Theoretical study of cluster decay from photonuclear reactions and its application to the ultra high energy cosmic rays

M. Kimura (RIKEN)

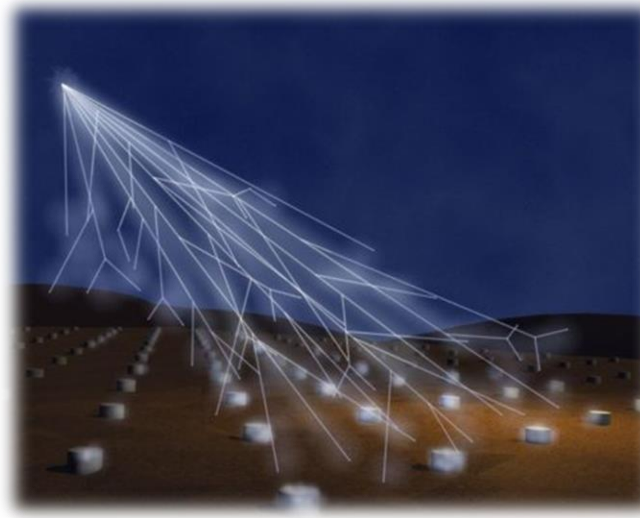
- ○ Introduction
- ○ Theoretical model
- ○ Results
- ○ Summary & Perspectives

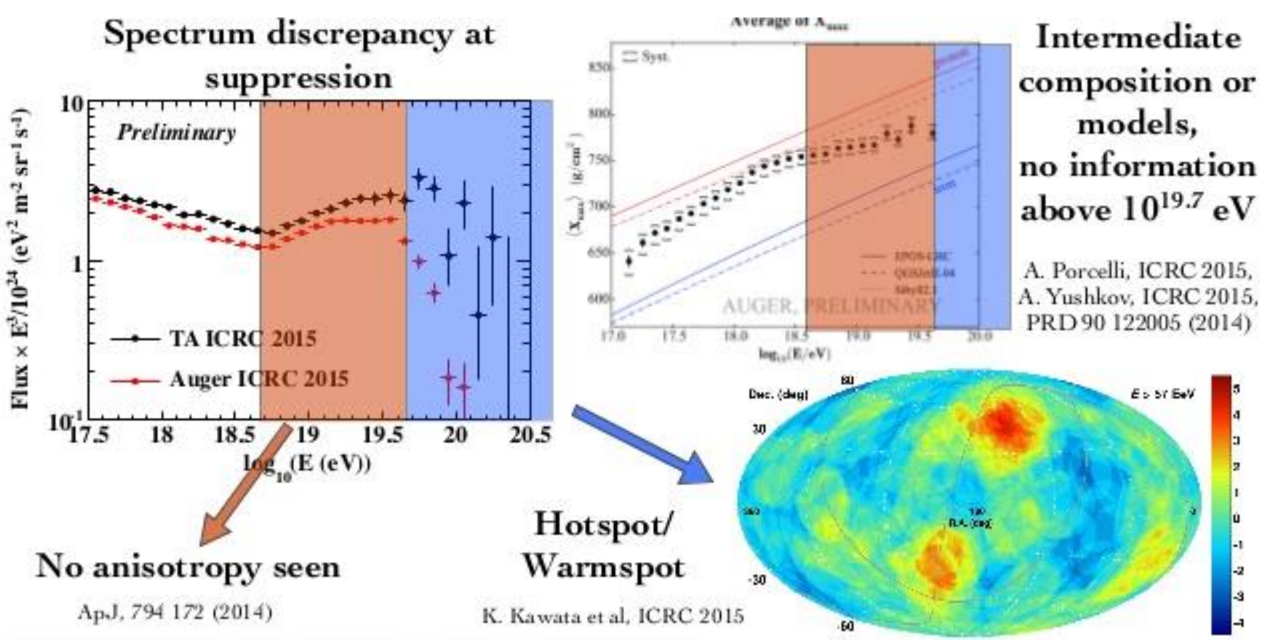
Introduction : UHECRs, photonuclear reactions and cluster decay

Ultra High Energy Cosmic Rays

– Its energy reaches 10^{20}eV
– Its source is unknown
(NS, Galactic core, ···)

