


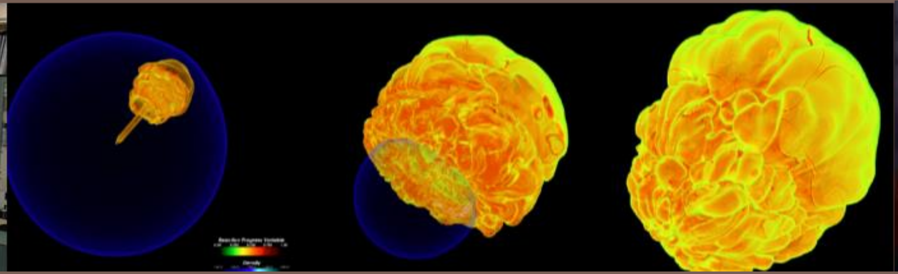
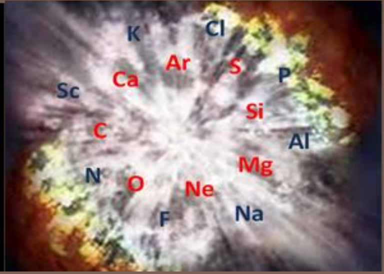

THE $^{12}C+^{12}C$ REACTION AT STELLAR ENERGIES

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[2] Joint Department for Nuclear Physics,

Lanzhou University and Institute of Modern Physics, CAS, China

FUS++ on "Heavy-Ion Fusion Far Below the Barrier“, January 20-21, 2022

Outline

- $^{12}C+^{12}C$ in stars
- Testing extrapolating model towards stellar energies
- Data compilation
- New Experimental techniques
- Summary and outlook

Eur. Phys. J. A (2021) 57:235
https://doi.org/10.1140/epja/s10050-021-00536-2

THE EUROPEAN PHYSICAL JOURNAL A

Review

Heavy-ion fusion reactions at extreme sub-barrier energies

C. L. Jiang[1,a], B. B. Back[1], K. E. Rehm[1], K. Hagino[2], G. Montagnoli[3], A. M. Stefanini[4]

Eur. Phys. J. A (2020) 56:87
https://doi.org/10.1140/epja/s10050-020-00075-2

THE EUROPEAN PHYSICAL JOURNAL A

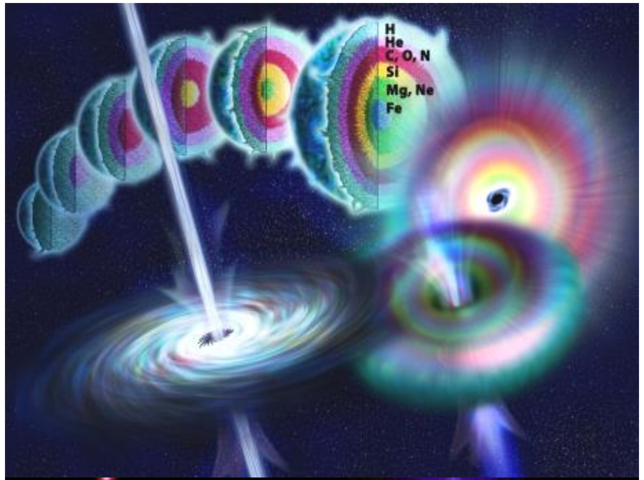
Letter to the Editor

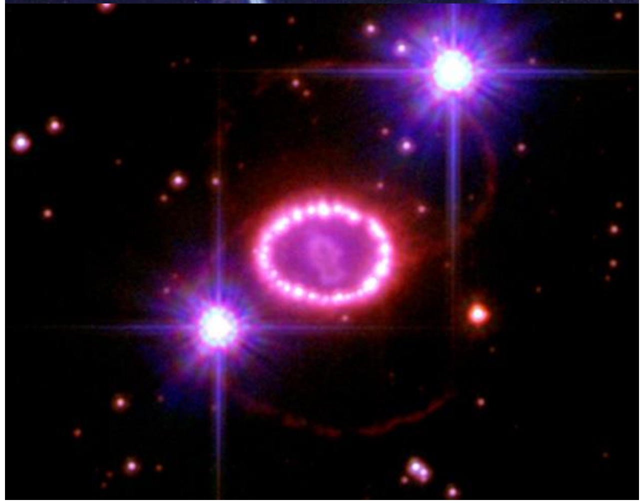
Status on $^{12}C + ^{12}C$ fusion at deep subbarrier energies: impact of resonances on astrophysical S^* factors

C. Beck[1,a], A. M. Mukhamedzhanov[2,b], X. Tang[3,4,c]

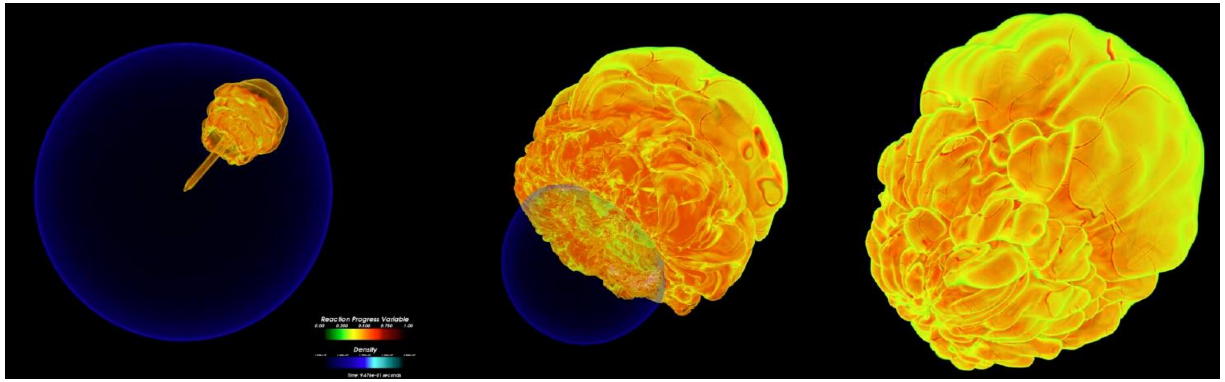
Carbon burning in the universe

Nucleosynthesis in massive stars

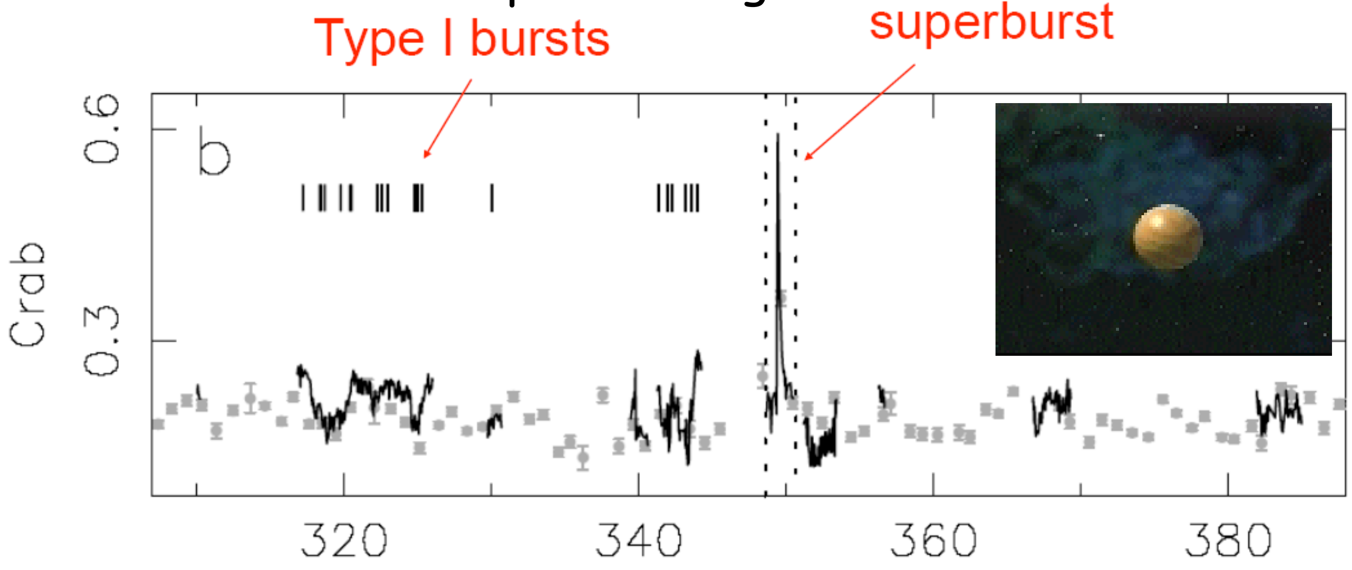




Ignition conditions in type Ia supernovae



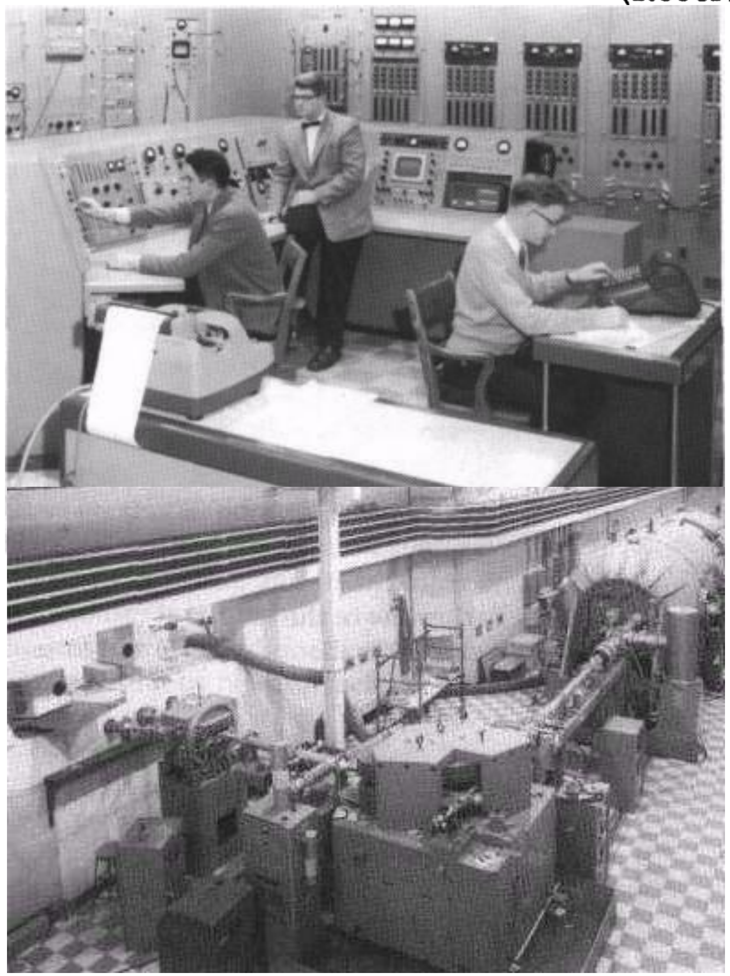
Candidate for Superburst ignition



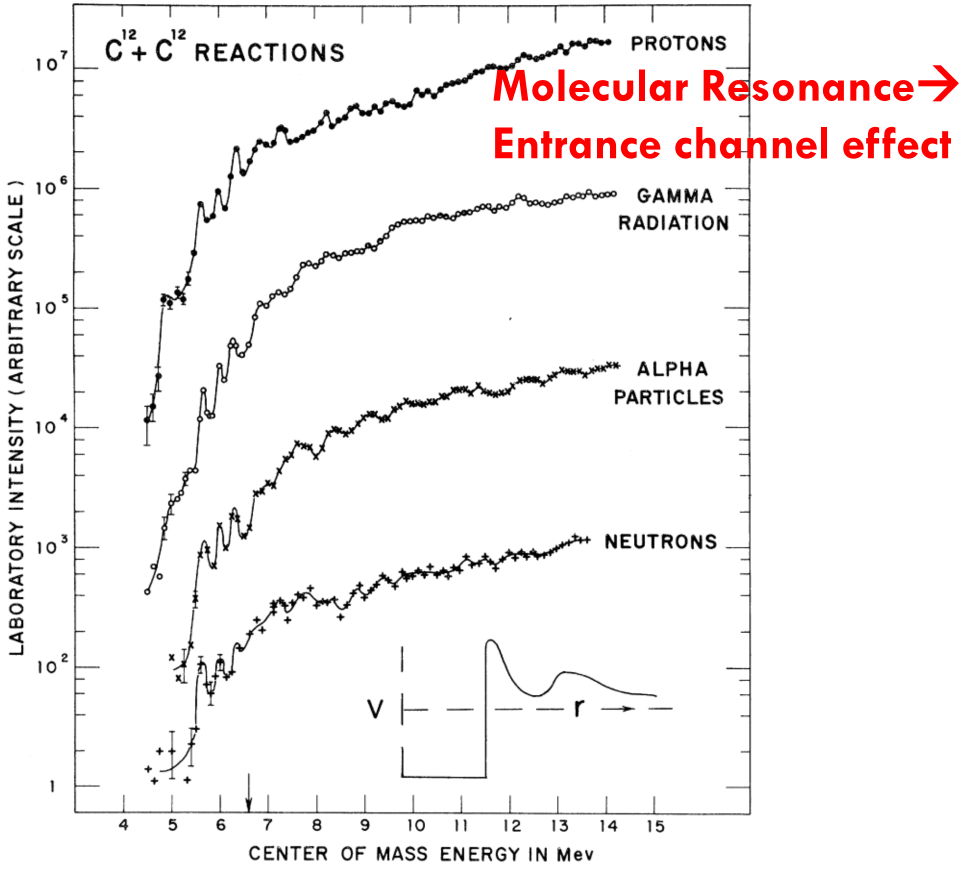
VOLUME 4, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1960

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)

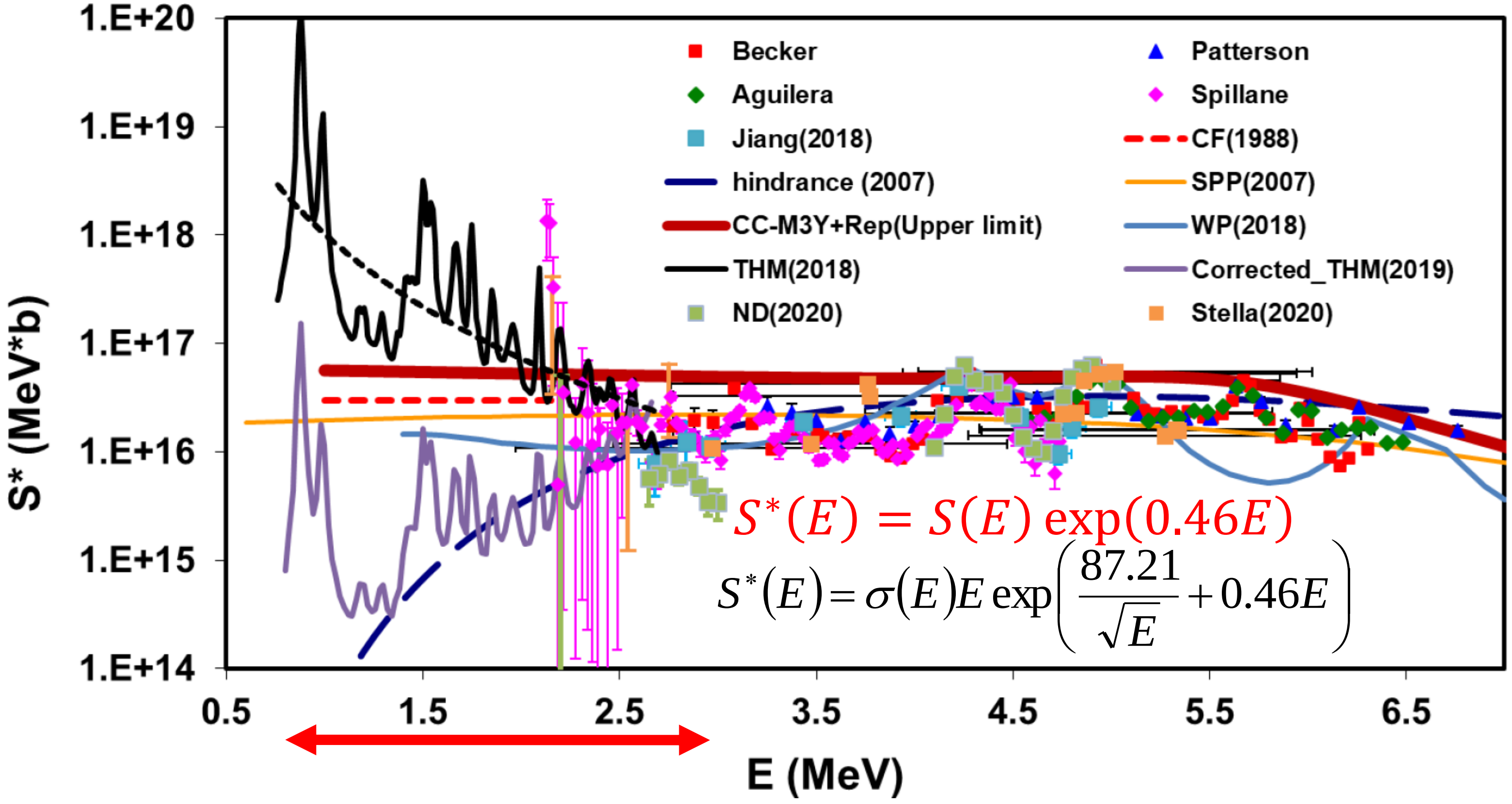


The world's first tandem accelerator installed at Chalk River in 1959.



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

Uncertain Cross section at stellar energies



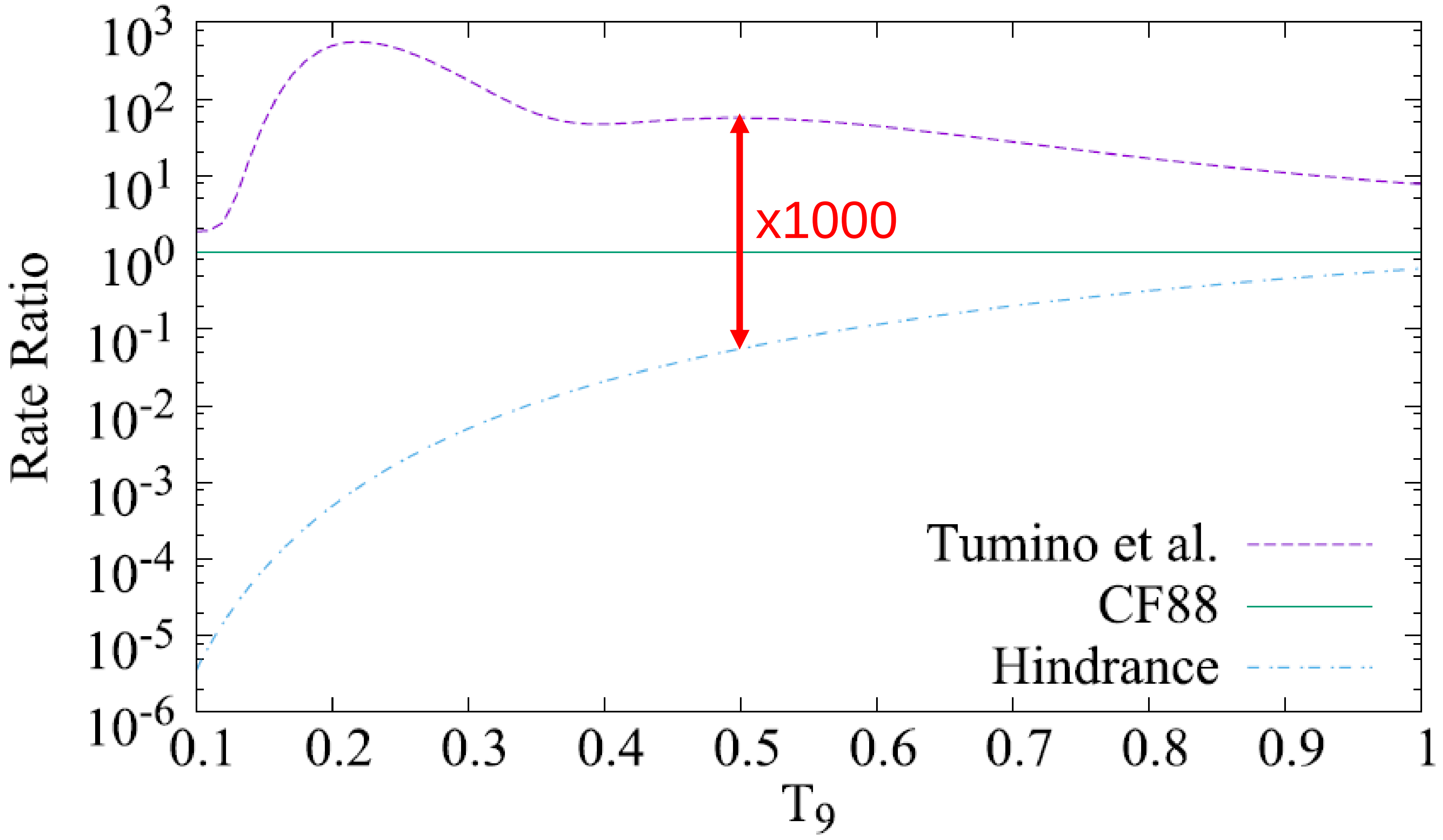
10^{-22} b 10^{-7} b

- 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

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

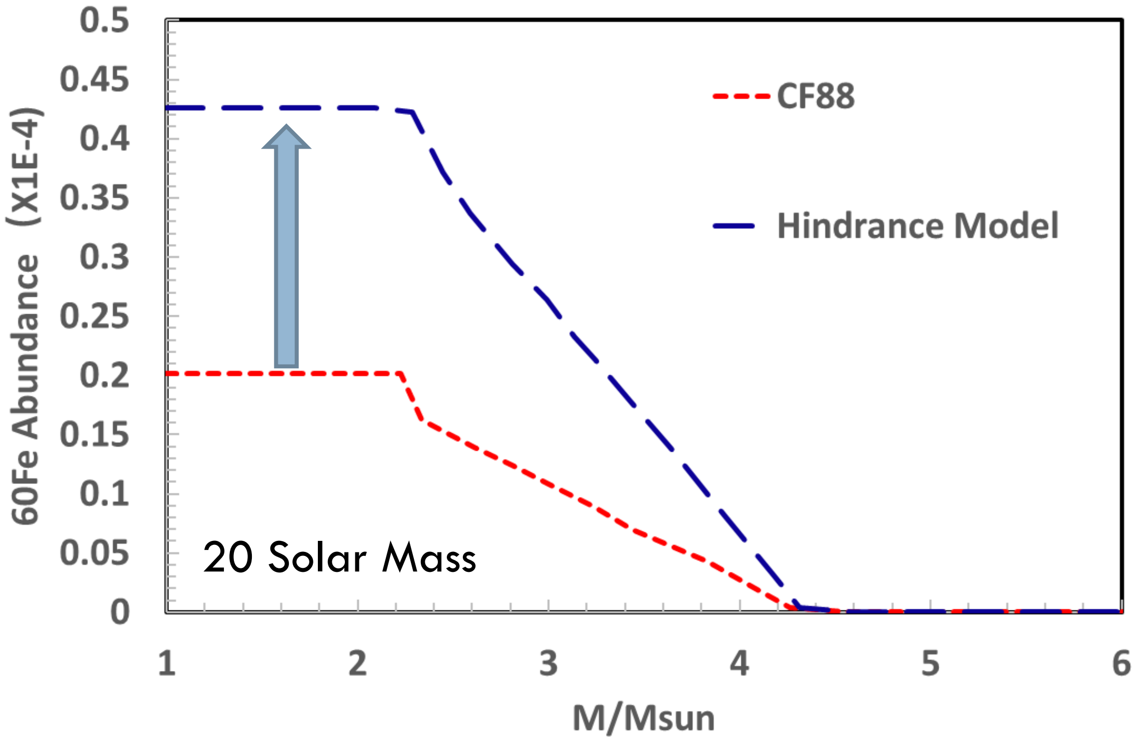
Beck, Mukhamedzhanov and Tang, Eur. Phys. J. A (2020) 56:87
Mukhamedzhanov, Kadyrov and Pang, Eur. Phys. J. A (2020) 56:233

