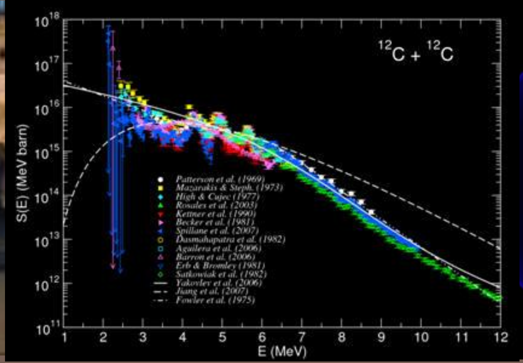
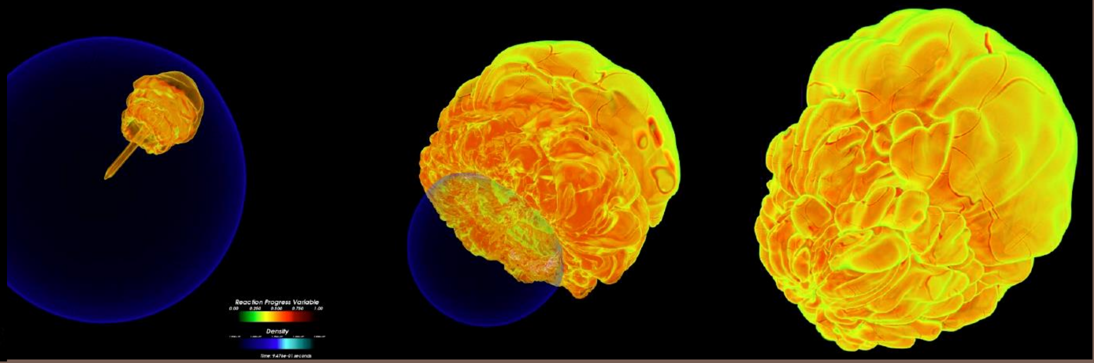






DIRECT MEASUREMENT OF THE $^{12}C+^{12}C$ FUSION REACTION

X.D. Tang[1,2]

On behalf of the Carbon Fusion Experiment (CARFUSE) Collaboration

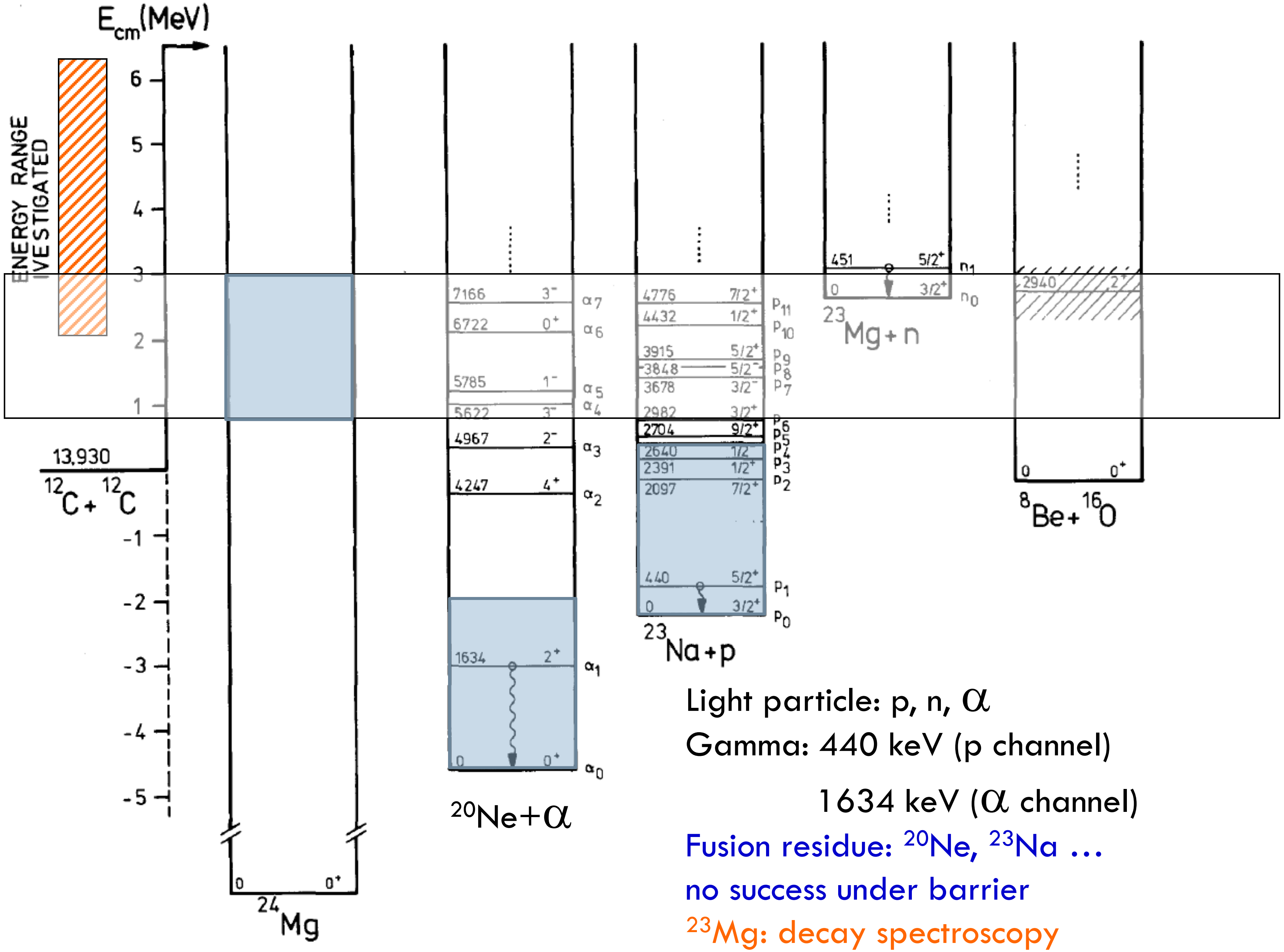
[1] Institute of Modern Physics, CAS, China

[2] Joint Department for Nuclear Physics, Lanzhou University and Institute of Modern Physics, CAS, China




Key reactions in nuclear astrophysics, Trento, ECT*, Feb. 16-22, 2025

CARbon FUSion Experiment (CARFUSE) @LEAF, IMP



Light particle: p, n, α

Gamma: 440 keV (p channel)

1634 keV (α channel)

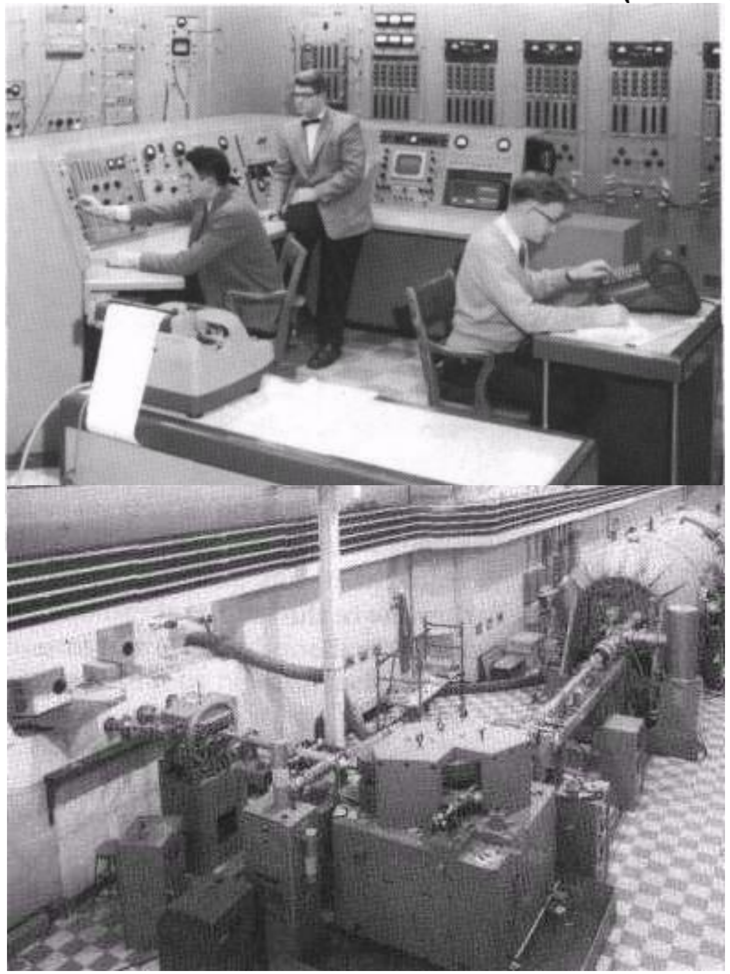
Fusion residue: ^{20}Ne, ^{23}Na …

no success under barrier

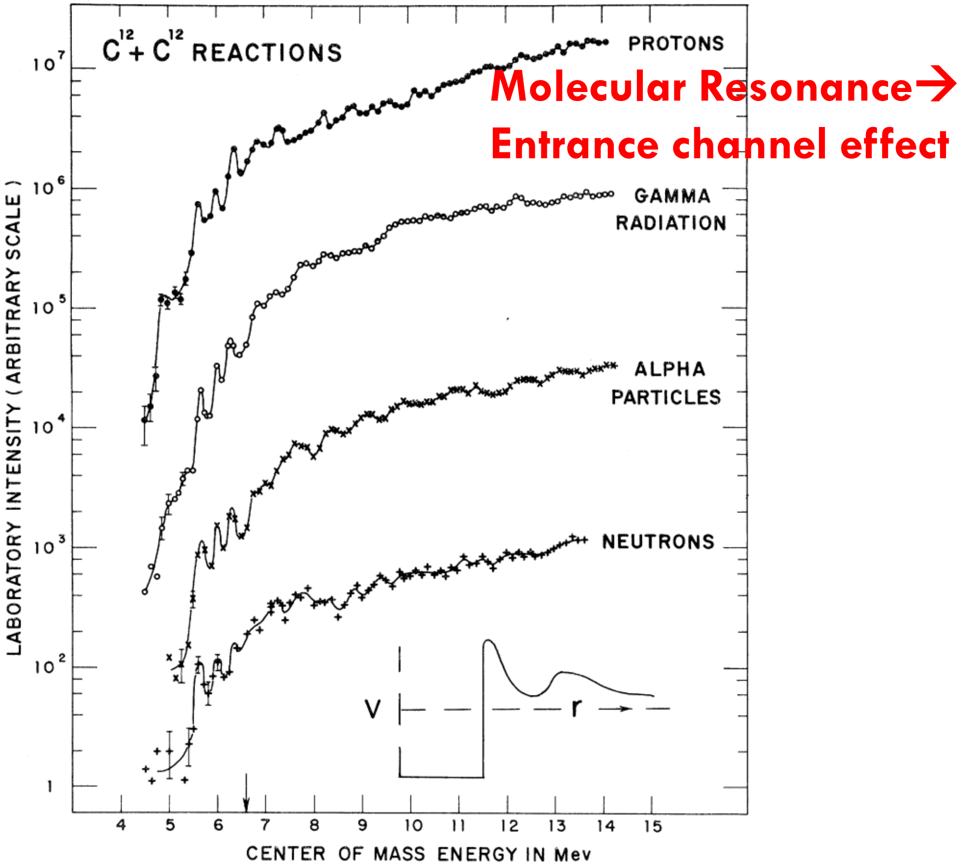
^{23}Mg: decay spectroscopy

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)



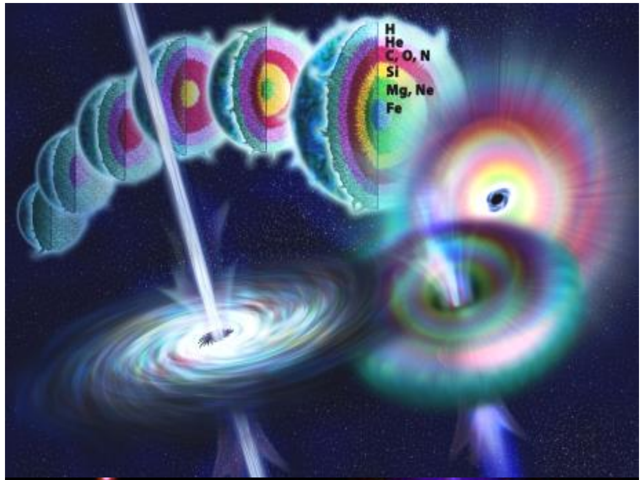
The world's first tandem accelerator installed at Chalk River in 1959.

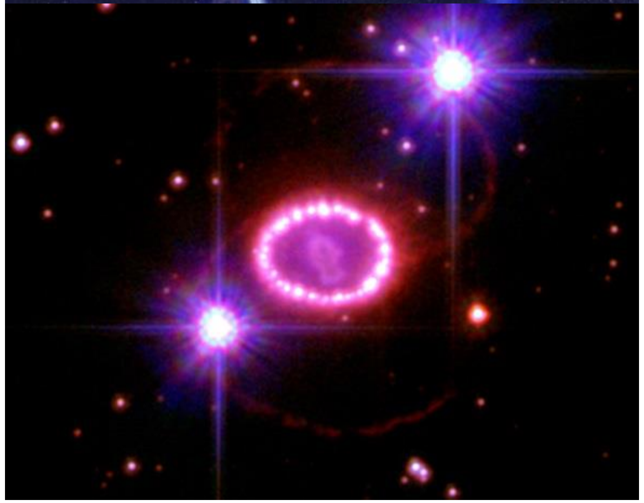


Molecular resonances in the $^{12}C+^{12}C$ fusion reaction measured by Almqvist et al., in 1960

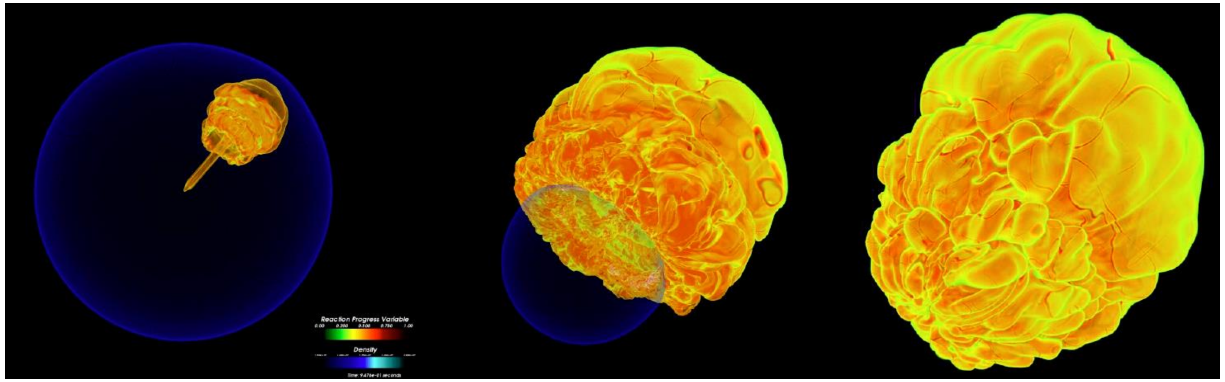
Carbon burning in the universe

Nucleosynthesis in massive stars

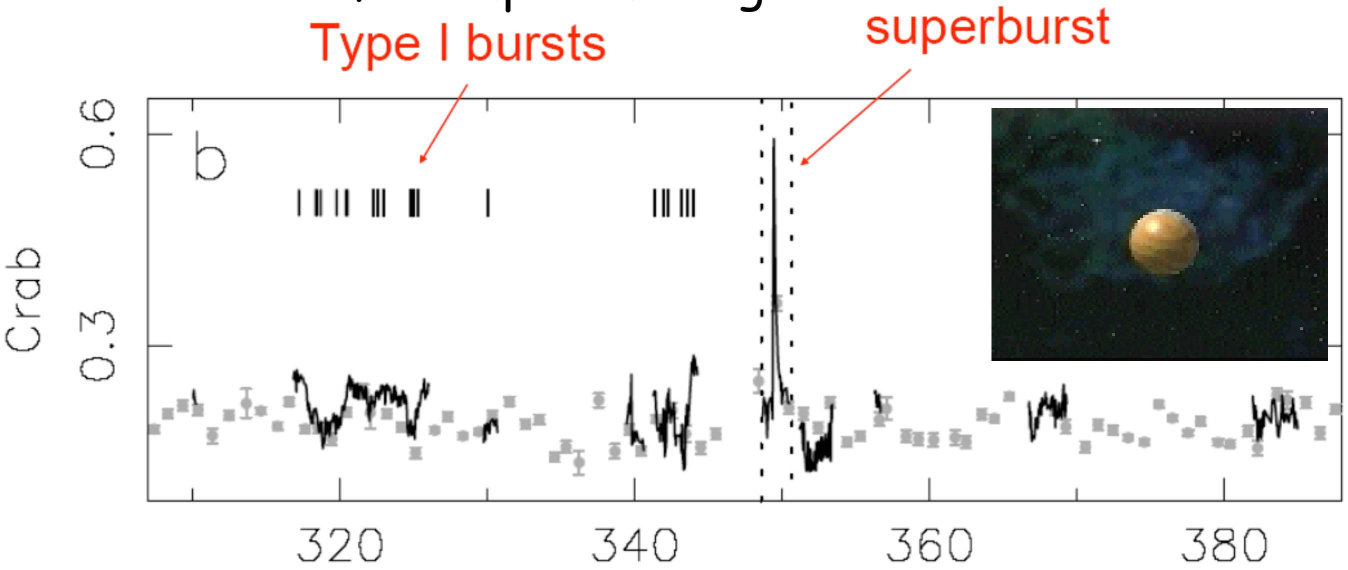




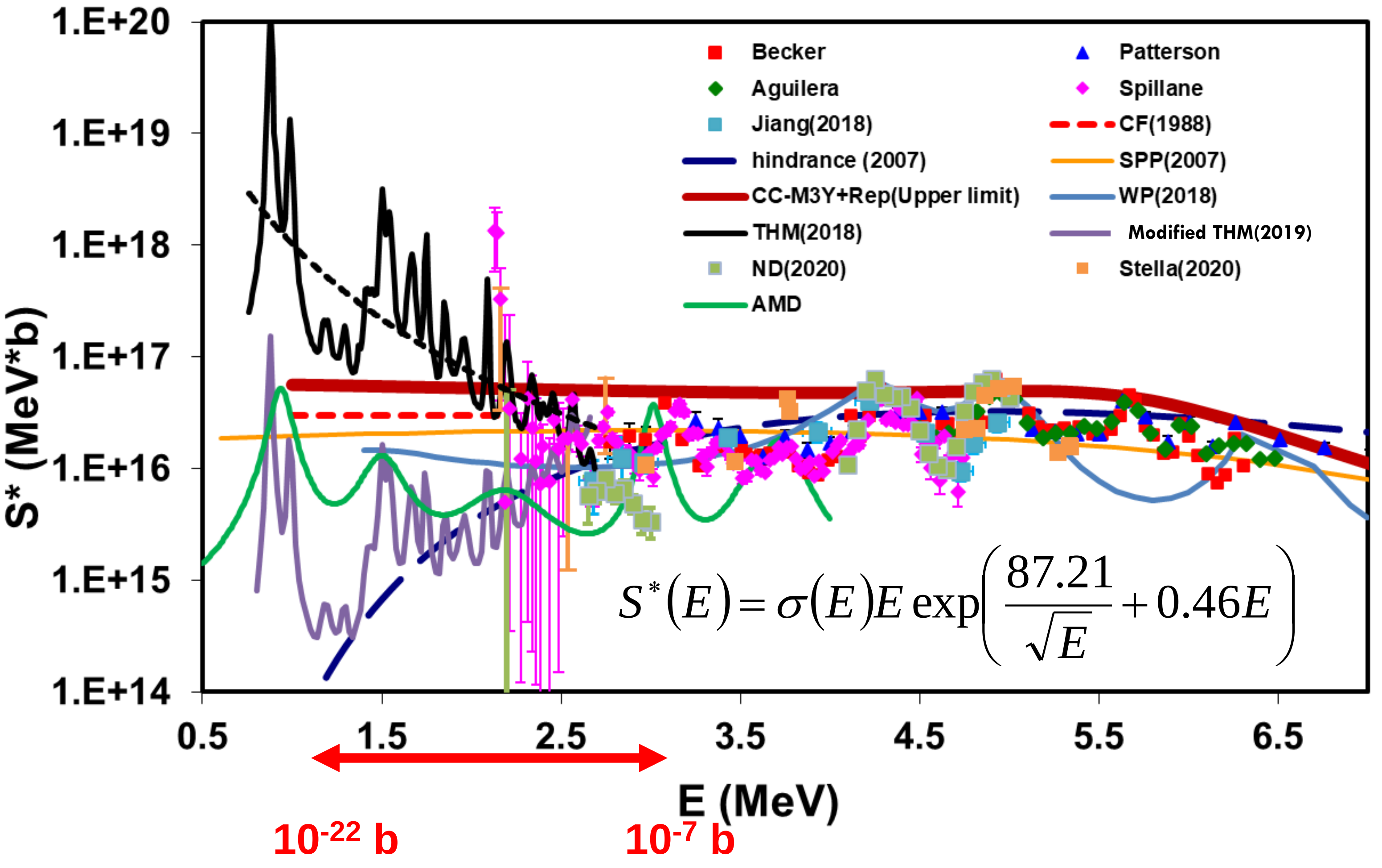
Ignition conditions in type Ia supernovae



