TEXAS A&M UNIVERSITY
Cyclotron Institute

Key Reactions in Nuclear
Astrophysics
ECT*-Trento, February 2025

Modeling ‘some’Key Reactions of Light Nuclei and *Alternative*

Theodoros Depastas[1], **Shuting Sun[2]**, **Hongbin He[2]**, **Hua Zheng[2]**
and Aldo Bonasera[1,3]

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[2] School of Physics and Information Technology, Shaanxi Normal University, Xi’an 710119, China

[3] Laboratori Nazionali del Sud, INFN, Catania 95123, Italy

Introduction: The Hybrid α-Cluster (HαC) & Neck (NM) models

H. Zheng and A. Bonasera. *Symmetry*, **13**:1777, 2021; A. Bonasera and J.B. Natowitz. *Phys Rev C*, **102**, 061602(R), 2020;
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- **Semi-classical model**
- **α-particles → fundamental d.o.f.**
- **Evolution →Hamilton Equations, interaction:**

$$\boxed{\mathscr{H} = T + E_F + V_B + V_c}$$

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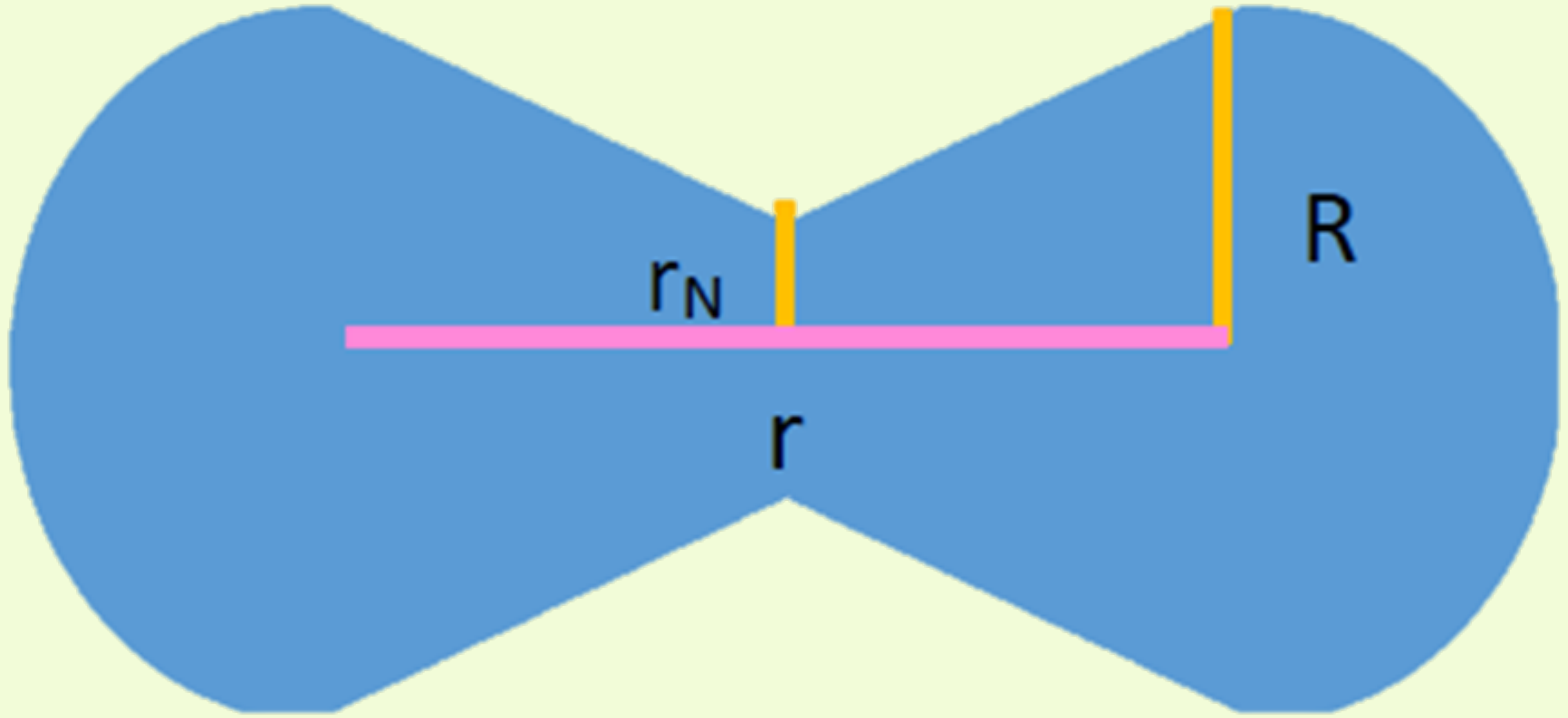
Neck Model (NM)

- **Classical limit of Wigner-transformed TDHF**
- **Macroscopic dynamics, d.o.f.→ neck radius & internuclear distance**
- **Interaction→ Bass potential + resonances, Coulomb, nucleon exchange through neck**
- **Neck radius → Volume conservation !**



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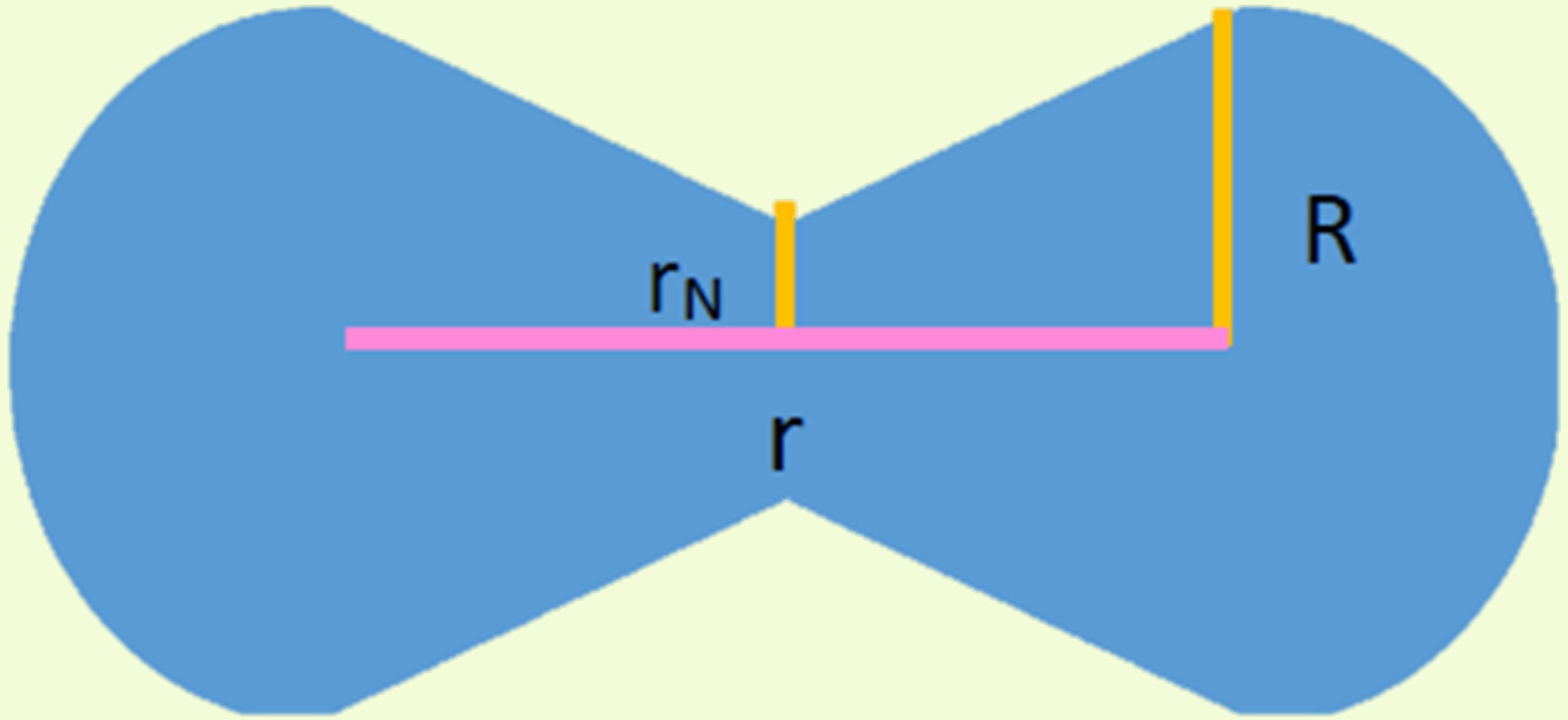

Already used for fusion, fission, ground and excited properties studies

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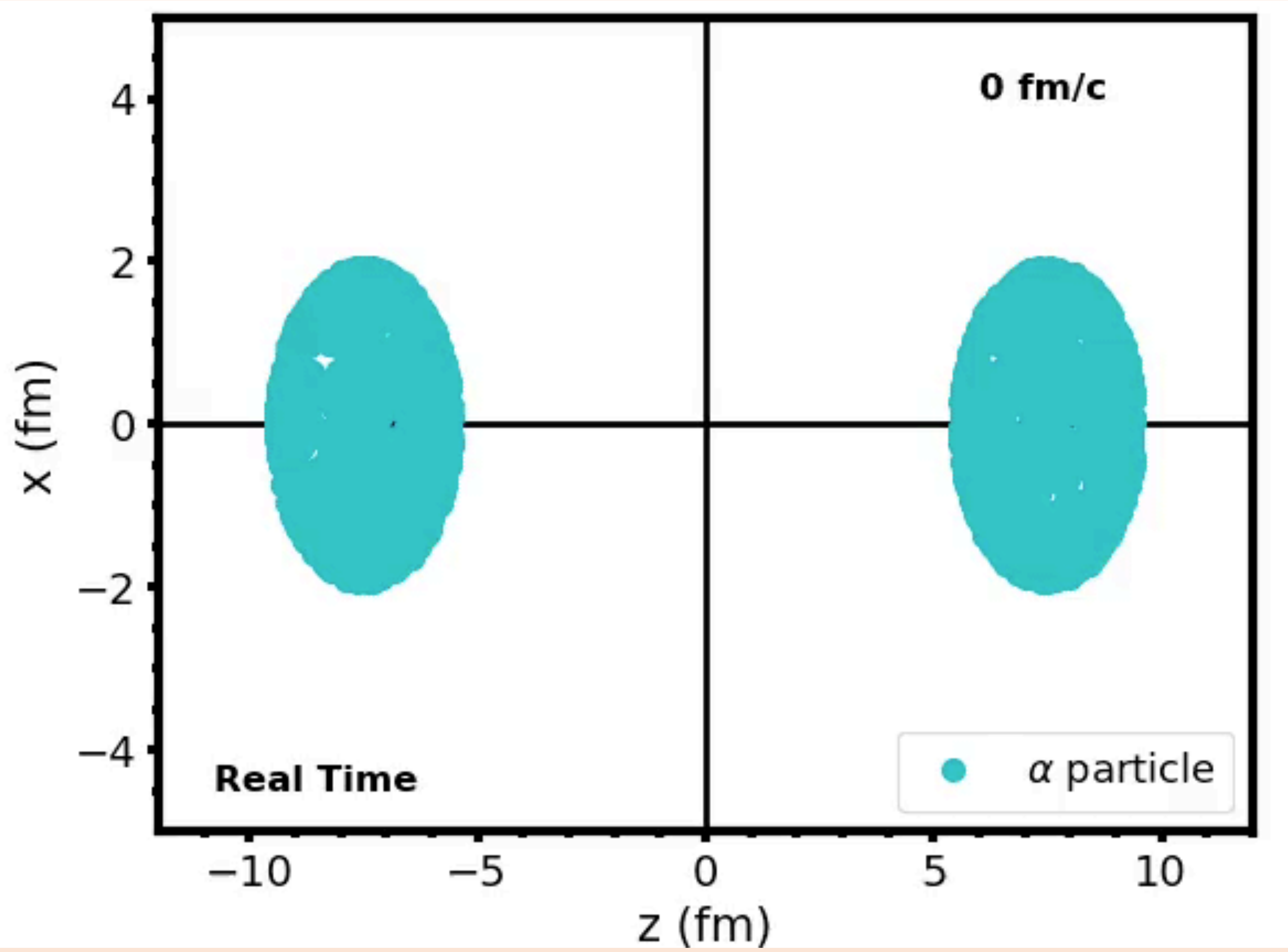
Quantum Tunneling & Imaginary Time



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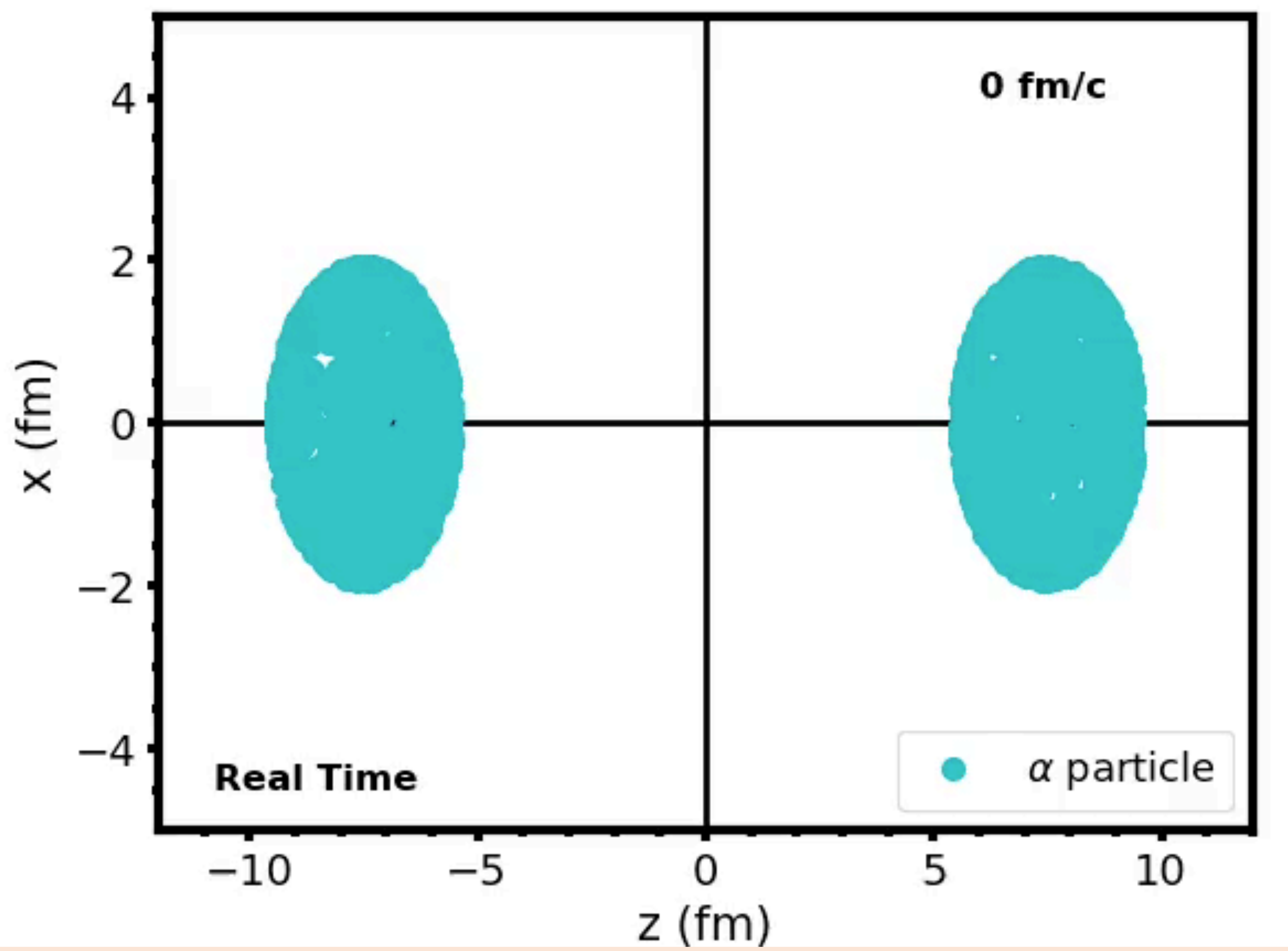
Quantum Tunneling & Imaginary Time

- Nuclei stop @ turning points→ Imaginary time evolution
- $t = i\tau$ and $P = -i\Pi$ → Forces change sign
  - Coulomb → attractive
  - Nuclear Interaction → Repulsive
- Return to real time → fusion

$^{12}C+^{12}C$, HαC model, 300 events, E_{cm}=3.5 MeV



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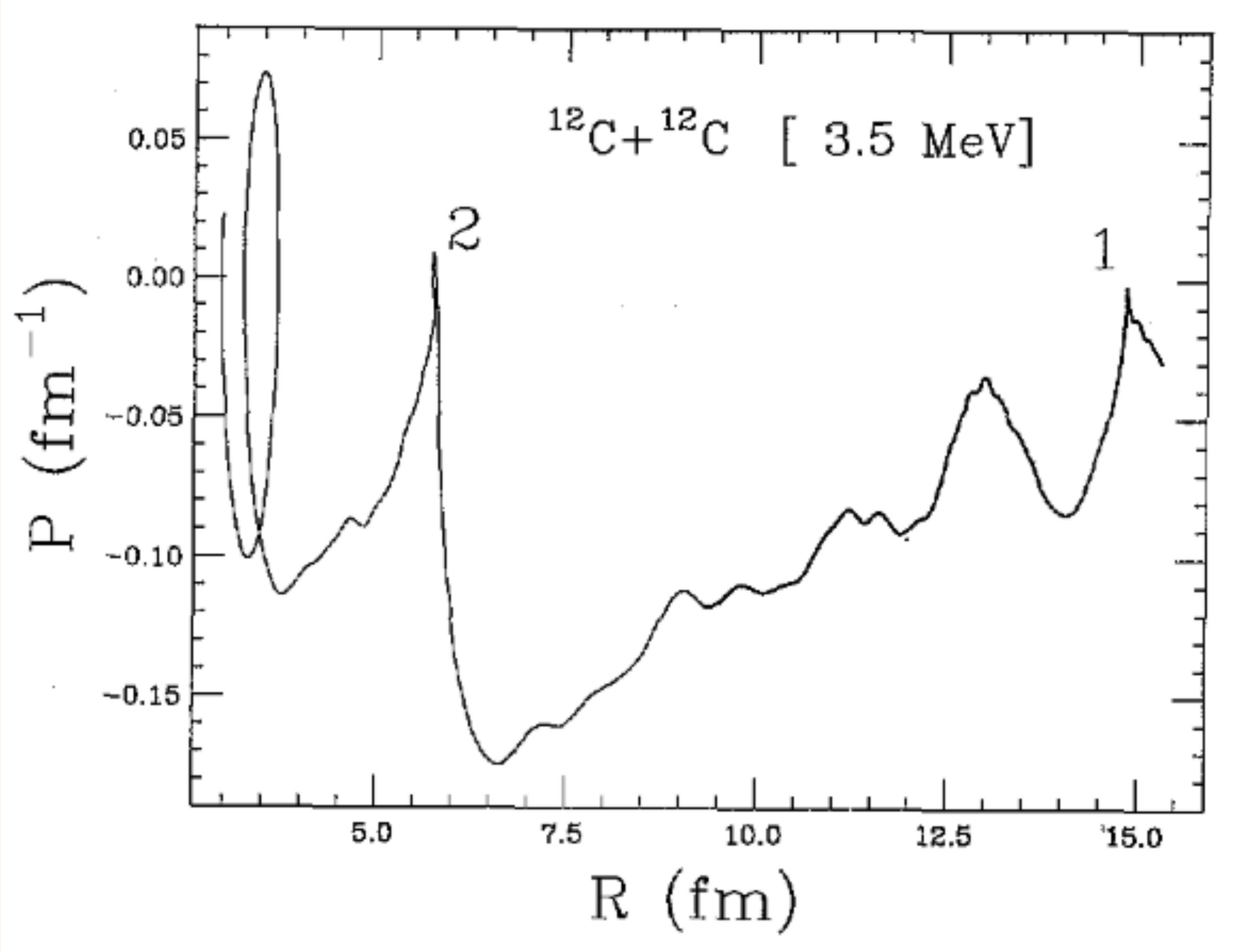

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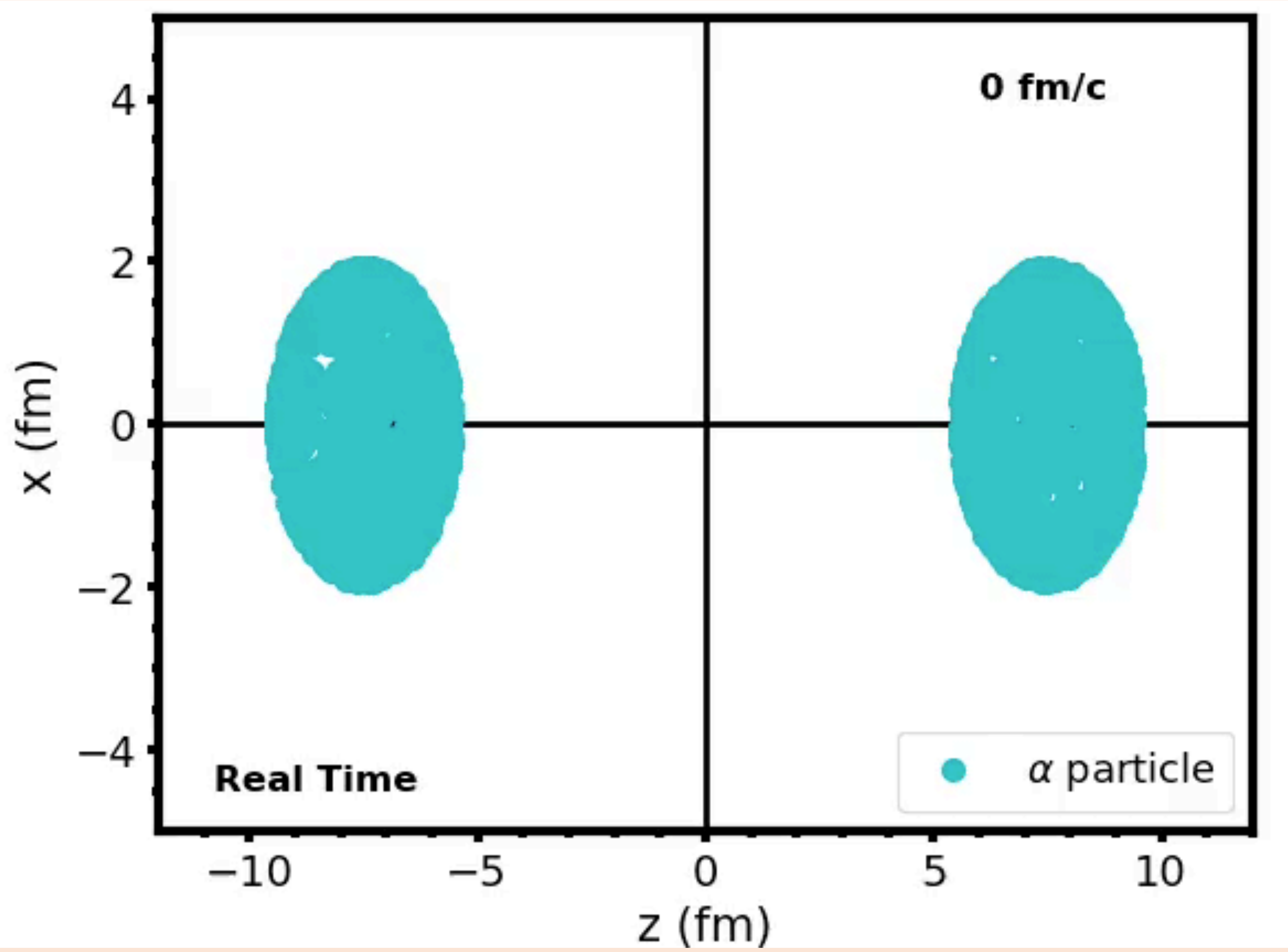

Cross sections:

$$\sigma(E) = \frac{\pi\hbar^2}{2\mu E}(1+\delta_{ab})\sum_{l=0}^{\infty}(2l+1)T_l,\ \ T_0 = \left(1+e^{2A/\hbar}\right)^{-1}$$

where $A = \int P dR$ → imaginary time action

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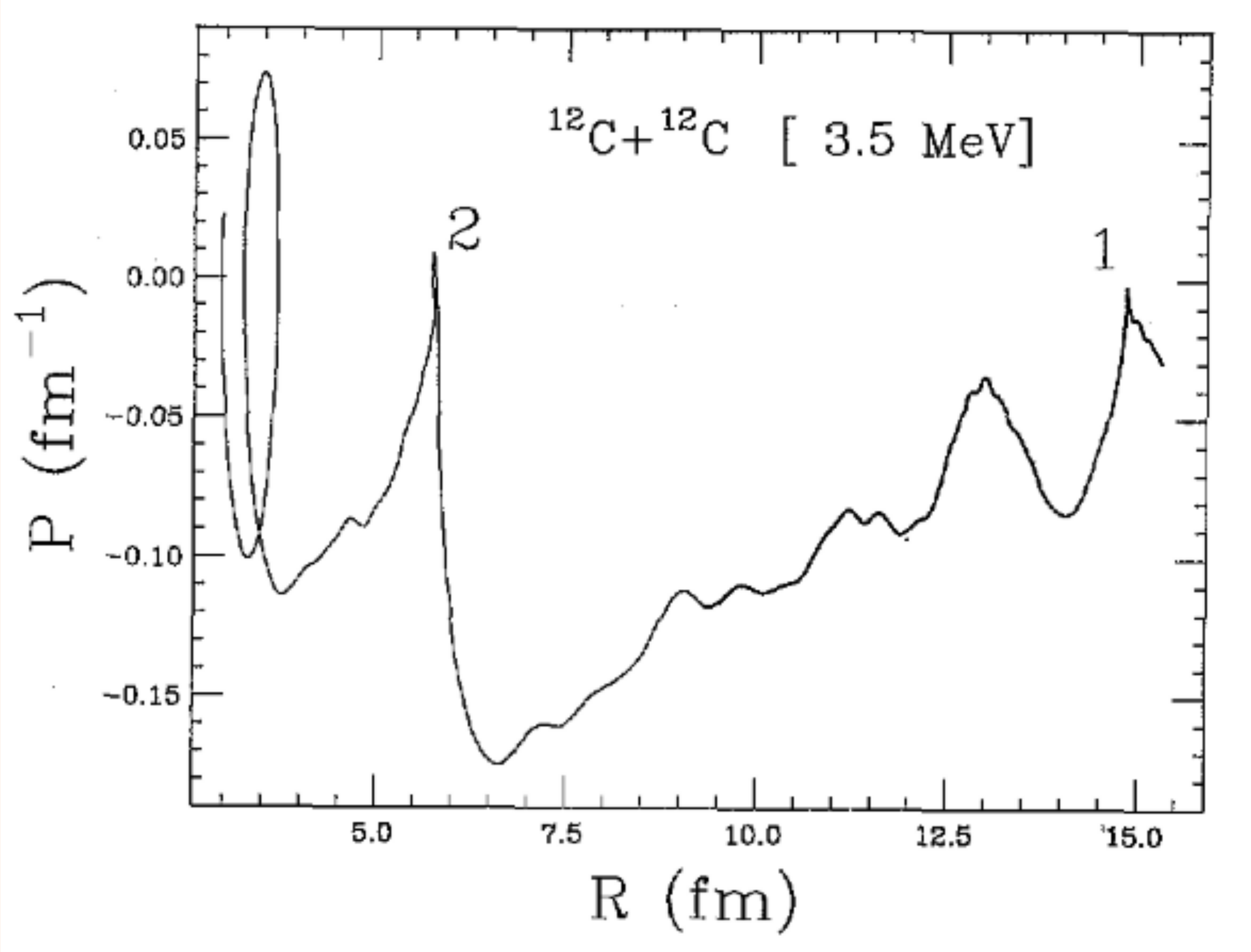

