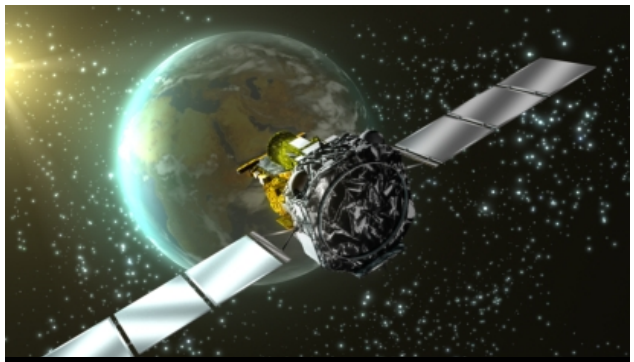
KEY REACTIONS & ROLES

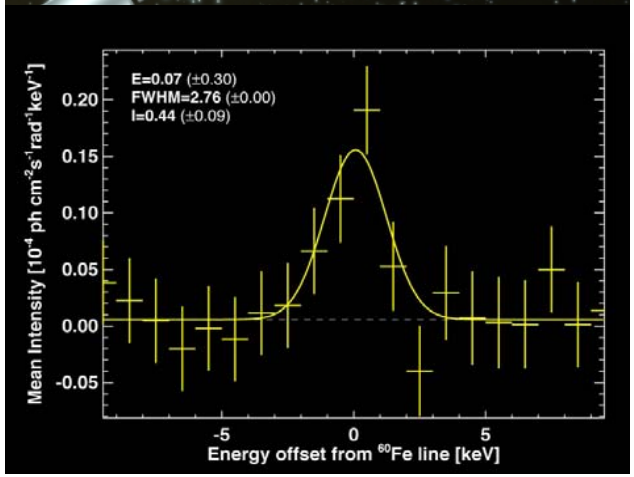
H BURNING — pp CHAIN / CNO CYCLE

He BURNING — $3\alpha \rightarrow {}^{12}C$; ${}^{12}C(\alpha,\gamma){}^{16}O$

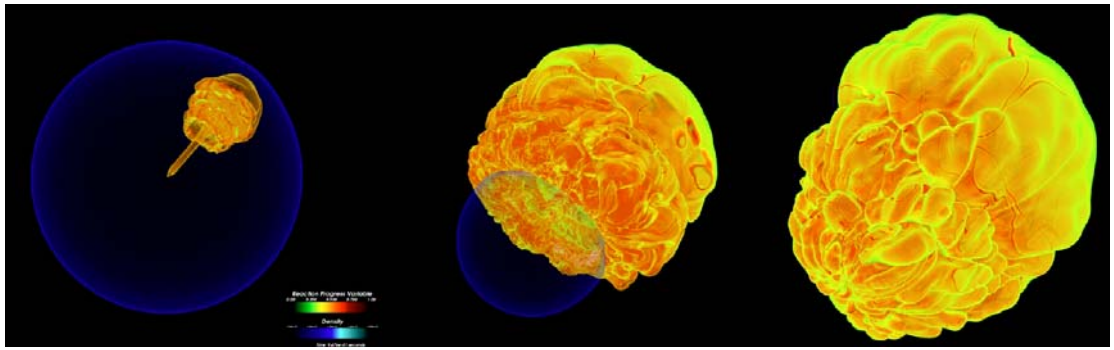
Carbon BURNING — ${}^{12}C + {}^{12}C \rightarrow \alpha + {}^{20}Ne$; $p + {}^{23}Na$

^{60}Fe Production in supernovae

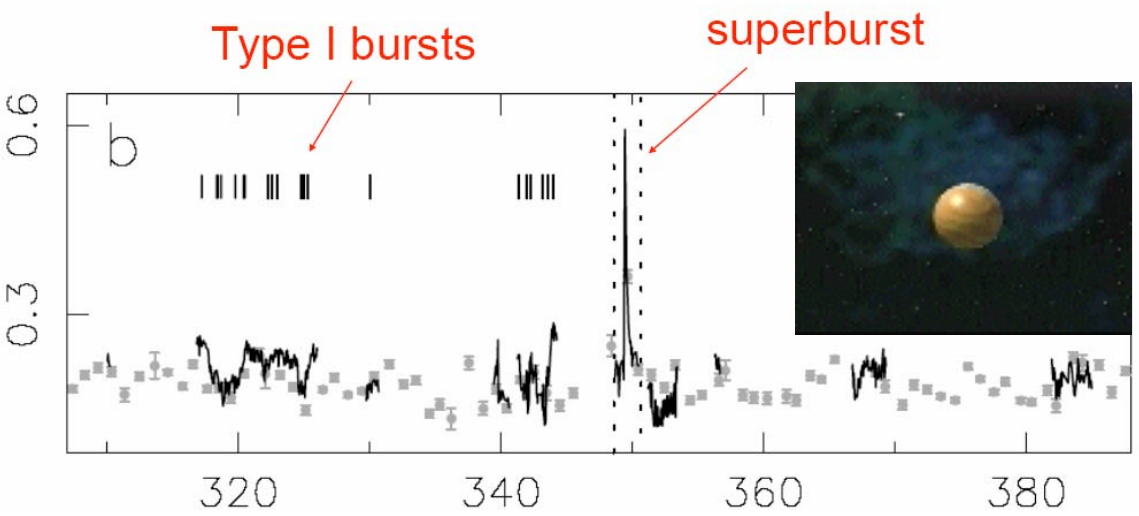




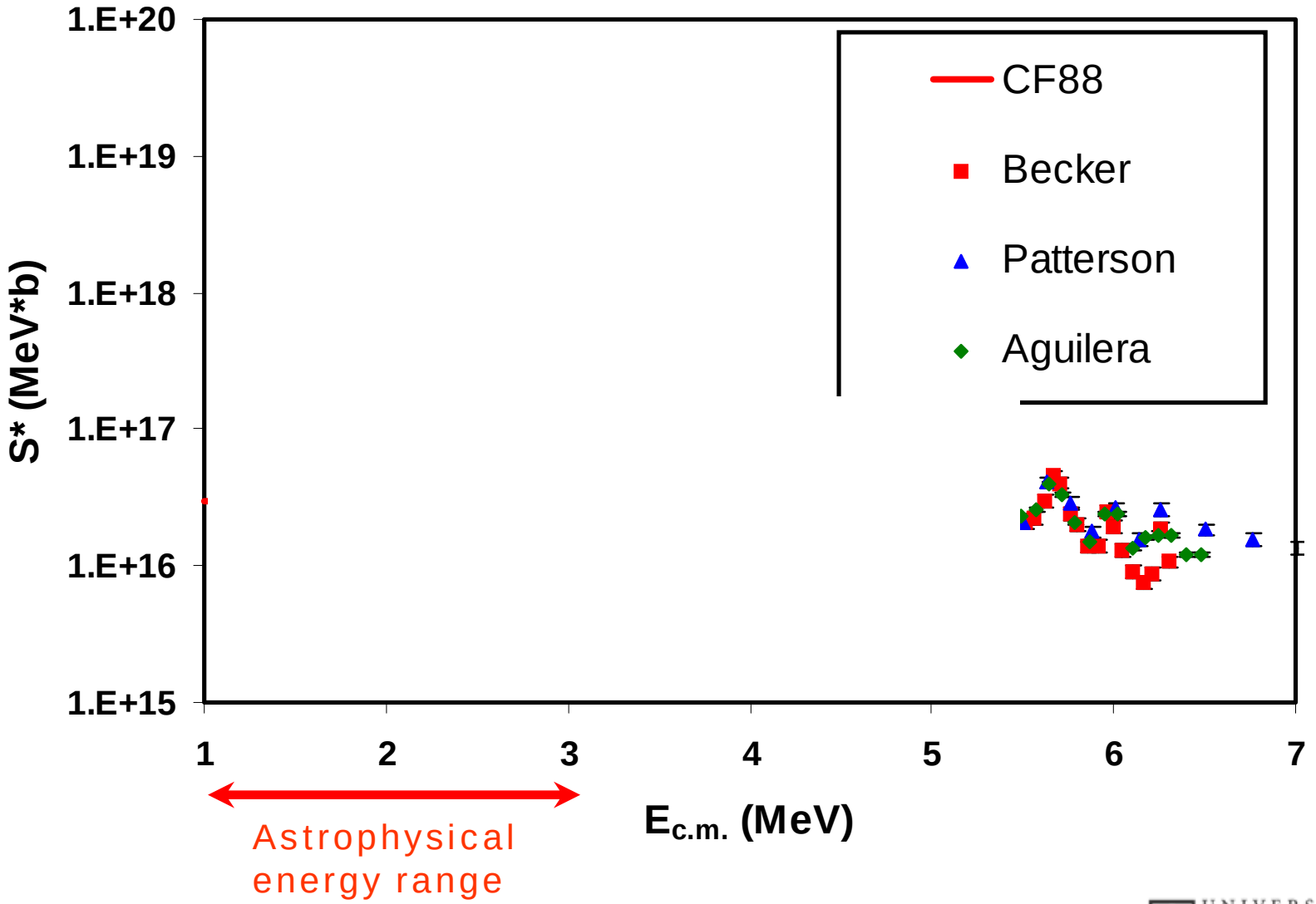
Ignition conditions in type Ia supernovae



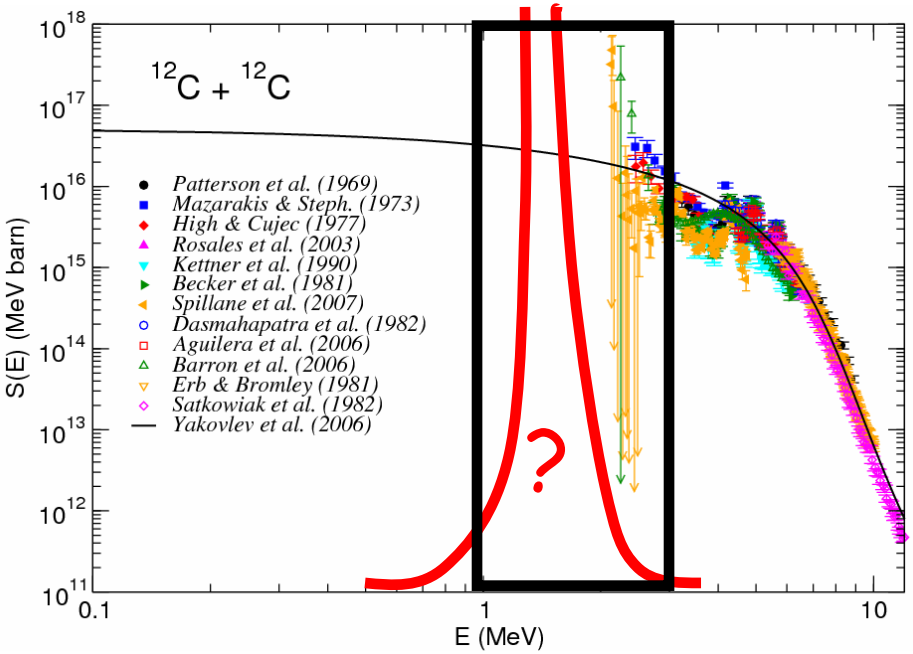
Candidate for Superburst ignition

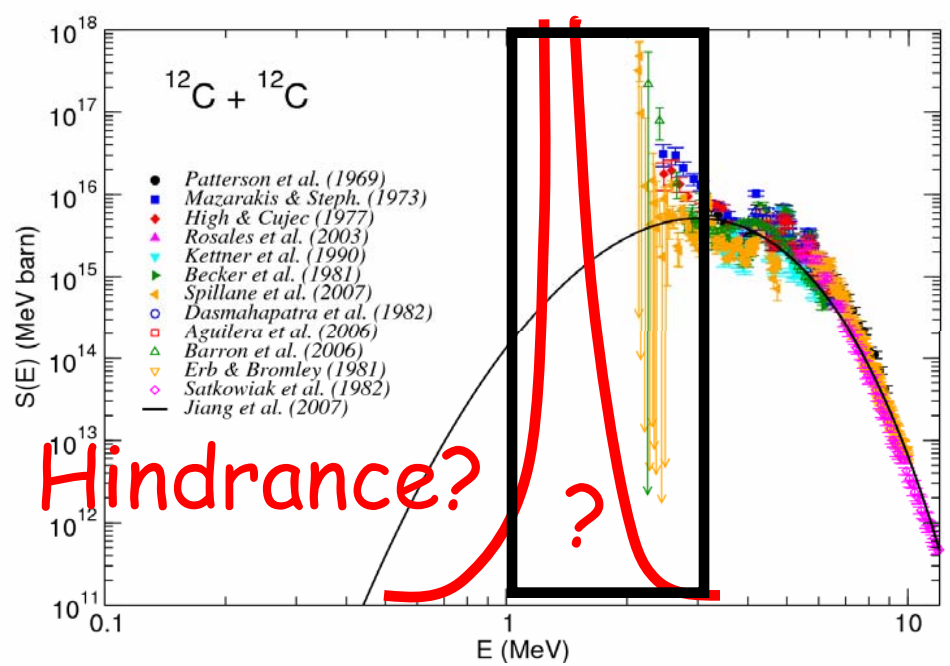


$$S^*(E) = \sigma E e^{(87.21/\sqrt{E} + 0.46E)}$$



Carbon burning in the labs

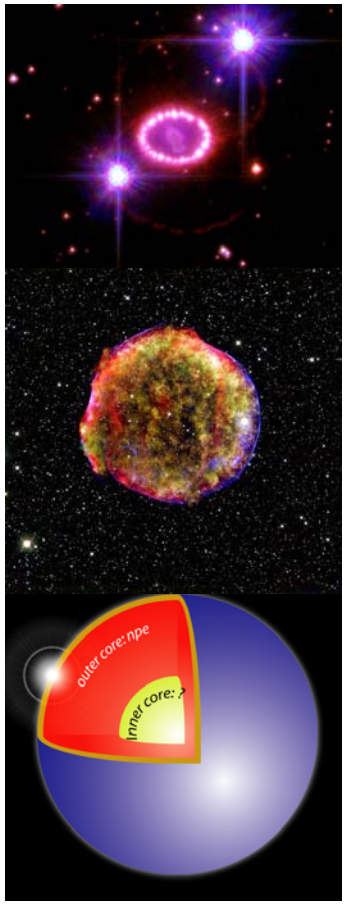




Gasques et al. PRC 72 (2005) 025806
Jiang et al. PRC 75 (2007) 015803

Challenge for **L**aboratory nuclear-**A**strophysics in **U**nderground and **S**urface **2009**: CLAUS2009

