

Welcome to Edinburgh

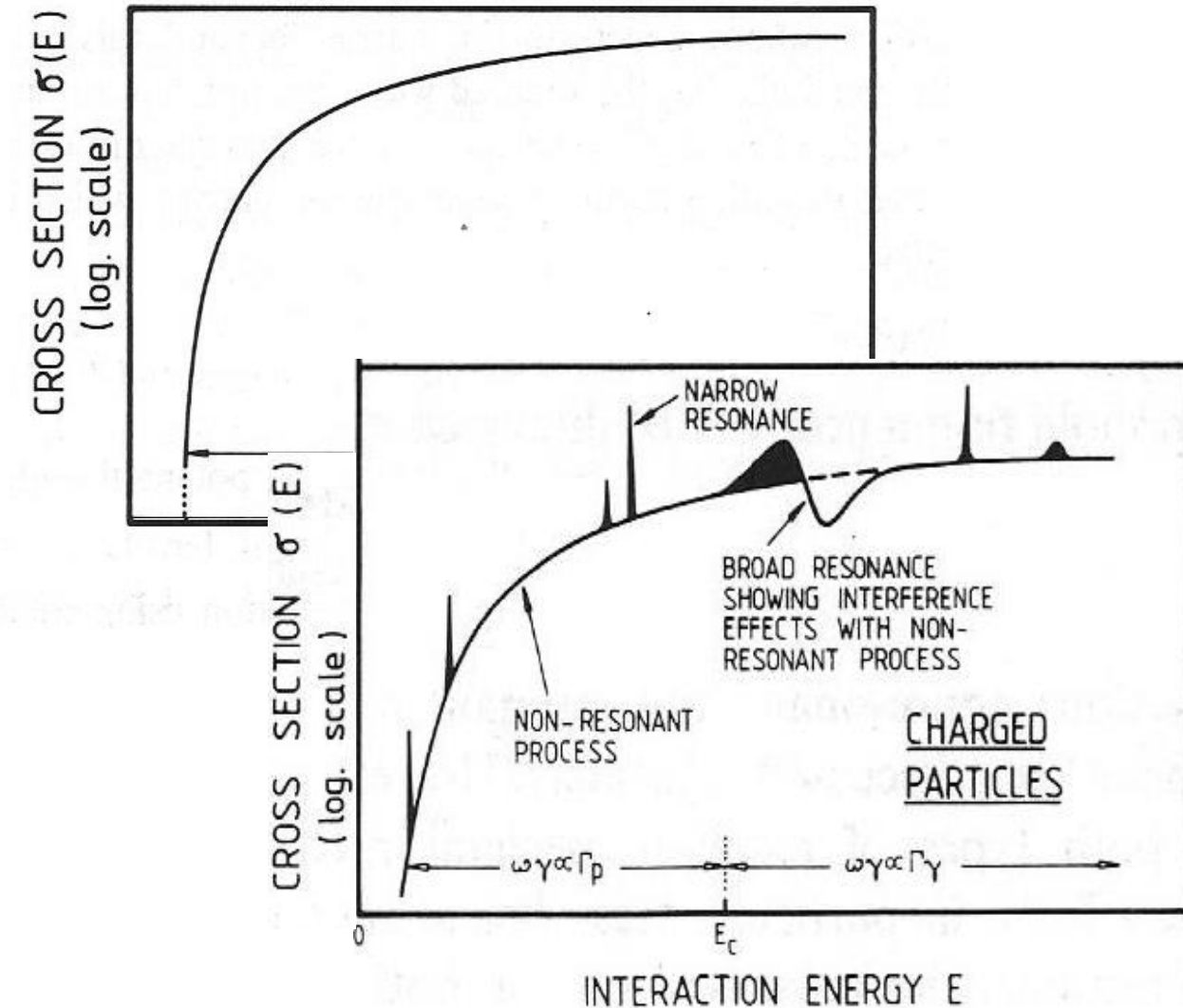
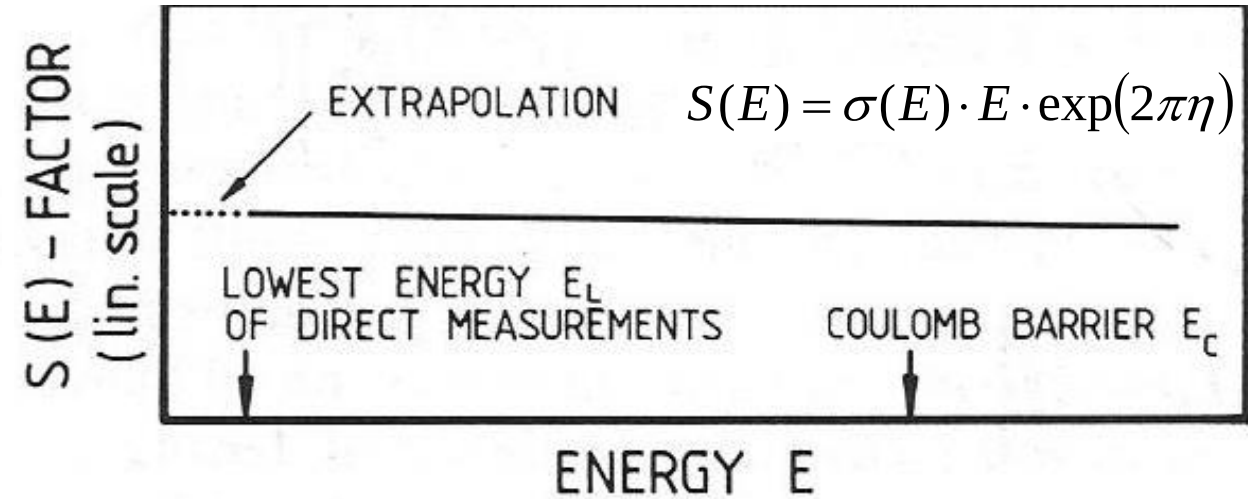


Purpose of Meeting and Topics of Interest

- Low energy extrapolation
 - Uncertainties in reaction cross sections
 - Alternative tools from plasma to THM
 - Uncertainties in screening and nuclear threshold effects
- Observational evidence
 - Solar CNO neutrinos
 - Early star nucleosynthesis patterns
 - White dwarf seismology
 - Black hole mass gaps
 - Type Ia supernovae and superbursts

Nuclear reaction rates depend on the cross section!

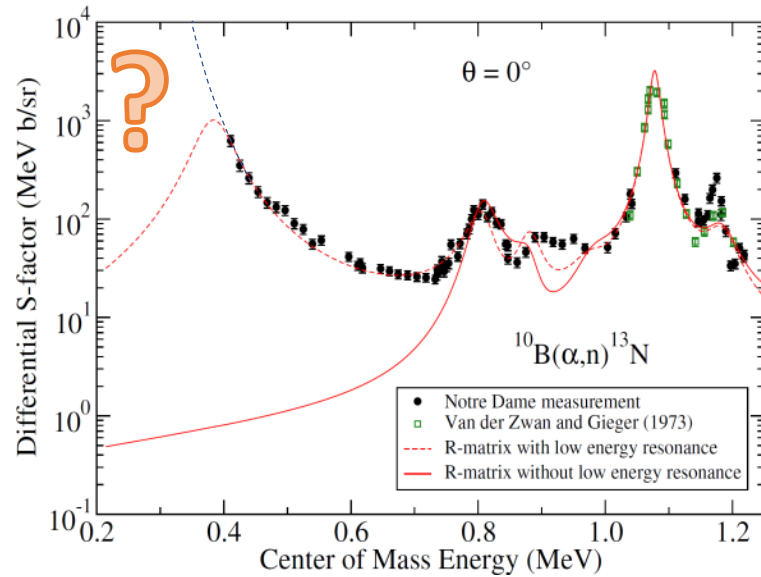
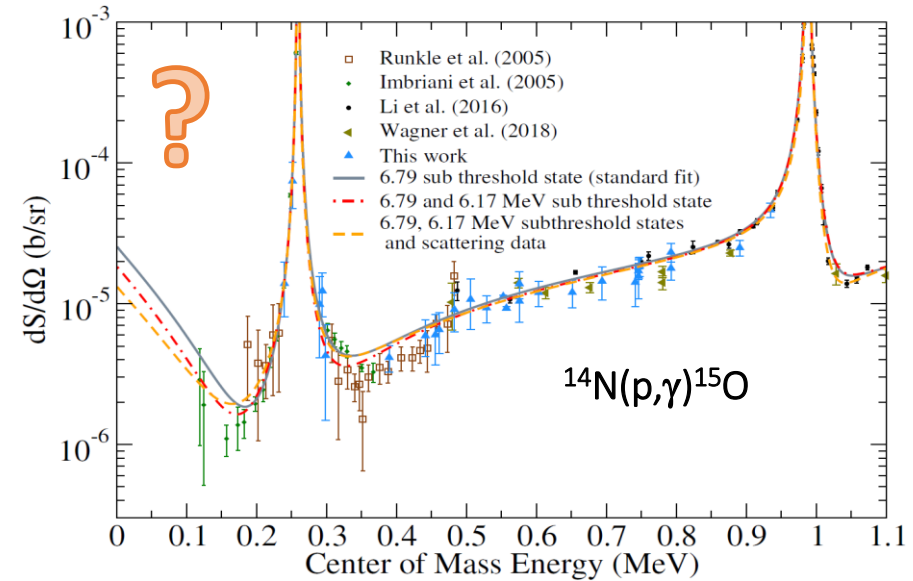
$$\langle \sigma v \rangle = \int \sigma(E) \cdot E \cdot \Phi(E) \cdot dE$$



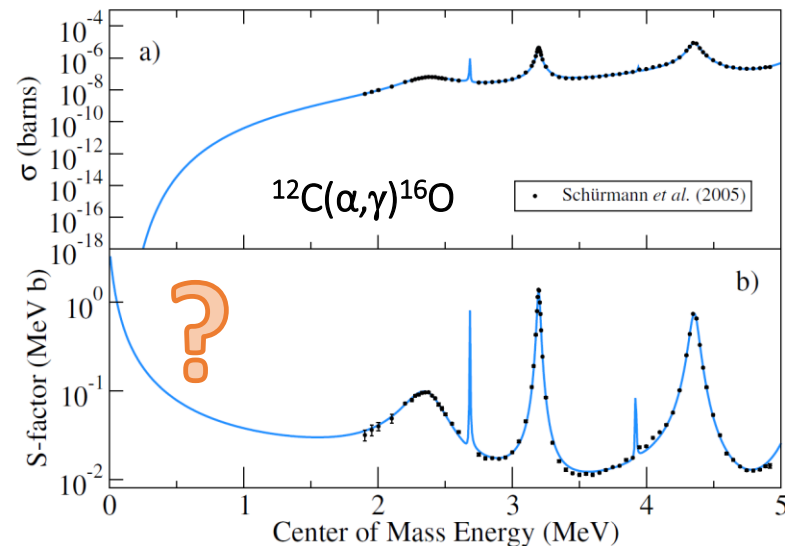
How reliable is the extrapolation of a nuclear cross sections over multiple orders of magnitude using approximation means?

Extrapolation challenges

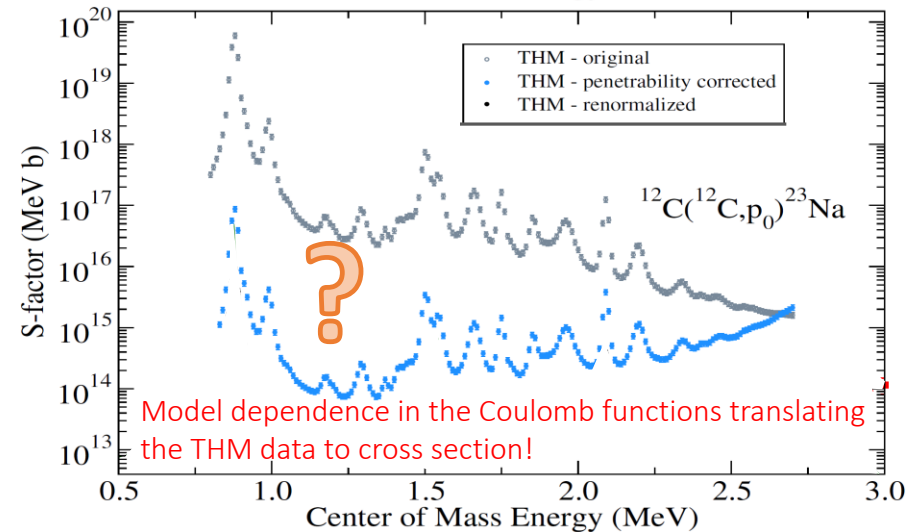
New data?



discrepancies?



Into the unknown?



Interpretation?

Do we know, or how well do we know the reaction processes at very low energies?

Reason for Uncertainty

1. We cannot measure at stellar temperature!

Except for few selected cases, with large uncertainty

2. We cannot remove the natural background!

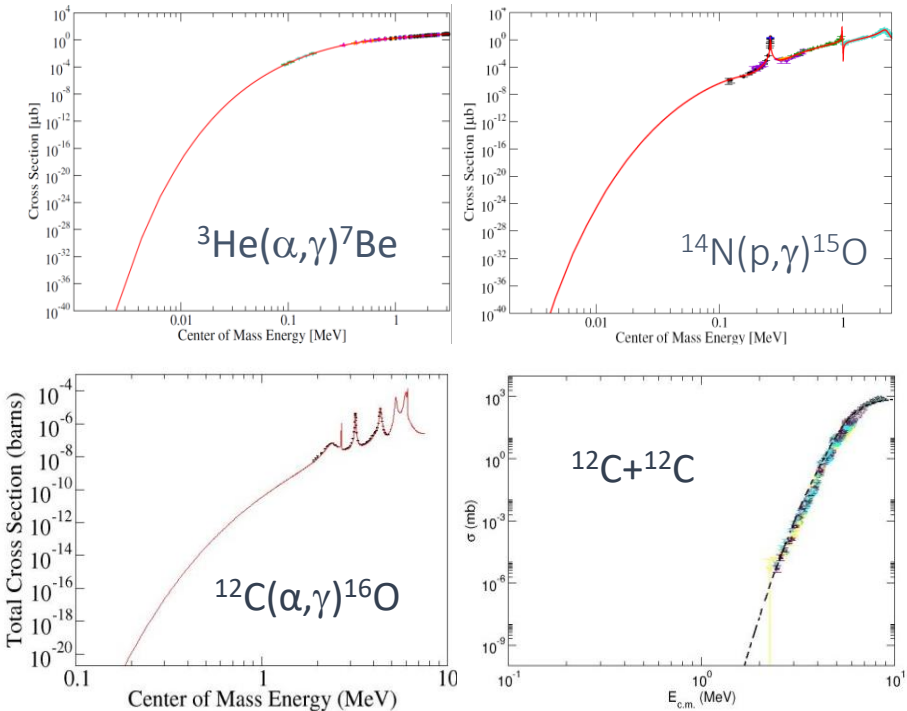
In a sufficient manner

3. We don't know the quantum physics at the threshold!

For achieving reliable extrapolation and corrections

4. We still apply the same formalism of the 1960s

Which may or may not be right



Point 1 and point 2 are given, can we do something about point 3 and point 4

Atomic interactions: electron screening, do we know electron screening in target or plasma?

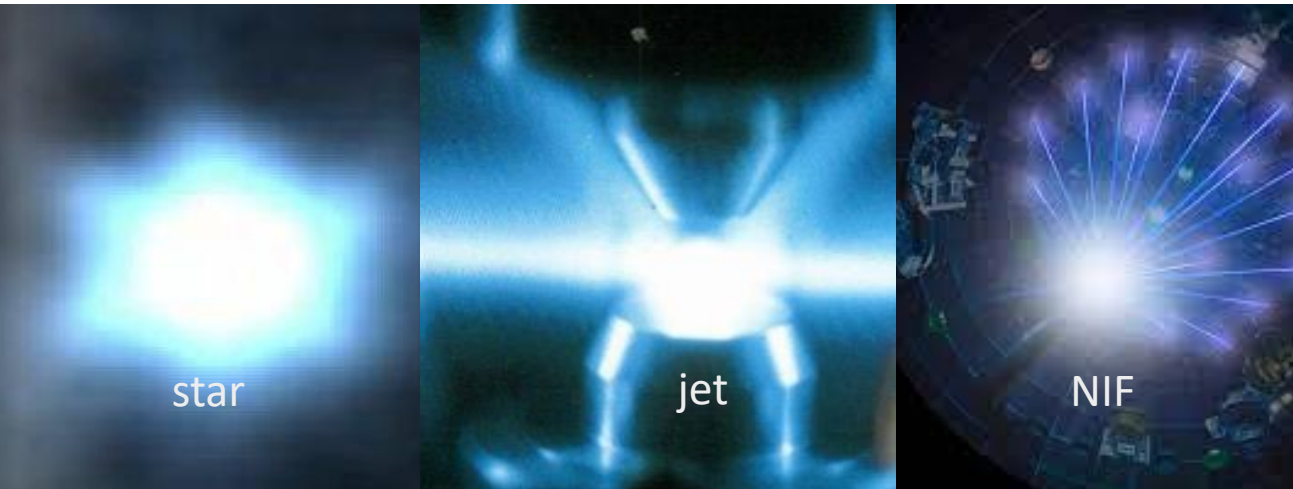
Threshold structures – alpha clustering: do we know the coupling of wave functions in the bound – unbound range?

Heavy ion interactions: Do we know the dynamics of nuclear fusion processes, does the formalism of the compound nucleus apply?

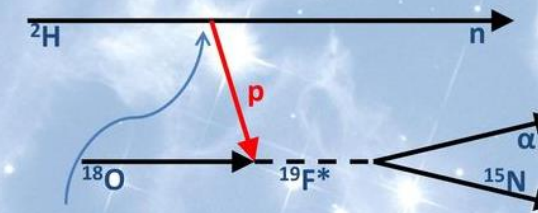
What is the impact of modeling inaccuracies in the quantum world of zero cross sections?

