CRIBの低エネルギー不安定核ビームを使った最近の天体核反応研究成果

東京大学
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in Collaboration with:

RIKEN, KEK, Kyushu, Tsukuba, Tohoku, Osaka (Japan),

McMaster (Canada), CIAE, IMP, Beihang (China), SKKU, Chung-Ang, IBS, Ehwa, SKKU (Korea), INFN LNL/LNS (Italy), Edinburgh (UK), IOP(Vietnam), ULB (Belgium) and others.

Topics

- **Brief introduction of our RI beam separator CRIB (CNS, U-Tokyo)**
- Recent Highlights of experimental projects at CRIB:
  1. Resonant scattering with thick-target method in inverse kinematics (TTIK)

^{25}Al+p: study for the ^{22}Mg(α,p) reaction in X-ray bursts

Project in collaboration with IMP, Lanzhou, China

Paper submitted to Phys. Rev. Lett., review in progress.

2. Trojan Horse experiment with RI beam

^{7}Be(n,p)/(n,α) in BBN

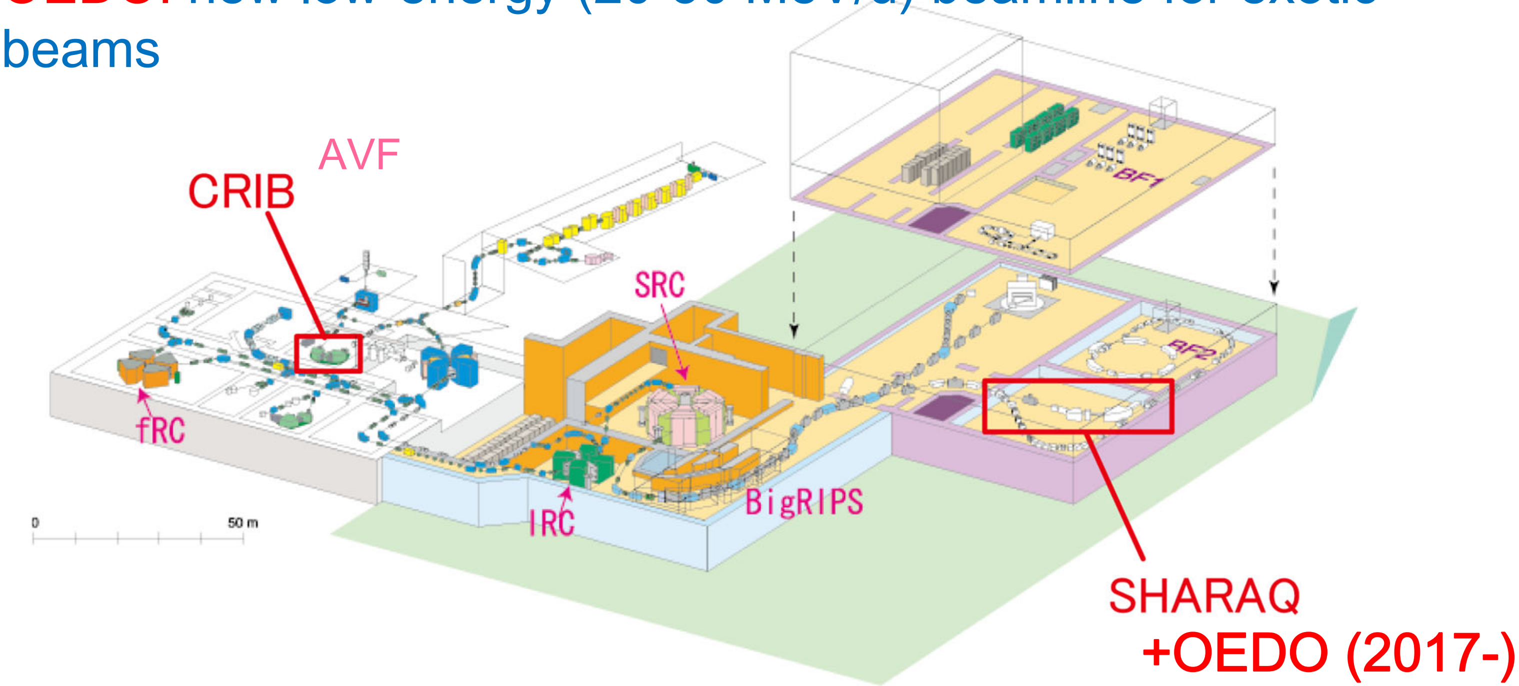
Project by Seiya Hayakawa (CNS, U-Tokyo)

Paper accepted at Astrophys. J. Lett. in May, 2021.

CRIB/OEDO in RIBF

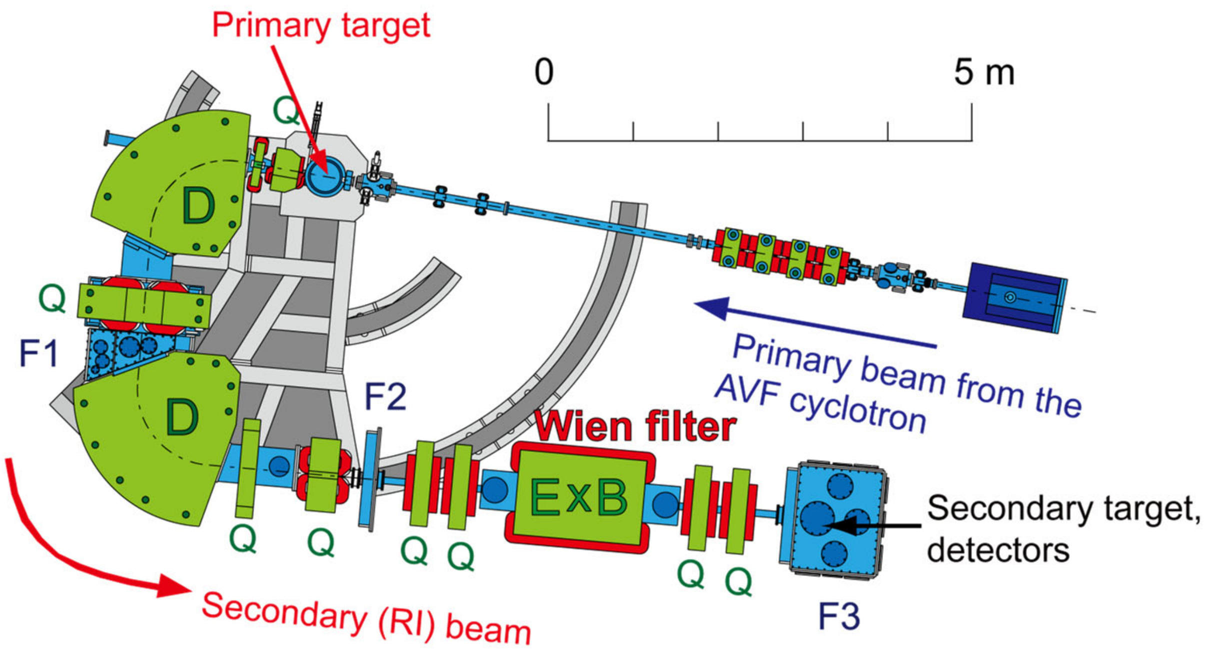
Facilities operated by CNS, the University of Tokyo in RIBF (RIKEN Nishina center)

- CRIB: RI beam separator for low-mass, low-energy (<10 MeV/u) RI beams
- SHARAQ: high resolution spectrometer
- OEDO: new low-energy (20-50 MeV/u) beamline for exotic beams



CRIB

- CNS Radio-Isotope Beam separator , constructed and operated by CNS, Univ. of Tokyo, located at RIBF (RIKEN Nishina Center).
  - Low-energy(<10MeV/u) RI beams by in-flight method.
  - Primary beam from K=70 AVF cyclotron.
  - Momentum (Magnetic rigidity) separation by “double achromatic” system, and velocity separation by a Wien filter.
  - Orbit radius: 90 cm, solid angle: 5.6 msr, momentum resolution: 1/850.

