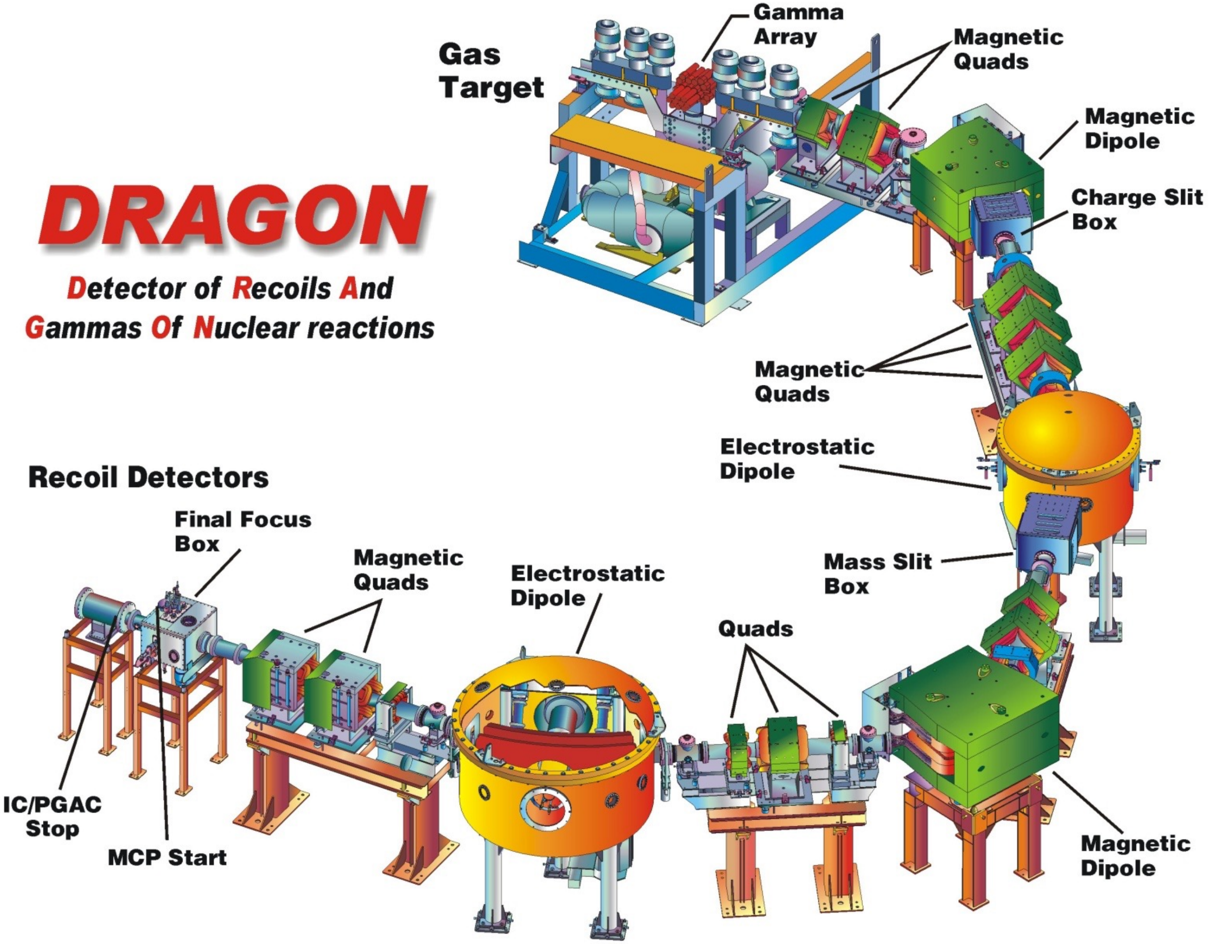
Reliable extrapolation necessitates understanding of the threshold effects and the various contributing resonant and non-resonant reaction mechanisms. That requires complementing low energy studies with measurements over a wide energy range!

Inverse kinematics with recoil separators

Number of successful measurements using inverse kinematics

First CTAG (Caltech) DRAGON (TRIUMF), and ERNA (Bochum)

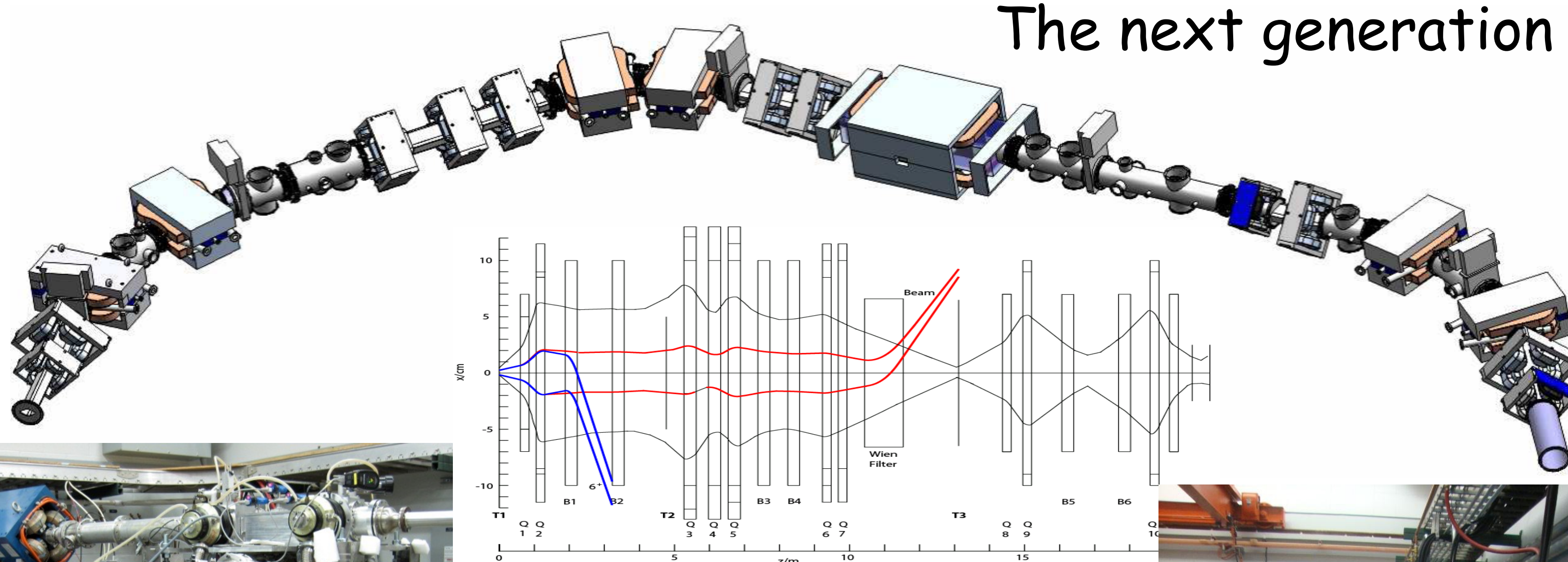
$^{3}He(\alpha,\gamma)^{7}Be$
$^{12}C(\alpha,\gamma)^{16}O$
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{17}O(\alpha,\gamma)^{21}Ne$
$^{40}Ca(\alpha,\gamma)^{44}Ti$

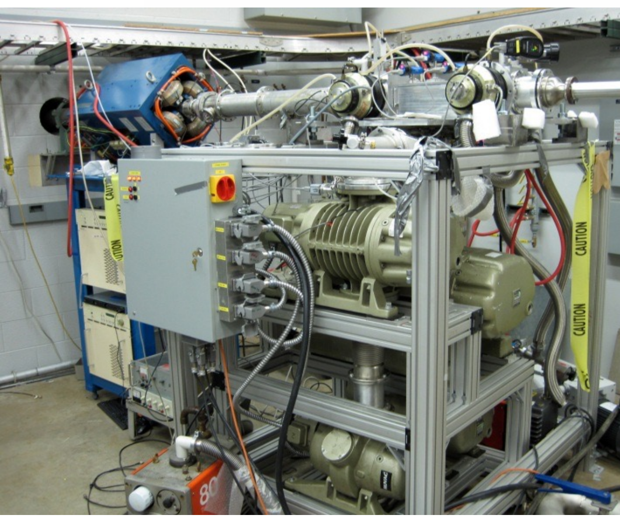


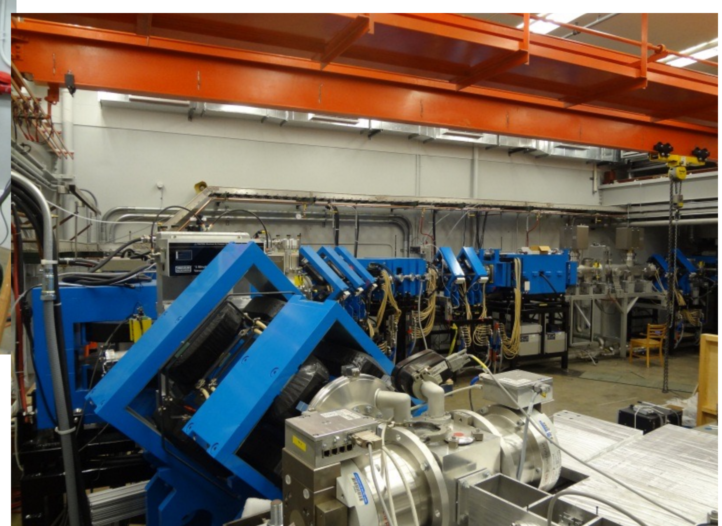
Efforts at Caserta, Italy, ERNA → DIOCLETIAN

