Status and Vision on the study of $^{12}C+^{12}C$ fusion

From the nuclear physics point of view

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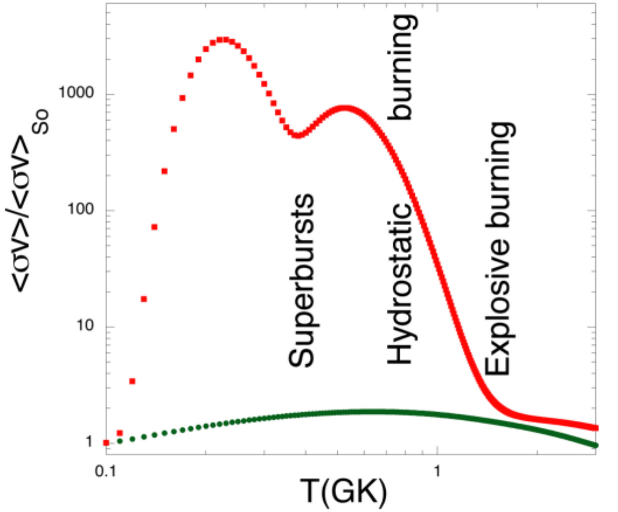
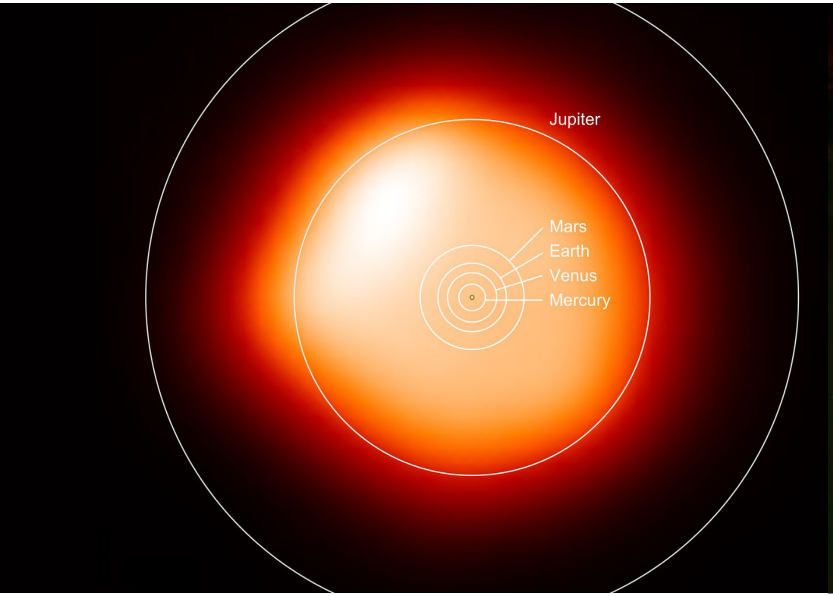
The astrophysics purpose
The history of fusion studies
The questions in extrapolation
Experimental techniques
Experimental results
Interpretation and uncertainties
Future efforts!

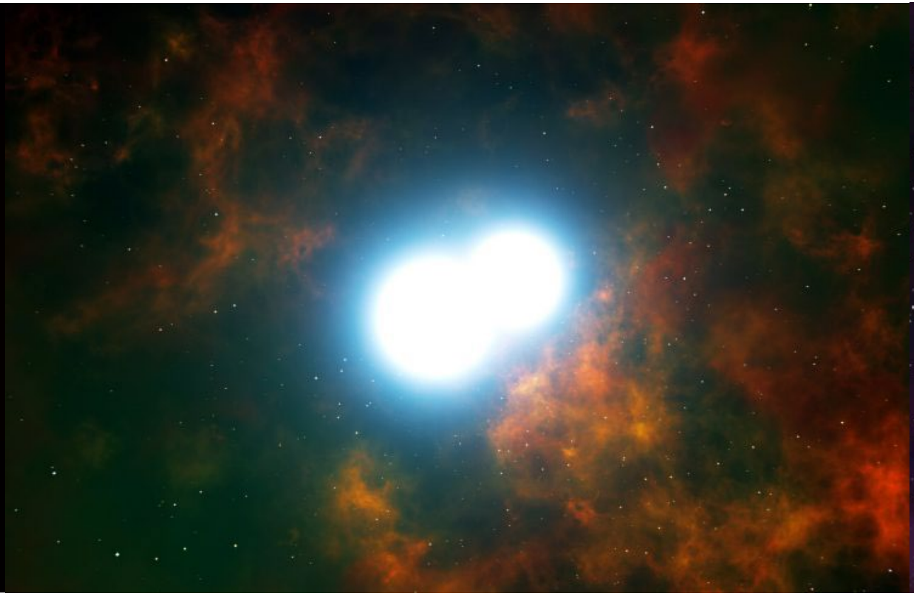
The stellar sites for ^{12}C+^{12}C fusion



In the temperature range 0.4 to 2.0 GK



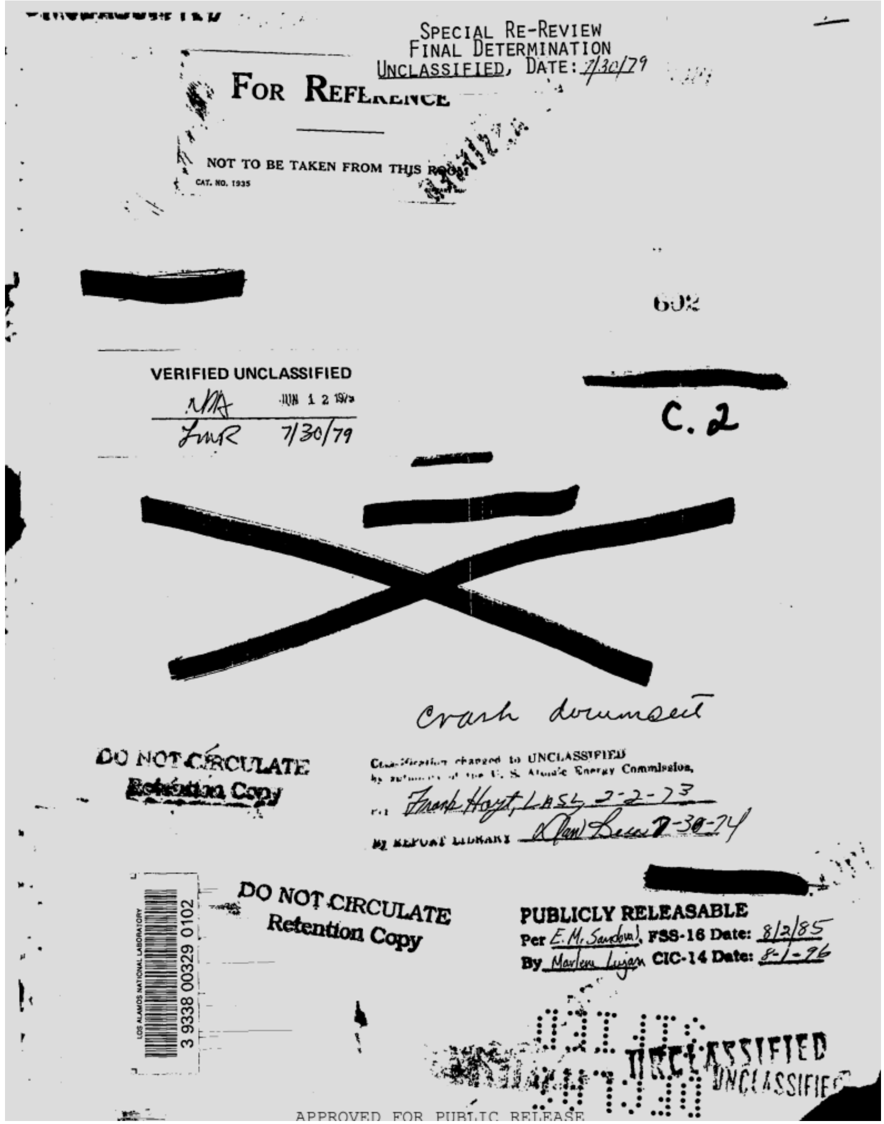
Betelgeuse at the on-set of carbon burning



Type Ia supernova as accreting or merging white dwarfs

Superbursts by carbon ignition in the upper crust of accreting neutron stars

History of fusion studies – fearing the ignition of the atmosphere via $^{14}N+^{14}N$ at fission bomb temperatures



SPECIAL RE-REVIEW
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By Marlene Lujan CIC-14 Date: 8-1-96

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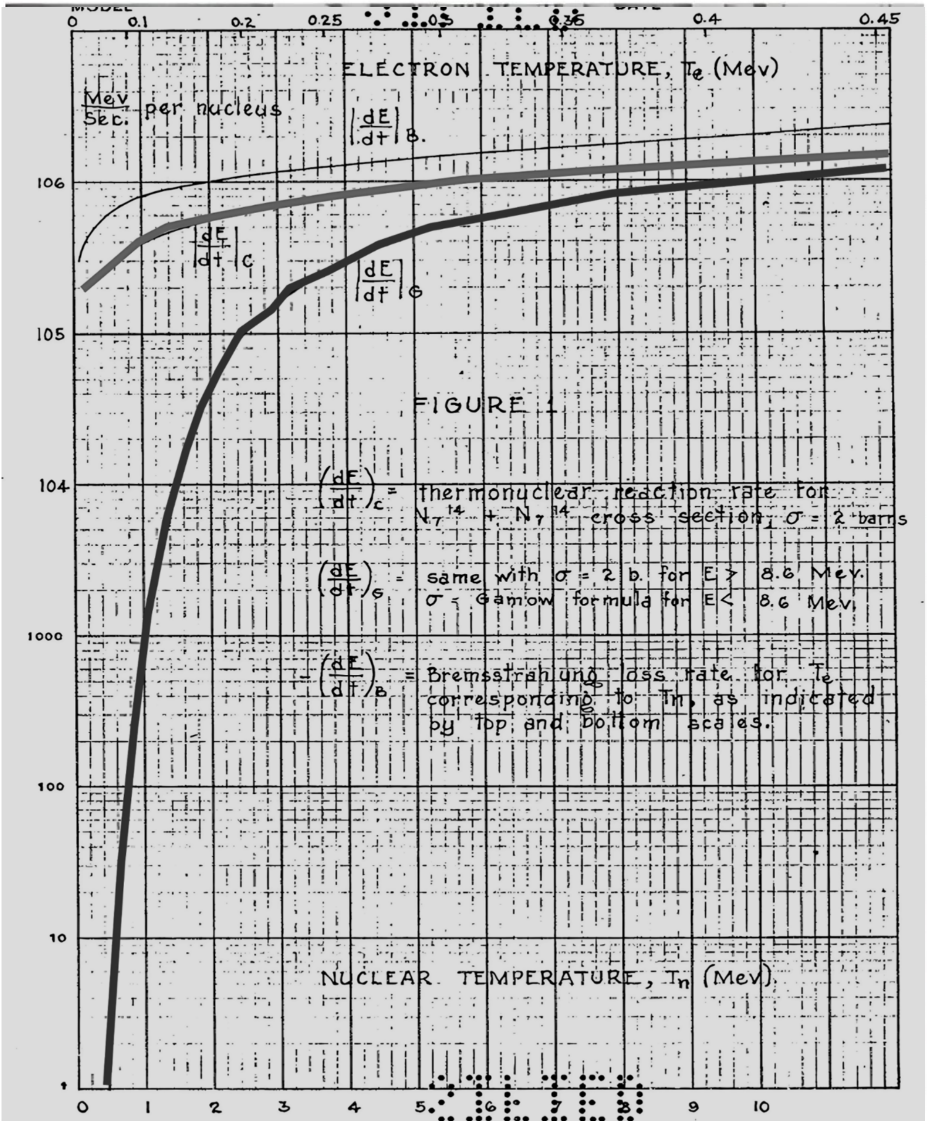
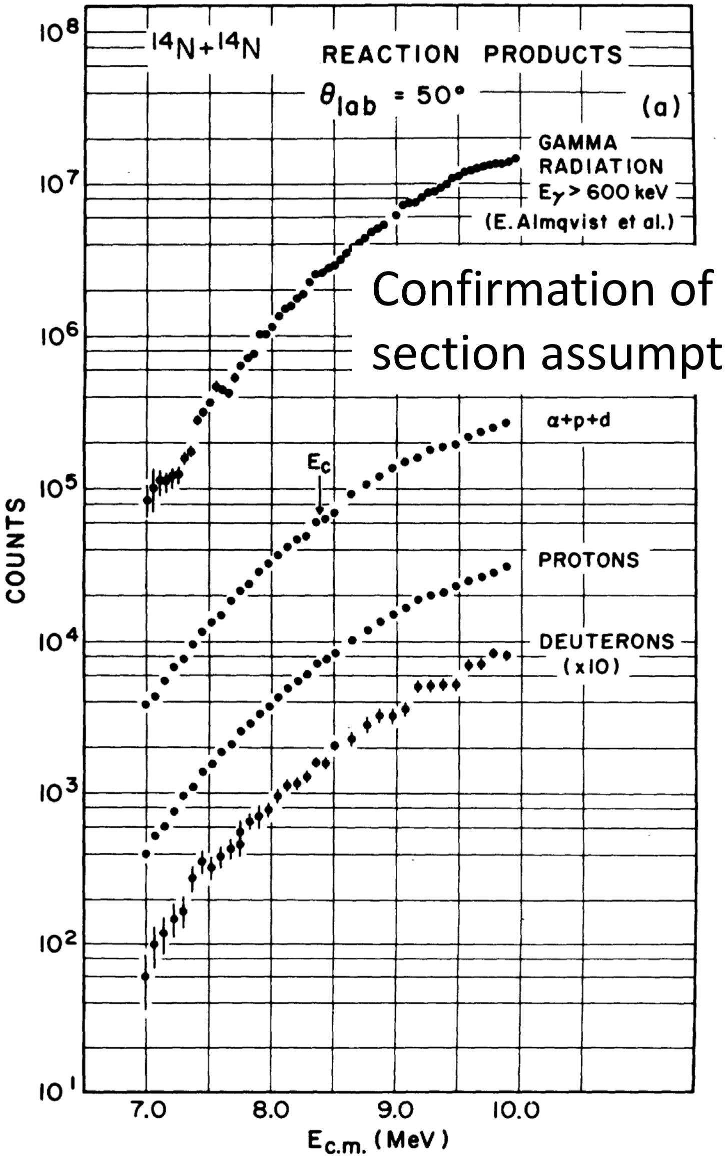