Candidate for Superburst ignition



Uncertain cross section at stellar energies

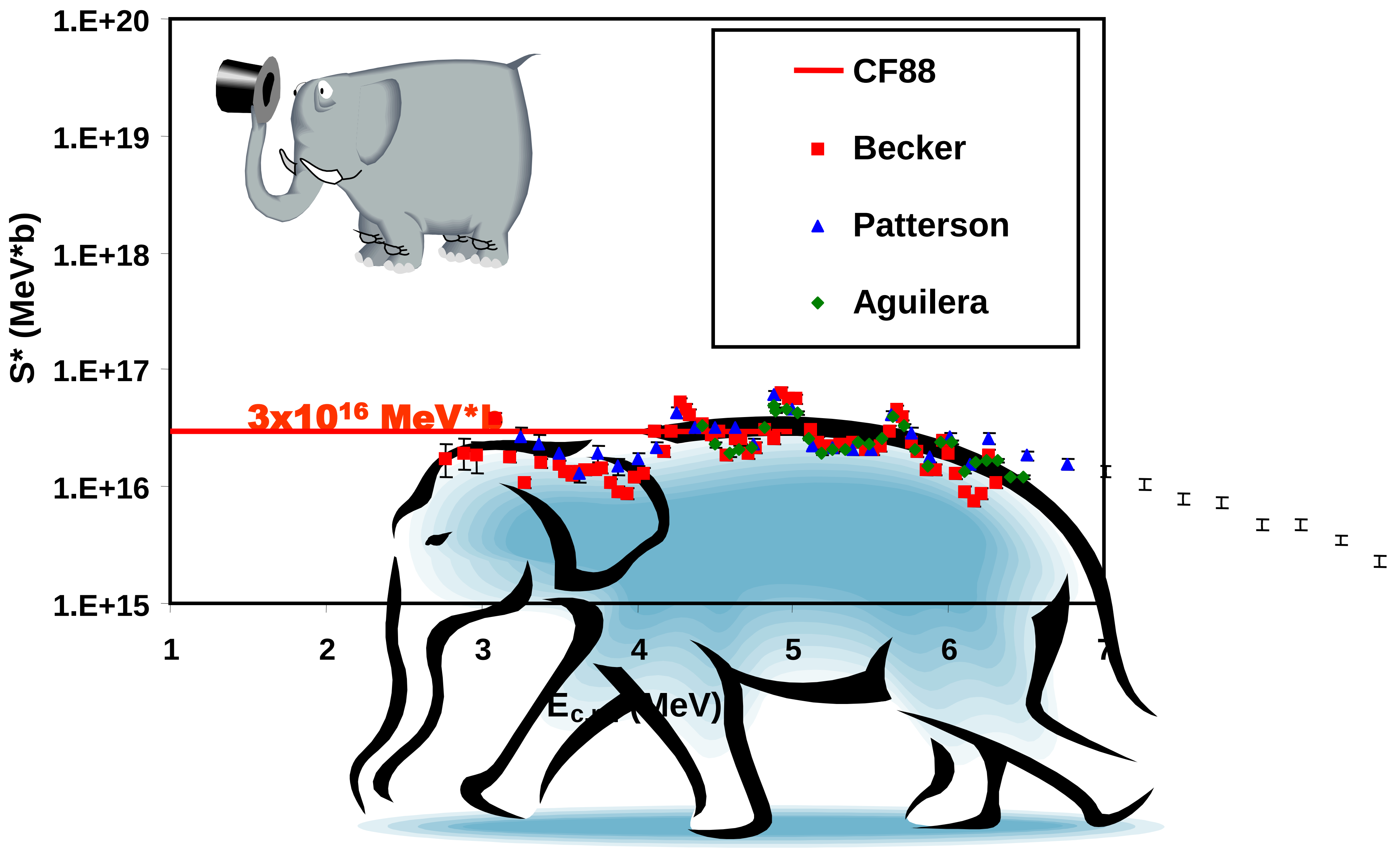


- Large difference between THM and Hindrance→Highly uncertain rate
- INDIRECT: Corrected THM exhibits a trend similar to Hindrance by replacing PWIA with DWIA
- Unknow resonances: Need better selection T=0, $J^\pi=0^+,2^+$

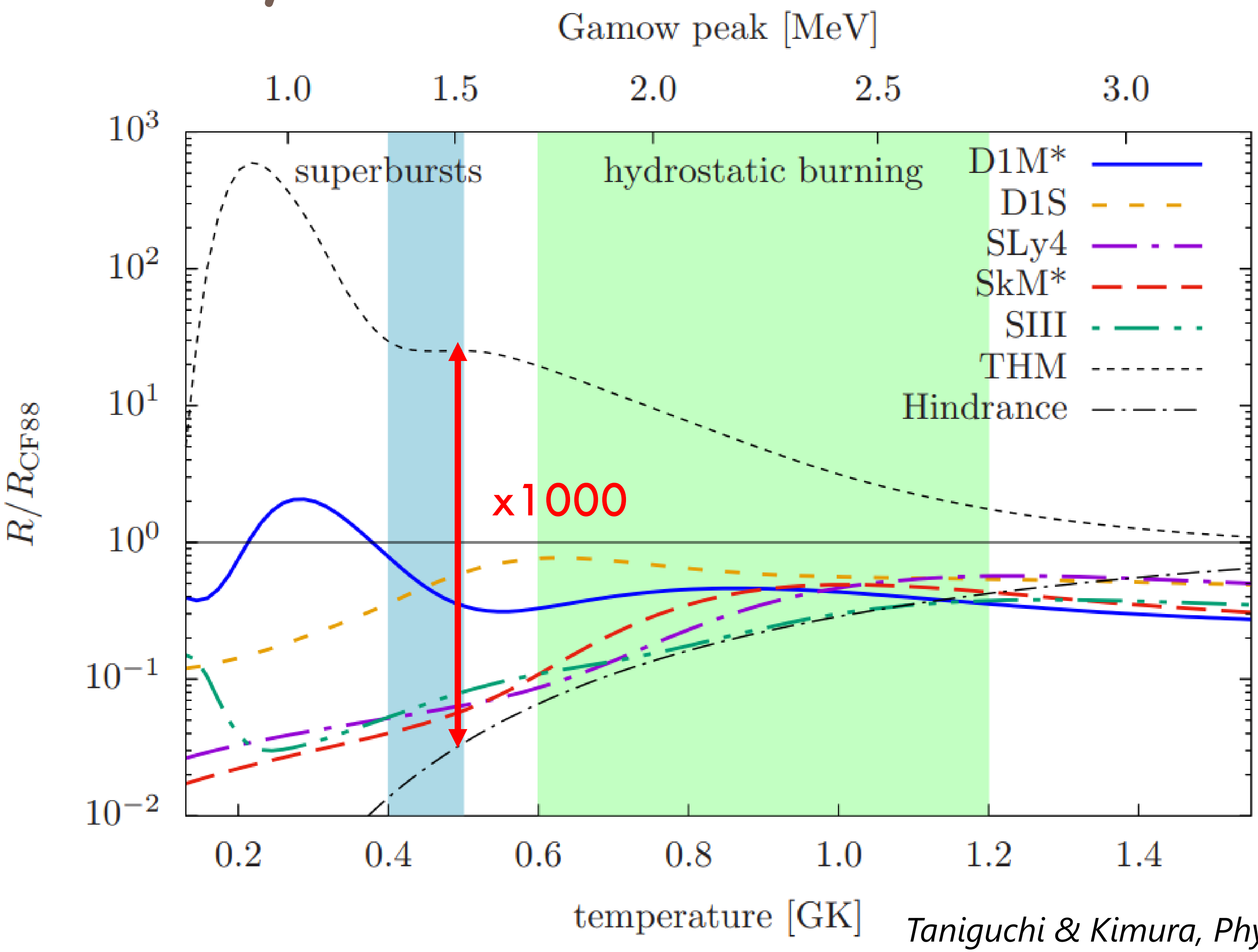
$^{12}C(^{12}C,p)^{23}Na$ (Q=2.24 MeV)
$^{12}C(^{12}C,\alpha)^{20}Ne$ (Q=4.62 MeV)
$^{12}C(^{12}C,n)^{23}Mg$ (Q=-2.62MeV)

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)

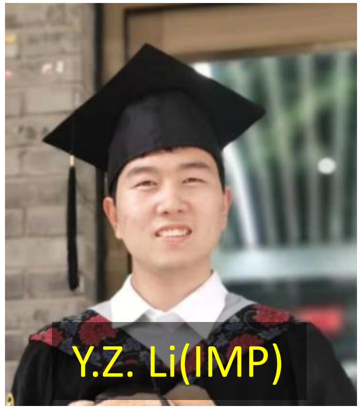
$$S^*(E) = \sigma E e^{(87.21/\sqrt{E} + 0.46E)}$$



Uncertainty in the reaction rate

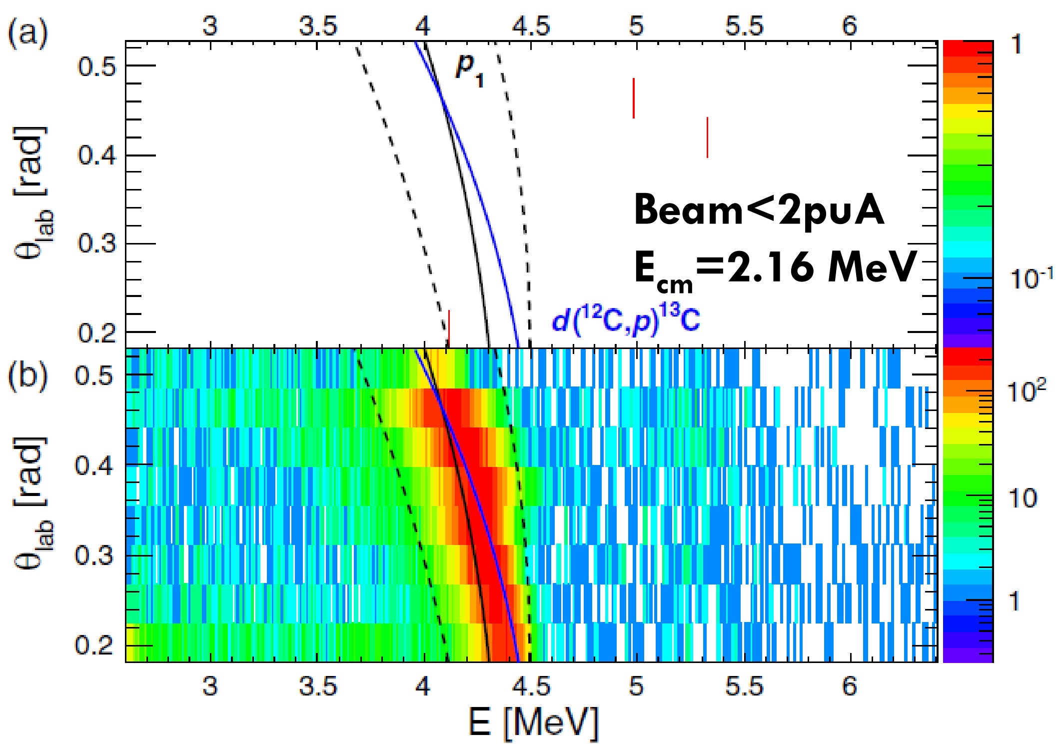


Taniguchi & Kimura, Phys. Lett. B 849 (2024) 138434

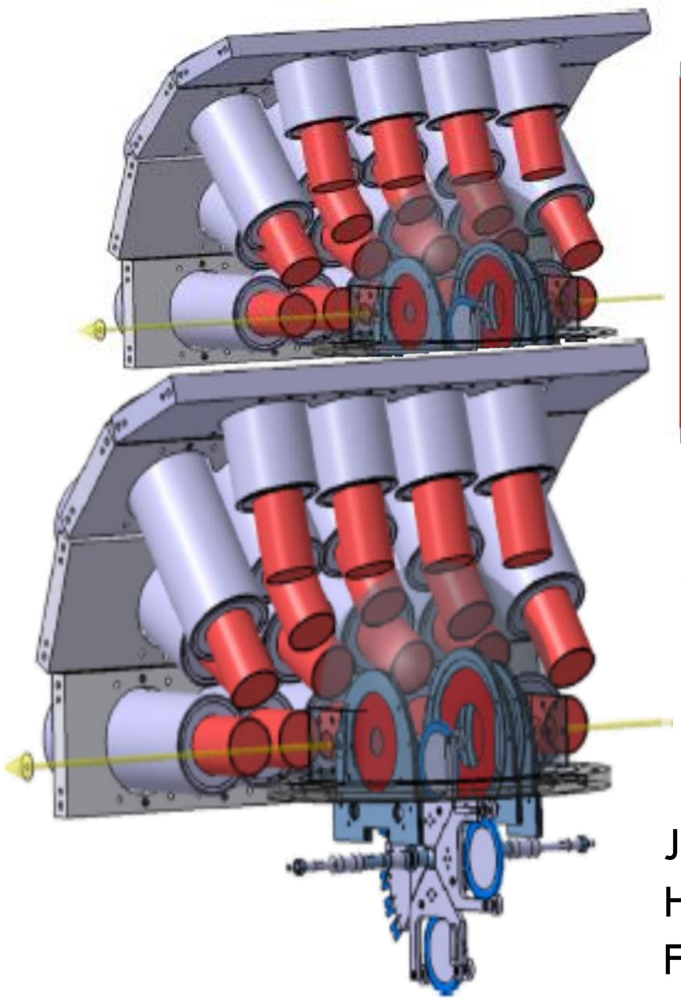


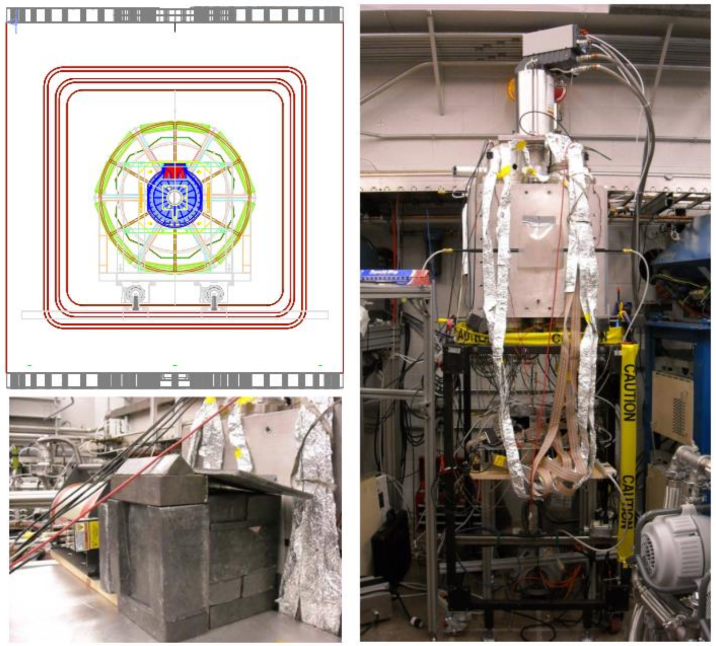
Direct Measurement of $^{12}C(^{12}C,a_{0,1})^{20}Ne$

Particle-γ coincidence at lower stellar energies



Fruet+ PRL(2020)





Beam<15puA

Jiang et al. (2012), Jiang et al. (2018) Heine et al. (2018), Tan et al. (2021), Fruet et al. (2021)

- ➢Particle-γ coincidence technique pushed the measurement down to sub-nb level
- ➢Only detect p_1 and α_1 channels

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

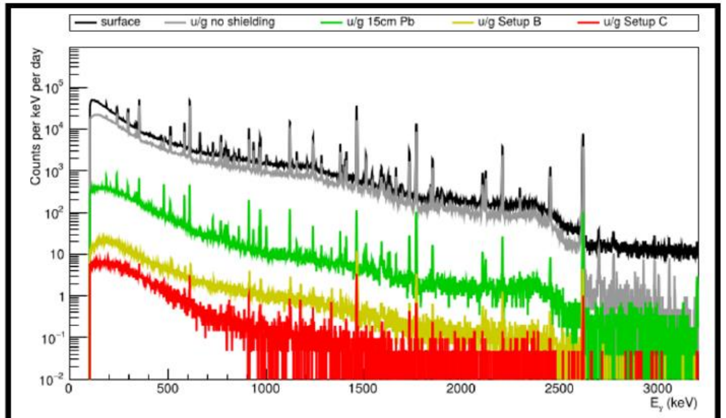


Figure 9a: *Environmental background in HPGe detectors in different shielding configurations.*

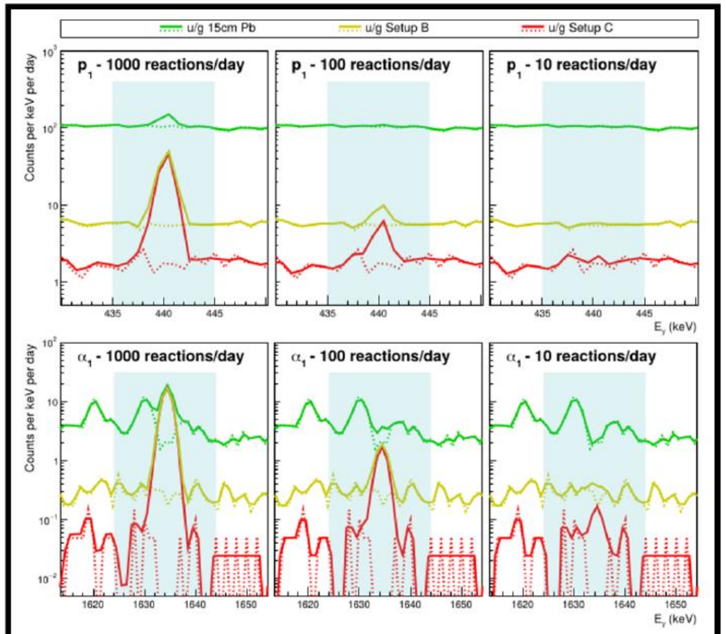
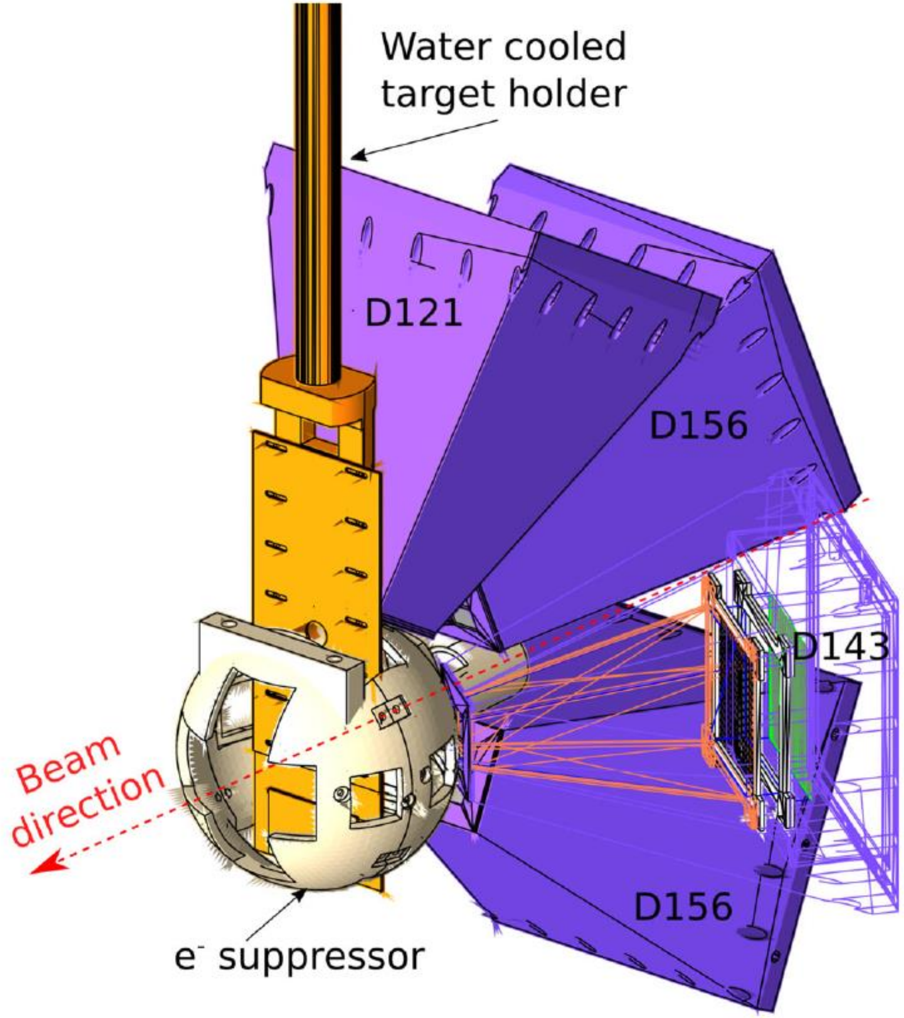
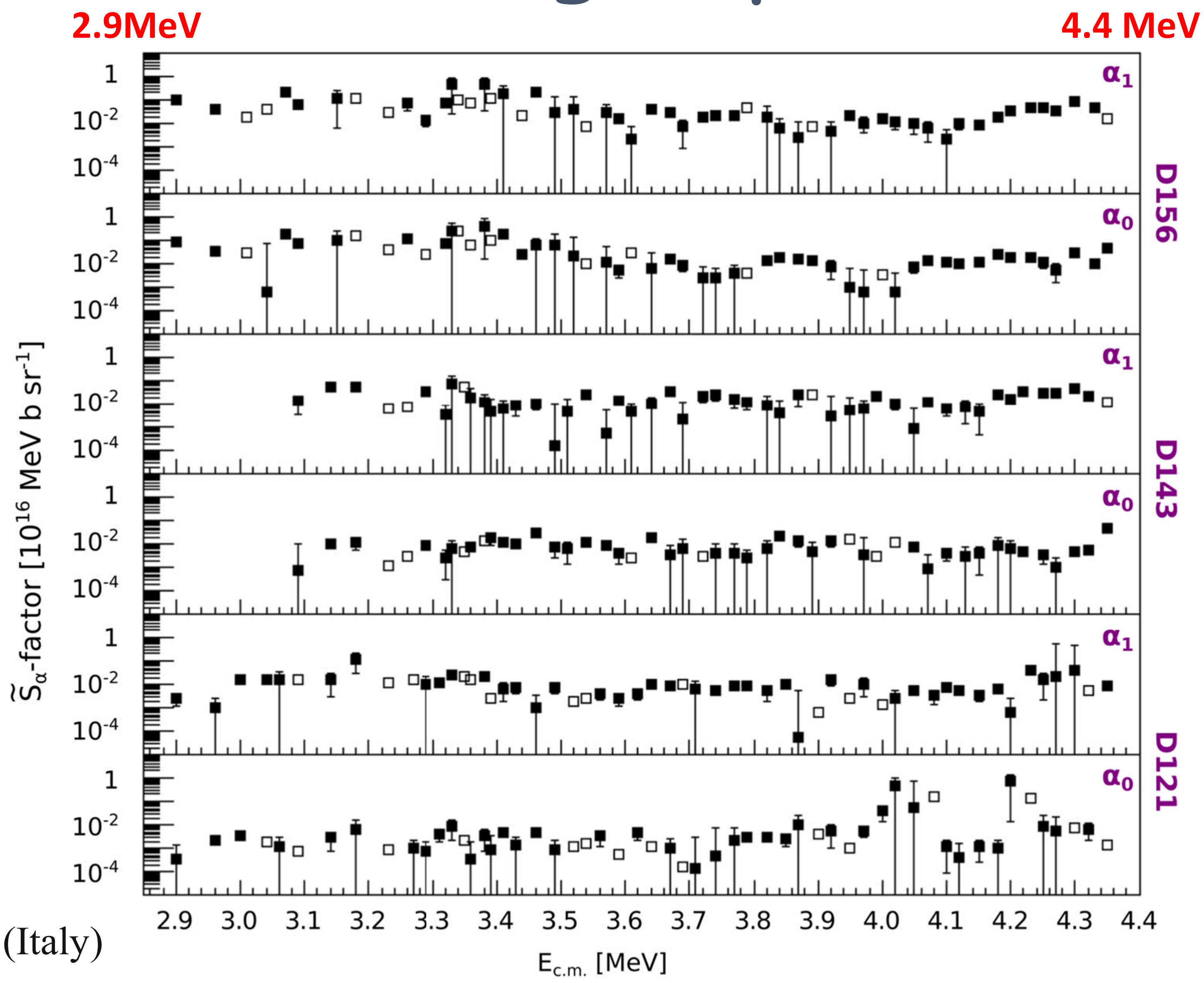


