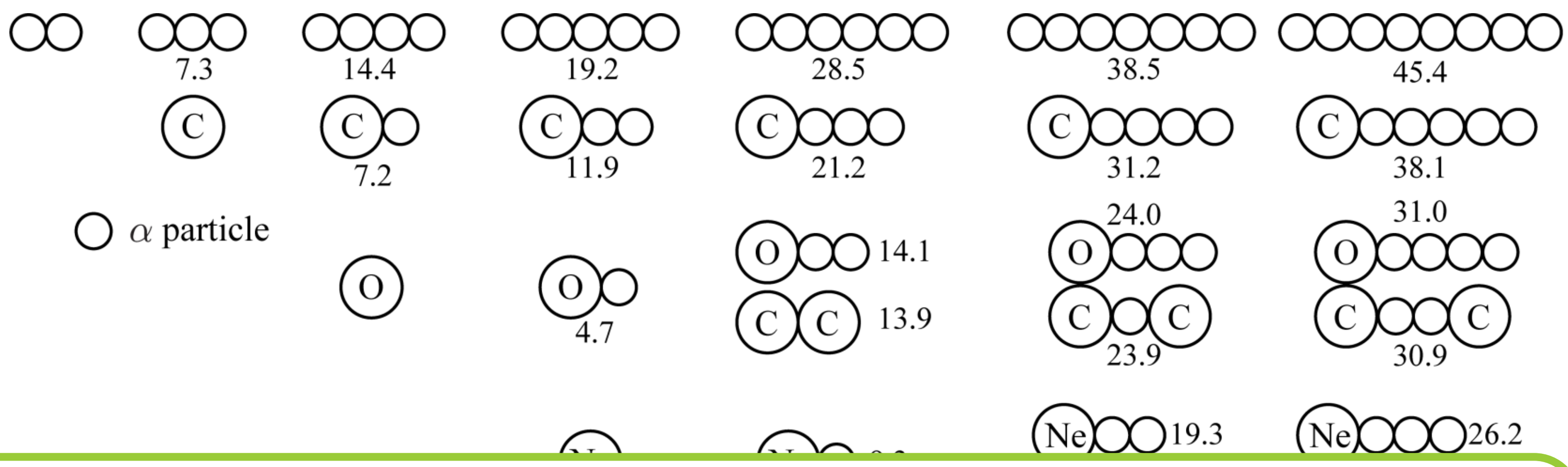
Carbon burning process studied by α inelastic scattering

