Fusion measurements of $^{12}C + ^{12}C$ at energies of astrophysical interest

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Why do we care about fusion of $^{12}C+^{12}C$?

- Ignition temp. in explosive scenarios
  - X-ray superbursts
  - Type Ia supernovae

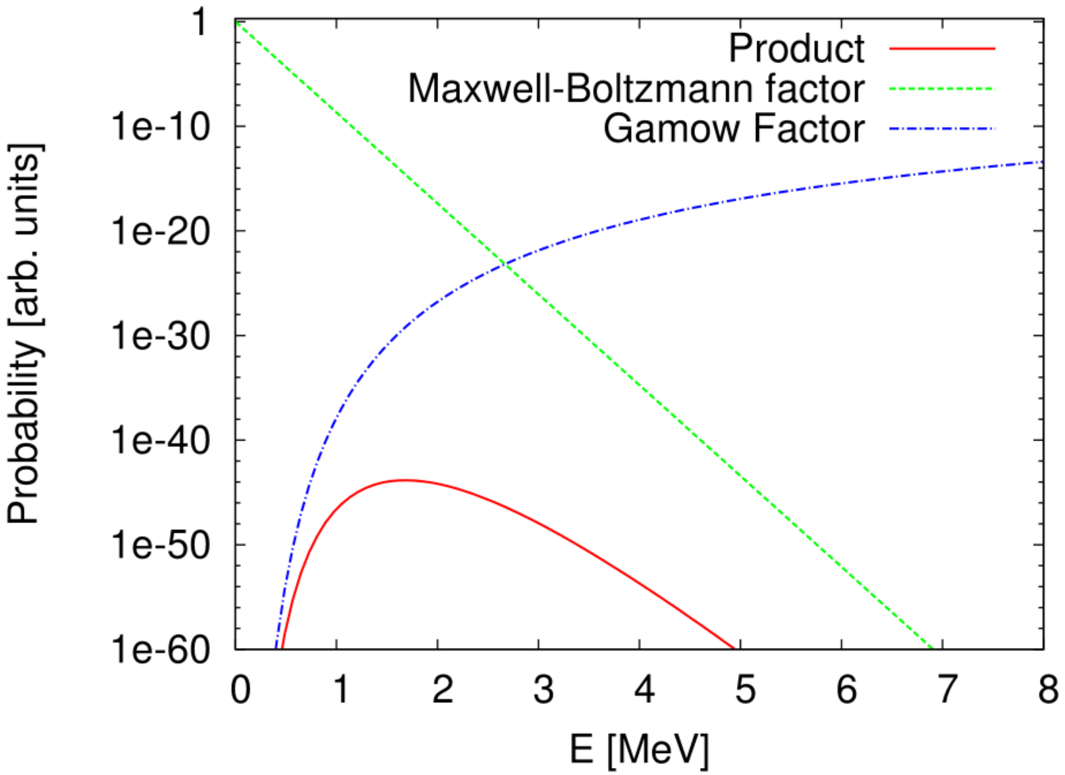
- Carbon burning in highly developed stars
  - If low-energy resonances → fast burning
  - If fusion hindrance → slow burning

• ^{12}C → stable, solid, abundant.
• Low-energy beam.
• Hasn't this been done before??

- Problems with existing data (low C.M. energies)
  - Low cross section (<10 nb!)
  - Large uncertainties (background, target impurities)
  - We still rely on extrapolations

What are energies of astrophysical interest?

- Depends on star temperature.
- In this case **1 < E$_{c.m.}$ < 3 MeV** (Gamow window)
- Well below Coulomb barrier (~7 MeV in CM).



A popular measurement

$$S(E) = \sigma E e^{2\pi\eta}$$

- Experimental limitations
  - Intense + low-E beam = difficult
  - Beam time! (few counts in ~10 h)
  - Target contaminants

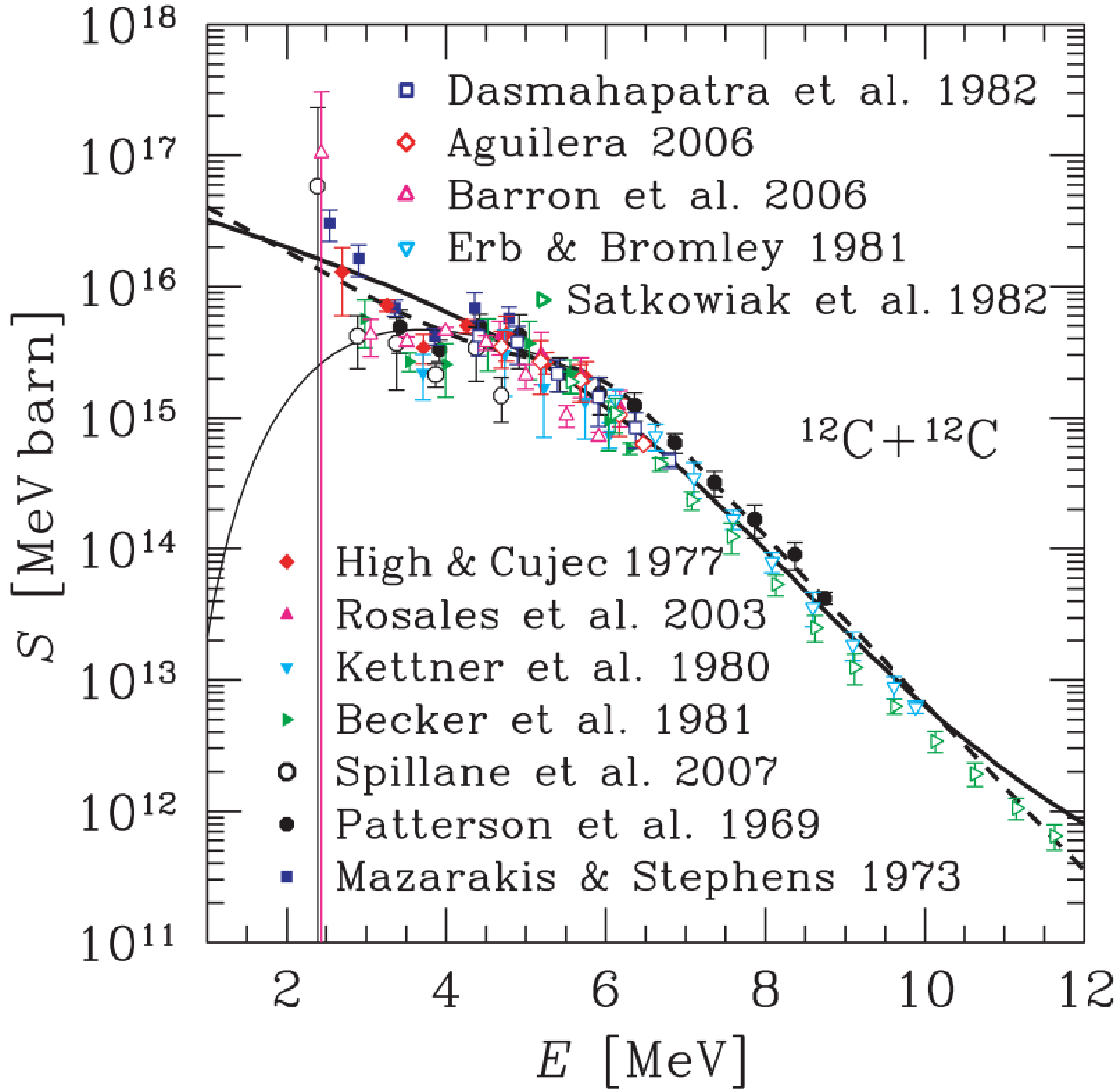


Image from Gasque, et al., Phys. Rev. C 72 025806 (2005)

