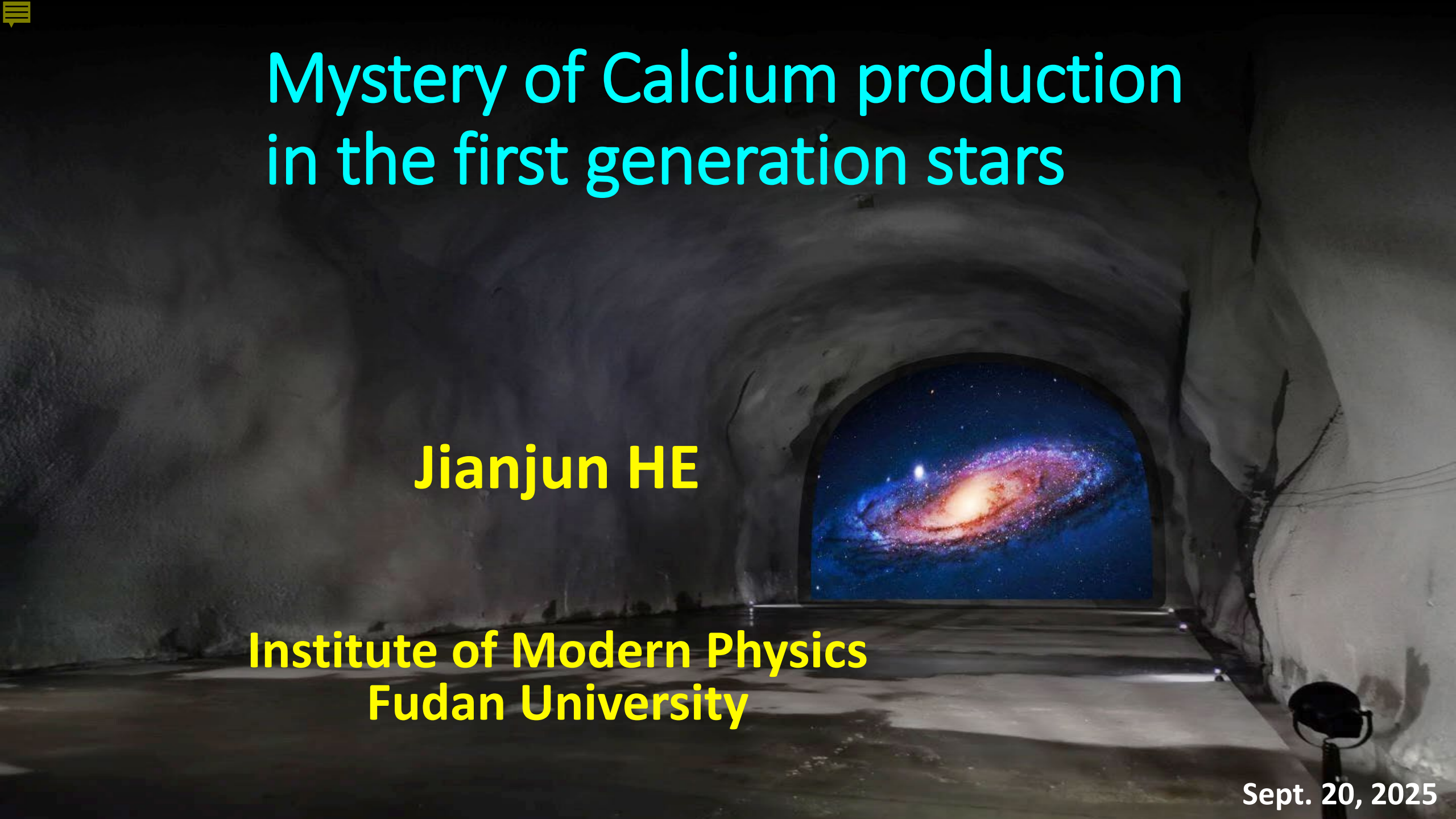


The background of the slide is a photograph of a dark, rocky tunnel. At the far end of the tunnel, there is a large, arched opening. Through this opening, a vibrant, colorful image of a spiral galaxy is visible, with a bright yellow and orange core and swirling arms of blue and purple. The tunnel walls are rough and textured, and the floor is dark and reflective.

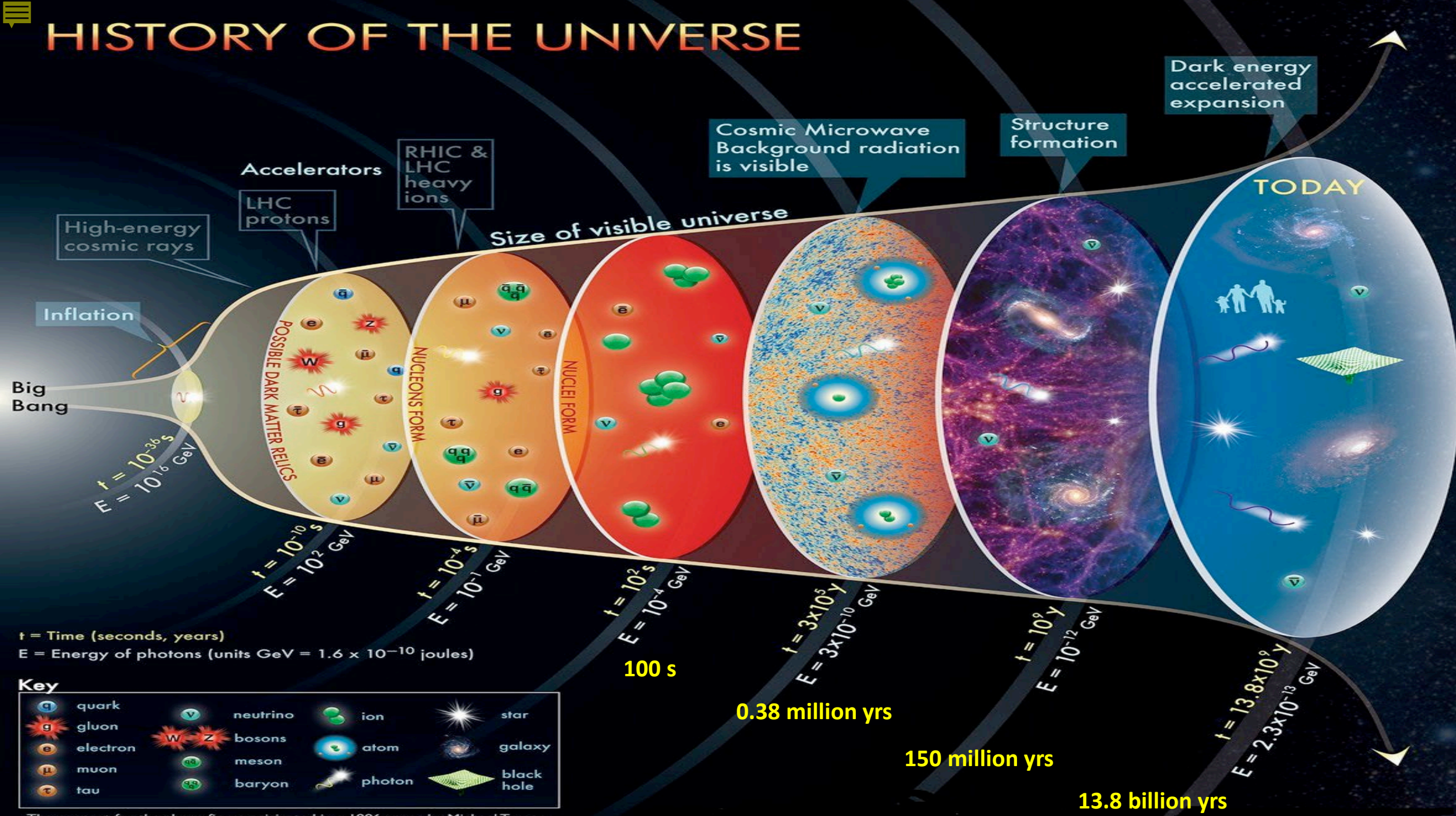
Mystery of Calcium production in the first generation stars

Jianjun HE

**Institute of Modern Physics
Fudan University**

Sept. 20, 2025

HISTORY OF THE UNIVERSE





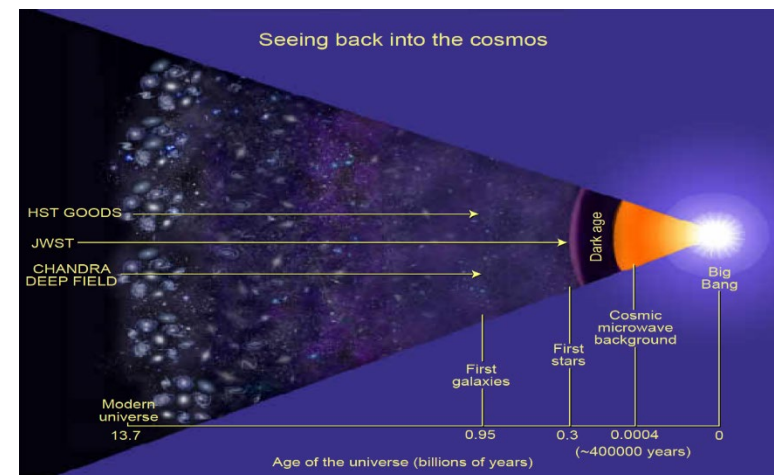
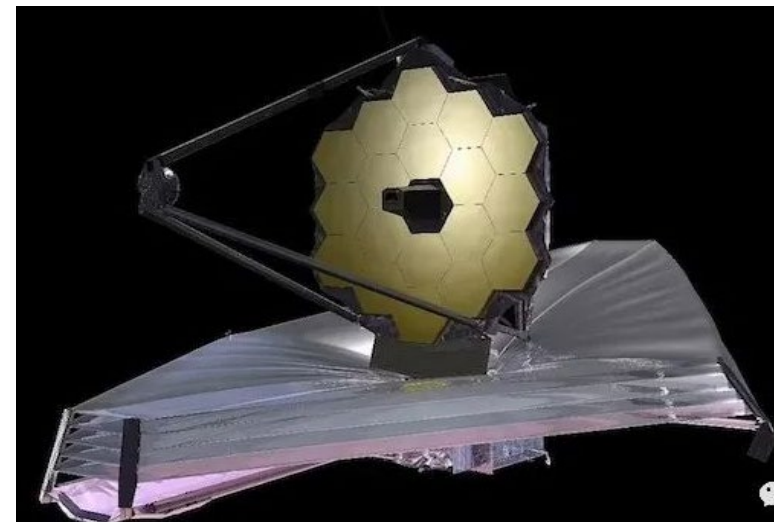
Today's main topic

The first generation stars (also called as the first stars, primordial stars, or Pop III stars)

James Webb Space Telescope (JWST)

● **JWST:** Directly observe the first stars, **seeing back into the cosmos**

According to the standard cosmology theory, during 380,000 to 150 million years after the Big Bang, there were no luminous objects during the so-called "Dark Age". After that, the first generation stars formed, and the first generation galaxies formed about 1 billion years later. One of the major scientific objectives of the Webb telescope is to study the "first rays of dawn" emitted by the first generation stars and galaxies in the universe.



The oldest star in the universe

- **Oldest star:** S.C. Keller et al., Nature 506(2014)463



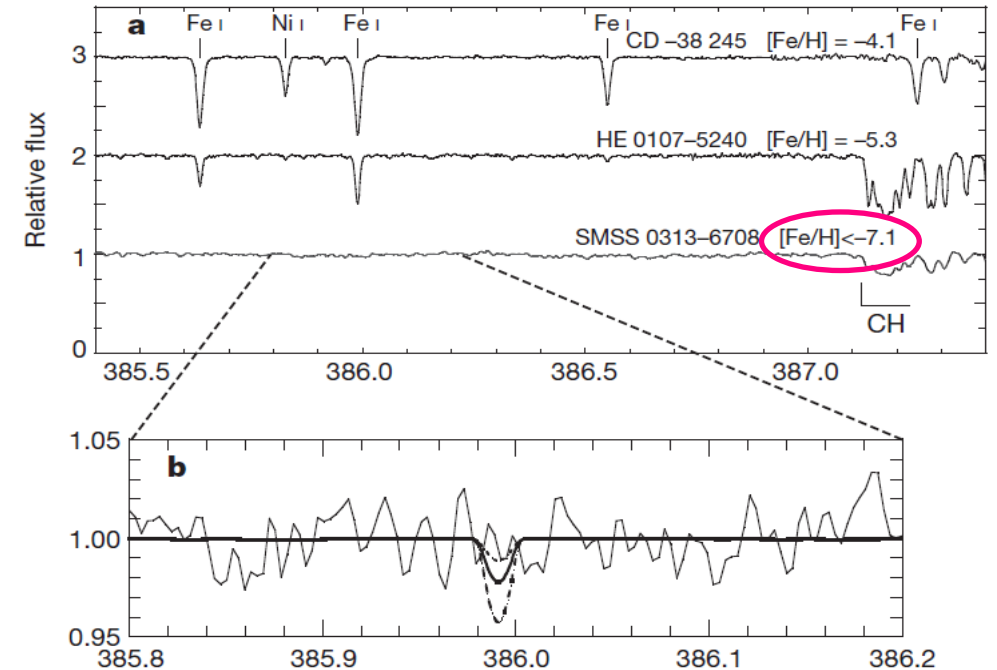
SMSS0318-6708

~6000 light year from Earth, formed shortly after the Big Bang.
It's the oldest star yet found.



Siding Spring Observatory

Extremely Metal Poor Stars (EMPs)



The oldest star in the universe

● Ca abundance

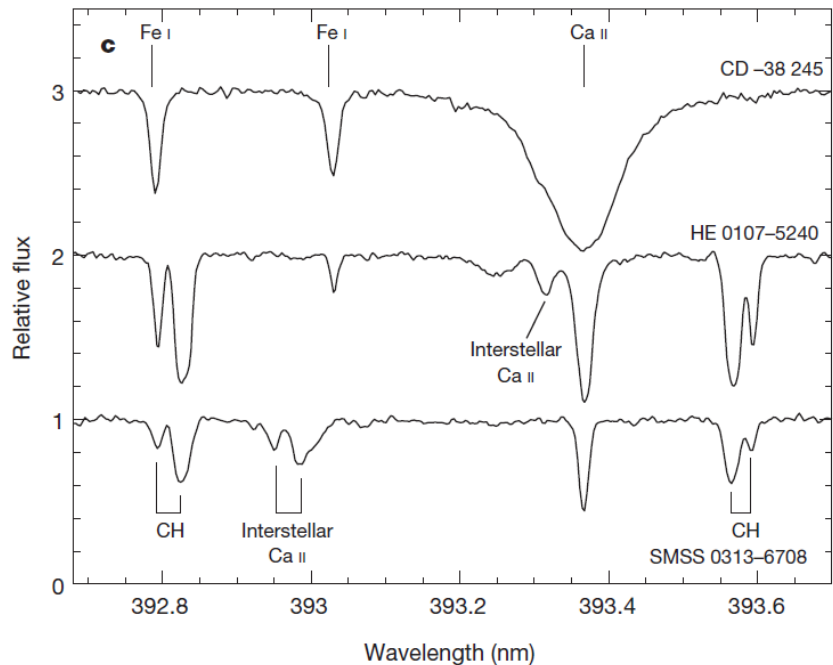


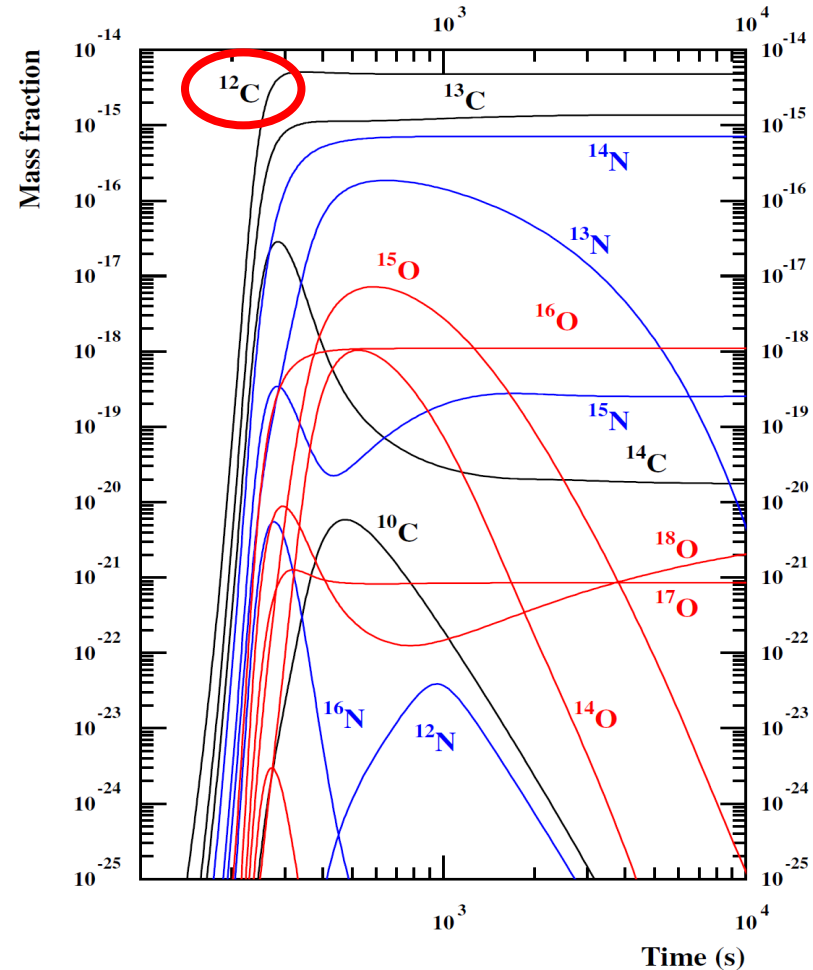
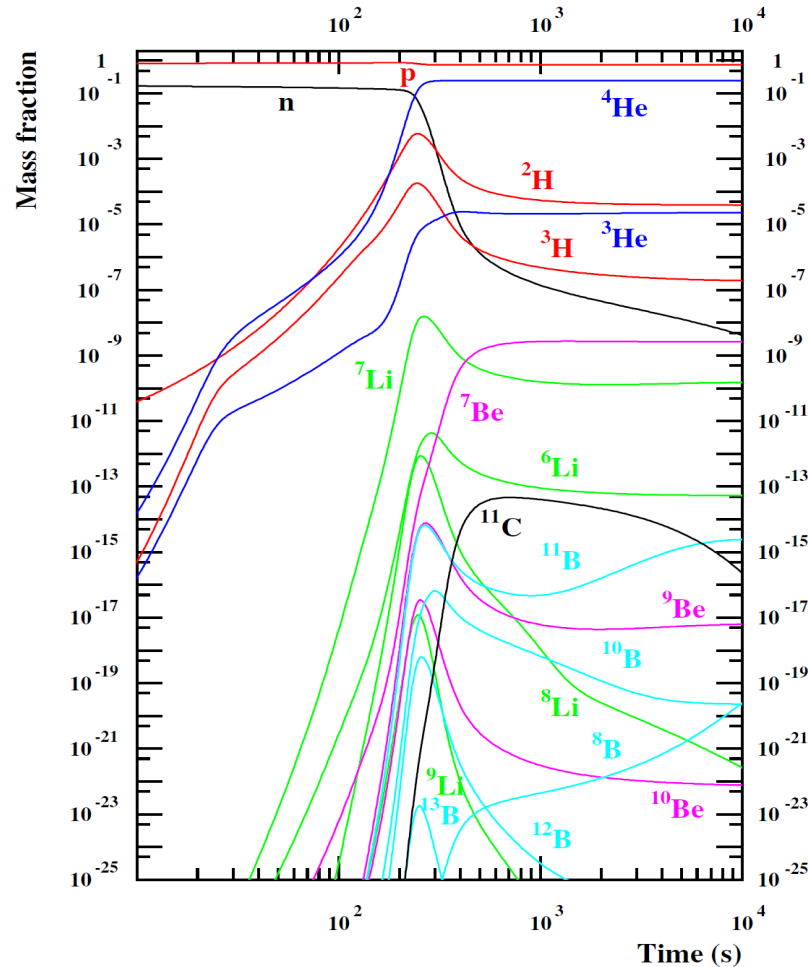
Table 1 | Chemical abundances of SMSS 0313–6708

