$^{12}C+^{12}C$ fusion astrophysical S-factor from a full-microscopic nuclear model

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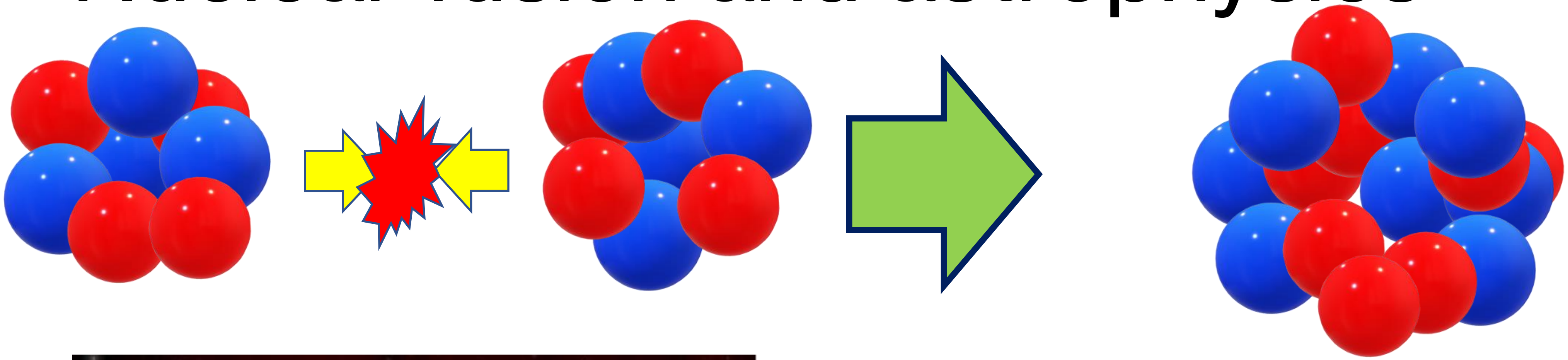
YKIS2022b

May 23-27, 2022

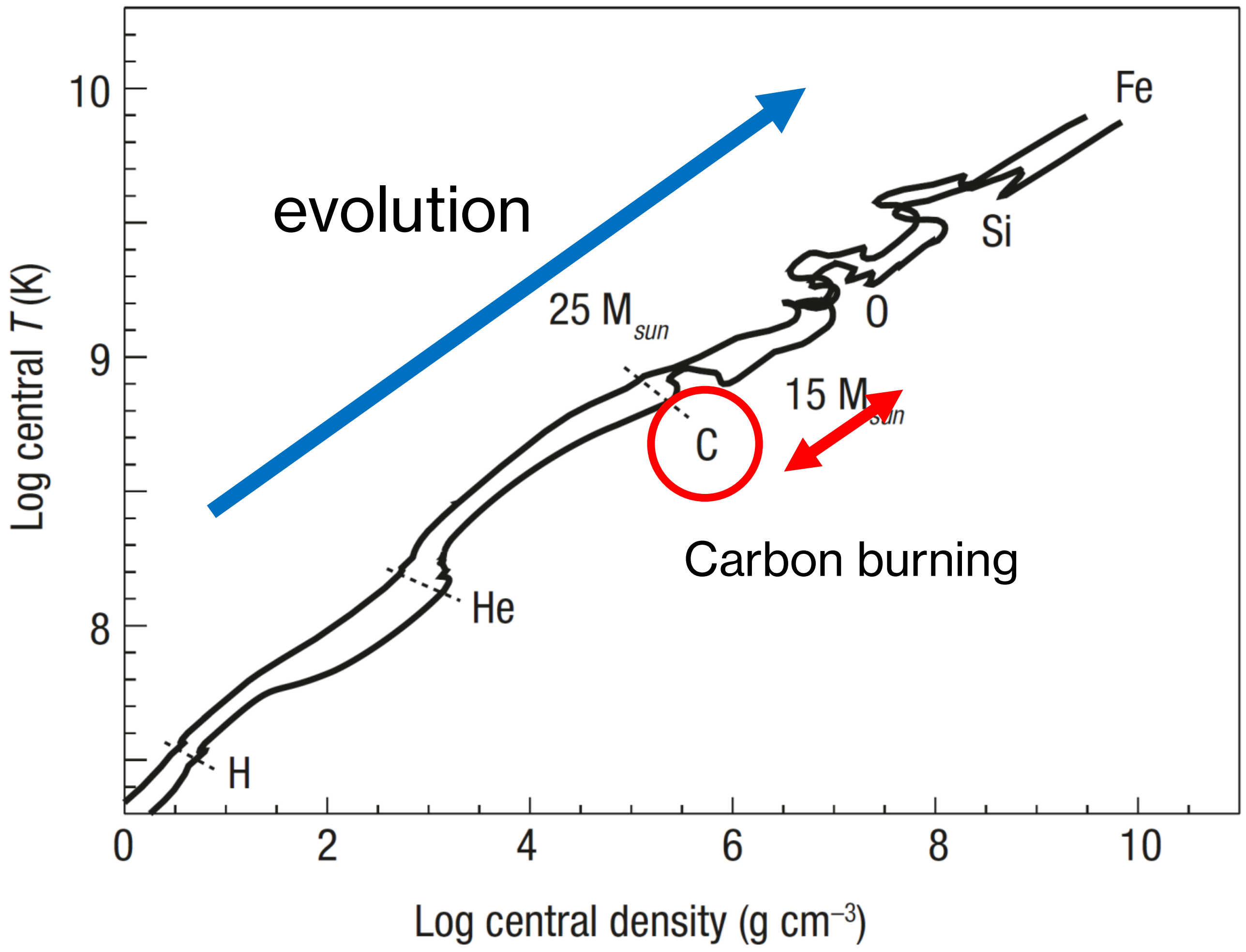
Nuclear fusion and astrophysics



- Nuclear fusion is energy source of various astrophysical phenomena.
- $^{12}C+^{12}C$ fusion is essential reaction.
  - Evolution of massive stars
  - Supernovae (type Ia)
  - X-ray superbursts