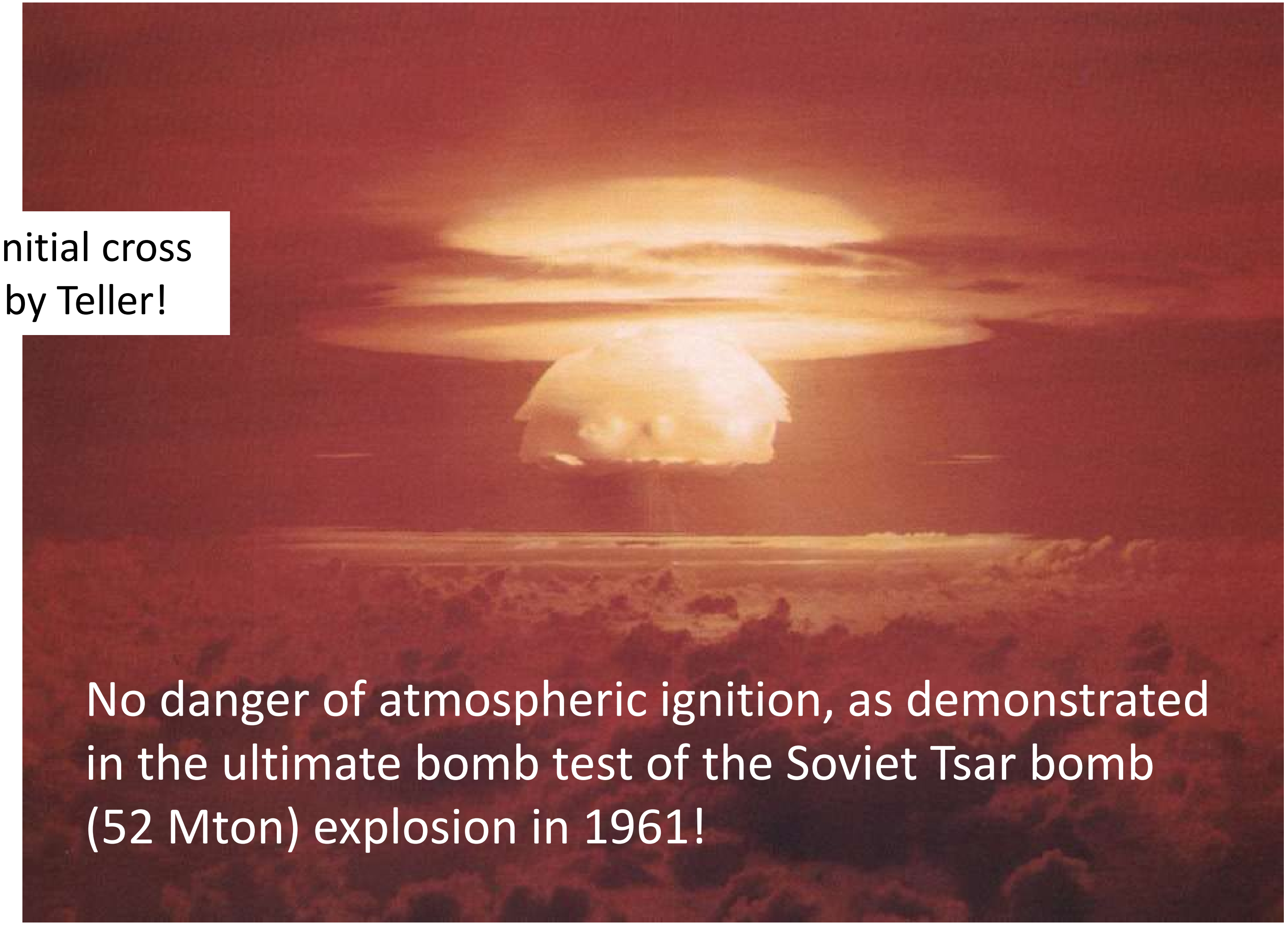
The disquieting feature is that the ‘safety factor’, i.e. the ratio of losses to gains of energy, decreases rapidly with initial temperature, and descends to a value of only about 1.6 beyond a 10-MeV temperature. It is impossible to reach such temperature unless fission bombs or thermonuclear bombs are used which greatly exceed the bombs now under consideration.

New 86” Cyclotron was installed in 1952 at Oak Ridge to measure heavy ion fusion $^{14}N+^{14}N$, $^{16}O+^{16}O$ etc. This was followed 10 years later by the installation of the 88” cyclotron in Berkeley

No Atmospheric Fires, but new Astrophysics

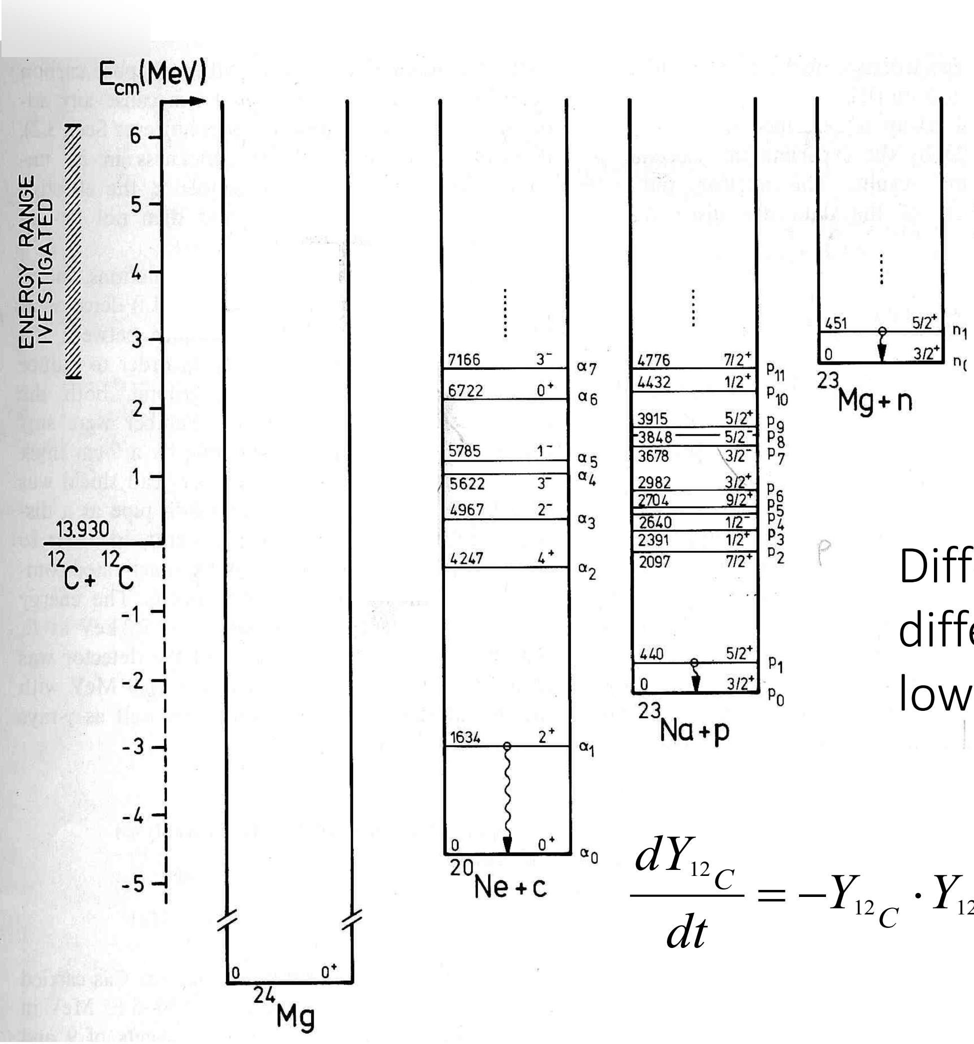


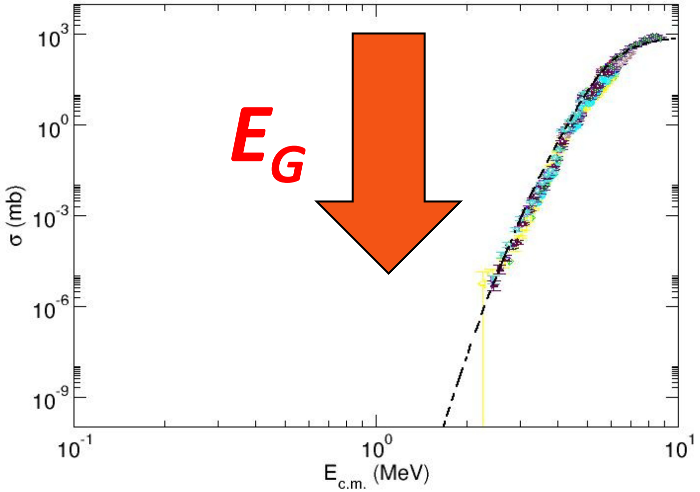
Confirmation of the initial cross section assumptions by Teller!



No danger of atmospheric ignition, as demonstrated in the ultimate bomb test of the Soviet Tsar bomb (52 Mton) explosion in 1961!

