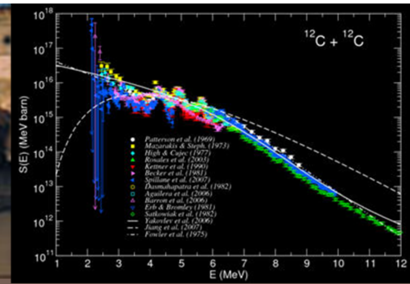
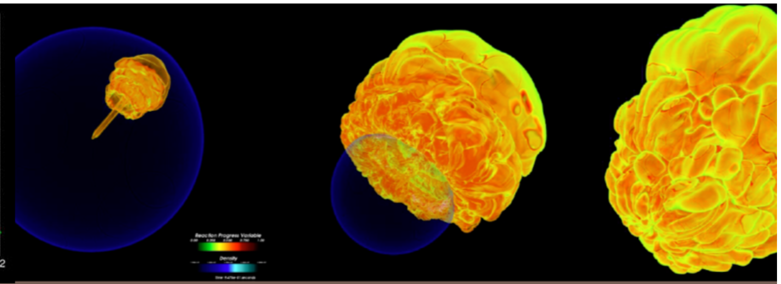






HEAVY ION FUSION REACTIONS IN STARS

X.D. Tang[1,2]

[1] *Institute of Modern Physics, CAS, China*

[2] *Joint Department for Nuclear Physics,*

Lanzhou University and Institute of Modern Physics, CAS, China

OMEG 2017, Daejeon, Korea, June 27-30, 2017

Outline

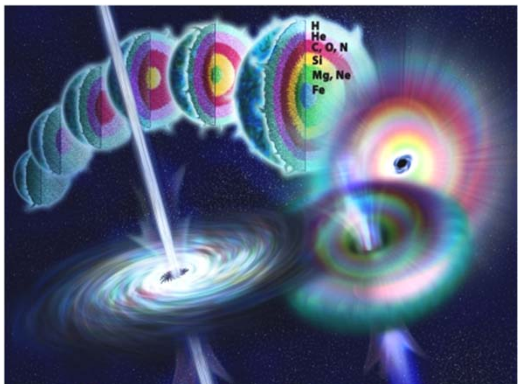
- Heavy ion fusion reactions in stars
- Review of $^{12}C+^{12}C$ at stellar energies
  → Total cross section
  → Resonance at 2.14 MeV
  → Branching ratio

- Fusion reaction with n-rich beams
- Summary

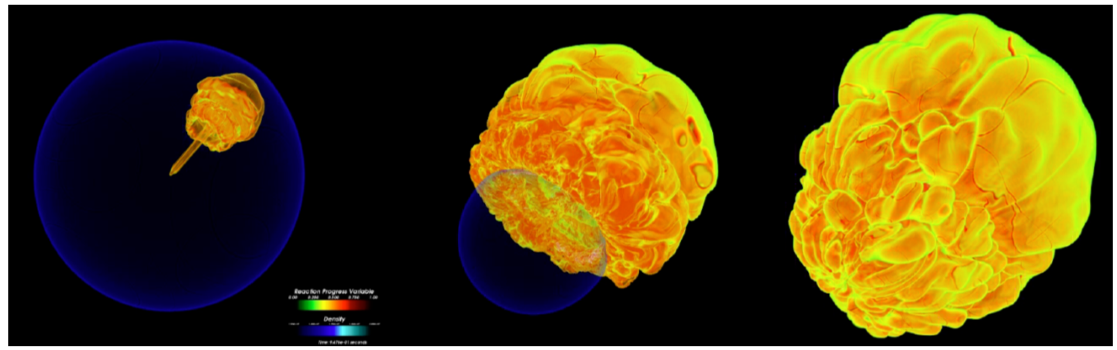
Famiano, HIRSCHI…'s talks

Carbon burning in the universe

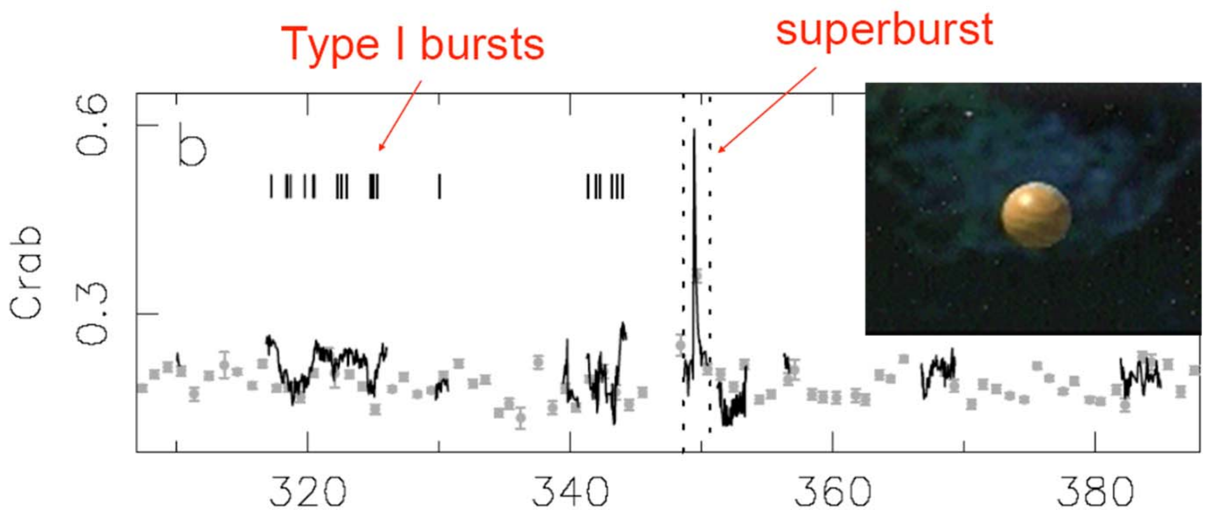
Nucleosynthesis in massive stars



Ignition conditions in type Ia supernovae



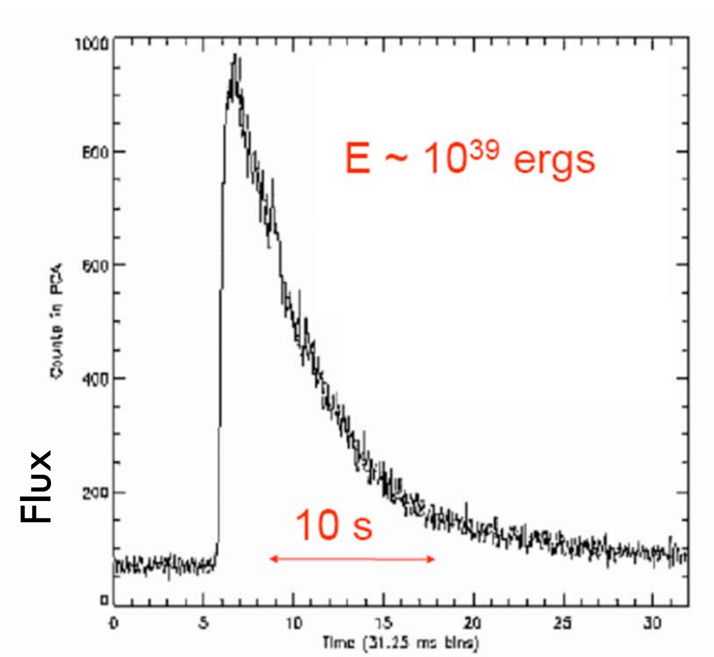
Candidate for Superburst ignition



Superburst

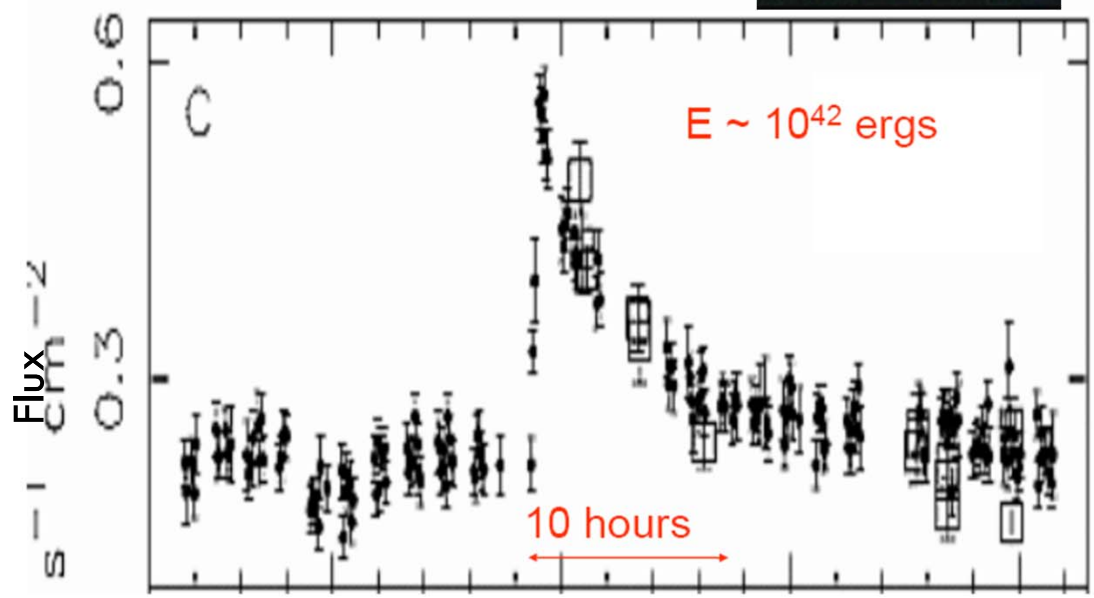
- Rare, long duration bursts
- Recurrence times 1-2 years, energies 10^{42} ergs.
- Triggered by ^{12}C+^{12}C fusion in the ashes left over after the rp-process

Normal Type Ia X-Ray Burst



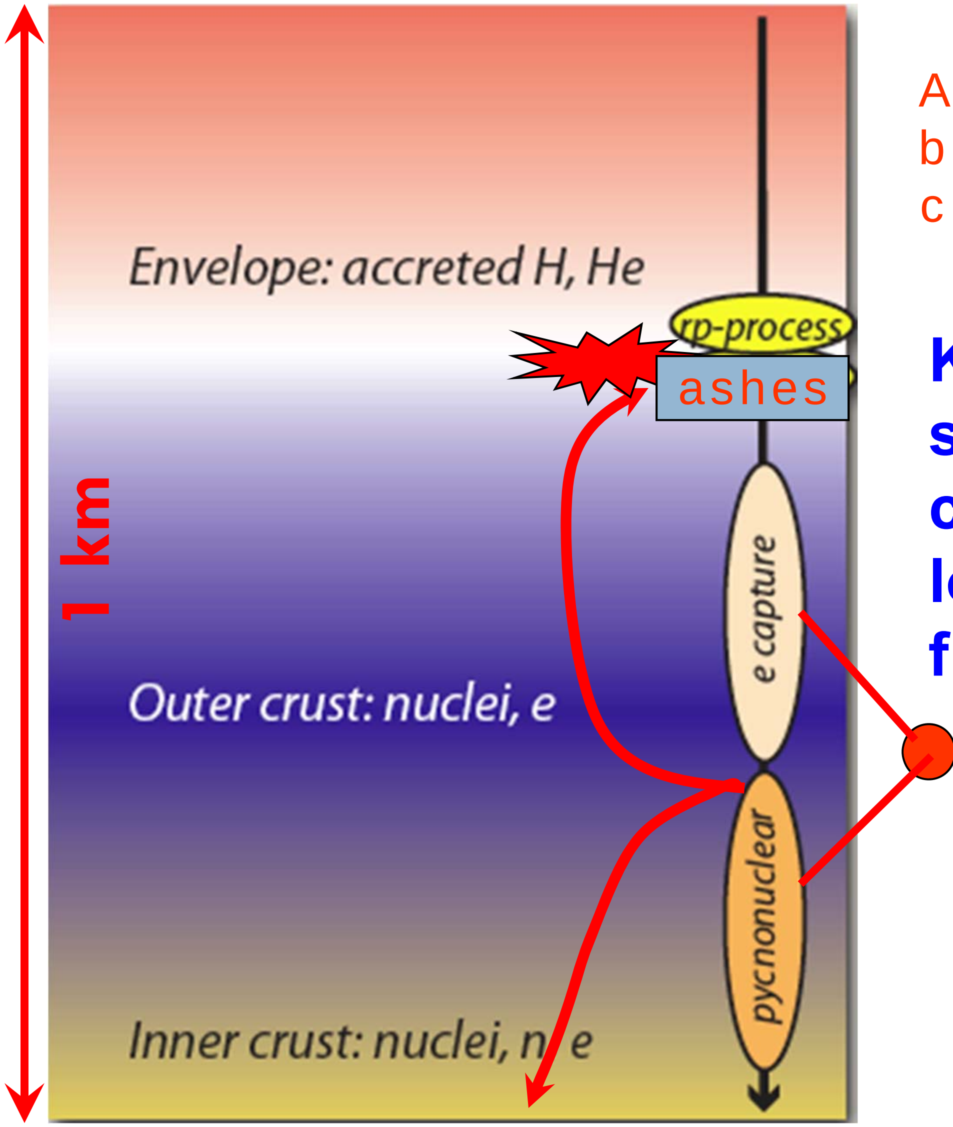
time

Superburst



time

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

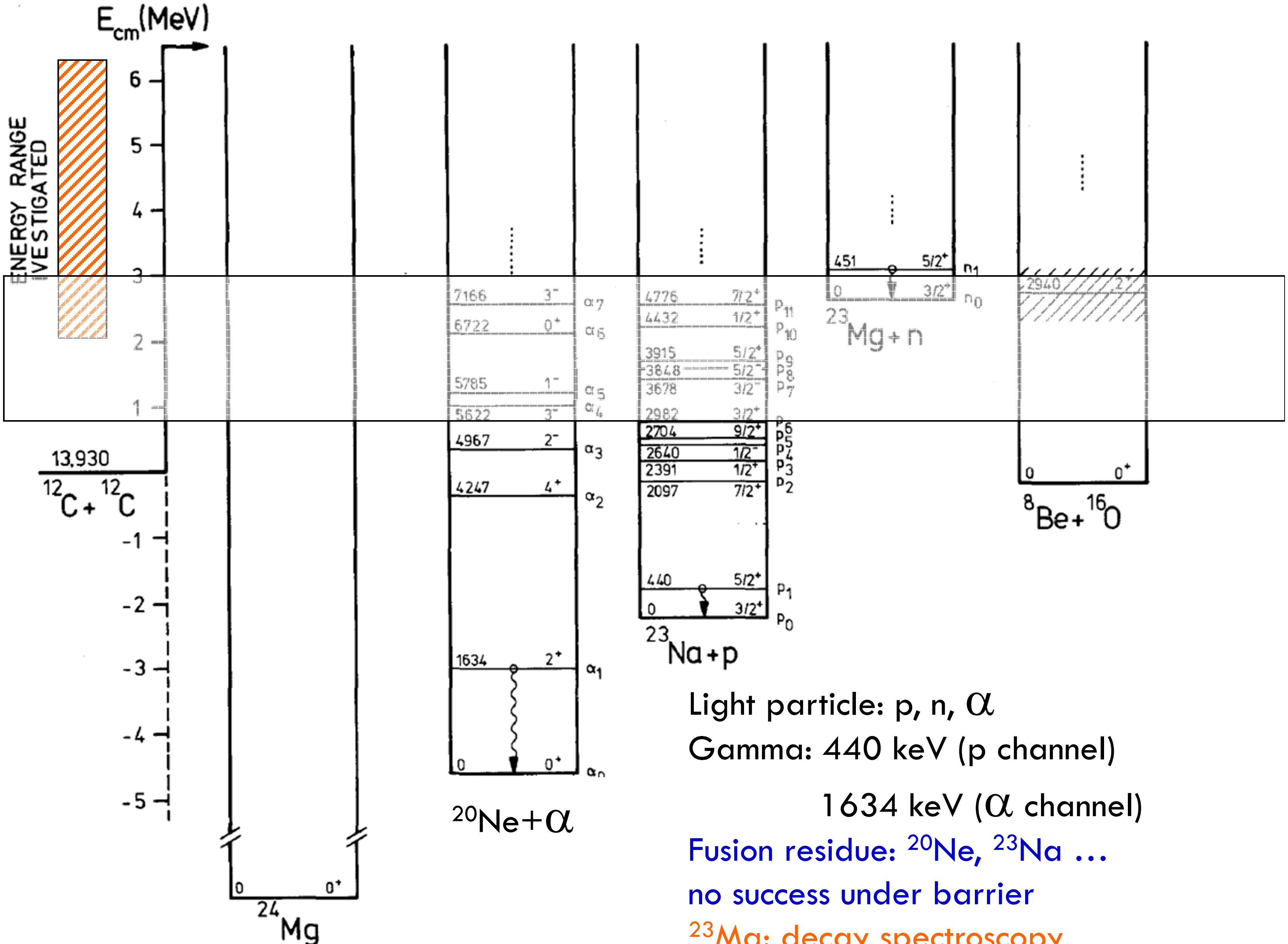
→crust conductivity

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

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

....