Extrapolations

References:
Fowler, et al., Annu. Rev. Astro. Astrophys. 13 69-112 (1975)
Gasque, et al., Phys. Rev. C 72 025806 (2005)
Jiang, et al., Phys. Rev. C 75 015803 (2007)
Becker, et al., Z. Phys. A 303 305-312 (1981)
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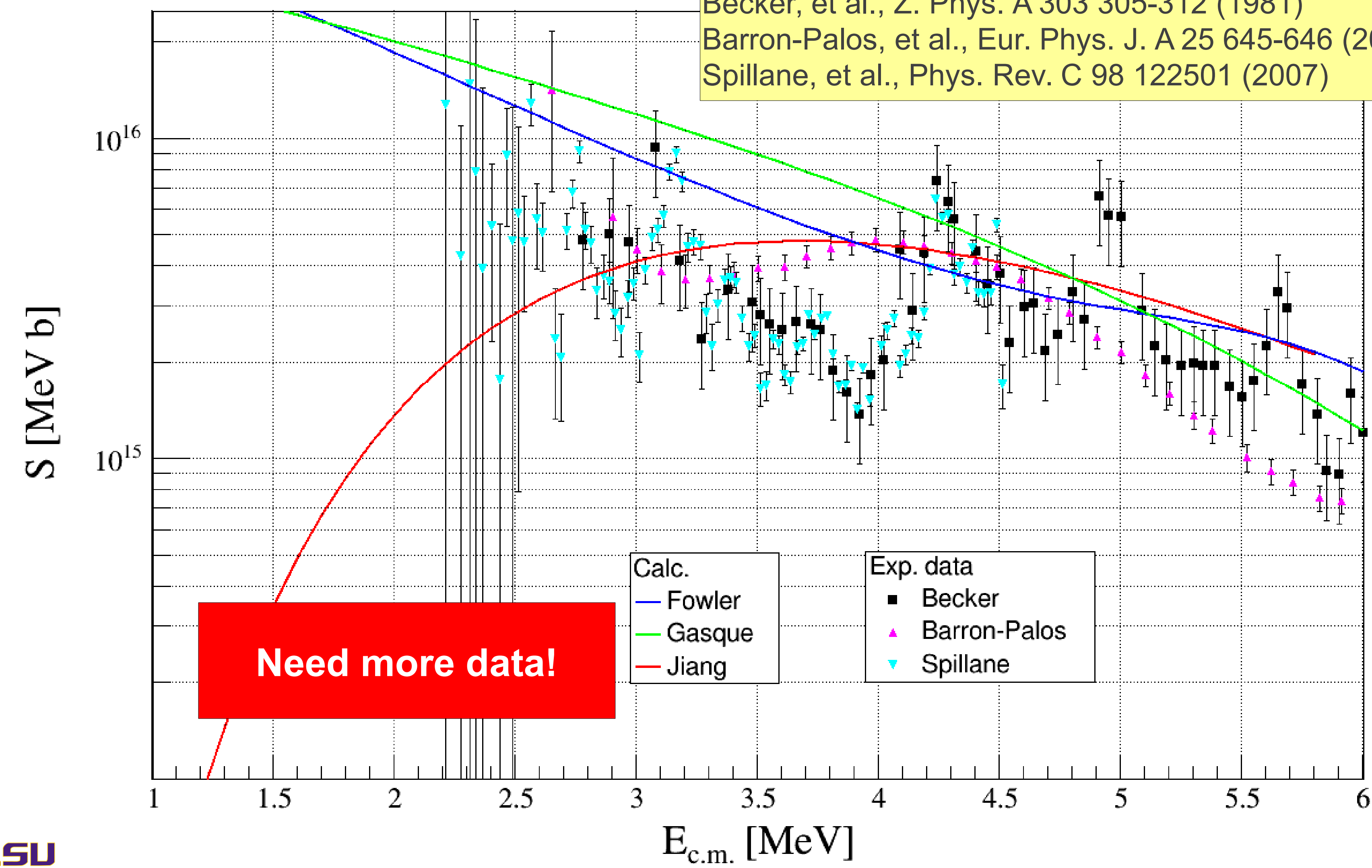
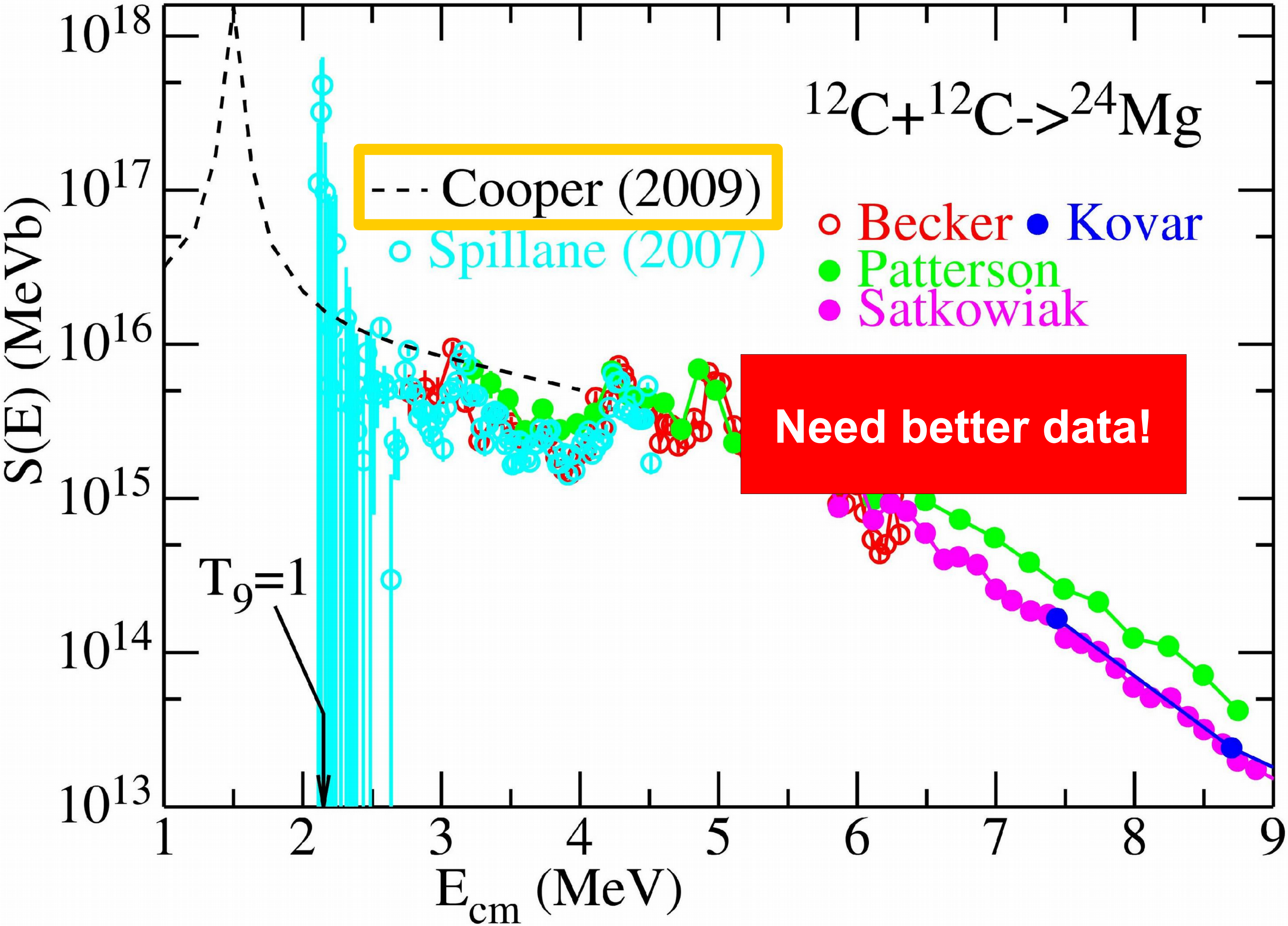
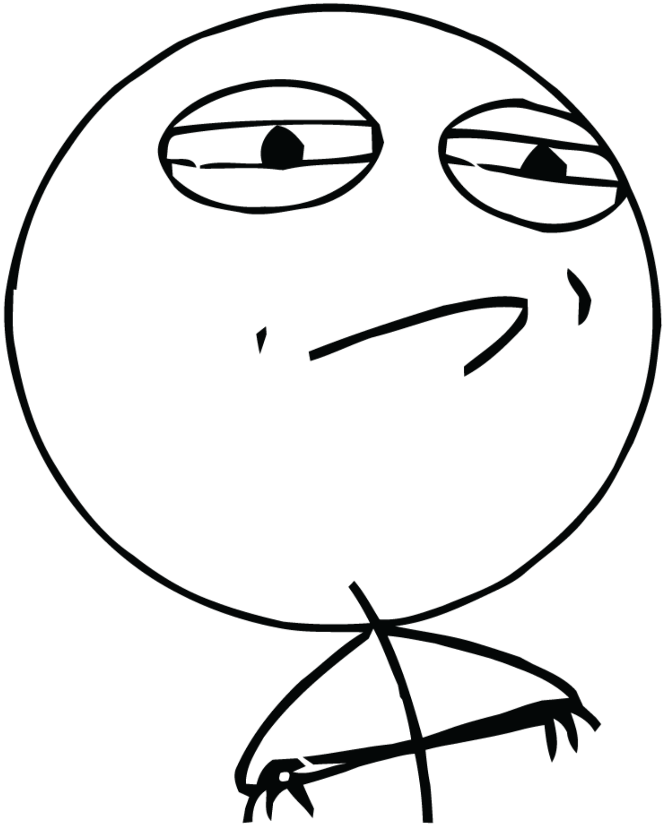
Spillane, et al., Phys. Rev. C 98 122501 (2007)




