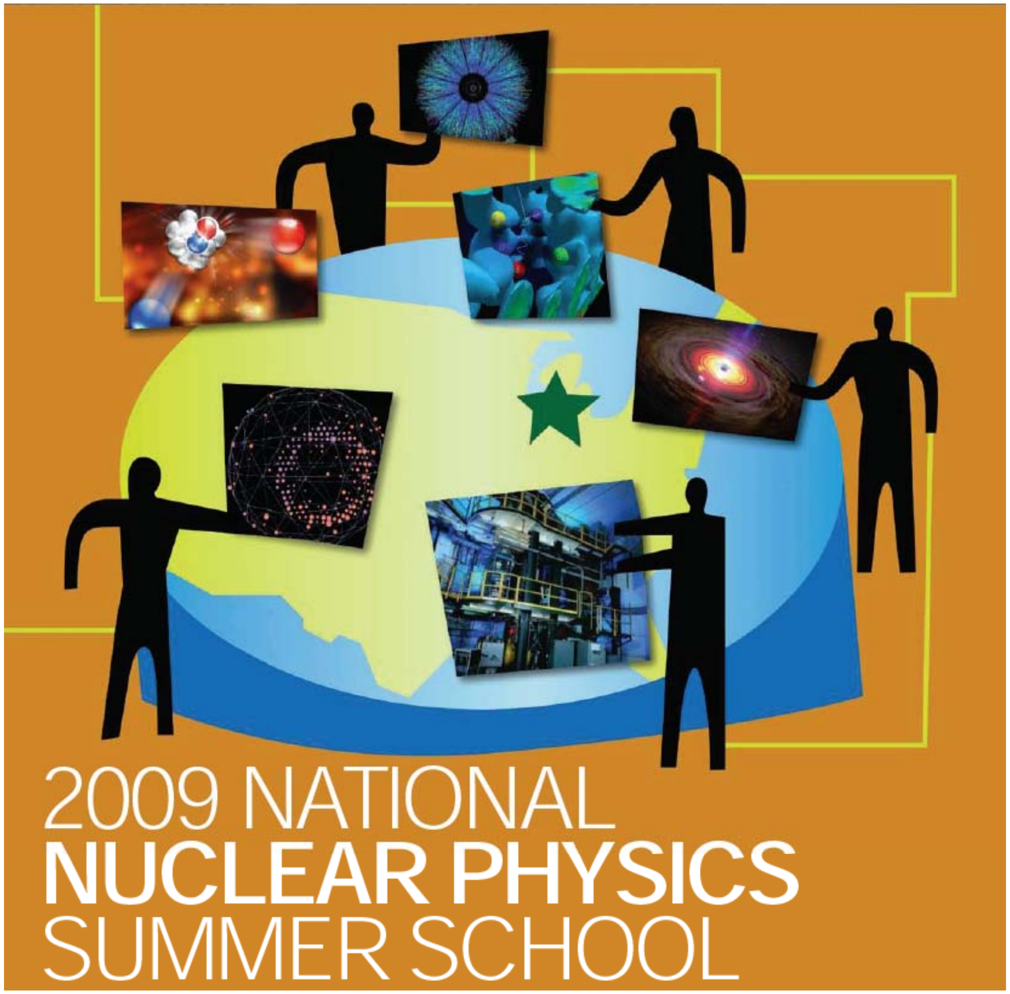
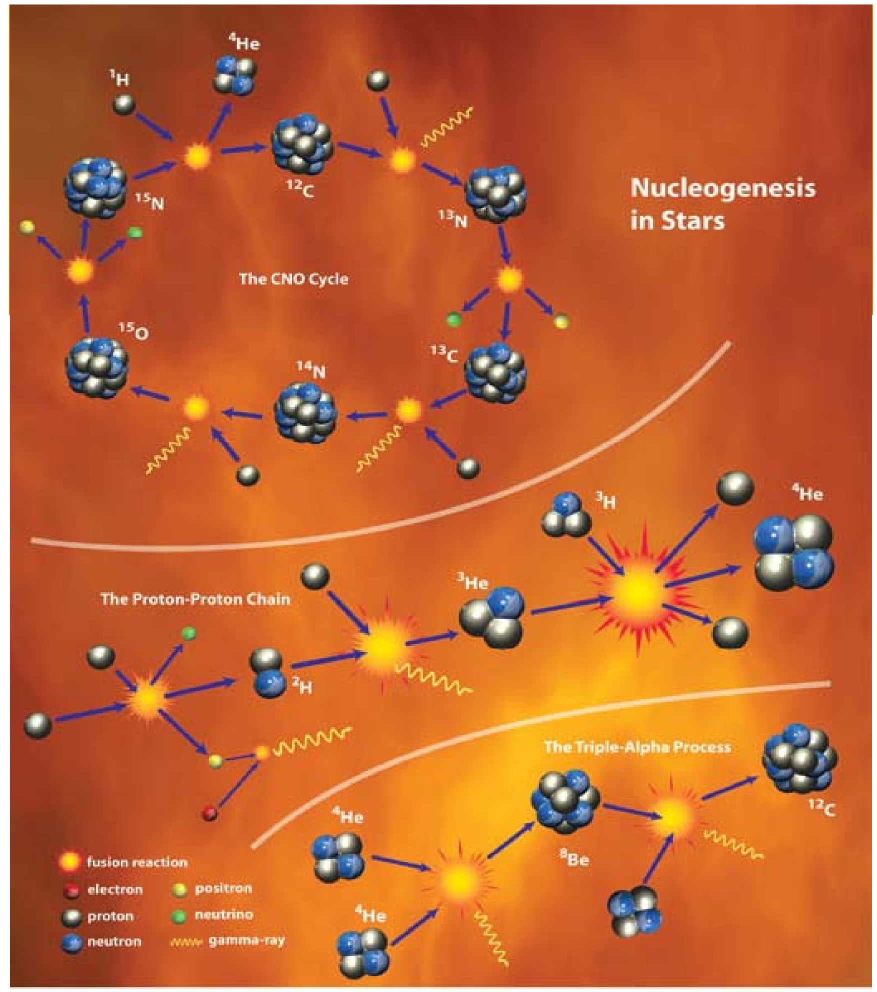
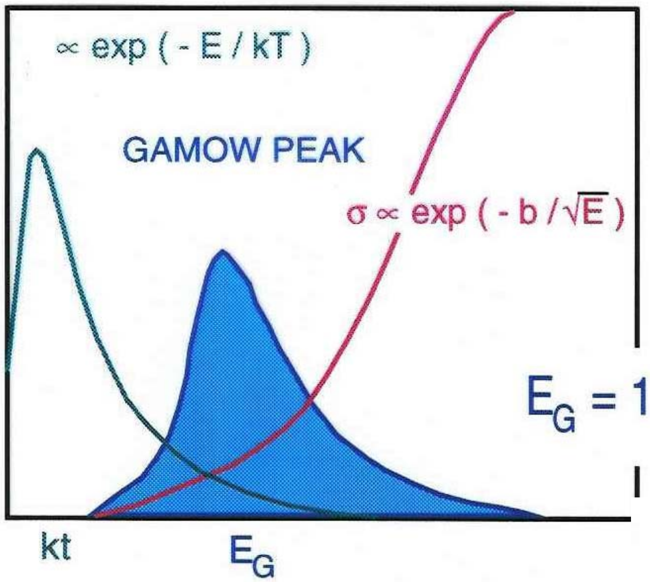
Experimental Methods and Techniques in Nuclear Astrophysics

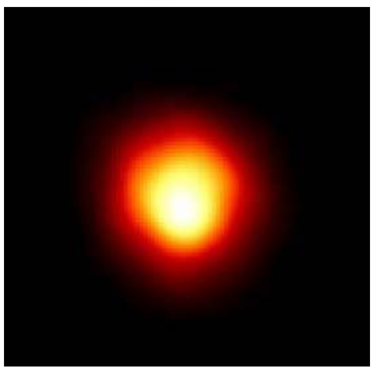


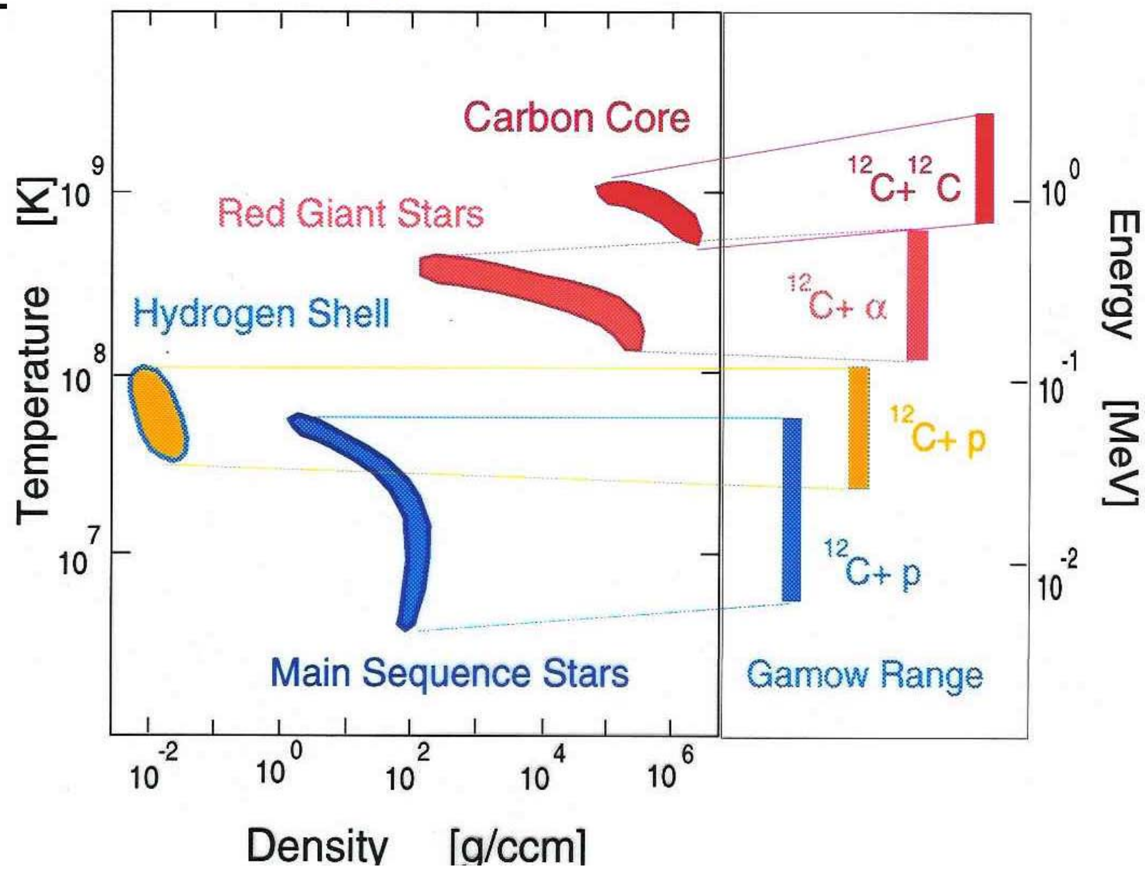


Stars are cold!!!

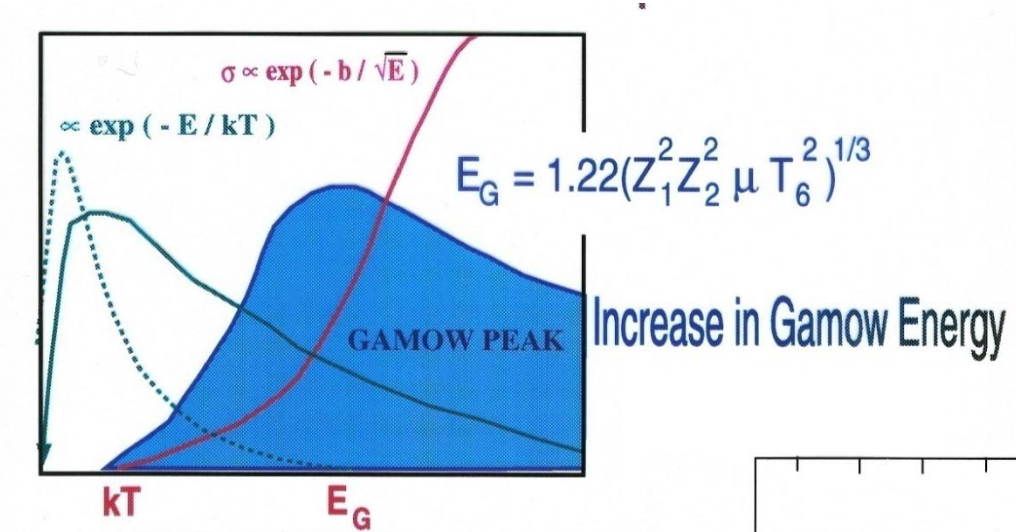


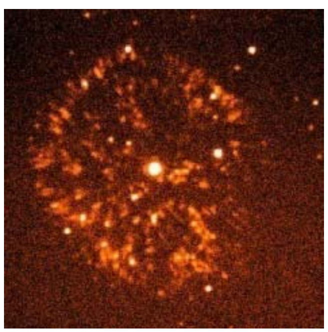
$$E_G = 1.22(Z_1^2 Z_2^2 \mu T_6^2)^{1/3}$$

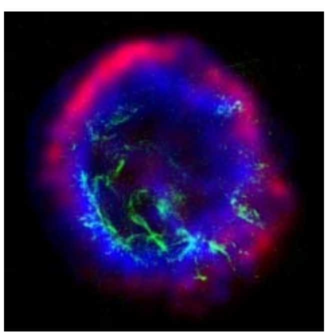


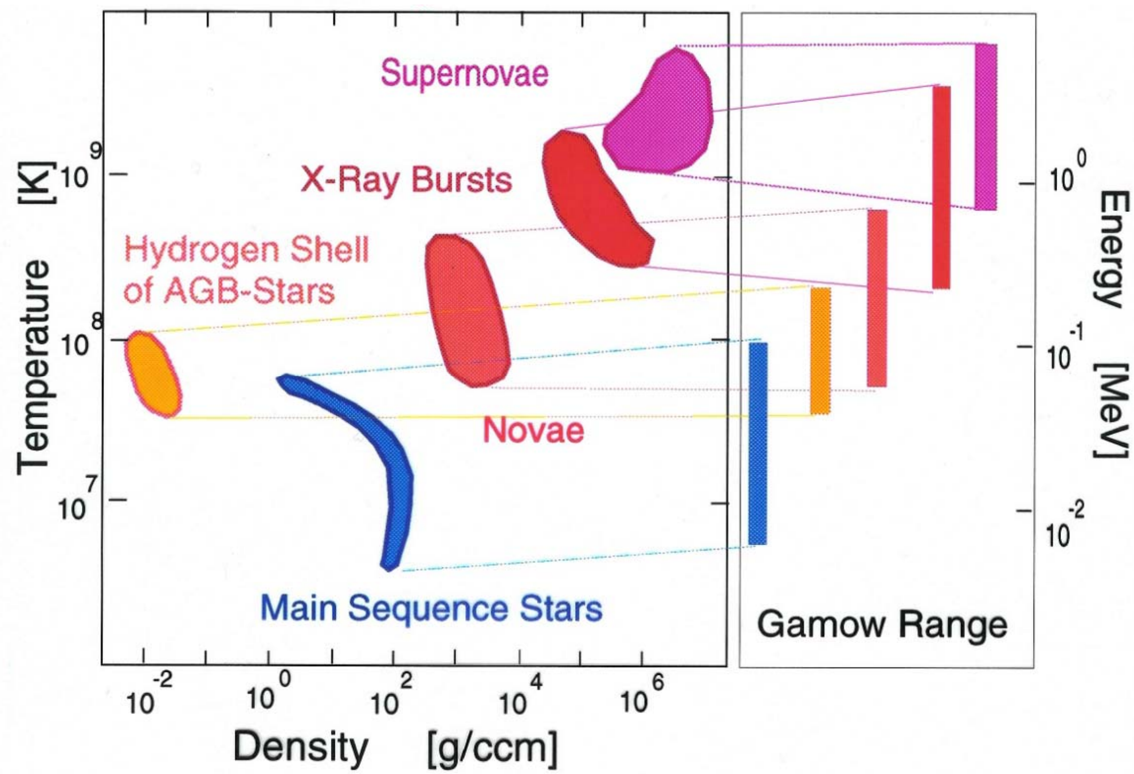


But some like it hot!!!







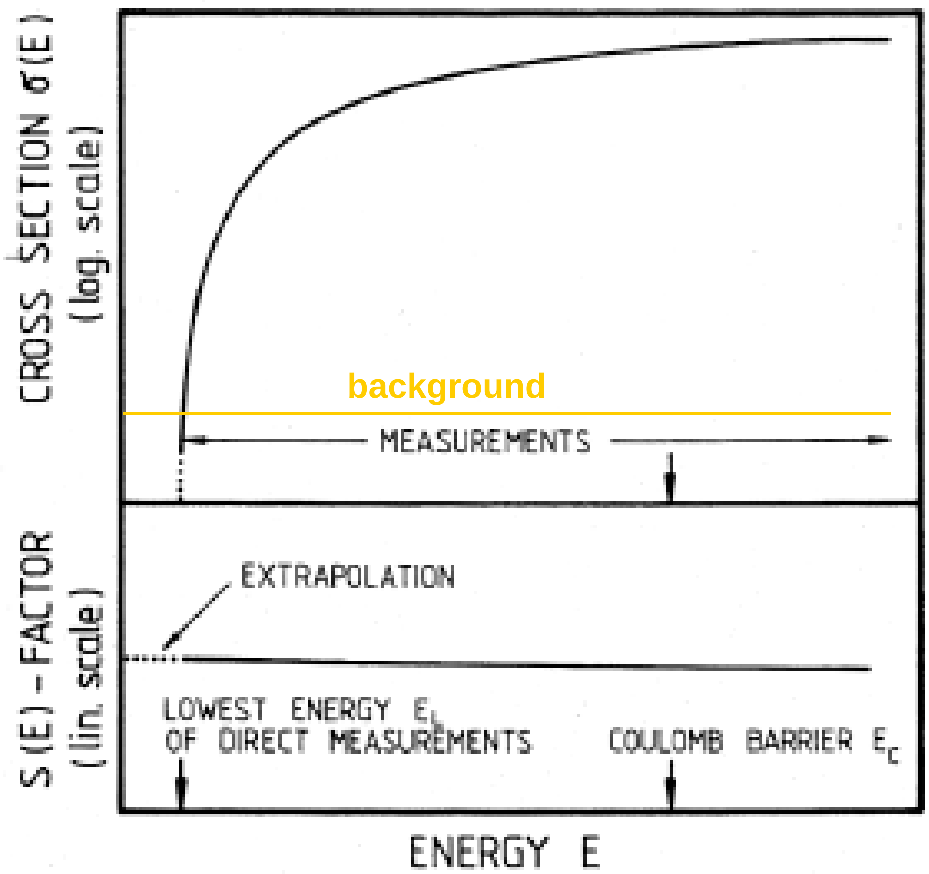


REACTION-RATE & S-FACTOR

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

Factorization of cross section into Coulomb part & “nuclear” component

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta)$$



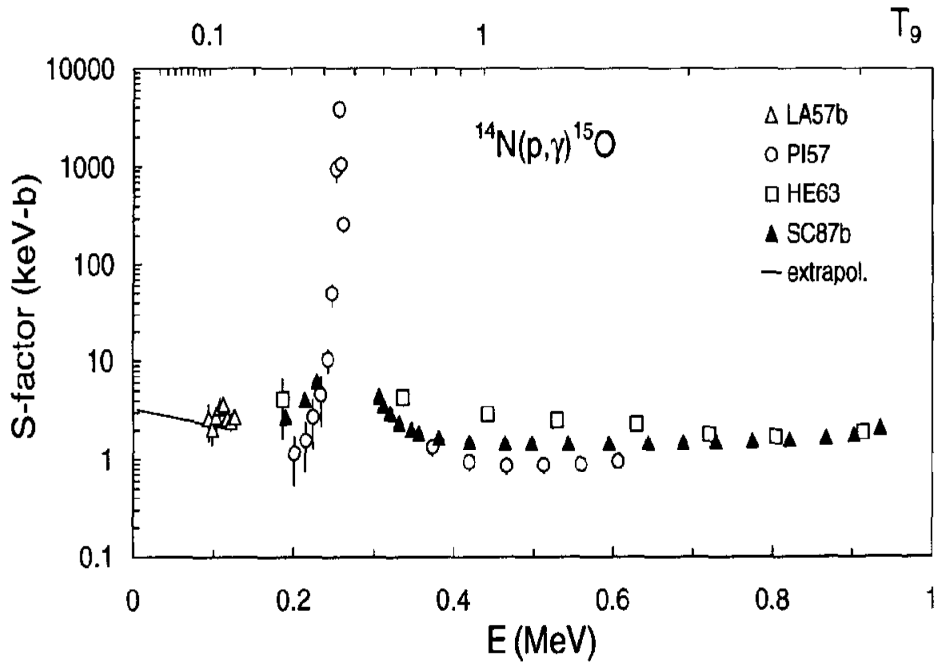
Classical Problem:
how reliable are the present low energy extrapolations?

