CNO break out in first stars: Direct measurement of the key $^{19}F(p,\gamma)^{20}Ne$ reaction in JUNA

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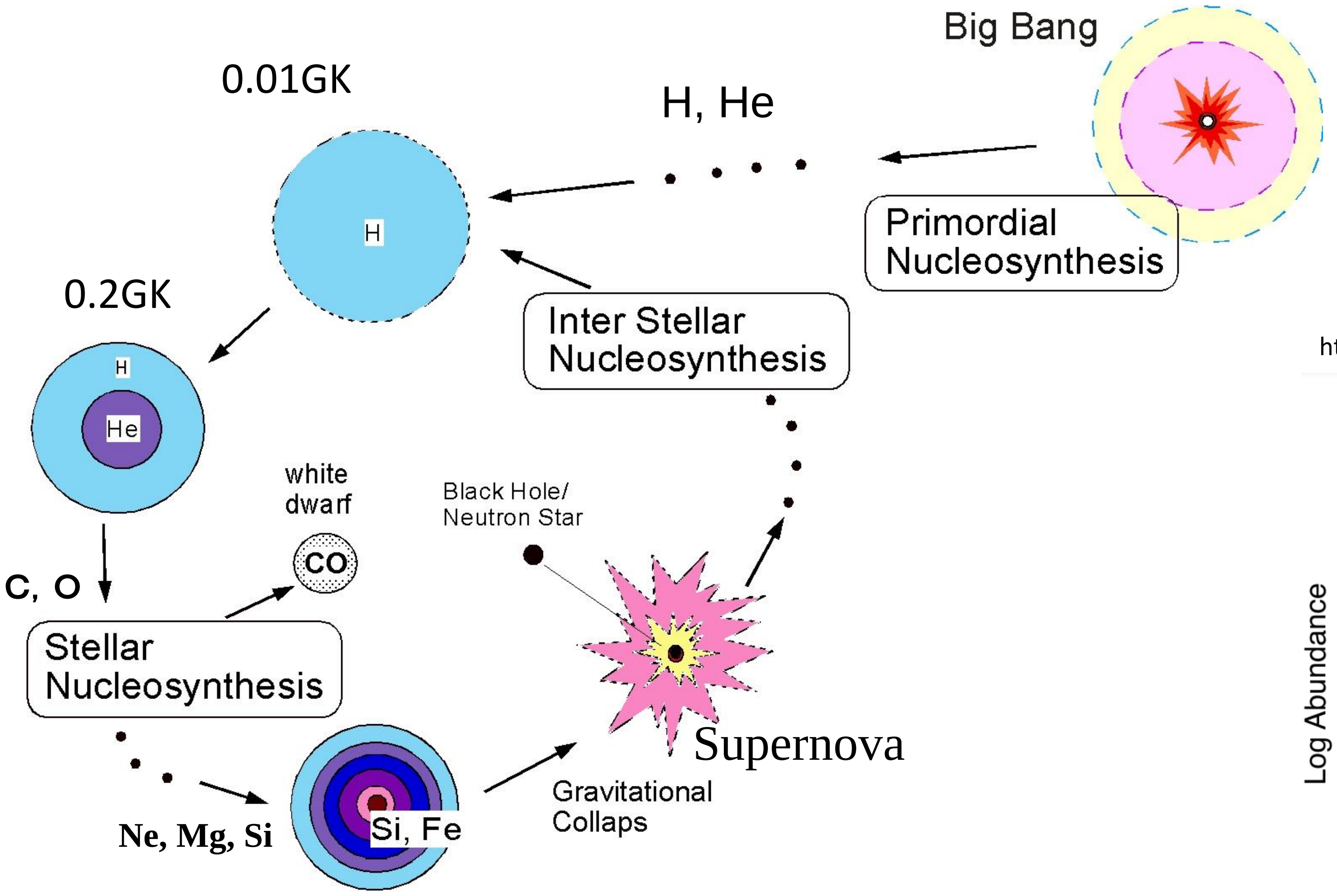
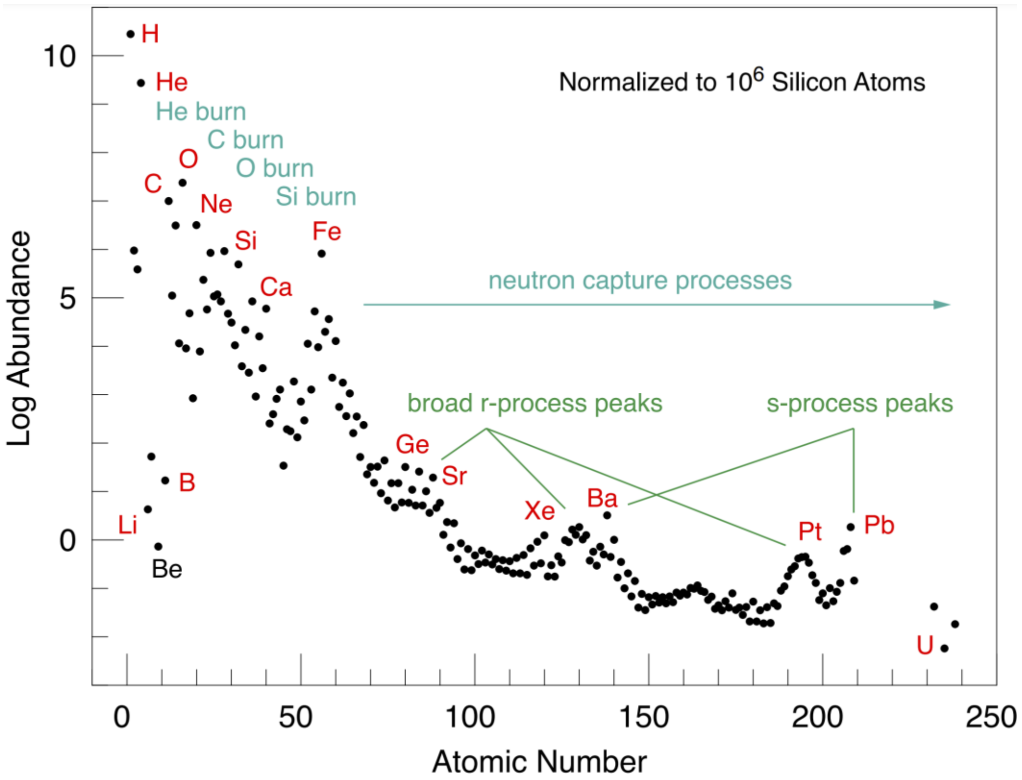
Nuclear Astrophysics



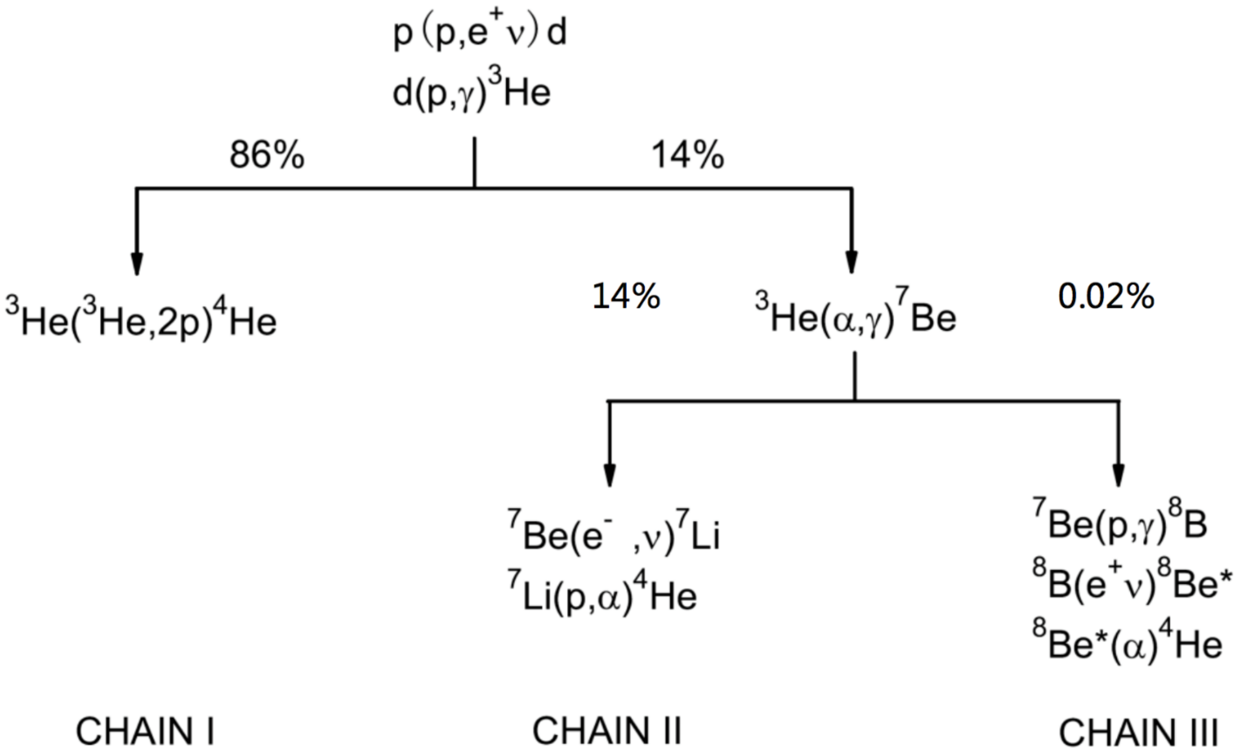
- Heavy elements were produced in stars
- Important Task: Measure important reaction cross sections