Element X	[X/H] _{1D, LTE}	[X/H] _{<3D>}
Li I	0.7*	0.7*
C (CH)	-2.4	-2.6 [†]
N (NH)	<-3.5	<-3.9 [†]
O I	<-2.3	<-2.4 [†]
Na I	<-5.5	<-5.5 [‡]
Mg I	-4.3	-3.8 [‡]
Al I	<-6.2	
Si I	<-4.3	
Ca II	-7.2	-7.0 [‡]
Sc II	<-5.0	
Ti II	<-6.3	
V II	<-3.3	
Cr I	<-6.3	
Mn I	<-5.8	
Fe I	<-7.3	<-7.1 [‡]
Co I	<-4.9	
Ni I	<-6.4	
Cu I	<-3.5	
Zn I	<-3.4	
Sr II	<-6.7	
Ba II	<-6.1	
Eu II	<-2.9	

- Supernova burst of a 60 M_☉ first star
- After explosion, the outer light elements being ejected and the inner heavy elements being fallen back onto the central black hole, and hence no iron was observed!
- Ca was thought to be produced by hot CNO breakout reactions

The oldest star in the universe

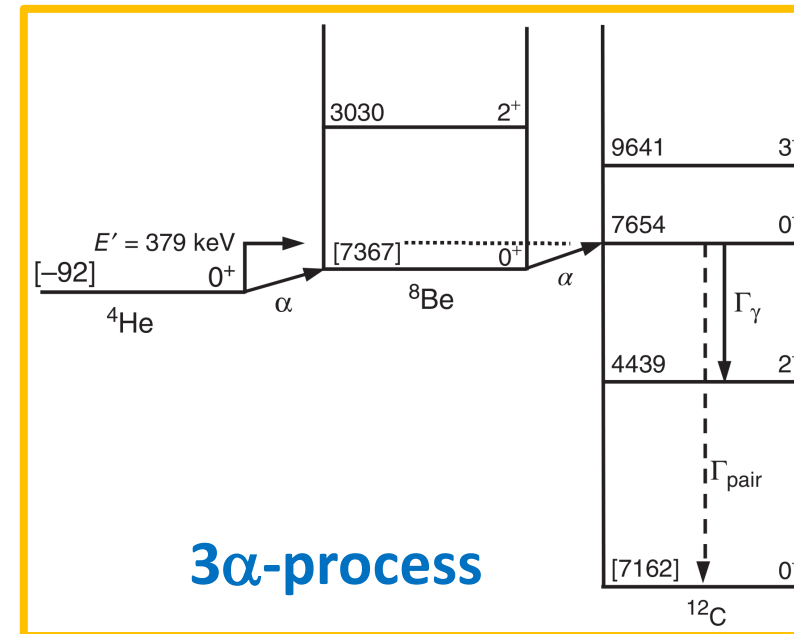
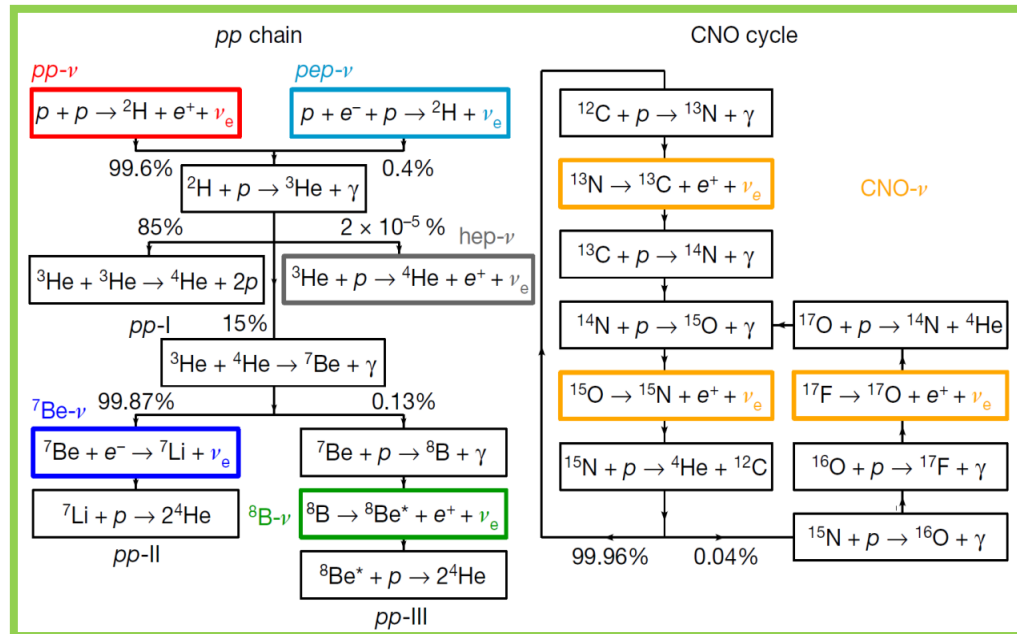
● Abundances of light nuclides @BBN ashes



The oldest star in the universe

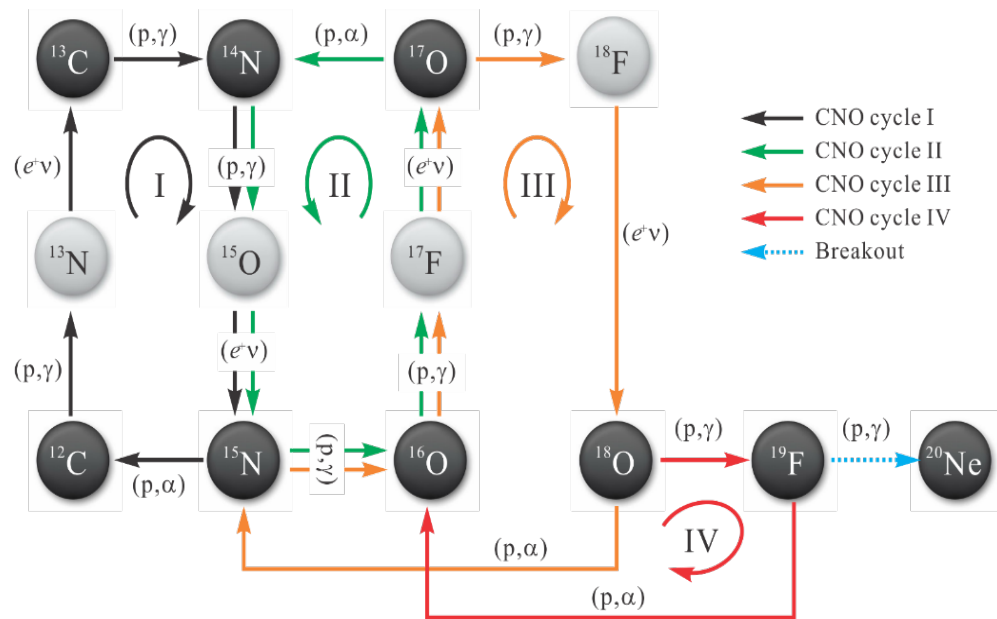
● Nucleosynthesis process @First stars :

First stars begin their lives with primordial composition and begin hydrogen burning via pp chains and contract until central temperature is high enough (~ 0.1 GK) to ignite the 3α -process. This bridges the mass 5 and mass 8 gaps, such that a small amount of CNO catalyst is formed, $X(^{12}\text{C}) \sim 10^{-9}$, which can kickstart the CNO cycle.

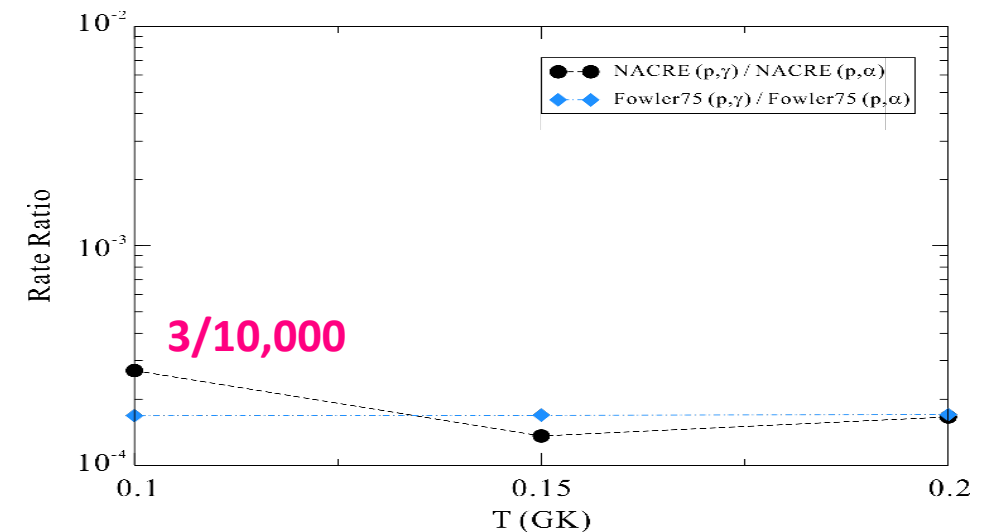


The oldest known star in the universe

● Breakout from CNO cycle



Competition between Breakout $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$ & Recycling $^{19}\text{F}(p,\alpha)^{16}\text{O}$



Some astrophysicists thought that the Ca abundance observed in the first star can not be reproduced by the stellar models. But, if reaction rate ratio of $(p,\gamma)/(p,\alpha)$ could be enhanced by 7 times or more, then Ca problem can be solved! Thus, these two reactions need to be measured directly.

I. Status of $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$ reaction

● @Notre Dame Univ.

PHYSICAL REVIEW C 77, 015802 (2008)

Measurement of the $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$ reaction and interference terms from $E_{\text{c.m.}} = 200\text{--}760\text{ keV}$

A. Couture,^{*} M. Beard, M. Couder, J. Görres, L. Lamm, P. J. LeBlanc, H. Y. Lee,[†] S. O'Brien, A. Palumbo,
E. Stech, E. Strandberg, W. Tan, E. Uberseder, C. Ugalde,[‡] and M. Wiescher
Nuclear Science Laboratory, University of Notre Dame, Notre Dame, Indiana 46556, USA

R. Azuma[§]
Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7
(Received 6 September 2007; published 10 January 2008)

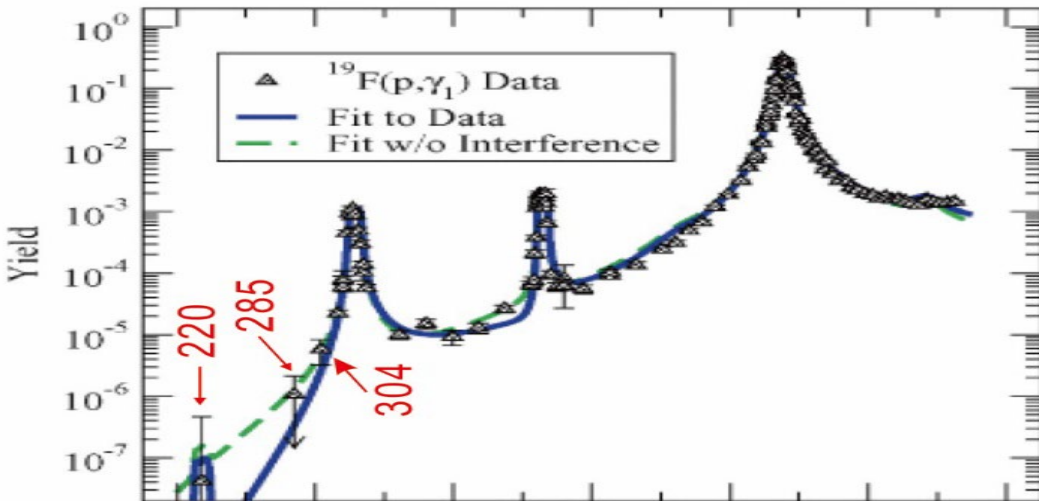
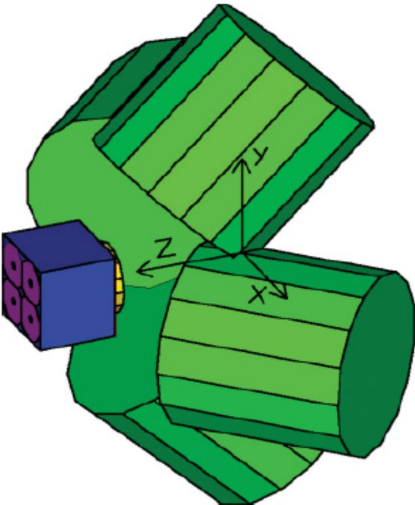


TABLE I. Measured resonance parameters.

Γ_p (eV)	Γ_{γ_1} (eV)	Γ_{α_2} (eV)	Γ (keV)
$E_{R,\text{c.m.}} = 213 \text{ keV } J^\pi = 2^-$			
Present	0.890^{+1346}_{-265} ^a	$0.011^{+0.003}_{-0.002}$	<0.06
$(p, \alpha_{2,3,4})^b$	0.94 ± 0.02	—	1000
$E_{R,\text{c.m.}} = 323 \text{ keV } J^\pi = 1^+$			
	Γ (keV)	Γ_p (eV)	Γ_{γ_1} (eV)
Present	2.08 ± 0.34	$35.8^{+5.6}_{-5.4}$	$0.107^{+0.024}_{-0.019}$
$(p, p_0)^c$	2.8	45	—
$(p, p')^d$	2.8	—	—
$(p, \gamma_1)^e$	—	—	0.28 ± 0.06
$(p, \alpha_{2,3,4})$	2.22 ± 0.04	—	2800



I. Status of $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$ reaction

● Recent evaluation

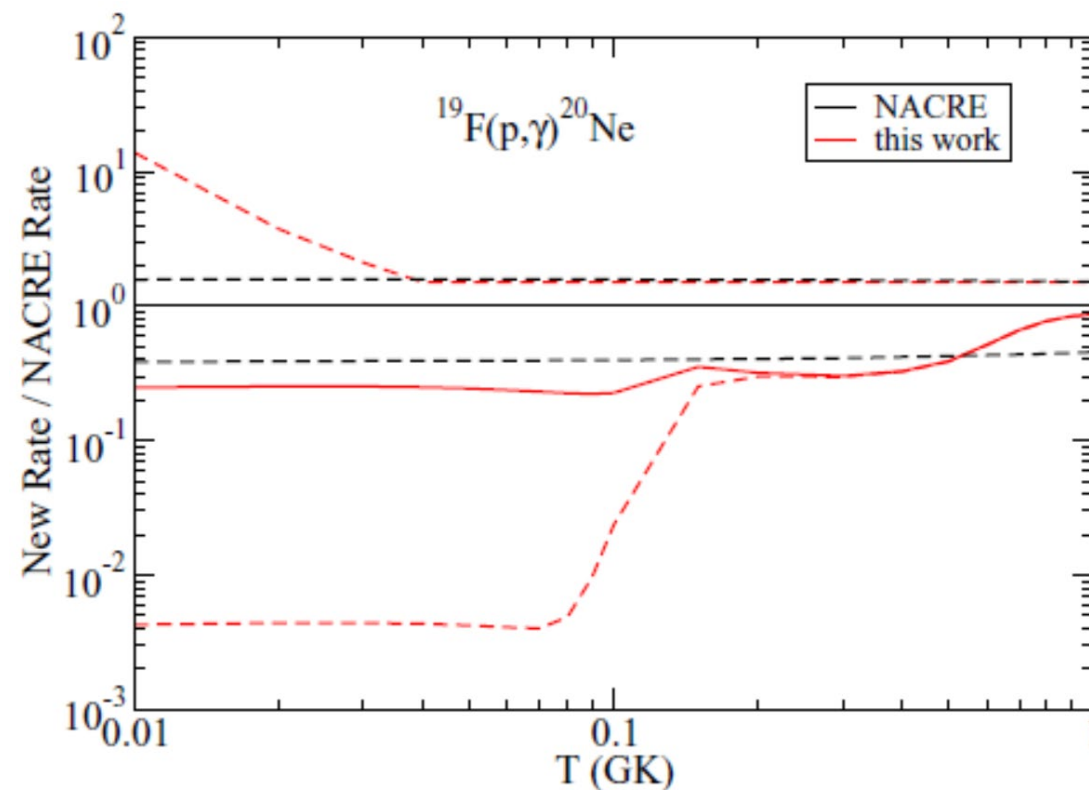
PHYSICAL REVIEW C **103**, 055815 (2021)

Editors' Suggestion

Featured in Physics

$^{19}\text{F}(p,\gamma)^{20}\text{Ne}$ and $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction rates and their effect on calcium production in Population III stars from hot CNO breakout

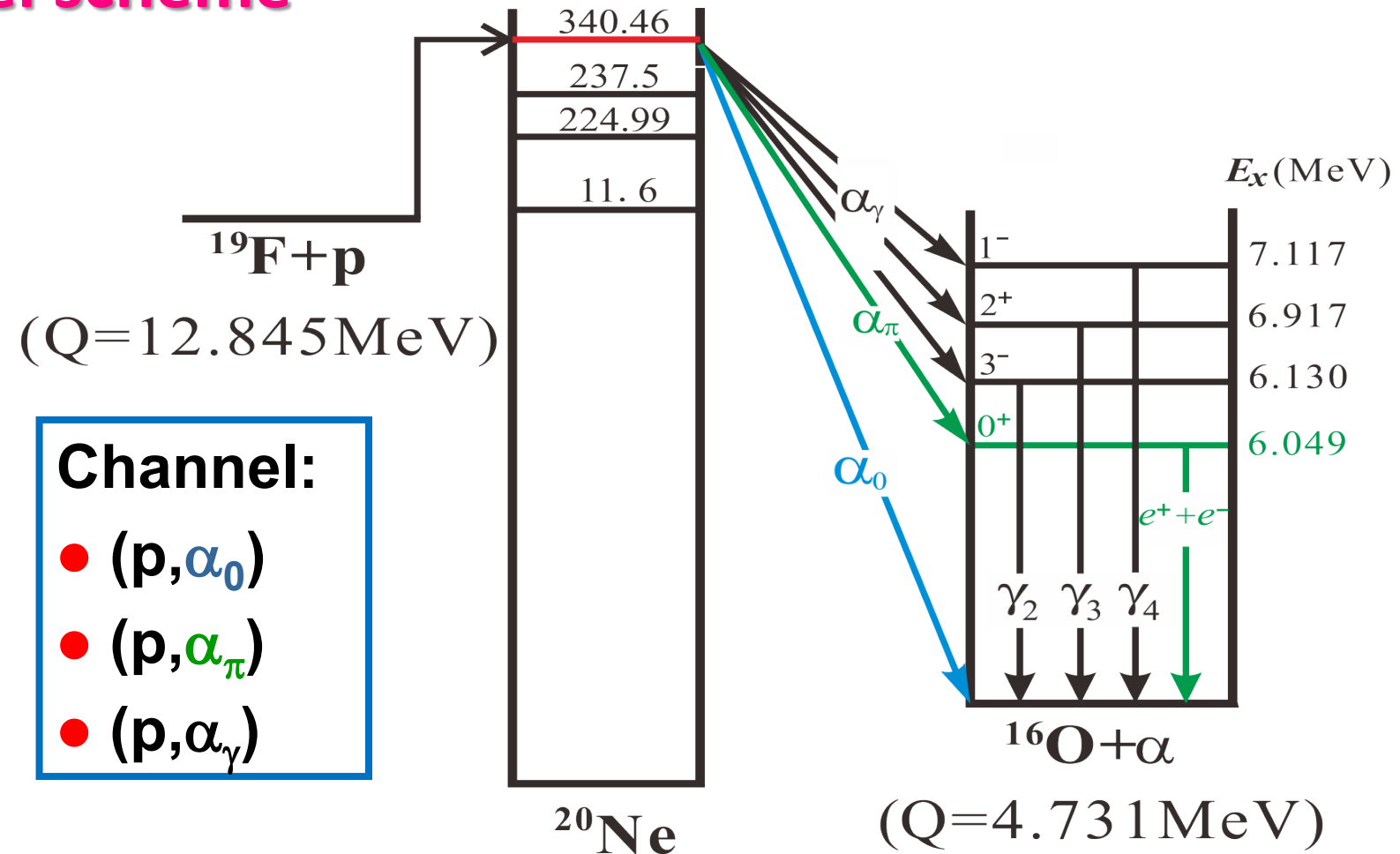
R. J. deBoer^{1,*}, O. Clarkson^{2,3,4}, A. J. Couture⁵, J. Görres¹, F. Herwig^{2,3,4}, I. Lombardo⁶,
P. Scholz¹ and M. Wiescher¹



The newly evaluated $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$ rate is ~ 4 times smaller than that of NACRE value, which makes the Ca problem even worse!

