Gamow Shell Model Studies of Selected Radiative-Capture Reactions in Nuclear Astrophysics

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2026.10

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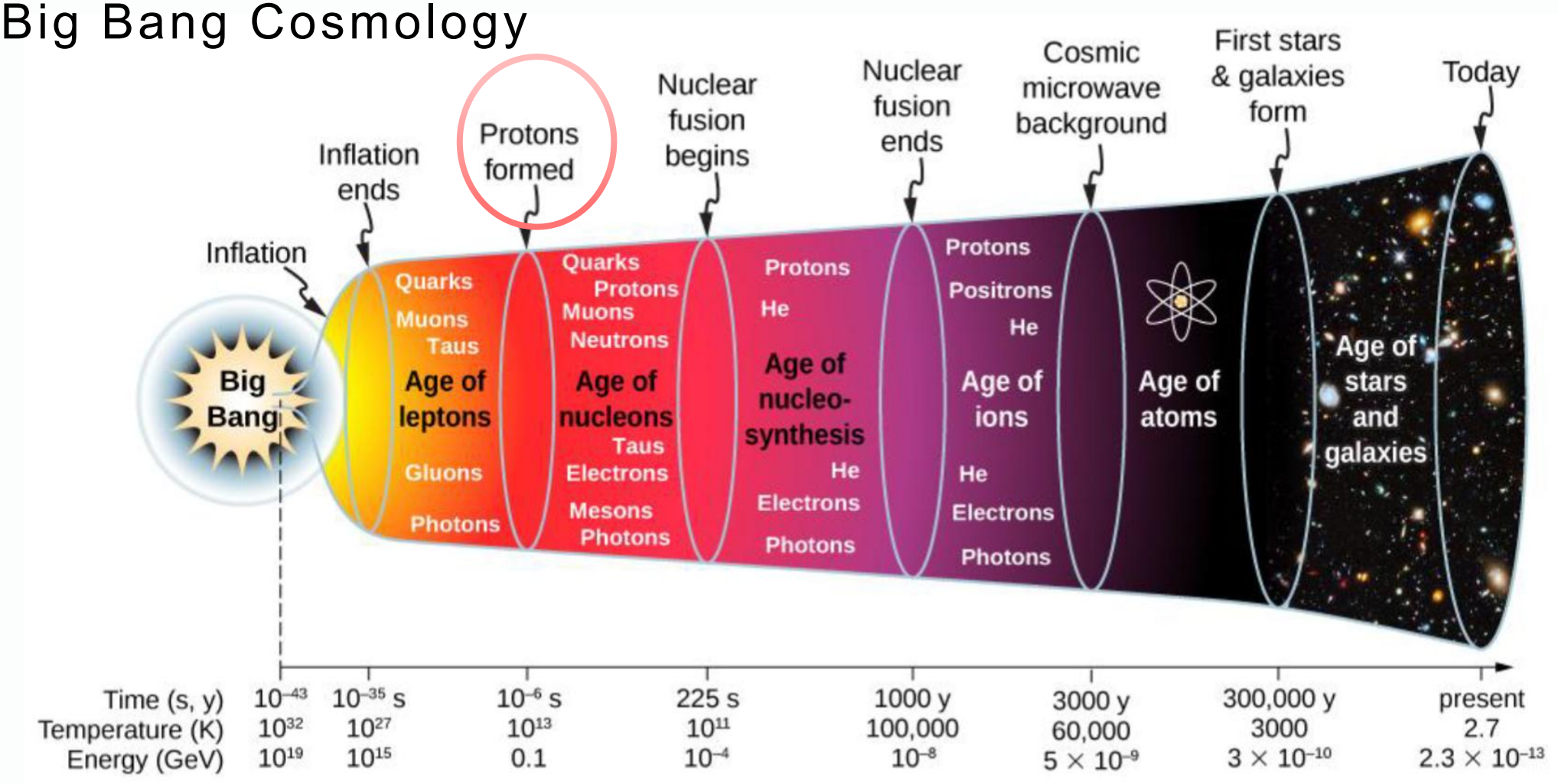
04. Summary

Background

01

Nuclear astrophysics reactions are crucial research topics in nuclear physics, nuclear astrophysics, astronomy and cosmology.

Big Bang Cosmology



Big Bang Nucleosynthesis: One of the three experimental pillars supporting standard Big Bang cosmology

$^{2}H, ^{3}He, ^{4}He, ^{7}Li, ...$

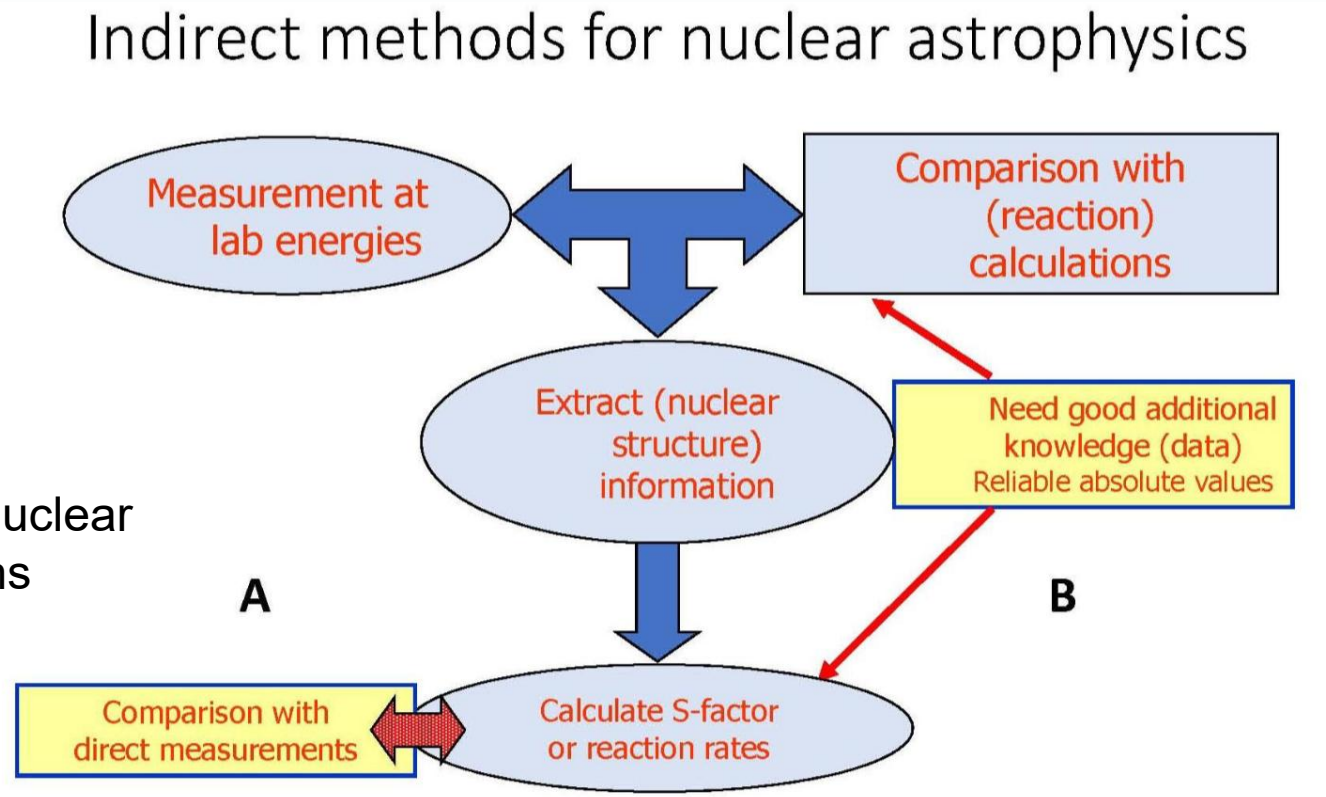
Experimental Studies of Nuclear Astrophysics Reactions
Indirect Methods

Direct measurement is extremely challenging!

Extremely low cross sections at astrophysically relevant energies (10^{-22}—10^{-7} **b**);

Extremely low signal-to-noise ratio

→ Use **nuclear structure parameters** to calculate nuclear astrophysics reaction data under laboratory conditions

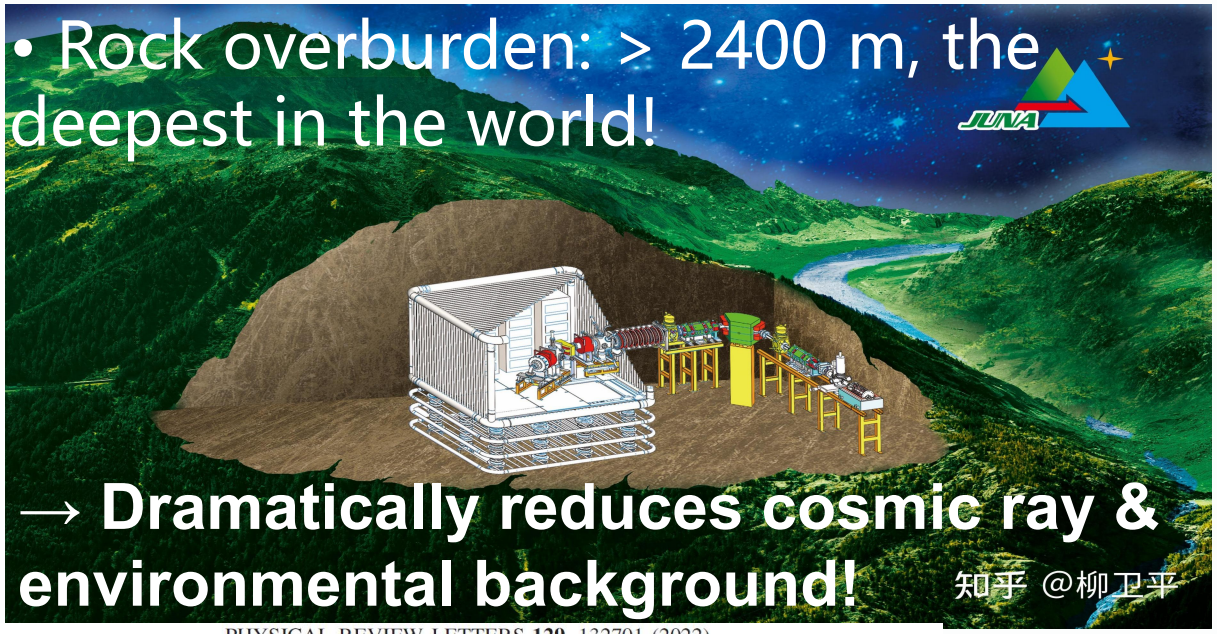


A. Coulomb Dissociation
B. Single-nucleon transfer reactions – the ANC method
C. Nuclear breakup reactions
D. The Trojan Horse Method
E. Spectroscopy of resonances, a wide category of reactions, types of experiments and theories.

L. Trache, F. Carstoiu, Indirect Methods in Nuclear Astrophysics, 2019

Direct Measurement of Nuclear Astrophysics Reactions

Jinping Underground Nuclear Astrophysics (JUNA) Experiment



THE ASTROPHYSICAL JOURNAL, 945:41 (10pp), 2023 March 1 https://doi.org/10.3847/1538-4357/acb7de
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New Determination of the $^{12}C(\alpha, \gamma)^{16}O$ Reaction Rate and Its Impact on the Black-hole Mass Gap

Yangping Shen[1], Bing Guo[1], Richard J. deBoer[2], Ertao Li[3], Zhihong Li[1], Yunju Li[1], Xiaodong Tang[4], Danyang Pang[5,6], Sucheta Adhikari[7], Chinmay Basu[8], Jun Su[9], Shengquan Yan[1], Qiwen Fan[1], Jiancheng Liu[1], Chen Chen[1], Zhiyu Han[1], Xinyue Li[1], Gang Lian[1], Tianli Ma[1], Wei Nan[1], Weike Nan[1], Youbao Wang[1], Sheng Zeng[1], Hao Zhang[1], and Weiping Liu[1]

Measurement of the $^{18}O(\alpha, \gamma)^{22}Ne$ Reaction Rate at JUNA and Its Impact on Probing the Origin of SiC Grains

L. H. Wang,[1] J. Su,[1,*] Y. P. Shen,[2,†] J. J. He,[1] M. Lugaro,[3,4,5,6,‡] B. Szányi,[3,4,7] A. I. Karakas,[6,8] L. Y. Zhang,[1] X. Y. Li,[1] B. Guo,[2] G. Lian,[2] Z. H. Li,[2] Y. B. Wang,[2] L. H. Chen,[2] B. Q. Cui,[2] X. D. Tang,[9] B. S. Gao,[9] Q. Wu,[9] L. T. Sun,[9] S. Wang,[10] Y. D. Sheng,[1] Y. J. Chen,[1] H. Zhang,[1] Z. M. Li,[1] L. Y. Song,[1] X. Z. Jiang,[1] W. Nan,[2] W. K. Nan,[2] L. Zhang,[2] F. Q. Cao,[2] T. Y. Jiao,[9] L. H. Ru,[9] J. P. Cheng,[1] M. Wiescher,[11,12] and W. P. Liu[2,13,§]

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Measurement of $^{19}F(p, \gamma)^{20}Ne$ reaction suggests CNO breakout in first stars

Liyong Zhang, Jianjun He, Richard J. deBoer, Michael Wiescher, Alexander Heger, Daid Kahl, Jun Su, Daniel Odell, Yinji Chen, Xinyue Li, Jianguo Wang, Long Zhang, Fuqiang Cao, Hao Zhang, Zhicheng Zhang, Xinzhi Jiang, Luohuan Wang, Ziming Li, Luyang Song, Hongwei Zhao, Liangting Sun, Qi Wu, Jiaqing Li, Baoqun Cui, ... Weiping Liu + Show authors

PHYSICAL REVIEW LETTERS 129, 132701 (2022)

Deep Underground Laboratory Measurement of $^{13}C(\alpha, n)^{16}O$ in the Gamow Windows of the *s* and *i* Processes

