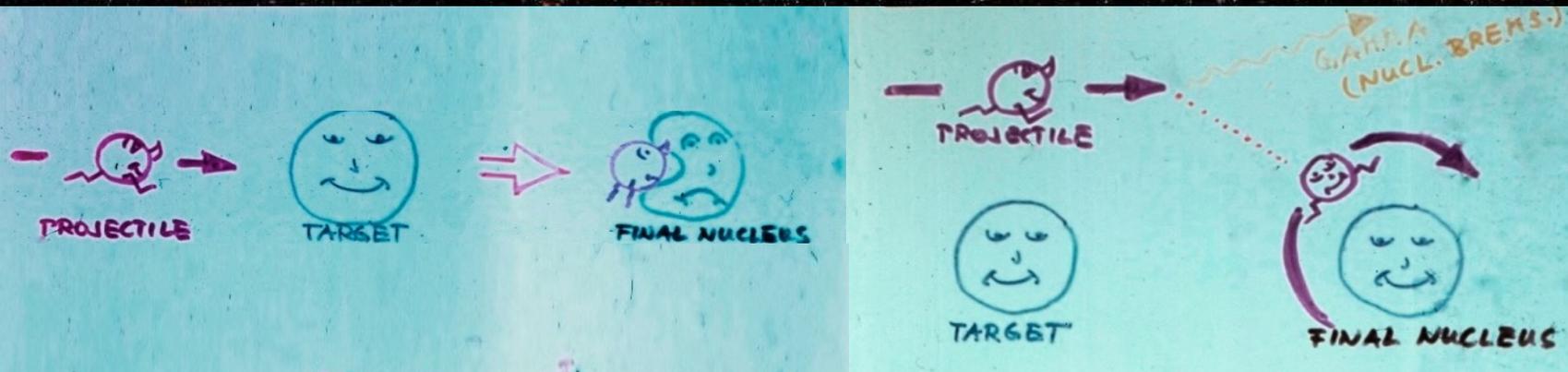
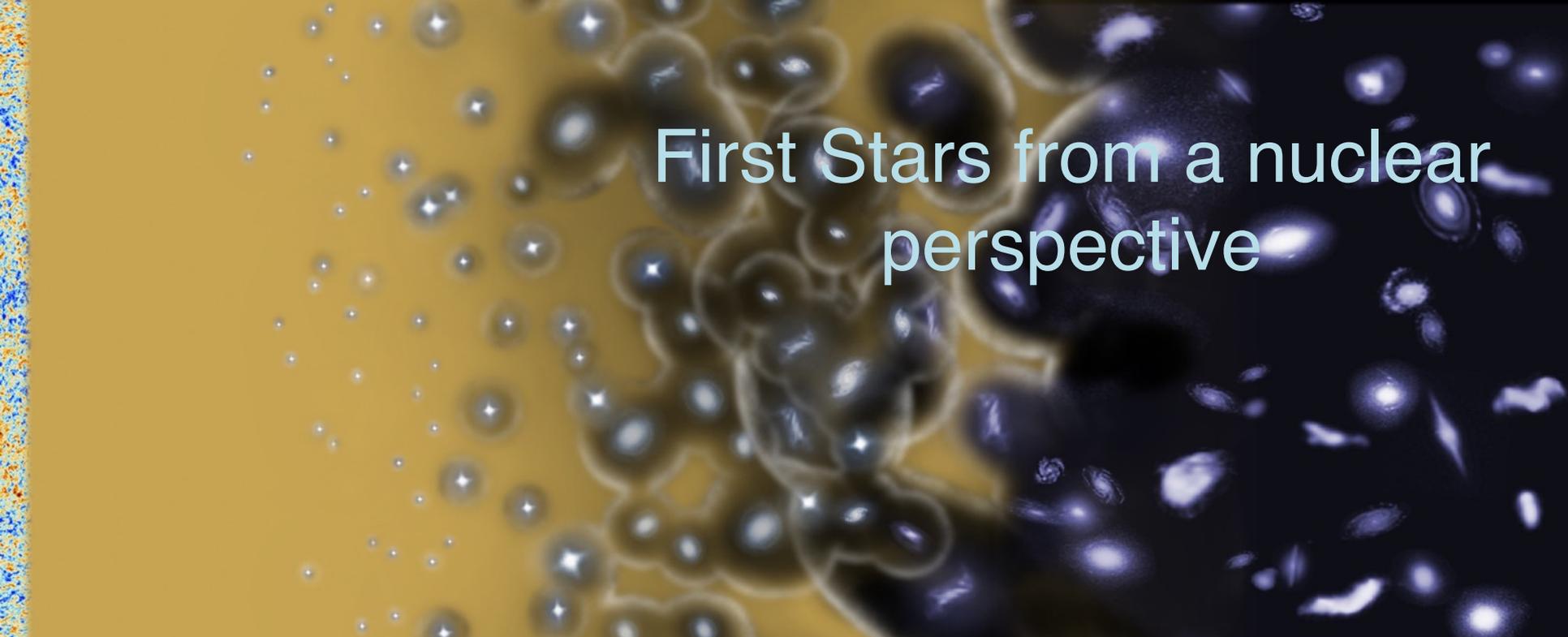


The Physics of Nuclear Reaction Rates



Michael Wiescher
University of Notre Dame

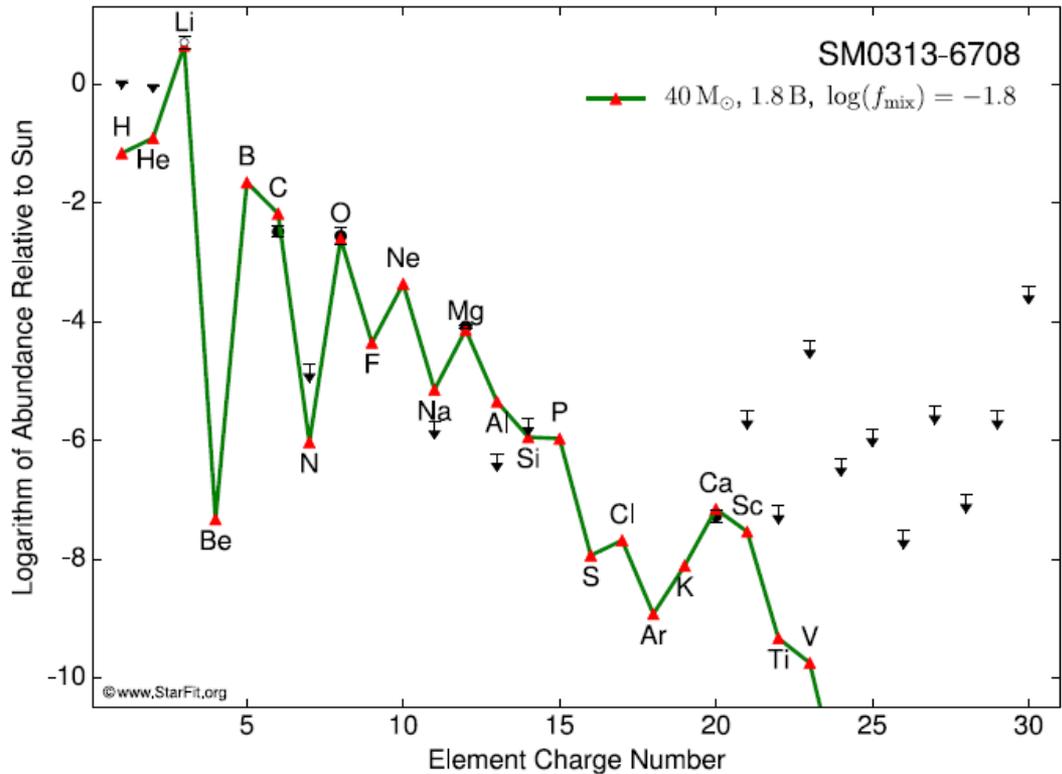
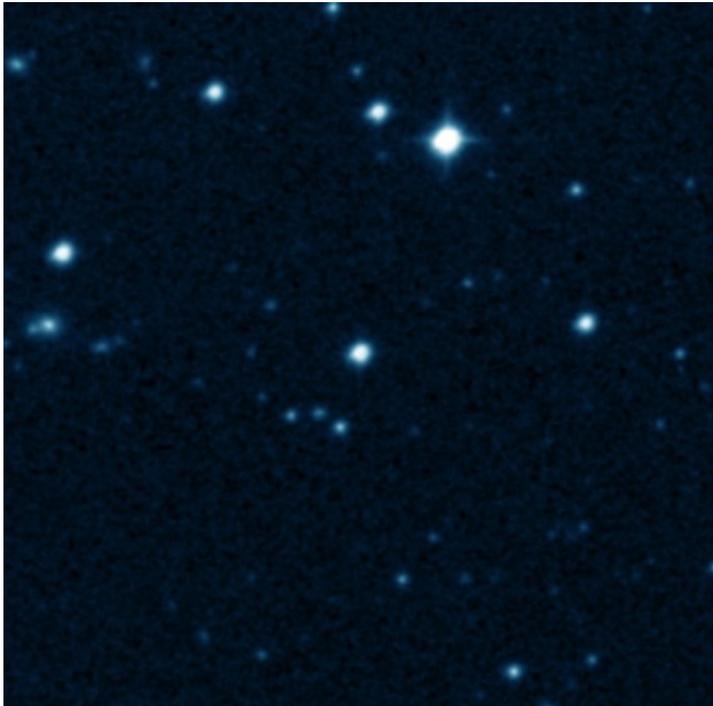
With special focus on Carbon and Oxygen



First Stars from a nuclear perspective

- Massive stars of up to several hundred solar masses collapsing under gravitational force
- No stabilization by the CNO cycles due to the lack of C and O in primordial matter
- Formation of C via the hot pp-chains ${}^2\text{H}+{}^1\text{H}$ and ${}^3\text{He}+{}^4\text{He}$ is limited by primordial deuterium and ${}^3\text{He}$ fuel
- Formation of ${}^{12}\text{C}$ by triple-alpha-process during pre-supernova contraction seems to be the most likely process
- The possibility of fusion on freshly produced carbon oxygen fuel.