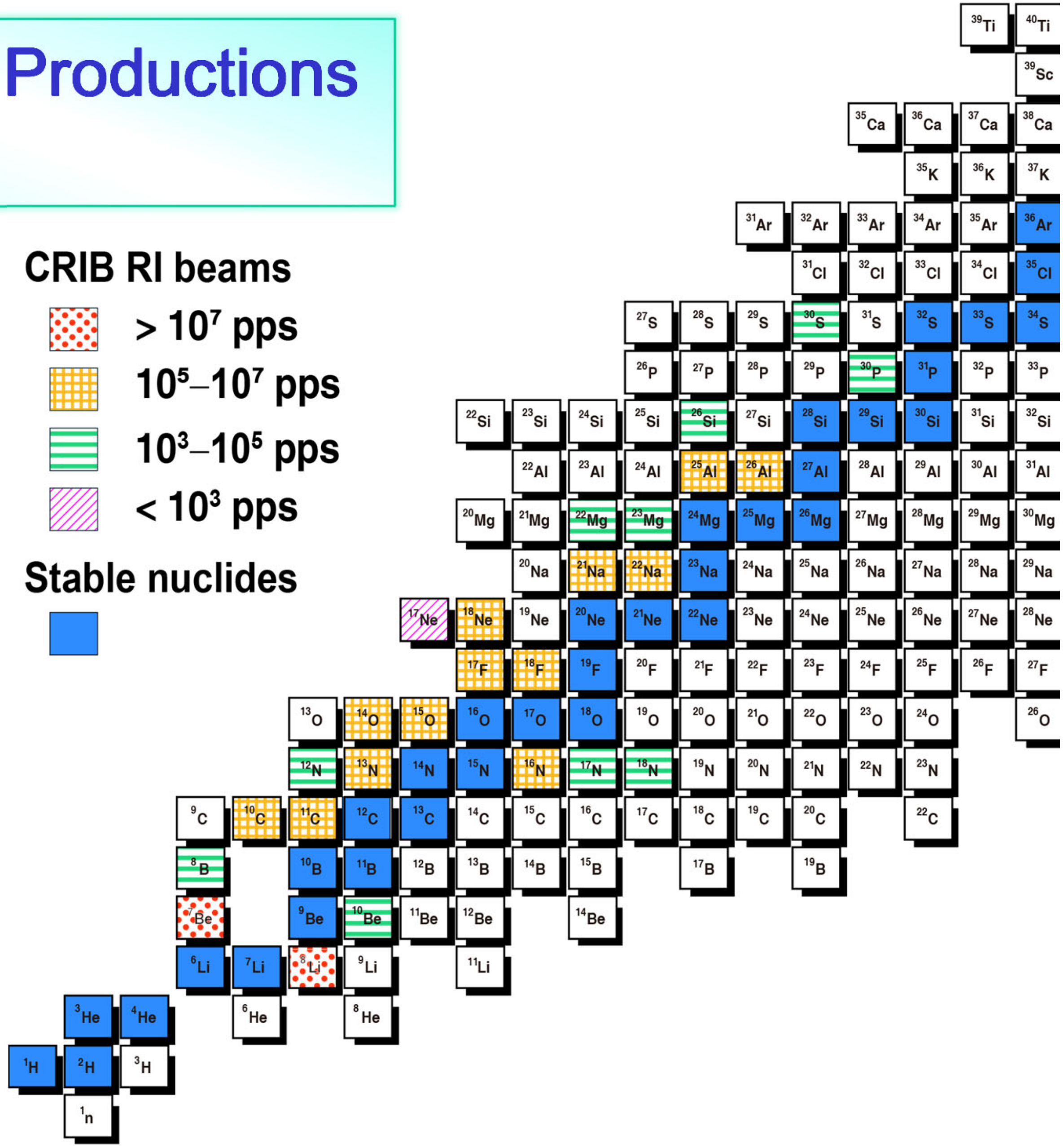


Low-Energy RI beam Productions at CRIB

2-body reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are mainly used for the production….large cross section

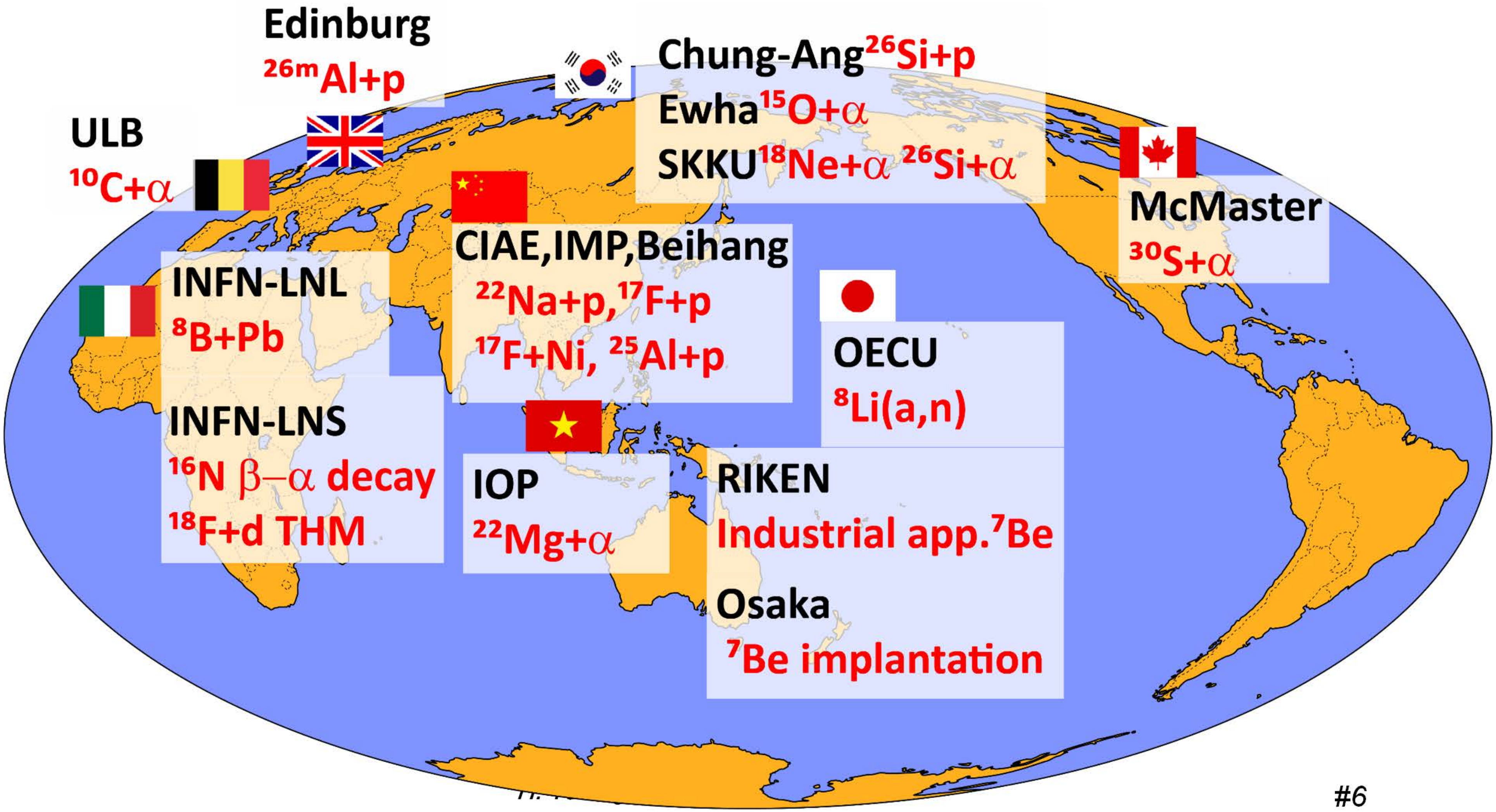
Many RI beams have been produced at CRIB: typically 10^4-10^6 pps

Higher intensity for ^{7}Be beam with cryogenic H_2 target: 3×10^8 pps.



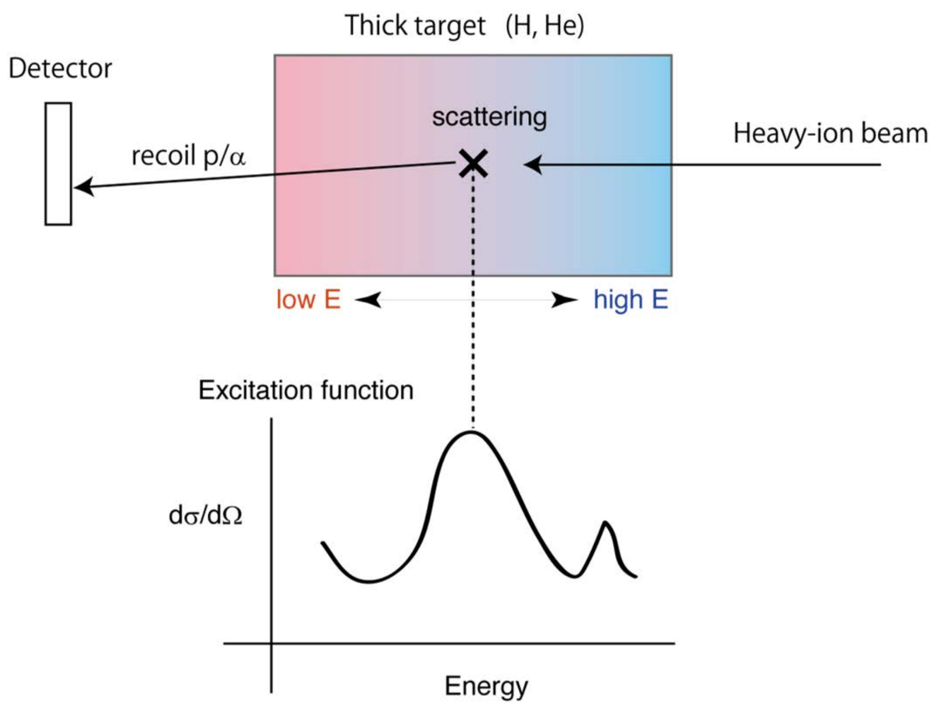
CRIB is collaborative

- Recent proposer group of CRIB experiments:



Method: the thick-target method in inverse kinematics

Measurement of resonance scattering



- Inverse kinematics… measurement is possible for short-lived RI which cannot be used as the target.
- Simultaneous measurement of the excitation function for certain energy range.(Small systematic error, no need to change beam energy.)
- The beam can be stopped in the target…measurement at θ_{cm}=180 deg. (where the potential scattering is minimal) is possible.

Courtesy of Dr. Hu Jun@IMP

Measurement of ^{25}Al+p elastic scattering relevant to the ^{22}Mg(α,p)^{25}Al reaction

Jun Hu, X.D. Tang, S.W. Xu, L.Y. Zhang, S.B Ma, N.T. Zhang, J.J. He,
H. Yamaguchi. K. Abe, S. Hayakawa, L. Yang, H. Shimizu, D. Kahl,
T. Teranishi, J. Su. H.W. Wang, B. Guo et al.,

Institute of Modern Physics, Chinese Academy of Sciences,
CNS, the University of Tokyo,
National Astronomical Observatories,
The University of Edinburgh,
CIAE, SINAP

