MRC-1: Low Energy Nuclear Reactions and Stellar Evolution

J I N A

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Spokesperson: M. Wiescher (Director)

nucleosynthesis & stellar evolution
s-process & AGB stars

Thermonuclear Reaction Rate Compilation

⇨ Goals!

⇨ Projects!

⇨ Conferences!

research activities 2005-2006

Focus-1:

- ⇨ Stellar Hydrogen burning in massive stars
- ⇨ Re-evaluation of CNO cycles

Focus-2:

- ⇨ Stellar He-burning
- ⇨ neutron sources for s-process

Focus-3:

- ⇨ nucleosynthesis in AGB stars
- ⇨ end-point of s-process

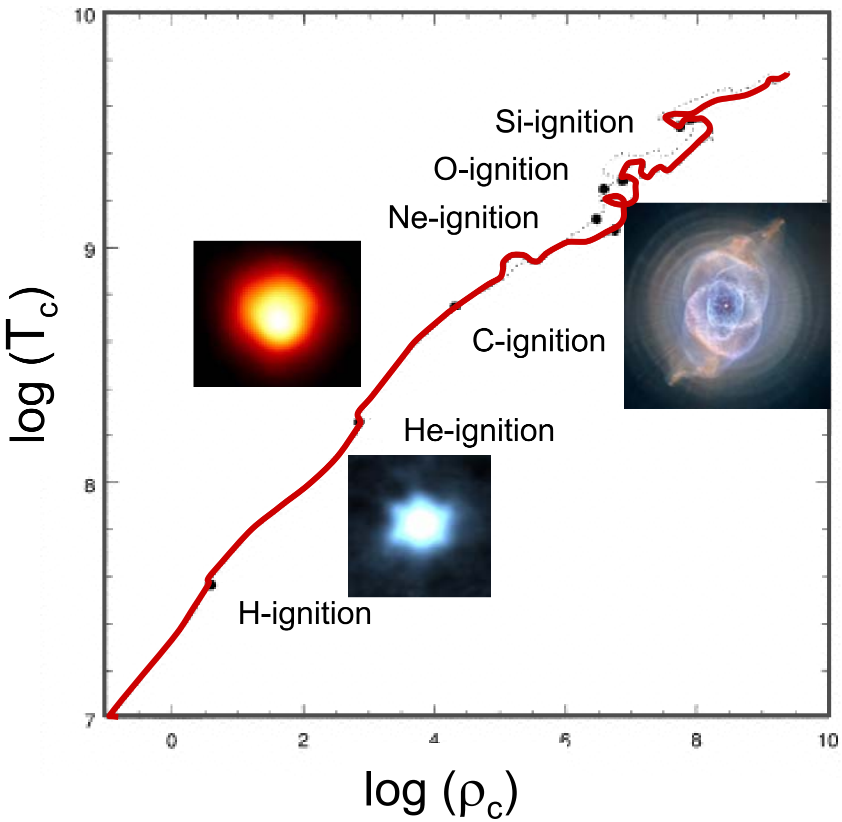
Focus-4:

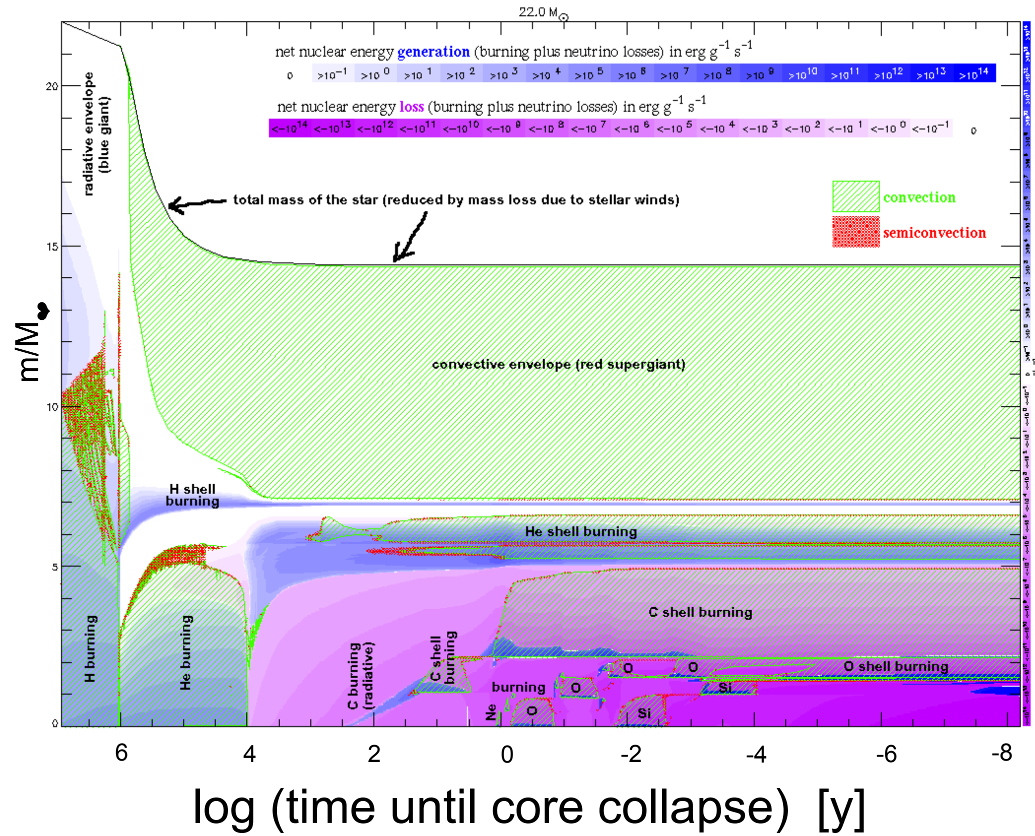
- ⇨ heavy ion burning in late stellar evolution

Focus-5:

- ⇨ thermonuclear reaction rate compilation

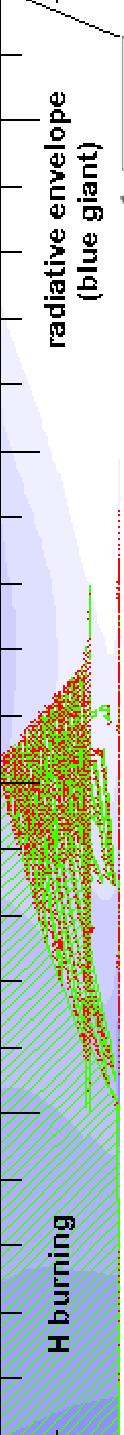
Nuclear burning & stellar evolution



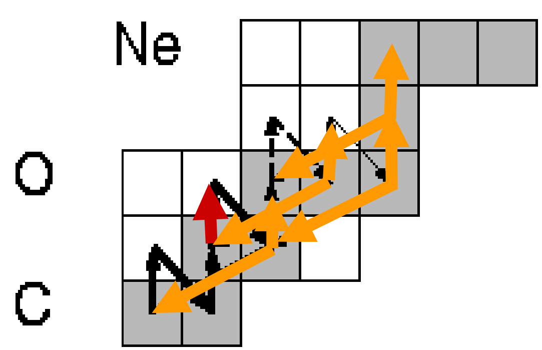


Each burning phase is determined by nuclear reactions in terms of

- energy generation,
- time scale
- nucleosynthesis



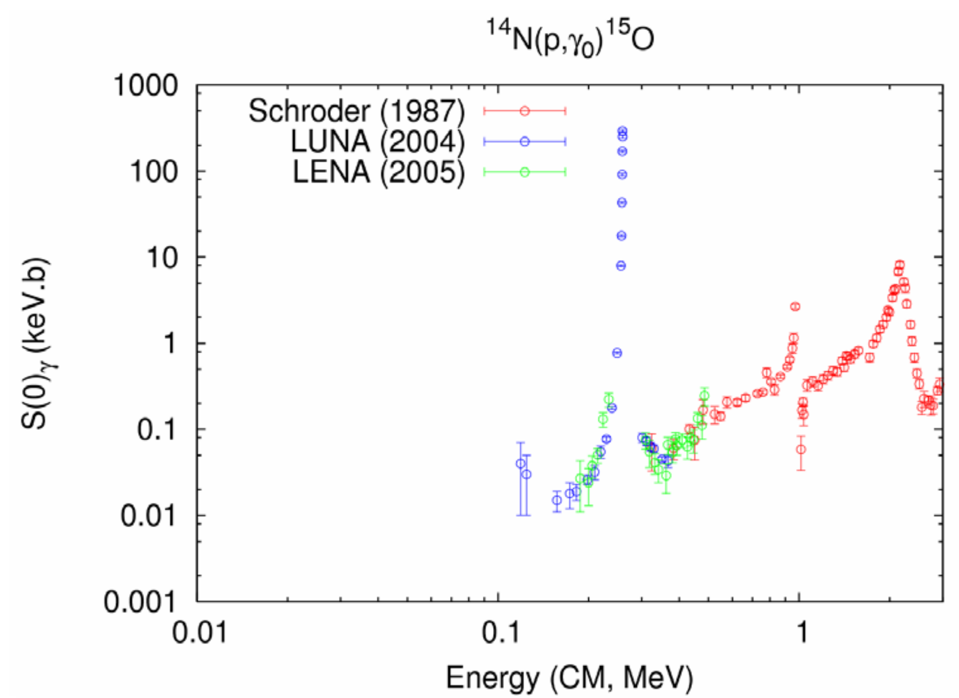
Stellar H-burning in massive stars

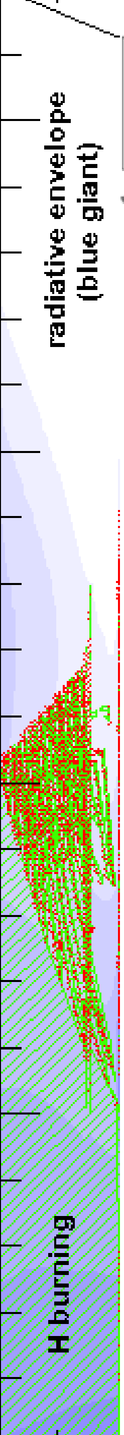


Low energy reactions often rely on unreliable extrapolation not including threshold effects such as sub-threshold resonances or interference patterns.

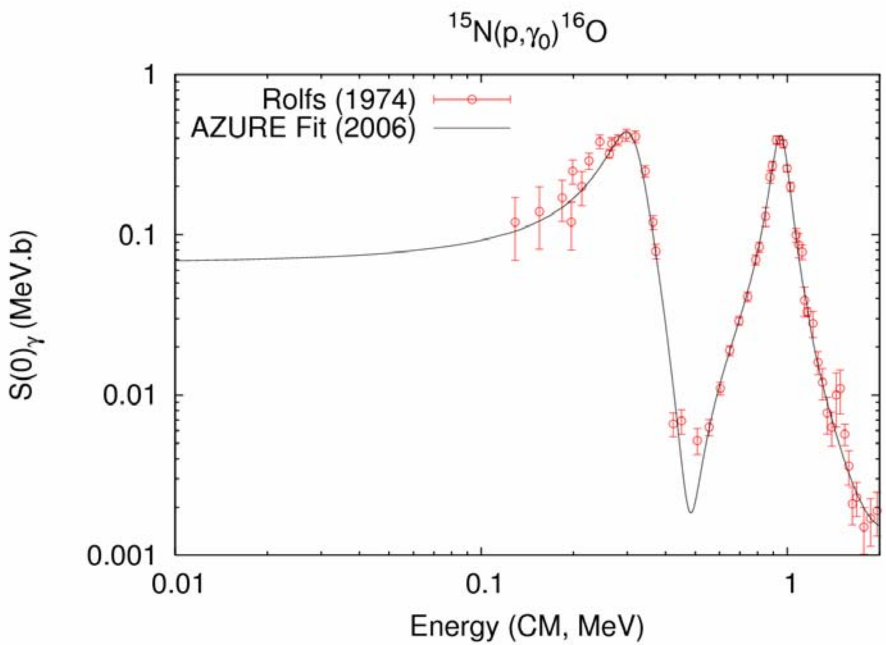
New development of multi-channel r-matrix code "AZURE" to fit all reaction and scattering channels parallel. First test case $^{14}N(p,\gamma)^{15}O$!

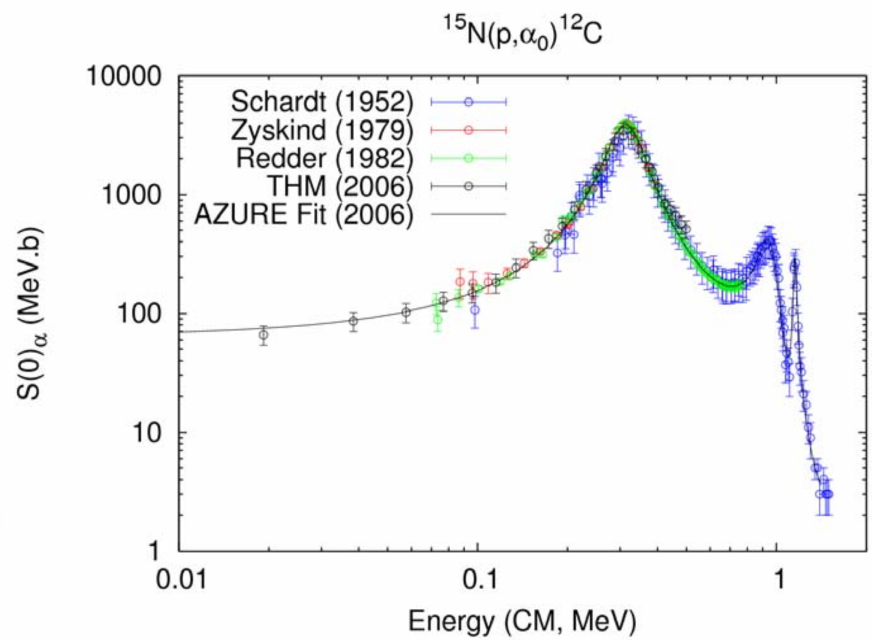
All CNO branch reactions $^{15}N(p,\gamma)(p,\alpha)$, $^{17}O(p,\gamma)(p,\alpha)$, $^{18}O(p,\gamma)(p,\alpha)$, and $^{19}F(p,\gamma)(p,\alpha)$, are presently being fitted with AZURE and are discussed for future underground or inverse kinematics measurements.





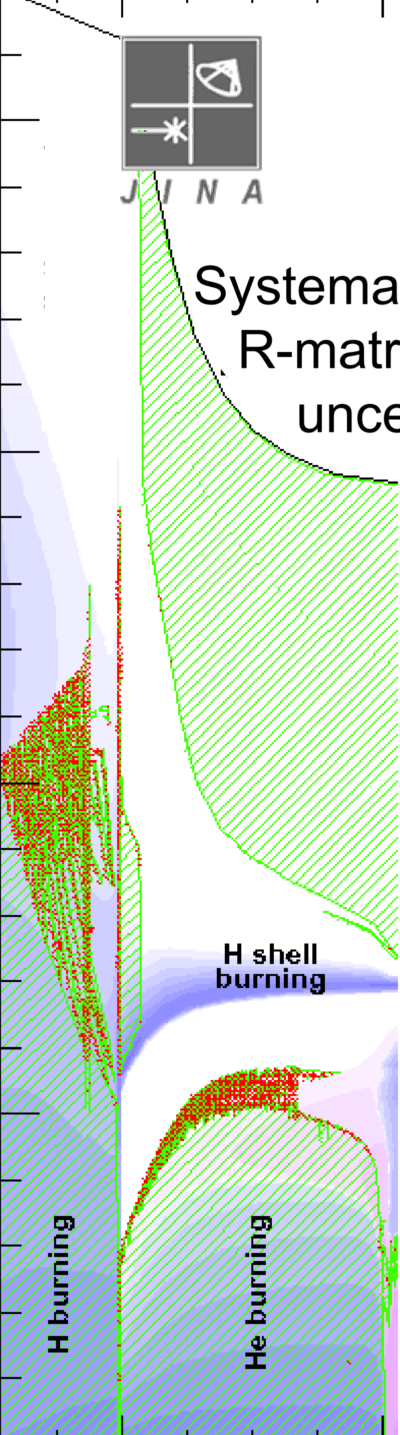
AZURE Extrapolations





New measurements are planned for $^{15}N(p,\gamma)$ at ND and LUNA to reduce the present uncertainty in the experimental data. These experiments will be complemented by a ne study of $^{15}N(p,p)$ elastic scattering to improve the r-matrix fit parameters.

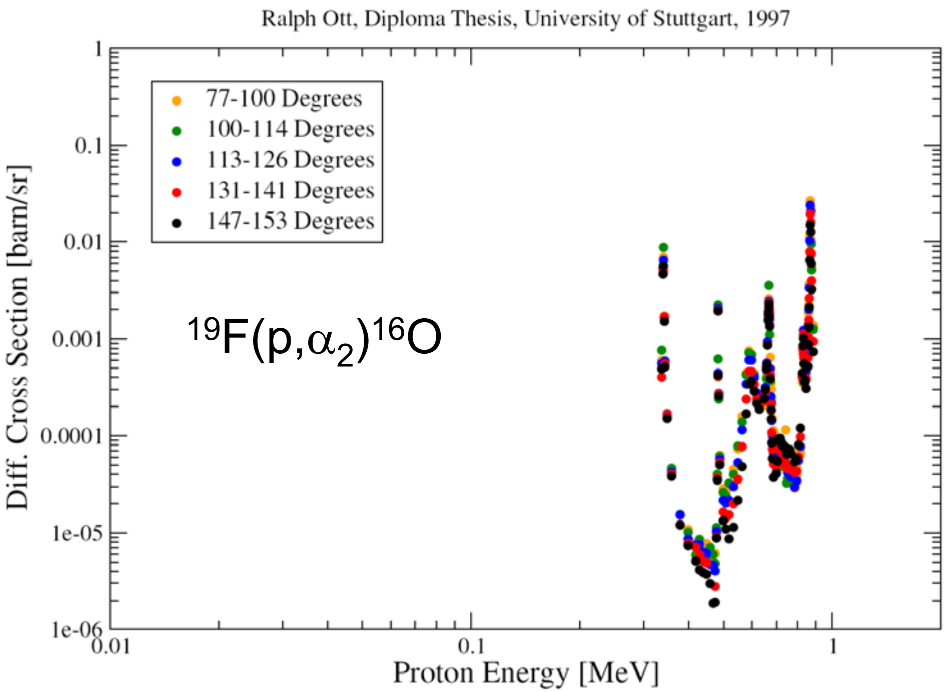
Present & future JINA projects in H-burning

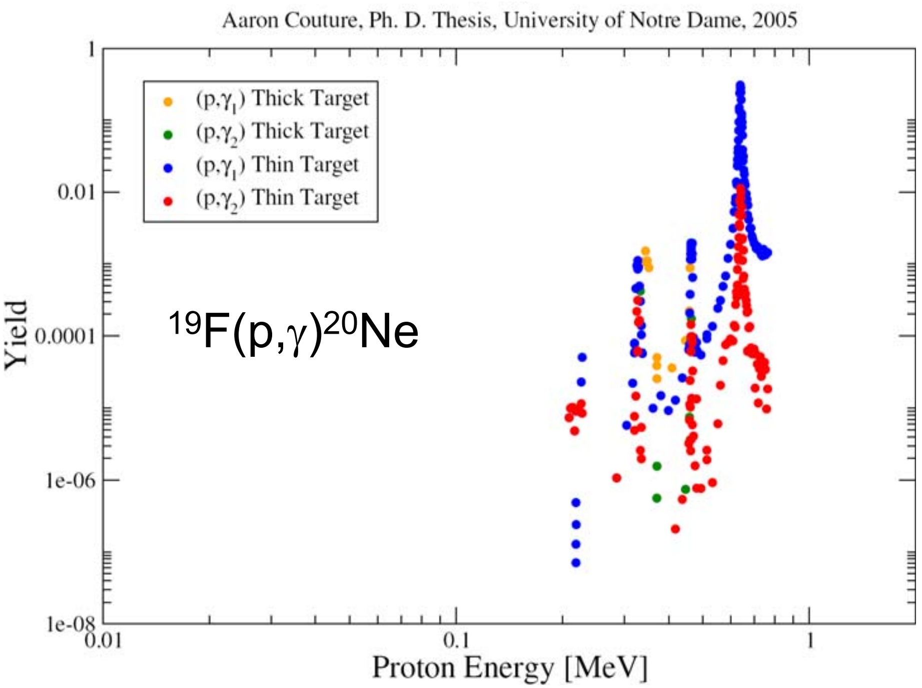


Systematic re-analysis of H-burning reactions using multi-channel R-matrix techniques for removing existing inconsistencies and uncertainties in the low energy extrapolation of existing data using also new, recently obtained experimental data.

