$^{12}C + {}^{12}C$: Status and Perspectives

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On behalf of the Carbon Fusion Experiment (CARFUSE) Collaboration

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OECE Symposium, Beihang, Nov. 5-6, 2026

Image: Rogelio Bernal Andreo (CC BY-SA 3.0), via Wikimedia Commons

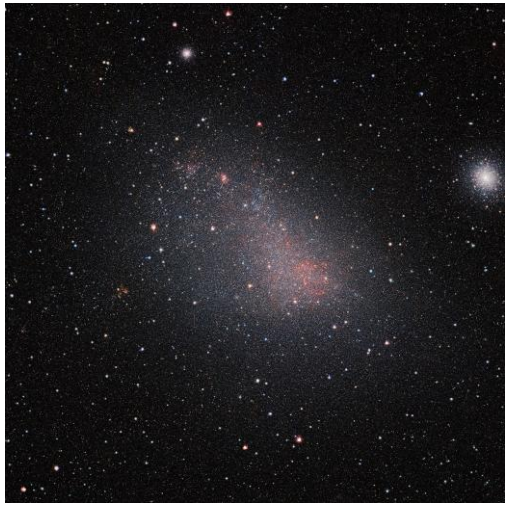
CARbon FUSion Experiment (CARFUSE) @LEAF, IMP



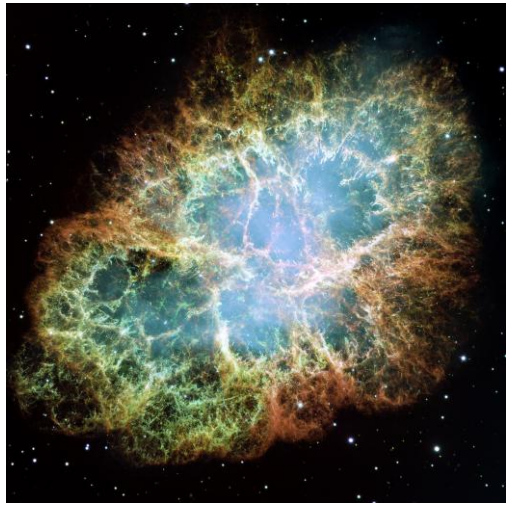
$^{12}C+^{12}C$ decides the fate



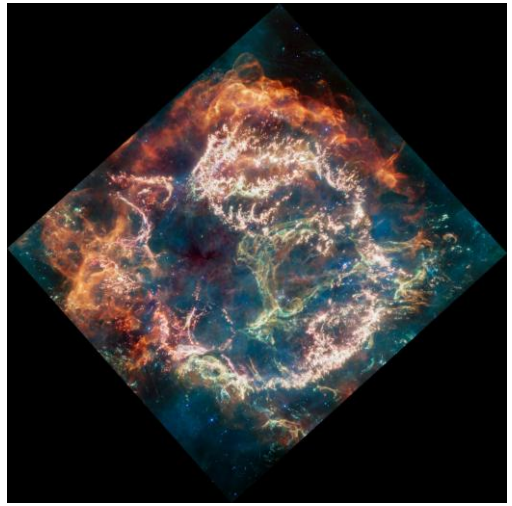
Sirius B (white dwarf)



SMC (SAGB



Crab Nebula



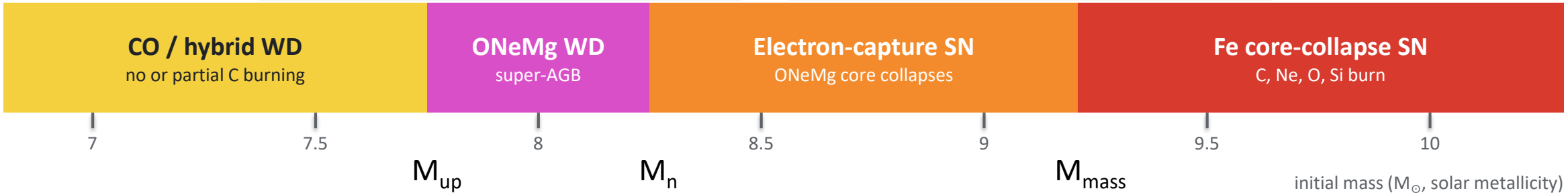
Cassiopeia A

≈ 50%

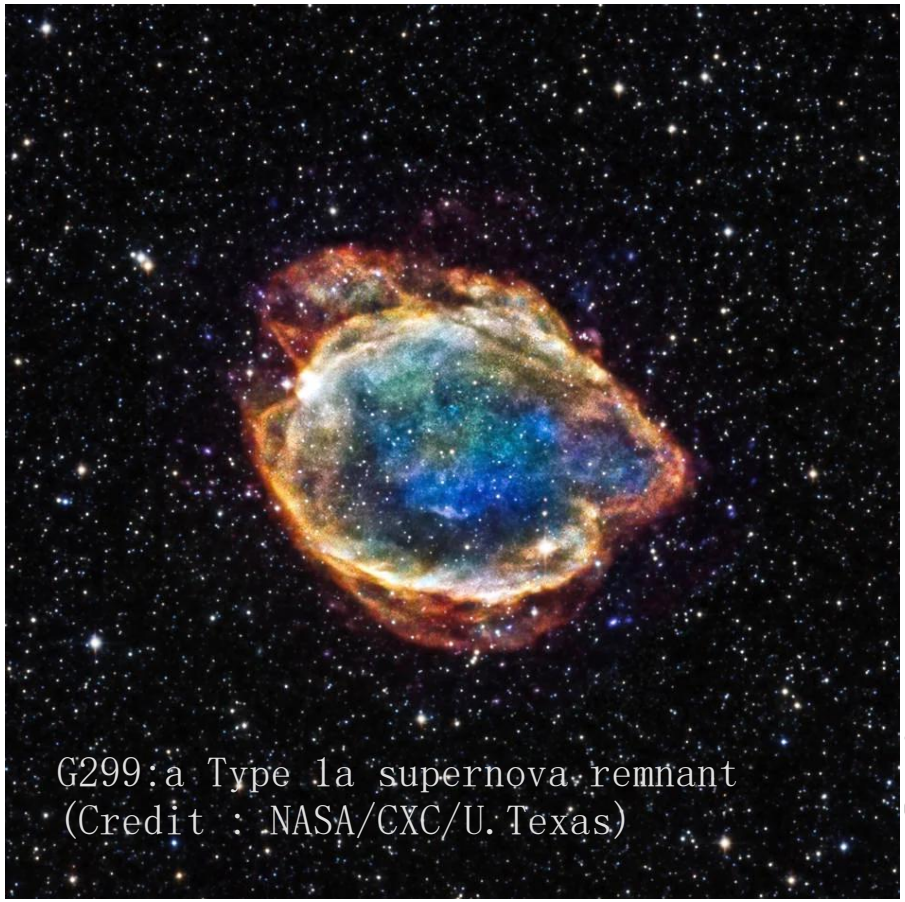
of stars > 7 $M_\odot$ (by number) lie in 7–12 $M_\odot$

4 fates

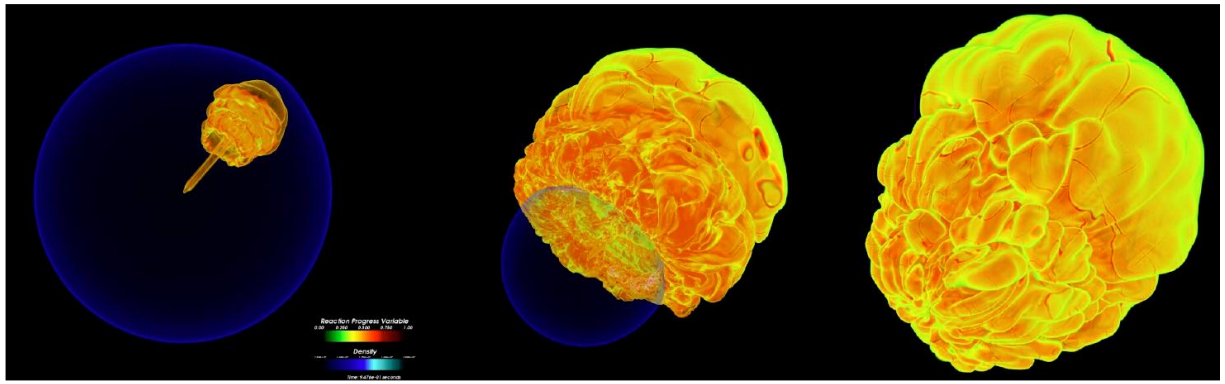
CO WD · ONeMg WD · ECSN · CCSN



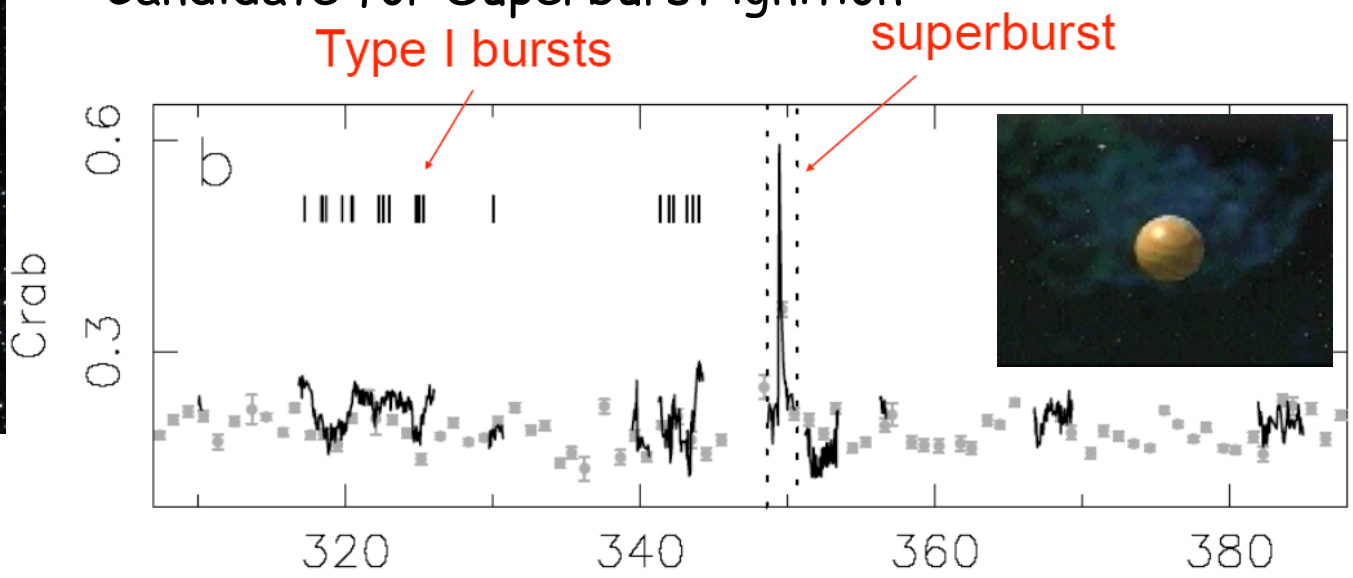
$^{12}C+^{12}C$ ignites Supernova and Supburst

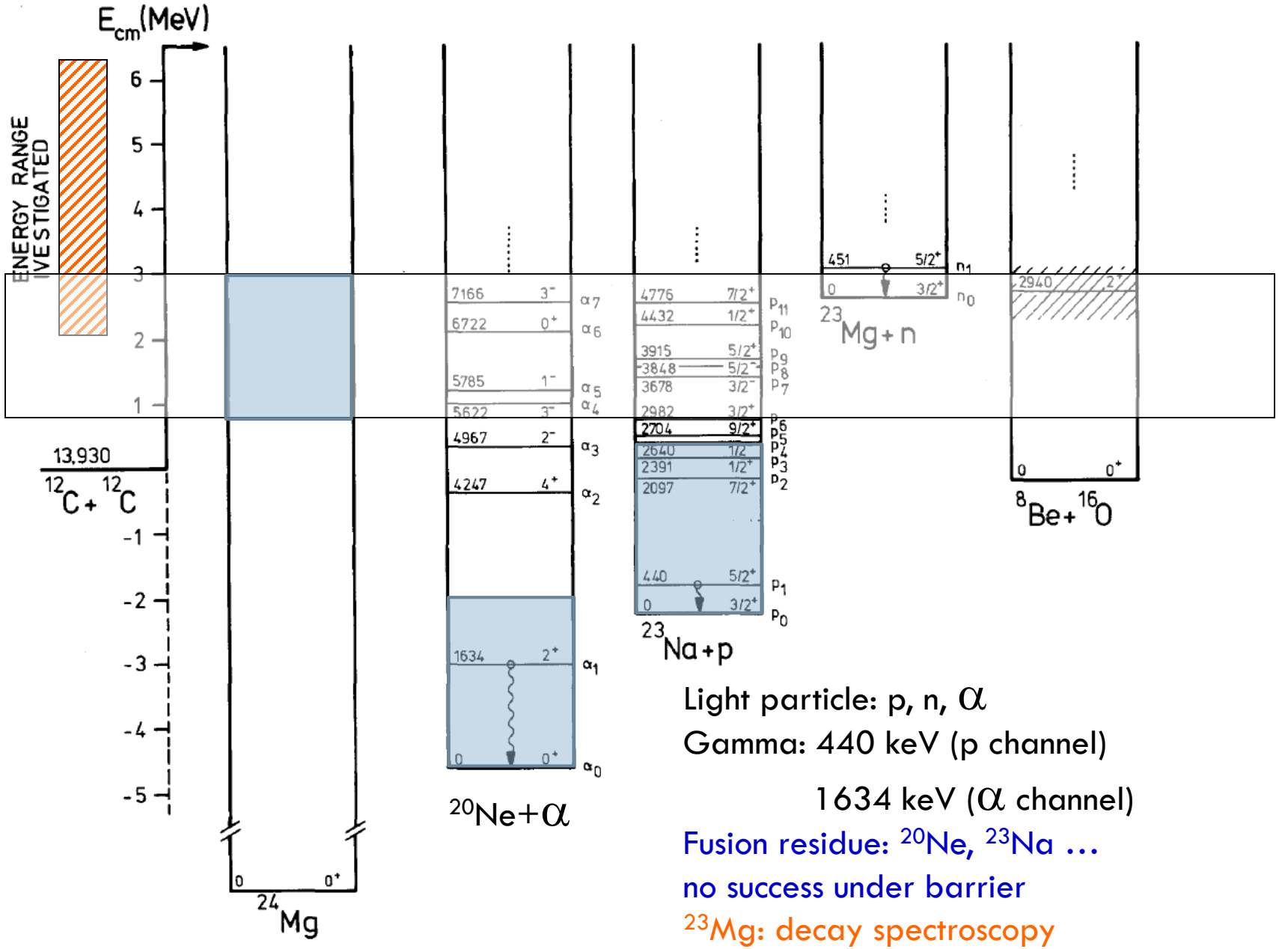


Ignition conditions in type Ia supernovae



Candidate for Superburst ignition





Light particle: p, n, α

Gamma: 440 keV (p channel)