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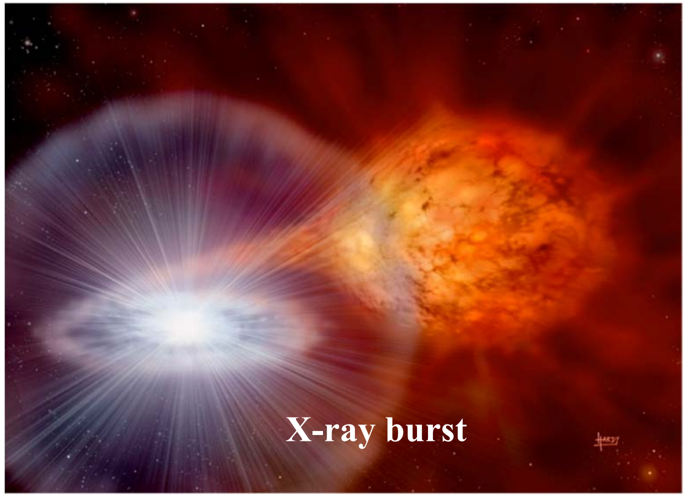
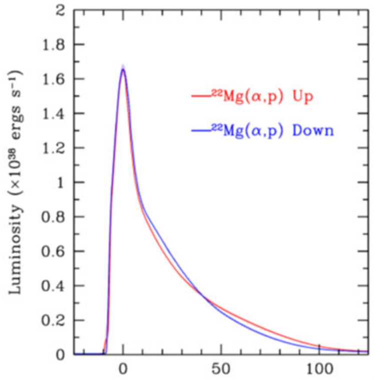
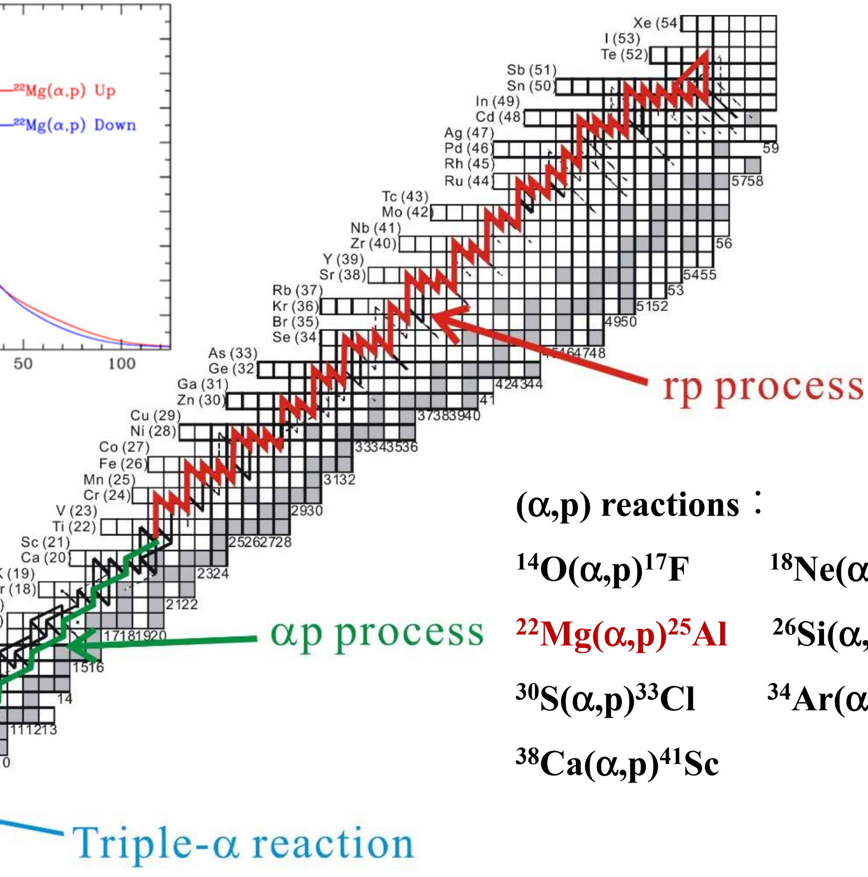
1.1 αp-process in Type I X-ray bursts







^{14}O(α,p)^{17}F(p,γ)**^{18}Ne(α,p)^{21}Na**(p,γ)**^{22}Mg(α,p)^{25}Al**(p,γ)**^{26}Si(α,p)^{29}P**(p,γ)**^{30}S(α,p)^{33}Cl**(p,γ)**^{34}Ar(α,p)^{37}K**(p, γ)**^{38}Ca(α,p)^{41}Sc**

(α,p) reactions：

^{14}O(α,p)^{17}F   **^{18}Ne(α,p)^{21}Na**

^{22}Mg(α,p)^{25}Al   **^{26}Si(α,p) ^{29}P**

^{30}S(α,p)^{33}Cl   **^{34}Ar(α,p)^{37}K**

^{38}Ca(α,p)^{41}Sc

1.2 Sensitivity study to the light curve of X-ray burst

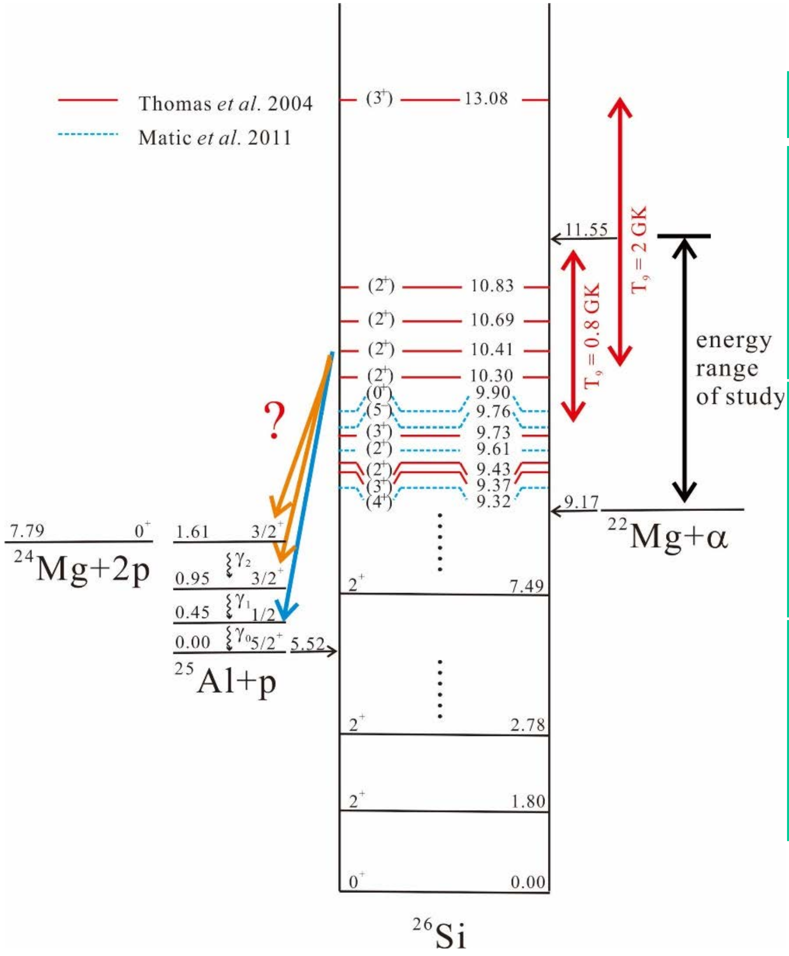
(α, p) reactions that impact the burst light curve in the multi-zone x-ray burst model.

Rank	αp-process reaction	Source of reaction rates adopted by multi-zone model
1.	$^{22}Mg(\alpha,p)^{25}Al$	Non-SMOKER
2.	$^{14}O(\alpha,p)^{17}F$	Hu *et al.* PRC 90 (2014) 025803
3.	$^{18}Ne(\alpha,p)^{21}Na$	He *et al.* PRC 88 (2013) 012801
4.	$^{26}Si(\alpha,p)^{29}P$	Non-SMOKER
5.	$^{30}S(\alpha,p)^{33}Cl$	D. Kahl *et al.* PRC 97 (2018)
6.	$^{34}Ar(\alpha,p)^{37}K$	Non-SMOKER
7.	$^{38}Ca(\alpha,p)^{41}Sc$	Non-SMOKER

Ref: Cyburt *et al.*, ApJ, 830 (2016) 55

$^{22}Mg(\alpha,p)^{25}Al$ could be the most sensitive reaction in the αp-process and may have a prominent impact on the burst light curve.

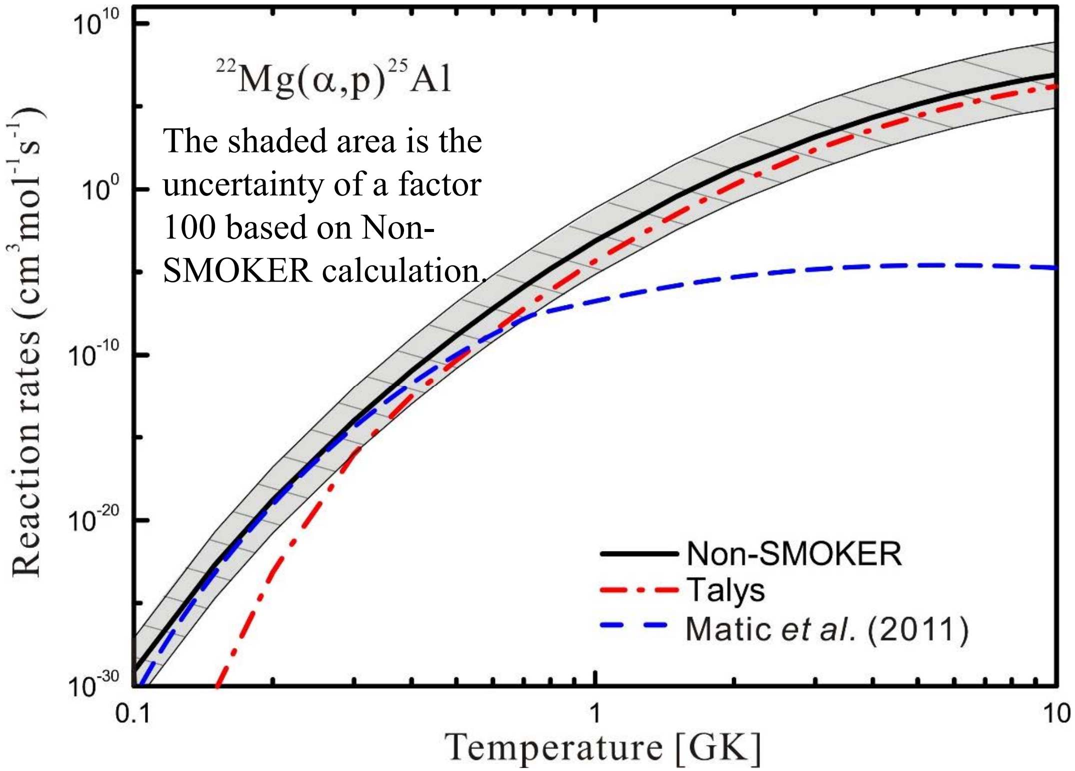
2.2 Status of level properties in ^{26}Si



Experimental technique	E_{res}	J^{π}	Γ_{p0}	$\Gamma_{p'}$	Γ_{α}
β-delayed proton measurement of ^{26}P Thomas et al. 2004	√ Ex>10 MeV	– Shell model calculation	–	–	–
^{28}Si(p,t)^{26}Si Matic et al. 2011	√ Ex<10 MeV	– Analog state assignment	–	–	–
^{25}Al+p scattering measurement above the α threshold of ^{26}Si (will be done)	√ Excitation function measurement	√ R-Matrix fitting	√ ^{25}Al (p, p)^{25}Al	√ ^{25}Al (p, p′)^{25}Al	–

All the previous measurements didn't touch the astrophysical interested energy region.