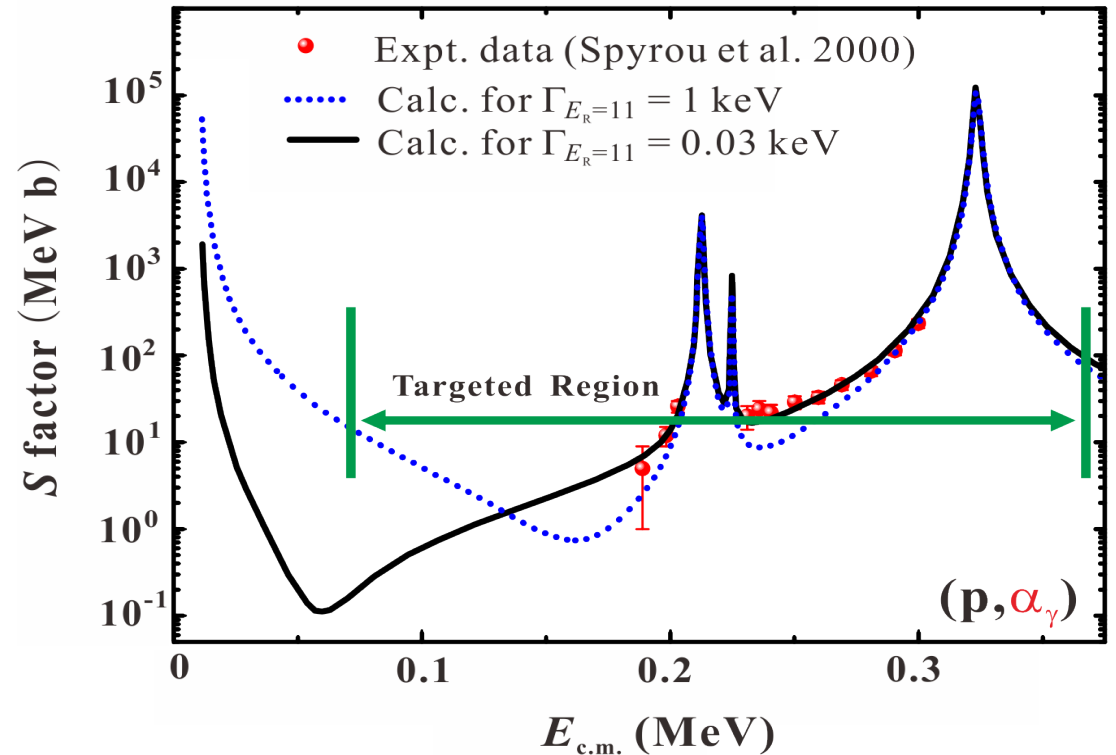
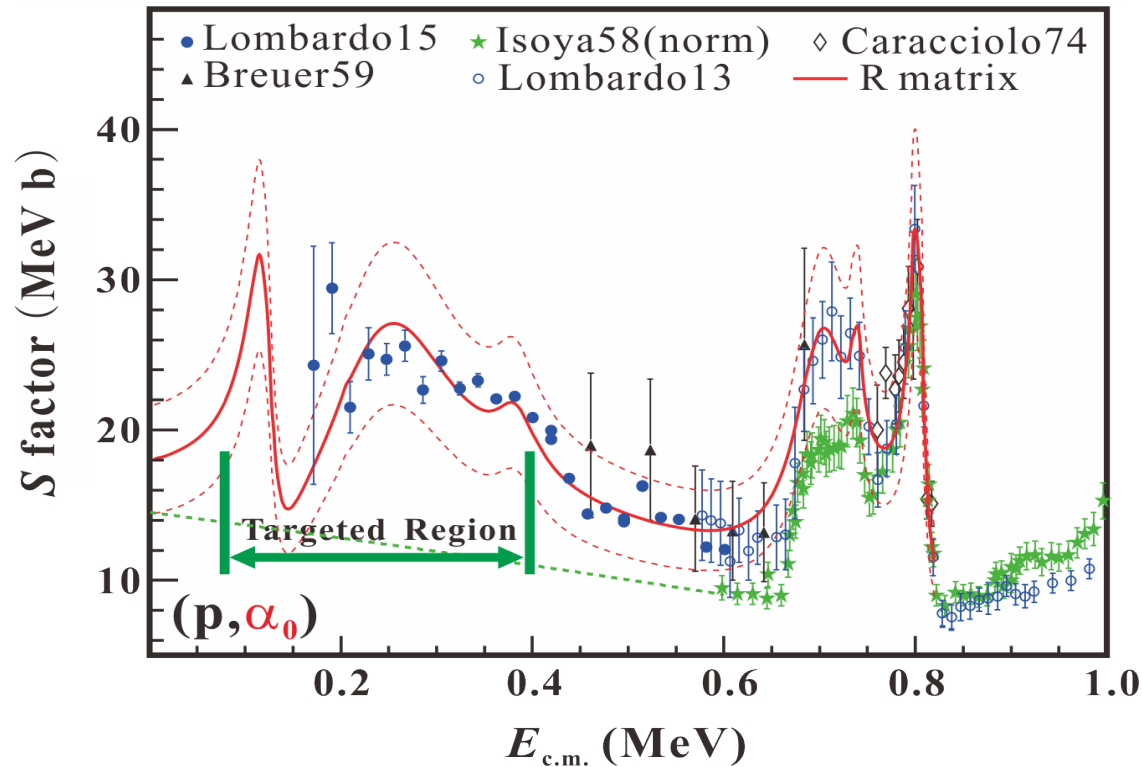
II. Status of $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ reaction

● Level scheme



II. Status of $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$ reaction

● Status & goal



Gamow window (70 ~ 350 keV)

No expt data below 200 keV ($\sigma \sim 10^{-12}$ b @ 70 keV), difficult to access in above-ground lab.

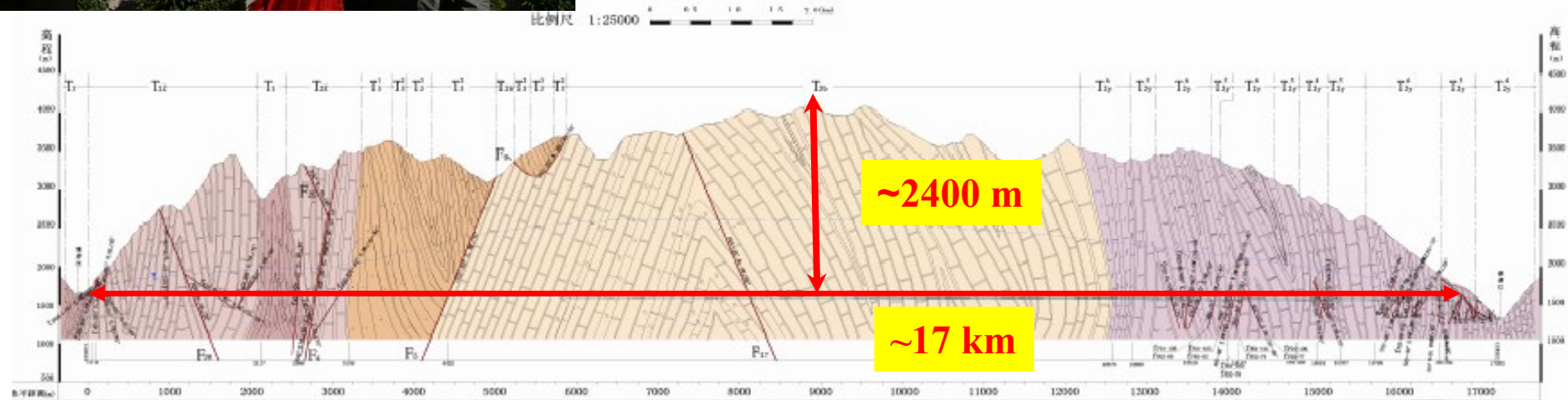


Challenge & Strategy

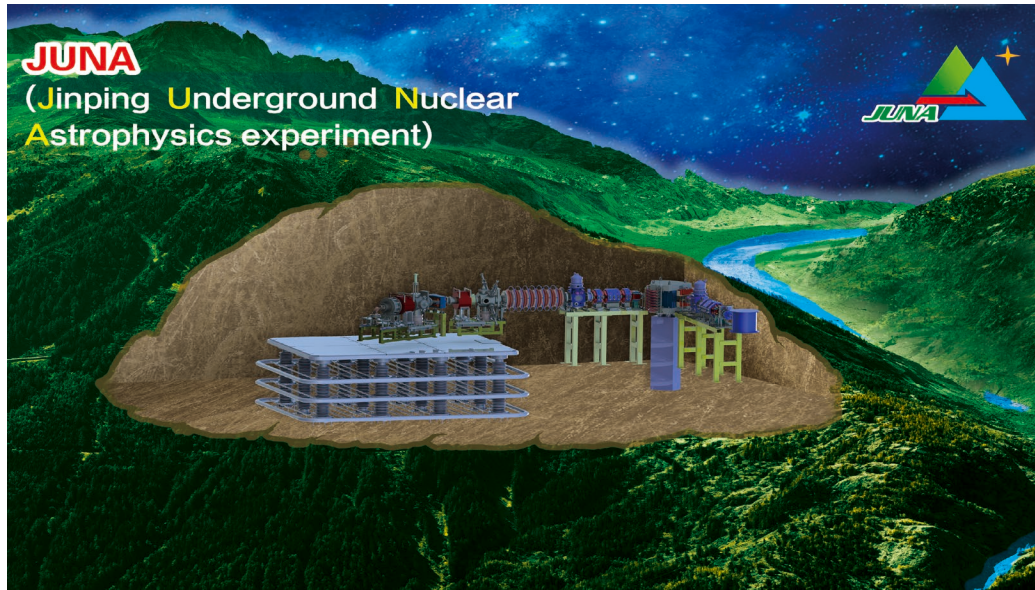
- Low background
- Intense beam
- Strong target
- High detection efficiency

China Jinping Underground Lab(CJPL)

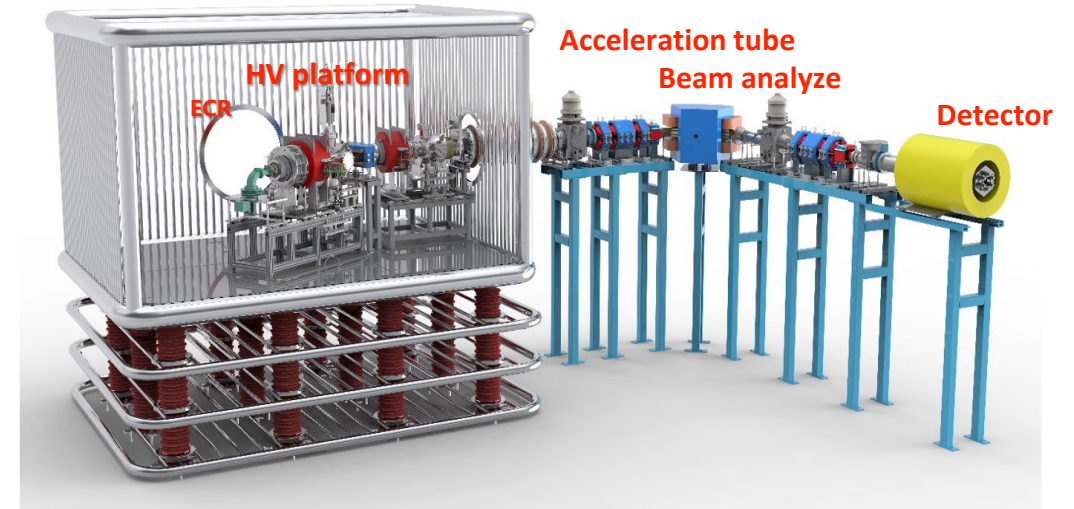
Kickoff on Dec. 12th, 2010



JUNA (Jinping Underground Nuclear Astrophysics experiment)

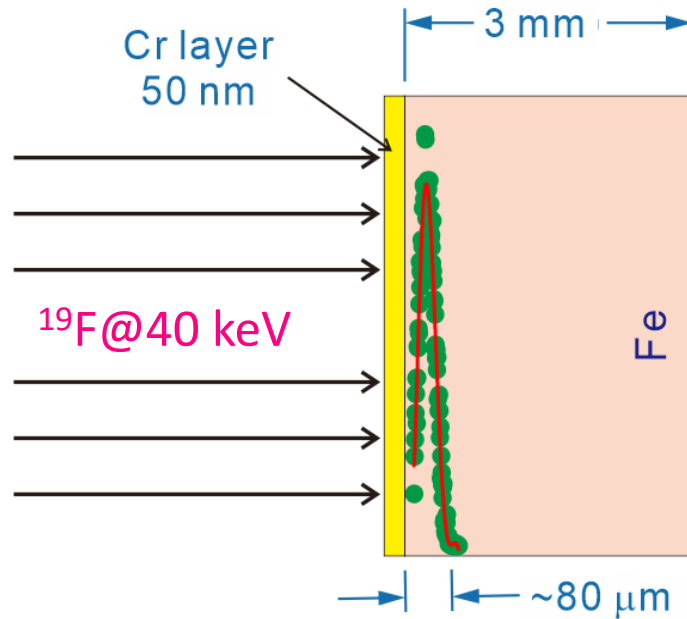


● JUNA I: 400 kV



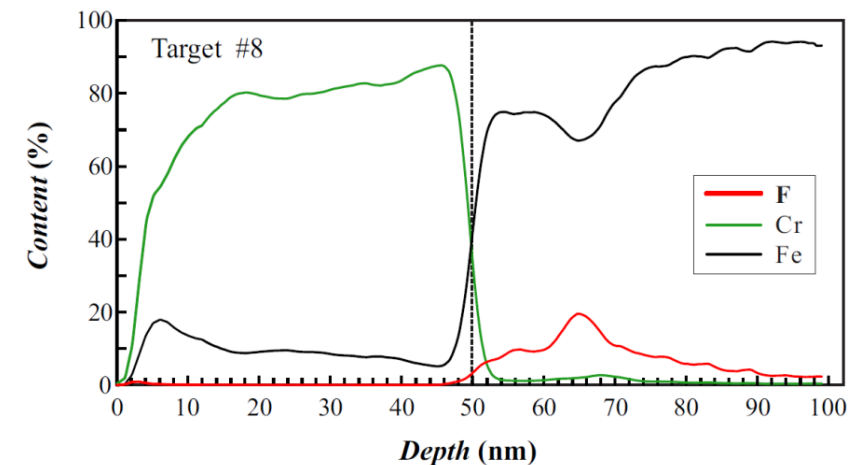
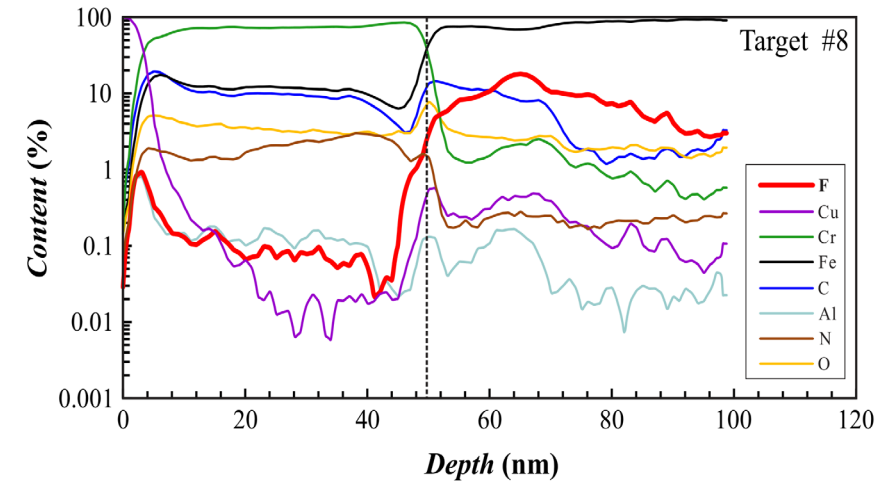
	Cosmic μ bkg ($\text{cm}^{-2} \text{s}^{-1}$)	Beam energy (keV)			Intensity (emA)		
		H^+	He^+	He^{2+}	H^+	He^+	He^{2+}
LUNA	2×10^{-8}	50-400	50-400	---	0.3~1	0.3~0.8	---
CASPAR	4×10^{-9}	100-1000	100-1000	---	0.1	0.1	---
JUNA	2×10^{-10}	50-400	50-400	100-800	10	10	2

R&D stable ^{19}F implanted targets



Implant Energy	40 keV
Cr protective foil	50 nm
Backing	Iron
Target loss	7% per 300 Coul

Atom Probe Tomography, APT

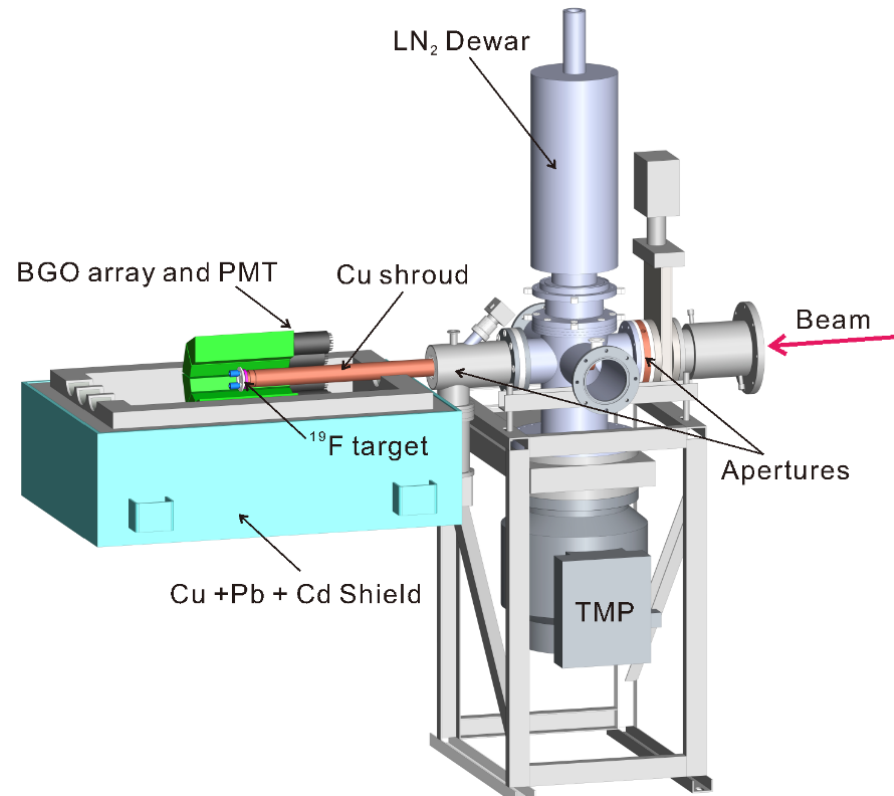


L.Y. Zhang, S.W. Xu, J.J. He* *et al.*, NIMB 438 (2019) 48

L.Y. Zhang, Y.J. Chen, J.J. He* *et al.*, NIMB 496 (2021) 9

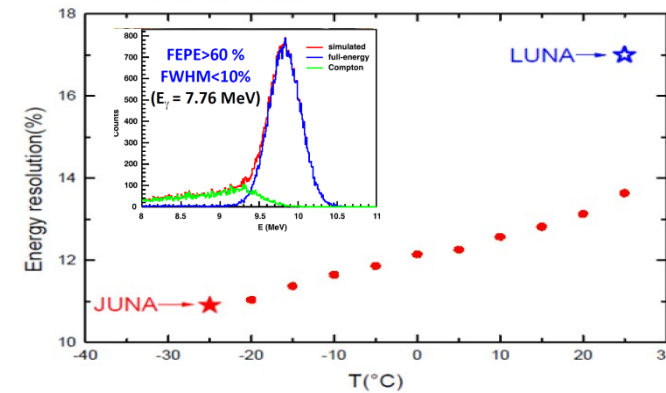
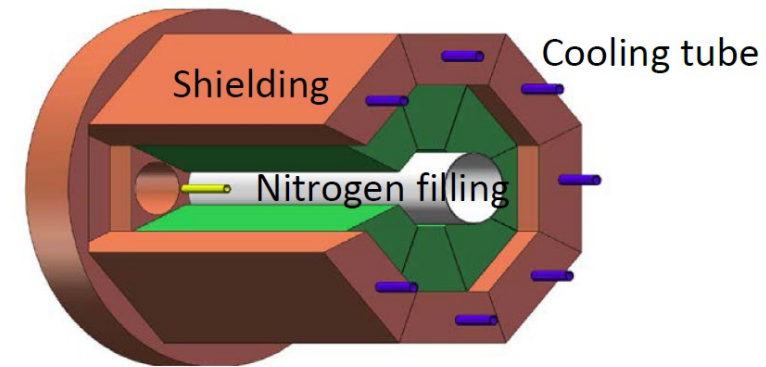
JUNA experiment campaign

