JUNA deep underground nuclear astrophysics studies

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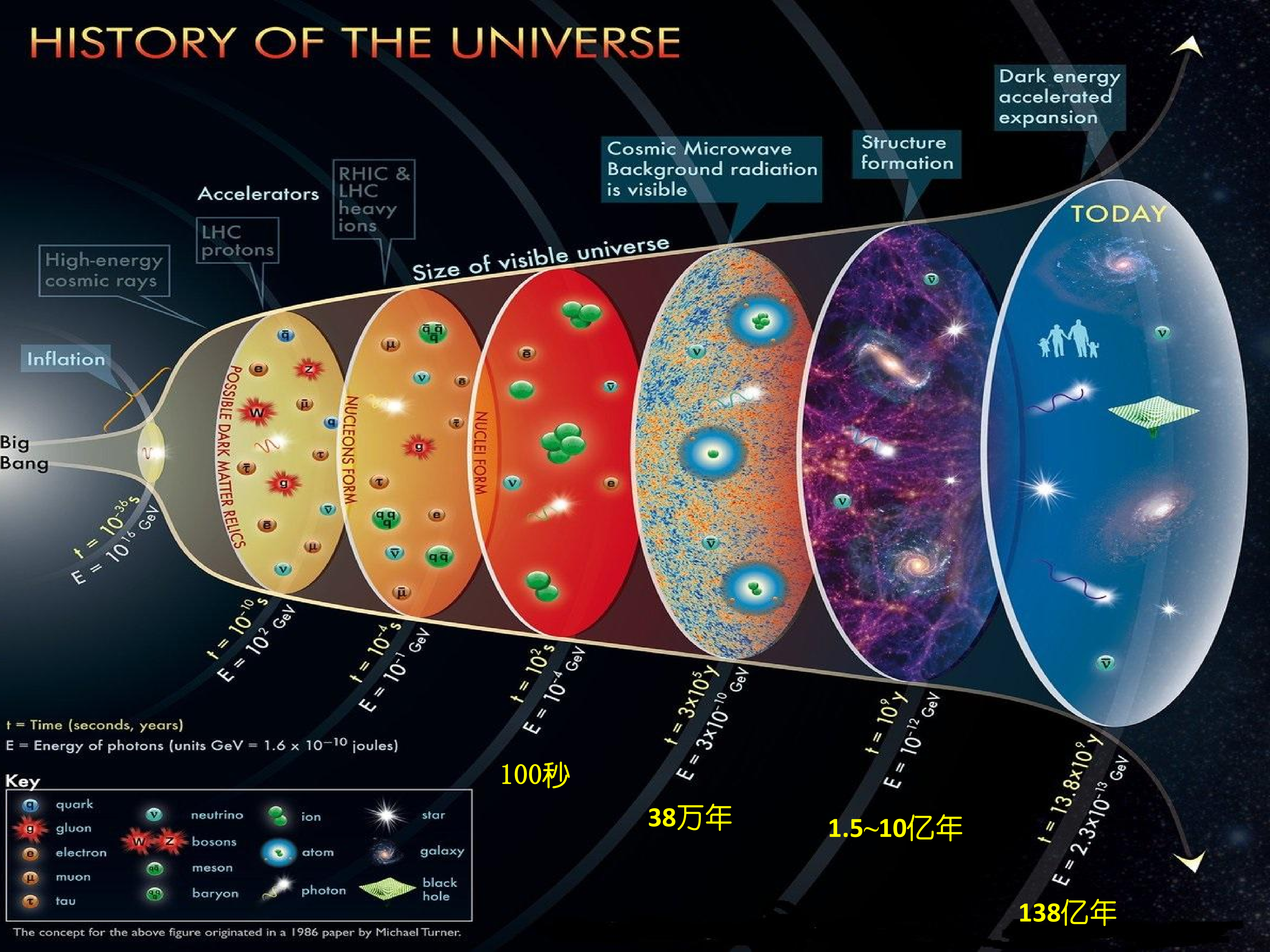
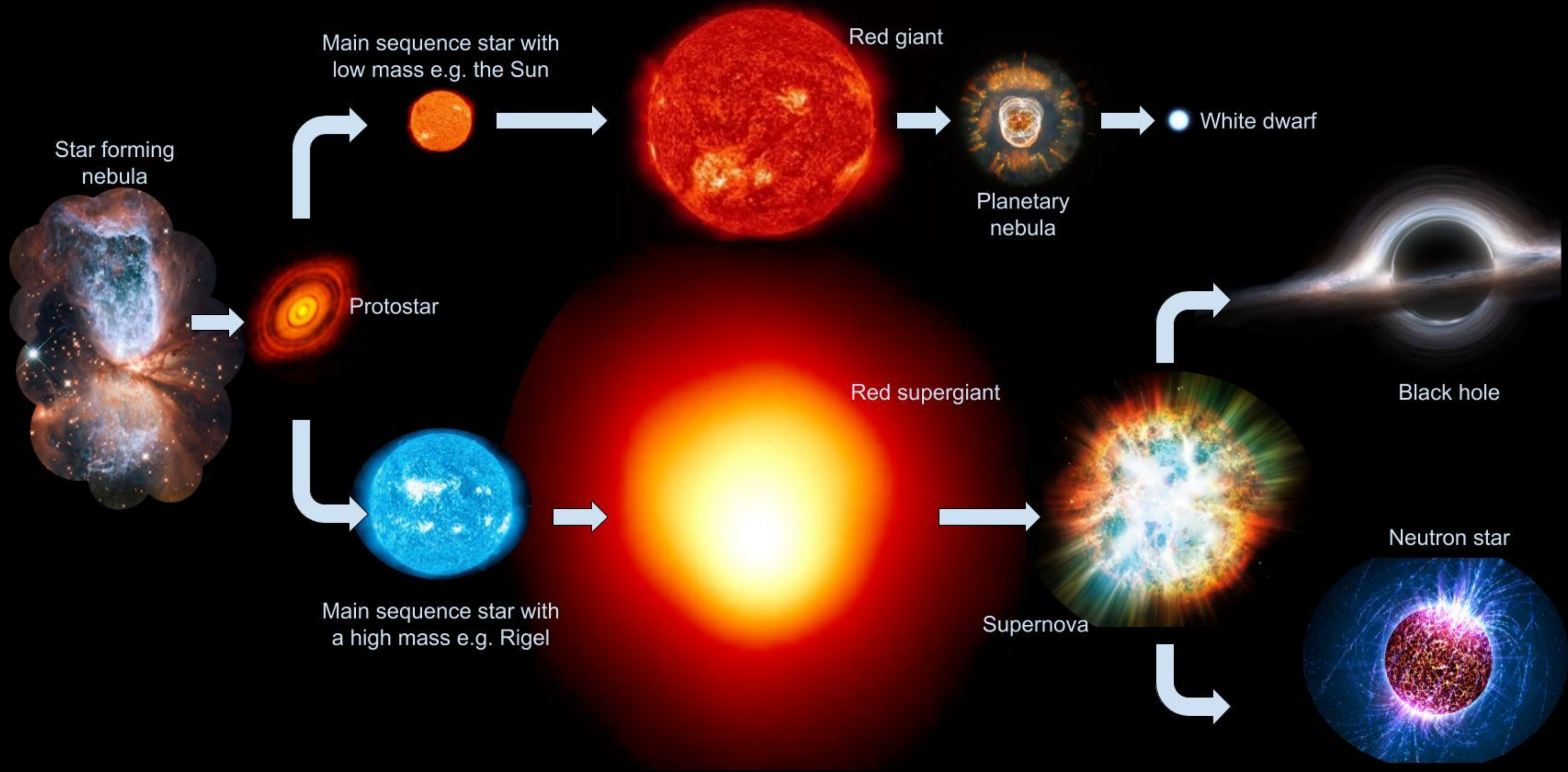
Aug. 12, 2023



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8x10^{9}$ y
$E = 2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
100秒
38万年
1.5~10亿年
138亿年
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.

Nuclear Astrophysics

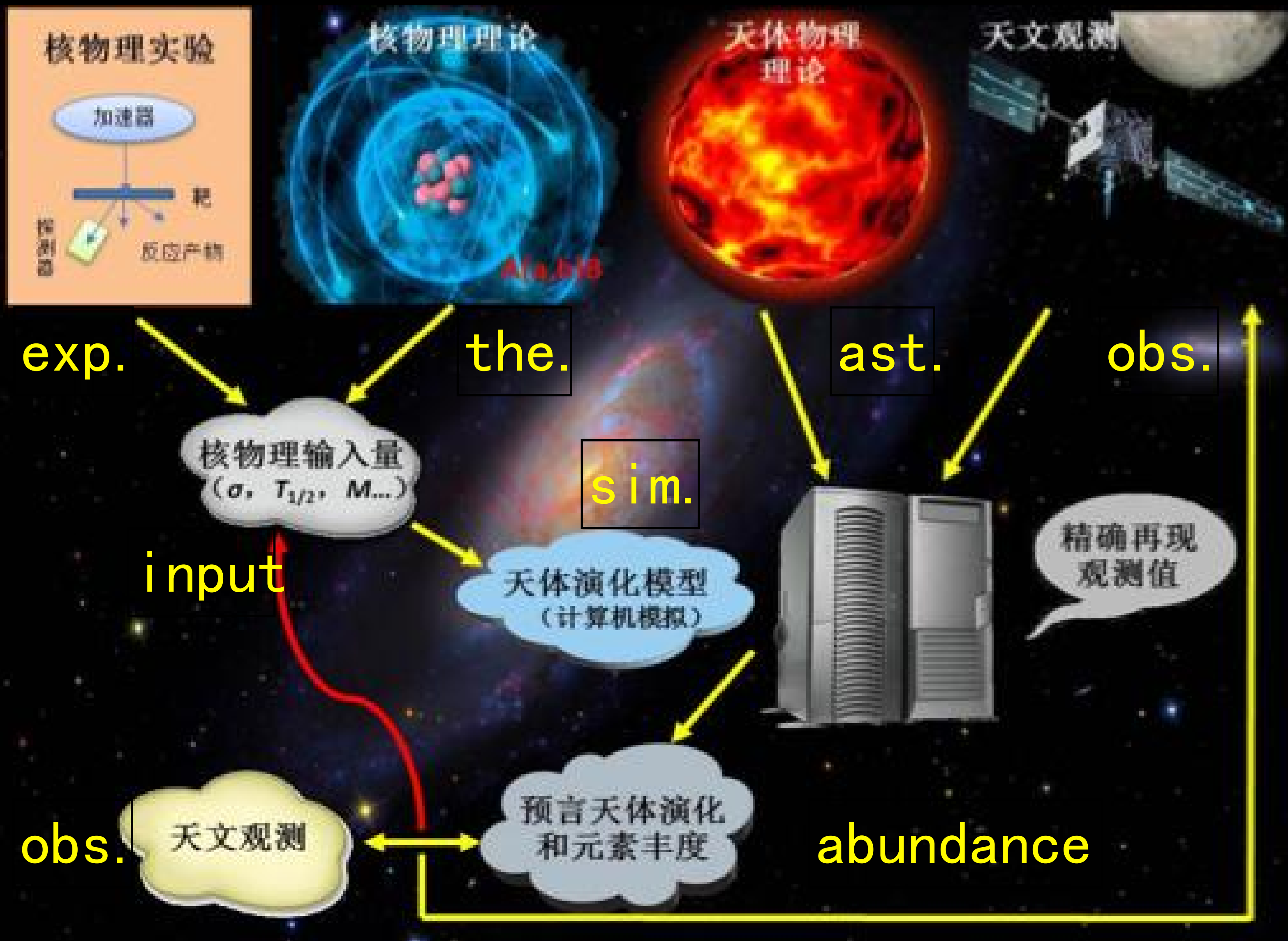


Nuclear processes: Provide energy for stars to resist gravitational contraction, and act the only mechanism for the synthesis of all elements (except hydrogen) in the universe

Research goal: The cutting-edge interdisciplinary field between micro nuclear physics and cosmic astrophysics, to explain the origin and evolution of cosmic elements, the generation and evolution of stellar energy, etc.

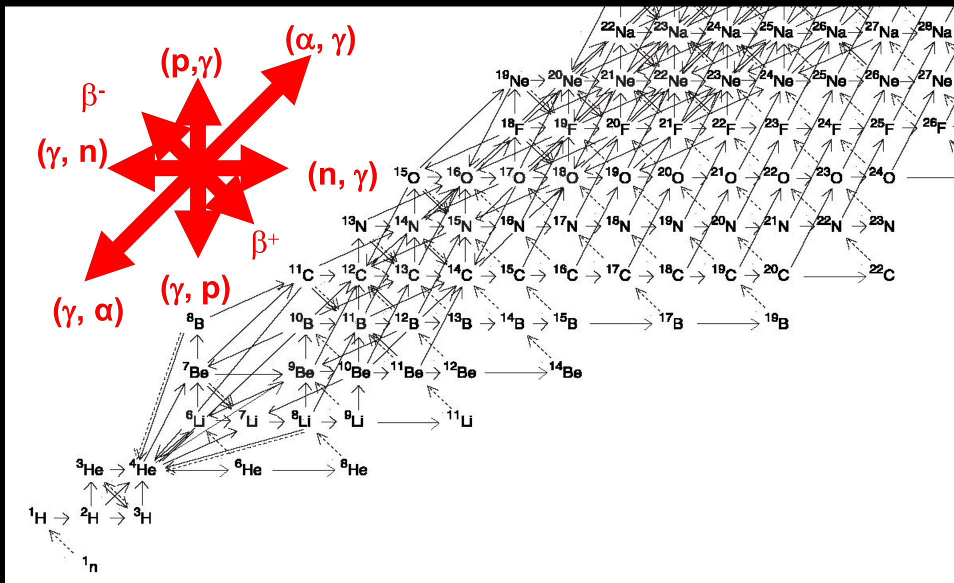
Nucl Phys Inputs: Nuclear mass, half-life, reaction cross section (or reaction rate), etc.

Nuclear Astrophysics



Nuclear Astrophysics

- **Nucleosynthesis network**



Cross section σ

$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho N_A \underbrace{<\sigma V>}_{} {}_{jk,i}\, Y_j Y_k + \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A{}^2 \underbrace{<\sigma V>}_{} {}_{jkl,i}\, Y_j Y_k Y_l$$

Decay half-life $\tau = 1/\lambda$

reaction rate $<\sigma v>$

NP-Input: Reaction rate

- **Definition of reaction rate:**

$$\langle \sigma v \rangle = \int \Phi(v) v \sigma(v)\, dv = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{3/2} \int \sigma(E) E \times e^{\left(-\frac{E}{kT}\right)}\, dE$$

- **Gamow peak**

The most effective energy region for nuclear burning (or reactions)

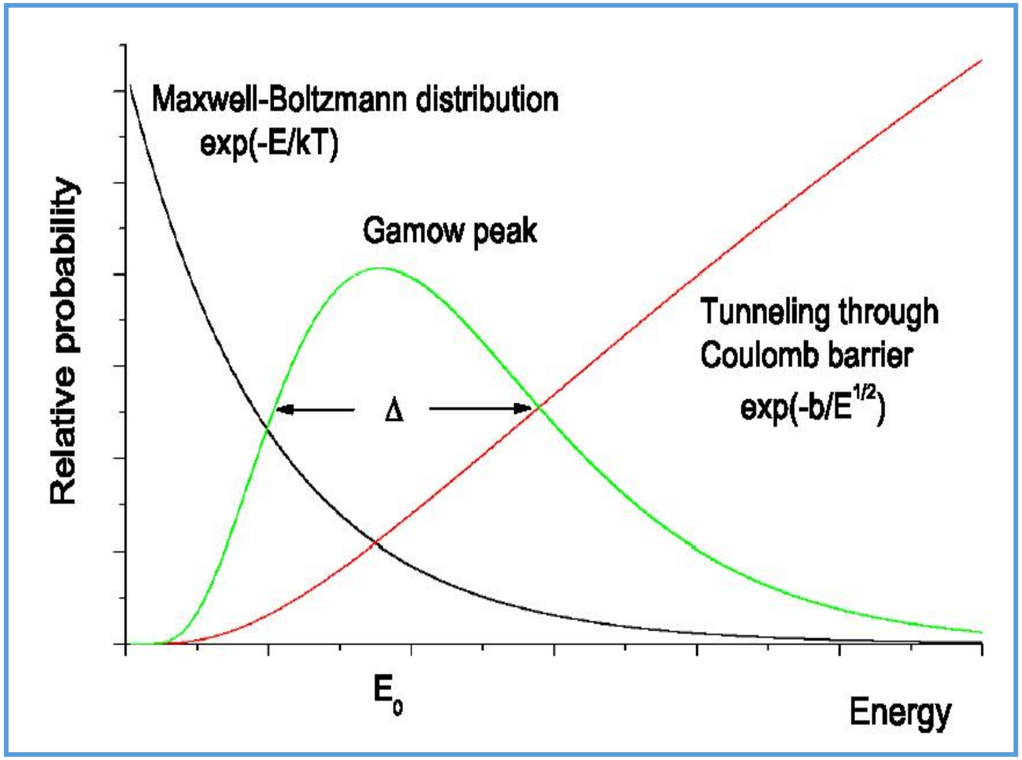
Peak location:

$E_0 = E_G^{1/3}(kT/2)^{2/3}$
$\quad = 1.22(Z_1^2 Z_2^2 \mu T_6^2)^{1/3}$ [keV]

with $\mu = A_1 \times A_2 / (A_1 + A_2)$ [amu]

1/*e* width:

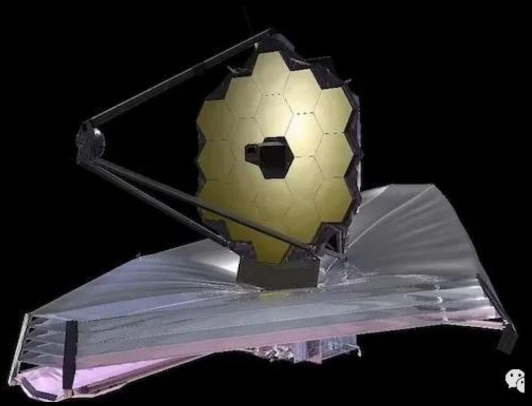
$\Delta E_0 = 4/3^{1/2} (E_0 kT)^{1/2}$ [keV]



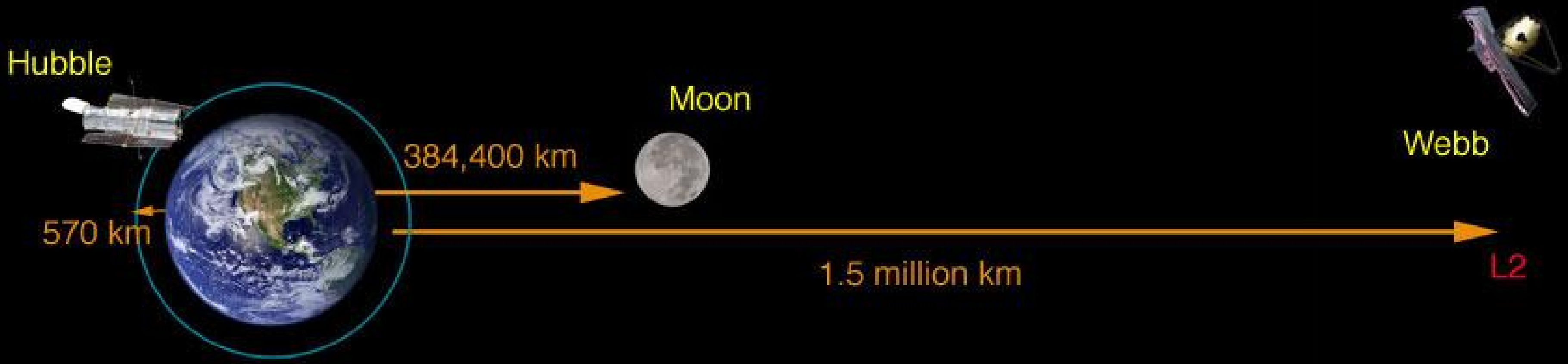
Today's topic

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

James Webb Space Telescope (JWST)



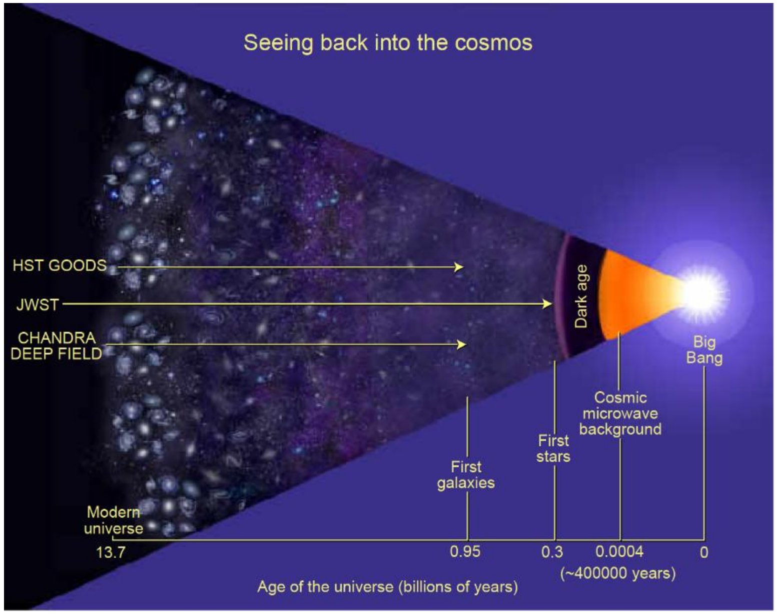
It is jointly developed by the NASA, the European Space Agency (ESA) and the Canadian Space Agency (CSA). The main mirror has an effective aperture of 6.5 meters and is composed of 18 hexagonal mirrors. The cost exceeds $10 billion and takes about 25 years. The gold-plated surface of the Webb telescope is eye-catching and is referred to as the "golden eye" by the press.



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

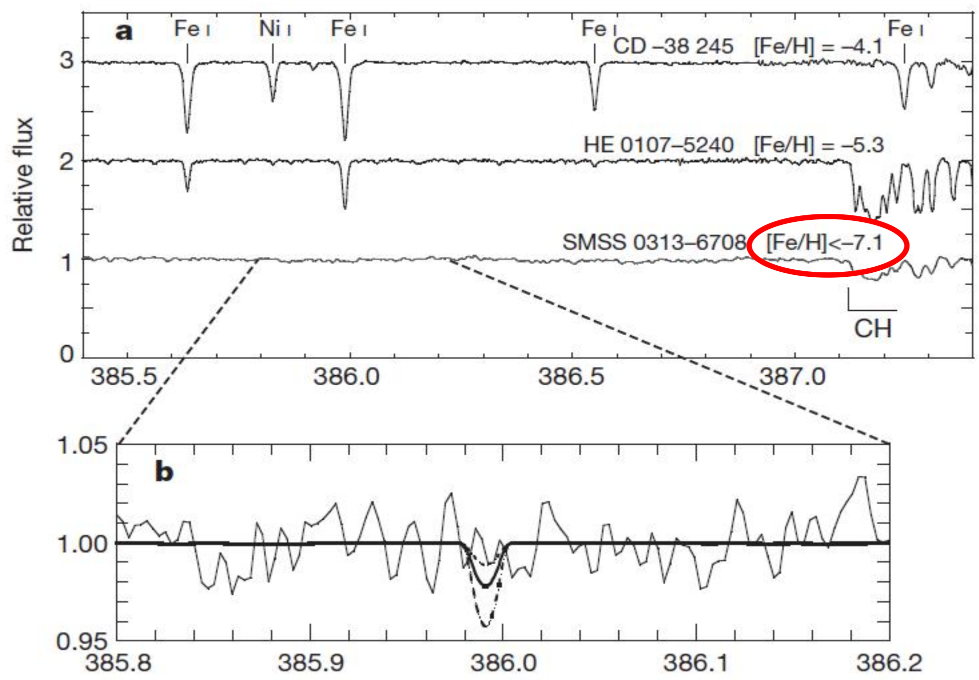
- **Oldest star:** **S.C. Keller et al., Nature 506(2014)463**

Siding Spring Observatory

SMSS0318-6708

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

Extremely Metal Poor Stars (EMPs)



The oldest star in the universe

Ca abundance

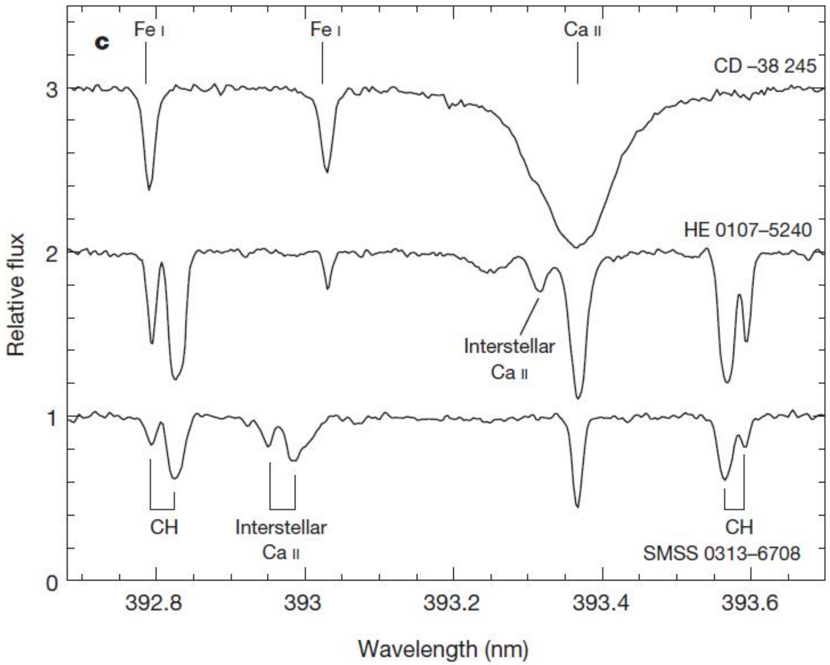


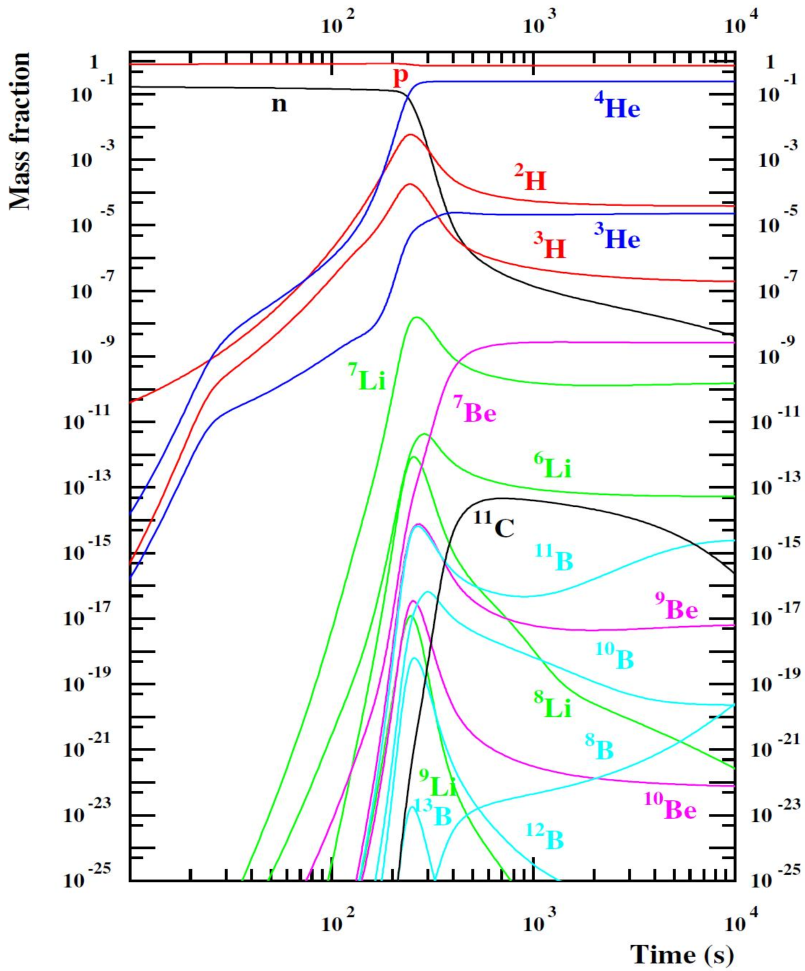
Table 1 | Chemical abundances of SMSS 0313−6708

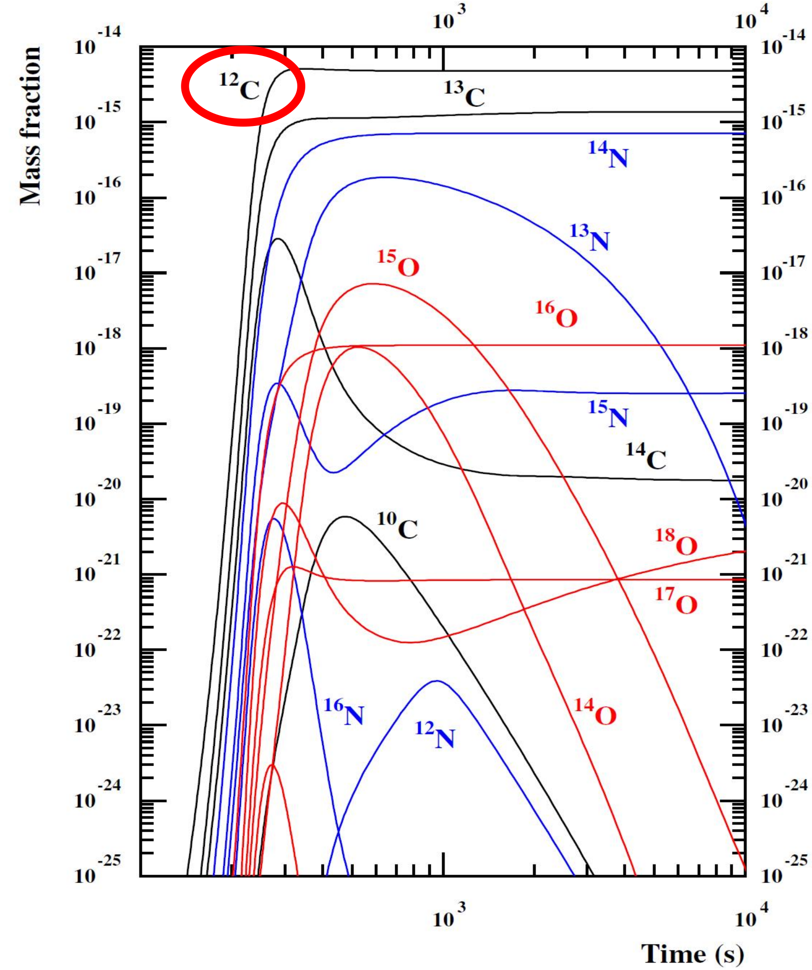
Element *X*	$[X/H]_{\text{1D, LTE}}$	$[X/H]_{\langle 3D \rangle}$
Li I	0.7*	0.7*
C (CH)	−2.4	−2.6†
N (NH)	<−3.5	<−3.9†
O I	<−2.3	<−2.4†
Na I	<−5.5	<−5.5‡
Mg I	−4.3	−3.8‡
Al I	<−6.2	
Si I	<−4.3	
Ca II	−7.2	−7.0‡
Sc II	<−5.0	
Ti II	<−6.3	
V II	<−3.3	
Cr I	<−6.3	
Mn I	<−5.8	
Fe I	<−7.3	<−7.1‡
Co I	<−4.9	
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$_\odot$ first star
- After explosion, the outer light elements being ejected and the inner heavy elements being fallen back onto the central black hole
- Ca produced by breakout reactions from the HCNO cycle