2.3 Status of $^{22}Mg(\alpha,p)^{25}Al$ astrophysical reaction rate



Large difference between the experiment and theoretical calculation.

The $^{22}Mg(\alpha,p)^{25}Al$ reaction rate as a function of the temperature for the Hauser-Feshbach predictions TALYS and non-SMOKER

MSU experiment

Randhawa et al., Phys. Rev. Lett (2020):

First direct measurement of $^{22}Mg(\alpha, p)$ with a 900 cps ^{22}Mg beam

Only for T>2.6 GK (cf. most relevant T range they claim: below 1 GK).

Reaction rate evaluated by extrapolation: close to the statistical-model calculation.

PHYSICAL REVIEW LETTERS **125,** 202701 (2020)

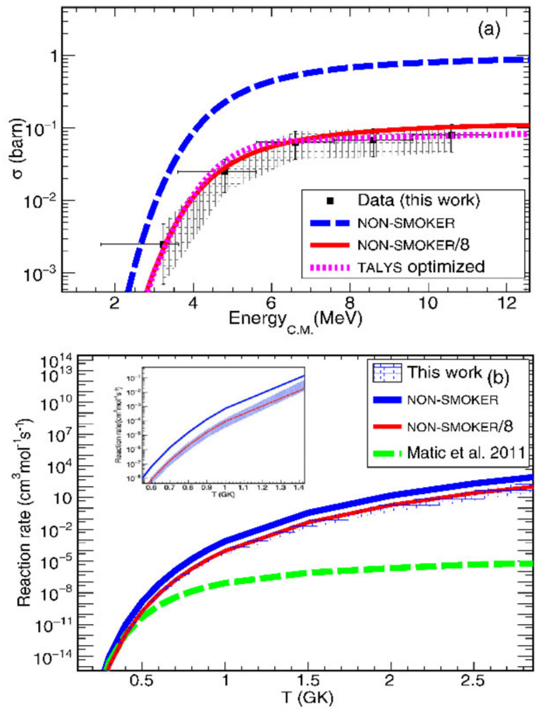
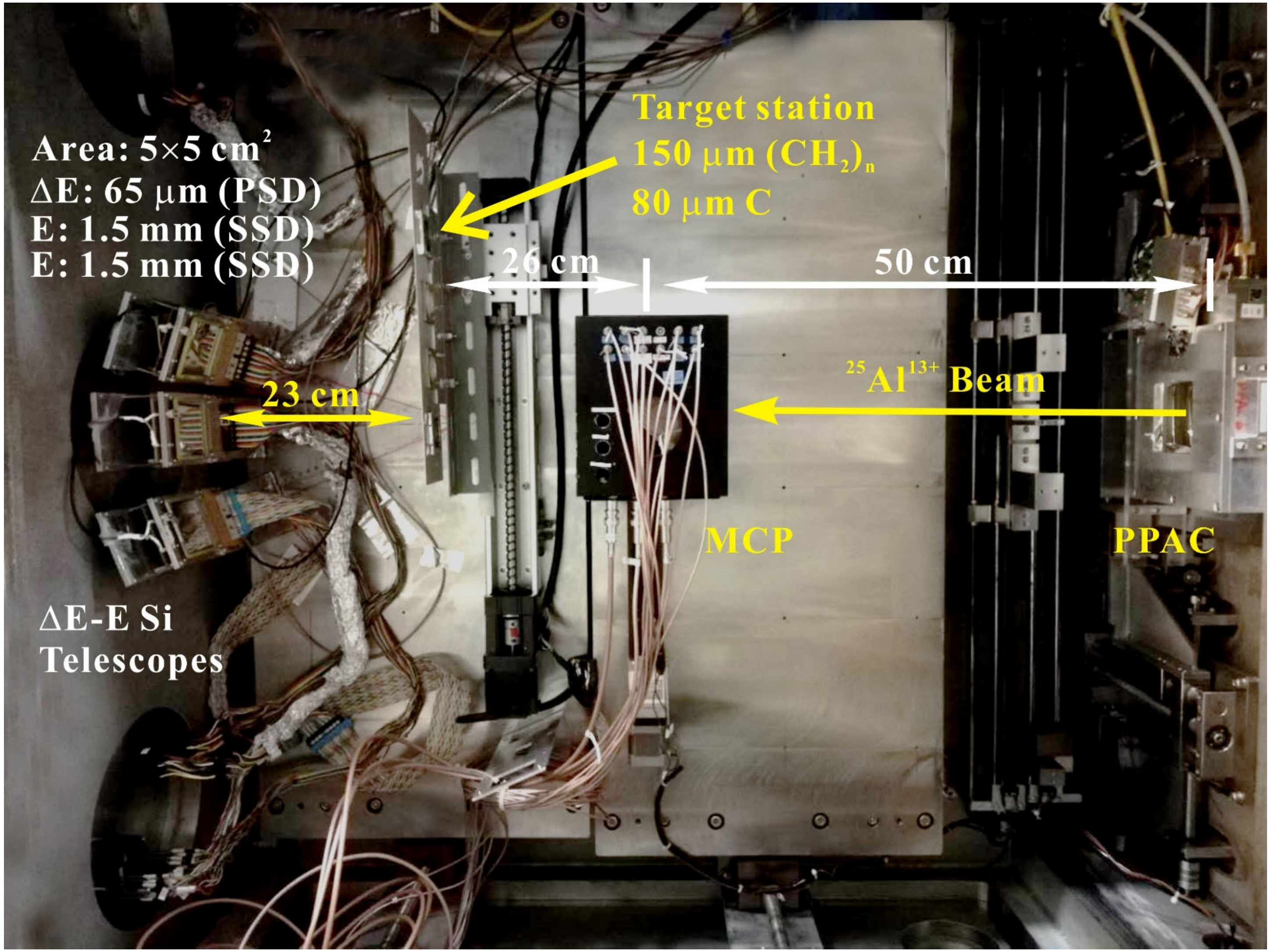


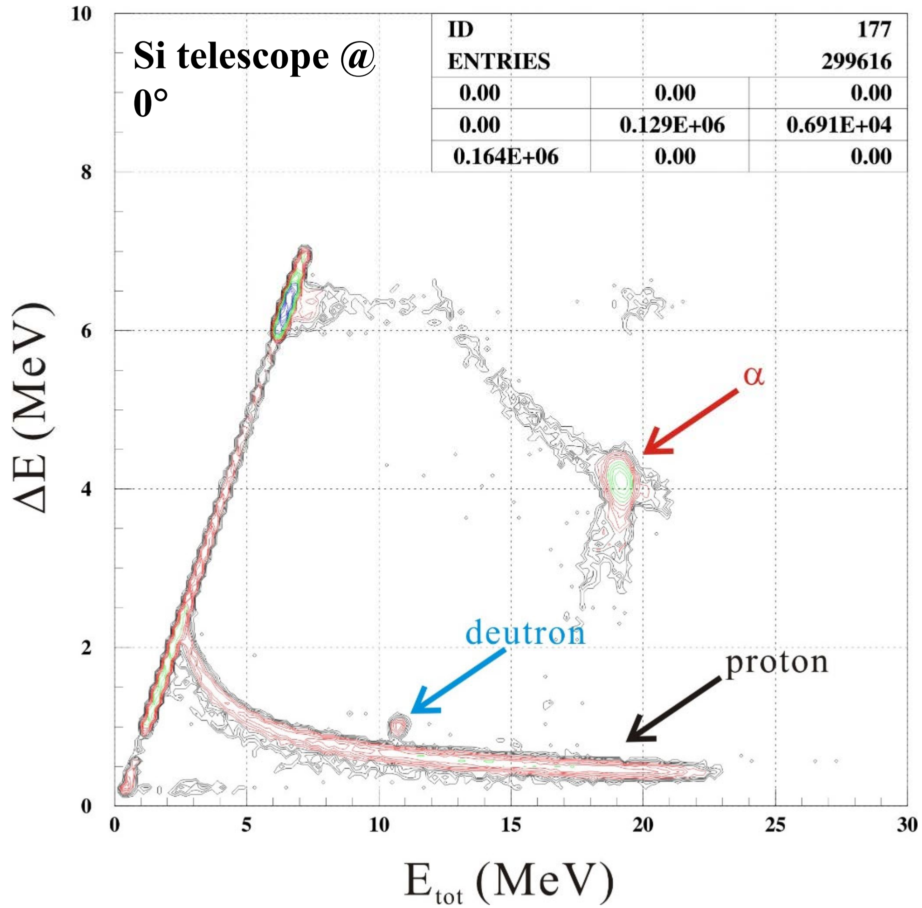
FIG. 3. Panel (a) shows the experimental cross sections obtained in the present work over a range of center-of-mass energies covered (black). For all the points, the cross section weighted energy is shown, which is the reason why horizontal error bars for the two lowest energy points are asymmetric. Panel (b) shows the reaction rate comparison of the current work to different model predictions and to the previous measurement by Matic *et al.* [11].