$^{12}C+^{12}C$ in laboratories



Light particle: p, n, α

Gamma: 440 keV (p channel)

1634 keV (α channel)

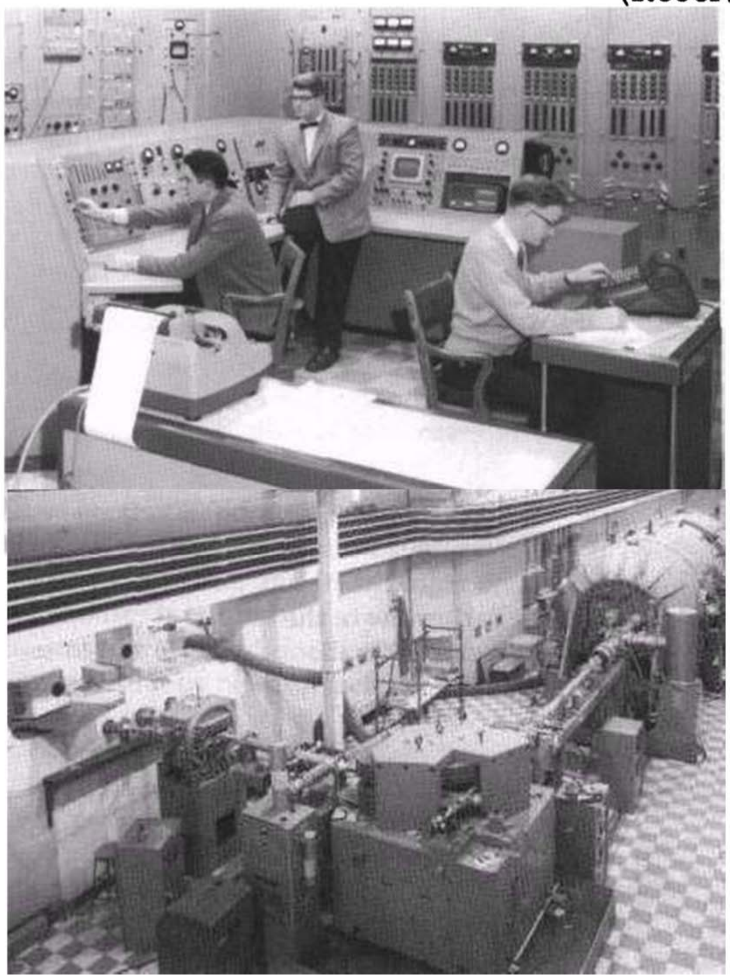
Fusion residue: ^{20}Ne, ^{23}Na …

no success under barrier

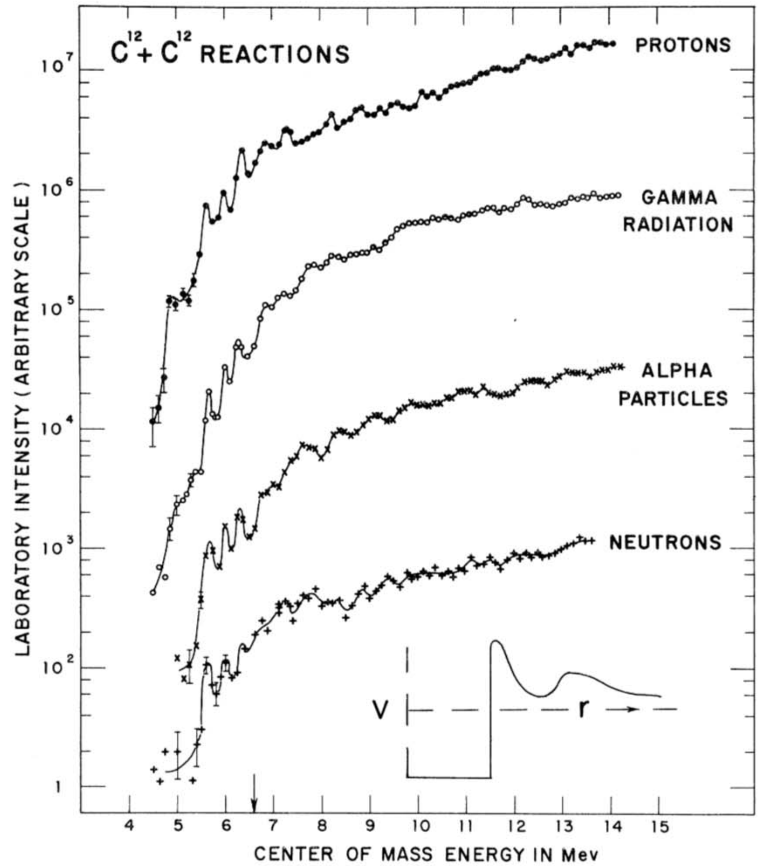
^{23}Mg: decay spectroscopy

RESONANCES IN C^{12} ON CARBON REACTIONS

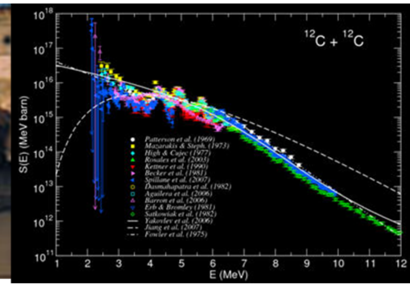
E. Almqvist, D. A. Bromley, and J. A. Kuehner
Atomic Energy of Canada Limited, Chalk River Laboratories, Chalk River, Ontario, Canada
(Received March 28, 1960)

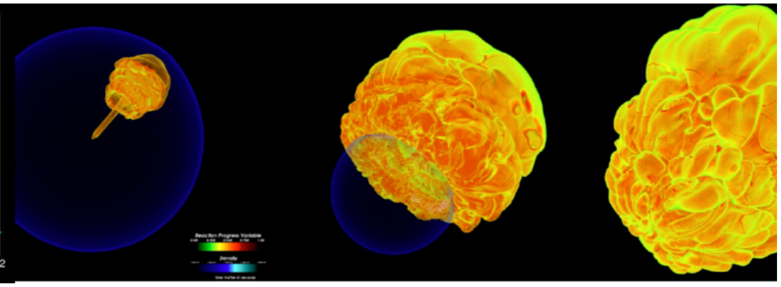


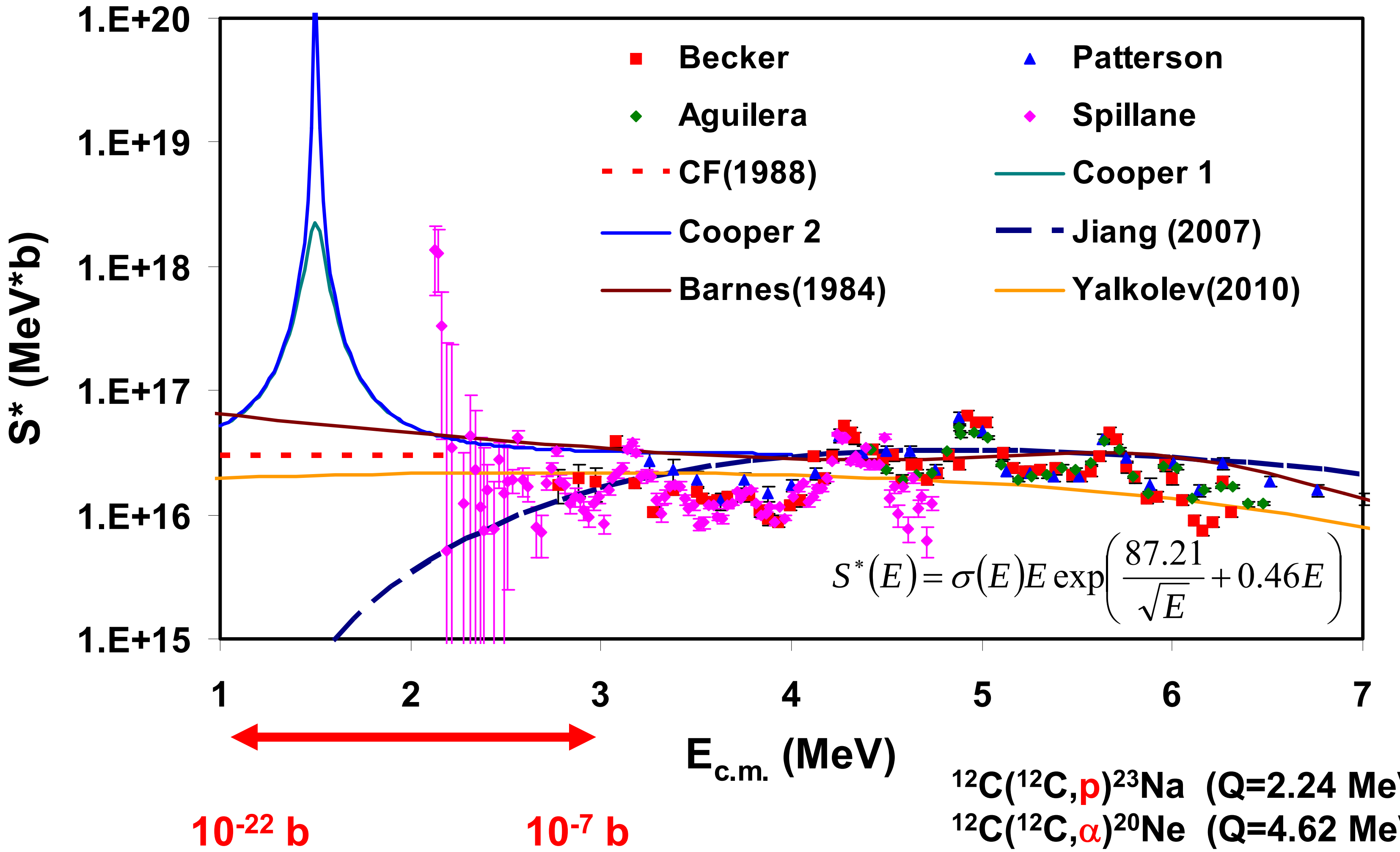
The world's first tandem accelerator installed at Chalk River in 1959.



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



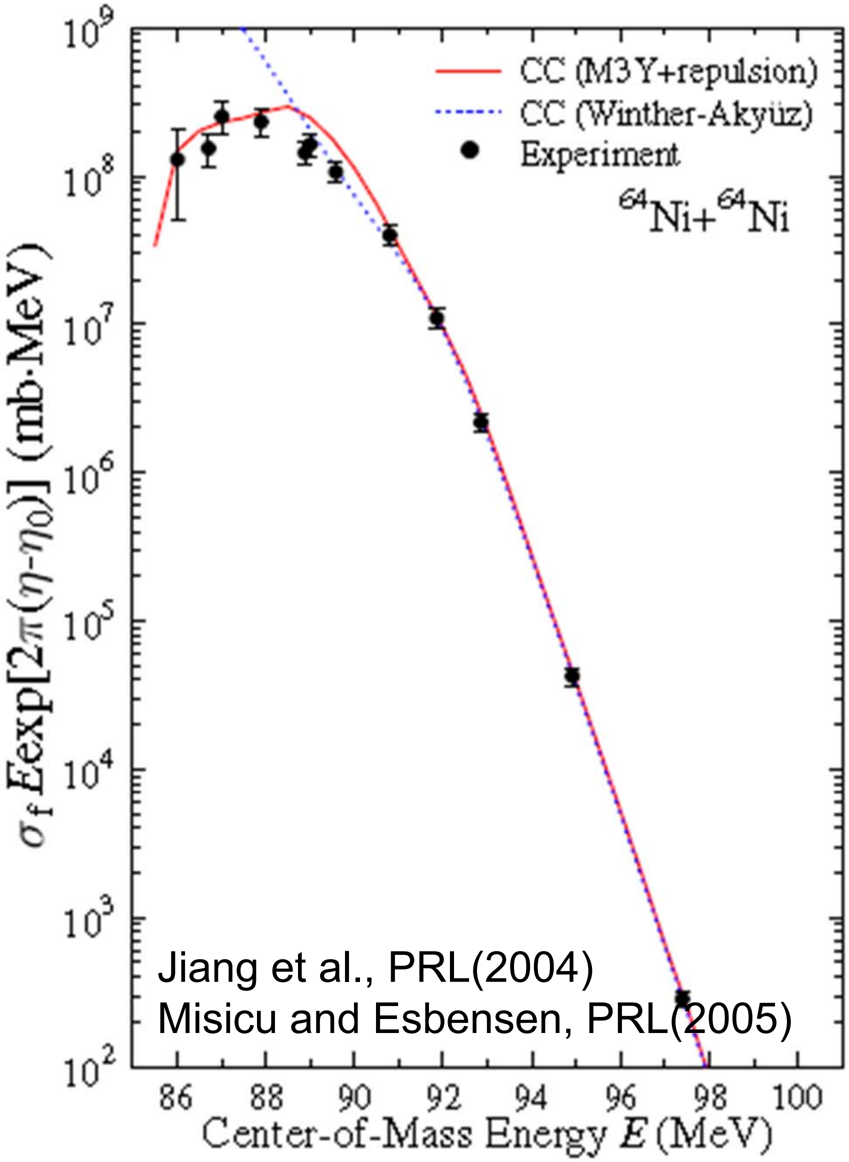


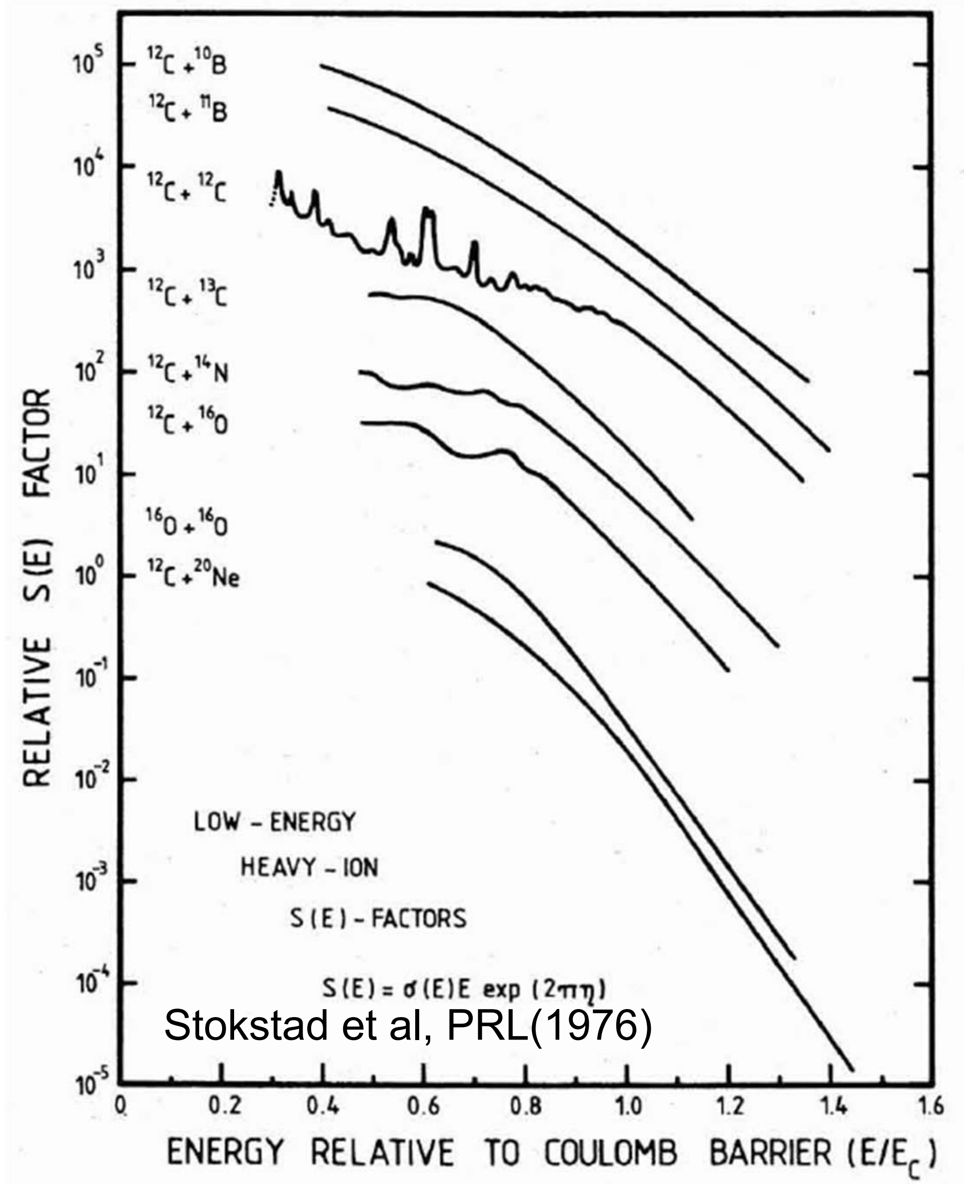


$^{12}C(^{12}C,p)^{23}Na$ (Q=2.24 MeV)

$^{12}C(^{12}C,\alpha)^{20}Ne$ (Q=4.62 MeV)

$^{12}C(^{12}C,n)^{23}Mg$ (Q=-2.62MeV)