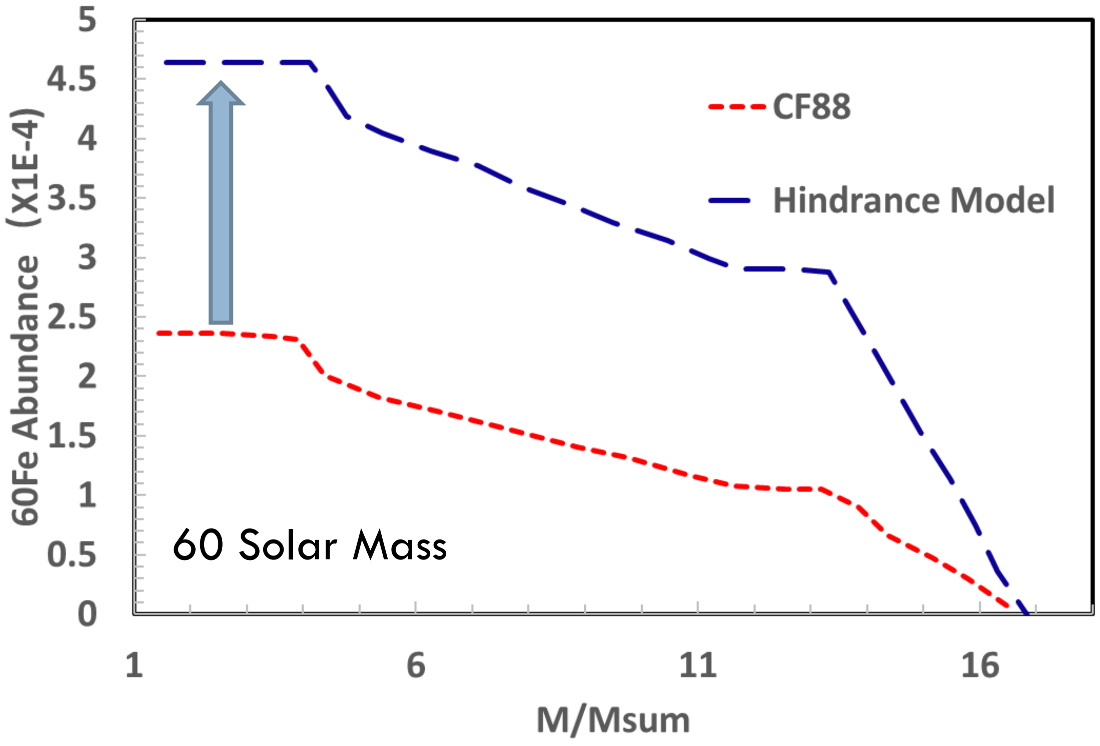
Uncertainty in the reaction rate



Mori, Famiano, Kajino, Kusakabe and Tang, MNAS (2019)

Impact on ^{60}Fe in massive stars

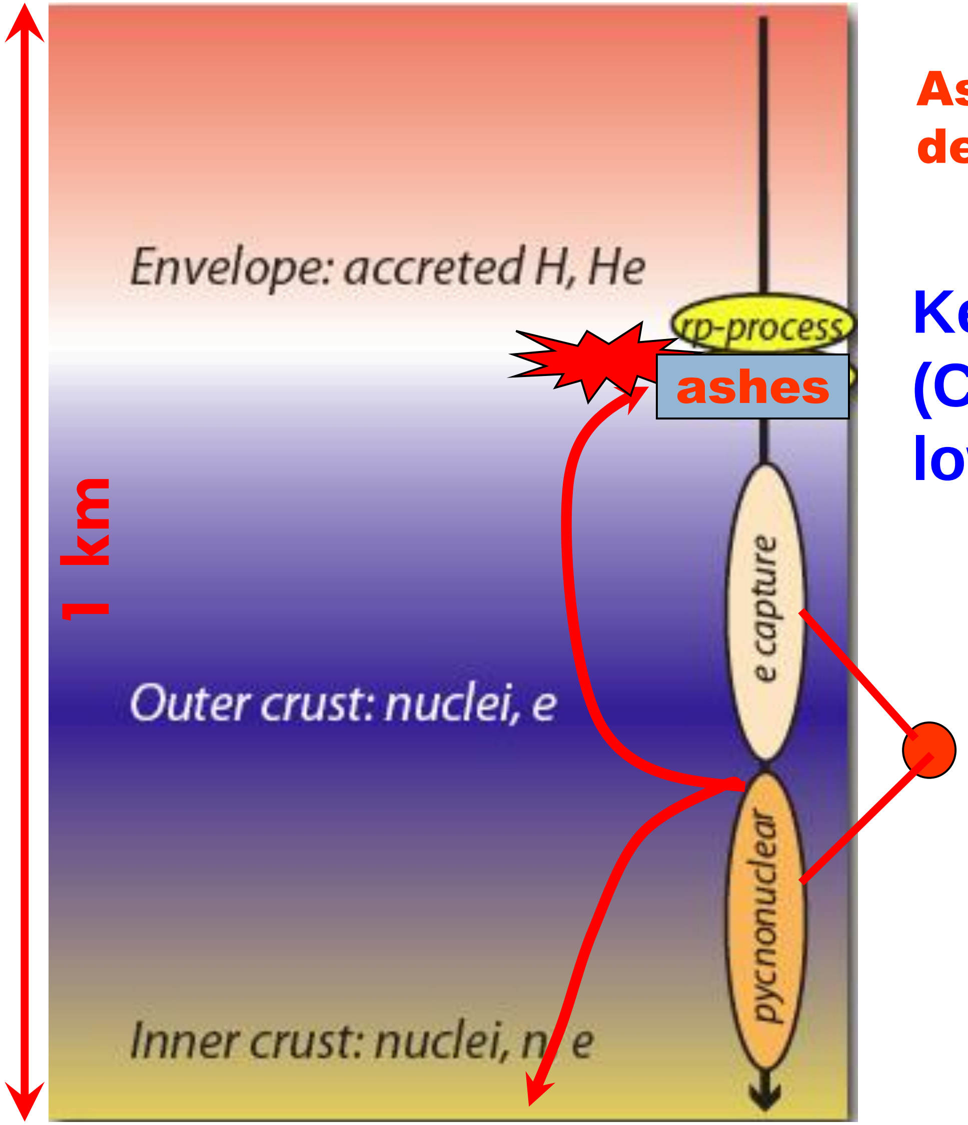




- The reduced rate based on the Hindrance model results in a significantly higher neutron production
- Enhanced ^{60}Fe production provided by the new reduced fusion rates would further enhance the already overpredicted ^{60}Fe abundance in the galaxy

Gasques et al. (2007); Other studies of massive stars by Bucher+(2015), Chieffi+ (2021) ,Monpribat+(2021)

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! ☹

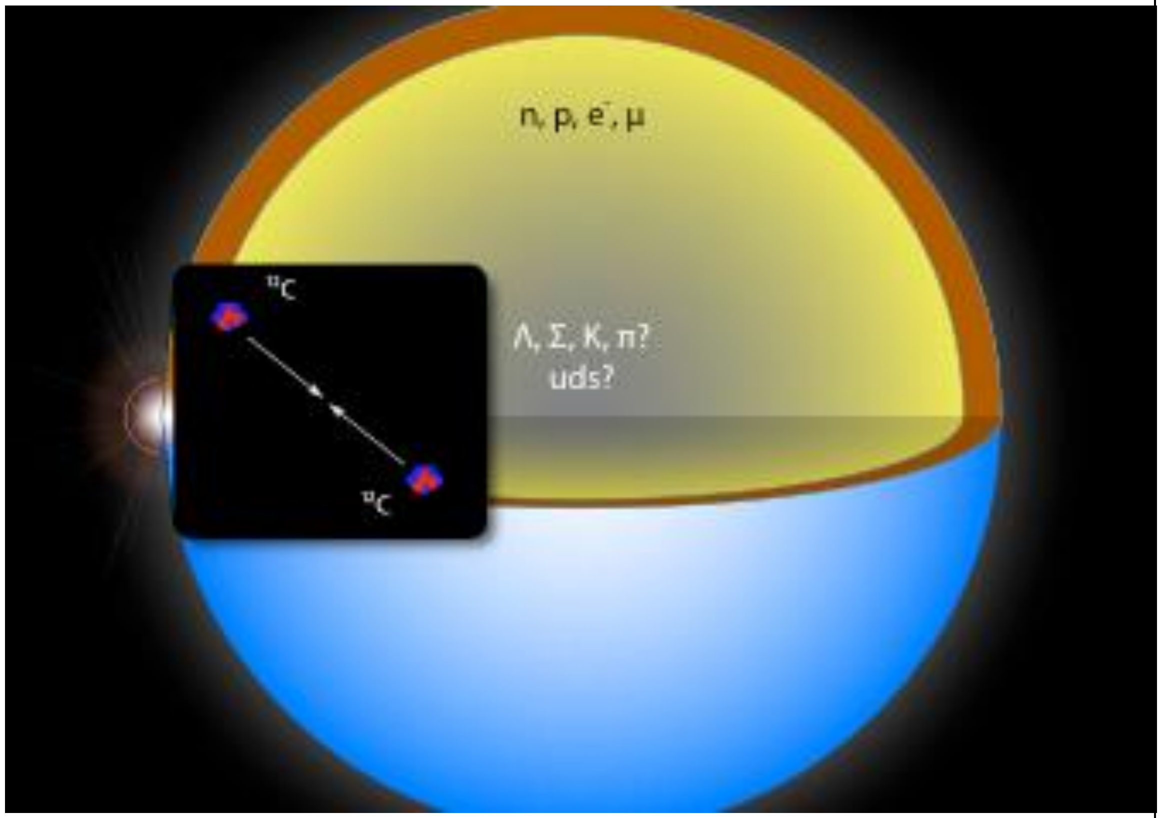
Crust processes
(EC, pycnonuclear fusion)
→crust heating and cooling
→crust conductivity

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

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

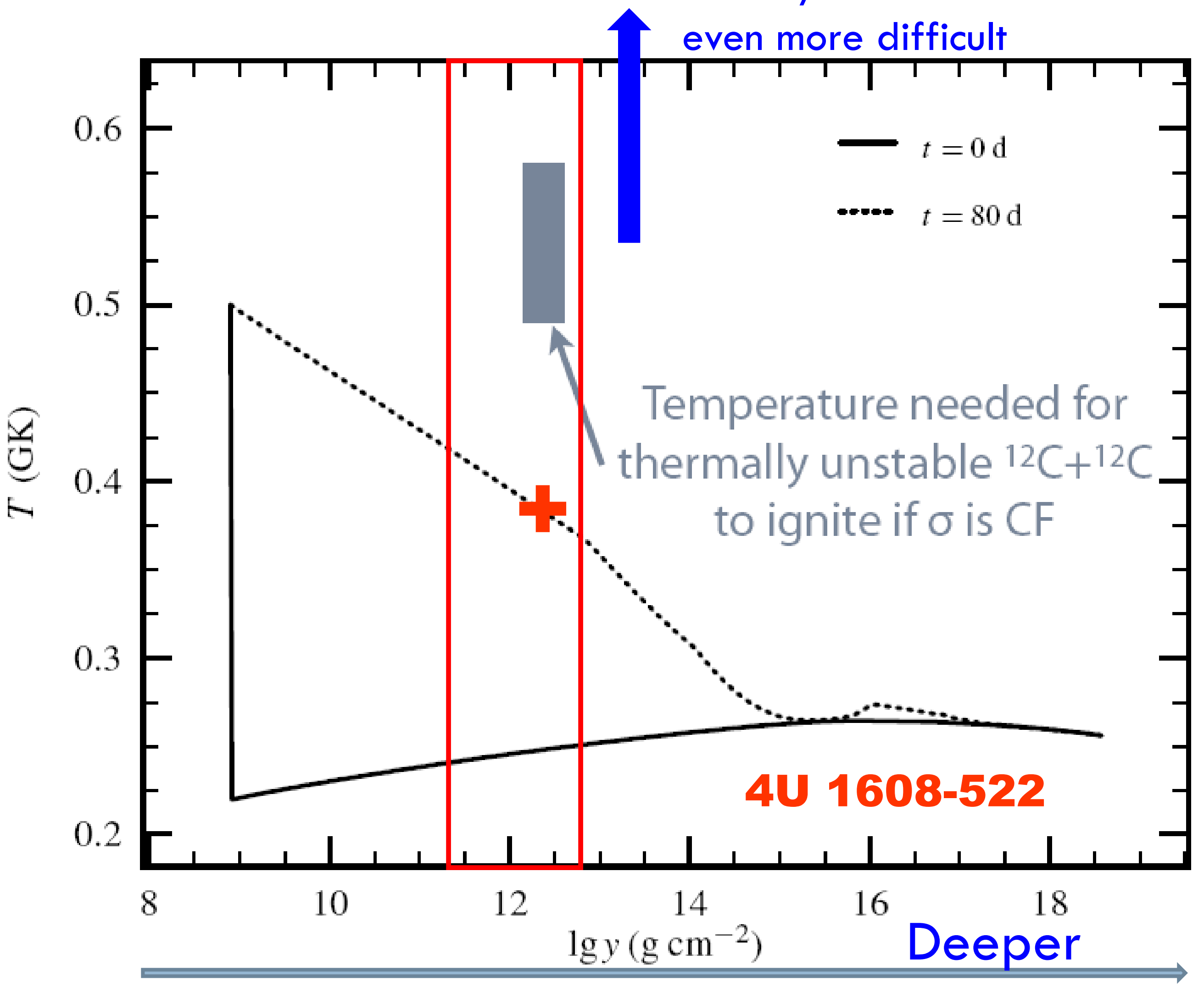
……..

Superburst Puzzle: the crust is too cold to ignite the carbon burning! How to ignite the carbon?



Picture by Ed Brown (MSU)

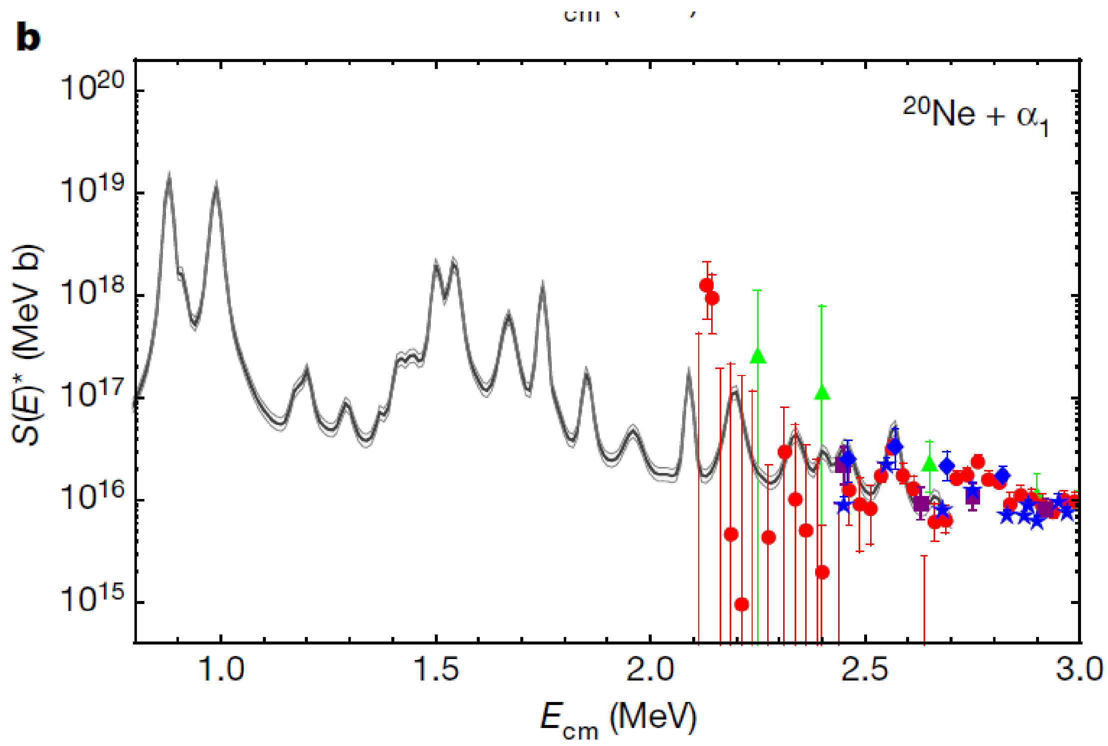
Rate by Hindrance will make it even more difficult

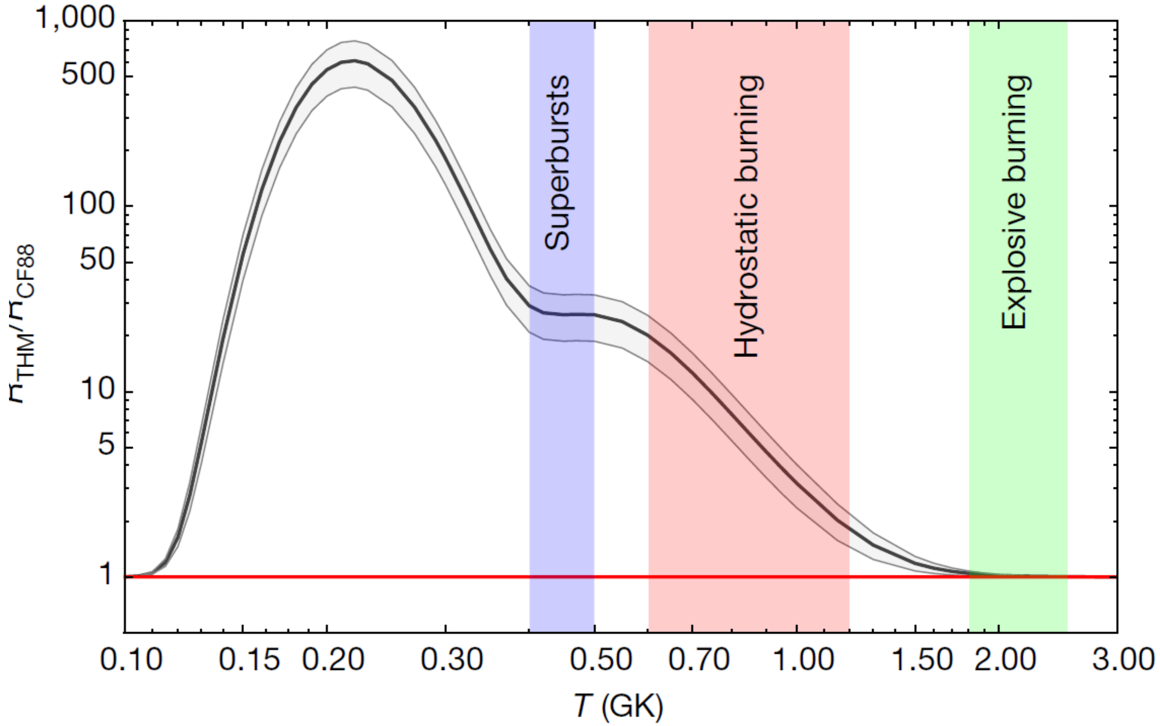


Type Ia supernova: Mori, Famiano, Kajino, Kusakabe, and Tang, MNRAS 482 (2019) L70

Keek et al. (2007), Astron. & Astrophys. 479: 177
Cooper, Steiner and Brown, ApJ (2009)