St. George Separator

The next generation

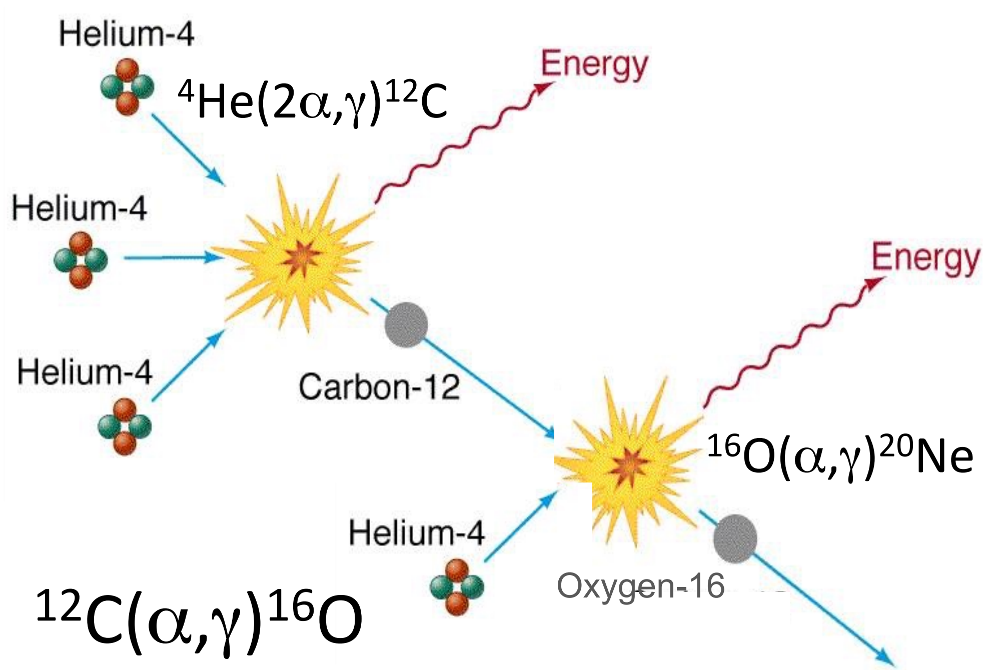


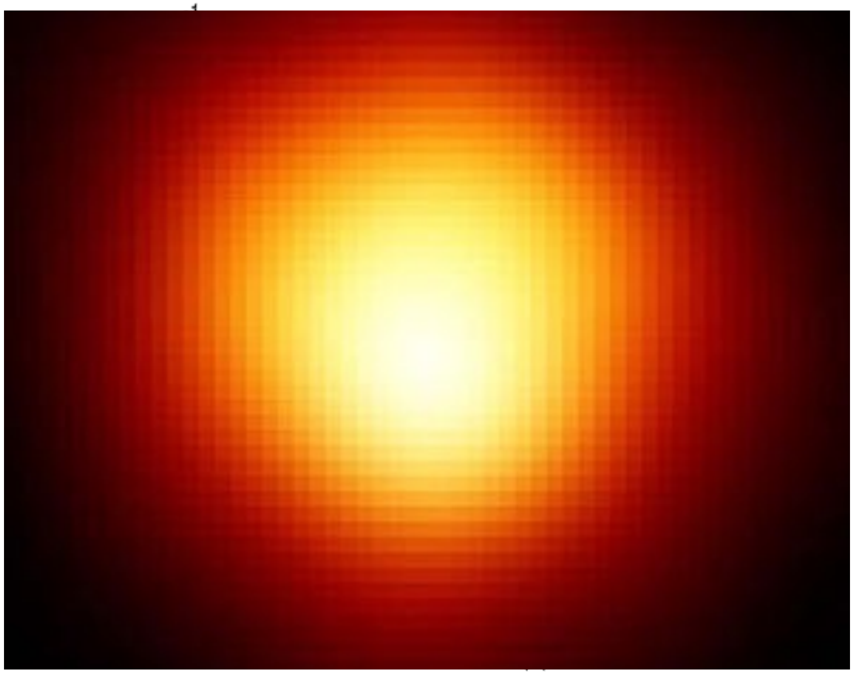




HIPPO jet gas target System (HIgh Pressure POint-like gas target)

Nucleosynthesis in He burning





The reactions determines the $^{12}C/^{16}O$ ratio in our universe! It also defines the late stellar evolution of massive stars, determines white dwarf matter, the ignition of supernovae type Ia, the standard candle for cosmological predictions.

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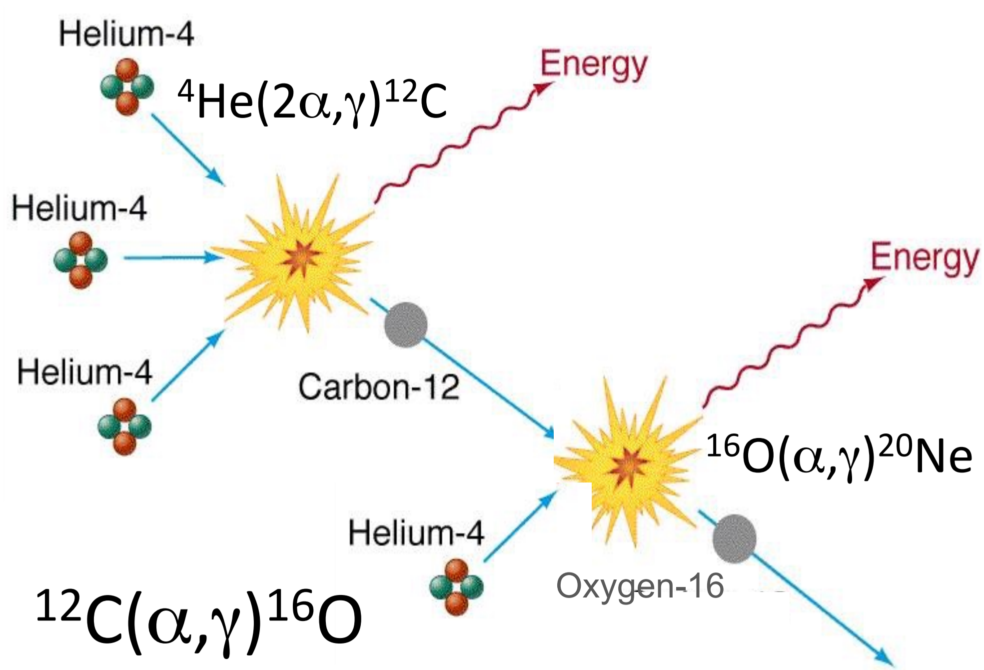

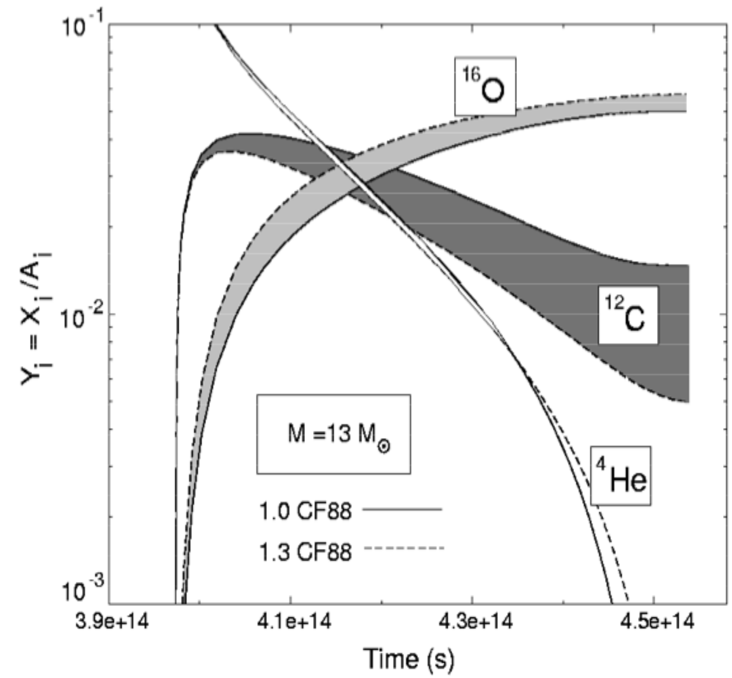

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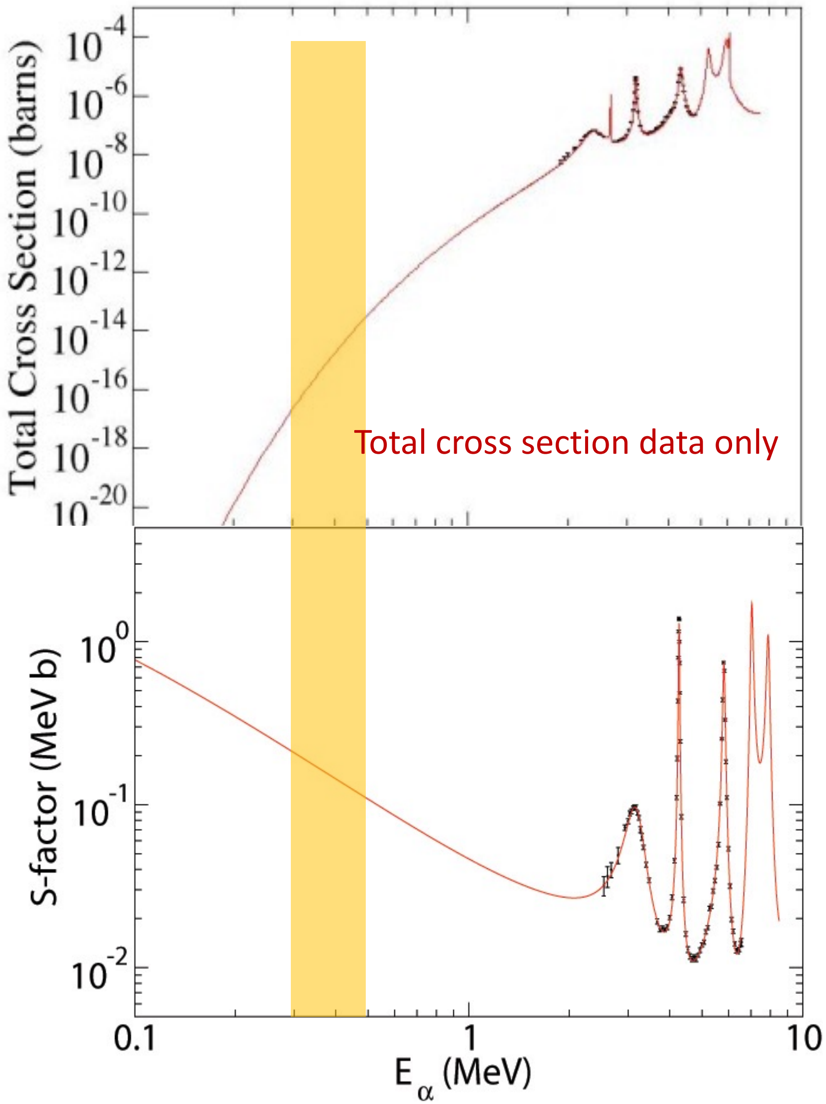
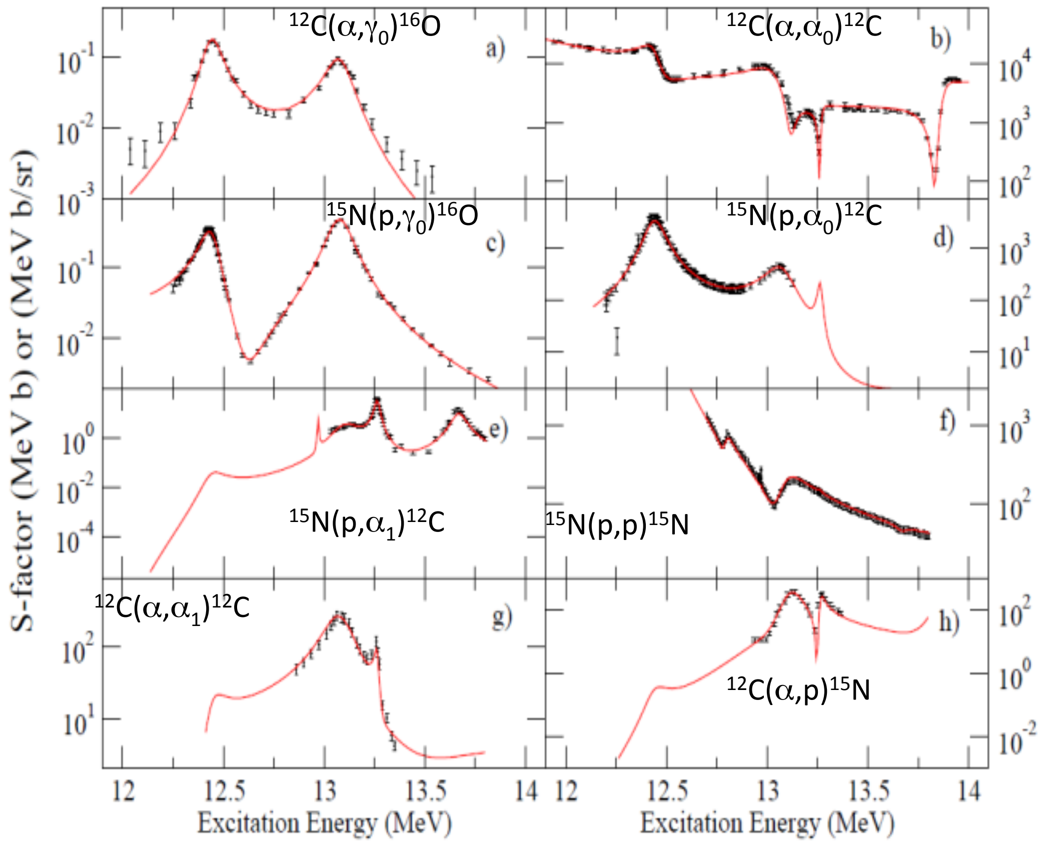
Energy Sources in Helium Burning