The problem with extrapolation

Introduction of large uncertainties, depending on method and reliability of extrapolation into the sub-sub-sub-sub Coulomb barrier range!

We need to account for all reaction contributions to extrapolate reliably:

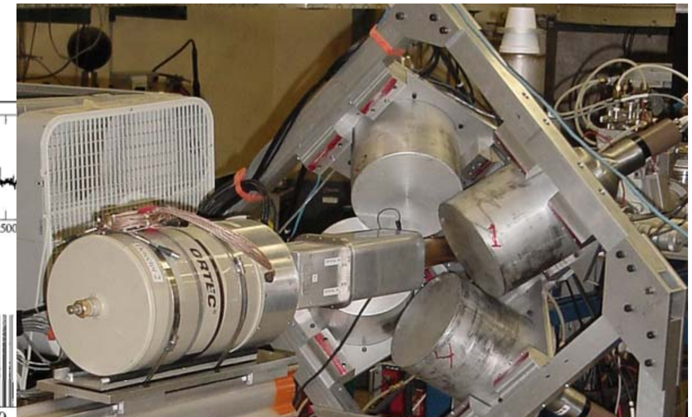
- direct component,
- resonance components
- interference structures
- all orbital momentum contributions
- all coupled channel contributions



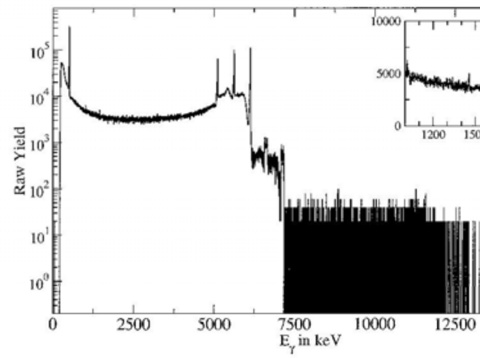
Main handicap for low energy studies:

- low reaction yield
- high background (natural, cosmic ray induced, beam induced)

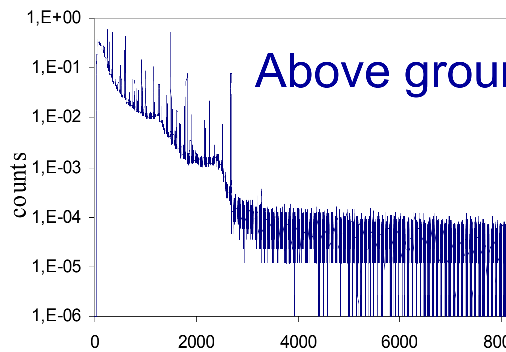
Sub Coulomb barrier studies in low background conditions



- Active shielding through coincidence requirements. background reduction by:
  $10^{-3} - 10^{-4}$

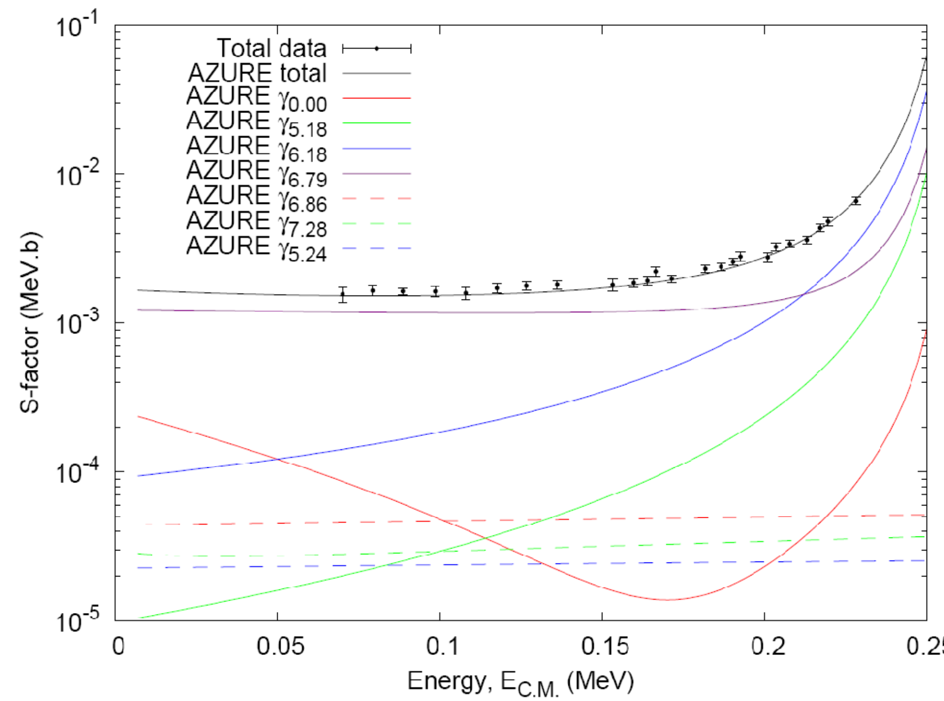


- Passive shielding by rock in deep underground environments (Gran Sasso). background reduction by:
  $10^{-4} - 10^{-6}$



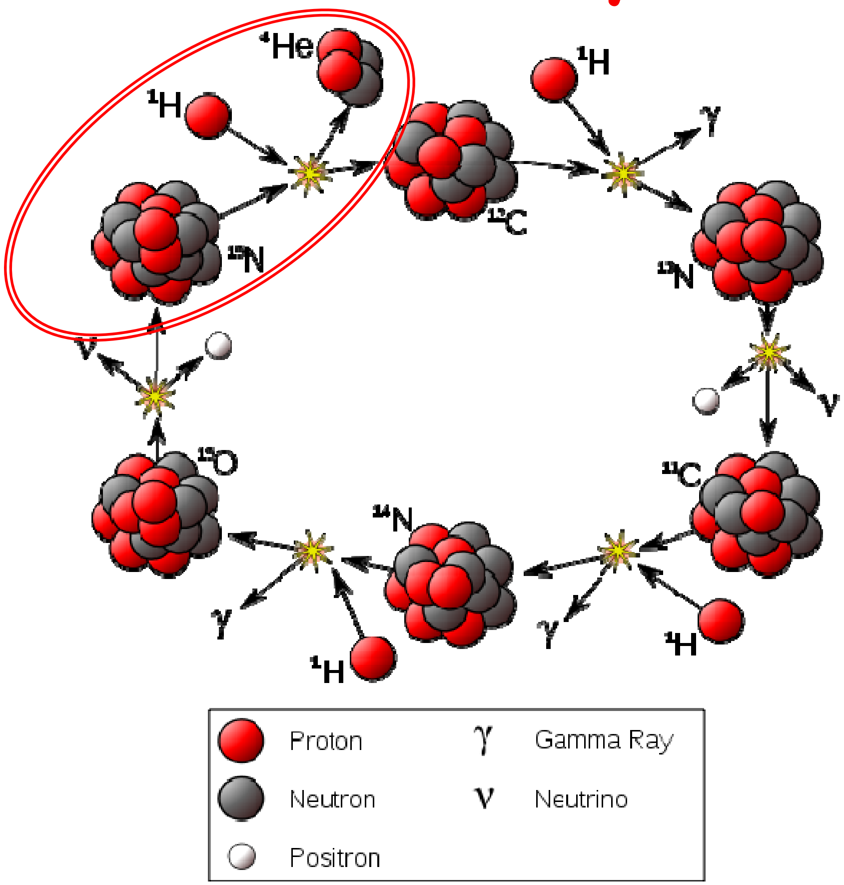
- Inverse kinematics with recoil separators such as: ERNA, DRAGON, and St. GEORGE, DIOCLETIAN

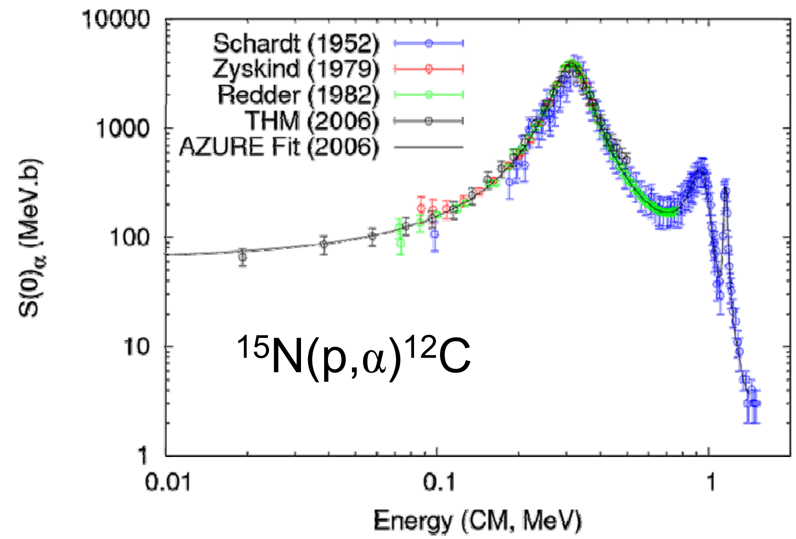
New low energy studies of the CNO cycles

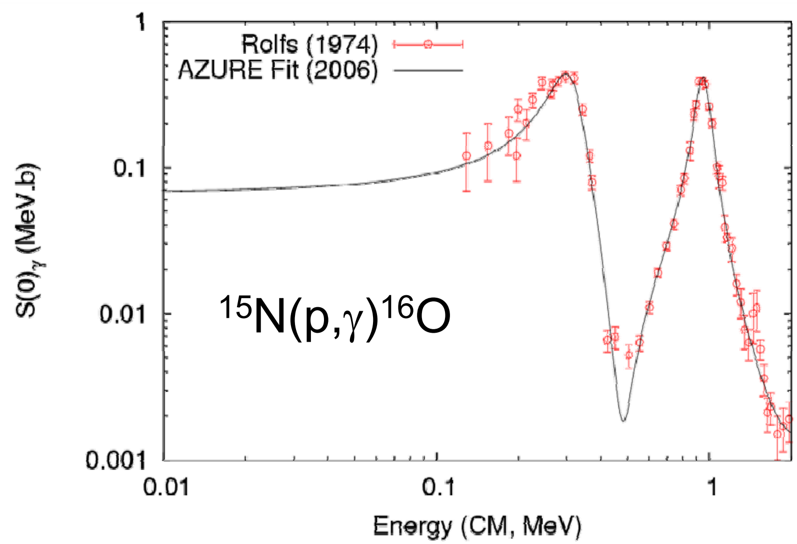


LUNA experiments successfully pushed experimental data range down to ~70keV. The extrapolation is based on an two independent R-matrix fits of all data over the entire energy range and all reaction channels and shows excellent agreement.

CNO cycles and R-matrix

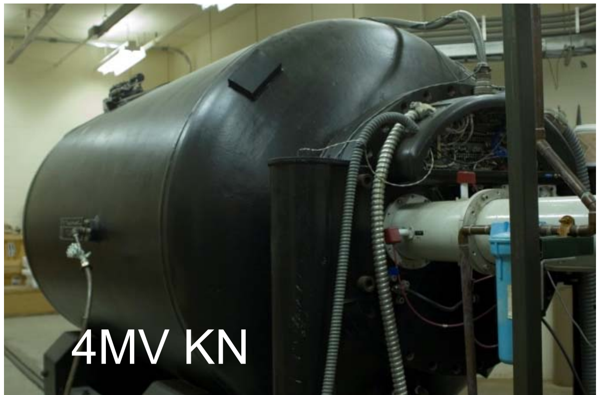


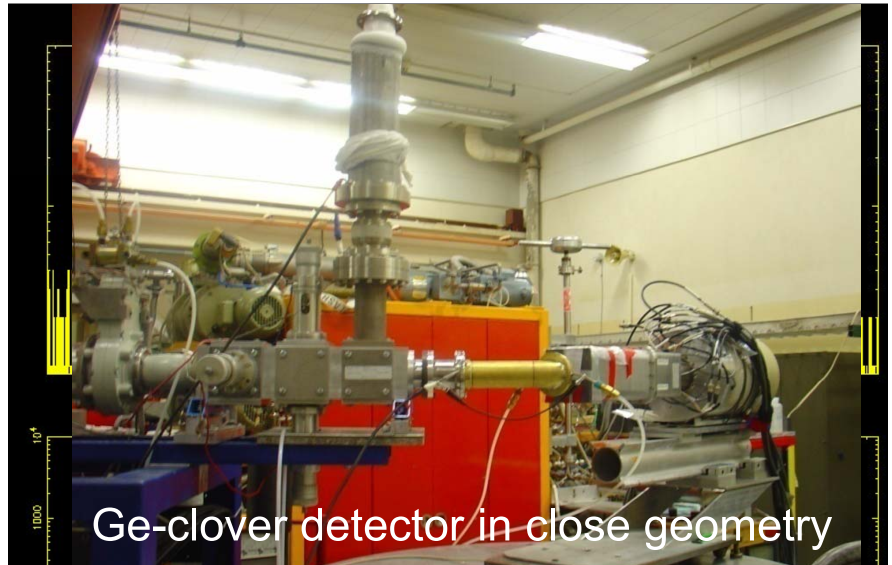




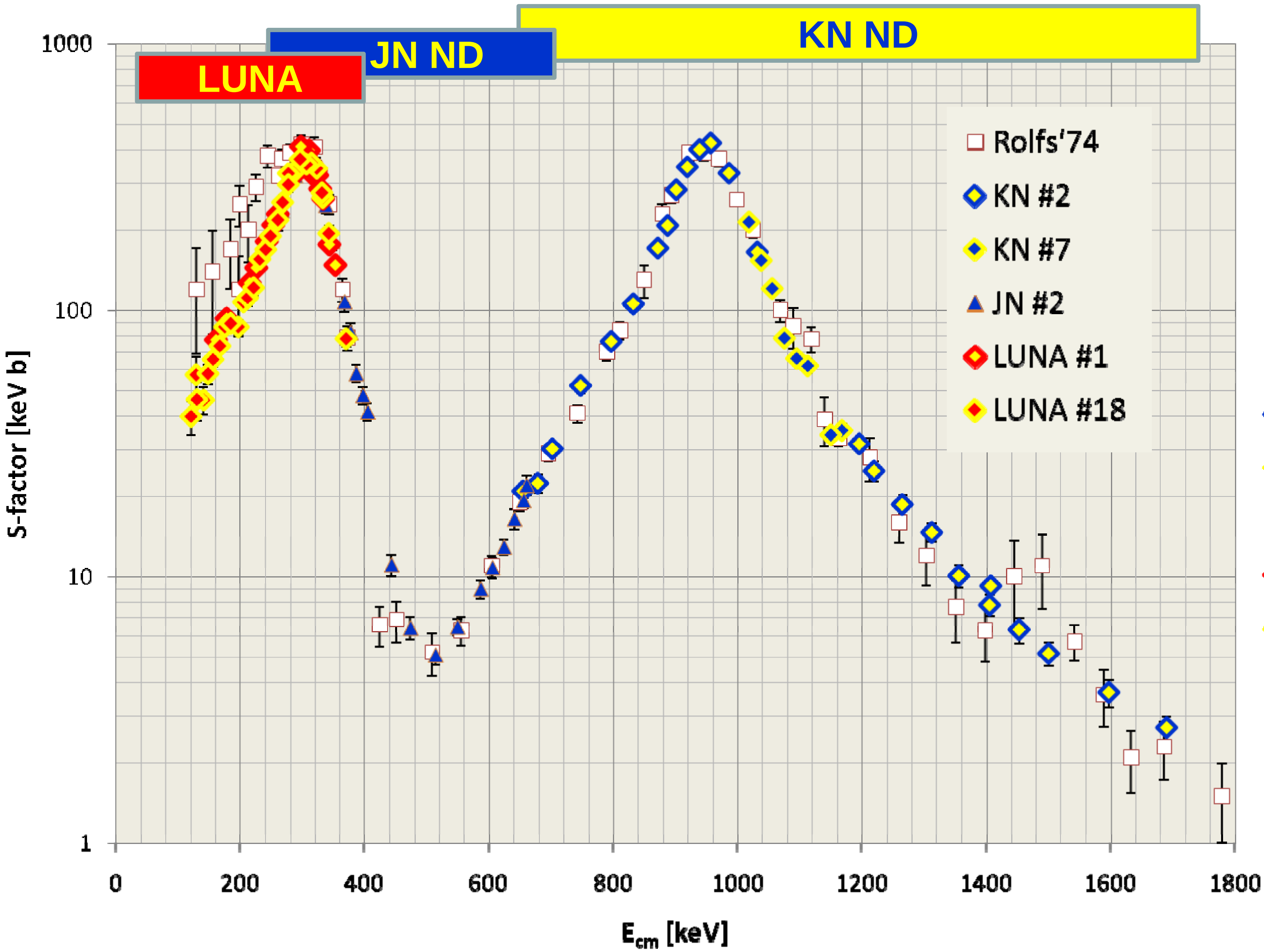
Systematic re-measurement of CNO capture reactions over a wide energy range for better S-factor extrapolation into stellar energy range

