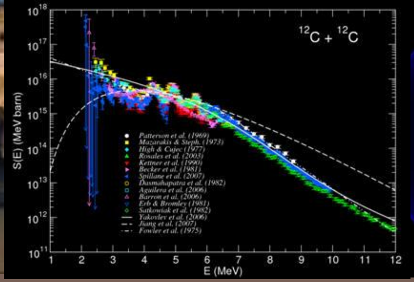

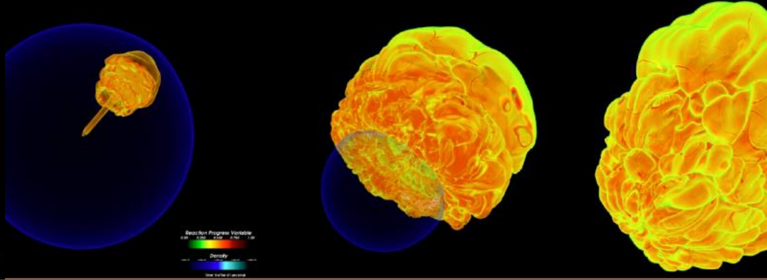

HEAVY ION FUSION REACTIONS IN STARS

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Lanzhou University and Institute of Modern Physics, CAS, China

SAKURA 2019, Tokai, Japan, Mar. 25-27, 2019

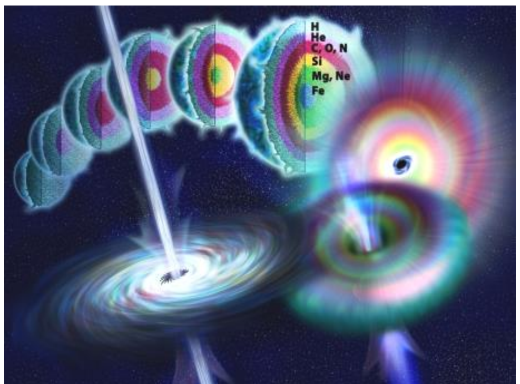
Outline

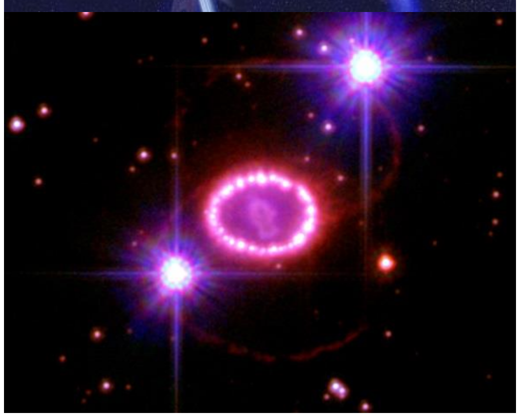
- Heavy ion fusion reactions in stars
- $^{12}C+^{12}C$ at stellar energies
  - → Brief review
  - → Correlation between carbon isotopes
  - → Upper limit
  - → Test of the predictive power of models

- Fusion reaction with n-rich beams
- Summary

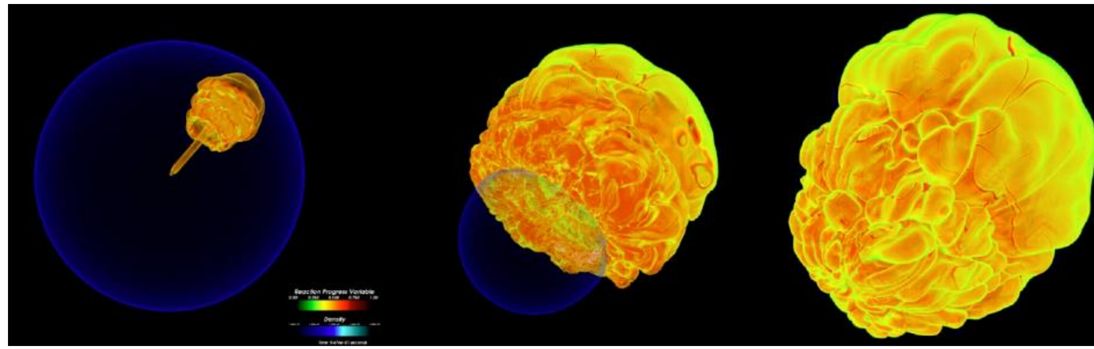
Carbon burning in the universe

Nucleosynthesis in massive stars

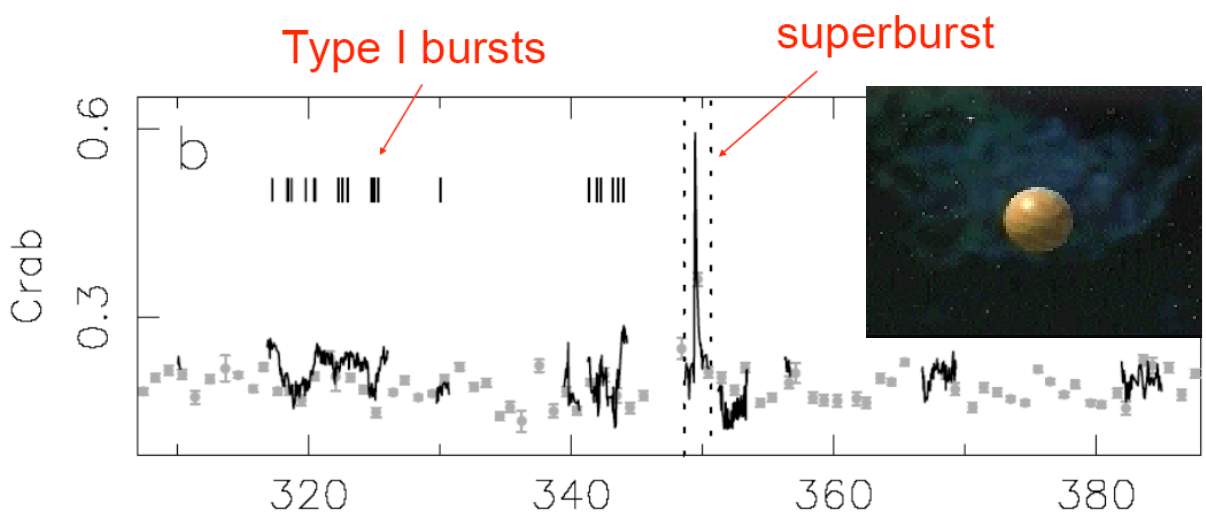




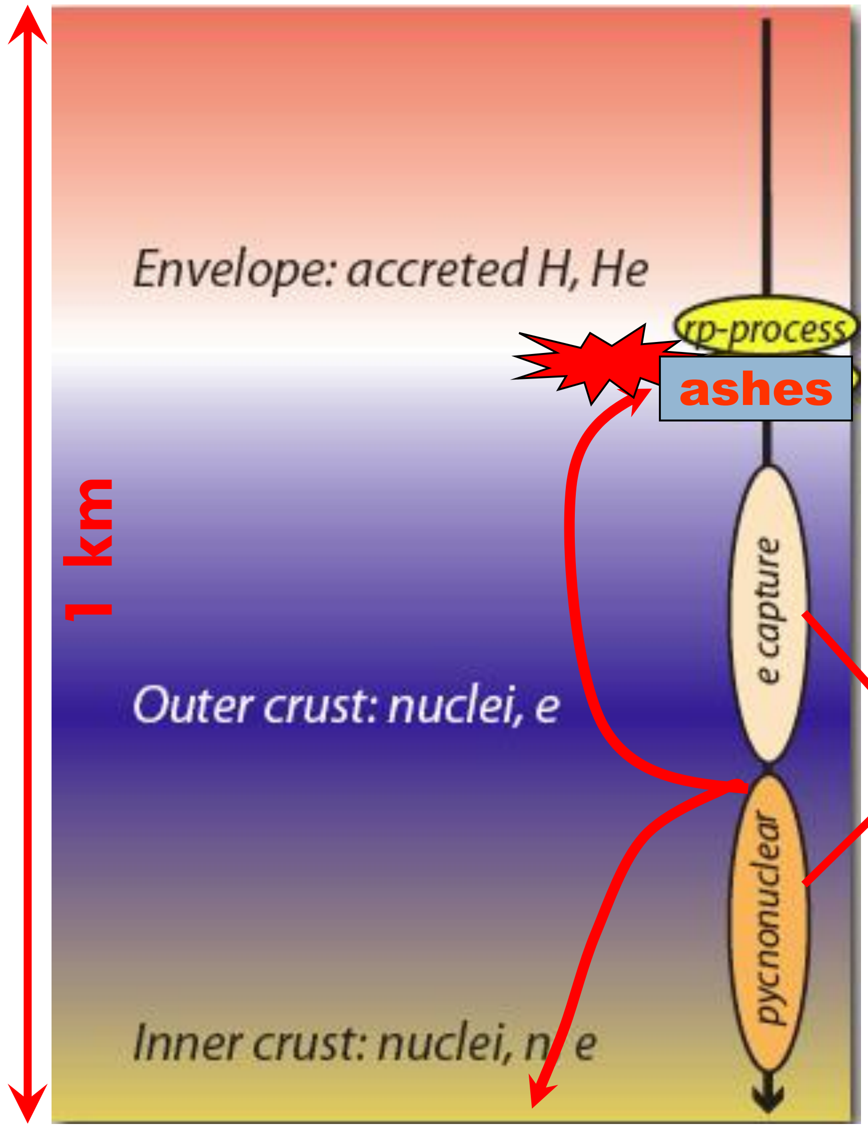
Ignition conditions in type Ia supernovae



Candidate for Superburst ignition



Superburst: ignited by Carbon burning



Picture by E. Brown (MSU)

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

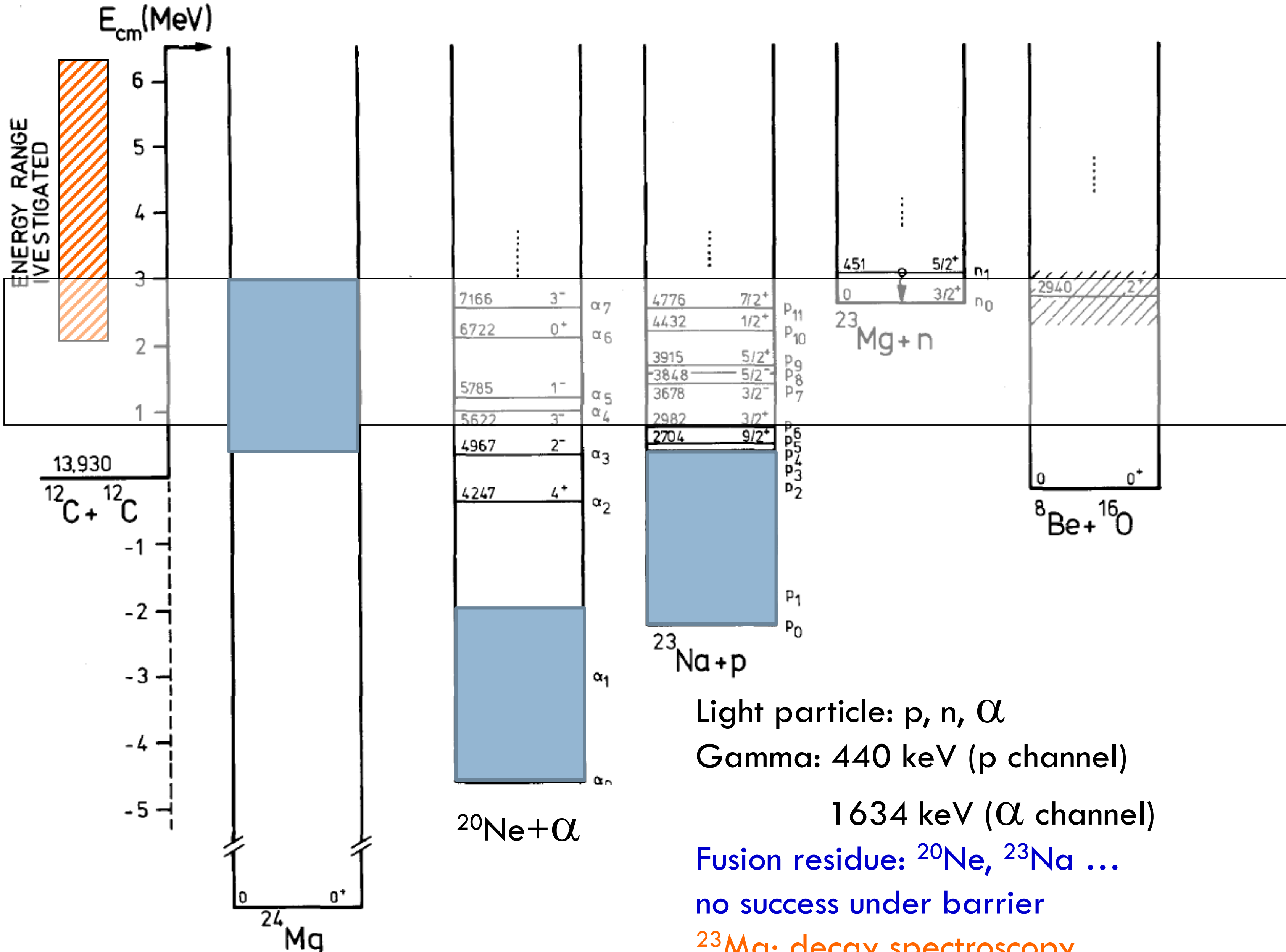
Key problem: With the standard rate (CF88), the crust temperature is too low to ignite the carbon fuel! ☹

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

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

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

……..



Light particle: p, n, α

Gamma: 440 keV (p channel)

1634 keV (α channel)

Fusion residue: ^{20}Ne, ^{23}Na …

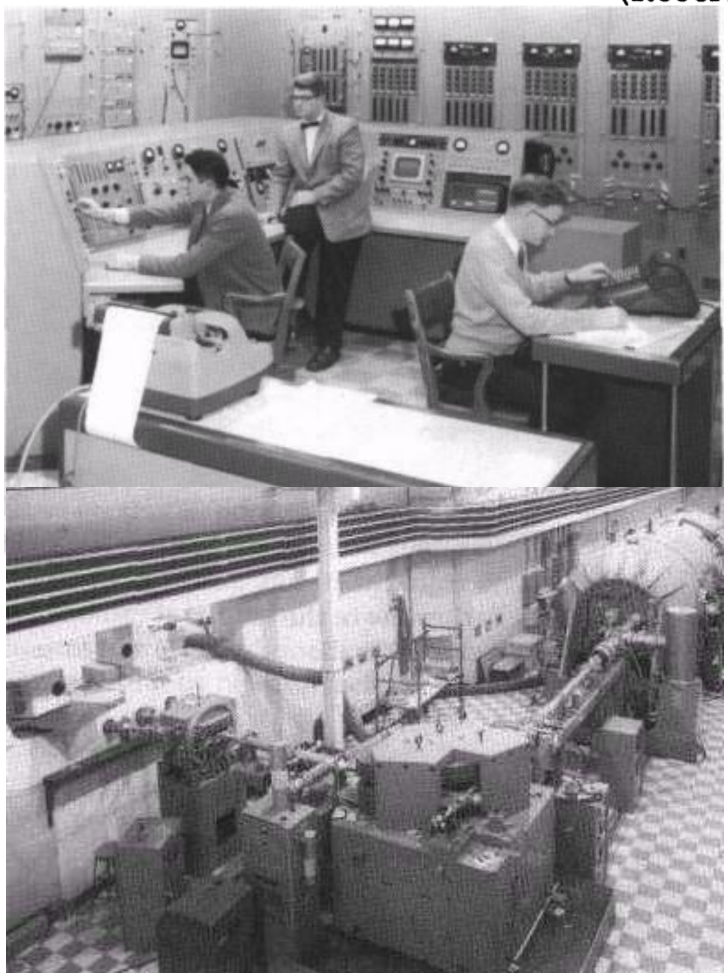
no success under barrier

^{23}Mg: decay spectroscopy

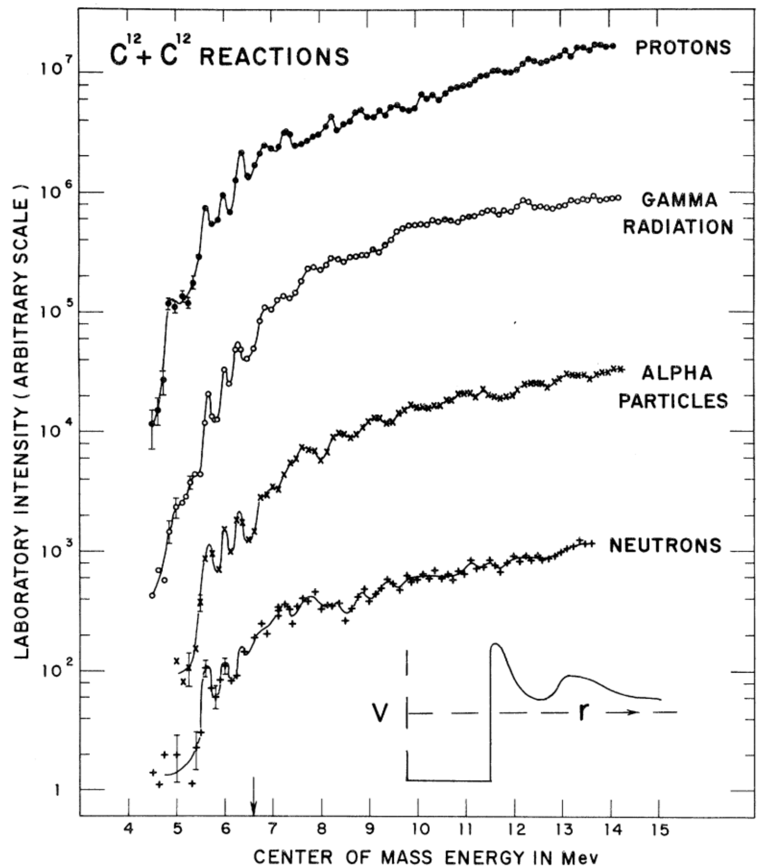
VOLUME 4, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1960

