微視的模型による
astrophysical S-factorの評価

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

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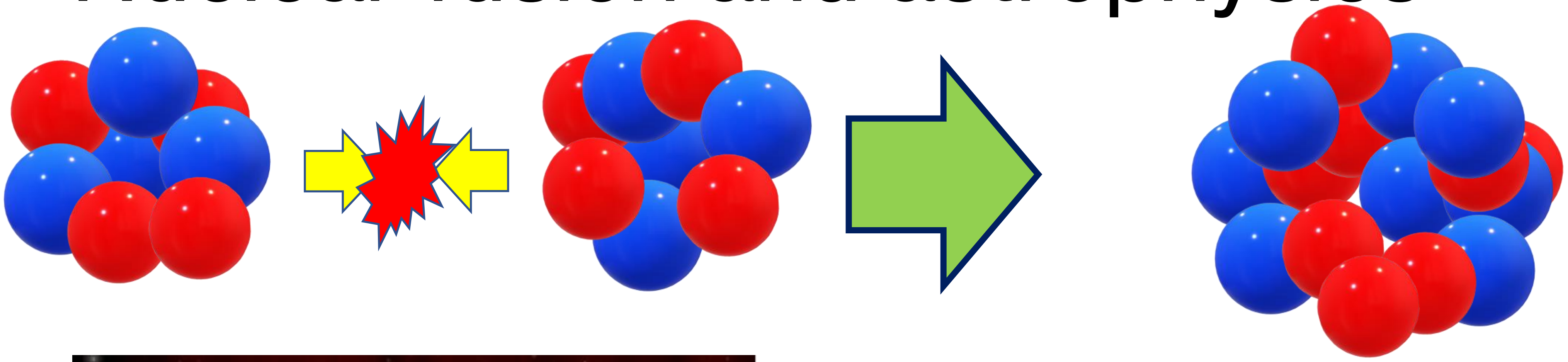
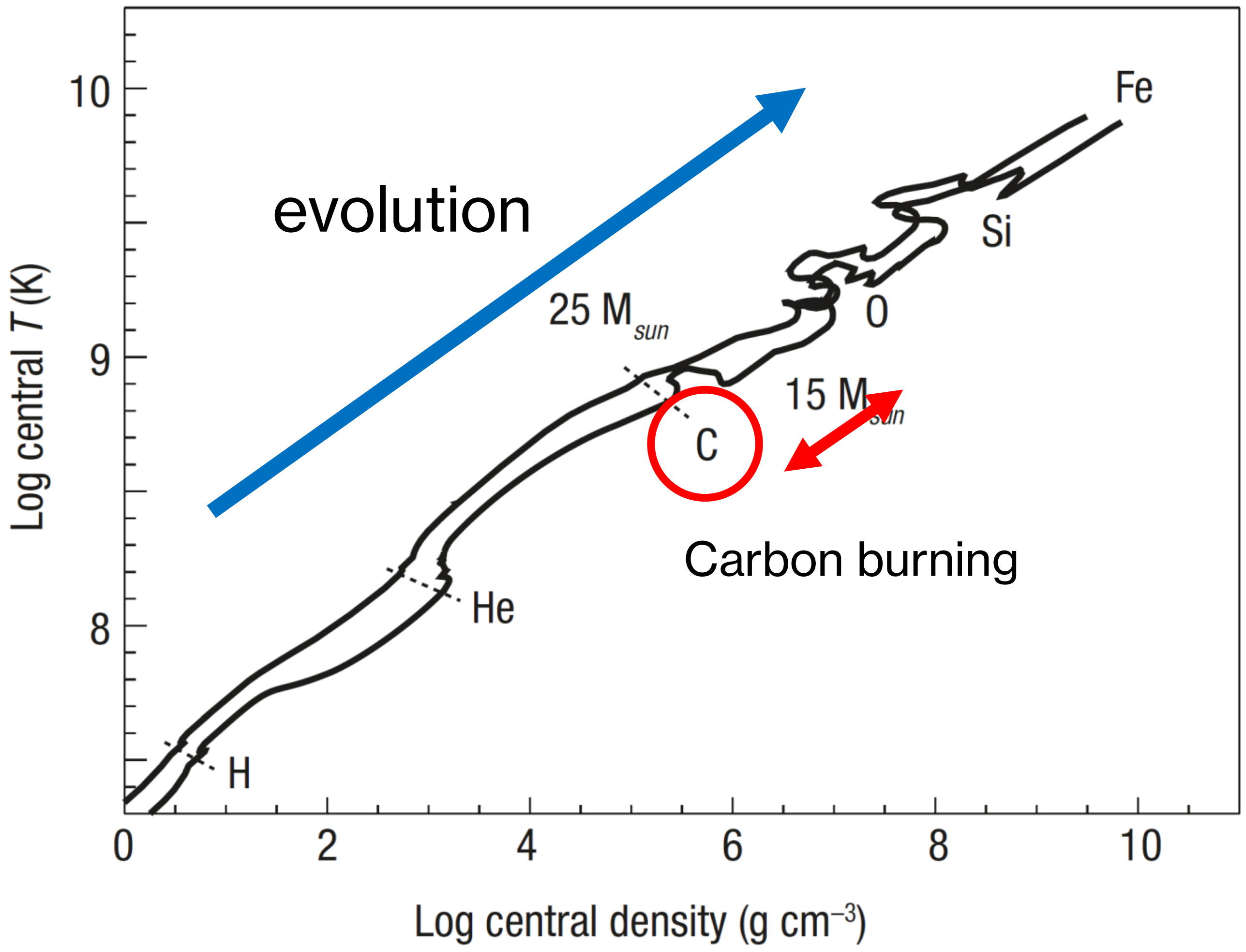
Nuclear fusion and astrophysics



- 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]