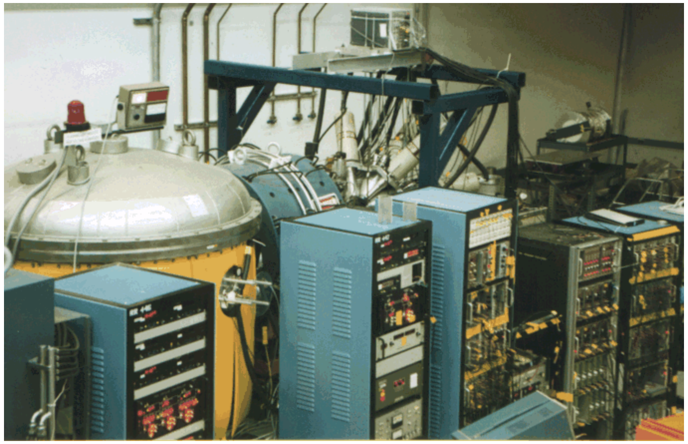




New low energy data are needed to improve reliability of R-matrix (AZURE) based cross section extrapolation.

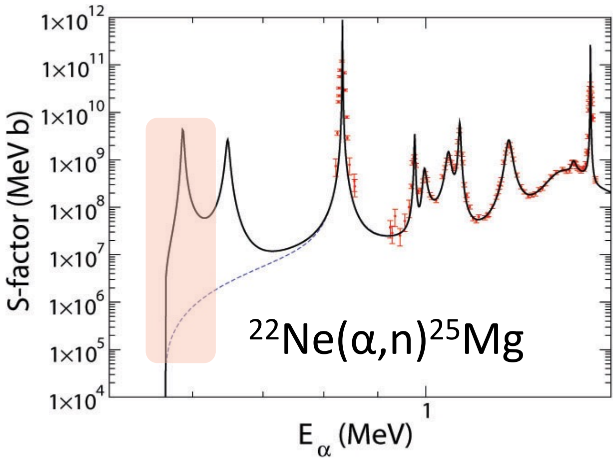
Indirect techniques to probe low energy nuclear structure and reaction features

Reaction rates are nuclear physics! Arbitrary scaling may be a useful phenomenological approach to probe their relevance, but nuclear structure and reaction theory is necessary for providing guidance and setting limits!

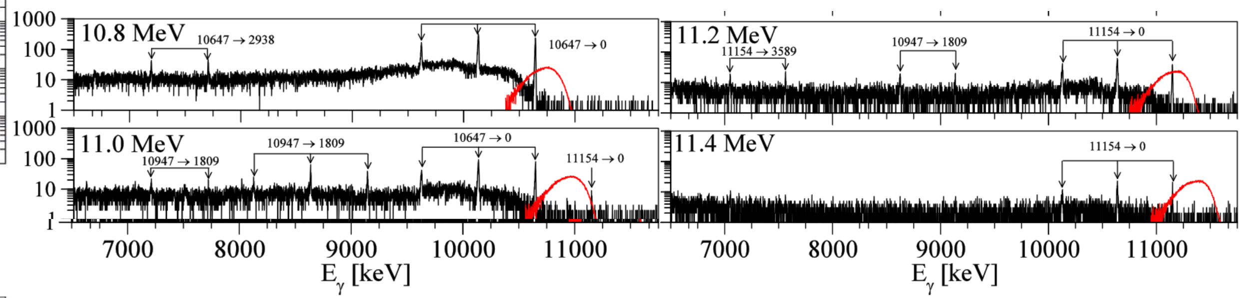



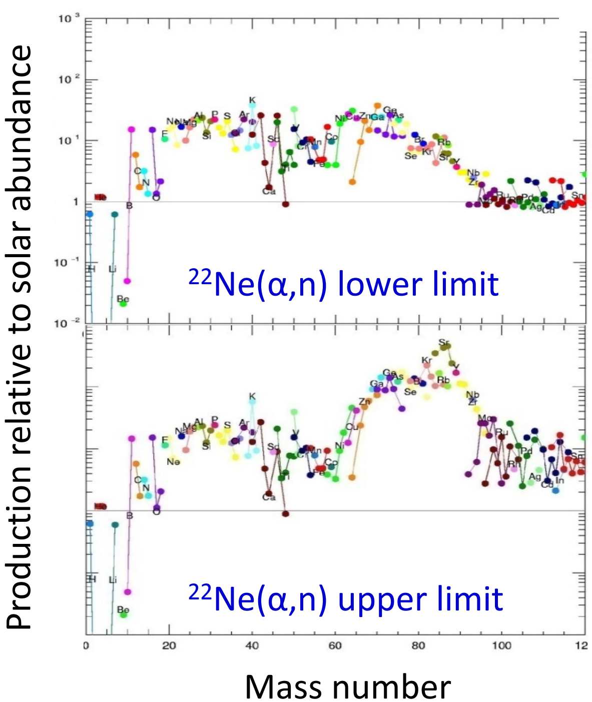

Single particle or alpha transfer are used as surrogates, THM/ANC methods, lifetime measurements, Coulomb dissociation studies, all provide a scale for low energy extrapolation! Yet direct measurements close to the stellar energy range are the ultimate goal!

Stellar Neutron Source

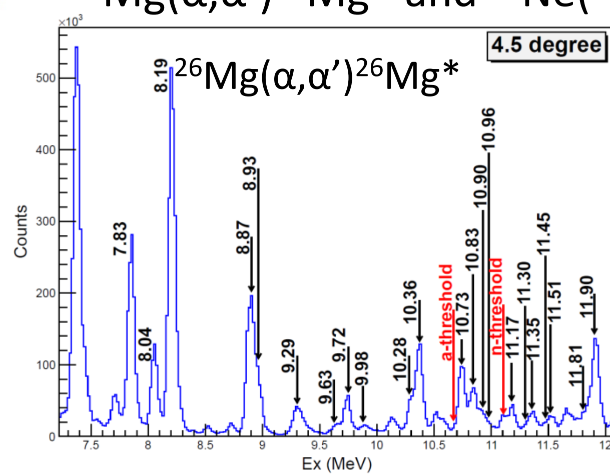


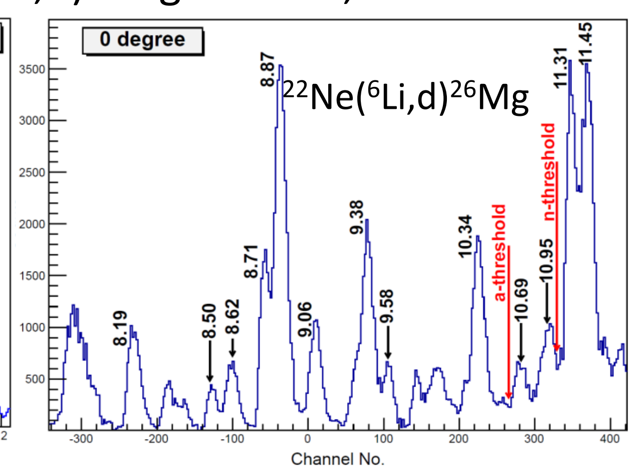
Alternative Approaches using photon techniques:
Mapping the excitation range in ^{26}Mg with:
$^{26}Mg(\gamma,\gamma')^{26}Mg^*$ and $^{26}Mg(\gamma,n)^{25}Mg$ at HIγS, TUNL
and $^{25}Mg(n,\gamma)^{26}Mg$ at n_ToF, CERN



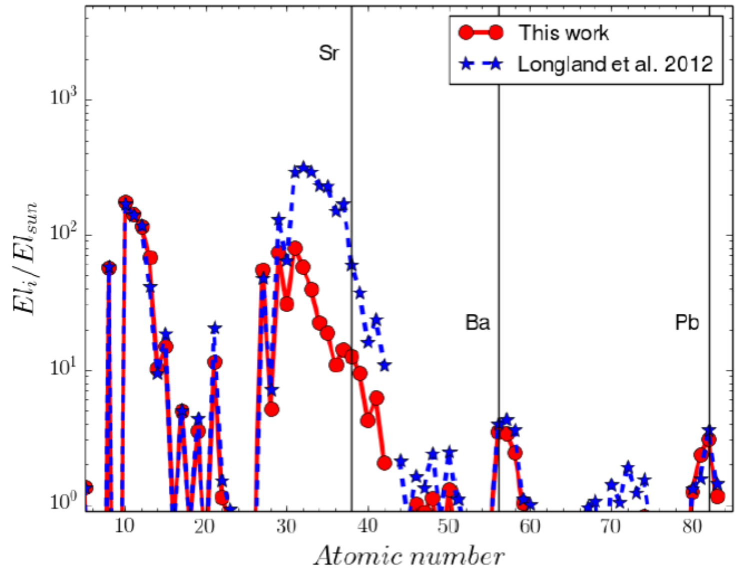


Indirect measures with scattering or transfer techniques:
Mapping the excitation range in ^{26}Mg with:
$^{26}Mg(\alpha,\alpha')^{26}Mg^*$ and $^{22}Ne(^6Li,d)^{26}Mg$ at RCNP, Osaka





Impact of measurements on s-process

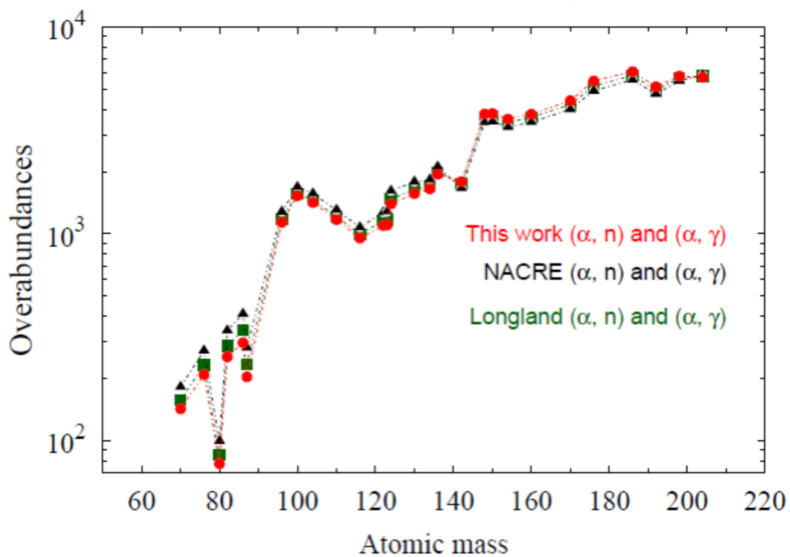


New results indicate a weaker role for the ^{22}Ne(α,n) neutron source in s-process environments due to the strength of the competing ^{22}Ne(α,γ) reaction!