THM: Carbon burning can trigger superbursts



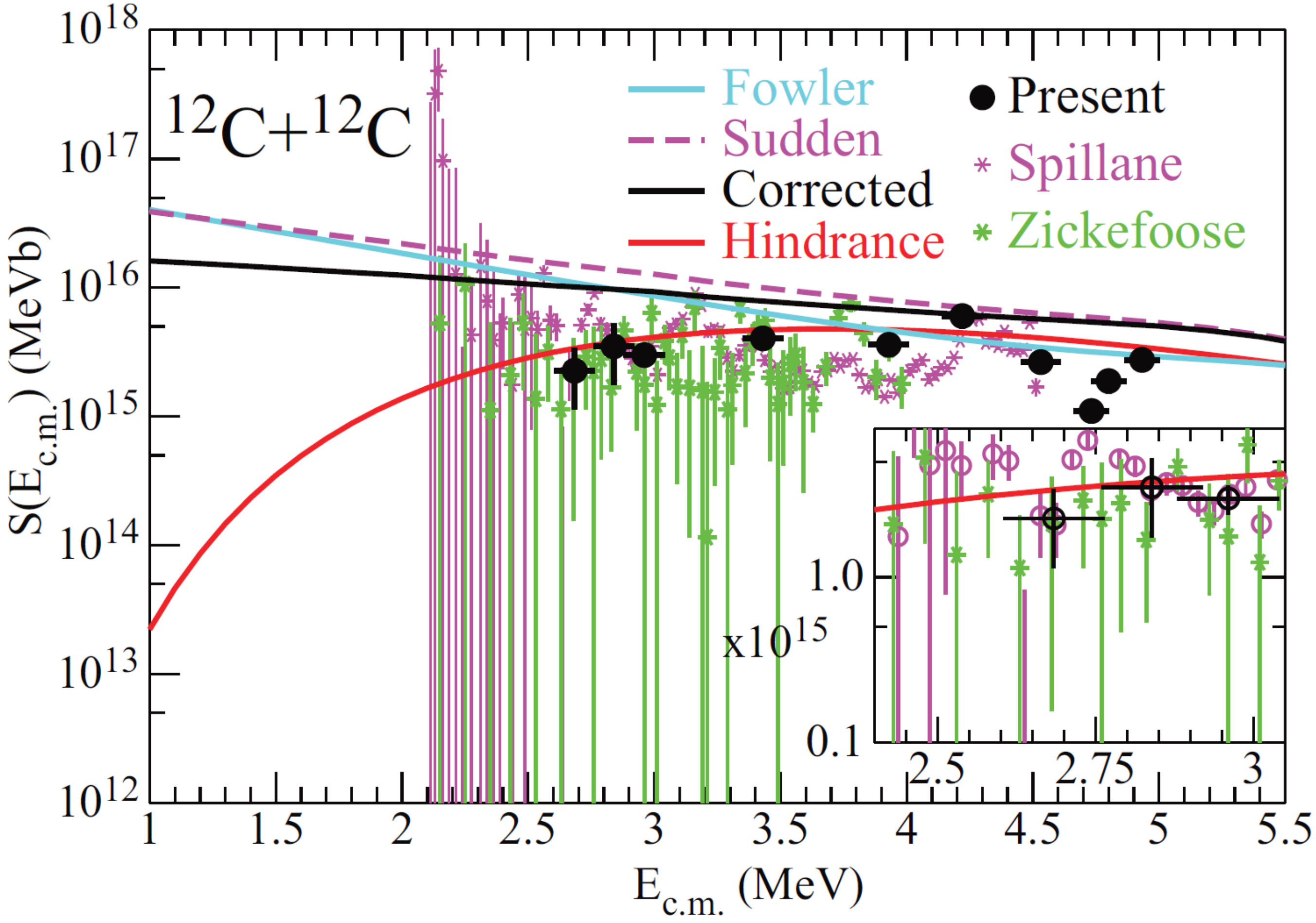


- ➢ Increase in the ^{12}C + ^{12}C fusion rate from resonances at astrophysical energies
- ➢ This change matches the observationally inferred ignition depths and can be translated into an ignition temperature below 0.5 GK, compatible with the calculated crust temperature

Tumino et al., Nature (2018)

Testing the predictive powers of Extrapolating models

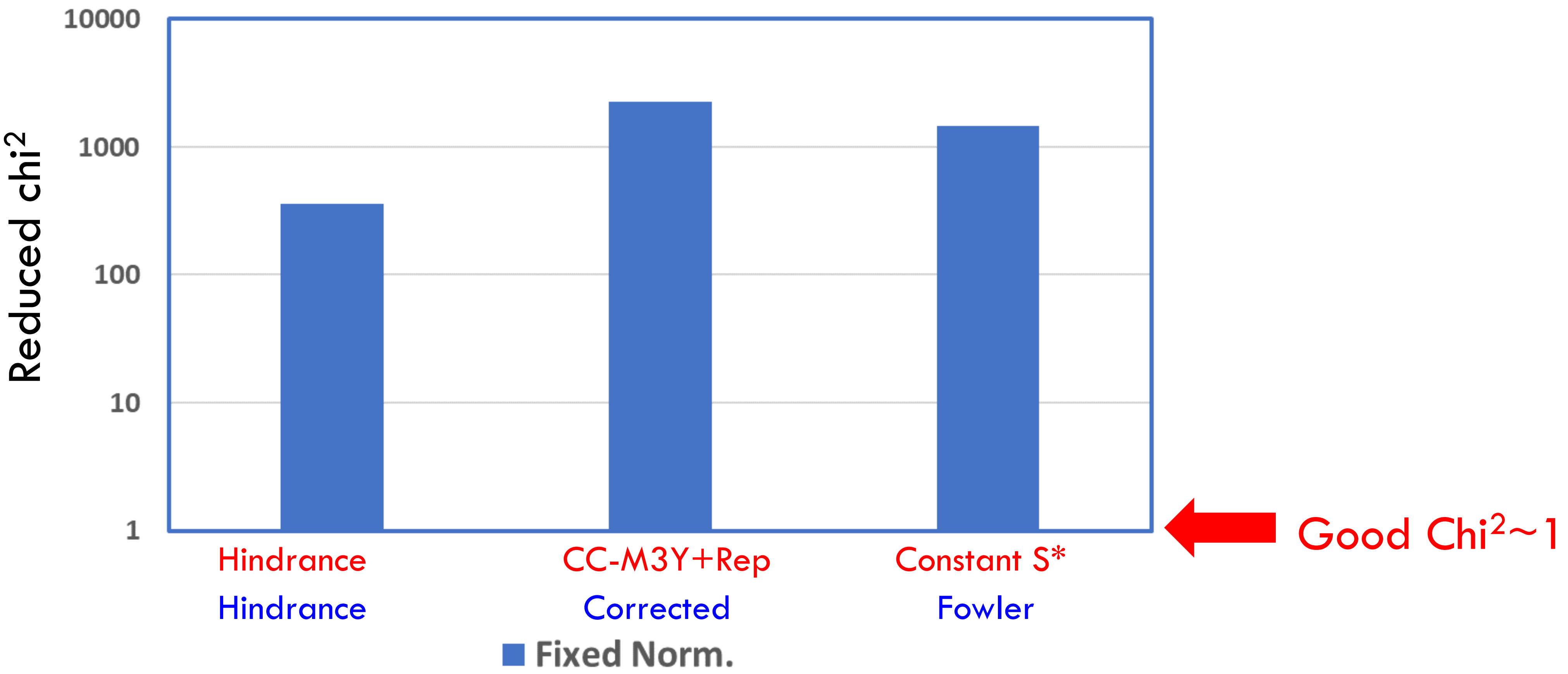
Hindrance effect found in the $^{12}C+^{12}C$ system?



“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)

Hindrance effect found in the $^{12}C+^{12}C$ system?



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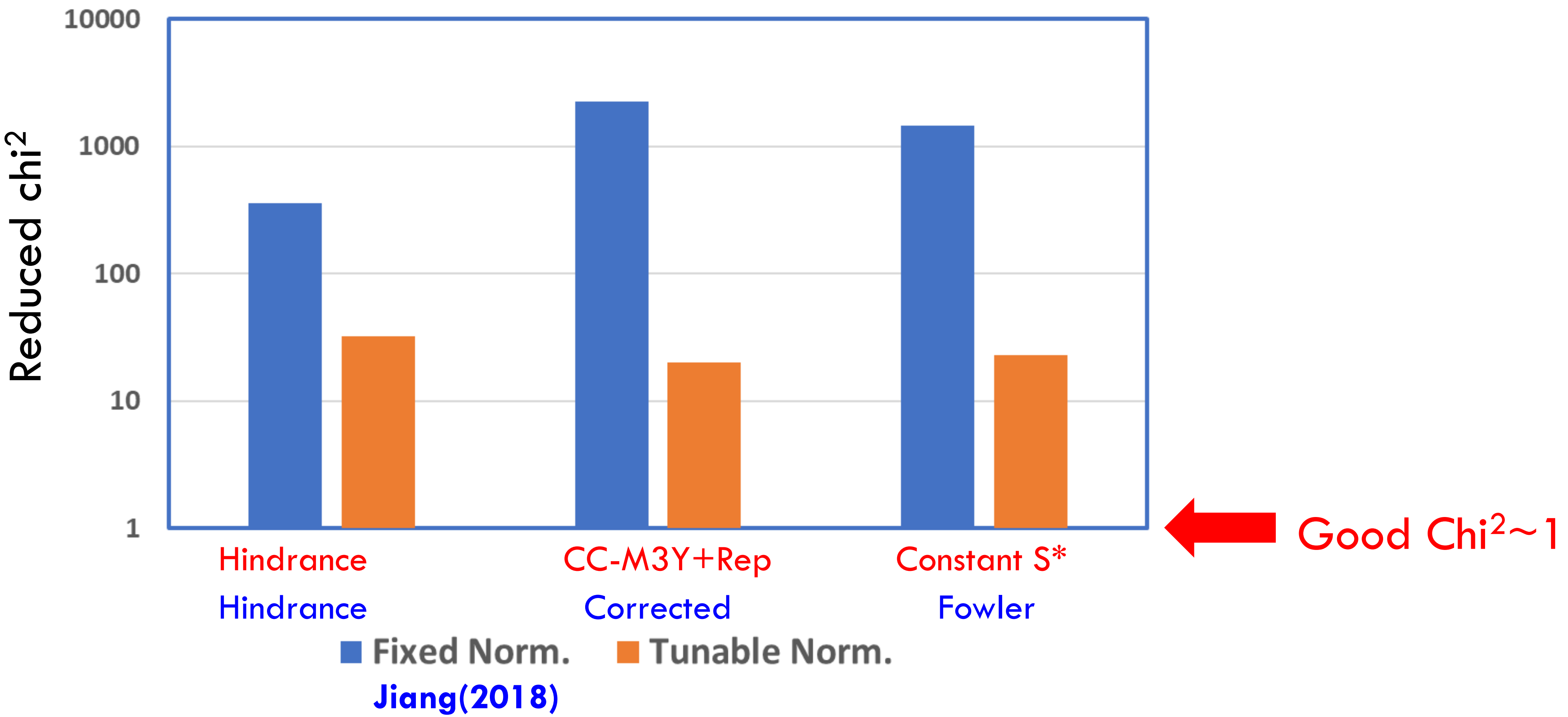
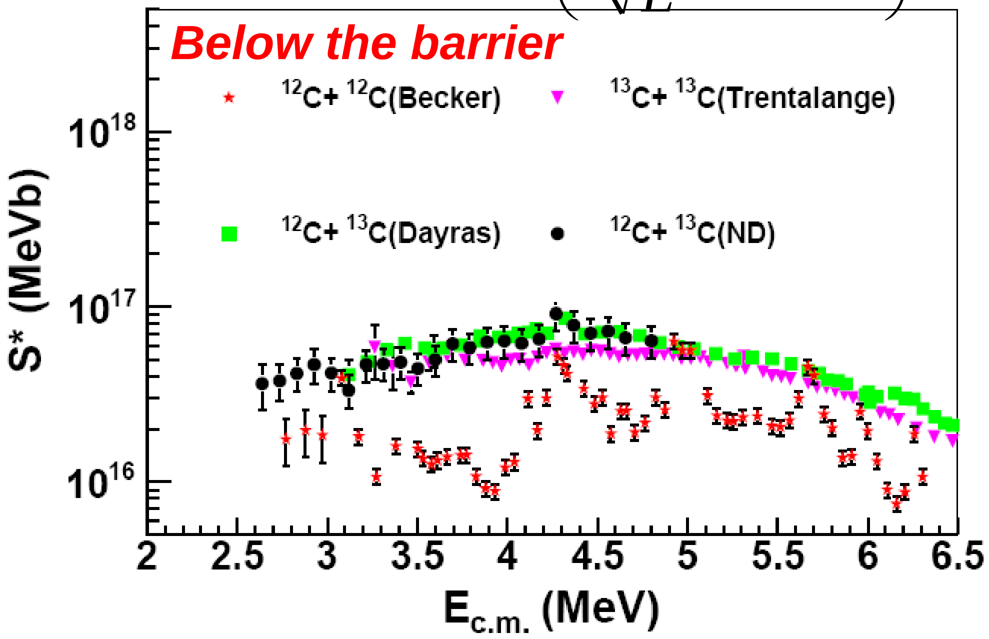
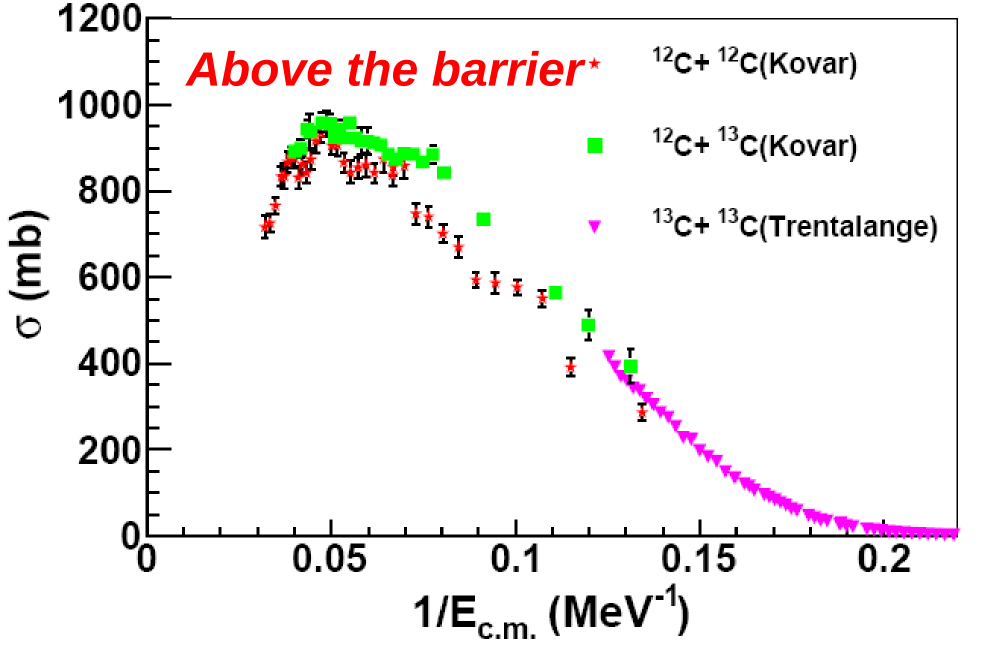


The complicated structure does not favor any model !

$$S^*(E) = \sigma(E) E \exp\left(\frac{87.21}{\sqrt{E}} + 0.46E\right)$$





Correlation among carbon isotope systems

A simple pattern for complicated resonances

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

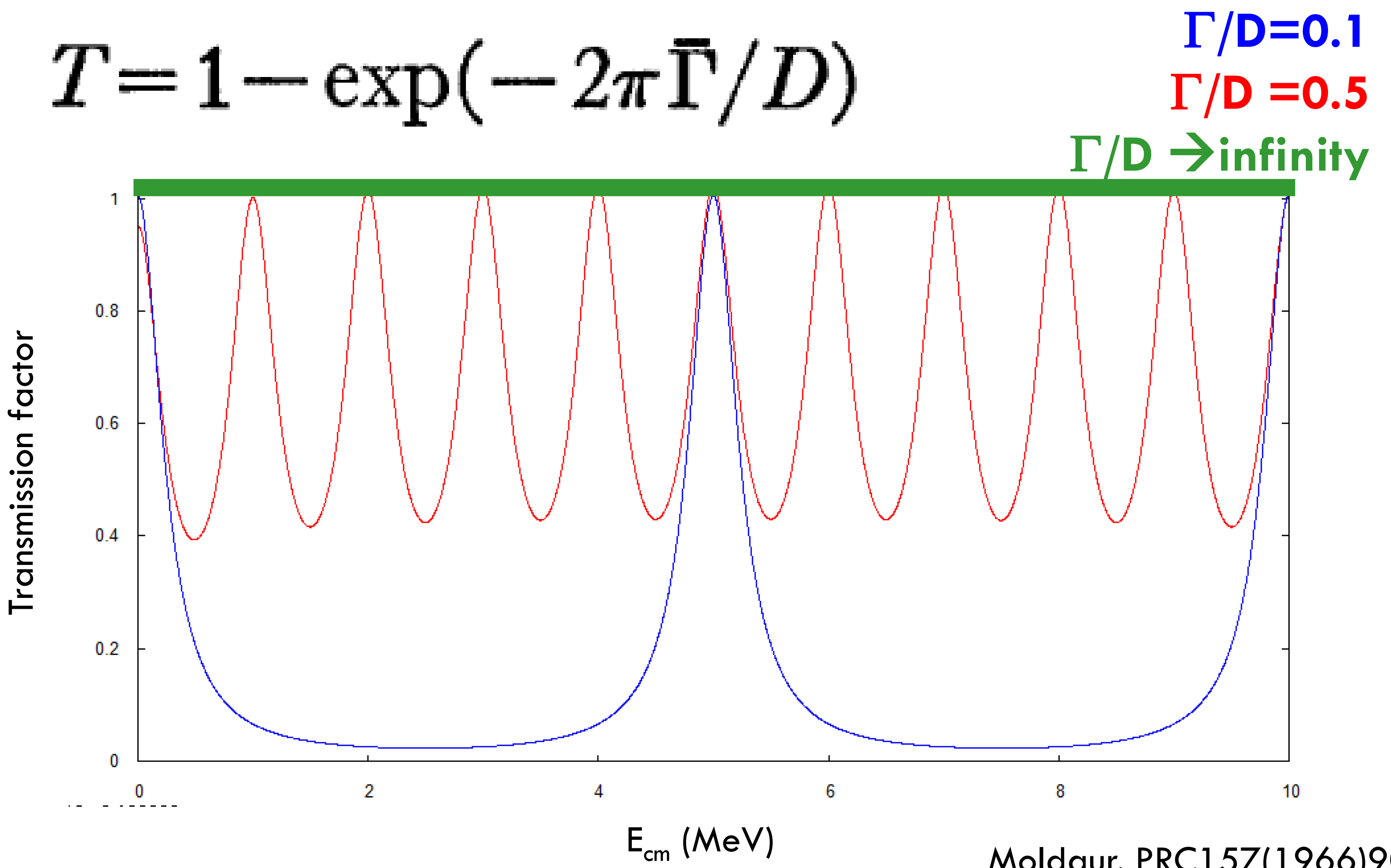
Only at resonant energies, the $^{12}C+^{12}C$ cross sections matches with those of $^{12}C+^{13}C$ and $^{13}C+^{13}C$!

Why?

Notani+ PRC(2011)