The oldest star in the universe

- **Abundances of light nuclides @BBN ashes**



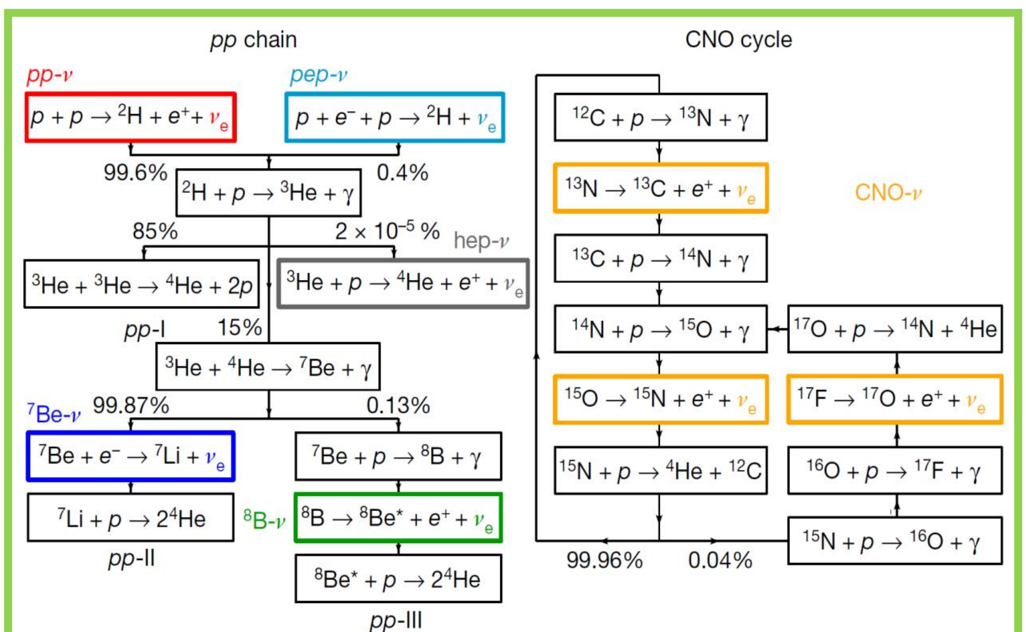


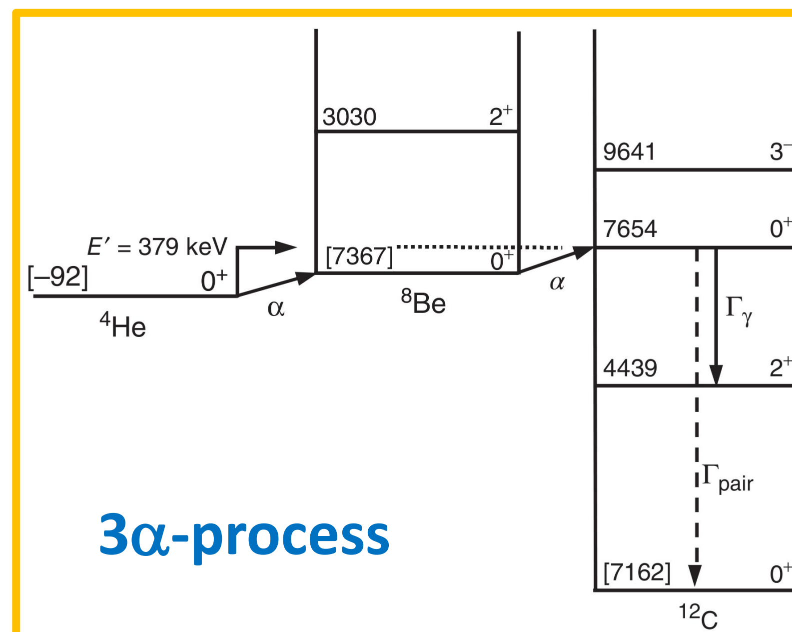
A. Coc *et al.*, Astrophys. J. 744(2012)158

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, $X(^{12}\mathrm{C}) \sim 10^{-9}$, which can kickstart the CNO cycle.

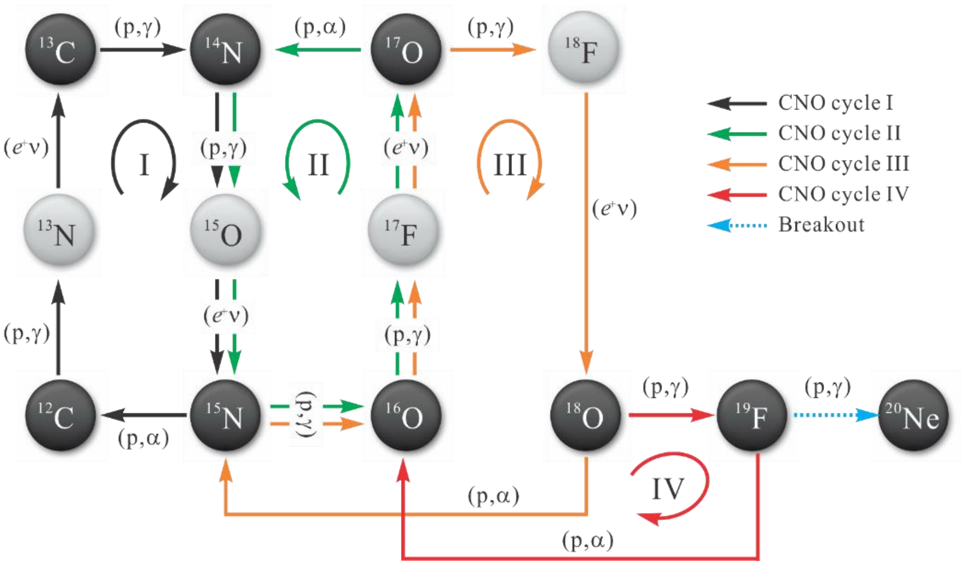




R.J. deBoer *et al*., Phys. Rev. C 103(2021)055815

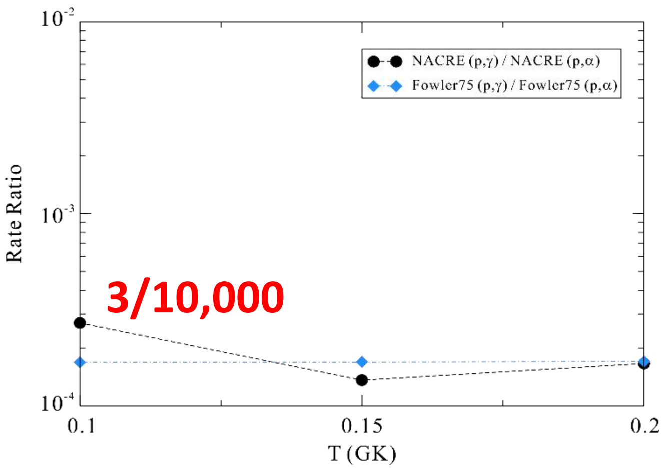
The oldest known star in the universe

- **Breakout from CNO cycle**



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

Their rate ratio determines the breakout flux



Model calc.: If reaction rate ratio of $(p,\gamma)/(p,\alpha)$ could be enhanced by 7 times or more, then Ca problem can be solved! Two reactions need to be measured directly.

O. Clarkson, F. Herwig, Mon. Not. R. Astron. Soc. 500(2021)2685

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

- **@Notre Dame Univ.**

PHYSICAL REVIEW C 77, 015802 (2008)

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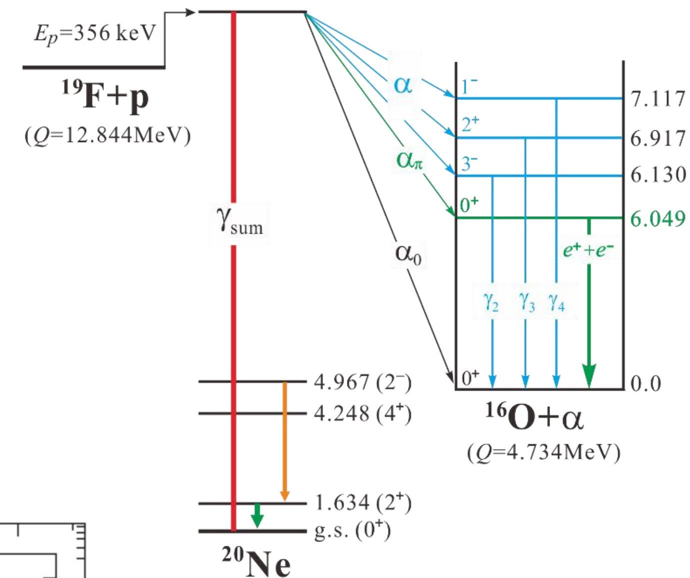
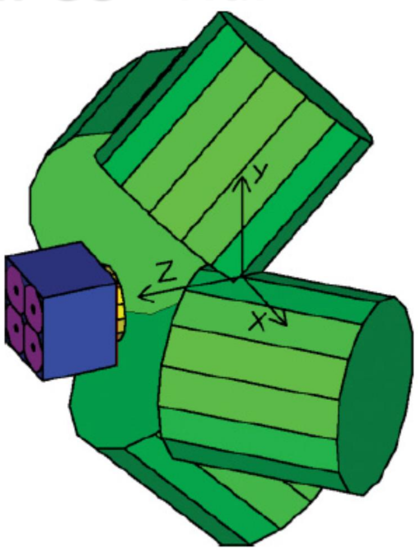
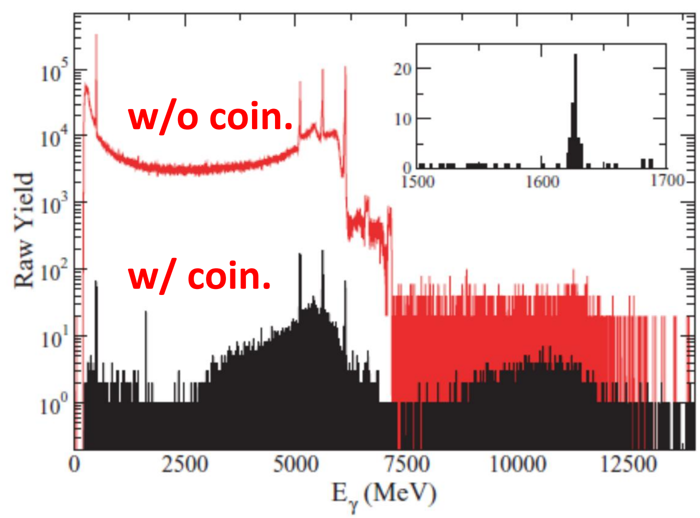


Proton beam current: 20 uA

HPGe + NaI





Coinc. technique can suppress the bk by 10,000 times!

A. Couture *et al.*, Phys. Rev. C 77(2008)015802

I. Status of ^{19}F(p,γ)^{20}Ne reaction

- **@Notre Dame Univ.**

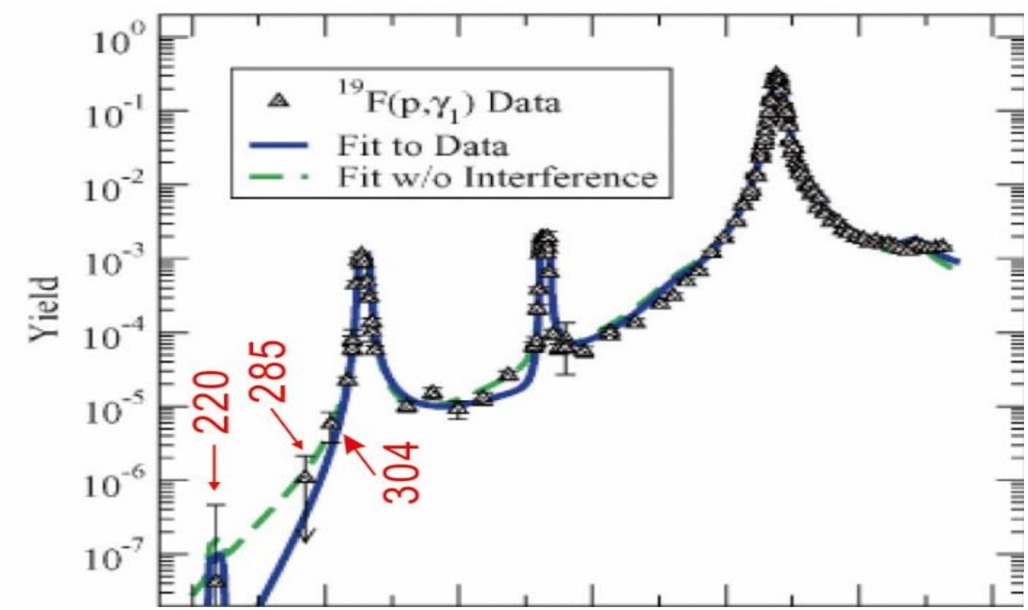


TABLE I. Measured resonance parameters.

Γ_p (eV)	Γ_{γ_1} (eV)	Γ_{α_2} (eV)		Γ (keV)
	$E_{R,\mathrm{c.m.}} = 213$ keV $J^\pi = 2^-$			
Present	$\mathbf{0.890^{1346}_{-265}}$ [a]	$\mathbf{0.011^{+0.003}_{-0.002}}$	$\mathbf{<0.06}$	$\mathbf{882^{+1346}_{-265}}$
$(p, \alpha_{2,3,4})$ [b]	0.94±0.02	–	–	1000
	$E_{R,\mathrm{c.m.}} = 323$ keV $J^\pi = 1^+$			
	Γ (keV)	Γ_p (eV)	Γ_{γ_1} (eV)	Γ_{α_2} (eV)
Present	**2.08±0.34**	$\mathbf{35.8^{+5.6}_{-5.4}}$	$\mathbf{0.107^{+0.024}_{-0.019}}$	$\mathbf{1971^{+369}_{-294}}$
(p, p_0) [c]	2.8	45	–	–
(p, p') [d]	2.8	–	–	–
(p, γ_1) [e]	–	–	0.28±0.06	–
$(p, \alpha_{2,3,4})$	2.22±0.04	–	–	2800

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

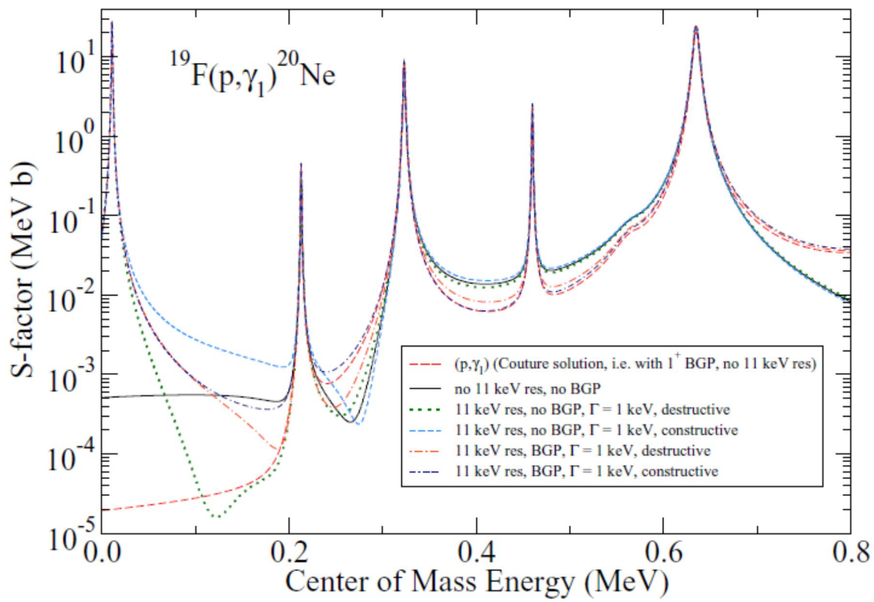
- **Recent evaluation**

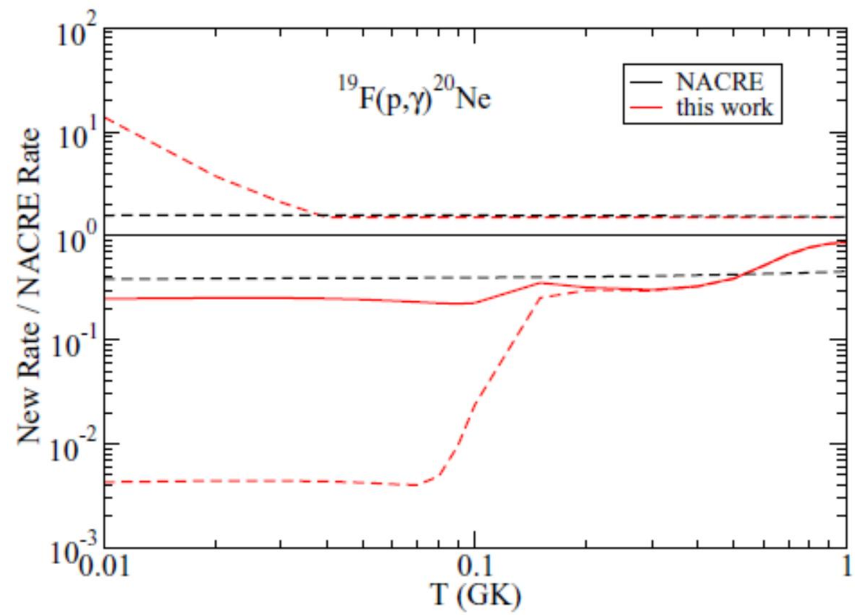
PHYSICAL REVIEW C **103**, 055815 (2021)

Editors' Suggestion | Featured in Physics

$^{19}F(p,\gamma)^{20}Ne$ and $^{19}F(p,\alpha)^{16}O$ 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. Couture,[5] J. Görres,[1] F. Herwig,[2,3,4] I. Lombardo,[6] P. Scholz,[1] and M. Wiescher[1]



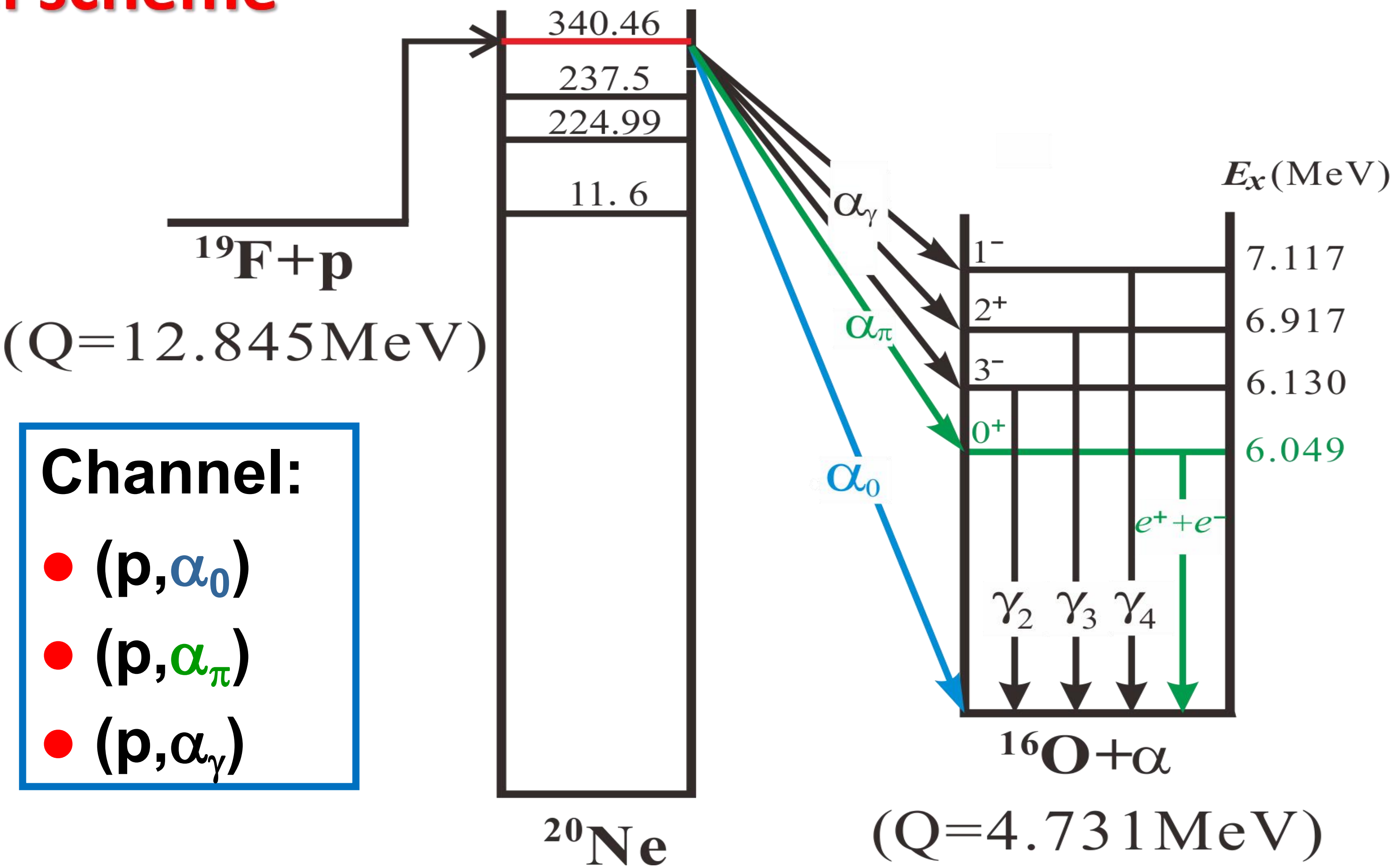


The newly evaluated $^{19}F(p,\gamma)^{20}Ne$ rate is ~4 times smaller than that of NACRE value, which makes the Ca problem even worse!

R.J. deBoer *et al.*, Phys. Rev. C 103(2021)055815

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

- **Level scheme**

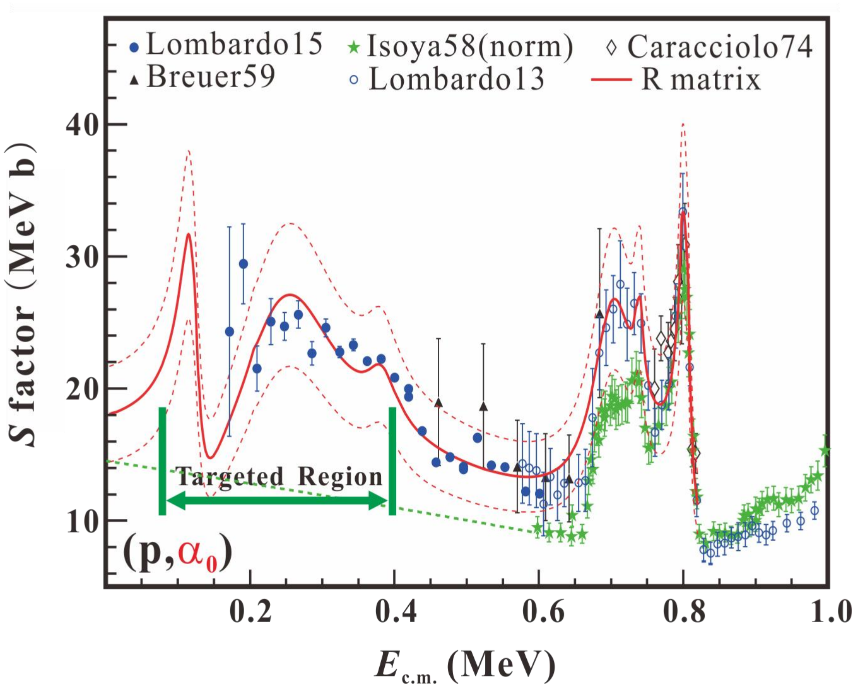


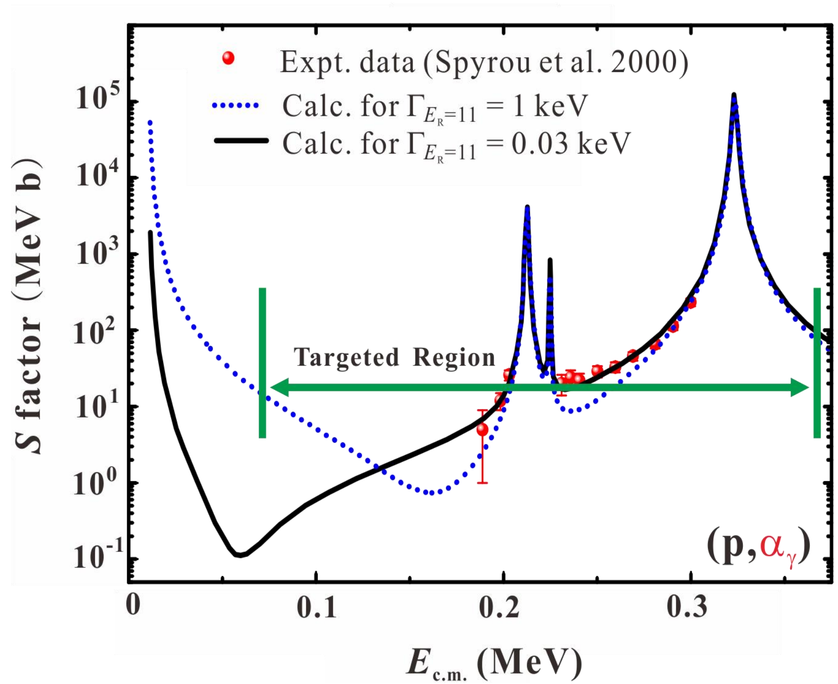
Channel:
- (p,α_0)
- (p,α_π)
- (p,α_γ)

J.J. He *et al.*, Sci. China-Phys. Mech. Astron. 59 (2016) 652001

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

Status & goal





Gamow window (70 ~ 350 keV)

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

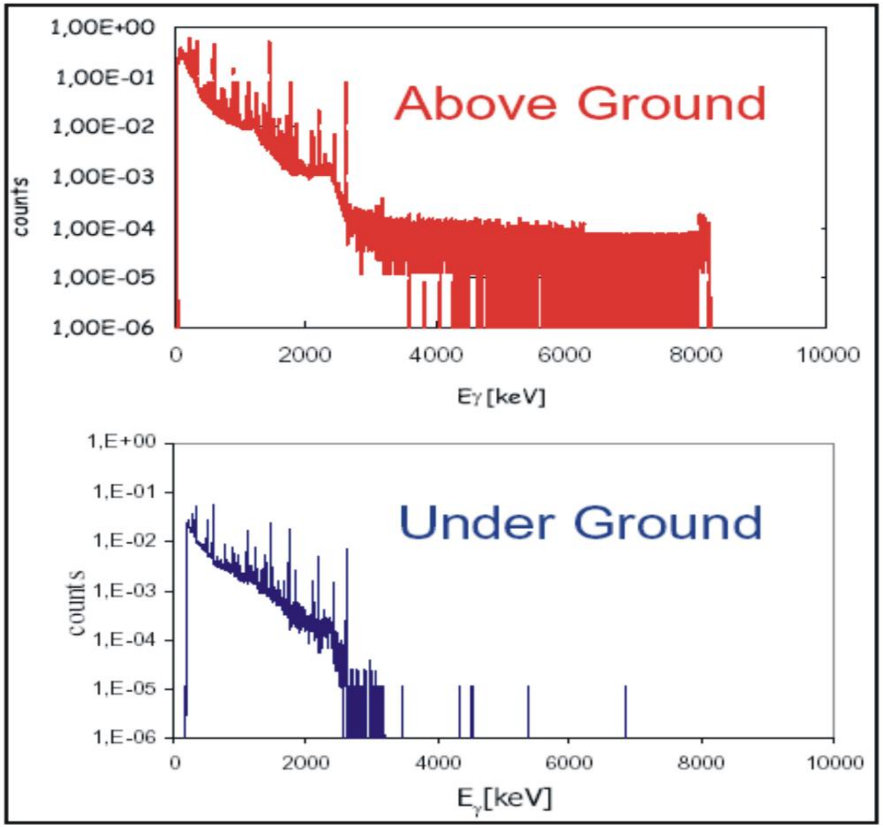
J.J. He *et al.*, Sci. China-Phys. Mech. Astron. 59 (2016) 652001

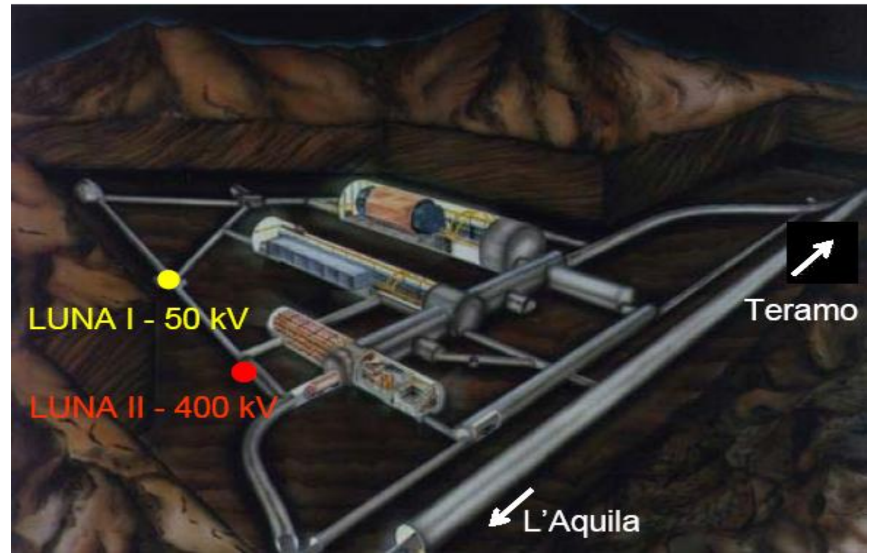
Challenge & Strategy

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

Advantage of underground γ detection

●LUNA @Gran Sasso, Italy



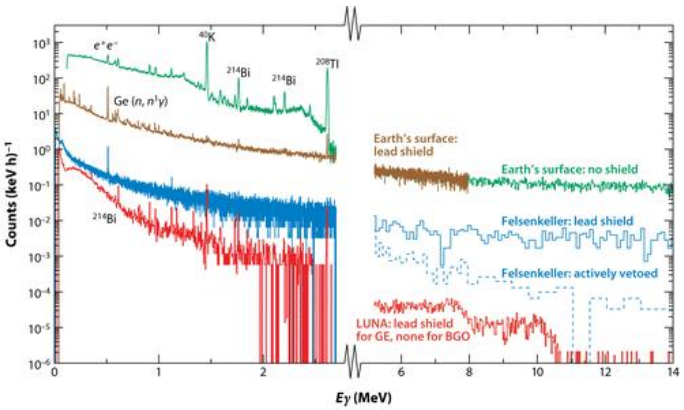


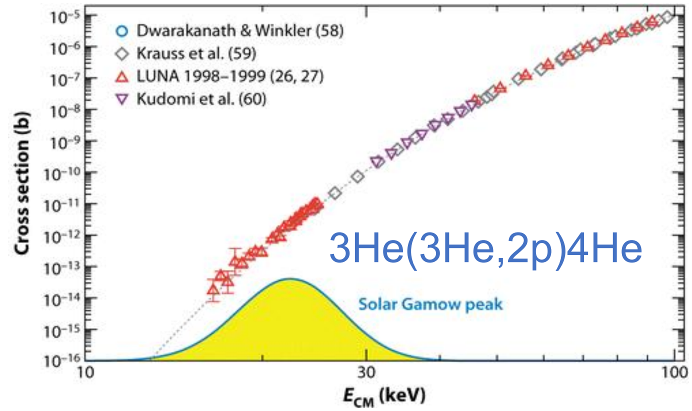
Advantage:

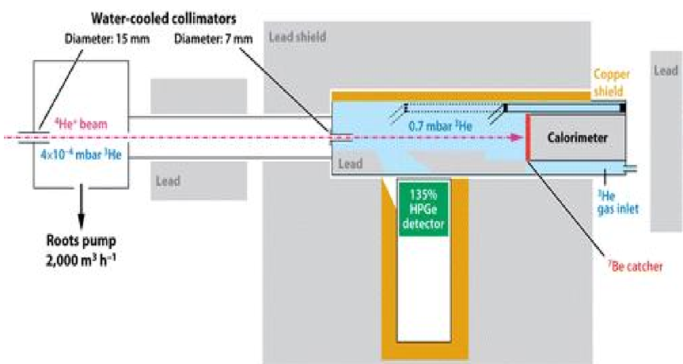
Deep underground Lab can reduce the background of γ-rays caused by cosmic-rays by over 10,000 times! The impact of thermal neutron flow will also be reduced by 1000 times!