RESONANCES IN C^{12} ON CARBON REACTIONS

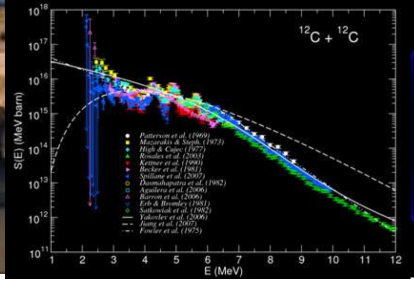
E. Almqvist, D. A. Bromley, and J. A. Kuehner
Atomic Energy of Canada Limited, Chalk River Laboratories, Chalk River, Ontario, Canada
(Received March 28, 1960)

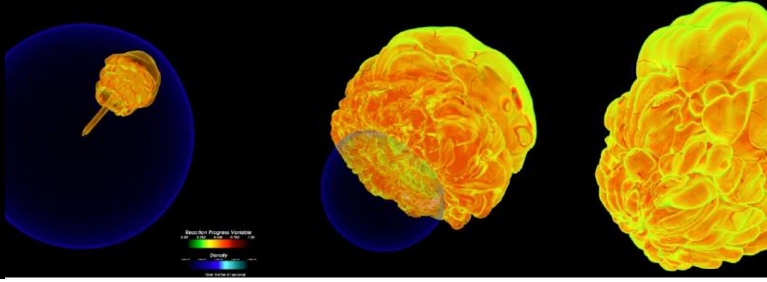


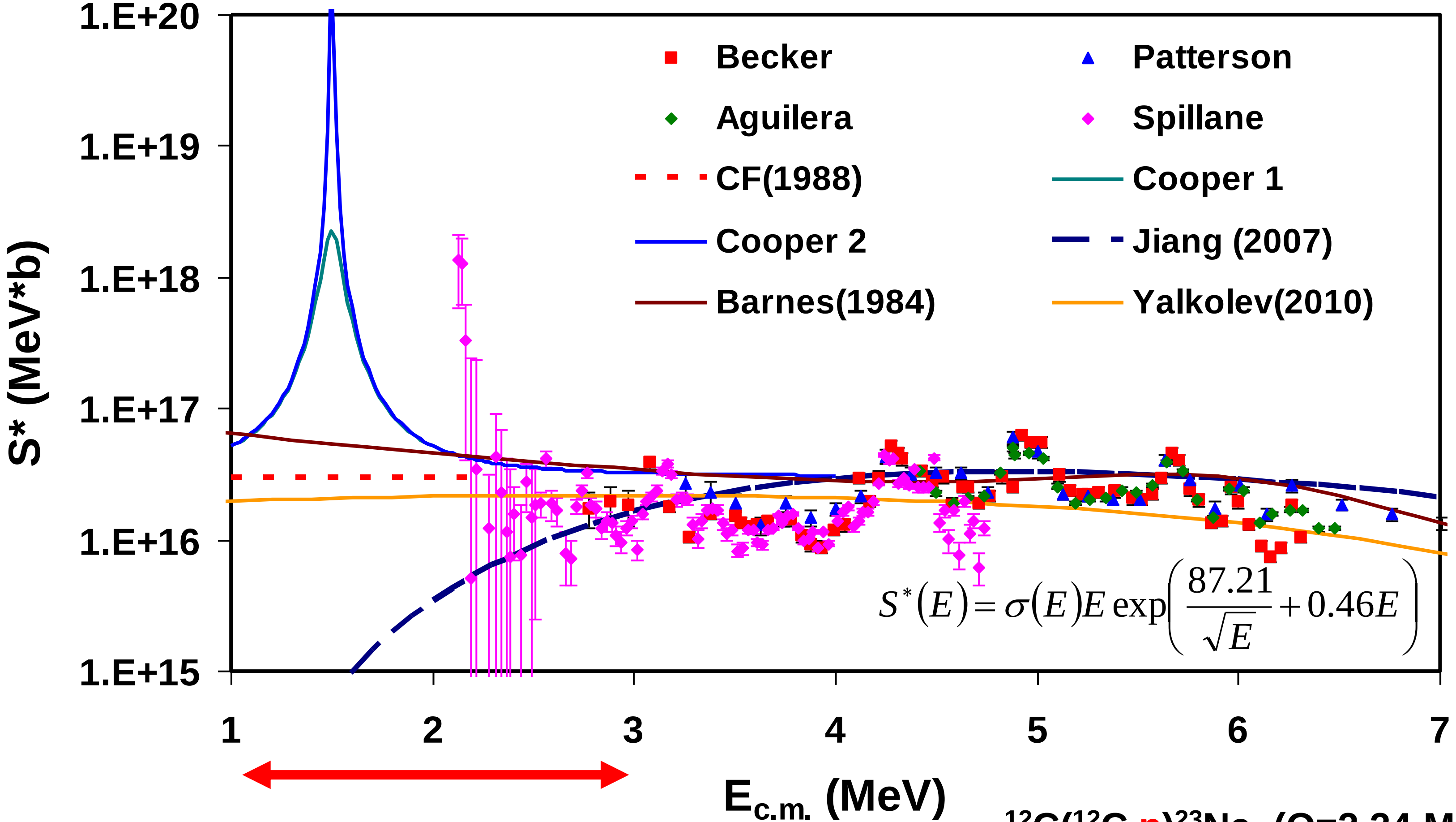
The world's first tandem accelerator installed at Chalk River in 1959.