Figure 9b: *Visualization of a hypothetical reaction yield (solid) on top of the background levels of shielded setups from Fig. 9a (dotted).*

Direct measurement with charged particles

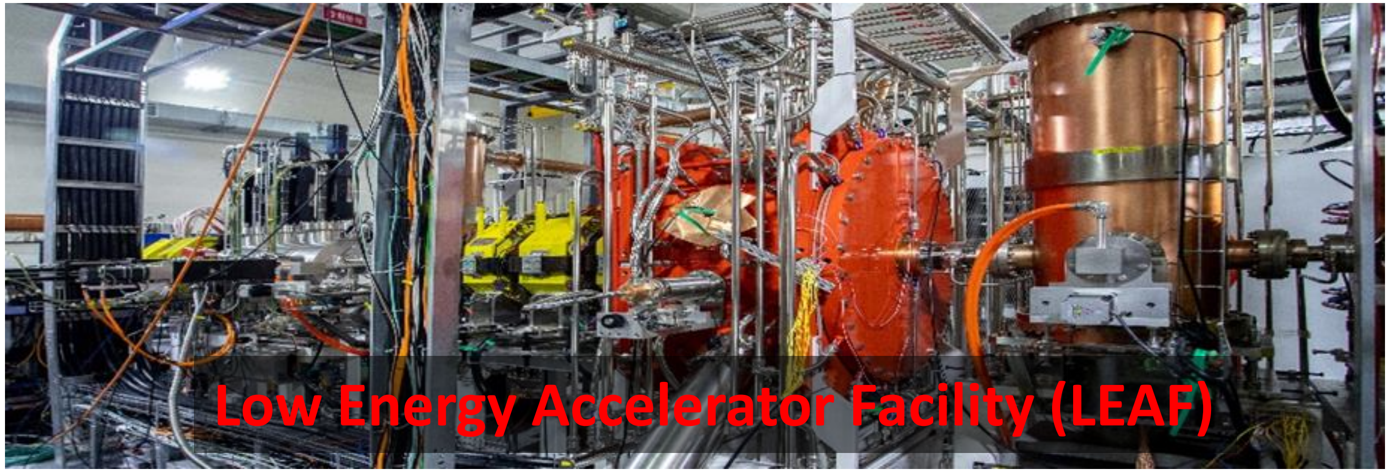


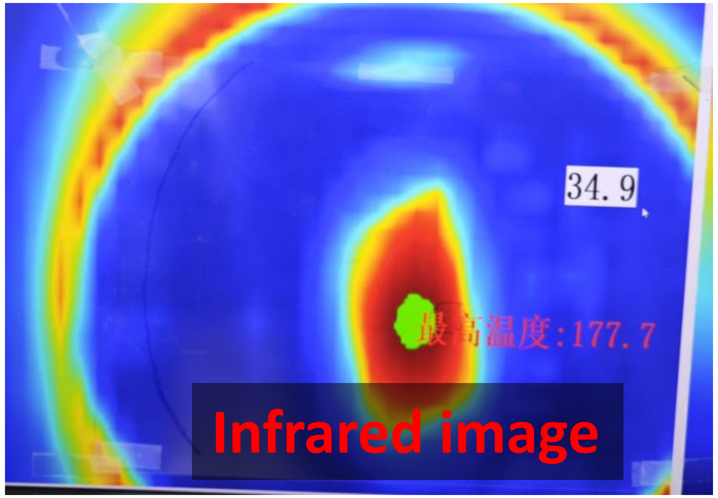
CIRCE Tandem Accelerator Laboratory in Caserta (Italy)

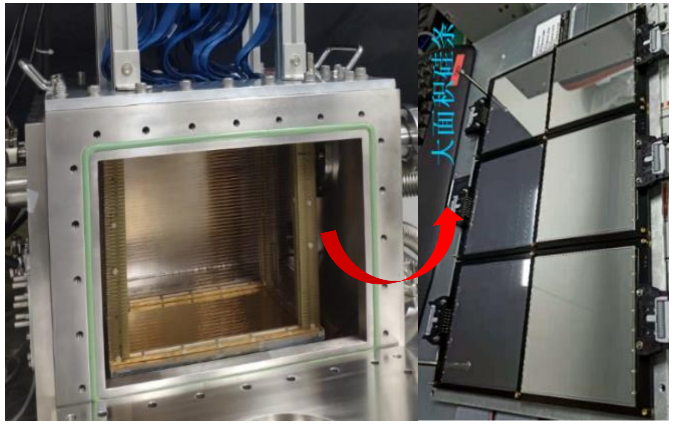


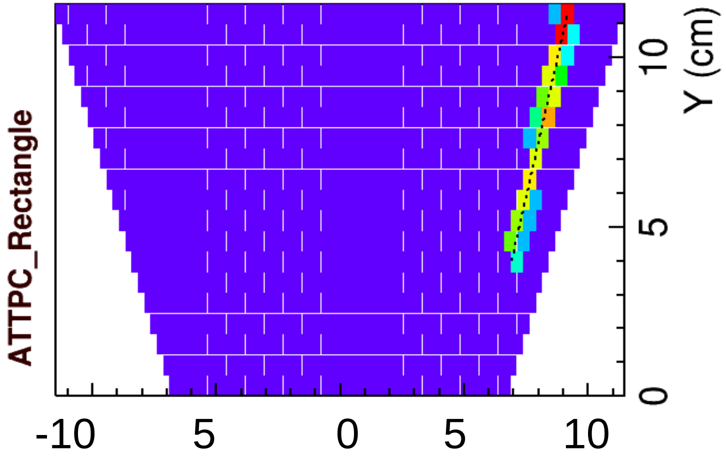
L. Morales-Gallegos et al., Eur. Phys. J. A (2024) 60:11

High Intensity+Time Projection Chamber





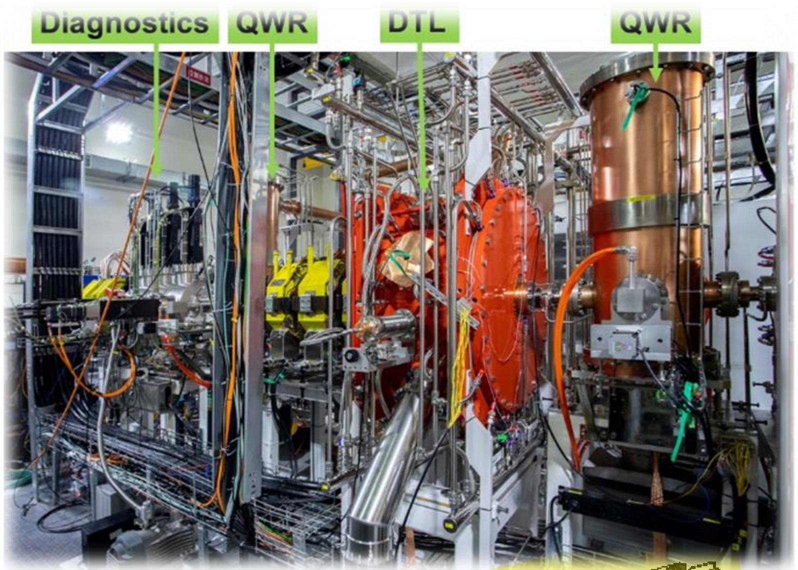


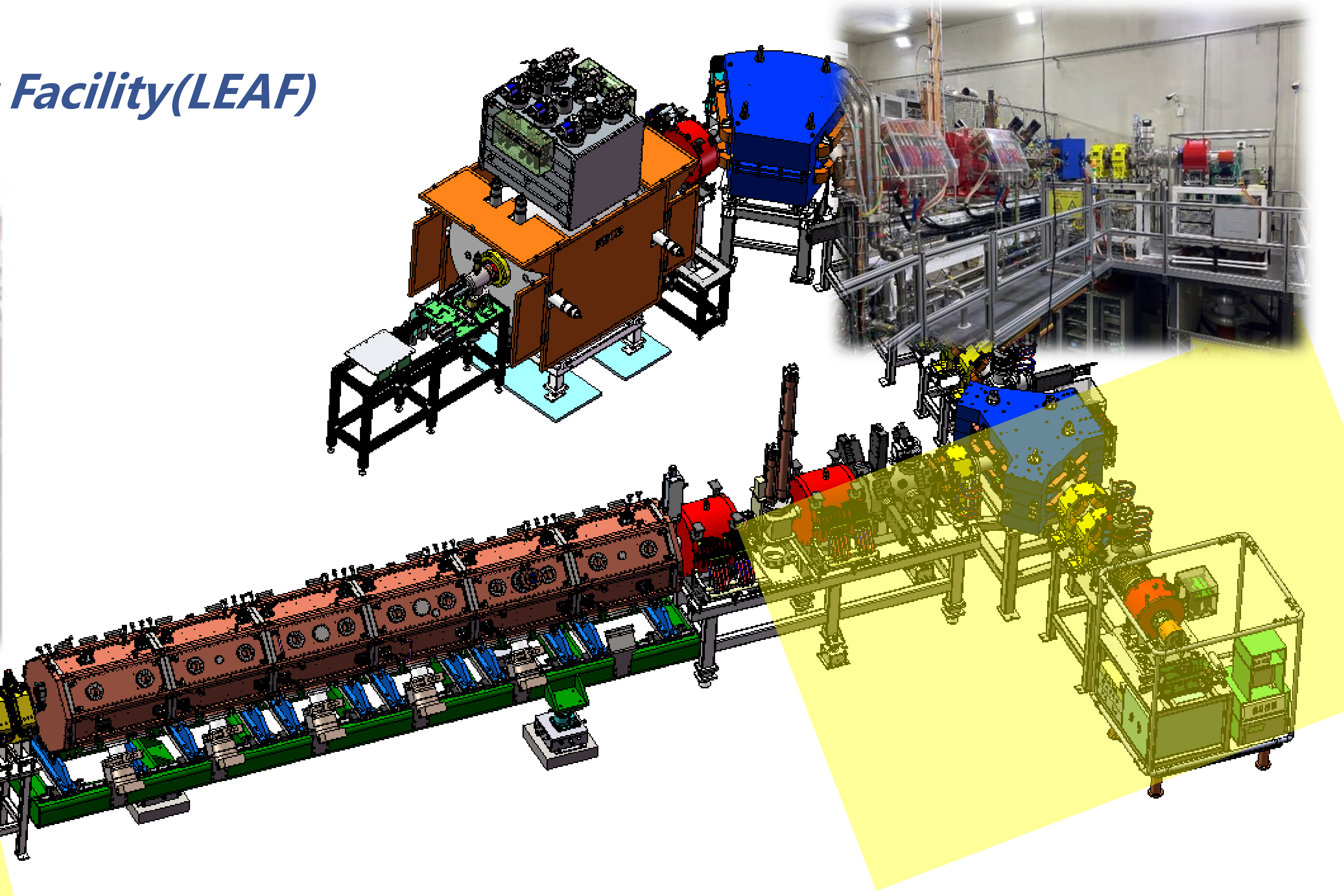


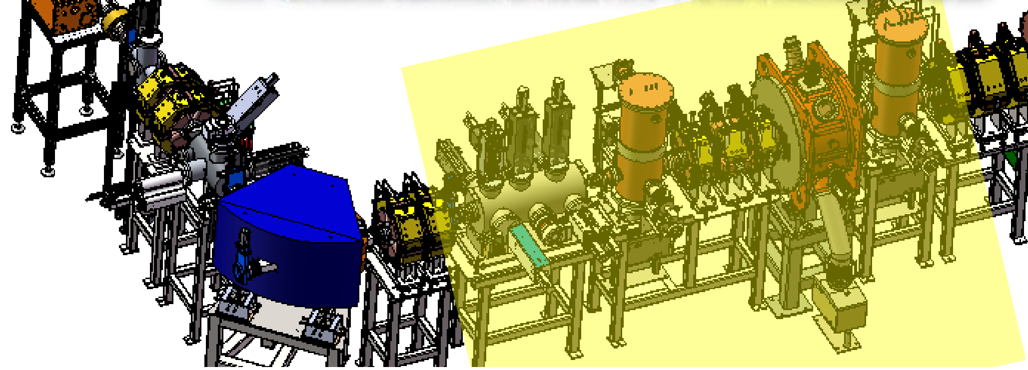
- LINAC: High Intensity beam up to few hundreds of puA
- TPC: Ultra sensitive tracking detector
- Complementary to LUNA-MV and other experiments

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

Low Energy Heavy Ion Accelerator Facility(LEAF)







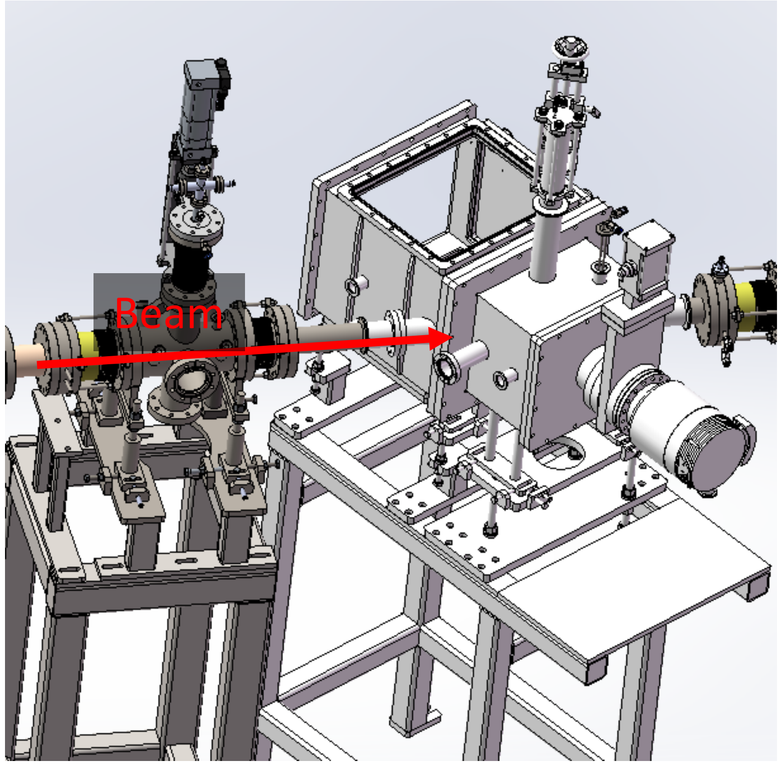
Yao Yang et al., NIMA 1039 (2022) 167095

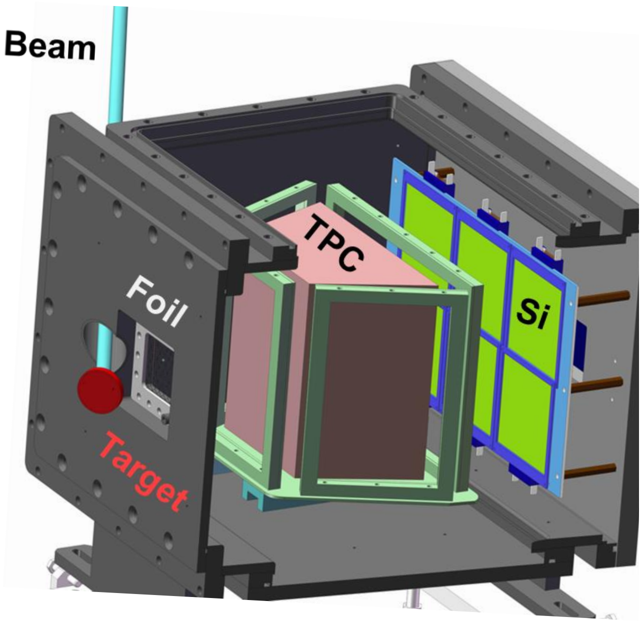
- **LEAF: 45GHz and 14.5GHz ECRs; 0.5MeV/u RFQ; 0.3MeV/u-0.7MeV/u DTL; Energy calibration by $^{12}C(p,g)$, p(15N,a)12C***
- **Maximum carbon beam intensity on target: ~200 puA (Spillane: 40puA); Energy Spread: <0.2%(s); Energy step size:~50 keV; beam time： ~1150 hr**

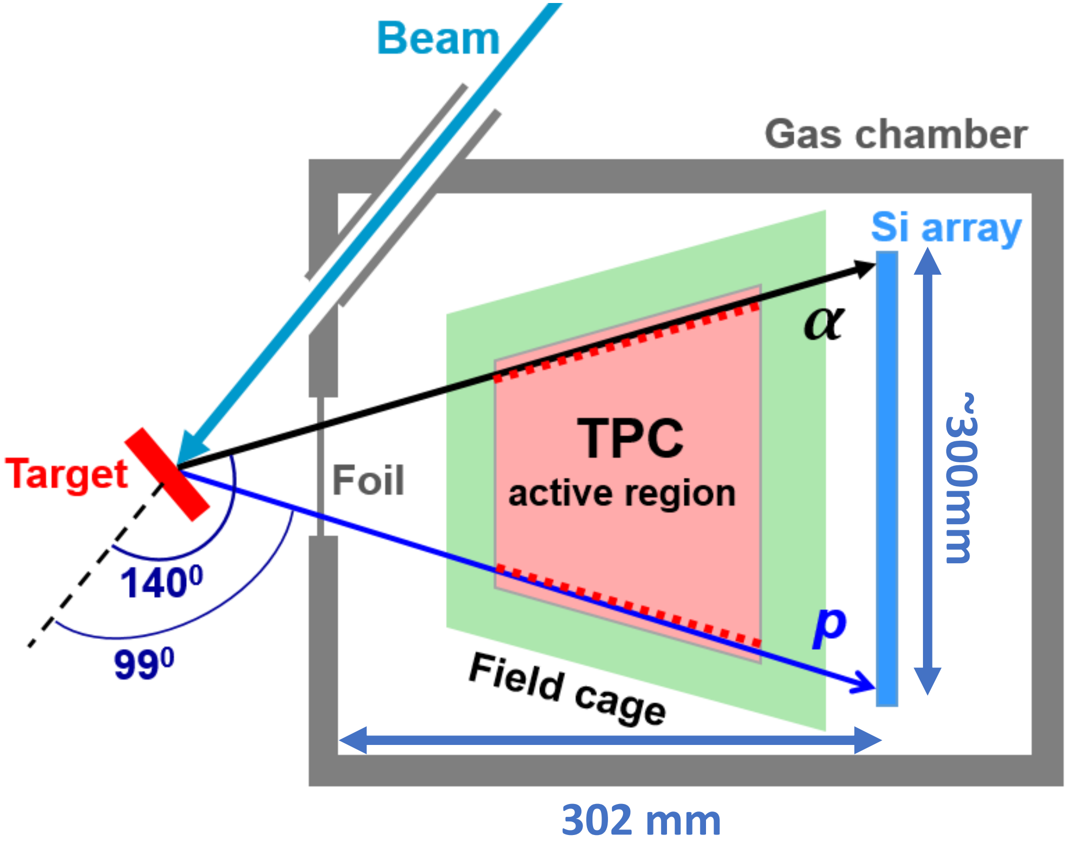
Courtesy of Yao Yang (IMP)

Detector setup

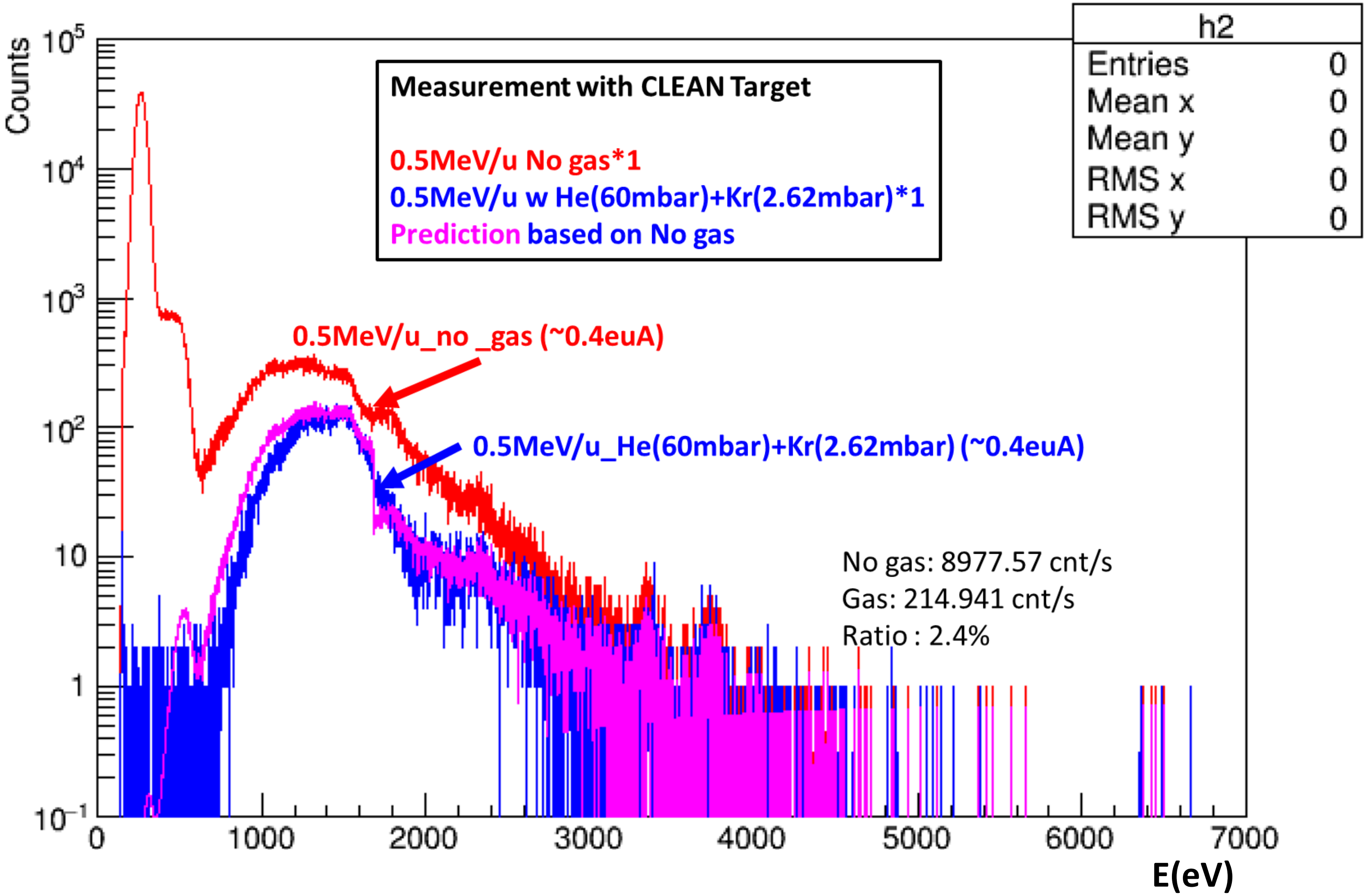
Time Projection Chamber (TPC) + Si array
- Background suppression via tracking
- Particle identification





