$^{12}C + ^{12}C$ Fusion S-factor from a Full-microscopic Nuclear Model

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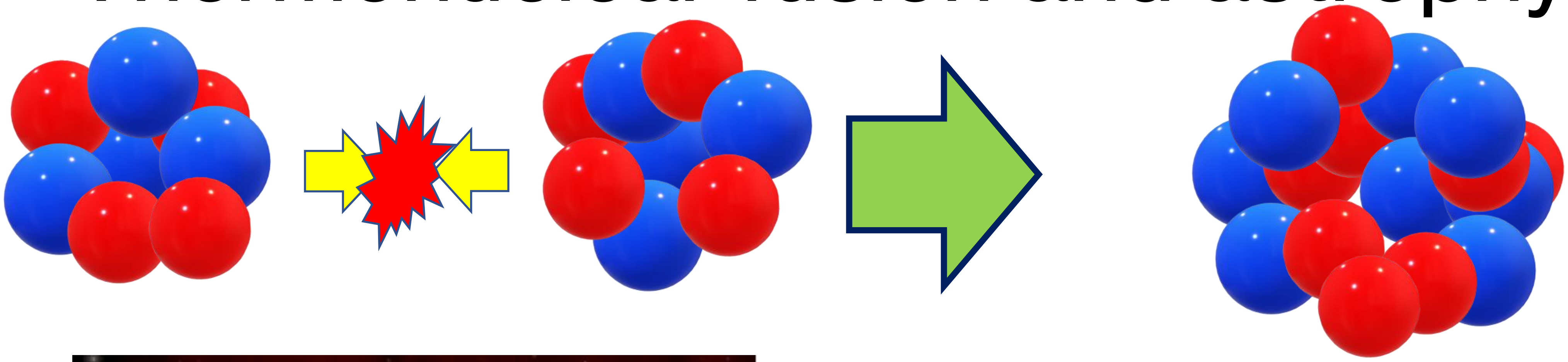
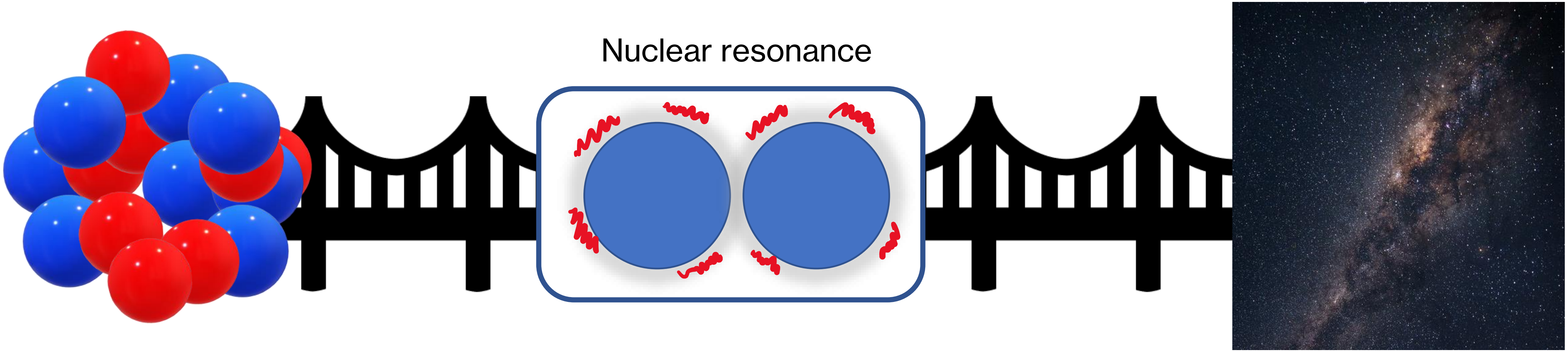
Thermonuclear fusion and astrophysics



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

- Thermonuclear fusion is energy source of various astrophysical phenomena.
  - Evolution of stars
  - Supernovae (type Ia)
  - <u>X-ray superbursts</u>
    - Nuclear fusion of accreting matter onto NSs