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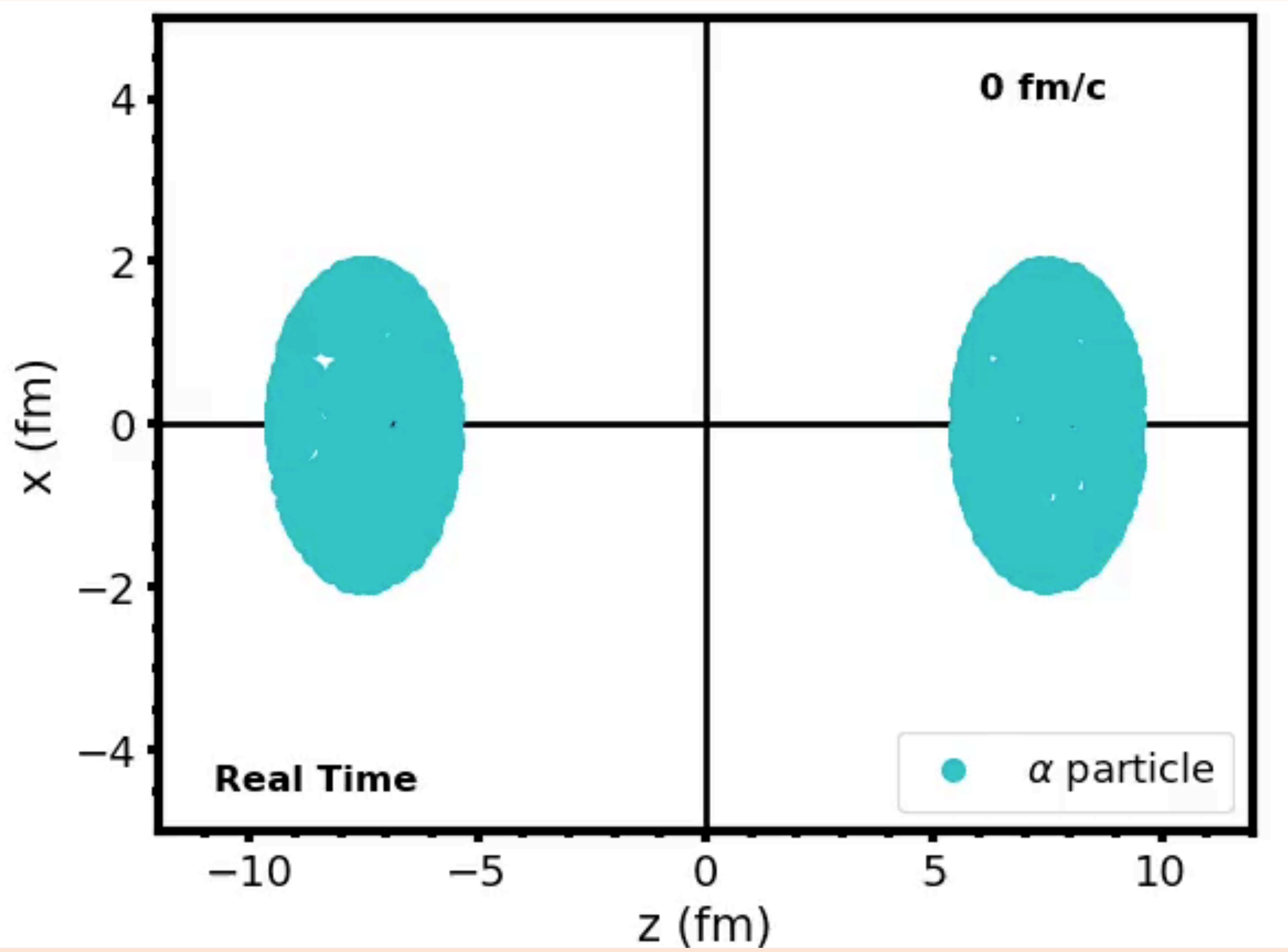

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Compound Nucleus Model

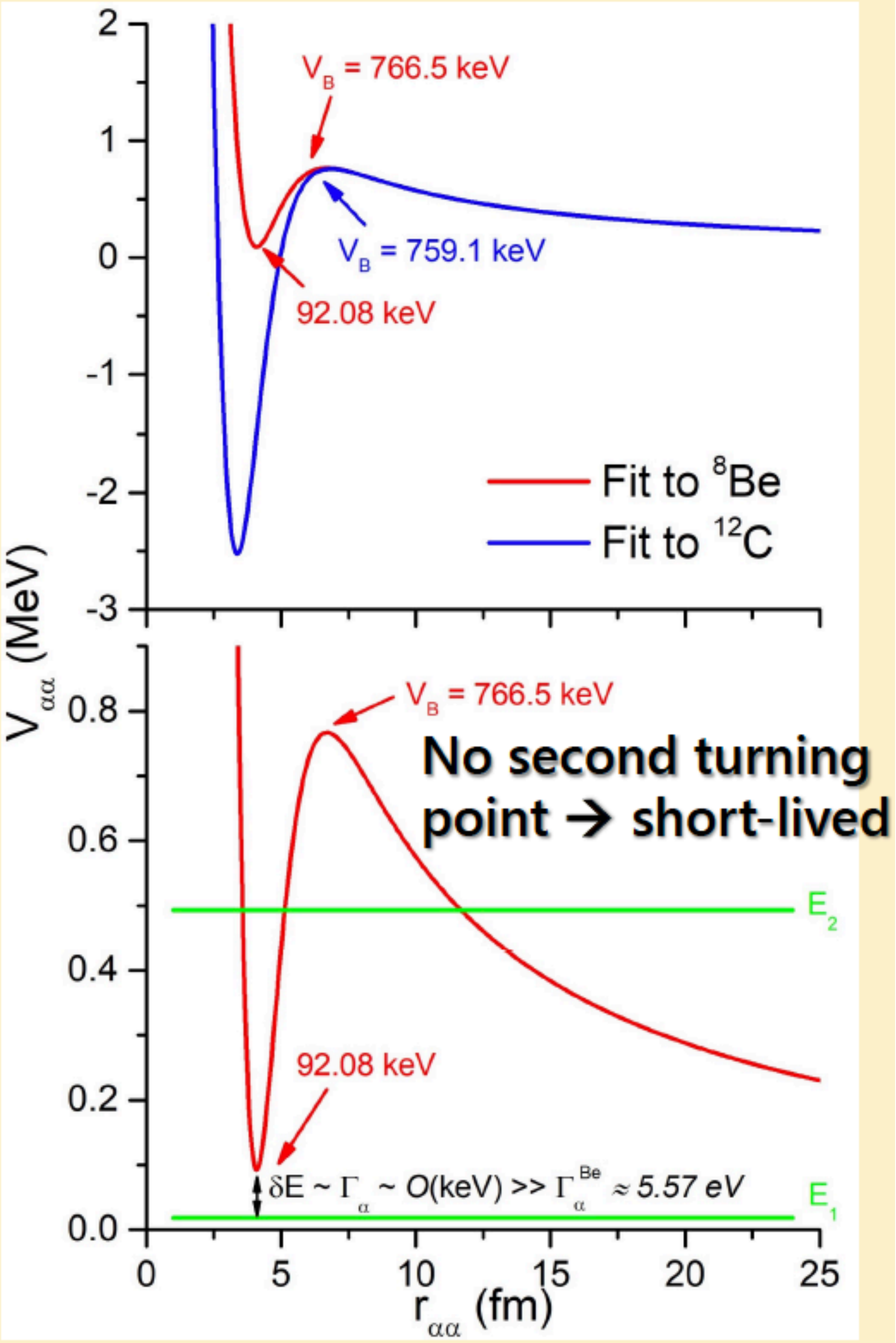
Two step Channel (Normalization of direct calculations)

1. $\alpha + \alpha \rightarrow {}^{8}Be^{*}$
2. ${}^{8}Be^{*} + \alpha \rightarrow {}^{12}C^{*} \rightarrow {}^{12}C + 2\gamma$ (~3%)

Discrepancies in reaction rates: ~ 10^{30}

Our Model	NACRE Formalism
$\sigma = \sigma_f \frac{\Gamma_\gamma}{\Gamma}$	$\sigma \approx \sigma_f \frac{\Gamma_\gamma}{\Gamma_\alpha}$
$\Gamma_\alpha = \hbar \frac{T_l}{\tau}$	$\Gamma_\alpha = \Gamma_\alpha^{(0)} \frac{T_l}{T_l^{(0)}}$
$\Gamma_\gamma = \Gamma_\gamma^{(0)} \left(\frac{E_\gamma}{E_\gamma^{(0)}}\right)^{2L+1} \frac{\Gamma_\alpha(E_{CM})}{\Gamma_\alpha^{(0)}}$	$\Gamma_\gamma = \Gamma_\gamma^{(0)} \left(\frac{E_\gamma}{E_\gamma^{(0)}}\right)^{2L+1}$

Assumption: γ-Matrix element ~ α-Matrix Element · Density ~ Γ_α



No second turning point → short-lived

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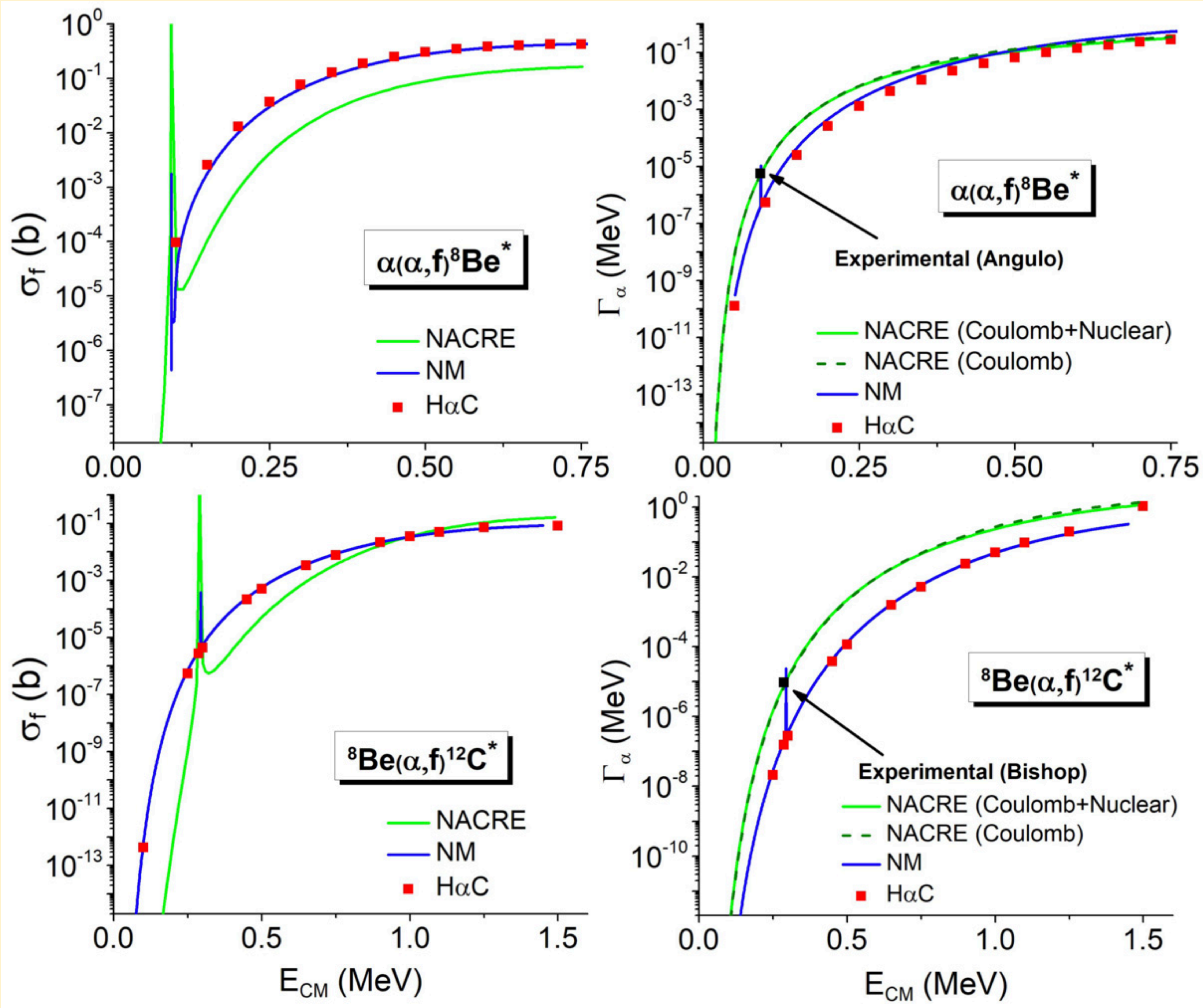
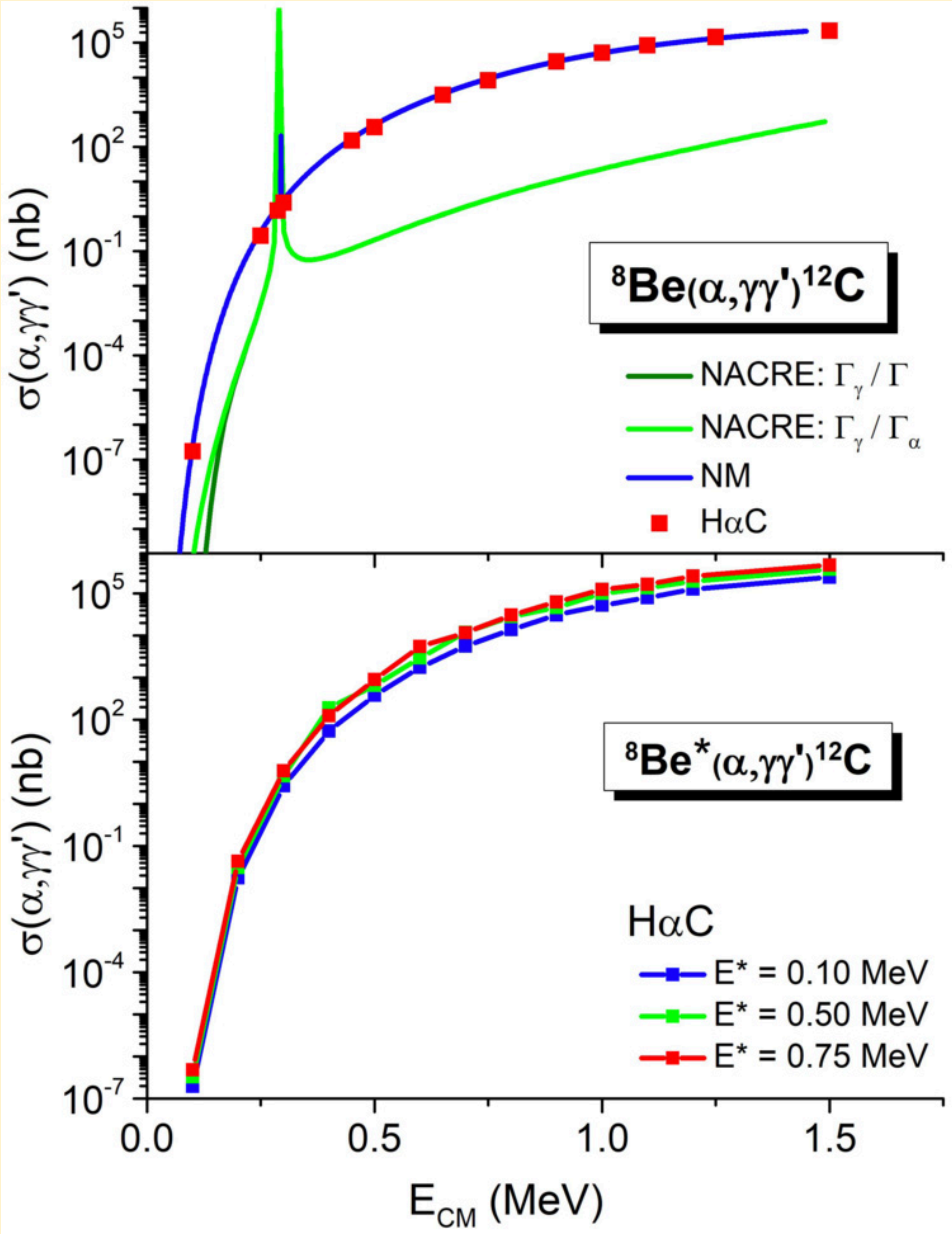
Phys. Lett. B 860 (2025) 139180





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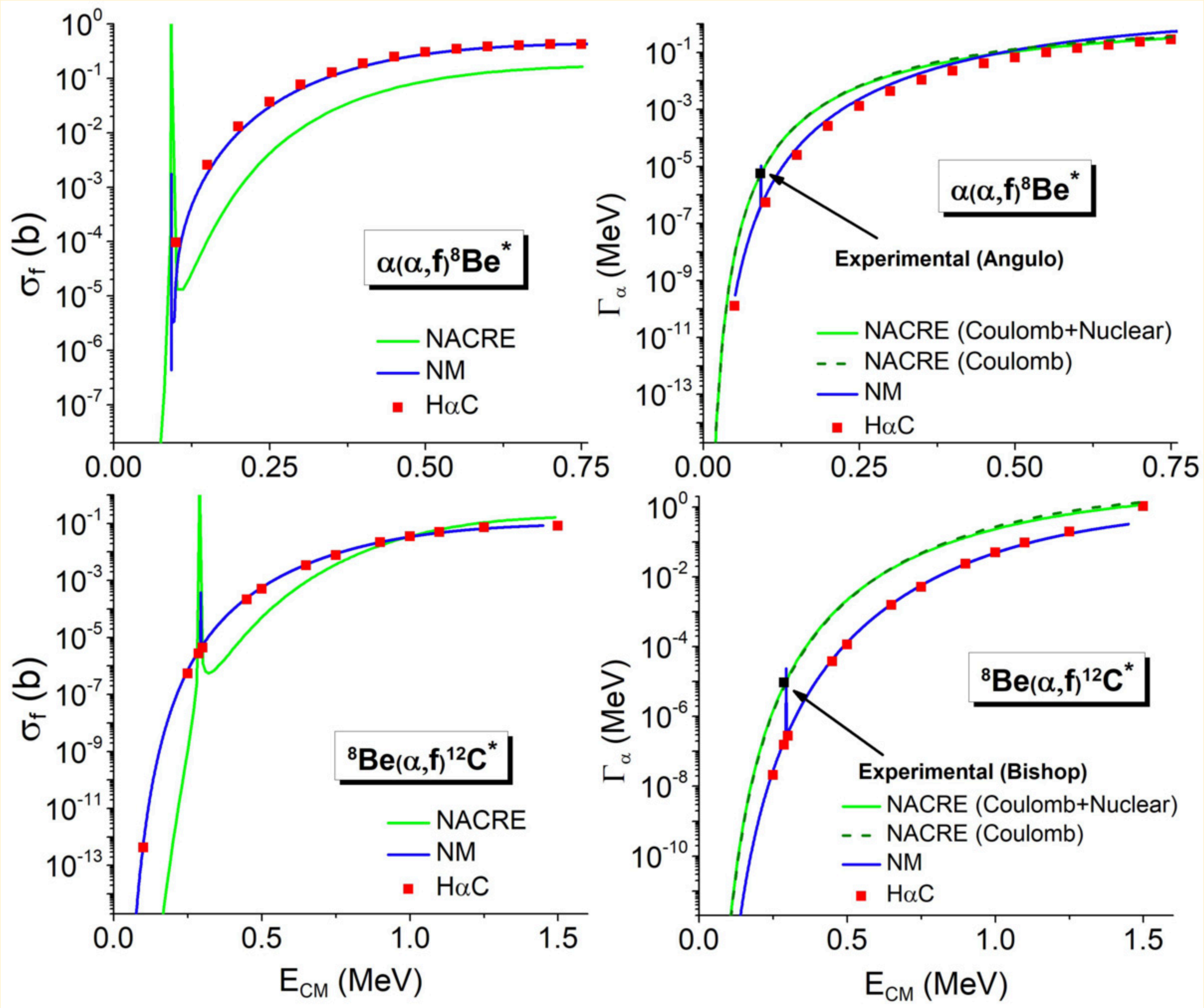

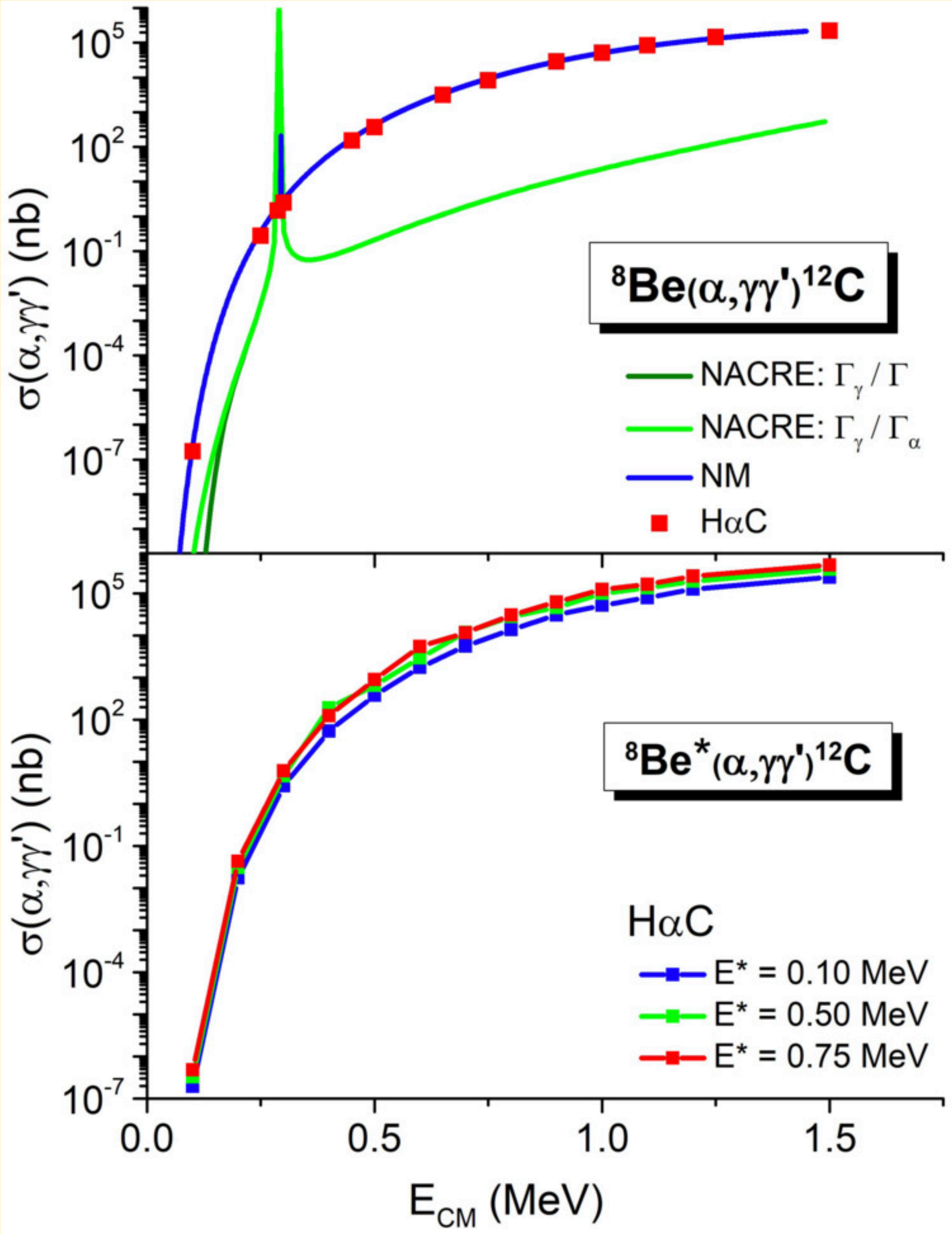

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Stellar Reaction Rates

Total reaction rate → integration from $E_{Be} = -Q = 92.08$ keV

NACRE → integration from 0 → x$10^{20\text{-}30}$ higher rates @ 10^7 K !

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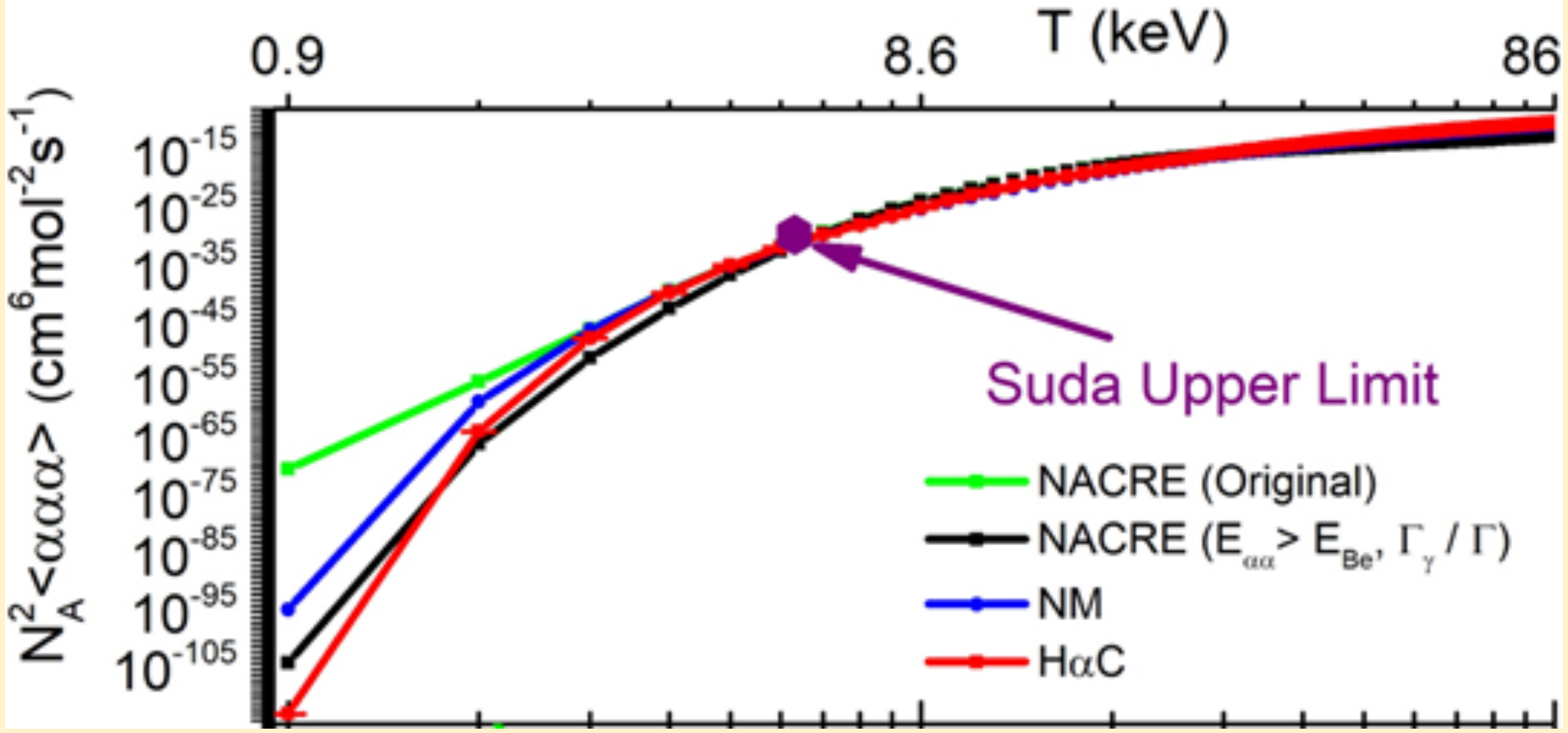

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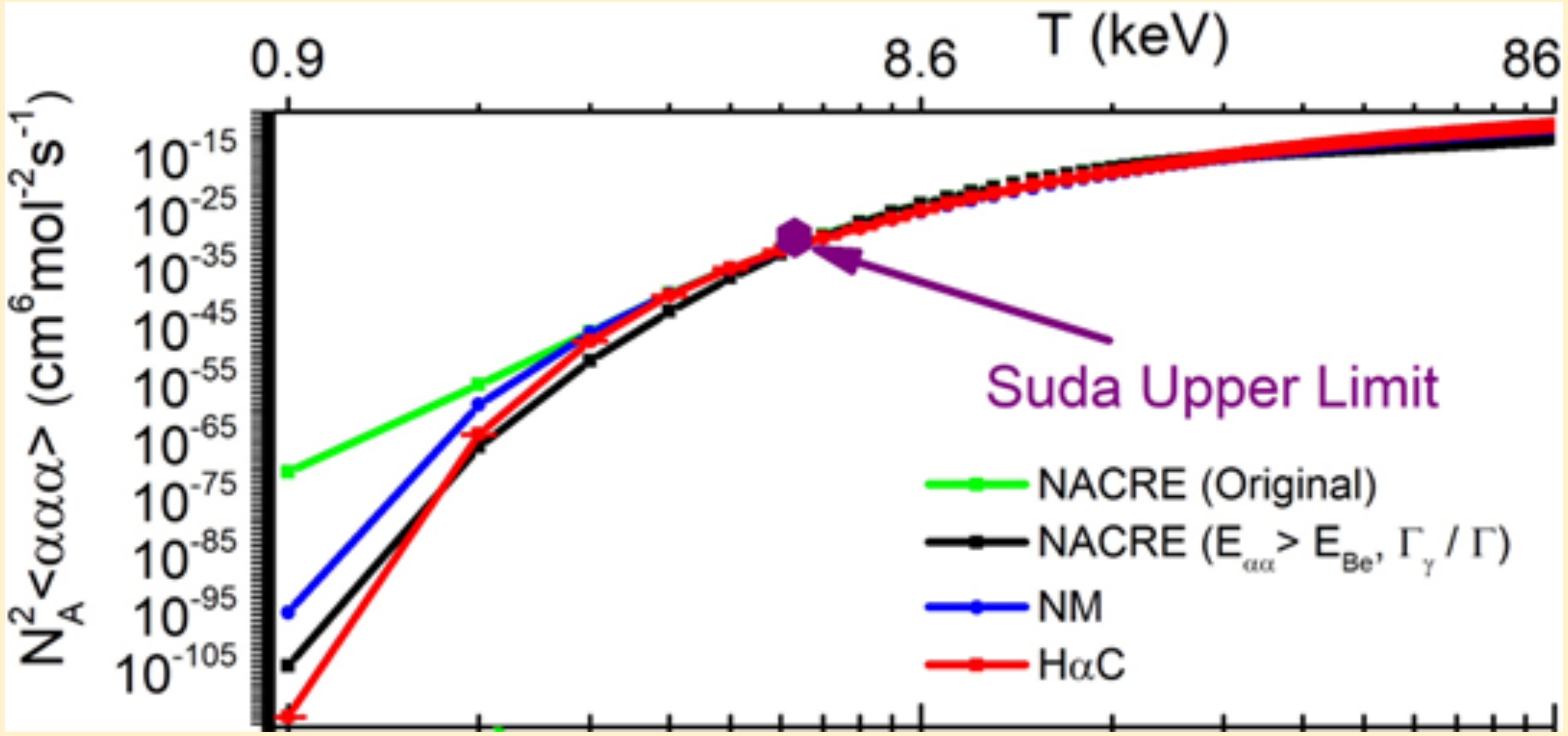