Measurements of $^{15}N(p,\gamma)^{16}O$

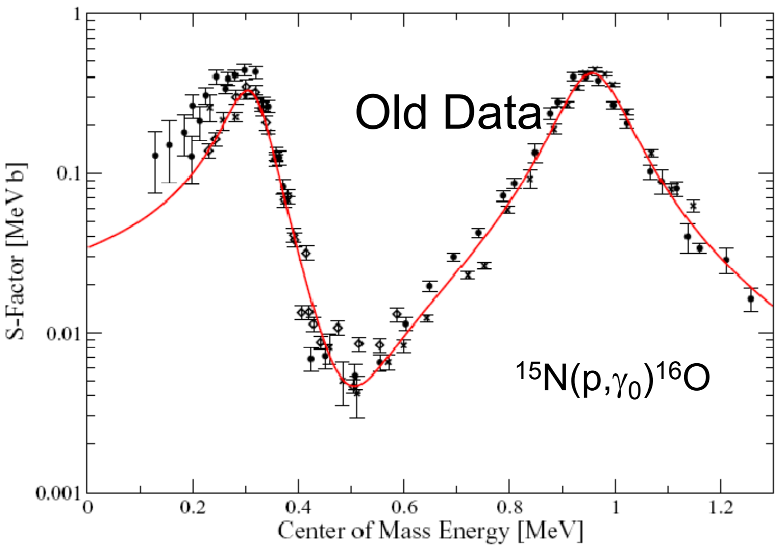


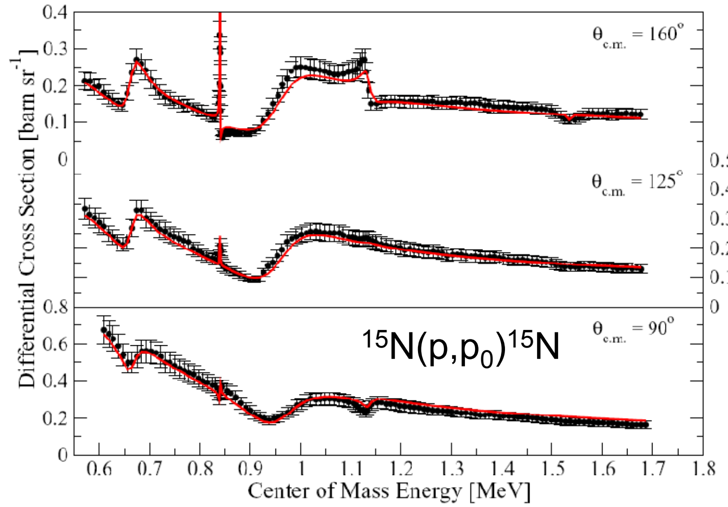


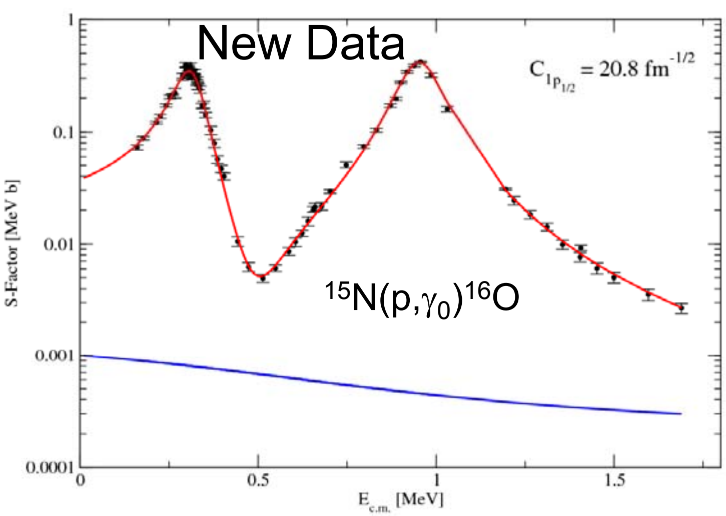
Low energy excitation curve

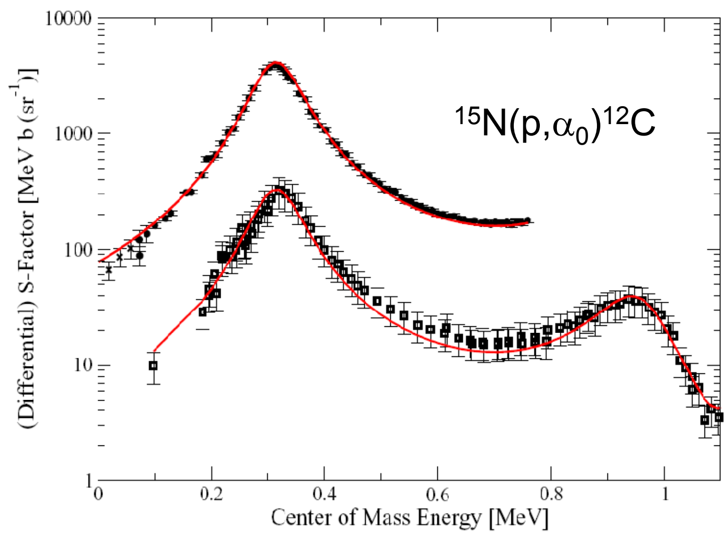


Analysis with multi-level, multi-channel R-matrix simulation









New Results since 2006

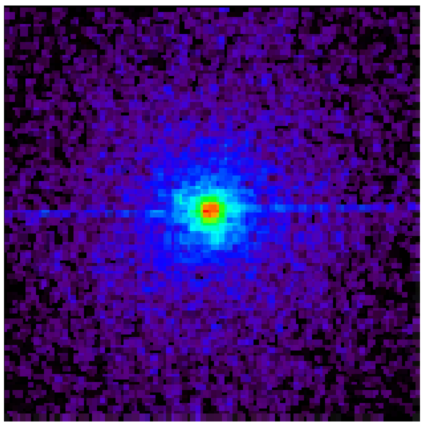
through new experimental data and re-analysis

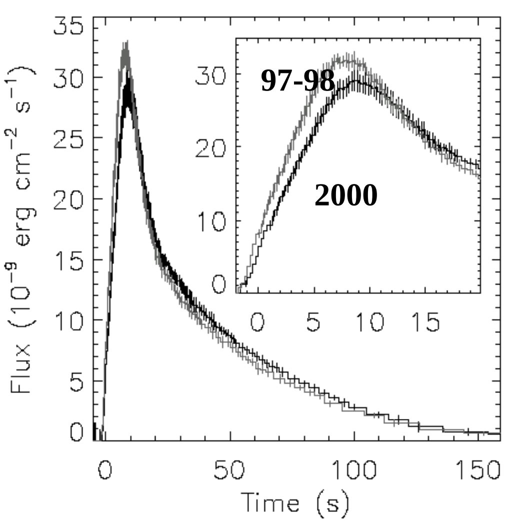
$^{12}C(p,\gamma)^{13}N$	S_0=1.8 keV-barn	(S_0=1.5 keV-barn)
$^{14}N(p,\gamma)^{15}O$	S_0=1.7 keV-barn	(S_0=3.2 keV-barn)
$^{15}N(p,\gamma)^{16}O$	S_0=34 keV-barn	(S_0=64 keV-barn)
$^{16}O(p,\gamma)^{17}F$	S_0=10.6 keV-barn	(S_0=9.3 keV-barn)

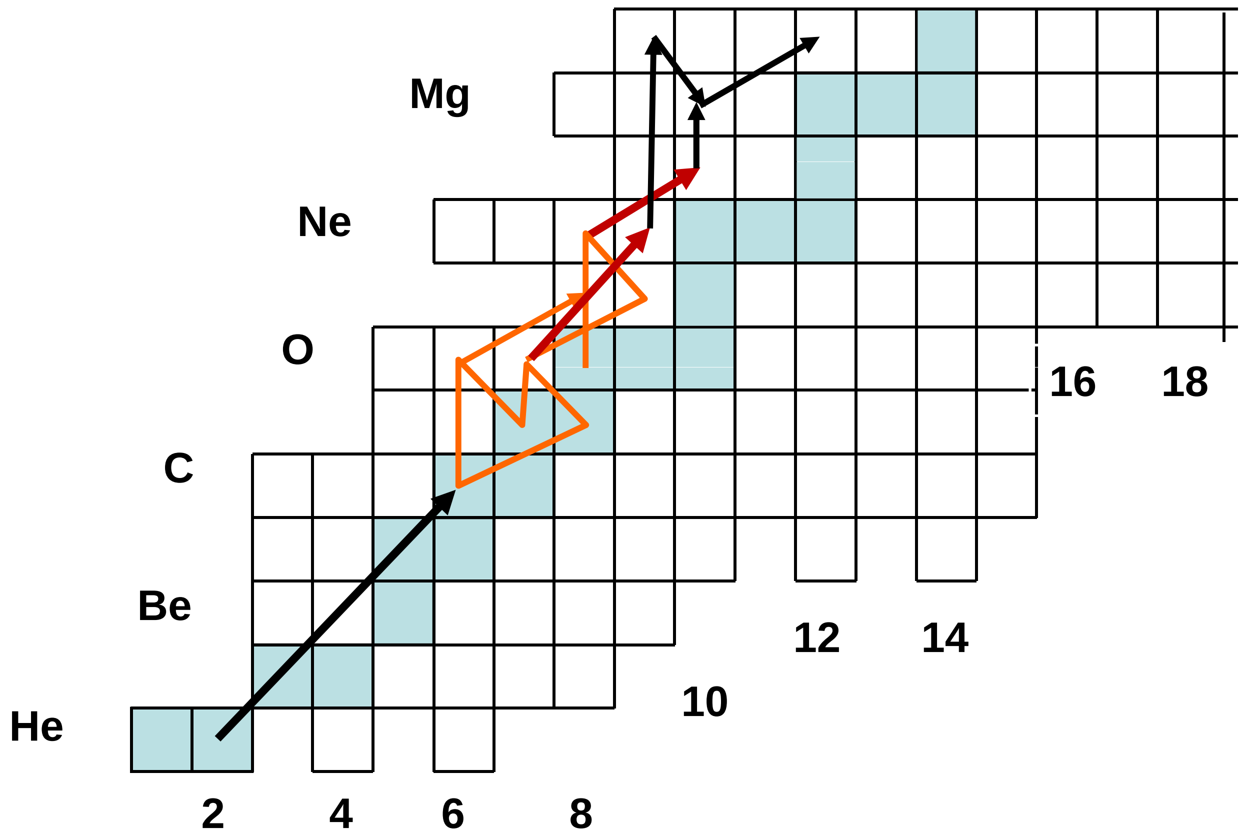
- Translates into reduction of CNO neutrino production,
- Resets CNO abundance predictions
- Impacts timescale of hydrogen burning in massive stars

The nuclear trigger of X-ray Bursts

break-out from HCNO cycles: $^{15}O(\alpha,\gamma)^{19}Ne$, $^{18}Ne(\alpha,p)^{21}Na$







Reaction Rate of $^{15}O(\alpha,\gamma)^{19}Ne$

- Reaction Rate

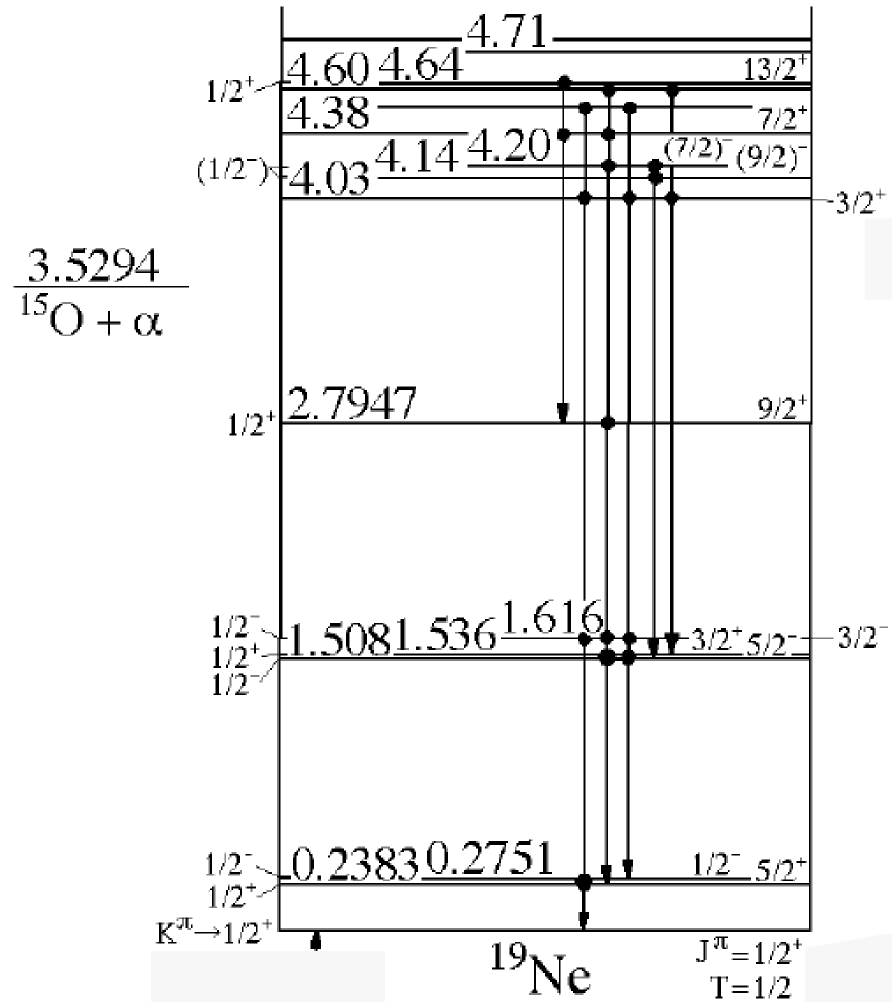
$$N_A < \sigma v > \propto T^{-3/2} \, \omega\gamma \, e^{-E_R/kT}$$

determined by resonance energy E_R and strength $\omega\gamma$

$$\text{where} \quad \omega\gamma = \frac{2J_R + 1}{(2J_P + 1)(2J_T + 1)} B_\alpha \Gamma_\gamma$$

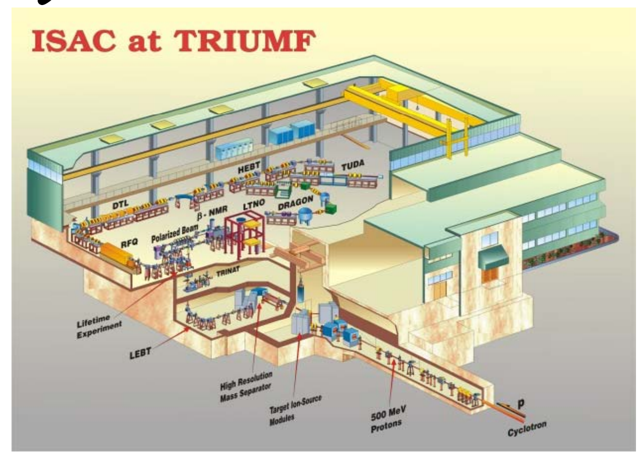
- Three measurable quantities characterize the resonance strength:

  J, Γ_γ, and B_α

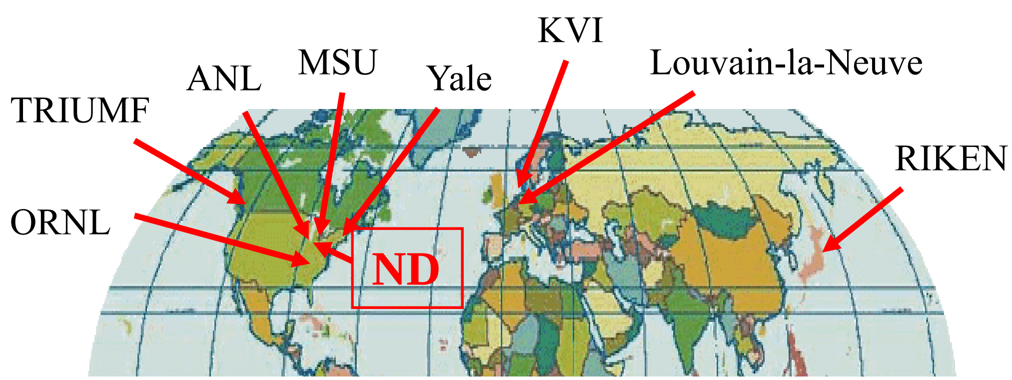


What experimentalists need to do for $^{15}O(\alpha,\gamma)^{19}Ne$

- Direct measurement is difficult!
  - An intense (10^{11} /s) radioactive ^{15}O beam gives a count rate of <1/hr (estimated at ISAC, TRIUMF)

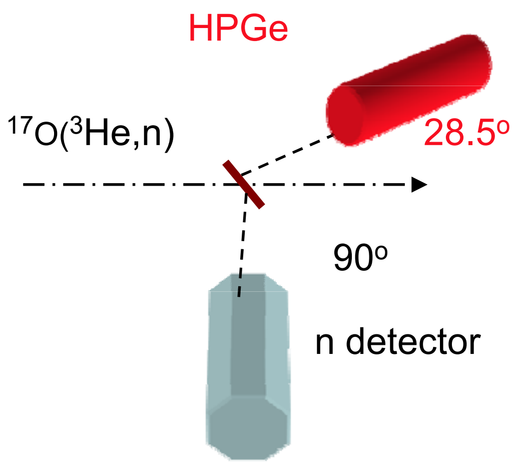


$$\omega\gamma = \frac{2J_R+1}{(2J_P+1)(2J_T+1)} \cdot \frac{\Gamma_\alpha \cdot \Gamma_\gamma}{\Gamma}$$
$$\sim B_\alpha \Gamma_\gamma$$
$$\sim Y(^{19}Ne)$$



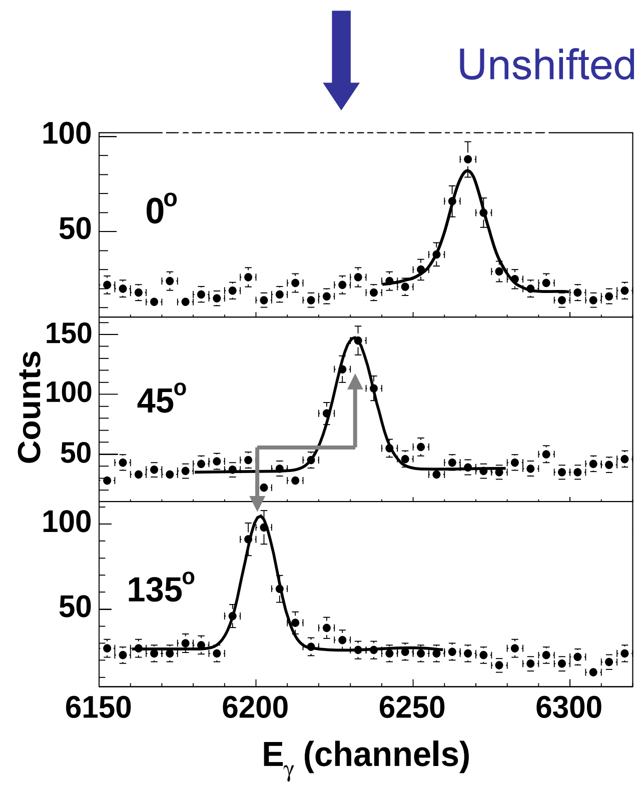
- Indirect method has been approached many times!
  - Populate α-unbound states in ^{19}Ne
  - Measure lifetimes or gamma widths — $^{17}O(^{3}He,n\text{-}\gamma)^{19}Ne$
  - Measure α-decay branching ratios B_α — $^{19}F(^{3}He,t\text{-}\alpha)^{19}Ne$

Probing the Structure



$$E_\gamma = E_{\gamma_0}(1 + F(\tau)\beta\cos\theta)$$

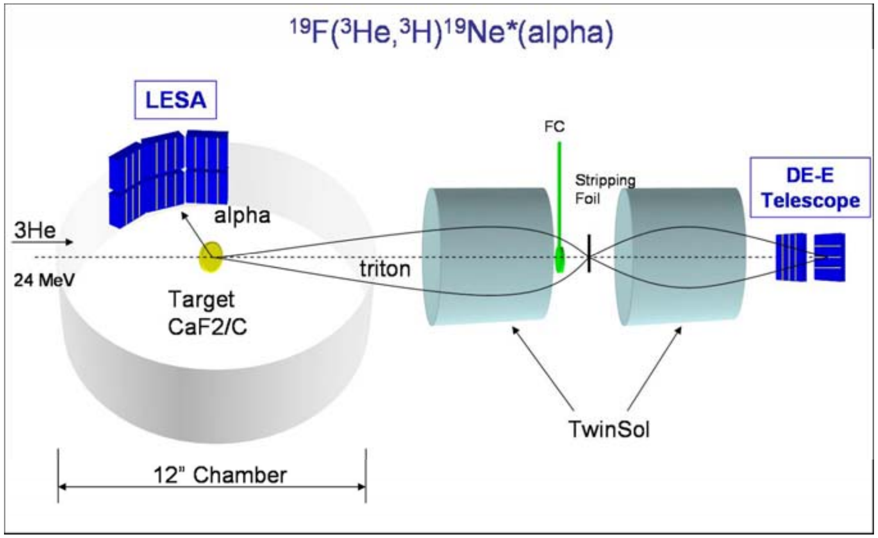
E_x = 4034.5±0.8 keV

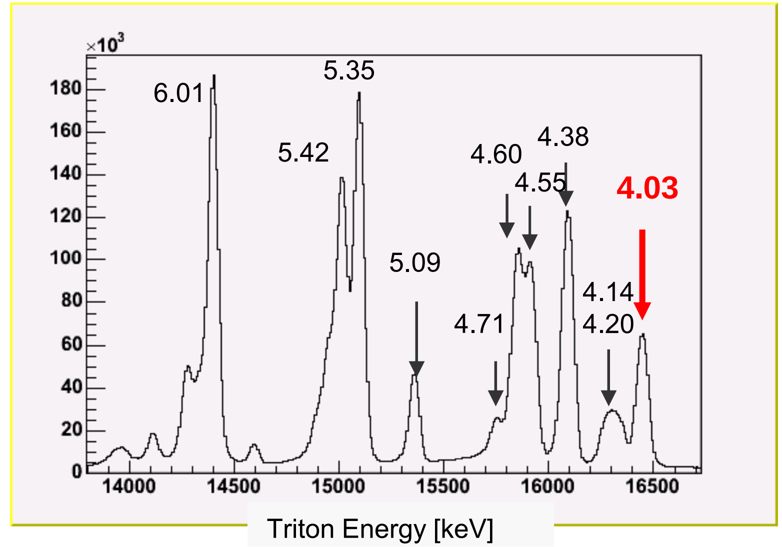


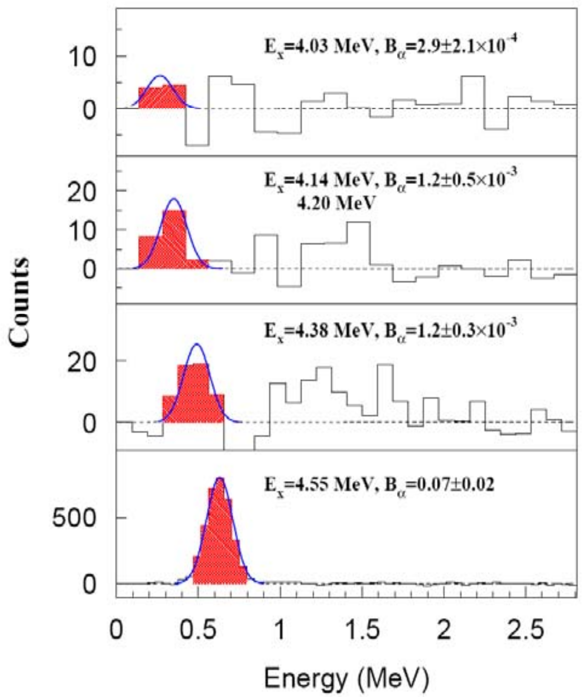
Measured lifetime τ= $13\pm^{9}_{6}$ fs
or $\Gamma=51\pm^{43}_{21}$ meV