– Its composition and energy distribution began to be measured

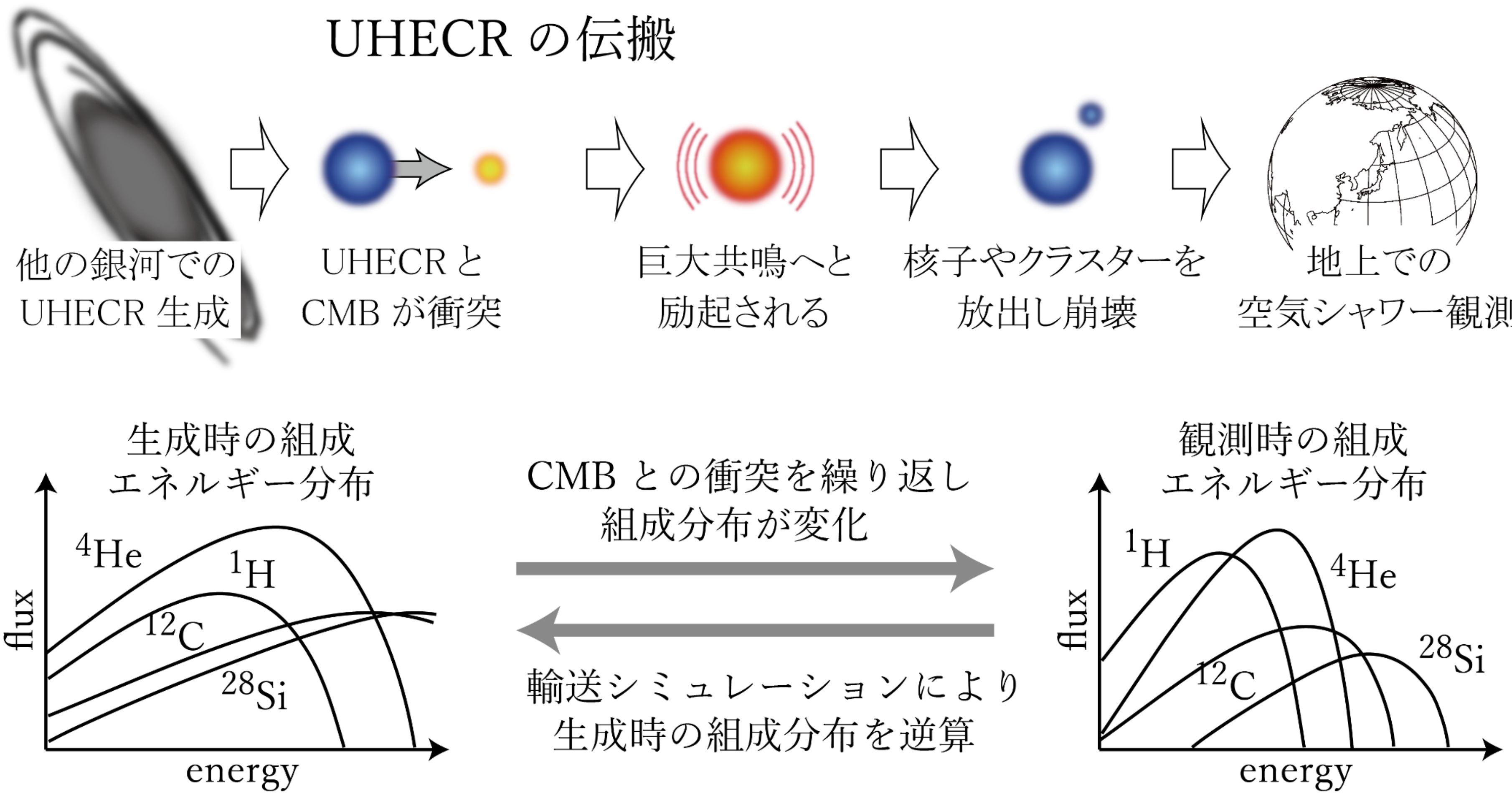




Introduction : UHECRs, photonuclear reactions and cluster decay

Nuclei accelerated at the source propagate colliding with CMB

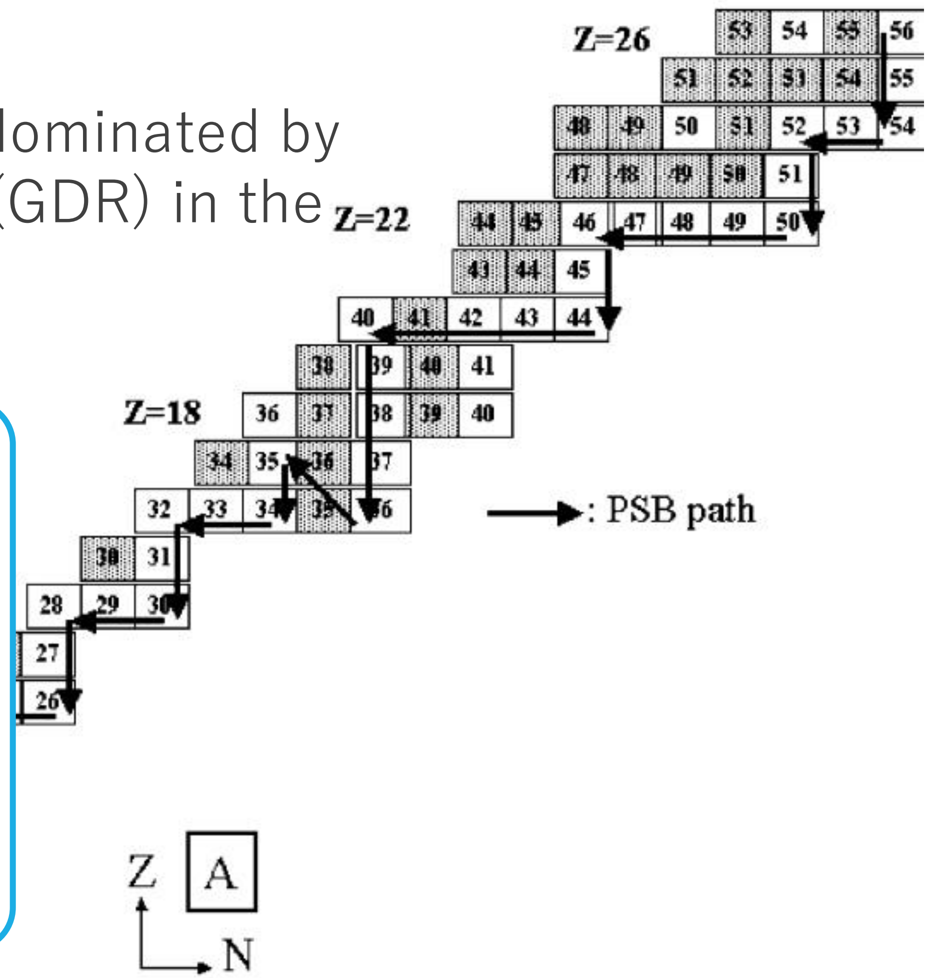
⇒ Transport simulation to know the composition at the source



Introduction : UHECRs, photonuclear reactions and cluster decay

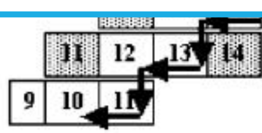
In the rest frame of nuclei, CMB corresponds to a broad-range of photon

Photo-nuclear cross-section is dominated by Giant electric dipole resonance (GDR) in the energy range of 10-50 MeV.