1634 keV (α channel)

Fusion residue: ^{20}Ne, ^{23}Na …

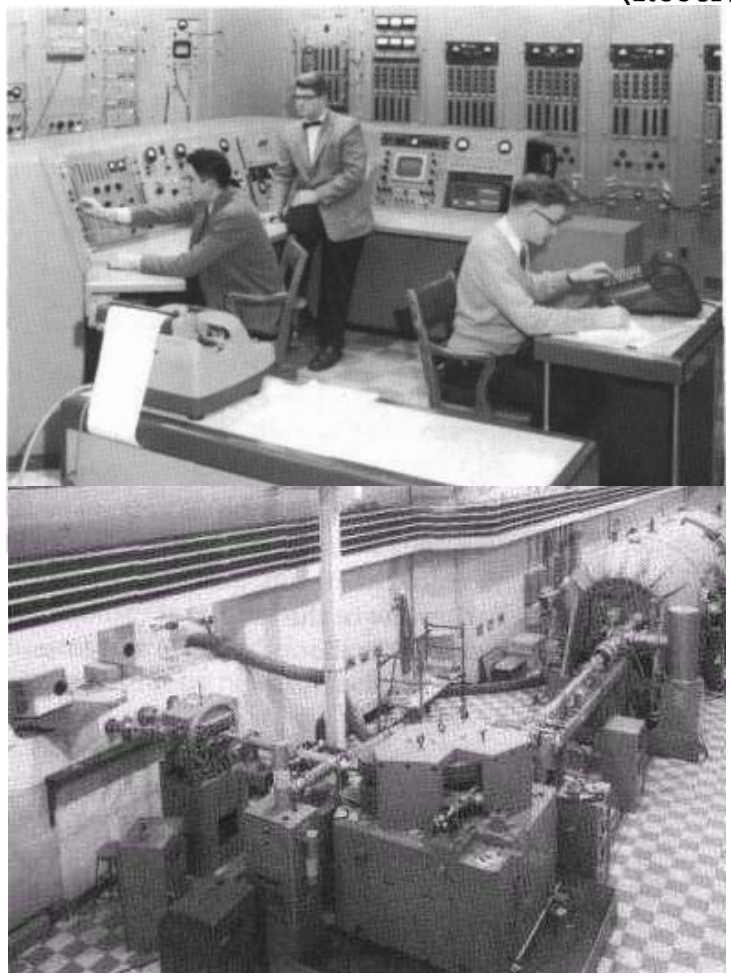
no success under barrier

^{23}Mg: decay spectroscopy

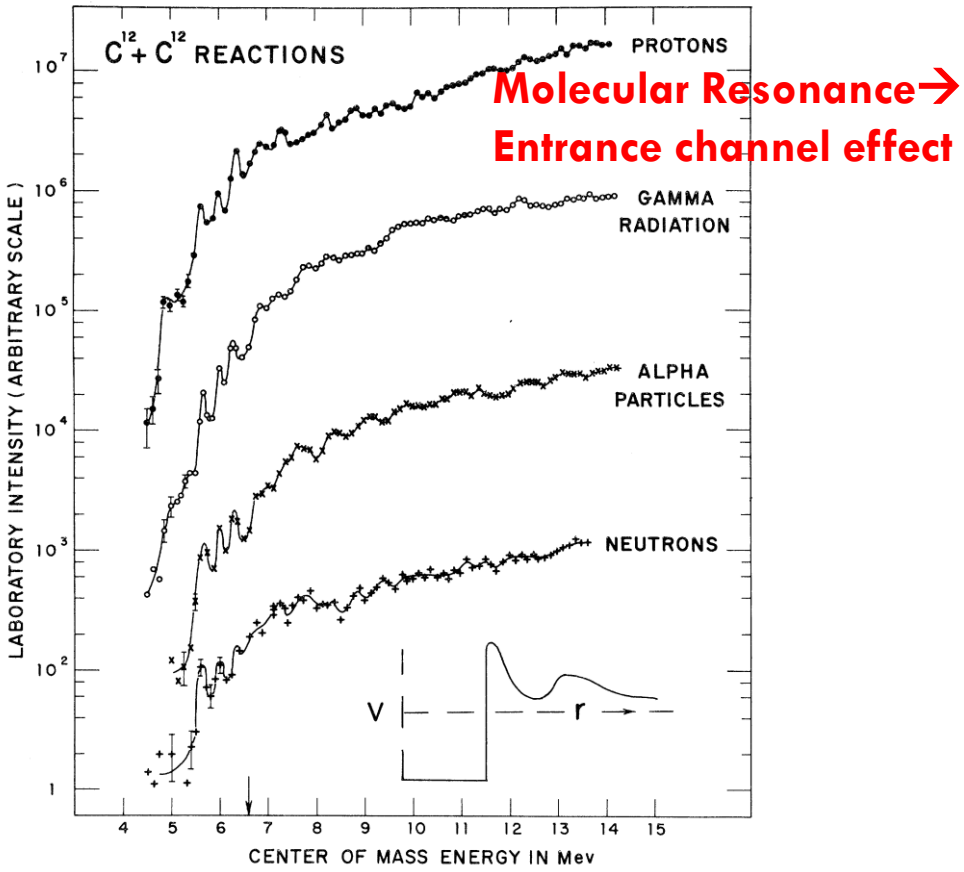
VOLUME 4, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1960

RESONANCES IN C^{12} ON CARBON REACTIONS

E. Almqvist, D. A. Bromley, and J. A. Kuehner
Atomic Energy of Canada Limited, Chalk River Laboratories, Chalk River, Ontario, Canada
(Received March 28, 1960)



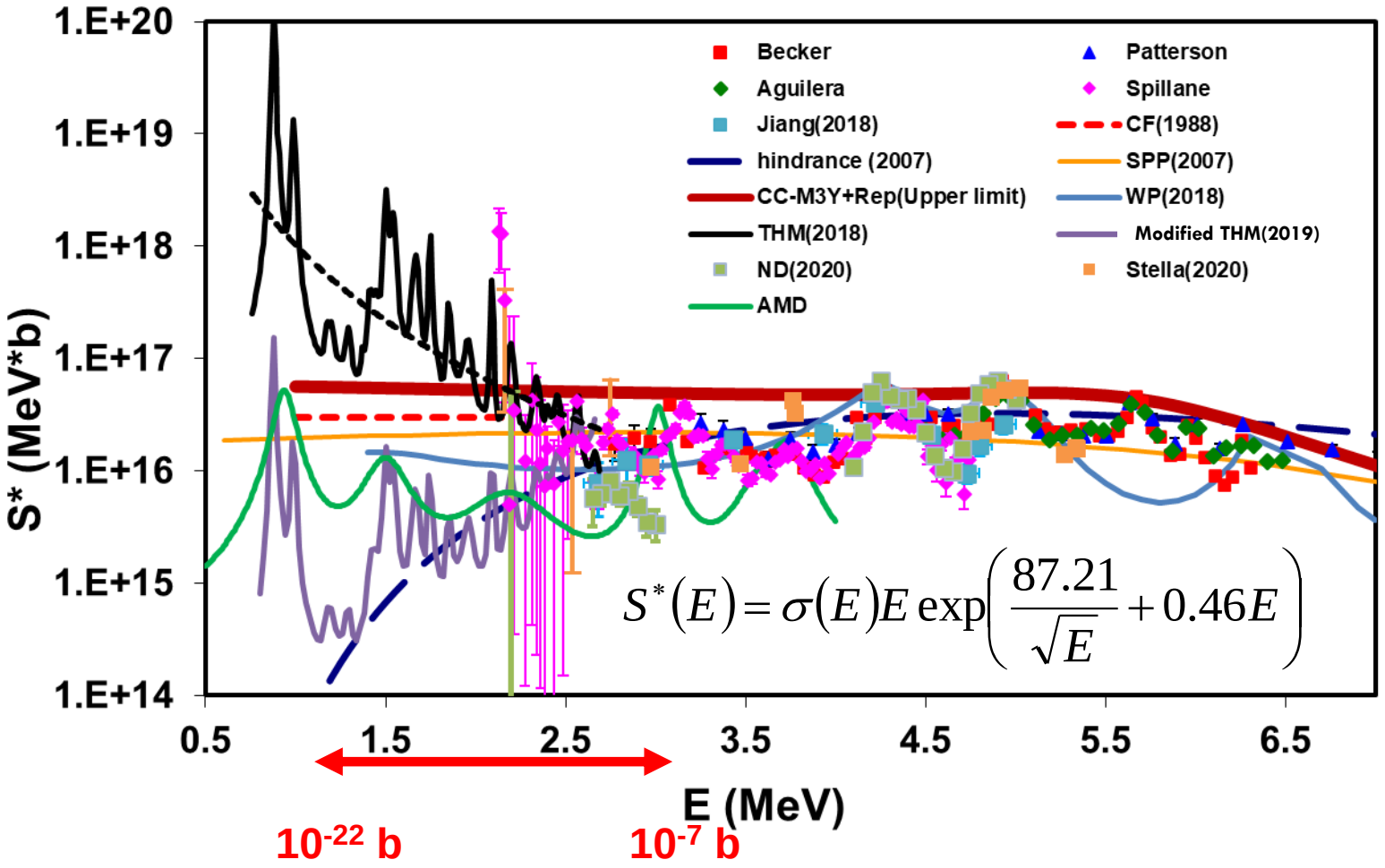
The world's first tandem accelerator installed at Chalk River in 1959.



Molecular Resonance→
Entrance channel effect

Molecular resonances at 5.68, 6.0, 6.32 MeV in the $^{12}C+^{12}C$ fusion reaction measured by Almqvist et al., in 1960

Uncertain cross section at stellar energies

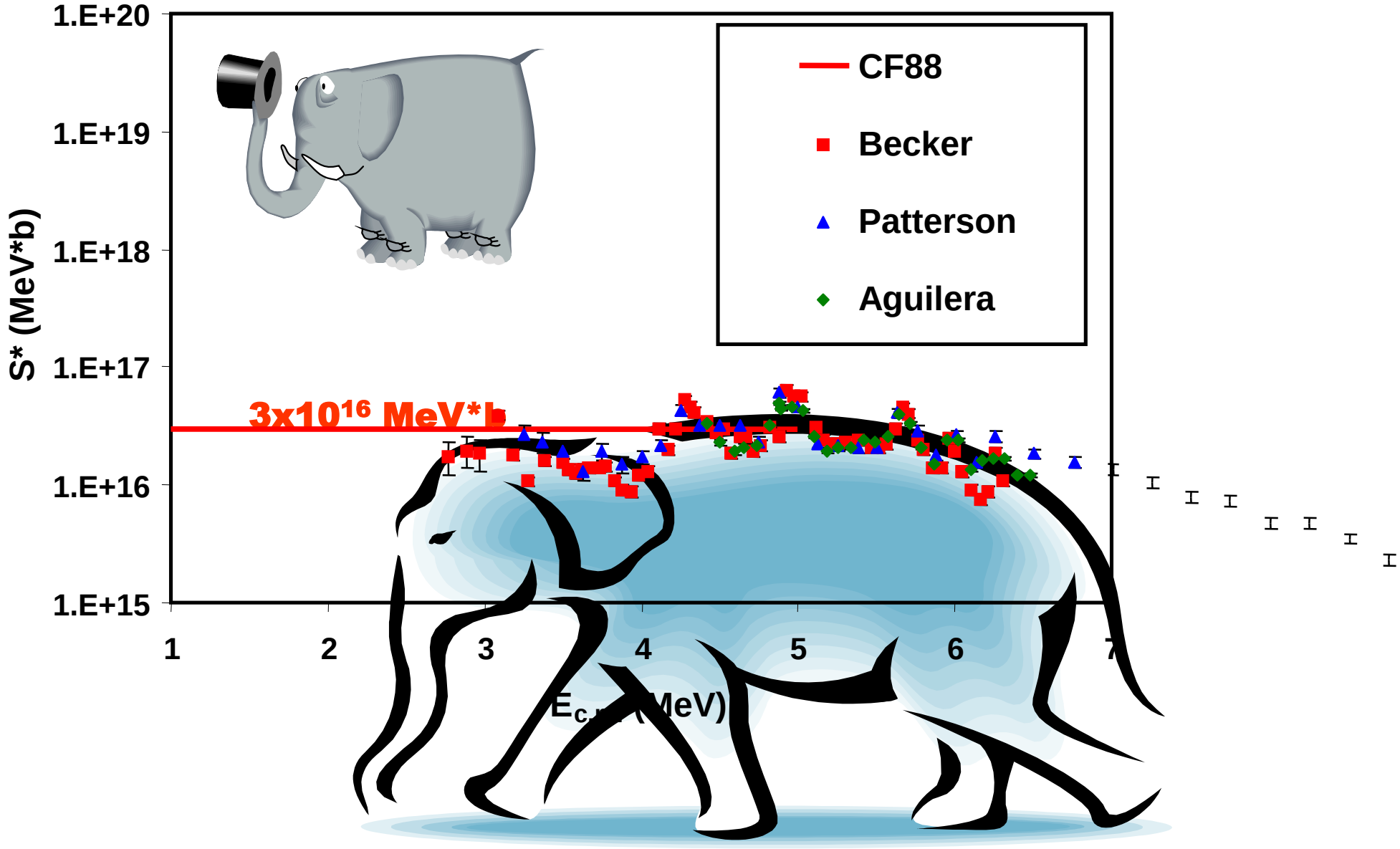


- Large difference between THM and Hindrance→Highly uncertain rate
- INDIRECT: Corrected THM exhibits a trend similar to Hindrance by replacing PWIA with DWIA
- Unknow resonances: Need better selection T=0, $J^{\pi}=0^{+},2^{+}$