TRIUMF 2006 τ= $11\pm^{8}_{7}$ fs
or $\Gamma=60\pm^{40}_{25}$ meV

LWFG86: Γ=73 meV

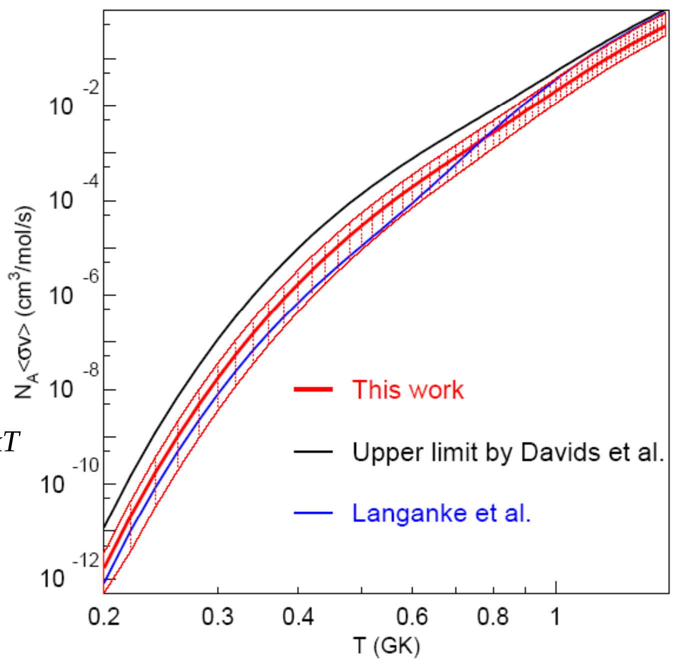




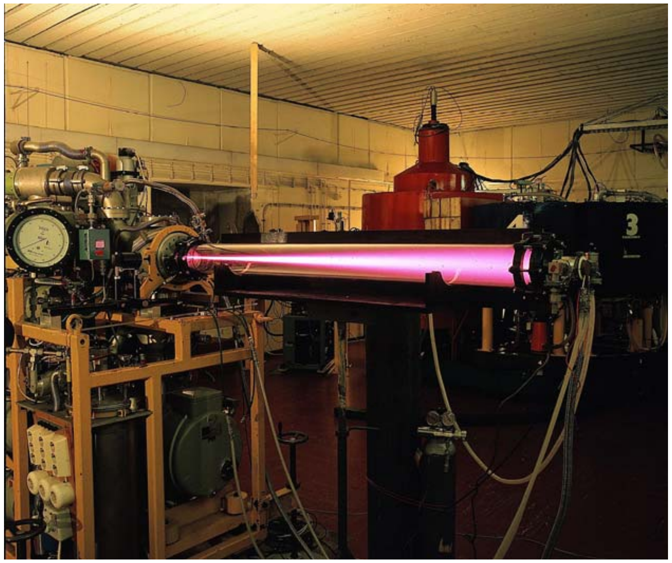


$$\omega\gamma = \frac{2J_R + 1}{(2J_P + 1)(2J_T + 1)} B_\alpha \Gamma_\gamma$$

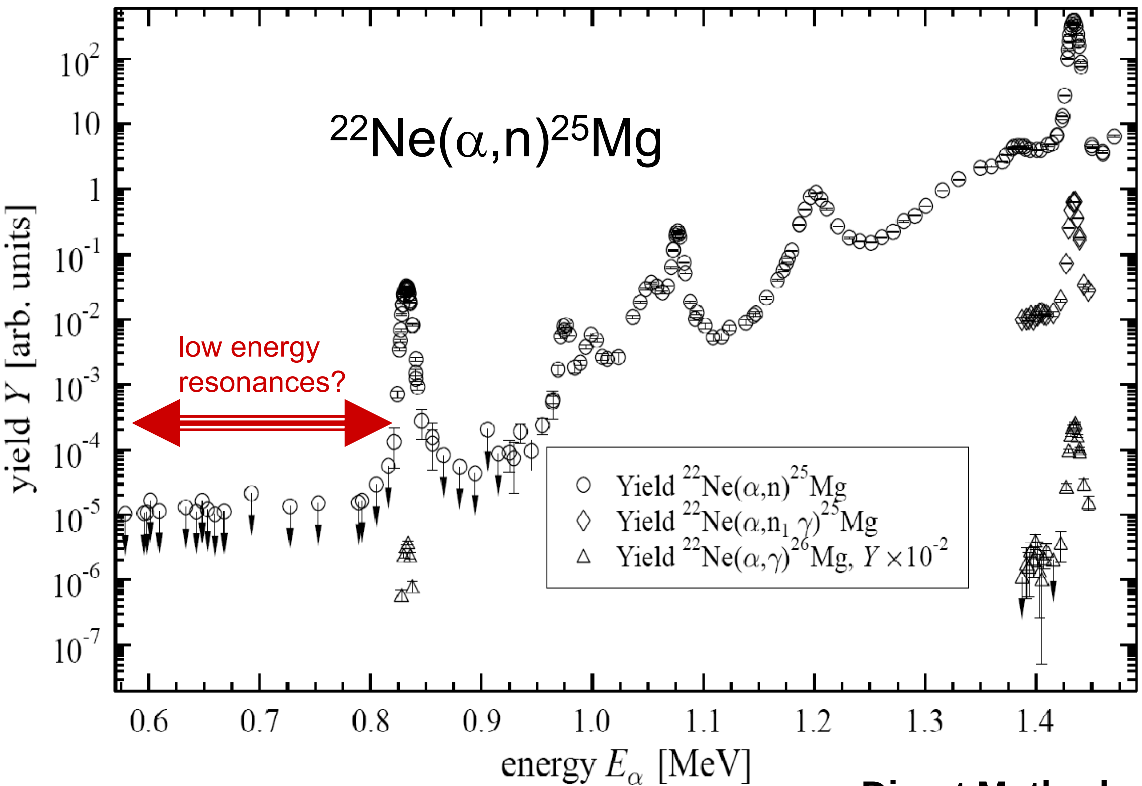
$$N_A < \sigma v > \propto T^{-3/2}\, \omega\gamma\, e^{-E_R/kT}$$



Stellar Neutron Source



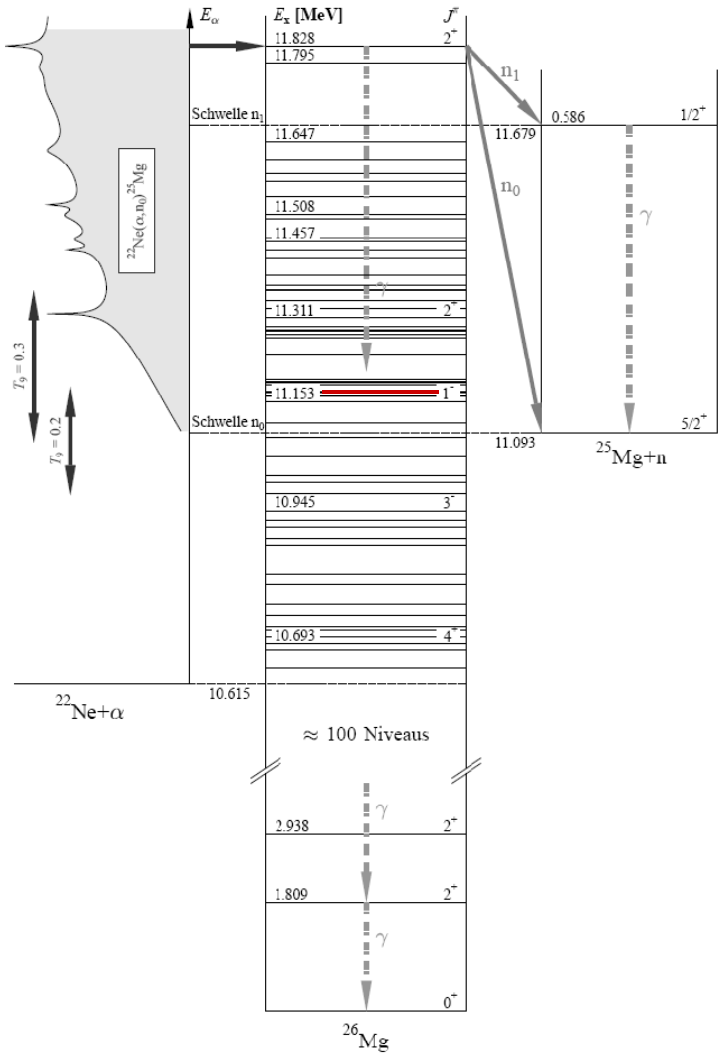
$^{14}N(\alpha,\gamma)^{18}F(\beta^+\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)$

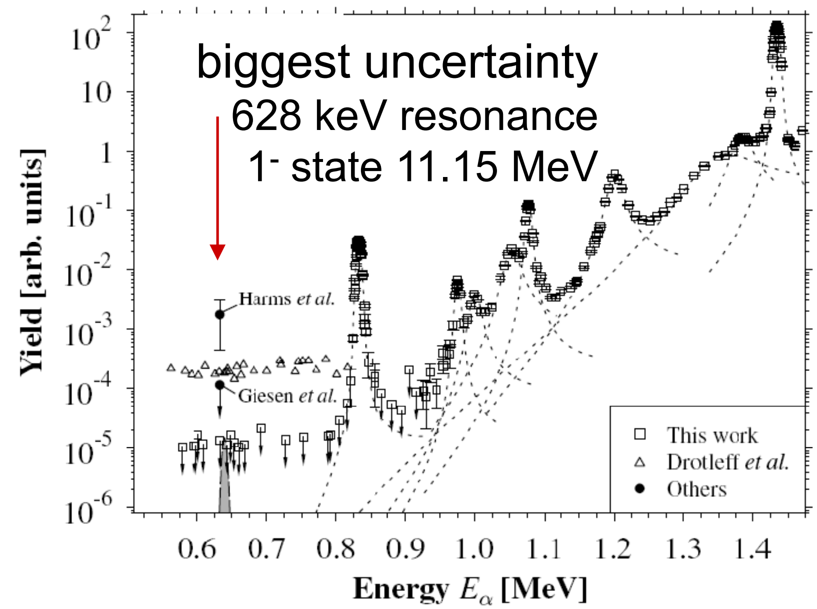


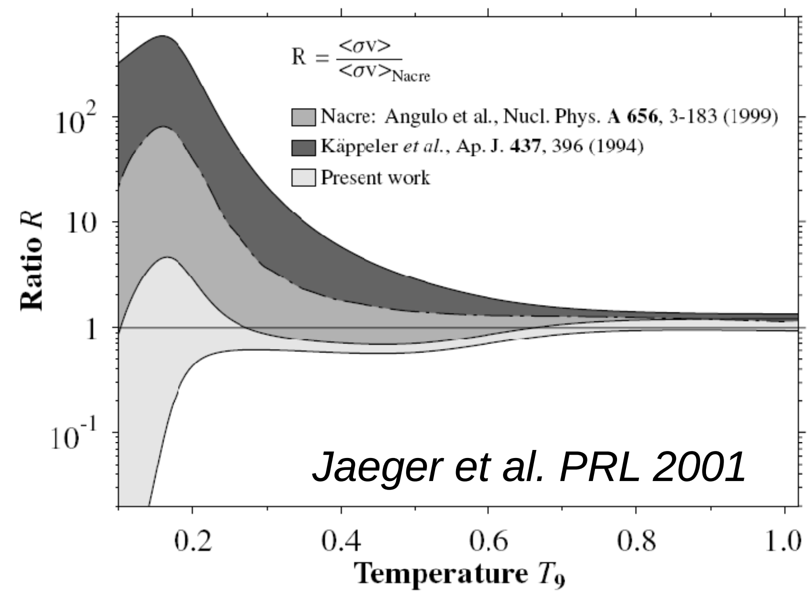
Direct Method
U. Stuttgart
U. Notre Dame

Uncertainties in neutron production

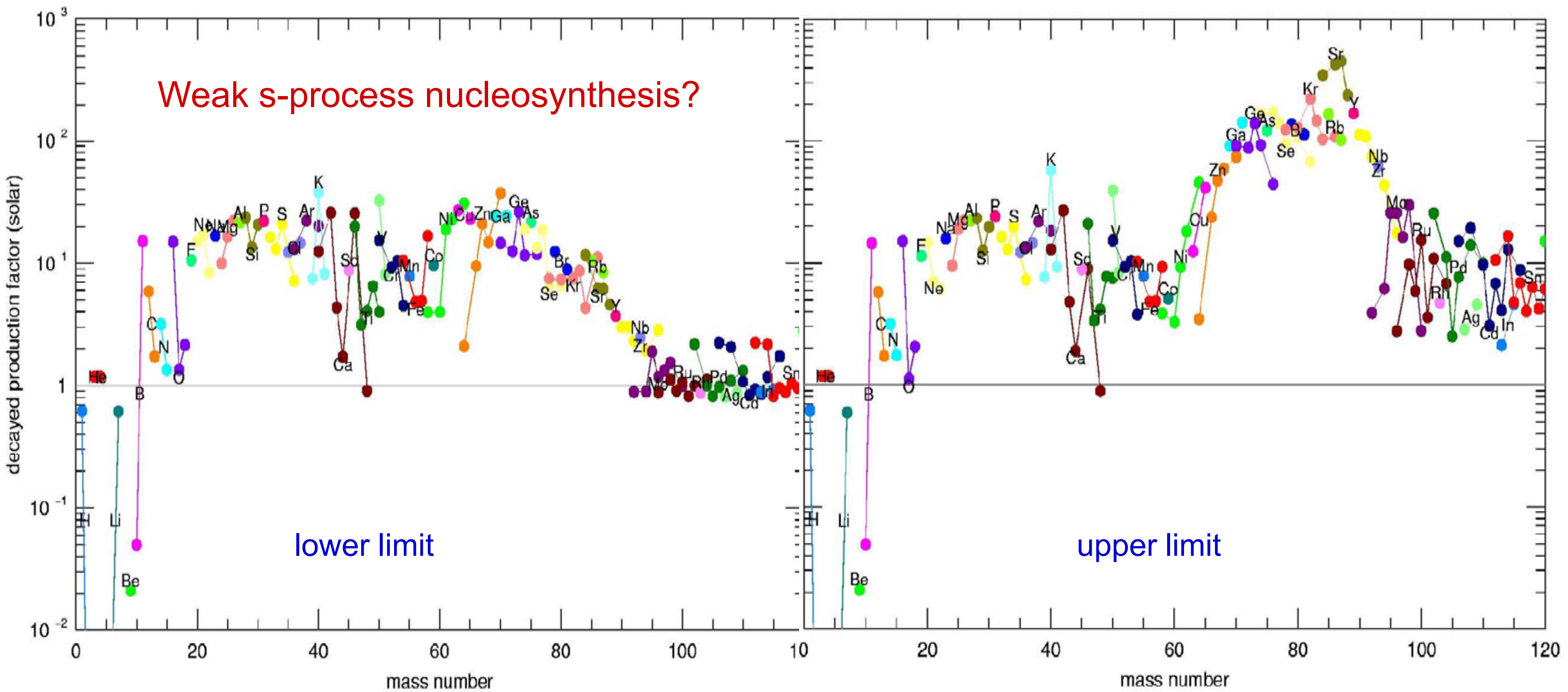
- Extrapolation to lower energies
- Impact of the $^{22}Ne(\alpha,\gamma)$ branch







Uncertainties and Consequences



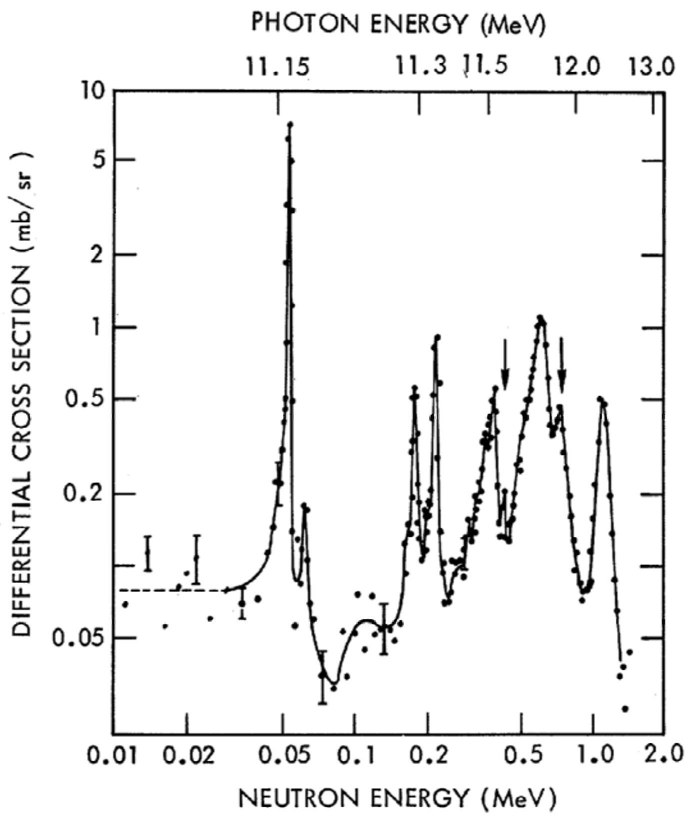
^{22}Ne(α,n) reaction rate determines s-process seed abundance for p-, and r-process analysis!