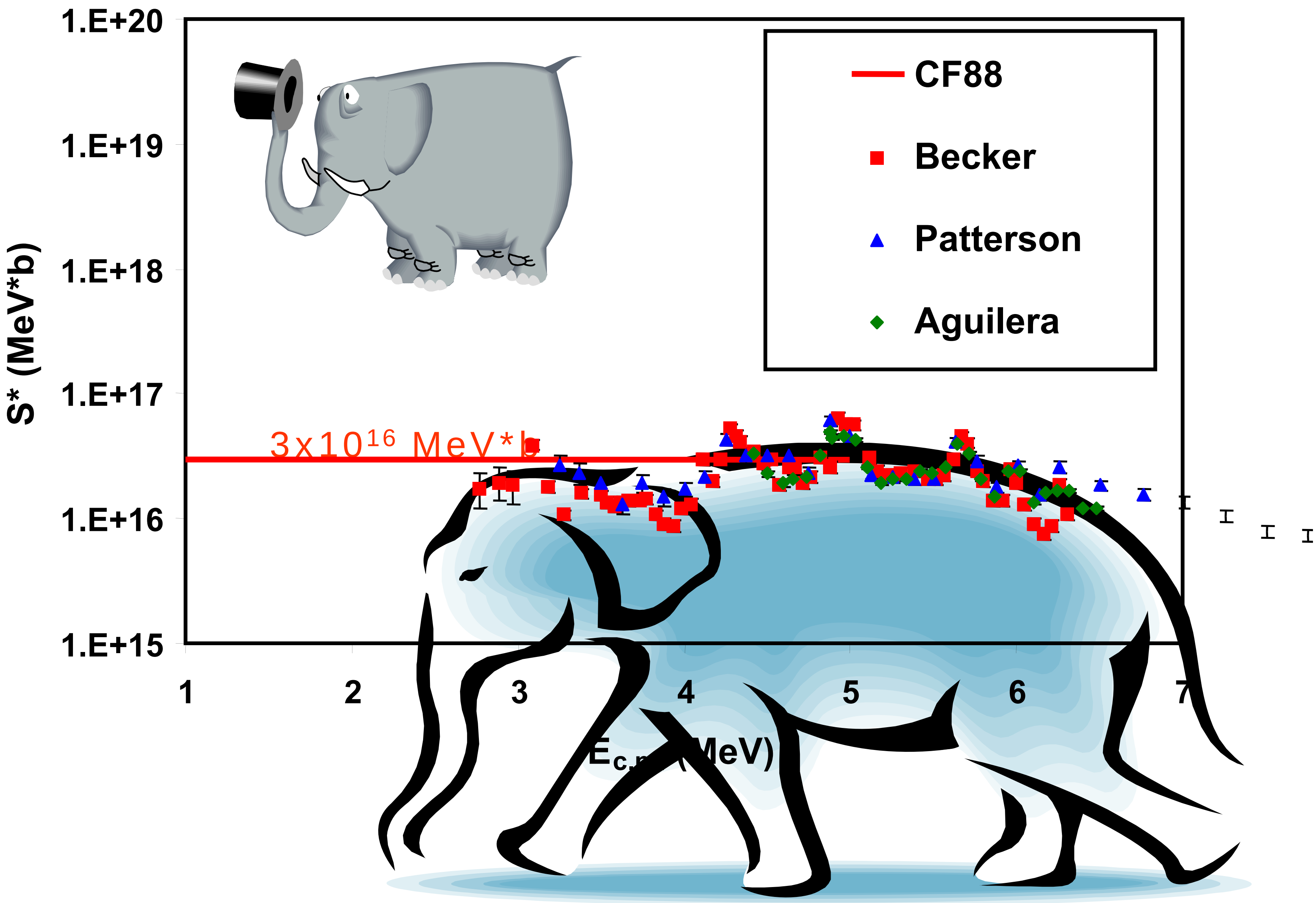


^{64}Ni+^{64}Ni

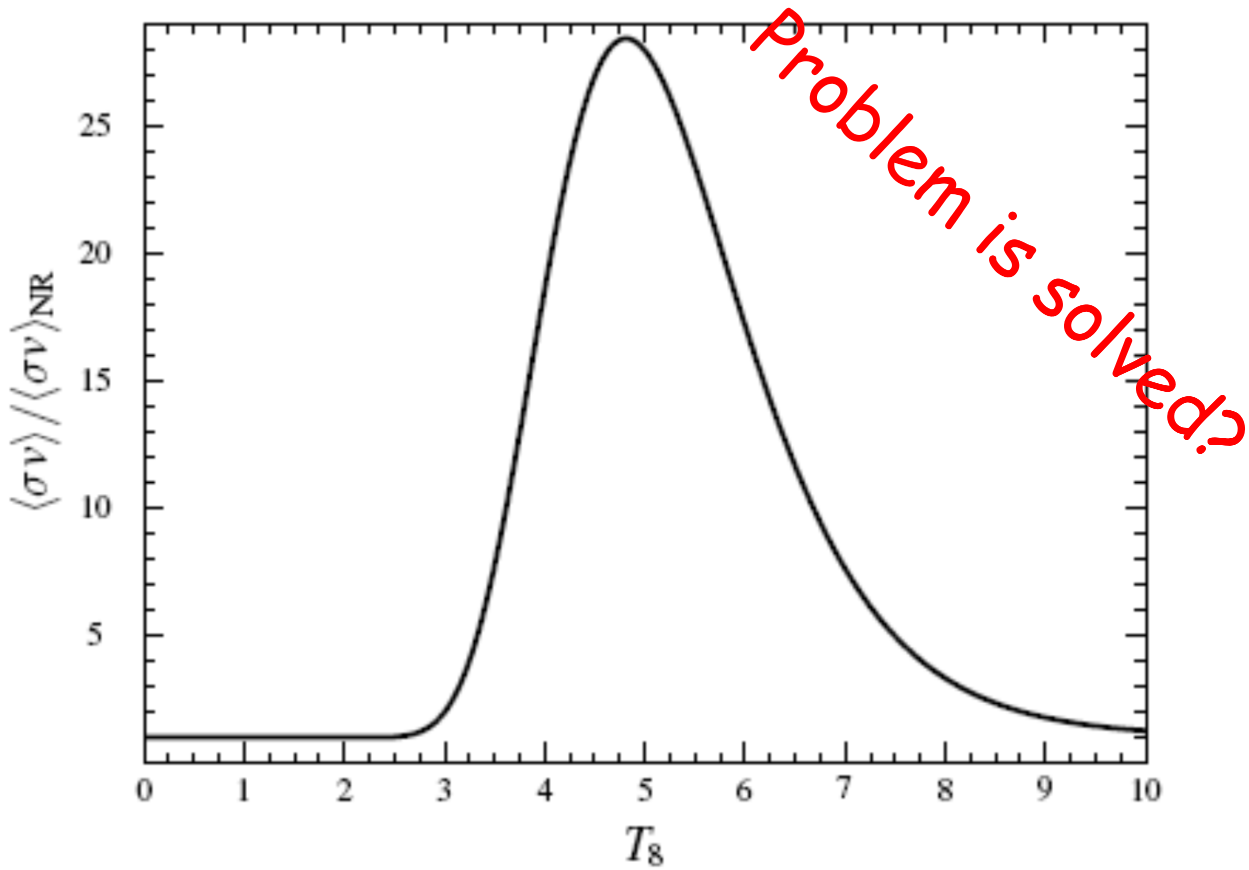
A<20

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

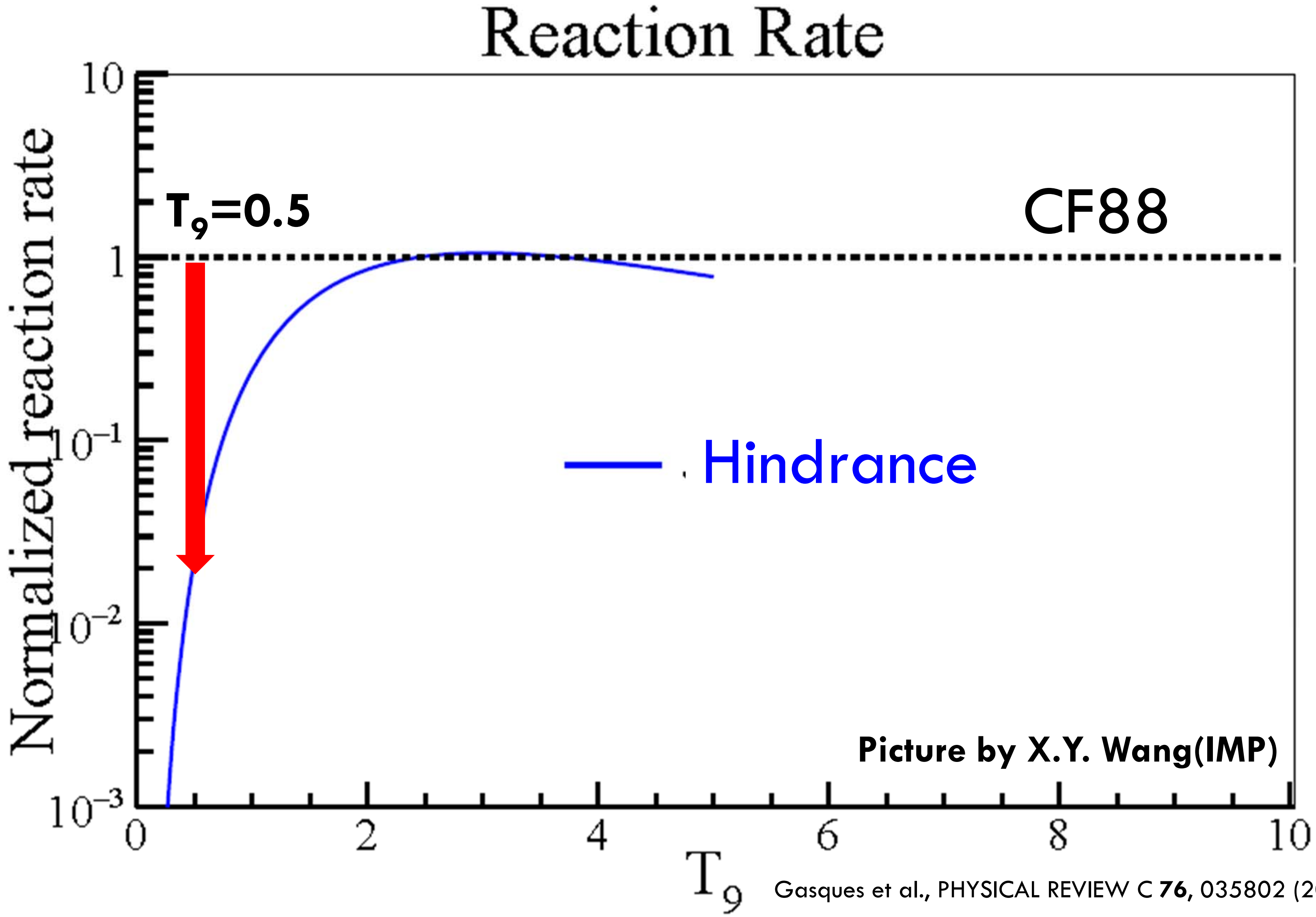
$$S^*(E) = \sigma E e^{(87.21/\sqrt{E}+0.46E)}$$



Solving the superburst problem with an artificial resonance at $E_{c.m.}$=1.5 MeV



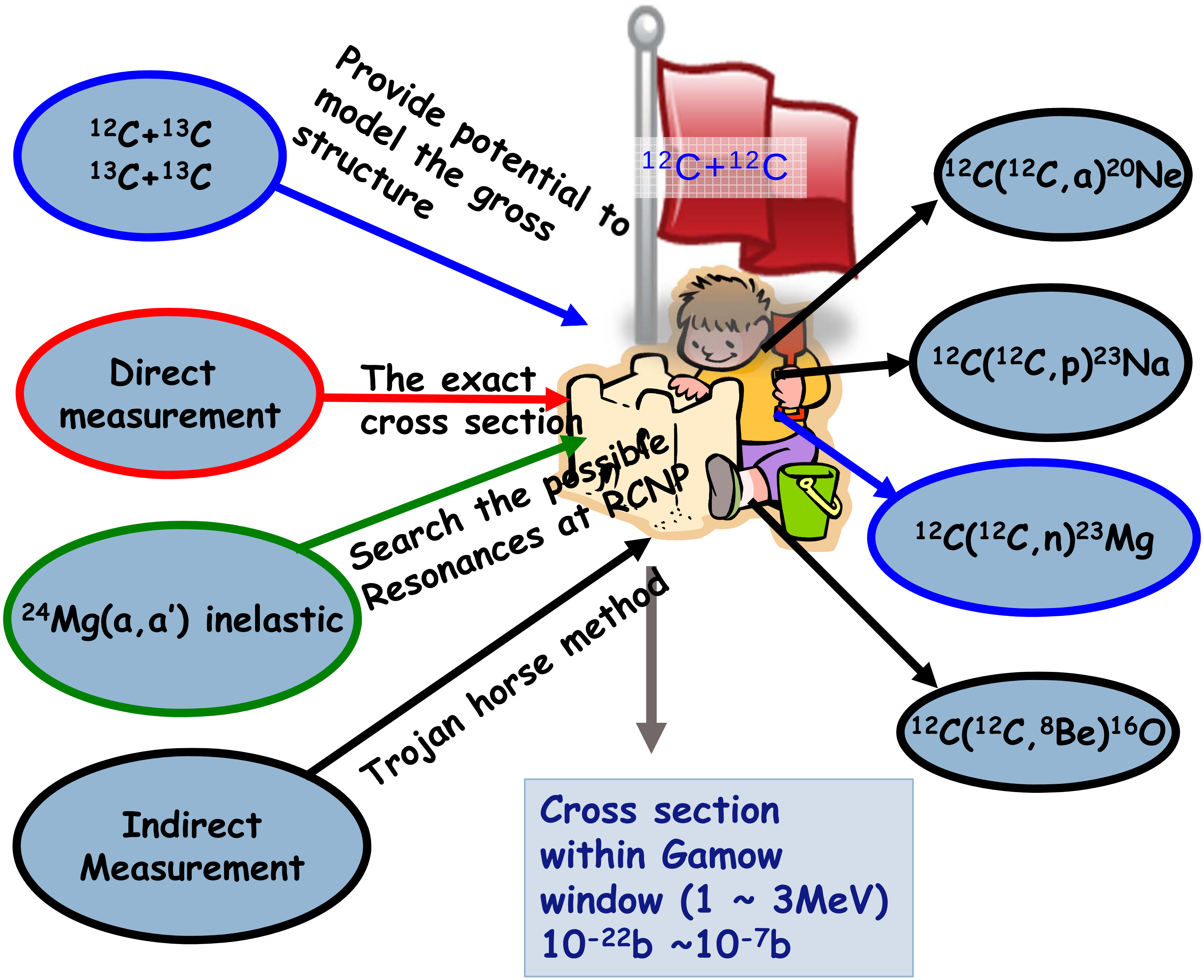
R. Cooper et al., APJ (2009) 702, 660

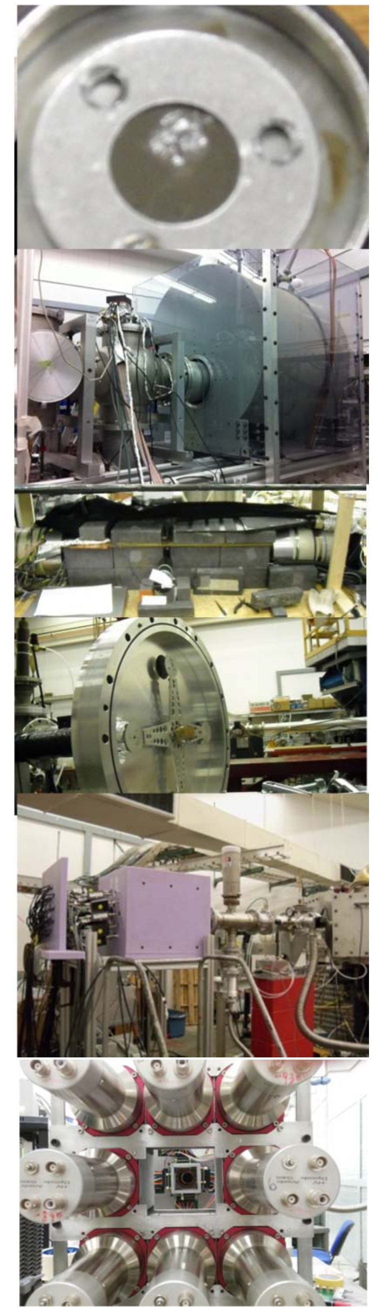


Gasques et al., PHYSICAL REVIEW C **76**, 035802 (2007)

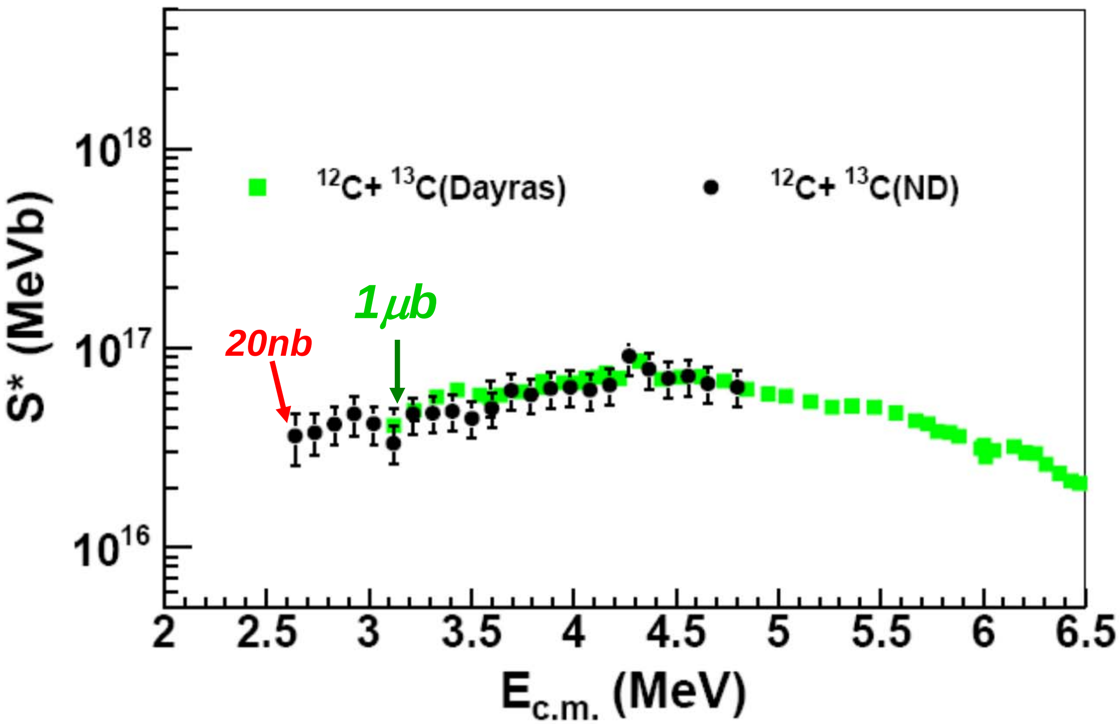
- **More difficult to ignite $^{12}C+^{12}C$ in superburst**
- **Shut off the pycnonuclear reactions in neutron crust**
- **Change ^{60}Fe, ^{26}Al production yields in massive stars**