● Experimental setup



Beam current: ~1 mA

● 4 π BGO γ -ray array

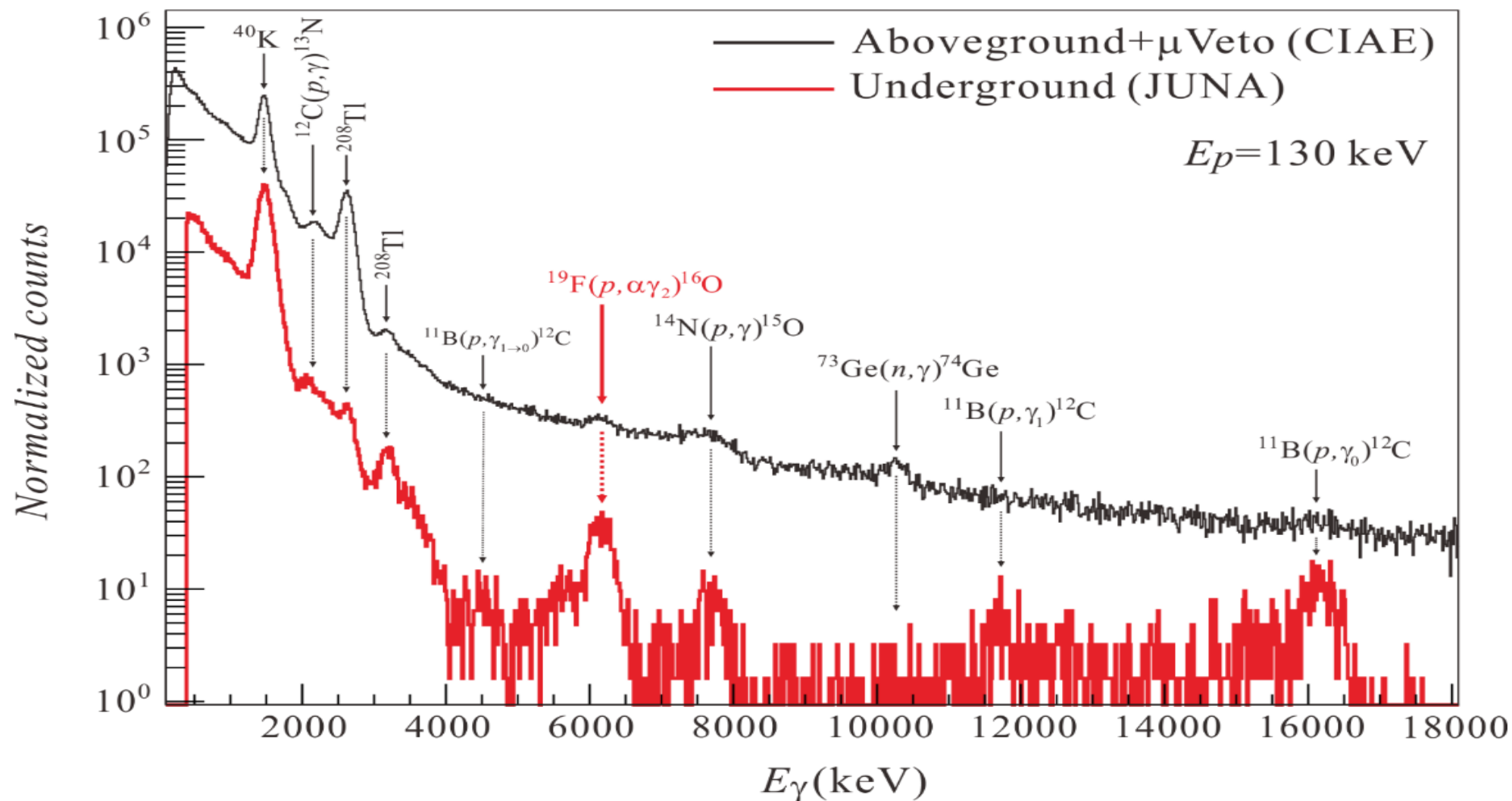


γ -ray @6130 keV

Resol.: ~6%, Effic.: ~60%

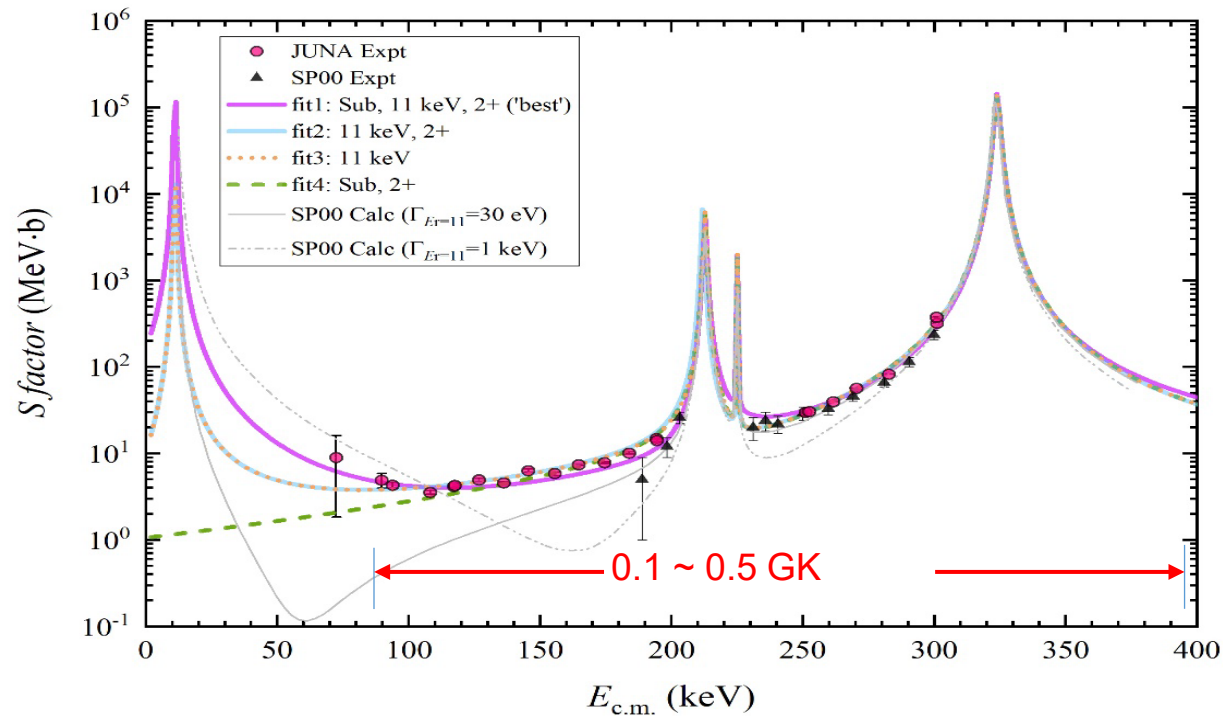
JUNA experiment campaign

● Advantage of underground lab



JUNA measurement of $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$

● Astrophysical S factor: $S(E) = E\sigma(E)/\exp(-2\pi\eta)$



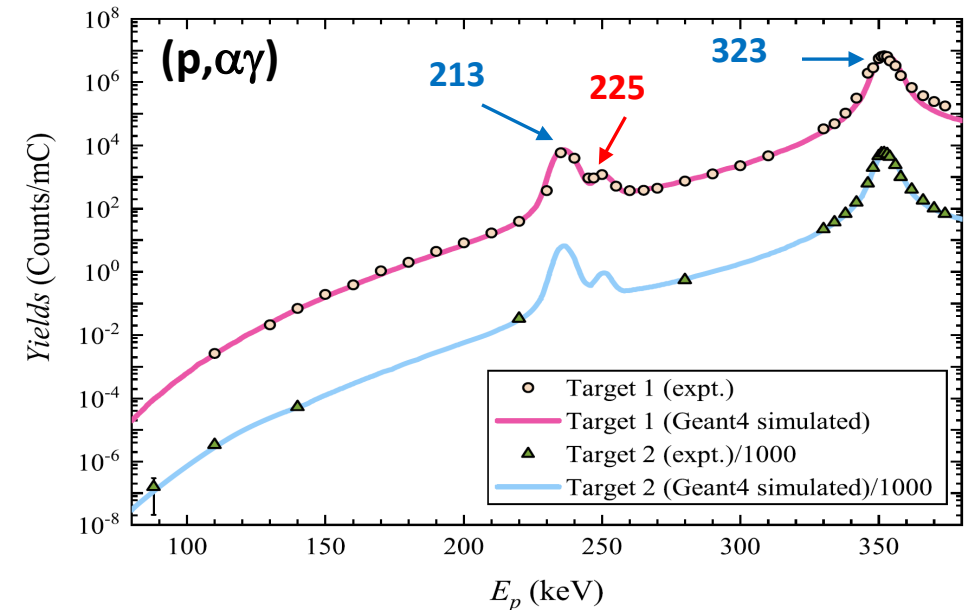
- ◆ Lowest energy region achieved
- ◆ Covering full AGB Gamow window
- ◆ Differ significantly with predictions

R-matrix calc.: R.J. deBoer, M. Wiescher

By GEANT4 simulation

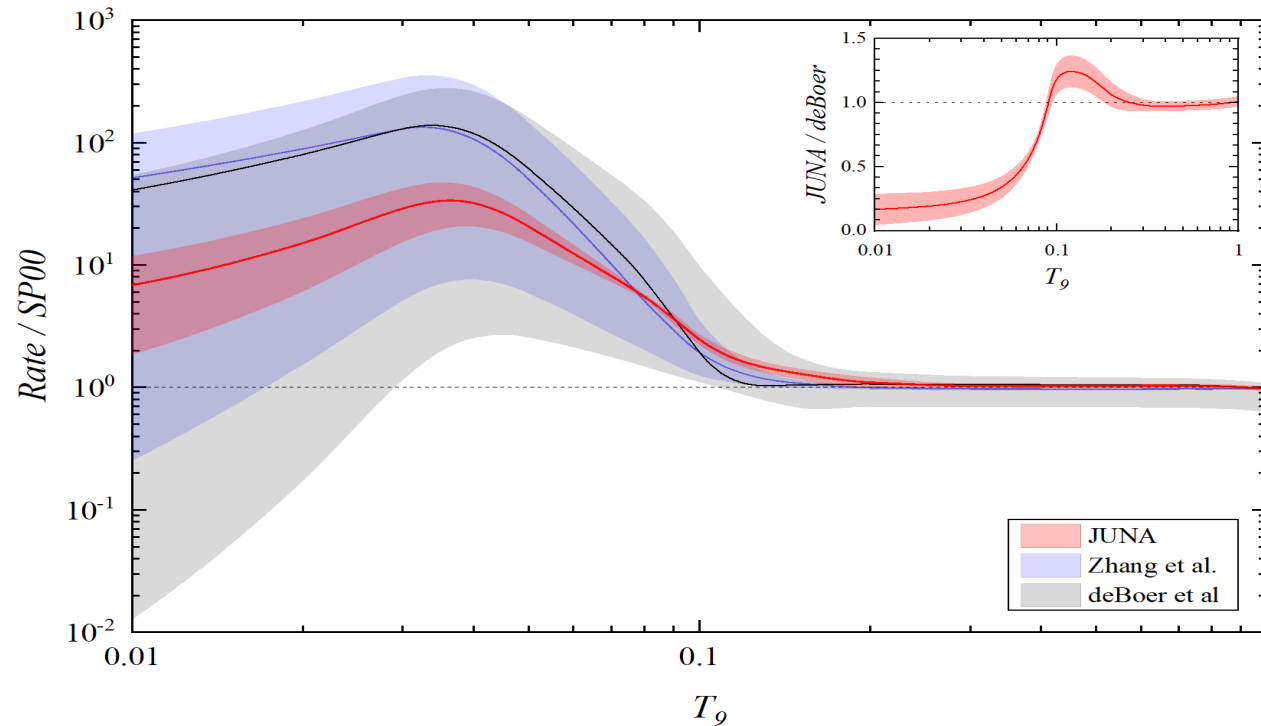
- 11-keV resonance
- Sub-threshold state
- Underlying α -cluster 2^+ state

Reaction yield



JUNA measurement of $^{19}\text{F}(\text{p}, \alpha\gamma)^{16}\text{O}$

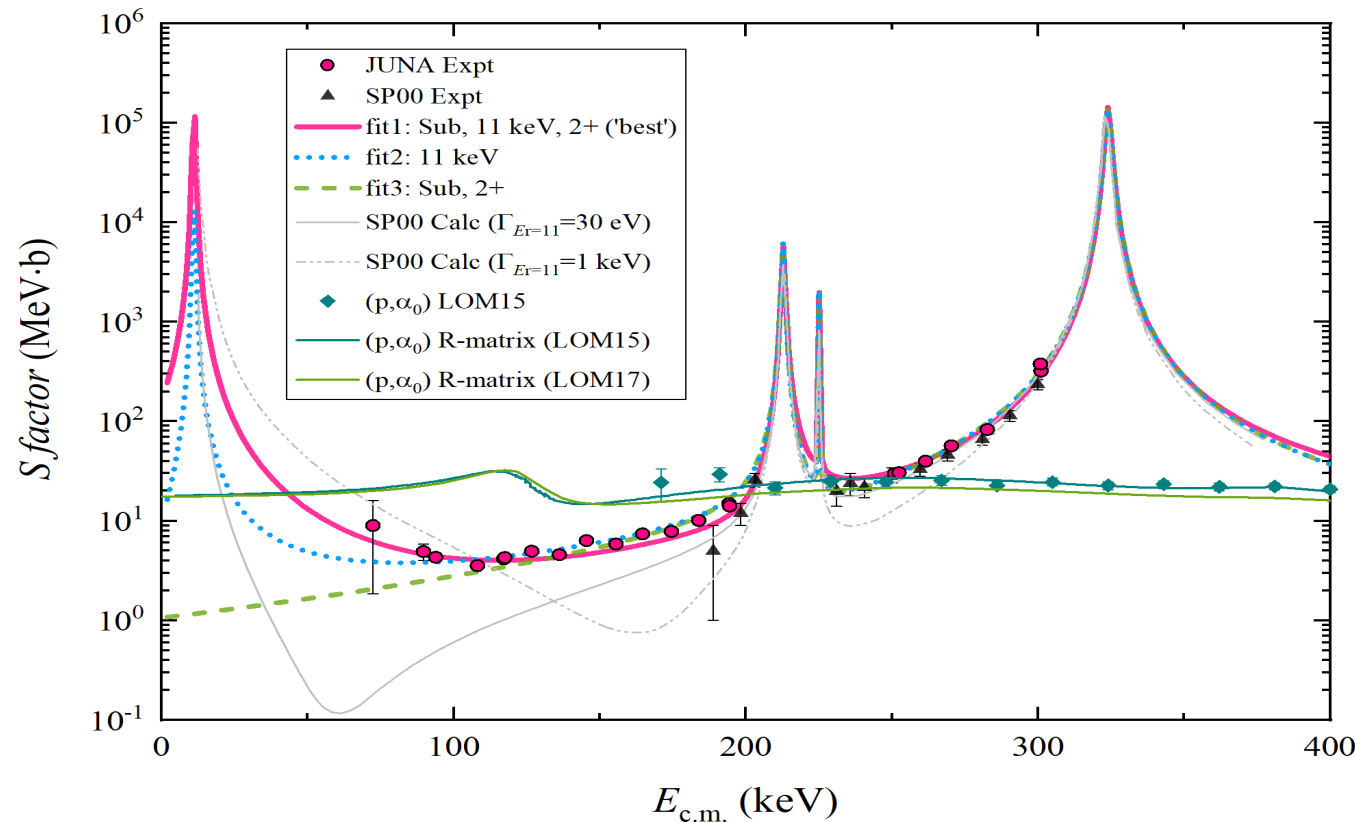
● Reaction rate



Our JUNA rate deviates significantly from the previous expectations by a factor of 0.2–1.3, and the associated uncertainties are reduced remarkably. At 0.1 GK, the uncertainty is reduced to about 10%.

JUNA measurement of $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$

● Role of $(p,\alpha\gamma)$ & (p,α_0) channels



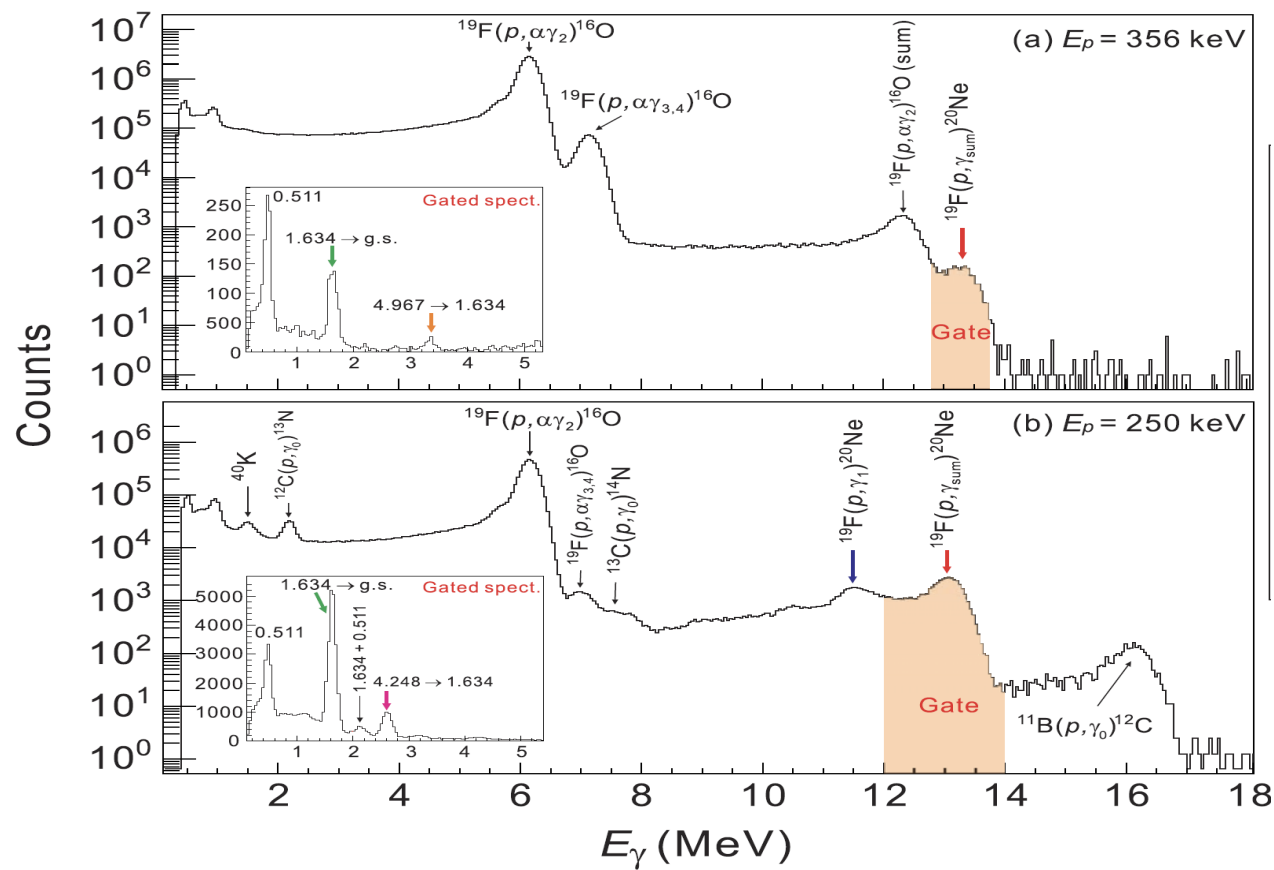
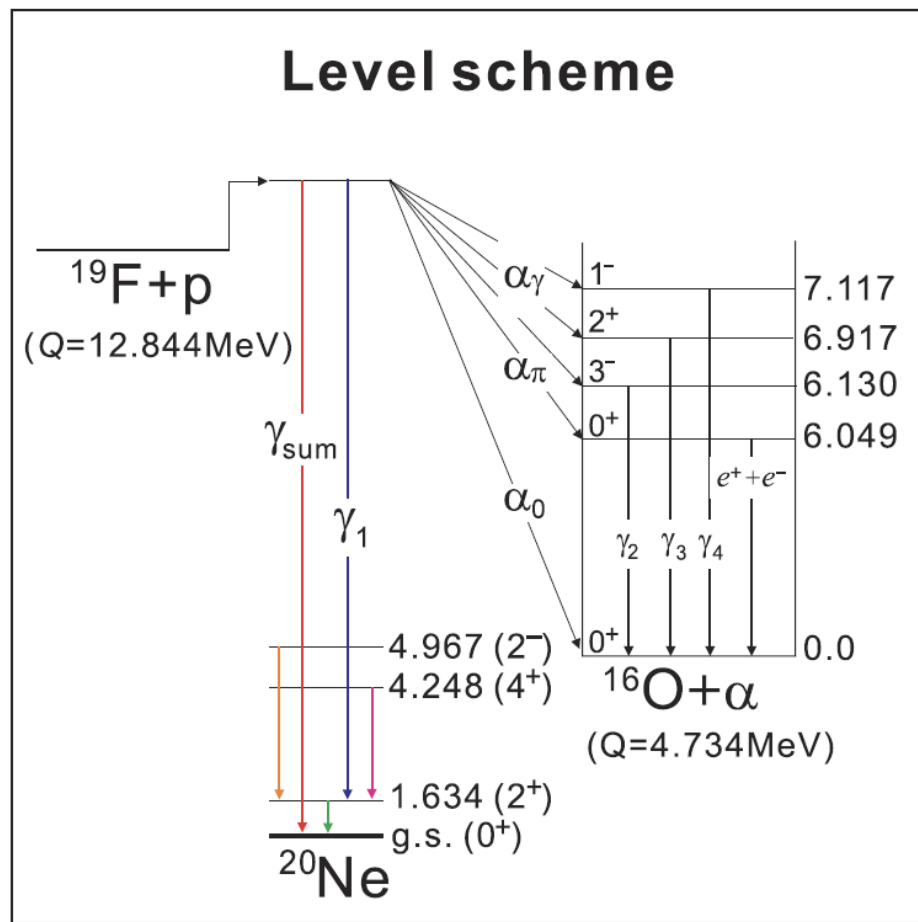
Conclusion:

In the region of 50 ~ 200 keV, (p,α_0) dominates the total cross section and hence the rate (< 0.12 GK) !

