

Present Status of Direct Measurements of $^{12}\text{C}+^{12}\text{C}$



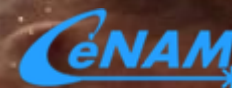
JINA-CEE



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University of Notre Dame

Atomic and Nuclear Quantum Effects
Near Threshold Workshop at Edinburgh



CeNAM/IReNA Workshop – Jun. 1, 2023

Acknowledgments

■ **12C+12C published: *PHYS. REV. LETT.* 124, 192702 (2020)**

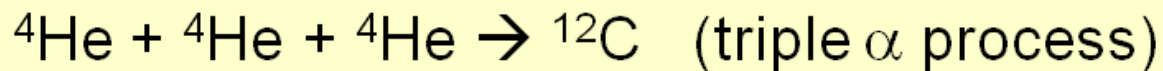
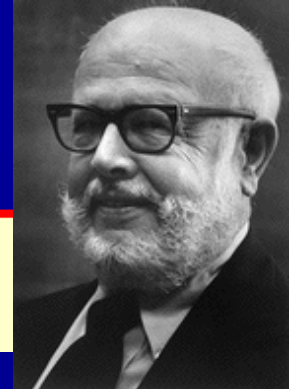
- S. Aguilar, A. Boeltzig, C. Dulal, R. deBoer, B. Frentz, G. Gilardy, S. Henderson, K. Howard, R. Kelmar, J.J. Kolata, J. Long, K. Macon, S. Moylan, G.F. Peaslee, M. Renaud, C. Seymour, B. Vande Kolk, M. Wiescher, University of Notre Dame
- E. F. Aguilera, P. Amador-Valenzuela, D. Lizcano, E. Martinez-Quiroz, ININ, Mexico
- $E_{cm}=2.2, 2.65-3.0, 4.1-5.0$ MeV

■ **12C+12C 2nd campaign: (to cover the gap between 3-4.1 MeV)**

- O. Gomez, A. Gula, K. Lee, A. Majumdar, S. Moylan, S. Shahina, M. Wiescher, University of Notre Dame
- E. F. Aguilera, D. Lizcano, E. Martinez-Quiroz, J. Morales-Rivera, ININ, Mexico



Bridge to Heavy Nuclei

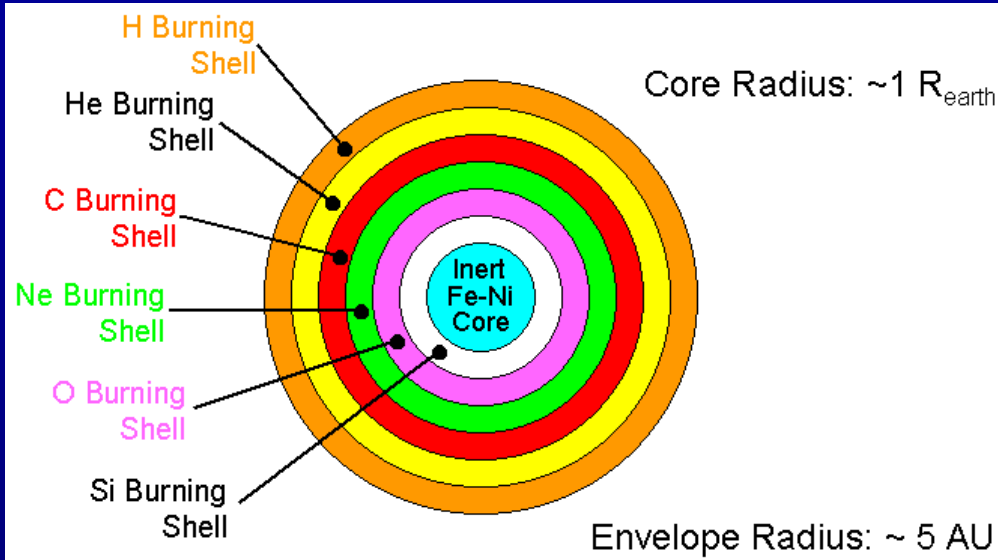


■ Critical triple alpha process

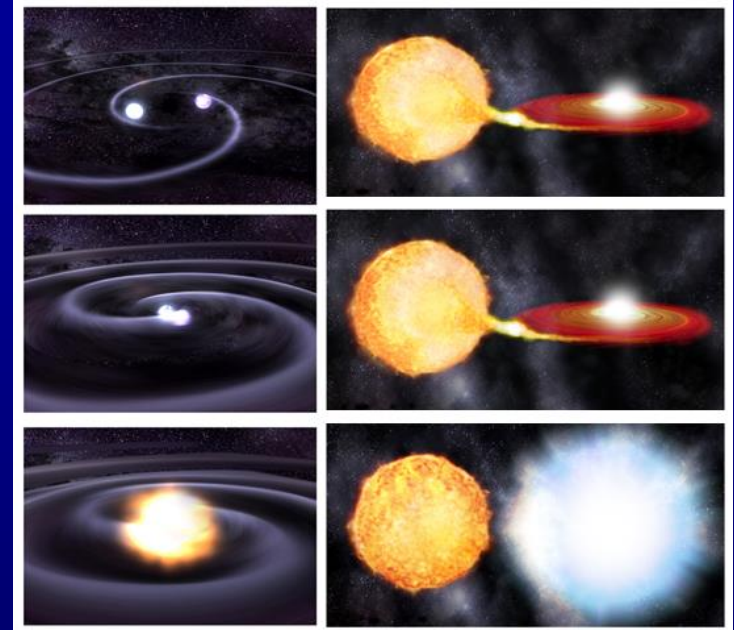
- First step: $\alpha + \alpha = {}^8\text{Be}$ (unbound by ~ 92 keV – decays back to 2α within $2.6\text{E-}16$ s)
- Second step: $\alpha + {}^8\text{Be} = {}^{12}\text{C}^*$ (would create ${}^{12}\text{C}$ at excitation energy of ~ 7.7 MeV)

- In early 1950s, Fred Hoyle first realized that the universe requires a resonance level in ${}^{12}\text{C}$ at ~ 7.7 MeV
- Shortly after, Fowler's group at Caltech discovered a state with the correct properties (0^+ at 7.654 MeV)

Carbon Fusion in Astrophysics



The double degenerate (left) and single degenerate (right) models of a type Ia supernova. Images taken from Wikipedia Commons and Discover Magazine.



- $^{12}\text{C} + ^{12}\text{C}$
- Late stellar burning in massive stars
- Type Ia supernova explosions
- Superbursts in accreting neutron stars

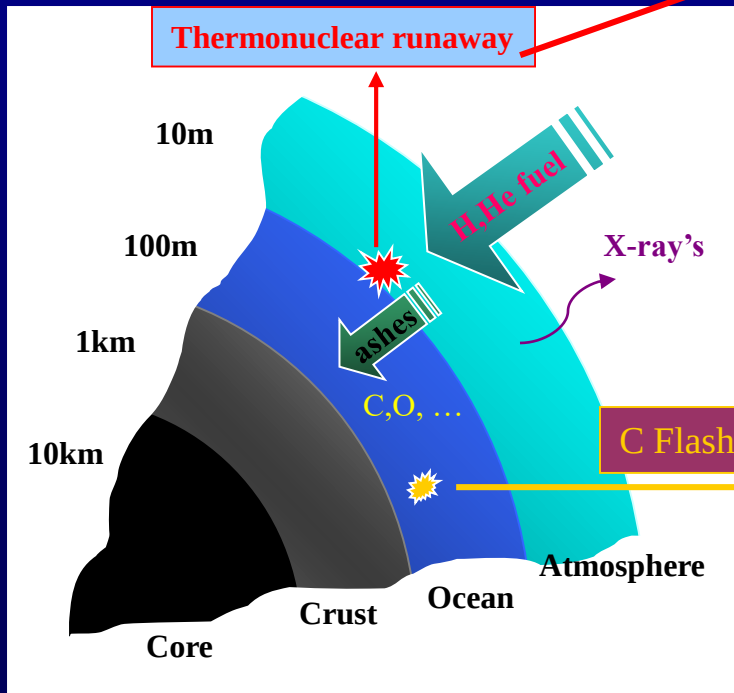
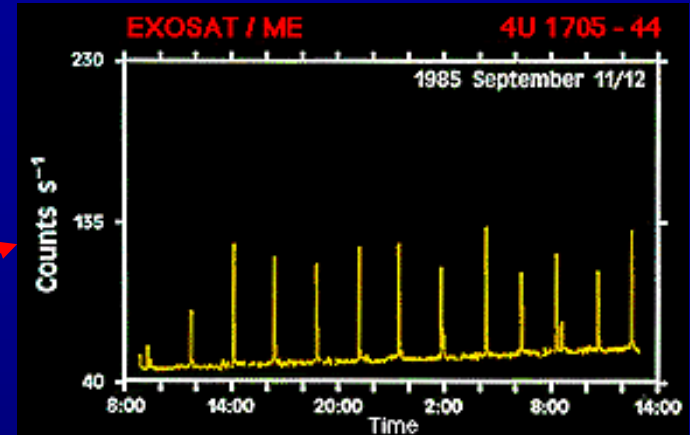


thermonuclear explosion

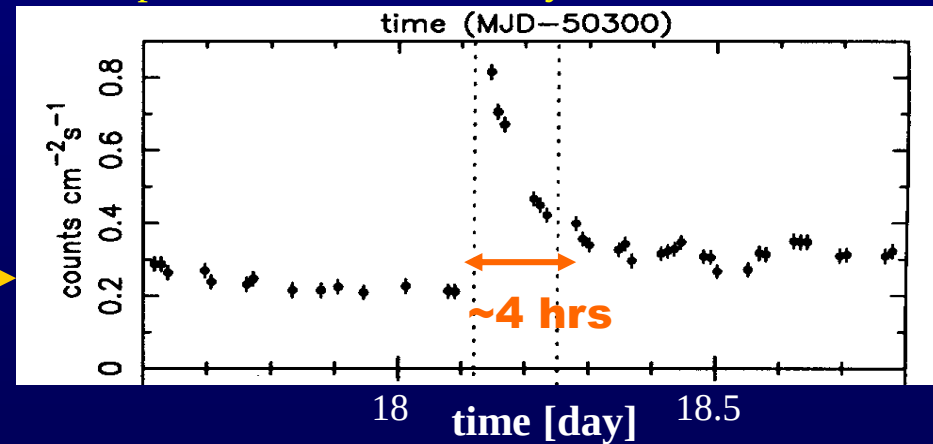
Photo Credit: David A. Hardy & PPARC

X-ray (Super)Bursts

- First X-ray burst: 3U 1820-30 by Grindlay et al, 1976
- Type I X-ray bursts: 10-100s, 10^{39} erg
 - Thermonuclear runaways from accreting neutron star of a close binary system
- Superbursts: 1000x stronger and longer