B. Gao,[1,2,3] T. Y. Jiao,[2,3] Y. T. Li,[2,3] H. Chen,[2,3] W. P. Lin,[4] Z. An,[4] L. H. Ru,[2] Z. C. Zhang,[2,3] X. D. Tang,[1,2,3,*] X. Y. Wang,[2,3] N. T. Zhang,[2,3] X. Fang,[5] D. H. Xie,[4] Y. H. Fan,[2,6] L. Ma,[4] X. Zhang,[4] F. Bai,[4] P. Wang,[4] Y. X. Fan,[4] G. Liu,[4] H. X. Huang,[7] Q. Wu,[8] Y. B. Zhu,[8] J. L. Chai,[8] J. Q. Li,[8] L. T. Sun,[8] S. Wang,[9] J. W. Cai,[2,3] Y. Z. Li,[2,3] J. Su,[7,10] H. Zhang,[7] Z. H. Li,[3,7] Y. J. Li,[7] E. T. Li,[11] C. Chen,[7] Y. P. Shen,[7] G. Lian,[7] B. Guo,[7] X. Y. Li,[10] L. Y. Zhang,[10] J. J. He,[10] Y. D. Sheng,[10] Y. J. Chen,[10] L. H. Wang,[10] L. Zhang,[7] F. Q. Cao,[7] W. Nan,[7] W. K. Nan,[7] G. X. Li,[7] N. Song,[7] B. Q. Cui,[7] L. H. Chen,[7] R. G. Ma,[7] Z. C. Zhang,[11] S. Q. Yan,[7] J. H. Liao,[7] Y. B. Wang,[7] S. Zeng,[7] D. Nan,[7] Q. W. Fan,[7] N. C. Qi,[12] W. L. Sun,[12] X. Y. Guo,[12] P. Zhang,[12] Y. H. Chen,[12] Y. Zhou,[12] J. F. Zhou,[12] J. R. He,[12] C. S. Shang,[12] M. C. Li,[12] S. Kubono,[13,14] and W. P. Liu[7,†]

ELSEVIER

Science Bulletin

Volume 67, Issue 2, 30 January 2022, Pages 125-132

Article

First result from the Jinping Underground Nuclear Astrophysics experiment JUNA: precise measurement of the 92 keV $^{25}Mg(p, \gamma)^{26}Al$ resonance

Jun Su [a b], Hao Zhang [a b], Zhihong Li [a c], Paolo Ventura [d], Yunju Li [a], Ertao Li [e], Chen Chen [a], Yangping Shen [a], Gang Lian [a], Bing Guo [a], Xinyue Li [b], Liyong Zhang [b], Jianjun He [b], Yaode Sheng [b], Yinji Chen [b], Luohuan Wang [b], Long Zhang [a], Fuqiang Cao [a], Wei Nan [a], Weike Nan [a]... Weiping Liu [a]

PHYSICAL REVIEW LETTERS 127, 152702 (2021)

Editors' Suggestion | Featured in Physics

Direct Measurement of the Astrophysical $^{19}F(p,\alpha\gamma)^{16}O$ Reaction in the Deepest Operational Underground Laboratory

L. Y. Zhang,[1] J. Su,[1] J. J. He,[1,*] M. Wiescher,[2,†] R. J. deBoer,[2] D. Kahl,[3] Y. J. Chen,[1] X. Y. Li,[1] J. G. Wang,[4] L. Zhang,[5] F. Q. Cao,[5] H. Zhang,[5] Z. C. Zhang,[6] T. Y. Jiao,[4] Y. D. Sheng,[1] L. H. Wang,[1] L. Y. Song,[1] X. Z. Jiang,[1] Z. M. Li,[1] E. T. Li,[6] S. Wang,[7] G. Lian,[5] Z. H. Li,[5] X. D. Tang,[4] H. W. Zhao,[4] L. T. Sun,[4] Q. Wu,[4] J. Q. Li,[4] B. Q. Cui,[5] L. H. Chen,[5] R. G. Ma,[5] B. Guo,[5] S. W. Xu,[4] J. Y. Li,[4] N. C. Qi,[8] W. L. Sun,[8] X. Y. Guo,[8] P. Zhang,[8] Y. H. Chen,[8] Y. Zhou,[8] J. F. Zhou,[8] J. R. He,[8] C. S. Shang,[8] M. C. Li,[8] X. H. Zhou,[4] Y. H. Zhang,[4] F. S. Zhang,[1] Z. G. Hu,[4] H. S. Xu,[4] J. P. Chen,[1] and W. P. Liu[5,‡]

Cosmic ray flux ~100 times lower than LUNA (Gran Sasso, Italy)!

Theoretical Methods for Nuclear Astrophysics Reactions

- **Microscopic Models**: based on **fundamental principles of quantum mechanics**, such as the treatment of all nucleons, with **exact antisymmetrization** of the **wave functions**.

  a) ab initio models: Caurier and Navrátil, 2006; Navrátil and Quaglioni, 2011, NCSM+RGM

  b) microscpic cluster model: P. Descouvemont

  c) GSM-CC: based on RGM, N. Michel, M. Płoszajczak

- **Potental model** $I_{if}^{\lambda}(E) = \int g_{L_i}^{J_i\pi_i}(E,r) r^{\lambda} g_{L_f}^{J_f\pi_f}(r) dr$

  scattering functions — bound-state wave functions

(i) the **nucleon-nucleon interaction** is replaced by a potential ***V(r)***
(ii) the wave functions of the unified nucleus can be described by a cluster structure with $A_1 + A_2$ nucleons
(iii) the **internal structure** of the nuclei does **not** play any role

C.A. Bertulani, Comput. Phys. Commun. 156, 123,2003.

The R-Matrix method $R_{if}(E) = \sum_{\lambda=1}^{N} \frac{\gamma_{\lambda i}\gamma_{\lambda f}}{E_\lambda - E}$

γ: reduced widths
(reduced width amplitudes correspond to wave functions of daughter nuclei in the composite system)

P.Descouvemont,and D.Baye, The R-matrix theory, Rep. Prog. Phys.73:036301(2010).

Theoretical Framework

02

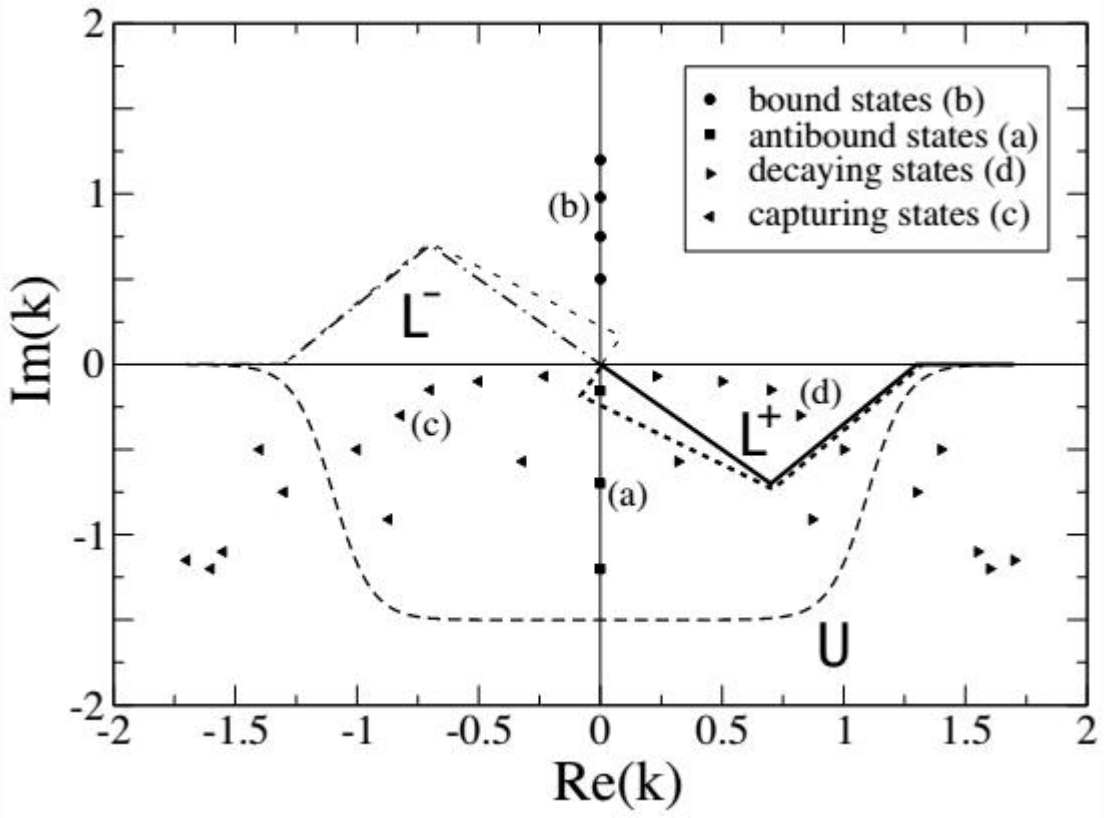
Gamow Shell model (GSM)

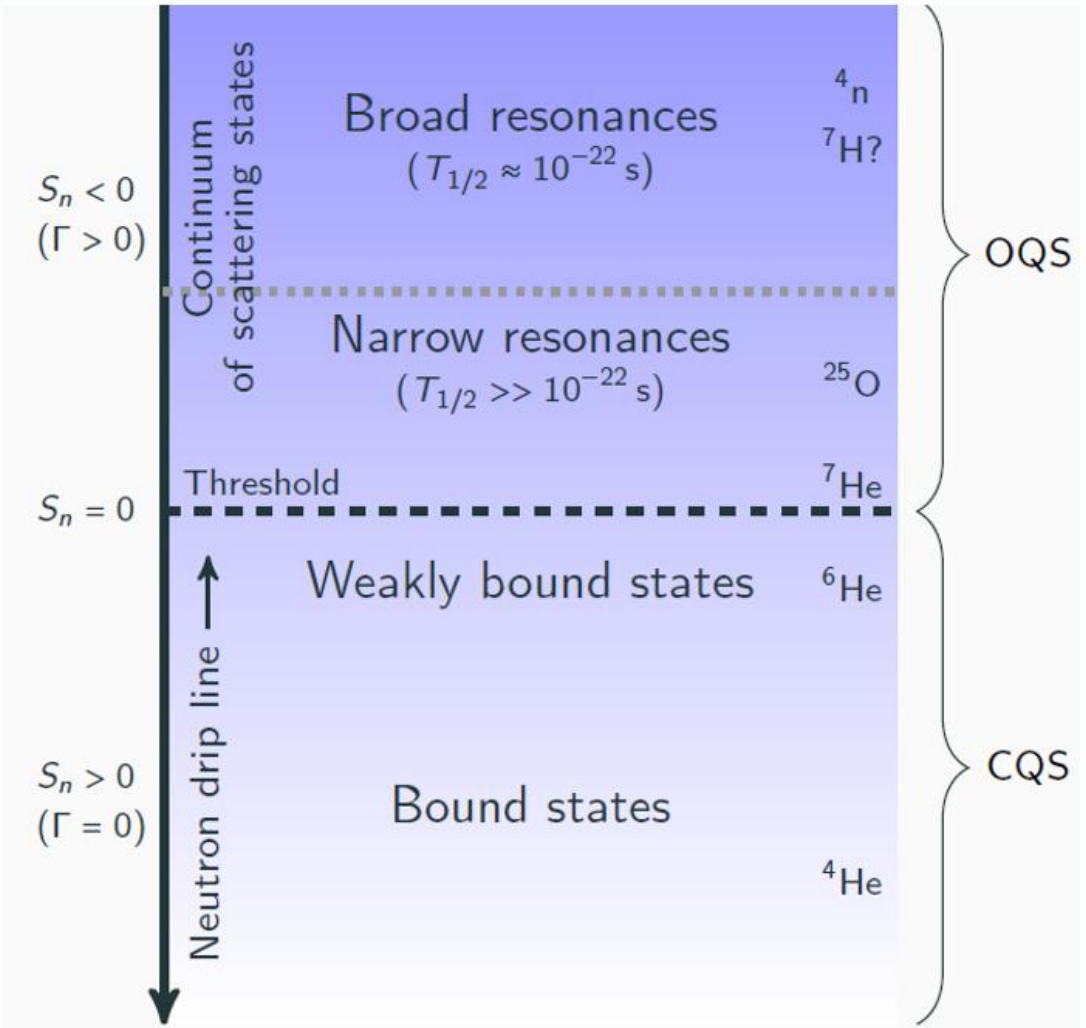
Quasi-stationary open quantum system extension of the SM

- Berggren completeness relation:

$$\sum_{n\in(b,d)} |\phi_{nlj}\rangle\langle\widetilde{\phi_{nlj}}| + \int_{L^+} |\phi_{lj}(k)\rangle\langle\widetilde{\phi_{lj}(k)}|\, dk = \mathbb{1}$$

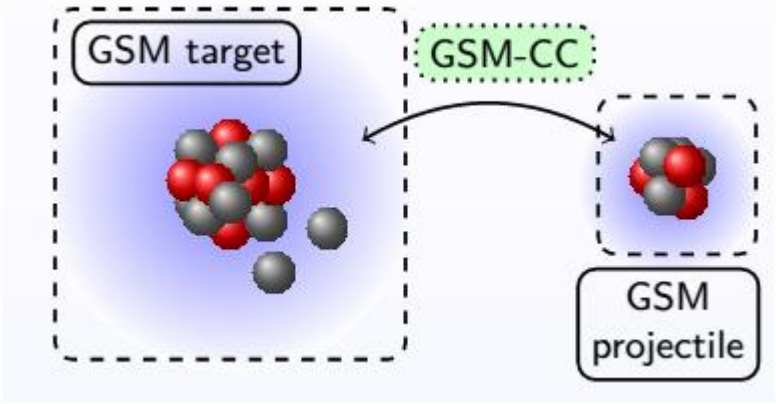
T. Berggren, Nucl. Phys. A 109, 265 (1968); N. Michel, J. Math. Phys., 49, 022109 (2008)





GSM-CC: Reconciliation of GSM with reaction theory using the **coupled-channel** formalism

Unification of nuclear structure and reactions based on the GSM



- Coupled-channel formalism
- Channel: $|c\rangle = |c_{\text{proj}}\rangle \otimes |c_{\text{targ}}\rangle$ where $c = \{q_0, q_1, \cdots, q_n\}$ is a set of considered quantum numbers of the target and the projectile
- Fully antisymmetrized calculation

- Unified approach:

$$\texttt{GSMCC}(A-a,a) \approx \texttt{GSM}(A)$$

$$\sum_c \int_0^\infty dr\, r^2 (H_{c',c}(r',r) - E N_{c',c}(r',r)) \frac{u_c(r)}{r} = 0$$

where $H_{c',c}(r',r) = \langle r', c'|\hat{H}|r, c\rangle$ and $N_{c',c}(r',r) = \langle r', c'|r, c\rangle$

