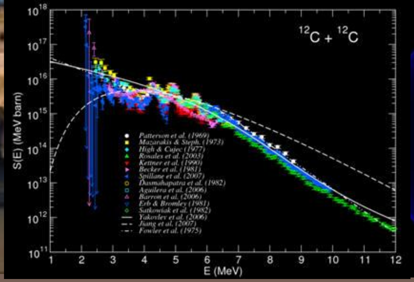

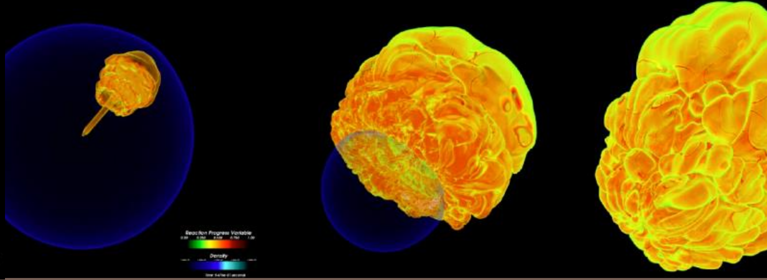

HEAVY ION FUSION REACTIONS IN STARS

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[1]Institute of Modern Physics, CAS, China

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Lanzhou University and Institute of Modern Physics, CAS, China

NSD 2019, Venice, Italy, May 12-17, 2019

Outline

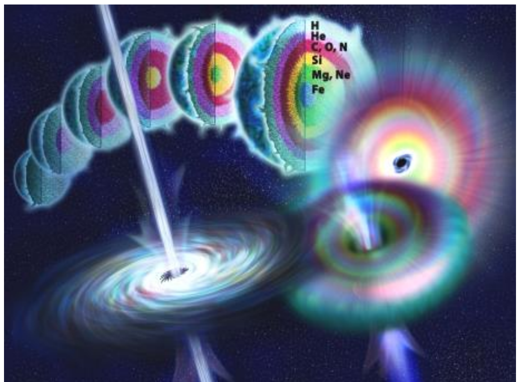
- Heavy ion fusion reactions in stars
- $^{12}C+^{12}C$ at stellar energies
  - → Brief review
  - → Correlation between carbon isotopes
  - → Upper limit
  - → Test of the predictive power of models
  - → New techniques

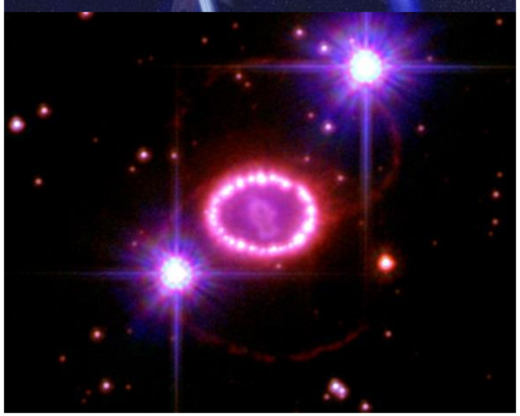
- Fusion reaction with n-rich beams
- Summary

Diaz-Torres, Monday
Montagnoli, Tueday
Jenkins, Tuesday
Tumino, Wednesday
Stefanini, NOW!

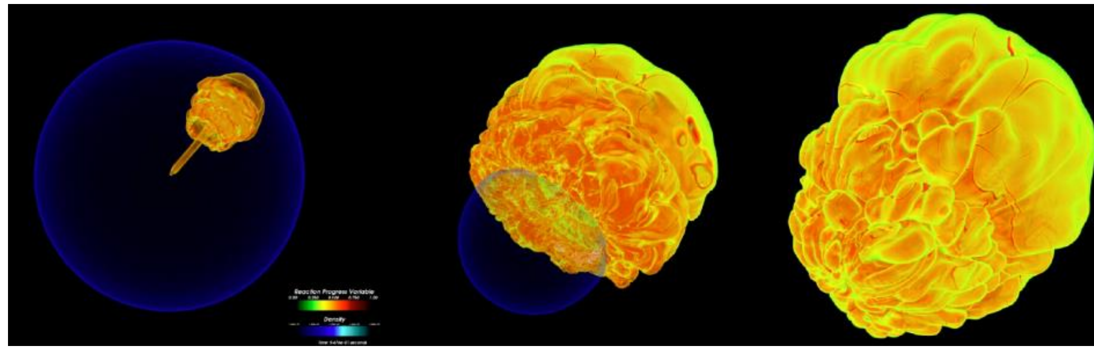
Carbon burning in the universe

Nucleosynthesis in massive stars

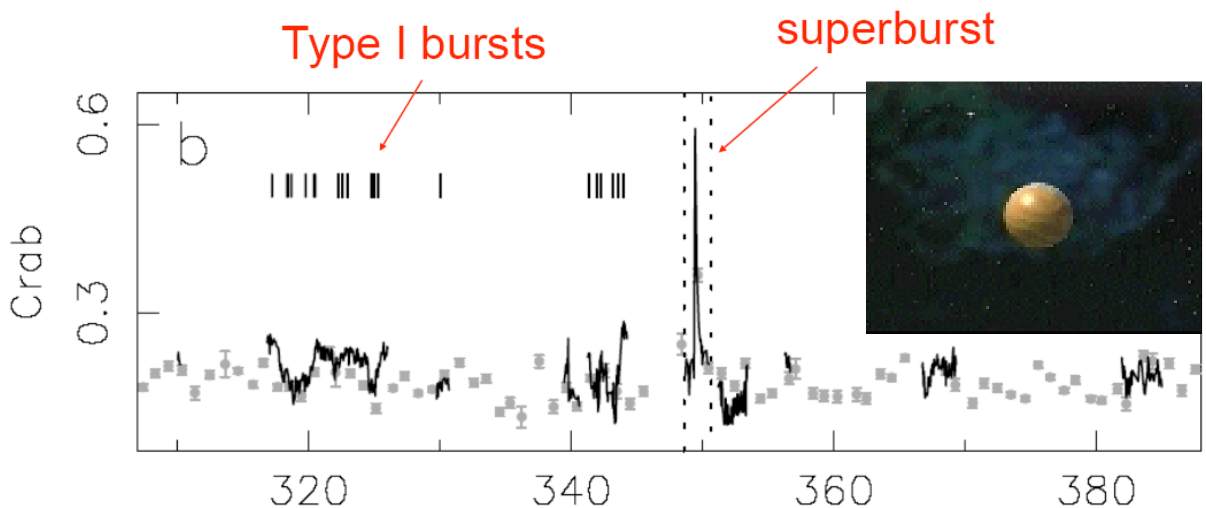




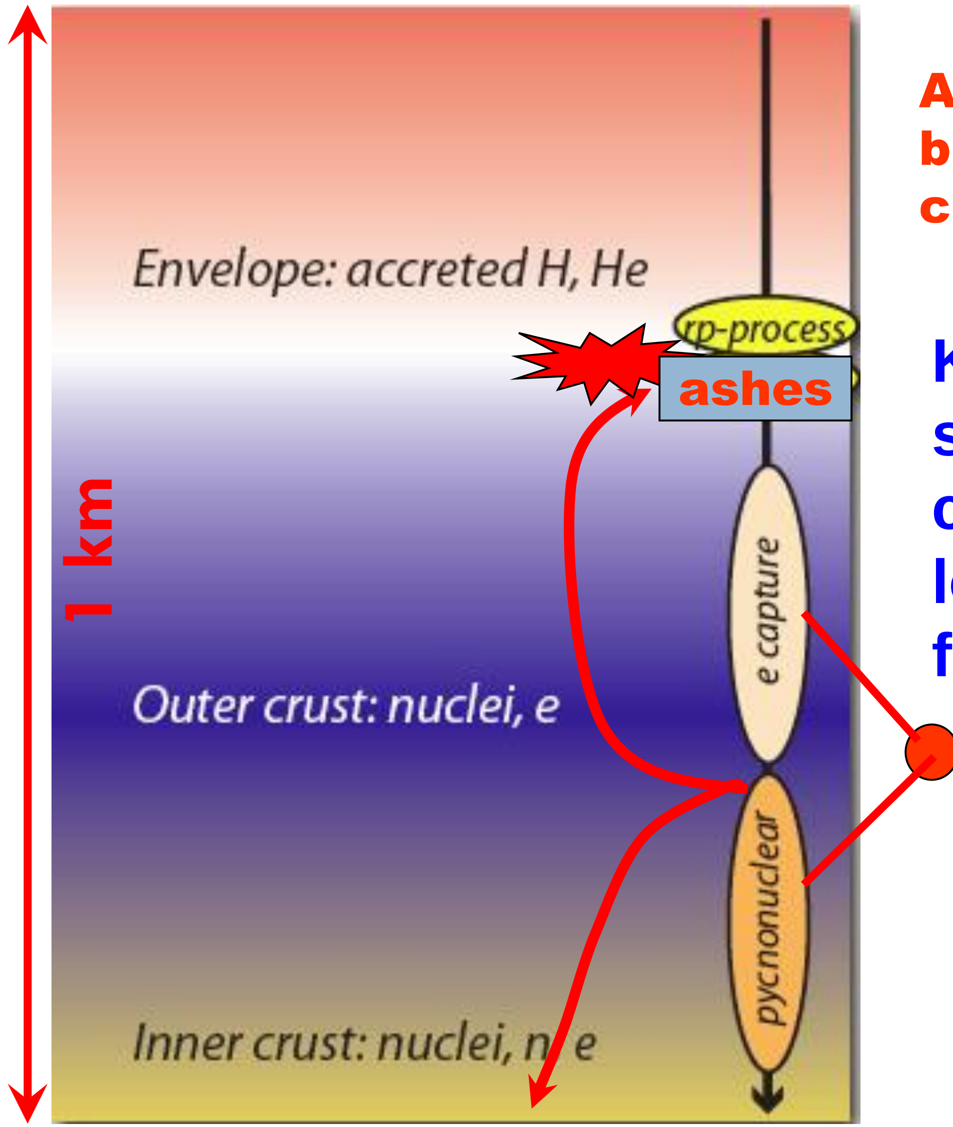
Ignition conditions in type Ia supernovae



Candidate for Superburst ignition



Superburst: ignited by Carbon burning



Ashes from rp process (He burning) deposit in the outer crust.

Key problem: With the standard rate (CF88), the crust temperature is too low to ignite the carbon fuel! ☹

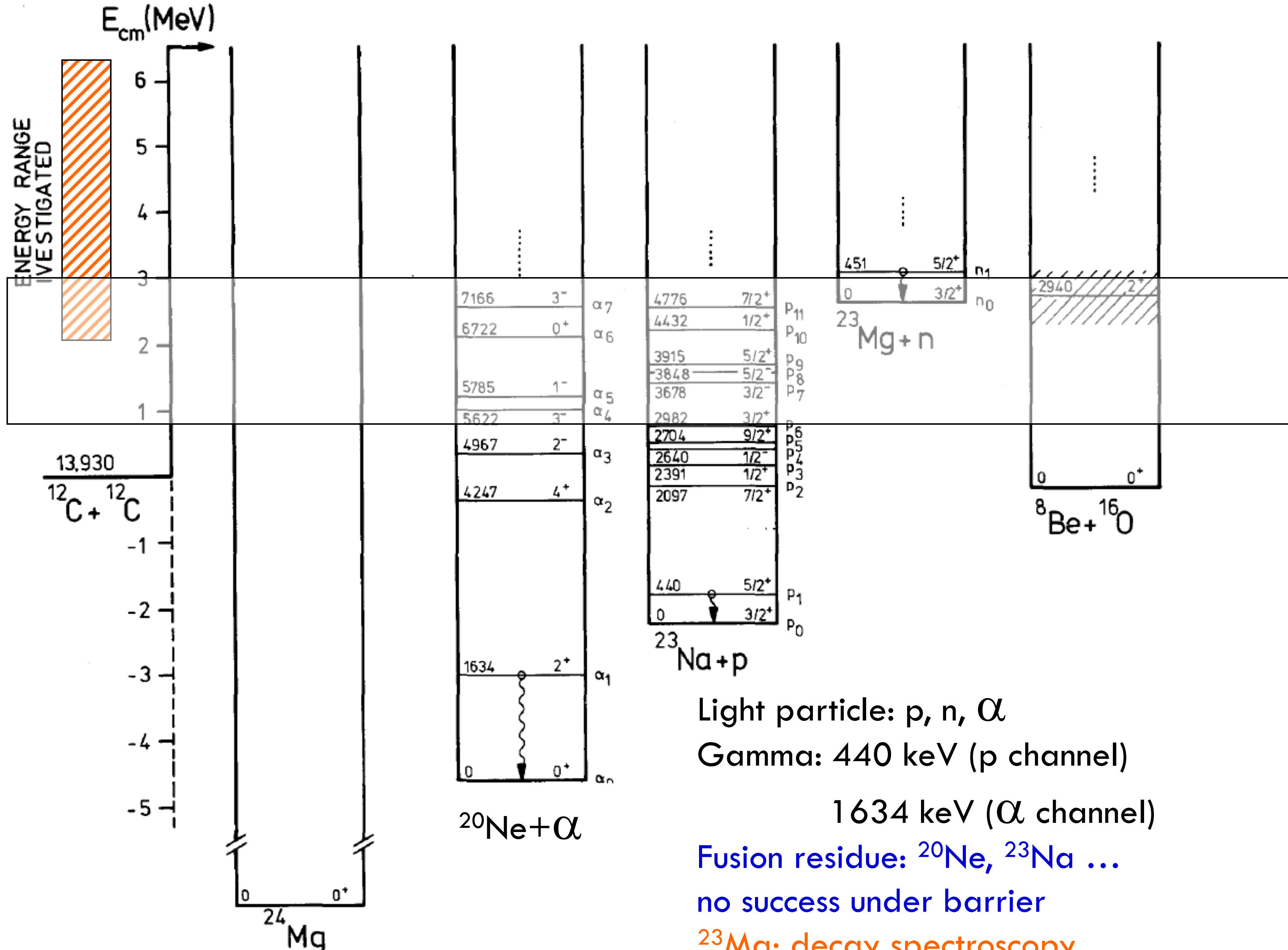
Crust processes
(EC, pycnonuclear fusion)
→crust heating and cooling
→crust conductivity

$^{24}O+^{24}O$

$^{34}Ne+^{34}Ne$

……..

Picture by E. Brown (MSU)



Light particle: p, n, α

Gamma: 440 keV (p channel)

1634 keV (α channel)

Fusion residue: ^{20}Ne, ^{23}Na …

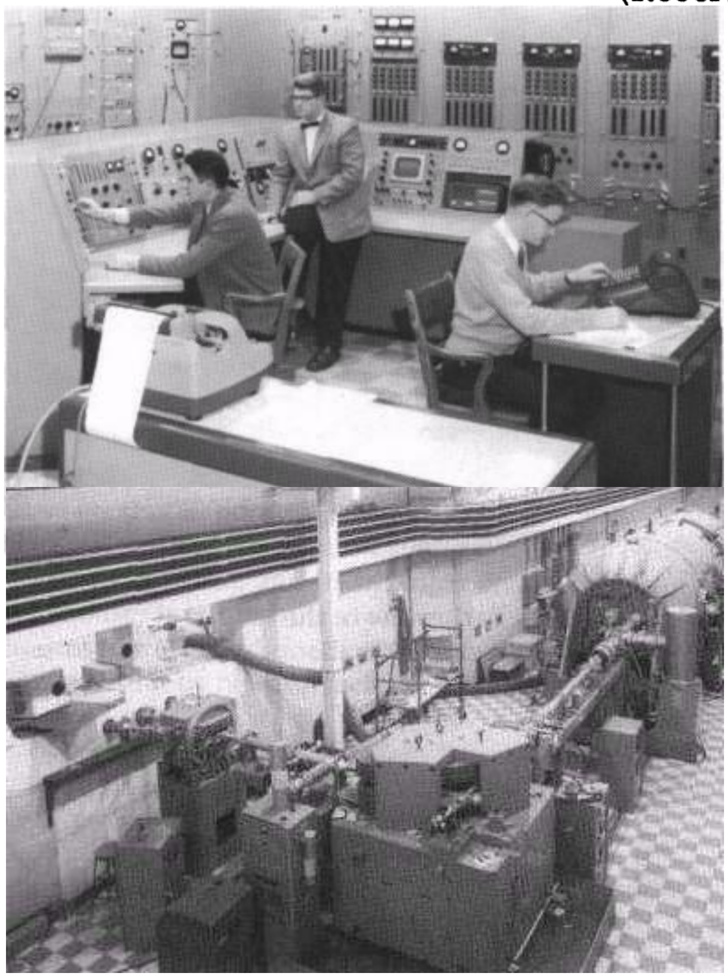
no success under barrier

^{23}Mg: decay spectroscopy

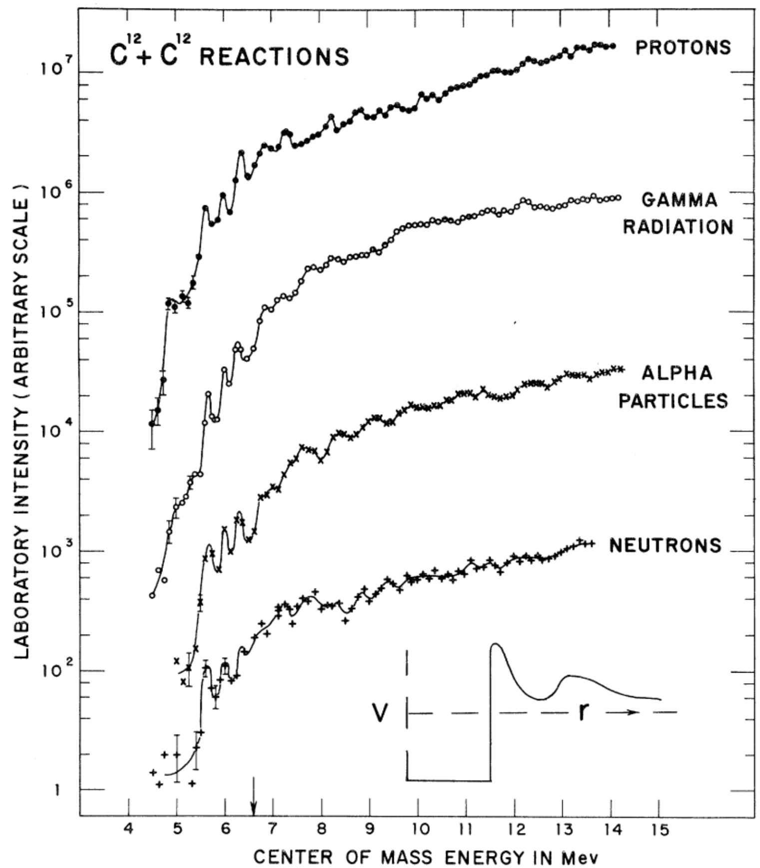
VOLUME 4, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1960

RESONANCES IN C^{12} ON CARBON REACTIONS

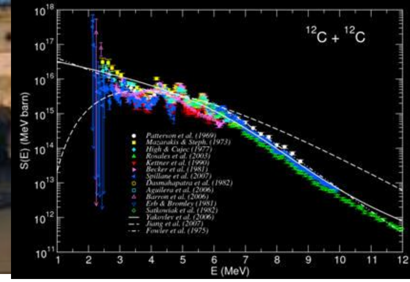
E. Almqvist, D. A. Bromley, and J. A. Kuehner
Atomic Energy of Canada Limited, Chalk River Laboratories, Chalk River, Ontario, Canada
(Received March 28, 1960)