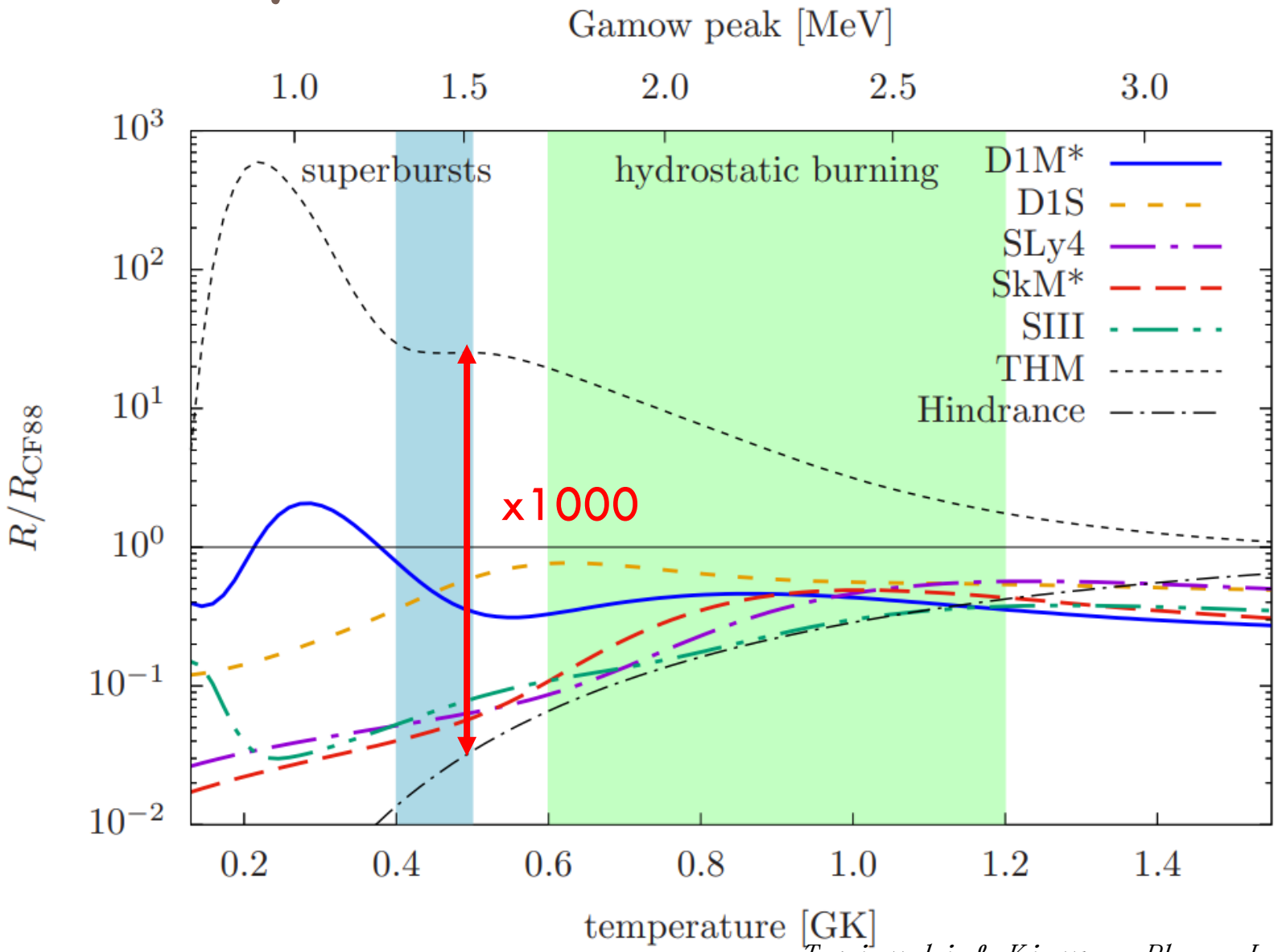
^{12}C(^{12}C,p)^{23}Na (Q=2.24 MeV)
^{12}C(^{12}C,α)^{20}Ne (Q=4.62 MeV)
^{12}C(^{12}C,n)^{23}Mg (Q=-2.62MeV)

Beck, Mukhamedzhanov and Tang, Eur. Phys. J. A (2020) 56:87
Mukhamedzhanov, Eur. Phys. J. A (2022) 58:71
Tang & Ru, EPJ Web of Conferences 260, 01002 (2022)

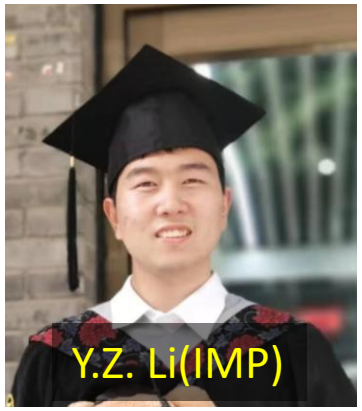
$$S^*(E) = \sigma E e^{(87.21/\sqrt{E} + 0.46E)}$$



Uncertainty in the reaction rate



Taniguchi & Kimura, Phys. Lett. B 849 (2024) 138434



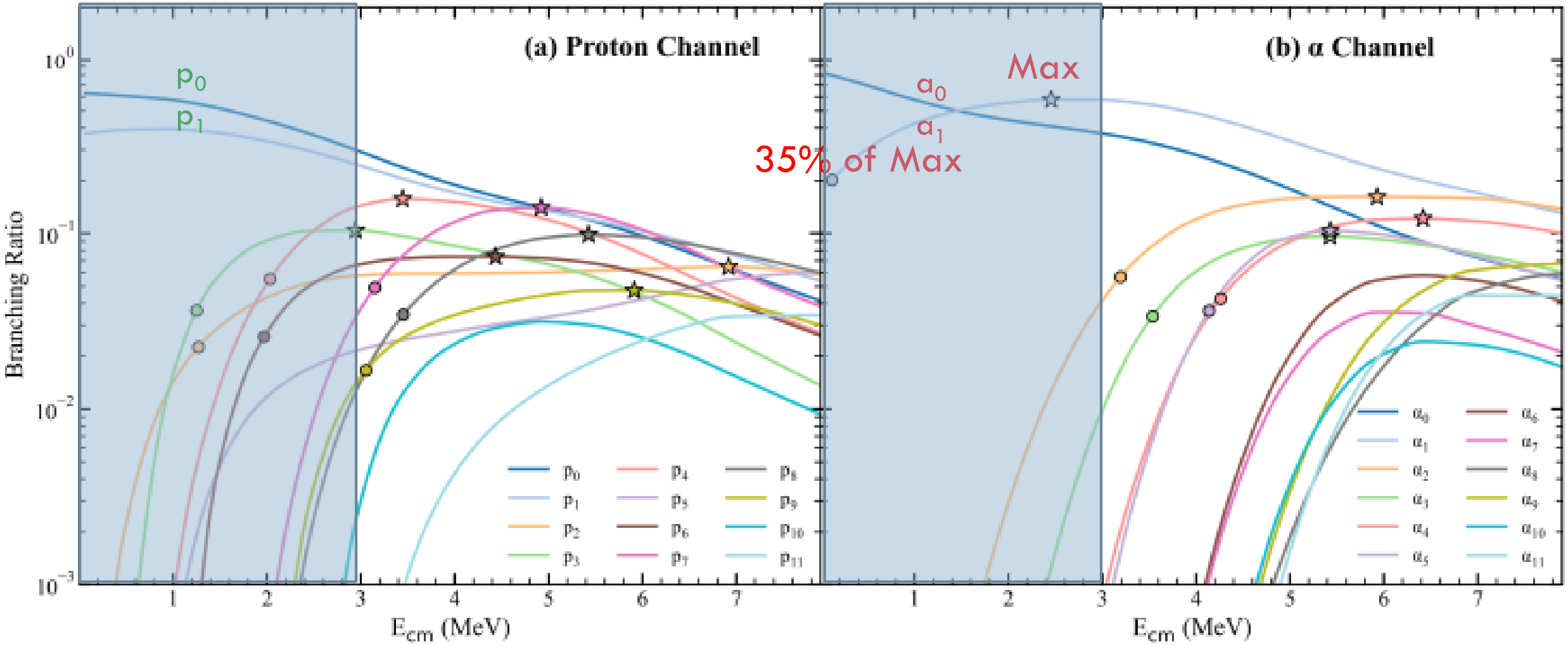




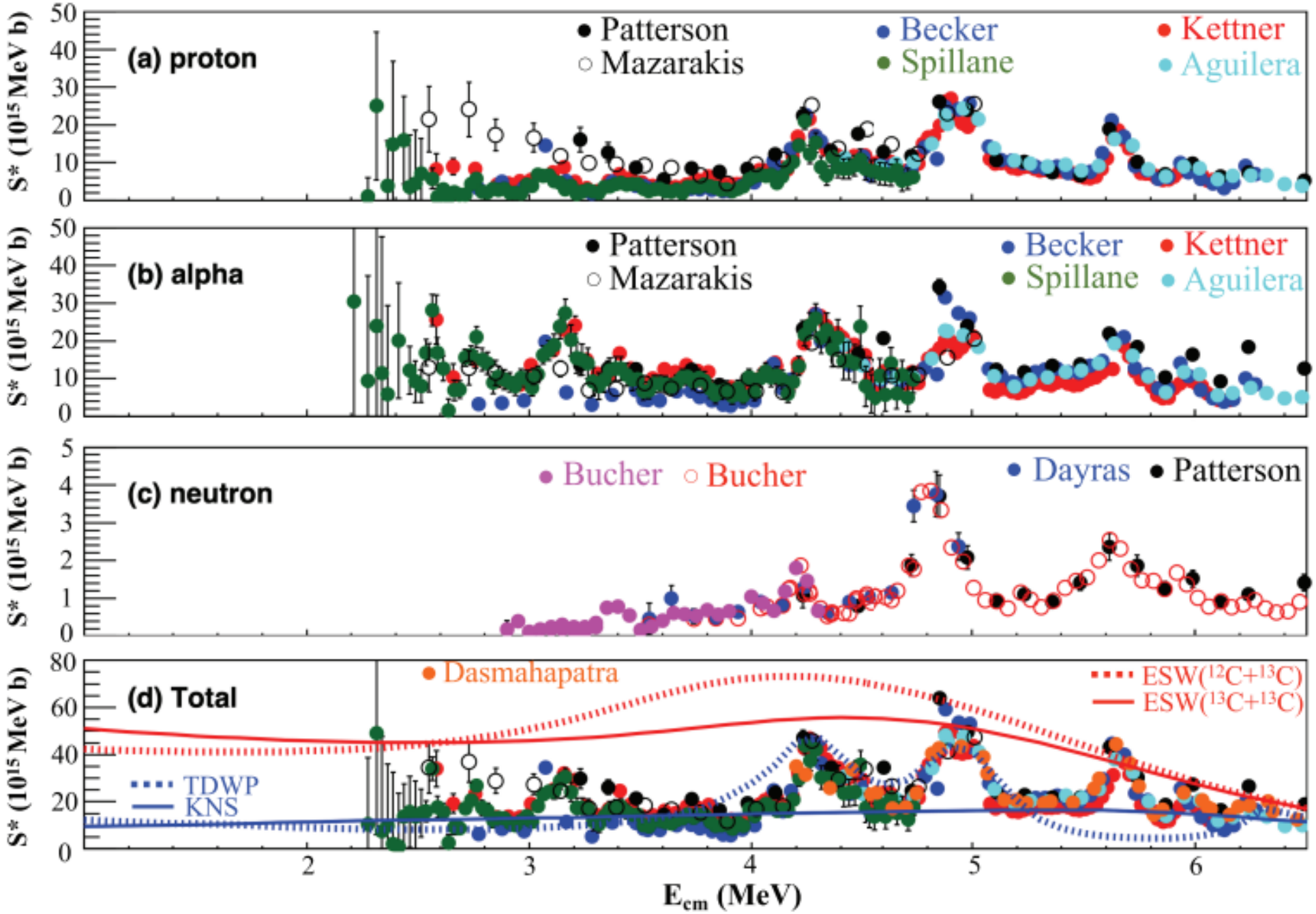
Direct Measurement of $^{12}C(^{12}C,a_{0,1})^{20}Ne$ & $^{12}C(^{12}C,p_{0,1})^{23}Na$

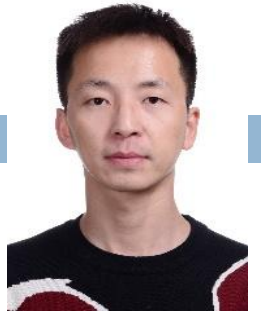
What are the important channels at stellar energies?

Statistical model prediction

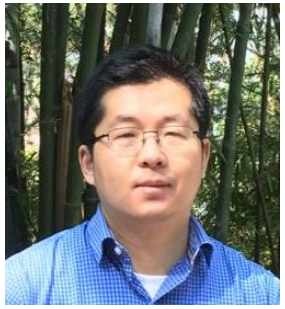


R.J. Yang, X. Fang et al., CPC(2026), doi:10.1088/1674-1137/ae823a





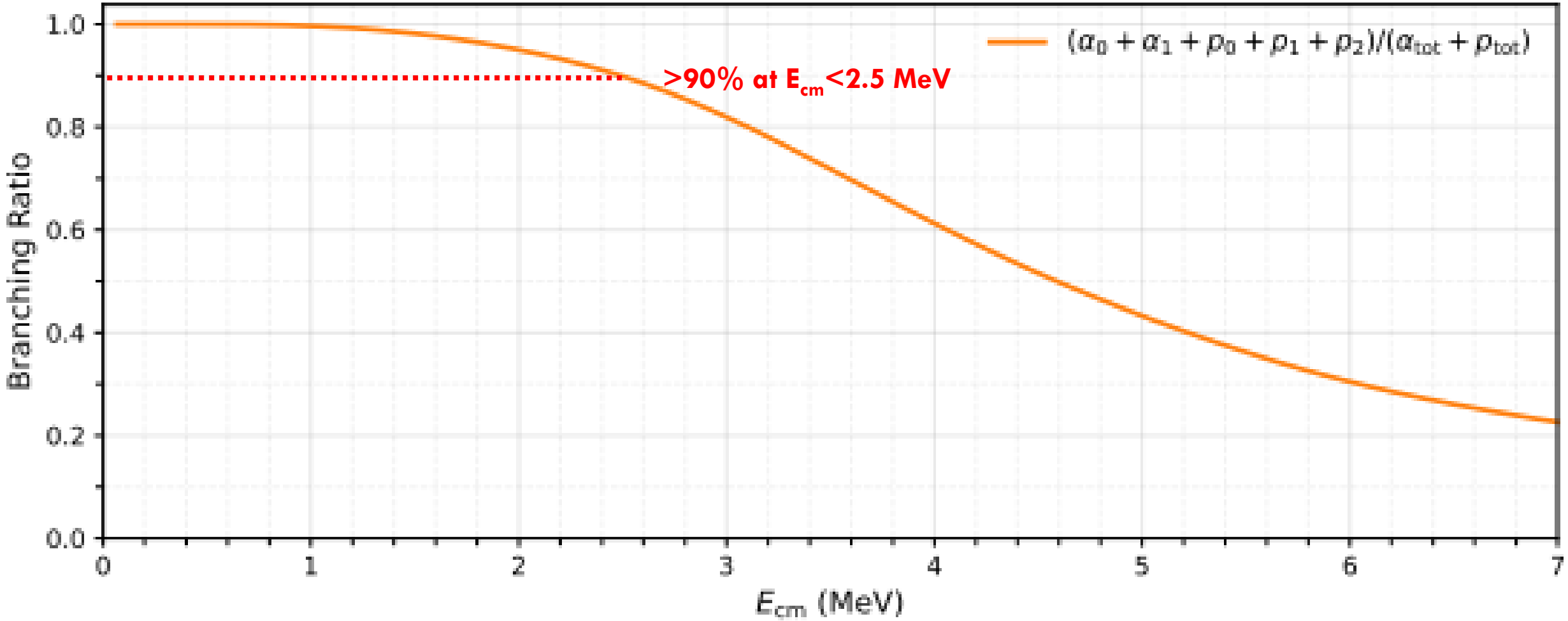
Y.J. Li(CIAE)