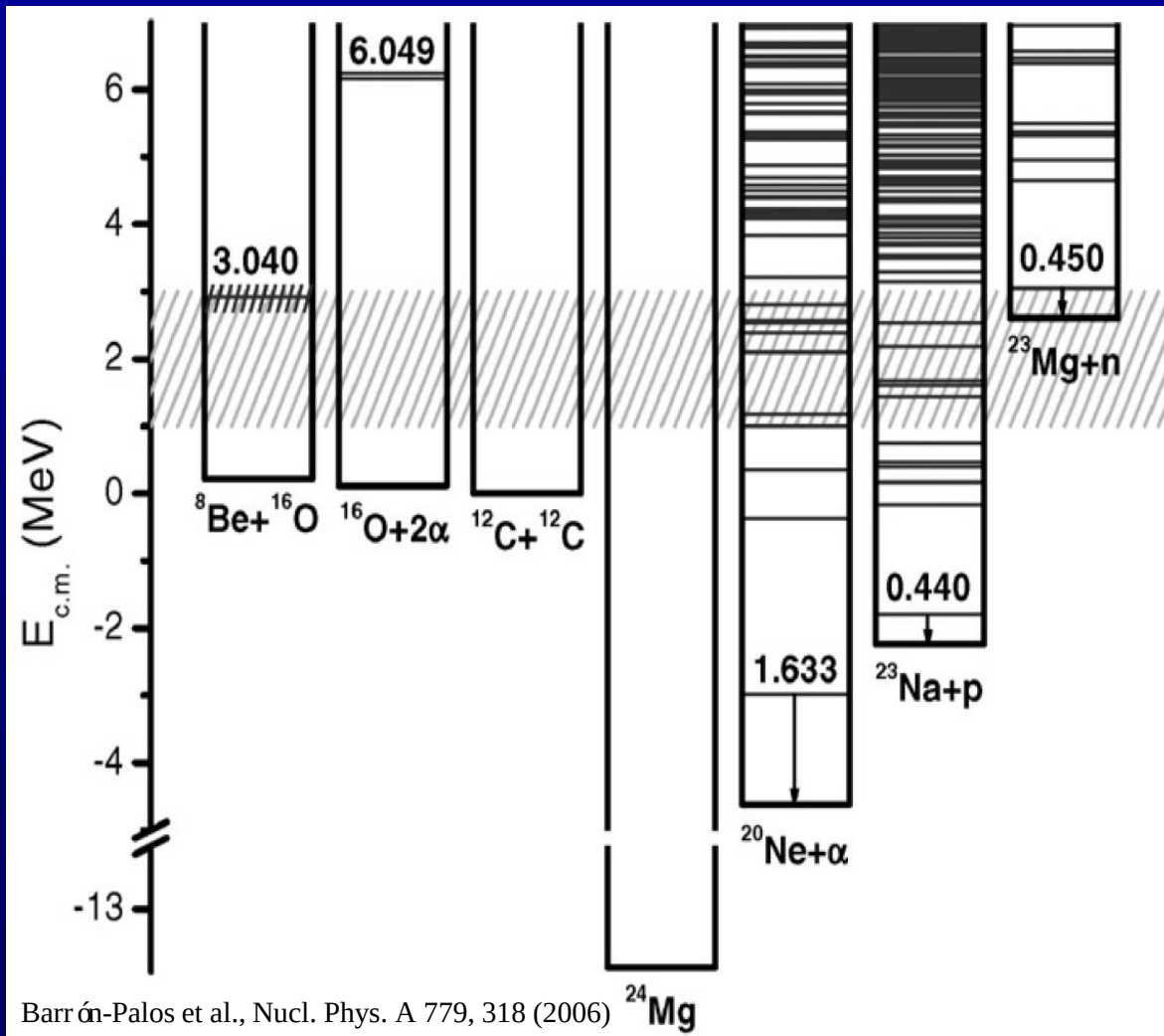


First SuperBurst: 4U 1735-44 by Cornelisse et al, 2000





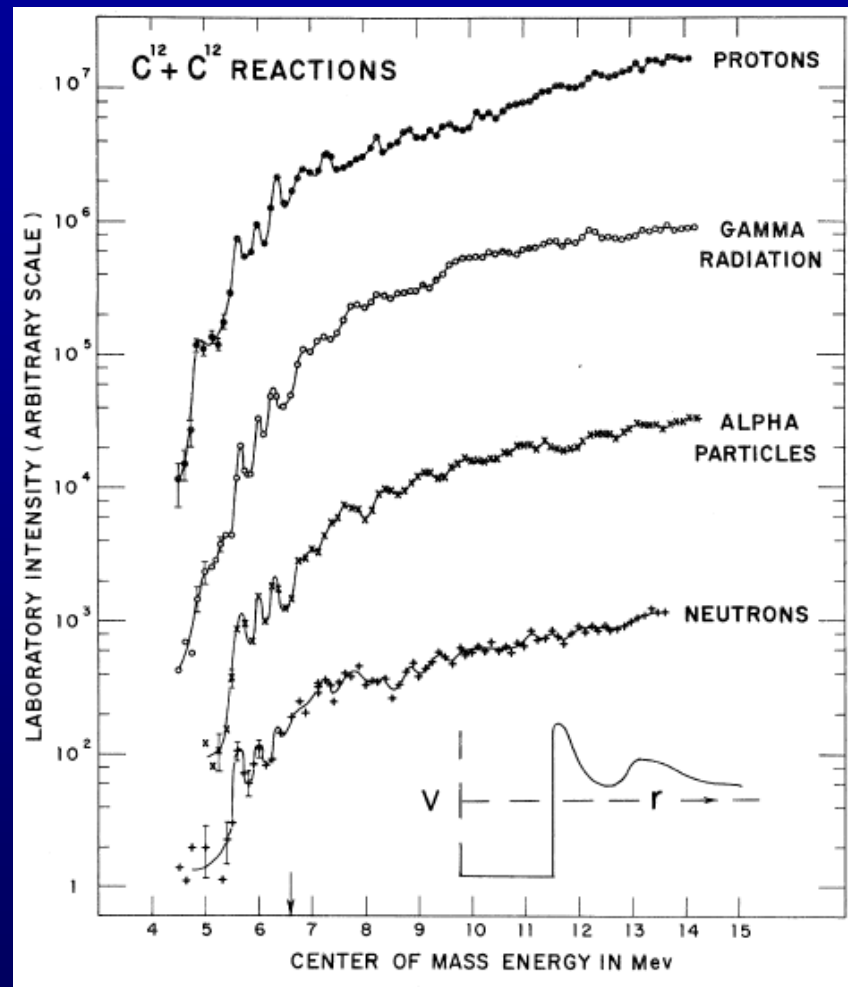
$^{12}\text{C}+^{12}\text{C}$ fusion reaction



- High Coulomb barrier $\rightarrow$ extremely low cross section
- Compound nucleus – Statistical Model
- Many open exit channels – coincidence technique

What at play for Carbon fusion?

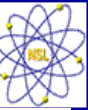
- Three major channels: p, α , n
- Resonance-like structures? Their nature?
- Is hindrance also at play in light fusion systems?
- How to increase sensitivity and reduce background for very low cross sections ($< \text{nb}$)?
 - High intensity beams
 - Pure targets
 - Coincidence technique with large detector arrays
 - Alternative methods



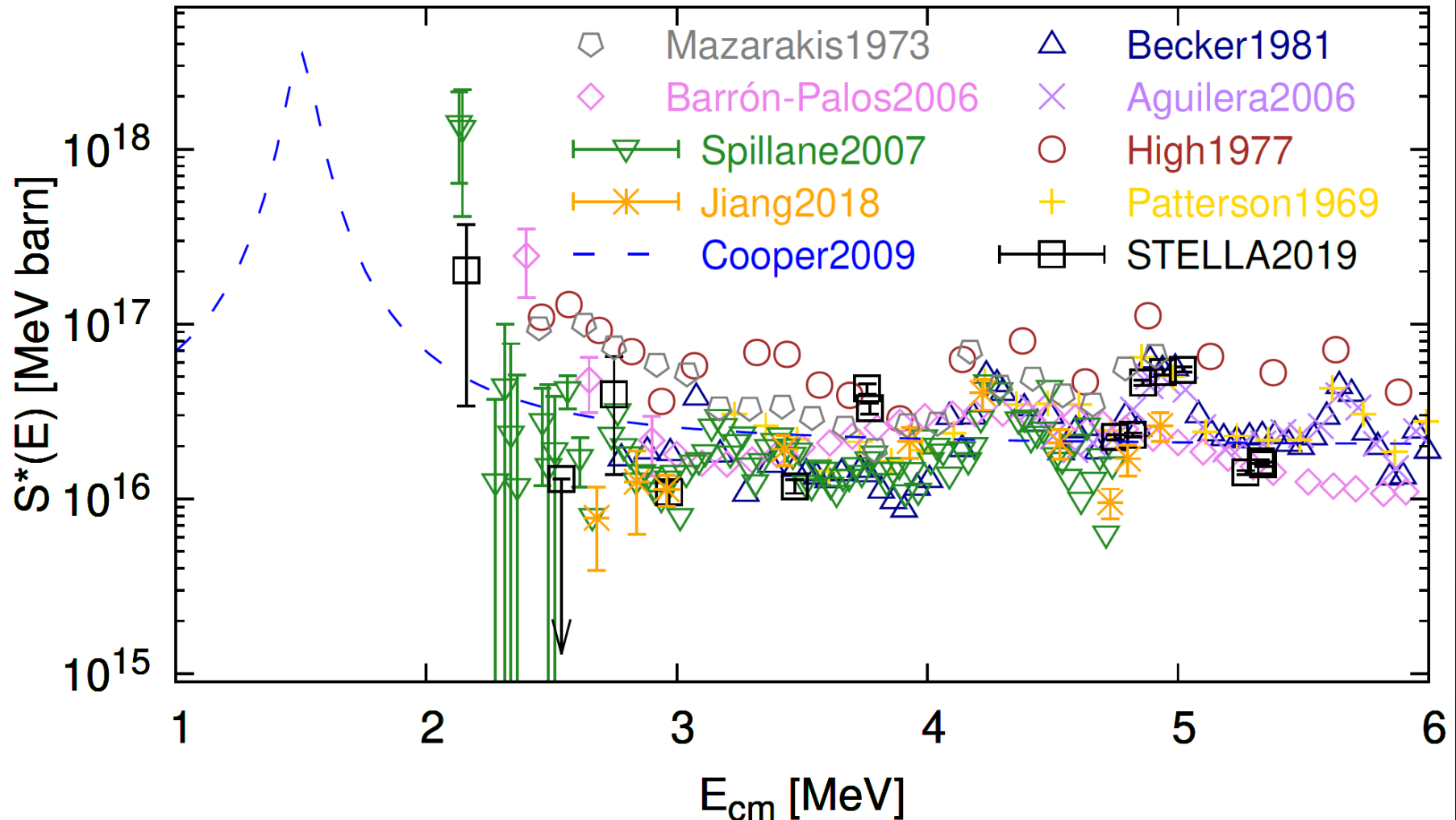
E. Almqvist et al., Phys. Rev. Lett. 4, 515 (1960)

More recent experimental works

- Previous works are mostly singles measurements, i.e., detection of either charged particles or gammas.
- Coincidence measurements (charged particle – gamma)
 - ANL, Jiang et al., PRC 97, 012801R, 2018
 - STELLA, Fruet et al., PRL 124, 192701, 2020
 - Notre Dame, Tan et al., PRL 124, 192702, 2020 + 2nd campaign
- Singles measurements (dE-E telescope for p/ α separation)
 - CIRCE-Caserta, Morales-Gallegos et al., Eur. Phys. J. A (2022) 58:65
- Indirect measurements (Trojan Horse Method, etc.)
 - THM, $^{12}\text{C}(^{14}\text{N},d)$, INFN, Tumino et al., Nature 557, 687 (2018)
 - $^{24}\text{Mg}(a,a')$, iThemba, Adsley et al., PRL 129, 102701 (2022)



Status: 12C+12C Fusion



- Test of doubtful resonances at 2.1 and 1.5 MeV.
- Use high intensity beam and coincidence and differential thick target techniques we developed at ND.



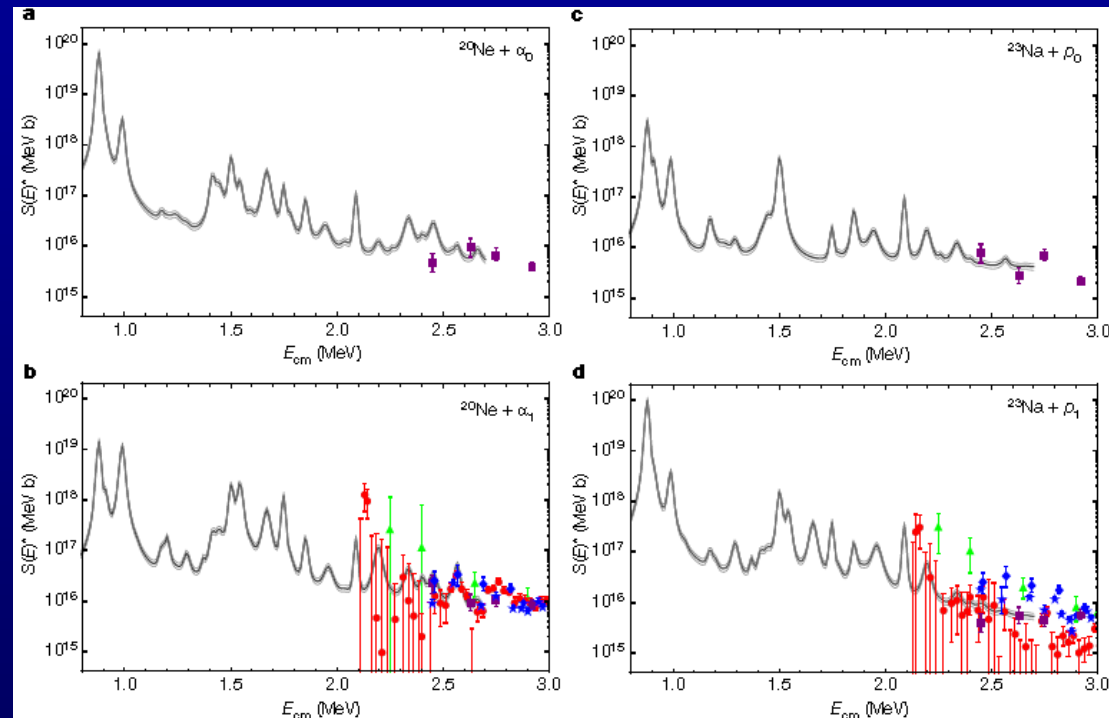
More resonances?

