MRC-1: Low Energy Nuclear Reactions and Stellar Evolution

J I N A

Michael Wiescher

Focus-1:
- ⇨ Stellar Hydrogen burning in massive stars
- ⇨ Re-evaluation of CNO cycles

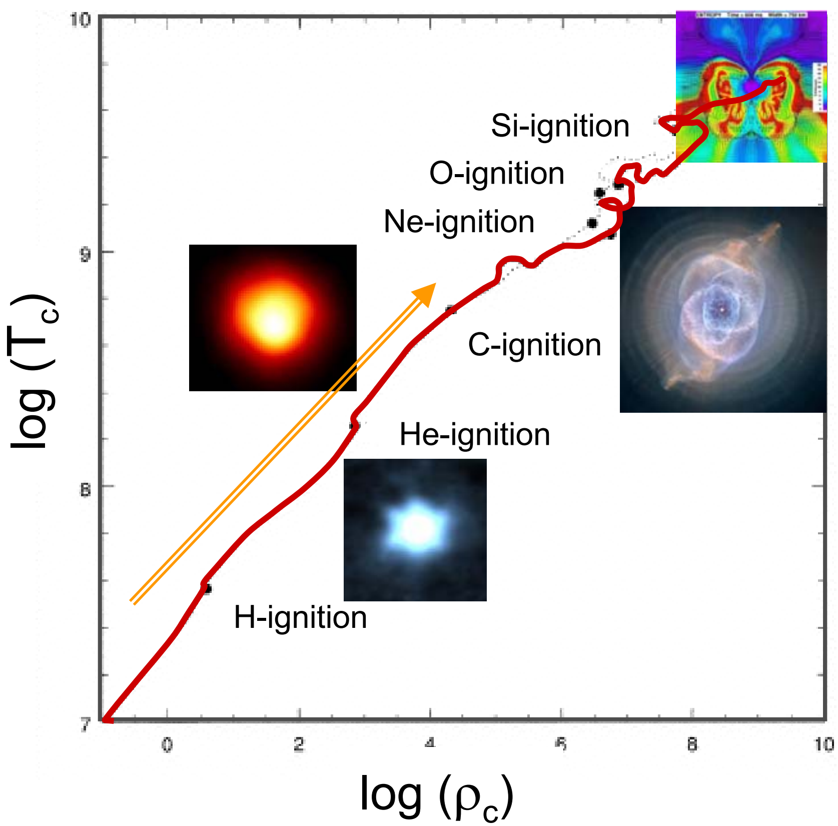
Focus-2:
- ⇨ Stellar He-burning
- ⇨ neutron sources for s-process

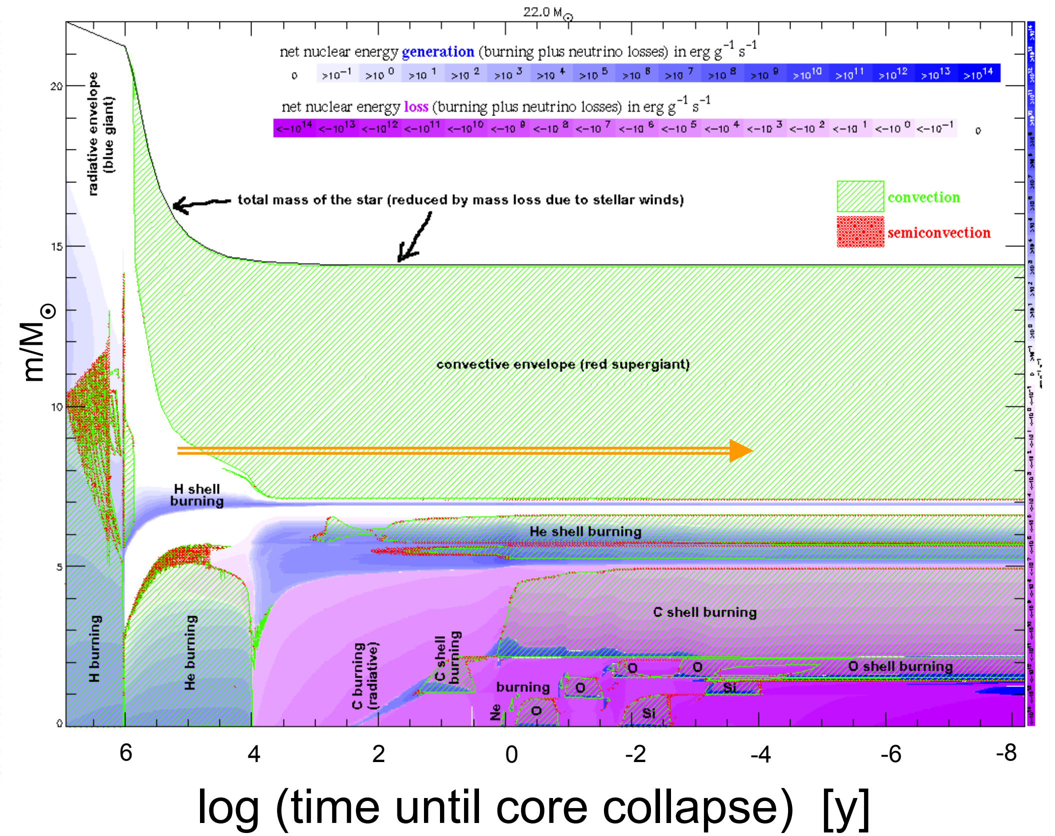
Focus-3: (see Falk Herwig, LANL)
- ⇨ s-process in AGB stars
- ⇨ branching & end-point of s-process

Focus-4:
- ⇨ charged particle reactions in AGB stars

S. Austin, MSU
A. Heger, LANL
F. Herwig, LANL
E. Rehm, ANL
J. Truran, UoC
M. Wiescher, ND

Nuclear burning & stellar evolution

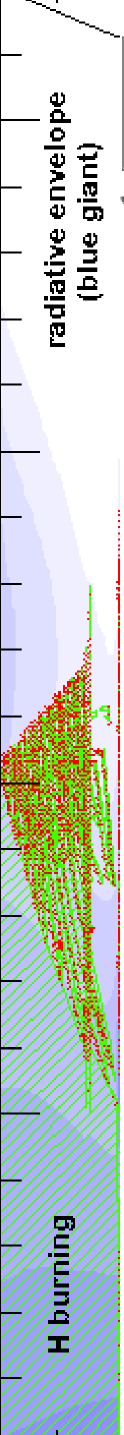




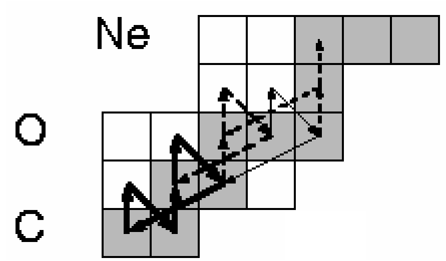
Each burning phase is determined by nuclear reactions in terms of

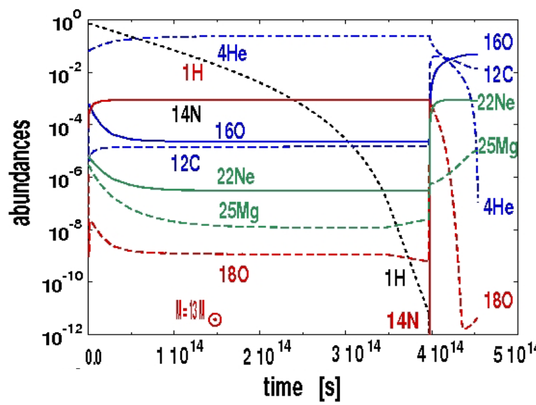
- energy generation,
- time scale
- nucleosynthesis

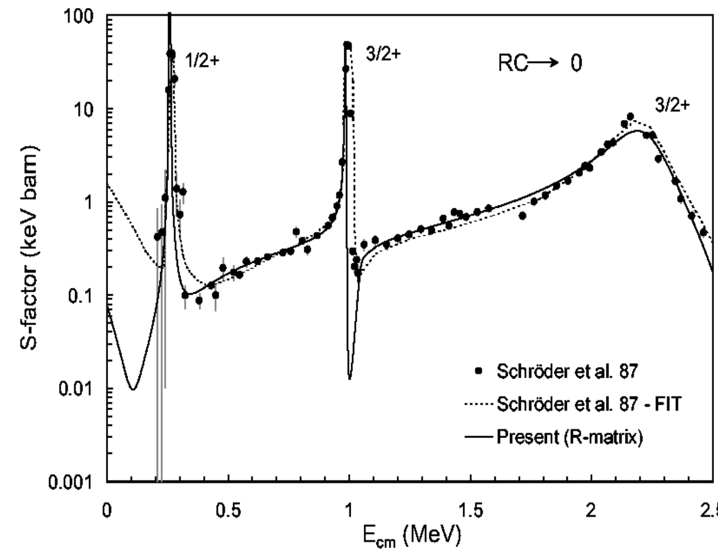
Stellar H-burning in massive stars



Low energy reactions rely on unreliable extrapolation

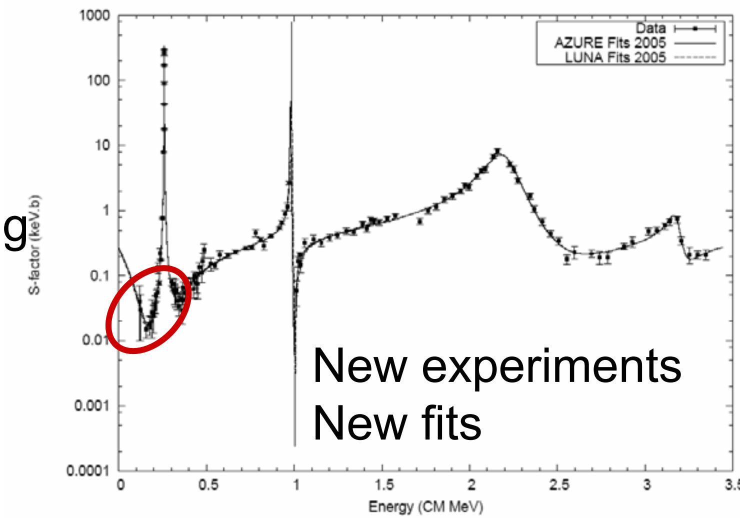






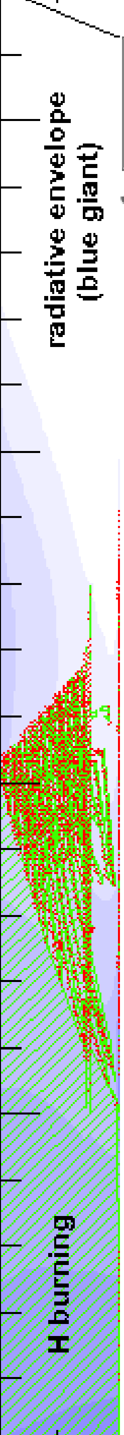
Re-evaluation of CNO reaction rates using JINA R-matrix code AZURE