X. Fang(SYSU)

Y.J. Li, X. Fang et al., Chinese Physics C Vol. 44, No. 11 (2020) 115001

Important channels: $a_{0,1}$ and $p_{0,1}$

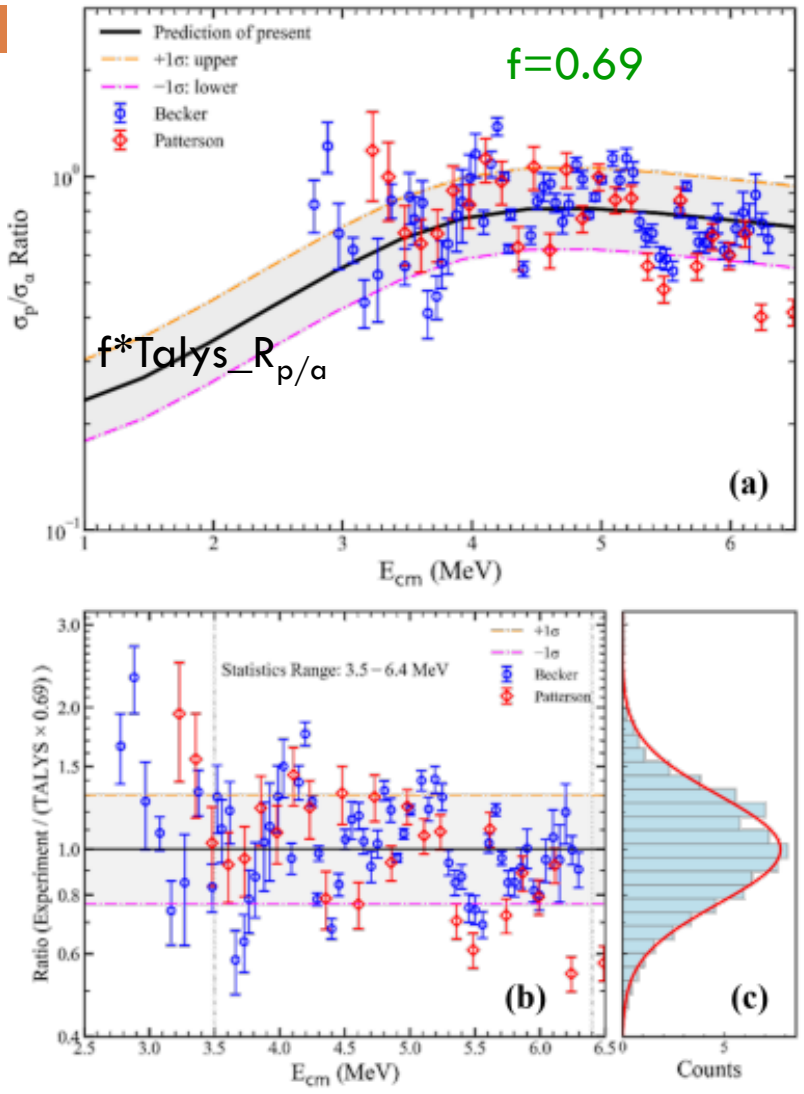


Courtesy of X. Fang (SYSU)

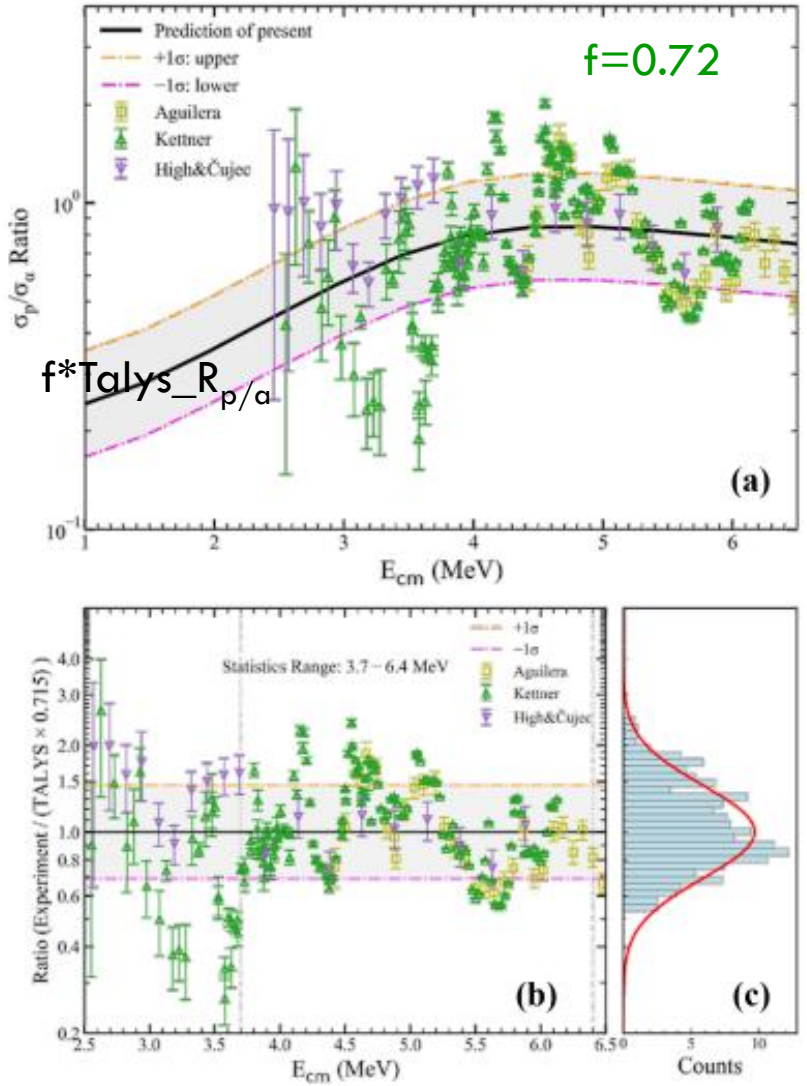
$R_{p/\alpha}=\sigma_p/\sigma_\alpha$ at stellar energies

$$R = \frac{(R_{p/\alpha}(E))_{\mathrm{exp}}}{f \times (R_{p/\alpha}(E))_{\mathrm{Talys}}}$$

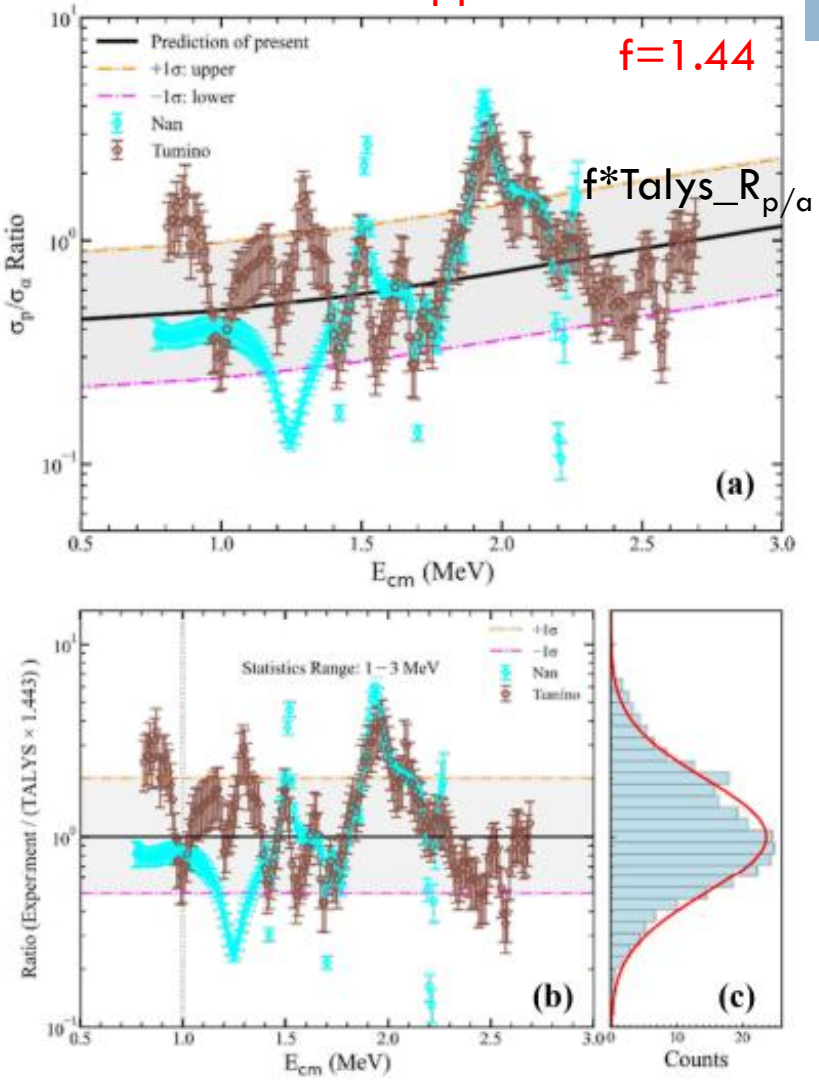
Direct approaches (particle)



Direct approaches (gamma)



Indirect approaches



R.J. Yang, X. Fang et al., CPC(2026), doi:10.1088/1674-1137/ae823a

Carbon fusion project at LUNA-MV

Massive lead shield and radon flushing → push sensitivity to better than 100 reactions/day



$^{12}C+^{12}C$ - γ measurements

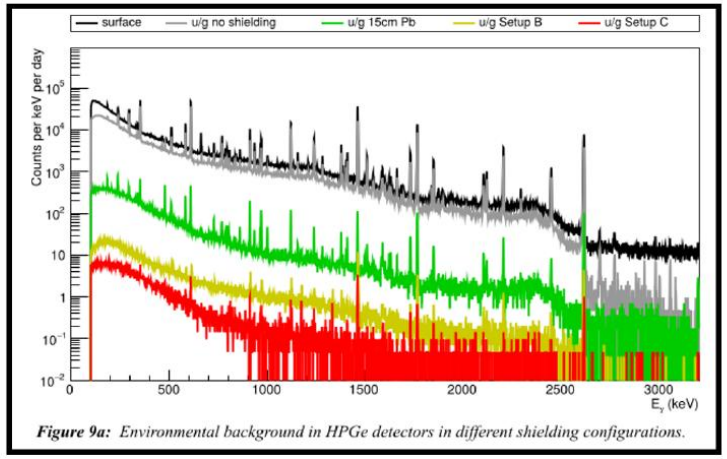


Figure 9a: Environmental background in HPGe detectors in different shielding configurations.

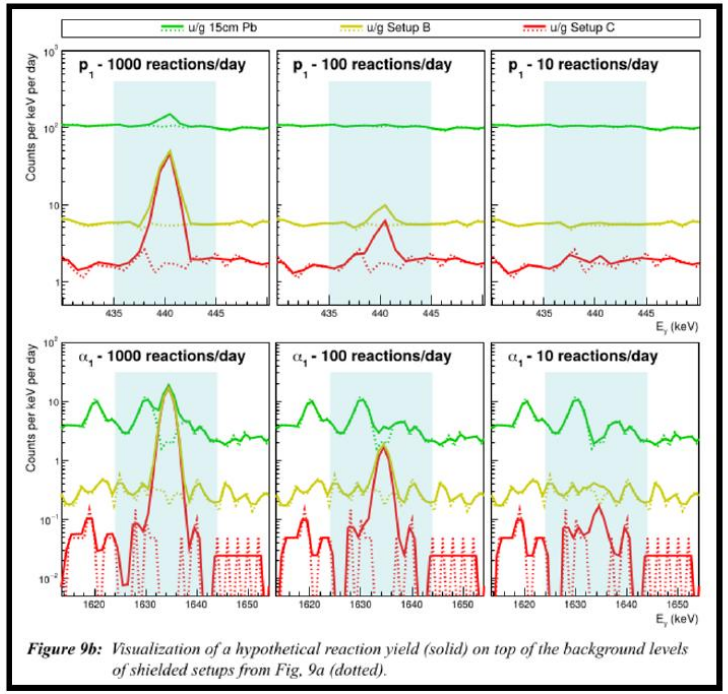
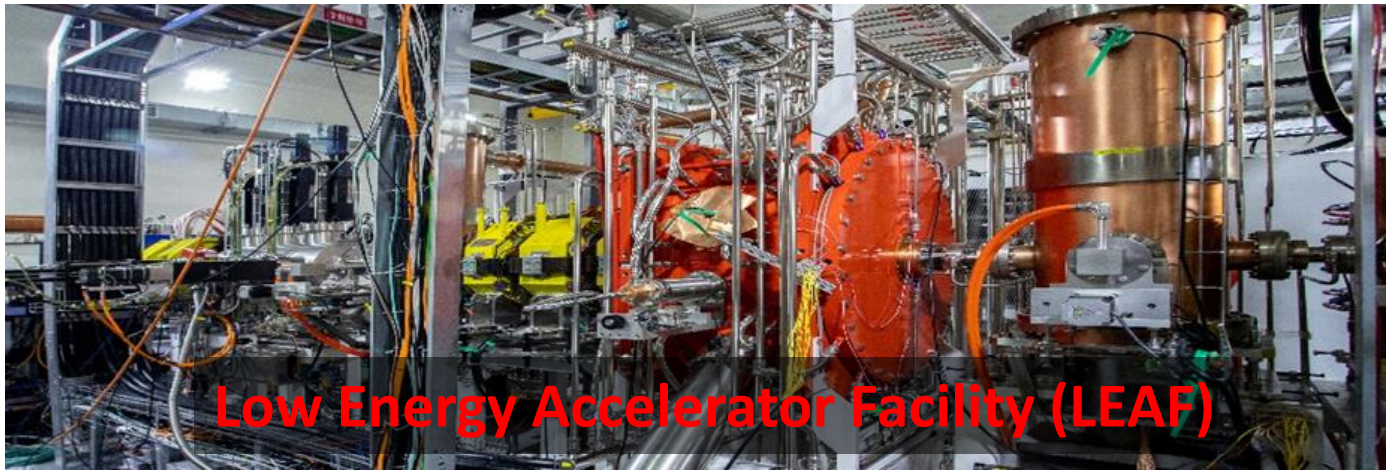
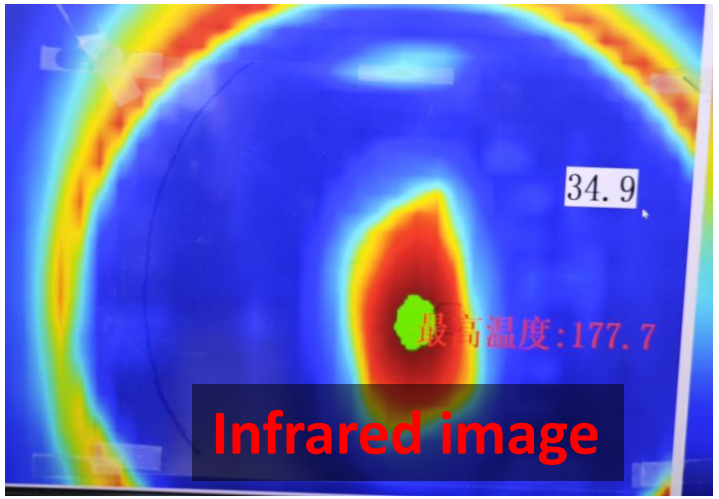
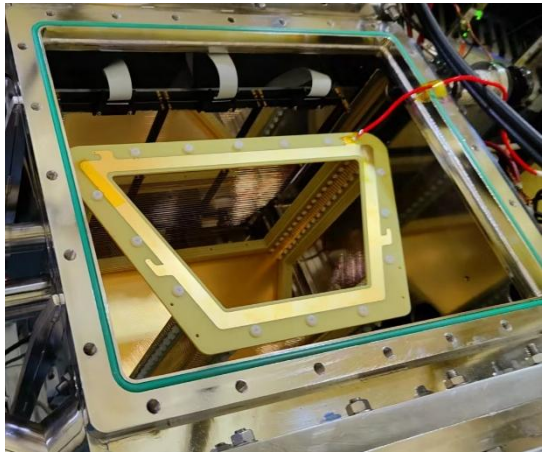