Experimental Setup at F3 focal plane

^{25}Al beam: 2 x 10^5 pps, 80% purity



Particle Identification for the Recoiling Particles

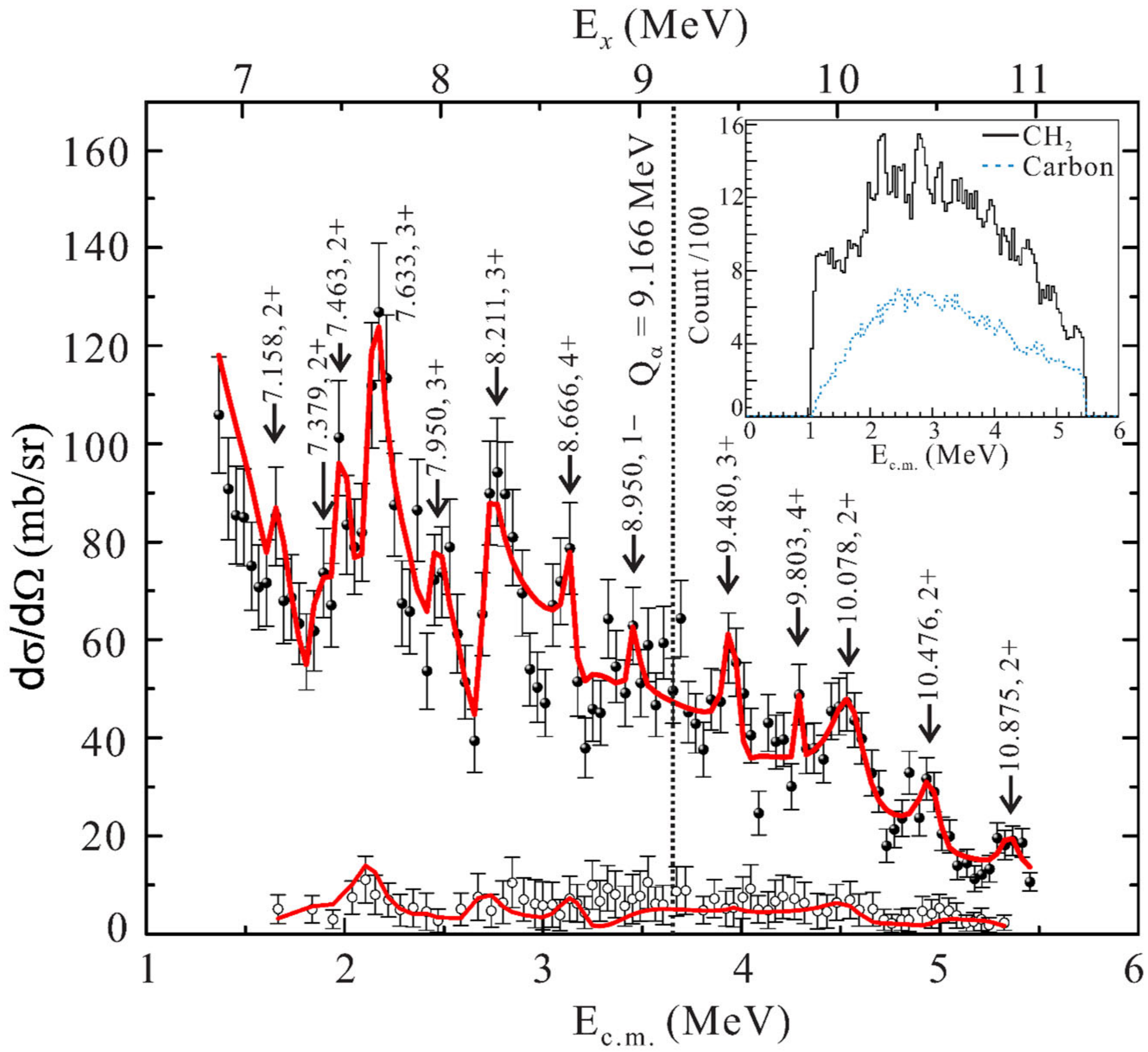


R-Matrix Fit Result

1. We observed 13 resonance states in ^{26}Si.

2. Elastic scattering and inelastic scattering spectra were fitted with common parameters.

2. The spin parities of 5 states above the α threshold were determined for the first time … reaction rate evaluated with parameters of those resonances



X-ray burst simulations

Light curves with new XRB model… Improved reproducibility

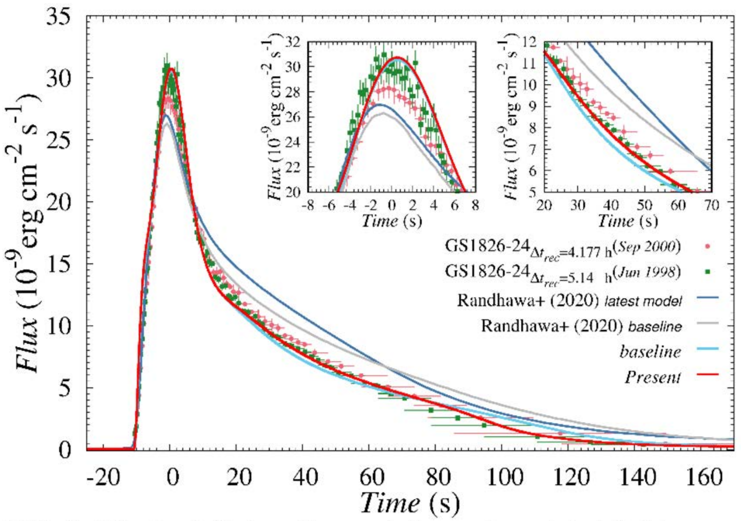


FIG. 3. The best fit *baseline* and *Present* modeled lightcurves to the observed lightcurve of epoch *Jun 1998*, and the best fit Randhawa *et al.* [22] lightcurves to epoch *Sep 2000*. The magnified lightcurves at the burst peak and t=20–70 s are shown in the left and right insets, respectively.

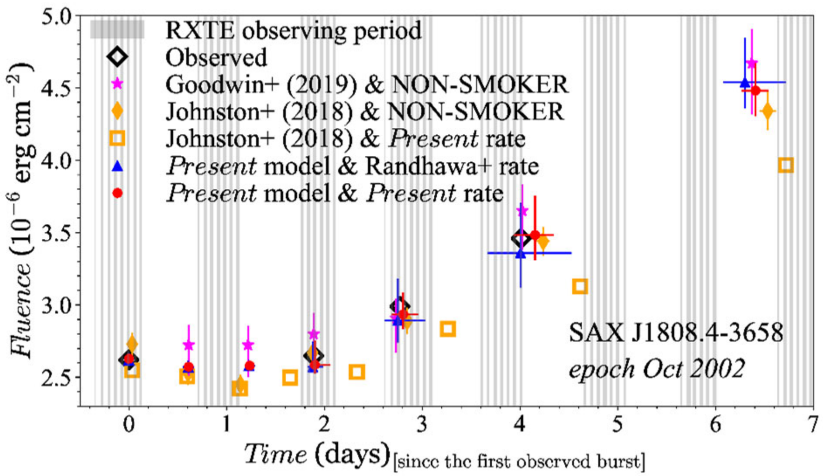
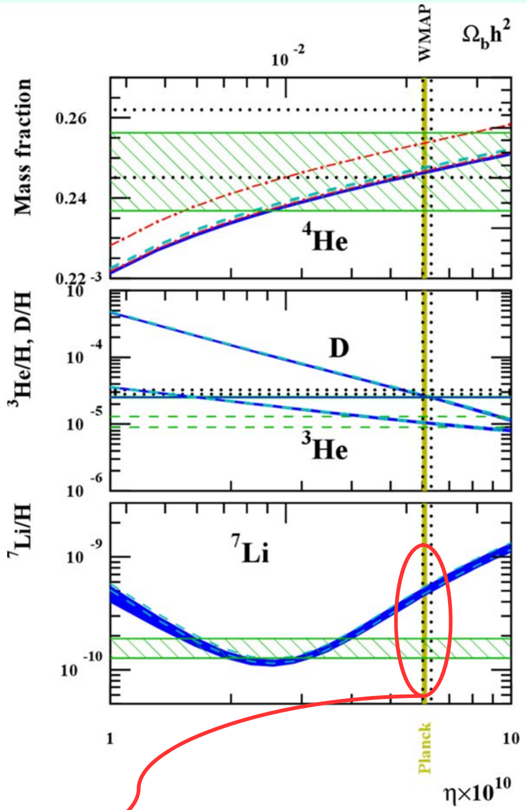
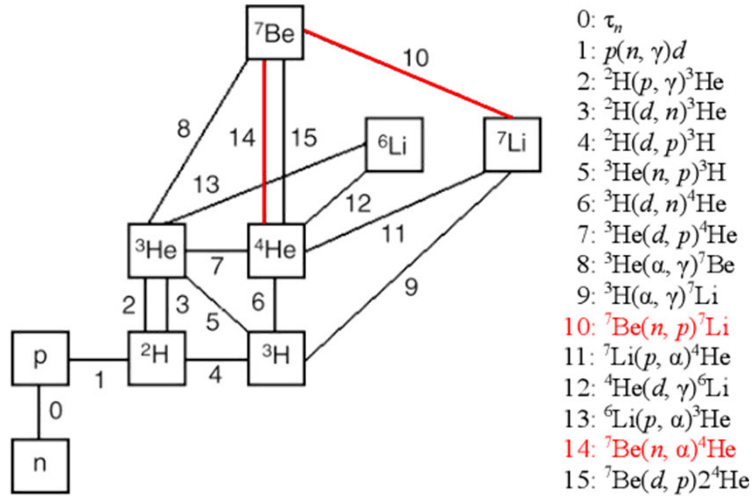


FIG. 4. The bursts' fluences (integration of flux over time) and times for SAX J1808.4-3658 burster, based on the RXTE observation [4], Johnston *et al.* [8] and Goodwin *et al.* [9] models, and present calculations. Johnston *et al.* [8] model is adopted to study the present and Randhawa *et al.* rates.