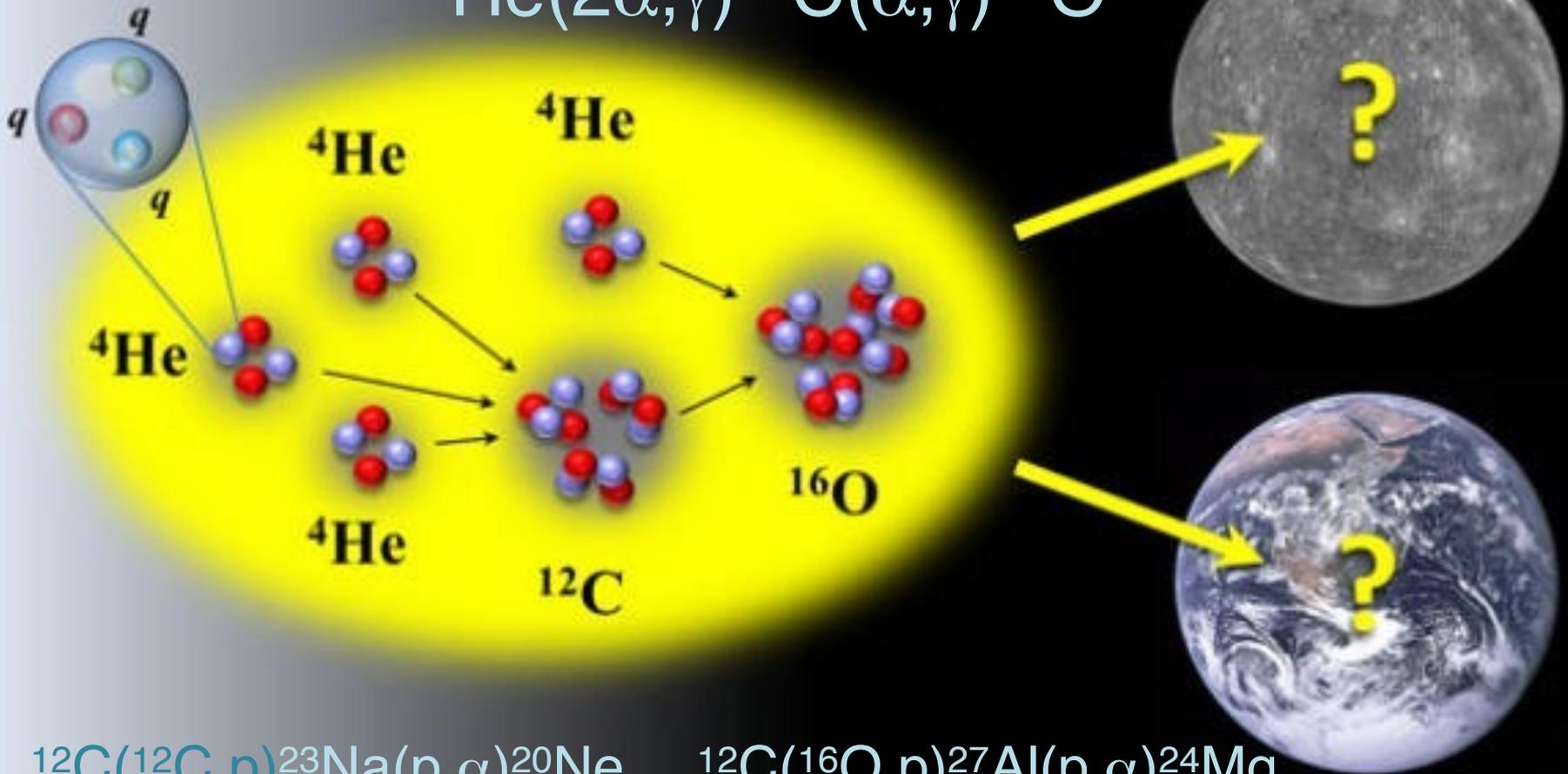
Early Stars and Early Element Synthesis



The element abundance pattern for SMSS 0313-6708 compared

to model values, SC et al. 2000, 1-4 (2014) doi:10.1038/nature12990

The Cosmo-Chemistry of Carbon and Oxygen



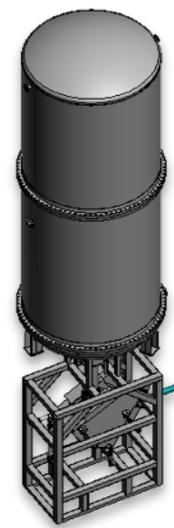
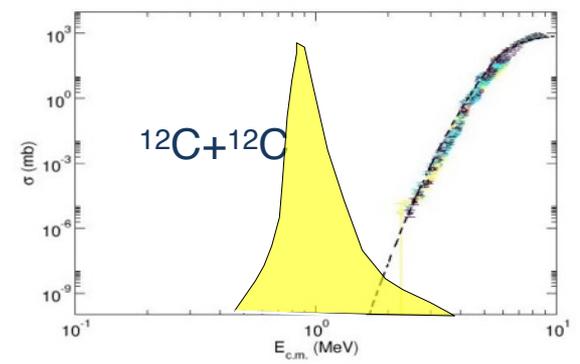
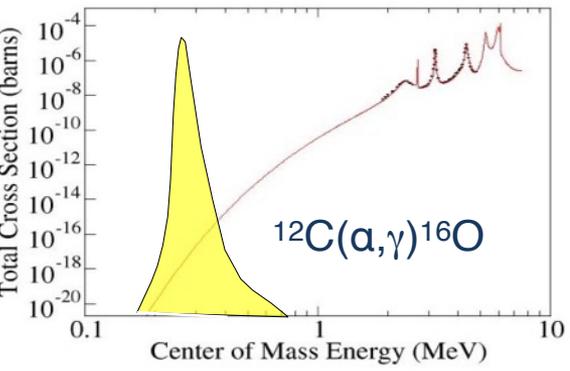
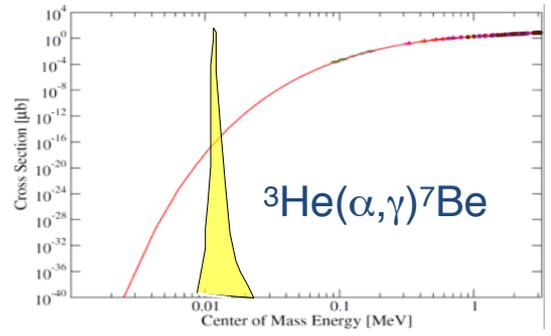
Experimental Techniques