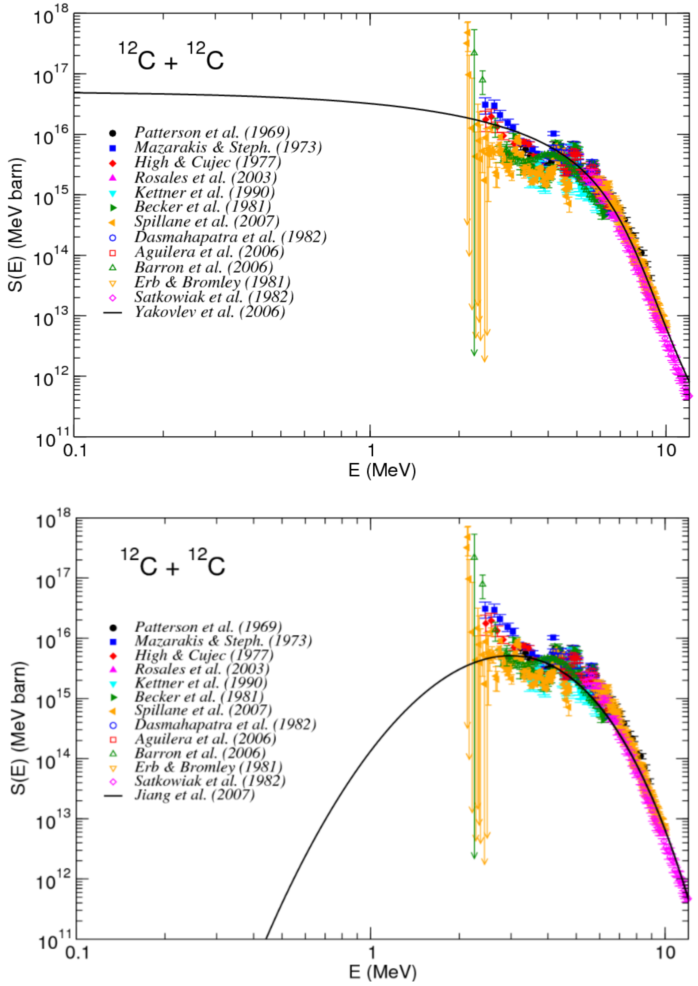
$^{12}C+^{12}C$ fusion reaction





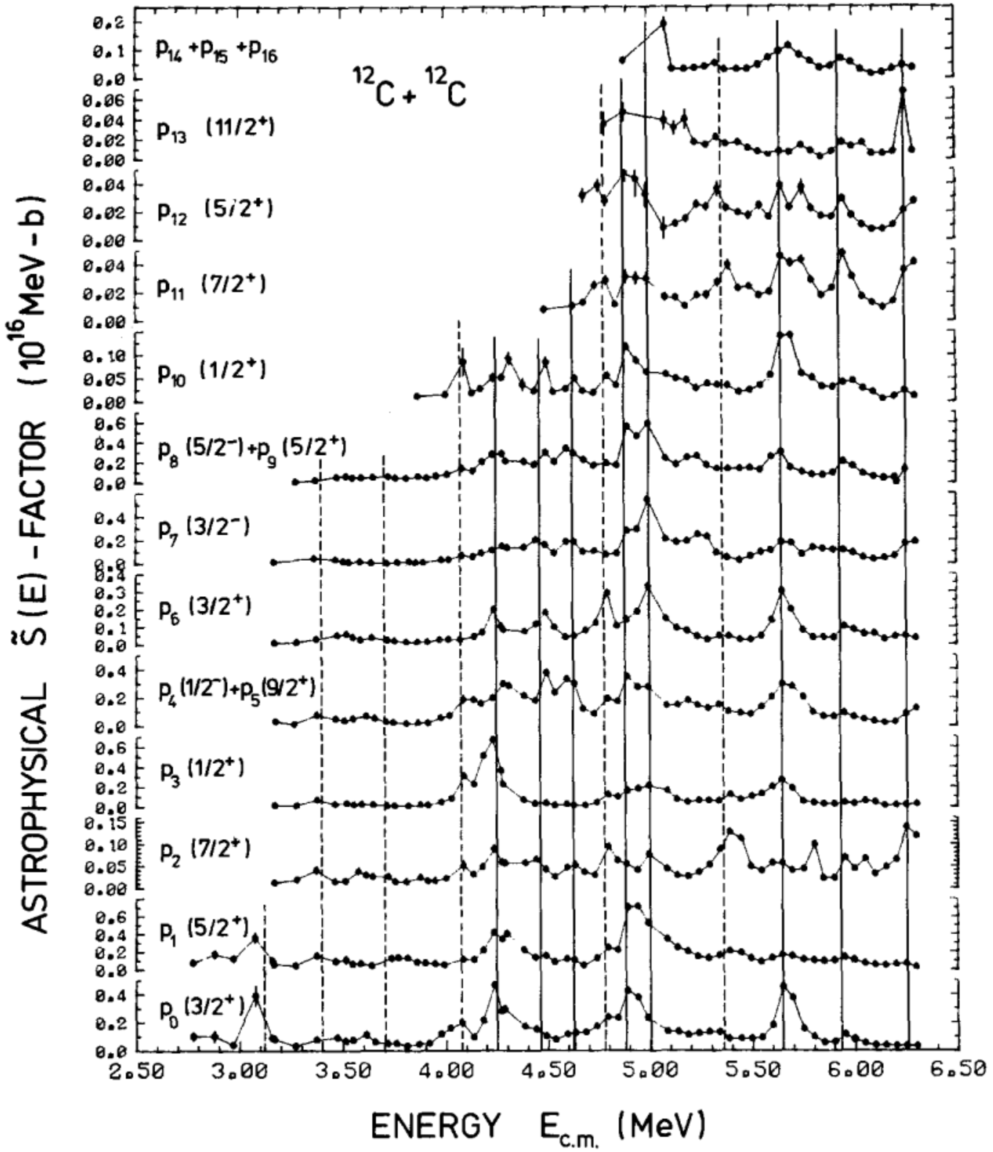
Different potential models lead to different ways to extrapolate the low energy cross section (S-factor).

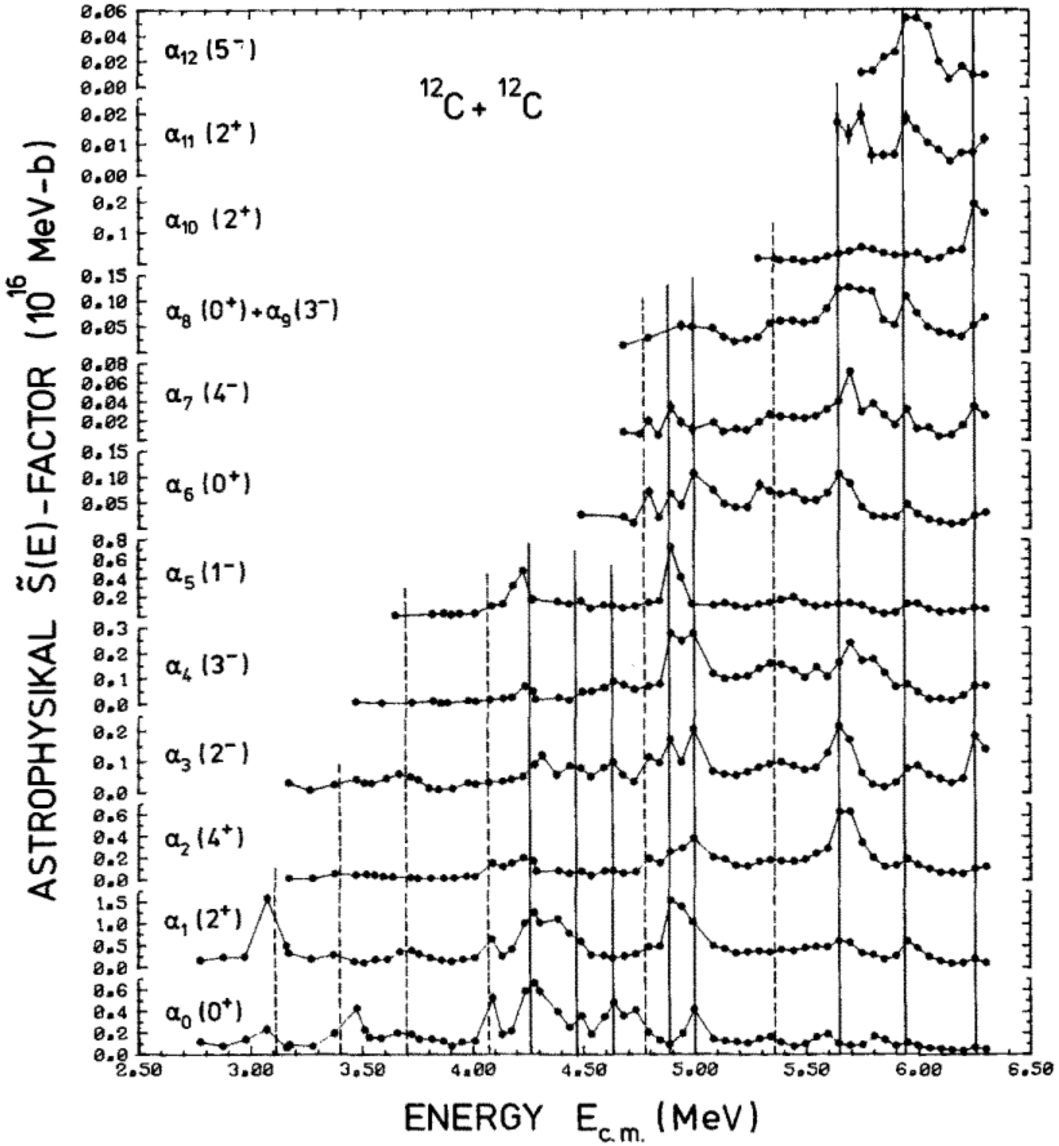
$$\frac{dY_{^{12}C}}{dt} = -Y_{^{12}C}\cdot Y_{^{12}C}\cdot\rho\cdot\left(\begin{array}{l} N_A\langle\sigma\upsilon\rangle_{^{12}C(^{12}C,\alpha)^{20}Ne} \\ +N_A\langle\sigma\upsilon\rangle_{^{12}C(^{12}C,p)^{23}Na} \\ +N_A\langle\sigma\upsilon\rangle_{^{12}C(^{12}C,n)^{23}Mg}\end{array}\right)$$



- 🟥 standard potential model
- 🟥 hindrance potential model

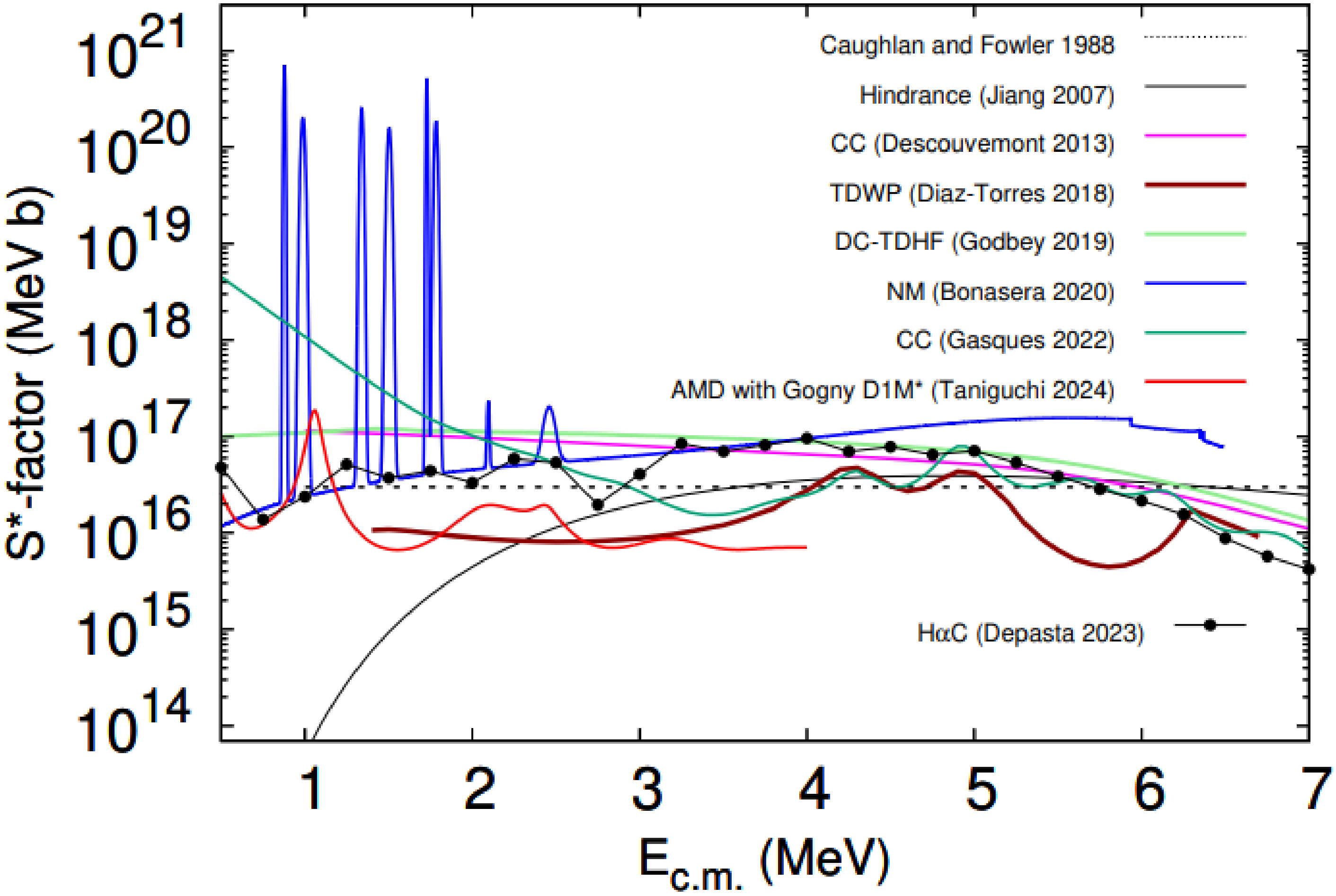
The branchings, determining ^{20}Ne/^{23}Na