Carbon fusion reaction





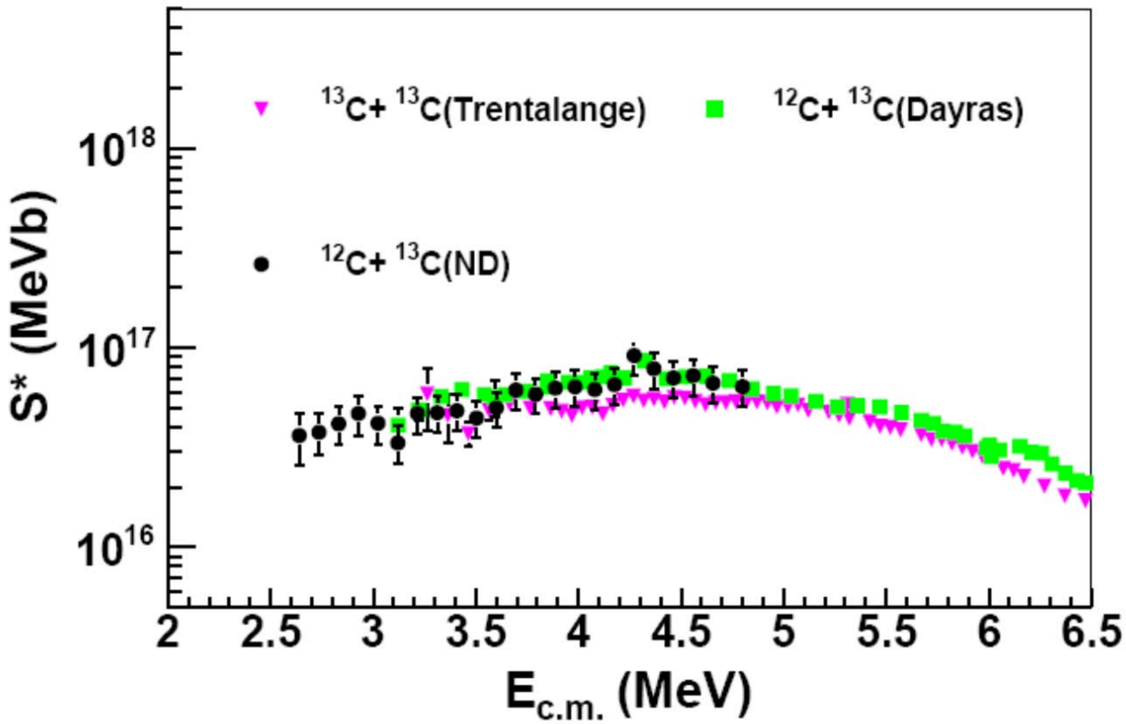
Upper limit of 12C+12C



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

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

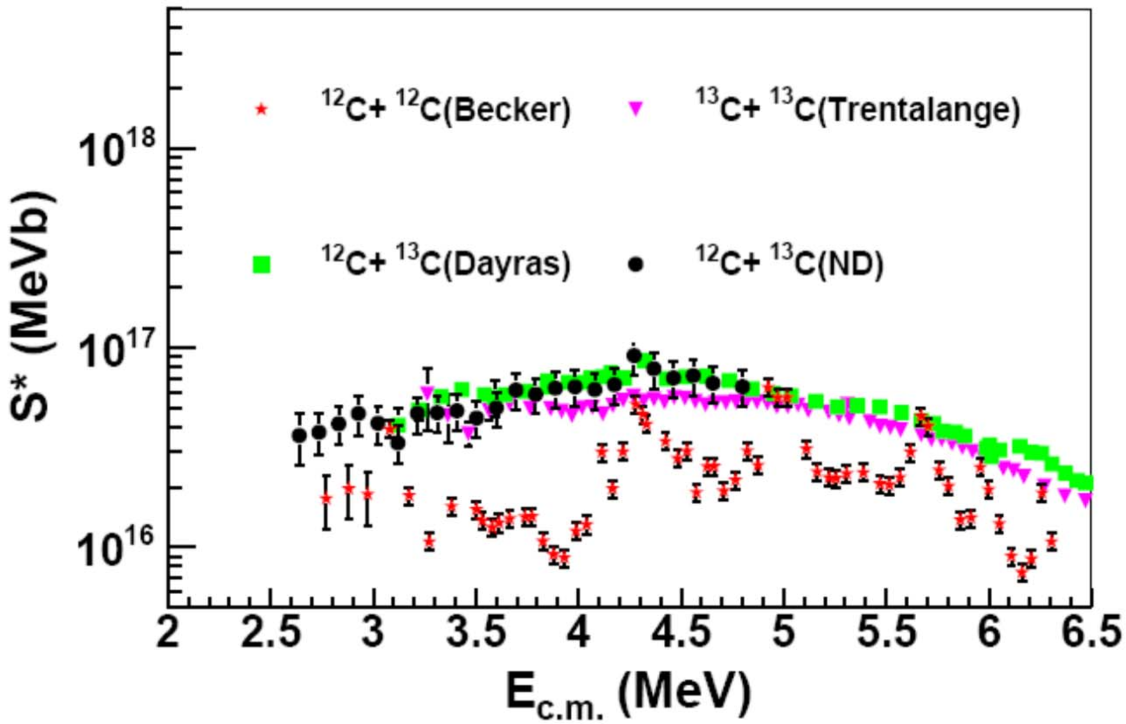
•*The smallest cross section has been pushed down by a factor of 50.*



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

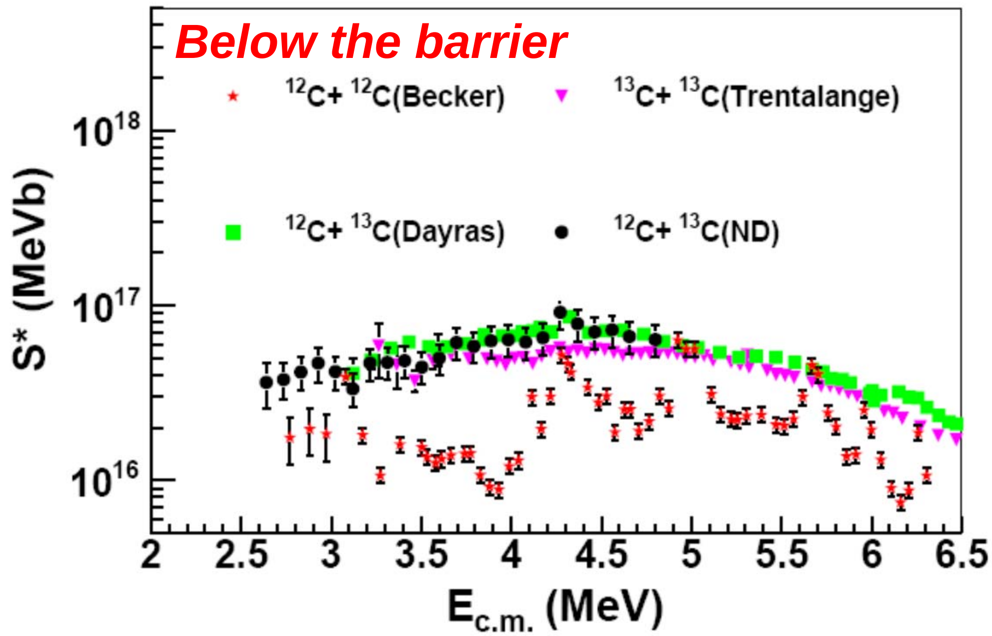
•***The isotope effect (difference in radius, mass) is negligible within the observed energy range!***

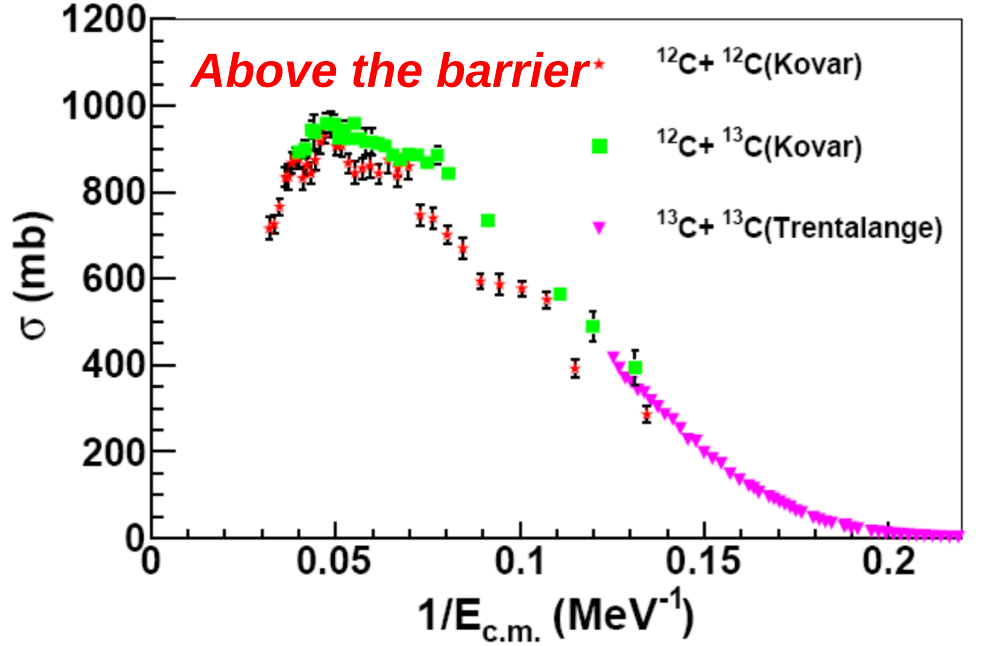
•***Where will the*** $^{12}C+^{12}C$ ***data show up?***



•*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 $^{13}C+^{13}C$!*





A simple pattern for complicated resonances

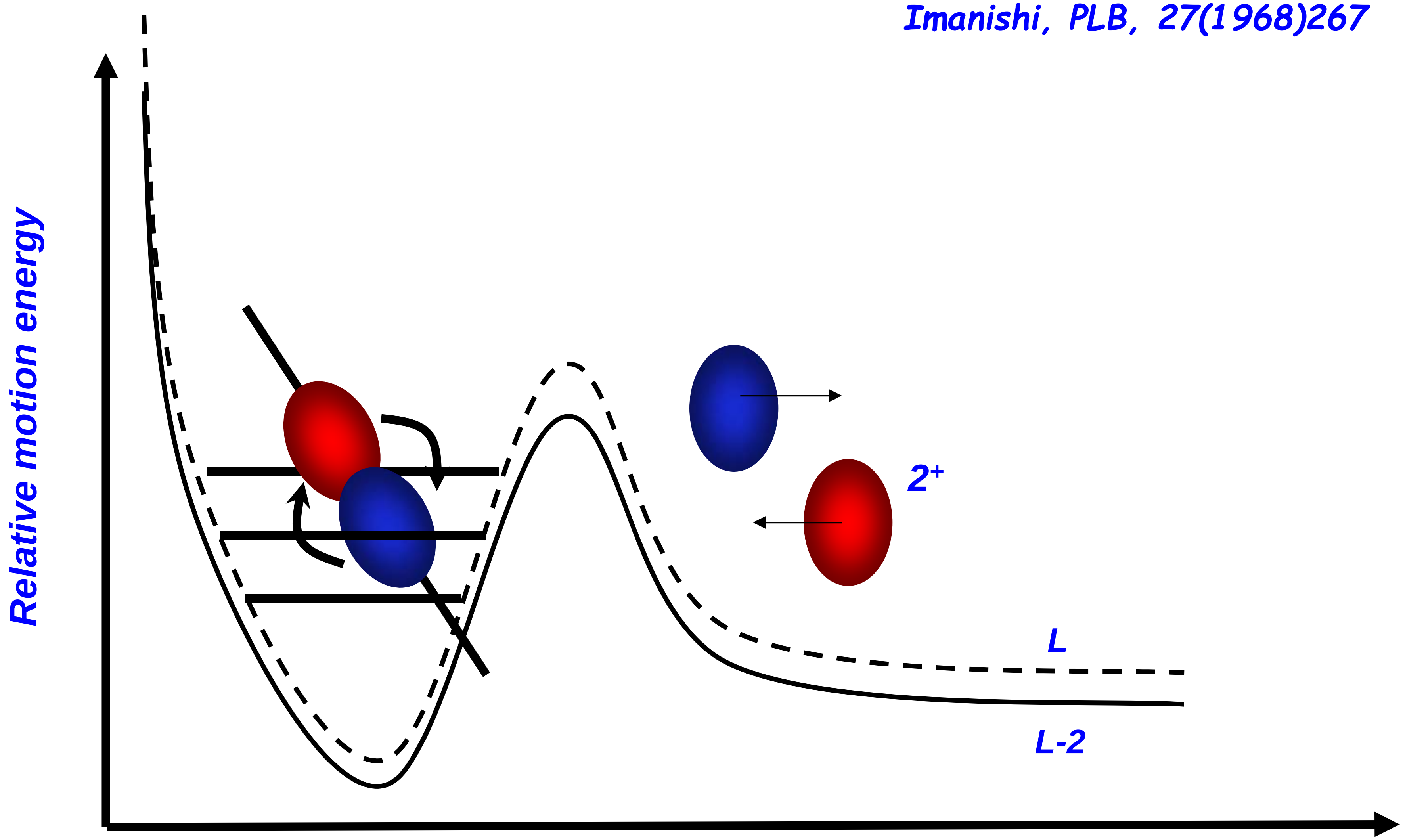
For most energies, the $^{12}C+^{12}C$ cross sections are suppressed!

• 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?

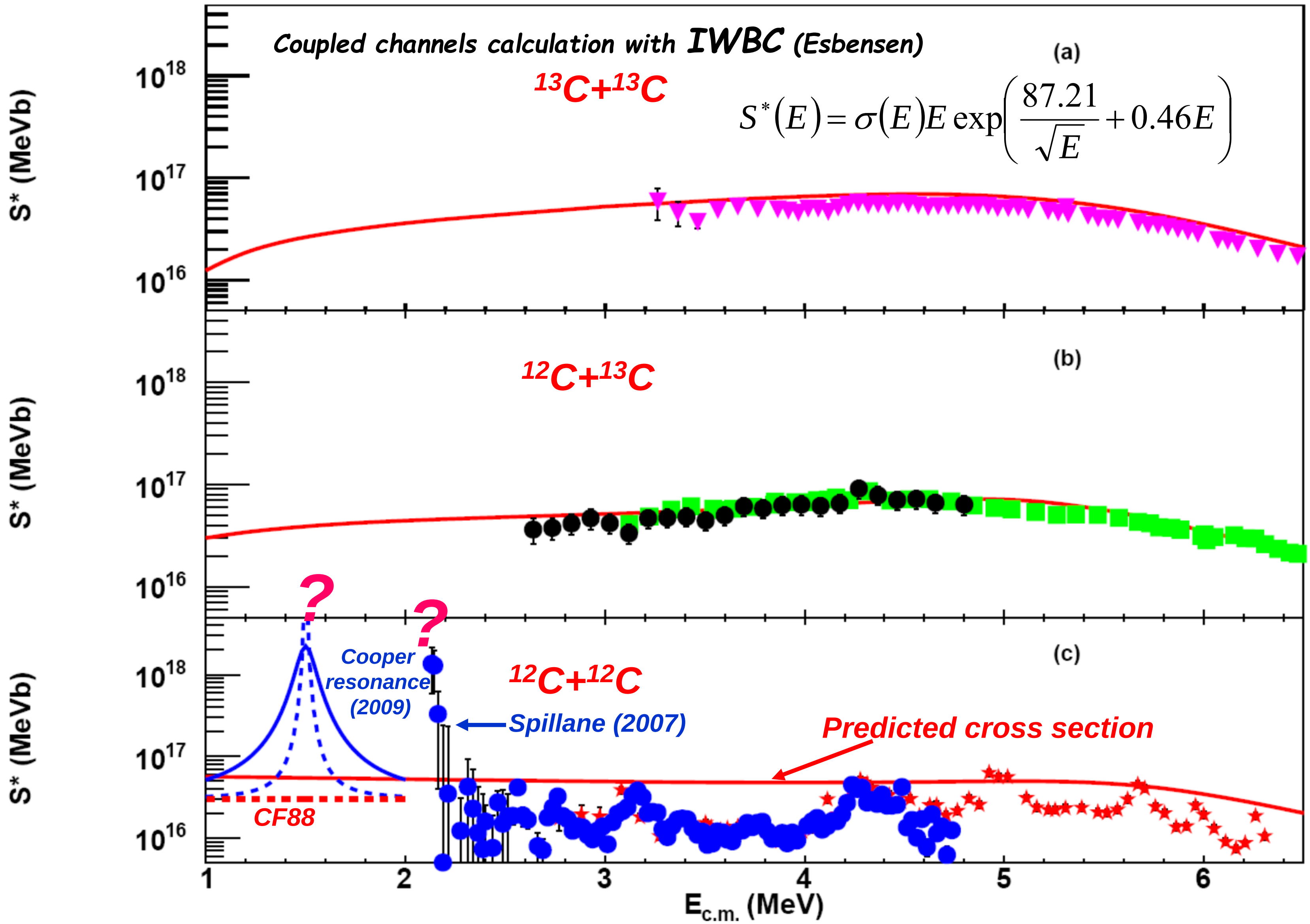
Nogami-Imanishi Model

Imanishi, PLB, 27(1968)267



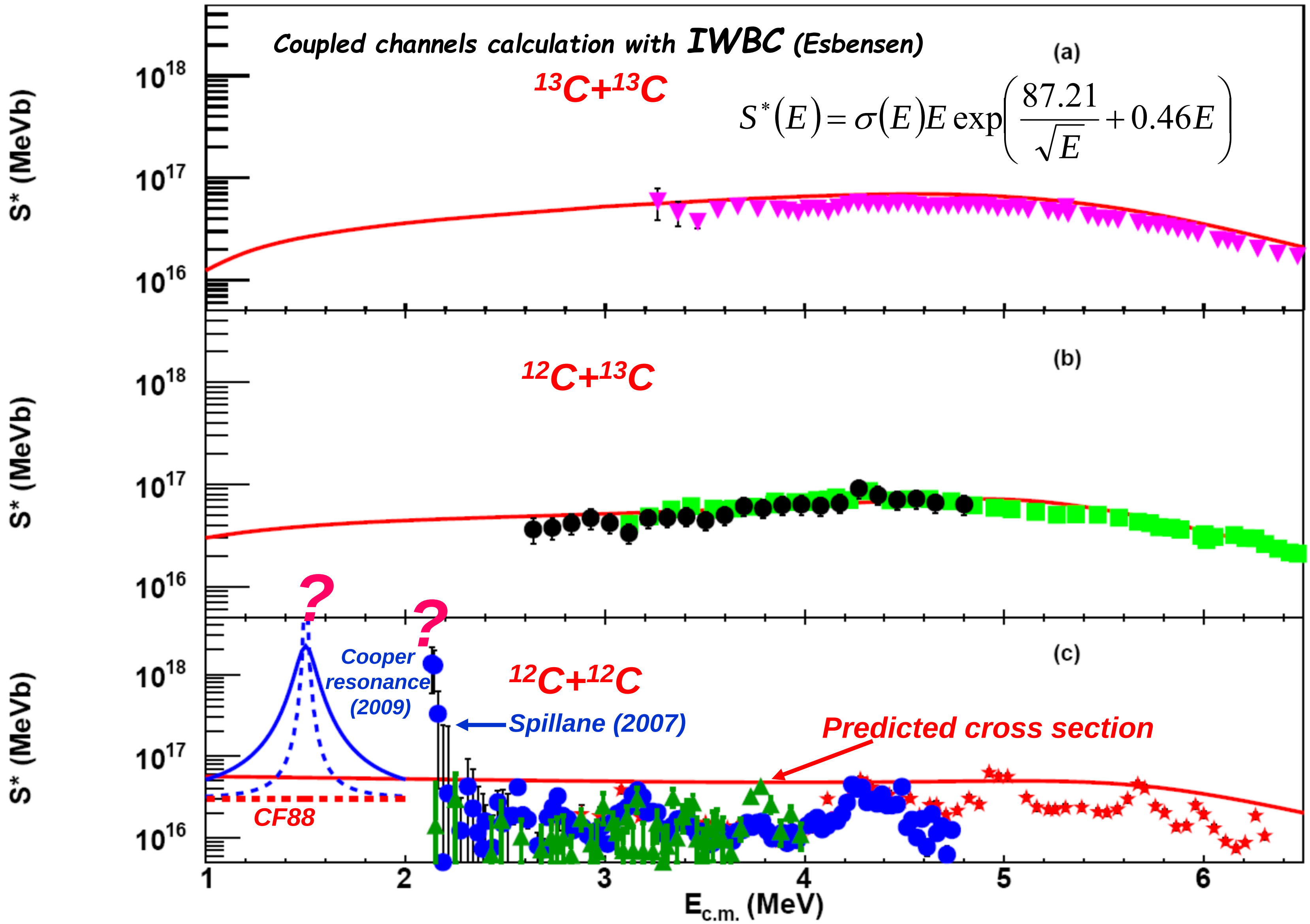
$^{12}C+^{12}C$ doorway state level density