Laboratory based nucleosynthesis

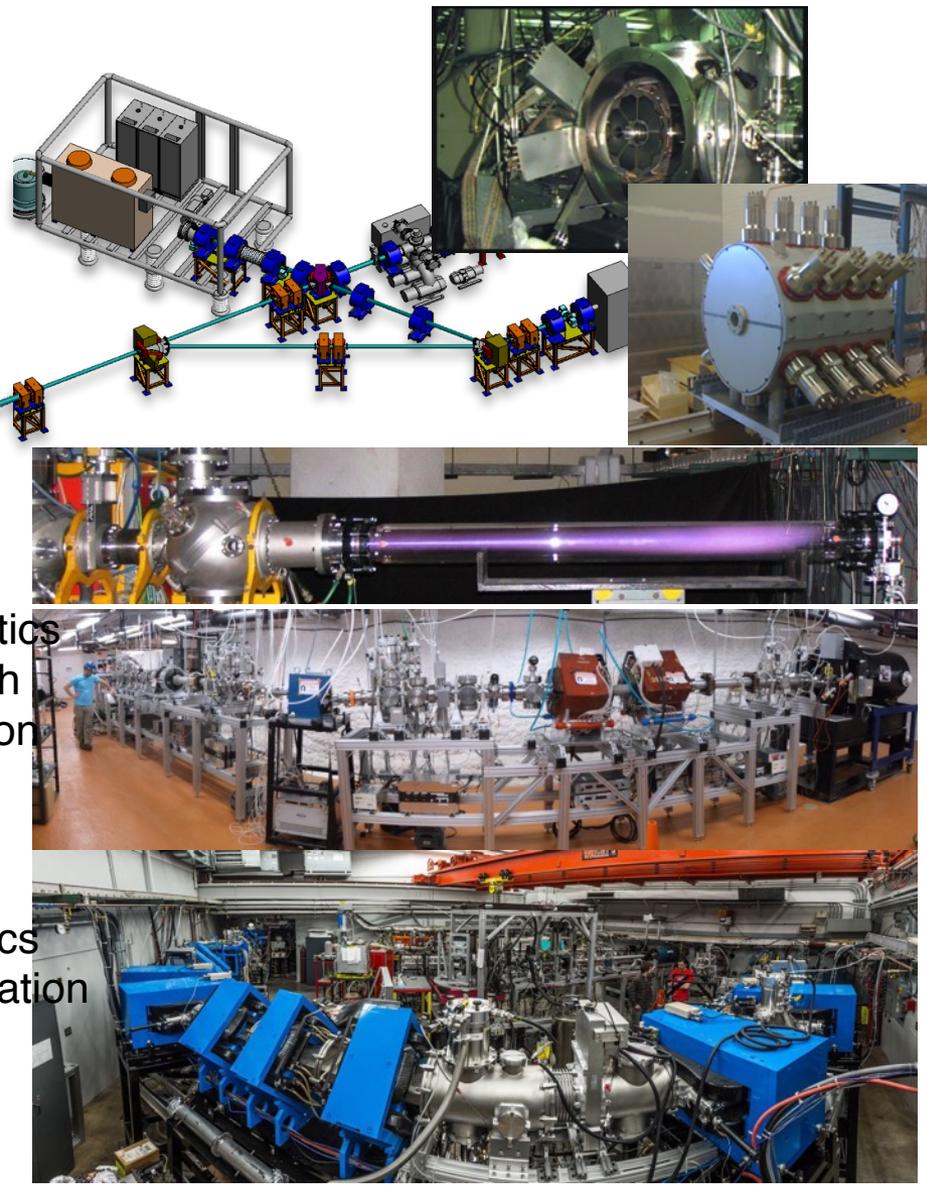


Experiments with Charged Particles



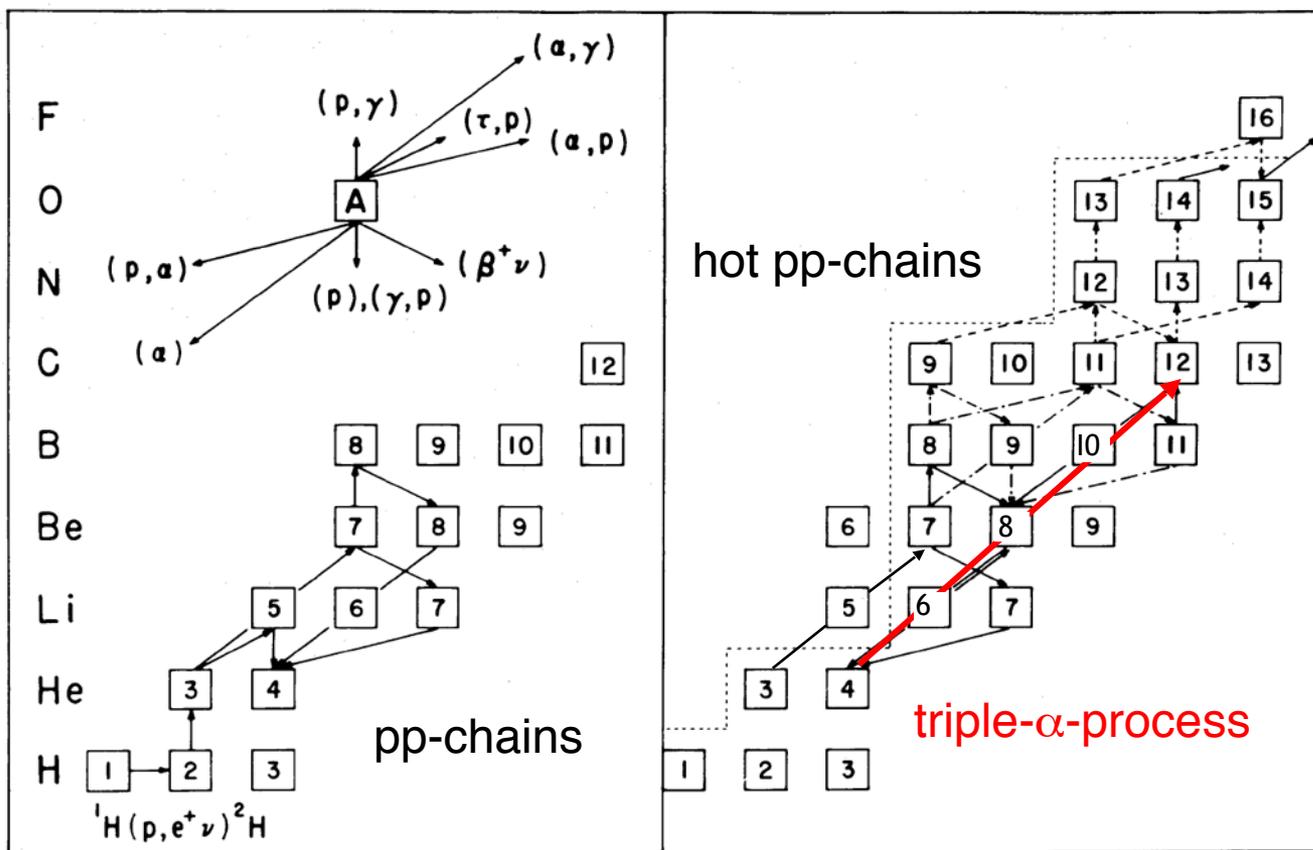
Forward kinematics
underground with
radiation detection

inverse kinematics
with recoil separation
and detection



The hot pp-chains

A way to by-pass the mass 5 and mass 8 gap in hydrogen/helium-rich environments

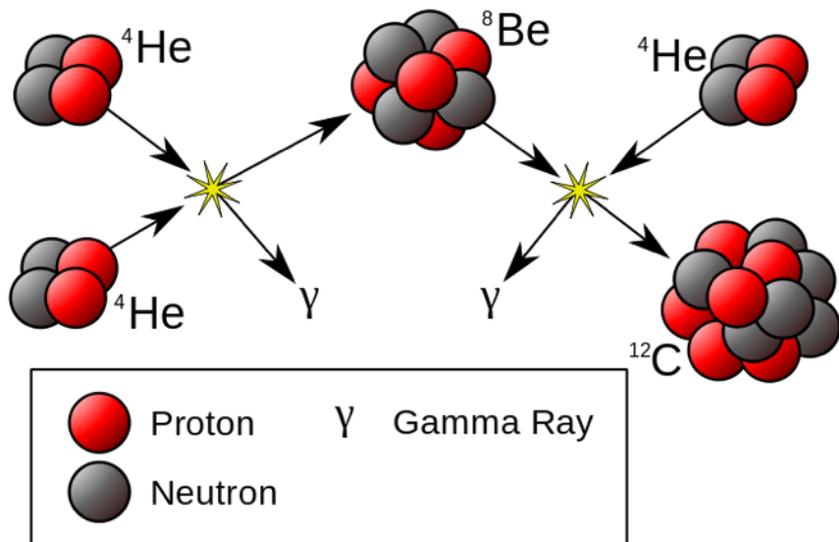


The reaction path is faster than a triple α but originates from ^7Be .

The ^7Be production depends on its feeding through the pp-chains and its initial primordial fuel.

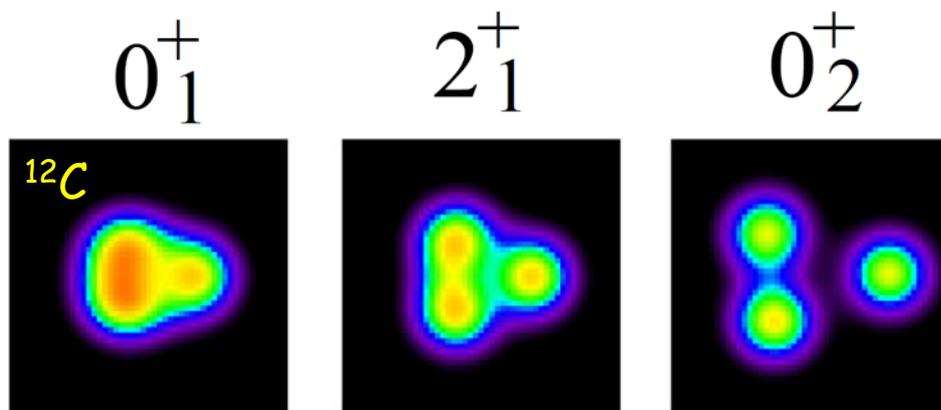
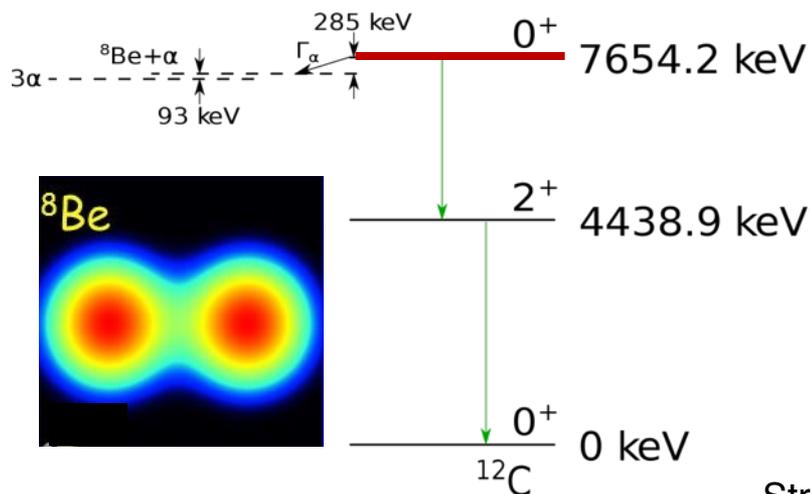
The p+p reaction is not fast enough to produce deuterium and the ^7Be production is limited by the existing amount of deuterium in the primordial fuel.