Nuclear structure

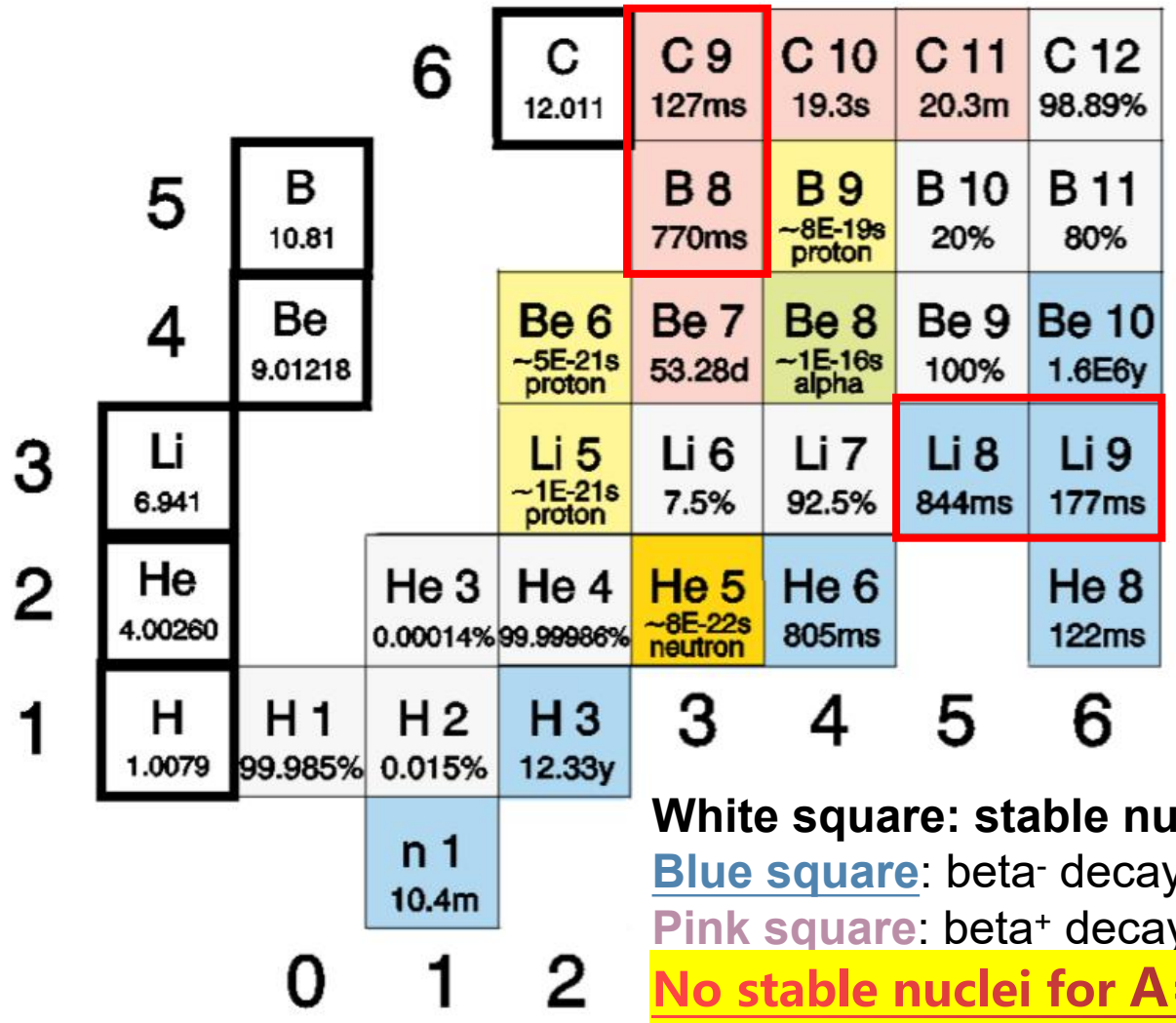


Nuclear reaction

Results & Discussion

03

$^{8}Li(n,\gamma)^{9}Li$ & $^{8}B(p,\gamma)^{9}C$



White square: stable nuclei

Blue square: beta^{-} decay

Pink square: beta^{+} decay

No stable nuclei for A=5,8 → **Mass Gap**

$^{8}Li(n,\gamma)^{9}Li$

- **The neutron radiative capture reaction of ^{8}Li has played important roles in the inhomogeneous big-bang nucleosynthesis and the r-process.**
  R. Malaney and W. F. Fowler, in Origin and Distribution of the Elements edited by G. J. Matthews (World Scientific, 1988), p. 780.
  V. D. Efros, W. Balogh, H. Herndl, R. Hofinger, and H. Oberhummer, Z. Phys. A: Hadrons Nucl. 355, 101 (1996).

Big Bang nucleosynthesis

After ^{7}Li creation

$$^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li}(\alpha,n)^{11}\mathrm{B}(n,\gamma)^{12}\mathrm{B}(\beta^{+})^{12}\mathrm{C}$$

$$^{7}\mathrm{Li}(n,\gamma)^{8}\mathrm{Li}(n,\gamma)^{9}\mathrm{Li}(\alpha,n)^{12}\mathrm{B}(\beta^{+})^{12}\mathrm{C}$$

$$^{8}\mathrm{Li}(\beta^{-})^{8}\mathrm{Be}(2\alpha)$$

r-process of the Type-II supernovae or neutron star mergers

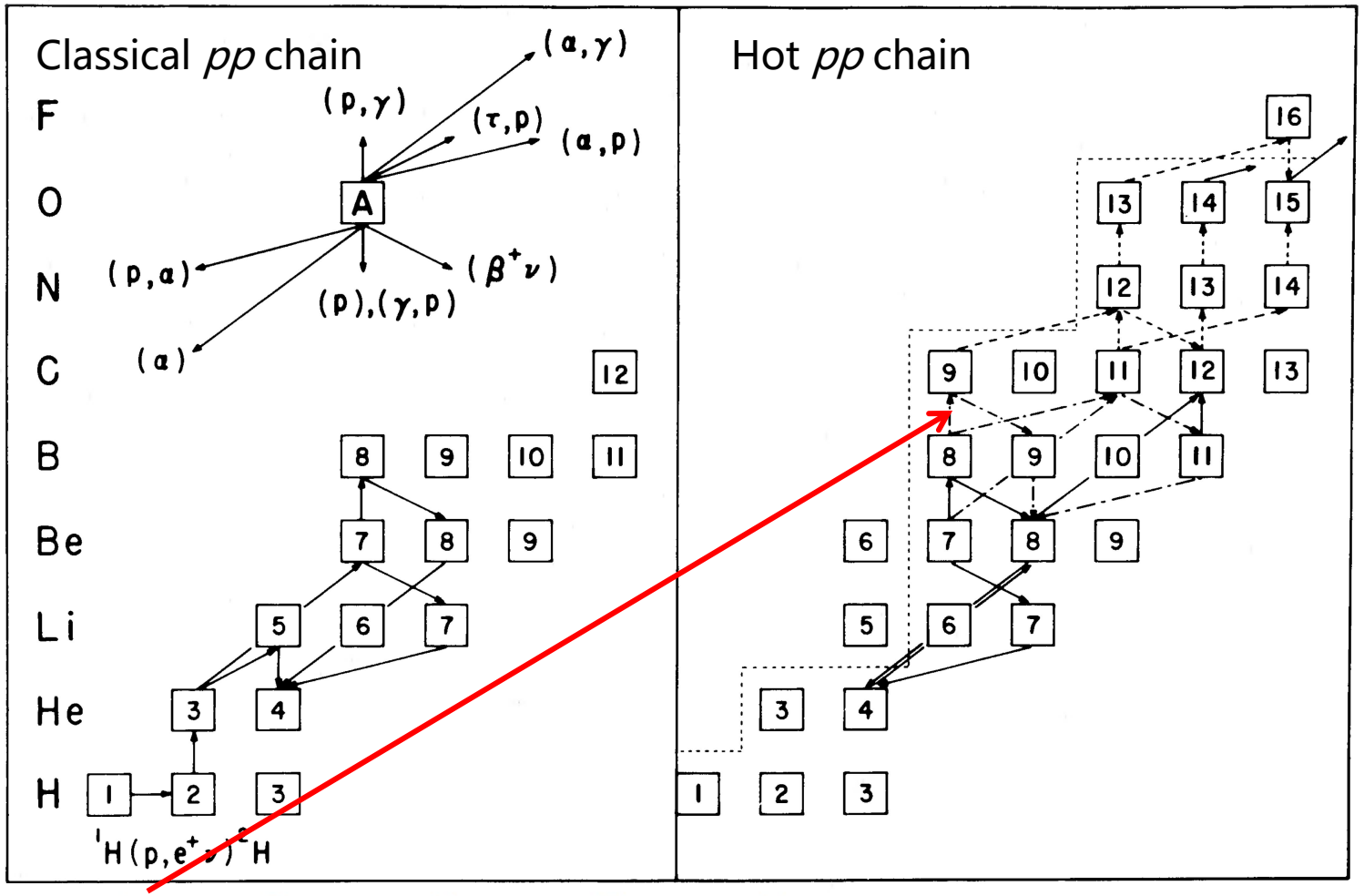
Bypass A=8 gap

$$^{4}\mathrm{He}(2n,\gamma)^{6}\mathrm{He}(2n,\gamma)^{8}\mathrm{He}(\beta^{-})^{8}\mathrm{Li}(n,\gamma)^{9}\mathrm{Li}(\beta^{-})^{9}\mathrm{Be}$$

$$\alpha+\alpha+\alpha \rightarrow {}^{12}\mathrm{C}$$

$$\alpha+\alpha+n \rightarrow {}^{9}\mathrm{Be}$$

$^{8}B(p,\gamma)^{9}C$ Proton Capture Reaction

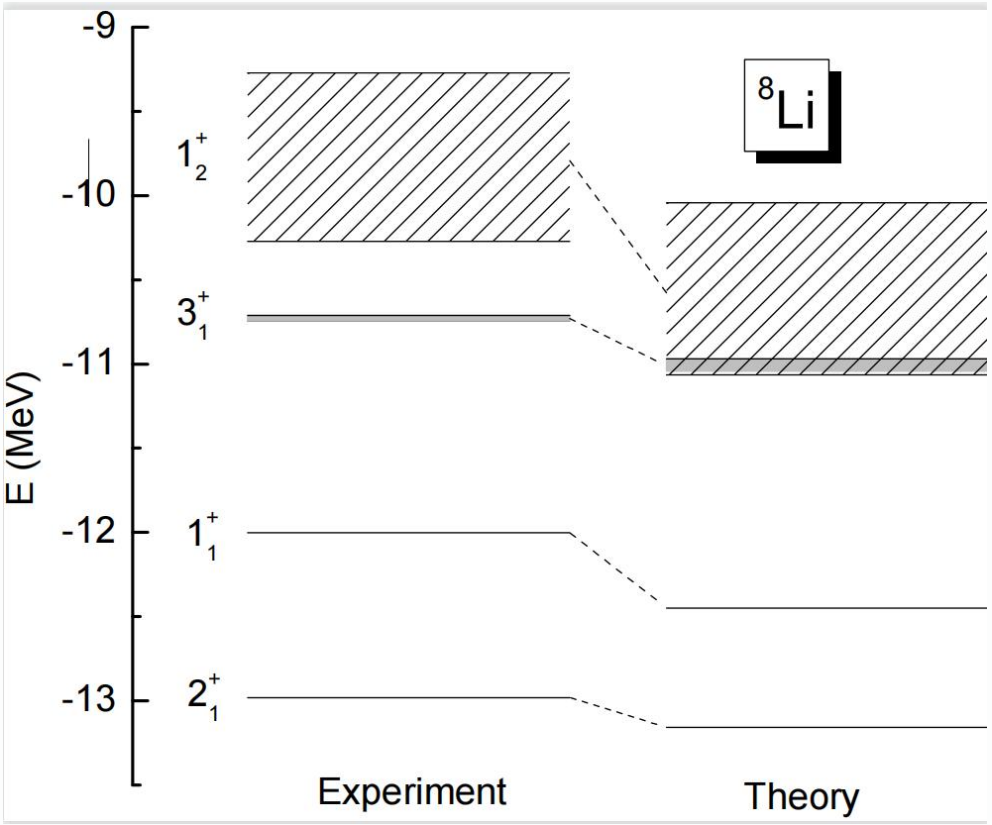


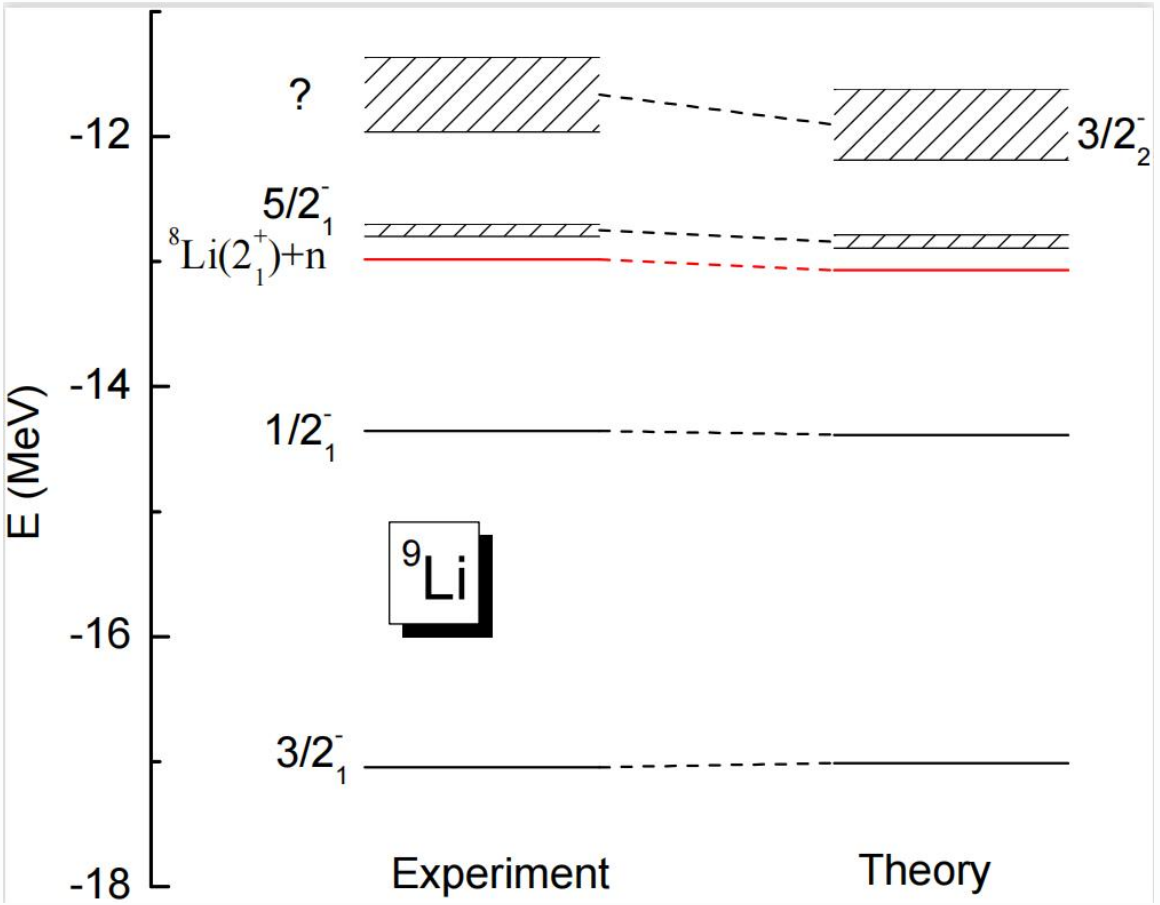
$$^{8}B(p,\gamma)^{9}C(\alpha,p)^{12}N(p,\gamma)^{13}O(\beta^{+}\nu)^{13}N(p,\gamma)^{14}O$$

In metal-poor supermassive stars at specific temperatures and high densities, the ^{8}B proton capture rate can exceed its beta decay rate, providing an alternative pathway for CNO nucleosynthesis.