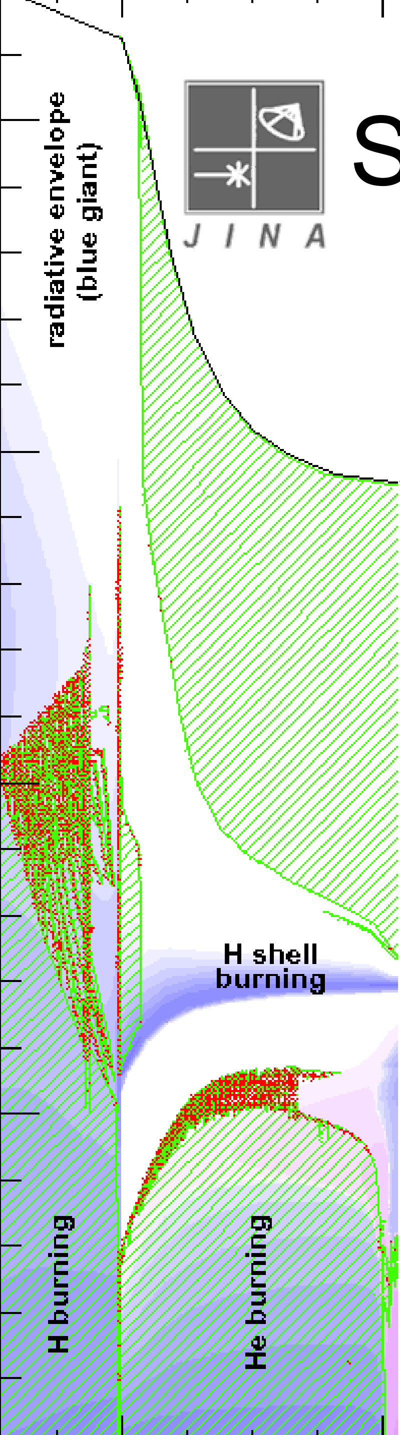
$^{10}B(p,\alpha)^{7}Be$ $^{10}B(p,\gamma)^{11}C$	early star nucleosynthesis expanded pp-chain	JINA R-matrix test
$^{17}O(p,\alpha)^{14}N$ $^{17}O(p,\gamma)^{18}F$	for CNO burning and O isotopic abundances	JINA-UNC R-matrix test
$^{19}F(p,\alpha)^{16}O$ $^{19}F(p,\gamma)^{20}Ne$	Fluorine nucleosynthesis leakage from CNO cycle	JINA-Stuttgart new data!
$^{20}Ne(p,\gamma)^{21}Na$	NeNa cycle in H-shell burning	JINA-UNC-IUSB new data!
$^{23}Na(p,\alpha)^{20}Ne$ $^{23}Na(p,\gamma)^{24}Mg$	NeNa cycle burning in H-shell burning	JINA R-matrix test

The fluorine link

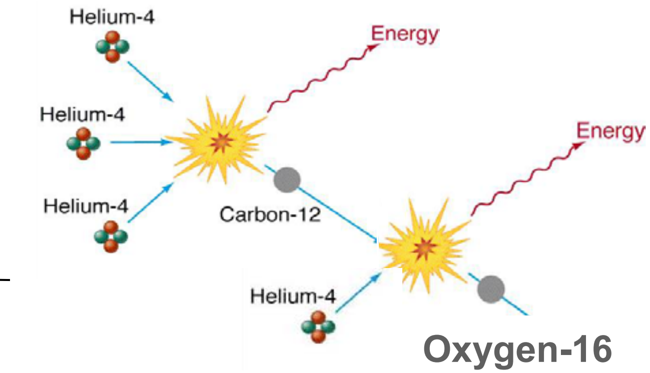




R-matrix analysis underway, but target corrections required!



Stellar He-burning in massive Stars



Two questions remain relevant:

- Energy production and timescale:

$^{4}He(2\alpha,\gamma)^{12}C(\alpha,\gamma)^{16}O(\alpha,\gamma)^{20}Ne$

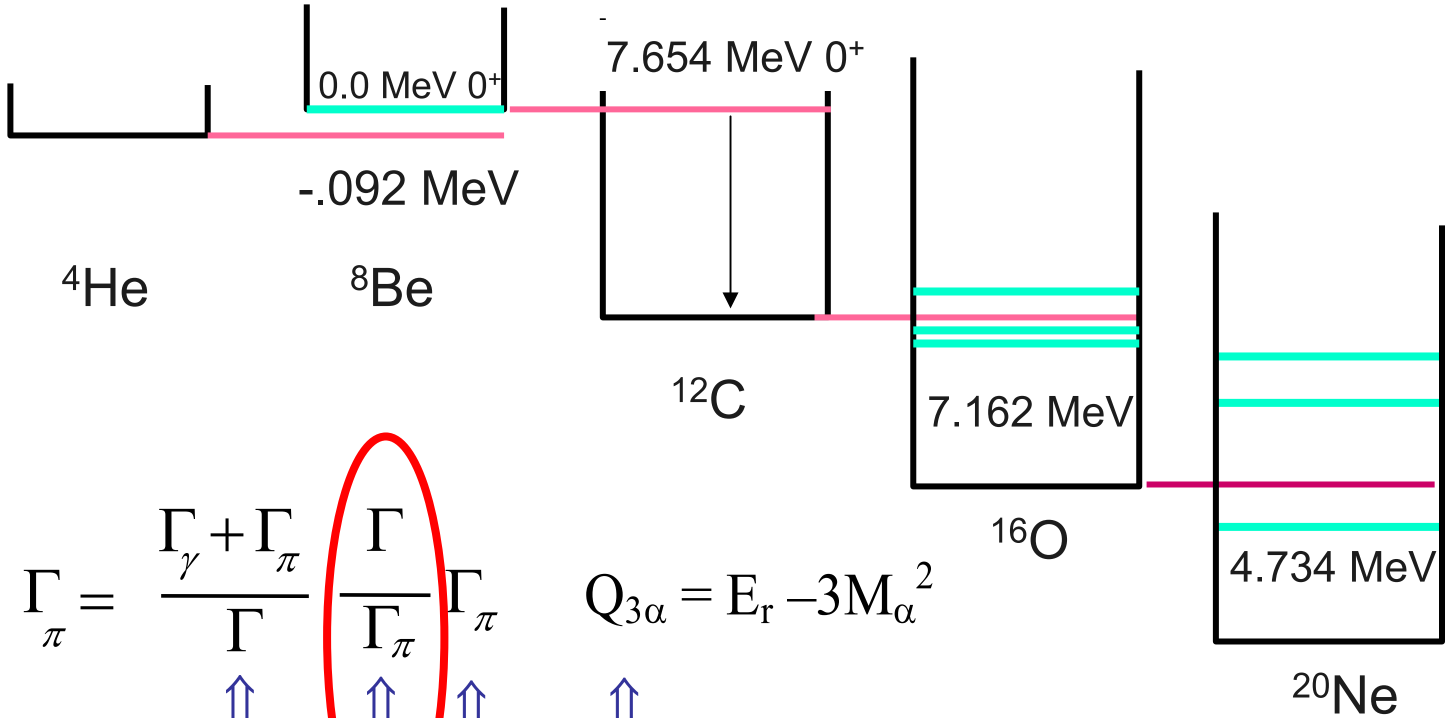
MSU/WMU ANL/NWU ND
& ND

- Neutron production for weak s-process:

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

Completed!

The $3\alpha \Rightarrow {}^{12}C \Rightarrow {}^{16}O \Rightarrow {}^{20}Ne$ reactions



$$\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma} \frac{\Gamma}{\Gamma_\pi} \Gamma_\pi \qquad Q_{3\alpha} = E_r - 3M_\alpha{}^2$$

% Rate uncertainty ⇑ 2.7 ⇑ 9.2 ⇑ 2.7 ⇑ 1.2

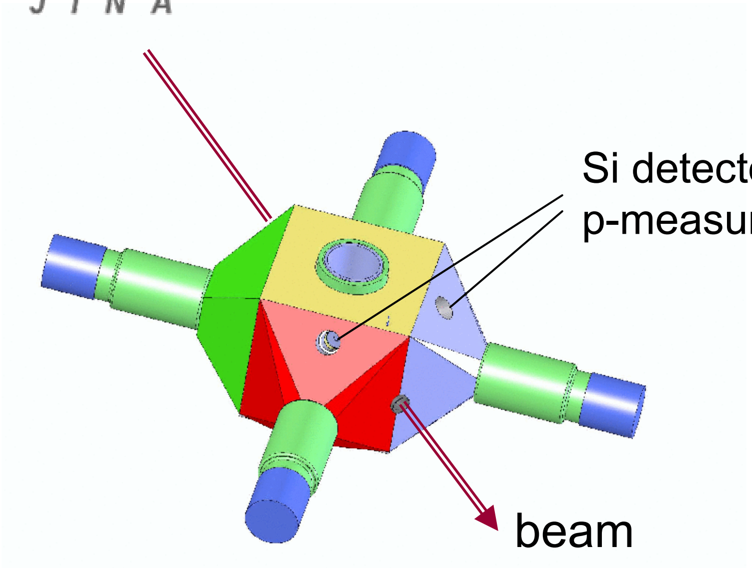
Current accuracy: ±10(12) % → Goal: ±6% → Need Γ_{rad} of 7.65 MeV state in ^{12}C

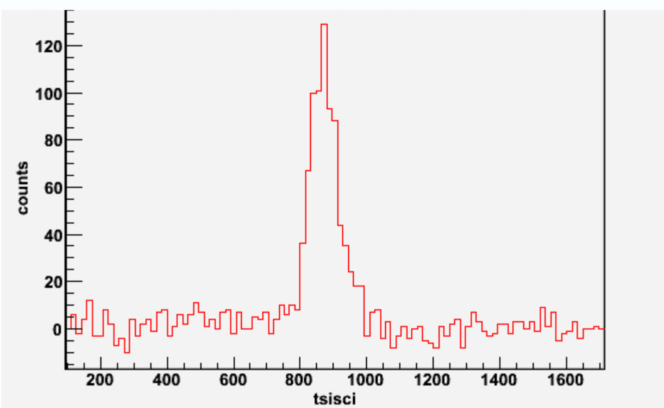
Measure $\Gamma_\pi/\Gamma \approx 6 \times 10^{-6}$ at Western Michigan University

Form Hoyle state $^{12}C(p,p')^{12}C^*$ at 10.56 MeV, detect pairs

Experimental Set-Up & first Test Results

Collaborators: Clarisse Tur, Sam Austin (MSU),
Alan Wuosmaa (WMU).





Time coincidence between the protons exciting the bound 6.05 MeV level in $^{16}O(p,p')^{16}O^*$ and the e^+-e^- pair decay to the ground state

RUN I: limited statistics (August 2006)

Beam halo was touching and activating the epoxy liner of the beam entrance/exit holes (despite heavy collimation) creating intolerable backgrounds beyond 10 nA => could only take very limited statistics

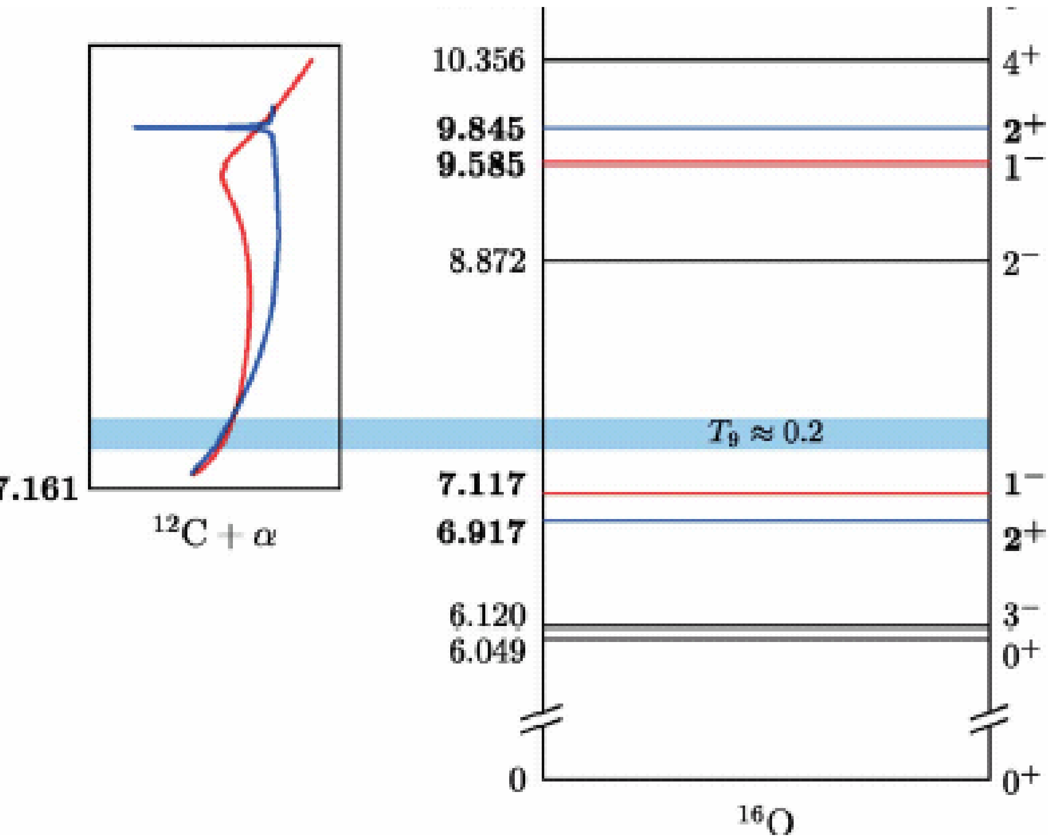
RUN II: (April 2007)

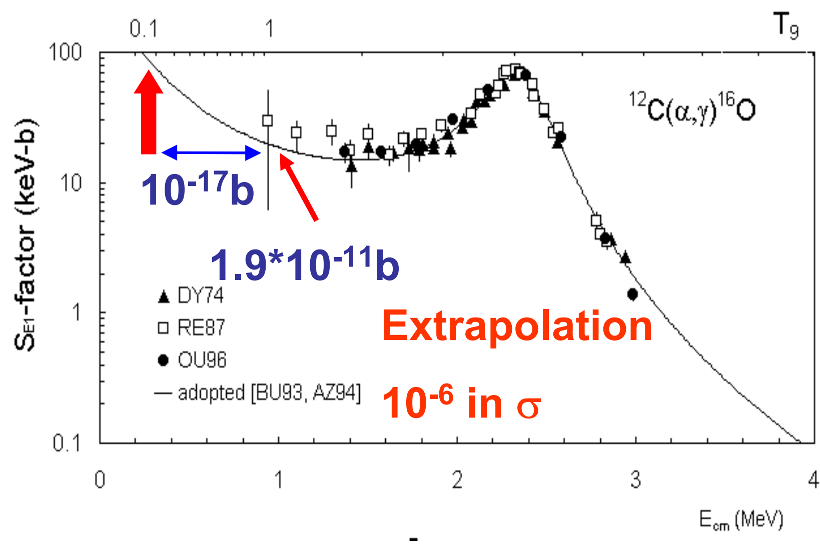
The detector has been modified:

- larger beam entrance and exit holes (1 cm), lined withTantalum.
- larger proton exit holes at 125 degrees
- new PMTs (larger photo-cathode area, better coupling to the scintillator)
- gain matching of the PMTs for the quadrants through an LED setup.

=> Will hopefully result in reduced background and much improved statistics.

Level structure of ^{16}O



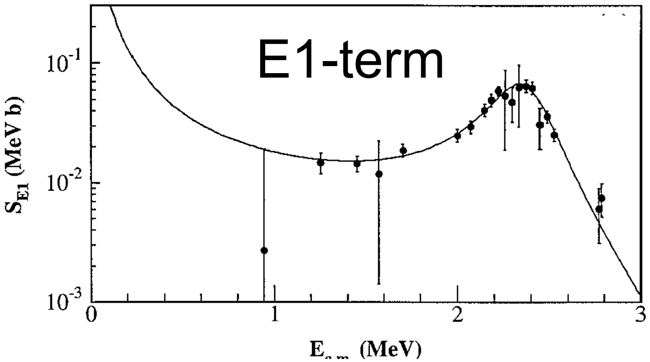


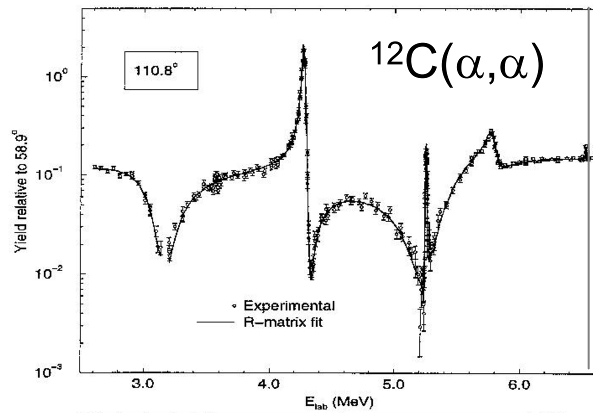
Interference between 1^- resonances determines the E1-term extrapolation

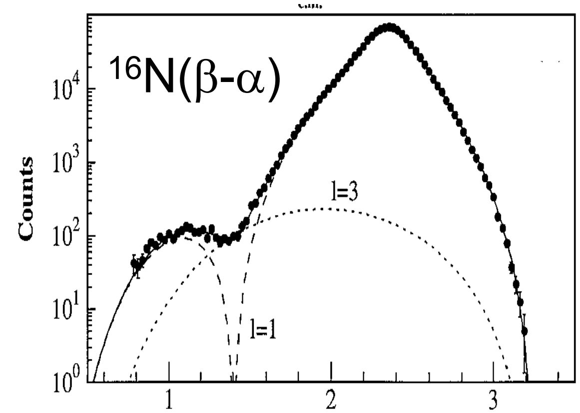
Interference between 2^+ resonances and E2 direct capture determines E2 term extrapolation to stellar energies.