M. Kimura (Hokkaido Univ.)
in collaboration with
Y. Taniguchi (Kagawa Col.)

Clusters and Reaction channels

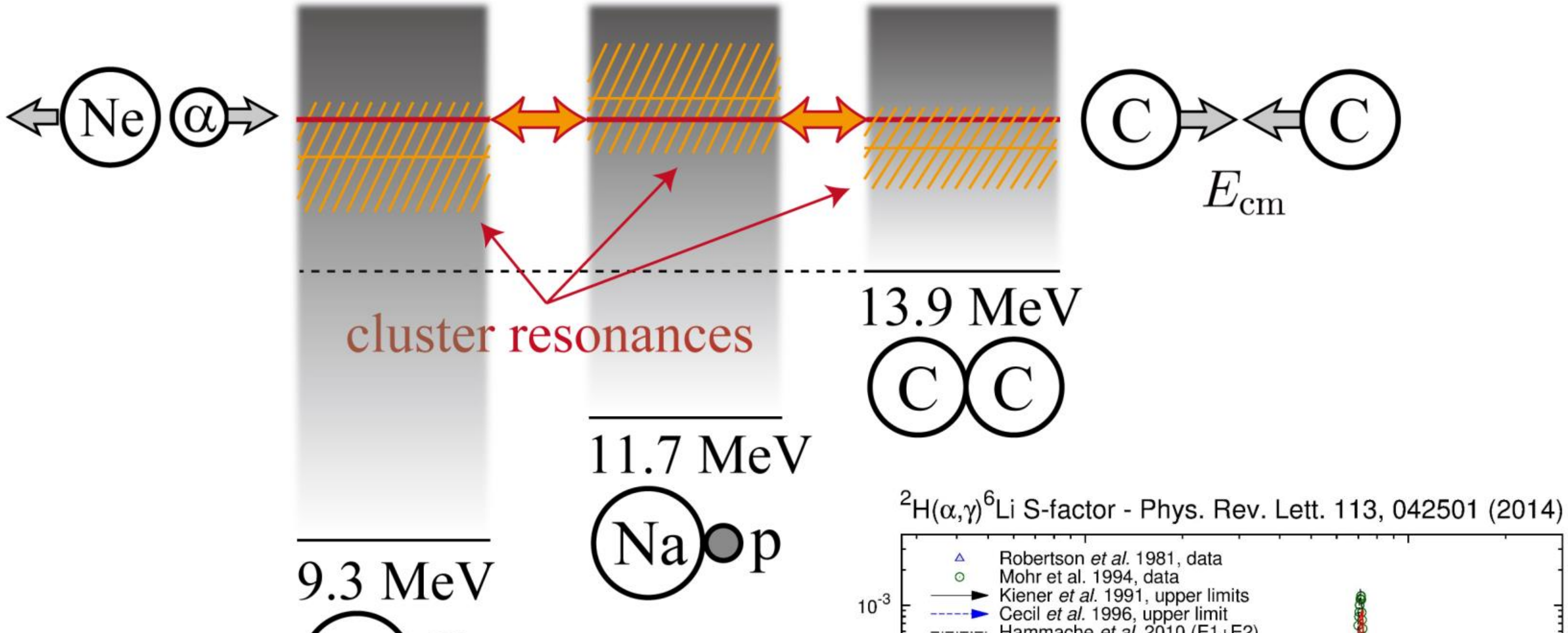


Ikeda diagram indicates

① cluster states at threshold energies

② relationship between clusters and reaction channels

Clusters and Reaction channels



Clusters & Reactions at Nuclear hierarchy

Universality: Hadron molecules, Atomic collisions

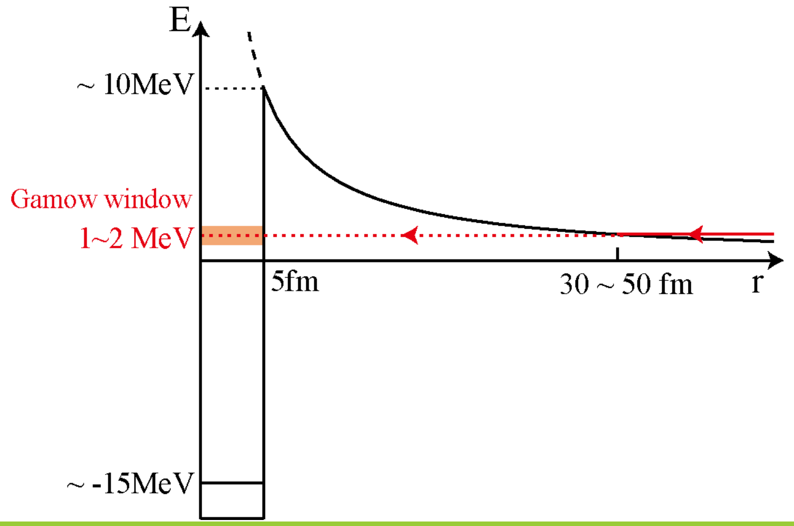
Uniqueness: Astrophysics, Origin of matter

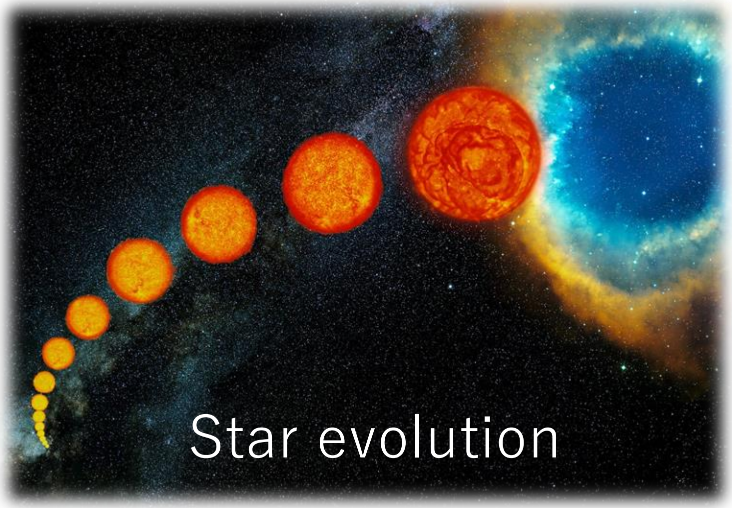
Clusters and Astrophysical Reactions

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow p + {}^{23}\mathrm{Na} + 2.2\mathrm{MeV}$$
$$\rightarrow \alpha + {}^{20}\mathrm{Ne} + 4.6\mathrm{MeV}$$

Fusion reactions of carbon and oxygen nuclei have great impact on the astrophysical phenomena