Evolution of massive stars

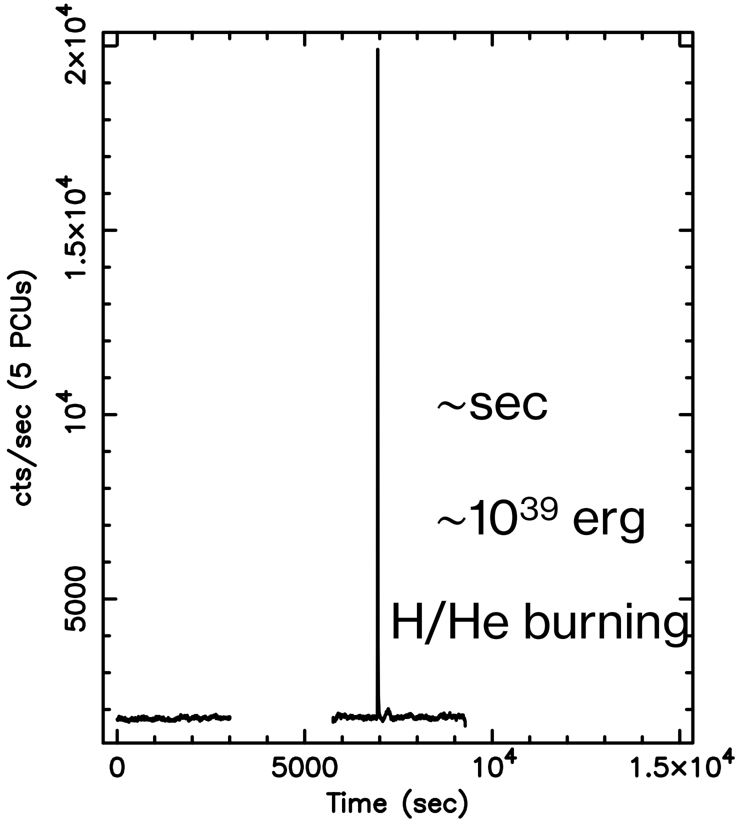


[S. E. Woosley, A. Heger, T. A. Weaver, Rev. Mod. Phys. **74**, 1015 (2002)]

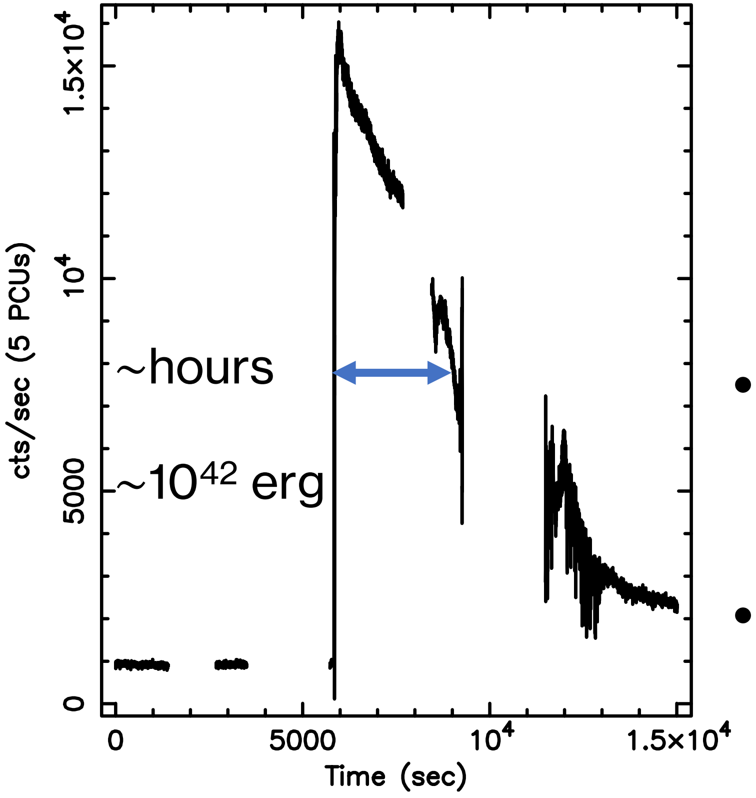
- Massive stars evolve through the carbon-burning process after the helium-burning process.
- The dominant reaction of the carbon-burning process is $^{12}C+^{12}C$ fusion.

X-ray superbutst

X-ray burst



X-ray superburst



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

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

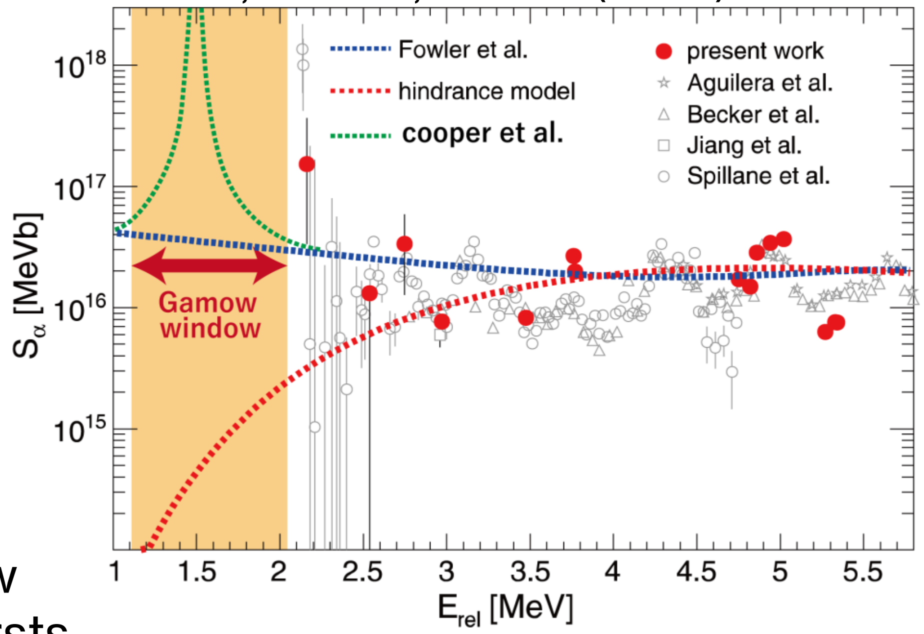
^{12}C+^{12}C fusion reaction in X-ray superbutst

$$^{12}\mathrm{C} + ^{12}\mathrm{C} \to p + ^{23}\mathrm{Na} + 2.2\mathrm{MeV}$$

$$\to \alpha + ^{20}\mathrm{Ne} + 4.6\mathrm{MeV}$$

Recent publications

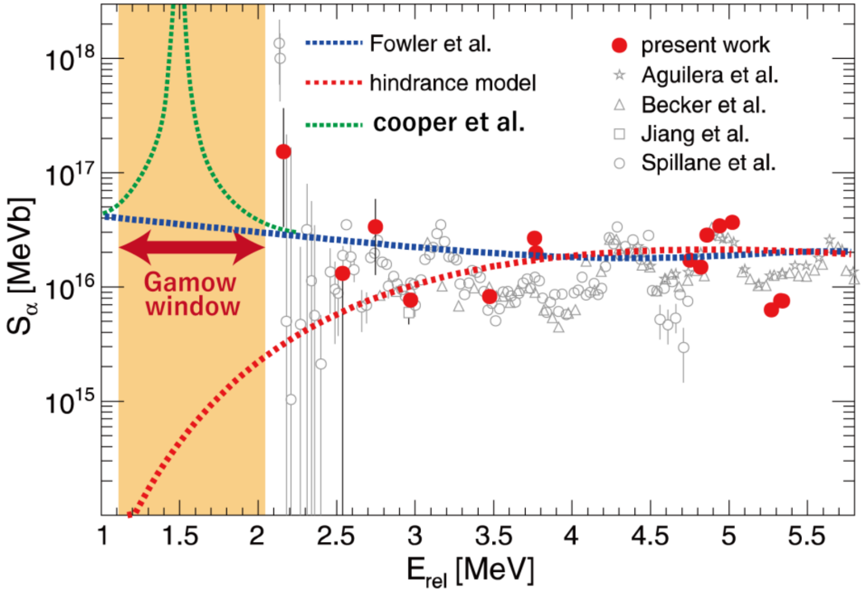
A. Tumino et al., Nature557, 687 (2018).
G. Fruet et al., PRL124, 192701 (2020).
W.P. Tan et al., PRL124, 192702 (2020).