$^{12}C+^{12}C\text{->}^{24}Mg$
Cooper (2009)
Spillane (2007)
Becker
Kovar
Patterson
Satkowiak
Need better data!
$T_9=1$
S(E) (MeVb)
E_{cm} (MeV)
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
1
2
3
4
5
6
7
8
9

CHALLENGE ACCEPTED



Cheng Lie (2009)

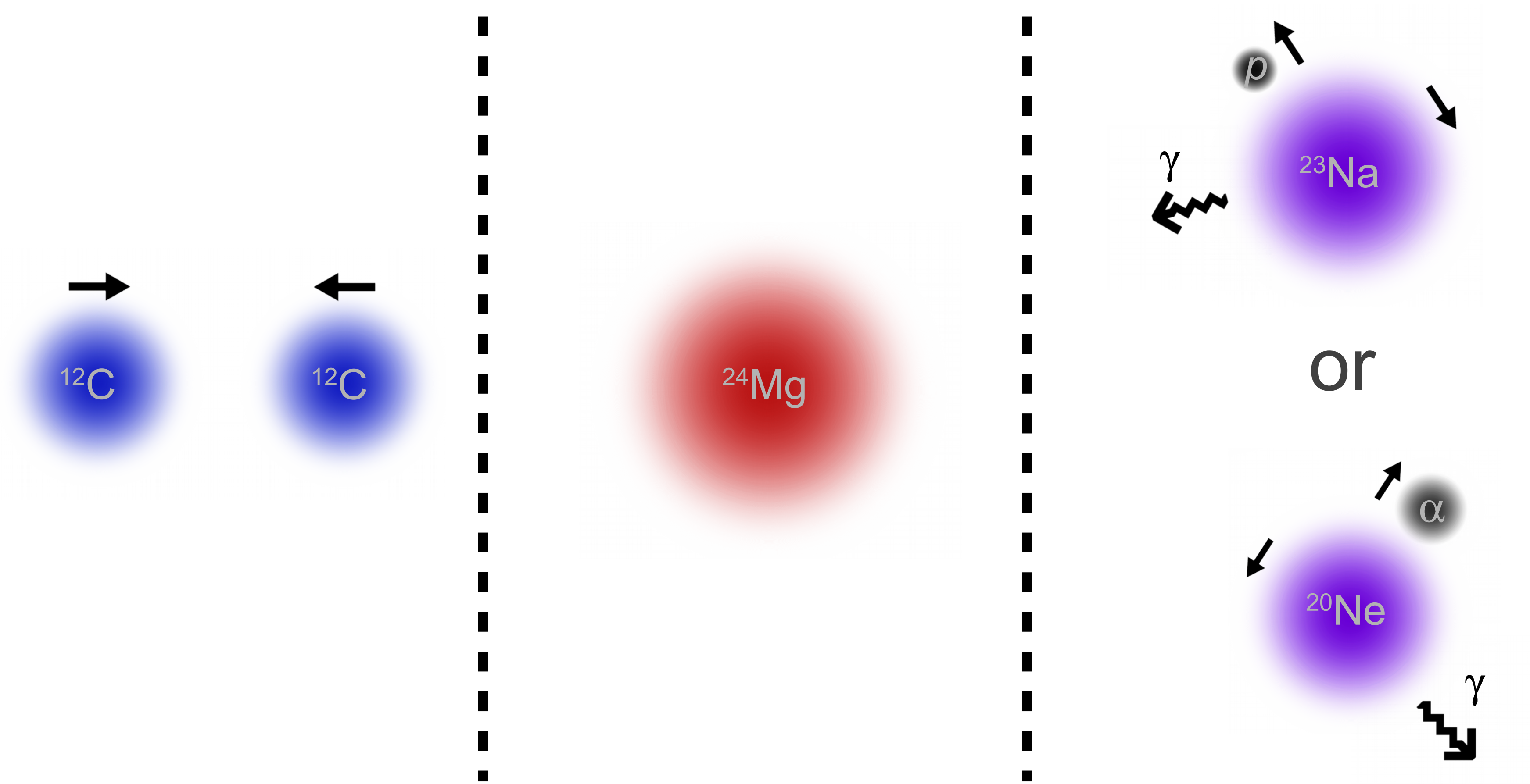
Need better data!