[https://www.news.gatech.edu/2014/09/19/thermonuclear-x-ray-bursts-neutron-stars-set-speed-record]

$^{12}C+^{12}C$ fusion reaction in massive stars

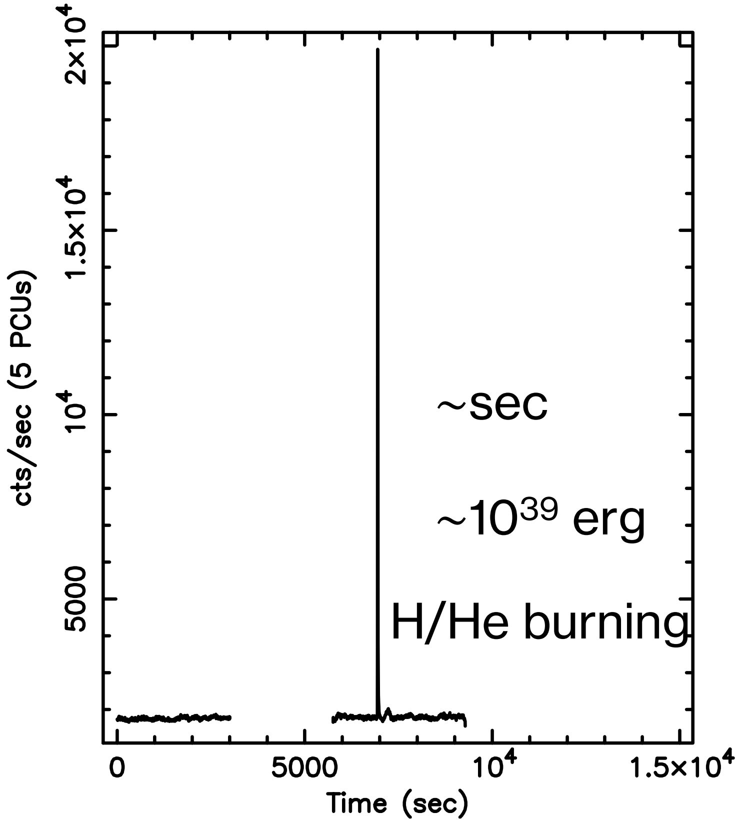


[S. E. Woosley, A. Heger, T. A. Weaver, Rev. Mod. Phys. **74**, 1015 (2002)]

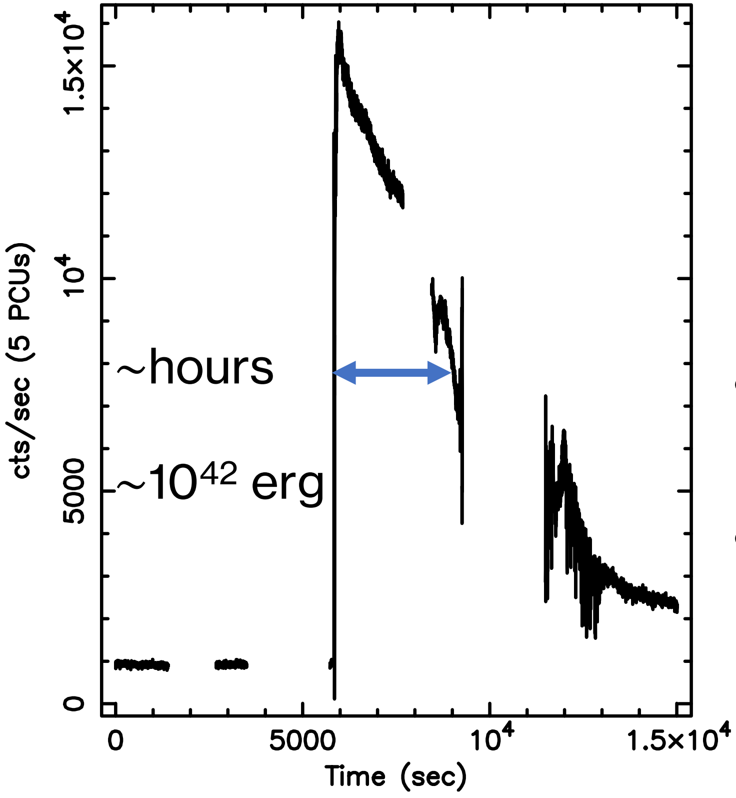
- Massive stars evolve through the carbon-burning process after the helium-burning.
- The primary reaction of the carbon-burning process.