JUNA measurement of $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$

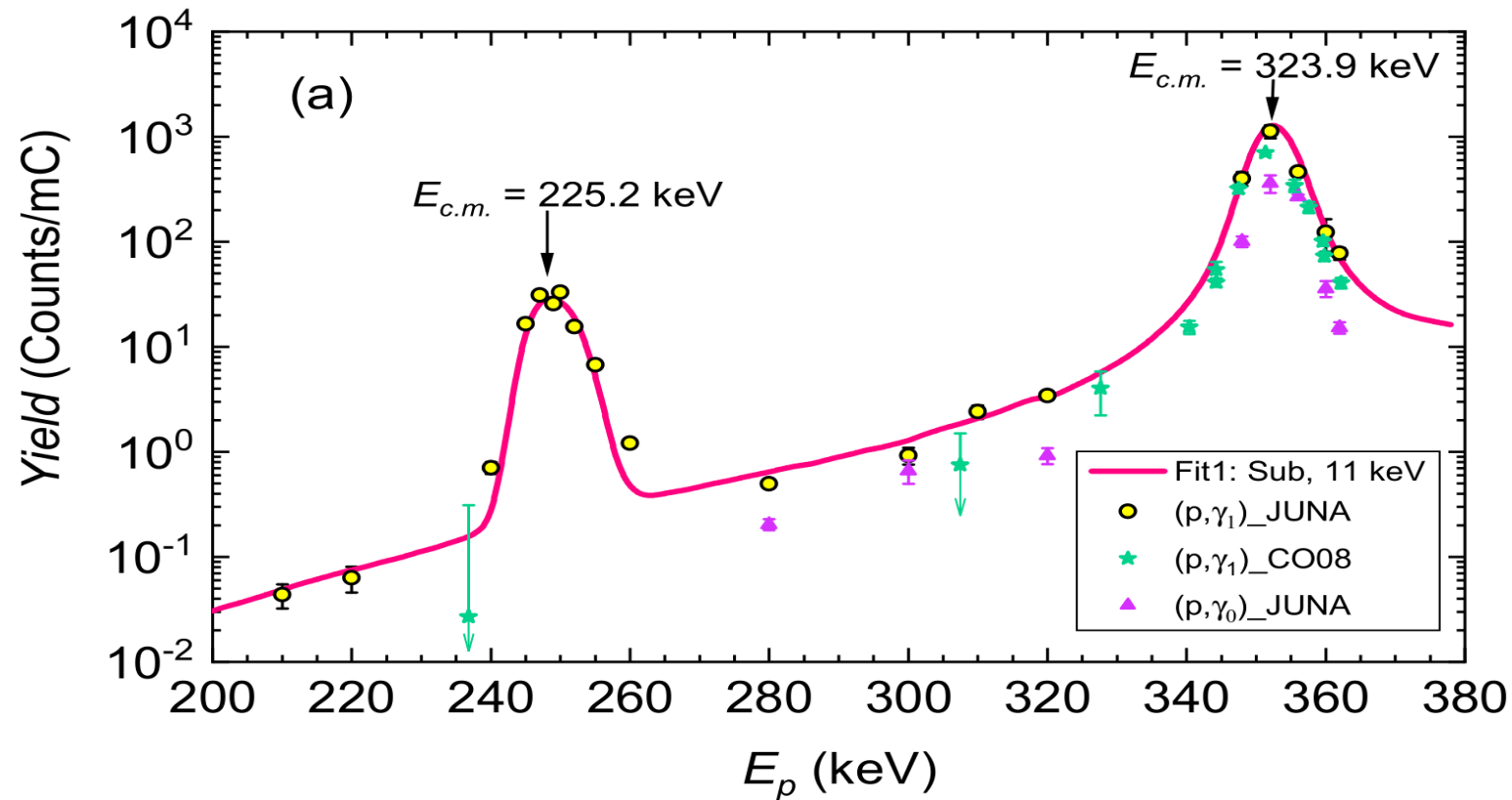
Proton beam current: ~ 1 mA (JUNA) (50 times higher than ND)

Summed γ -ray spectra & coinc. spectra



JUNA measurement of $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$

● A new resonance!

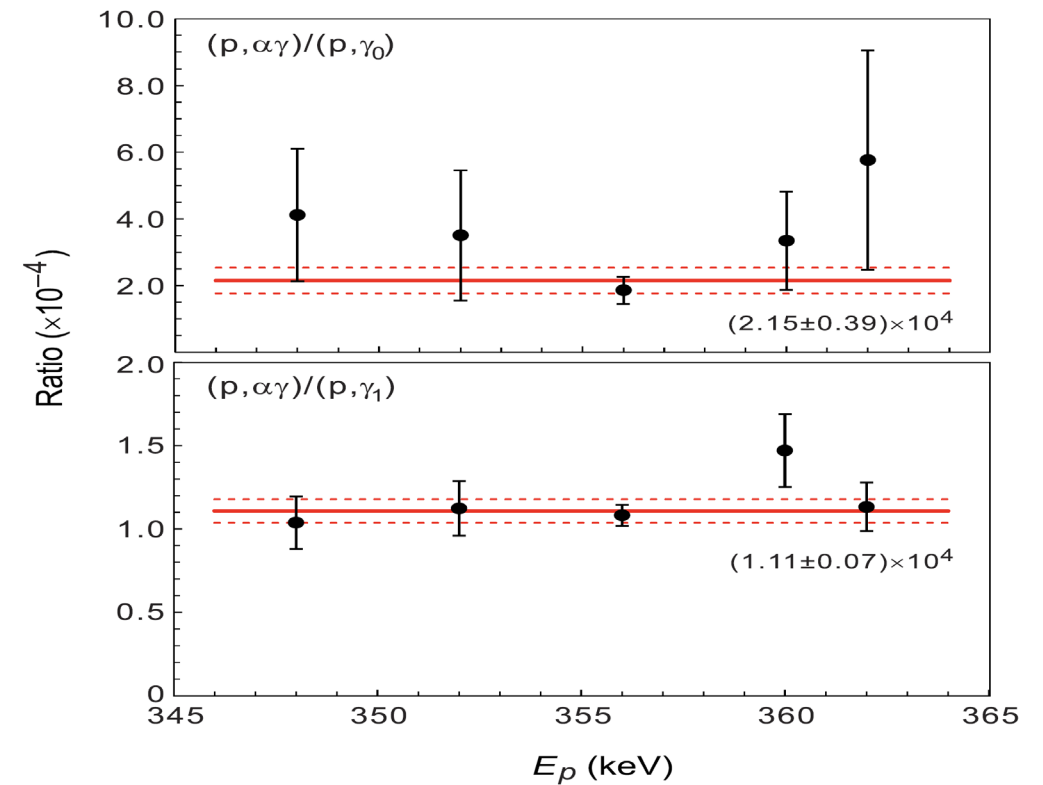
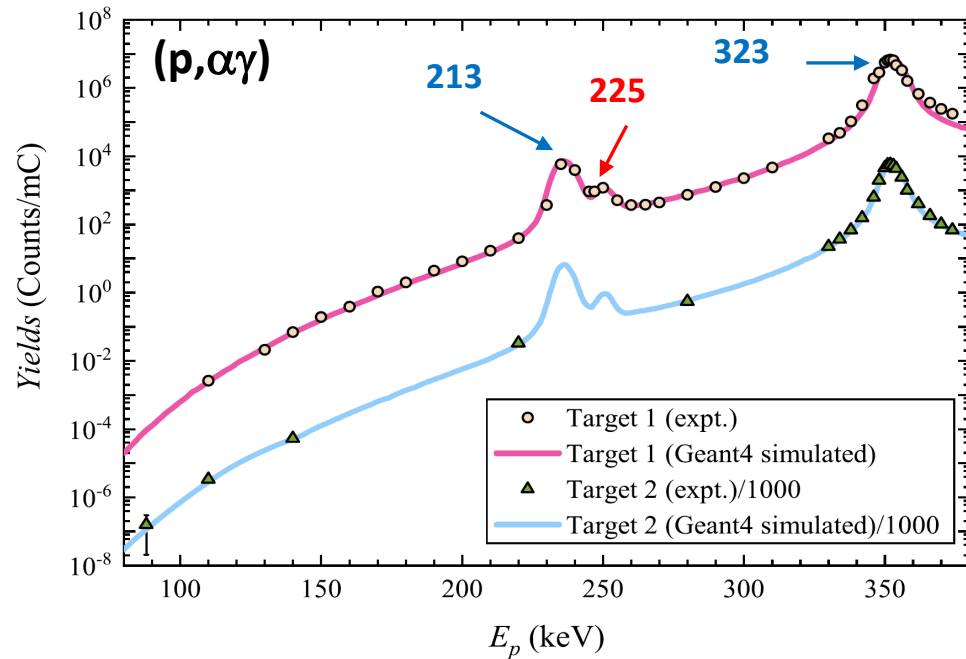


- Measured down to the lowest energy of $E_{c.m.}=186 \text{ keV}$
- Observed a new resonance at 225 keV for the first time

JUNA measurement of $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$

● Relative measurement to:

$(p,\alpha\gamma)$ strength of 323-keV resonance $\omega\gamma_{(p,\alpha\gamma)} = 23.1 \pm 0.9$ eV (3.9%)



323-keV resonance:

$$\omega\gamma_{(p,\gamma_1)} = 2.09 \pm 0.21 \text{ meV}; \omega\gamma_{(p,\gamma_0)} = 1.07 \pm 0.21 \text{ meV}$$

$$\omega\gamma_{(p,\gamma_{\text{tot}})} = 3.16 \pm 0.33 \text{ meV}$$

$$\text{NACRE value: } \omega\gamma_{(p,\gamma_{\text{tot}})} = 5 \pm 3 \text{ meV}$$

JUNA measurement of $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$

Table 1 | Relevant resonance strengths $\omega\gamma_{\text{tot}}$

E_{COM} (keV)	E_x (MeV)	J^π	$\omega\gamma_{\text{tot}}$ (meV)		ANC (fm $^{-1/2}$)	Γ_{a_2} (eV)	Γ_{γ_1} (eV)
			Present	NACRE ³			
-448	12.396(4) ^a	1 ⁺			15 ^b	60 $^{+40}_{-30}$	<3.4
11	12.855(4) ^a	1 ⁺			1.14 $\times 10^{-28}$ ^c	-590 $^{+230}_{-290}$	<4.8
212.7(10)	13.057	2 ⁻	<4.2 $\times 10^{-3}$	<1.3(13) $\times 10^{-3}$			
225.2(10)	13.069	3 ⁻	4.19(33) $\times 10^{-2}$	8%			
323.9	13.168(2) ^b	1 ⁺	3.16(33)	10%	5(3)	60%	

Values are determined for the $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$ reaction (with total errors listed in parentheses). R -matrix fit parameters are tabulated, including sub-threshold and near-threshold 11-keV resonances as shown in Fig. 1b. The fit includes the additional levels and from ref.⁵ as fixed background terms. See Methods for details.

E_x values fixed to those determined in previous analyses are indicated by: ^aref.³⁹, ^bref.⁵, ^cref.²⁶, where the corresponding uncertainties are adopted.

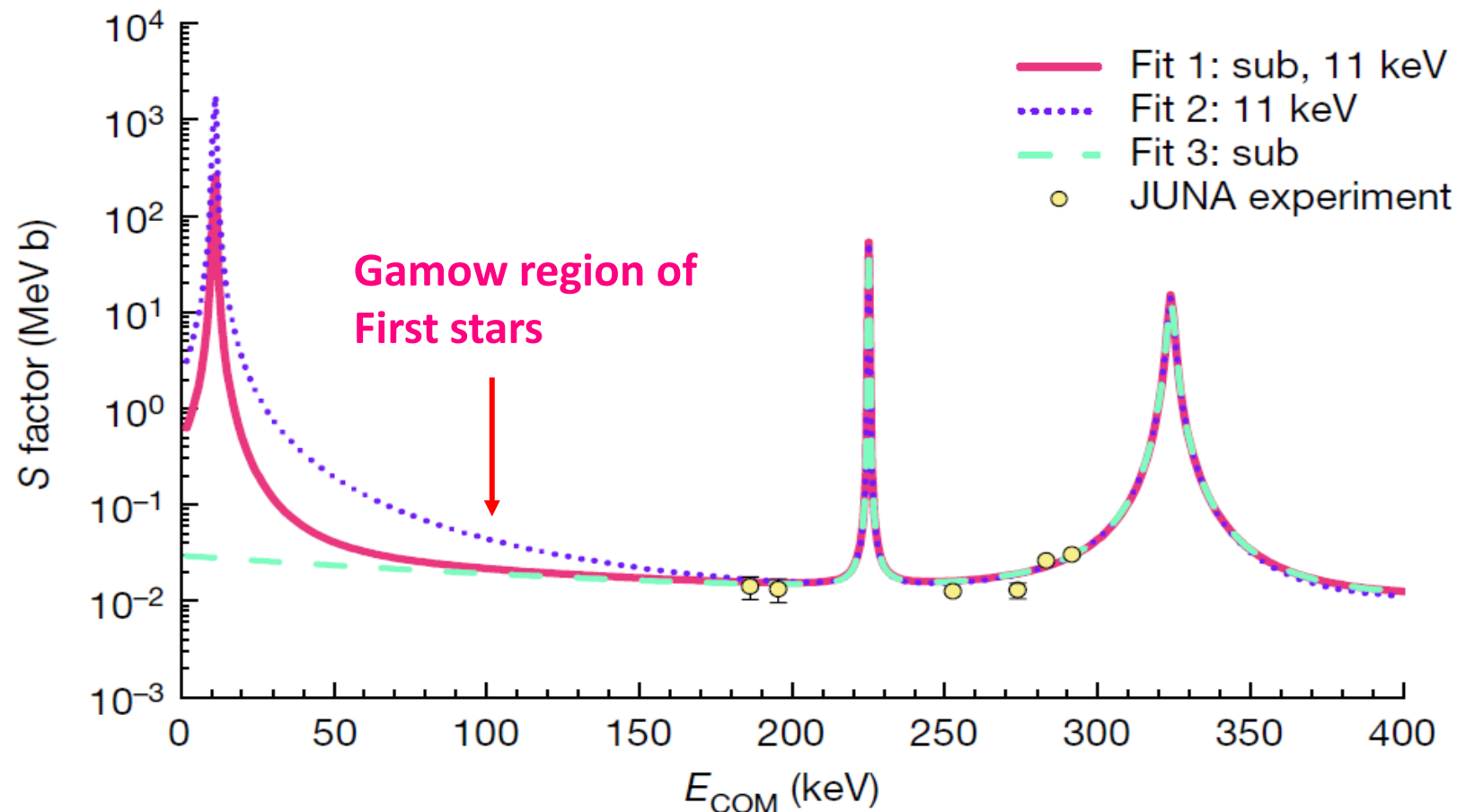
JUNA measurement of $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$

● Astrophysical S factor:

$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

R-matrix calculations

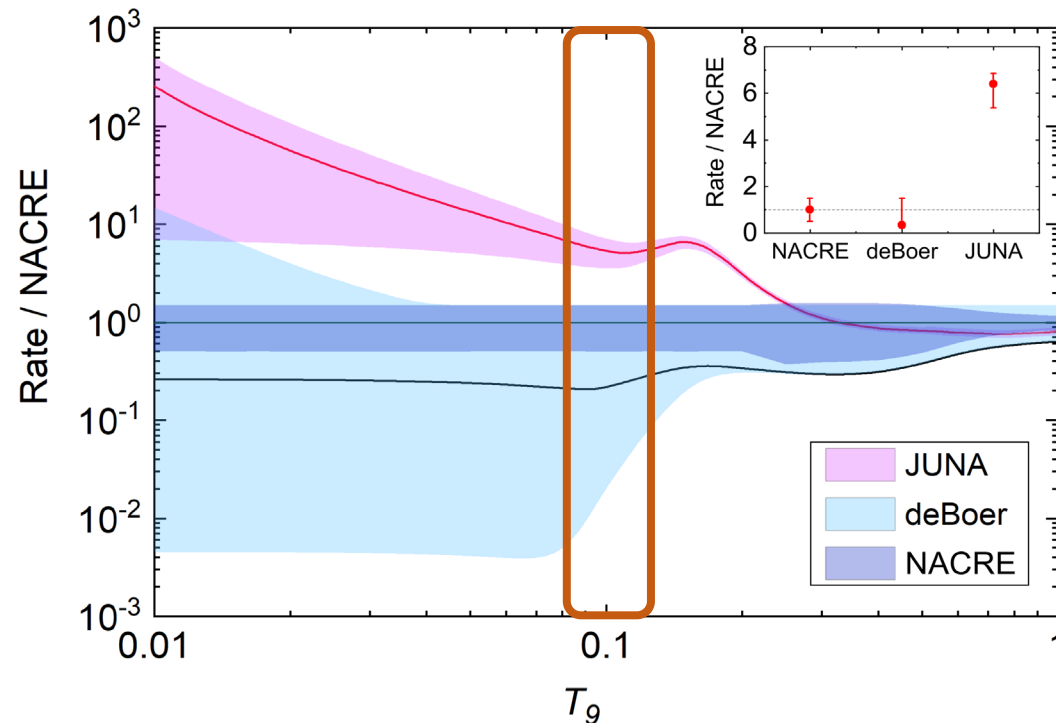
DeBoer, Wiescher, Odell



JUNA measurement of $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$

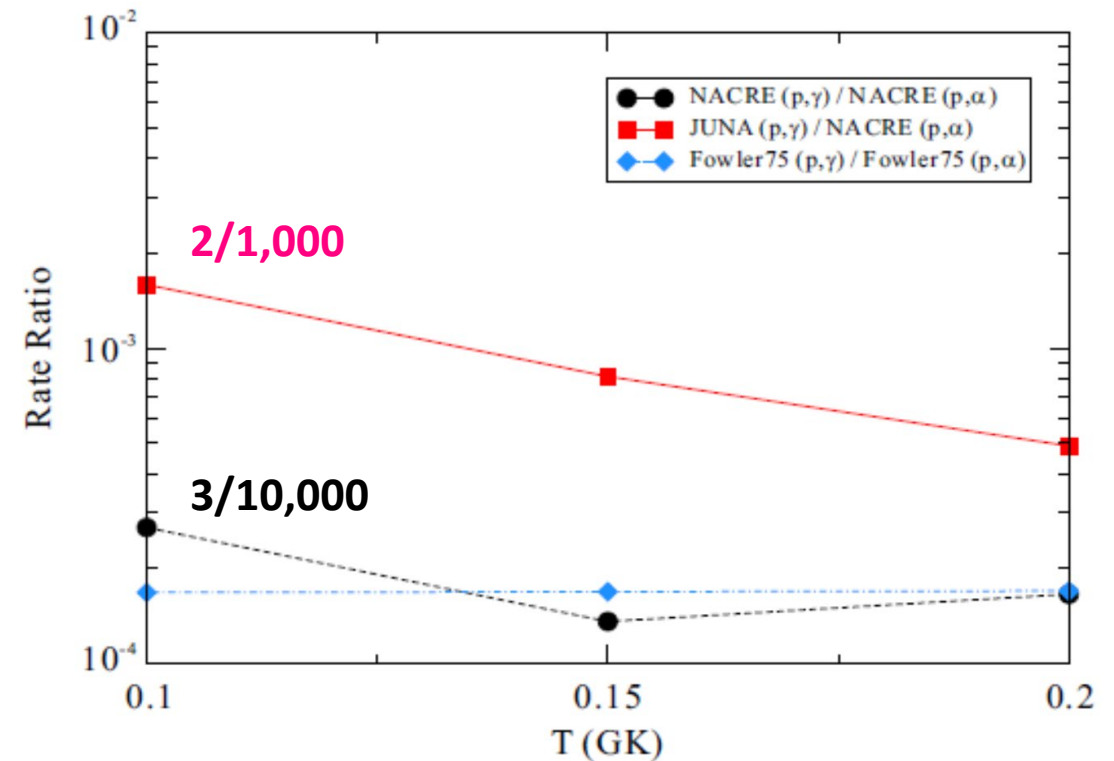
● New reaction rate:

- ◆ 7.4 times larger than previous estimation at 0.1 GK; 200 times larger around 0.01 GK
- ◆ 3 times more precise at 0.1 GK



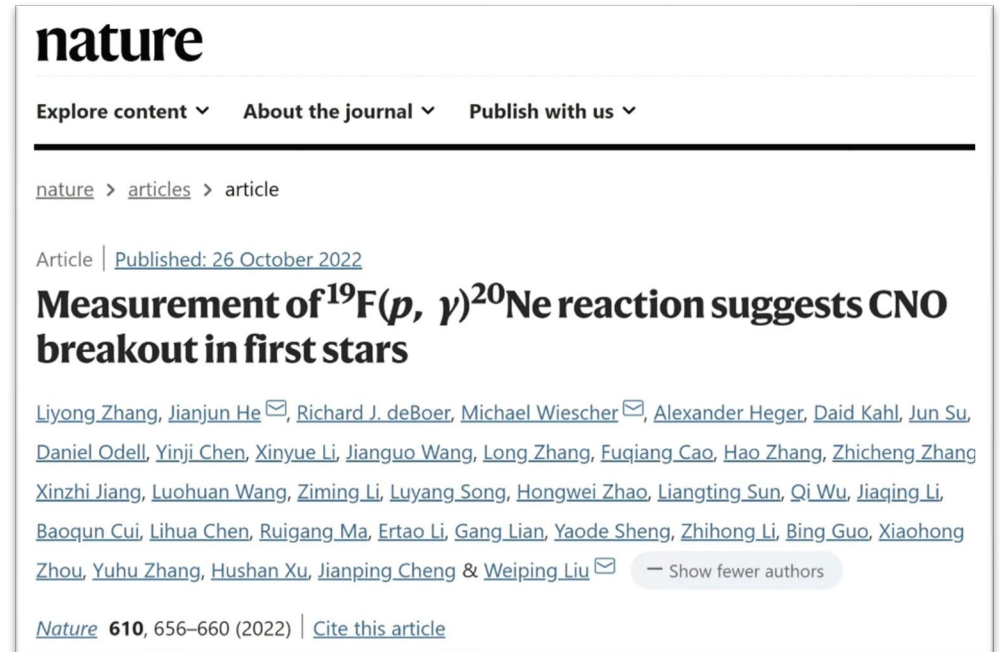
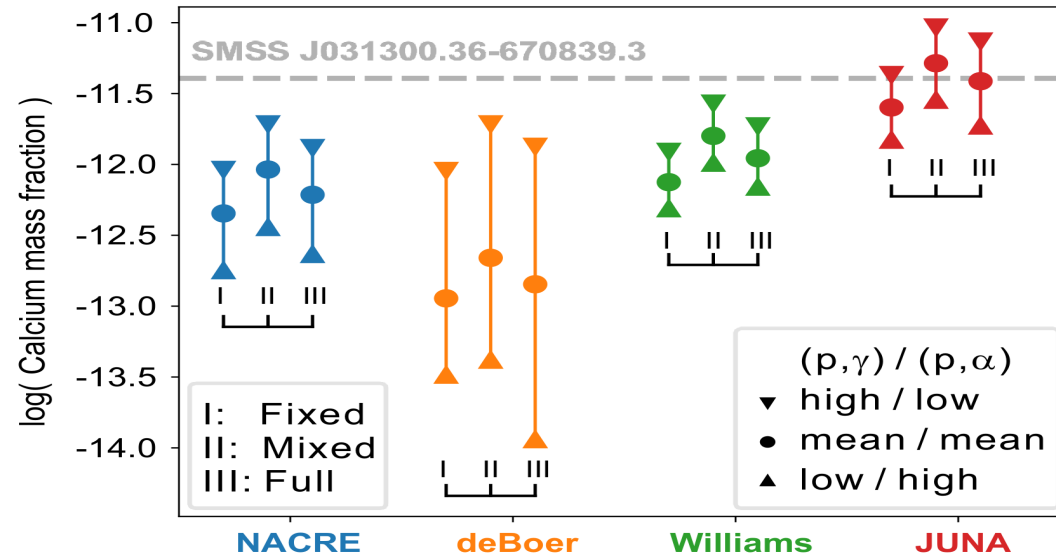
Reaction rate ratio

$$^{19}\text{F}(p,\gamma)^{20}\text{Ne} / ^{19}\text{F}(p,\alpha)^{16}\text{O}$$



JUNA measurement of $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$

● Model calc. (A. Heger @Monash Univ.)

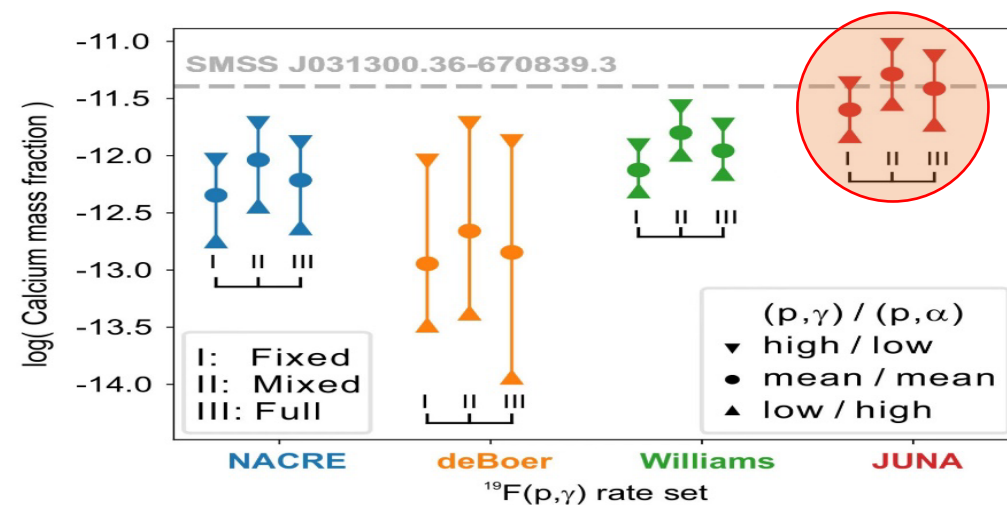
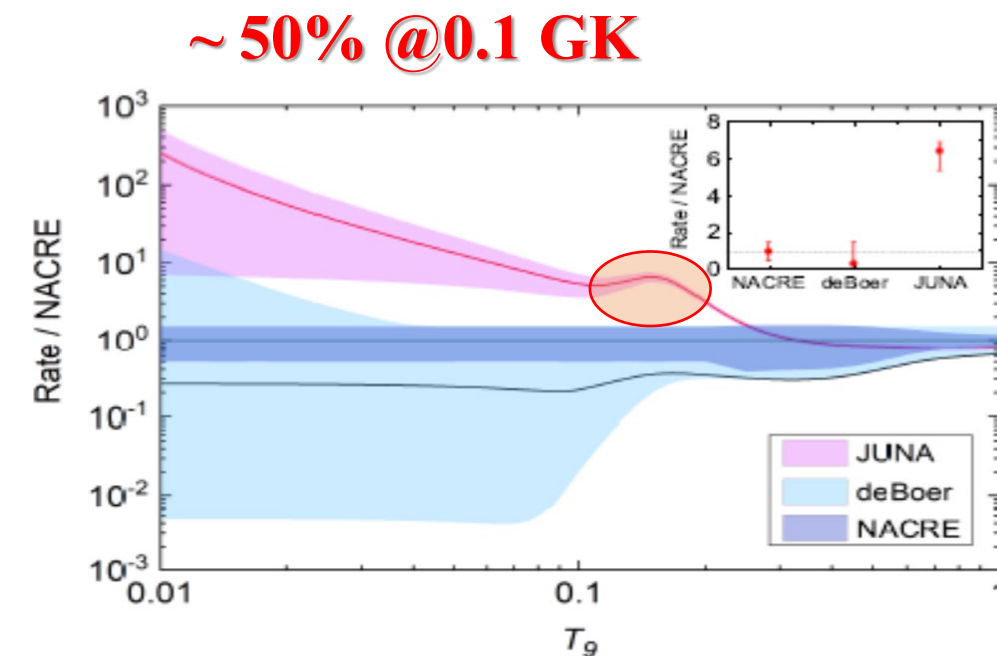
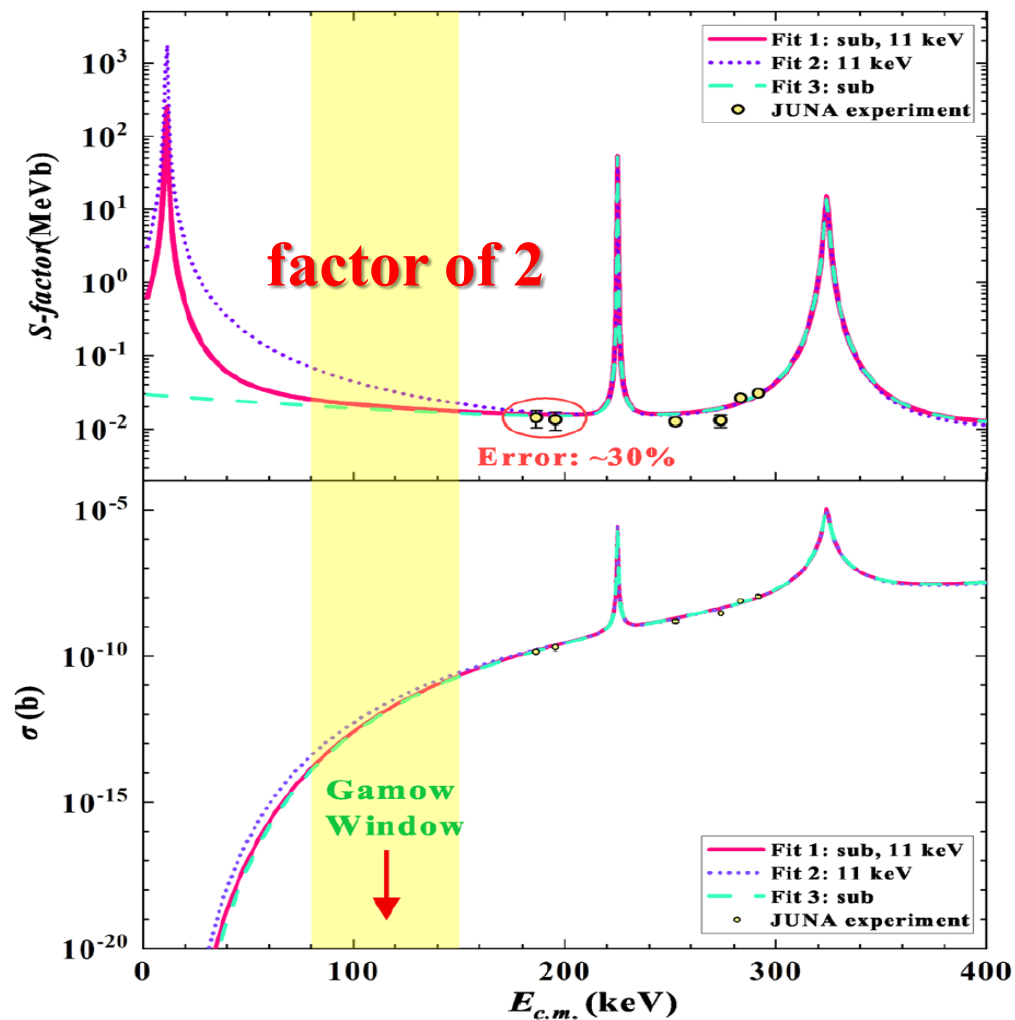


Astrophysical implications:

- ◆ Reproduce observed ^{40}Ca abundance, and verified hypothesis that calcium comes from a key breakout reaction of CNO cycle, revealing origin of calcium in the first stars.
- ◆ Support the *faint* supernova model

JUNA prospect for $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$

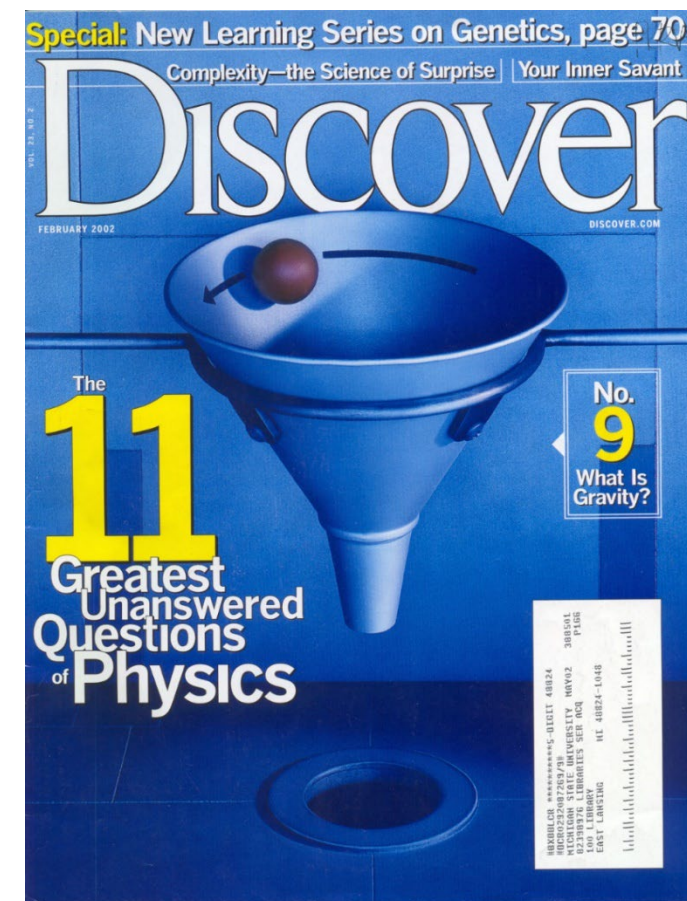
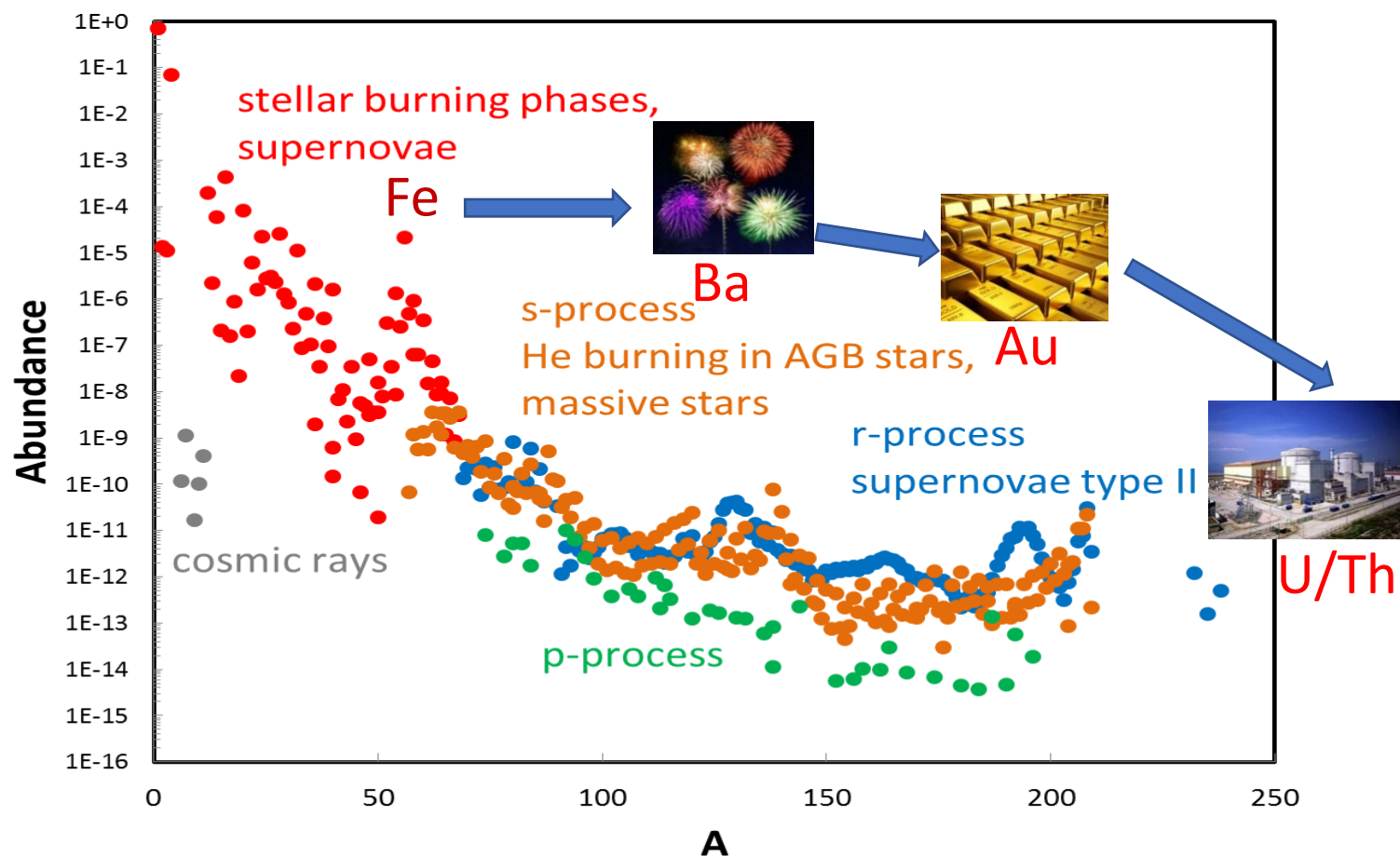
JUNA will restart soon!



Origin of heavy elements

★ The 11 Greatest Unanswered Questions of Physics (2002, Discovery)

Question 3: How were the elements from iron to uranium made ?