https://cococubed.com/images/astro101/abundances_atomic_number_clear.pdf

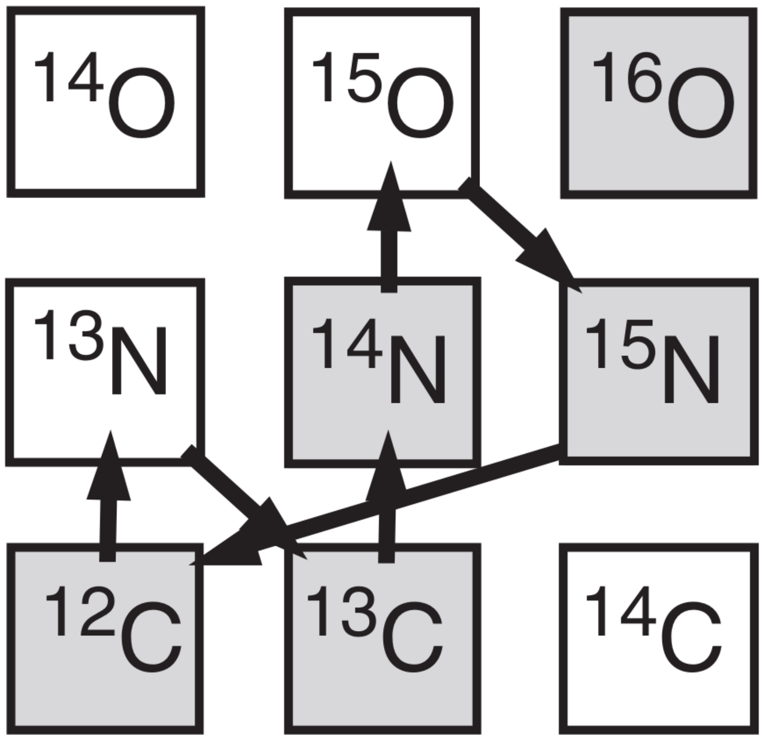


First stars: Hydron burning

p-p Chains



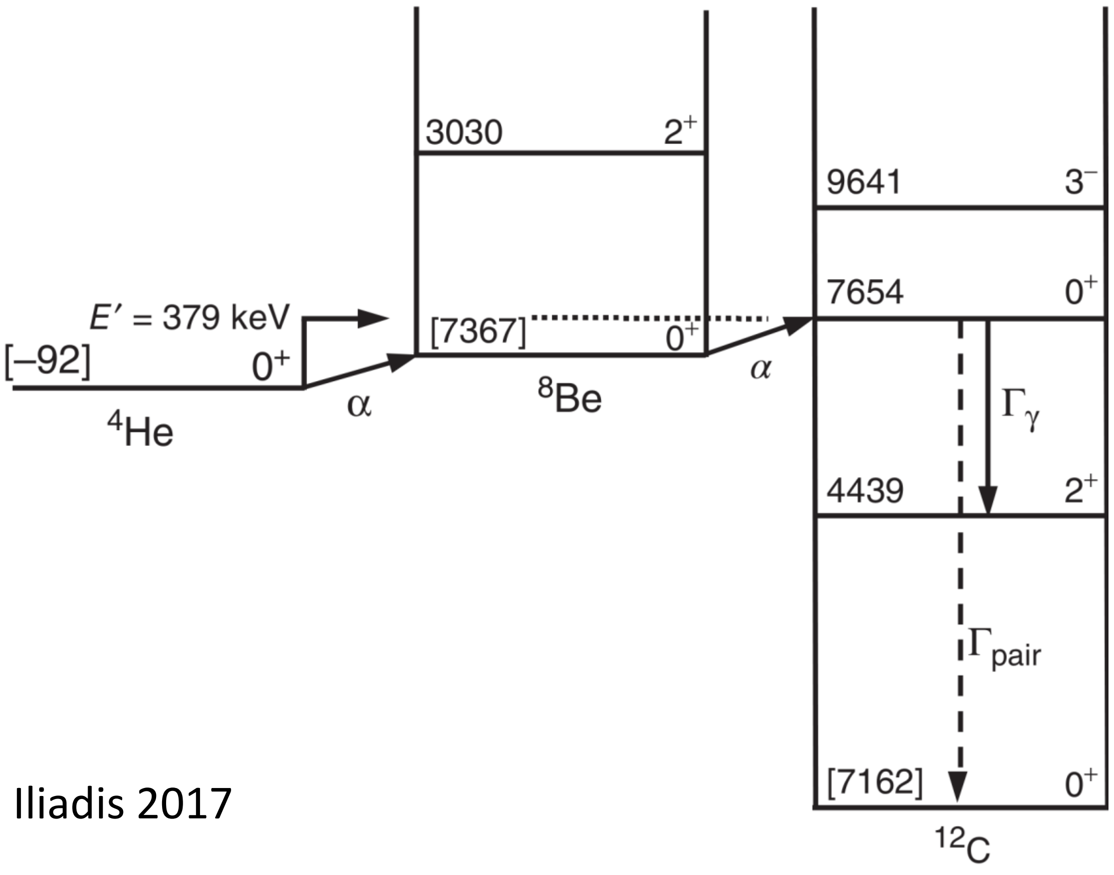
CNO cycles

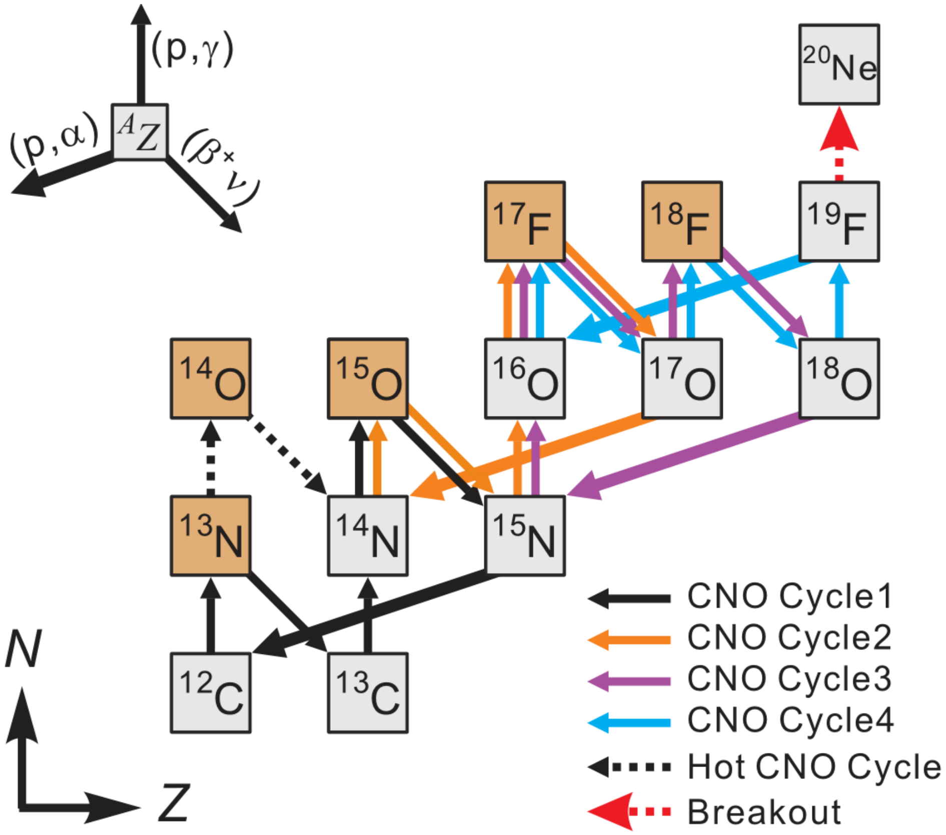


Iliadis 2017

First stars: Hydron burning

triple-α process produce ^{12}C and CNO cycles started





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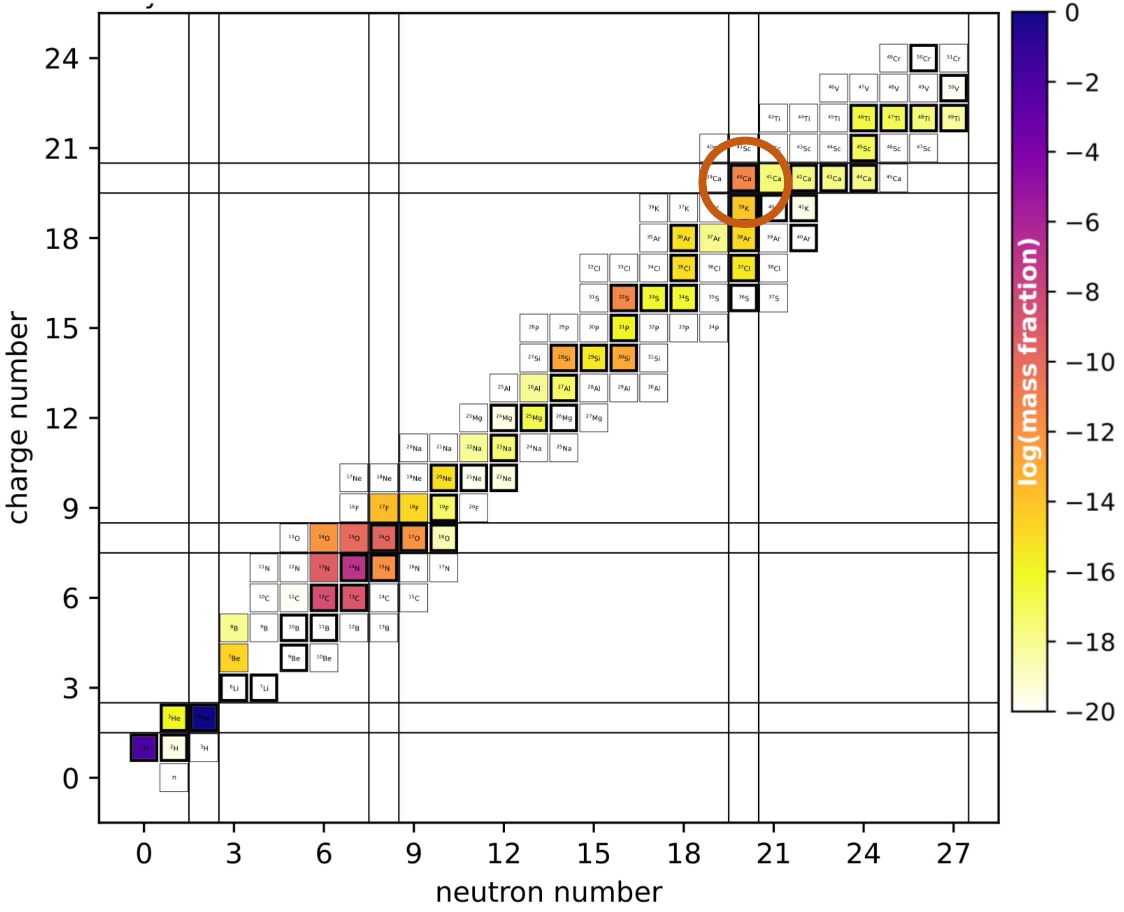
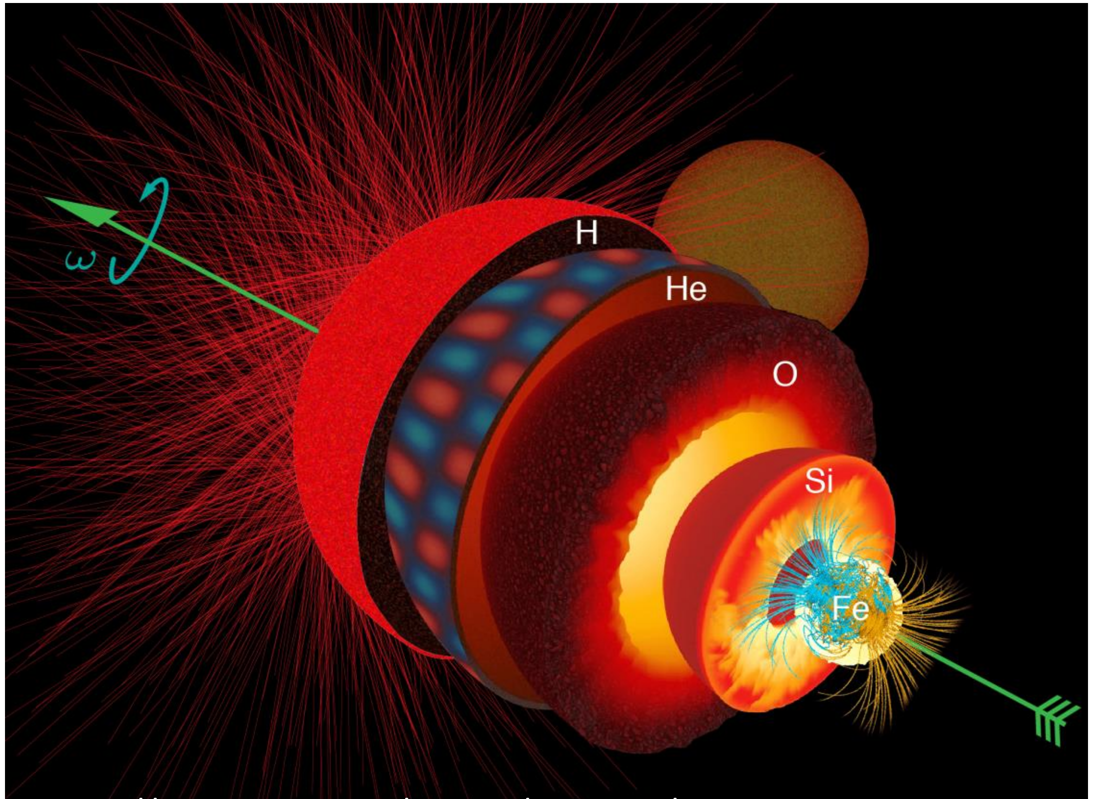
Hydrogen or silicon burning?

Ca can be produced during hydrogen burning via proton capture reactions (no iron produced)





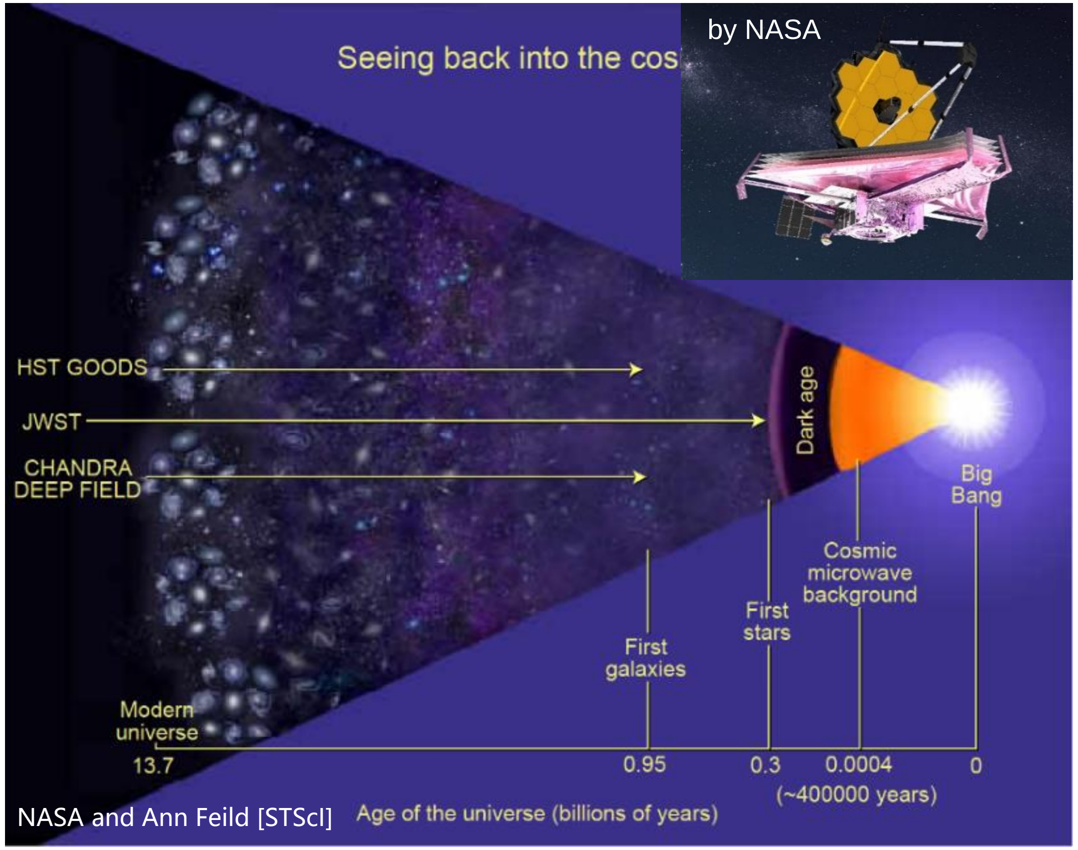
https://cococubed.com/images/astro101/massive_star_onion.png