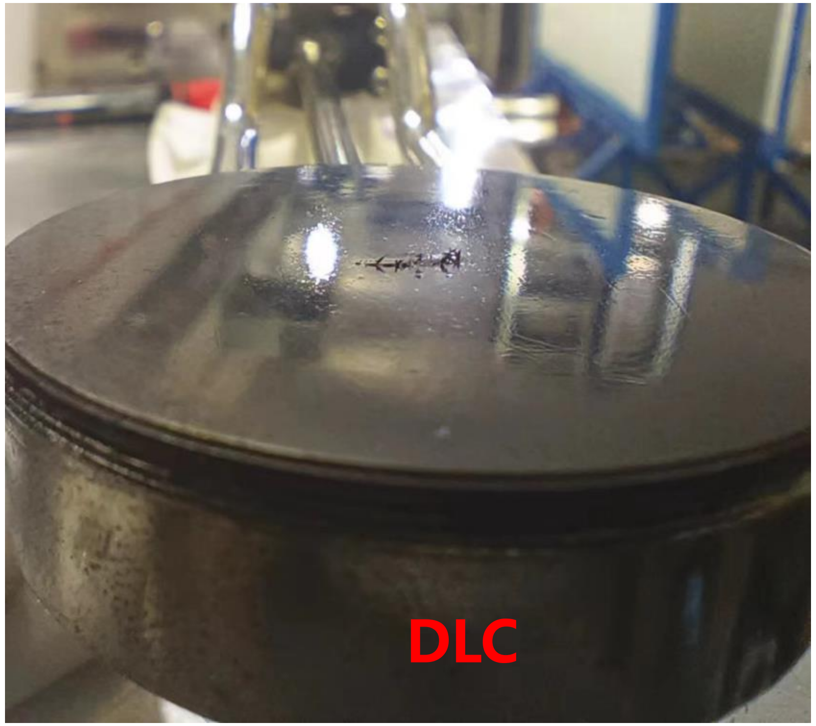


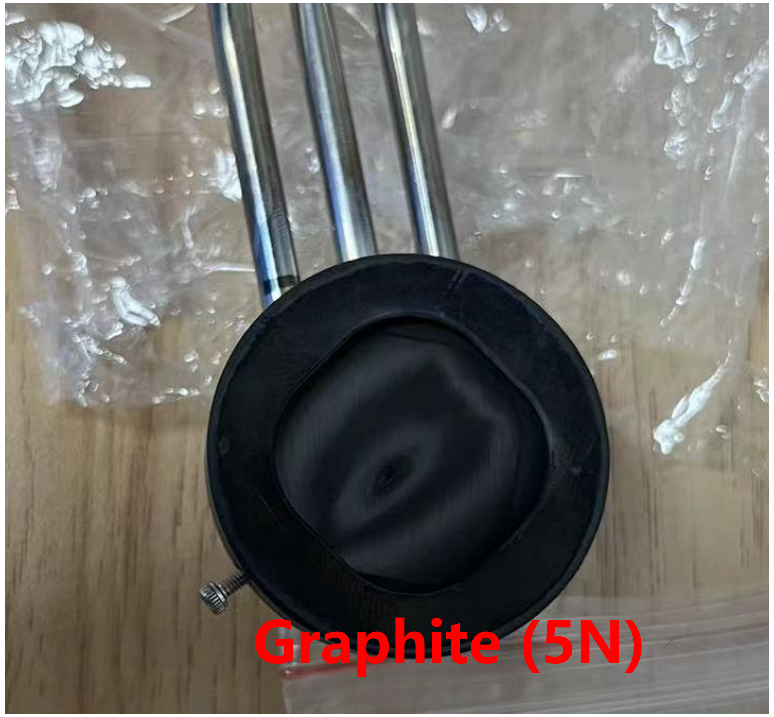
X-ray and other beam induced background



- Using MicroMegas gas to control the Ion Back Flow(IBF)
- Alpha: Ar(5%)+CO2(5%)+He(90%); Proton: Ar(35%)+CO2(15%)+Kr(50%)

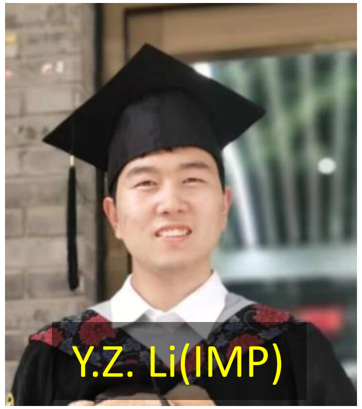
High Power Carbon with High Purity

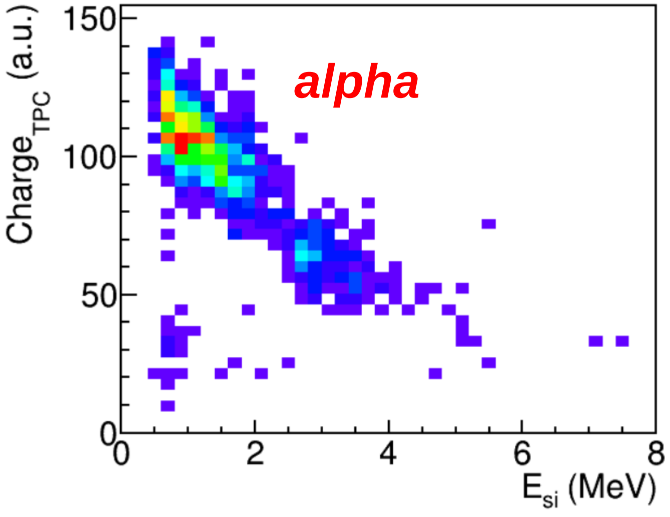


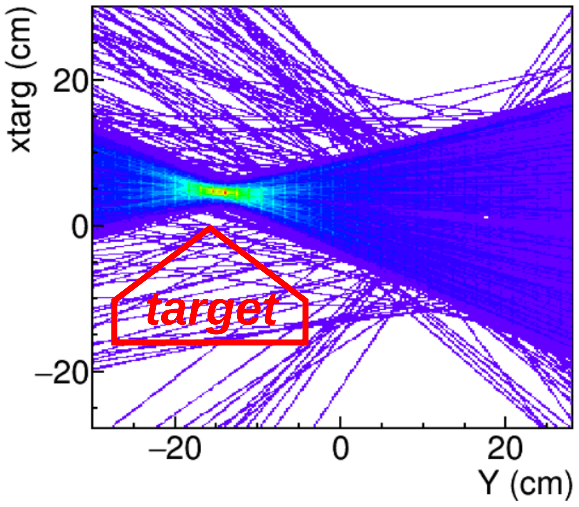


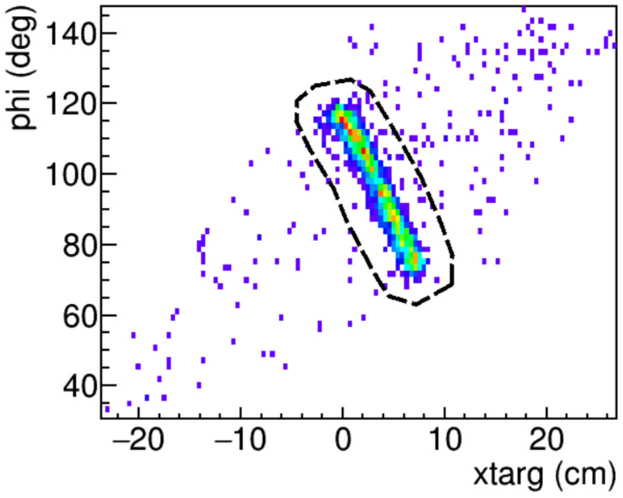
- **Improving thermal conductivity using flexible graphene**
- **Carbon targets: Diamond like carbon(DLC), Heated graphite (5N), Highly Ordered Pyrolytic Graphite High (HOPG)**

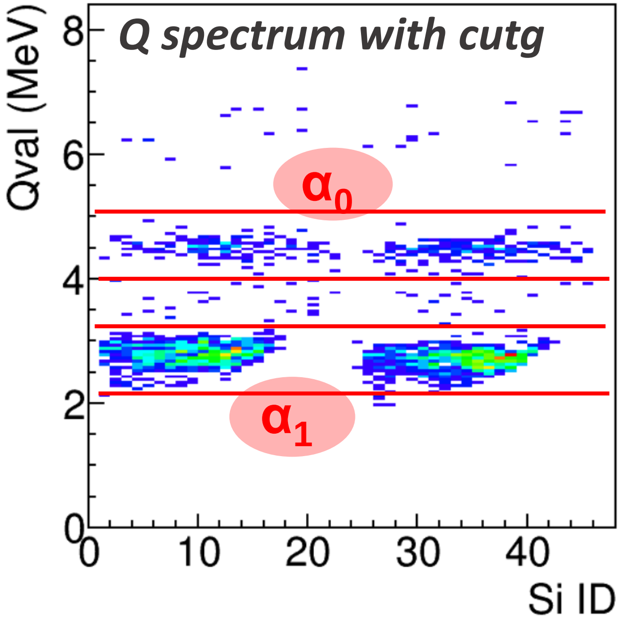
Analysis： E_{cm}=2.72MeV with Graphite (5N)