Carbon burning in the universe

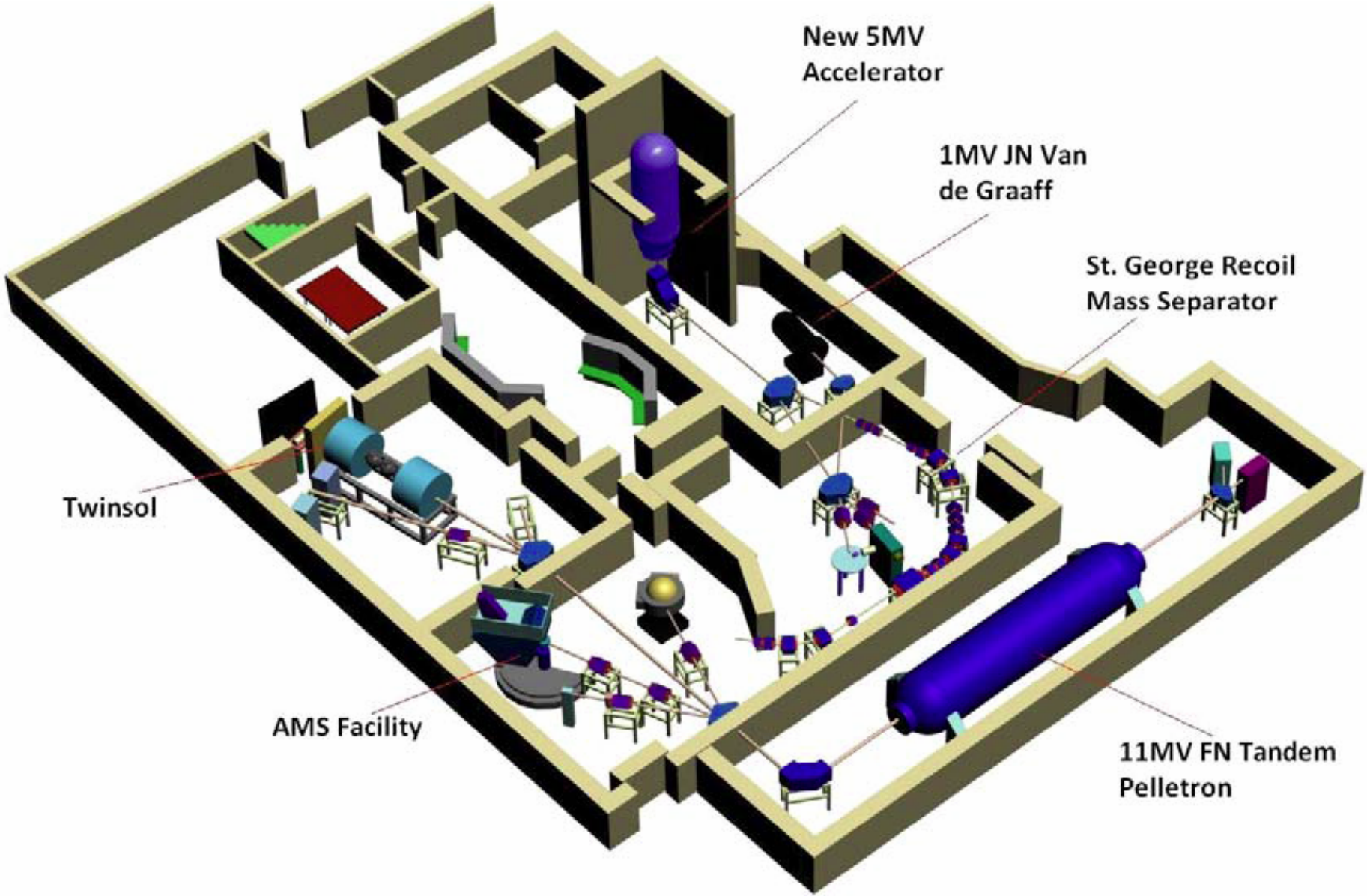


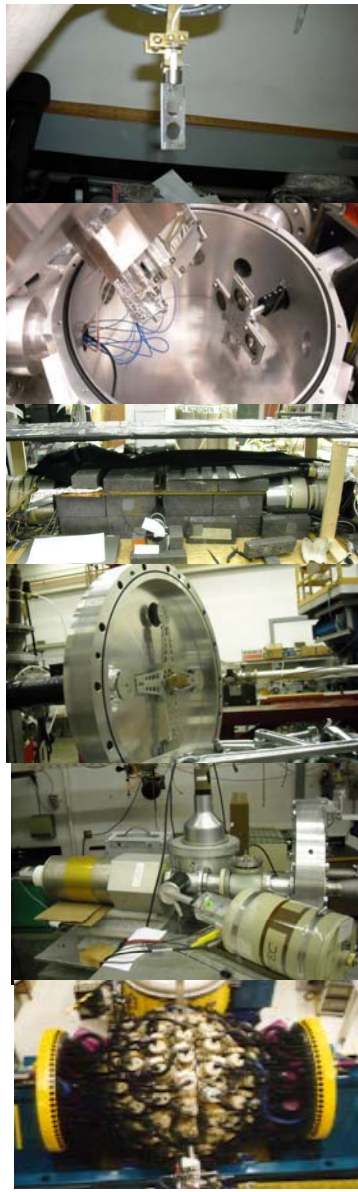
The extrapolation to low energy is uncertain ... and more experimental and theoretical studies are urgently needed.

Fowler, Nobel Lecture (1983)

burning phase. The fusion of three alpha particles to ^{12}C followed by the $^{12}C(\alpha,\gamma)$ reaction characterizes the red giant phase of stars and sets the stage for subsequent burning phases, such as carbon burning through $^{12}C + ^{12}C$ fusion and oxygen burning characterized by $^{16}O + ^{16}O$ fusion. These key reactions of late stellar burning are the main energy sources of the star and determine the duration of the respective burning phases. The extremely small cross sections of the stellar reaction rates result in the long lifetimes of stars but represent the main challenge to a direct experimental study of these reactions. While great progress has been made in

Nuclear Science Advisory Committee Long Range Plan 2007


New 5MV
Accelerator
1MV JN Van
de Graaff
St. George Recoil
Mass Separator
Twinsol
AMS Facility
11MV FN Tandem
Pelletron



$^{12}C+^{12}C$

$^{12}C+^{13}C$
$^{13}C+^{13}C$

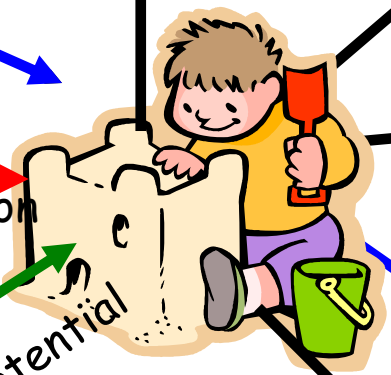
Provide potential to model the smooth behavior

Direct measurement

The exact cross section

$^{24}Mg(a,a')$ inelastic

Locate the potential resonances



$^{12}C(^{12}C,a)^{20}Ne$

$^{12}C(^{12}C,p)^{23}Na$

$^{12}C(^{12}C,n)^{23}Mg$

$^{12}C(^{12}C,^{8}Be)^{16}O$

Projects

- Empirical correlation between $^{12}C+^{12}C$, $^{12}C+^{13}C$ and $^{13}C+^{13}C$ fusion cross sections (2007-2011)
- Neutron branching in $^{12}C+^{12}C$ fusion (2009-)
- New technique to search the $^{12}C+^{12}C$ resonances (Sept. 2011)
- New development at ND (2011-)
- Complimentary approach: $^{24}Mg(\alpha,\alpha')$ at RCNP (Nov. 2011)

The $^{12}C+^{13}C$ experiment

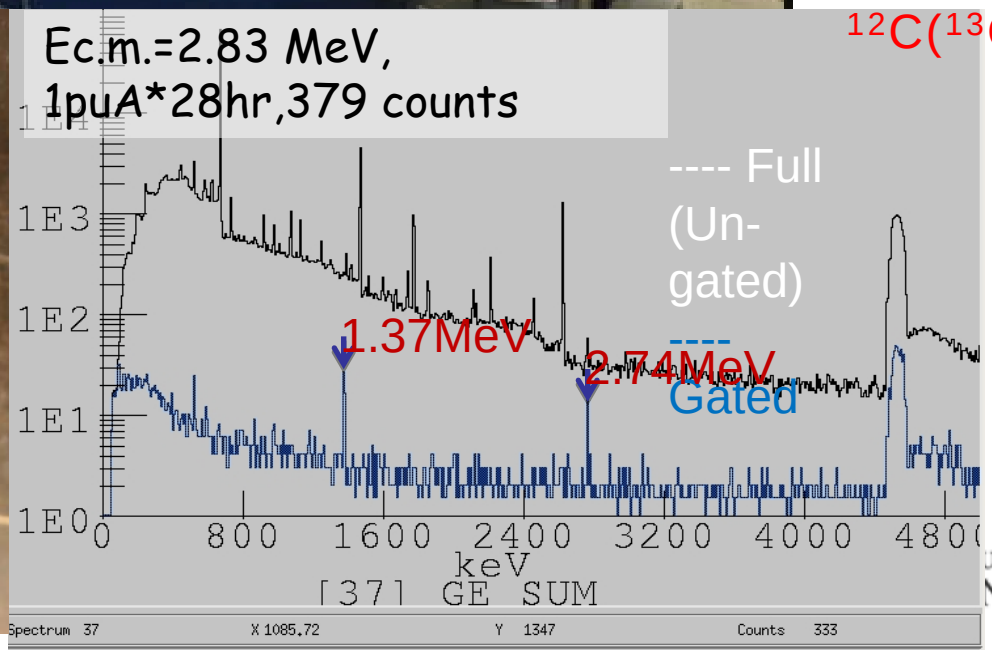
Carbon stripping (100 enA)
Gas stripping

20 eμA $^{13}C^{-}$

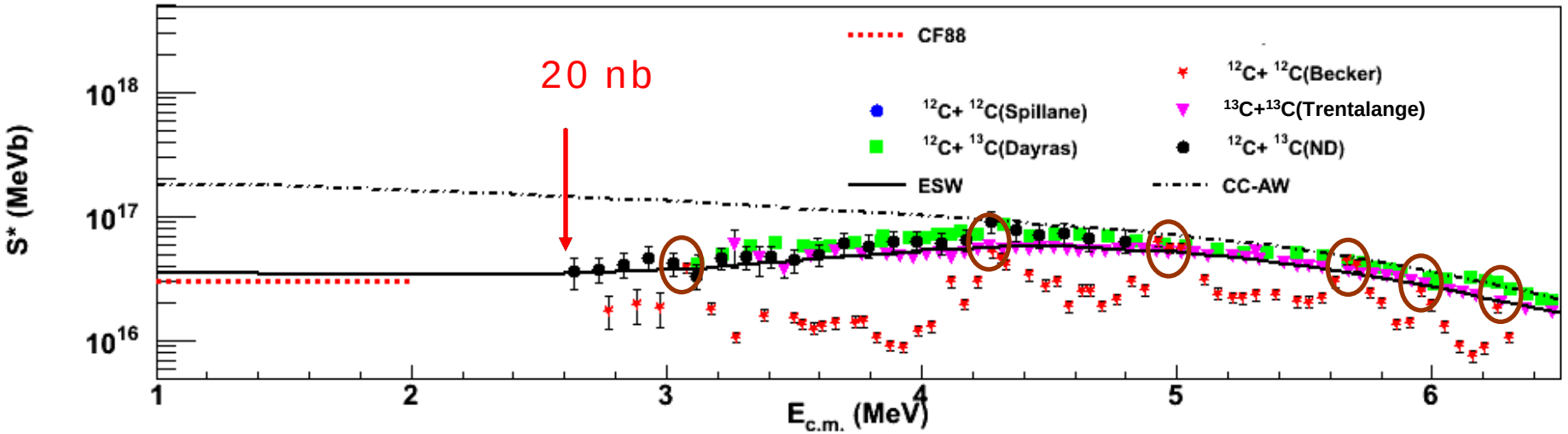
2 eμA $^{13}C^{2+}$

graphite disk

$^{12}C(^{13}C,^{24}Na)p$

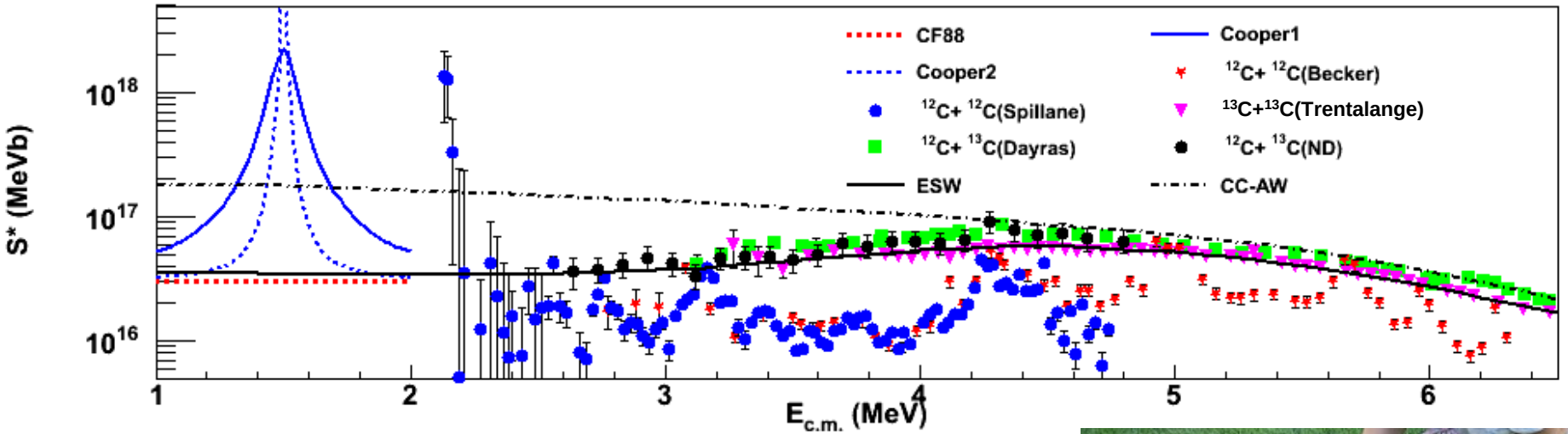


Extrapolation with the $^{12}C+^{12}C$ resonant cross sections



- **Fit resonant cross sections with ESW (Best upper limit)**
- **CC-AW calculation (always over-predict xsecs at low Es, Safe upper limit)**
- The **first quantitative description** of the $^{12}C+^{12}C$ resonant cross sections!

Systematics vs. Spillane's Experiment

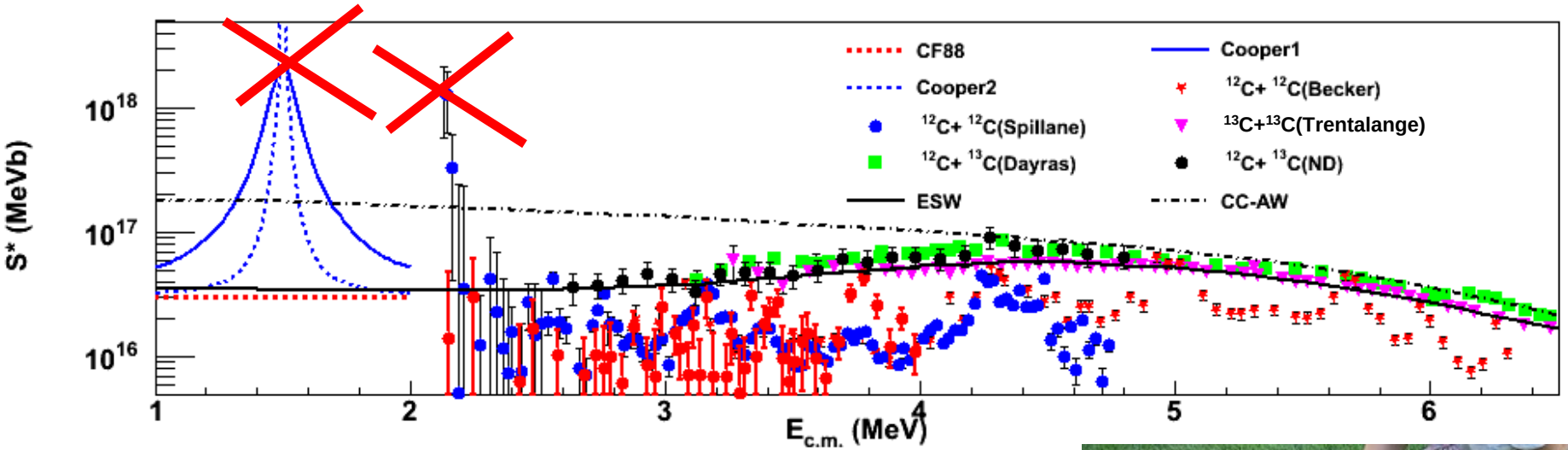


- Our theory claims: $^{12}C+^{13}C$ (or $^{13}C+^{13}C$)> $^{12}C+^{12}C$

- The strong resonance at 2.14 MeV:
the failure of our empirical relationship ?