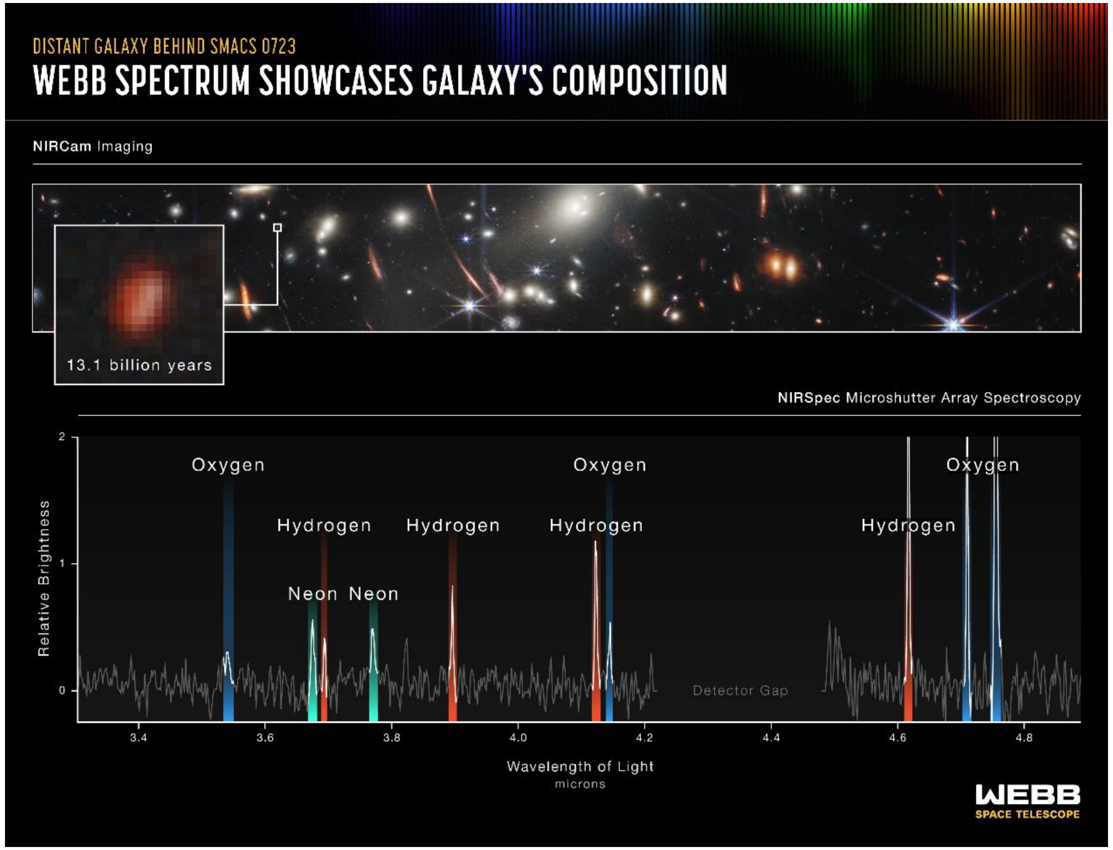
Ca can also be produced in the Si shell, and ejected together with iron via supernova burst

Observe the elemental abundance of first stars

First stars: Observation

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





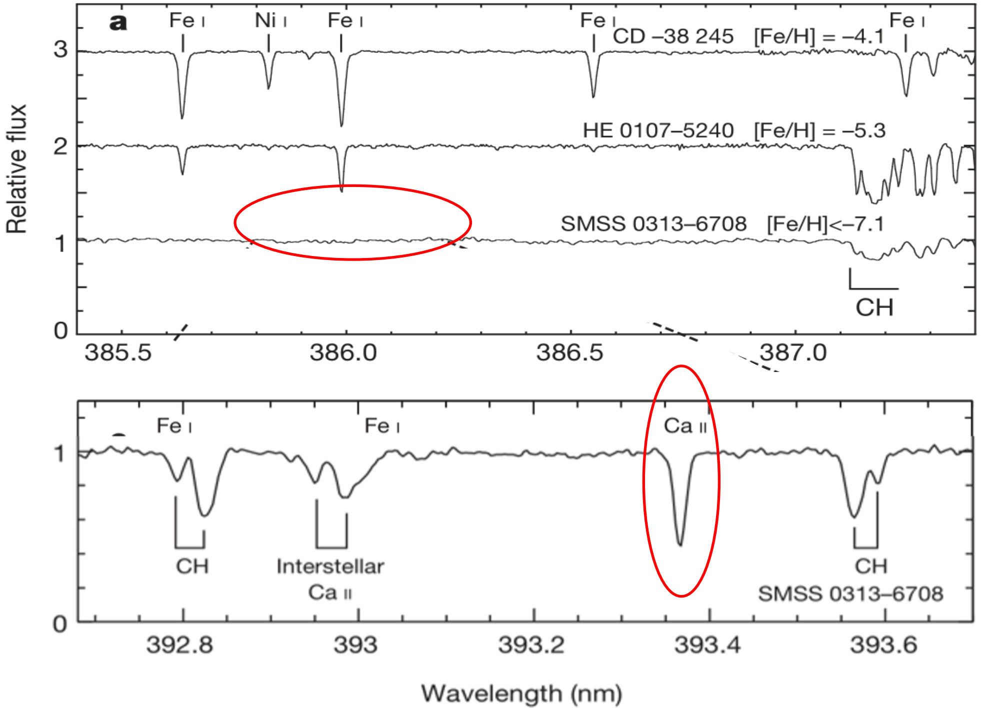
Analyze the spectrum, get elemental abundance information

First stars: Observation

First stars -> Supernova -> nebula -> second generation star(SMSS 0313-6708)

S.C. Keller et al., Nature 506 (2014) 463

~6000 light year from Earth, formed 13.7 billion years ago, shortly after the Big Bang. It' s the oldest star yet found.



The oldest star, SM0313-6718:

- Ca were observed without Fe
- Ca could be produced during hydrogen burning stage
- **The $^{19}F(p,\gamma)^{20}Ne$ reaction should be 7-10 times larger to reproduce the Ca abundance**

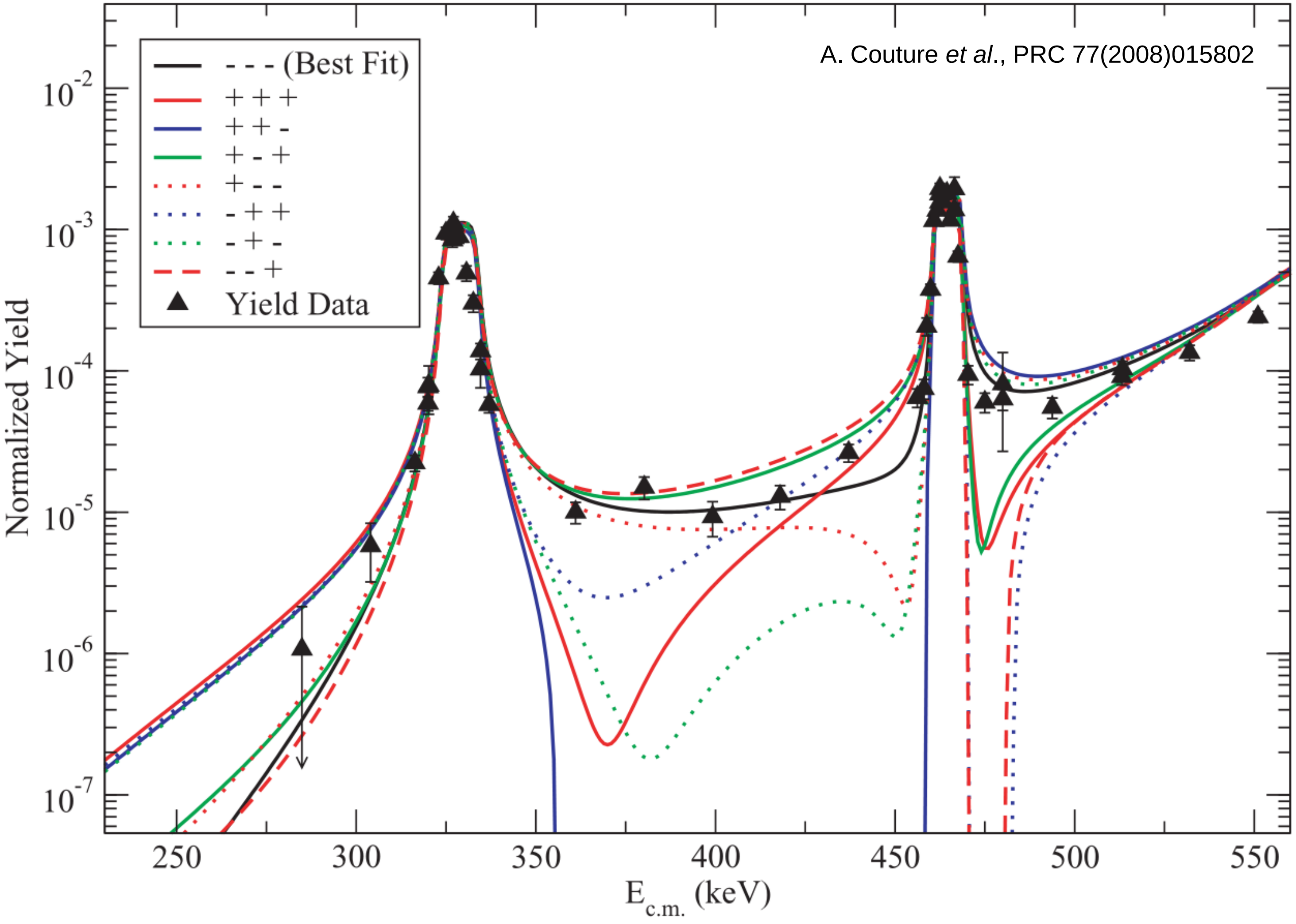
$^{19}F(p,\gamma)^{20}Ne$: Experimental measurement

Recent measurement:

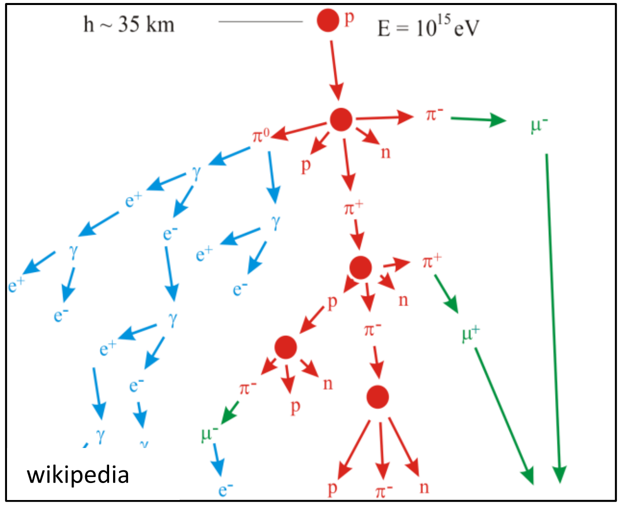
- Experimental data: ~300 keV
- Gamow window : 100 keV
- Possible resonance not observed

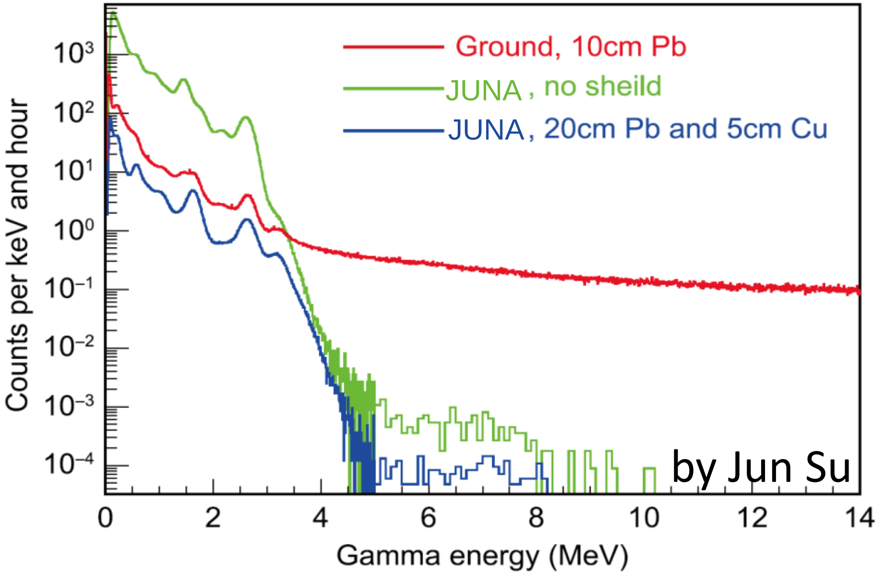
Challenges due to extremely low cross section:

- Cosmic ray induced background
- Target stability



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



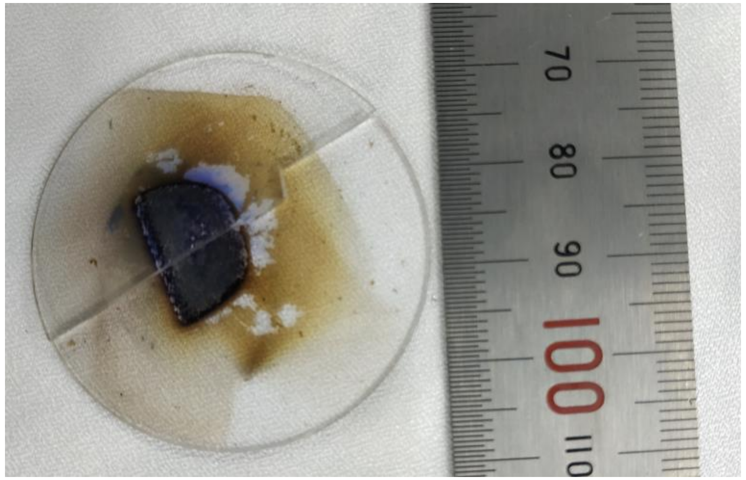


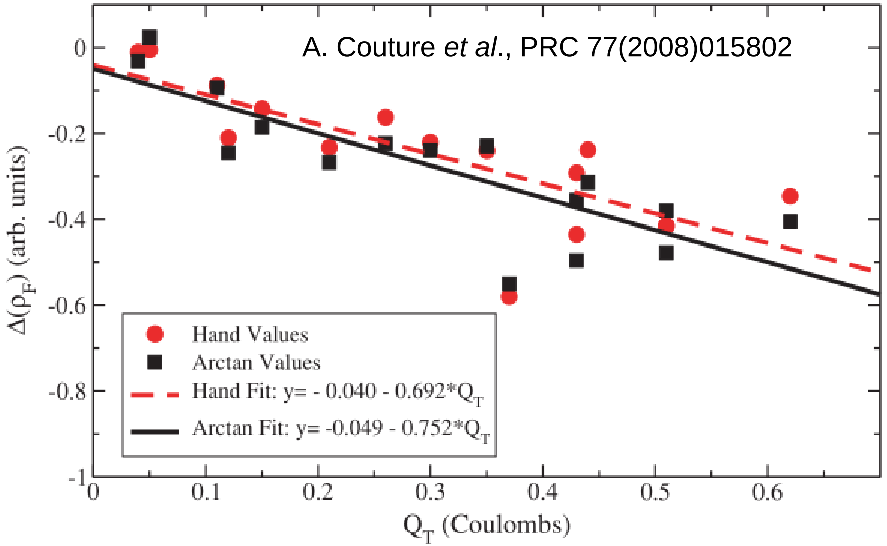
Cosmic-ray induced background:

- high energy proton hit on atmosphere atoms, produce μ
- μ loss energy in detectors, produce background single

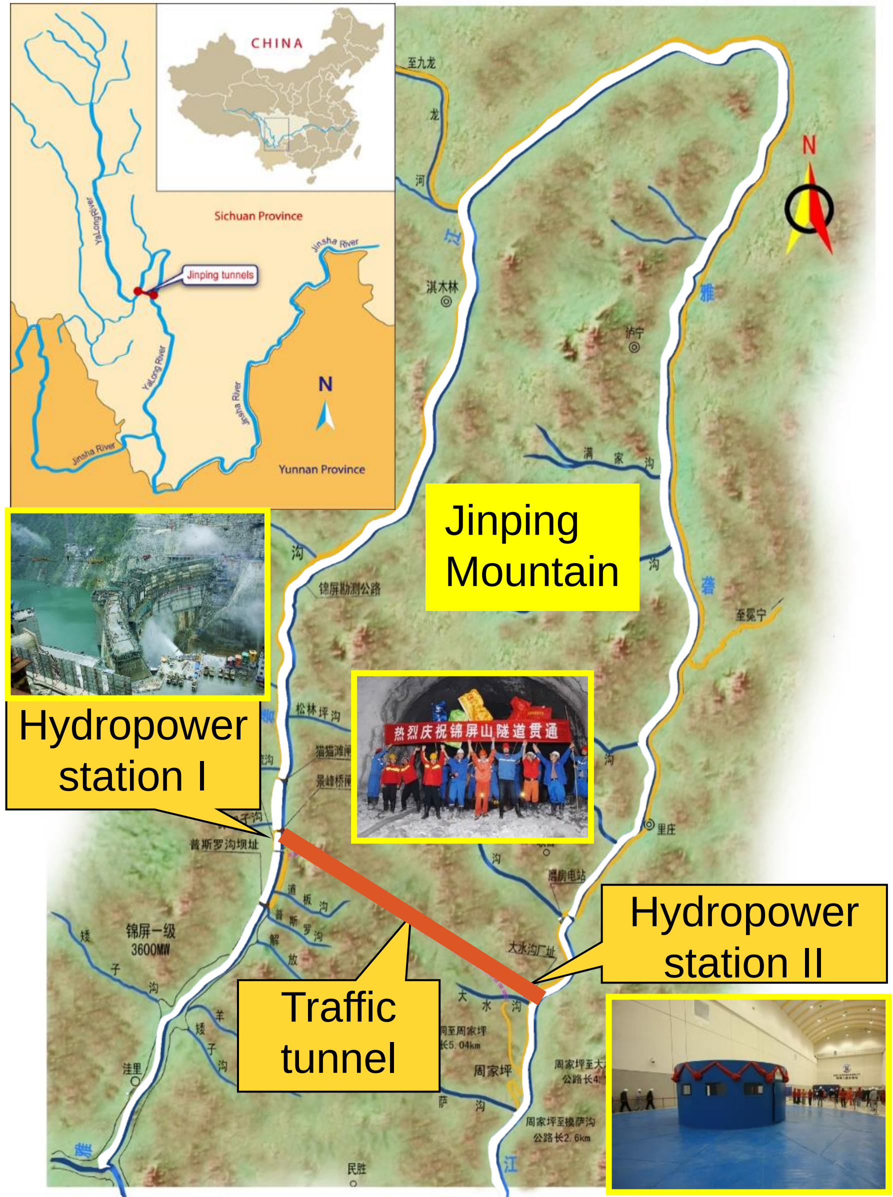
Target stability:

- Heat damage
- Target atom loss
- Change of composition
- Contamination atoms

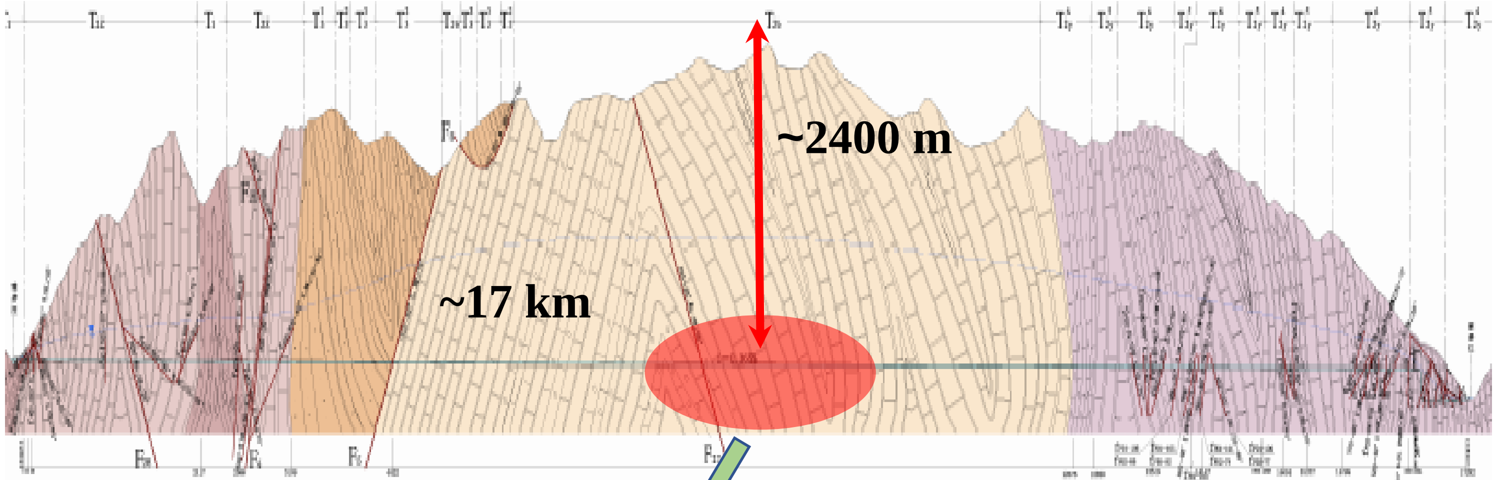




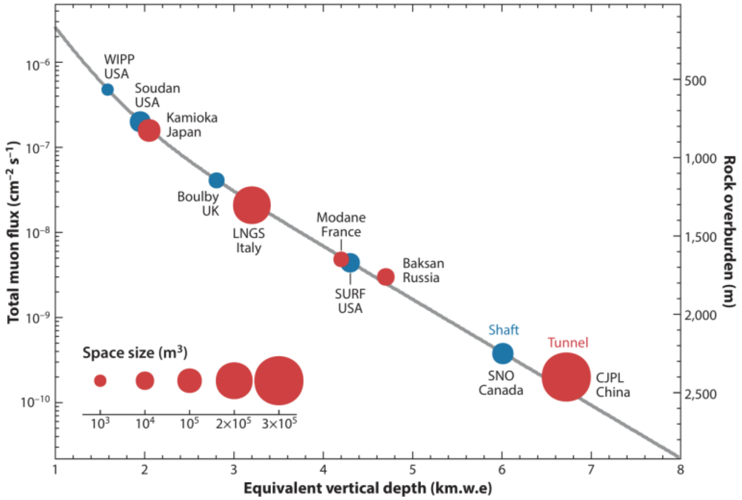
Reduce the cosmic-ray background



JUNA: Jinping Underground Nuclear Astrophysics experimental facility

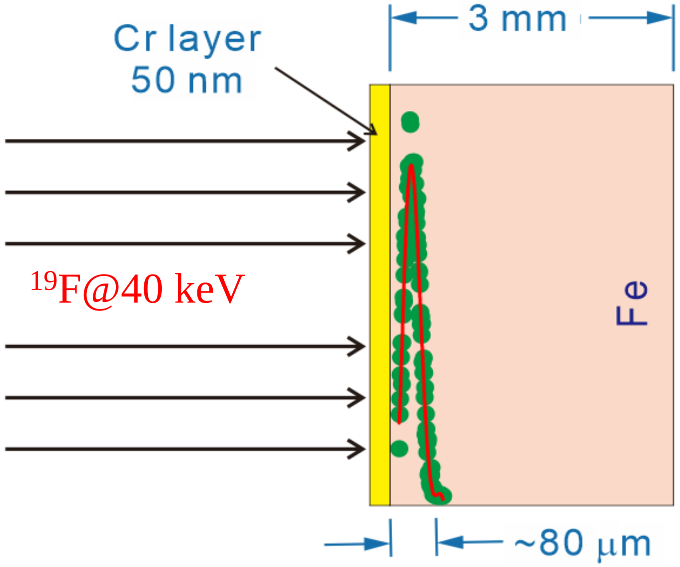


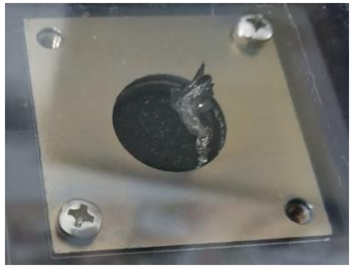
~10^4 γ-ray background reduction

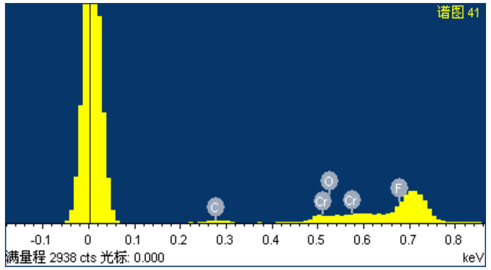


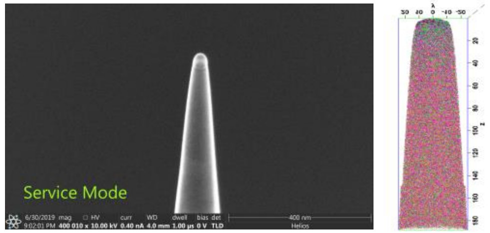
Stable ^{19}F target

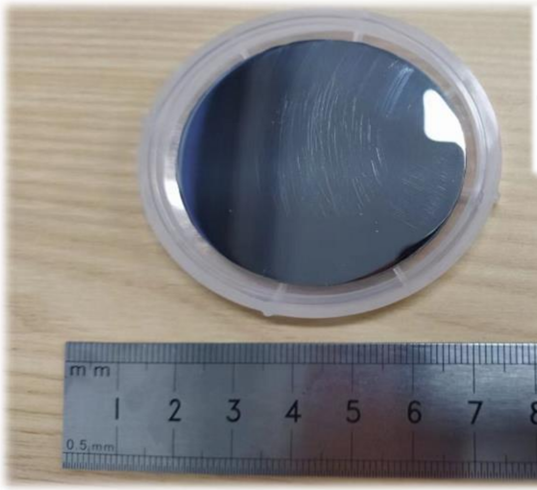
- Implant ^{19}F into Fe backing
- Apply Cr foil to protect ^{19}F
- No material loss after 200 C proton bombardment

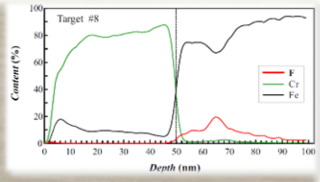


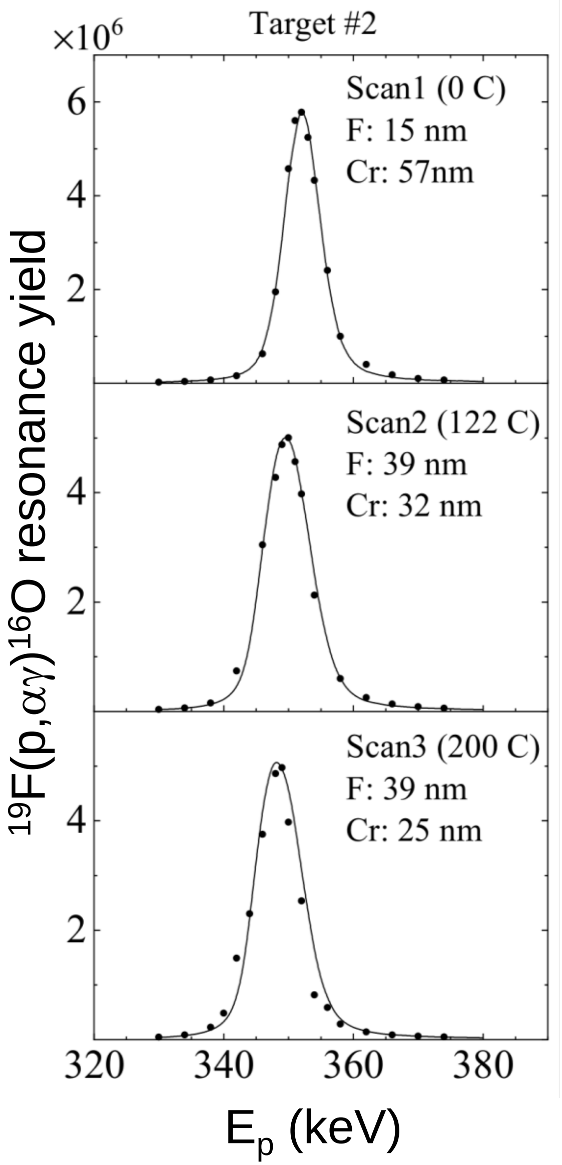












L.Y. Zhang *et al.*, Nucl. Instr. Meth. B 438（2019）48
L.Y. Zhang *et al.*, Nucl. Instr. Meth. B 496（2021）9

