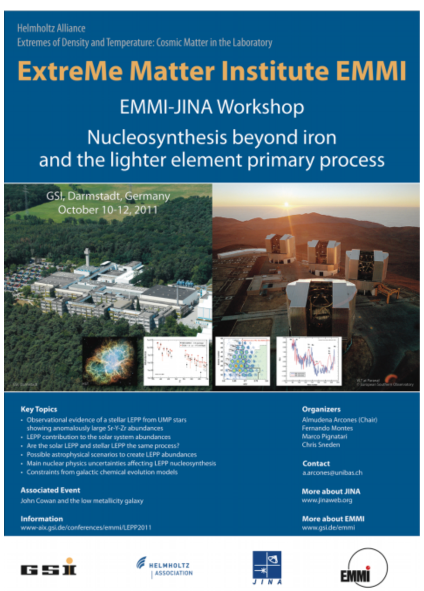
The $^{12}C(^{12}C,n)^{23}Mg$ Reaction: A Potential Neutron Source for the Weak S-Process



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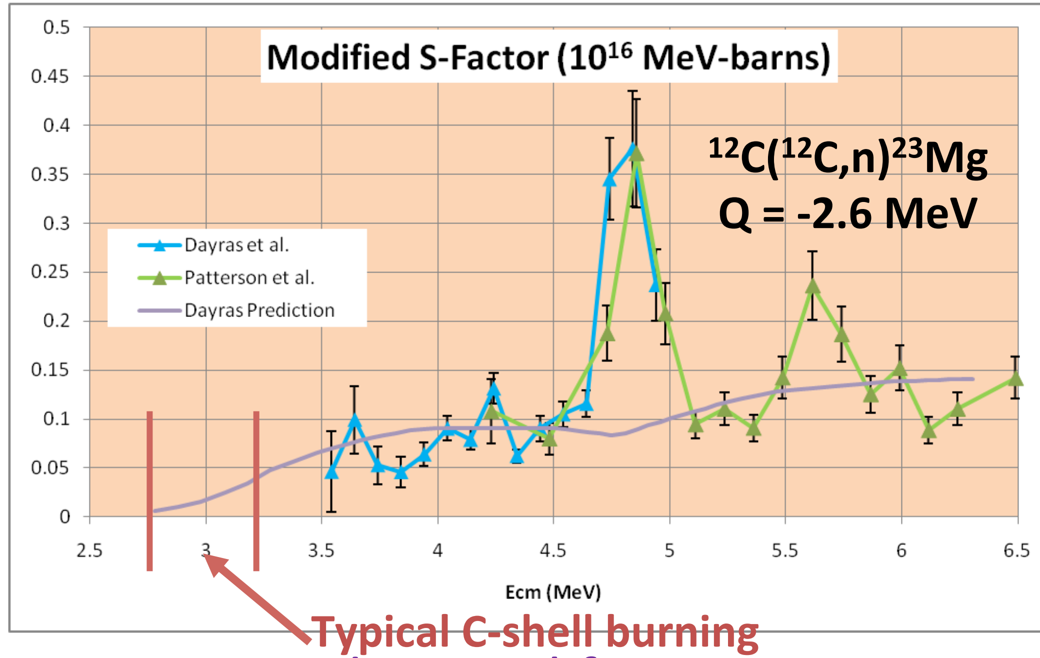
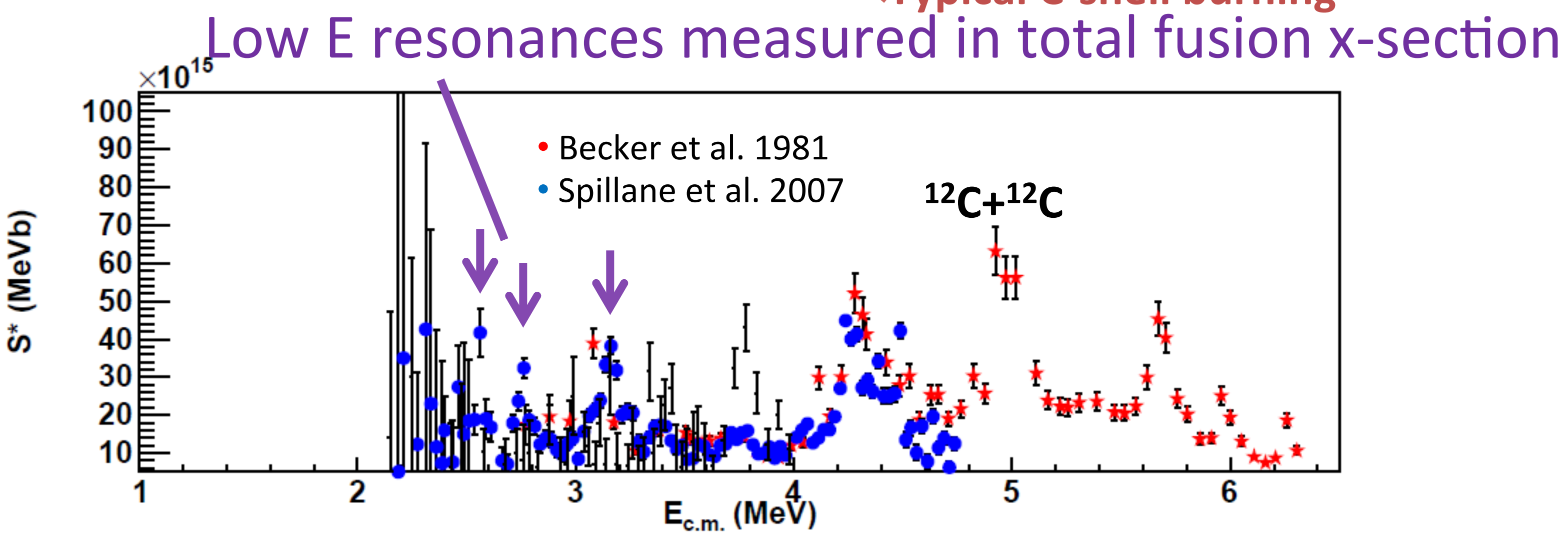
Outline

- Motivation
  - Uncertain reaction rate
  - Synthesis of light elements above iron
- Measurement of $^{12}C(^{12}C,n)^{23}Mg$
  - Results & Challenges
- Improved Extrapolation—Isospin Symmetry
  - Measurement of $^{12}C(^{12}C,p)^{23}Na$
- Effects on the Astrophysical Reaction Rate
- Conclusions