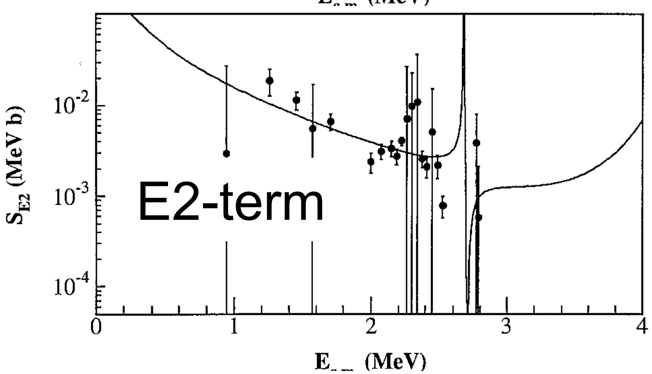
JINA Goal R-Matrix Analysis

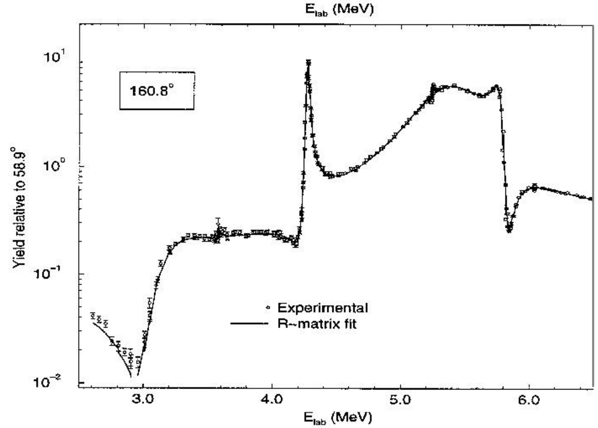
of combined data set: $^{12}C(\alpha,\gamma)$, $^{12}C(\alpha,\alpha)$, $^{16}N(\beta\text{-}\alpha)$ ... $^{12}C(^{6}Li,d)$
to reduce the overall uncertainty in a consistent manner!

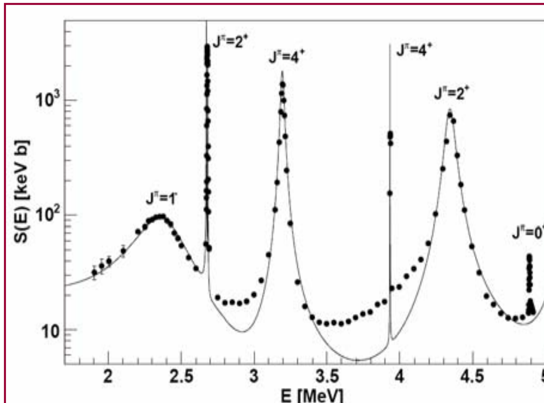


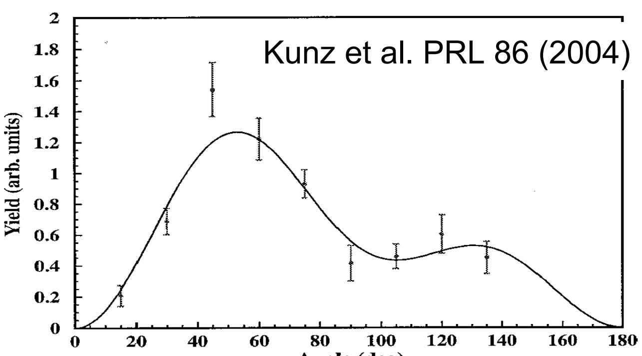










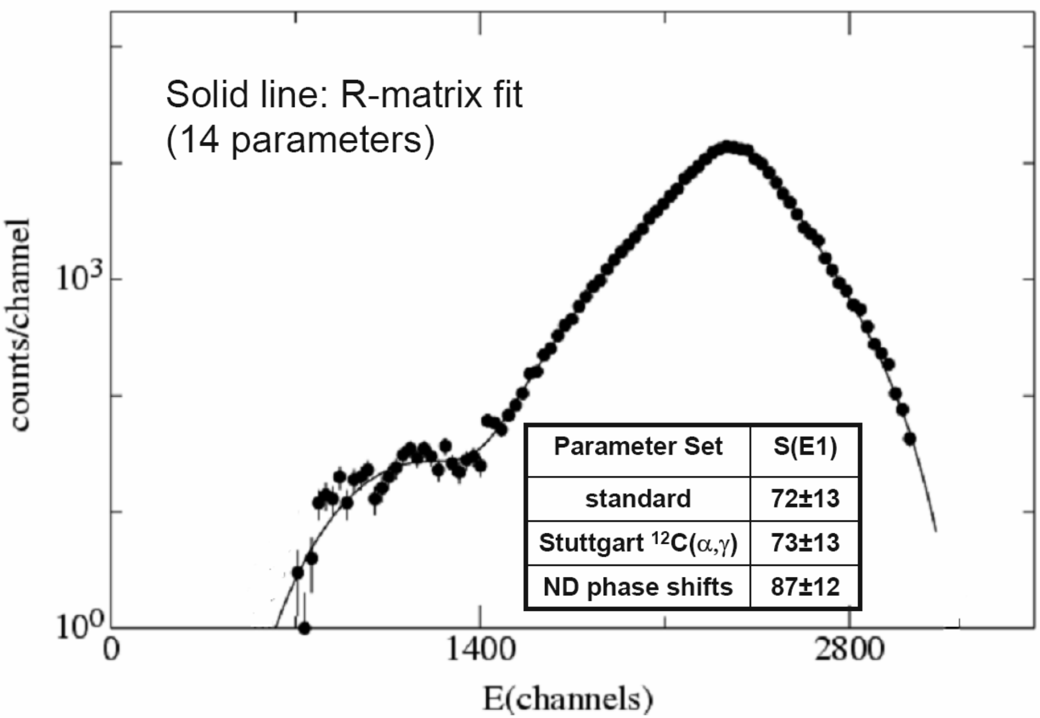


S_{E1}≈83 keV barn, S_{E2}≈85 keV-barn
arguments & experiments will continue!!!

New Measurements of the β-delayed α decay of ^{16}N

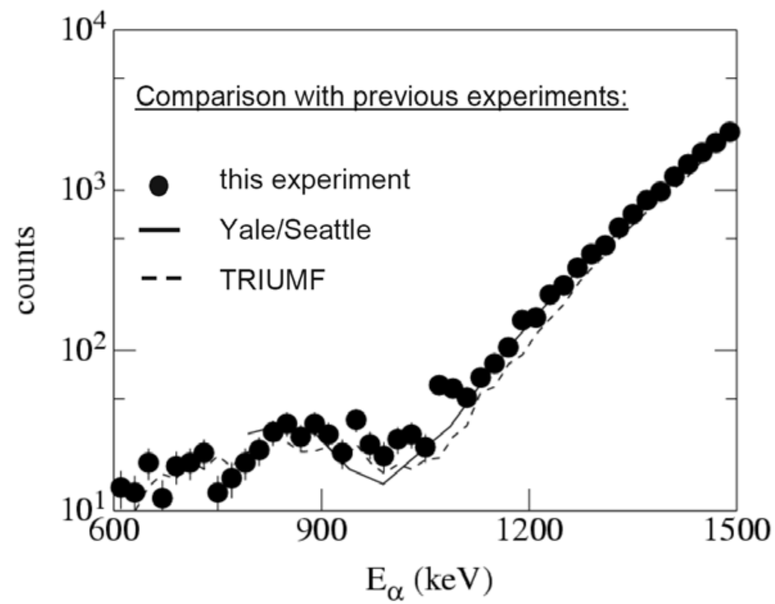
• Mainz (1969-1974)	Si	35 μ
• TRIUMF (1993-1997)	Si	11-16 μ
• Yale (1993-1997)	Si	50 μ
• Seattle (1994-1995)	Si	? μ

^{16}N produced at Atlas and implanted and analyzed in newly designed ionization chamber

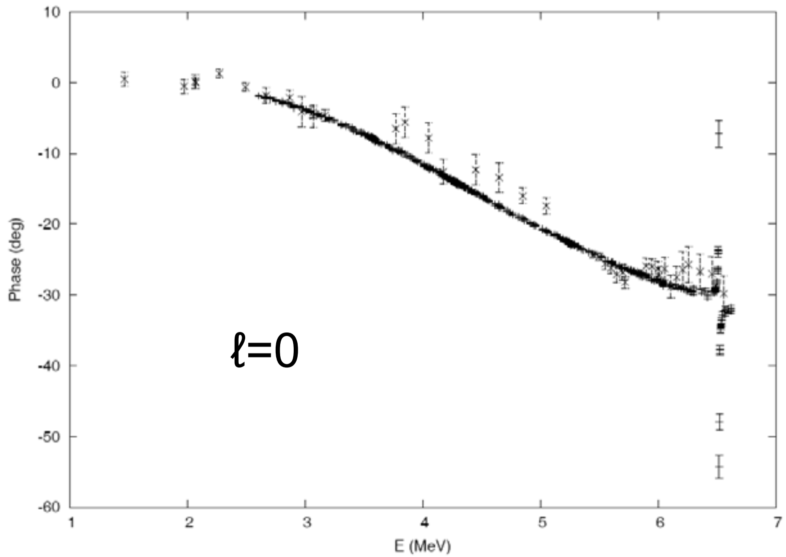


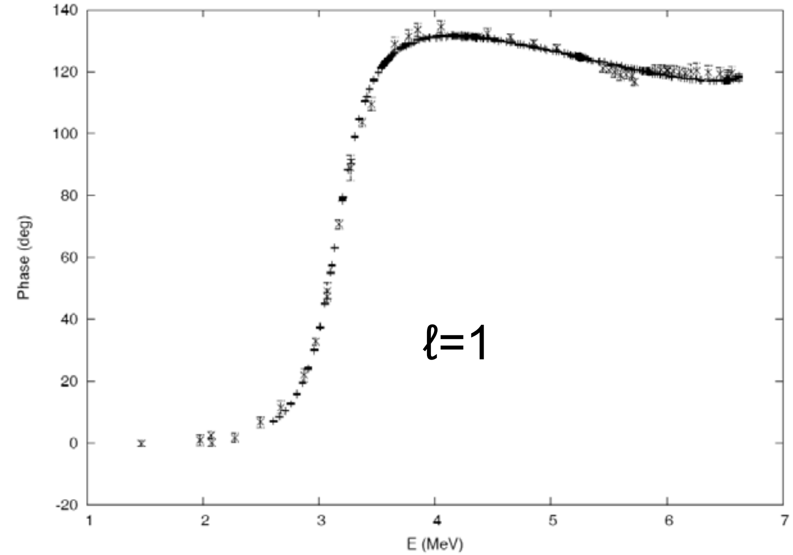
Parameter Set	S(E1)
standard	72±13
Stuttgart $^{12}C(\alpha,\gamma)$	73±13
ND phase shifts	87±12

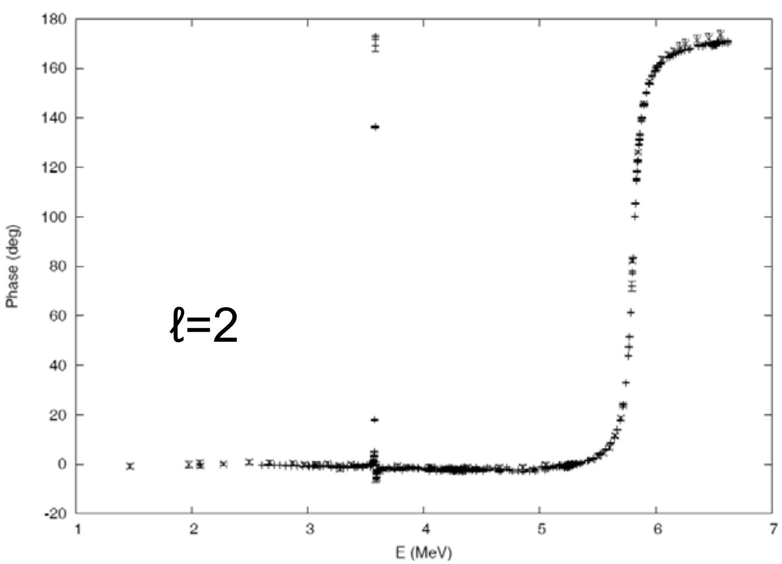
Collaborators: ANL, Hebrew U., Northwestern, Ohio U., UNC, WMU)

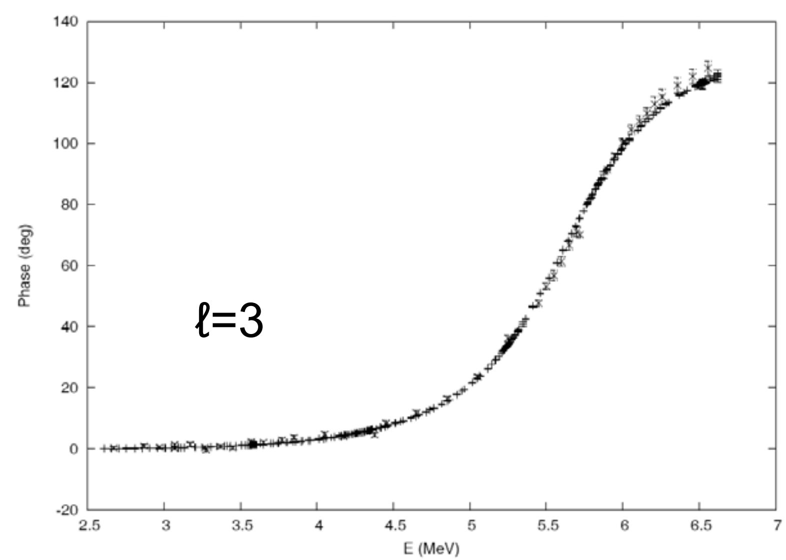


Reanalysis of Notre Dame TRIUMF $^{12}C(\alpha,\alpha)$ Data for Phase Shift

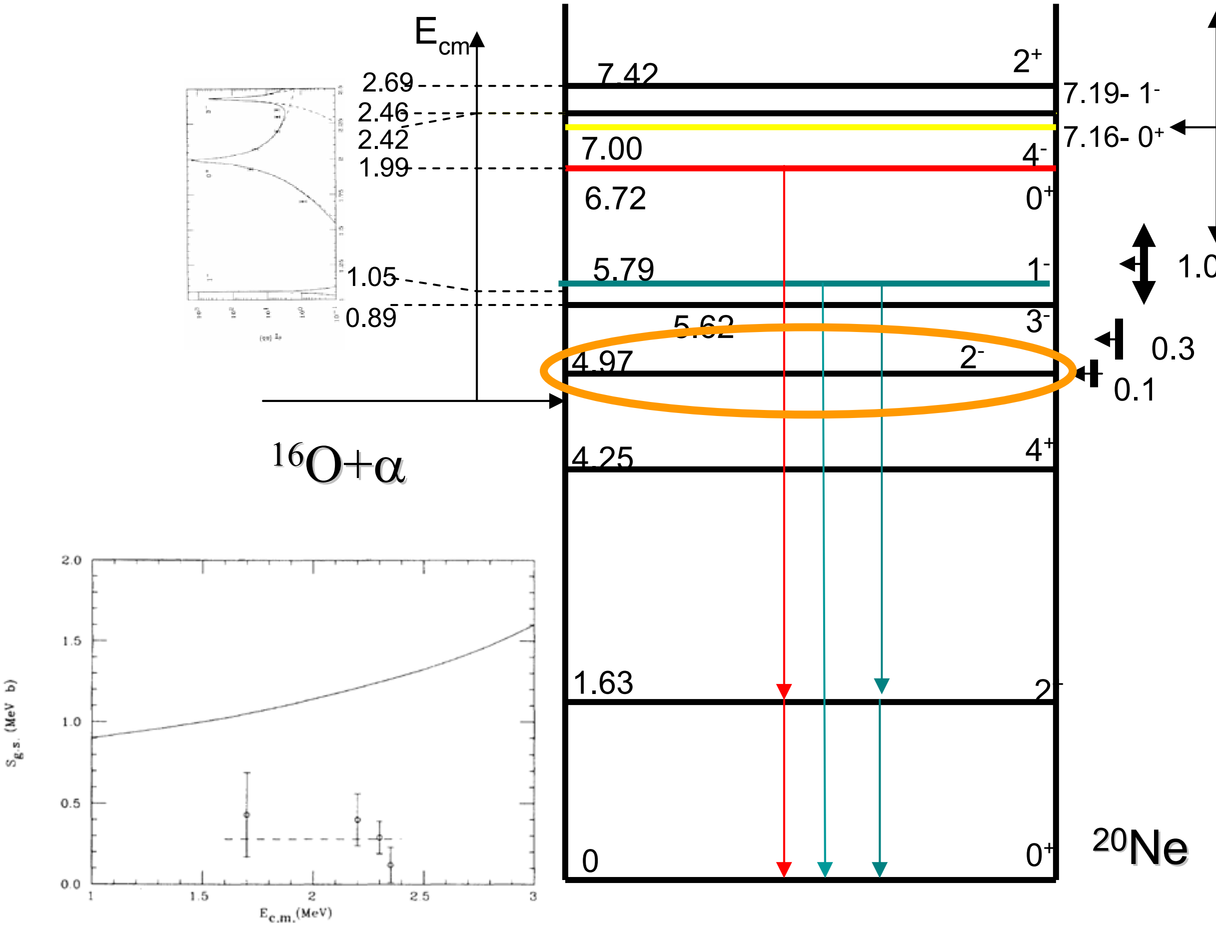








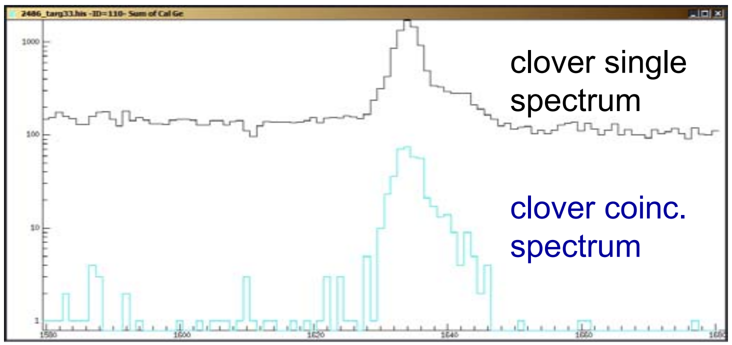
$^{16}O(\alpha,\gamma)^{20}Ne$

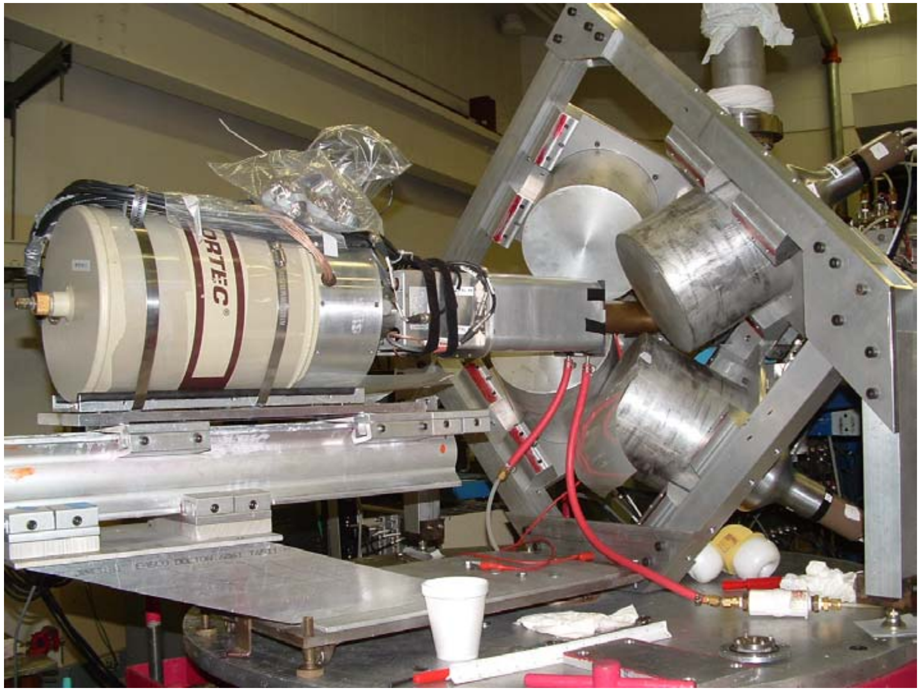


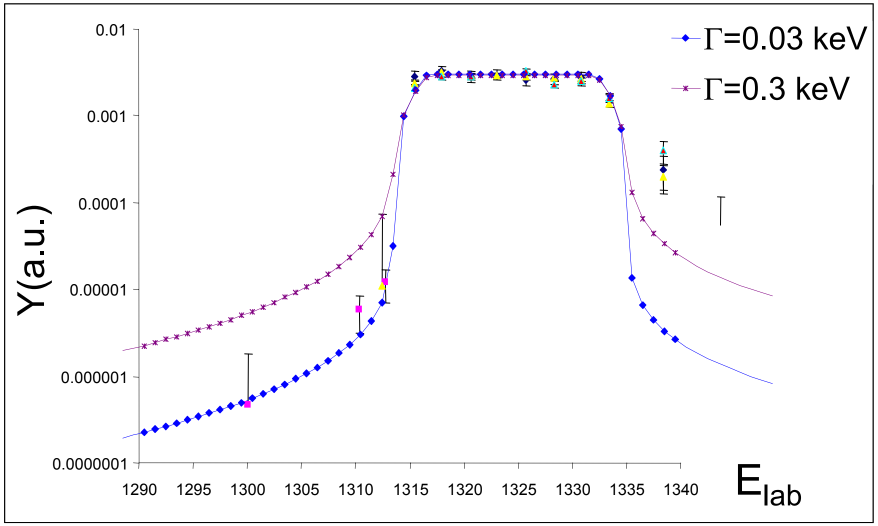
The subsequent alpha capture reaction $^{16}O(\alpha,\gamma)$ is supposedly weak and the rate is expected to be dominated by the direct capture component plus tails and interference of near by resonances. New experiments have been performed at Stuttgart and Notre Dame to determine the low energy extrapolation of the cross section.