All CNO reactions are presently being fitted and are discussed for measurement

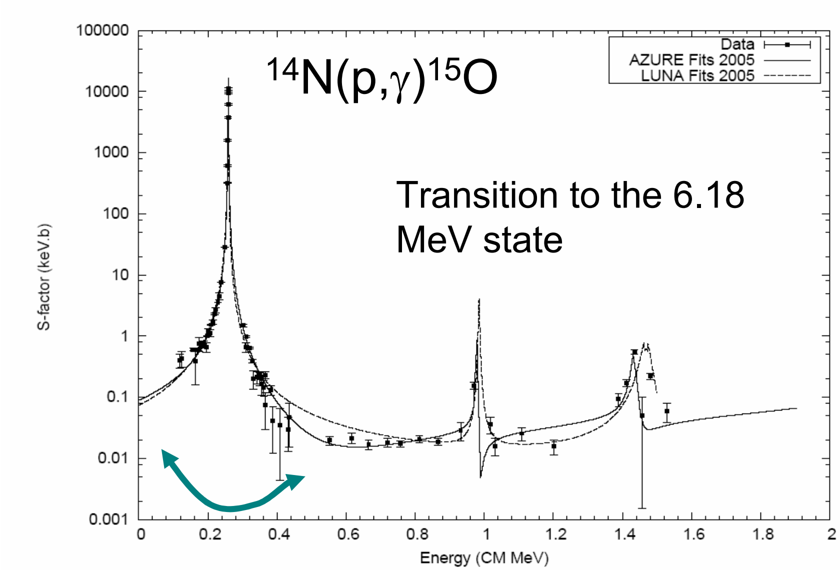


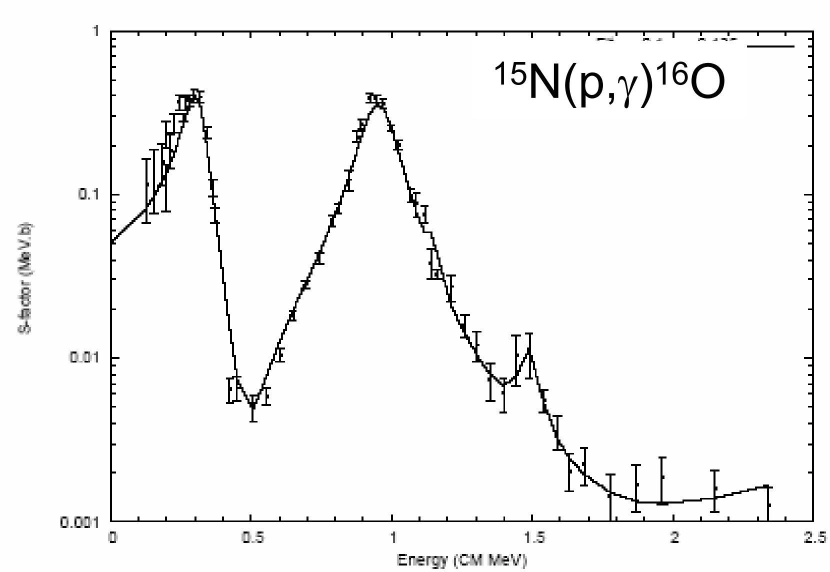
New experiments
New fits

R-Matrix School; October, 2004



AZURE Extrapolations



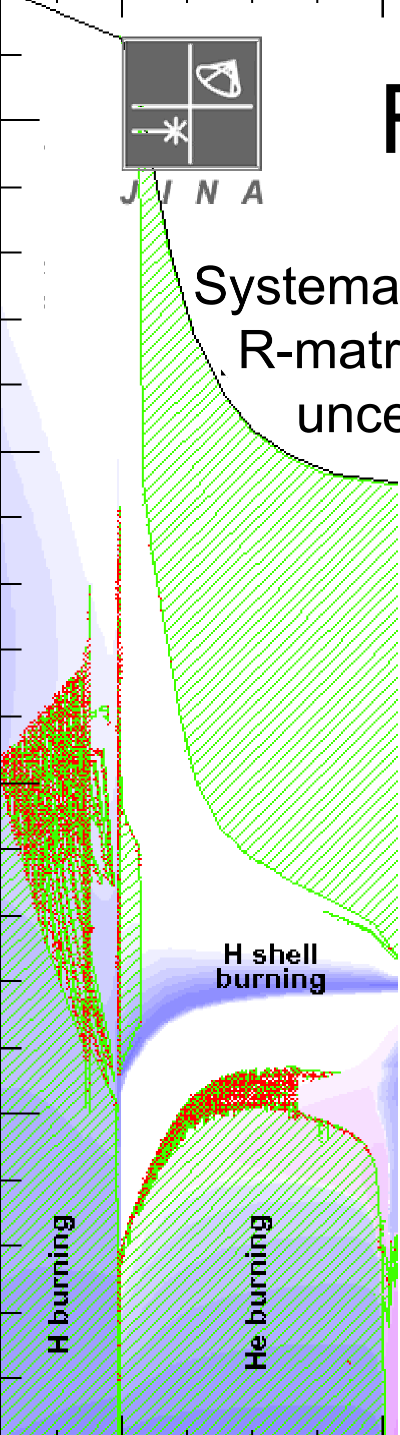


Impact of 0.5 MeV?

20% reduction in S-factor

Extrapolations in multi-channel R-matrix techniques based on:
(p,p) elastic scattering data
(p,γ) capture reaction data
(p,α) nuclear reaction data

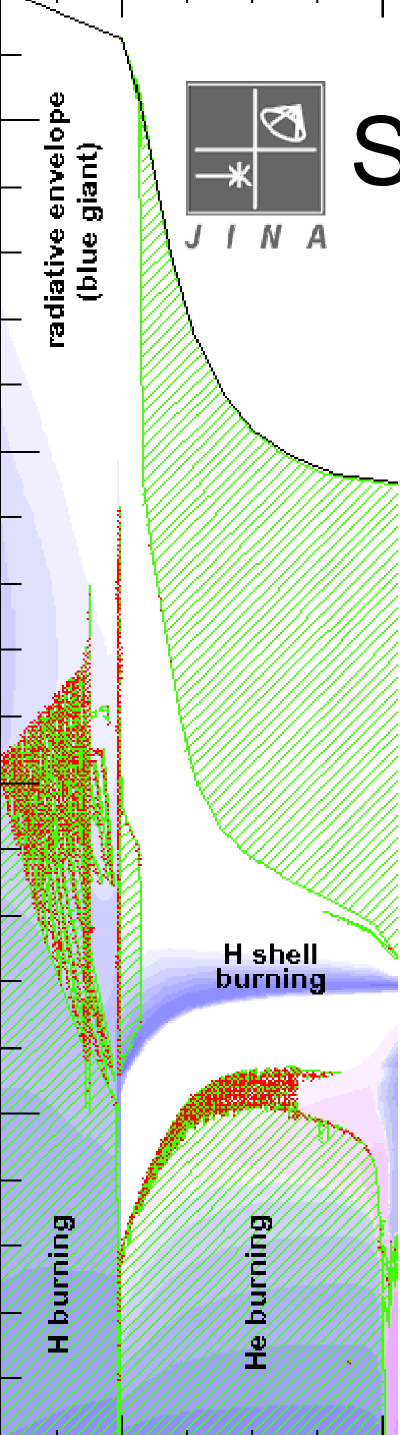
New measurements are planned between JINA, LENA, LUNA to compare and evaluate shielding techniques for underground accelerator at DUSEL



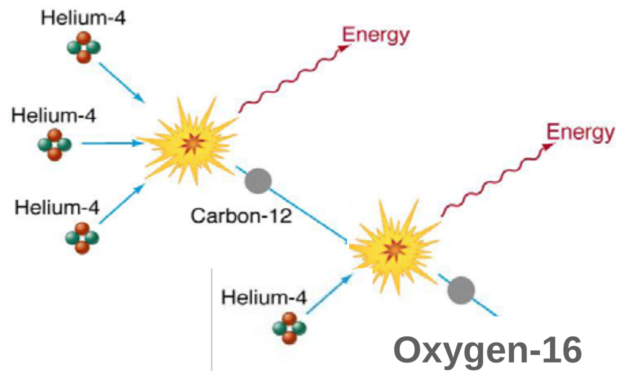
Future JINA projects in H-burning

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 new data!
$^{17}O(p,\alpha)^{14}N$ $^{17}O(p,\gamma)^{18}F$	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



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

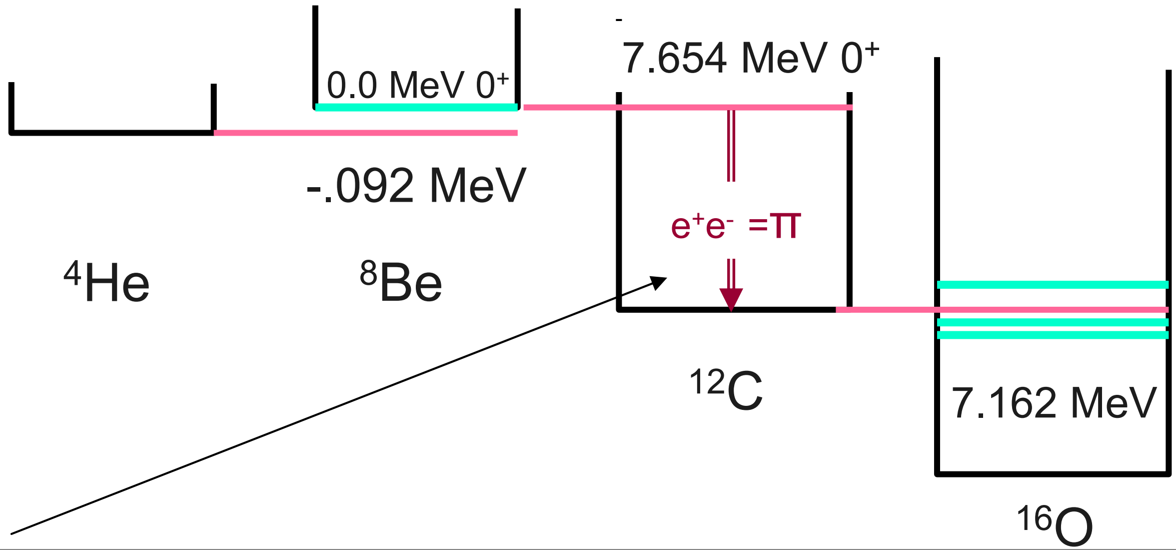
- Neutron production for weak s-process:

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

$^{22}Ne(\alpha,\gamma)$

Completed!