JUNA: Jinping Underground Nuclear Astrophysics experimental facility

Weiping Liu

PI $^{12}C(\alpha,\gamma)^{16}O$

Xodoiang Tang

PI $^{13}C(\alpha,n)^{16}O$

Zhihong Li

PI $^{25}Mg(p,\gamma)^{26}Al$

Jianjun He

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

Gang Lian

PI 共用平台

People in our group

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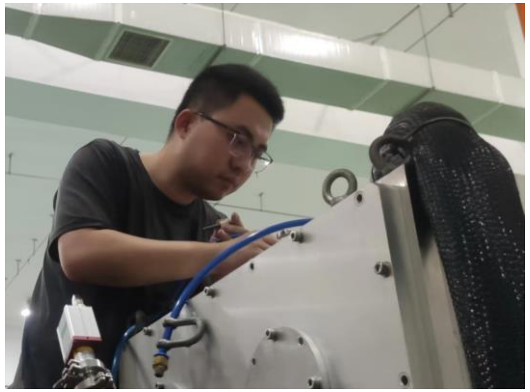
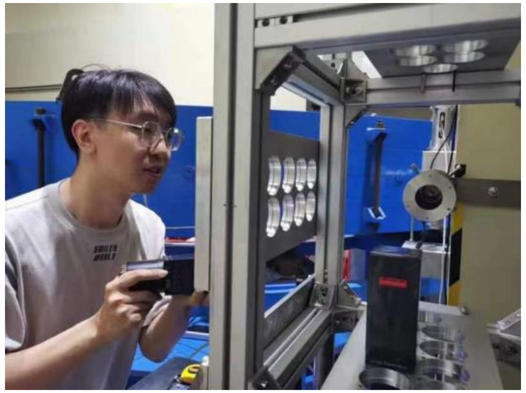
Prof. Jun Su
Associate Prof. Liyong Zhang
Postdoctor Xinyue Li


Hao Zhang


Yaode Sheng

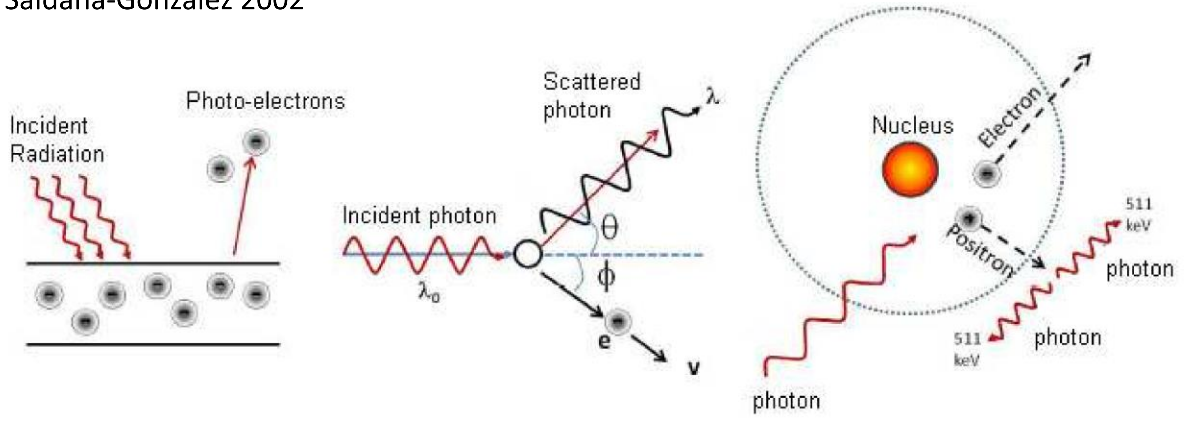

Zhilin Sheng and Shen Lin


Xin Chen

From left to right： Fuqiang Cao, Long Zhang, Zhicheng Zhang, Xinyue Li, Luohuan Wang, Liyong Zhang, Jianjun He, Jun Su, Xinzhi Jiang, Luyang Song, Ziming Li, and Yinji Chen

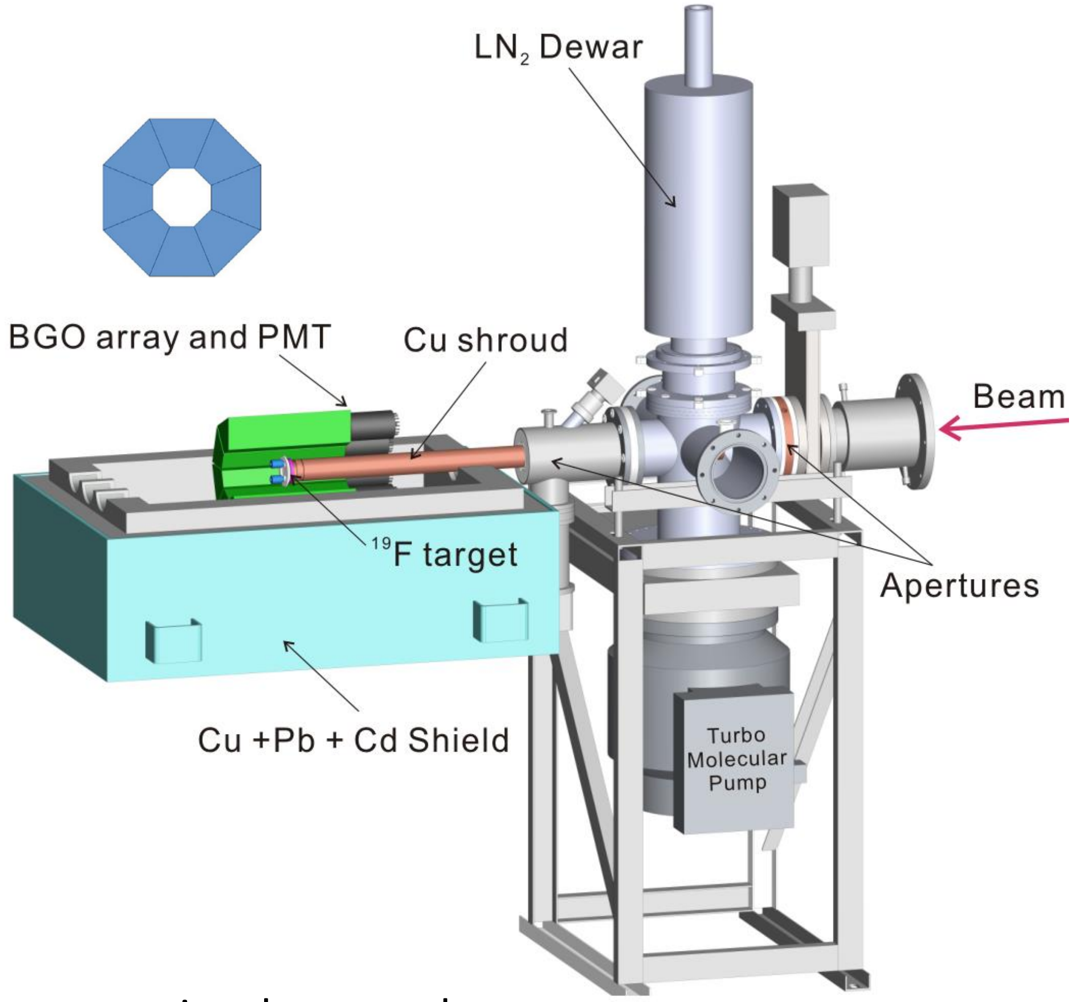
^{19}F(p,γ)^{20}Ne: Experimental setup

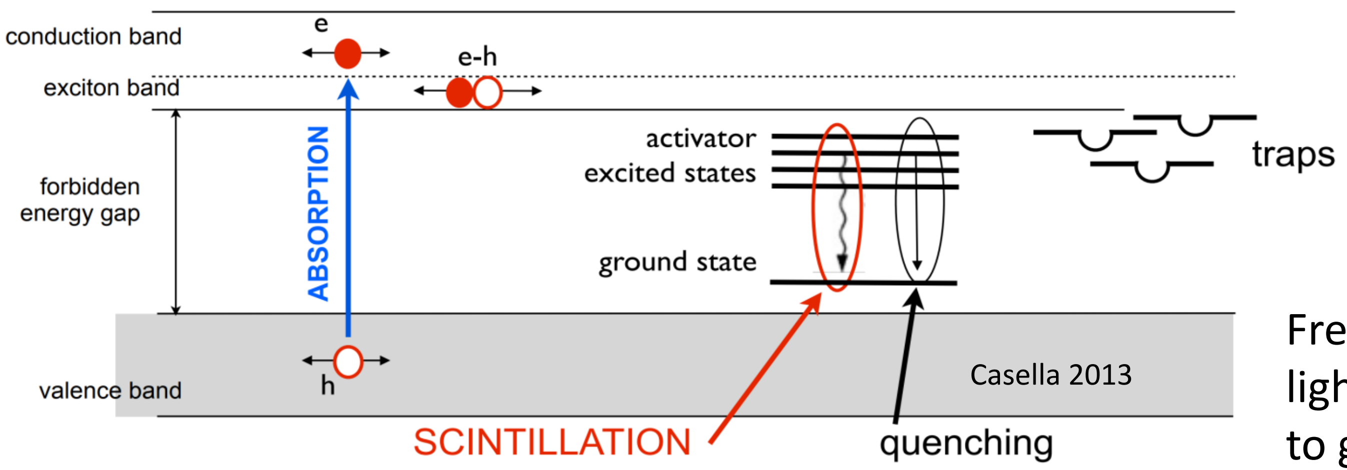
Saldana-Gonzalez 2002



(a) Photoelectric effect (b) Compton effect (c) Pairs production

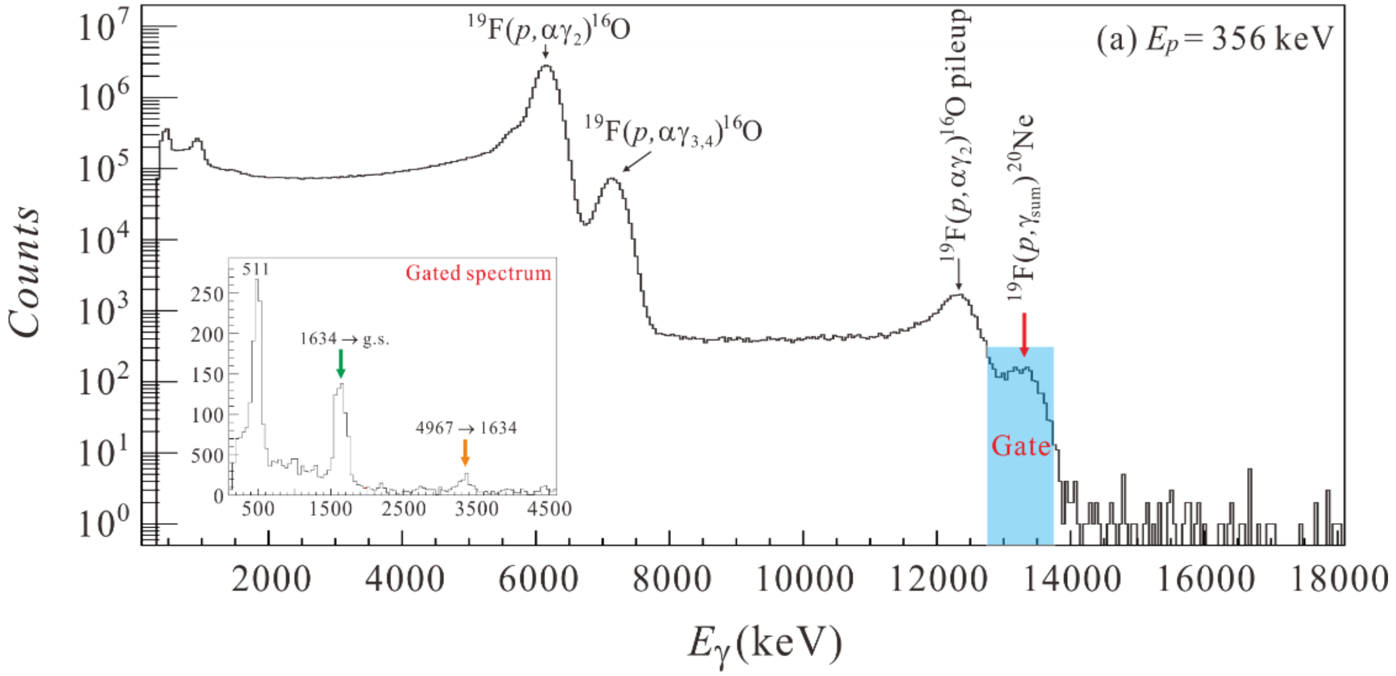
γ rays absorbed by the crystal, produce free electrons