^{8}Li(n,γ)^{9}Li : spectra

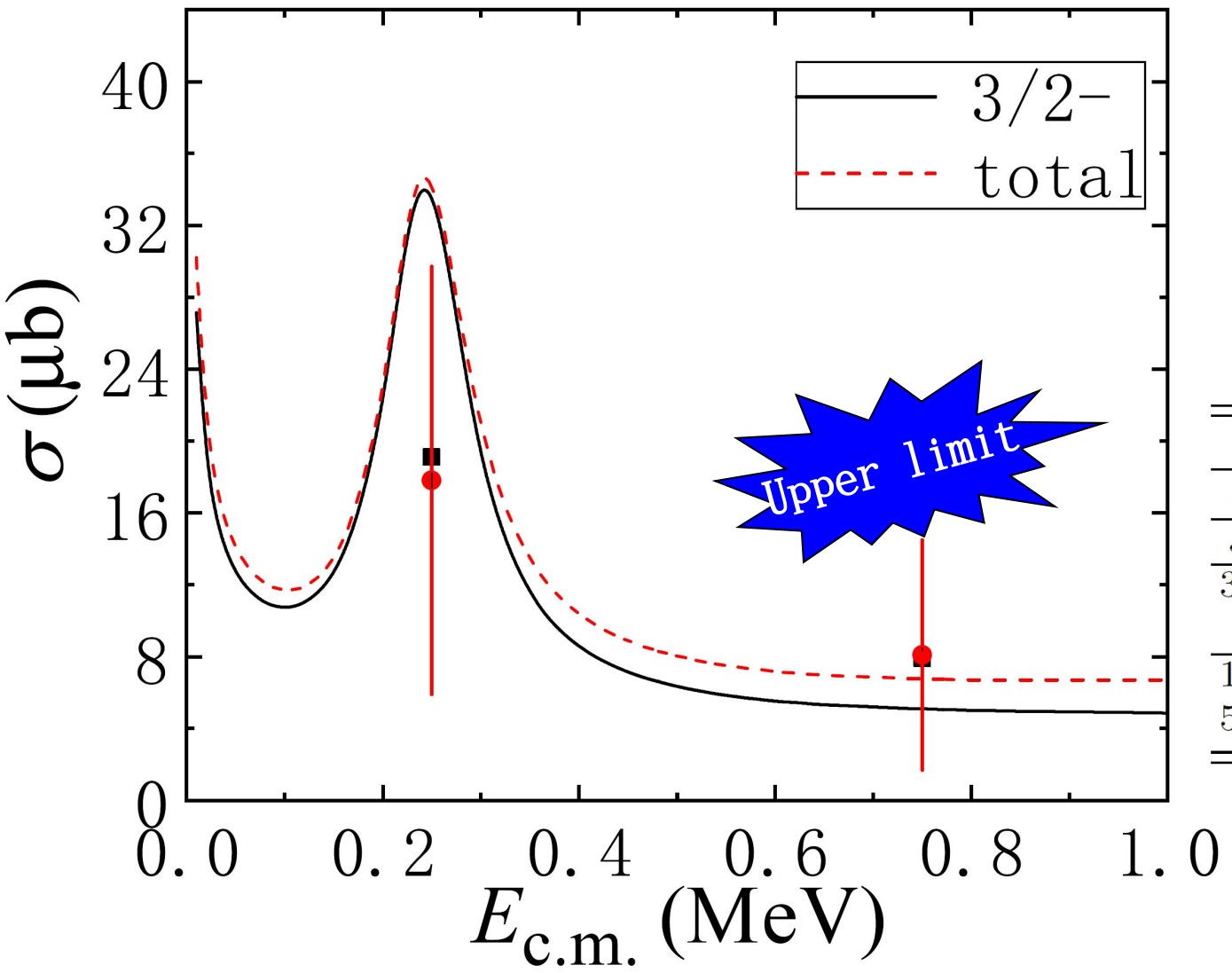
- ^{8}Li target: 2^{+},1^{+} (bound) 3^{+}(resonances)
- ^{9}Li composite system: $3/2^{-}$, $1/2^{-}$ (bound), $5/2^{-}$, $3/2^{-}_{2}$ (resonances).
- Channels: $[^{8}\mathrm{Li}(J^{\pi}_{\mathrm{targ}}) \otimes p(l,j)]^{J^{\pi}_{f}}$



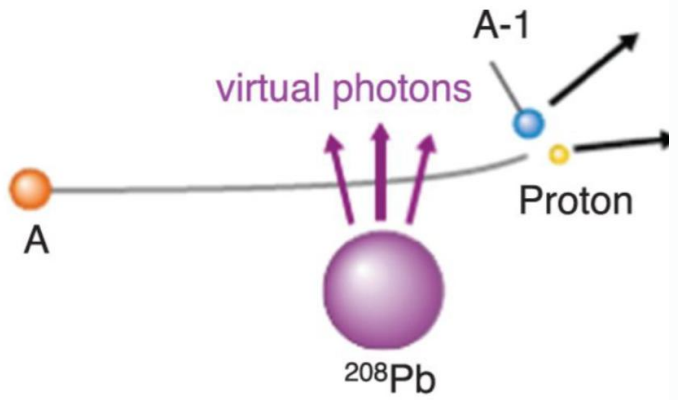


Guoxiang Dong, Xiaobao Wang, N. Michel, M. Płoszajczak, Phys. Rev. C 105, 064608 (2022)

^{8}Li(n,γ)^{9}Li: total cross section



Coulomb dissociation method



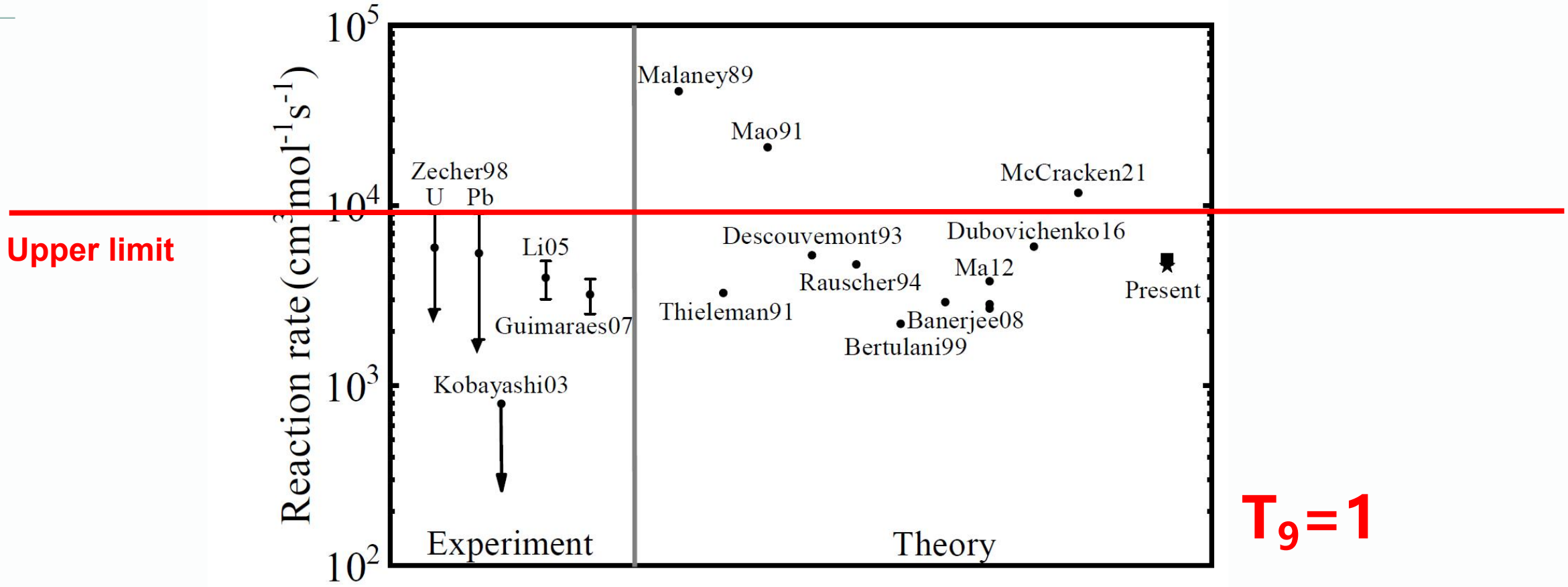
electric field "felt" by the projectile

GSM-CC			Experiment [11]		
$\tilde{E}_n$	0.25 MeV	0.75 MeV	$\tilde{E}_n$	0.25 MeV	0.75 MeV
J^π	σ (μb)	σ (μb)	Target	σ (μb)	σ (μb)
$3/2^-$	15.23	5.24	U	19.1±10.4	7.9±5.5
			Pb	17.8±11.9	8.1±6.4
$1/2^-$	0.80	0.59			
$5/2^-$	0.54	1.11			

Energy bins:

E_n: 0.25MeV ⟶ [0.0, 0.5] MeV

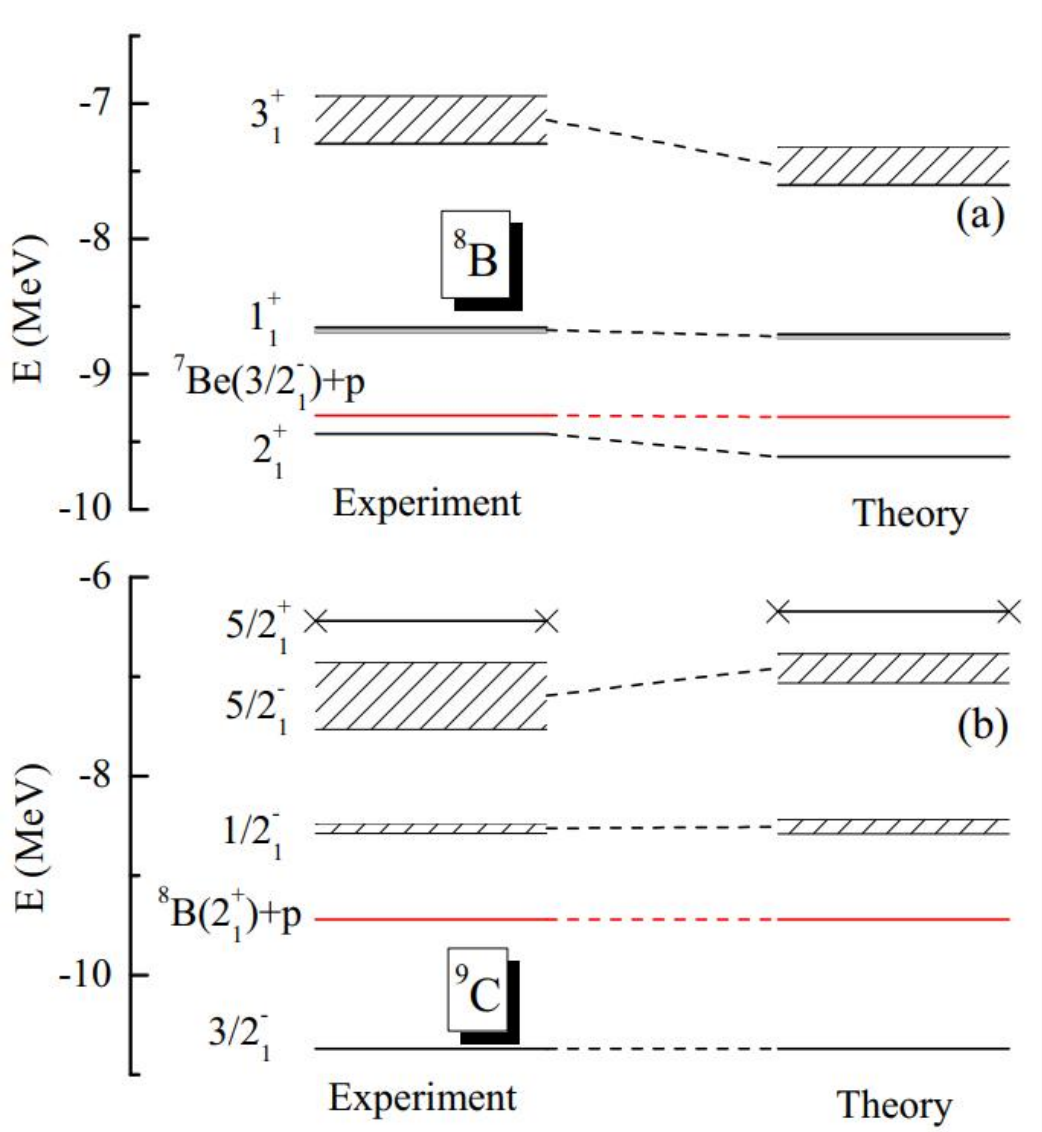
E_n: 0.75 MeV ⟶ [0.5, 1.0] MeV



Conclusions:

- Our theoretical calculations are consistent with previous experimental data and most theoretical predictions.
- The relatively large ^{8}Li neutron capture cross section indicates this reaction can play an important role in Big Bang nucleosynthesis.