The triple-alpha-process



Three particle fusion that may occur by different reaction pathways:

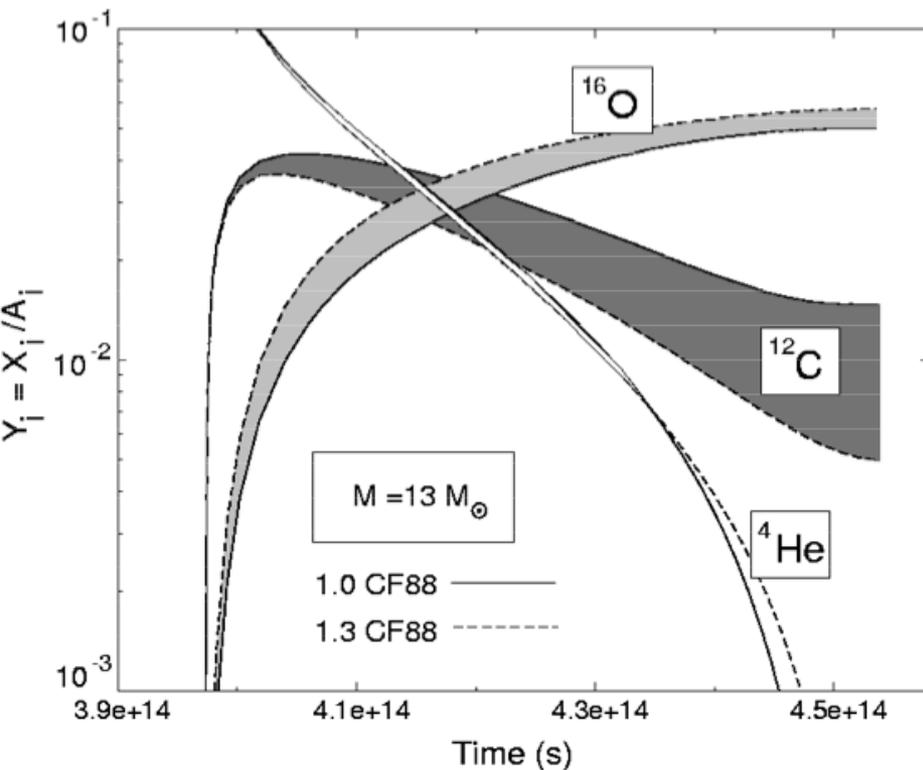
- Single step process (more likely for high density environments)
- Two step sequence (handicap is short-lived ^8Be in equilibrium abundance)
- Unbound 0^+ alpha-cluster state in ^{12}C (Hoyle state) saves the day since it adds a resonant component.



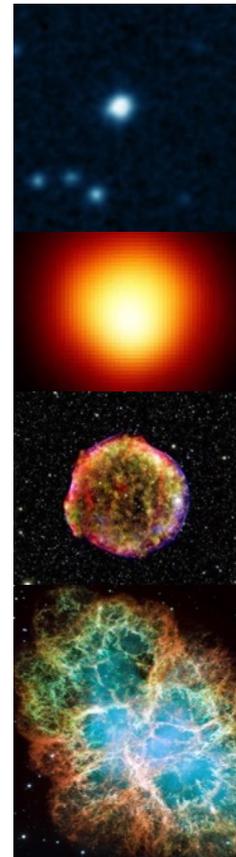
Structure simulations by Kanada En'yo and co-workers

The “holy Grail”

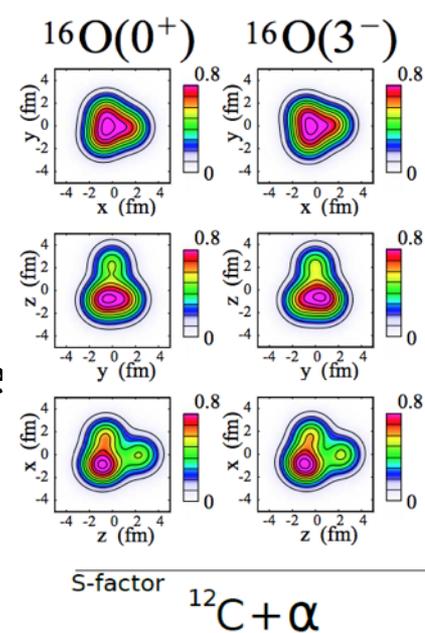
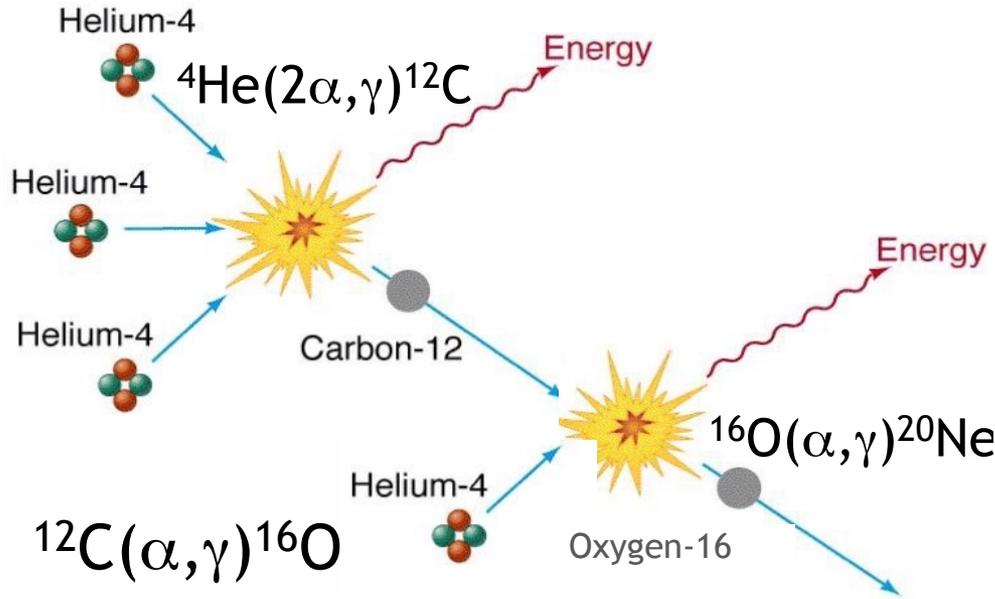
The step after carbon is being formed in a high temperature density environment: $^{12}\text{C}(p,\gamma)^{13}\text{N}$ triggering the CNO cycle leading to ^{14}N
 $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ determining the early $^{12}\text{C}/^{16}\text{O}$ ratio



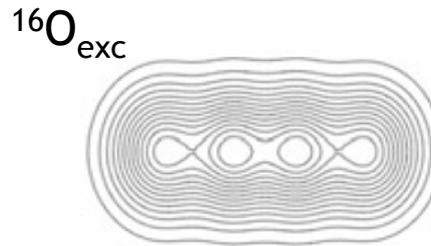
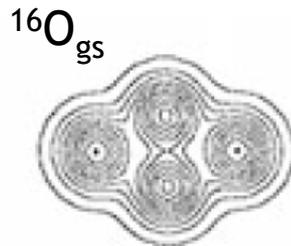
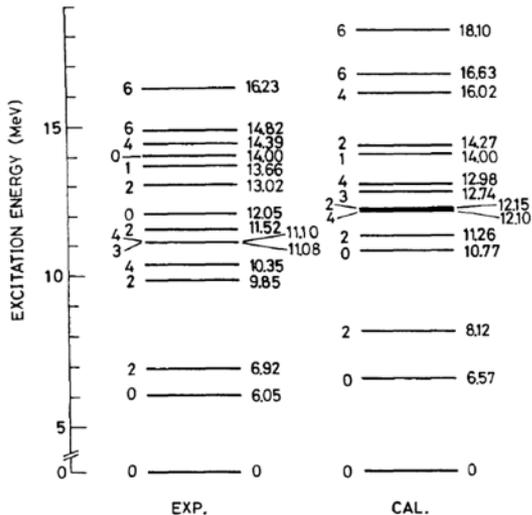
- First stars, defines initial Carbon and/or Oxygen ratio
- Late Stellar Evolution determines Carbon and/or Oxygen phase
- Type Ia Supernova central carbon burning of C/O white dwarf
- Type II Supernova shock-front nucleosynthesis in C and He shells of pre-supernova star