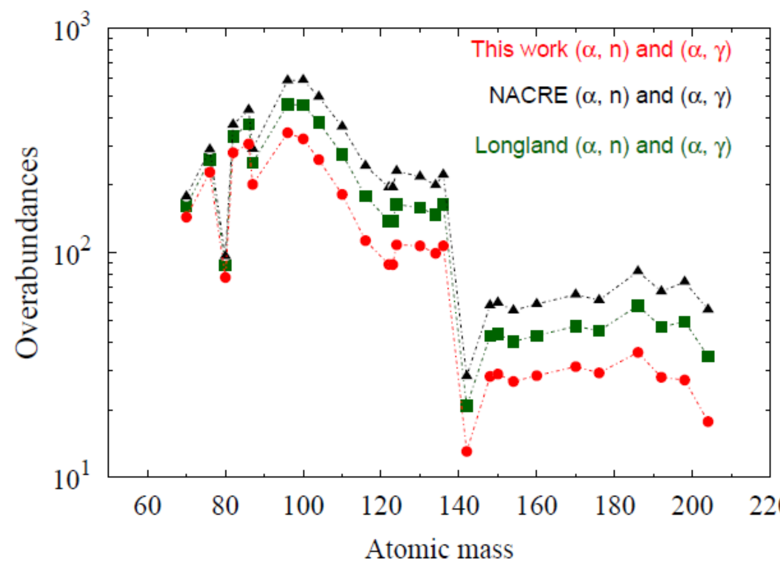
Weak s-process nucleosynthesis in a 25M_o star affecting nucleosynthesis up to mass A=100.

Main s-process in 3M_o and 5M_o AGB stars enriching heavy mass abundances up to Pb-Bi

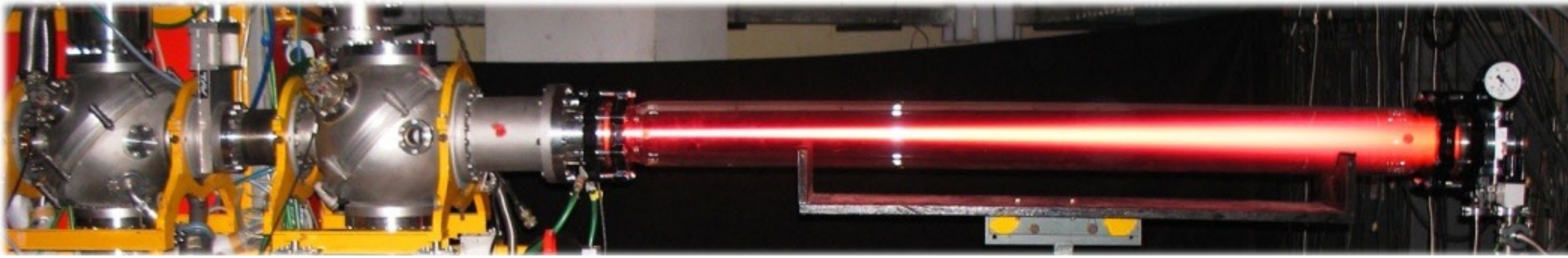
M = 3 M_o; [Fe/H] = -1

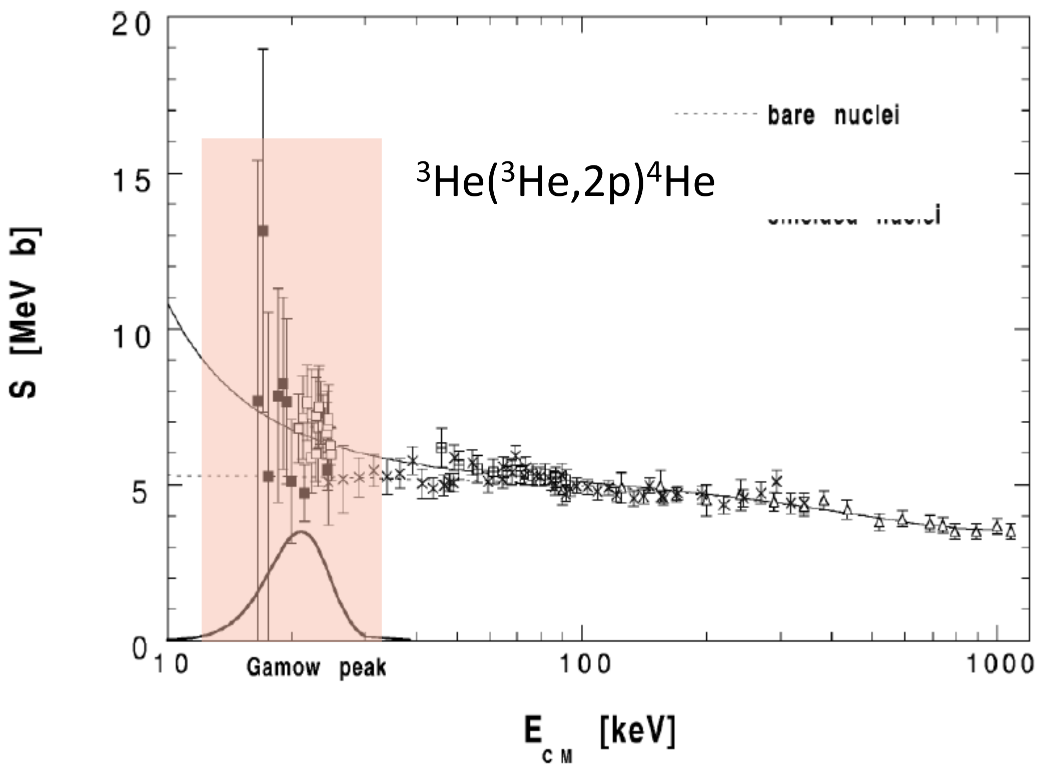


M = 5 M_o; [Fe/H] = -0.3



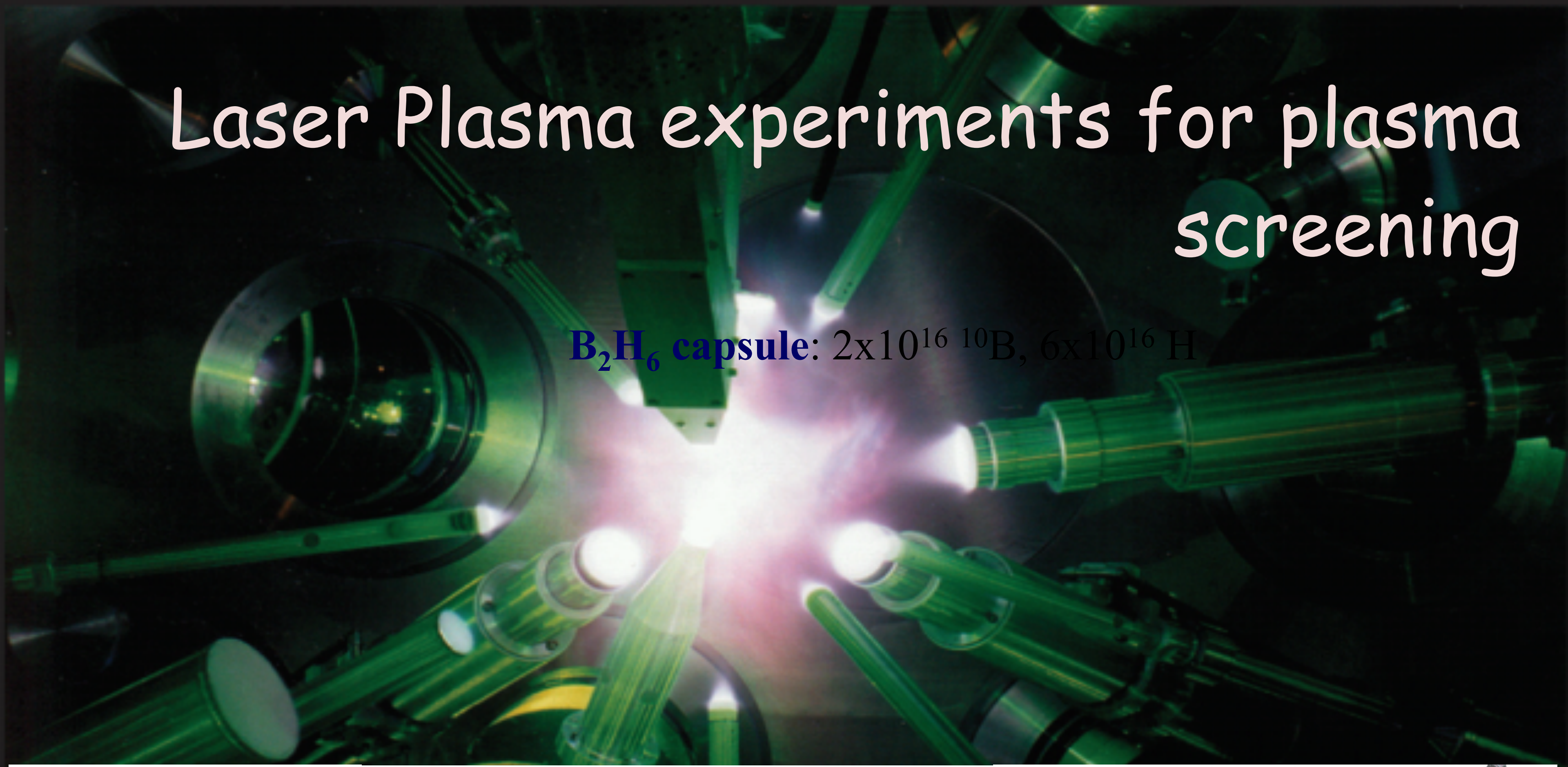
Low energy challenges in experiment and stellar plasma environments



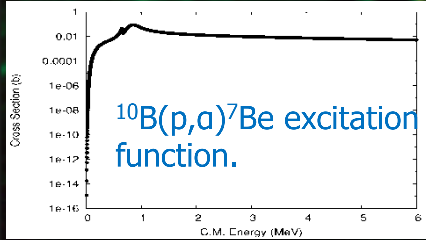


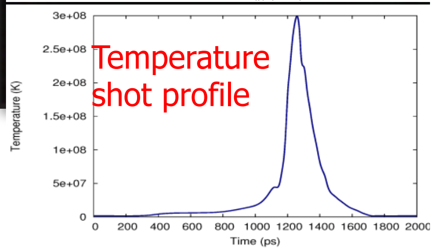
The S-factor increase at low beam energies indicates strong electron screening by the low density target plasma. This effect is also expected for high density stellar plasma conditions. This observation of screening requires additional experiment studies to improve the reliability of S-factor