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





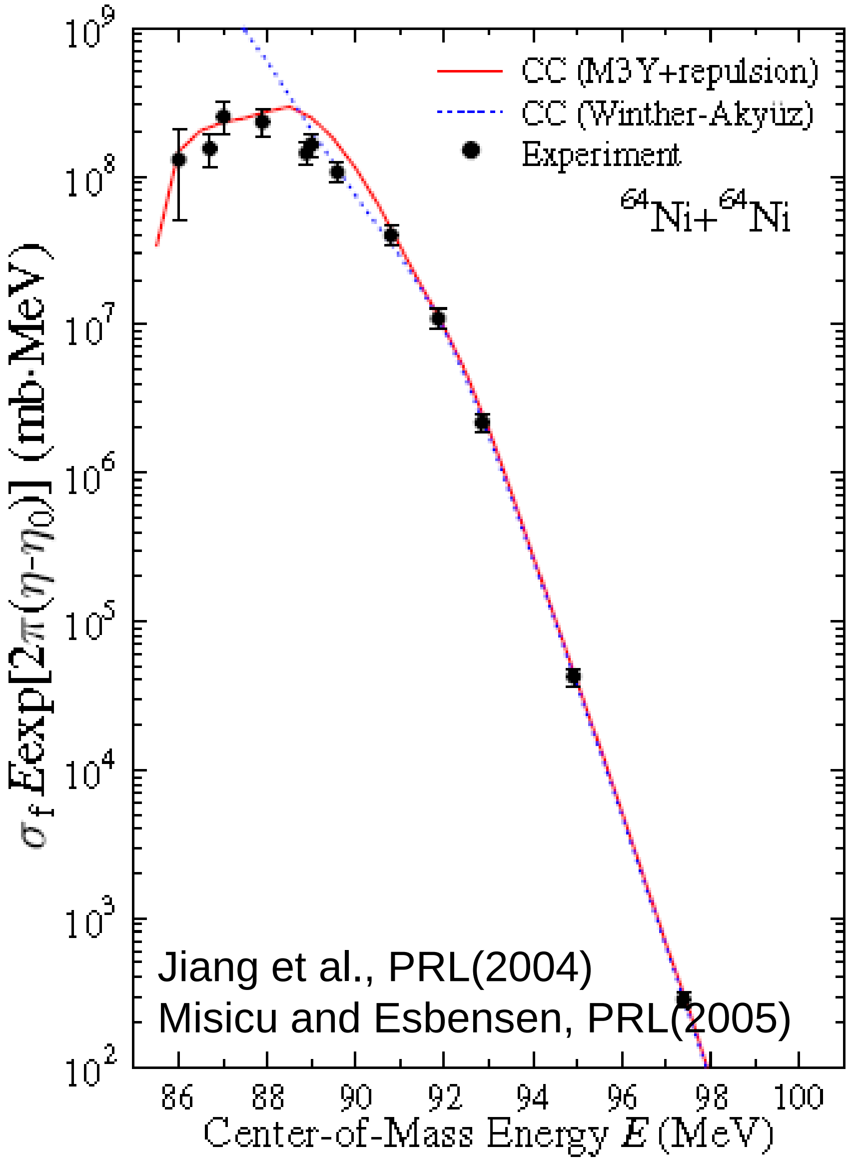


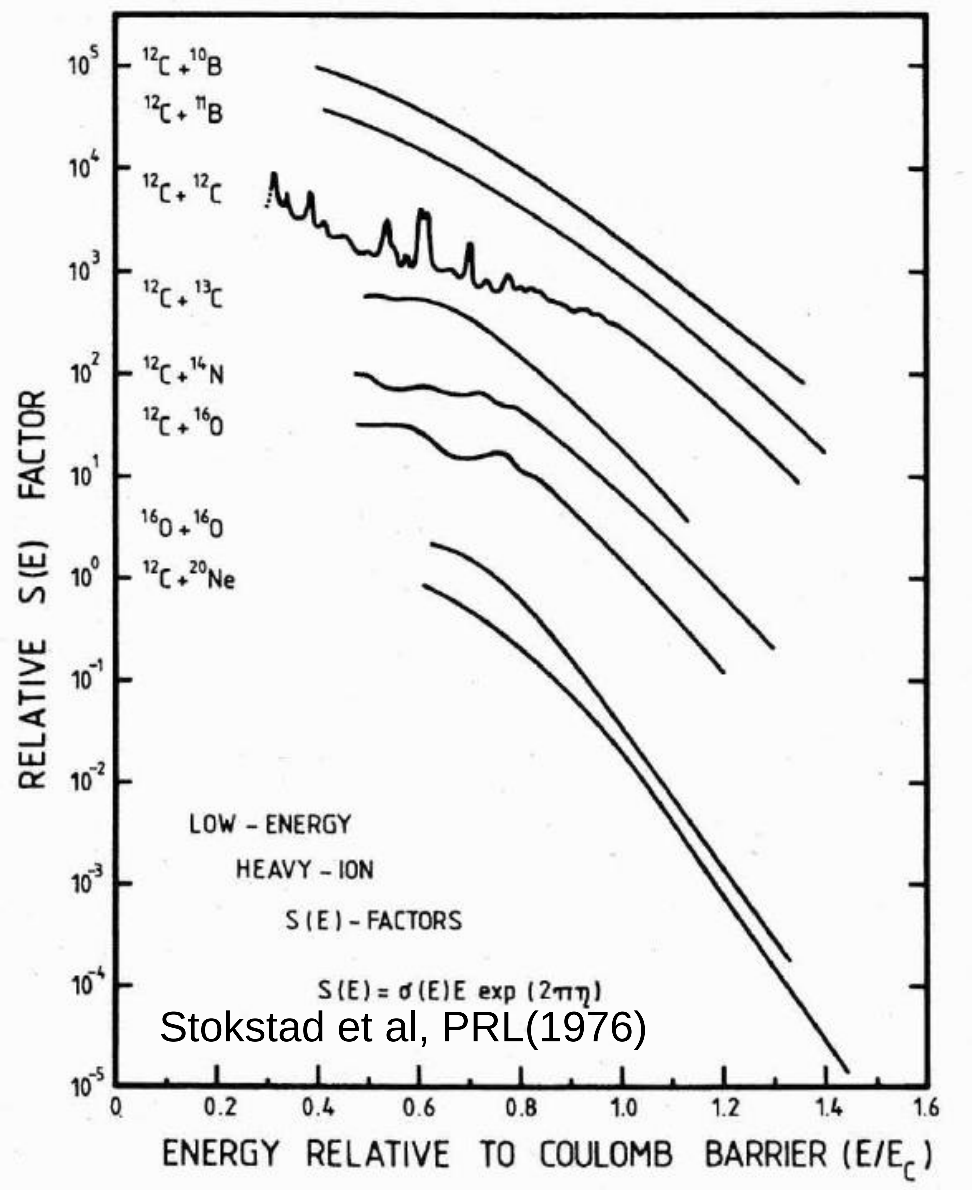
10^{-22} b 10^{-7} b

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

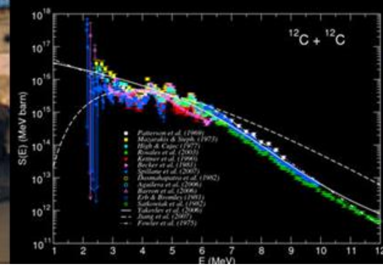


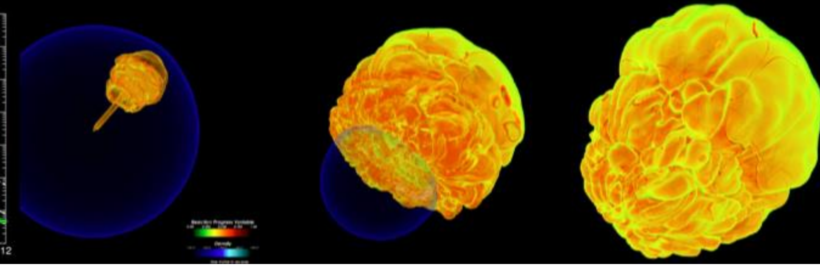


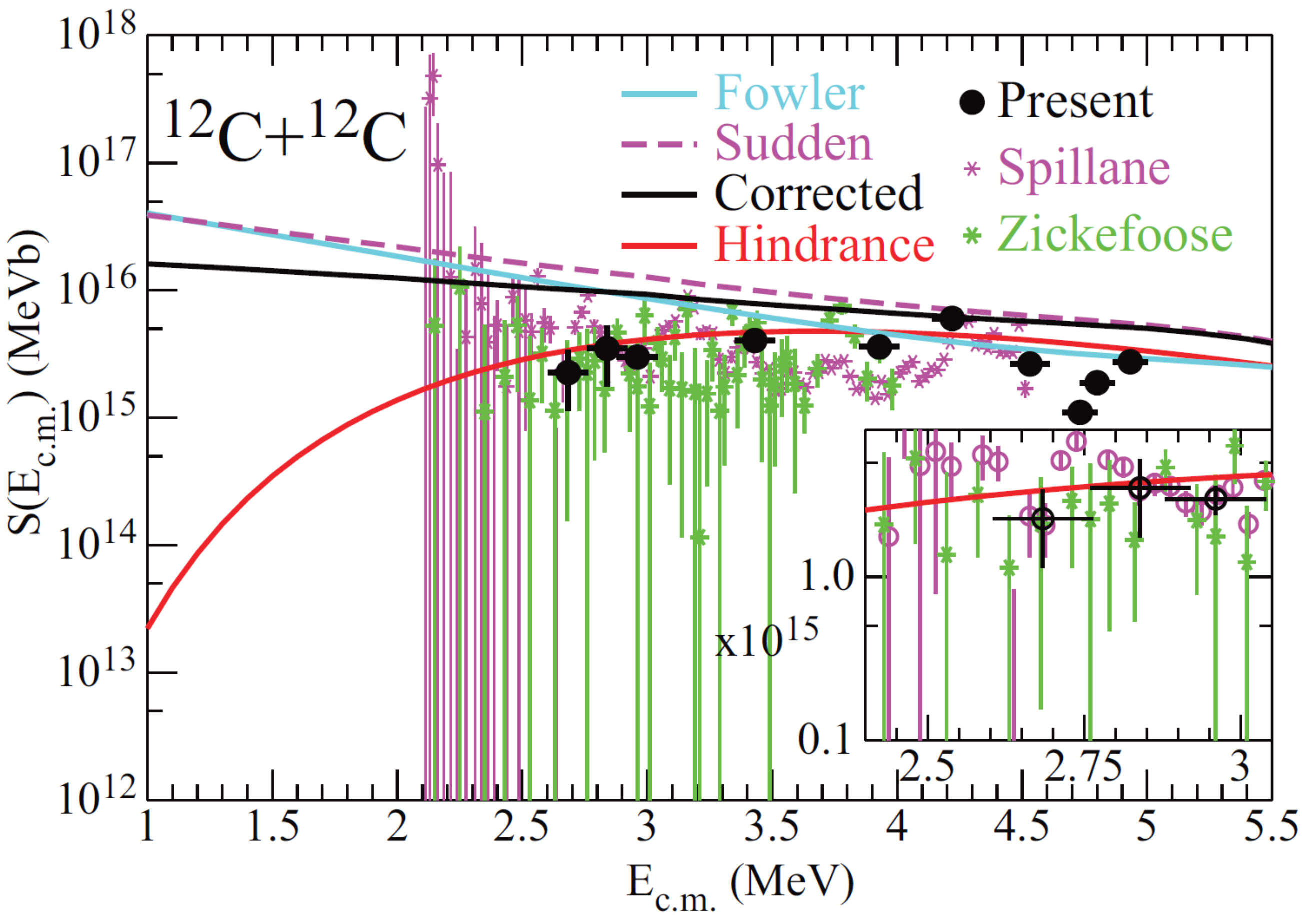
^{64}Ni+^{64}Ni

A<20

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



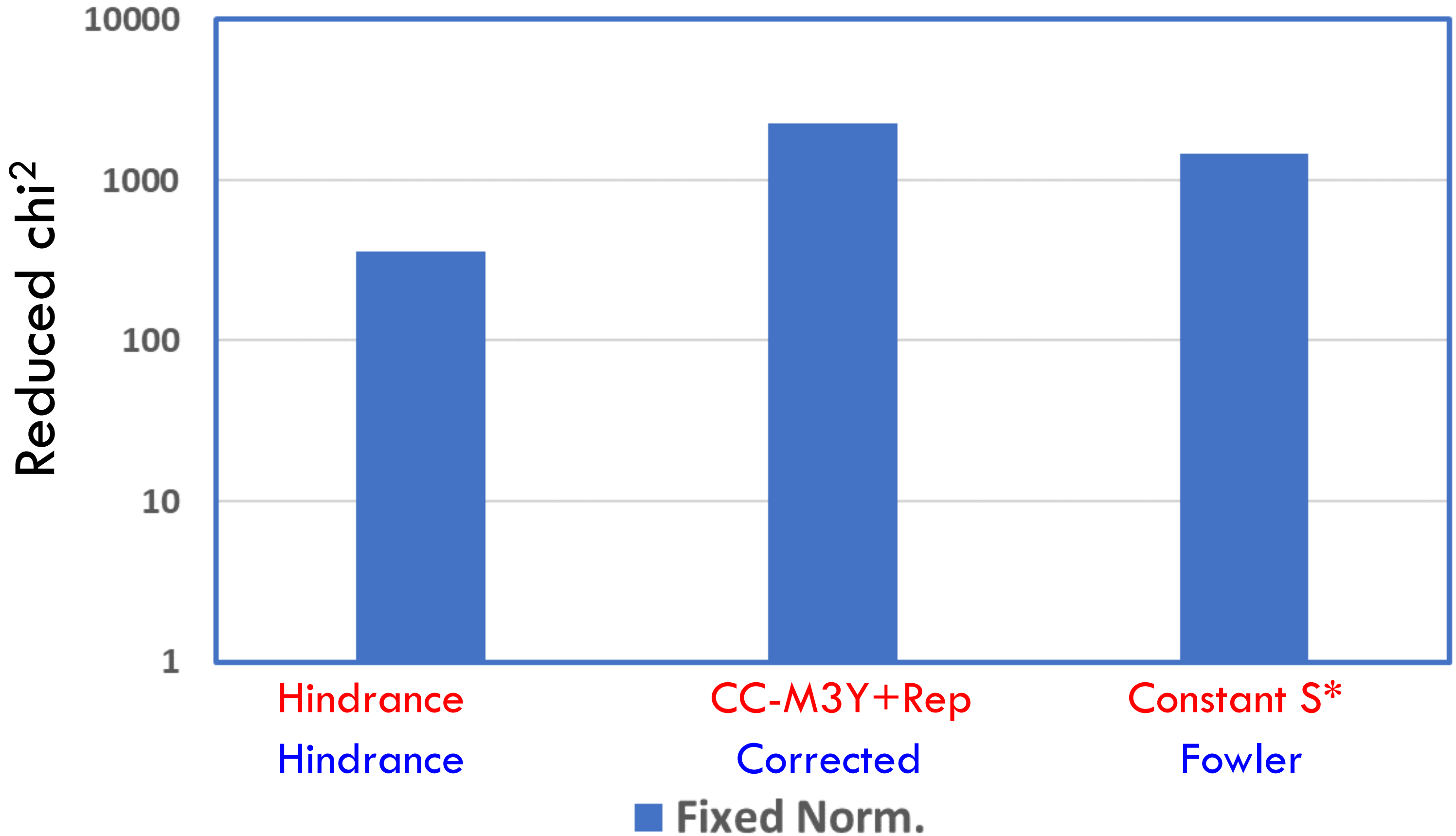




"It is found that the astrophysical *S* factor exhibits a maximum around *E*cm = 3.5–4.0 MeV,…"

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

Not clear conclusion yet



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

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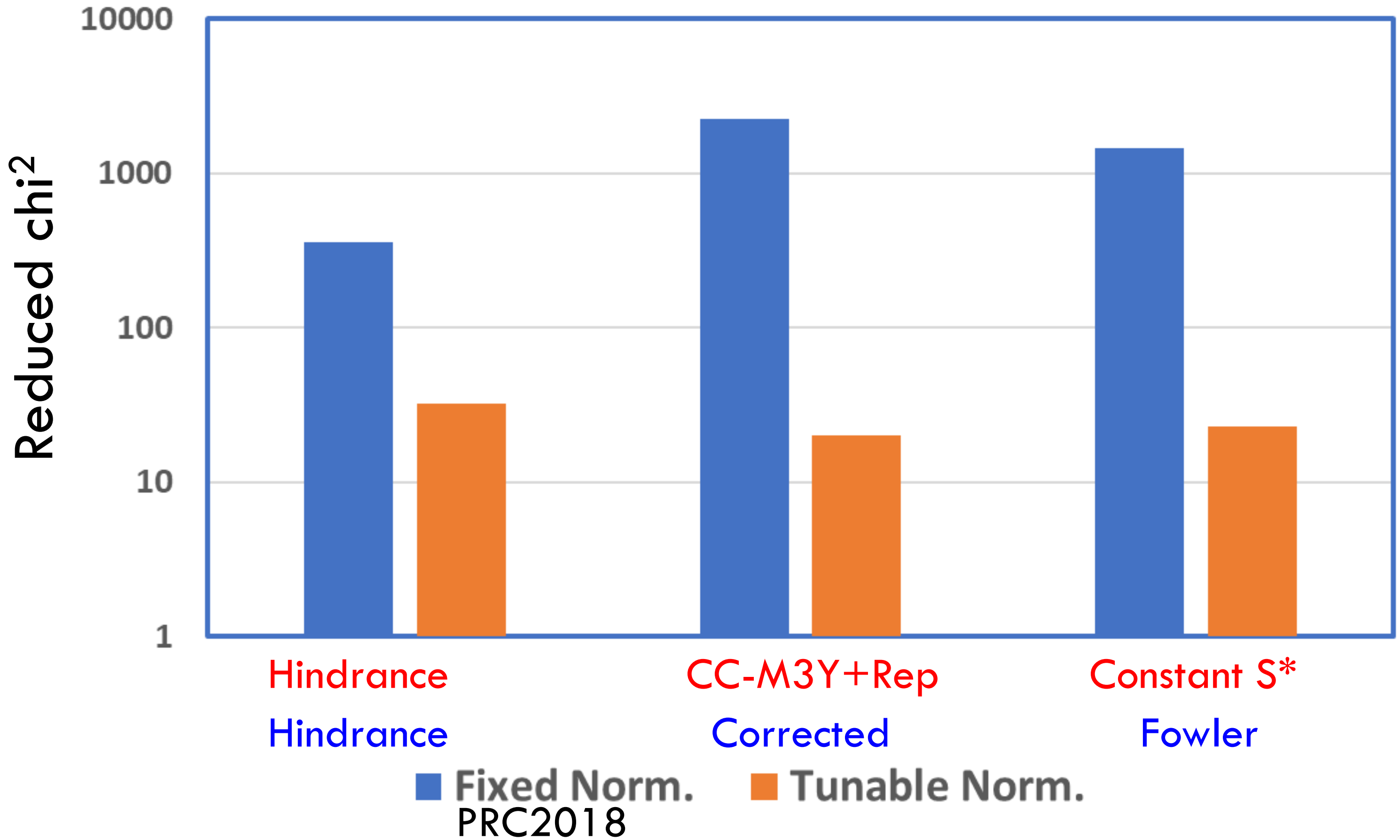
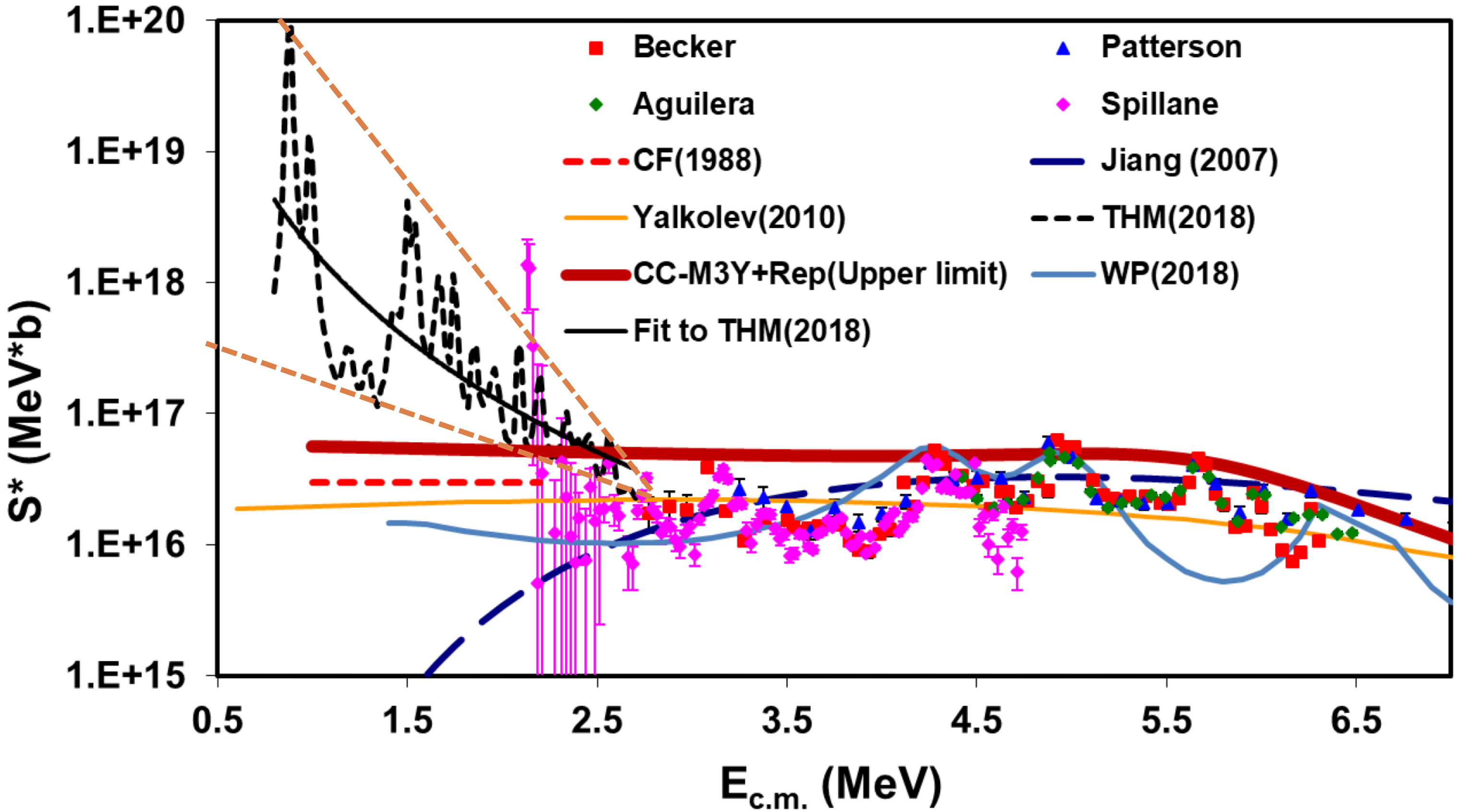


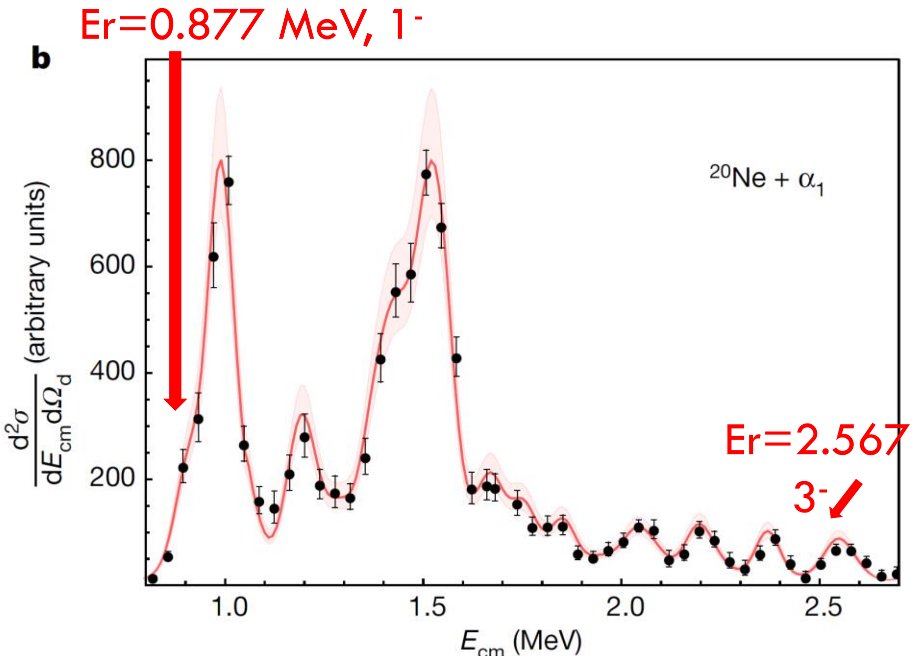
The complicated structure does not favor any model !

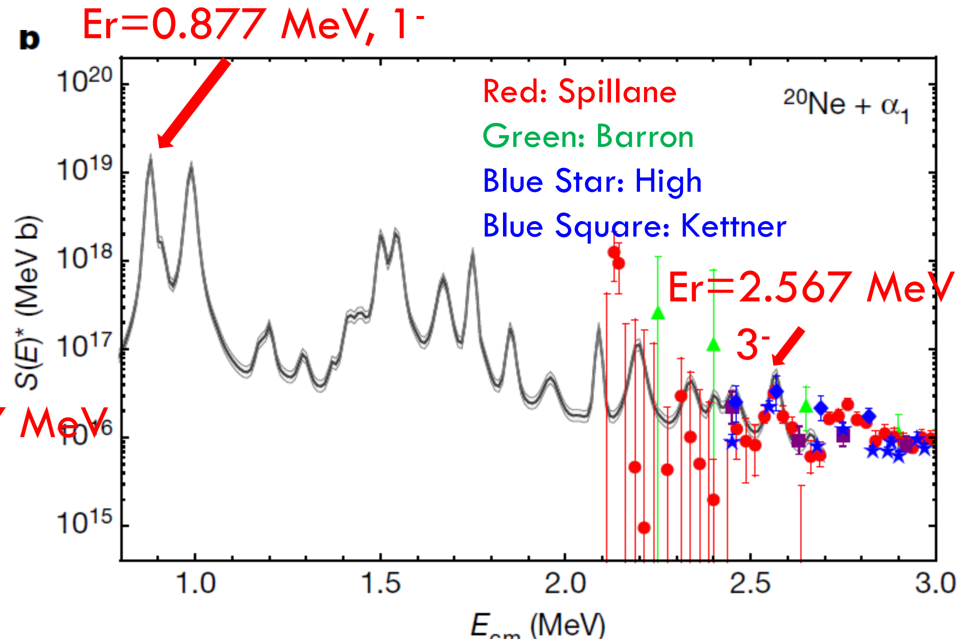
INDIRECT MEASUREMENT using Trojan Horse Method



Why are the resonances obtained by THM so special that they may change the slope?