Quantities to study
- ○ Cross section of GDR
- ○ Decay branching ratio

$$
\begin{aligned}
A+\gamma \rightarrow\ A^* &\rightarrow (A\text{-}1)^* + n,\ p \\
&\rightarrow (A\text{-}2)^* + d \\
&\rightarrow (A\text{-}4)^* + {}^4\mathrm{He}
\end{aligned}
$$



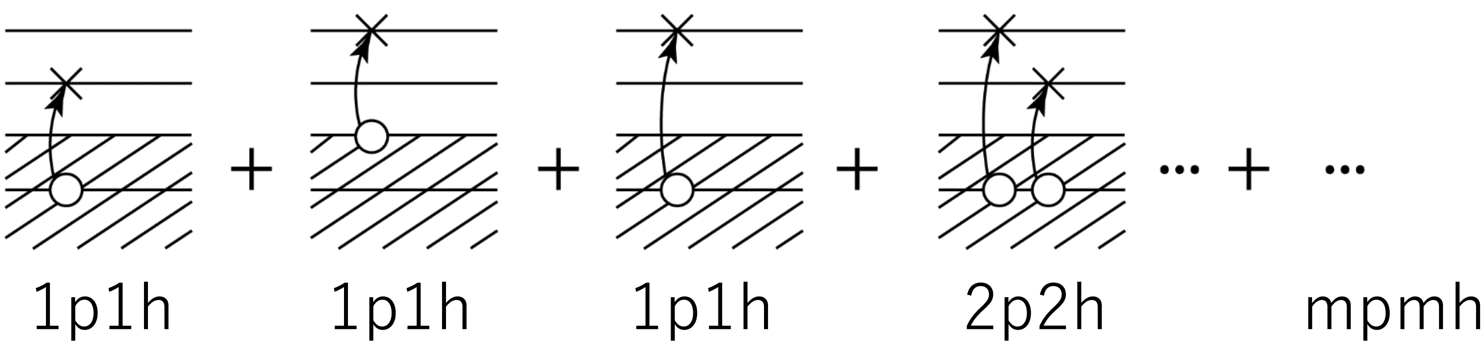
E. Khan, et al., Astro. Phys. 23, 191 (2005).

Problems to be solved

○Cross section(GDR)
○Branching ratio of GDR

$$
\begin{aligned}
A+\gamma \rightarrow \; A^* &\rightarrow (A\text{-}1)^* + n,\, p \\
&\rightarrow (A\text{-}2)^* + d \\
&\rightarrow (A\text{-}4)^* + {}^4He
\end{aligned}
$$

We need to take into account multi-particle-hole contributions to take into account cluster emission



Problems to be solved

○Cross section(GDR)
○Branching ratio of GDR

$$A+\gamma \rightarrow A^* \rightarrow (A\text{-}1)^* + n, p$$
$$\rightarrow (A\text{-}2)^* + d$$
$$\rightarrow (A\text{-}4)^* + {}^4He$$

In N=Z nuclei, we also need to take into account isospin selection rule

$${}^{16}O(T=0) + \gamma \Rightarrow {}^{16}O^*(T=1) \;\not\Rightarrow\; {}^{12}C(g.s, T=0) + \alpha$$

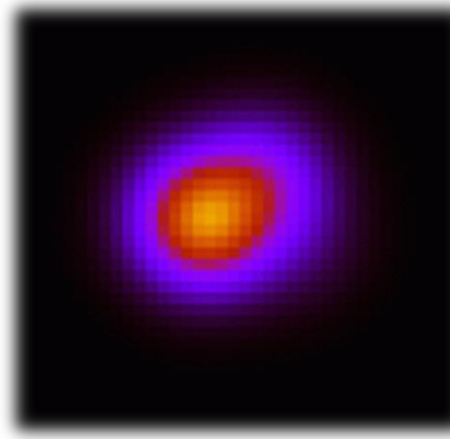
In N=Z nuclei, T=0 cluster decay is suppressed, but the extent of this suppression is unknown.
There is also an effect of isospin mixing

Time-dependent approach

◎ Microscopic Hamiltonian

$$H = \sum_{i=1}^{A} t(i) - t_{cm} + \sum_{i<j}^{A} v(ij)$$

^{6}He (6核子系)