X-ray superburst

X-ray burst



X-ray superburst

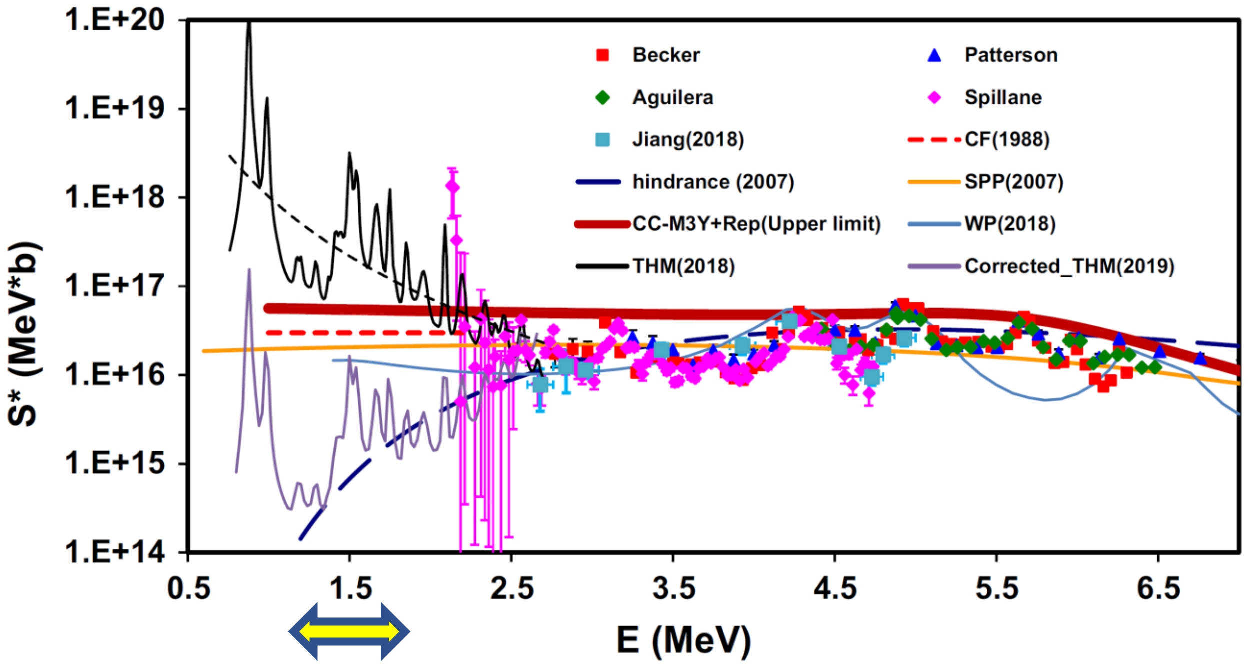


[E. Kuulkers, NPB**132**, 466 (2004)]

- X-ray superbutsts are explosional flashes in space.
- $^{12}C+^{12}C$ fusion reaction of the accreting matter is considered the trigger.

Uncertainties of ^{12}C + ^{12}C fusion reaction cross section

$$S^*(E) = E\sigma(E)\exp\left(2\pi\eta + 0.46\ \mathrm{MeV}^{-1}E\right)$$

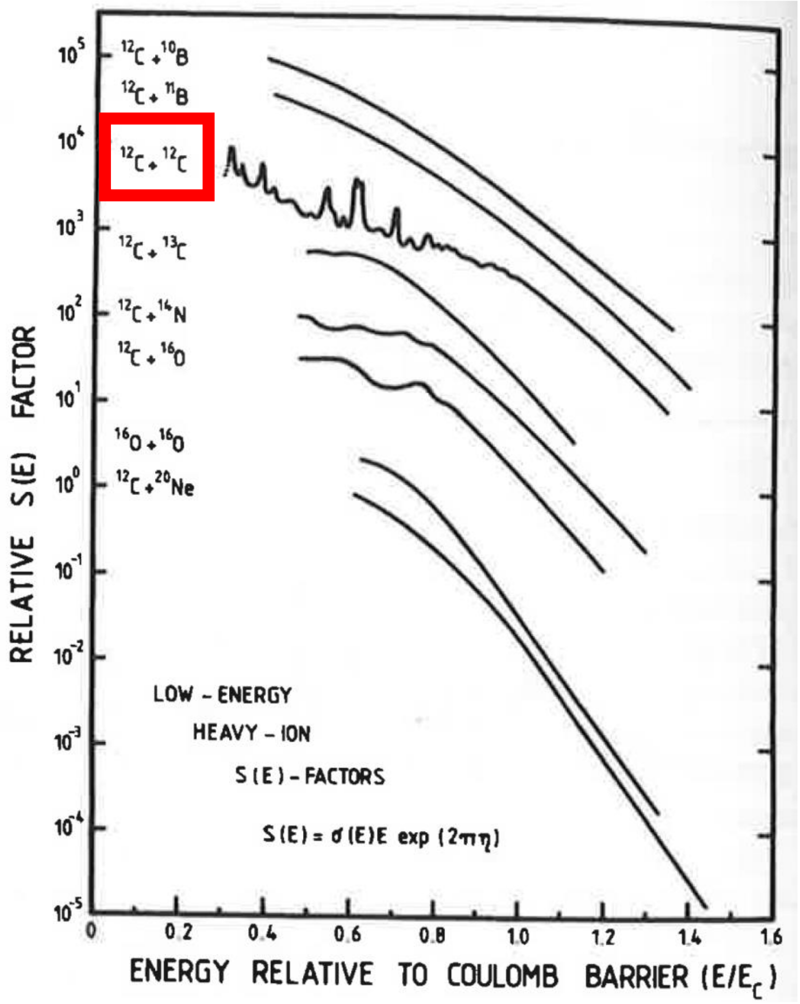


Gamow window
of X-ray superbursts
[R. L. Cooper+, ApJ **702**, 660 (2009)]

[Original fig. : C. Beck et al, EPJA56, 87 (2020)]

- Experiments
  - **No direct experiments** in E < 2 MeV.
  - The indirect THM experiment (Tumino et al.) obtains a large S-factor, but the analysis is under discussion.
- Theories (just extrapolations)
  - Constant: CF88.
  - Strong suppression in the low-energy region: Hindrance model

Resonance-state dominance in $^{12}C + ^{12}C$ fusion reaction



- S-factors of $^{12}C + ^{12}C$ fusion reaction has a significant peak structure.
- **Narrow-resonance contributions** are essential.