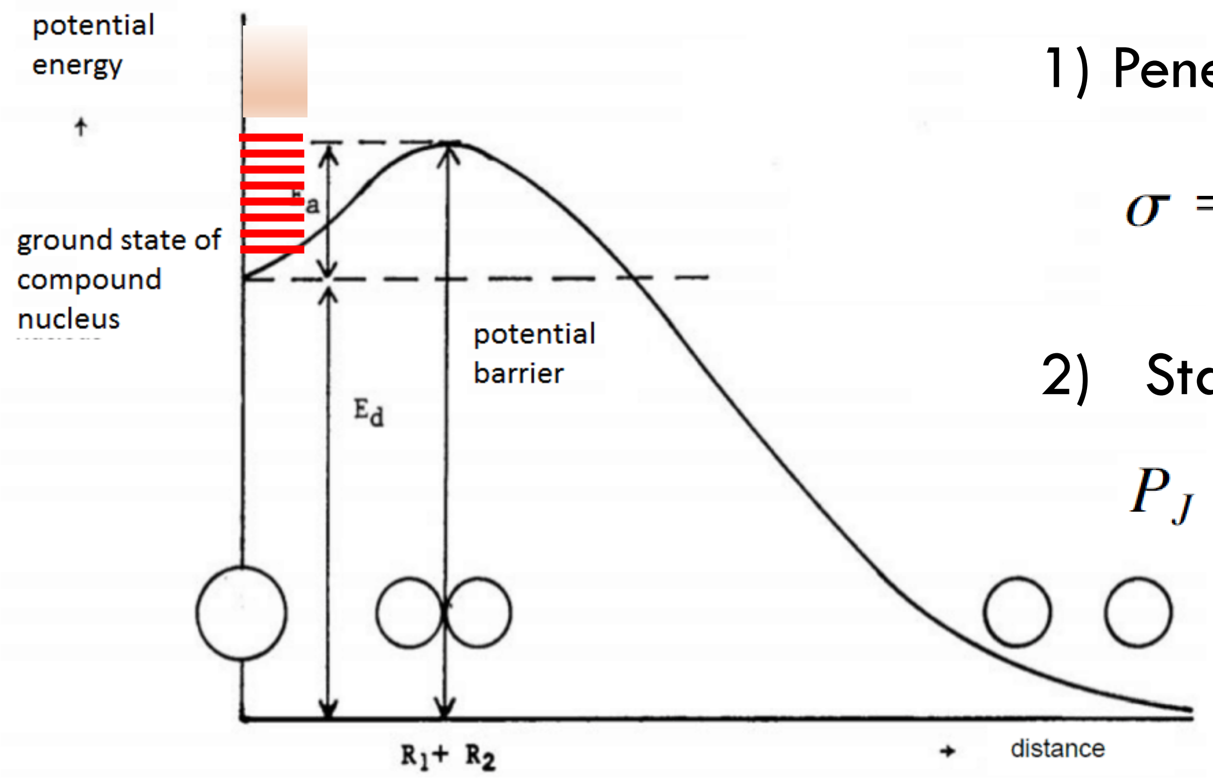
Correlation between carbon isotopes

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



Moldaur, PRC157(1966)907

Correlation among carbon isotope systems



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

1) Penetration

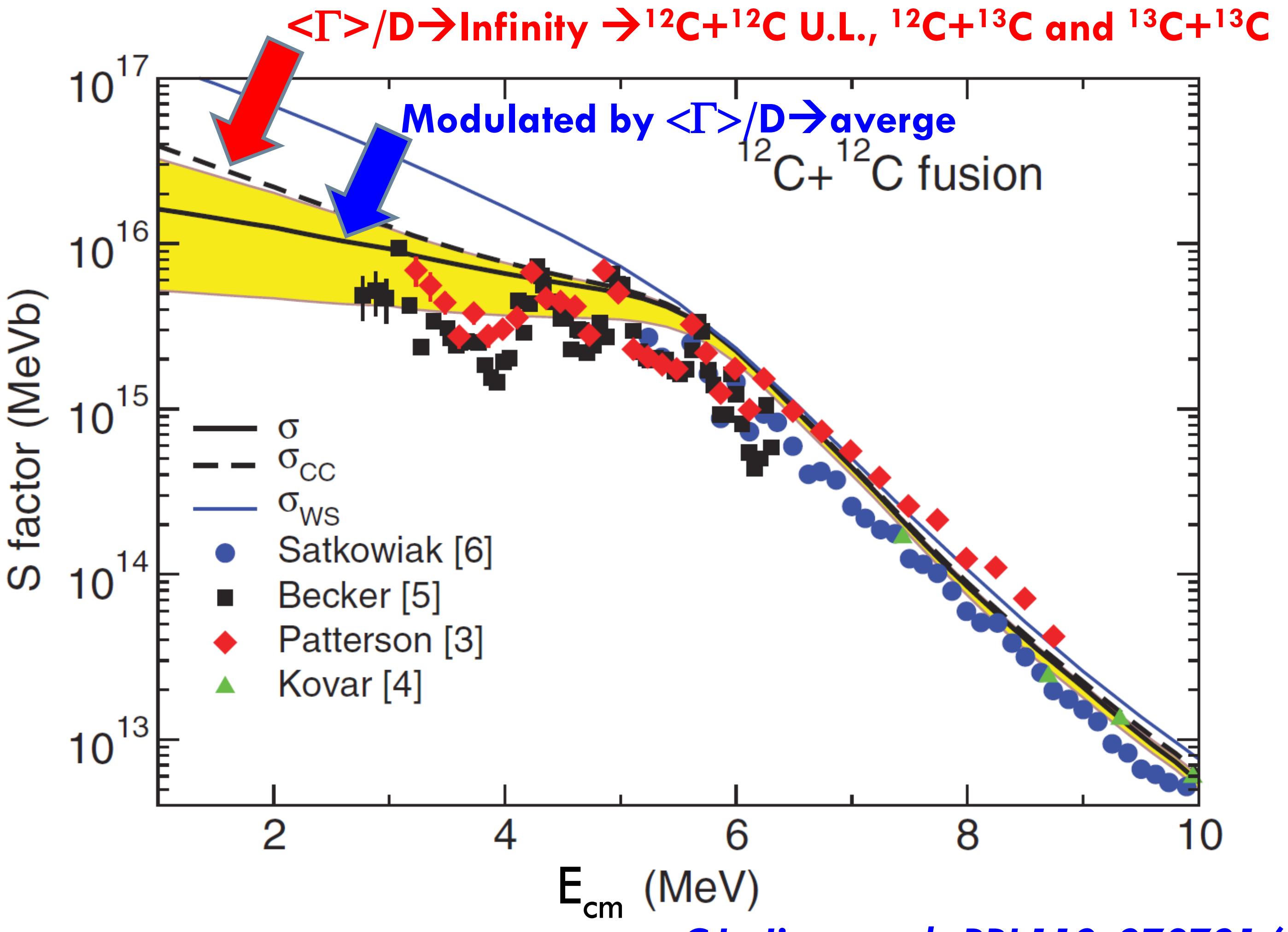
$$\sigma = \sum_J \sigma^J_{CC}$$

2) States for fusion

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

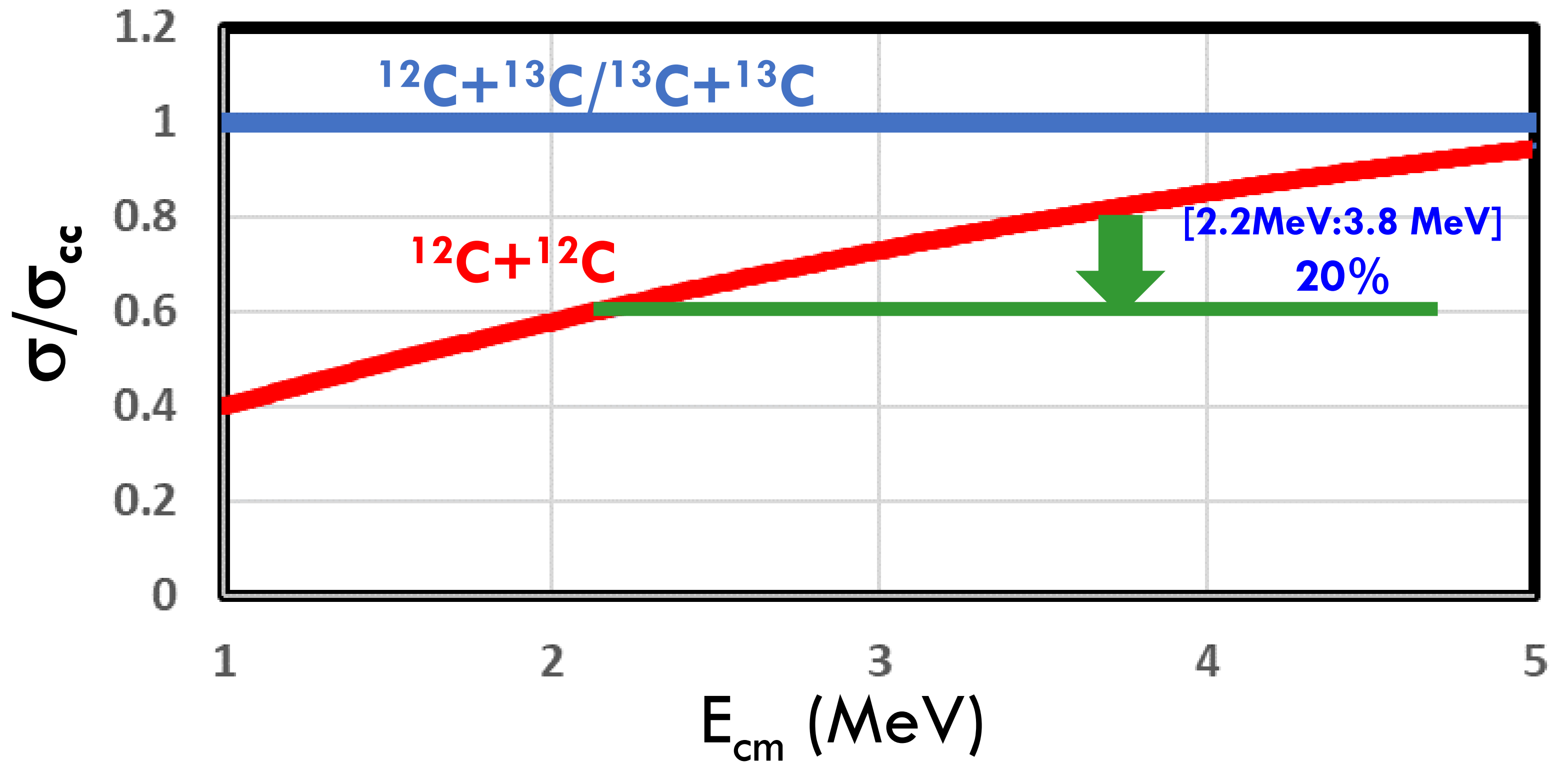
C.L. Jiang et al., PRL110, 072701 (2013)

Correlation between carbon isotopes



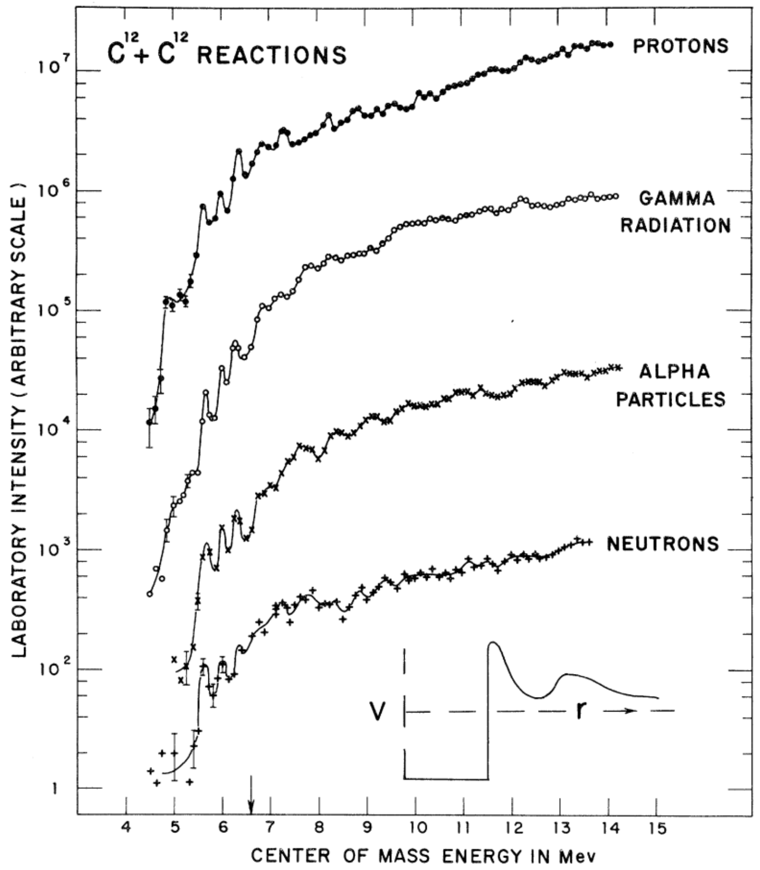
C.L. Jiang et al., PRL110, 072701 (2013)

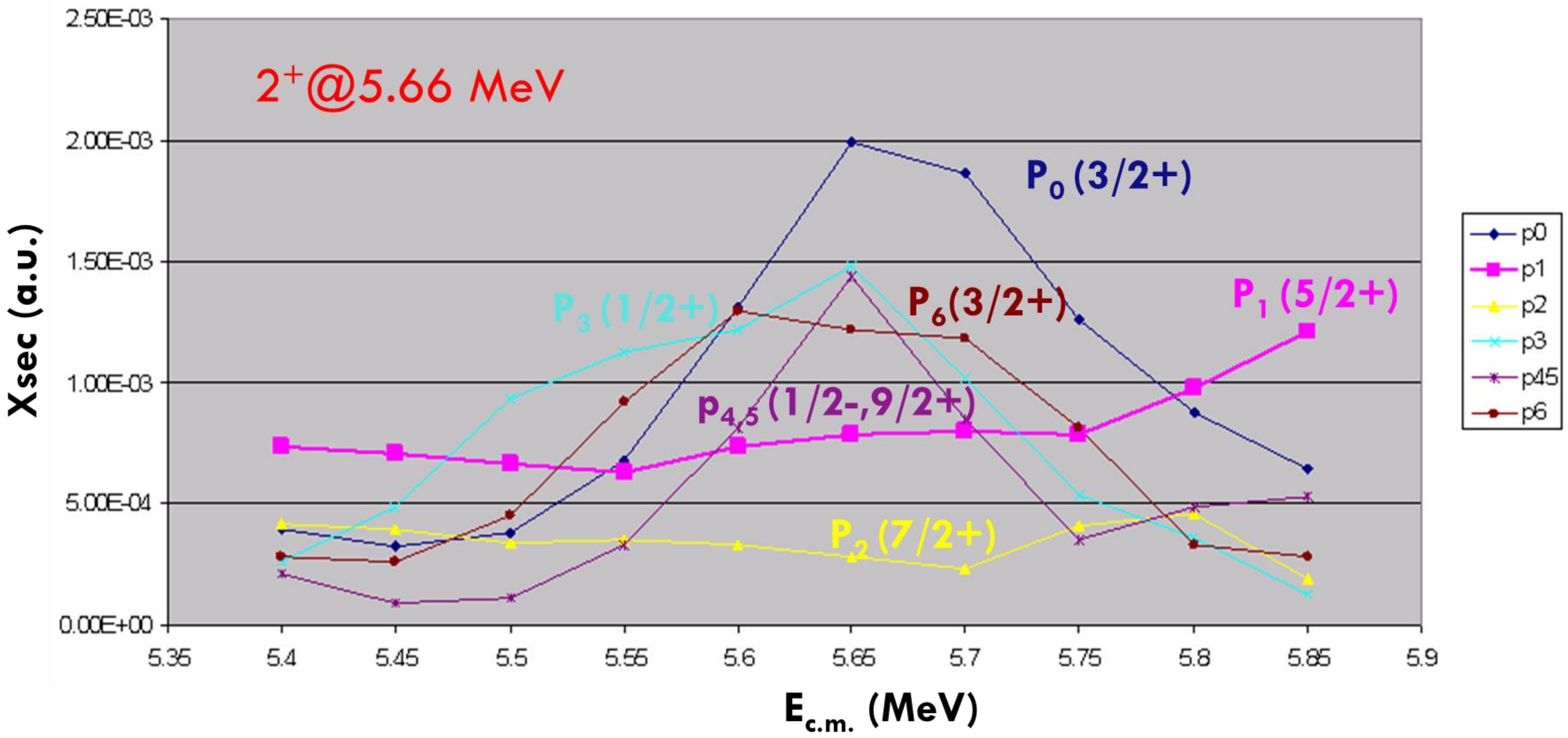
Correlation among carbon isotope systems



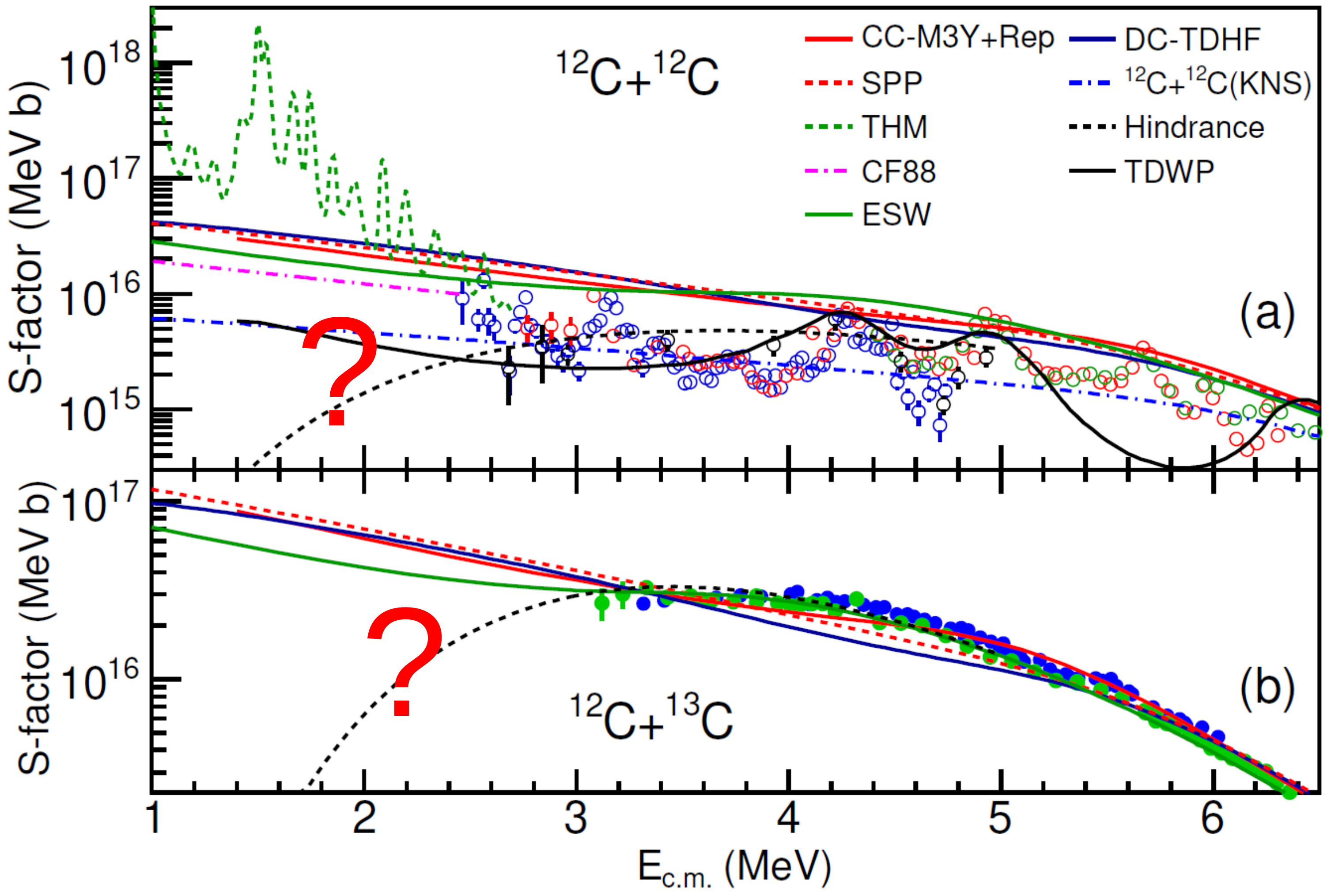
- Suppression of low level density is a slow varying effect
- Shape of averaged xsec is mostly determined by upper limit (σ_{cc})
- $^{12}C+^{13}C$ fusion cross section can constrain the upper limit

Molecular Resonances in entrance channel form intermedia structure



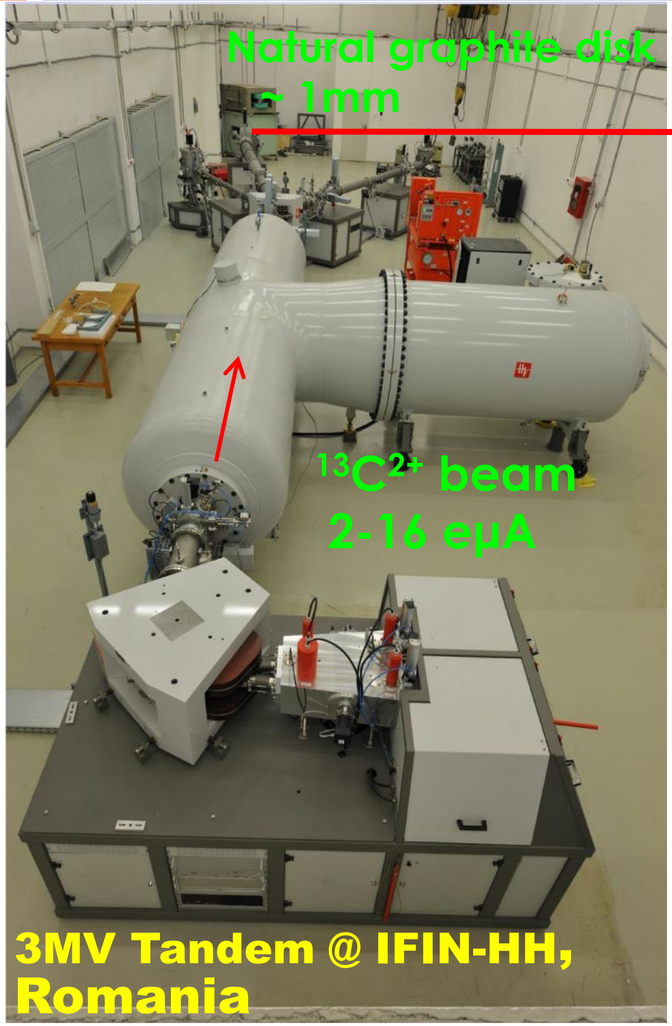


Testing the extrapolating models



- Hindrance model, a global phenomenological model based on the systematics observed in systems with 64 <A<30
- Should work for both $^{12}C+^{12}C$(upper limit) and $^{12}C+^{13}C$

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

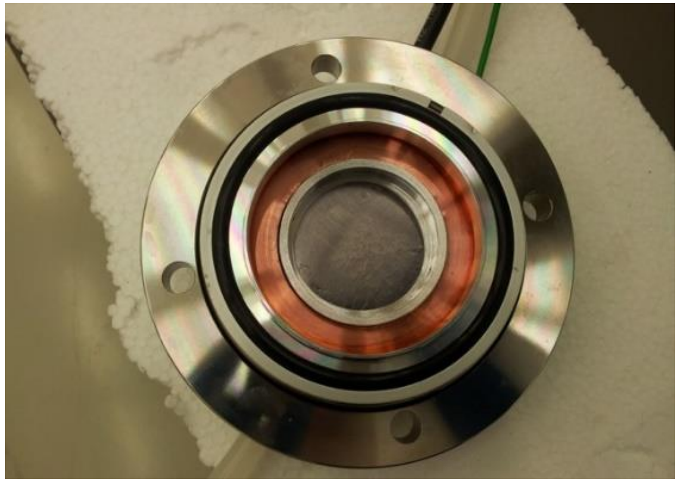


Online irradiation

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

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

1369-2754 keV γ rays



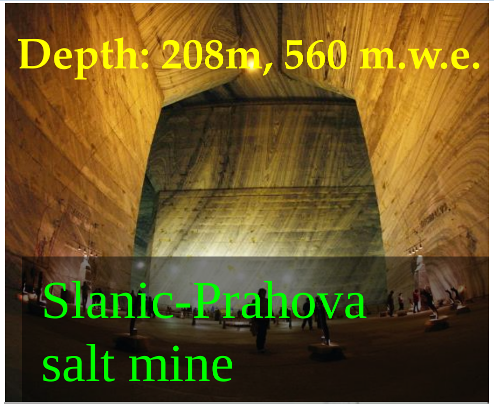
- **HF theory calibrated by exp. → Branching ratio**
- **Obtaining the total fusion cross section**