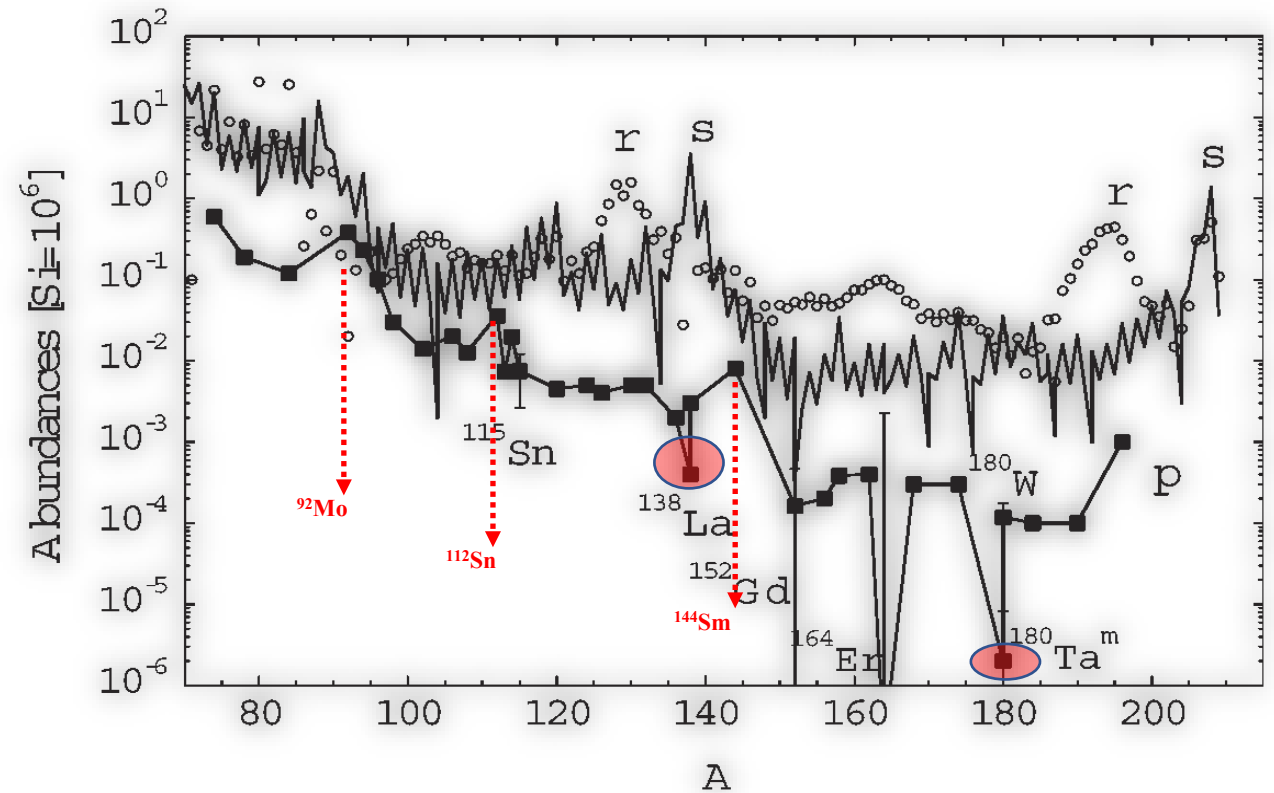
Origin of p-nuclei

List of p-nuclei

35 neutron-deficient isotopes from Se to Hg

Nucleus	Natural abundance (%)	Abundance 10^6 Si Anders&Grevesse
74Se	0.89	0.55
78Kr	0.35	0.153
84Sr	0.56	0.132
92Mo	14.84	0.378
94Mo	9.25	0.236
96Ru	5.54	0.103
98Ru	1.87	0.035
102Pd	1.02	0.0142
106Cd	1.25	0.0201
108Cd	0.89	0.0143
113In	4.29	0.0079
112Sn	0.97	0.0372
114Sn	0.66	0.0252
115Sn	0.34	0.0129
120Te	0.09	0.0043
124Xe	0.09	0.00571
126Xe	0.09	0.00509
130Ba	0.106	0.00476
132Ba	0.101	0.00453
138La	0.09	0.000409
136Ce	0.185	0.00216
138Ce	0.251	0.00284
144Sm	3.07	0.0008
152Gd	0.2	0.00066
156Dy	0.06	0.000221
158Dy	0.1	0.000378
162Er	0.14	0.000351
164Er	1.61	0.00404
168Yb	0.13	0.000322
174Hf	0.16	0.000249
180Ta	0.012	2.48E-06
180W	0.12	0.000173
184Os	0.02	0.000122
190Pt	0.014	0.00017
196Hg	0.15	0.00048

Solar abundance of p-nuclei



Origin of p-nuclei

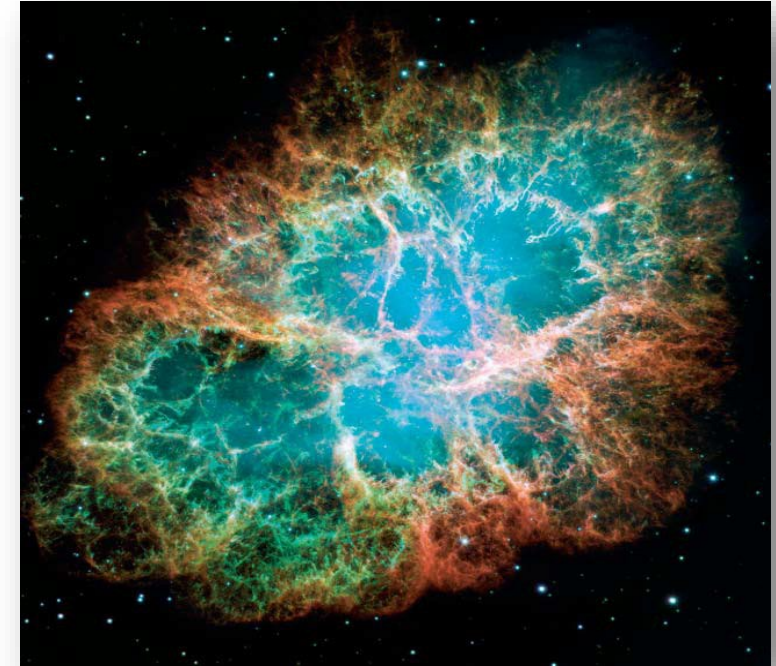
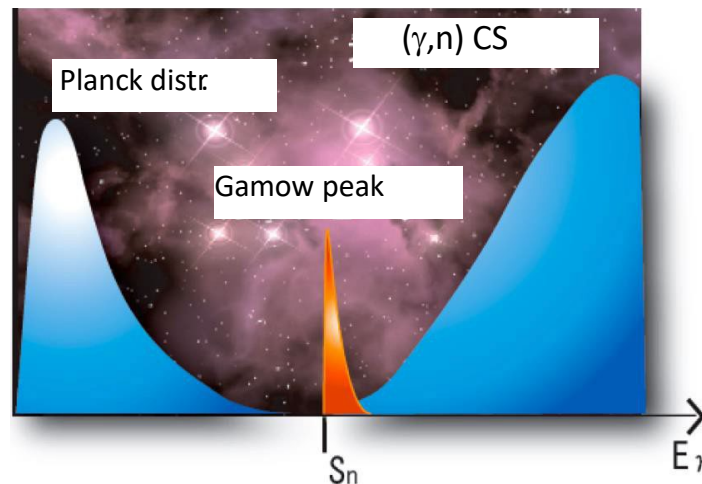
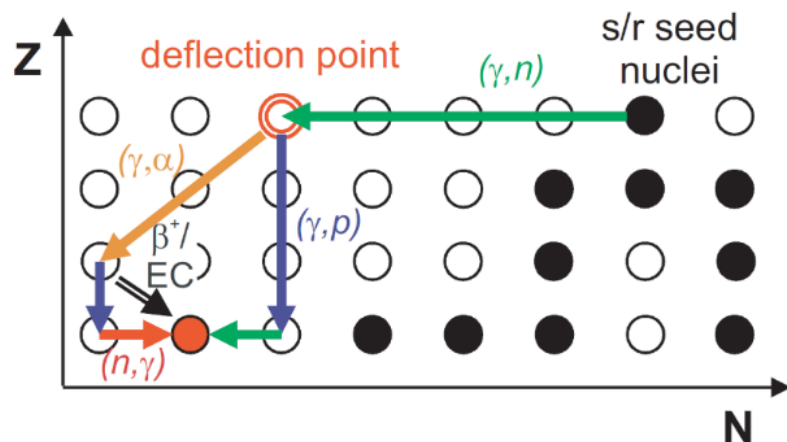
● Stellar site for p-nuclei production

Type II SN burst of massive stars (O&Ne-rich layer)

Woosley & Howard, APJS36(1978)285; Rayet et al., A&A 22(1990)271

◆ Typical Temp.: 2 ~ 3 GK; Gamow Energy: several MeV

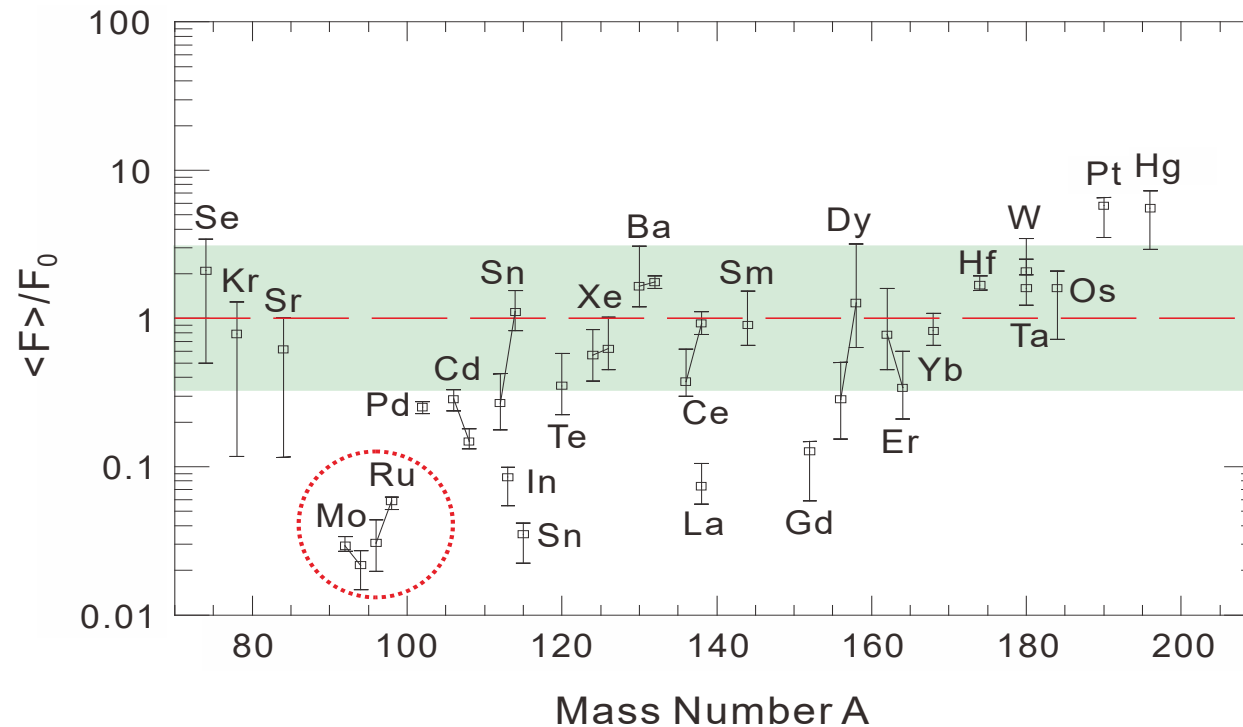
● p-process



In stellar models, there are $\sim 2,000$ nuclides and 20,000 nuclear reactions involved: it primarily relies on statistical models, with very limited experimental data!

Origin of p-nuclei

● Underproduction problem (esp. Mo & Ru)



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SENSITIVITY OF p -PROCESS NUCLEOSYNTHESIS TO NUCLEAR REACTION RATES IN A $25 M_{\odot}$ SUPERNOVA MODEL

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Uncertainties in the production of p nuclides in thermonuclear supernovae determined by Monte Carlo variations

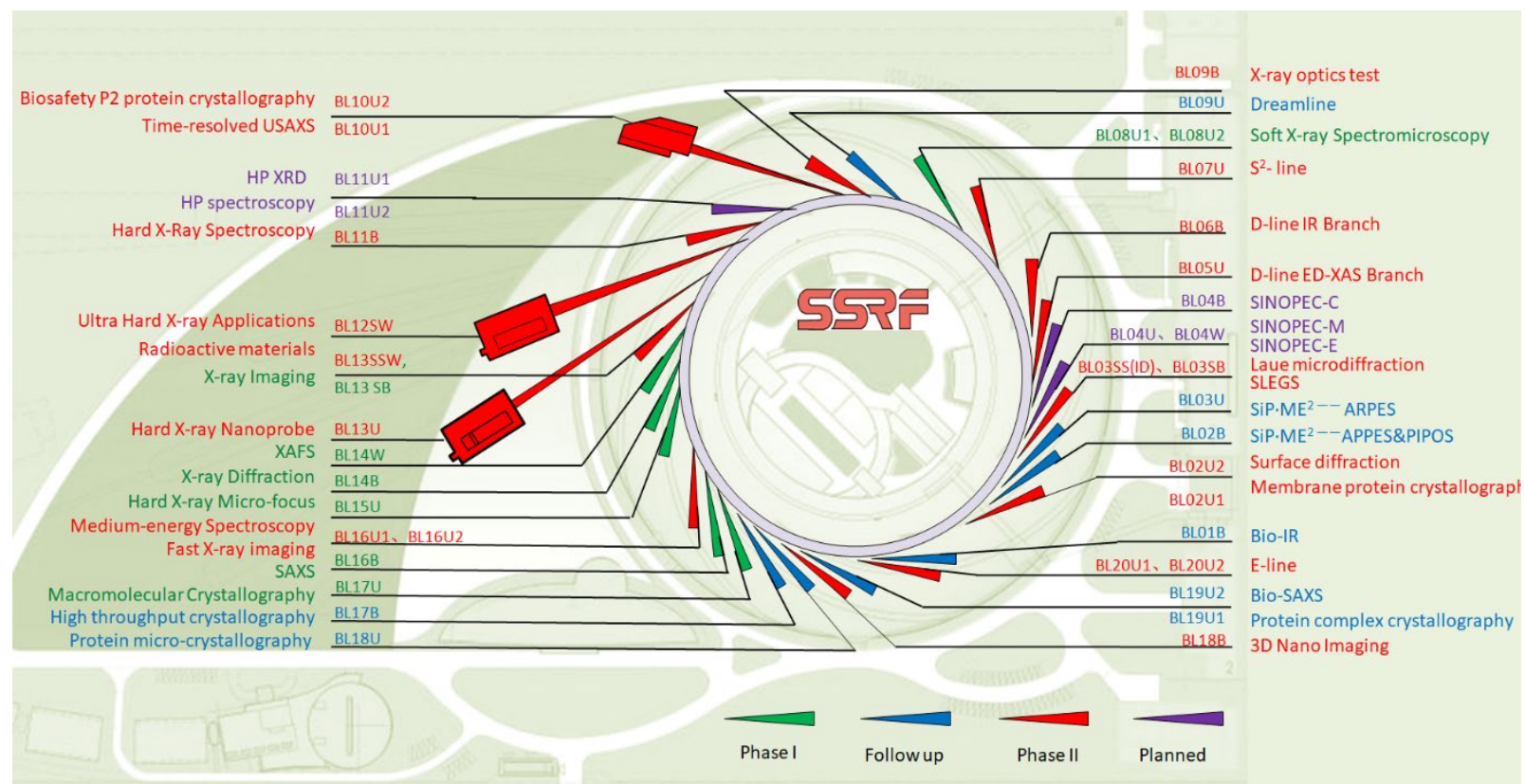
N. Nishimura(西村信哉),^{1,2★†} T. Rauscher,^{3,4†} R. Hirschi,^{2,5†} A. St. J. Murphy,^{6†}
G. Cescutti^{4,7†} and C. Travaglio^{8†}

Shanghai Radiation Synchrotron Facility (SSRF)

Shanghai Light Source (上海光源)

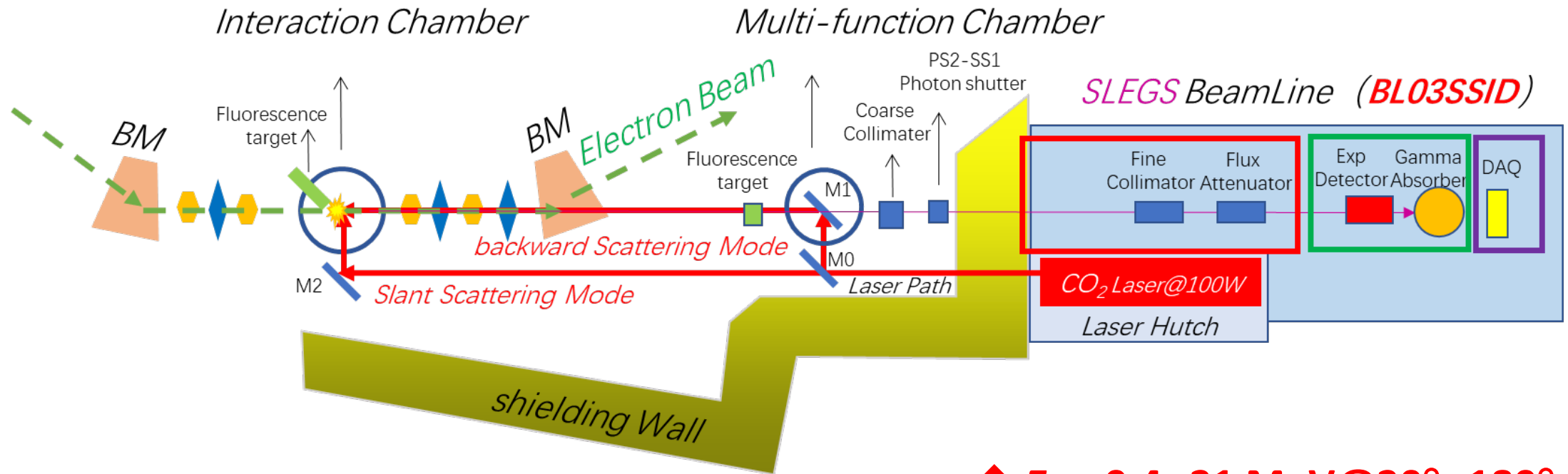
- Energy: $E_e = 3.5$ GeV
- Current: $I_e > 240$ mA
- Mean lifetime: $t_e > 16$ h

Shanghai Laser Electron Gamma Source (SLEGS)



SLEGS beamline

● Layout



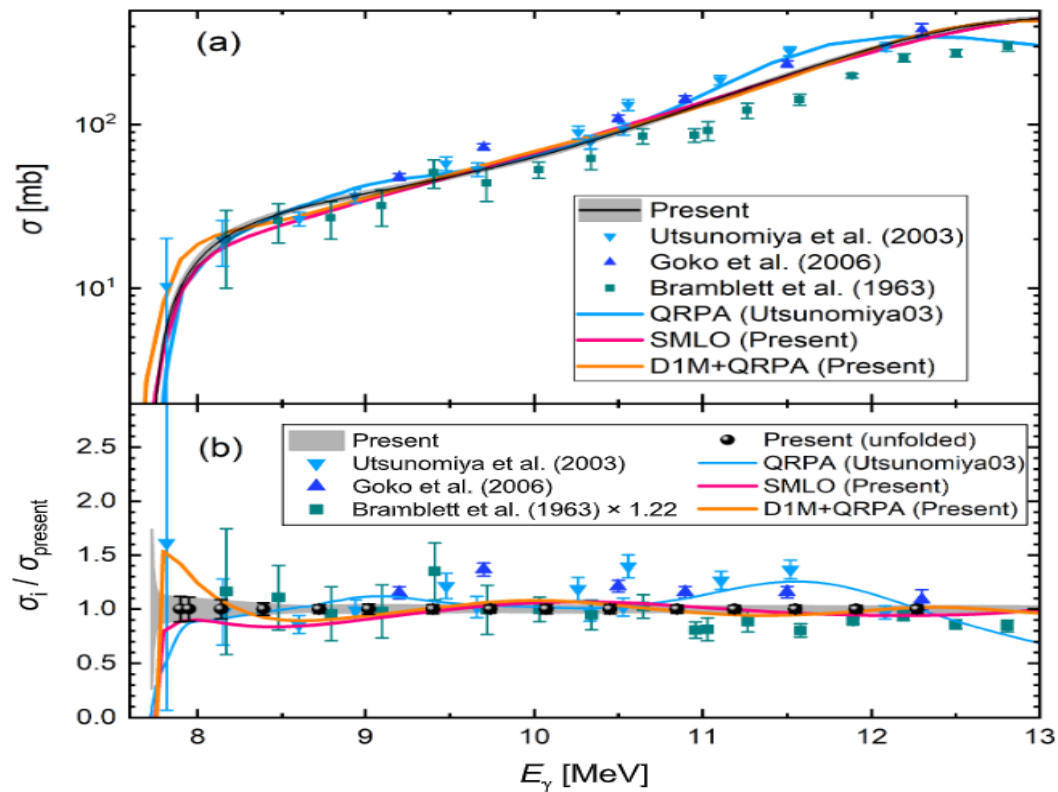
SLEGS is the first Laser-Compton Scattering (LCS) facility to realize the high-flux laser Compton in slant-scattering mode, which can provide more convenient energy scanning capability.