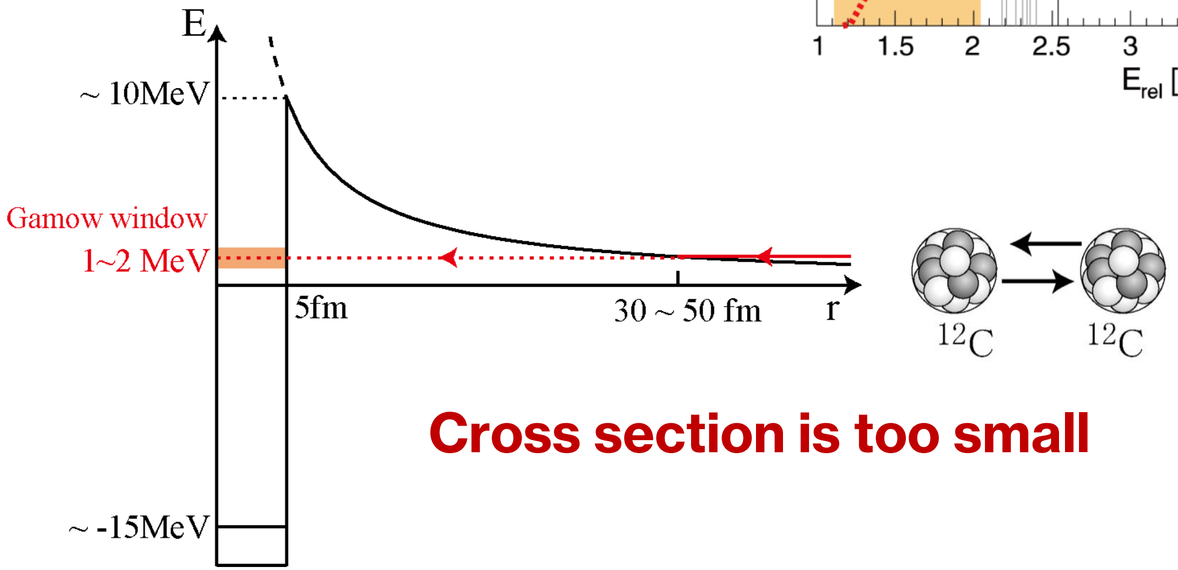


Gamow window
of X-ray superbursts
[R. L. Cooper+, ApJ **702**, 660 (2009)]

$^{12}C+^{12}C$ fusion reaction in the universe

◎ It is very hard to access the Gamow window because the cross sections are very small
⇒ **Theoretical estimations as a guide!**