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Astrophysical limits (Suda) :

- **Max rate in FGB stars → observed luminosity**
- **Min Temperature dependence → He-flashes in AGB stars**

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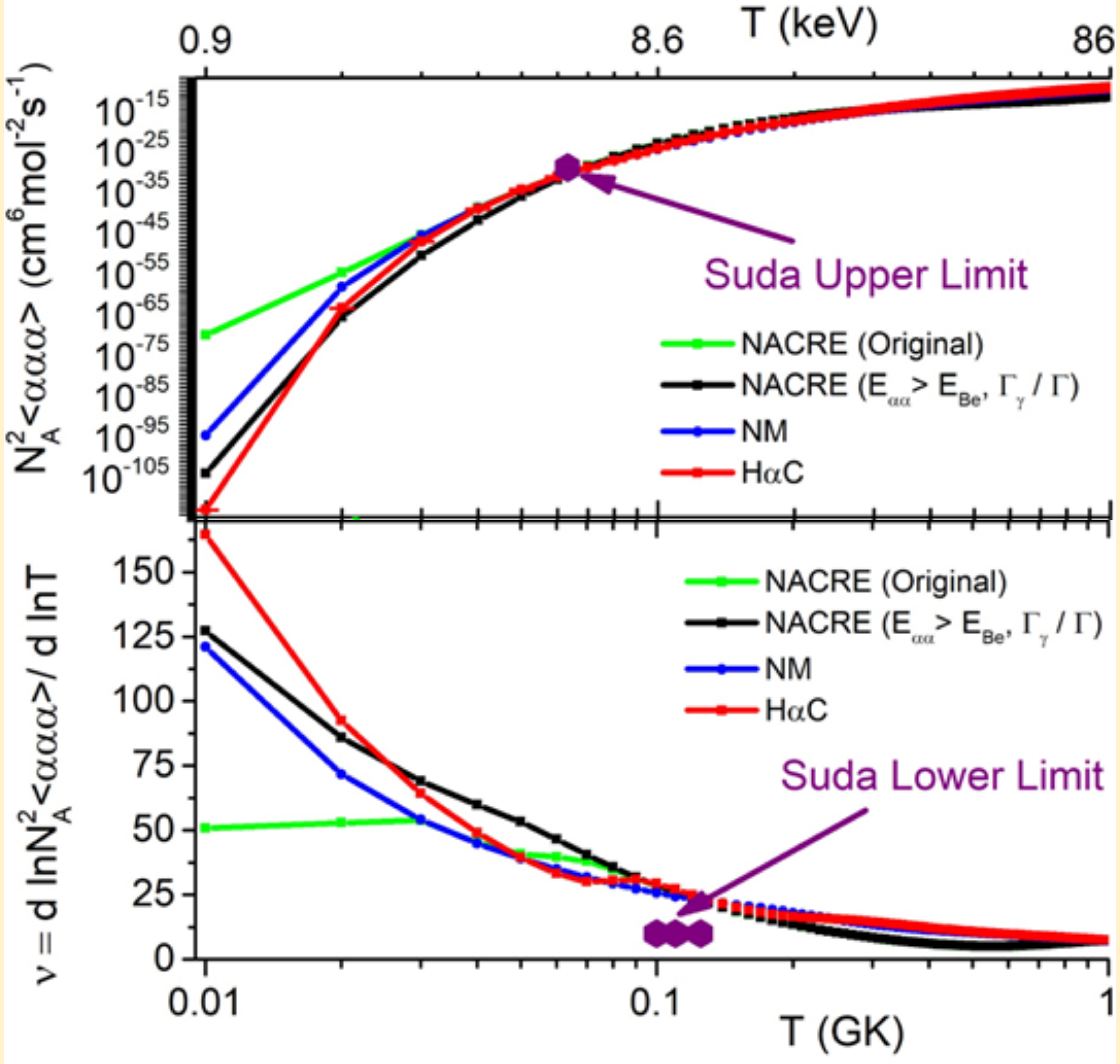

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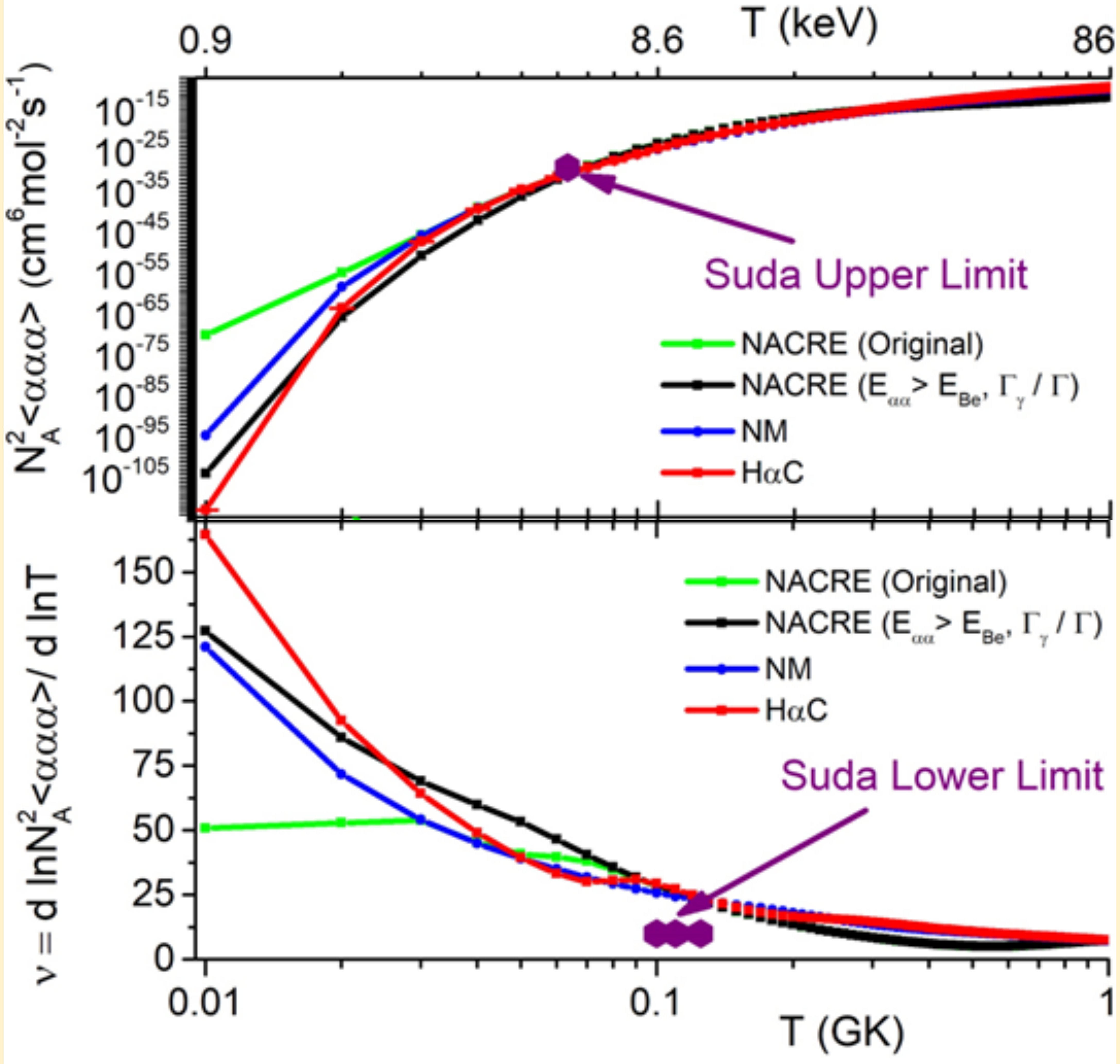

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Stringer Constraints (Nuclear) are required !
Possible THM experiment

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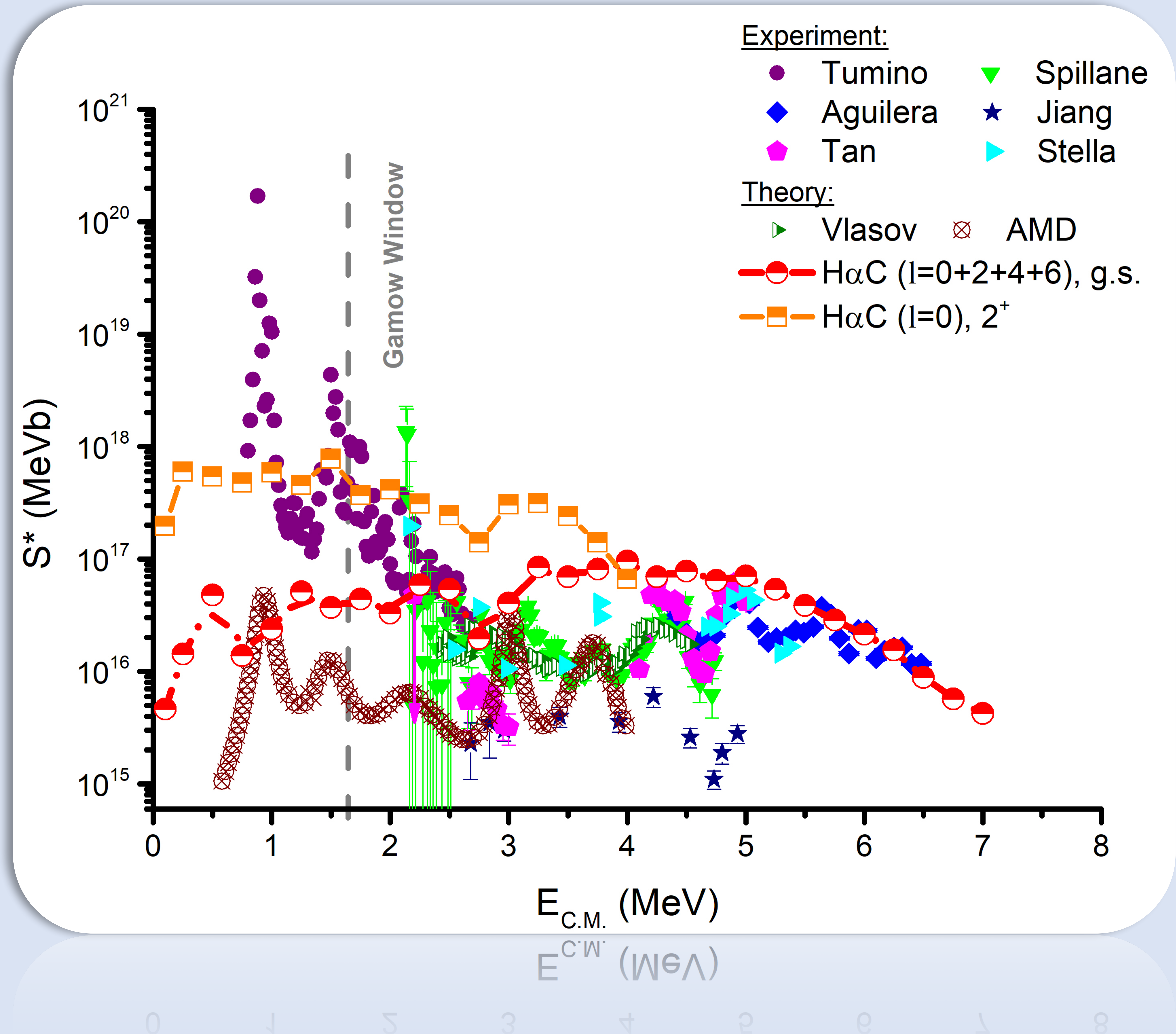

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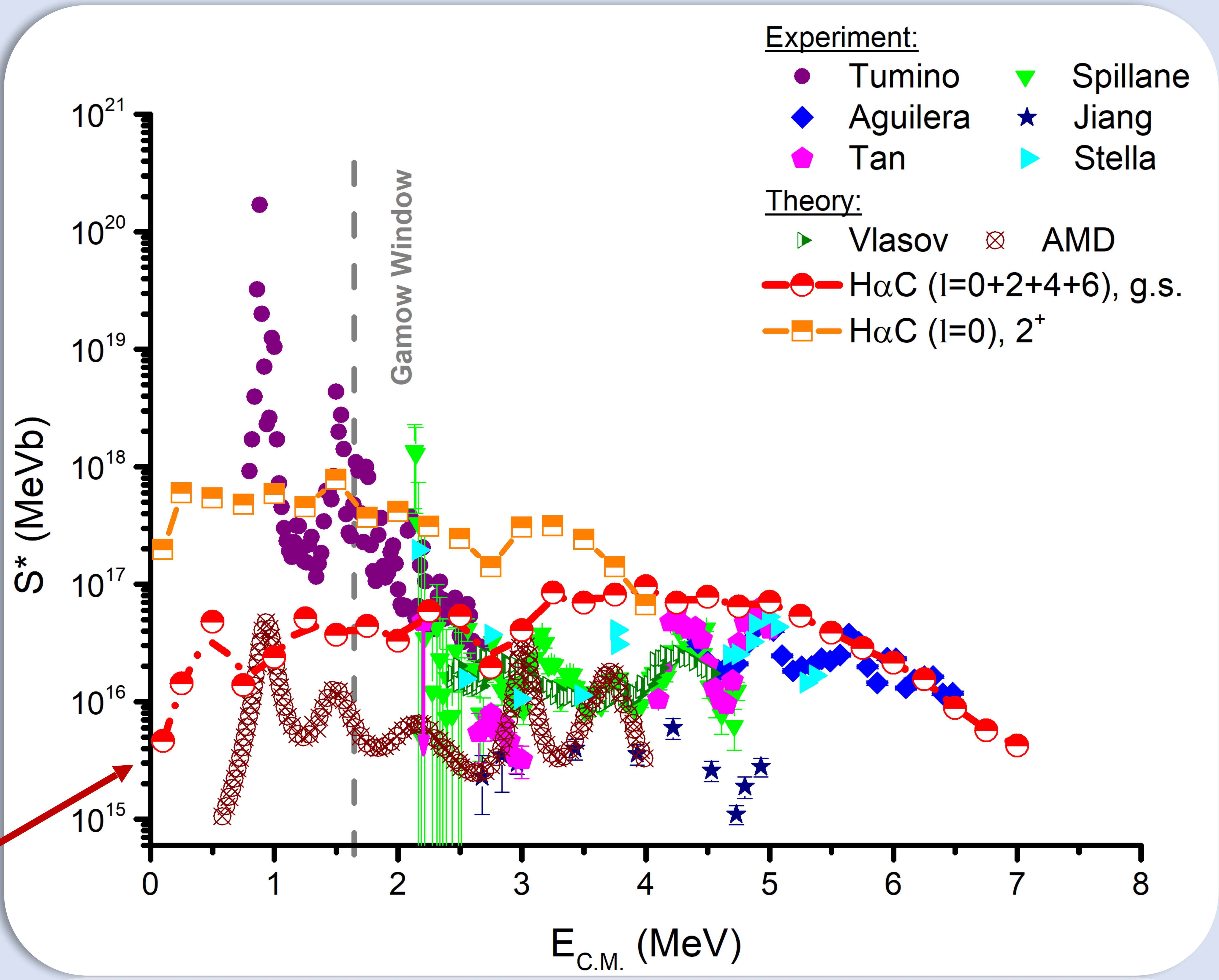

HαC model (ground state fusion)

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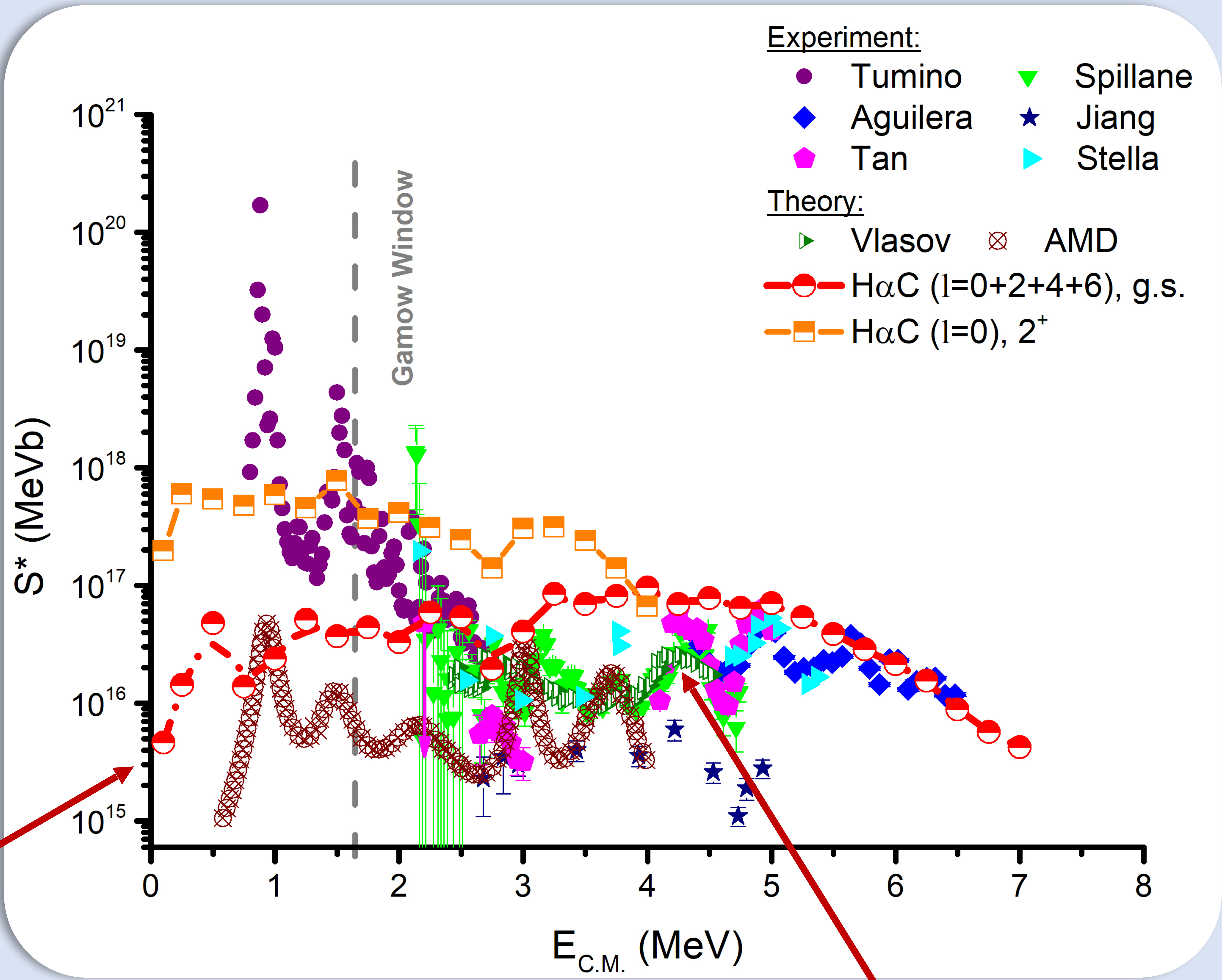

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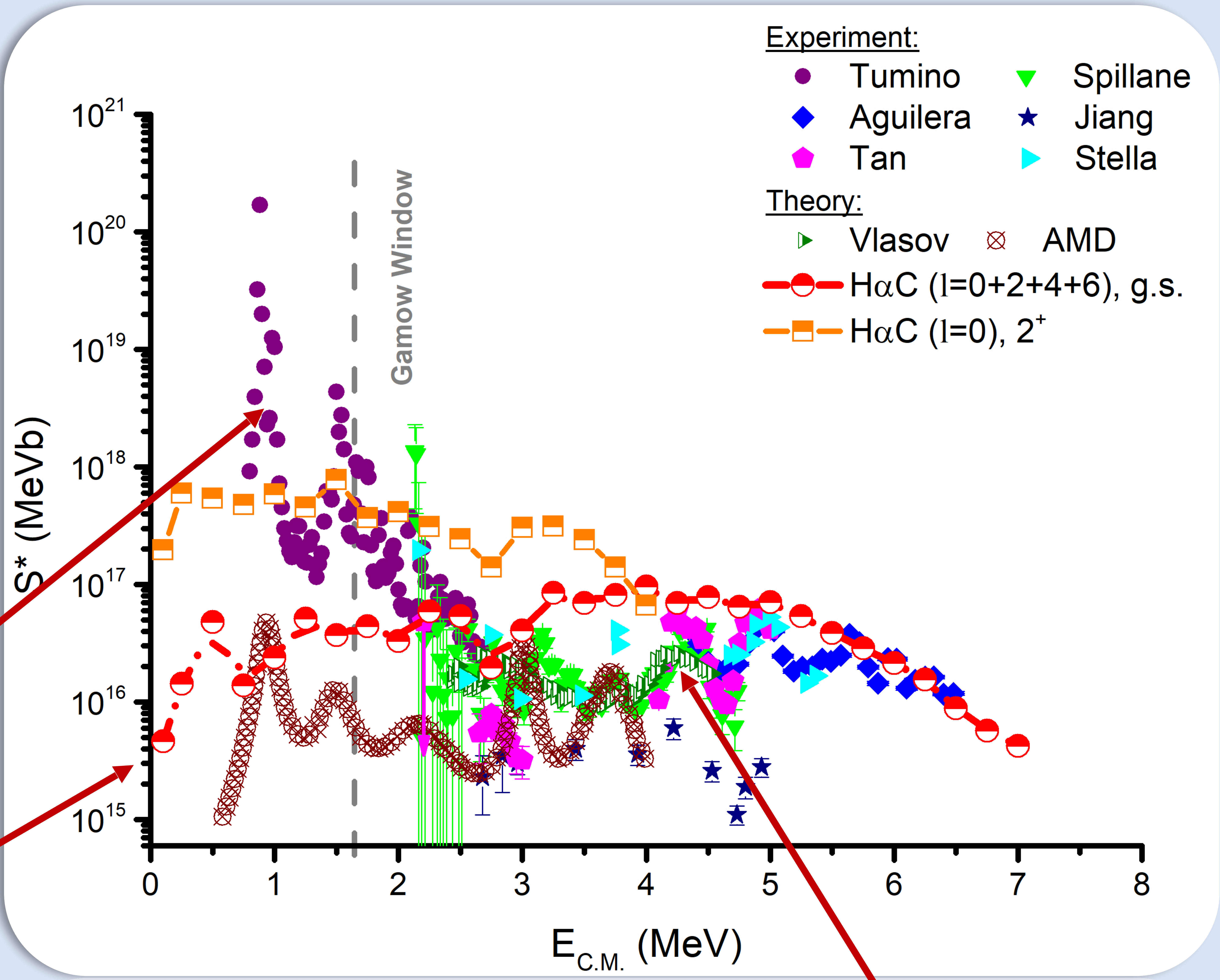

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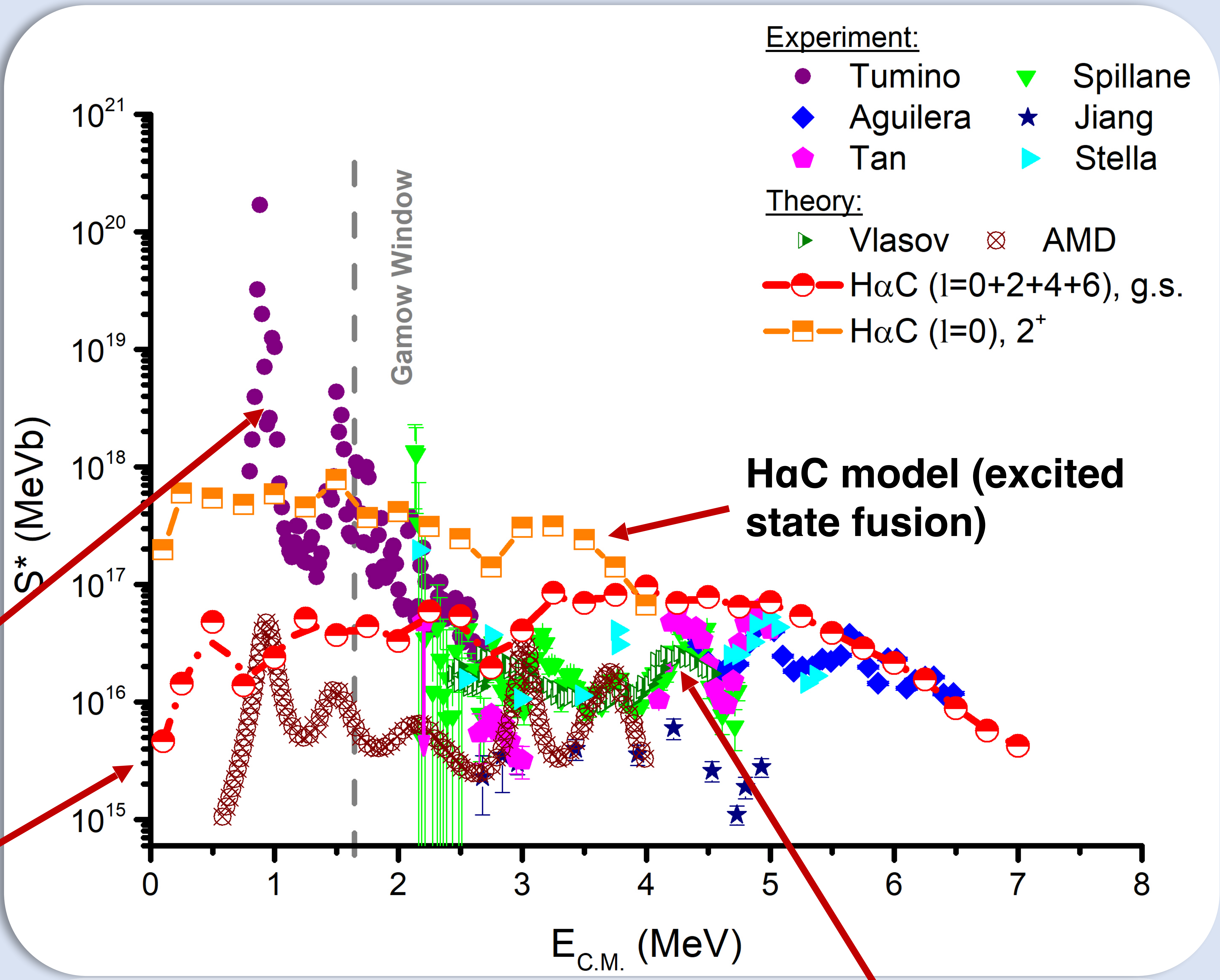
- Trojan Horse Method → Low energy measurements
- Fusion with 2^+ excited state → Possible THM study



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Sub-barrier Resonant Structures

D. Youngblood, Y. L. *et al*, *Phys. Rev. C* **80** (2009) 064318; T. Depastas, S.T. Sun, H. Zheng and A. Bonasera, *Phys Rev* C **108**, 035806 (2023) .