$^{8}B(p,\gamma)^{9}C$: spectra

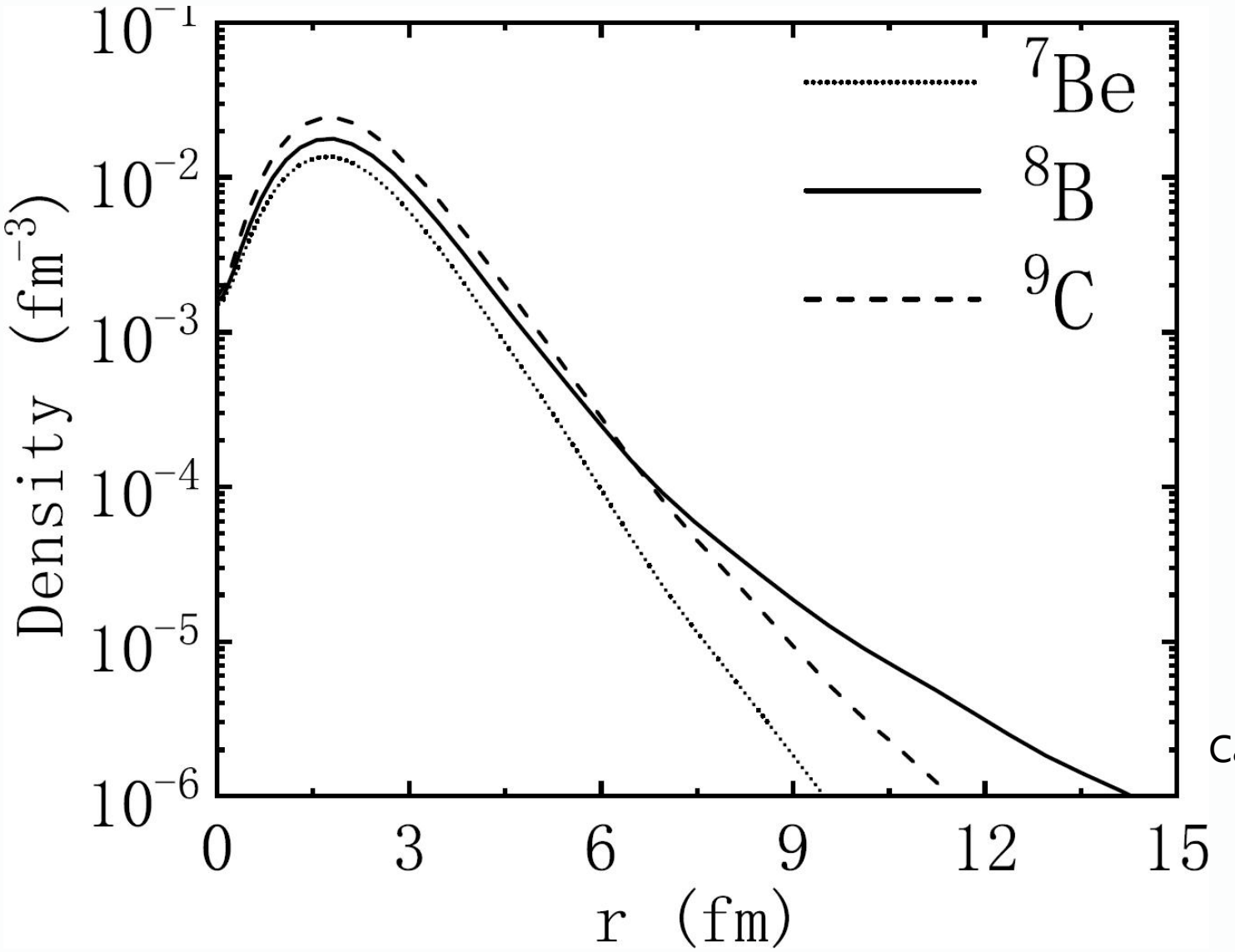


	Theory			Experiment		
	J^π	E(MeV)	Γ(keV)	J^π	E(MeV)	Γ(keV)
^{8}B	2^+_1	0.000	–	2^+_1	0.000	–
	1^+_1	0.891	27.90	1^+_1	0.7695(25)	35.6 (6)
	3^+_1	2.149	280.51	3^+_1	2.32(20)	350 (30)
^{9}C	$3/2^-_1$	0.000	–	$3/2^-_1$	0.000	–
	$1/2^-_1$	2.231	143.62	$1/2^-_1$	2.218(11)	52(11)
	$5/2^-_1$	3.822	297.91	$5/2^-_1$	3.549(20)	673(50)
	$3/2^+_1$	4.361	323.398	$5/2^+_1$[a]	4.40(4)	2750(110)
	$5/2^+_1$	4.395	327.96			
	$1/2^+_1$	5.067	359.231	?	5.75(4)	601(50)

[a]The latest measured energy of $5/2^+_1$ is 4.3 (3) MeV, and width is $4.0^{+2.0}_{-1.4}$ MeV [32].

Guoxiang Dong, Xiaobao Wang, N. Michel, M. Płoszajczak, Phys. Rev. C 107, 044613 (2023)

^{8}B Density Distribution

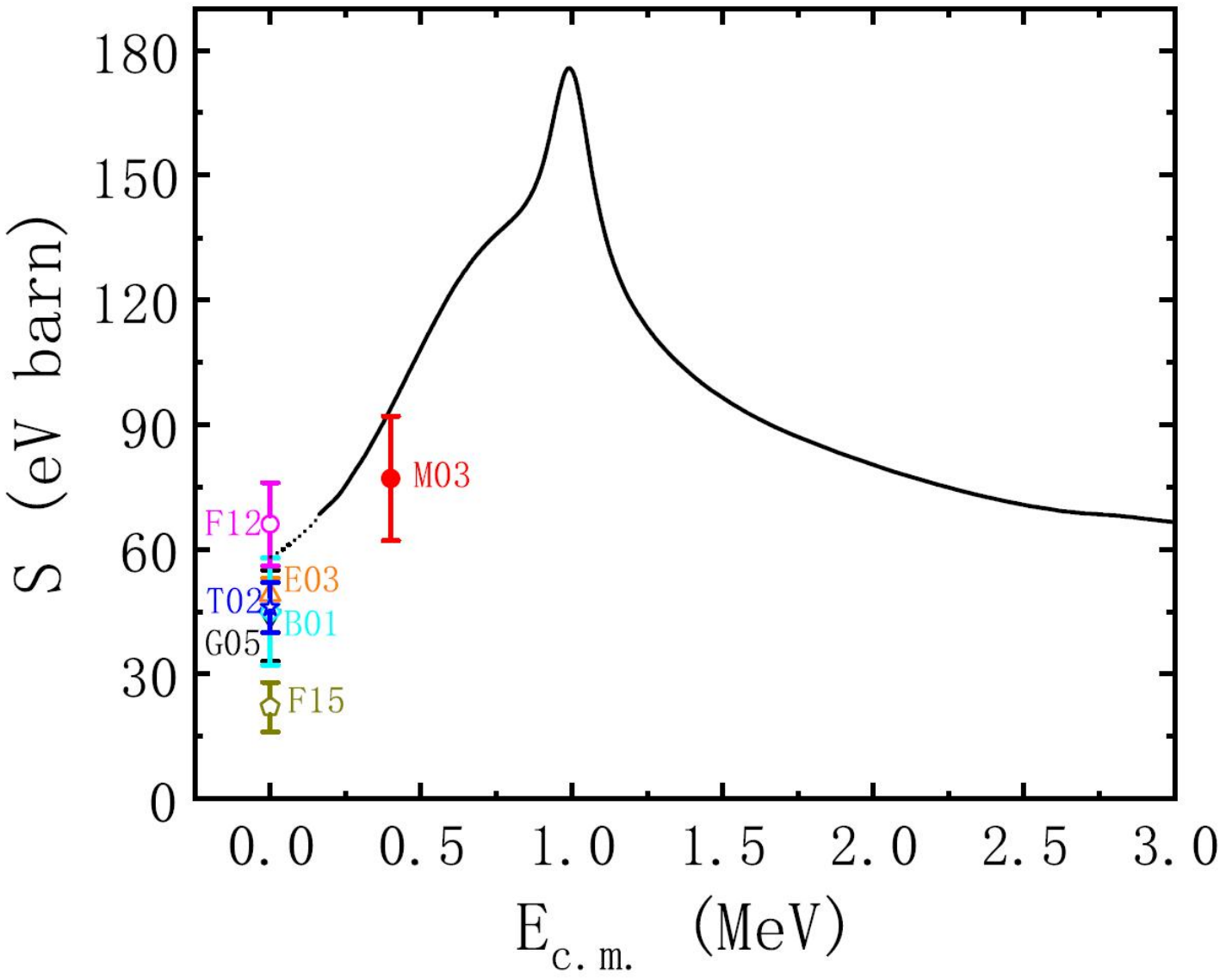


8B, EXP	Rm (fm)	Rp (fm)	Rn (fm)
Tanihata 1988	2.38(4)	2.45(5)	2.27(4)
Negoita 1996	2.55(8)	2.76(8)	2.16(3)
Carstoiu 2007	2.60(4)		
Dobrovolsky 2019	2.58(6)	2.76(9)	2.25(3)

Calculation:

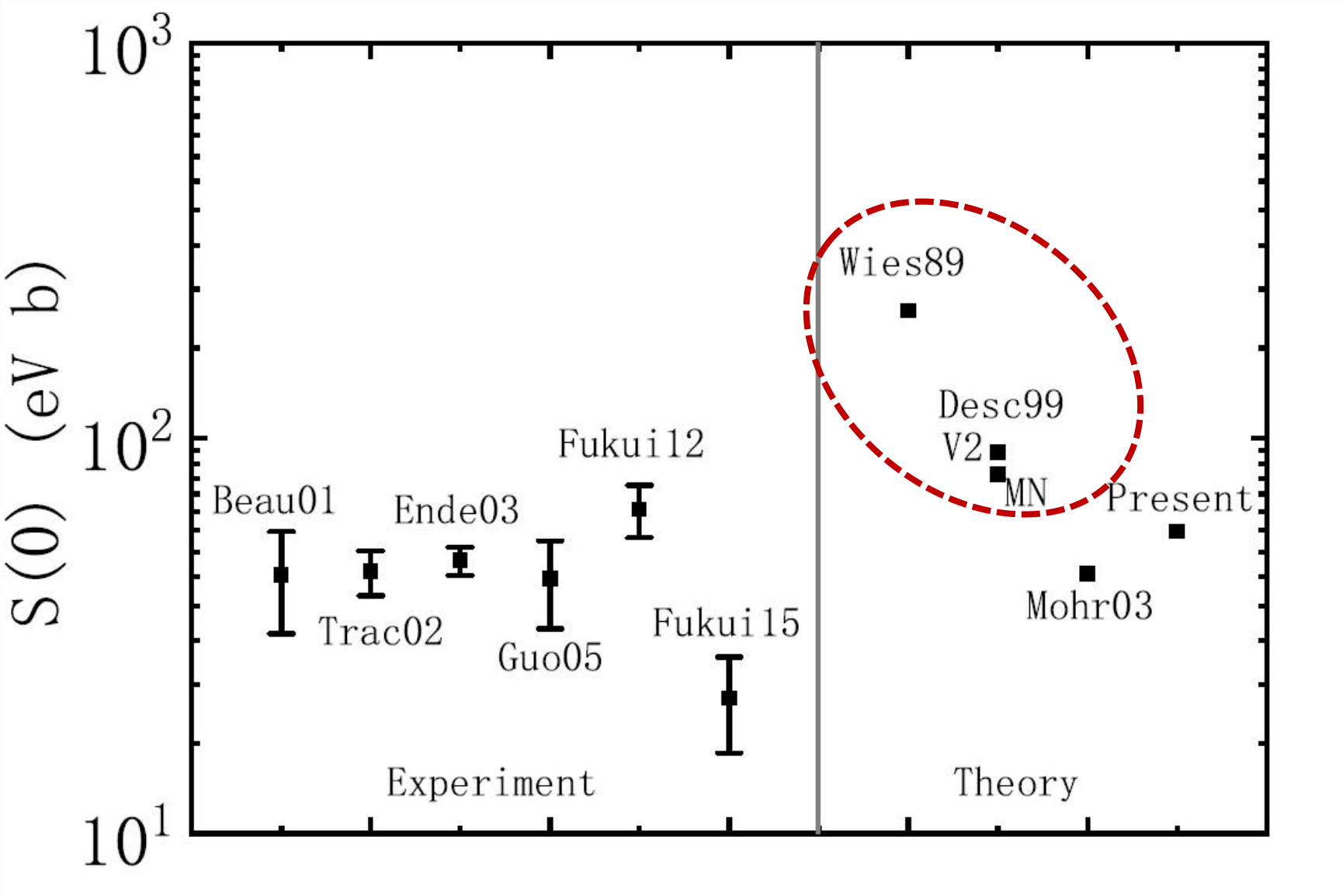
Rm=2.482 fm; Rp=2.633 fm; Rn=2.208 fm

S-factor: Total $S = S^{E1} + S^{M1} + S^{E2}$

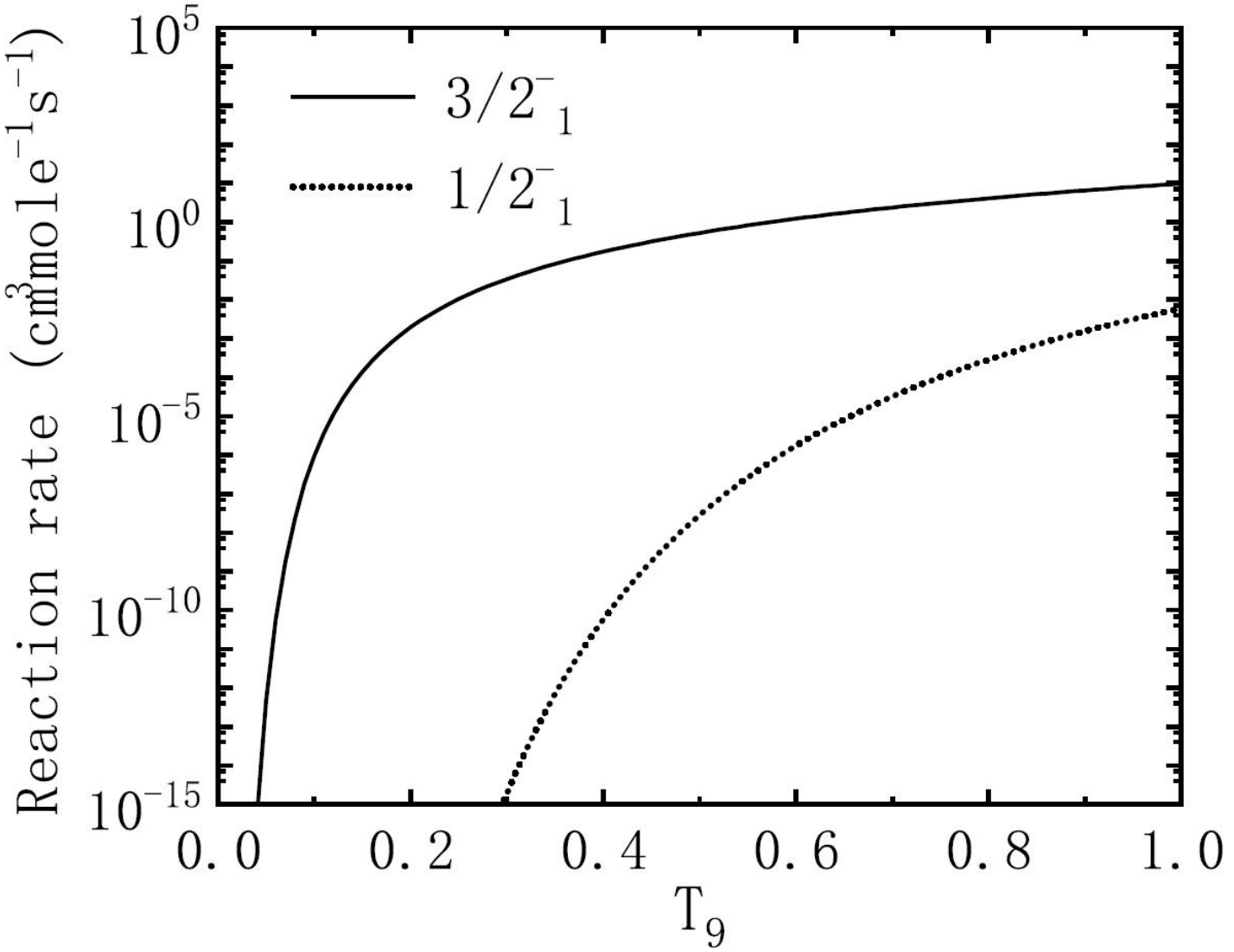


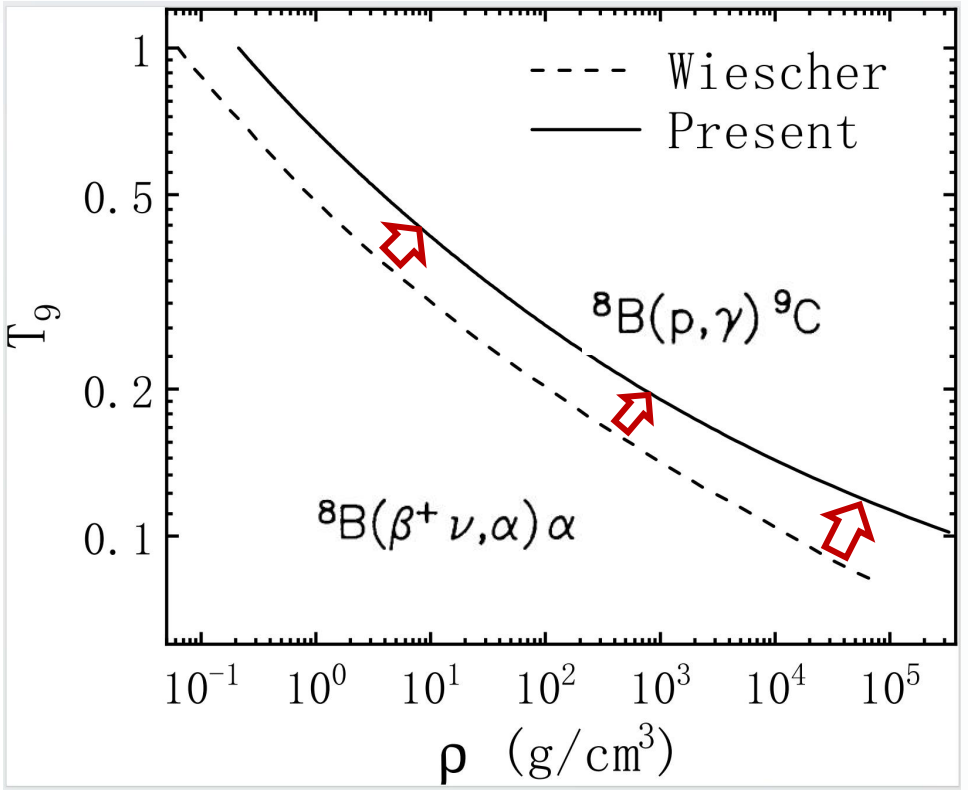
ANC method	S(**E=0 MeV**)	error
Beaumel01	45	13
Trache02	46	6
Enders_2003	49	4
Guo05	44	11
T. Fukui 2012	66	10
T. Fukui 2015	22	6

Coulomb dissociation	S[**E=(0.2,0.6) MeV**]	error
Motobayashi_2003	**77**	**15**


10^3
10^2
10^1
S(0) (eV b)
Beau01
Trac02
Ende03
Guo05
Fukui12
Fukui15
Experiment
Wies89
Desc99
V2
MN
Present
Mohr03
Theory

Astrophysical reaction rate





Our work indicates that the optimal temperature for ⁹C formation is **T_9 ~ 0.14–0.84**

Wiescher et al., APJ 343, 352 (1989):
T_9~ 0.07--0.70

T_9: 10^9 K

Conclusions

- GSM-CC calculated S(0) values are close to most indirect measurements but lower than previous theoretical predictions

- GSM-CC predicts the critical temperature and density for $^{8}B(p,\gamma)^{9}C$ proton capture are higher than previous theoretical expectations.

$^{8}Li(n,\gamma)^{9}Li$ and $^{8}B(p,\gamma)^{9}C$ both play crucial roles in bypassing the A=8 mass gap.

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$^{19}F(p, \gamma)^{20}Ne$

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Measurement of $^{19}F(p, \gamma)^{20}Ne$ reaction suggests CNO breakout in first stars

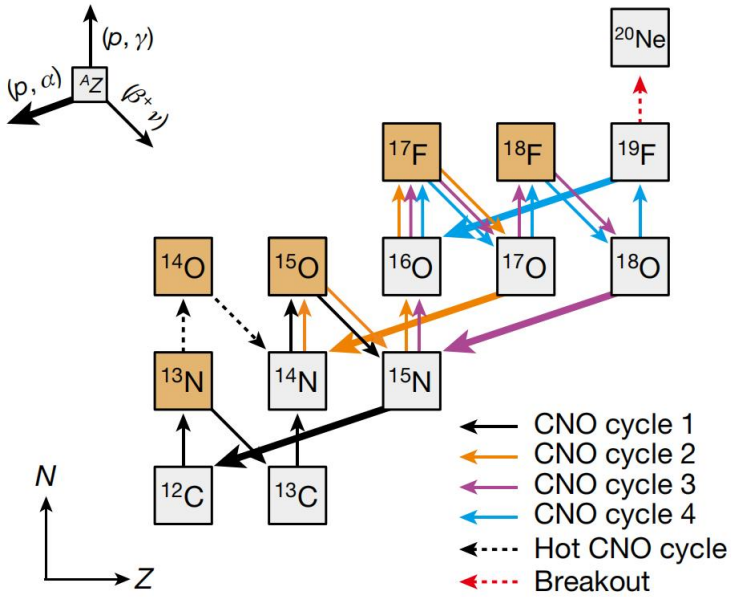
Liyong Zhang, Jianjun He ✉, Richard J. deBoer, Michael Wiescher ✉, Alexander Heger, Daid Kahl, Jun Su, Daniel Odell, Yinji Chen, Xinyue Li, Jianguo Wang, Long Zhang, Fuqiang Cao, Hao Zhang, Zhicheng Zhang, Xinzhi Jiang, Luohuan Wang, Ziming Li, Luyang Song, Hongwei Zhao, Liangting Sun, Qi Wu, Jiaqing Li, Baoqun Cui, ... Weiping Liu ✉ + Show authors

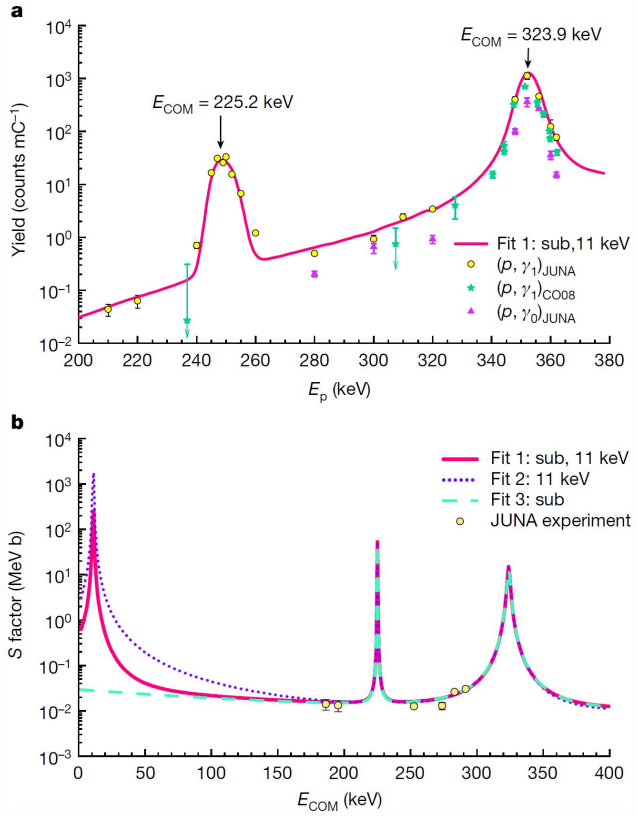
Nature **610**, 656–660 (2022) | Cite this article

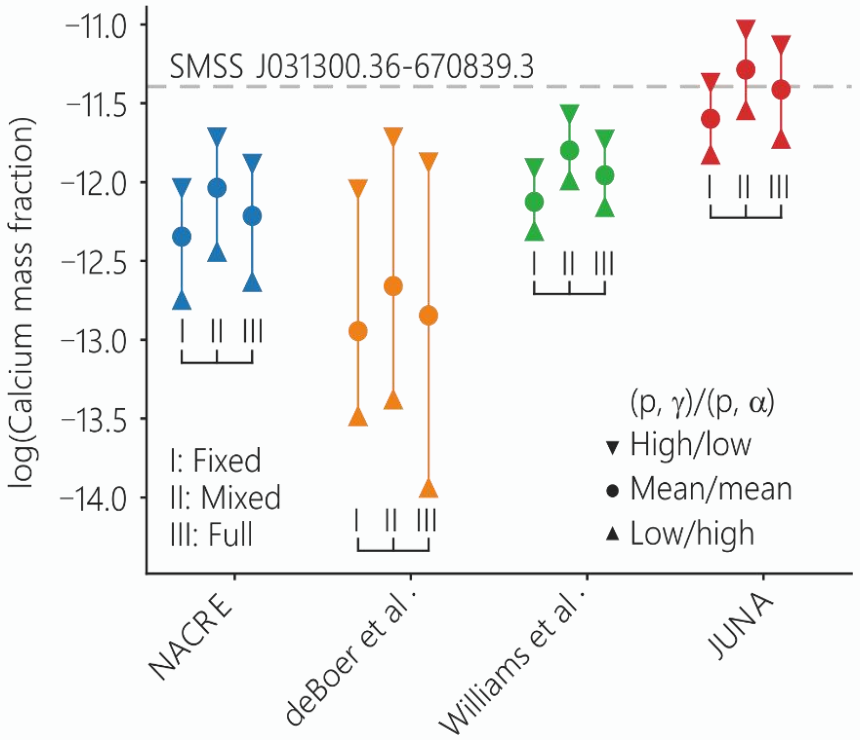
The **only** process to **break out** of the **CNO** cycle at temperature **below 0.1 GK** and may serve as **the origin of calcium** in **first generation of stars** after the Big Bang

Stellar model: 19F(p,gamma) as the origin of calcium abundance in the most metal-poor star known in the universe (SMSS0313-6708)

However, Using the **NACRE rate**, predicted Calcium abundances were about **one order of magnitude too low**!



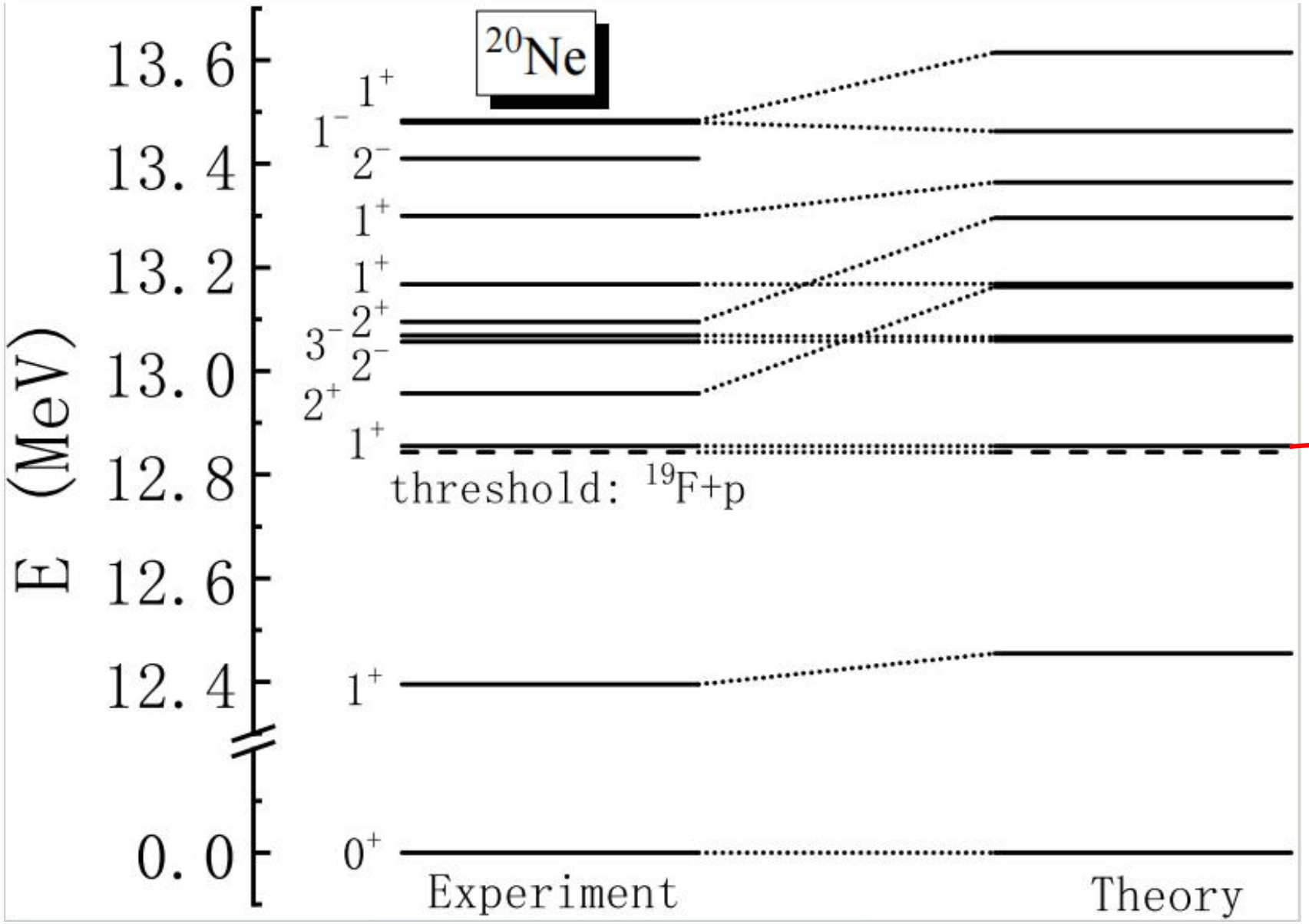




JUNA Experiments confirmed NACRE was too small. Actual reaction rate is 5–7 times larger!

