JUNA progress：Jinping underground nuclear astrophysics experiment

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第16届交叉前沿研讨会，南开大学

Thanks NSFC, Yalong power, THU, CAS and CNNC

北京師範大學 BEIJING NORMAL UNIVERSITY
中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences
中国原子能科学研究院 中核集团 CHINA INSTITUTE OF ATOMIC ENERGY
雅砻江流域水电开发有限公司 YALONG RIVER HYDROPOWER DEVELEPOMENT COMPANY, LTD.
南方科技大学 SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY
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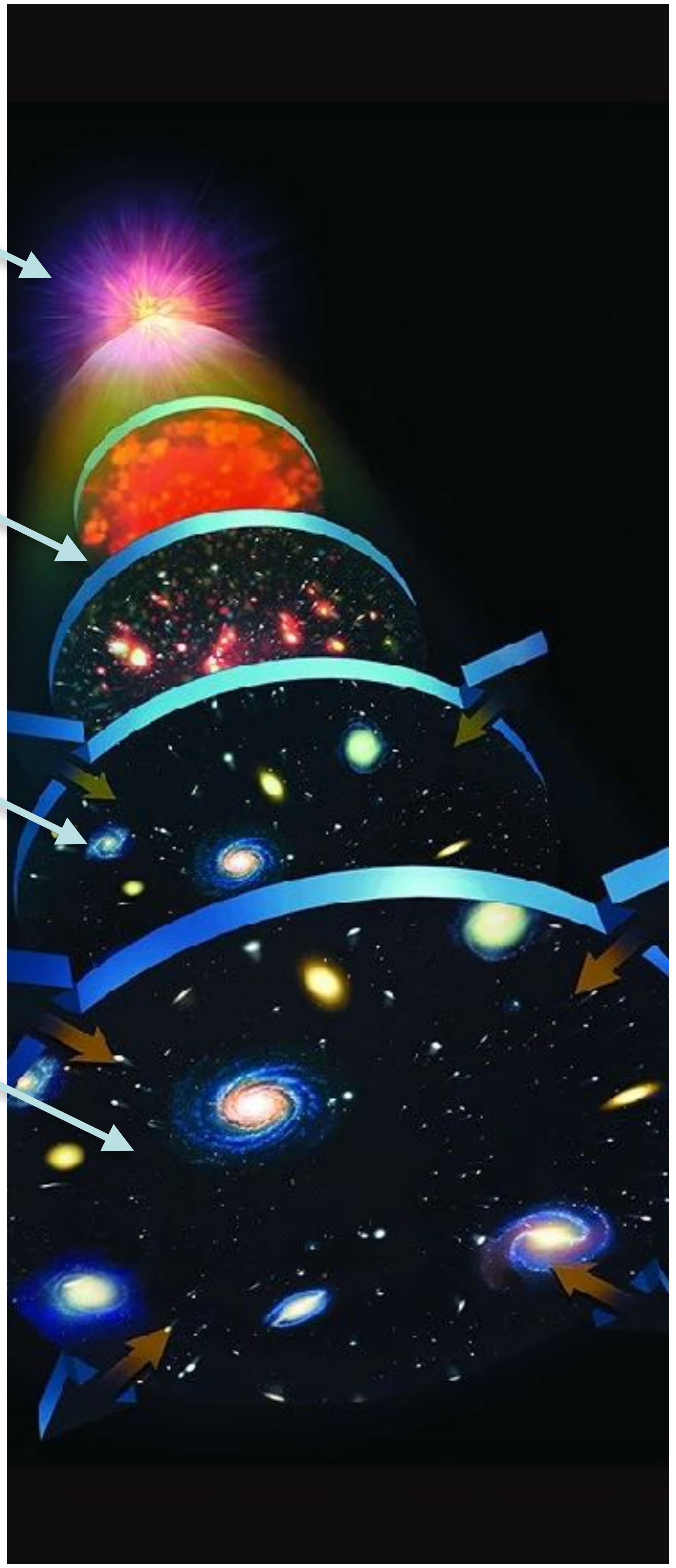
四川大學 SICHUAN UNIVERSITY
深圳大学 SHENZHEN UNIVERSITY
中山大學 SUN YAT-SEN UNIVERSITY
清華大學

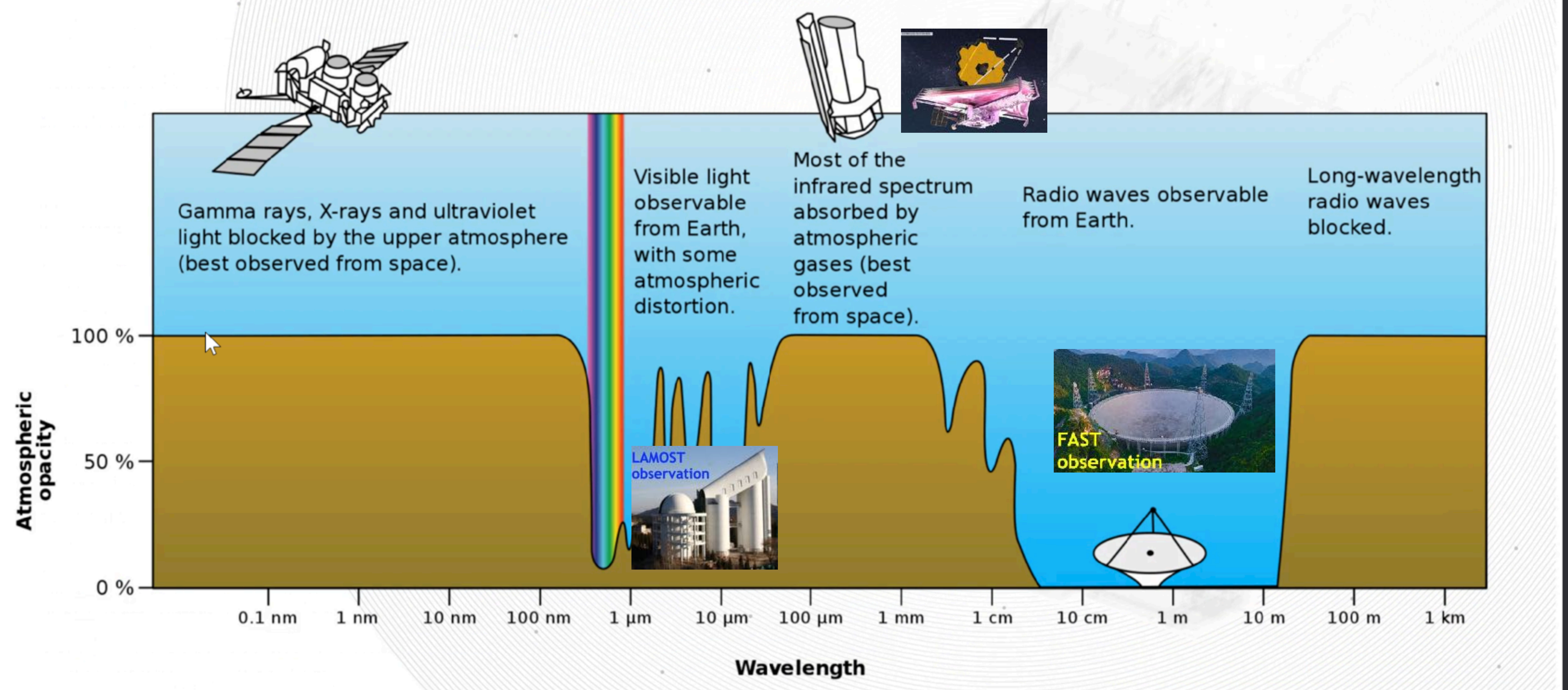

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Important discoveries in nuclear astrophysics

- 3K cosmic microwave background radiation, 1965, experimental evidence for big bang theory
- Understanding of solar neutrinos, 1960, triggers neutrino oscillation hypothesis
- ^{26}Al γ-ray detection, 1980, Direct support for explosive nuclear processes, Birth of γ-ray astronomy SB 67(2022)125
- Detection of SN1987A supernova explosion, 1987, understanding of origin of heavy elements PRL 2022, in press
- Experimental explanation for missing of solar neutrinos, 2003, confirmation of neutrino oscillations PRL 77(1996)611
- Detection of gravitational waves, 2016, the birth of multi-messenger astronomy

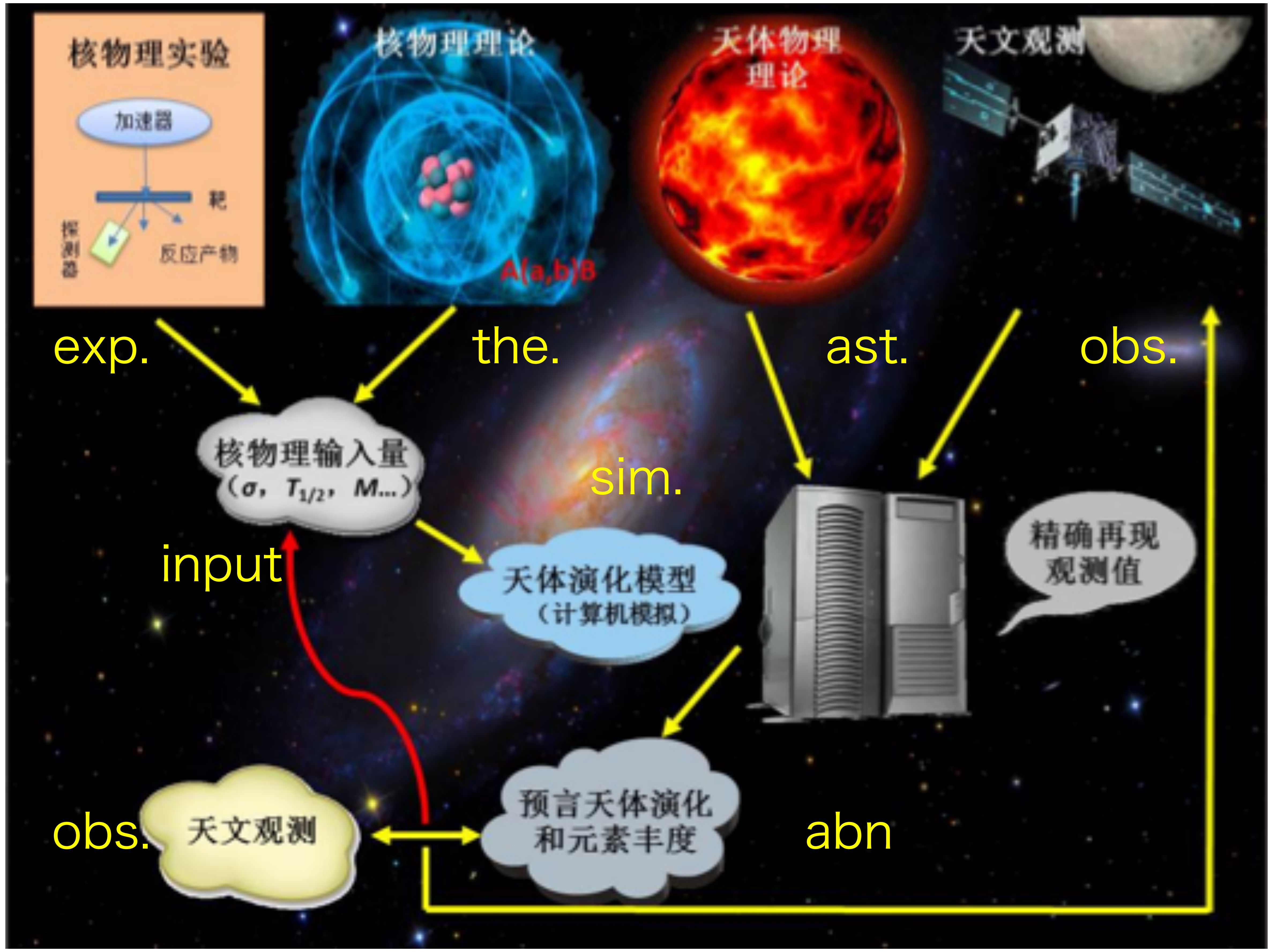


我们所能看到的

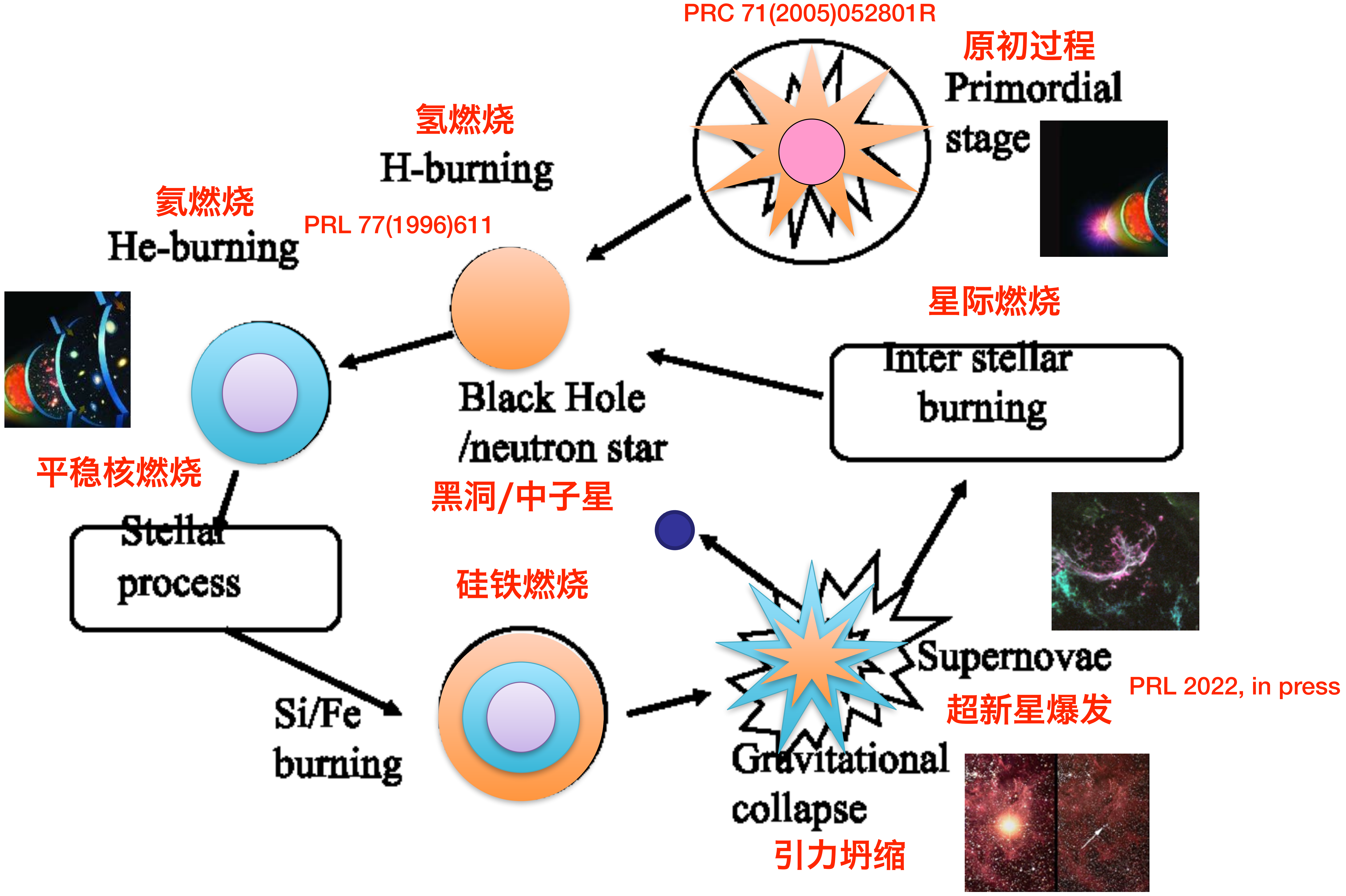

Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gases (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.
LAMOST observation
FAST observation
100 %
50 %
0 %
Atmospheric opacity
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength

nuclear astrophysics：解释我们所看到的

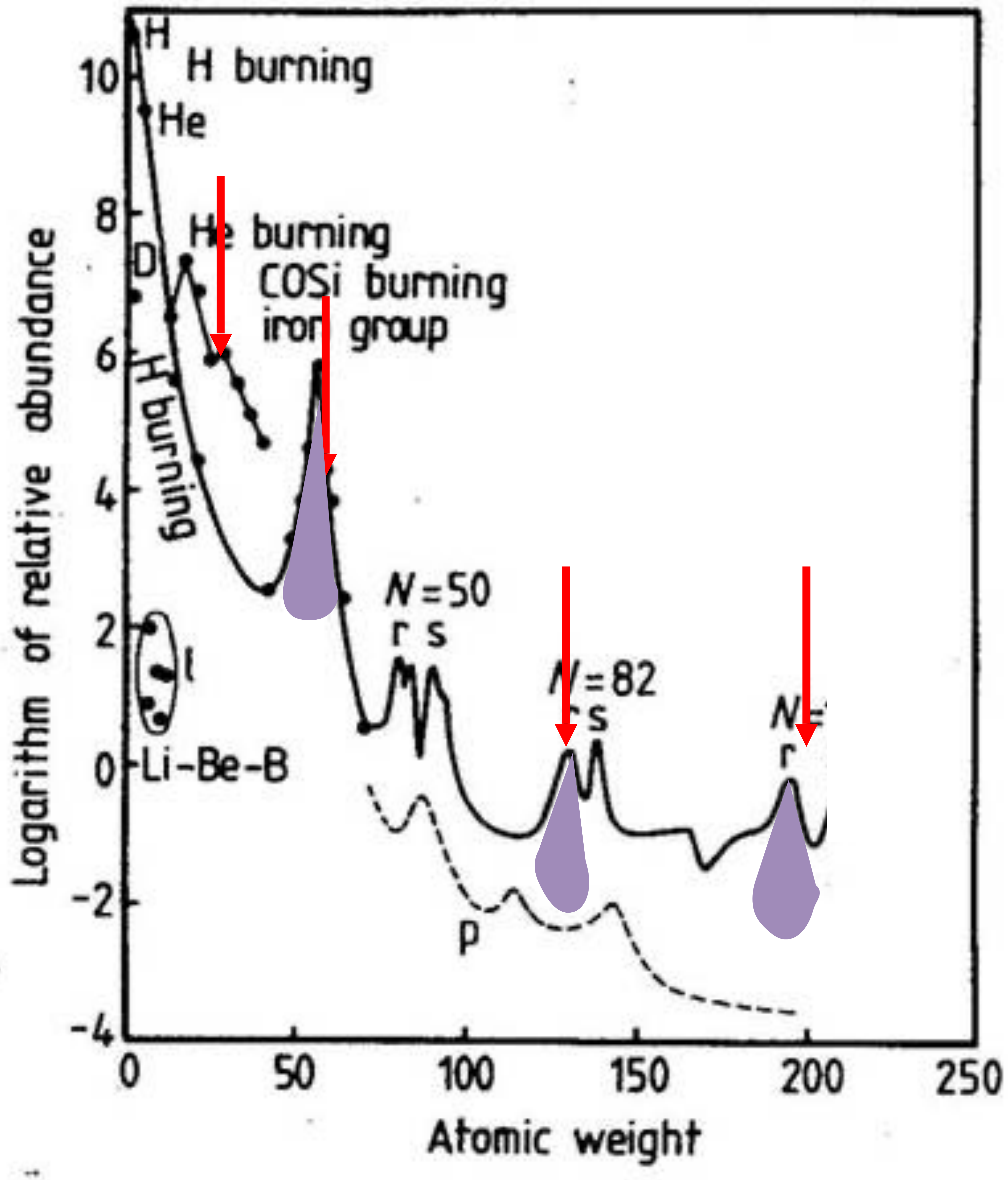
- NP, microscopic, 10^{-15} m, —>observation, cosmic, 10^{14} m, truly interdisciplinary
- For energy production and element synthesis in star



Life of star

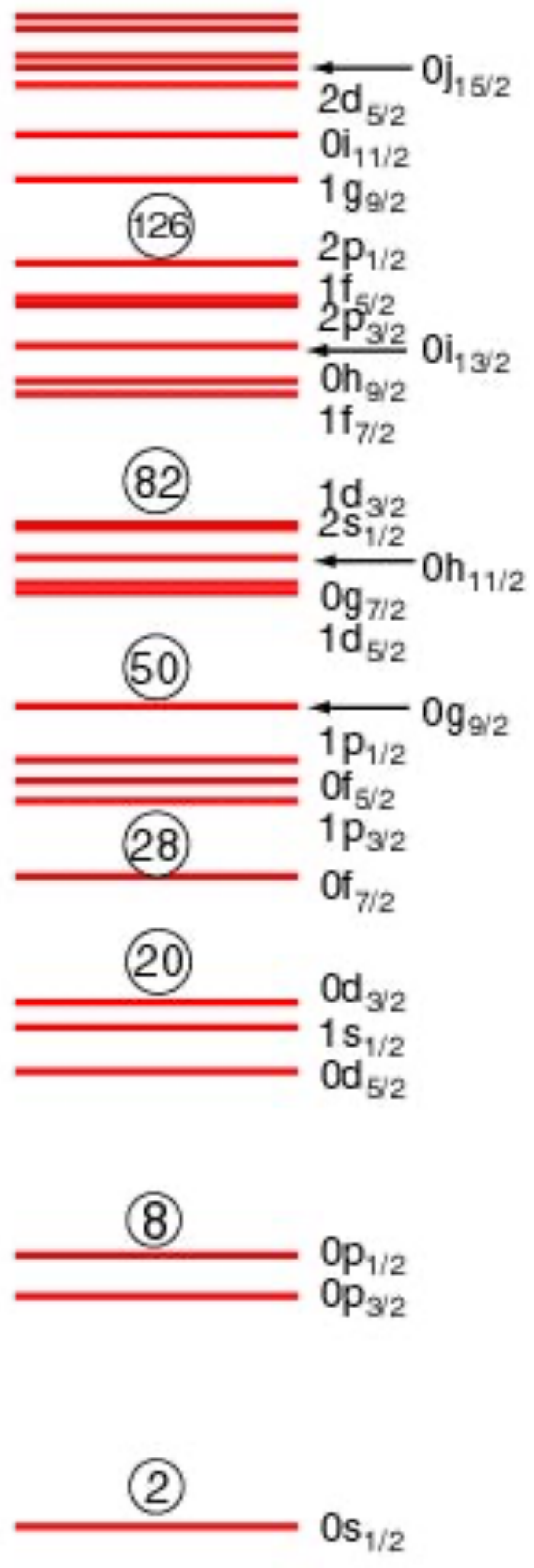


PRC 71(2005)052801R
原初过程
Primordial stage
氢燃烧
H-burning
氦燃烧
He-burning
PRL 77(1996)611
星际燃烧
Inter stellar burning
Black Hole /neutron star
黑洞/中子星
平稳核燃烧
Stellar process
硅铁燃烧
Si/Fe burning
Supernovae
超新星爆发
PRL 2022, in press
Gravitational collapse
引力坍缩



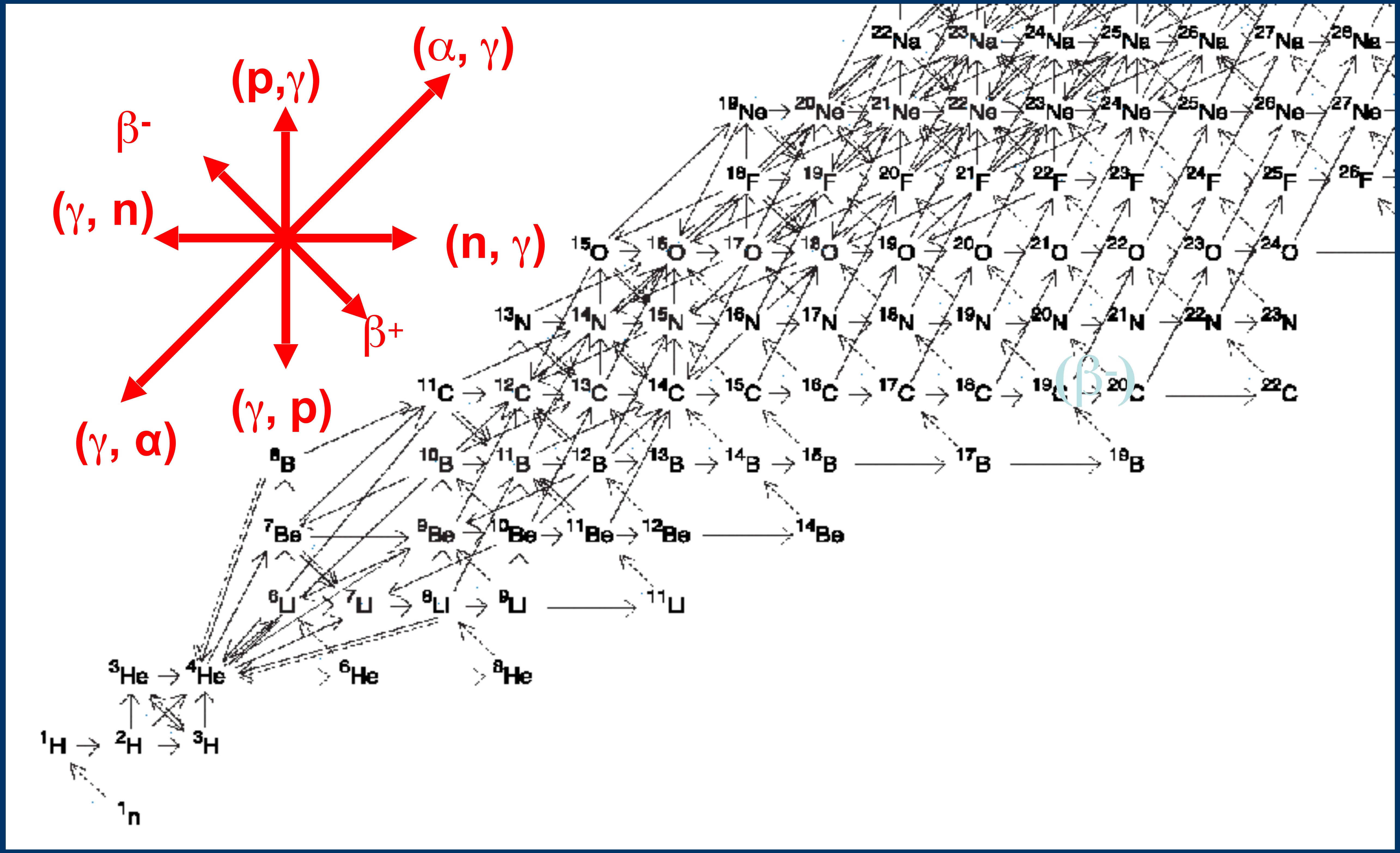
Nuclear Reactions: Alchemists in the Universe

Peaks are the birthmark of nuclear physics: the magic number of the nuclear shell model



Shell Model of Nuclei

Element synthesis network



Cross section

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

Decay half-life

几个原子核的能级决定了宇宙和人类的命运！

JUNA

α

0+

α

7.65 0+

^{4}He

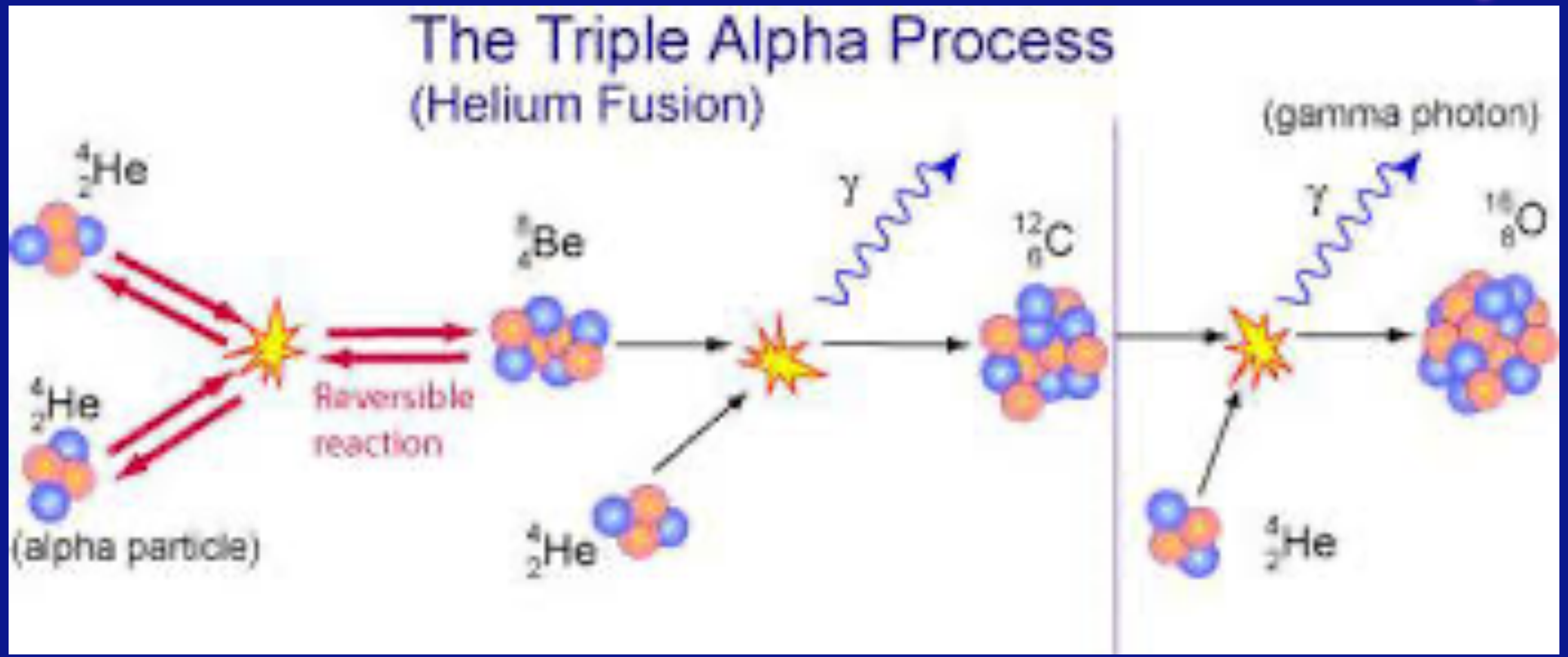
^{8}Be

3α 反应

桥梁

1954, Hoyle态，很舒服，
有了碳基生命

Fred Hoyle (1915-2001)



William A. Fowler (1911–1995)
Rev.Mod.Phys. 56 (1984) 149-179

8.87 2-

调节器

α

7.12 1-

^{12}C

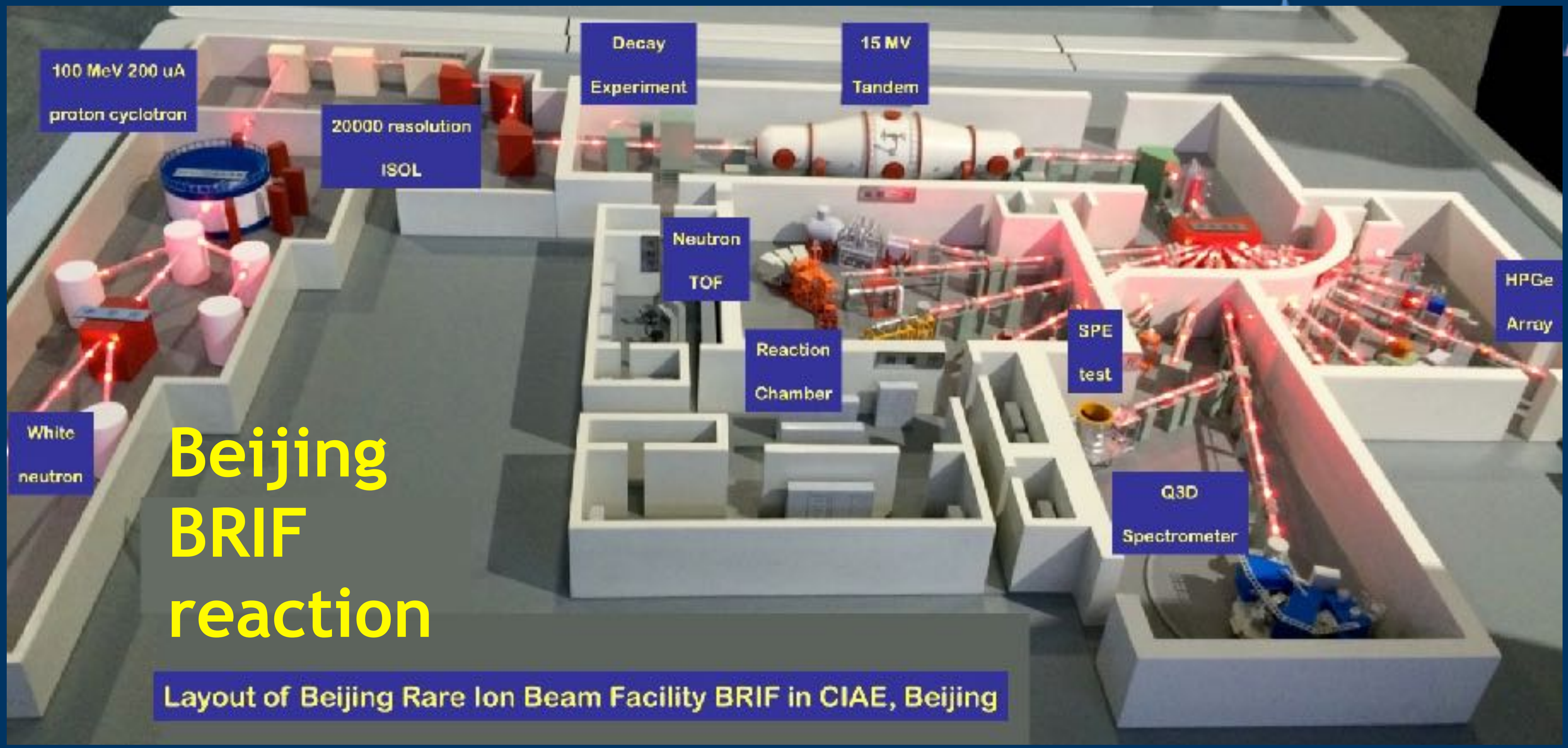
$^{12}C(\alpha,\gamma)^{16}O$ “圣杯”反应

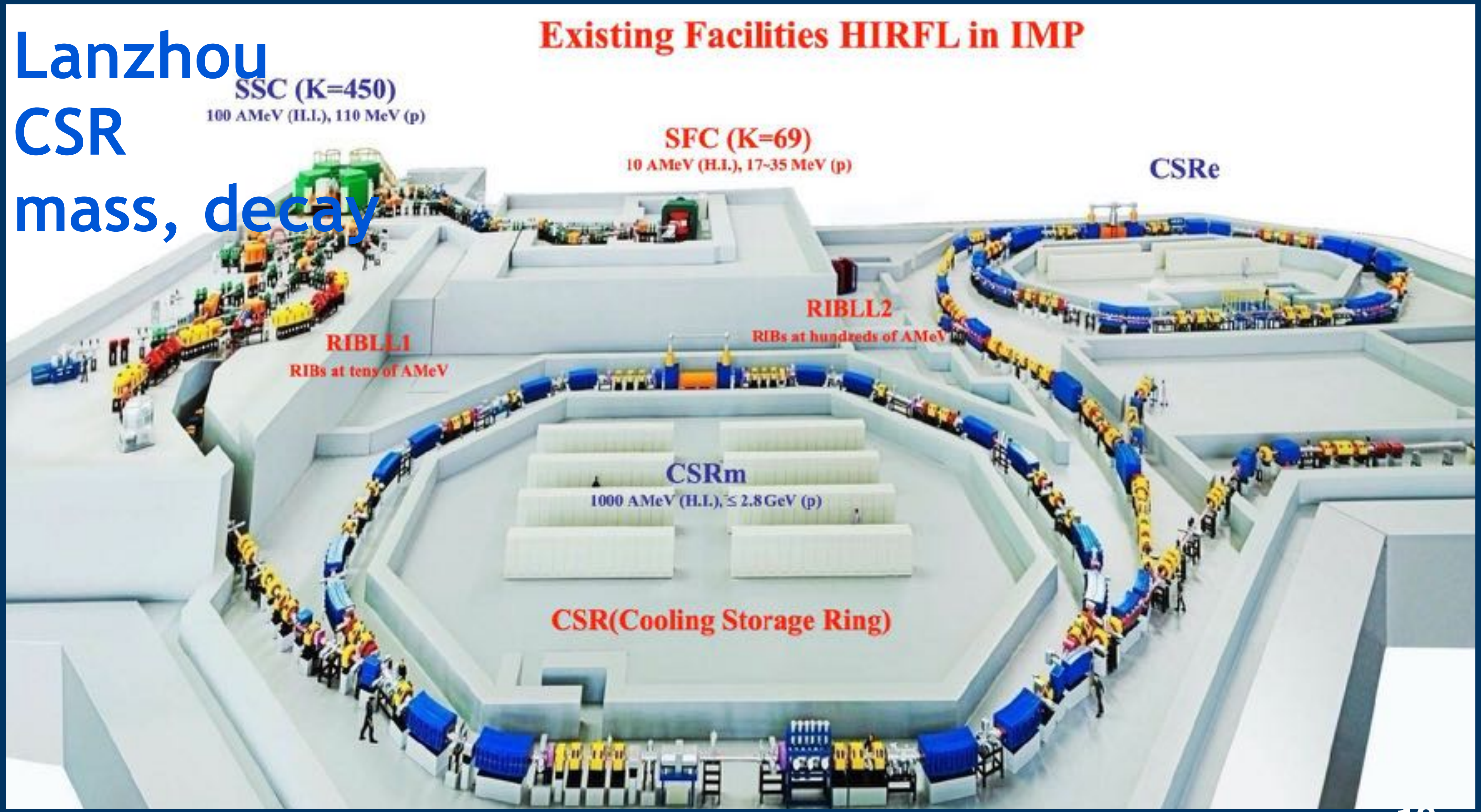
很合适，太阳可以燃烧
数十亿年；我们也有足
够氧气呼吸

^{16}O

from “Claudon in the universe”

Major facilities in China





W. P. Liu, 2022, NuSYS

Joint efforts 方法论

Reaction

LUNA, CASPAR, JUNA...

Direct in Gamow window (underground)

TRIUMF, NSCL,...

Direct in higher energy

CIAE, TAMU, CNS...

In-direct measurements

RIBF, CSR, NSCL...

Nuclear decay

CSR, GSI, TRIUMF...

Nuclear mass

Nuclear astrophysics and sensitivity study

Shell model and mean field calculation

Shell model and mean field calculation

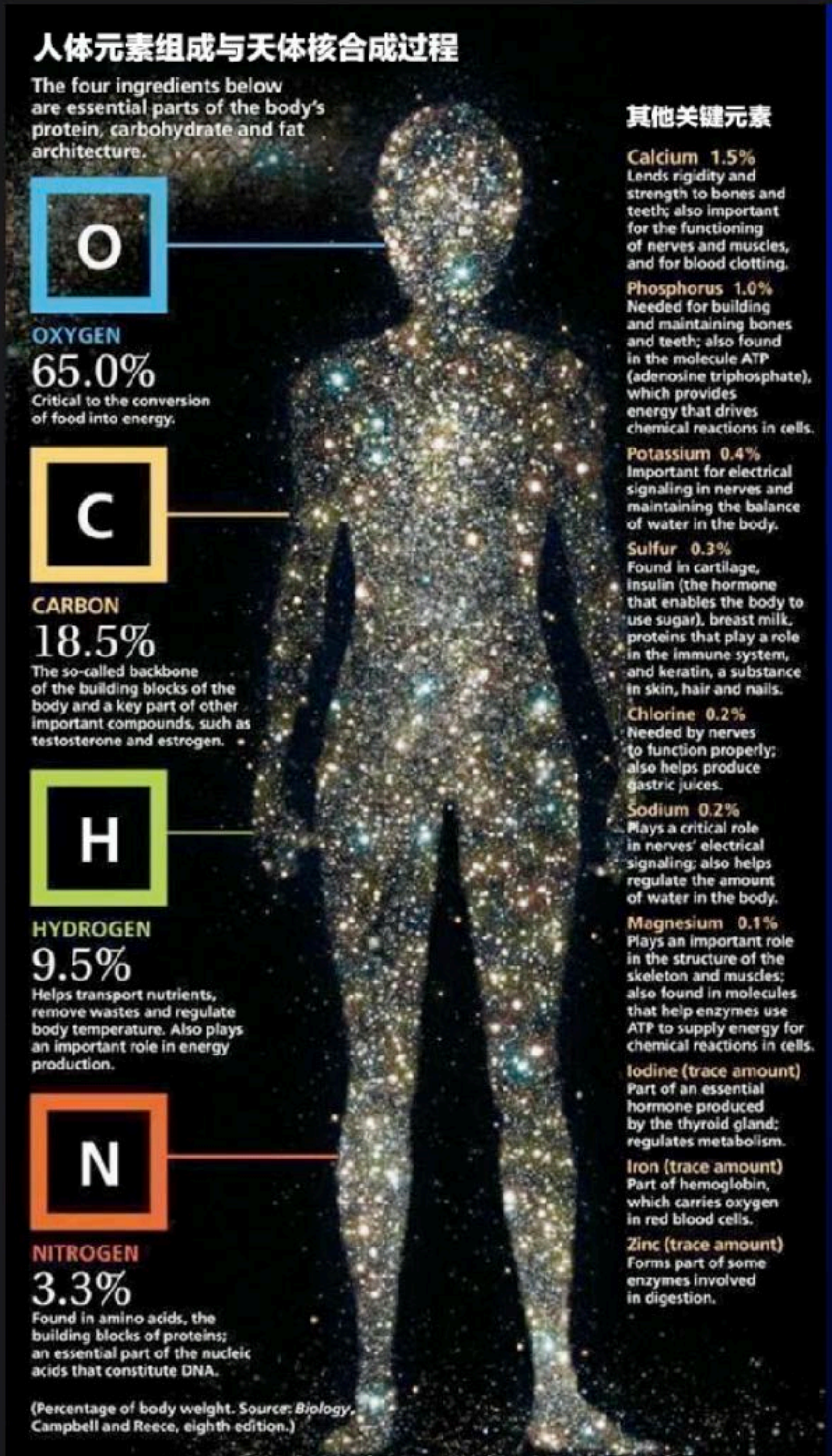
Reaction rate database

RECLIB...