Nuclear Structure Challenges

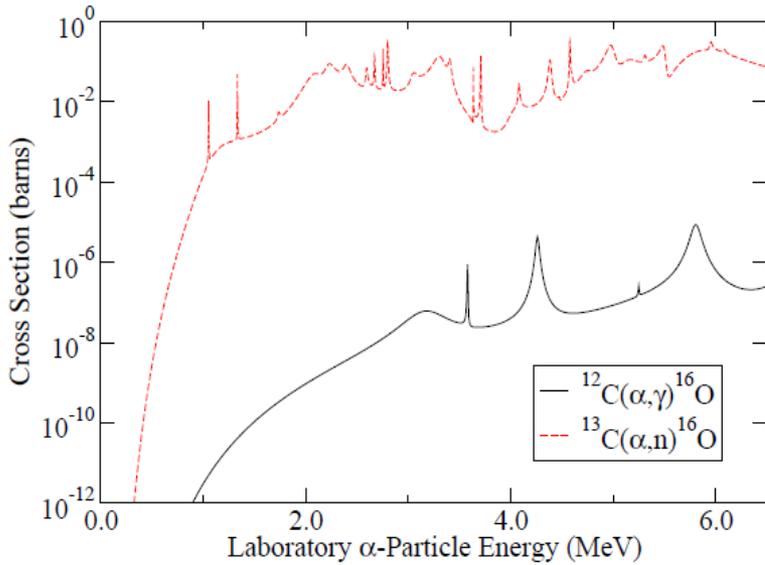


E_x (MeV)	J^π
13.02 13.09	1^- 2^+
12.44	1^-
12.05	0^+
11.52 11.60	3^- 2^+
11.10	4^+
10.36	4^+
9.84	2^+
9.59	1^-
stellar energy range	
7.12	1^-
6.92	2^+
6.13	3^-
6.05	0^+
0	0^+

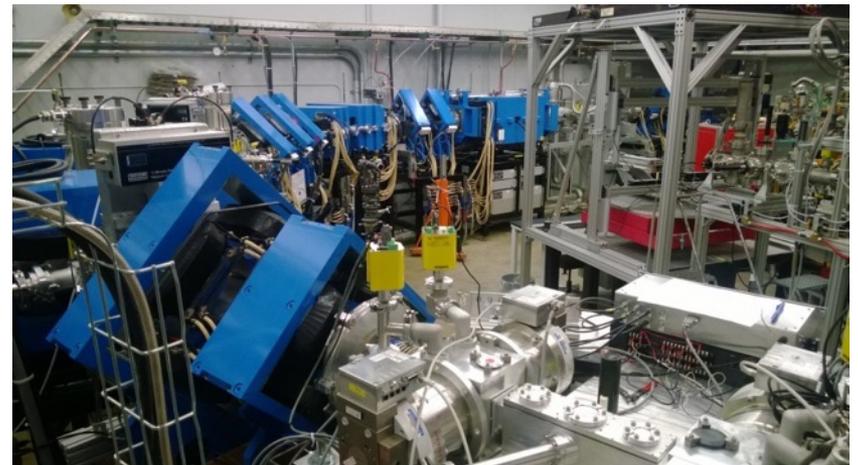
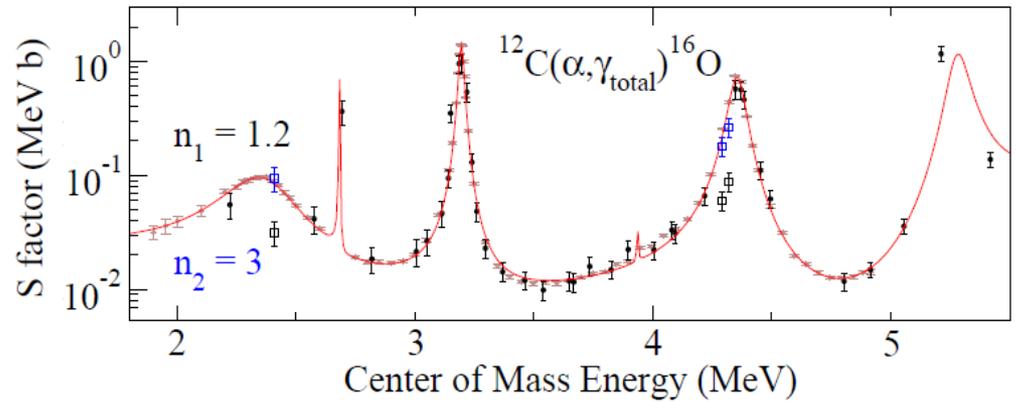


Alpha cluster structure configurations in ^{16}O

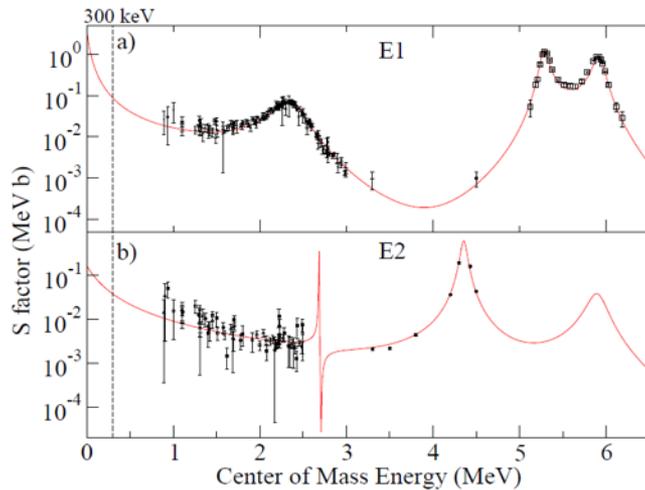
Experimental Efforts



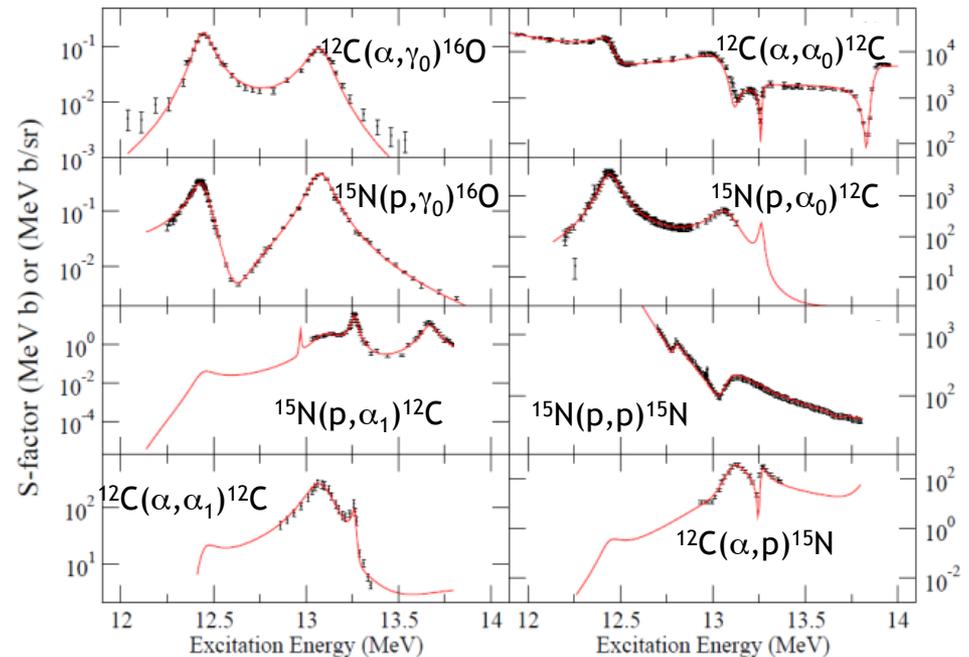
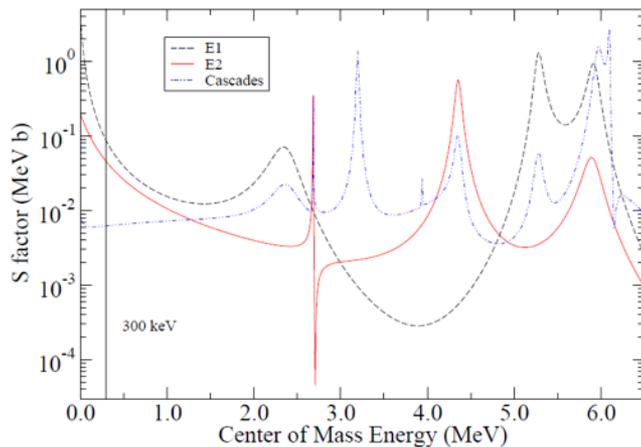
Conversion of cross section data to S-factor