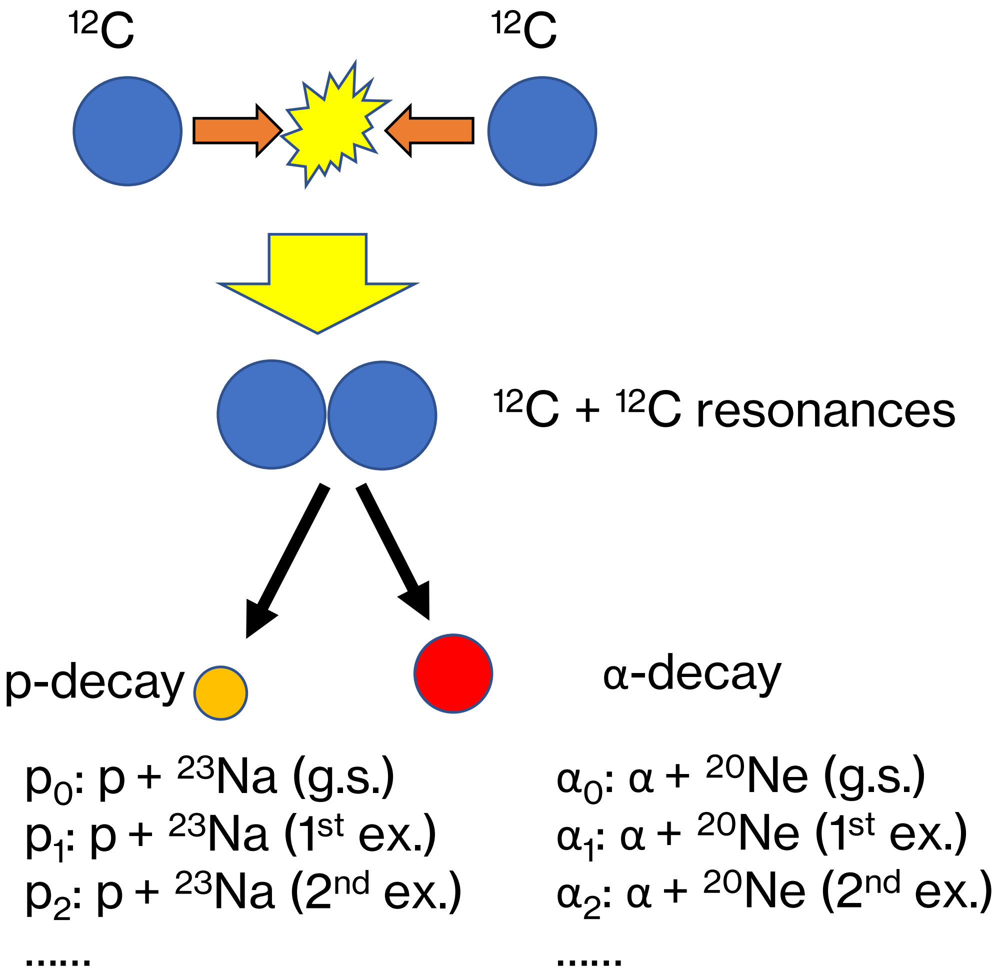
→Theoretical estimation of $^{12}C+^{12}C$ fusion rate with resonance effects

[Rolfs and Rodney, Cauldrons in the Cosmos (1988)]

Theoretical difficulties of low-energy ^{12}C+^{12}C fusion reaction

- Rearrangement of many nucleons
  - Entrance: ^{12}C + ^{12}C
  - Exit: α + ^{20}Ne, p + ^{23}Na
- Channel coupling effects are essential.
- Unknown macroscopic coupling potentials

→**Microscopic framework**

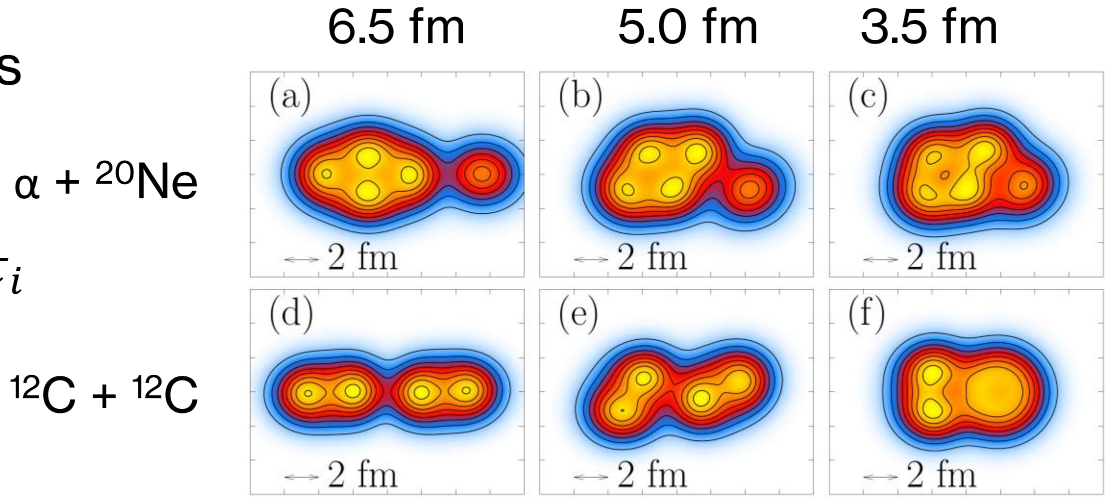


Framework: Antisymmetrized molecular dynamics (AMD)

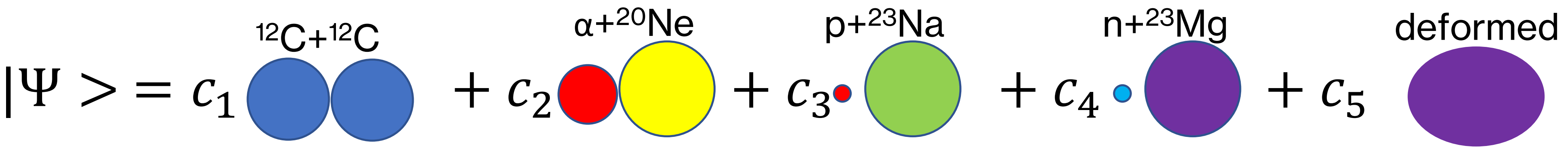
- Slater determinant of deformed Gaussian wave packets

$$|\Phi> = \mathcal{A}|\varphi_1, \varphi_2, \ldots, \varphi_A>$$

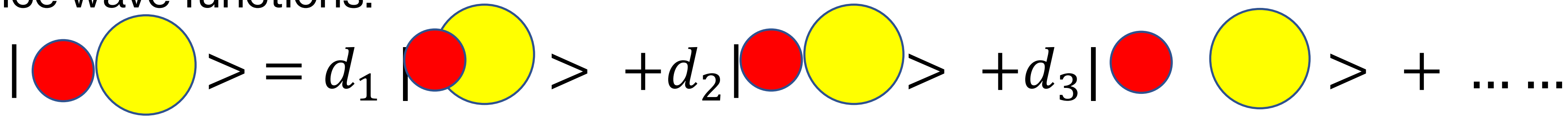
$$\varphi_i(\mathbf{r}) = \exp\left[-\frac{1}{2}(\mathbf{r}-\mathbf{Z}_i)\cdot \mathrm{M}(\mathbf{r}-\mathbf{Z}_i)\right] \otimes \sigma_i \otimes \tau_i$$