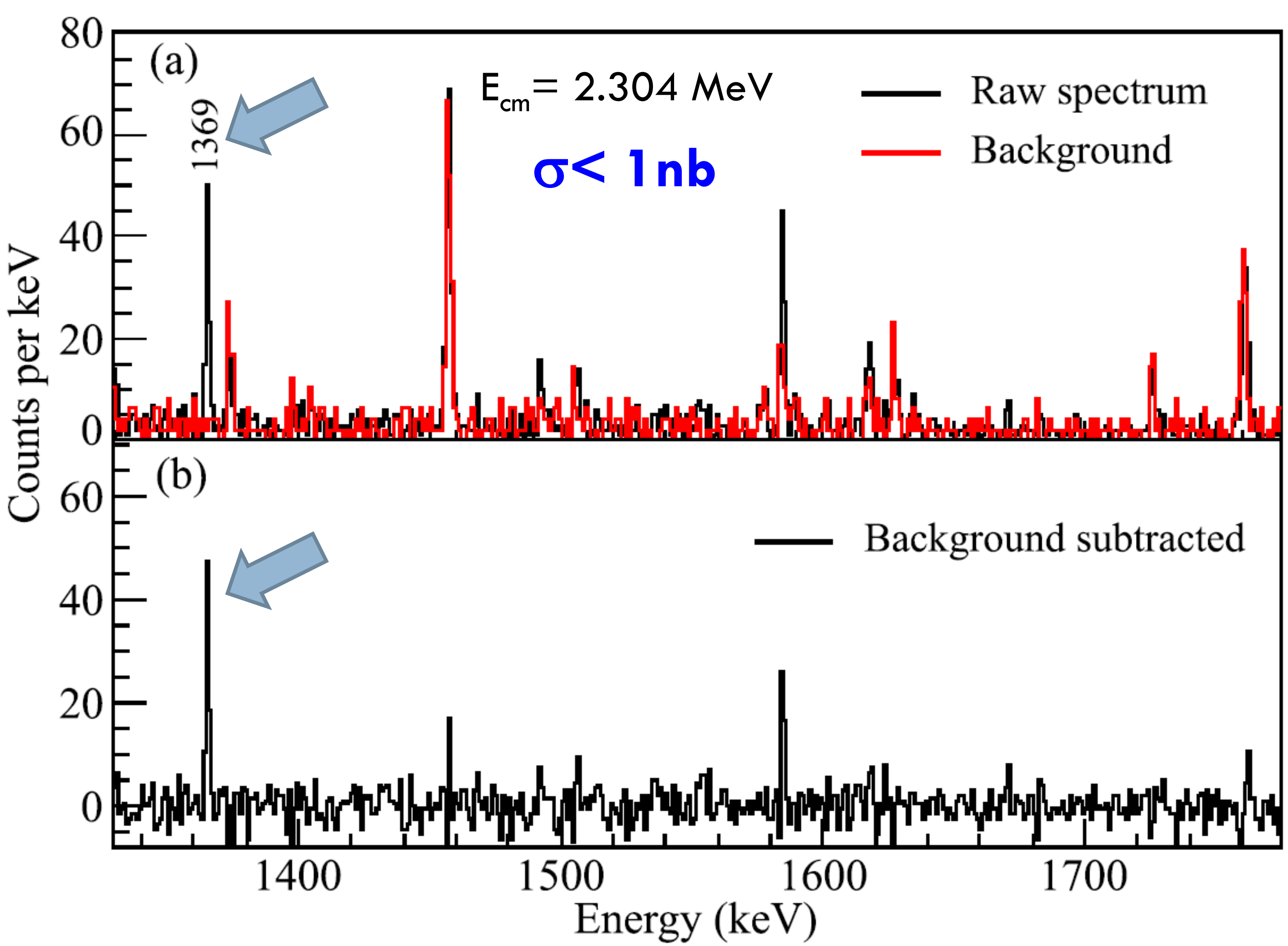
N.T.Zhang(IMP)

D. Tudor (IFIN-HH)

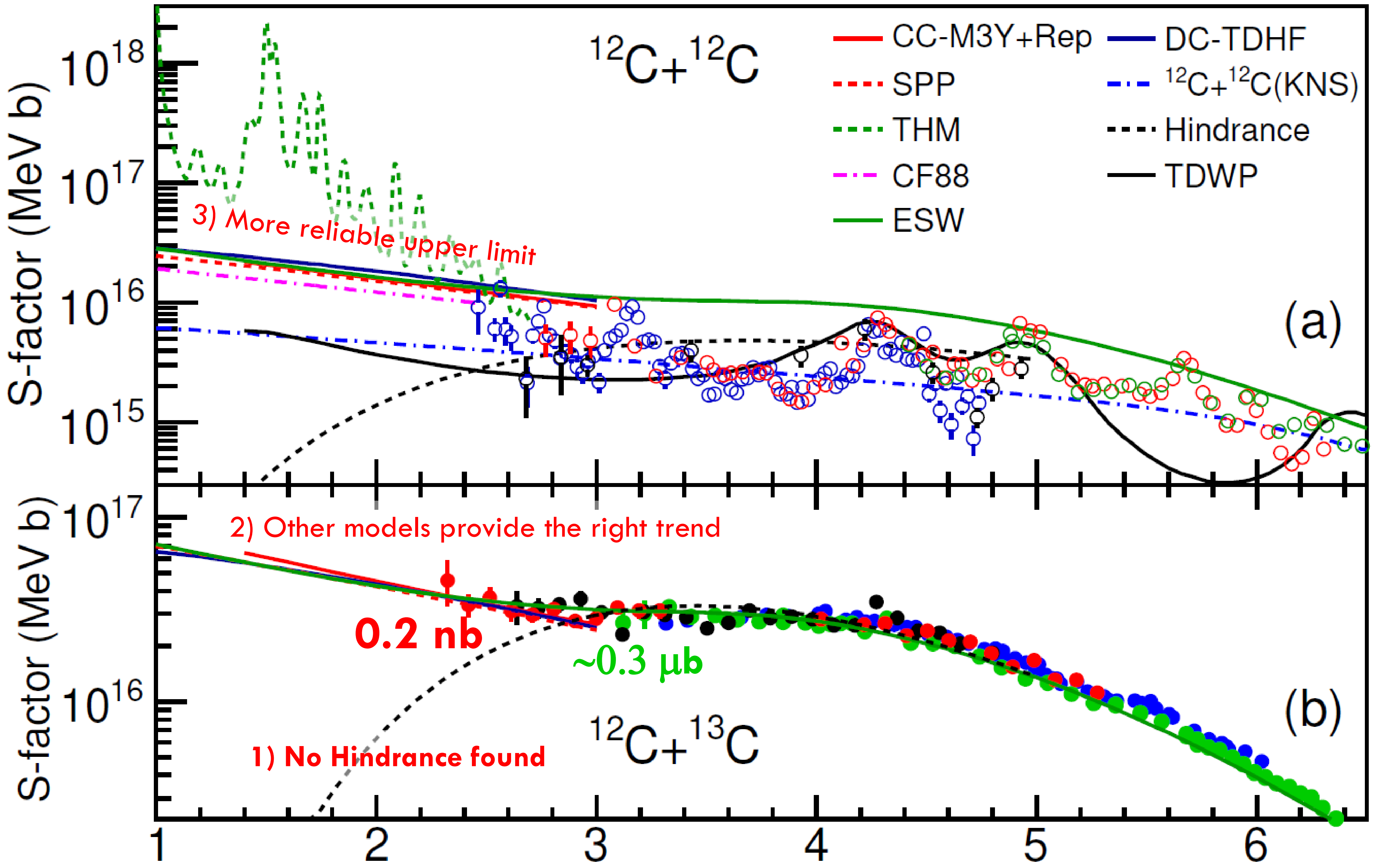
L. Trache (IFIN-HH)

Low level background counting





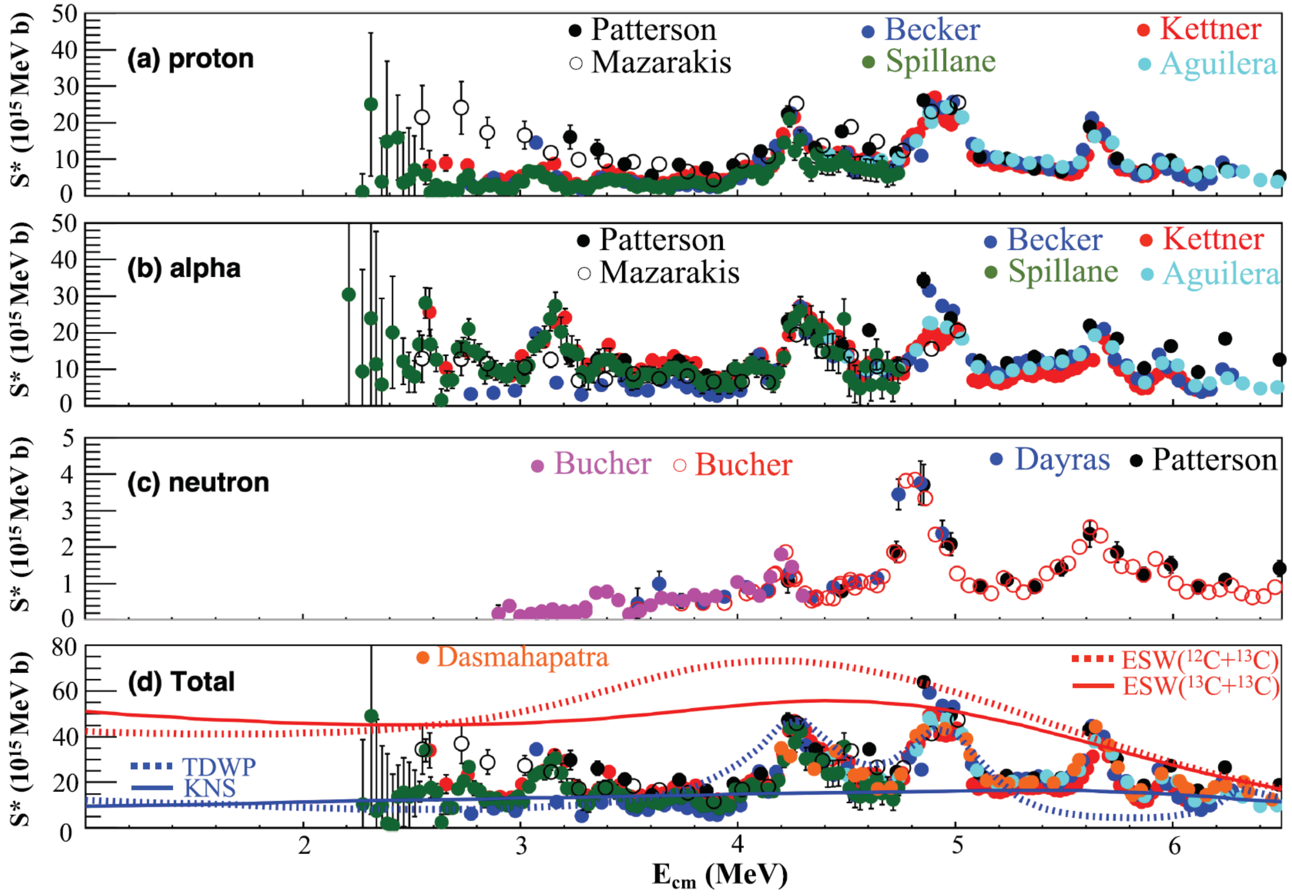
Radiations: 3.4 days measurements: 3.9 days

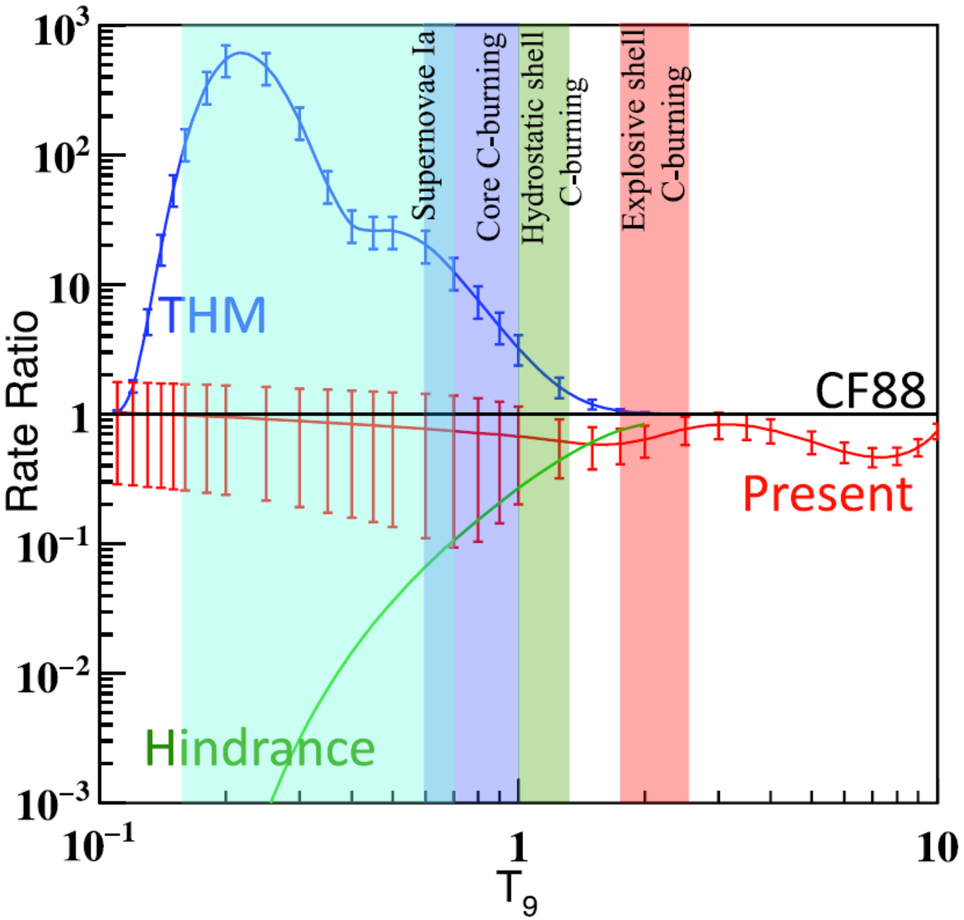


N.T. Zhang and D.Tudor et al., PLB(2020)
Godbey, C. Simenel and A. S. Umar, PRC(2019)

New rate

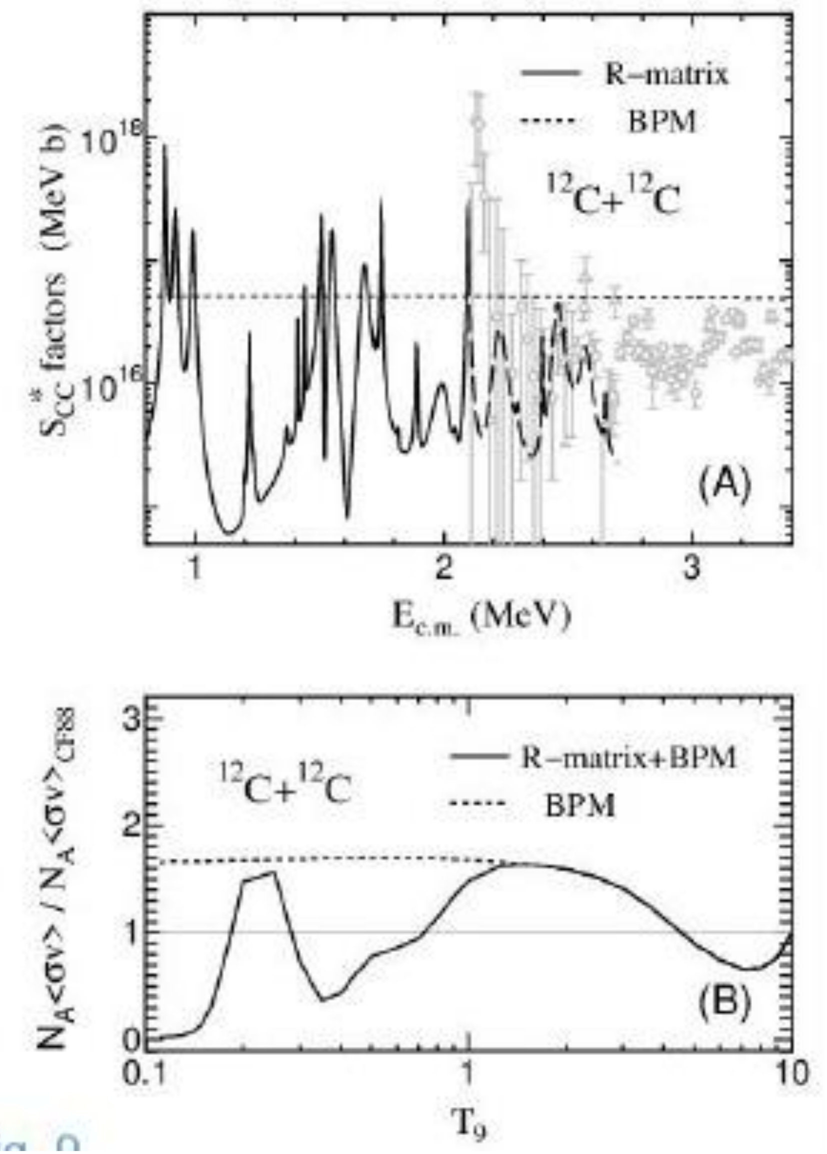
Y.J.Li, X.Fang+ (2020), DOI: 10.1088/1674-1137/abae56





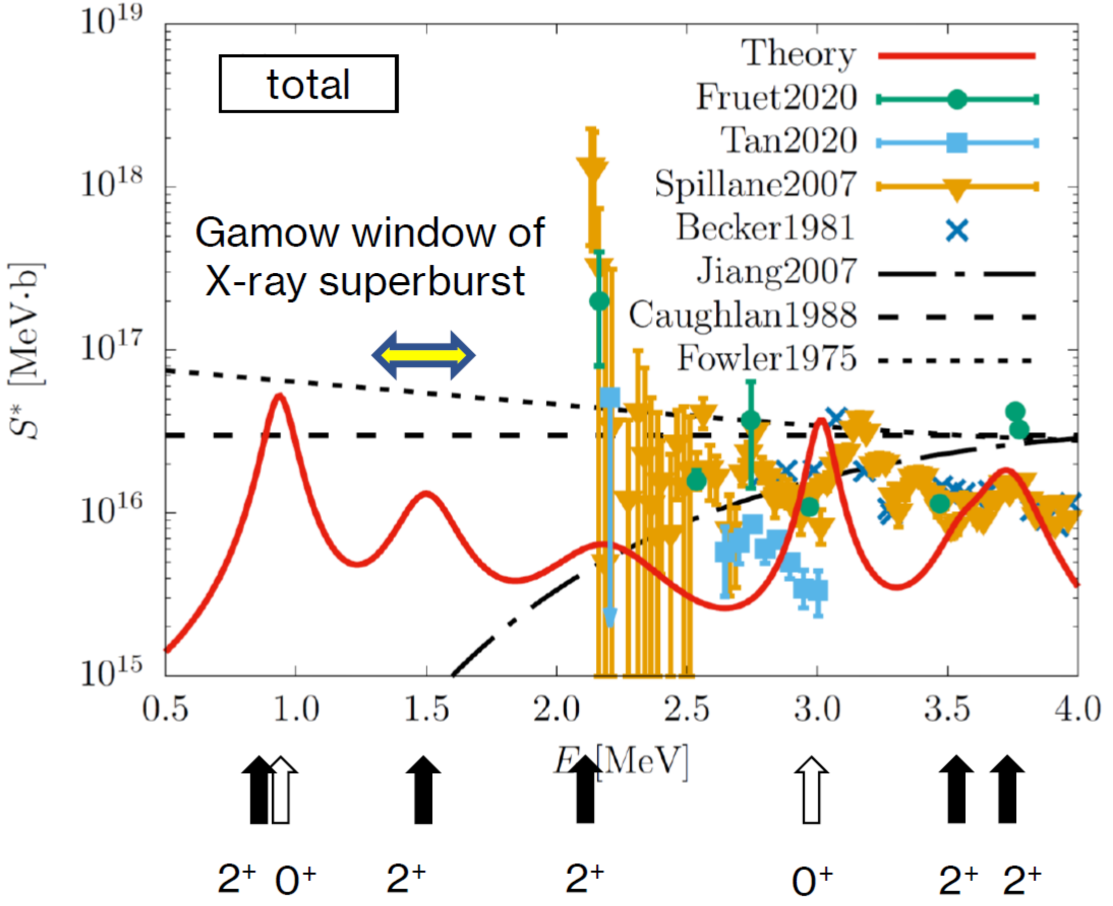
- Combining **the new upper limits with the empirical lower limit and the prediction of TDWP**, the 12C+12C S* factors are better constrained despite the unknown resonances within the unmeasured energy range.
- Revision is needed if there are currently unknown relatively strong resonances

R-matrix approach



Katsuma, NIC Poster session

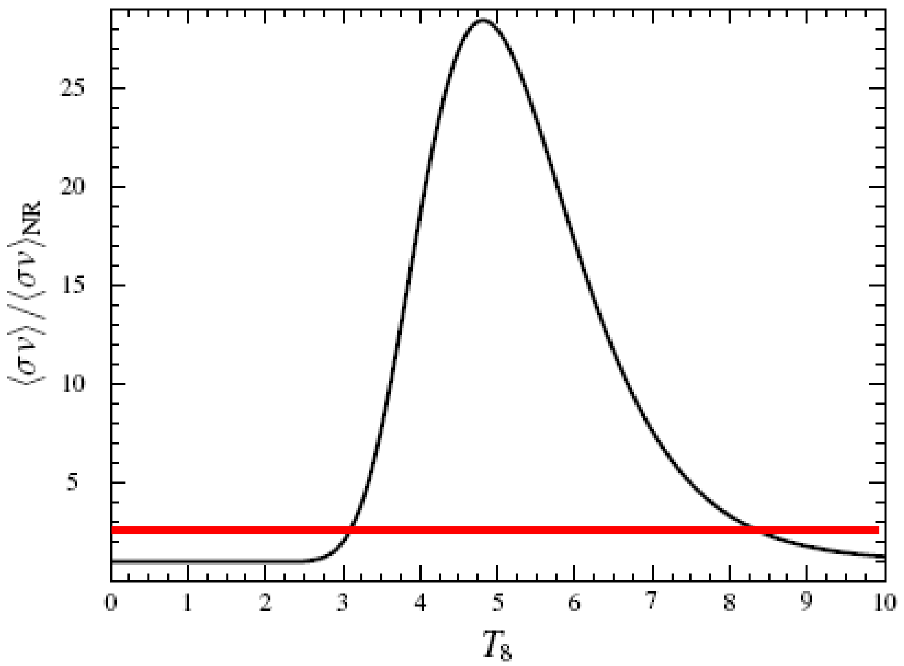
AMD microscopic model



Contradictory to the hindrance model, we conclude that there is **no low-energy suppression of the S-factor**