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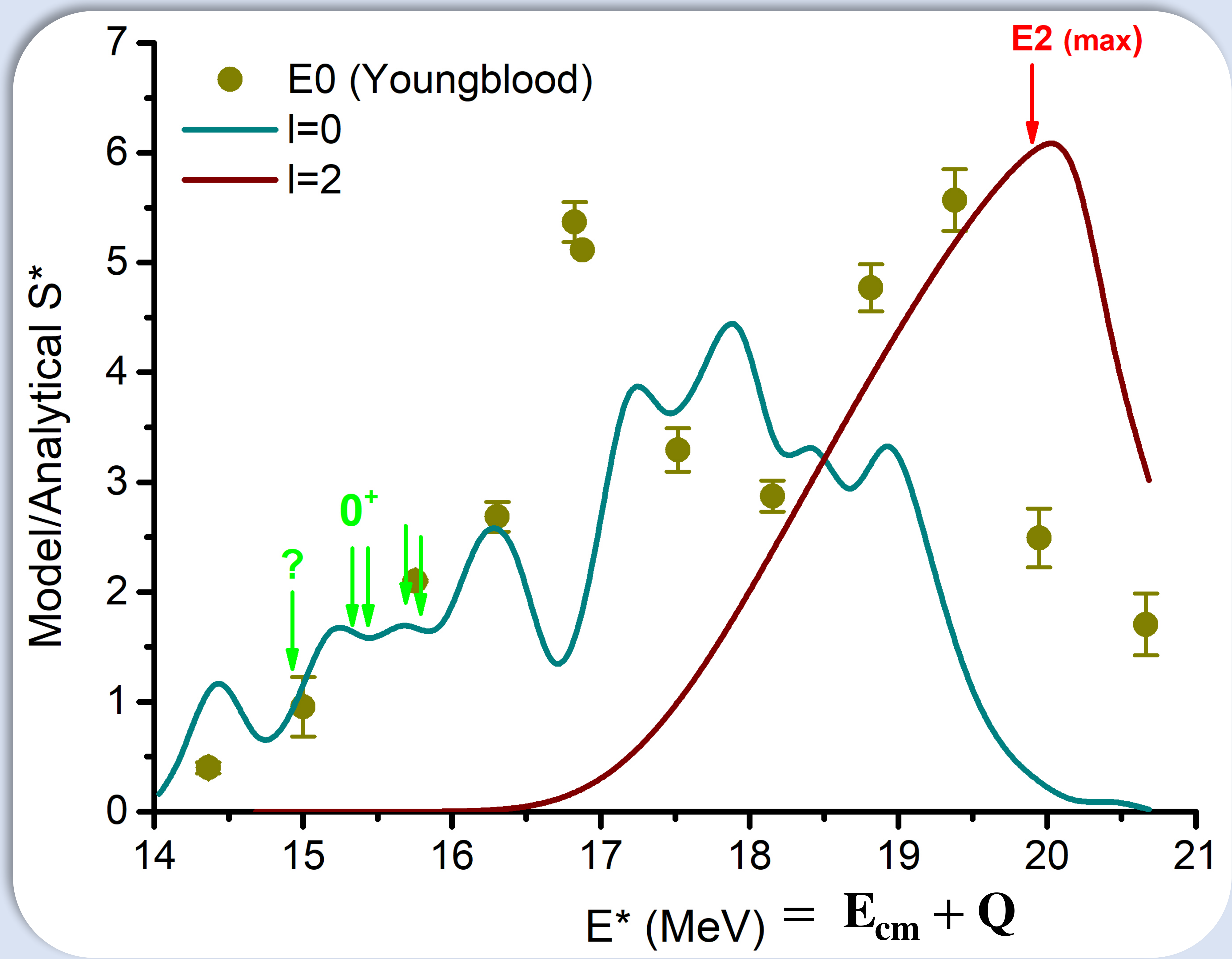

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- **Similar low energy monopole & quadruple spectra**
- **IMT study → Probe for sub-barrier dynamics**

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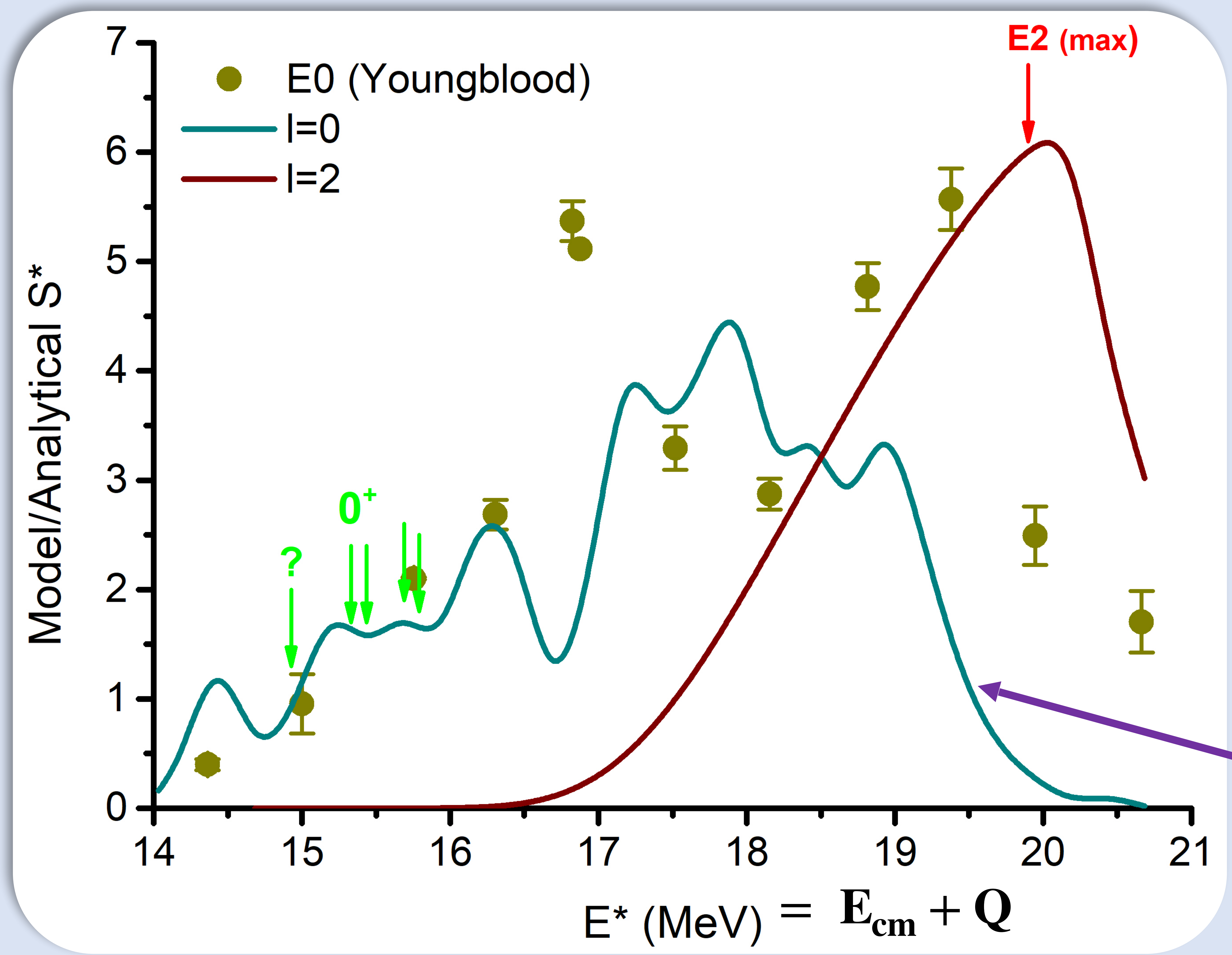
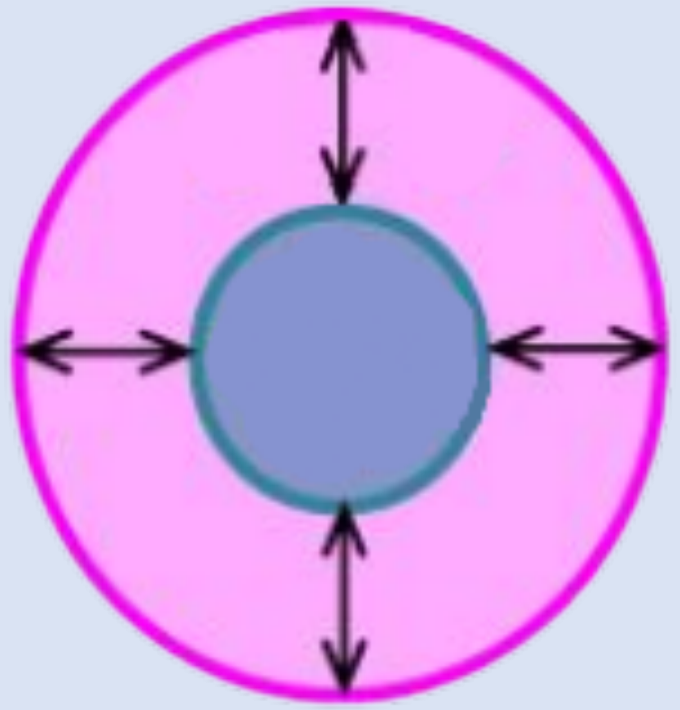


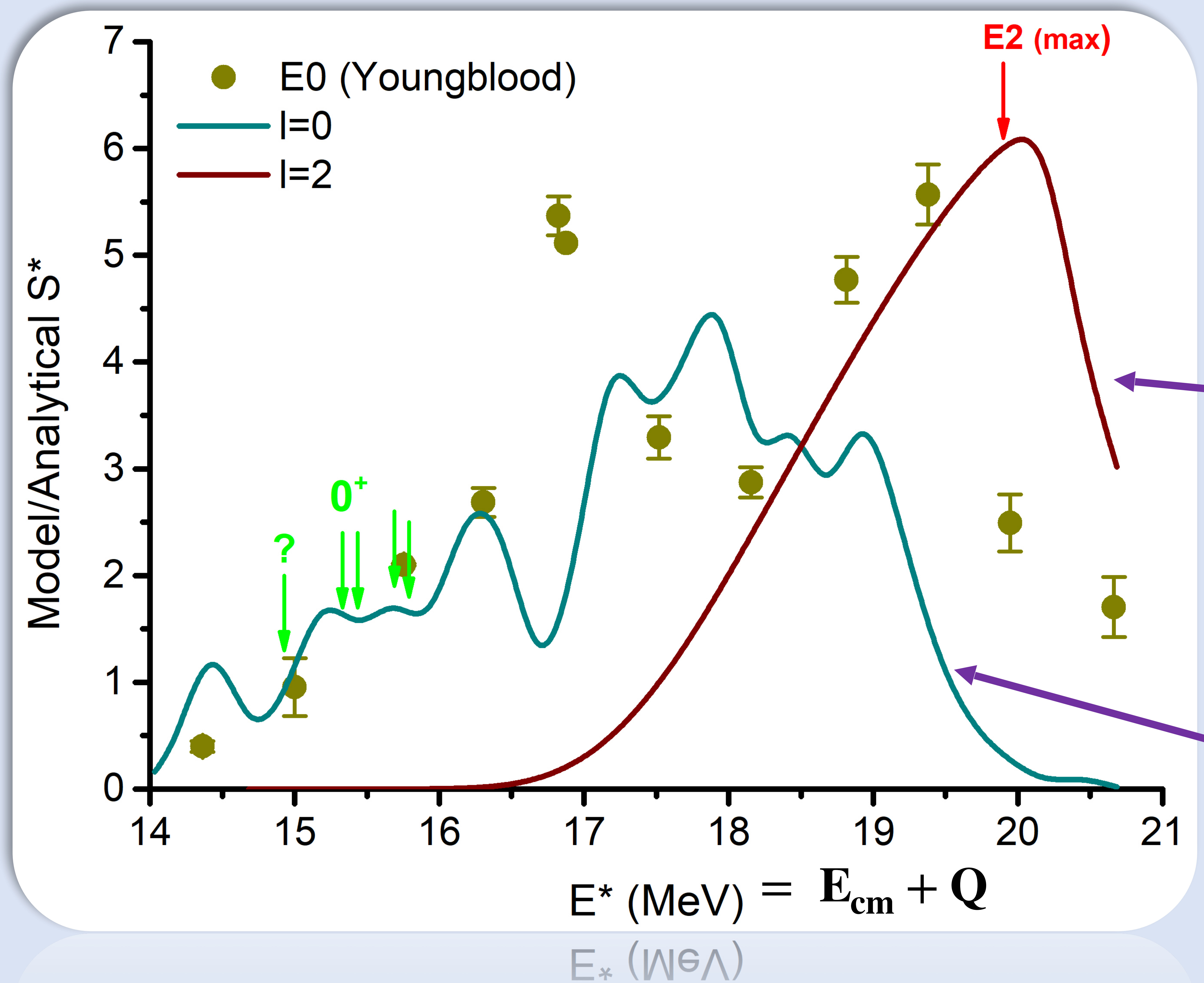


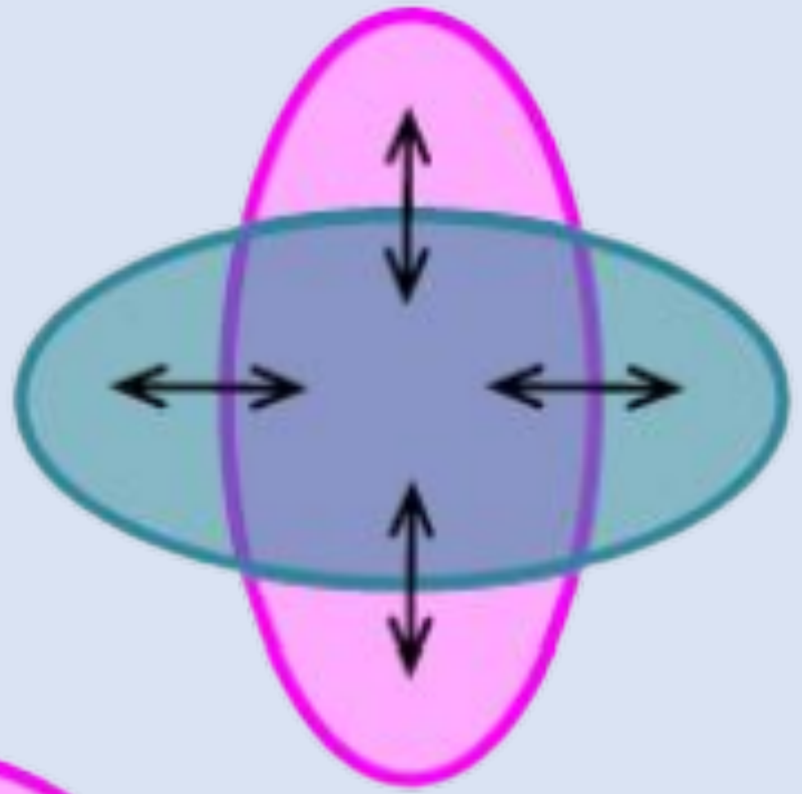
Monopole (l=0) Resonance

D. Youngblood, Y. L. *et al*, *Phys. Rev. C* **80** (2009) 064318; T. Depastas, S.T. Sun, H. Zheng and A. Bonasera, *Phys Rev* C **108**, 035806 (2023) .

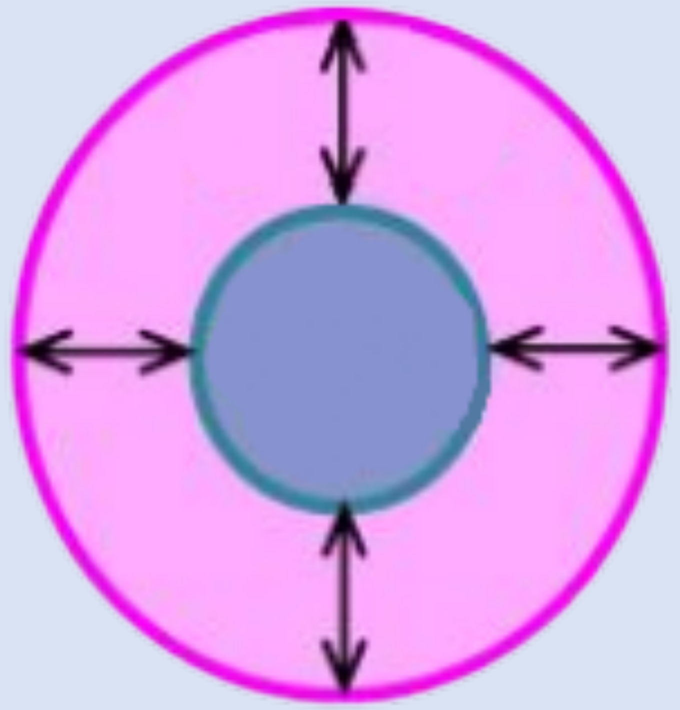
Sub-barrier Resonant Structures

- **Oscillations of the S* factor → collective resonances**
- **Similar low energy monopole & quadruple spectra**
- **IMT study → Probe for sub-barrier dynamics**





Quadruple (l=2) Resonance



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Neck model in imaginary times

PHYSICAL REVIEW C **102**, 061602(R) (2020)

Neck model in imaginary times

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The probability of fusion for the *l* th-partial wave is given by

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Neck model in imaginary times

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Neck model in imaginary times

PHYSICAL REVIEW C **102**, 061602(R) (2020)

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Bass potential as:

Neck model in imaginary times

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$$V_B \to V_B[1 + g(x, \gamma, \sigma)],$$

Neck model in imaginary times

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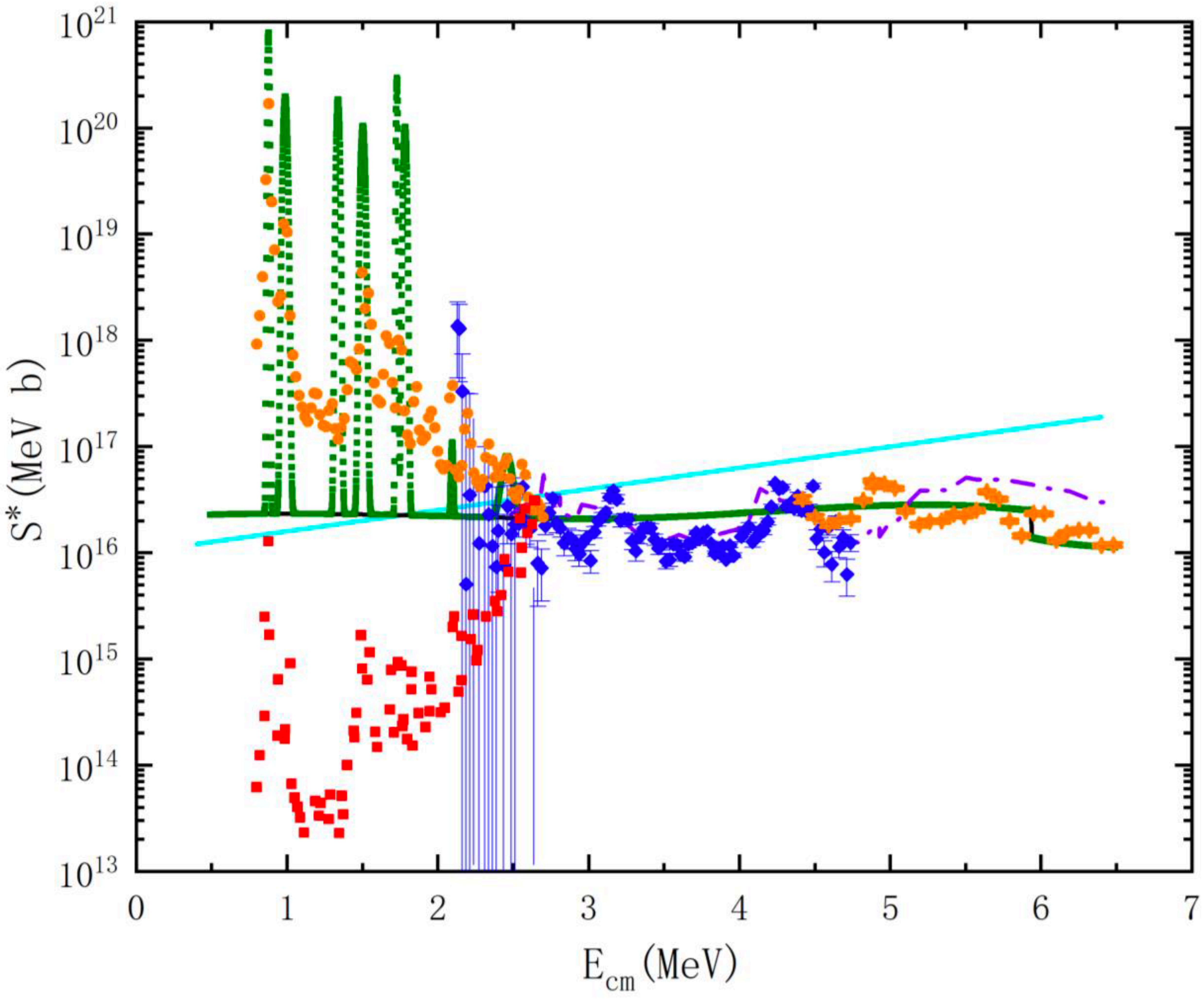

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Neck model in imaginary times

The probability of fusion for the *l* th-partia

) (2020)

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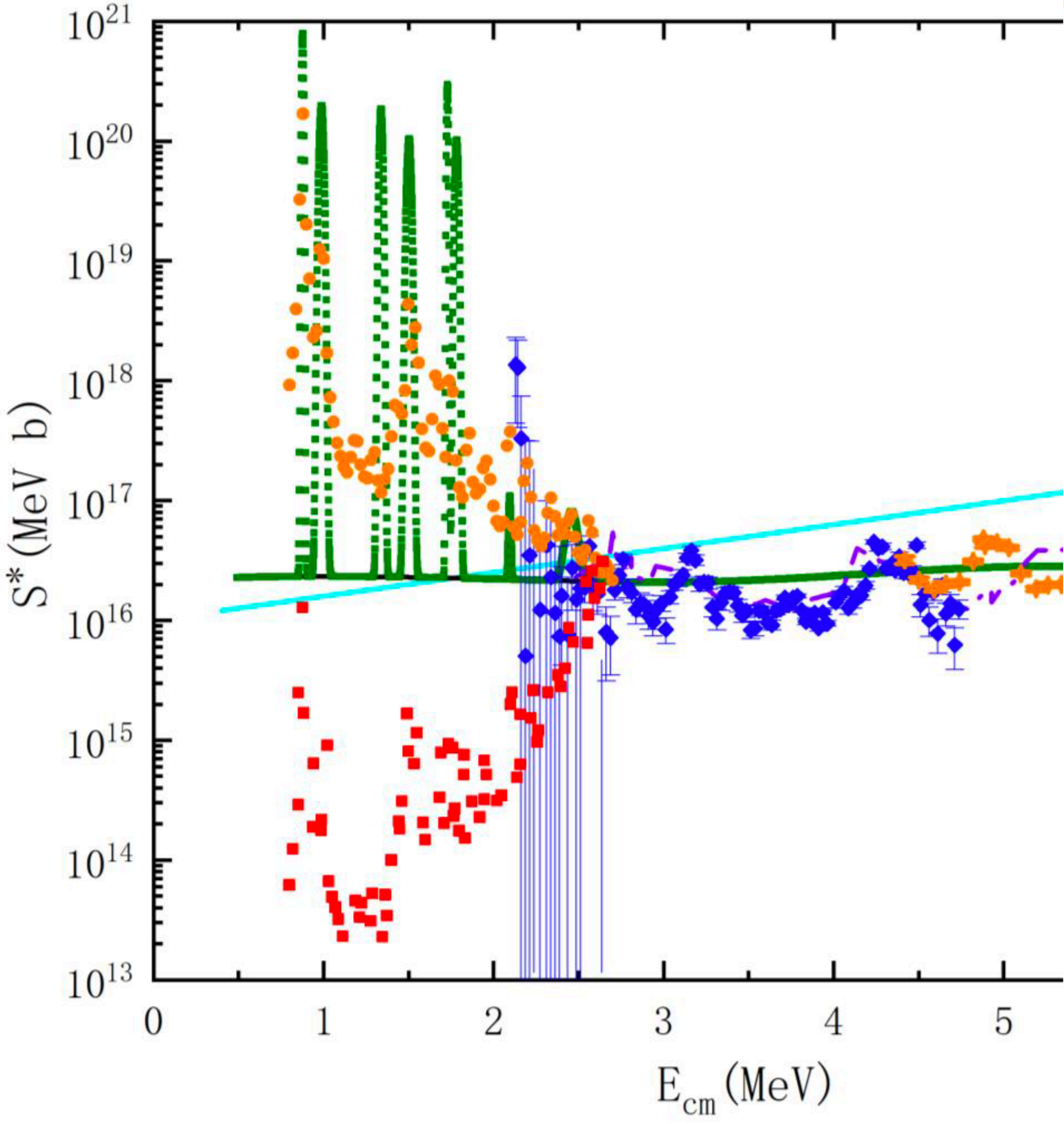
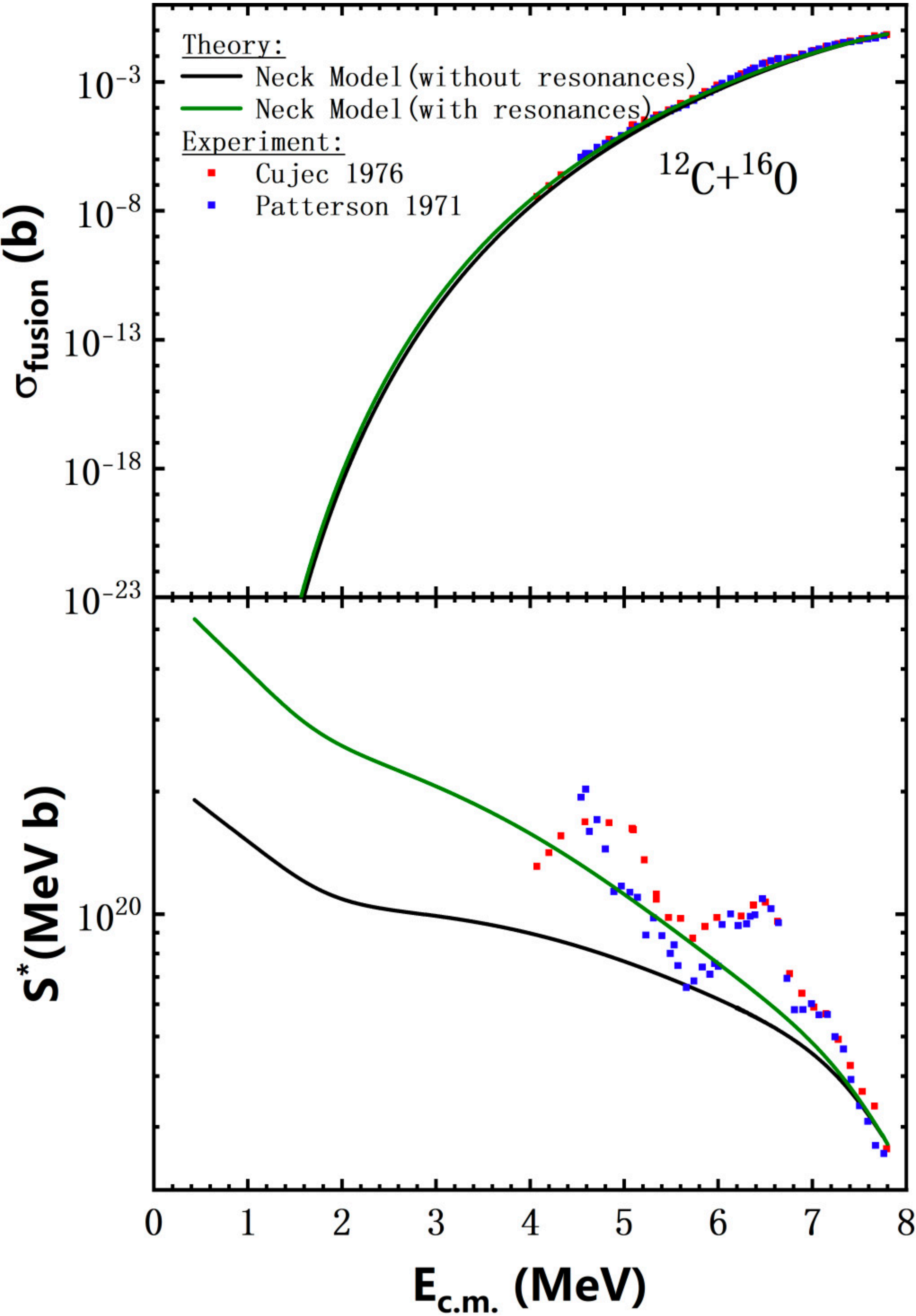
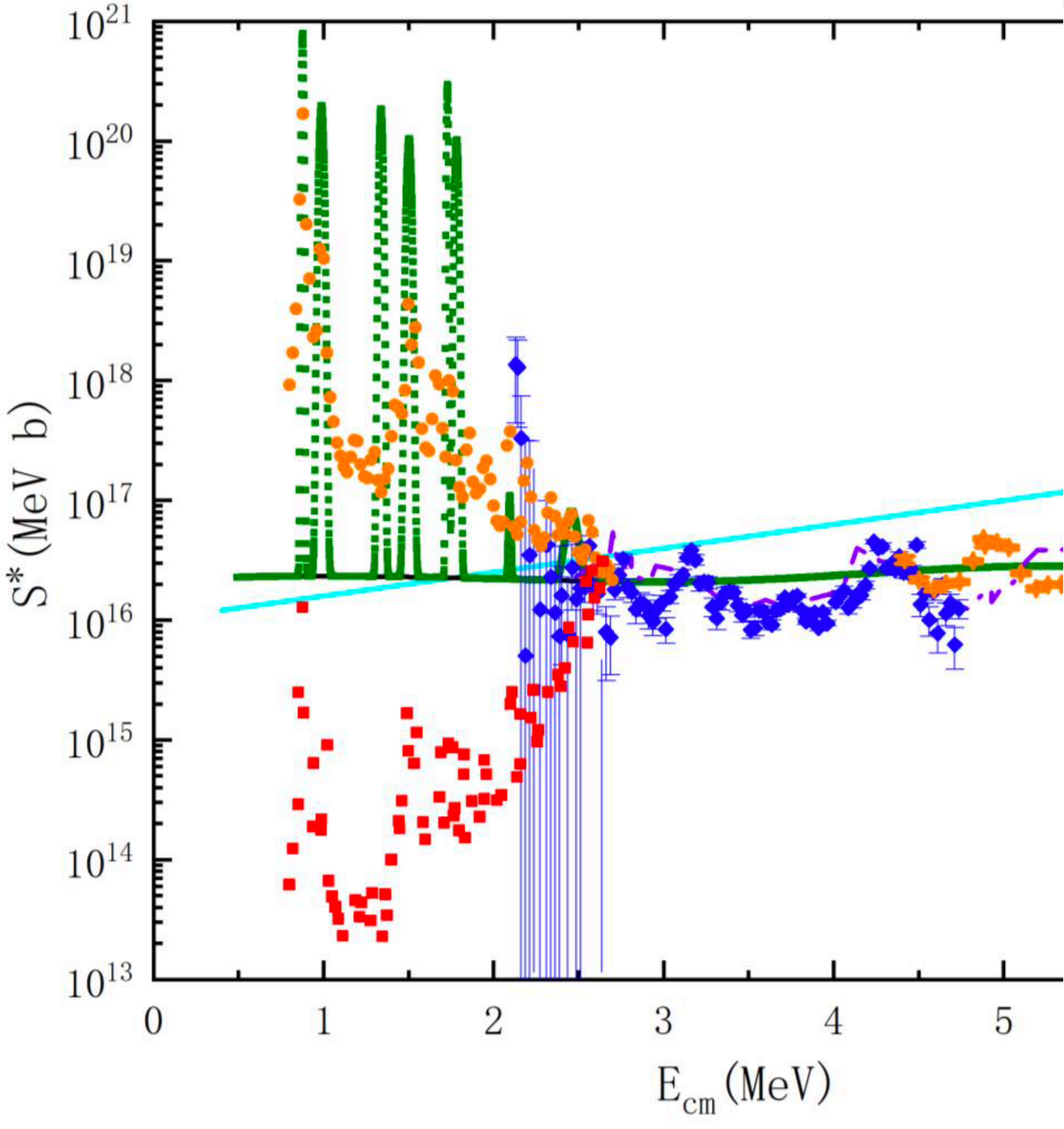
$+ g(x, \gamma, \sigma)],$