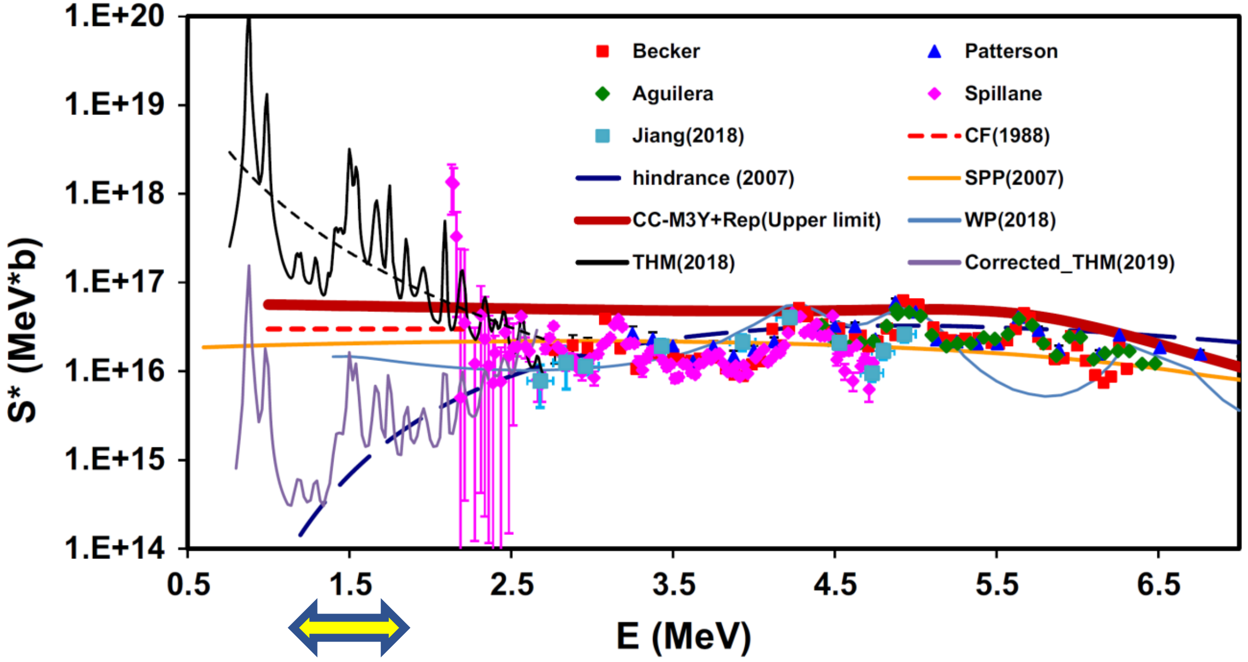
Nuclear resonances as the “bridge” between nuclear physics and astrophysics



- The **nuclear fusion reaction rate** is essential for the astrophysical phenomena.
- The **nuclear fusion reaction rate** is obtained from the **fusion reaction cross sections**.
- **Nuclear resonances** enhance the **fusion cross sections** in orders of magnitude.

$^{12}C + ^{12}C$ fusion reaction cross section and the Gamow window of X-ray superbursts

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

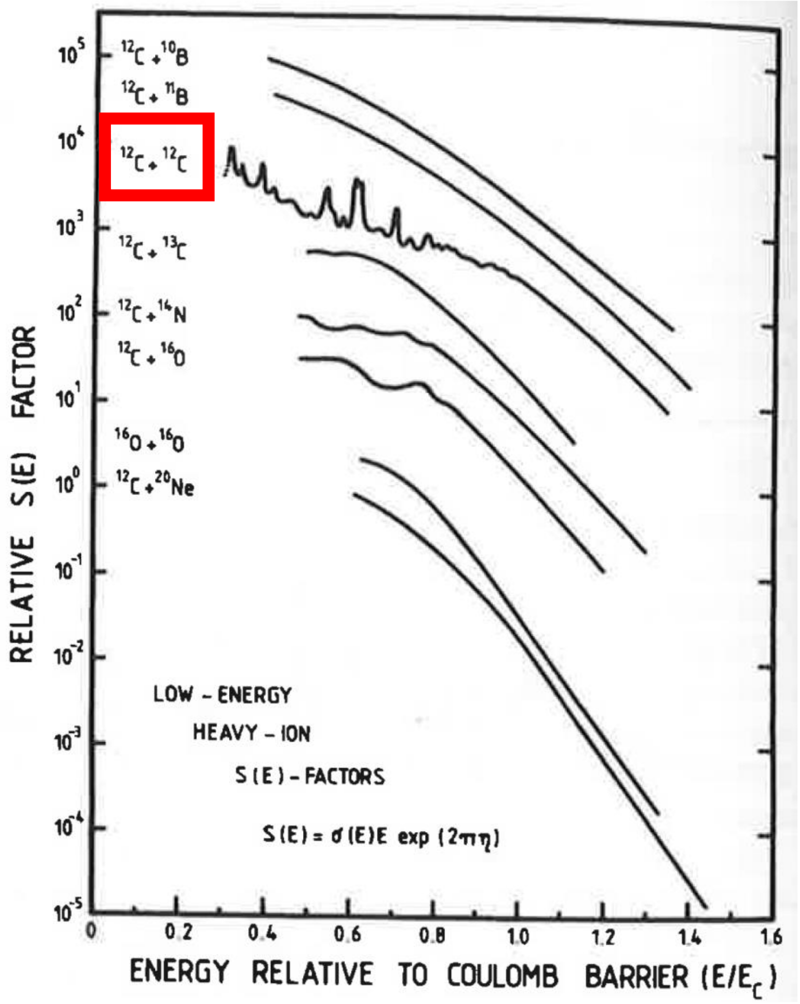


Gamow window
of X-ray superbursts
[R. L. Cooper+, ApJ **702**, 660 (2009)]

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

- The **resonance around E ~ 1.5 MeV** has been proposed to explain the **X-ray superbursts**.
- Experimental data are insufficient in E < 2 MeV.
  - **No direct experiments** in E < 2 MeV.
  - The indirect experiment with the THM [Tumino+, Nature (2018)] has **uncertainties** in the analysis.
- The fusion cross sections with E < 2 MeV are just **extrapolations** from the higher energy data.
  - CF1988: overestimation
  - Hindrance model
  - The effects of **resonances** are **averaged**.
- Reliable theoretical calculations including **resonant effects** are required.

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



- S-factors of $^{12}C + ^{12}C$ fusion reaction has a significant peak structure.
- Contributions of **narrow-resonance states** are dominant.