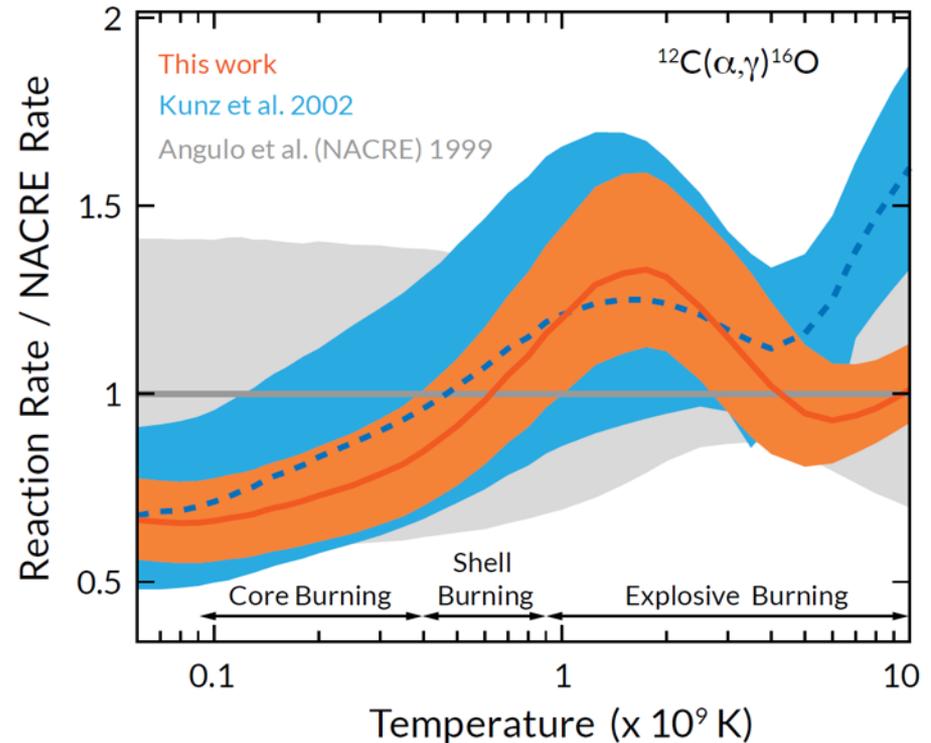
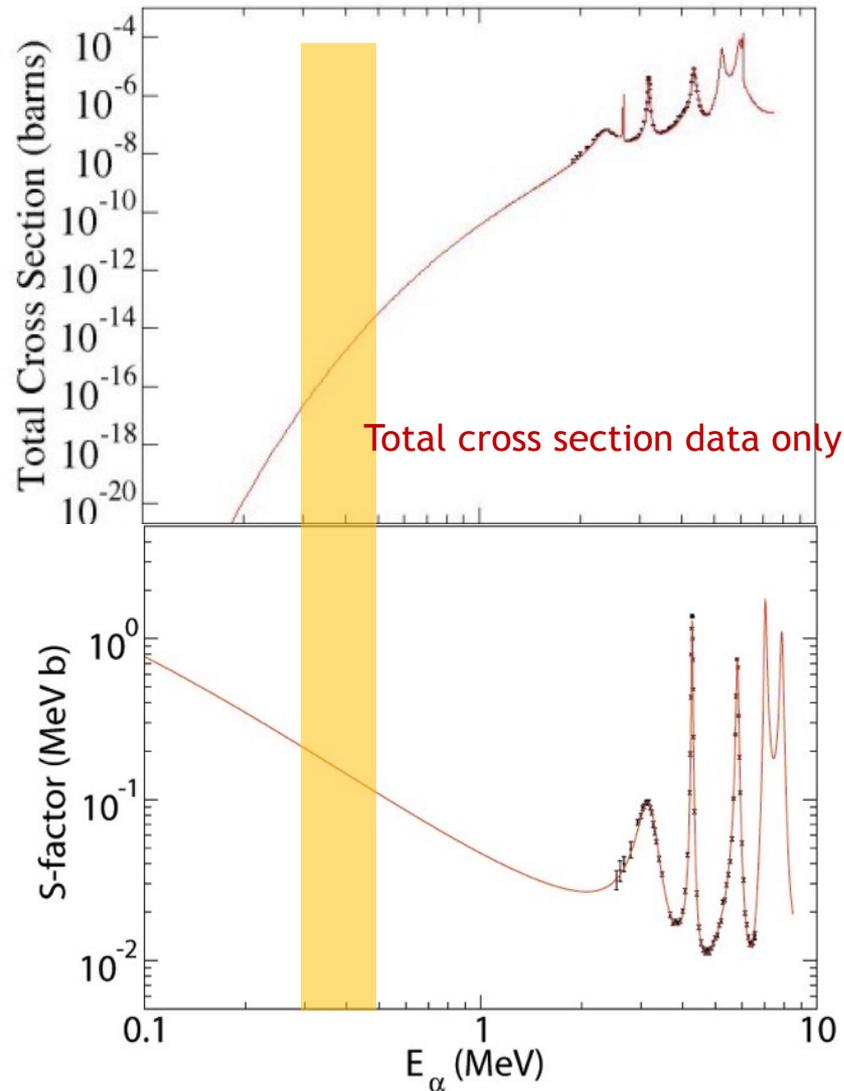
Direct Capture, Resonances, Subthreshold States and Interference between all of them



No first principle calculations possible?
 Phenomenological fits of all data available
 through all reaction channels possible for the
 compound nucleus ^{16}O !



R-Matrix Analysis phenomenology, but ...

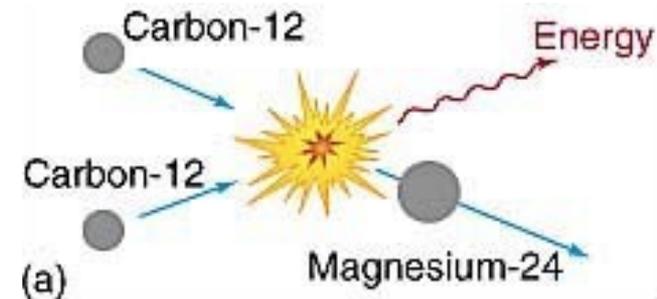


R-matrix (AZURE) based cross section extrapolation on the basis of all existing reaction data through ^{16}O compound nucleus give 15%-20% uncertainty in reaction rate extrapolation.

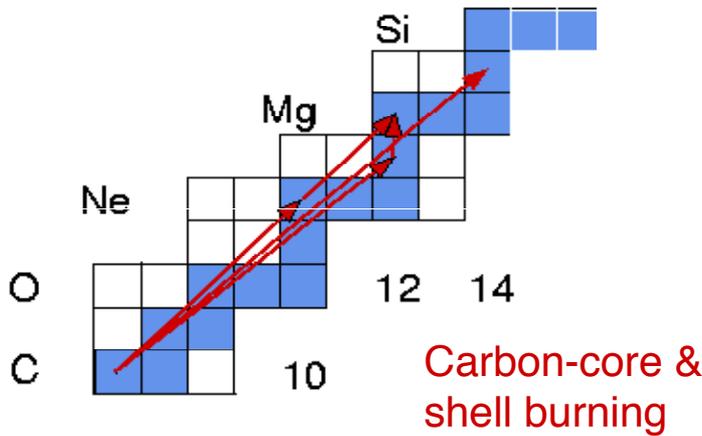
Fusion Reactions in Stars



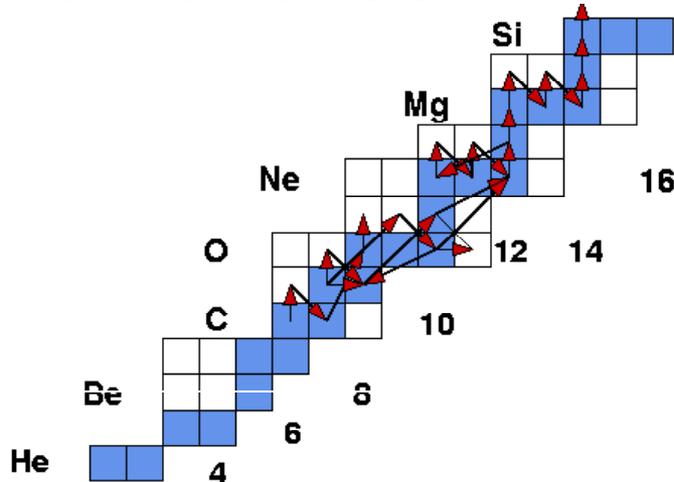
- First stars: fusion for mid-mass elements
- Late stars: post-red-giant stellar evolution, carbon and oxygen burning
- Ignition of type Ia supernovae
- Ignition of superbursts



Predictions for $^{12}\text{C}+^{12}\text{C}$ & $^{12}\text{C}+^{16}\text{O}$



H/He-induced reactions



$$^{12}\text{C}(^{12}\text{C}, p)^{23}\text{Na} \quad Q = 2.240 \text{ MeV}$$

$$^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne} \quad Q = 4.617 \text{ MeV}$$

$$^{12}\text{C}(^{12}\text{C}, n)^{23}\text{Mg} \quad Q = -2.598 \text{ MeV}$$

$$^{16}\text{O}(^{12}\text{C}, p)^{27}\text{Al} \quad Q = 7.170 \text{ MeV}$$

$$^{16}\text{O}(^{12}\text{C}, \alpha)^{24}\text{Mg} \quad Q = 6.771 \text{ MeV}$$