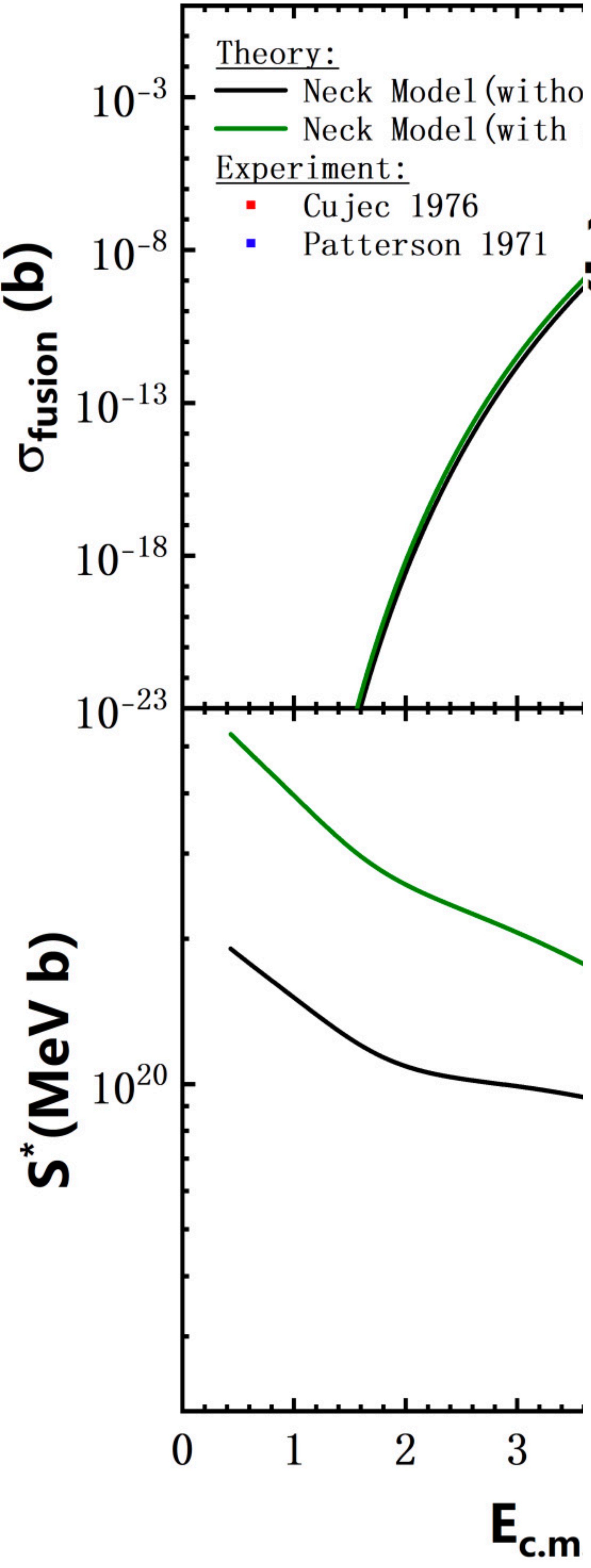


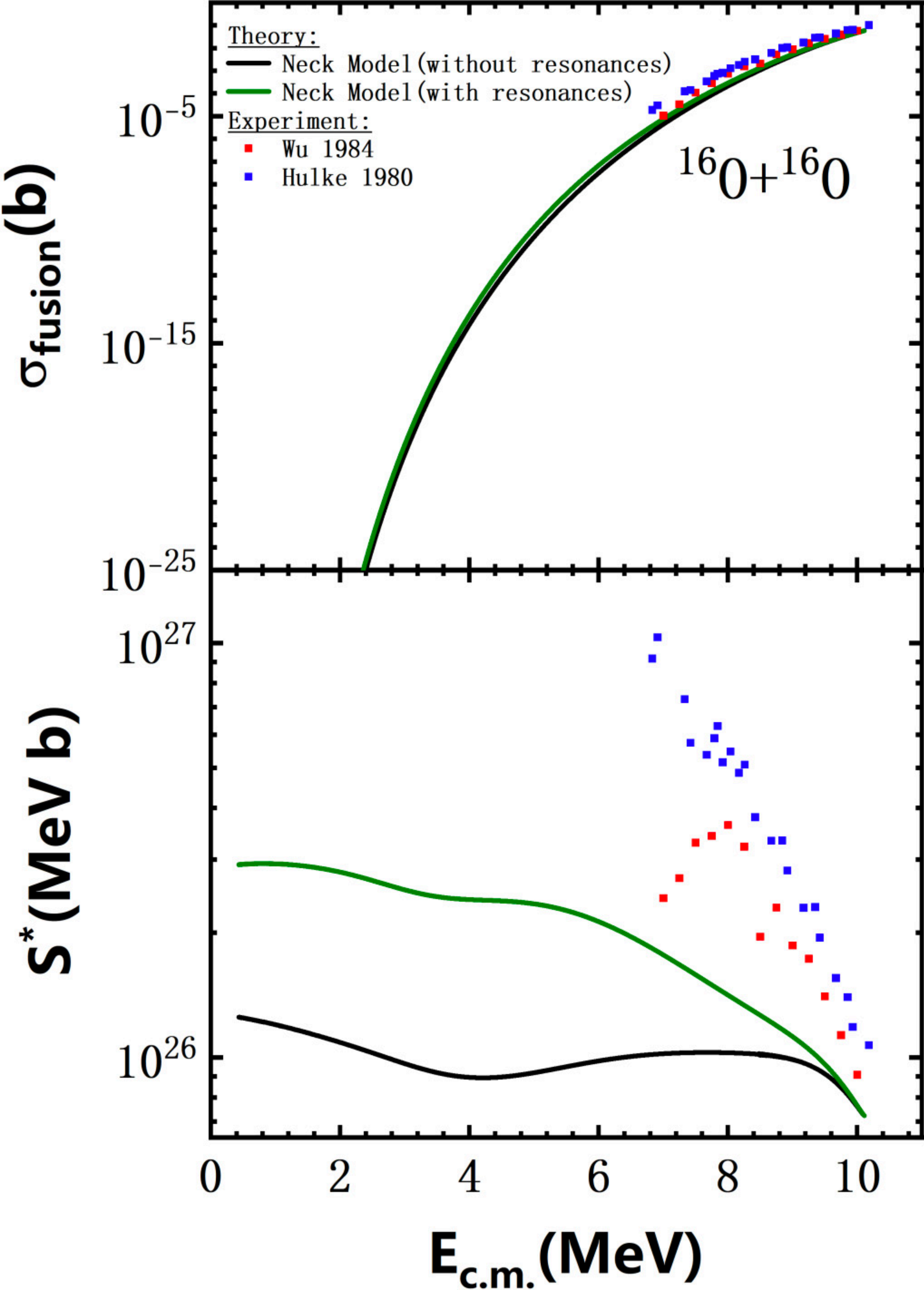


Neck model in imaginary times

The probability of fusion for the *l* th-partia

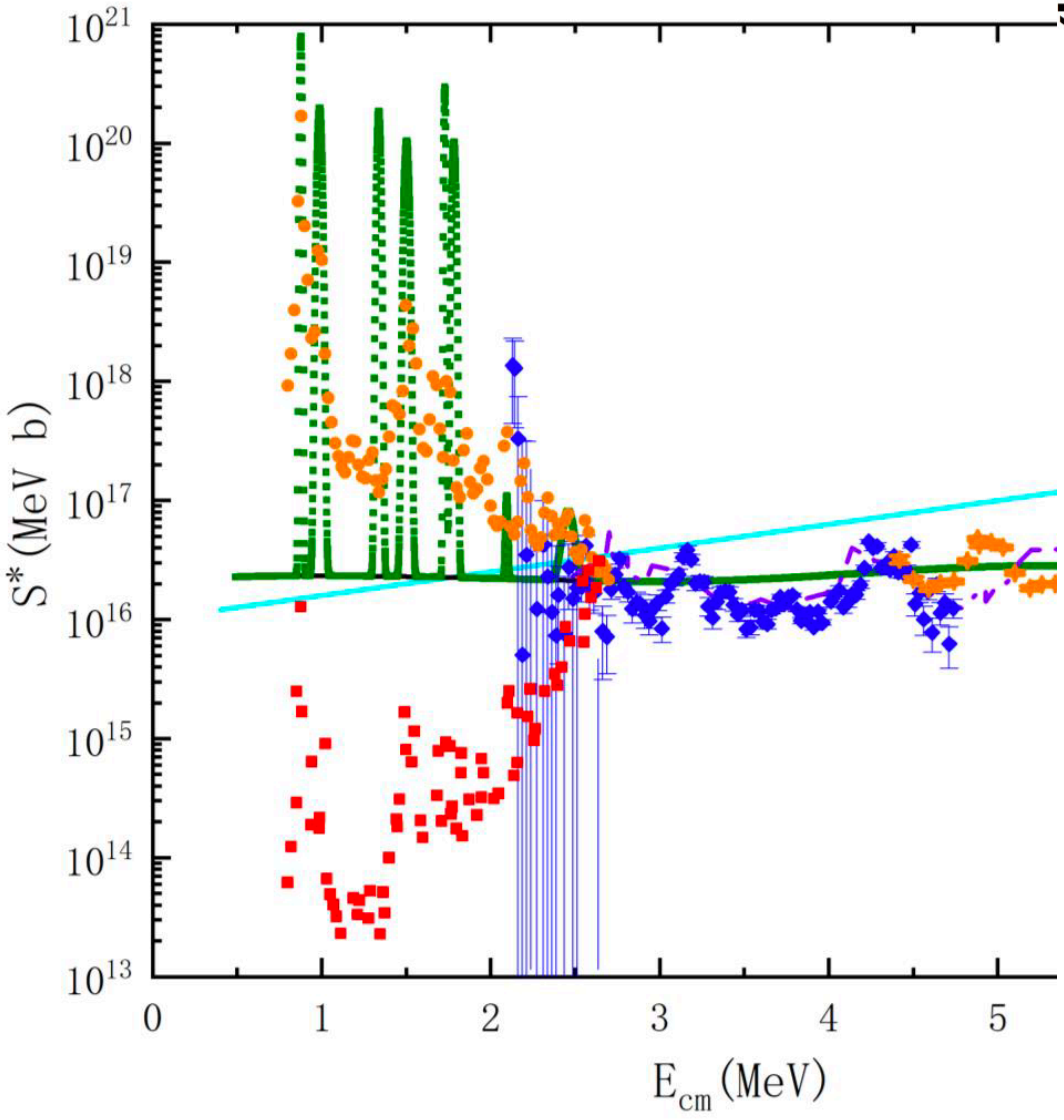


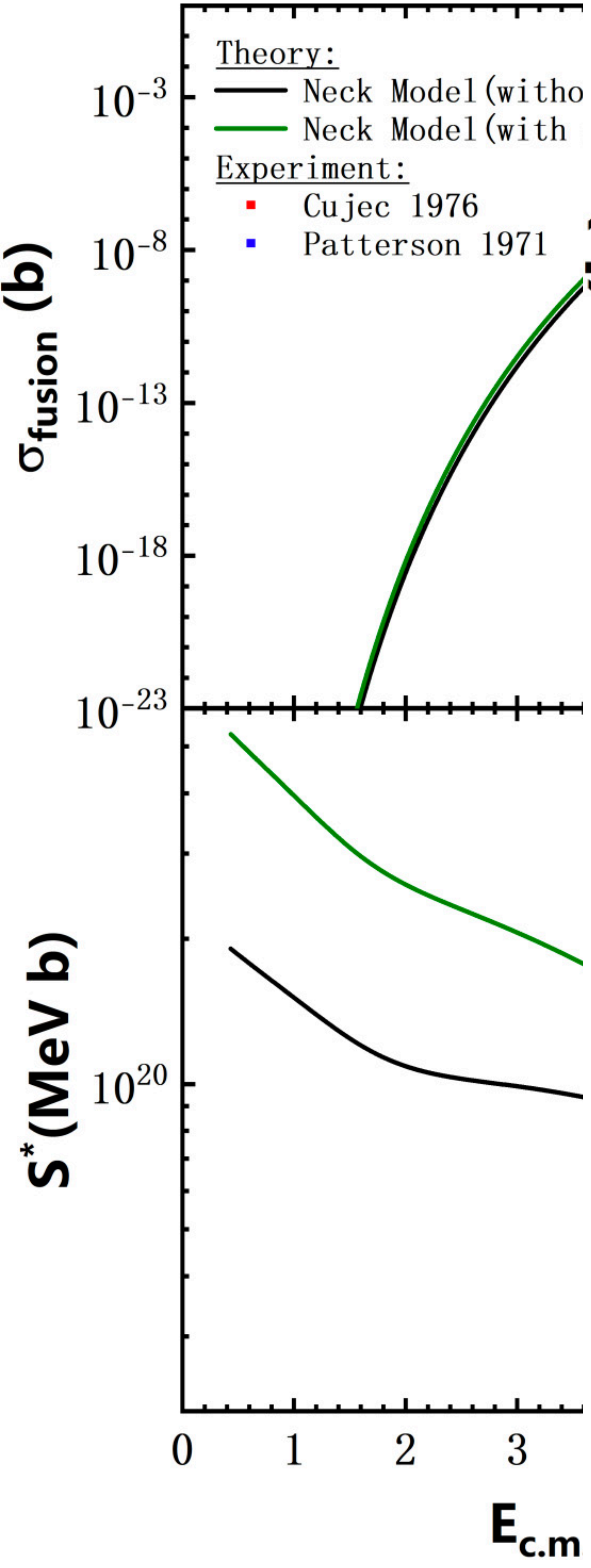


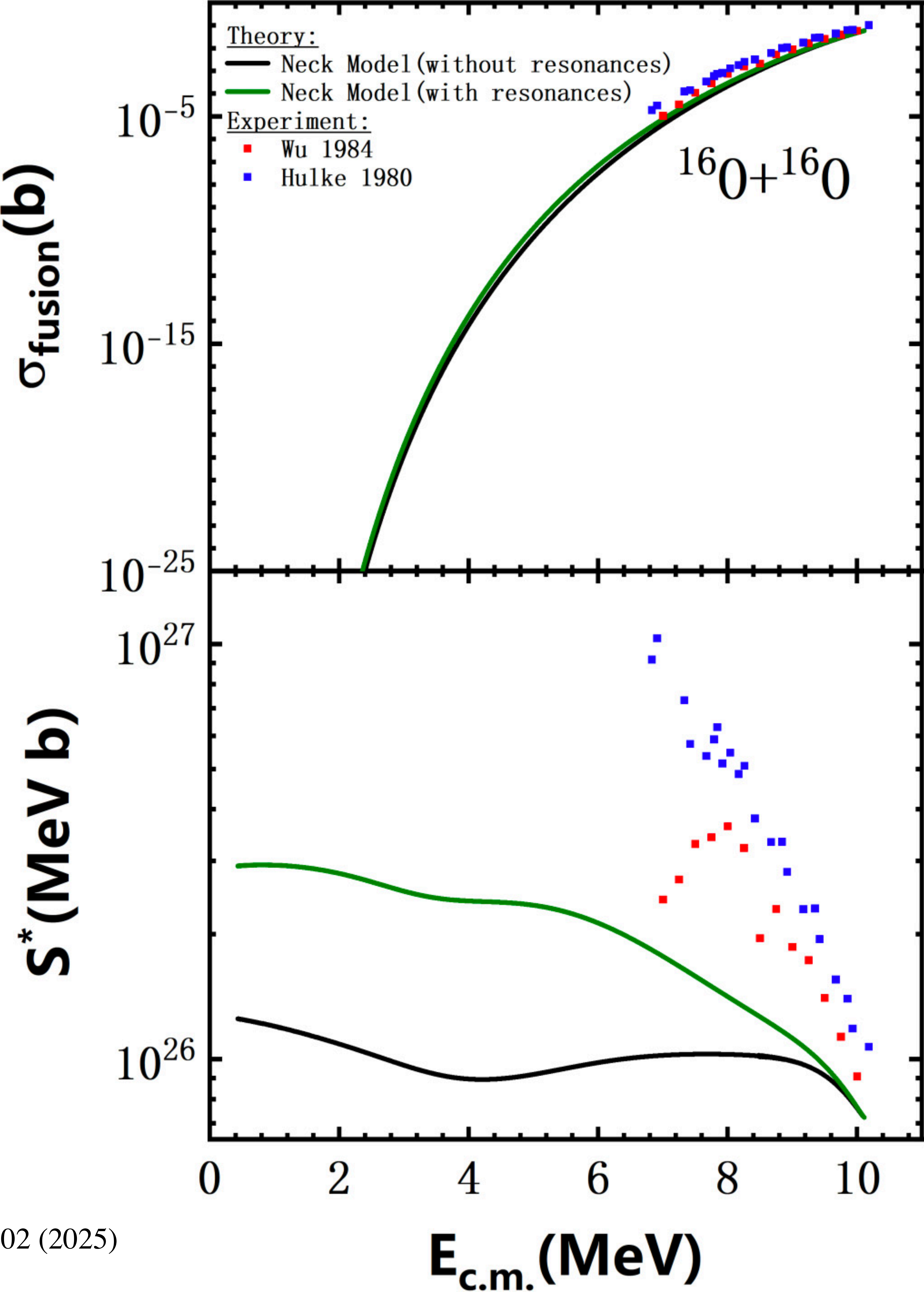


Neck model in imaginary times

The probability of fusion for the *l* th-partia





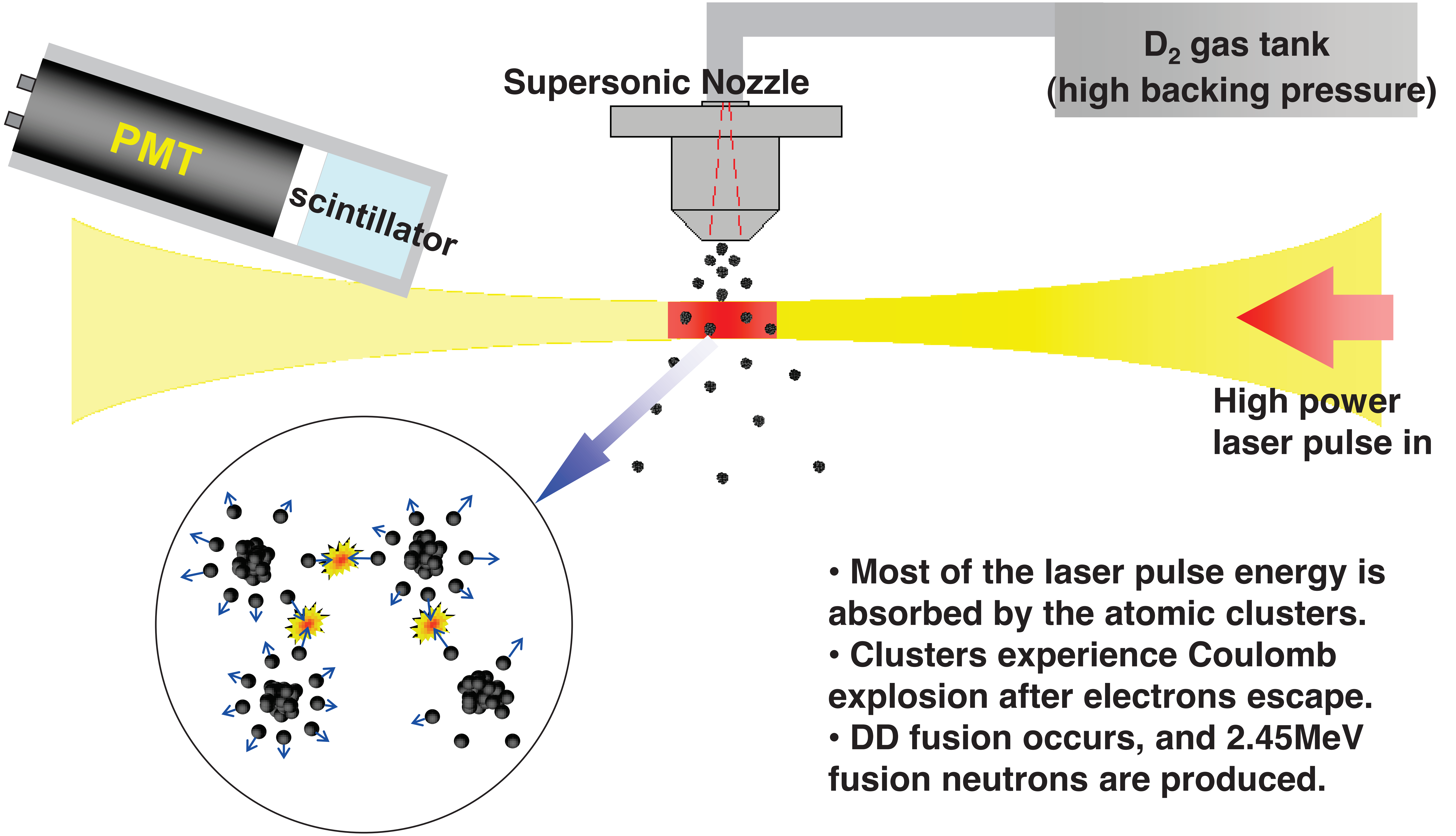


PHYSICAL REVIEW C 111, 014602 (2025)

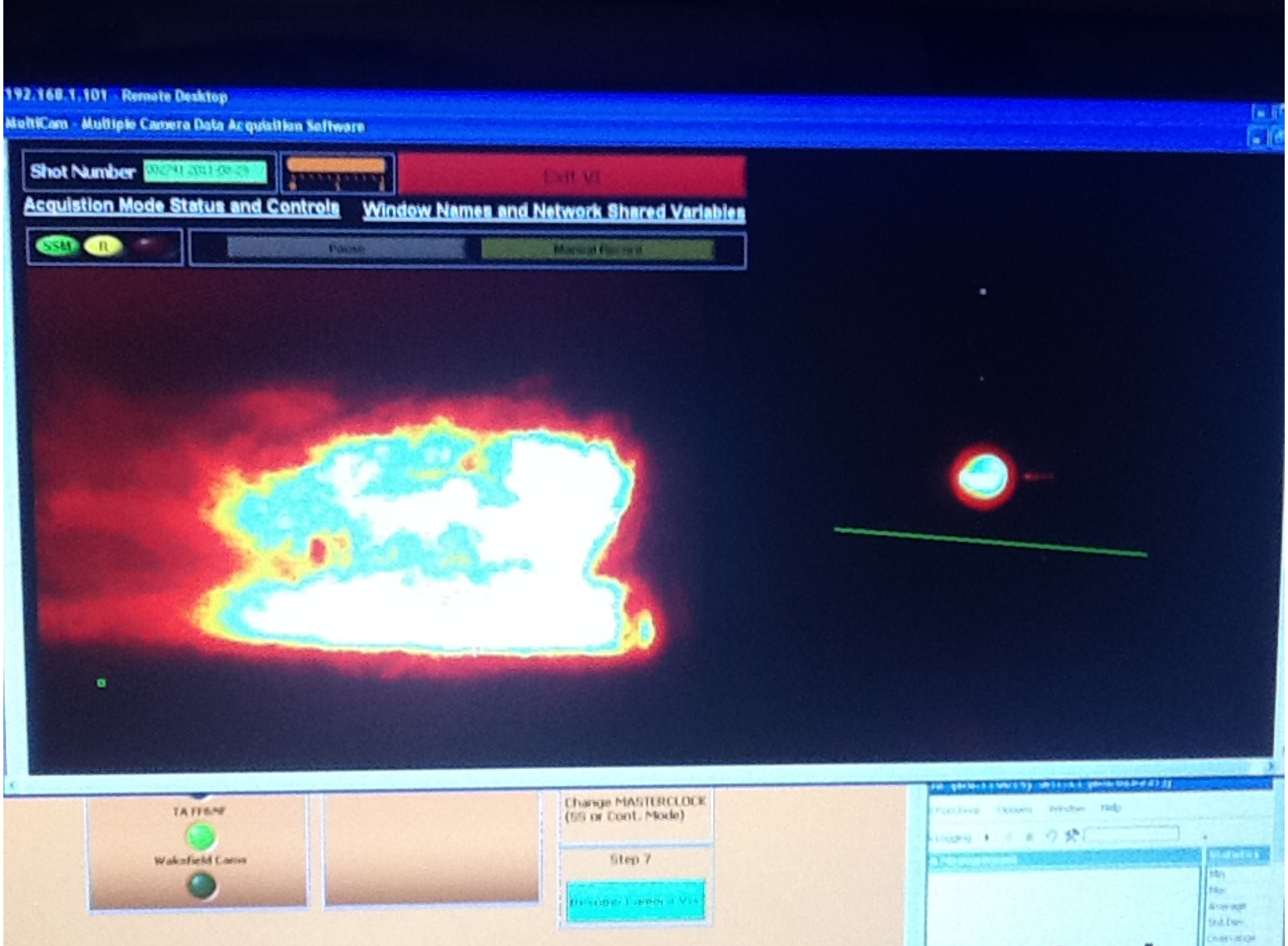
ALTERNATIVELY

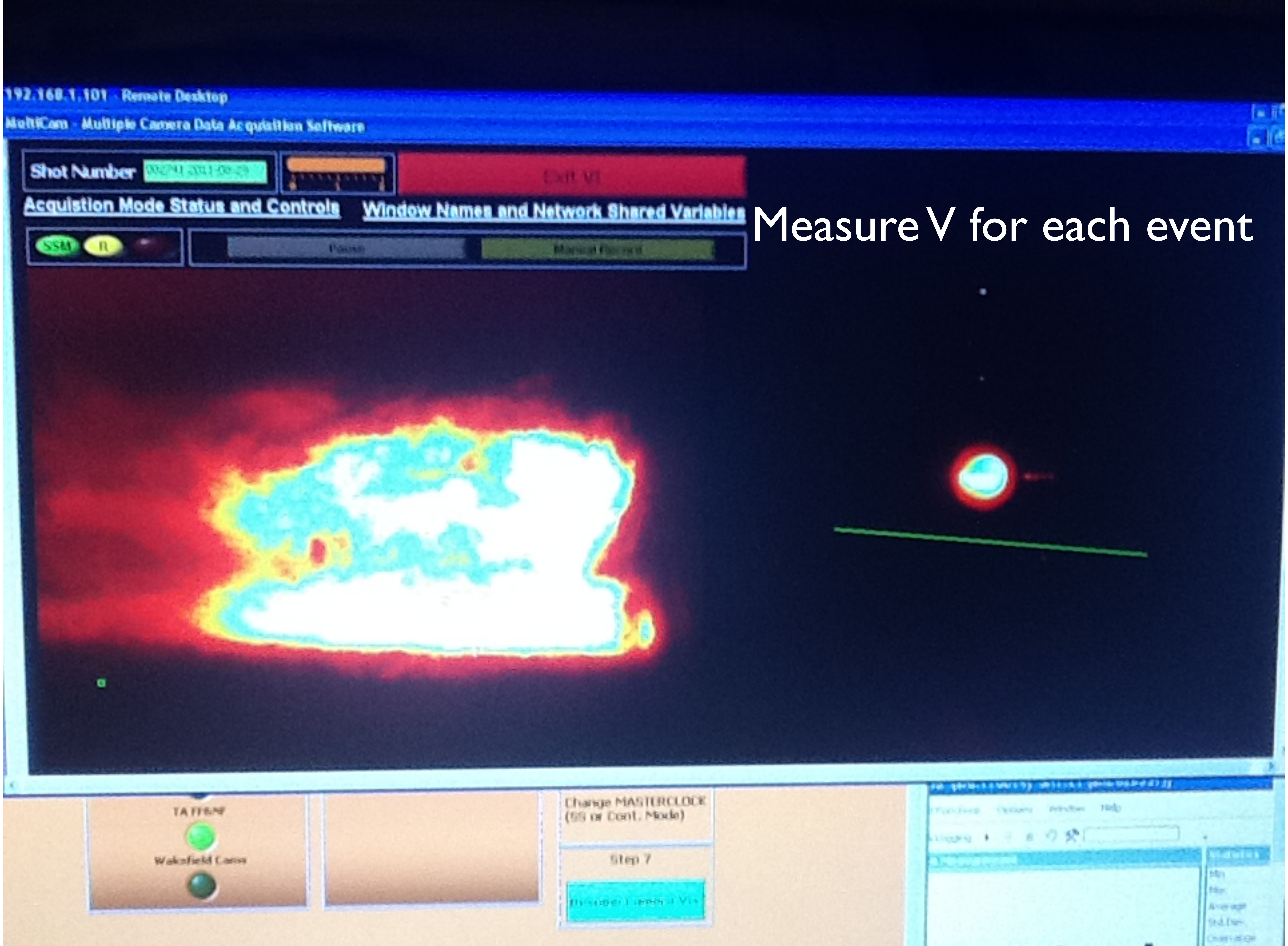
High power laser can be used to generate neutrons from the fusion reaction