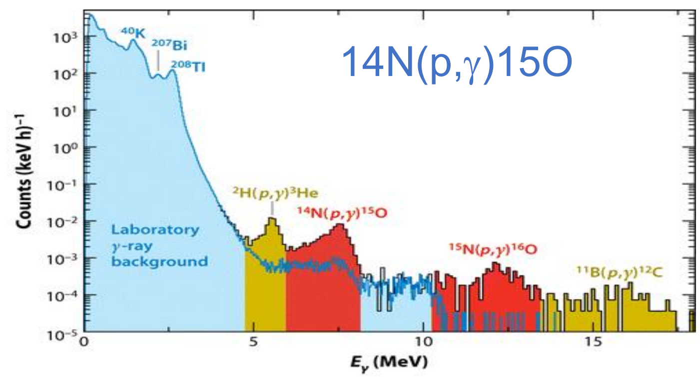
C. Broggini *et al.*, Annu. Rev. Nucl. Part. Sci., 60(2010)53

LUNA achievements









^{3}He(^{3}He,2p)^{4}He
PRL82(1999)5205

^{2}H(^{3}He,p)^{4}He
PLB482(2000)43

^{2}H(p,γ)^{3}He
NPA 706(2002)203

^{3}He(α,γ)^{7}Be
PRL 97(2006)122502

^{14}N(p,γ)^{15}O
PLB 591(2004)61

^{15}N(p,γ)^{16}O
PRC82, 055804(2010)

^{17}O(p,γ)^{18}F
PRL 109, 202601(2012)

^{25}Mg(p,γ)^{26}Al
PLB 707(2012) 60

^{22}Ne(p,γ)^{23}Na： F. Cavanna *et al.*, PRL 115(2015)252501

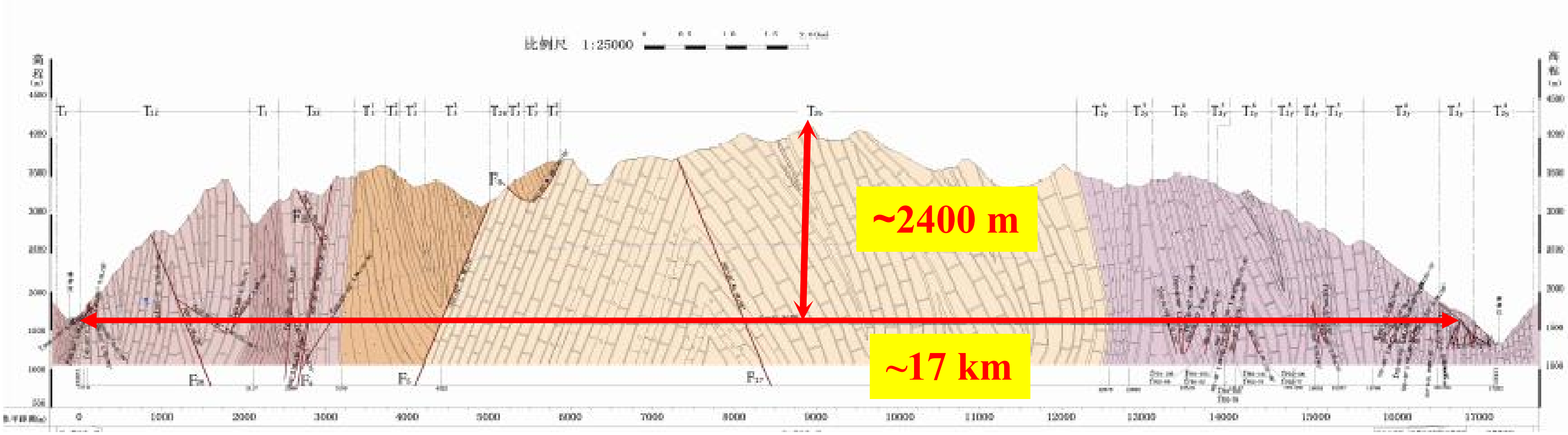
D(p,γ)^{3}He: V. Mossa *et al.*, Nature 587(2020)210

^{13}C(α,n)^{16}O: F. Ciani *et al.*, PRL 127(2021)152701

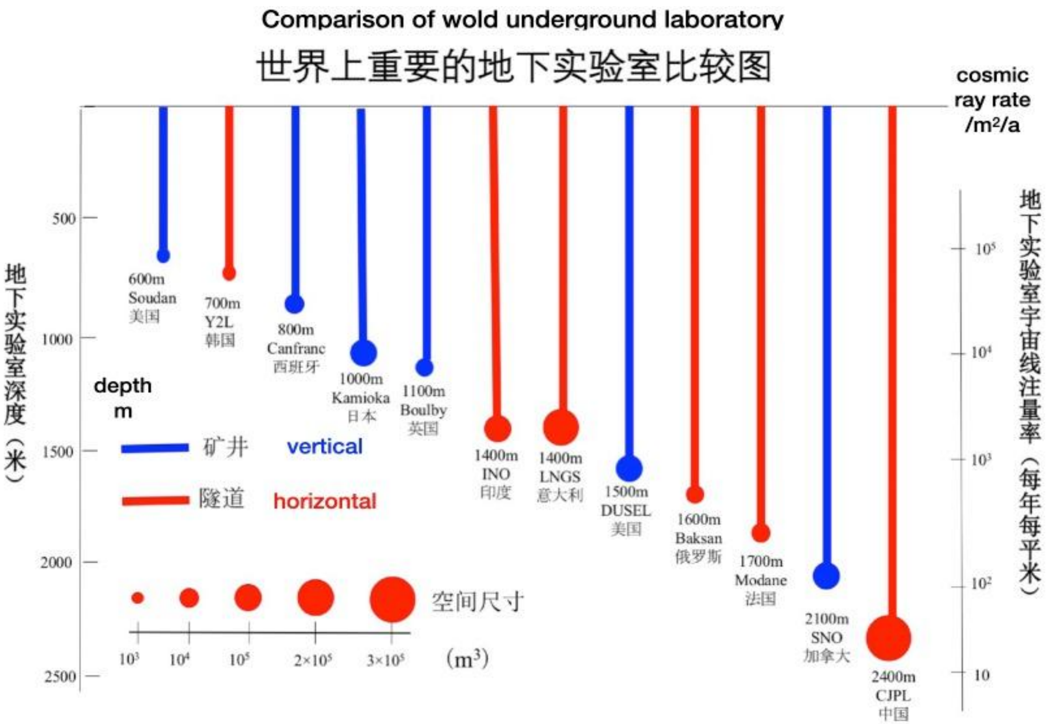
C. Broggini *et al.*, Annu. Rev. Nucl. Part. Sci., 60(2010)53

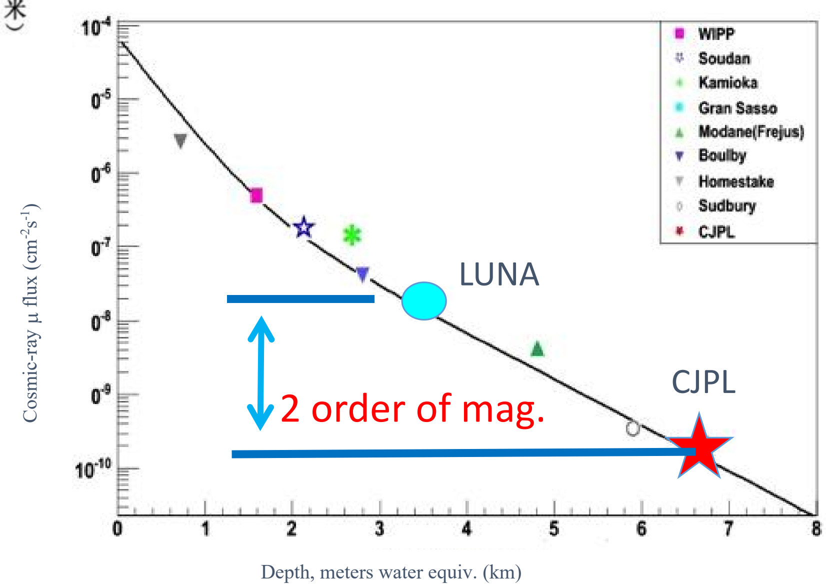
China Jinping Underground Lab(CJPL)

2010.12.12日正式启用

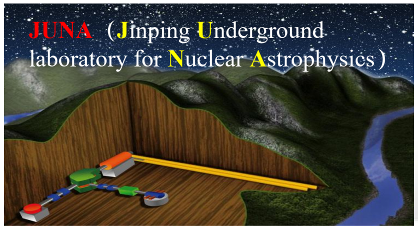


China Jinping Underground Lab(CJPL)





Jinping Underground laboratory for Nuclear Astrophysis (JUNA) project



Weiping Liu

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

Xiaodong Tang

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

Zhihong Li

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

Jianjun He

PI $^{19}F(p,\alpha)^{16}O$

Gang Lian

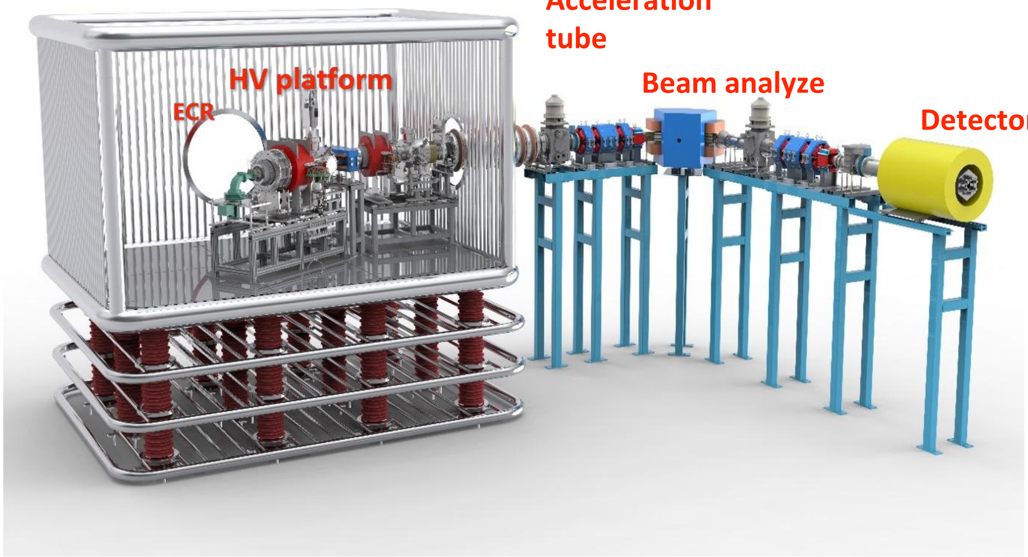
PI Platform

The JUNA project

JUNA (Jinping Underground laboratory for Nuclear Astrophysics)

Facility comparison

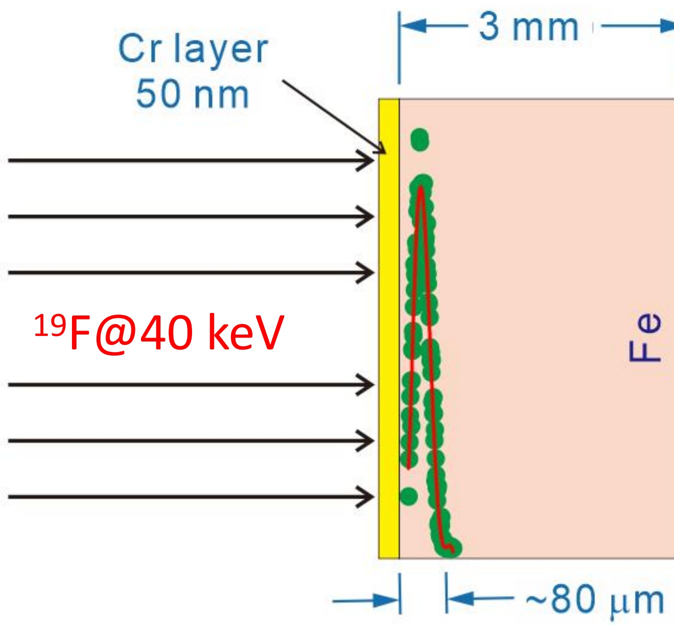
- **JUNA I: 400 kV**



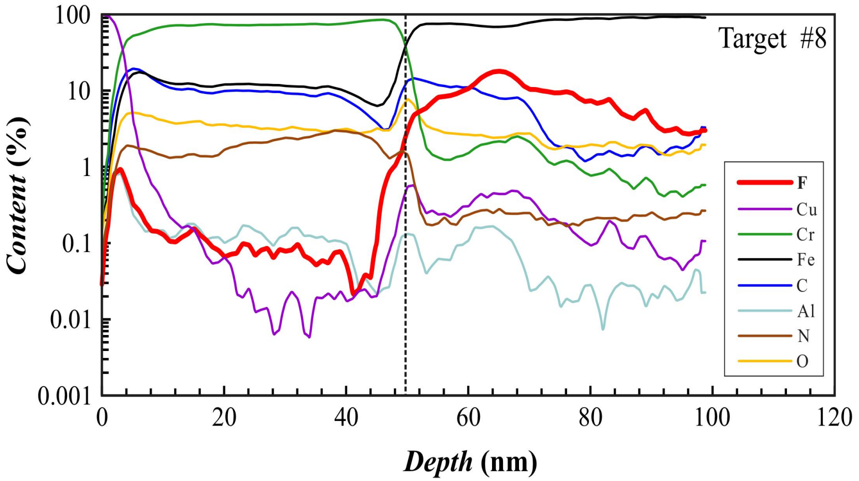
	Cosmic μ bkg ($cm^{-2}\,s^{-1}$)	Beam energy（keV）			Intensity（emA）		
		H^+	He^+	He^{2+}	H^+	He^+	He^{2+}
LUNA	2×10^{-8}	50-400	50-400	---	0.3~1	0.3~0.8	---
CASPAR	4×10^{-9}	100-1000	100-1000	---	0.1	0.1	---
JUNA	2×10^{-10}	50-400	50-400	100-800	10	10	2

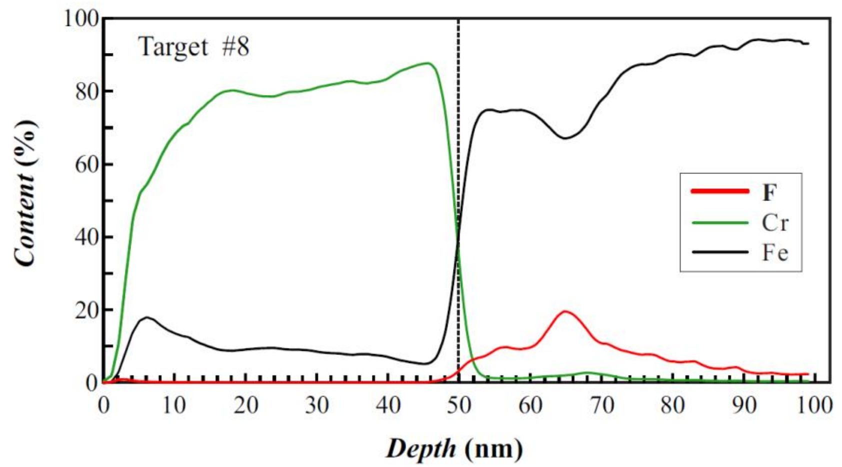
Q. Wu, L.T. Sun *et al.*, NIMA 830(2016)214

R&D stable ^{19}F implanted targets



Atom Probe Tomography, APT

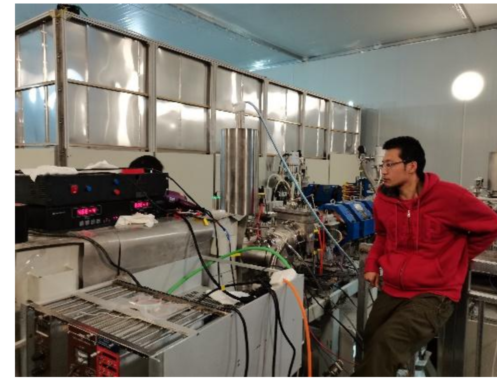


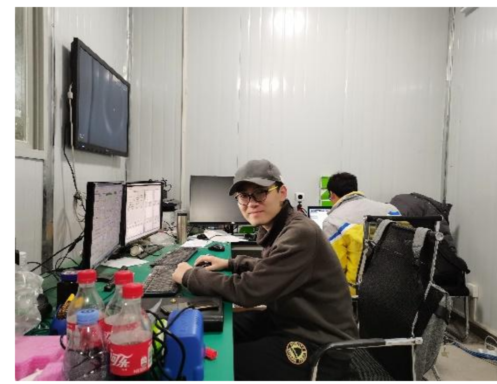


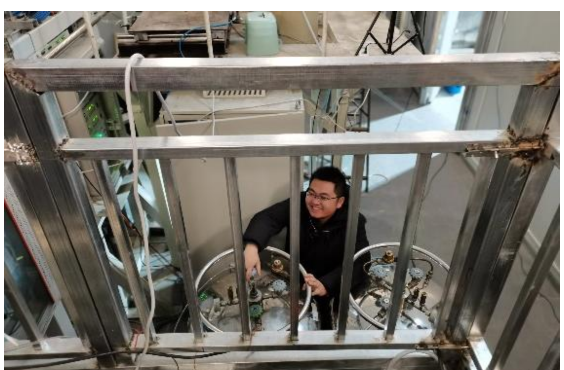
Implant Energy	40 keV
Cr protective foil	50 nm
Backing	Iron
Target loss	5% per 100 Coul

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

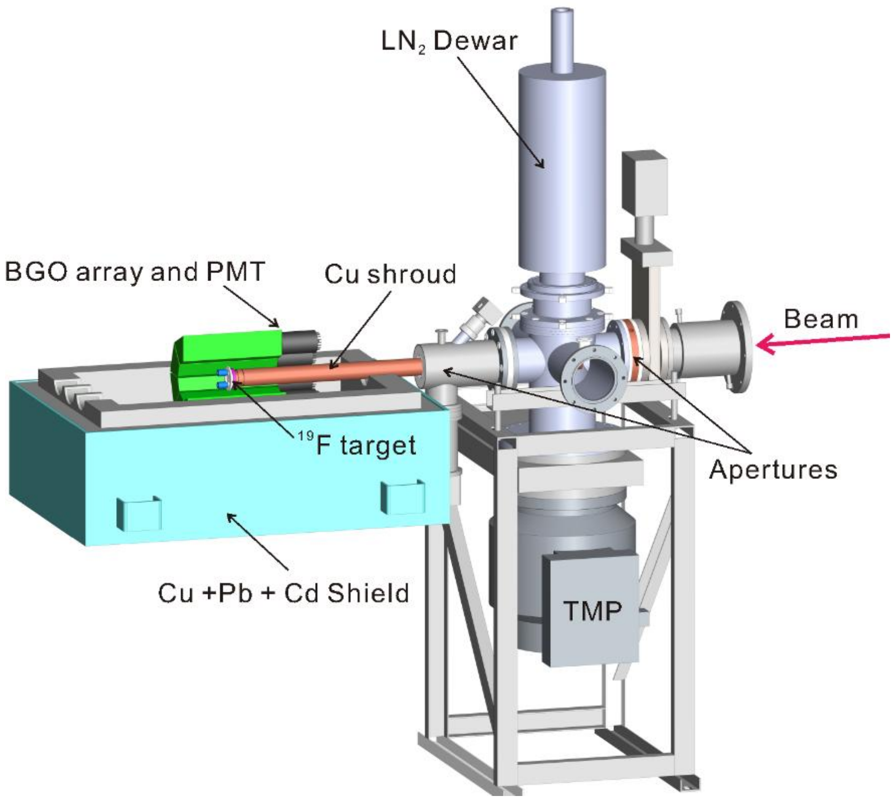




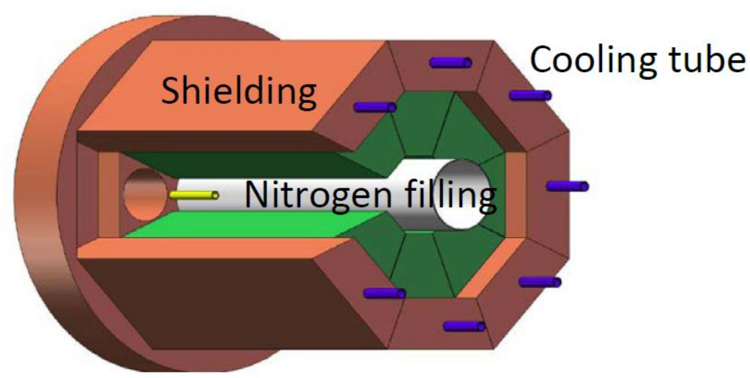


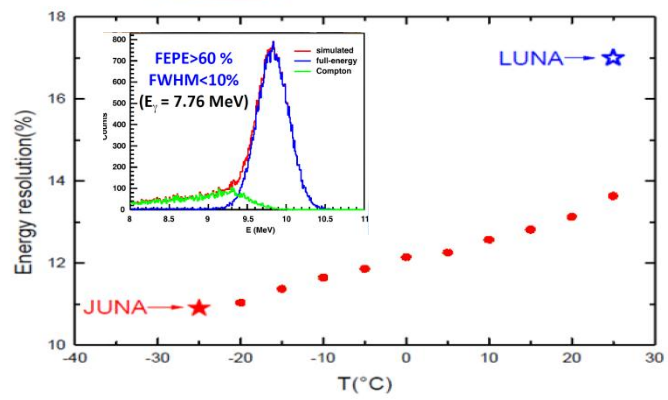
JUNA experiment campaign

- **Experimental setup**



- **4π BGO γ-ray array**



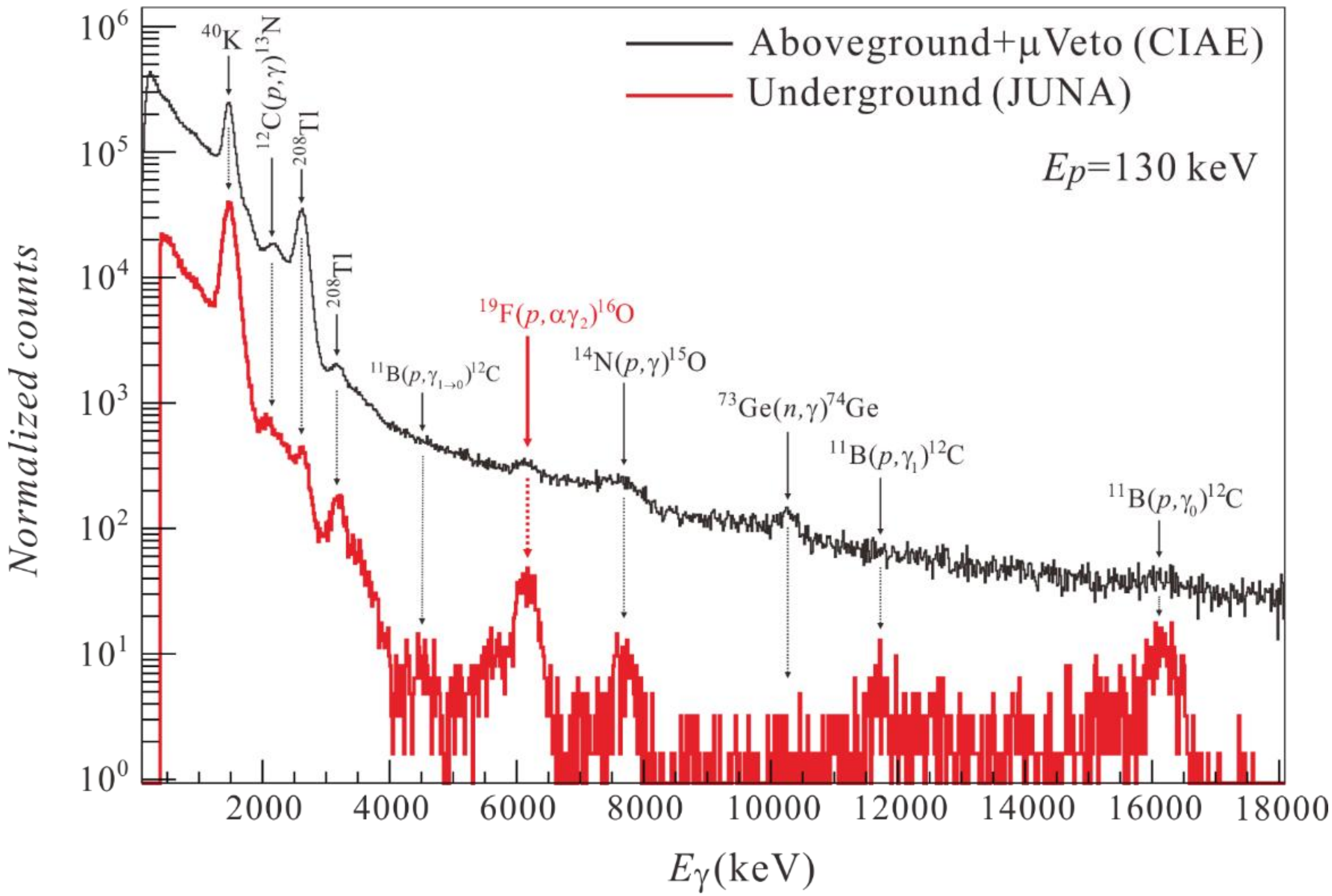


γ-ray @6130 keV

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

JUNA experiment campaign

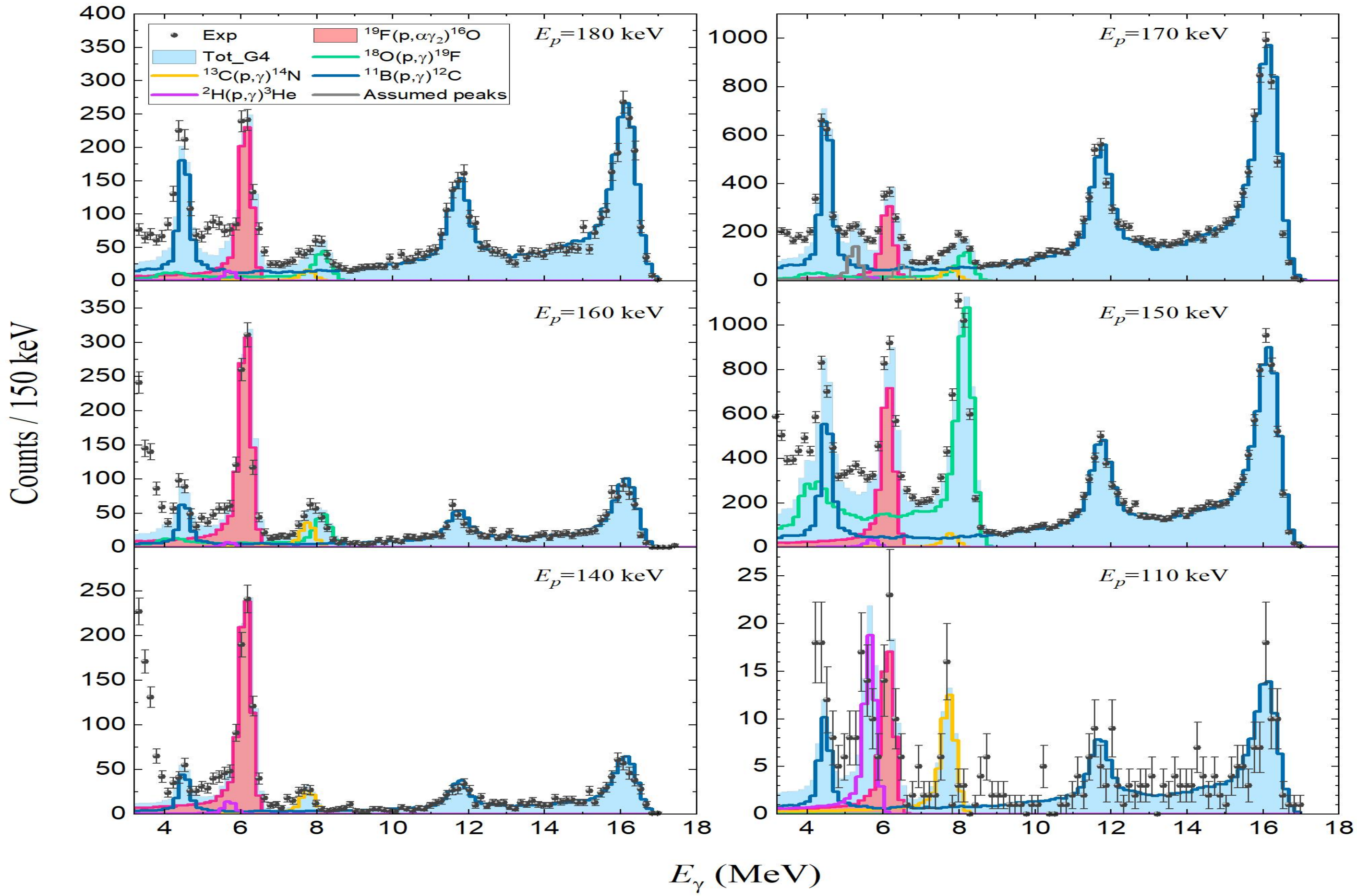
- **Advantage of underground lab**



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

JUNA measurement of ^{19}F(p,αγ)^{16}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