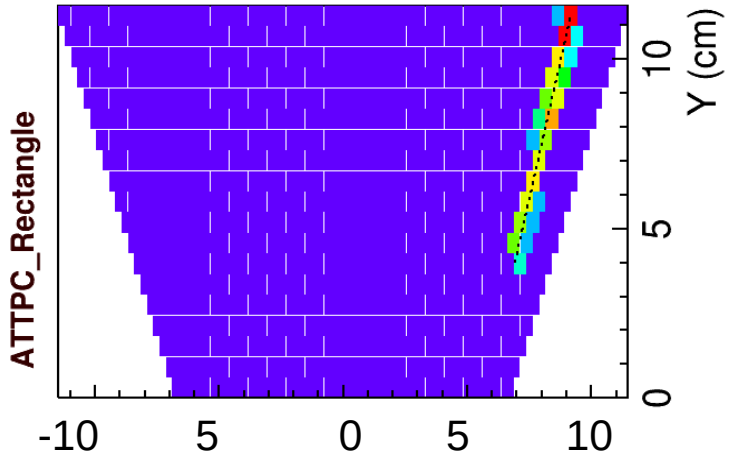
Figure 9b: Visualization of a hypothetical reaction yield (solid) on top of the background levels of shielded setups from Fig. 9a (dotted).

High Intensity+Time Projection Chamber







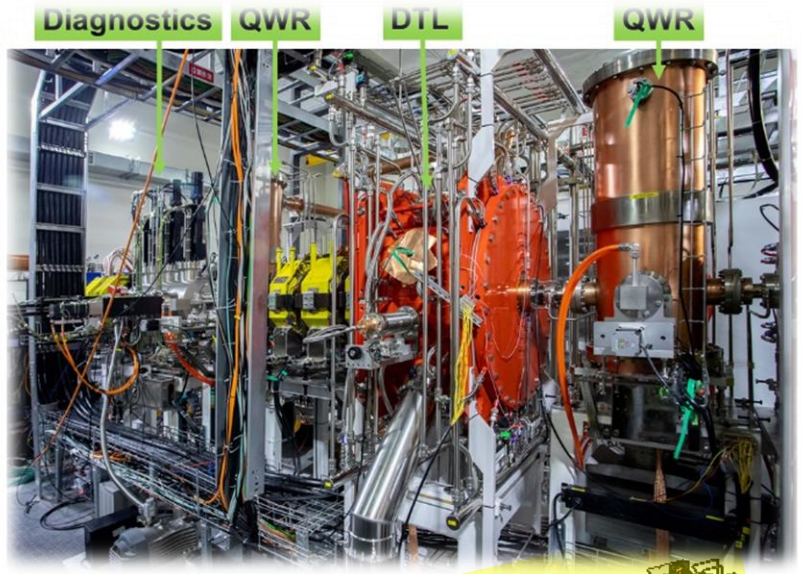




- LINAC: High Intensity beam up to few hundreds of puA
- TPC: Ultra sensitive tracking detector
- Complementary to LUNA-MV and other experiments

Z.C.Zhang+ NIMA(2021)
Doi: 10.1016/j.nima.2021.165740

Low Energy Heavy Ion Accelerator Facility(LEAF)

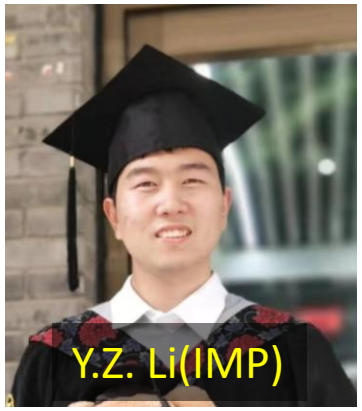


Yao Yang et al., NIMA 1039 (2022) 167095

- LEAF: 45GHz and 14.5GHz ECRs; 0.5MeV/u RFQ; 0.3MeV/u-0.7MeV/u DTL; Energy calibration by $^{12}C(p,g)$, p(15N,a)12C*
- Maximum carbon beam intensity on target: ~200 puA (Spillane: 40puA); Energy Spread: <0.2%(σ); Energy step size:~50 keV; beam time： ~1150 hr

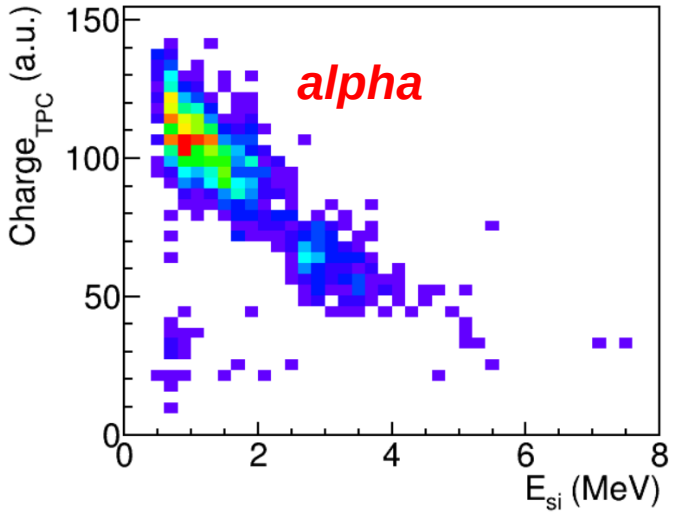
Courtesy of Yao Yang (IMP)

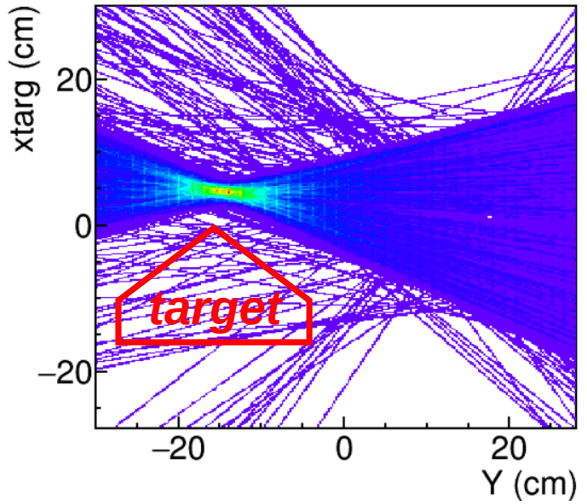
Analysis： E_{cm}=2.72MeV with Graphite (5N)