Nuclear fusion from laser-cluster interaction

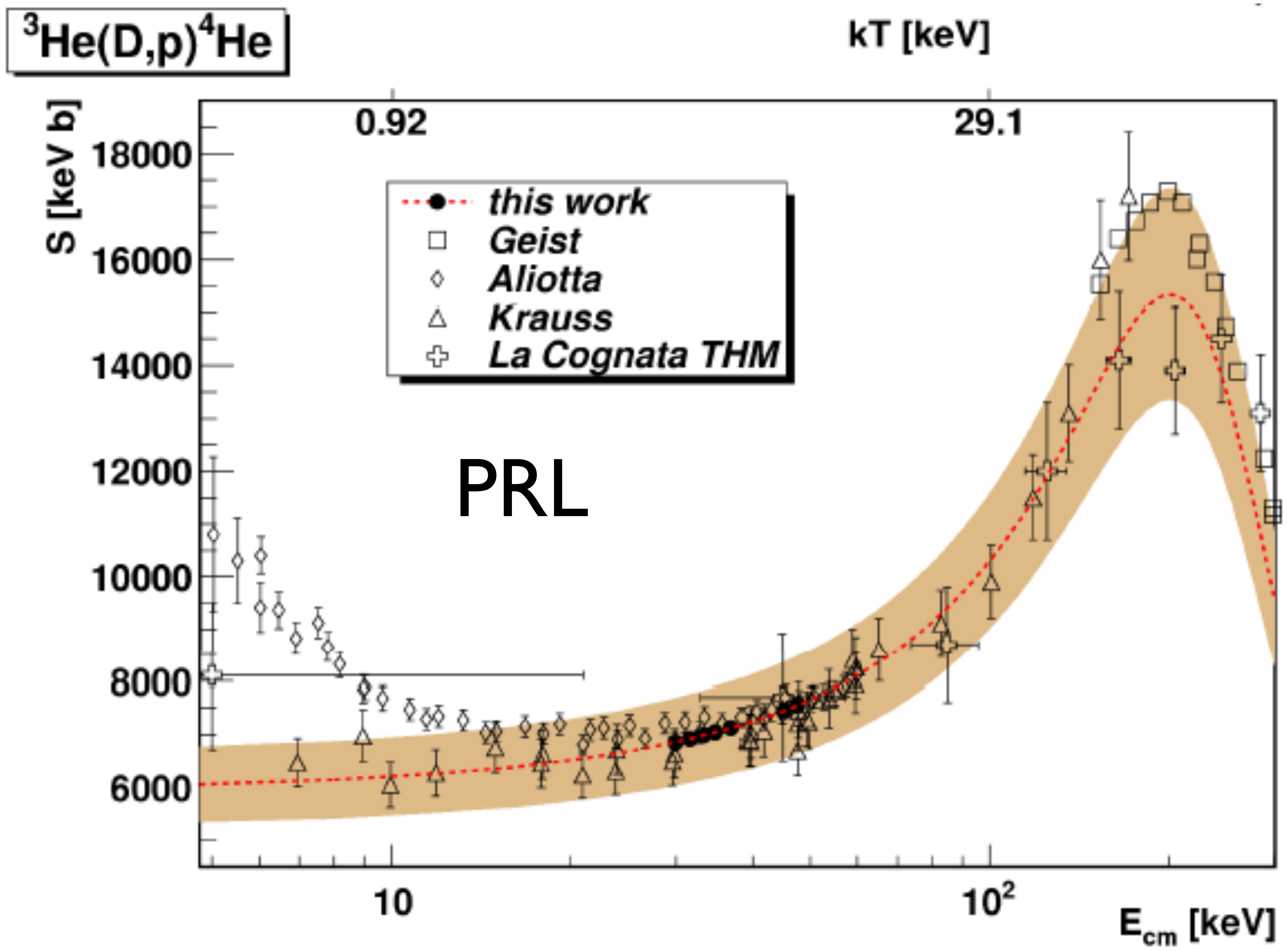


- Most of the laser pulse energy is absorbed by the atomic clusters.
- Clusters experience Coulomb explosion after electrons escape.
- DD fusion occurs, and 2.45MeV fusion neutrons are produced.

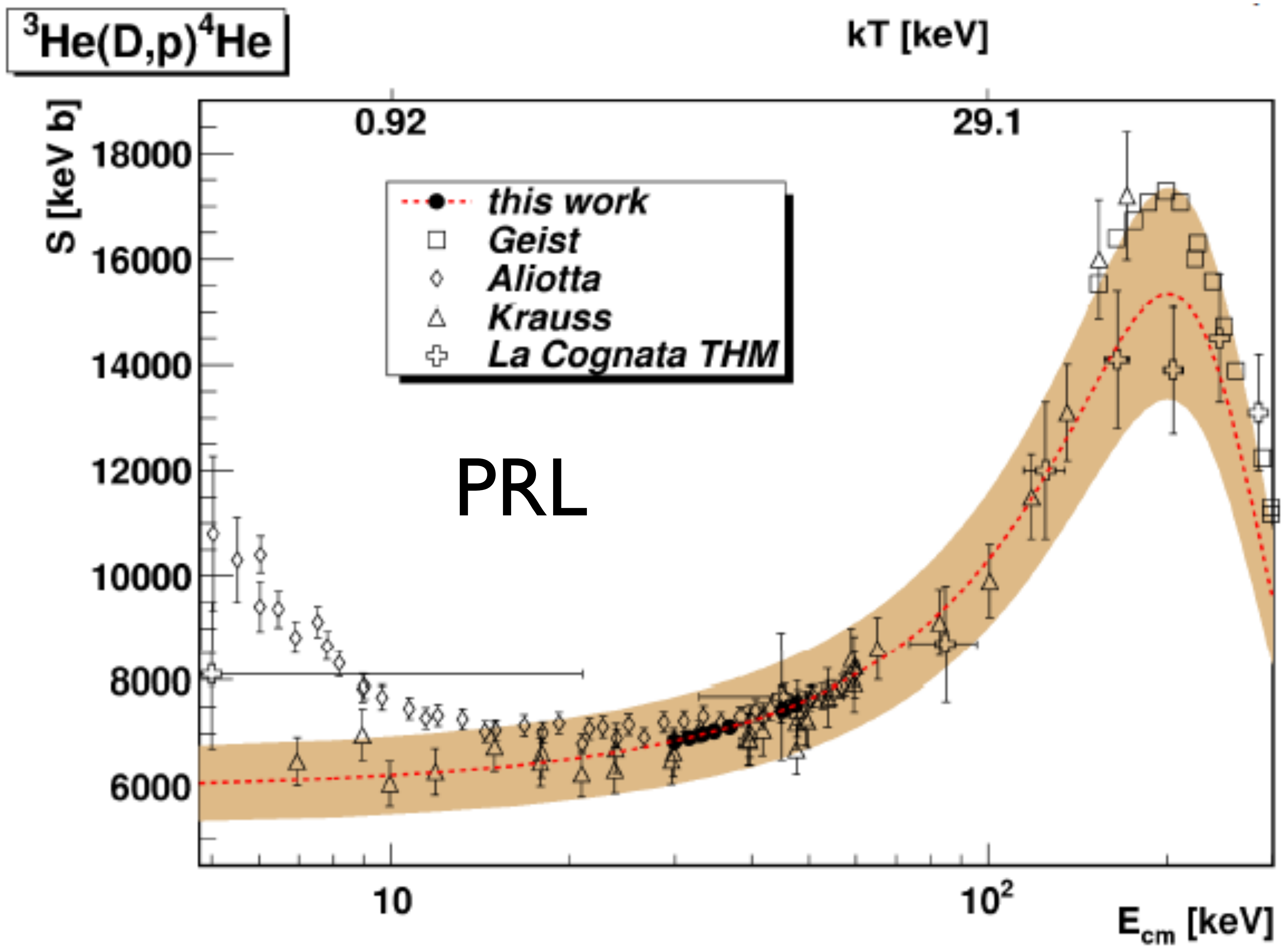

192.168.1.101 - Remote Desktop
MultiCam - Multiple Camera Data Acquisition Software
Shot Number
Exit VI
Acquistion Mode Status and Controls
Window Names and Network Shared Variables
SSM
R
Pause
Manual Record
TA FF&NF
Wakefield Cams
Change MASTERCLOCK (SS or Cont. Mode)
Step 7



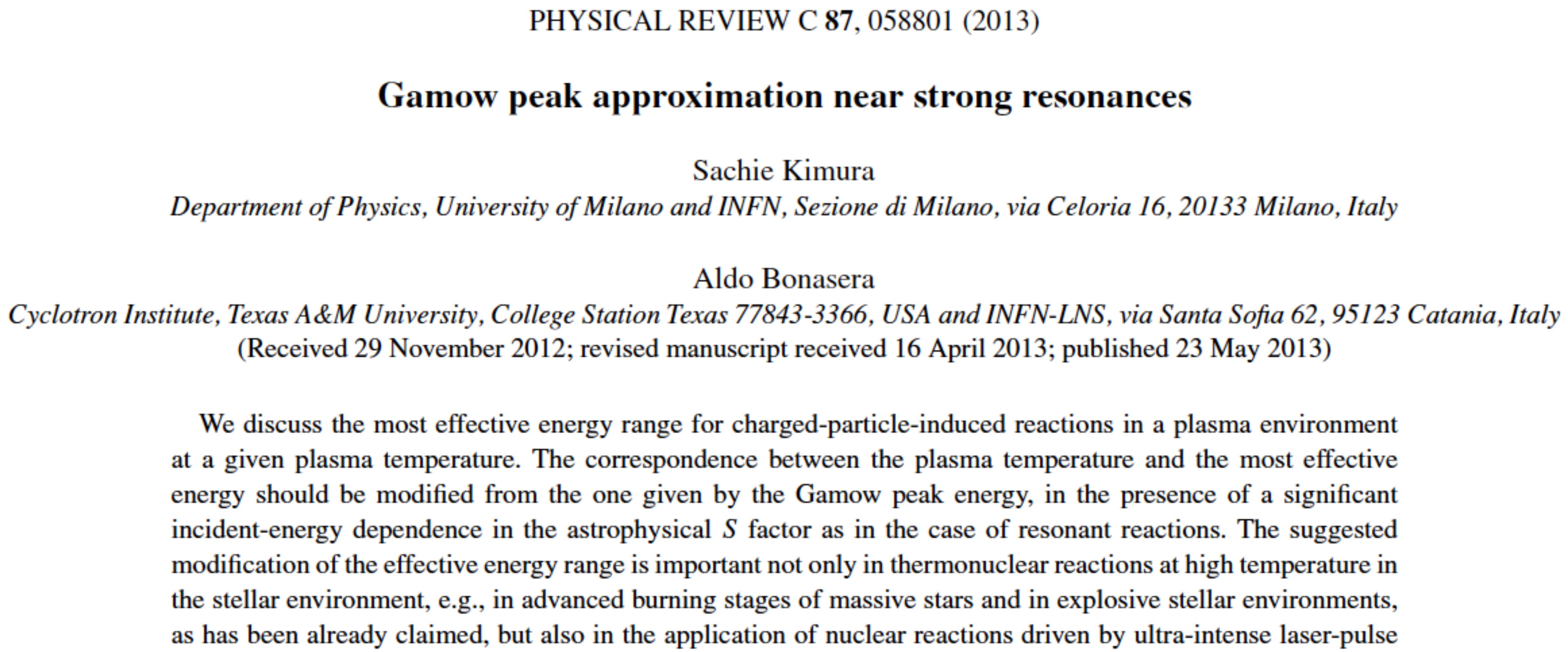
Measure V for each event


$^3He(D,p)^4He$
kT [keV]
0.92
29.1
S [keV b]
18000
16000
14000
12000
10000
8000
6000
this work
Geist
Aliotta
Krauss
La Cognata THM
10
10^2
E_{cm} [keV]

PRL



PRL


PHYSICAL REVIEW C **87**, 058801 (2013)

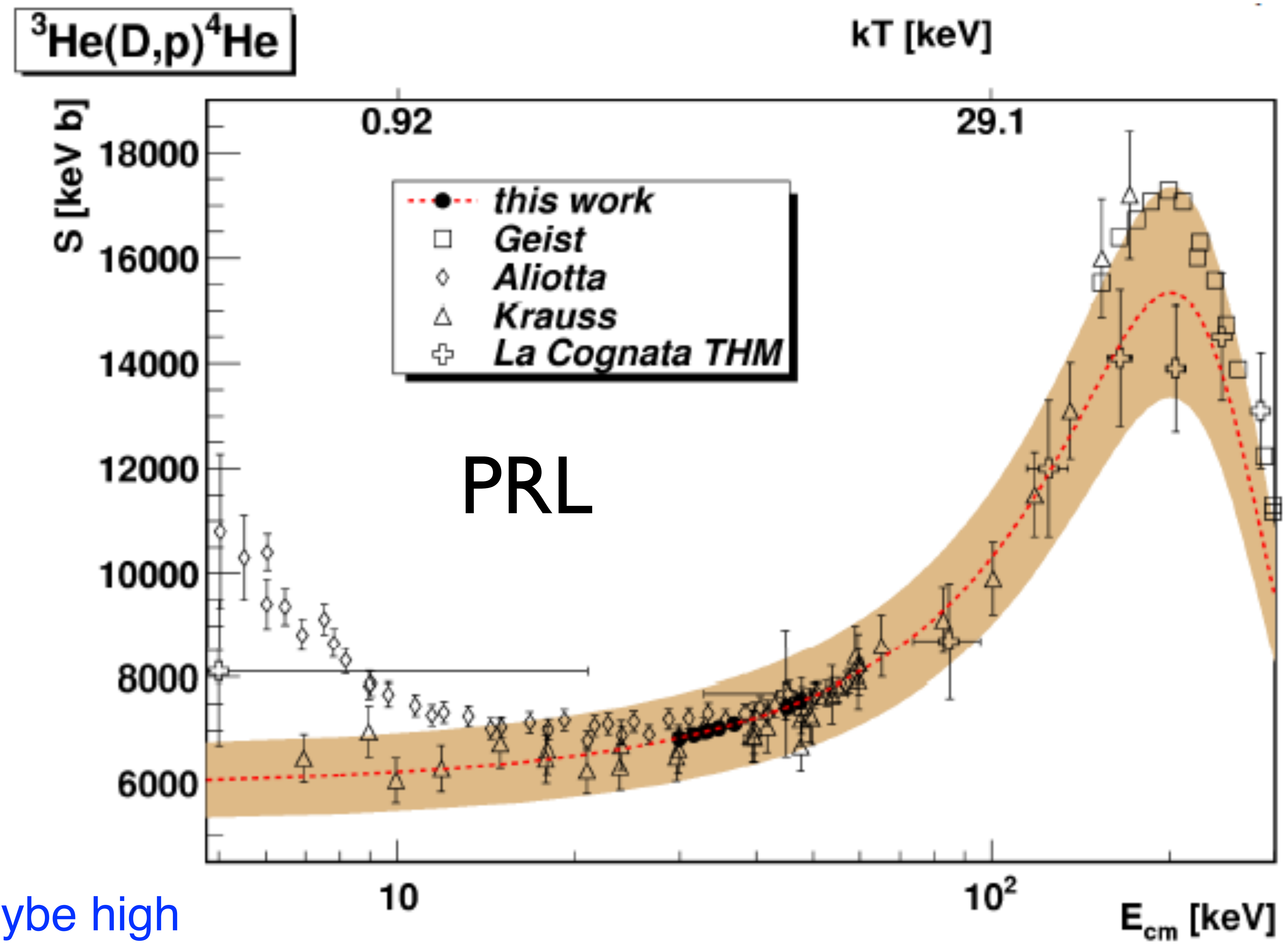
Gamow peak approximation near strong resonances

Sachie Kimura
Department of Physics, University of Milano and INFN, Sezione di Milano, via Celoria 16, 20133 Milano, Italy

Aldo Bonasera
Cyclotron Institute, Texas A&M University, College Station Texas 77843-3366, USA and INFN-LNS, via Santa Sofia 62, 95123 Catania, Italy

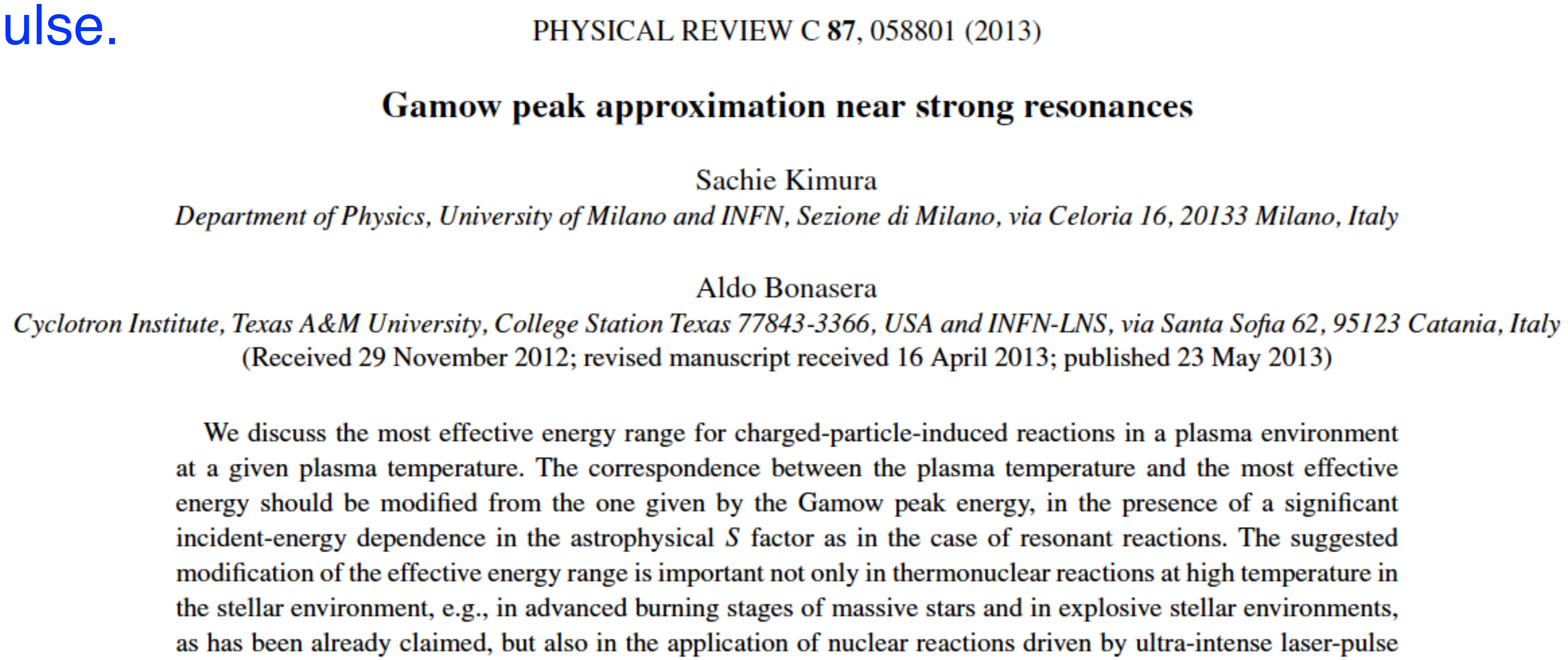
(Received 29 November 2012; revised manuscript received 16 April 2013; published 23 May 2013)

We discuss the most effective energy range for charged-particle-induced reactions in a plasma environment at a given plasma temperature. The correspondence between the plasma temperature and the most effective energy should be modified from the one given by the Gamow peak energy, in the presence of a significant incident-energy dependence in the astrophysical *S* factor as in the case of resonant reactions. The suggested modification of the effective energy range is important not only in thermonuclear reactions at high temperature in the stellar environment, e.g., in advanced burning stages of massive stars and in explosive stellar environments, as has been already claimed, but also in the application of nuclear reactions driven by ultra-intense laser-pulse



PRL

Here maybe high repetition laser low energy fs pulse.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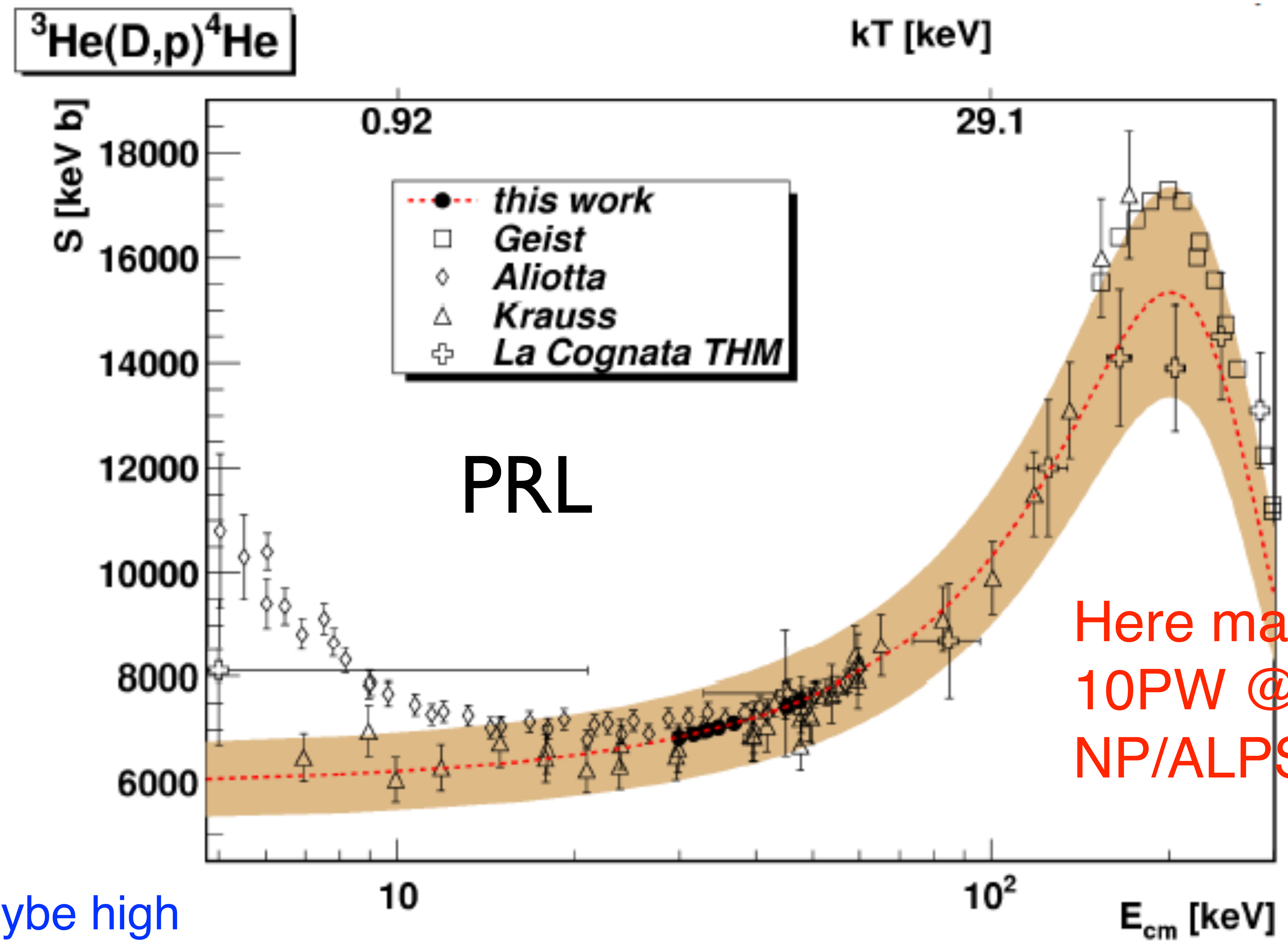
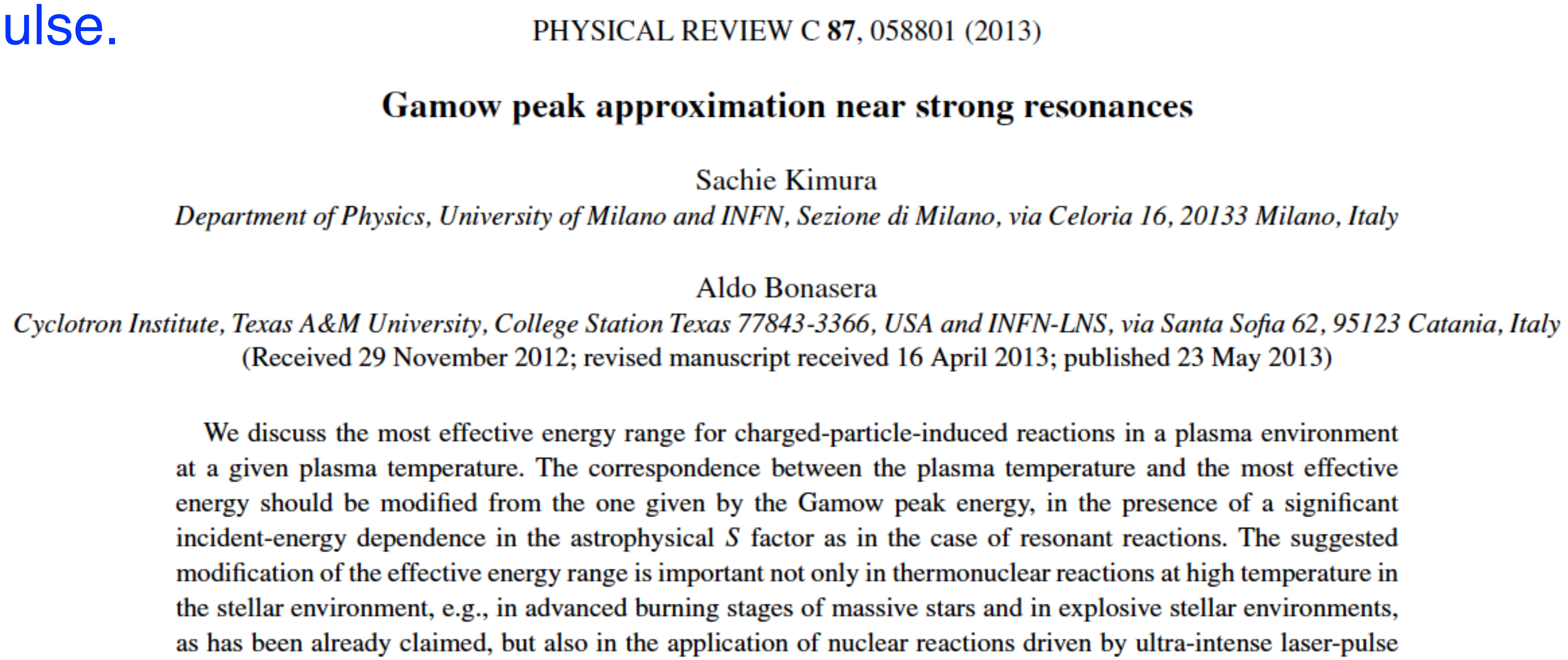


PRL

Here maybe the 10PW @ELI-NP/ALPS/MED

Here maybe high repetition laser low energy fs pulse.