Electron Screening in Cold and Hot Environments

From Plasma to THM



In the “Trojan Horse Method” (THM) the astrophysically relevant reaction, in particular $^{18}\text{O}(p,\alpha)^{15}\text{N}$, is studied through an appropriate three-body process $\rightarrow {}^2\text{H}(^{18}\text{O},\alpha^{15}\text{N})n$:

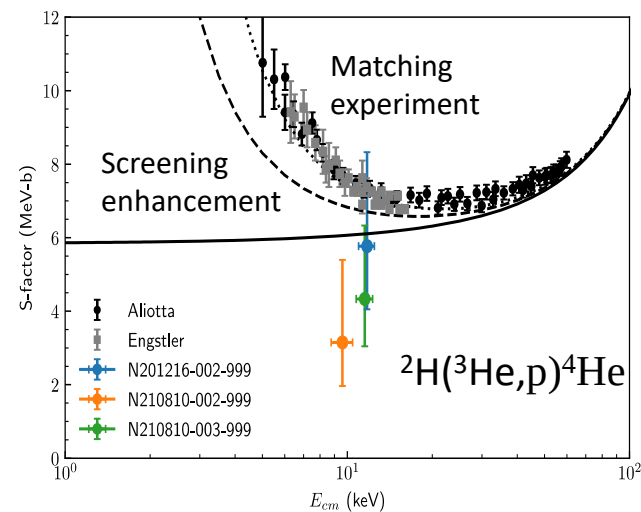
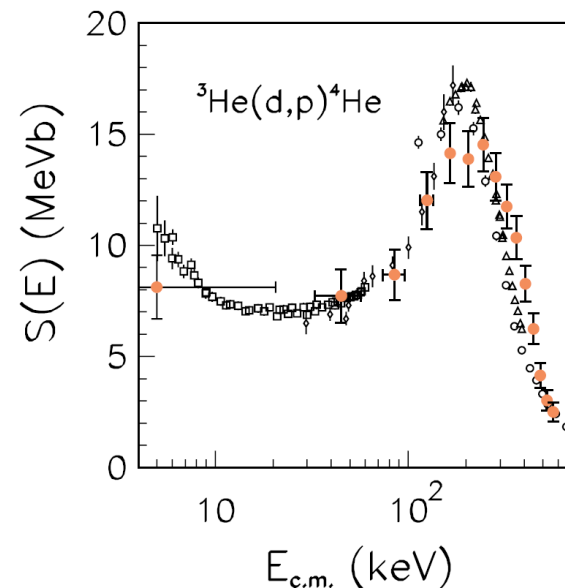


The process is a transfer to the continuum where proton (p) is the transferred particle

Upper vertex: direct deuteron breakup

THM

Standard R-Matrix approach cannot be applied to extract the resonance parameters of the $^{18}\text{O}(p,\alpha)^{15}\text{N} \rightarrow$ Modified R-Matrix is introduced instead

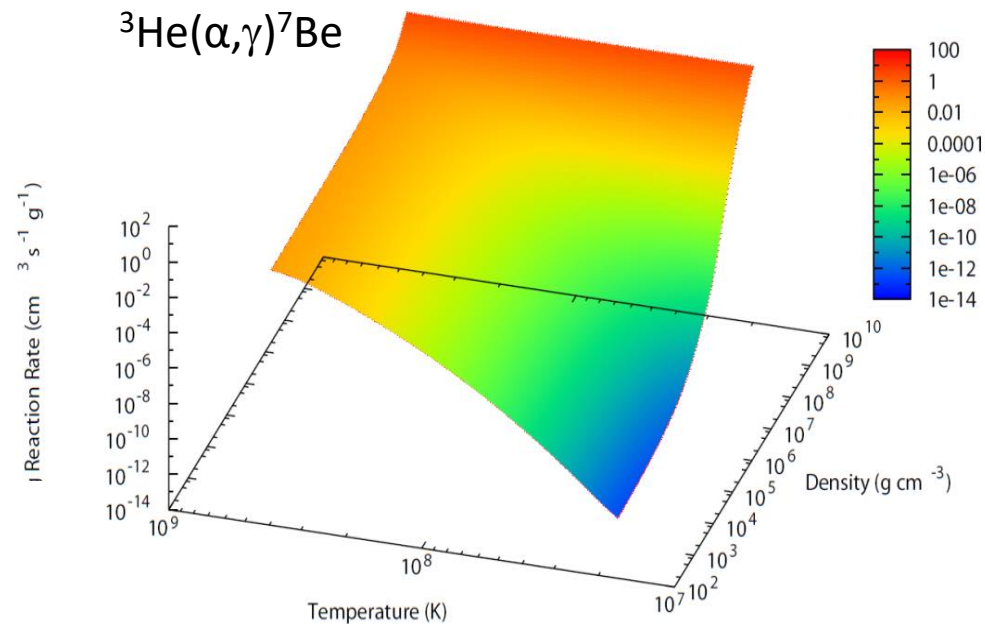
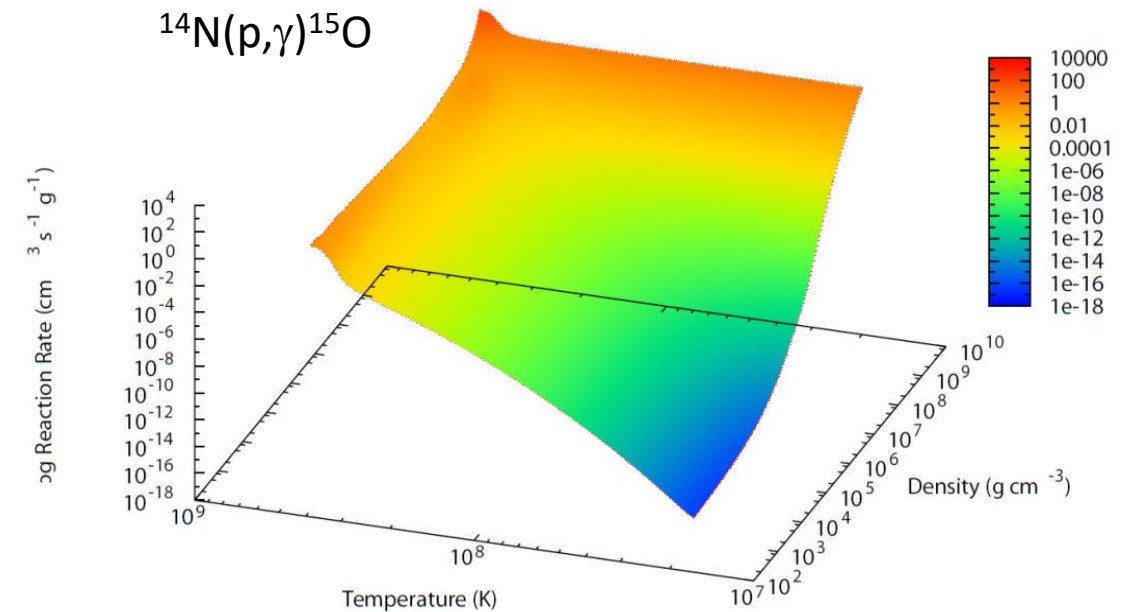


Are these disagreements in the data for real?
What causes the screening enhancement factor in the theoretical predictions?

Electron Screening

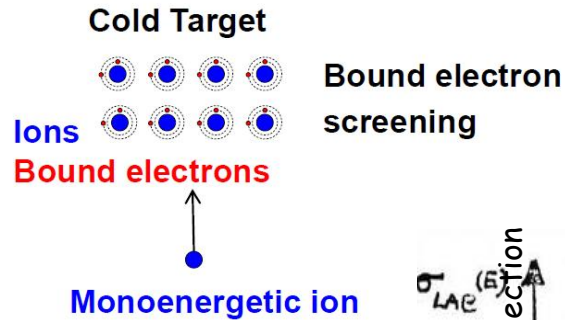
Gamow Window

$$N_A \langle \sigma v \rangle = \sqrt{\frac{8}{\pi \cdot \mu}} \cdot (kT)^{-3/2} \cdot \int_0^{\infty} E \cdot f_{sc}(E) \cdot \sigma(E) \cdot \exp\left(-\frac{E}{kT}\right) dE$$



Are such conditions achievable on earth to test the theoretical predictions for electron screening?

Electron Screening in Stars and Laboratory



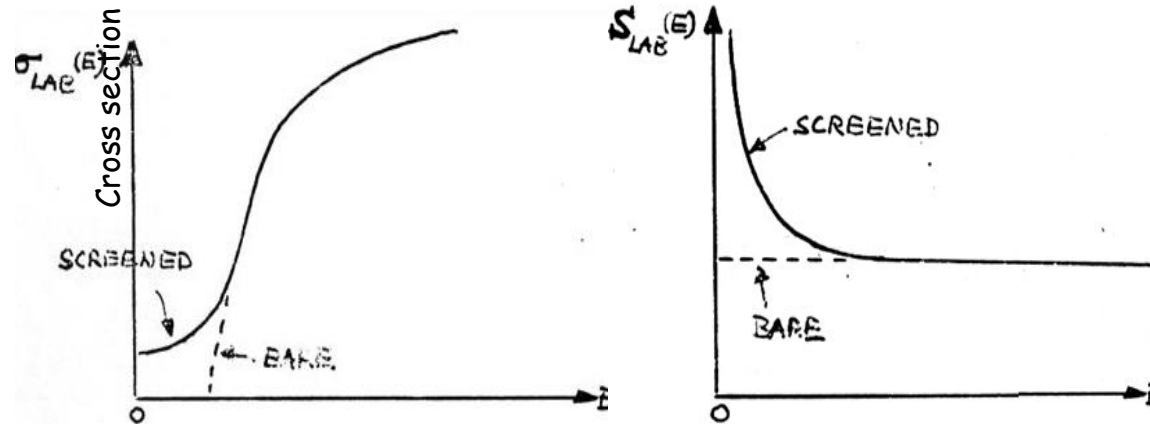
Deflective Coulomb Potential: U_{Cb}
Electron Screening Potential: U_{sc}

$$U_{Cb} = \frac{Z_1 \cdot Z_2 \cdot e^2}{r} - U_{sc}(E)$$

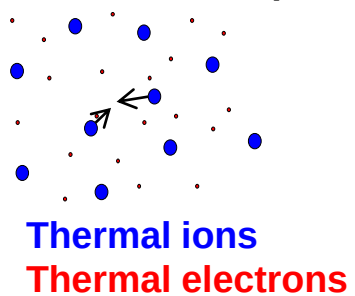
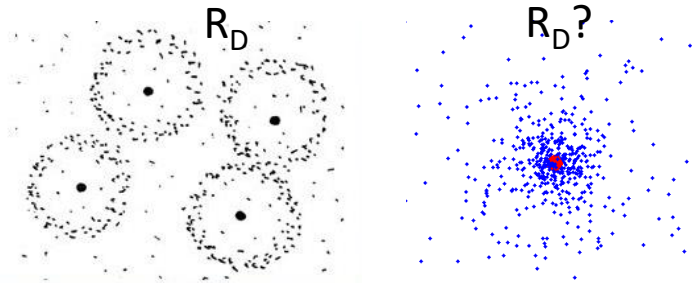
$$U_{sc}(E) = \frac{Z_1 \cdot Z_2 \cdot e^2}{R} \quad R: \text{radius of electron cloud}$$

$$\sigma_{sc}(E) = f_{sc}(E) \cdot \sigma_{bn}(E)$$

$$\text{for } E \gg U_{sc}: f_{sc}(E) = \exp\left(\frac{U_{sc}(E)}{kT}\right)$$



Dense and hot plasma



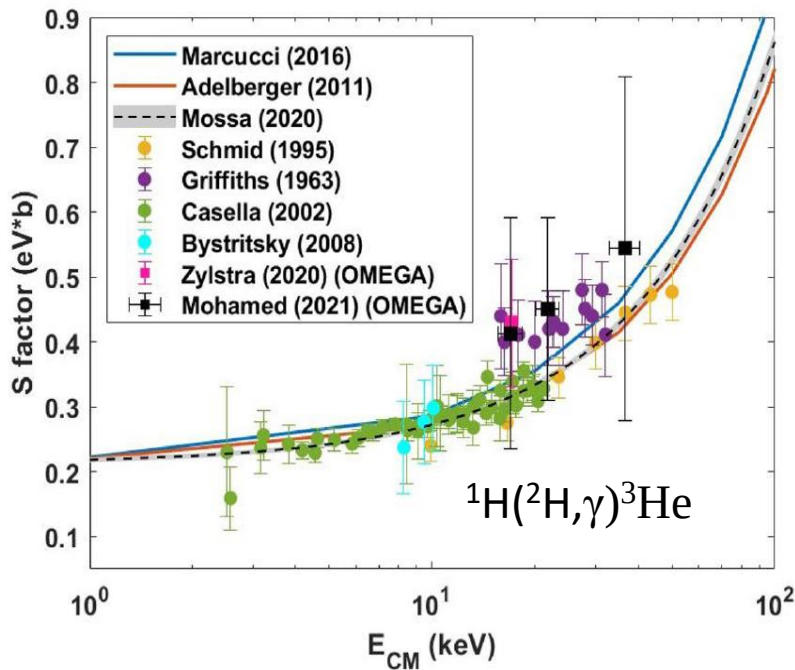
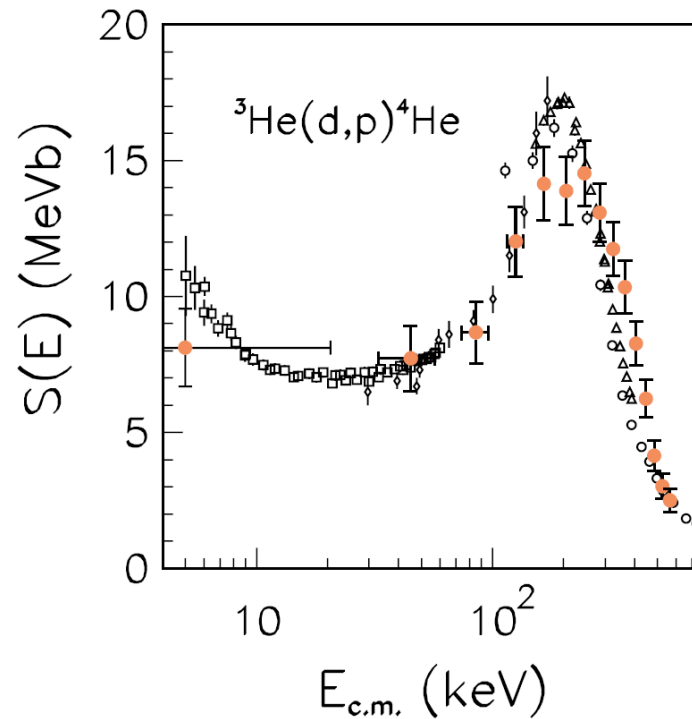
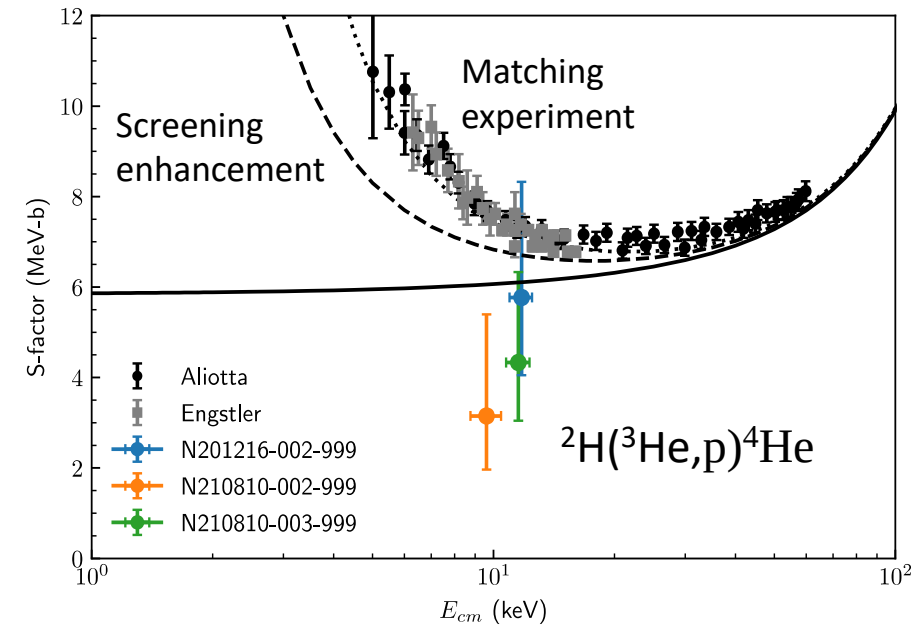
$$R_D = \sqrt{\frac{kT}{4\pi \cdot e^2 \cdot \rho \cdot N_A \cdot \xi}}$$

$$\xi = \sum_i (Z_i^2 + Z_i) \cdot \frac{X_i}{A_i}$$

$$f_{sc}(E) \approx 1 + \frac{U_{sc}(E)}{kT} + \dots$$

Debye Hückel Theory: screening effect increases with density; from weak to strong screening!