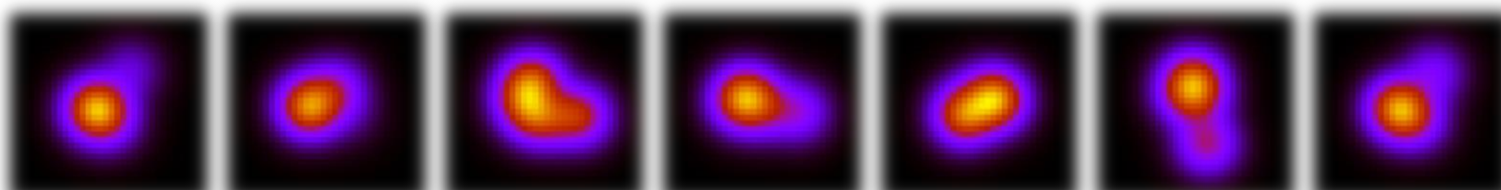
◎ Time-dependent wave packets

$$\Phi(t) = \mathcal{A}\{\, \phi(\boldsymbol{Z}_1(t)), ..., \phi(\boldsymbol{Z}_A(t)) \,\}$$

$$\phi(\boldsymbol{Z}_i(t)) = \exp\{\, -\nu(\boldsymbol{r} - \boldsymbol{Z}_i(t))^2 \,\}\, (\alpha_i(t)\, |\uparrow\rangle + \beta_i(t)\, |\downarrow\rangle)$$

◎ Equation of motion for the centroids of the wave packet

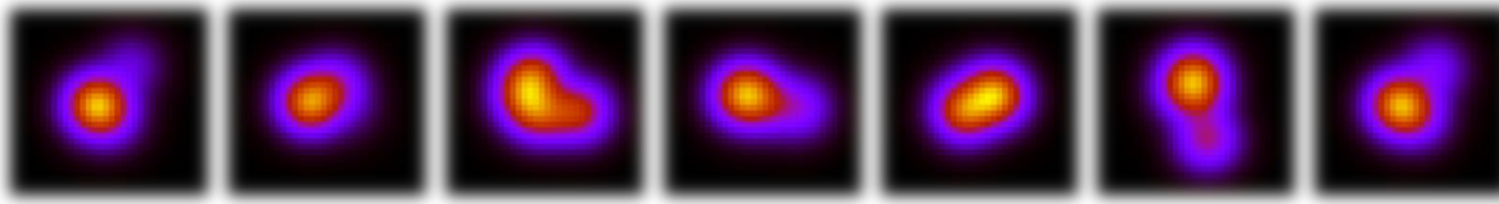
$$i\hbar \frac{d\boldsymbol{Z}_i(t)}{dt} = \sum_j C_{ij}^{-1} \frac{\partial \mathcal{H}}{\partial \boldsymbol{Z}_j^*(t)}$$



t = 0 fm/c　100 fm/c　200 fm/c　300 fm/c　400 fm/c　500 fm/c　600 fm/c　…

Time-dependent approach

◎ The ensemble of wave functions is ergodic
and follows quantum statistics



t = 0 fm/c 100 fm/c 200 fm/c 300 fm/c 400 fm/c 500 fm/c 600 fm/c …

With a sufficiently long time evolution, all possible states emerge.

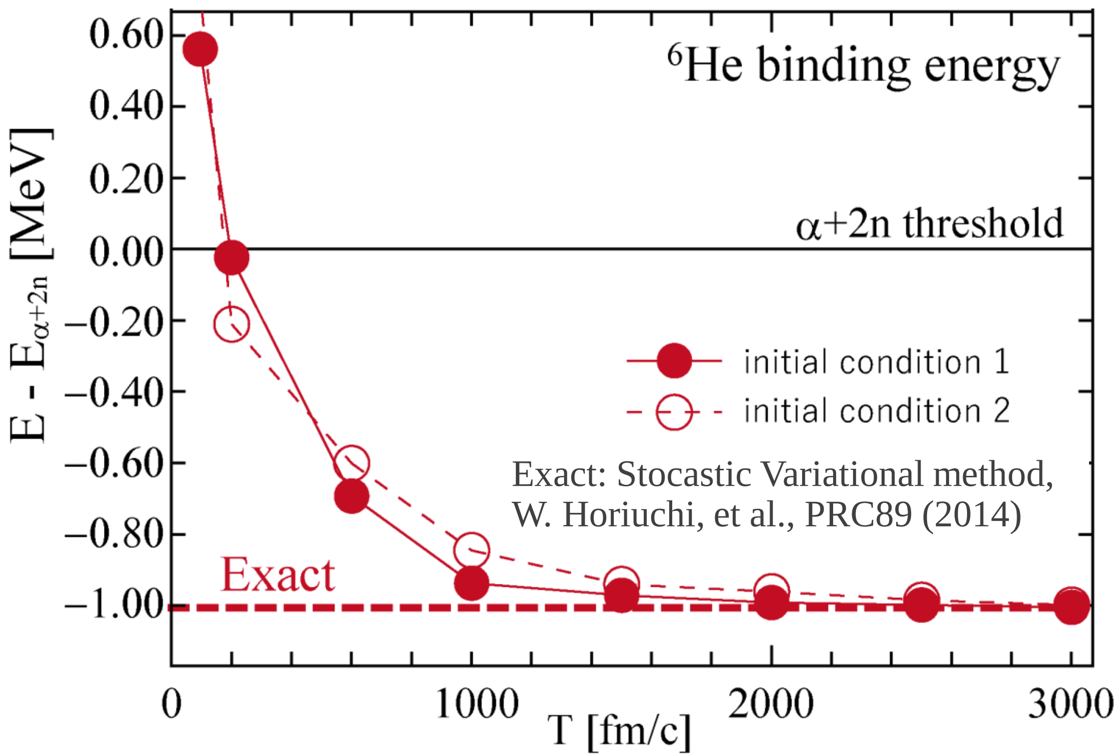
More frequent appearance of quantum states at set temperatures

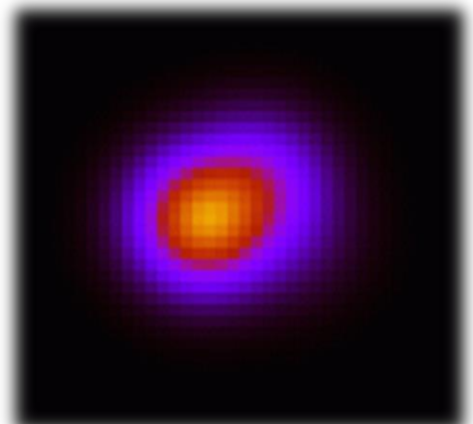
J. Schnack and H. Feldmeier, NPA601, 181 (1996).
A. Ono and H. Horiuchi, PRC53, 845 (1996), PRC53, 2341 (1996).