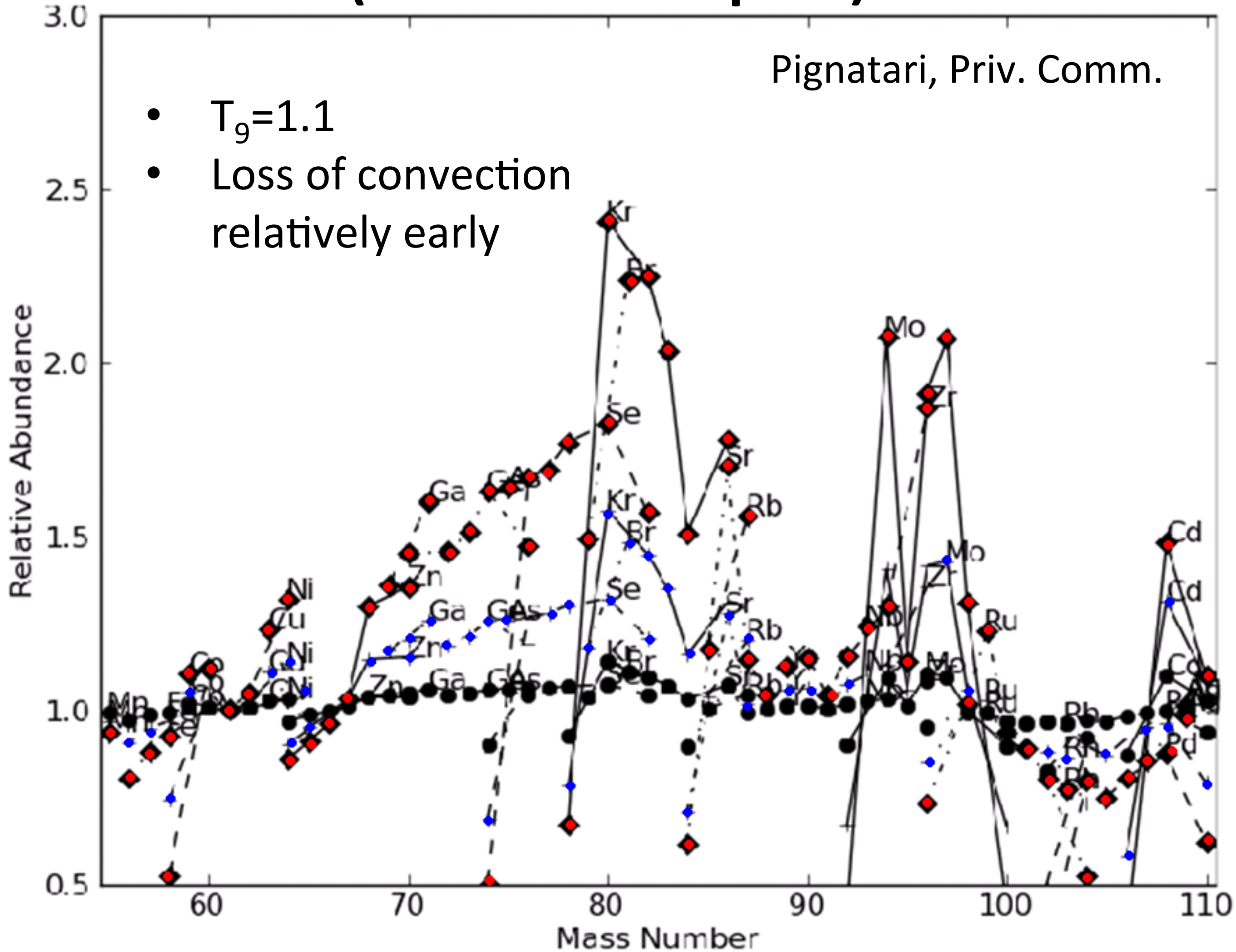
Uncertainty in Reaction Rate

- Resonances form important contribution to excitation function
- Resonance structure continues to lowest energies
- Current rate cannot account for resonances



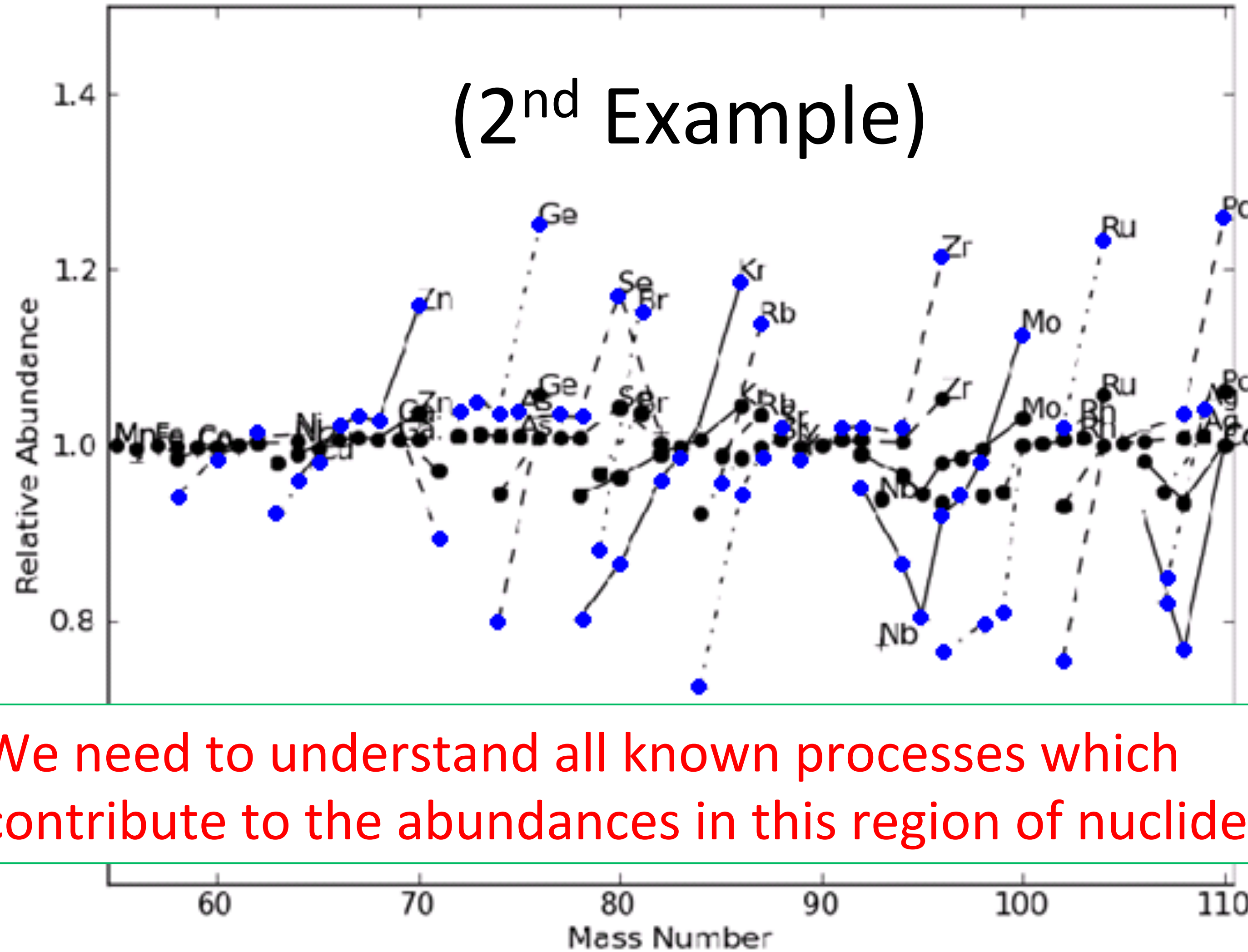


Effect on Carbon-Shell Yields (1st example)



$^{12}C(^{12}C,n)$ rate varied by factors 2, 5, 10

(2nd Example)



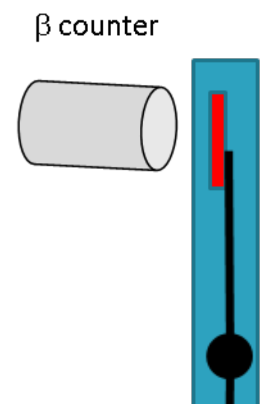
We need to understand all known processes which contribute to the abundances in this region of nuclides!