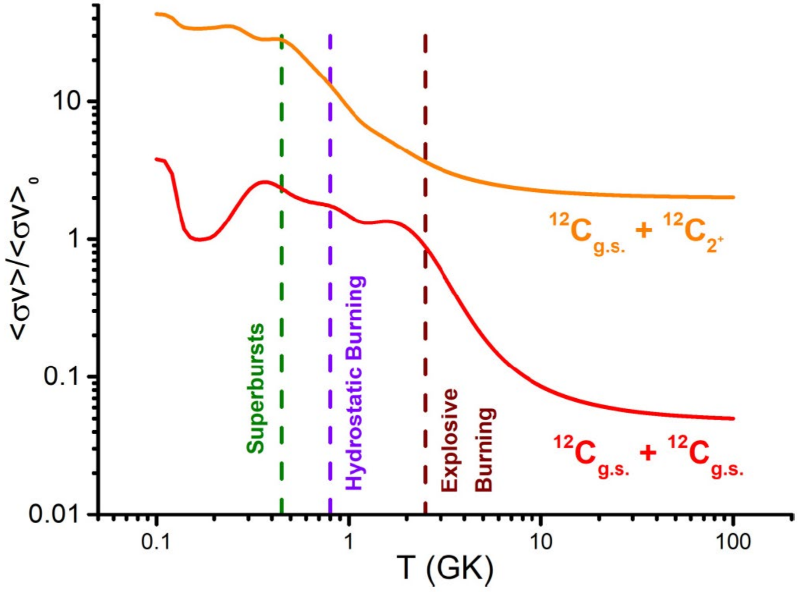
Becker et al. 1981

Theory predictions for the total S-factor



$$S^*(E_{\mathrm{C.M.}}) = E_{\mathrm{C.M.}}\sigma(E_{\mathrm{C.M.}})e^{\xi/\sqrt{E_{\mathrm{C.M.}}}+0.46E_{\mathrm{C.M.}}}$$
$$= S(E_{\mathrm{C.M.}})e^{0.46E_{\mathrm{C.M.}}},$$

$$\xi = Z_aZ_b\pi e^2\sqrt{2\mu}/\hbar = 87.23\ \mathrm{MeV}^{1/2}.$$



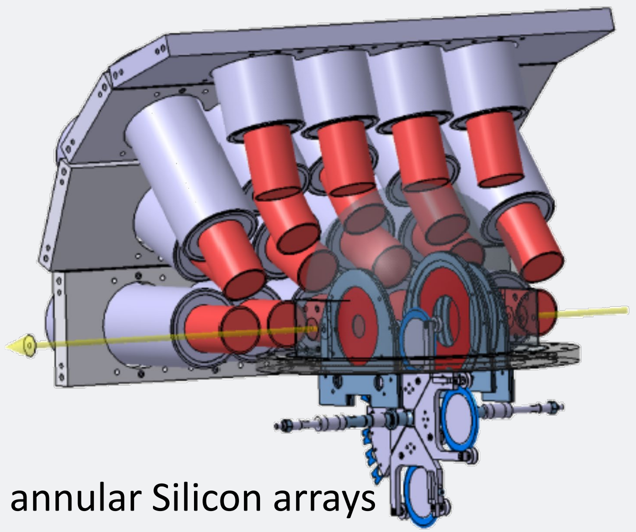
The S(E)-factor determines the fusion rate

$$\langle\sigma v\rangle = \sqrt{\frac{8}{\mu\pi(kT)^3}}\int_0^\infty S(E)e^{-\frac{\xi}{\sqrt{E}}-\frac{E}{kT}}dE.$$

Particle, Gamma, and coincidence studies

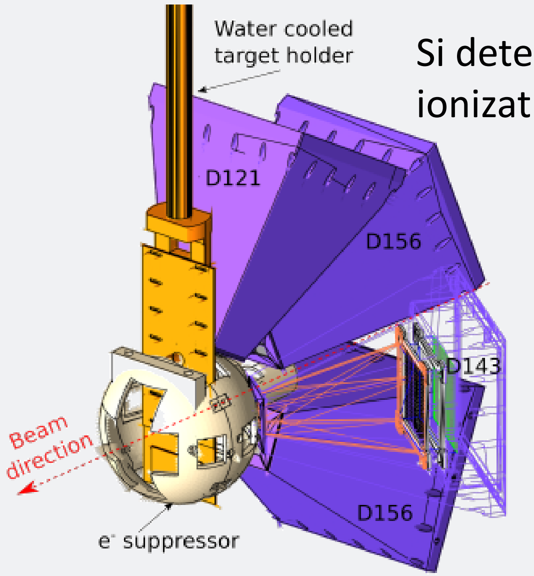
Bochum Experiment by Becker et al. (1981): particle spectroscopy
Catania Experiment by Tumino et al. (2018): indirect THM approach
Caserta Experiment by Zickefoose et al. (2018): gamma spectroscopy
Argonne Experiment by Jiang et al. (2018): particle-gamma coincidence
Strasbourg Experiment by Fruet et al. (2020): particle-gamma coincidence
Caserta Experiment by Morales Gallegos et al (2023): particle spectroscopy
Notre Dame Experiment by Tan et al. (2020, 2024): particle-gamma coincidence

STELLA Array at Strasbourg



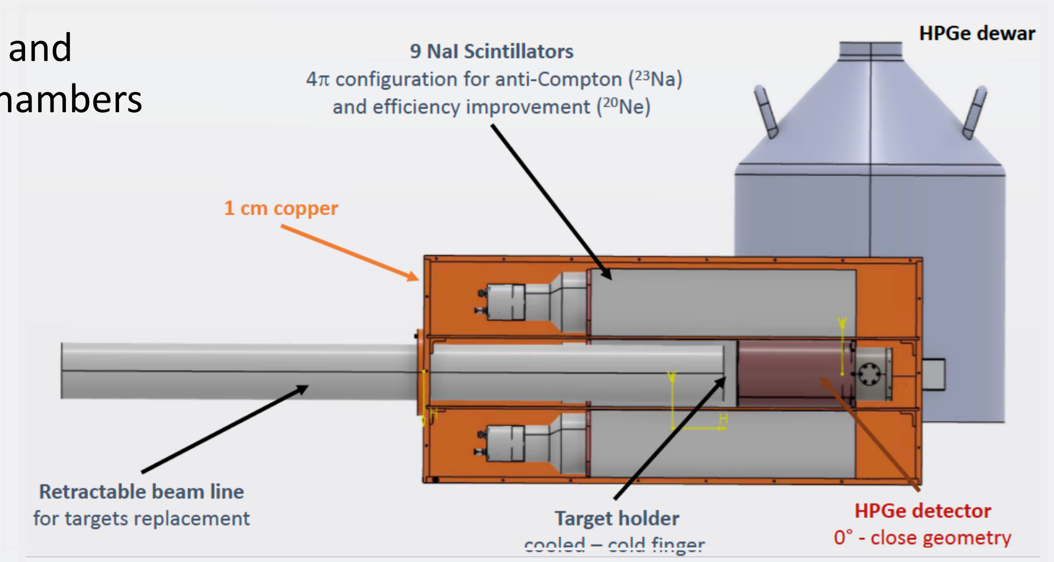
Three annular Silicon arrays with $LaBr_3(Ce)$ gamma detectors surrounding the thin carbon targets