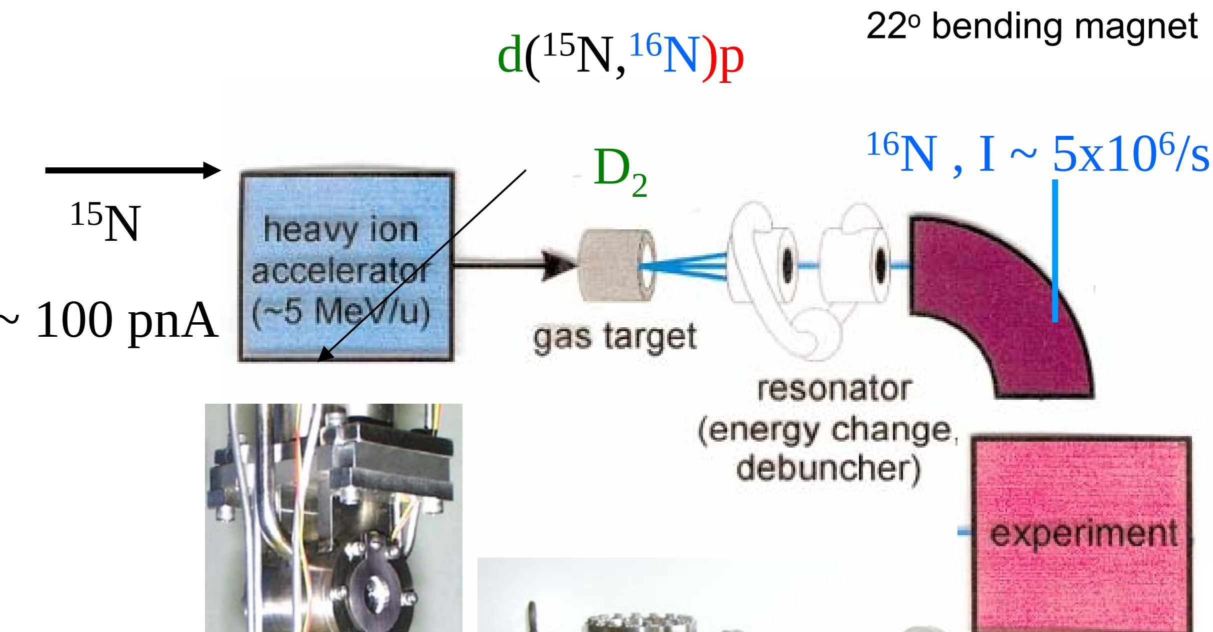
Triple alpha and the Holy Grail

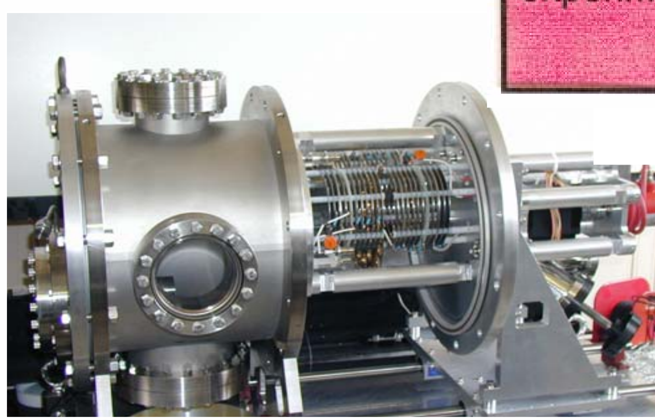


^{4}He(2α,γ+e^+e^-)	Reduce 9% uncertainty in $\Gamma_\pi/\Gamma \approx 6 \times 10^{-6}$ by pair-production measurement: ^{12}C(p,p')^{12}C*(π)^{12}C Collaboration: WMU & NSCL/MSU; Status: experimental design completed and GEANT simulated; measurements start summer 2006

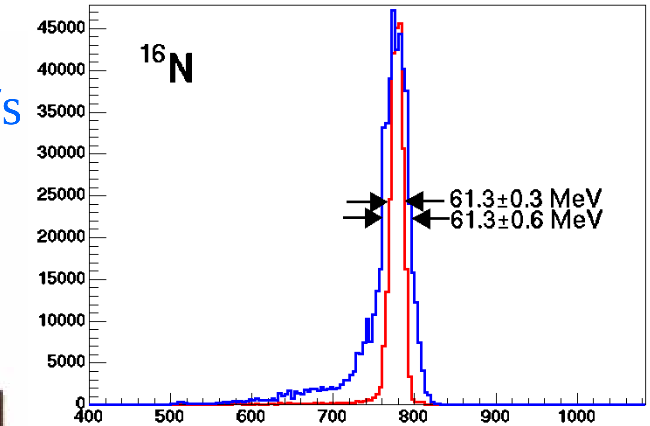
^{12}C(α,γ)^{16}O	Improvement of previous ^{16}N(β-α)^{12}C measurements (reduction of β-background and ^{17}N,^{18}N beam impurities Collaboration: ANL, NWU, ...; Status: experiment completed with new detector design; data analyzed, S(E1)=83 keV-barn, error analysis not final yet

Radioactive Beam Production

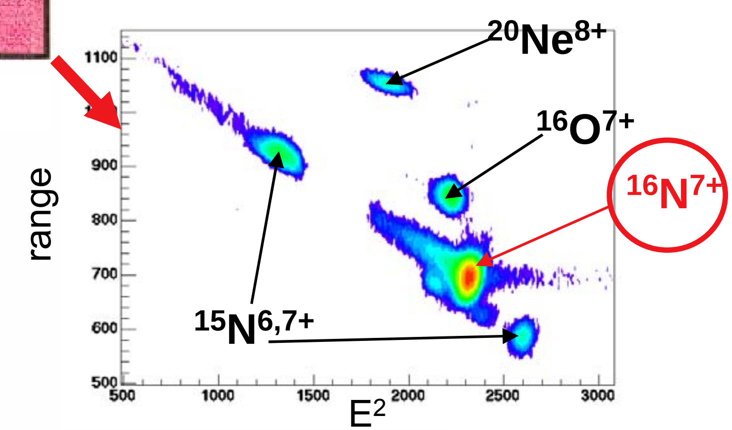




Ionization-Chamber



Particle identification

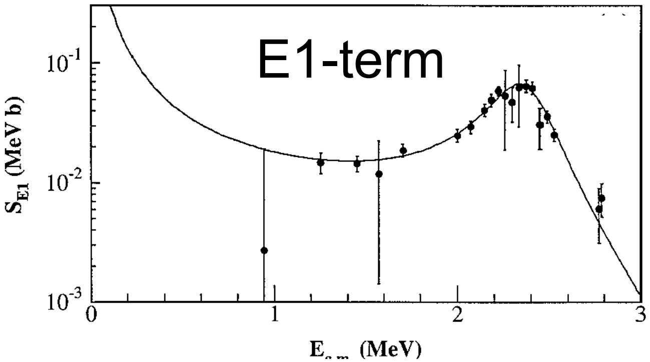


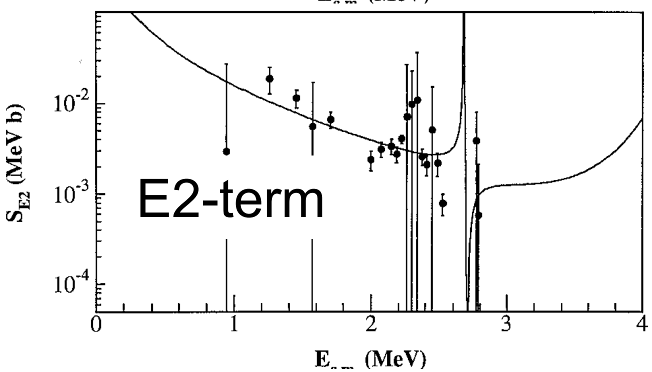
ANL-NWU et al.

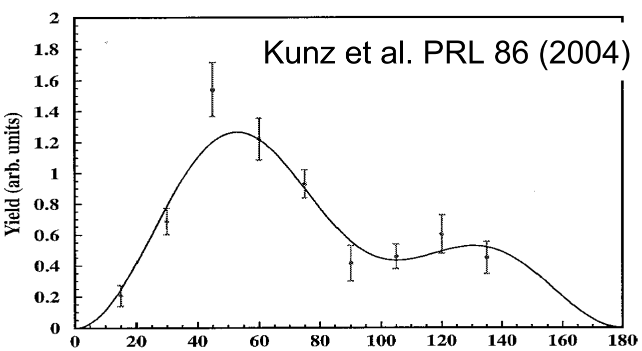
83±?? keV-barn

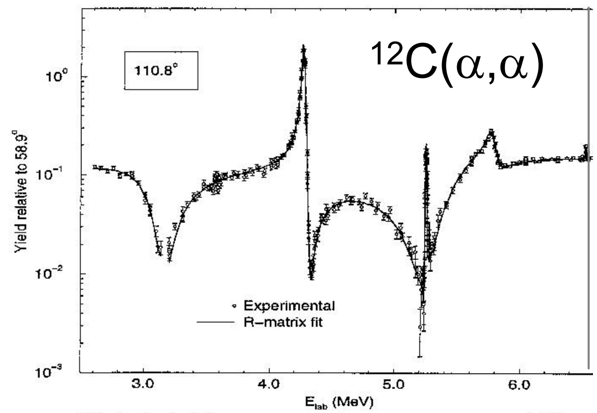
JINA Goal R-Matrix Analysis

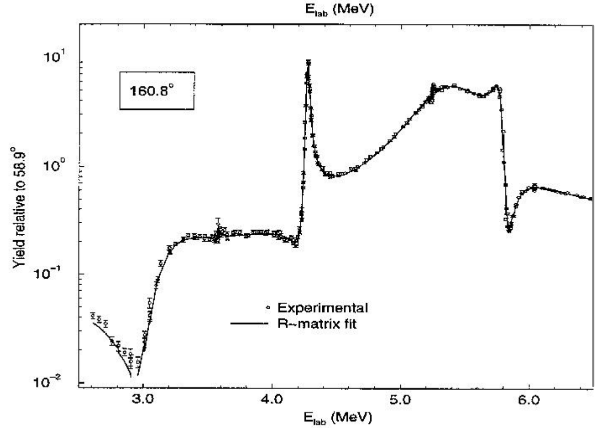
of combined data set: $^{12}C(\alpha,\gamma)$, $^{12}C(\alpha,\alpha)$, $^{16}N(\beta\text{-}\alpha)$ ... $^{12}C(^{6}Li,d)$
to reduce the overall uncertainty in a consistent manner!