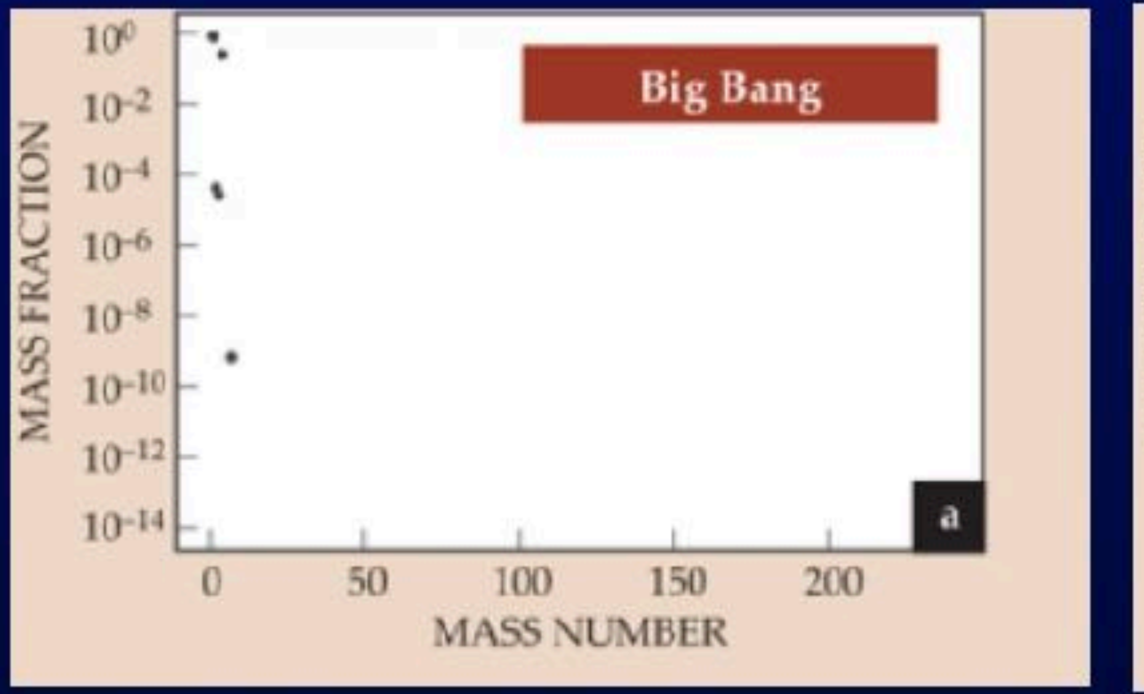
Nuclear input database

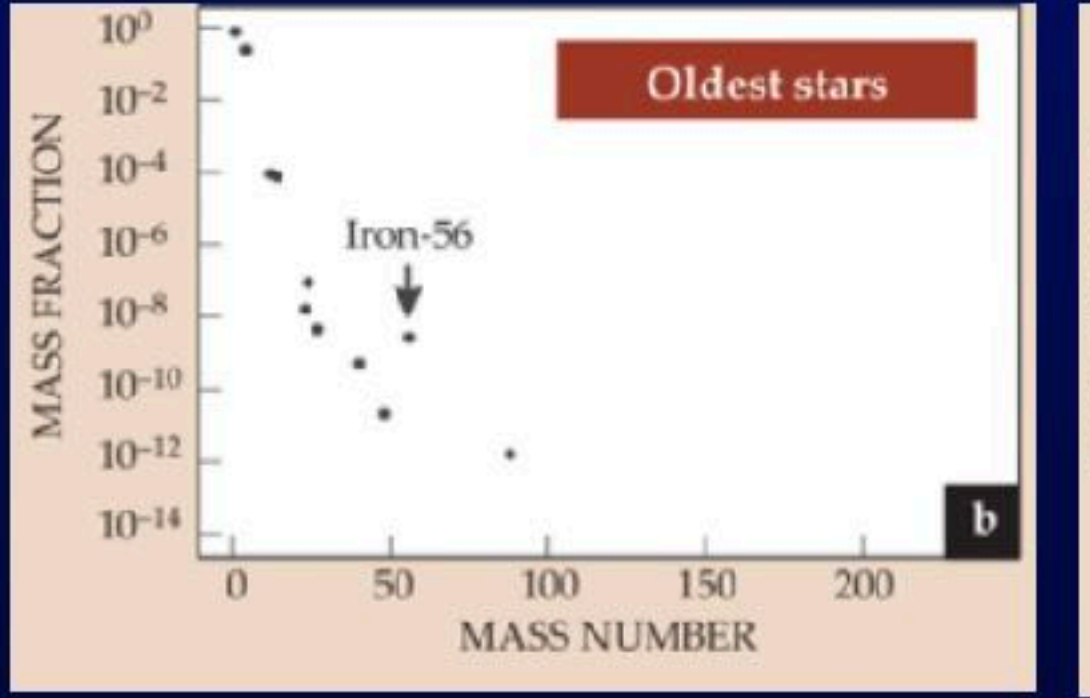
AME...

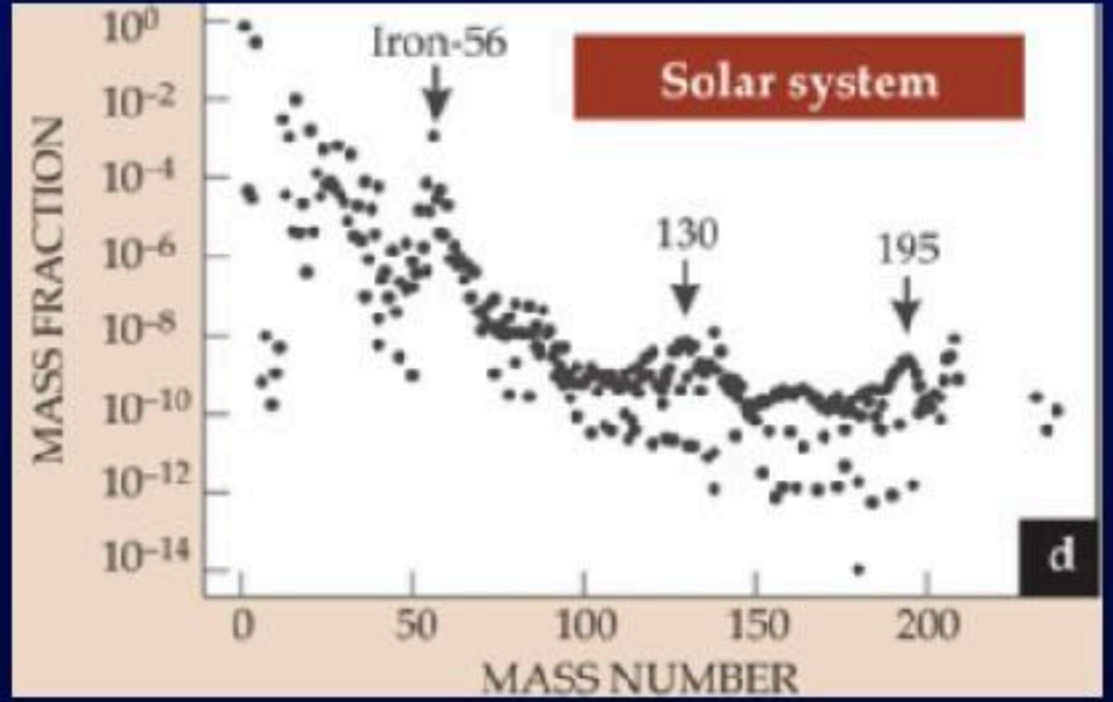
Mass and decay rate database



我们从哪里来，到哪里去？Where







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

桥梁

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

粮食

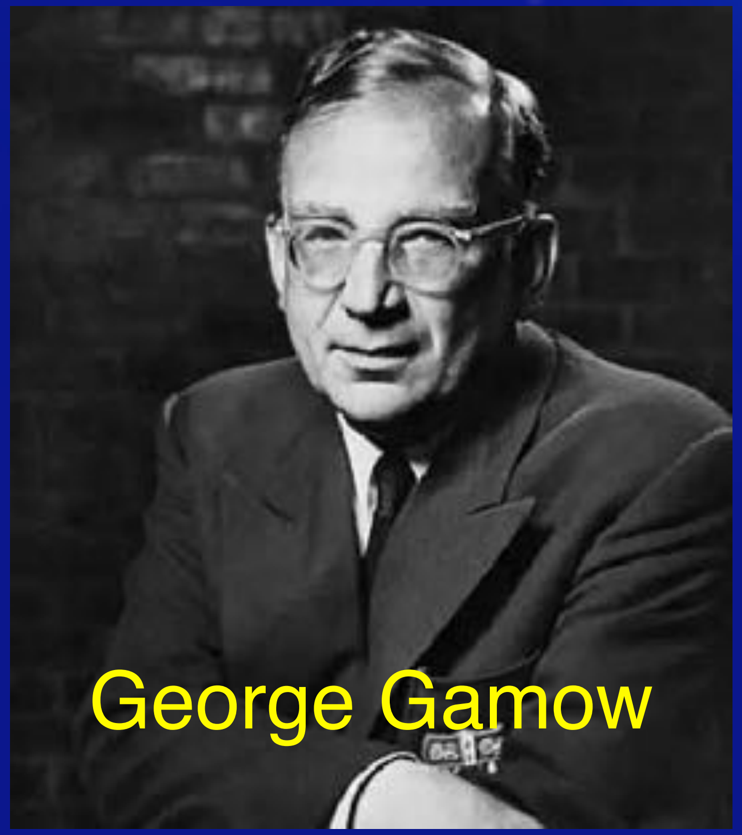
需要超大曝光 High exposure

coulomb term

$$\sigma(E) = S(E)e^{-2\pi\eta}\frac{1}{E}$$

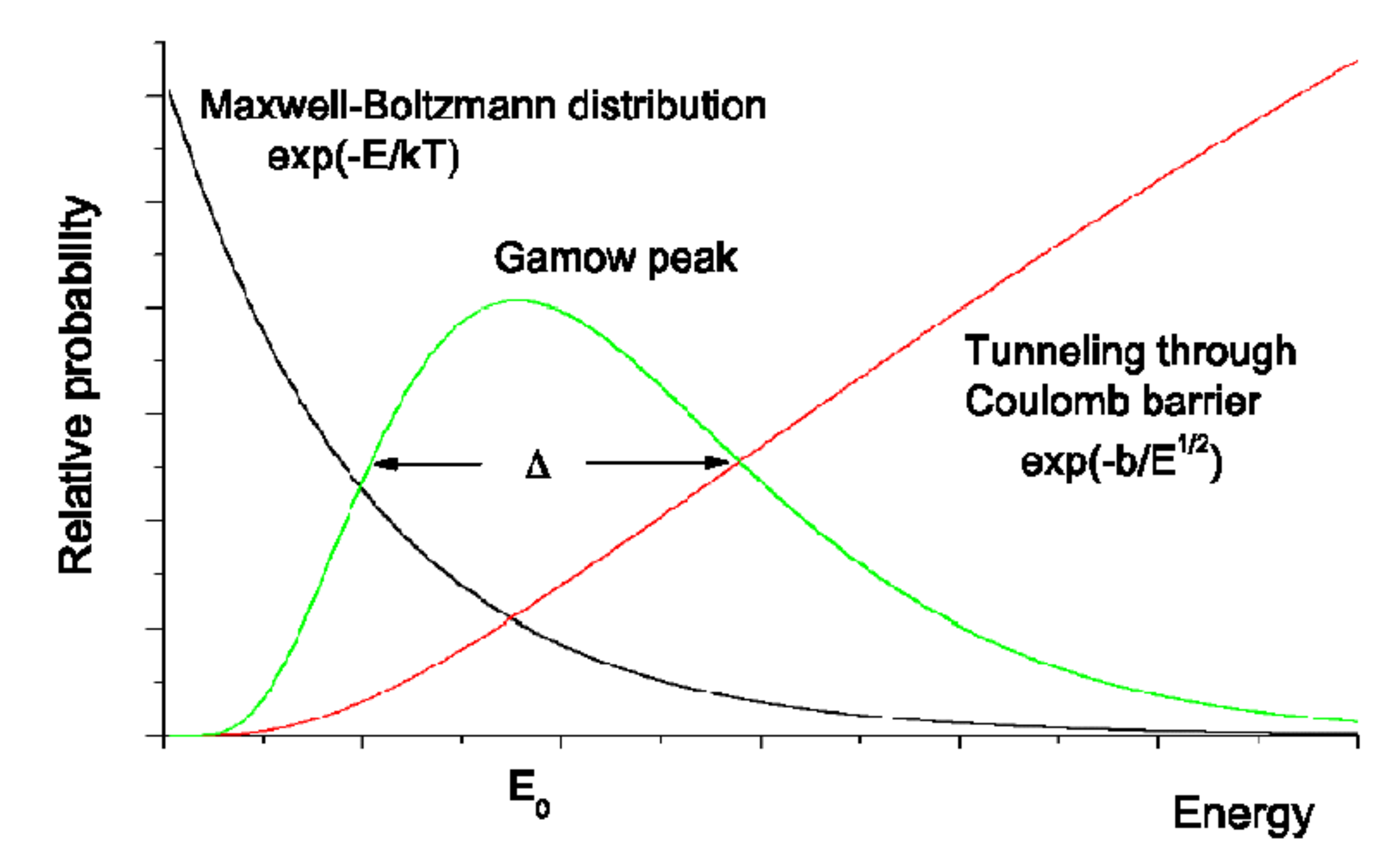
astrophysical s factor

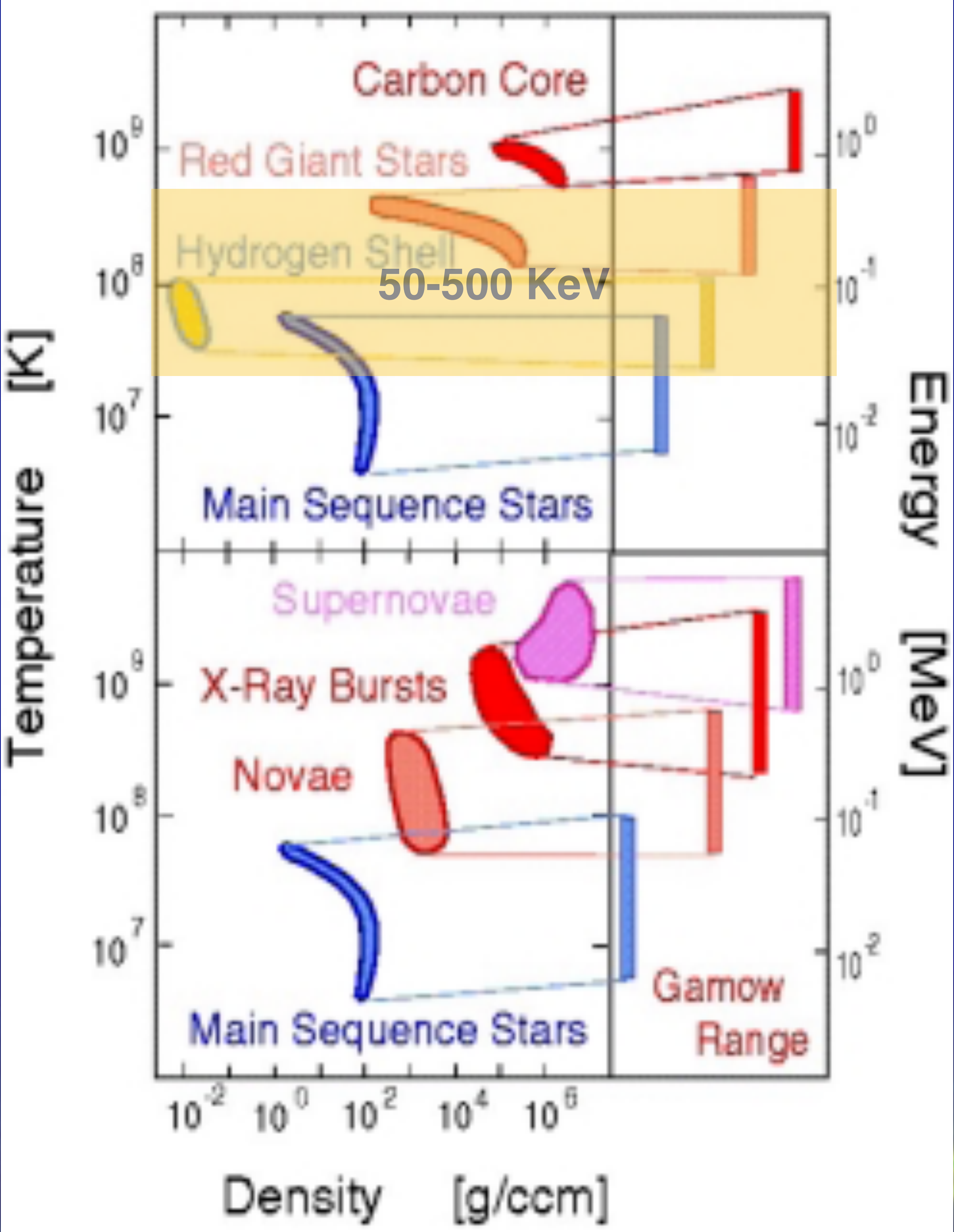
$$\eta = 0.1575 Z_1 Z_2 \sqrt{M/E}$$



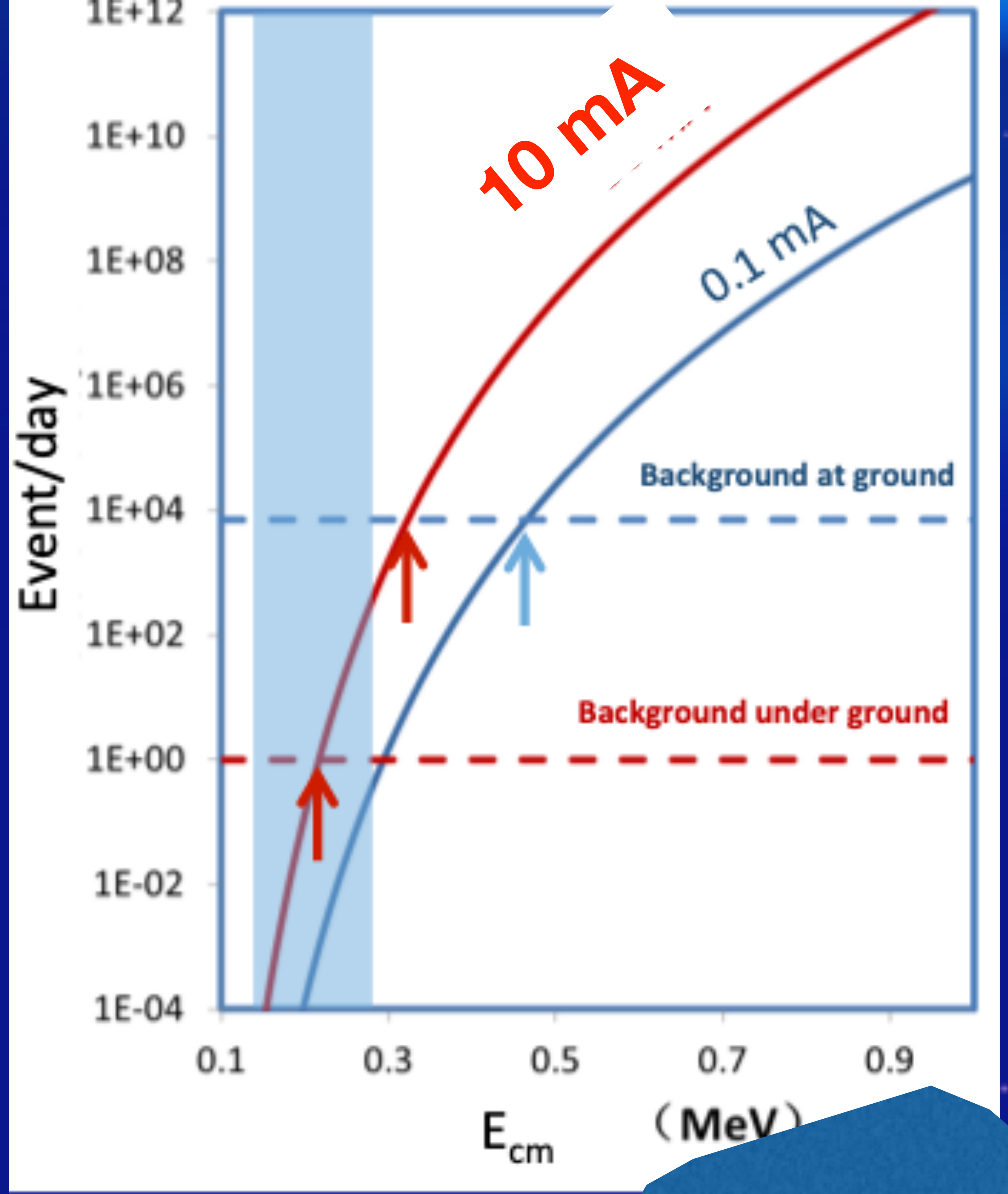
$$E_0 = 0.1220\left(Z_0^2 Z_1^2 \frac{M_0 M_1}{M_0+M_1} T_9^2\right)^{1/3} \quad \text{(MeV)}$$

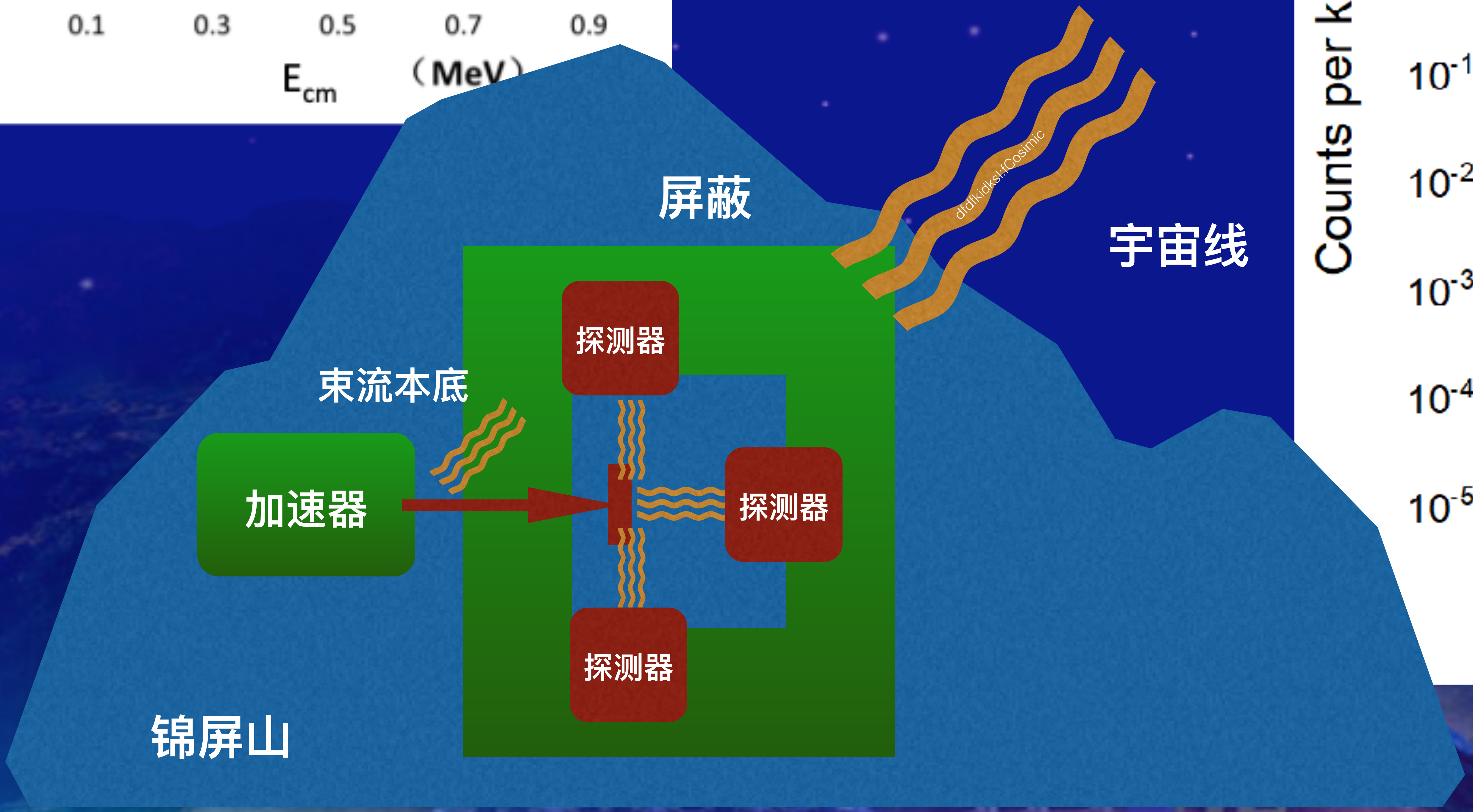
Gamow window

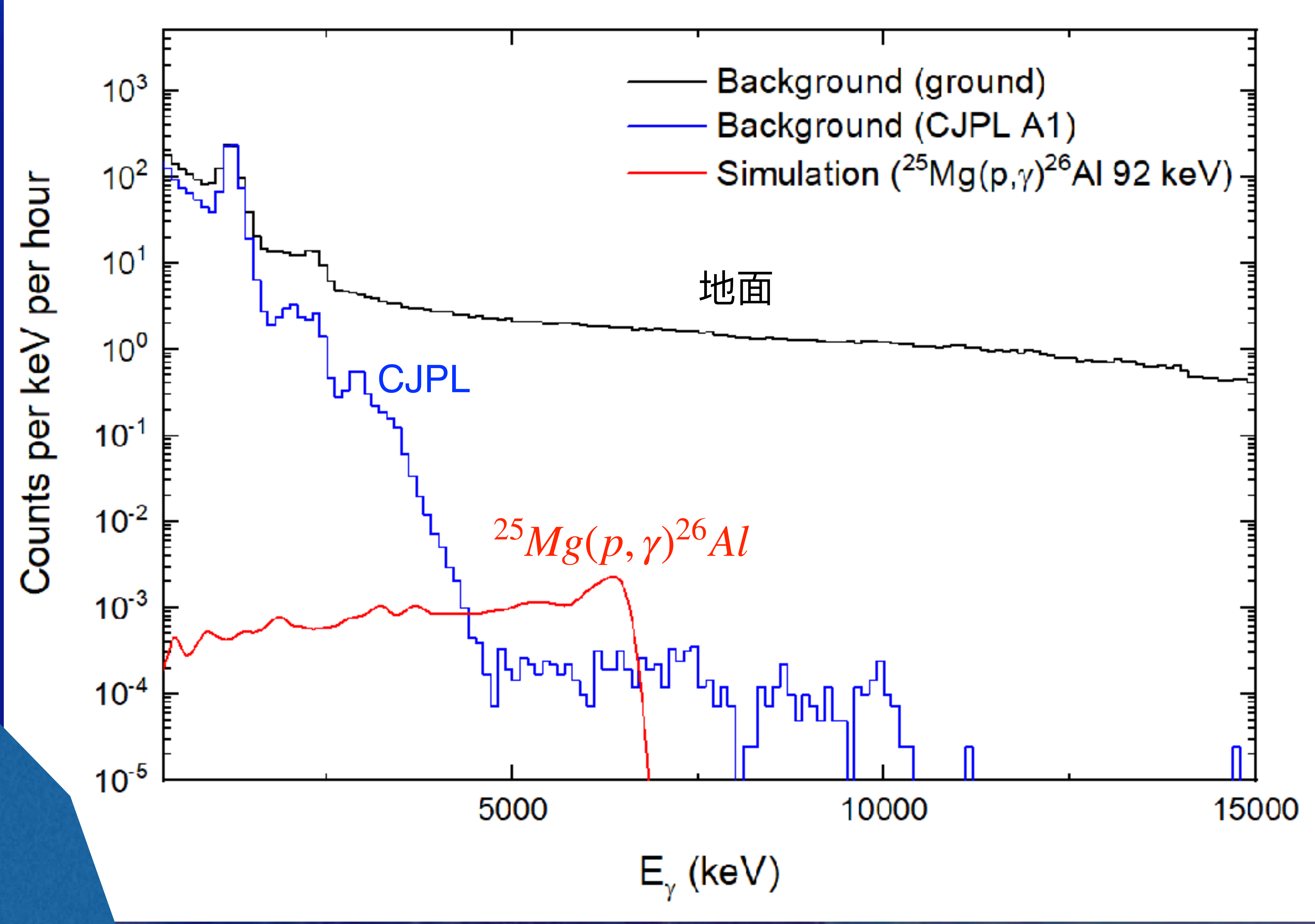




需要大海捞针 Why underground

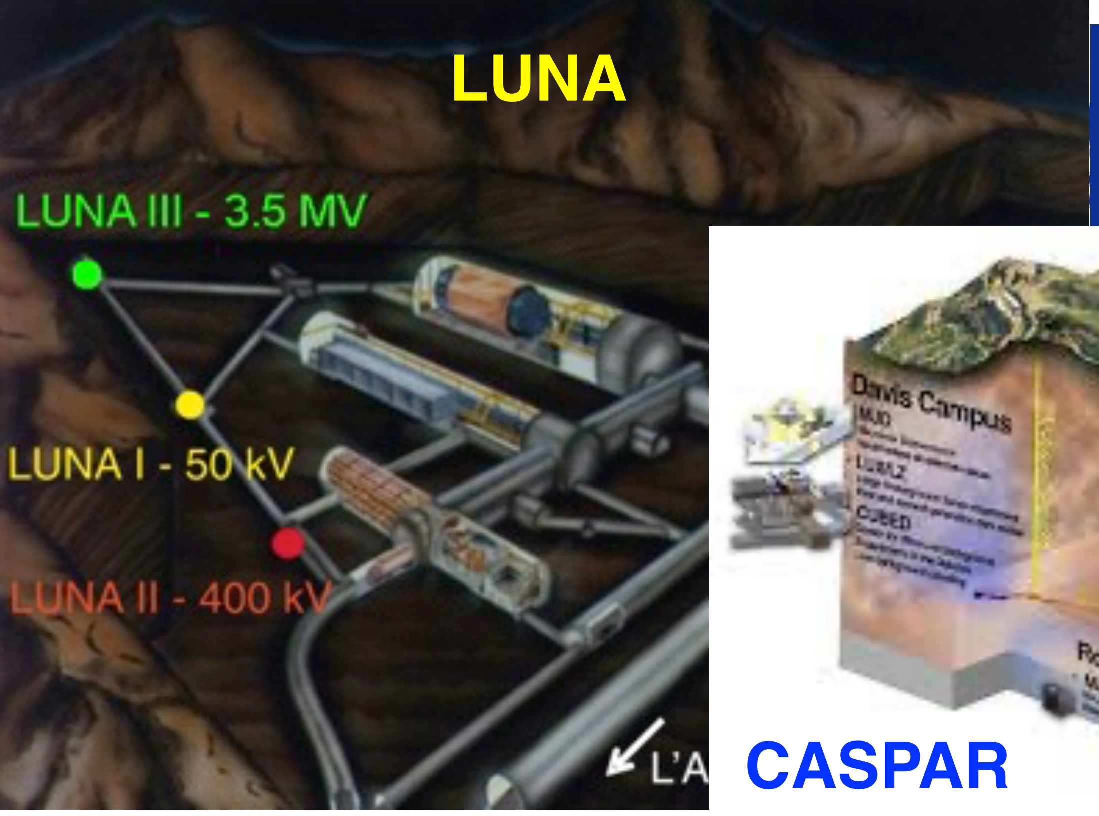


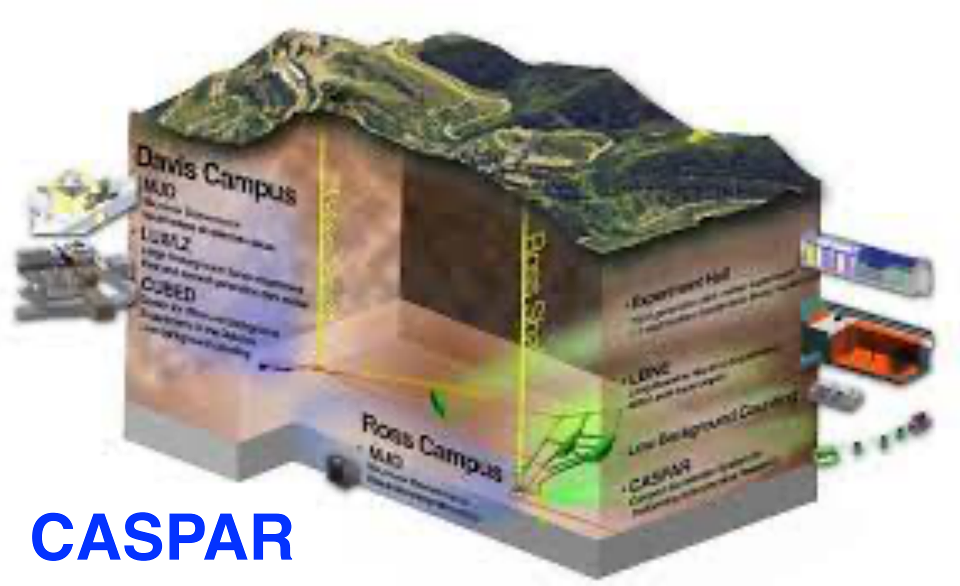




WPL et al., Sci. China 59(2016)2

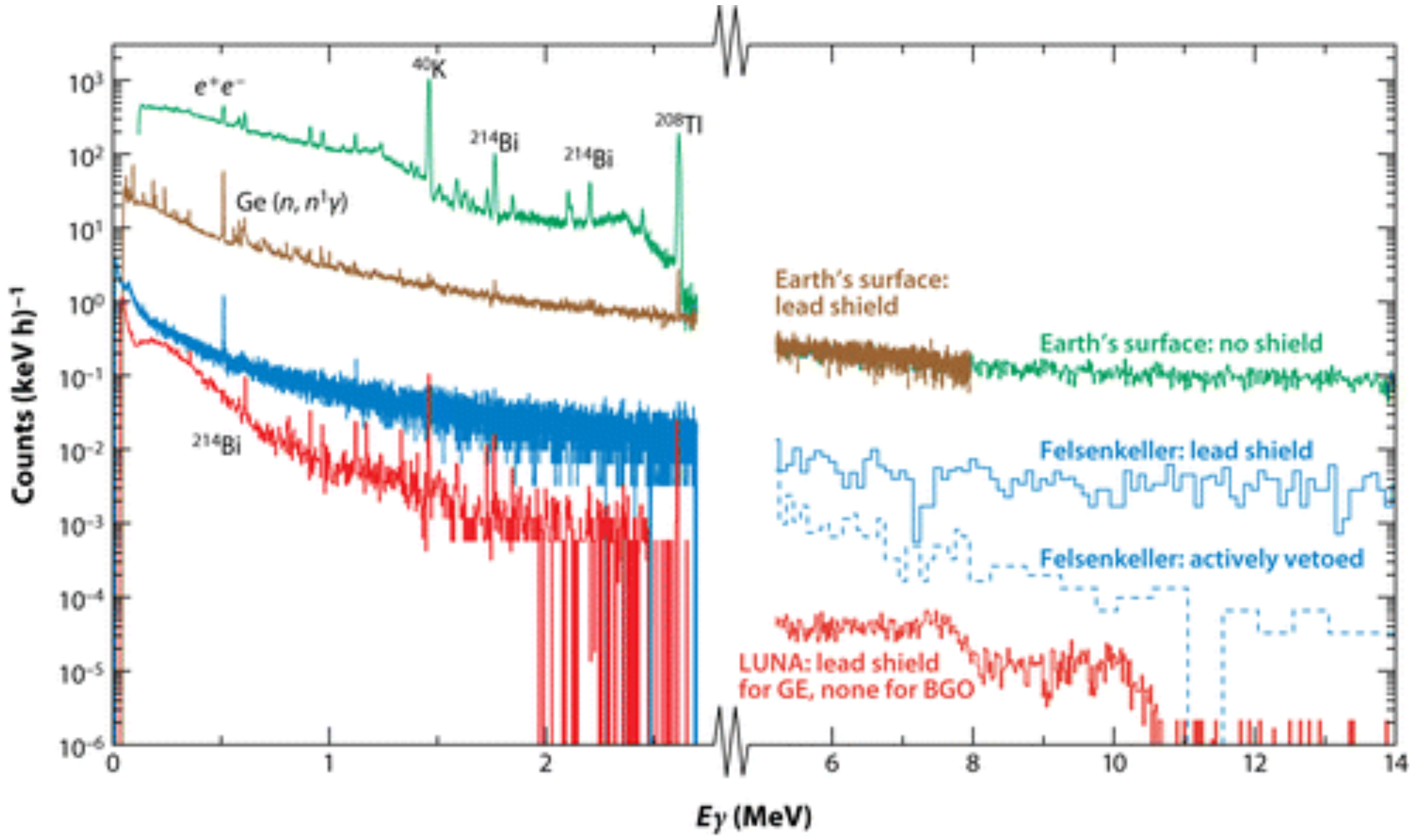
LUNA and CASPAR nuclear astrophysics

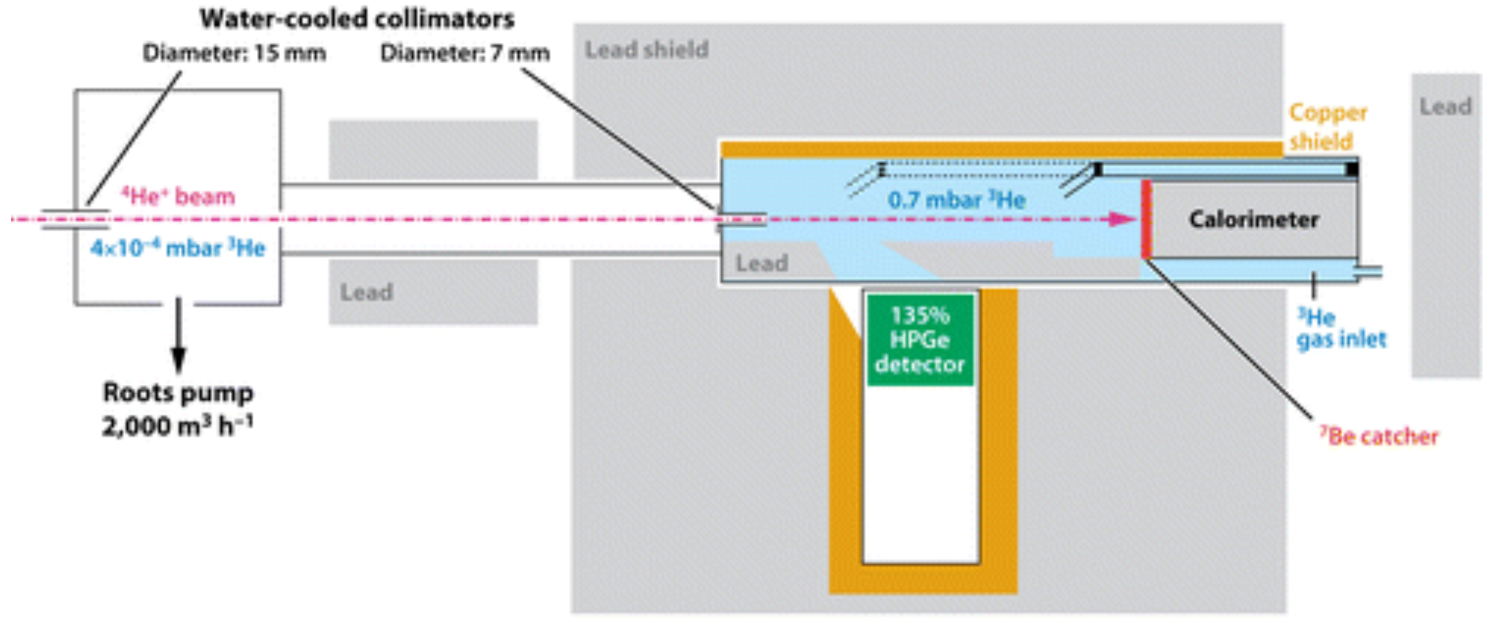




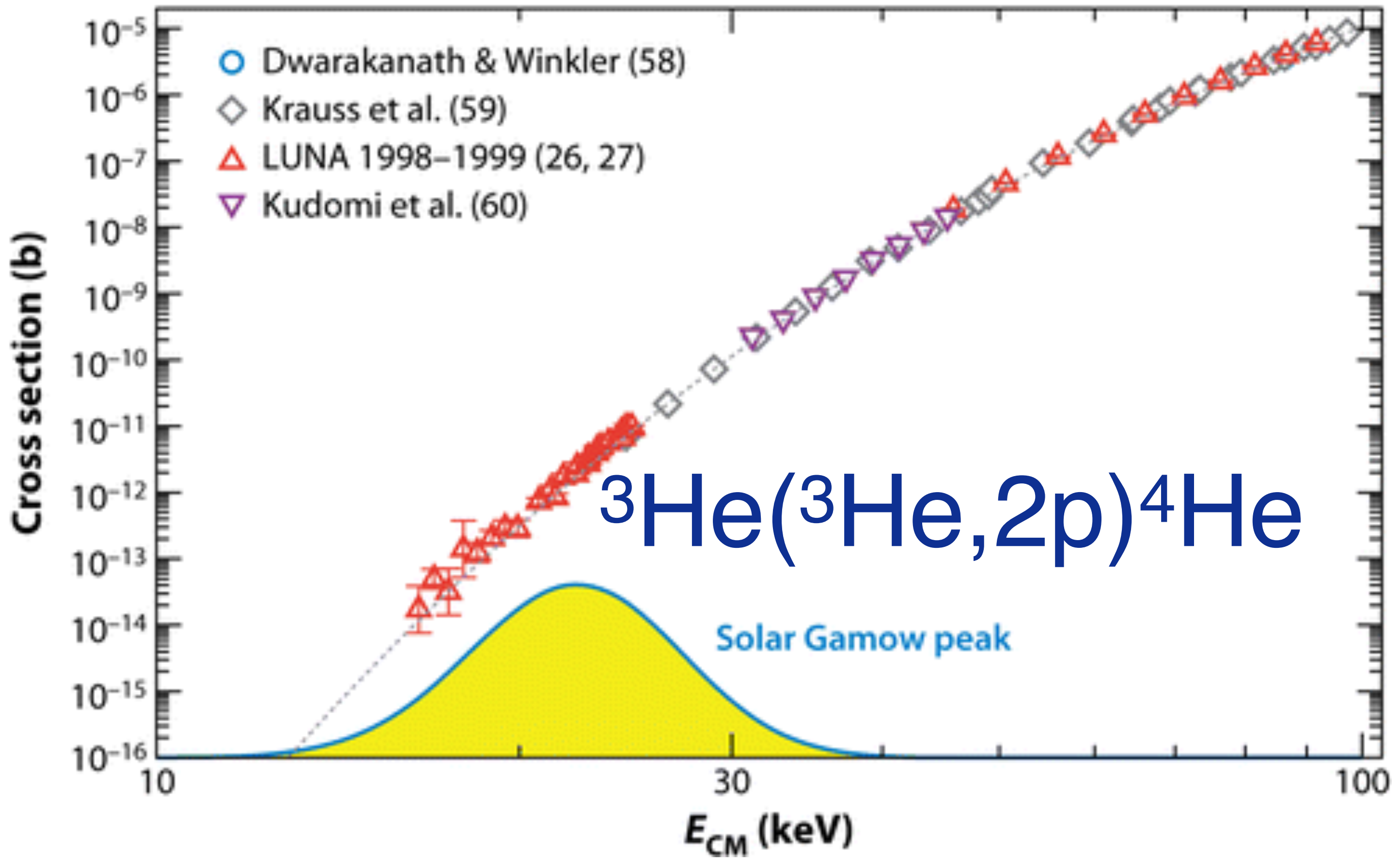
CASPAR

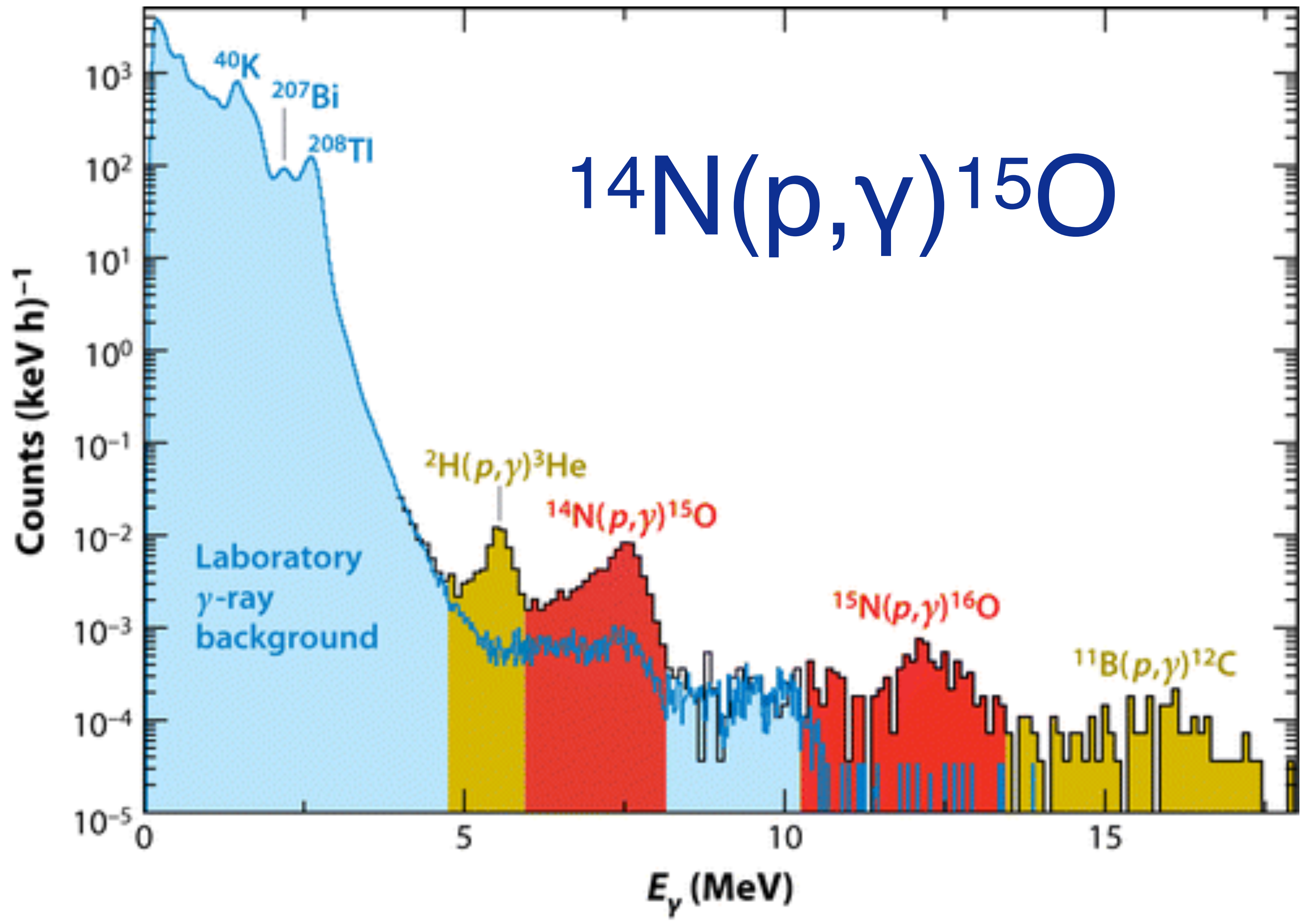
F. Cavanna et al., PRL 115(2015)252501, $^{22}Ne(p,\gamma)^{23}Na$.
F. Ciani et al. PRL 127(2021)152701, $^{13}C(\alpha,n)^{16}O$
V. Mossa et al., Nature 587(2020)210 , $D(p,\gamma)^{3}He$
A. C. Dombos et al., PRL 128(2022)162701, $^{18}O(\alpha,\gamma)^{22}Ne$