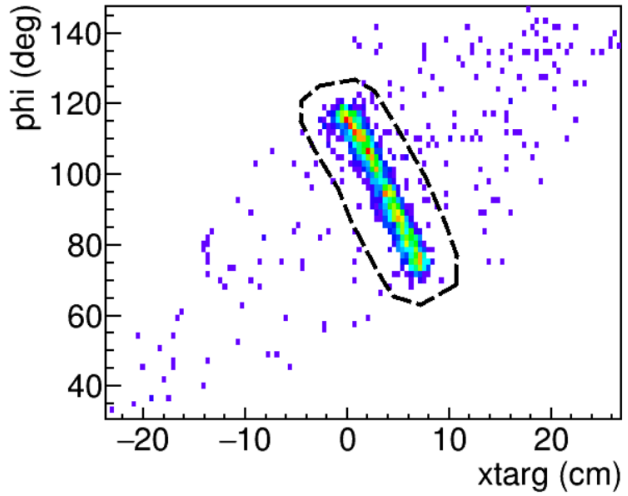


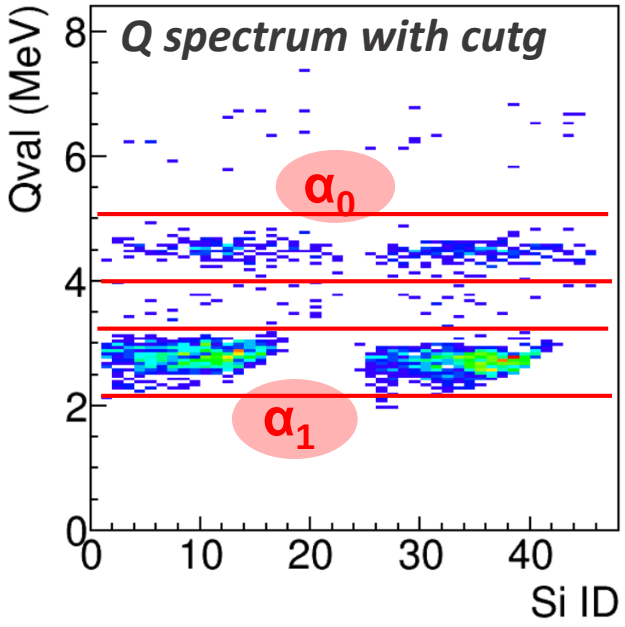


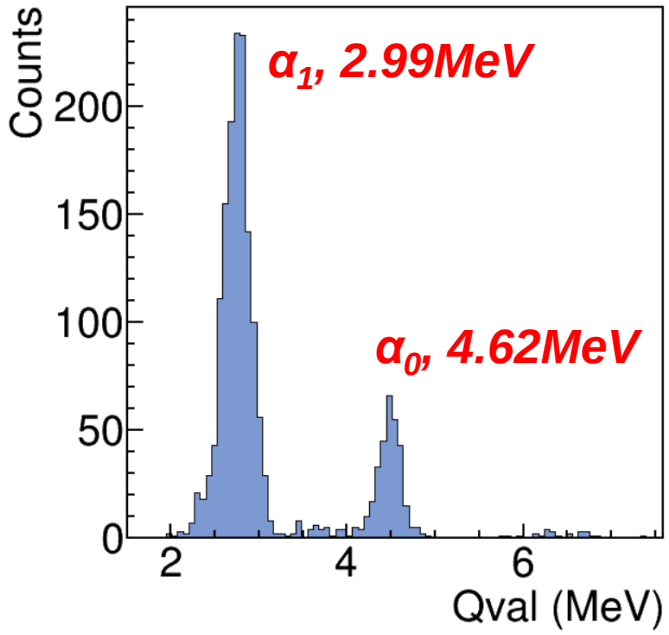


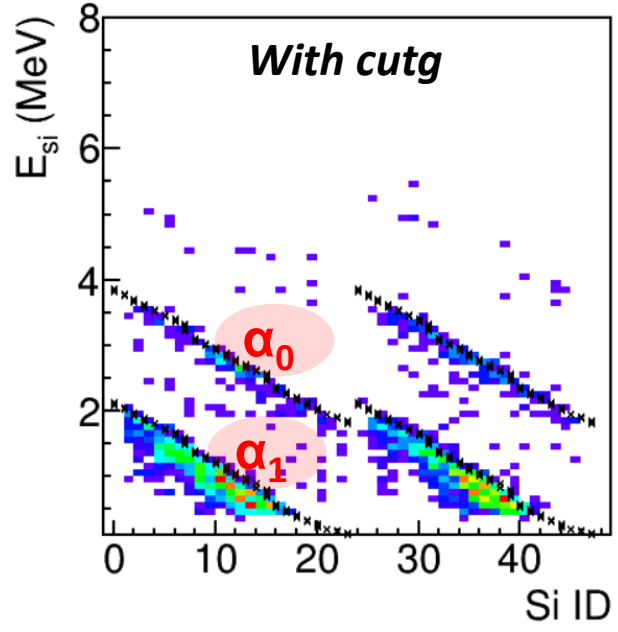






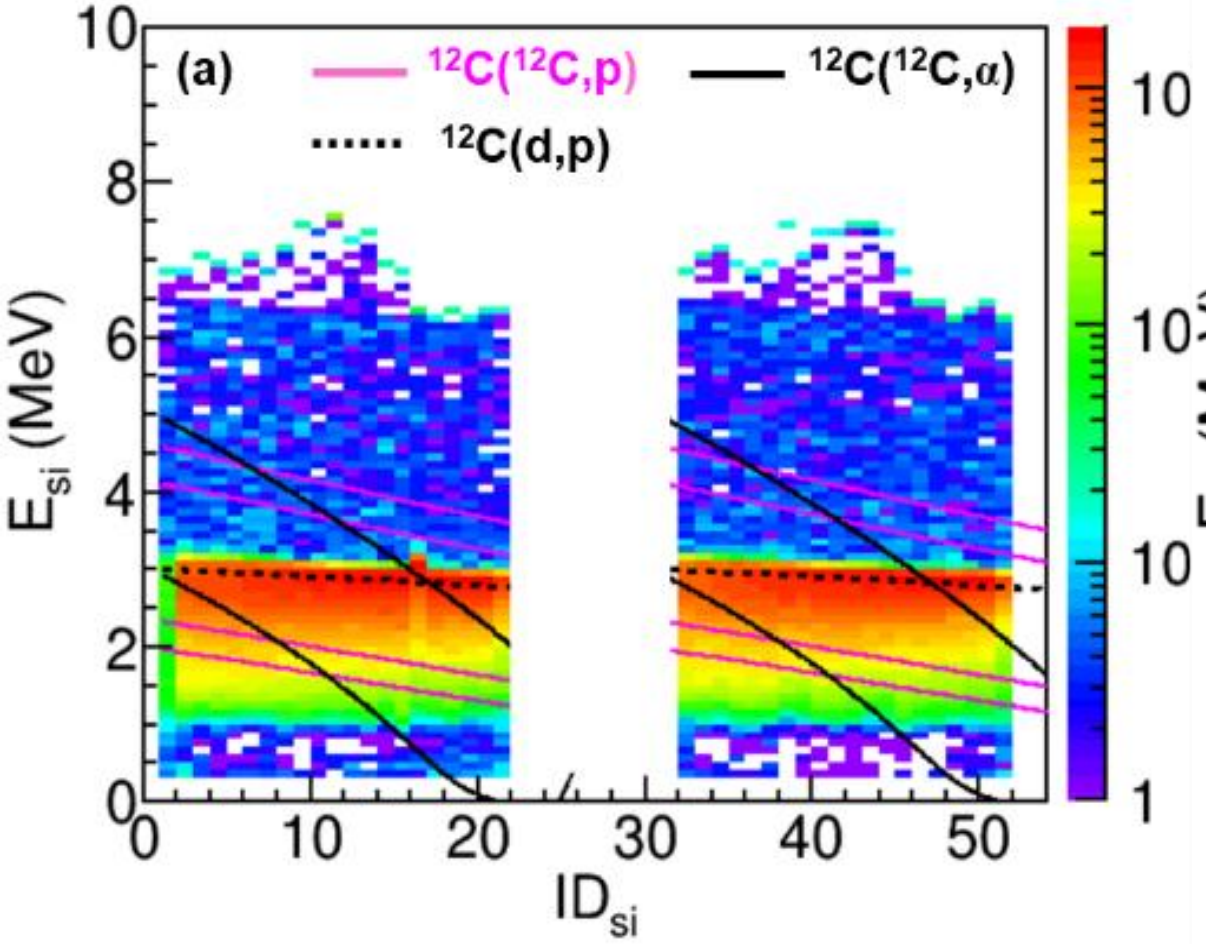


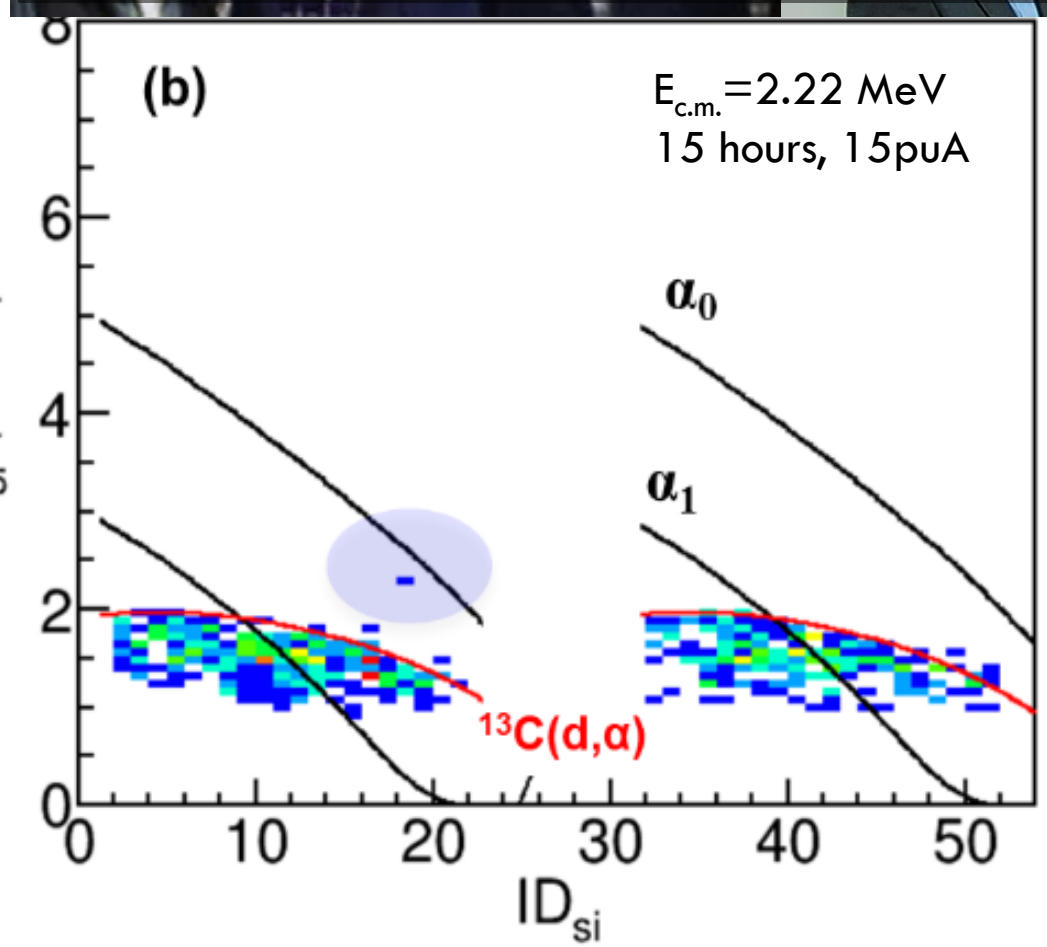




Another result with HOPG @$E_{c.m.}$=2.2MeV



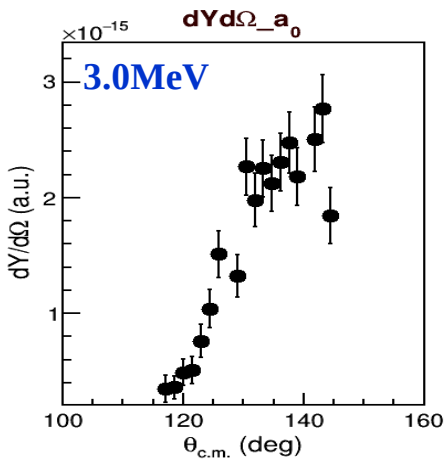


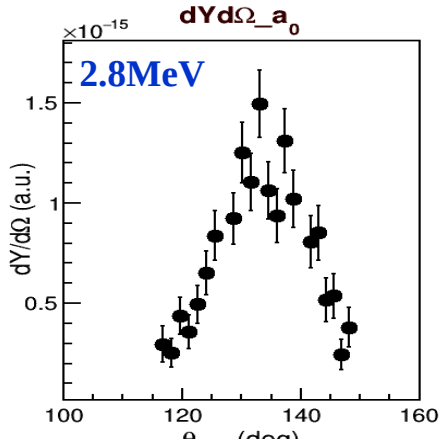


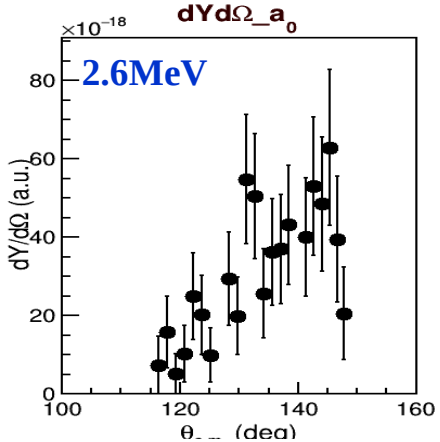
Clear identification with cuts in the energy loss and tracks in TPC

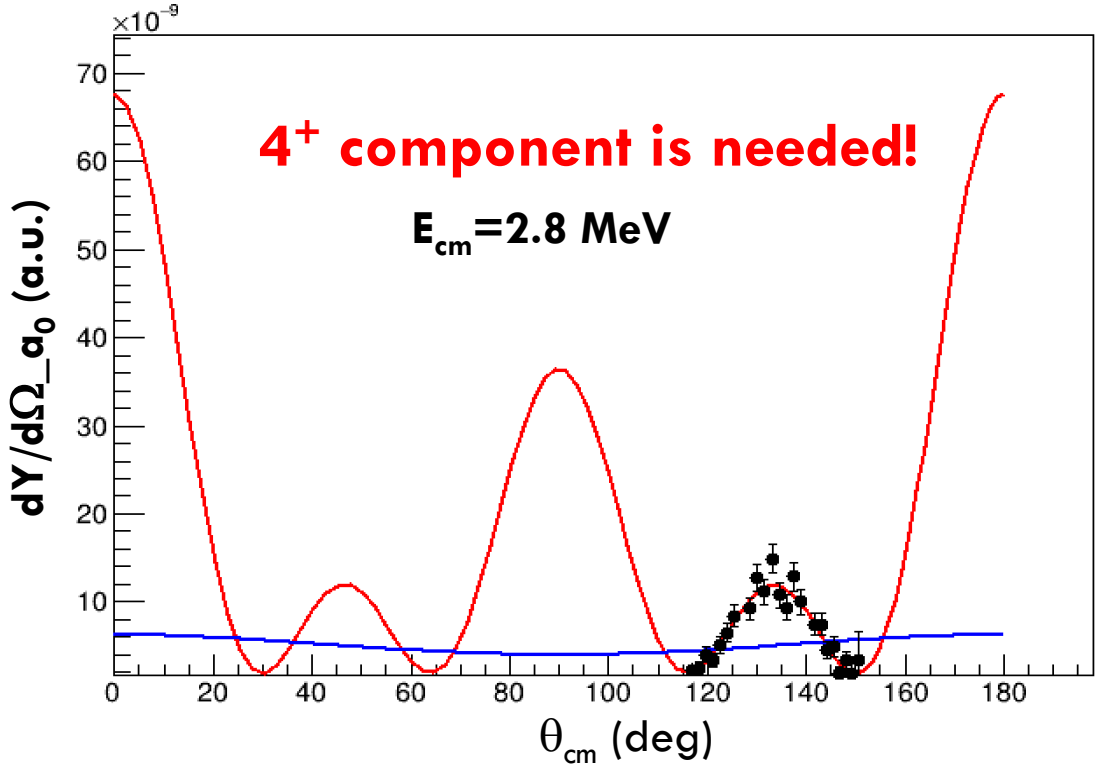
Wang et al., NST(2025)

Determination of J^{π} of E_{cm}=2.76 (MeV)