Cosmological ^{7}Li problem



A. Coc et al. J. Cos. Astropart. Phys. 2014

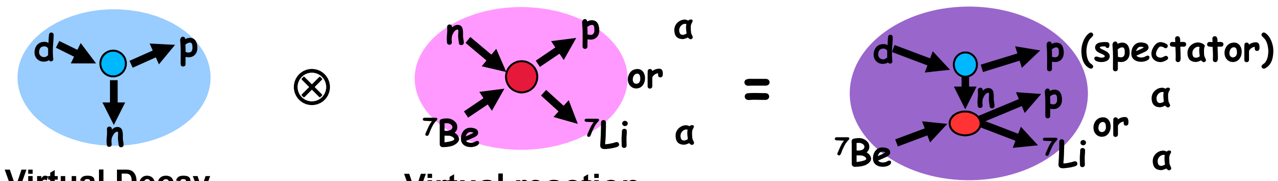


Iocco et al. Phys. Rep. 2009

- ^{7}Li problem... disagreement between theory and observation by a factor of 3−4
  - Due to CMB obs.? Low-metallicity stars obs.? Standard BBN model? Nuclear Physics?
  - ^{7}Be abundance in the end of BBN determines ^{7}Li predominantly
  - $p(n,\gamma)d$, ^{3}He$(d,p)^4$He, ^{7}Be$(n,p)^7$Li, ^{7}Be$(n,\alpha)^4$He, ^{7}Be$(d,p)2\alpha$, etc.
- Temperature ~ $10^{10} - 3\times10^8$ K, Energy: 1 MeV − 25 keV

Trojan Horse Method for RI + neutron

- Trojan Horse method: (Spitaleri+ Phys. Atom. Nucl. 2011)
- $^{7}Be(n,p)^{7}Li$, $^{7}Be(n,\alpha)^{4}He$ via $^{2}H(^{7}Be,^{7}Lip)^{1}H$, $^{2}H(^{7}Be,\alpha\alpha)^{1}H$
- PWIA applicable when Quasi-free mechanism is dominant



Virtual Decay | Virtual reaction | 3-body Reaction

$$\text{(Kinematic Factor)}\cdot|\Phi(P_s)|^2 \times \frac{d\sigma^{HOES}}{d\Omega} \propto \frac{d^3\sigma}{d\Omega_p\, d\Omega_{7Li}\, dE_{cm}}$$

Calculated by Monte Carlo simulation

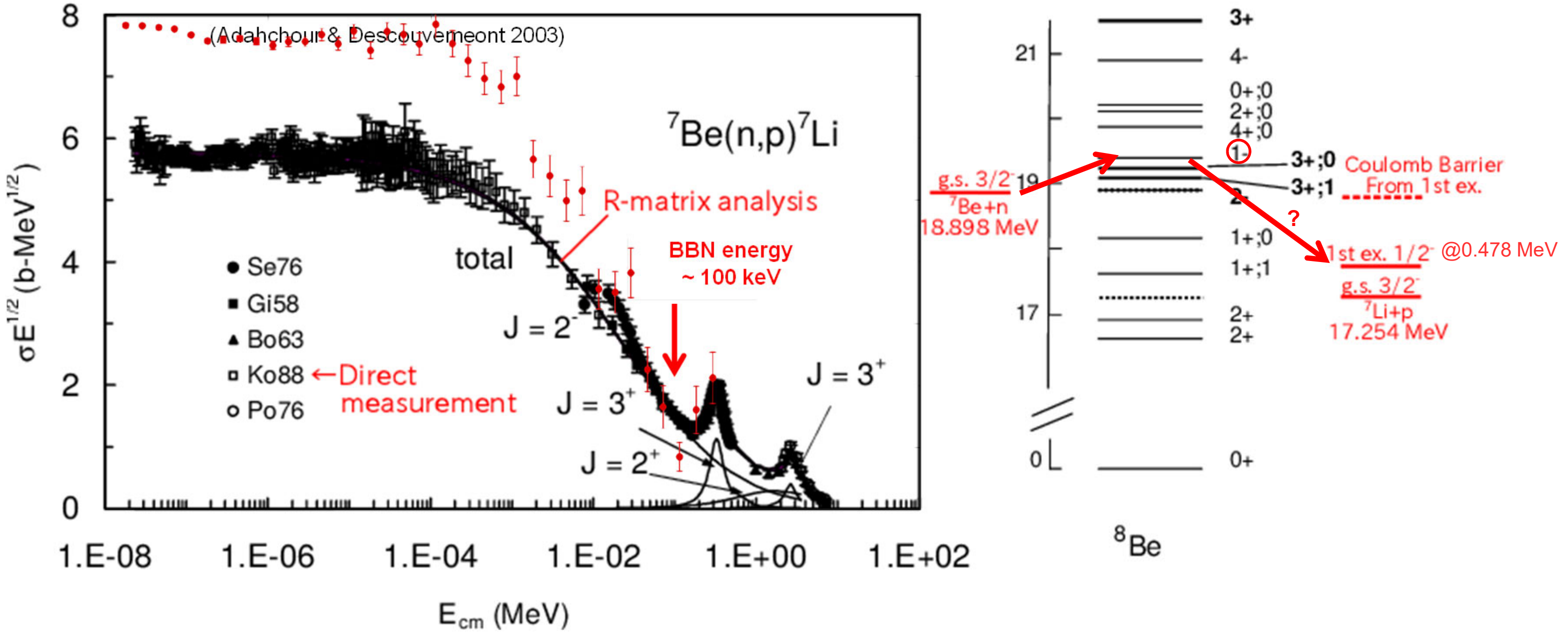
Half-off energy-shell 2-body cross section

Measured at $E_{d\text{-}7Be}$ > Coulomb barrier

↑

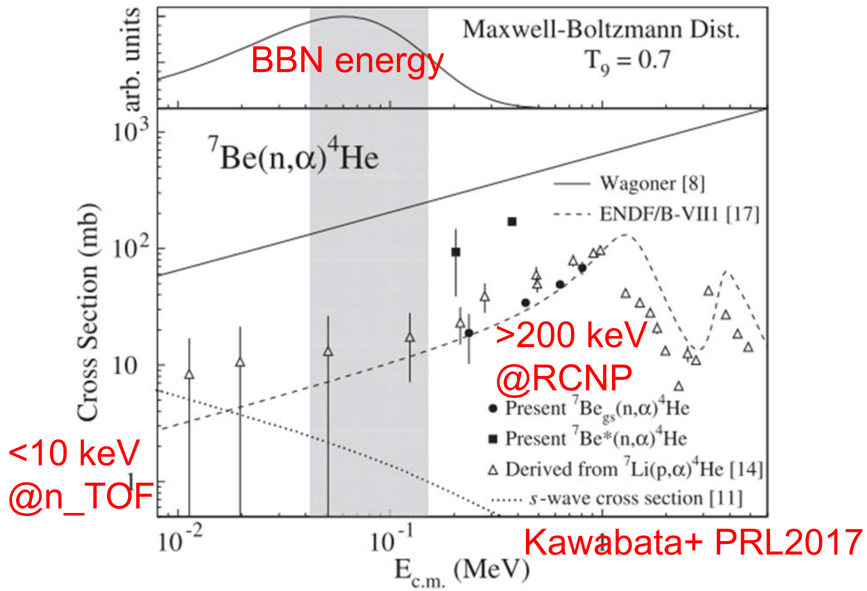
σ^{OES} = Normalization × σ^{HOES} × Penetrability

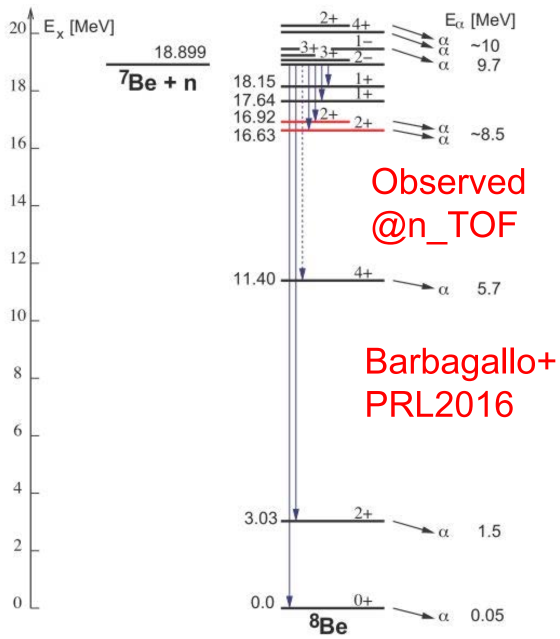
$^{7}Be(n, p)^{7}Li$ (Q = 1.644 MeV)



- Sensitivity: $\partial \log Y_{7Li} / \partial \log \langle \sigma v \rangle_{7Be} = -0.71$ (Coc & Vangioni 2010, Cyburt+ 2016, etc.)
  If 5 × higher rate ➡ ^{7}Li problem solved
- Direct measurement up to 13.5 keV, time-reversal reactions at higher energies.
- R-matrix analysis: Adahchour & Descouvemont 2003.
- New n_TOF measurement: enhancement below BBN energies (Damone+ PRL 2018)

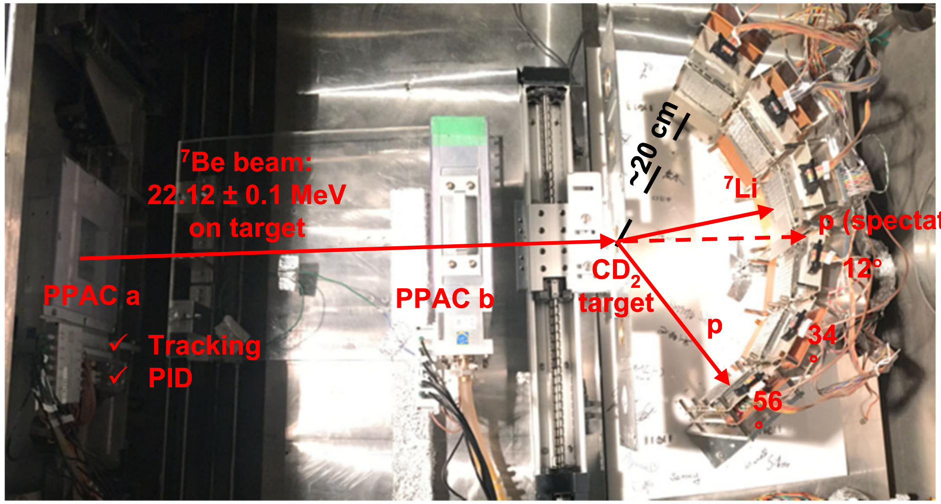
$^{7}Be(n,\alpha)^{4}He$ (Q = 18.990 MeV)





- Hou et al. PRC 2015: evaluation from $^{4}He(\alpha,p)^{7}Li$
- Barbagallo et al. PRL 2016: s-wave measurement @ nTOF
- Kawabata et al. PRL 2017: p-wave measurement @RCNP
- Lamia et al. APJ 2017: evaluation of $^{7}Li(p,\alpha)$ data measured by THM.
- Recent works consistent... Yet no direct data in the BBN range.