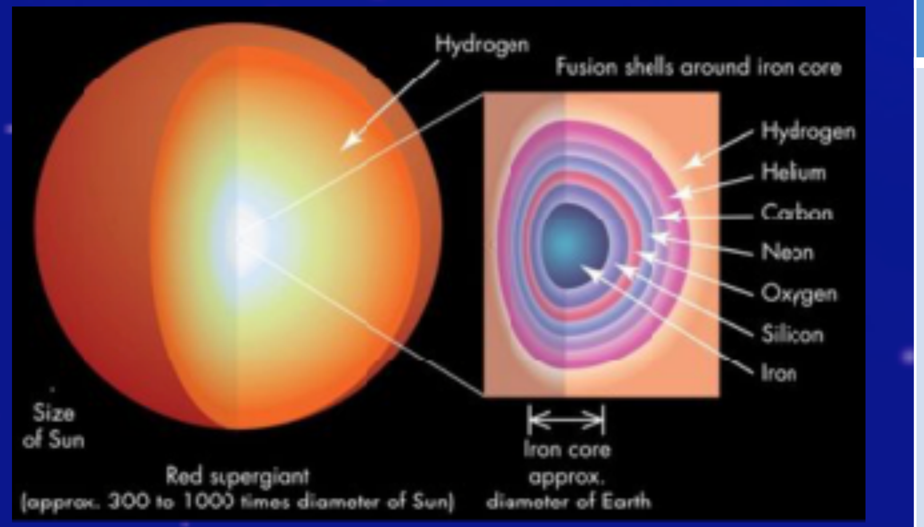
Broggini C, et al. 2010.
Annu. Rev. Nucl. Part. Sci. 60:53–73

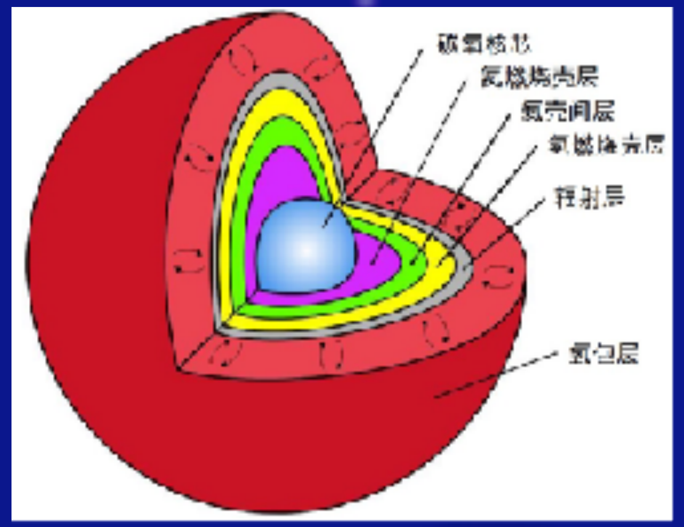


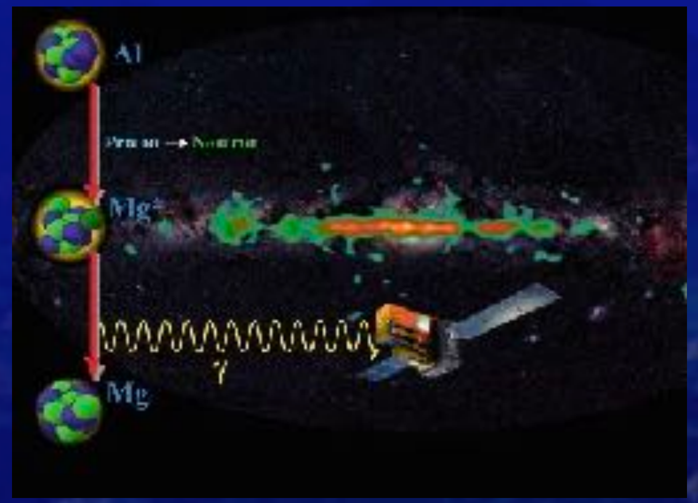


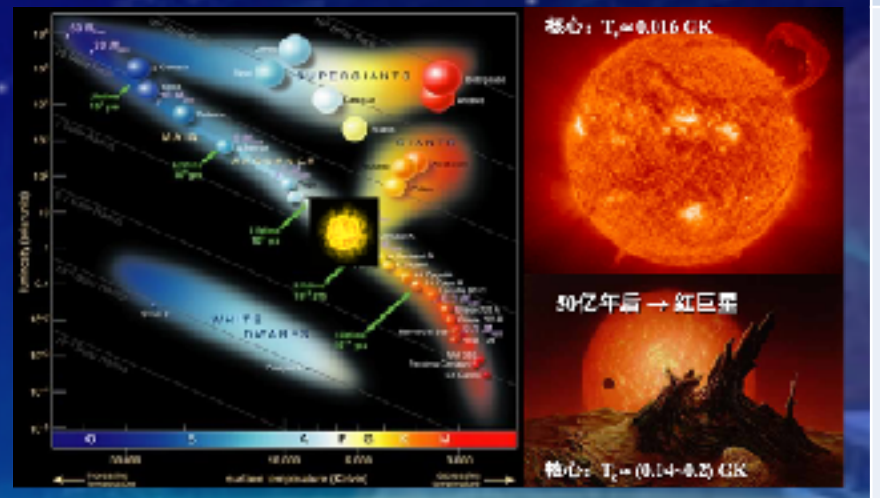
$^{3}He(^{3}He,2p)^{4}He$
PRL82(1999)5205
$^{2}H(^{3}He,p)^{4}He$
PLB482(2000)43
$^{2}H(p,\gamma)^{3}He$
NPA 706(2002)203
$^{3}He(\alpha,\gamma)^{7}Be$
PRL 97(2006)122502
$^{14}N(p,\gamma)^{15}O$
PLB 591(2004)61
$^{15}N(p,\gamma)^{16}O$
PRC82, 055804(2010)
$^{17}O(p,\gamma)^{18}F$
PRL 109, 202601(2012)
$^{25}Mg(p,\gamma)^{26}Al$
PLB 707(2012) 60

Uncertainty remained for key reactions 天时

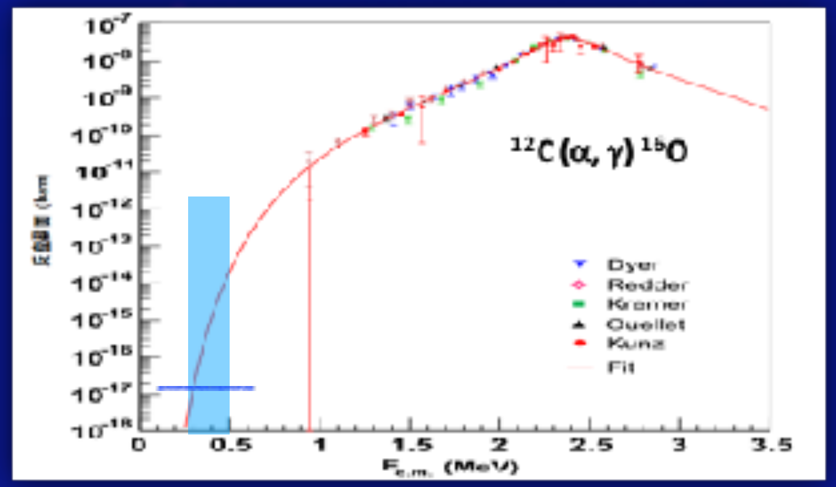




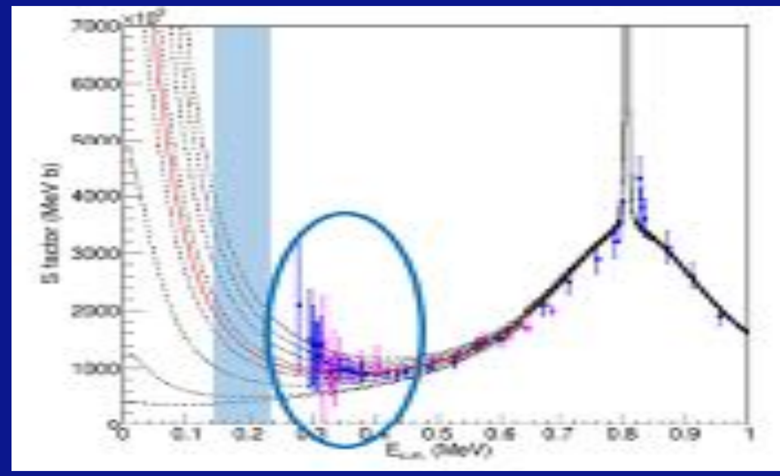




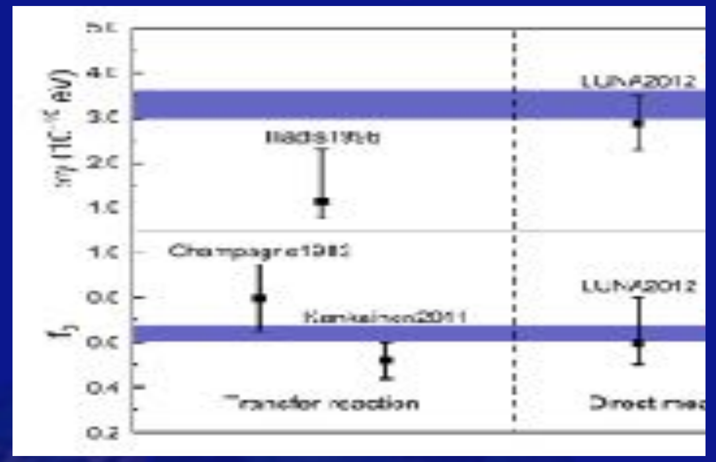
Physics	Reaction	Current	Desired
Massive star	$^{12}C(\alpha,\gamma)^{16}O$	60% 890 keV	20% 220-380 keV
s-process neutron source	$^{13}C(\alpha,n)^{16}O$	60% 230 keV	10% 140-230 keV
Galaxy ^{26}Al source	$^{25}Mg(p,\gamma)^{26}Al$	20% 92 keV	5% 50-300 keV
F, Ca aboundace	$^{19}F(p,\alpha)^{16}O$ $^{19}F(p,\gamma)^{20}Ne$	80 % 189 keV upper limit 240keV	5 % 50-250 keV 5 % 200 keV



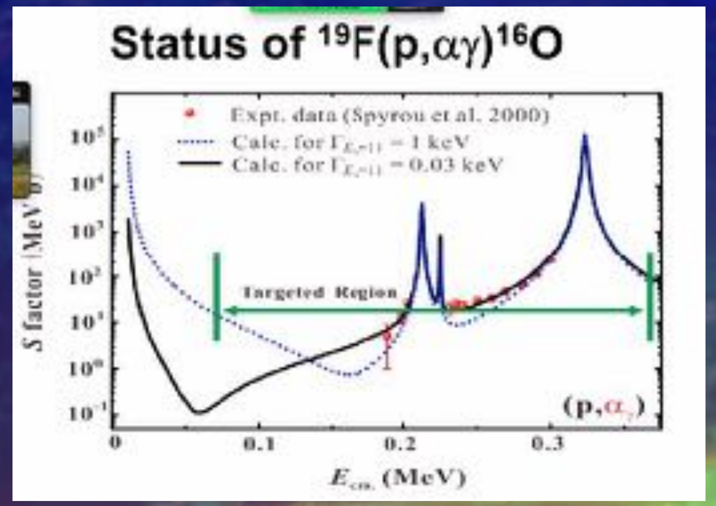
R. J. deBoer et al., RMP vol. 89, 2017



Y. P. Shen, B. Guo, WPL, PPNP 119(2021)103857



G.F. Ciani et al. PRL 127(2021)152701

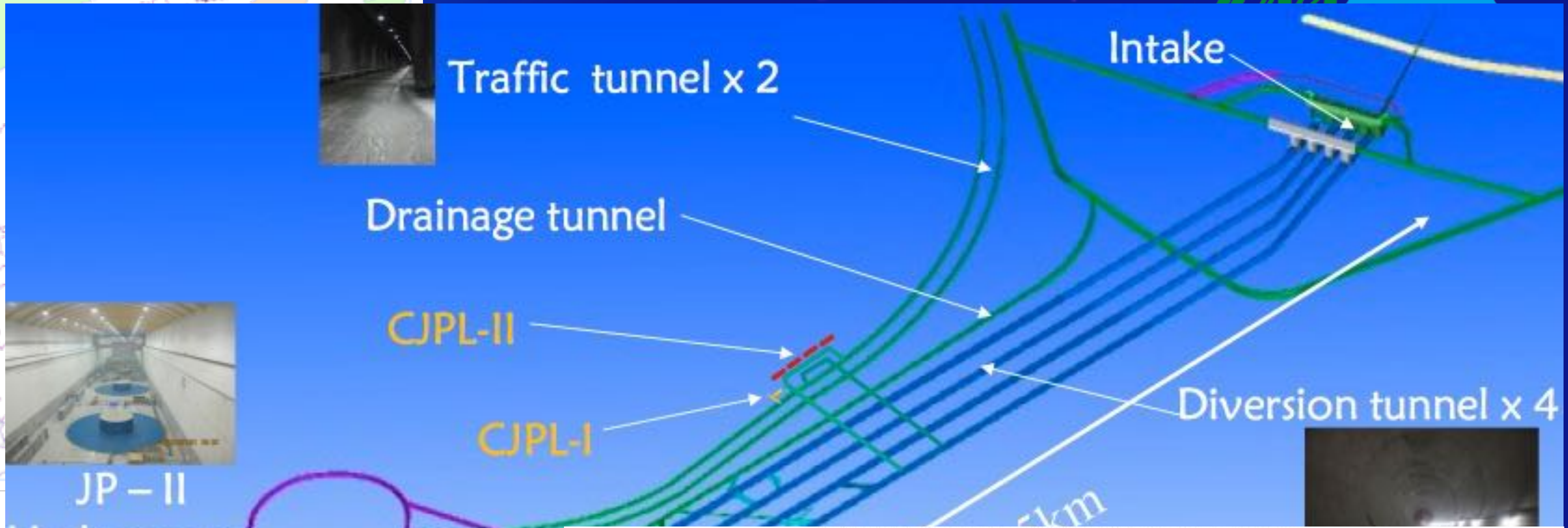


J. J. He et al., Sci. China Phys 59 (2016) 652001

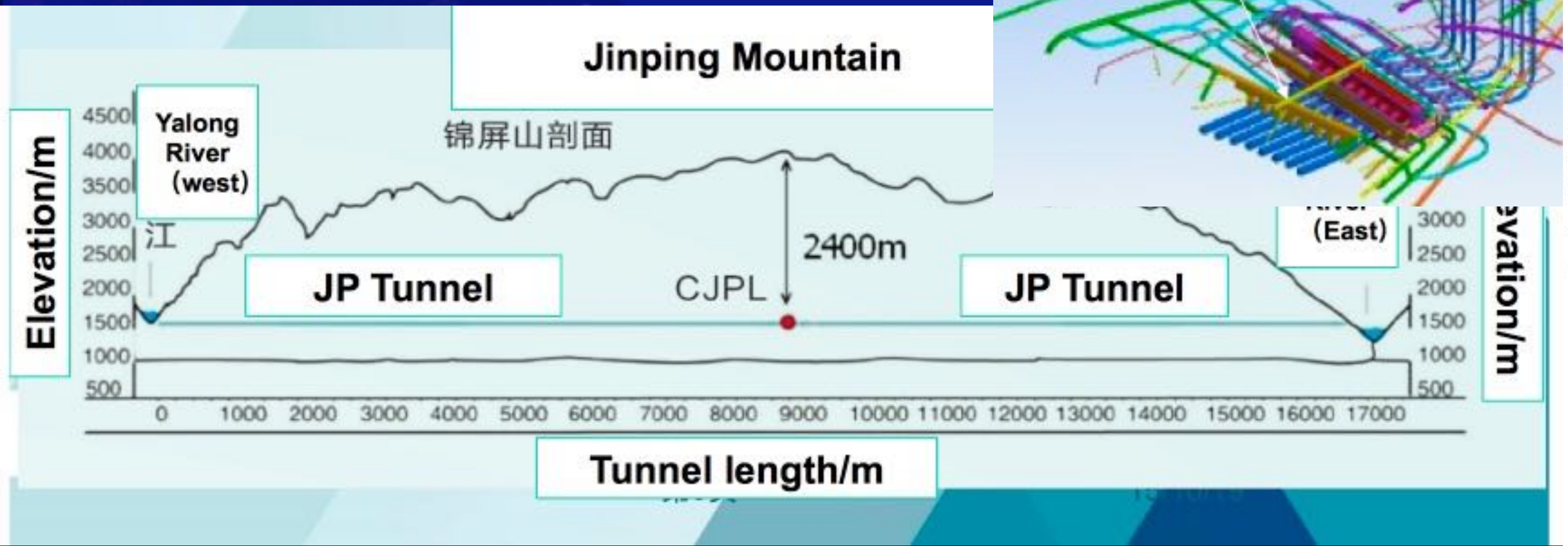
WPL et al., Sci. China 59(2016)2

CJPL

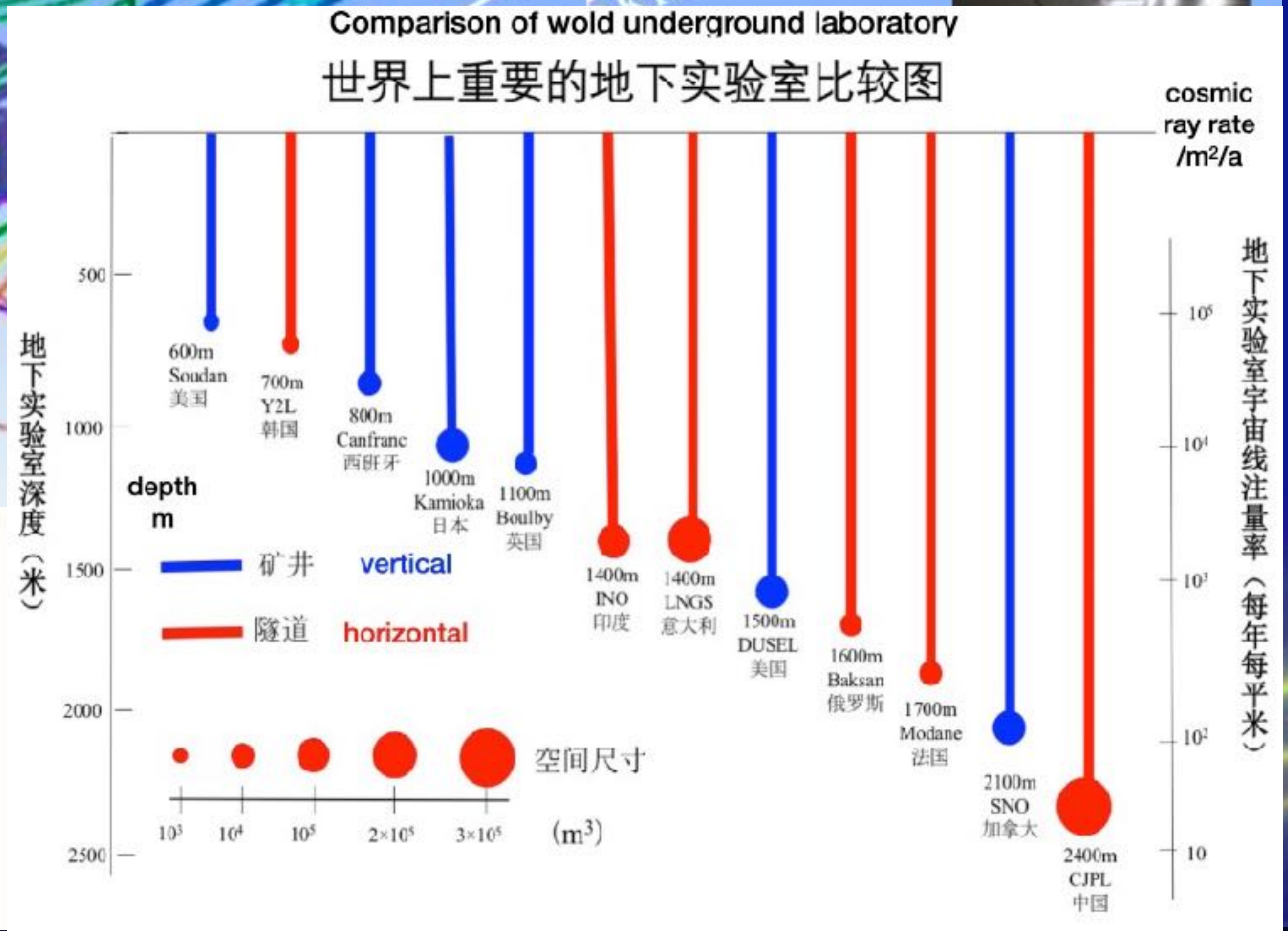
贡嘎山
7556
雅
理
塘
河
砻
江
渡
河
Jinping tunnels
⊙西昌
江



Traffic tunnel x 2
Intake
Drainage tunnel
CJPL-II
CJPL-I
Diversion tunnel x 4
JP – II
Hydropower
station

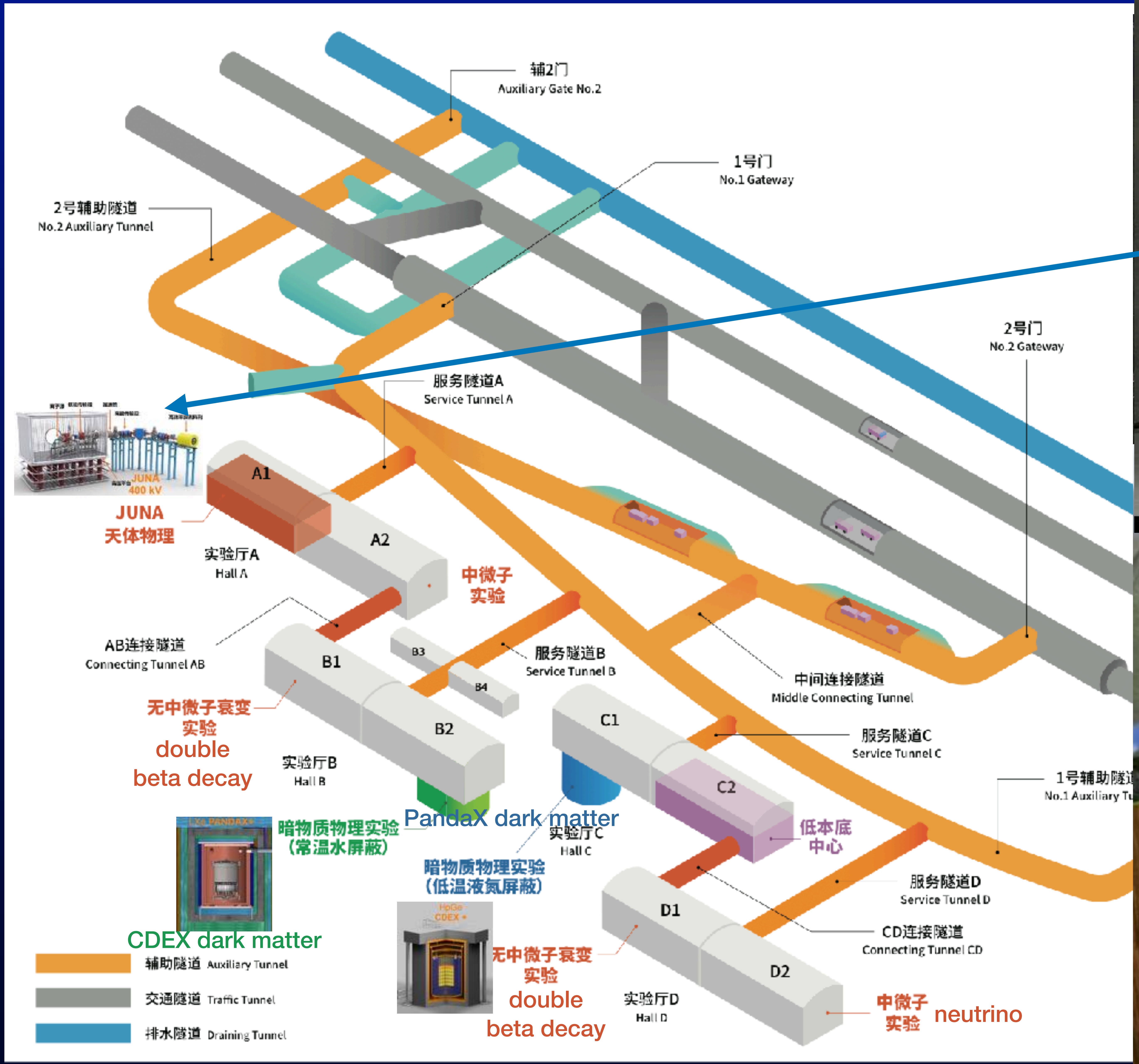


Jinping Mountain
Yalong
River
(west)
锦屏山剖面
Elevation/m
4500
4000
3500
3000
2500
2000
1500
1000
500
江
JP Tunnel
CJPL
2400m
JP Tunnel
(East)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
Tunnel length/m



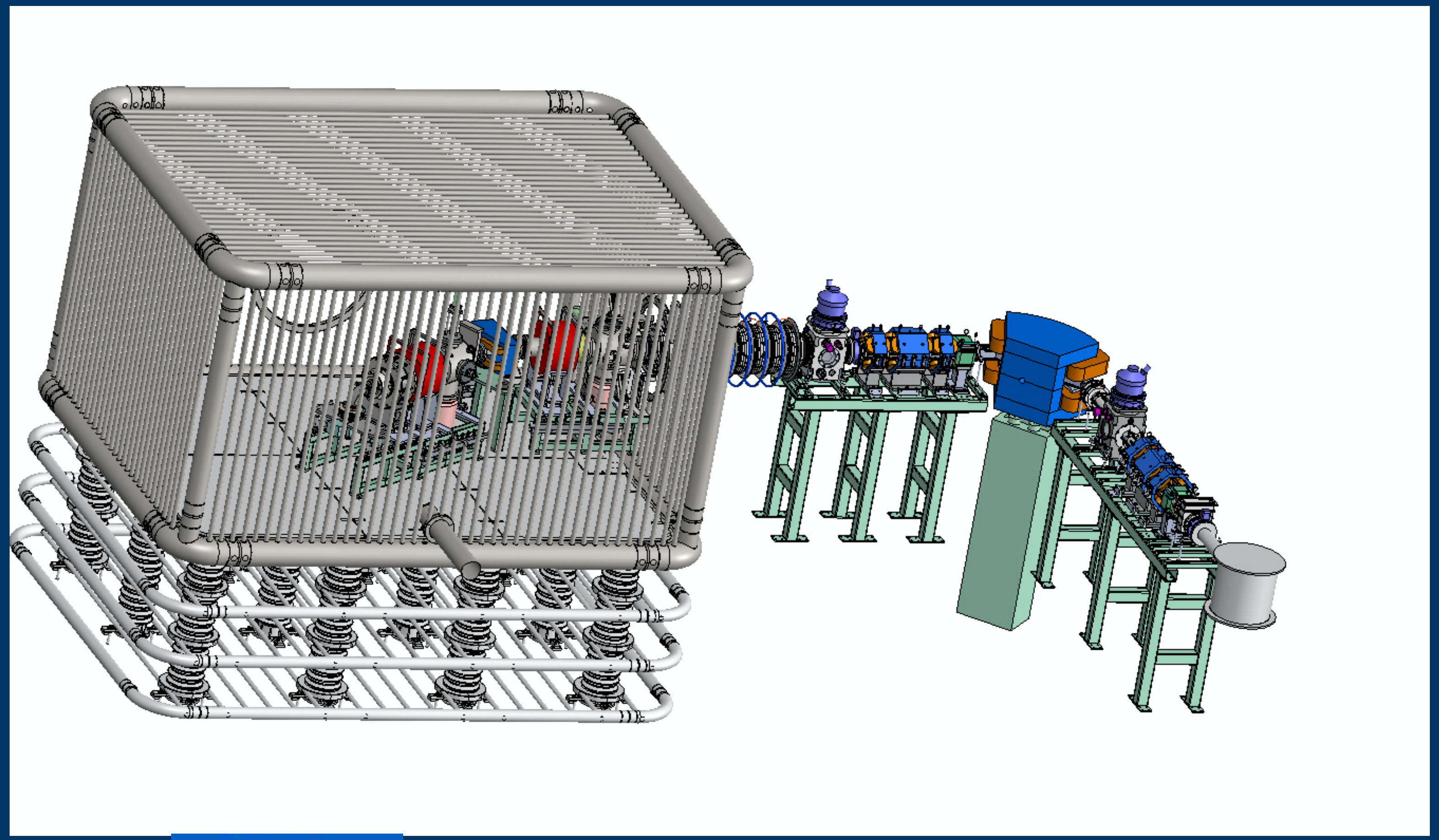
Comparison of wold underground laboratory
世界上重要的地下实验室比较图
cosmic
ray rate
/m²/a
地下实验室深度（米）
depth
m
500
1000
1500
2000
2500
600m Soudan 美国
700m Y2L 韩国
800m Canfranc 西班牙
1000m Kamioka 日本
1100m Boulby 英国
1400m INO 印度
1400m LNGS 意大利
1500m DUSEL 美国
1600m Baksan 俄罗斯
1700m Modane 法国
2100m SNO 加拿大
2400m CJPL 中国
矿井 vertical
隧道 horizontal
空间尺寸
10³
10⁴
10⁵
2×10⁵
3×10⁵
(m³)
地下实验室宇宙线注量率（每年每平米）
10⁶
10⁴
10³
10²
10

Most silent location: CJPL



JUNA dream team

JUNA



Group leader

Weiping Liu, CIAE/ SUSTech

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

PI

Yangping Shen, CIAE

Jun Su, BNU

中国原子能科学研究院 中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

中国科学院近代物理研究所 IMP Institute of Modern Physics, Chinese Academy of Sciences

SDIC 国投集团 SDIC GROUP

雅砻江流域水电开发有限公司 YALONG RIVER HYDROPOWER DEVELOPMENT COMPANY, LTD.

Acc. installation
Arjun Li

A1 construction
Hongwei Yang

Site support
Xiaopan Cheng

Acc. operation
Long Zhang

Bing Guo
$^{22}Ne(\alpha,n)^{25}Mg$
CIAE

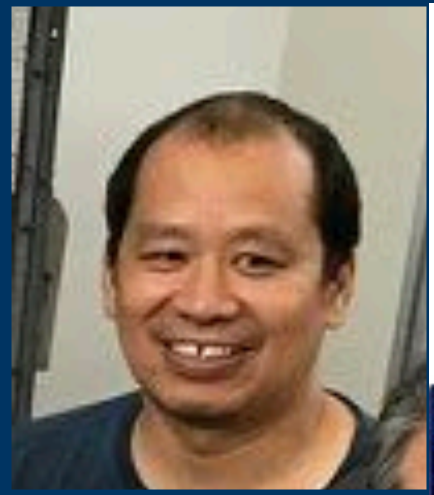
Shuo Wang
$^{14}N(p,\gamma)^{15}O$
SDU

Xiaodong Tang
$^{13}C(\alpha,n)^{16}O$
Ion source IMP

Zhihong Li
$^{25}Mg(p,\gamma)^{26}Al$
CIAE
Jun Su, BNU

Jianjun He
$^{19}F(p,\alpha)^{16}O$
BNU

Gang Lian
Lab. exp. sup.
CIAE



Bao Quncui,CIAE
Liangting Sun, IMP
Ion source and acc.