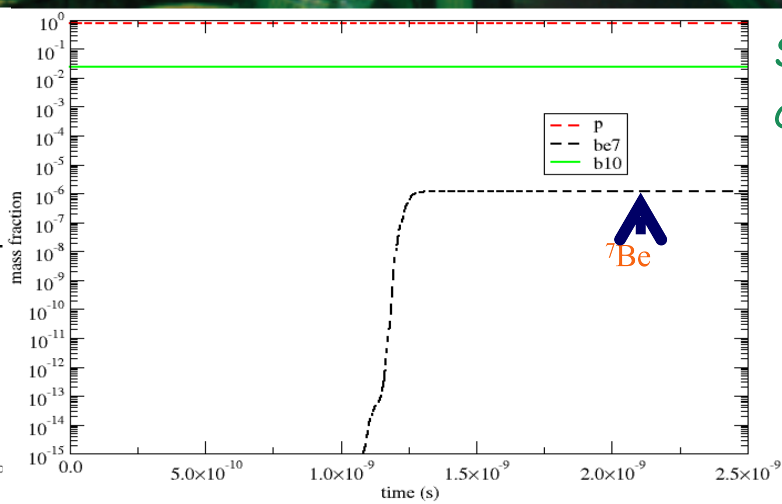
Laser Plasma experiments for plasma screening



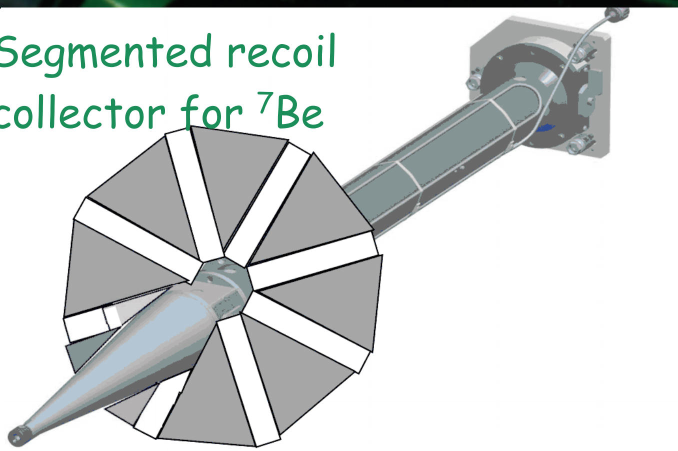
B_2H_6 capsule: 2×10^{16} ^{10}B, 6×10^{16} H







Segmented recoil collector for ^7Be

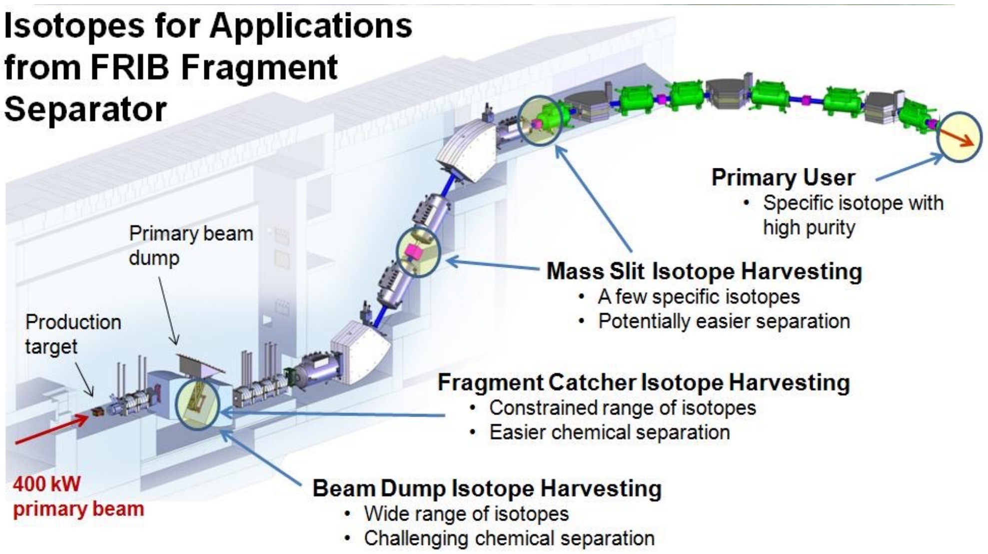


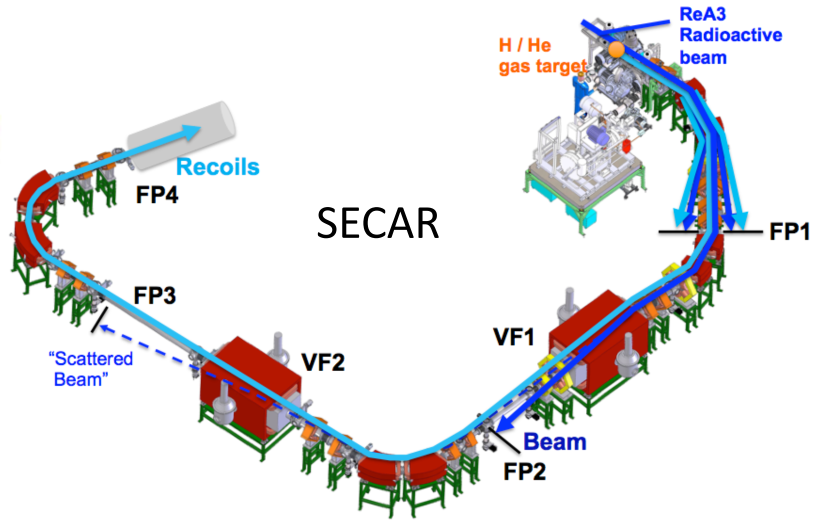
Radioactive beam facilities

FAIR, FRIB, REX-Isolde, RIKEN, SPES, SPIRAL and more to come …

Requirements for studies in nuclear astrophysics,

- ➢ Reactions: radioactive beam 0.1<E<2MeV/u studies using recoil separators
- ➢ Decay properties: stopping and collection with tape or trap





Inverse kinematics experiments with intense radioactive beams.

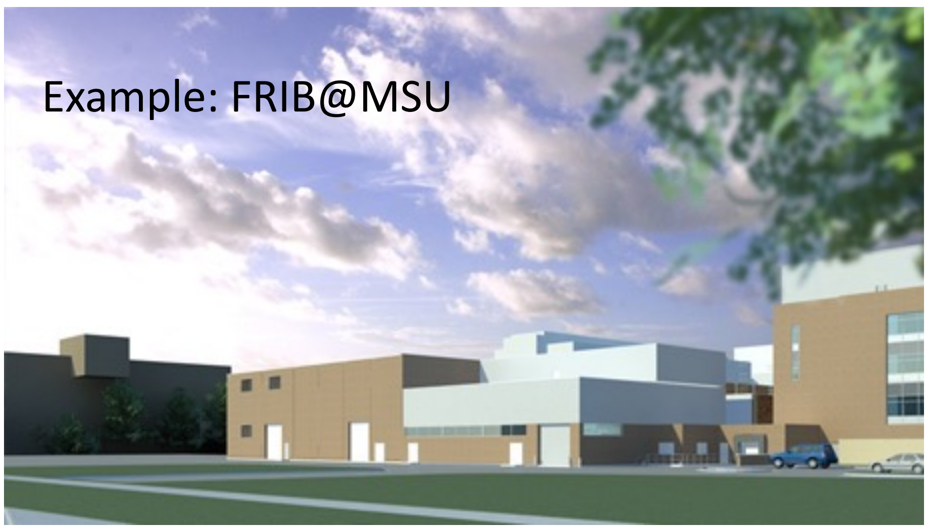
Complementary studies using indirect techniques are necessary!

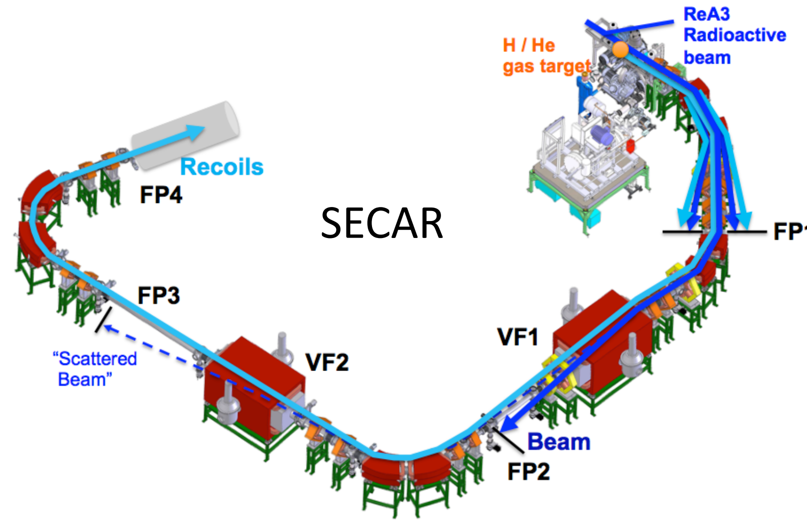
Radioactive beam facilities

FAIR, FRIB, REX-Isolde, RIKEN, SPES, SPIRAL and more to come …

Requirements for studies in nuclear astrophysics,

- Reactions: radioactive beam 0.1<E<2MeV/u studies using recoil separators
- Decay properties: stopping and collection with tape or trap