GHASTLY Array at Caserta



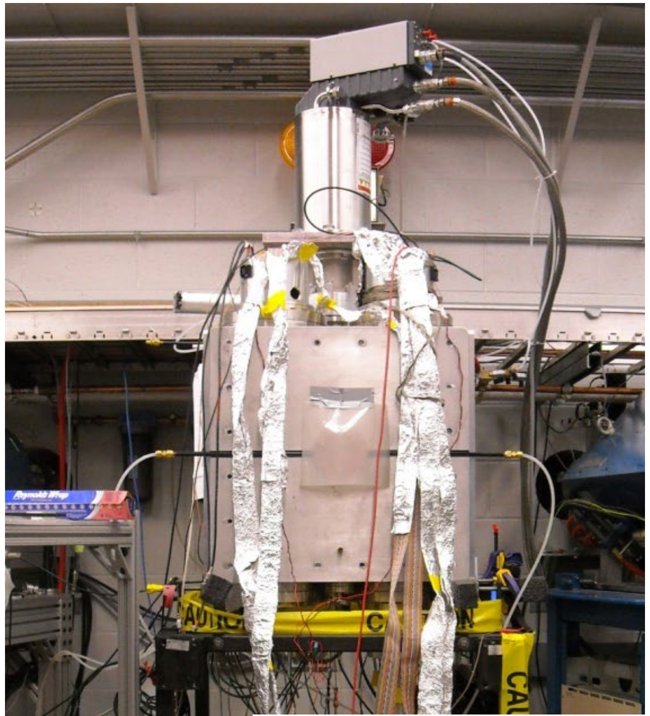
Si detectors and ionization chambers

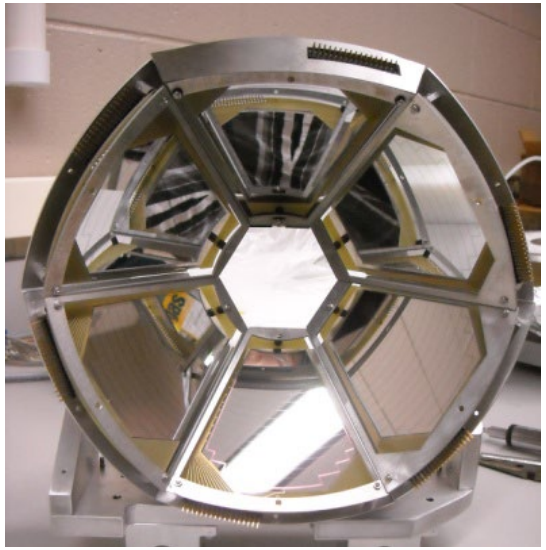
Compton suppressed Ge detectors at LUNA



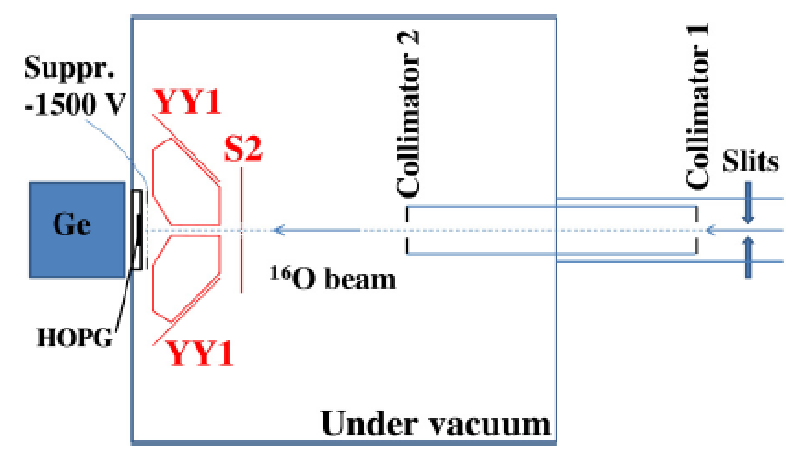
under testing in LNGS

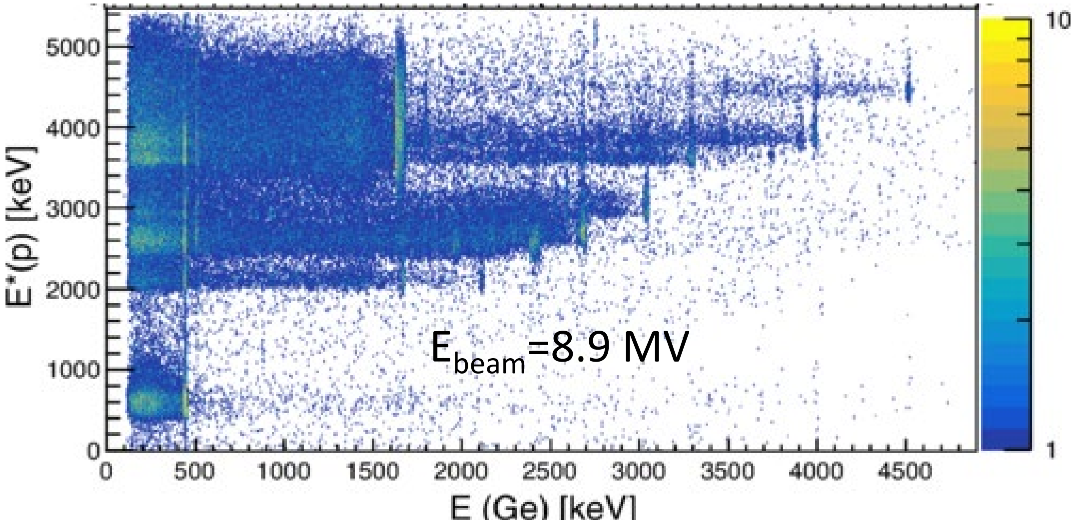
Experimental Status at Notre Dame



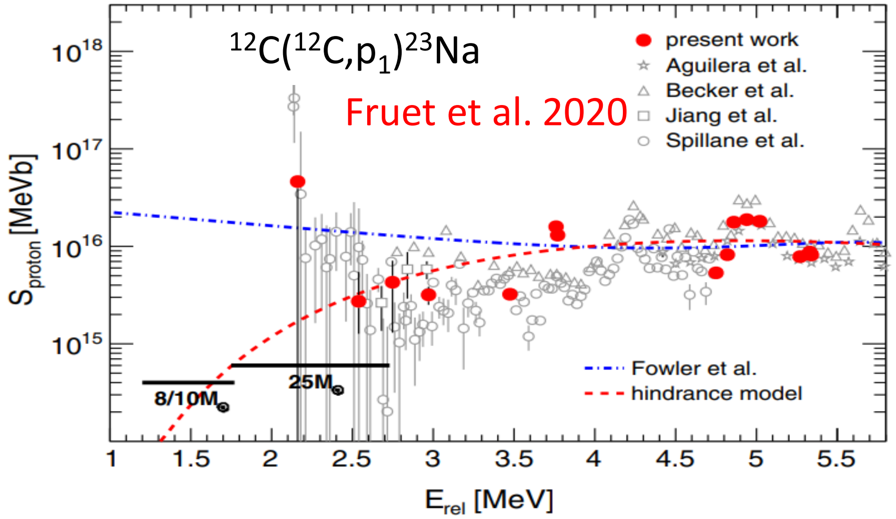


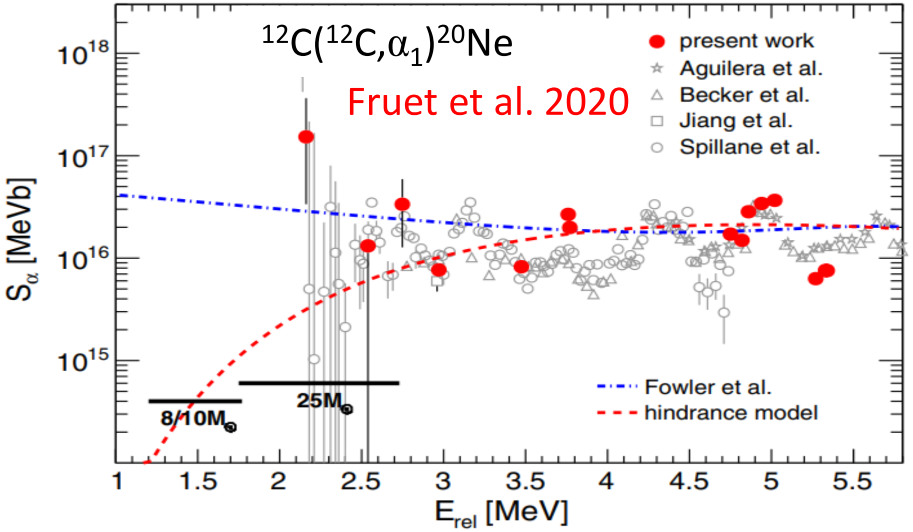
Particle-Gamma coincidence methods have been used for particle identification and background suppression. Experiments and analysis is completed (2024)!

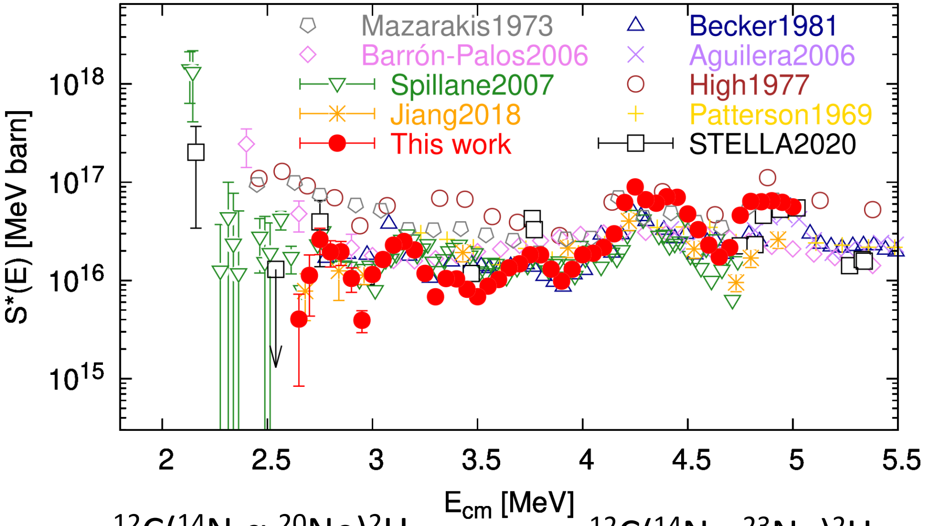




Unknown features – resonances- clusters?



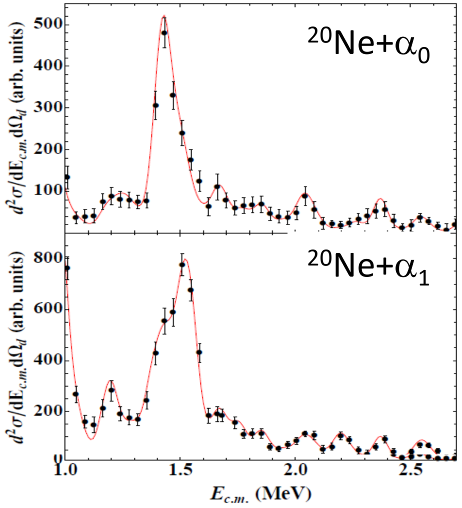




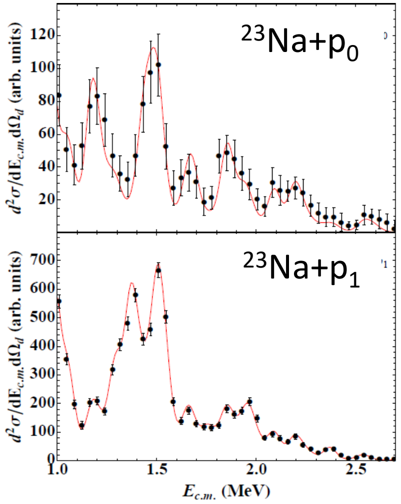
Emergence of resonance structures after correction for energy loss effects

Fruet et al. (2020)
Tan et al. (2020,2024)

$^{12}C(^{14}N,\alpha\ ^{20}Ne)^2H$



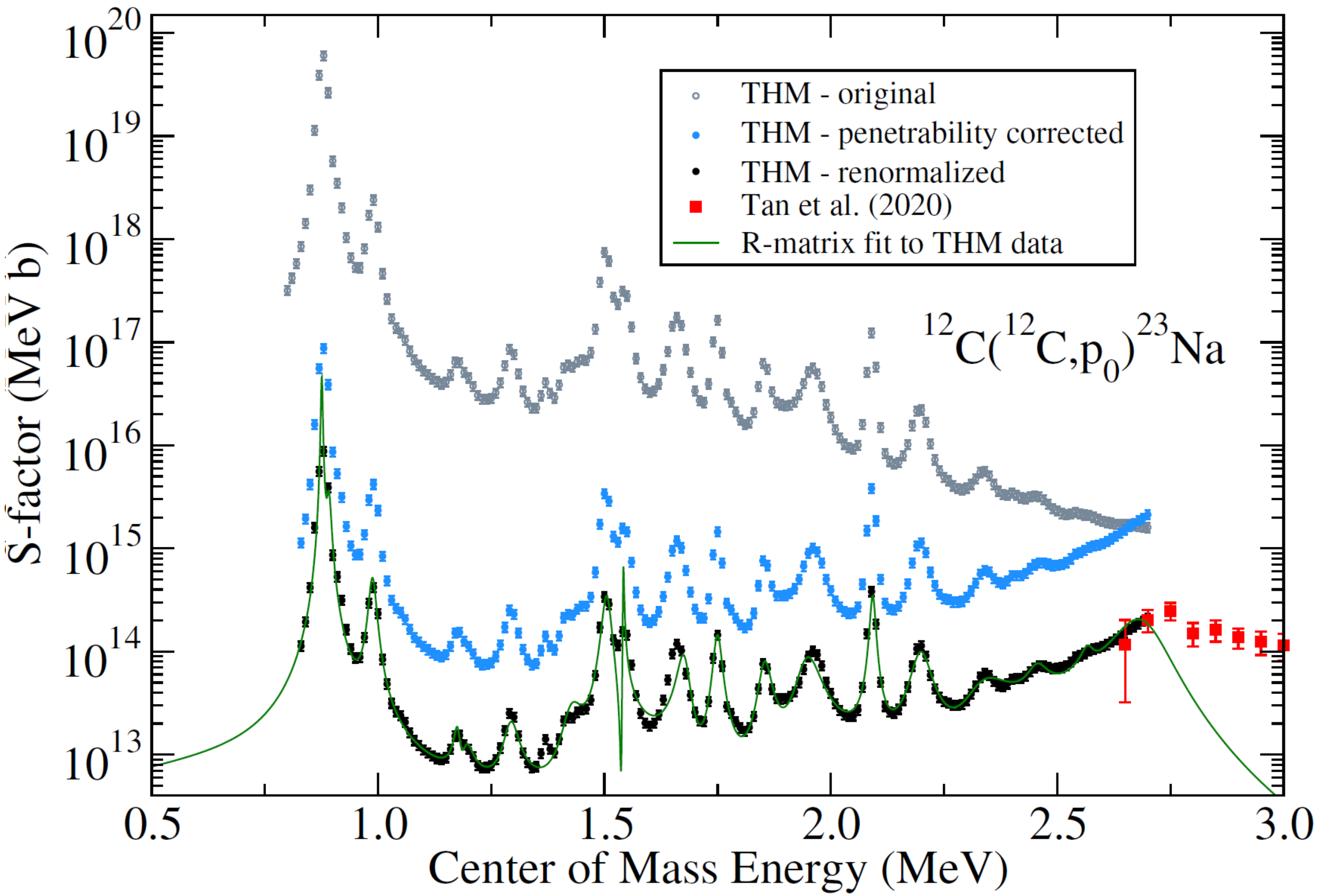
$^{12}C(^{14}N,p^{23}Na)^2H$



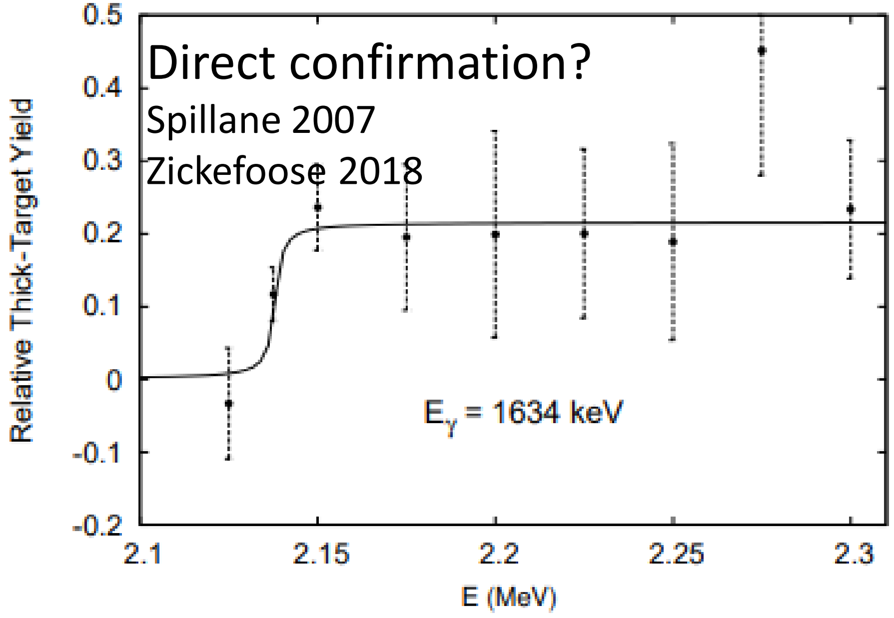
Low energy resonance features around $E_{cm} \approx 1.5$ and 2.1 MeV identified in THM experiment!
Tumino et al. 2018

What are the model dependent uncertainties in converting structure data to reaction data?

Low energy extrapolation – a remaining question!