Supported by the National Natural Science Foundation of China, Grant No. 11490560, 2015

WPL et al., Sci. China 59(2016)2

JUNA Milestone

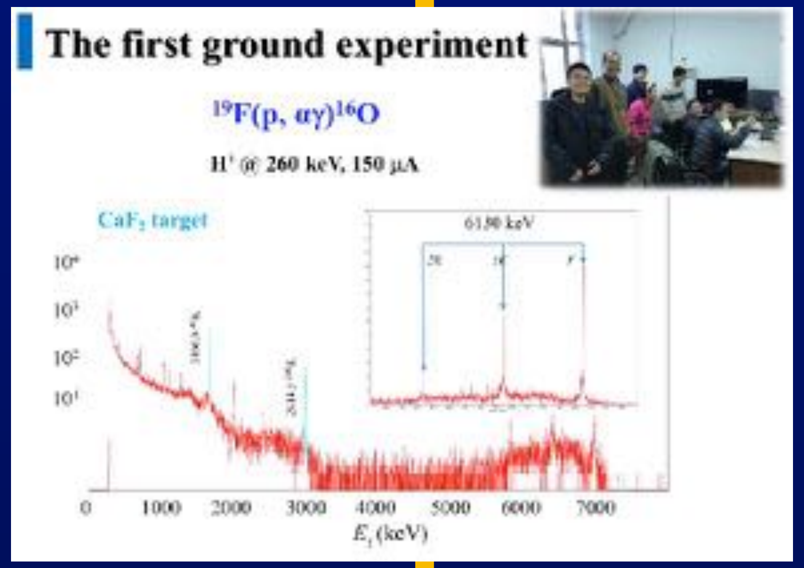
Aug. 2013
Startup meeting

Jan. 2015
Project inauguration

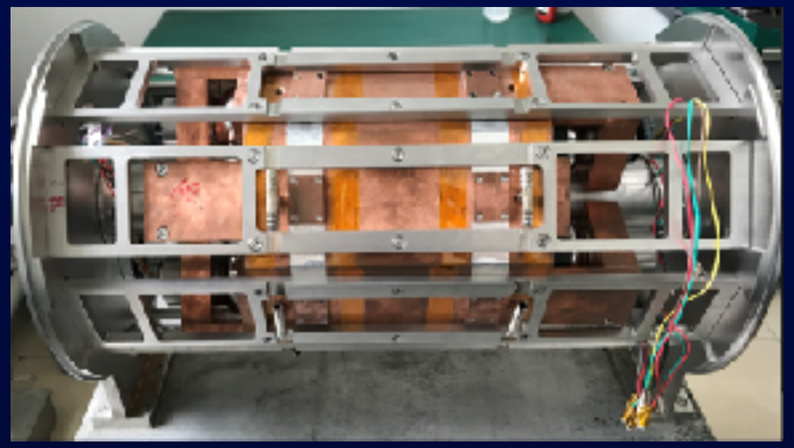
Mar. 2016
On site start

May 2017
Beam on ground

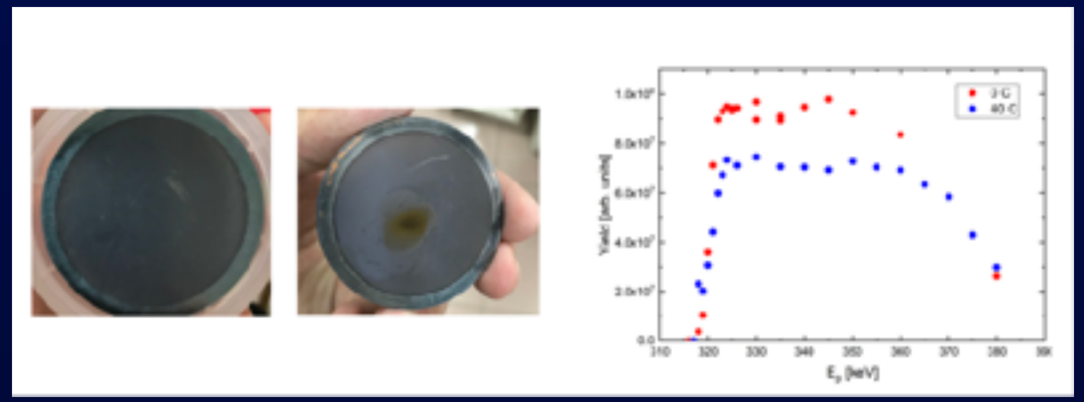
Dec. 2017
3 mA on ground



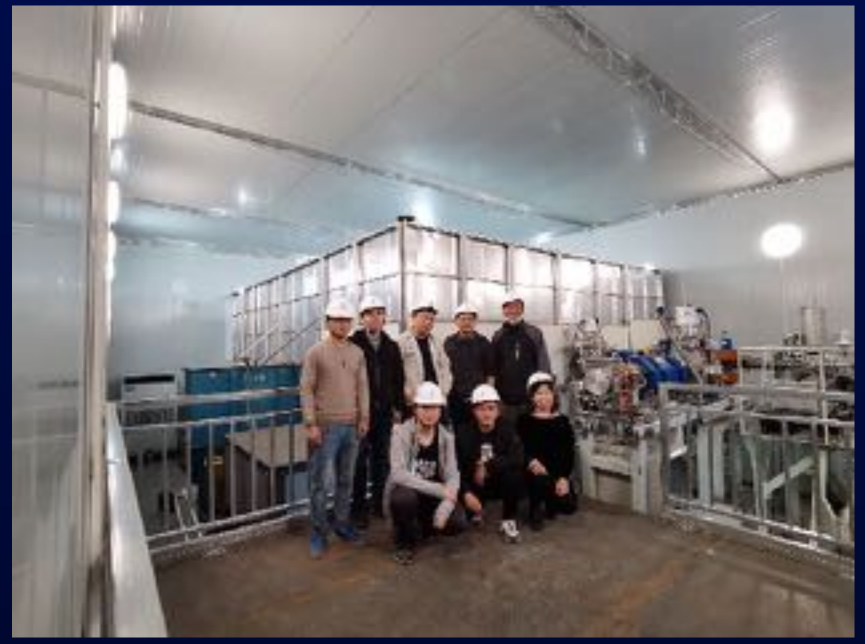
Dec. 2018
Det. Ready
Beam 10 mA



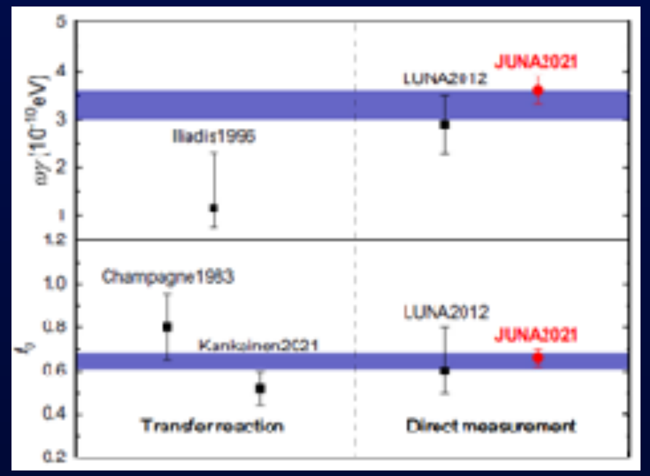
April 2019
Target ready
Acc. Ready



Dec. 2020
Beam underground



May 2021
^{25}Mg, ^{19}F, ^{13}C and ^{12}C data ready

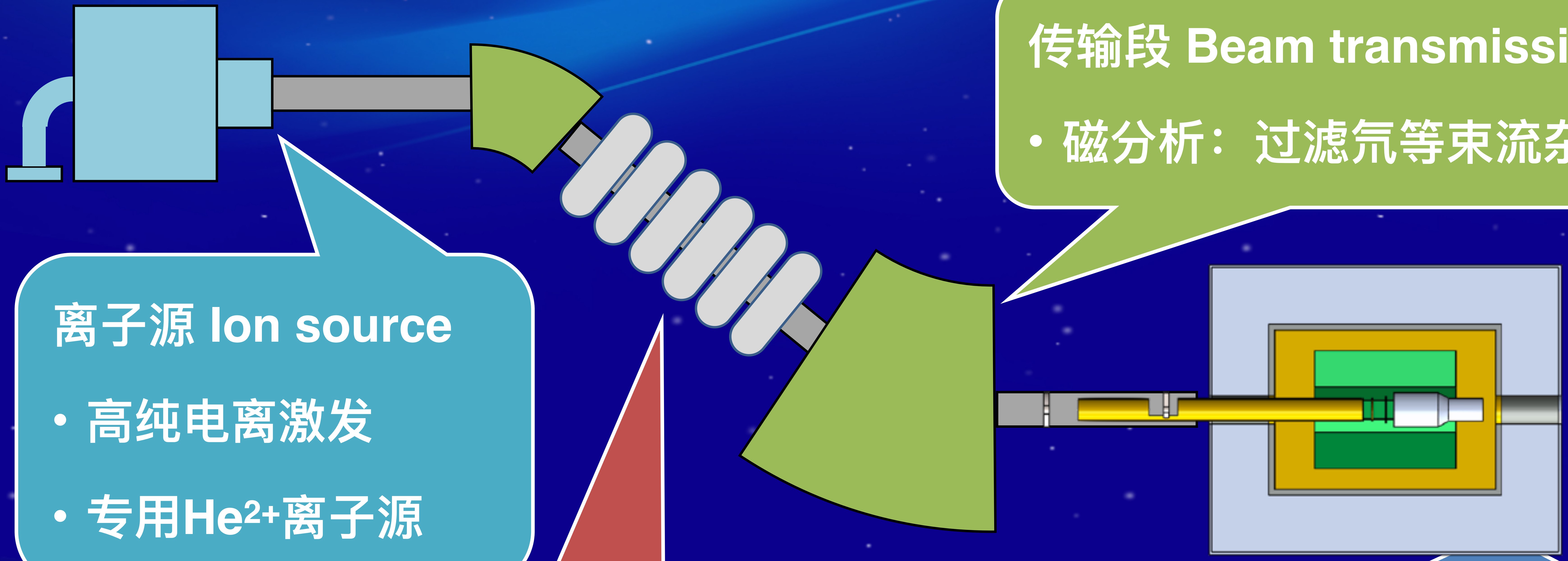


Dec. 2021
Project commission

WPL et al., Sci. China 59(2016)2

极低本底获得—全面的本底控制 Ultra-low background

PI: G. Lian, CIAE



离子源 Ion source

- 高纯电离激发
- 专用He^{2+}离子源

传输段 Beam transmission

- 磁分析：过滤氘等束流杂质

加速段 Accelerator tube

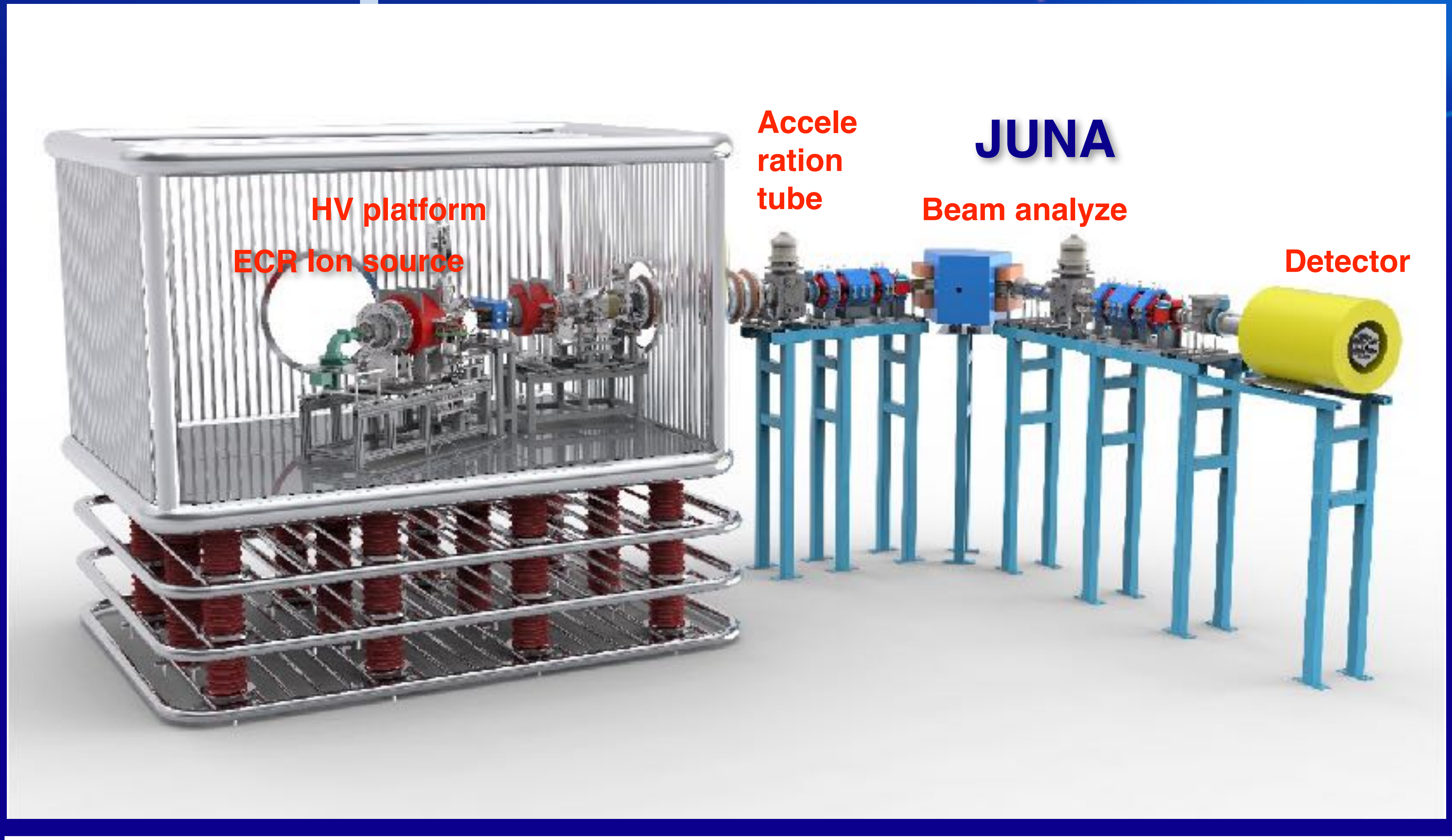
- 选用低本底材料
- 提高传输效率（>90%）

实验终端 Experimental terminals

- 铅、铜、镉等复合材料屏蔽
- 高纯度同位素靶（99.99%）
- 波形甄别技术
- 多重数反符合探测技术

国际最强流深地核天体物理JUNA experiment

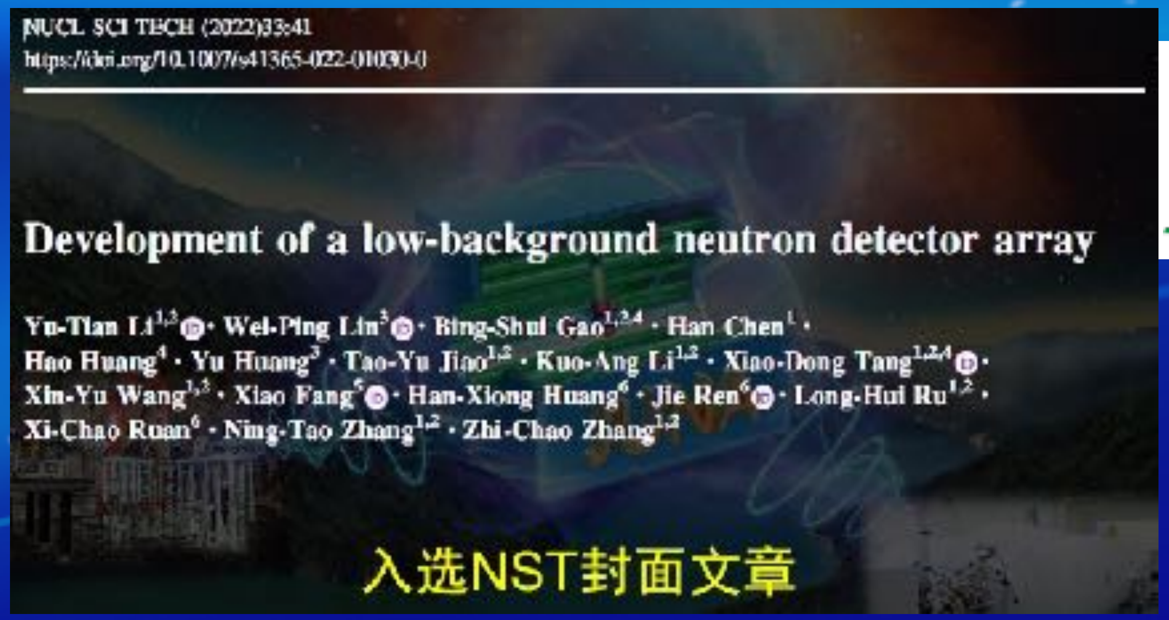
锦屏深地核天体物理实验
Jinping Underground Nuclear Astrophysics Experiment



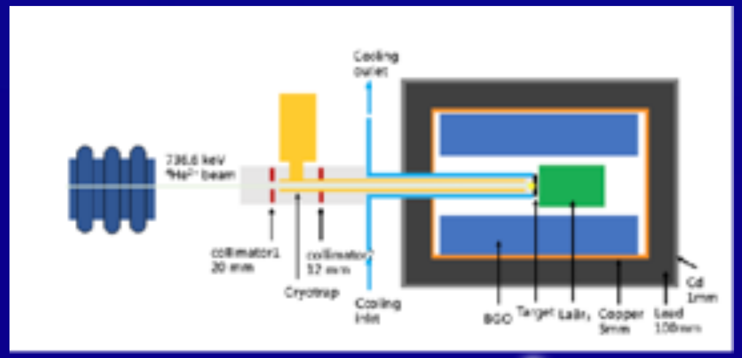
	cosmic μ bkg (cm^{-2} s^{-1})	beam energy（keV)			beam intensity（emA)			energy stability
		H^+	He^+	He^{2+}	H^+	He^+	He^{2+}	
LUNA	2×10^{-8}	50-400	50-400	---	0.3~1	0.3~0.8	---	0.05%
CASPAR	4.4×10^{-9}	100-1000	100-1000	---	0.1	0.1	---	0.05%
JUNA	**2×10^{-10}**	50-400	50-400	**100-800**	**10**	**10**	**2**	**0.04%**

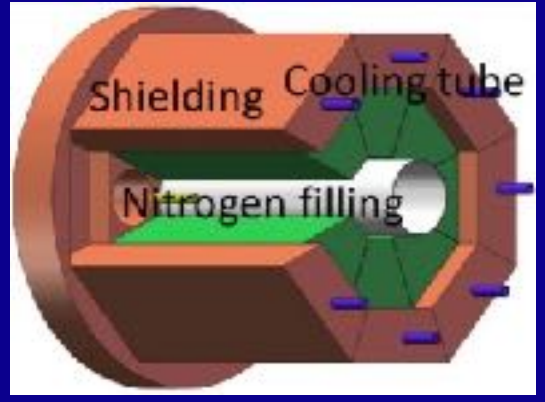
WPL et al., Sci. China 59(2016)2

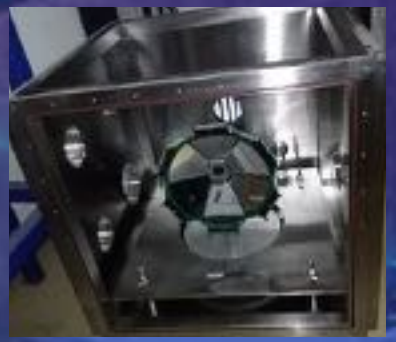
先进探测器技术
Detector tech.



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







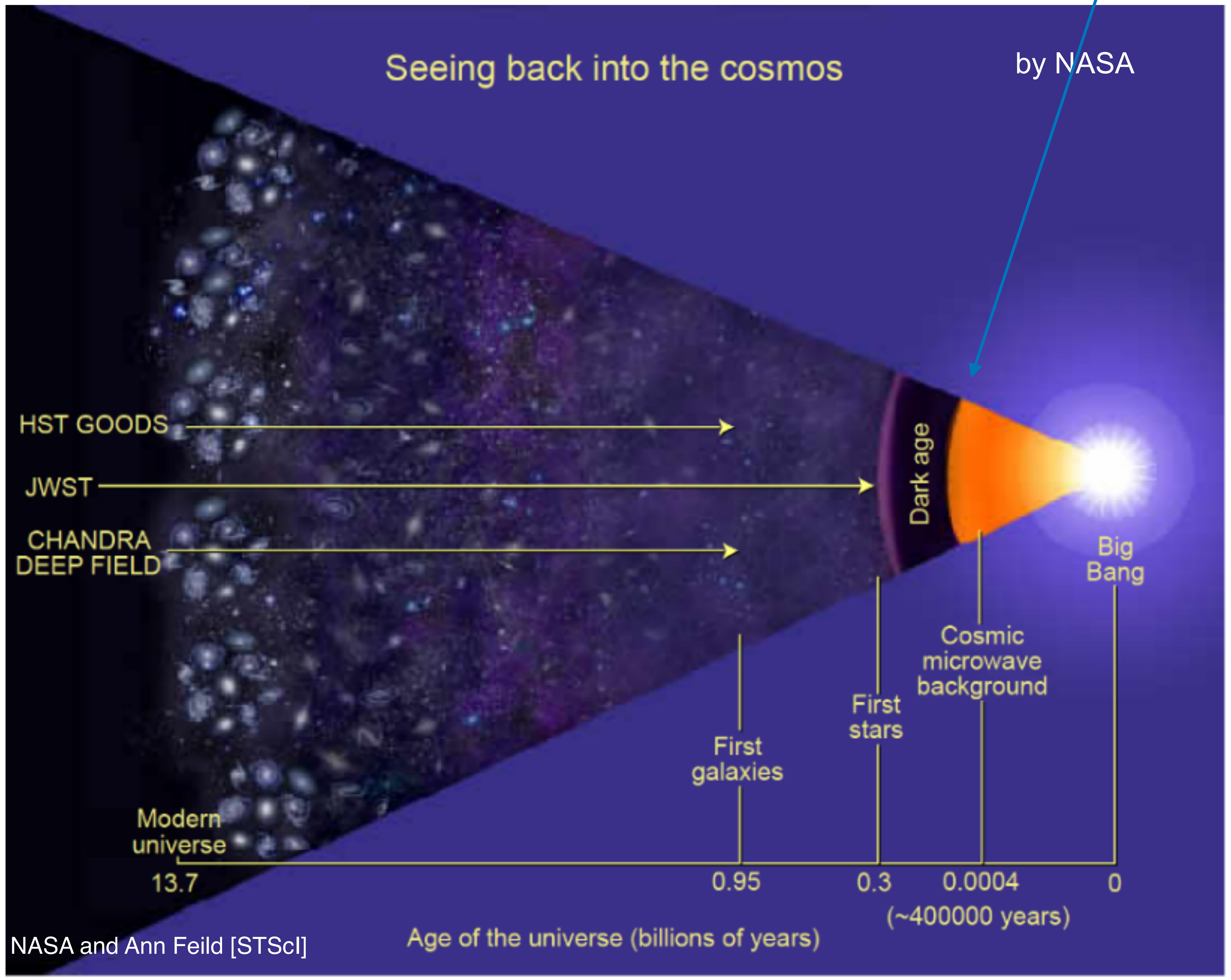
核反应 reaction	采用技术 technology	发表文章 publication	国外记录 world best	我们达到 JUNA
^{12}C	BGO+LaBr		down to 891 keV	down to 552 keV
^{25}Mg	BGO array X8	Atomic ST 52(2018)140	resolution17 %	11 %
^{13}C	^{3}He array X24	NST33(2022) 41, cover story	Exptripolation	Self consisitent
^{19}F	Charged particle array		170 keV	down to 100 keV

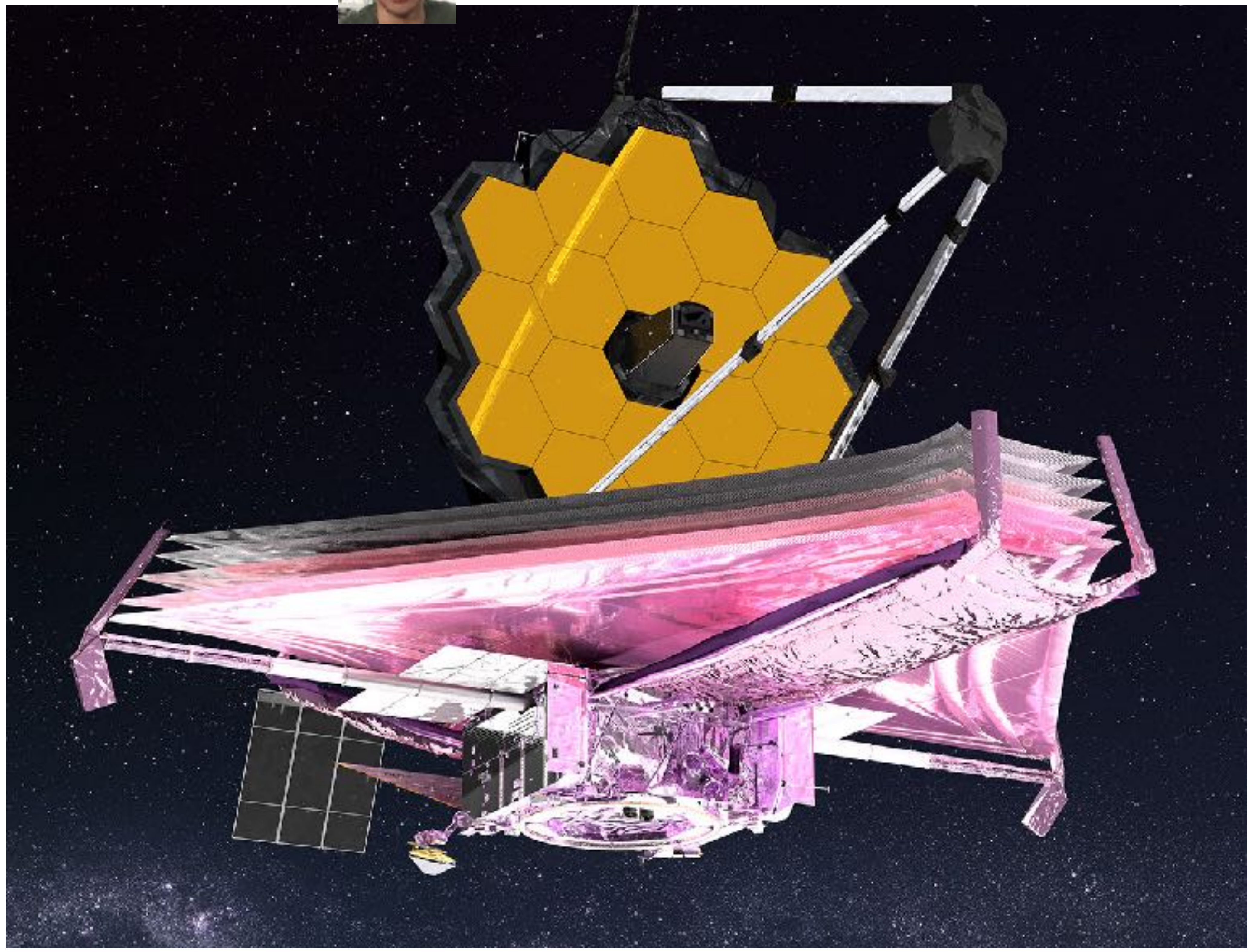
第一代恒星 First stars

PI: J. J. HE, BNU

L. Y. ZHANG, BNU

- 产生重元素，形成新的恒星 Produce heavy elements
- 重新点亮宇宙，结束宇宙“黑暗时代” End of “Dark age”



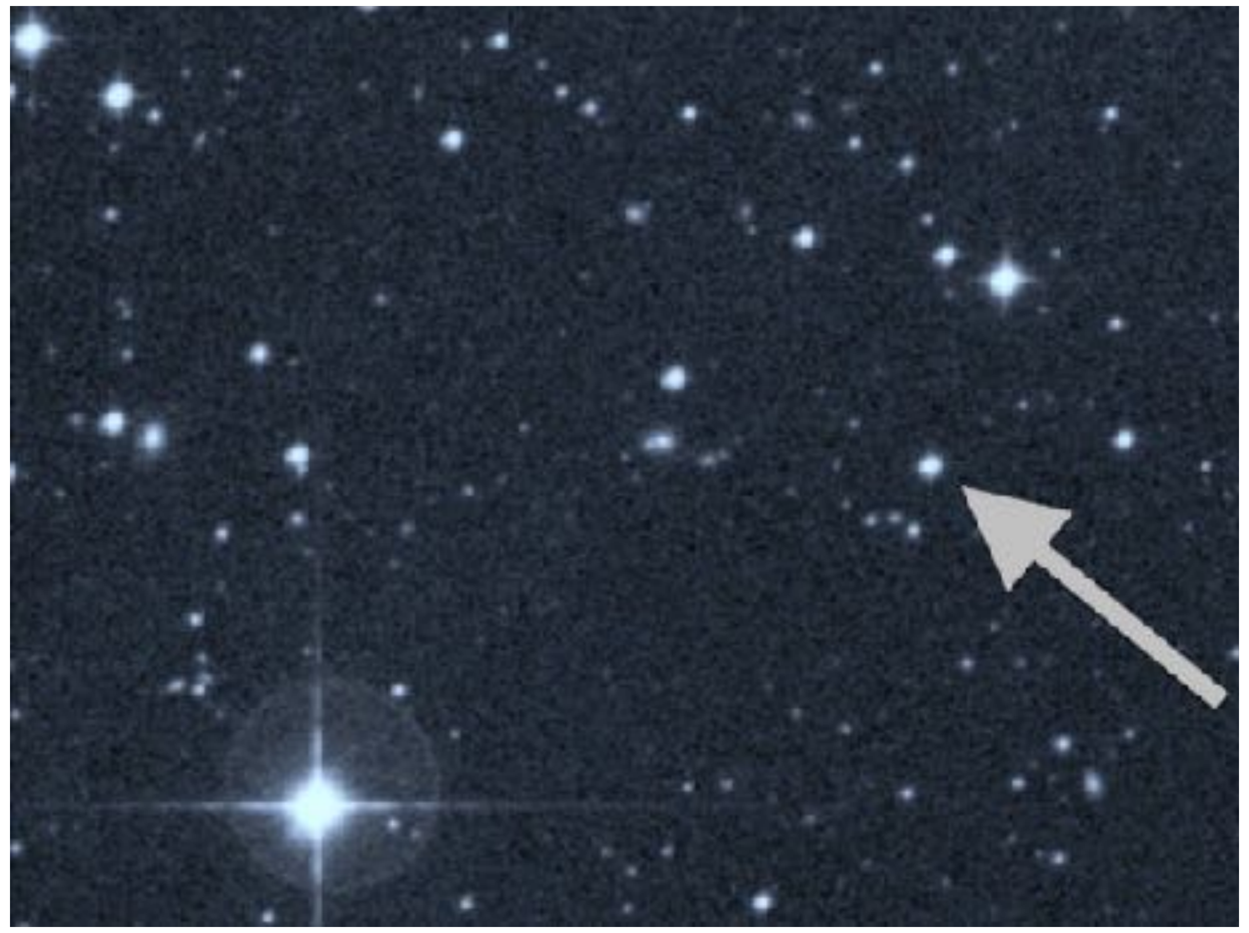


詹姆斯韦布望远镜 JWST

- 探索宇宙黑暗时代后的第一缕曙光 First lights
- 星系形成和演化 Galaxy evolution
- 恒星及其行星系统形成和演化 Star evolution

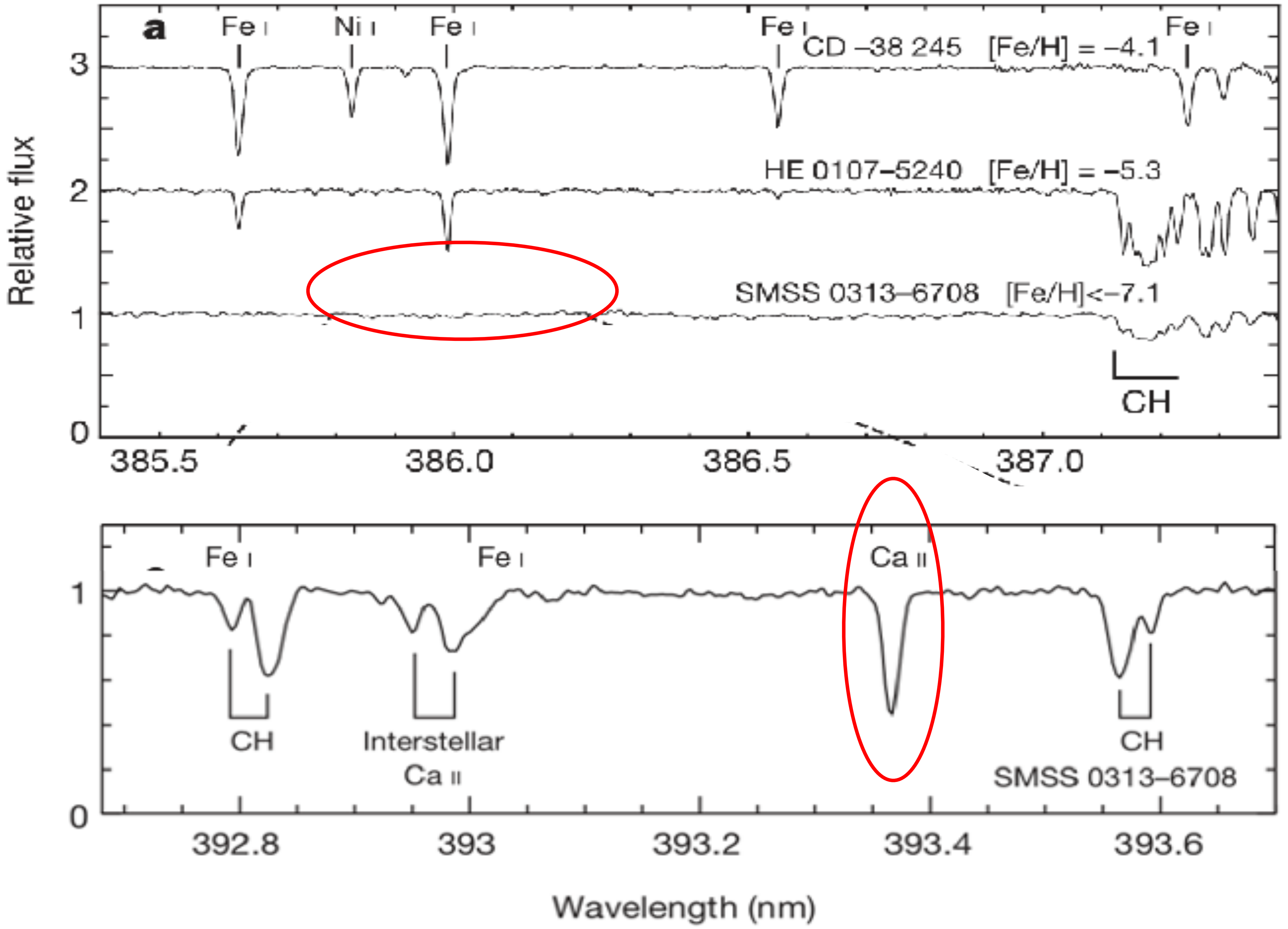
天文观测发现钙元素 Where is Ca come from?

第一代恒星 -> 超新星爆发 -> 星云 ->第二代恒星(SMSS 0313-6708，红巨星)



最古老的恒星，距地球6000光年。是一颗K型红巨星，其内部重元素主要来自于第一代恒星
Oldest star

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



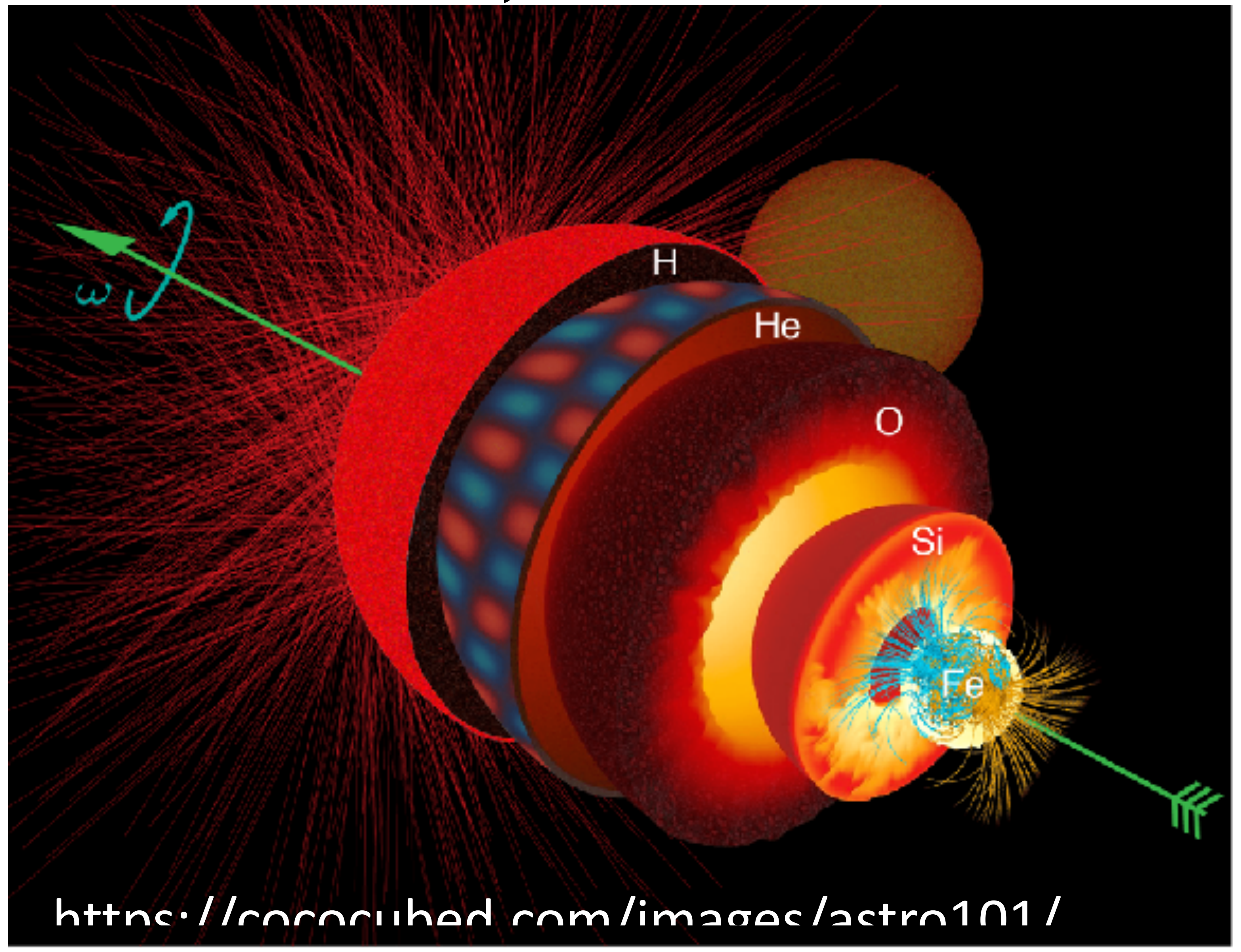
最古老的恒星，SMSS 0313-6708：

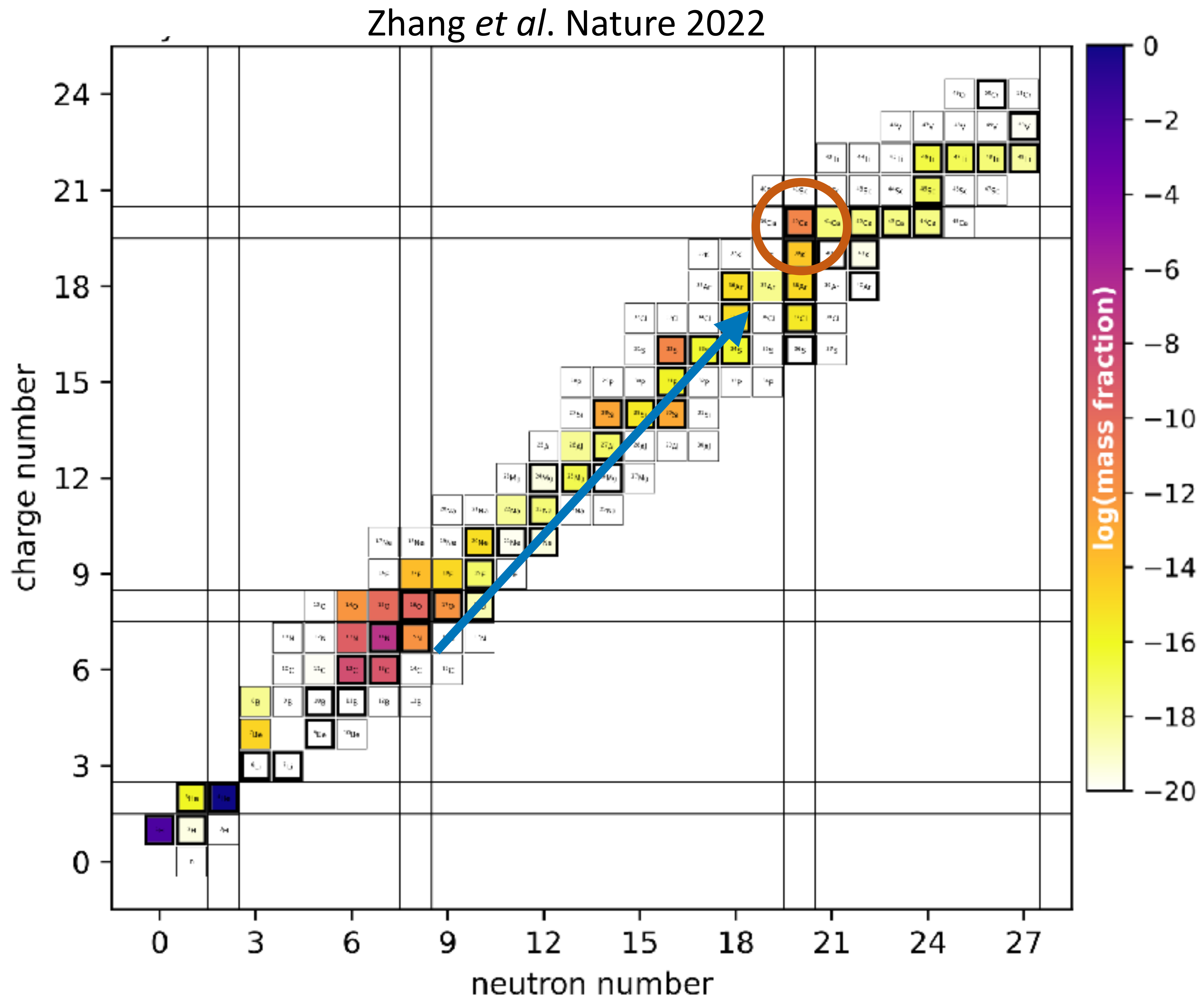
- 观测到了Ca峰，但没有看到铁 See Ca, but not Fe
- Ca来自于超新星爆发？氢燃烧？

钙元素合成机制 Two ways to make Ca

No. 1: Ca 可以产生恒星演化末期的硅燃烧壳层，并通过超新星爆发抛散到宇宙空间 From Si burning with Fe

爆发能量大，内层物质被抛散出去，**会同时产生其它重元素，比如铁**





Interestingly, the calcium released in our model of a 60 M progenitor is not synthesized in the supernova explosion itself; rather it is produced during the stable hydrogen-burning phase. In the metal-free progenitor, thermal equilibrium is obtained only once the core of the star obtains significantly higher temperature and density compared with metal-rich stars. Under such conditions the triple-alpha process enables the synthesis of small amounts of carbon, nitrogen, and oxygen that subsequently catalyse the CNO energy production cycle. Calcium production is the result of breakout from the CNO-cycle.

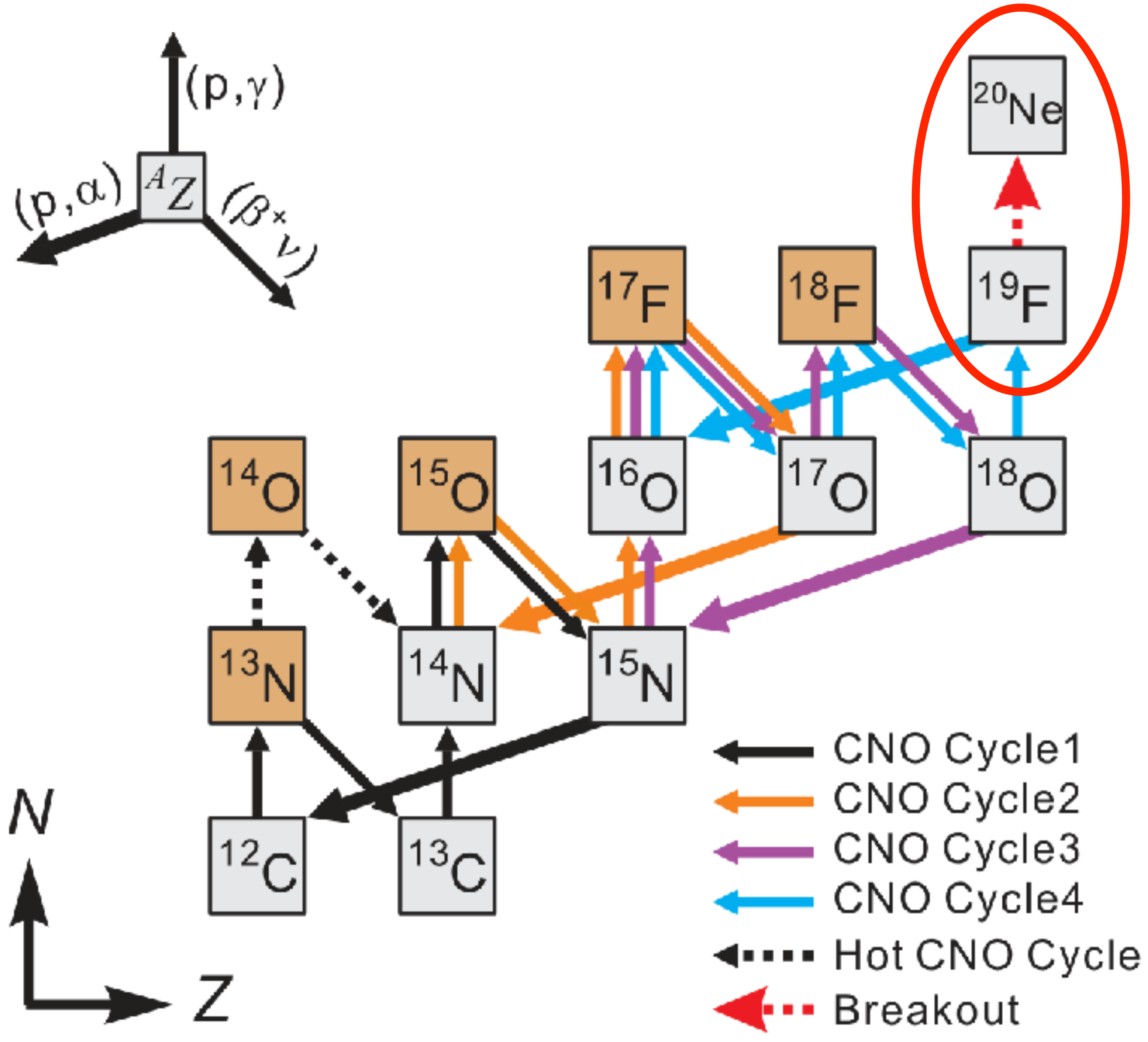
No. 2：Ca也可以产生自恒星的氢燃烧阶段，超新星爆发时只需要抛散外层物质即可，爆发能量小，不会产生重元素 From H burning no Fe: most likely

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

第一代恒星中的氢燃烧 But seeds not enough?

Ca计算丰度比天文观测值低10-100倍, much less Ca with extrapolation

精确测量^{19}F(p,γ)^{20}Ne反应截面，重现天文观测丰度 need to measure!



碳氮氧循环CNO cycles：Why ^{19}F(p,γ)^{20}Ne?