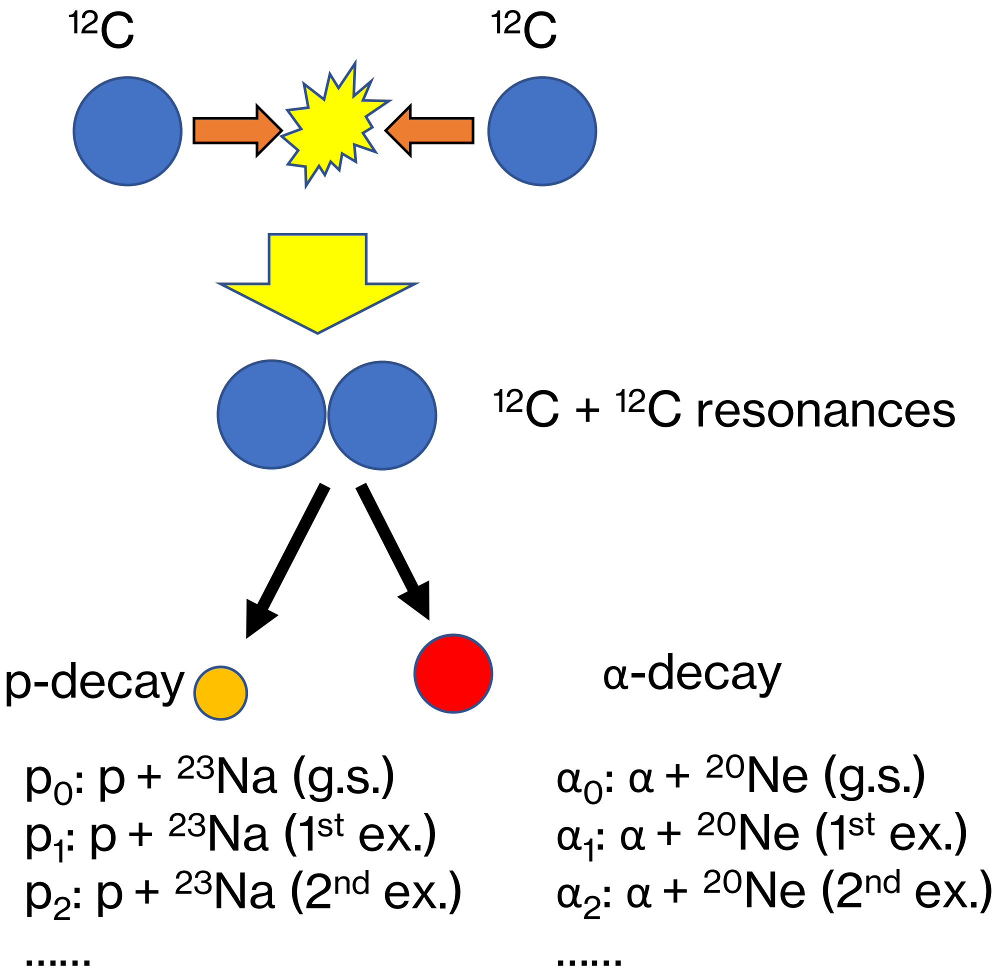
[Rolfs and Rodney, Cauldrons in the Cosmos (1988)]

Calculation of $^{12}C + {}^{12}C$ fusion cross sections

- **Narrow-resonance cross sections** are calculated from the **decay widths** of the **entrance** and **exit** channels.

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

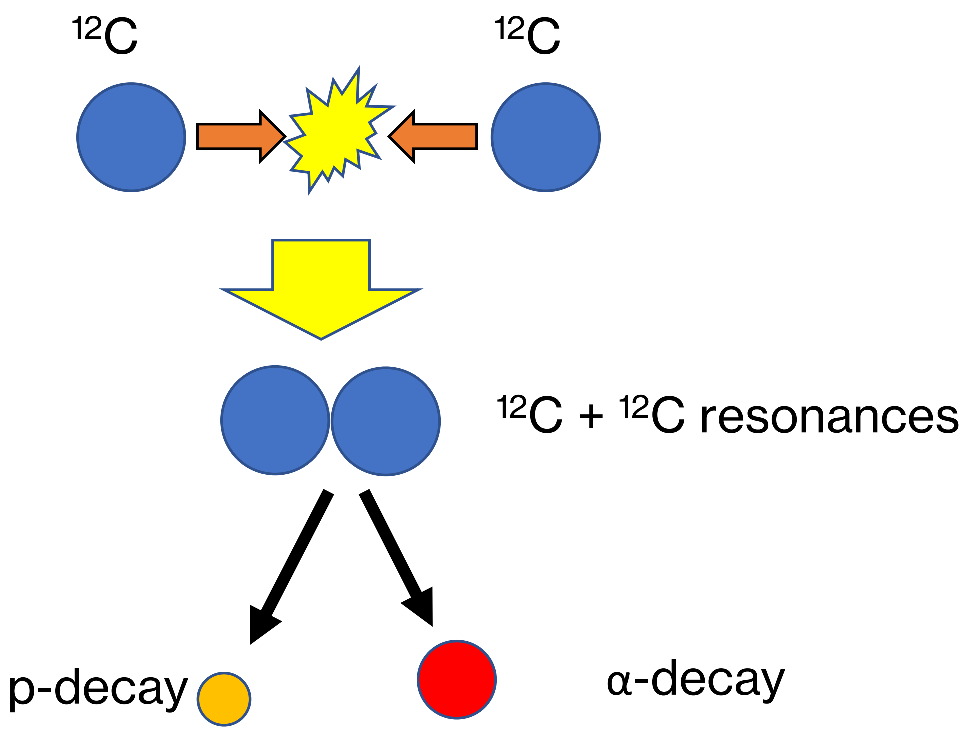
- Channels
  - Entrance: $^{12}C + {}^{12}C$
  - Exit: $\alpha + {}^{20}Ne$, $p + {}^{23}Na$



Why full-microscopic?