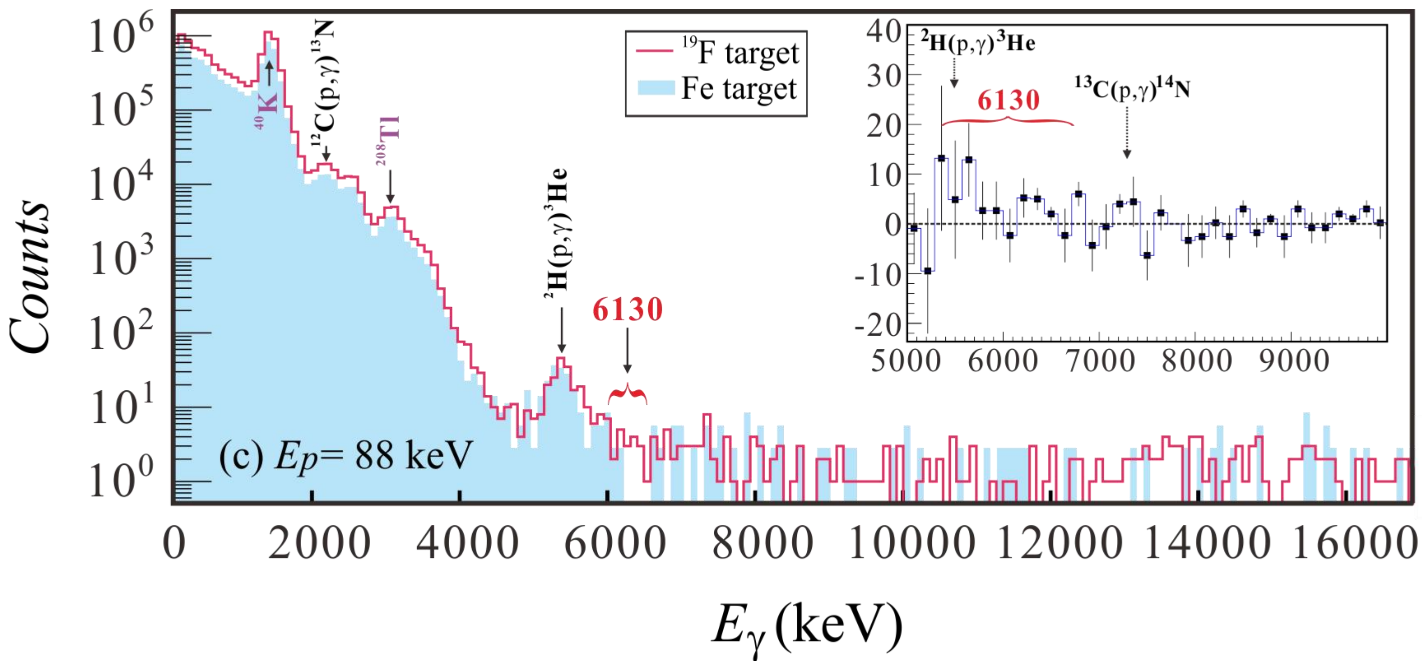
JUNA measurement of $^{19}F(p,\alpha\gamma)^{16}O$

- **Lowest energy achieved**

Energy point: $E_{c.m.}$ = 72.4 keV; **Beam current:** ~1 mA

Machine Time: 46.5 h; **Challenge:** deuteron contam.

Net counts: 30 ± 26 (80% err)

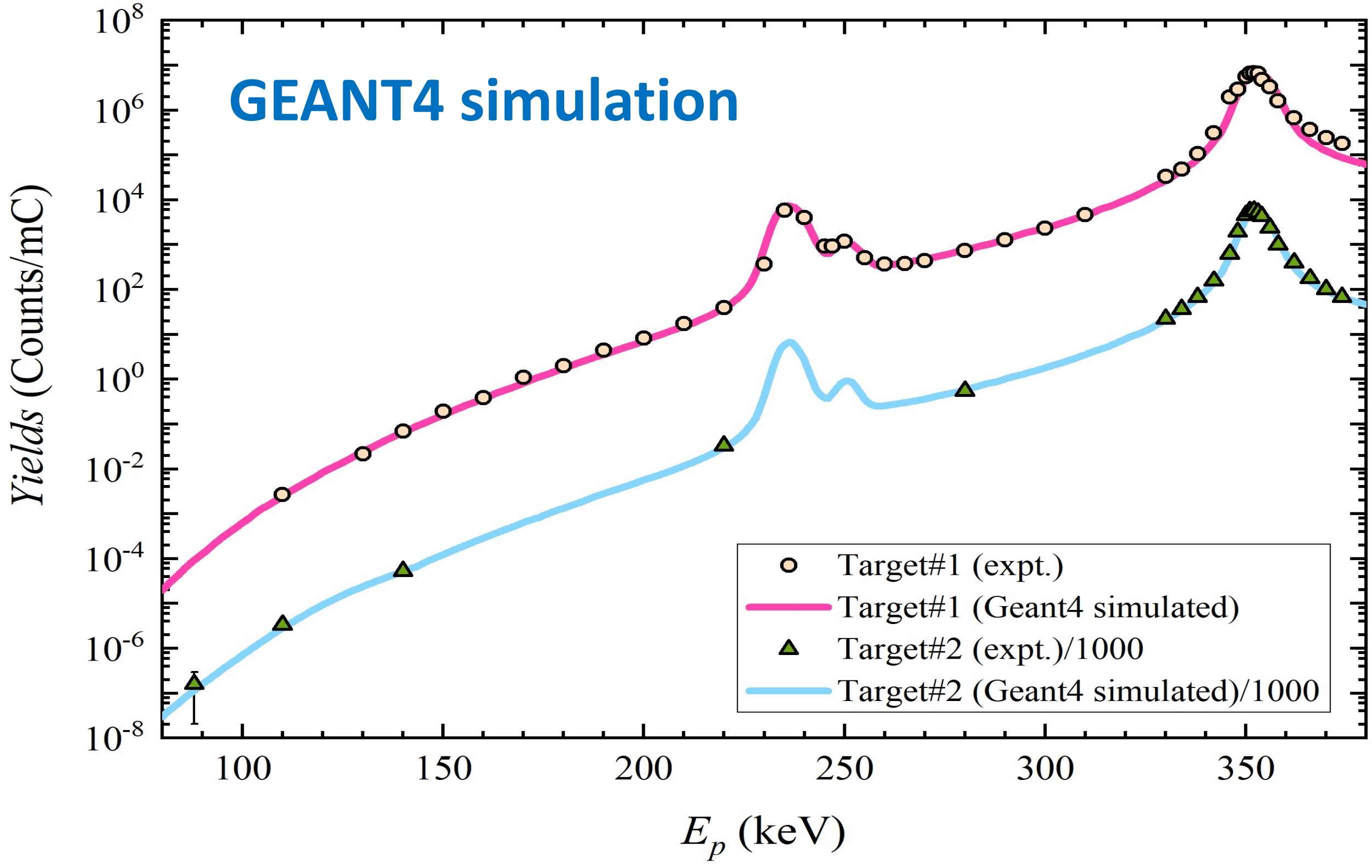


L.Y. Zhang, J. Su, J.J. He* *et al.*, Phys. Rev. Lett. 127(2021)152702

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

- **γ-ray yields**

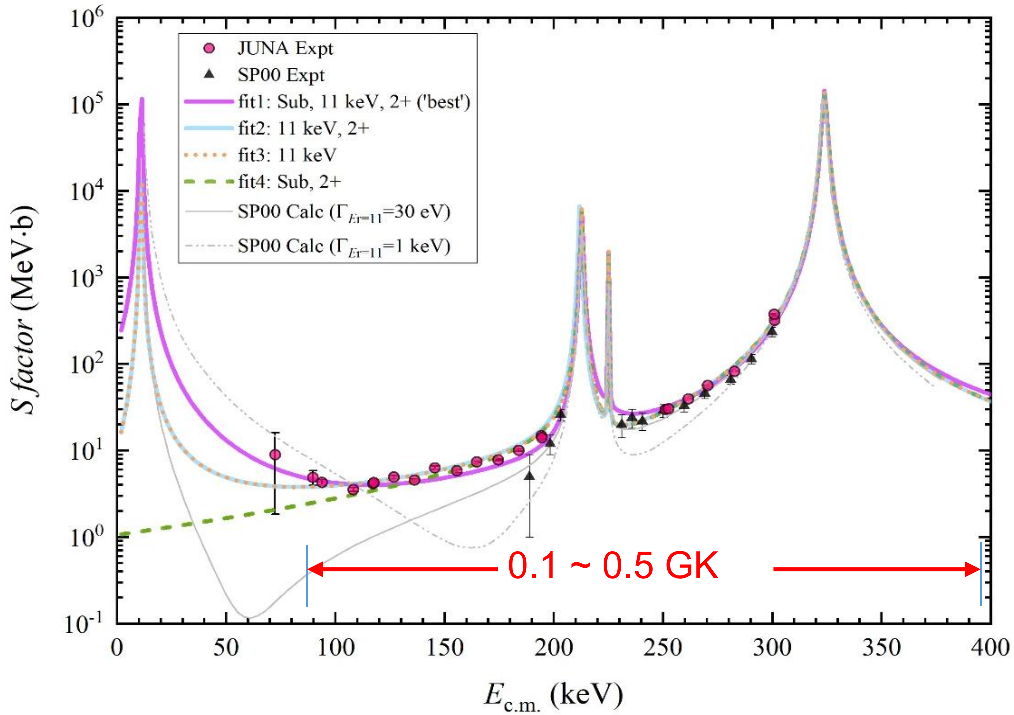
***R*-matrix fit**
(by deBoer & Wiescher)



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

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

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



By GEANT4 simulation

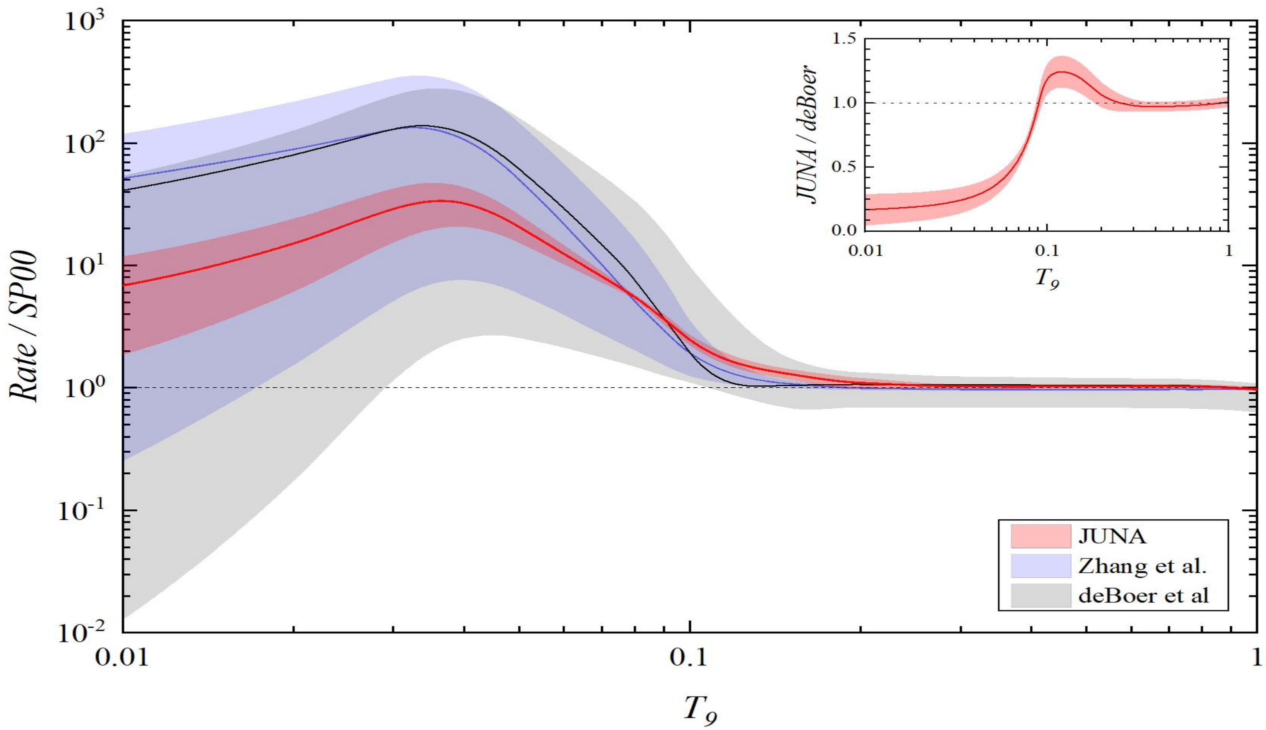
- 11-keV resonance
- Sub-threshold state
- Underlying α-cluster 2^+state

- Lowest energy region achieved
- Firstly covering full AGB Gamow window
- Expt data differ significantly with predictions

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

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

- **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%.

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

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

● Publication

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,‡]

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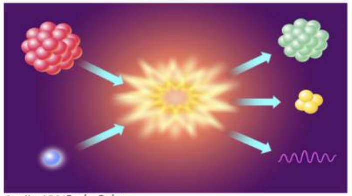
Physics   SYNOPSIS

Pinning Down the Fate of Fluorine

The first results from the Jinping Underground Nuclear Astrophysics particle accelerator refine a key reaction rate for the destruction of fluorine in stars.

By Christopher Crockett

The origin of fluorine is puzzling. The element is absent in the main nuclear reactions in stars, making it hard to figure out how it is formed. Fluorine is also easily destroyed by run-ins with protons and helium nuclei, destructive reactions whose contributions to fluorine's lifecycle have yet to be pinned down because of difficulties in measuring the requisite reaction rates. A new particle accelerator in China could help in solving that problem, as its first results provide sharply reduced uncertainties in one fluorine reaction, fluorine atoms and protons convert to oxygen and helium atoms and gamma rays [1]. While many of the details of fluorine's origin and fate remain a mystery, these new reaction rates will help refine ongoing calculations of this element's abundance in the cosmos.



Credit: APS/Carin Cain

The Jinping Underground Nuclear Astrophysics (JUNA) experimental facility is a recent addition to the deepest operational particle physics lab in the world. Sitting beneath 2400 meters of rock, JUNA's accelerator is well shielded from the cosmic rays that have hindered other attempts to directly measure a particular transformation of fluorine to oxygen at the proton energies relevant to the interiors of stars.

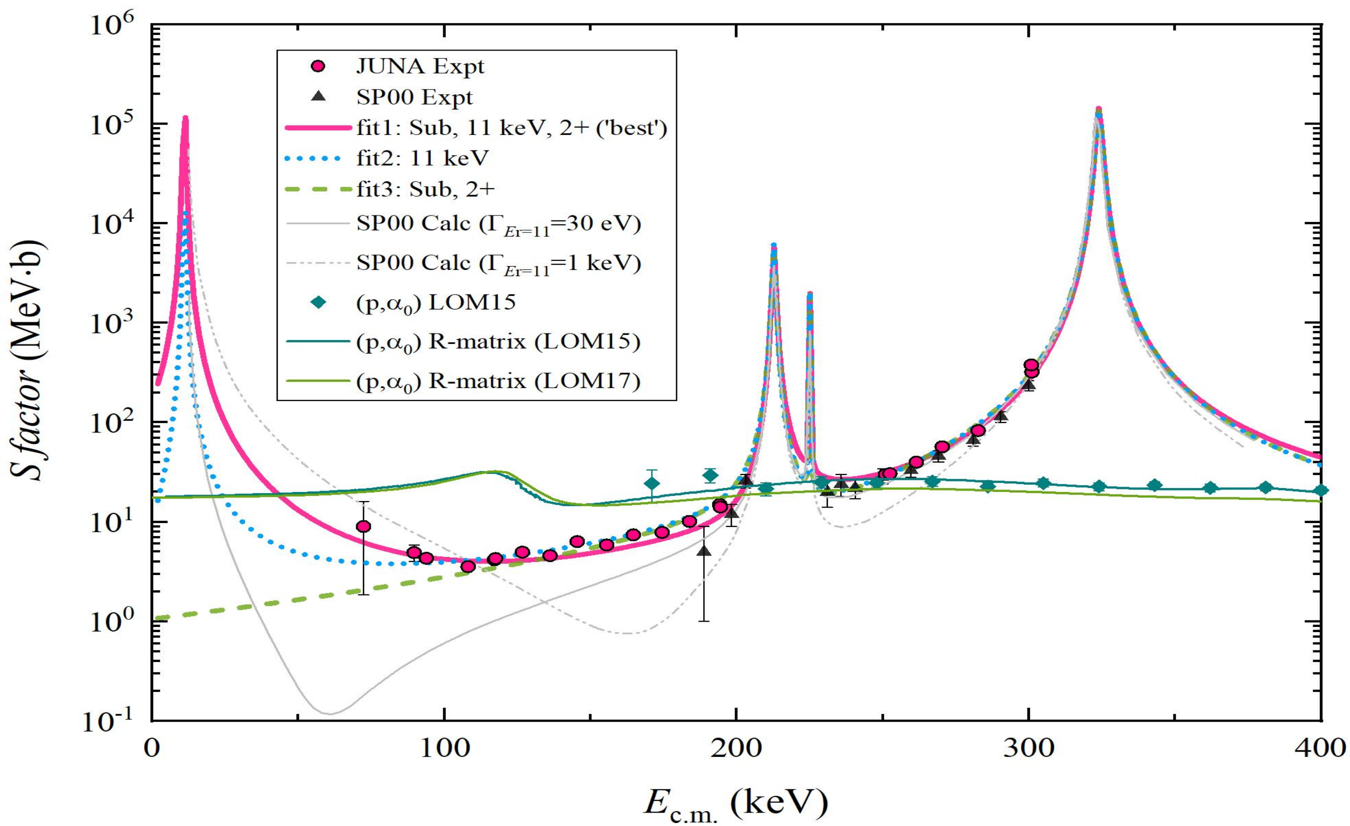
For their inaugural experiment, researchers bombarded two fluorine targets with proton beams that had energies as a low as 76.2 keV—an unprecedently small value—and recorded the ensuing shower of gamma rays. From those measurements, they calculated that fluorine converts to oxygen via this reaction channel at a rate ranging from 1.23×10^{-64} cm^{3}s^{-1}mol^{-1} to $1.29 \times 10^{+5}$ cm^{3}s^{-1}mol^{-1} depending on the reaction temperature. Over the temperature range of interest to astrophysics, the error in the measurements was below 10%, down from orders of magnitude, because of the ultralow cosmic-ray background and high intensity of the proton beam.

Christopher Crockett is a freelance writer based in Arlington, Virginia.

REFERENCES

1. L. Y. Zhang *et al.*, "Direct measurement of the astrophysical ^{19}F($p,\alpha\gamma$)^{16}O reaction in the deepest operational underground laboratory," **Phys. Rev. Lett. 127, 152702 (2021).**

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



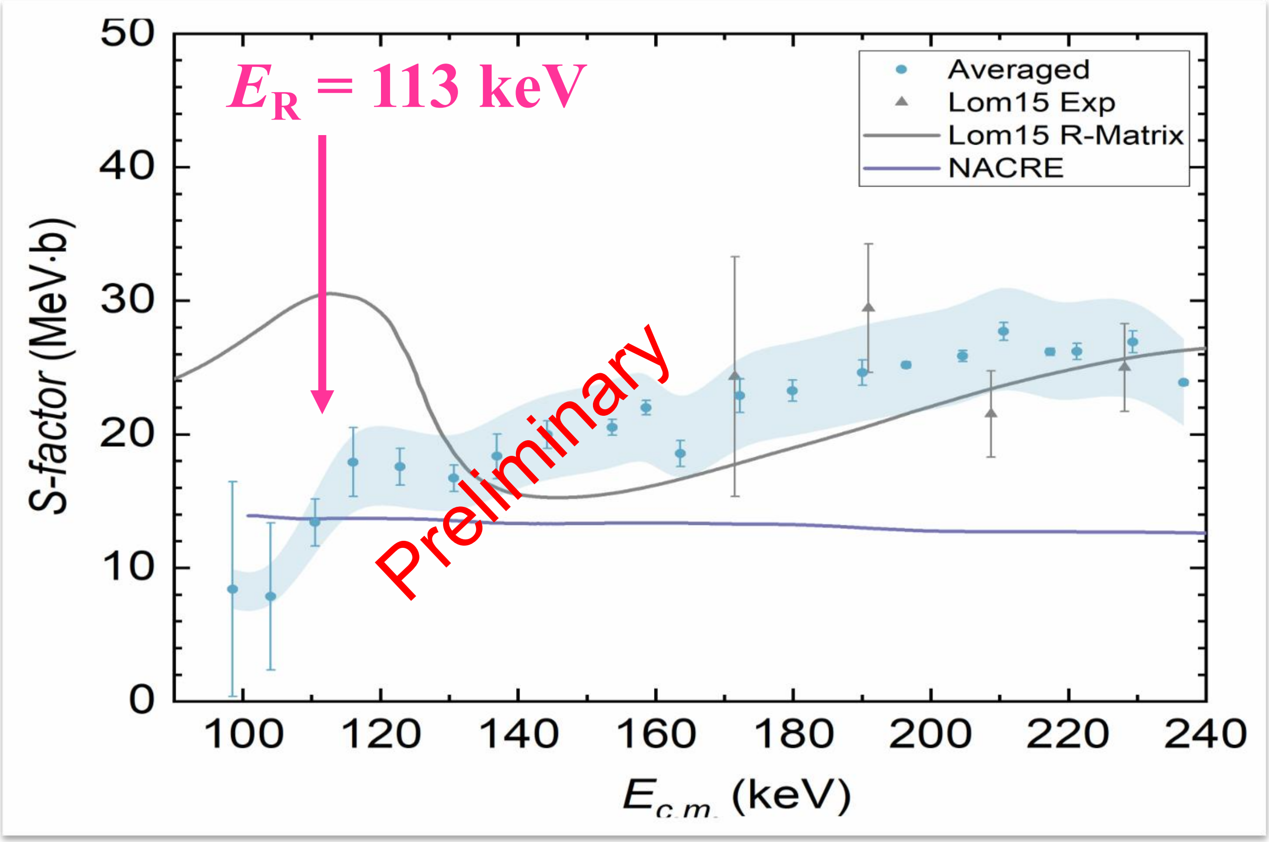
Conclusion:

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

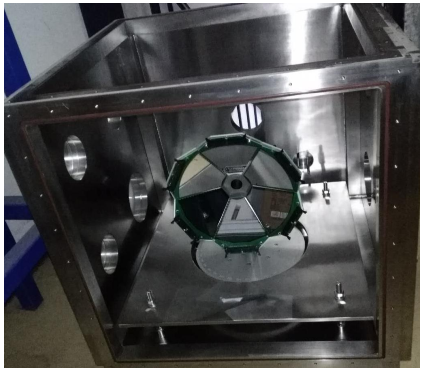
L.Y. Zhang *et al.*, Phys. Rev. C

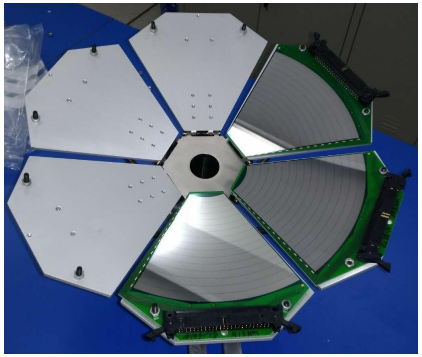
New aboveground $^{19}F(p,\alpha_0)^{16}O$ expt

@Hefei, China



Si array





Around 100 keV region, no obvious resonance peak was observed!

In progress…

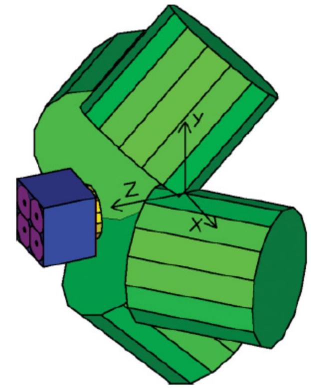
Y.J. Chen *et al.*, NIMA (2023)

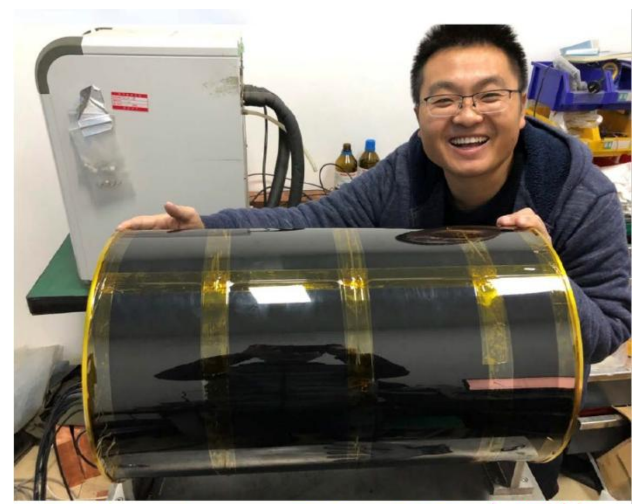
JUNA measurement of $^{19}F(p,\gamma)^{20}Ne$

One-day campaign: Jan. 24~25, 2021

Proton beam current: ~1 mA (JUNA)

	JUNA	ND
Beam current	1 mA	20 uA
Detector	BGO	HPGe+NaI
Det. efficiency (@E_γ = 6 MeV)	60%	?