- New THM measurement: many resonances between $E_{\text{cm}} = 1 \text{ MeV}$ and 2.5 MeV are claimed

- $^{12}\text{C}(^{14}\text{N}, ^2\text{H})^{24}\text{Mg}^* \rightarrow \text{p}/\alpha$ channels at INFN

- Orders of magnitude increase on reaction rate

- Tumino et al., Nature 557, 687 (2018)



Counter-arguments

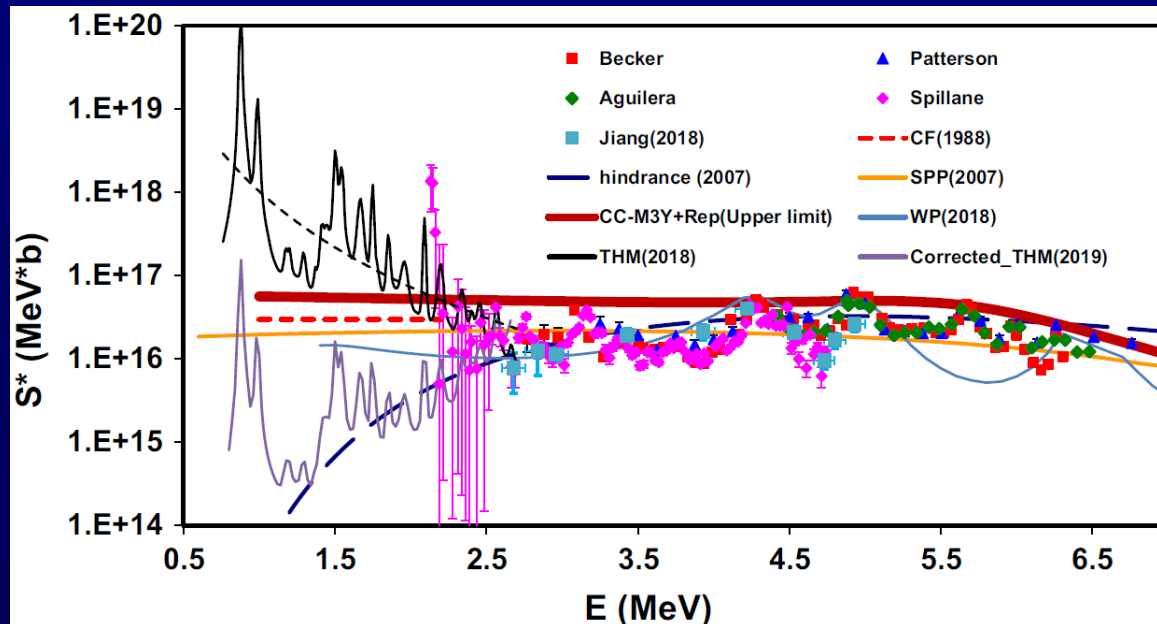
- Mukhamedzhanov, Pang & Kadyrov, Phys. Rev. C 99, 064618 (2019); Beck, Mukhamedzhanov & Tang, Eur. Phys. J. A 56, 87 (2020)

Final verdict: direct measurement

Two Issues Near Threshold

- Resonance-like structures at lower energies?
- What is the trend of the S-factor (going up or down)?
 - Hindrance effect?
- Only experimental data can finally resolve the issues !

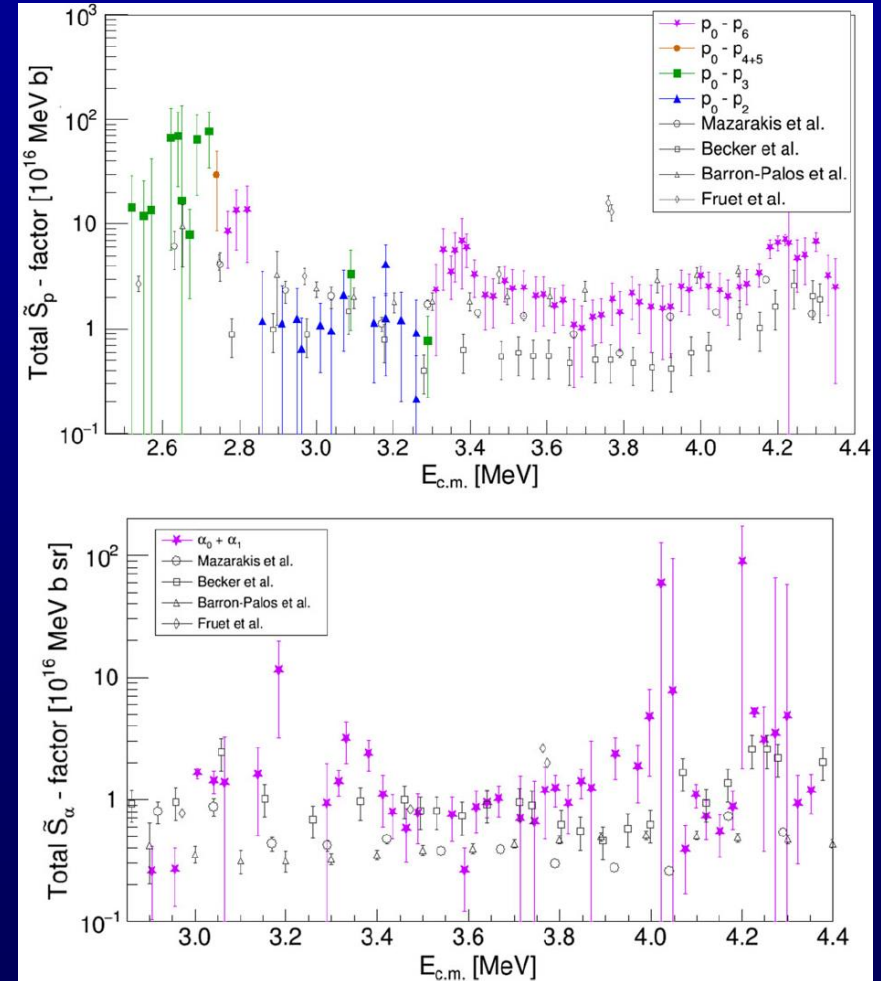
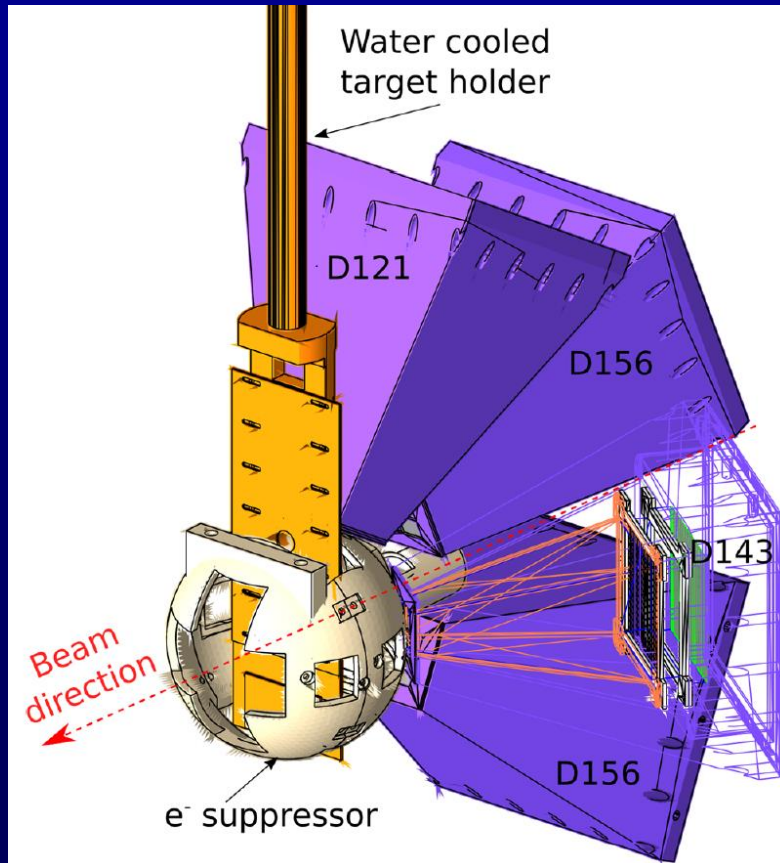
Beck et al., Eur. Phys. J. A 56, 87 (2020)



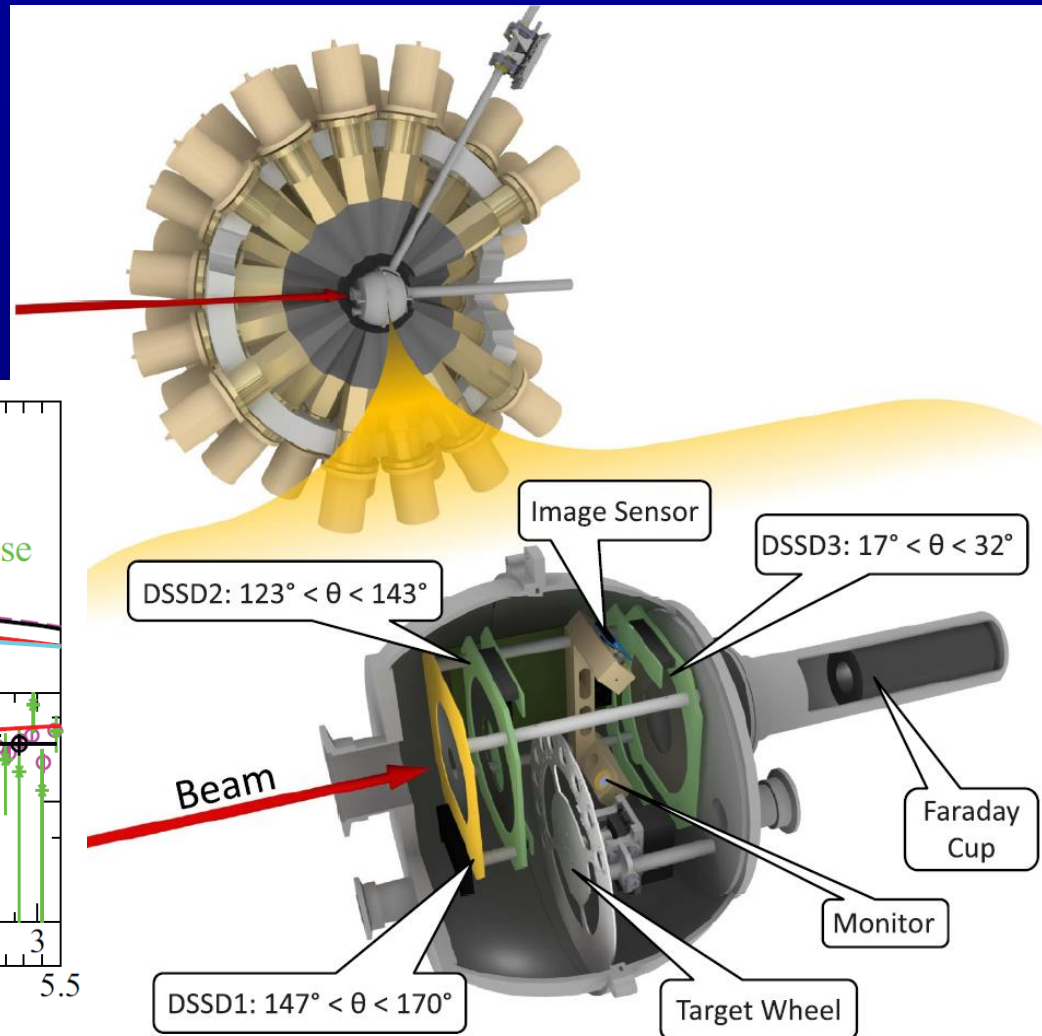
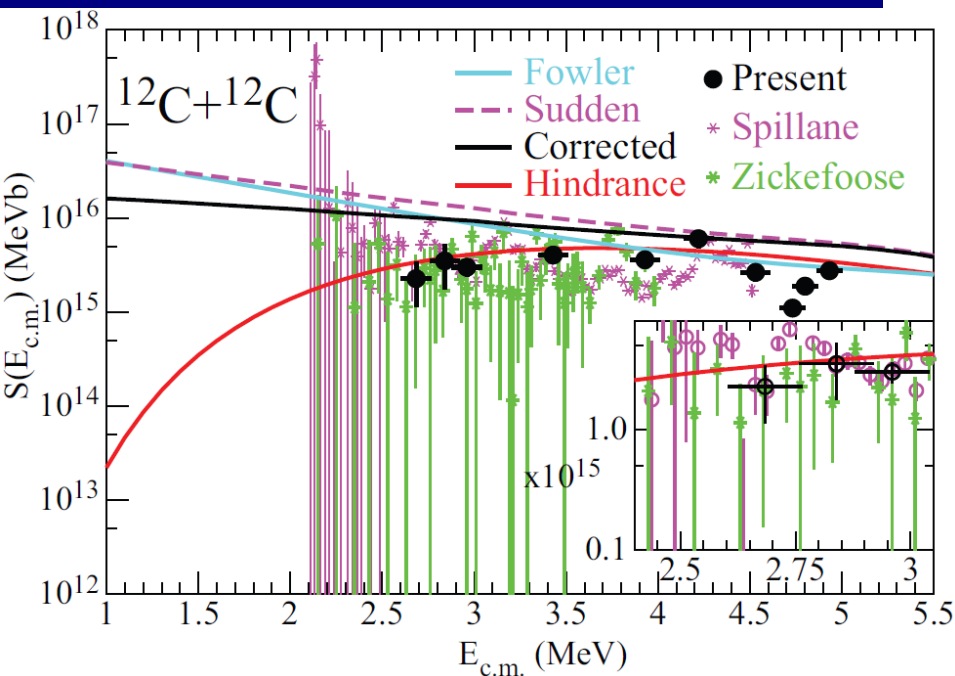
Singles Measurement using Telescopes