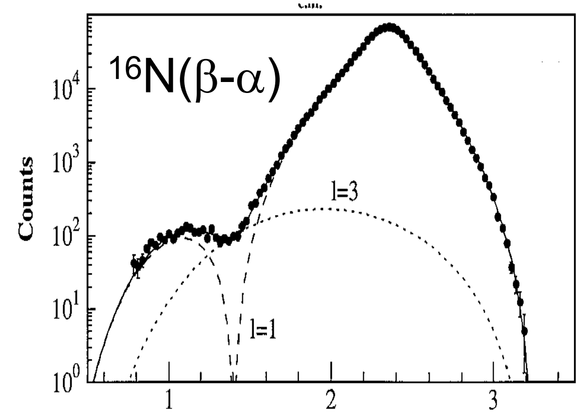


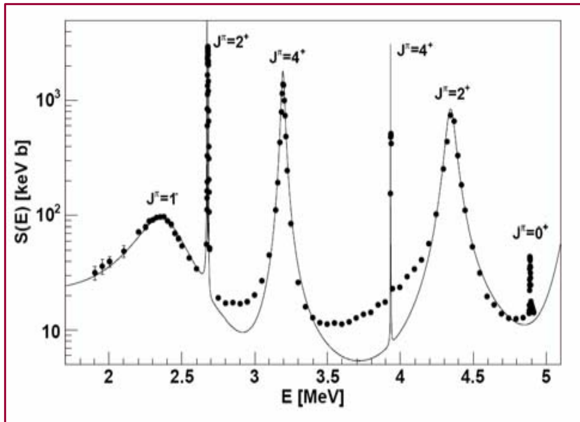






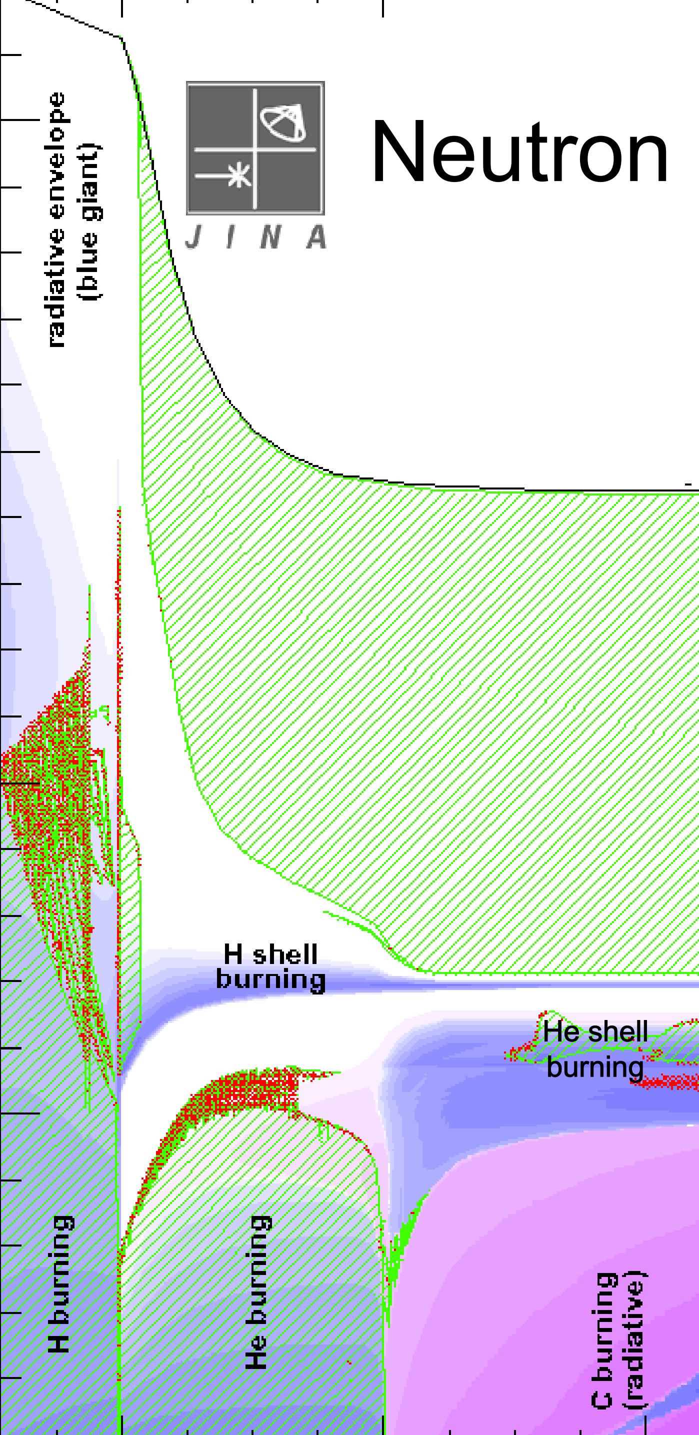






S_{E1}≈83 keV barn, S_{E2}≈85 keV-barn
arguments & experiments will continue!!!

Neutron Sources in Stellar He-Burning



Neutron sources are produced by:

- provision of fuel material by mixing processes
- production by nuclear reaction sequences

Mixing of H into Carbon rich He-Burning zone

$$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)$$

Main s-process in AGB stars!

He-burning on the ashes of CNO cycle

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

Weak s-process in RGB stars!

Hot He-burning conditions on CNO ashes

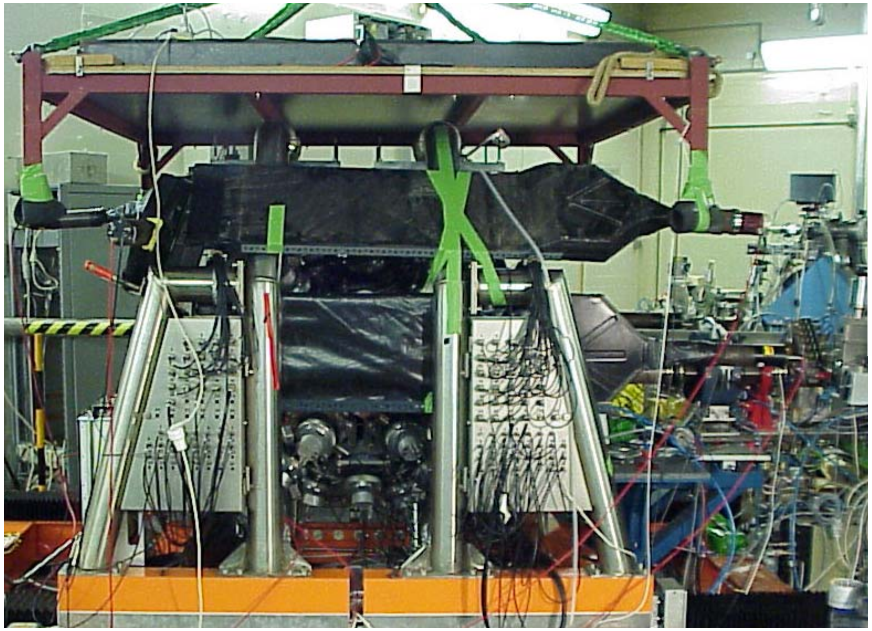
$$^{14}N(\alpha,\gamma)^{18}F(\alpha,p)^{21}Ne(\alpha,n)$$

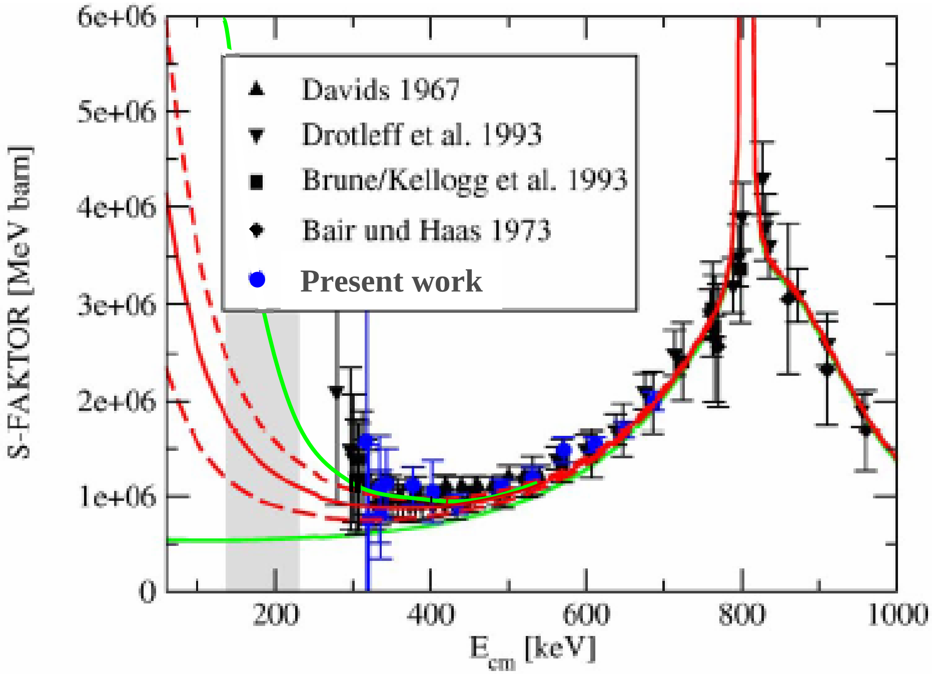
neutron source for n-process?

New Measurements on $^{13}C(\alpha,n)^{16}O$

Experimental collaboration: ND-FZK

Previous experiments indicate large uncertainty in the low energy range! This is due to interference with sub-threshold levels in ^{17}O!



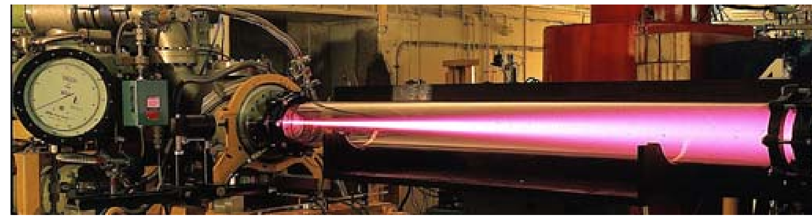


Present analysis of impact of results in the framework of an AGB star model.

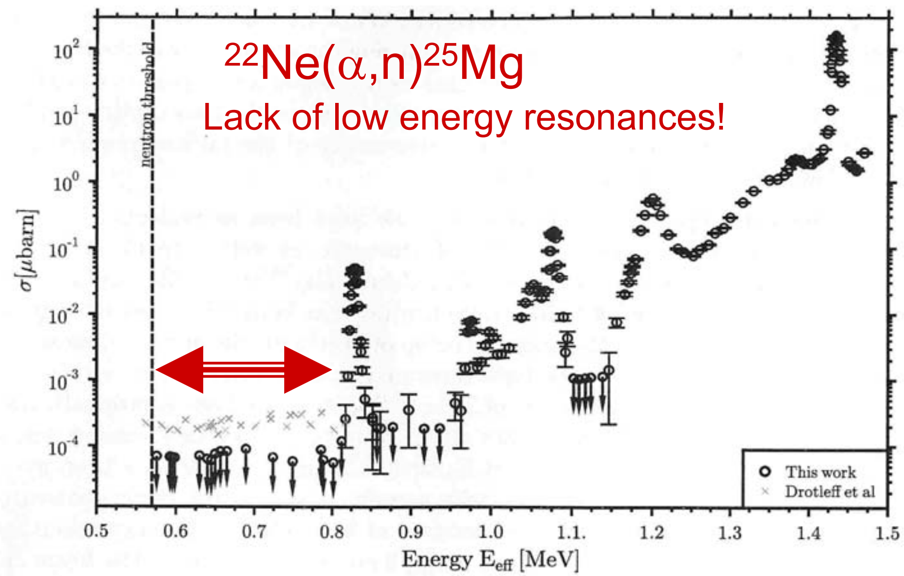
Collaboration: LANL-ND-Torino

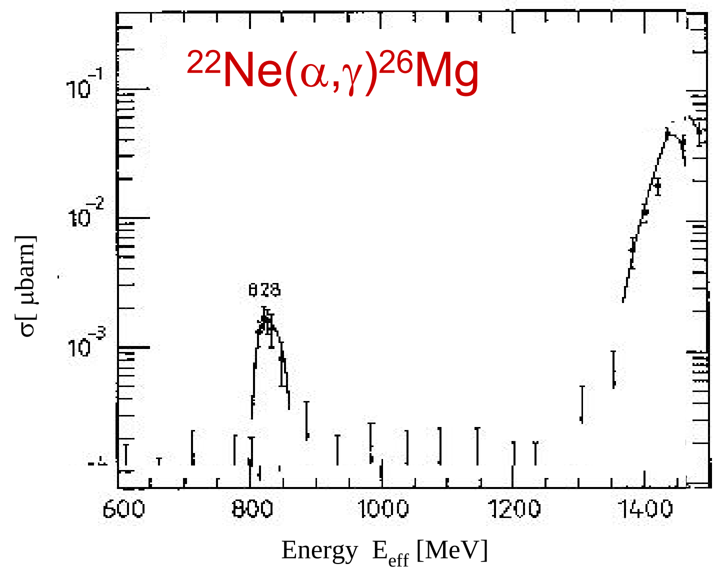
$^{22}Ne(\alpha,n)$ in Stellar He Burning

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



- Lowest resonance at $E_R \approx 830$keV, lower energy resonances anticipated;
- The two channels operate through different resonance states?
- Similar strength suggests comparable rates. reduction in neutron production!





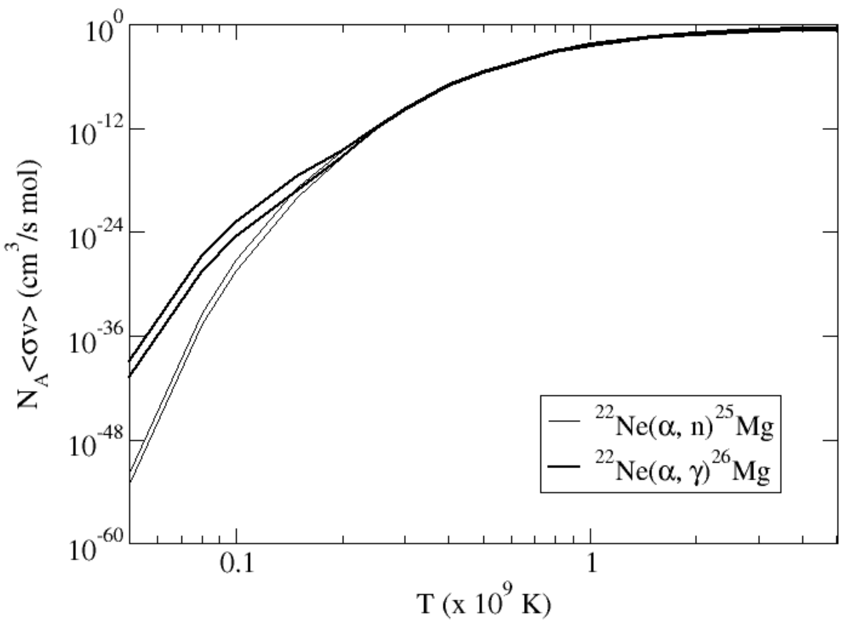
Main problem is background reduction of ~0.1 neutrons/s!