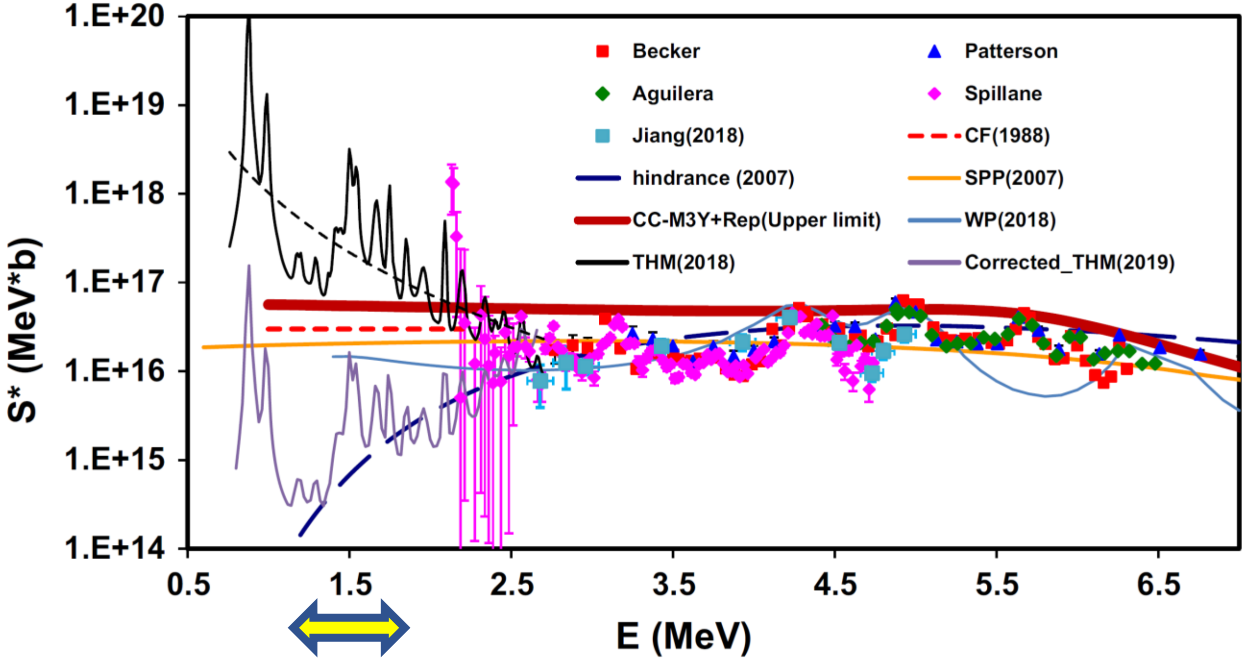




Cross section is too small

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

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

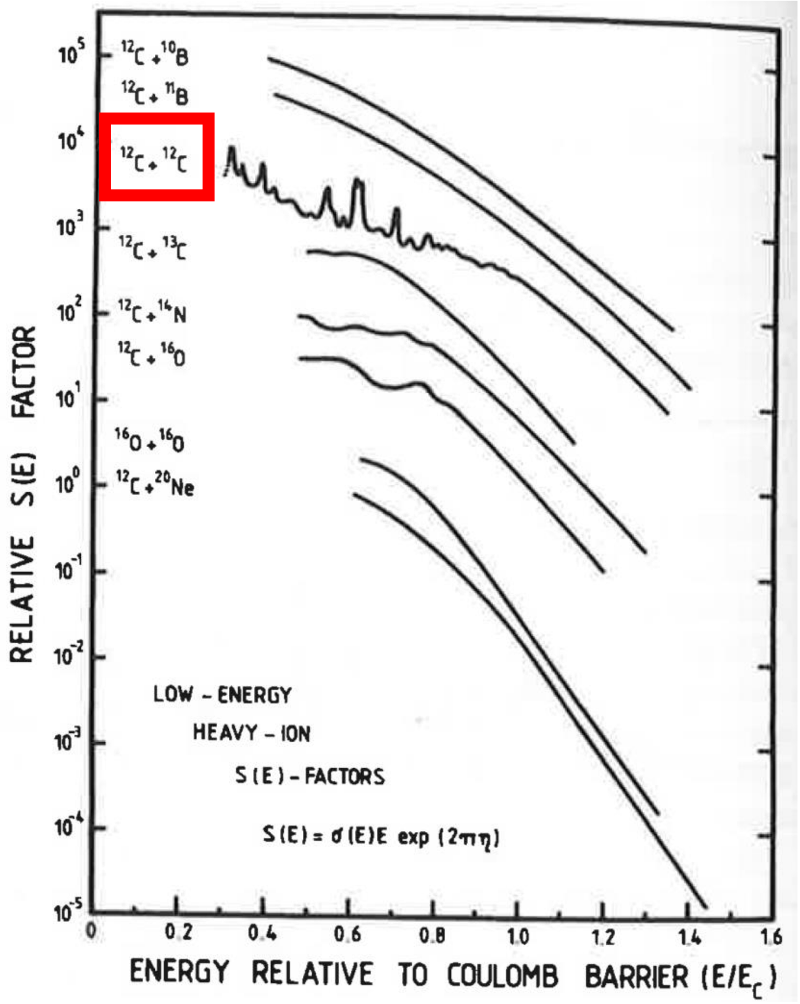


Gamow window
of X-ray superbursts
[R. L. Cooper+, ApJ **702**, 660 (2009)]

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

- Experiments
  - **No direct experiments** in E < 2 MeV.
  - The estimation from the indirect THM experiment is under discussion.
- Theories (just extrapolations)
  - Constant: CF1988 etc.
  - Strong suppression in the low-energy region: Hindrance model

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



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

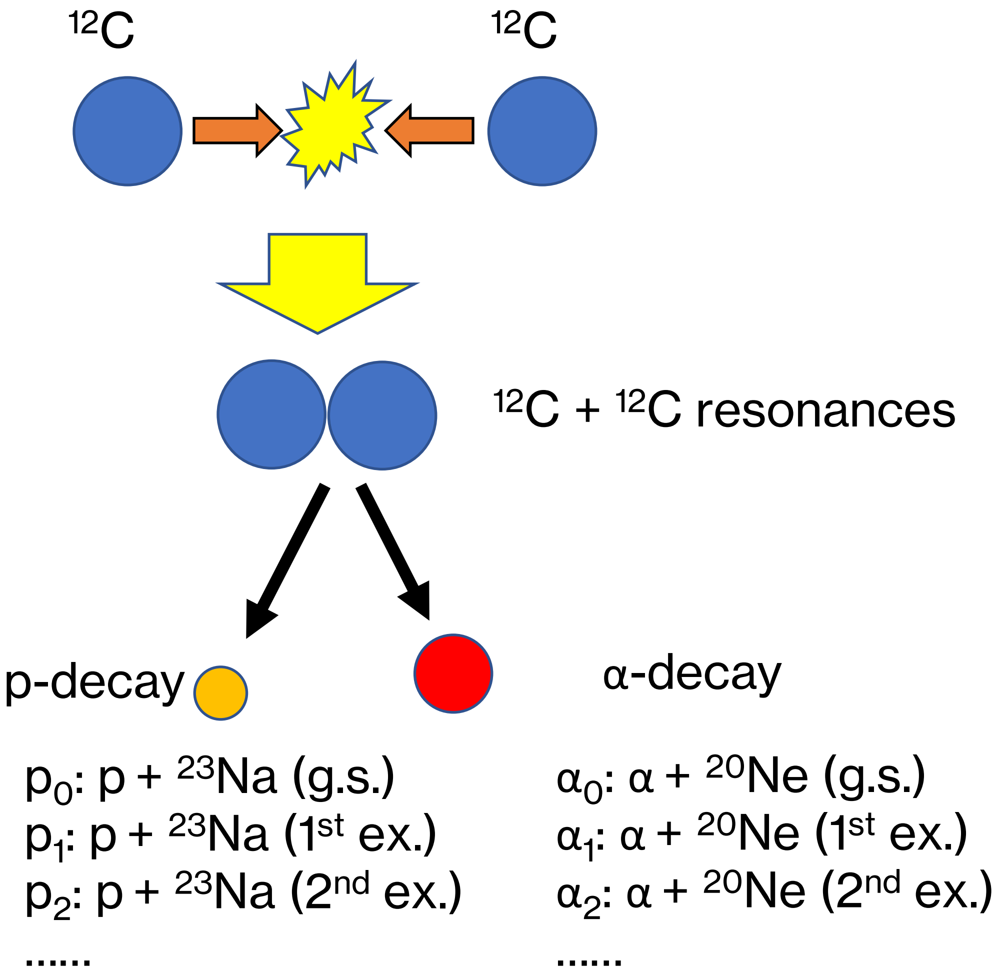
- S-factors of $^{12}C + ^{12}C$ fusion reaction has a significant peak structure.
- Contributions of **narrow-resonance states** are dominant.

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

Difficulties of calculation of ^{12}C + ^{12}C fusion cross sections

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

→**Microscopic framework**



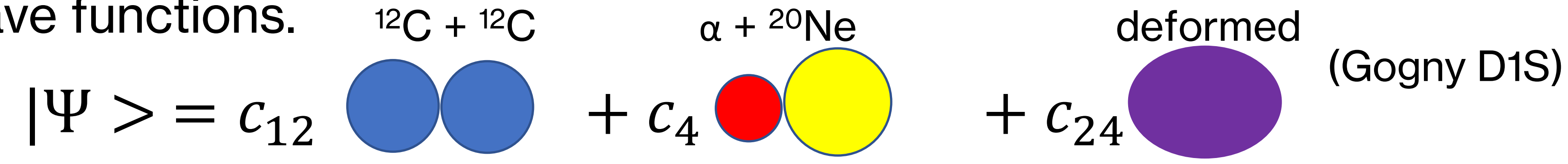
Framework: Antisymmetrized molecular dynamics (AMD)