Fusion of $^{12}C + ^{12}C$ (center of mass)

1. Acceleration

2. Fusion

3. Evaporation

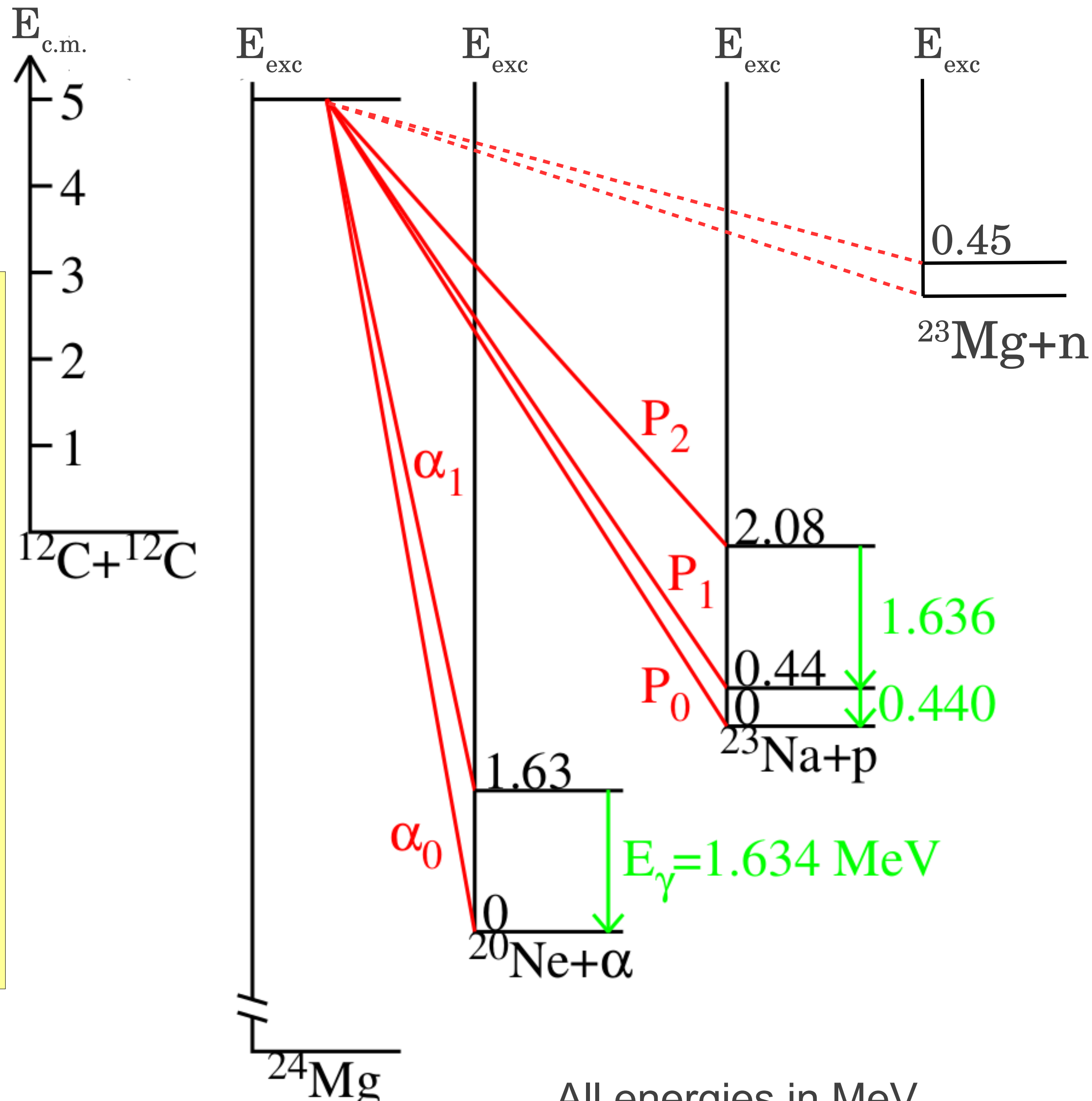


^{24}Mg decay scheme

We have developed a coincidence technique of γ rays and charged particles.
[Jiang *et al.*, Nucl. Instru. Meth. A **682**, 12 (2012)]

Effectively **suppresses** the **background**.

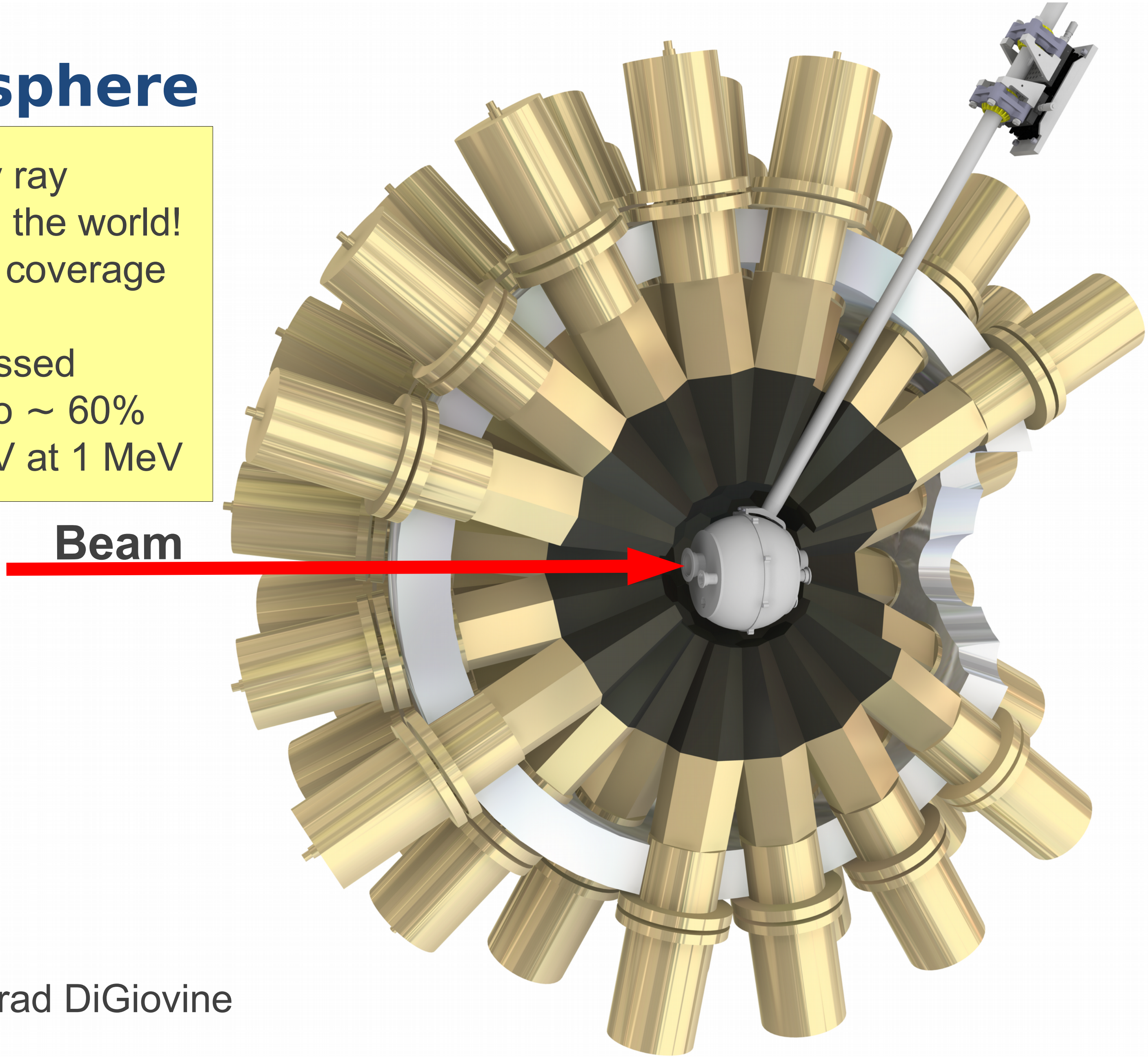
We use a compact array of silicon detectors placed at the center of Gammasphere.