- $^{12}C + {}^{12}C \rightarrow {}^{24}Mg^* \rightarrow \alpha + {}^{20}Ne$
  $\rightarrow {}^{24}Mg^* \rightarrow p + {}^{23}Na$
- Rearrangement of many particles.
- Strong channel couplings.

- By using a **full-microscopic nuclear model**, we can treat them with a **nucleon-nucleon interaction**.
- Phenomenological coupling potentials are not necessary.



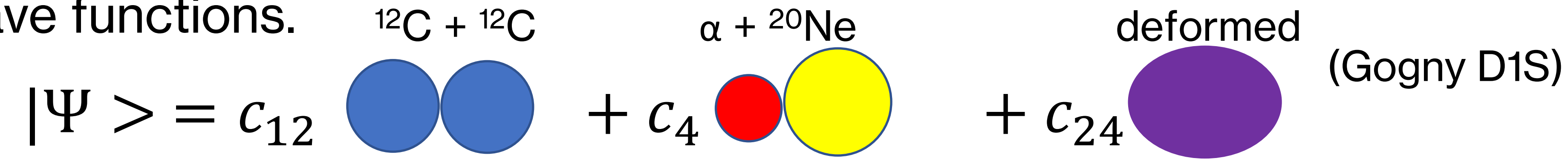
Framework: Antisymmetrized molecular dynamics (AMD)

- Slater determinant of deformed Gaussian wave packets

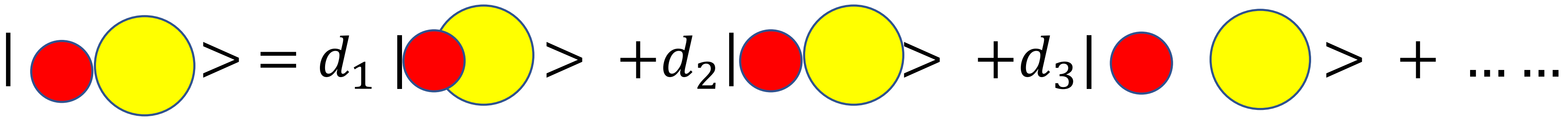
$$|\Phi> = \mathcal{A}|\varphi_1, \varphi_2, \dots, \varphi_A>$$

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

- Coupling of the entrance and exit channels are treated by linear combination of basis wave functions.



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



- Diagonalization of Hamiltonian with the Gogny D1S effective interaction (density functional).

Decay widths

- The Breit-Wigner formula

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

$$\Gamma = \Gamma_\alpha + \Gamma_p$$

$$\Gamma_\alpha = (\Gamma_\alpha / \Gamma_{\alpha 1}) \cdot \Gamma_{\alpha 1}$$

$$\Gamma_p = (\Gamma_p / \Gamma_{p1}) \cdot \Gamma_{p1}$$

exp. data by Becker+, Z. Phys. 303, 305 (1981)

- The R-matrix theory

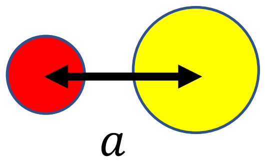
$$\Gamma_{C_1+C_2} = \frac{2ka}{F_l(ka)^2 + G_l(ka)^2} \frac{3\hbar^2}{2\mu a^2} \theta^2_{C_1+C_2}$$

$$Q = \frac{k^2}{2\mu}$$

a: channel radius

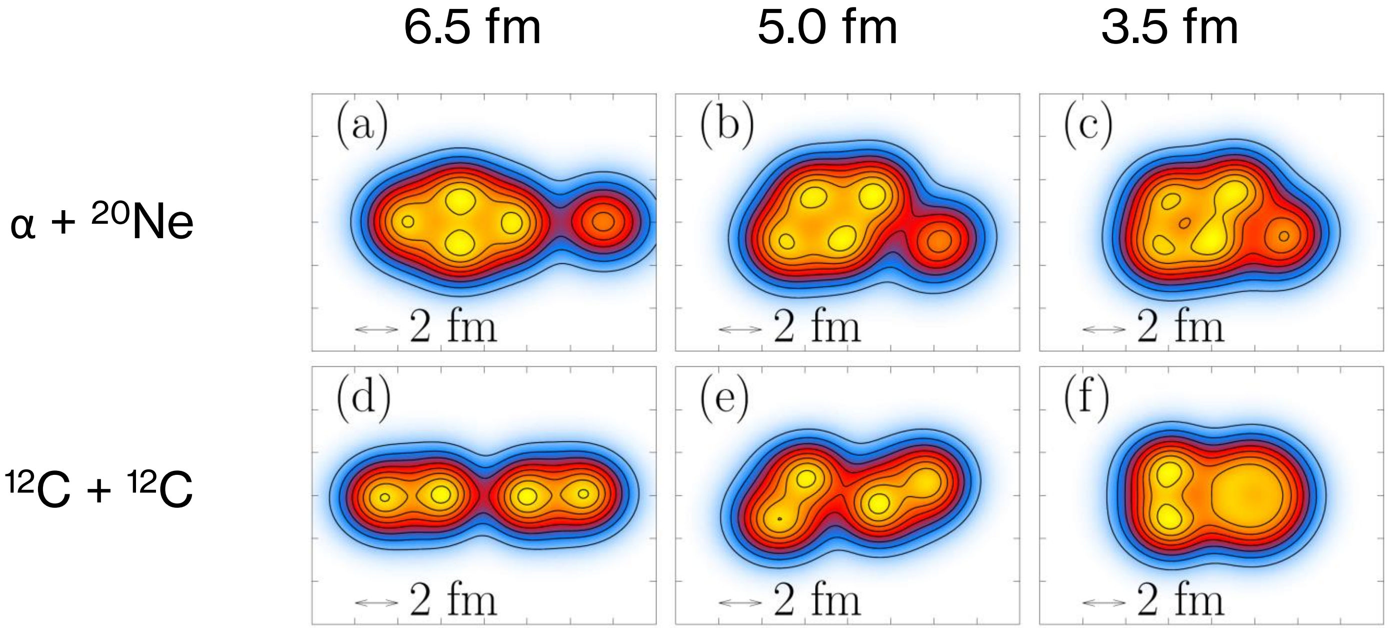
(Dimensionless)Reduced width amplitude at channel radius a