- 绝大部分反应率被限制在CNO附近
- 少量反应流通过一系列(p,γ)反应以及$β^+$衰变进入重核区，并最终合成双幻核^{40}Ca
- ^{19}F(p,γ)^{20}Ne是从CNO循环突破到NeNa循环的唯一通道，对最终合成的^{40}Ca丰度有决定性影响

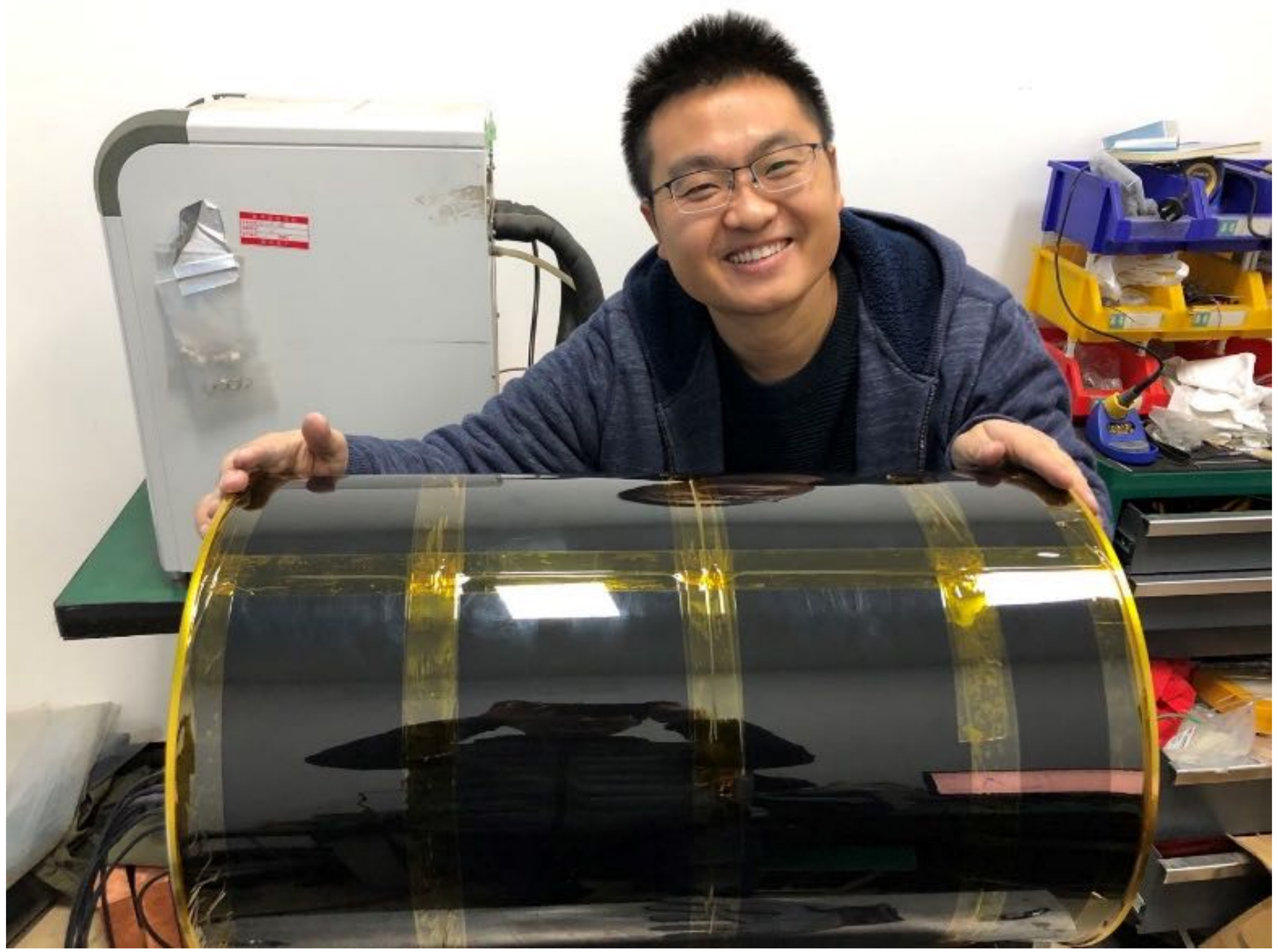
Experimental information is sparse about the competing ^{19}F(p, γ)^{20}Ne reaction which would trigger the break-out from the CNO cycles. While it is generally believed that this reaction channel is negligible compared with the (p, α) channel [79], this claim still needs to be experimentally confirmed. The measurements are difficult because of the enormous background count rate from the ^{19}F(p, αγ)^{16}O reaction. The presently tabulated reaction rate is estimated to be weaker by about four orders of magnitude and therefore, is only scaled to

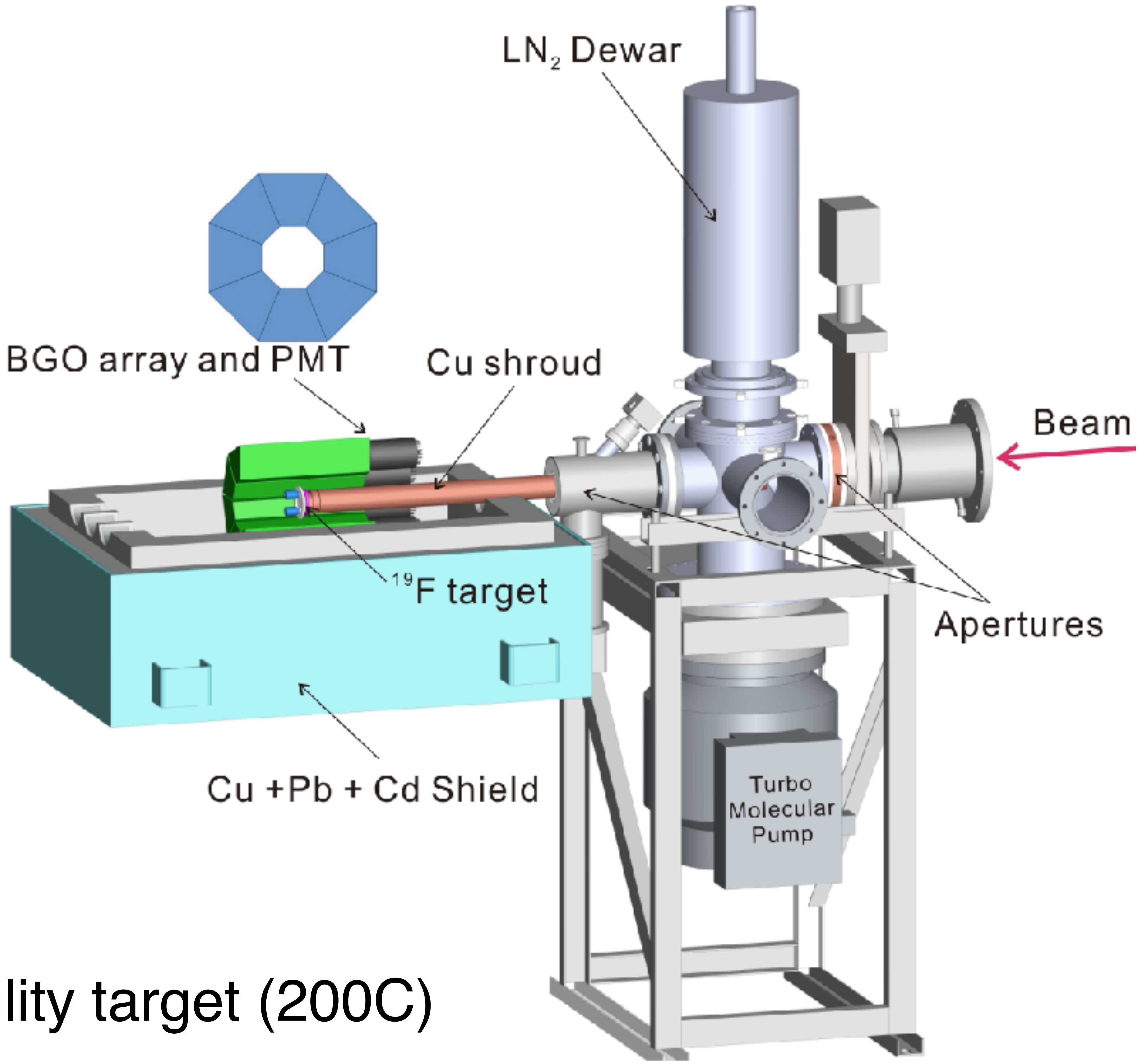
TOPICAL REVIEW

Break-out reactions from the CNO cycles

To cite this article: M Wiescher et al 1999 J. Phys. G: Nucl. Part. Phys. 25 R133

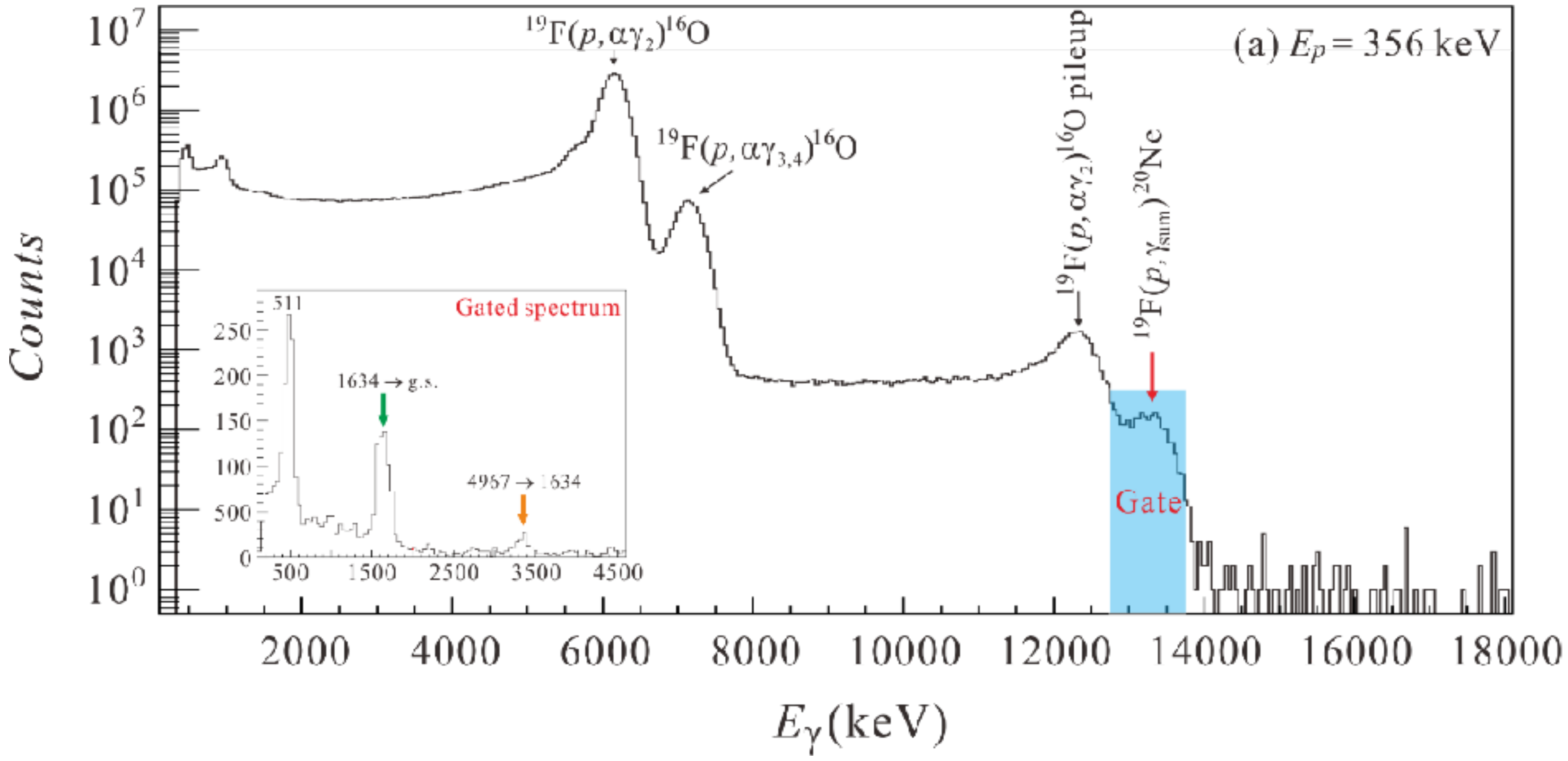
$^{19}F(p,\gamma)^{20}Ne$实验装置 key to success

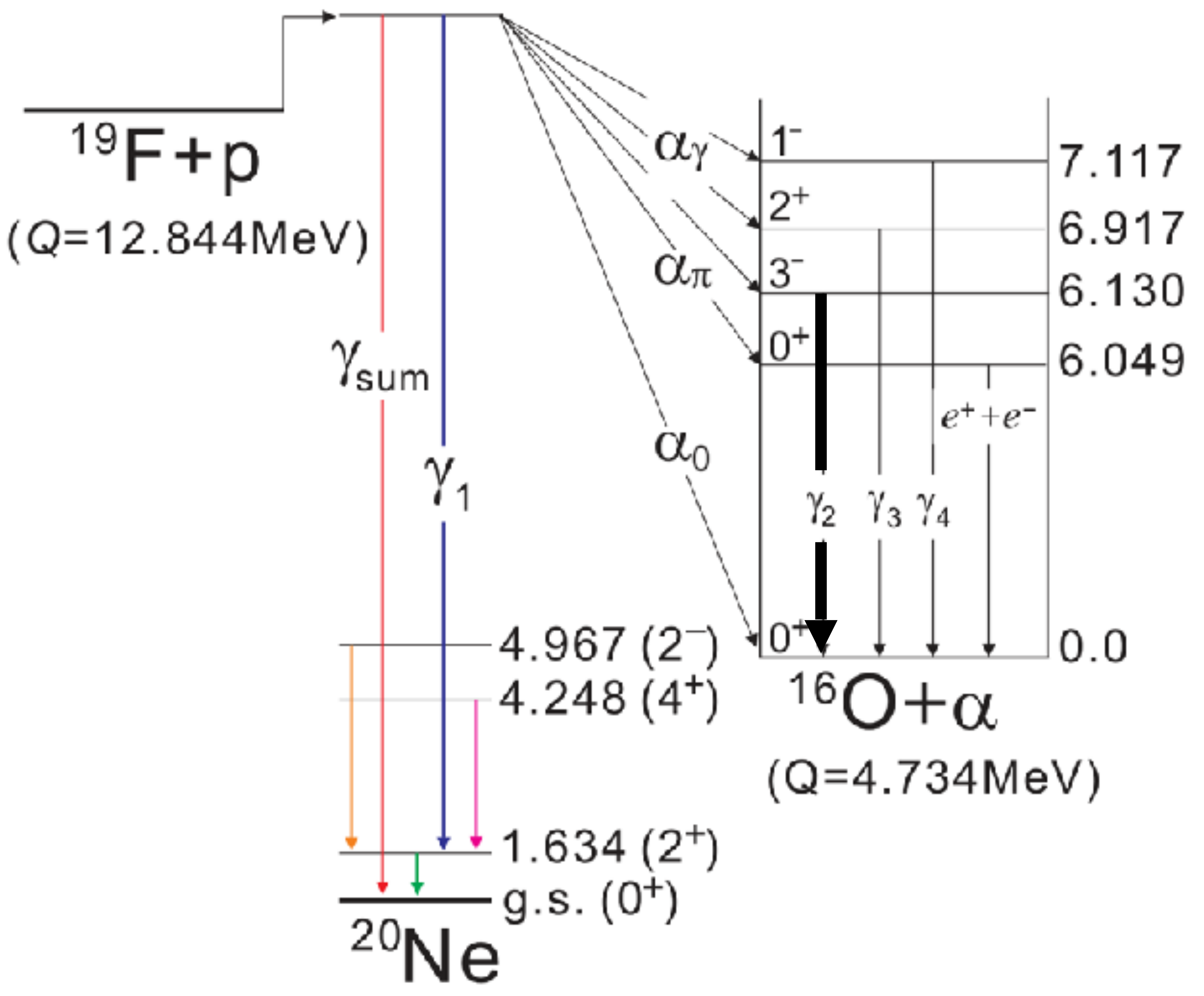


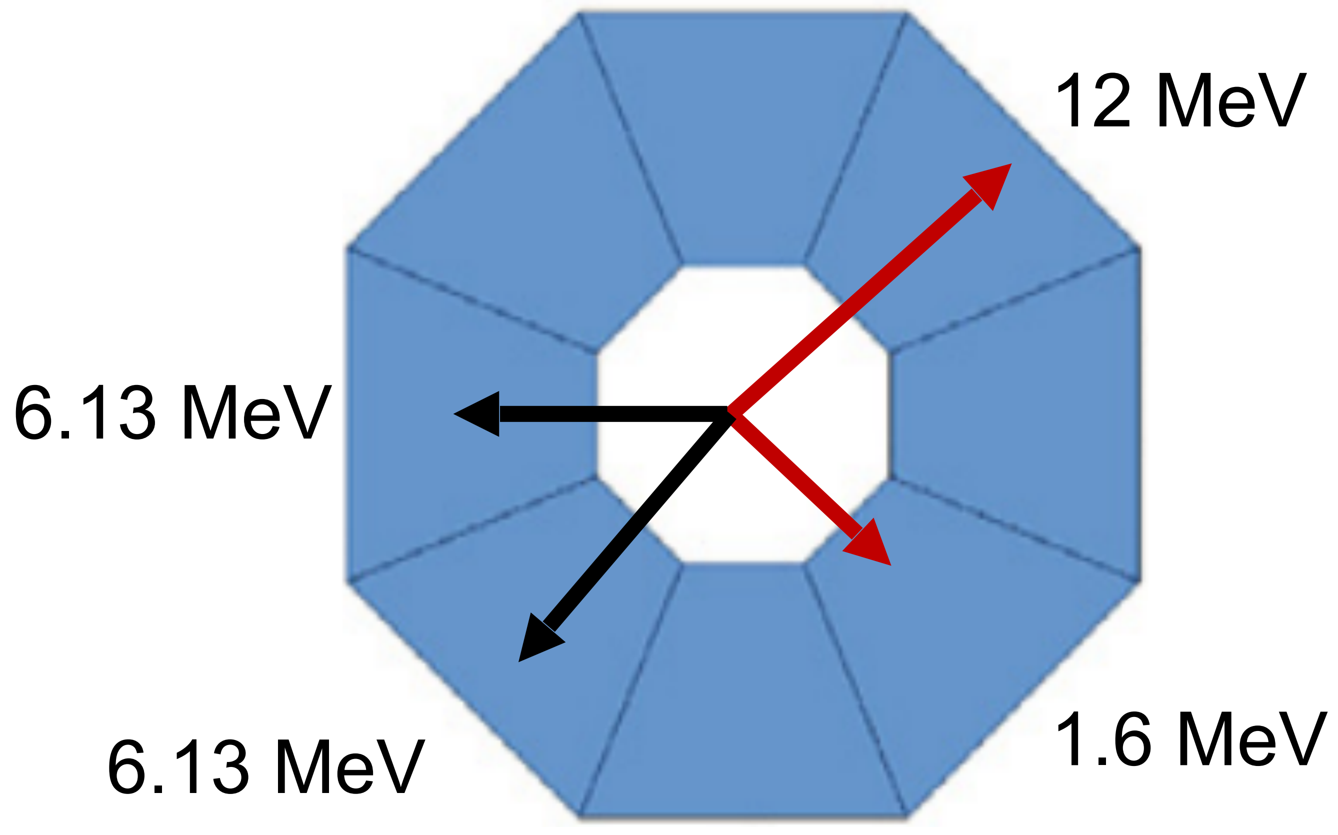


- CJPL-II A1 ultra low cosmic ray
- 2 mA质子束轰击^{19}F靶 high intensity beam, high durability target (200C)
- BGO测量γ射线 sigmented BGO with high efficitency (60%) and resolution (11%)

符合测量方法 coincidence method

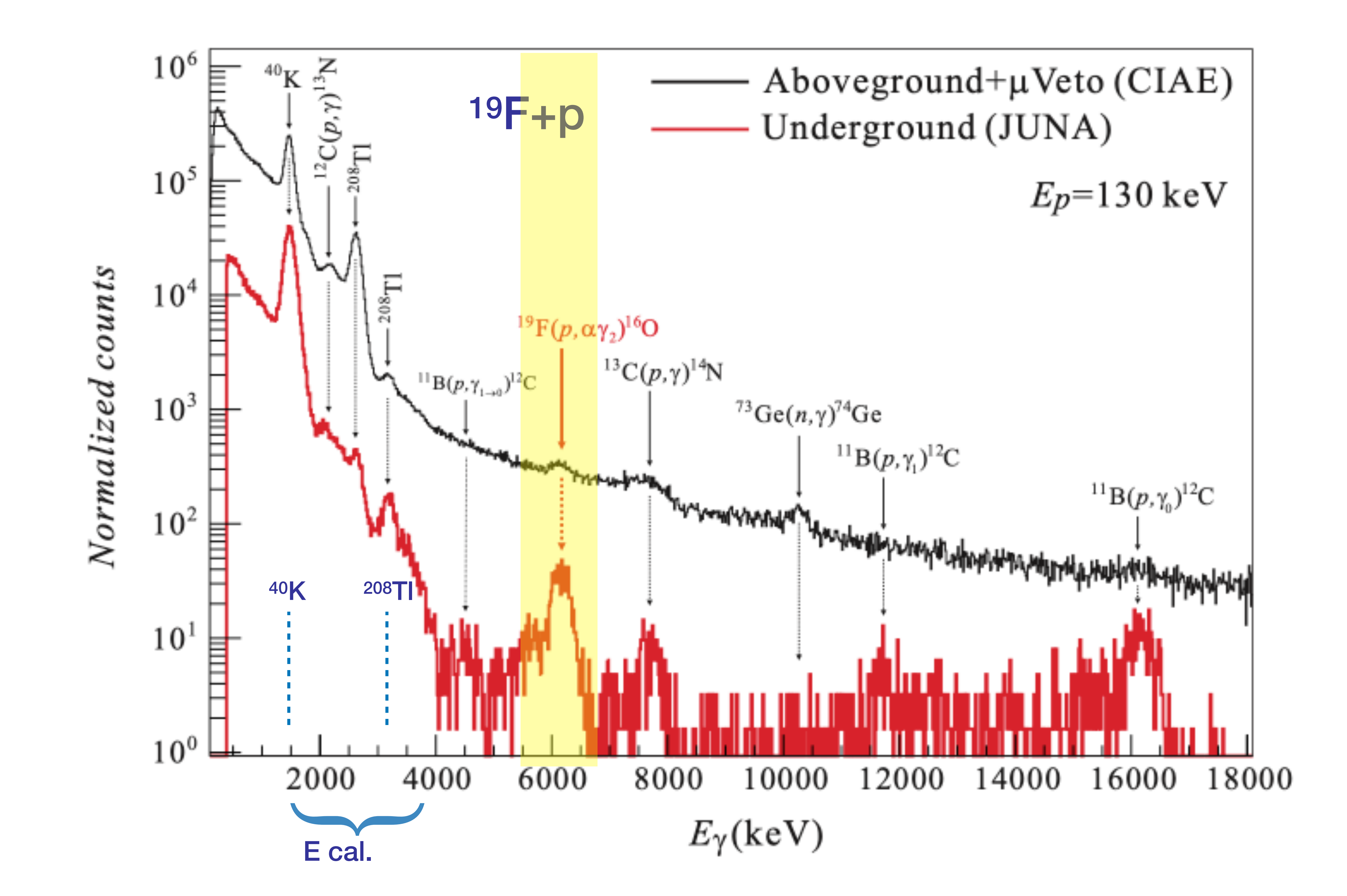


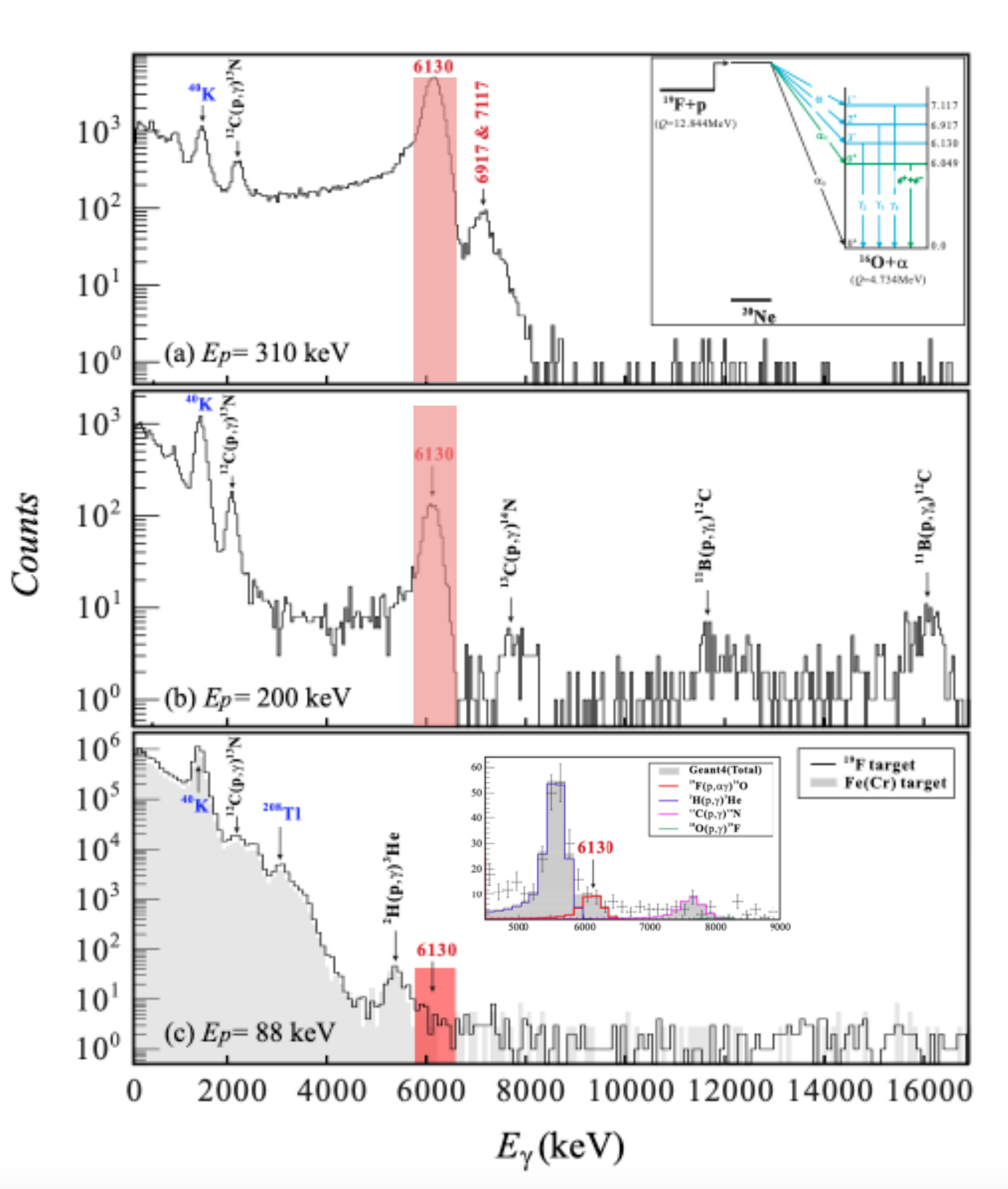




- 通过第一激发态级联衰变
- 单谱与总谱符合测量，降低堆积和本底

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

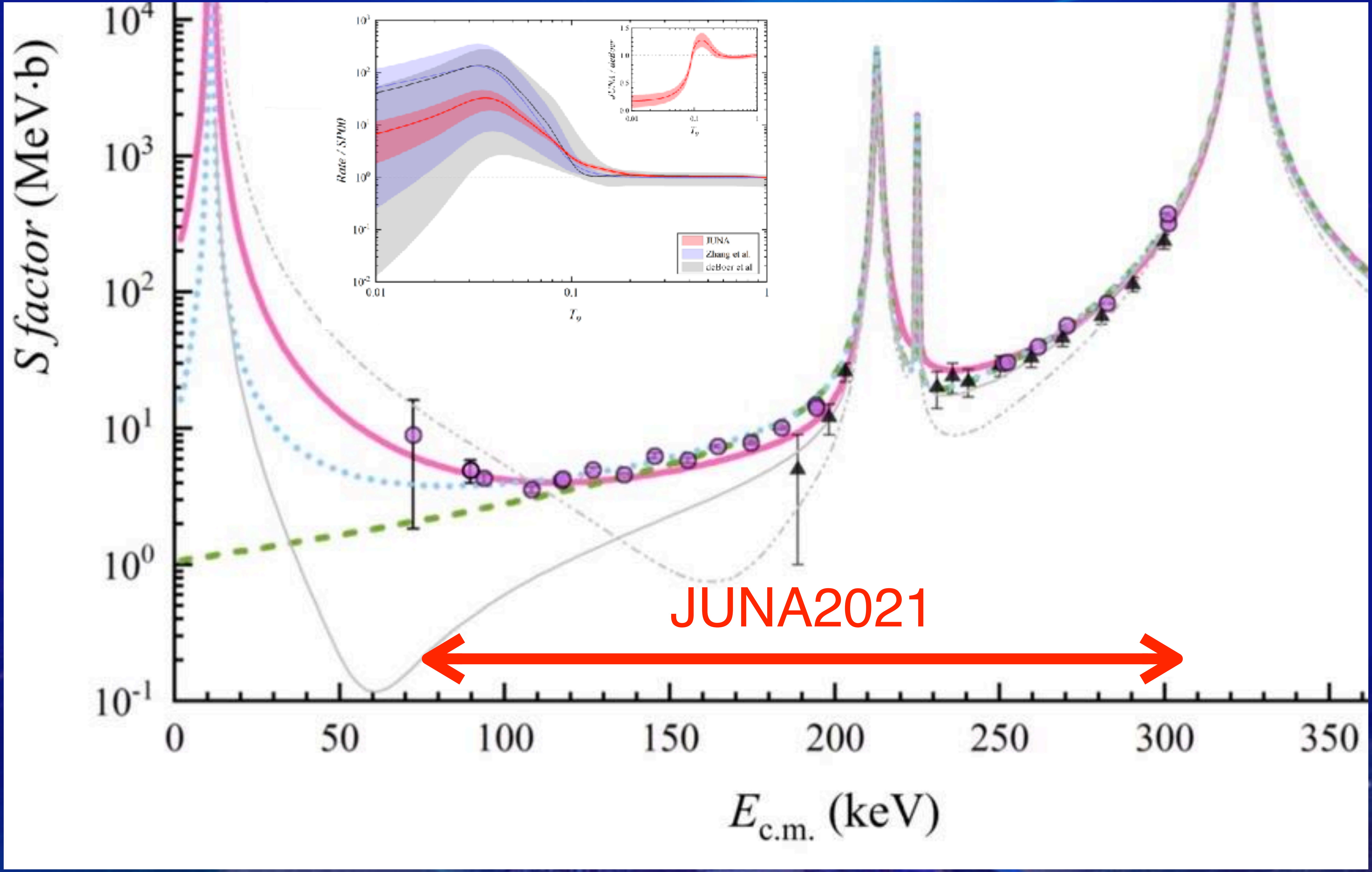




- ^{19}F implatation+ Cr coding， long durabilty with 2 mA
- L.Y. Zhang, Y.J. Chen, J.J. He* et al., Nucl. Instr. Meth. B 496(2021)9

L.Y. Zhang, J. Su, J. J. He*, …, WPL*, $^{19}F(p,\alpha\gamma)^{16}O$, PRL 127(2021)152702. editor suggestions

$^{19}F(p,\alpha\gamma)^{16}O$ reaches Gamow window



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,[2,1] 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,[5] 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,†]

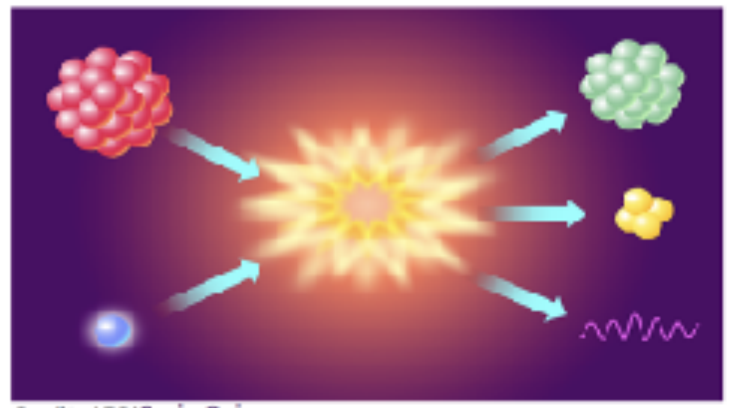
Physics — SYNOPSIS

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 $1.23 \times 10^{-14}\ cm^3 s^{-1} mol^{-1}$ 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.

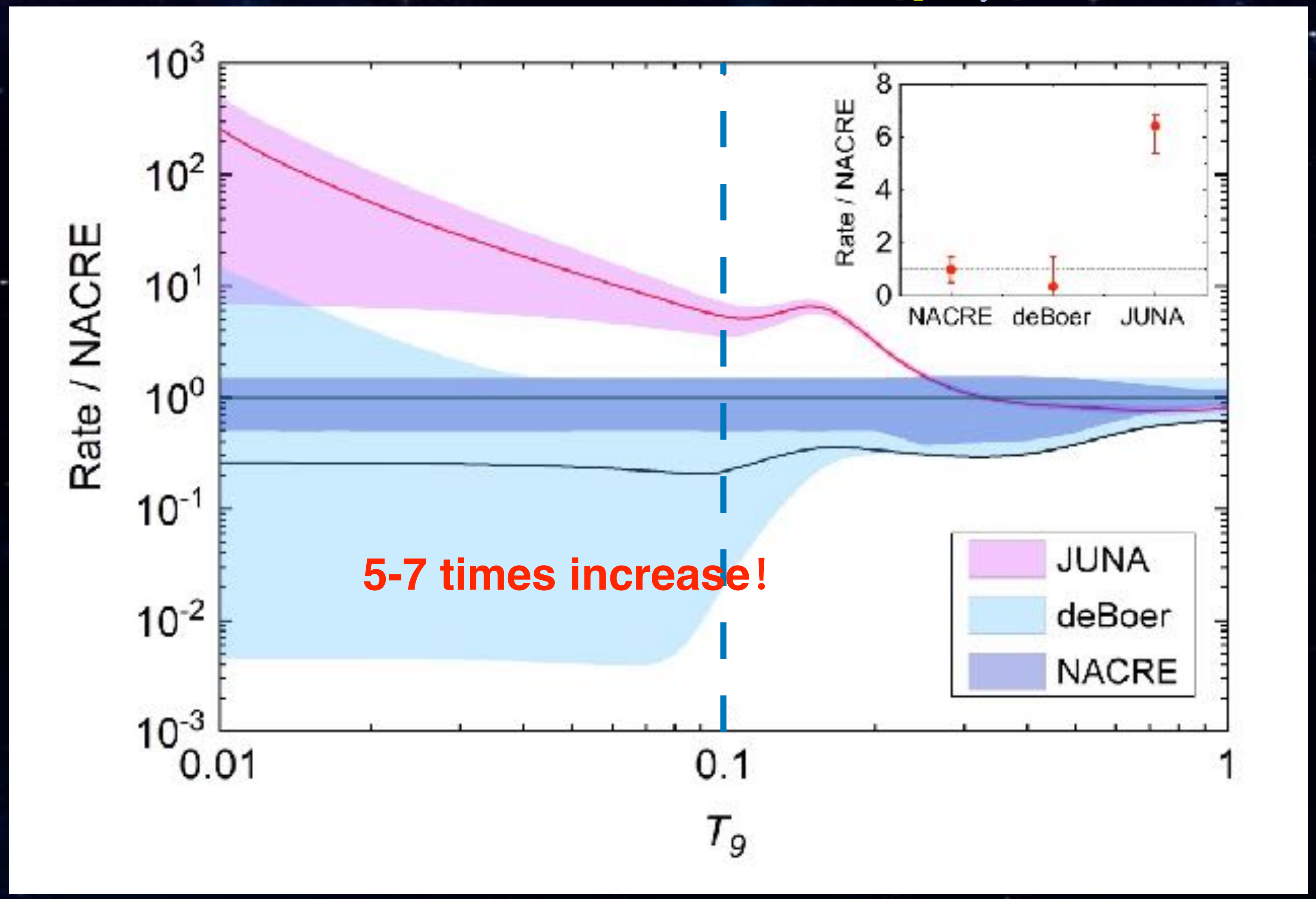
Christopher Crockett is a freelance writer based in Arlington, Virginia.

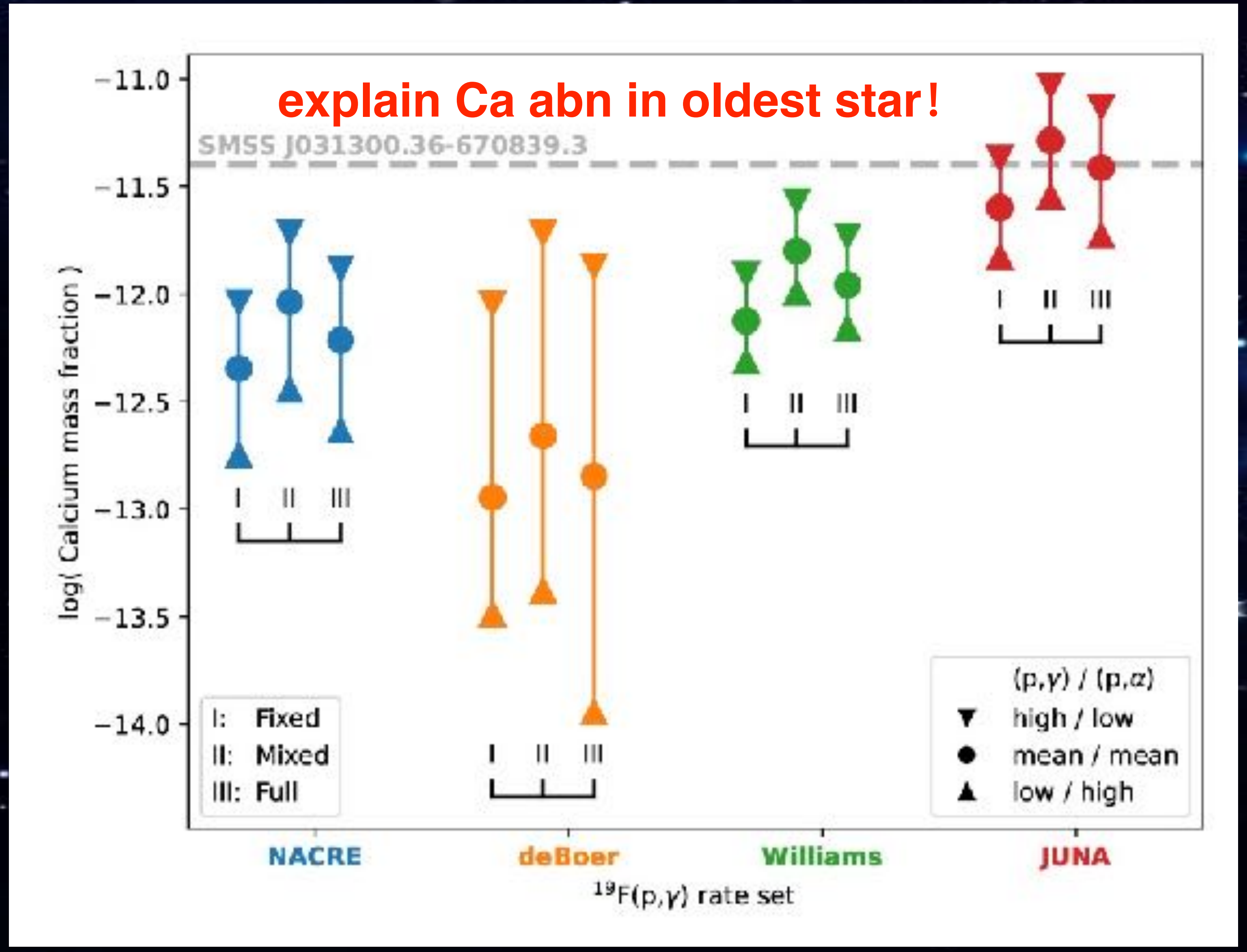
REFERENCES

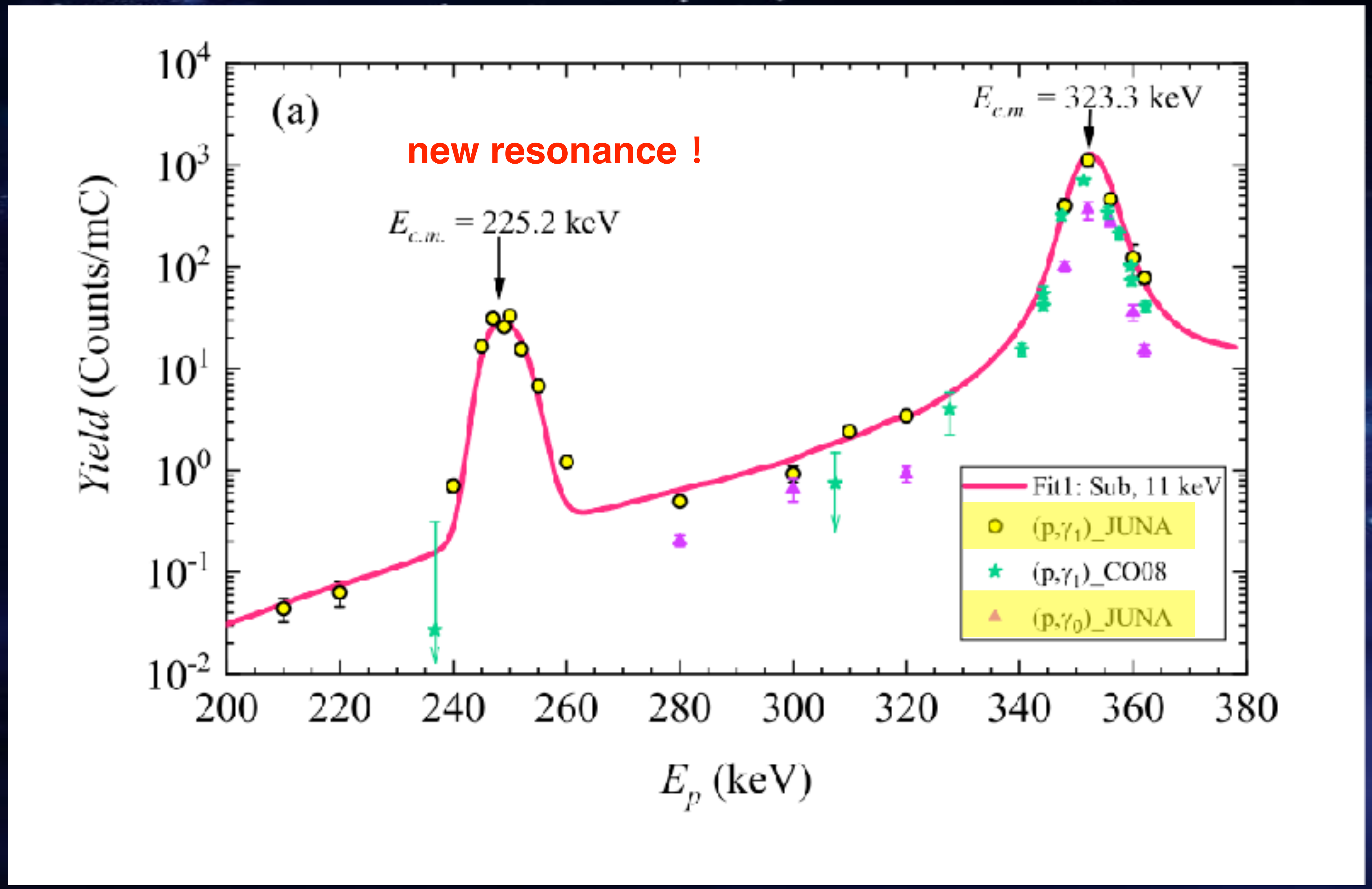
1. L. Y. Zhang *et al.*, "Direct measurement of the astrophysical $^{19}F(p,\alpha\gamma)^{16}O$ reaction in the deepest operational underground laboratory," Phys. Rev. Lett. 127, 152702 (2021).