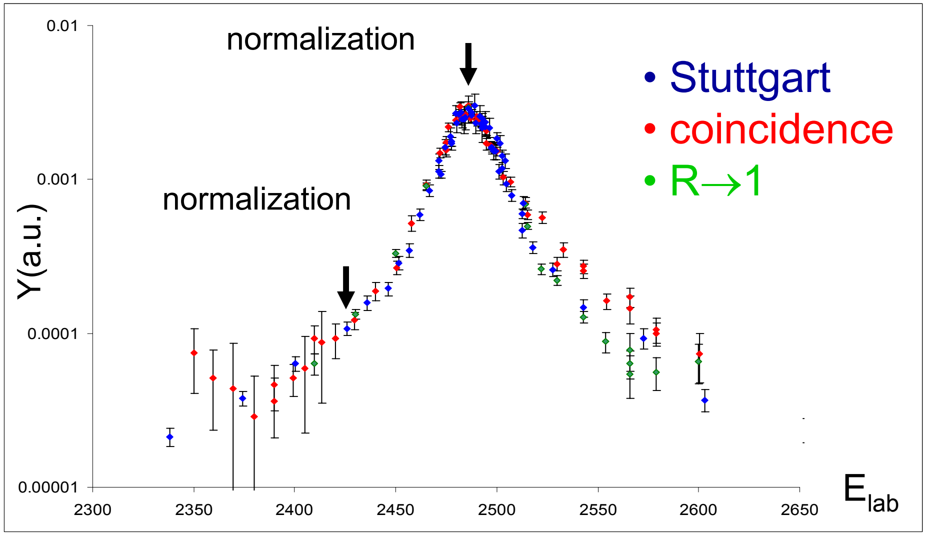
Theoretical predictions: Langanke Z. Phys.A325, 317 (1984)
Experimental results: Hahn et al. PRC 36, 892 (1987)

Detection Coincidence for Background Reduction

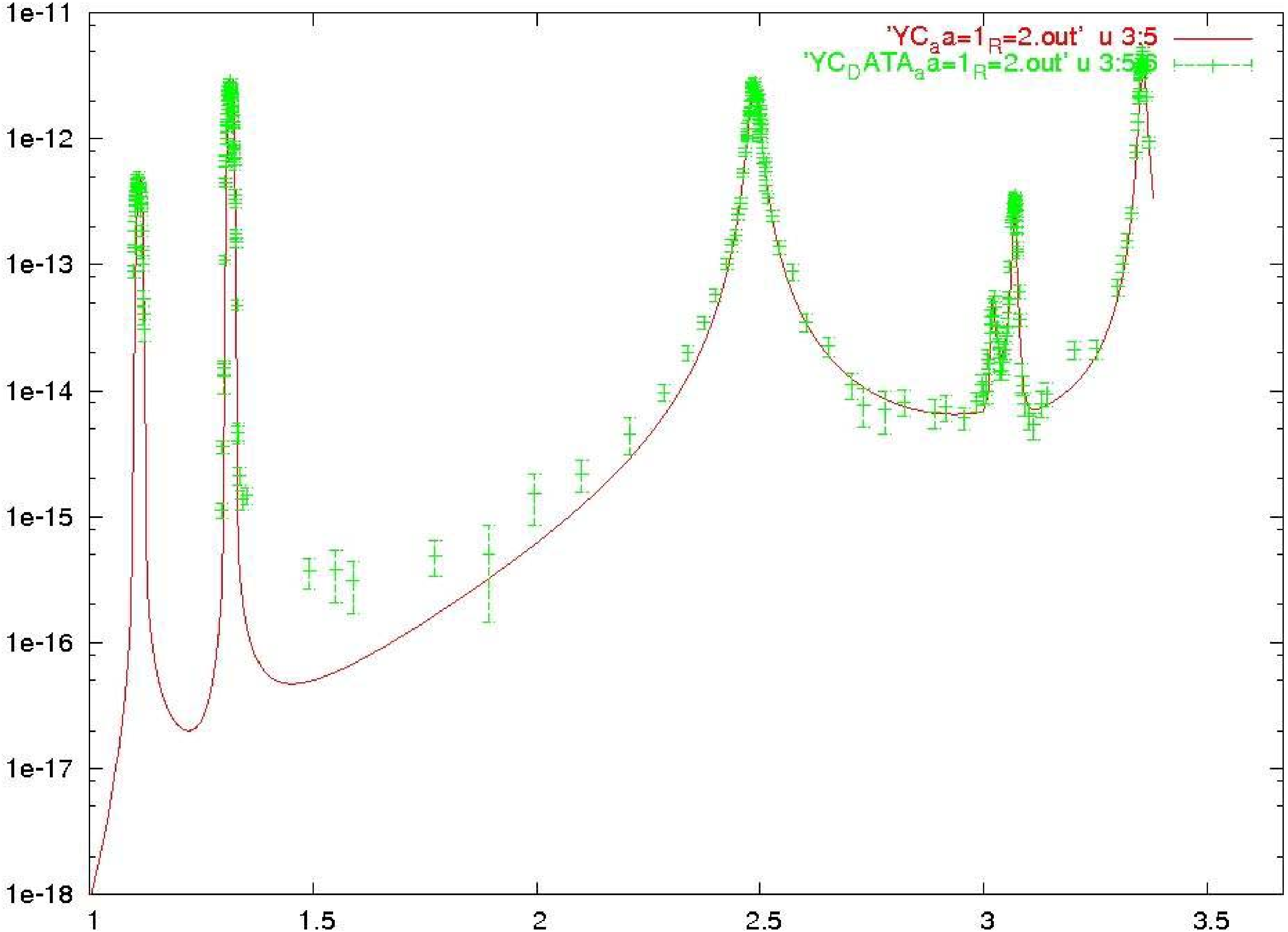








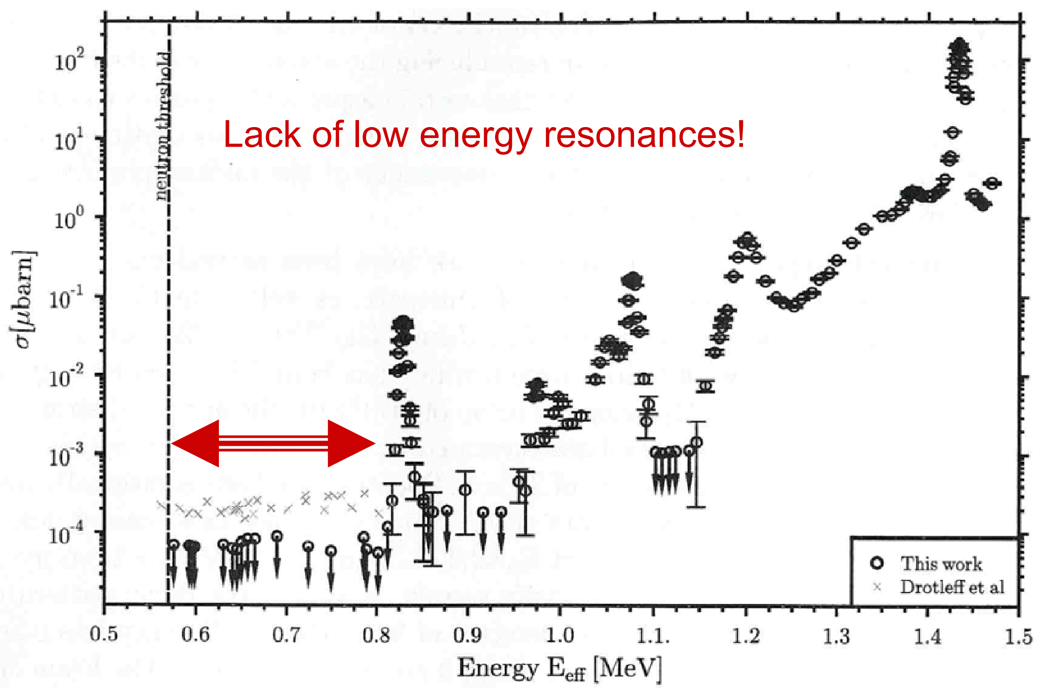
Preliminary results and r-matrix fits

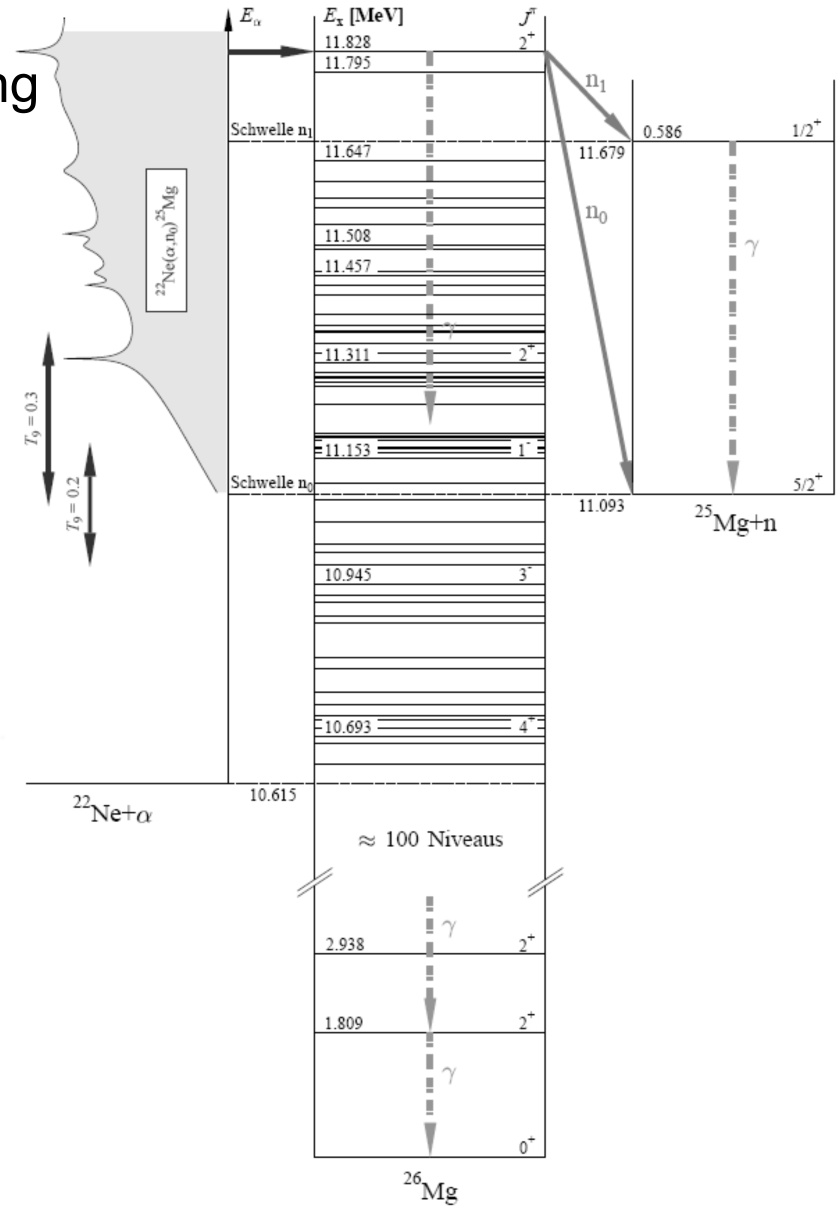


$^{22}Ne(\alpha,n)$ IN STELLAR He BURNING

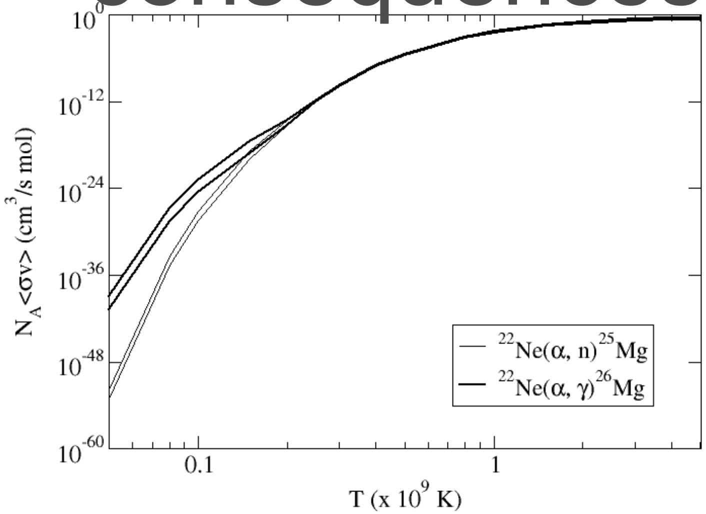
Production from the ^{14}N ashes of CNO burning

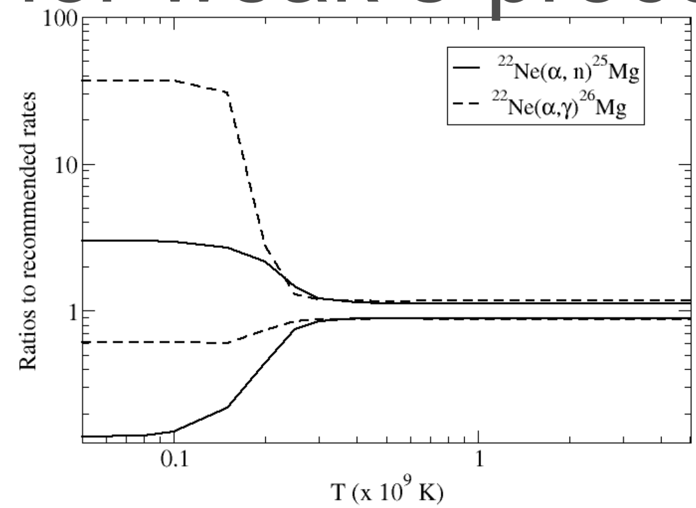
Production: $^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne$
triggering: $^{22}Ne(\alpha,\gamma)^{26}Mg$, $^{22}Ne(\alpha,n)^{25}Mg$



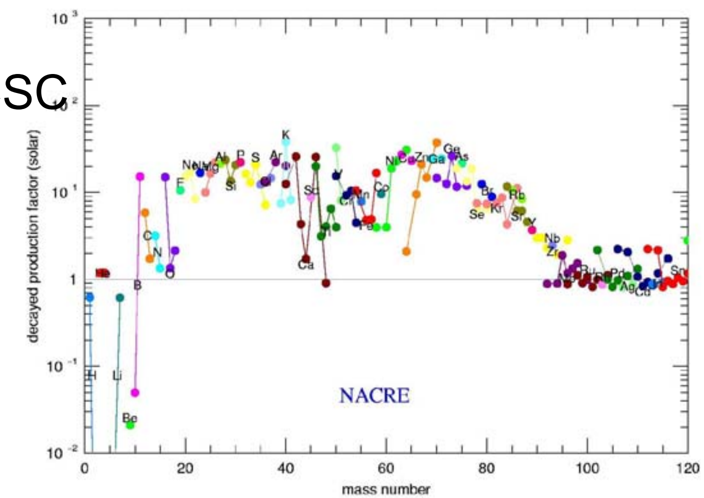


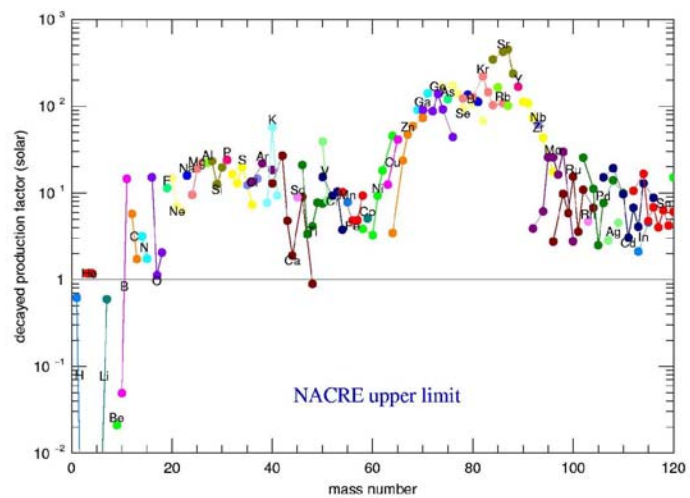
Present uncertainties and consequences for weak s-process