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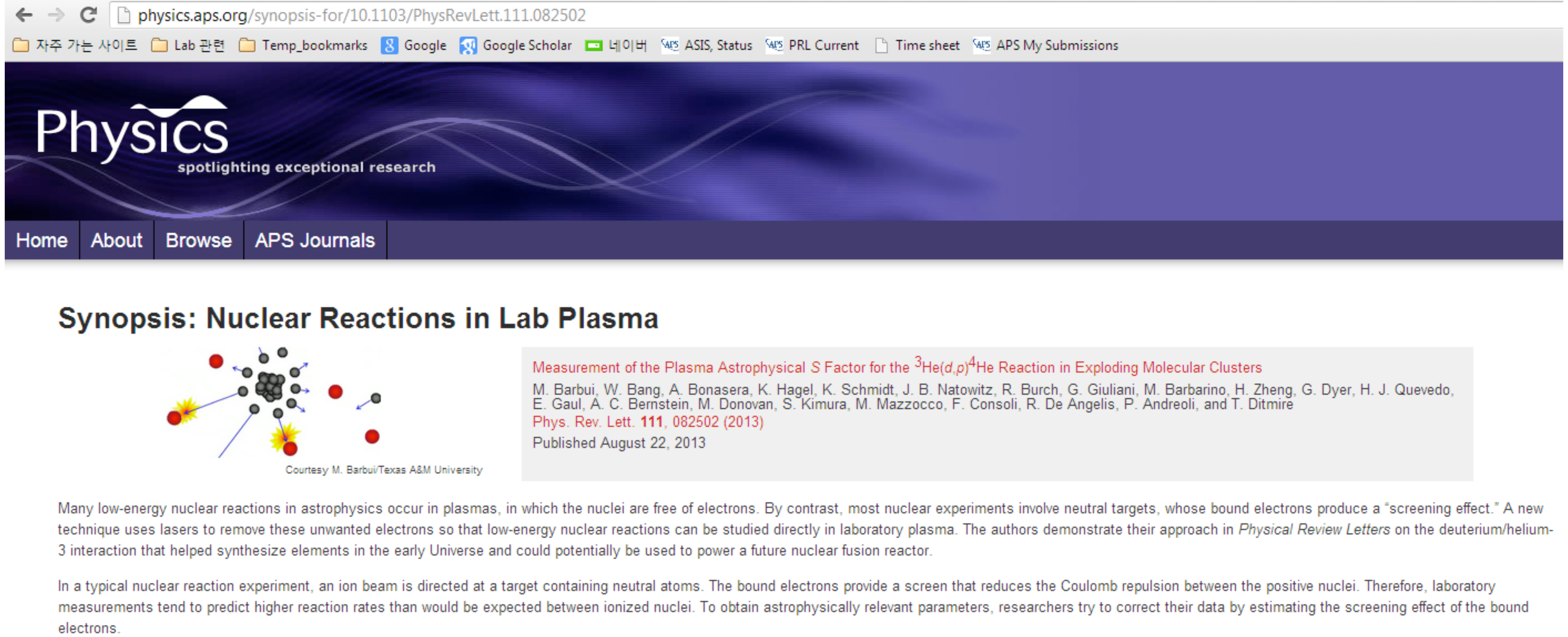
PHYSICAL REVIEW LETTERS

Measurement of the Plasma Astrophysical S Factor for the $^3\mathrm{He}(^2\mathrm{H}, p)^4\mathrm{He}$ Reaction in Exploding Molecular Clusters

M. Barbui,[1,*] W. Bang,[2,†] A. Bonasera,[3,1] K. Hagel,[1] K. Schmidt,[1] J. B. Natowitz,[1] R. Burch,[1] G. Giuliani,[1]
M. Barbarino,[1] H. Zheng,[1] G. Dyer,[2] H. J. Quevedo,[2] E. Gaul,[2] A. C. Bernstein,[2] M. Donovan,[2] S. Kimura,[4]
M. Mazzocco,[5] F. Consoli,[6] R. De Angelis,[6] P. Andreoli,[6] and T. Ditmire[2]

[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[2]*Center for High Energy Density Science, C1510, University of Texas at Austin, Austin, Texas 78712, USA*
[3]*INFN- Laboratori Nazionali del Sud, Via S. Sofia 62, 95125 Catania, Italy*
[4]*Department of Physics, Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy*
[5]*Dipartimento di Fisica e Astronomia Università degli Studi di Padova and INFN Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy*
[6]*Associazione Euratom—ENEA Sulla Fusione, Via E. Fermi 45, CP 65-00044 Frascati, Rome, Italy*

(Received 1 July 2013)



Synopsis: Nuclear Reactions in Lab Plasma

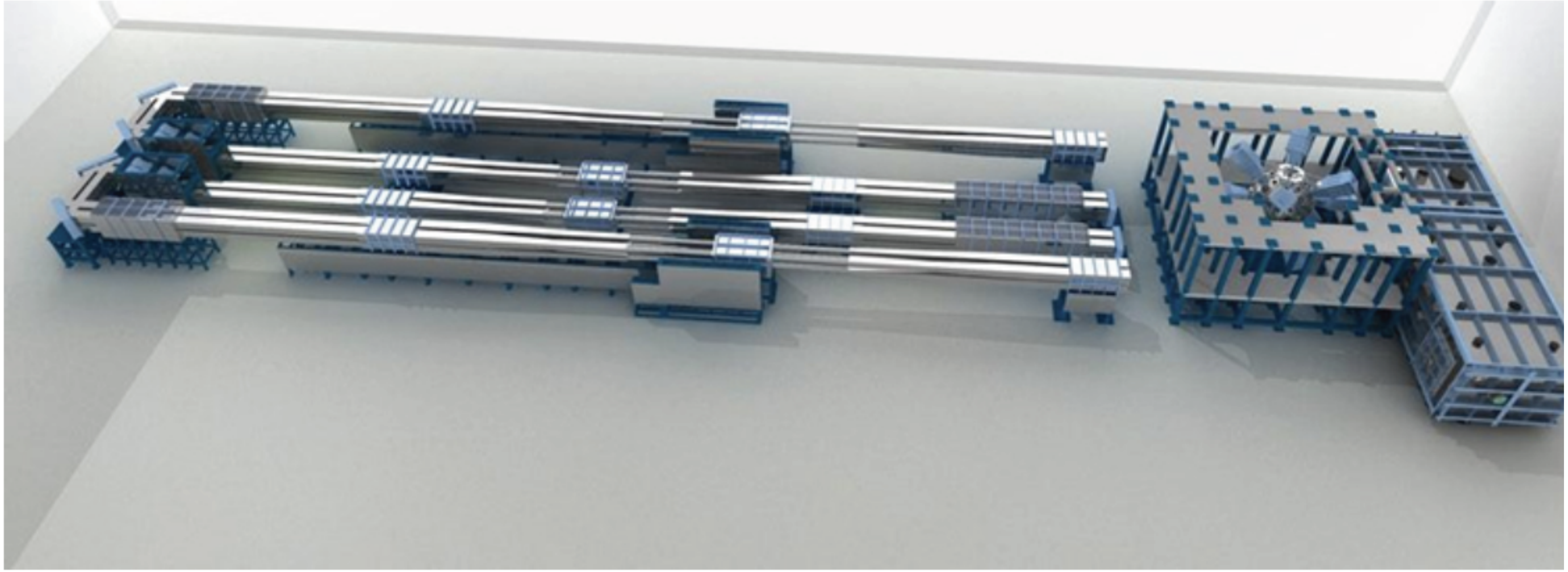
Courtesy M. Barbui/Texas A&M University

Measurement of the Plasma Astrophysical *S* Factor for the $^3\mathrm{He}(d,p)^4\mathrm{He}$ Reaction in Exploding Molecular Clusters
M. Barbui, W. Bang, A. Bonasera, K. Hagel, K. Schmidt, J. B. Natowitz, R. Burch, G. Giuliani, M. Barbarino, H. Zheng, G. Dyer, H. J. Quevedo, E. Gaul, A. C. Bernstein, M. Donovan, S. Kimura, M. Mazzocco, F. Consoli, R. De Angelis, P. Andreoli, and T. Ditmire
Phys. Rev. Lett. **111**, 082502 (2013)
Published August 22, 2013

Many low-energy nuclear reactions in astrophysics occur in plasmas, in which the nuclei are free of electrons. By contrast, most nuclear experiments involve neutral targets, whose bound electrons produce a "screening effect." A new technique uses lasers to remove these unwanted electrons so that low-energy nuclear reactions can be studied directly in laboratory plasma. The authors demonstrate their approach in *Physical Review Letters* on the deuterium/helium-3 interaction that helped synthesize elements in the early Universe and could potentially be used to power a future nuclear fusion reactor.

In a typical nuclear reaction experiment, an ion beam is directed at a target containing neutral atoms. The bound electrons provide a screen that reduces the Coulomb repulsion between the positive nuclei. Therefore, laboratory measurements tend to predict higher reaction rates than would be expected between ionized nuclei. To obtain astrophysically relevant parameters, researchers try to correct their data by estimating the screening effect of the bound electrons.

SGII-U



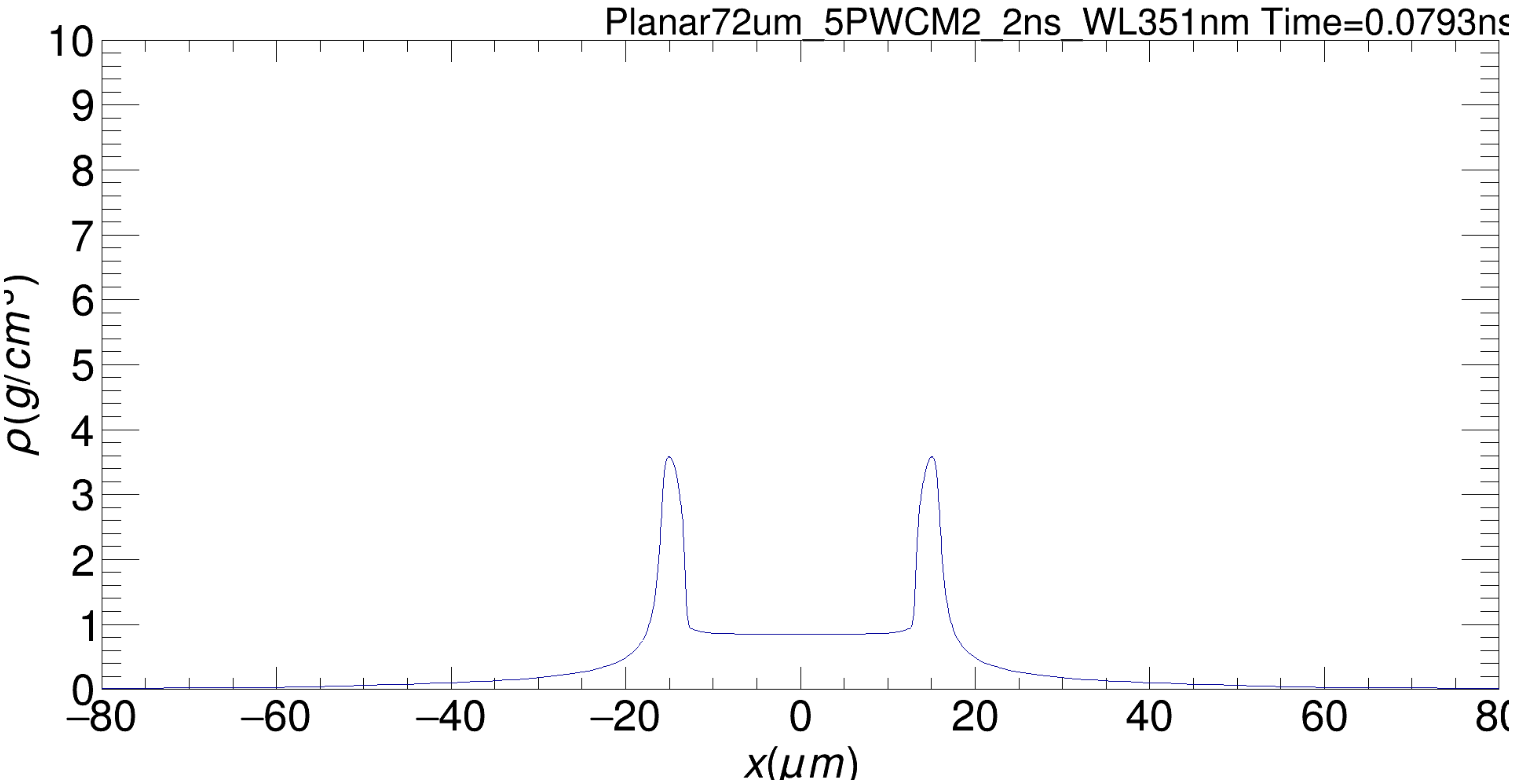
operating since 2011

8 beams output 40 kJ/3 ns/1 ω, 24 kJ/3 ns/3 ω

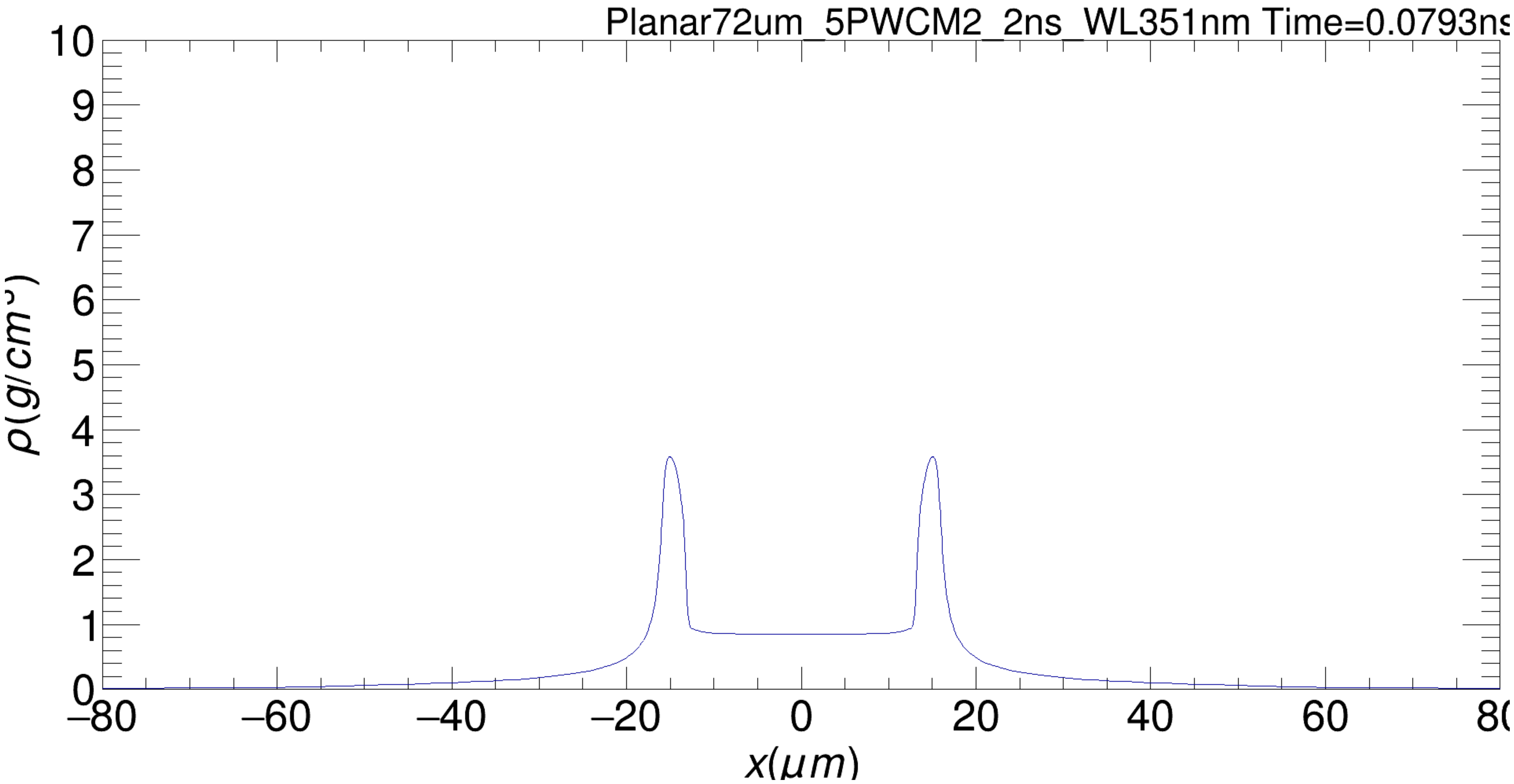
PW laser (1.5kJ, 2ps, 2011)

for SINAP\SIOM\TAMU\INFN\IMUN

Collaboration



Planar72um_5PWCM2_2ns_WL351nm Time=0.0793ns
ρ(g/cm³)
10
9
8
7
6
5
4
3
2
1
0
−80
−60
−40
−20
0
20
40
60
80
x(μm)


Planar72um_5PWCM2_2ns_WL351nm Time=0.0793ns
$\rho(g/cm^3)$
10
9
8
7
6
5
4
3
2
1
0
−80
−60
−40
−20
0
20
40
60
80
$x(\mu m)$

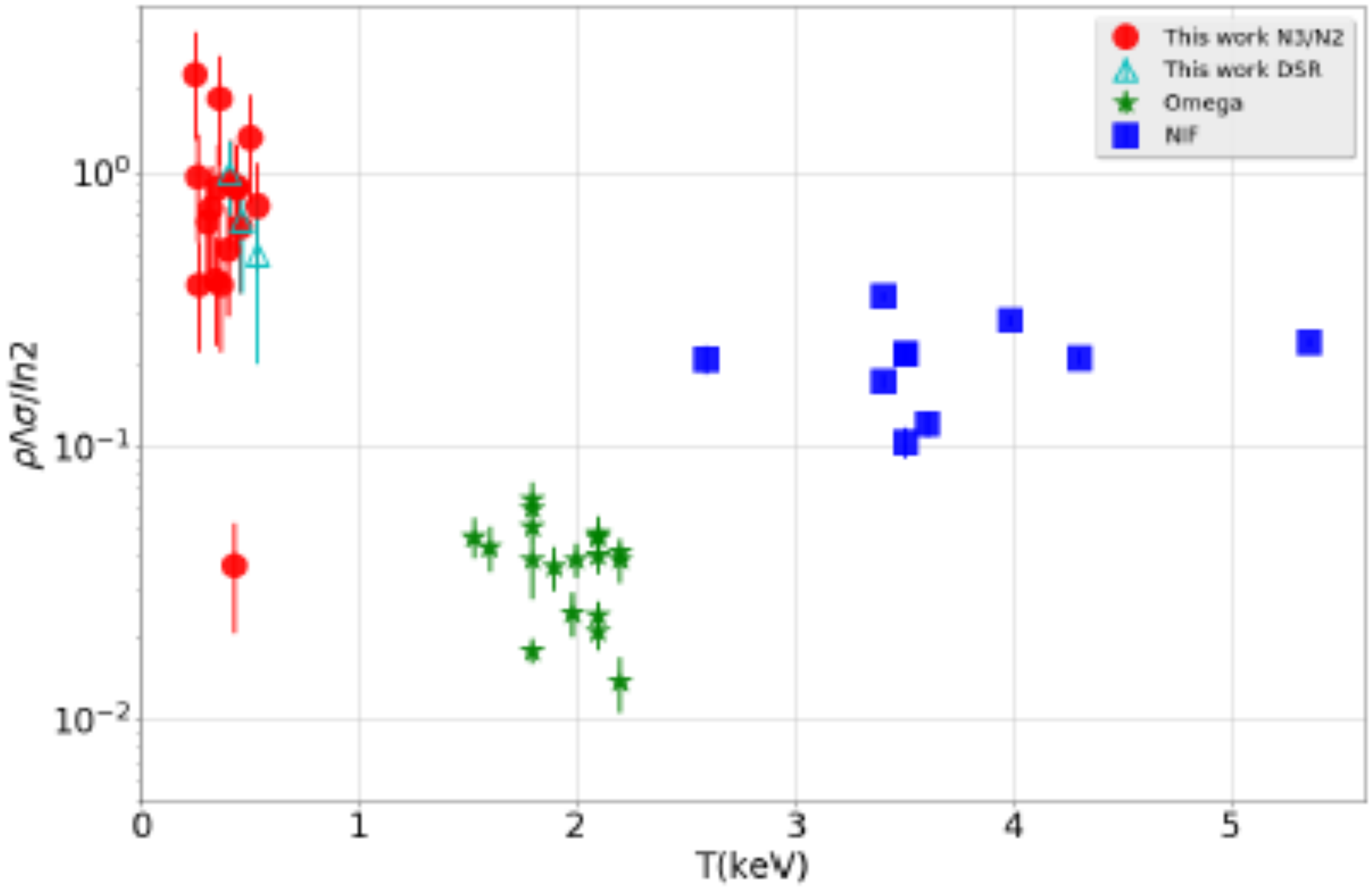


Figure 4: (color online) $\Lambda\rho\sigma/\ln 2$ obtained from eq.(4) vs T from eq.(1). Omega and NIF data are derived from the experiments[25], using the Down Scatter Ratio[21,23]. Our results using the DSR method (N4/N3) are given by the open triangle symbols in good agreement with the N3/N2 ratios..

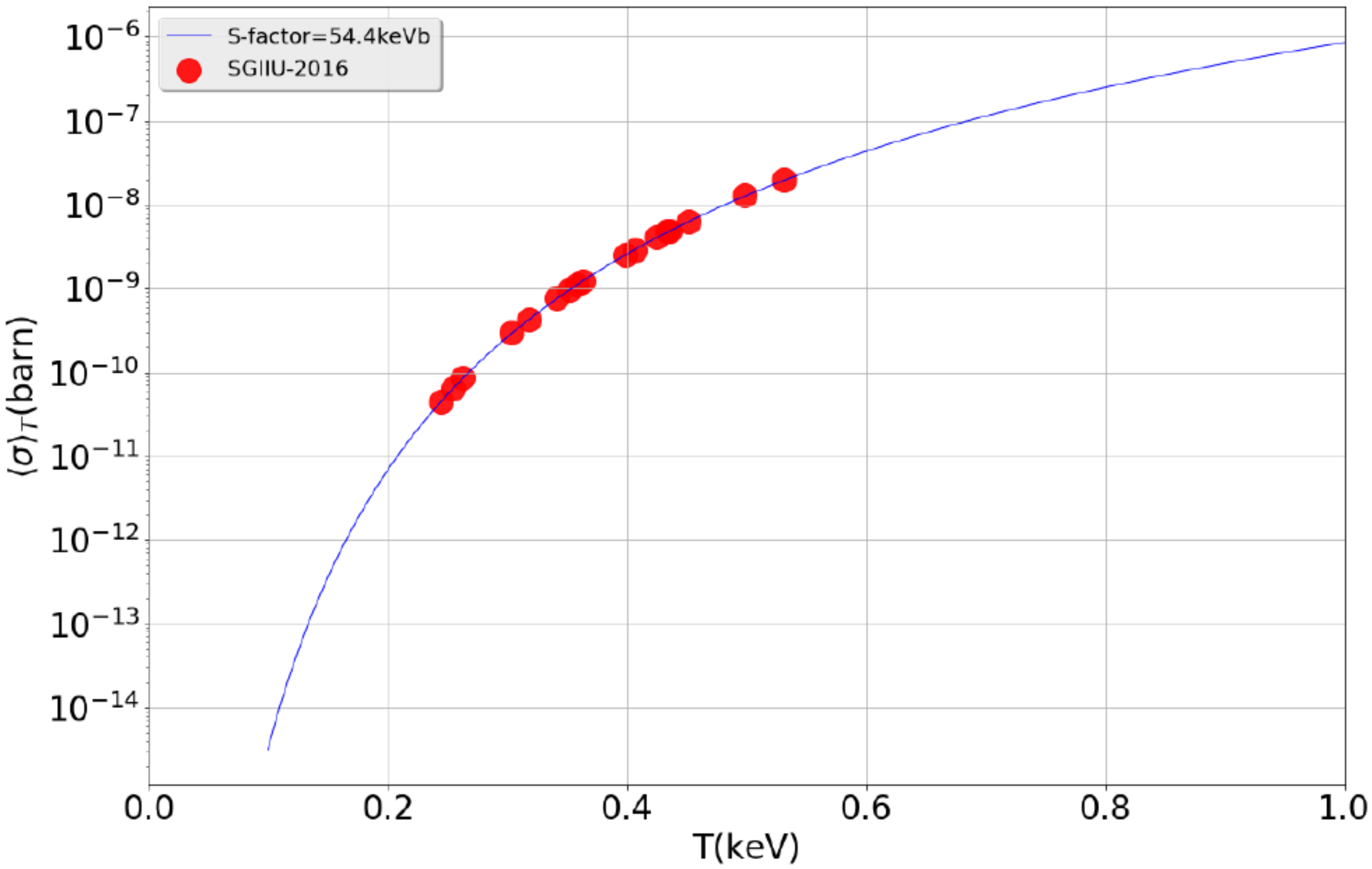


Figure 5: (color online) The average cross section as function of temperature with Maxwell-Boltzmann distribution, expressed by eq. (6) . The red points are the experimental cross section data from eq.(5).