- Late C shell—convective until SN explosion
- Low initial C due to mixing with previous C-shells
- Initial T_9 ~ 1.0 peaking to 1.36 near end
- 2, 5 factor increase over Dayras rate

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

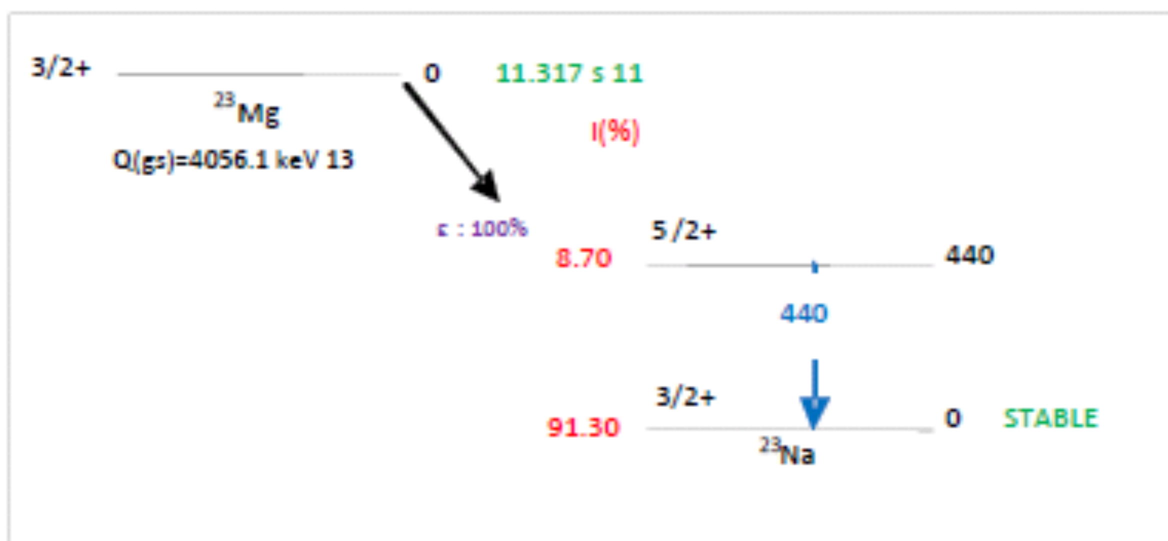
- Patterson et al. 1969: thin target, count β+
- Dayras et al. 1977: thin target, count γ 440 & 511 keV
- Notre Dame 2011: thin & thick targets, count β+