All energies in MeV

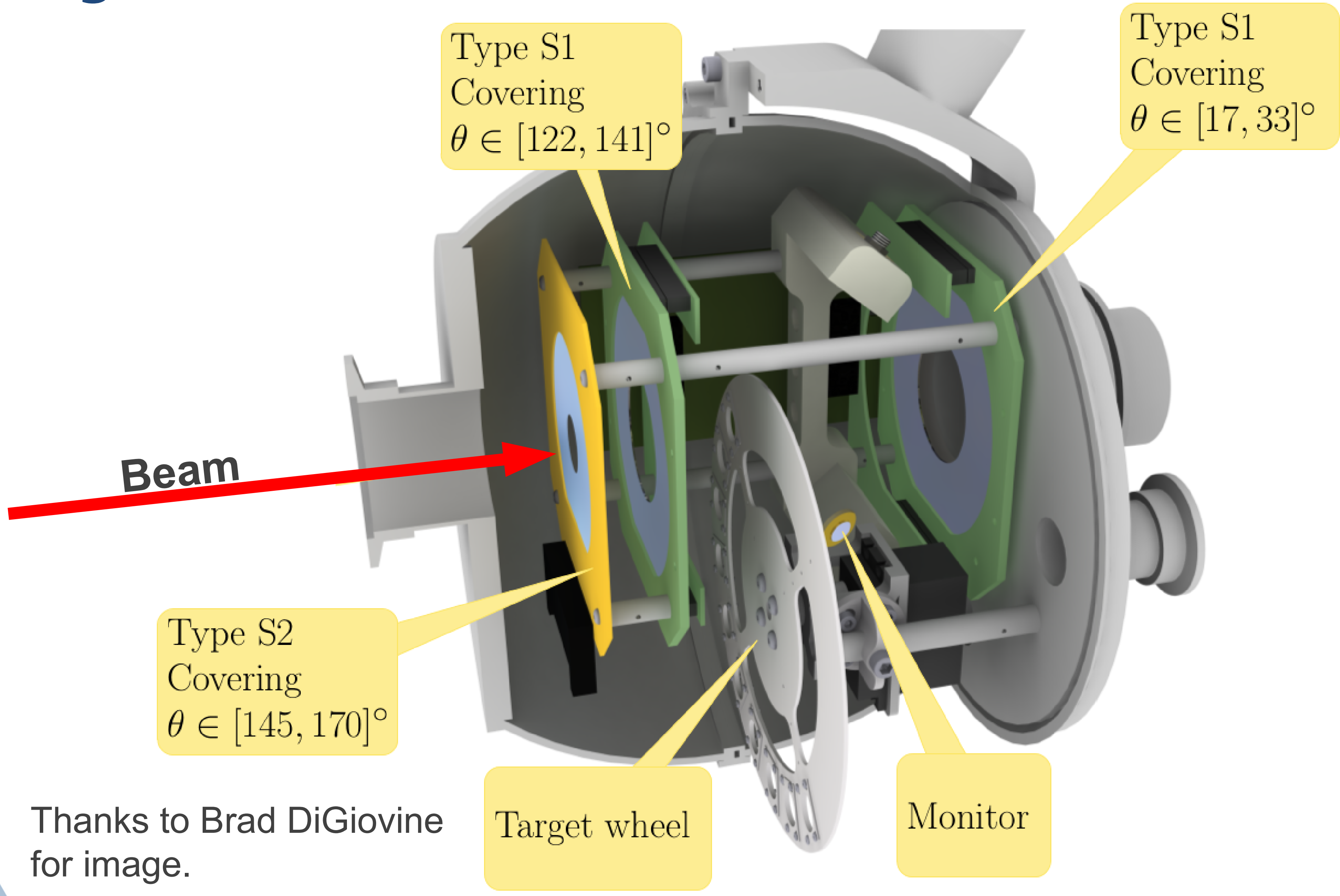
Gammasphere

- One of the best γ ray spectrometers in the world!
- ~ 4π solid angle coverage
- ~ 10% efficiency
- Compton suppressed
- Peak-to-total ratio ~ 60%
- Energy res. 3 keV at 1 MeV