Morales-Gallegos et al., Eur. Phys. J. A 58, 65 (2022)

- Detect protons and alphas using dE-E technique
- IC + SSD, three angles: 121, 143, 156 degrees
- Thick target: HOPG



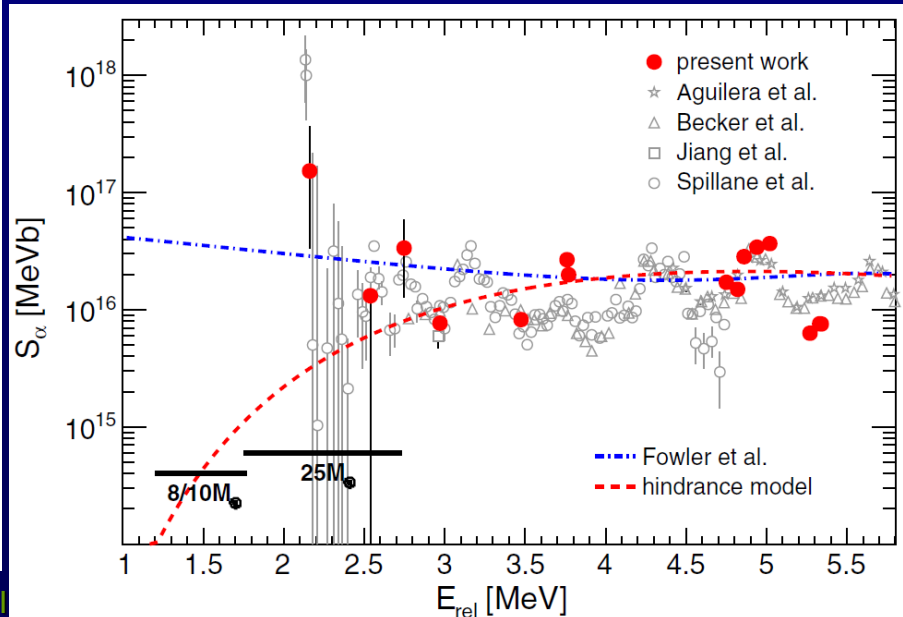
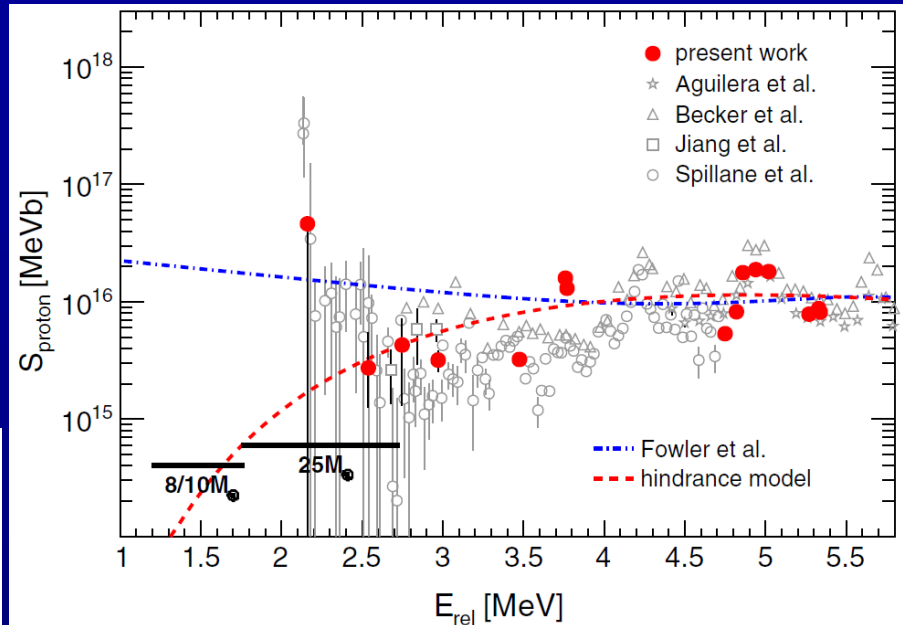
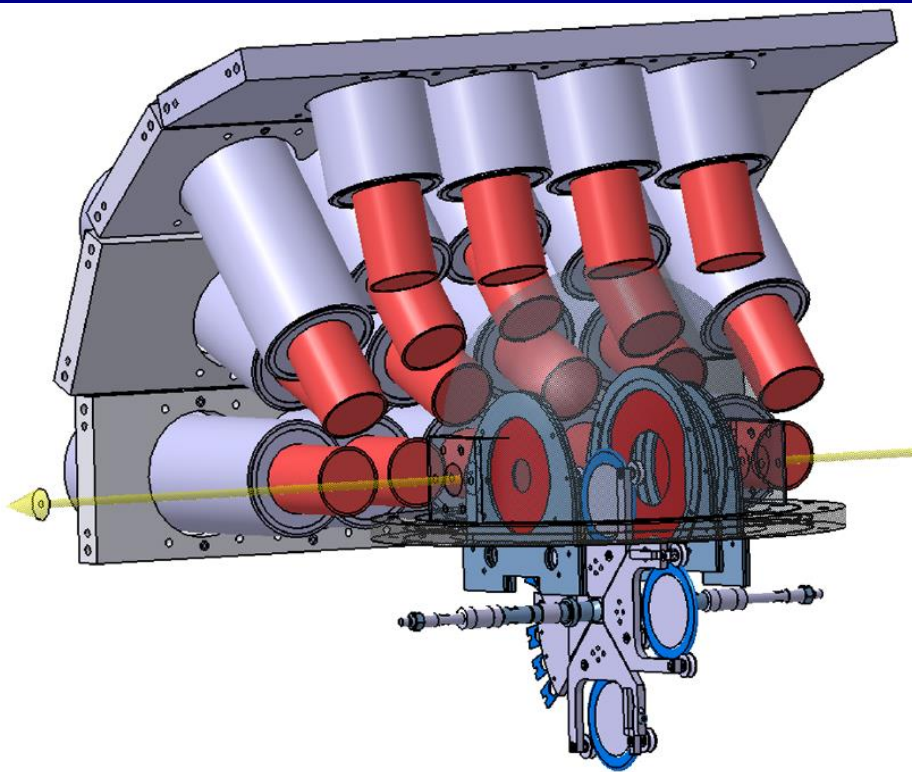
- Thin targets: $30\text{--}50\text{ }\mu\text{g}/\text{cm}^2$
- ^{12}C Beam: up to $0.6\text{ }\mu\text{A}$
- Gammasphere + Silicon



STELLA Coincidence Measurement

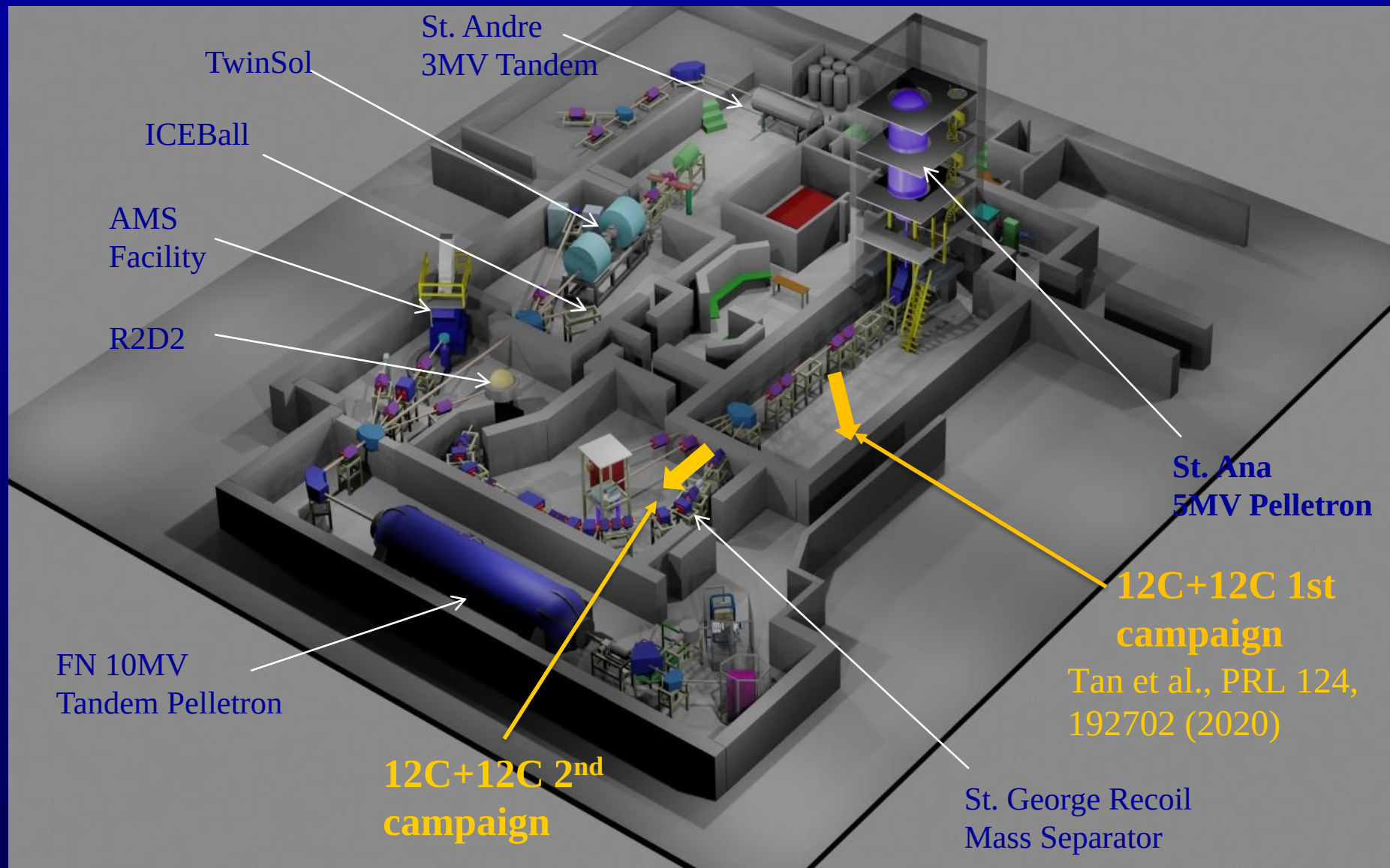
Fruet et al., PRL 124, 192701 (2020)

- Thin target: 20-70 $\mu\text{g}/\text{cm}^2$
- Beam: up to 2 $\text{p}\mu\text{A}$
- LaBr₃ + Silicon

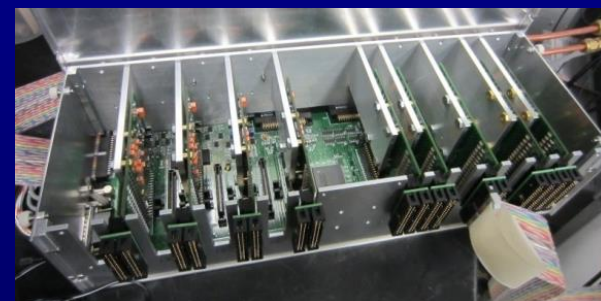
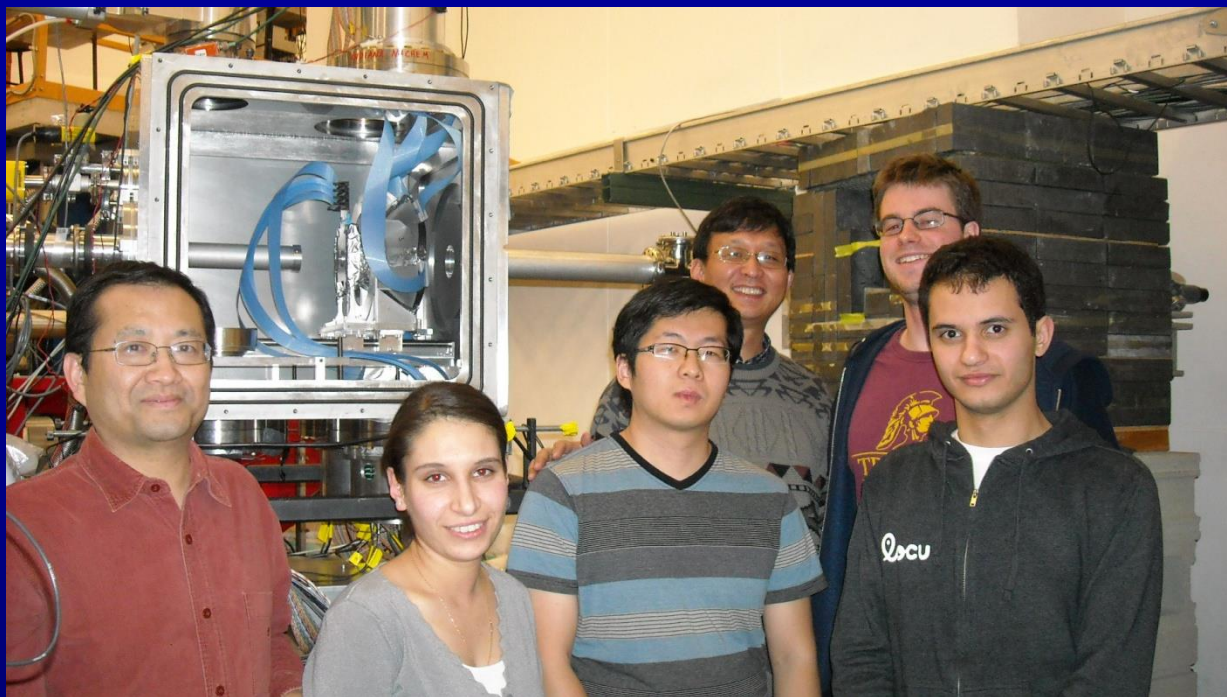