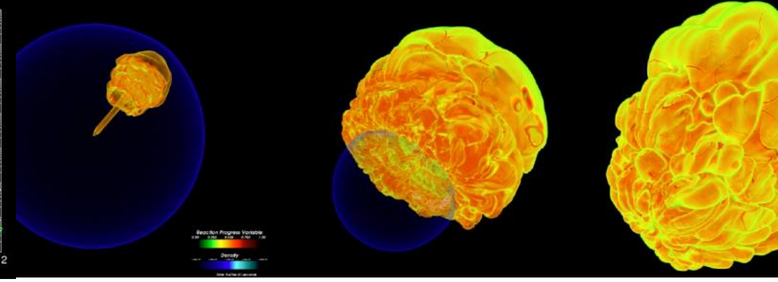


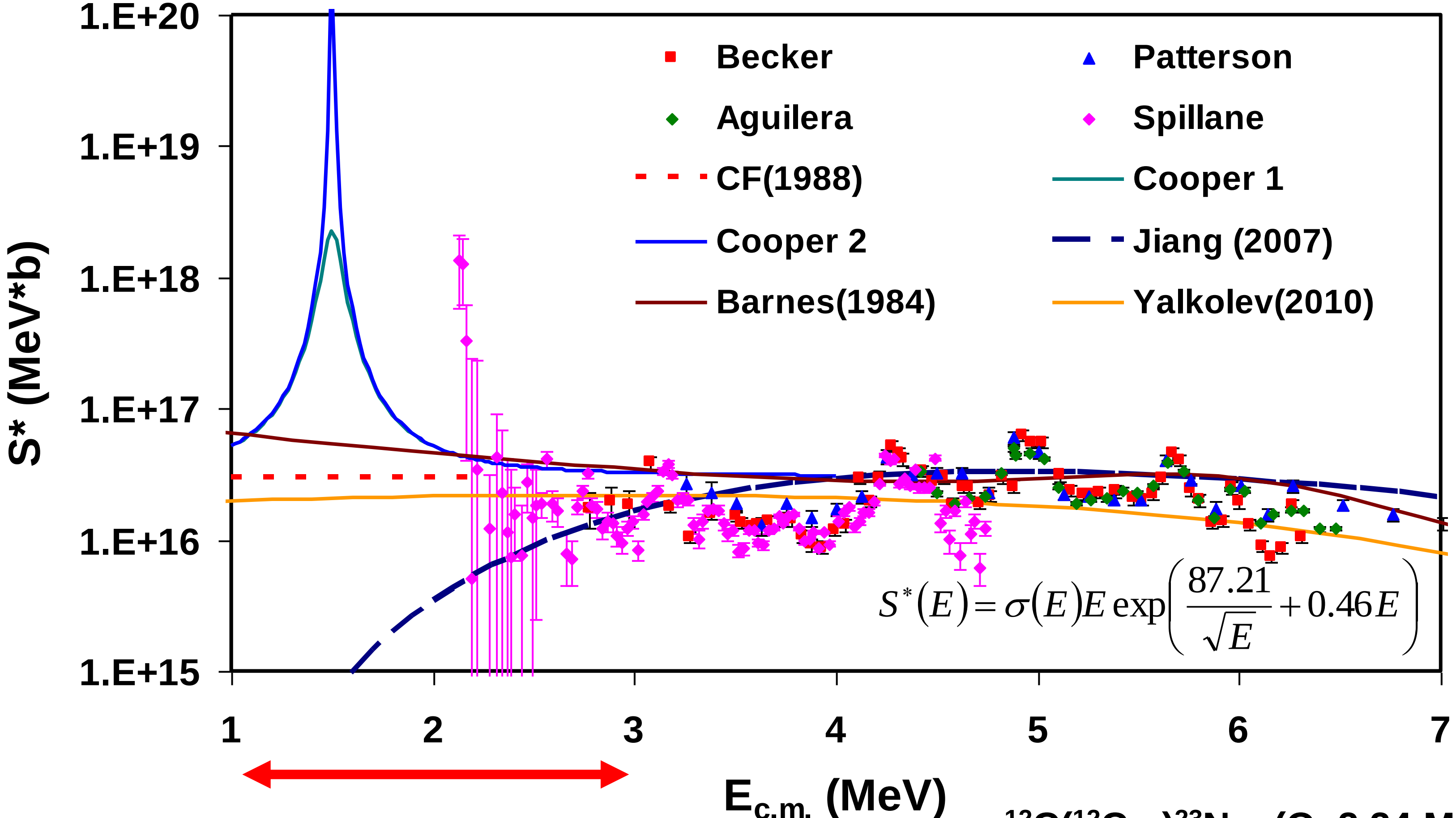
The world's first tandem accelerator installed at Chalk River in 1959.



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



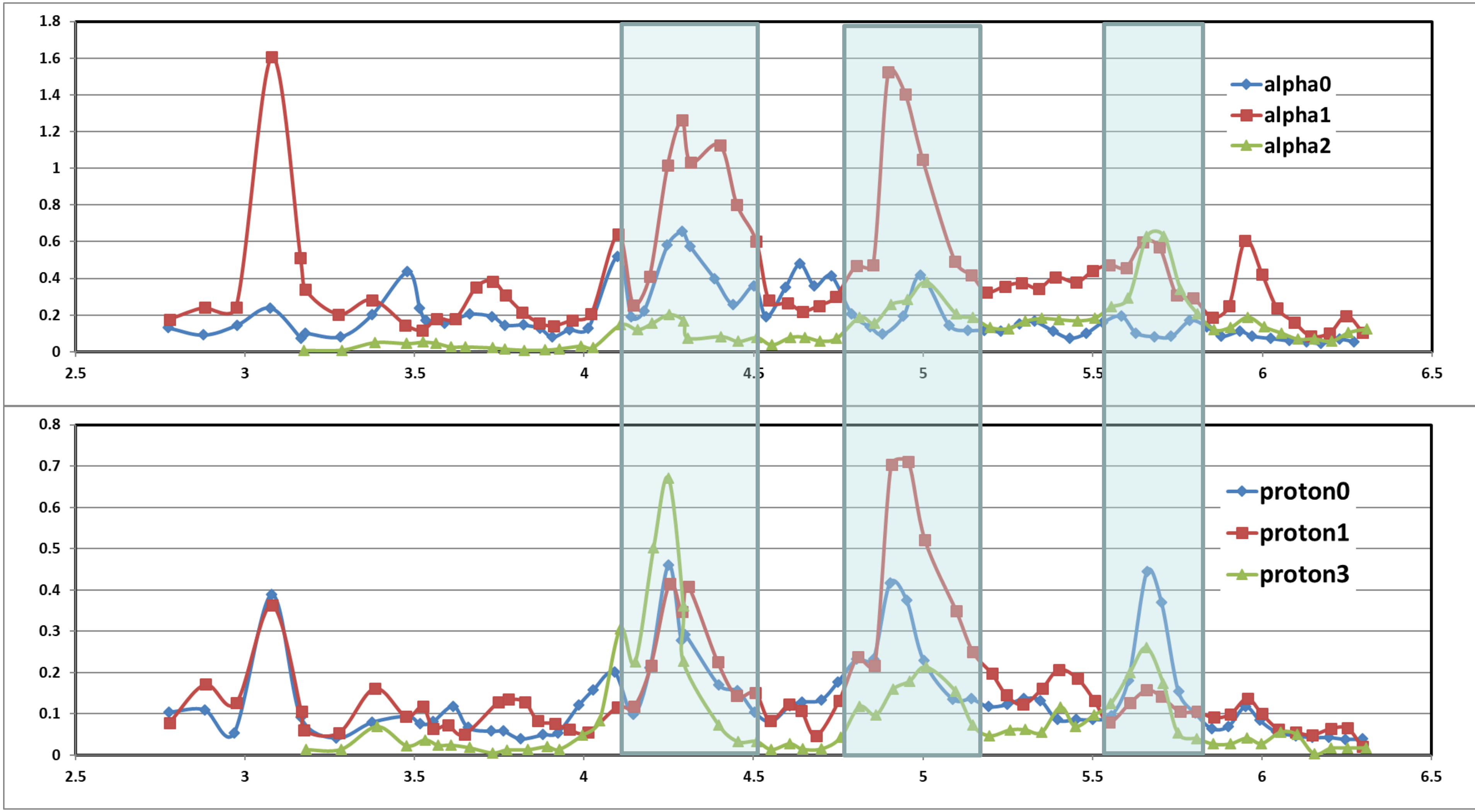




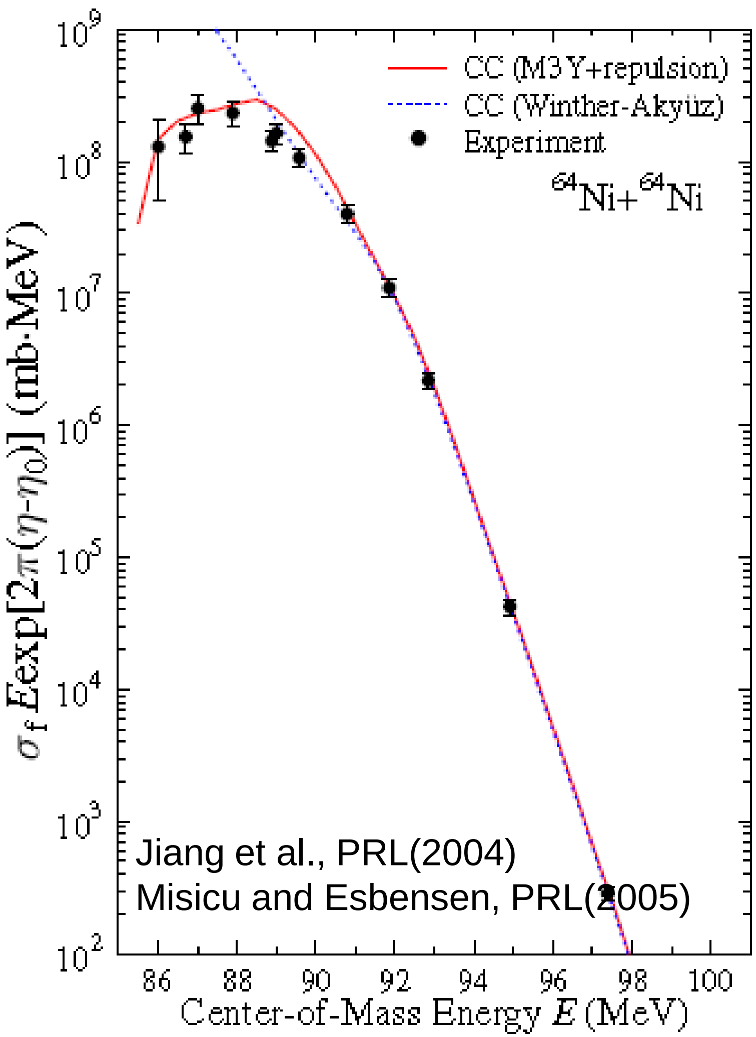
10^{-22} b 10^{-7} b

$^{12}C(^{12}C,p)^{23}Na$ (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)

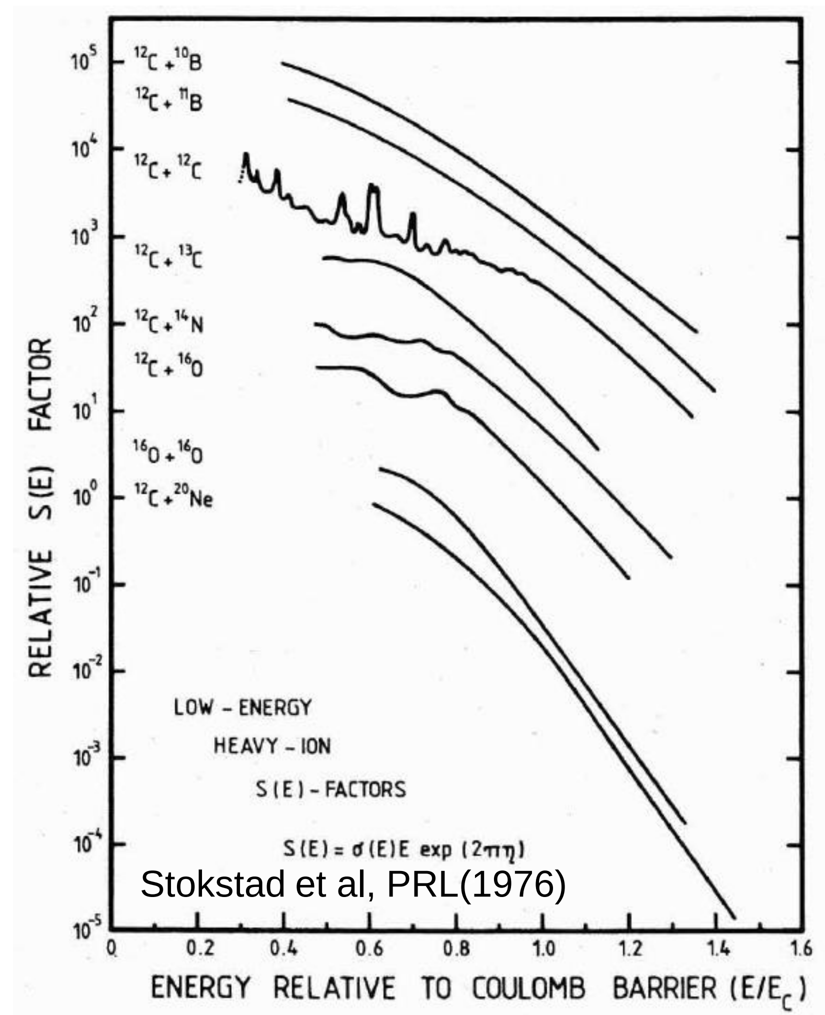
Fragmented resonances



- Hindrance: Coupled channel with standard potential overpredicts
- S-factor maximum found in $^{12}C+^{24}Mg$ (Montagnoli); How about lighter system?



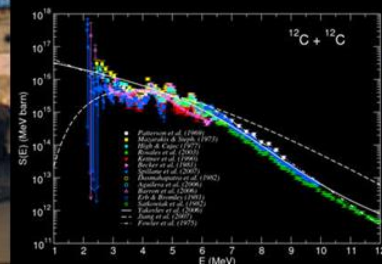
$^{64}Ni+^{64}Ni$

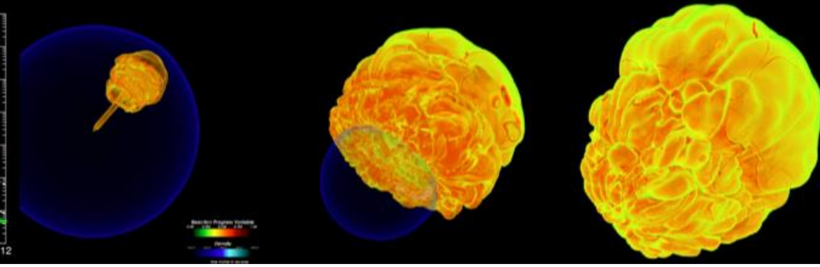


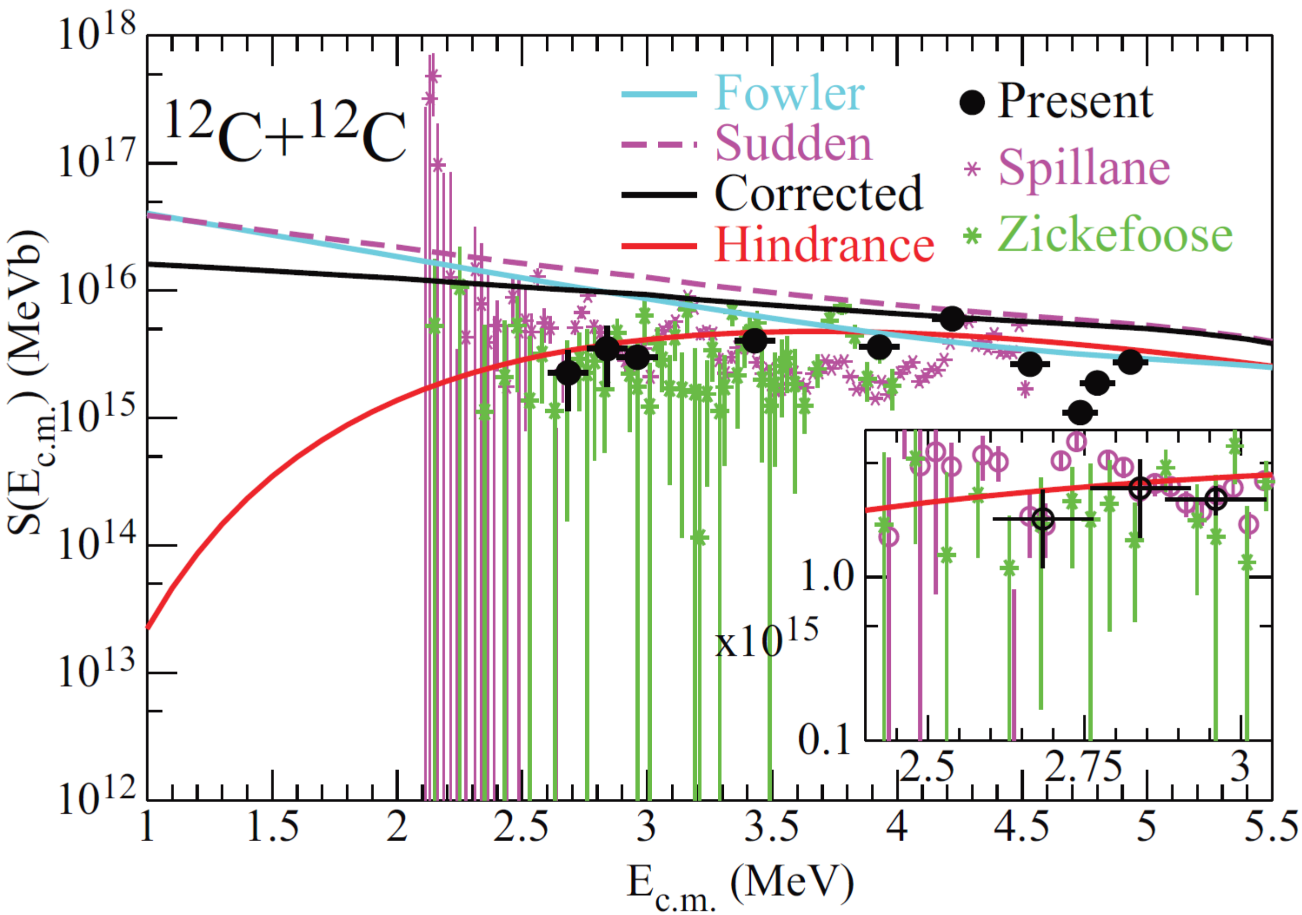
A<20

Stefanini's talk

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



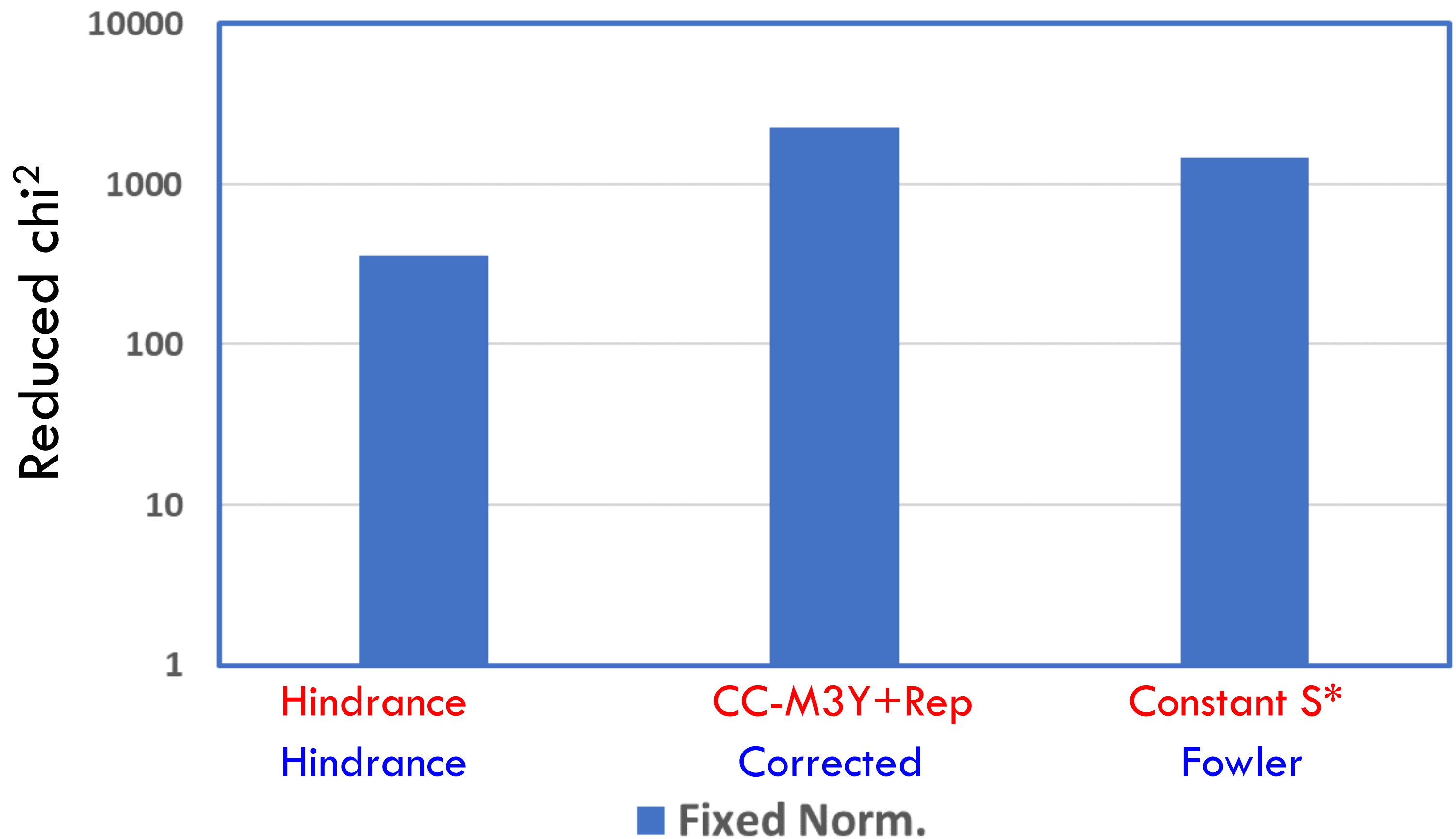




"It is found that the astrophysical *S* factor exhibits a maximum around *E*cm = 3.5–4.0 MeV,…"