Their reaction rates have been studied for 40 years since 1980's





Clusters and Astrophysical Reactions

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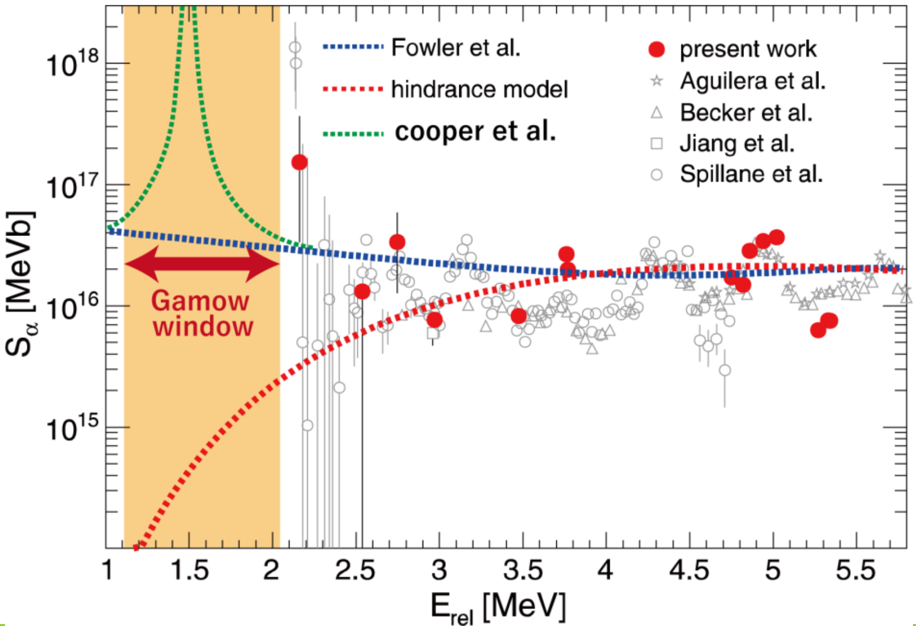
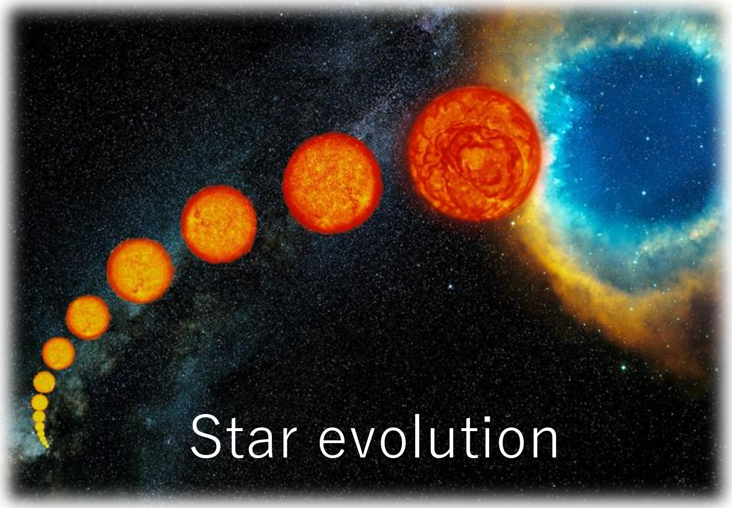
Recent publications