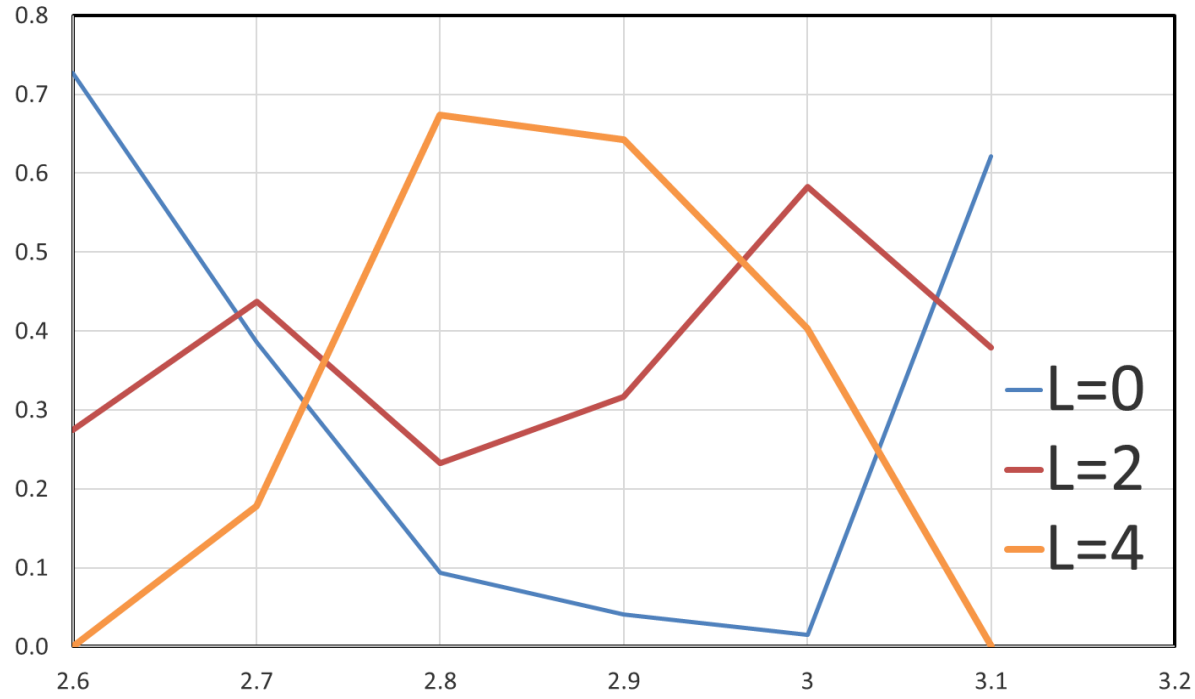




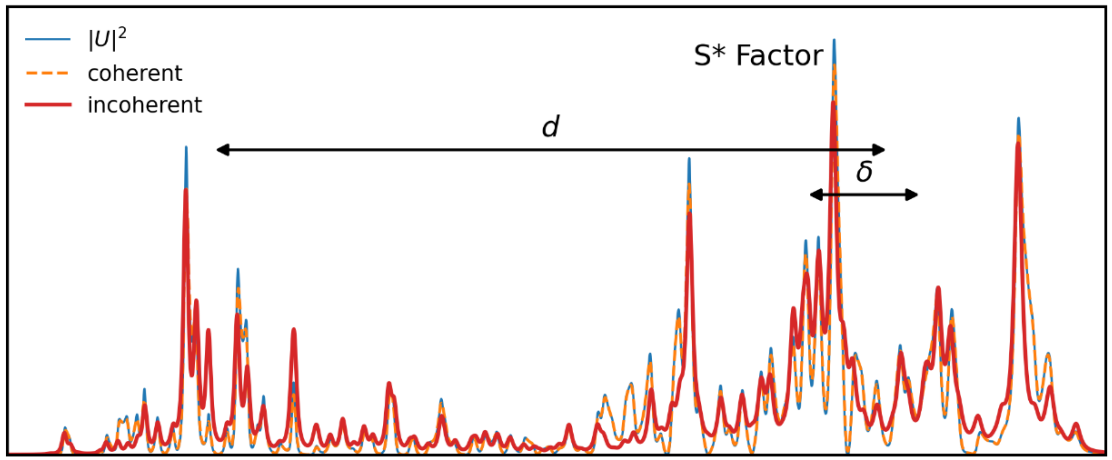


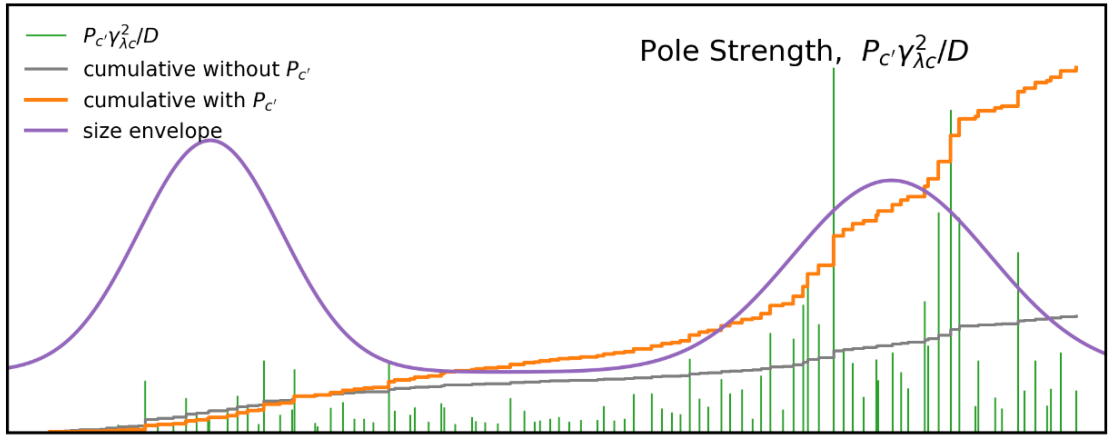


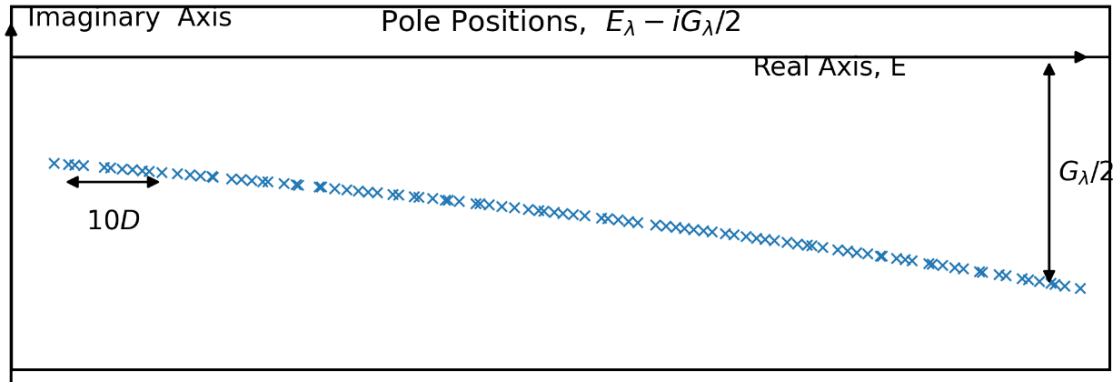
Contibution of difference spin




HOW TO EXTRAPOLATE
TOWARDS LOWER ENERGIES
STEP 1: STAY CALM.
STEP 2: TRUST YOUR MODEL.
STEP 3: PRETEND YOU SEE WHAT THE DATA WILL SEE.
THE MODEL
LAND OF MEASURED DATA
(SAFE AND COMFORTABLE)
1. CHOOSE A GOOD COMPANION: THEORY →
2. IGNORE THE FOG.
(IT'S BASICALLY STATISTICAL.)
3. WALK WITH CONFIDENCE.
(EVEN IF YOU CAN'T SEE.)
DOWN THERE BE UNKNOWN RESONANCES, THRESHOLDS, AND OTHER SCARY THINGS... BUT PROBABLY NOT TODAY.
LOWER ENERGIES
(THE UNKNOWN)
REMEMBER:
EXTRAPOLATION
=
EDUCATED GUESS
+
HOPIUM
÷
REALISM
WORKS MOST OF THE TIME!*
* UNTIL IT DOESN'T. THEN IT'S CALLED A NEW DISCOVERY.



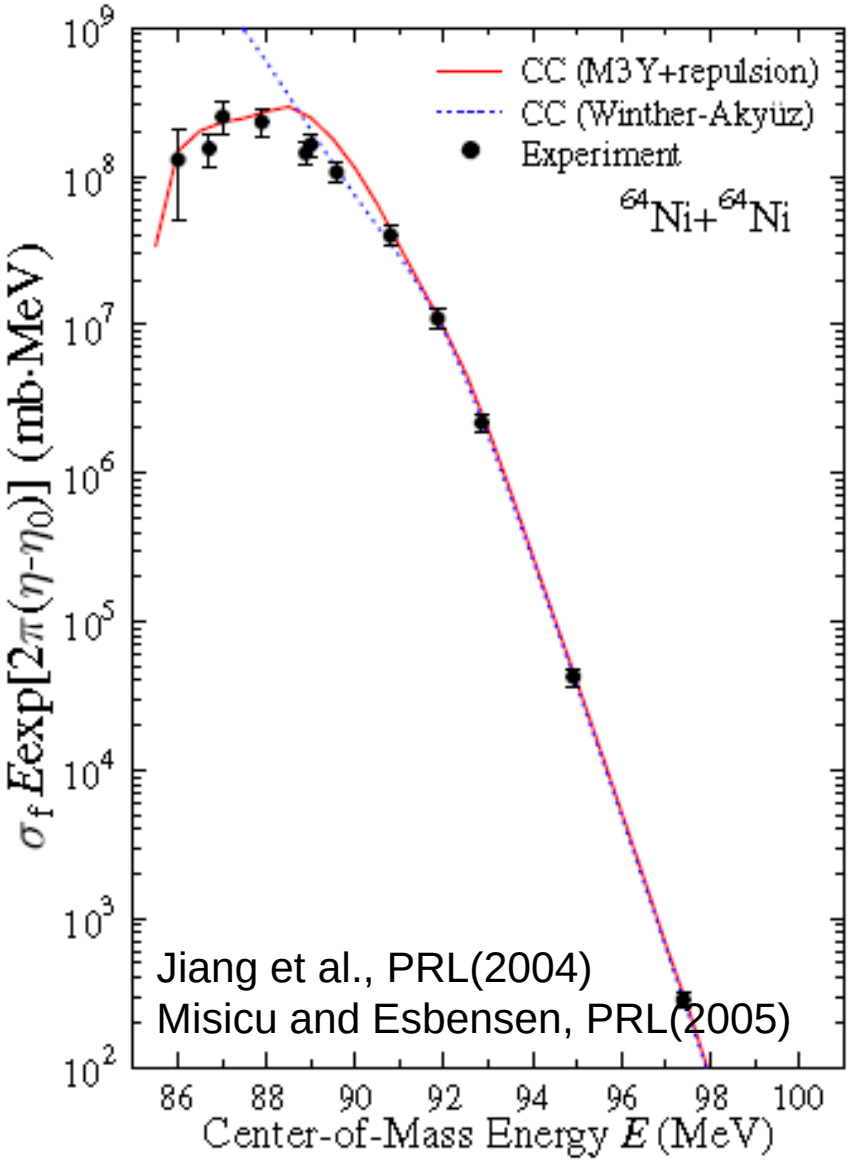


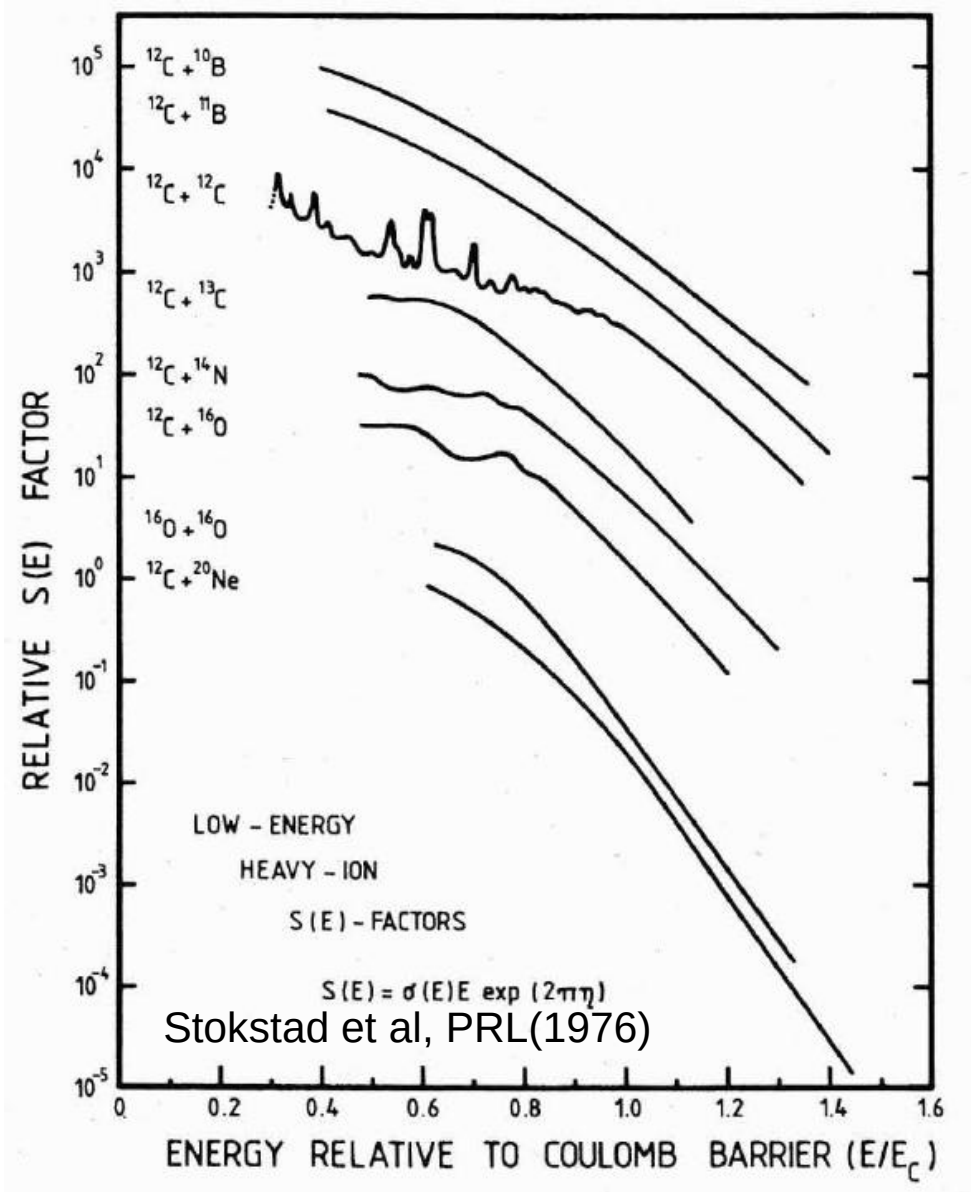


- level width: Γ
- level spacing: D
- size-resonance spacing: d

- Finite averaging Interval: δ

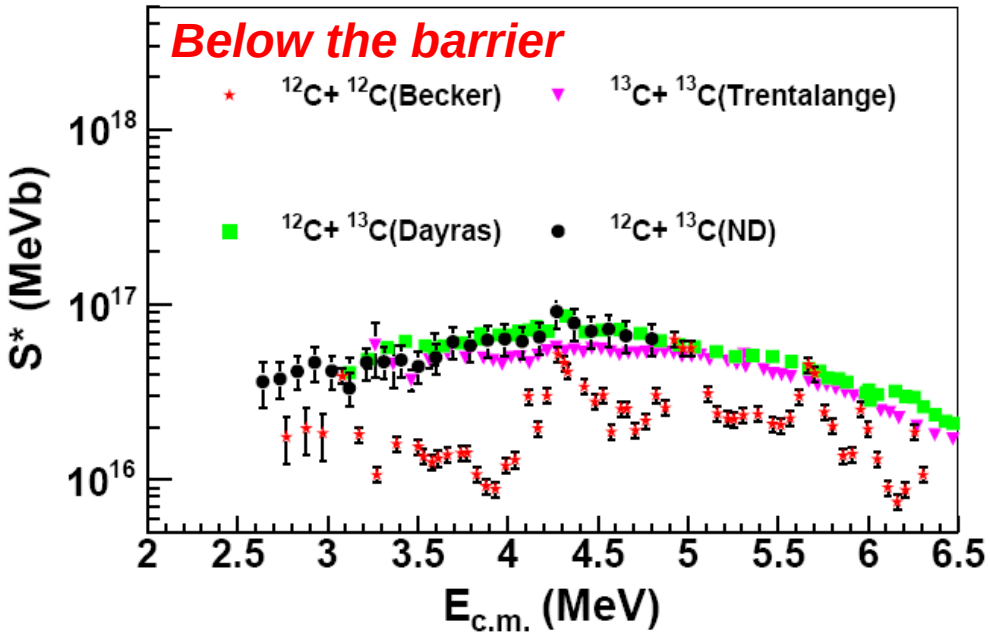
Advances in Nuclear Physics: E. Vogt(1968)

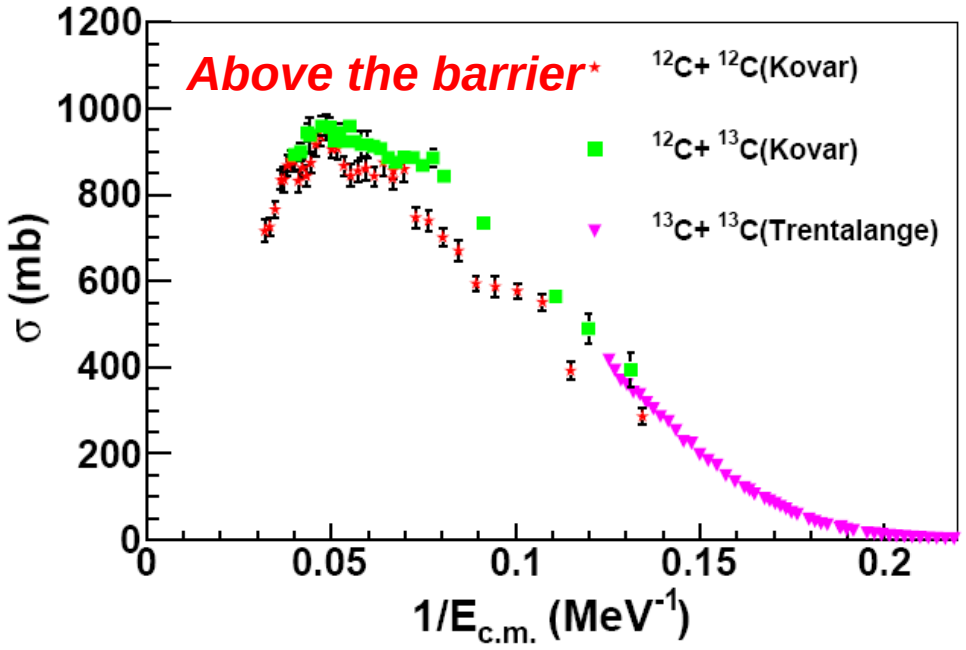




^{64}Ni+^{64}Ni **A<20**

Origin is under debate. Pauli exclusion, dissipative effects,…





Correlation among the carbon isotope systems



For most energies, the $^{12}C+^{12}C$ cross sections are suppressed!