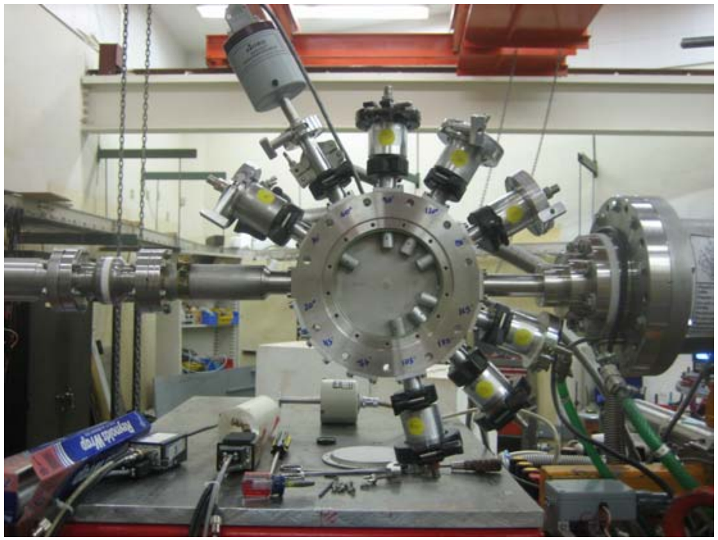
Heger, LANL
Woosley, UCSC

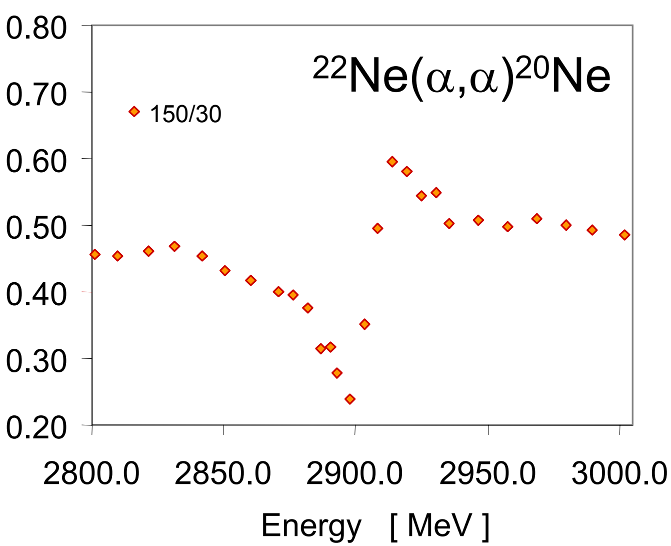


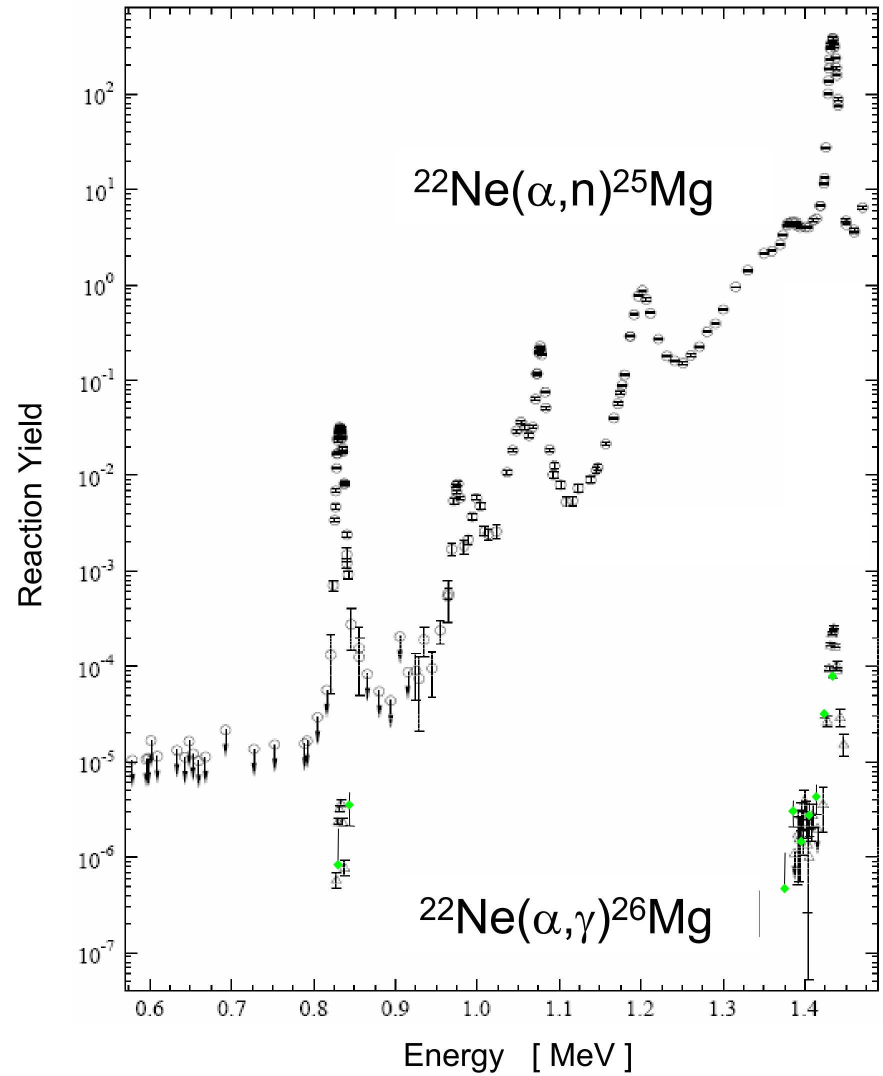


Variation between limits suggests considerable affect on weak s-process abundance distribution; severe consequences for p-process predictions!

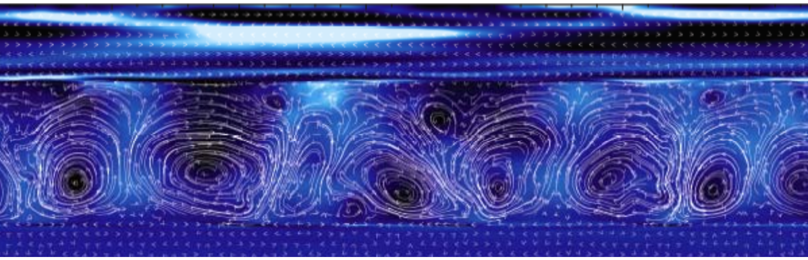
$^{22}Ne(\alpha,\gamma)$, (α,α) for r-matrix analysis

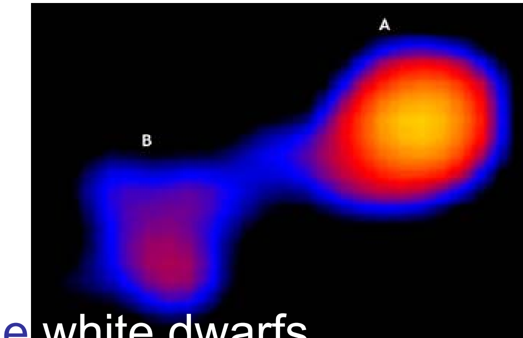






The final fate of stars





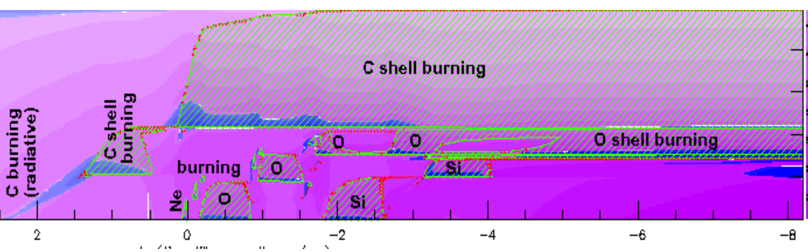
become white dwarfs

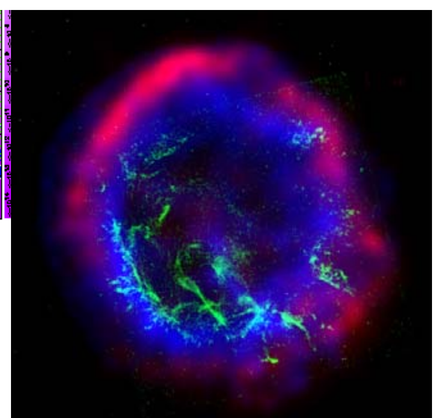
Post RGB low mass AGB stars
form AGB stars & planetary nebulae

⇒ the site of the
main s-process

If in binary systems
⇒novae, type I SN

MRC-3



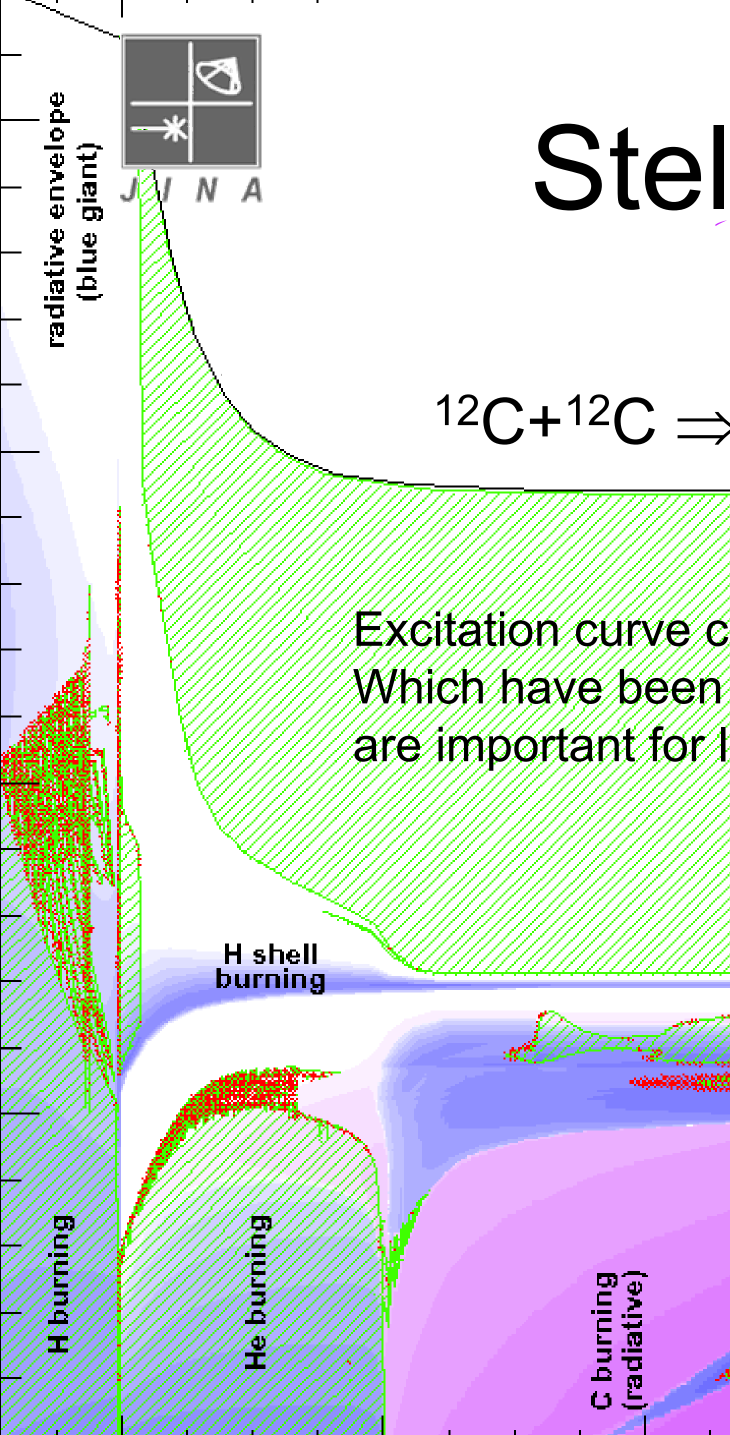


Post RGB massive stars develop
to core collapse and type II SN

⇒Supernova shockfront
⇒the site of the r-process

MRC-2

⇒ the site of the
weak s-process



Stellar C Burning

$$^{12}C + ^{12}C \Rightarrow \begin{cases} ^{24}Mg + \gamma, & Q = 13.93\ \text{MeV} \\ ^{23}Na + p, & Q = 2.24\ \text{MeV} \\ ^{20}Ne + \alpha, & Q = 4.62\ \text{MeV} \end{cases}$$

Excitation curve characterized by several low energy resonances
Which have been a matter of debate for quite some time. Two questions are important for low energy extrapolation:

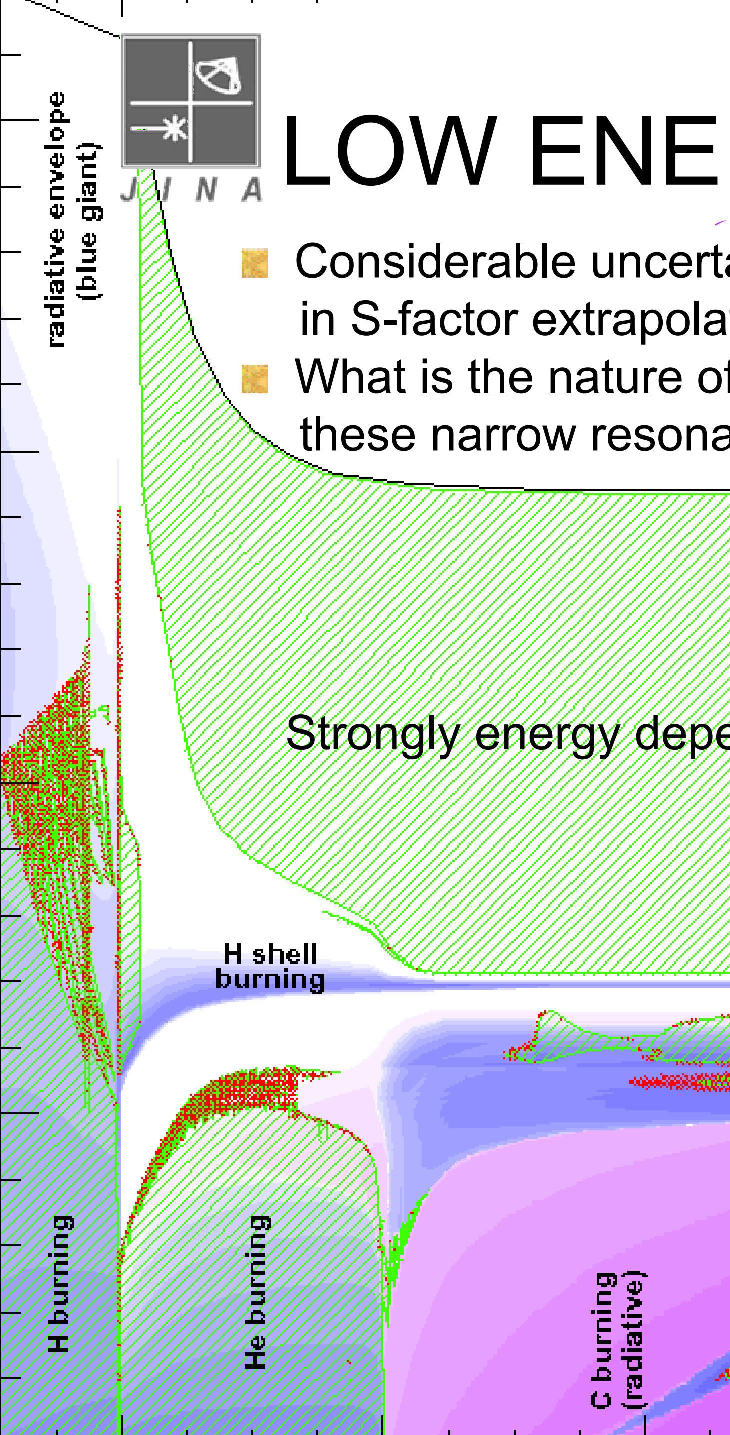
- Absolute cross section to determine fusion ignition point conditions
- Branching in p, α channel to investigate subsequent nucleosynthesis

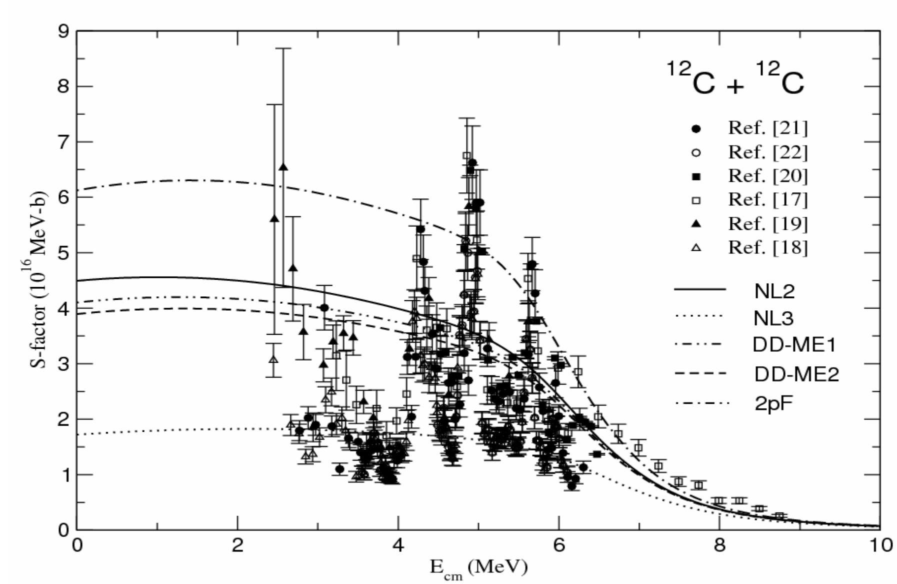
Question about s-process in C-burning
$^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)$
Depends on p,α-production in $^{12}C+^{12}C$

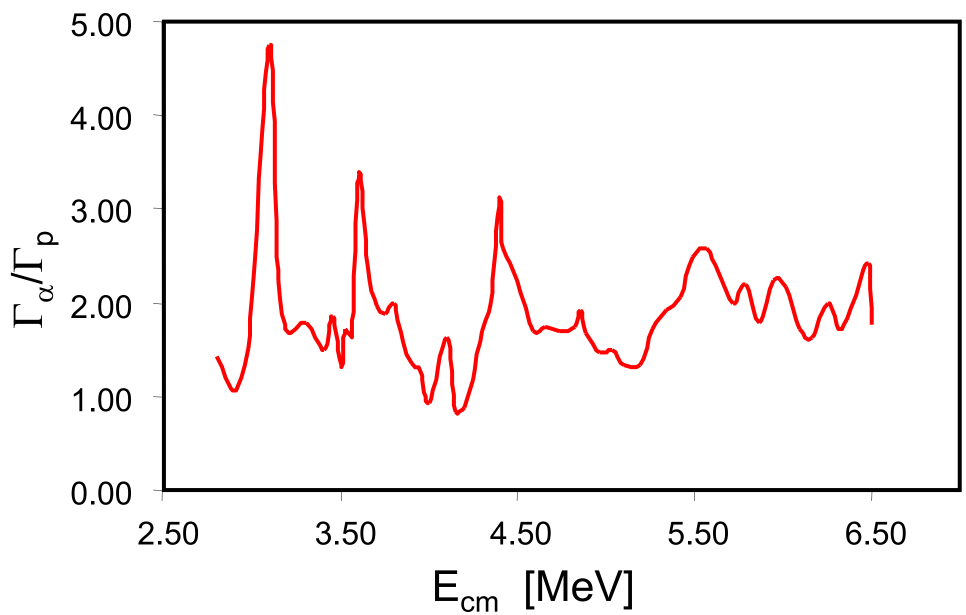
LOW ENERGY EXTRAPOLATION

- Considerable uncertainty in S-factor extrapolation!
- What is the nature of these narrow resonances?