Counting Station

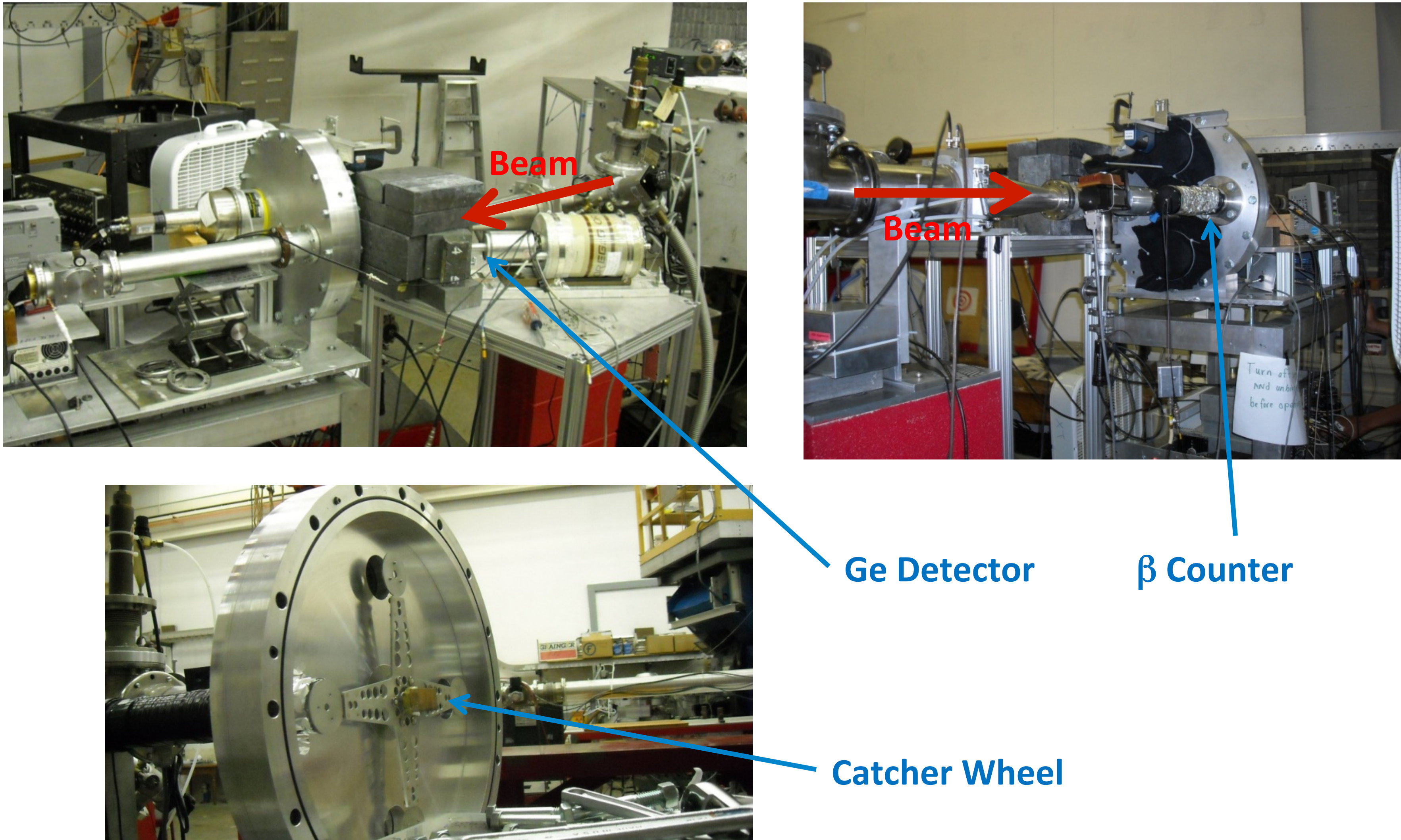


^{12}C E

Our S



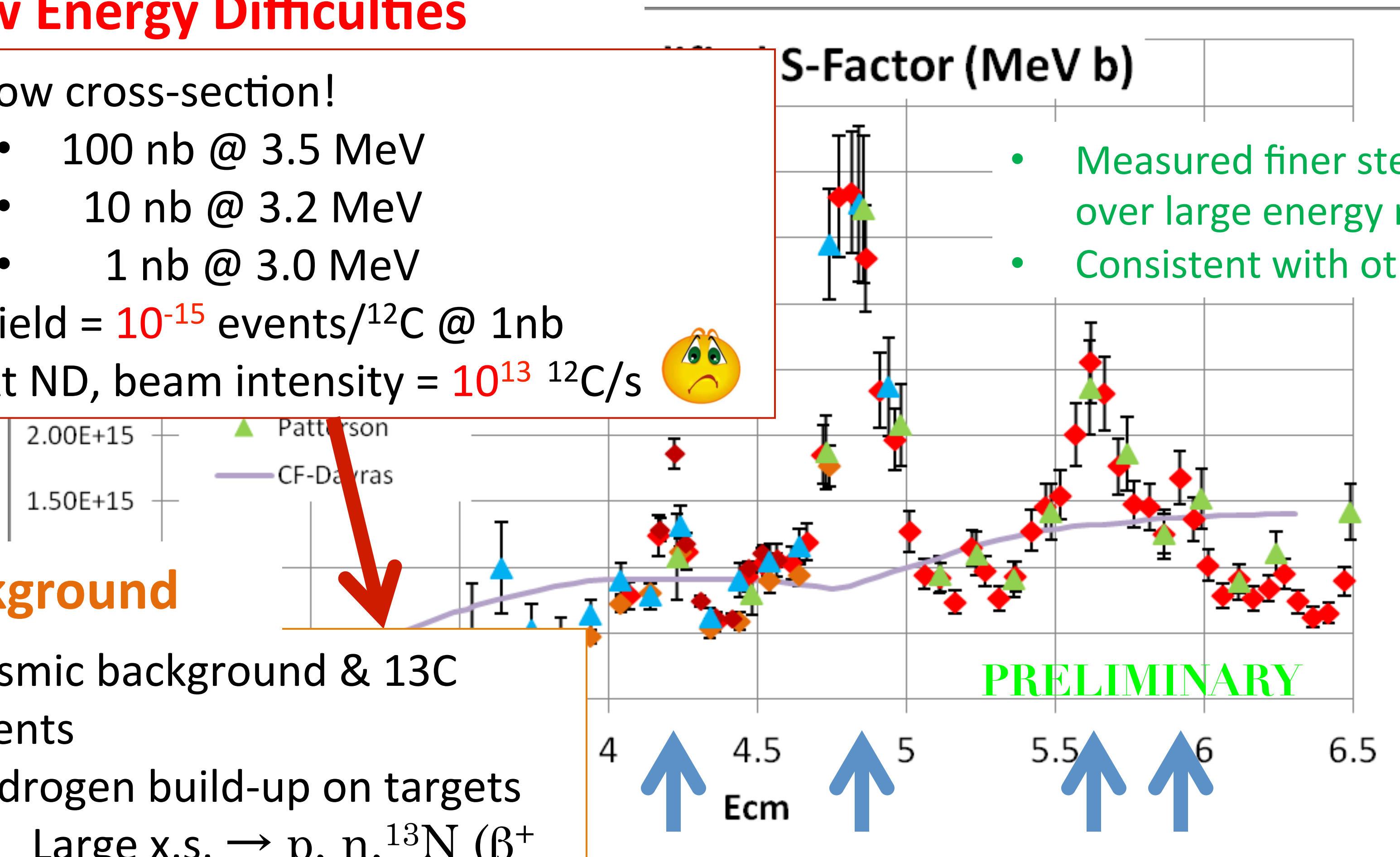
Experiment at Notre Dame



Experimental Results

Low Energy Difficulties

- Low cross-section!
  - 100 nb @ 3.5 MeV
  - 10 nb @ 3.2 MeV
  - 1 nb @ 3.0 MeV
- Yield = 10^{-15} events/^{12}C @ 1nb
- At ND, beam intensity = 10^{13} $^{12}C/s$



- Measured finer step size over large energy range
- Consistent with others

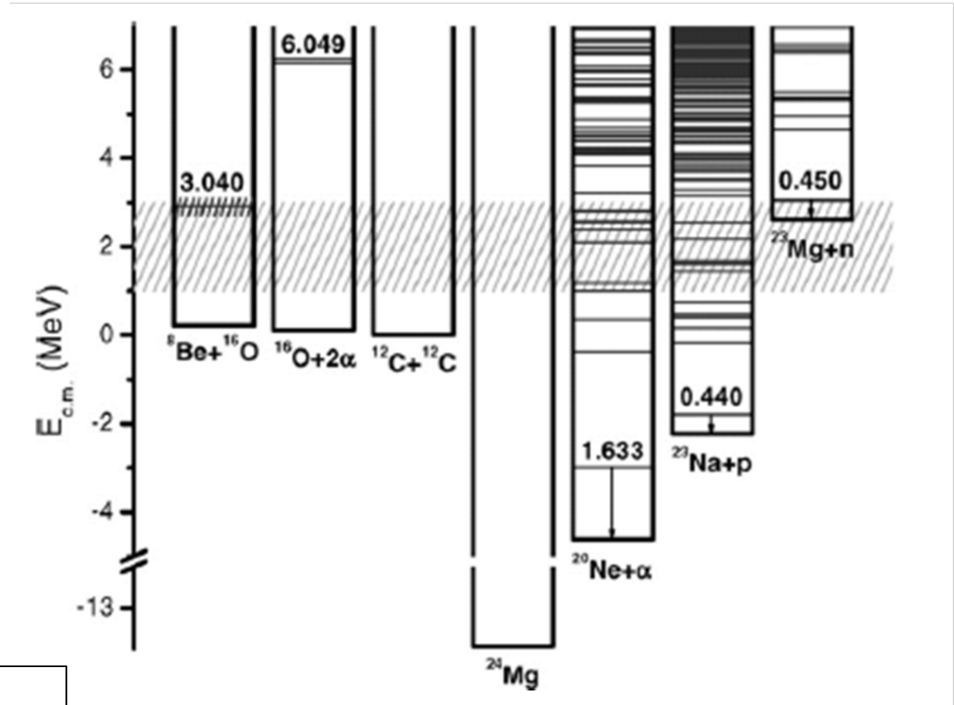
Background

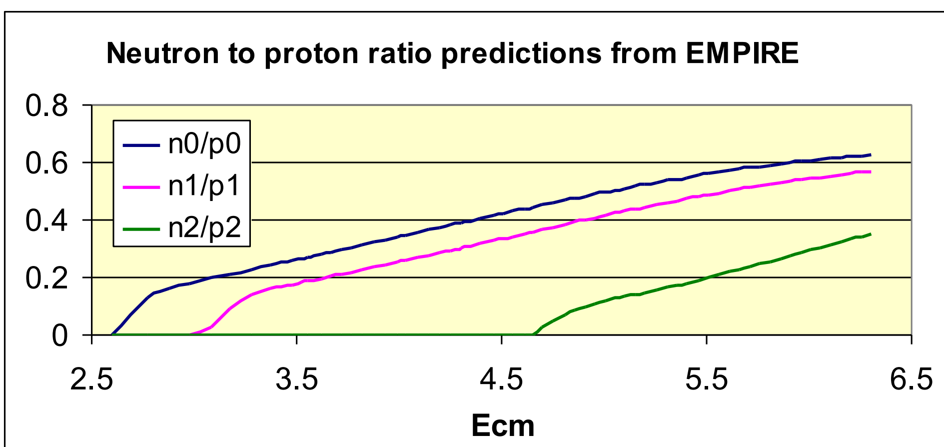
- Cosmic background & 13C events
- Hydrogen build-up on targets
  - Large x.s. $\rightarrow$ p, n, ^{13}N (β^+ emitter)

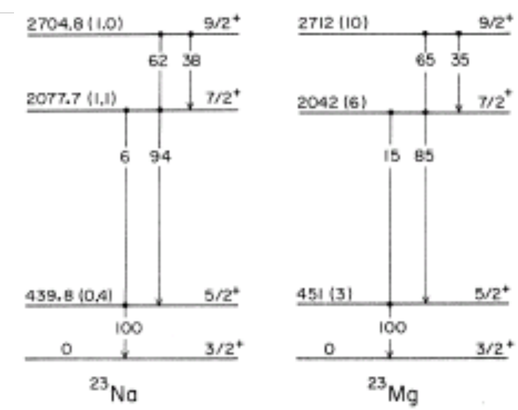
Note consistent resonance energies

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 $\sigma(n_i)/\sigma(p_i)$

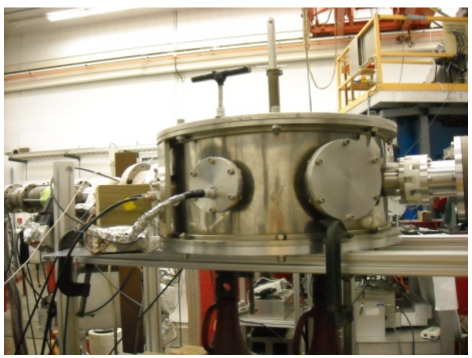




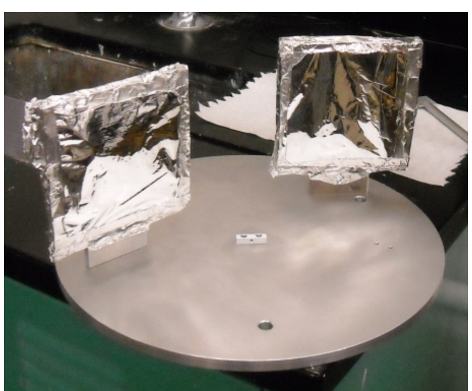


$^{12}C(^{12}C,p_i)$ Measurements!