- No confirmation of the 2.14 MeV yet:
it may be a mistake in …..?

Systematics wins!

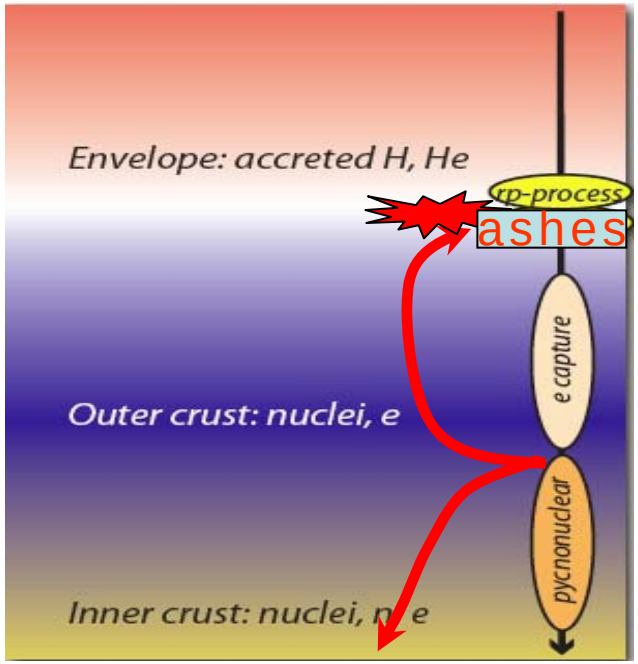


- The **preliminary** data from the recent experiment at Naples* **SUPPORT** our finding!
- No evidence for strange strong resonance!
- For the Ecm=1.5 MeV resonance:

Safe upper limit: 6 x Fowler rate

Best estimated upper limit: ~ Fowler rate

* Dr. Zickefoose, U. Connecticut thesis, 2011



If the rate can not be that high, there must be some physics missing in the superburst model.

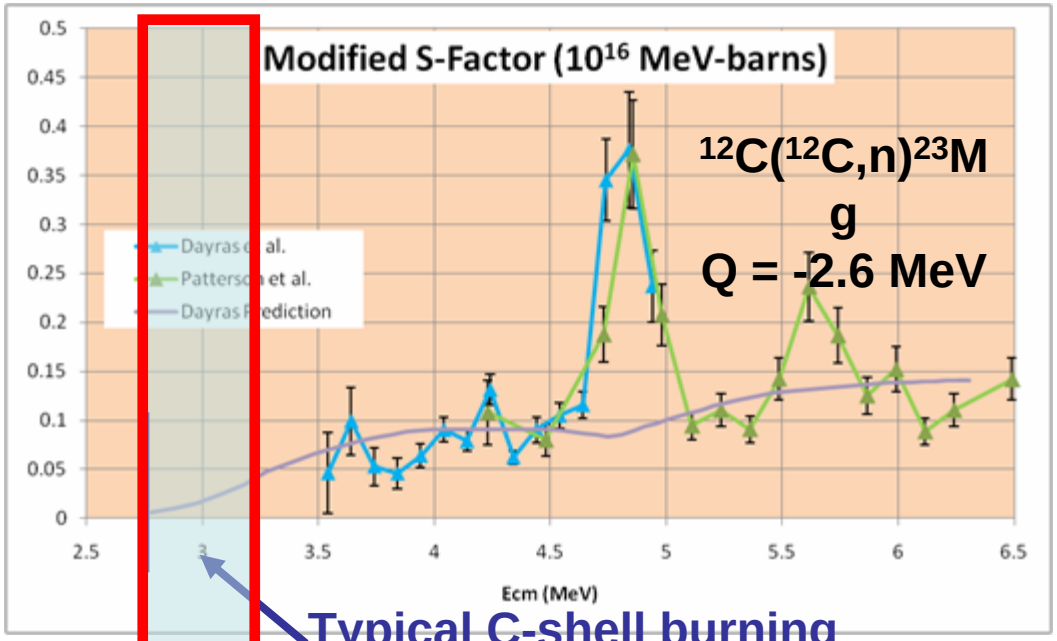
- Unknown process to heat up the crust to higher temperature.
- Carbon burning is not the one triggering superbursts!

To be submitted to PRC

Uncertainty in the $^{12}C(^{12}C,n)^{23}Mg$ reaction rate

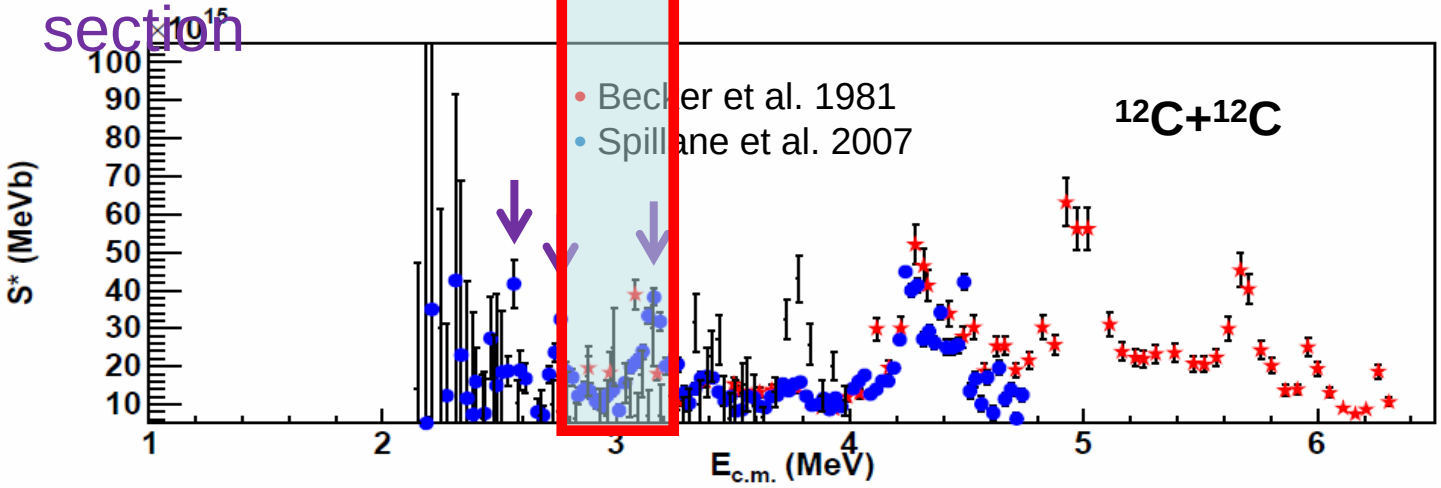
Potential neutron source for weak s-process;

Any resonances within the important energy range:
2.6 MeV<Ecm<3.2 MeV?

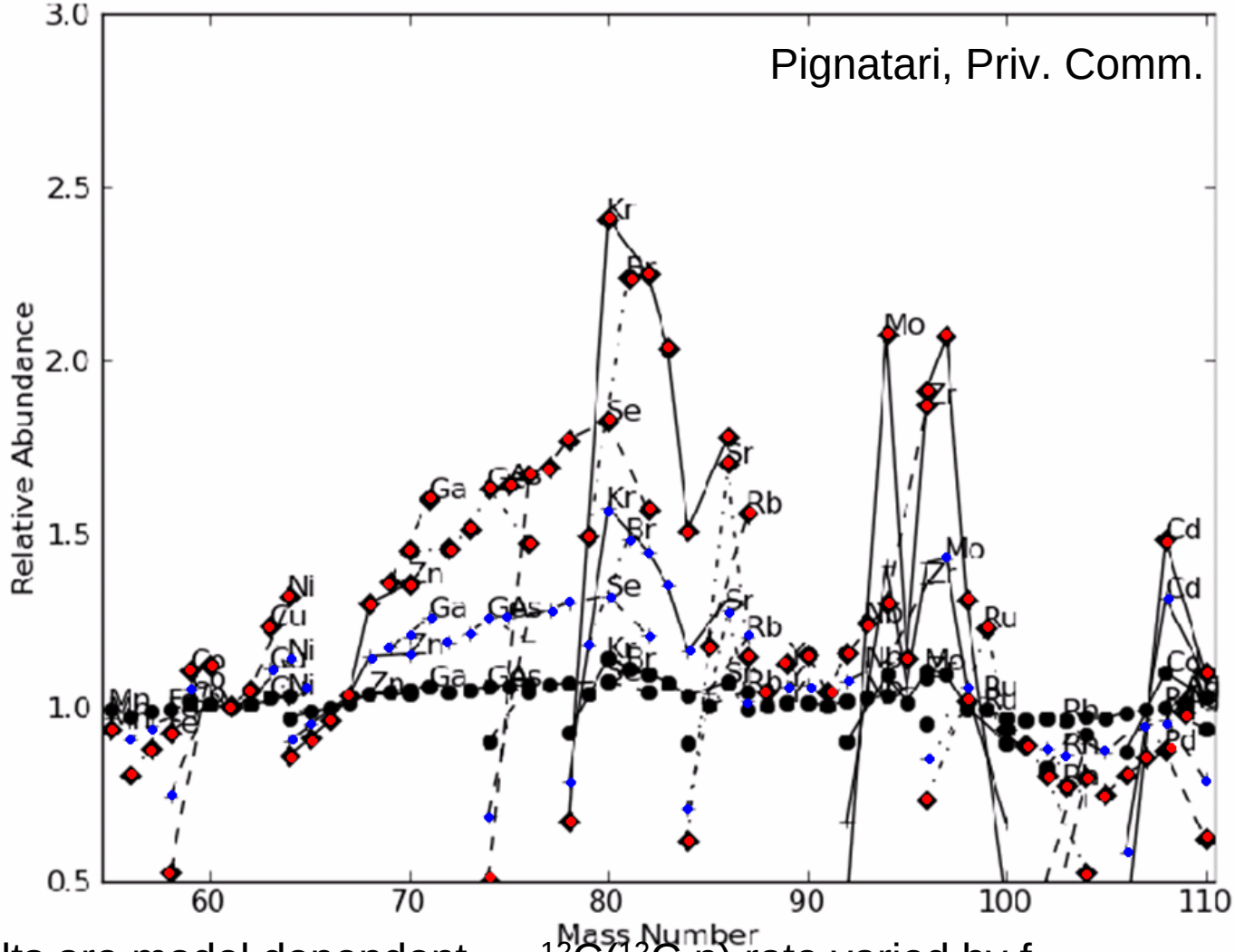


Typical C-shell burning

Low E resonances measured in total fusion x-section

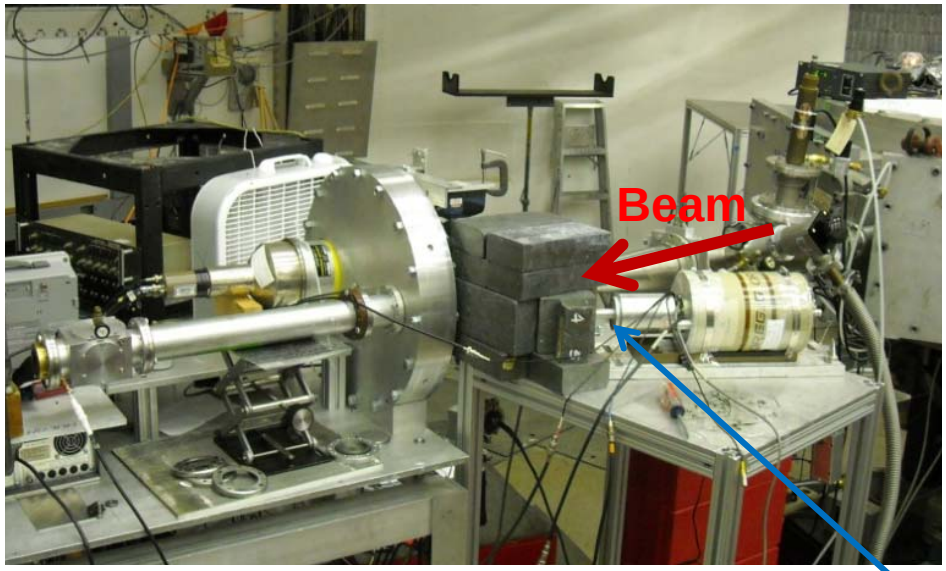


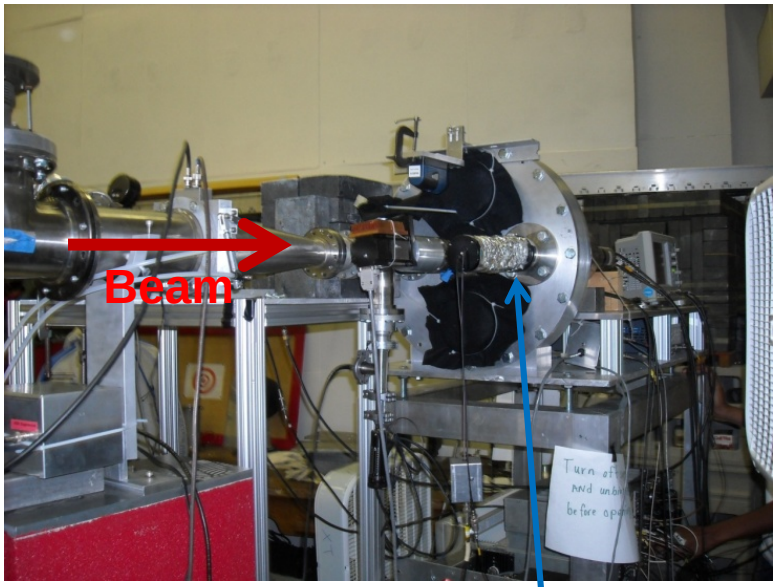
Effect on Abundances

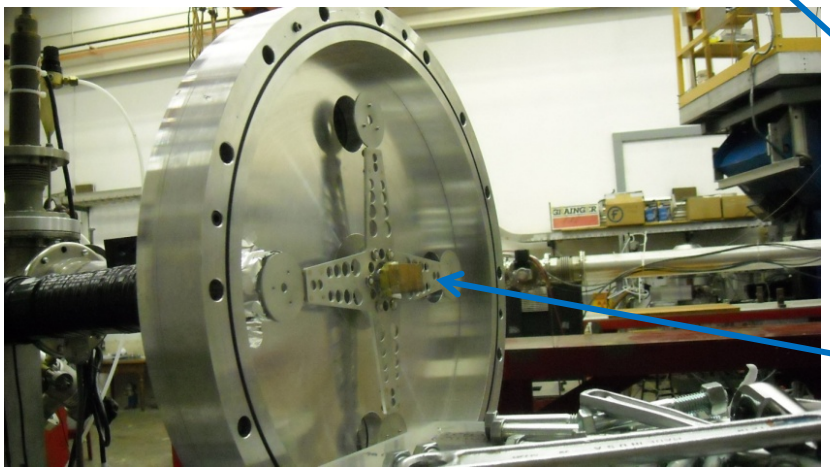


Results are model dependent-----$^{12}C(^{12}C,n)$ rate varied by factors 2, 5, 10