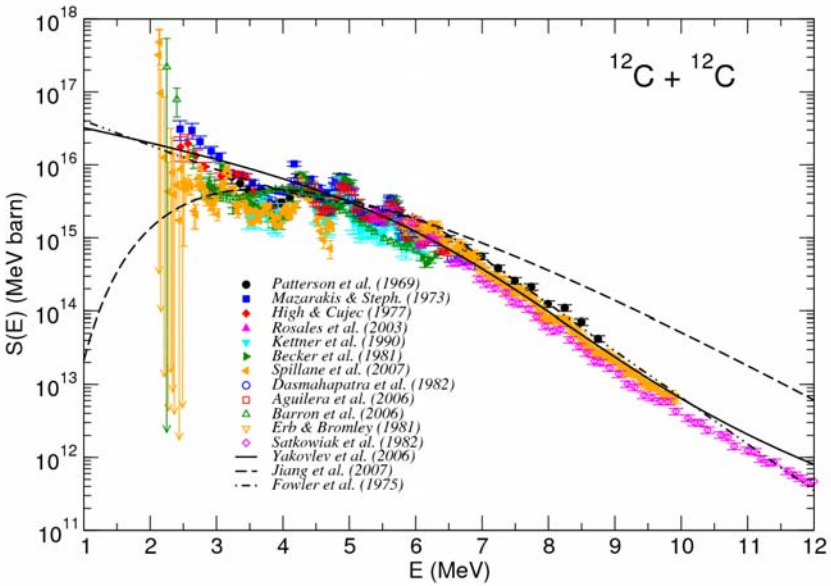
Strongly energy dependent

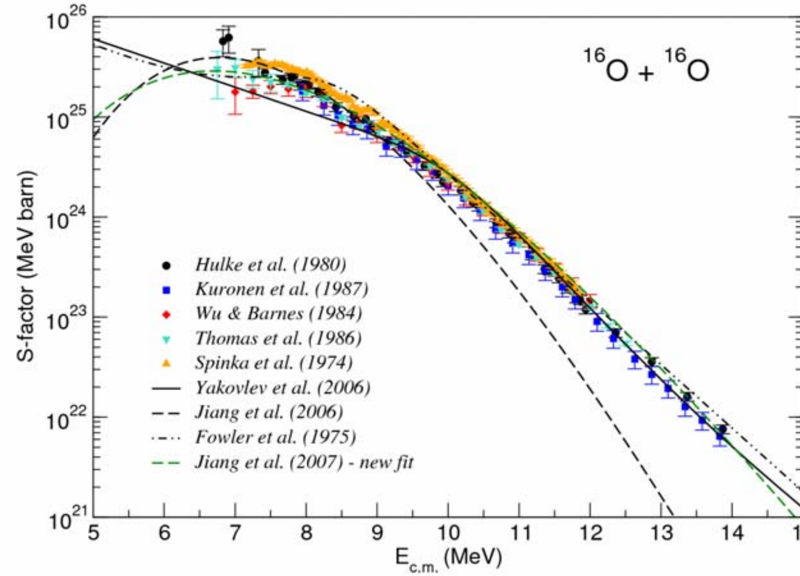


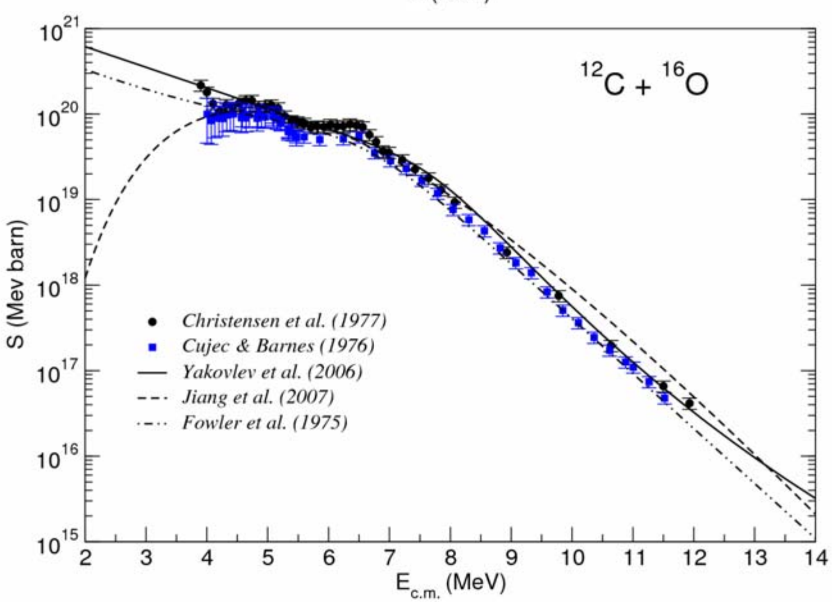




Low energy fusion cross sections



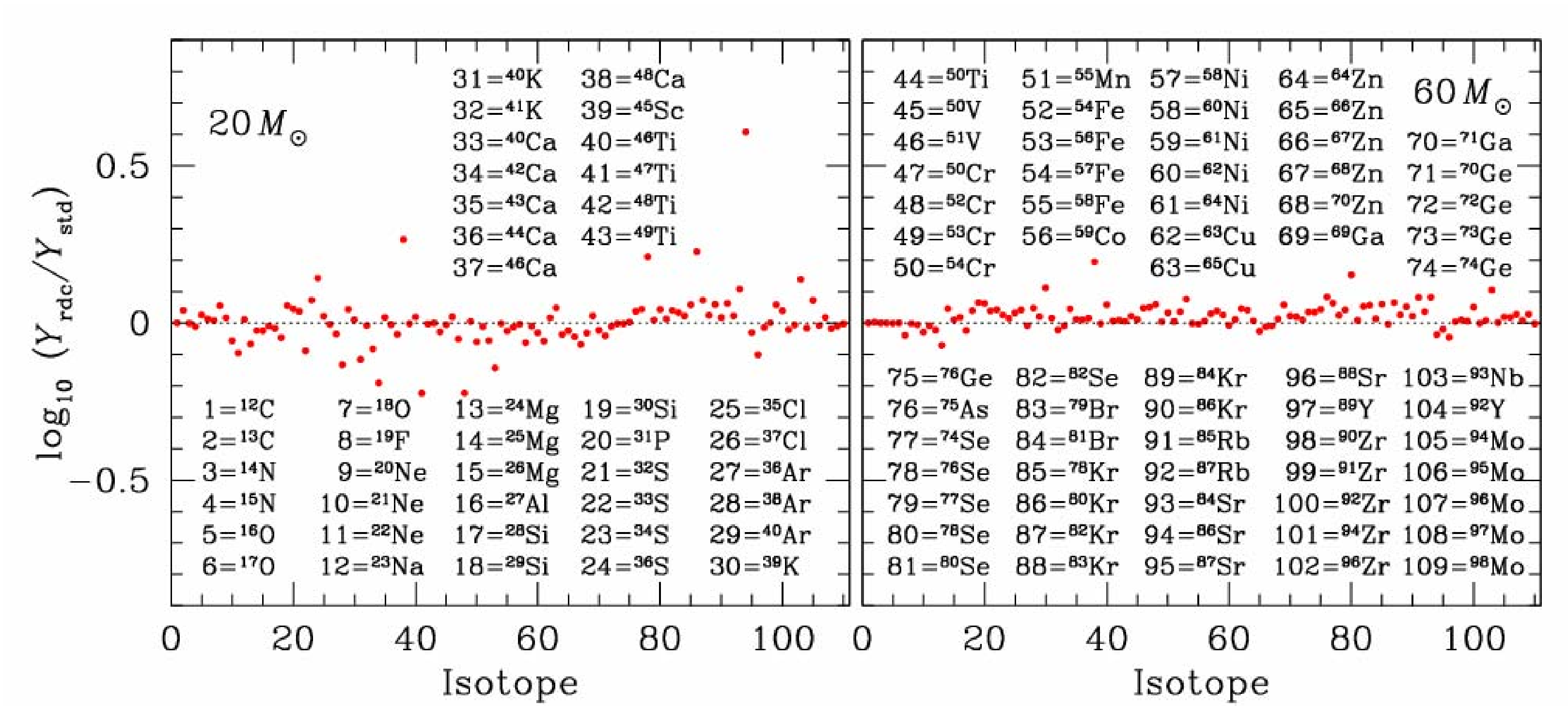




S-factor measurements and predictions for low energy fusion reactions in late stellar C and O burning. Is there a nuclear hindrance factor reducing the fusion cross section at low energies? (Esbensen 2005)

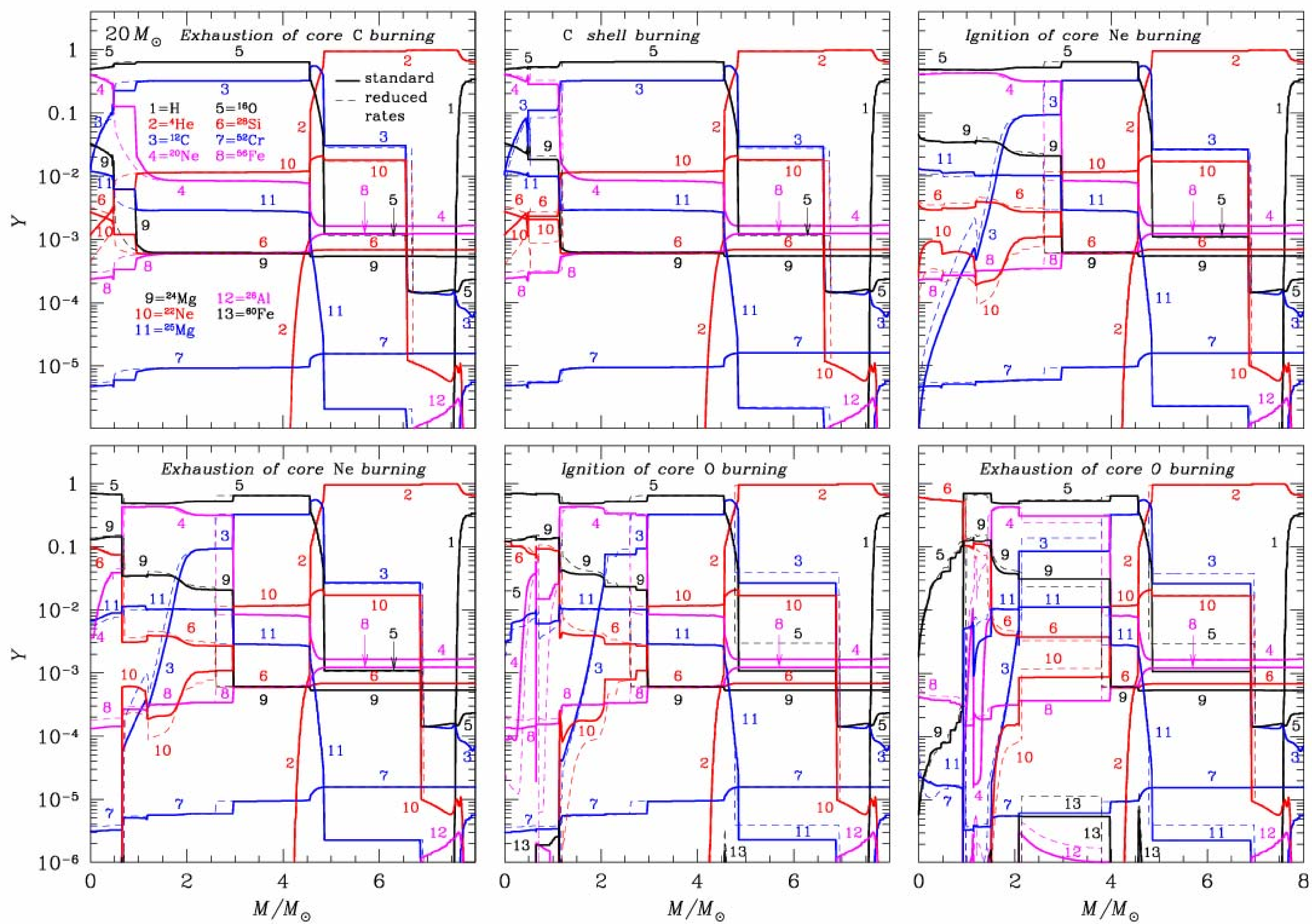
Caughlan et al. 1988
Gasques et al. 2006
Jiang et al. 2007

Consequences for late stellar burning

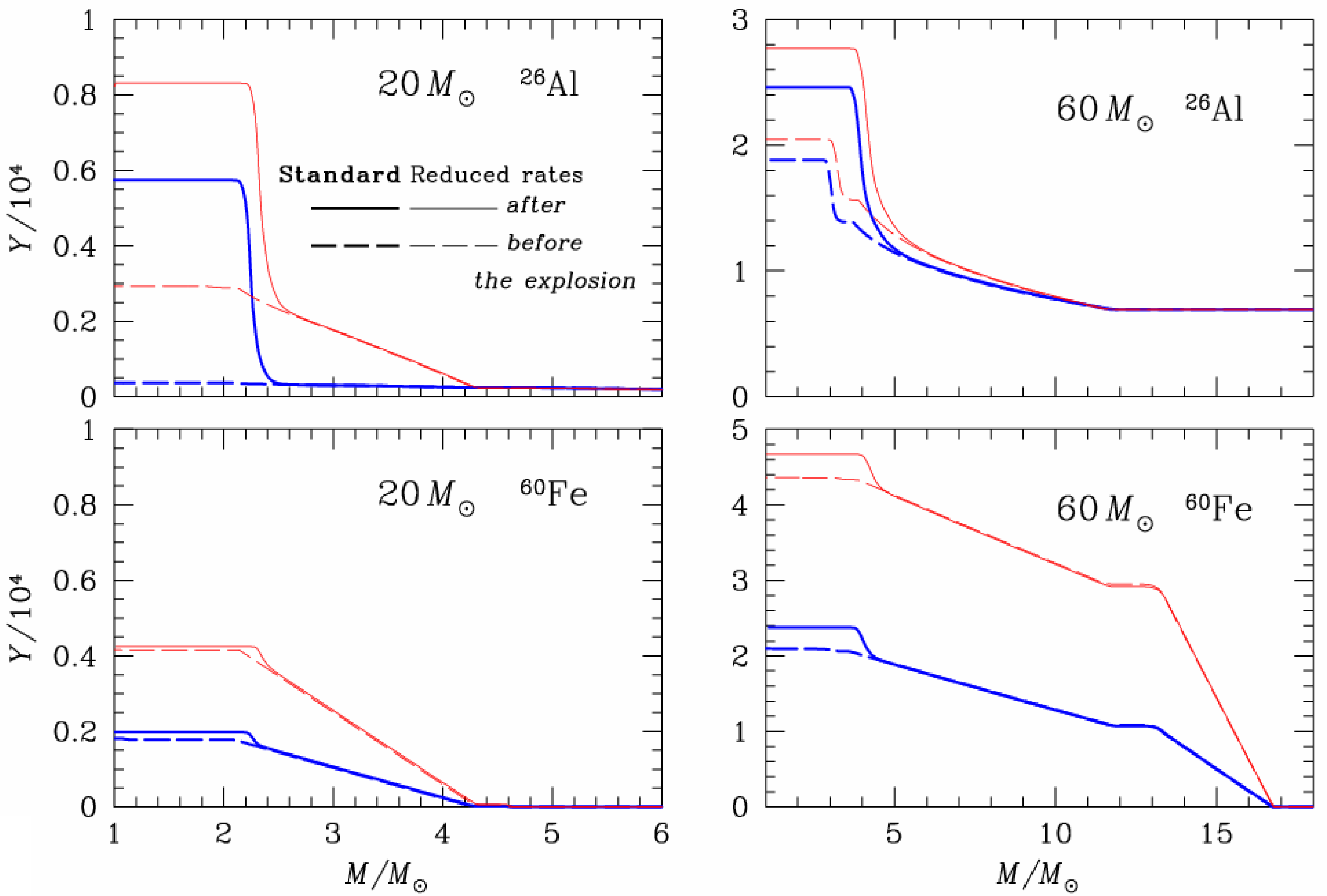


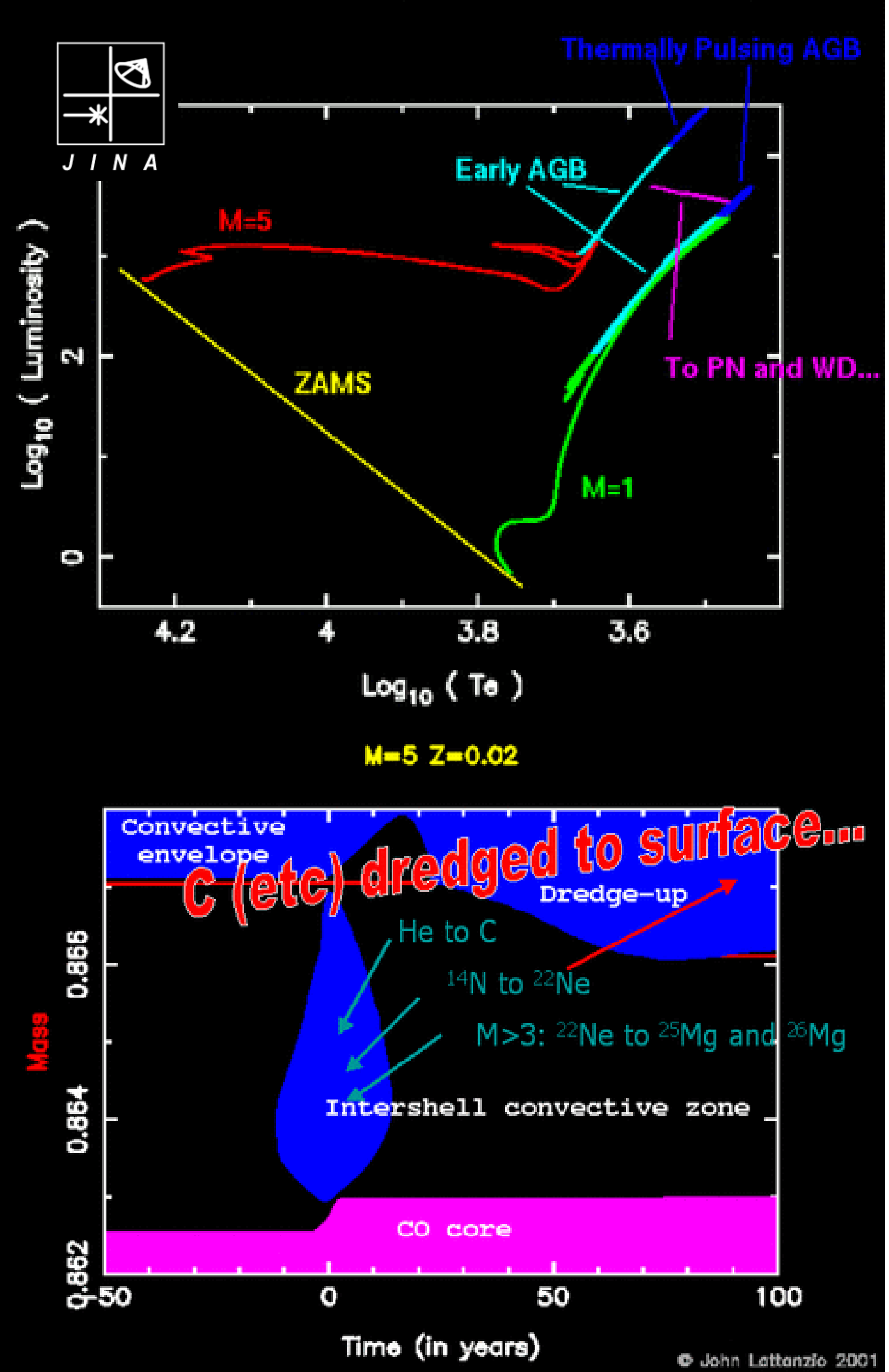
Simulations performed for 20 and 60 $M_\odot$ stars, no major differences for nucleosynthesis except a significant increase in abundance for the long-lived radioactive isotopes ^{26}Al and ^{60}Fe. That needs further investigation.

Abundance evolution in late stellar burning

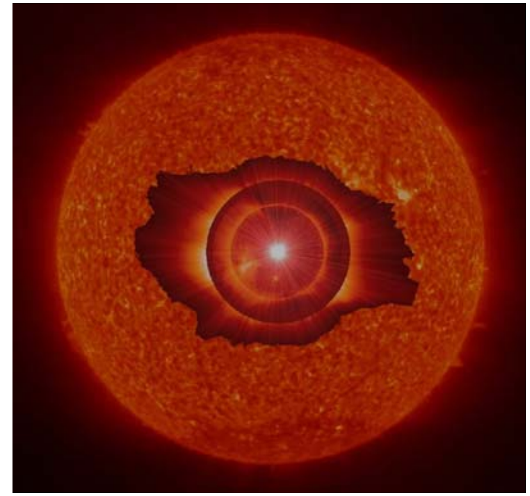


Production of Galactic radioactivity?