Superposition of the wave functions will provide an accurate description of ground state and GDR

Time-dependent approach

Benchmark in ^{6}He





^{6}He (6 nucleons)

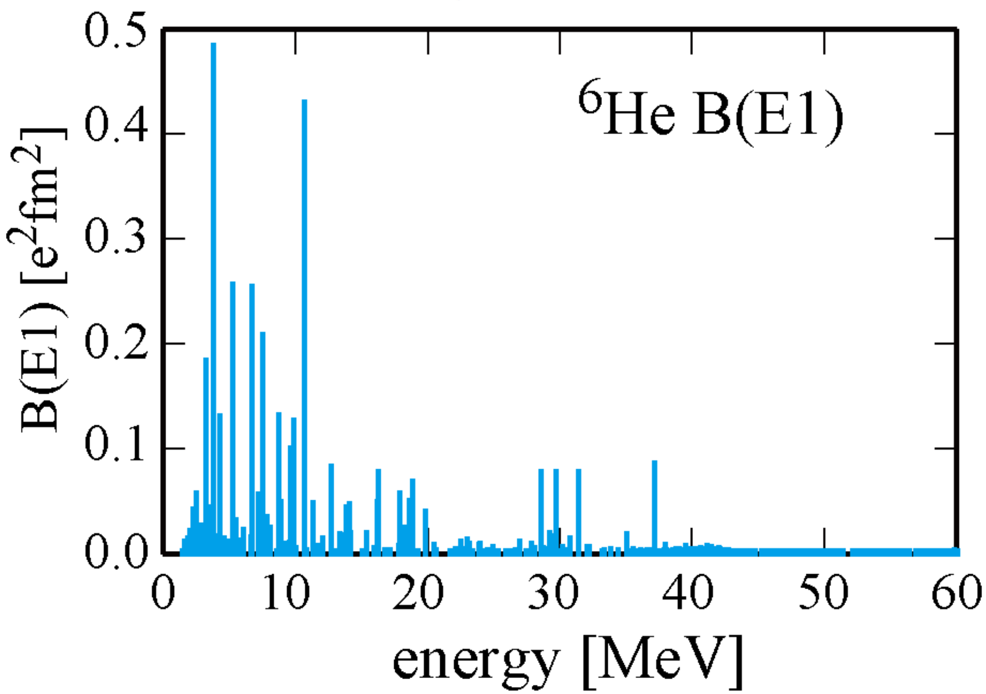
	S_{2n}	proton radius	neutron radius
Present calc.	-1.01 MeV	1.83 fm	2.64 fm
Exact	-1.01 MeV	1.83 fm	2.65 fm

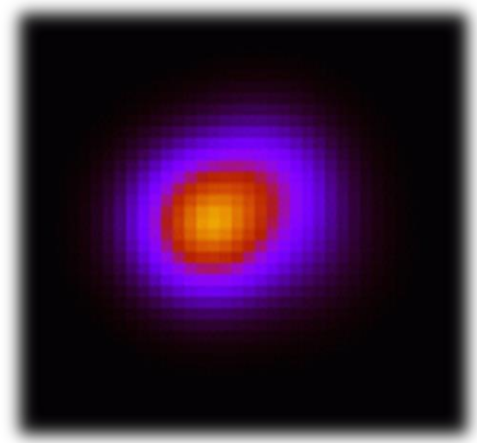
Time-dependent approach

E1 strength

Excited states are also obtained from the same ensemble.
Directly calculate the E1 transition intensities from the ground state to the excited states

$$B(E1; 0_1^+ \to 1_n^-) = \sum_\mu |\langle \Psi_n^{1^-\mu} | \mathcal{M}_\mu(E1) | \Psi_1^{0^+0} \rangle|^2$$