TANIGUCHI+, Physics Letters B 823(2021)136790

Impact to Superburst model



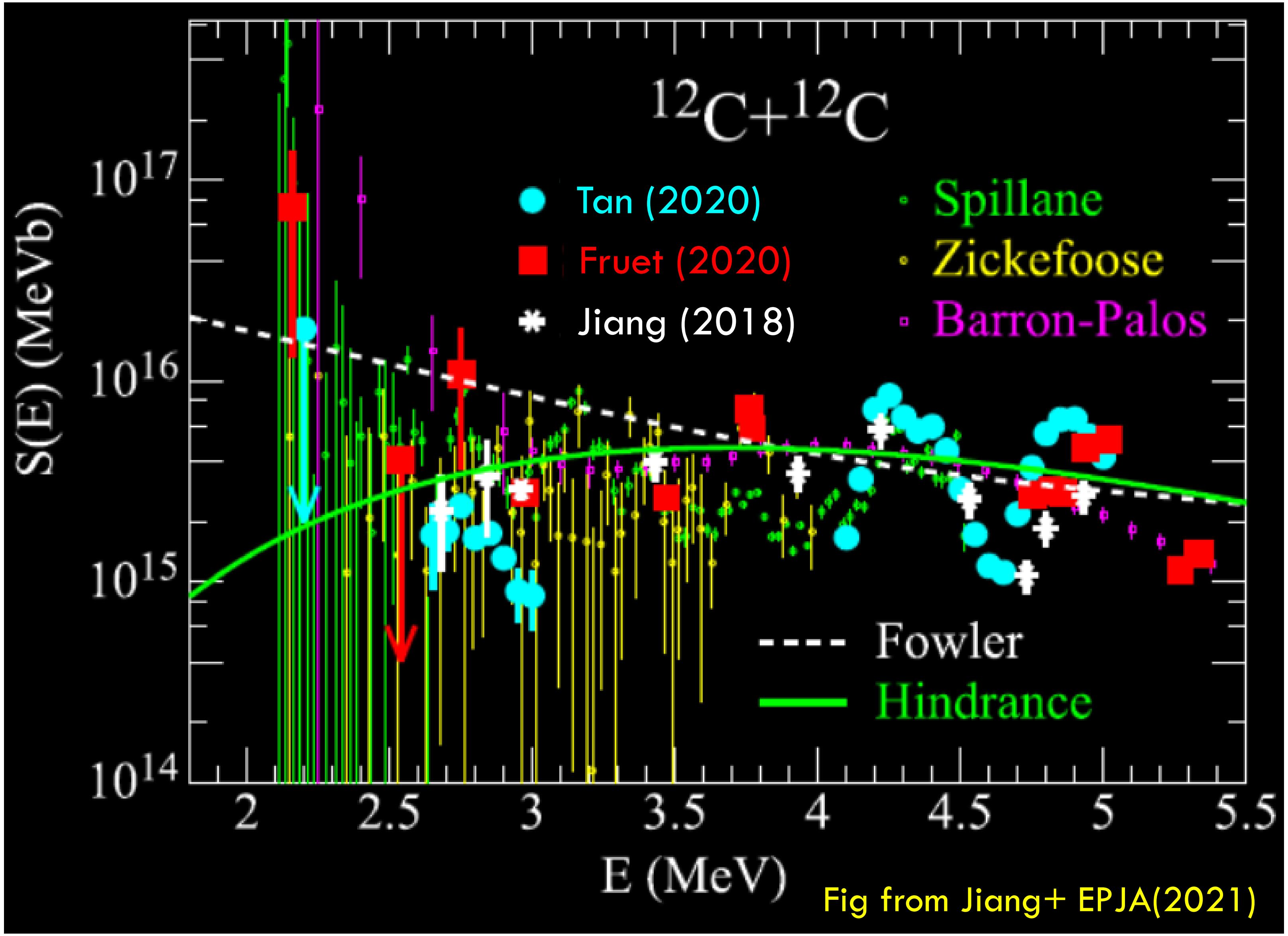
If the rate can not be as that high, there must be **some physics missing** in the superburst model.

•**Unknown process to heat** up the crust to higher temperature.
•**Carbon burning is not the one triggered** the superbust!

Communication with Ed. Brown

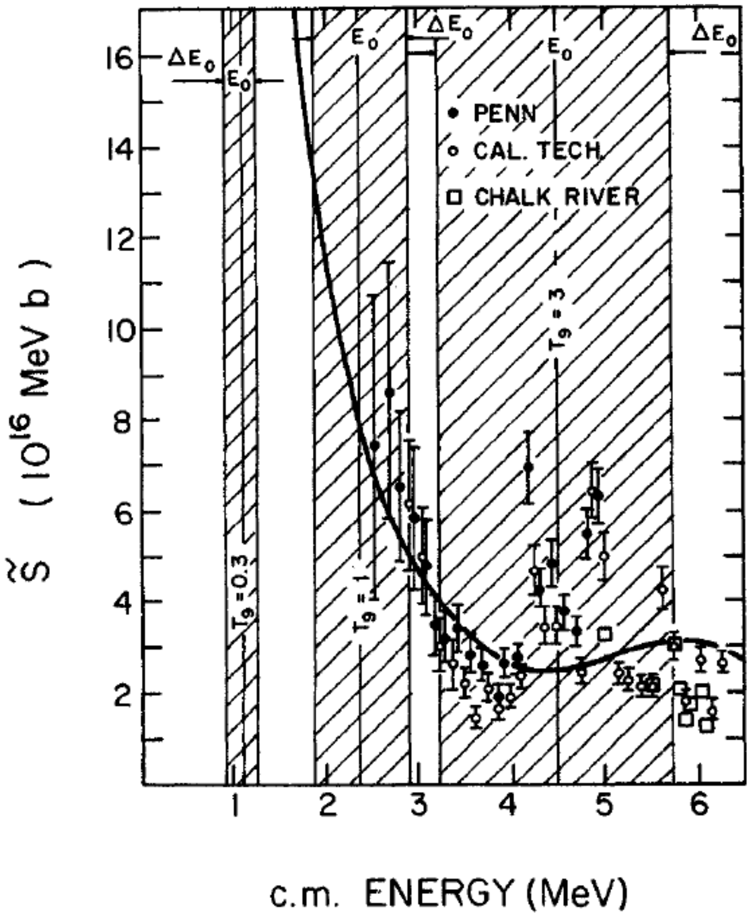
Data Compilation

Why are these data so different from each other?

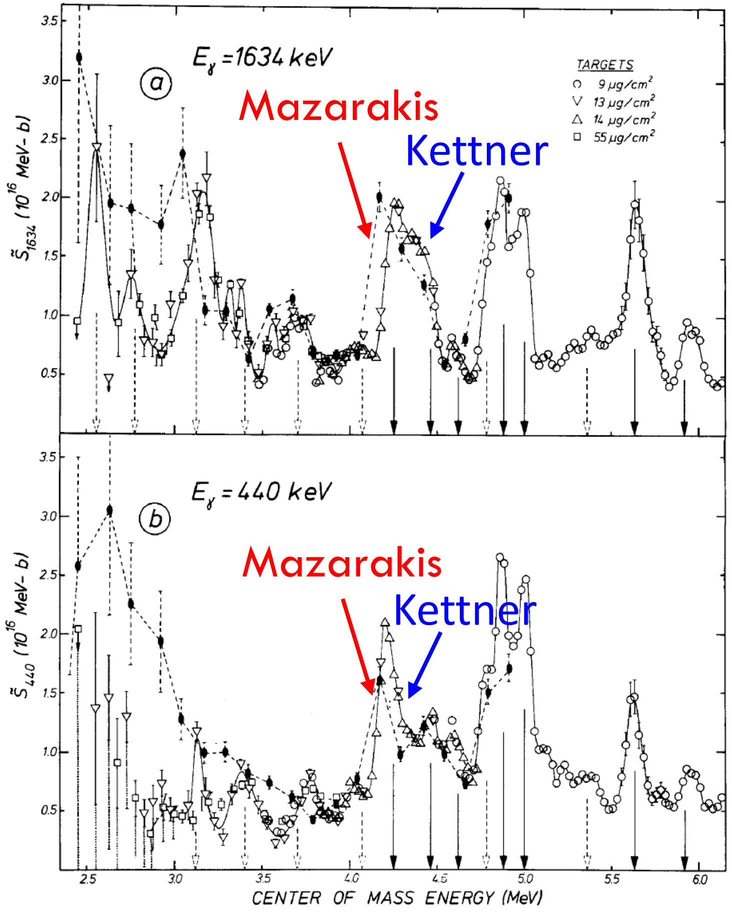


- Correct energy calibration
- Correct background evaluation
- Converting the observed partial cross section into the total fusion cross section using reliable branching ratio with the correct systematic uncertainty
- Angular distribution

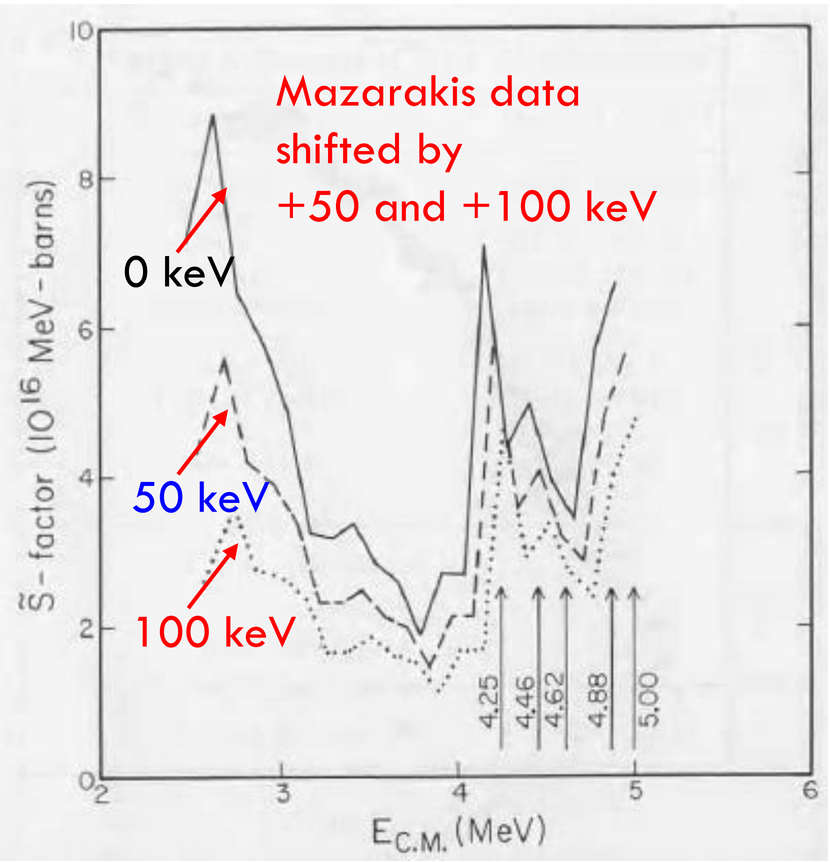
Energy calibration is very important!



Mazarakis et al. (1973)



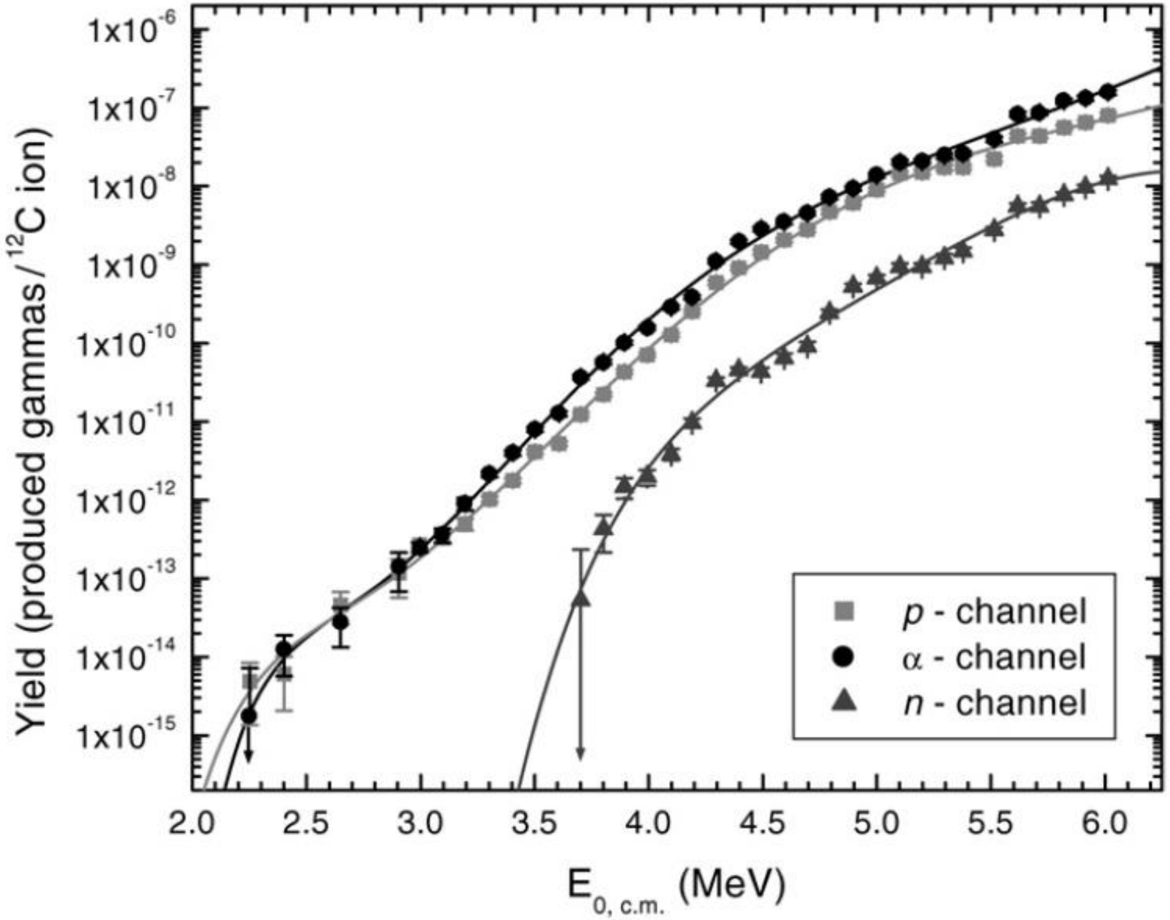
Kettner et al. (1980)

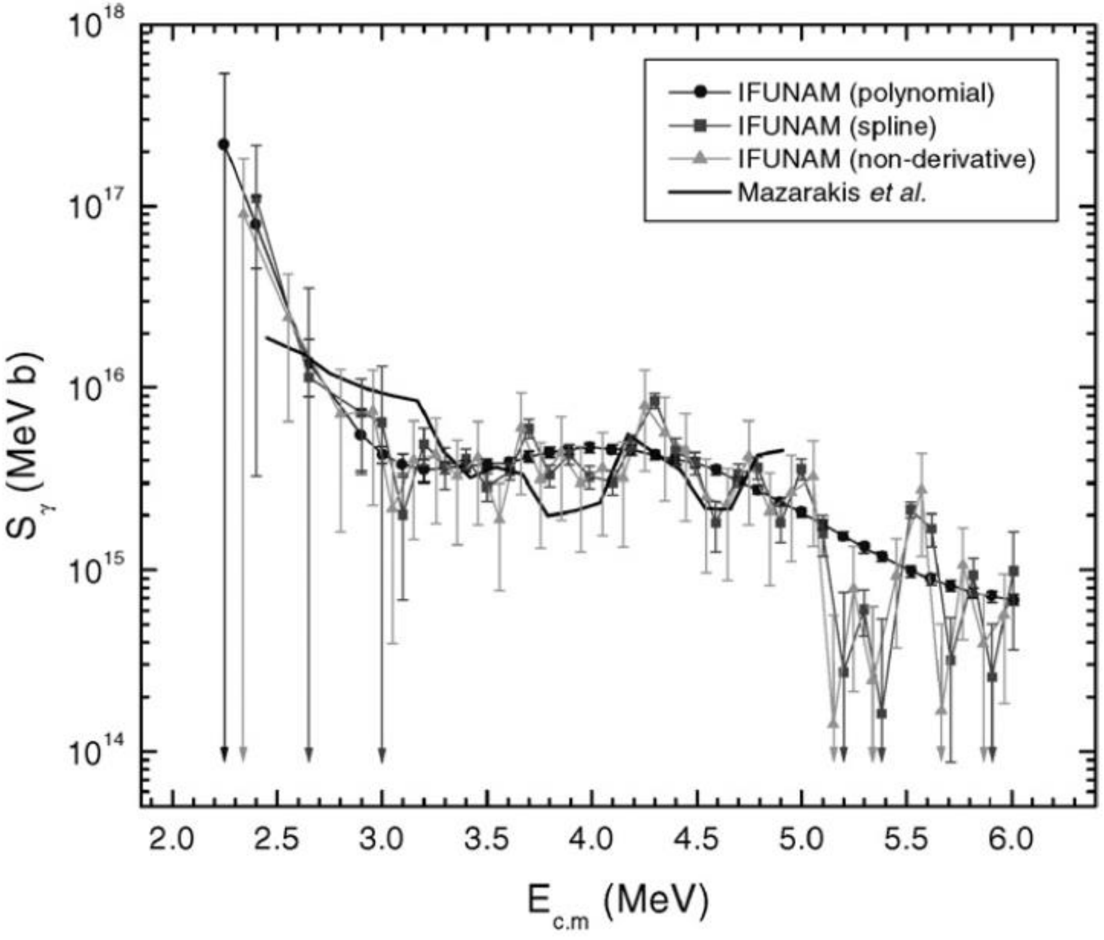


Barnes, Trentalange and Wu (1985)

- Observed rise in the nuclear factor at the lowest energies may be interpreted as "absorption under the barrier“
- Dismissed due to the error in energy calibration

Another absorption under barrier?

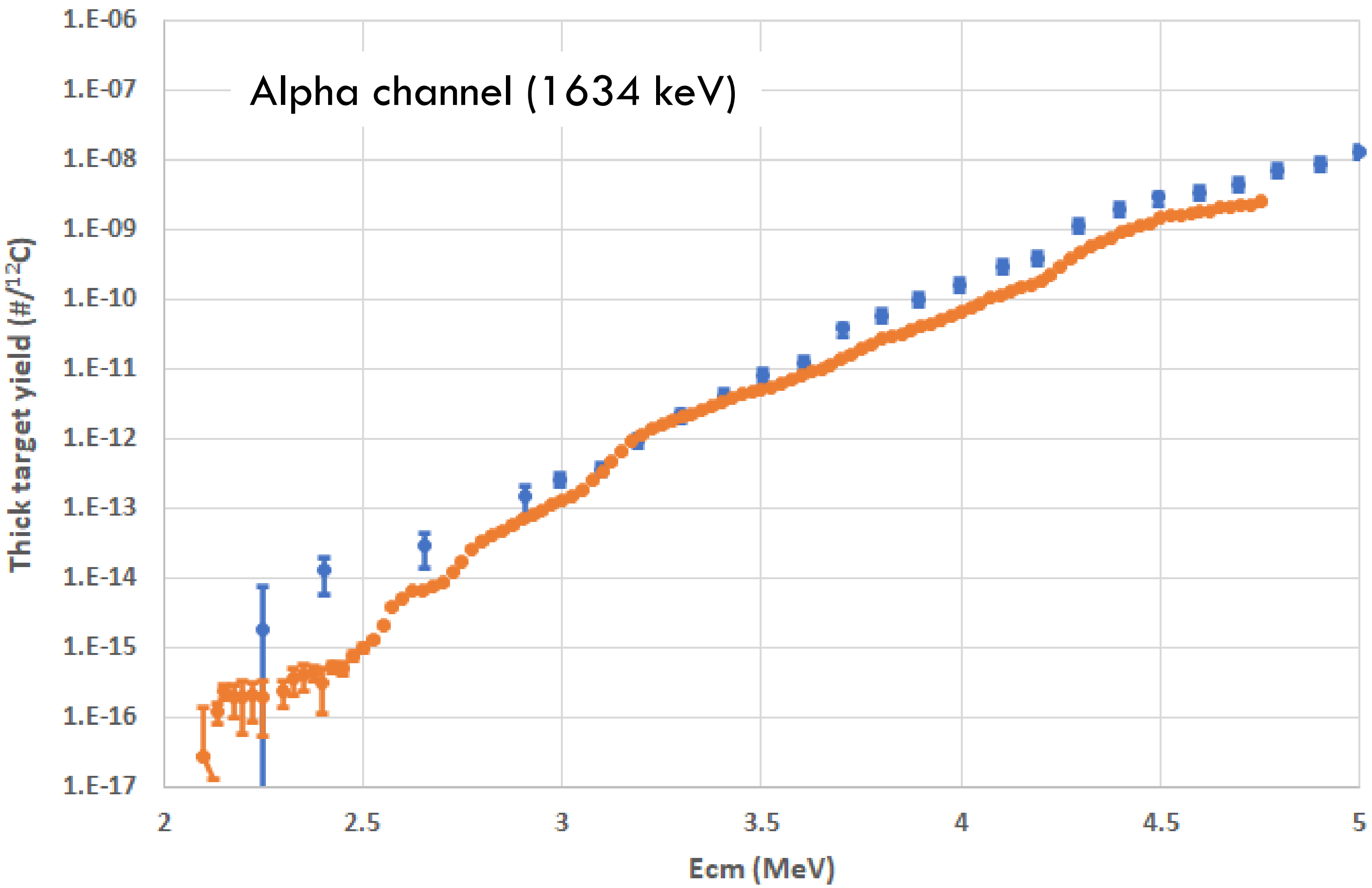




- Seems to support the result of Mazarakis
- Smoothing the thick target yield → wash out all the resonance→Unable to check the energy calibration

Barrón-Palos et al., NPA(2006)

Another absorption under barrier?