Experiment







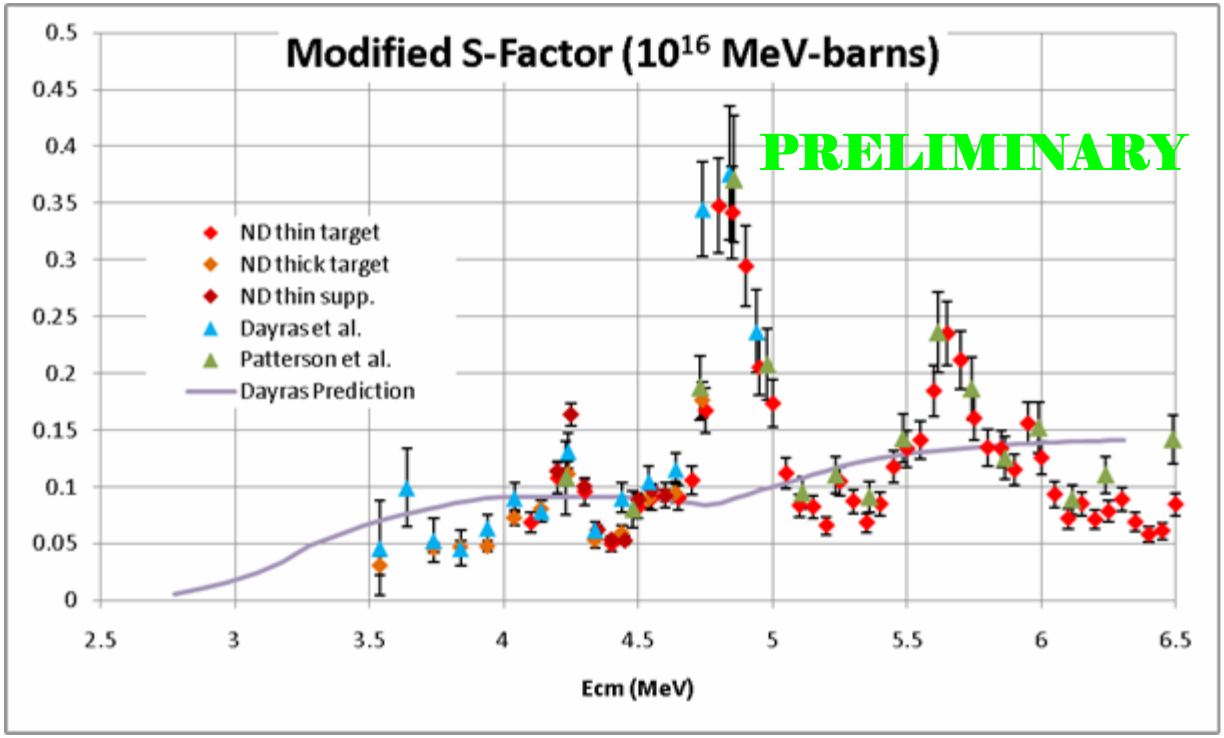
Ge Detector

β Counter

Catcher Wheel

Results

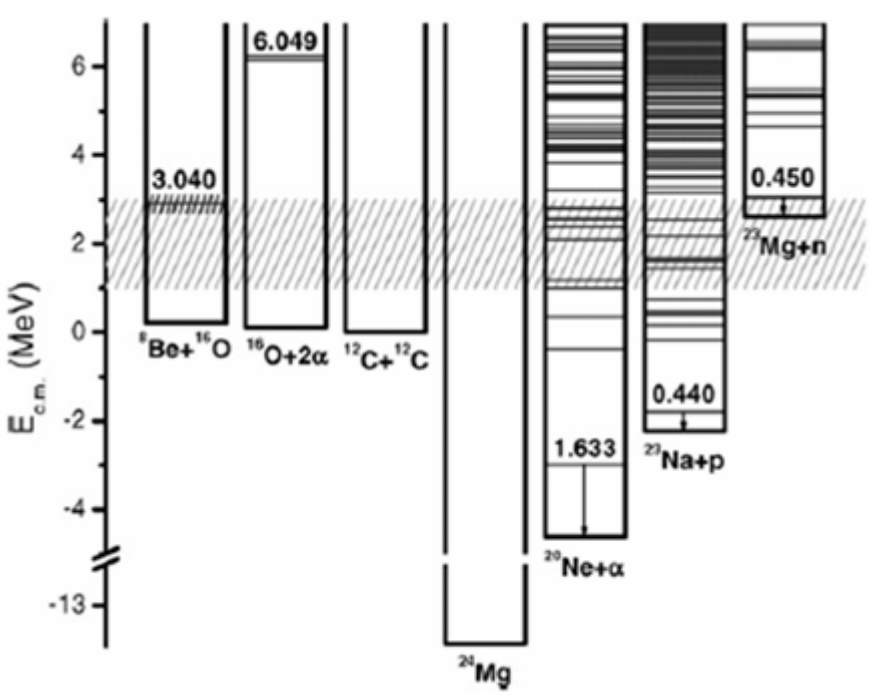
- Largest range and finest step size ever measured
- Used thin and thick targets with consistent results

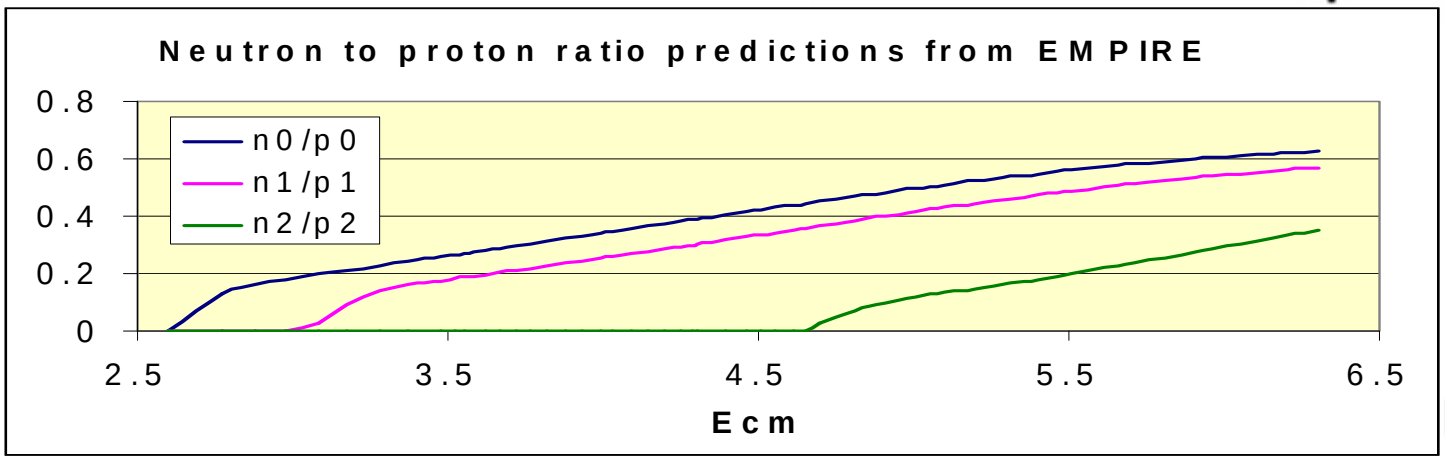


Low E measurments hindered by low yield, high background….
(H contamination, cosmic rays, ^{13}C)

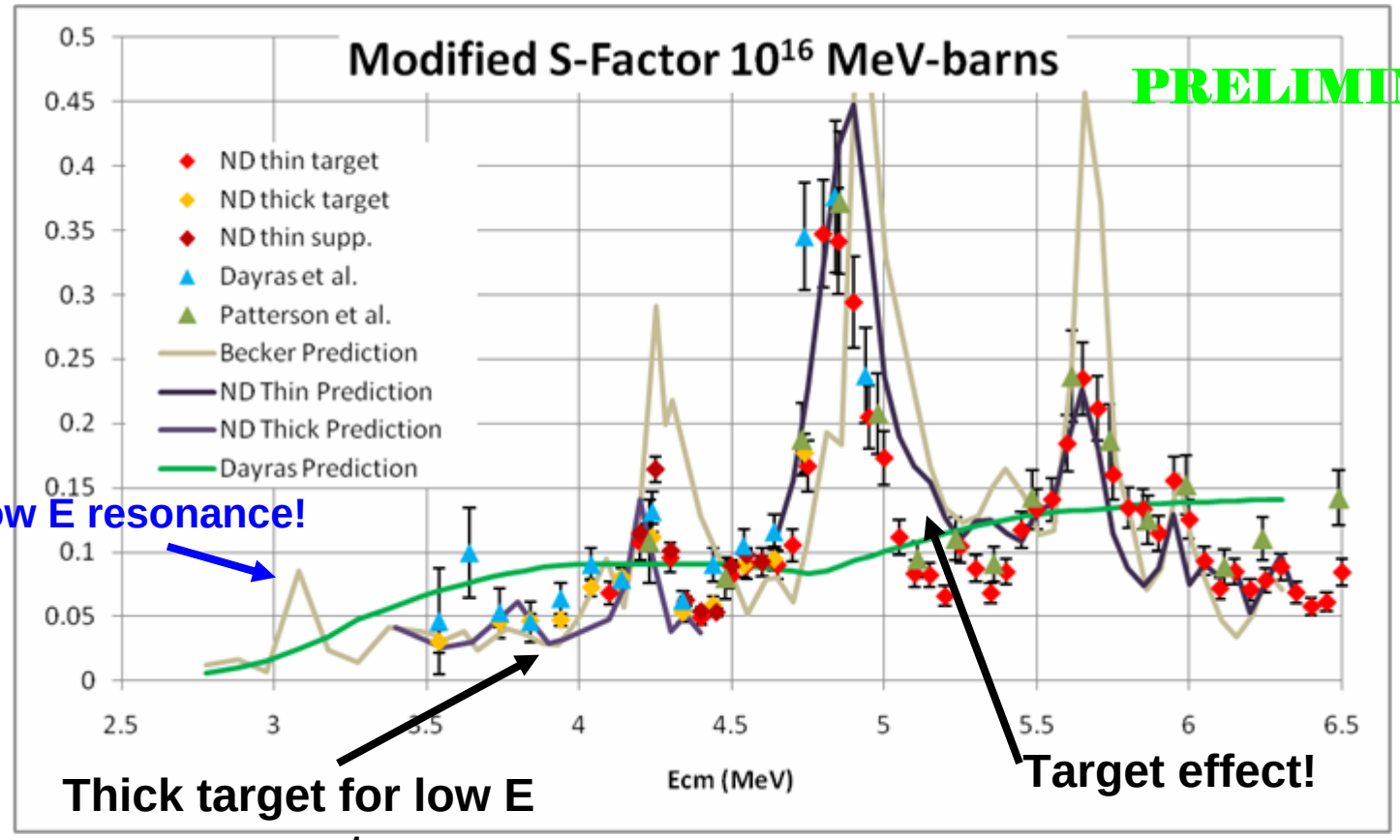
Mirror Symmetry: A New Way to Extrapolate

- Extrapolation based on mirror system $^{12}C(^{12}C,p)$
  - Lower energy measurements (Q=+2.2MeV)
  - Structure effects should be same for both
- Use statistical model to calculate ratio $\sigma(n_i)/\sigma(p_i)$



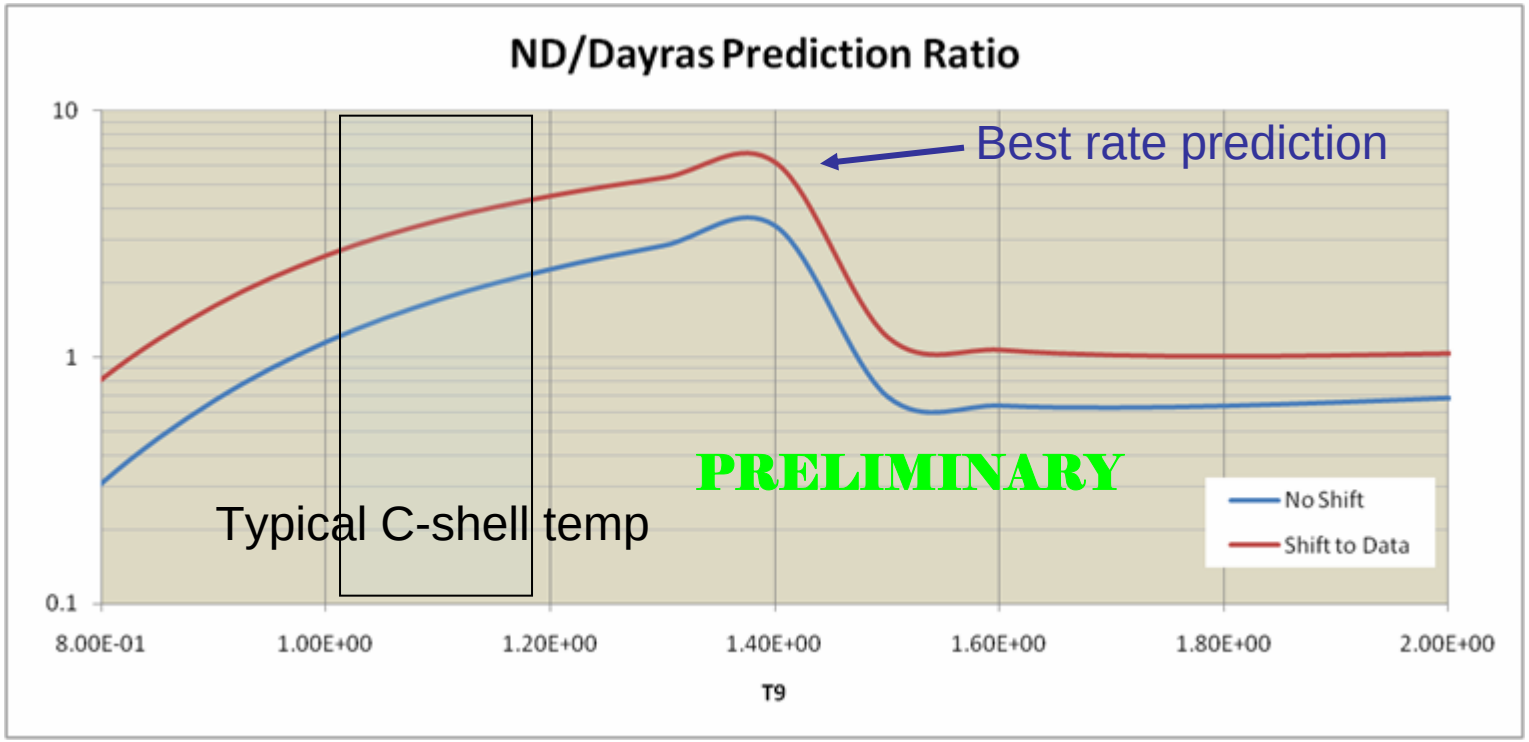


New Extrapolation



- Number of resonances reproduced, but strength & position needs improvement
- Preliminary ND results indicate better agreement