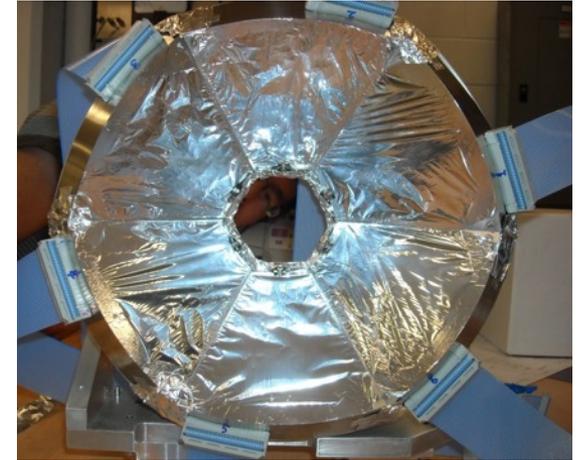
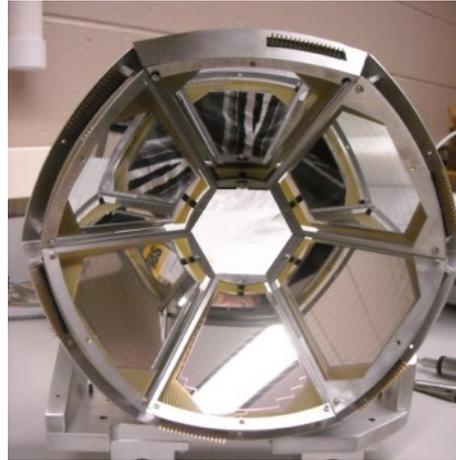
$$^{16}\text{O}(^{12}\text{C}, n)^{27}\text{Si} \quad Q = -0.424 \text{ MeV}$$

$$^{16}\text{O}(^{16}\text{O}, p)^{31}\text{P} \quad Q = 7.628 \text{ MeV}$$

$$^{16}\text{O}(^{16}\text{O}, \alpha)^{28}\text{Si} \quad Q = 9.594 \text{ MeV}$$

$$^{16}\text{O}(^{16}\text{O}, n)^{31}\text{S} \quad Q = 1.499 \text{ MeV}$$

Experimental Status



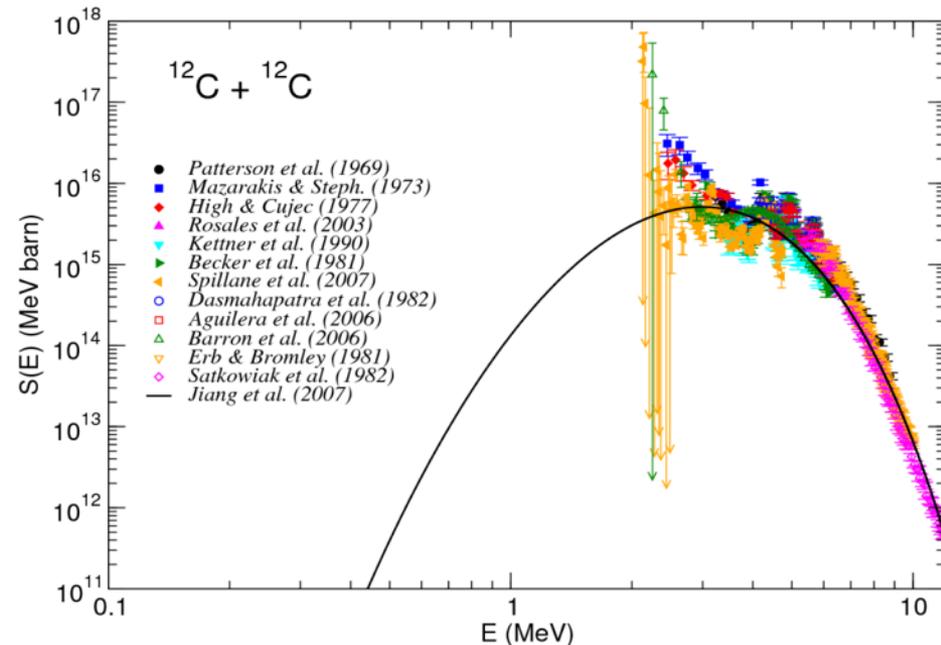
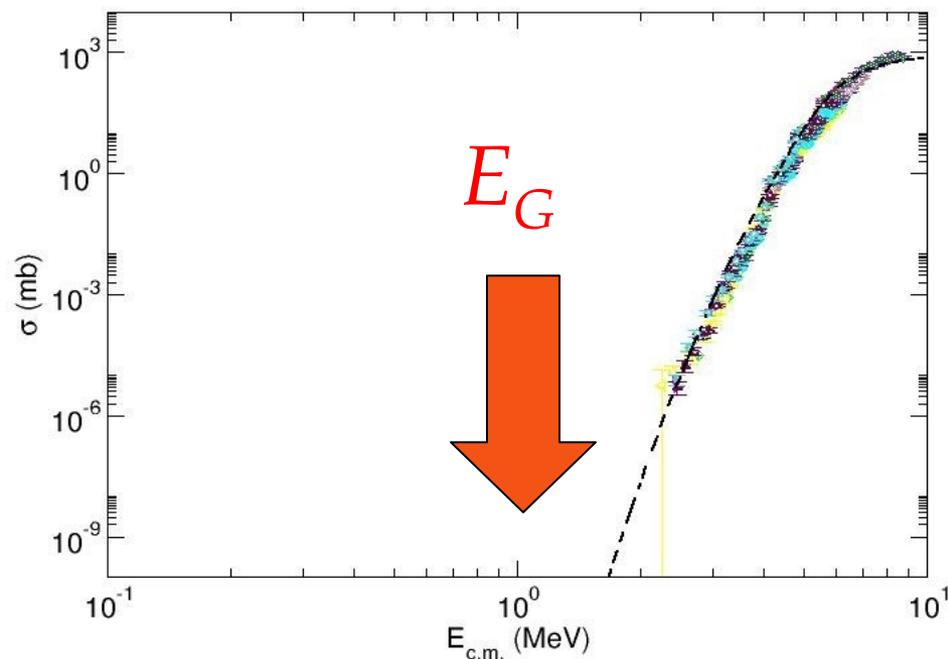
New detector and coincidence measurement arrangements are necessary for background suppression and particle identification. First test experiments are now completed



Gamma-particle coincidence measurements are helpful for identifying particle decay channels

Cross section predictions in potential model with/without hindrance factor

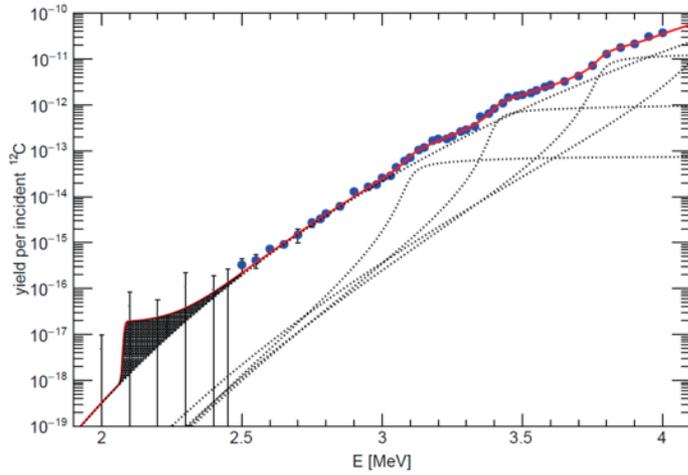
Different potential models lead to different ways to extrapolate the low energy cross section (S-factor).



Caughlan & Fowler ADND 1988
Gasques et al. PRC 2005
Yakovlev et al. PRC 2006
Jiang et al. PRC 2007

 standard potential model
 hindrance potential model

Molecular Cluster Resonances?