Costa et al, A&A 2000
Arnould & Goriely, PR, 2003
Heger et al., ApJ 2007

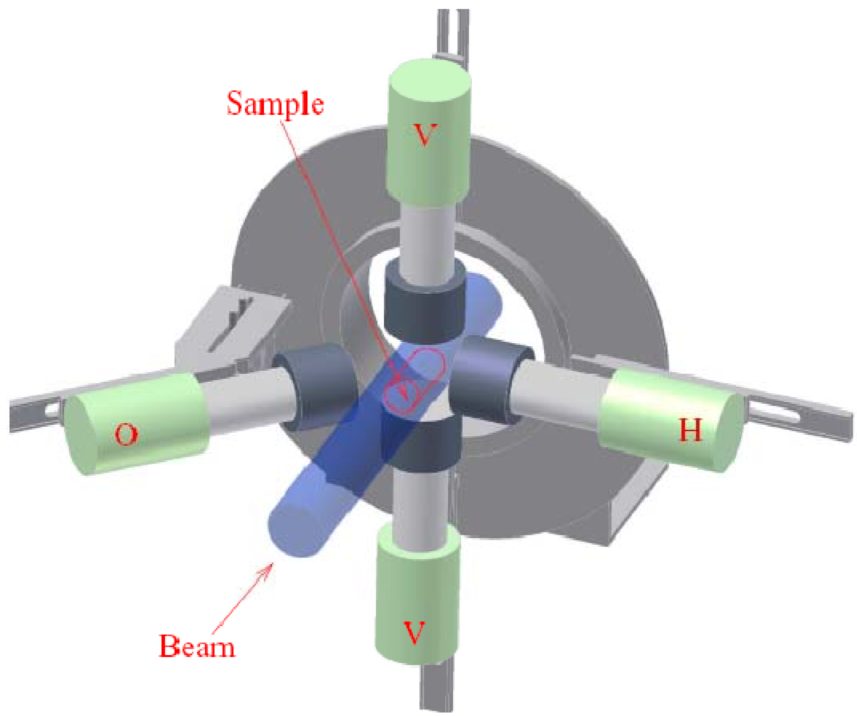
First measurement at HIγS

^{26}Mg(γ,n)^{25}Mg with 13.3 MeV Bremsstrahlung γ-radiation suggests possible 1^{-} state at 11.153 MeV

Berman et al PRL 1969

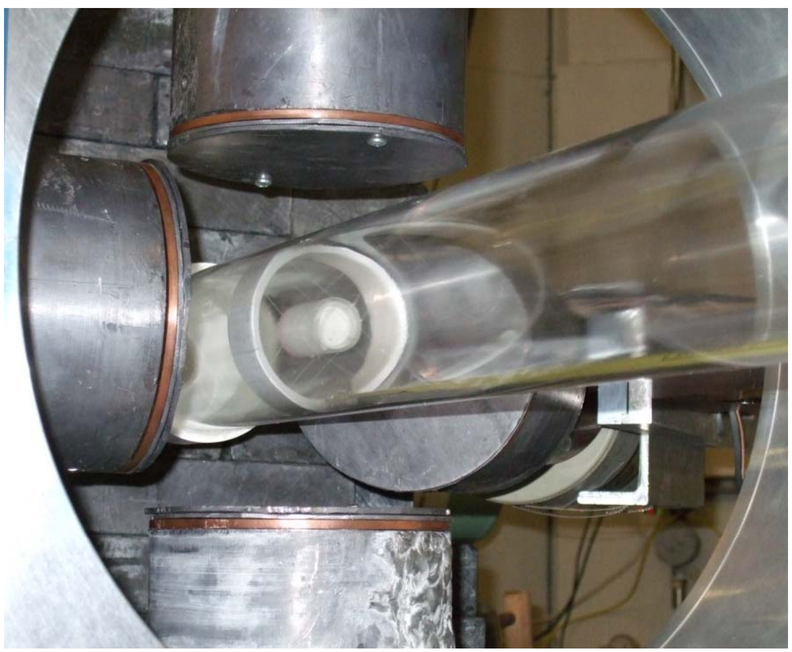


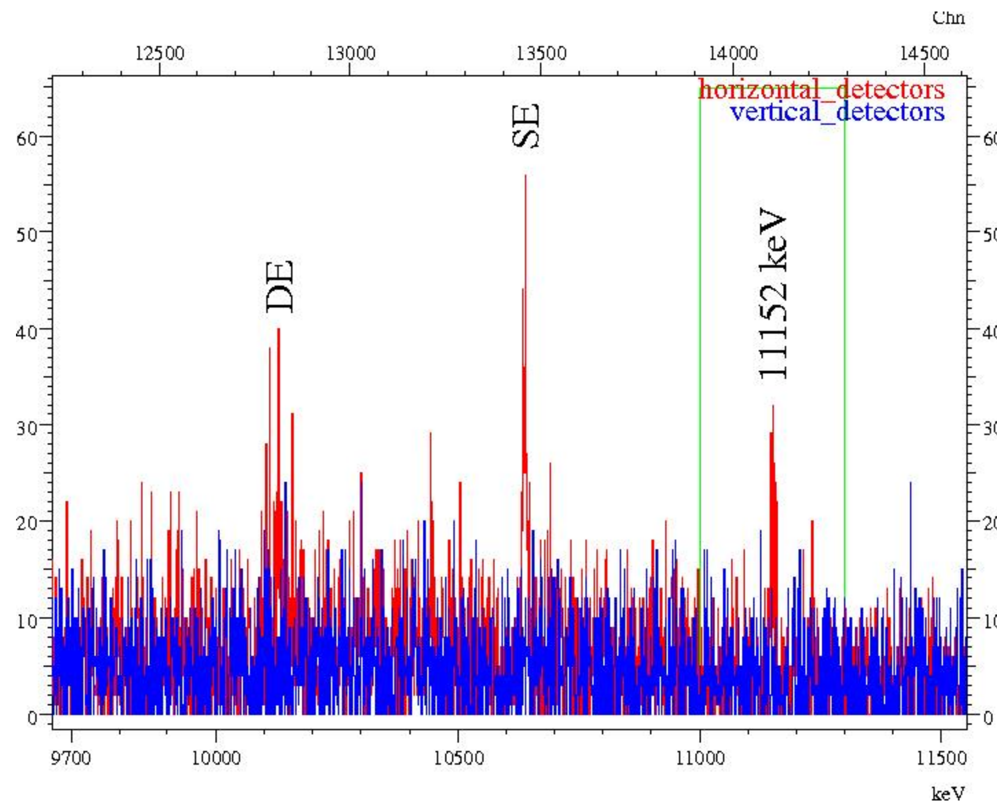
New experiment with polarized mono-energetic γ radiation to probe the level structure and spin assignments in ^{26}Mg through a measurement of the analyzing power.



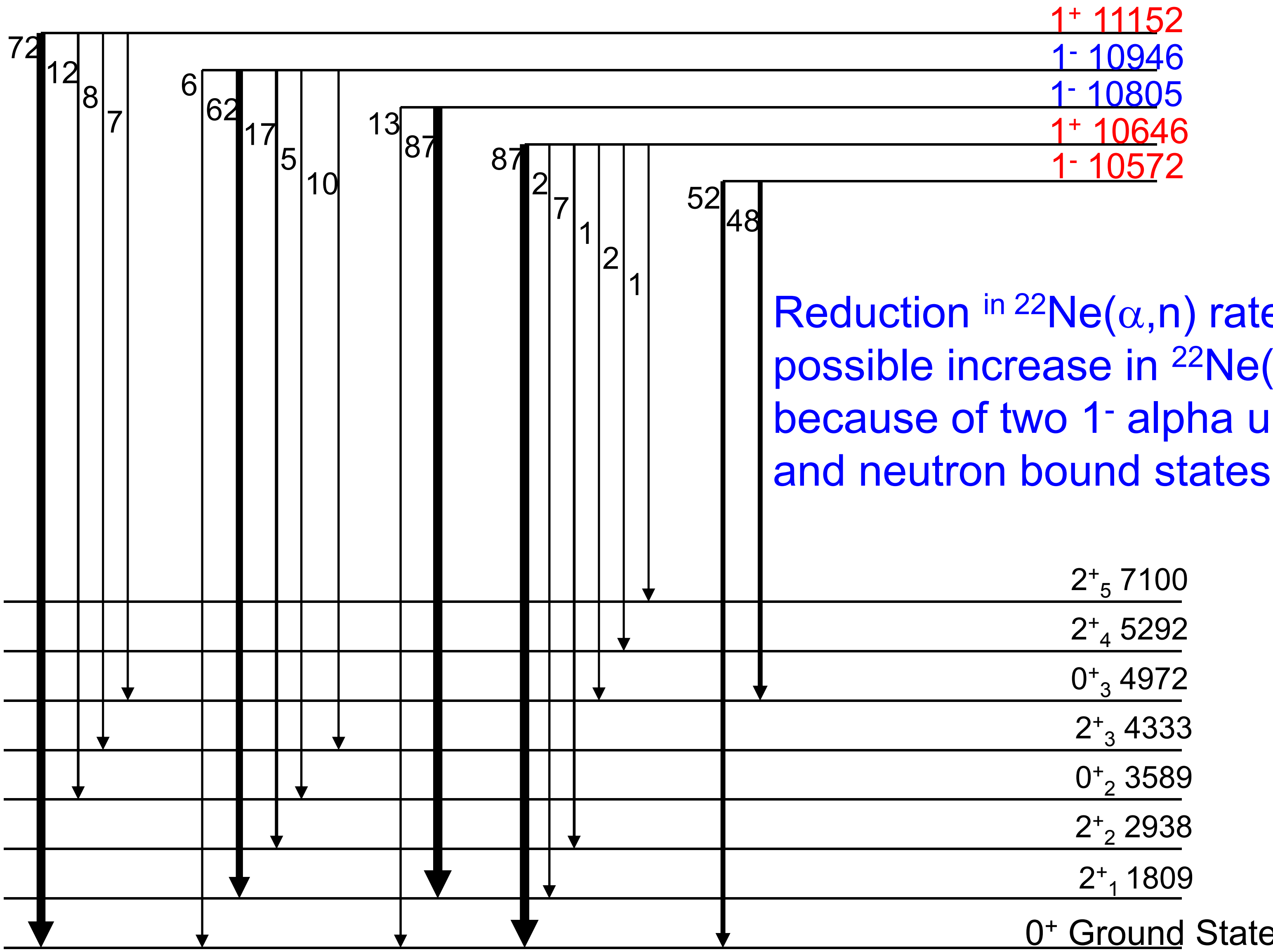
Revised spin assignment

$^{26}Mg(\gamma,\gamma')^{26}Mg$ with 11.3 MeV γ-radiation to probe γ-decay of critical 11.153 state near neutron threshold. Analyzing power measurement indicates 1^+ assignment for the level. The level cannot contribute to the $^{22}Ne+\alpha$ reaction channel!



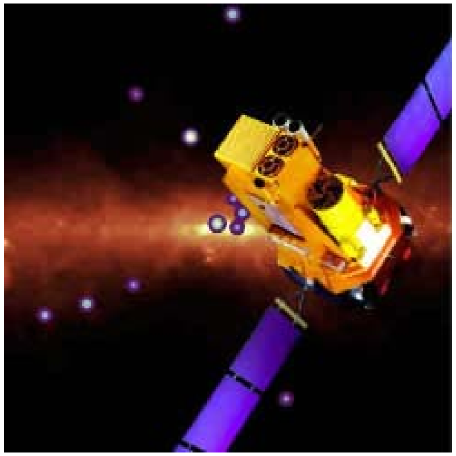


Consequence for neutron production



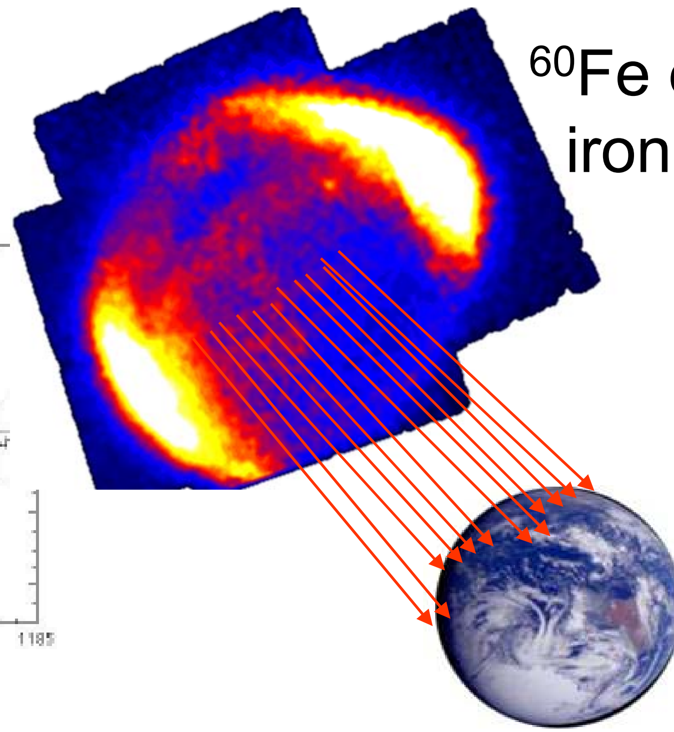
Reduction in $^{22}Ne(\alpha,n)$ rate, with possible increase in $^{22}Ne(\alpha,\gamma)$ rate because of two 1^- alpha unbound and neutron bound states in ^{26}Mg.

Origin of ^{60}Fe

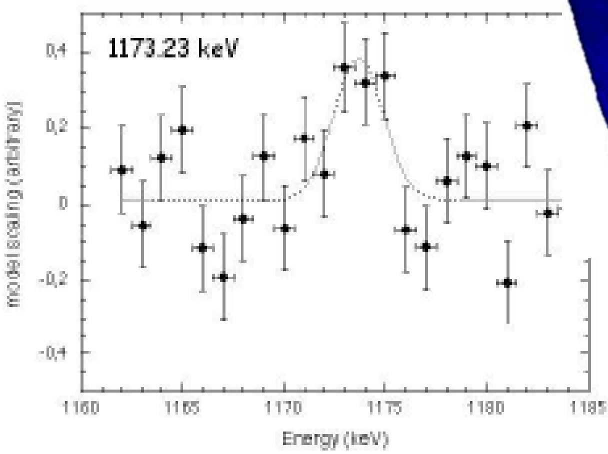


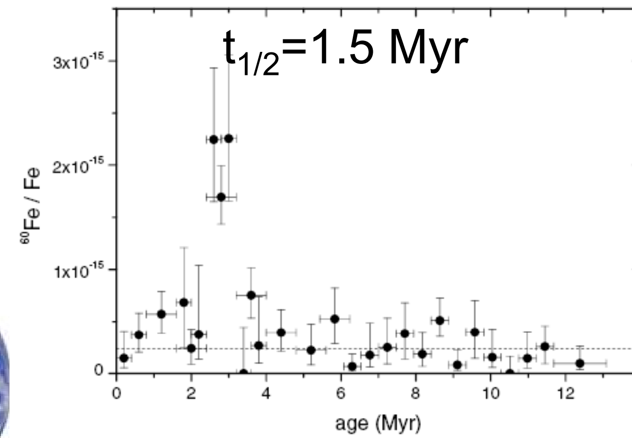
Observed: ^{26}Al/^{60}Fe=0.08-0.22

Detection of ^{60}Fe with INTEGRAL



^{60}Fe enrichment in deep sea iron manganese sediments

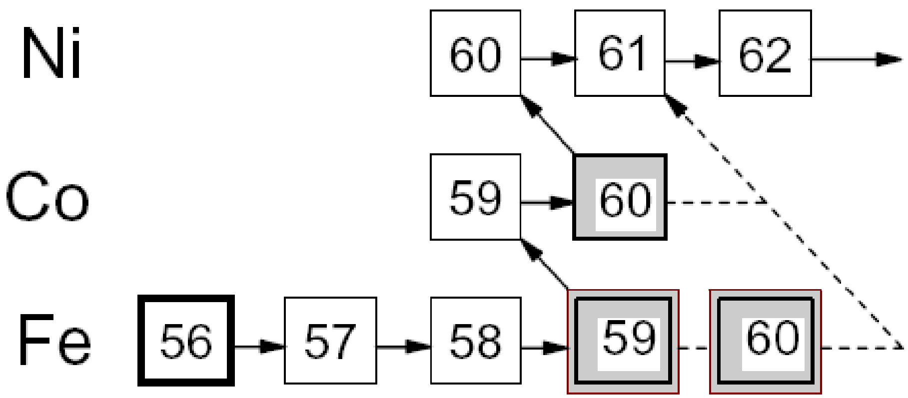




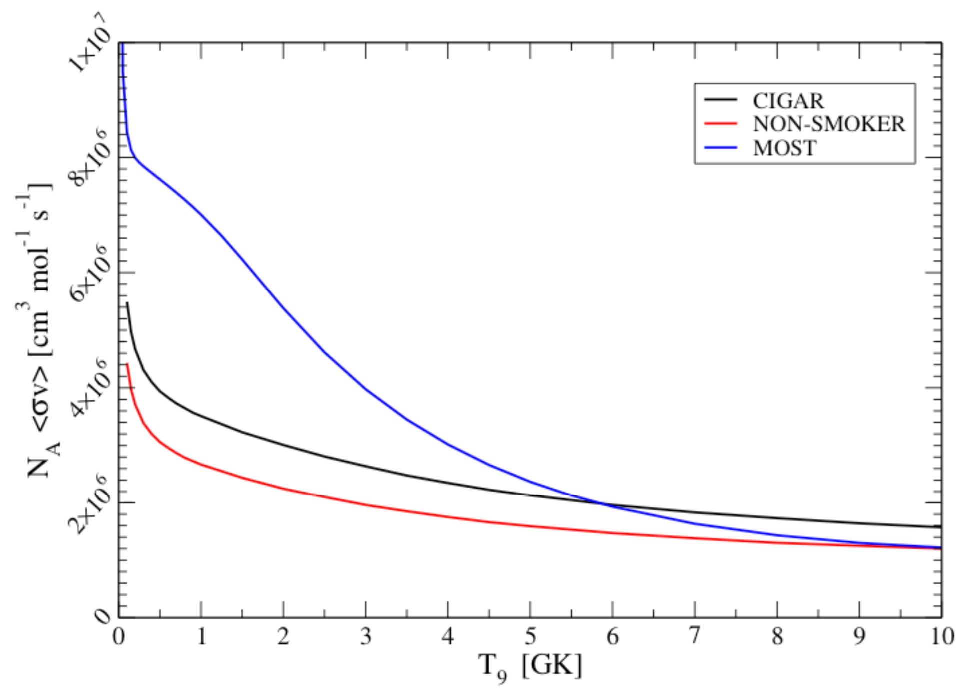
Exposure, distance, time … depends on ^{59}Fe(n,γ)^{60}Fe(n,γ) rates

Observational evidence for nearby Supernova 2.8 Myr ago at a distance of ~10pc!

^{60}Fe measurements

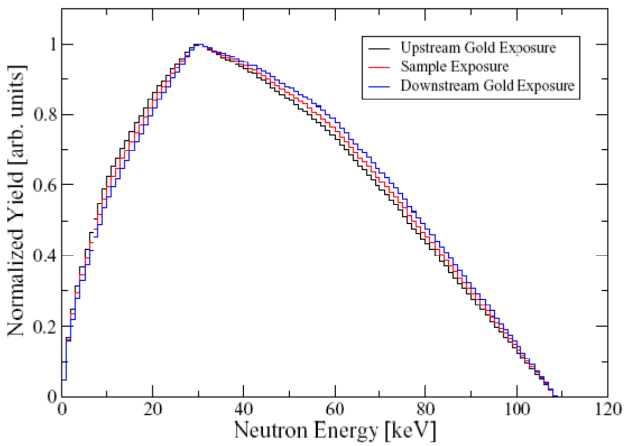


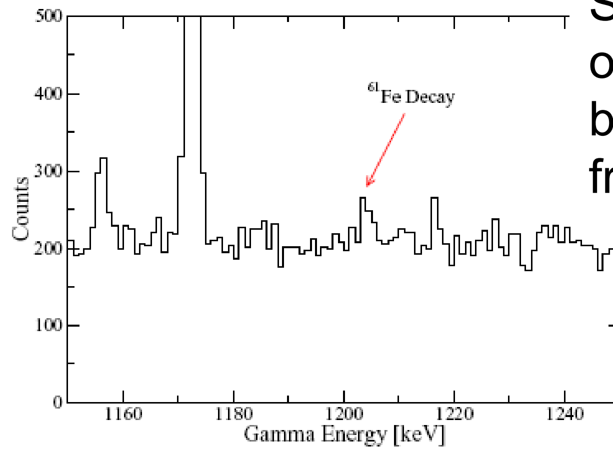
The production of ^{60}Fe by neutron capture prior to core collapse depends strongly on the uncertain cross sections of ^{59}Fe(n,γ)^{60}Fe and ^{60}Fe(n,γ) ^{61}Fe.



Measurement of neutron capture reactions important since Hauser Feshbach simulations are not reliable in this mass range.