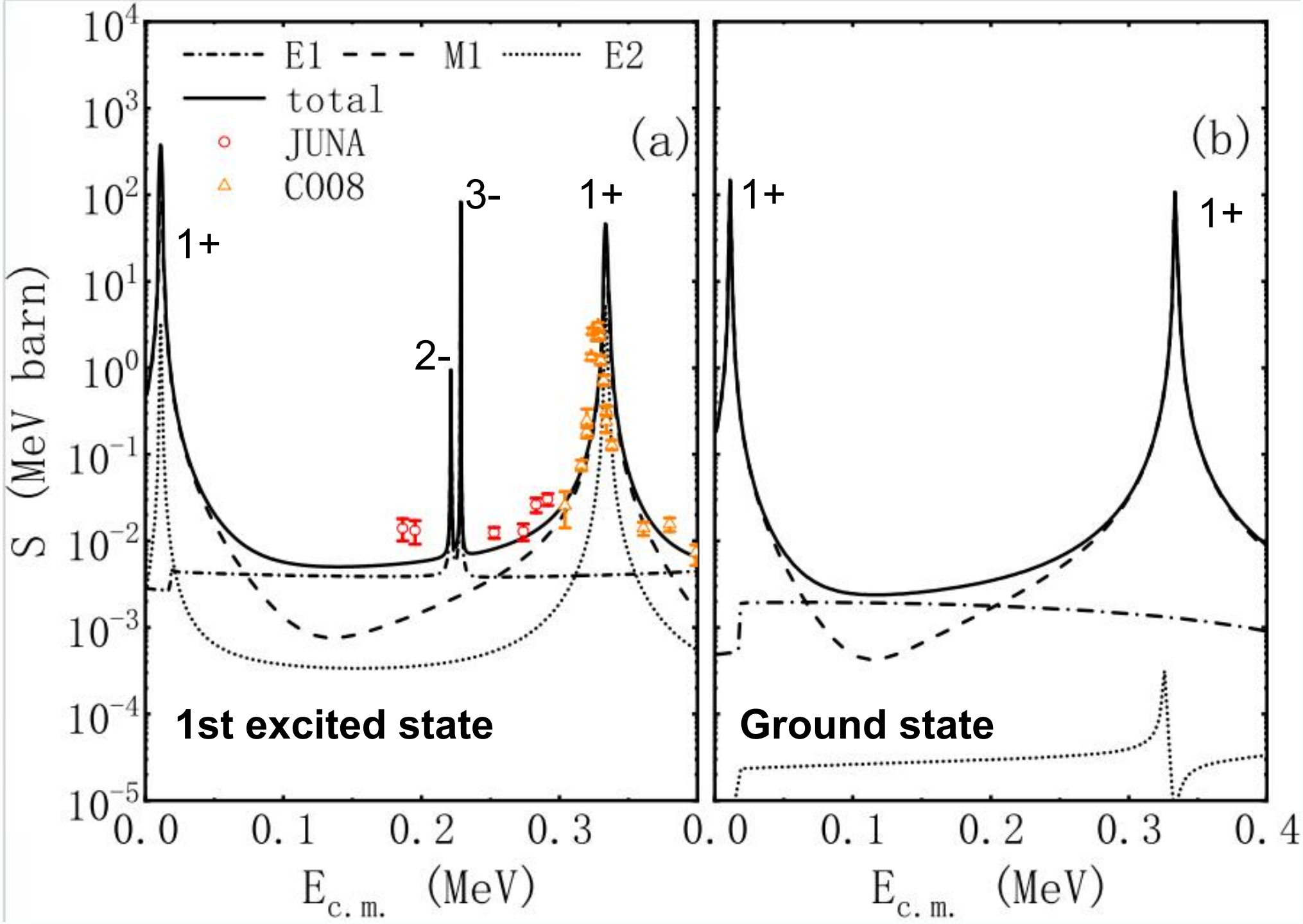
→ **Solves the calcium abundance origin puzzle!**

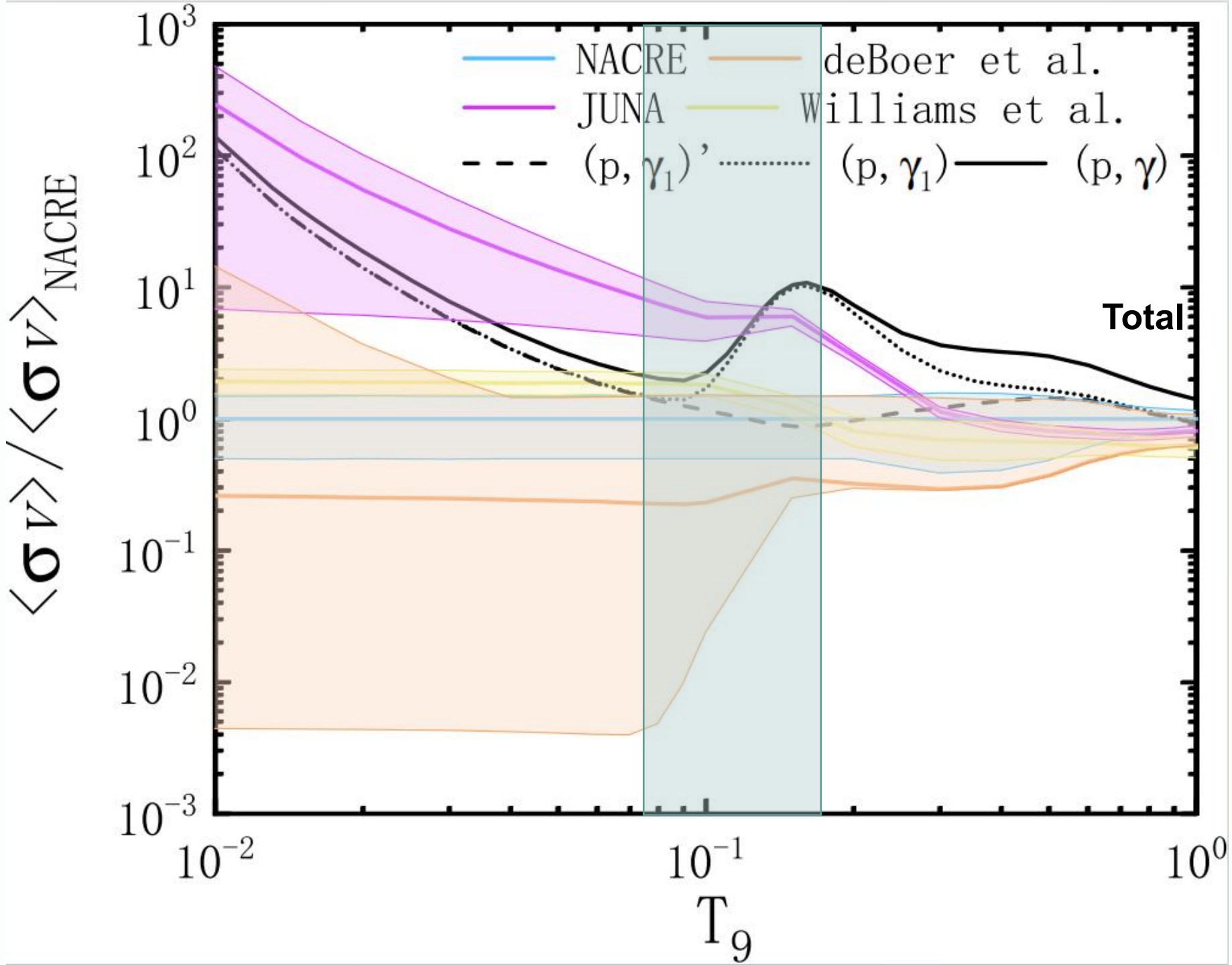
$^{19}F(p,\gamma)^{20}Ne$: spectra



~10keV!

Guoxiang Dong, Xiaobao Wang, N. Michel, M. Płoszajczak, Phys. Rev. C 110, L061601 (2024)


E1
M1
E2
total
JUNA
C008
(a)
(b)
1+
3-
2-
1+
1+
1+
S (MeV barn)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.0
0.1
0.2
0.3
0.4
$E_{c.m.}$ (MeV)
1st excited state
Ground state



JUNA:

5.4~7.4 × NACRE at around 0.1 GK, which explain the origin of calcium in the early stars

GSM-CC:

2.24 × NACRE at 0.1 GK

10.3 × NACRE at 0.15 GK

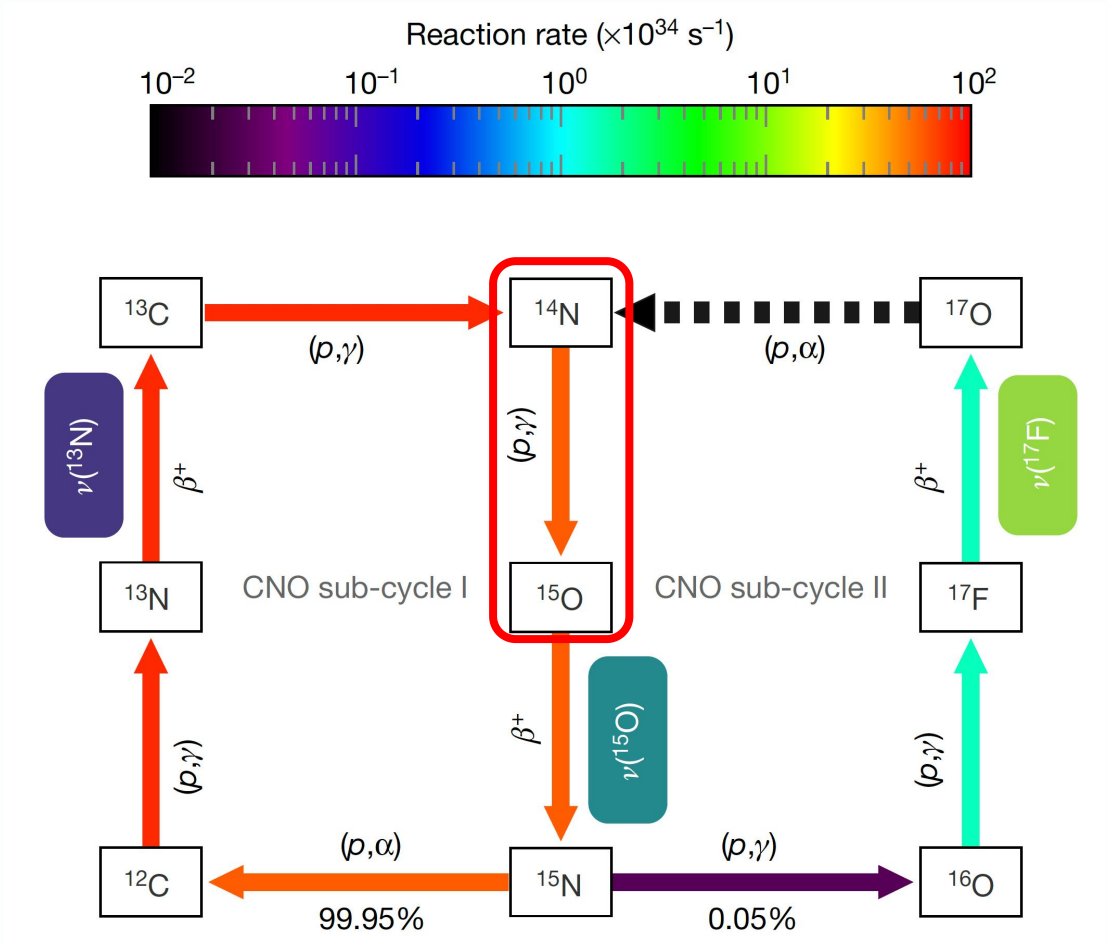
Conclusions

- Theoretical calculations of $^{19}F(p,\gamma)^{20}Ne$ reaction rate are close to JUNA results, higher than previous estimates.
- Theory also shows that the $^{19}F(p,\gamma)^{20}Ne$ cross section is large enough to suppress ^{19}F from returning to CNO cycle via (p,α) reaction.
- This breakout reaction may explain the calcium abundance origin in first-generation stars.

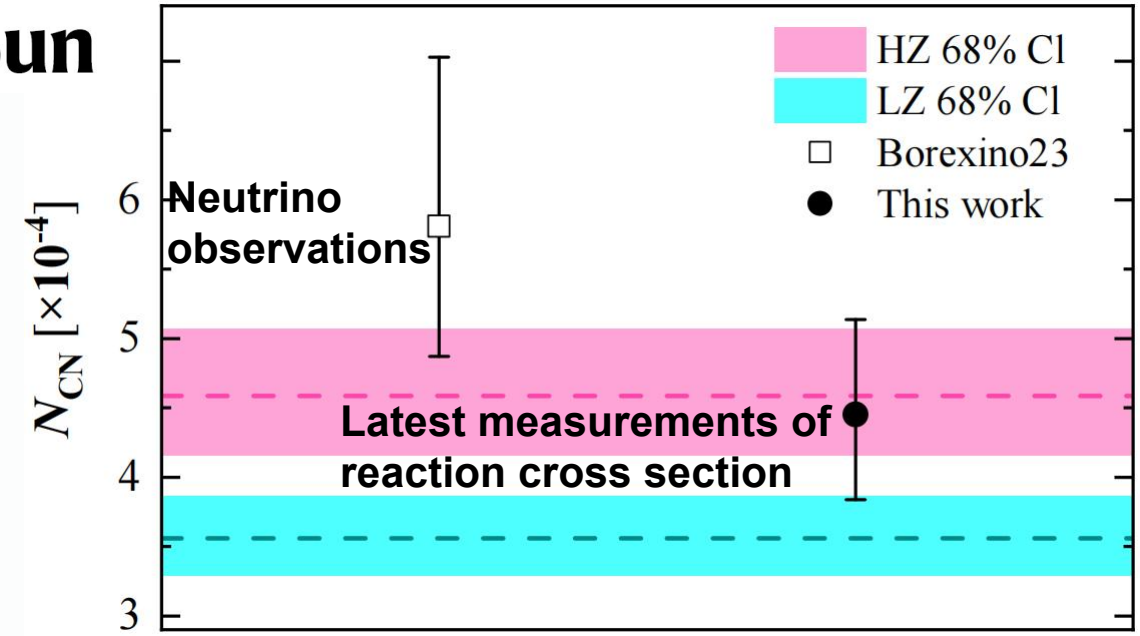
$^{14}N(p, \gamma)\ ^{15}O$: the ***slowest*** reaction in the **CNO**

Article

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun



Solar metallicity problem



Enhanced S-Factor for the $^{14}N(p,\gamma)^{15}O$ Reaction and Its Impact on the Solar Composition Problem