- Slater determinant of deformed Gaussian wave packets

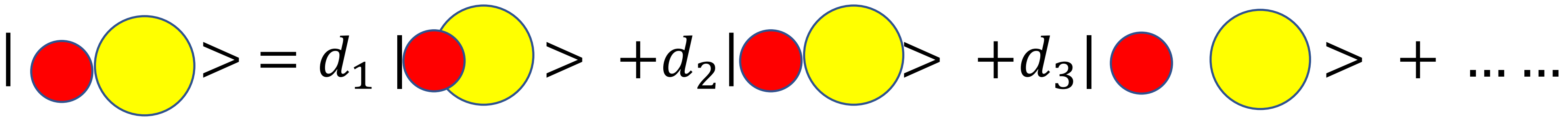
$$|\Phi> = \mathcal{A}|\varphi_1, \varphi_2, \ldots, \varphi_A>$$

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

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

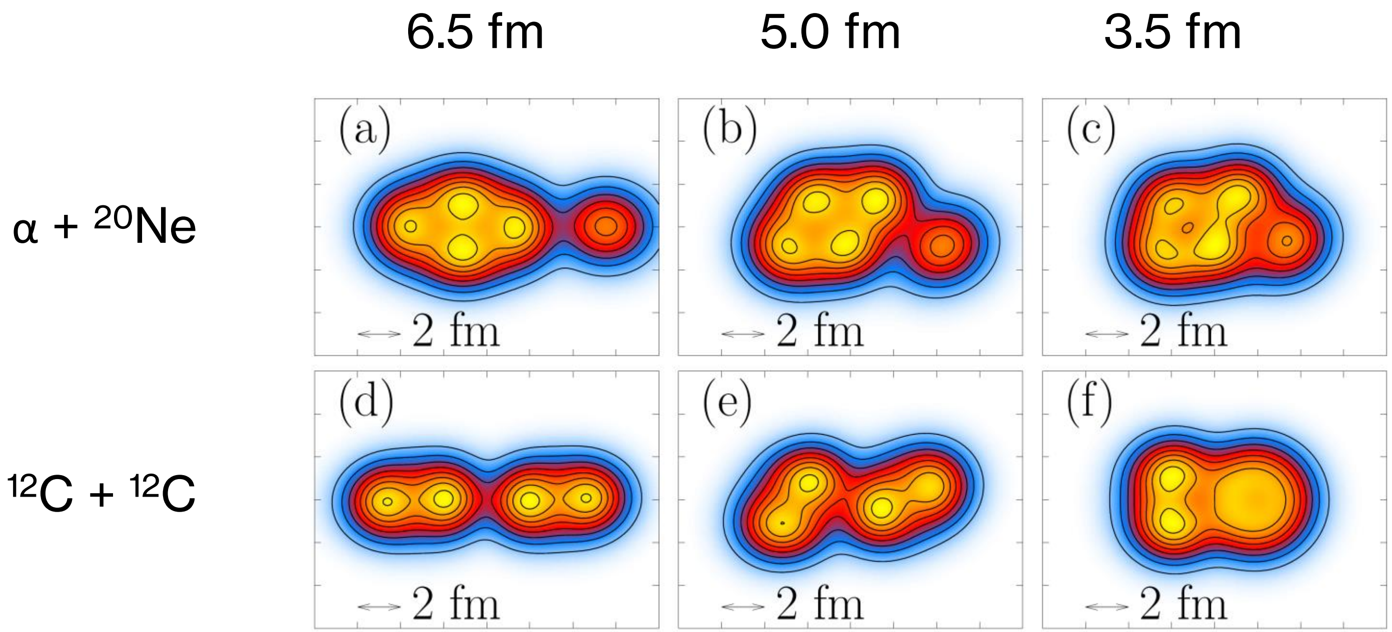


- Fusion and decay dynamics are also treated by a linear combination of various inter-nuclear distances wave functions.



- Diagonalization of Hamiltonian with the Gogny D1S effective interaction (density functional) after parity and angular-momentum projection.

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



- Energy variation with the constraint on inter-nuclear distance and quadrupole deformation
- Coupling of the entrance (^{12}C + ^{12}C) and exit (α + ^{20}Ne) channels
- Rotation of clusters

Fusion cross sections and Decay widths

- The Breit-Wigner formula

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

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

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

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

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

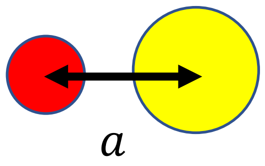
- The R-matrix theory

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

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

a: channel radius

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

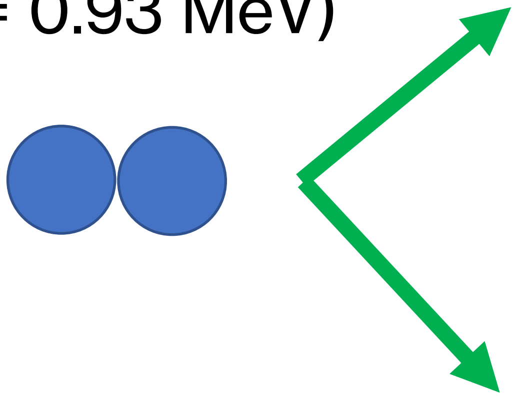


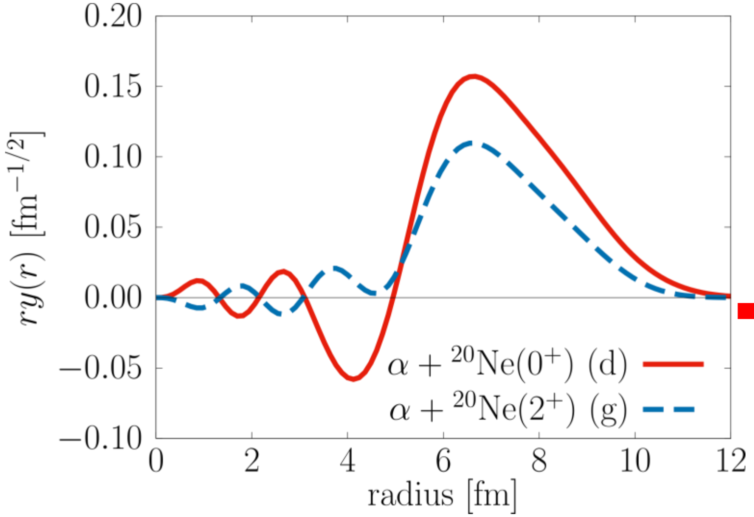
Laplace expansion method [Chiba+, PTEP (2017)]