Probability of existence of clusters



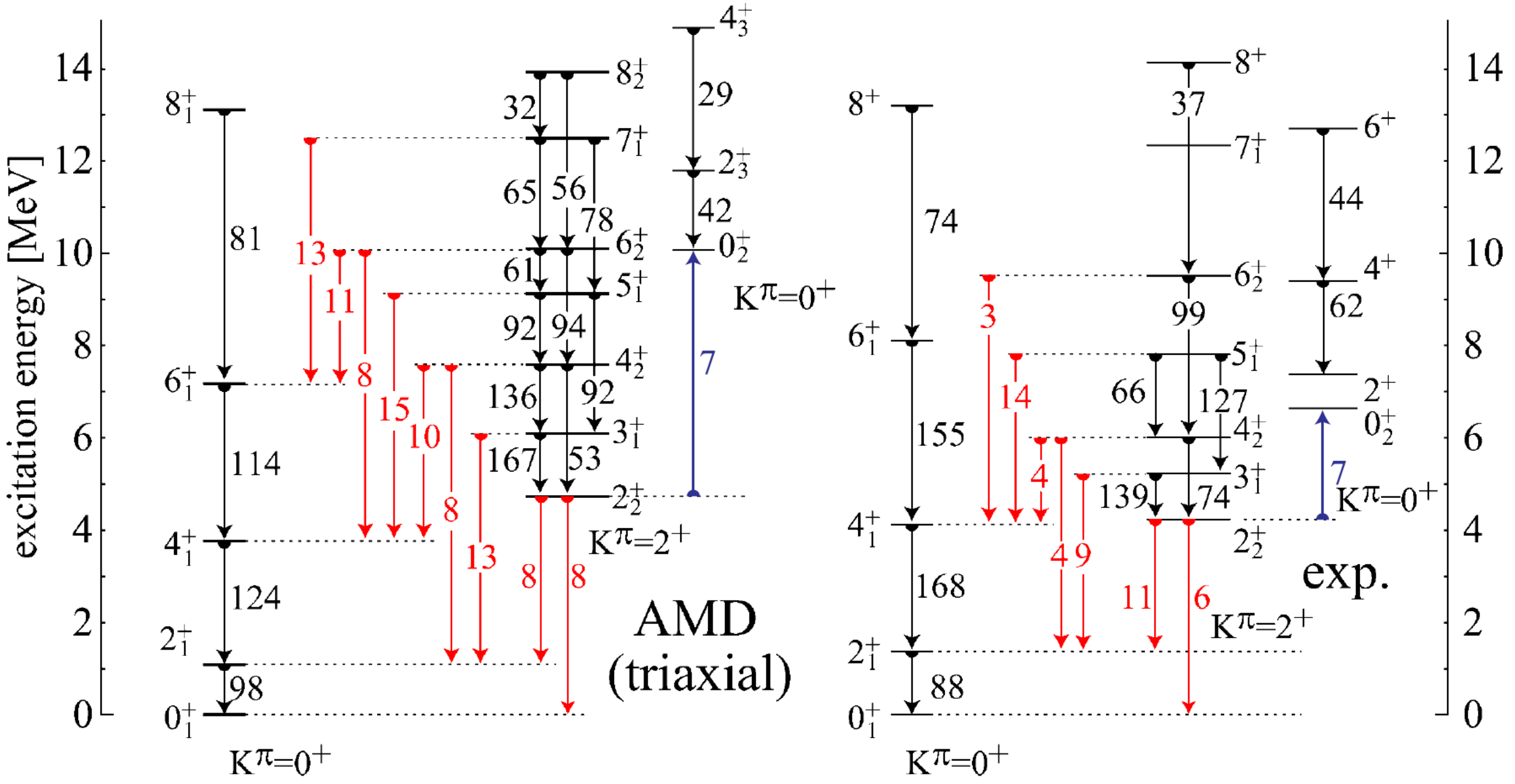
Laplace expansion method [Chiba+, PTEP (2017)]

Examples of the basis wave functions of the multi-configuration mixing



- Coupling of the entrance (^{12}C + ^{12}C) and exit (α + ^{20}Ne) channels
- Rotation of clusters