Predict $^{12}C+^{12}C$ cross sections 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)

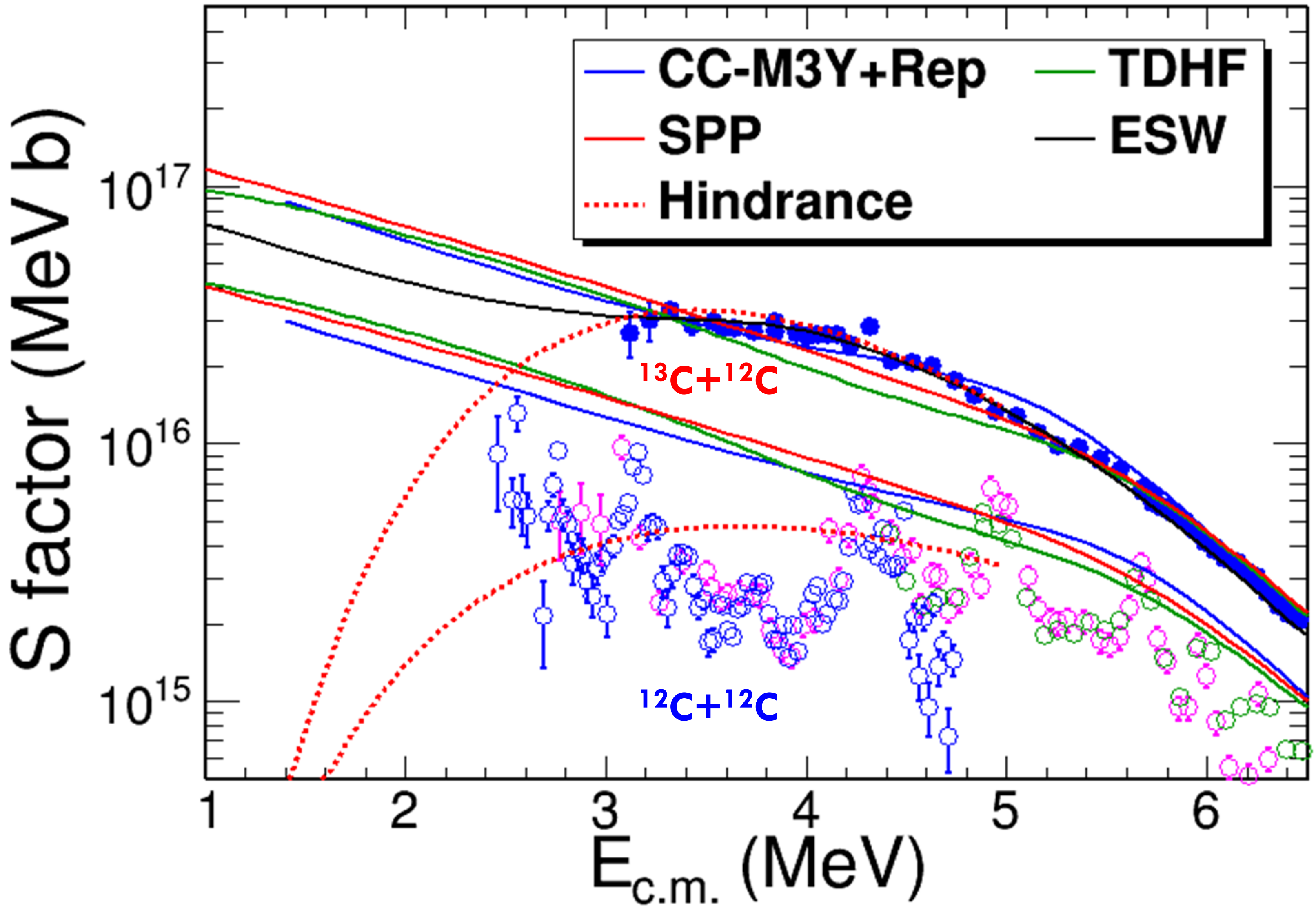
Predict $^{12}C+^{12}C$ cross sections with a constrained potential



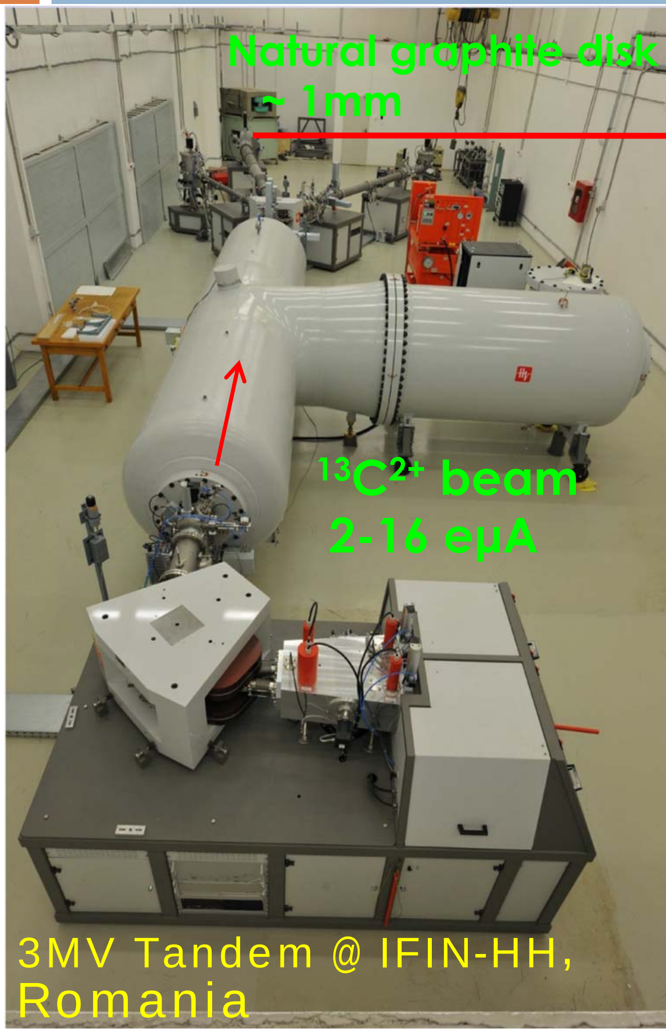
H. Esbensen et al., Phys. Rev. C 84, 064613 (2011); Jiang et al.Phys.Rev.Lett. 110, 072701 (2013)
M. Notani et al., Phys. Rev. C 85, 014607 (2012)

Test of predictive power of models

Test of Predictive Power



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

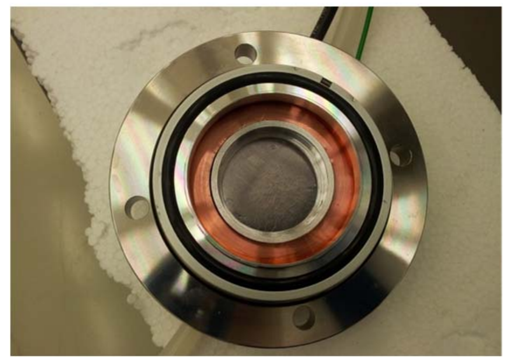


Online irradiation

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

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

1369-2754 keV γ rays

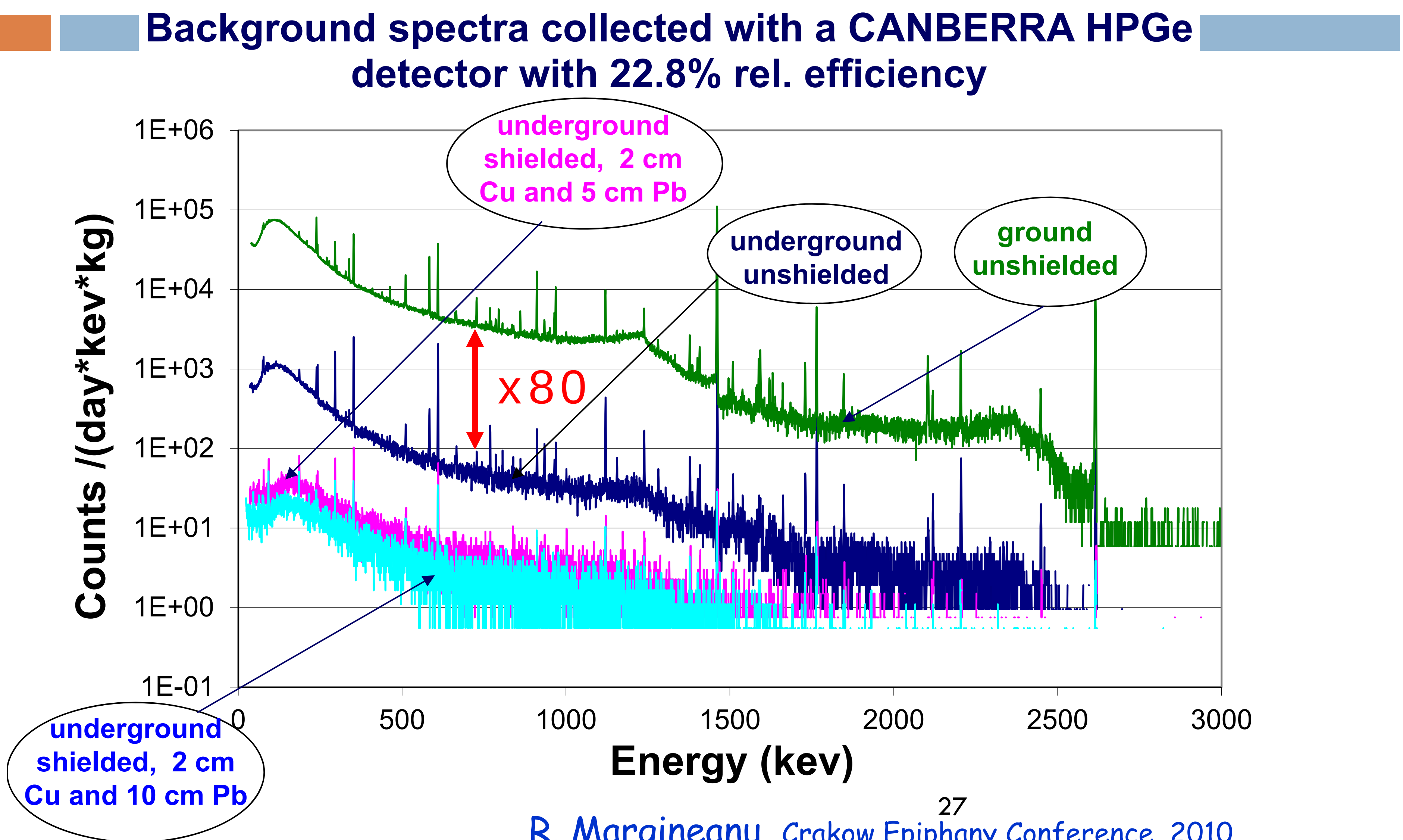


- **HF theory calibrated by exp. → Branching ratio**
- **Obtaining the total fusion cross section**