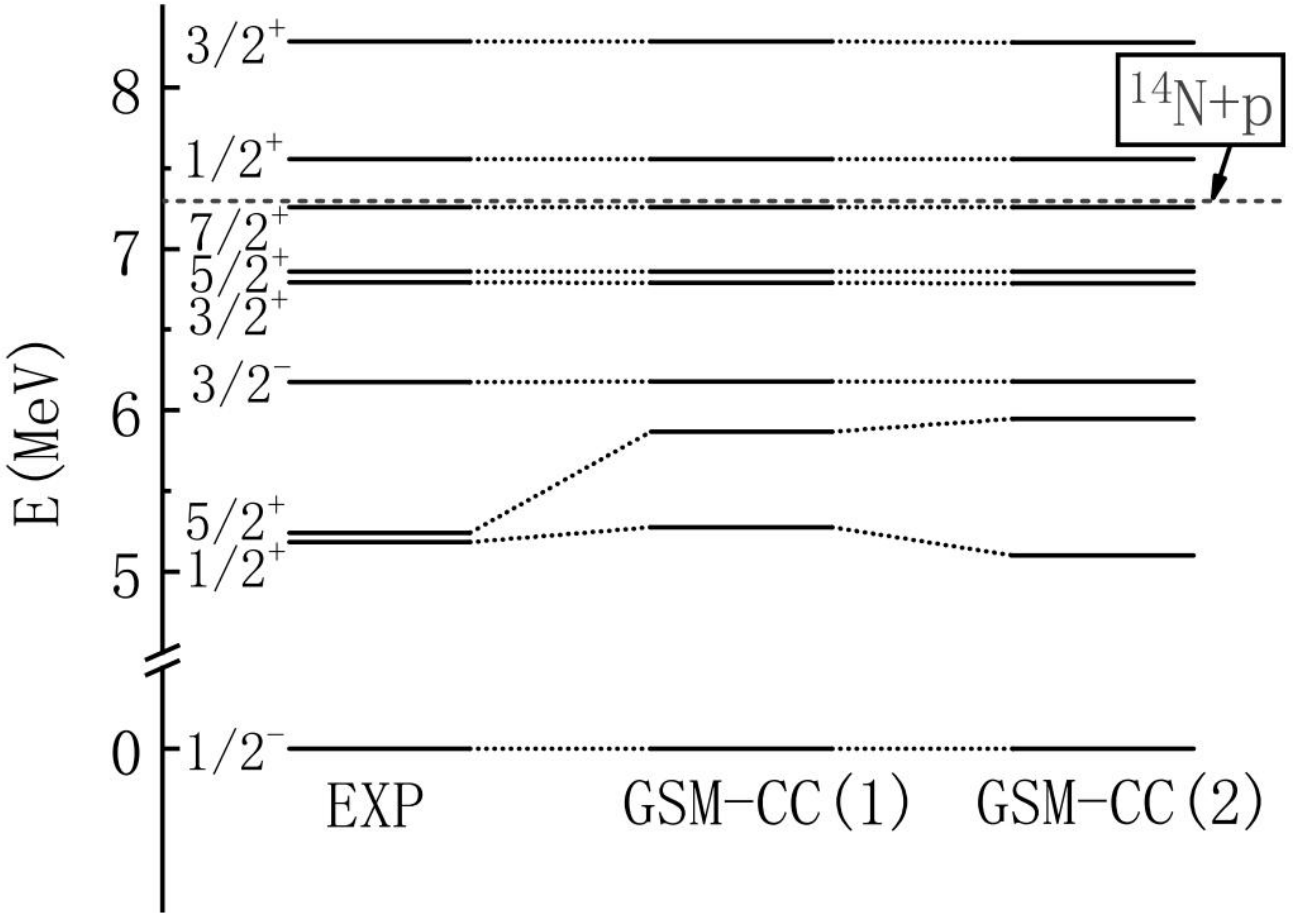
X. Chen[1], J. Su[1,*], Y. P. Shen[2,†], L. Y. Zhang[1], J. J. He[3,1], S. Z. Chen[4], S. Wang[5], Z. L. Shen[1], S. Lin[1] *et al.*

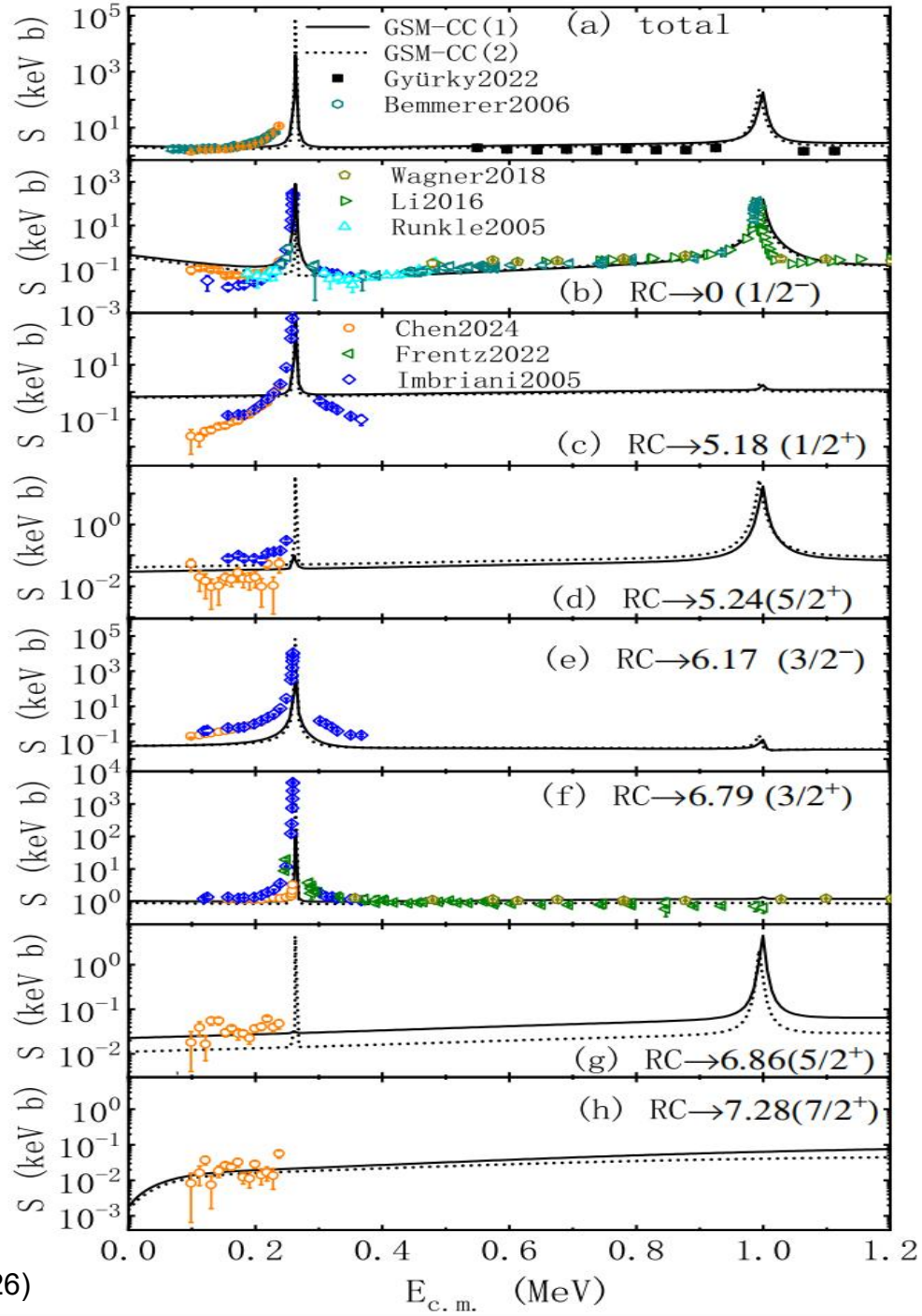
Hide

Phys. Rev. Lett. 135, 232701 (2025)

L. Y. Song[1], H. Zhang[3,1], L. H. Wang[6], X. Z. Jiang[1], L. Wang[1], Y. T. Huang[1], Z. W. Qin[1], F. C. Liu[1], Y. D. Sheng[1], Y. J. Chen[3,1], Y. L. Lu[1], X. Y. Li[3], J. Y. Dong[2], Y. C. Jiang[2], Y. Q. Zhang[2], Y. Zhang[2], J. W. Tian[2], D. Xiao[4], Y. Zhang[4], Z. M. Li[7], X. C. Han[5], J. J. Wei[8], H. Li[8], Z. An[9], W. P. Lin[9], B. Liao[1], H. N. Liu[1], F. S. Zhang[1], M. L. Qiu[1], C. Xu[1], S. L. Jin[10], F. Lu[11], J. F. Chen[12], W. Nan[2], Y. B. Wang[2], Z. H. Li[2], B. Guo[2], Y. Q. Gu[13], and W. P. Liu[14,2,‡]

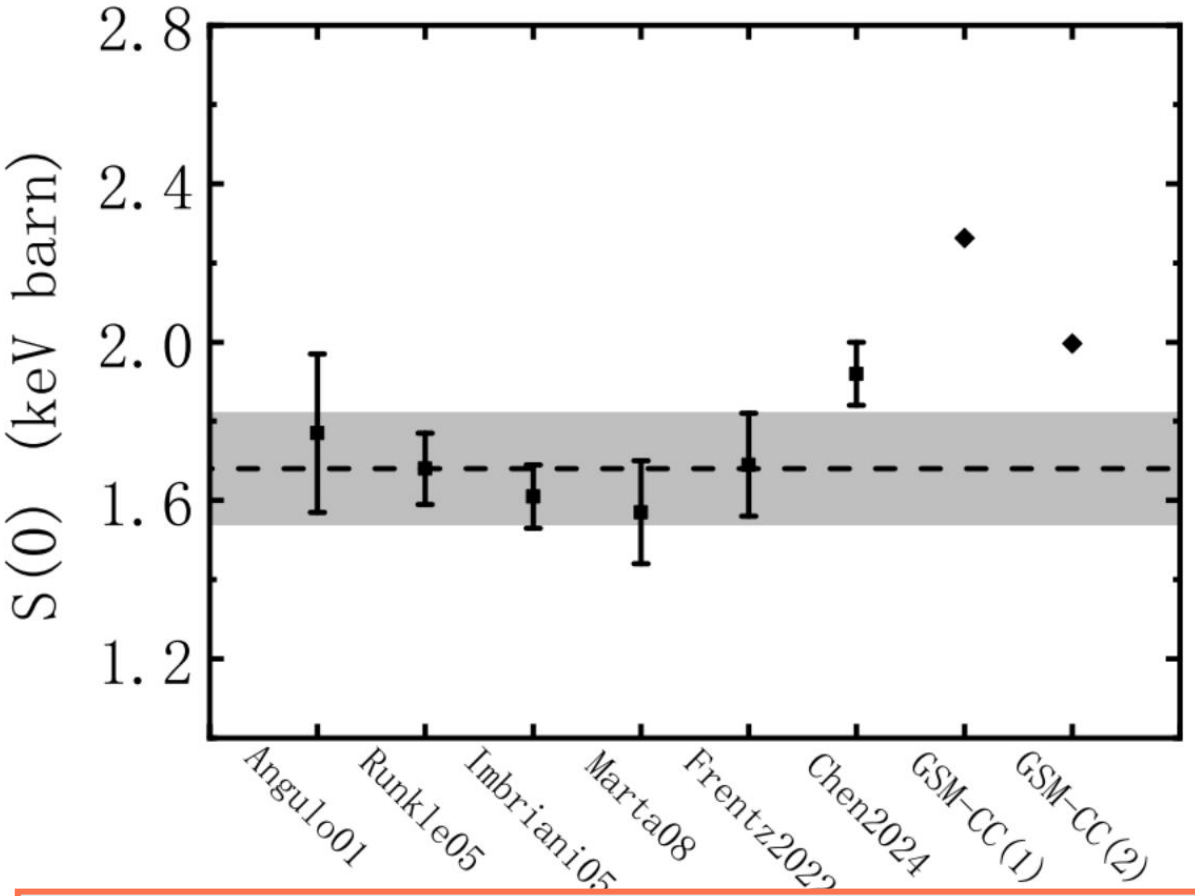
$^{14}N(p, \gamma)\ ^{15}O$

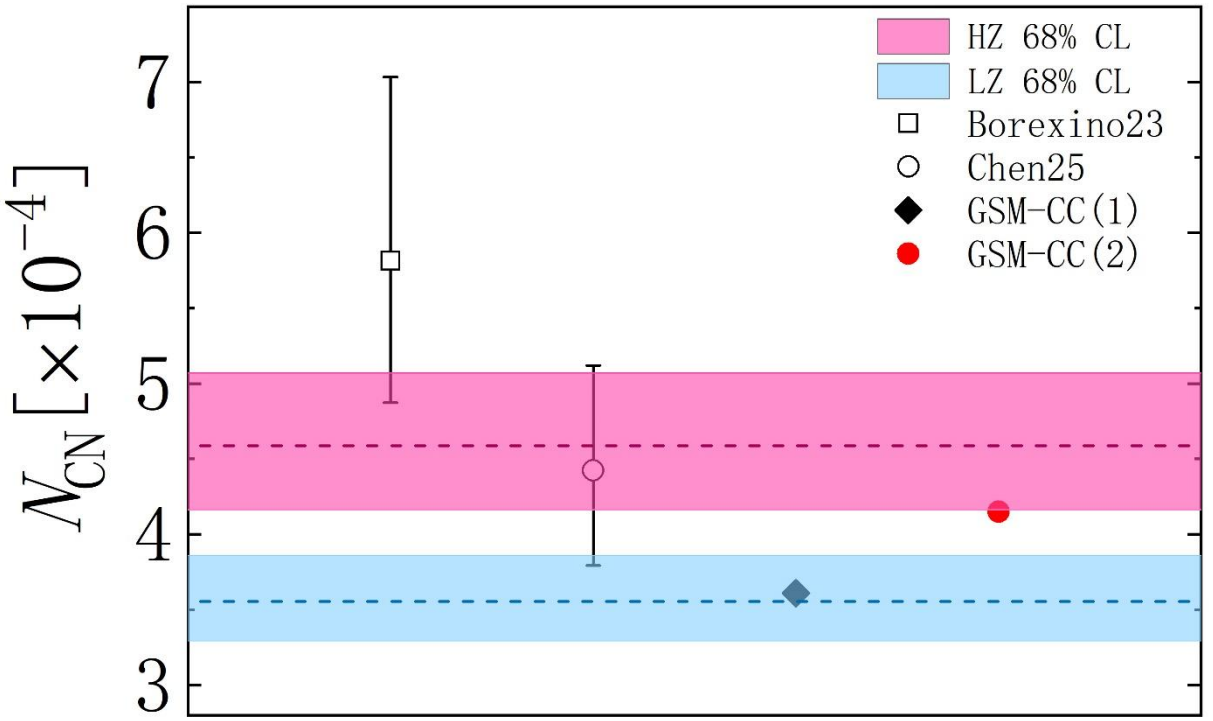




Guoxiang Dong, Xiaobao Wang, N. Michel, M. Płoszajczak, Phys. Rev. C 113, L032801 (2026)

$^{14}N(p, \gamma)\ ^{15}O$





Theoretical calculations of $^{14}N(p,\gamma)^{15}O$ reaction rate are close to HINEG measurements, ~14% higher than SF-III.

→ Provides prediction for solving the solar composition problem and CNO neutrinos

SUMMARY

- We conducted microscopic theoretical studies of selected key nuclear reactions affecting astrophysical processes

- Theoretical calculations are in good agreement with existing experimental data

- Due to the reliable extrapolation of microscopic theory, our results can provide assistance for nuclear experiments and nuclear astrophysics problems

THANKS!