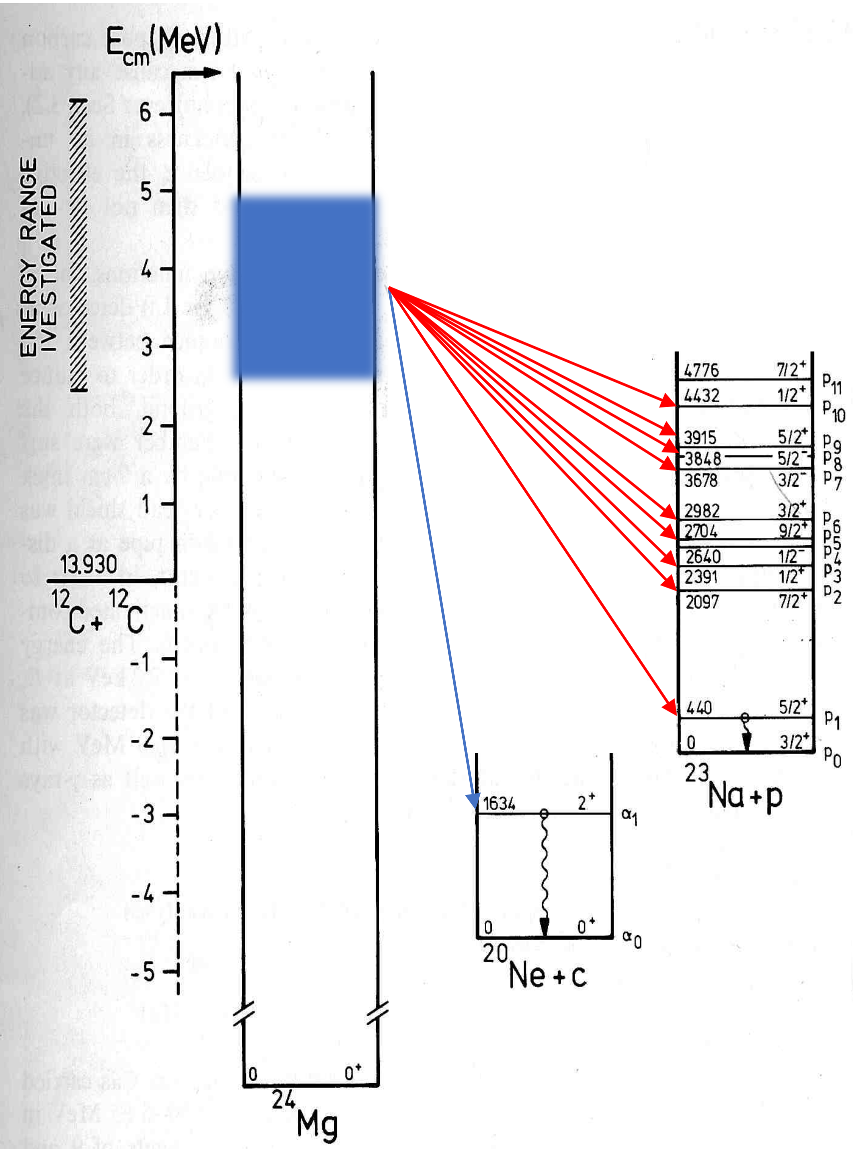
What is the nature of these states? Compound resonances or dynamical coupling of the wave functions. Will it impact the ignition of type Ia supernovae and superbursts in accreting neutron stars?

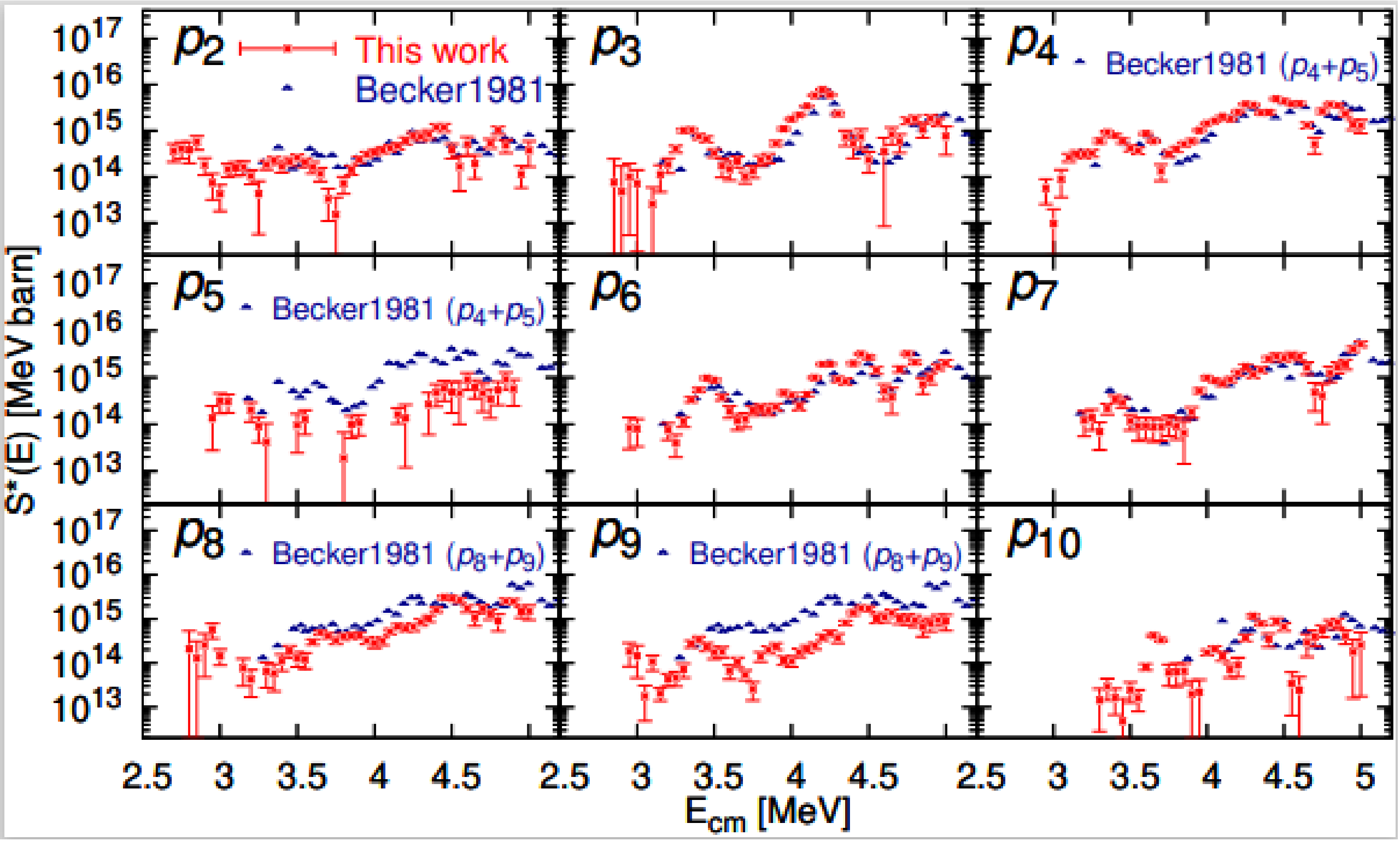

Direct confirmation?

Spillane 2007

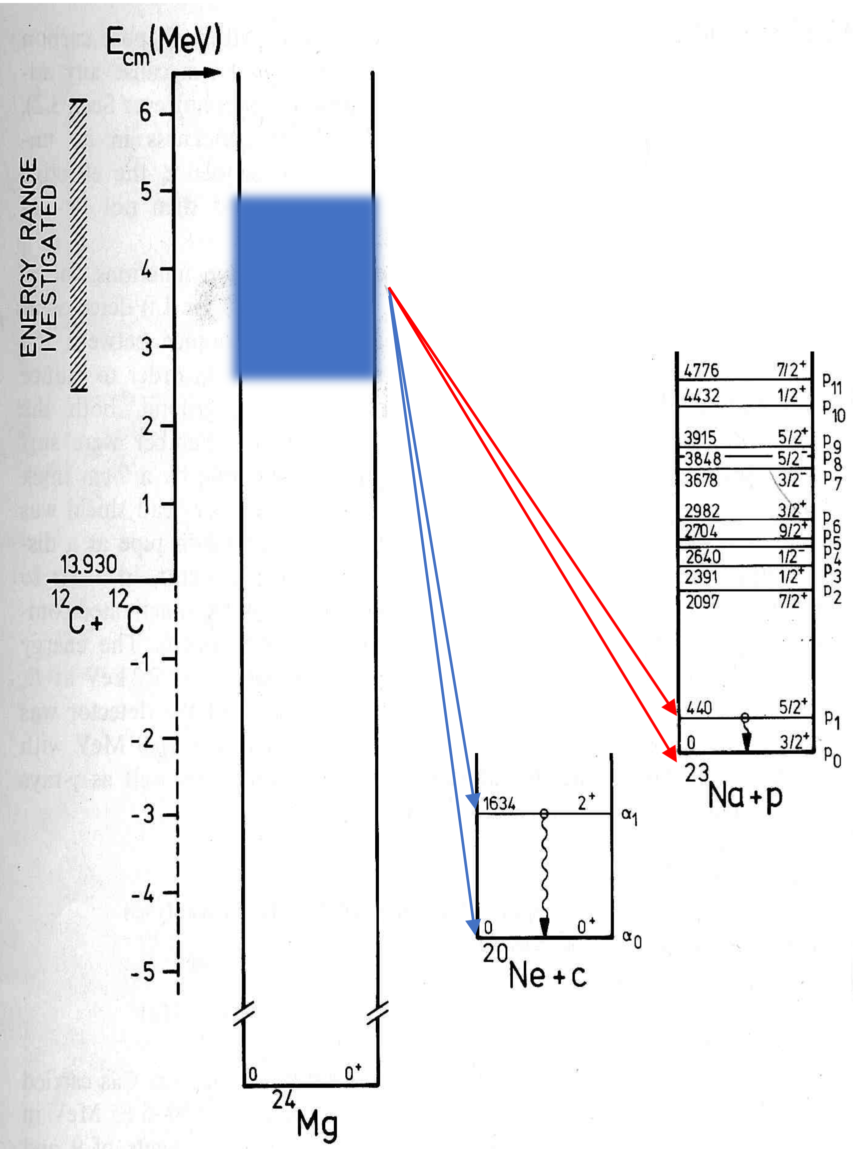
Zickefoose 2018

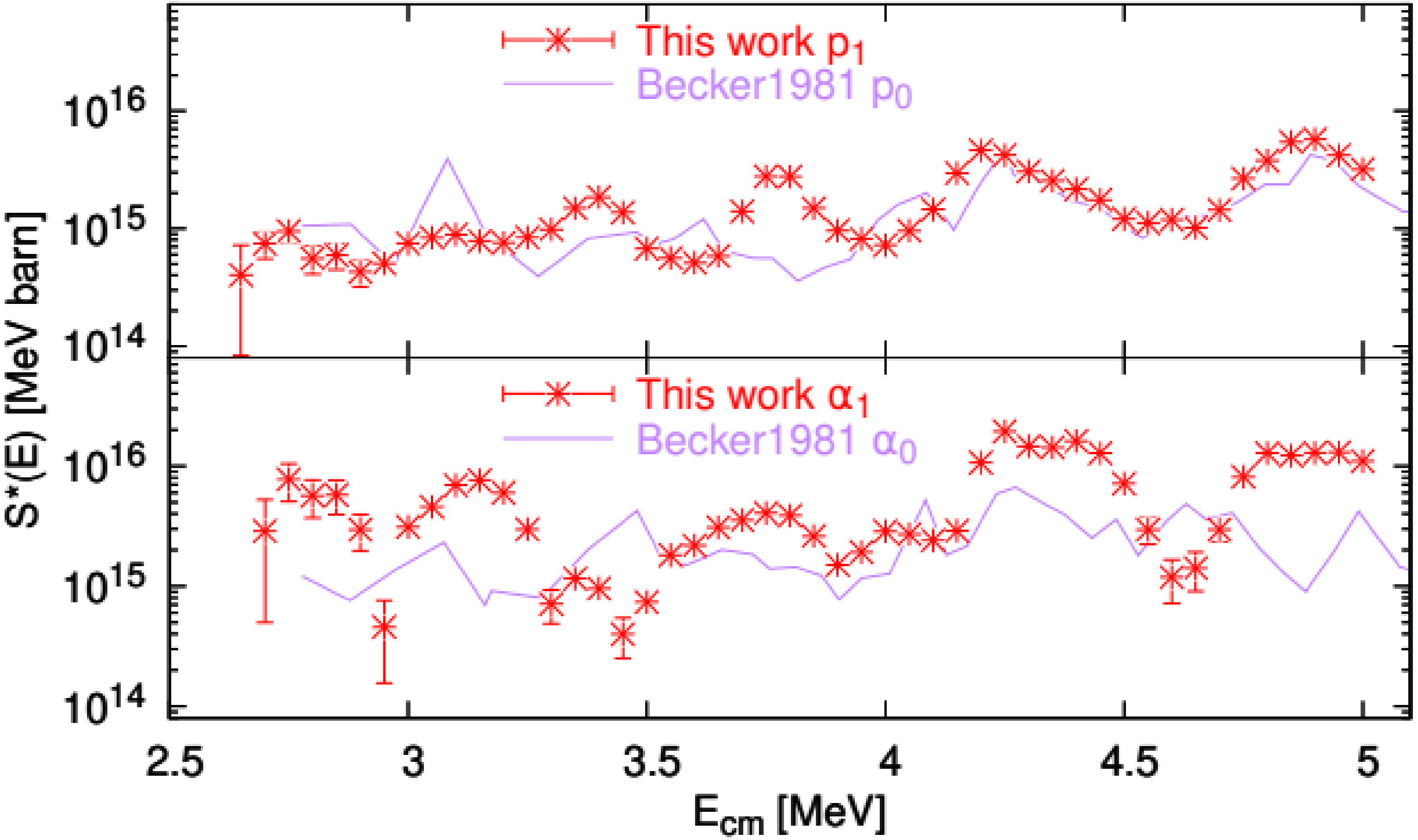
Observed exit channels confirm resonance structure