A. Tumino et al., Nature557, 687 (2018).
G. Fruet et al., PRL124, 192701 (2020).
W.P. Tan et al., PRL124, 192702 (2020).





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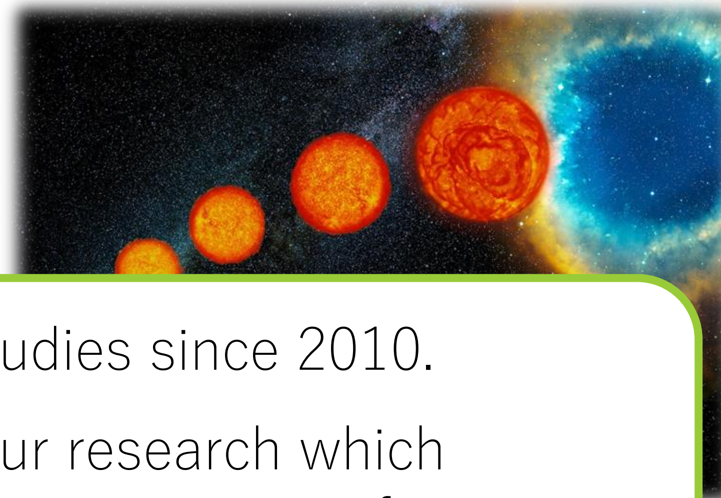
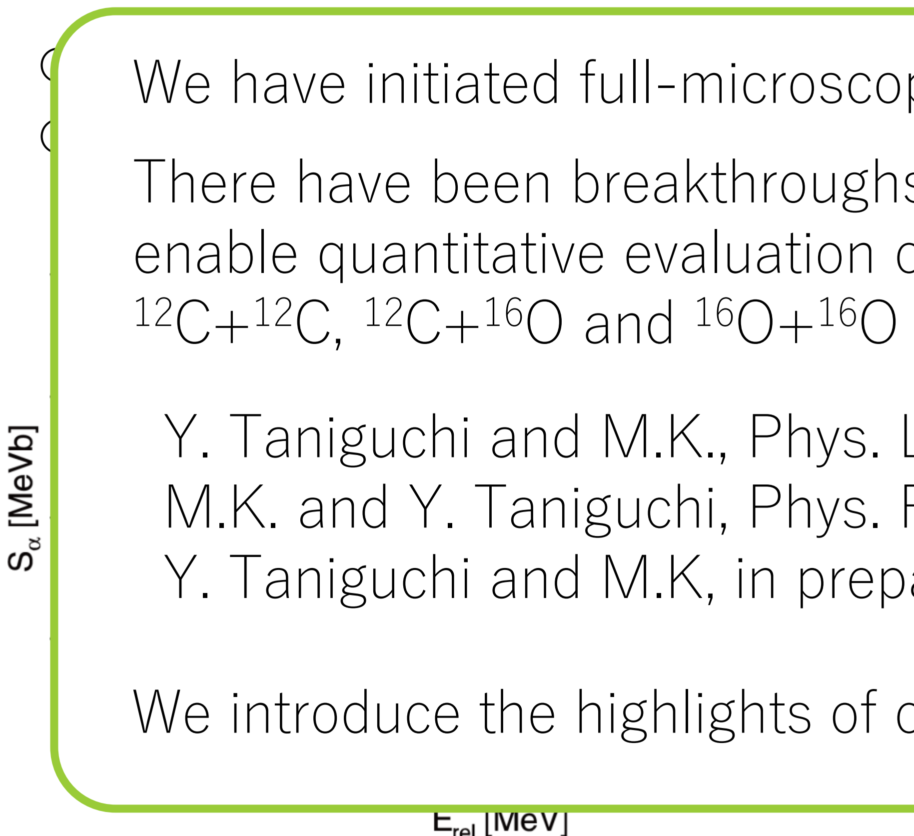


Theoretical studies are important, but $\cdots$



We have initiated full-microscopic studies since 2010.

There have been breakthroughs in our research which enable quantitative evaluation of the reaction rates for ^{12}C+^{12}C, ^{12}C+^{16}O and ^{16}O+^{16}O fusion.

Y. Taniguchi and M.K., Phys. Lett. B800, 135086 (2020)
M.K. and Y. Taniguchi, Phys. Rev. C102, 024325 (2020)
Y. Taniguchi and M.K, in preparation

We introduce the highlights of our results and perspectives

Advances in full-microscopic model approach

① description of various cluster channels and their coupling within a single framework

○ Antisymmetrized Molecular Dynamics (AMD)

$$\hat{H} = \sum_{i}^{A} \hat{t}_i - \hat{t}_{c.m.} + \sum_{i<j}^{A} \hat{v}_{\mathrm{GognyD1S}}(r_{ij}) + \sum_{i<j}^{Z} \hat{v}_{\mathrm{Coulomb}}(r_{ij})$$

(Gogny D1S interaction)

Each nucleon is described by independent wave packet

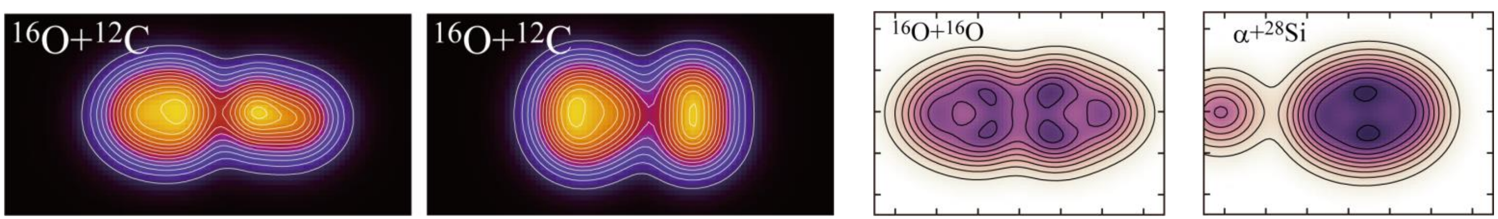
$$\Psi^{\pi} = \frac{1+\pi\hat{P}_r}{2}\Psi_{int} = \frac{1+\pi\hat{P}_r}{2}\mathcal{A}\{\varphi_1, \varphi_2, ..., \varphi_A\}$$