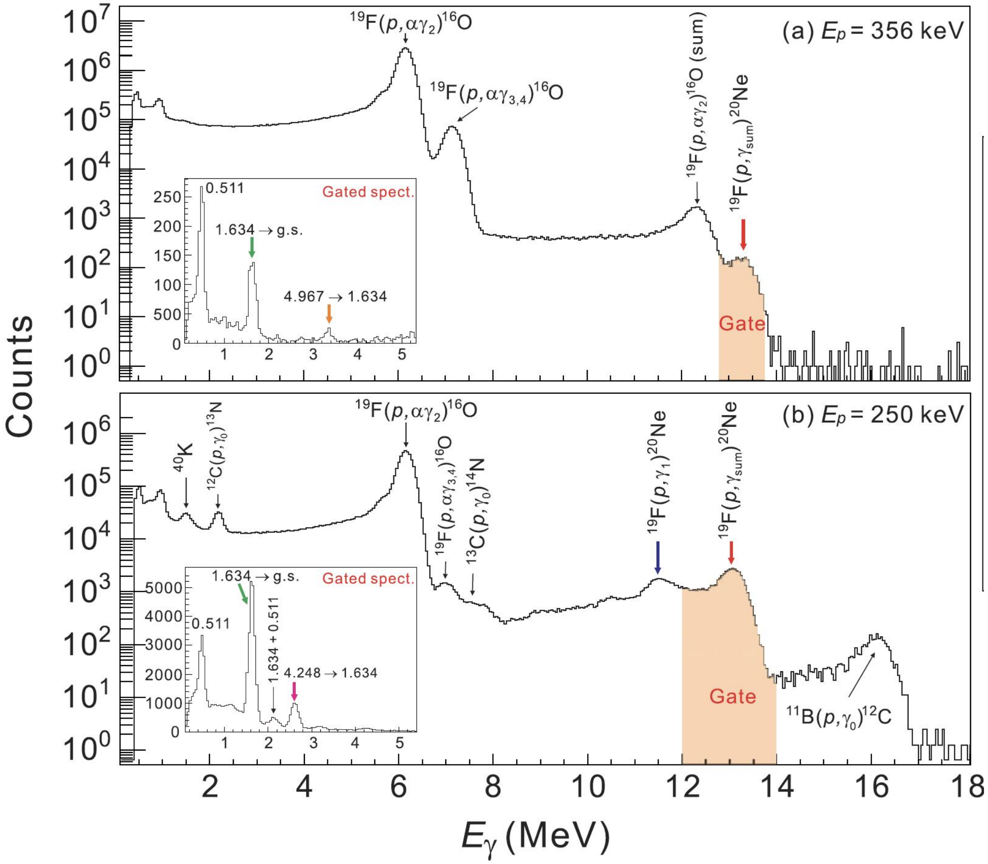


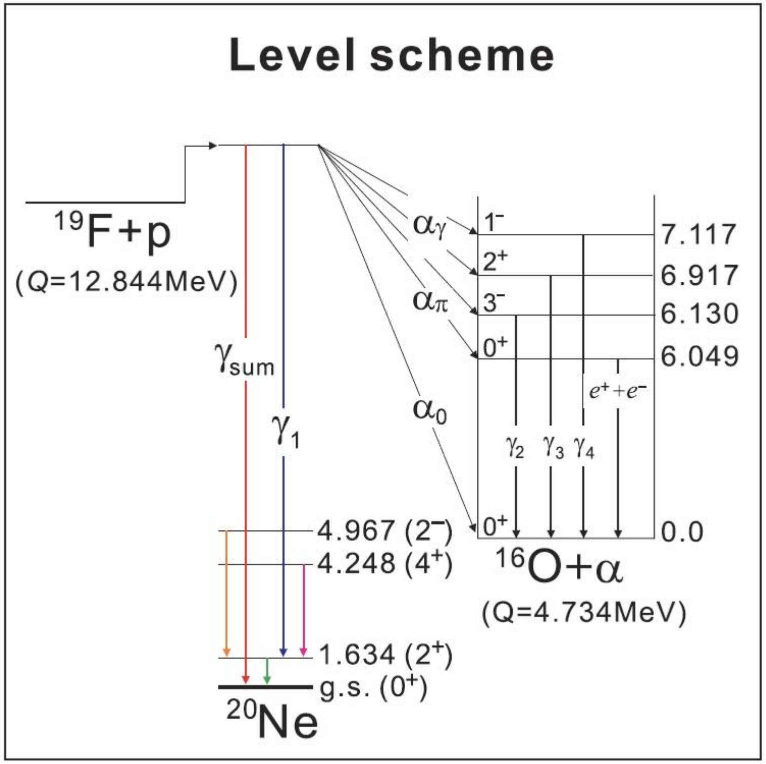
Jinping Gamma Tube (JGT, 金刚筒)

One-day @JUNA equiv. to hundred days @ND!

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

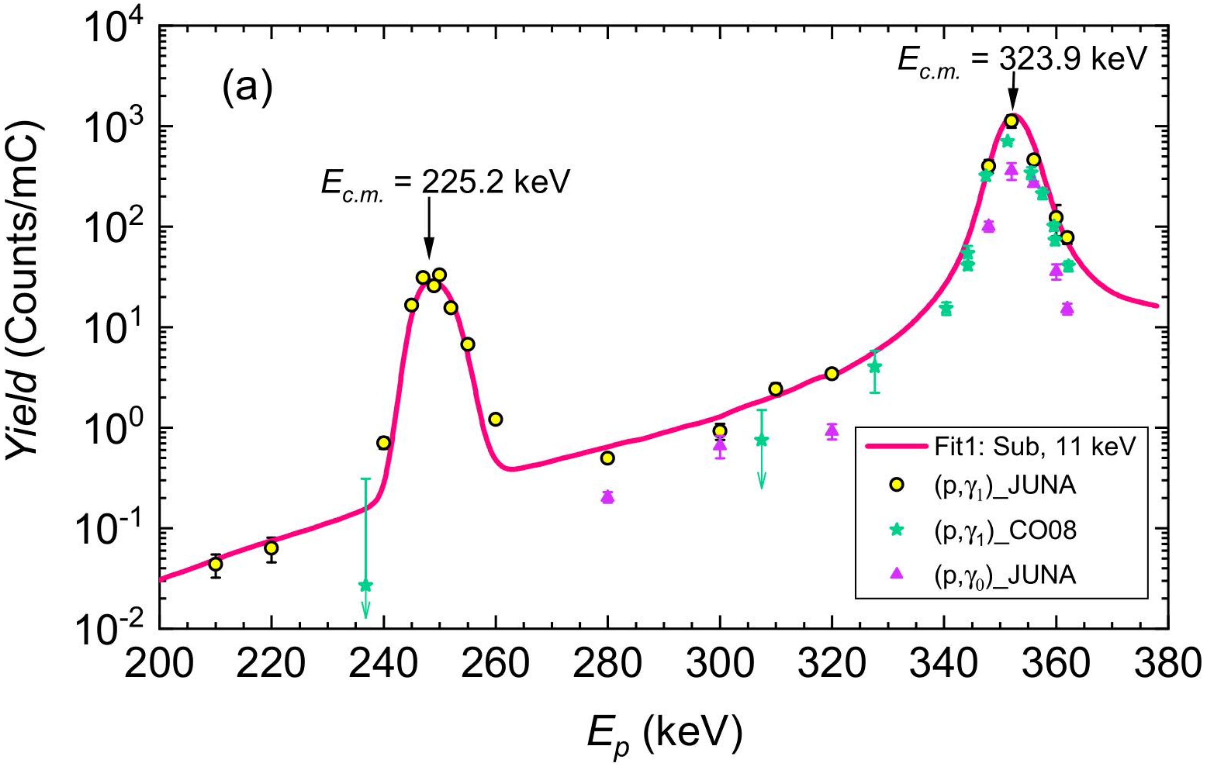
- **Summed γ-ray spectra & coincidence spectra**





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

- **A new resonance!**



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

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

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

			$\omega\gamma_{tot}$ (meV)				
E_{COM} (keV)	E_x (MeV)	J^π	Present	NACRE[3]	ANC ($fm^{-1/2}$)	Γ_{α_2} (eV)	Γ_{γ_1} (eV)
−448	12.396(4)[a]	1^+			15[b]	60^{+40}_{-30}	<3.4
11	12.855(4)[a]	1^+			1.14×10^{-28} [c]	-590^{+230}_{-290}	<4.8
212.7(10)	13.057	2^-	$<4.2\times10^{-3}$	$<1.3(13)\times10^{-3}$			
225.2(10)	13.069	3^-	$4.19(33)\times10^{-2}$				
323.9	13.168(2)[b]	1^+	3.16(33)	5(3)			

Values are determined for the $^{19}F(p,\gamma)^{20}Ne$ 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: [a]ref.[39], [b]ref.[5], [c]ref.[26], where the corresponding uncertainties are adopted.

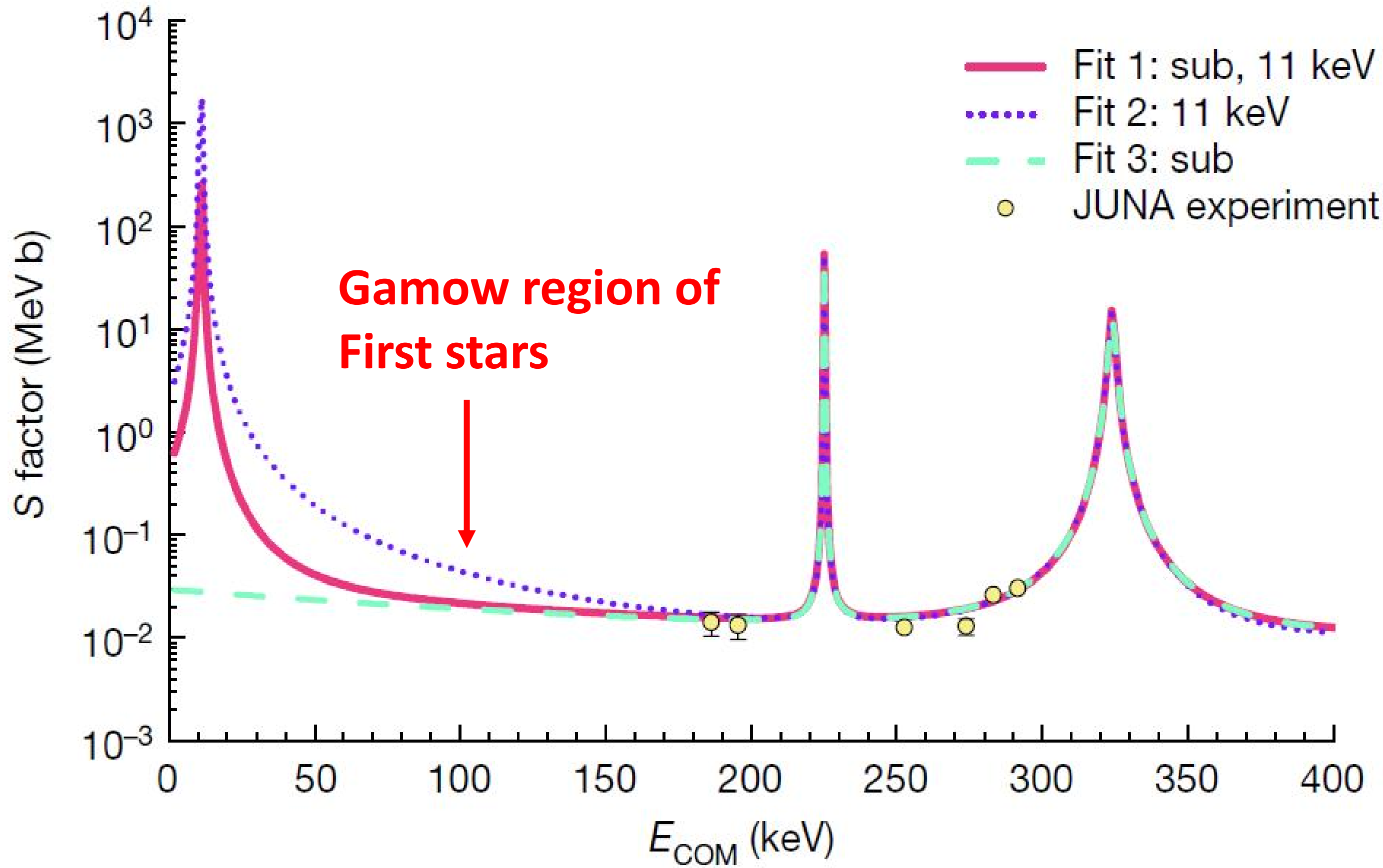
JUNA measurement of $^{19}F(p,\gamma)^{20}Ne$

- **Astrophysical *S* factor:**

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

***R*-matrix calculations**

DeBoer, Wiescher, Odell



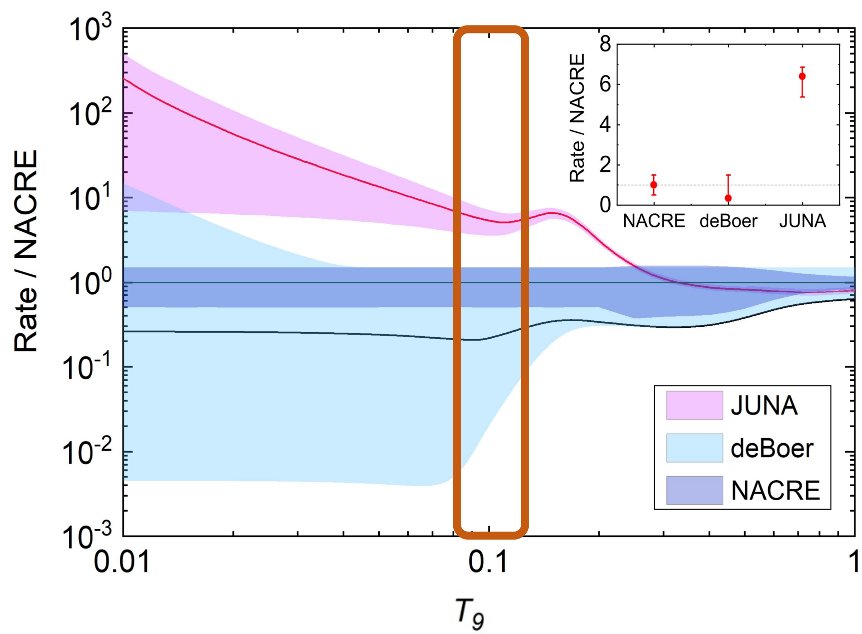
JUNA measurement of $^{19}F(p,\gamma)^{20}Ne$

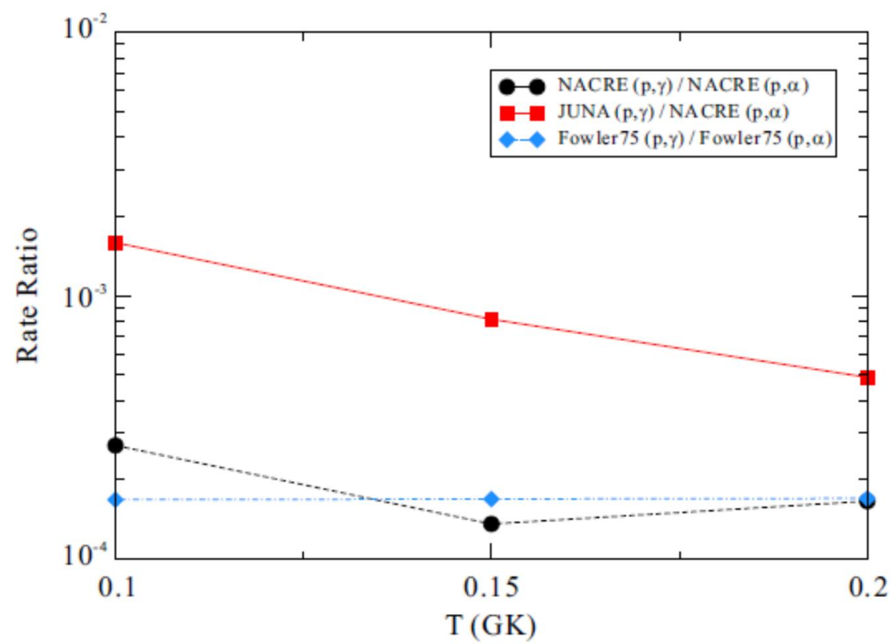
New reaction rate:

- 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

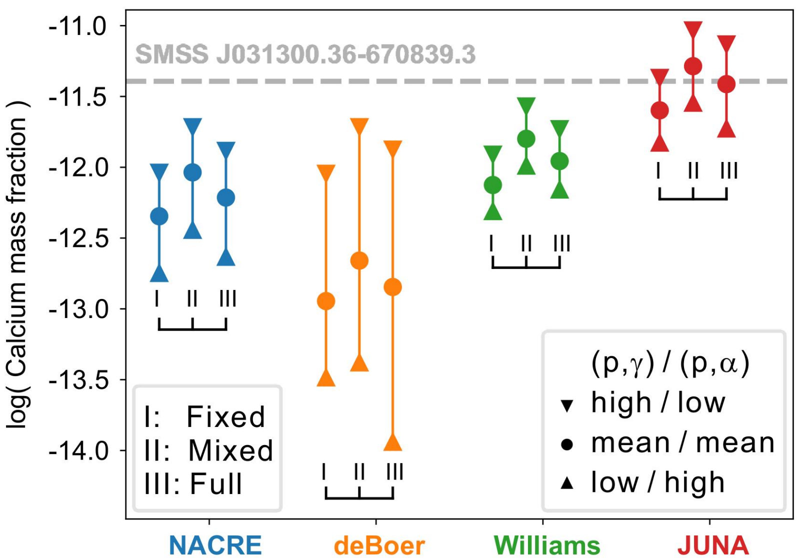
$^{19}F(p,\gamma)^{20}Ne$ / $^{19}F(p,\alpha\gamma)^{16}O$





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

A. Heger's model calculations



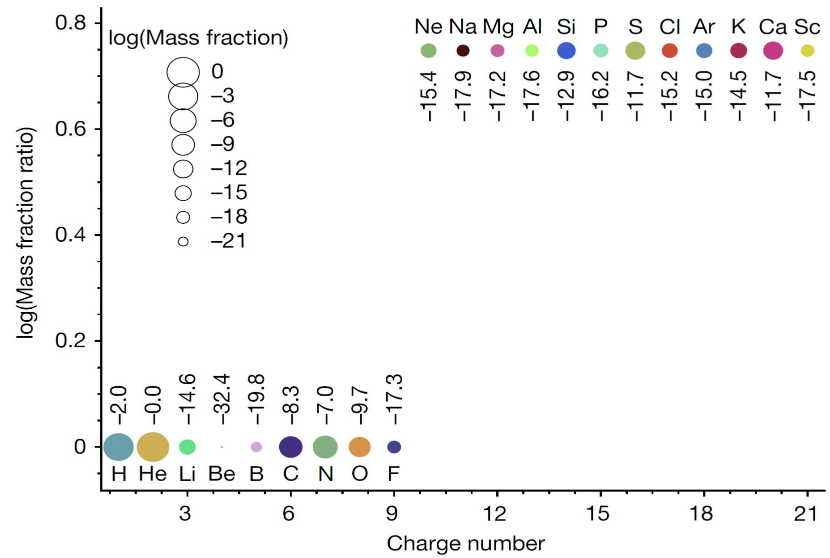


Fig. 4 | Ratio of final abundances of using our JUNA mean $^{19}F(p,\gamma)$ rate compared to using the NACRE[3] mean rate. Both use the NACRE mean $^{19}F(p,\alpha)$

Astrophysical implications:

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

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

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

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Article | Published: 26 October 2022

Measurement of ^{19}F(p, γ)^{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 Baoqun Cui, Lihua Chen, Ruigang Ma, Ertao Li, Gang Lian, Yaode Sheng, Zhihong Li, Bing Guo, Xiaoh Zhou, Yuhu Zhang, Hushan Xu, Jianping Cheng & Weiping Liu — Show fewer authors

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

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NEWS AND VIEWS | 26 October 2022

An underground route to grasping the Milky Way's oldest stars

Nuclear-fusion experiments performed deep under Earth's surface reveal one possible scenario that could have resulted in the chemical abundances found in an ancient star in the Milky Way.

Marco Pignatari & Athanasios Psaltis

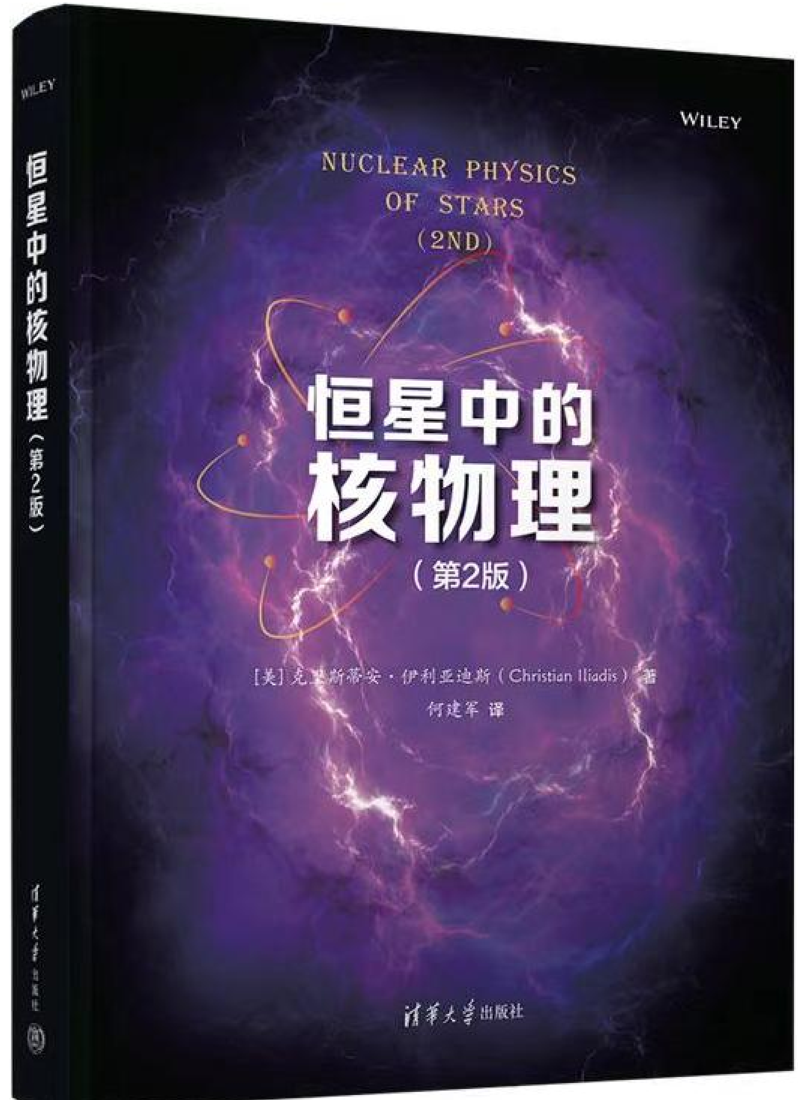
Recommended Books

W.D. Arnett and J.W. Truran	*Nucleosynthesis* The University of Chicago Press, 1968
H. Reeves	*Stellar evolution and Nucleosyntheis* Gordon and Breach Sci. Publ. New York, 1968
J. Audouze and S. Vauclair	*An introduction to Nuclear Astrophysics* D. Reidel Publ. Company, Dordrecth, 1980
D.D. Clayton	*Principles of Stellar evolution and nucleosynthesis* The University of Chicago Press, 1983
E. Böhm-Vitense	*Introduction to Stellar Astrophysics*, vol. 3 Cambridge University Press, 1992
C.E. Rolfs and W.S. Rodney	*Cauldrons in the Cosmos* The University of Chicago Press, 1988 (…the "Bible")
C. Iliadis	*Nuclear Physics of Stars* Weinheim, Wiley, 2007

Recommended Books

Chinese version of Nuclear Physics of Stars

Translated by Jianjun HE



北京師範大學
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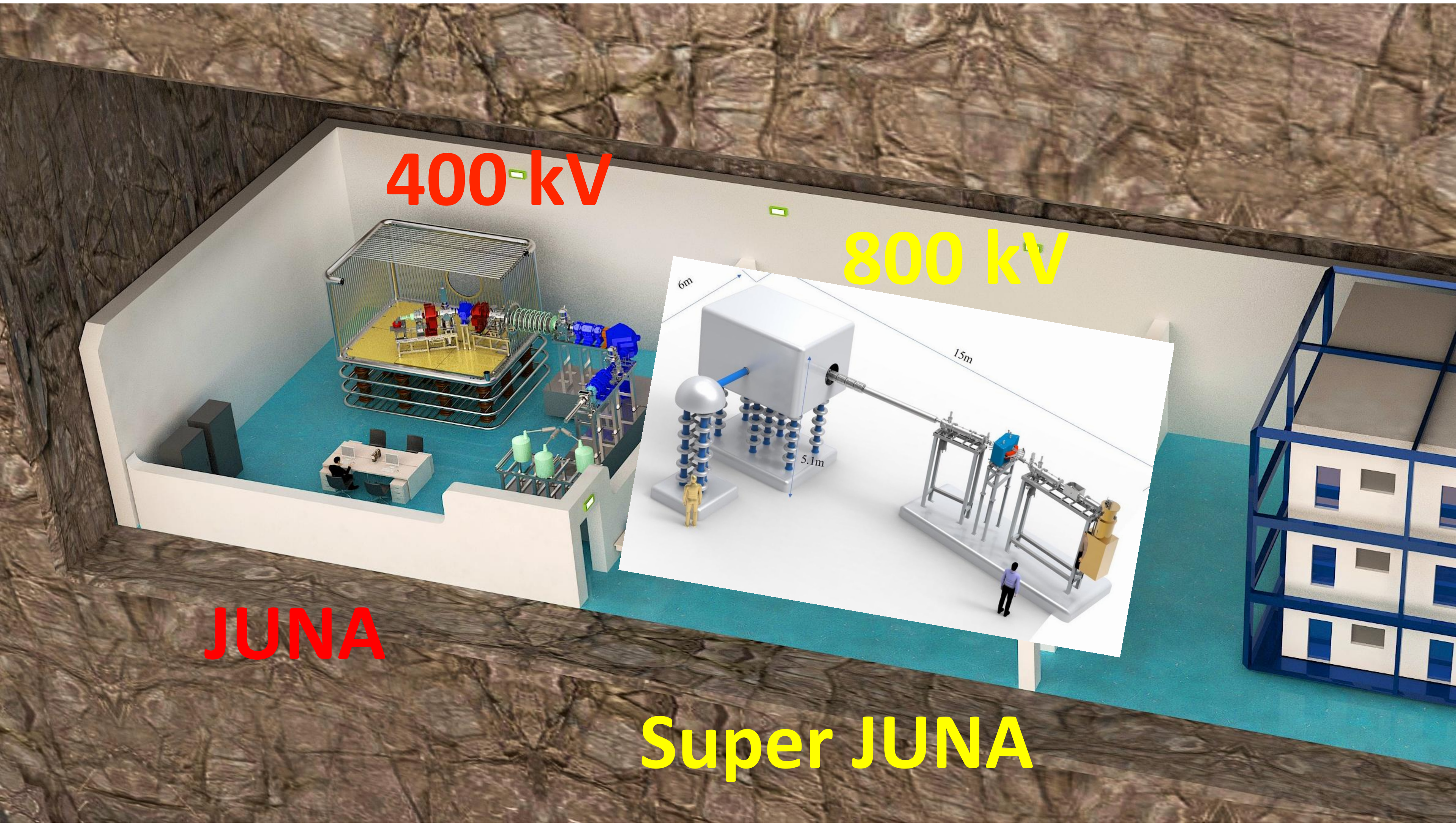
Thanks very much for your attention!



The future

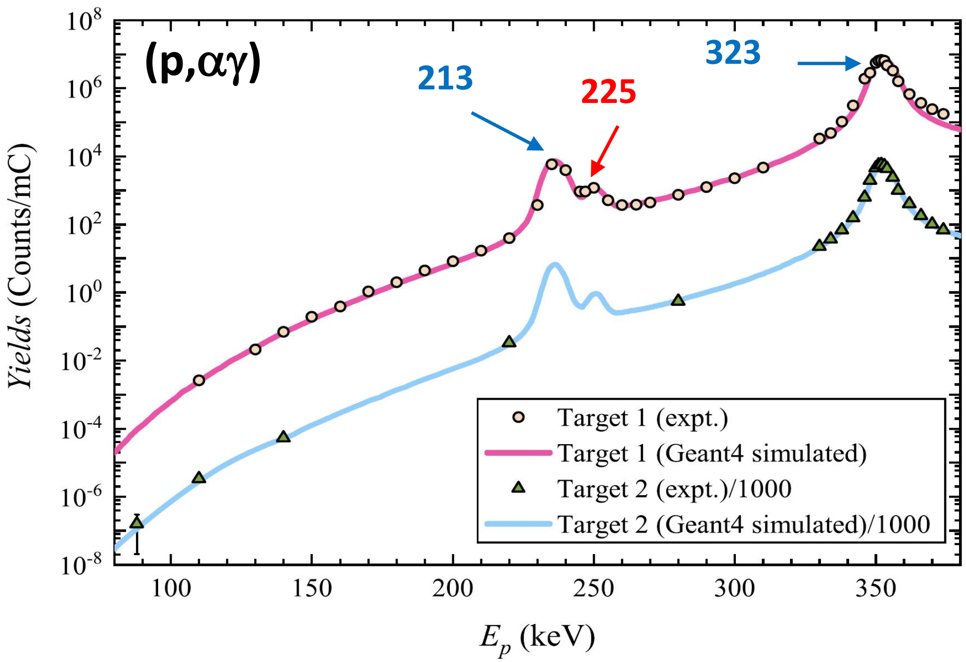
锦屏深地核天体物理实验
Jinping Underground Nuclear Astrophysics Experiment

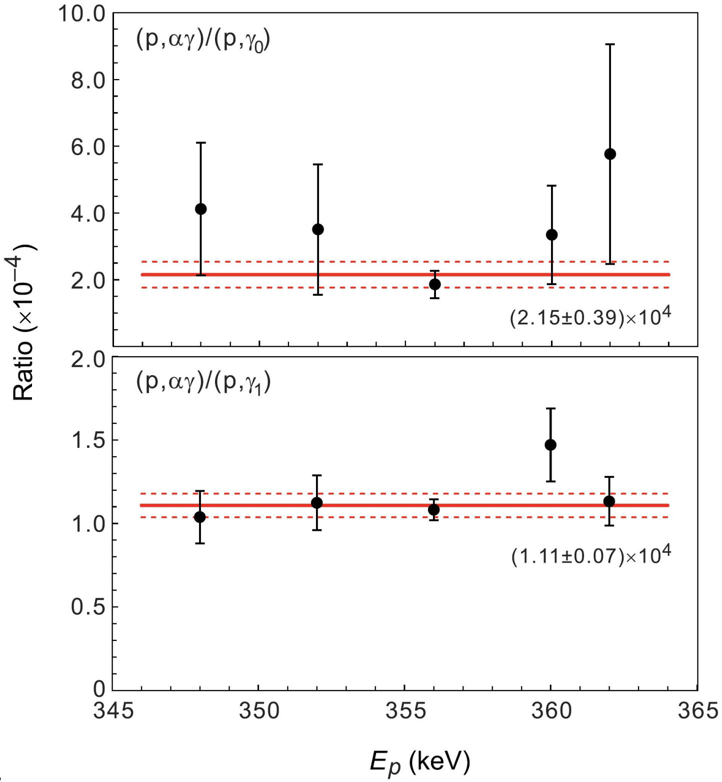


JUNA measurement of $^{19}F(p,\gamma)^{20}Ne$

- **Relative measurement to:**

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





323-keV resonance:

$\omega\gamma_{(p,\gamma 1)}$=2.09±0.21 meV; $\omega\gamma_{(p,\gamma 0)}$=1.07±0.21 meV

$\omega\gamma_{(p,\gamma tot)}$=3.16±0.33 meV

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

Remarks

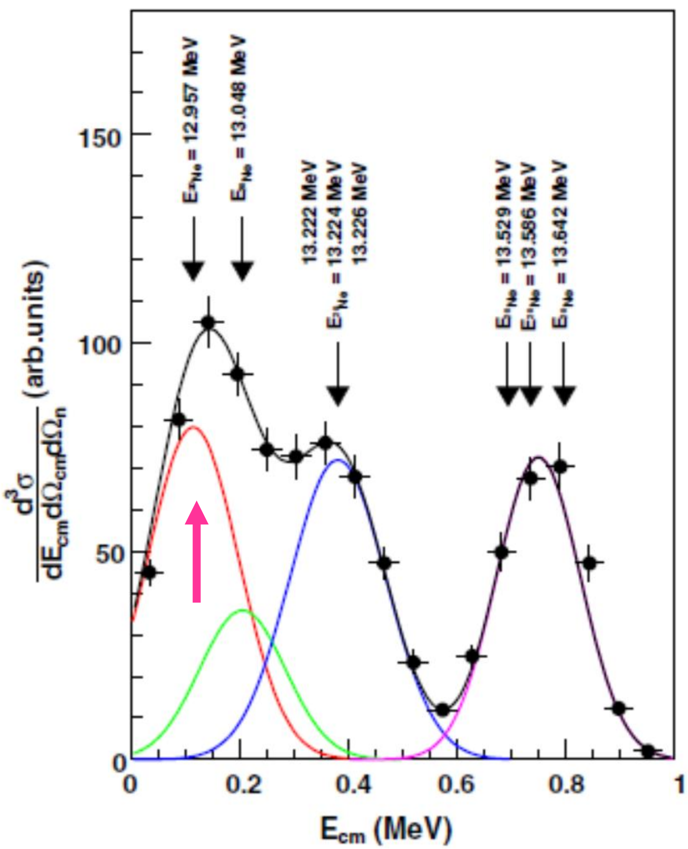
- We measured the $^{19}F(p,\alpha\gamma)^{16}O$ cross section down to $\sim$70 keV at JUNA, covering the full Gamow window of astrophysics interests.
- New and precise reaction rate was determined based on the solid experimental ground.
- In the 50 $\sim$ 200 keV region, (p,α_0) dominates the total cross section and hence the rate below 0.12 GK! This channel still needs future experimental investigations.