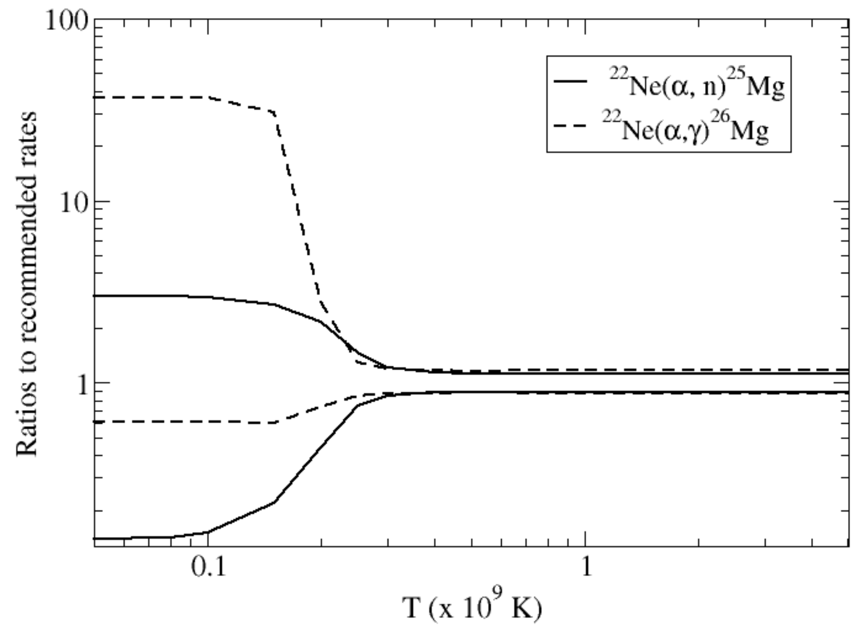
Competing resonances suggests reduction of neutron production!

REACTION RATE ESTIMATES

Resonance parameters determined by

- Re-analysis of $^{25}Mg(n,\gamma)$ data by Koehler et al. 2000 (new n-ToF experiment)
- Analysis of $^{22}Ne(^{6}Li,d)$ transfer data
- Shell model calculations
- Cluster model calculations

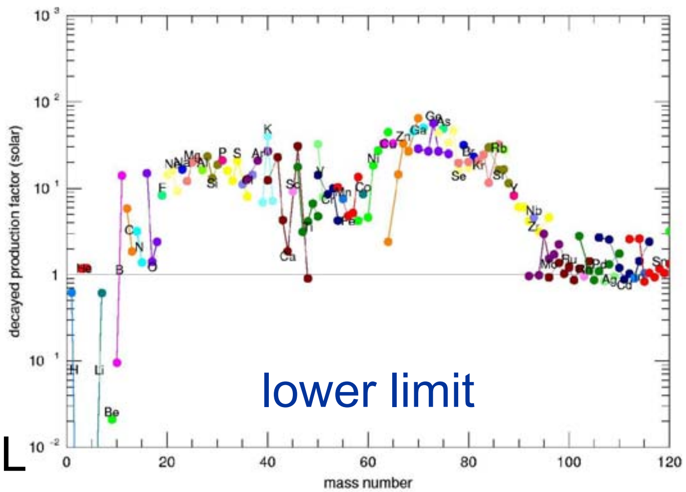


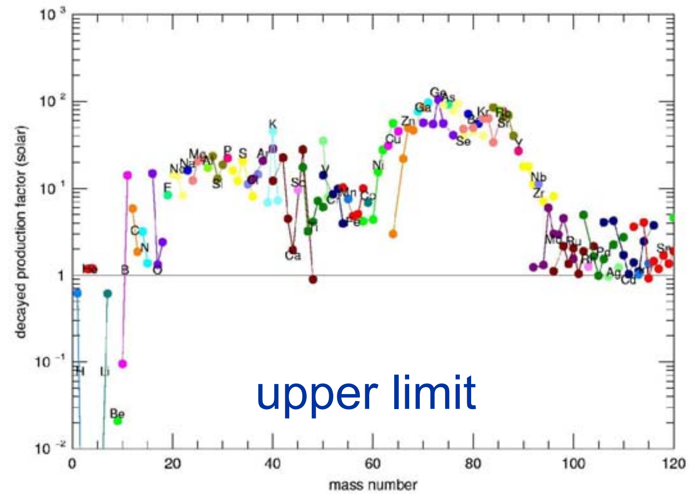


Low energy resonance contributions in the $^{22}Ne(\alpha,\gamma)^{26}Mg$ channel, the cross-over depends critically on resonances and resonance parameters within 500-800 keV.

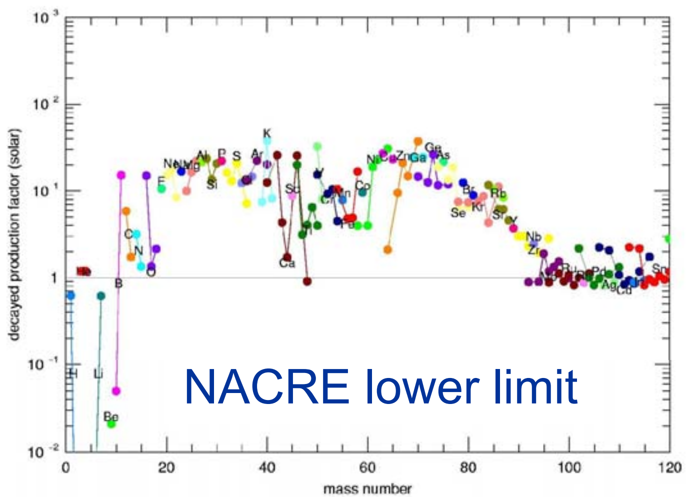
Considerable uncertainties remain, low energy measurements are still necessary!

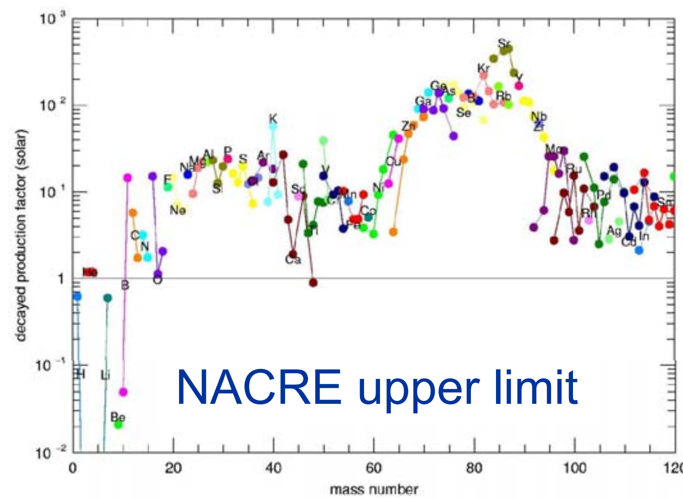
Consequences for weak s-process





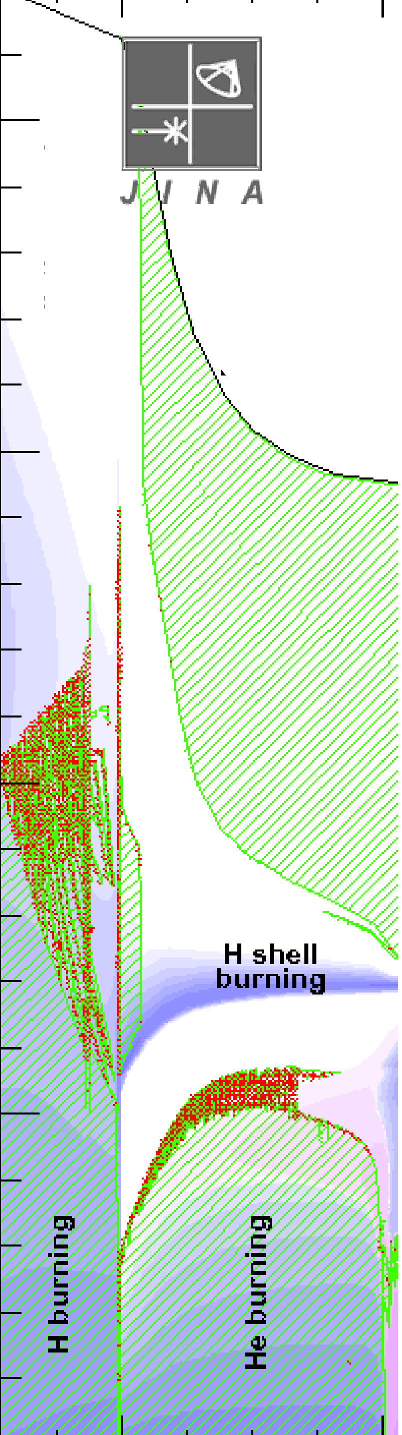
Heger, LANL
Woosley, UCSC; further studies are being performed with U. Torino, McMaster U., LANL





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

Present & future JINA projects in He-burning



Measurements:

- $^{4}He(2\alpha,\gamma)^{12}C$ by pair-production study; (WMU, MSU ~2007)
- $^{12}C(\alpha,\gamma)^{16}O$ by β-delayed α-decay; (ANL-NW ...~ 2006
- $^{16}O(\alpha,\gamma)^{20}Ne$ by direct measurement; first test studies (ND-LUNA)
- $^{22}Ne(\alpha,\gamma)^{26}Mg$ by direct measurement & inverse kinematics (ND)

Modeling:

First modeling studies for impact of these reactions completed!
Further studies planned for the conditions of stellar evolution of:

- massive stars: UCSC-LANL-ND, INFN Frascati-ND
- AGB stars: LANL-Monash-MSU, LANL-McMaster-ND

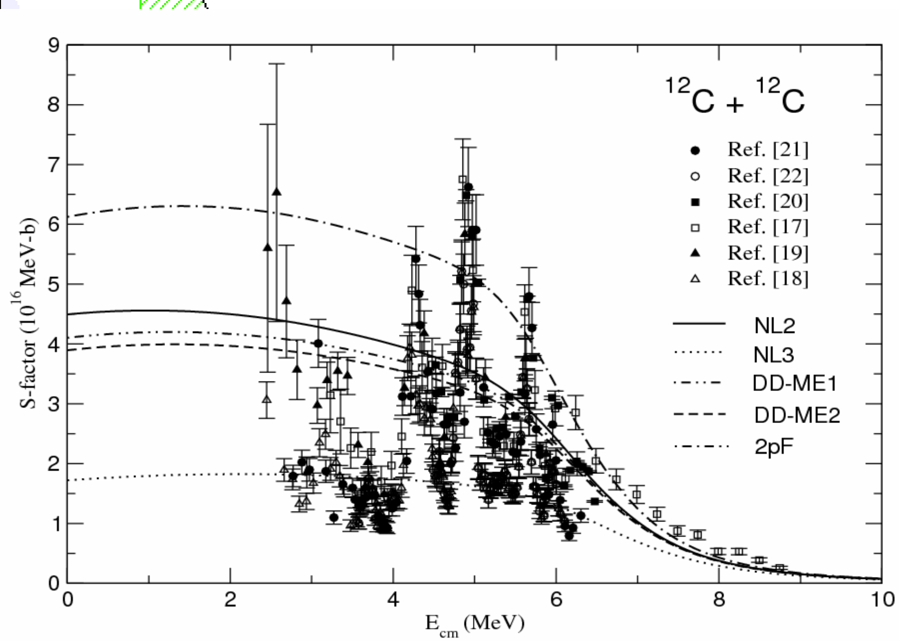
Technical Developments:

- Gastarget System for high intensity beams (Rhinoceros)
- Recoil Separator for inverse kinematics (St. George)

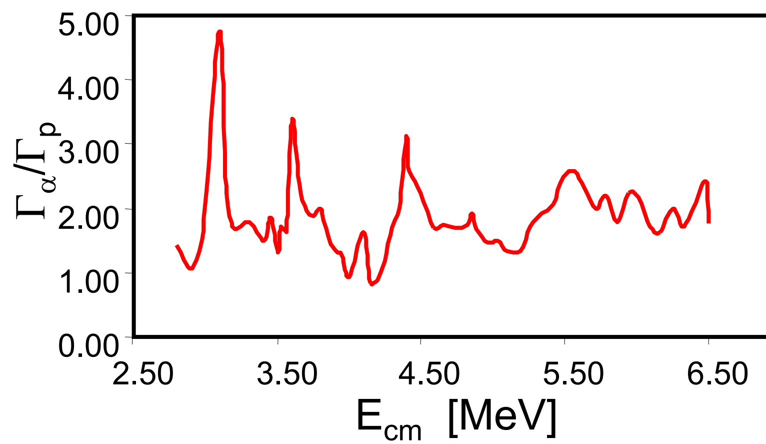
: Stellar C Burning

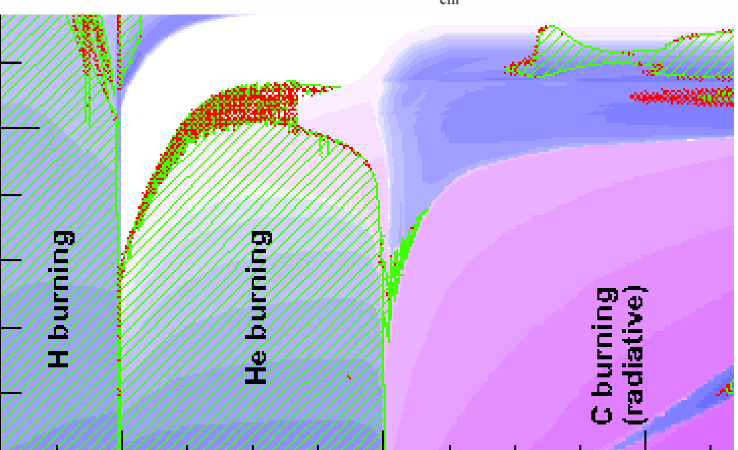
$^{12}C+^{12}C \Rightarrow$

$^{24}Mg+\gamma$,	Q=13.93 MeV
$^{23}Na+p$,	Q= 2.24 MeV
$^{20}Ne+\alpha$,	Q= 4.62 MeV



- ❑ Absolute cross section to determine fusion ignition point conditions
- ❑ Branching in p, α channel to investigate subsequent nucleosynthesis (s-process)



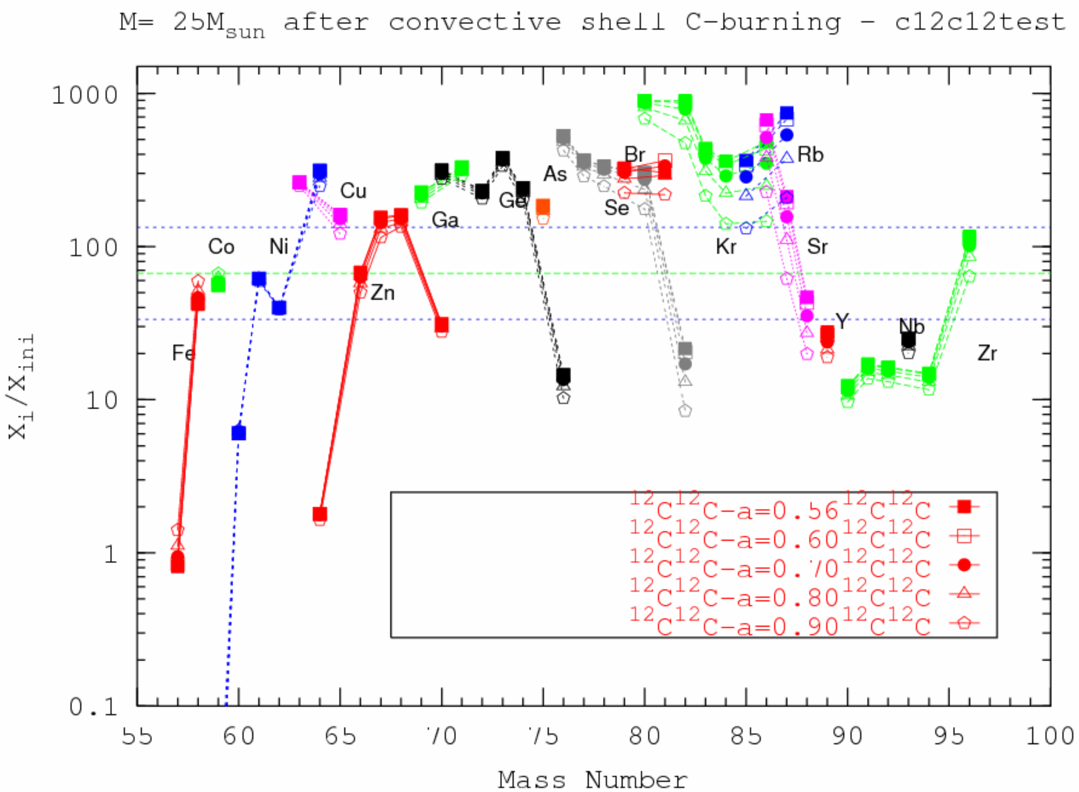


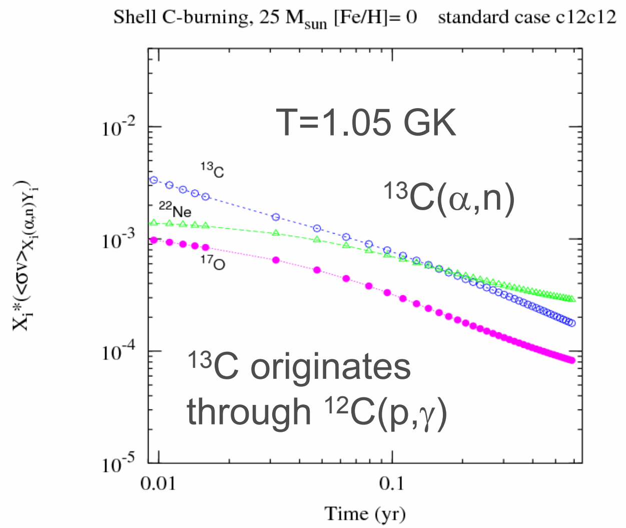
Question about s-process in C-burning

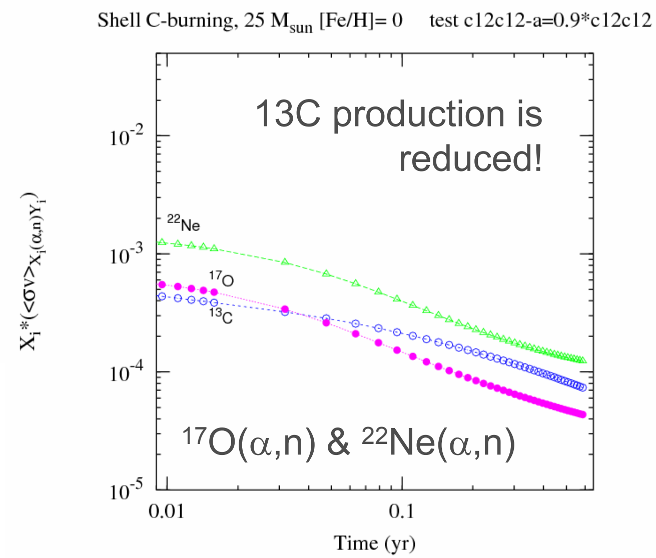
$^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)$

Depends on p,α-production in $^{12}C+^{12}C$

Consequences for neutron production and s-process





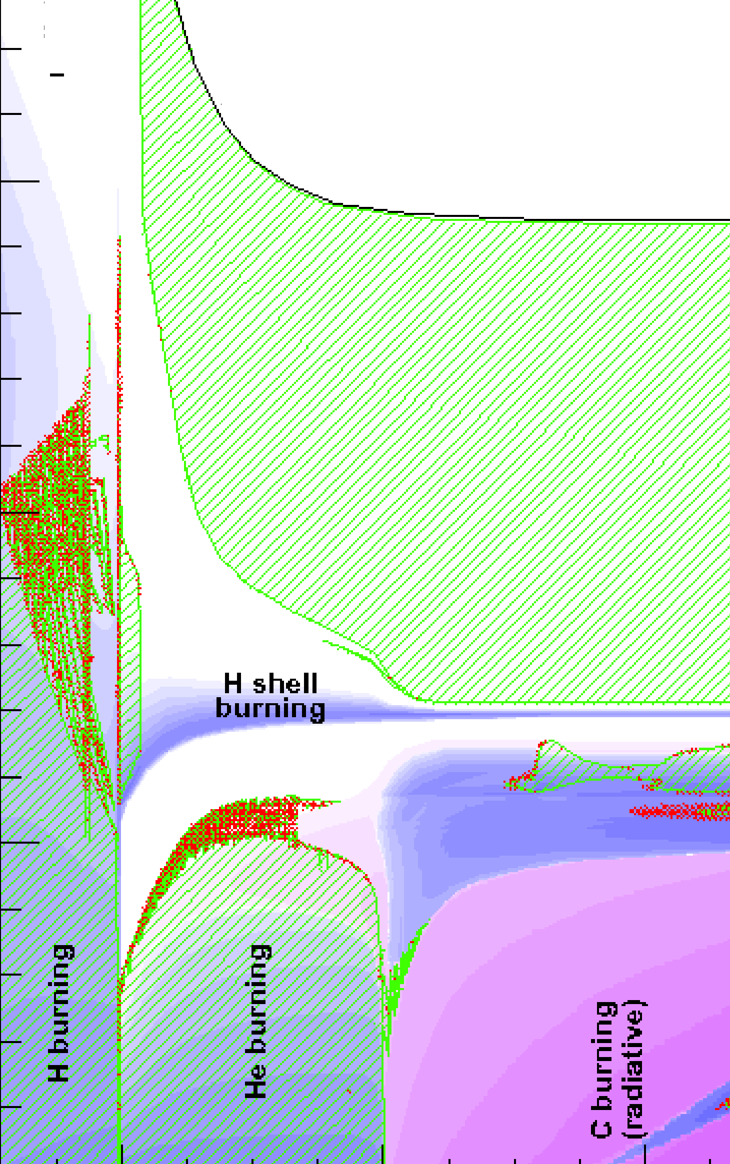


New and different neutron sources!!!

Project by Pignatari et al. (Torino-LANL-ND)

Present and Future Projects in stellar C-burning

Long range future developments!