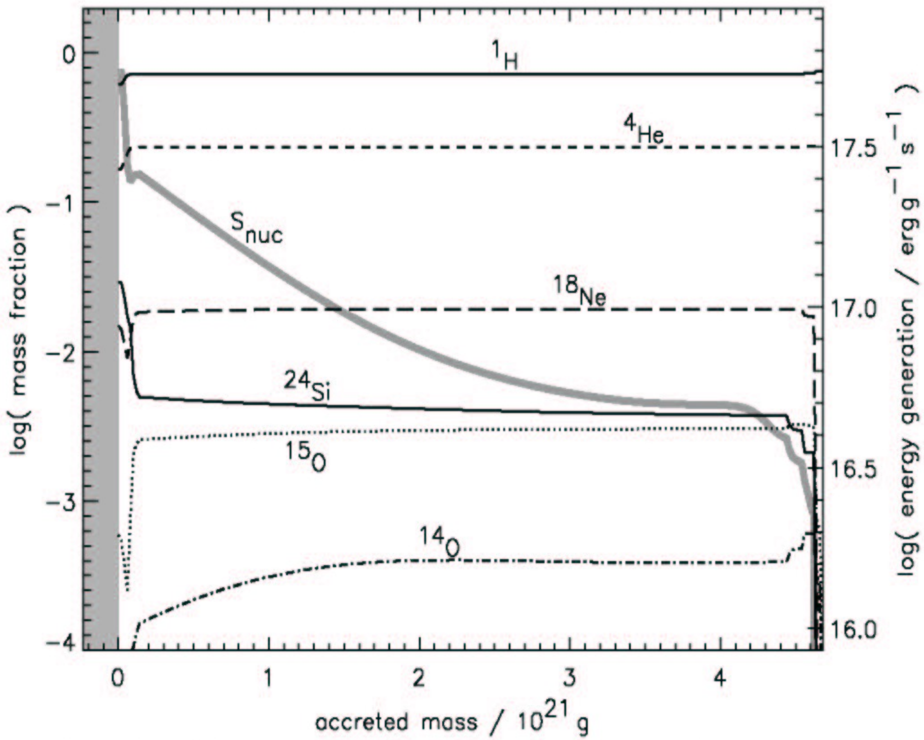


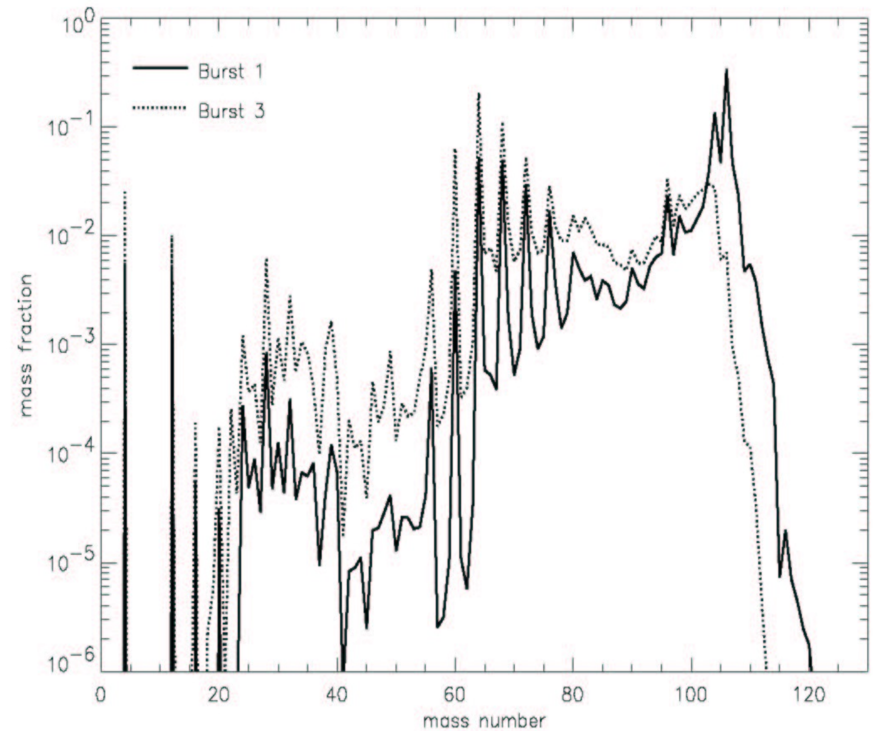
Inverse kinematics experiments with intense radioactive beams.

Complementary studies using indirect techniques are necessary!

Thermonuclear Runaways

Hot CNO cycles, driven by capture, limited by β decay
αp-process and rp-process driven by capture reactions





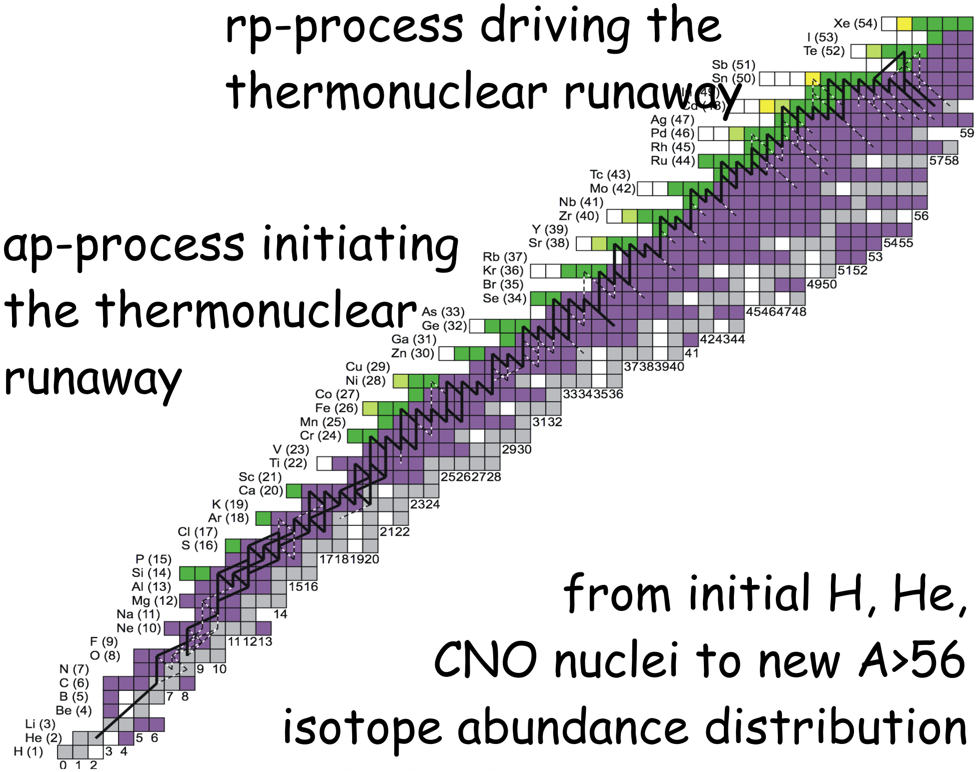
Thermonuclear Runaways

Hot CNO cycles, driven by capture, limited by β decay

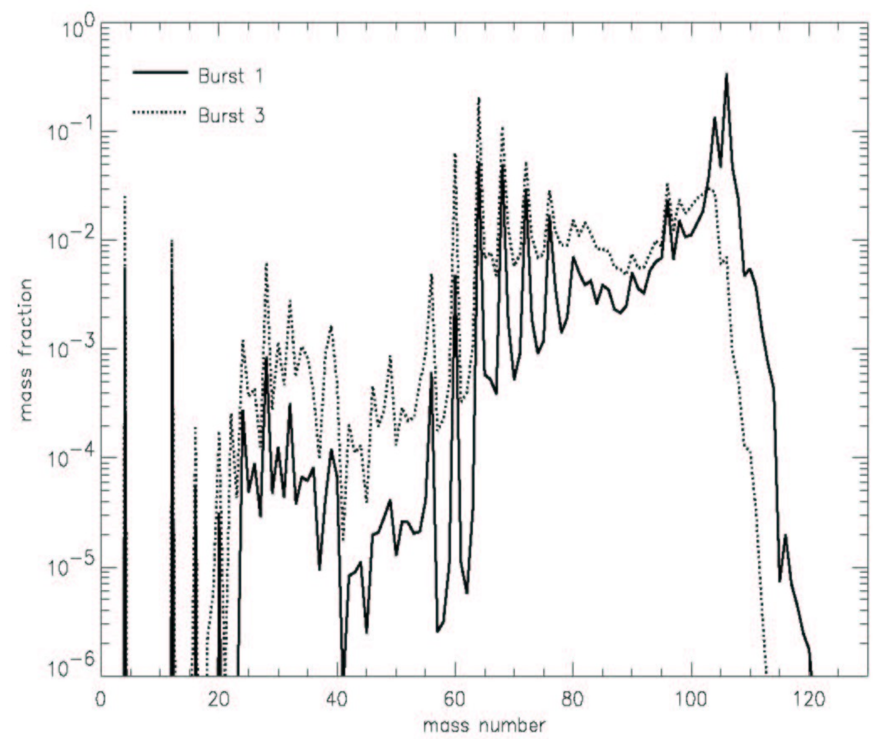
ap-process and rp-process driven by capture reactions

rp-process driving the thermonuclear runaway

ap-process initiating the thermonuclear runaway

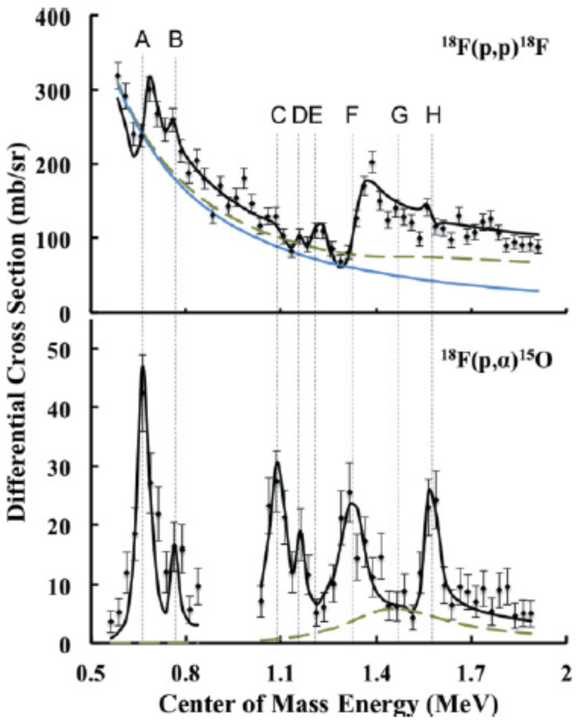


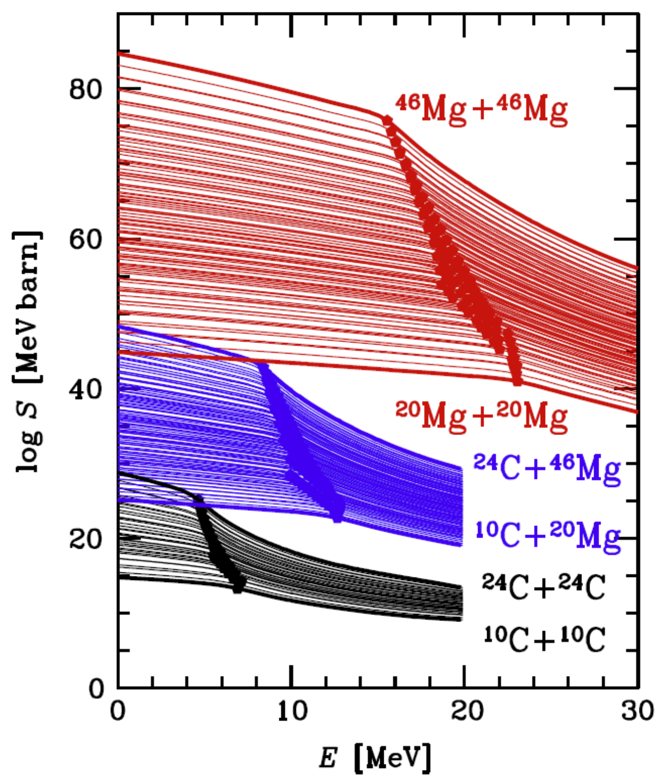
from initial H, He, CNO nuclei to new A>56 isotope abundance distribution