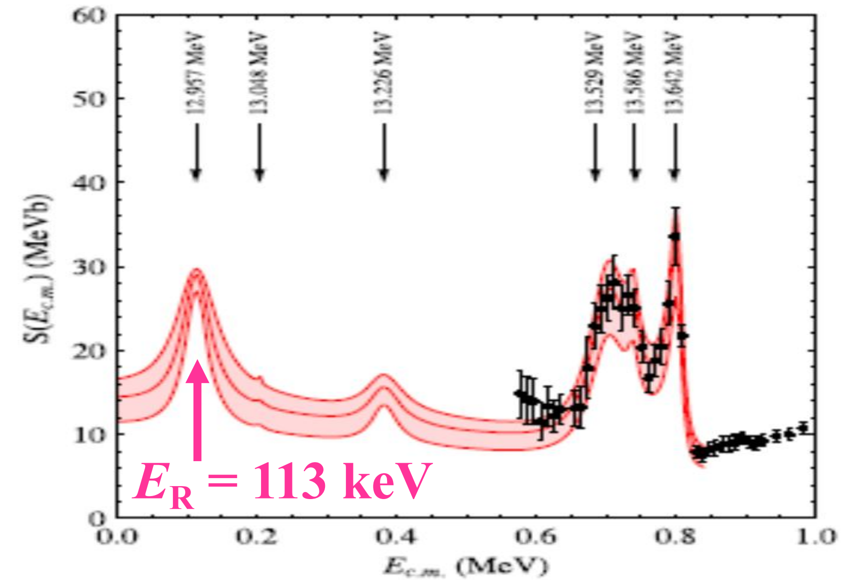
About $^{19}F(p,\alpha_0)^{16}O$

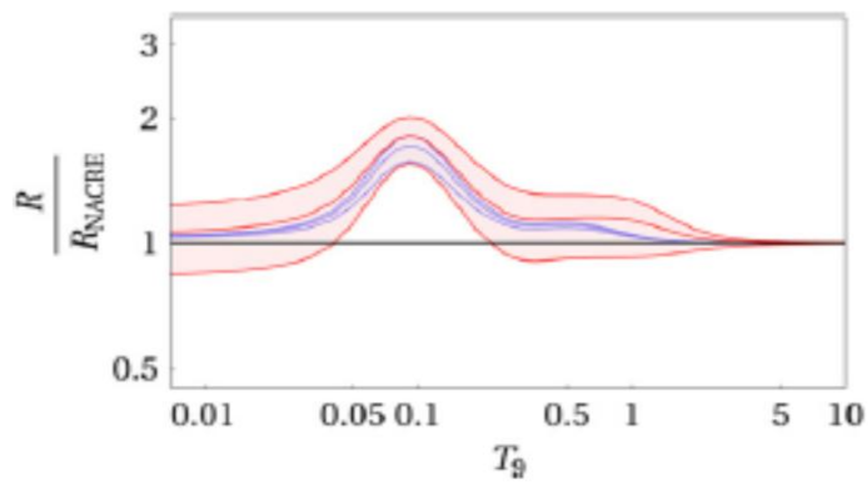
- **Catania group's work**

Trojan-Horse Method (THM)

$^{2}H(^{19}F,\alpha_0{}^{16}O)n$



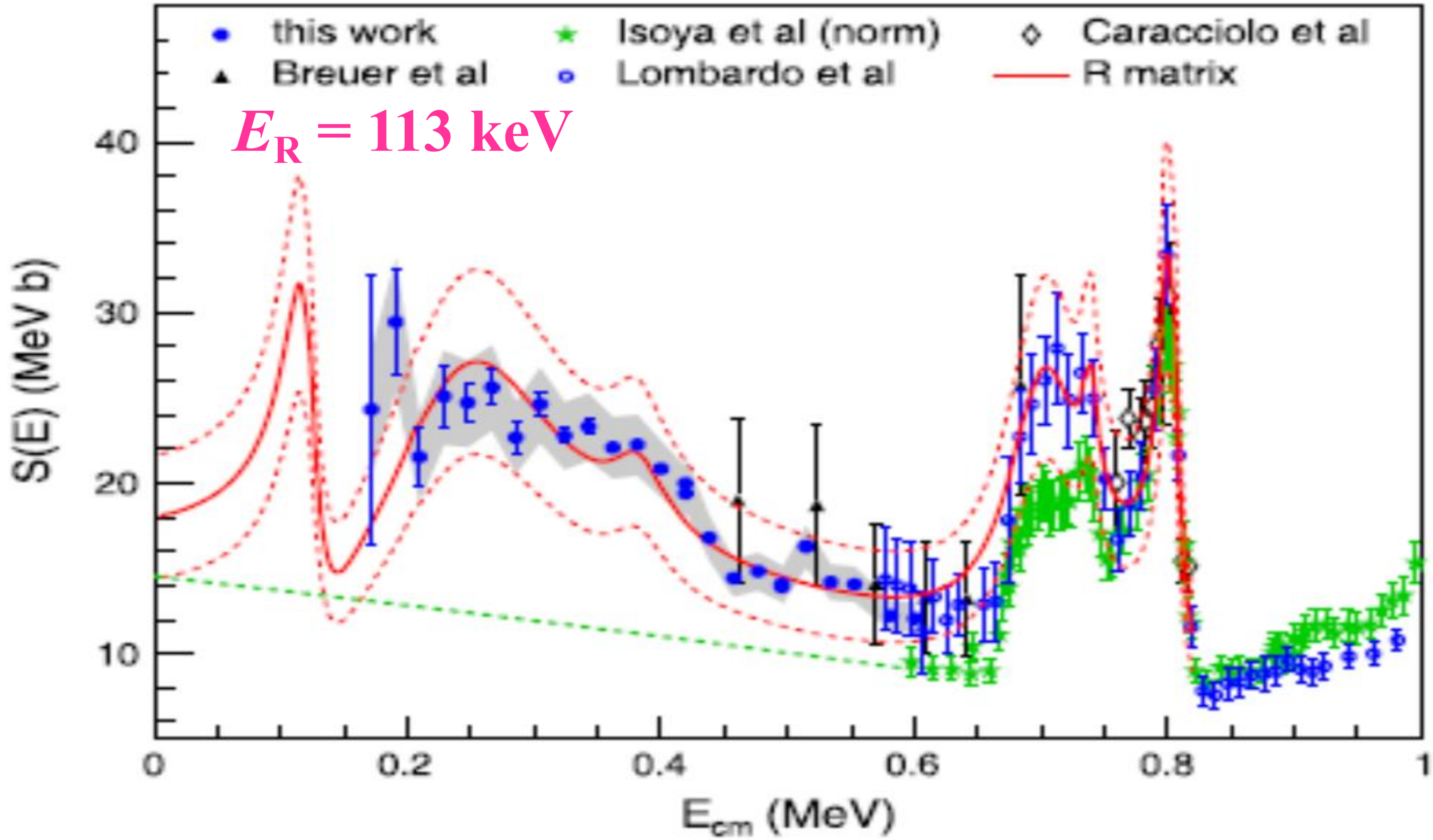




M. La Cognata *et al.*, Astrophys. J. 739 (2011) L54
M. La Cognata *et al.*, Astrophys. J. 805 (2015) 128

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

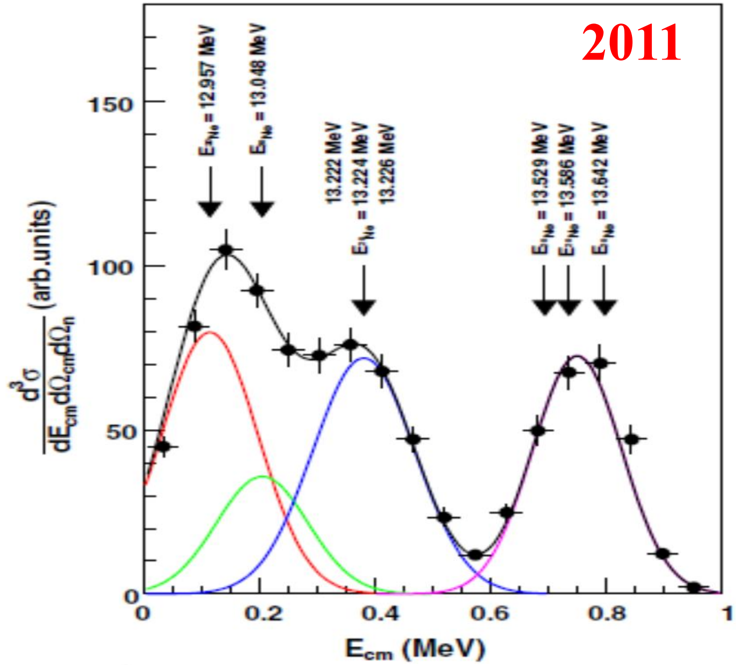
- **Lombardo *et al.*'s direct measurements**

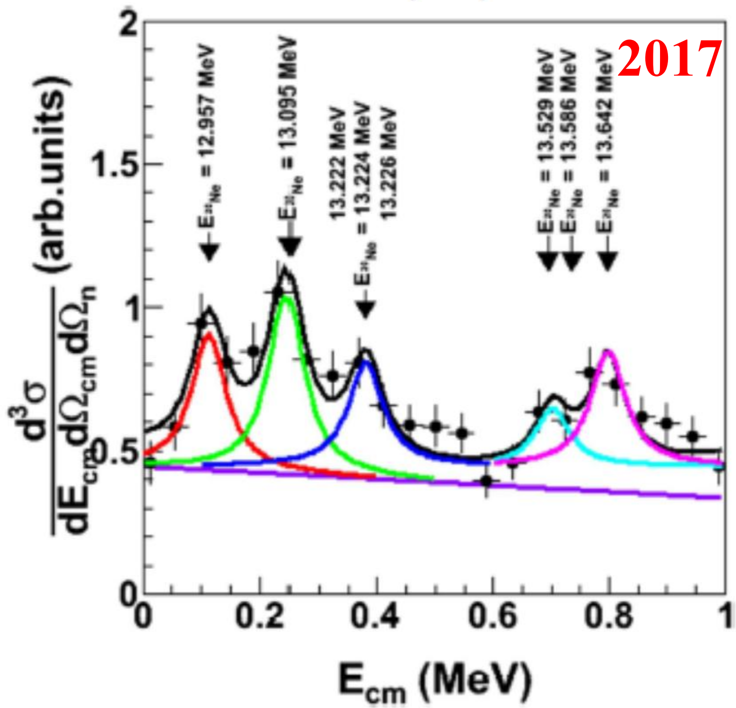


I. Lombardo *et al.*, Phys. Lett. B 748 (2015) 178

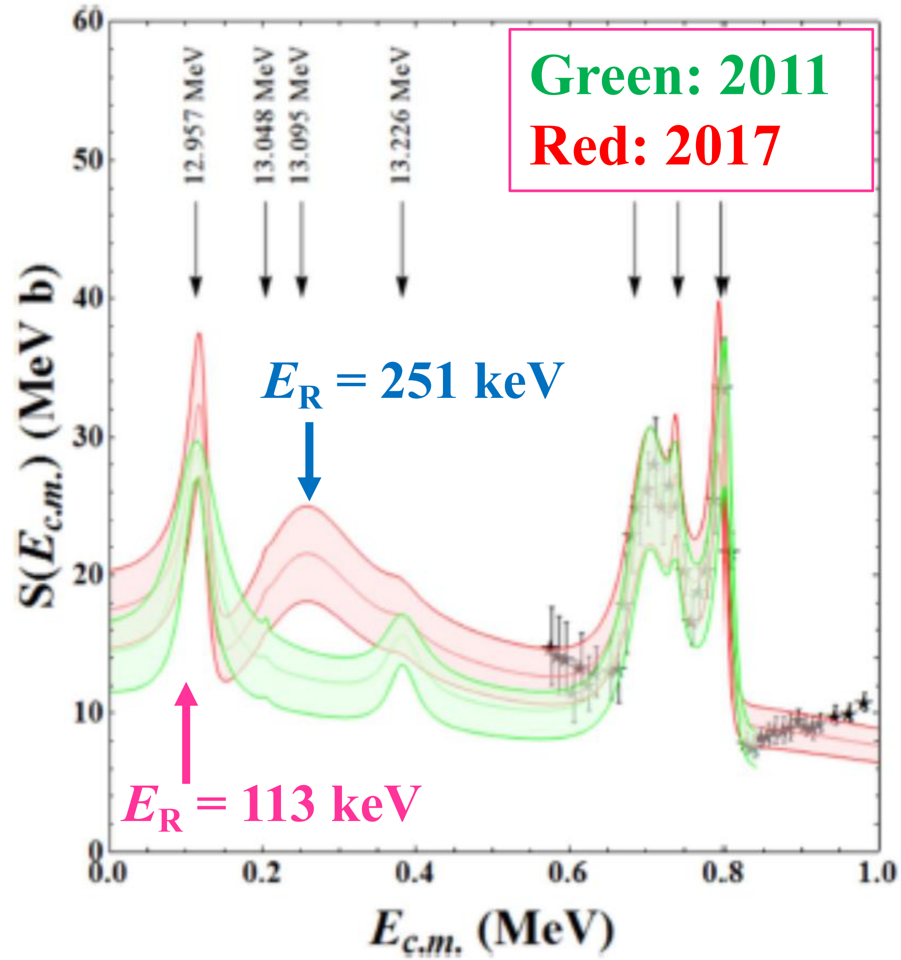
I. Lombardo *et al.*, J. Phys. G: Nucl. Part. Phys. 40 (2013) 125102

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





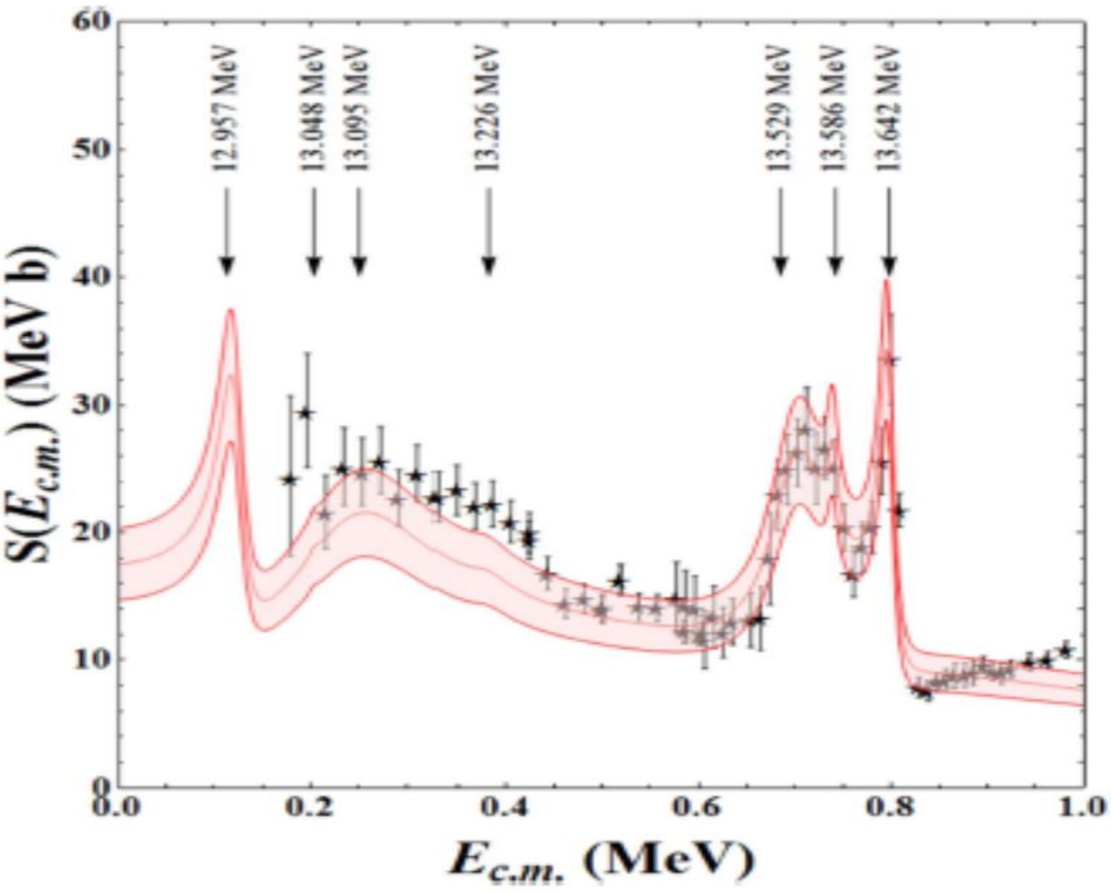
Trojan-Horse Method (THM)



I. Indelicato *et al.*, Astrophys. J. 845(2017)19

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

- **THM & Direct measurement**



I. Indelicato *et al.*, Astrophys. J. 845(2017)19

总结

- 在锦屏深地，我们将CNO循环中的^{19}F(p,γ)^{20}Ne突破反应推进到186 keV能区, 并发现了一个位于225 keV的新共振态。
- 新的反应率比NACRE推荐的要大得多，在0.1 GK温度处大4.7~7.5倍，在0.01 GK温度处大200多倍。不确定度比之前理论外推小好几个数量级。
- 基于新的反应率，模型研究显示出从“温”CNO循环中一个较强的突破，这是之前从未预想到的。并且，可以解释第一代恒星中Ca等元素的丰度，强烈支持大质量Pop III恒星的弱超新星演化模型，有力排除了其他演化假设。
- 期待这一结果能够对未来JWST对宇宙早期恒星丰度观测产生影响。

未来研究课题

太阳中微子&金属度问题

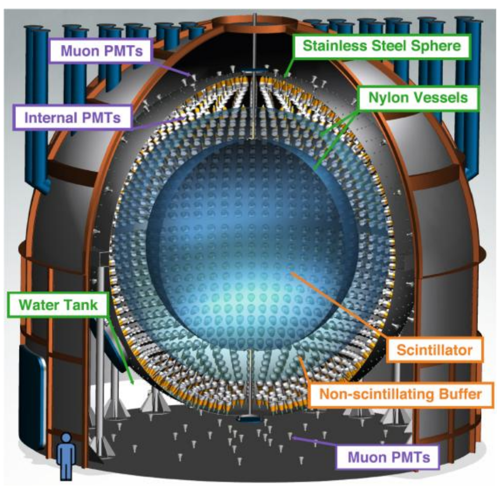
太阳金属丰度：

早期光谱观测： $Z = 1.7\sim2.0\%$

日震学： $Z = 1.8\%$

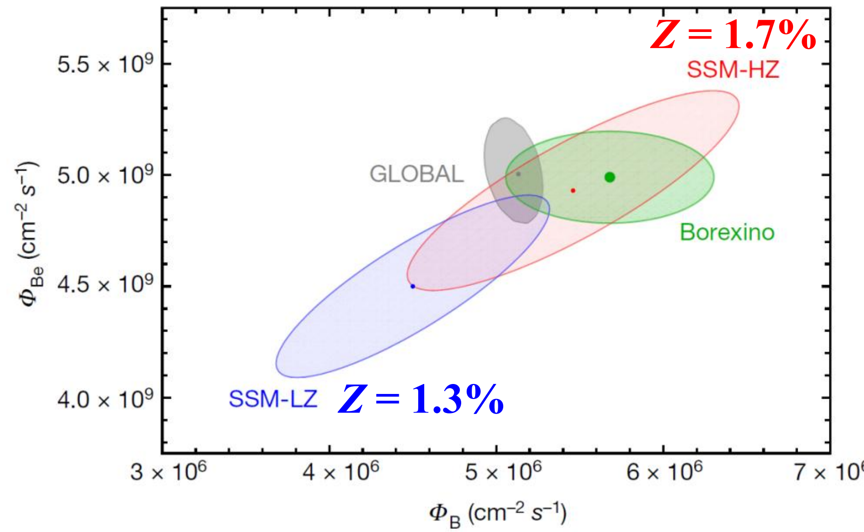
2009年光谱观测： $Z = 1.3\%$

Borexino Collab., Nature 562(2018)505



$\phi(^7Be) = (4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^9$ (精度~3%)

$\phi(^8B) = (5.68^{+0.39}_{-0.41}{}^{+0.03}_{-0.03}) \times 10^6$ (精度~7%)



Finally, the Borexino measurements can be used to test the predictions of SSMs with different metallicity. Indeed, the assumed metallicity determines the opacity of solar plasma and, as a consequence, regulates the central temperature of the Sun and the branching ratios of the different *pp*-chain terminations. To perform this test, we use only the results for ^{7}Be and ^{8}B neutrinos, whose fluxes are very different in the HZ- and the LZ-SSM theoretical predictions (differences of 9% and 18%, respectively). Figure 4 shows the results of Borexino (green-shaded ellipse), together with the predictions for the HZ- and LZ-SSMs[18] (red- and blue-shaded ellipses, respectively). Note that the errors in the Borexino measurements are in both cases smaller than the theoretical uncertainties. The theoretical error budget is dominated by uncertainties on the astrophysical factor S_{34} of the ^{3}He + ^{4}He reaction, on the opacity of the Sun, and on the astrophysical factor S_{17} of the p + ^{7}Be reaction as discussed in ref. [18].