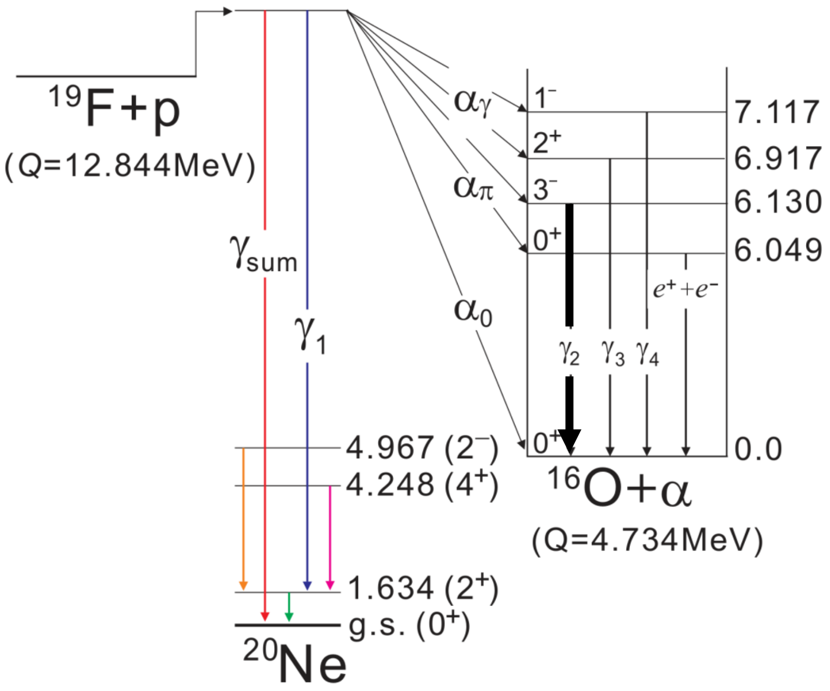


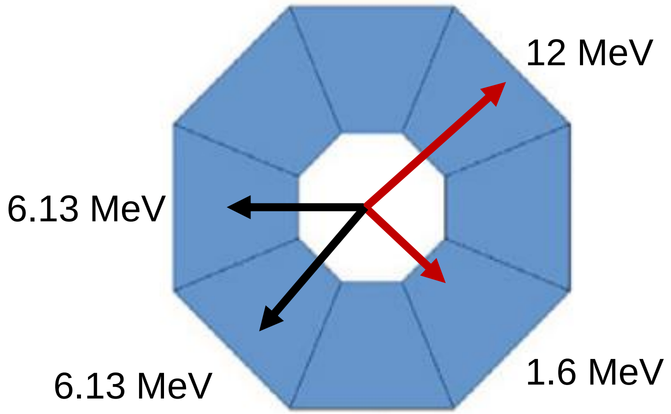


Free electrons excite the crystal atom, light emitted when excited atom decay to ground states

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

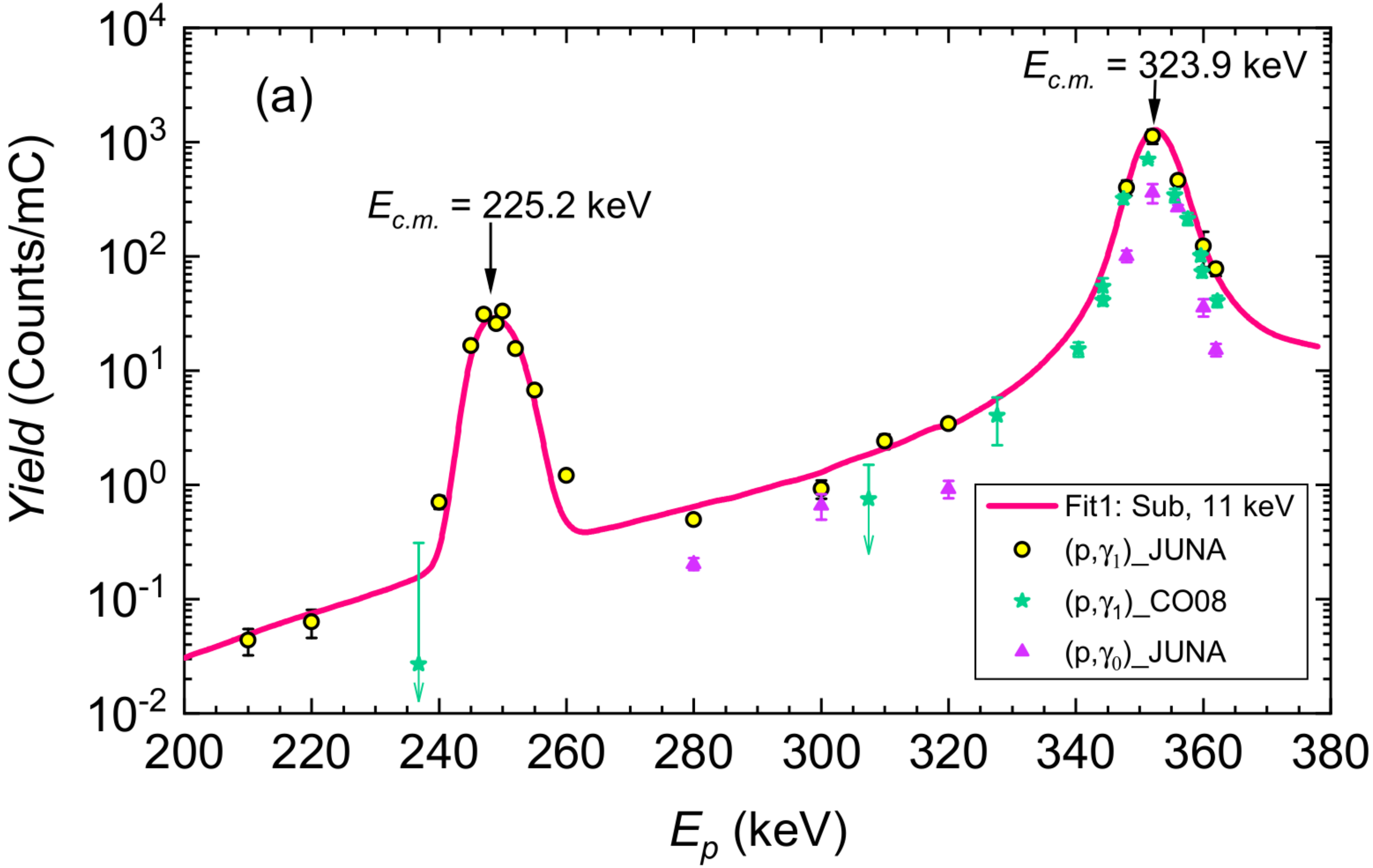






- Most transition decays via the 1.63 MeV state
- Coincidence between the ‘sum’ and ‘single’ energy further reduced the background

$^{19}F(p,\gamma)^{20}Ne$: A new resonance

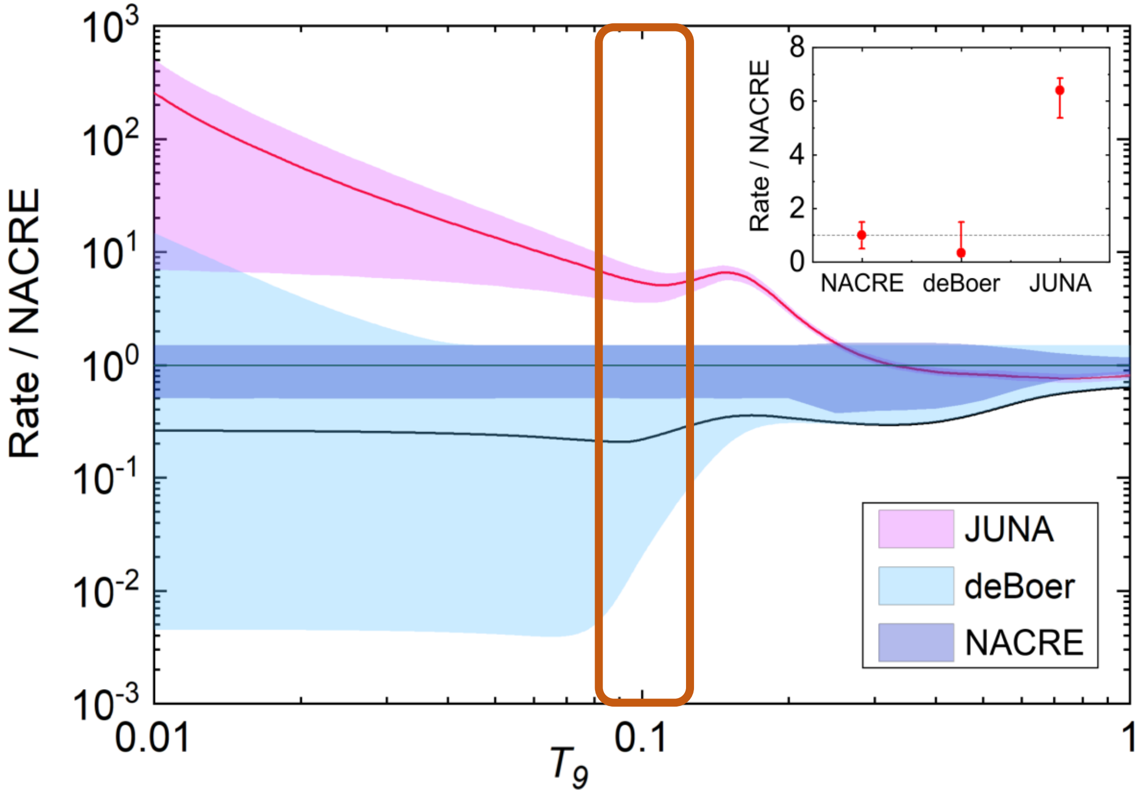


- The $^{19}F(p,\gamma)^{20}Ne$ reaction was measured to the lowest energy of $E_{c.m.}$=186 keV
- A new resonance at 225 keV was observed for the first time
- R-Matrix analyze was applied to get full energy region data

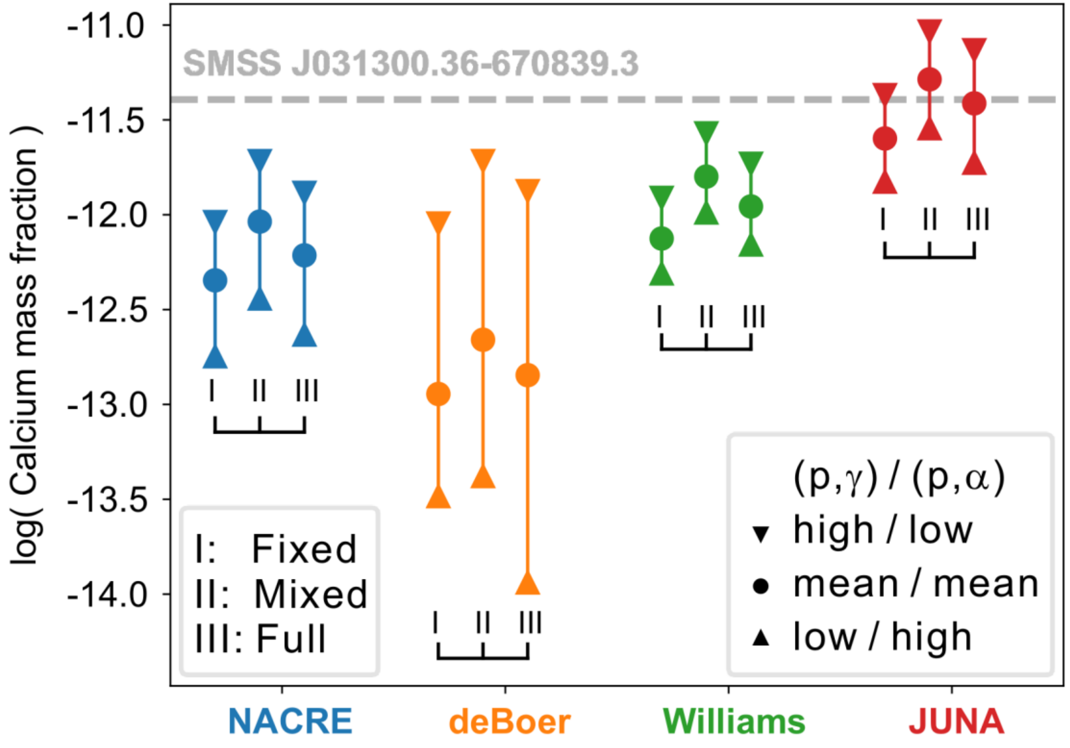
Reproduce the observed ^{40}Ca abundance

New reaction rate:

- 7.4 times larger than previous estimation
- 3 times more precise



L.Y. Zhang, J.J. He, R. J. deBoer *et al.*, Nature **610** 656 (2022)



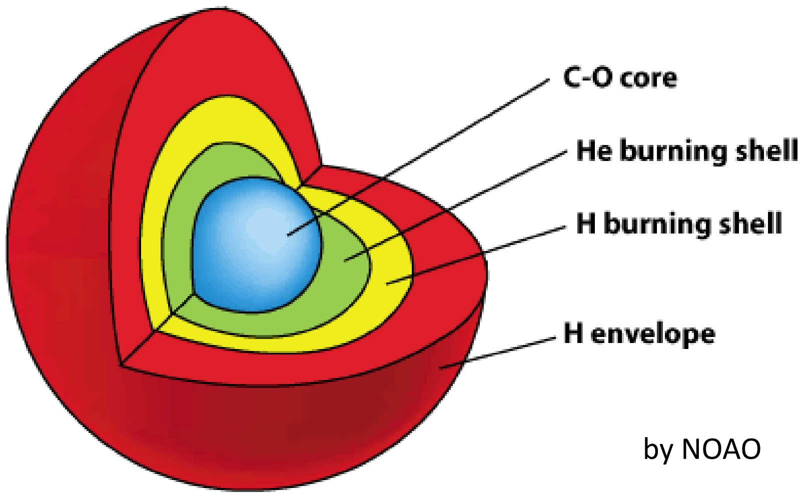
Astrophysical influences:

- Reproduced the observed ^{40}Ca abundance, and may reveal the nature of calcium production
- Support the ***faint*** supernova model