THM measurement, Tumino et al., Nature (2018)





$$S(E) \sim \underline{KF(E)}\, \frac{d^2\sigma^{THM}}{dE\, d\Omega_{\mathbf{k}_{sF}}}\, \underbrace{\frac{1}{\frac{d\sigma^{DW}(E,\cos\theta_s)}{d\Omega_{\mathbf{k}_{sF}}}}}_{\text{DWBA}}\, \underbrace{\frac{e^{\pi(\eta_{sb}+\eta_{sB}-\eta_{sF})}}{|N(E)|^2}}_{\text{3-body interaction}}$$

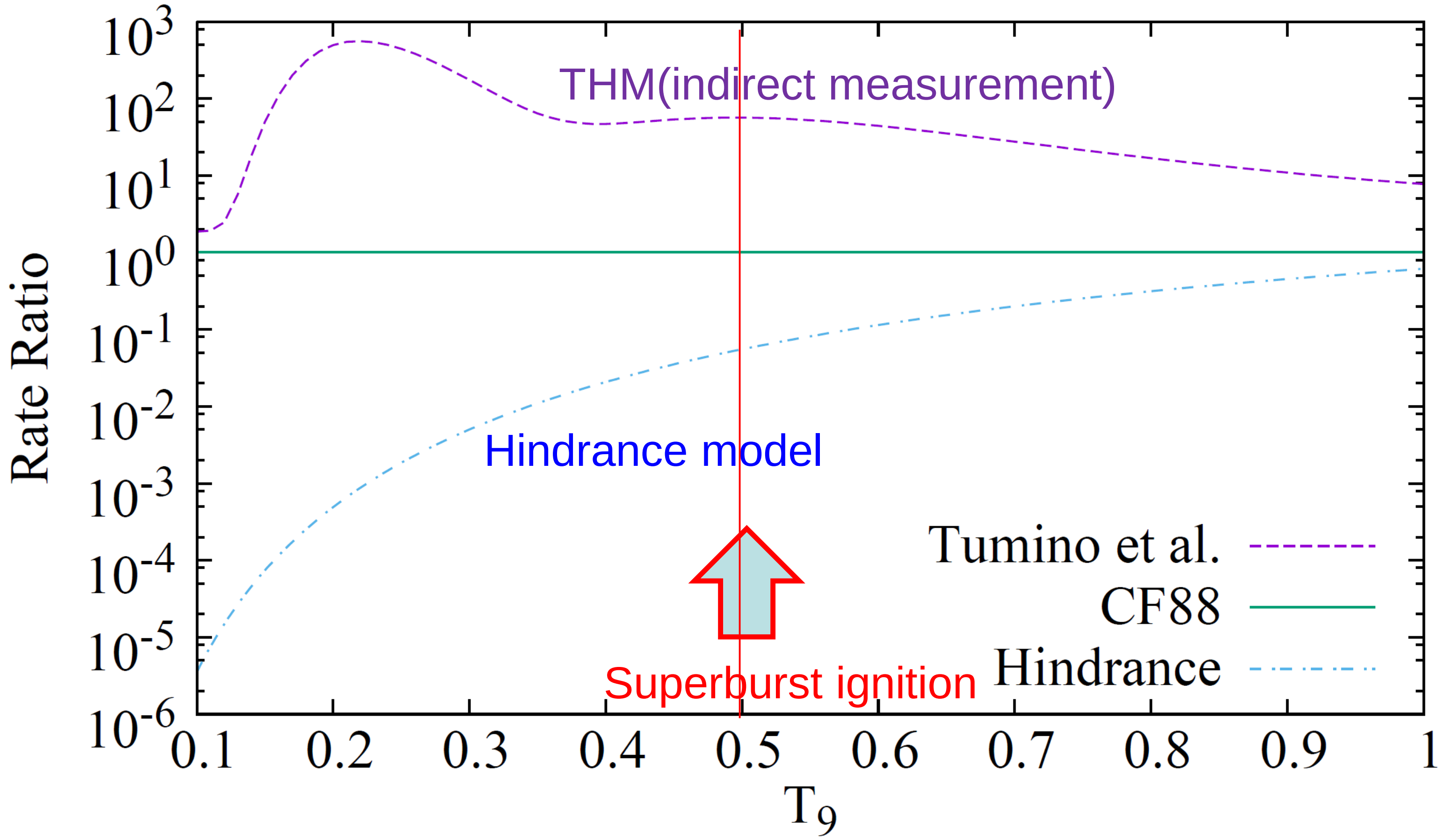
DWBA **3-body interaction**

- Inclusion of $1^-, 3^-$,.. violates QM → Does THM really populate the 12C+12C res.
- Unreliable J^π assignment → unreliable KF factor (P_l depends on l and R)
- Simple plane wave approximation does not work!

  Ecm(12C+12C)=2.66 MeV: Ecm(d+24Mg*)=0.90 MeV→under the barrier

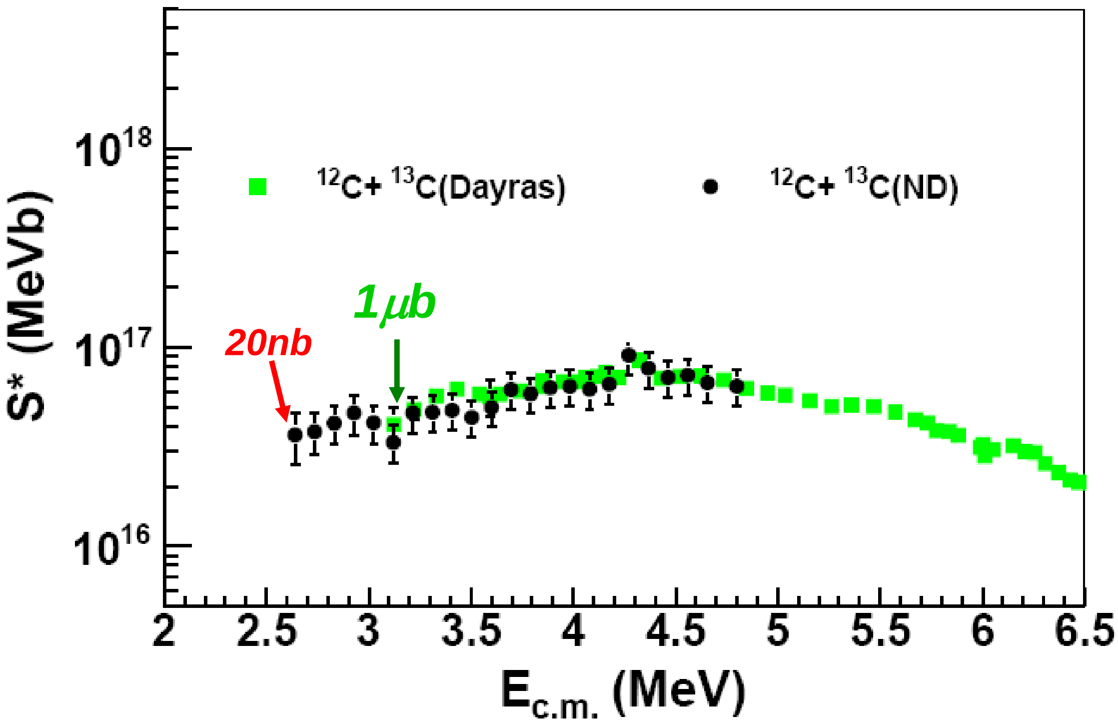
  Ecm(12C+12C)= 0.8 MeV: Ecm(d+24Mg*)=2.75 MeV→above the barrier
- Interaction of **d-24Mg* in the intermediate state** and **final state 3-body interaction** should be considered

Mukhamedzhanov, Tang and Pang **arXiv:1806.05921 [nucl-ex]**



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

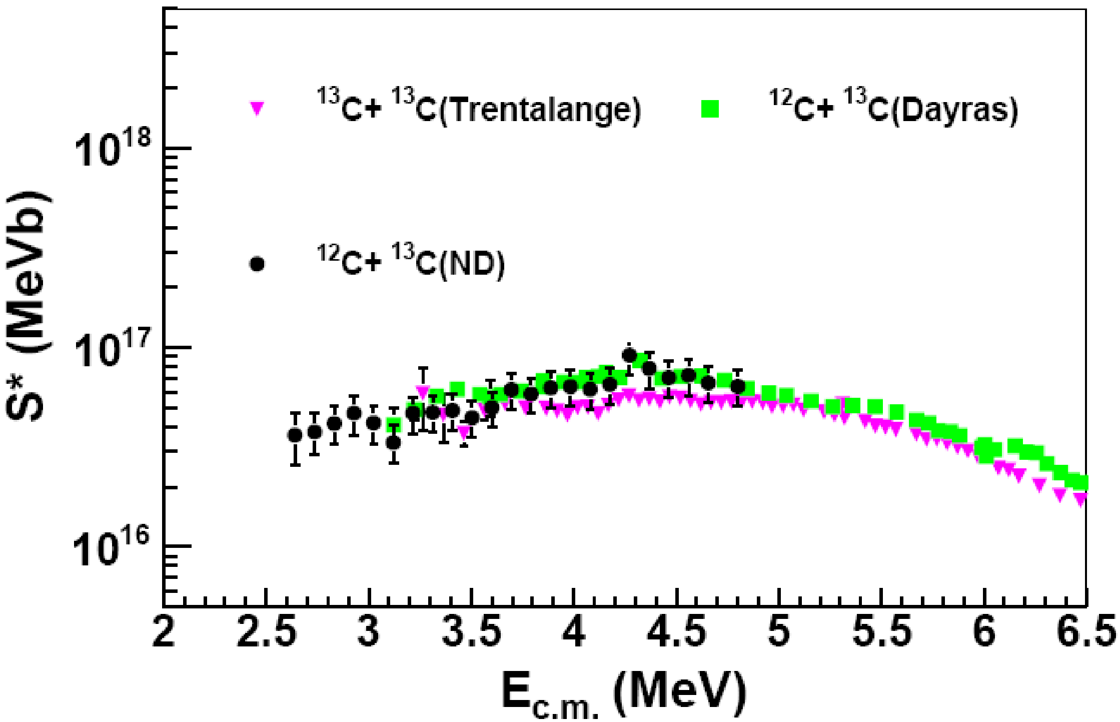
Correlation between carbon isotope systems



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

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

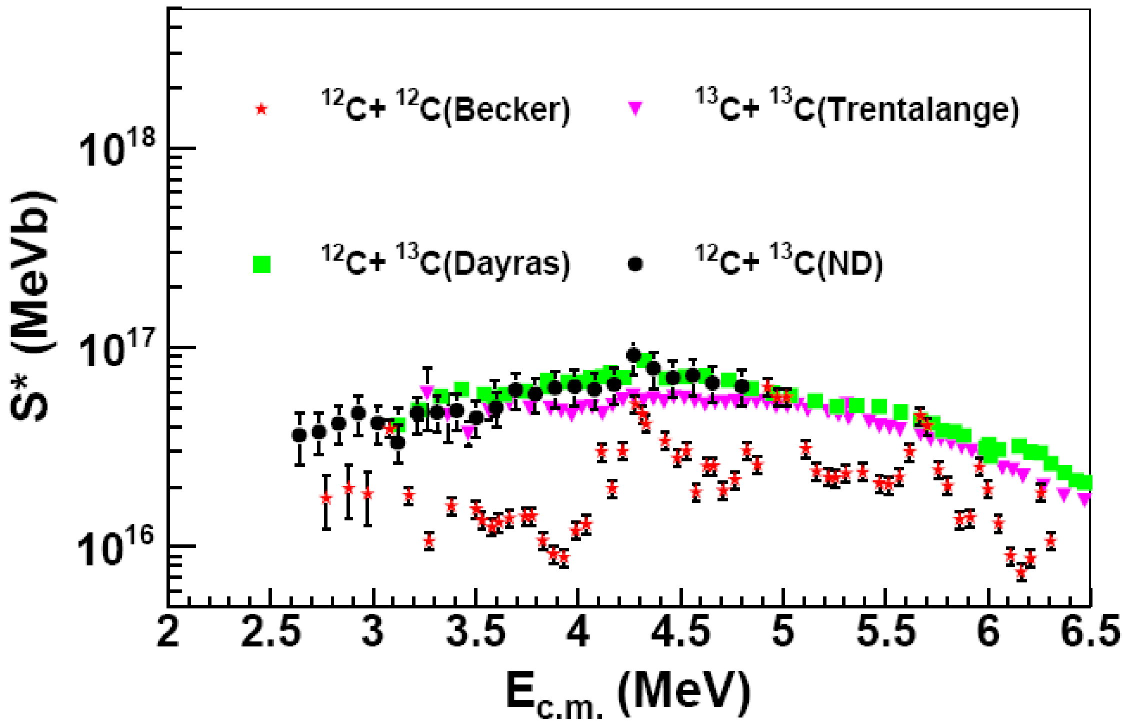
- ***The smallest cross section has been pushed down by a factor of 50.***



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

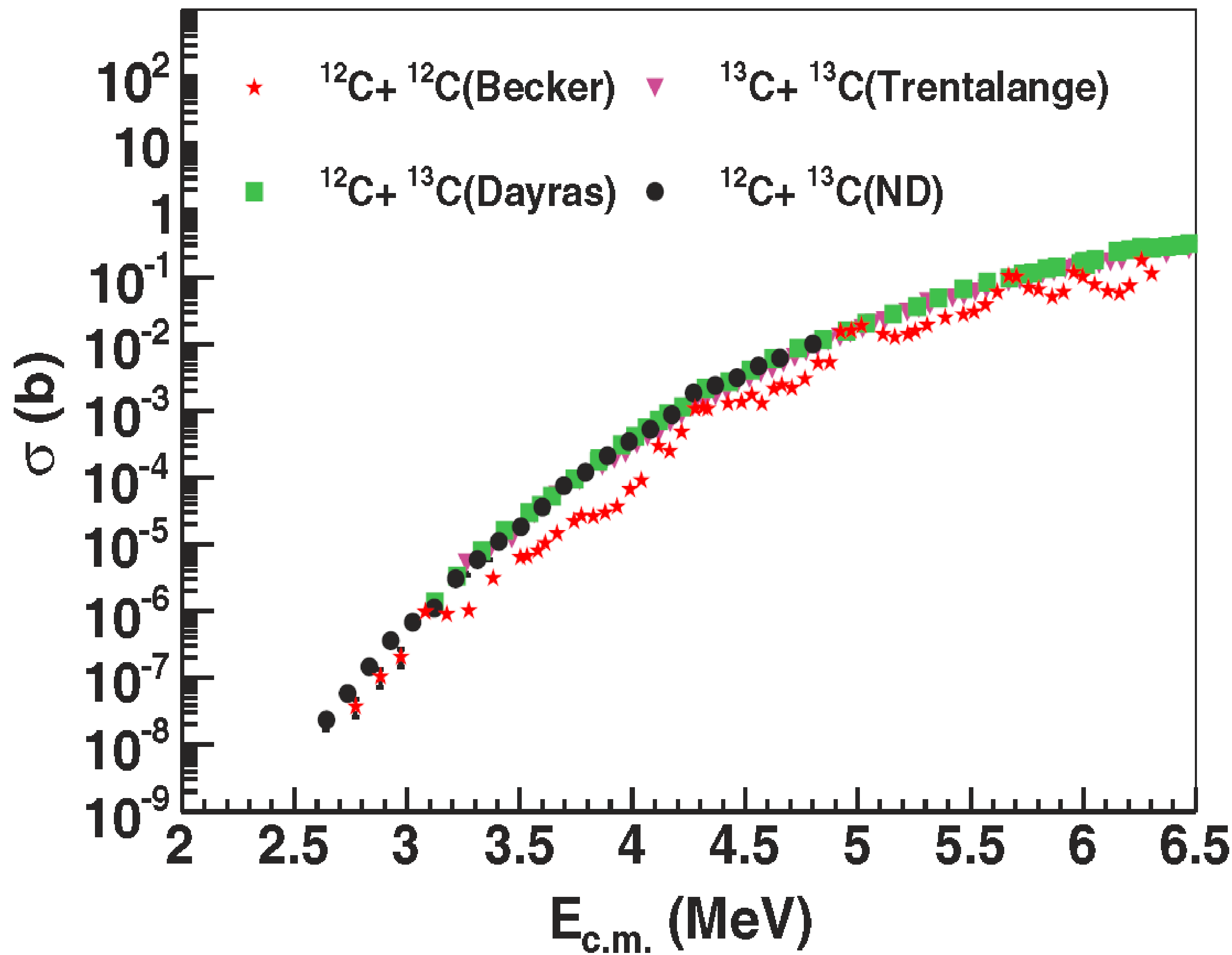
•The isotope effect (difference in radius, mass) is negligible within the observed energy range!