C.L. Jiang et al., PRC **97**, 012801(R) (2018)

Not clear conclusion yet



"It is found that the astrophysical *S* factor exhibits a maximum around *E*cm = 3.5–4.0 MeV,…"

C.L. Jiang et al., PRC **97**, 012801(R) (2018)

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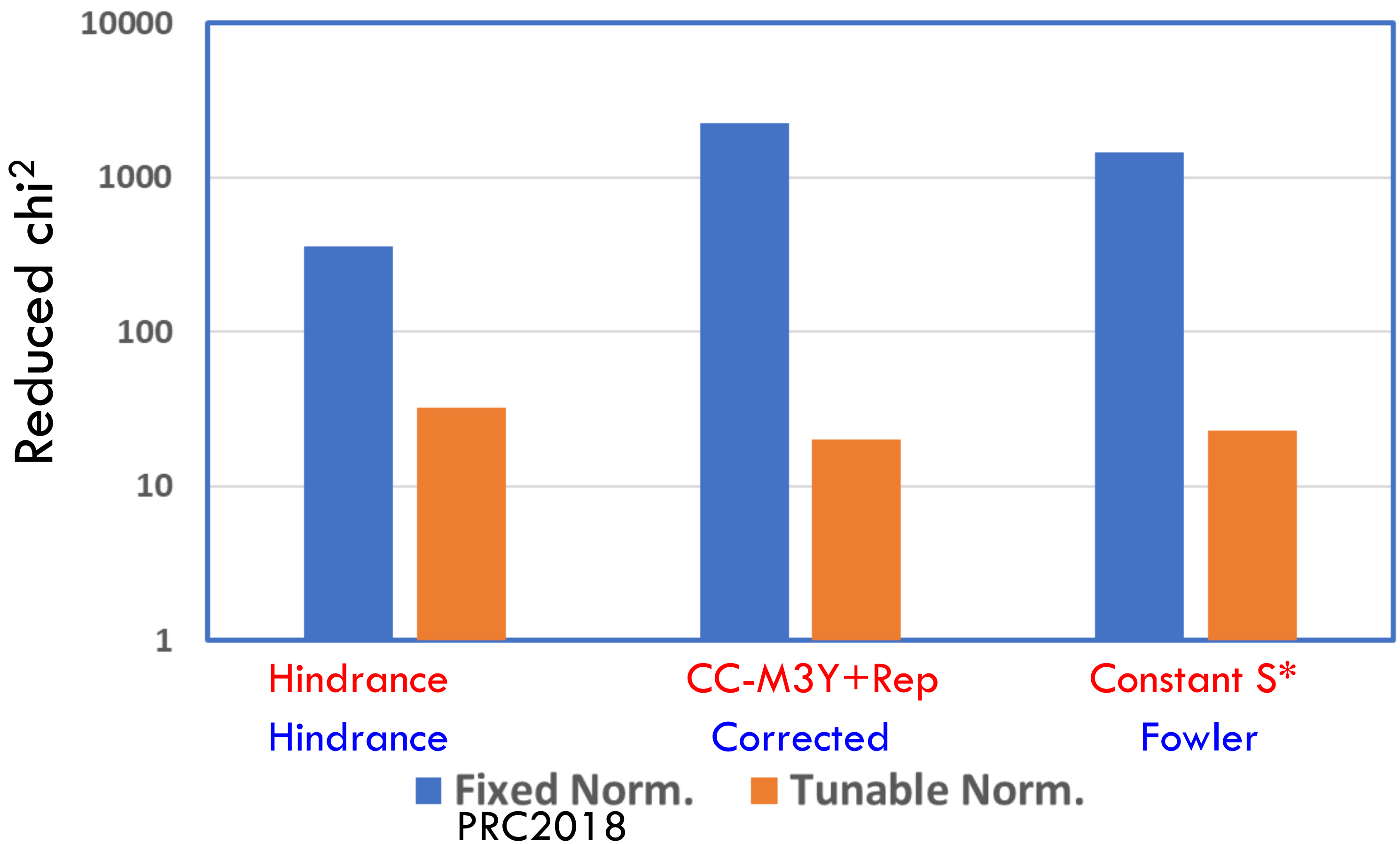
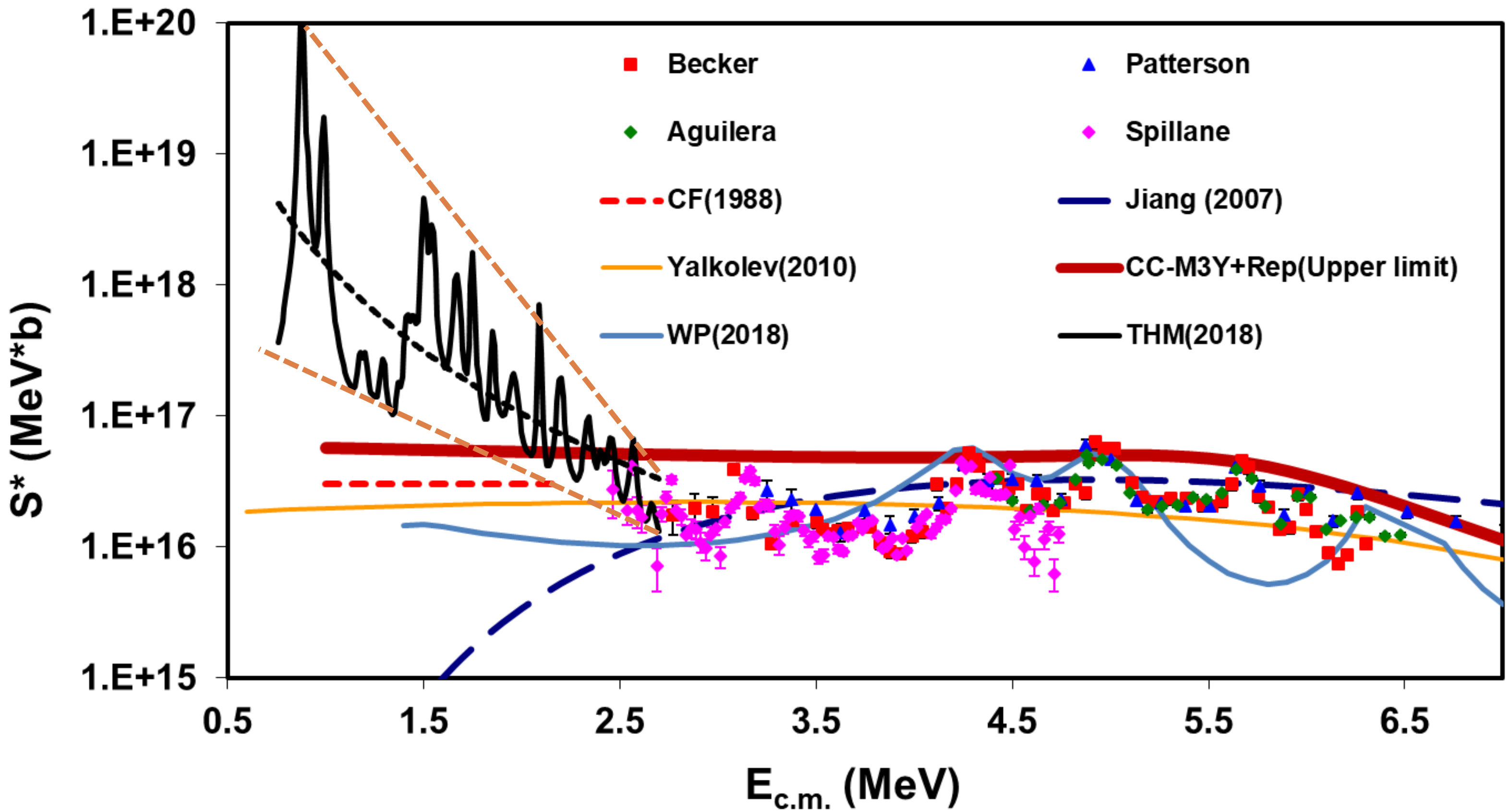


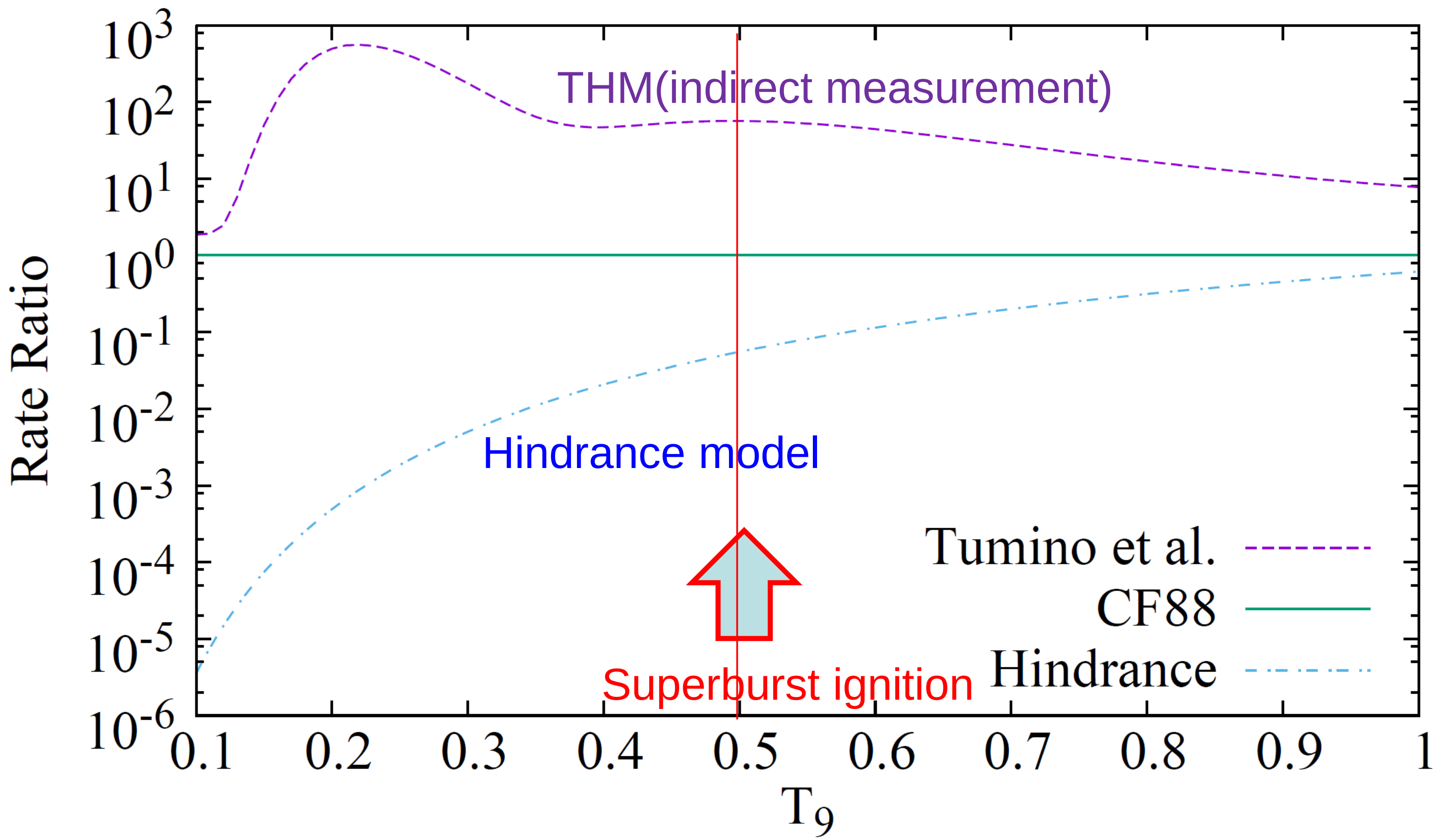
The complicated structure does not favor any model !

INDIRECT MEASUREMENT using Trojan Horse Method



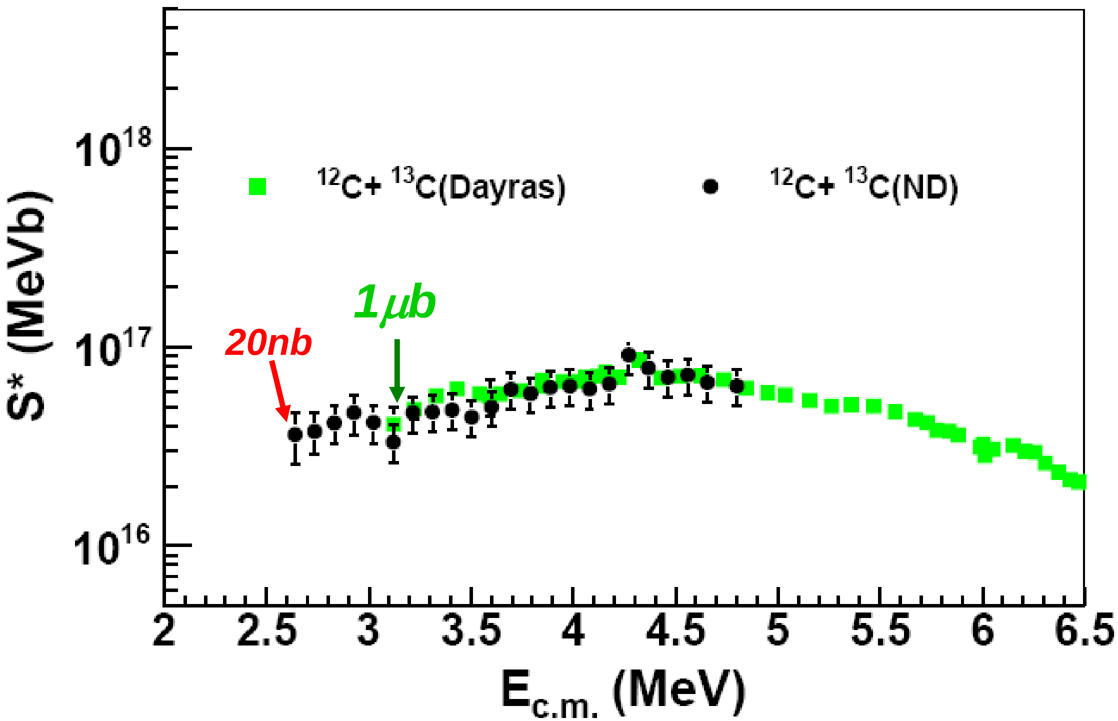
- **THM exhibits: Rich resonances(0^+,2^+,4^+,6^+,…); Different trend from the direct measurements observed at higher energies**

Tumino et al., Nature (2018); A. Mukhamedzhanov, X. Tang, and D. Pang, (2018), arXiv:1806.05921 [nucl-ex]
A. M. Mukhamedzhanov and D. Y. Pang, (2018), arXiv:1806.08828 [nucl-th]; A. Tumino et al., (2018), arXiv:1807.06148 [nucl-ex]



Kanji Mori et al, arXiv:1810.01025, MNRAS (2018)

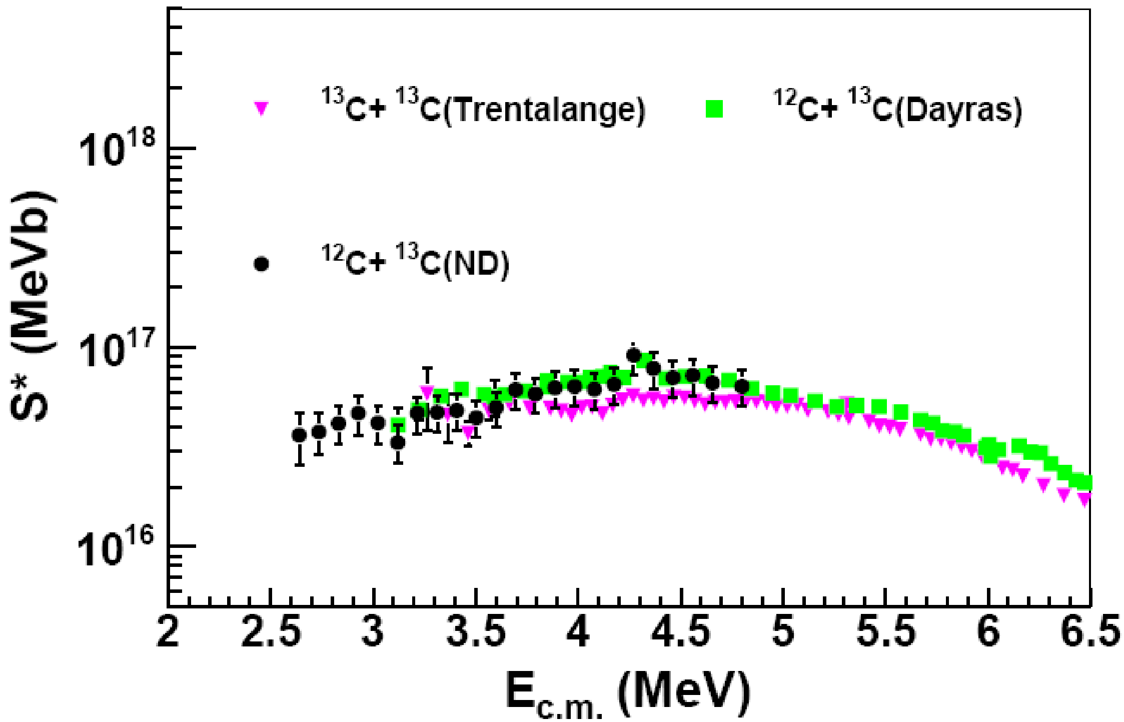
Correlation between carbon isotope systems



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

•The new $^{12}C+^{13}C$ data follows the trend of the old data.