Experiments:

$^{12}C(^{12}C,p)^{23}Na$, $^{12}C(^{12}C,\alpha)^{20}Ne$, p, α, γ spectroscopy

- first test studies completed (ND, ININ, TRIUMF)
- future experiments presently in planning (ND)

Modeling:

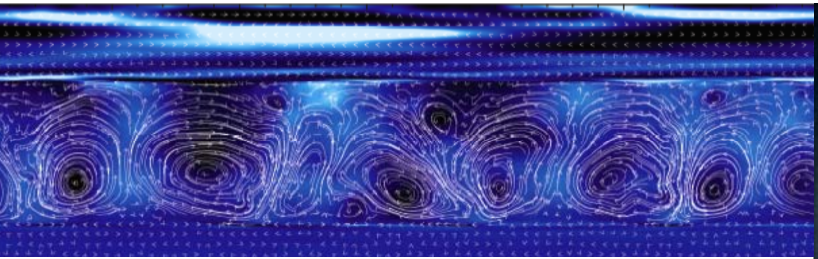
s-process nucleosynthesis conditions

- first parameter study of core carbon and shell carbon burning completed (LANL-Torino-ND)

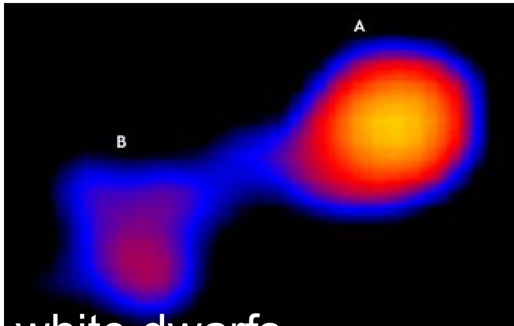
Nuclear Modeling:

alpha & molecular cluster configuration predictions with GCM, FMD models; (UNAM, GSI, ND)

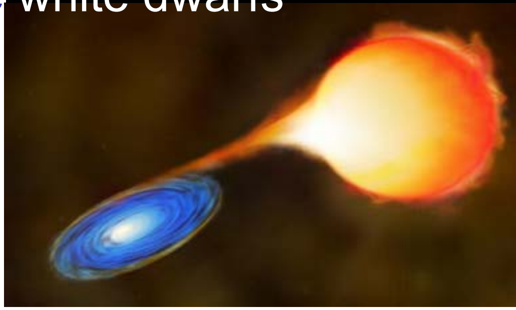
The final fate of stars



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



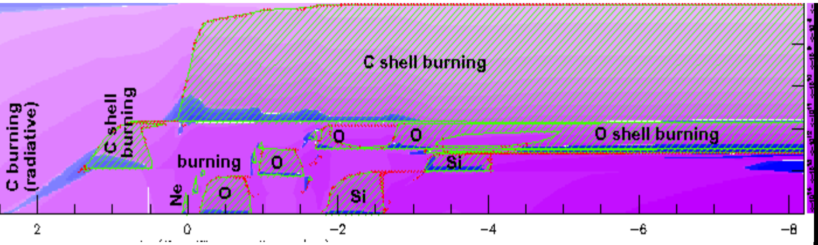
become white dwarfs



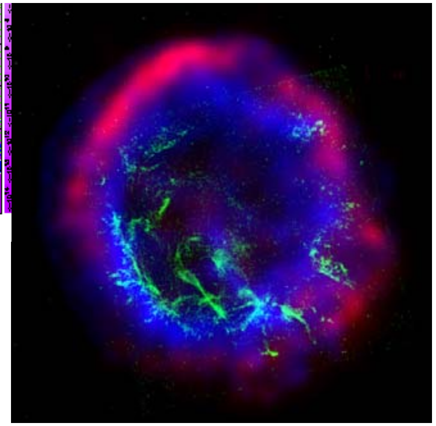
⇒ the site of the
main s-process

If in binary systems
⇒novae, type I SN

MRC-3



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



⇒ Supernova shock front
⇒ the site of the r-process

MRC-2

⇒ the site of the weak s-process

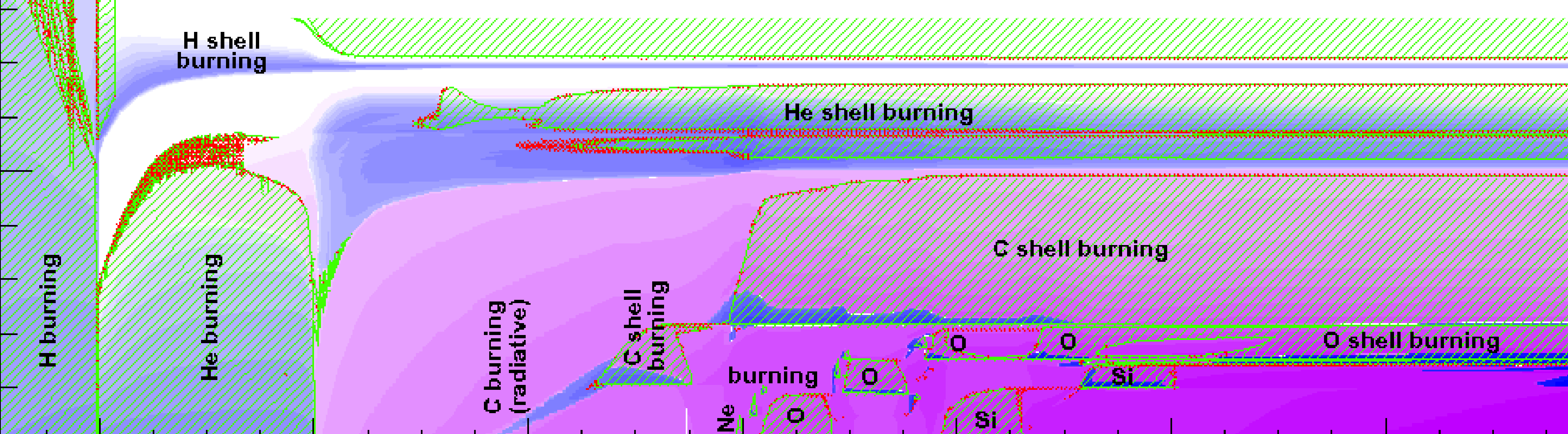
LANL, LANSCE, n_ToF, FZK

Present and future activities

End point of s-process: origin of Pb isotopes: (FZK, n_ToF, Torino, ND)
s-process branchings as stellar thermometer: (FZK, n_ToF, ND)
(LANL, U. Chicago, MSU, ND)

Production of fluorine in AGB stars;
experiments: $^{19}F(p.\alpha)$, $^{19}F(\alpha,p)$, $^{19}F(n,\gamma)$ (ND, FZK, U. Stuttgart)
modeling: (LANL, Torino, Cambridge)

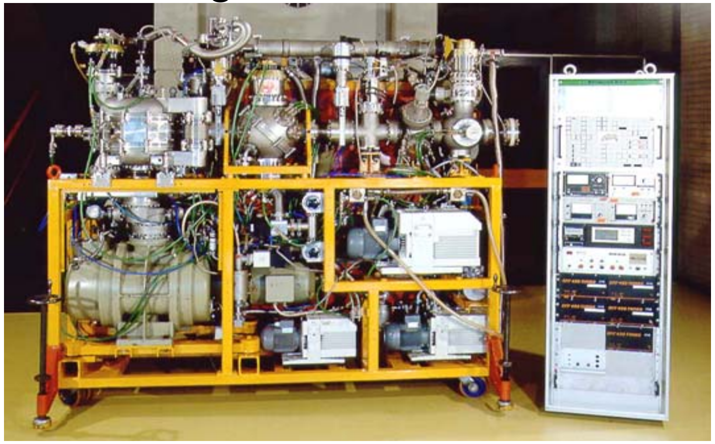
Mg, Si production in AGB stars;
experiments: $^{24}Mg(\alpha,\gamma)^{28}Si$, $^{25}Mg(n,\gamma)^{26}Mg$, $^{26}Mg(n,\gamma)^{27}Mg$ (ND, FZK)



Auxiliary instrumentation

- accelerator age is limiting factor for required heavy ion beam
- ^{14}N and ^{20}Ne tests showed considerable strains on ion source
- new accelerator funding is being argued for (ND development)

Gas Target RHINOCEROS



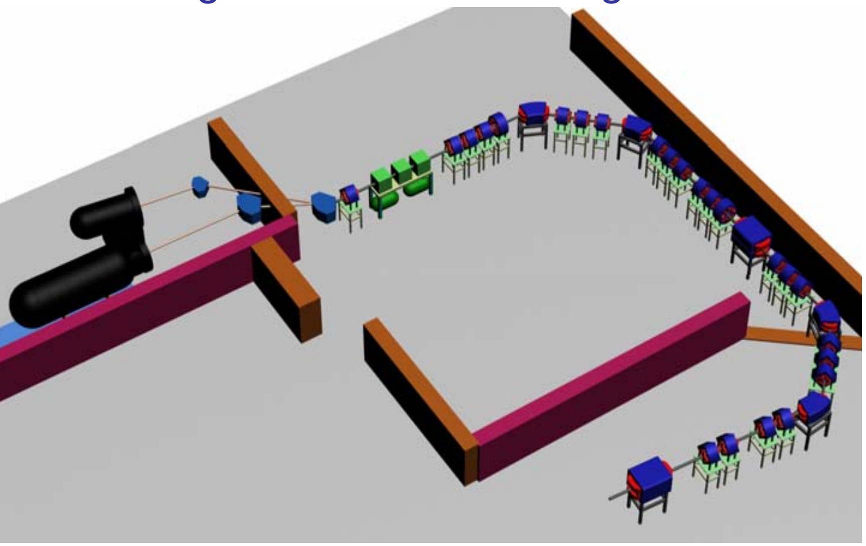
Purchased from Stuttgart 2005 has been installed spring 2006. Test have been successfully completed. The experimental program will start by July 2006.

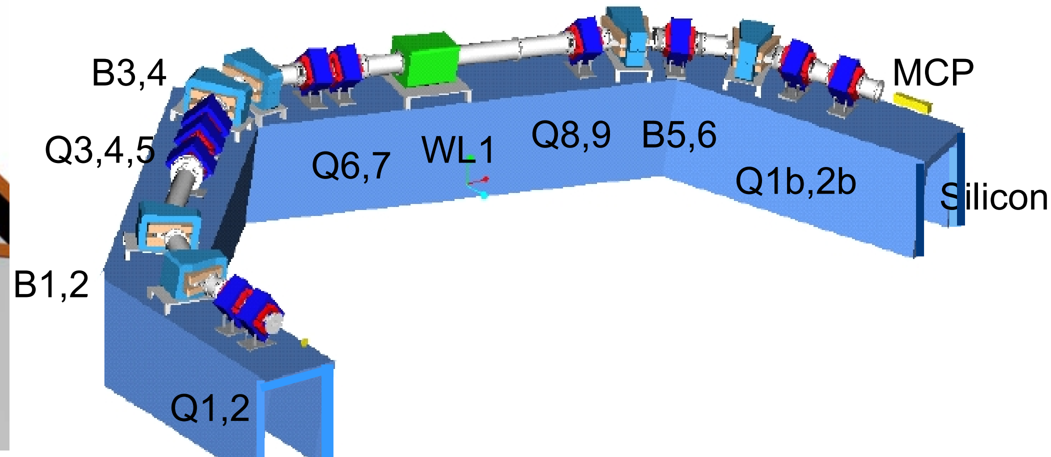
6 MV HVE Singletron

Additional development for ECR source mounted in the terminal is required. Development project between UNC and ND groups has been initiated. New developments through proposed collaboration with LBNL