Comparison after screening corrections



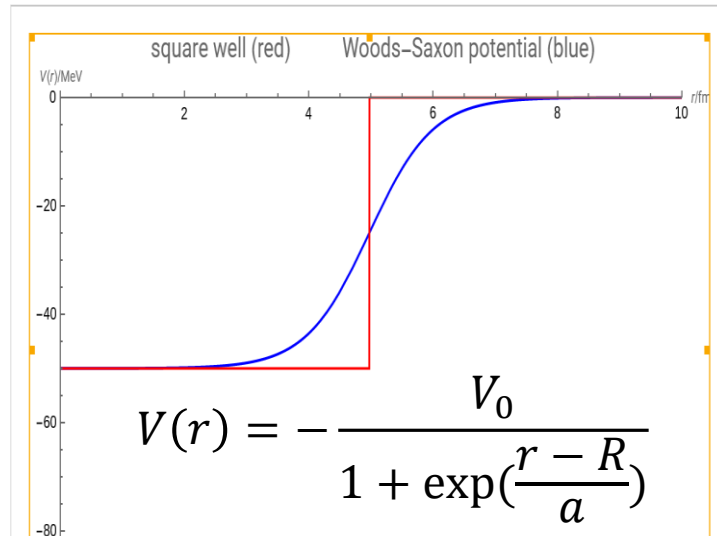
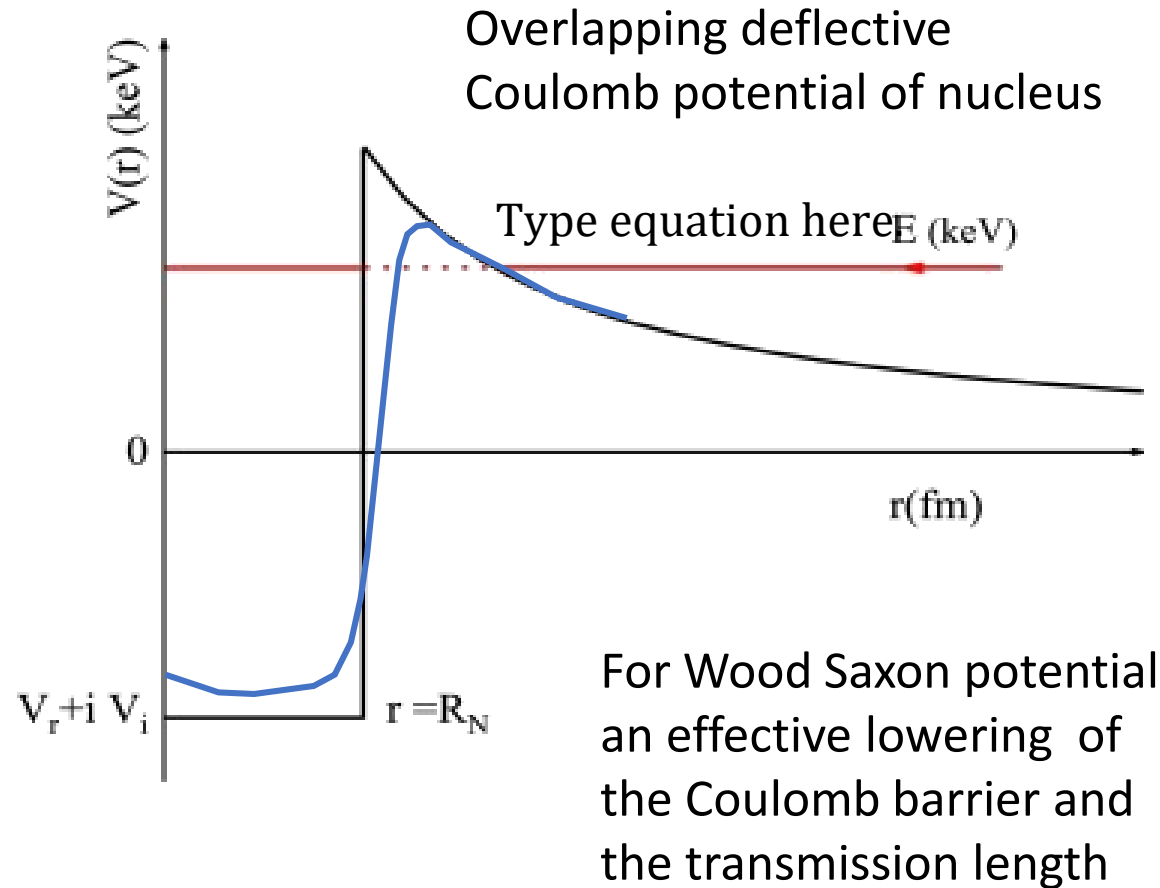
How good is our conversion from laboratory screening to plasma screening or vice versa? How well defined is the Debye radius and other rather approximate parameters in the Debye-Hückel theory?

$$\frac{f_{star}}{f_{lab}} = \exp\left(\frac{U_{sc}^{star} - U_{sc}^{lab}}{kT}\right)$$

$$= \exp\left(\frac{Z_1 \cdot Z_2 \cdot e^2}{kT} \cdot \left(\frac{1}{R_D} - \frac{1}{R_A}\right)\right)$$

The choice of the nuclear potential and the impact on the Coulomb potential

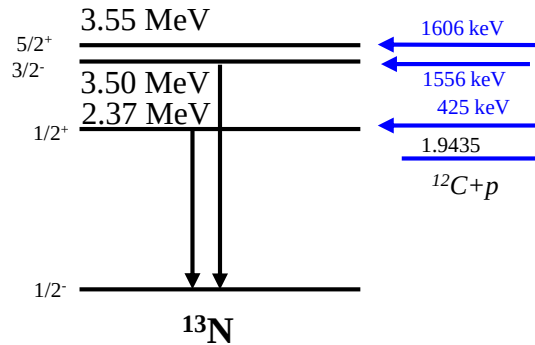
Nuclear Square Well versus Wood Saxon potential with a diffuseness $a=0.65$.



Modern R-matrix simulations are based on square well potential, how strong is the subsequent potential effect?

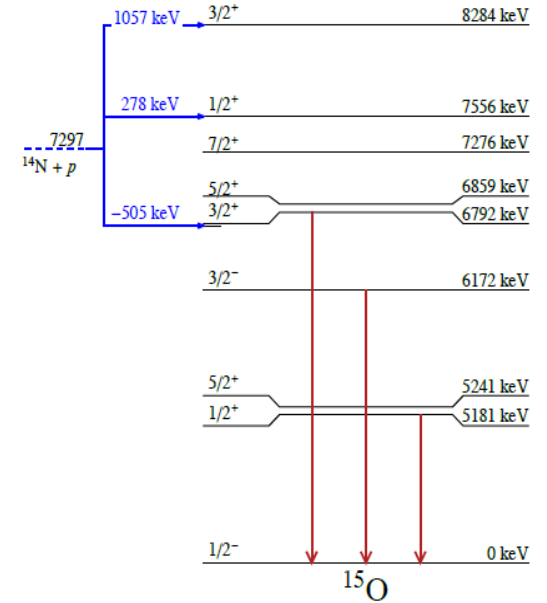
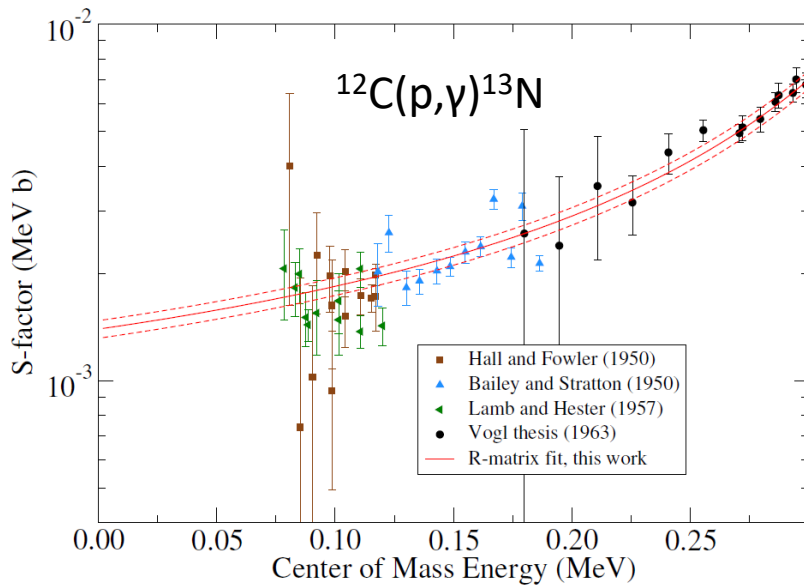
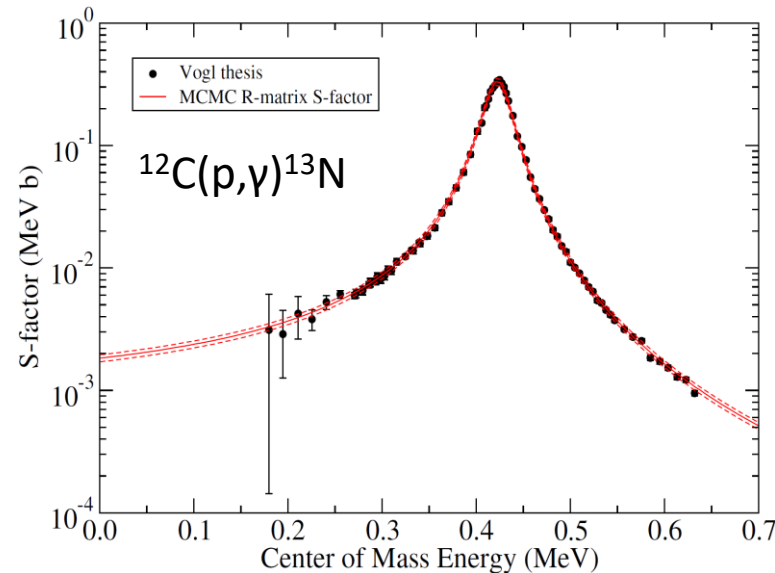
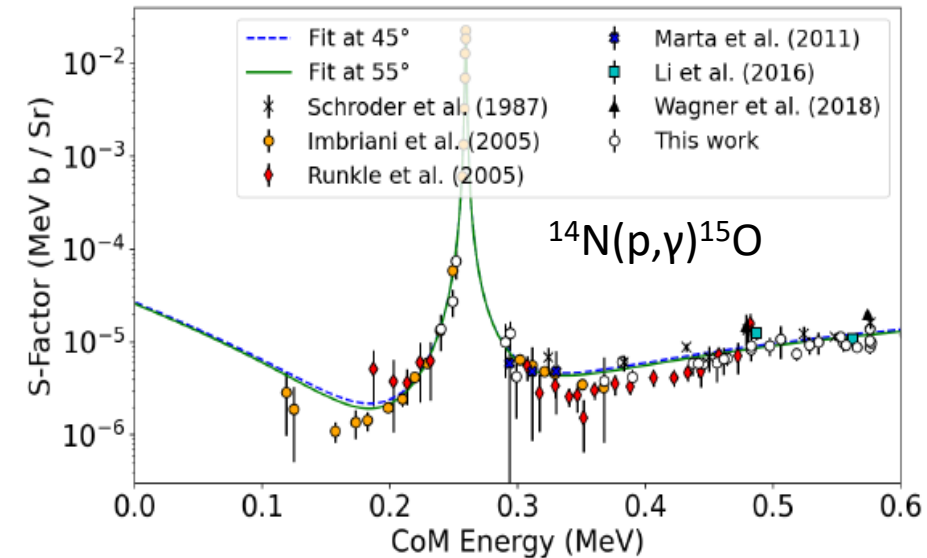
Neutrinos as Observable Signatures

Status of Neutrino-Sources

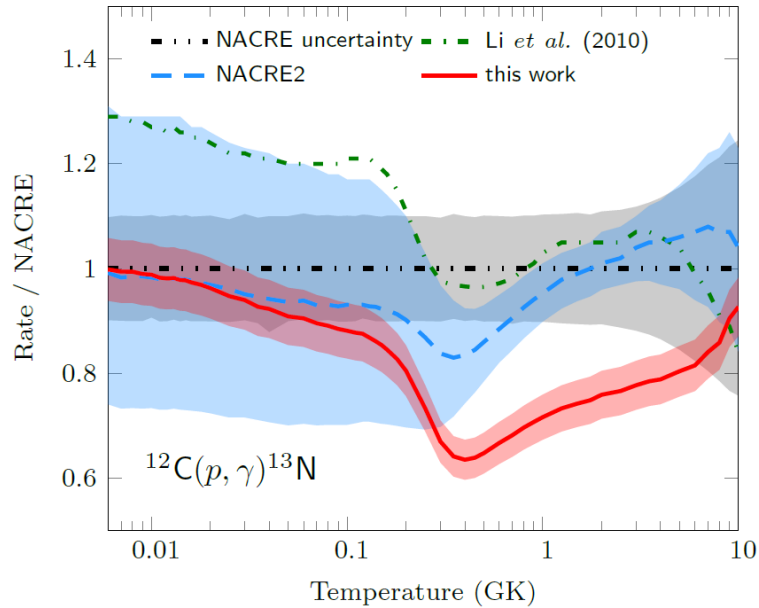


Neutrino Activity

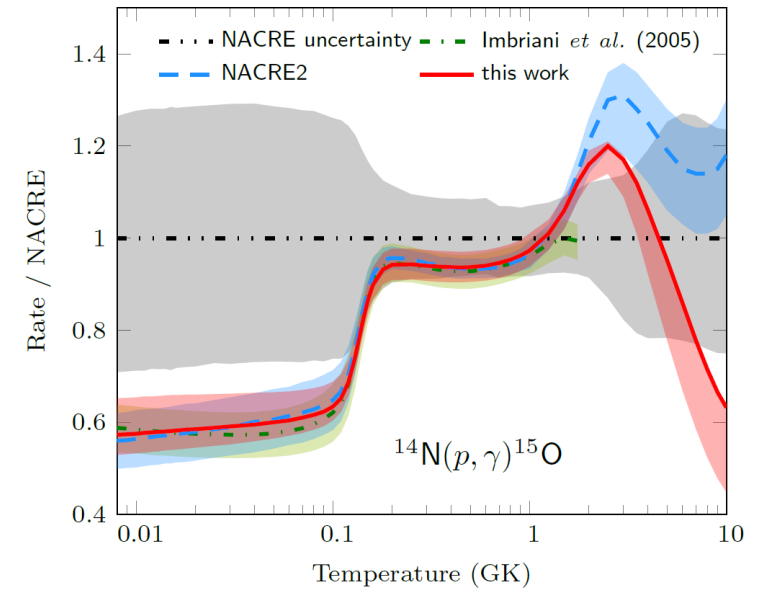
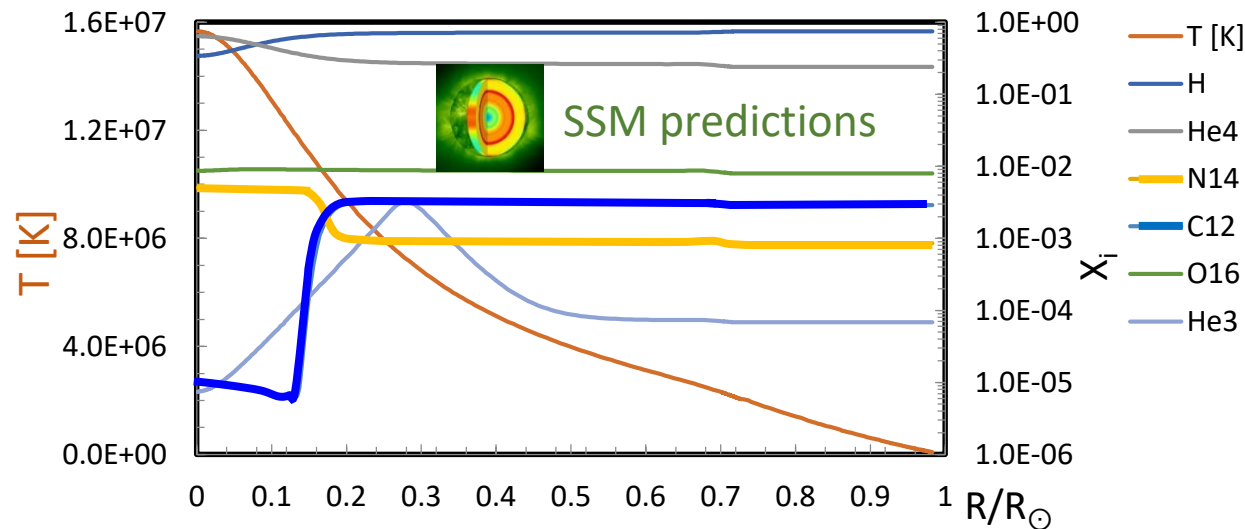
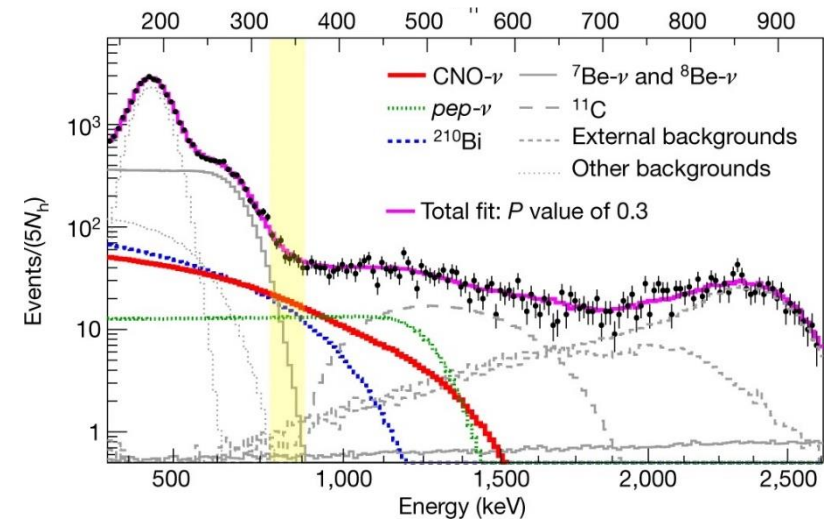
$$A_\nu = \lambda \cdot N = \lambda \cdot \rho \cdot N_A \cdot \frac{X}{A}$$