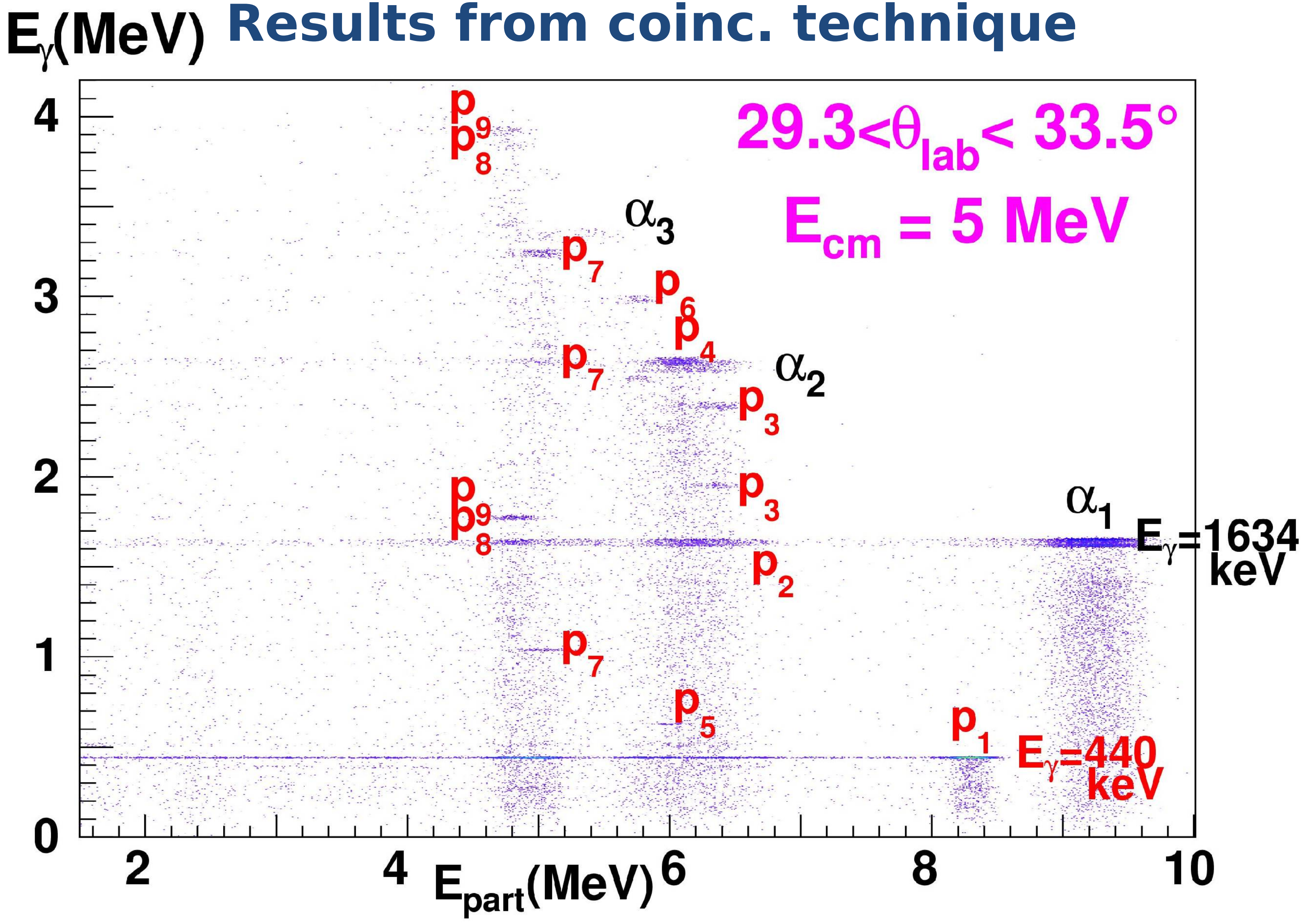
Thanks to Brad DiGiovine for image.

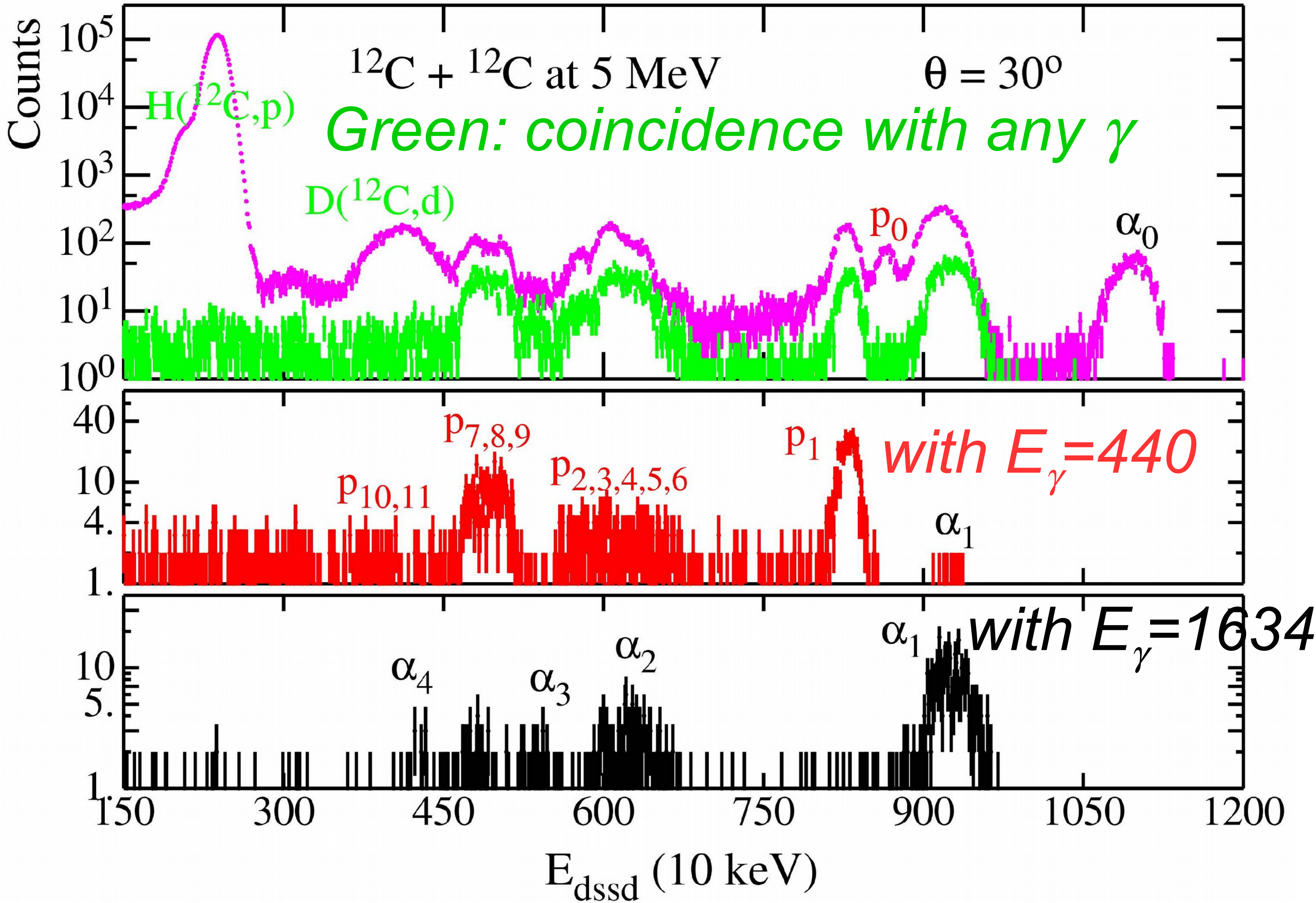
Target and Si detector chamber



Thanks to Brad DiGiovine for image.