^{60}Fe(n,γ) activation experiment

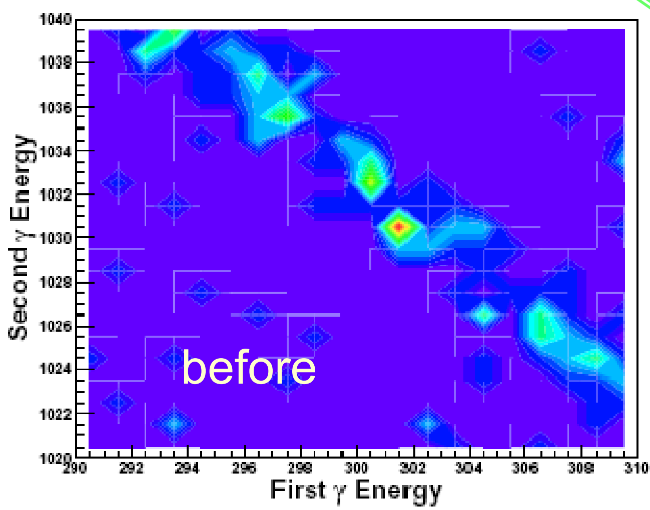


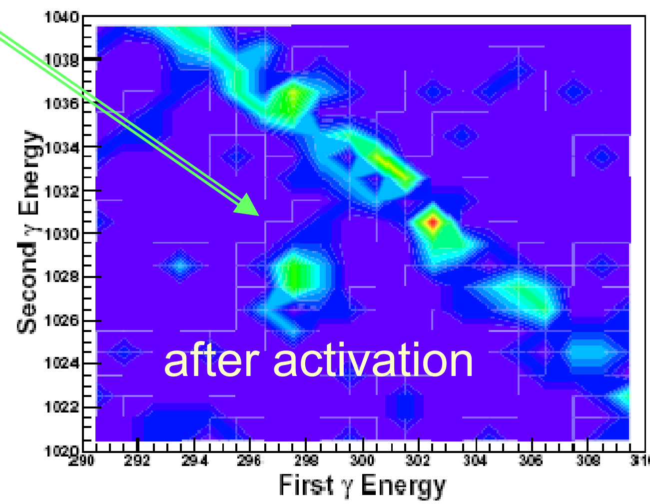


Summed γ-spectrum of ^{61}Fe decay, the background yields from ^{60}Co decay

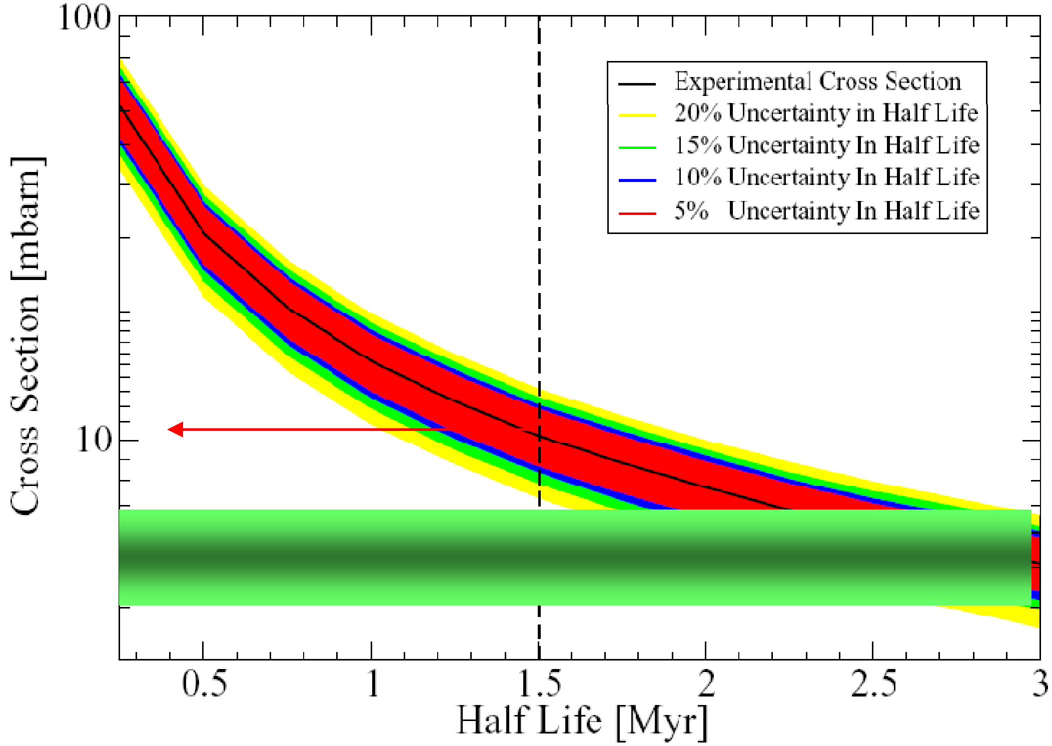
Coincidence requirement between 229 keV and 1027 keV cascade transitions in ^{61}Fe. ($t_{1/2}$=5.98 min)

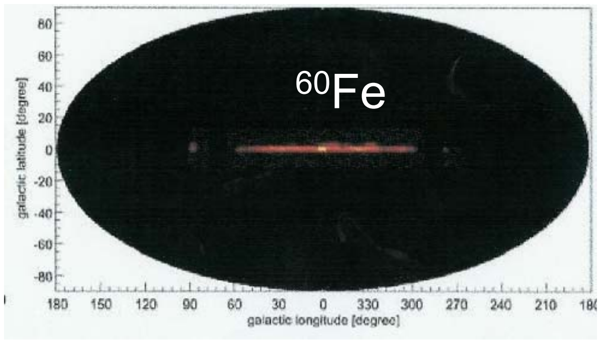
Sample contains $7 \cdot 10^{15}$ ^{60}Fe atoms





$^{60}Fe(n,\gamma)$ cross section at 25 keV





Hauser Feshbach model prediction: ~5 mbarn

Significant deviation which suggests reduction in ^{60}Fe production!

Result scales with half life value, confirmation of literature value necessary!

$T_{1/2}$ = 1.5 Myr ⇒ 2.6 Myr ???

(PSI - TU Munich, FZK Karlsruhe – VERA, Vienna, NSCL/MSU – Notre Dame)

Uncertainties in the $^{12}C+^{12}C$ fusion rate?

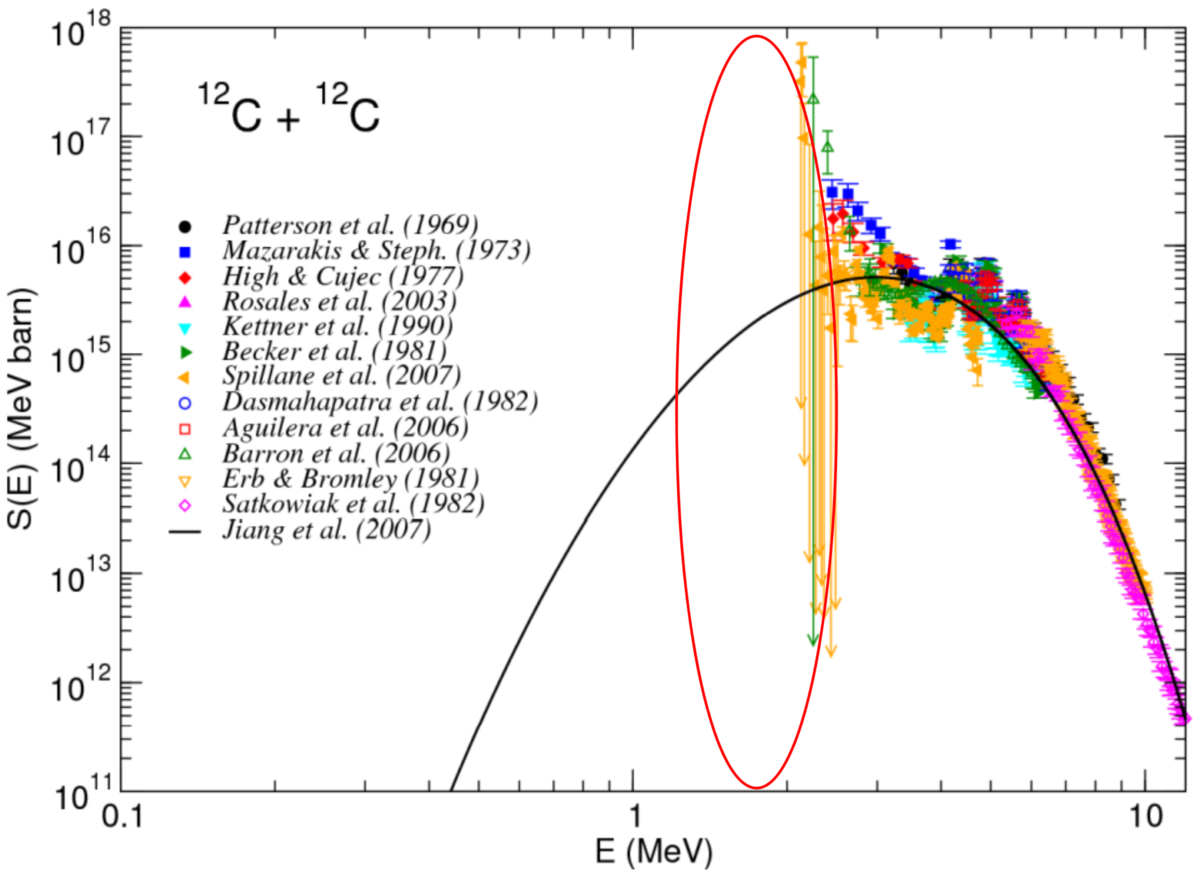
Consequences for:

- Stellar Carbon burning
- Type Ia supernova ignition
- Superburst ignition conditions

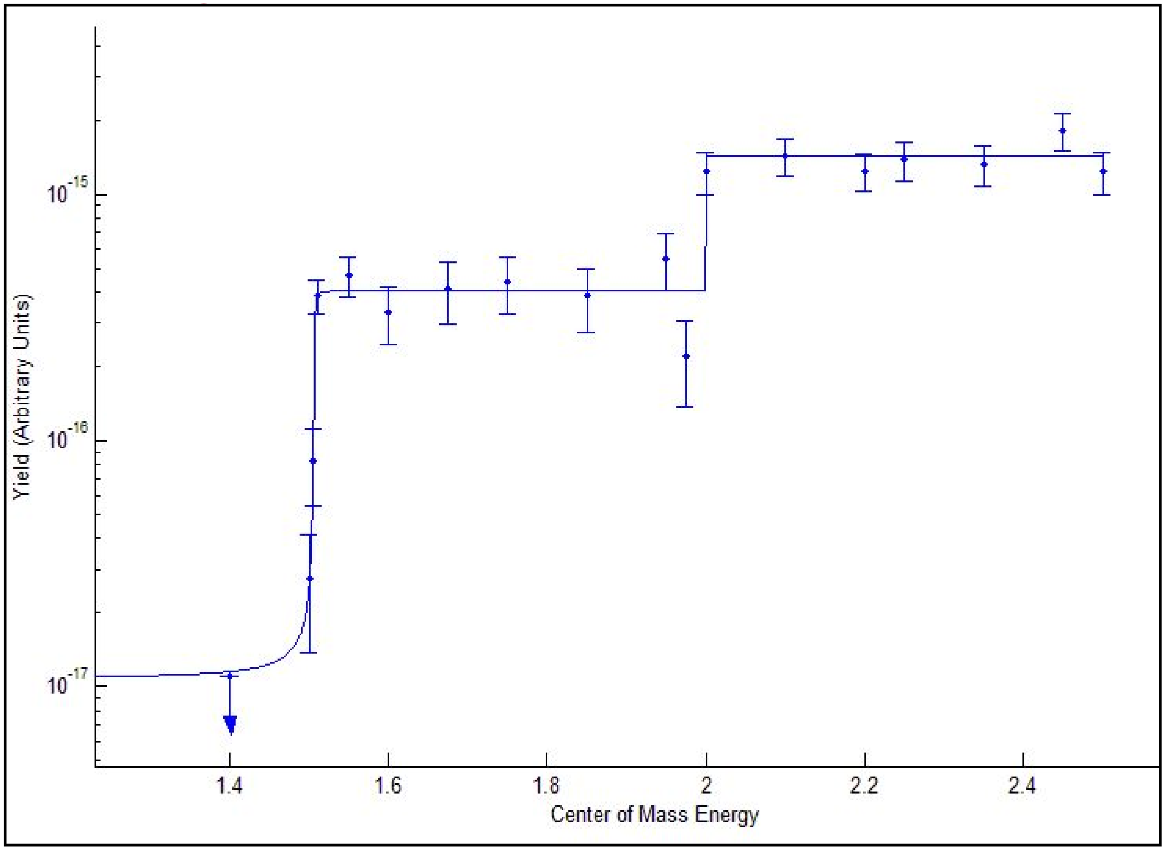
Different potential models lead to different ways to extrapolate the low energy cross section (S-factor).

- standard potential model
- hindrance potential model

Caughlan & Fowler ADND 1988
Gasques et al. PRC 2005
Yakovlev et al. PRC 2006
Jiang et al. PRC 2007



Resonance Structures in $^{12}C+^{12}C$



Recent data suggest strong but narrow resonance structures in the $^{12}C+^{12}C$ reaction system. The data point towards a ^{12}C configuration without a specific preference for the subsequent proton or alpha decay! The branching ratio is very uncertain.

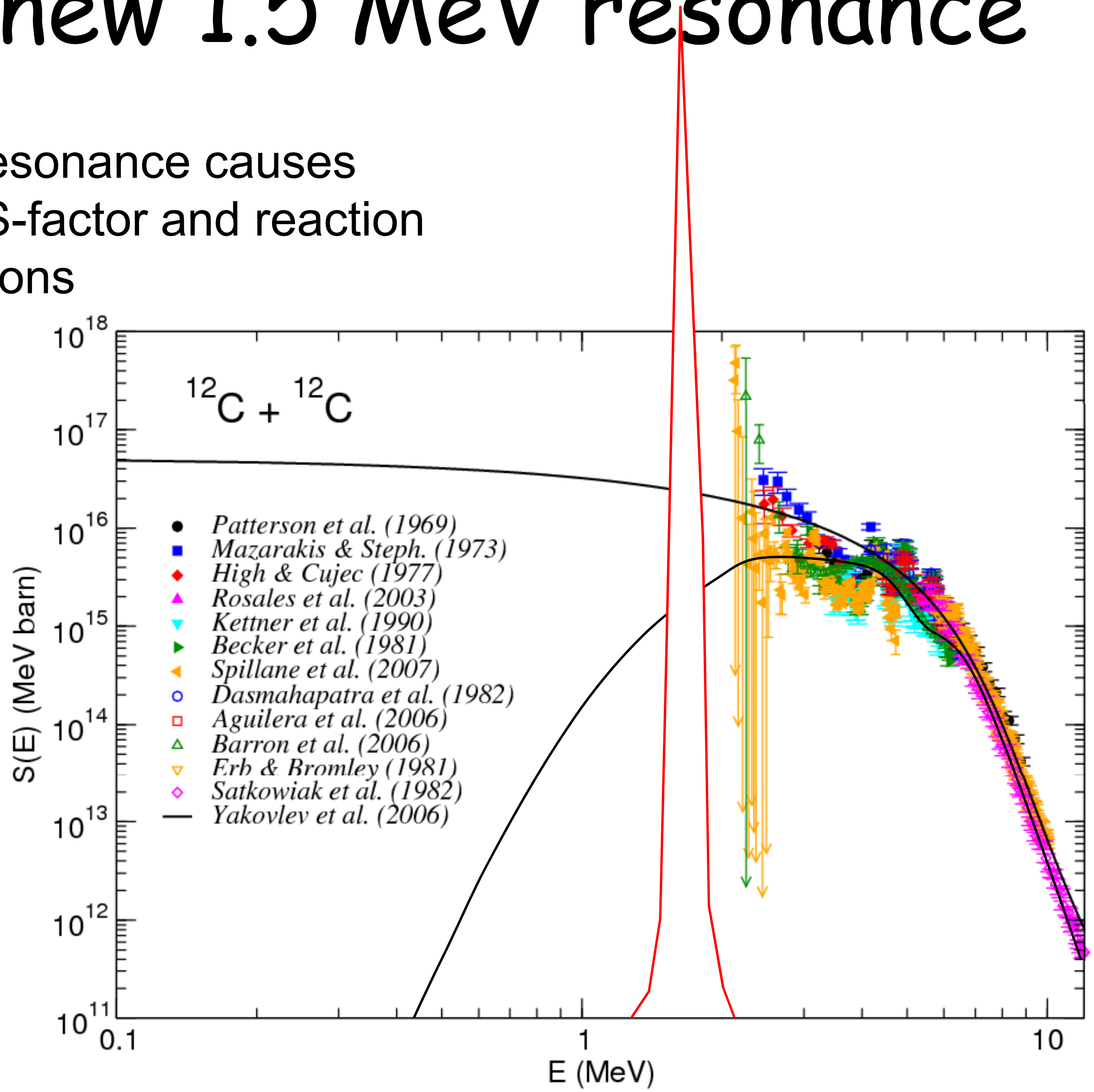
Spillane et al. PRL 2007
Zickefoose et al. Capri 2009

Thick target technique indicates low energy resonance at 1.5 MeV in the $^{12}C+^{12}C \Rightarrow ^{23}Na+p$ channel.

Location of new 1.5 MeV resonance

Strong, molecular $^{12}C+^{12}C$ resonance causes enormous enhancement of S-factor and reaction rate at stellar burning conditions

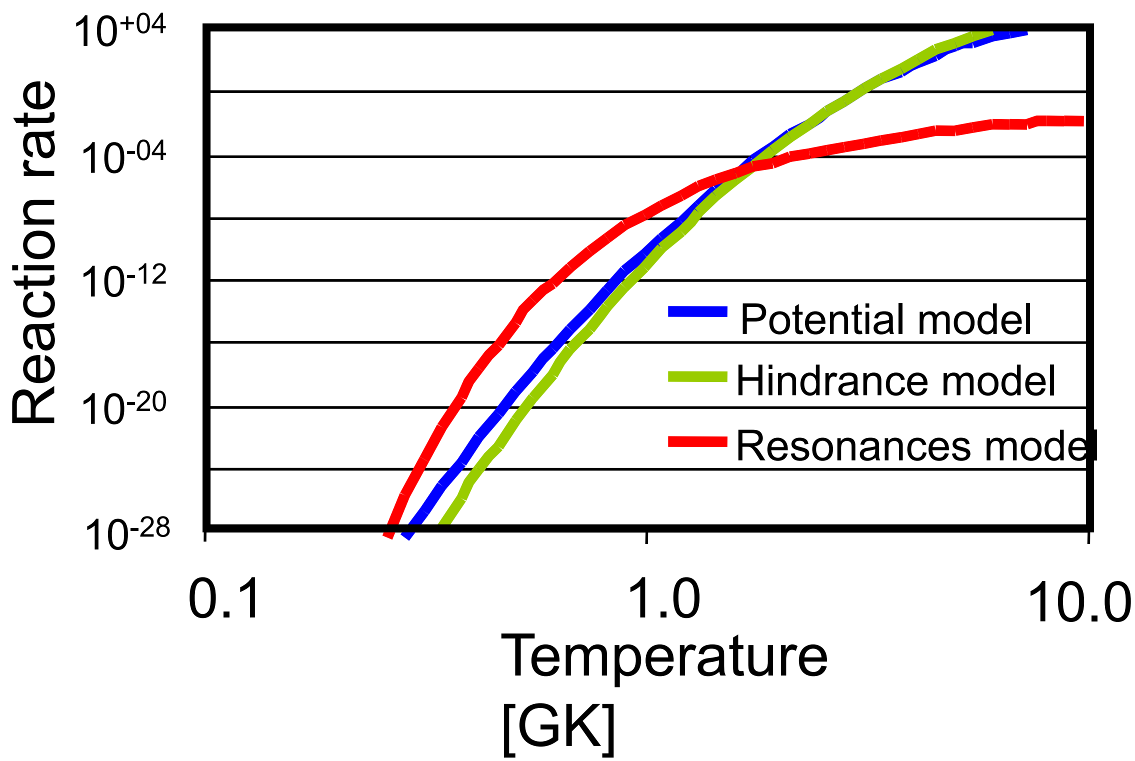
- standard potential model
- low energy resonances