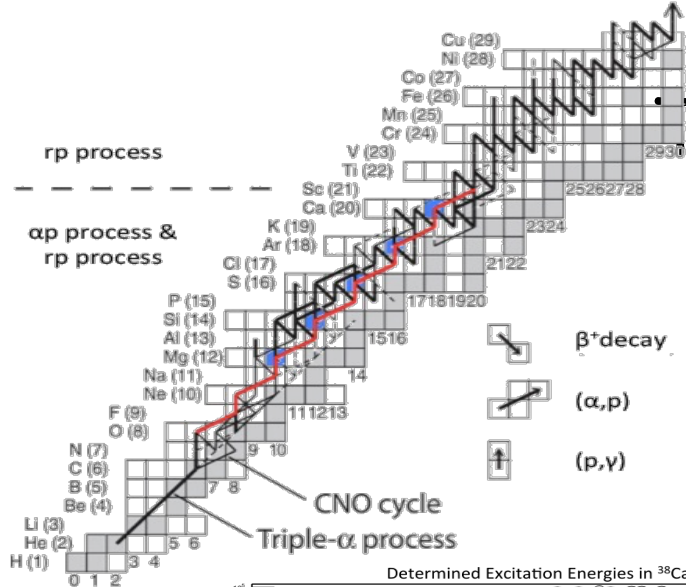
Most critical Reactions

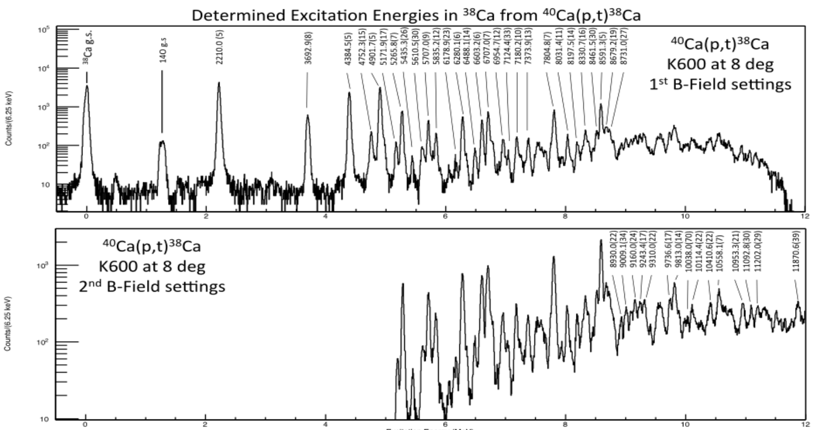
- Break-out from hot CNO cycles: $^{15}O(\alpha,\gamma)^{19}Ne$ $^{18}Ne(\alpha,p)^{21}Na$
- αp-process: $^{22}Mg(\alpha,p)^{25}Al$, $^{26}Si(\alpha,p)^{29}P$, $^{30}S(\alpha,p)^{33}Cl$, $^{34}Ar(\alpha,p)^{37}K$
- rp-process: $^{25}Al(p,\gamma)^{26}Si$, $^{56}Ni(p,\gamma)^{57}Cu$, $^{60}Zn(p,\gamma)^{61}Ga$ & Sn-Sb cycle
- Fusion reactions in pycno-nuclear burning of C to Ne isotopes

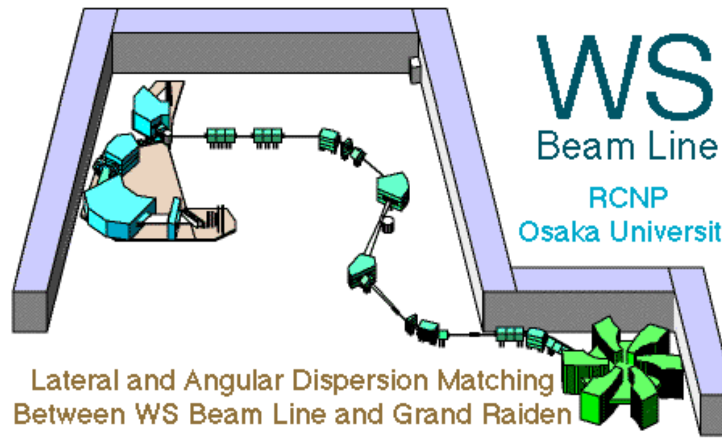


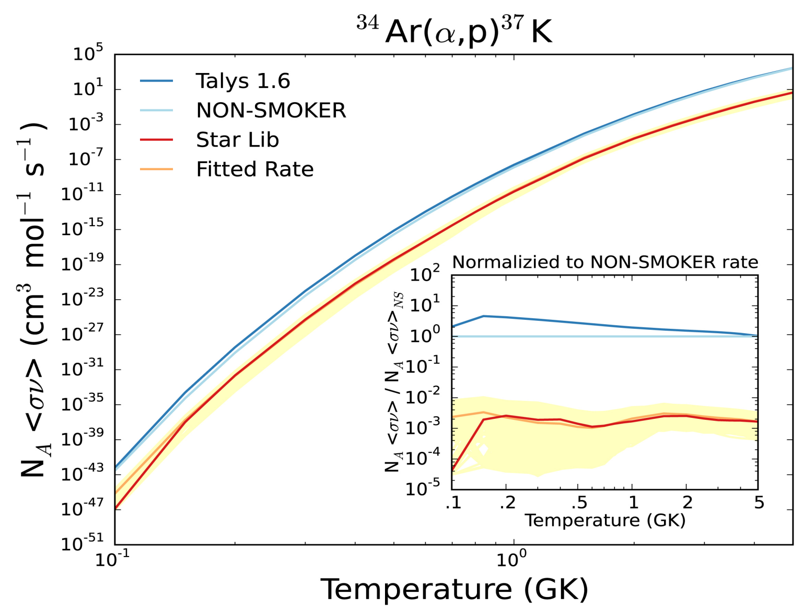


Transfer studies for probing resonance levels



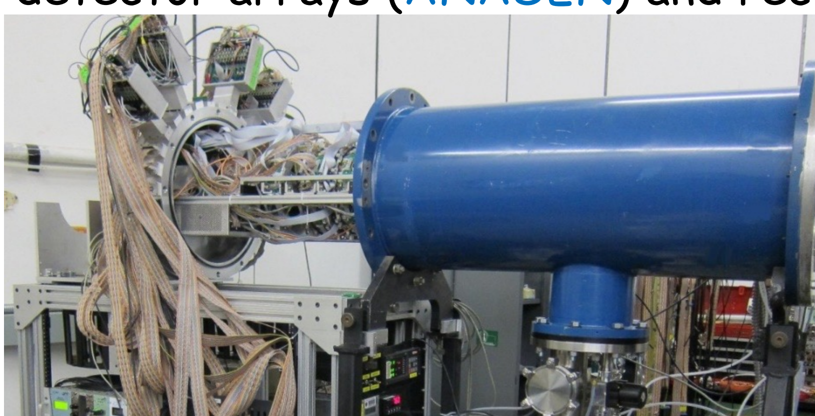


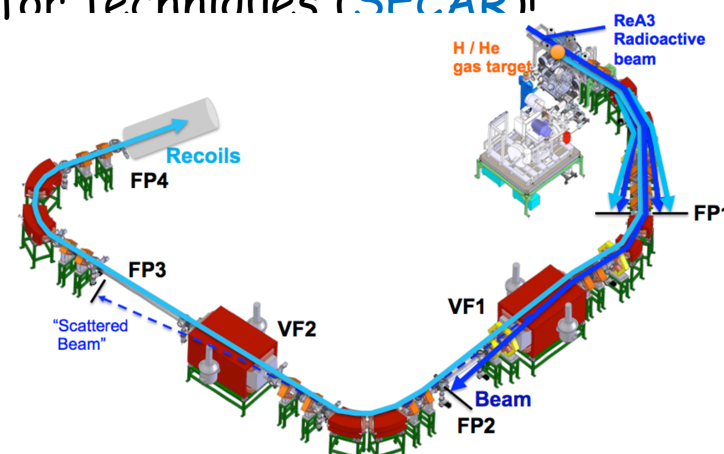




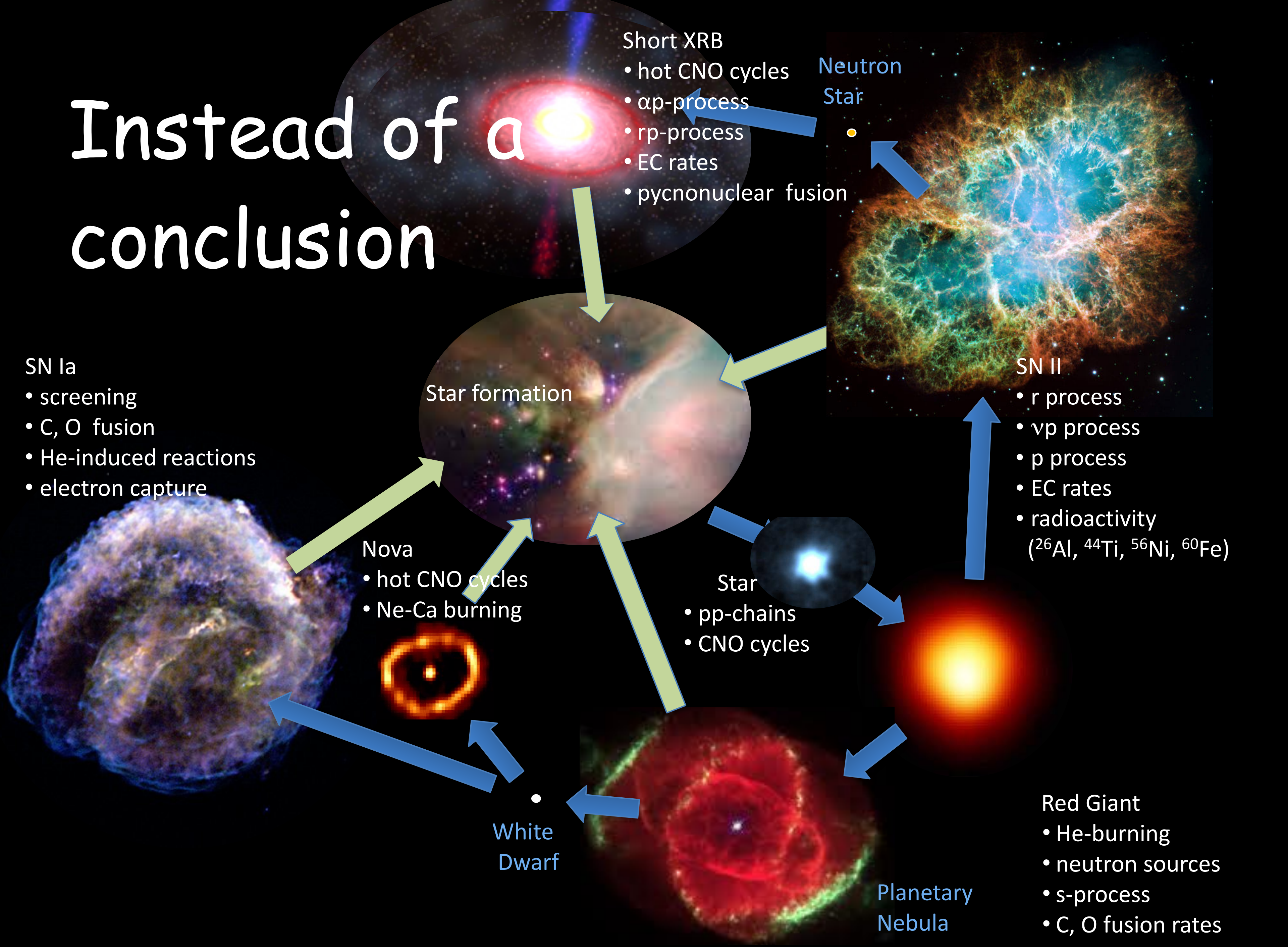
ANASEN & SECAR

Nuclear astrophysics experiments in inverse kinematics using multiple particle detector arrays (ANASEN) and recoil separator techniques (SECAR)!