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

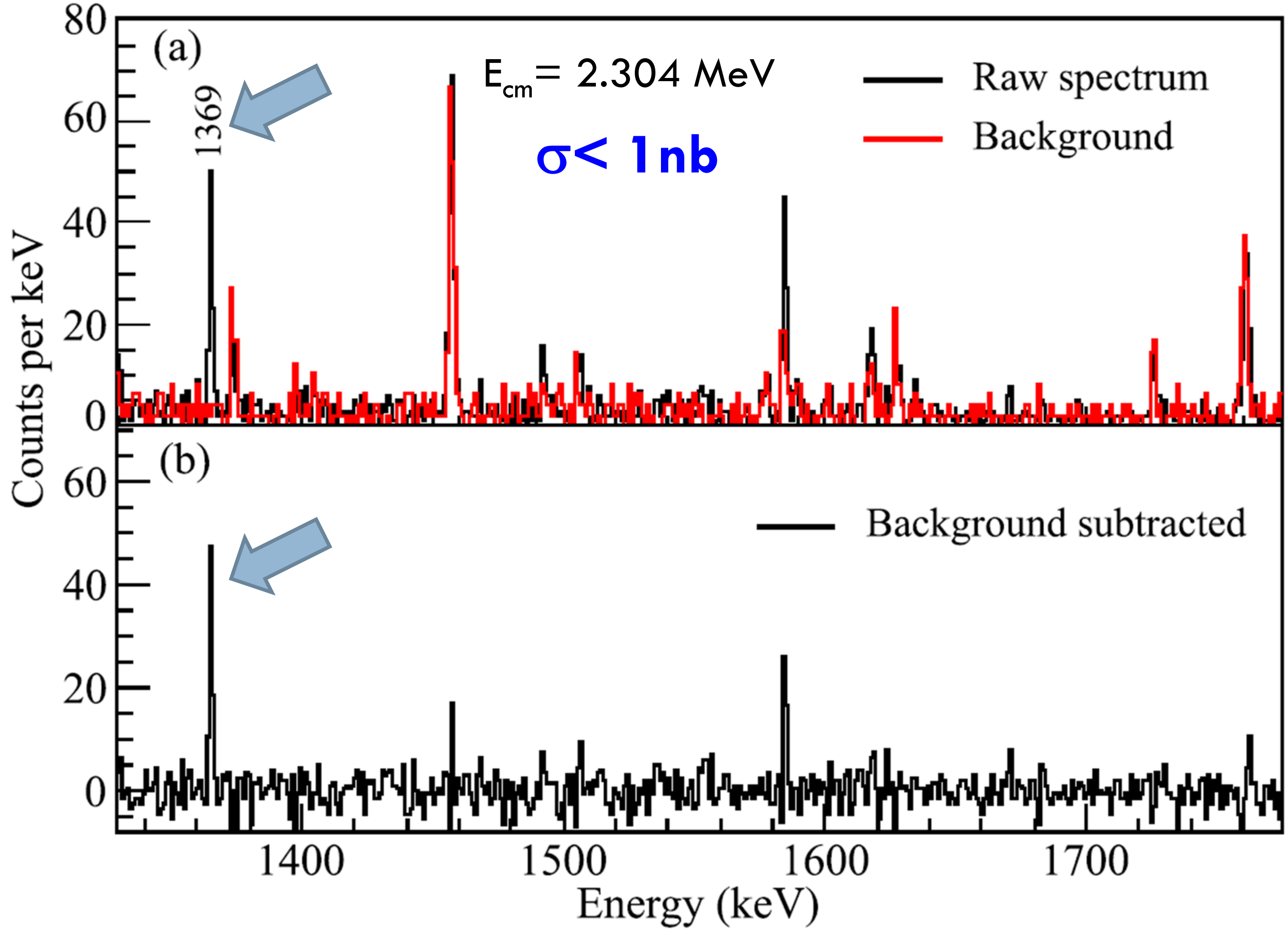
Offline γ-ray counting

Background in the underground



R. Margineanu, Crakow Epiphany Conference, 2010

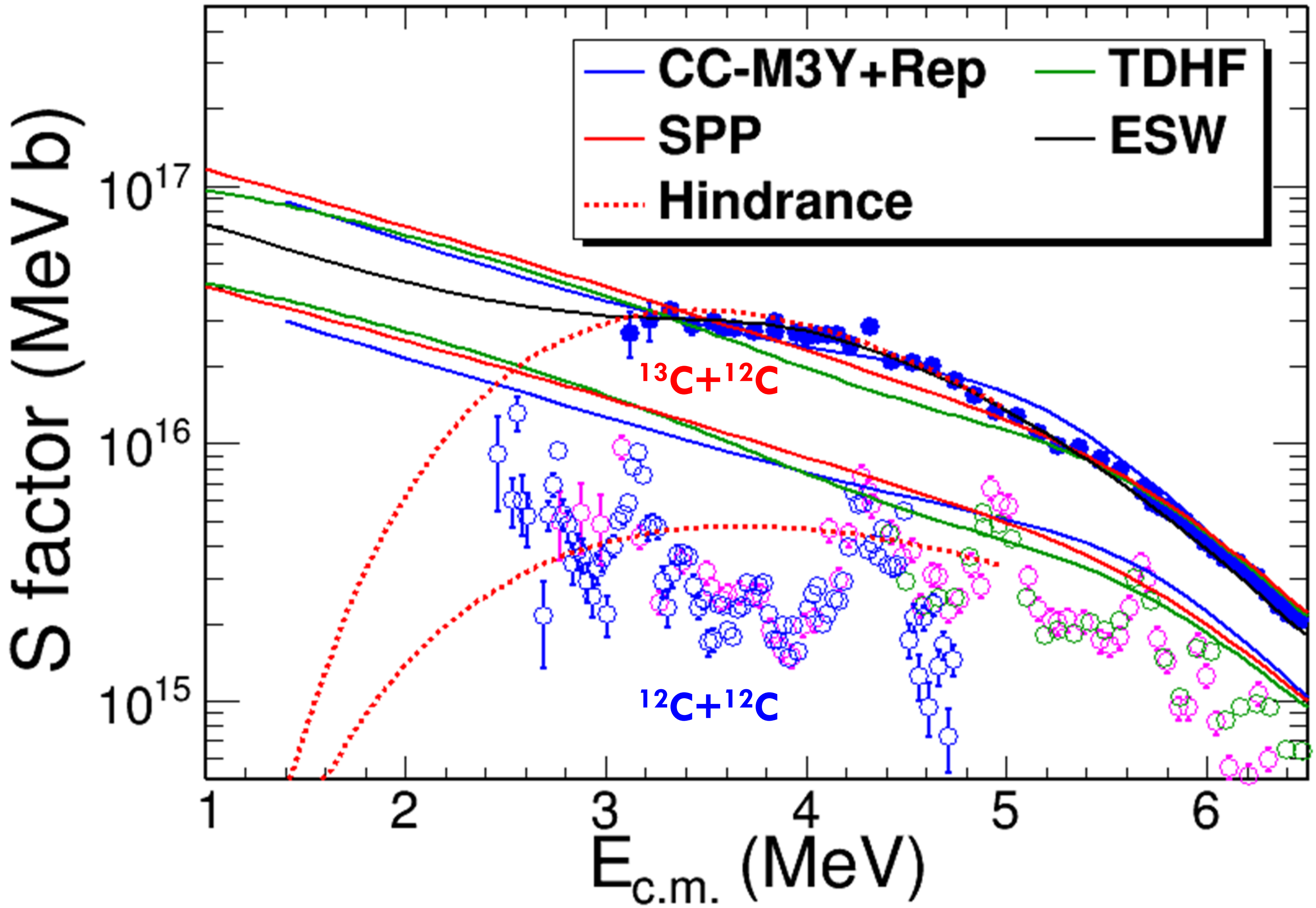
Low level background counting



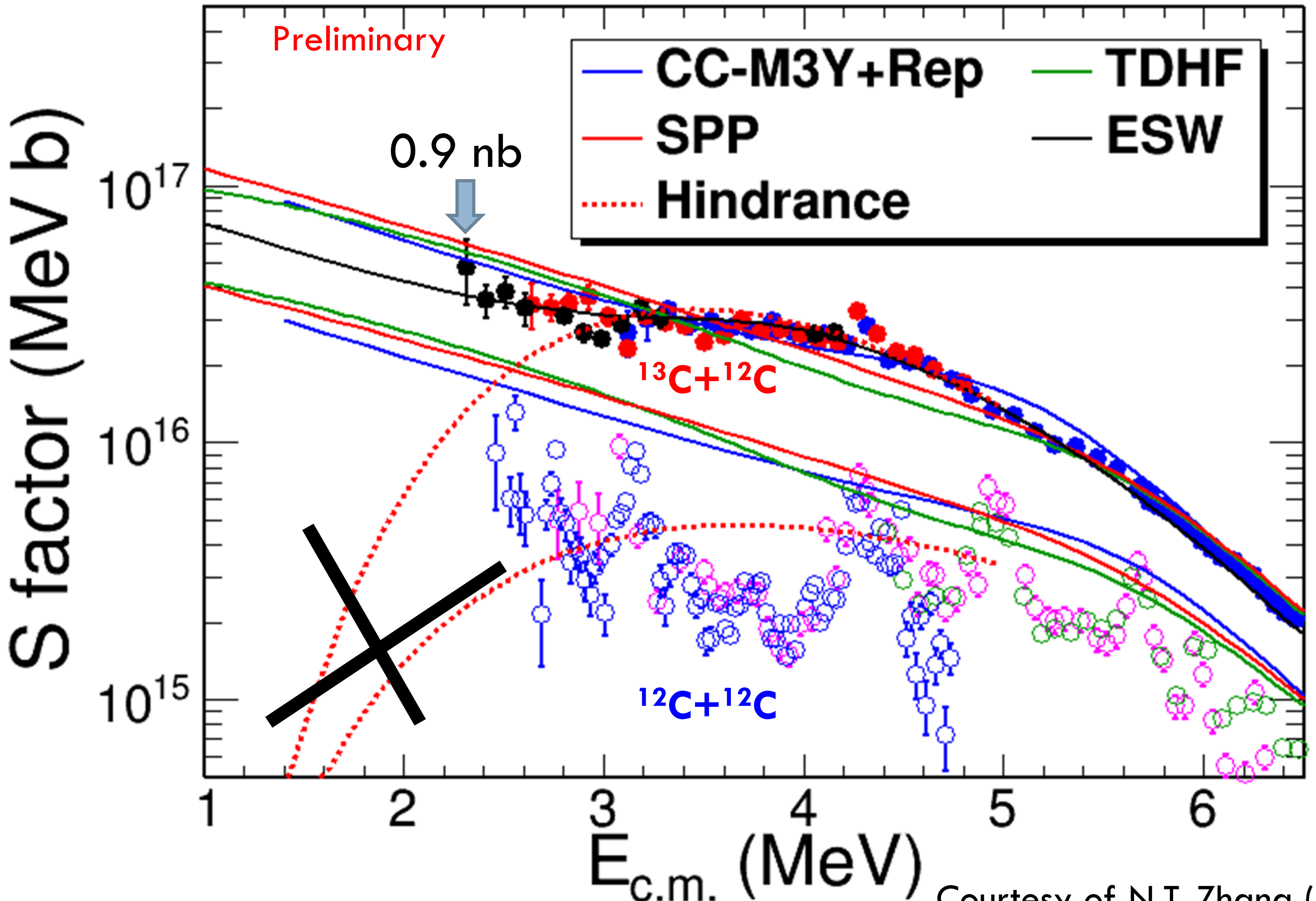
Radiations: 3.4 days

measurements: 3.9 days

Test of Predictive Power

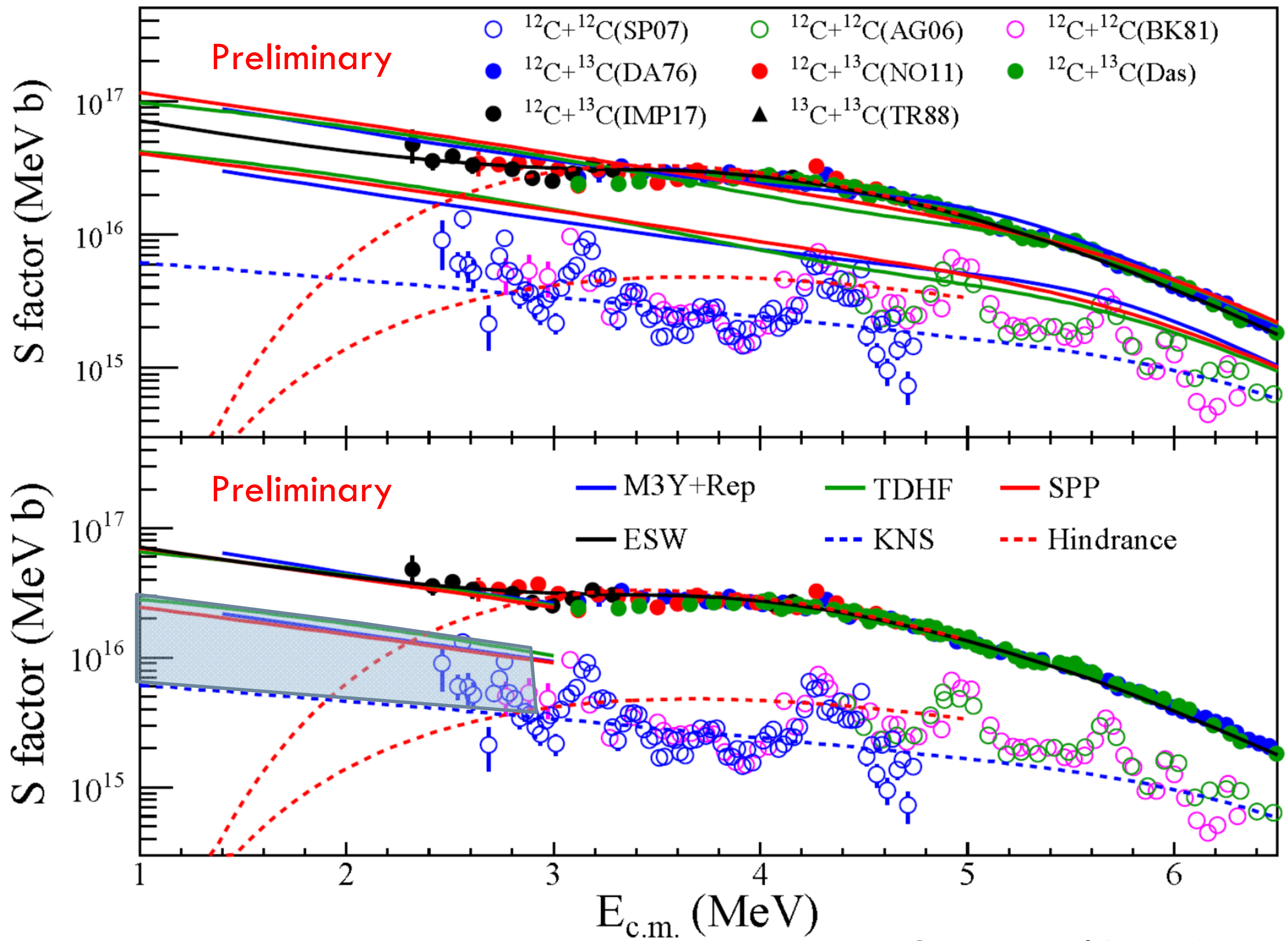


Test of Predictive Power



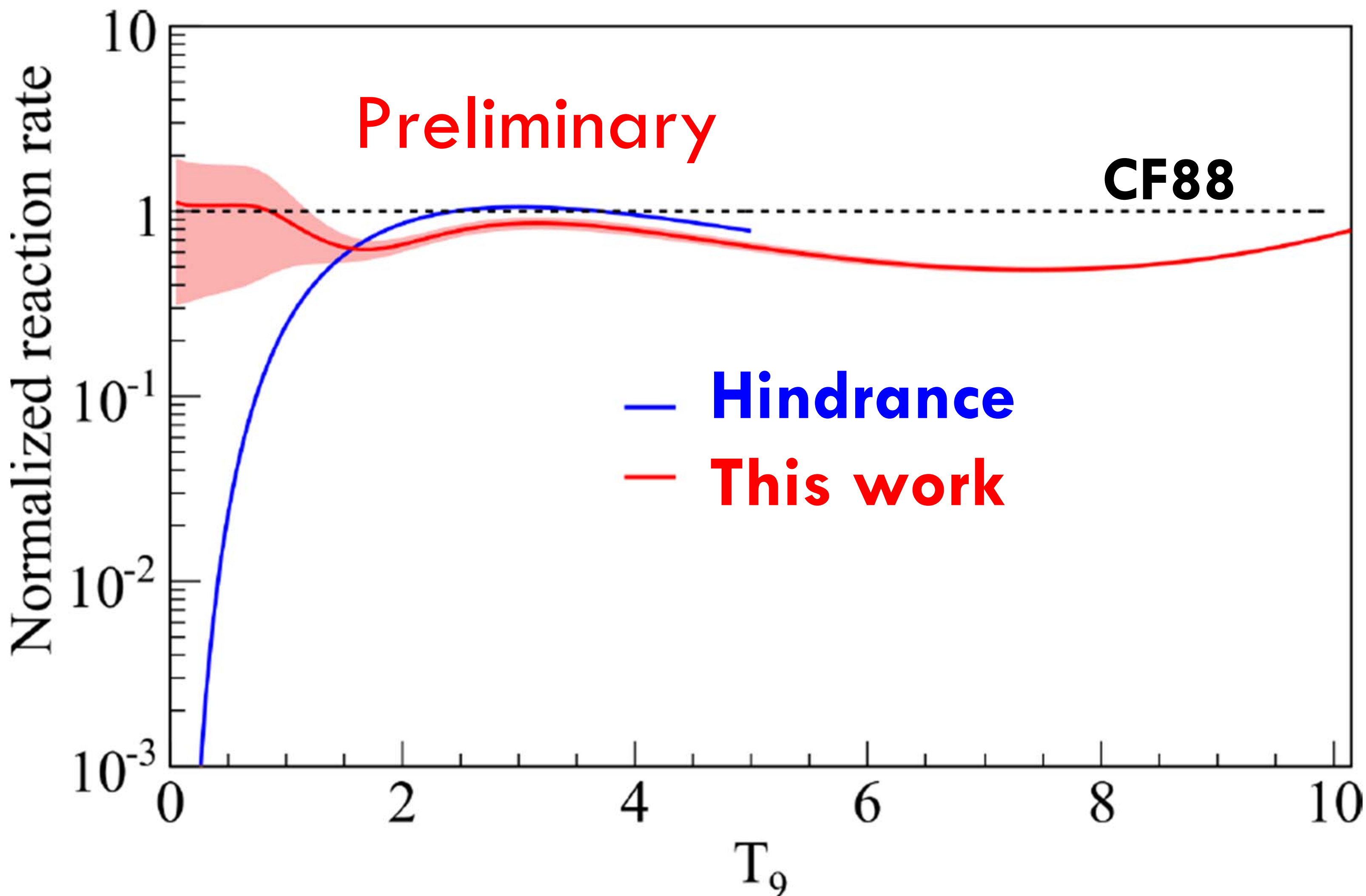
Courtesy of N.T. Zhang (IMP)

Upper and lower limits



Courtesy of N.T. Zhang (IMP)

Reaction rate recommendation



Courtesy of N.T. Zhang (IMP)

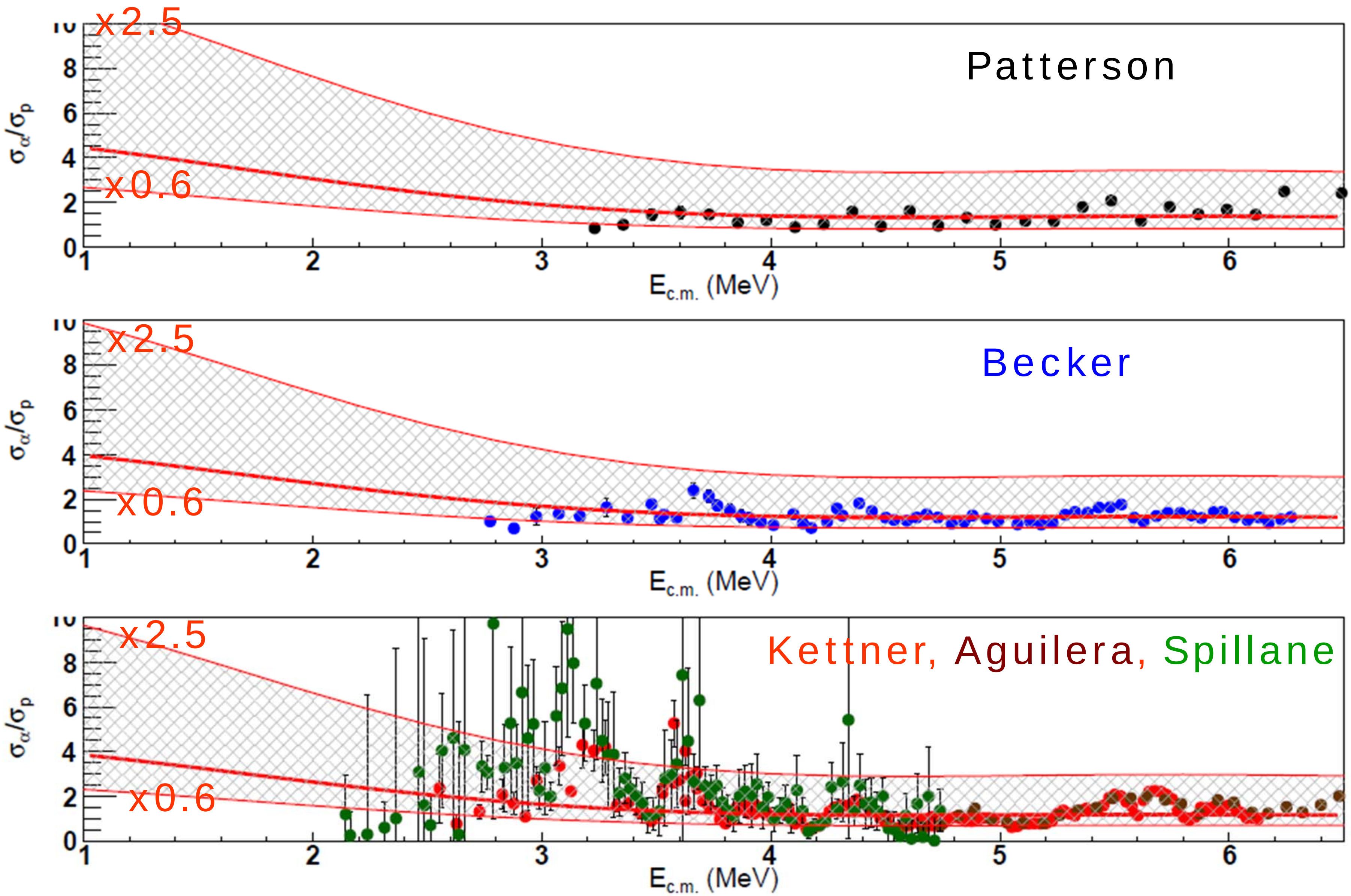
Resonances in 12C+12C

Branching ratio:

$^{12}C(^{12}C,a)^{20}Ne$

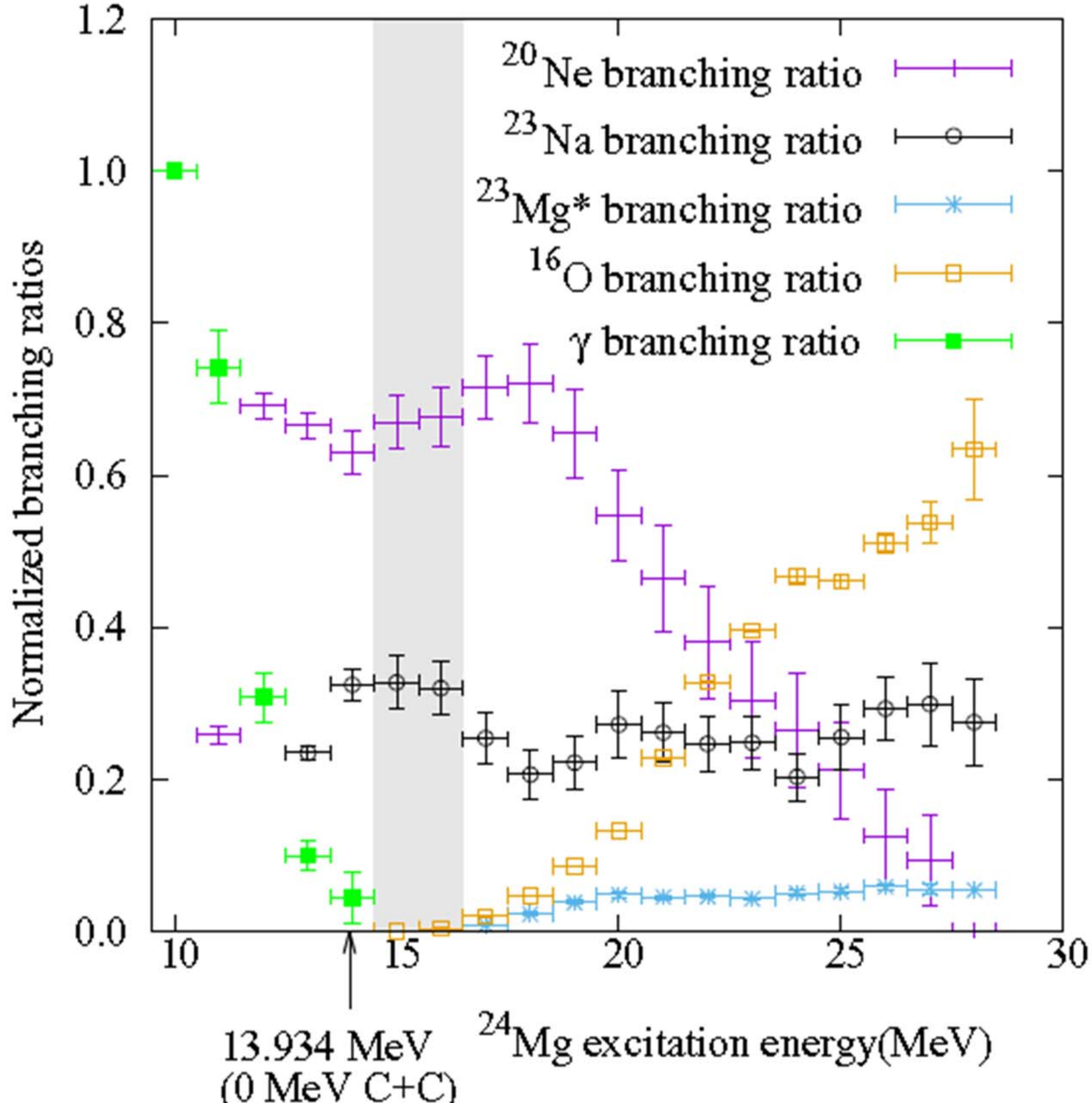
$^{12}C(^{12}C,p)^{23}Na$

$^{12}C(^{12}C,n)^{23}Mg$



- CF88 recommends s_a/s_p=1.3; But It may not be true.
- The Spillane resonance is too strong to fit in this fig