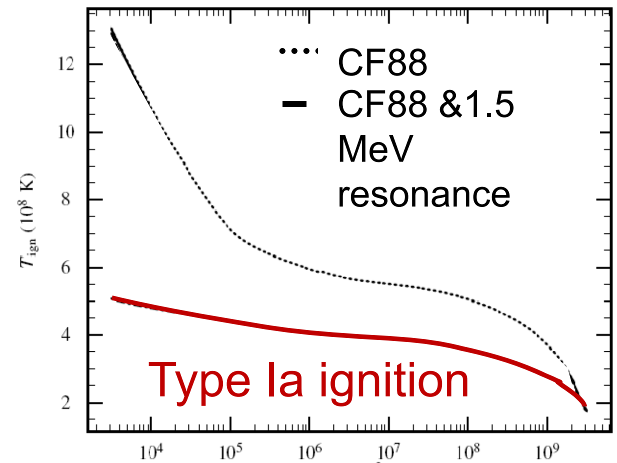


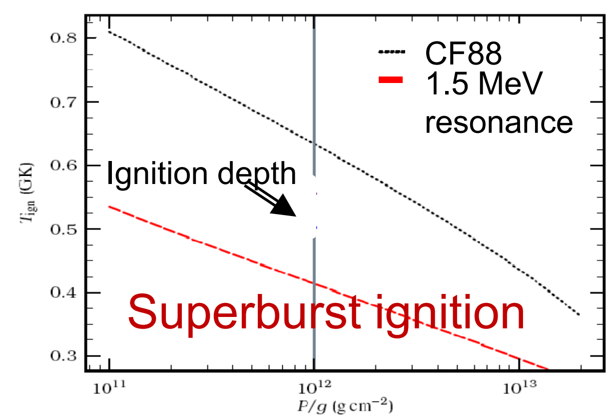
Caughlan & Fowler ADND 1988
Gasques et al. PRC 2005
Spillane et al. PRL 2007
Zickefoose et al. Capri 2009

Impact of a 1.5 MeV resonance

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

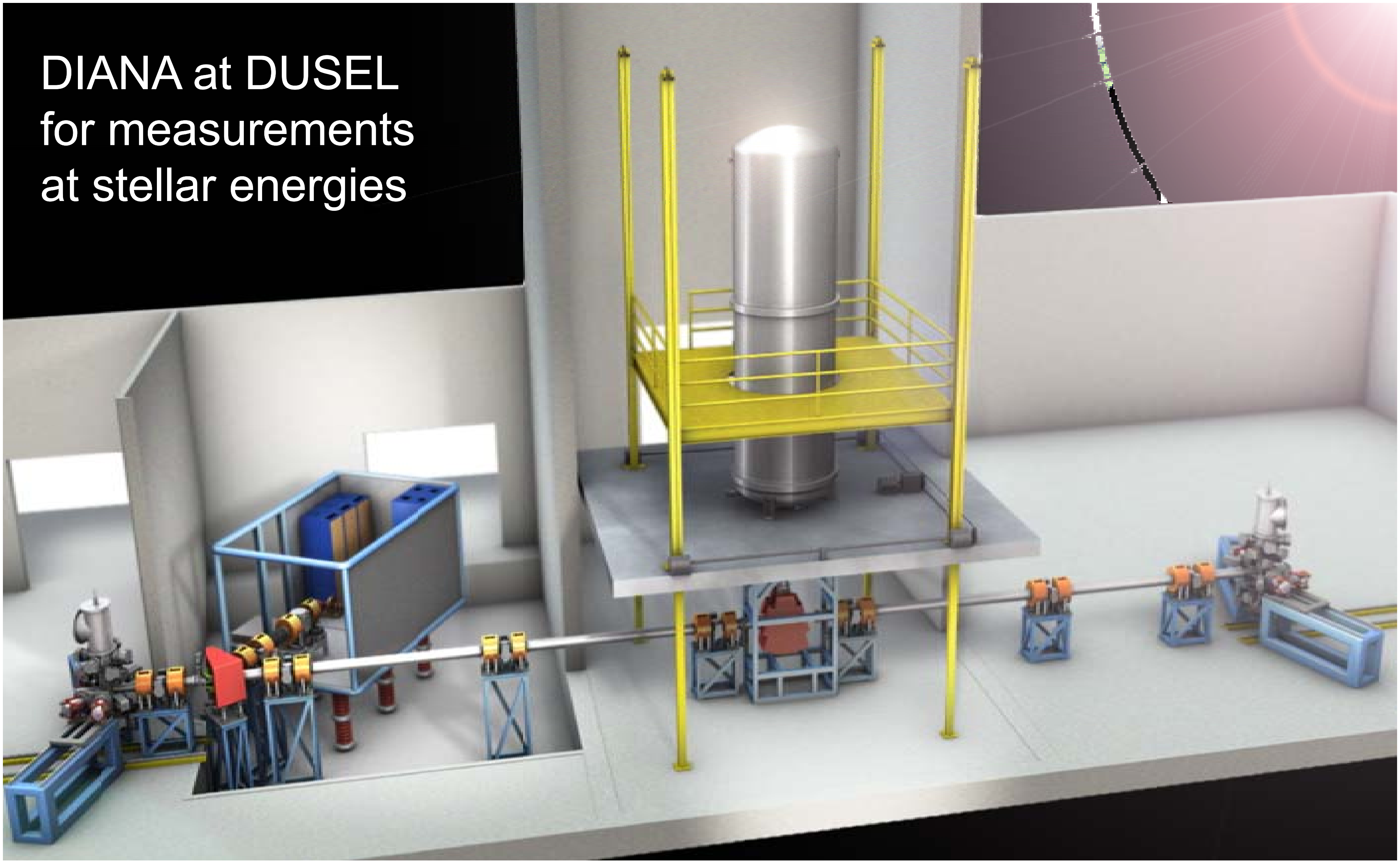




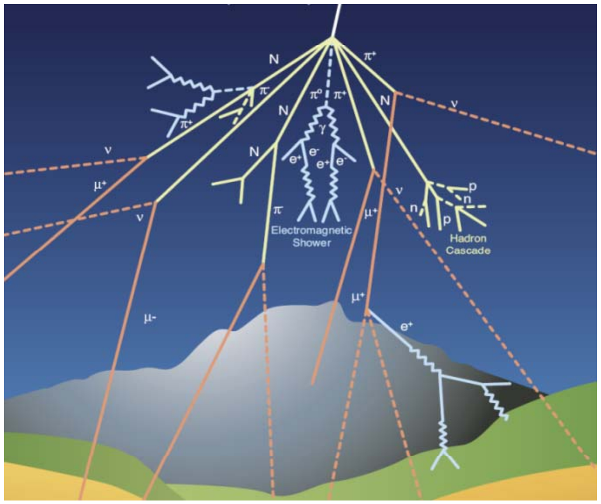


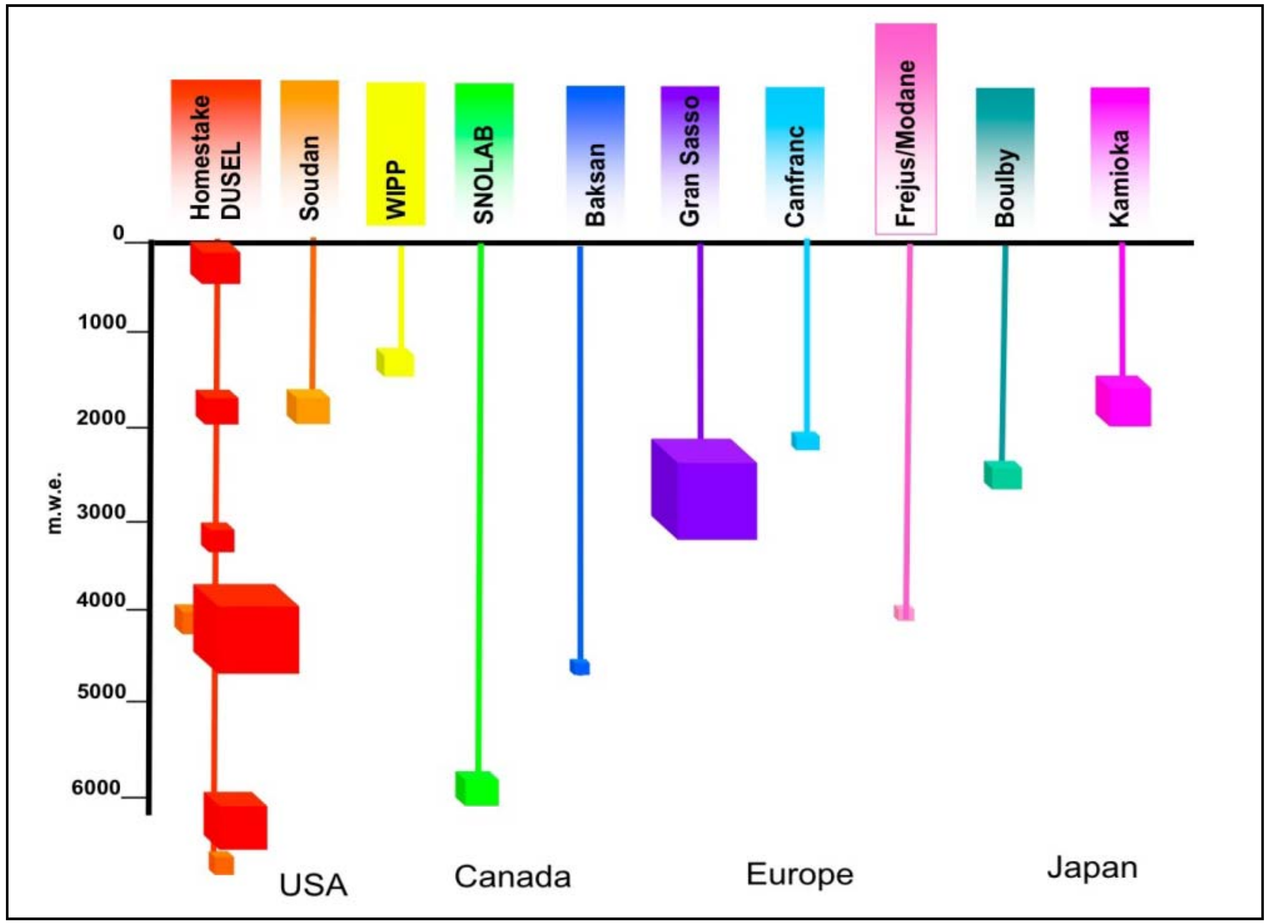
Future Facilities in Nuclear Astrophysics

Towards low energies - underground



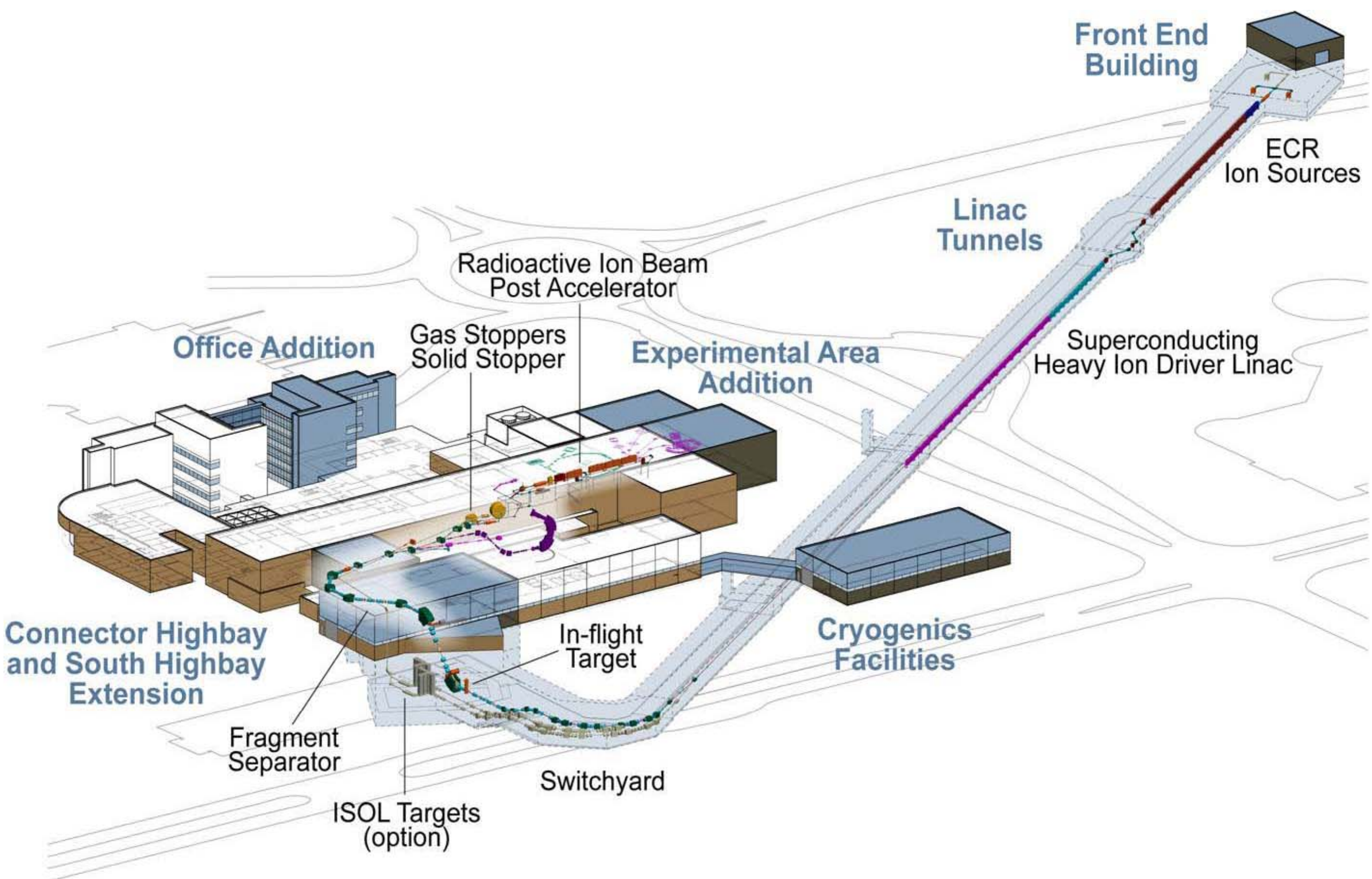
International Situation

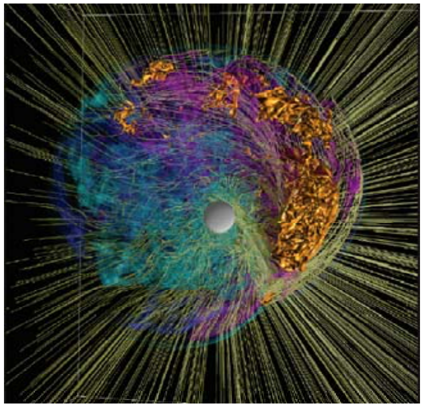


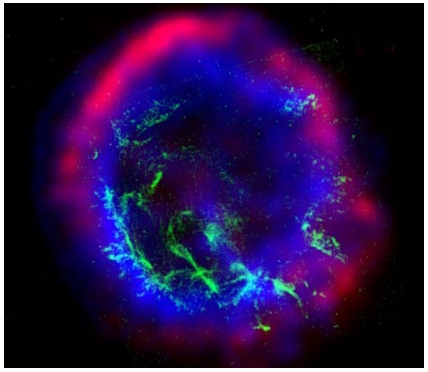


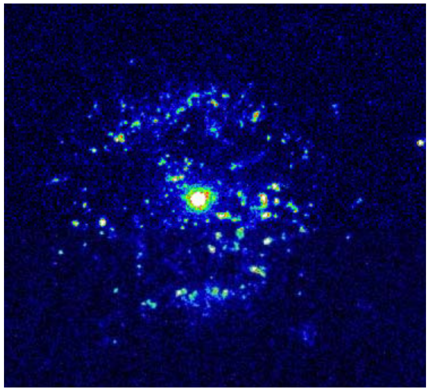
Away from Stability!

Understanding nuclear processes at the extreme density and temperature conditions of stellar environments!



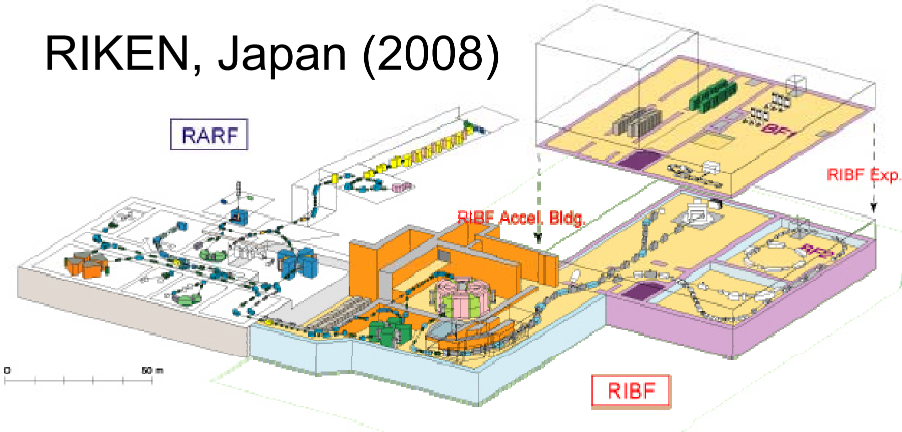




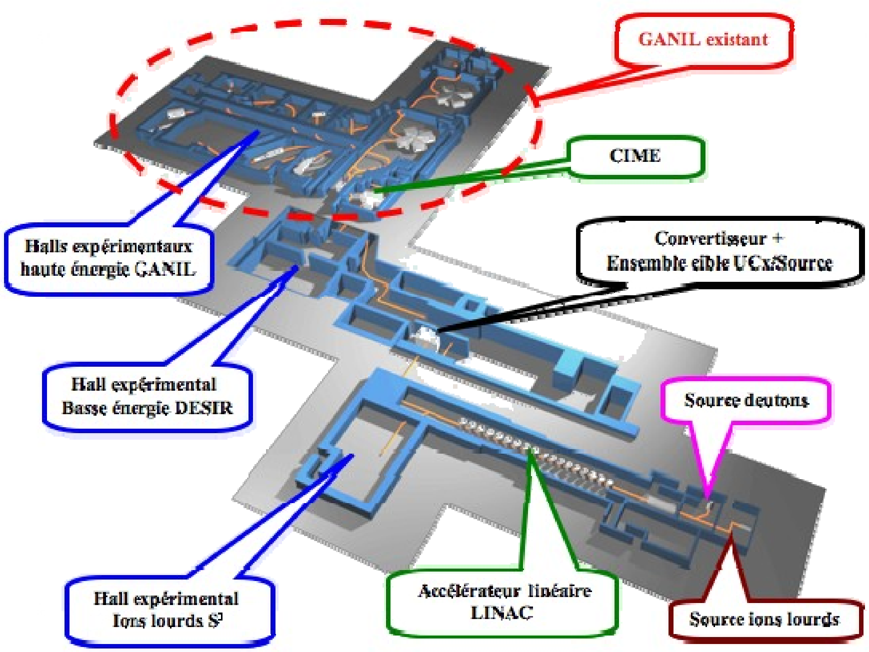


Alternatives

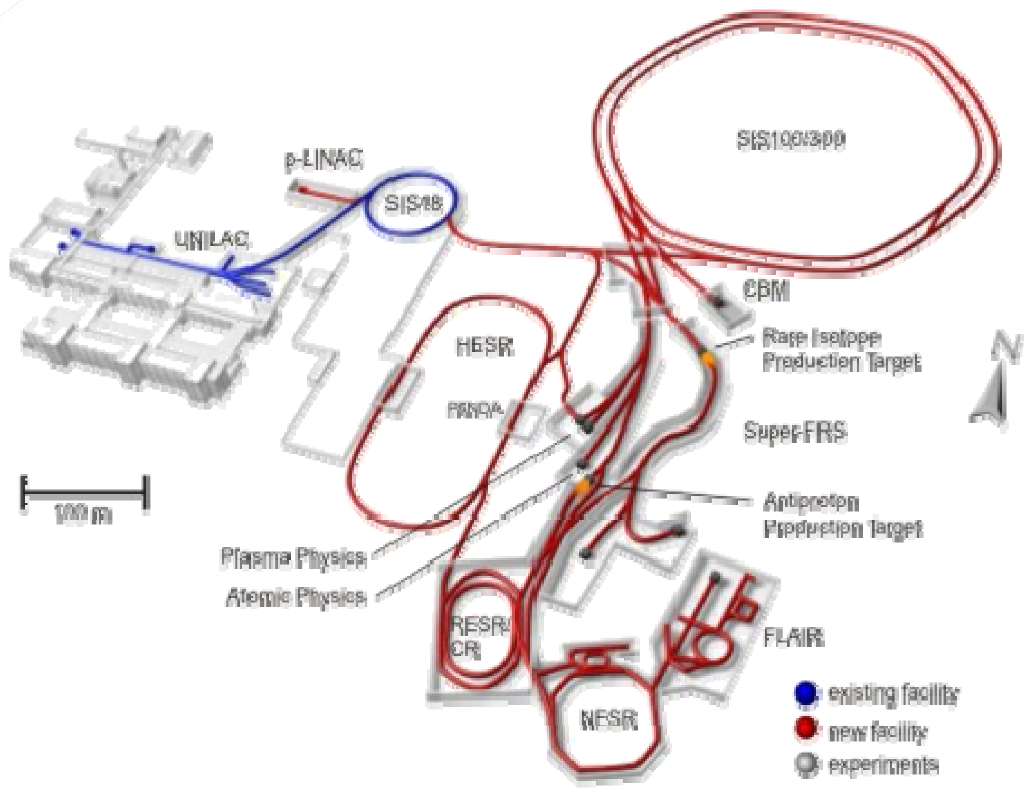
RIKEN, Japan (2008)