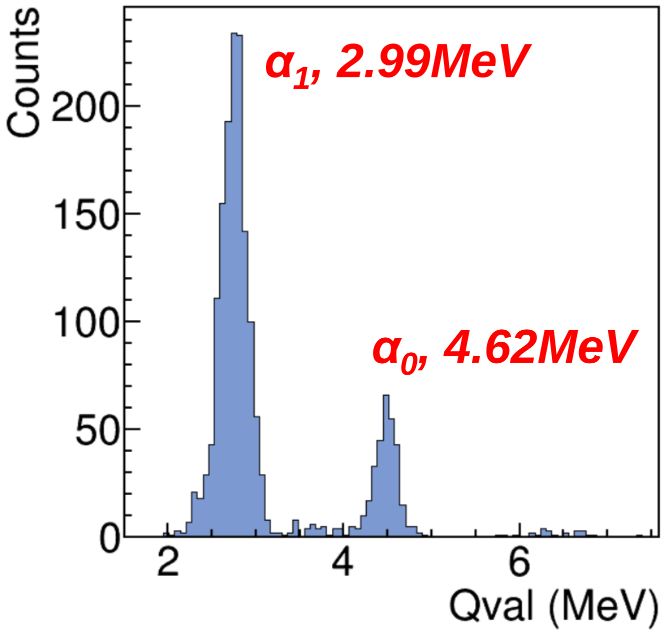


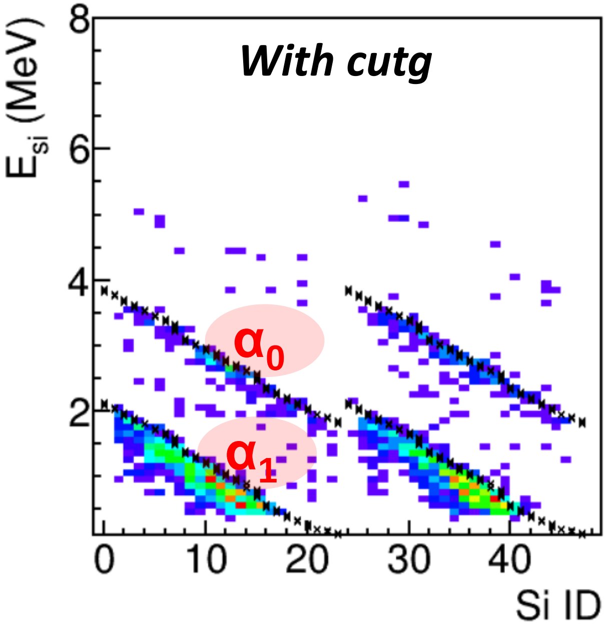




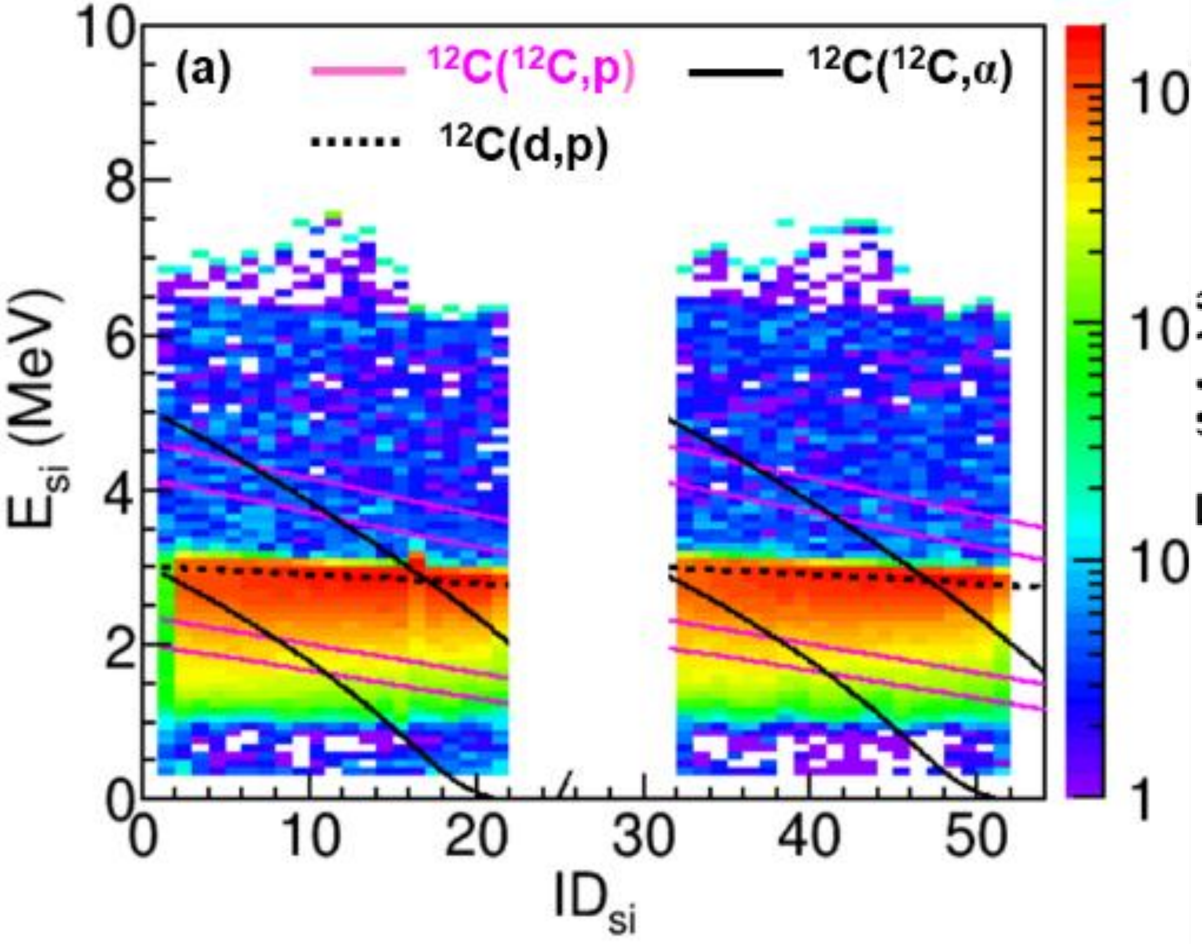


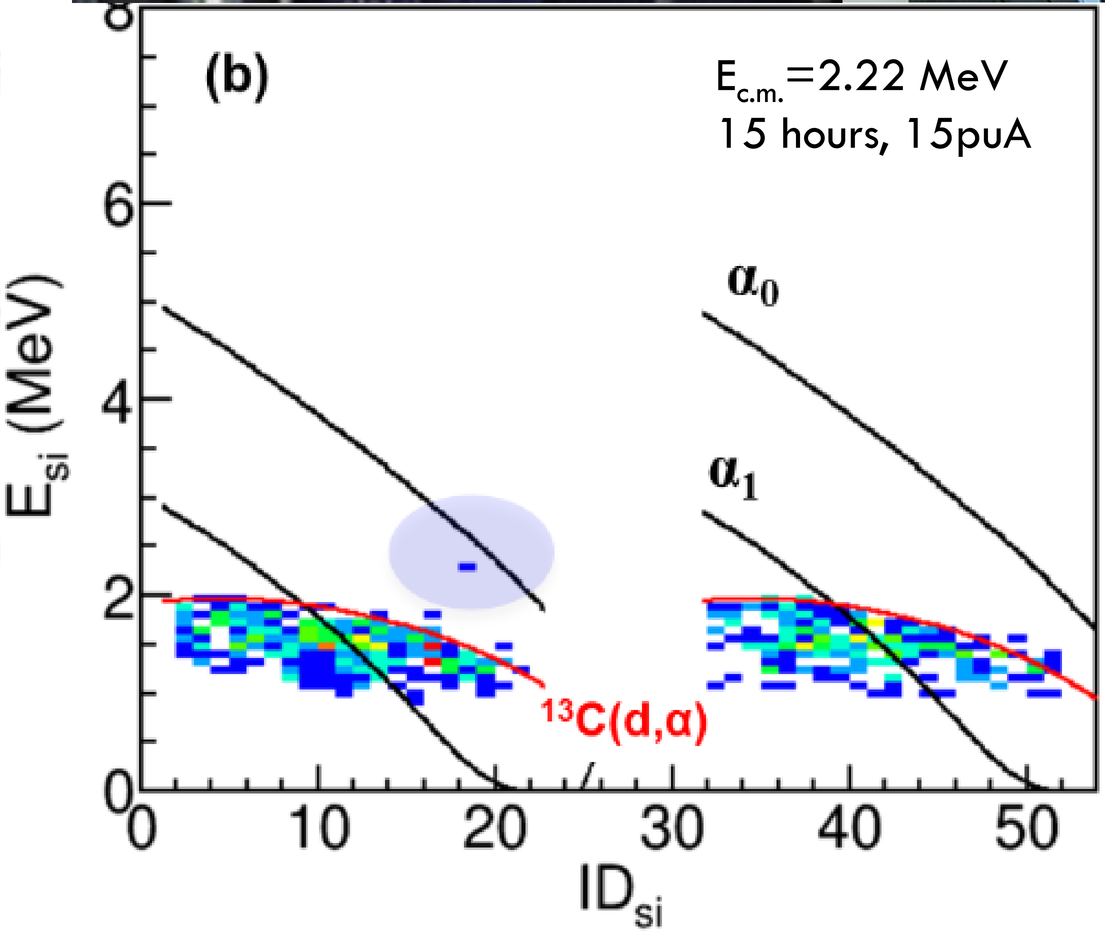






Another result with HOPG @$E_{c.m.}$=2.2MeV

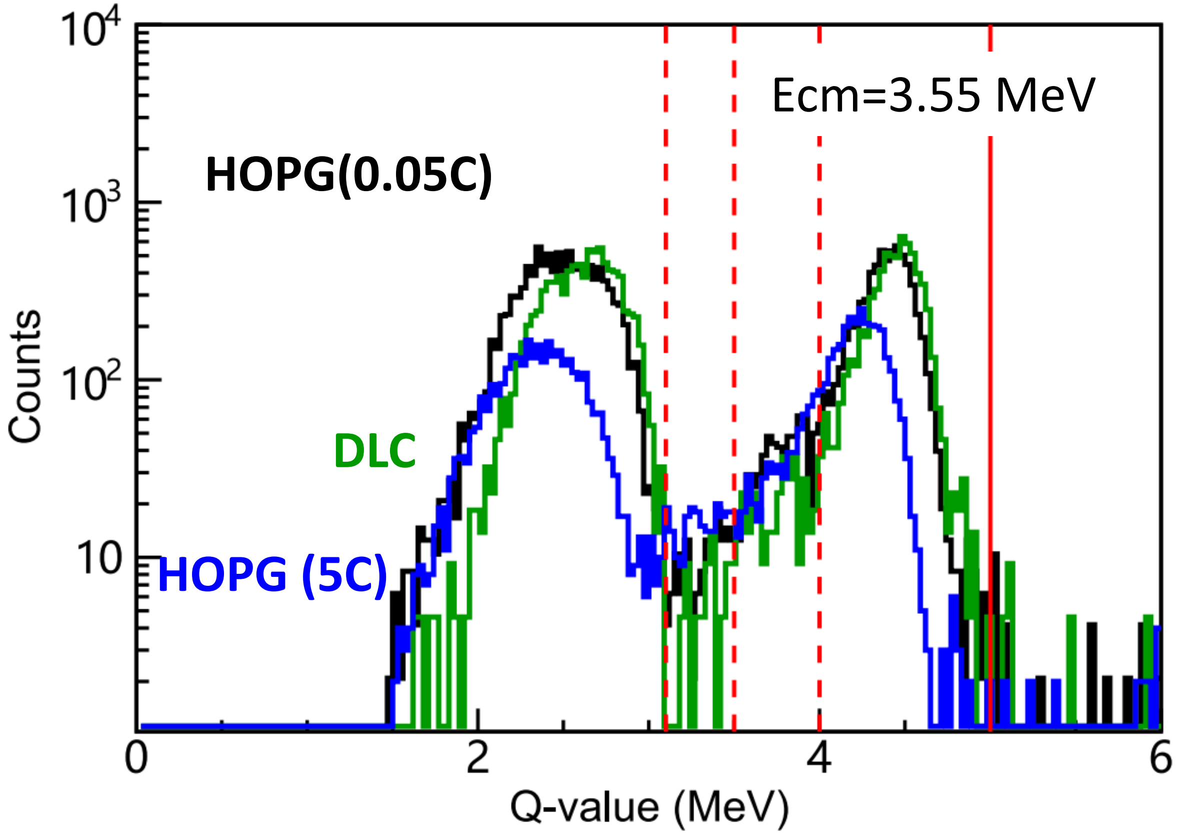


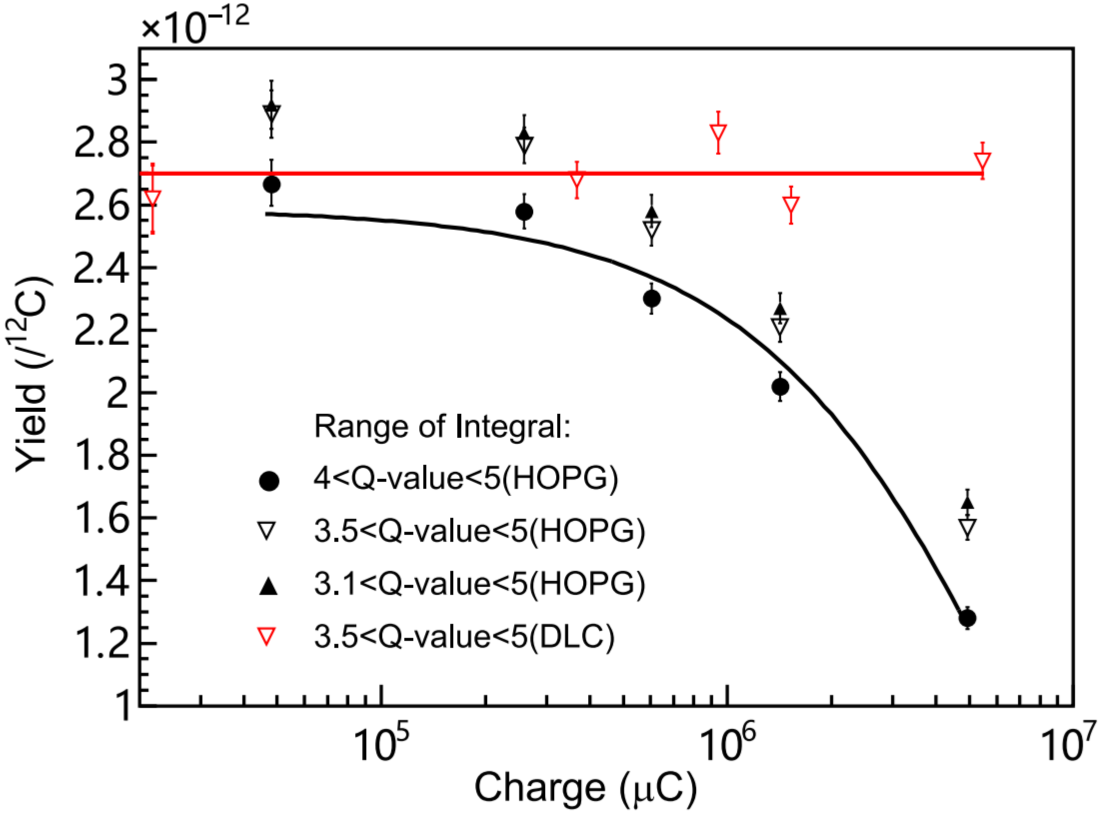


Clear identification with cuts in the energy loss and tracks in TPC

Accepted by NST

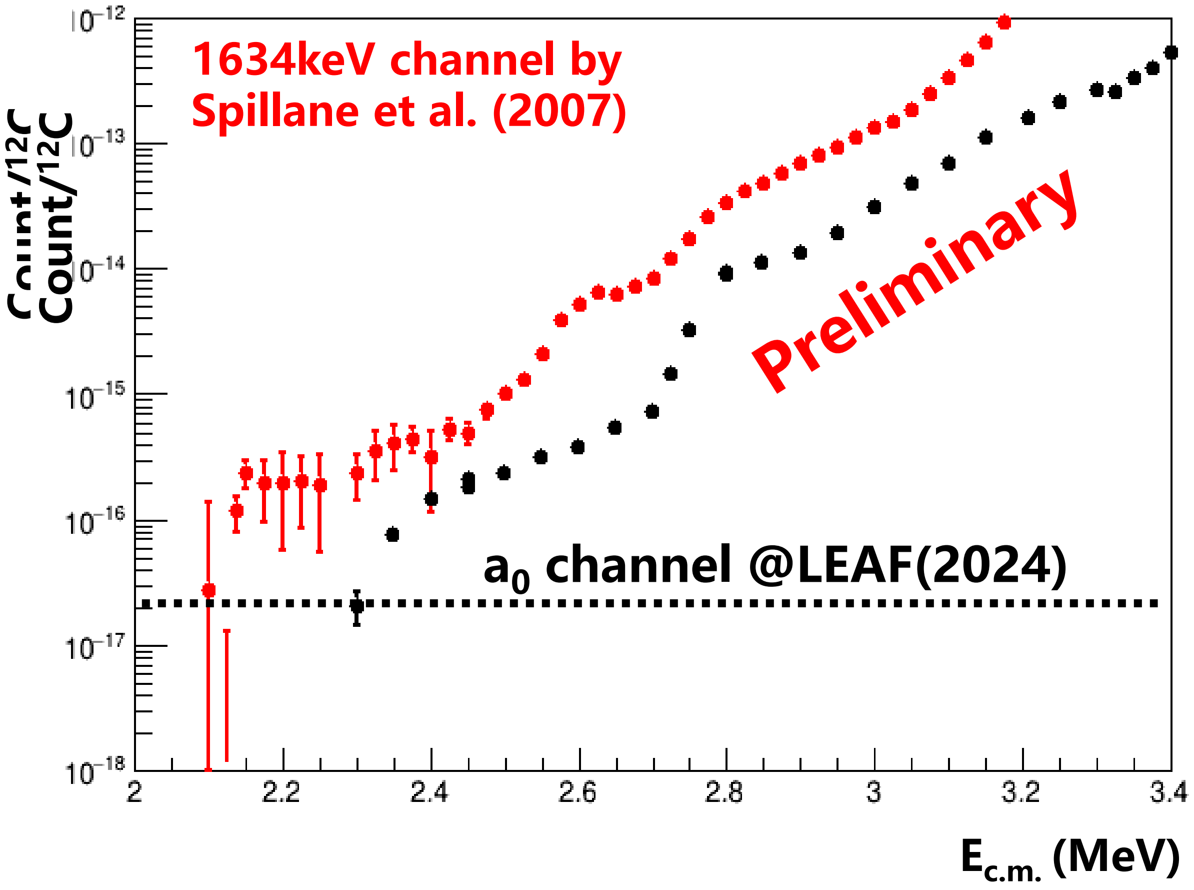
Degrading of the HOPG target

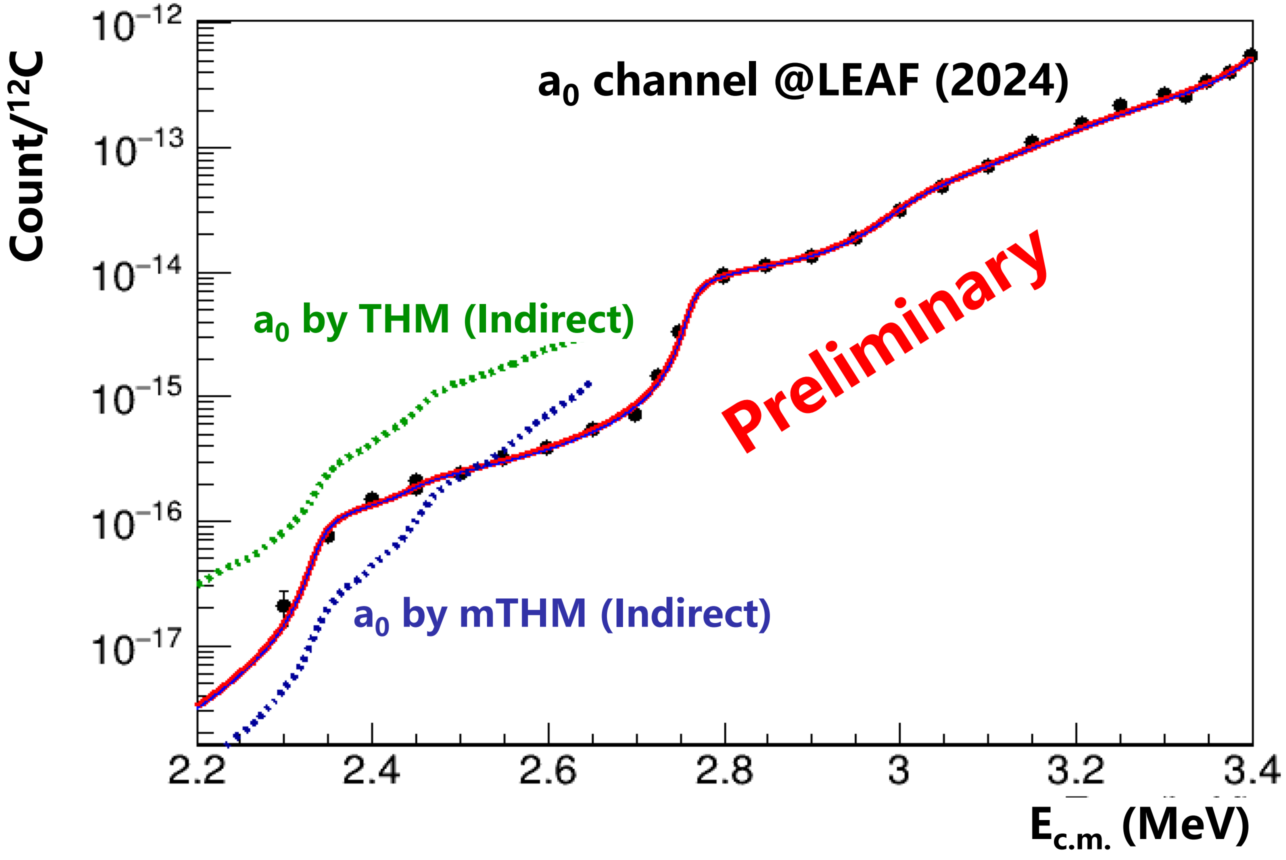




Wang et al., (2024), Tan et al., (2024)

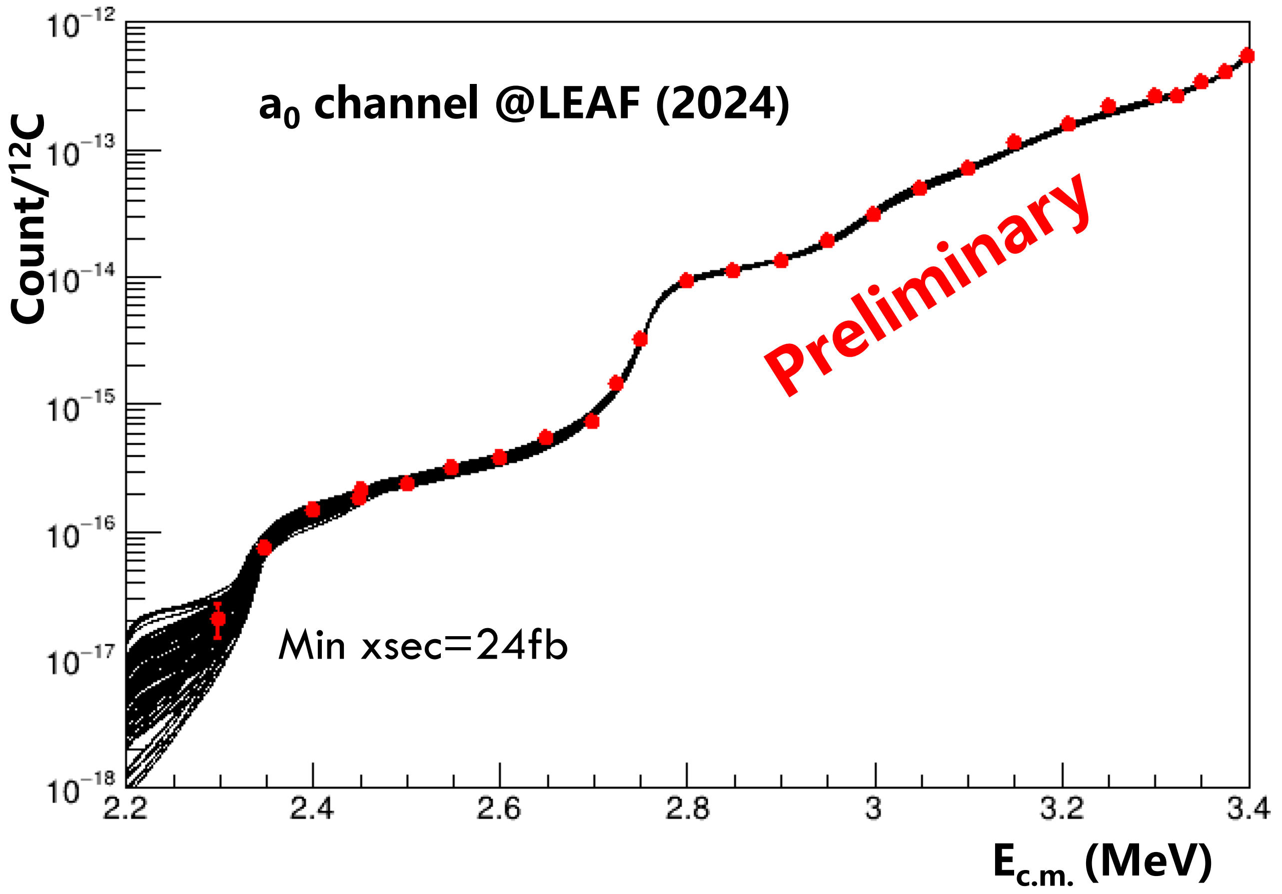
Preliminary results

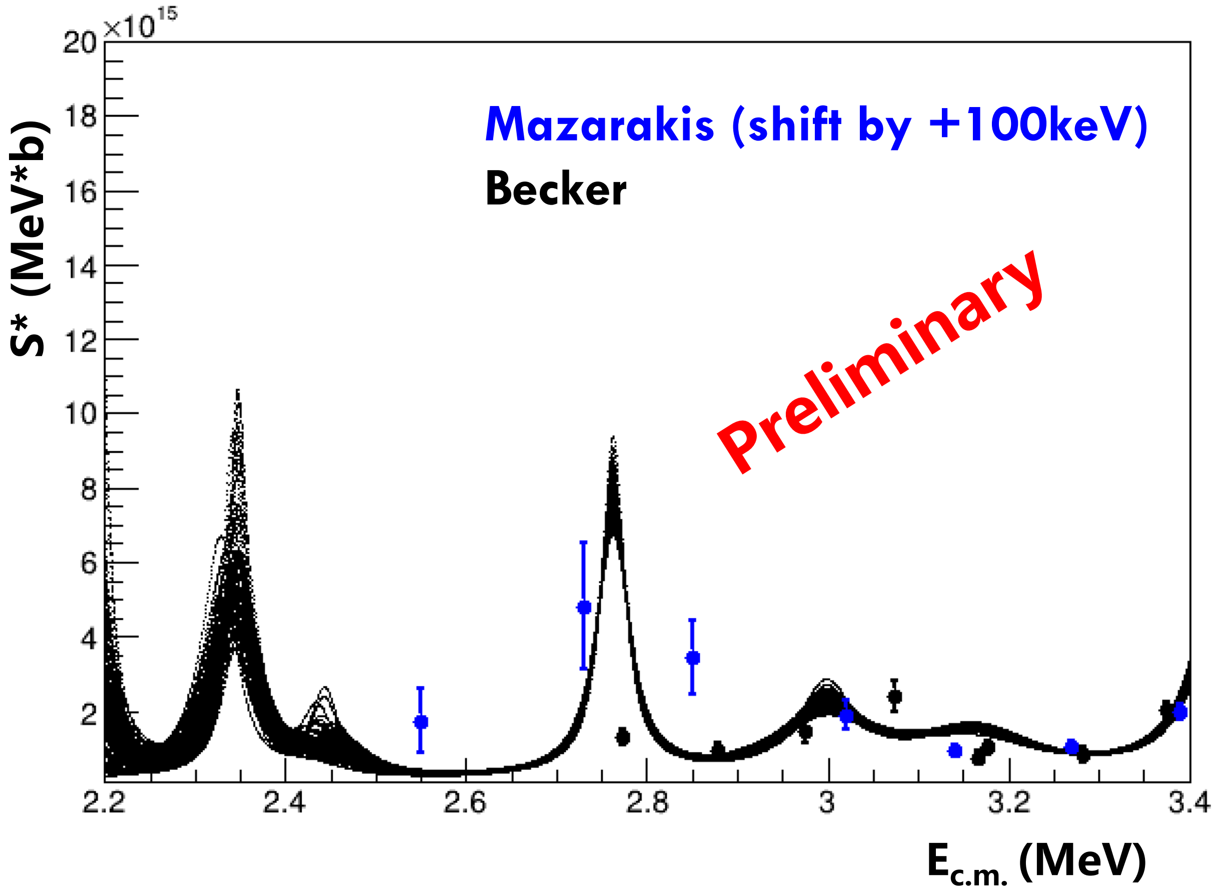


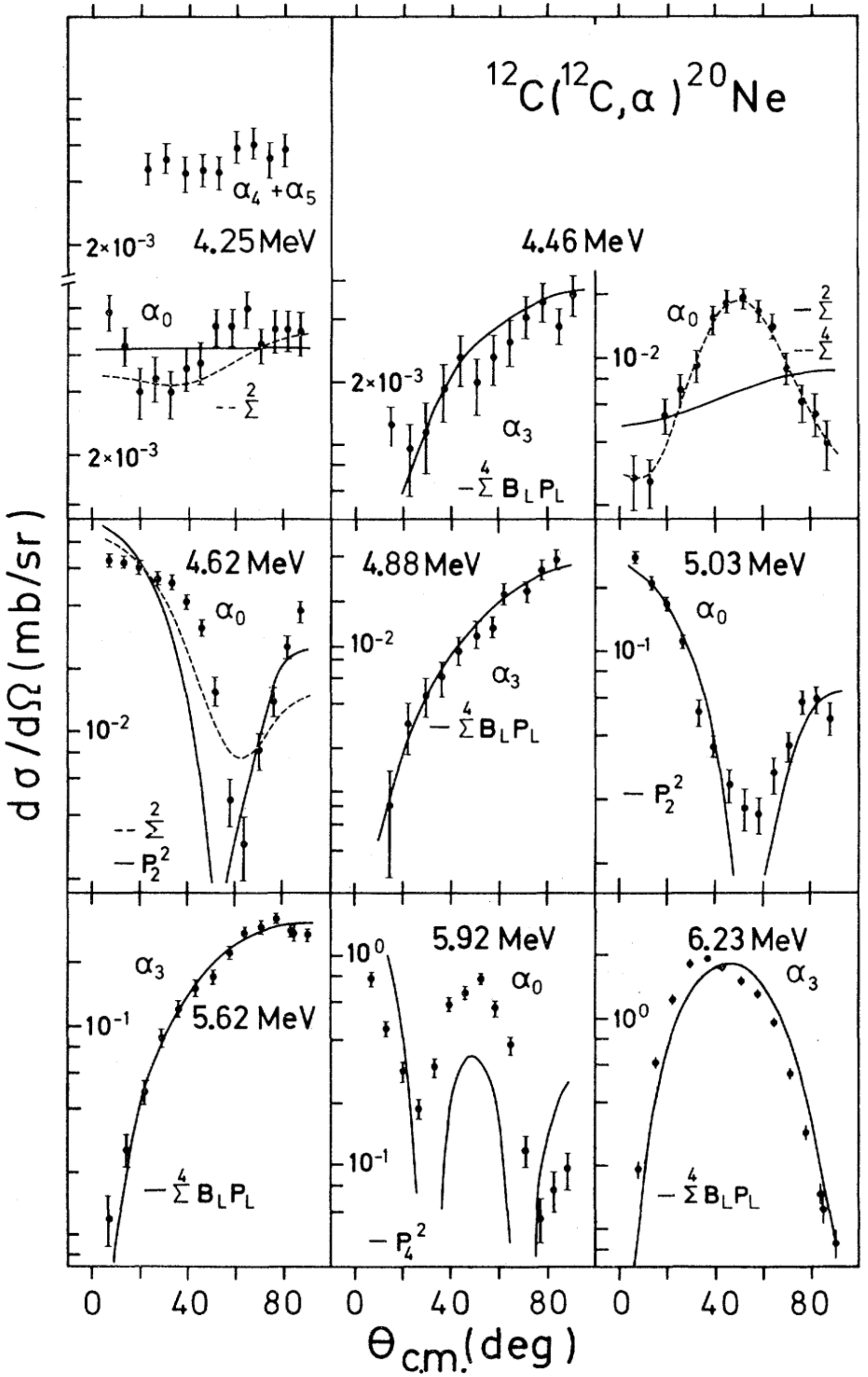


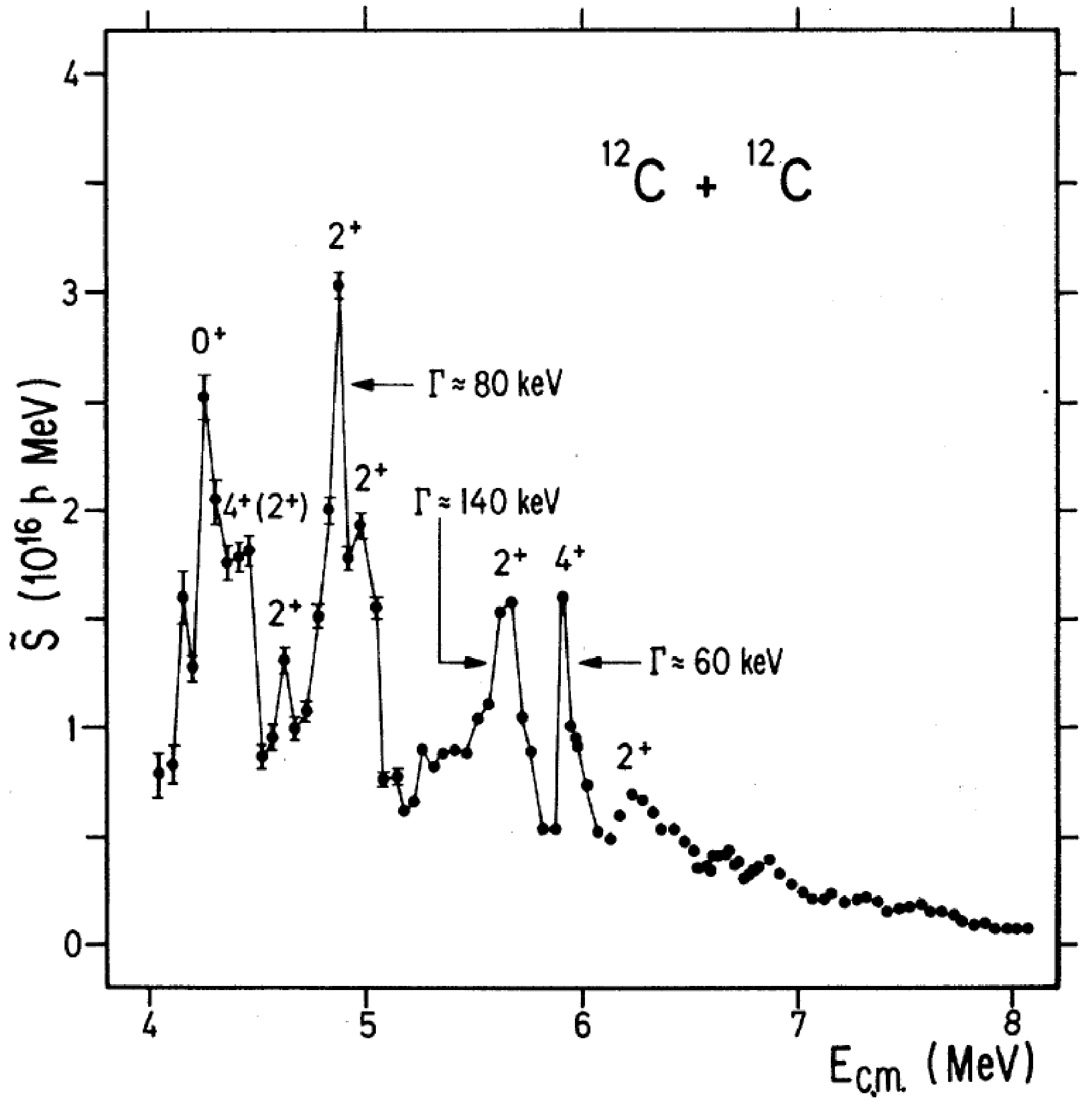
- First direct measurement of a_0 channel at energies below E_{cm}=2.5 MeV with a sensitivity better than the a_1 channel measured by Spillane et al. (2007)
- The thick target yields of direct measurement disagree with THM and mTHM