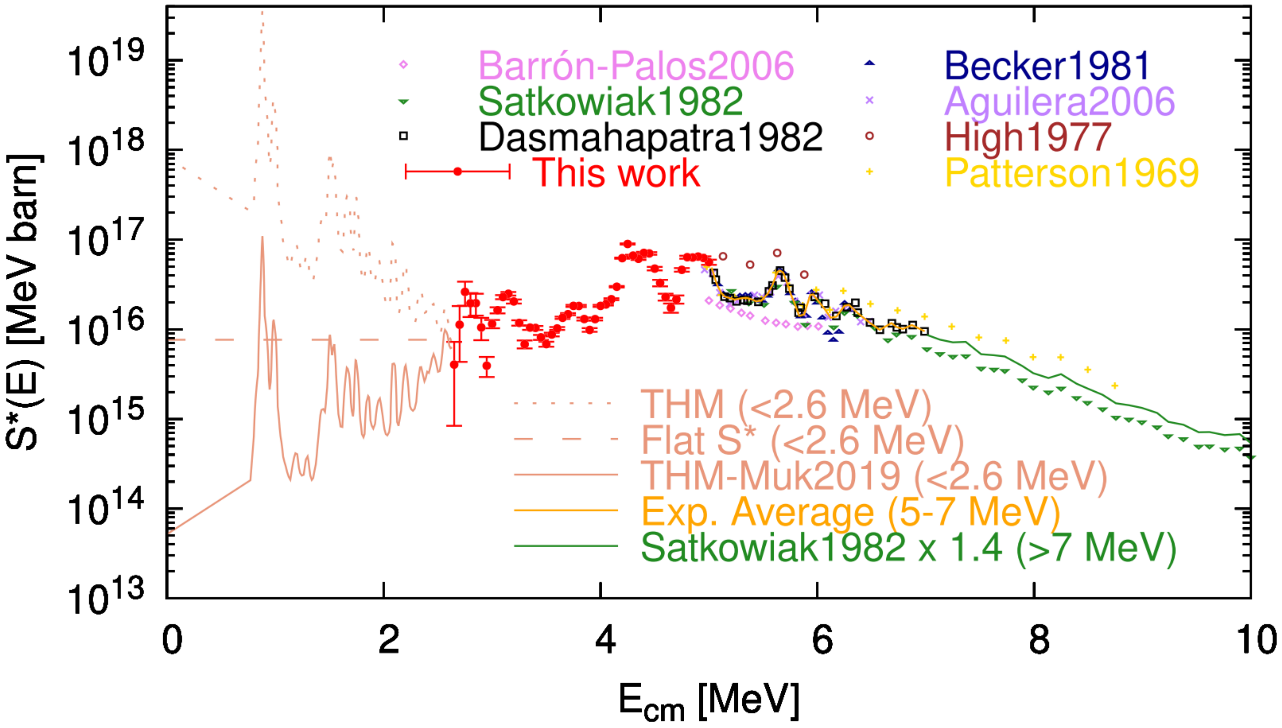


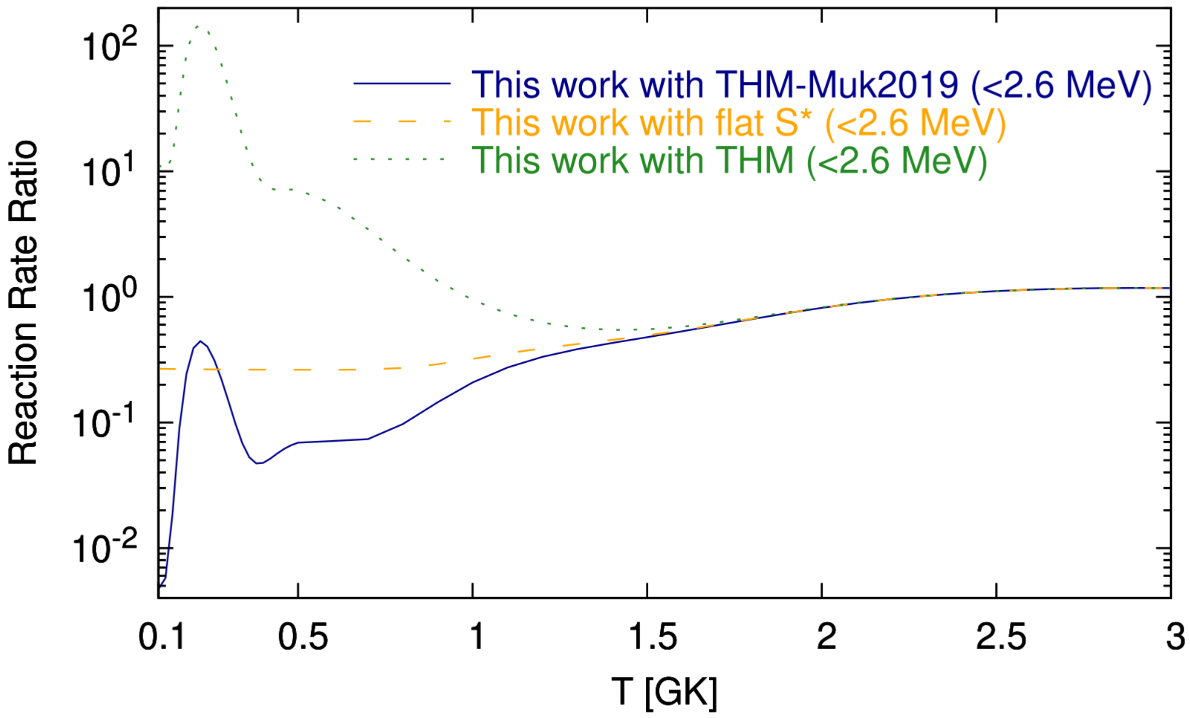
The ground state transition normalized to particle detector experiment





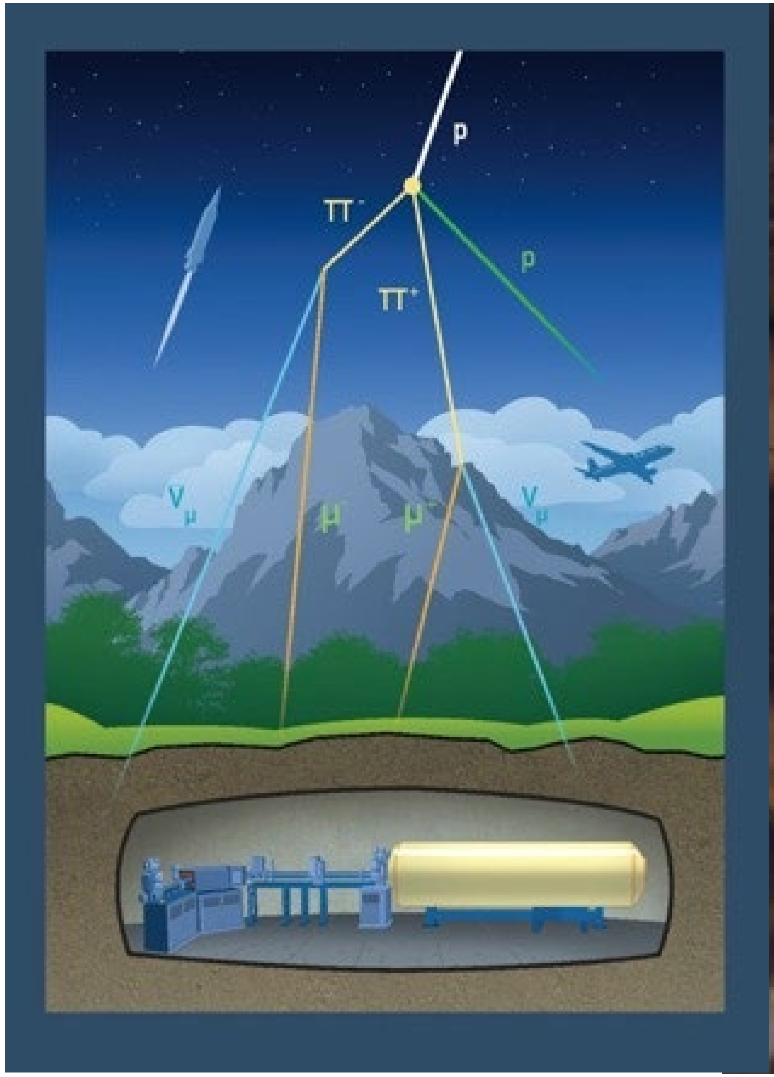
From S-factor to Reaction Rate

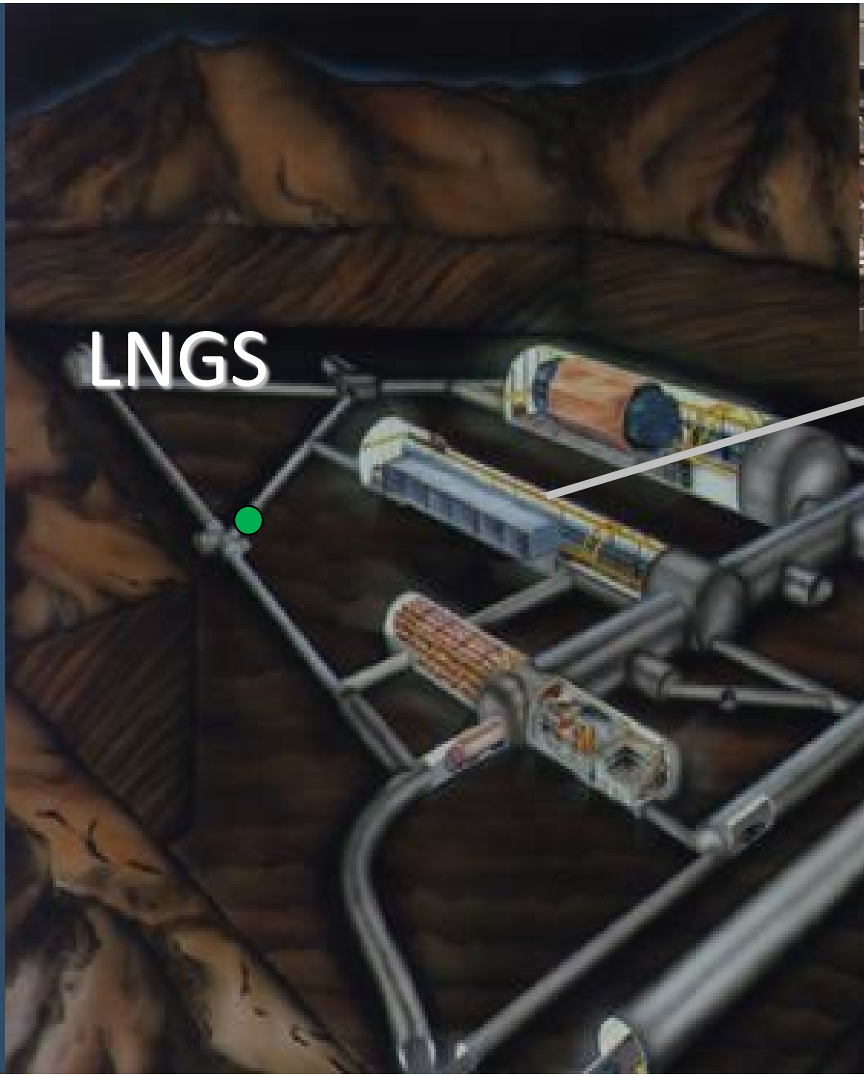


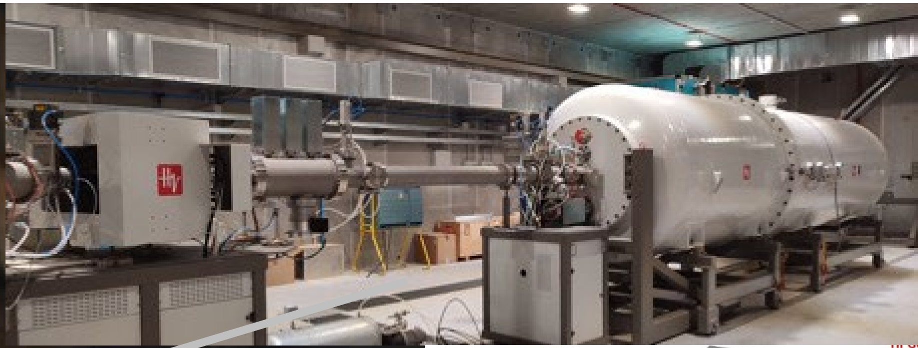


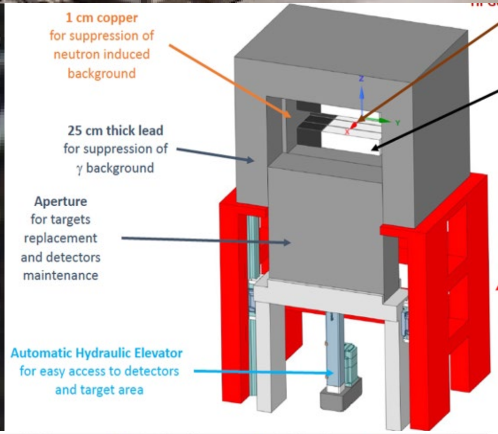
The goal is to extent direct measurements towards lower energies in an underground environment (LUNA-MV) and also seek for alternative THM reactions, $^{13}C(^{12}C,^{24}Mg)n$ not involving charged particles spectators to confirm present results and interpretation (Texas A&M)