L.Y. Zhang, J. Su, J. J. He*, …, WPL*, $^{19}F(p,\alpha\gamma)^{16}O$, PRL 127(2021)152702. editor suggestions

New excitement from JUNA $^{19}F(p,\gamma)^{20}Ne$: CNO break out, explain Ca in oldest known star







L. Y. Zhang, J. J. He, …, WPL, Nature 610(2022)656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Article | Published: 26 October 2022

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

Liyong Zhang, Jianjun He, Richard J. deBoer, Michael Wiescher, Alexander Heger, Daid Kahl, Jun Su, Daniel Odell, Yinji Chen, Xinyue Li, Jianguo Wang, Long Zhang, Fuqiang Cao, Hao Zhang, Zhicheng Zhang, Xinzhi Jiang, Luohuan Wang, Ziming Li, Luyang Song, Hongwei Zhao, Liangting Sun, Qi Wu, Jiaqing Li, Baoqun Cui, Lihua Chen, Ruigang Ma, Ertao Li, Gang Lian, Yaode Sheng, Zhihong Li, Bing Guo, Xiaohong Zhou, Yuhu Zhang, Hushan Xu, Jianping Cheng & Weiping Liu

— Show fewer authors

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

Nuclear physics is the reason to explain Ca abundance in oldest known star! And this will help to support more JWST followup results!

国内外学术界的反响和评价

2006诺贝尔物理奖获得者约翰·马瑟John C. Mather：

祝贺你们的新测量，我觉得它们相当重要。

Dear Weiping Liu,

Congratulations on your new measurements; they seem quite important.

All of our JWST public release photos posted at the NASA web sites are available for you and Nature to use for a cover image. For example:
https://www.flickr.com/photos/nasawebbtelescope/

If you wish to observe with the JWST, we expect to announce the next call for proposals in November, and they will be due in January. But stay tuned to our announcements for more details.

I'm cc'ing my NASA email address for further discussions.

Dr. John C. Mather
jmather1@umd.edu

天文学家对产生钙和其他元素的来源感到的困惑，现在可以在深地实验找到解决方案。该实验可以对古老恒星SMSS0313-6708的化学丰度提供解释—这还将对我们对宇宙中其他恒星的理解产生影响。
该工作是JUNA首批实验之一，这些实验已经为模拟宇宙中的恒星提供了宝贵的信息。JUNA实验现在可以达到改进模拟所需的精度并将它们与天文观测进行比较，这一事实表明，对于探索宇宙中恒星的演化来说，确实是一个激动人心的时代。

我们工作被Nature选为亮点文章，平均10篇Nature文章中才会有1篇入选，为此Nature组织科学家对成果进行介绍，在同期Nature上的”News and Views"上发表

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NEWS AND VIEWS | 26 October 2022

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

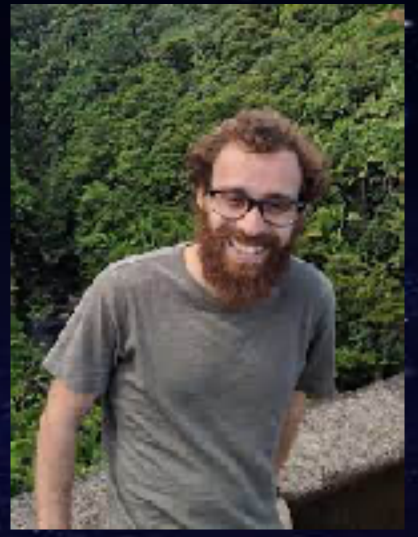
Nuclear-fusion experiments performed deep under Earth's surface reveal one possible scenario that could have resulted in the chemical abundances found in an ancient star in the Milky Way.

Marco Pignatari & Athanasios Psaltis

When the first stars in the Milky Way formed around 13 billion years ago, they consisted mainly of hydrogen and helium. But other chemical elements – the heaviest being calcium – have been detected in the atmosphere of one of the oldest-known stars, an amazing object known as SMSS0313-6708 that lies just 1,800 parsecs from Earth[1]. Astronomers and astrophysicists were puzzled, and started to look for ways in which calcium and the other elements could have been made. The solution, it seems, might be found under Earth's surface. In a paper in *Nature*, Zhang *et al.*[2] report nuclear-physics experiments that could support one explanation for the chemical abundances found in SMSS0313-6708 – with implications for our understanding of other stars in the Universe.

Zhang and colleagues' work was one of the first experiments planned for JUNA[15]. Such underground nuclear laboratories are already producing invaluable information for researchers simulating stars in the cosmos. The fact that these experiments can now achieve the precision necessary to improve the simulations and compare them with astronomical observations shows that this is an exciting era indeed for probing the evolution of stars in the Universe.

Marco Pignatari



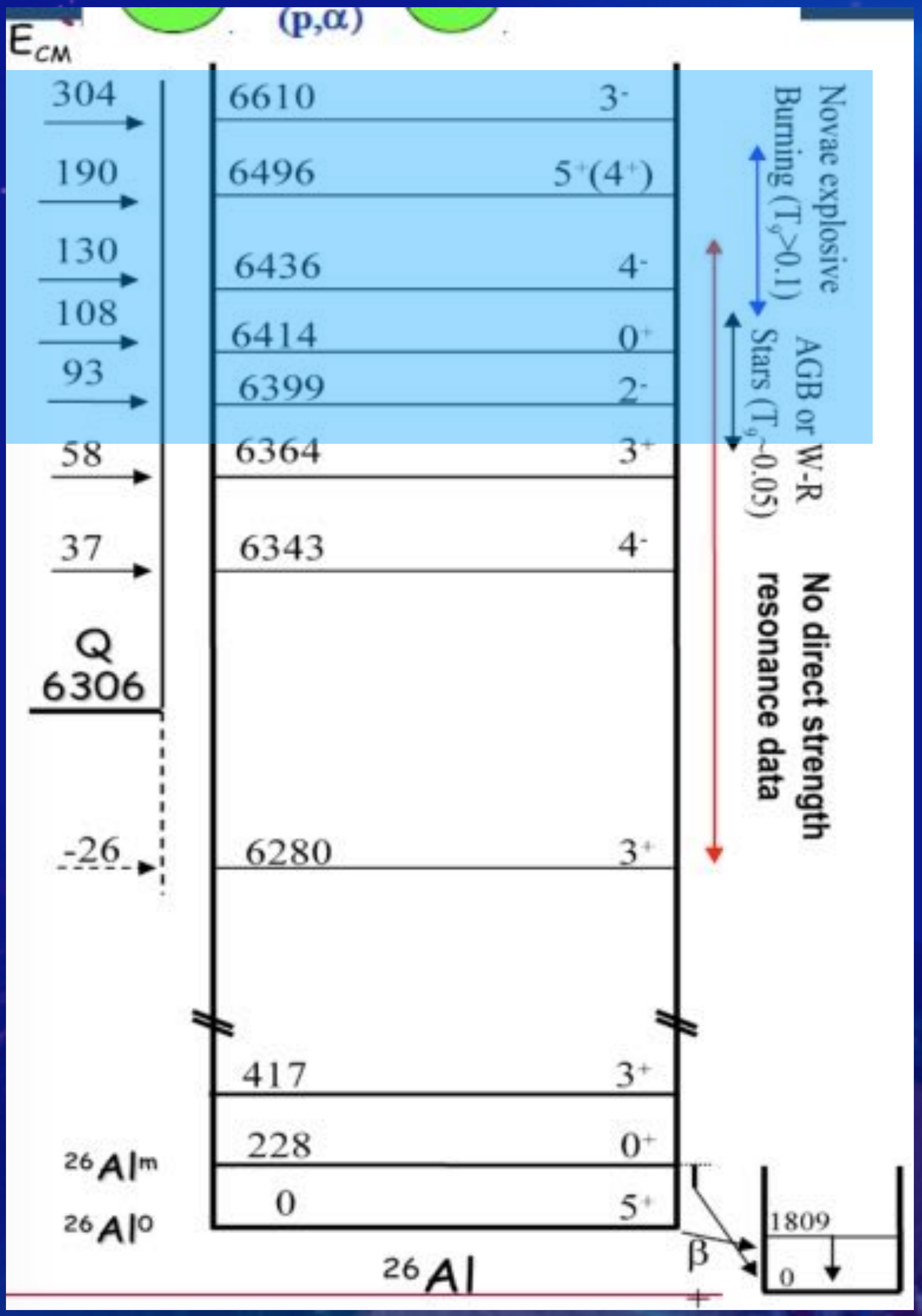
Athanaiscs. Psalits

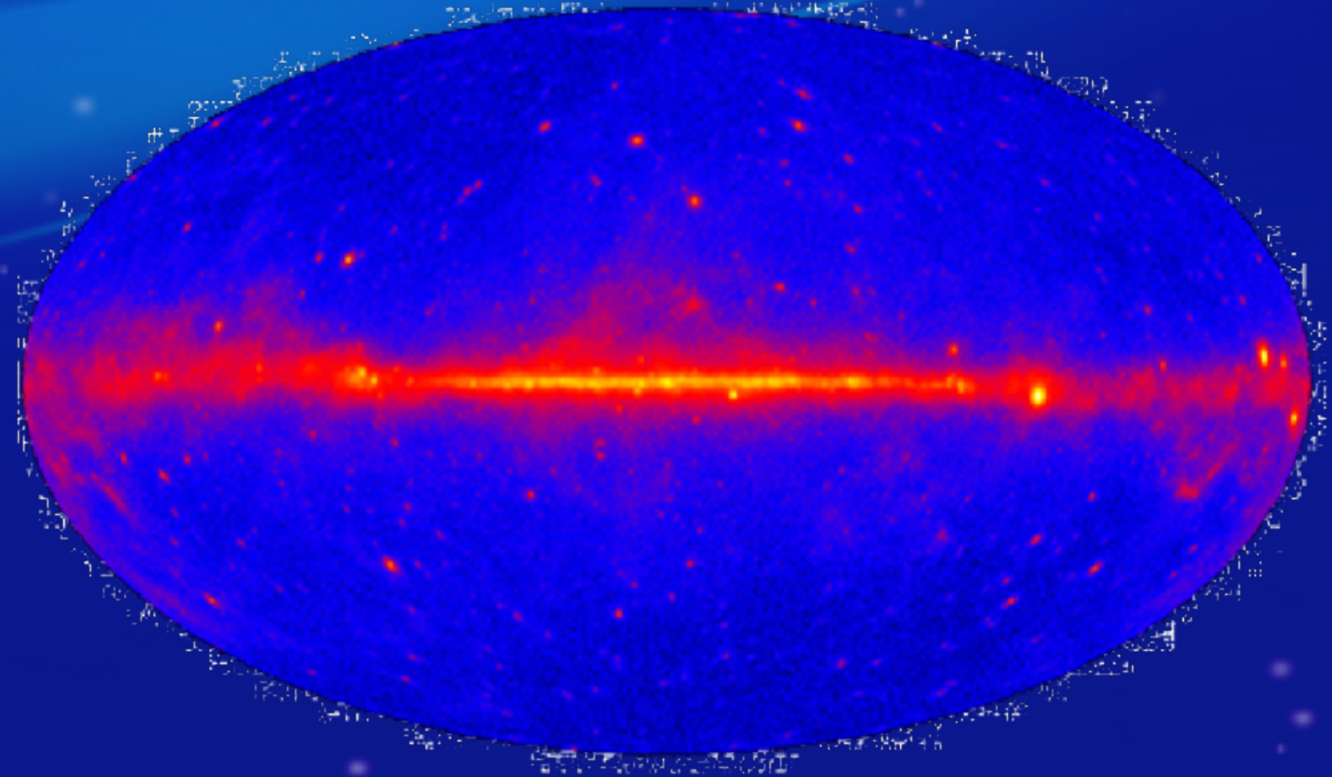
$^{25}Mg(p,\gamma)^{26}Al$ physics 伽马天文反应

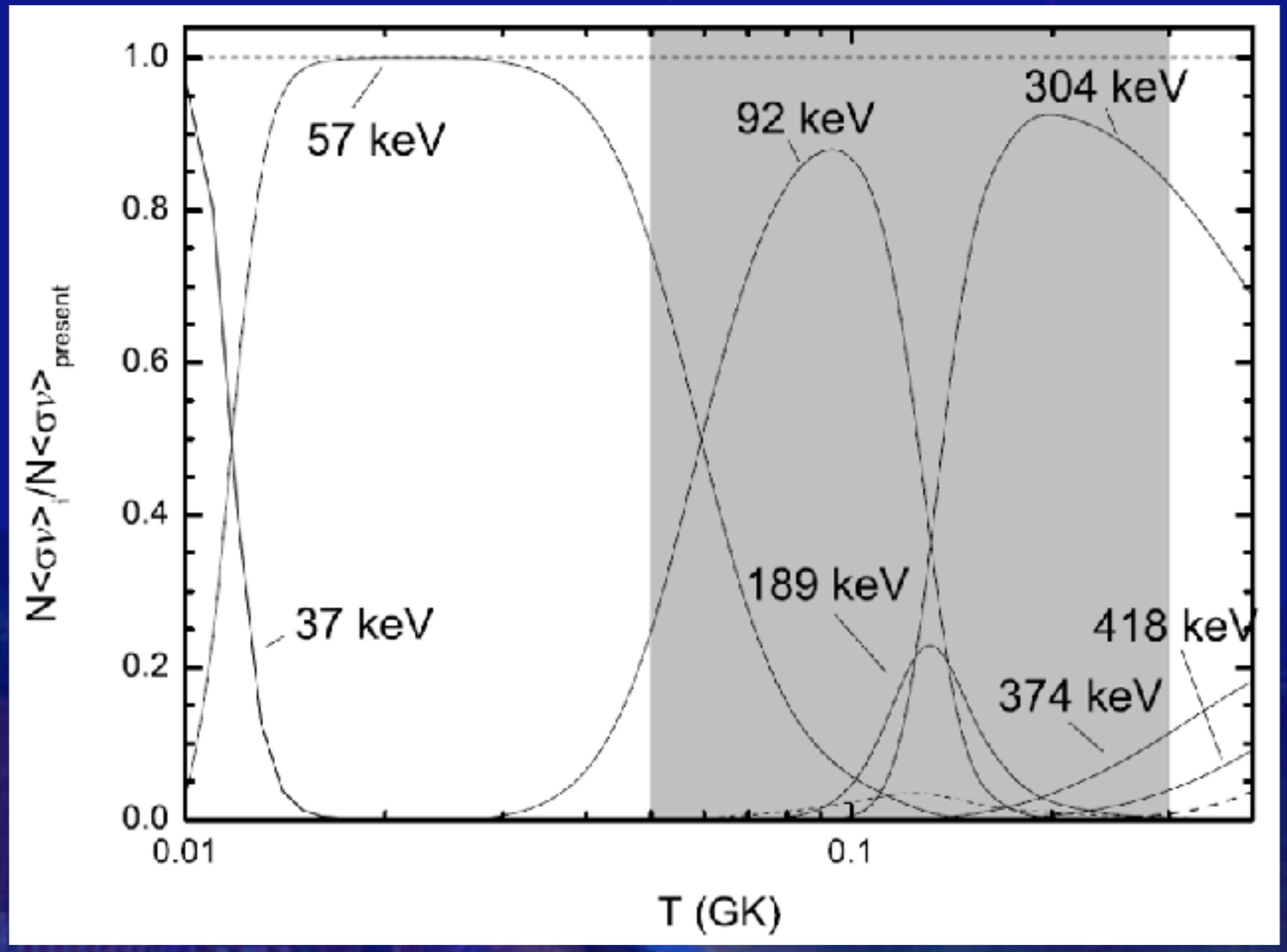
PI: Z. H. Li, CIAE

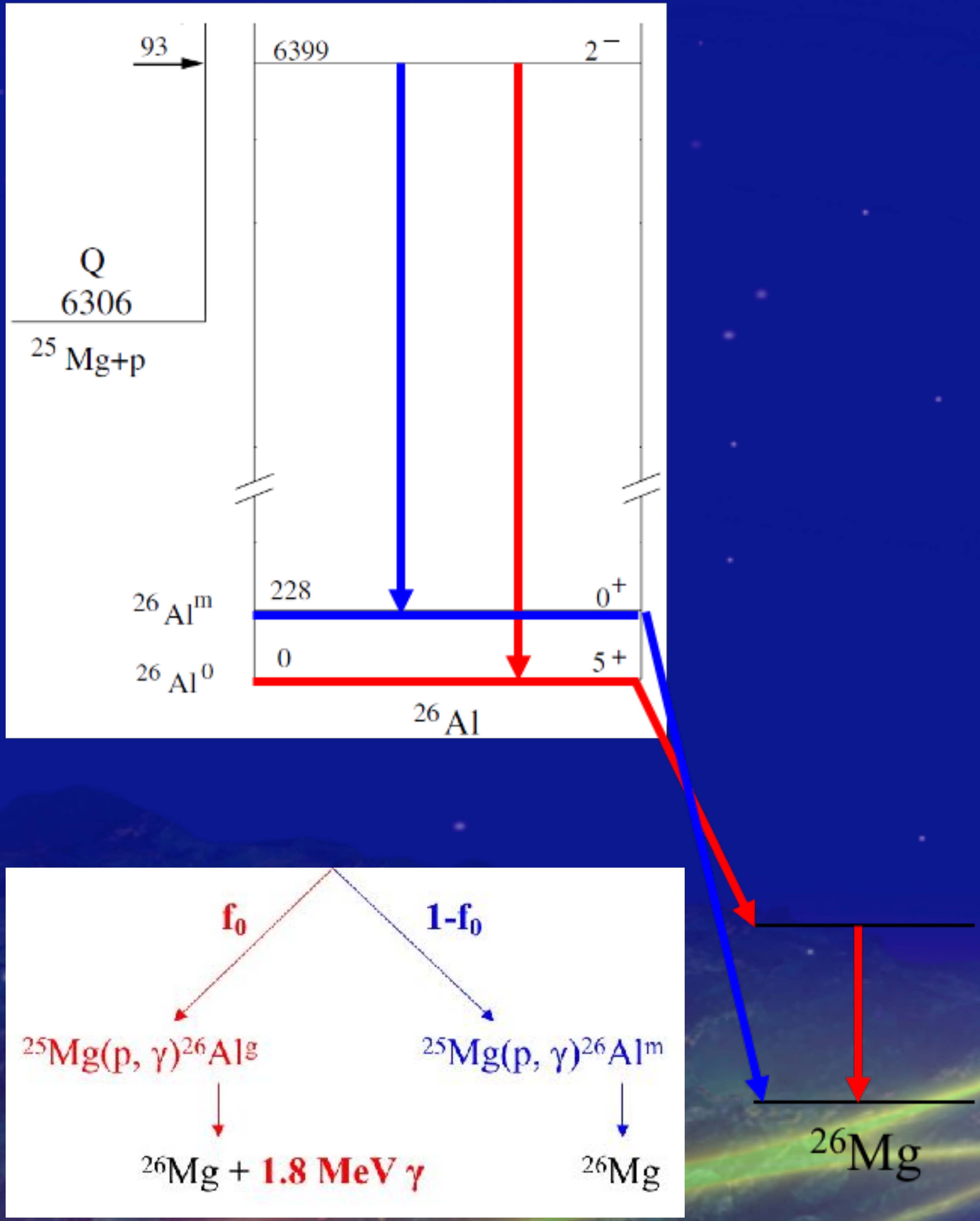
J. Su, CIAE/BNU

Exp.: Jan. 1-15, 2021





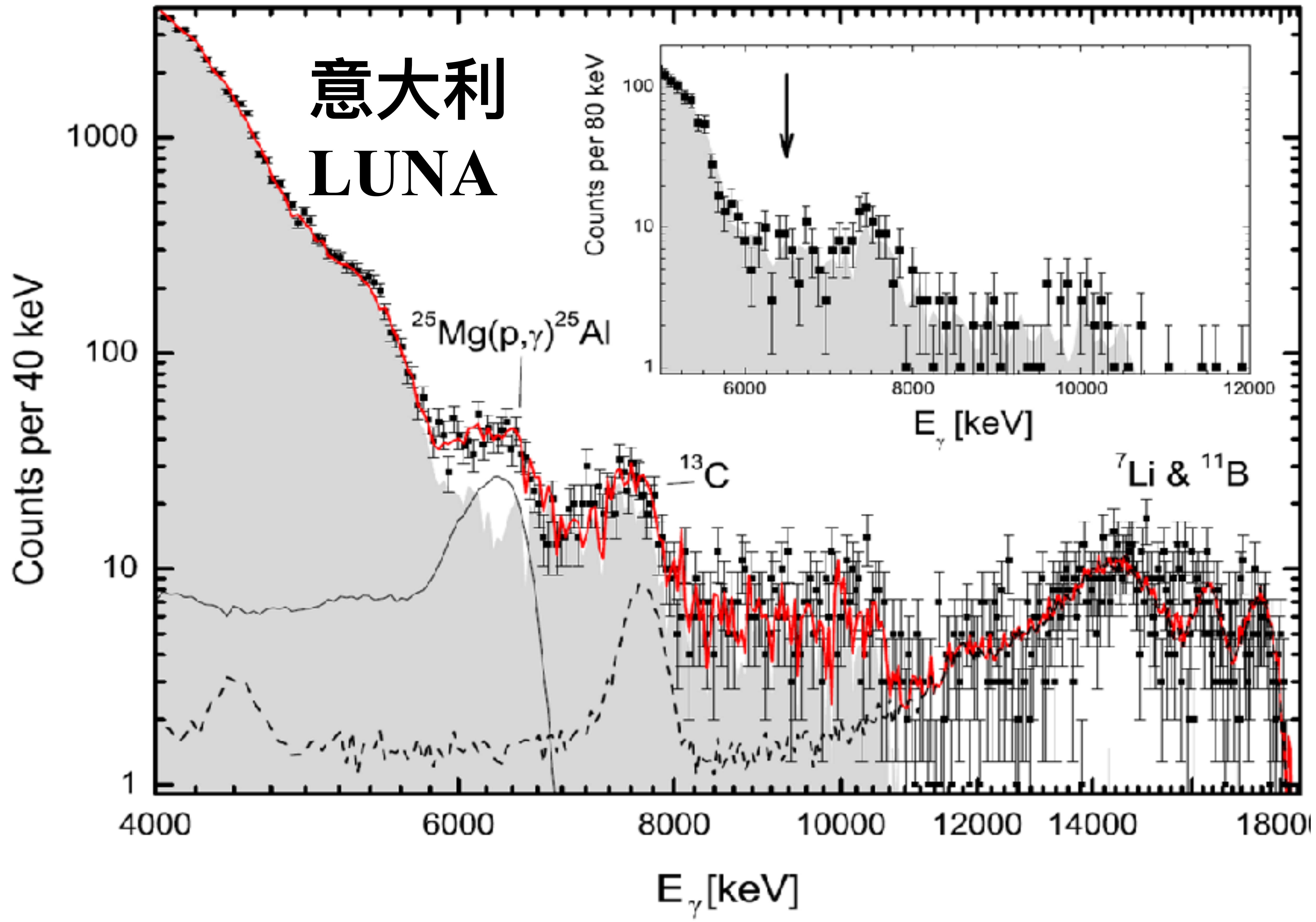


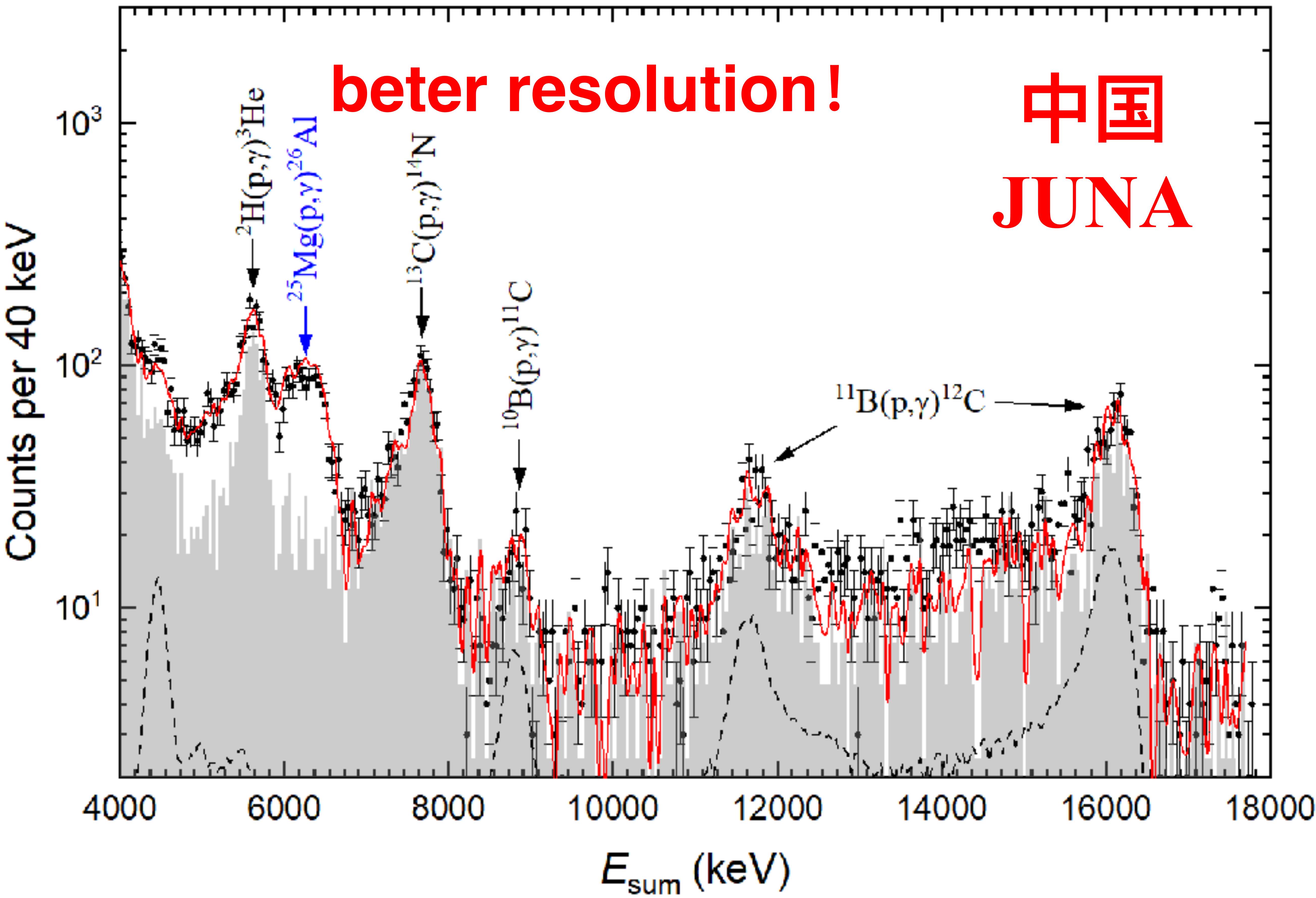


Z. H. Li et al., Sci. China Phys 58. 082002(2015), J. Su et al., Science Bulletin, 67(2022)2（封面文章）

中核集团 中国原子能科学研究院 China Institute of Atomic Energy

JUNA vs. LUNA





52 days (S+N)， 370 C

signal： 410

strength： 2.9±0.6×10^{-10} eV

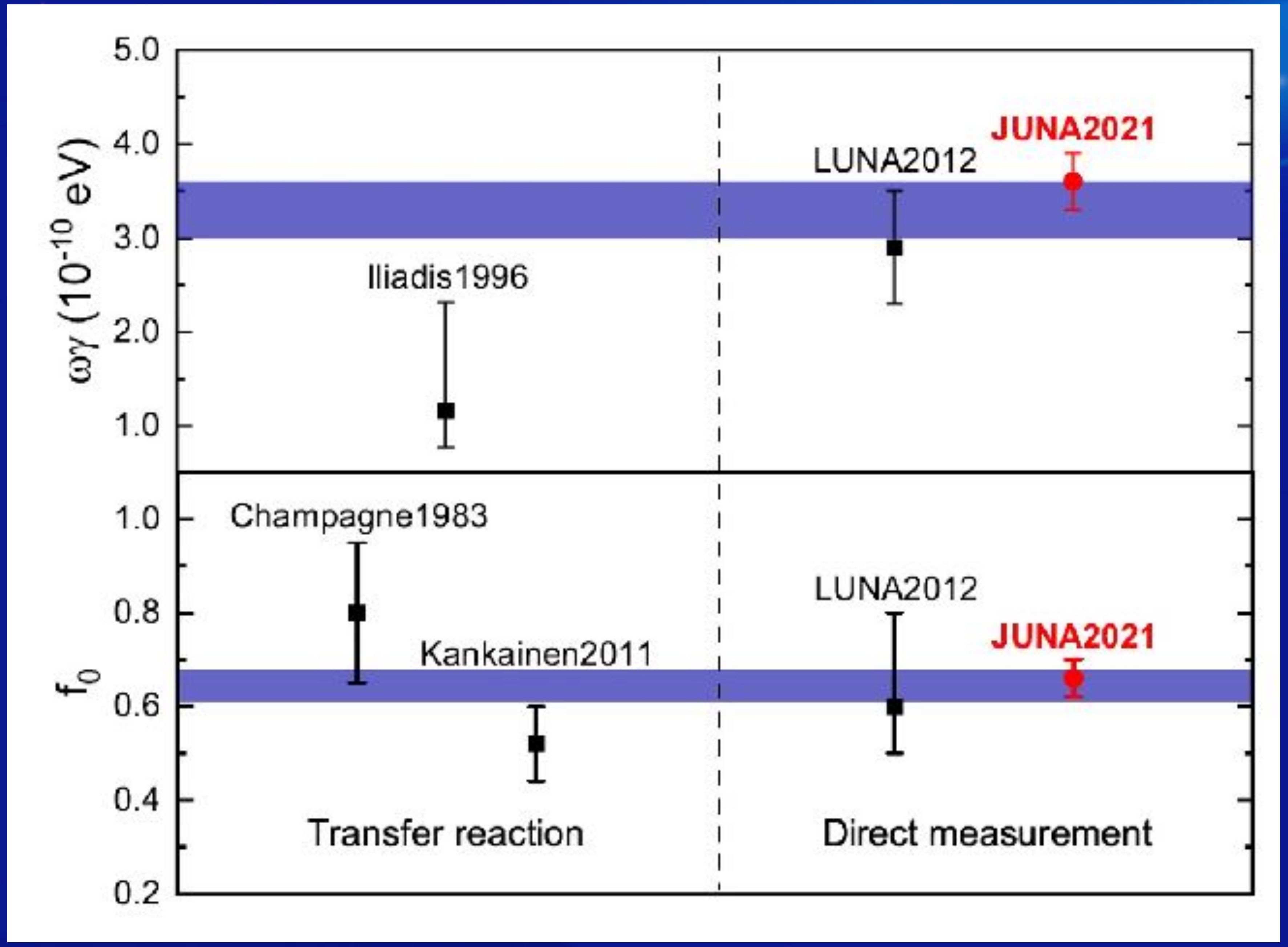
15days(S+N)， 1008 C

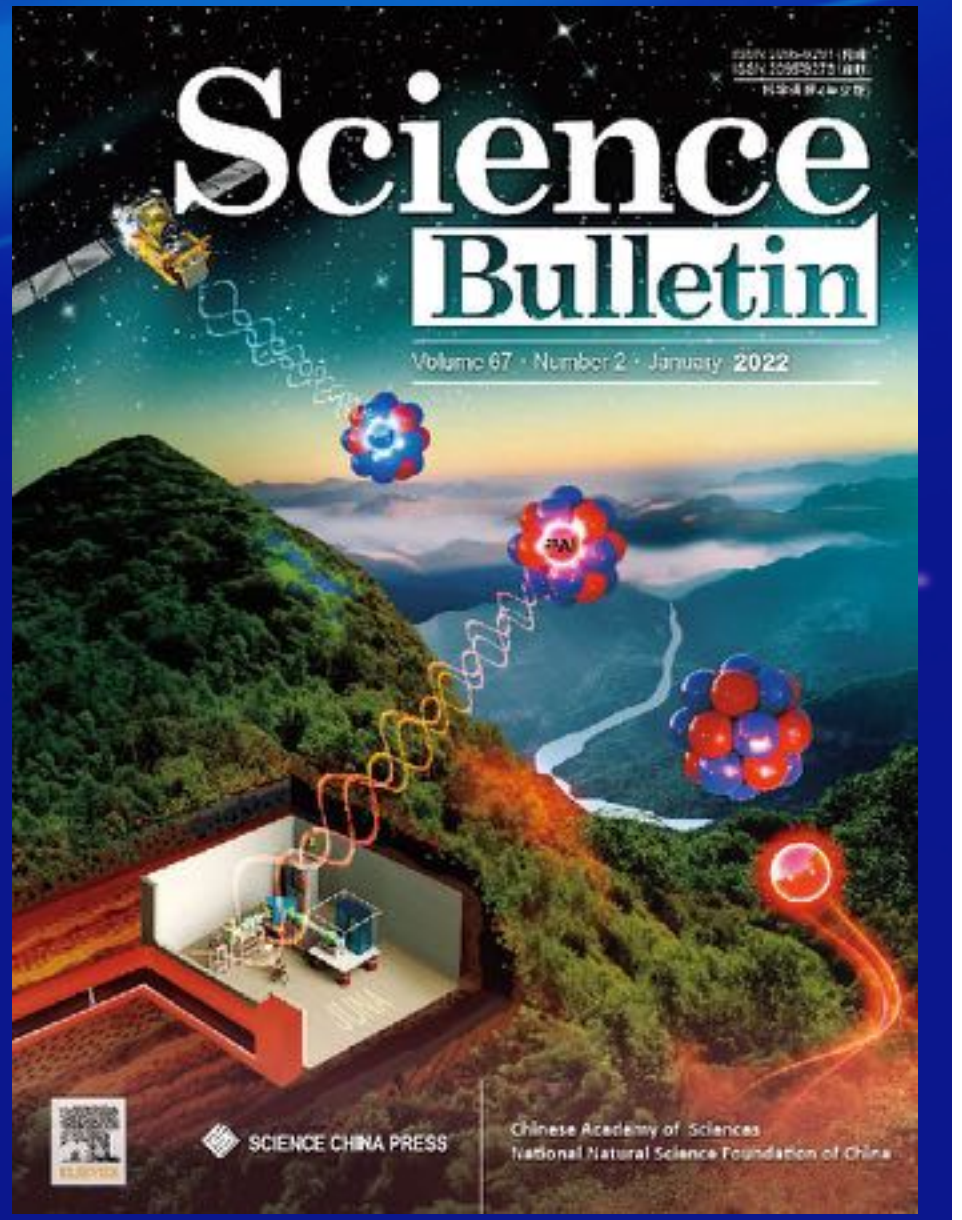
signal： 1225

strength： 3.8±0.4×10^{-10} eV

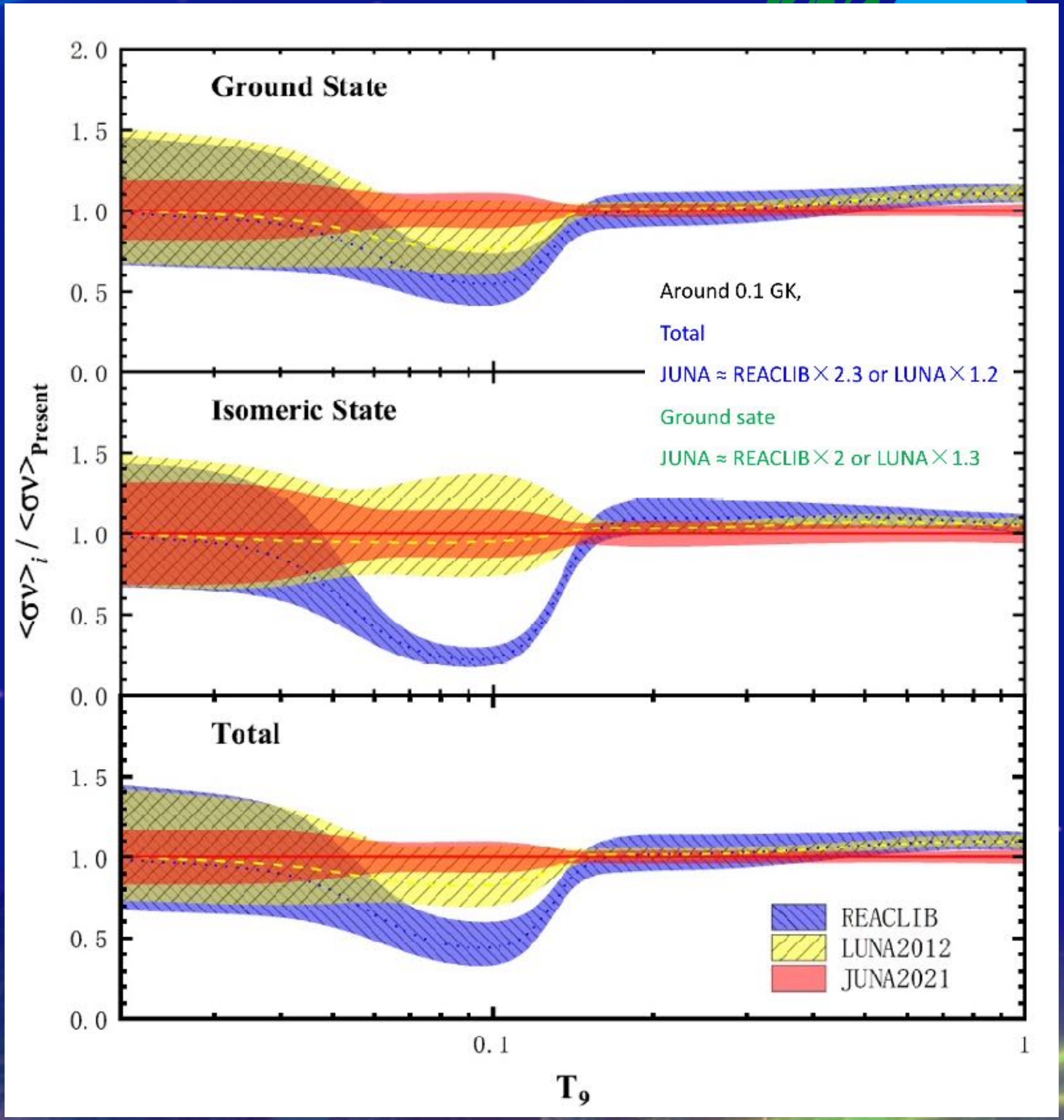
J. Su, Z. H. Li*,…., WPL*, Science Bulletin, 67(2022)2, cover paper

Results and implication 最精确





IF>20



BRIF in-direct

Y. J. Li, Z. H. Li, E. T. Li, X. Y. Li, T. L. Ma, Y. P. Shen, J. C. Liu, L. Gan, Y. Su, L.-H. Qiao, *et al.*, Phys. Rev. C **102**, 025804 (2020).