Lab Layout at Notre Dame



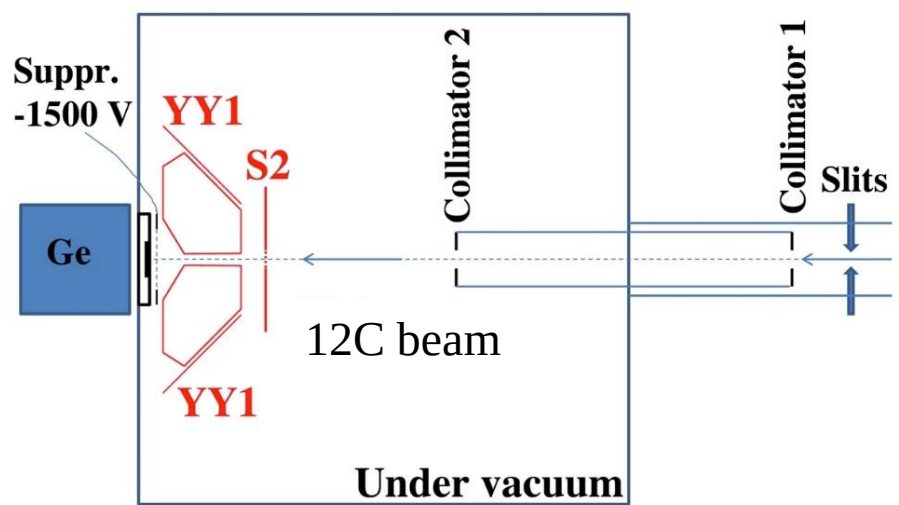
Silicon detector Array at Notre Dame (SAND)



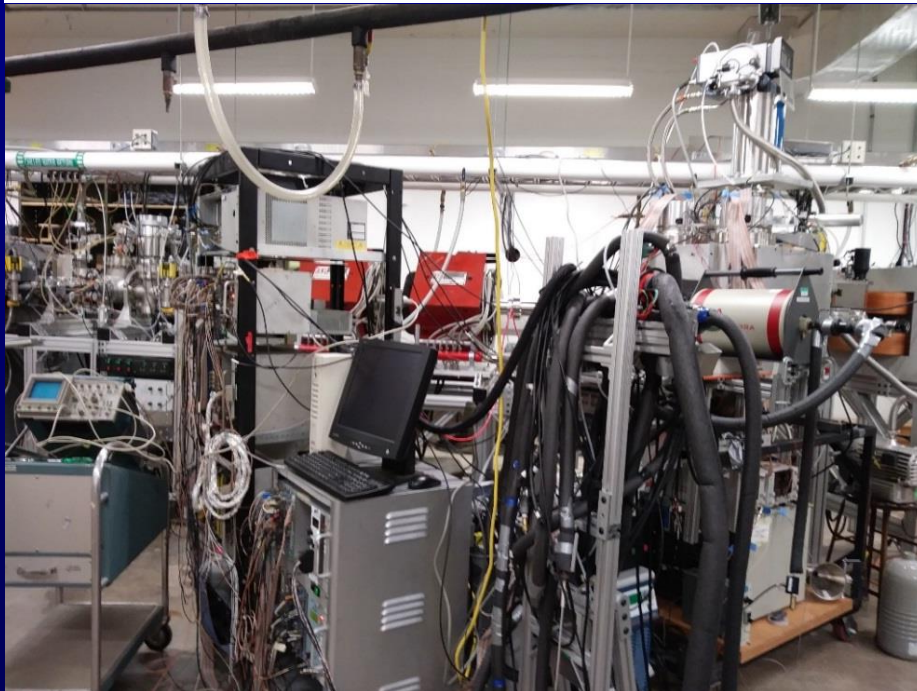
■ SAND: six YY1 silicon detectors and one S2 silicon detector, covering angles from 102° to 150° and 151° to 170° , respectively. The solid angle covered by the detectors was 4.1% of 4π for each YY1, and 5.4% of 4π for S2

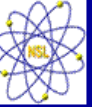


Coincidence Setup for $^{12}\text{C}+^{12}\text{C}$

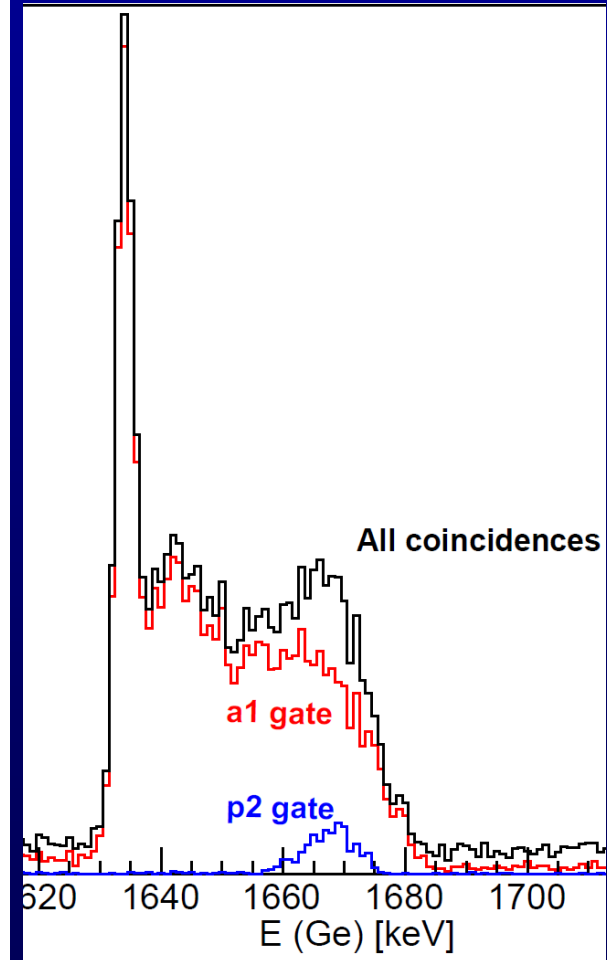
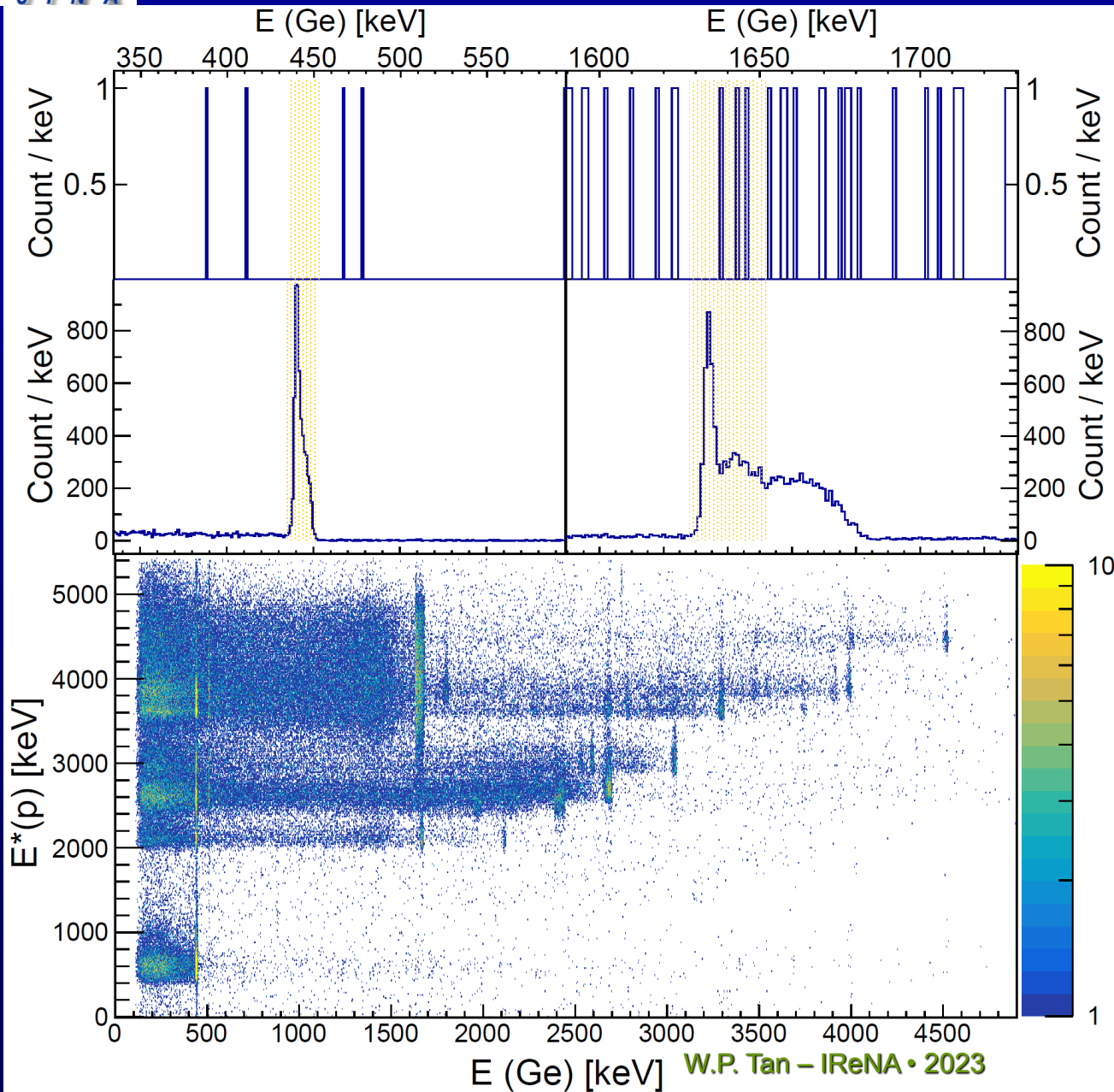


- at 5U, Notre Dame
- HOPG thick target
- $^{12}\text{C}^{2+}/^{12}\text{C}^{4+}$, 13 pμA
- $E_{\text{cm}} = 2.2\text{--}5\text{ MeV}$
- Particle-gamma coincidences
 - Timing gates as well
- Differential thick target approach
 - Steps of 50 keV
- Doppler effect helps separation
 - $\alpha 1$ (1634 keV, 0.73 ps)
 - p2 (1636 keV, 24 fs)
- Background / Contamination
 - Deterium for particle spectra
 - ^{23}Na for gamma spectra