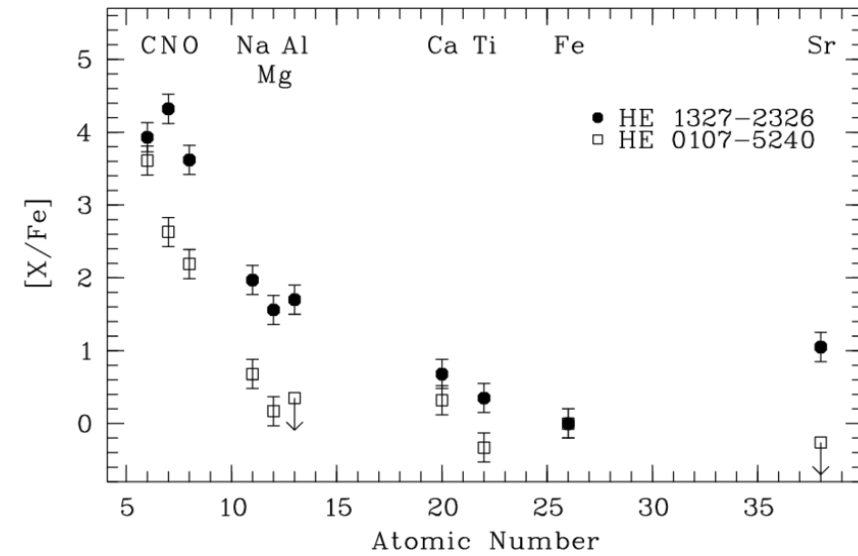
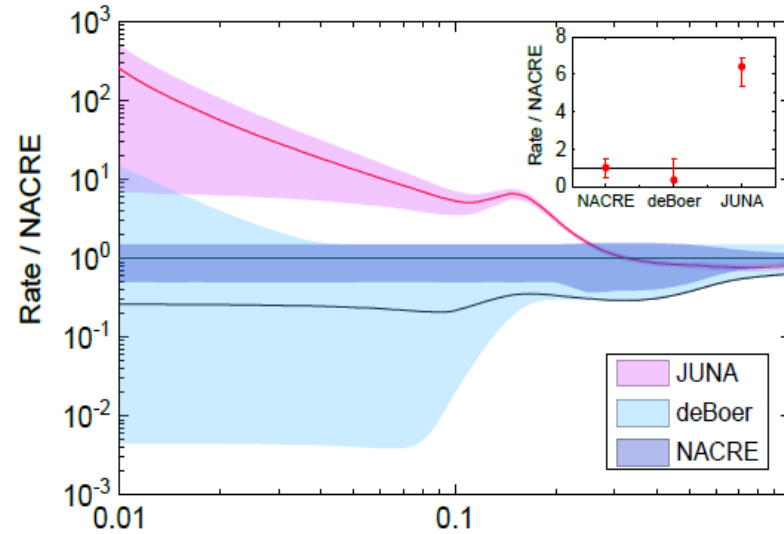
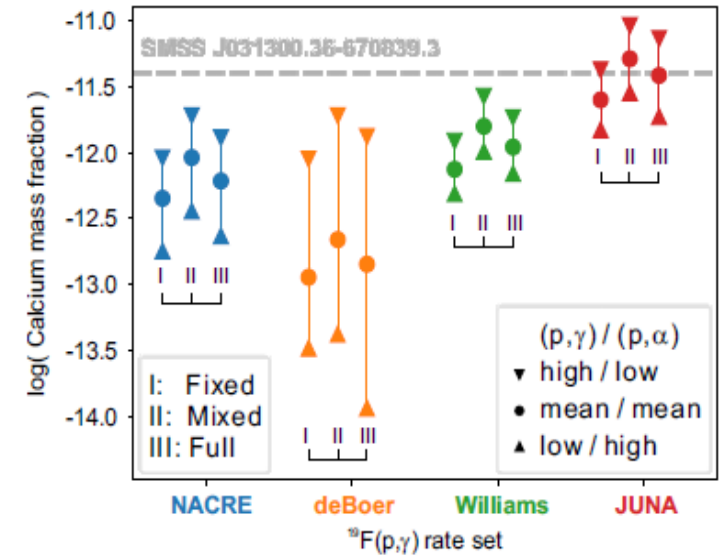
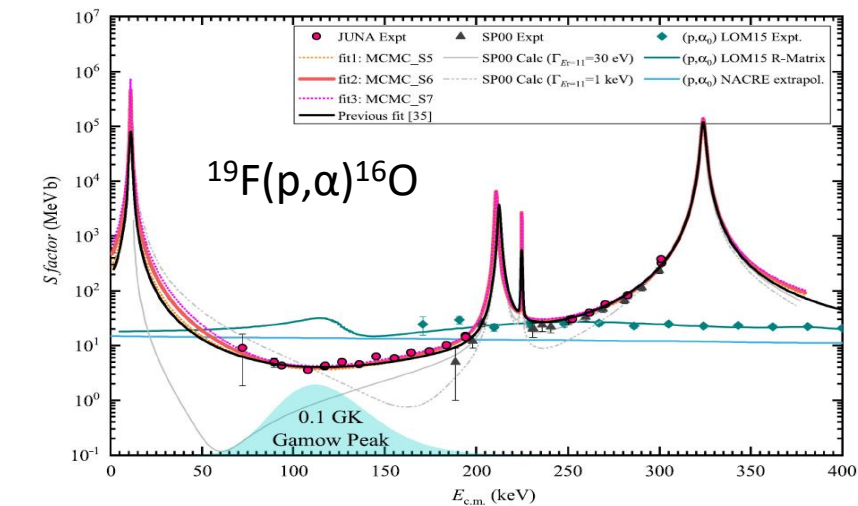
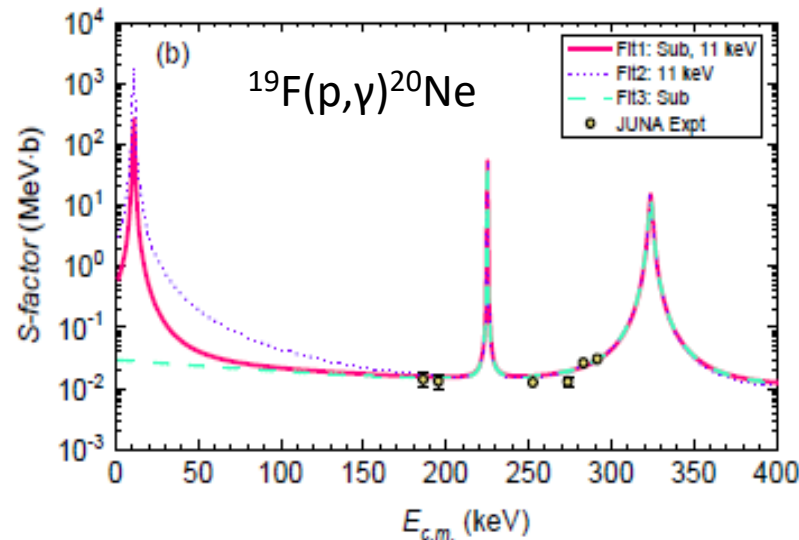
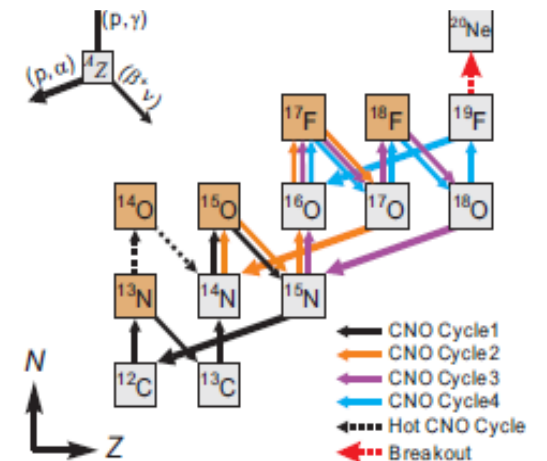
CNO Neutrinos & the metallicity of the solar core



To what level of accuracy are reaction data needed in view of uncertainties in the standard solar model and the observational CNO neutrino results



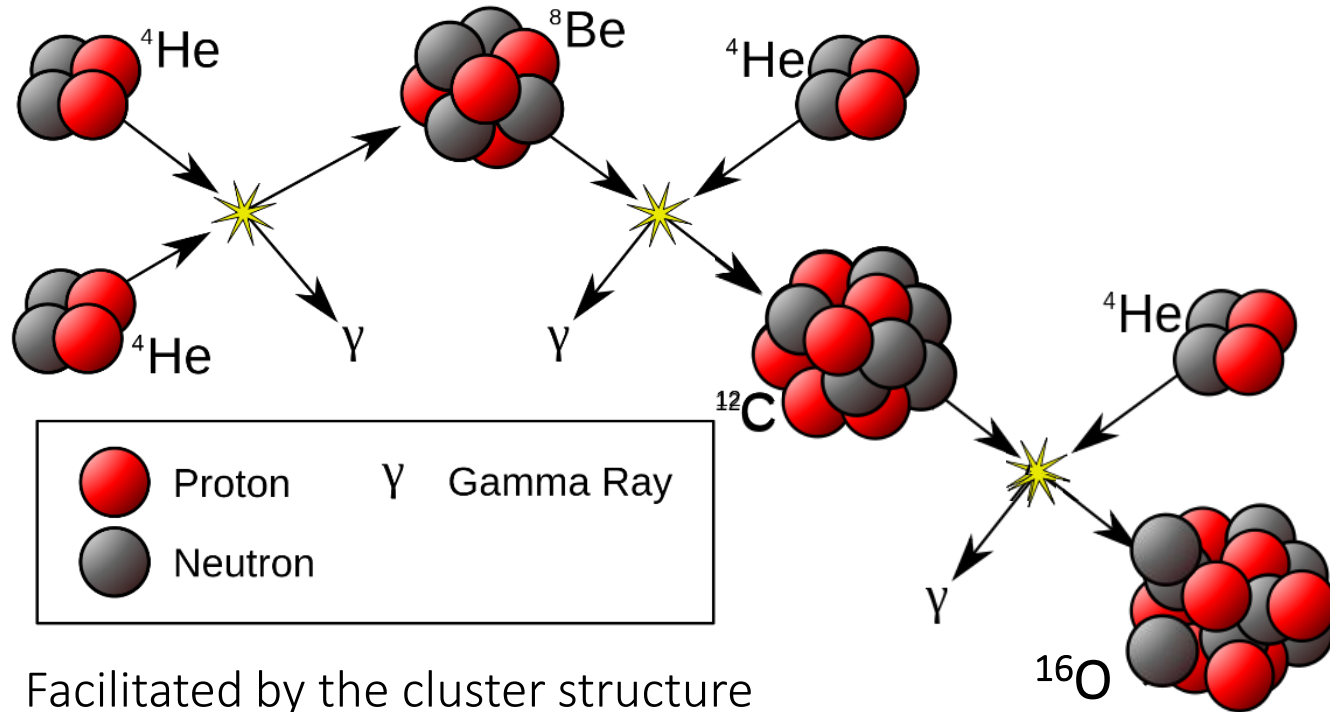
$^{19}\text{F}(p,\gamma)^{20}\text{Ne}$, break-out from cold CNO cycle



-- $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ --

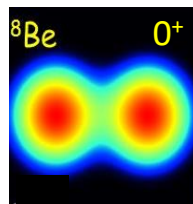
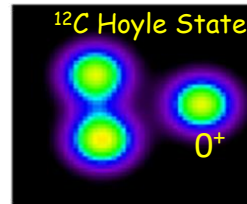
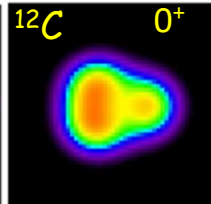
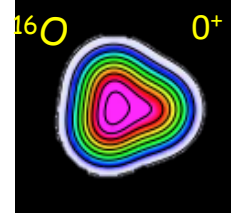
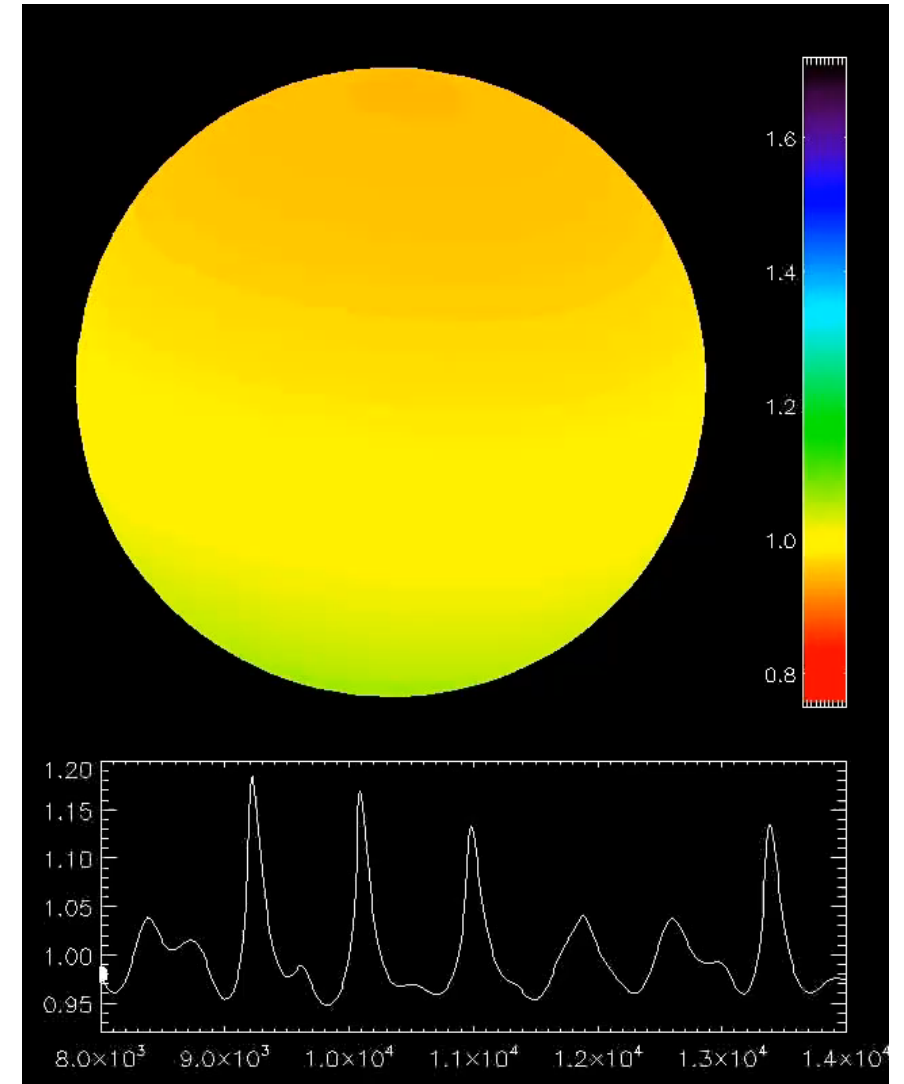
WD seismology and BH mass-gap

Triple alpha process followed by $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

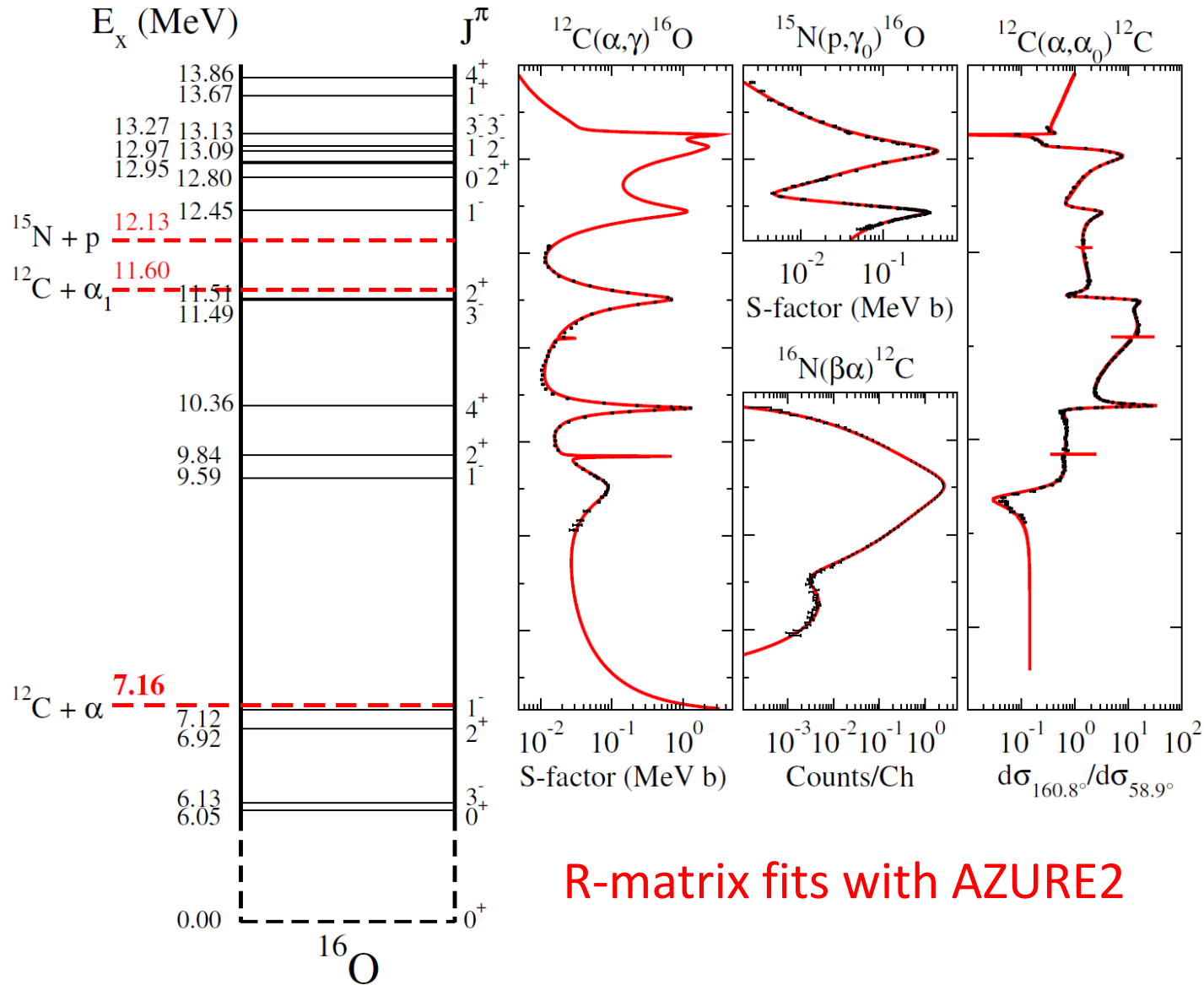


Facilitated by the cluster structure of the ^8Be and the ^{12}C Hoyle State

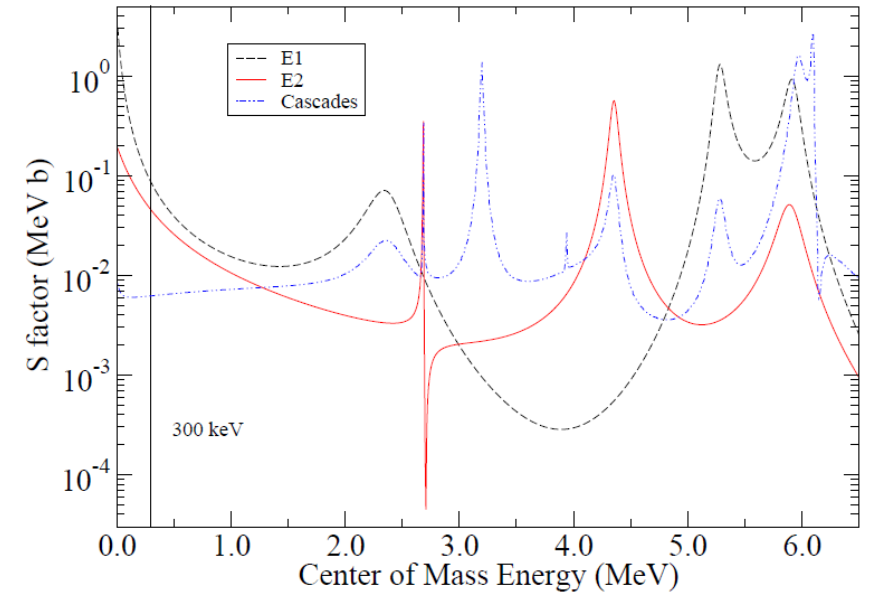
Y. Kanada En'yo, M. Kimura,
A. Ono, Prog. of Theo. Exp.
Phys..2012 (2012) 01A202