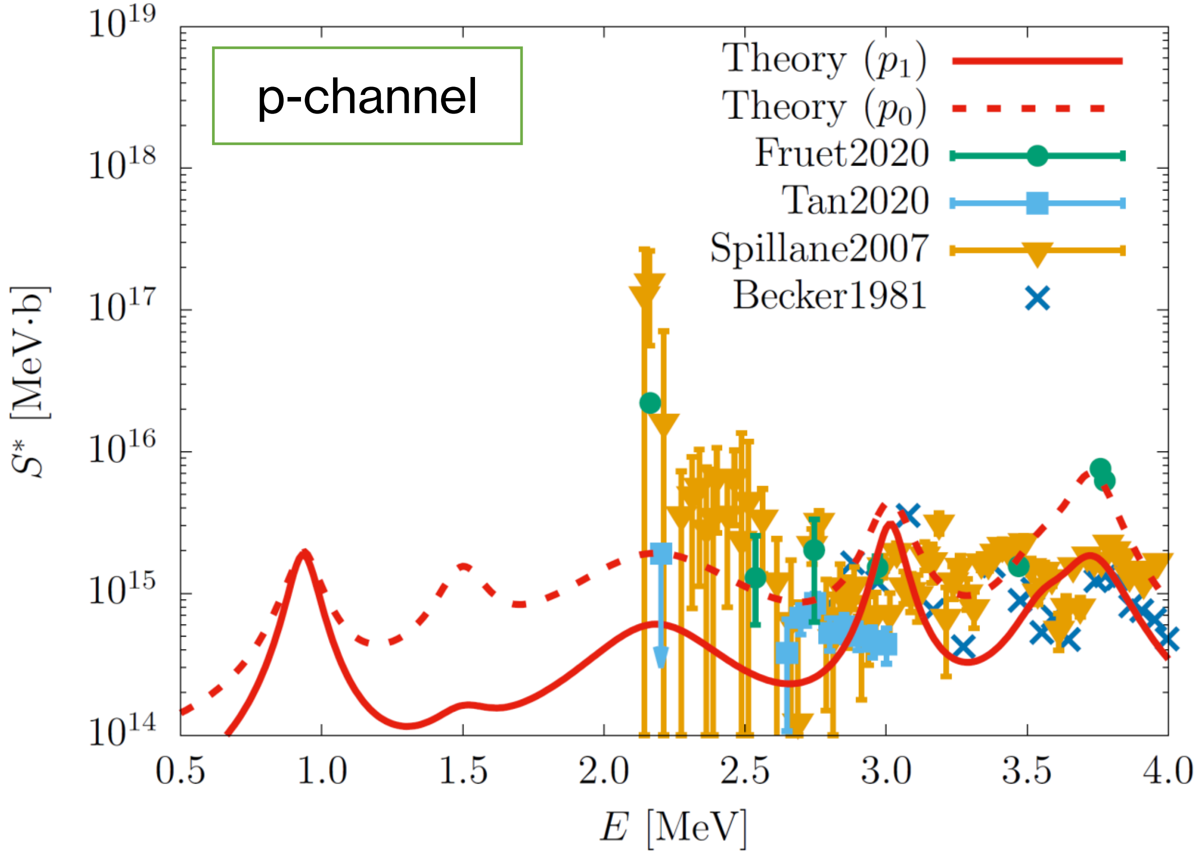
Low-lying states of ^{24}Mg

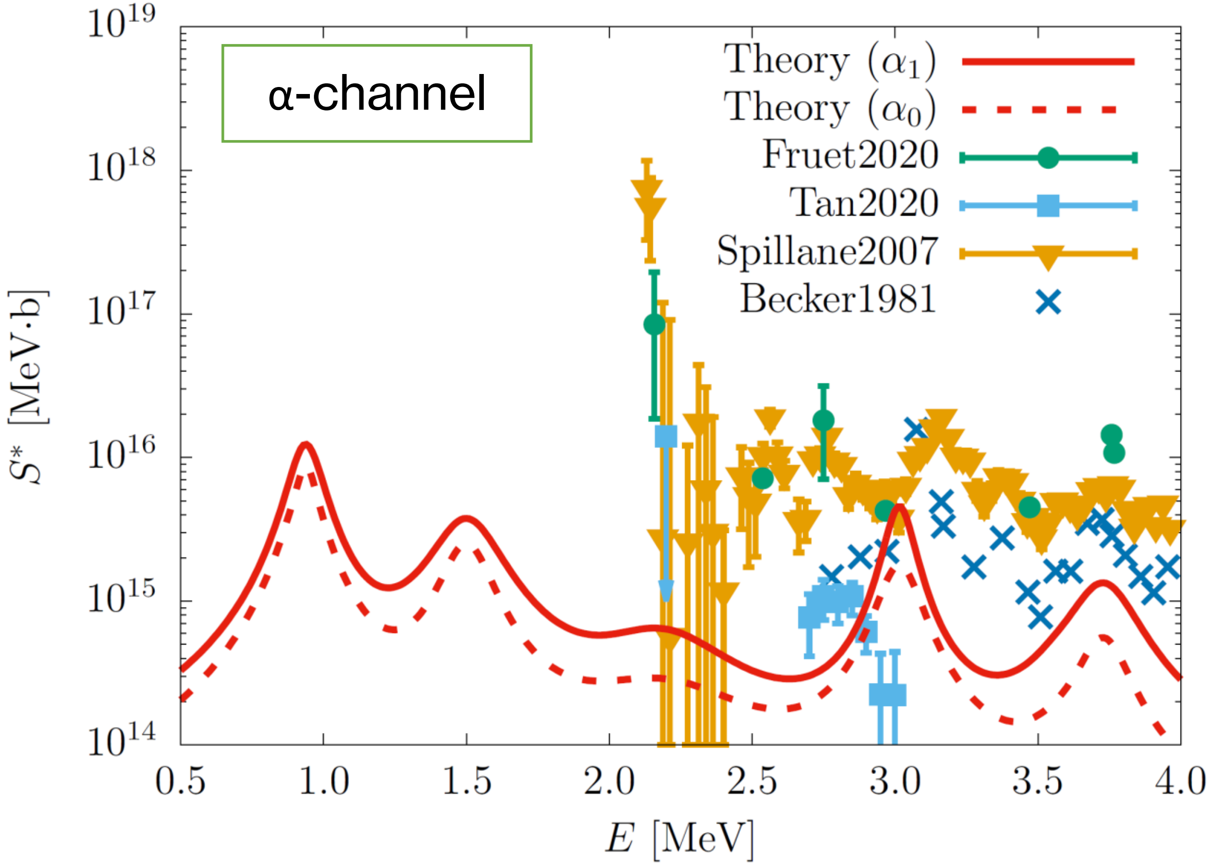


[M. Kimura et al, PTP127, 287 (2012)]

- Low-lying states of ^{24}Mg are well reproduced.
- Framework of AMD with Gogny D1S force works well for ^{24}Mg.