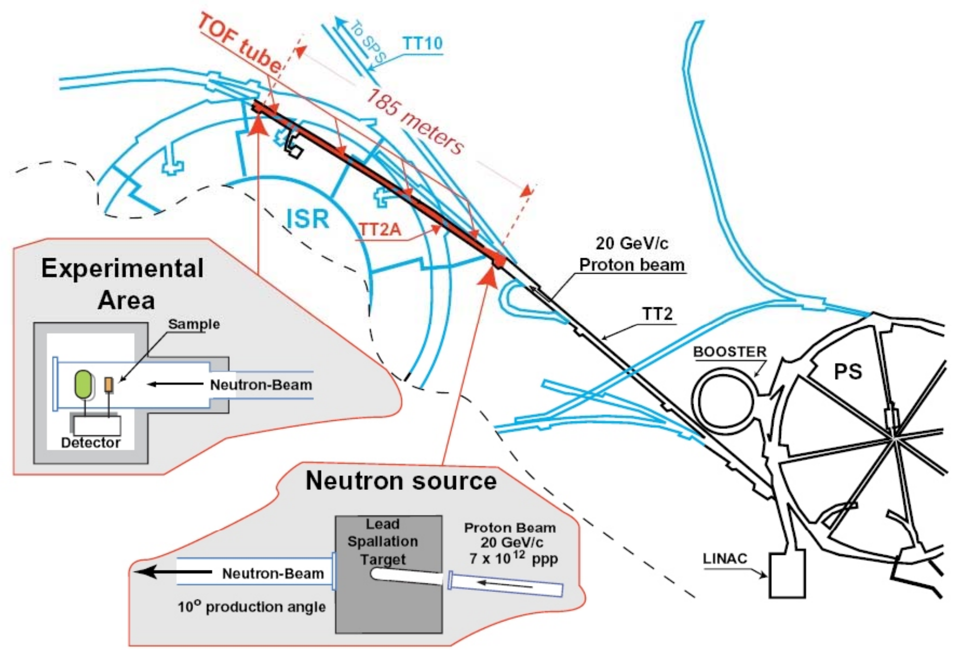
GANIL, France (2013)

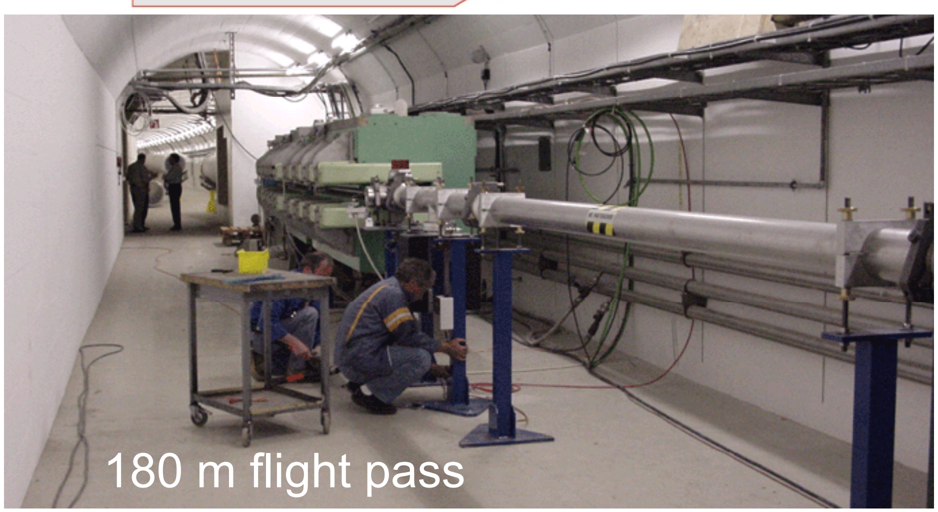


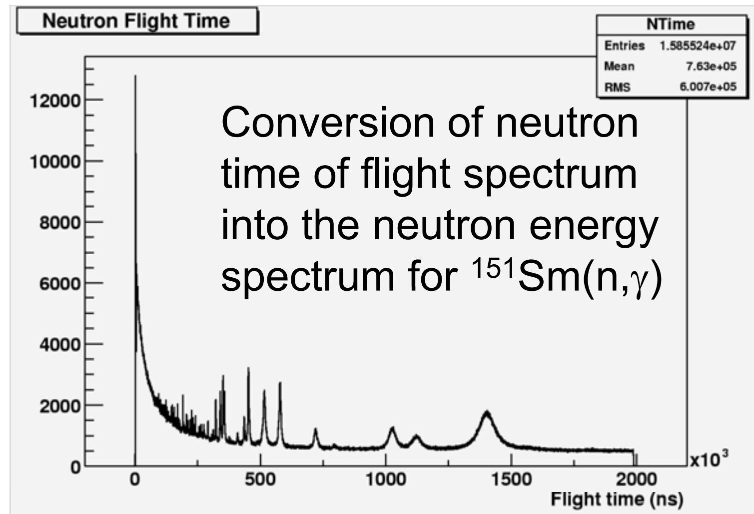
GSI/FAIR Germany (2015)

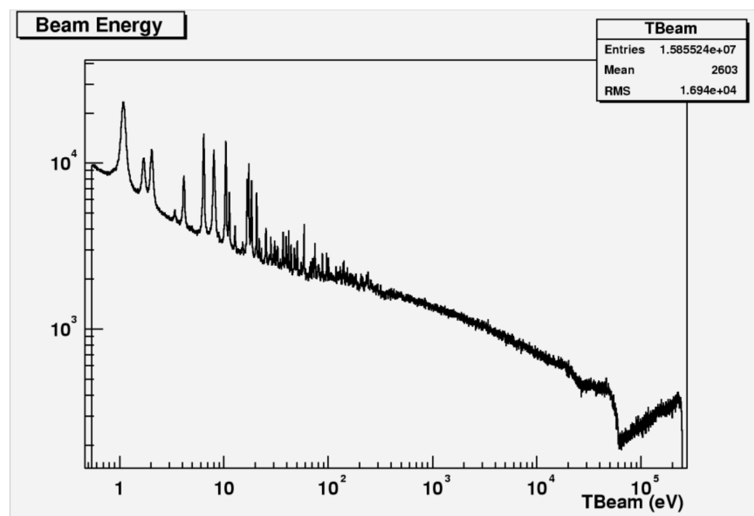


Neutron spallation sources for s-process neutron capture studies

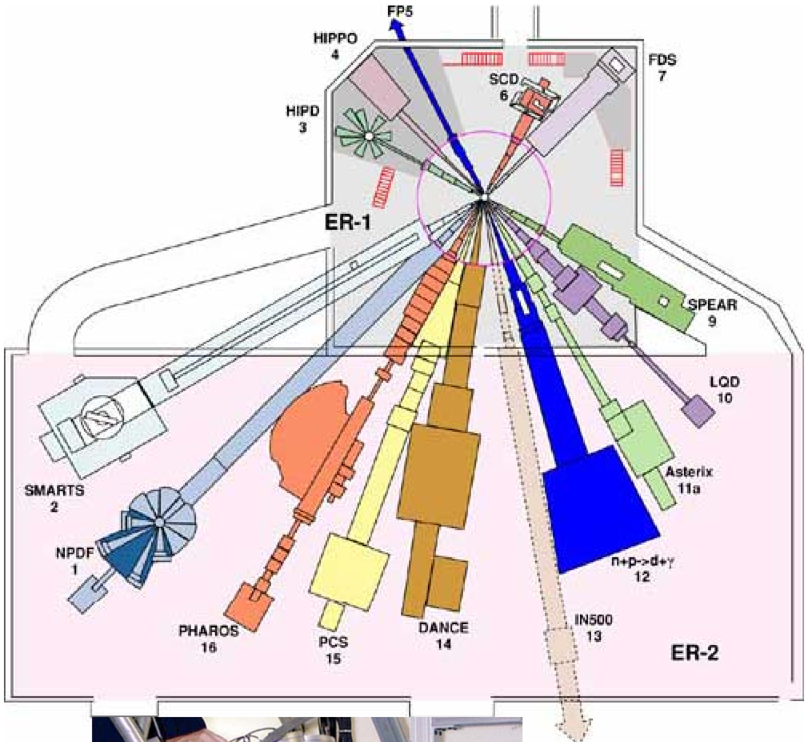


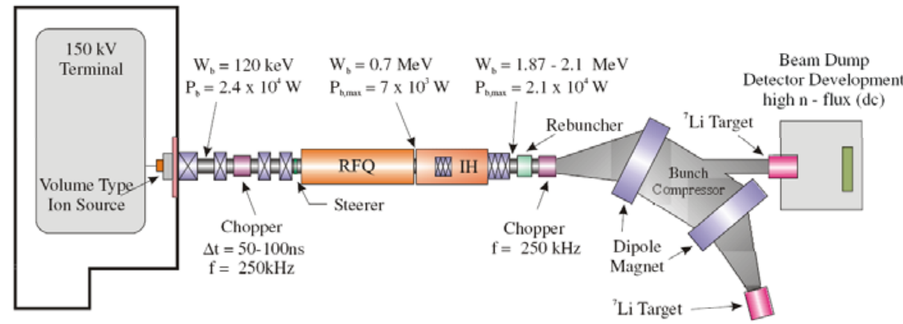






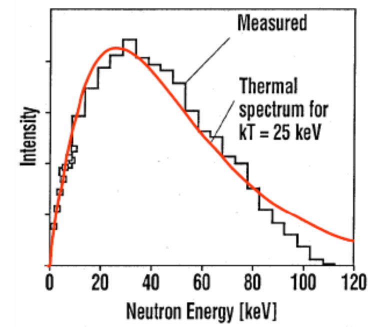
Other Facilities LANSCE & FRANZ

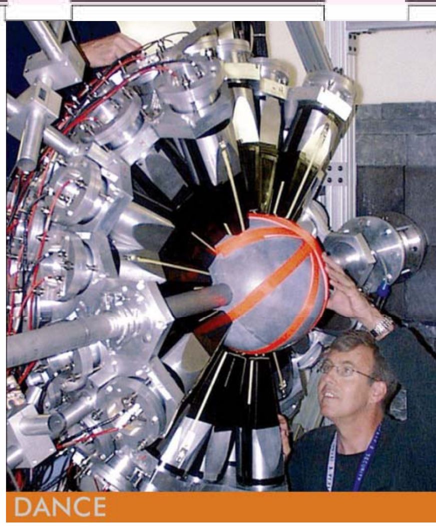




- Extracted source current : 200 mA dc
- Pulsed beam target : 10^7 n / cm²s at
- 'Straight' beam target : 10^8 n / cm²s

Frankfurt Neutron Source FRANZ with the FZK Ba_2F detector array.

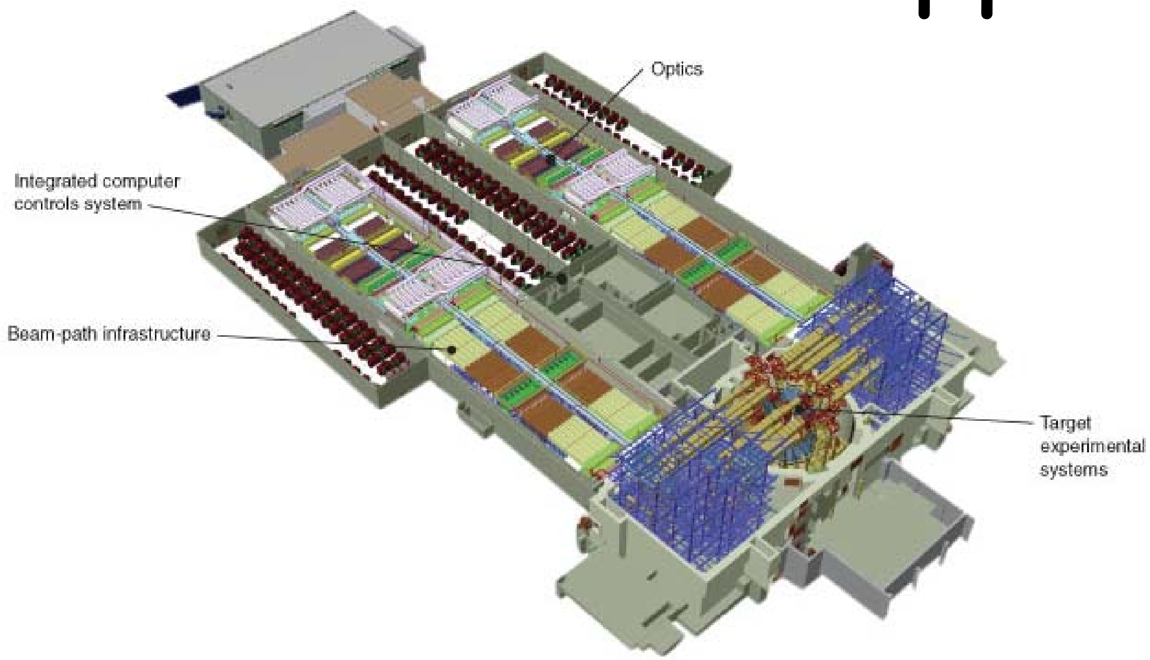




Neutron ToF facility at Los Alamos National Laboratory, with DANCE Ba_2F detector array

Towards Reality? Astrophysics at NIF

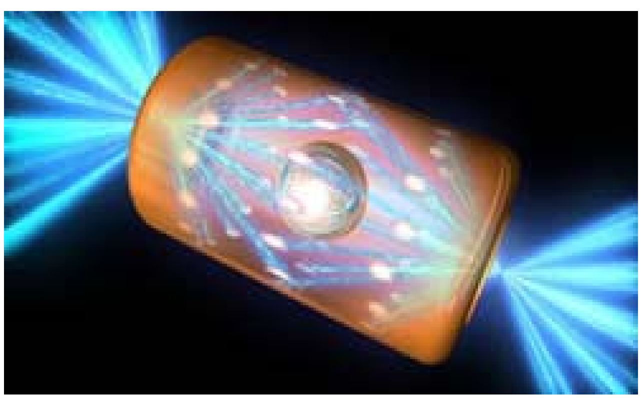
The laser approach NIF

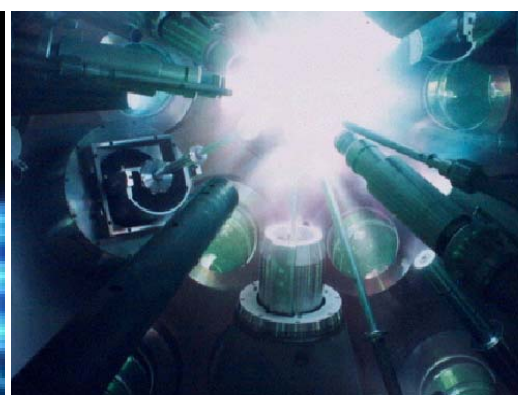


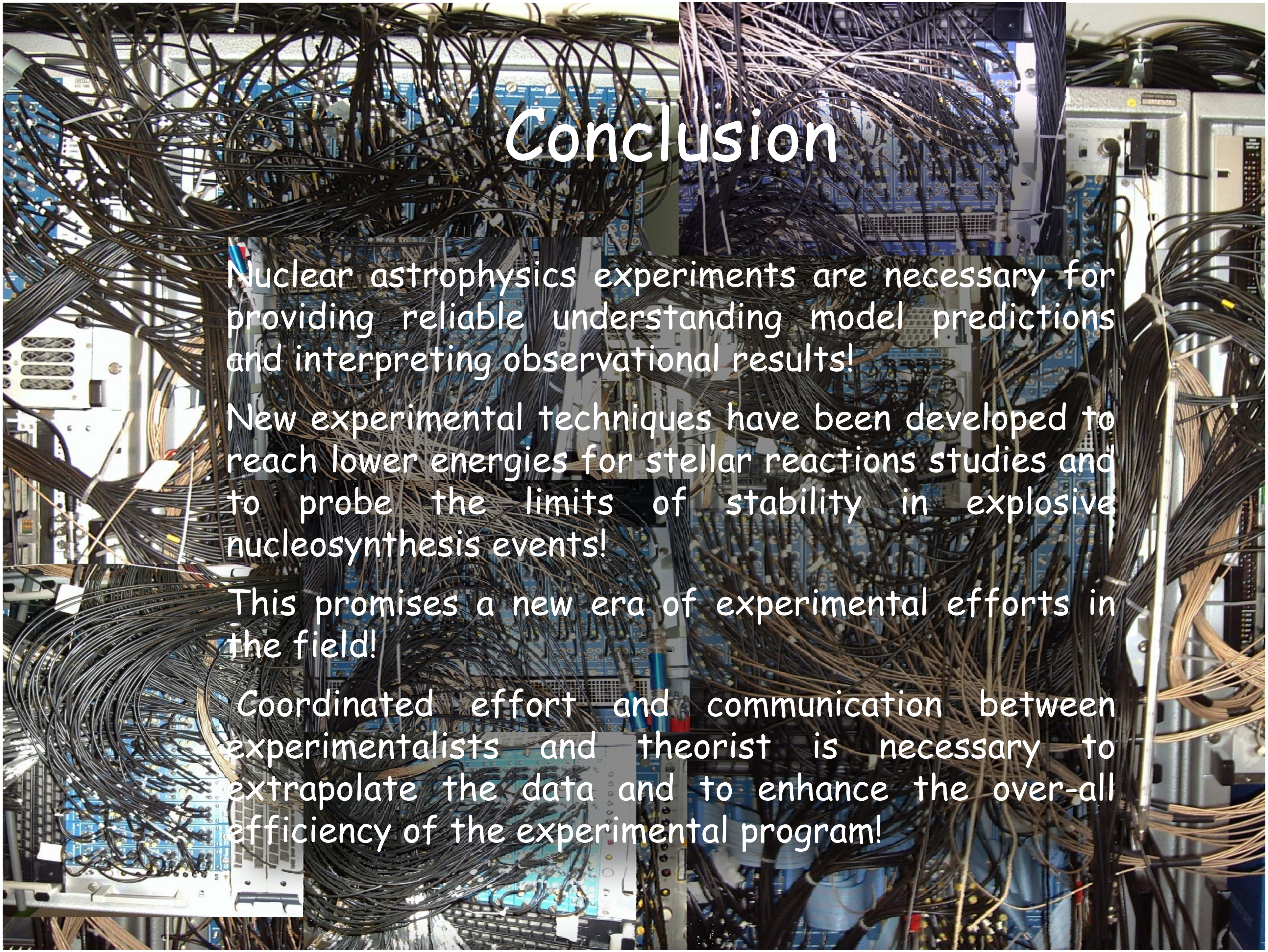
short period: t = 20 – 200 ps
high temperature: T = 15 GK
high density: ρ = 1000 g/cm^3

1. Charge particle reactions
2. Neutron capture reactions

Fast electronics and data processing required







Conclusion

Nuclear astrophysics experiments are necessary for providing reliable understanding model predictions and interpreting observational results!

New experimental techniques have been developed to reach lower energies for stellar reactions studies and to probe the limits of stability in explosive nucleosynthesis events!

This promises a new era of experimental efforts in the field!

Coordinated effort and communication between experimentalists and theorist is necessary to extrapolate the data and to enhance the over-all efficiency of the experimental program!