Experimental setup



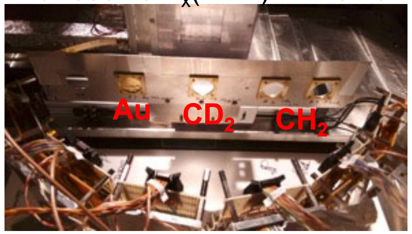
- 6 ΔE-E position sensitive silicon telescopes
- ^{7}Li-p and α-α coincidence measurements

… spectator not measured

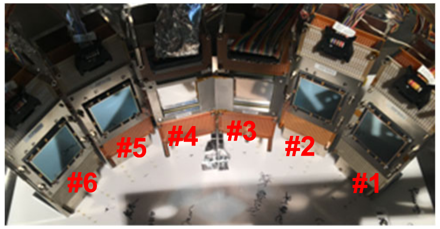
- CD_2: 64 μg/cm^2

➡ ΔE_{beam} ~ 150 keV

➡ To resolve $E_x(^{7}\mathrm{Li}^{1st})$ = 478 keV

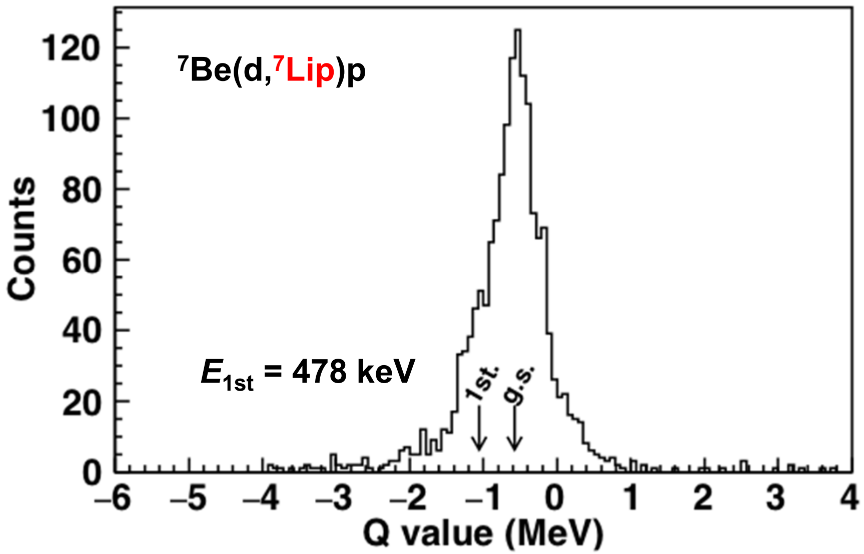


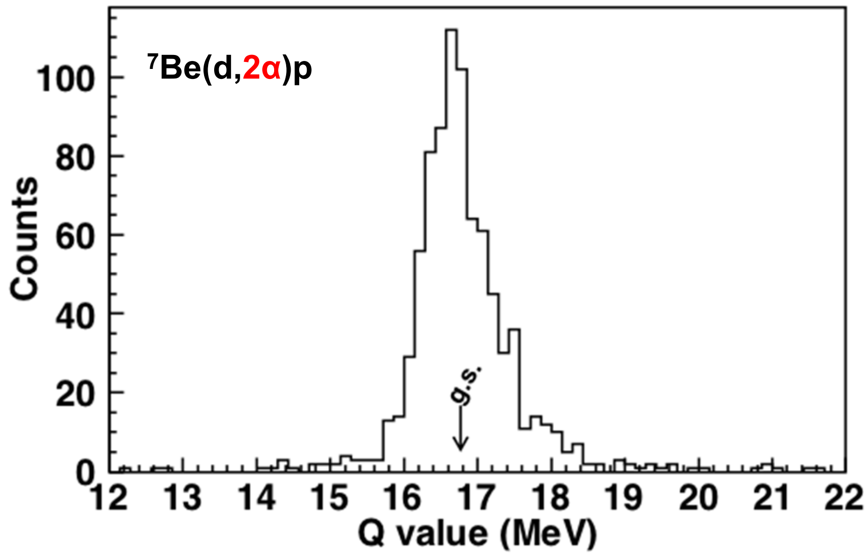
- Hamamatsu Charge-division PSD: position resolution ~ 0.5 mm



➡ Total angular resolution (PPACs & PSDs & alignment) ~ 0.5° ➡ ΔE_{cm} ~ 60 keV

Q-value spectra of the 3-body channels





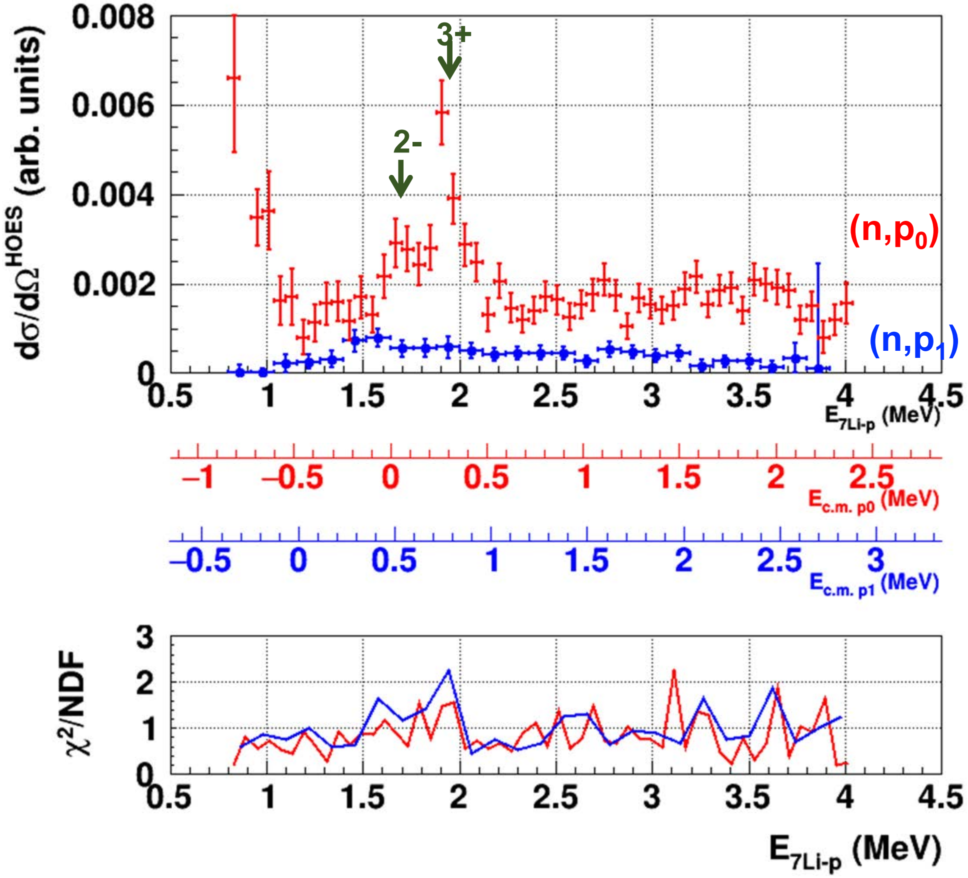
Reaction	*Q*-value (MeV)
p+2α	16.766
^{7}Li+2*p*	-0.589
^{7}Be+*n*+*p*	-2.225
^{5}He+*p*+^{3}He	-4.547

$Q_{3body} = E_1 + E_2 + E_3 - E_{beam}$

$\Delta Q_{3body} \sim \sqrt{(\Delta E_1^2 + \Delta E_2^2 + \Delta E_3^2 + \Delta E_{beam}^2)}$