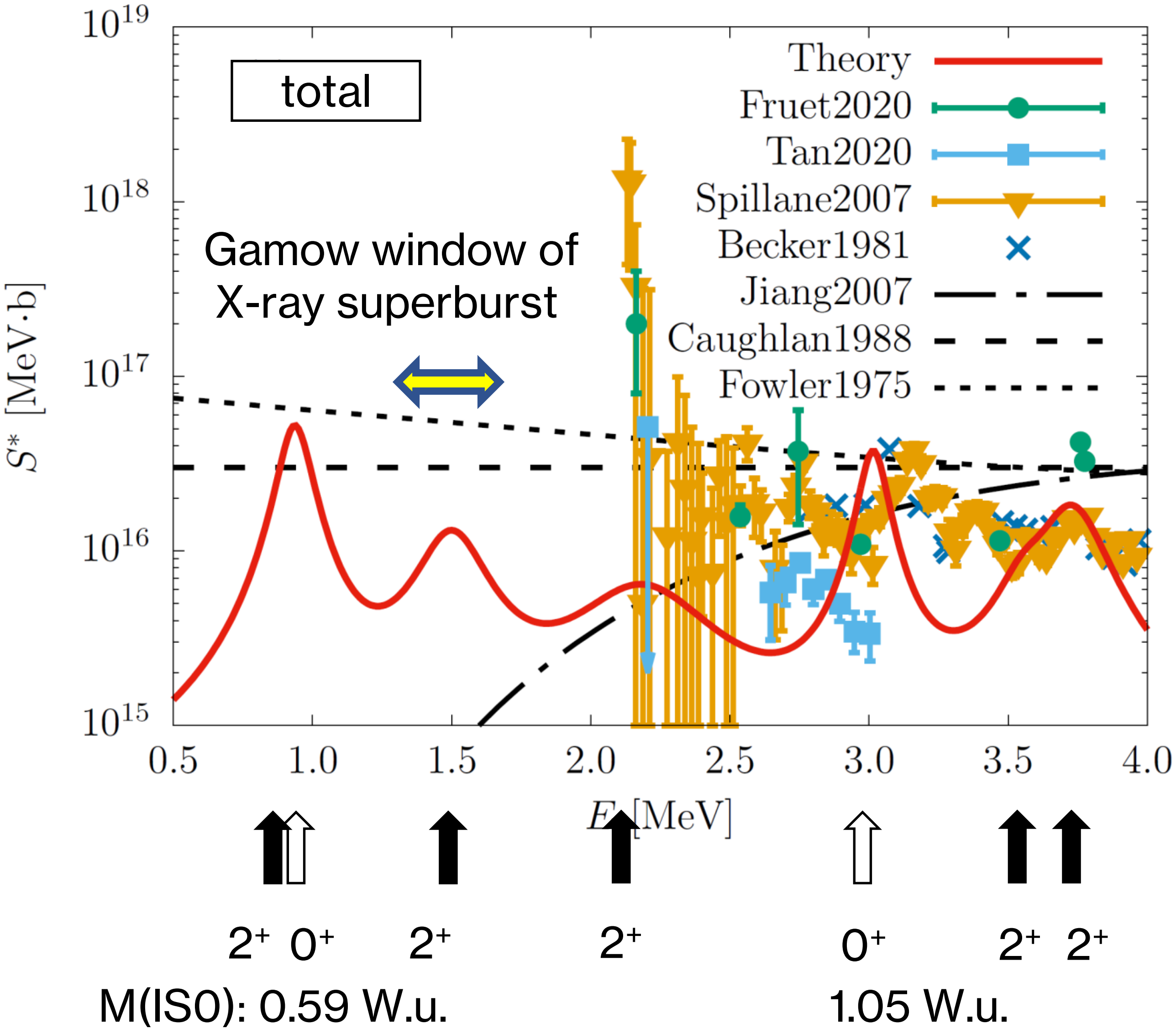
S factors of the p and α-decay cannels





- Existence of the 2.1-MeV and 3.8-MeV resonances are reproduced.
- The S_{p1} factors are reproduced well at the E > 3 MeV region.
- The $S_{\alpha 1}$ factors are underestimated.