$$\varphi_i(\boldsymbol{r}) \propto \exp\left\{-\boldsymbol{\nu_x}\left(x - \frac{\boldsymbol{Z_{ix}}}{\sqrt{\boldsymbol{\nu_x}}}\right)^2 - \boldsymbol{\nu_y}\left(y - \frac{\boldsymbol{Z_{iy}}}{\sqrt{\boldsymbol{\nu_y}}}\right)^2 - \boldsymbol{\nu_z}\left(z - \frac{\boldsymbol{Z_{iz}}}{\sqrt{\boldsymbol{\nu_z}}}\right)^2\right\} \otimes \{\boldsymbol{a_i}|\uparrow\rangle + \boldsymbol{b_i}|\uparrow\rangle\} \otimes (|n\rangle \text{ or } |p\rangle)$$

○ Constraint on the inter-nuclear distance

Reaction channels are controlled

Y. Taniguchi et al., Phys. Lett. B800, 135086 (2020)



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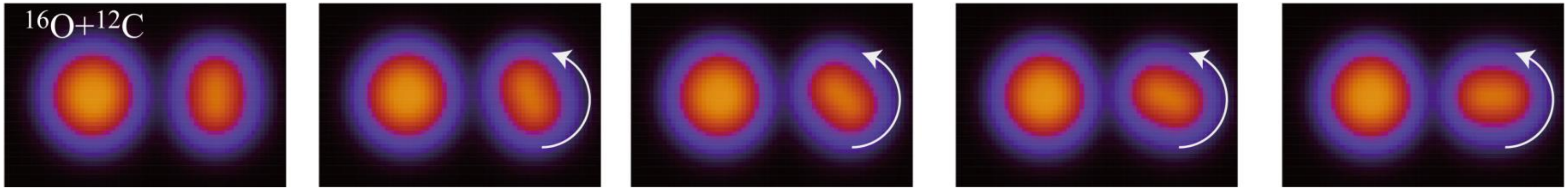
② rotational excitation of clusters is also incorporated

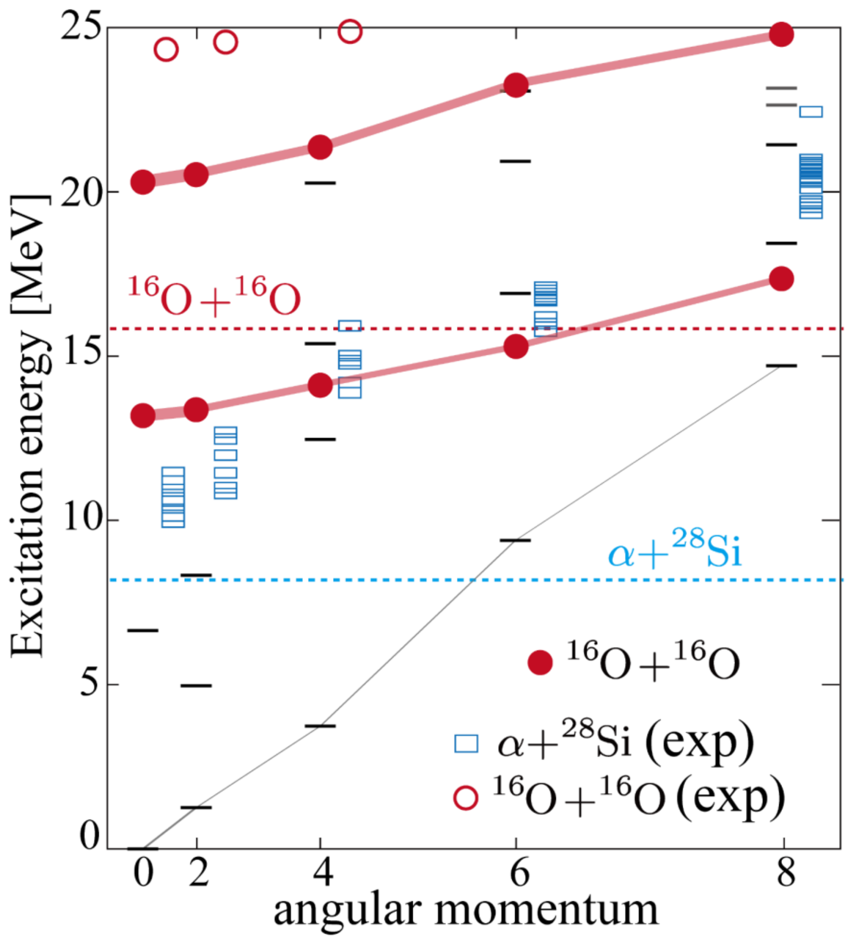
Y. Taniguchi et al., Phys. Lett. B800, 135086 (2020)