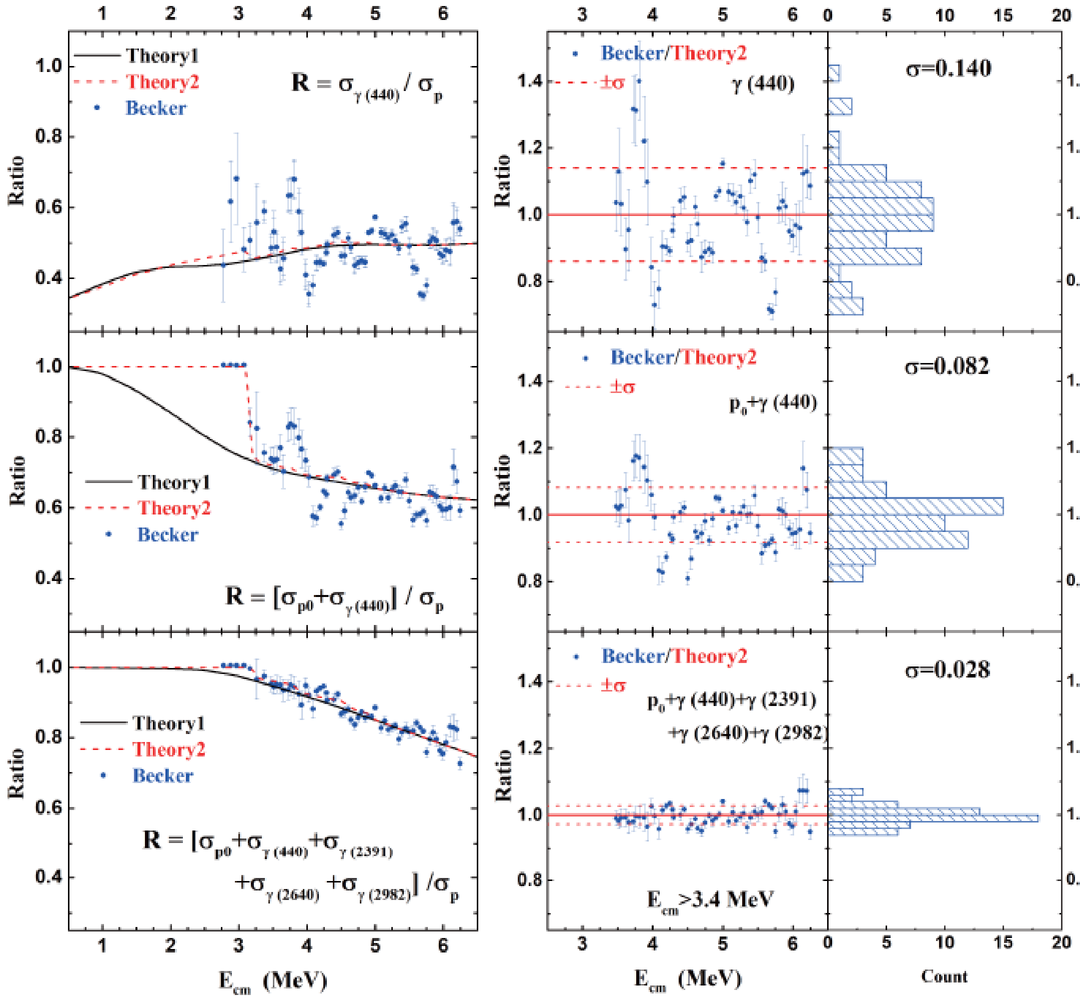
Barrón-Palos et al., (2006)

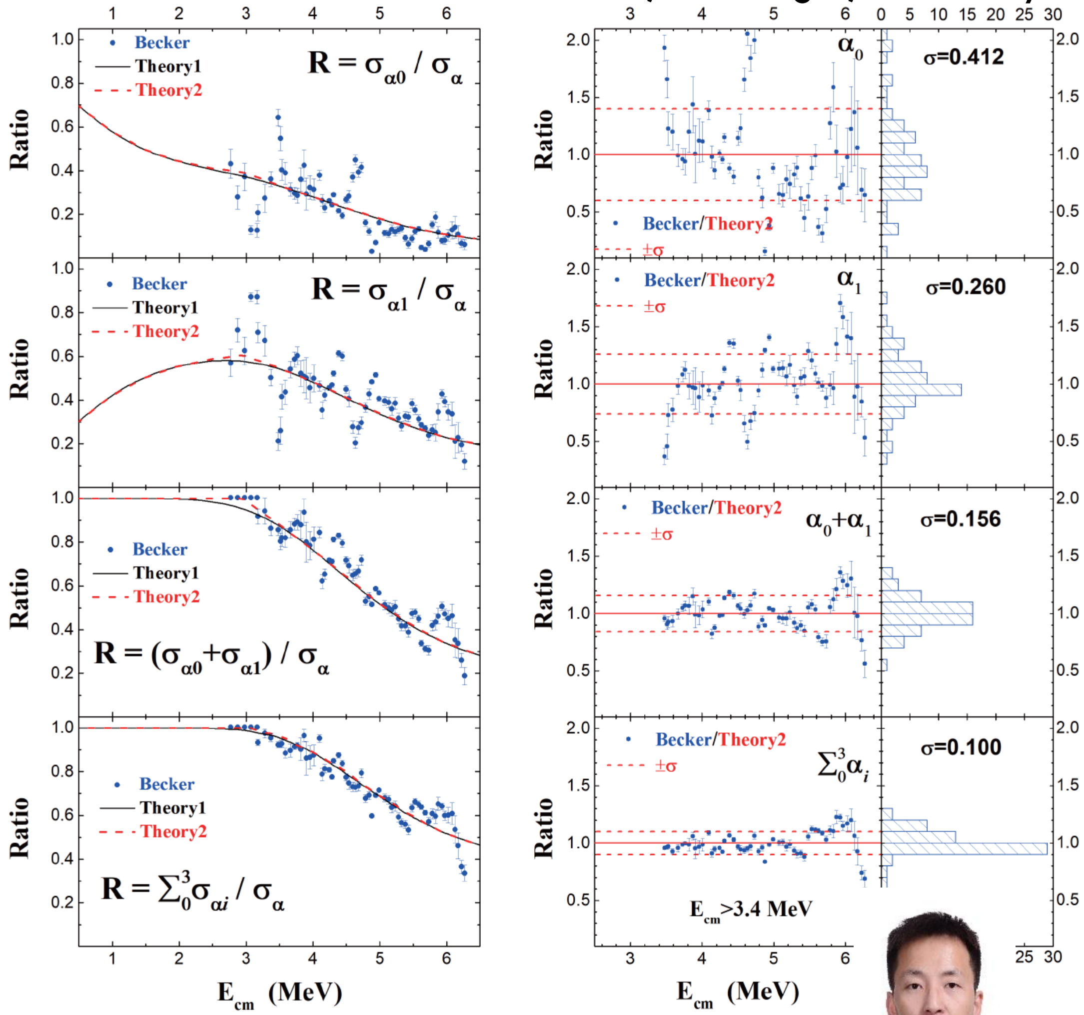
Spillane, Thesis, U. Conn (2007)

- Thick target yield comparison shows significant discrepancy, possibly due to unknow background

Converting the observed to the total cross section using statistical model

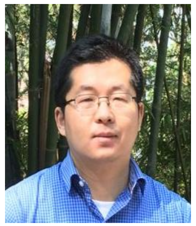
Y.J. Li, X. Fang+, Chin. Phys. C (2020)





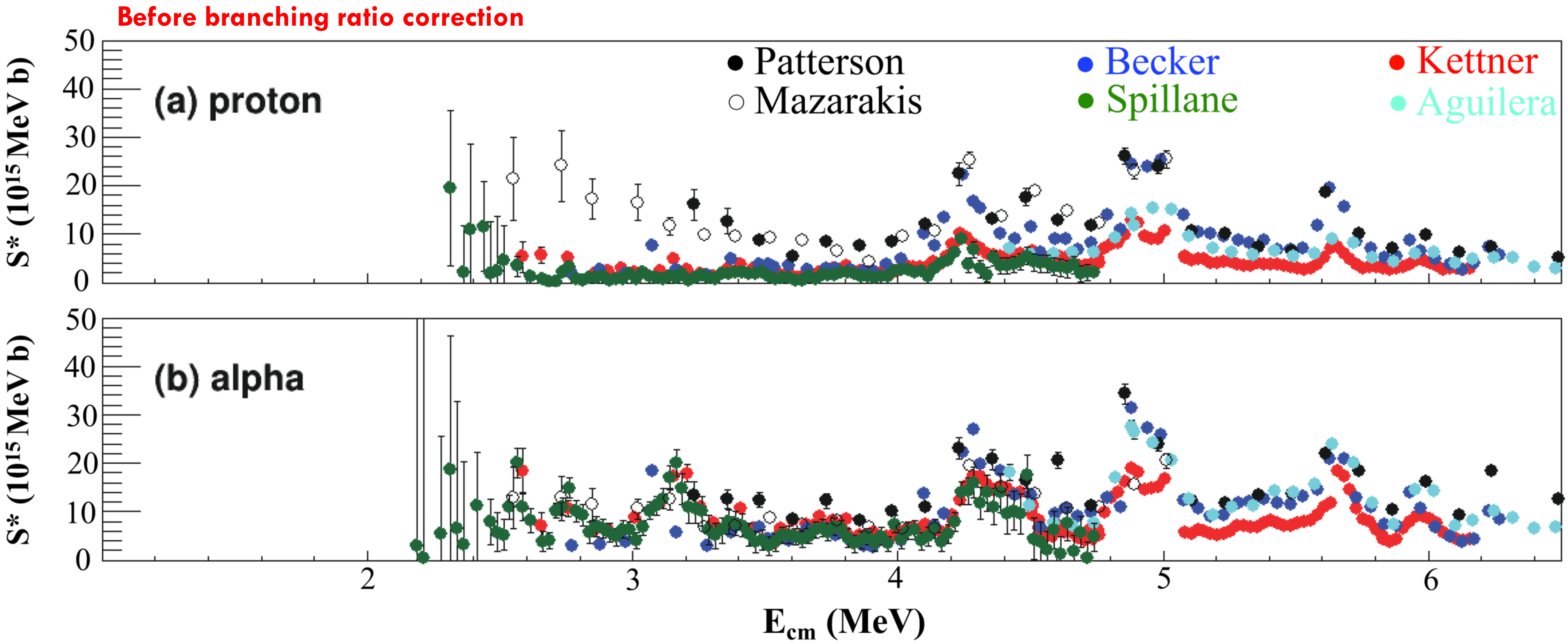
- Resonance results in fluctuation in the branching ratio
- Less fluctuation if more channels are included (larger branching ratio)

Y.J. Li(CIAE)

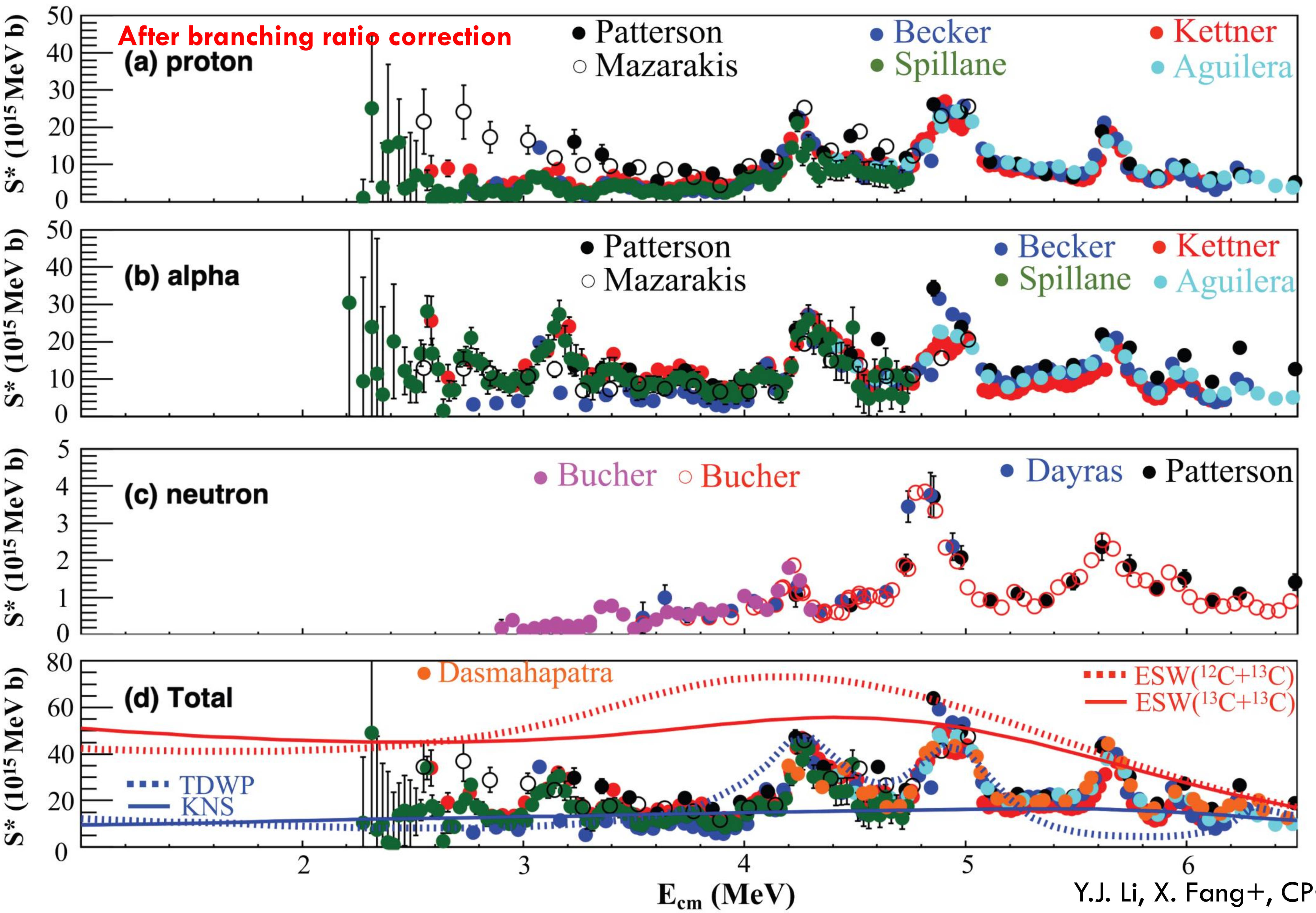


X. Fang(SYSU)

Converting the observed to the total cross section using statistical model

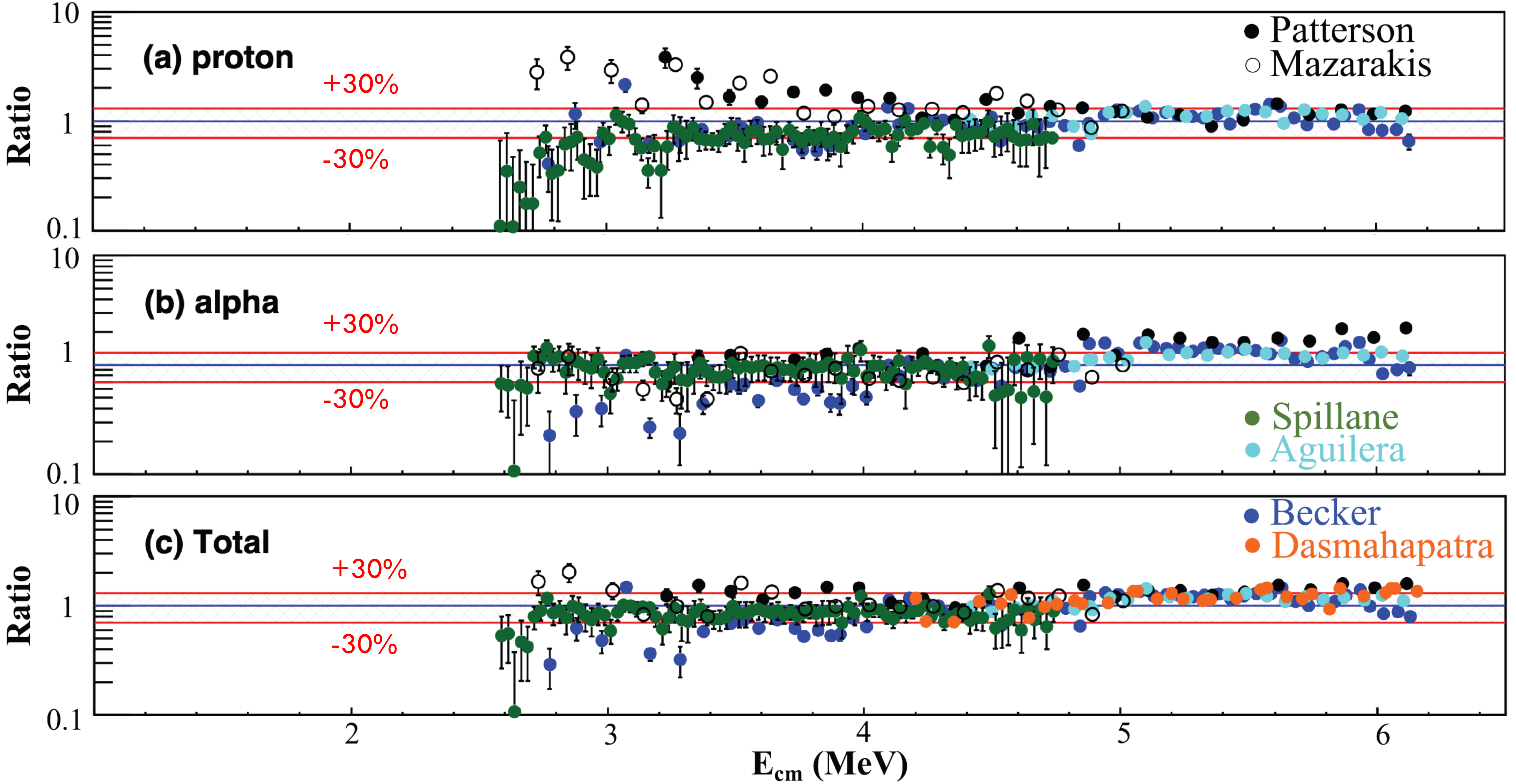


Y.J. Li, X. Fang+, CPC (2020)



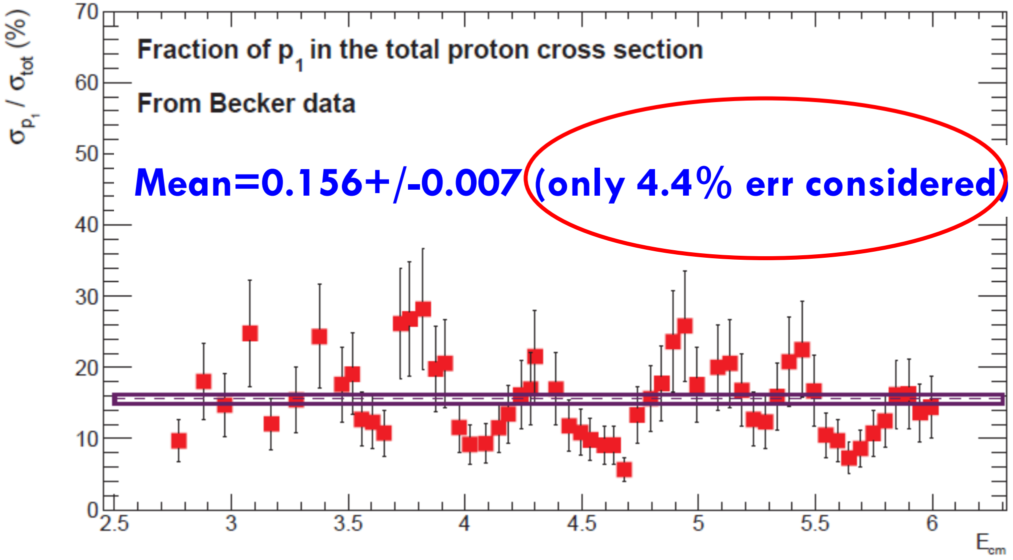
Y.J. Li, X. Fang+, CPC (2020)

Ratios of various S* factors to baseline S* factors (Kettner)