Physics Letters A 383 (2019) 2285–2289

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Nuclear probes of an out-of-equilibrium plasma at the highest compression

G. Zhang [a,b,*], M. Huang [c], A. Bonasera [d,e,*], Y.G. Ma [f,b,i,*], B.F. Shen [g,h,*], H.W. Wang [a,b], W.P. Wang [g], J.C. Xu [g], G.T. Fan [a,b], H.J. Fu [b], H. Xue [b], H. Zheng [j], L.X. Liu [a,b], S. Zhang [c], W.J. Li [b], X.G. Cao [a,b], X.G. Deng [b], X.Y. Li [b], Y.C. Liu [b], Y. Yu [g], Y. Zhang [b], C.B. Fu [k], X.P. Zhang [k]

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[b] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*
[c] *College of Physics and Electronics Information, Inner Mongolia University for Nationalities, Tongliao, 028000, China*
[d] *Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA*
[e] *Laboratori Nazionali del Sud, INFN, via Santa Sofia, 62, 95123 Catania, Italy*
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[i] *University of the Chinese Academy of Sciences, Beijing 100080, China*
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A R T I C L E   I N F O

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Available online 30 April 2019
Communicated by F. Porcelli

Keywords:
Laser plasma
Nuclear astrophysics
Inertia confinement fusion
High-energy-density plasma

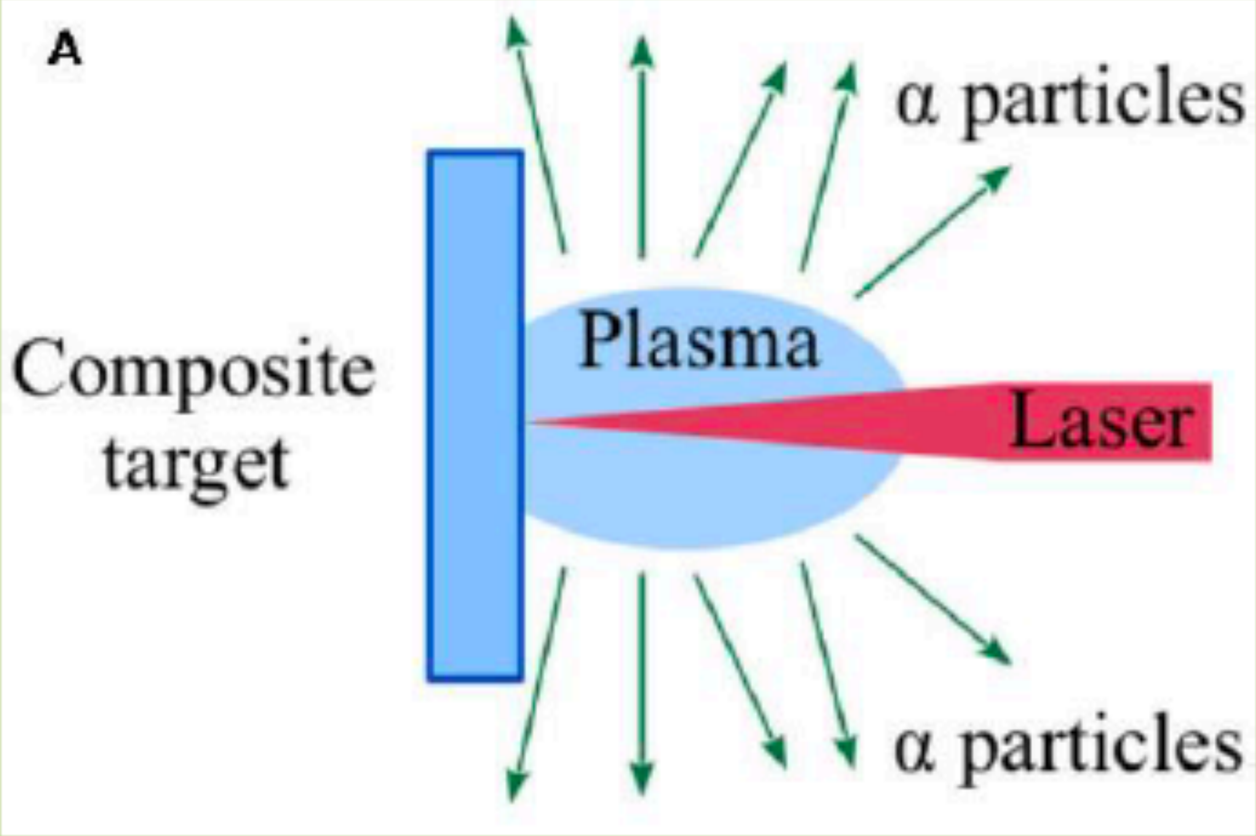
A B S T R A C T

We report the highest compression reached in laboratory plasmas using eight laser beams, $E_{laser} \approx 12$ kJ, $\tau_{laser} = 2$ ns in third harmonic on a CD_2 target at the ShenGuang-II Upgrade (SGII-Up) facility in Shanghai, China. We estimate the deuterium density $\rho_D = 2.0 \pm 0.9$ kg/cm^3, and the average kinetic energy of the plasma ions less than 1 keV. The highest reached areal density $\Lambda \rho_D = 4.8 \pm 1.5$ g/cm^2 was obtained from the measured ratio of the sequential ternary fusion reactions ($dd \rightarrow t+p$ and $t+d \rightarrow \alpha+n$) and the two body reaction fusions ($dd \rightarrow {}^3He + n$). At such high densities, sequential ternary and also quaternary nuclear reactions become important as well (i.e. $n(14.1\ MeV)+{}^{12}C \rightarrow n'+{}^{12}C^*$ etc.) resulting in a shift of the neutron (and proton) kinetic energies from their birth values. The Down Scatter Ratio (DSR-quaternary nuclear reactions) method, i.e. the ratio of the 10-12 MeV neutrons divided by the total number of 14.1 MeV neutrons produced, confirms the high densities reported above. The estimated lifetime of the highly compressed plasma is 52 ± 9 ps, much smaller than the lasers pulse duration.

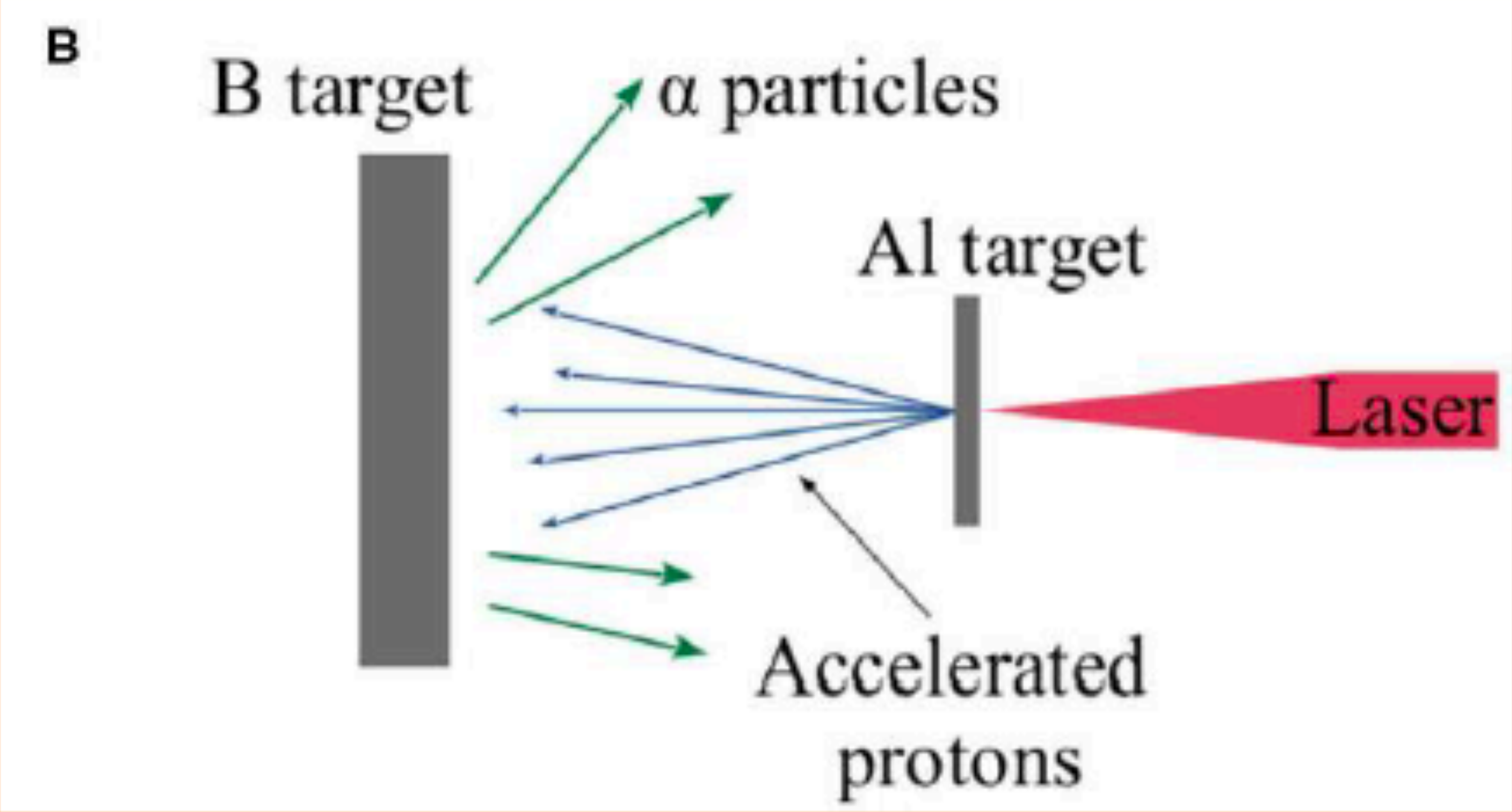
Laser-initiated $^{11}B(p,\alpha)2\alpha$ nuclear reaction

- Two main approaches followed to trigger fusion reactions from H and ^{11}B in laser-matter experiments (Scheme A and B)

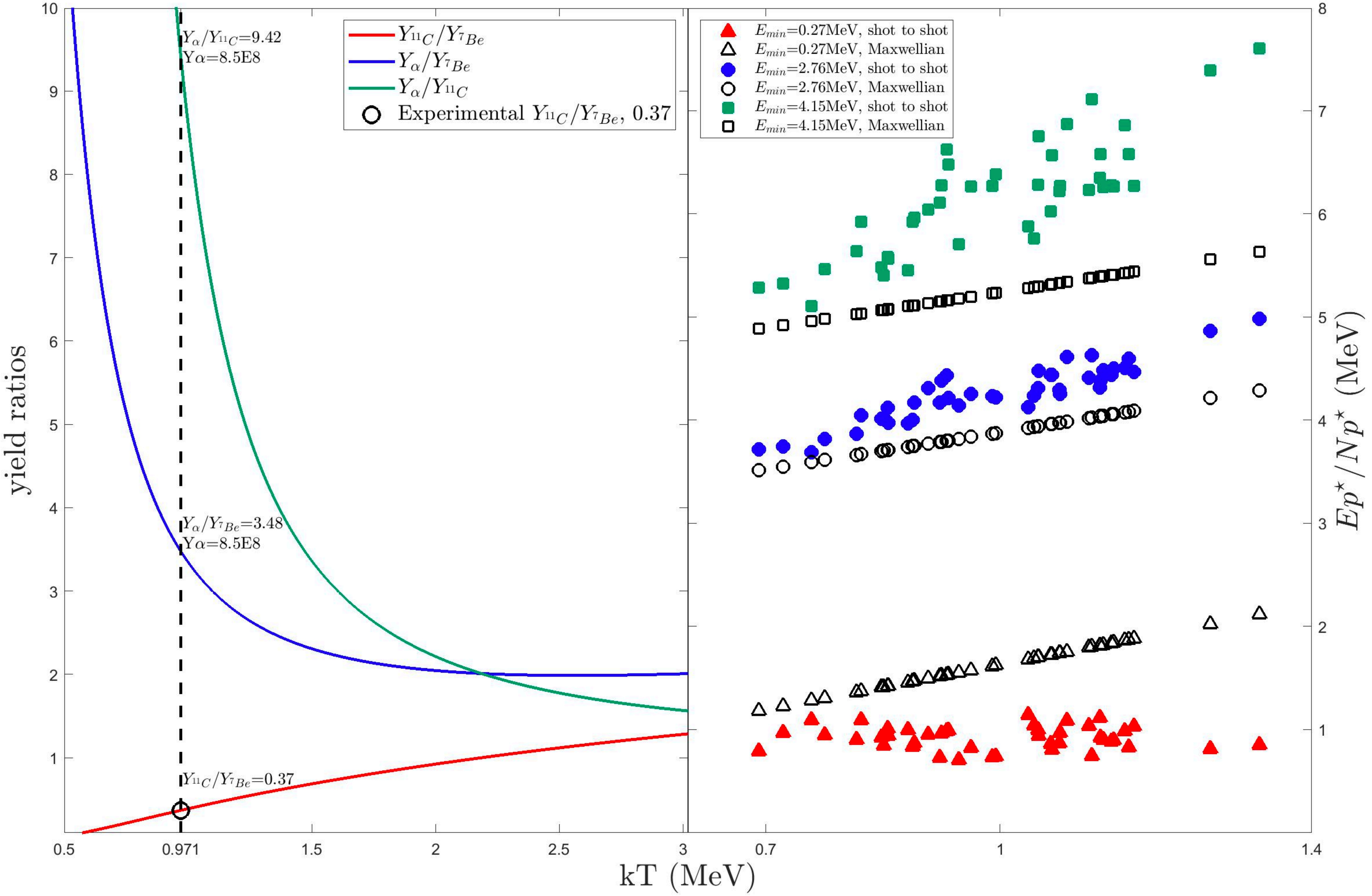
Scheme A: Laser on target
-H and B plasma by laser pulses on composite targets: i.e. B-doped plastic, BN or Si enriched with H and B.
-ns and/or ps/fs laser pulses.

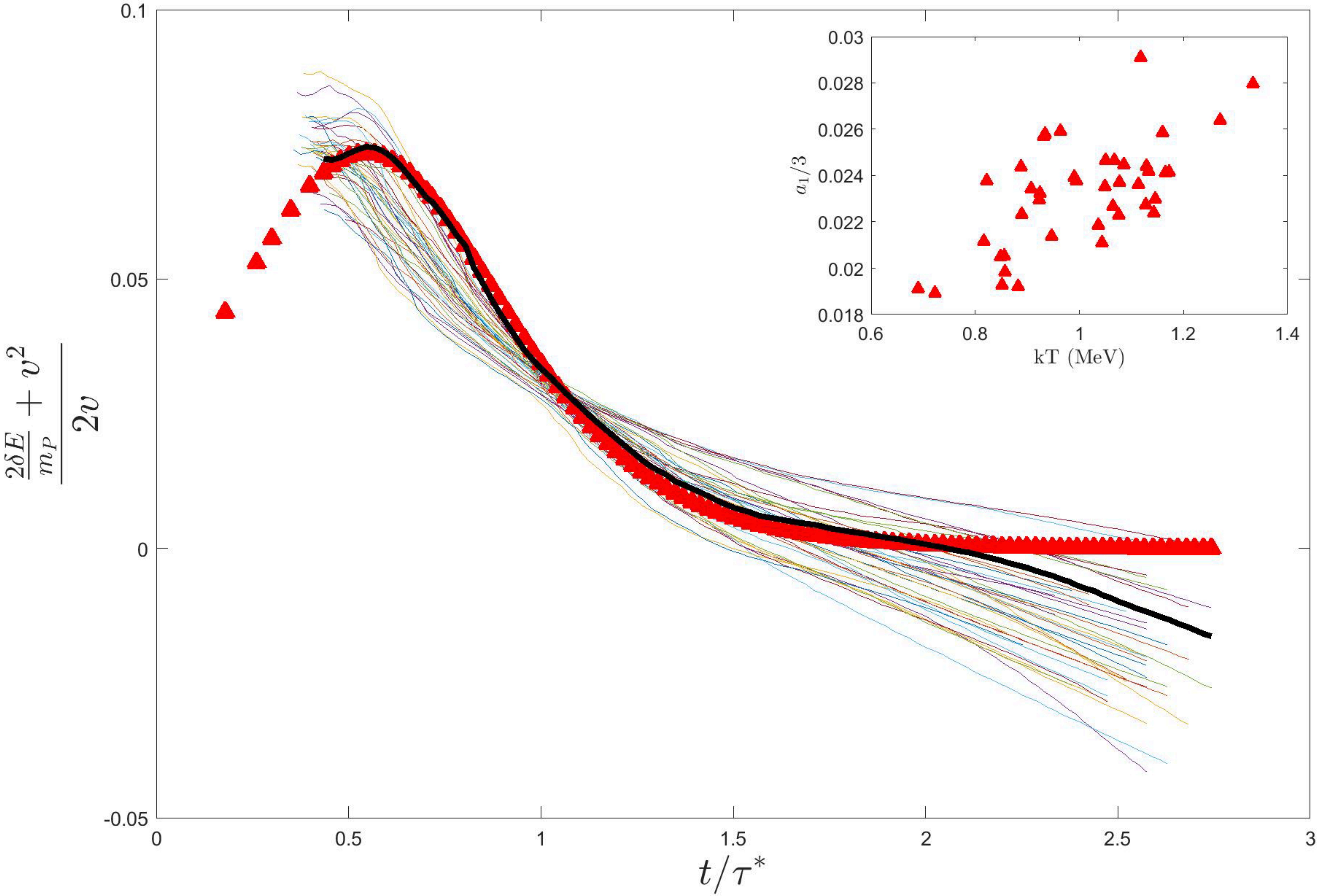


Scheme B: Pitcher-Catcher
-Laser accelerated protons sent to a borate target or to a borated plasma.
-ps or fs laser pulses

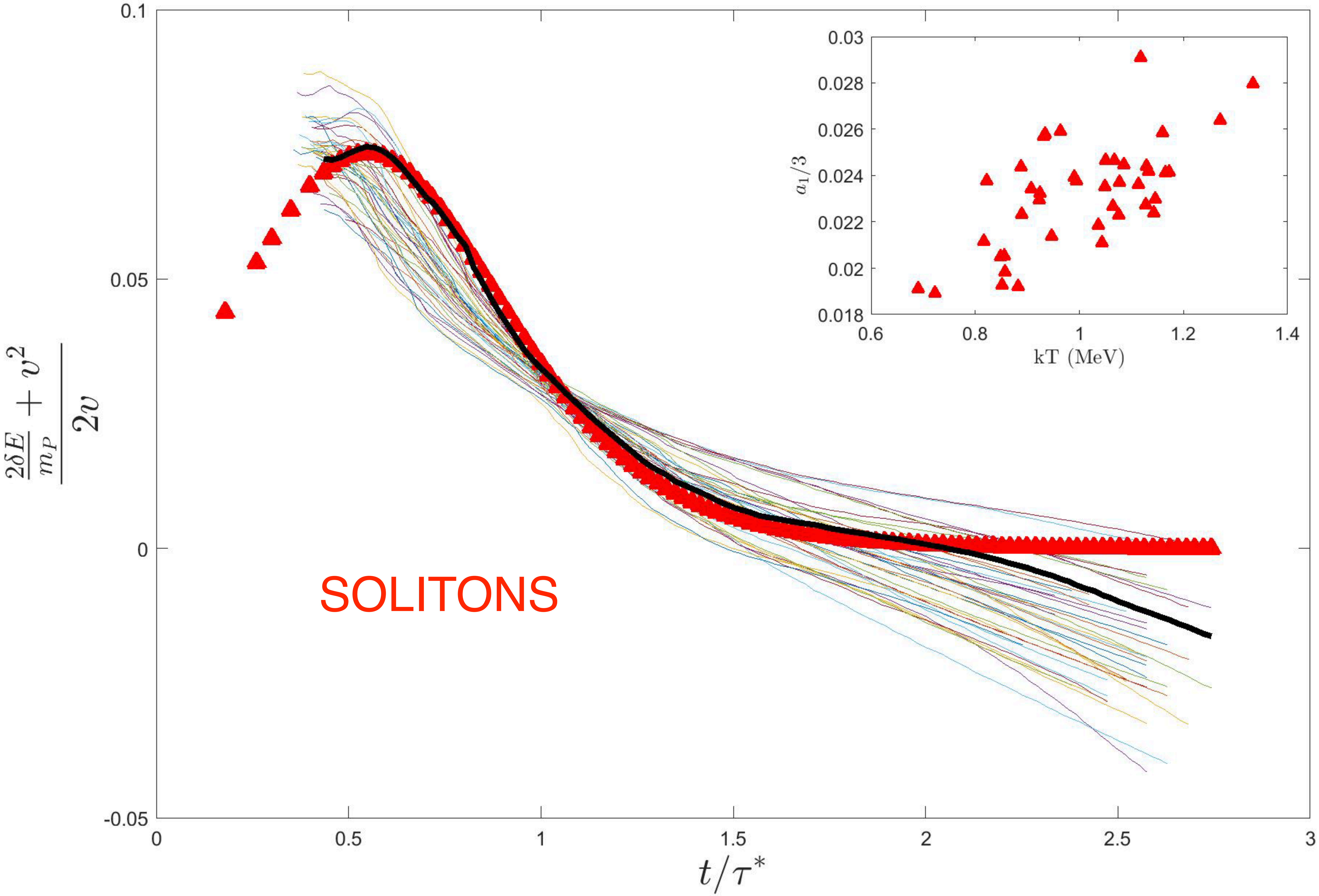


[1] Consoli F. Frontiers in Physics (2020) 8, 561492

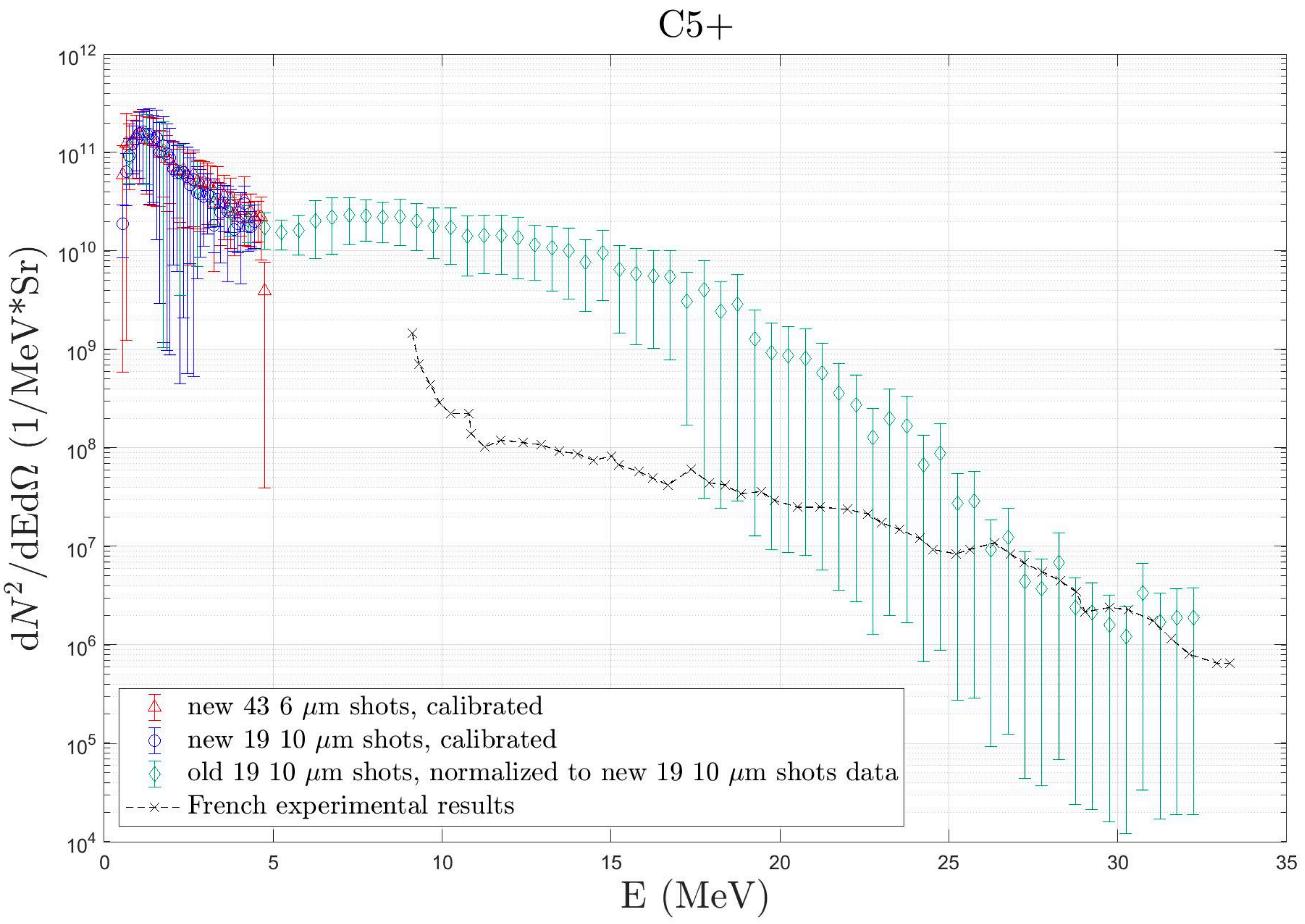

$Y_{^{11}C}/Y_{^7Be}$
$Y_\alpha/Y_{^7Be}$
$Y_\alpha/Y_{^{11}C}$
Experimental $Y_{^{11}C}/Y_{^7Be}$, 0.37
$Y_\alpha/Y_{^{11}C}$=9.42
Yα=8.5E8
$Y_\alpha/Y_{^7Be}$=3.48
Yα=8.5E8
$Y_{^{11}C}/Y_{^7Be}$=0.37
yield ratios
10
9
8
7
6
5
4
3
2
1
0.5
0.971
1.5
2
2.5
3
kT (MeV)
E_{min}=0.27MeV, shot to shot
E_{min}=0.27MeV, Maxwellian
E_{min}=2.76MeV, shot to shot
E_{min}=2.76MeV, Maxwellian
E_{min}=4.15MeV, shot to shot
E_{min}=4.15MeV, Maxwellian
$Ep^\star/Np^\star$ (MeV)
8
7
6
5
4
3
2
1
0.7
1
1.4

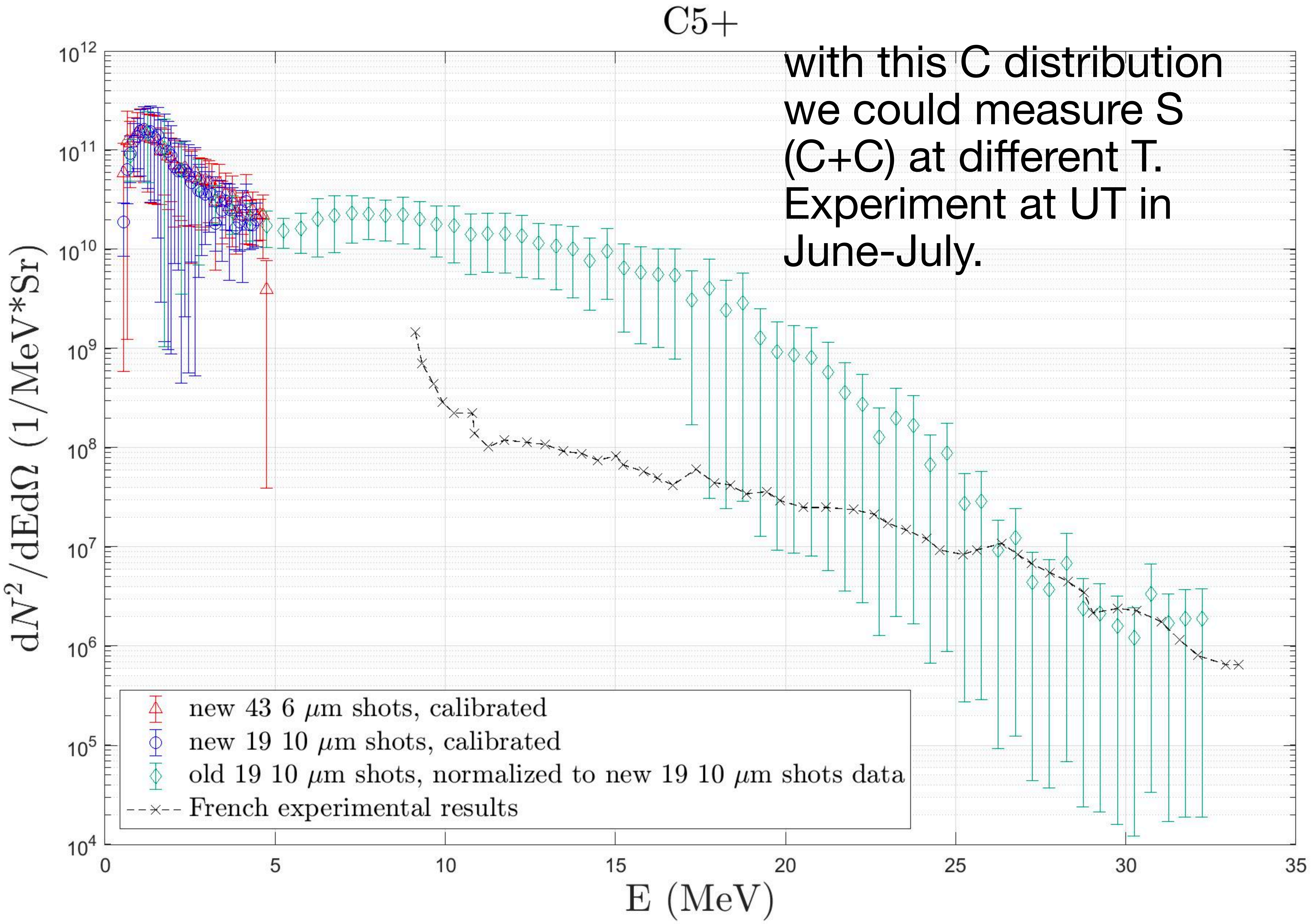


0.1
0.05
0
-0.05
0
0.5
1
1.5
2
2.5
3
t/τ^*
$\frac{\frac{2\delta E}{m_P} + v^2}{2v}$
0.03
0.028
0.026
0.024
0.022
0.02
0.018
0.6
0.8
1
1.2
1.4
$a_1/3$
kT (MeV)


0.1
0.05
0
-0.05
0
0.5
1
1.5
2
2.5
3
$\frac{\frac{2\delta E}{m_P} + v^2}{2v}$
t/τ^*
0.03
0.028
0.026
0.024
0.022
0.02
0.018
$a_1/3$
0.6
0.8
1
1.2
1.4
kT (MeV)

SOLITONS


C5+
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
$dN^2/dEd\Omega$ (1/MeV*Sr)
0
5
10
15
20
25
30
35
E (MeV)
new 43 6 μm shots, calibrated
new 19 10 μm shots, calibrated
old 19 10 μm shots, normalized to new 19 10 μm shots data
French experimental results



with this C distribution we could measure S (C+C) at different T. Experiment at UT in June-July.

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