- ◆ E_{γ} : 0.4~21 MeV@20°~180°
- ◆ Flux: 10^5 ~ 10^8 phs/s
- ◆ Resolution: 6~18%

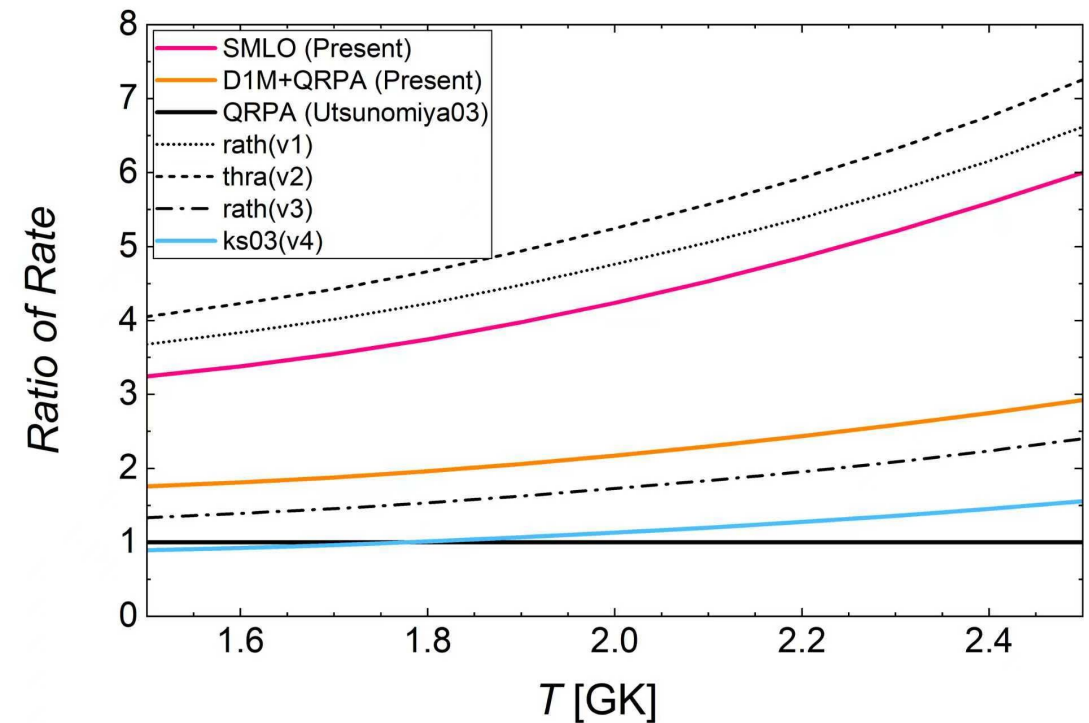
Recent progress at SLEGS

● $^{181}\text{Ta}(\gamma, n)^{180}\text{Ta}$ @SLEGS

➤ **photoneutron cross sections** (collaboration with Prof. Goriely)



➤ **Compare to other reaction rates**



➤ **More precise photoneutron cross sections are obtained (3.5~7.2 times)**

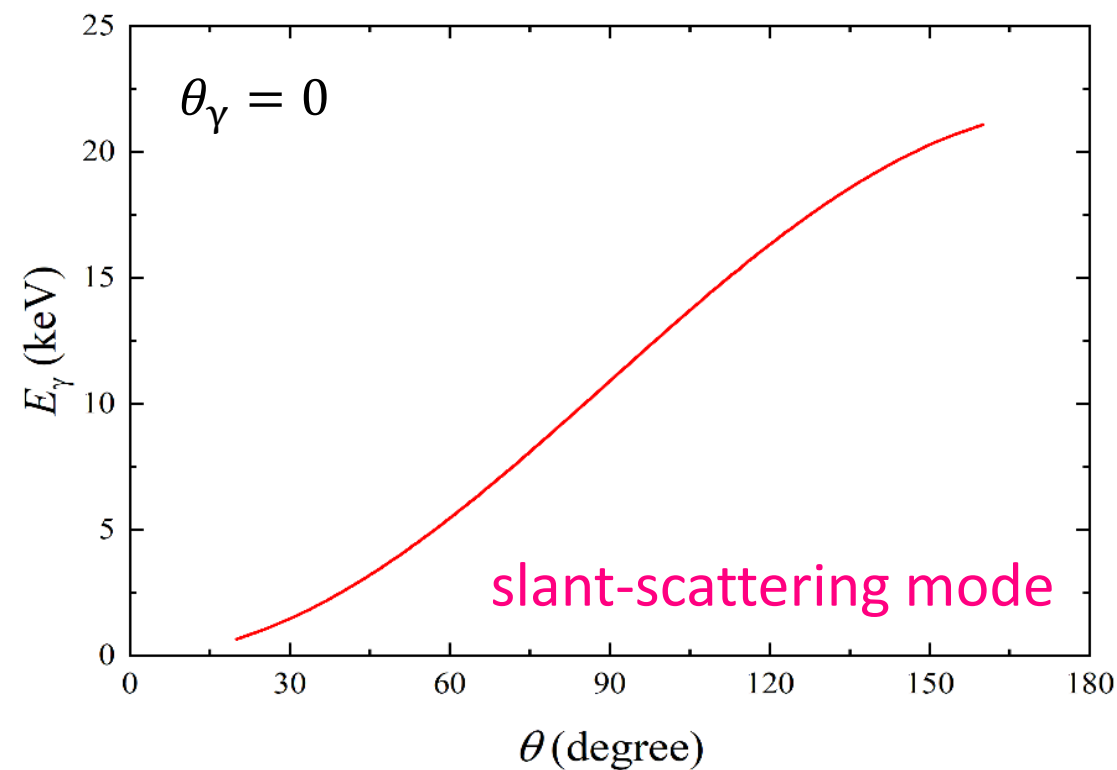
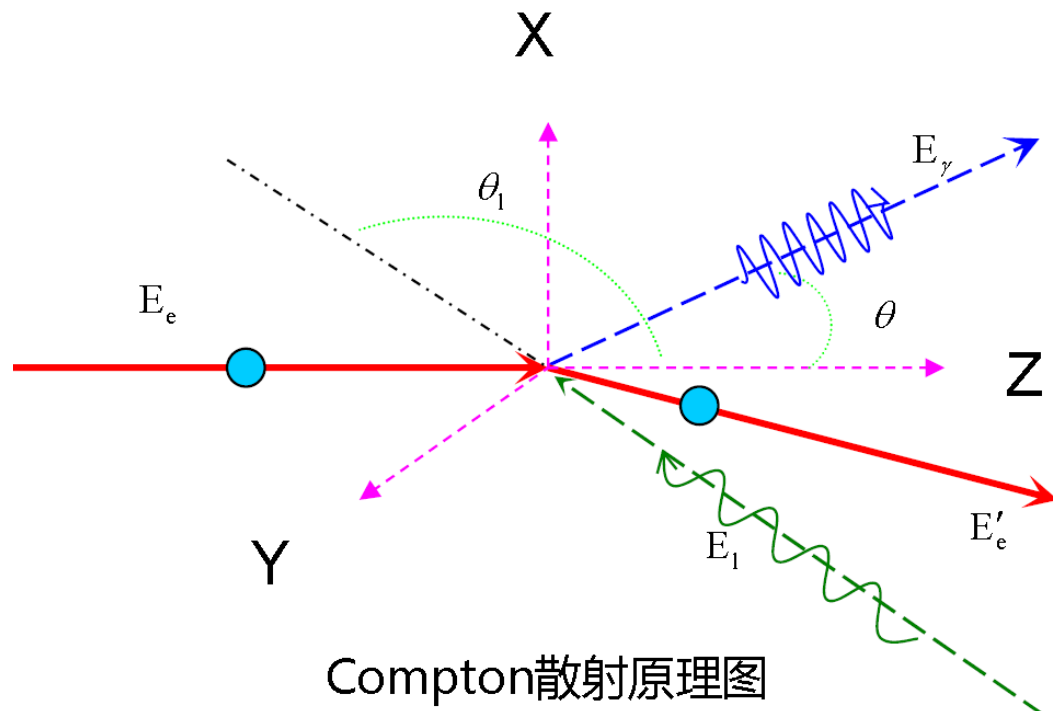
➤ **TALYS model is strongly constrained (SMLO)**



Thanks very much for your attention!

SLEGS platform

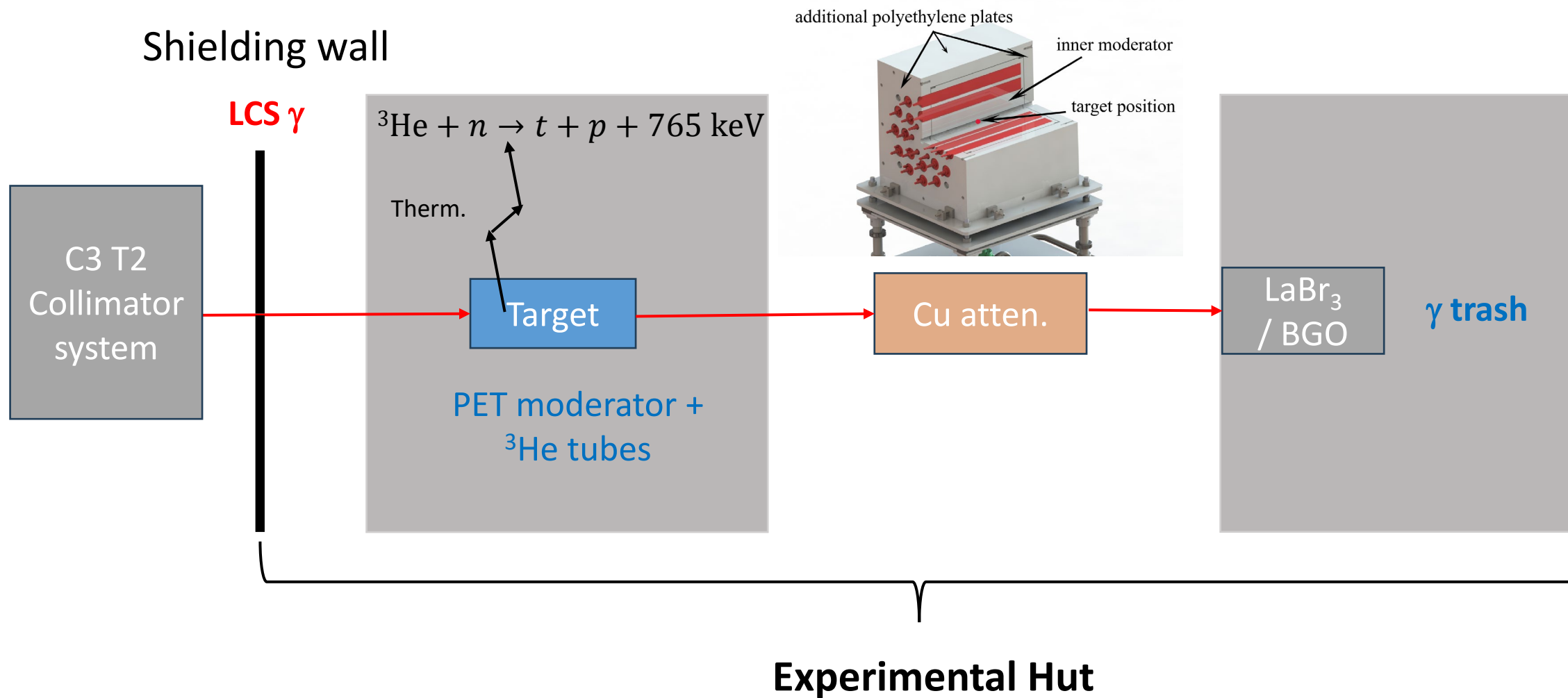
● Laser-Compton Scattering (LCS)



$$E_\gamma = \frac{E_l (1 - \beta \cos \theta_L)}{1 - \beta \cos \theta + \frac{E_l \{1 - \cos(\theta_L - \theta)\}}{E_e}}$$

SLEGS beamline

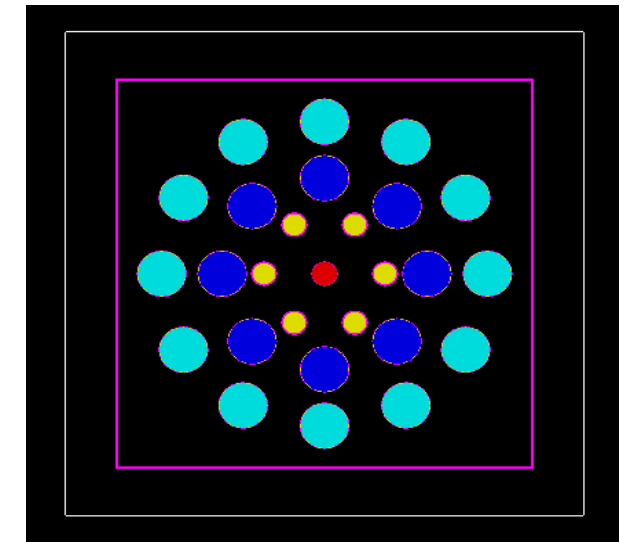
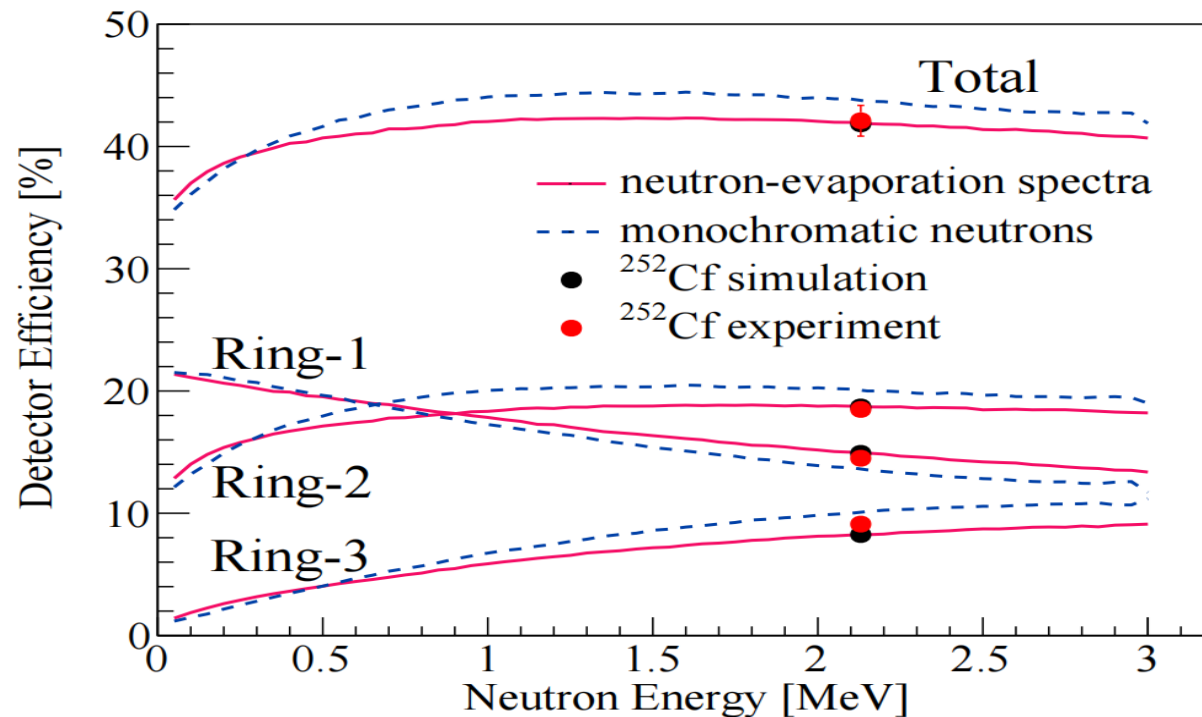
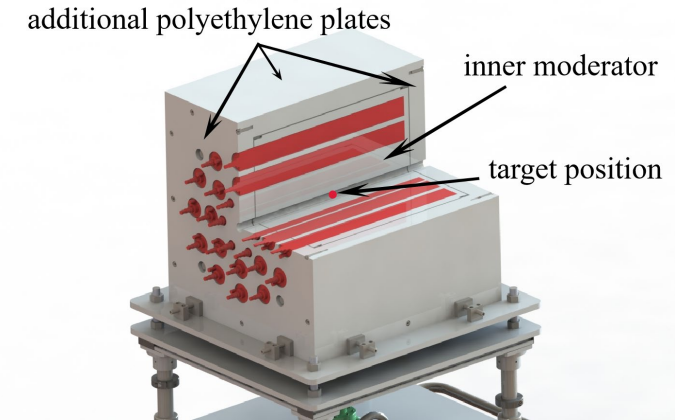
● Experimental setup for photoneutrons



SLEGS beamline

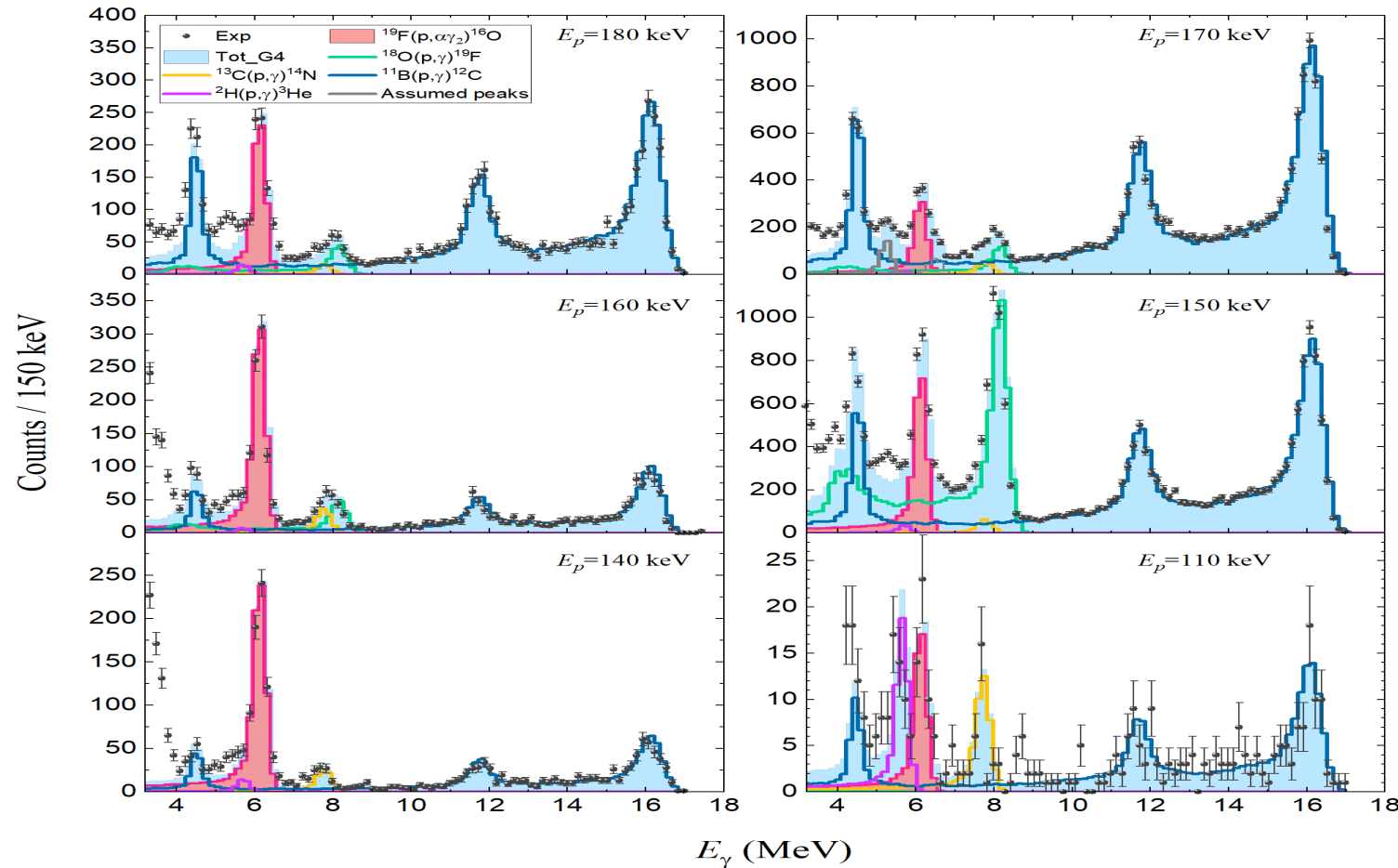
● 4 π flat efficiency neutron detector (FED)

- ◆ 26 ^3He tubes (2 atm)
- ◆ 4 π solid angle coverage
- ◆ Efficiency: 35~42% for $E_n=0.05\sim 3$ MeV



JUNA measurement of $^{19}\text{F}(\text{p},\alpha\gamma)^{16}\text{O}$

● Typical γ -ray spectra (Contamination ^{11}B , ^{13}C , ^{18}O , D)



L.Y. Zhang, J. Su, J.J. He* *et al.*, Phys. Rev. Lett. 127(2021)152702

L.Y. Zhang *et al.*, Phys. Rev. C 106(2022)055803

JUNA measurement of $^{19}\text{F}(\text{p},\gamma)^{20}\text{Ne}$

● Contribution of the 214-keV res. (<10%)