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



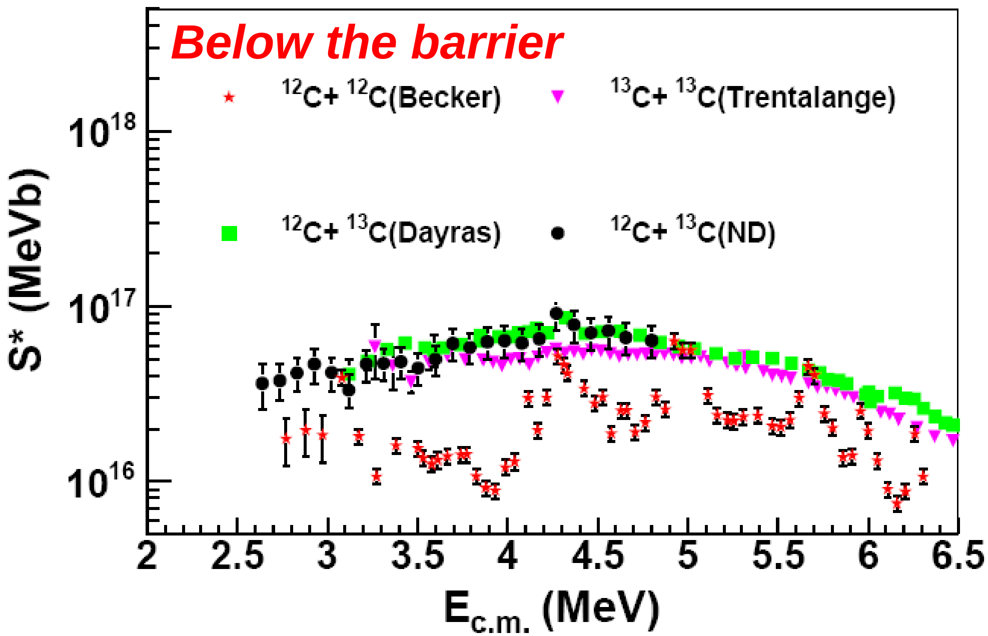
•*For most energies, the ^{12}C+^{12}C cross sections are suppressed!*

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

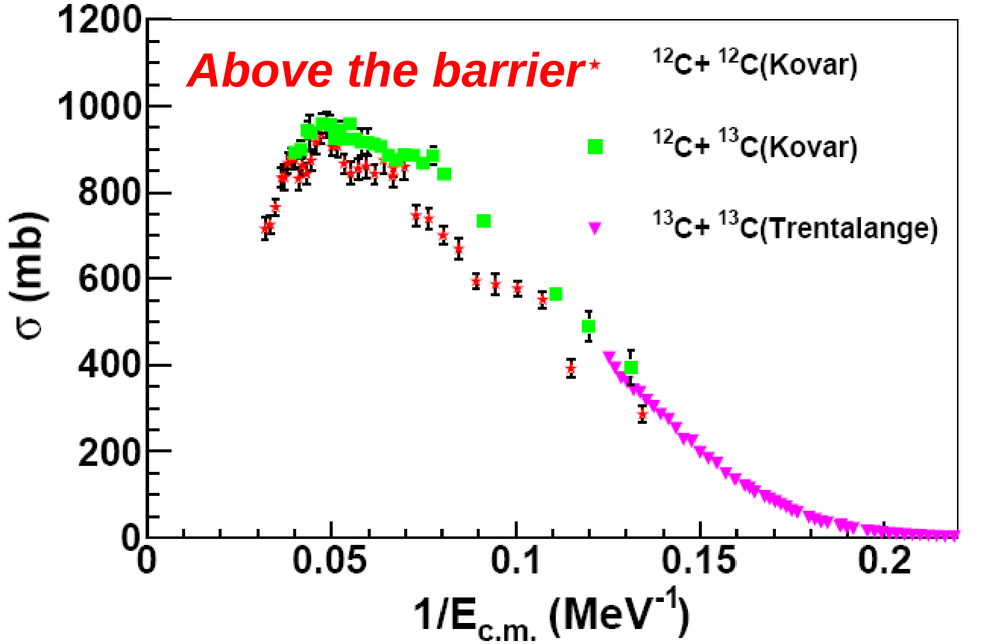


$^{12}C+^{12}C$(Becker)
$^{13}C+^{13}C$(Trentalange)
$^{12}C+^{13}C$(Dayras)
$^{12}C+^{13}C$(ND)
σ (b)
$E_{c.m.}$ (MeV)
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5

A simple pattern for complicated resonances



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

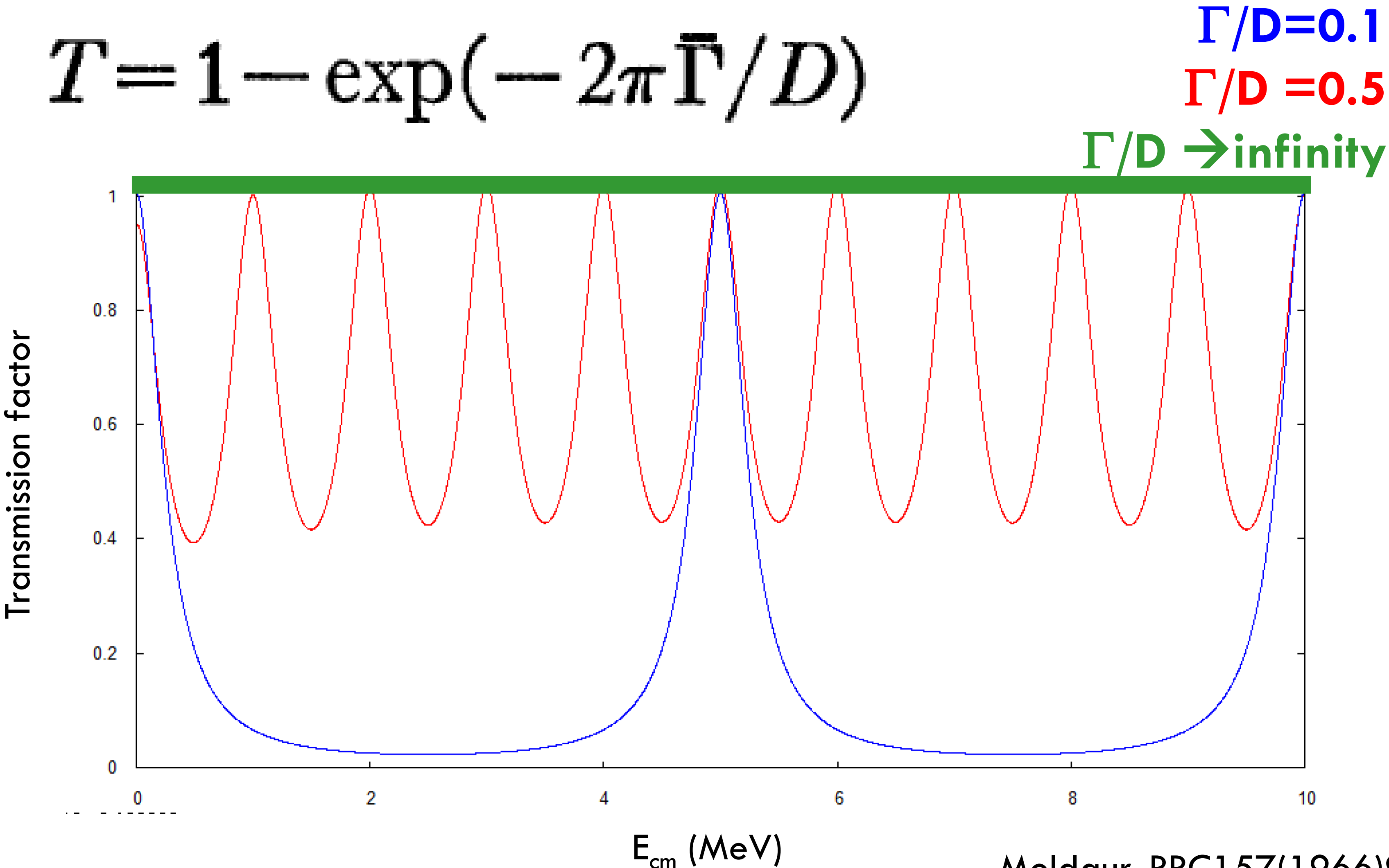


Only at resonant energies, the $^{12}C+^{12}C$ cross sections matches with those of $^{12}C+^{13}C$ and $^{13}C+^{13}C$!

Why?

Correlation between carbon isotopes

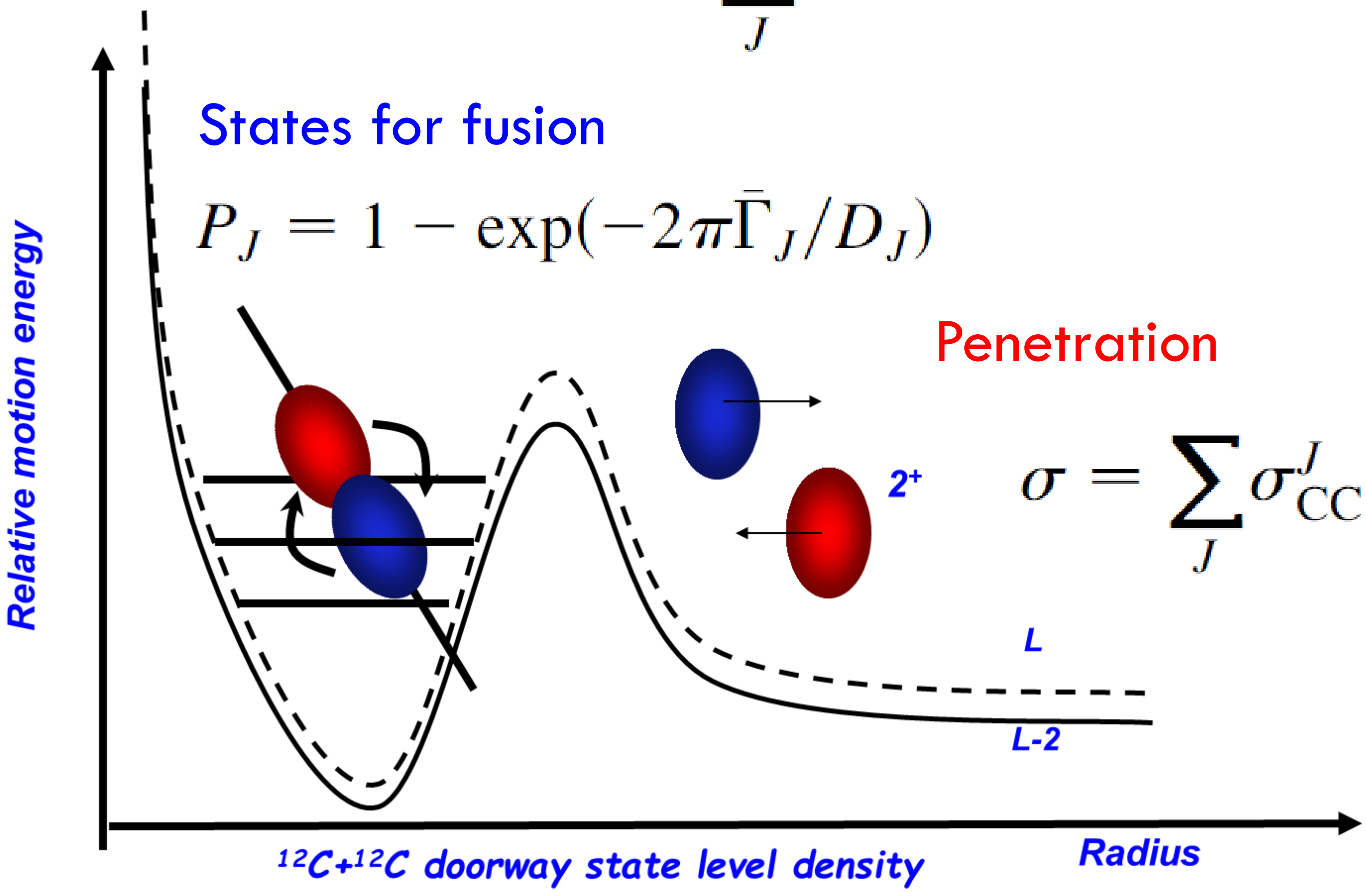
$$T = 1 - \exp(-2\pi\bar{\Gamma}/D)$$



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

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

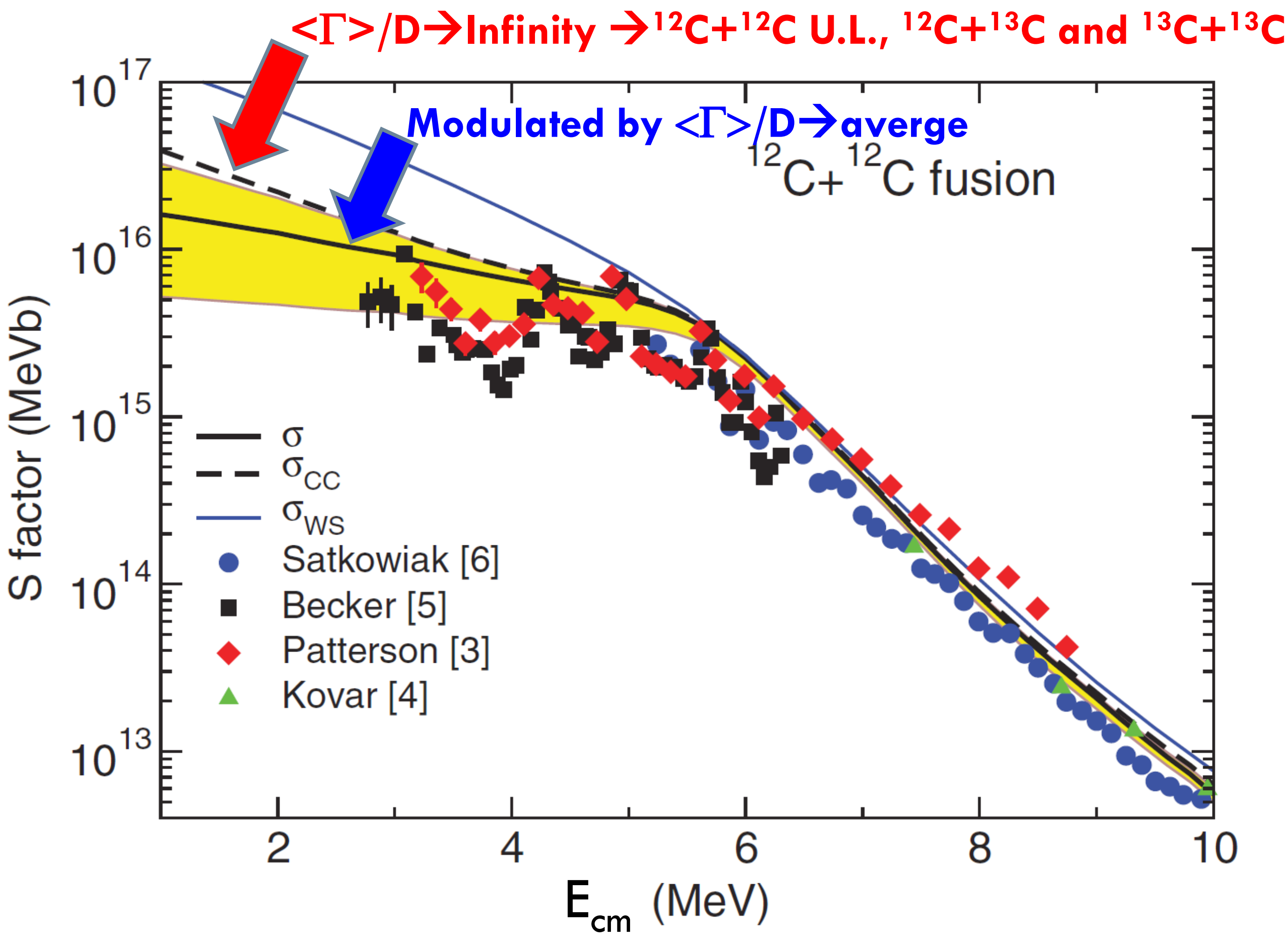
High level density systems: $^{12}C+^{13}C$, $^{13}C+^{13}C \rightarrow P_J=1$

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

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

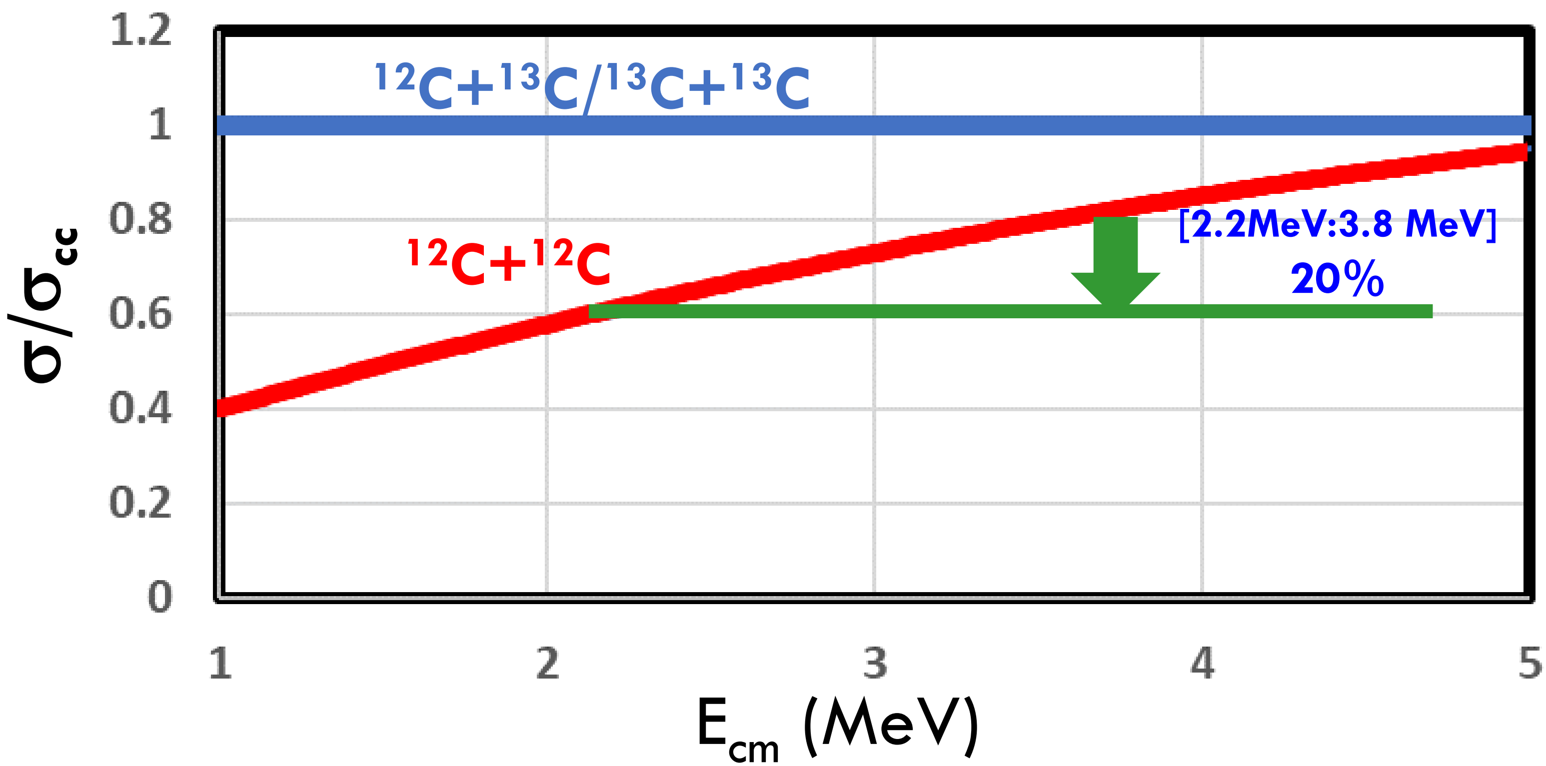
C.L. Jiang et al., PRL110, 072701 (2013)