Results from coinc. technique

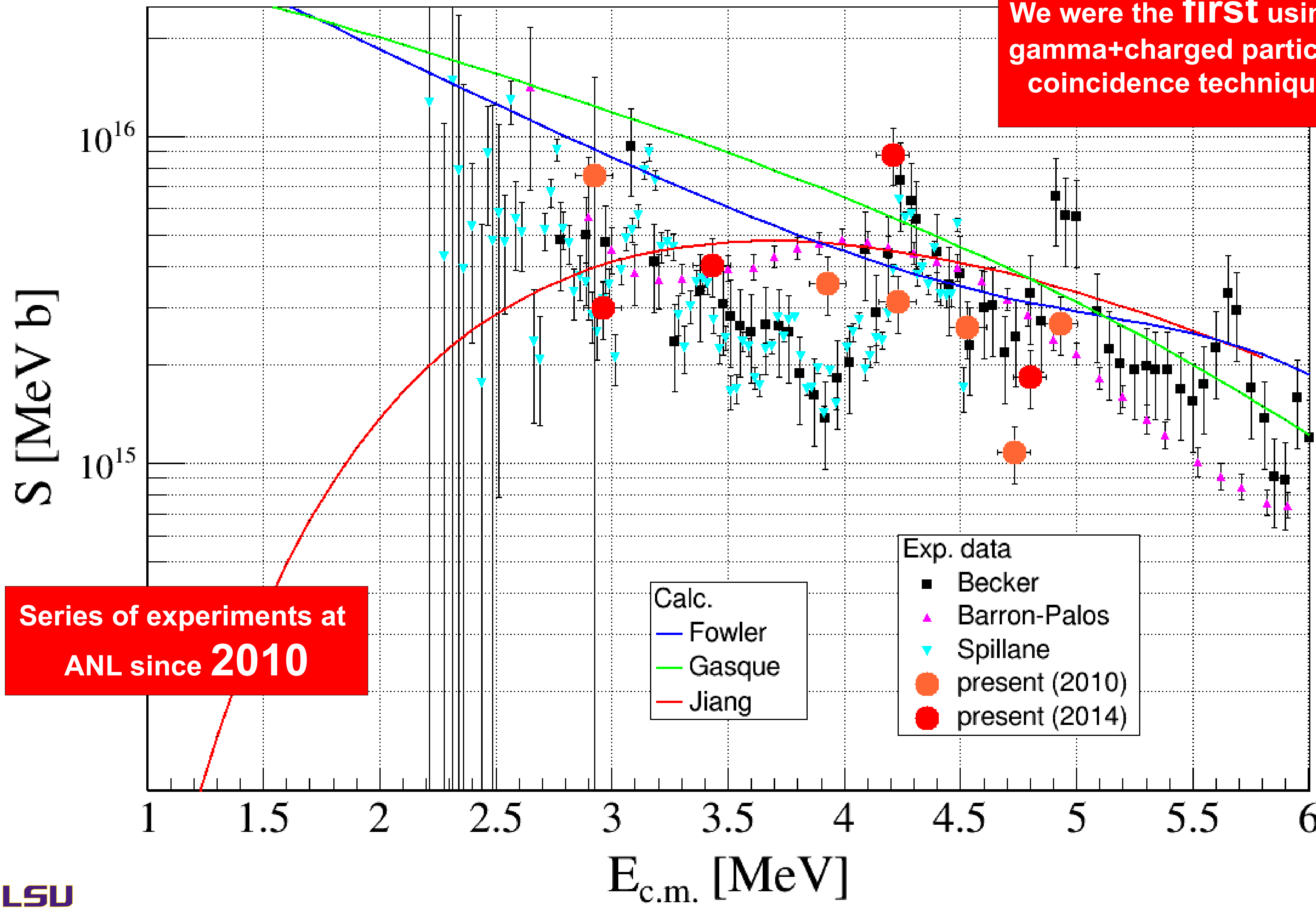




Counts
$^{12}C + ^{12}C$ at 5 MeV
$\theta = 30^o$
$H(^{12}C,p)$
Green: coincidence with any γ
$D(^{12}C,d)$
p_0
α_0
$p_{7,8,9}$
p_1
with E_γ=440
$p_{10,11}$
$p_{2,3,4,5,6}$
α_1
with E_γ=1634
α_4
α_3
α_2
E_{dssd} (10 keV)

Preliminary results

We were the first using gamma+charged particle coincidence technique



Series of experiments at ANL since 2010

Summary

- The cross section of the $^{12}C+^{12}C$ fusion reaction at energies well below the Coulomb barrier is important for models of stellar nucleosynthesis (Type Ia supernovae, X-ray superbursts).

- We were the first to measure the cross section using coincidence technique (since 2010).

- Our near-**background-free** measurements are consistent with previous measurements in the high-energy region but our lowest energy measurement indicates a fusion cross section slightly lower than those obtained with other techniques.

- The ramifications of using the **fusion hindrance extrapolation** method on simulations of the late stages of giant star evolution are substantial

- More data is needed for $E_{c.m.}$<2.9 MeV.

Perspectives

- New measurements around $E_{c.m.}$ = 2.8 MeV will be carried out at ANL using the gamma and charged particle coincidence technique.
- Exact energy will depend on 2-day measurement.
- The new data might help to discern between the extrapolations at low energy:
  - Fowler → 'normal'
  - Cooper → low-E resonance
  - Jiang+Esbensen → hindrance

Collaboration

Fusion measurements of $^{12}C+^{12}C$ at energies of astrophysical interest

D. Santiago-González[1,2], C. L. Jiang[2], K. E. Rehm[2], M. Alcorta[3], S. Almaráz-Calderón[4], M. L. Avila[2], A. D. Ayangeakaa[2], B. B. Back[2], D. Bourgin[5], B. Bucher[6], M. P. Carpenter[2], S. Courtin[5], H. M. David[2], C. M. Deibel[1], C. Dickerson[2], B. DiGiovine[2], X. Fang[7], J. P. Greene[2], F. Haas[5], D. J. Henderson[2], R. V. F. Janssens[2], D. Jenkins[8], J. Lai[1], T. Lauritsen[2], A. Lefebvre-Schuhl[9], D. Montanari[5], R. C. Pardo[2], M. Paul[10], D. Seweryniak[2], X. D. Tang[11], C. Ugalde[2], S. Zhu[2]