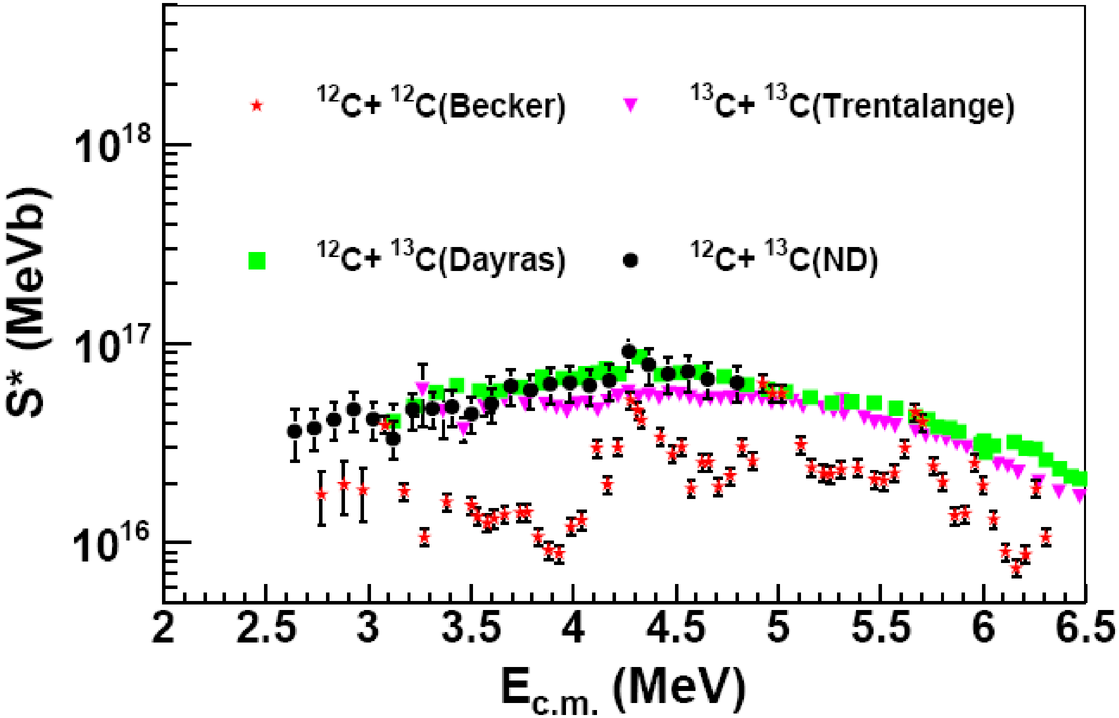
•The smallest cross section has been pushed down by a factor of 50.



•*^{13}C+^{13}C agrees with ^{12}C+^{13}C!*

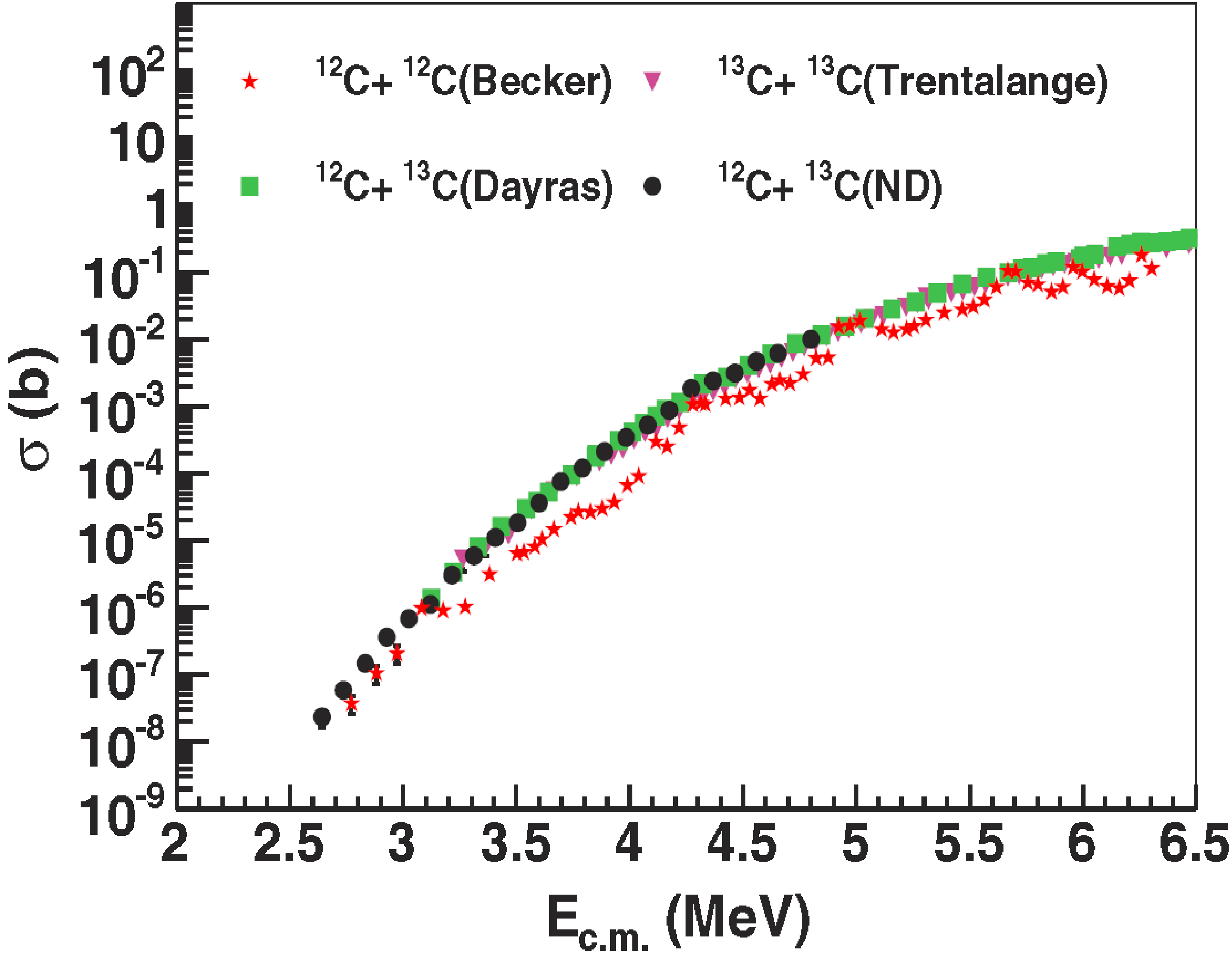
•*The isotope effect (difference in radius, mass) is negligible within the observed energy range!*

•*Where will the ^{12}C+^{12}C data show up?*

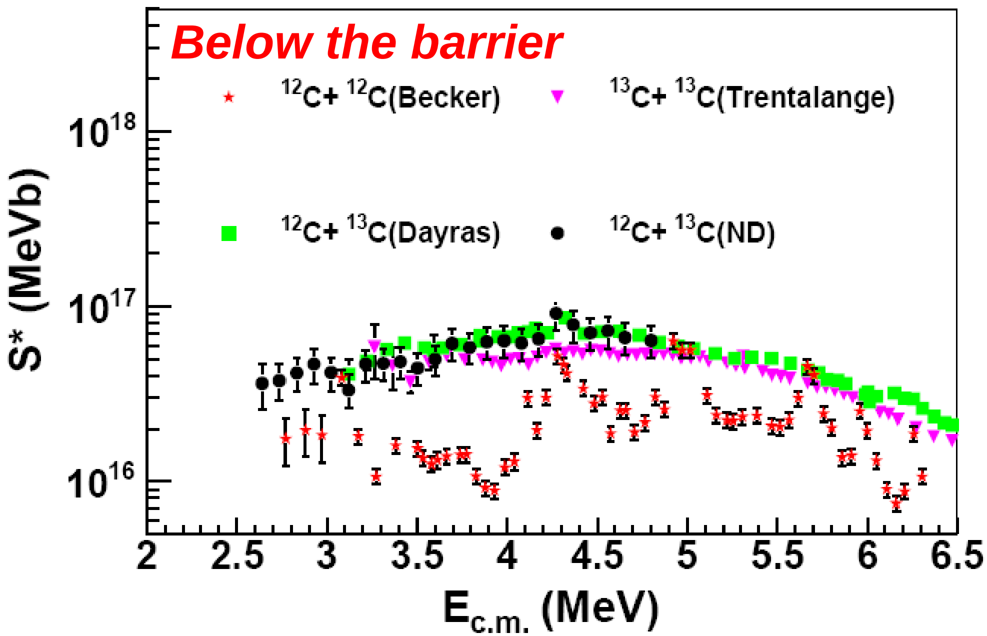


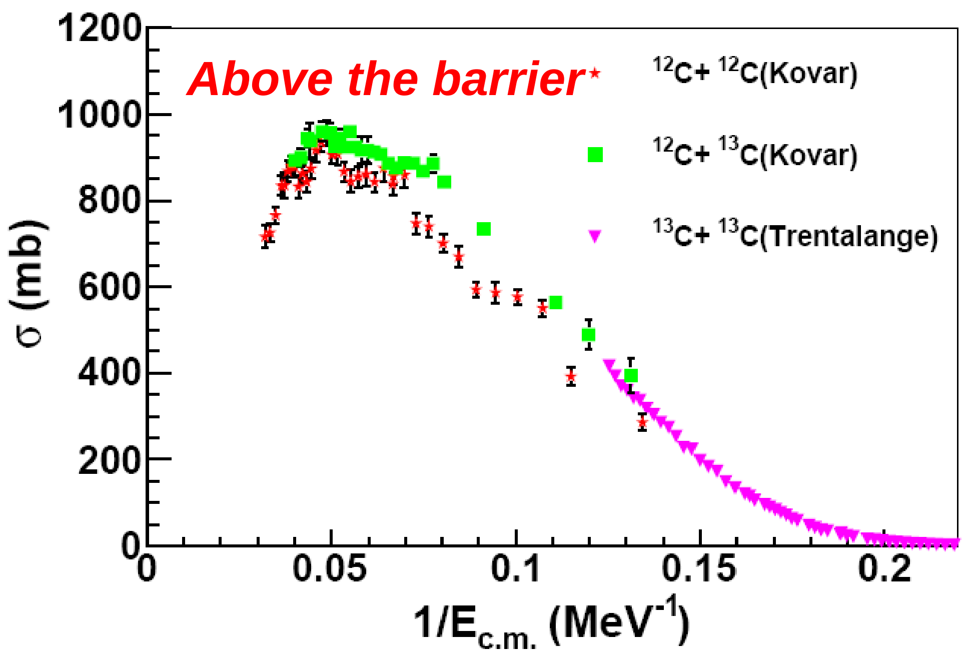
•*For most energies, the $^{12}C+^{12}C$ cross sections are suppressed!*

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



12C+ 12C(Becker)
13C+ 13C(Trentalange)
12C+ 13C(Dayras)
12C+ 13C(ND)
σ (b)
E c.m. (MeV)
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5





A simple pattern for complicated resonances

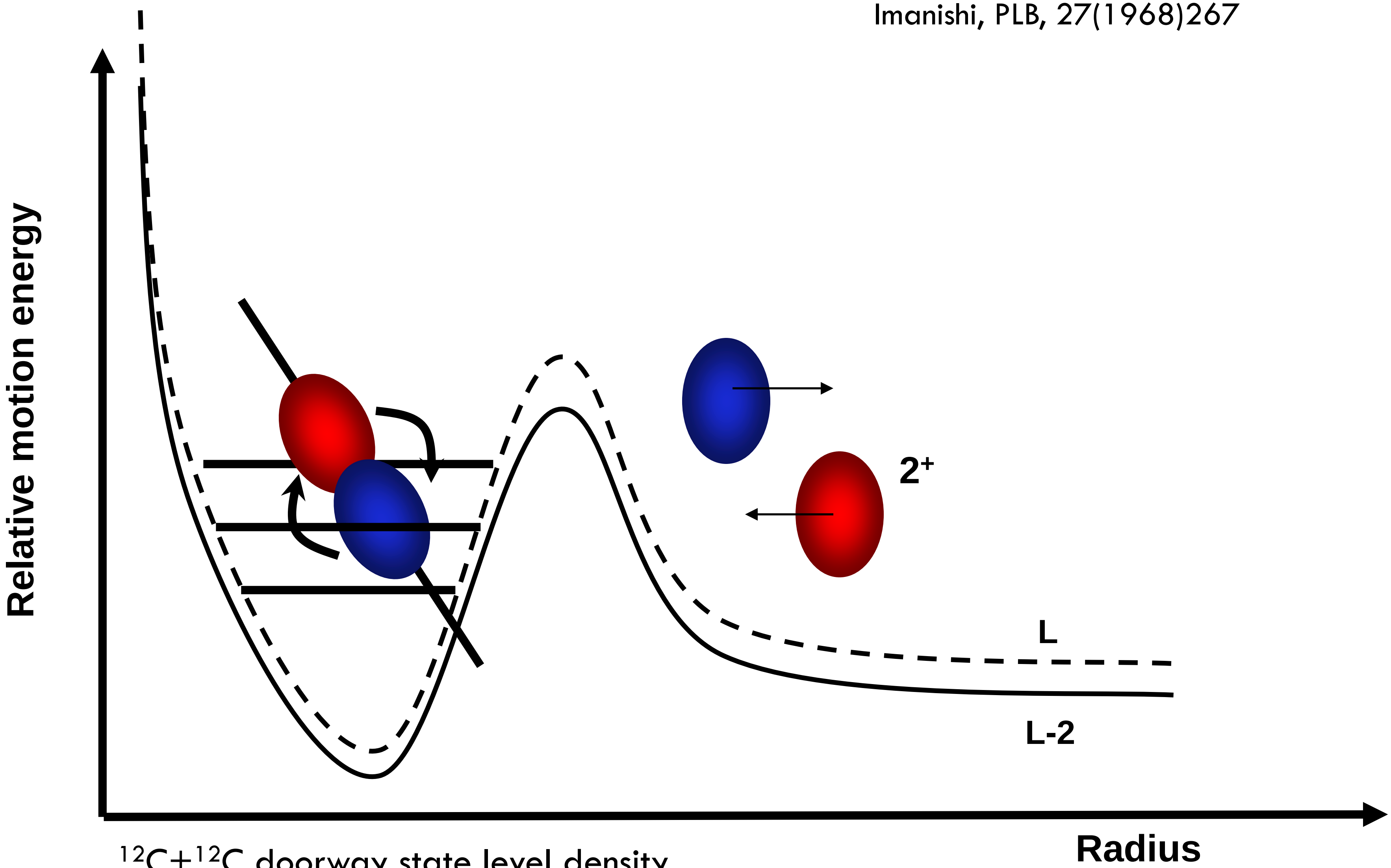
- For most energies, the $^{12}C+^{12}C$ cross sections are suppressed!

- 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?

Nogami-Imanishi Model

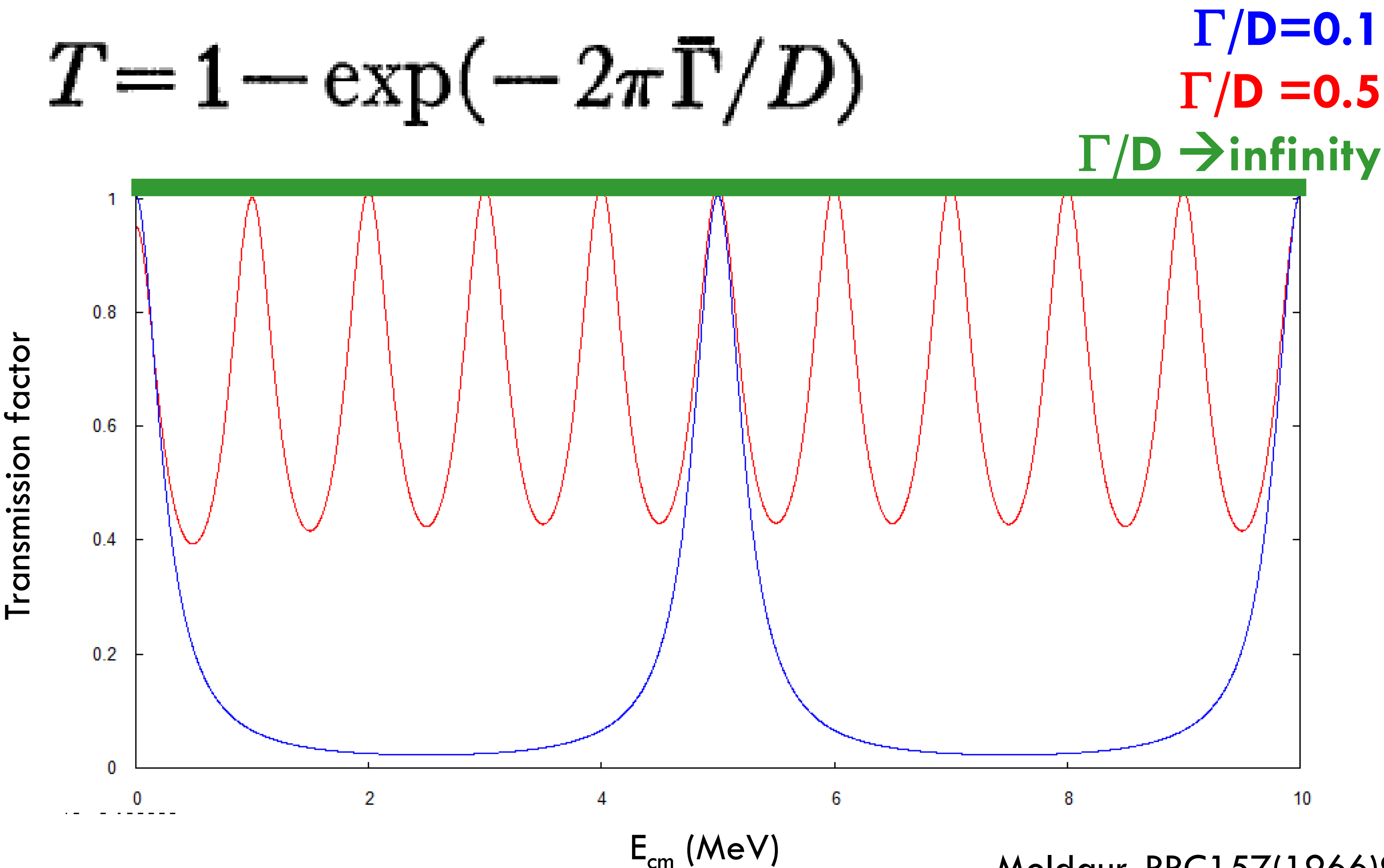
Imanishi, PLB, 27(1968)267



$^{12}C+^{12}C$ doorway state level density

Correlation between carbon isotopes

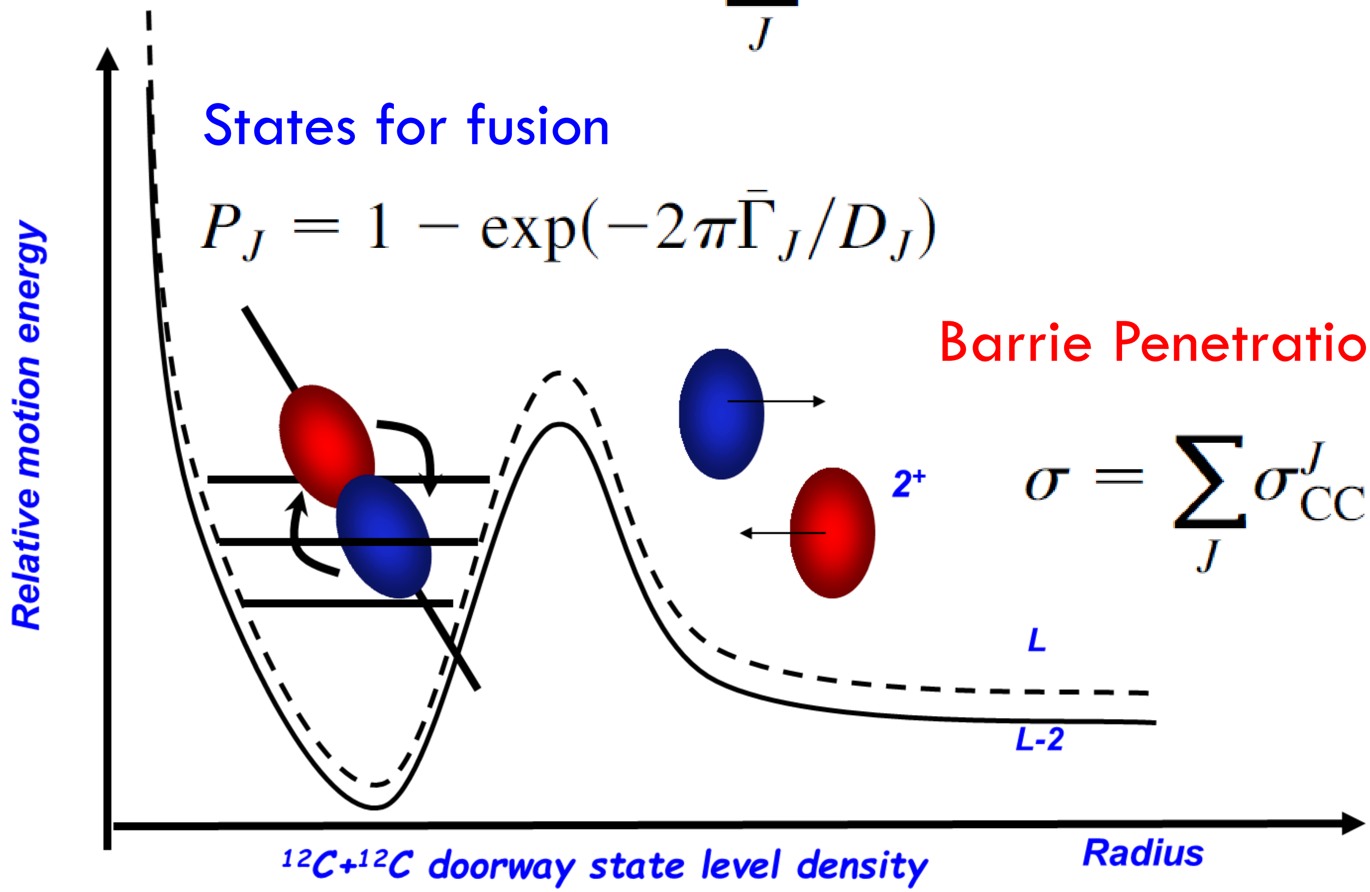
$$T = 1 - \exp(-2\pi\bar{\Gamma}/D)$$



Moldaur, PRC157(1966)907

Correlation between carbon isotopes

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



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

Correlation between carbon isotopes

$$\sigma = \sum_J \sigma_{\mathrm{CC}}^J P_J \qquad P_J = 1 - \exp(-2\pi\bar{\Gamma}_J/D_J)$$