Error analysis using Monte Carlo Method

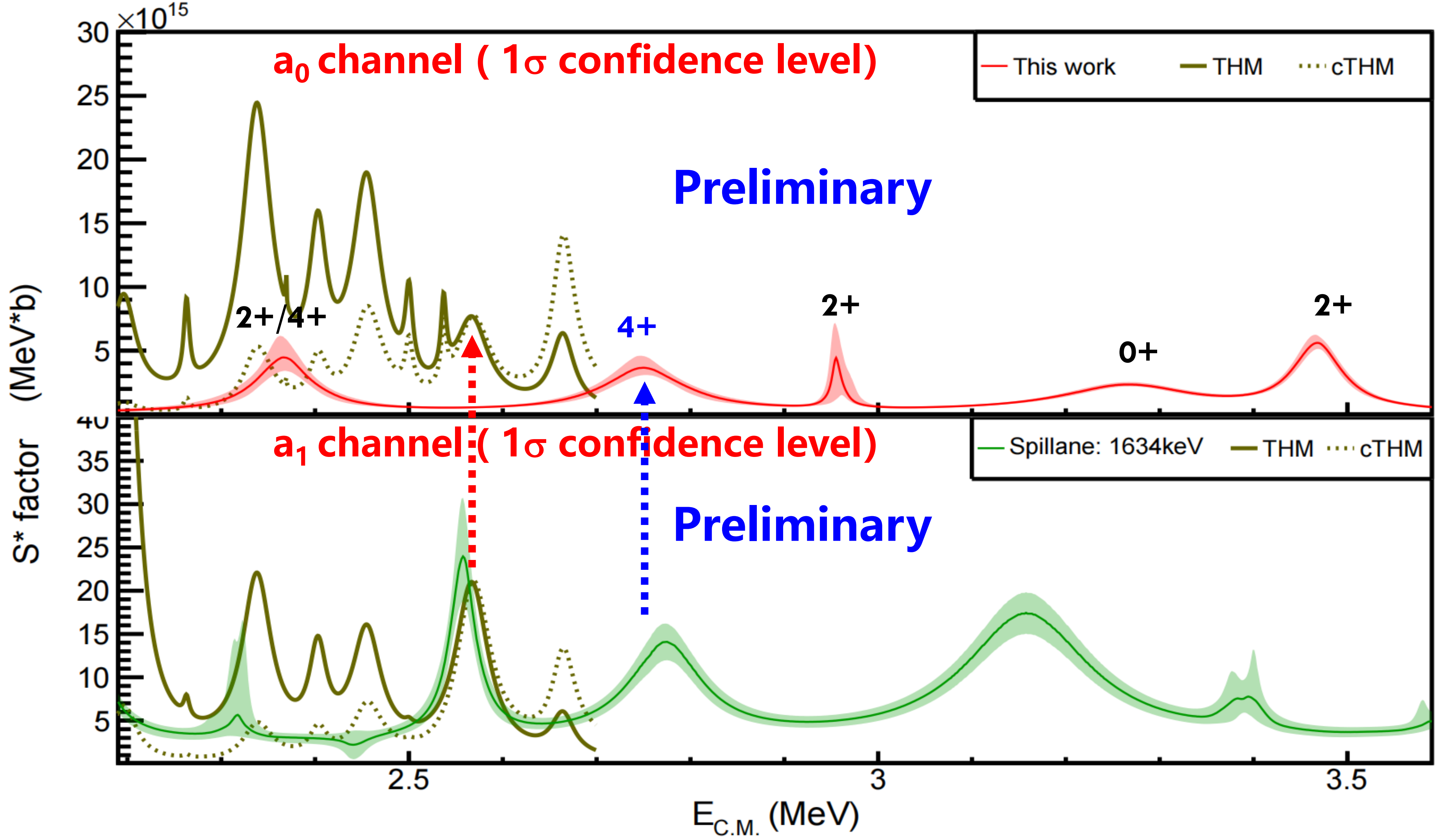






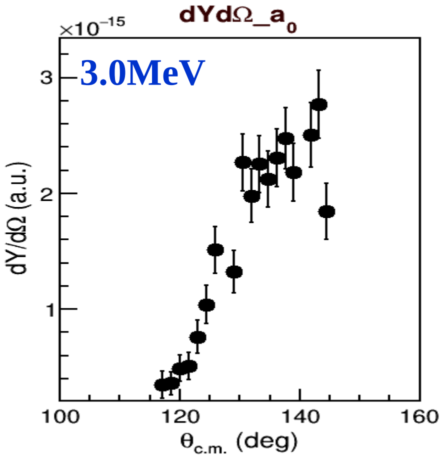


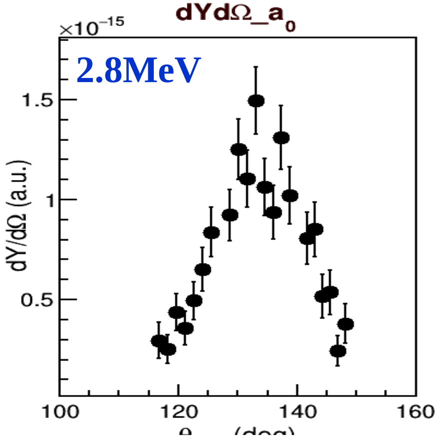
Galster et al., PRC(1977)

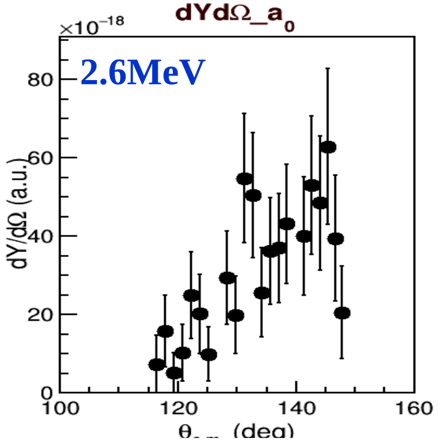


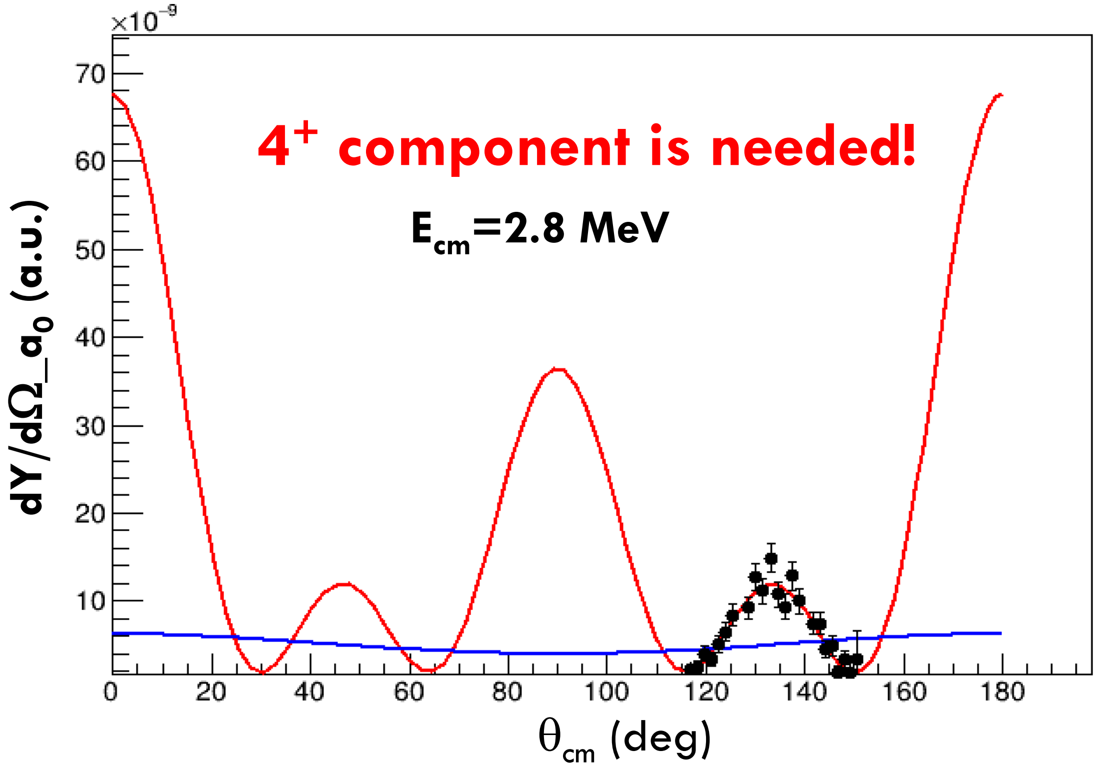
- 2.567MeV (0+) observed in THM does not appear in the direct measurement
- Spin/Parity assignment seems to agree with the Taniguchi&Kimura prediction of 0+/2+

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

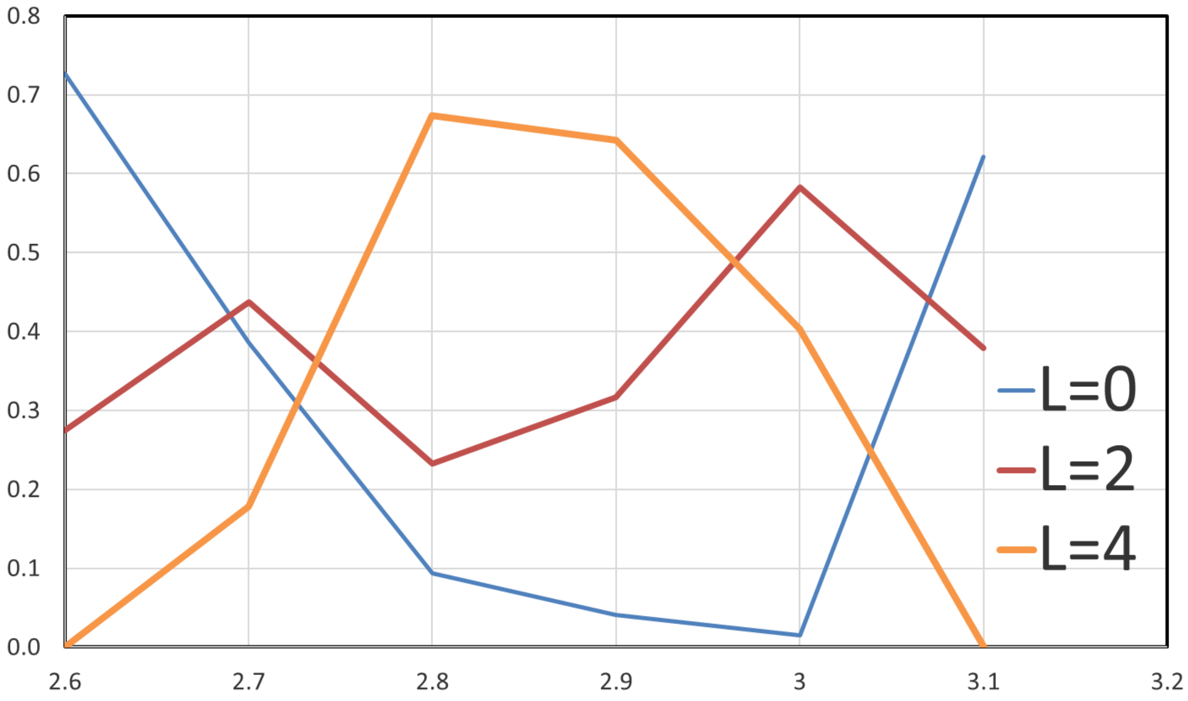








Contibution of difference spin



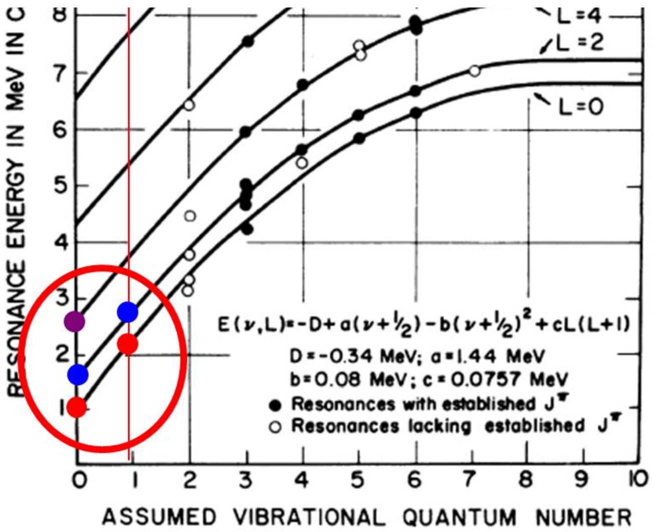
Algebraic approach to nuclear quasimolecular spectra

F. Iachello
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 96511
and Kernfysisch Versneller Instituut, University of Groningen, Groningen, The Netherlands
(Received 17 July 1980)

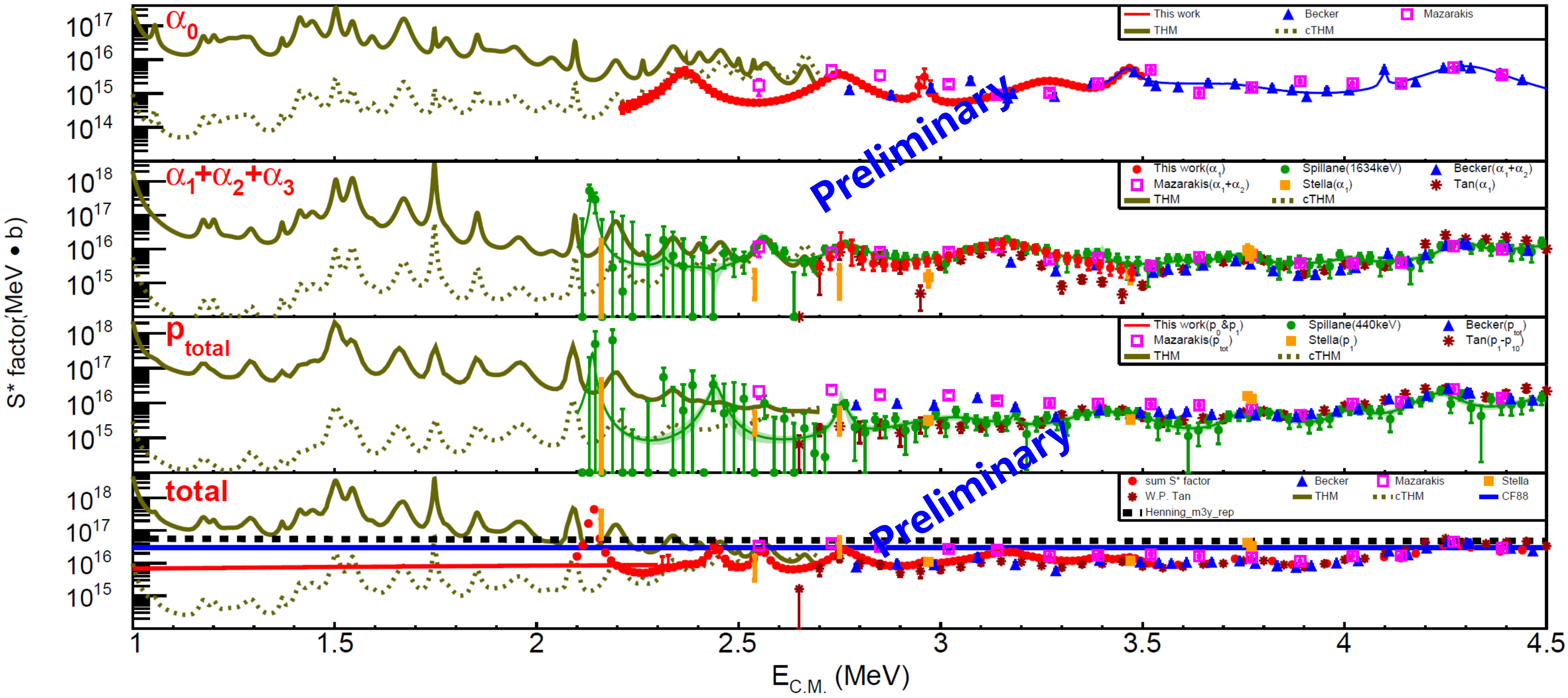
PHYSICAL REVIEW C VOLUME 23, NUMBER 6 JUNE 1981

Rotational and vibrational excitations in nuclear molecular spectra

K. A. Erb and D. A. Bromley
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut
(Received 17 July 1980)

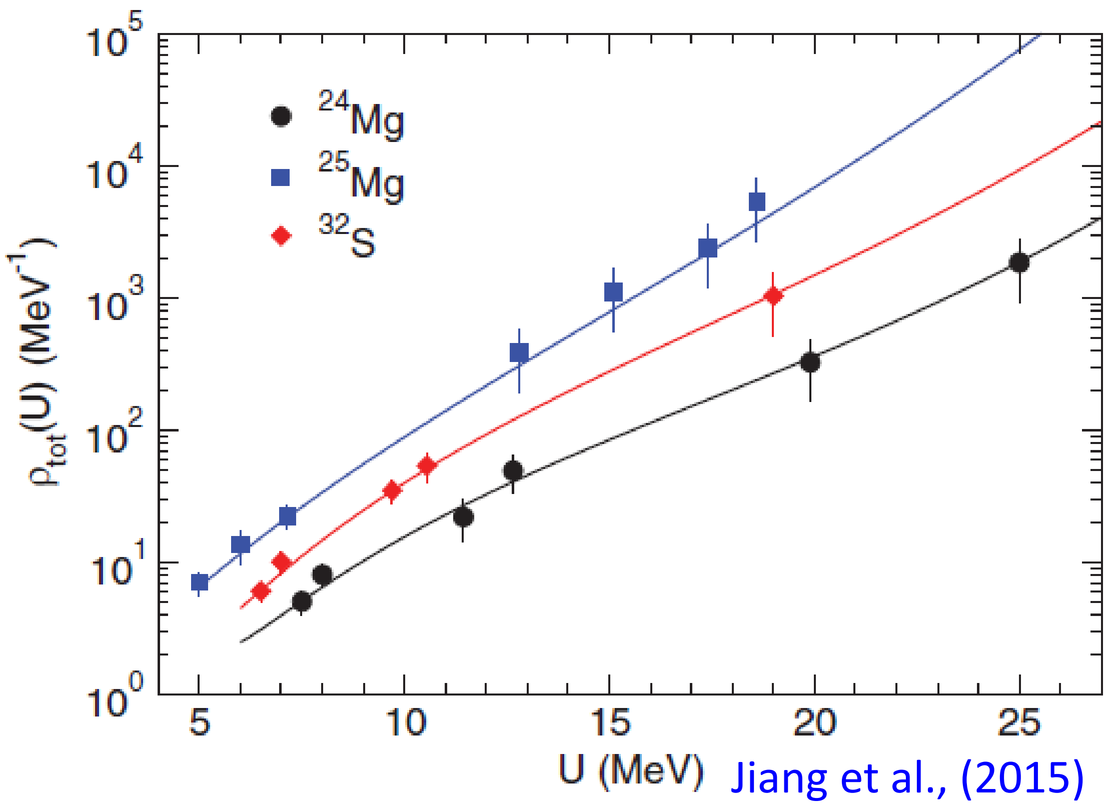


Prediction of 4^+ state at 2.55 MeV is confirmed by our experiment!