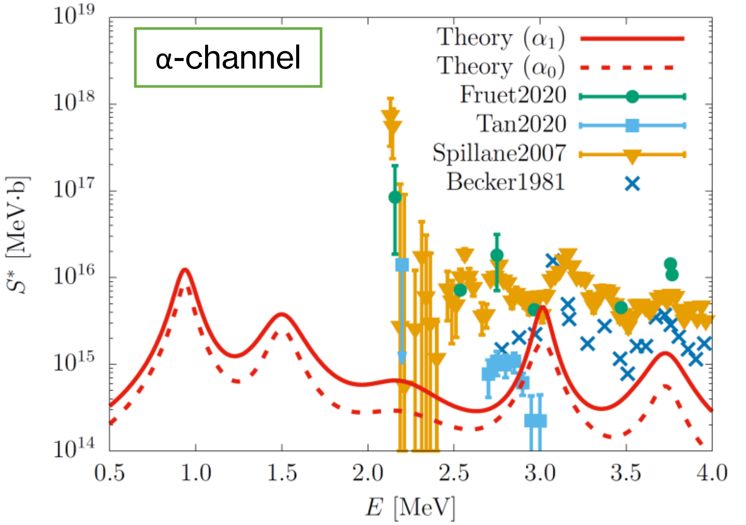
Relative wave function and S-factor of each channel

α channel

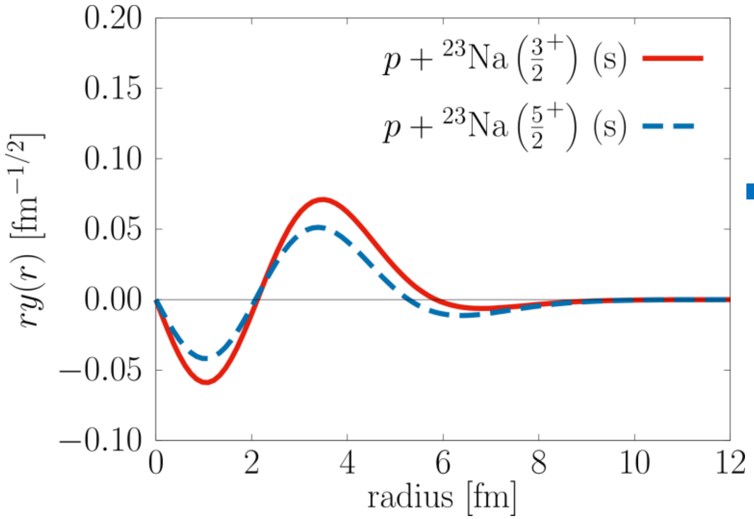
2^+ resonance
(Ecm = 0.93 MeV)