Correlation between carbon isotopes



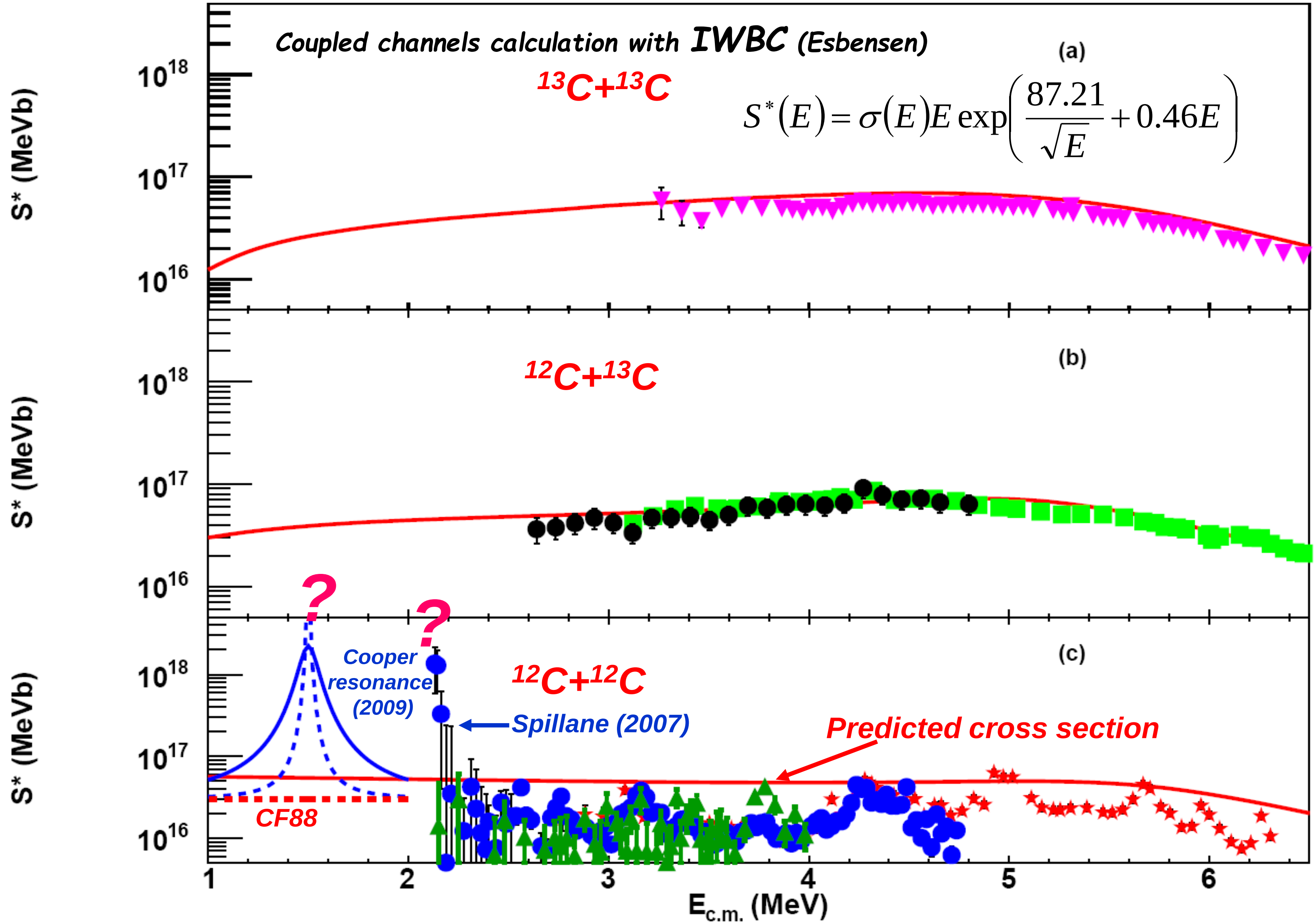
C.L. Jiang et al., PRL110, 072701 (2013)

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)

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
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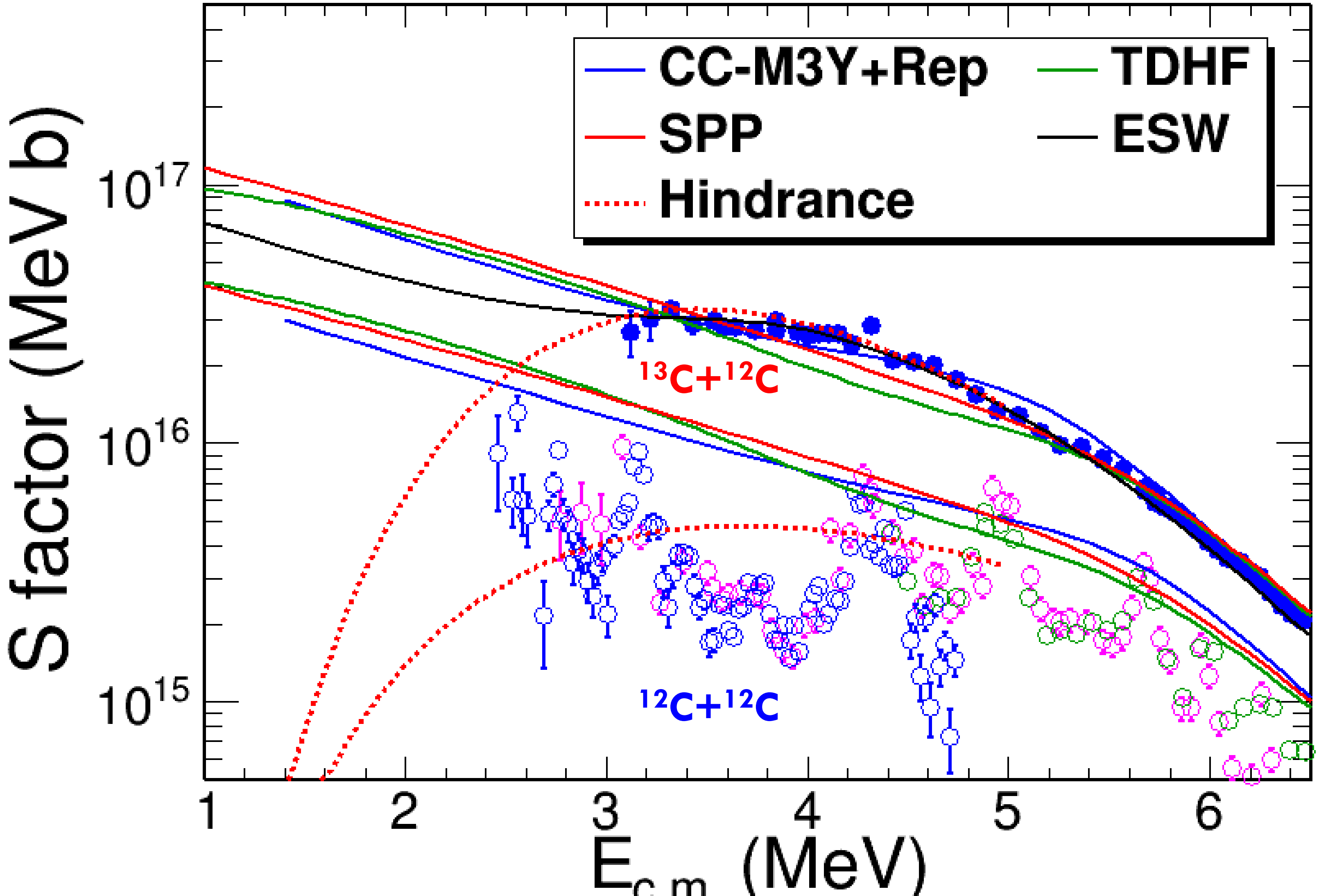
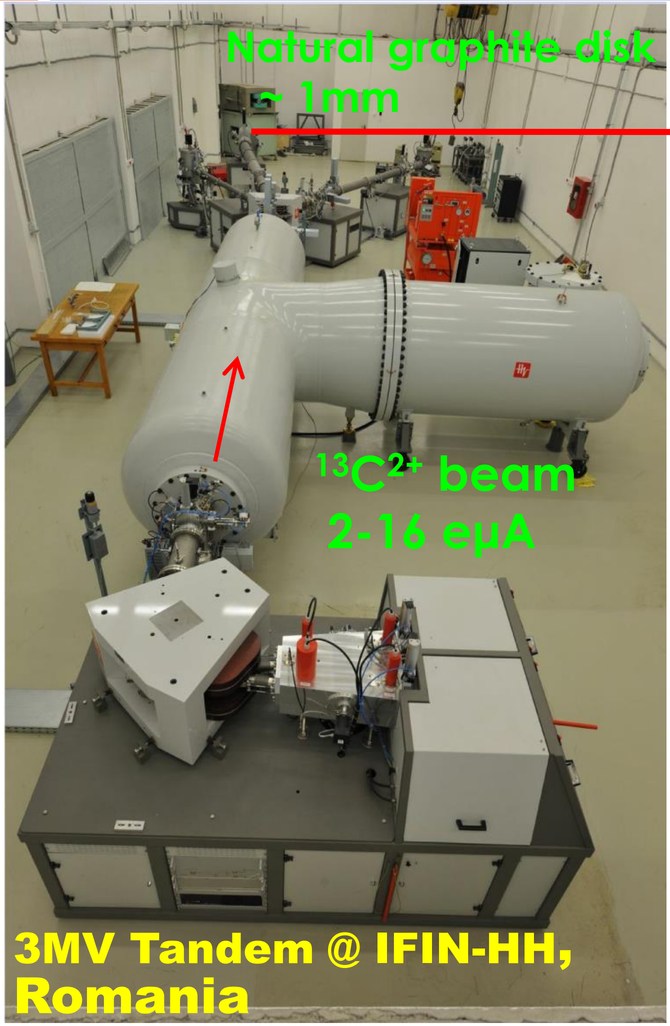
China Institute of Atomic Energy, Beijing 102413, P.R. China
A.S. Umar
Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA
Y. Xu
Extreme Light Infrastructure-Nuclear Physics, RO-077125, Magurele, Romania