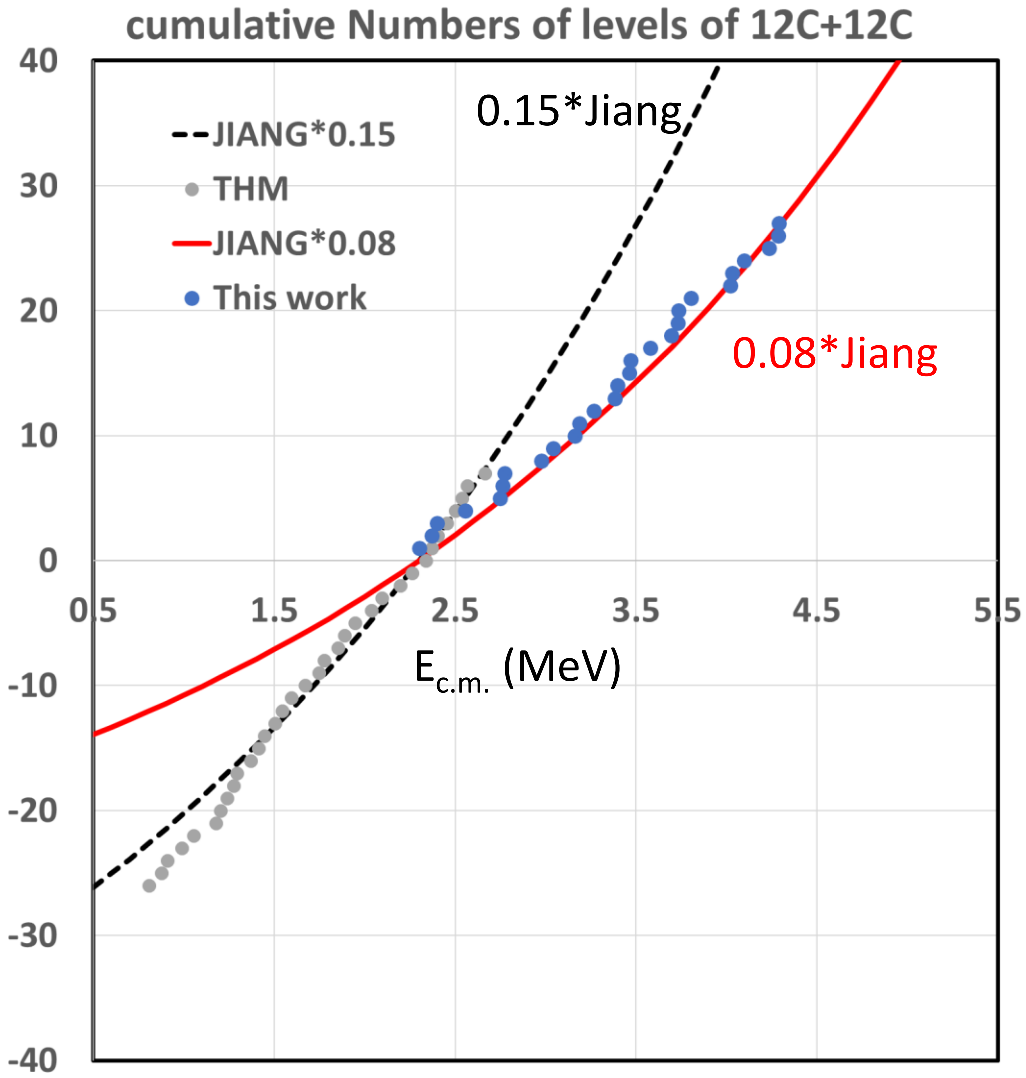


α_0
$\alpha_1+\alpha_2+\alpha_3$
p_{total}
total
This work
Becker
Mazarakis
THM
cTHM
This work(α_1)
Spillane(1634keV)
Becker($\alpha_1+\alpha_2$)
Mazarakis($\alpha_1+\alpha_2$)
Stella(α_1)
Tan(α_1)
This work(p_0&p_1)
Spillane(440keV)
Becker(p_{tot})
Mazarakis(p_{tot})
Stella(p_1)
Tan(p_1-p_{10})
sum S* factor
Stella
W.P. Tan
CF88
Henning_m3y_rep
Preliminary
Preliminary
S* factor (MeV • b)
$E_{C.M.}$ (MeV)

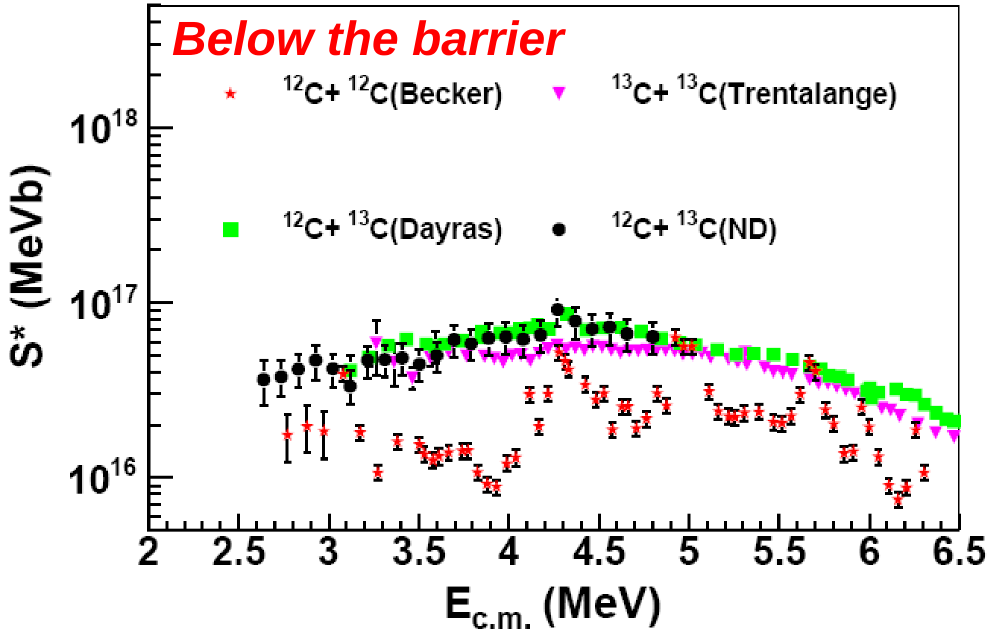
Level density of the $^{12}C+^{12}C$ resonances

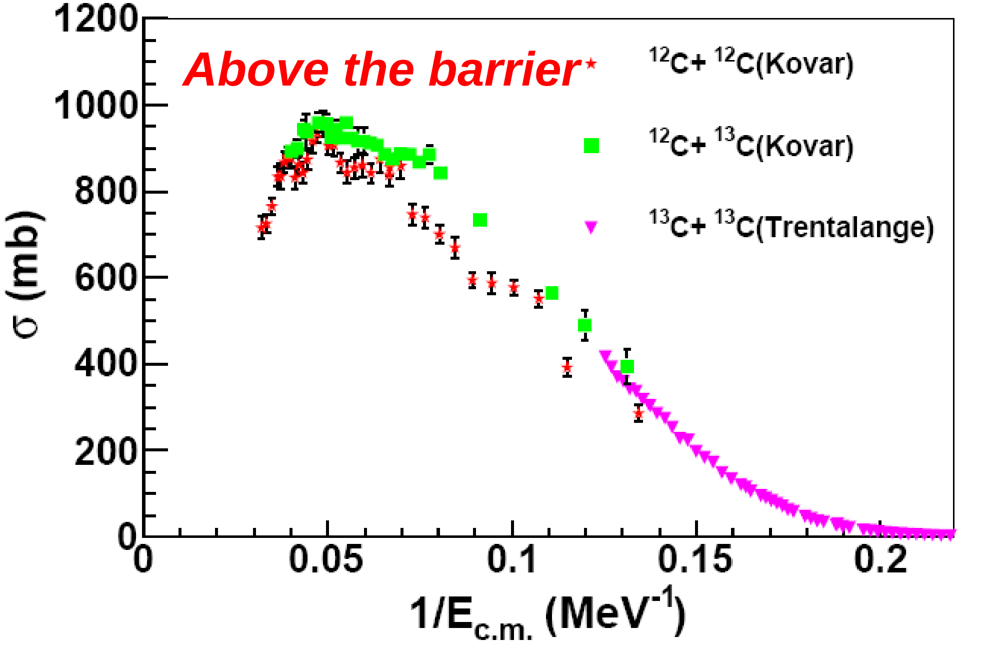


Jiang et al., (2015)



- **Direct measurement: 27 resonances observed within [2.3:4.3MeV]**
- **Jiang's level density needs to be scaled by 0.08!**





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)

Correlation between carbon isotopes

Averaged S*

$$\sigma = \sum_J \sigma^J_{CC} P_J$$

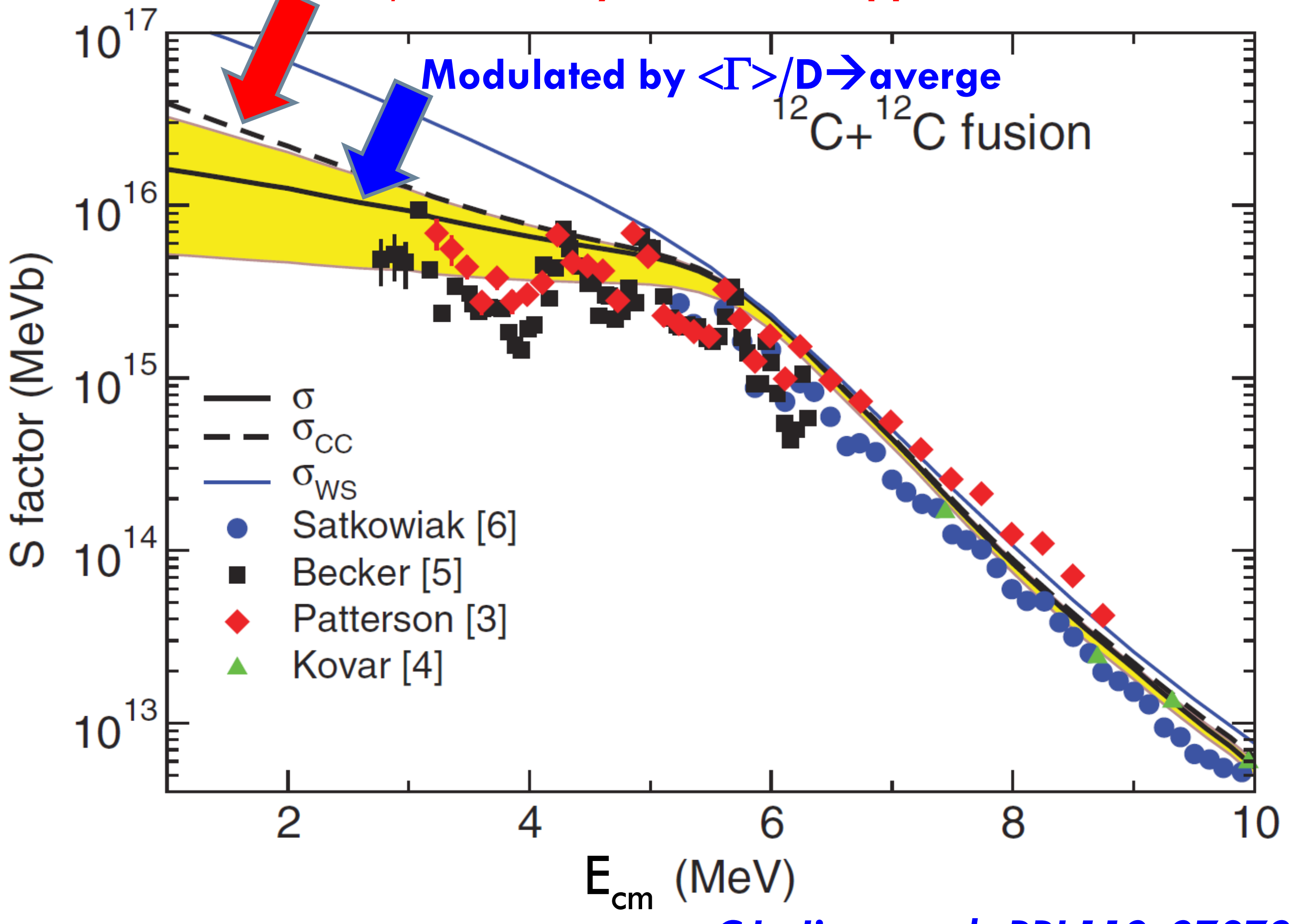
States for fusion

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

Γ: resonance width

D: resonance spacing

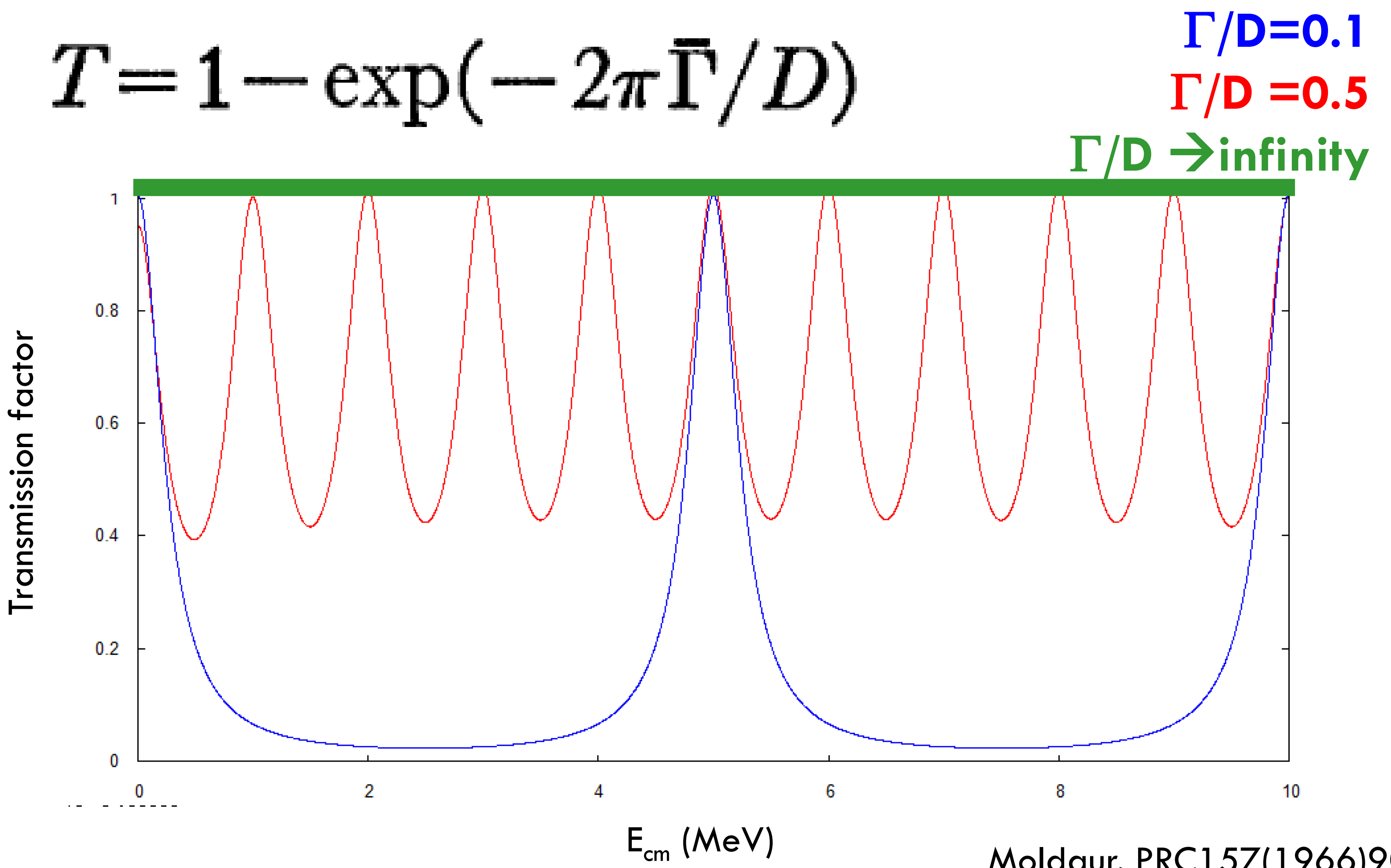
$\langle\Gamma\rangle/D \rightarrow$ Infinity $\rightarrow$ $^{12}C+^{12}C$ Upper Limit, $^{12}C+^{13}C$ and $^{13}C+^{13}C$



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

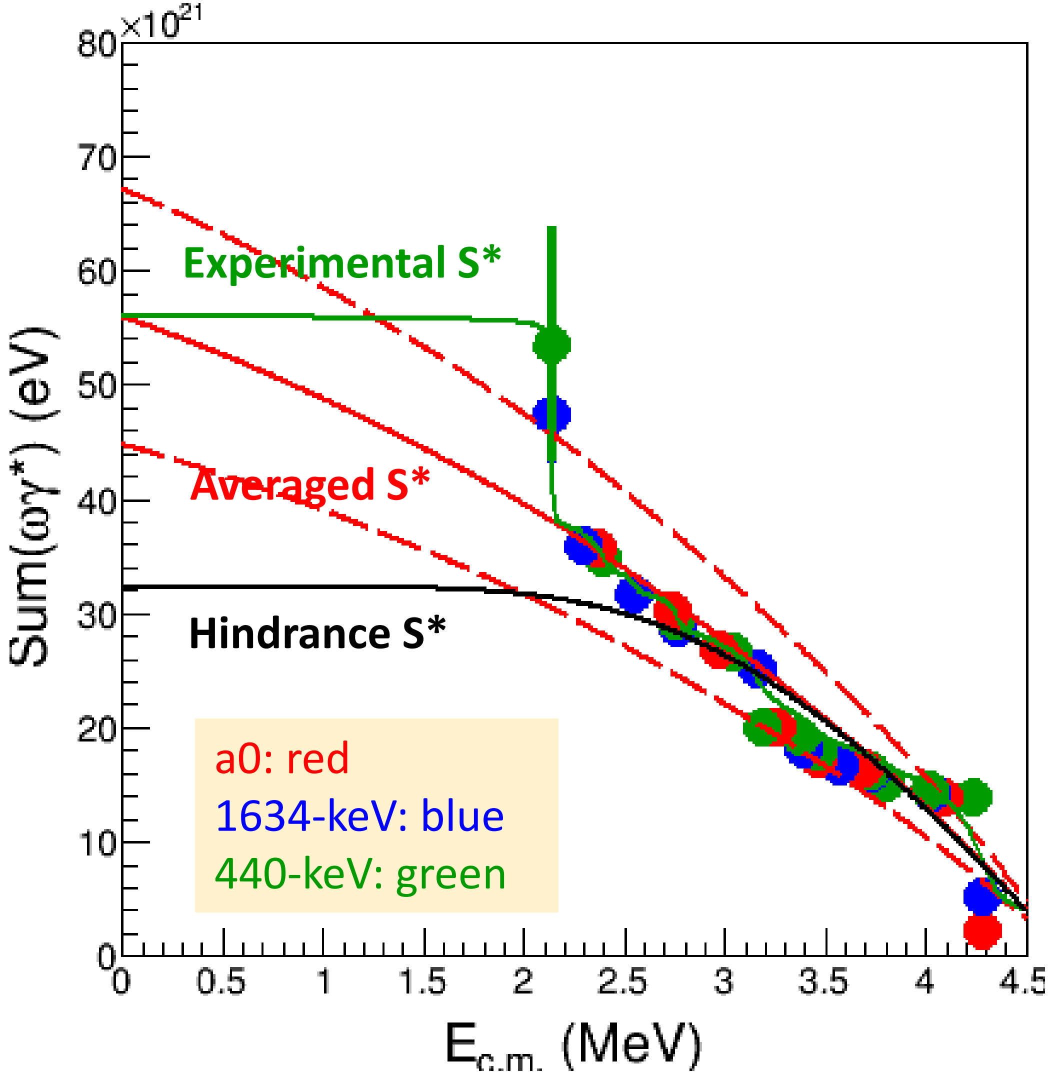
Correlation between carbon isotopes

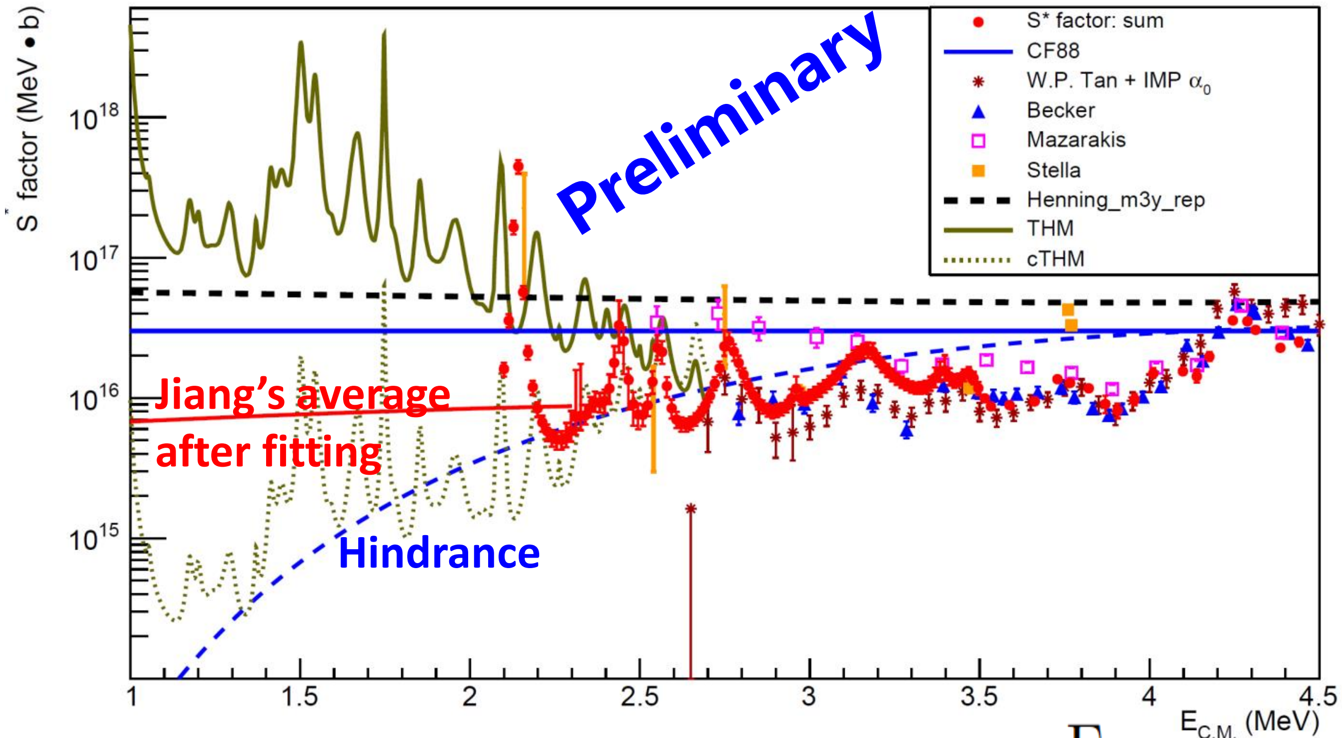
$$T = 1 - \exp(-2\pi\bar{\Gamma}/D)$$



Moldaur, PRC157(1966)907

Sum(ωγ*) vs. Er(MeV)