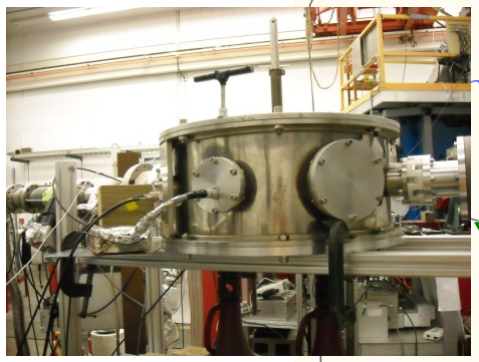
New Reaction Rate

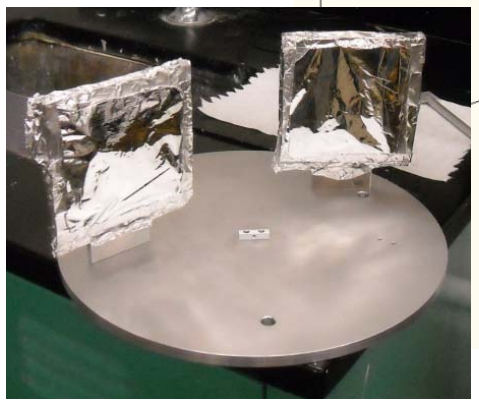


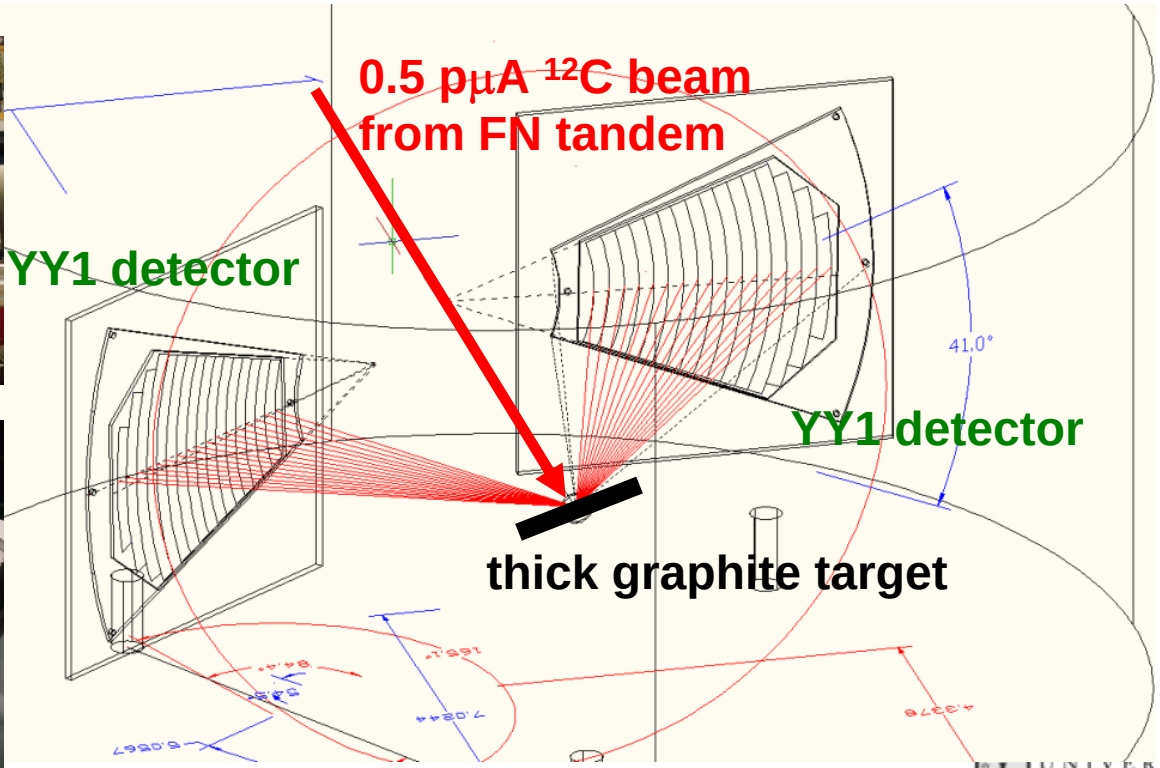
- Renormalize and align Becker prediction with experimental data
- Rate sensitive to low energy resonance
  - Position and strength need to be precisely determined
- Factor 5 increase in rate at shell carbon burning temperatures
- Will finish in 2012.

Thick target method to map the $^{12}C+^{12}C$ resonances

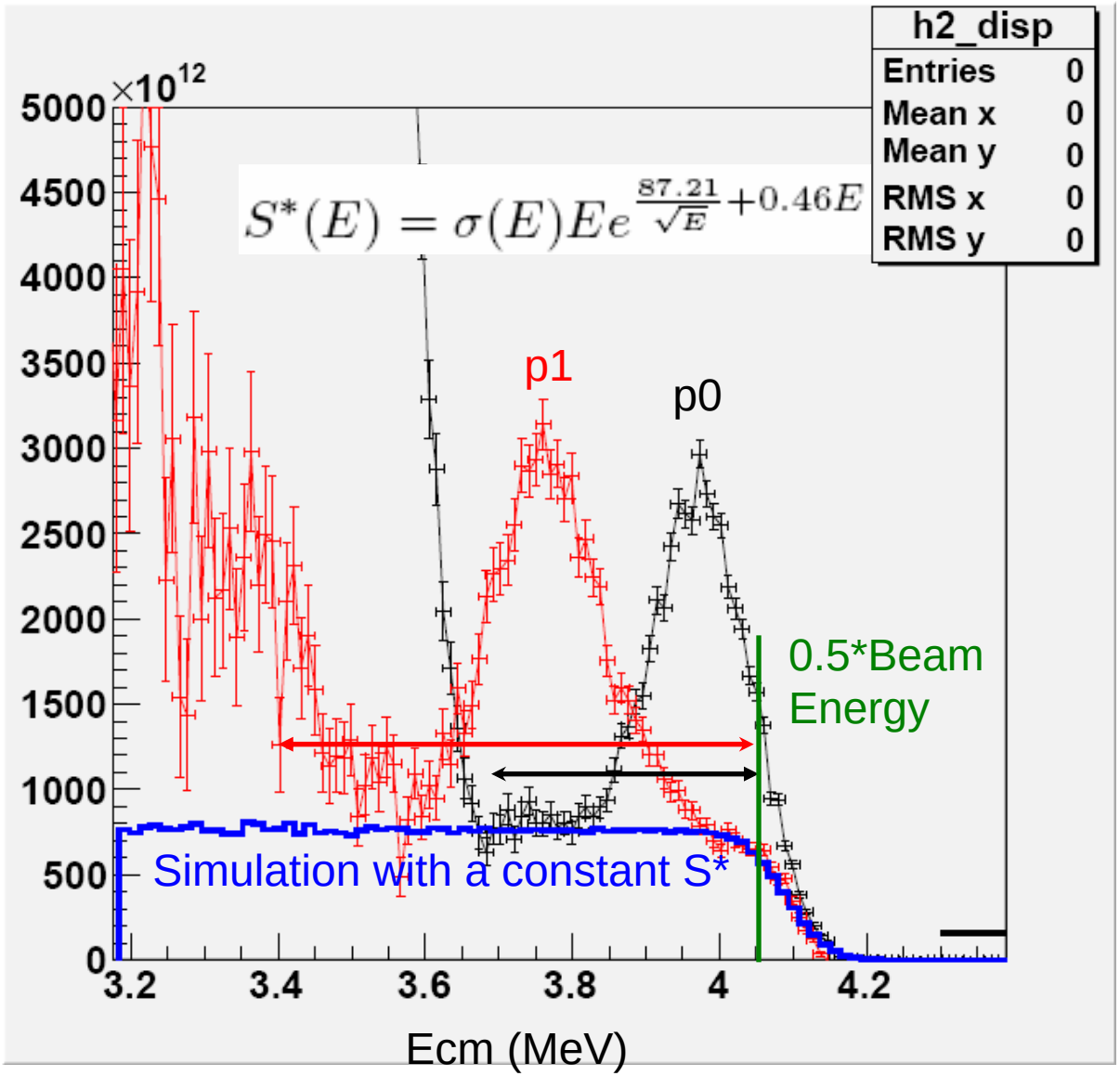
- Two YY1 detectors at backward angle, covered with Al foil to stop everything but protons
- Use a 1mm thick target



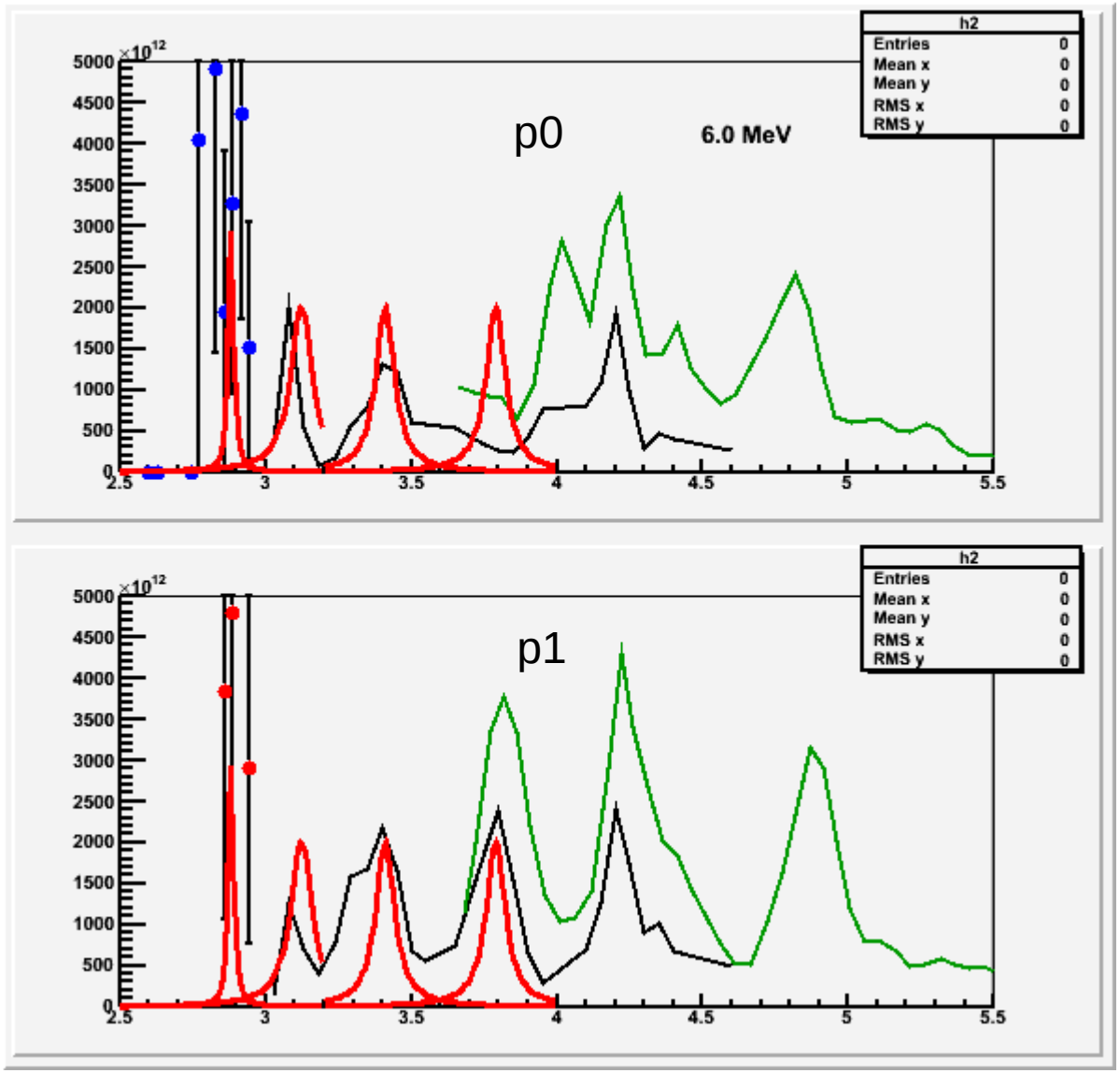




S* factor extracted from E_{beam}=8.2 MeV



Scan resonance in a wide range of 3 MeV<Ecm<5.3 MeV

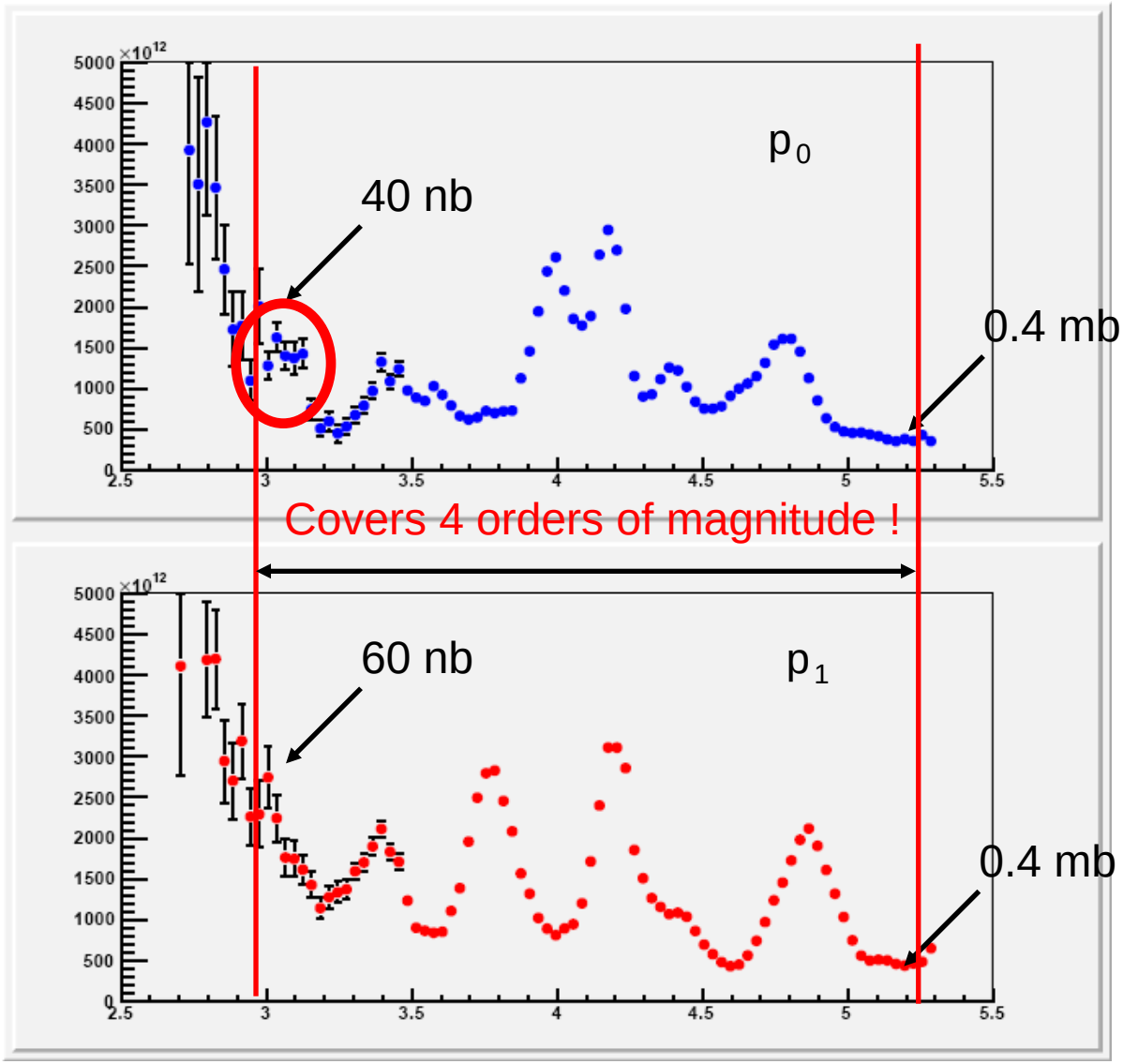


Thin target

Differential thick target

Resonance reported by Zickfoose (the magnitudes are arbitrary)

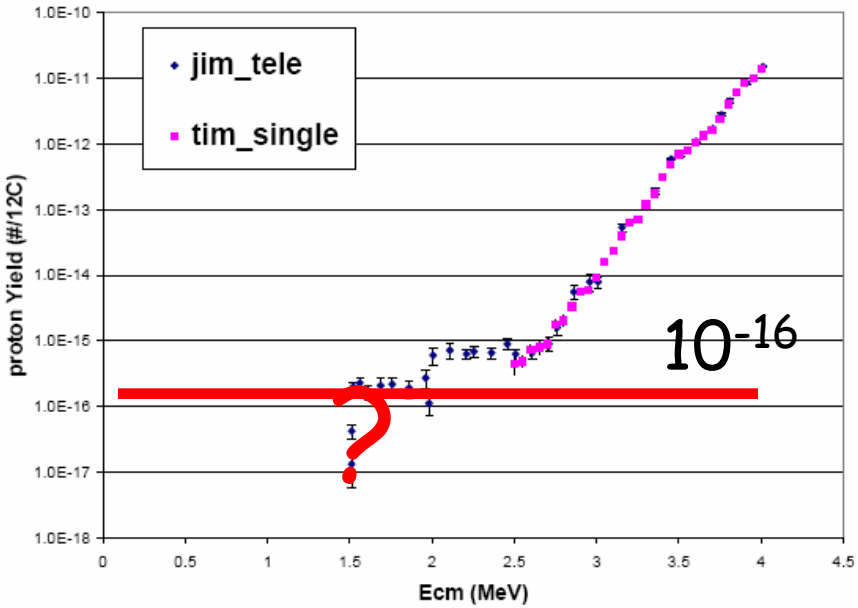
Combined S* factors from a series of thick target measurements