From Cluster Configuration to Cross Section



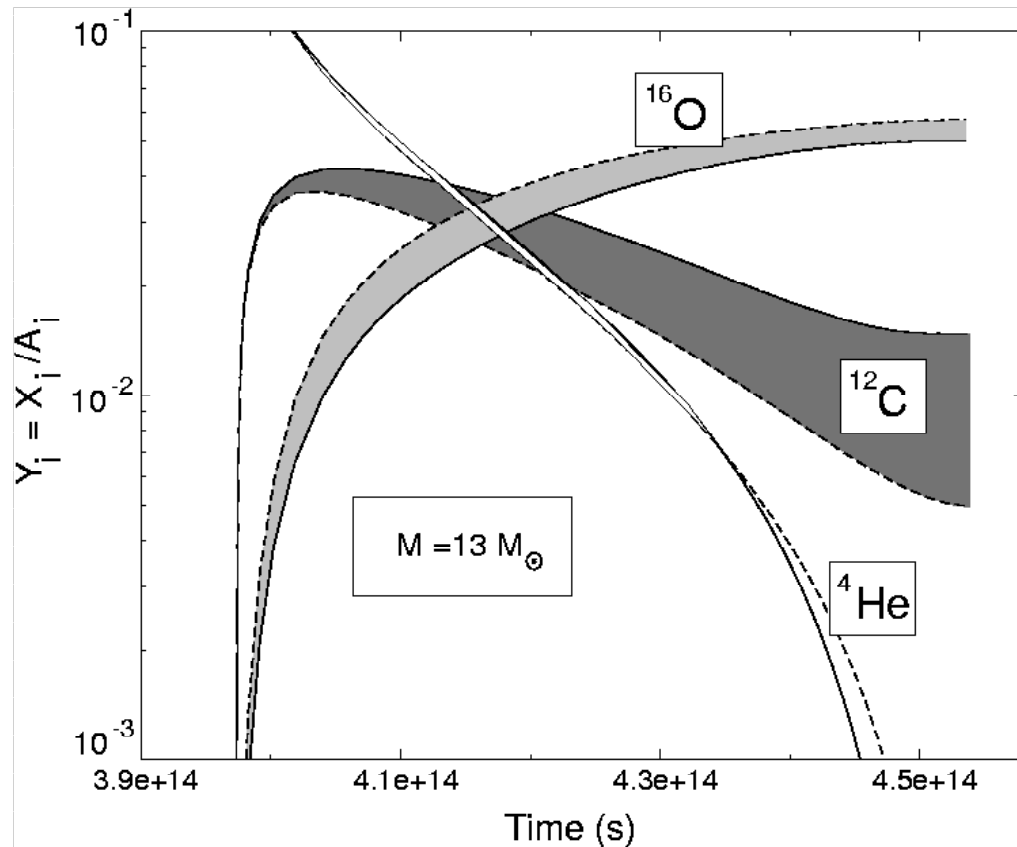
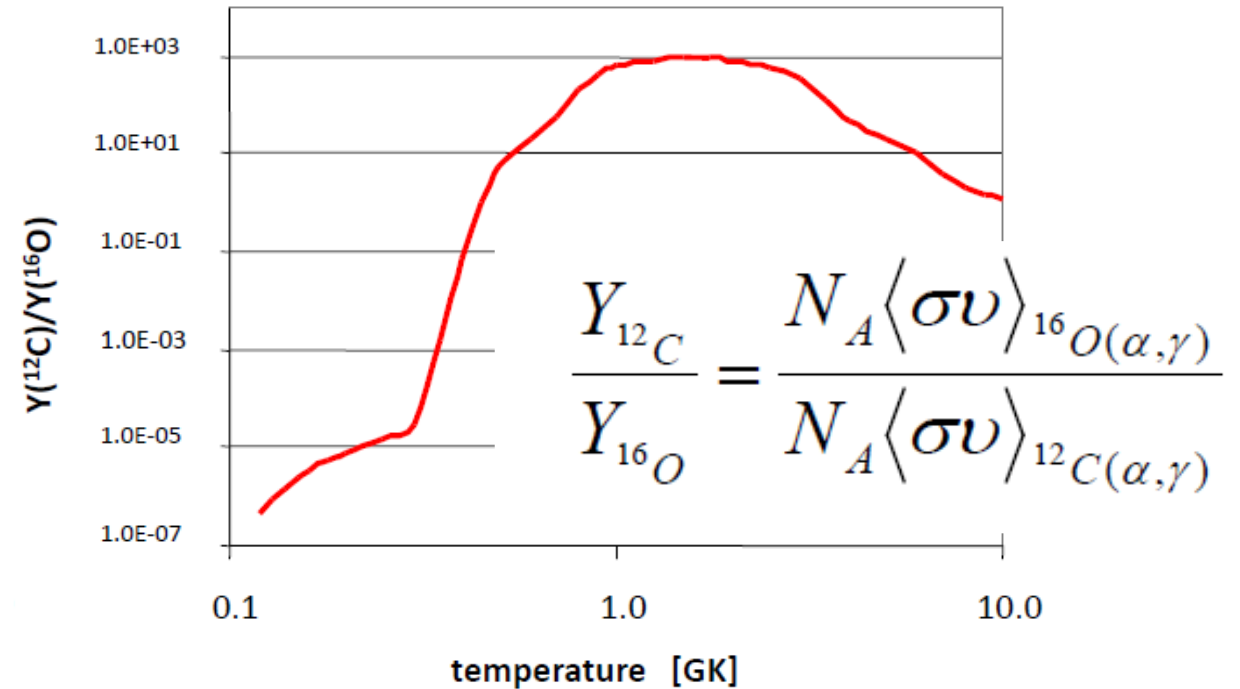
R-matrix fits with AZURE2



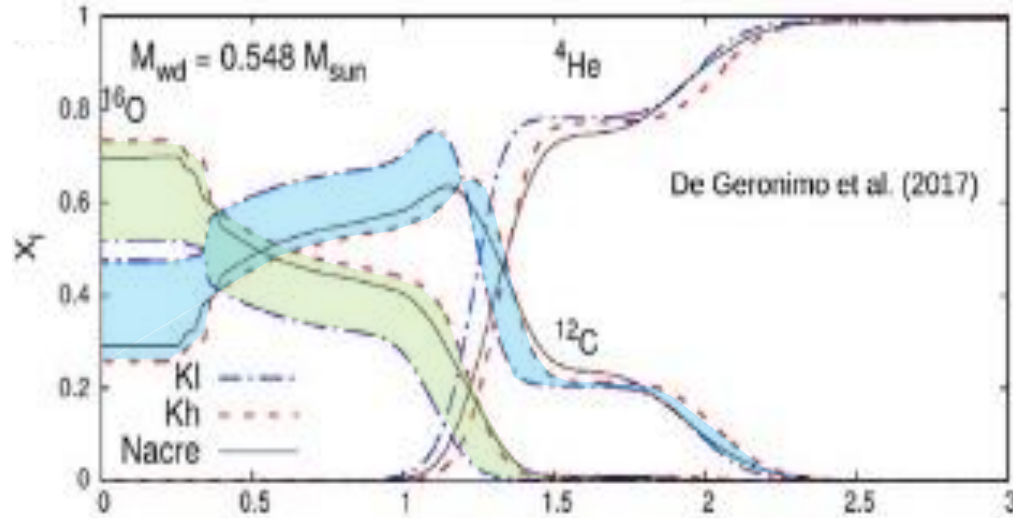
Different E1, E2, and cascade reaction components, reflecting the interference patterns between 0^+ states and 2^+ states with direct capture transitions.

Carbon oxygen balance

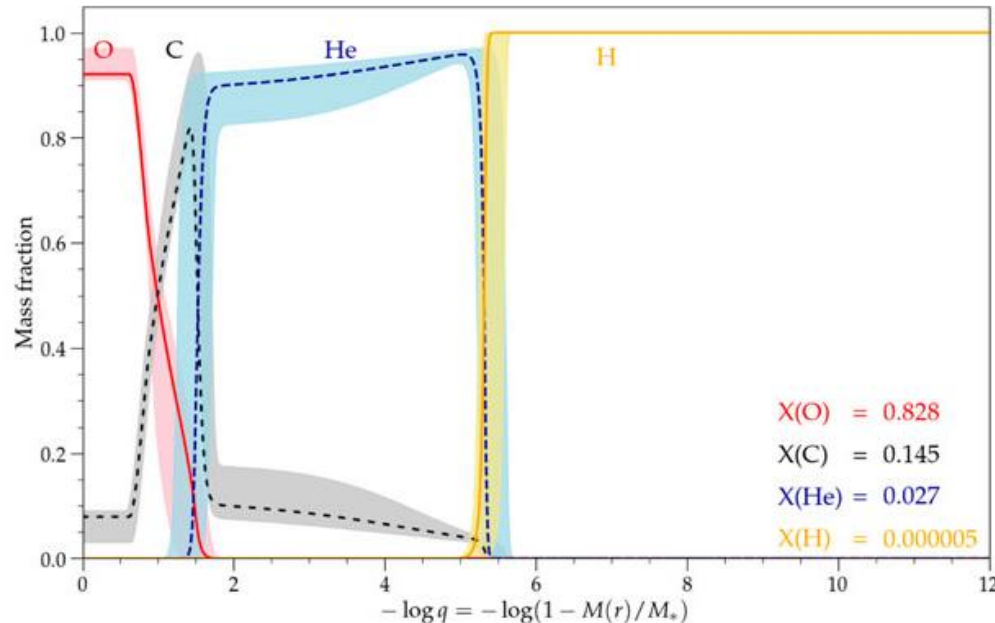
$$\frac{dY_{16O}}{dt} = -Y_{16O} \cdot Y_{4He} \cdot \rho \cdot N_A \langle \sigma v \rangle_{16O(\alpha,\gamma)} + Y_{12C} \cdot Y_{4He} \cdot \rho \cdot N_A \langle \sigma v \rangle_{12C(\alpha,\gamma)} = 0$$



White Dwarf Composition from Astro-seismology



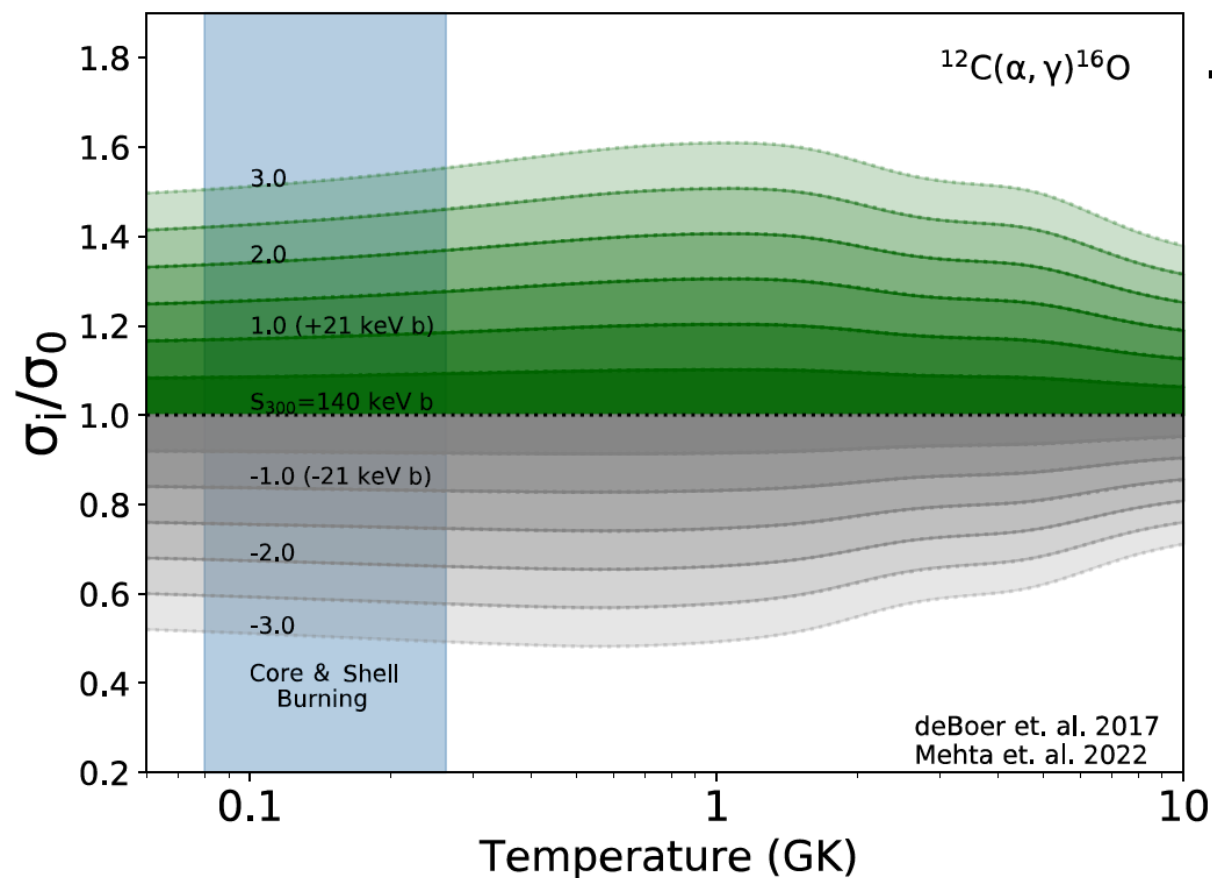
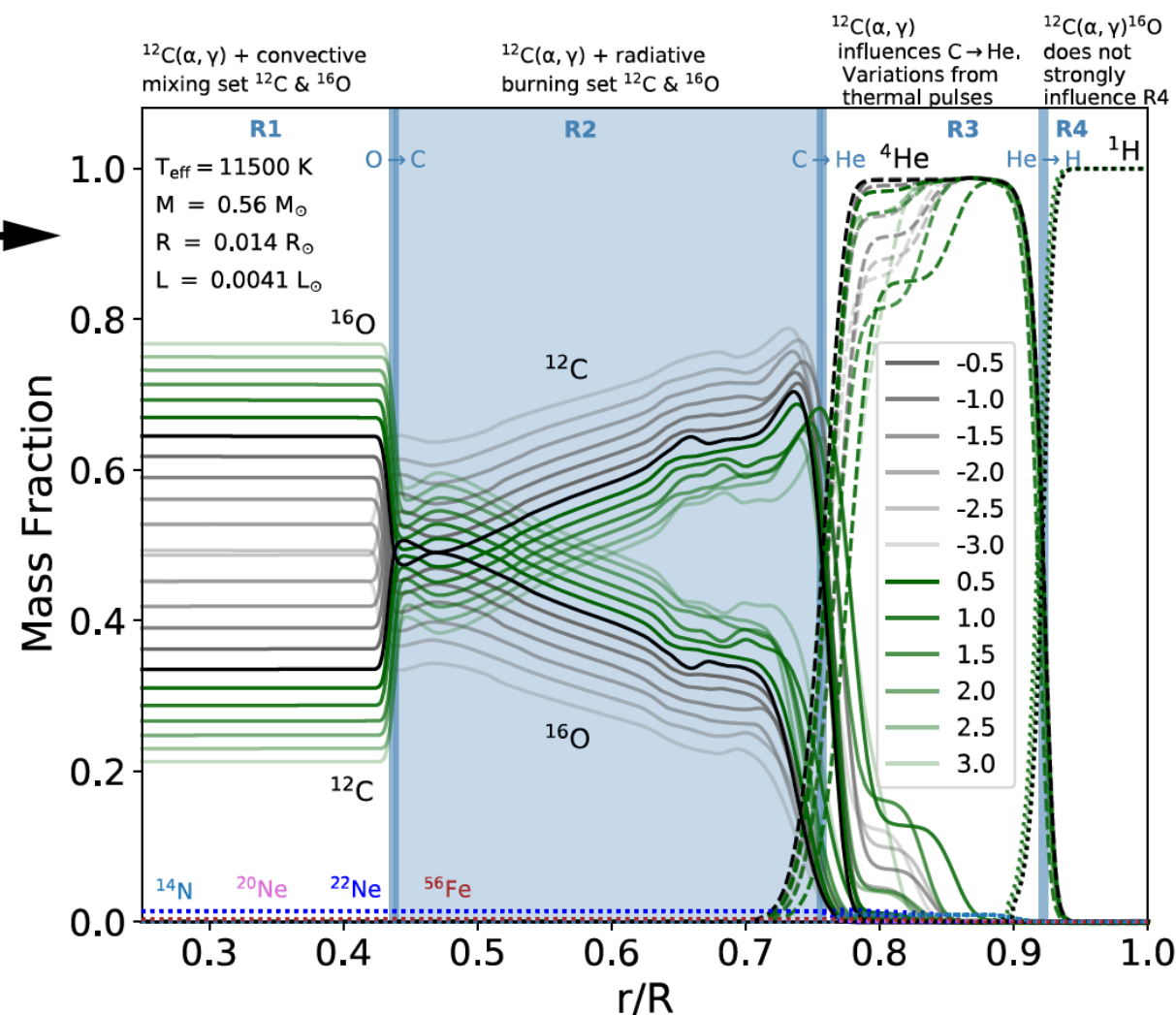
Composition profiles of helium, carbon, and oxygen as functions of the fractional mass depth in a typical DA white dwarf produced by assuming different nuclear reaction rates in evolution calculations.