AGB Star Nucleosynthesis



Site for main s-process with:

- carbon pocket $^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)$
- and He-flash $^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)$ n source

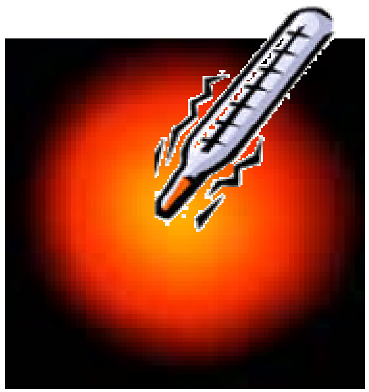
Important aspects:

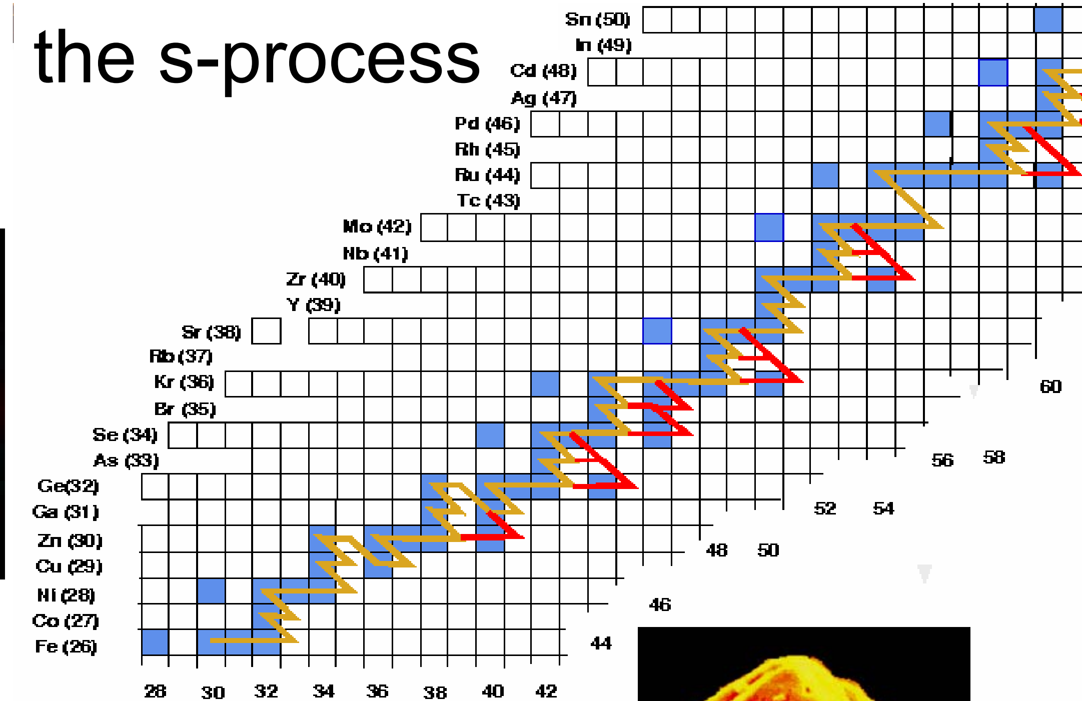
- Main s-process (r-process=1-s-process)
- Branching points as thermometer
- Charged particle nucleosynthesis for monitoring convection and dredge up

Neutron induced processes in stars

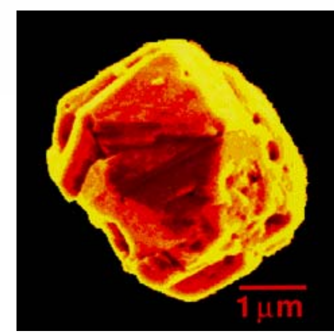
RGB stars
AGB stars

Thermometer
Pycnometer
Barometer
Neutrometer



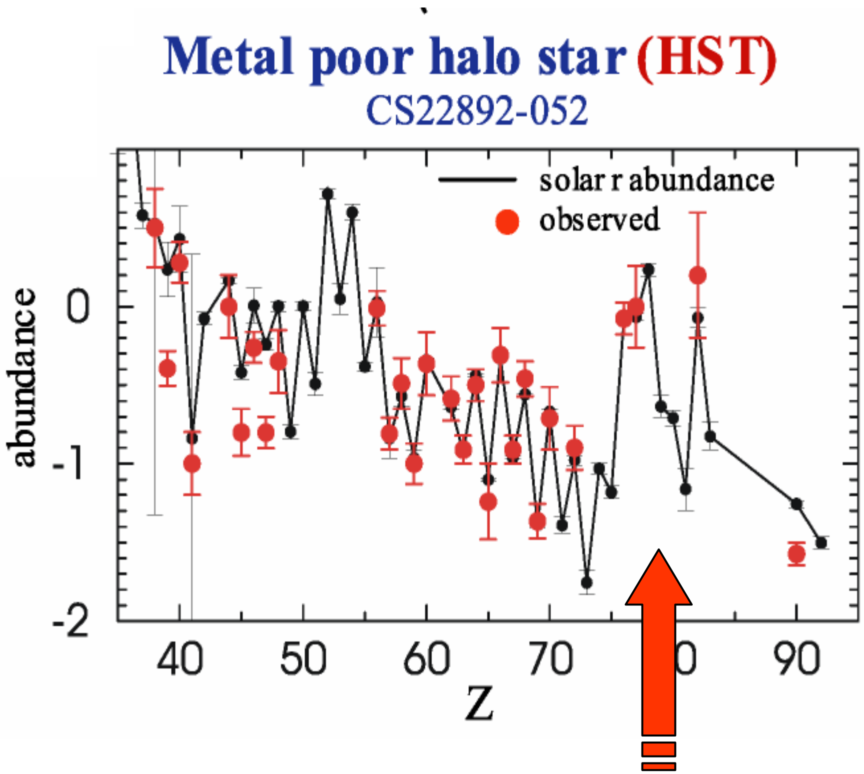


Observational signature
are isotopic abundances in pre-solar grains

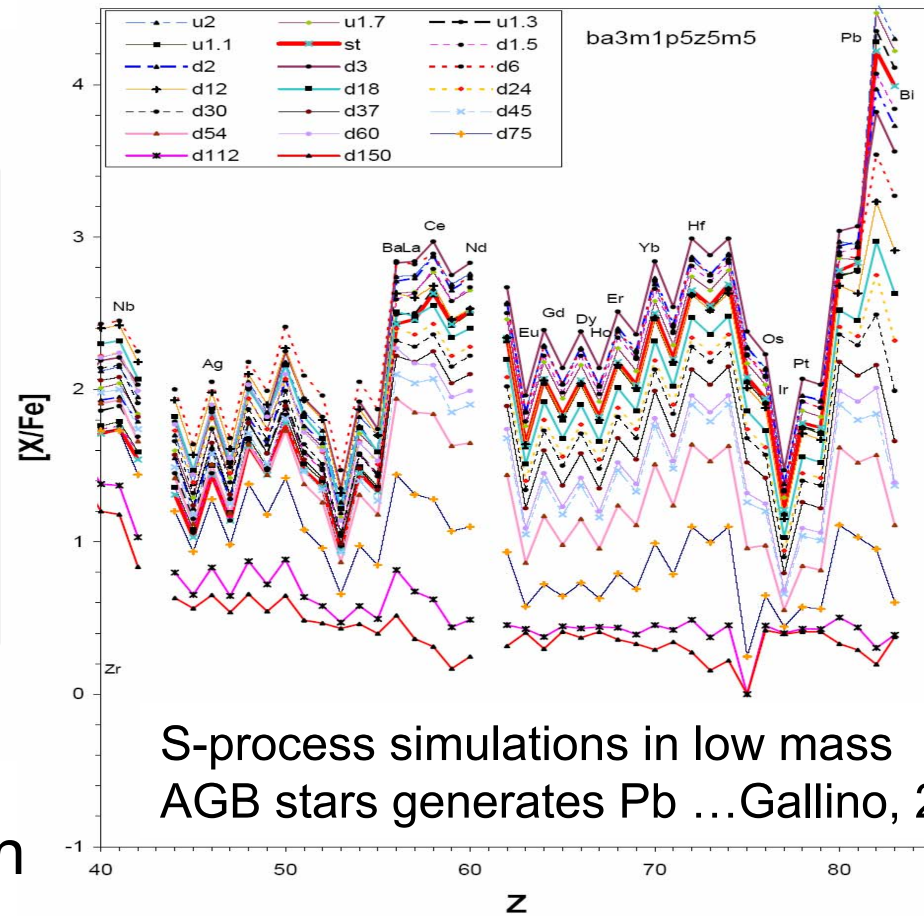


Collaboration and involvement of A. Davis, U. Chicago
Modeling and simulation by Falk Herwig, LANL

End-Points of s-Process Pb



Old star abundance distribution points to r-process origin of Pb

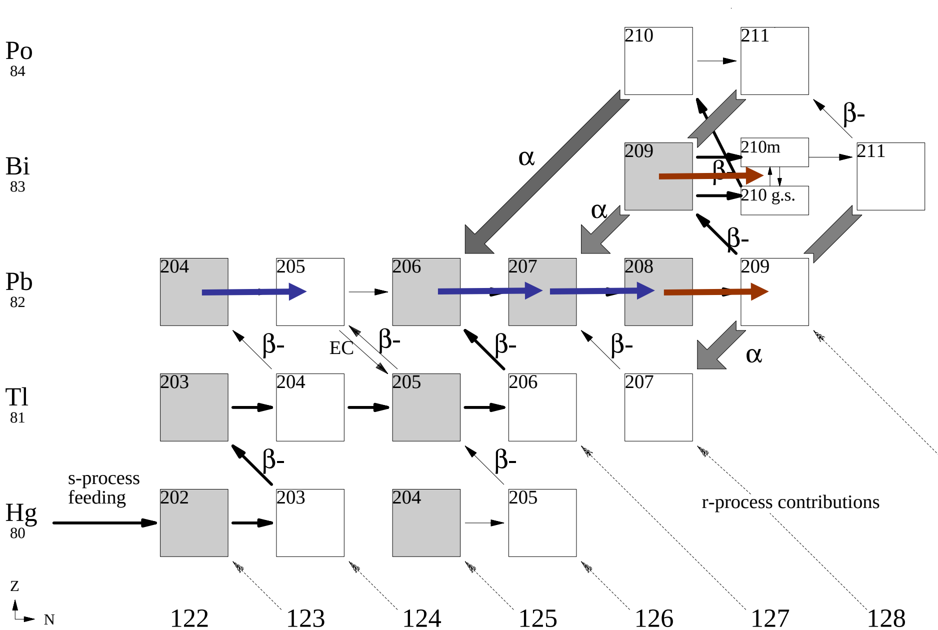


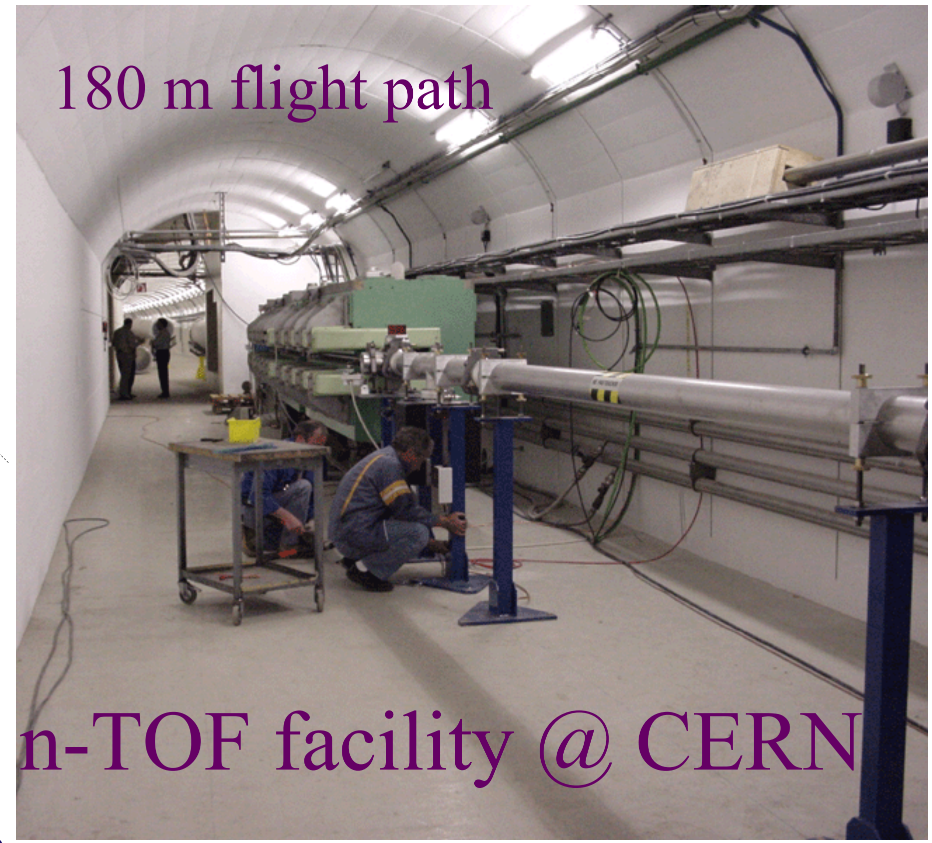
S-process simulations in low mass AGB stars generates Pb …Gallino, 2005

n-capture on stable Pb isotopes needed!

Neutron Capture on Pb & Bi Isotopes

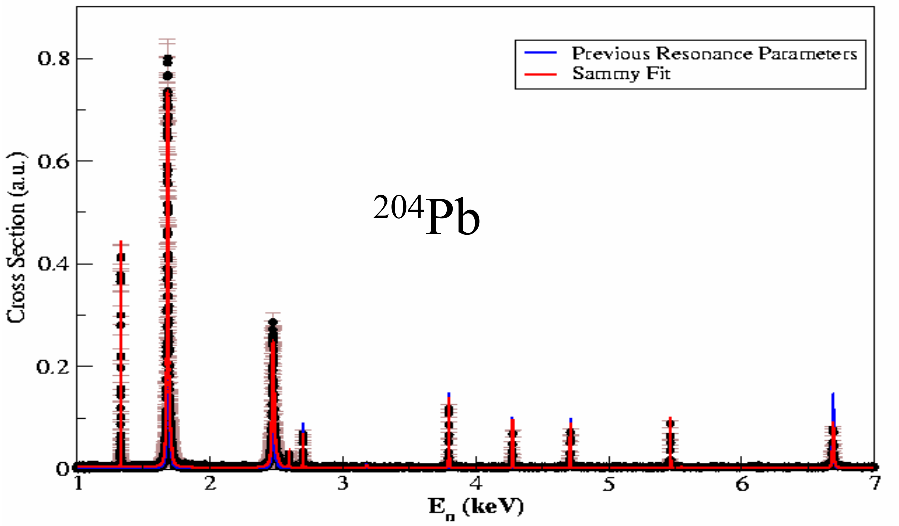
To map the endpoint of the s-process and determine s-process versus r-process contributions to the production of Pb and Bi!

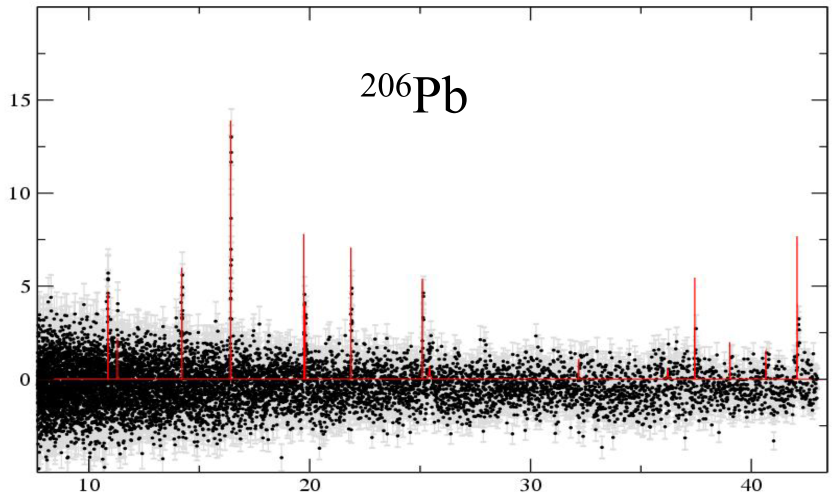




Measurements of: ^{204}Pb(n,γ), ^{206}Pb(n,γ), ^{207}Pb(n,γ), ^{208}Pb(n,γ), and ^{209}Bi(n,γ) at the CERN n-ToF Facility are completed and published!

Data Analysis with r-Matrix



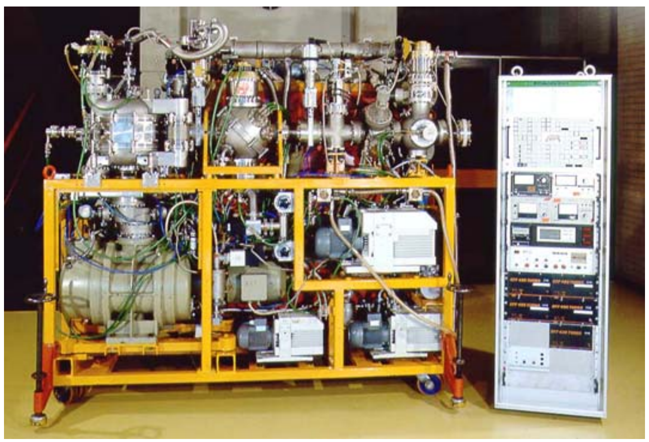
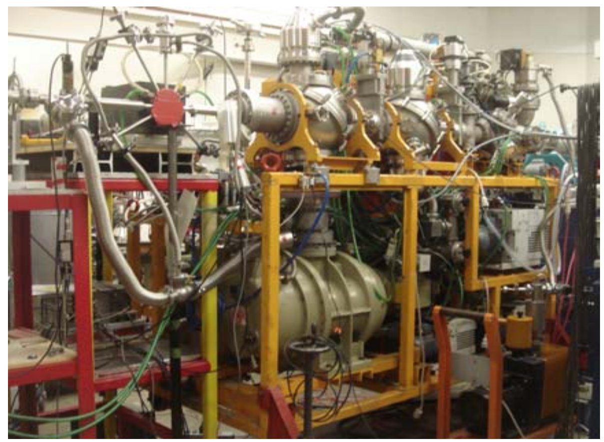


General agreement in neutron capture cross sections, but considerable reduction of uncertainties compared to previous results. New s-process simulations (Gallino, Herwig) are in preparation for concluding the project and investigating the impact on s-process abundances of Pb isotopes .