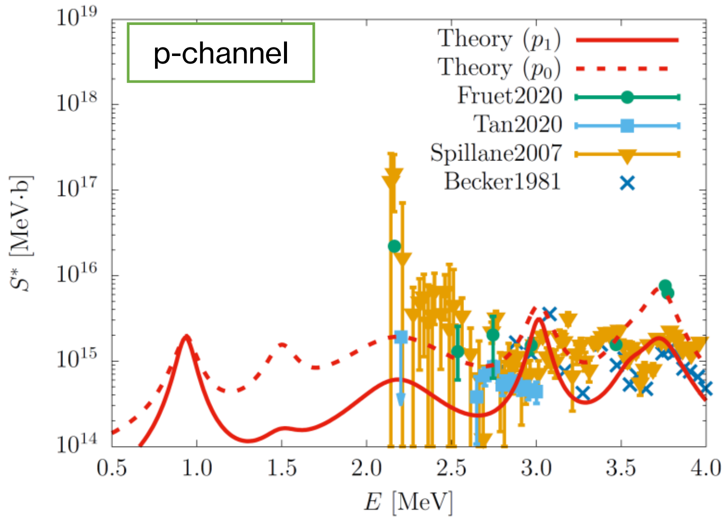




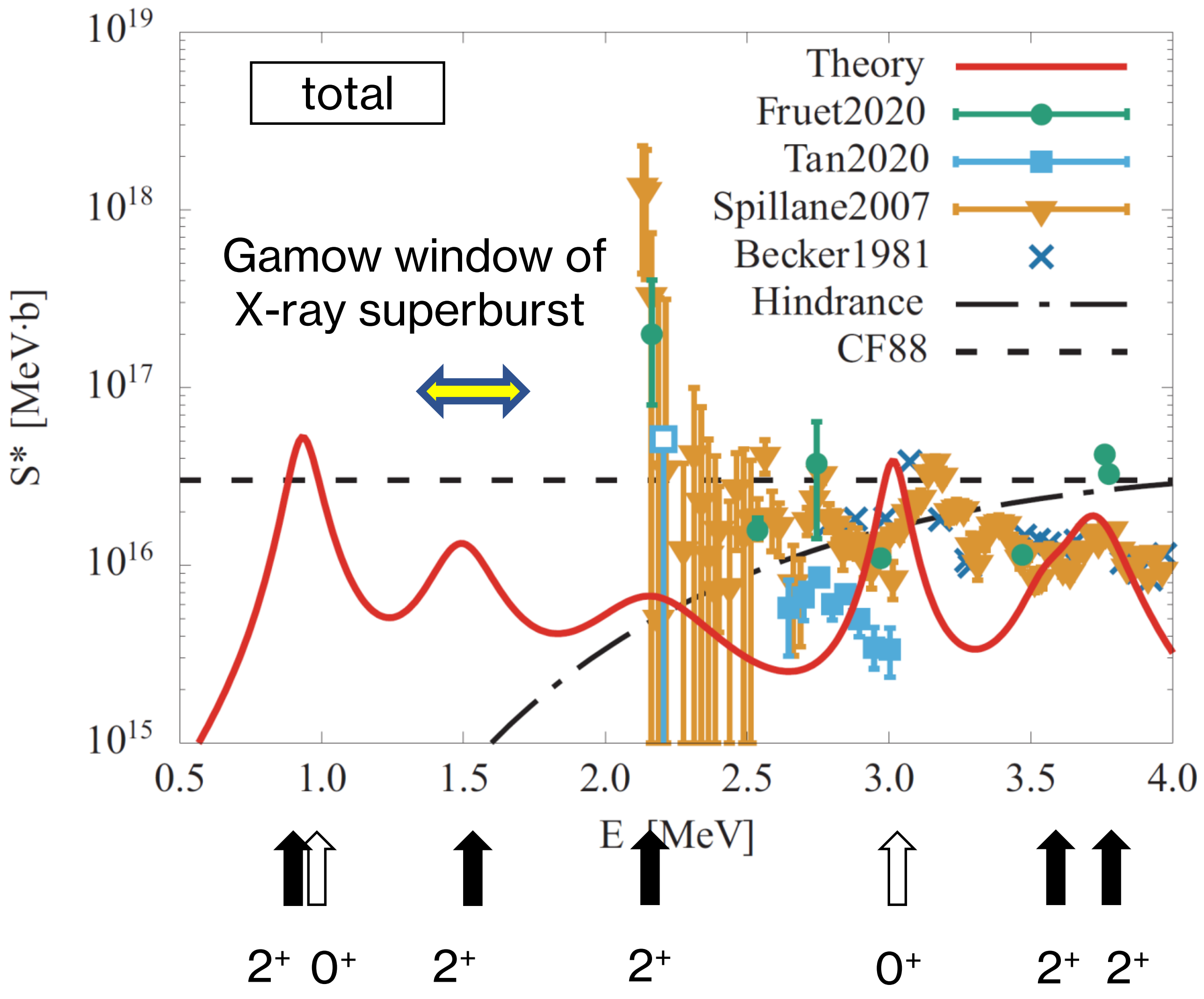


p channel





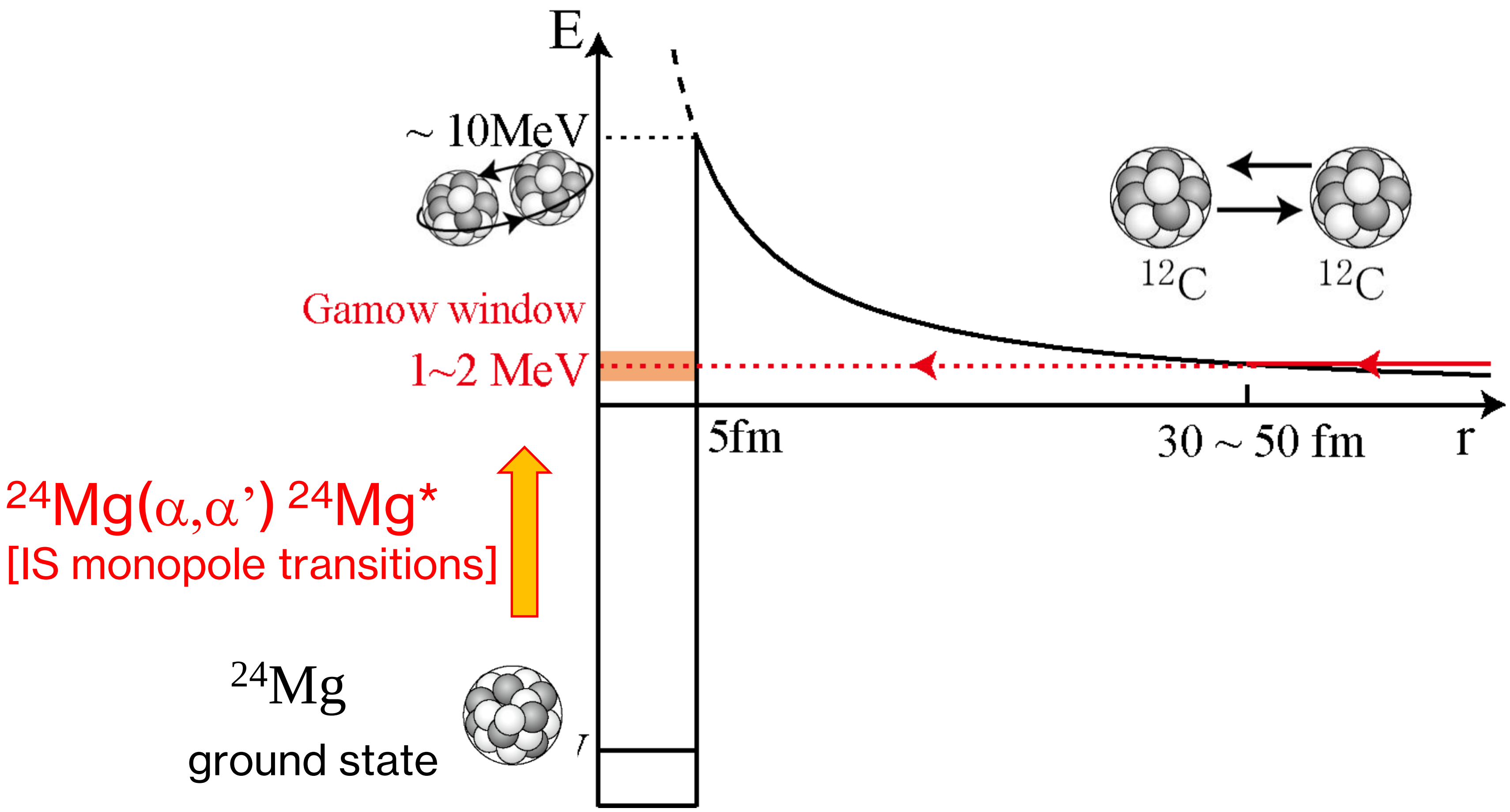
Astrophysical S factor



- Reproduced in E > 3 MeV region
- **Much larger** S factors than the **hindrance extrapolation**
- The 1.5-MeV resonance is predicted.
  - Trigger of X-ray superburst?
  - $(\omega\gamma) \sim 10^{-10}$ eV is two orders smaller than the Cooper's scenario.
- $\Gamma \sim 10^{-2}$-10^{-1} MeV

A novel approach to the cluster resonances

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

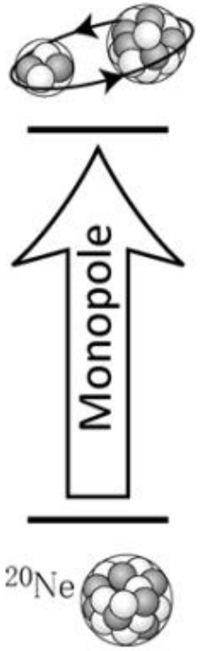


IS monopole strengths and clusters

"Cluster resonances have strong transition strengths"
Analytical proof, **Model independent**!