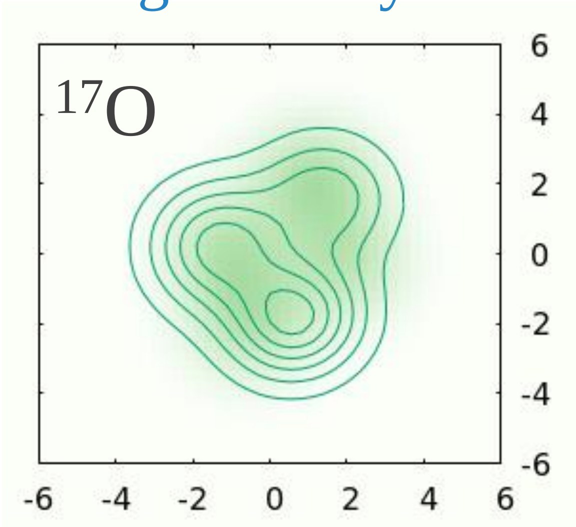


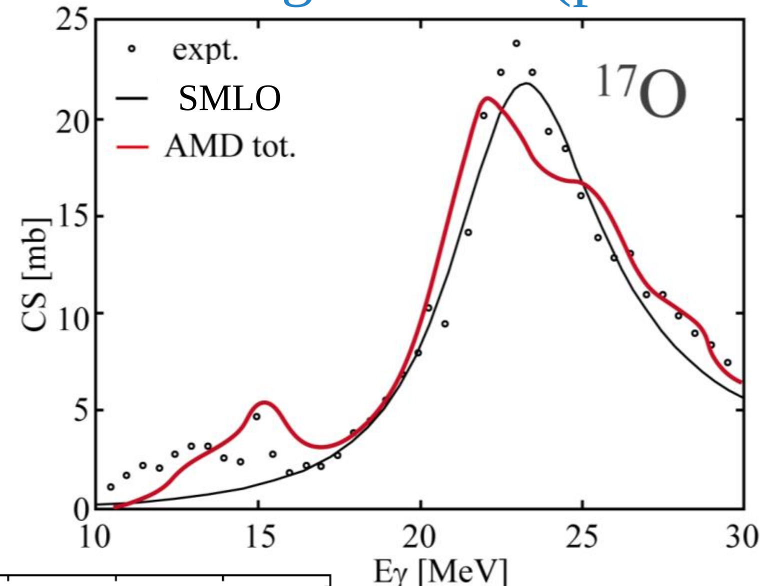


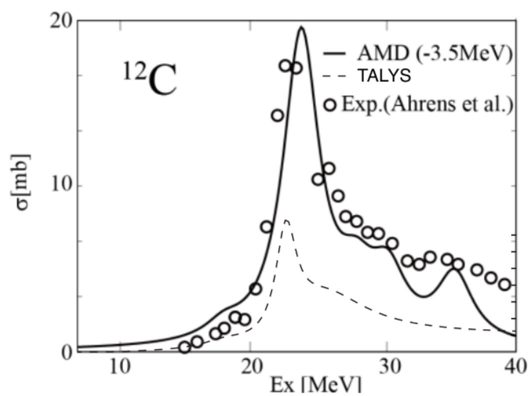
^{6}He (6 nucleons)

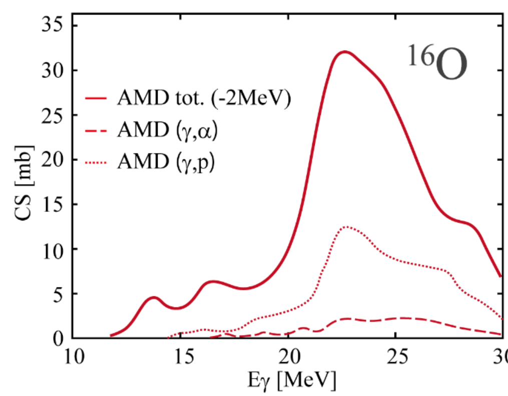
Results: Photo-nuclear cross sections

E1 strengths are systematically calculated for light nuclei (psd-shell)









Parameters of Hamiltonian are optimized by using ML

Hamiltonian: Minnesota Pot. + LS + FR-3body

Decay widths and branching ratio

Decay widths are estimated from reduced amplitudes

$A \to A_1 + A_2$ decay width

$$\Gamma = 2P_\ell(a)\frac{\hbar^2}{2\mu a}|ay_\ell(a)|^2$$

penetration   reduced amp.

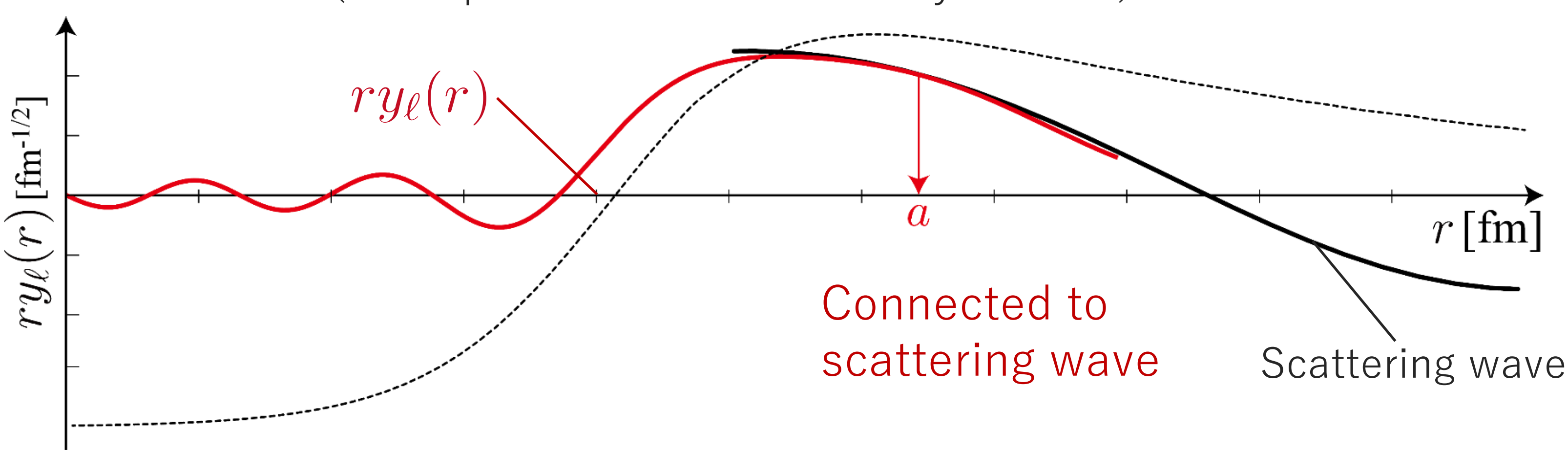
Penetration factor

$$P_\ell(a) = \frac{ka}{F_\ell^2(ka) + G_\ell^2(ka)}$$

Reduced amp.