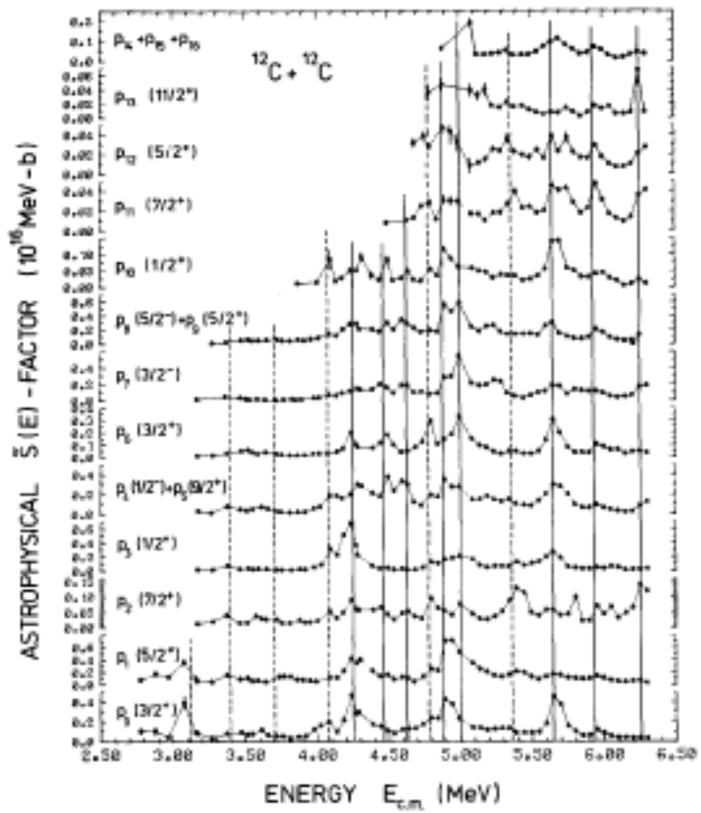
- Use Becker et al. 1981 measurements for extrapolation
- Recent measurements at ND to provide check for Becker et al.