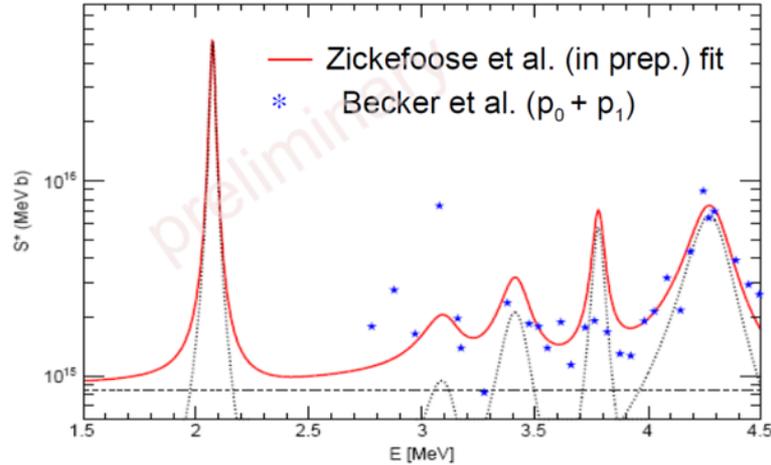
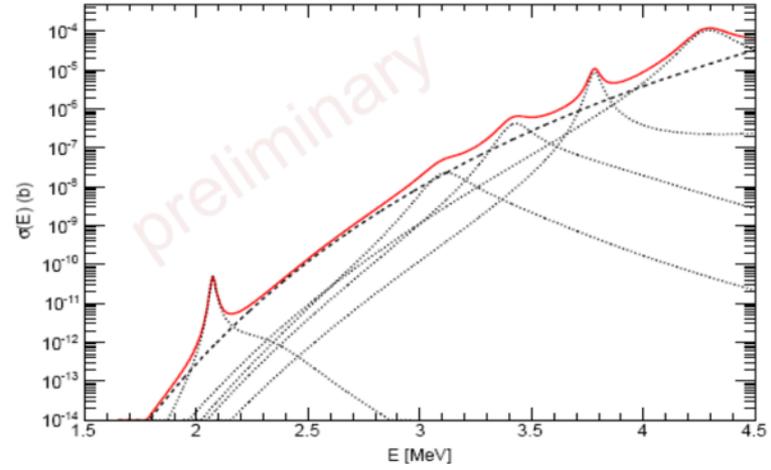
Much speculation about lower energy resonances at ~ 1.5 MeV

$$\omega \gamma = \omega \Gamma_p$$

Resonance strength corresponds to width of the fusion channel!

$$\Gamma_e(E) = \frac{2\pi^2}{\hbar \mu R_0} P_e(E, R_0) \theta_e^2$$

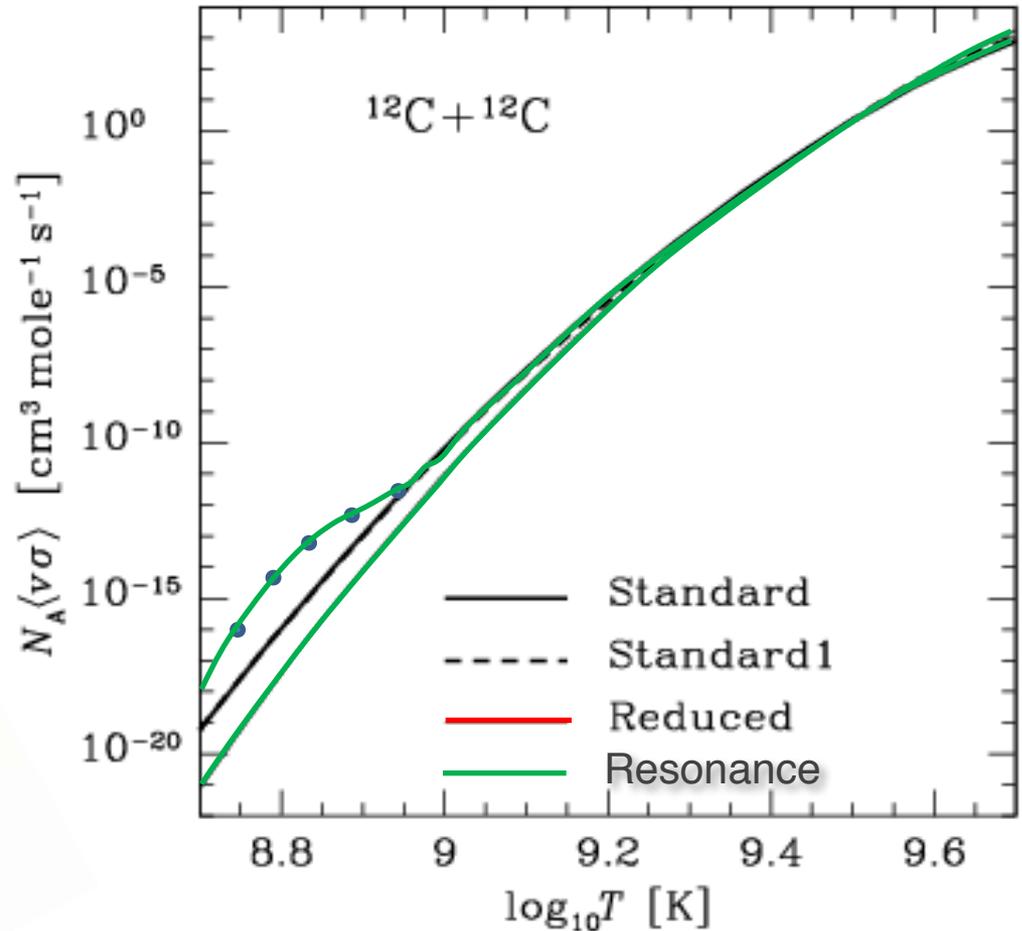
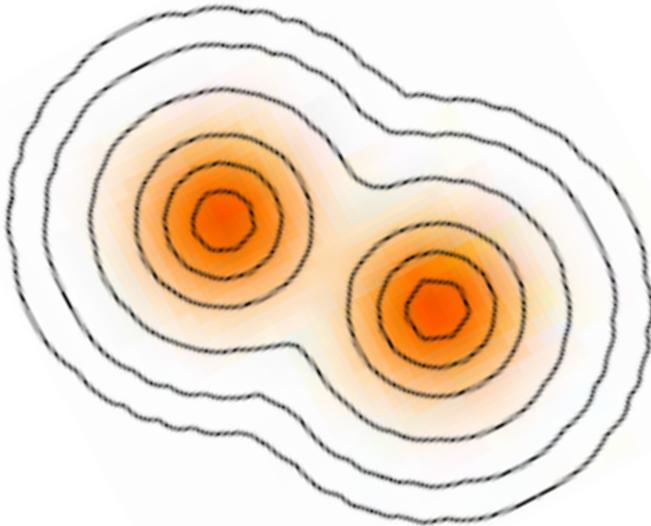
E. P. Wigner, Am. J. Phys. 17 (1949) 99



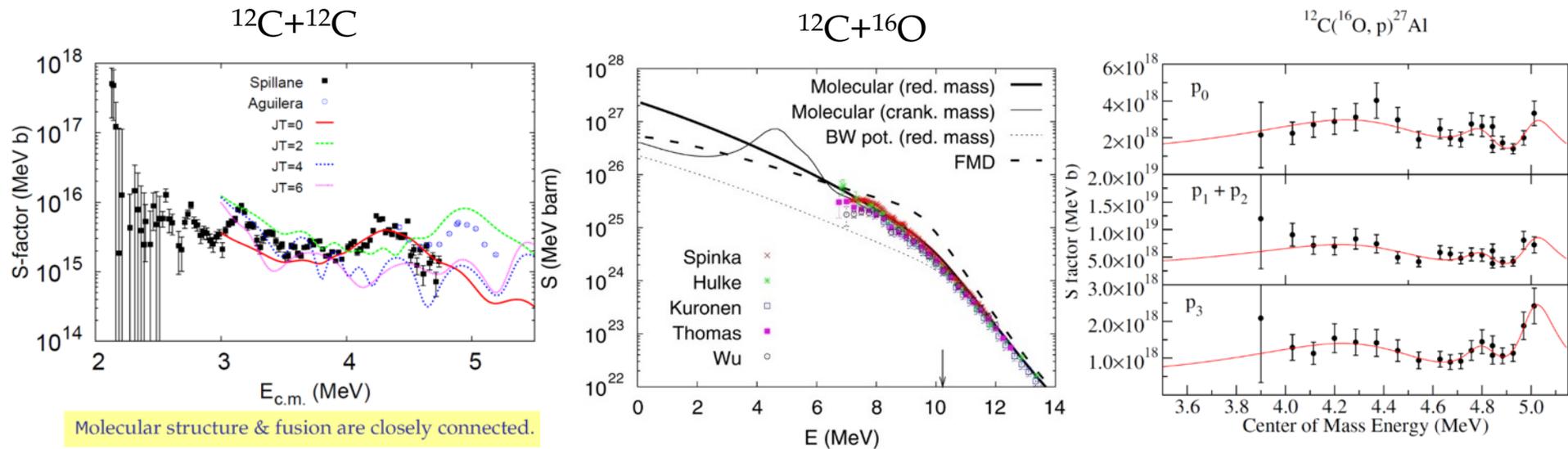
The Wigner limit sets the limit for the strength of the partial channel Γ_{12C} !

Impact on $^{12}\text{C}+^{12}\text{C}$ fusion

The width of the ^{12}C partial channel and the estimated resonance strength $\omega\gamma$ corresponds to the Wigner limit; it would represent a pronounced molecular $^{12}\text{C}-^{12}\text{C}$ configuration for that specific resonance in the compound nucleus ^{24}Mg



Dynamical and phenomenological Models for Molecular Cluster Resonances



Reaction model approach Alexis Diaz-Torres

R-matrix approach AZURE

More to be done to learn about the fusion mechanism and the impact of structure!

Conclusion

- Nuclear structure and reaction mechanism is of relevance for nuclear astrophysics!
- The reaction rates depend on the underlying structure and reaction mechanism. They don't scale!
- Only first survey relevance for scaling studies!
- Hydrogen burning is dictated by the single particle structure of nuclei (shell model)!
- Helium burning by the alpha cluster structure of nuclei (cluster model)!
- And “maybe” heavy ion burning is dictated by the molecular structure of nuclei!
- Further experiments are needed to delineate the components!