- Coupling of <u>all entrance and exit channels</u> is treated by a linear combination of basis wave functions.



- Fusion and decay dynamics are also treated by a linear combination of various inter-nuclear distance wave functions.



- Diagonalization of Hamiltonian with the <u>Gogny D1S</u> density functional after parity and angular-momentum projection.

Fusion cross sections and Decay widths

- The Breit-Wigner formula

$$\sigma(E) \propto \frac{\pi}{k^2} \frac{\Gamma_{ent}\Gamma_{exit}}{(E-E_R)^2 + \Gamma^2/4}$$

- The R-matrix theory

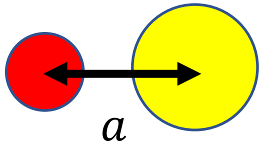
$$\Gamma_{\mathrm{C_1+C_2}} = \frac{2ka}{F_l(ka)^2 + G_l(ka)^2} \frac{3\hbar^2}{2\mu a^2} \theta^2_{\mathrm{C_1+C_2}}$$

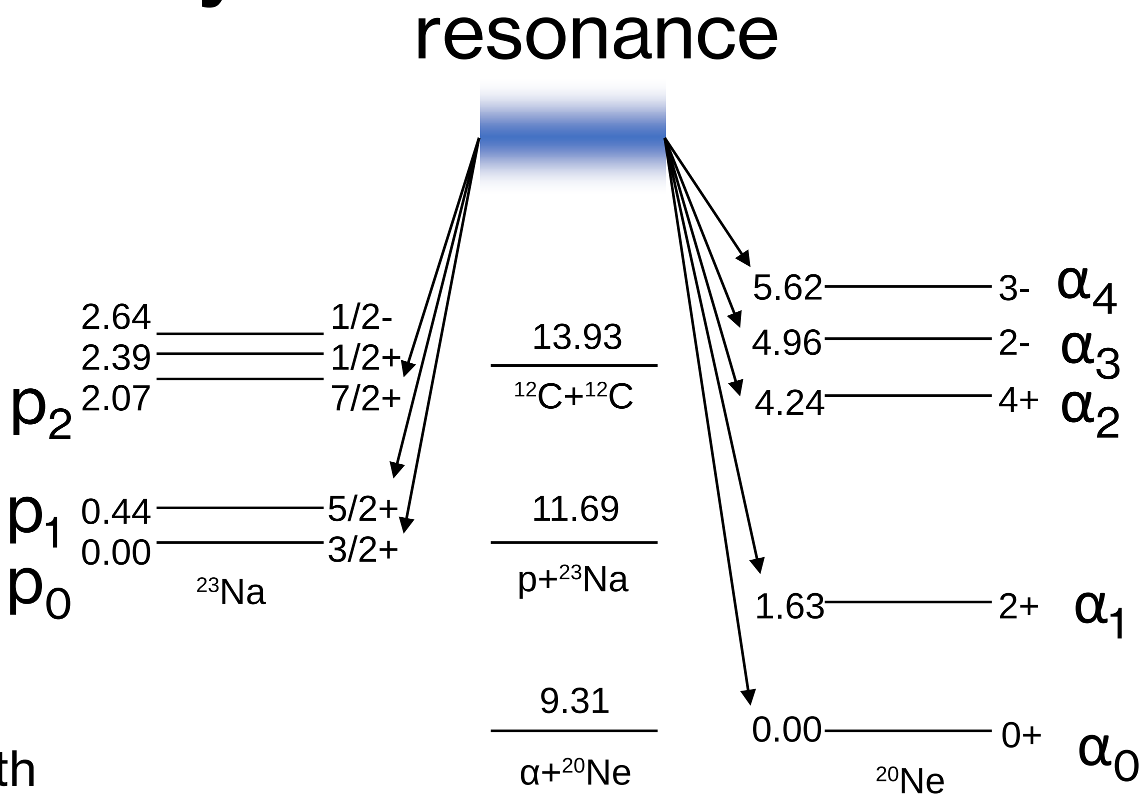
$$Q + E = \frac{\hbar^2 k^2}{2\mu}$$

a: channel radius

(Dimensionless)Reduced width amplitude at channel radius a
Probability of existence of clusters