Test of Predictive Power



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

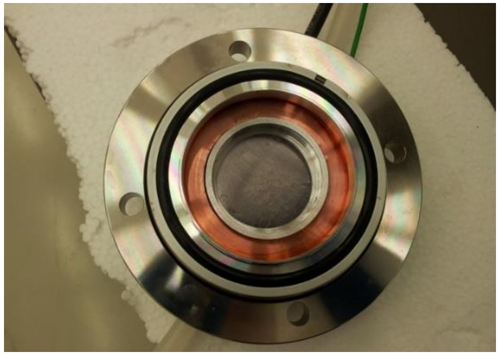


Online irradiation

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

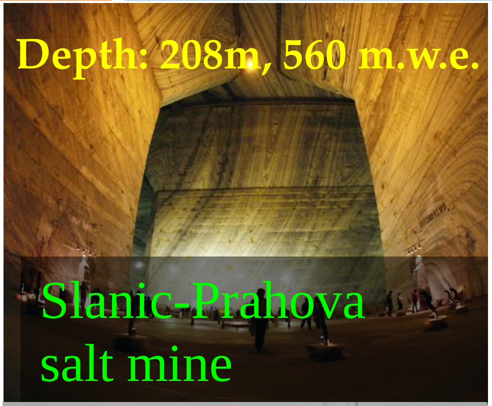
^{24}Na: $T_{1/2}$=15 hr

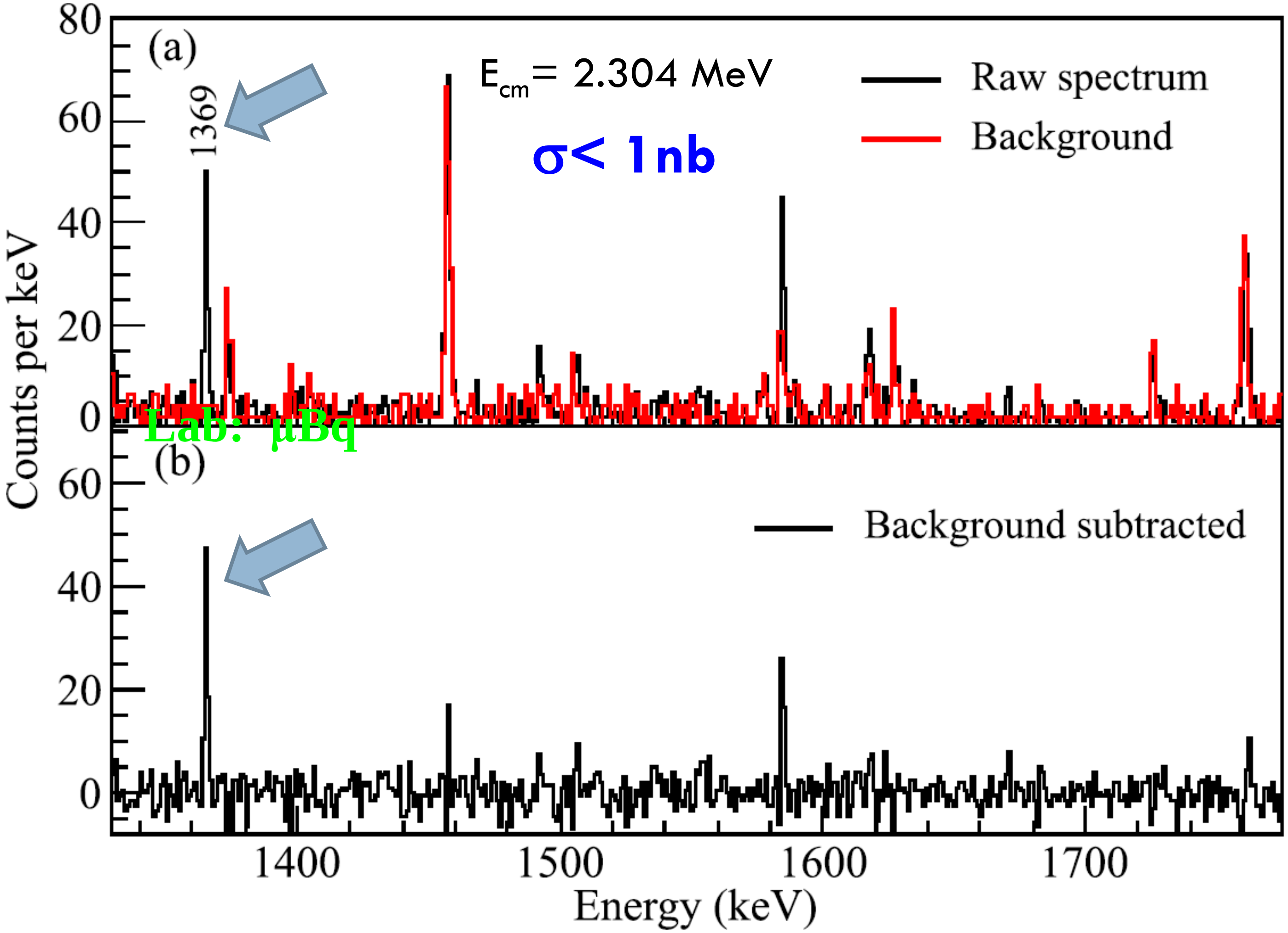
1369-2754 keV γ rays



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

Low level background counting

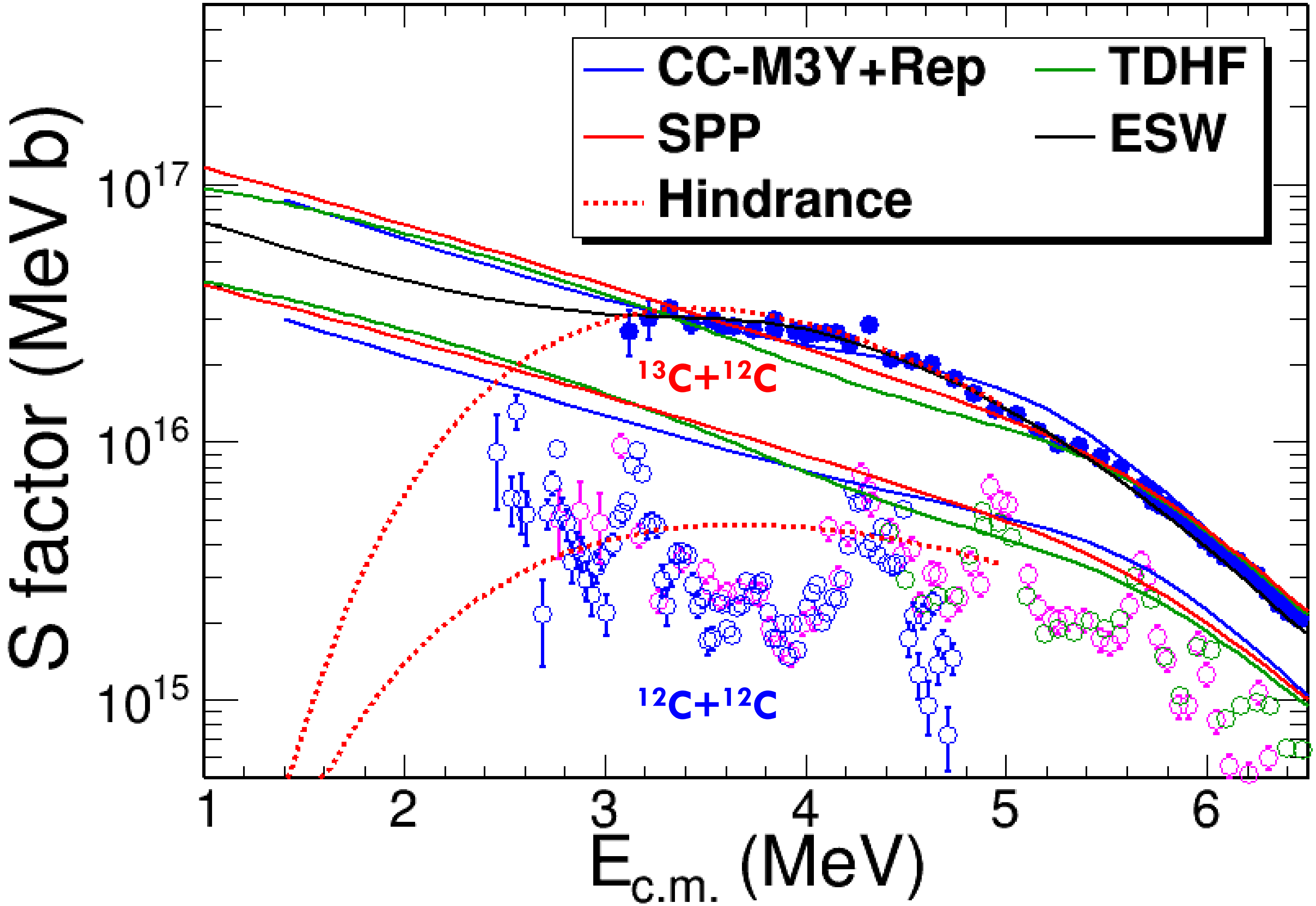




Radiations: 3.4 days

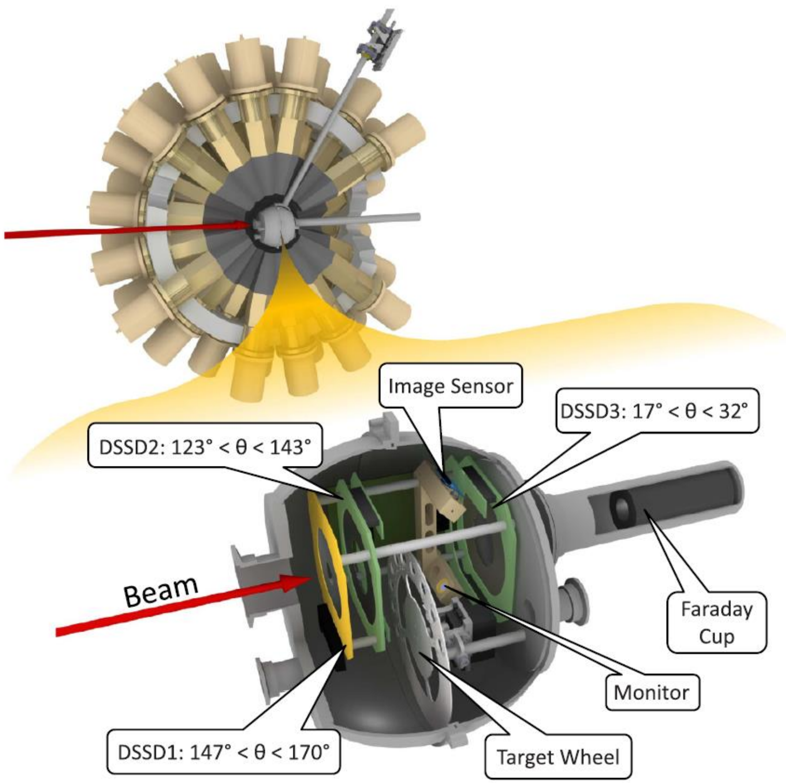
measurements: 3.9 days

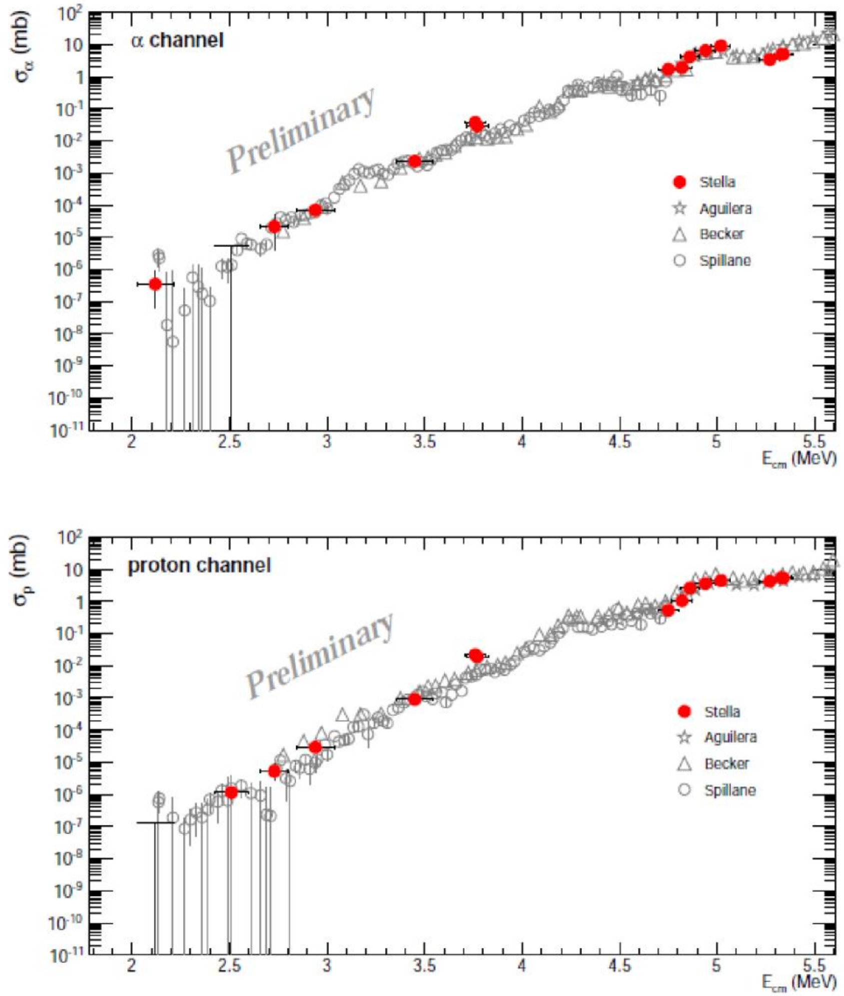
Test of Predictive Power



Particle-Gamma Coincidence

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

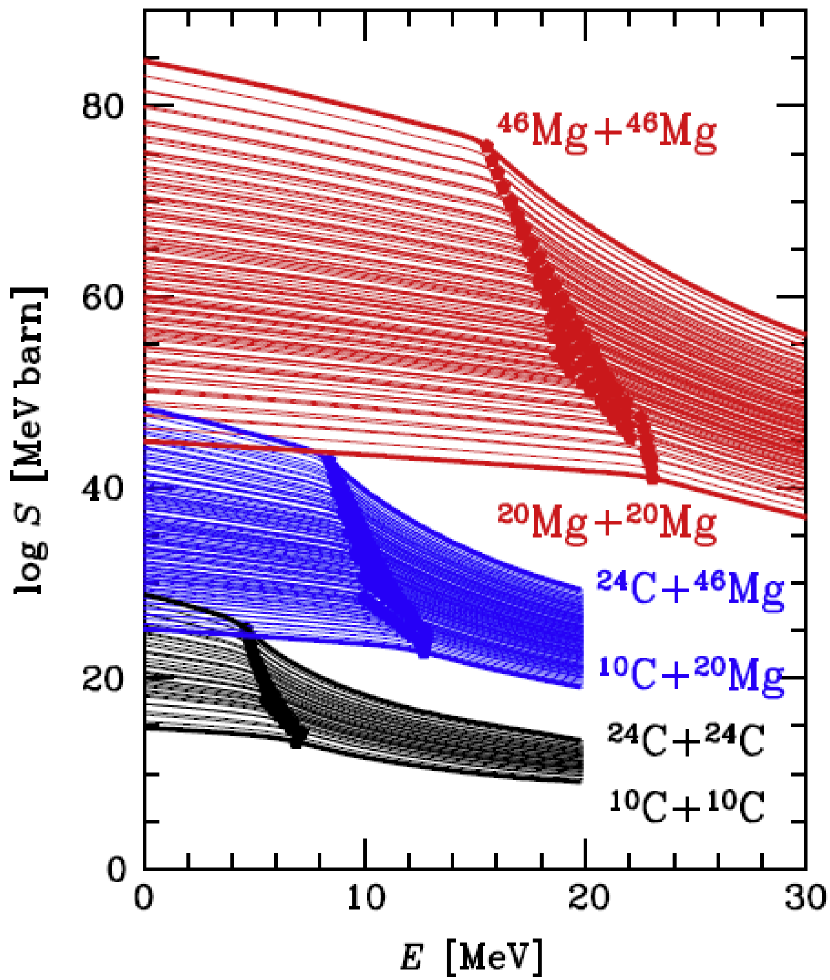




G. Fruet, Ph. D Thesis, Universite de Strasbourg

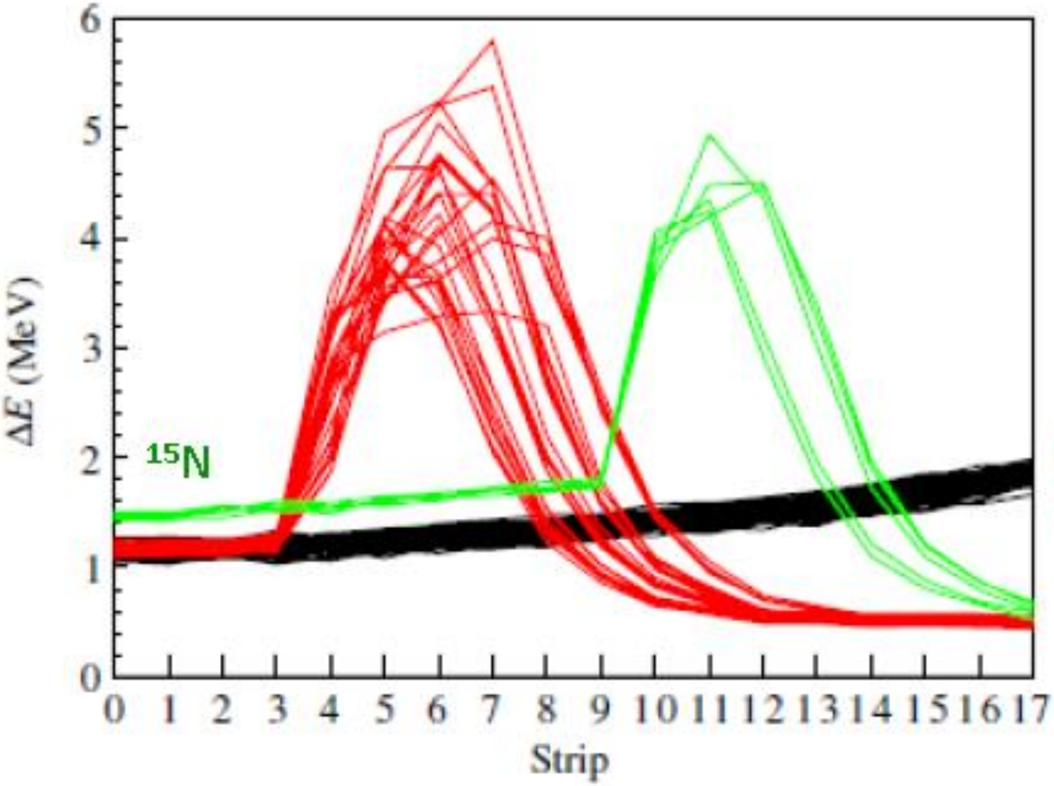
Fusion reactions of n-rich nuclei

H.I. Fusion in crust

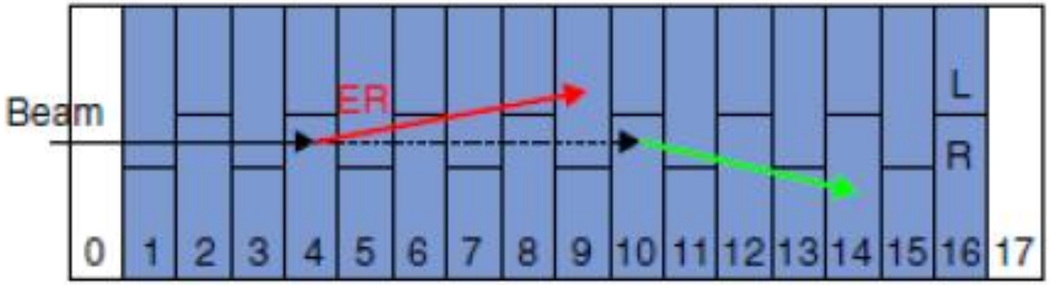


M. Beard et al. / Atomic Data and Nuclear Data Tables 96 (2010) 541–566

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

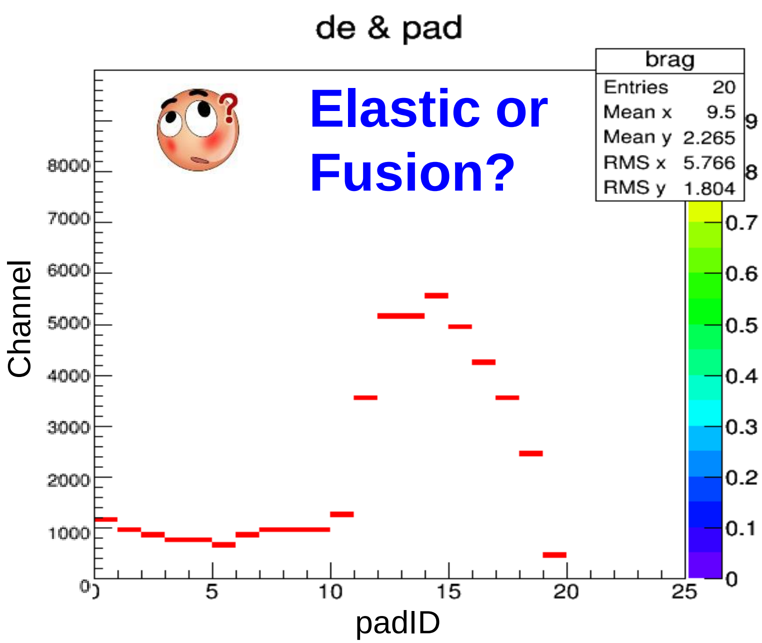


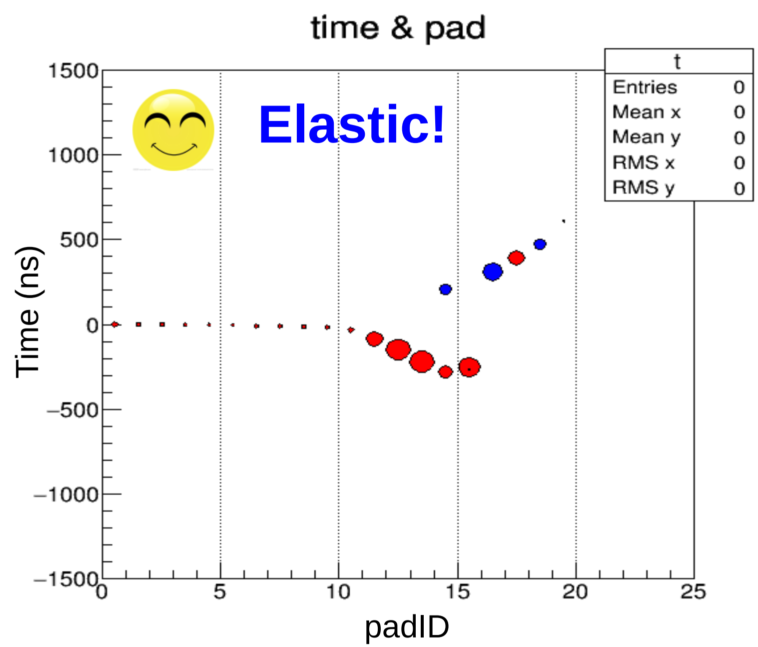
Black: beam of ^{15}C
Red: Fusion between ^{15}C and ^{12}C
Green: fusion between ^{15}N and ^{12}C