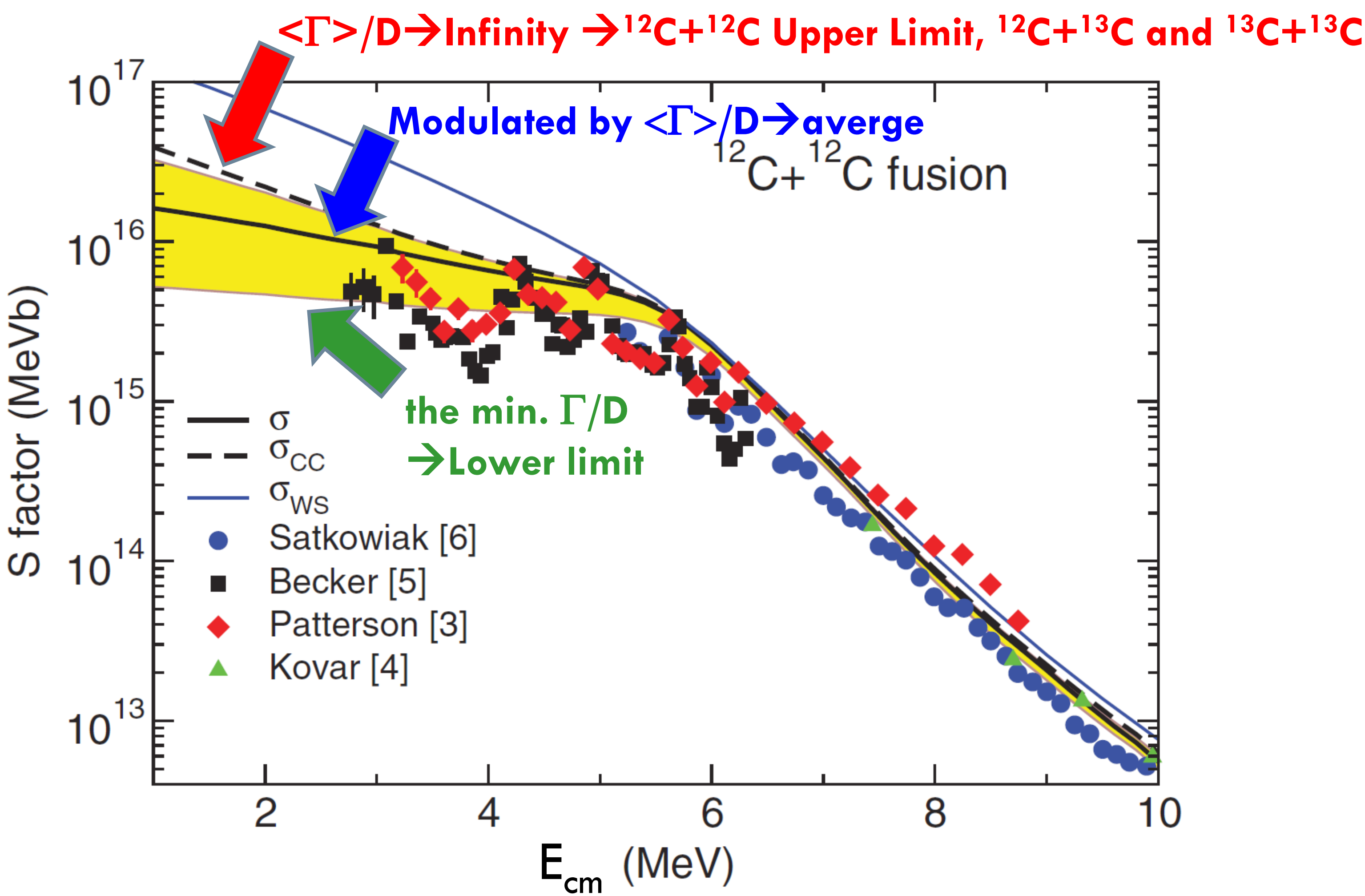
High level density systems: $^{12}C+^{13}C$, $^{13}C+^{13}C \rightarrow P_J=1$

Low level density system: $^{12}C+^{12}C$

System	Q(MeV)	Vc(MeV)	$(\Gamma/D)c$
12C+12C	13.9	6.7	0.7
12C+13C	16.3	6.56	120
13C+13C	22.5	6.48	2210

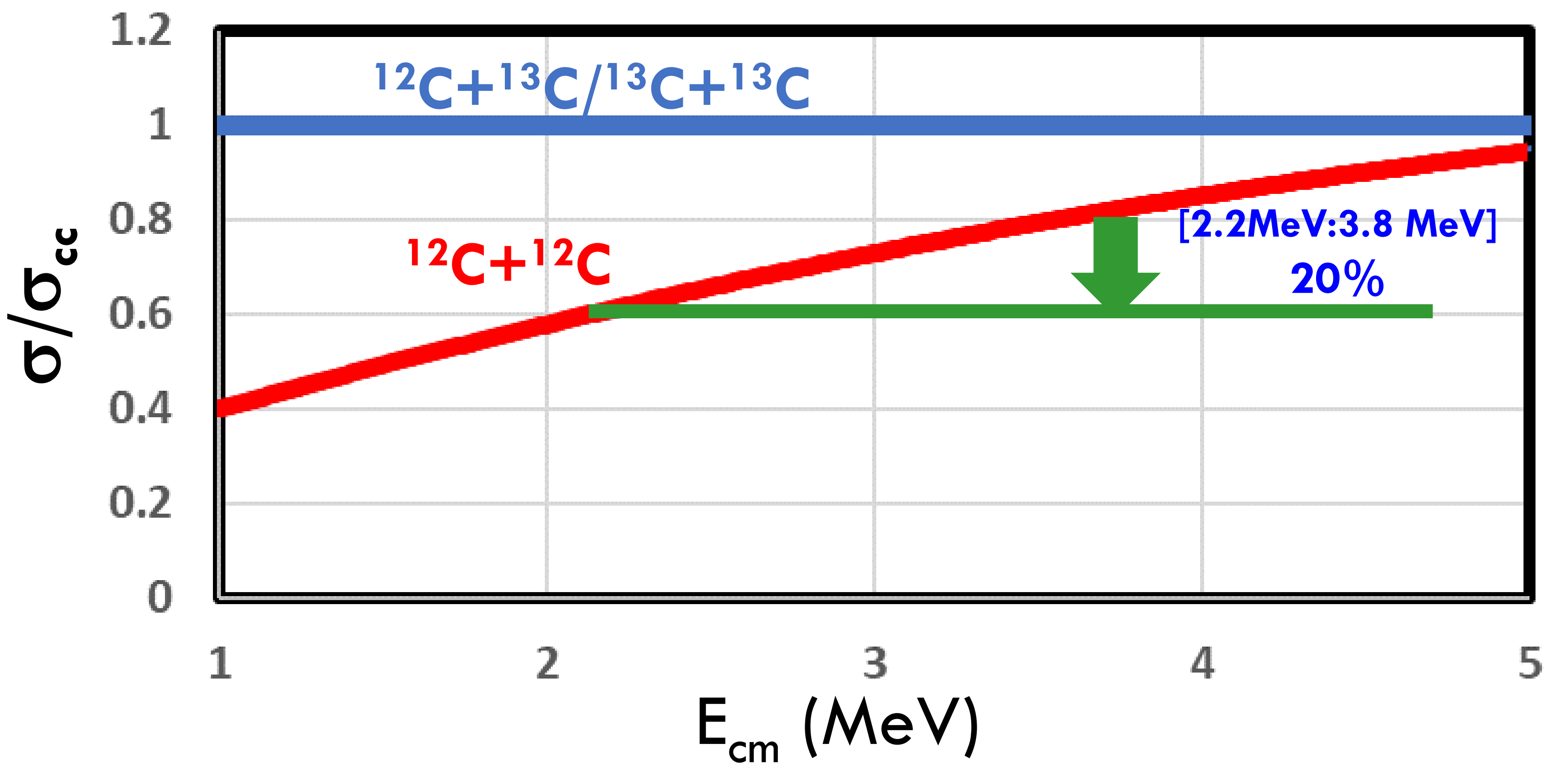
C.L. Jiang et al., PRL110, 072701 (2013)

Correlation between carbon isotopes



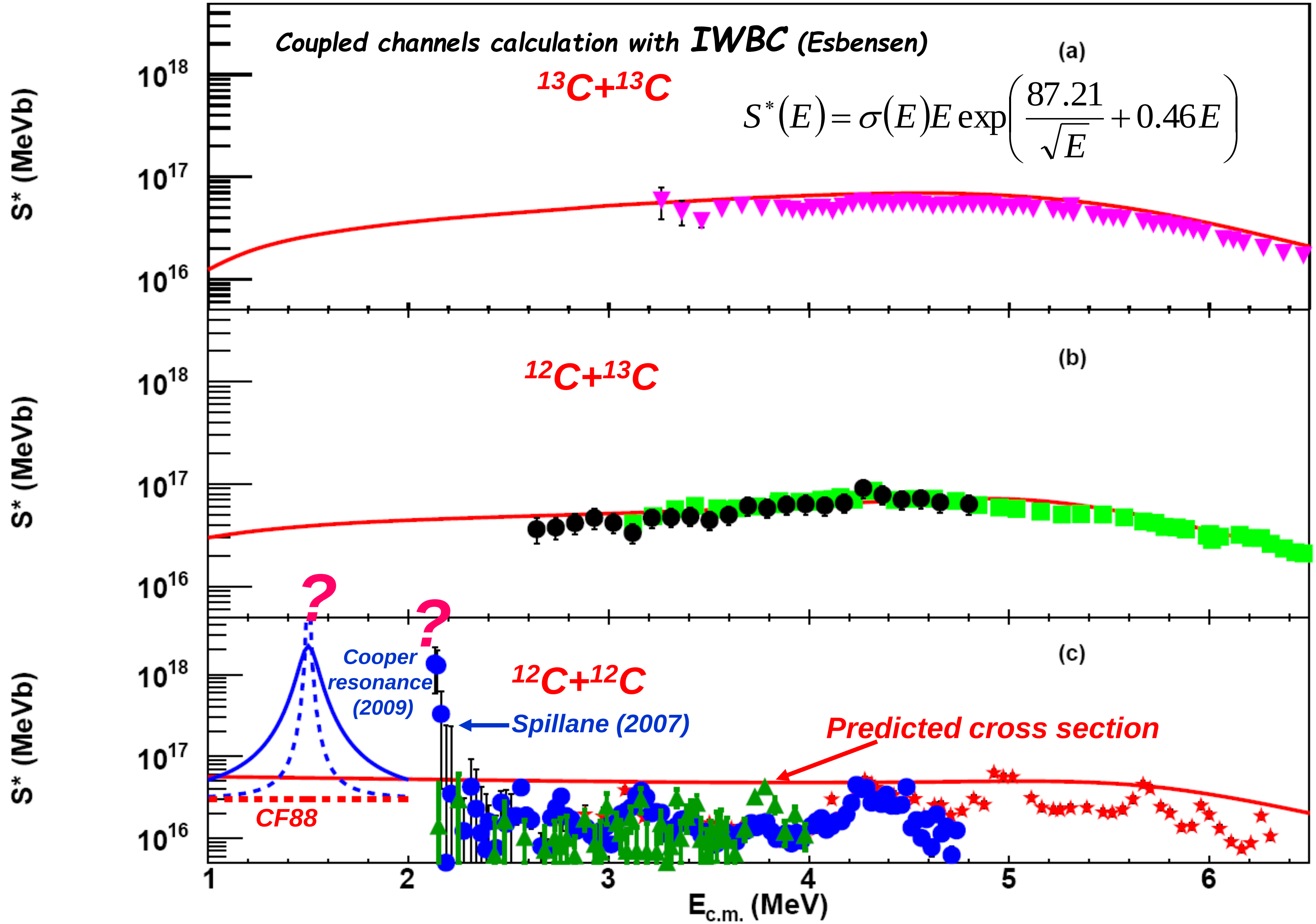
C.L. Jiang et al., PRL110, 072701 (2013)

Correlation between carbon isotopes



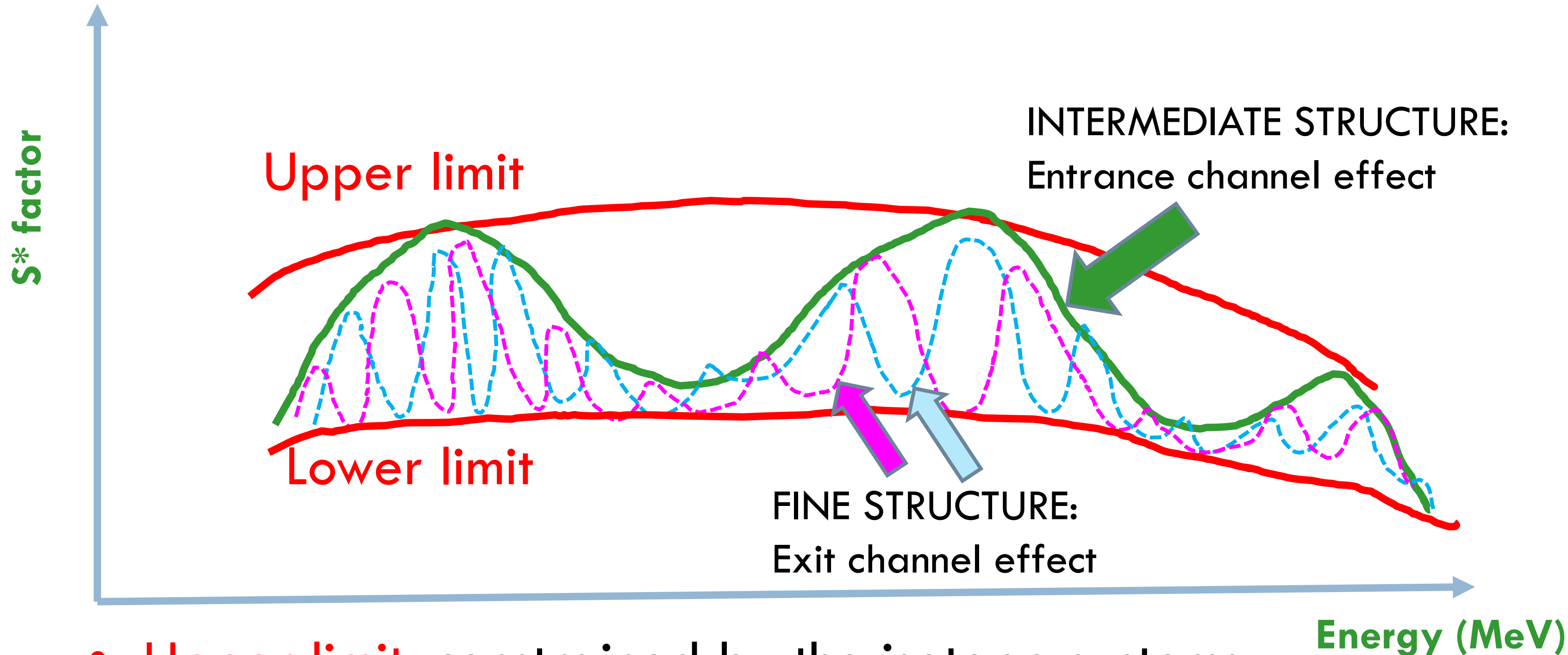
- Suppression of low level density is a slow varying effect
- Shape of averaged xsec is mostly determined by upper limit

Predicting $^{12}C+^{12}C$ upper limit with a constrained potential



H. Esbensen et al., Phys. Rev. C 84, 064613 (2011); Jiang et al.Phys.Rev.Lett. 110, 072701 (2013)
M. Notani et al., Phys. Rev. C 85, 014607 (2012)

Sketch of $^{12}C+^{12}C$ by An Experimentalist

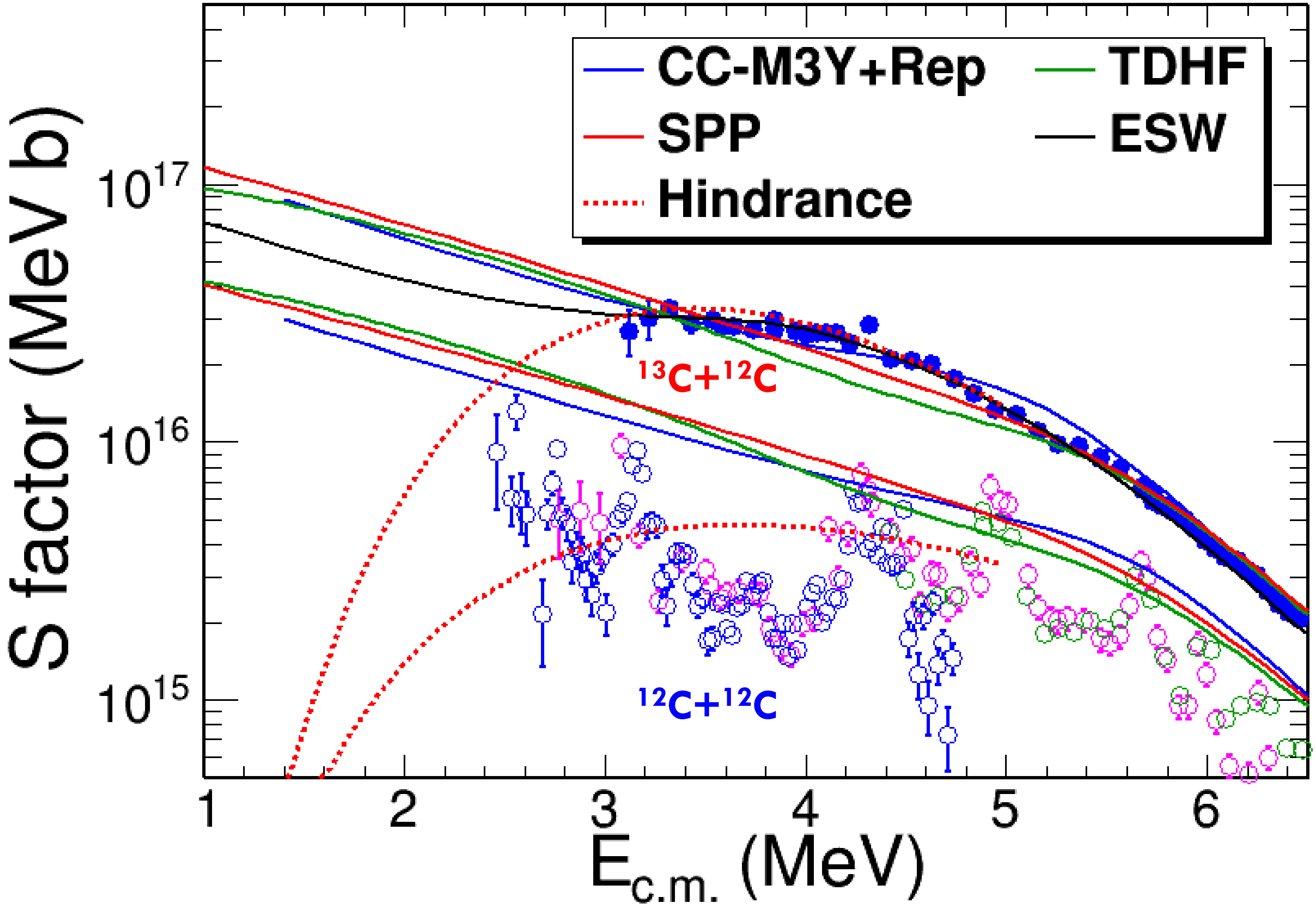


- Upper limit: constrained by the isotope systems
- Intermediate structure: constrained by the sum of all the observed channels
- Fine structure: $a+^{20}Ne$, $^{24}Mg(a,a')$……