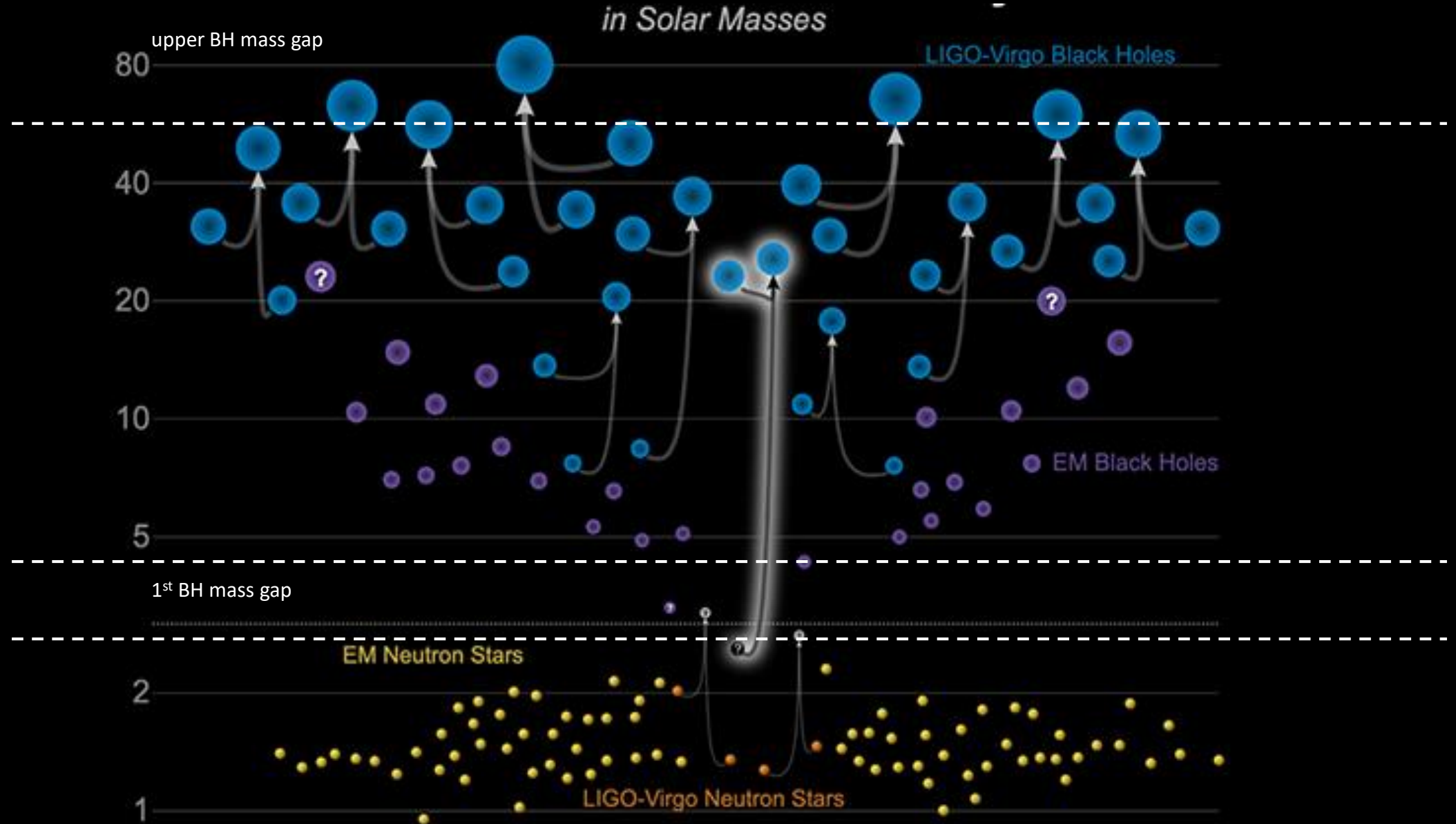
Chemical stratification of White Dwarf SDSS J1136 + 0409. Distribution of oxygen (in red), carbon (in grey), helium (in blue), and hydrogen (in orange) obtained from the optimal seismic model within the range of uncertainties.

Uncertainties

An increase in the rate would help, but there is a lot of uncertainty in the convection conditions!

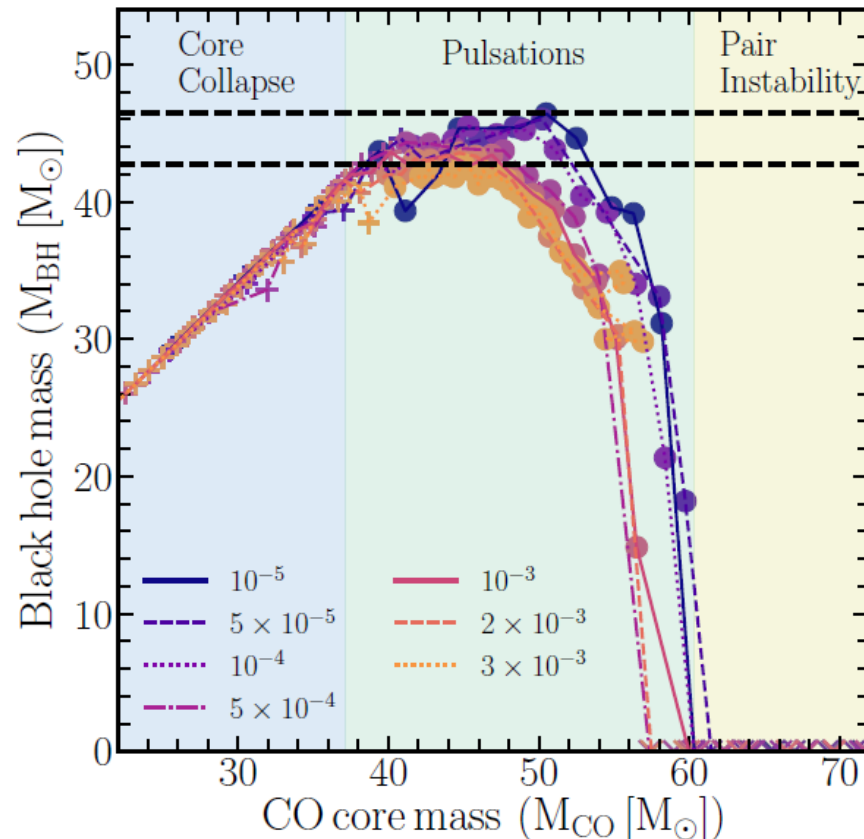
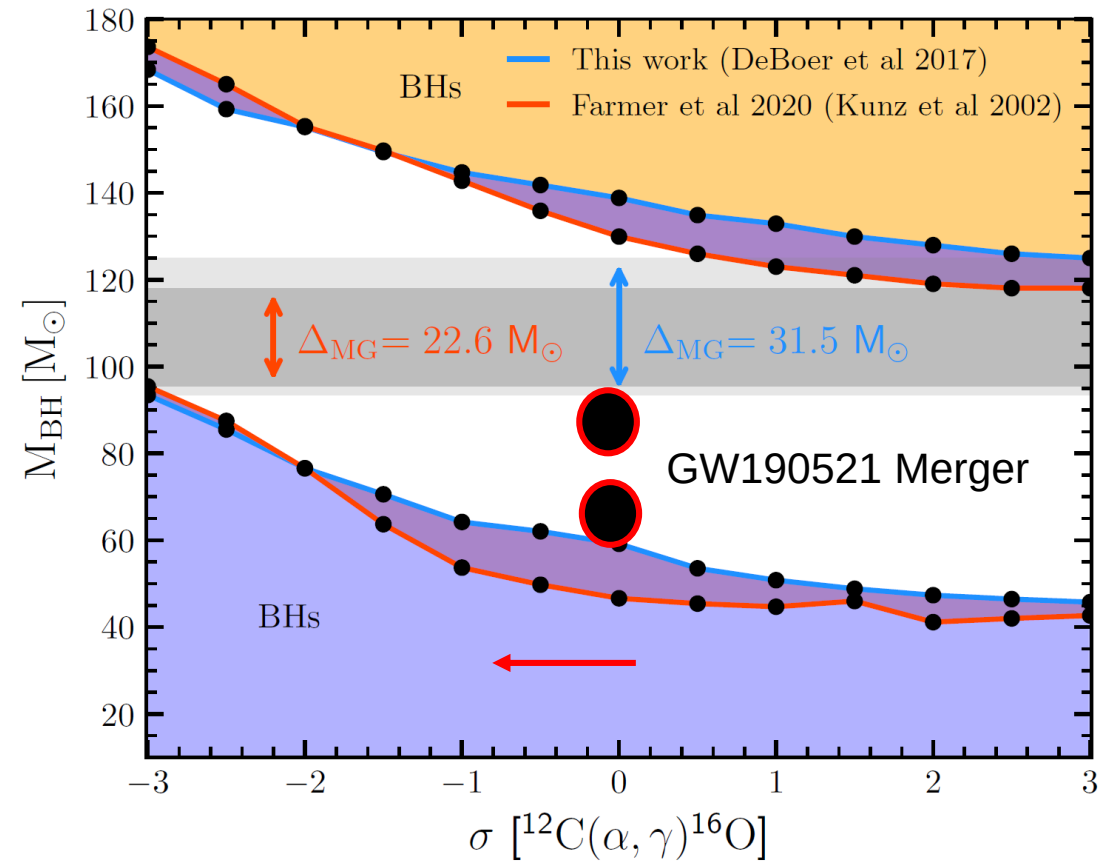


Masses in the Stellar Graveyard



Impact on pair production supernovae

For a very massive star internal γ rays become so energetic that they trigger pair production, destabilizing the stellar core. This causes explosive oxygen burning ($^{16}\text{O}+^{16}\text{O}$) disrupting the star without remnant (NS or BH). This causes a mass gap in the black hole distribution. The mass limits are determined by $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$! A reduction of the rate would improve, but there is a lot of uncertainty in the mixing prescriptions.

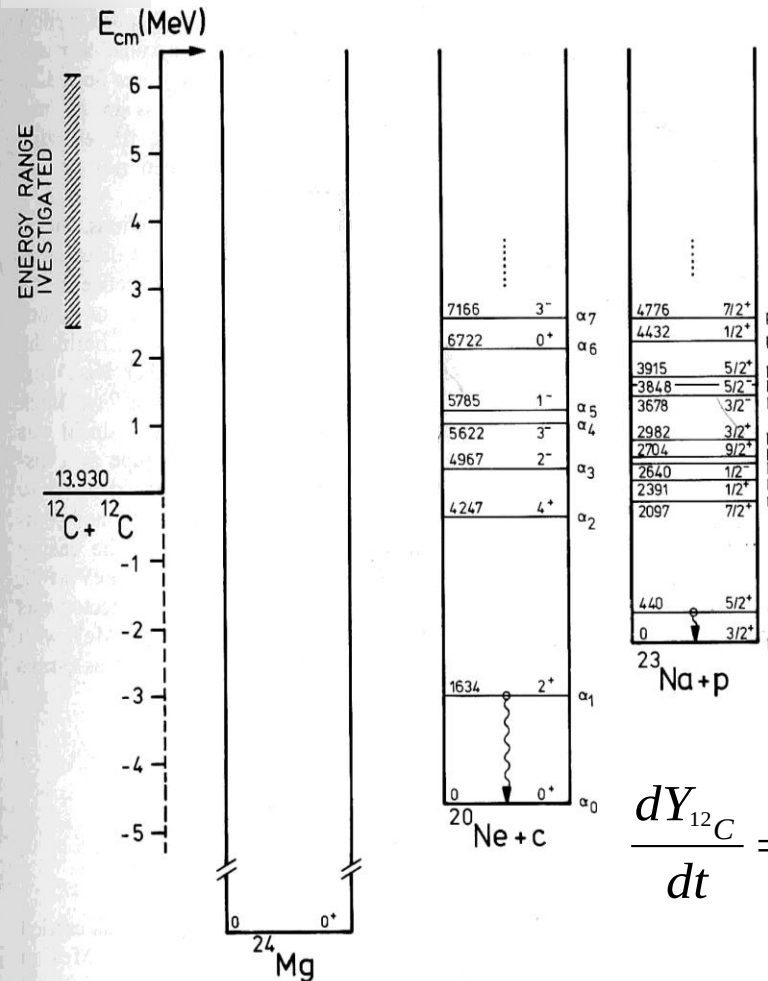
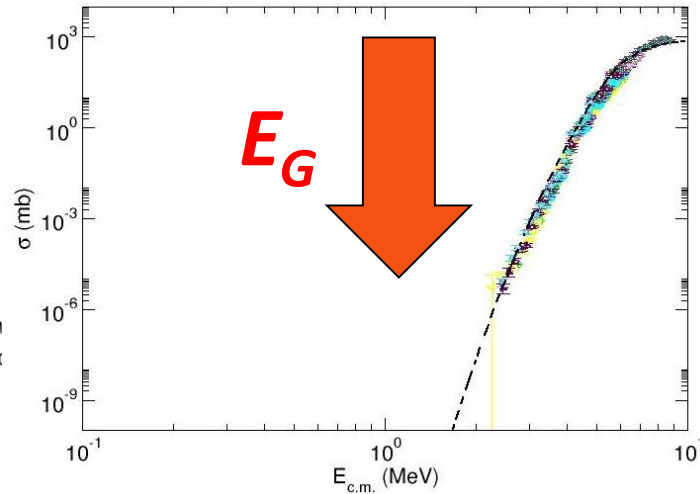


Carbon Fusion

The problem of Hindrance

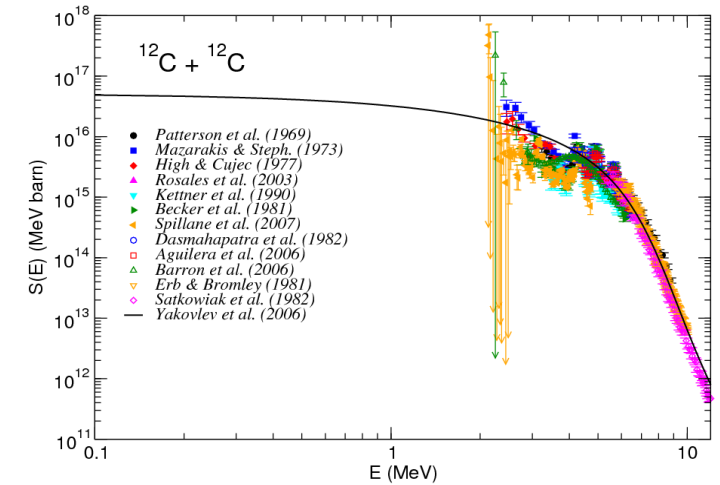
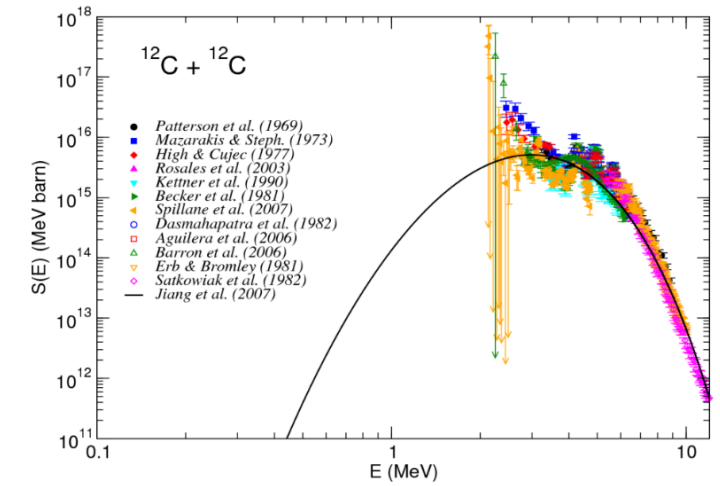
The nature of low energy resonances