T. Yamada et al., PTP120, 1139 (2008)

$$\mathcal{M}_{\mu}^{IS0} = \sum_{i=1}^{A} (\boldsymbol{r}_i - \boldsymbol{r}_{\rm cm})^2 = \sum_{i \in C_1} \xi_i^2 + \sum_{i \in C_2} \xi_i^2 + \frac{C_1 C_2}{C_1 + C_2} \boldsymbol{r}^2$$



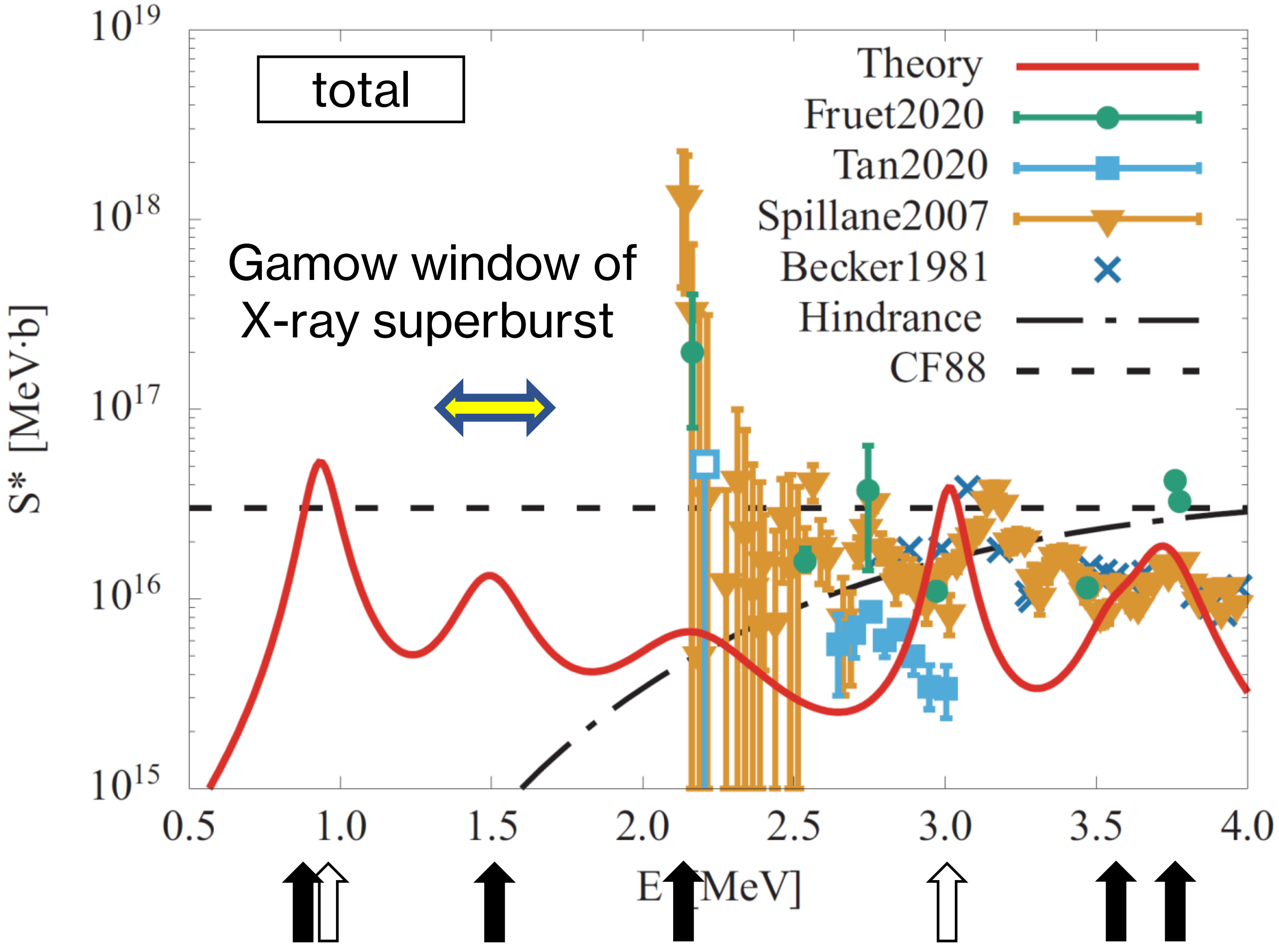
Analytical estimate of transition matrix

$$M^{IS0} = \langle \Phi(0^+_{\rm ex}) | \mathcal{M}^{IS0} | \Phi(0^+_1) \rangle$$
$$= f_{N_0+2} \sqrt{\frac{\mu_{N_0}}{\mu_{N_0+2}}} \langle R_{N_0 0} | r^2 | R_{N_0+2 0} \rangle$$
$$\simeq 7.67\, f_{N_0+2} = 5.5\,{\rm fm}^2$$ (for $\alpha+^{16}$O resonance)

Single particle estimate

$$M^{IS0}_{\rm WU} = \frac{3}{5}(1.2 A^{1/3})^2 \simeq 6.3\,{\rm fm}^2$$ (for $\alpha+^{16}$O resonance)

M(ISλ) values

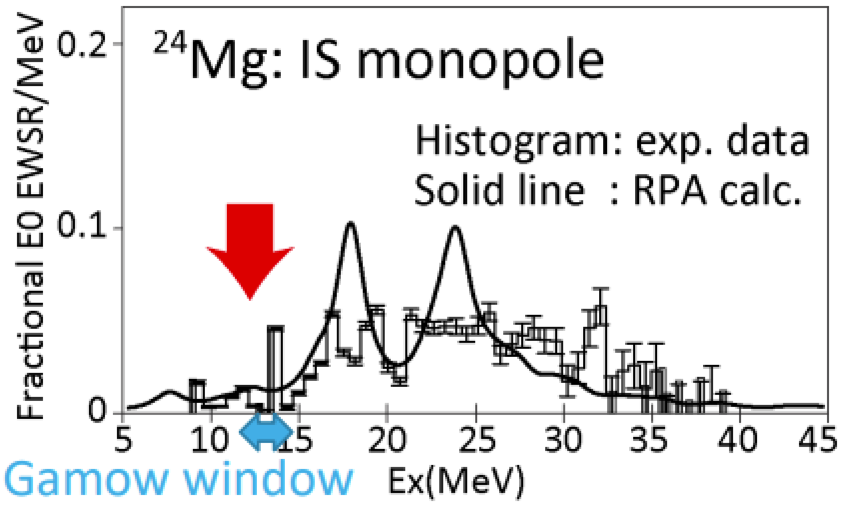


M(IS0): 0.59 W.u. 1.05 W.u.
M(IS2): 1.56 W.u. 1.04 W.u. 0.51 W.u.

- The M(IS0) operator has a term to excite inter-cluster motion.
  [Kawabata et al, PLB646 (2007)]
  [Yamada et al, PTP120 (2008)]
- M(ISλ ↑) values have an order of W.u.
- Inelastic scattering is a suitable probe of resonances essential for low-energy fusion reactions.

IS monopole strengths by (α,α') reactions

X. Chen et al.,PRC80, 014312 (2009).



◎ The observed data shows the resonances in the Gamow window

◎ They are not described by RPA

⇒ They are different from the ordinary collective states

"Some (many) of them must be the di-nuclear resonances"

Summary

- The ^{12}C + ^{12}C fusion astrophysical S factors are reasonably reproduced using a full-microscopic framework.
- No hindrance effects due to contributions of low-energy resonances.
- Inelastic scattering is a suitable probe of low-energy ^{12}C + ^{12}C resonances.