Detector chamber at ND

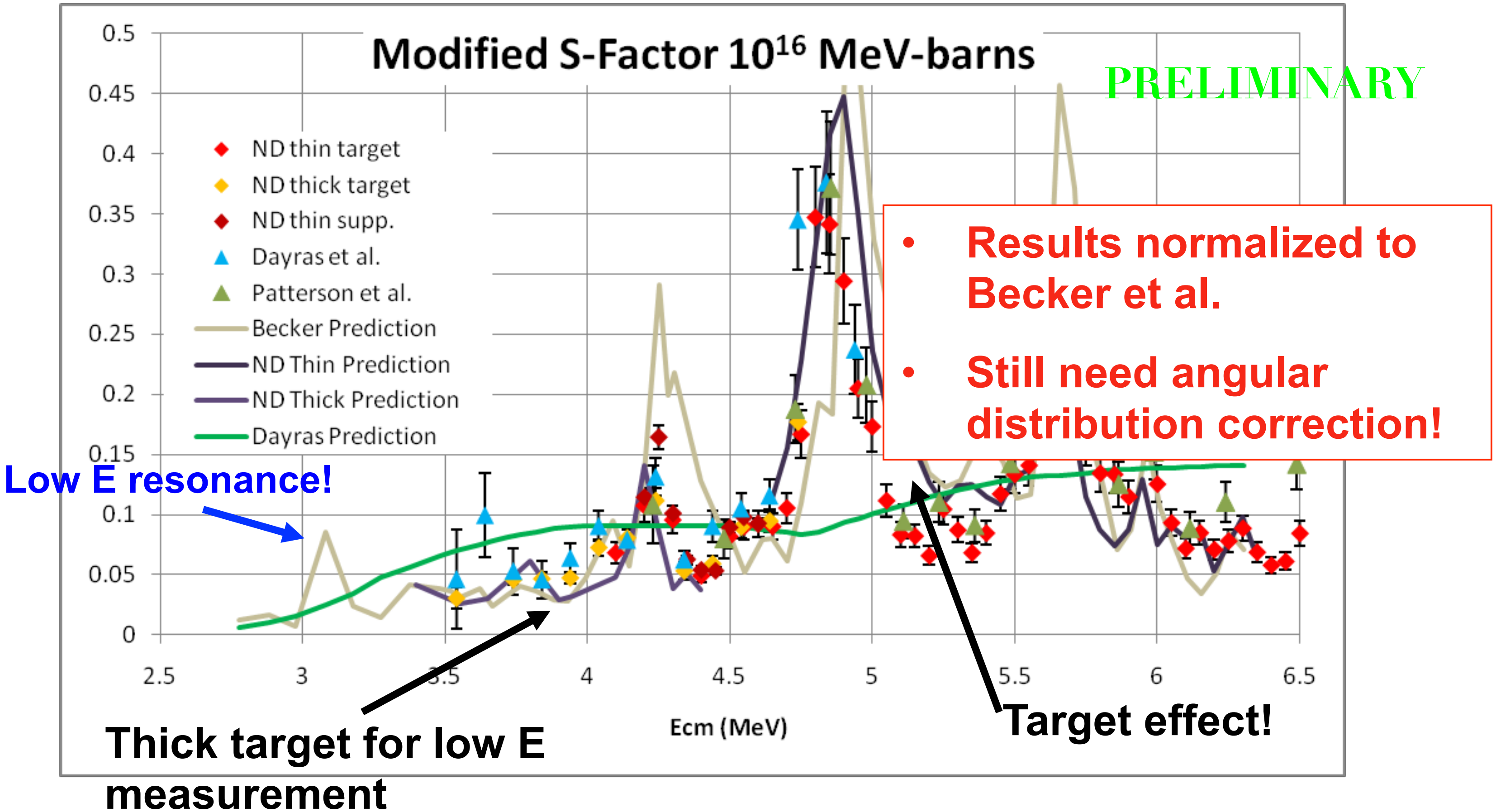


YY1 Si strip detectors



Becker et al. 1981

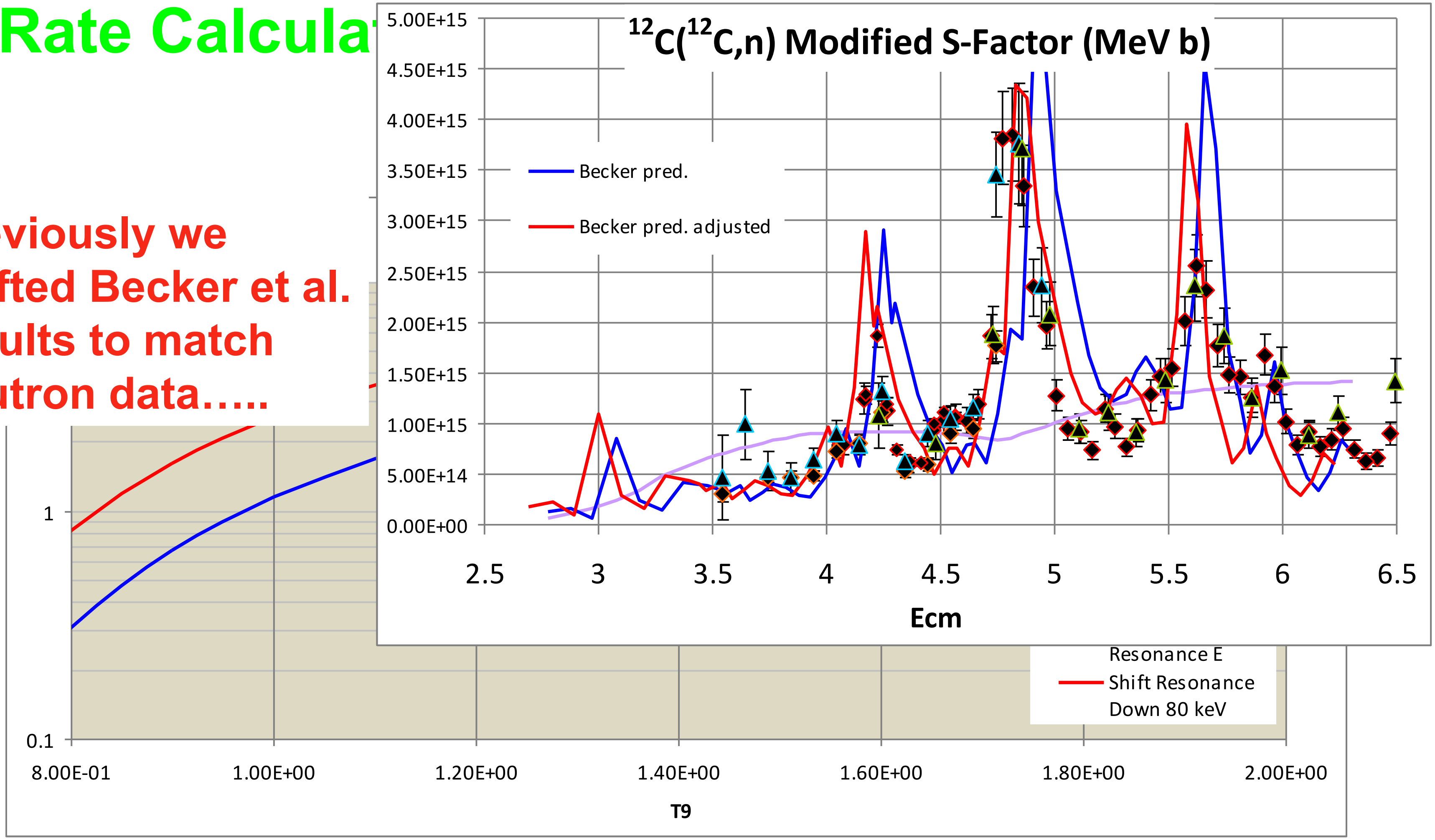
New Extrapolation



- Number of resonances reproduced, but strength & position needs improvement
- Preliminary ND results provide better match to resonance energies

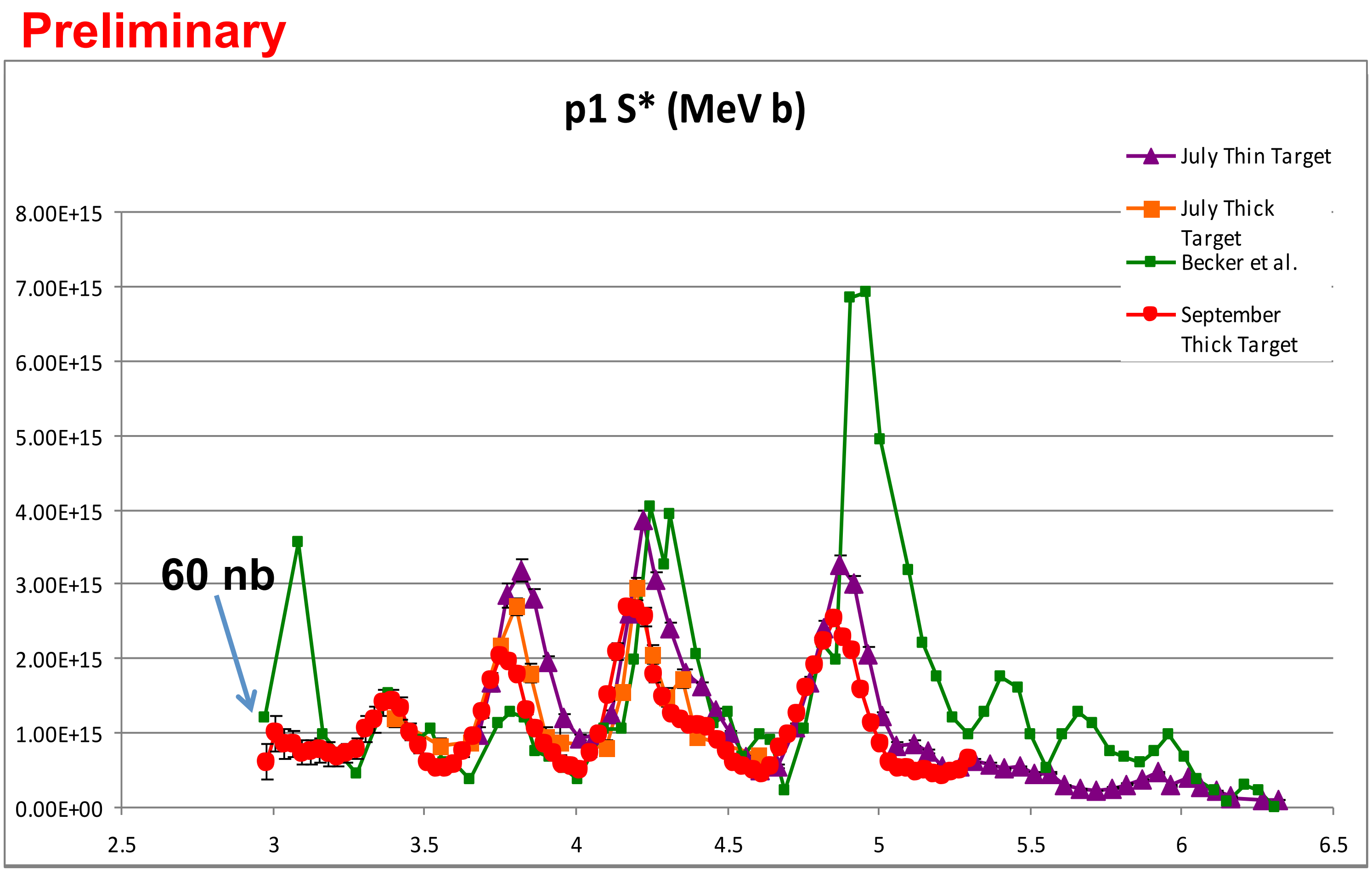
Rate Calcula

Previously we shifted Becker et al. results to match neutron data…..