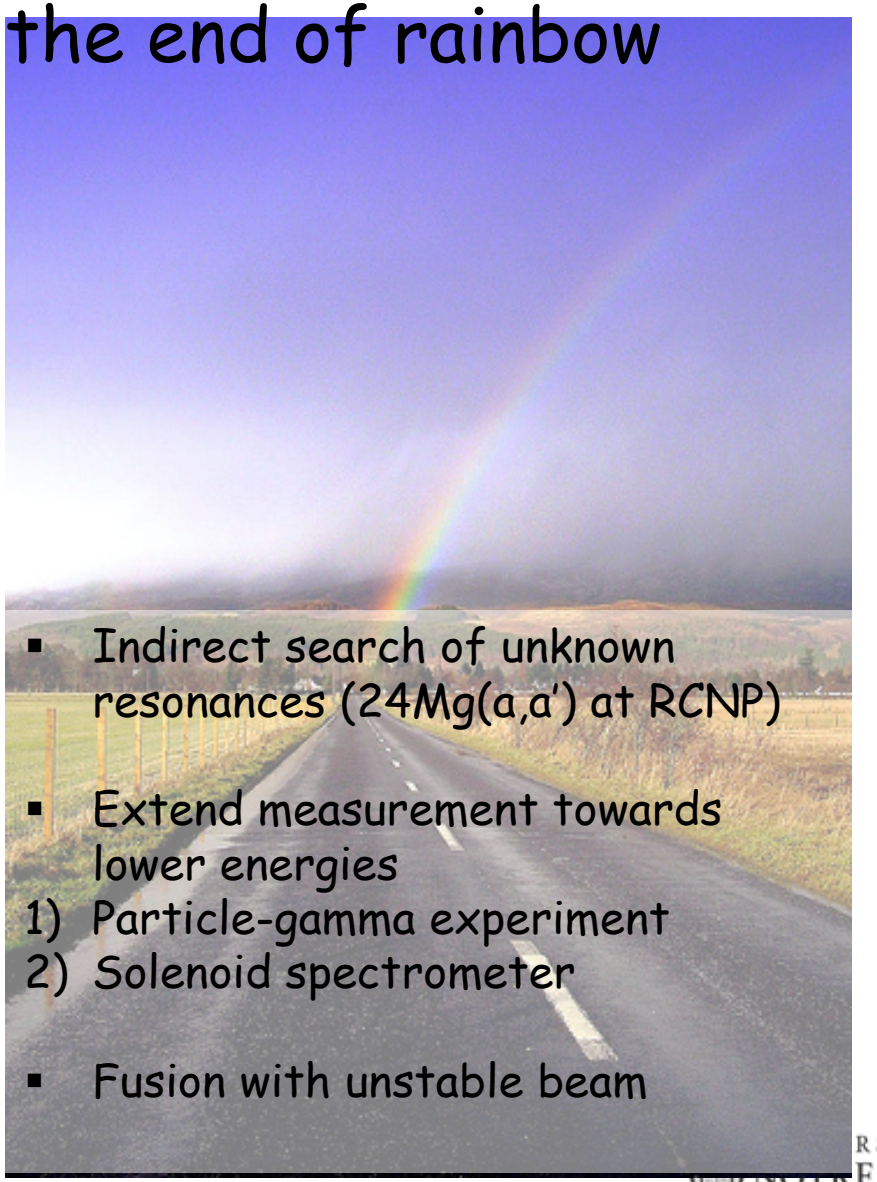
To be submitted to NIM

Future experiments

Find treasure at the end of rainbow



Earlier preliminary result from U. Conn+Naples+Bochum, May 2009



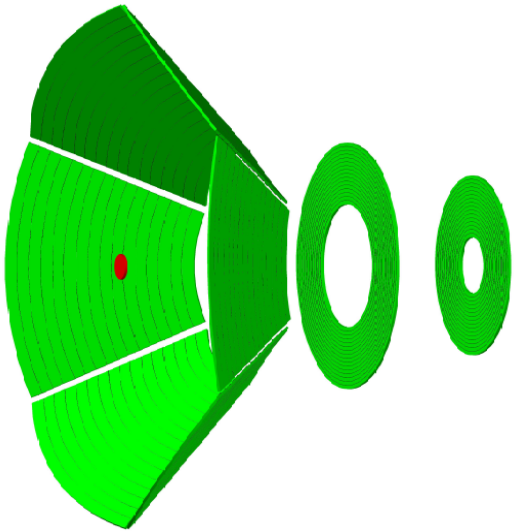
- Indirect search of unknown resonances (24Mg(a,a') at RCNP)
- Extend measurement towards lower energies
  1) Particle-gamma experiment
  2) Solenoid spectrometer
- Fusion with unstable beam

Notre Dame-ANL-IU carbon fusion experiment

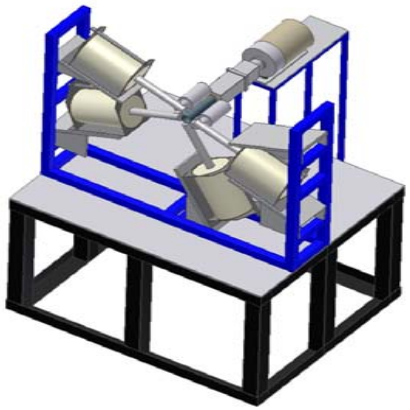
ANL
C.L. Jiang
H. Esbensen
K.E. Rehm

IU
R. De. Souza

CIAE
W.P. Liu and his group



- Additional 100K support from NSF
- Silicon (4 months)
- Electronics (2-4 months)
- Chamber (3 months)
- New Accelerator (First test beam at Feb. 2011)



Georgina at ND

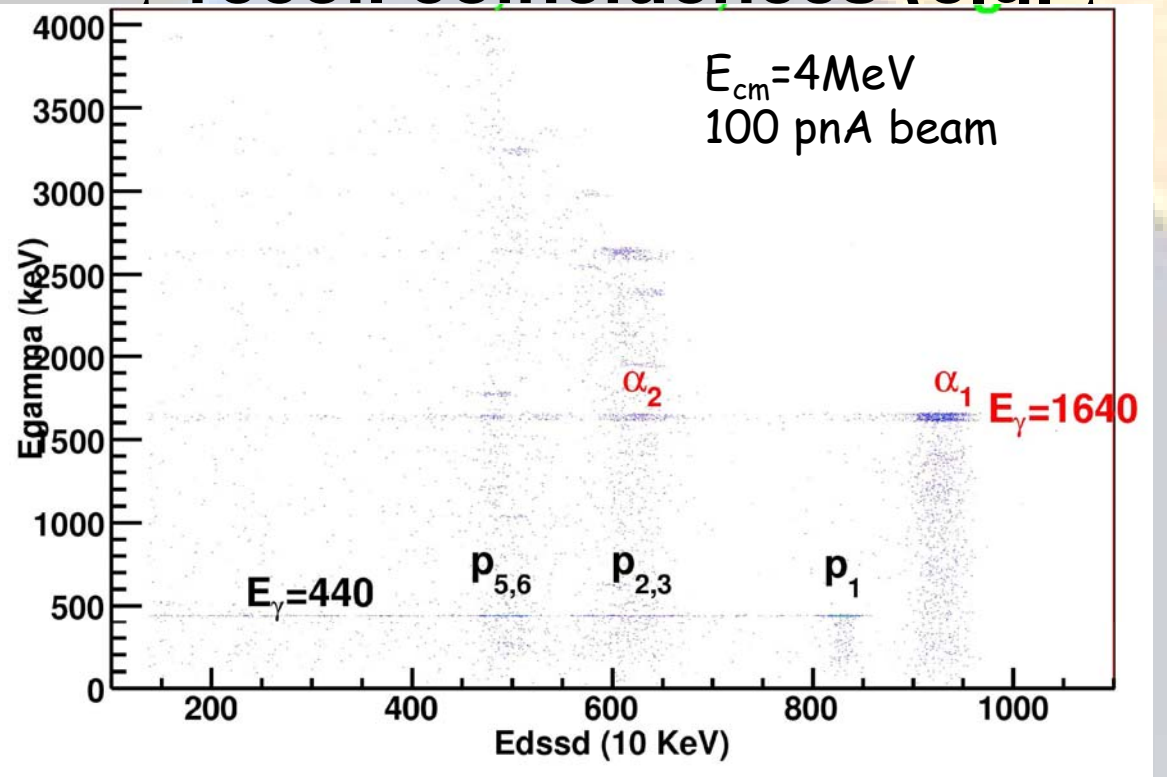
A 5 MV Pelletron with ECR source in terminal. Will be installed at the end of 2011.

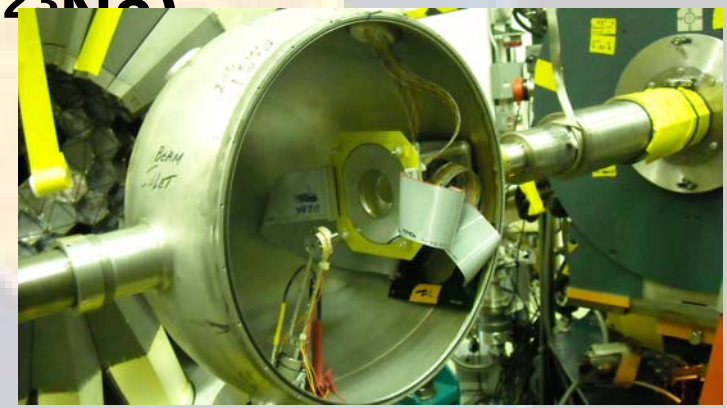
Extension of $^{12}C + ^{12}C$ towards lower energies:

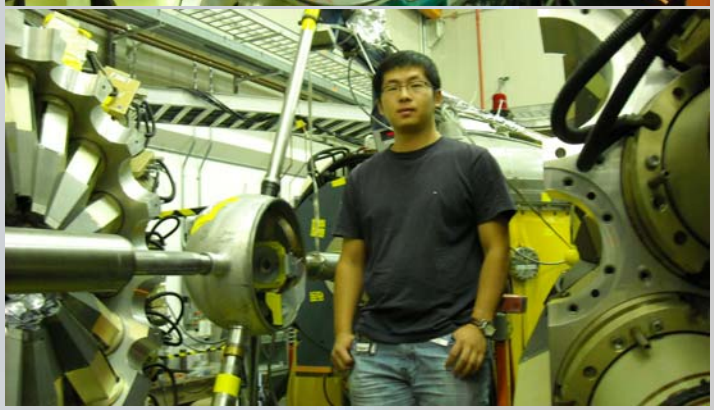
Particle-γ coincidences (e.g. p - γ or $\alpha - \gamma$)

Particle-recoil coincidences (e.g. p – ^{23}Na)

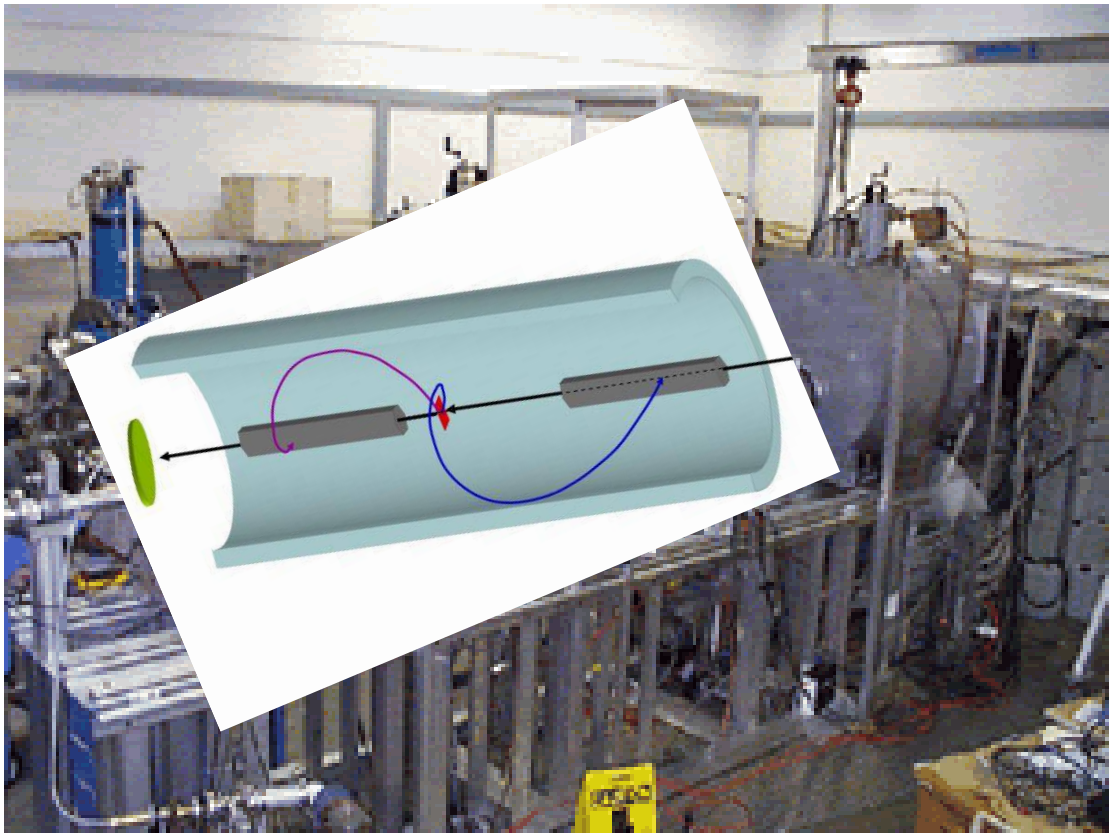
γ-recoil coincidences (e.g. γ – ^{23}Na)





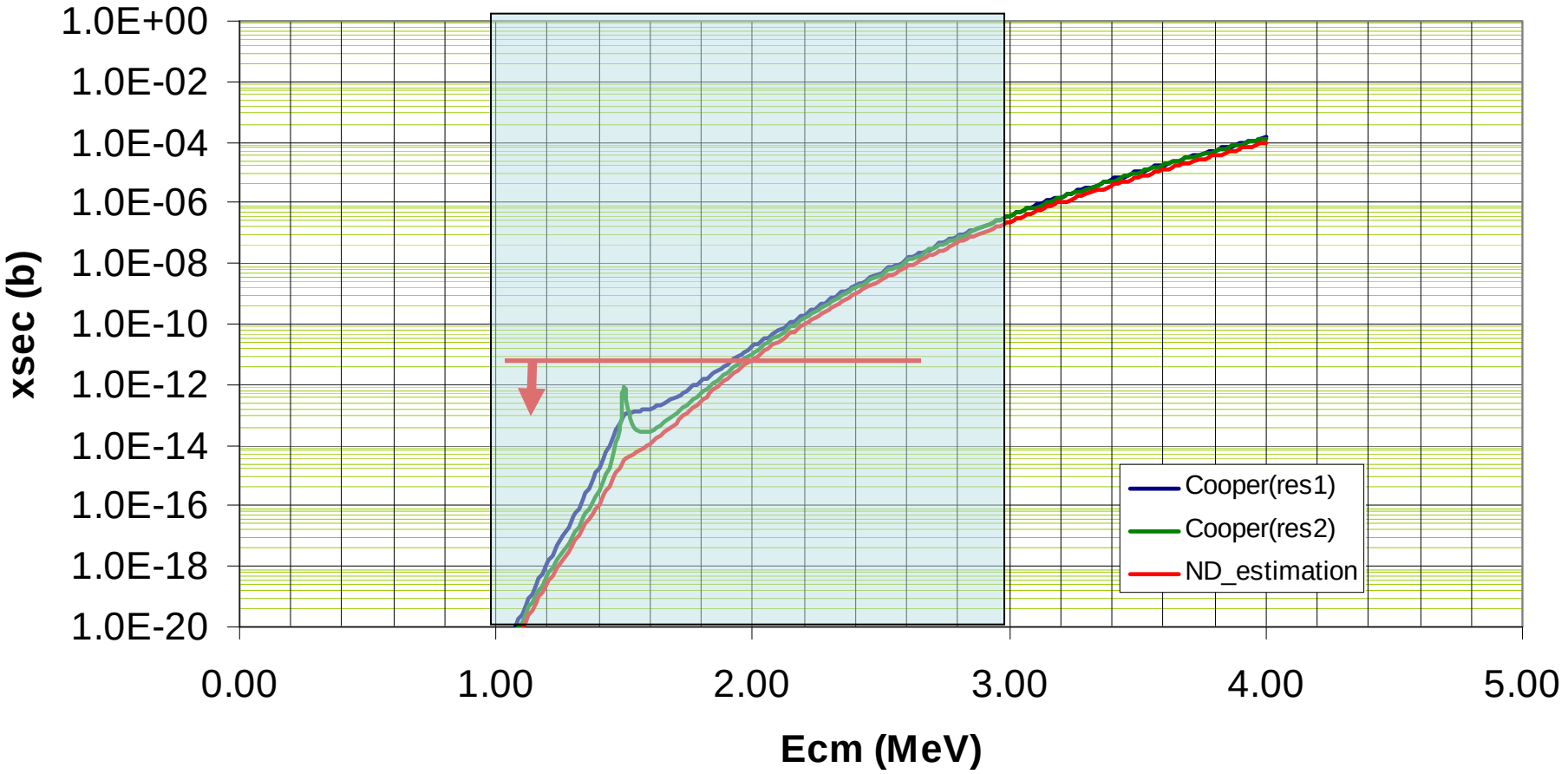


Solenoid Spectrometer for Nuclear Astrophysics (SSNAP)



High efficiency, good resolution, economic upgrade!
CIAE has interest to develop similar spectrometer. Collaboration between CIAE, ANL and ND will expedite the progress.