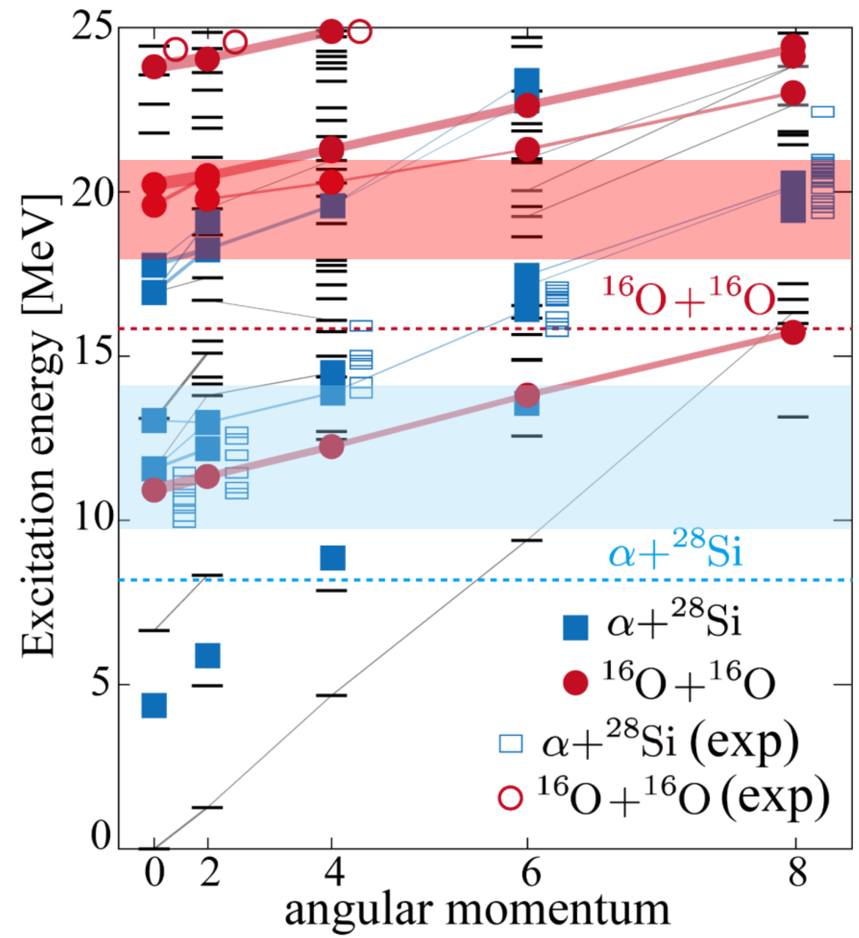
Advances in full-microscopic model approach

Many resonances are predicted in the Gamow window

M.K and H. Horiuchi, PRC69, (2004)



M.K and Y. Taniguchi, PRC102, (2020)



Advances in full-microscopic model approach

③ Decay width and decay branch of the resonances

Laplace expansion method: Y. Chiba and M.K., PTEP2017, 053D01 (2017)

Partial decay width $\Gamma = 2P_\ell(a)\frac{\hbar^2}{\quad}|a y_\ell(a)|^2$

○ These procedure determines resonance parameters

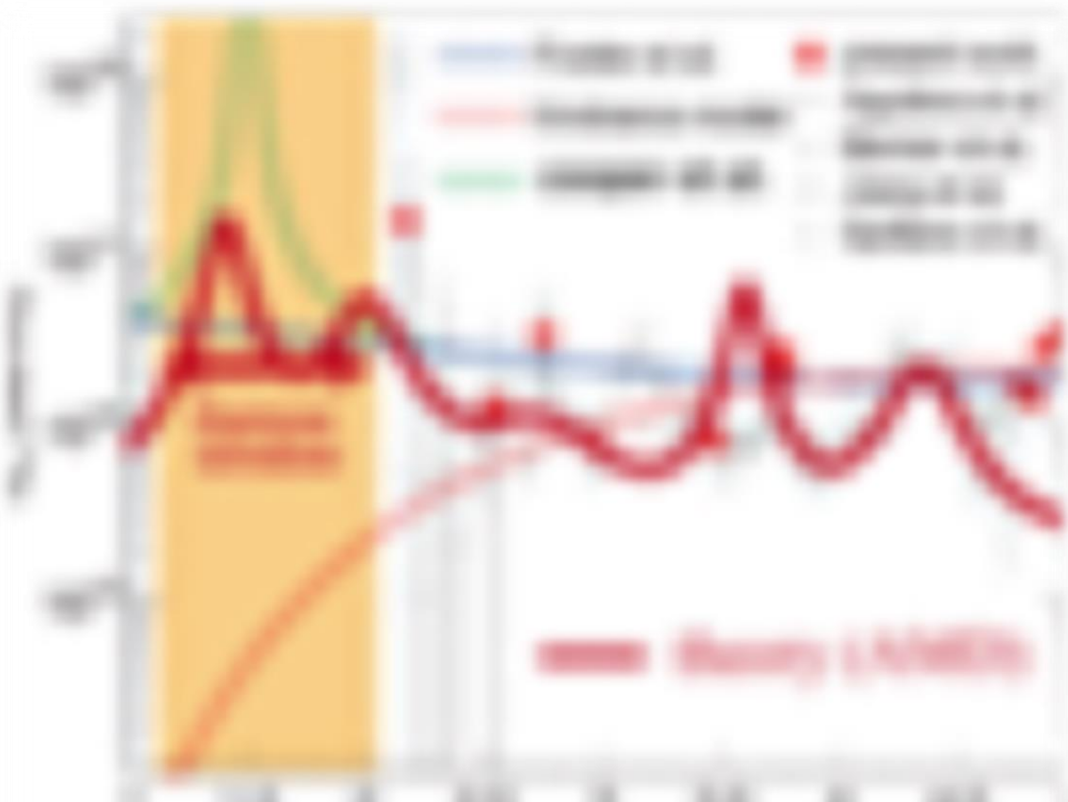
$$E_{\mathrm{R}}, \Gamma_p, \Gamma_\alpha, \Gamma_{\mathrm{C}}, \ldots$$