$$ry_\ell(r) = r\sqrt{\frac{A!}{A_1!A_2!}}\langle Y_\ell(\hat{r})\phi_{A_1}\phi_{A_2}|\Psi\rangle$$

(overlap between res. and decay channel)



◎ RWA is calculated by Laplace expansion

Y. Chiba and M.K., PTEP2017, 053D01 (2017)

Decay width and branching ratio

Comparison ^{16}O and ^{17}O

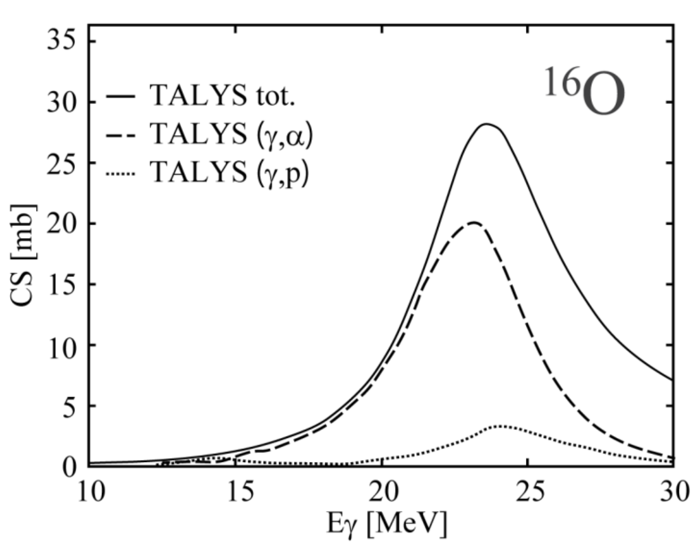
No experimental data for branching ratio

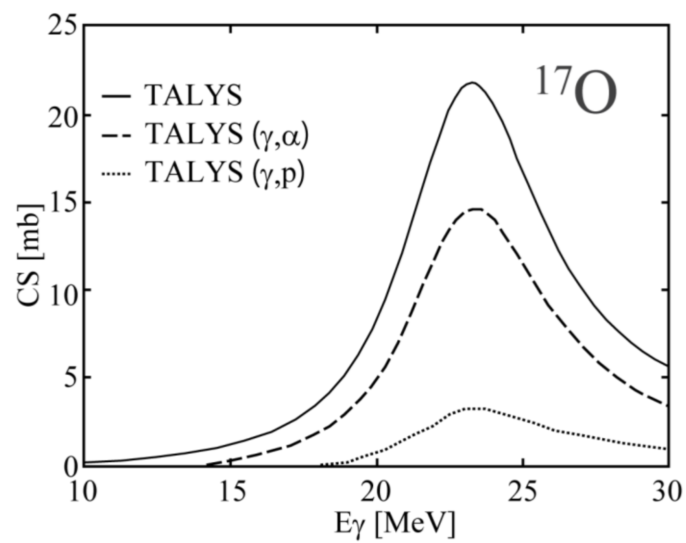
Estimation by TALYS code is not reliable

◎ Level density fitted to heavier mass system is applied.
Hence, no accuracy for light nuclei.