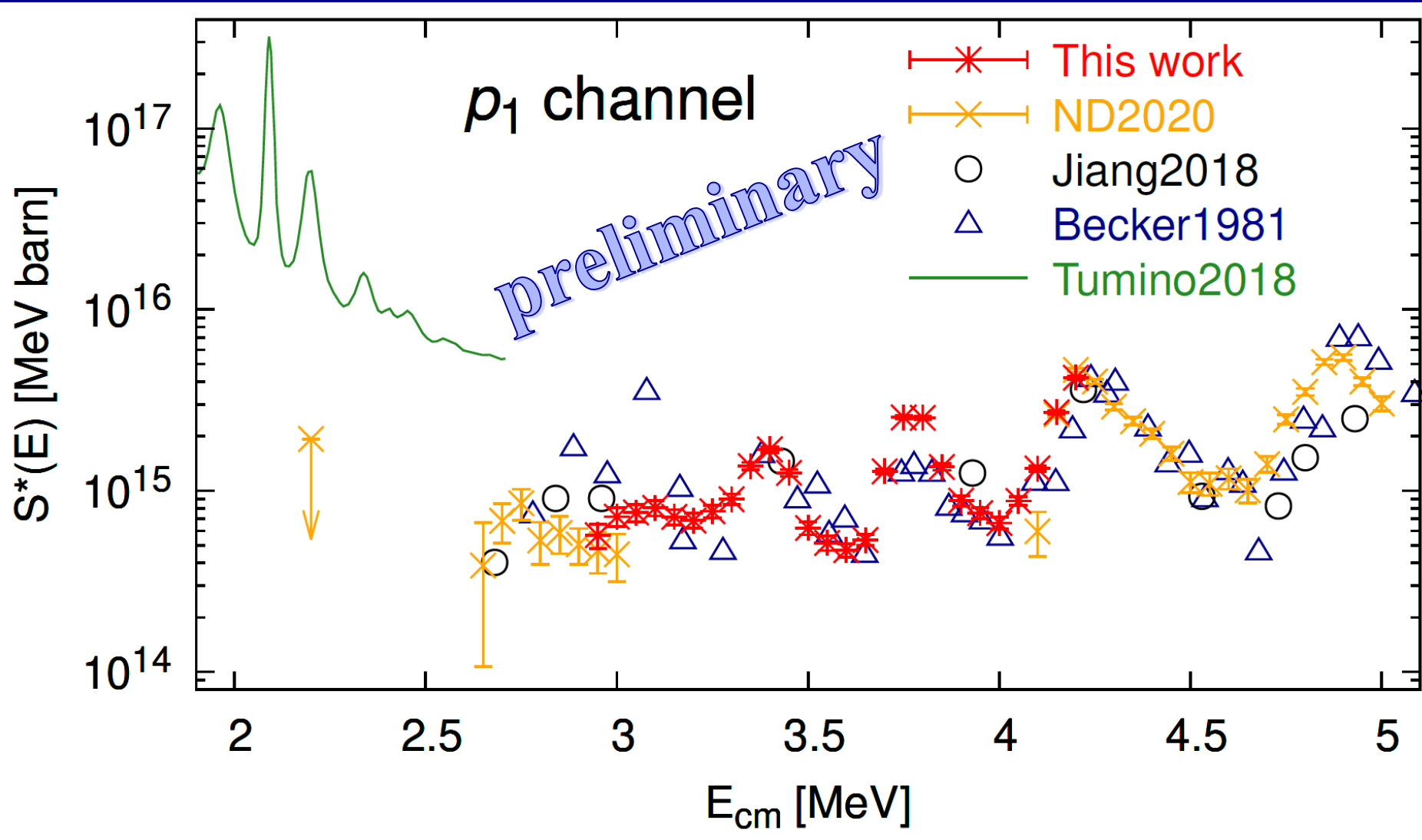




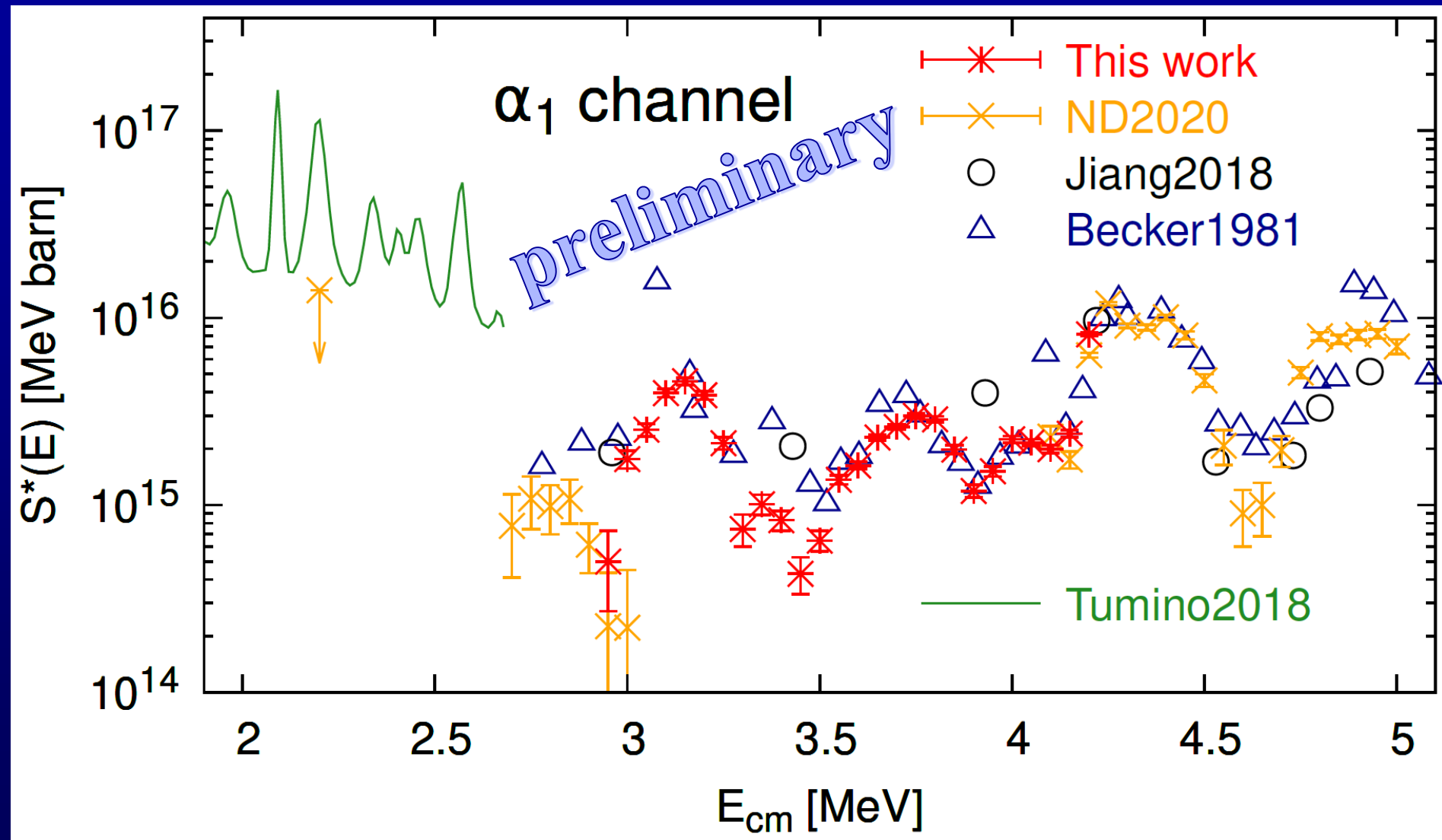
$^{12}\text{C}+^{12}\text{C}$ Coincidences

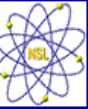


$S^*(E)$ factor for p_1



$S^*(E)$ for α -1





Other proton channels



$1/2^+$ 4429.63 0.21 fs 2

$5/2^+$ 3914.6 6.9 fs 14

$5/2^-$ 3847.9 87 fs 21

$3/2^-$ 3677.9 21 fs 3

$3/2^+$ 2982.0 3.3 fs 4

$9/2^+$ 2703.8 88 fs 7

$1/2^-$ 2640.5 76 fs 9

$1/2^+$ 2390.9 0.60 ps 14

$7/2^+$ 2076.2 27 fs 3

$5/2^+$ 440.2 1.14 ps 7

$3/2^+$ 0.0 stable

$^{23}_{11}\text{Na}_{12}$

p_{10}

p_9

p_8

p_7

p_6

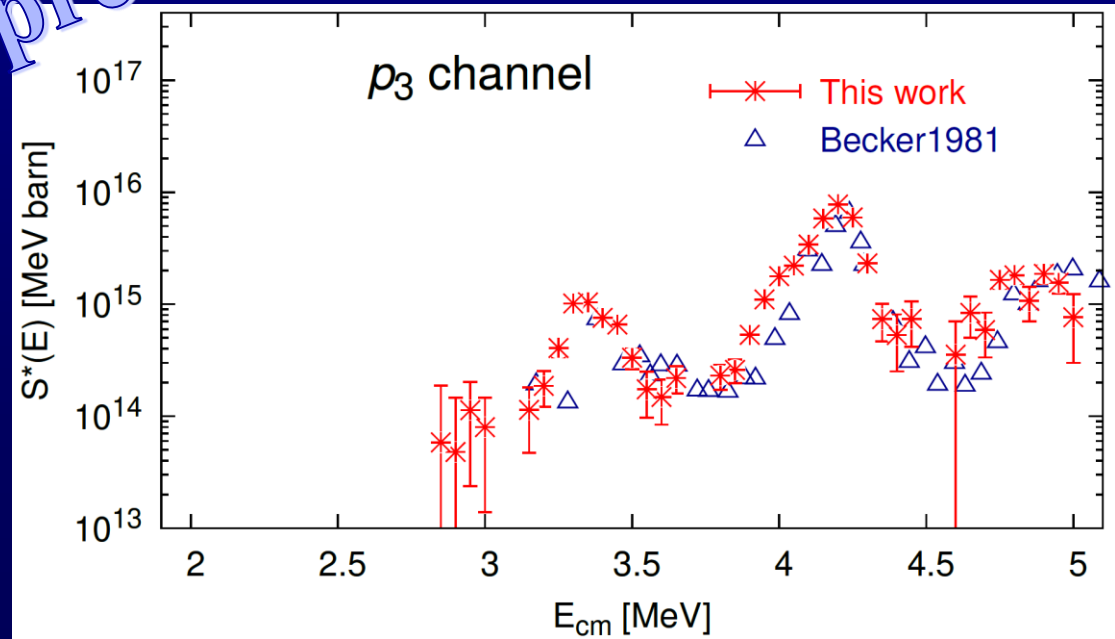
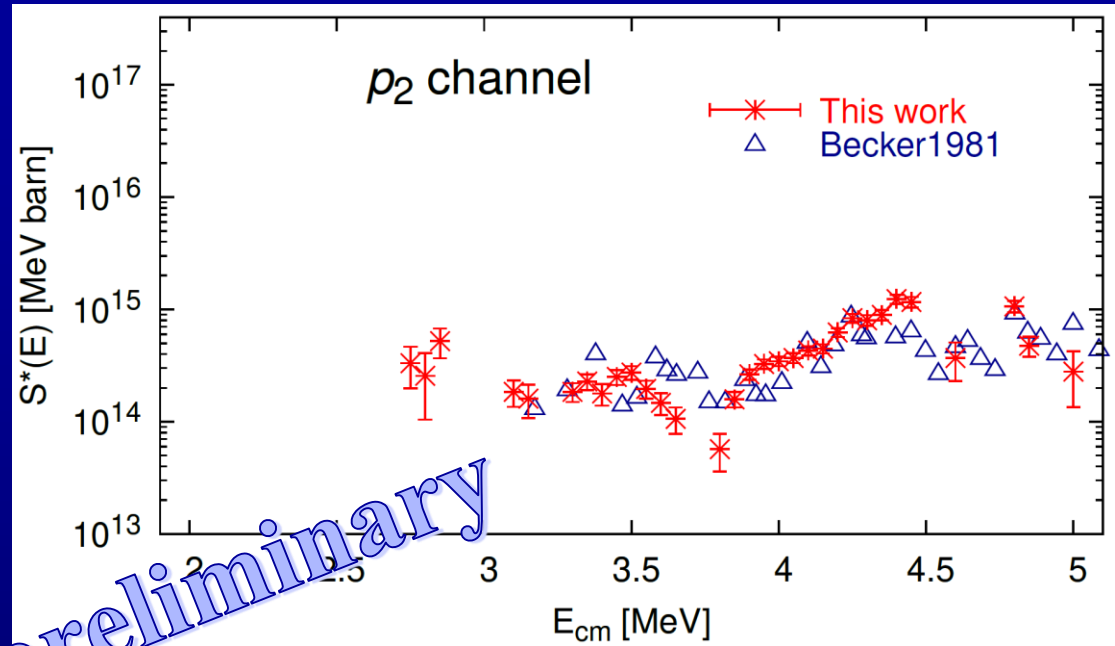
p_5