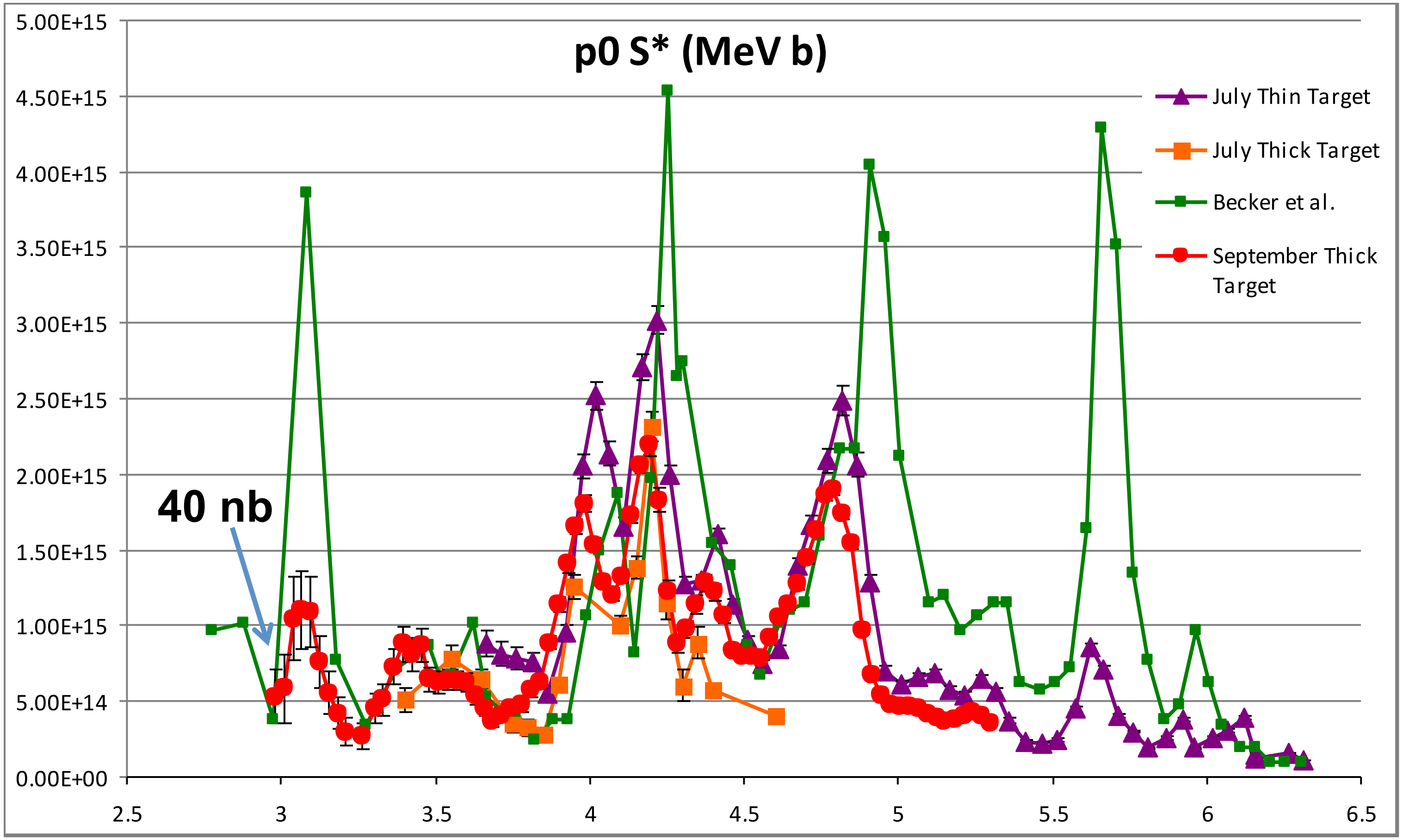
Rate sensitive to resonance energy.

Most recent results (a few days ago) indicate there is no 3.1 MeV resonance in p1 channel ! Need more work on normalization and energy correction.



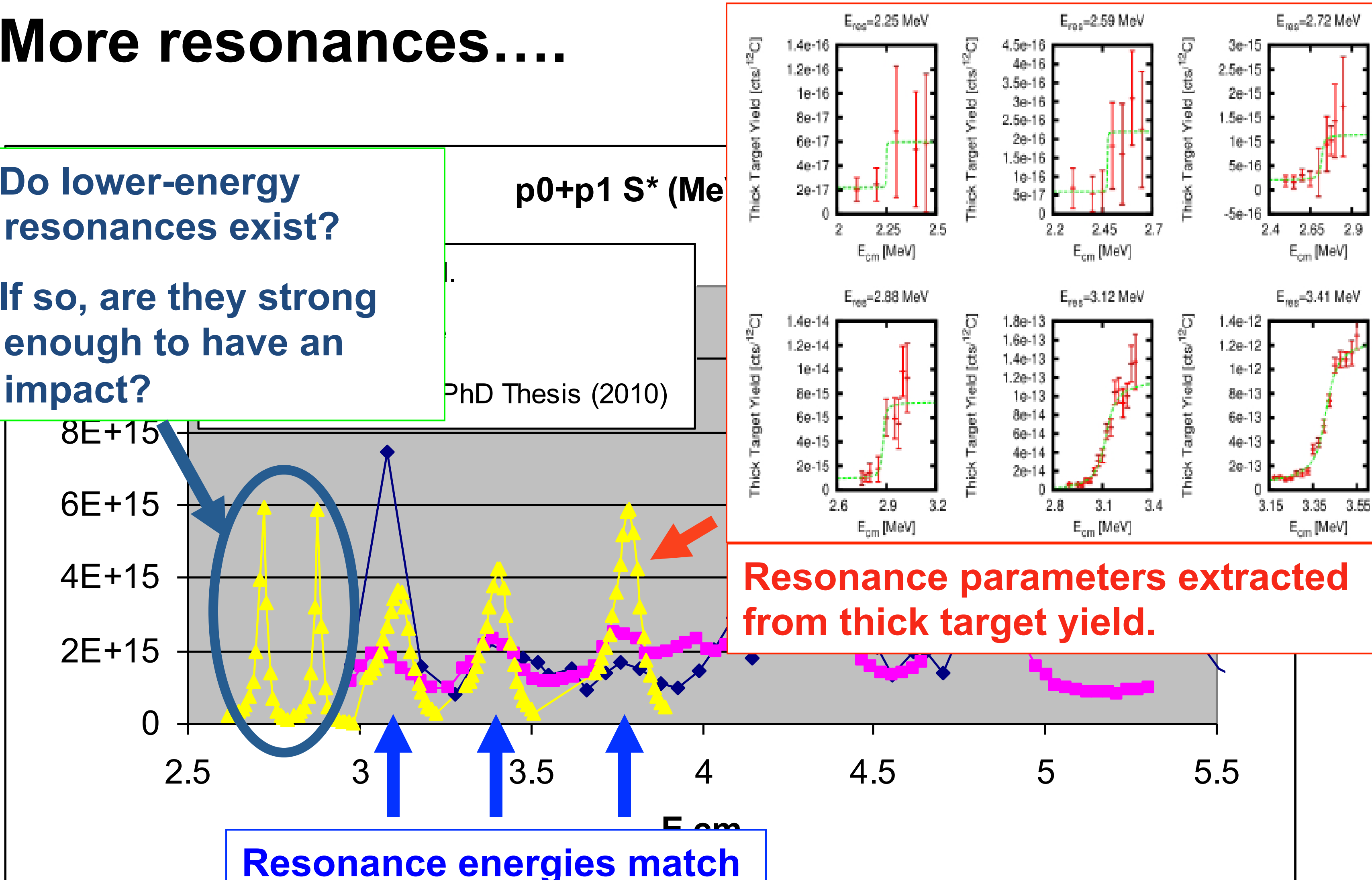
But the results do indicate the existence of the 3.1 MeV resonance in p0 channel!

Preliminary



More resonances….

1. Do lower-energy resonances exist?
2. If so, are they strong enough to have an impact?



Resonance parameters extracted from thick target yield.

Resonance energies match well, but strengths differ.

Conclusions

- Resonant structure of $^{12}C+^{12}C$ likely plays a role in astrophysical reaction rates making reliable extrapolations difficult
- Direct measurements are hindered by low x.s. and high background
- Isospin symmetry can be used to predict resonant structure in $^{12}C(^{12}C,n)$
- Preliminary results indicate low-energy resonance(s) may marginally enhance rate, but more analysis and experiment(s) are still needed

Thank You!