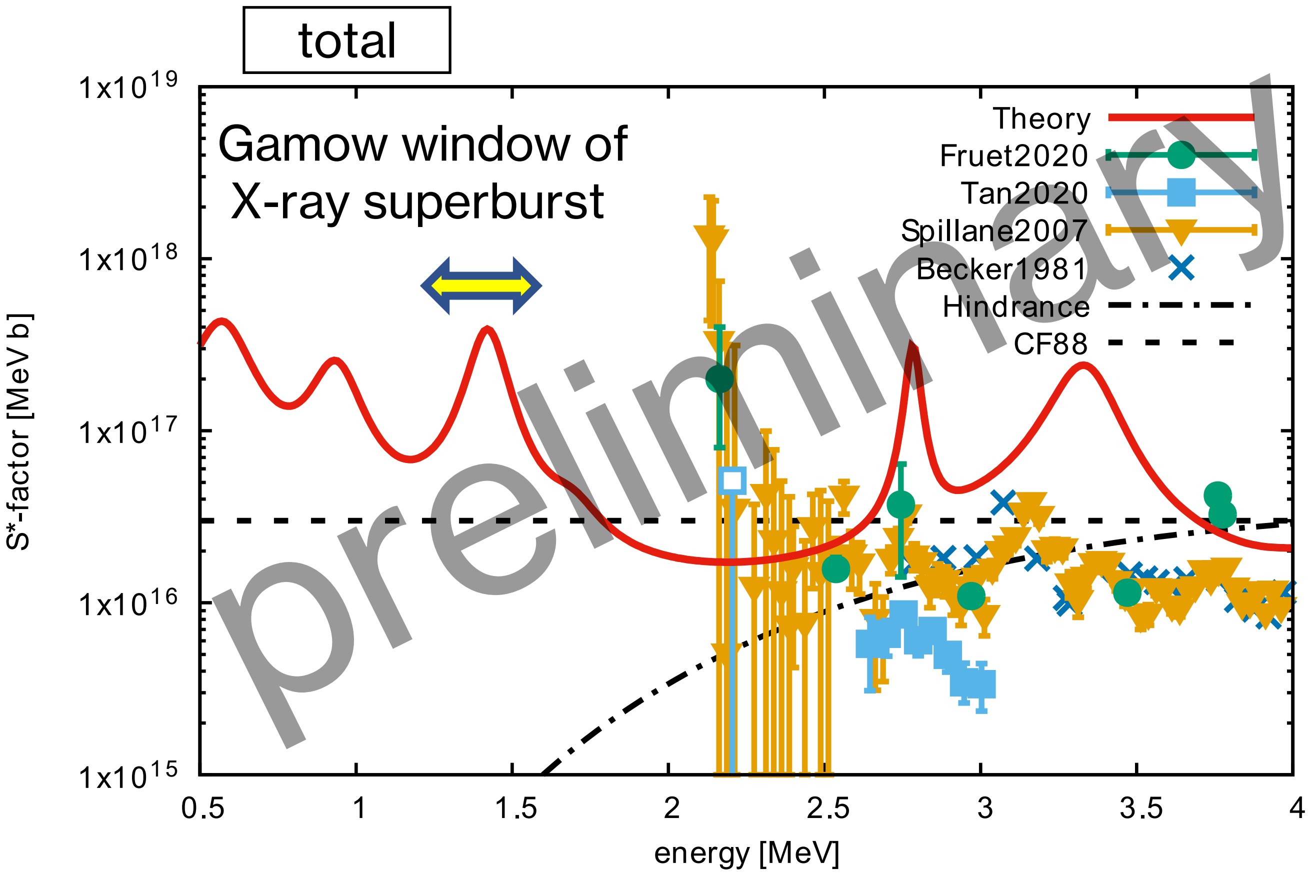
Laplace expansion method
[Chiba+, PTEP (2017)]





$$\Gamma = \Gamma_{\alpha 0} + \Gamma_{\alpha 1} + \cdots + \Gamma_{\alpha 4}$$
$$+\Gamma_{p0} + \Gamma_{p1} + \Gamma_{p2}$$

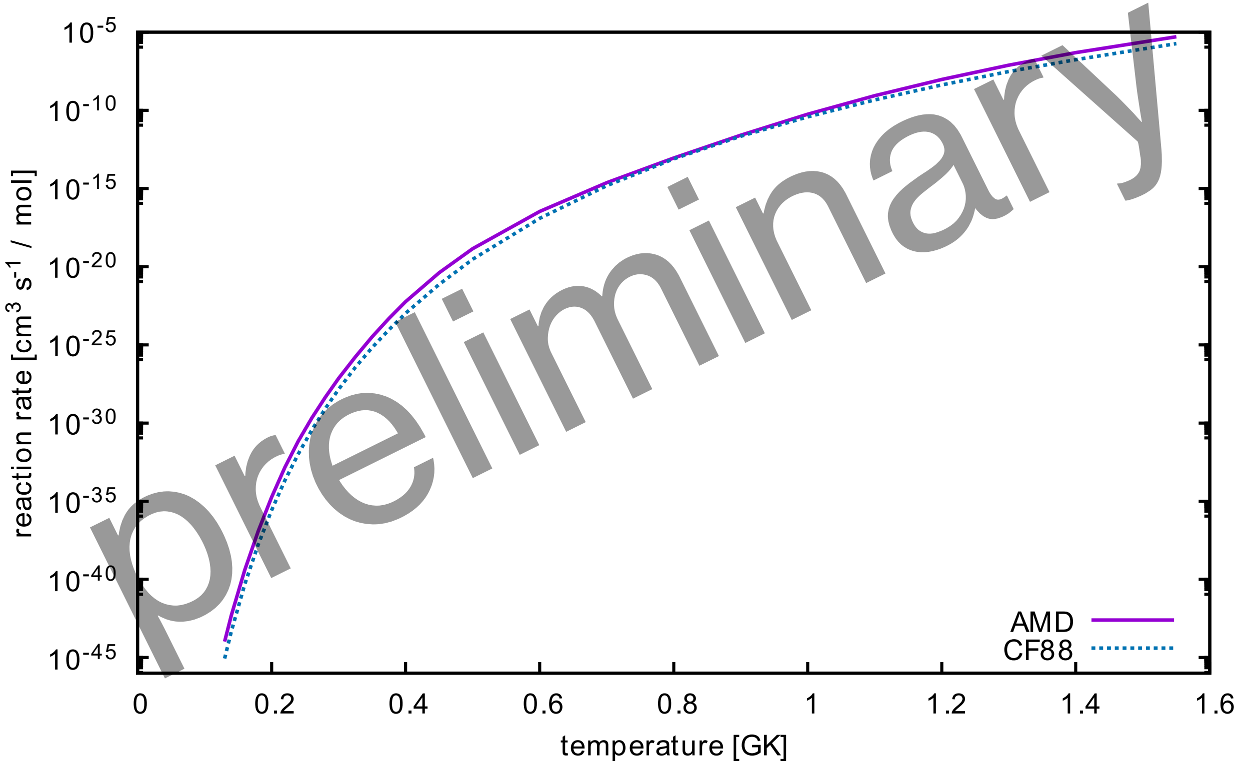
Astrophysical S factor



- Peak structure due to resonances.
- **Much larger** S factors than the **hindrance extrapolation.**
- A resonance is in the Gamow window of X-ray superbursts.