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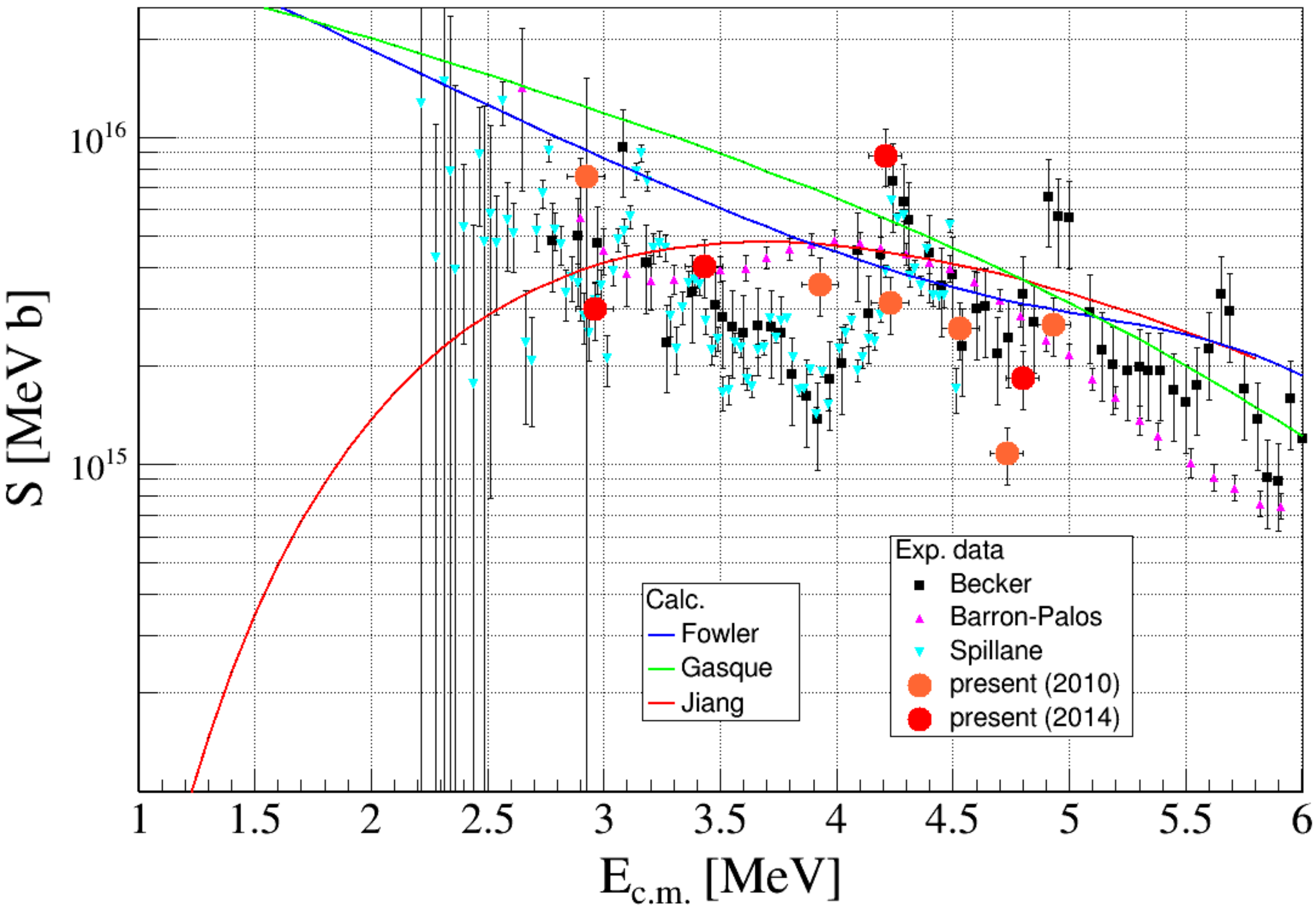

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Backup slides

Calc. fusion rates in different stellar env.

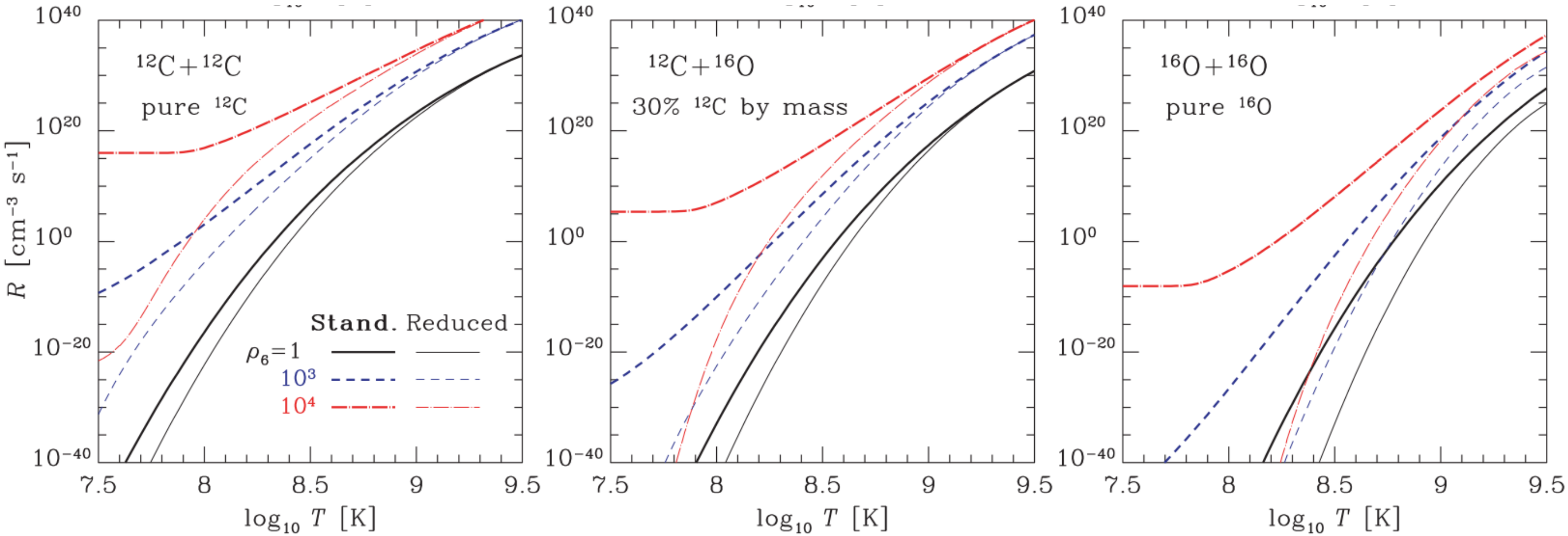

FIG. 1. (Color online) (Top) Astrophysical factors for the ^{12}C+^{12}C, ^{12}C+^{16}O, and ^{16}O+^{16}O reactions versus center-of-mass energy E of colliding nuclei. Various symbols show experimental data. (Middle) Normalized rates of these reactions versus temperature neglecting plasma screening effects. (Bottom) Rates of the same reactions versus temperature for three values of the density ($\rho = 10^6$, 10^9, and 10^{10} g cm^{-3}, $\rho_6 \equiv \rho/10^6$ g cm^{-3}) in pure carbon matter (left), in a C-O mixture with 30% of carbon by mass (middle), and in pure oxygen matter (right). Thick lines refer to standard S-factors (either recent model calculations [1,2], denoted as Standard, or the formalism of Fowler *et al.* [5,6]. denoted as Standard1); thin lines refer to reduced S-factors (Jiang *et al.* [12]). See text for details.

Ref: Gasque, et al., Phys. Rev. C 72 025806 (2005)

Fusion hindrance [Jiang, et al., PRC 79, 044601 (2009)]

- one has to rely on extrapolation techniques.
- In the past, all extrapolations used optical model calculations which predicted a continuously rising S factor.
- Recent fusion experiments with medium-mass systems have revealed a hindrance of the fusion cross section which leads to a maximum of the S factor, followed by a decrease toward lower energies.
- For these medium-mass systems, which all have negative Q values, a maximum of the S factor should be expected because of
- energy conservation.
- While this hindrance has been associated with the incompressibility of nuclear matter at large density overlaps [41], a fully reliable theoretical description of the cross sections at sub-barrier energies has yet to be developed.
- Extending the systematics developed at first for systems with
- a negative Q value to the fusion of light heavy ions leads
- to cross sections which are quite different from the ones
- obtained from optical model calculations. Other calculations
- within the frameworks of the two-center shell model or
- fermionic molecular dynamics give cross sections which