Auxiliary instrumentation for long term experimental program

- gas target system
- recoil separator
- new accelerator

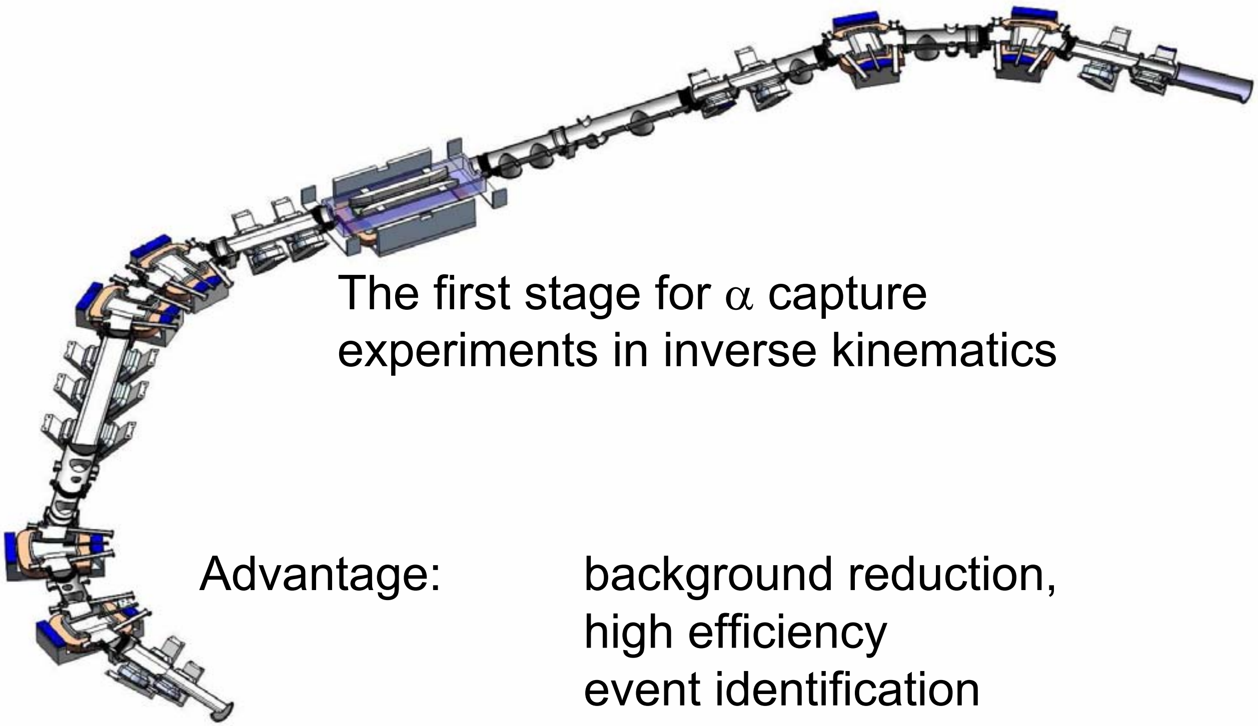
Gas Target RHINOCEROS

Purchased from Stuttgart, Germany, converted to US power and frequency ($50K special grant from Notre Dame), and renamed RHINO! Tested and operated for different proton and alpha capture as well as elastic scattering experiments.

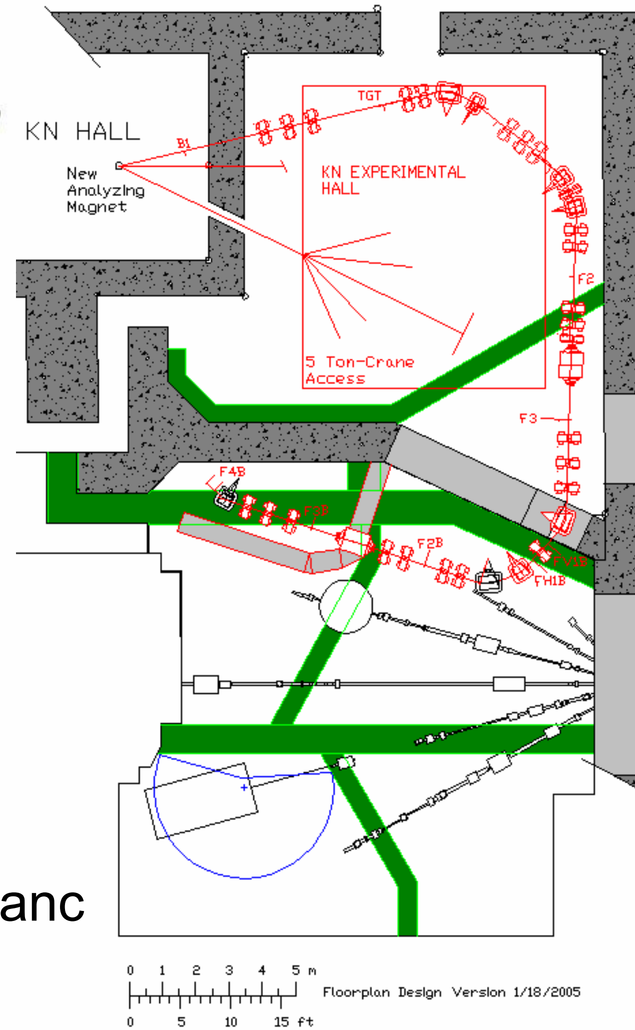
Development of St. George Recoil Separator

STrong **G**radient **E**lectromagnetic **O**nline **R**ecoil separator for capture **G**amma ray **E**xperiments



The first stage for α capture experiments in inverse kinematics

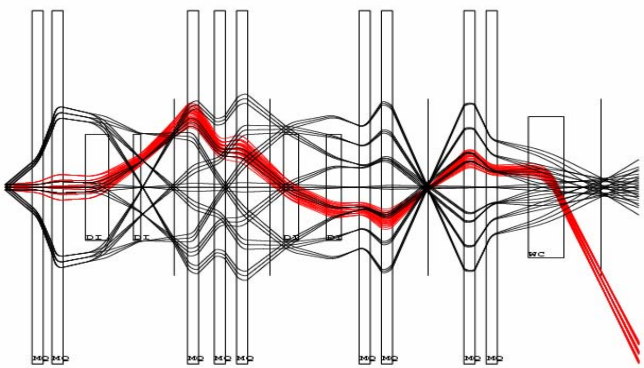
Advantage: background reduction, high efficiency event identification



G. Berg, M. Couder, J. Görres, L.O. Lamm, P.J. LeBlanc

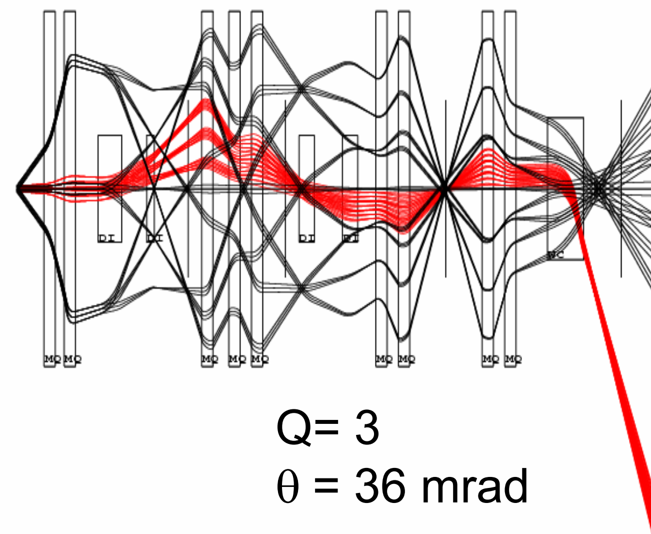
Inverse kinematics beam trajectory simulation with 2nd & higher order effects

$^{22}Ne(\alpha,\gamma)^{26}Mg$ @ 8 MeV



Q= 4
θ = 21 mrad

$^{22}Ne(\alpha,\gamma)^{26}Mg$ @ 2 MeV

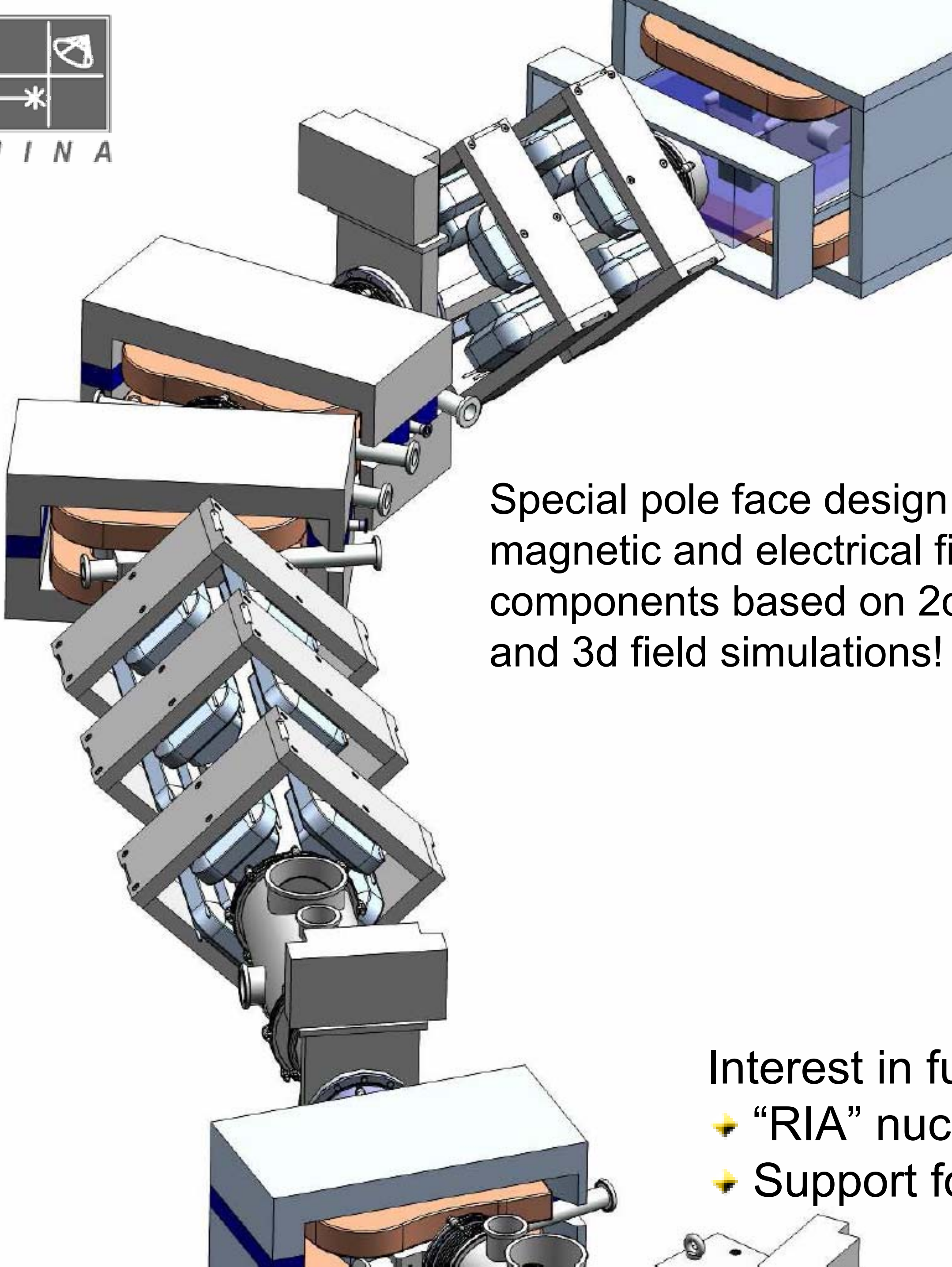


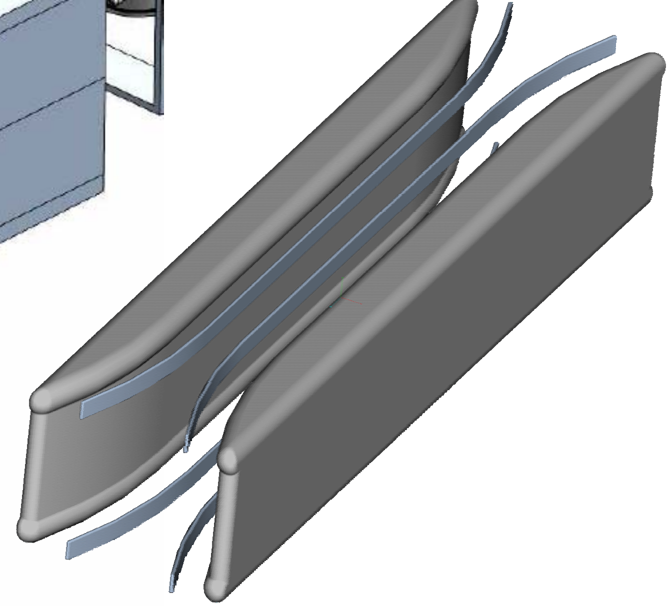
^{26}Mg

^{22}Ne

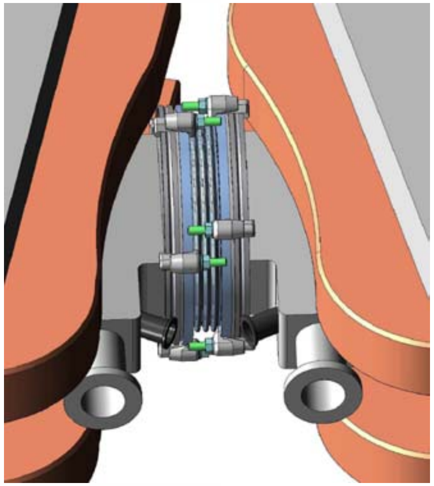
Q= 3
θ = 36 mrad

- Dipole and quadrupole design specified and completed
- order to Bruker, special 2d, 3d field design studies
- \$ 1.5M Notre Dame support for infrastructure development
- \$ 150K NSF supplemental funds for increase in Copper and decrease in US \$ value





Special pole face design for magnetic and electrical field components based on 2d and 3d field simulations!

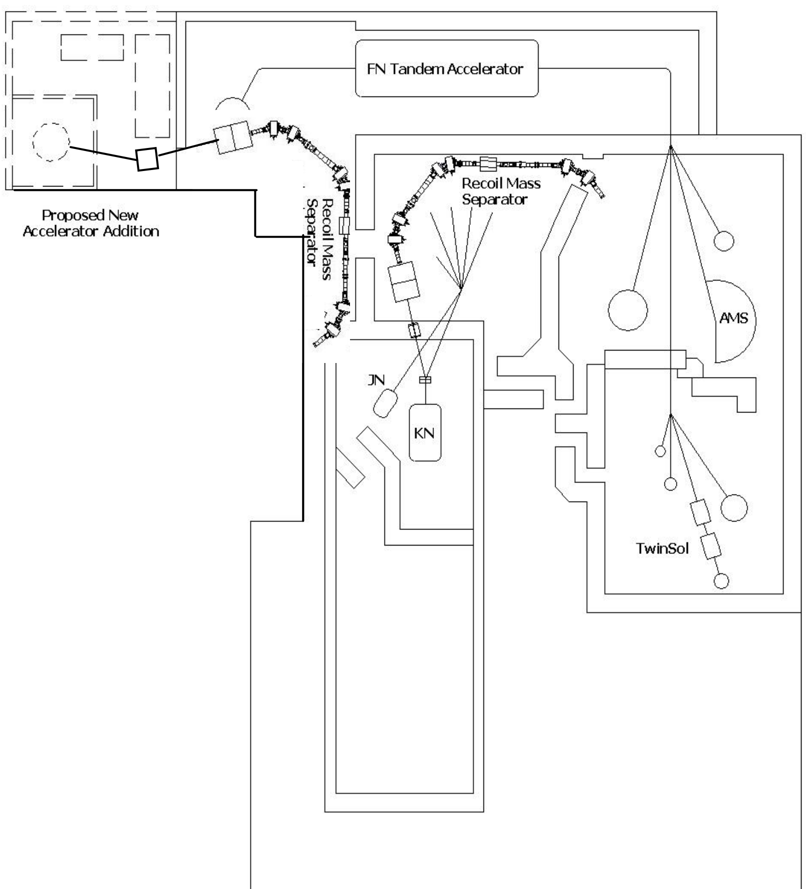


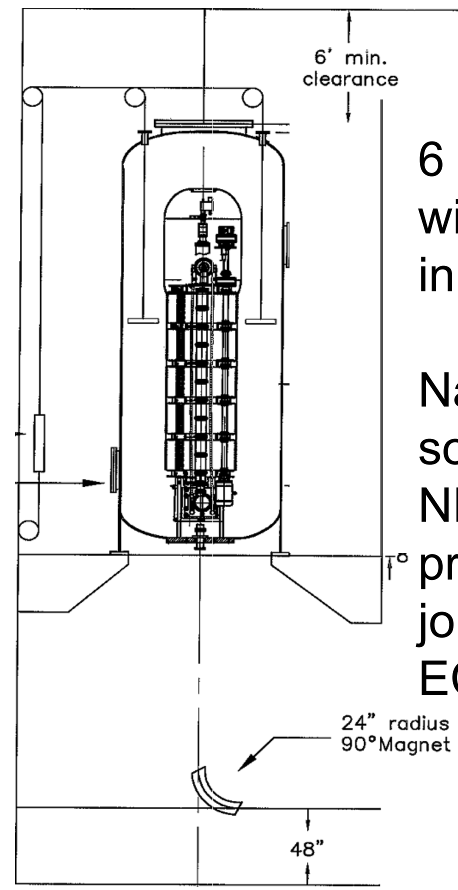
Interest in future applications:

- "RIA" nuclear astrophysics recoil separator
- Support for Wien Filter at TRIUMF

Stable Beam Accelerator for Nuclear Astrophysics

MRI proposal for $ 2M to NSF with $ 2.0M matching funds from Notre Dame for purchasing and installing a new low energy heavy ion accelerator.





6 MV Pelletron with ECR source in terminal.

Nanogam ECR source offered by NEC, new design proposed to NSF jointly with LBNL ECR group.

2006 JINA Conference Program related to MRC1

“Massive Stellar Progenitors, The Final Days of Burning"
March 9-10, 2006, Santa Barbara , CA
Organizers: S. Austin, L. Bildsten, M. Wiescher

“The First Stars and Evolution of the Early Universe”
June 19 - 21, 2006, Seattle, WA
Organizers: T. Abel, T. Beers, A. Heger

“Compiled Data Requirements for Modeling in Nuclear Astrophysics”
June 23-24, 2006, Basel, Switzerland
Organizers: F.K. Thielemann, M. Wiescher

“The Status of 12C(α, γ)16O,
the "Holy Grail" of Nuclear Astrophysics”
December 15, 2006, Caltech, Pasadena, CA
Organizers: B. Filippone, M. Wiescher

MRC1 conferences in 2007

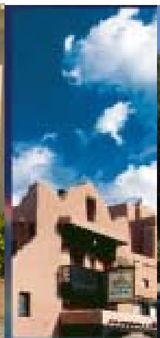
- Workshop on experimental opportunities for nuclear astrophysics at the Frankfurt neutron source of the Stern-Gerlach-Zentrum - The FRANZ Neutron Source
  Forschungszentrum Karlsruhe & Frankfurt University, Germany, May 21 - 23, 2007

- CARINA-JINA on "Nuclear Physics Data Compilation for Nucleosynthesis Modeling"
  ECT*, Trento, Italy, May 29 - June 1, 2007

- Conference on "First Stars III"
  Santa Fe, New Mexico, USA, July 16 - 20, 2007

- Nuclear Astrophysics: Beyond the First 50 Years
  California Institute of Technology, Pasadena, CA, USA, July 24 - 28, 2007






Next Year Goals

1. Completion of AZURE and CNO analysis
2. Re-measurement of critical CNO reactions and reaction parameters
3. $^{15}N(p,\gamma)$, $^{14}N,^{15}N(p,p)$

4. Completion of measurements for critical He-burning reactions
5. $^{12}C(\alpha,\gamma)$, $^{16}O(\alpha,\gamma)$, $^{24}Mg(\alpha,\gamma)$
6. Triple-alpha, $^{22}Ne(\alpha,\gamma)$, $^{22}Ne(\alpha,\alpha)$

7. Carbon and Oxygen fusion measurements

8. Completion of neutron poison studies (n-ToF) $^{23}Na,^{25}Mg,^{26}Mg(n,\gamma)$

9. Installation of St. George recoil separator