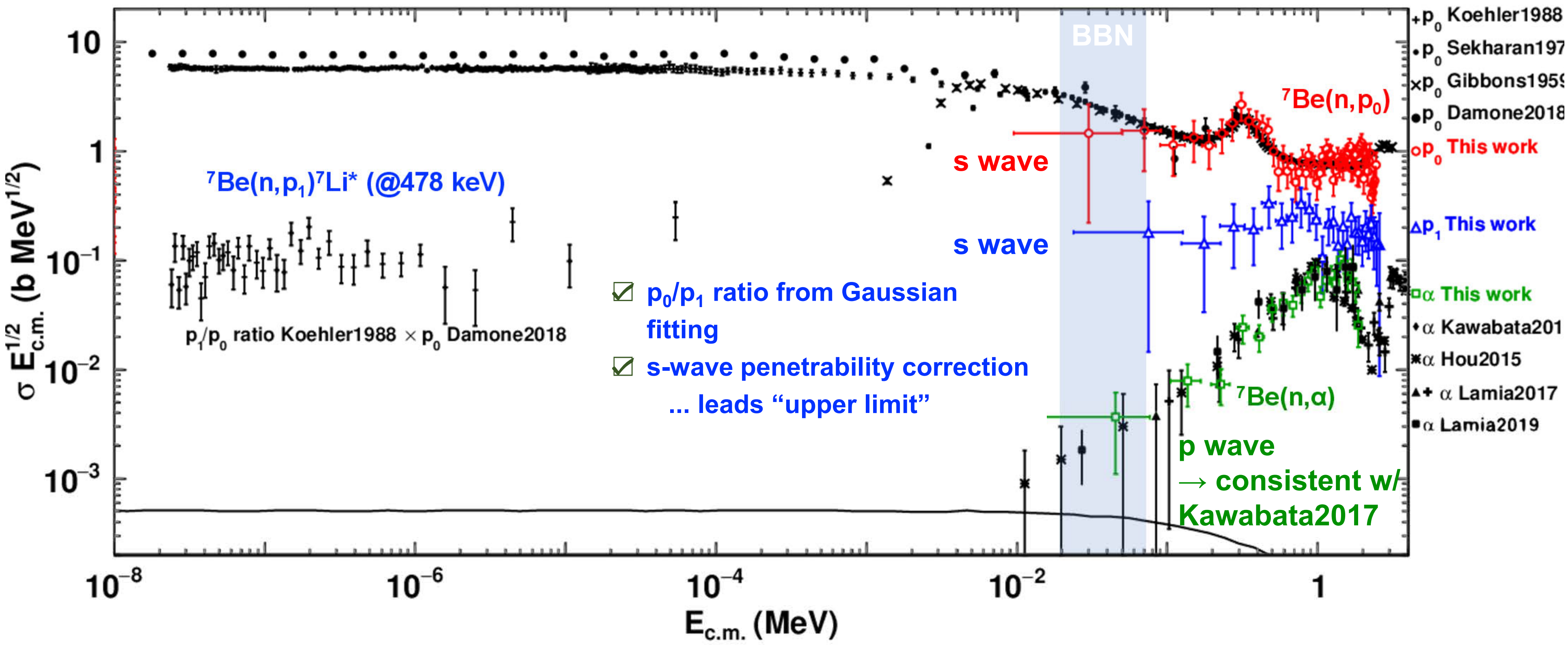
~ 200 keV expected with 64 μg/cm^2 CD_2

Gaussian fitting to Q-value spectra

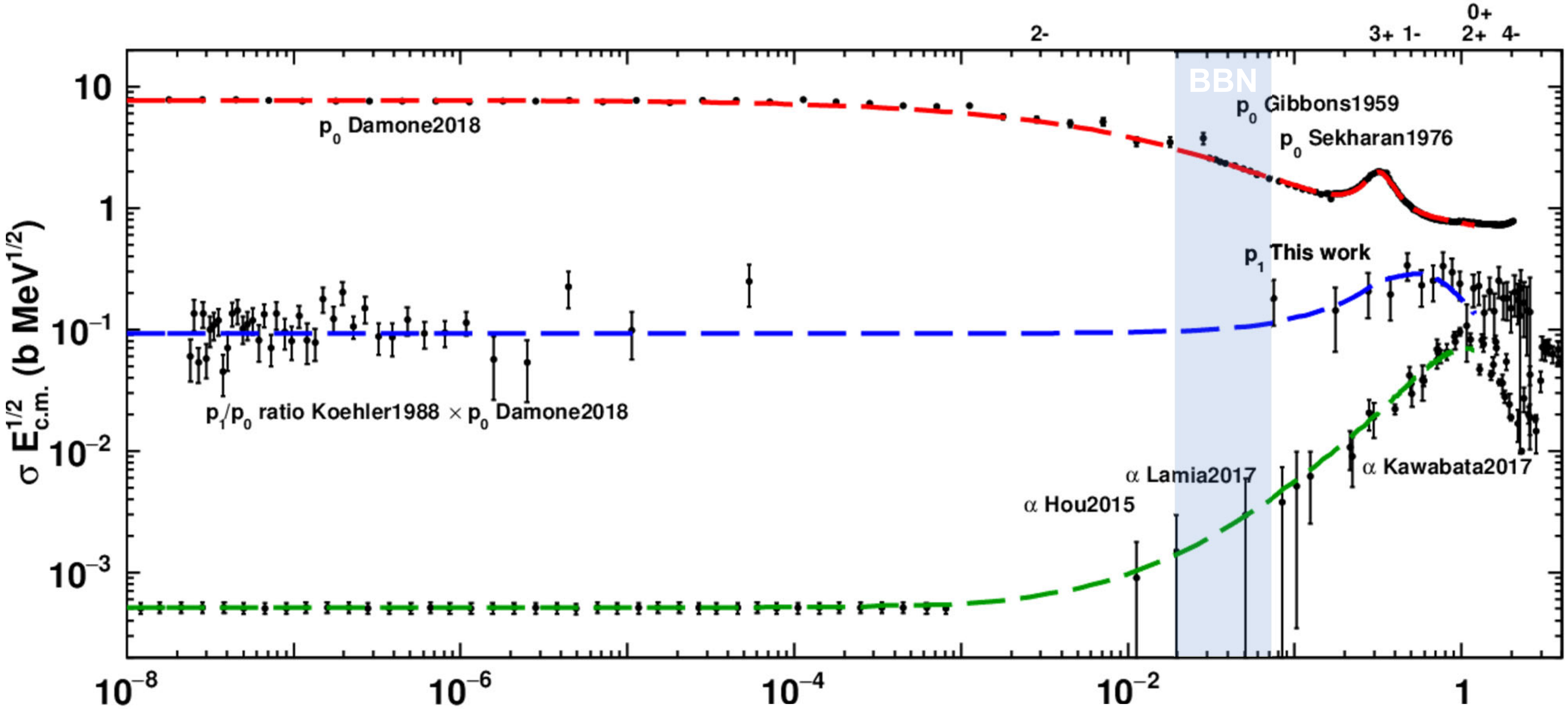


- Isotropy assumed (as no strong angular dependence seen)
- Checked systematic change of widths & peaks
  ➡ Reduces errors

^{7}Be(n,p$_0$), (n,p$_1$) & (n,α$_0$) cross sections by CRIB



(Preliminary) R-matrix fitting by AZURE2



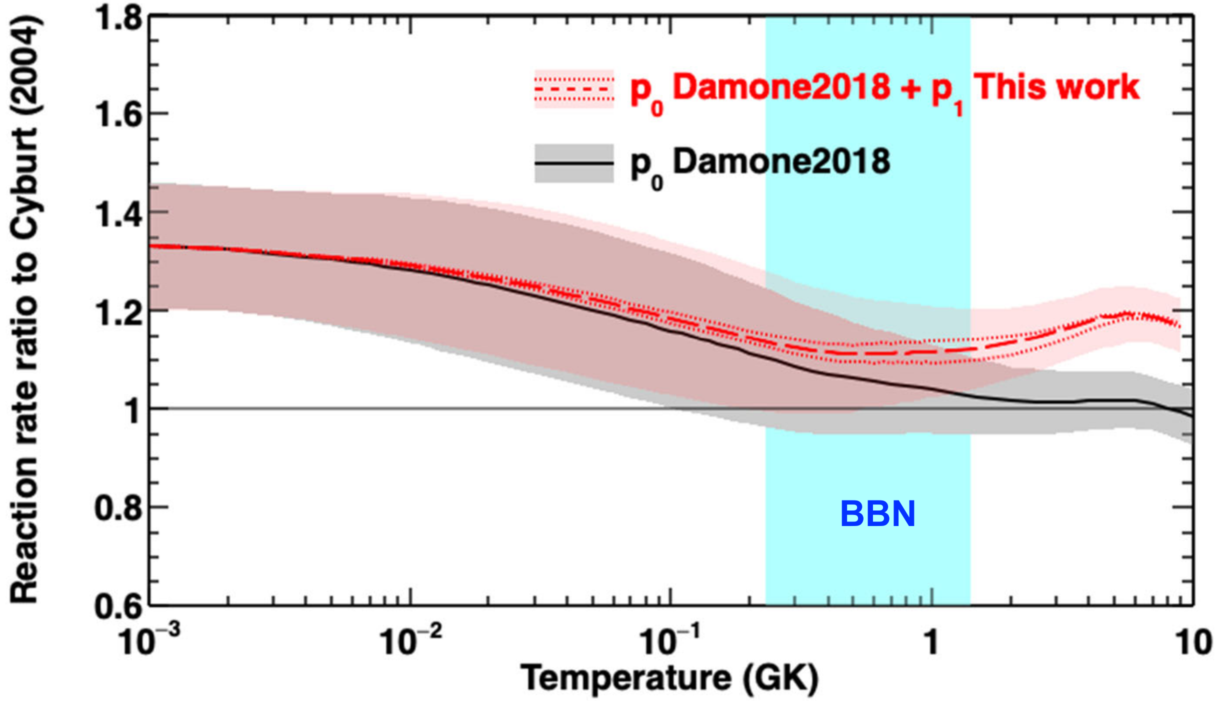
Condition (starting from simple assumptions):

- ☑ Fix known J^π and $E_{resonance}$ (except 1-)
- ☑ Adopt $l \leqq 3$
- ☑ Exclude no neutron emission states
- ☑ Fit Only $E_{c.m.}$ < 1.2 MeV

Procedure:

- ☑ Start from (n,p_0) channel with Ada.&Desc.2003 parameters.
- ☑ Fit only (n,p_1) and (n,α) channels.
- ☑ Fit (n,p_0) channels again.
- ☑ Fix converged parameters and iterate.
- ☑ χ^2 converged (preliminary): χ^2_{p0}/NDF = 1.59, χ^2_{p1}/NDF = 1.33, χ^2_{α}/NDF = 0.68

Revised ^{7}Be(n,p) Reaction rate



n_TOF result (Damone+ PRL2018):
~ 5% higher rate in BBN range
➡ 96% ^{7}Li abundance

This work:
~ 15±15% higher rate (preliminary)
➡ ~ 90% ^{7}Li abundance (preliminary)
(with the sensitivity
$\partial \log Y_{7Li} / \partial \log\langle \sigma v \rangle_{7Be} = -0.71$)

Recent ^{7}Be+d work @ FSU
(Rijal+ PRL122, 182701 (2019)):
Resonance of (d,α) channel just in BBN Gamow window
➡ ~ 87% ^{7}Li abundance?
-> (Errata) the effect seems to be much smaller.

Summary

- CRIB is a low-energy RI beam facility in RIBF operated by CNS, University of Tokyo, providing low-energy (< 10MeV/u) RI beams of good intensity and purity.

- Interests on indirect determination of astrophysical reactions, using RI beams:
  - Proton/alpha resonant scattering to study resonance properties
  - Indirect method measurements (THM and ANC)
  - ^{26}Al isomeric beam for the cosmic gamma-rays (not discussed today)

- Visit CRIB webpage for more information. http://www.cns.s.u-tokyo.ac.jp/crib/crib-new/