○ Assuming narrow and isolated resonances, we estimate astrophysical S-factor

$$\sigma_{\mathrm{BW}}(E) = \frac{\Gamma}{2\pi}\frac{1}{(E-E_R)^2+\Gamma^2/4} \times \frac{\pi\hbar^2}{2\mu E}\frac{(2J_{\mathrm{C}}+1)}{(2J_\alpha+1)(2J_{\mathrm{Ne}}+1)}\frac{\Gamma_{\mathrm{C}}\Gamma_\alpha}{\Gamma}$$

$$S(E) = E\sigma_{\mathrm{BW}}(E)\exp\{2\pi\eta(E)\}$$

$^{12}C+^{12}C$ reaction rate from theory

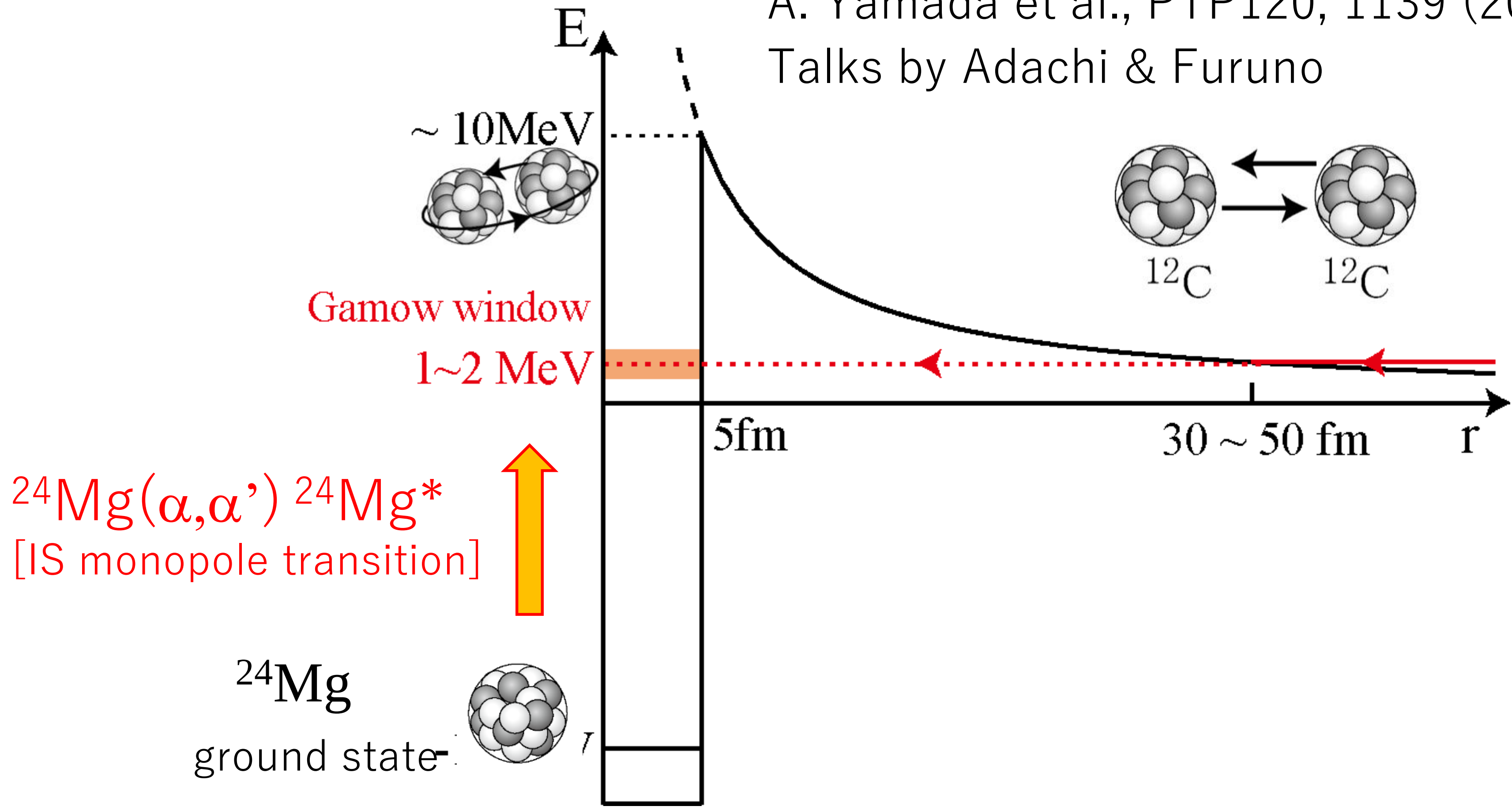


- S-factor is described surprisingly well
- No hindrance
- Resonances within the Gamow window

How can we trust theoretical prediction?

The isoscalar monopole transition induced by alpha inelastic reaction can populate cluster resonances easily.

A. Yamada et al., PTP120, 1139 (2008).
Talks by Adachi & Furuno



Perspectives

◎ Systematic evaluation of the reaction rates will be made for $^{12}C+^{12}C$, $^{12}C+^{16}O$ and $^{16}O+^{16}O$