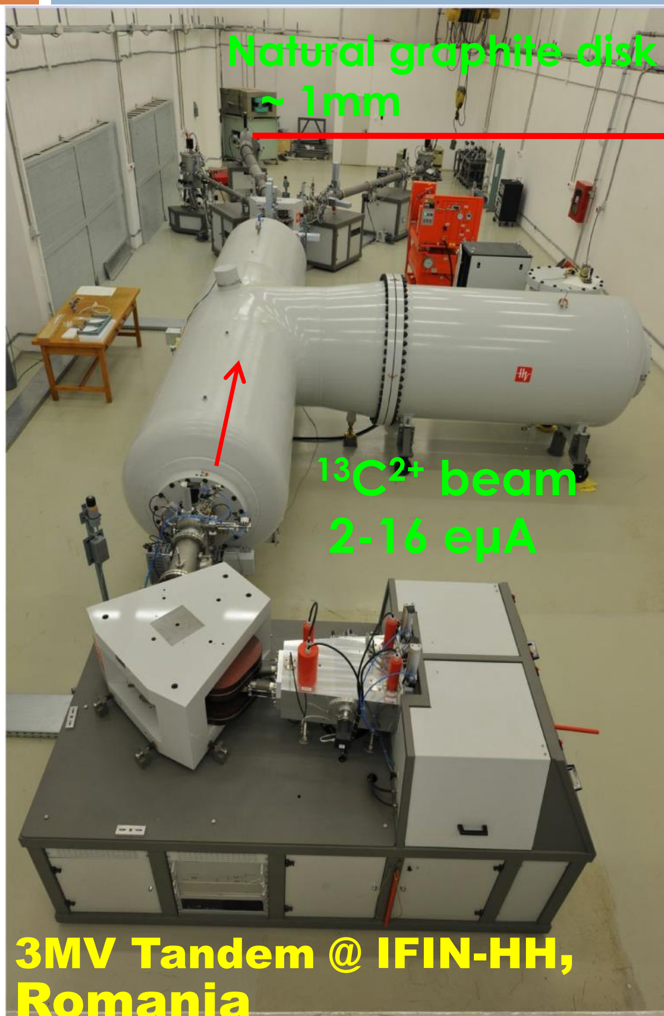
Test of predictive power of models

N.T. Zhang, X.Y. Wang, H. Chen, Z.J. Chen, W.P. Lin, W.Y. Xin, and S.W. Xu
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
D. Tudor, A.I. Chilug, I.C. Stefanescu, M. Straticiuc, I. Burducea, D.G.
Ghita, R. Margineanu, C. Gomoiu, A. Pantelica, D. Chesneanu, and L. Trachey
Horia Hulubei National Institute of Physics and Nuclear Engineering, IFIN-HH, Magurele 077125, Romania
X.D. Tang
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China and
Joint department for nuclear physics, Lanzhou University and Institute of Modern Physics,
Chinese Academy of Sciences, Lanzhou 730000, China
B. Bucher
Idaho National Laboratory, Idaho Falls, Idaho 83415, USA
L.R. Gasques
Departamento de Fsica Nuclear, Instituto de Fsica da Universidade de S~ao Paulo, S~ao Paulo, Brazil
K. Hagino
Department of Physics, Tohoku University, Sendai 980-8578, Japan and
Research Center for Electron Photon Science, Tohoku University, 1-2-1 Mikamine, Sendai 982-0826, Japan
S. Kubono
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China and
RIKEN Nishina Center, RIKEN, 2-1 Hirosawa, Saitama 351-0198, Japan
Y.J. Li and C.J. Lin
China Institute of Atomic Energy, Beijing 102413, P.R. China
A.S. Umar
Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA
Y. Xu
Extreme Light Infrastructure-Nuclear Physics, RO-077125, Magurele, Romania

Test of Predictive Power



$^{13}C+^{12}C$ Experiment

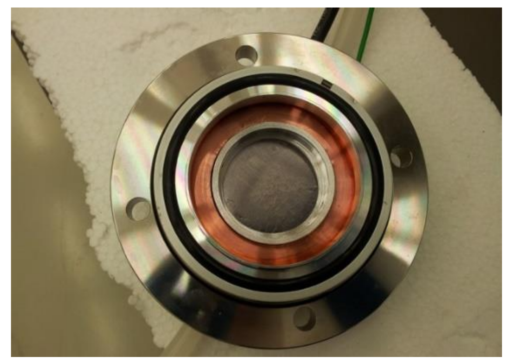


Online irradiation

$^{12}C(^{13}C, p)\ ^{24}Na$

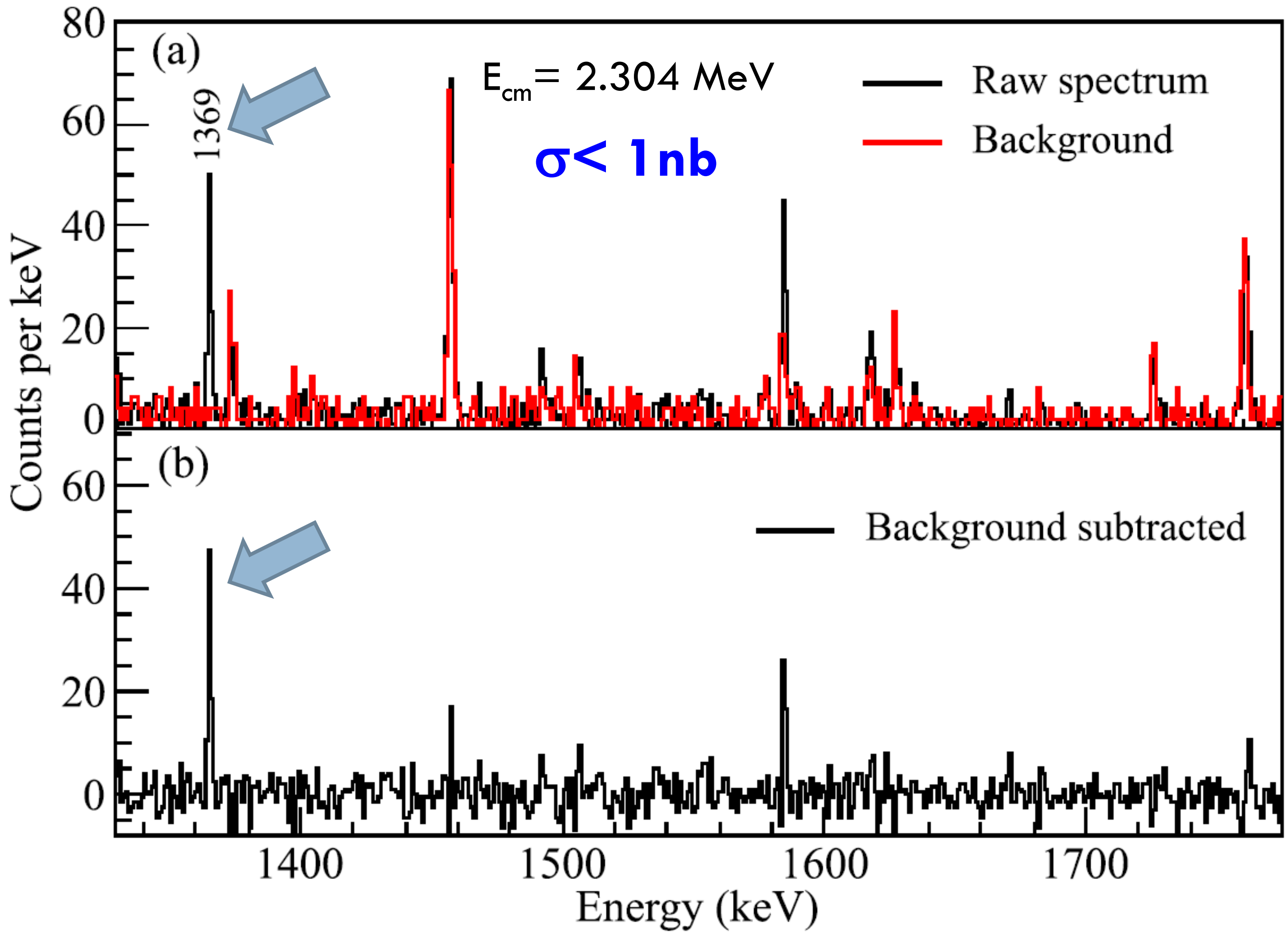
^{24}Na: $T_{1/2}$=15 hr

1369-2754 keV γ rays



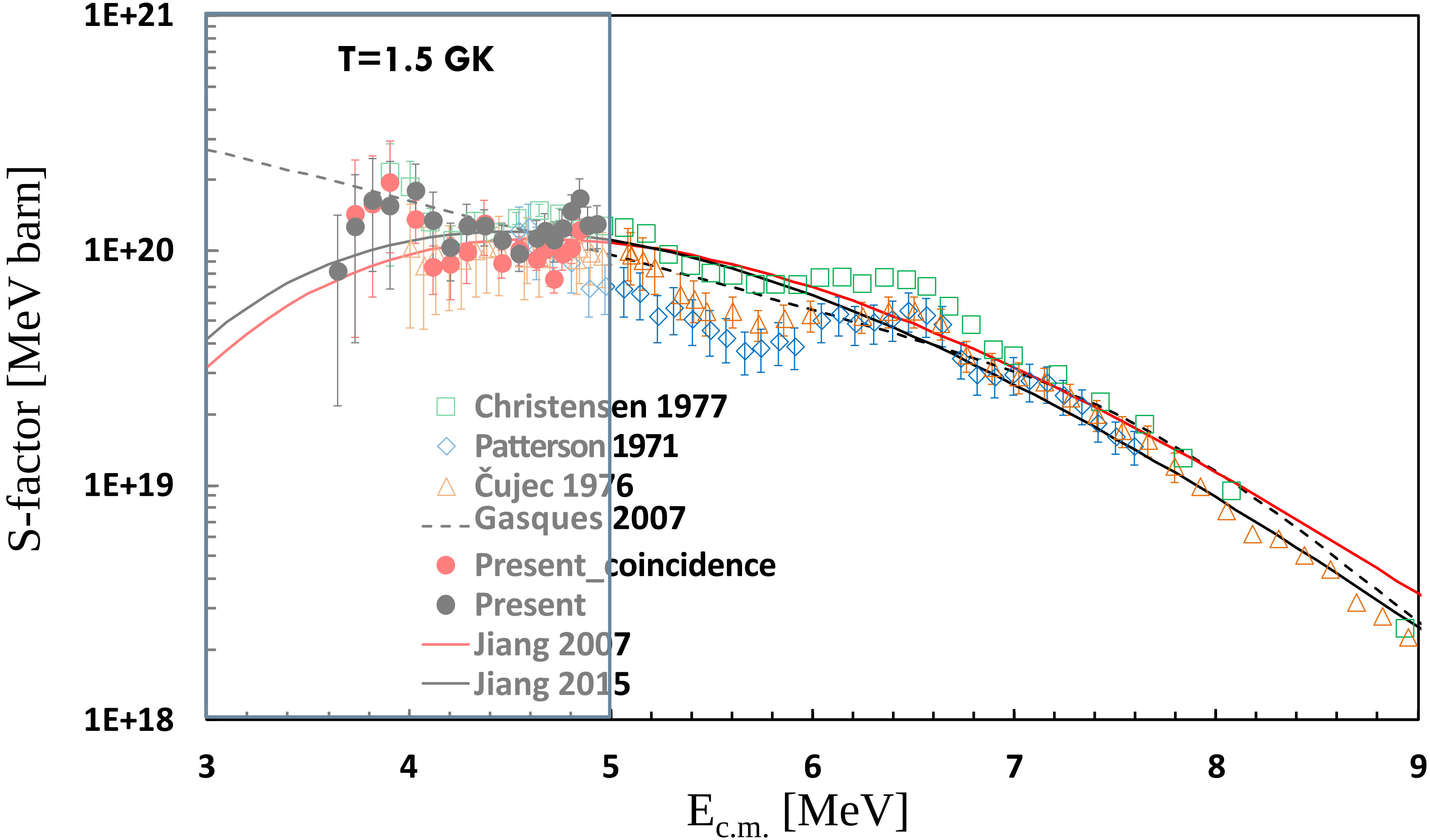
- HF theory calibrated by exp. → Branching ratio
- Obtaining the total fusion cross section

Low level background counting



Radiations: 3.4 days measurements: 3.9 days

$^{12}C+^{16}O$: S factor maxima?

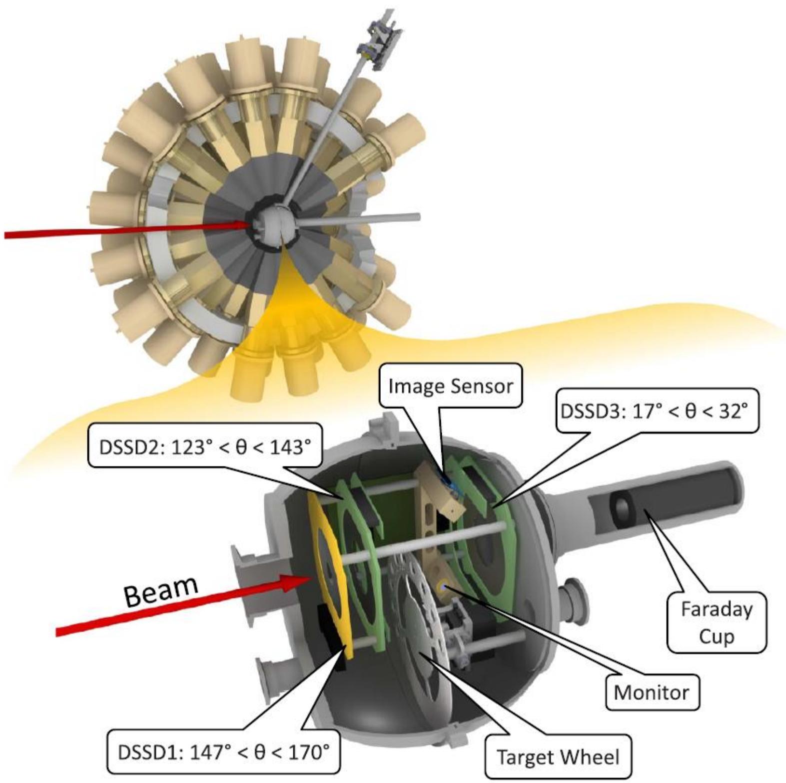


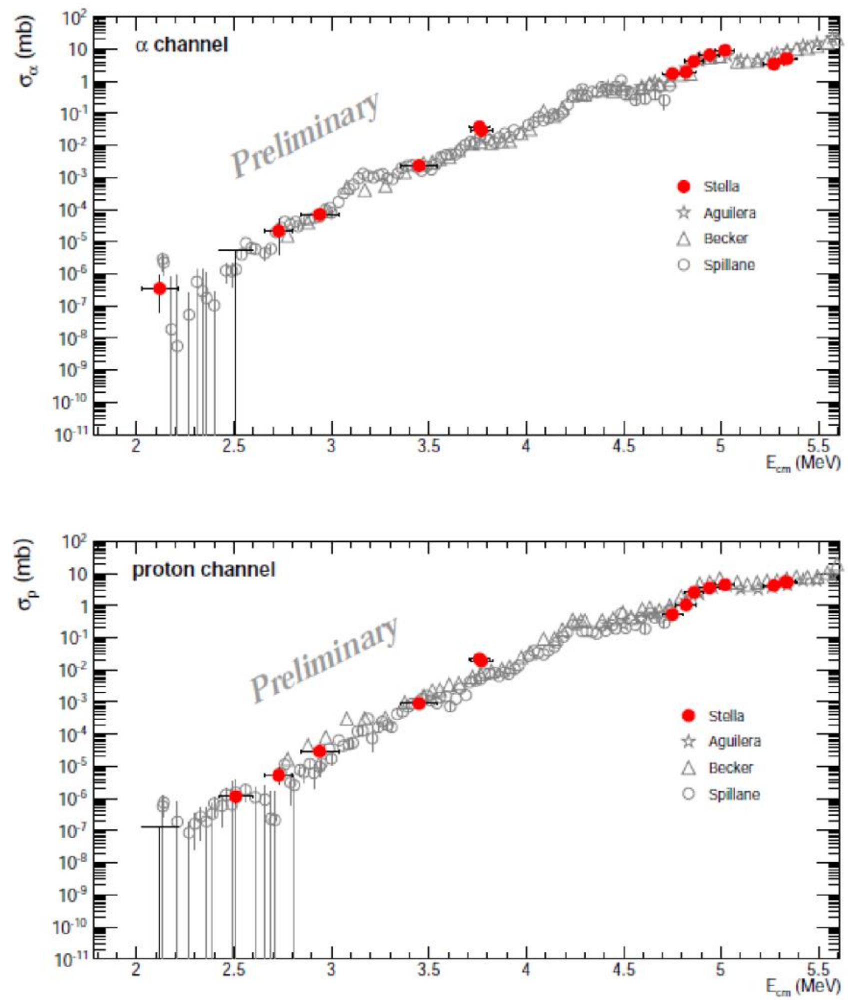
- There might be a s-factor maxima. But resonant-like structure complicates….
- Studying of $^{13}C+^{16,17,18}O$, $^{12}C+^{17,18}O$ will be highly valuable