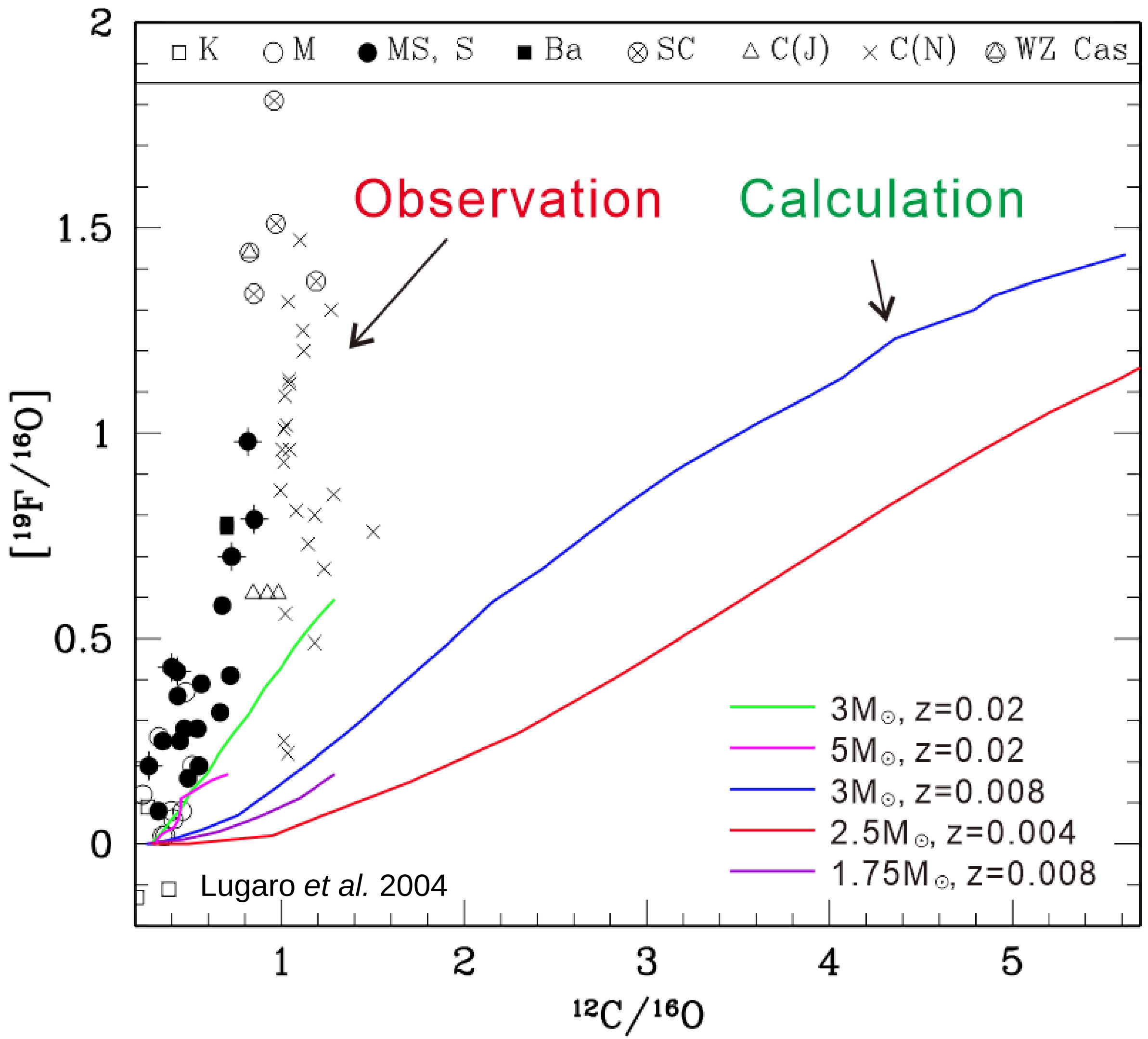
The fluorine overabundance problem

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

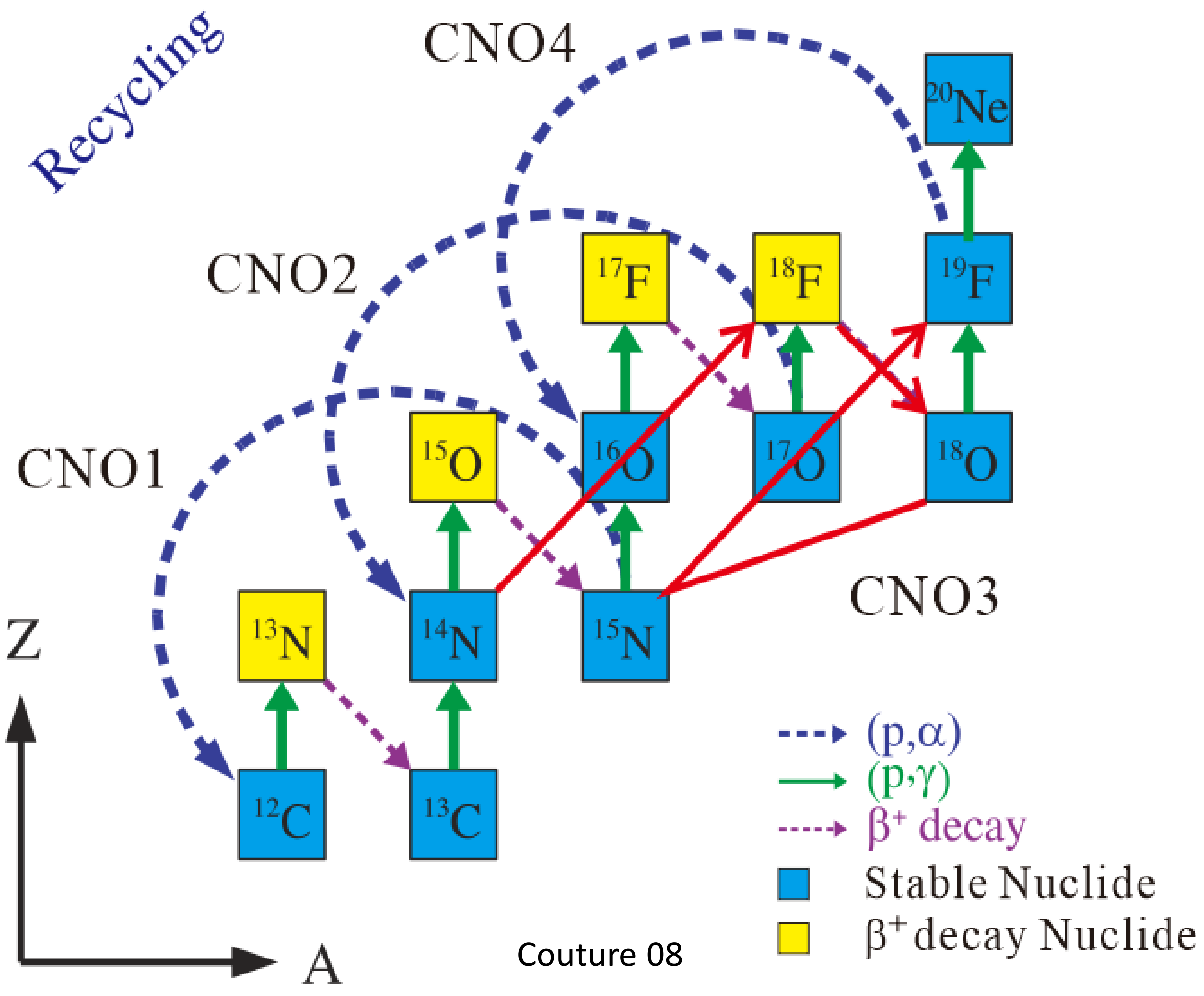
- ^{19}F could be produced in AGB stars
- The observed ^{19}F abundance is much higher than calculated ones
- Need to precisely measure the $^{19}F(p,\alpha\gamma)^{16}O$ reaction cross section



Asymptotic Giant Branch, AGB star



$^{19}F(p,\alpha\gamma)^{16}O$ reaction in AGB stars

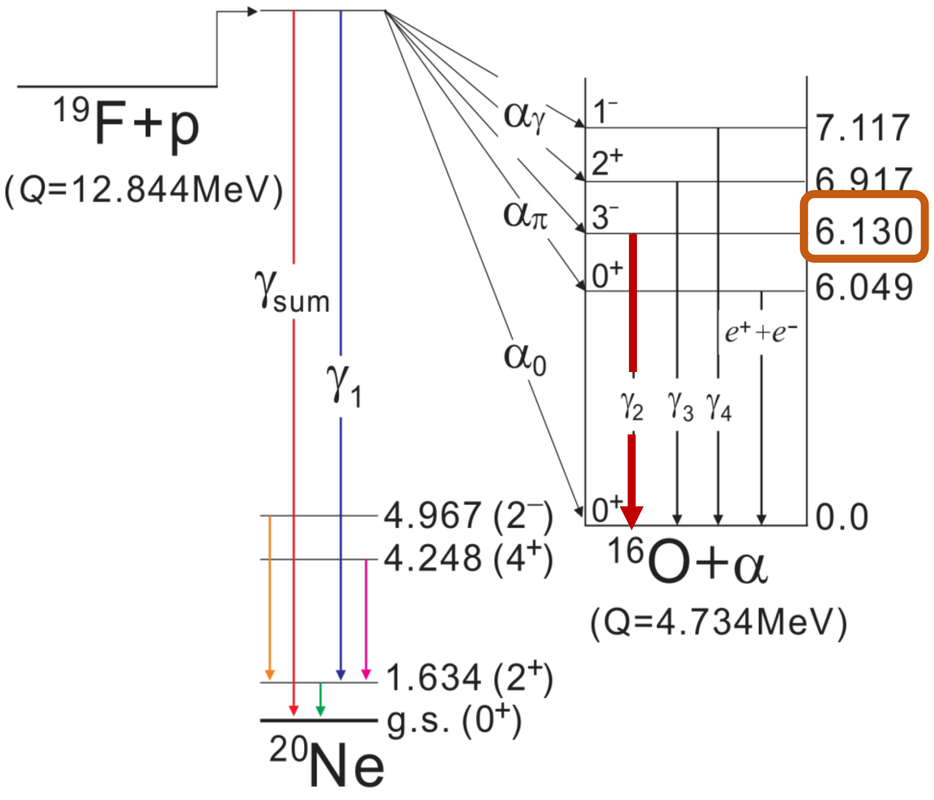


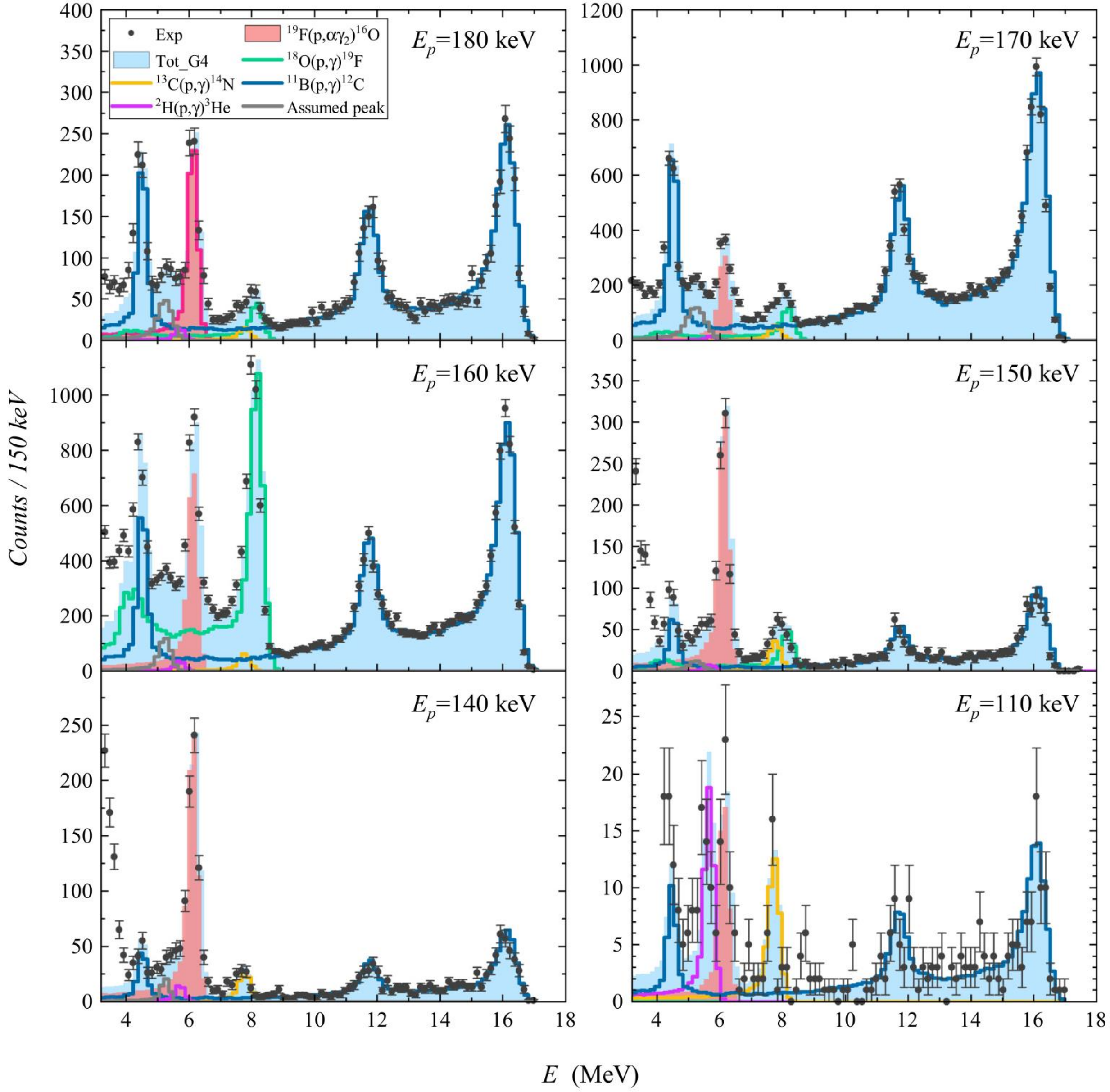
Couture 08

Destruct Reactions:

- $^{19}F(p,\alpha)^{16}O$
- $^{19}F(\alpha,p)^{22}Ne$
- $^{19}F(p,\gamma)^{20}Ne$
- $^{19}F(\alpha,\gamma)^{23}Na$

$^{19}F(p,\alpha\gamma)^{16}O$: Fluorine over abundance problem

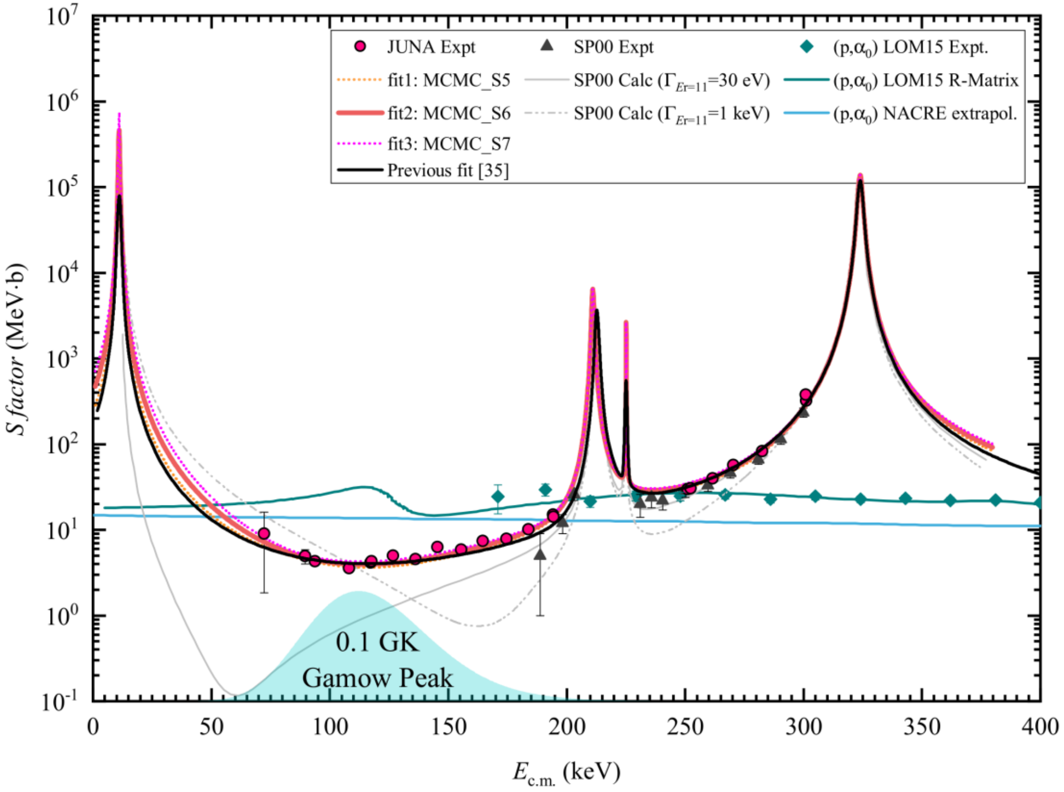


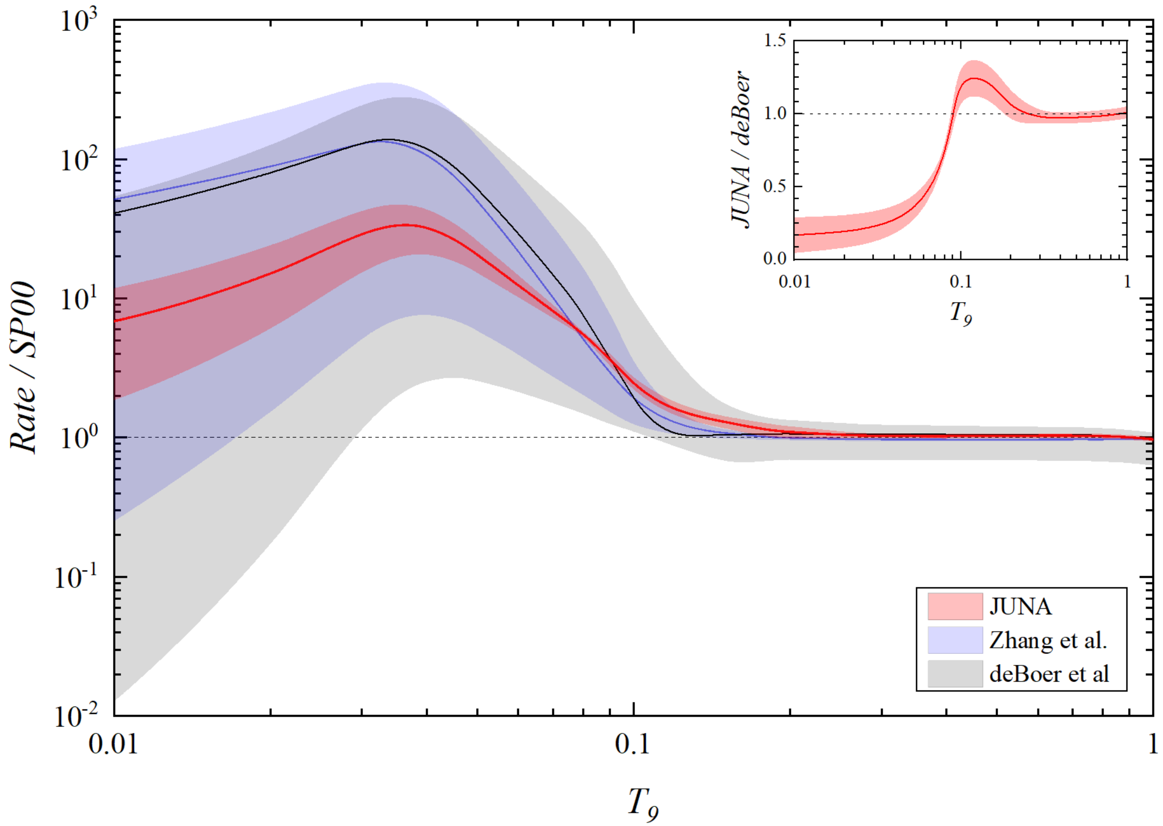


- Focused on the 6.130 MeV transition
- More sensitive to target contaminations

First measurement in the Gamow window

- First measurement in Gamow window of AGB stars
- Uncertainty was reduced by 10^3
- Clarified the contribution of (p,$\alpha\gamma$) channel





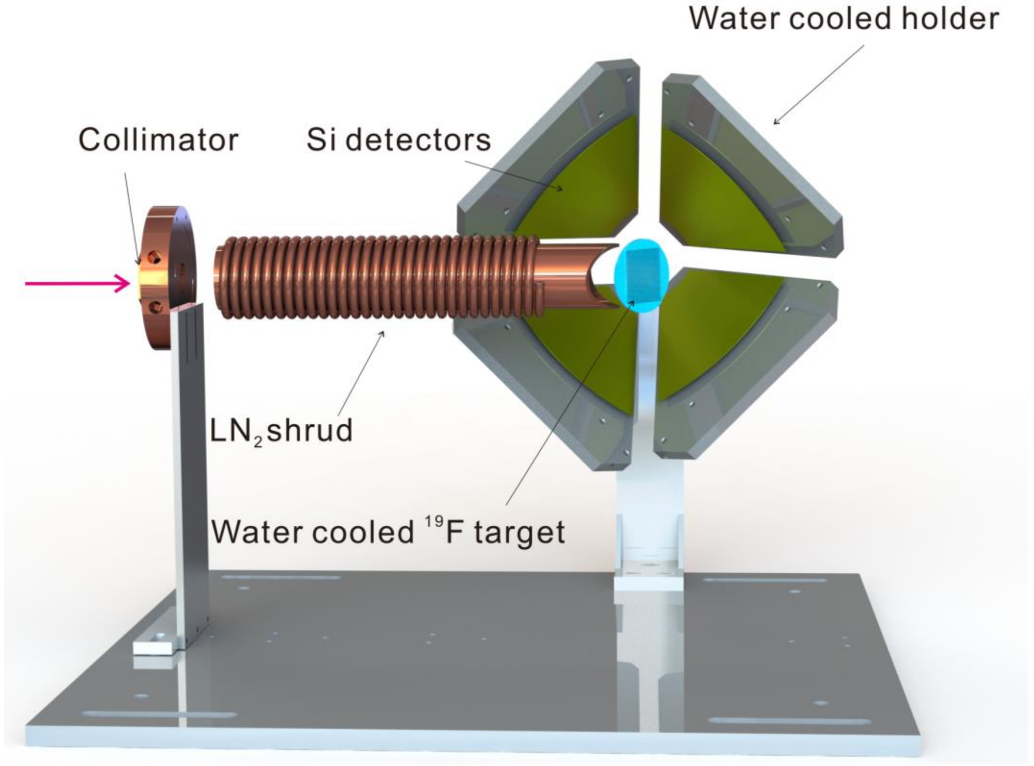
L.Y. Zhang, J. Su, J.J. He *et al.*, Phys. Rev. Lett. 127(2021)152702

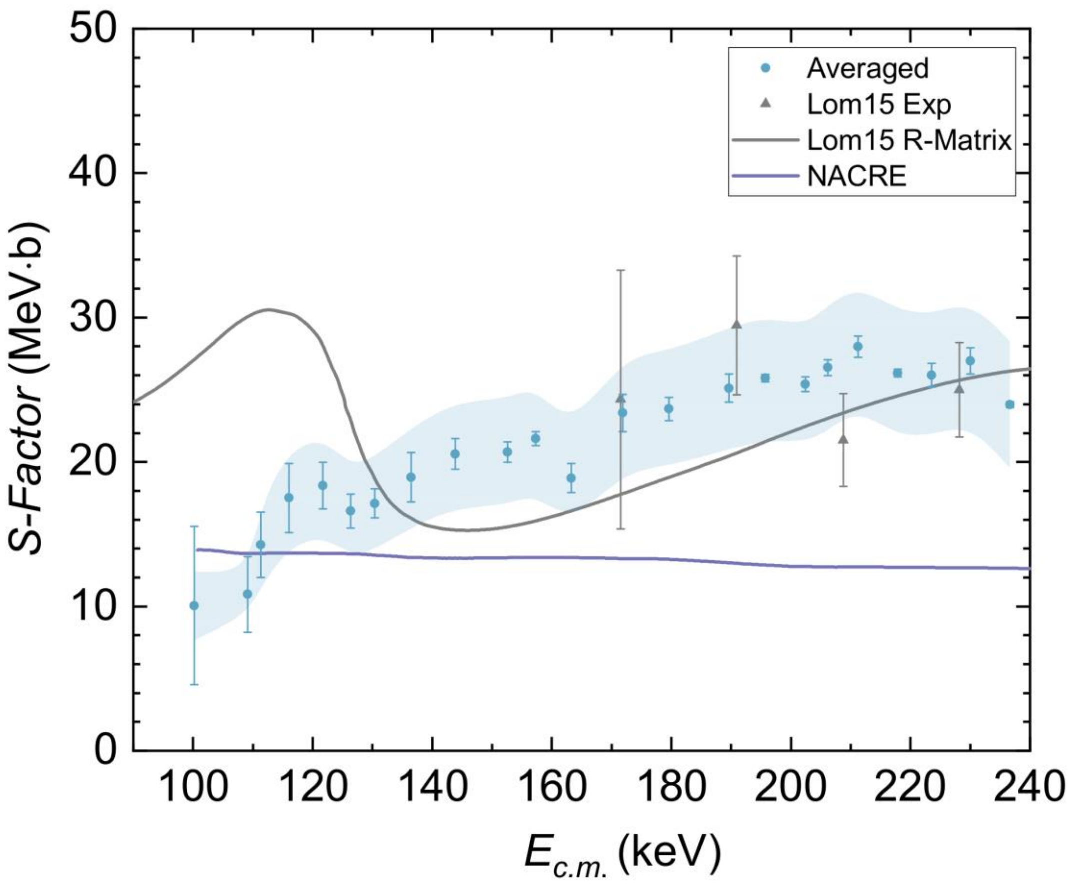
L.Y. Zhang, J. Su, J.J. He *et al.*, Phys. Rev. C. 106, 055803 (2022)

$^{19}F(p,\alpha_0)^{16}O$: Dominate at low energies

$^{19}F(p,\alpha_0)^{16}O$:

- Measured in above-ground lab (HINEG, High Intensity DT fusion Neutron Generator)
- 3 mA proton beam + stable ^{19}F targets
- Position sensitive silicon detectors





- Lowest energy region
- R-matrix analyzing in progress
- No resonance was observed, the (p,α_0) channel contribution may be reduced

Summary

- First stars formed out of the matter of the Big Bang
- Hydrogen were burned via CNO cycles, and ^{40}Ca could be produce via the $^{19}F(p,\gamma)^{20}Ne$ breakout reaction
- A new resonance at $E_{c.m.}$=225 keV were found in JUNA
- The new rate can reproduce the observed Ca abundance of the first stars
- Our results strongly support the faint supernova model
- The $^{19}F(p,\alpha\gamma)^{16}O$ and $^{19}F(p,\alpha_0)^{16}O$ reaction were also measured, which are critical for the fluorine over abundance problem in AGB stars

Thank you