Prediction for the new low energy limit

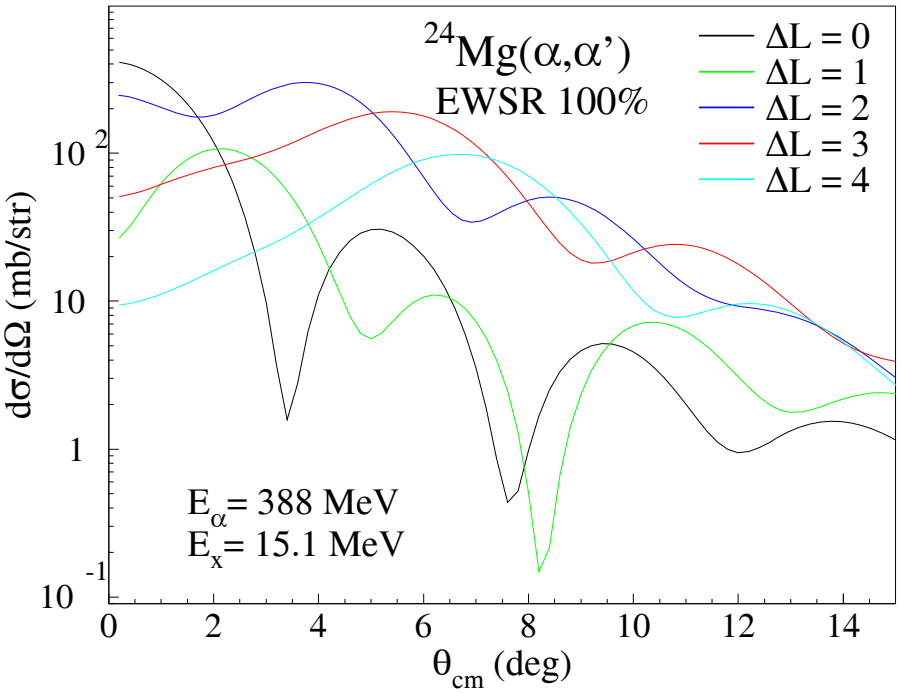


Naples : 10 puA beam; 1.5% eff.; proton channel only ; **0.5 evt/days;**
ND-ANL-IU: >40 puA beam; 45% eff.; both proton and alpha; **4*30*2 evt/days;**

If add particle + gamma coincidence: 240*8% evt/days

Long Range Plan: DUSEL or CJPL

Search of the potential resonances in the $^{12}C+^{12}C$ fusion reaction using charged-particle decays from the $^{24}Mg(\alpha,\alpha')^{24}Mg^*$ reaction (Nov. 2011)

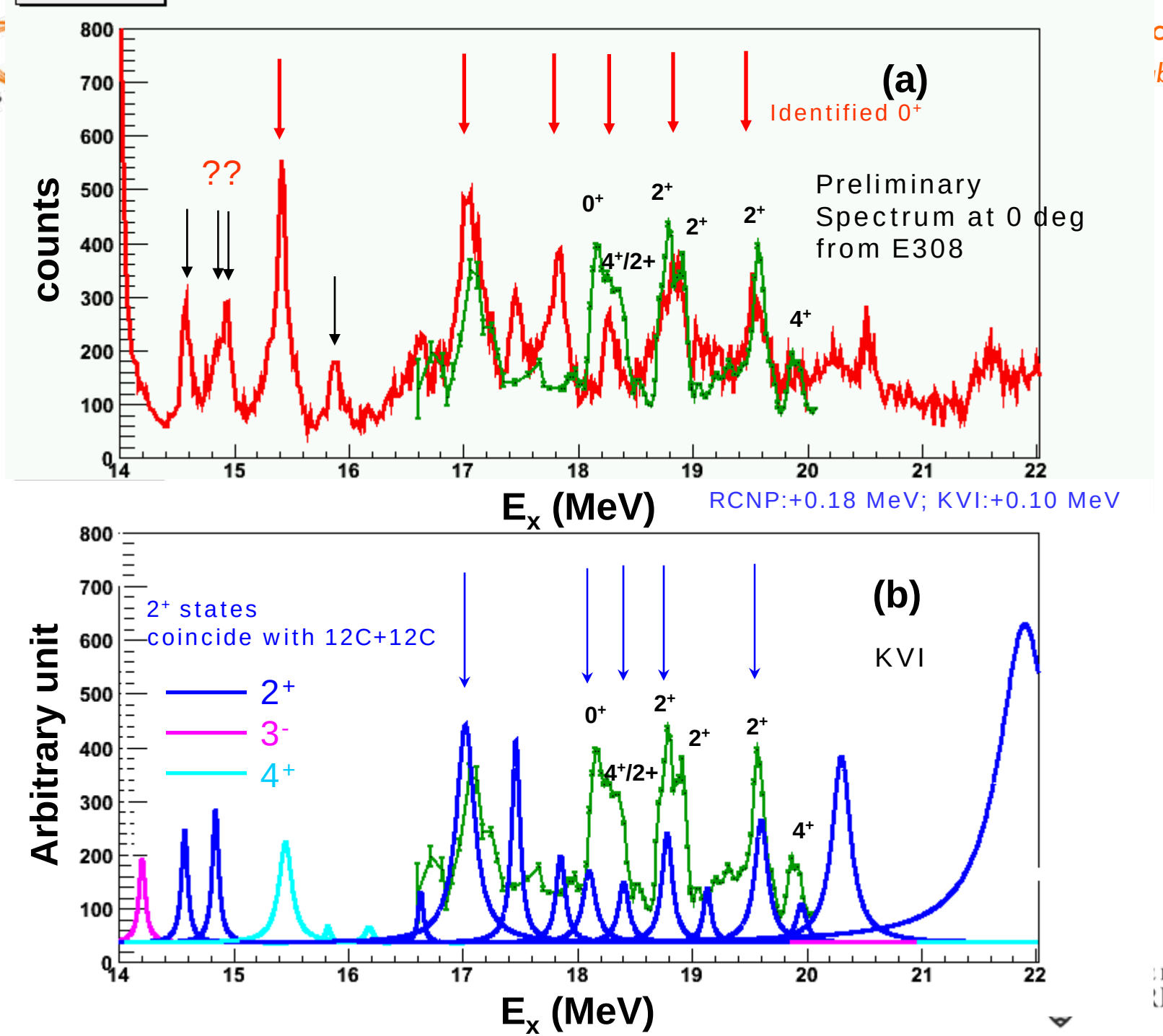


Grand Raiden at RCNP, Osaka University

Precise energy calibration (<20 keV) → confirm the correlation

Excellent energy resolution (<50 keV) → Resolving states

Measurement of angular distribution →Check spin assignment

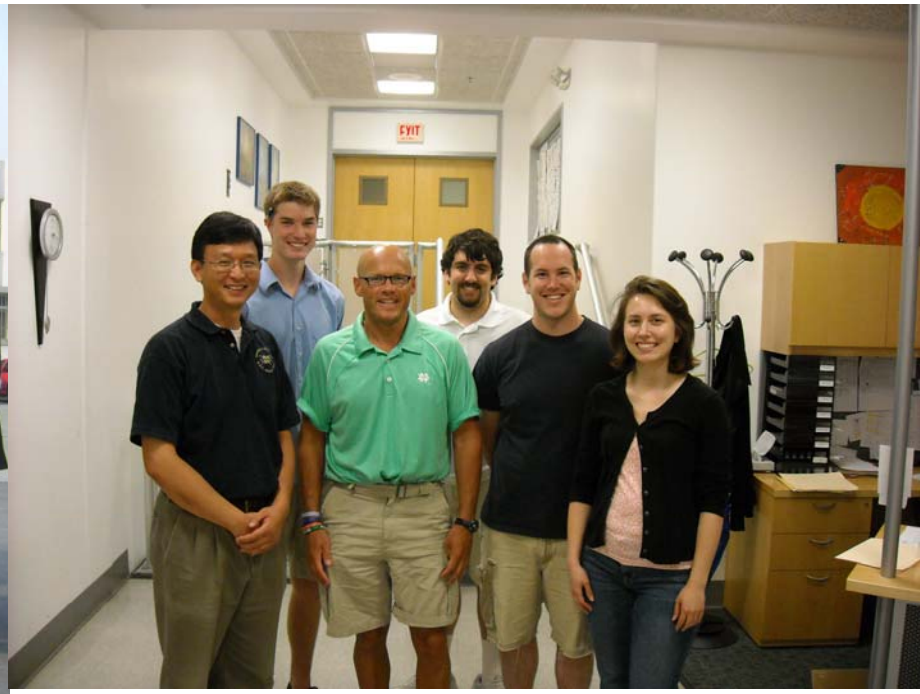

(a)
Identified 0+
??
Preliminary
Spectrum at 0 deg
from E308
counts
0+
2+
2+
2+
4+/2+
4+
Ex (MeV)
RCNP:+0.18 MeV; KVI:+0.10 MeV
(b)
KVI
2+ states
coincide with 12C+12C
2+
3-
4+
Arbitrary unit
0+
2+
2+
2+
4+/2+
4+
Ex (MeV)

Summary

- A new reach program centering on sub-barrier heavy ion fusion has been established successfully at Notre Dame.

- The proposed new developments,
  particle-gamma array and
  solenoid spectrometer
  coupling with the forthcoming new accelerator,
  will provide us the best opportunity than ever to address the key problems in nuclear astrophysics.

Collaboration is critical for the success!



PHYSICAL REVIEW C 76, 035802 (2007)

Implications of low-energy fusion hindrance on stellar burning and nucleosynthesis

L. R. Gasques
Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia and Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA

E. F. Brown
Department of Physics & Astronomy and Joint Institute for Nuclear Astrophysics, National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

A. Chieffi
Istituto Nationale di Astrofisica, Osservatorio Astronomico di Roma, Via Frascati 33, I-00040 Monteporzio Catone, Italy

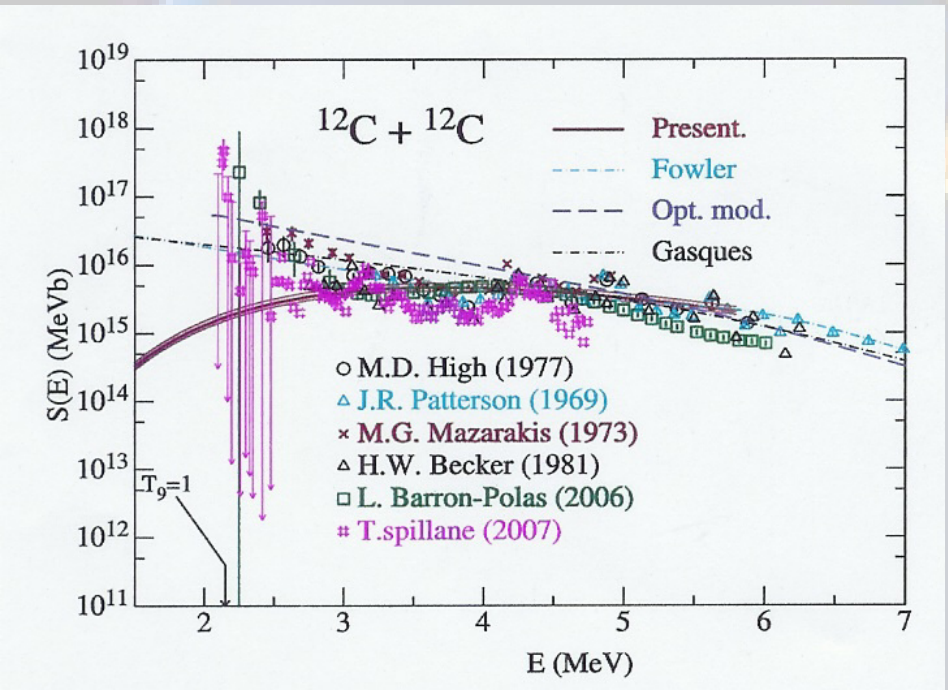
C. L. Jiang
Physics Division, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439, USA

M. Limongi
Istituto Nationale di Astrofisica, Osservatorio Astronomico di Roma, Via Frascati 33, I-00040 Monteporzio Catone, Italy

C. Rolfs
Experimentalphysik III, Ruhr-Universität Bochum, Bochum, Germany

M. Wiescher
Department of Physics and Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA

$^{12}C + {}^{12}C$ fusion



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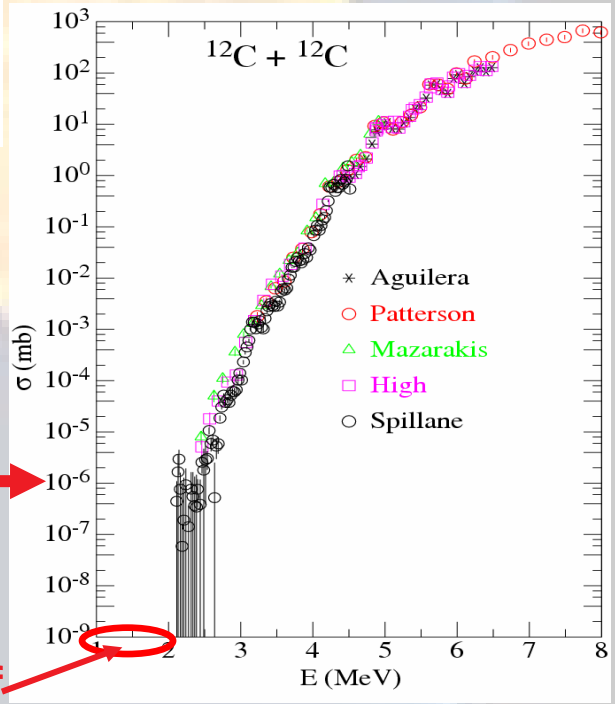
Region of interest