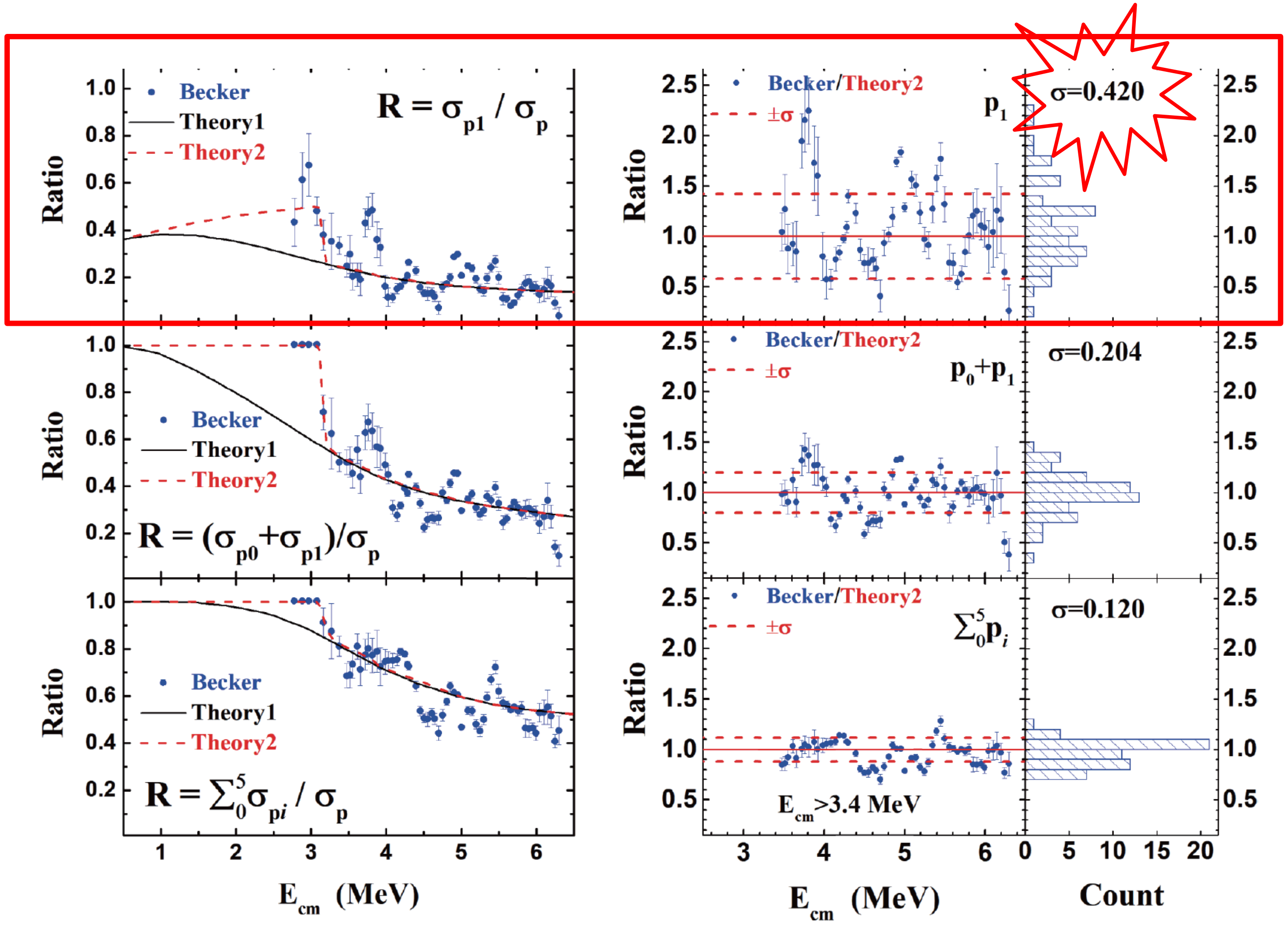


Converting the observed to the total cross section using statistical model

Distribution of the fraction of the p1 channel in the total cross section of the proton channel : $\sigma_{p1}/\sigma_{ptot}$



Fruet et al., Ph.D. Thesis (2019)

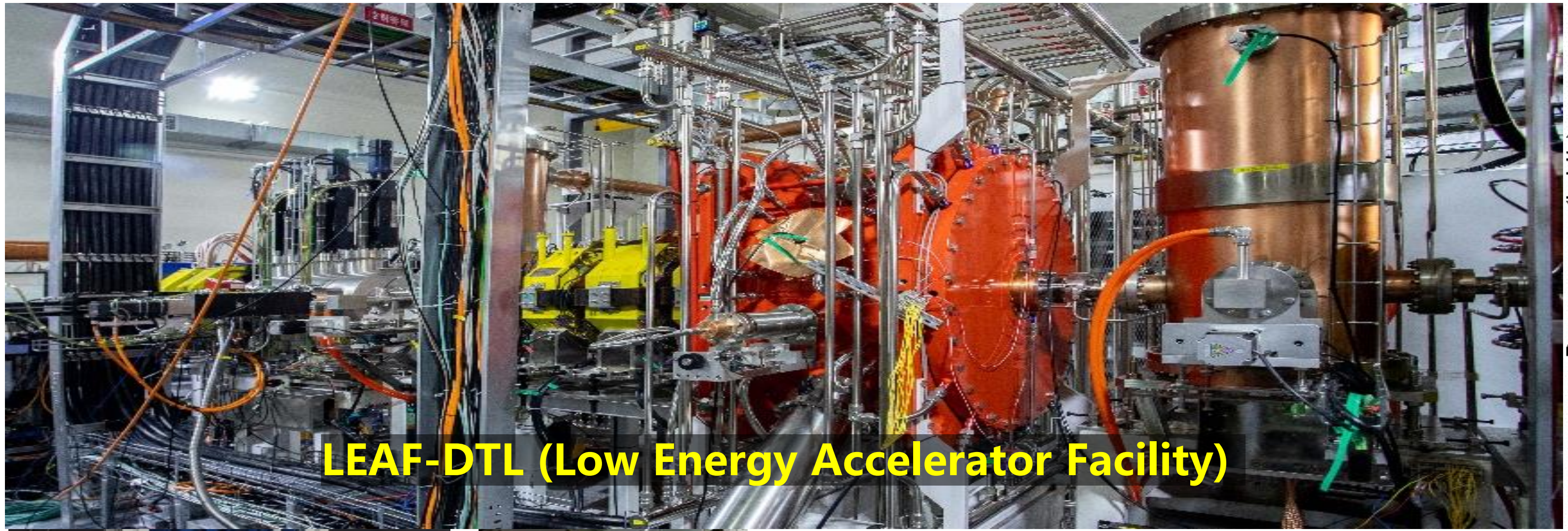


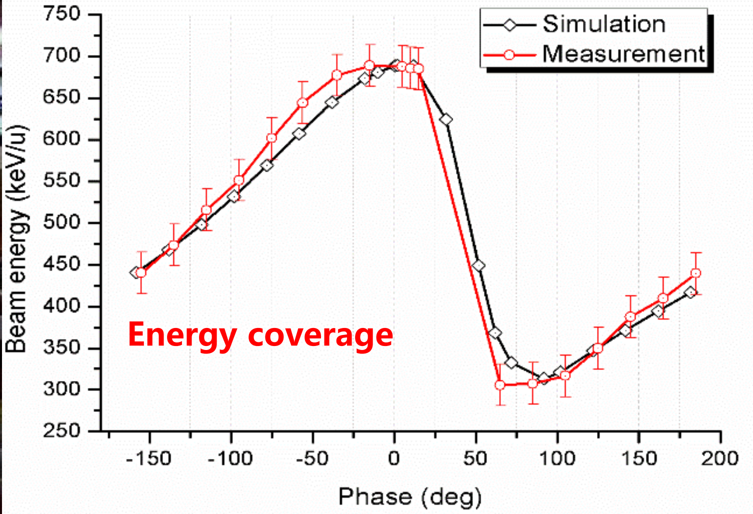
Y.J. Li, X. Fang+, CPC (2020)

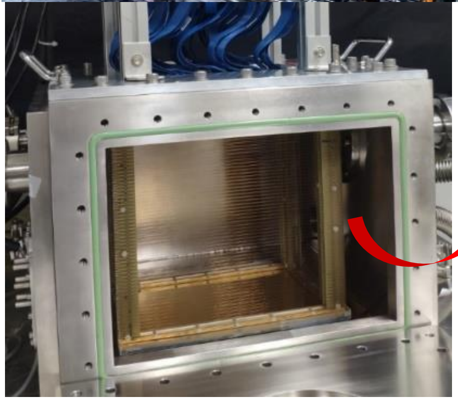
Mean value is not constant and does not describe the fluctuation of the branching ratio!

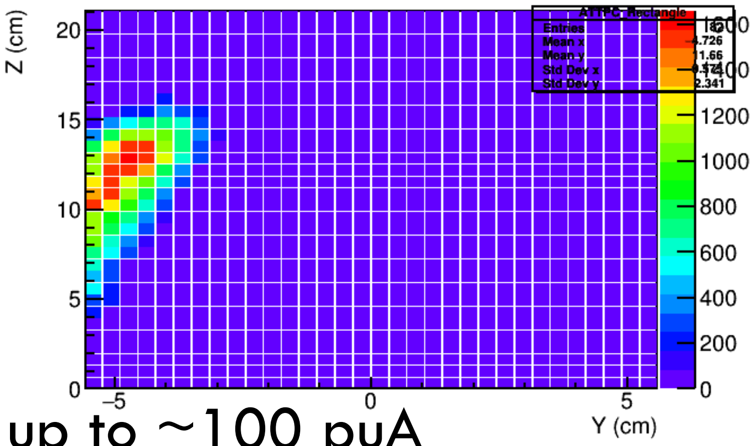
New technique to challenging the limit

High Intensity+Time Projection Chamber





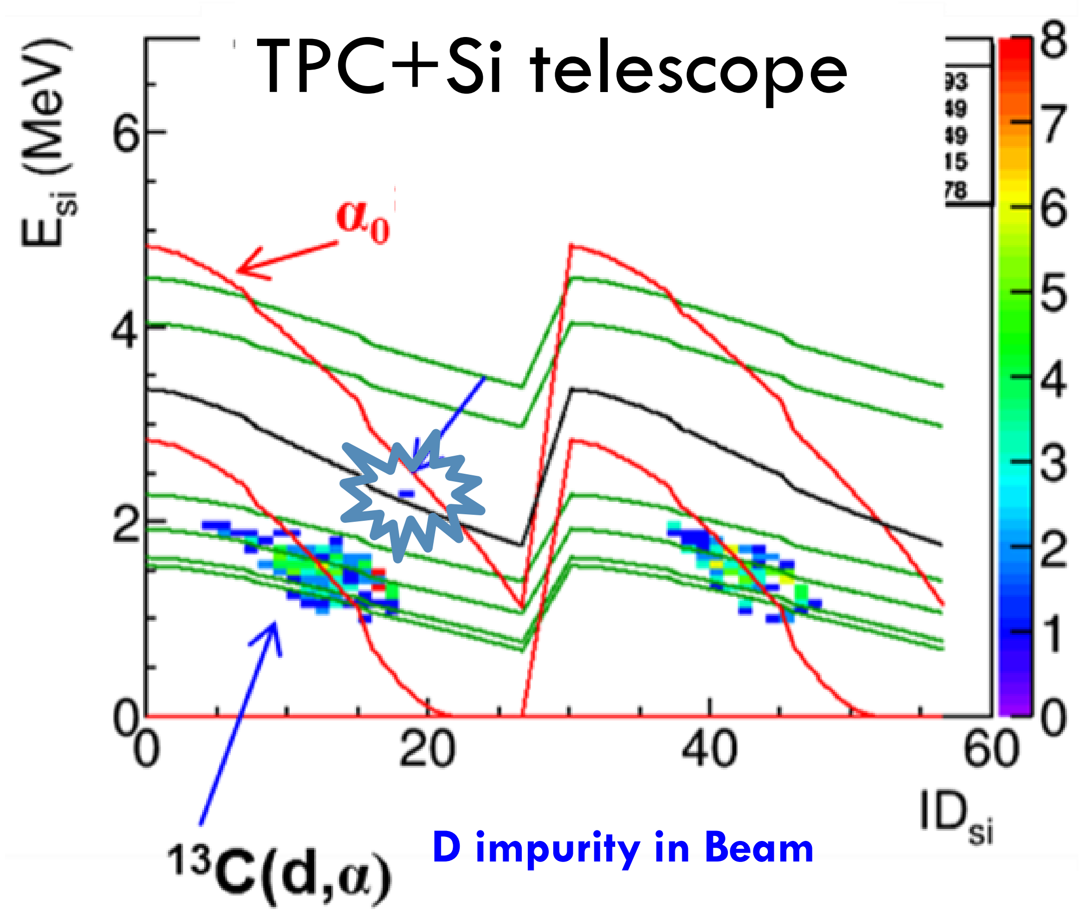


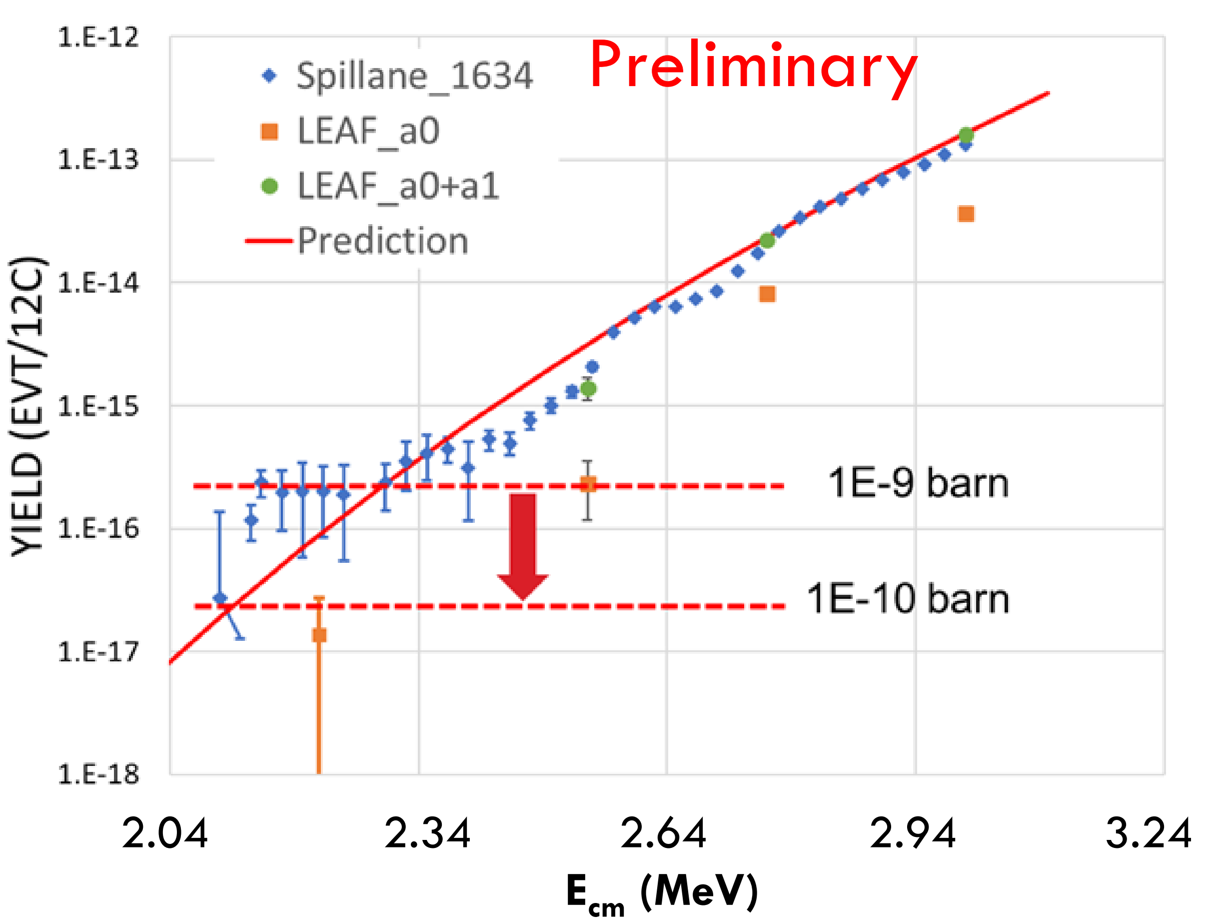


- LINAC: High Intensity beam up to ~100 puA
- TPC: Ultra sensitive tracking detector
- Complimentary to LUNA-MV and JUNA-2

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

High Intensity Beam+Time Projection Chamber

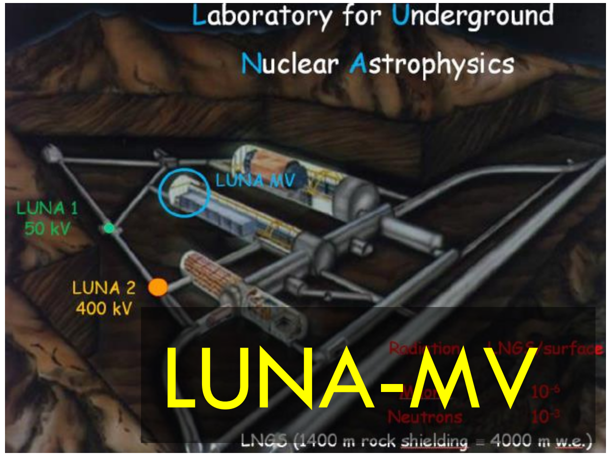


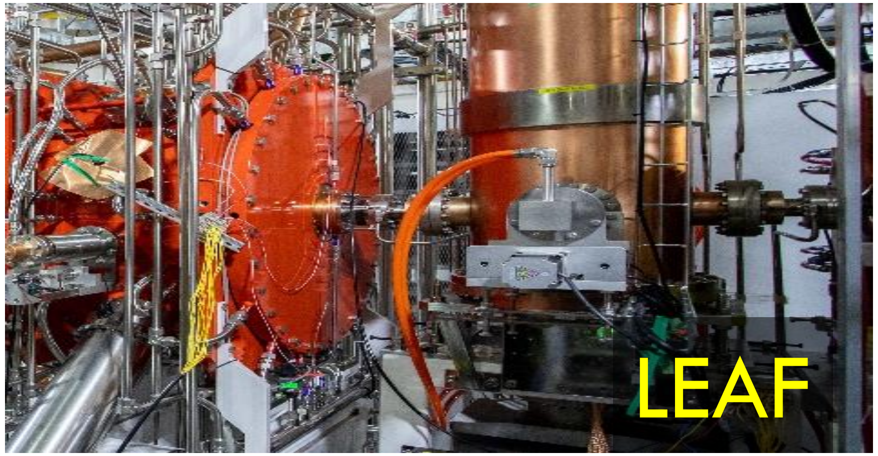


- **Setting a new record on the thick target yield sensitivity of 1.4E-17 evt/^{12}C in $^{12}C(^{12}C,a_0)^{20}Ne$**
- **Promising technique to check the Spillane resonance@ Ecm=2.14 MeV**

Summary and outlook

- Direct measurement does not support the indirect measurement
- $^{12}C+^{12}C$: too complicated to favor any model
- $^{12}C+^{13}C$: NO S-factor maximum; Confirm other model predictions → More reliable upper and lower limits
- New technique (eg. Particle+gamma coincidence, Time Projection Chamber, underground facilities) further push the limit in the stellar energy range
- Nuclear structure experiment and theory are needed to better understand the origin of the resonance; Nuclear reaction theory needed to provide better extrapolation





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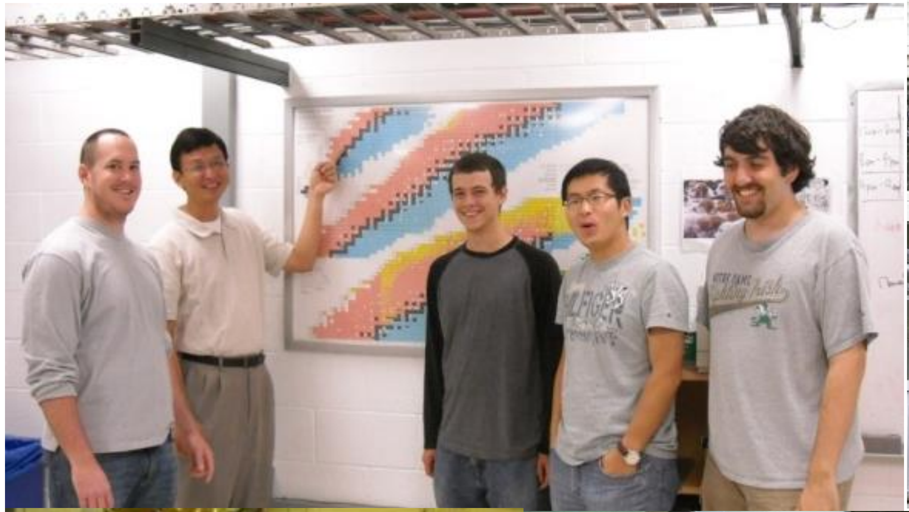



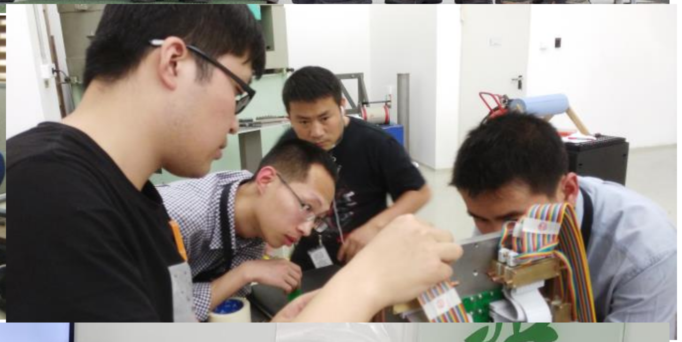
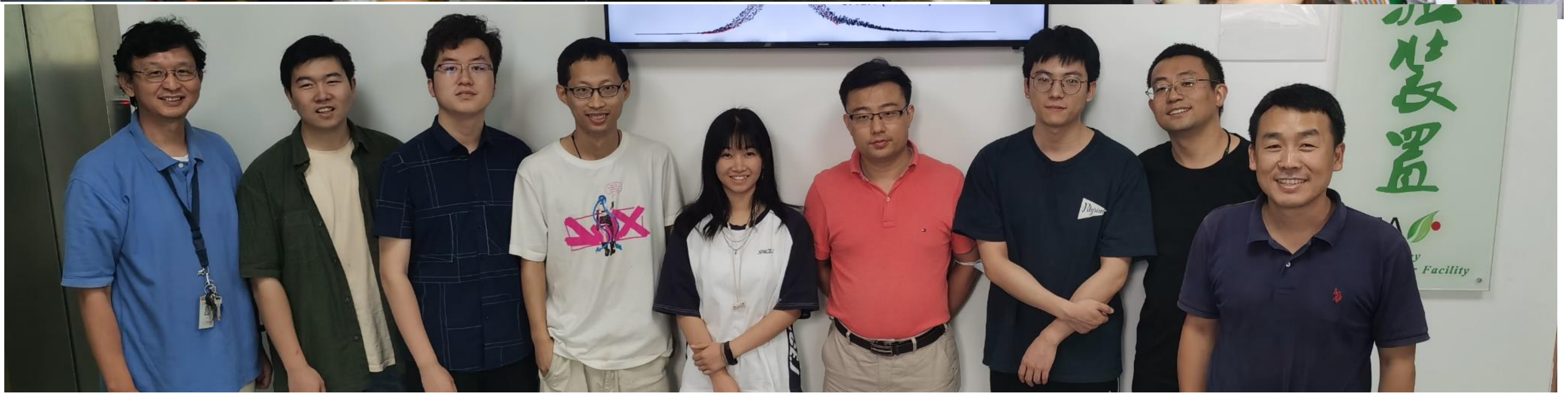
装置
Facility


LEAF 平台 0.3 ~ 0.7 MeV/u 能区 $^{12}C + ^{12}C$ 熔合反应研究
第一阶段实验顺利完成