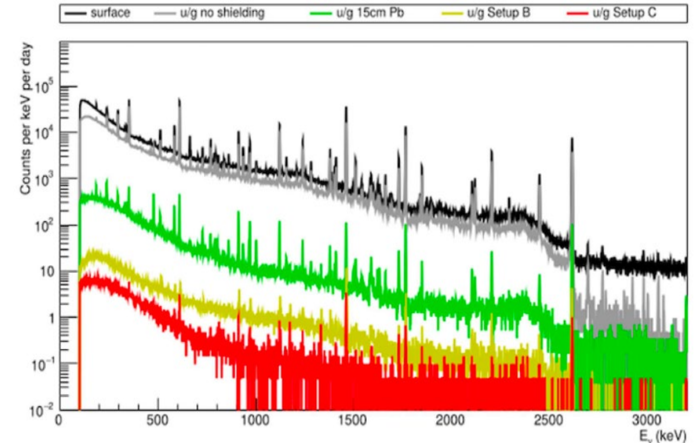
New Initiatives underground



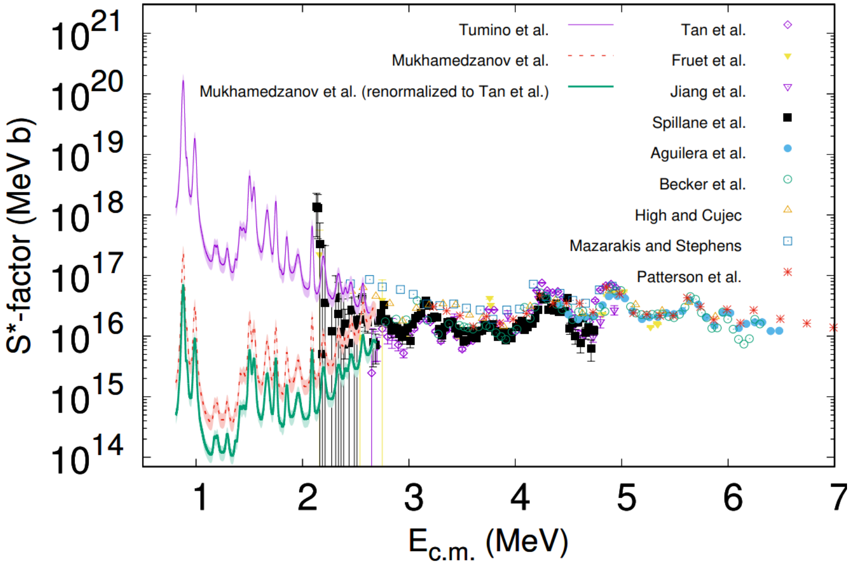


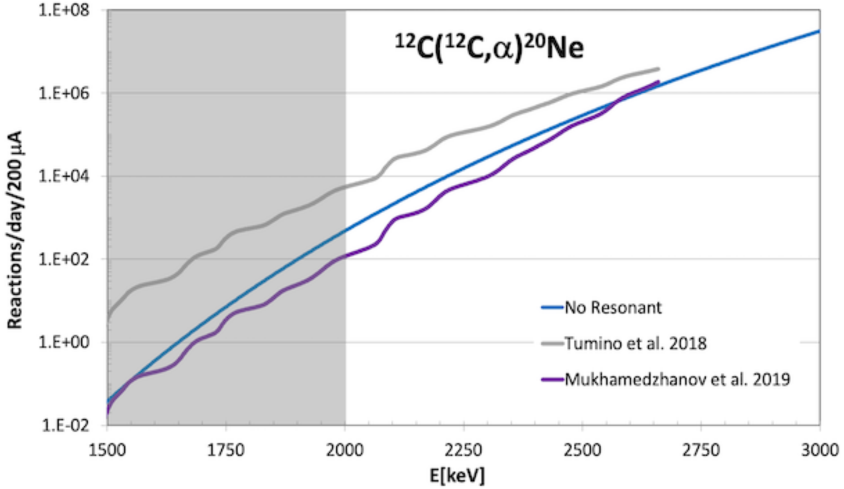


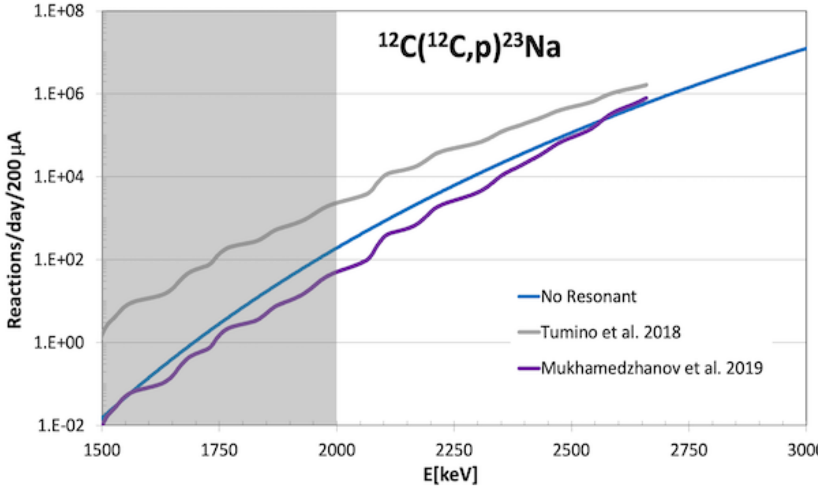




New underground initiatives at LUNA-MV



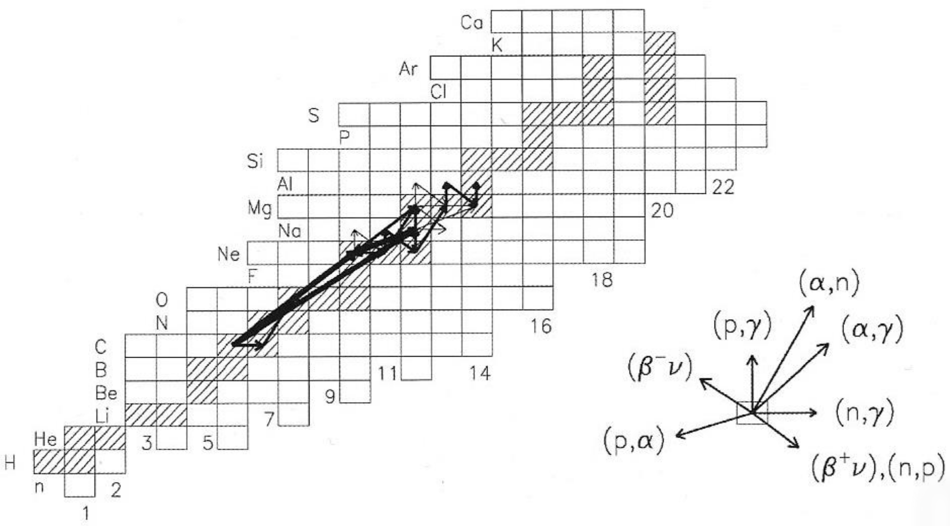




Anticipated sensitivity in count rate down to 1.5 MeV center of mass!

Other Aspects to consider

$T=0.9$ GK, $\rho=10^5$ g/cm^3, $t=5.2\times10^{10}$ s



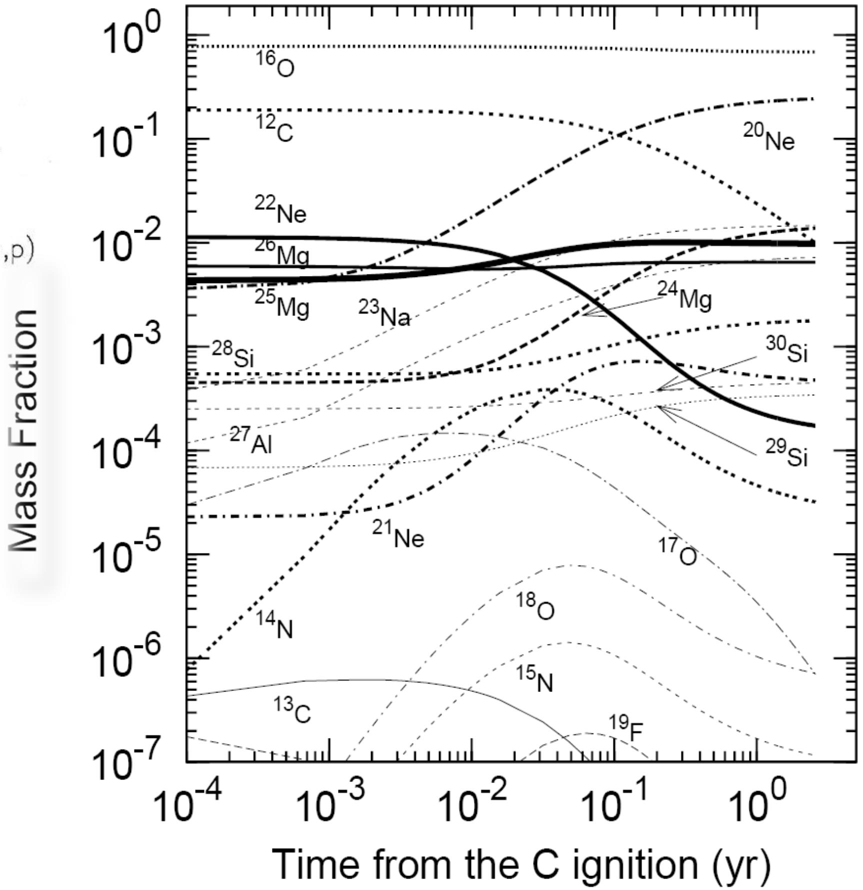
Release of protons, alphas during carbon burning:

$^{12}C(p,\gamma)^{13}N$ $\quad$ $^{12}C(\alpha,\gamma)^{16}O$

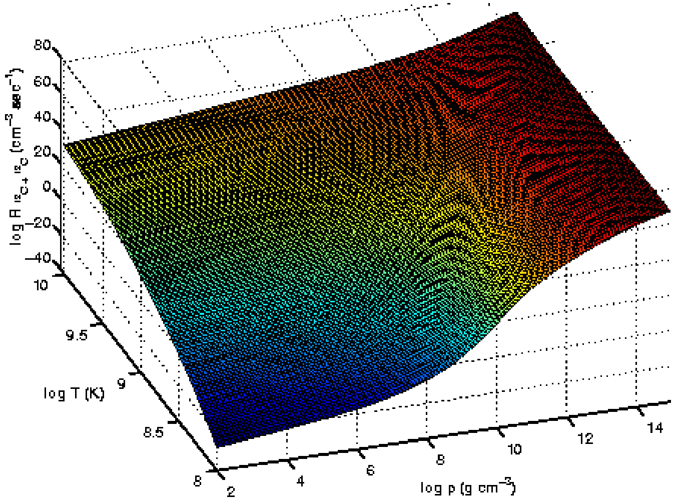
$^{20}Ne(p,\gamma)^{21}Na$ $\quad$ $^{20}Ne(\alpha,\gamma)^{24}Mg$

$^{23}Na(p,\alpha)^{20}Ne$

Alpha capture reactions are weaker than proton capture! Enrichment in ^{20}Ne and ^{24}Mg.



For high density environments from thermonuclear supernova to superbursts, strong electron screening needs to be considered!



Conclusion

Considerable achievements with direct and indirect reaction studies:

- Resonance features are confirmed at low energies
- Nature of resonances not confirmed – compound cluster configurations or dynamical features

- THM approach successful, but discrepancies in interpretation!
- Strength of resonances not confirmed – Model dependencies in reaction conversion

- Hindrance is still a matter of debate

Future Studies based on direct and indirect techniques:

- Further direct fusion studies at lower energies needed!
- Indirect probe of ^{24}Mg compound by alpha and proton induced reactions to generate better R-matrix input!
- Further experiments using different THM systems needed!

Thank You!

Data comparison at three angles