Development of St. George Recoil Separator

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

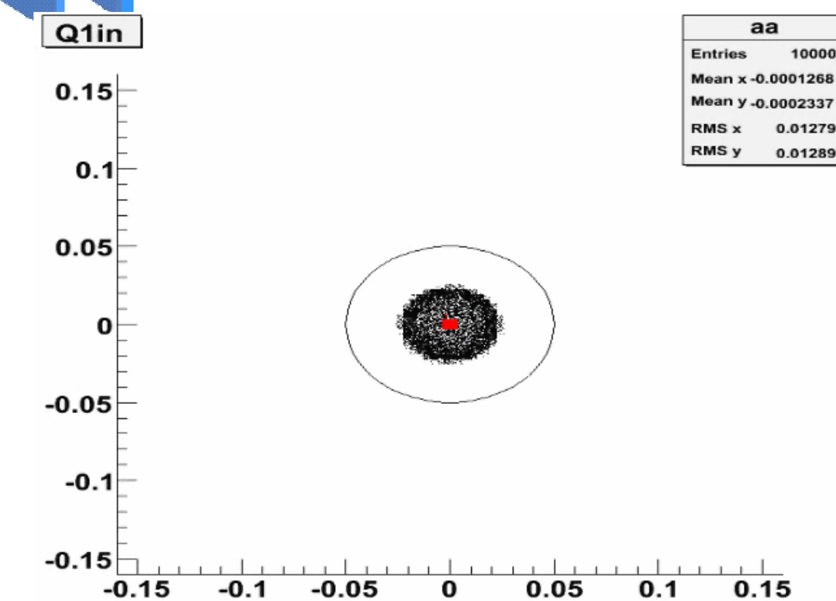




Low energy inverse kinematics experiments with intense heavy ion beams to probe stellar energy range

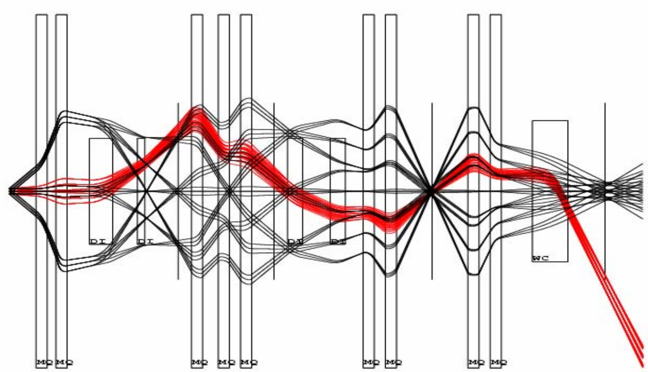
Advantage: background reduction, high efficiency event identification

G. Berg, M. Couder, J. Görres, L. Lamm, P.J. LeBlanc, E. Stech, J. Hinnefeld (IUSB)



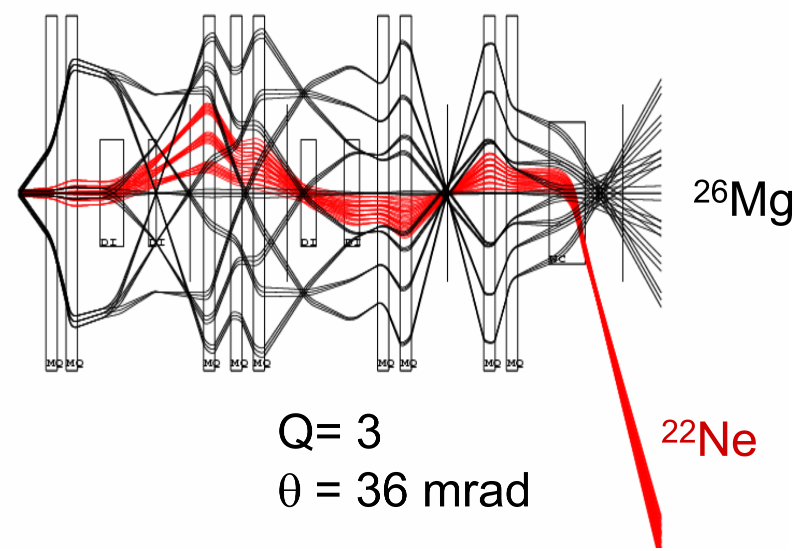
Inverse kinematics beam trajectory simulation with 2nd & higher order effects

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



Q= 4
θ = 21 mrad

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

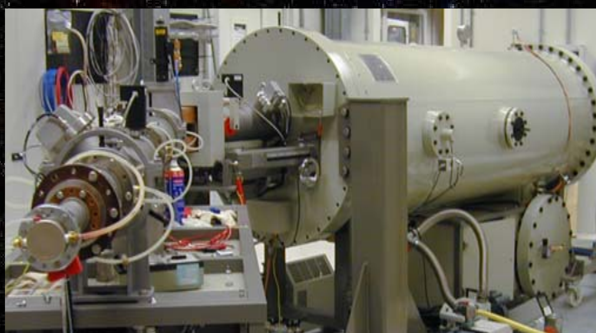


Q= 3
θ = 36 mrad

- ❑ Development work completed
- ❑ Dipole and quadrupole design specified
- ❑ First bids received (Bruker, Danfysik, SigmaPhi…
- ❑ \$-collapse, 2 step design, ~\$ 1,000,000 for 1st step

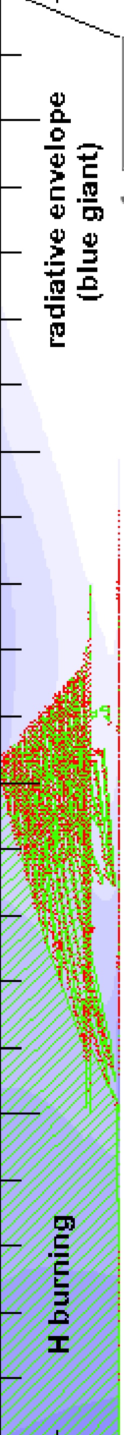
JINA – Underground?

Low energy measurements are handicapped by natural neutron background
Low reaction yield (<1event/day) and background events (~0.1event/s)
Reduction of muon induced neutron background underground by 10^{-4}-10^{-6}



Experiments are discussed for the LUNA facility in Gran Sasso Lab.
Limited to energy range <400keV

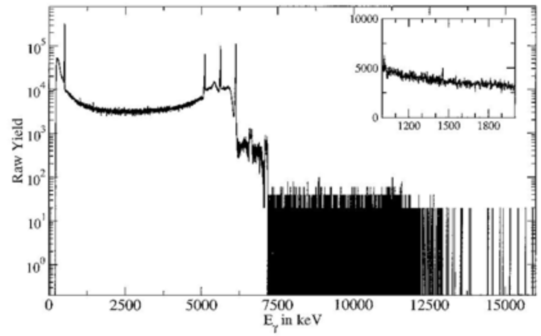
Limitations by neutrons from natural α radioactivity and beam induced neutrons!!!

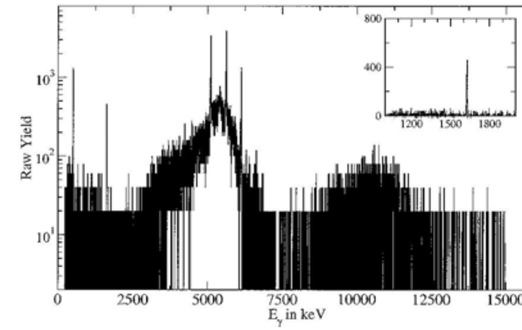


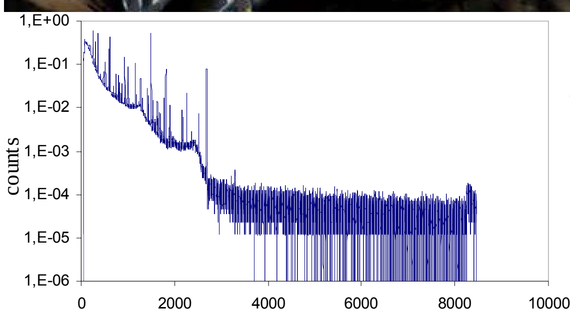
JINA-DUSEL?

Low cross sections, high background

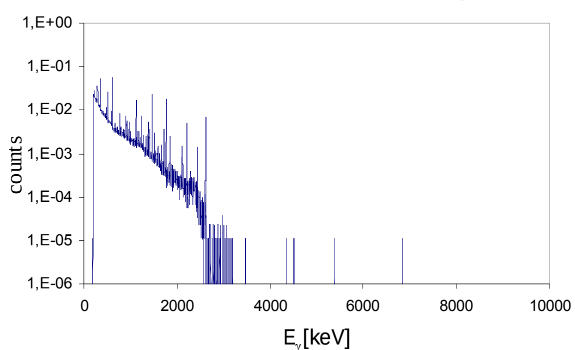
beam induced background







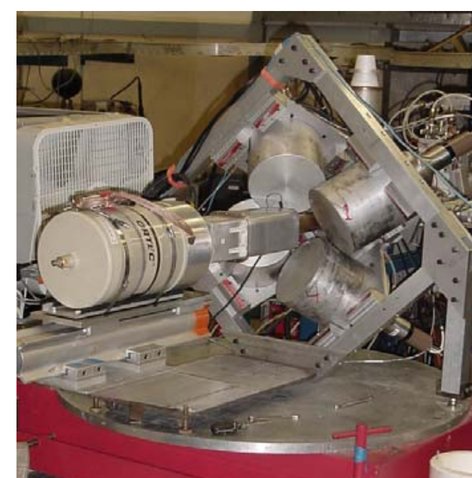
Cosmic ray background
& natural radioactivity!!!



Cosmic ray induced background ⇒ passive rock shielding
Natural radioactivity background ⇒ active shielding
Beam induced background ⇒ active shielding by event identification

$10^{-4} – 10^{-6}$ rejection !

Long range goal is: inverse kinematics & recoil separator with 10^{-20} rejection.



JINA conferences on MRC-1 related topics

The First Stars and Evolution of the Early Universe

INT, Seattle, USA, June 19 - July 21, 2006

Observers watch experimenters!!!

The Workshop on "The Final Days of Stellar Burning"

Santa Barbara, USA, March 9 - 10, 2006

The School on Astrophysical Reaction Networks

University of Notre Dame, IN, USA, June 20 - July 1, 2005

The Physics of the s-Process

Center for Physics, Aspen, Colorado, USA, May 29 - June 12, 2005

R-Matrix School at Notre Dame

University of Notre Dame, USA, October 4-15, 2004

The 7th Torino Workshop on Nucleosynthesis in AGB Stars

University of Cambridge, UK, August 2-6, 2004

Workshop on an underground accelerator for nuclear astrophysics

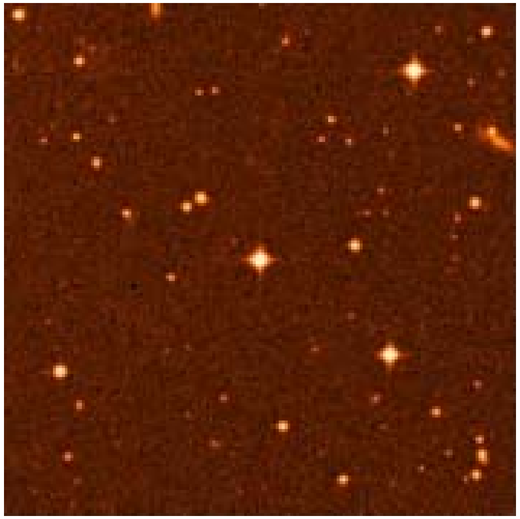
Tucson, AZ, USA, Oct. 27-28, 2003

Long range goals and opportunities

The First Stars and Evolution of the Early Universe
June 19 to July 21, 2006

Discussion of aspects of nucleosynthesis in first generation stars!

Organizers: Tom Abel, Timothy Beers, Alex Heger, Yong Qian



Observation spectroscopy of early stars indicates new signatures for nucleosynthesis in first star generations, new opportunities for JINA experimenters and modelers!