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



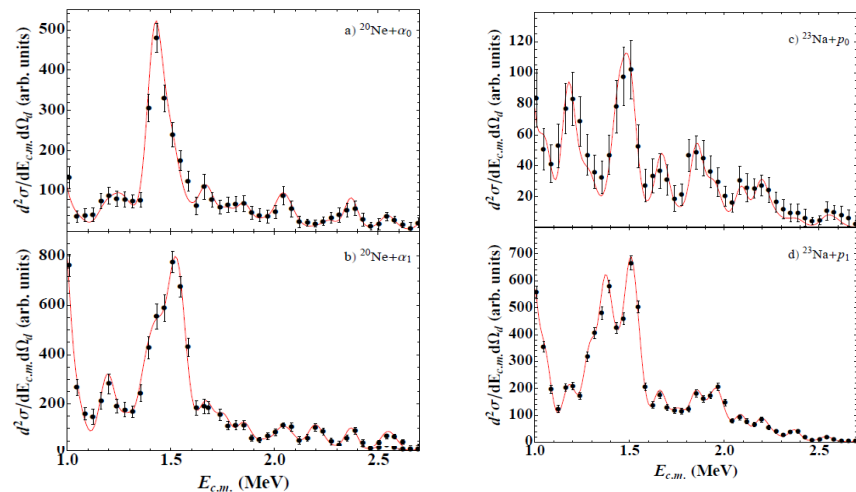
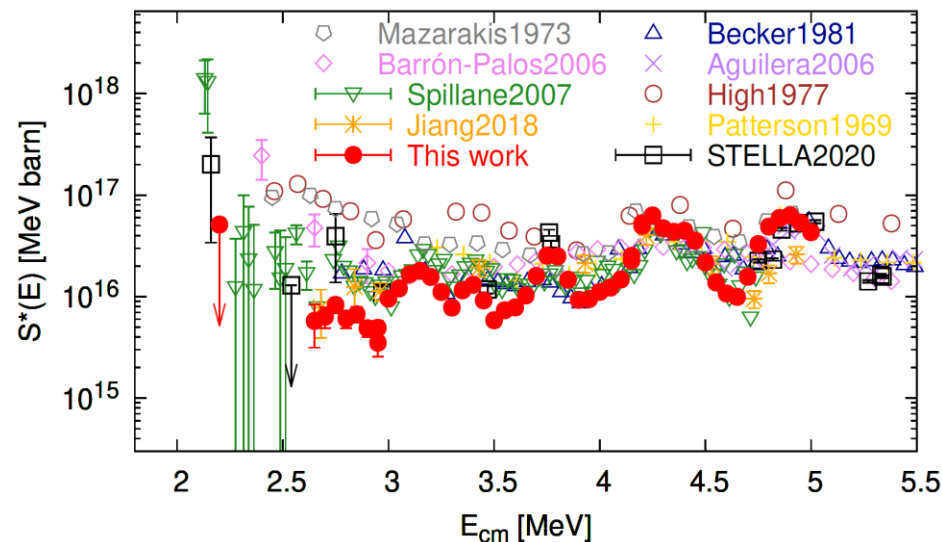
Different potential models lead to different ways to extrapolate the low energy cross section (S-factor).

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

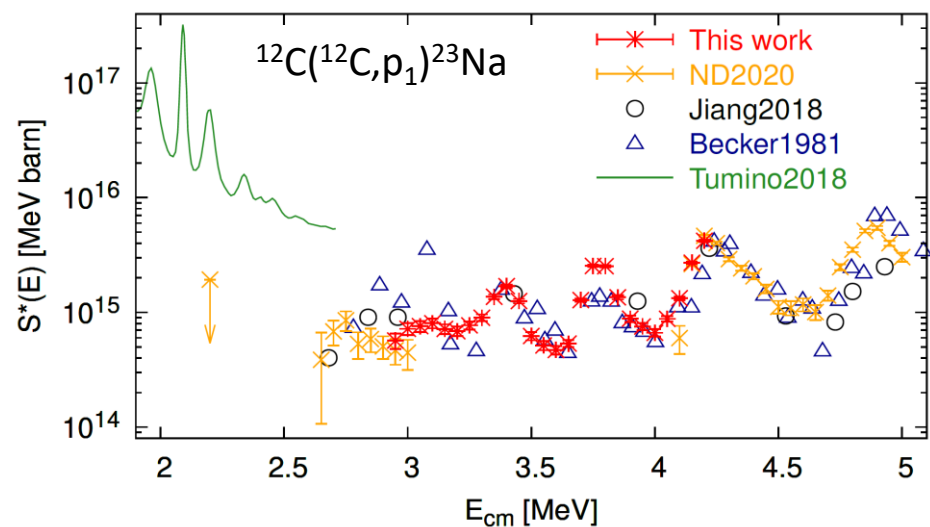
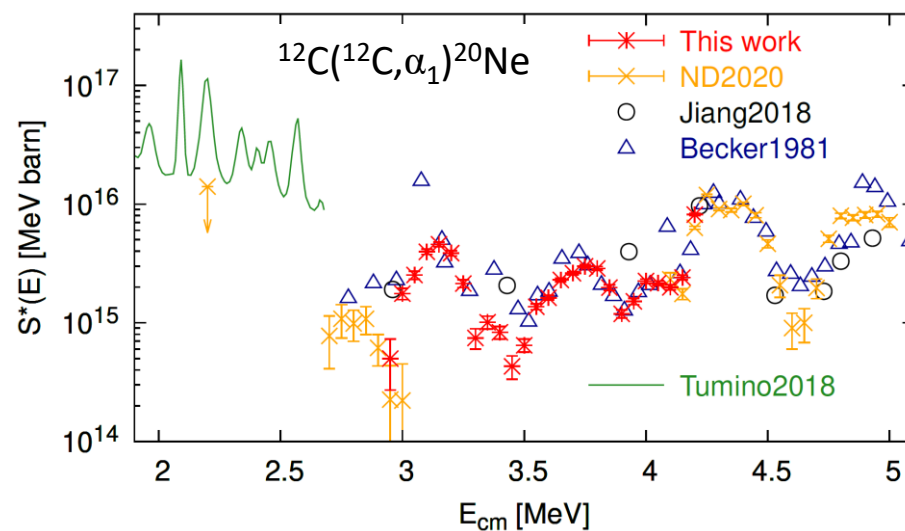


- standard potential model
- hindrance potential model

Unknown features



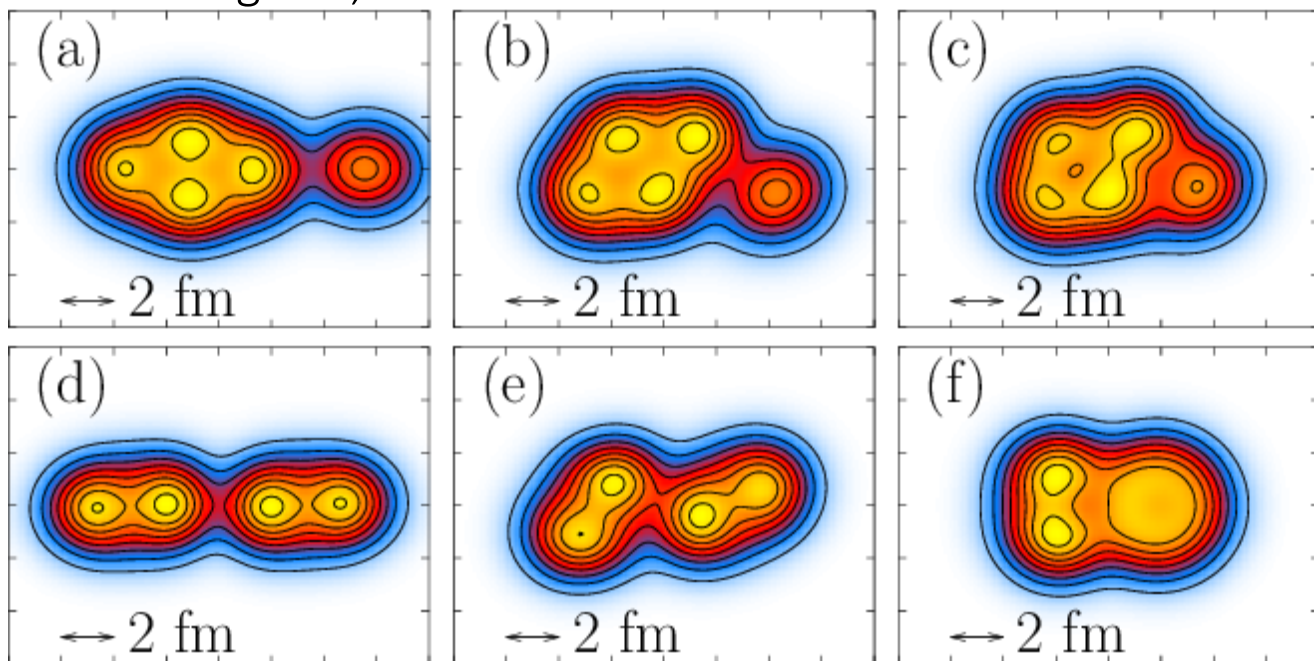
Low energy resonance features identified in THM experiment



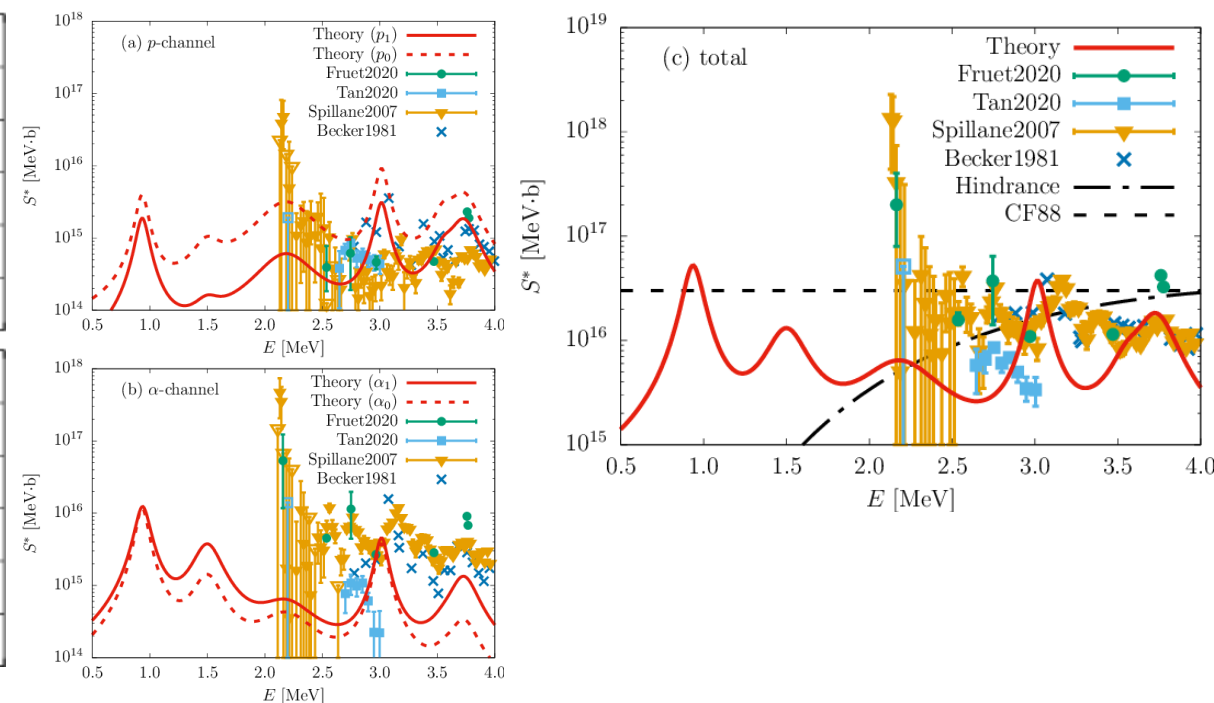
Emergence of clear resonance structures after correction for energy loss effects

C12+12C fusion S*-factor from a full-microscopic nuclear model

Y. Taniguchi, M. Kimura

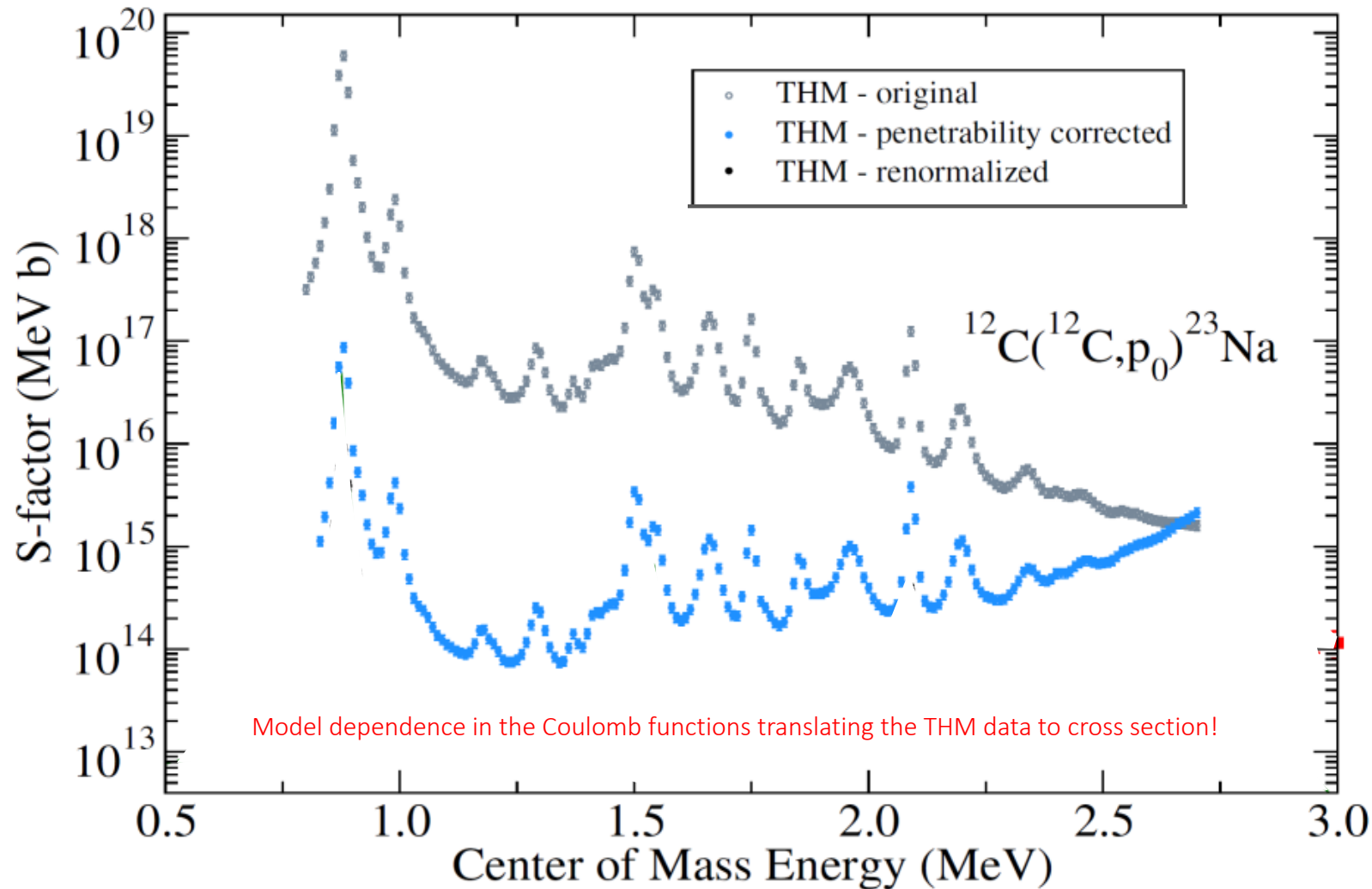


The wave functions for the (a)–(c) $\alpha + ^{20}\text{Ne}$, and (d)–(f) $^{12}\text{C} + ^{12}\text{C}$ channels obtained by the energy variation. The inter-nuclear distance is 6.5, 5.0, and 3.5 fm from left to right.