Summary of the research activities from 2007-2011

Hydrogen Burning (collaboration with C. Spitalleri's group)
• study $^{17}O(p,a)^{15}N$ using THM, performed at Notre Dame at 2007

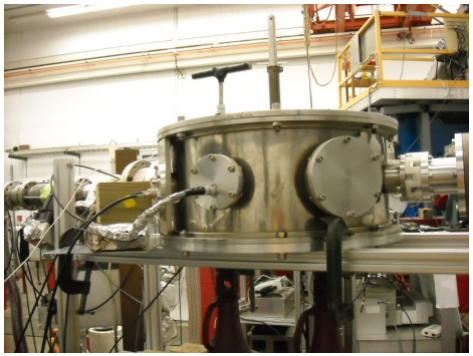
Helium Burning (collaboration with K. E. Rehm's group.)
•^{12}B and ^{12}N decay experiment→3a process
•^{16}N decay experiment→$^{12}C(\alpha,\gamma)^{16}O$
(X. Tang et al., Phys. Rev. Lett. 99, 052502 (2007)
Phys. Rev. C 81, 045809 (2010))

Carbon Burning
▪Limits on the molecular resonance strengths of the $^{12}C+^{12}C$ fusion reaction
▪Neutron branching ratio of the $^{12}C+^{12}C$ fusion reaction
▪Development of new techniques for heavy ion fusion reaction at sub-barrier energies

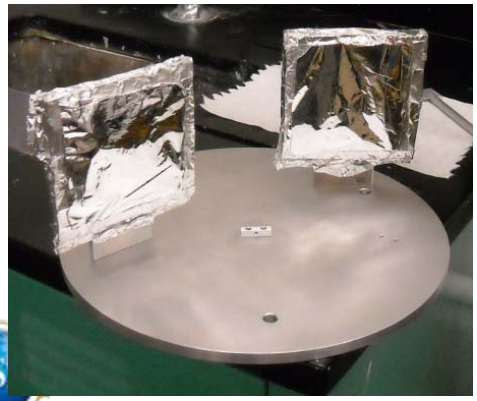
Hindrance effect in Sub-barrier fusion (collaboration with C.L. Jiang at ANL, A. Stefanini at LNL)
▪Ca+Ca isotope fusion [Phys. Rev. C 82, 041601] Published at Oct 19, 2010

$^{12}C(^{12}C,p_i)$ Measurements!

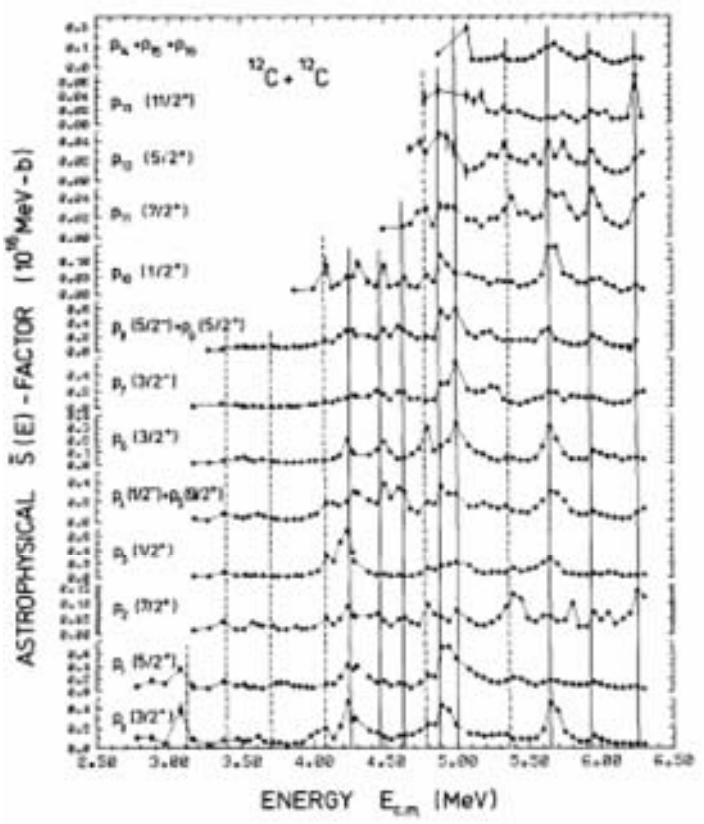
- Use Becker et al. 1981 measurements for extrapolation
- Experiment at ND (2 weeks ago) to provide check for Becker et al. measurements



Detector chamber at ND

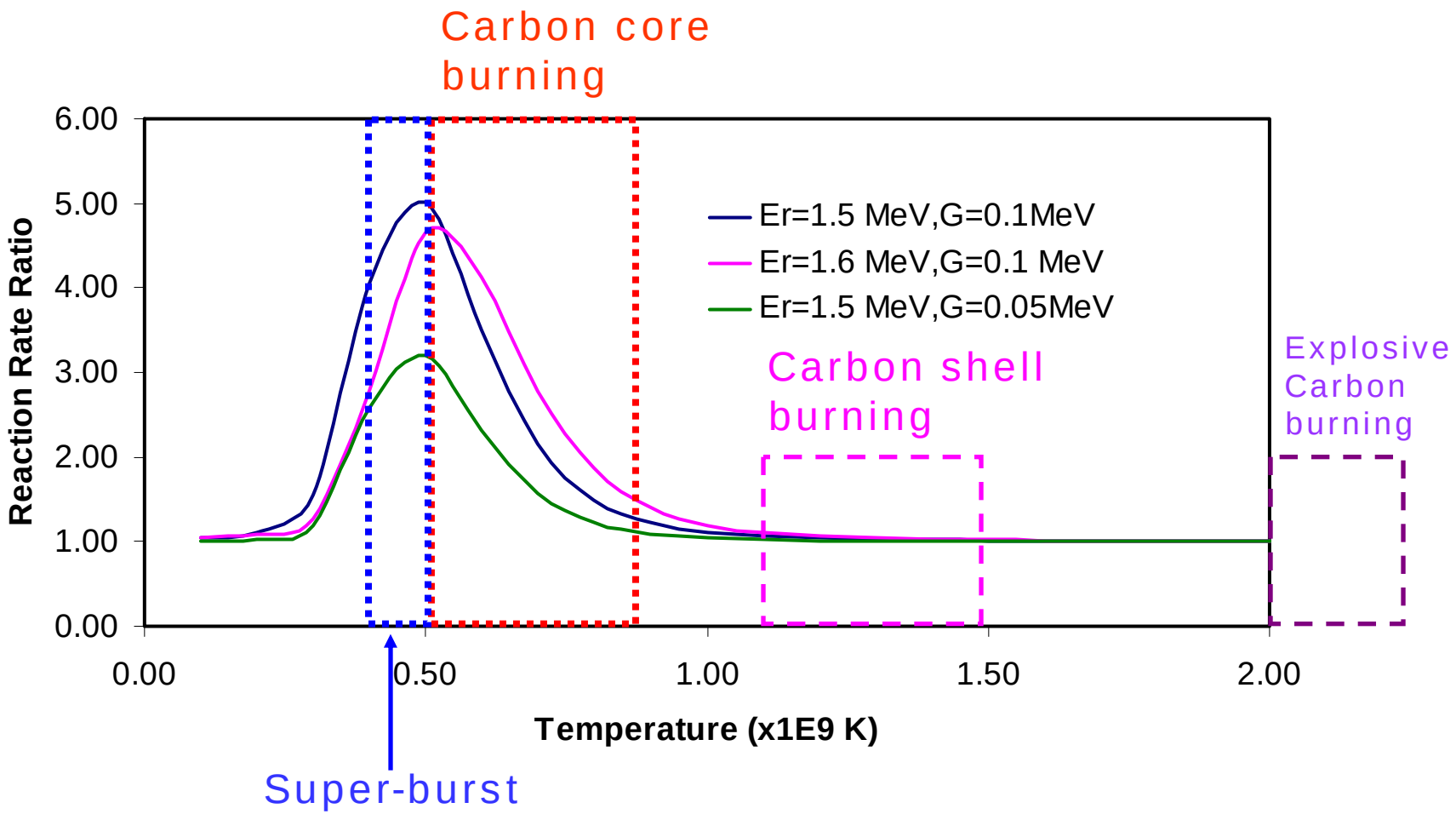


YY1 Si strip detectors

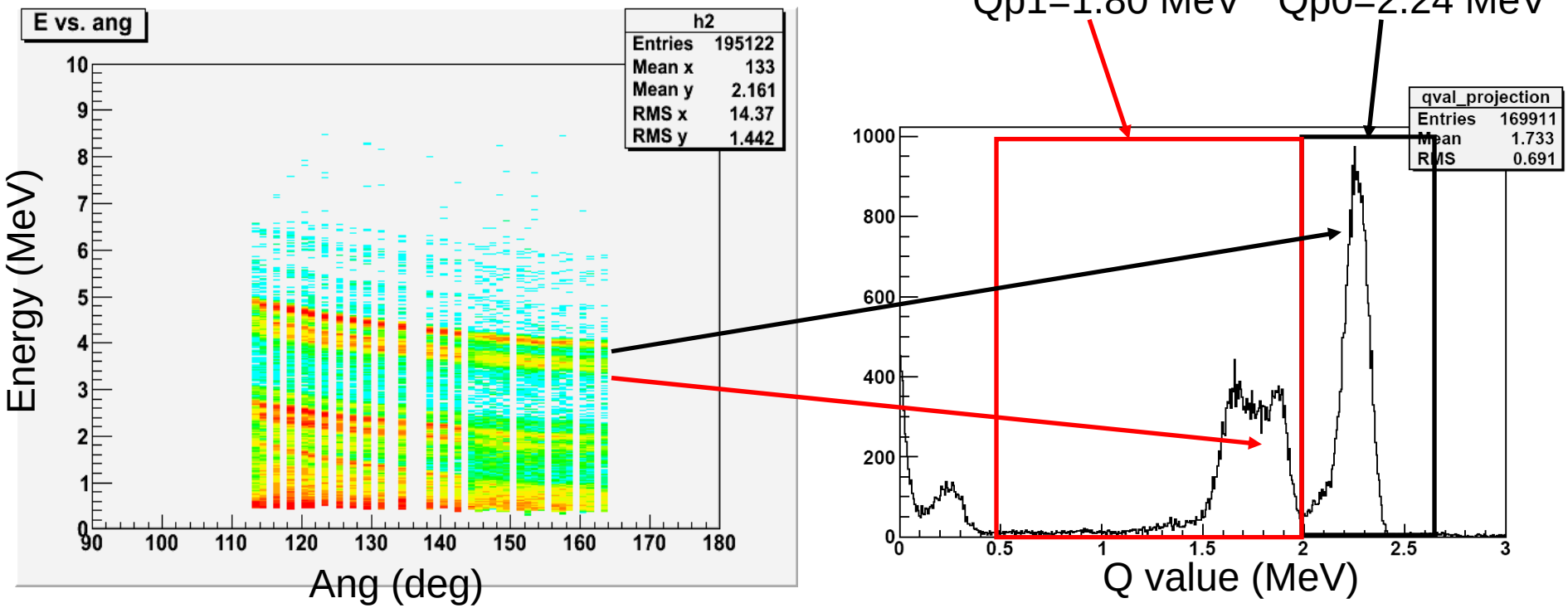


Becker et al. 1981

Impact of the potential resonances to astrophysical reaction rate



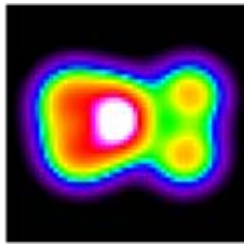
Thick target measurement at 8.2 MeV

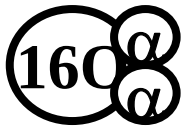


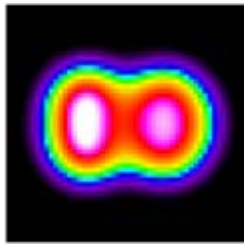
$$Q = (\frac{M_a}{M_B} - 1)E_a + (\frac{M_b}{M_B} + 1)E_b - 2\frac{\sqrt{M_a M_b E_a E_b}}{M_B}\cos\theta$$

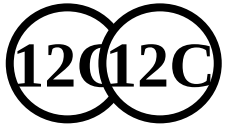
Beam energy (E_a) varies continuously from the initial beam energy (8.2 MeV) down to 0 MeV. → Bad Q value resolution

$^{12}C+^{12}C$ cluster components in ^{24}Mg (g.s.)







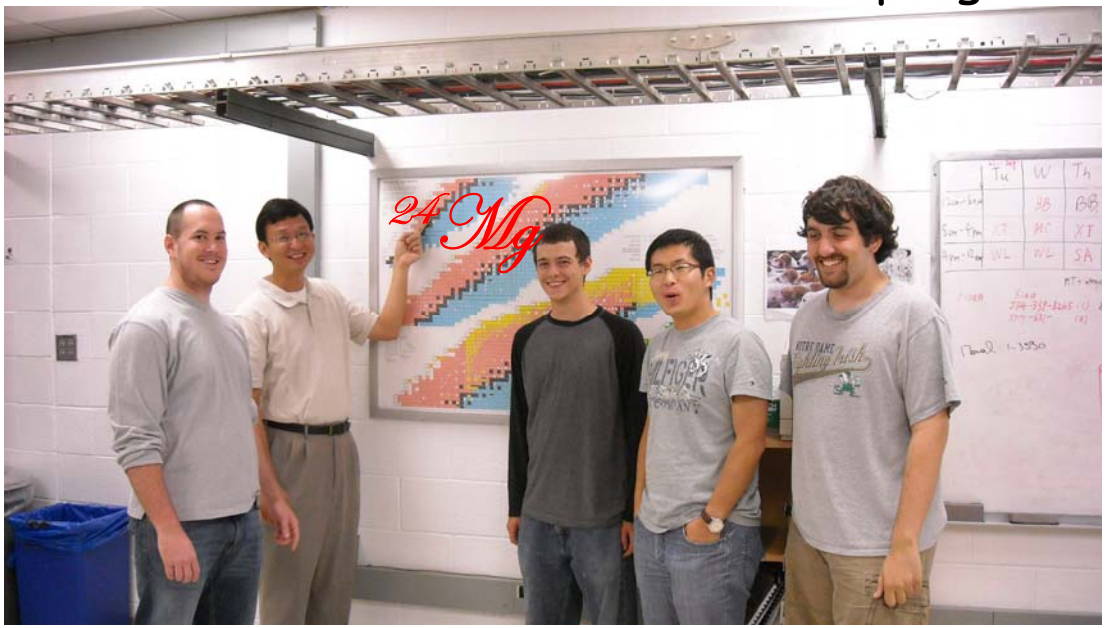


AMD+GCM calculation by Y. Kanada-Enyo

Therefore, the $^{12}C+^{12}C$ resonant states could be strongly populated by the $^{24}Mg(\alpha,\alpha')$!

Carbon burning and more

A new research program in NSL



The 2011 dream team:
Coach: X. Tang (Prof.)
Supernova players:
B. Bucher (Grad.)
X. Fang (Grad.)

A. Alongi (Undergrad.)
C. Cahillane (Undergrad.)
P. Mooney (Undergrad.)
P. McIntrye (Ungdergrad.)
A. Erdman (Undergrad.)

Some key players who have contributed in the carbon burning project from 2007 to 2009:
M. Notani (postdoc, 2007-2009)
Visiting students from Surrey: P. Davies (2007), S. Thomas (2008)
Grad: C. Ma (master, 2007-2009)
REU: N. Schroeder, A. Hillmer, G. Buffaloe(F), C. Garcia(F), A. Moncion, E. Dahlstrom (F)
Undergrad: D. Cerrone (2006-2009)