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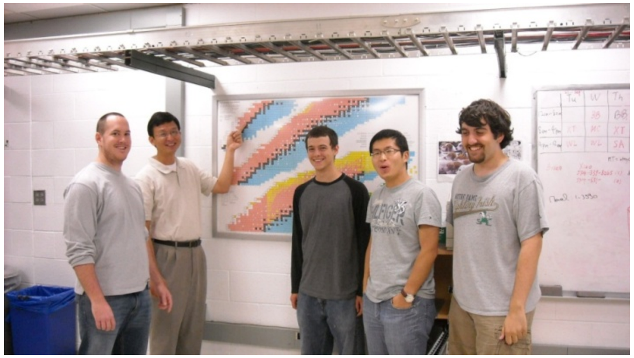
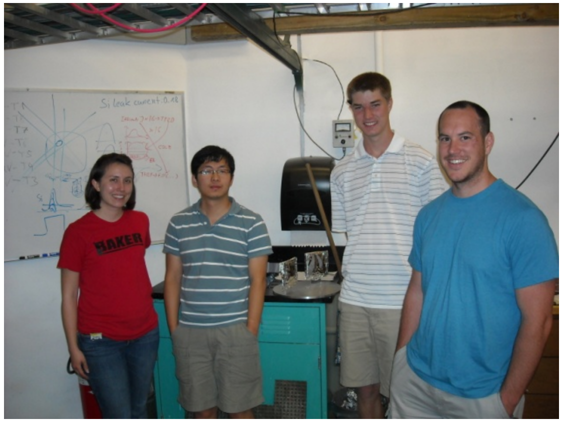
Nuclear Science Lab: S. Almaraz-Calderon, A. Ayangeakaa, A. Best, M. Couder, J. DeBoer, W. Lu, D. Patel, N. Paul, A. Roberts, R. Talwar, A. Kontos, M. Smith, S. Lyons





But Wait!

- Funny Behavior @ T_9 = 1.5
- Dayras low T parameters wrong
- Must re-fit data to get correct parameters

$$B_n(T_9) = \frac{\int_{E_t}^{\infty} \beta_n(E) S(E) \exp\{-[(E_G/E)^{1/2} + E/kT]\} dE}{\int_0^{\infty} S(E) \exp\{-[(E_G/E)^{1/2} + E/kT]\} dE},$$

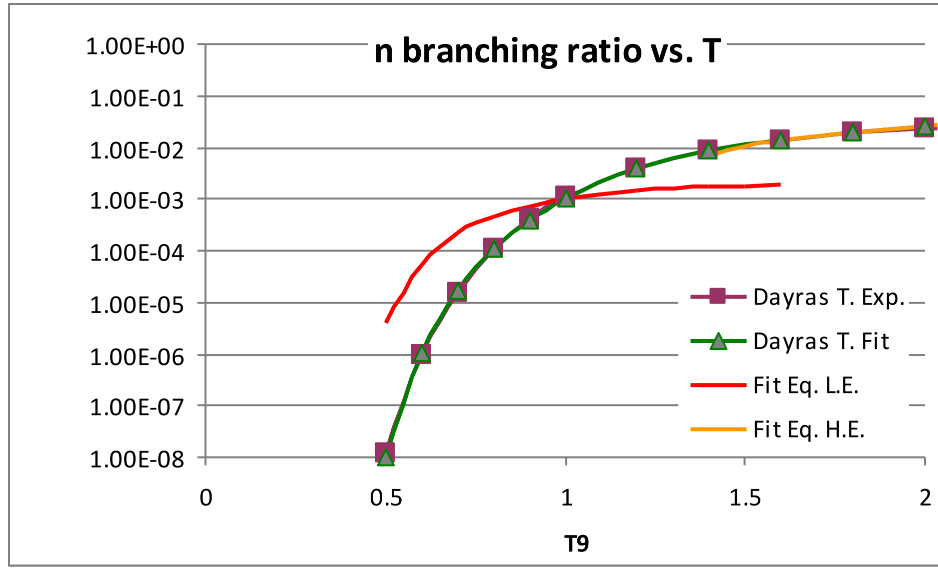
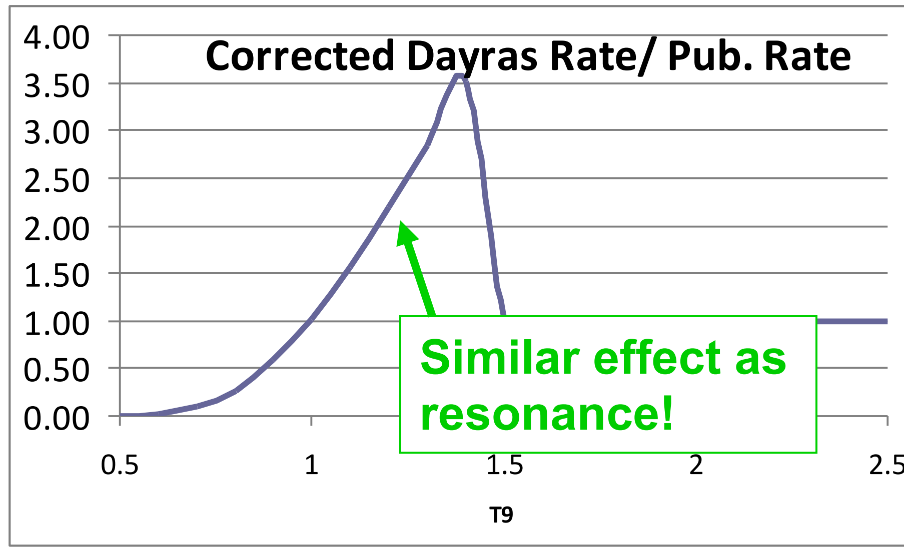


TABLE 4
Neutron branching ratio as a function of temperature

T_9	E_0 (MeV)	Δ (MeV)	$B_n(T_9)$ this exp	fit	old
0.5	1.49	0.58	1.15(−08)	1.04(−8)	2.67(−9)
0.6	1.68	0.67	9.42(−7)	1.07(−6)	3.03(−6)
0.7	1.85	0.75	1.57(−5)	1.71(−5)	1.22(−4)
0.8	2.01	0.84	1.05(−4)	1.06(−4)	9.47(−4)
0.9	2.17	0.92	4.03(−4)	3.84(−4)	3.11(−3)
1.0	2.32	1.00	1.08(−3)	1.00(−3)	6.25(−3)
1.2	2.59	1.15	4.01(−3)	3.78(−3)	1.24(−2)
1.4	2.85	1.30	8.76(−3)	9.12(−3)	1.61(−2)
1.6	3.09	1.43	1.42(−2)	1.37(−2)	1.80(−2)
1.8	3.32	1.57	1.94(−2)	1.97(−2)	1.89(−2)
2.0	3.53	1.69	2.42(−2)	2.49(−2)	1.94(−2)
2.2	3.73	1.81	2.86(−2)	2.93(−2)	1.96(−2)
2.6	4.11	2.04	3.63(−2)	3.62(−2)	1.98(−2)
3.0	4.45	2.26	4.23(−2)	4.13(−2)	1.99(−2)
3.5	4.84	2.51	4.74(−2)	4.58(−2)	2.00(−2)
4.0	5.20	2.75	5.06(−2)	4.88(−2)	2.00(−2)
4.5	5.53	2.96	5.25(−2)	5.08(−2)	2.00(−2)
5.0	5.83	3.17	5.37(−2)	5.22(−2)	2.00(−2)



$$B_n(T_9) = 0.859 \exp\{-[(0.766/T_9^3)(1+0.0789T_9+7.74T_9^3)]\}, \quad 0.5 \leq T_9 \leq 1.5, \qquad \text{8a)}$$

$$B_n(T_9) = 0.055[1-\exp\{-(0.789T_9-0.976)\}], \quad 1.5 \leq T_9 \leq 5.0. \qquad \text{(8b)}$$

Dayras et al. 1977