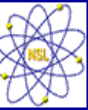
p_4

p_3

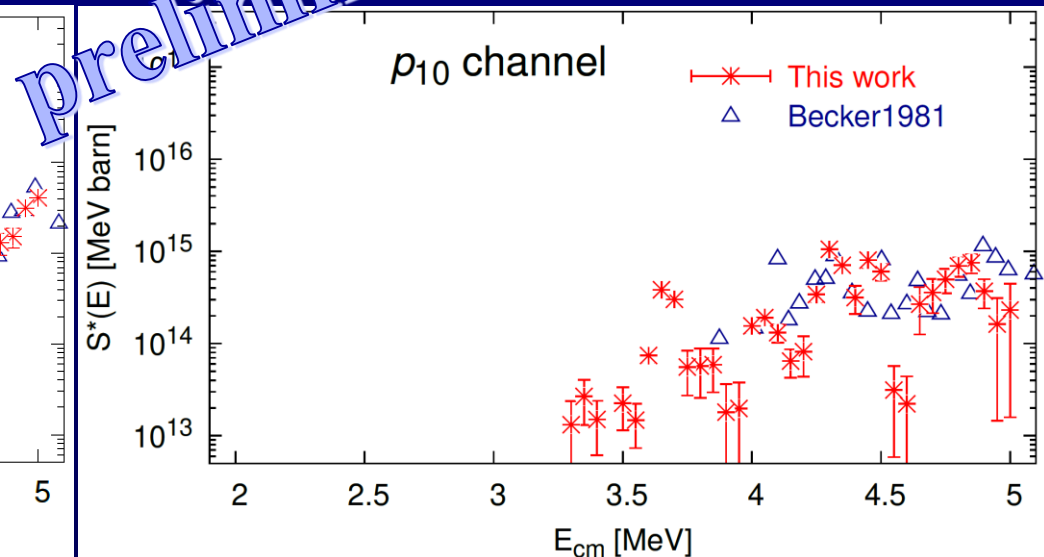
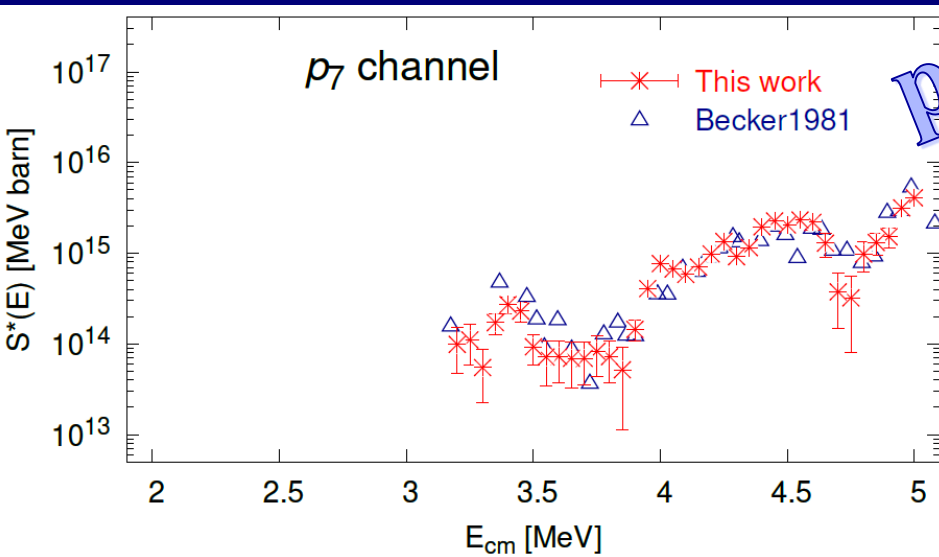
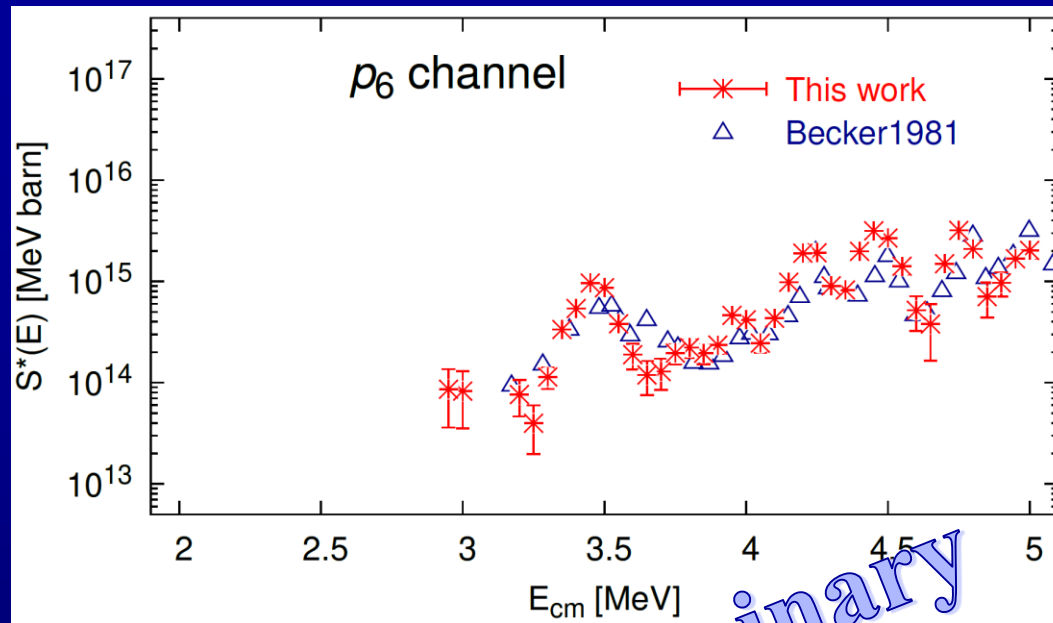
p_2

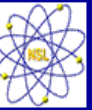
p_1



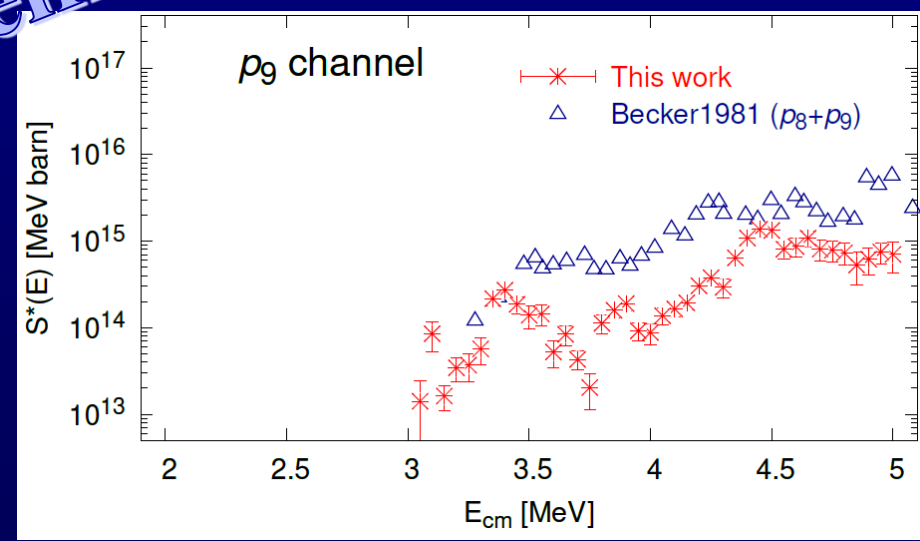
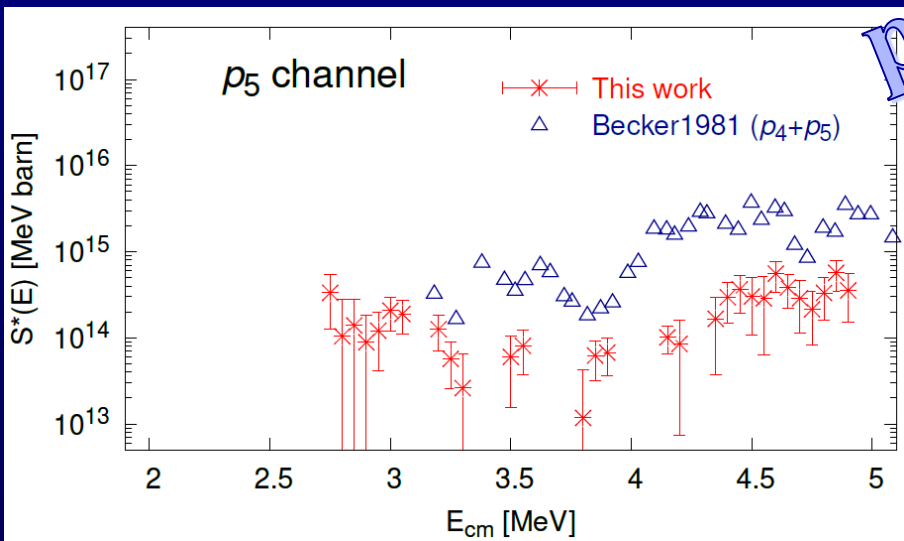
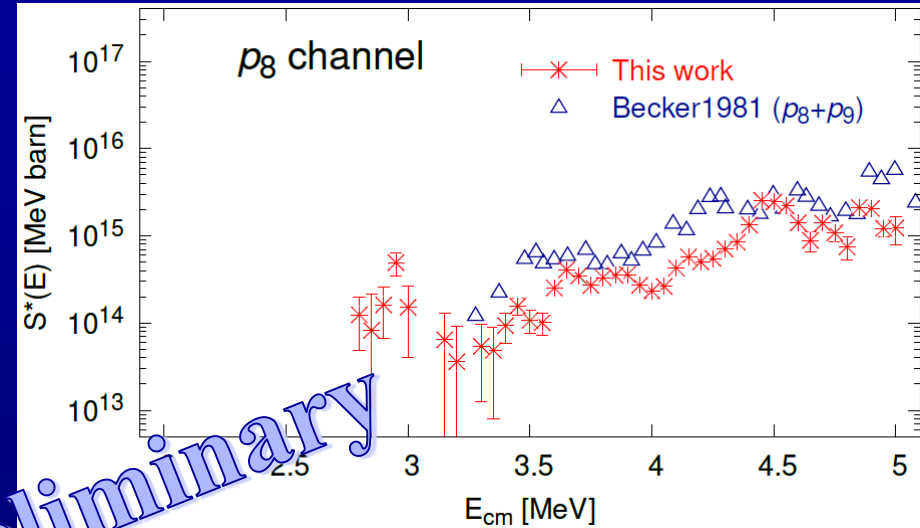
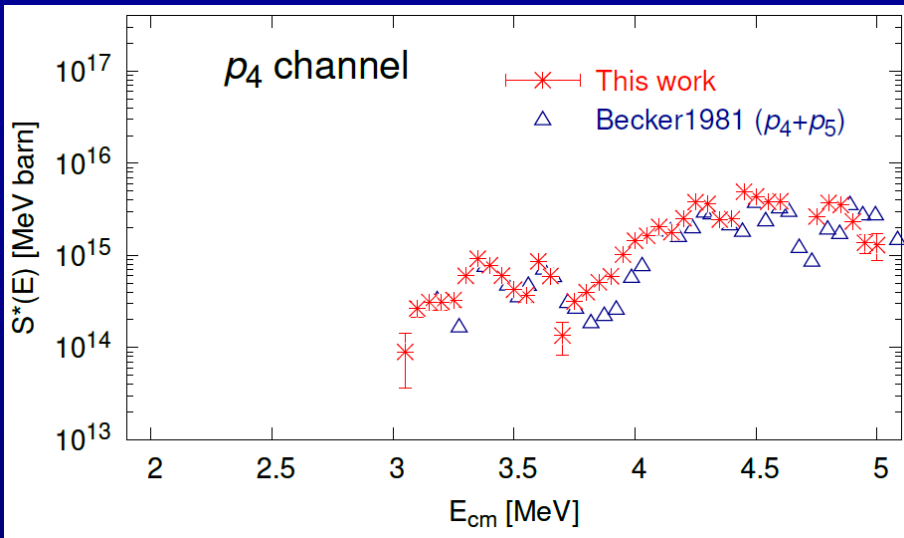