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

$$<\sigma\rho>\propto \frac{1}{(k_BT)^{3/2}}\int_0^\infty S(E)\exp\left(-\frac{E}{k_BT}-2\pi\eta\right)dE$$

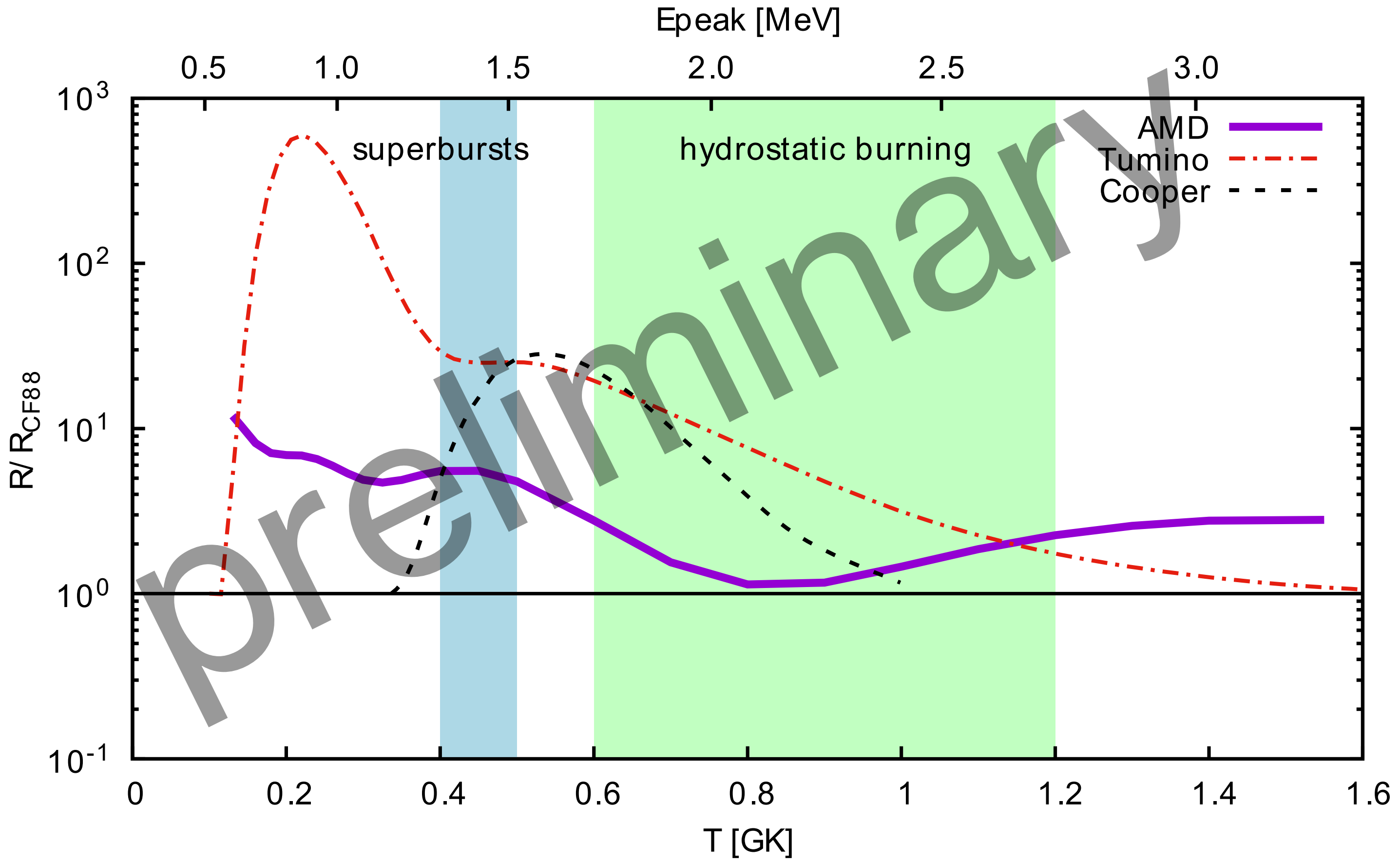


- Reasonable $^{12}C+^{12}C$ fusion reaction rate is obtained.

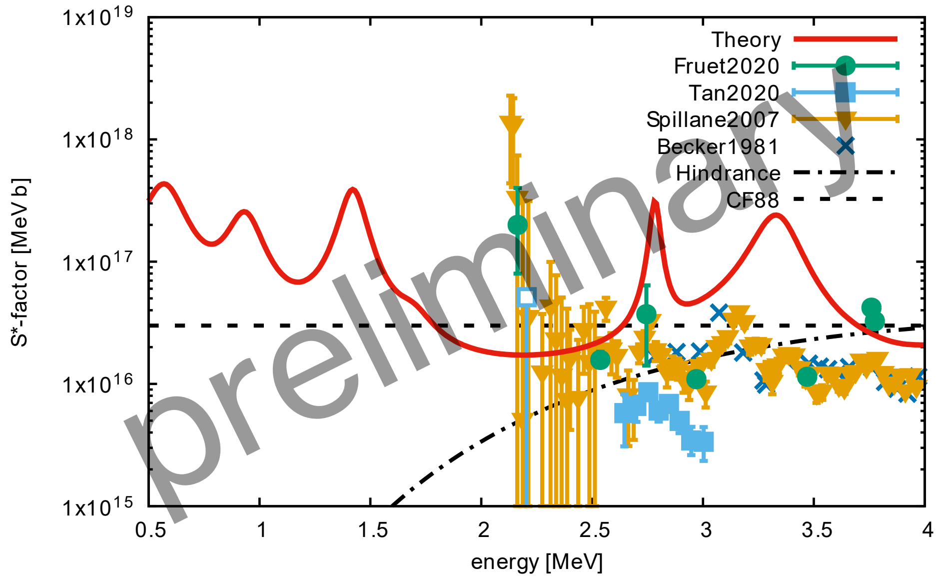
$^{12}C+^{12}C$ fusion reaction rate (detail)