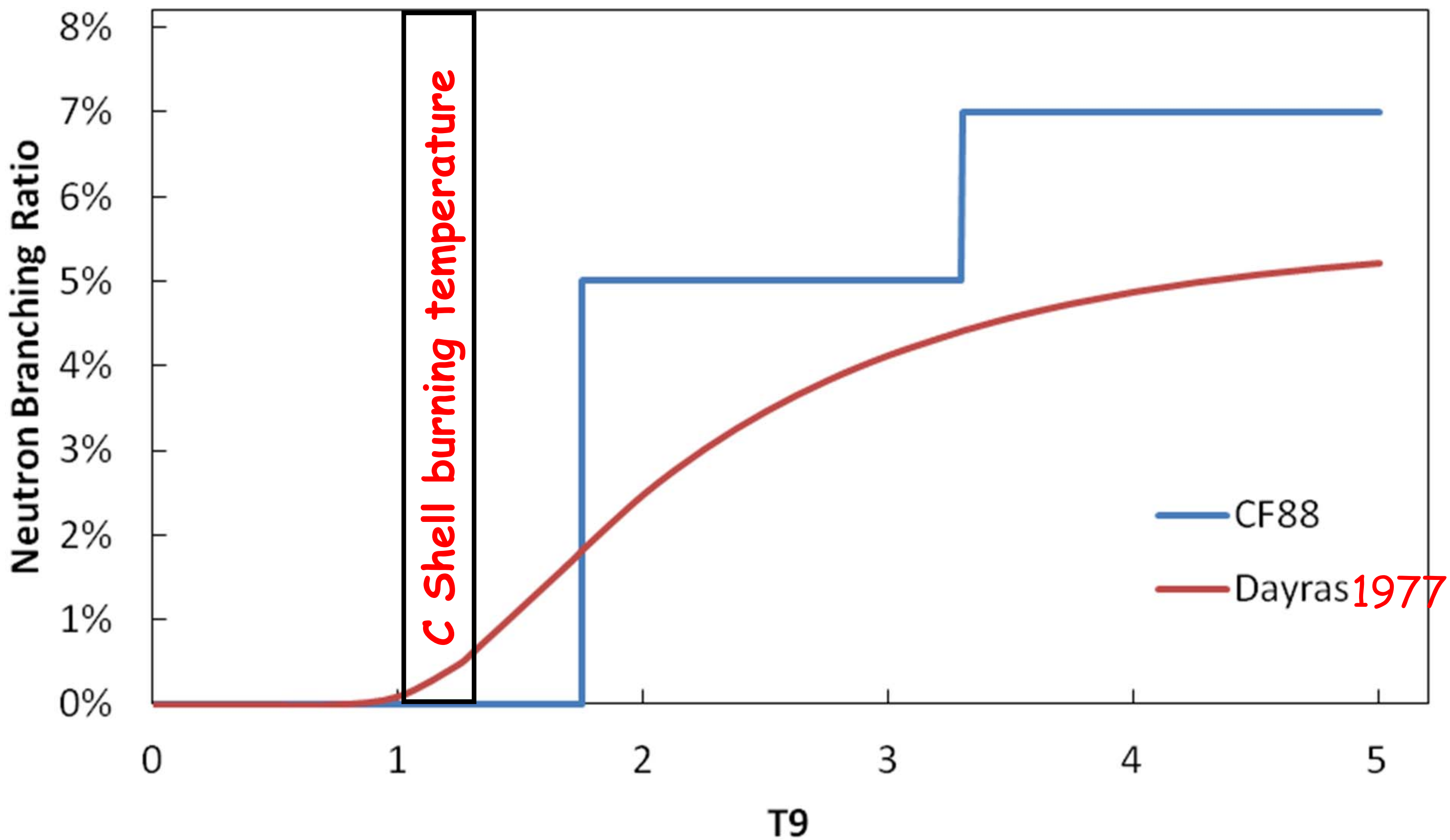
Decay branching ratios of excited 24Mg



However, spin population is different

PHYSICAL REVIEW C **95**, 015805 (2017)

Branching ratio of 12C(12C,n) is not zero! Check your rate!



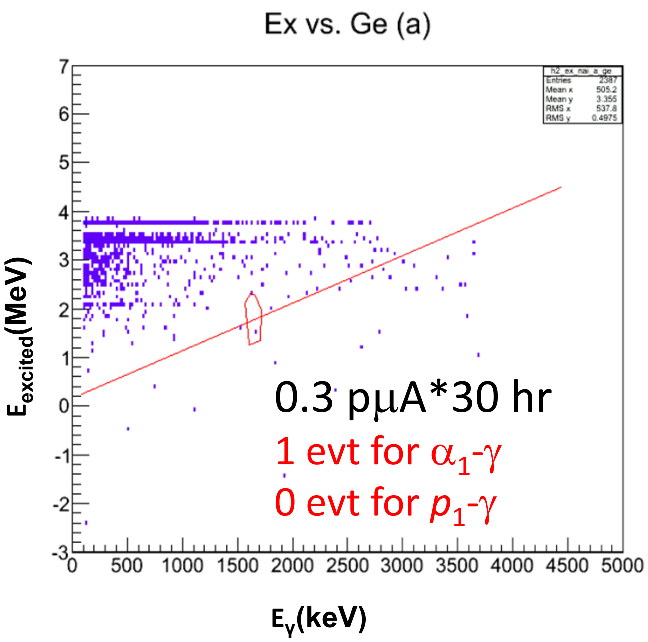
- Important for 23Na, 27Al productions 200 solar mass Pop-III star
- Modest impact to weak S process in 18 solar mass Pop-I star

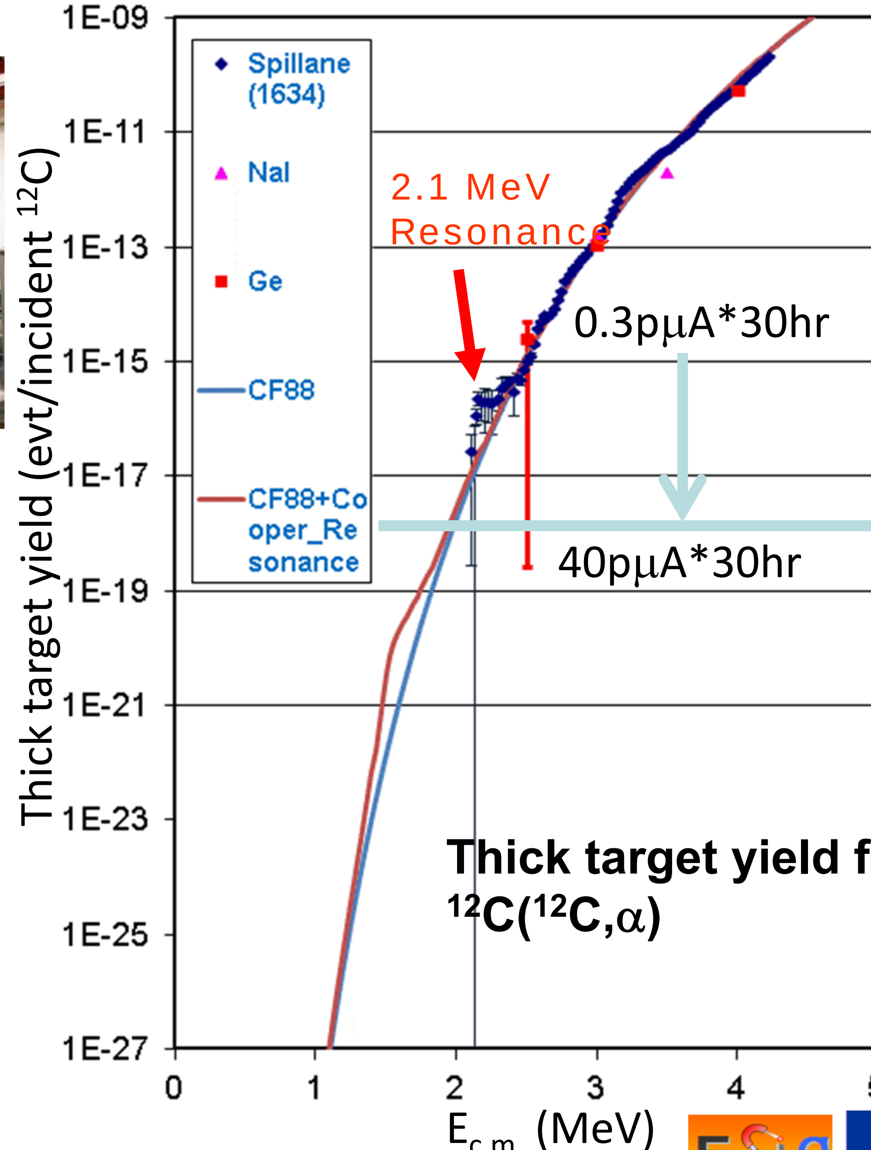
Bucher et al., PRL 114, 251102 (2015)

New method to measure 12C+12C at stellar energies

Carbon Fusion Project

Approach with particle-gamma coincidence

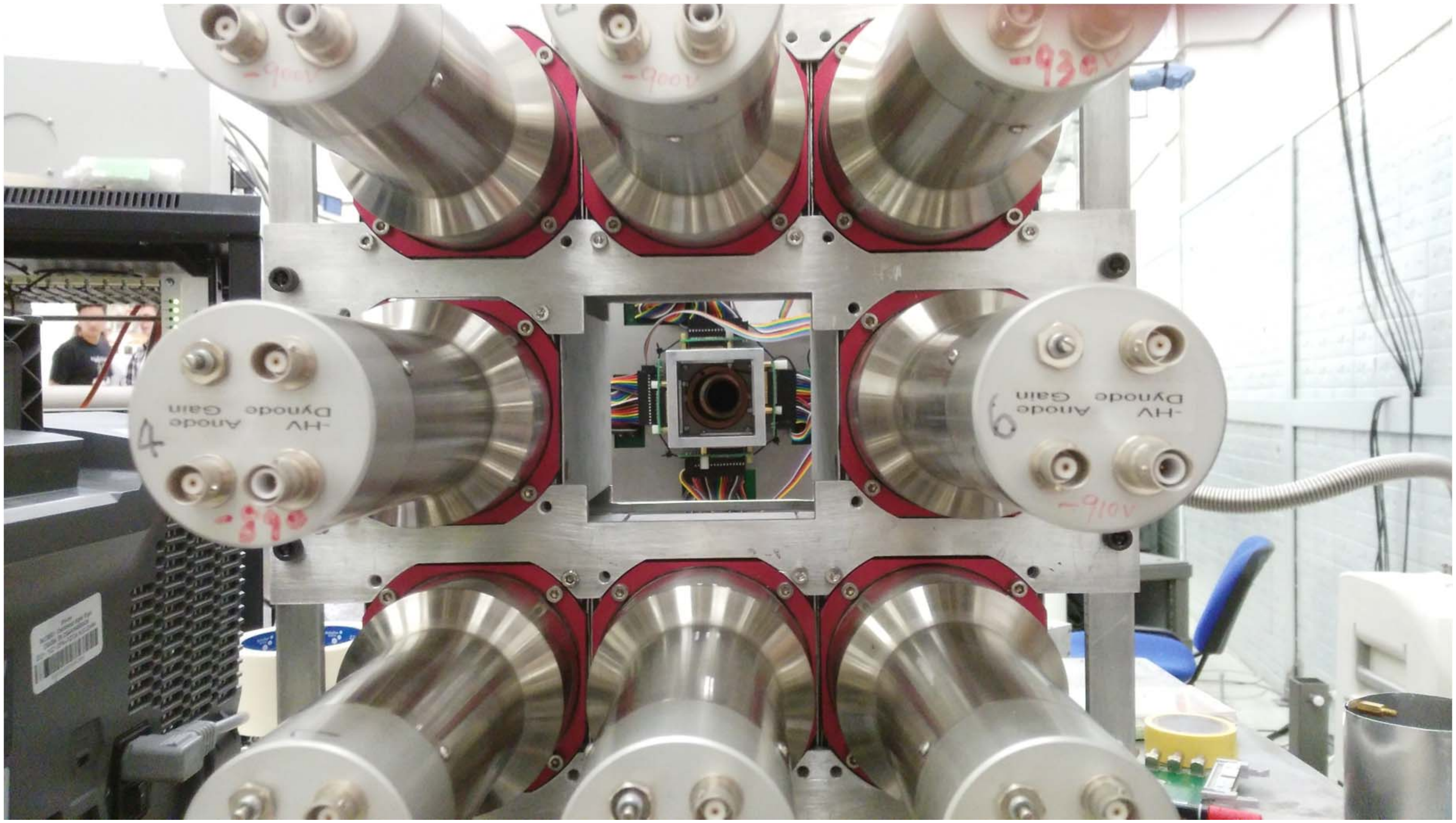




Using ASIC readout system provided by UW

Proposed by Jiang et al., NIMA (2012)

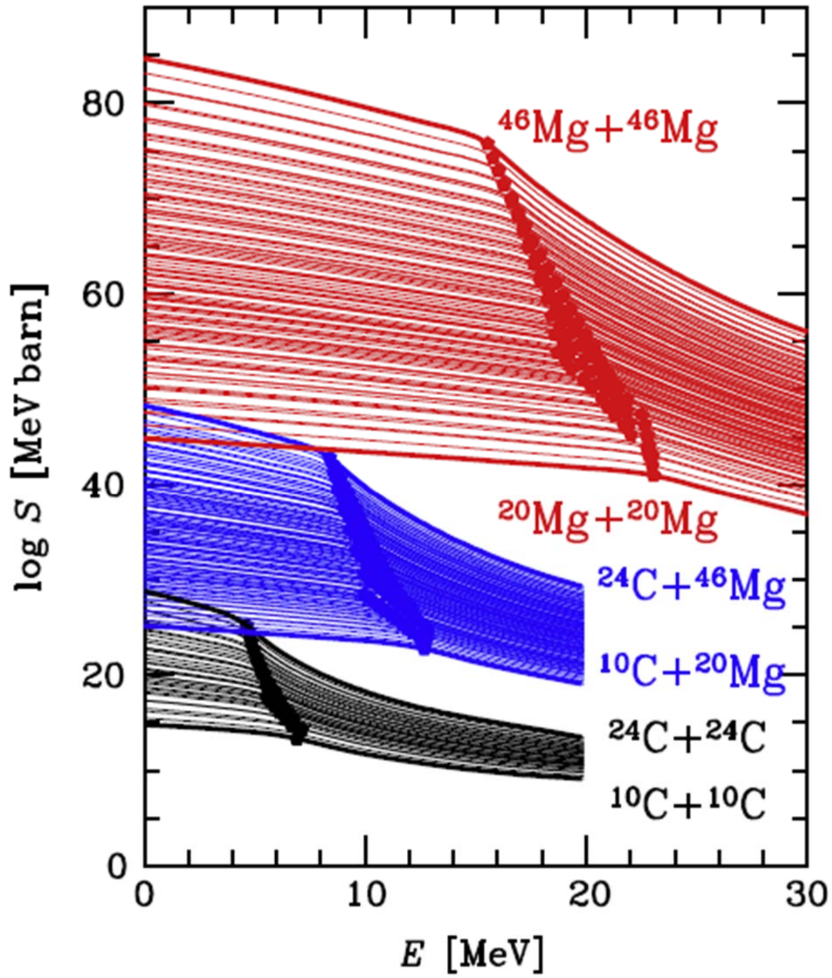
Measurement of $^{12}C+^{12}C$



Silicon+NaI array (IMP and IFIN-HH collaboration)

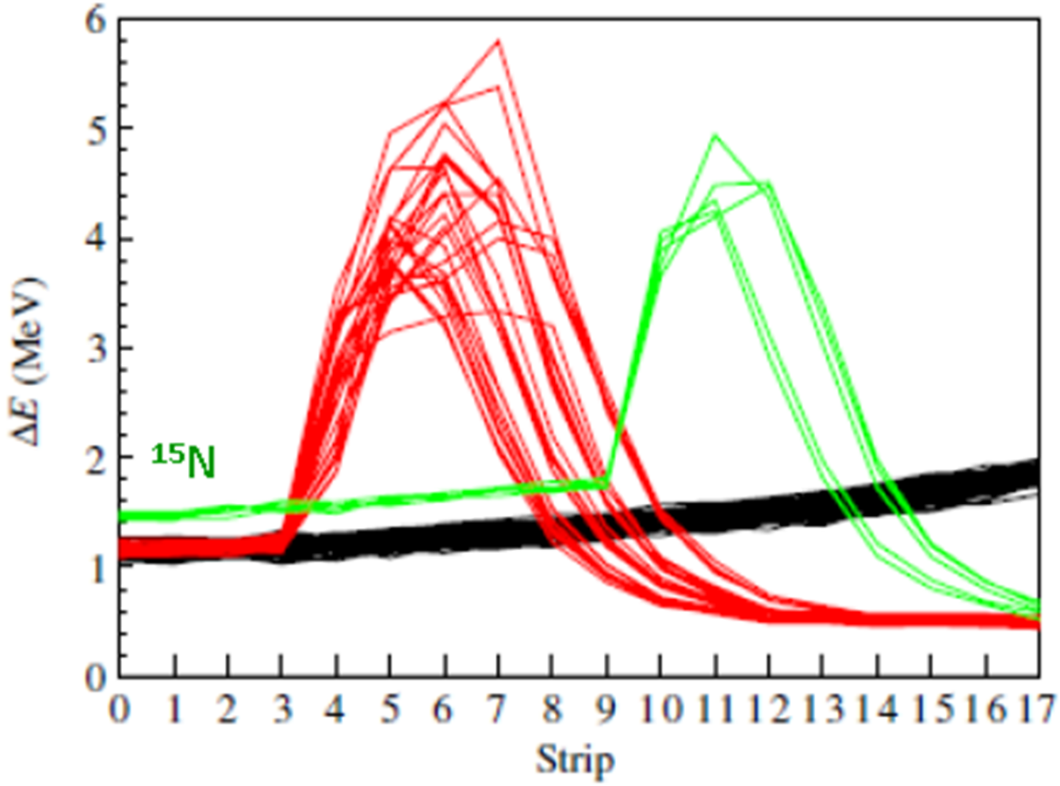
Fusion reactions of n-rich nuclei

H.I. Fusion in crust



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

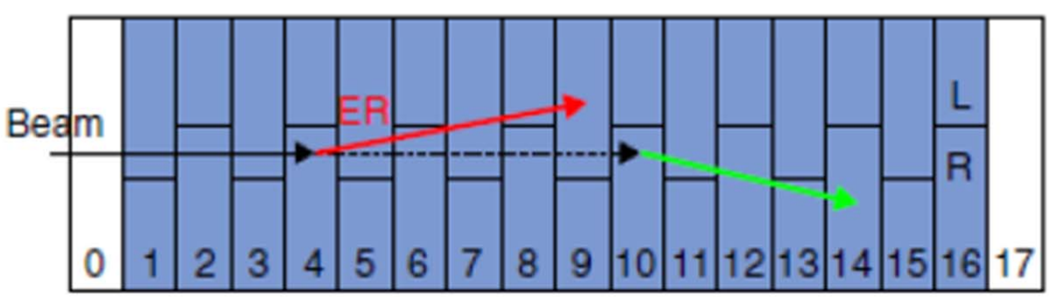
Fusion $^{15}C + ^{12}C$ (CH_4)