◎ Isospin selection rule is not taken account

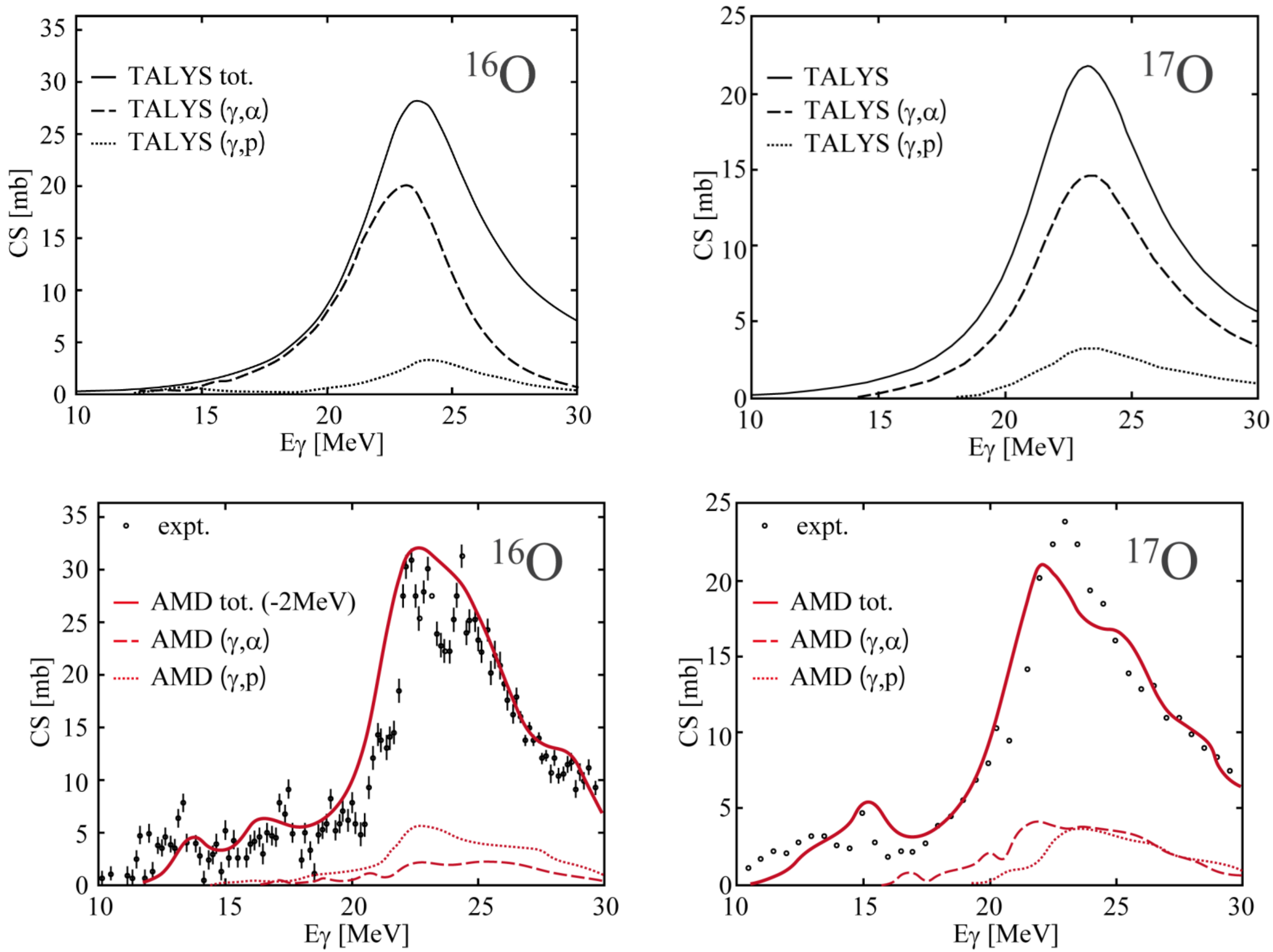
$$^{16}O(T=0) + \gamma \quad \Rightarrow \quad ^{16}O^*(T=1) \quad \cancel{\Rightarrow} \quad ^{12}C(g.s,\ T=0) + \alpha$$





Decay width and branching ratio

◎ Suppression of (γ,α) compared to



Summary

◎ Motivation

- UHECR and photonuclear reaction
- Energy & strength of GDR, its decay BR
- Systematic survey of light nuclei

○Study of GDR in light nuclei

- Time-dependent approach to GDR
- Fitting of Hamiltonian parameters with Baysian Opt. and Eigenvalue continuation method
- Decay BR from GDR has been estimated.
  Considerably different from TALYS

○Perspectives

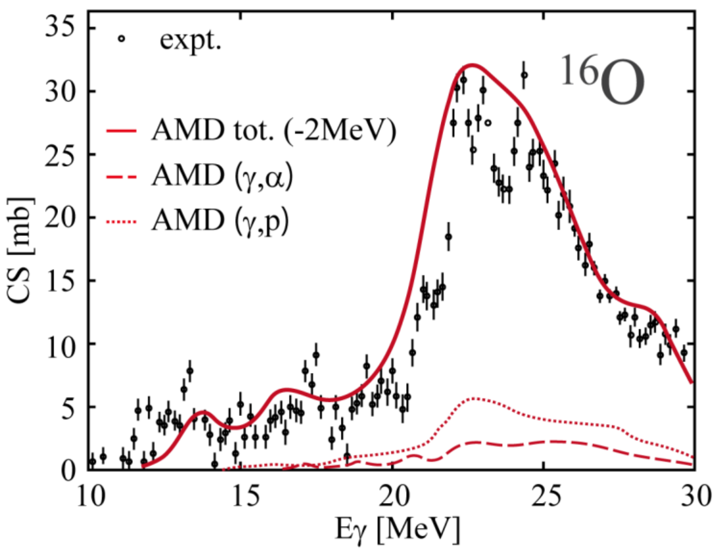
- Publication as a database
- Application to transport model

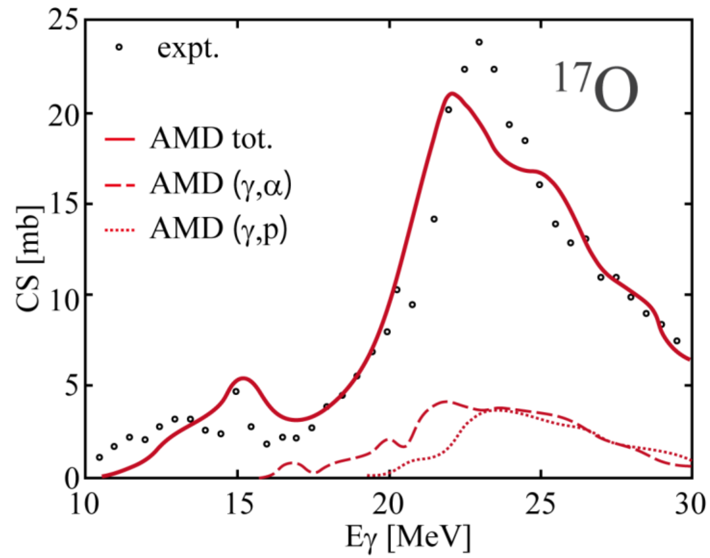
まとめと展望

進捗と展望

◎ 予備的結果

– 少数系でのベンチマーク
– 酸素同位体の光吸収断面積と分岐比





◎ 展望と課題

– 機械学習アルゴリズムによる精度向上
– クラスター形成・崩壊とアイソスピン混合の検討