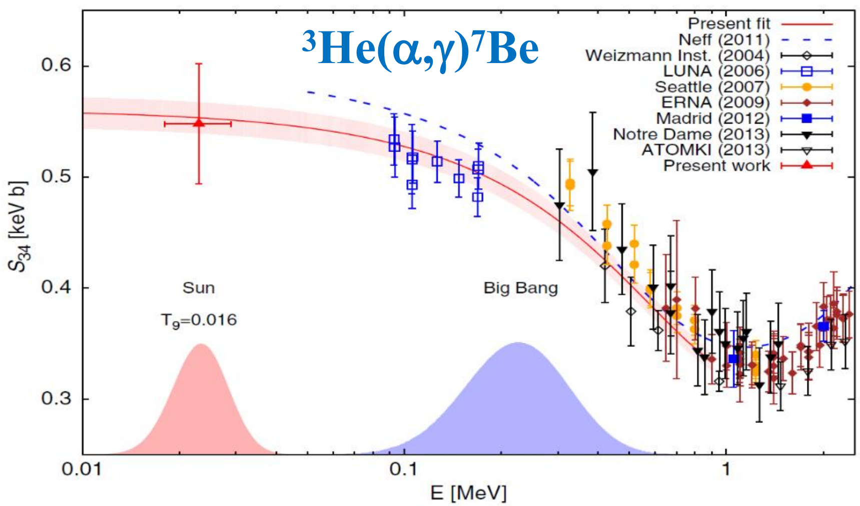
未来研究课题

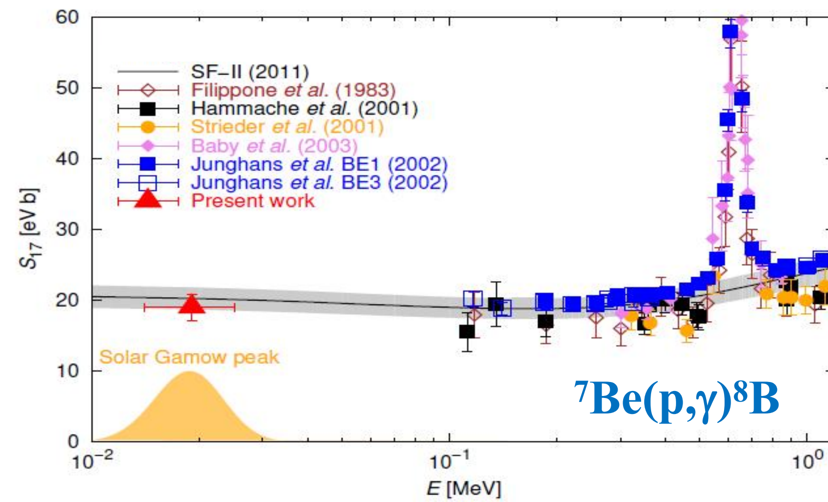
太阳中微子&金属度问题

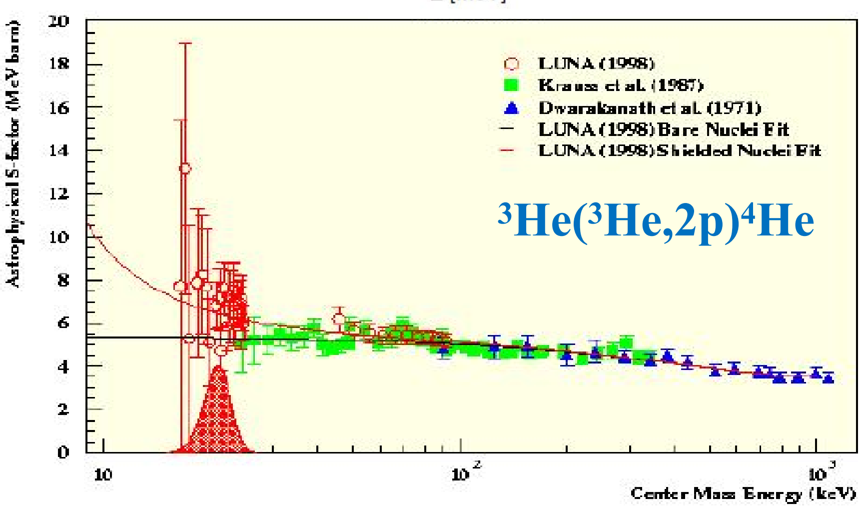
发展现状、趋势、挑战

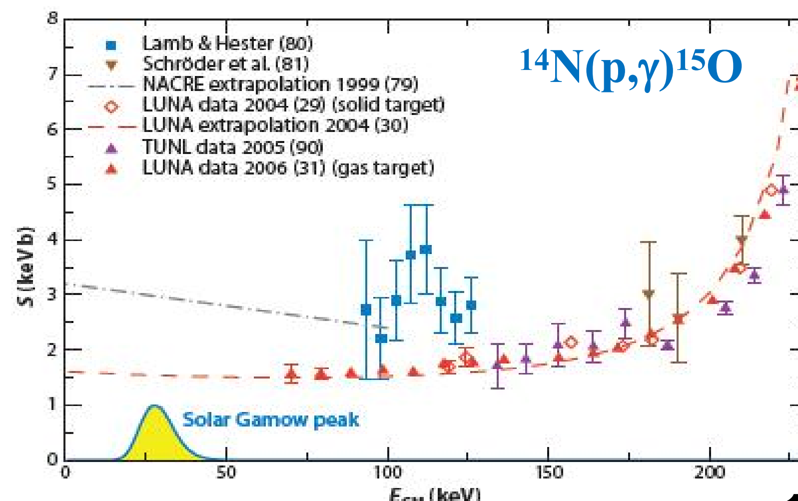
模型精度要求2%

深地实验室环境





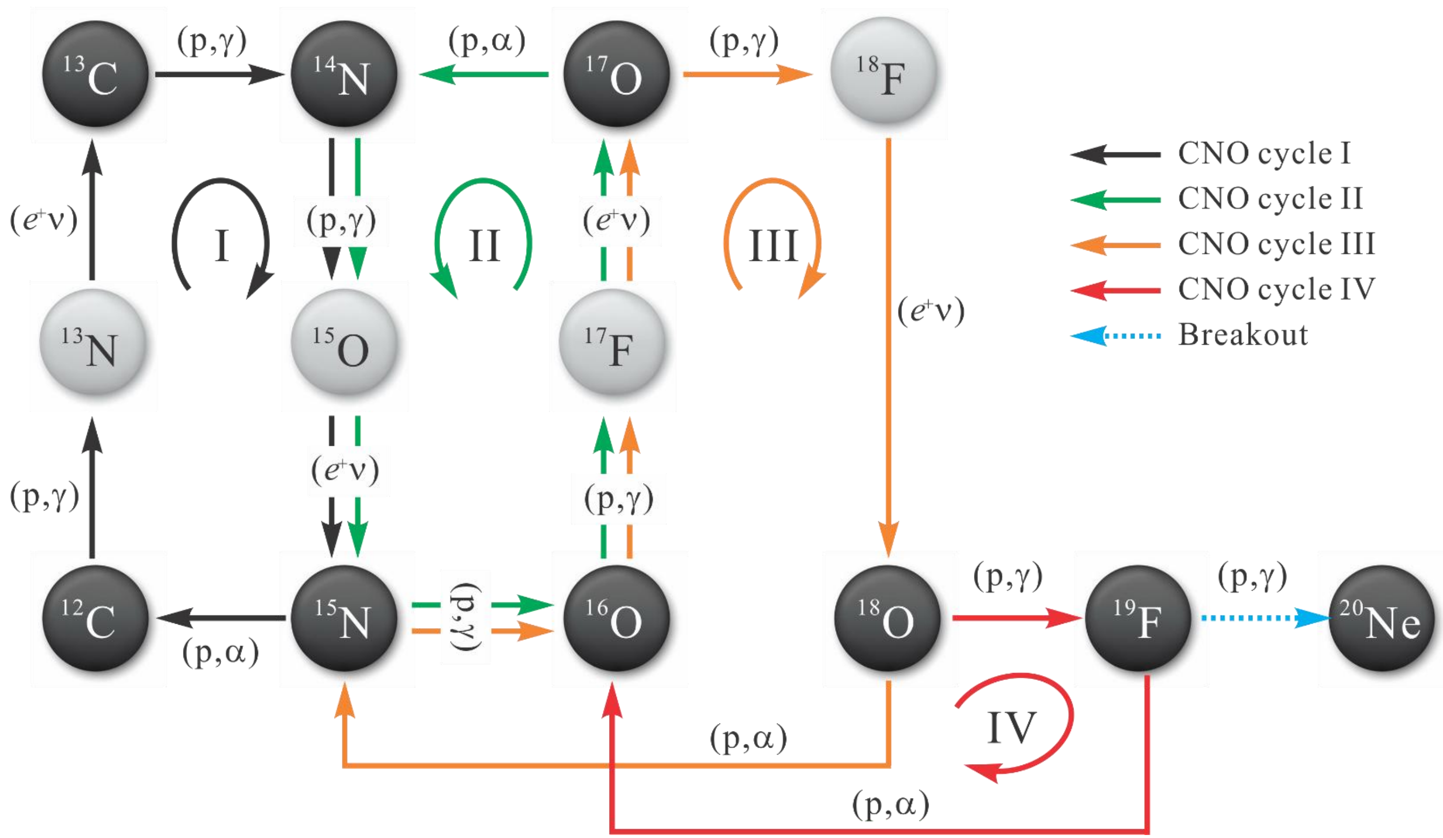




宇宙中已知最老的恒星

典型温度：～0.1 GK

CNO循环

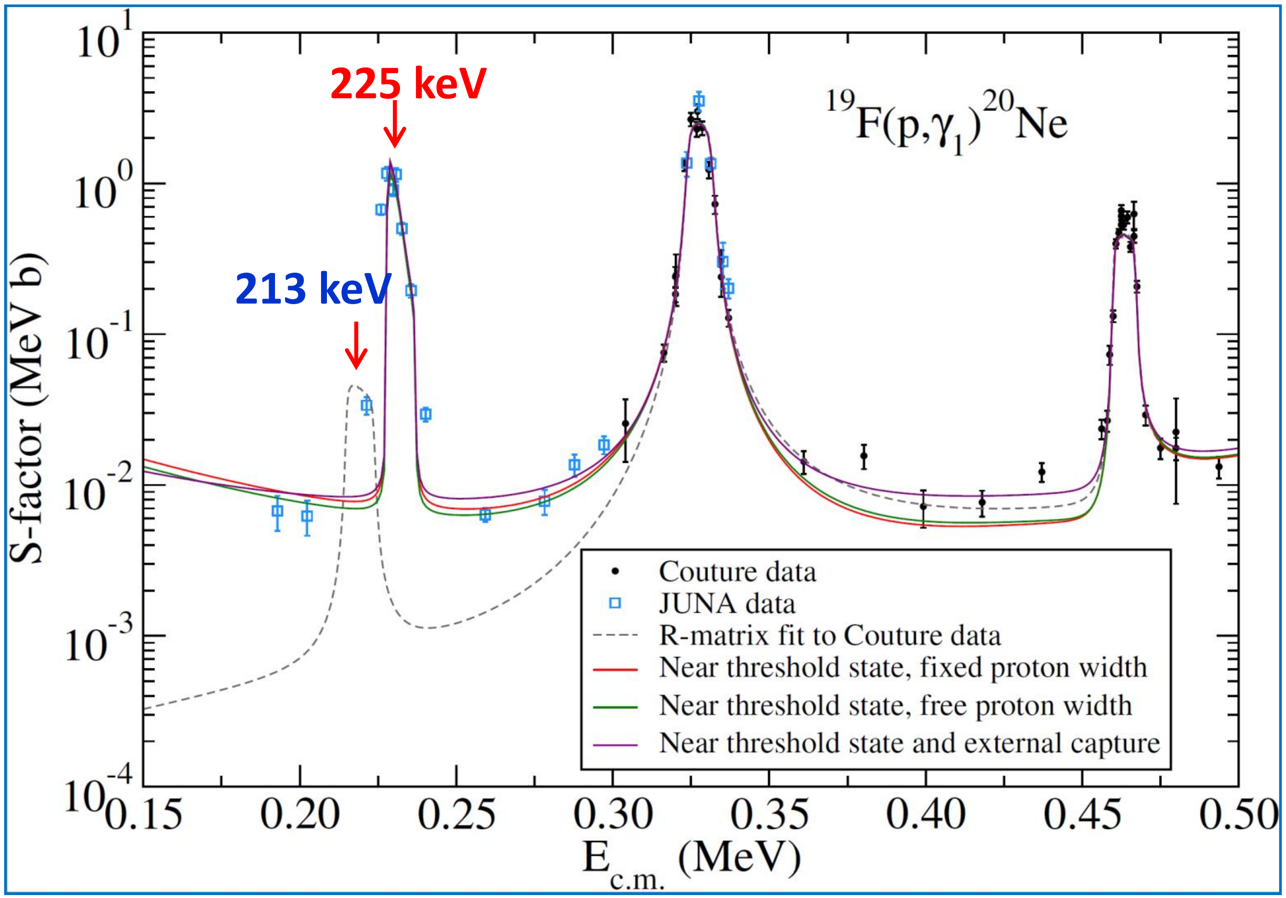


M. Wiescher et al., Annu. Rev. Nucl. Part. Sci. 60 (2010) 381

锦屏实验测量

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

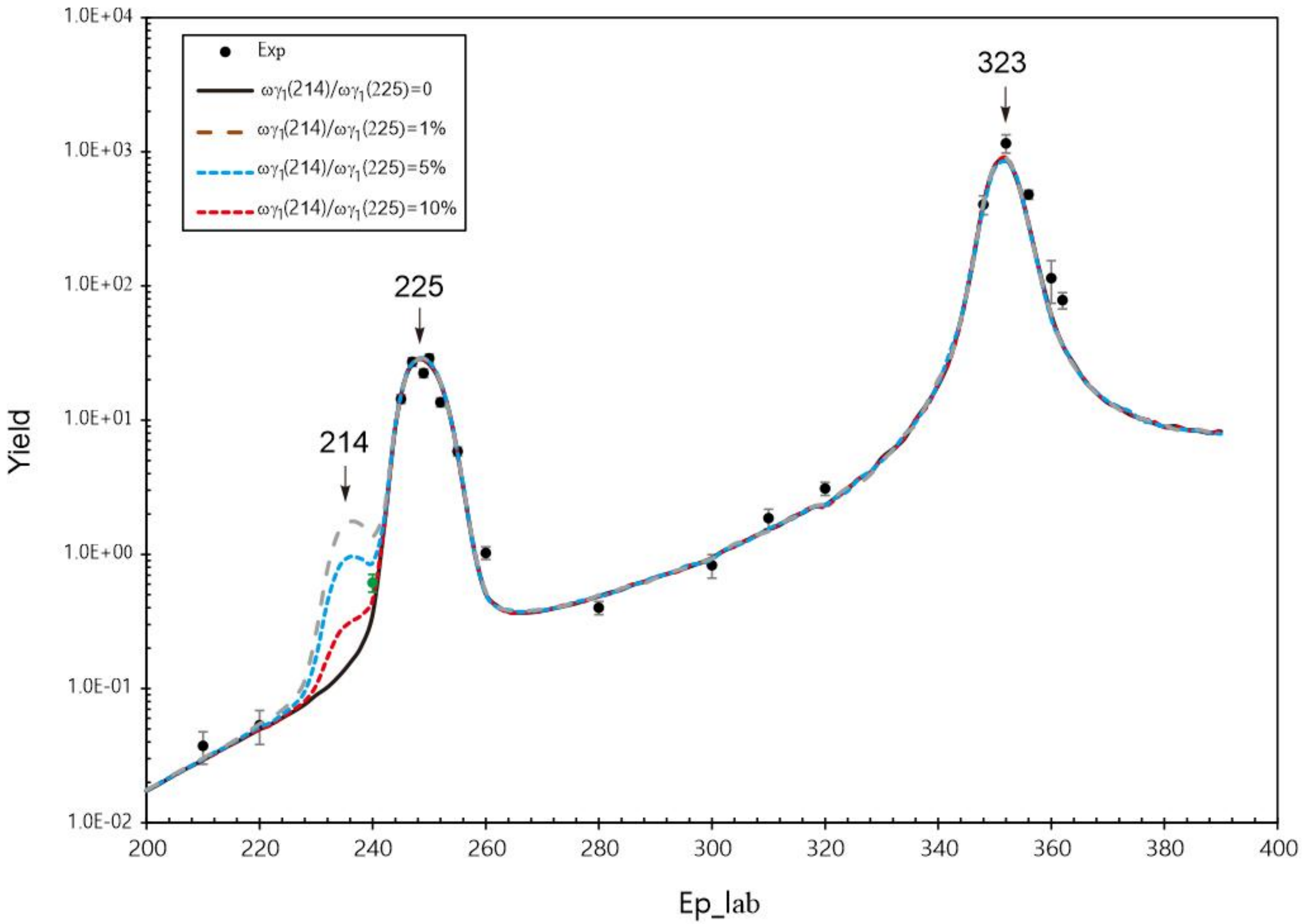
（*R*-matrix计算, DeBoer & Wiescher等人）



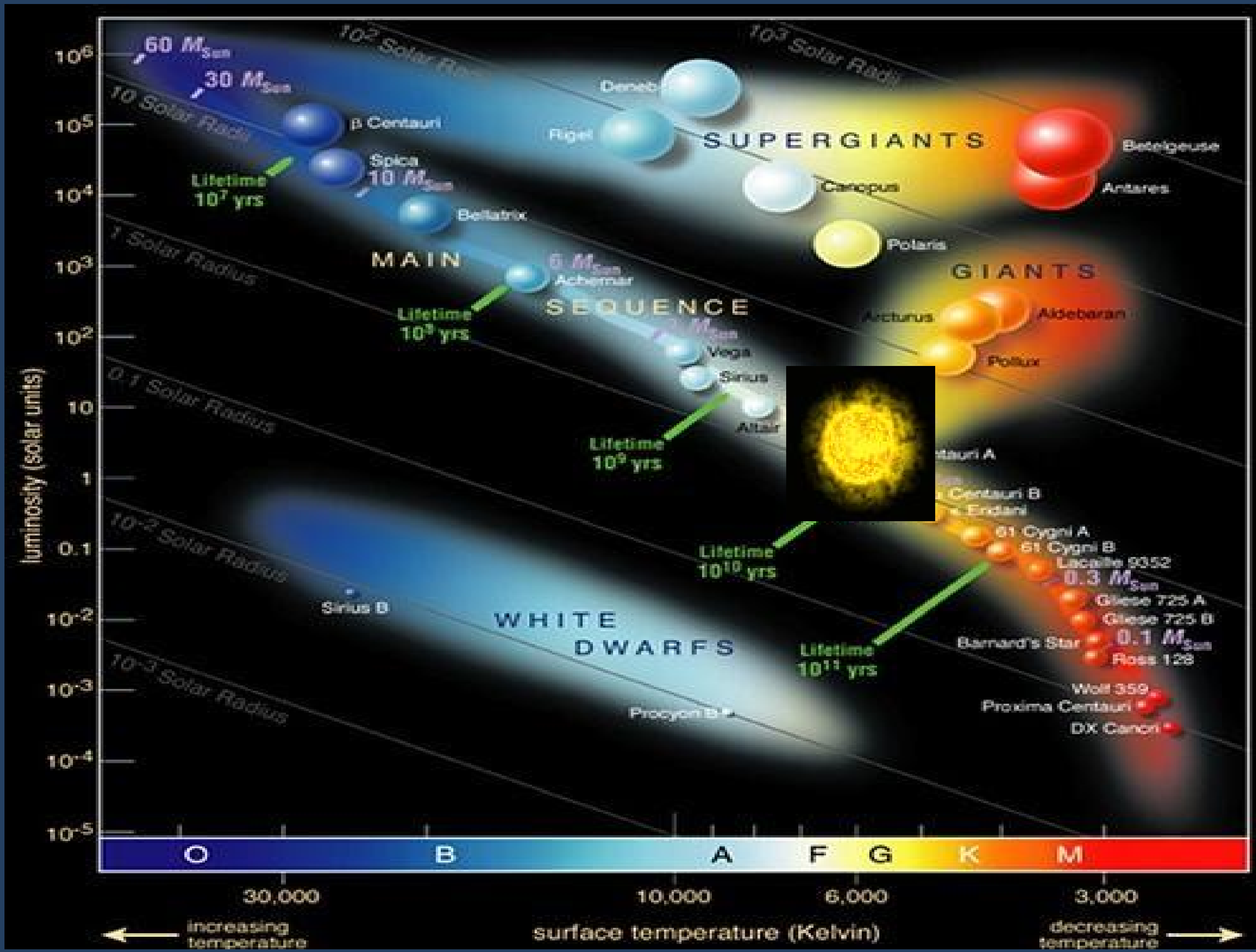
R.J. deBoer *et al.*, PRC103(2021)055815

锦屏实验测量

214-keV共振的贡献（5~10%）



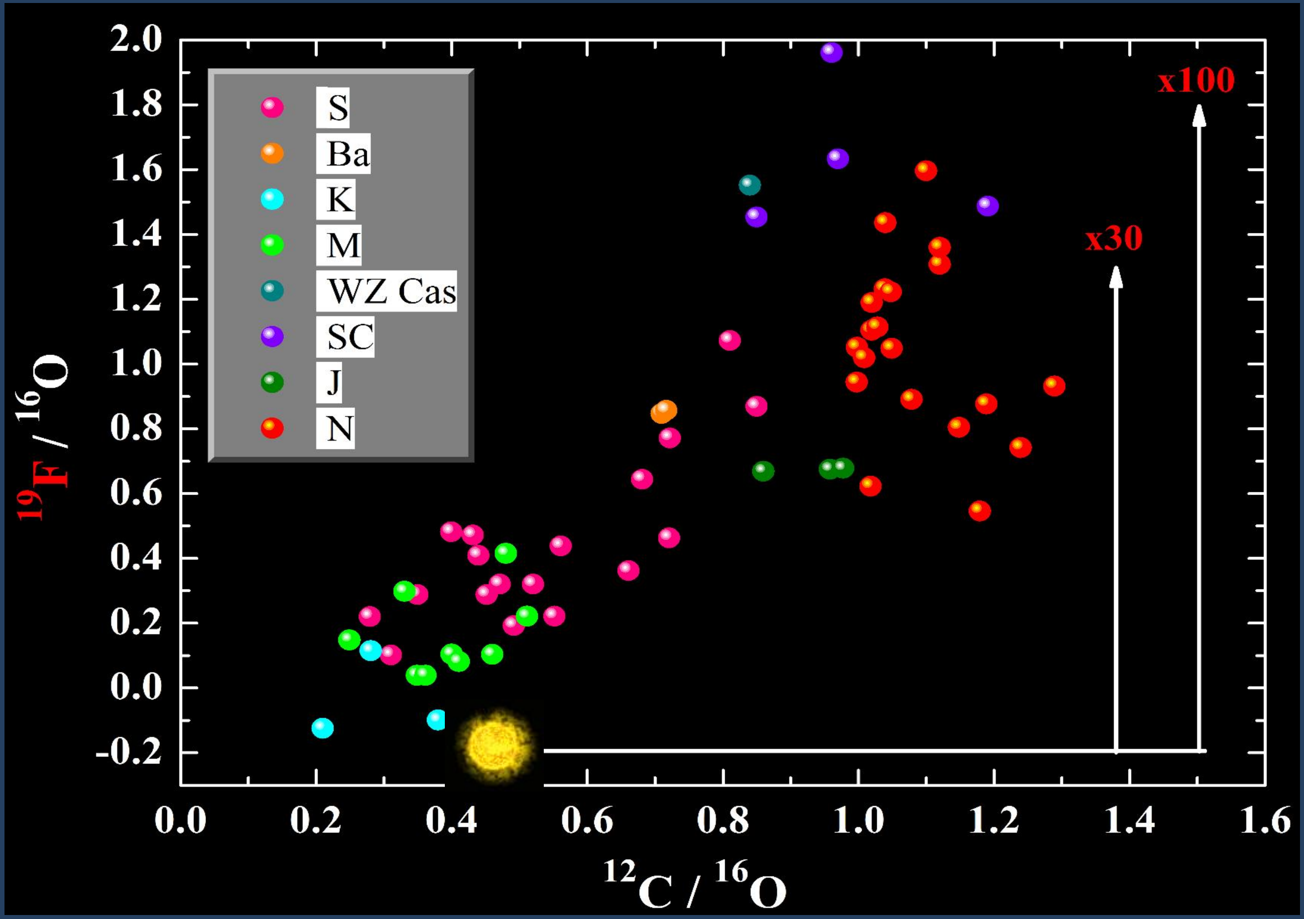
Scientific motivation



J.J. He *et al.*, Sci. China-Phys. Mech. Astron. 59(2016)652001

Scientific motivation

F-overabundance in AGB stars



Standard AGB models cannot explain the observed F-overabundance phenomenon. Nucleosynthesis model needs precise cross section data relevant to ^{19}F production and destruction reactions.

Scientific motivation

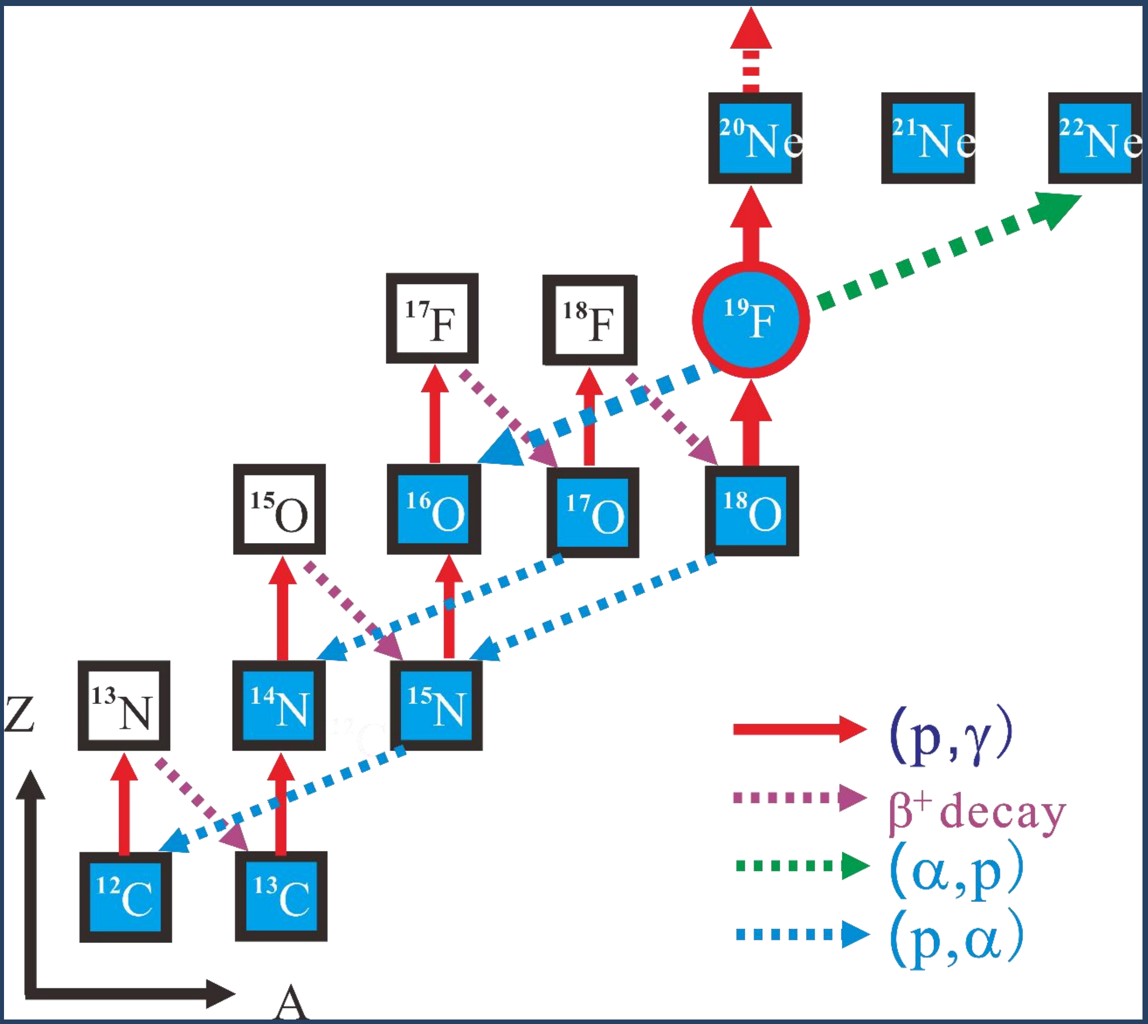
Nucleosynthesis network & reactions

Production:

- [x] $^{18}O(p,\gamma)^{19}F$
- [ ] $^{15}N(\alpha,\gamma)^{19}F$
- [ ] $^{14}N(\alpha,\gamma)^{18}F$
- [ ] $^{14}C(\alpha,\gamma)^{18}O$

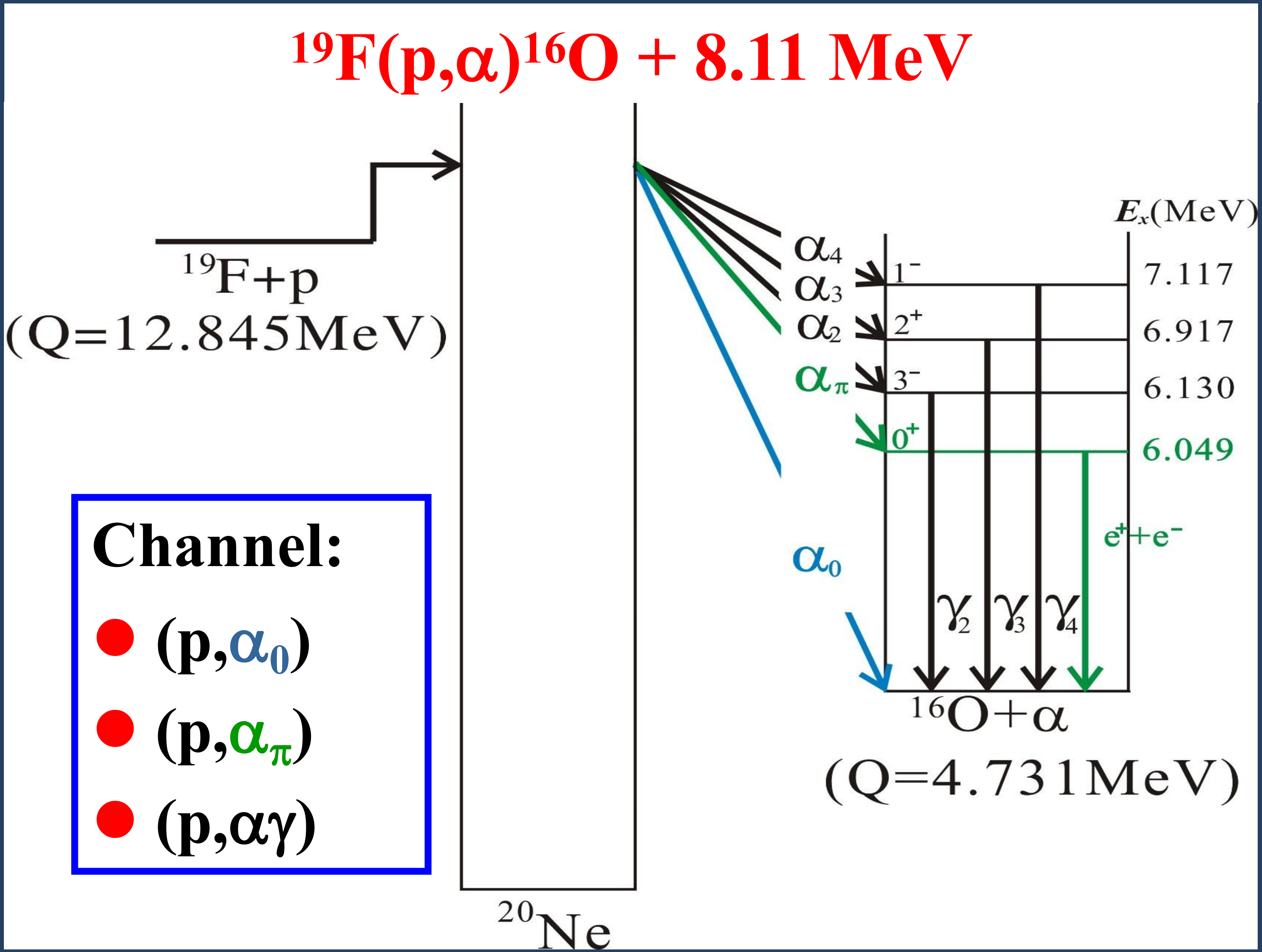
Destruction:

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



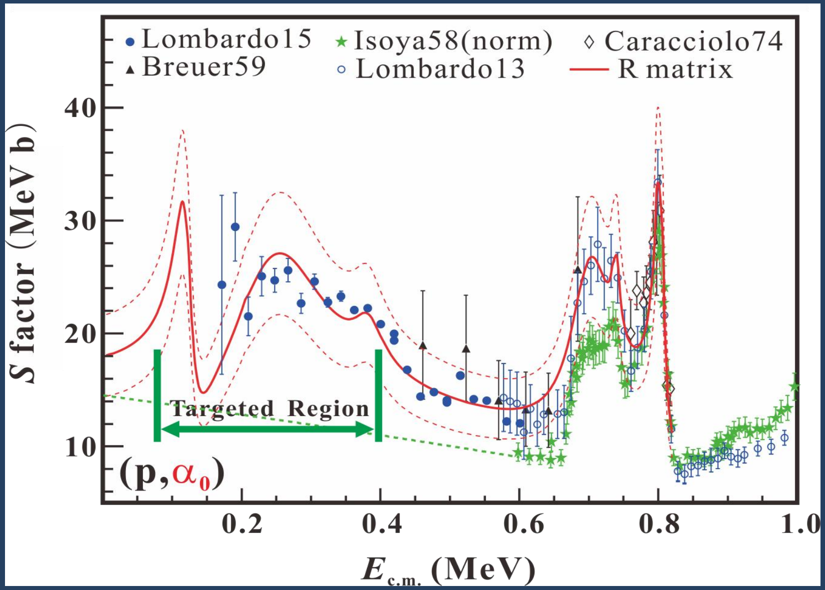
Scientific motivation

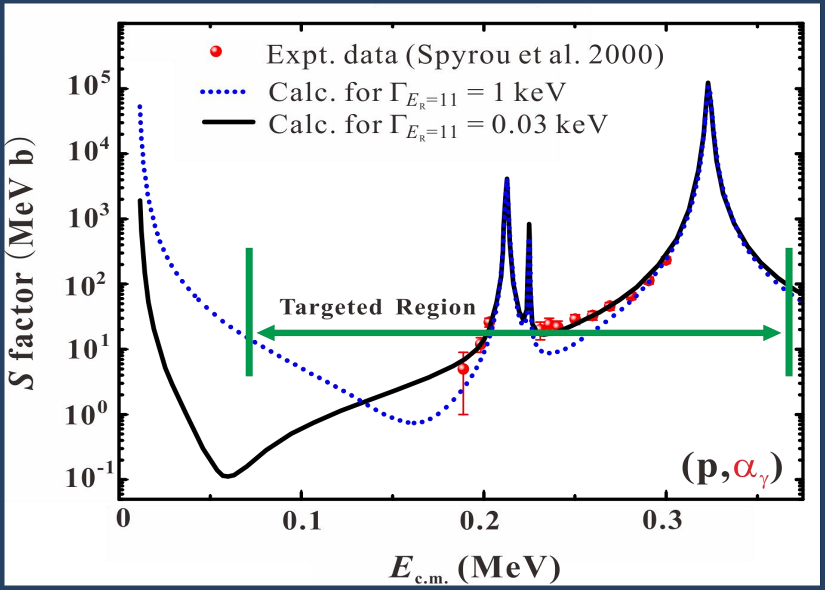
Reaction Scheme

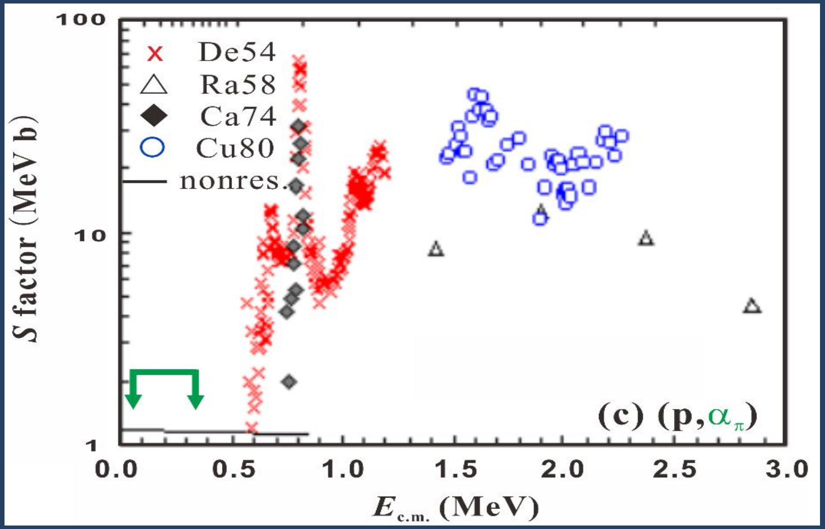


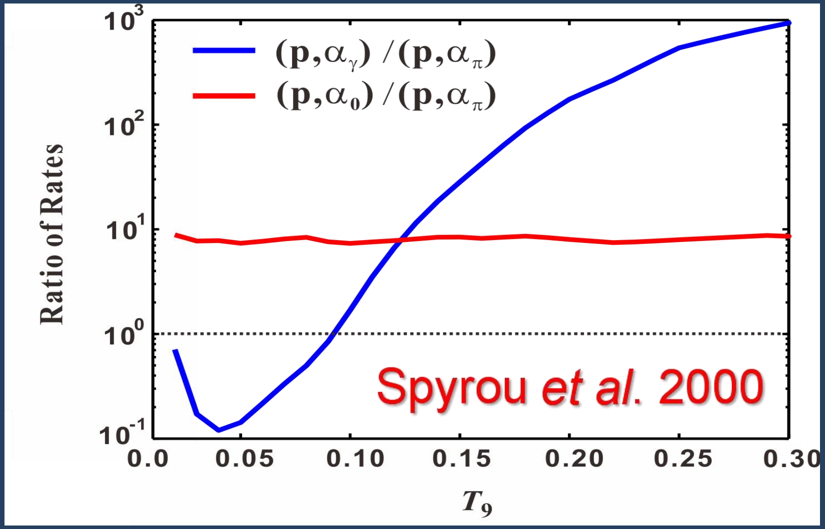
Scientific motivation

Status



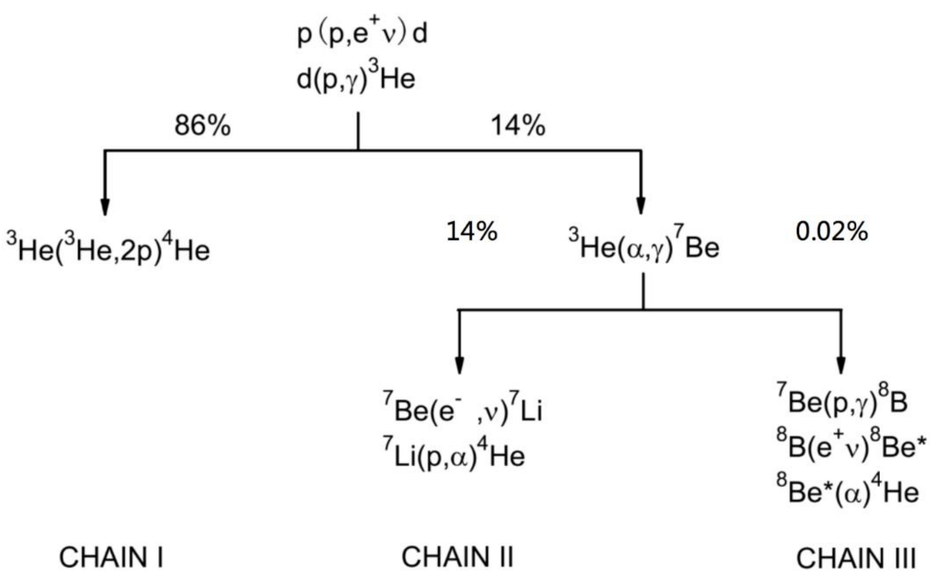




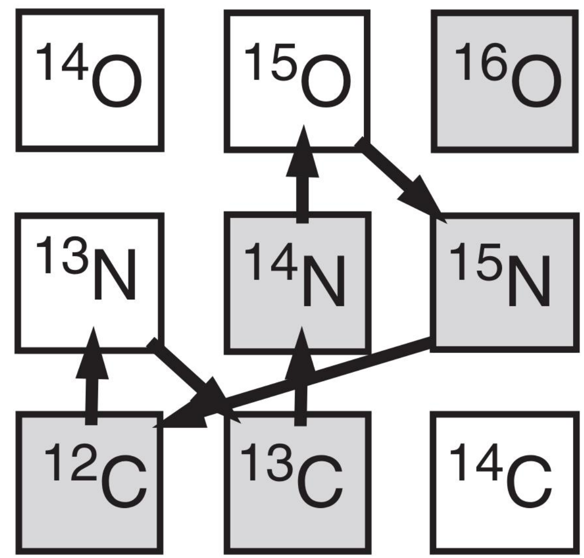


First stars: Hydron burning

p-p Chains



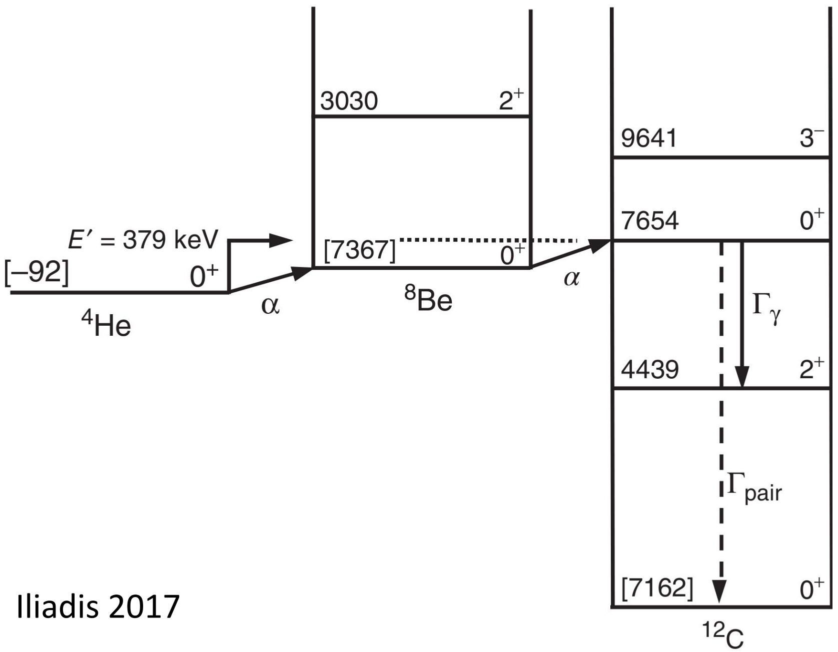
CNO cycles



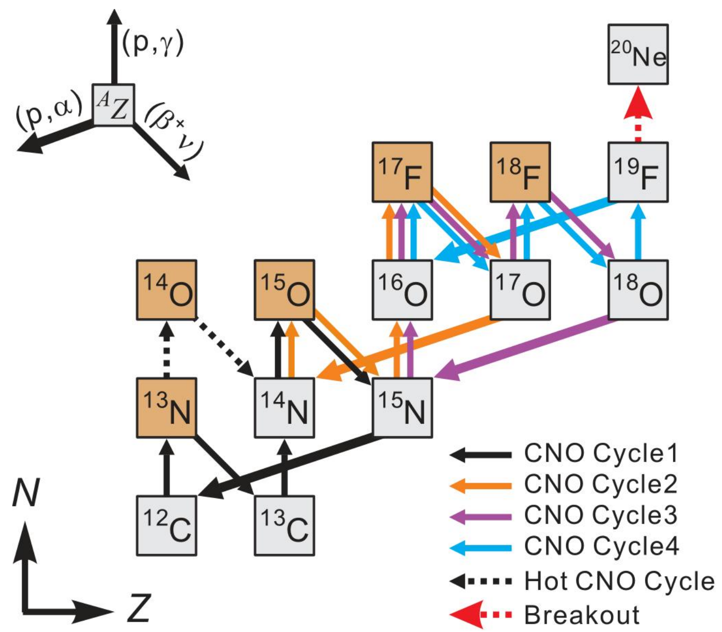
I l i a d i s
2017

First stars: Hydron burning

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

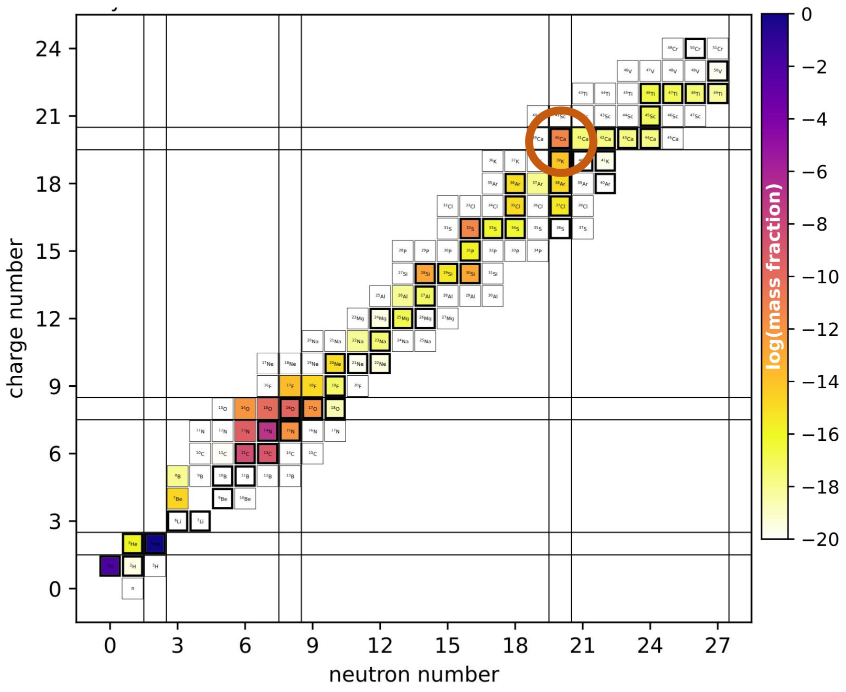


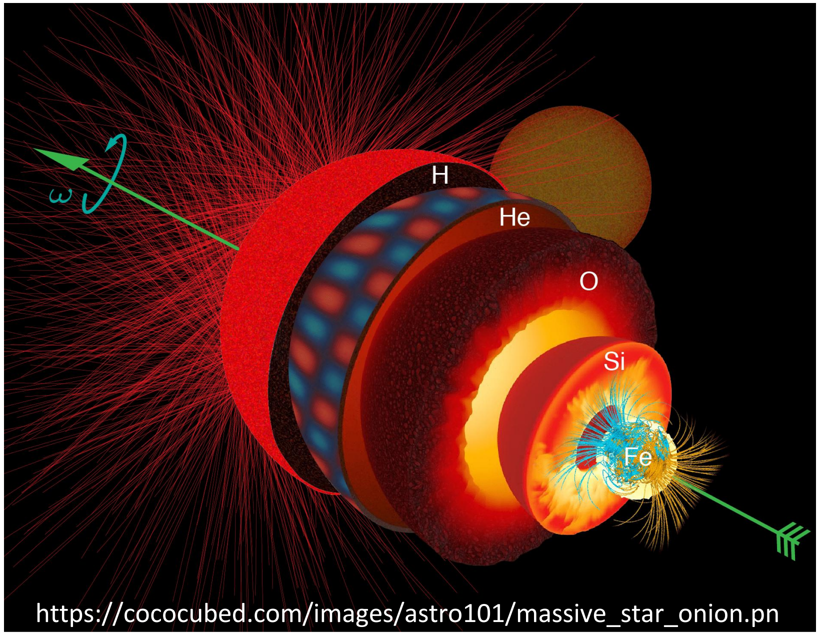
Iliadis 2017



Hydrogen or silicon burning?

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

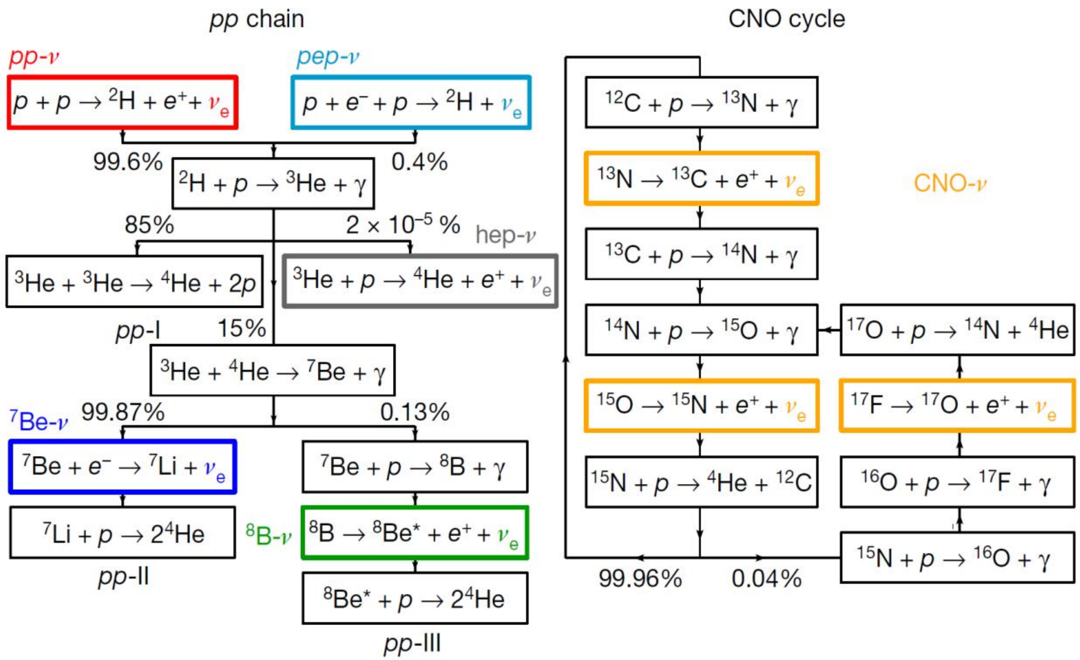


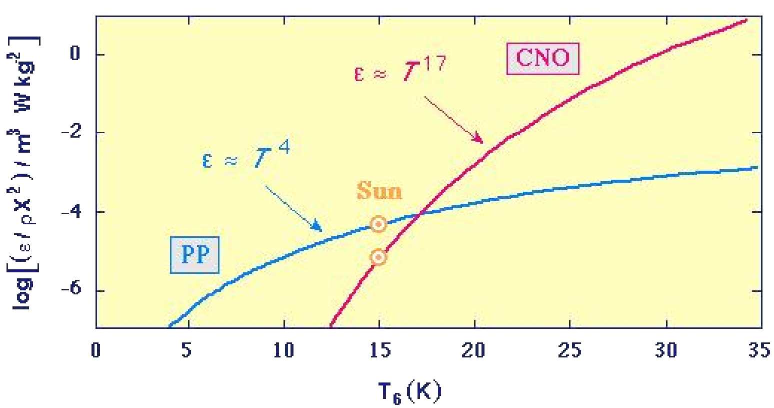


Ca can also be produced in the Si shell, and ejected together with iron via supernova burst

Observe the elemental abundance of first stars

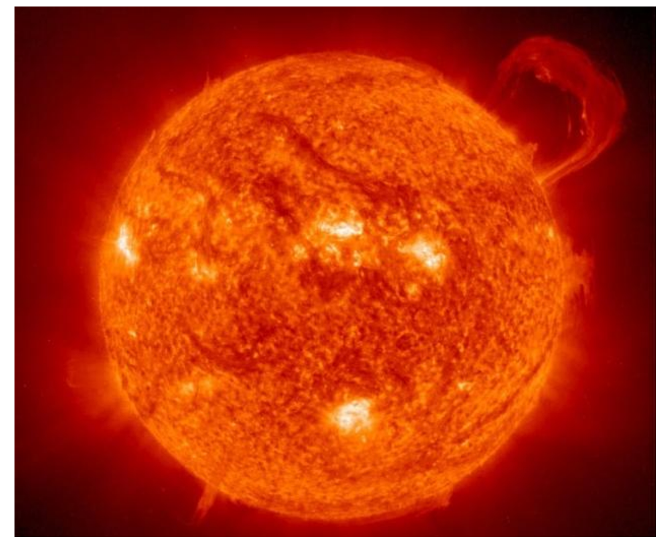
Our Sun





Core temperature @Sun:

0.016 GK



E.G. Adelberger et al., Rev. Mod. Phys. 83(2011)195

Possible sources of Fluorine

- **Core-collapse SN** (ν-spallation on ^{20}Ne)

  Woosley & Haxton, Nature 334, 45 (1988)

- **Wolf-Rayet star – Helium burning**

  Meynet & Arnould, A&A 355, 176 (2000)

- **AGB star – Helium shell burning (observed)**

  A. Jorissen et al., A&A 261, 164 (1992)

Key reactions relevant to ^{19}F

F production:

- ☐ $^{15}N(\alpha, \gamma)^{19}F$
- ☐ $^{14}N(\alpha, \gamma)^{18}F$

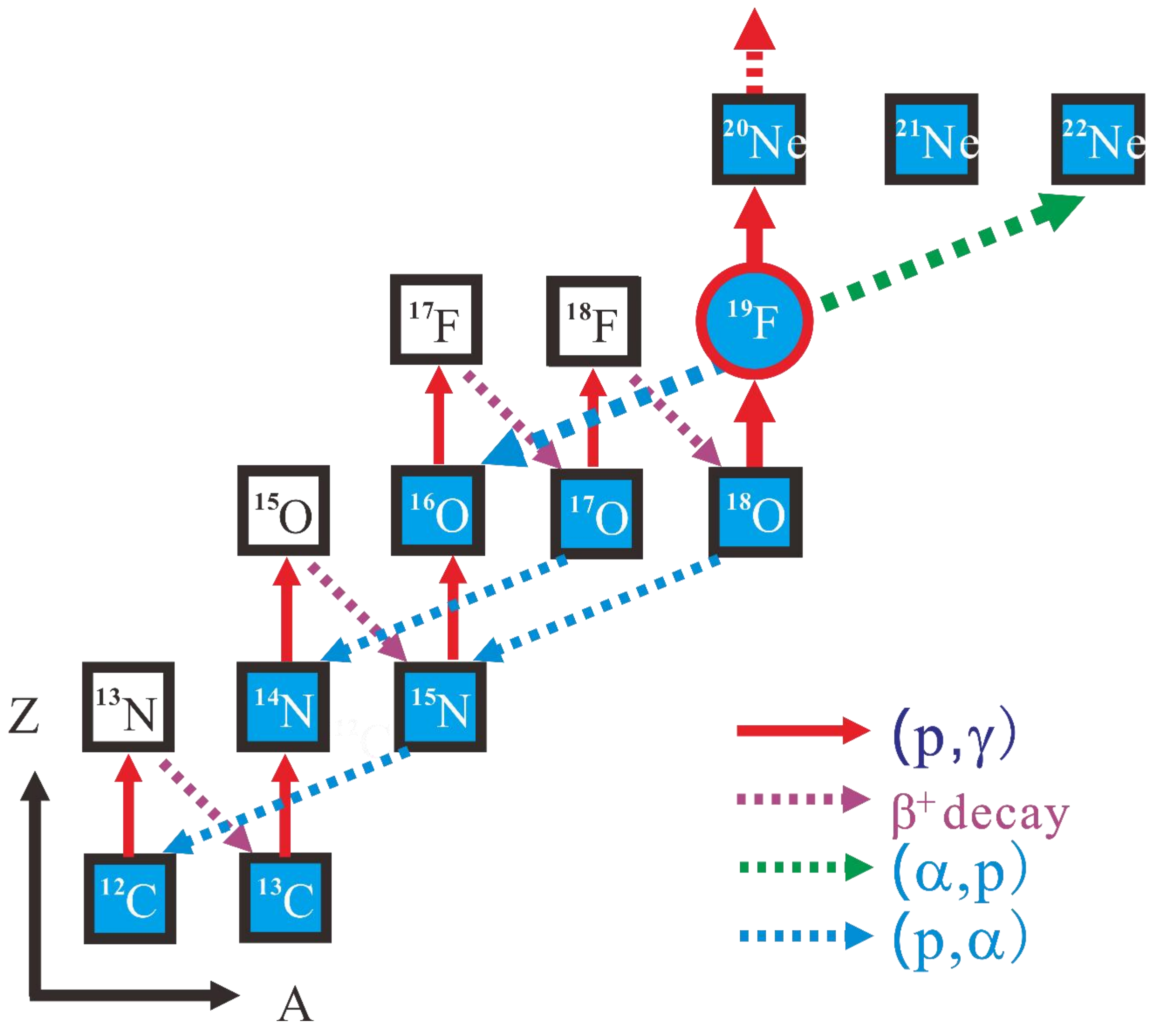
F destruction:

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

where,

☑: This JUNA work

☐: Future plan



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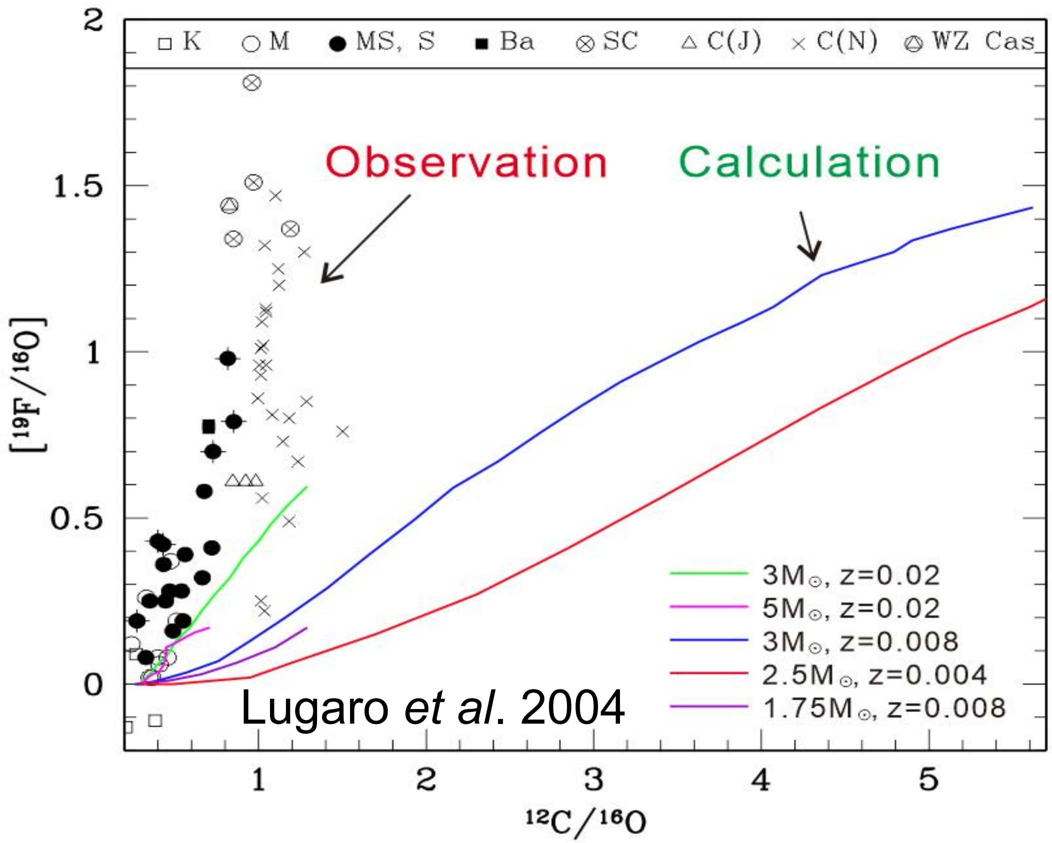
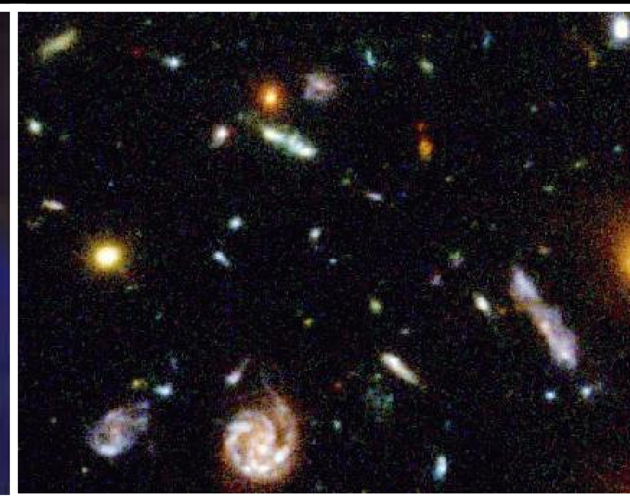
Fluorine overabundance in AGB stars



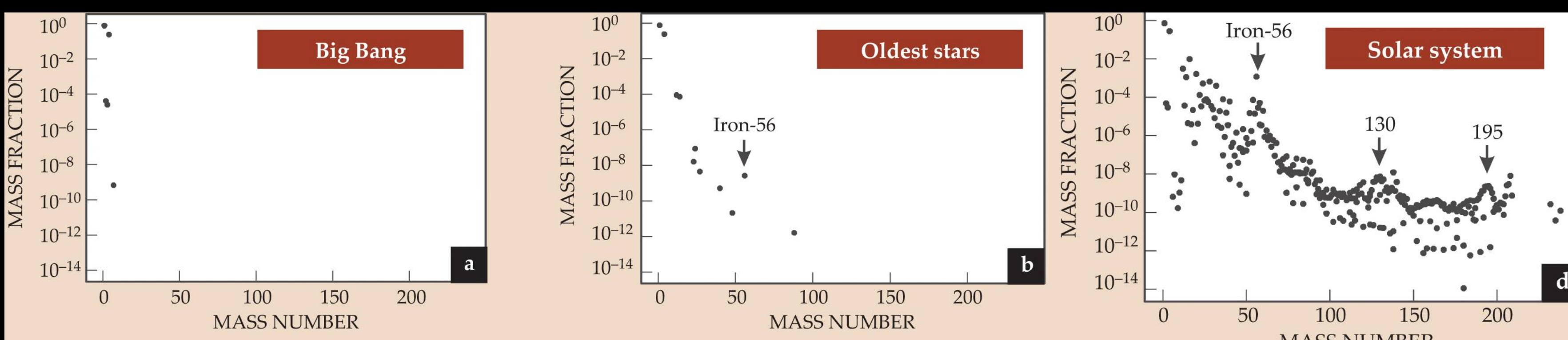
Standard AGB models cannot explain the observed F overabundance phenomenon. Nucleosynthesis model needs precise cross section data relevant to ^{19}F production and destruction reactions.

M. Lugaro *et al*., ApJ 615 (2004) 934

Origin of Elements in the Cosmos



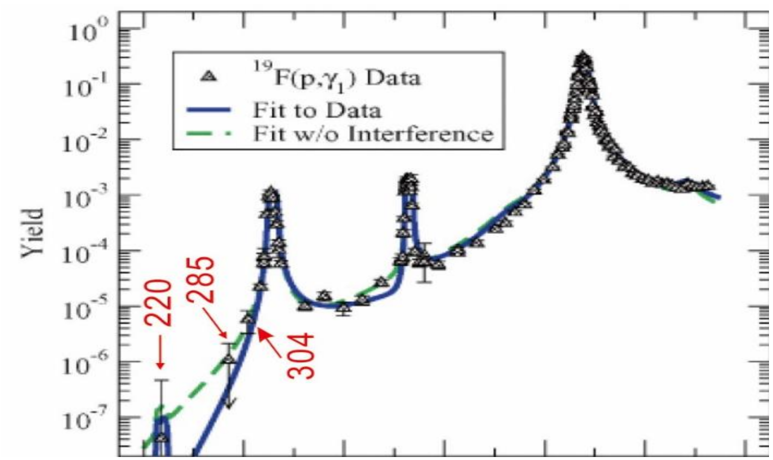
Time



C.E. Sagan: We are made of star stuff.

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

- **@Notre Dame Univ.**



Couture's phD thesis (2005)

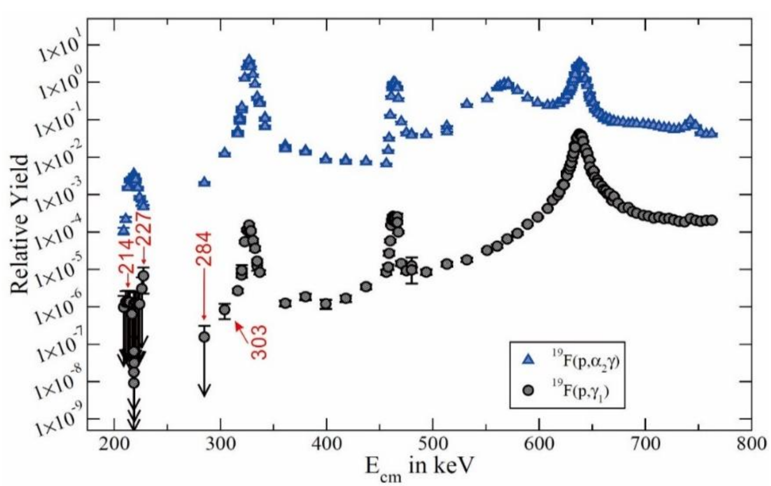


TABLE I. Measured resonance parameters.

Γ_p (eV)	Γ_{γ_1} (eV)	Γ_{α_2} (eV)		Γ (keV)
	$E_{R,\mathrm{c.m.}} = 213$ keV $J^\pi = 2^-$			
Present	$\mathbf{0.890^{1346}_{-265}}$[a]	$\mathbf{0.011^{+0.003}_{-0.002}}$	**<0.06**	$\mathbf{882^{+1346}_{-265}}$
$(p, \alpha_{2,3,4})$[b]	0.94±0.02	–	–	1000
	$E_{R,\mathrm{c.m.}} = 323$ keV $J^\pi = 1^+$			
	Γ (keV)	Γ_p (eV)	Γ_{γ_1} (eV)	Γ_{α_2} (eV)
Present	**2.08±0.34**	$\mathbf{35.8^{+5.6}_{-5.4}}$	$\mathbf{0.107^{+0.024}_{-0.019}}$	$\mathbf{1971^{+369}_{-294}}$
(p, p_0)[c]	2.8	45	–	–
(p, p')[d]	2.8	–	–	–
(p, γ_1)[e]	–	–	0.28±0.06	–
$(p, \alpha_{2,3,4})$	2.22±0.04	–	–	2800