Instead of a conclusion



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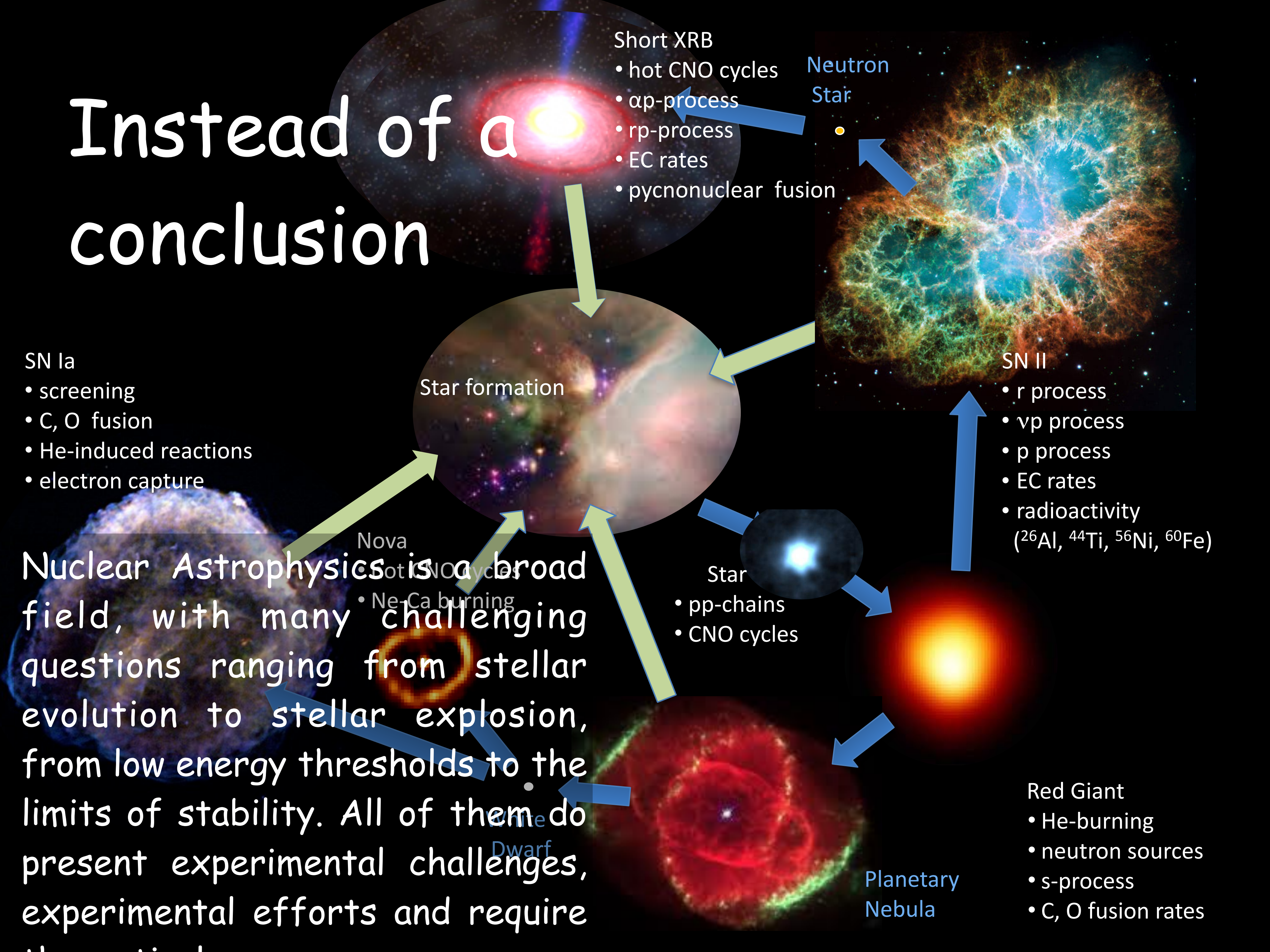
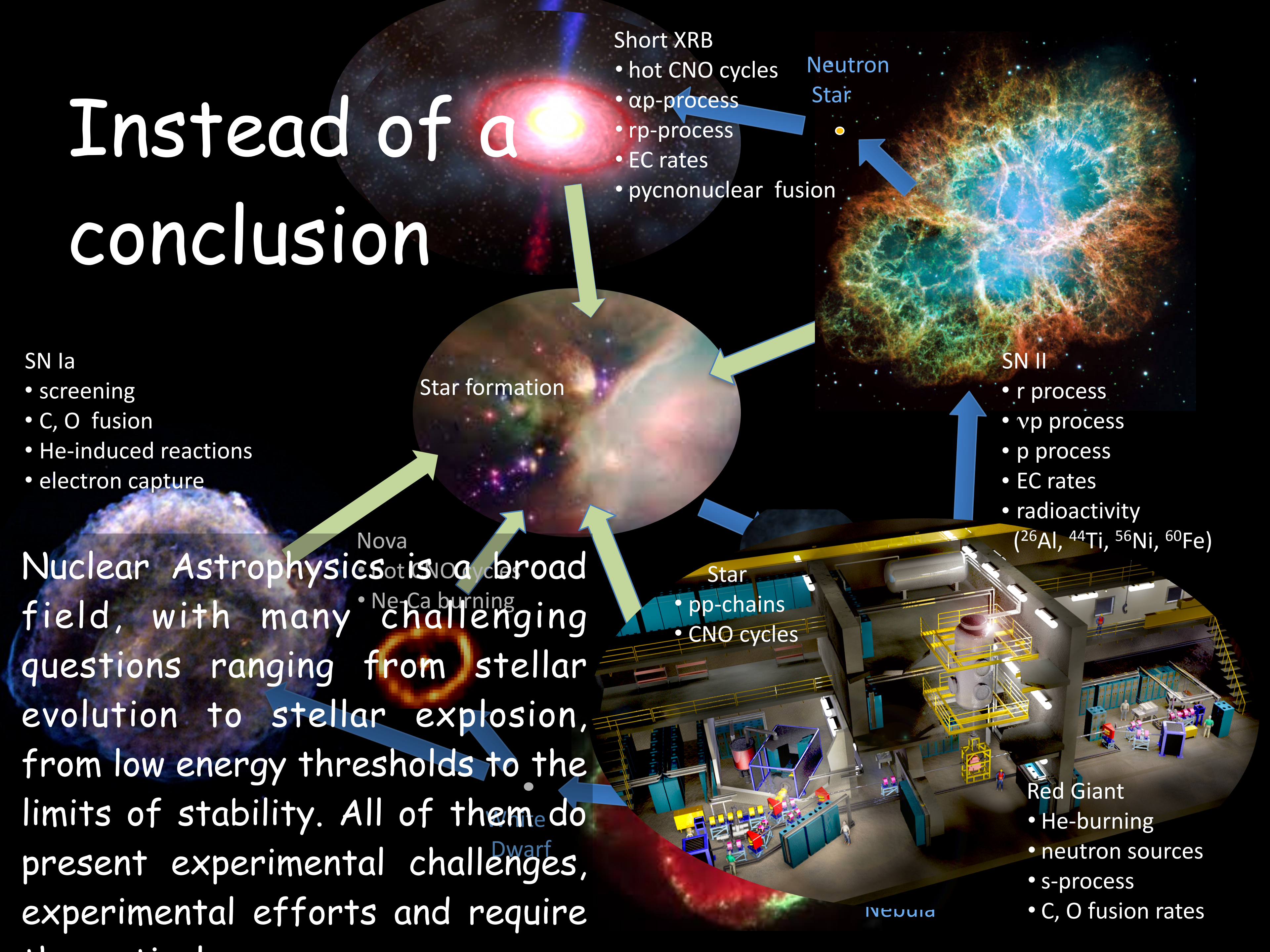


Nuclear Astrophysics is a broad field, with many challenging questions ranging from stellar evolution to stellar explosion, from low energy thresholds to the limits of stability. All of them do present experimental challenges, experimental efforts and require

Instead of a conclusion



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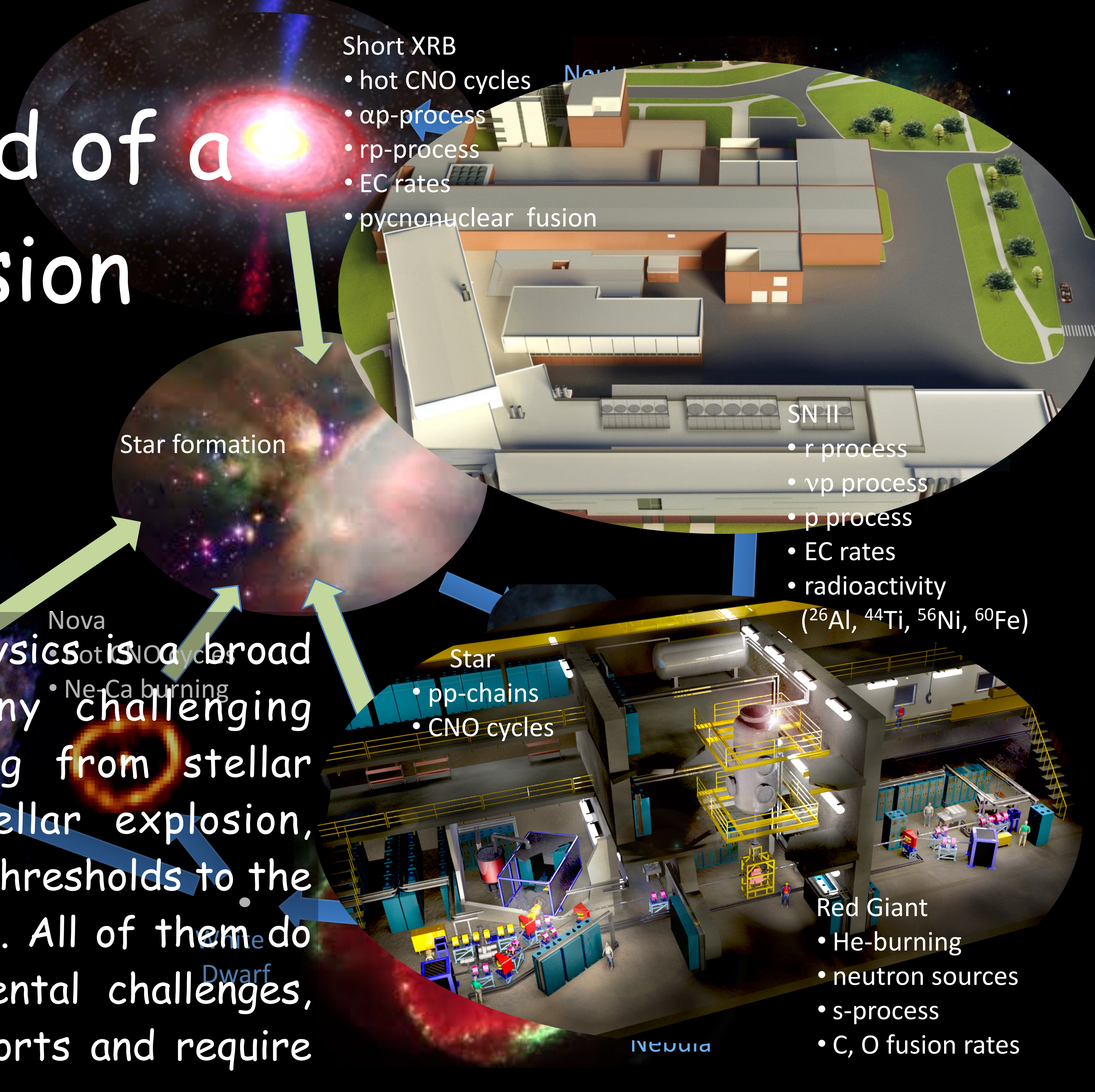

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