X. Fang et al., PRC(2018)

Particle-Gamma Coincidence

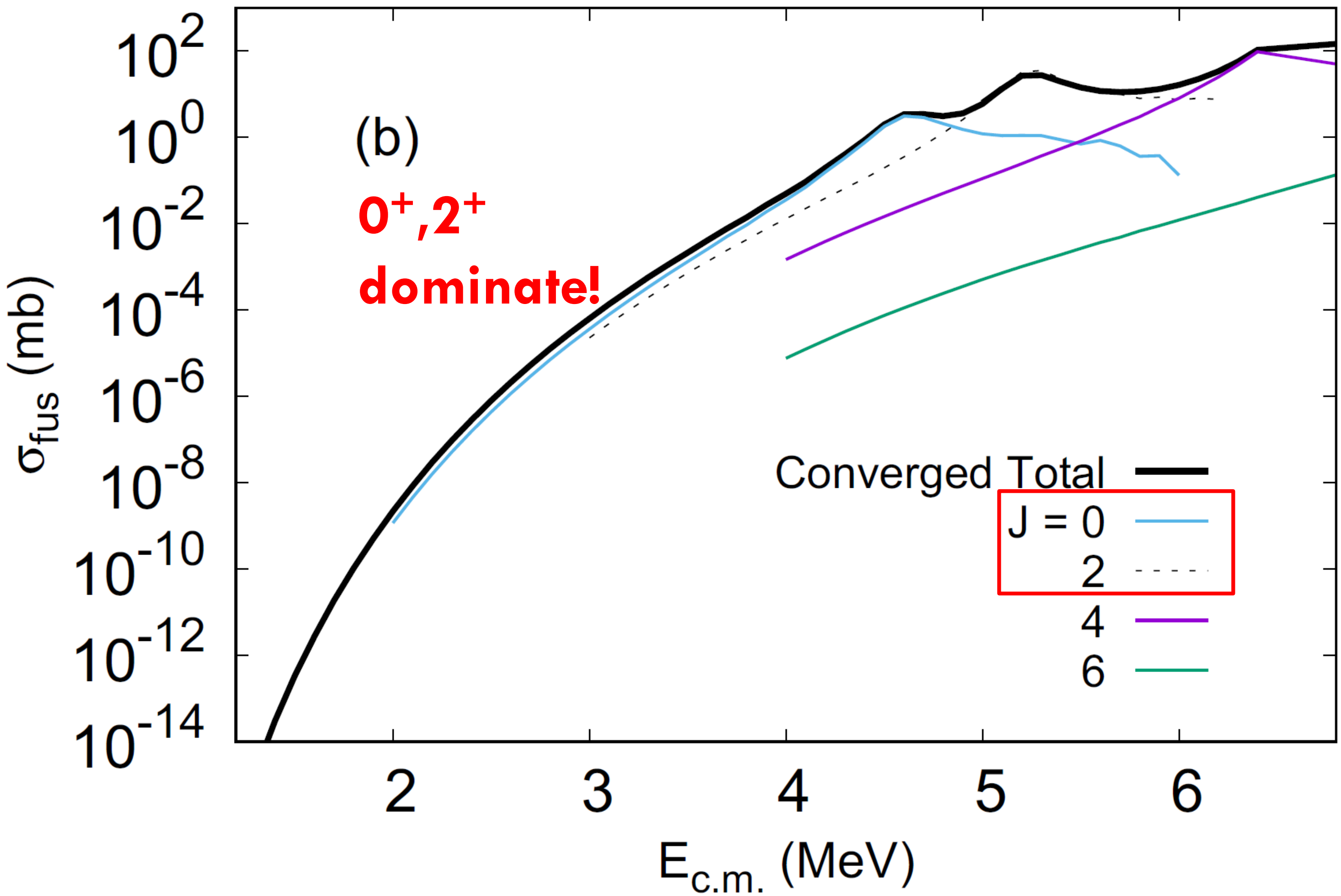
- Developed at ANL for the study of $^{12}C+^{12}C$ (Silicon array + GammaSphere)
- New experiment at France (Silicon array + LaBr)





G. Fruet, Ph. D Thesis, Universite de Strasbourg

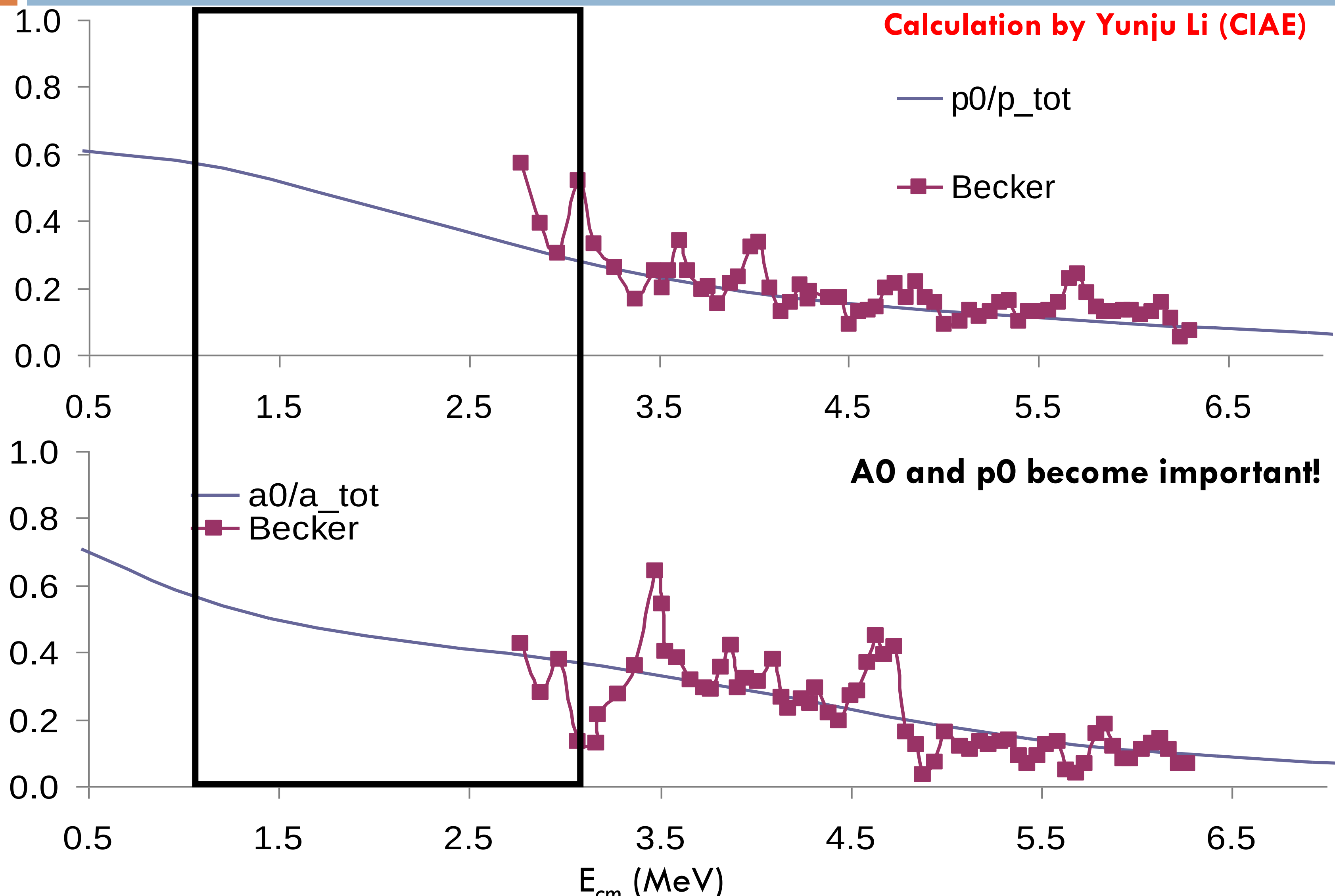
Spin population at Lower Energies



A. Diaz-Torres and M. Miescher, PRC **97**, 055802 (2018)

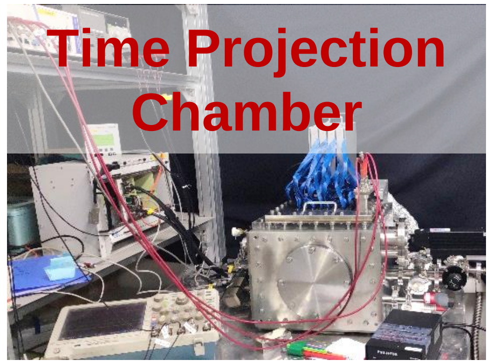
Branching ratio for ground state transitions

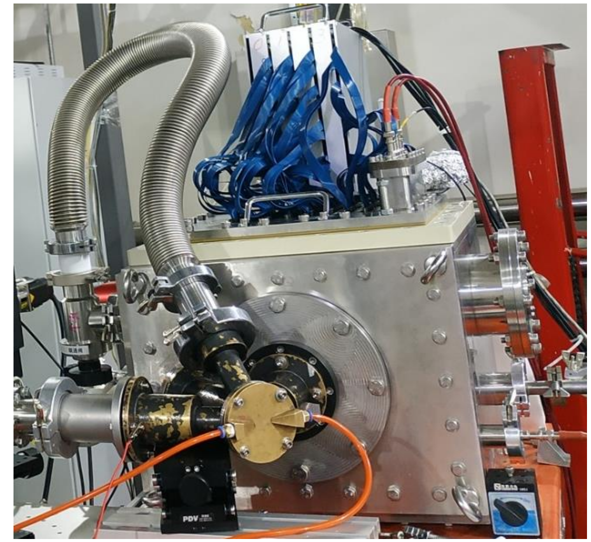
Only gamma detection is not sufficient……

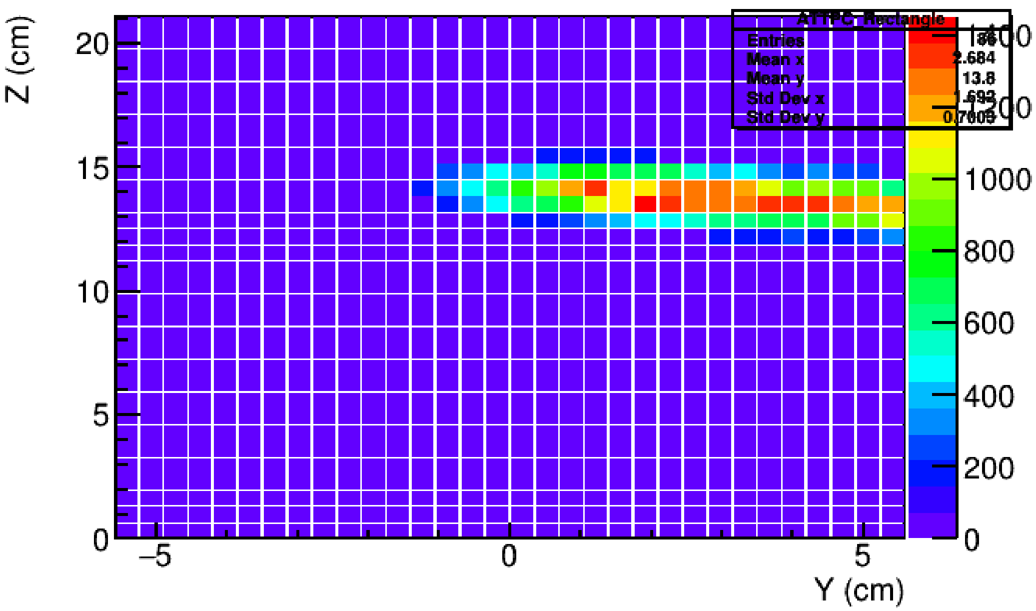


New approaches: Time Projection Chamber

$^{12}C(^{12}C,a_0)$ at E_{cm}=3 MeV



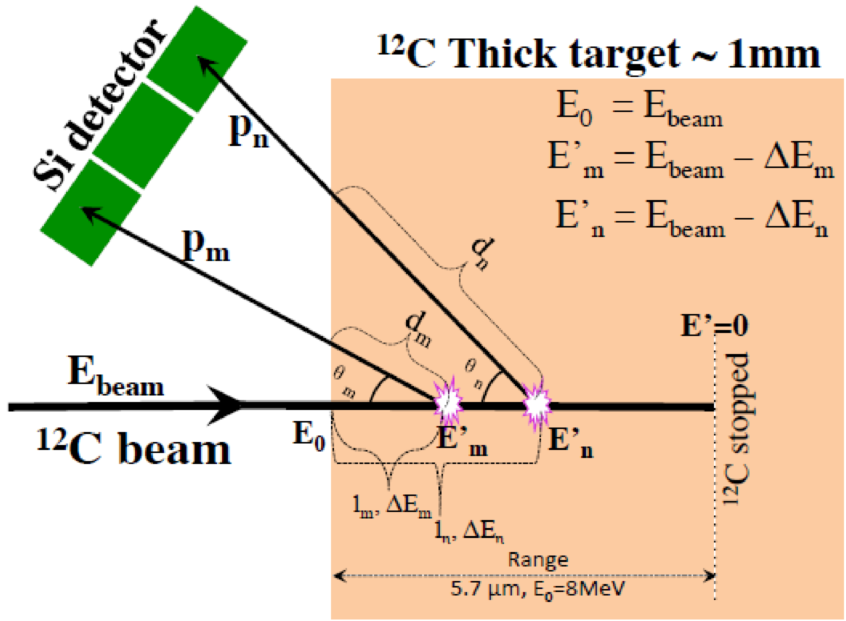


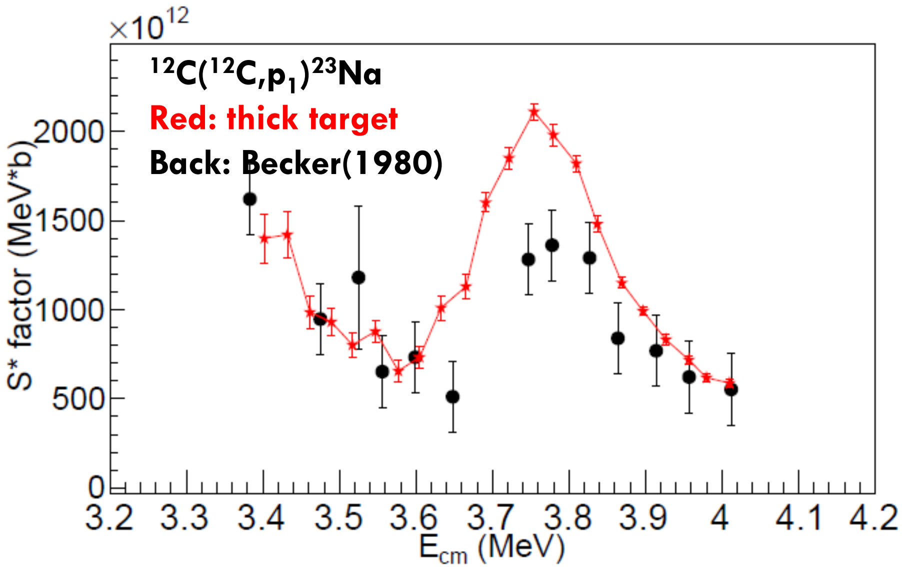


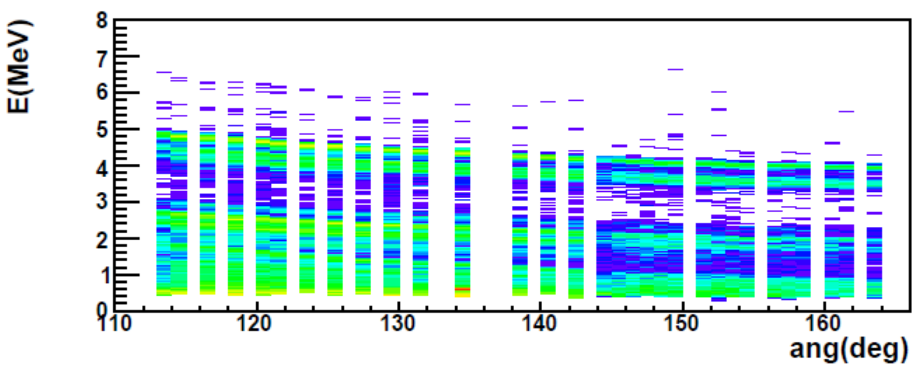
- LINAC: High Intensity beam up to few hundreds of puA
- TPC: Ultra sensitive tracking detector
- Background: zero background in 10 hour

N.T. Zhang, C.G. Lu, Z.C. Zhang, X.Y. Wang et al, IMP

New approaches: Efficient Thick Target







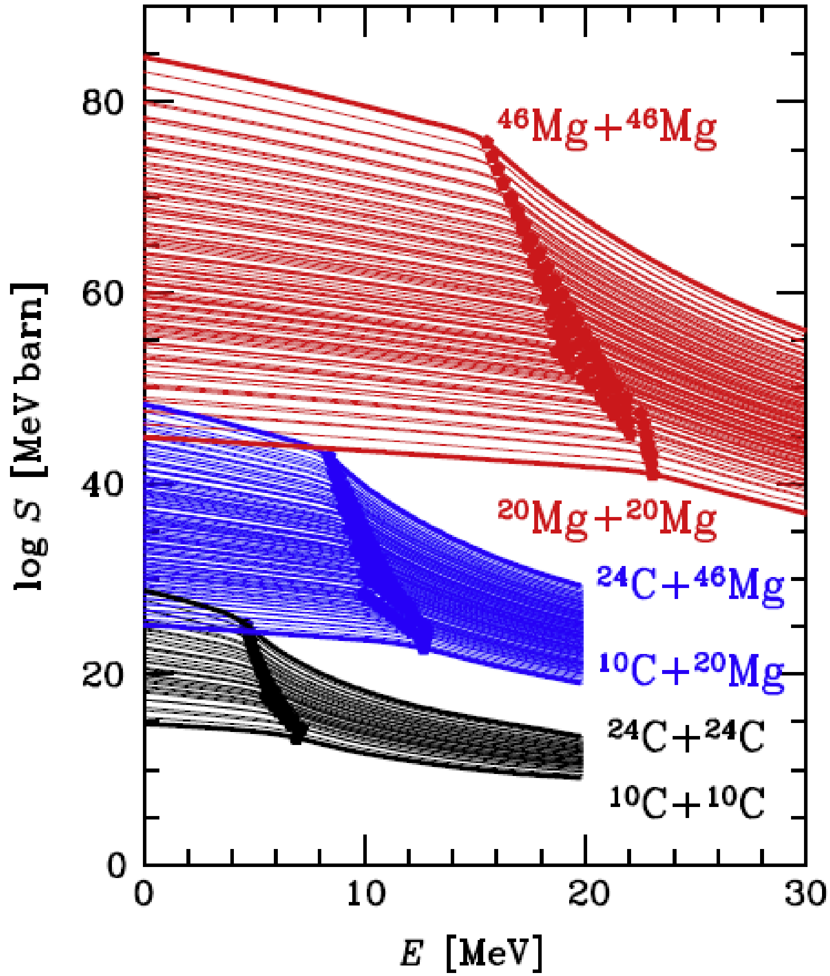
A clear identification of reaction channel such as STELLAR

- possible to determine the reaction energy of ^{12}C using the proton energy and angle
- 10 energy pt. scanning→1 fixed energy

X.D. Tang, X. Fang, B, Bucher, W.P. Tan et al. Arxiv1905.02054; Accepted by NST

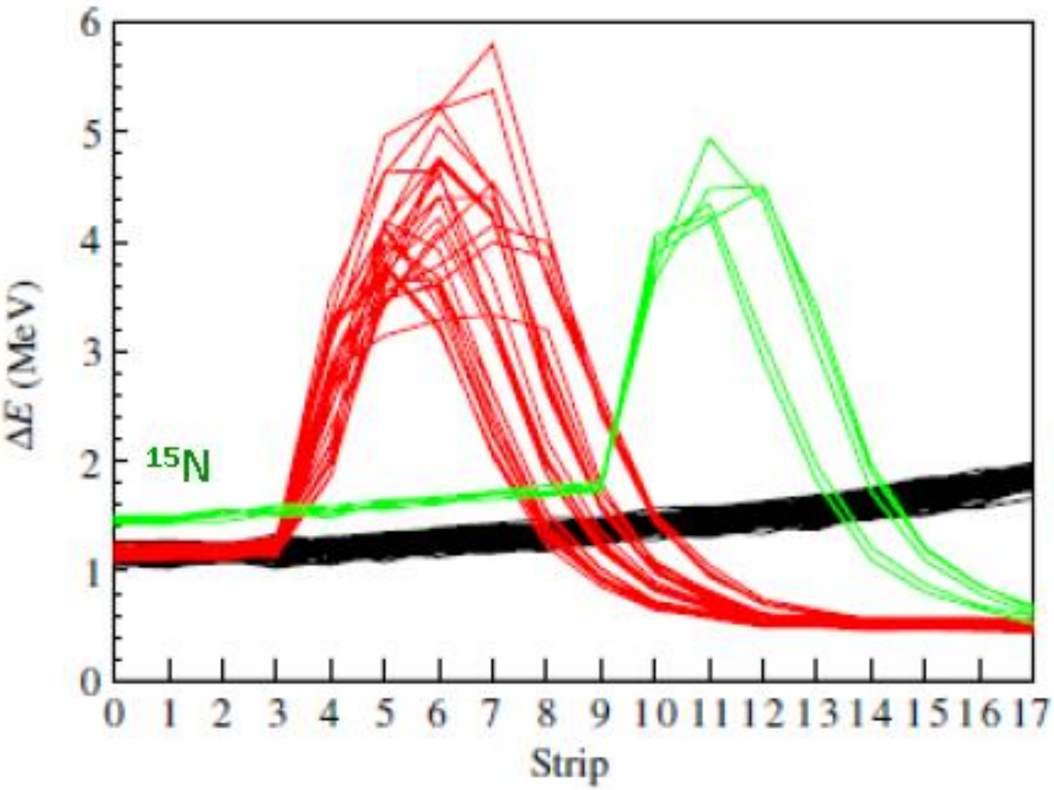
Fusion reactions of n-rich nuclei

H.I. Fusion in crust

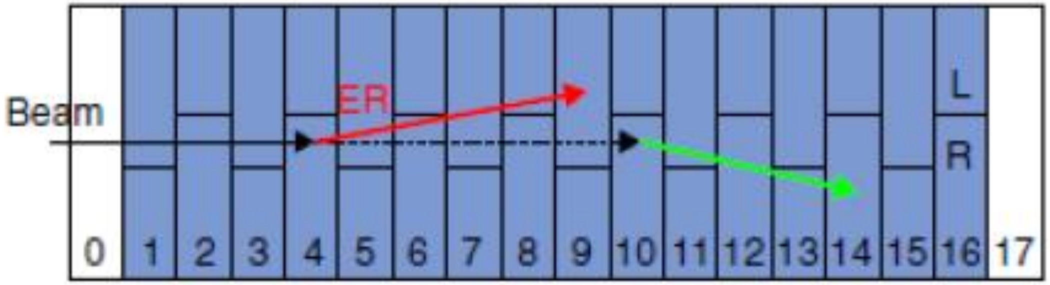


M. Beard et al. / Atomic Data and Nuclear Data Tables 96 (2010) 541–566

Fusion $^{15}C + ^{12}C$ (CH_4)