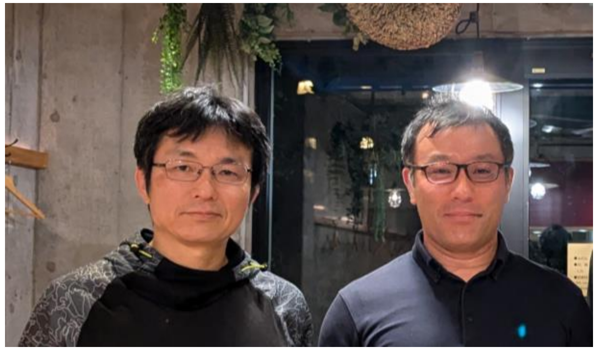


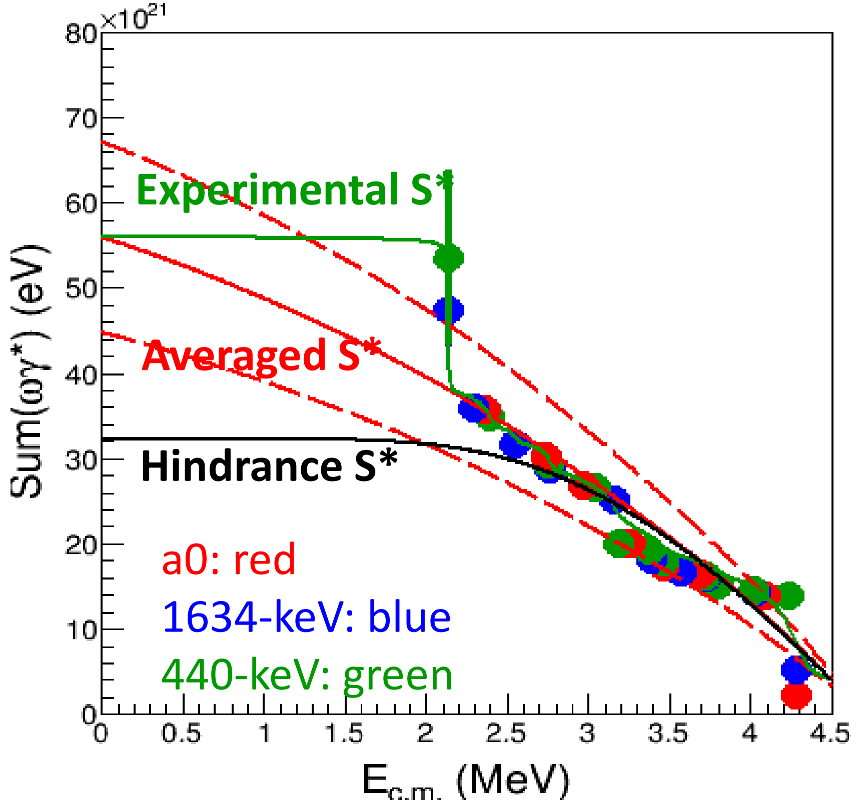
$$\omega\gamma = (2J+1)(1+\delta_{12})\Gamma_{^{12}C+^{12}C}(E_R)\frac{\Gamma_b}{\Gamma}$$

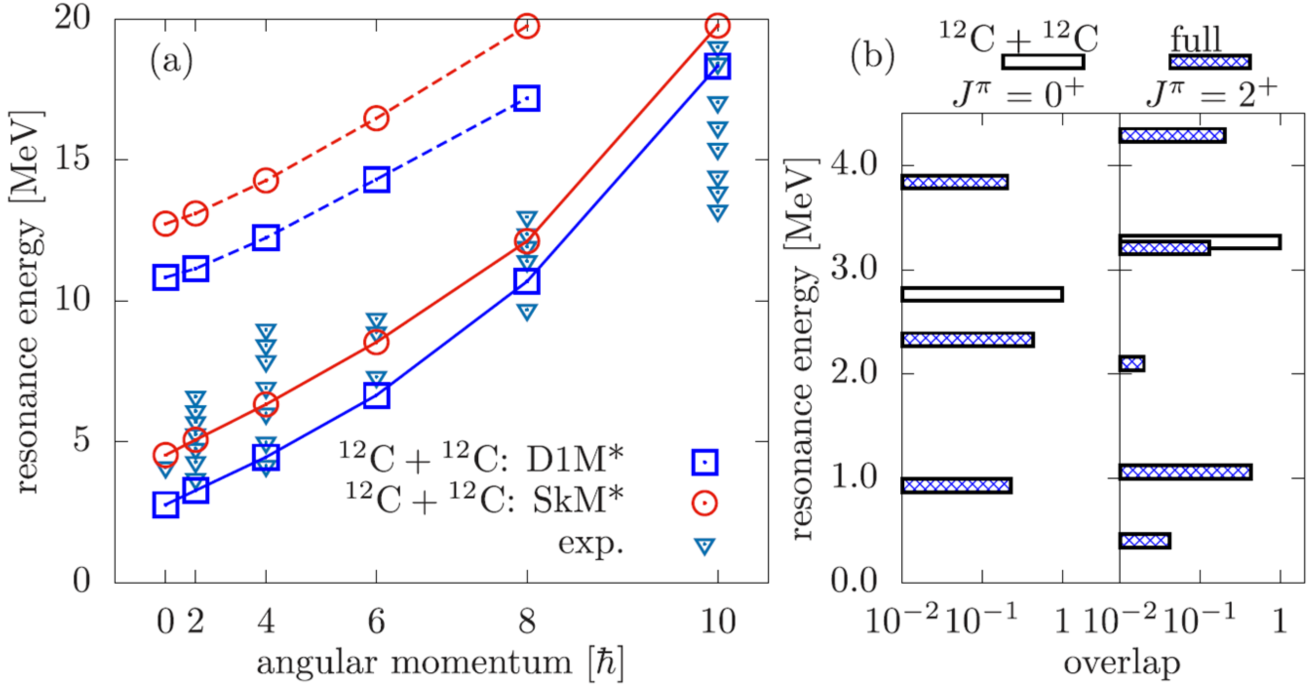
$$\omega\gamma^* = \omega\gamma e^{\left(\frac{87.21}{\sqrt{E_R}}+0.46E_R\right)}$$

$$\int S^*(E)dE = S^*_{max}\frac{\pi\Gamma}{2} = \frac{2\pi\hbar^2}{\mu}\frac{\omega^*\gamma}{\Gamma}\frac{\pi\Gamma}{2} = \frac{\pi^2\hbar^2}{\mu}\omega\gamma^*$$

Sum rule of the molecular resonance





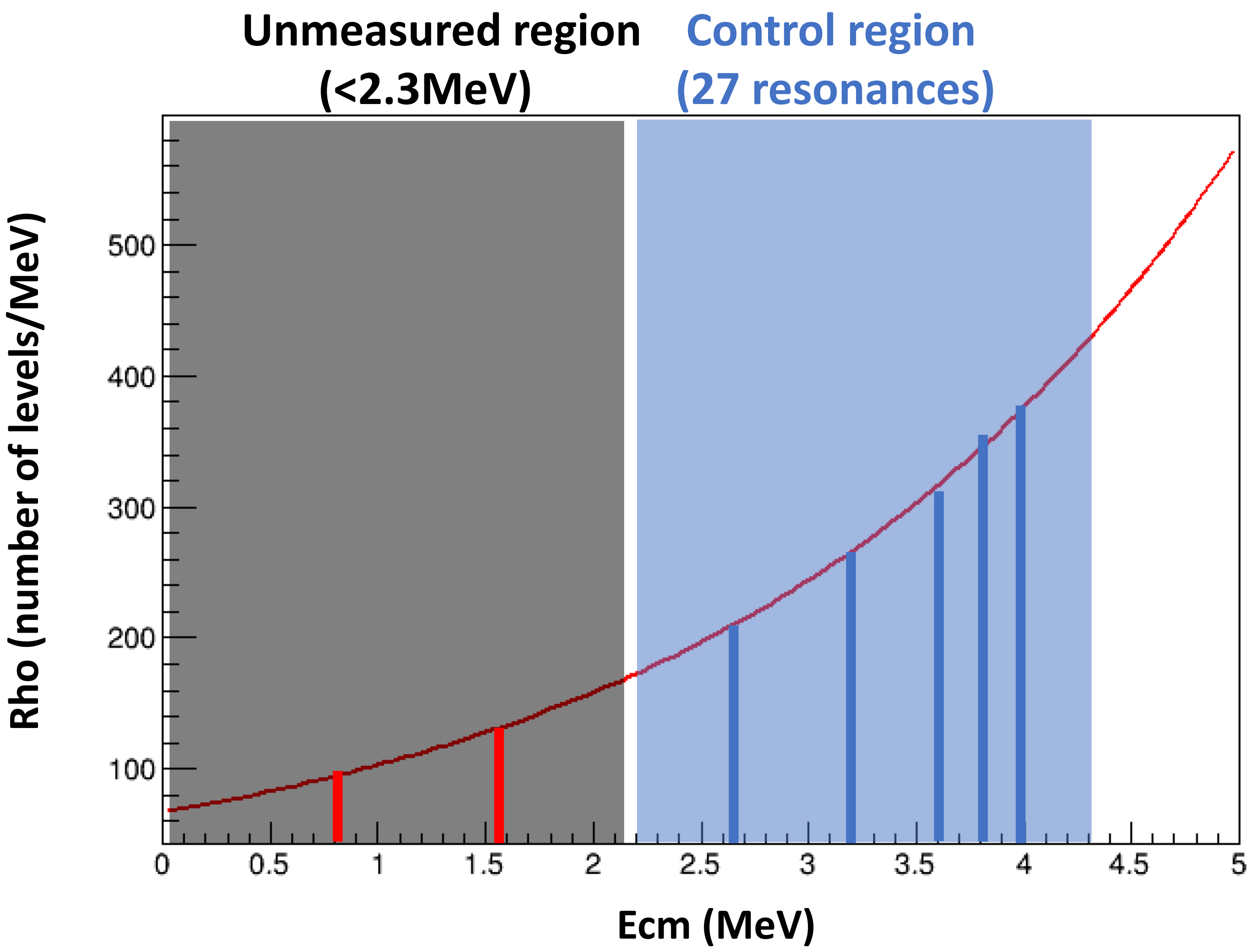


Taniguchi and Kimura, PLB(2024)

The $^{12}C+^{12}C$ resonance can be fragmented into small resonances due to the coupling to various decay channels, but the sum of the strength (after correcting for the penetration effect) should remain same

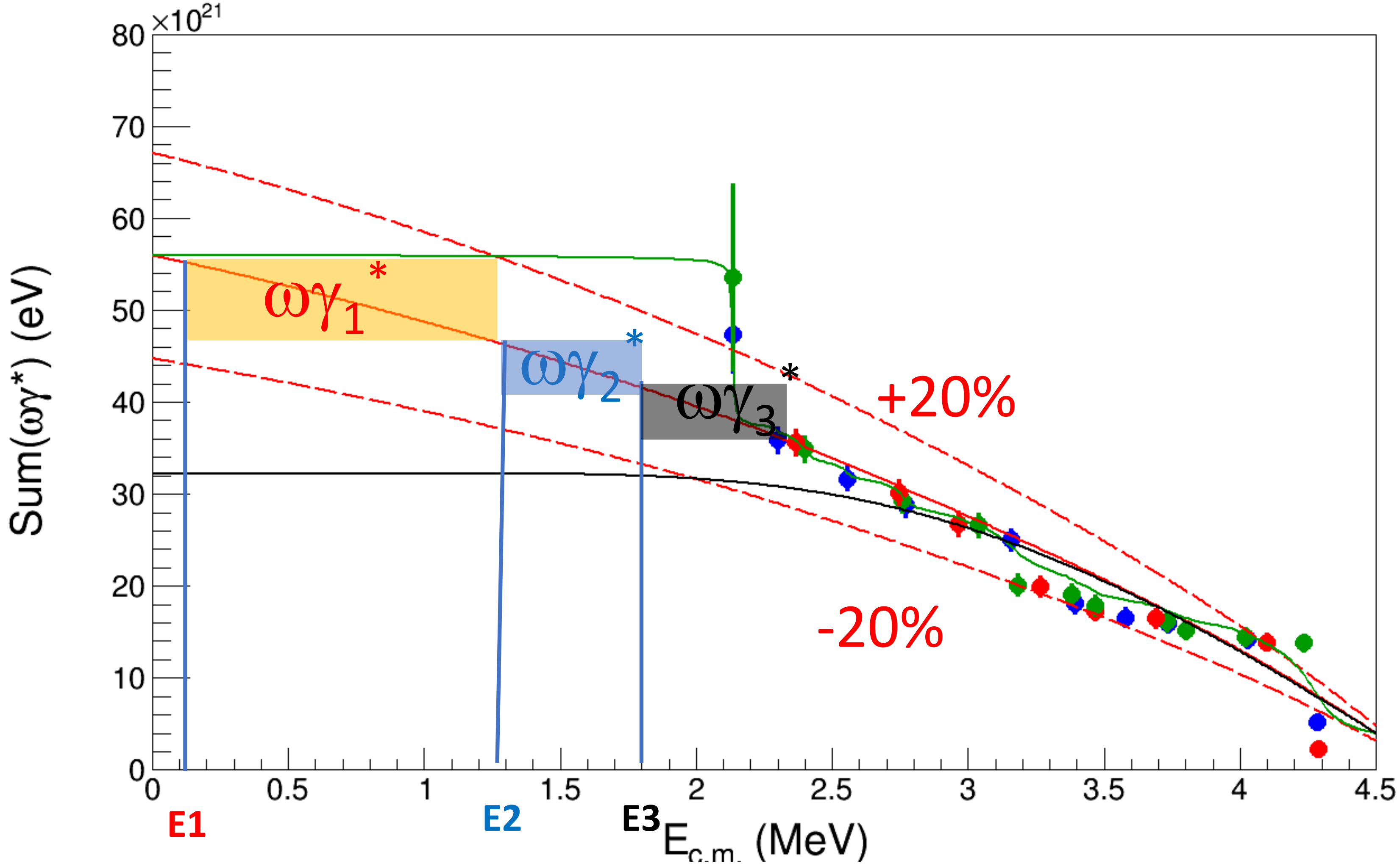
Extrapolation
Towards lower energies
Using statistical model approach

Faked resonances using Monte Carlo method

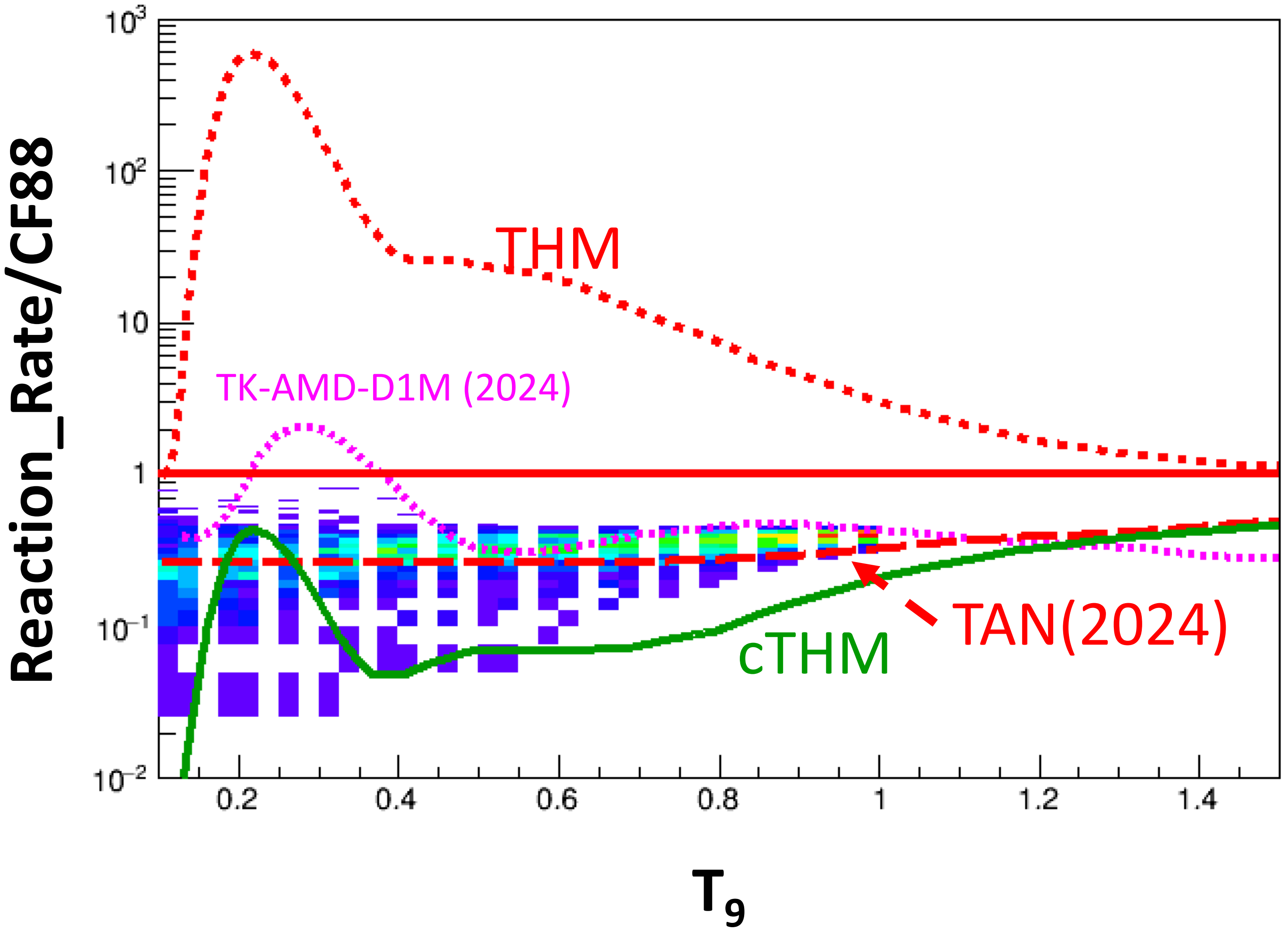


Levels in the unmeasured energy range are generated with a level density constrained by direct measurement

Sum(ωγ*) vs. Er(MeV)

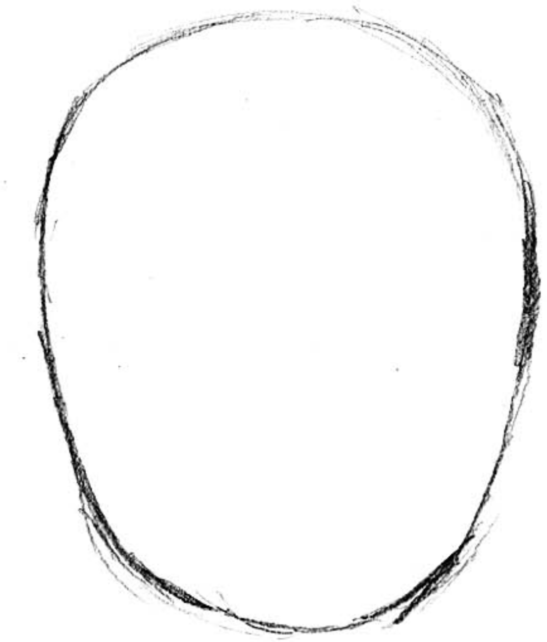


Reaction rate based on Monte carlo

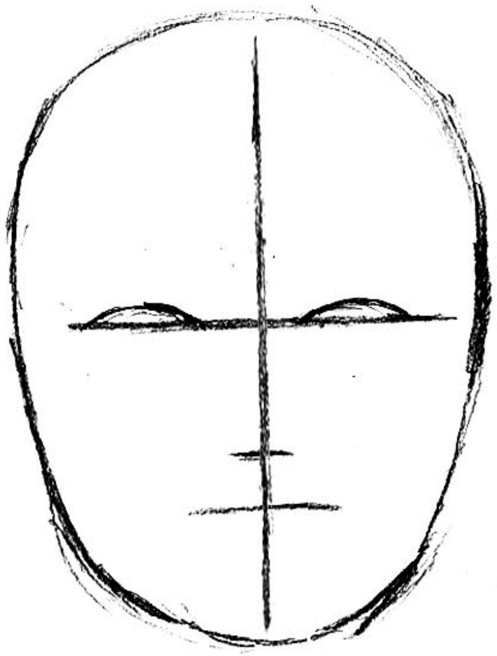


Nature of the $^{12}C+^{12}C$ molecular resonance determines extrapolation

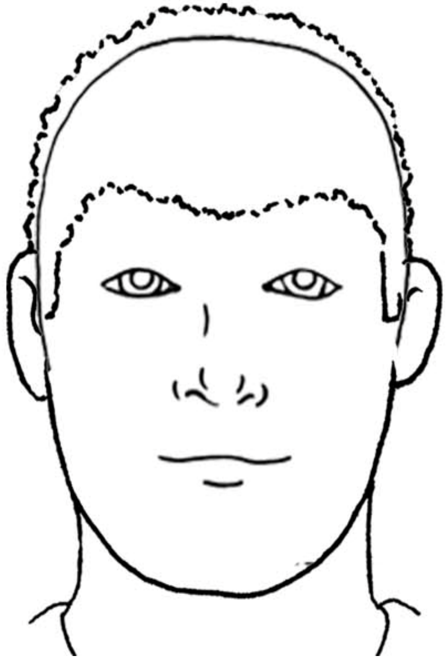
Resonant Energy, Strength, Penetration Factor



Gross structure
(averaged xsec, Upper/lower limits)



Intermediate Structure
(structure of total fusion xsec)



Fine Structure
(Structure in decay channels)

Summary

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

→First direct measurement of a0 below 2.5 MeV indicates the needs of improving the THM/cTHM

→Our analysis suggests that statistical model is applicable at low energies

- **Indirect (THM, 24Mg(a,a'))+Direct measurements** 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