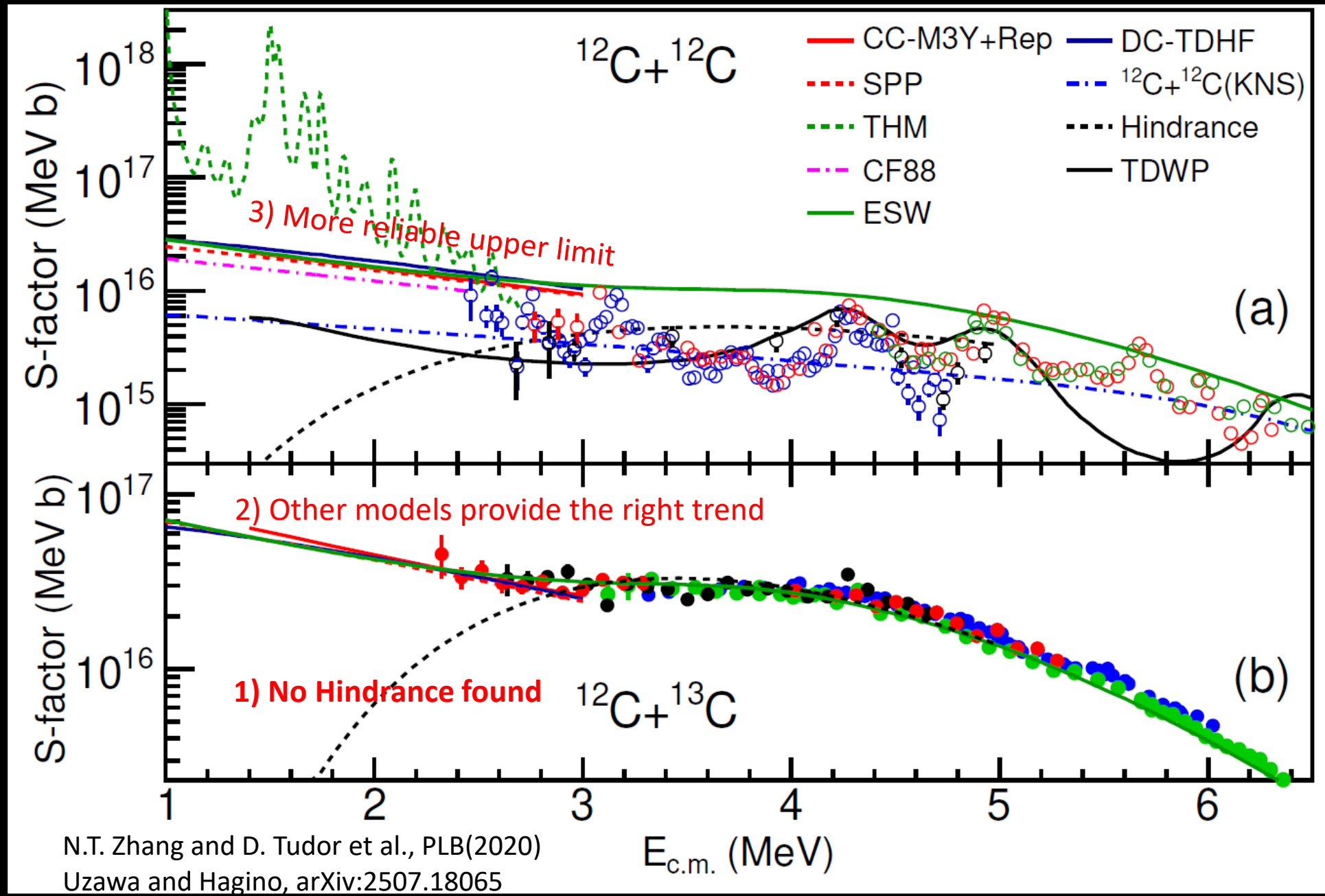


Only at resonant energies, the $^{12}C+^{12}C$ cross sections matches with those of $^{12}C+^{13}C$ and $^{13}C+^{13}C$!

Why?

M. Notani et al., Phys. Rev. C 85, 014607 (2012)

Test of hindrance and upper limit of $^{12}C+^{12}C$ based on systematics



N.T. Zhang and D. Tudor et al., PLB(2020)
Uzawa and Hagino, arXiv:2507.18065



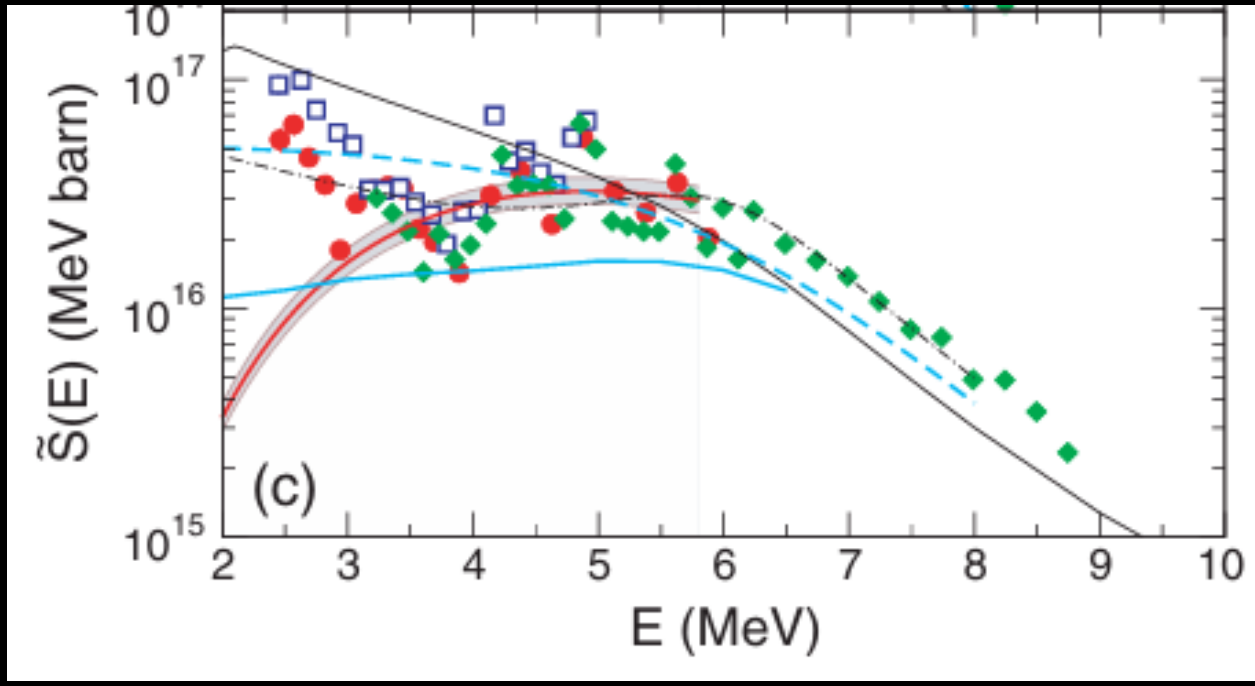
N.T.Zhang(IMP)



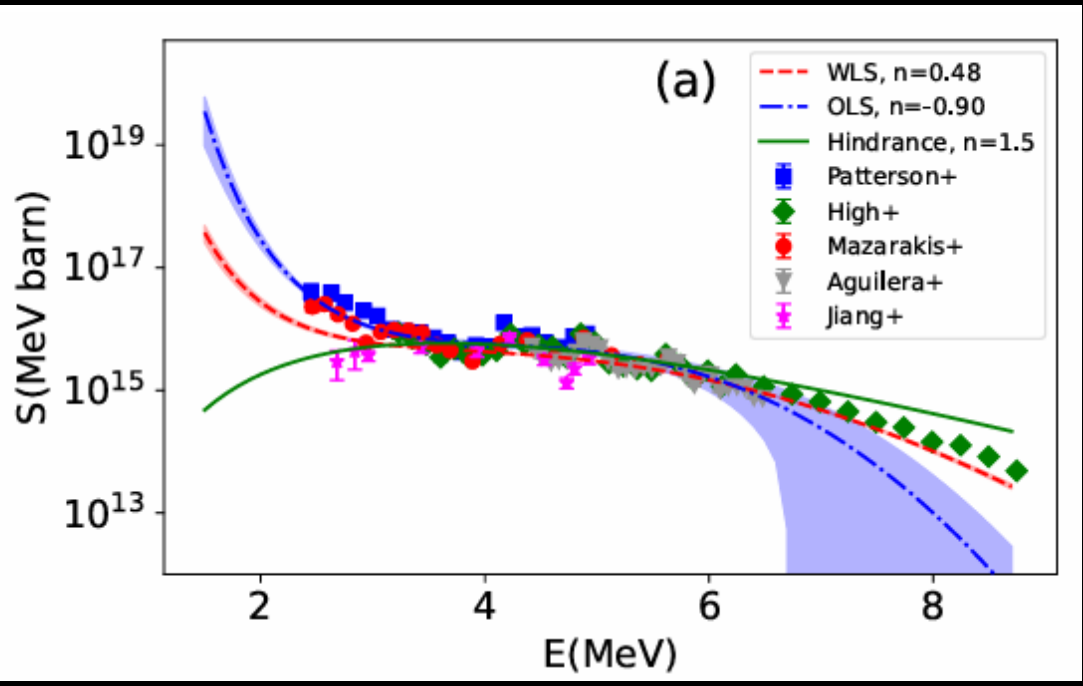
D. Tudor (IFIN-HH)



L. Trache (IFIN-HH)



Jiang, Rehm, Back, and Janssens, PRC(2007)



Uzawa & Hagino, PRC(2025)

Key Finding: Re-evaluates the logarithmic slope parametrization $L(E) = A + B/E^n$ originally restricted to $n = 1.5$ by C. L. Jiang et al. (PRC 2007). By releasing the fixed constraint on n, the best fit yields n values significantly below 1.5, leading to the **absence of fusion hindrance** at astrophysical energies for both the $^{12}\mathrm{C} + ^{12}\mathrm{C}$ and $^{12}\mathrm{C} + ^{13}\mathrm{C}$ reactions.

Correlation between carbon isotopes

Averaged S*

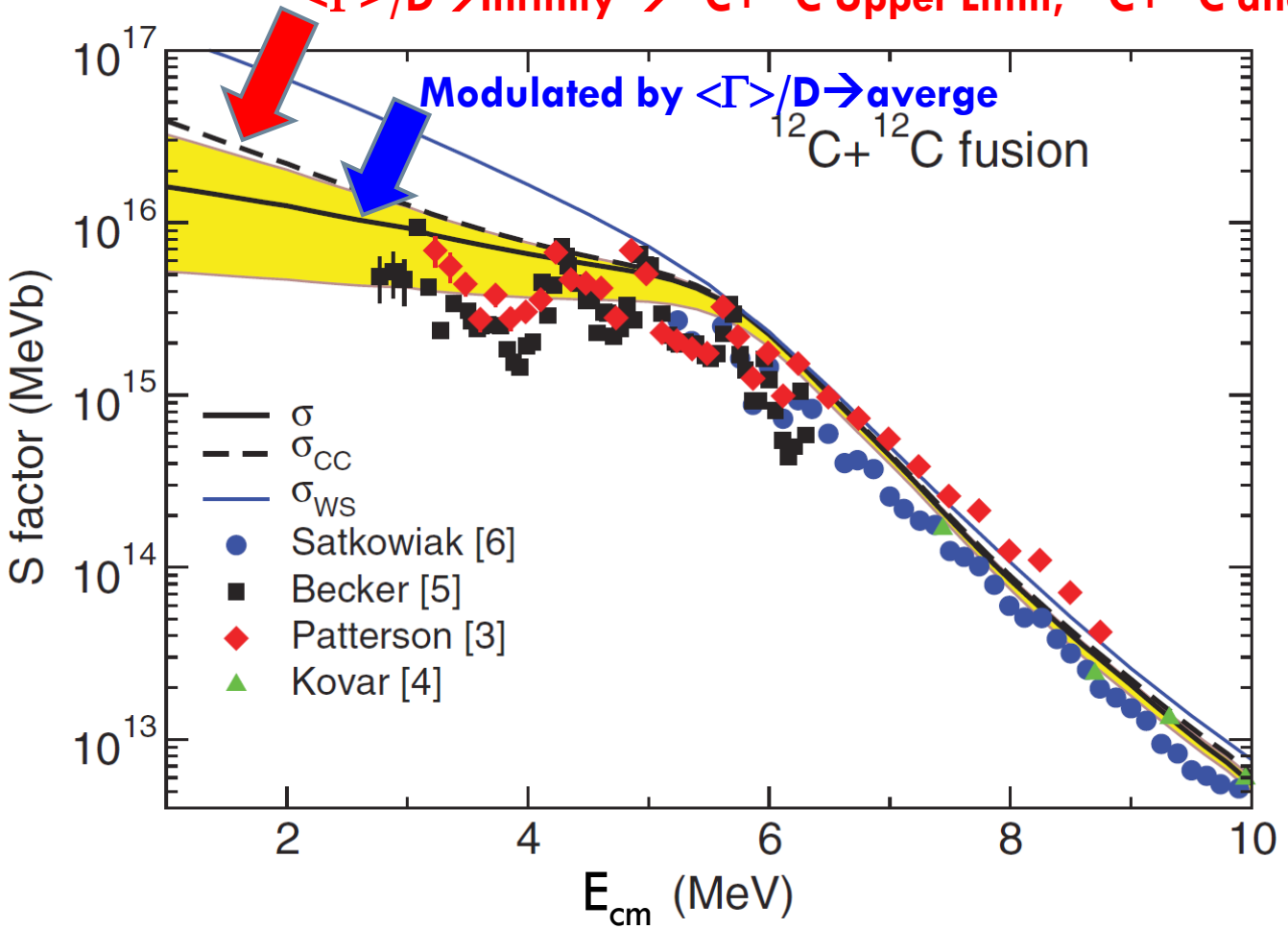
$$\sigma = \sum_J \sigma_{CC}^J P_J$$

States for fusion

$$P_J = 1 - \exp(-2\pi\bar{\Gamma}_J/D_J)$$

Γ: resonance width
D: resonance spacing

<Γ>/D→Infinity →^{12}C+^{12}C Upper Limit, ^{12}C+^{13}C and ^{13}C+^{13}C



C.L. Jiang et al., PRL110, 072701 (2013)

Summary

- Our direct measurement of $^{12}C+^{12}C$

→First direct measurement of a_0 and p_{01} below 2.5 MeV indicates the needs of improving the THM/cTHM

→Lower level density and less opening channels →S* factor lower than CF88

- **Indirect (THM, 24Mg(a,a'))+Direct measurements+Theory(R-matrix,Cluster,..)** will provide best extrapolation; **Strongly coupled plasma screening** needs to be studied
- **Collaboration will end up with better science!**




Collaborators at ND, RCNP, IFIN-HH, USTC and CIAE