E_x (keV)[a]	$\omega\gamma$ (eV)	f_0
37.1 ± 0.1	$(4.5 \pm 1.8) \times 10^{-22}$[b]	0.79 ± 0.05[b]
57.7 ± 0.1	$(2.9 \pm 0.5) \times 10^{-13}$[c]	0.81 ± 0.05[b]
92.1 ± 0.2	$(3.8 \pm 0.3) \times 10^{-10}$[d]	0.66 ± 0.04[d]
189.6 ± 0.1	$(9.0 \pm 0.6) \times 10^{-7}$[b]	0.75 ± 0.02[b]
304.1 ± 0.1	$(3.1 \pm 0.1) \times 10^{-2}$[e]	0.859 ± 0.01[e]

JUNA underground

JUNA ground

J. Su, Z. H. Li*,…., WPL*, Science Bulletin, 67(2022)2,cover paper

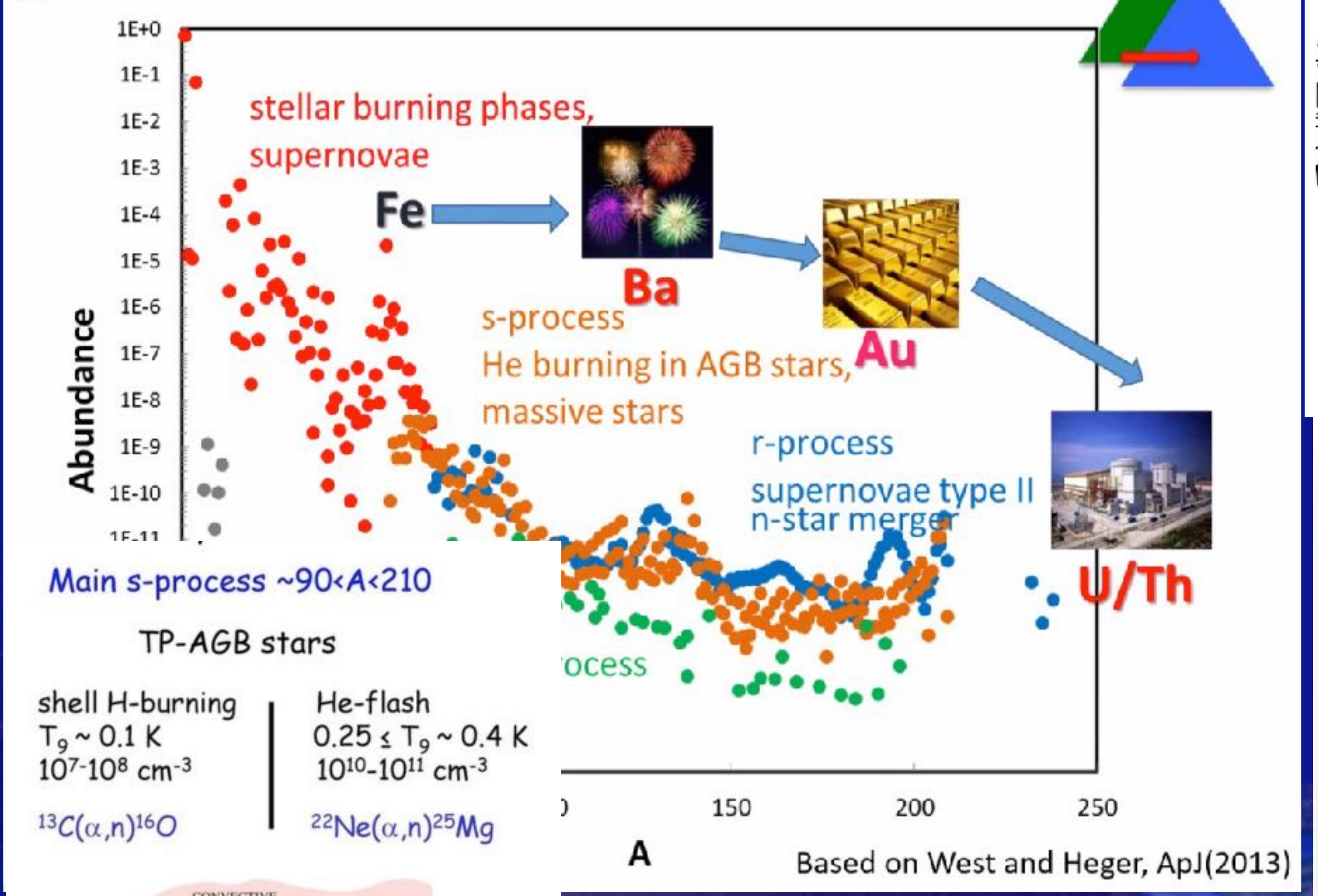
$^{13}C(a,n)^{16}O$中子源反应 neutron source reaction

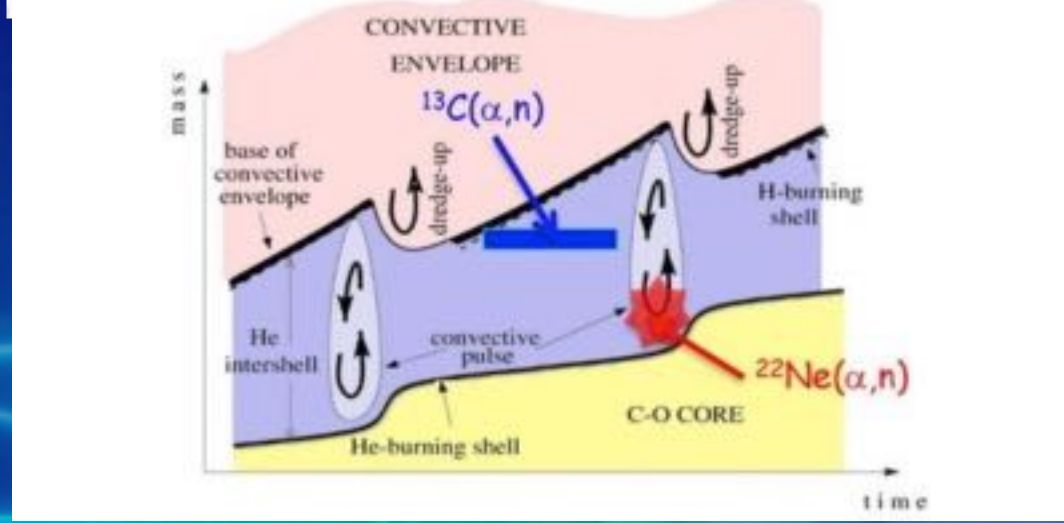
PI: X. D. Tang, IMP

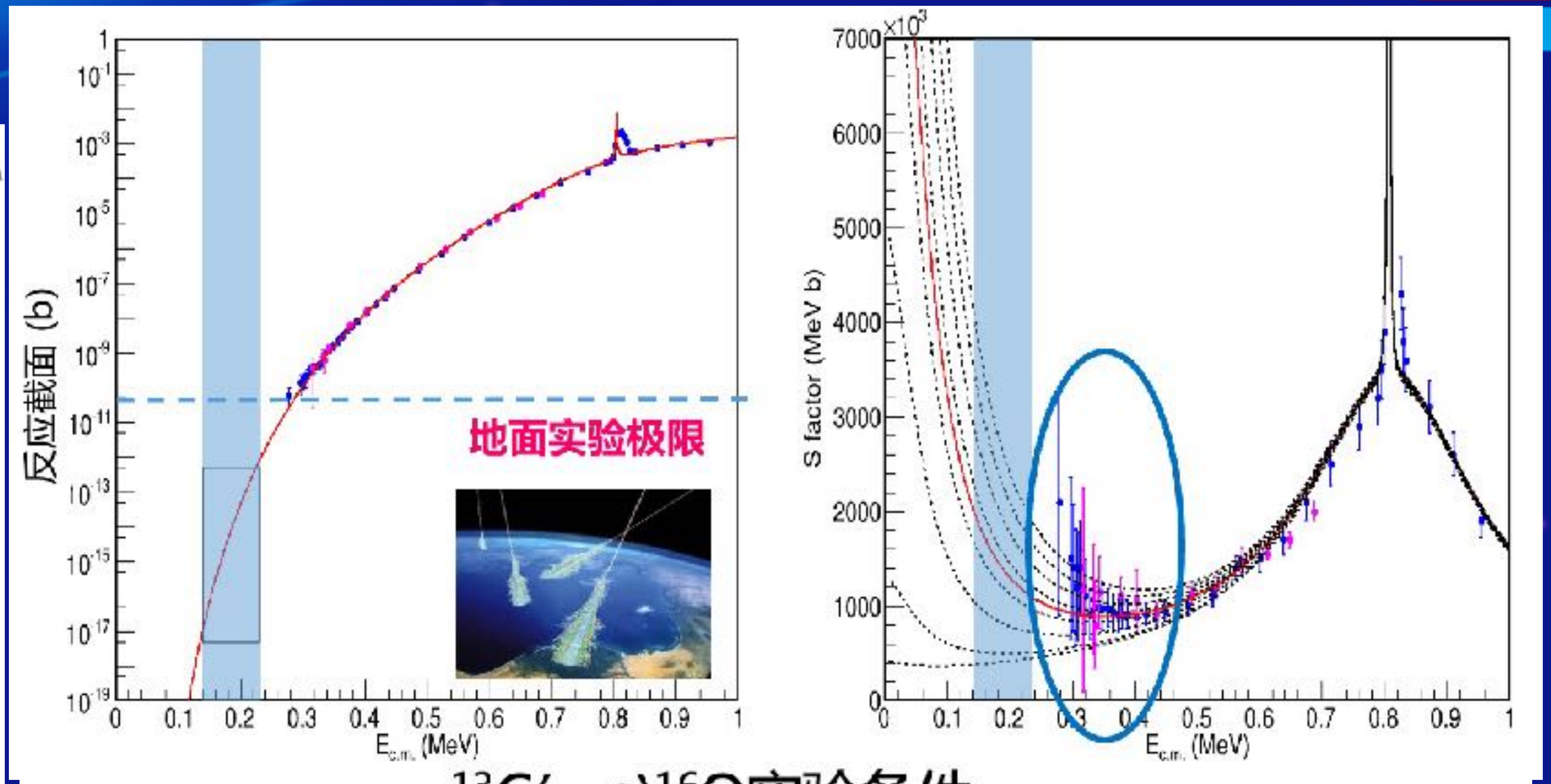
B. Gao, IMP

Exp.: Jan. 27-Feb. 16, 2021

Origin of Heavy elements







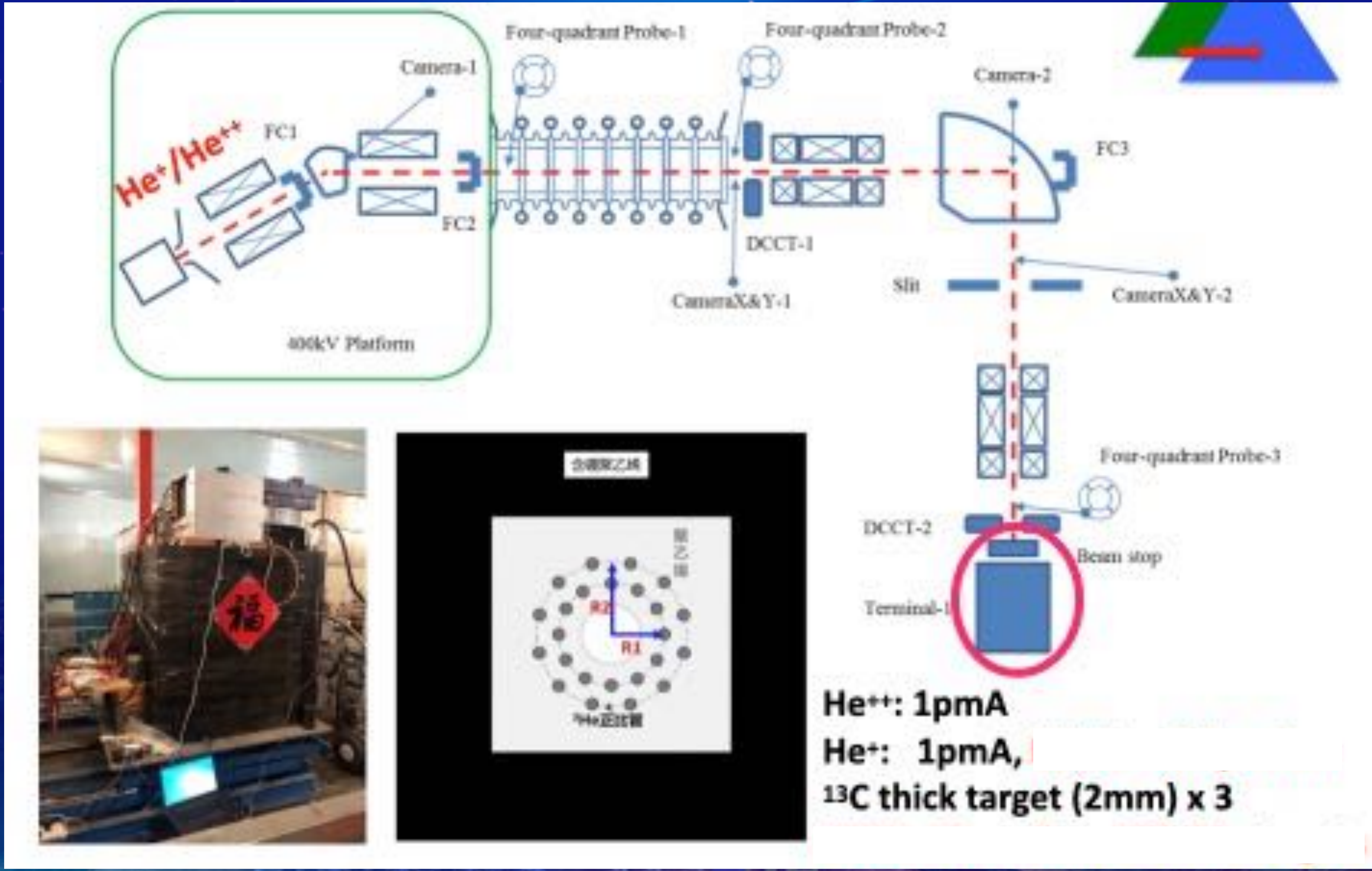
$^{13}C(\alpha,n)^{16}O$实验条件

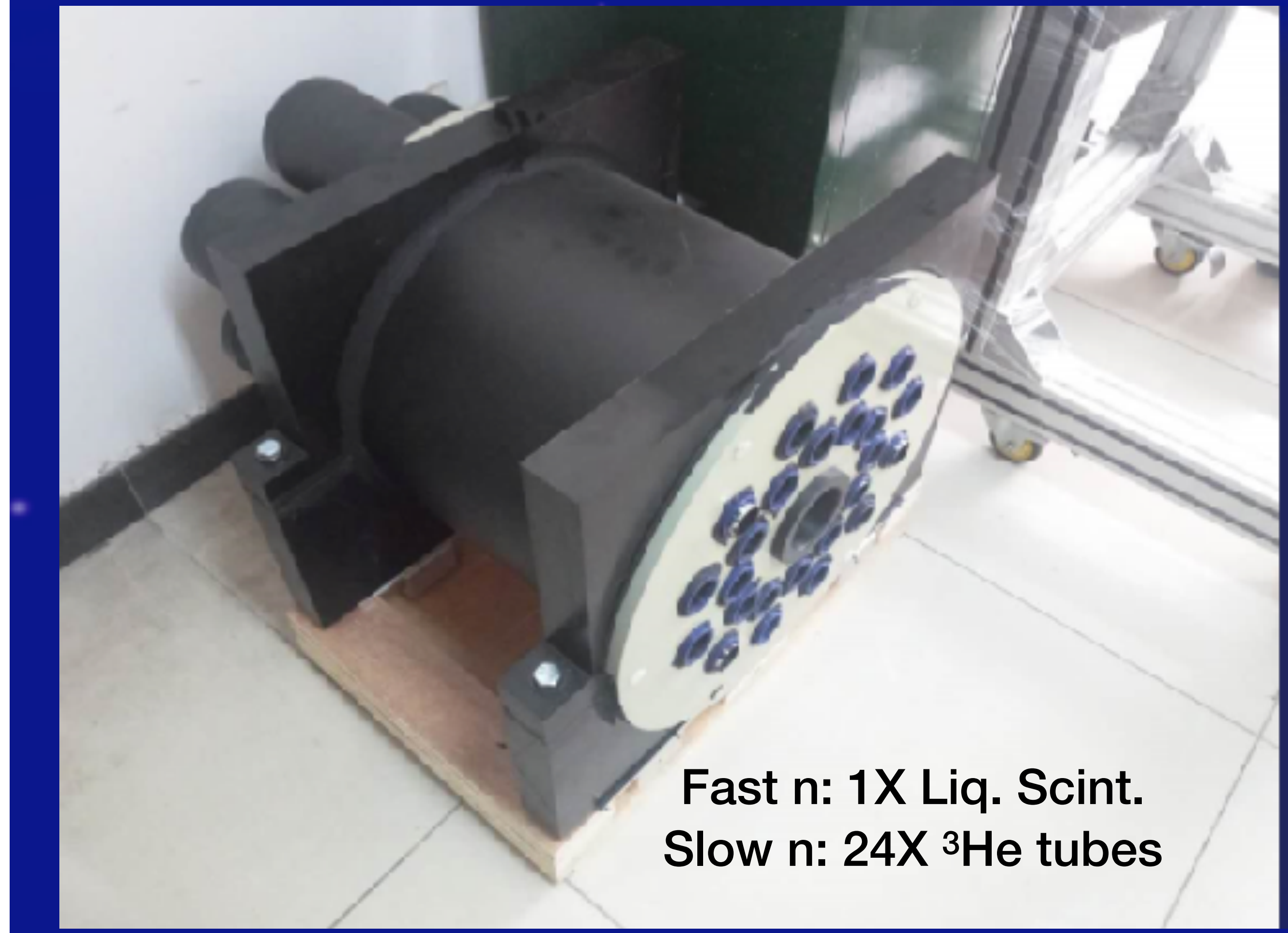
指标	LUNA (意大利)	JUNA (中国)
束流强度 beam (粒子毫安)	~0.15	~2
靶数目 target	>100	3
能区 (MeV) energy	0.23-0.31	0.24-1.2
束流时间（天）	240	14

流强优势、高功率厚靶技术、低本底多电荷态离子源使我们用更短时间（1/17的时间），在更宽的能区（0.24-1.2 MeV）提供基准数据

B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(α,n)^{16}O$, PRL 129(2022)132701

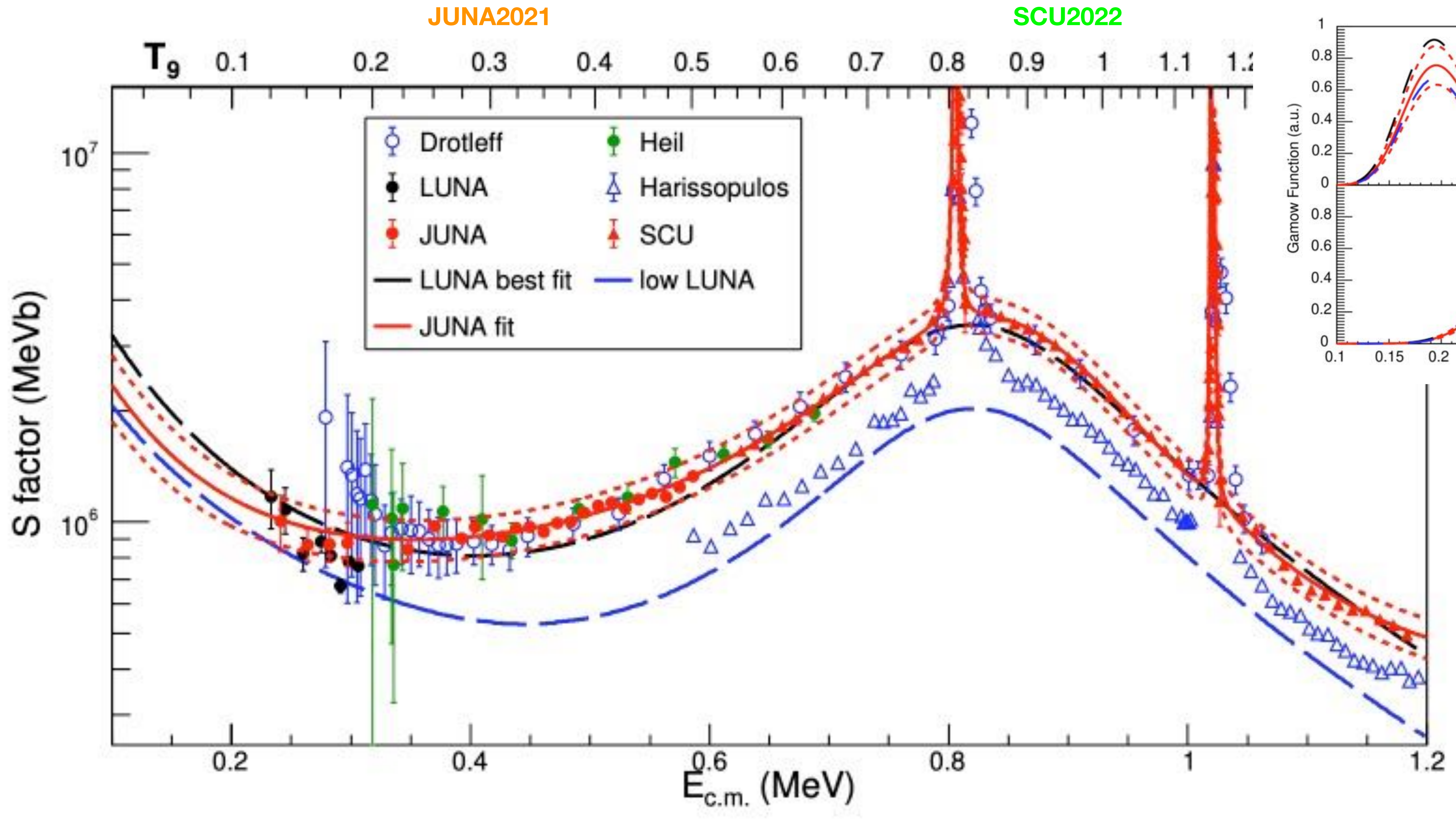
$^{13}C(\alpha,n)^{16}O$ status

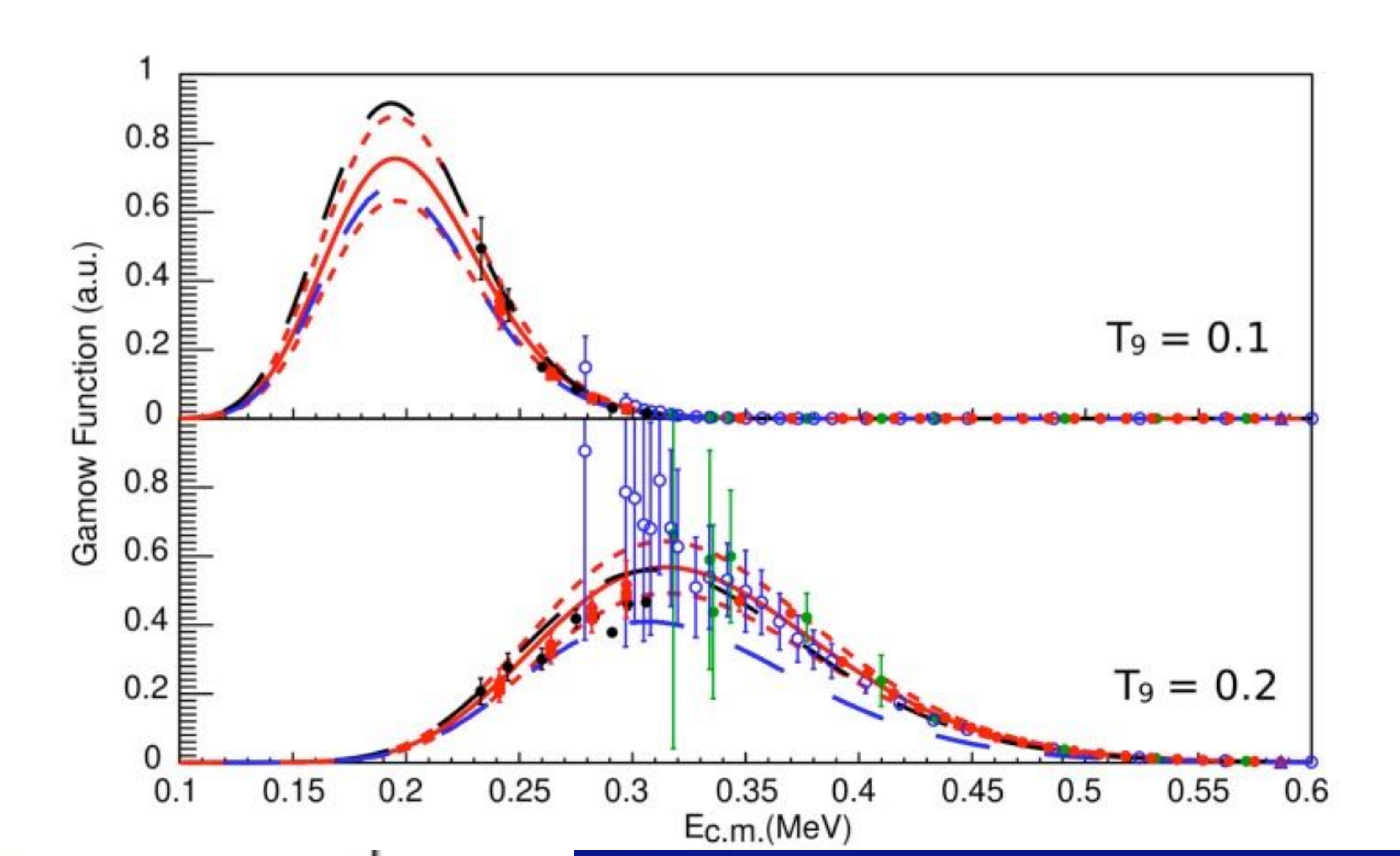




B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(\alpha,n)^{16}O$, PRL 129(2022)132701

$^{13}C(\alpha,n)^{16}O$: solve the uncertainty

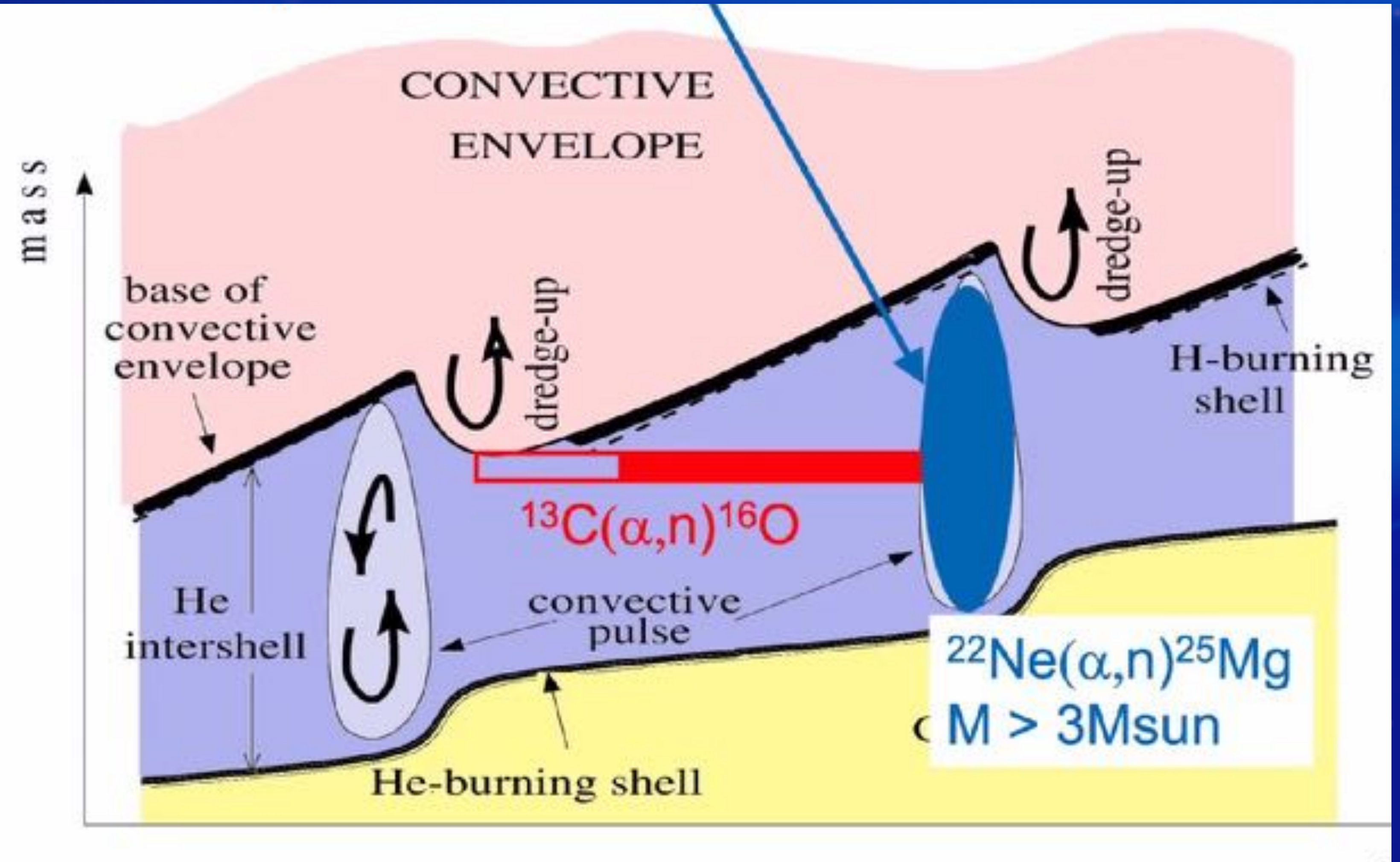




- mA thick target, differential method to pin down thickness
- magnetic removal of He^{2+}, cover 0.4 MeV to 0.8 MeV (JUNA), cover i-process; to 1.2 MeV tandem, calibration of eff. , cross check other date
- n background 5/ hour, 2.5 MeV eff. 25%, good S/N

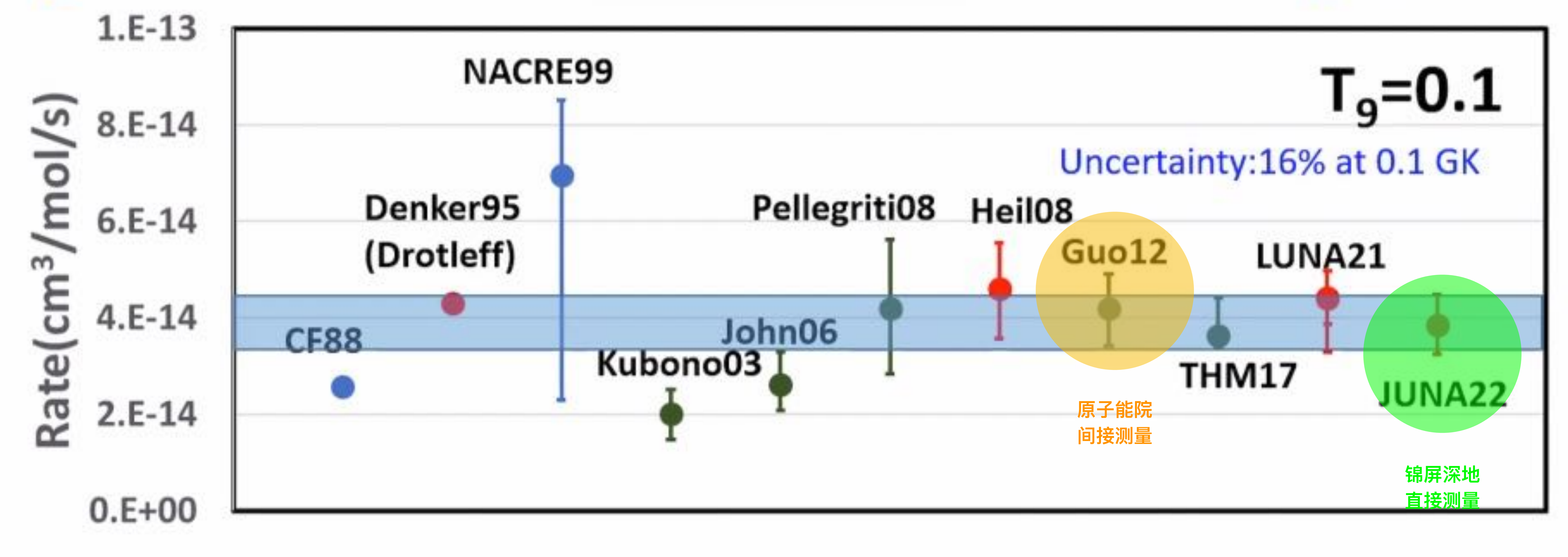
B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(\alpha,n)^{16}O$, PRL 129(2022)132701

恒星中子源30年探寻30 years research



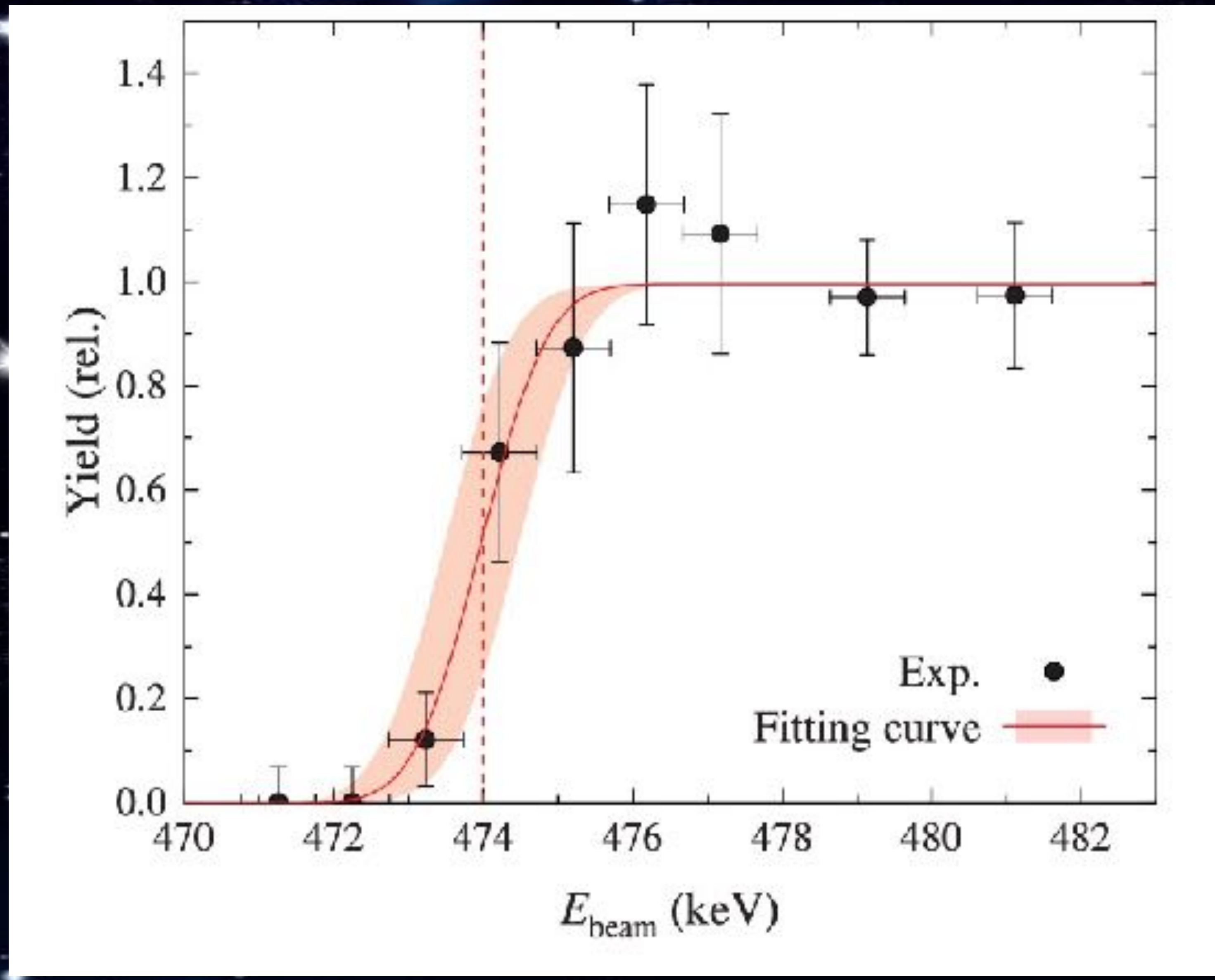
The significant reduction in uncertainty is fantastic. Now I believe that the work is a major achievement in experimental nuclear astrophysics …

the new underground and new above ground measurements are smoothly continuous over a large energy range, thereby providing a much improved and more precise s-factor than previously available



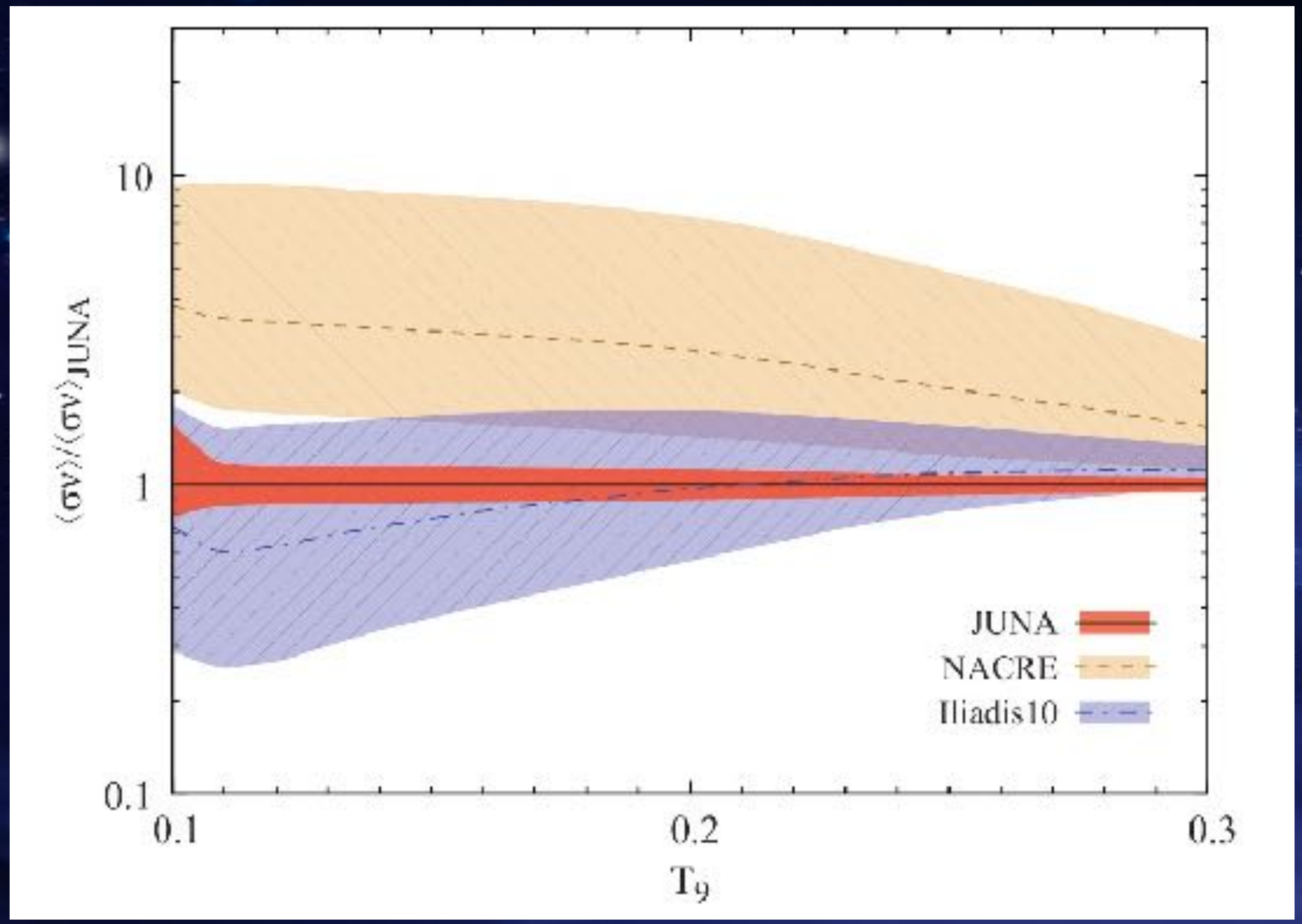
B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(\alpha,n)^{16}O$, PRL 129(2022)132701
B. Guo*, Z. H. Li,…, WPL*, Astrophys. J. 756(2012)193.

New result from JUNA $^{18}O(a,\gamma)^{22}Ne$: trace back AGB mass via SiC radius

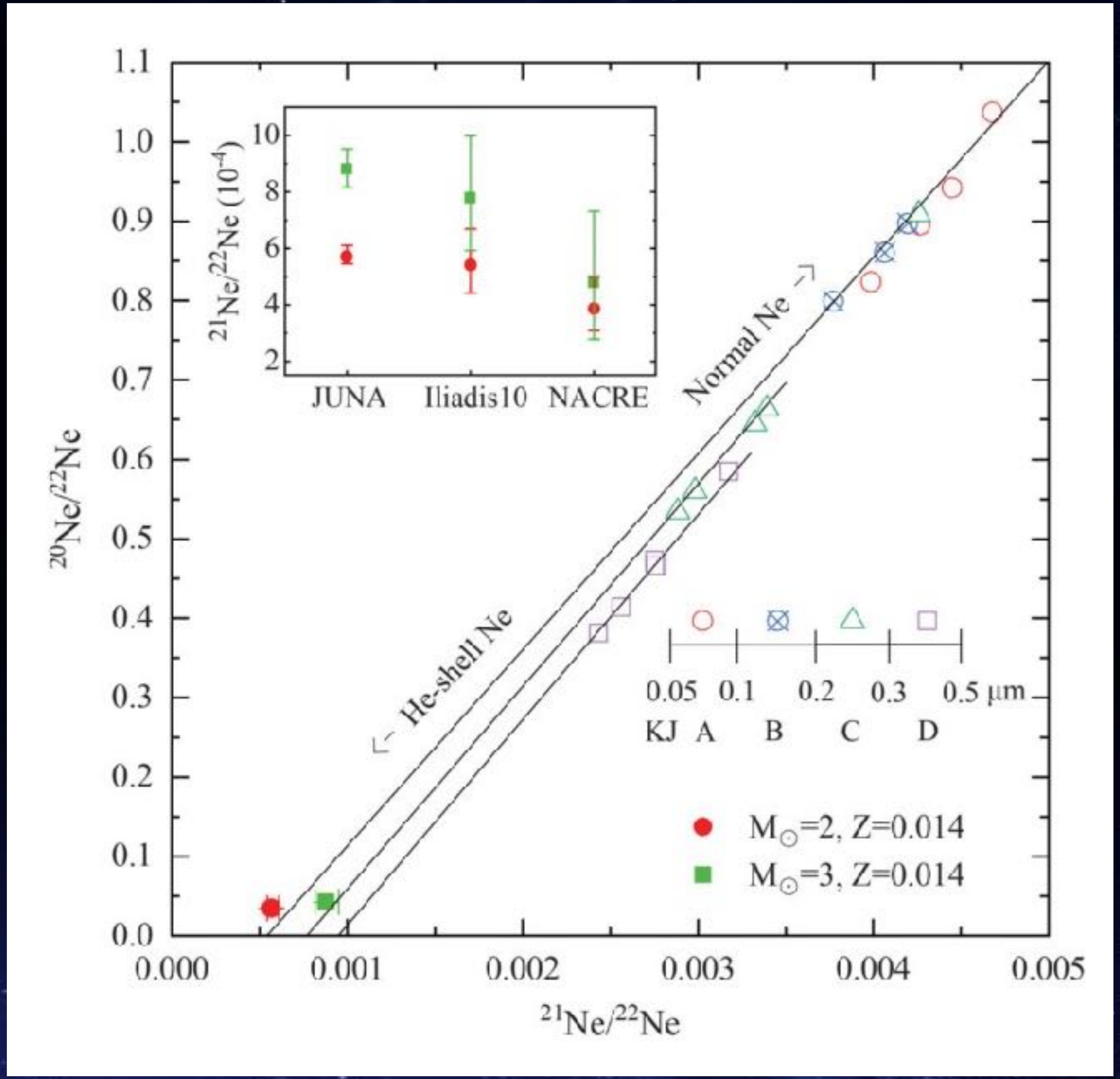


Thick target yield curve of the 470 keV resonance.