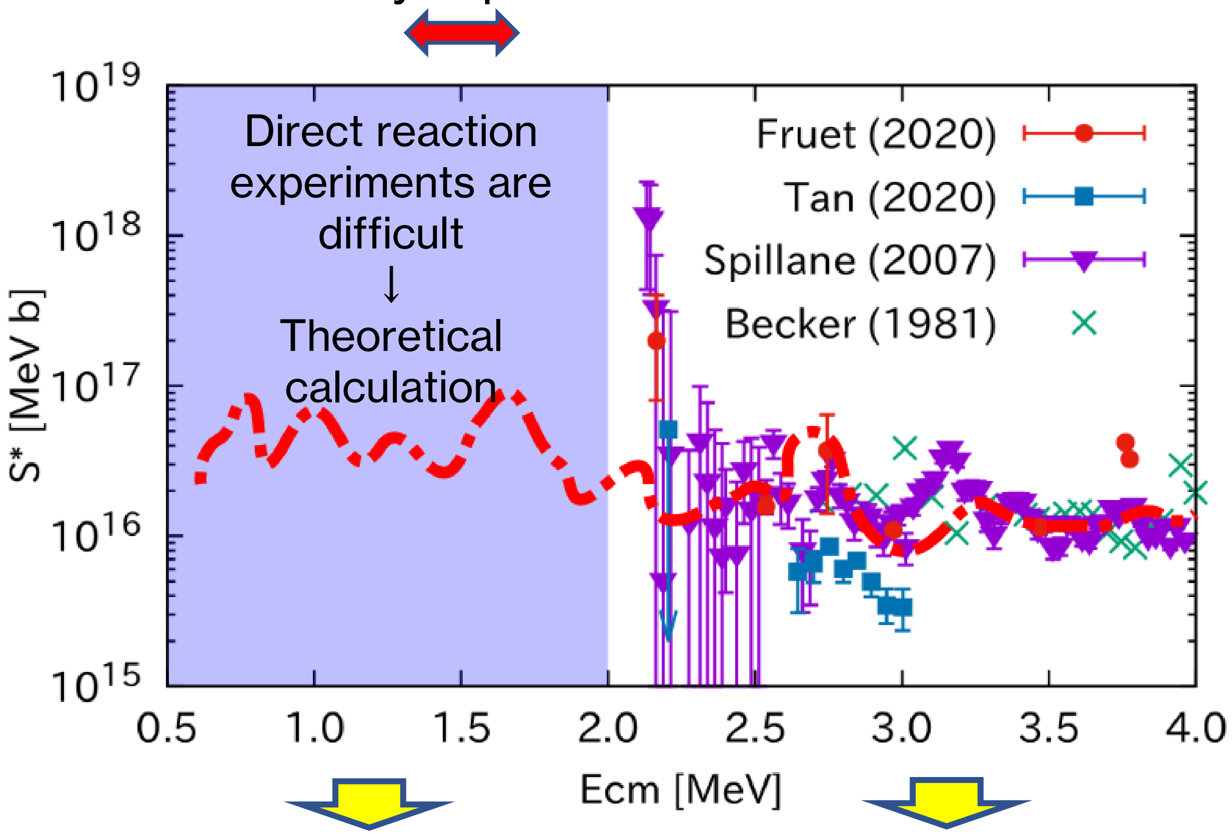
Astrophysical S factor



- The 1.5-MeV resonance is predicted.
  - Related to **X-ray superburst**?
- Theoretical S factors are **much larger** than the **hindrance extrapolation** (Jiang2007) in E < 2 MeV.
  - Contributions of **resonances** are **dominant**.
- We plan to compare with inelastic scattering data to check the reliability of the wave functions.
  - Matrix elements (IS0, ...)
  - Spin and parity
  - Branching ratio

Strategy to the reliable fusion cross sections

Gamow window of
X-ray superburst



Inelastic scattering (IS0, ...)

Fusion cross sections by direct reaction experiments

1. Calculate **wave functions of resonances** and **fusion cross sections.**
2. Check the reliability of wave functions with comparison with experimental data.
    - **Fusion cross sections** by direct fusion reactions
    - **Transition strengths** of IS0, ..., by inelastic scattering

Other systems

- $^{12}C + ^{16}O$
- $^{16}O + ^{16}O$
- ......

Summary

- We have investigated the properties of the $^{12}C + ^{12}C$ resonances using the antisymmetrized molecular dynamics.
- We have treated the coupling of the entrance ($^{12}C + ^{12}C$) and exit channels ($\alpha + ^{20}Ne$) explicitly and rotation of clusters.
- The astrophysical S factors are reasonably reproduced.
- Low-energy resonance states with $E < 2$ MeV are predicted, which may be important for X-ray superbursts.
- We plan to compare with inelastic scattering data to check the reliability of the wave functions of the $^{12}C + ^{12}C$ resonances with $E < 2$ MeV.
- Our method can apply to other reactions such as $^{16}O + ^{16}O$, $^{12}C + ^{16}O$, and so on.