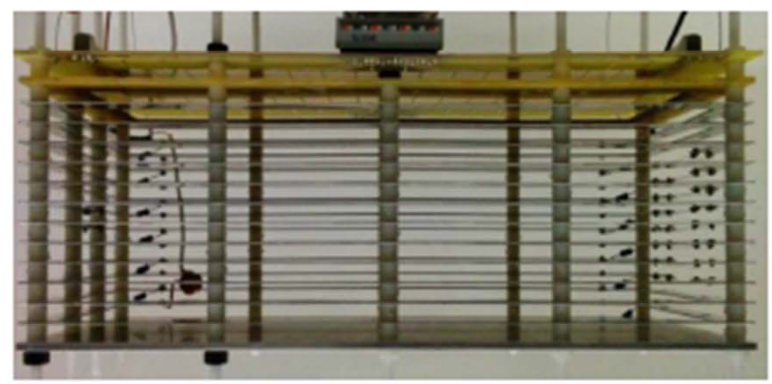


Black: beam of ^{15}C

Red: Fusion between ^{15}C and ^{12}C

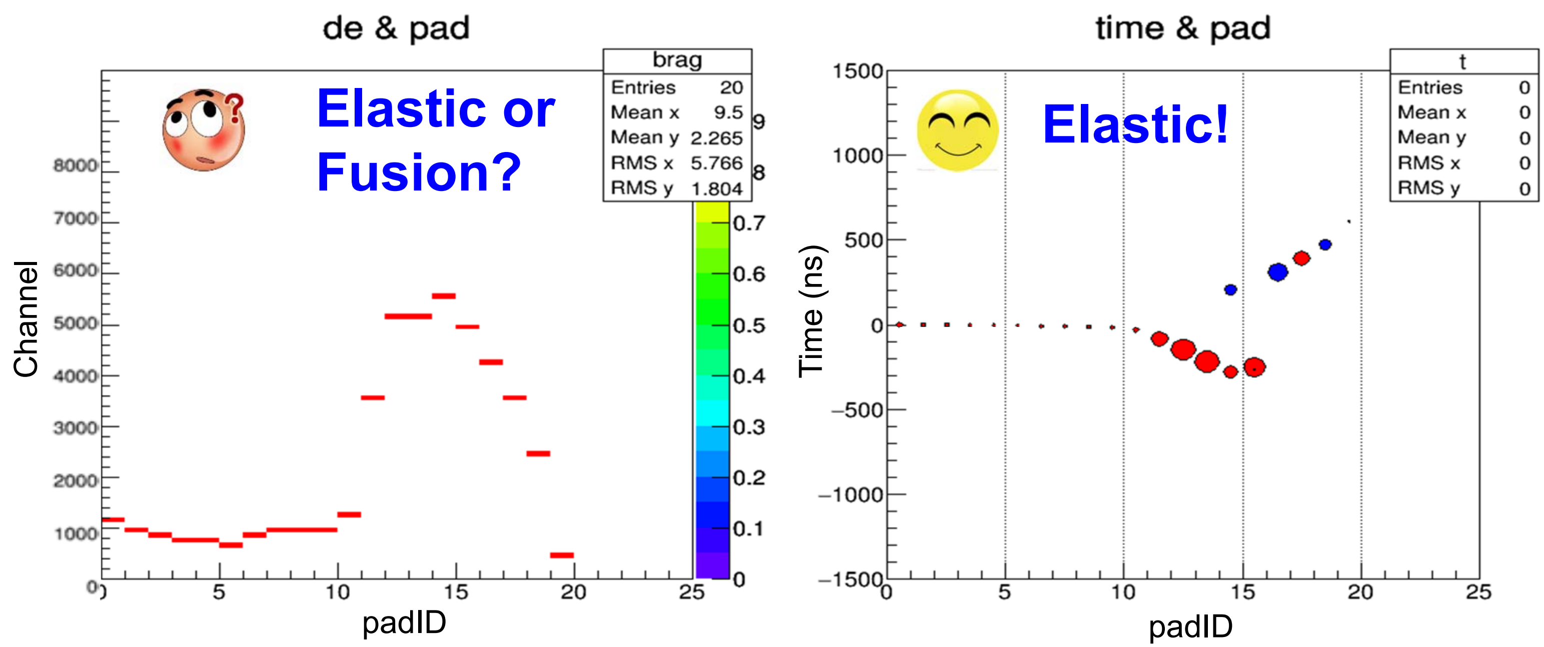
Green: fusion between ^{15}N and ^{12}C





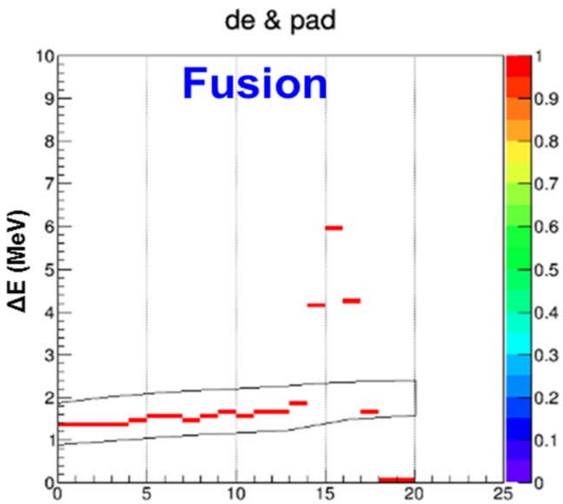
 Rehm (ANL)

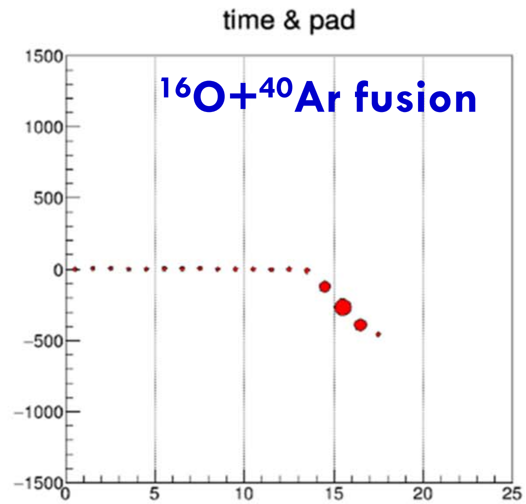
Limitation of MUSIC

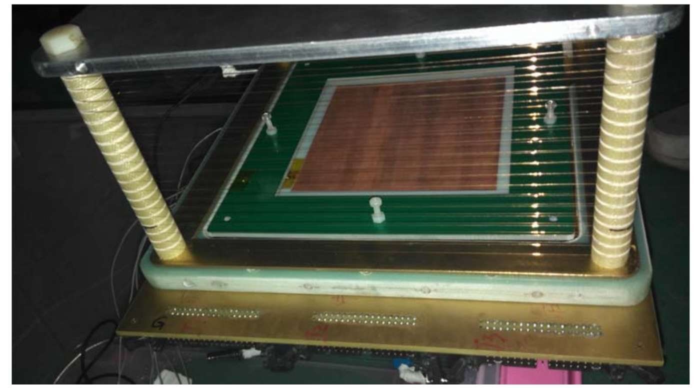


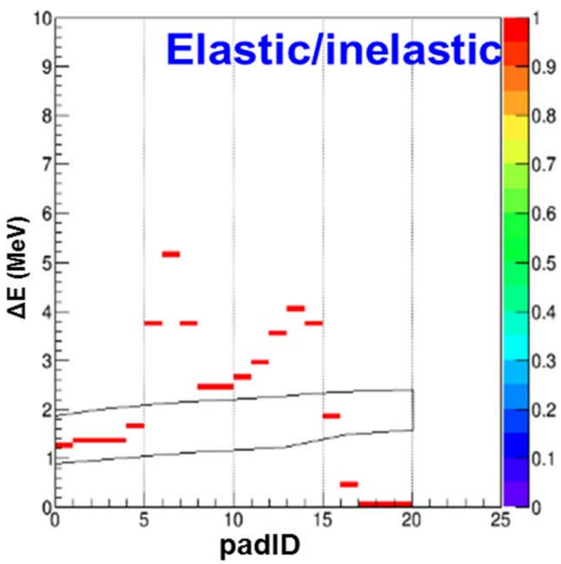
With drift time, the fusion cross section of $^{13}C+^{12}C$ could be pushed down to 6 MeV. About 17% systematic error is due to misjudge of elastic scattering.

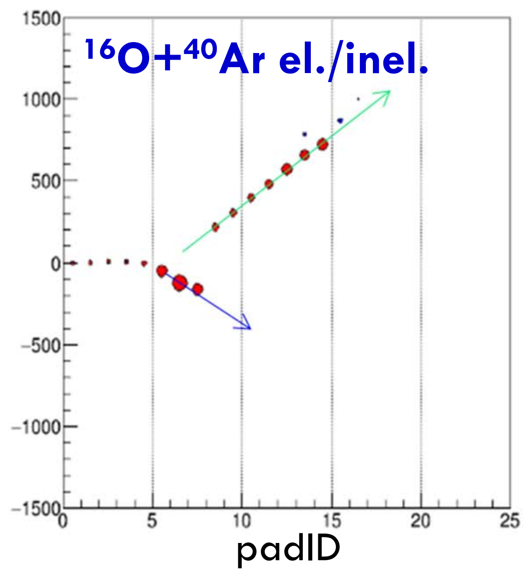
EXPLOSIVE BURNING (fusion with n-rich beam)

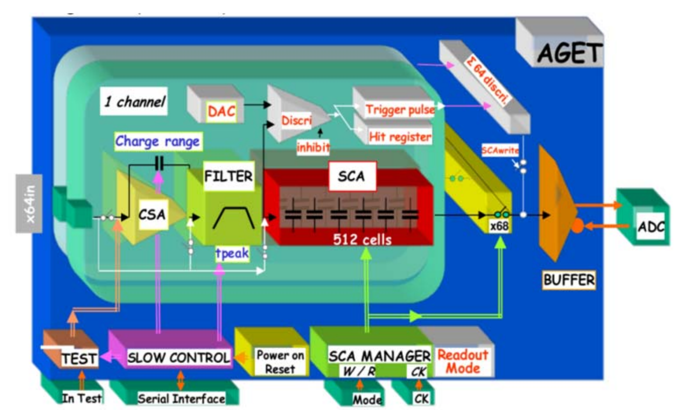






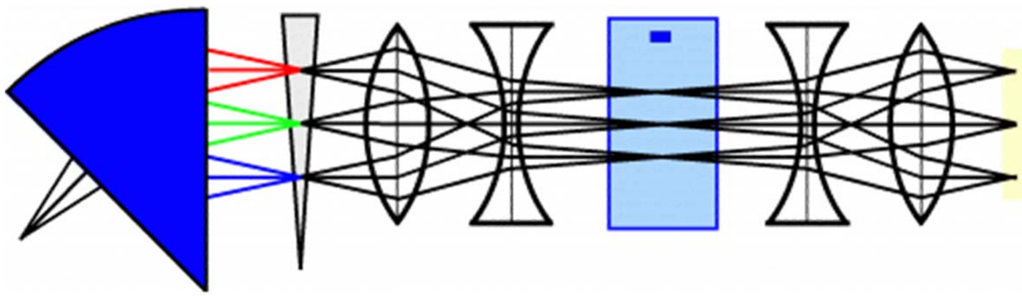




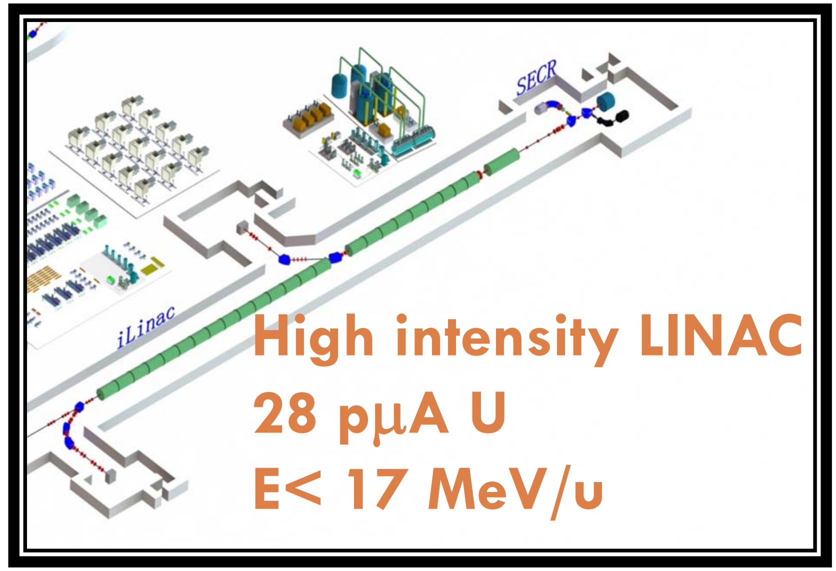


- The first TPC experiment at HIFRL
- Fusion inside of neutron star crust: ^{24}O+^{24}O

Low energy n-rich beam facilities



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



KOBRA at RAON (2021)

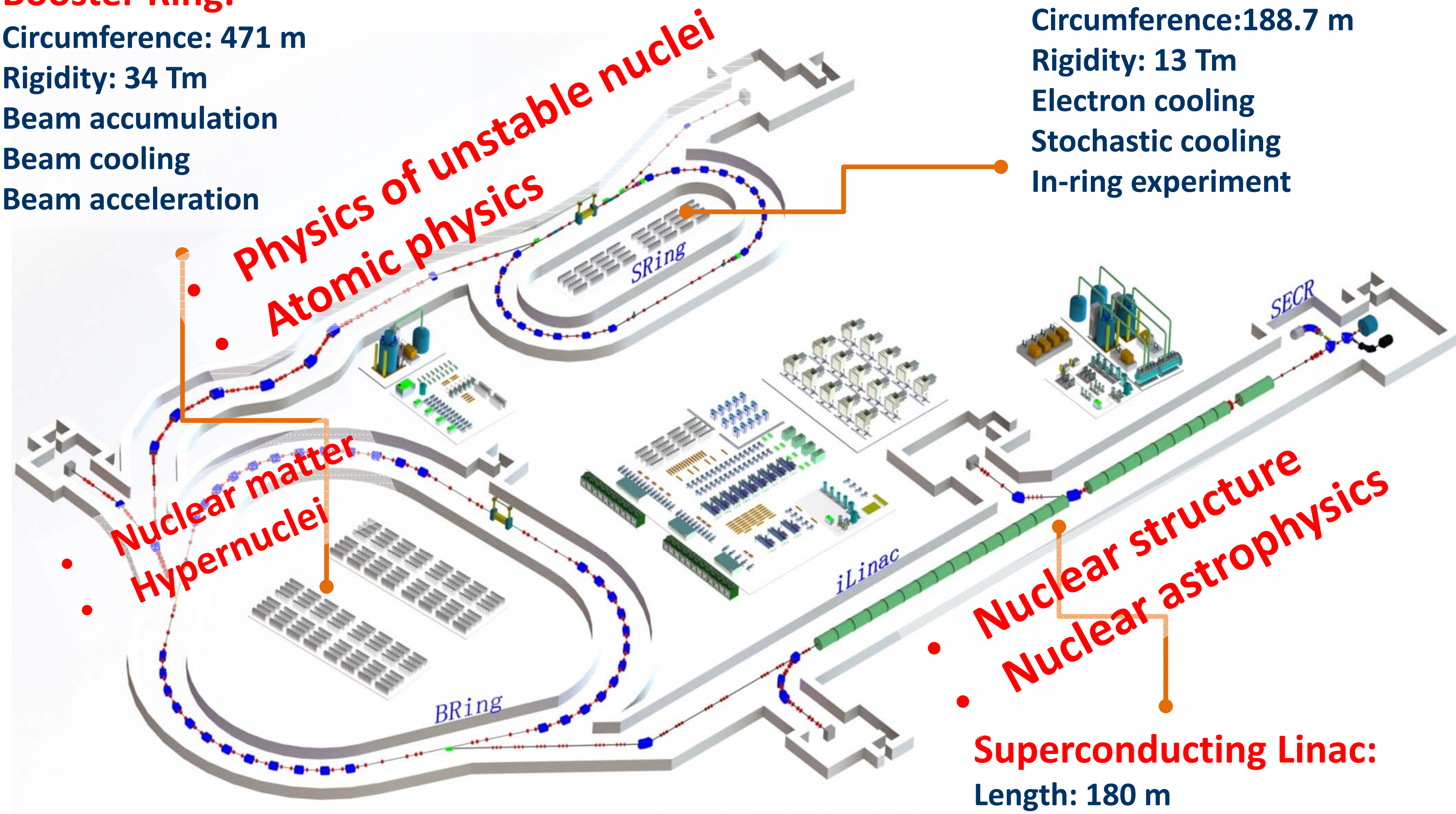
TSR at HIAF (2022)

High Intensity heavy ion Accelerator Facility (HIAF)

The approved budget is 1.5 billion CNY for machine construction

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

Courtesy of X.H. Zhou

Summary

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

→Hindrance model based on systematics does not work

→Upper and lower limits are proposed

→New techniques needed

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