More proton channels

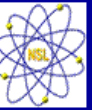




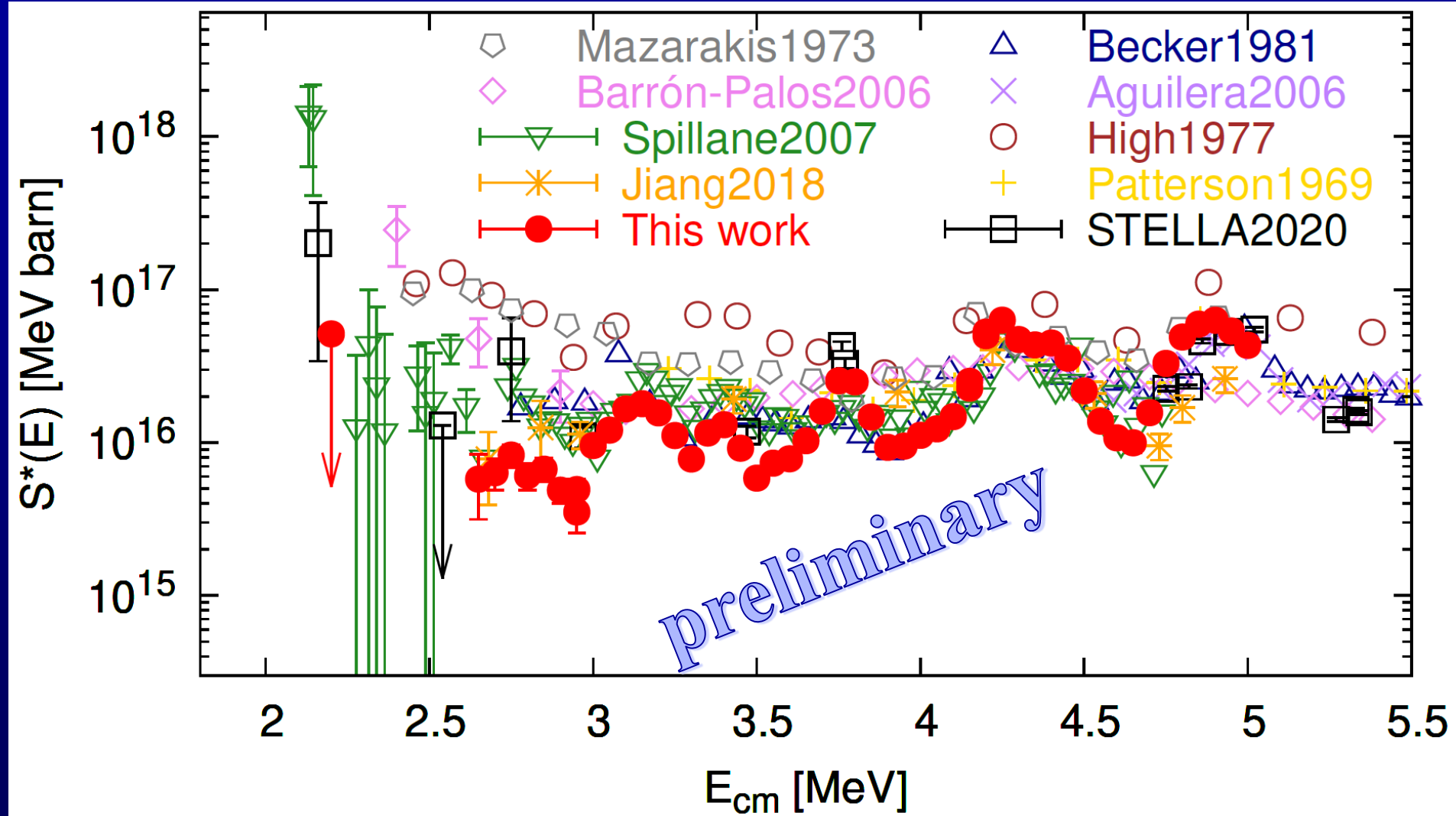
Even more proton channels



preliminary

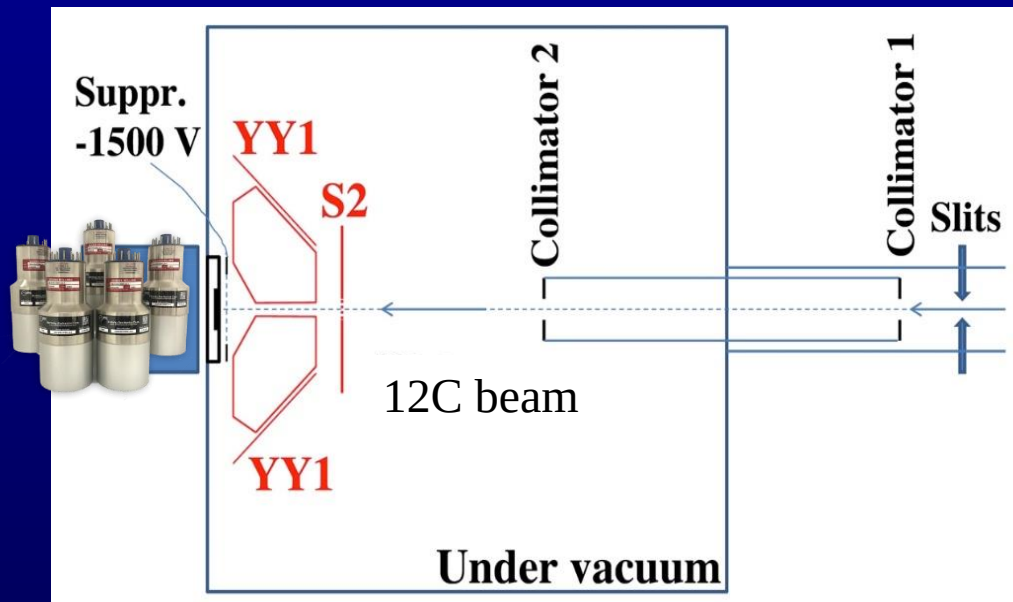


Total S-factor of $^{12}\text{C}+^{12}\text{C}$



Outlook on Coincident Measurements

- Better detectors: more efficient, better timing
- Higher intensity beams
- Less background: go underground

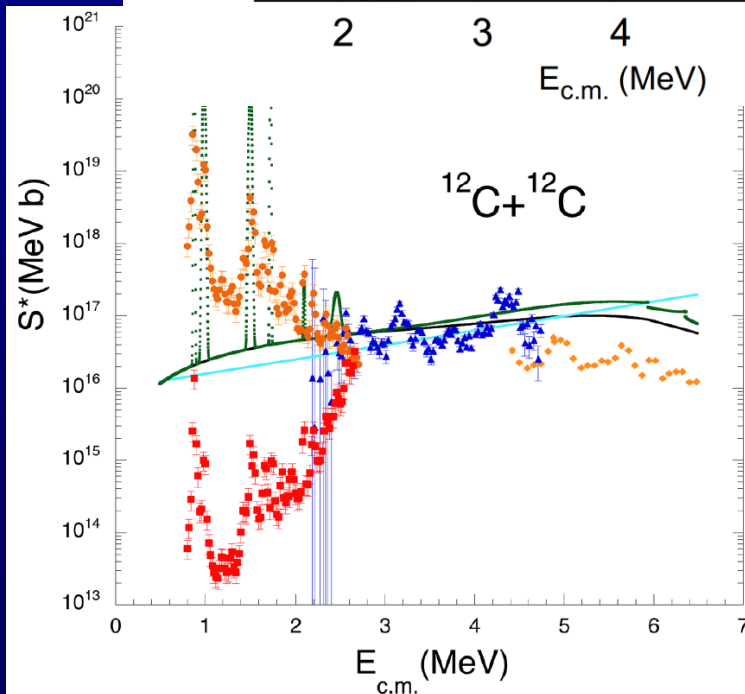
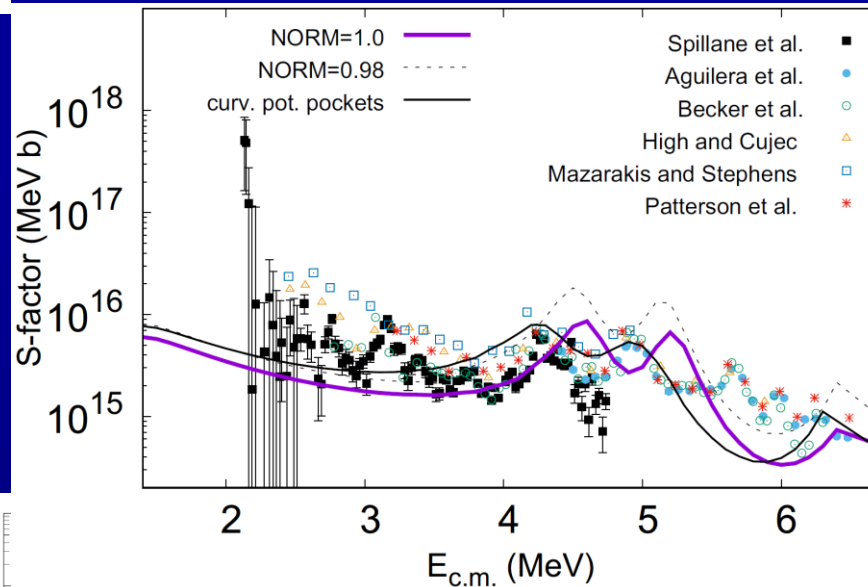


See talk by Gianluca Imbriani

Comparisons with Theories

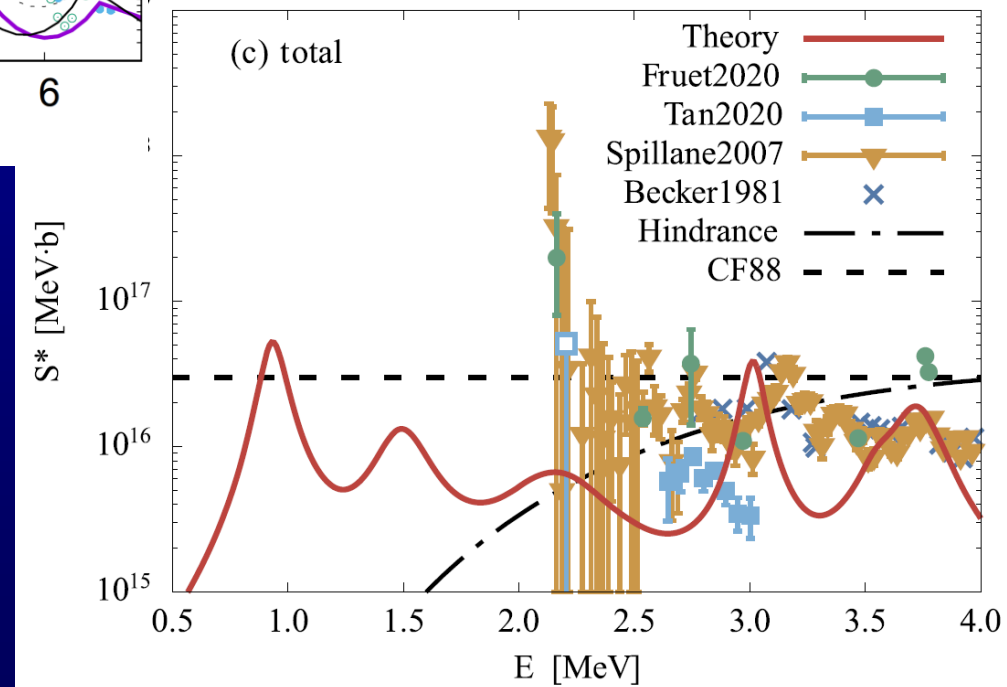
TDWP: Diaz-Torres1 & Wiescher,
PRC **97**, 055802 (2018)

See talk by Alexis Diaz-Torres



Mean field theory: Bonasera & Natowitz,
PRC **102**, 061602(R) (2020)

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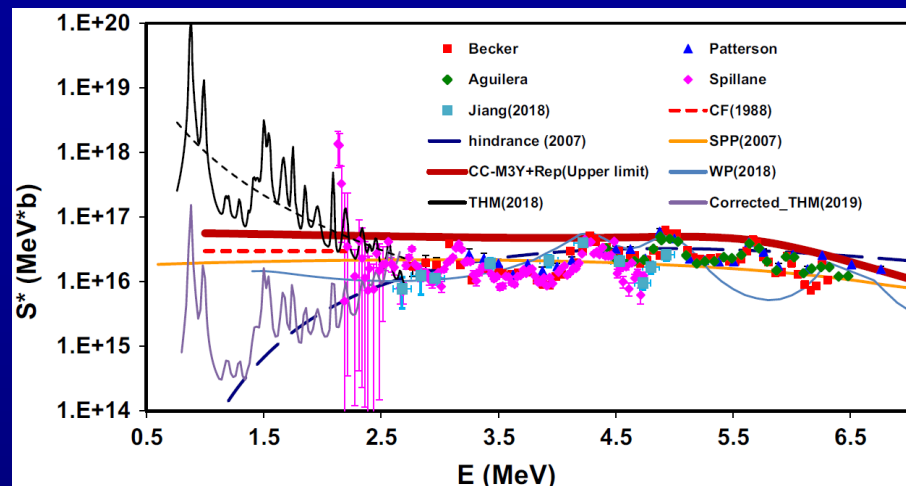
AMD: Taniguchi & Kimura,
Phy. Lett. B **823** (2021) 136790

Alternative Methods and Merging Data

How to merge indirect and direct data?

- Direct Data can reach about 2 MeV in center of mass, but for anything below, we need help from indirect approaches
- New THM effort by Gogachev et al. at Texas A&M

See talk by Aurora Tumino



Beck et al., Eur. Phys. J. A 56, 87 (2020)

- More partial channel data (besides $p_0, p_1, \alpha_0, \alpha_1$) are needed
- More angular distributions are also helpful
- Merge all the data using an approach similar to R-Matrix

See talk by James deBoer



Summary

- Better direct measurements are critical for determining the trend and resonance structures of the S-factor near threshold.
 - guiding better theoretical calculations
 - matching indirect data (e.g., from THM) at even lower energies
- Coincidence approach is the way to go at lower energies.
 - More efficient detectors, more intense beams, and less background (e.g., underground)
- More partial channel results are needed.