 Rehm (ANL)

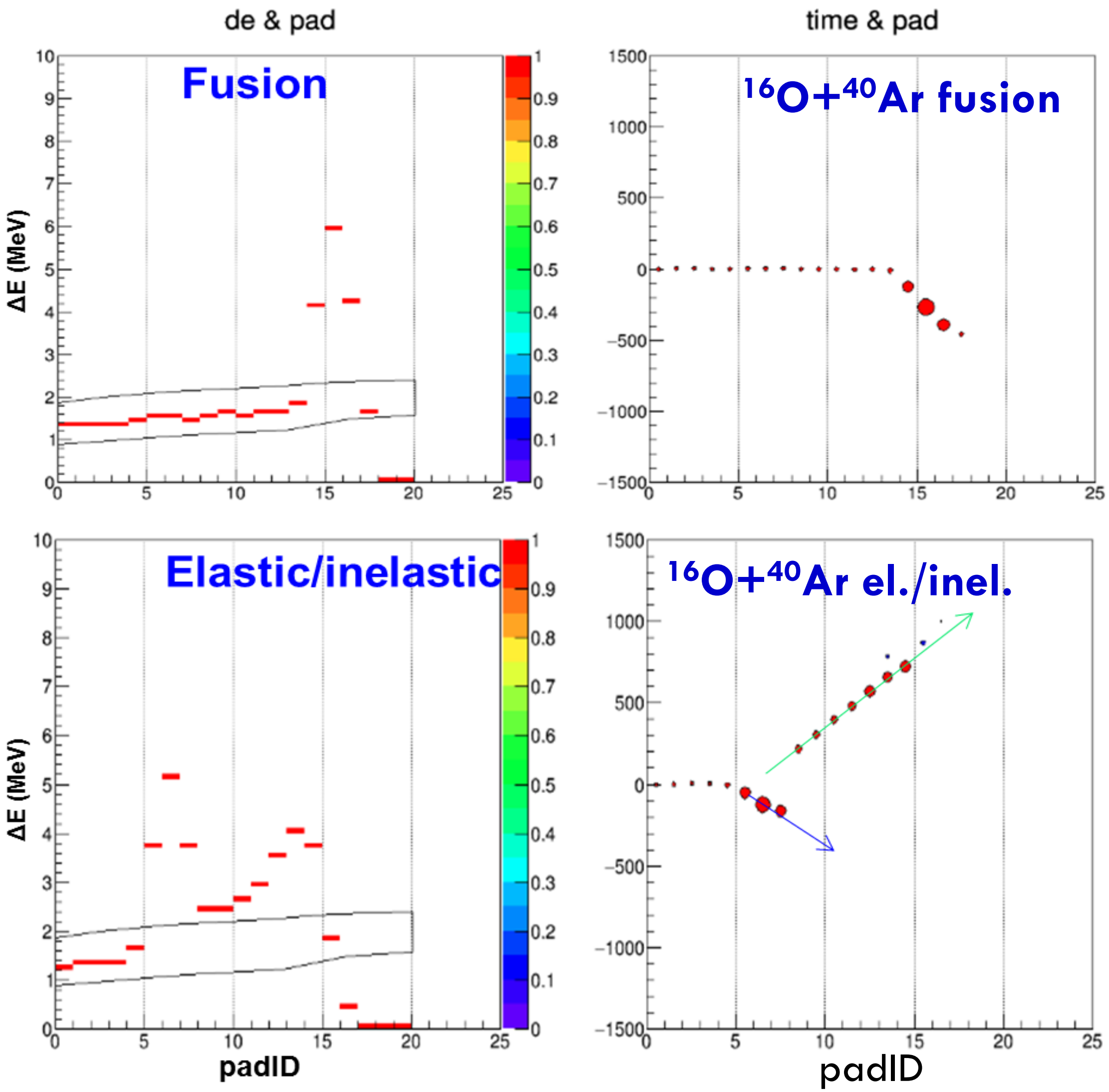
Limitation of MUSIC

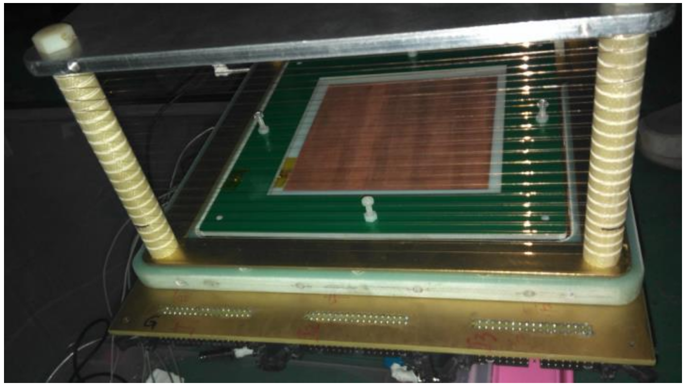


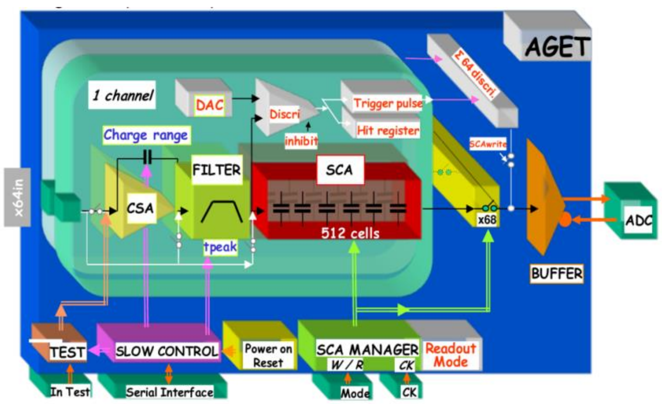


With drift time, the fusion cross section of $^{13}C+^{12}C$ could be pushed down to 6 MeV. About 17% systematic error is due to misjudge of elastic scattering.

EXPLOSIVE BURNING (fusion with n-rich beam)

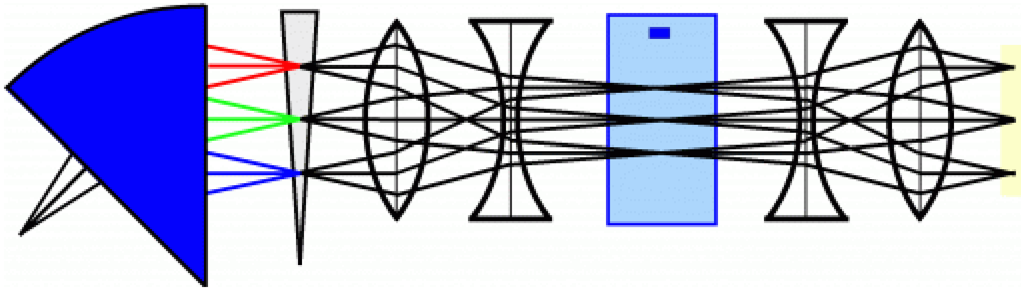




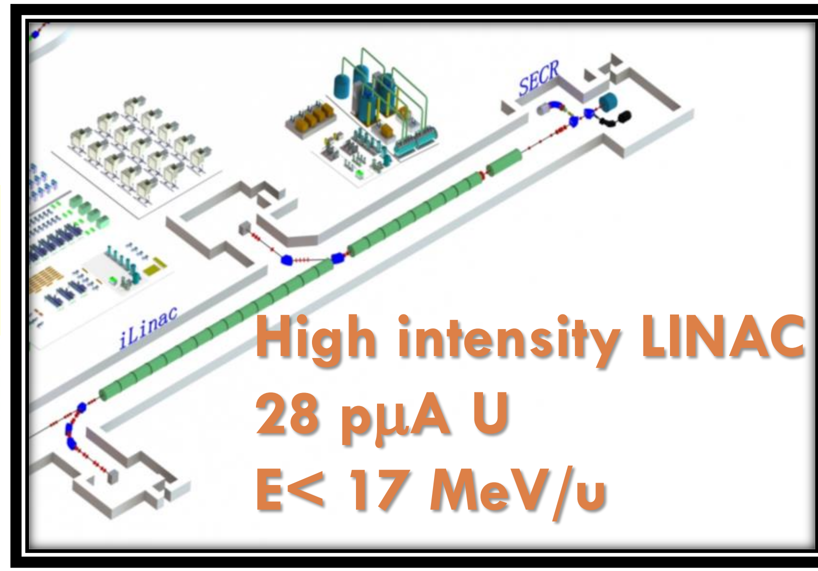


- The first TPC experiment at HIFRL
- Fusion inside of neutron star crust: $^{24}O+^{24}O$

Low energy n-rich beam facilities



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



KOBRA at RAON (2021)

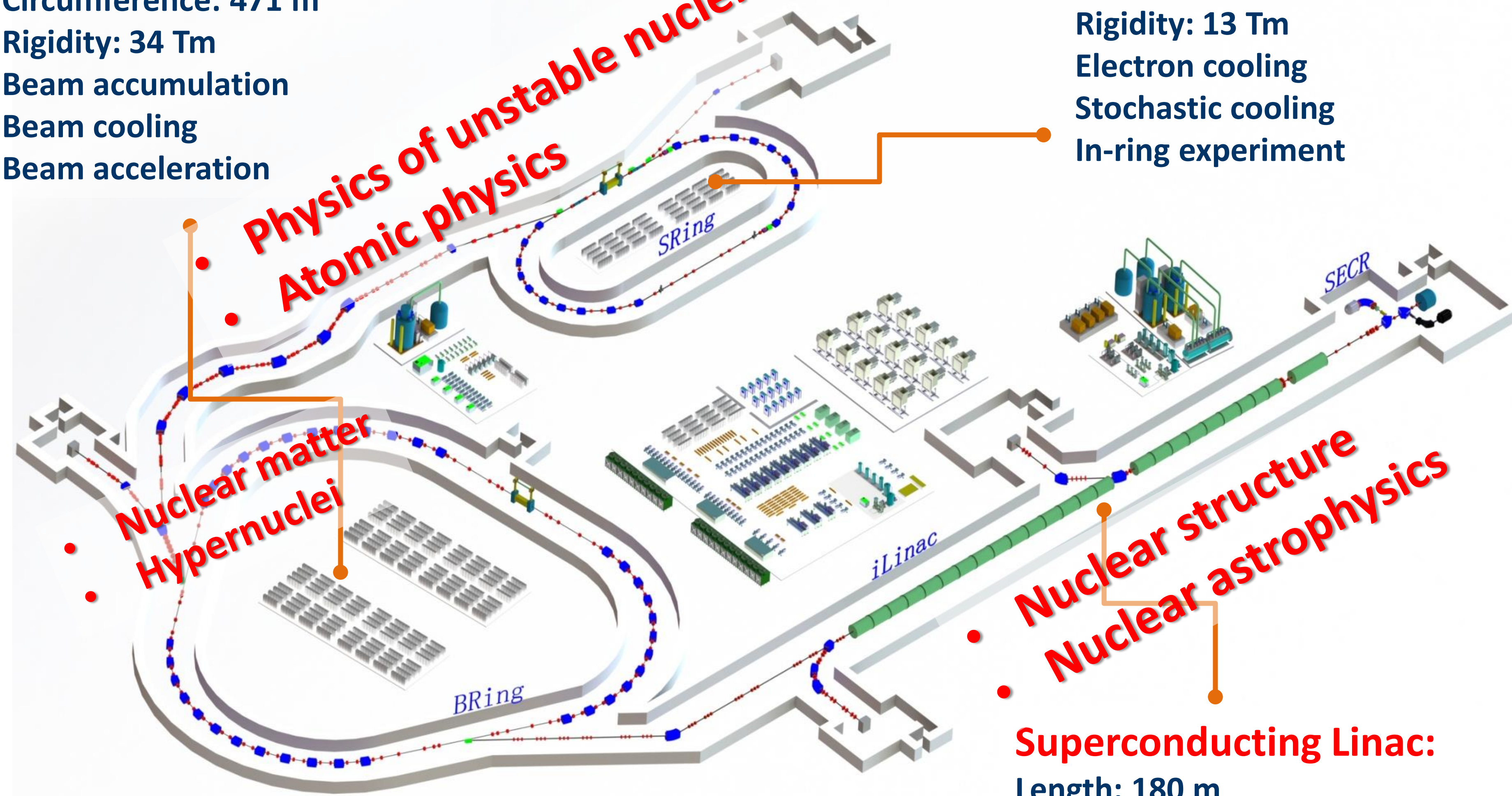
TSR at HIAF (2022)

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



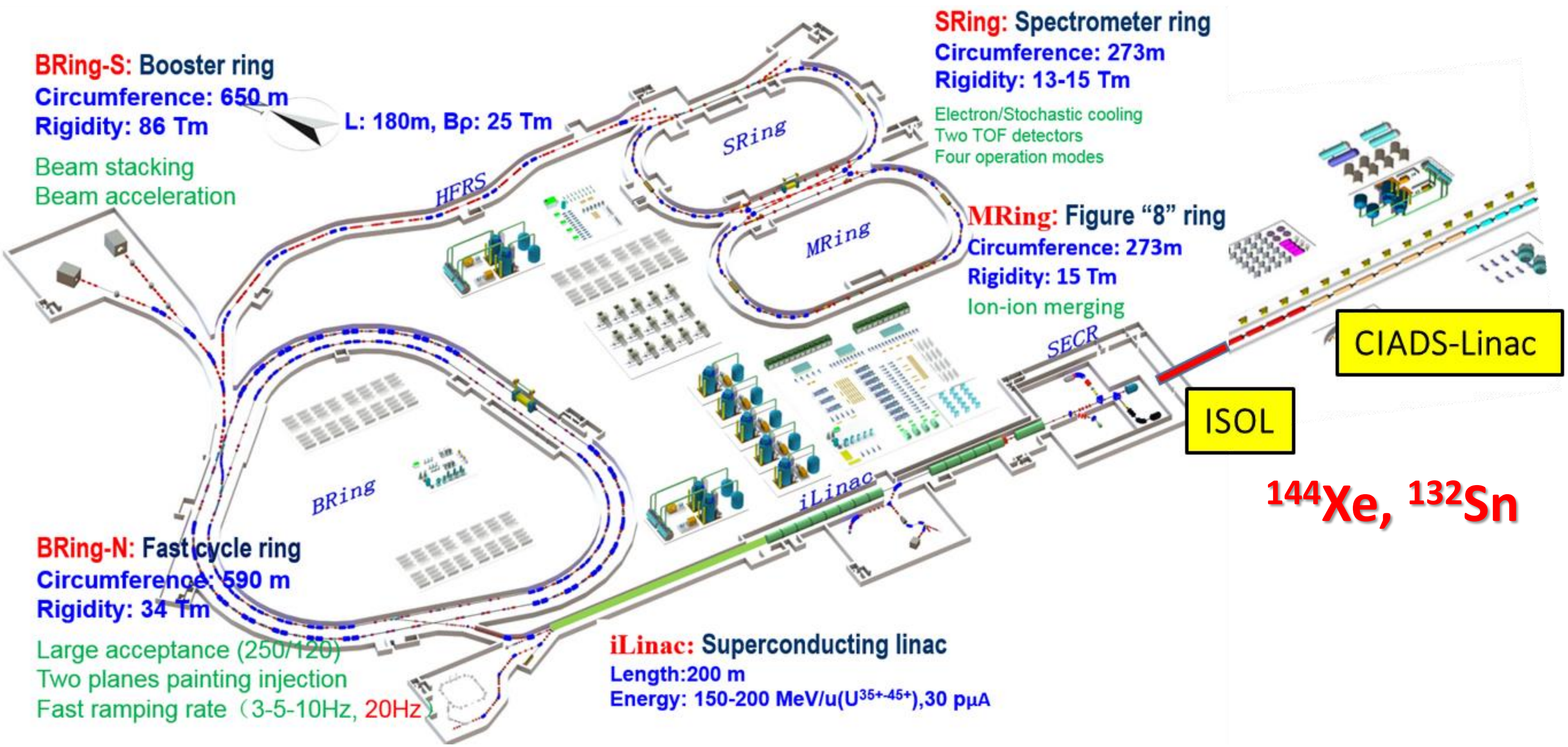
Superconducting Linac:
Length: 180 m
Energy: 17 MeV/u (U^{34+})
CW and pulse modes (1 emA)

Courtesy of X.H. Zhou

High Intensity heavy ion Accelerator Facility (HIAF)

HIAF-U: 2023-2028

Merging beam: $^{132}Sn+^{132}Sn$



^{144}Xe, ^{132}Sn

MNT,PF,Fusion with n-rich beams

Summary

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

→Hindrance model is not a good global model

→Reliable upper limit is established

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