$$< \sigma\rho > \propto \frac{1}{(k_B T)^{3/2}} \int_0^\infty S(E) \exp\left(-\frac{E}{k_B T} - 2\pi\eta\right) dE$$

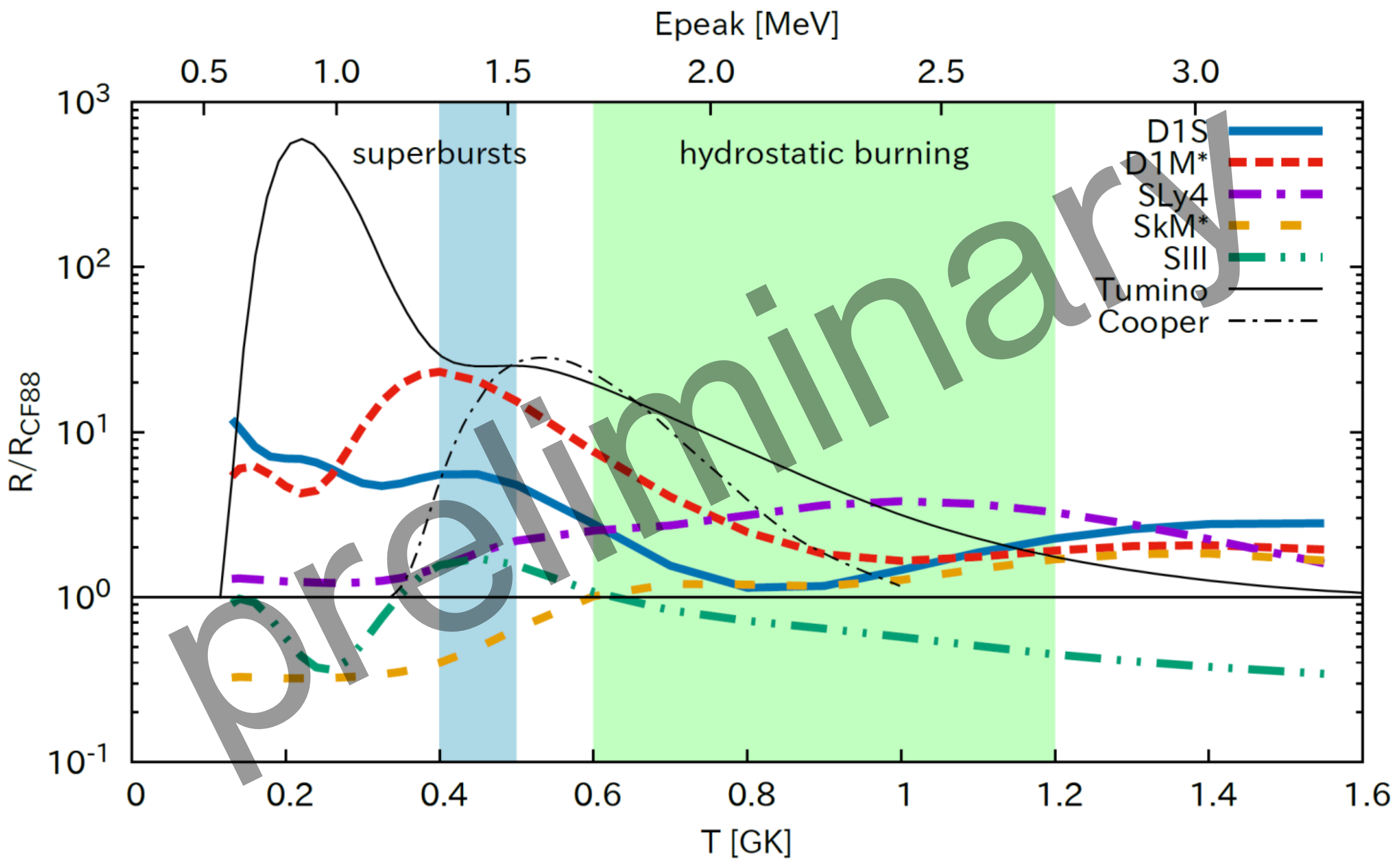
Gamow peak: $\Delta E = 4\sqrt{\frac{E_p k_B T}{3}}$



- The same order as CF88.
- Each resonance is sensitive to the rate at low temperature due to a narrow Gamow peak.



Density functional dependence for $^{12}C+^{12}C$ fusion reaction rate



- Gogny (finite range)
  - D1S
  - D1M*
- Skyrme (zero range)
  - SLy4
  - SkM*
  - SIII

- In T < 0.6 GK, Gogny functionals obtain larger rates.
- Longer range of attractive ^{12}C-^{12}C inter-nuclear potential?

Summary

- The $^{12}C+^{12}C$ fusion S-factor is calculated microscopically.
  - Channel coupling of all exit and entrance channels is treated using a nucleon-nucleon interaction.
  - All exit channels under the $^{12}C+^{12}C$ threshold are treated.
  - No hindrance effects due to contributions of low-energy resonances.
- $^{12}C+^{12}C$ fusion reaction rate is estimated in the same order as CF88 with the Gogny D1S.
- Analysis of density functional dependence for the fusion reaction rate is ongoing.