Calculated and observed modified astrophysical S*-factors in the (a) p_1 and (b) α_1 channels. The calculated S*-factors in the p_0 and α_0 channels are also shown for the comparison. Panel (c) compares the calculated and observed total S*-factors with the evaluations

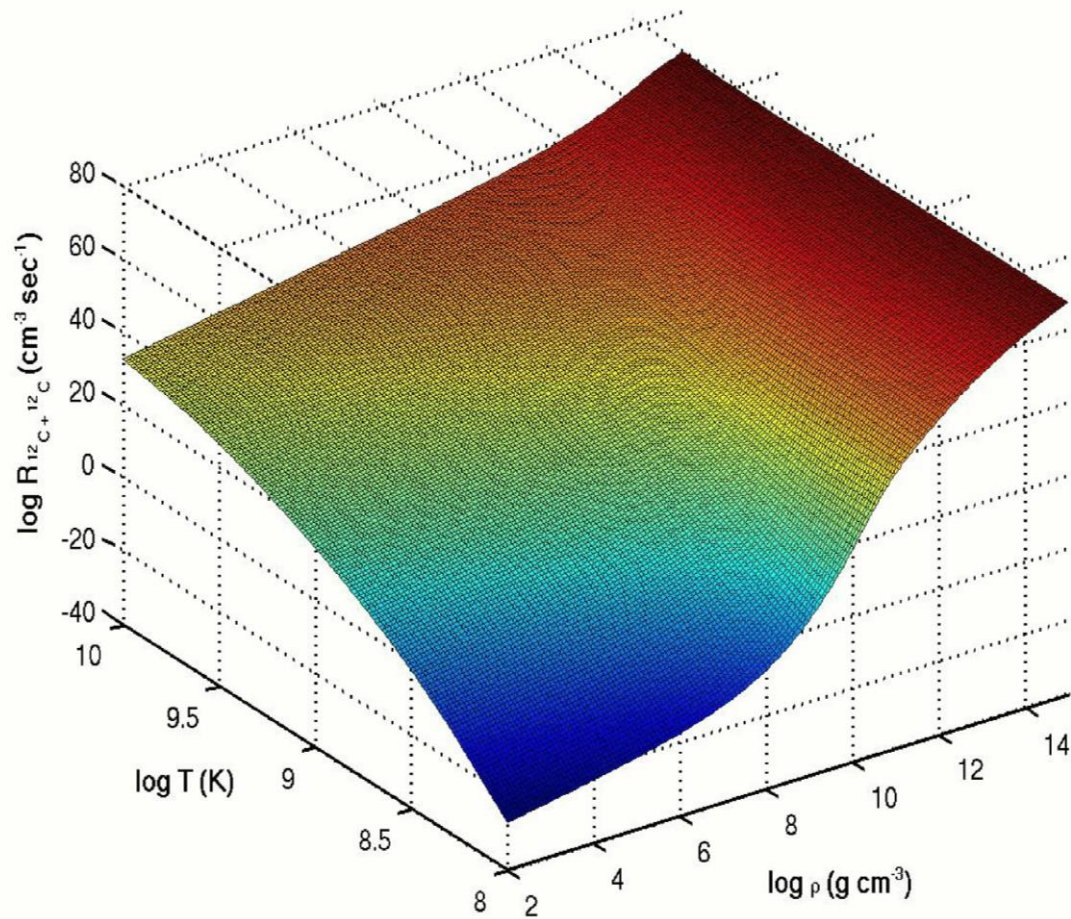
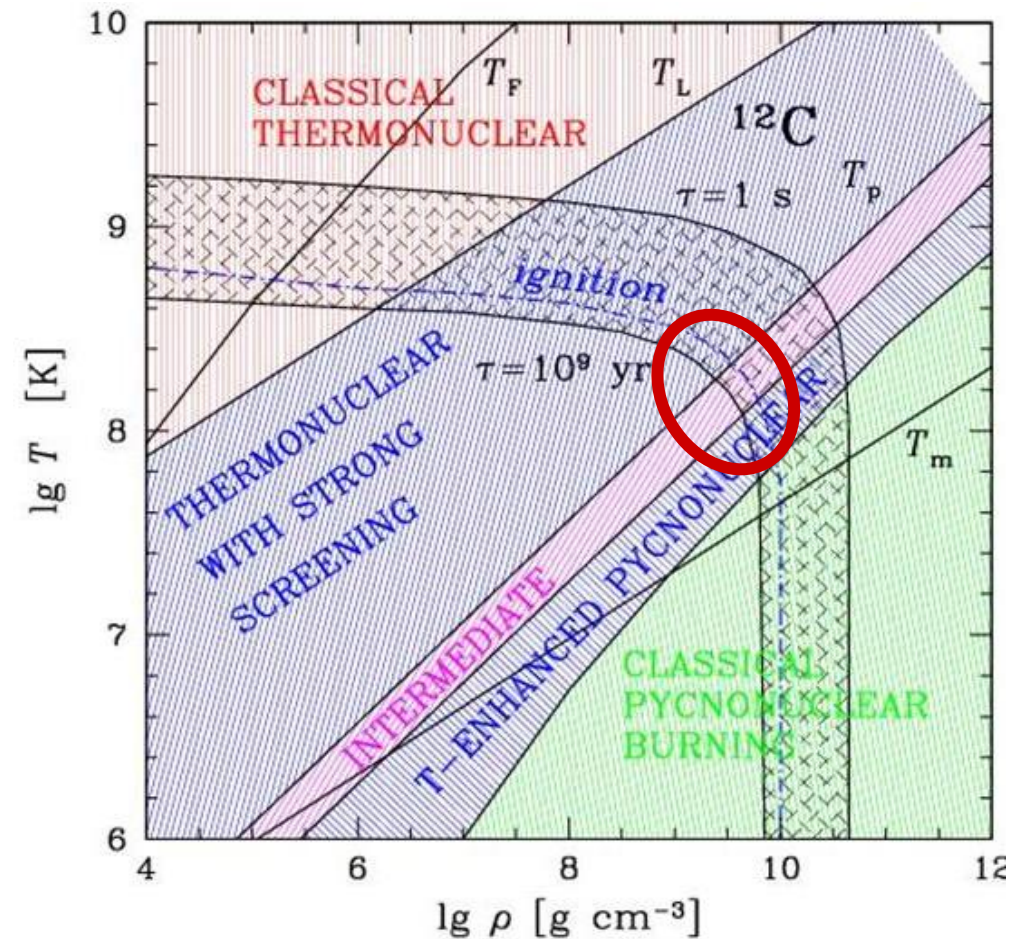
Low energy extrapolations



What is the nature of these states?

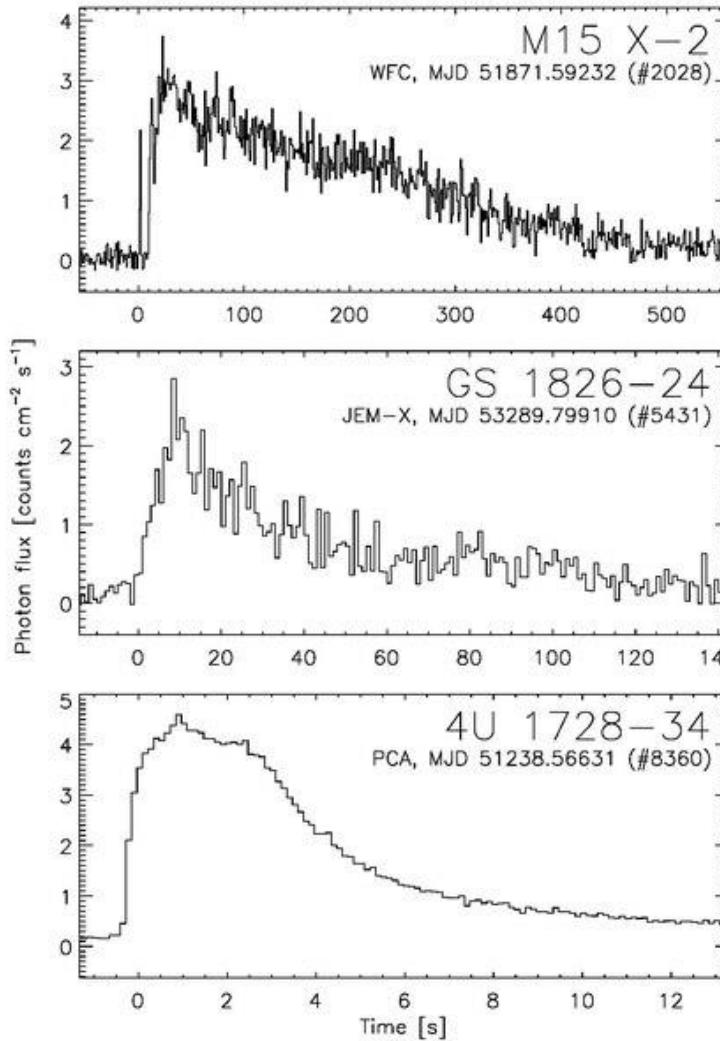
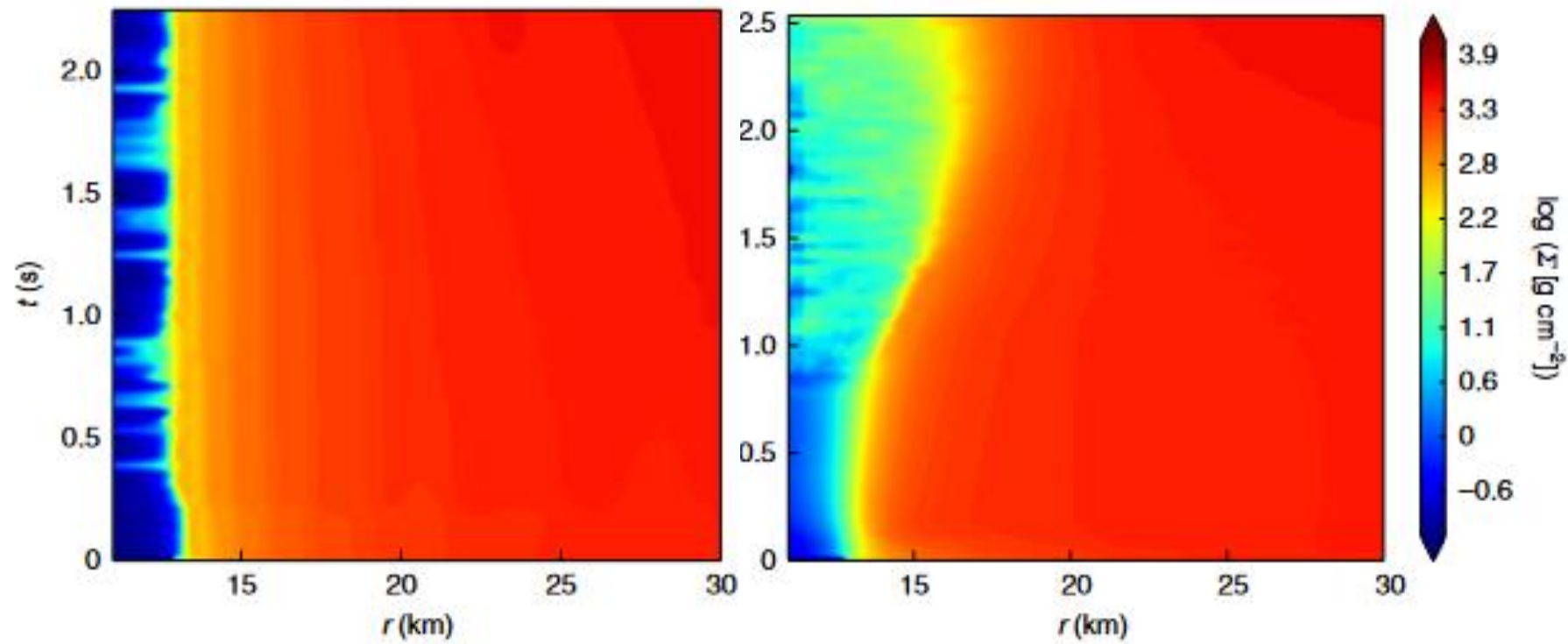
1. Compound resonances or dynamical coupling of the eave functions.
2. What is the overall effect in view of strong screening regimes?
3. To what effect will a better knowledge of these quantum effects help to inform us about the dense matter conditions determining the onset of type Ia supernovae and superbursts?

The Environmental Component in the $^{12}\text{C}+^{12}\text{C}$ Rate



Fusion ignites at high temperatures and/or high densities, the impact in the rate on the basis of different resonance predictions need to be explored

Ignition Conditions?



Large uncertainties in the nature and in the actual ignition conditions in type Ia supernovae in accreting (or merging) white dwarfs or in the atmosphere of neutron stars, Shock reflection models might provide insight in the nature of neutron star crust!

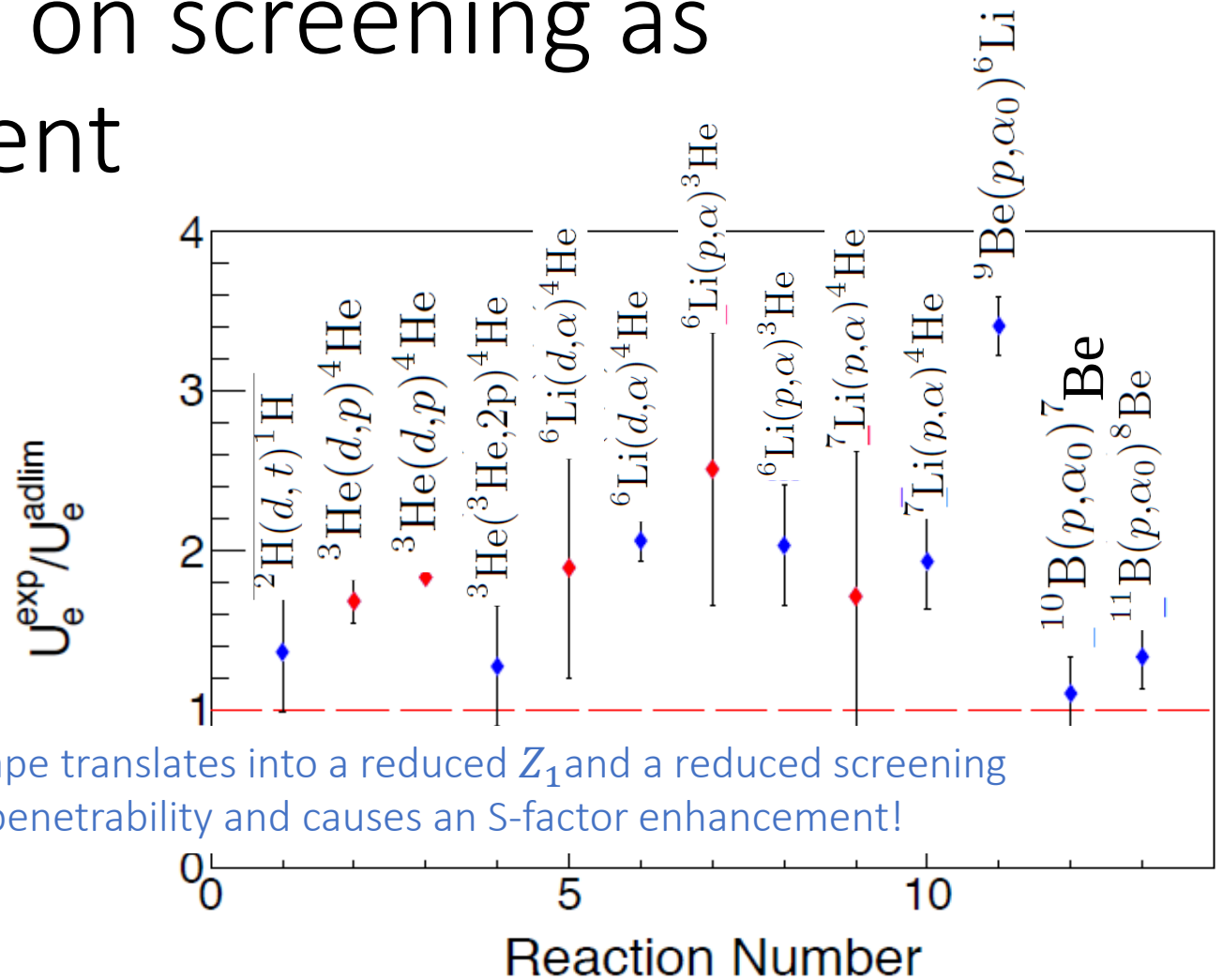
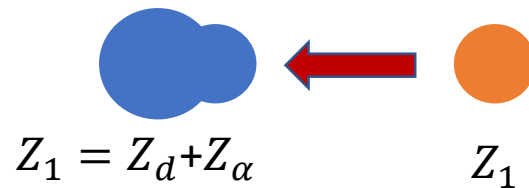
Welcome again and enjoy the meeting!



Clusterization effects on screening as cause for enhancement

Cold plasma screening studies at low energies complementing NIF studies

- $^2\text{H}(d,p)^3\text{He}$
- $^3\text{He}(d,p)^4\text{He}$
- $^3\text{He}(^3\text{He},2p)^4\text{He}$
- $^6\text{Li}(d,\alpha)^4\text{He}$
- $^6\text{Li}(p,\alpha)^3\text{He}$
- $^7\text{Li}(p,\alpha)^4\text{He}$
- $^9\text{Be}(p,\alpha)^6\text{Li}$
- $^{10}\text{B}(p,\alpha)^7\text{Be}$
- $^{11}\text{B}(p,\alpha)^8\text{Be}$



$^6\text{Li}, ^7\text{Li}, ^{10}\text{B}, ^{11}\text{B} + p/d/^3\text{He}$

$$f_{\text{screen}} = \exp\left(\pi \cdot \eta(E) \cdot \frac{U_{\text{electron}}}{E}\right)$$

$$\eta(E) = \frac{Z_1 \cdot Z_2}{v/c} \alpha$$

From plasma to target

Only fractional ionization occurs in target material depending on target composition.

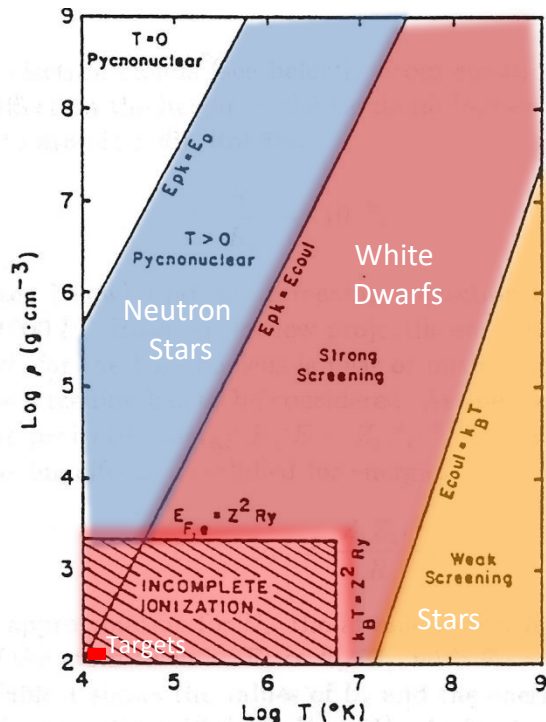
Accelerator experiment based screening measurements don't reveal full plasma screening information and need correction



Metal conductor with free electrons moving between bound target ions



Cold MB distribution with partially ionized target particles



$$U_{Cb} = \frac{Z_1 \cdot Z_2 \cdot e^2}{r} - U_{sc}(E)$$

$$U_{sc}(E) = \frac{Z_1 \cdot Z_2 \cdot e^2}{R_A}$$

$$R_A \text{ Atomic Radius } R_A \cong \frac{R_B}{(Z_2 - x)}$$

$$R_B \text{ Bohr Radius } R_A = 0.52918 A$$

$$R_D \text{ Debye Radius } R_D = \sqrt{\frac{kT}{4\pi \cdot e^2 \cdot \rho \cdot N_A \cdot \xi}}$$