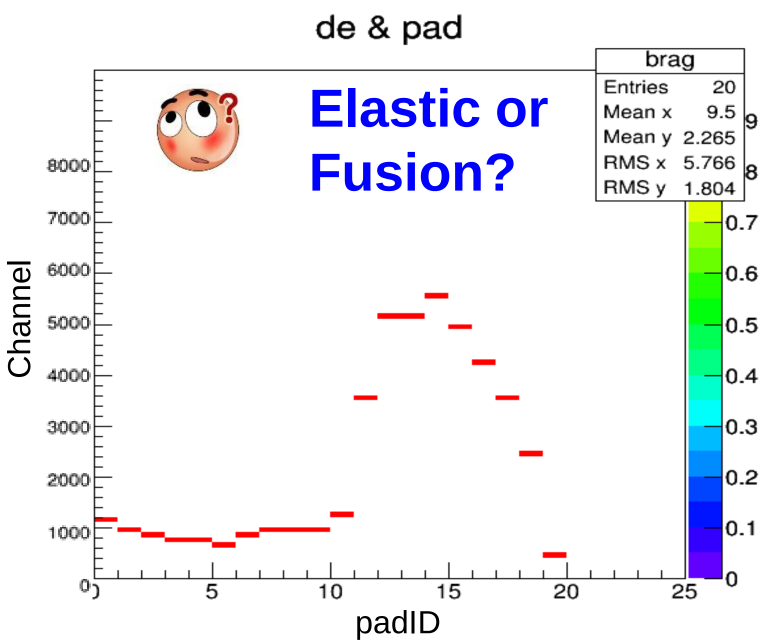


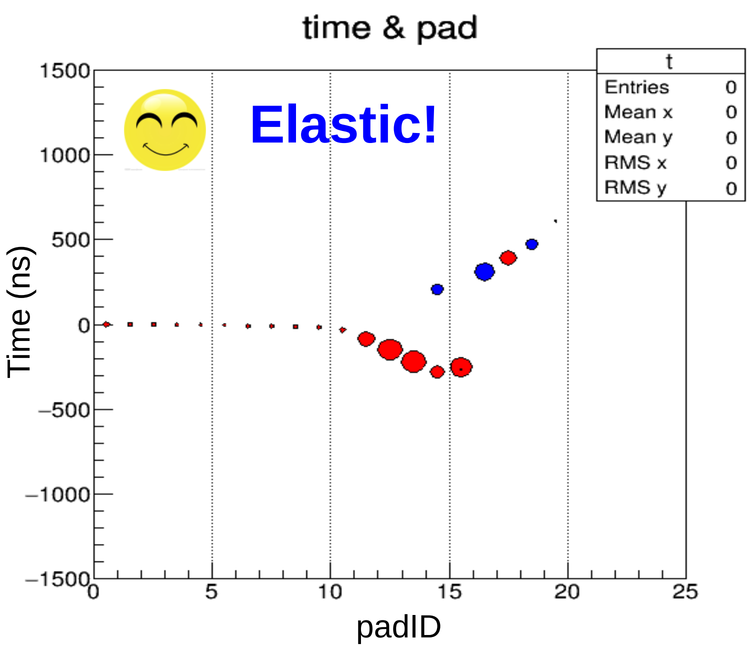
Black: beam of ^{15}C
Red: Fusion between ^{15}C and ^{12}C
Green: fusion between ^{15}N and ^{12}C



 Rehm (ANL)

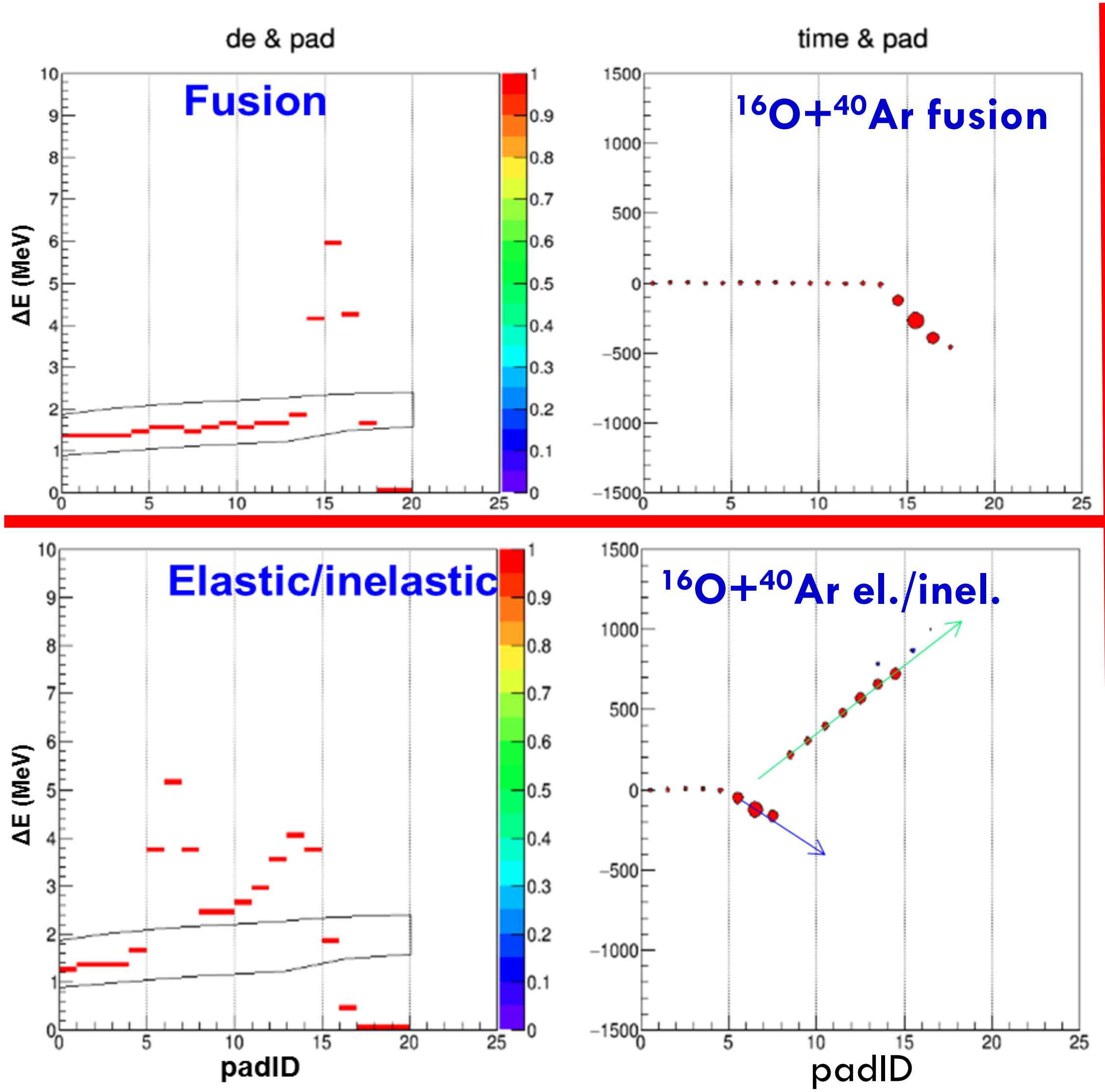
Limitation of MUSIC

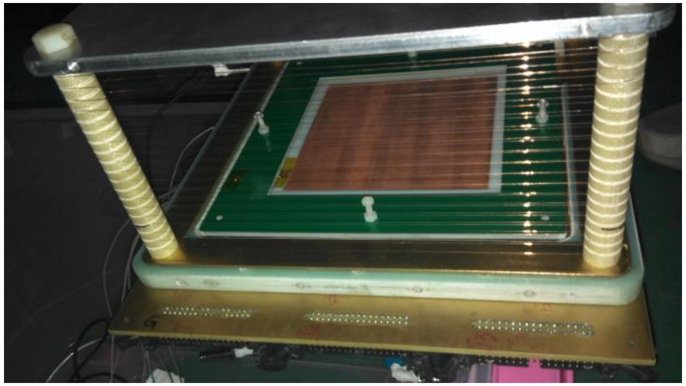


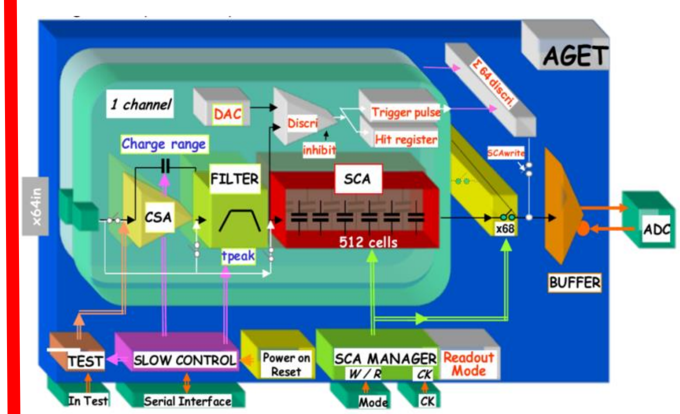


With drift time, the fusion cross section of $^{13}C+^{12}C$ could be pushed down to 6 MeV. About 17% systematic error is due to misjudge of elastic scattering.

EXPLOSIVE BURNING (fusion with n-rich beam)

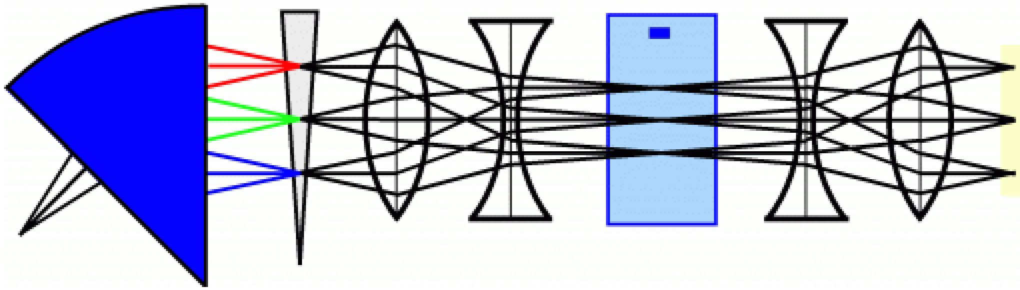






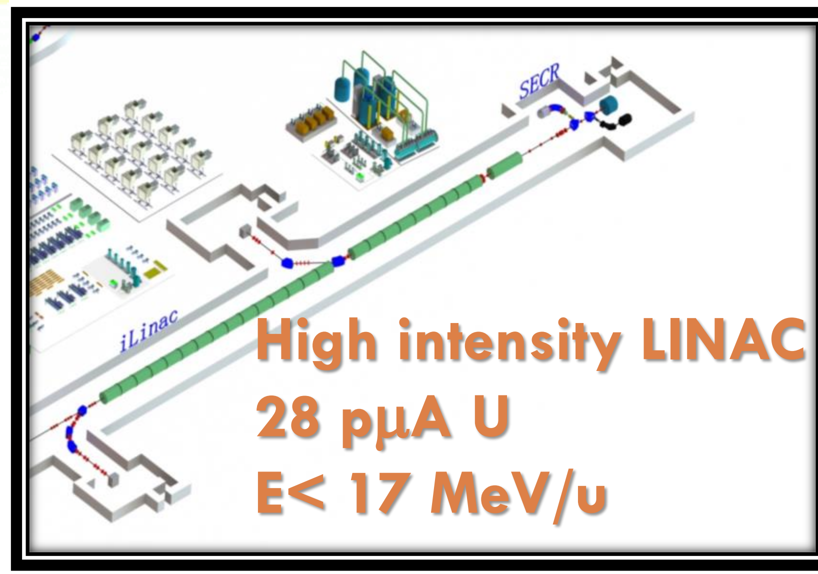
- The first TPC experiment at HIFRL
- Fusion inside of neutron star crust: $^{24}O+^{24}O$

Low energy n-rich beam facilities



RIBLL1 at IMP, CRIB(CNS) at RIKEN
OEDO (CNS) at RIKEN (Present)

KOBRA at RAON (2021)

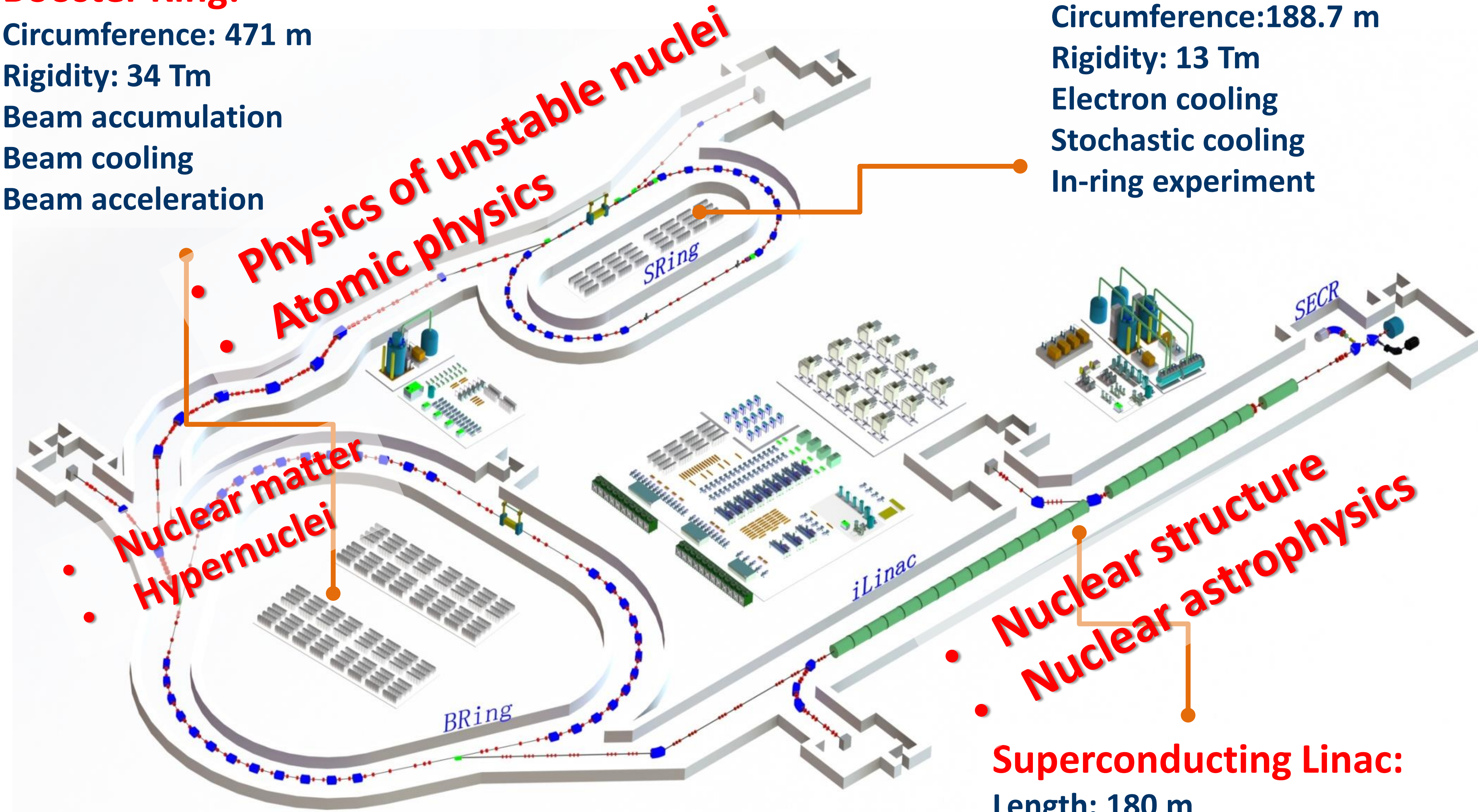


High Intensity heavy ion Accelerator Facility (HIAF)

HIAF: 2018-2025

Booster Ring:
Circumference: 471 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

Spectrometer Ring:
Circumference:188.7 m
Rigidity: 13 Tm
Electron cooling
Stochastic cooling
In-ring experiment



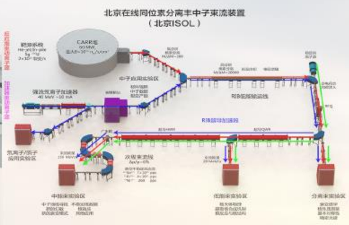
Superconducting Linac:
Length: 180 m
Energy: 17 MeV/u (U^{34+})
CW and pulse modes (1 emA)

Courtesy of X.H. Zhou

第一届核物理青年科学家学校

The 1ST NUclear physics School for Young Scientists (NUSYS)

Aug.12nd - Aug.17th 2019 *Lanzhou · China* *https://indico.ihep.ac.cn/event/9962*



*** The School Master ***
Y.L. Ye (PKU)

*** The Organizing Committee ***

D.Q. Fang (FDU)	B. Guo (CIAE)
Z. Liu (IMP)	Y.F. Niu (LZU)
B.H. Sun (BUAA)	X.D. Tang (IMP)
Z.G. Xiao (THU)	X.F. Yang (PKU)

Core Courses

Nuclear Structure	Theory	H. Toki, RCNP
	Experiment	A.N. Andreyev, York U
Nuclear Reaction	Theory	M. Kimura, Hokkaido U
	Experiment	G.V. Rogachev, TAMU
Nuclear Astrophysics	Theory	M. Lugaro, HAS
	Experiment	H. Yamaguchi, U. Tokyo
Beam Optics		D. Bazin, MSU

Frontier Lectures

The Frontiers of Nuclear Physics	H. Sakurai, RIKEN
Nuclear Cluster	Y.L. Ye, PKU
High Energy Nuclear Physics	Y.G. Ma, FDU / SINAP
Hypernuclear Physics	T. Saito, RIKEN
Active Target Experiment	D. Bazin, MSU
Future Facilities In Asia	X.H. Zhou, IMP W.P. Liu, CIAE S.C. Jeong, RISP

- POSTER: Poster abstract+Recommendation are mandatory **DEADLINE: JUNE 3, 2019**
- FREE: Local expense is covered by the school
- AWARD: The 3 best presenter will receiver “ANPHA Awards for young scientist”

Summary

- $^{12}C+^{12}C$

→S-factor maximum does not exit in carbon isotope systems

→Confirm other model prediction→More reliable upper and lower limits

→New techniques needed

- Fusion with neutron-rich beams at new facilities
- Collaboration will end up with better science!