◎ Consistency with the (α , α ') experiment will be investigated

◎ Fusion reaction process will be described more carefully

Closed channel method:

E. Hiyama, Y. Kino and M. Kamimura, PPNP51, 223 (2003)

$$\Psi_{\mathrm{scatt}} = \sum_p b_p \Psi_p + \sum_c \mathcal{A}\{\,\phi_{\mathrm{c1}}\phi_{\mathrm{c2}}\chi(\boldsymbol{r})\,\}$$

$$b_p = -\frac{1}{\varepsilon_p - E}\langle \Psi_p | H - E | \mathcal{A}\{\,\phi_{\mathrm{c1}}\phi_{\mathrm{c2}}\chi(\boldsymbol{r})\,\}\rangle$$

Summary

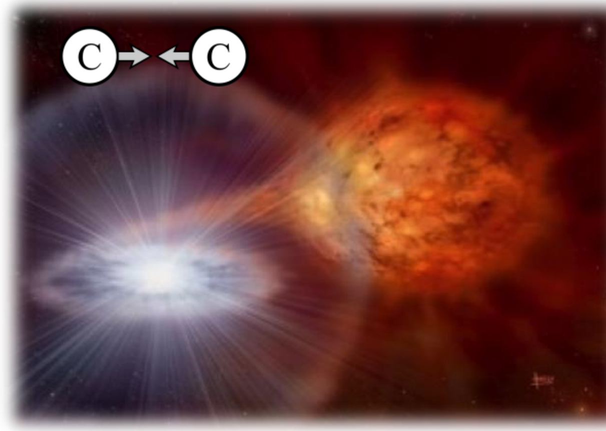
Summary

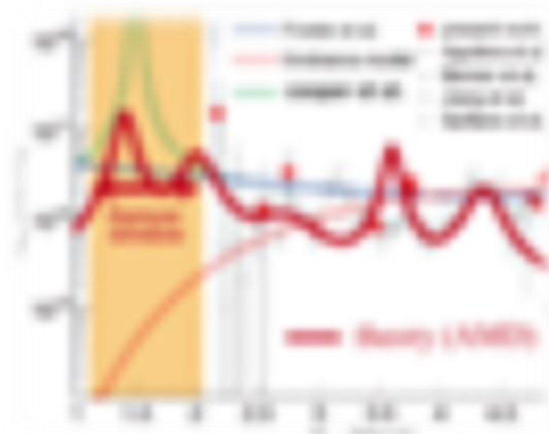
◎ Ikeda diagram shows the relationship between clusters and reactions

◎ Universality & Uniqueness

◎ Clusters have great impact on stellar fusion reactions

◎ Recent advances in microscopic theoretical calculations





Perspective

◎ Systematic evaluation of the reaction rates

◎ Microscopic description of the fusion reaction process