J. Su, BNU



JUNA results with previous values reported by NACRE and Iliadis

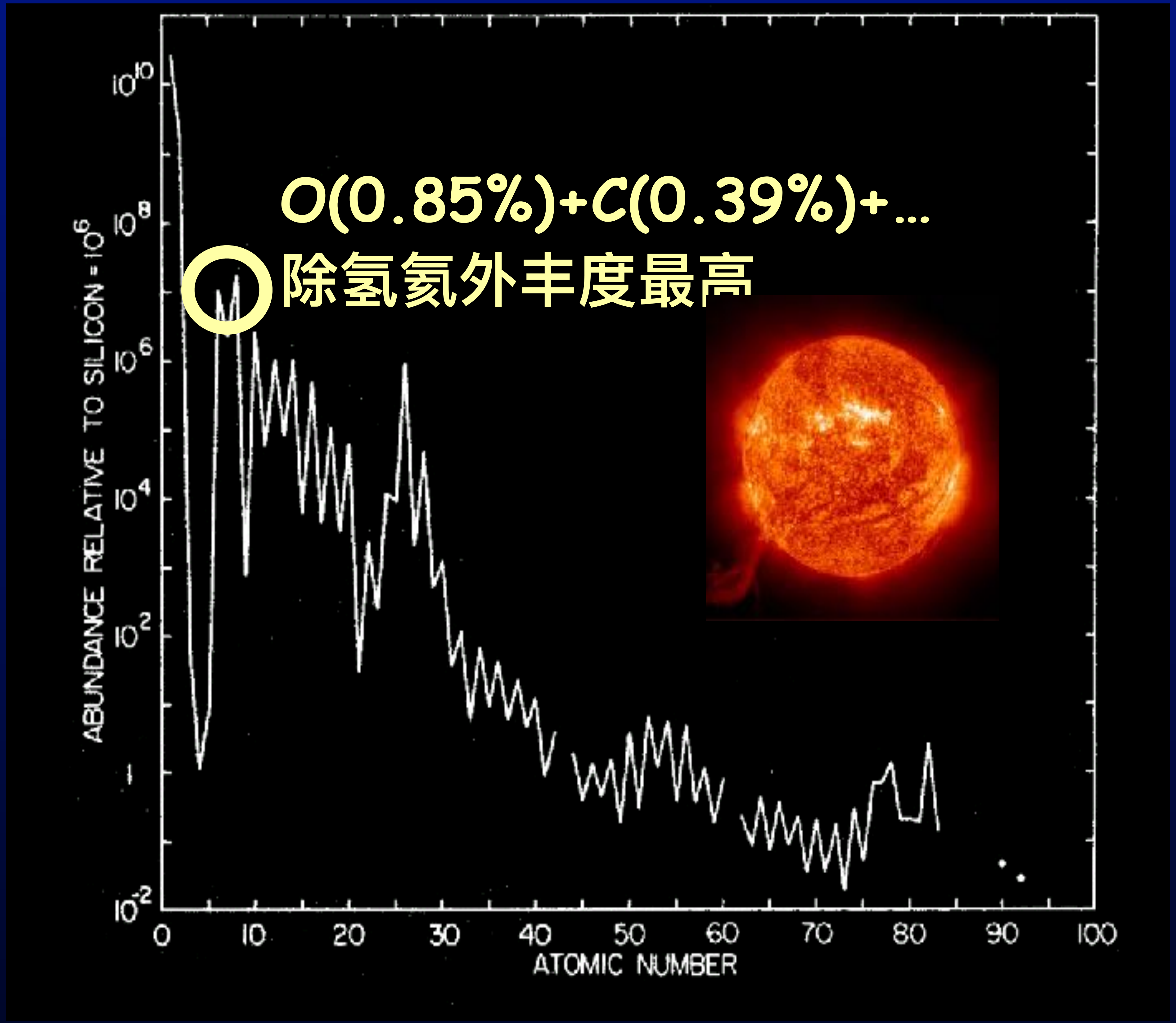


Ne isotope ratios in AGB models (filled symbols) using the JUNA rates and meteoritic stardust SiC grains of different sizes from Lewis et al. (open symbols). The top- left inset shows the $^{21}Ne/^{22}Ne$ ratios calculated with different reaction rates.

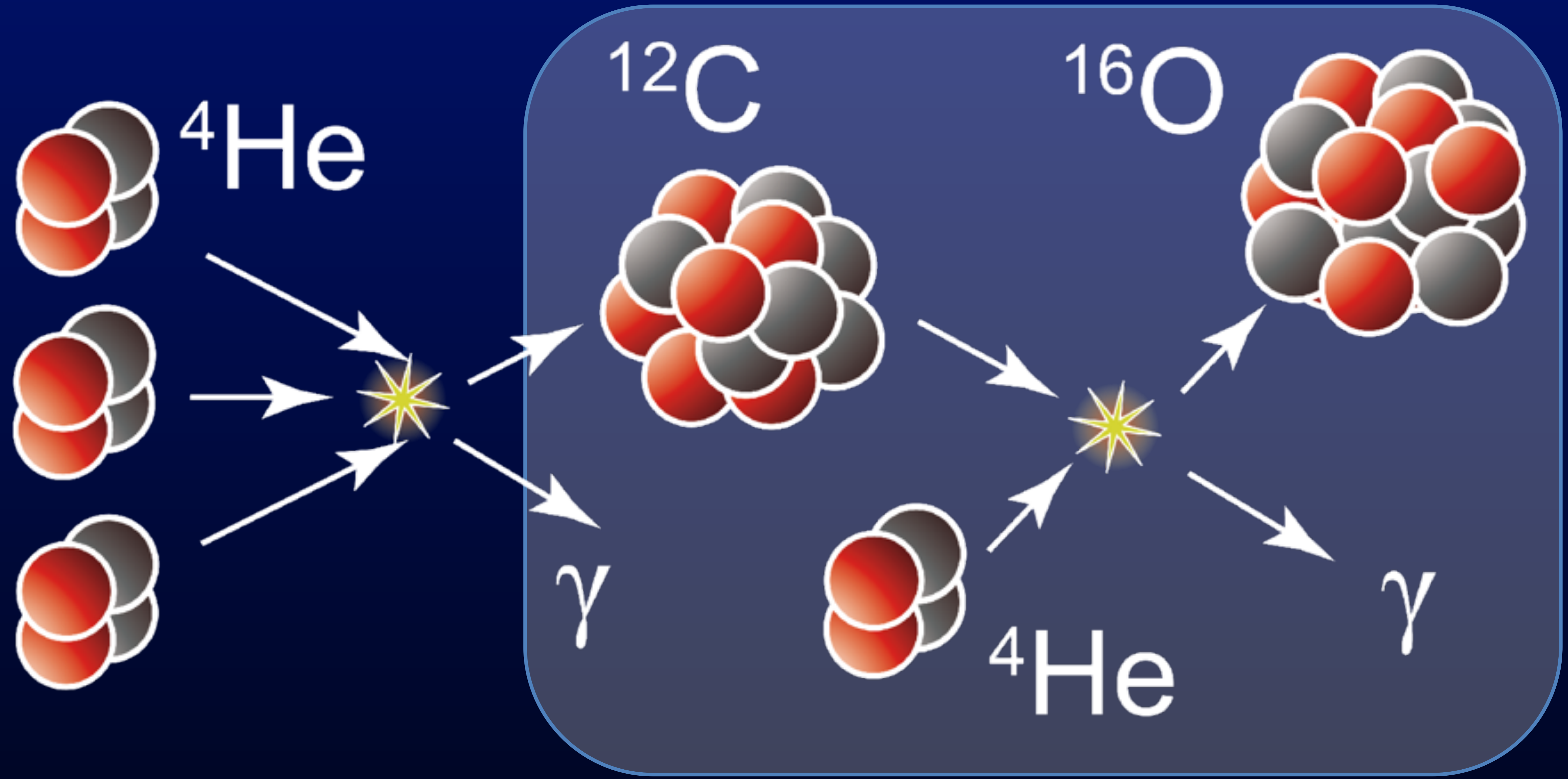
L. H. Wang, J. Su*, …, WPL*, PRL 130(2023)092701

圣杯反应 $^{12}C(\alpha,\gamma)^{16}O$ 首个深地直接测量

JUNA合作组/CIAE
谌阳平、苏俊、连钢、柳卫平等

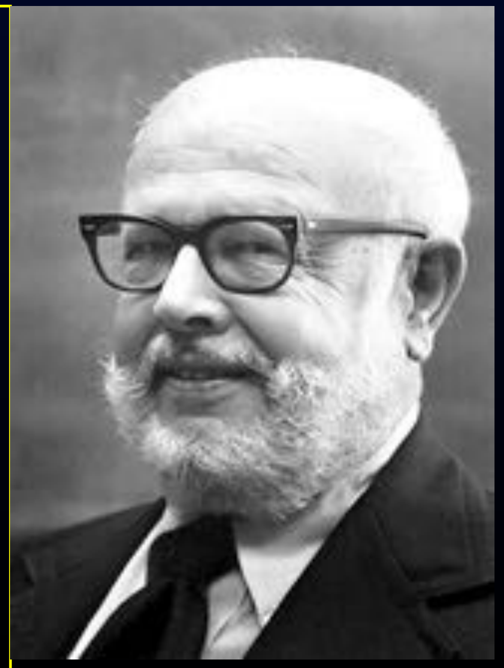


- $^{12}C(\alpha,\gamma)^{16}O$决定**碳氧比例**
- 影响恒星演化和几乎全部核素丰度
- 被称为"**圣杯反应**"



我们人体中绝大部分是碳和氧。在化学和生物的层面上，我们已经基本上理解了他们。**可是在核天体物理的层面上，我们还并不理解我们身体中的碳和氧是怎么产生的。**

William A. Fowler, 1983年诺贝尔物理奖得主

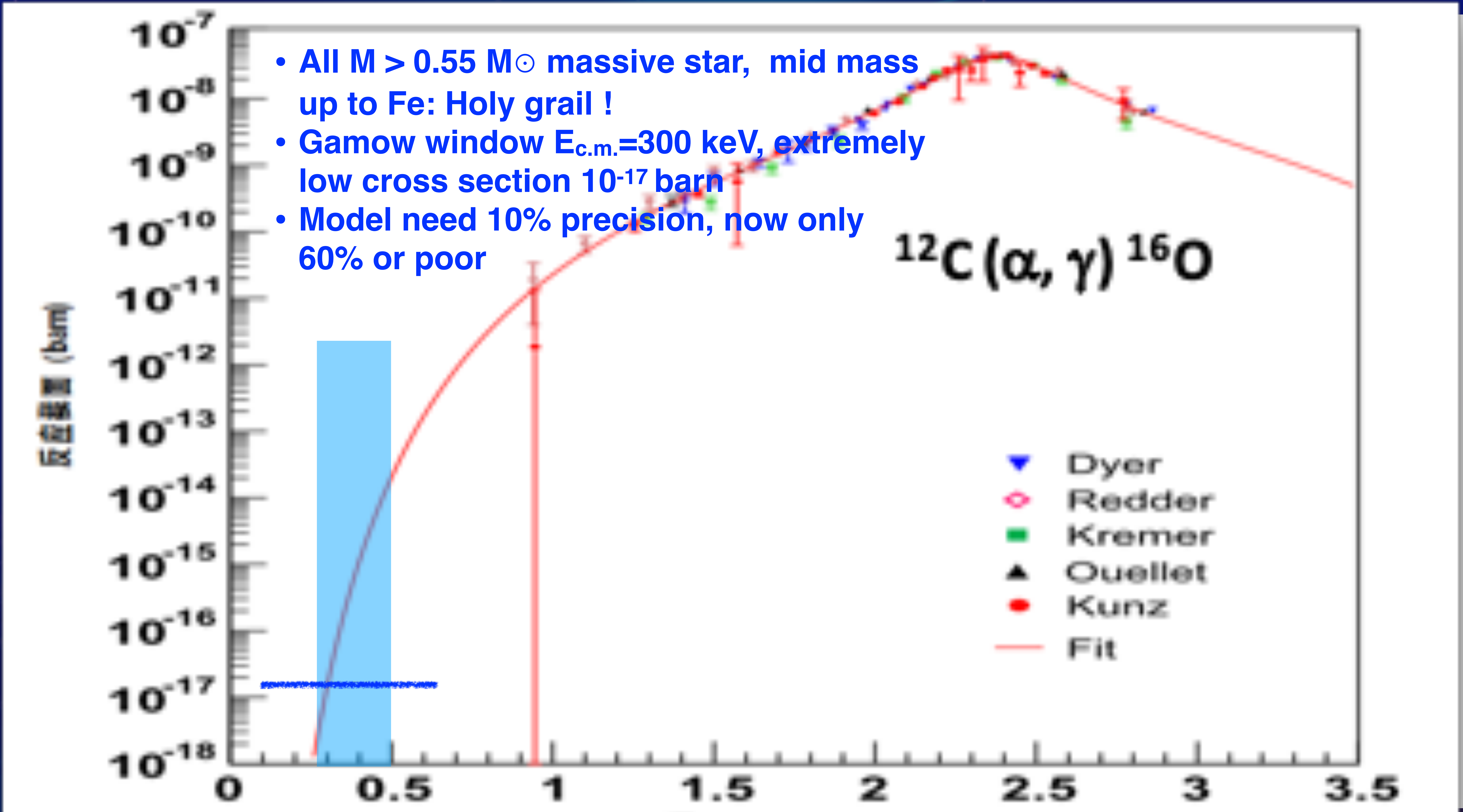


Big question, big impact, big challenge 圣杯

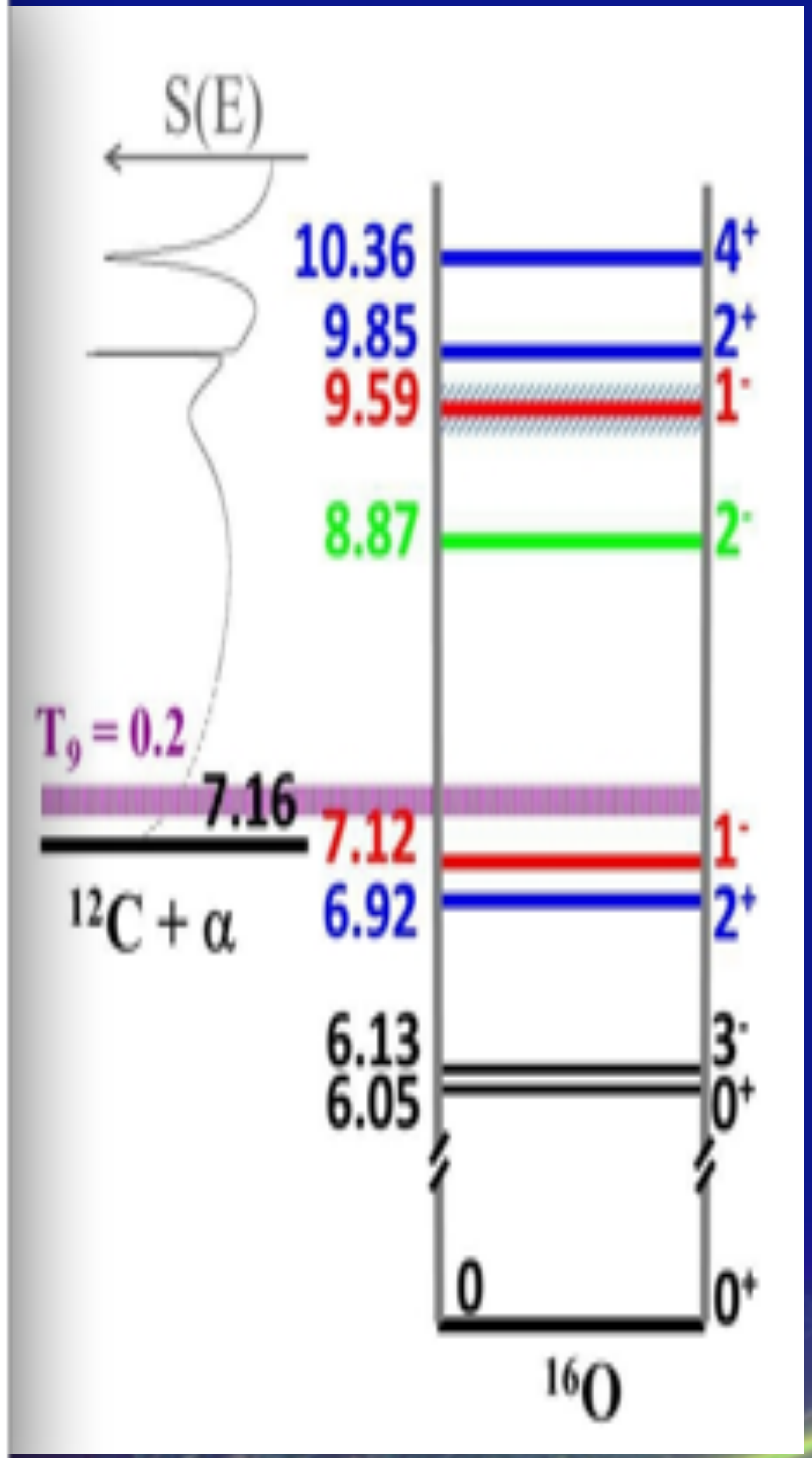
PI: WPL/Y. P. Shen, CIAE

Exp.: Feb. 26-Apr. 18, 2021

- All M > 0.55 M⊙ massive star, mid mass up to Fe: Holy grail !
- Gamow window $E_{c.m.}$=300 keV, extremely low cross section 10^{-17} barn
- Model need 10% precision, now only 60% or poor



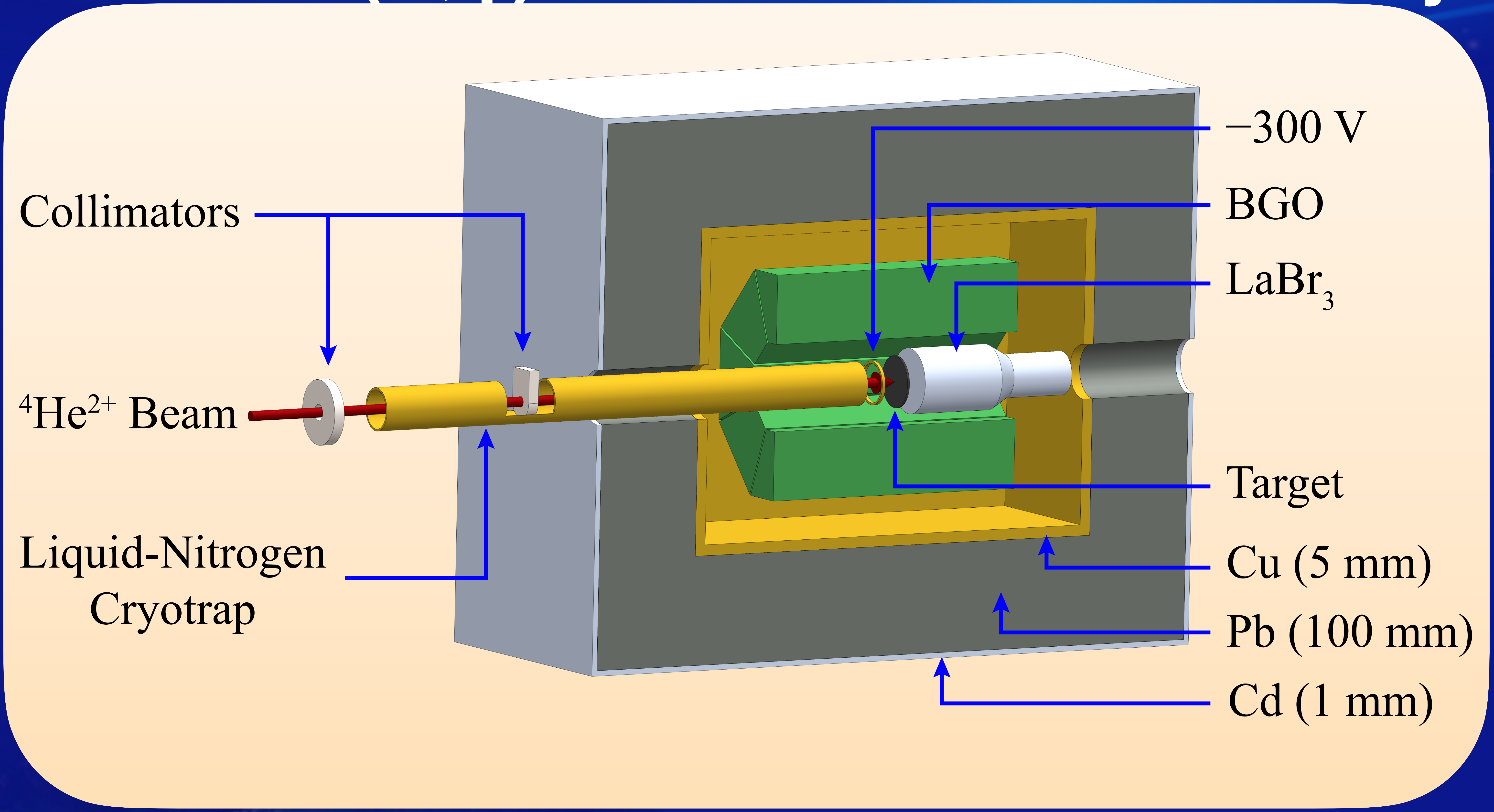
R. J. deBoer et al., RMP vol. 89, 2017

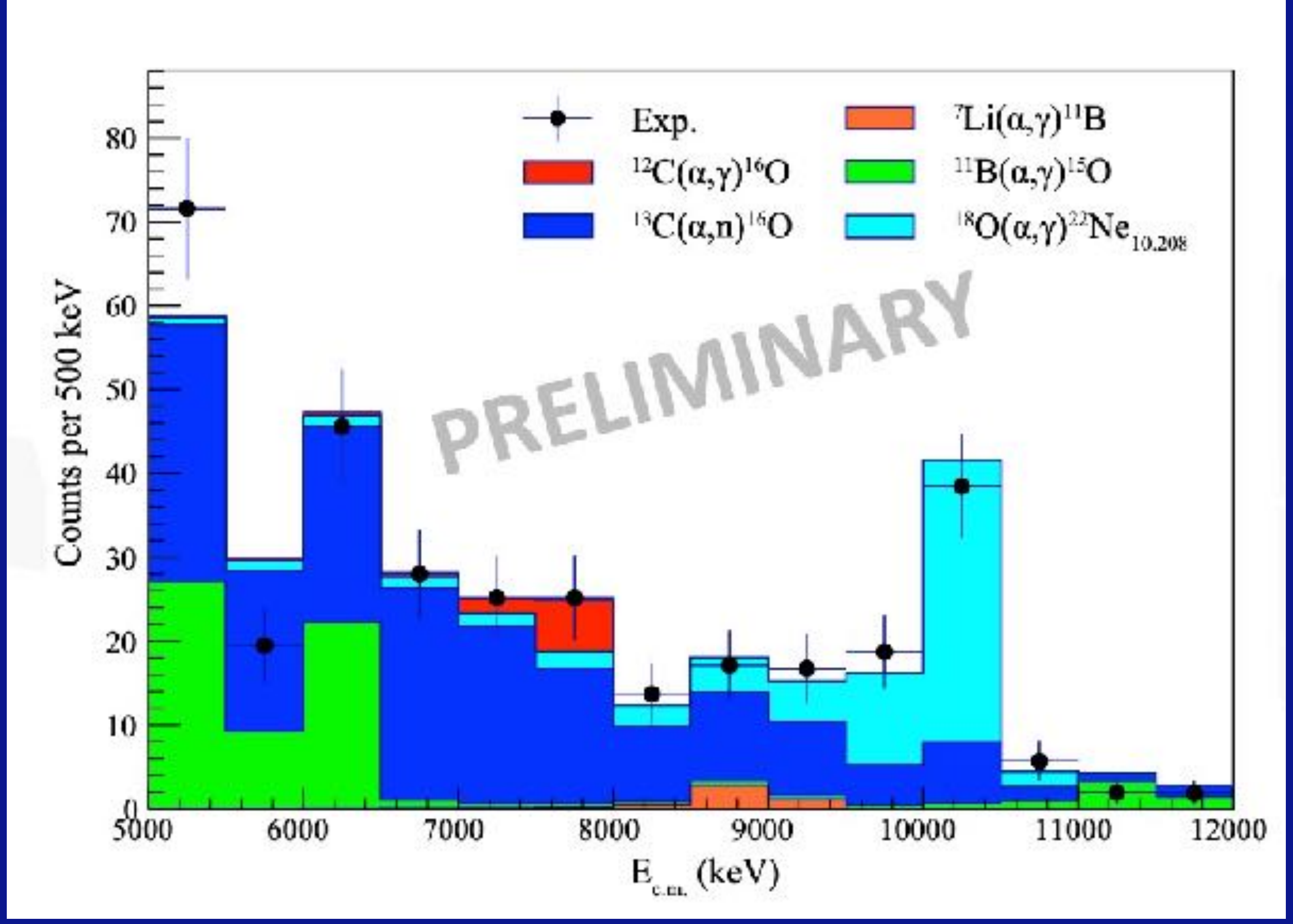


B. Guo, Z. H. Li, …, WPL,, APJ 756, 193 (2012)

Y. P. Shen, B. Guo, …, WPL, PRL 124, 162701(2020)

$^{12}C(\alpha,\gamma)^{16}O$ ： more sensitivity 最灵敏

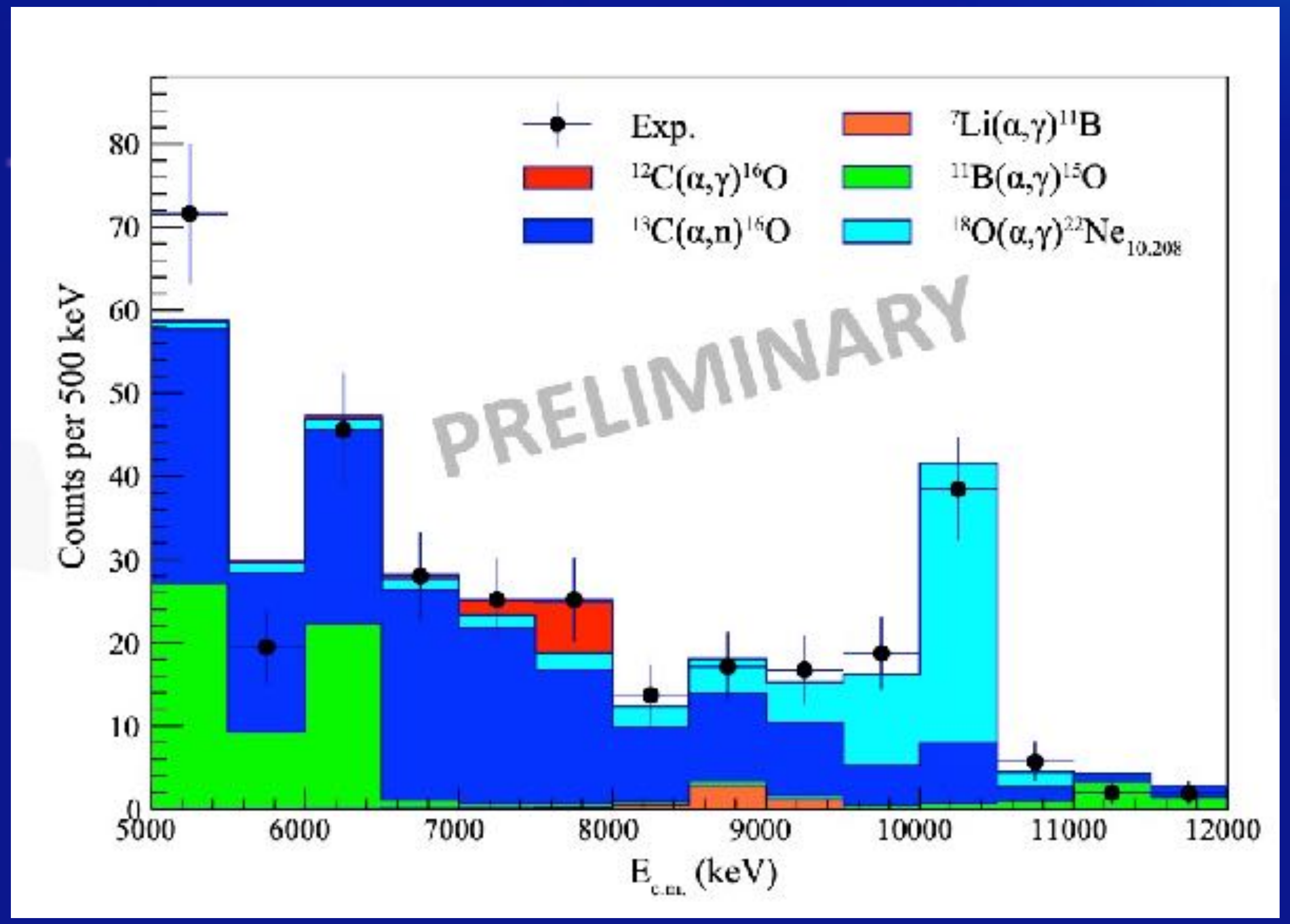




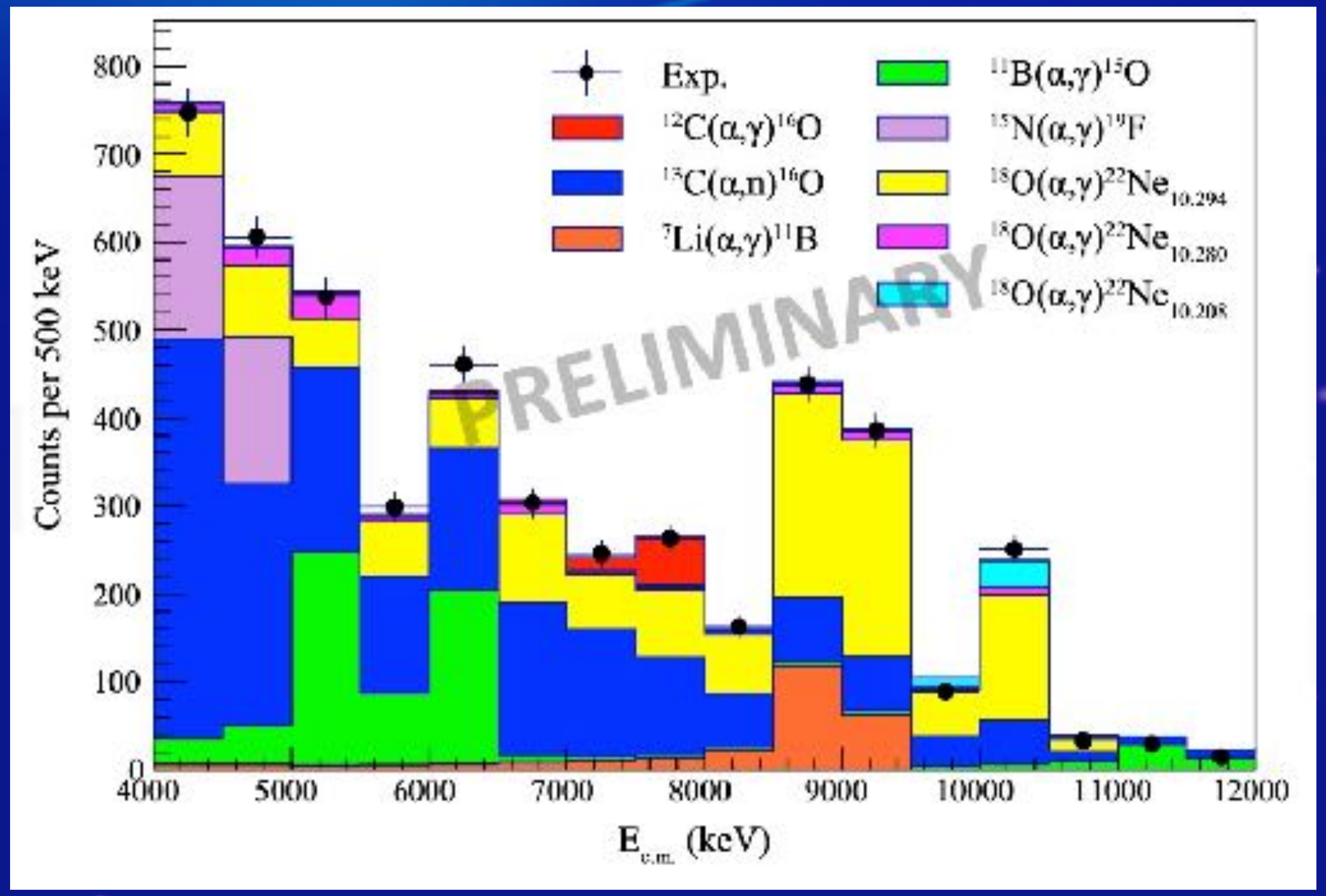
- FCVA implantation CTi thick targets
- durability >280 C @800 keV He^{2+}, with only 25% loss
- BGO+$LaBr_3$ (Lanthanum bromide) veto
- wide energy search for best S/N, 552 keV is best, other suffer from $^{18}O(\alpha,\gamma)^{22}Ne$ contaminations
- sensitivity of 10^{-12} b @$E_{c.m.}$ = 552 keV

$^{12}C(\alpha,\gamma)^{16}O$ ： preliminary results after 60 years

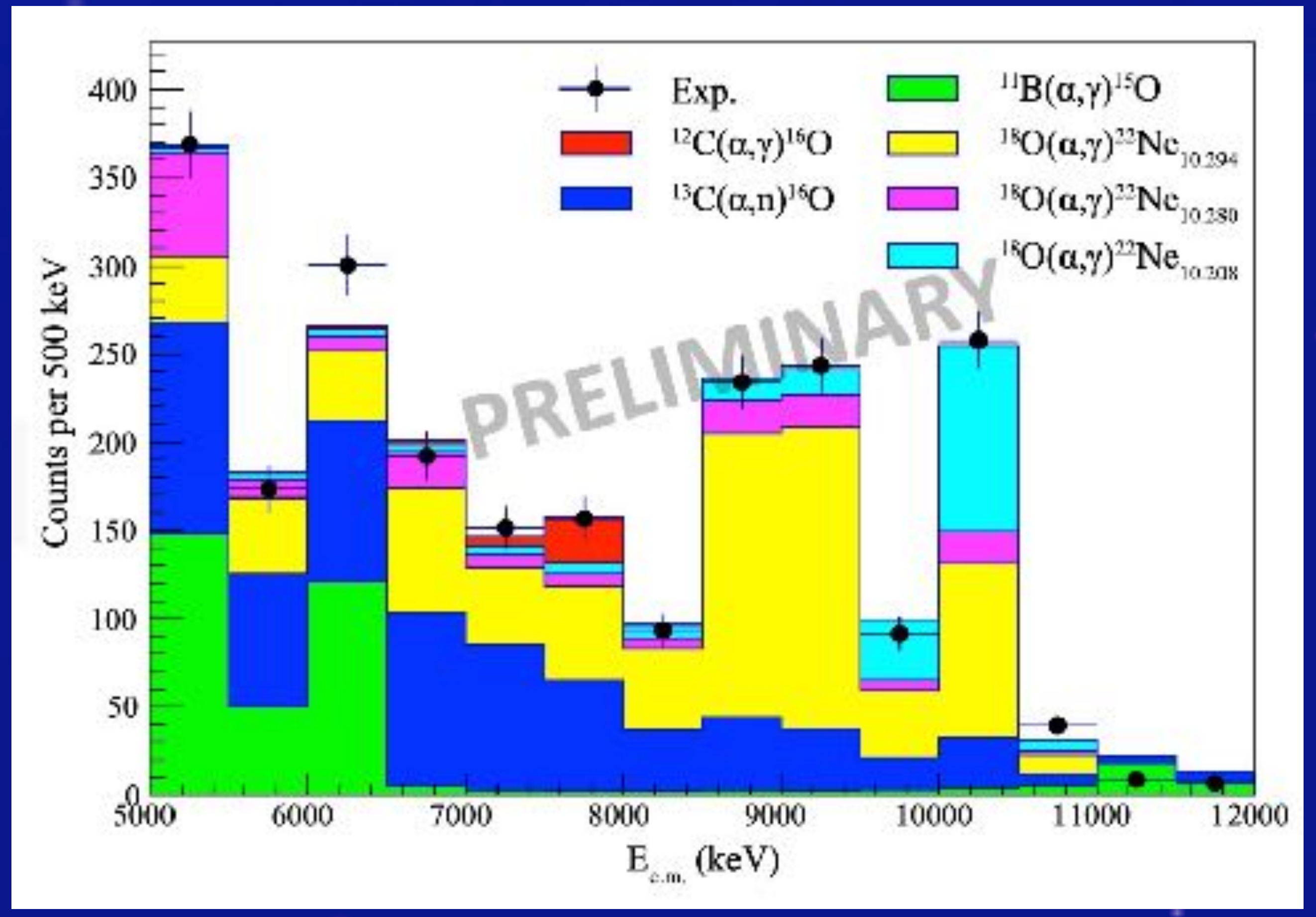
552 keV, 126 C

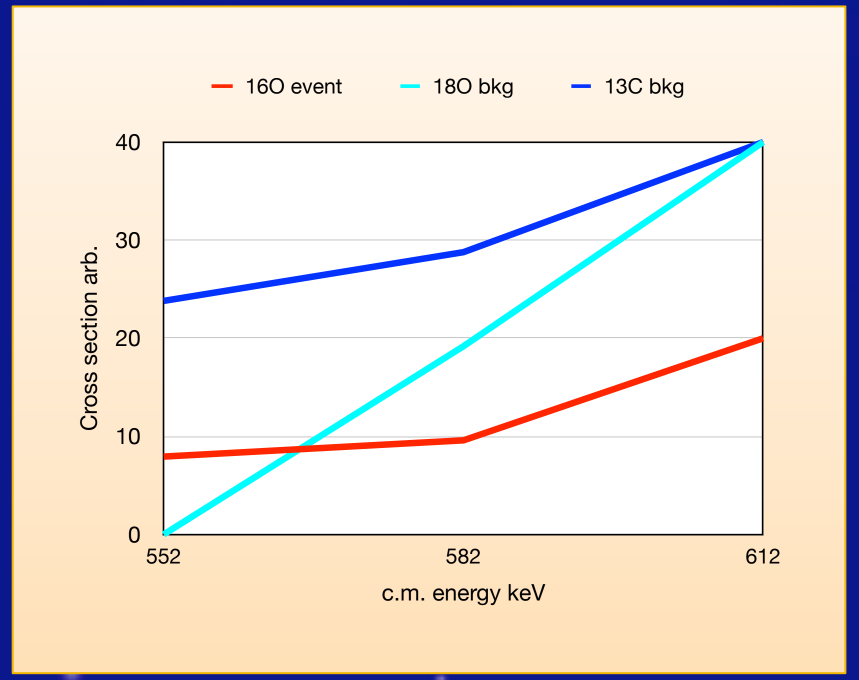


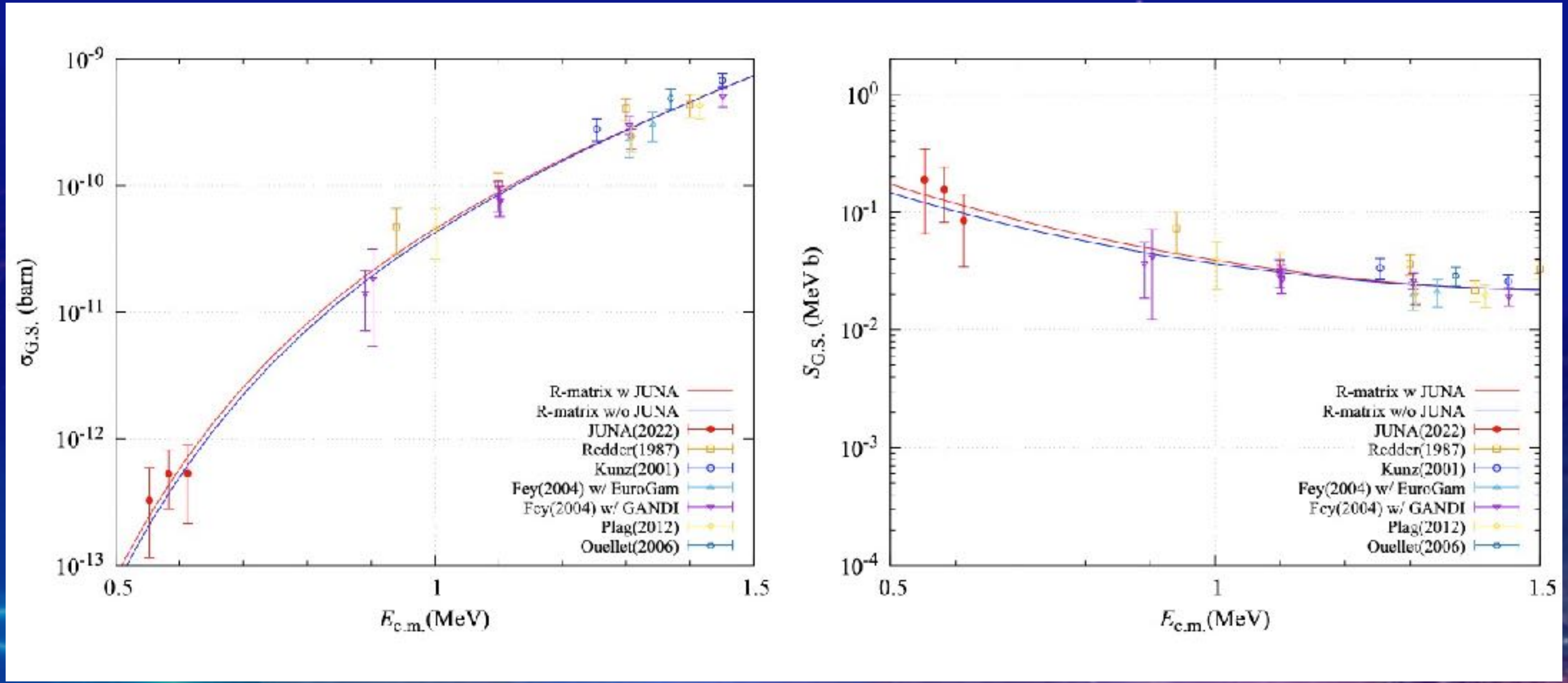
582 keV, 417 C

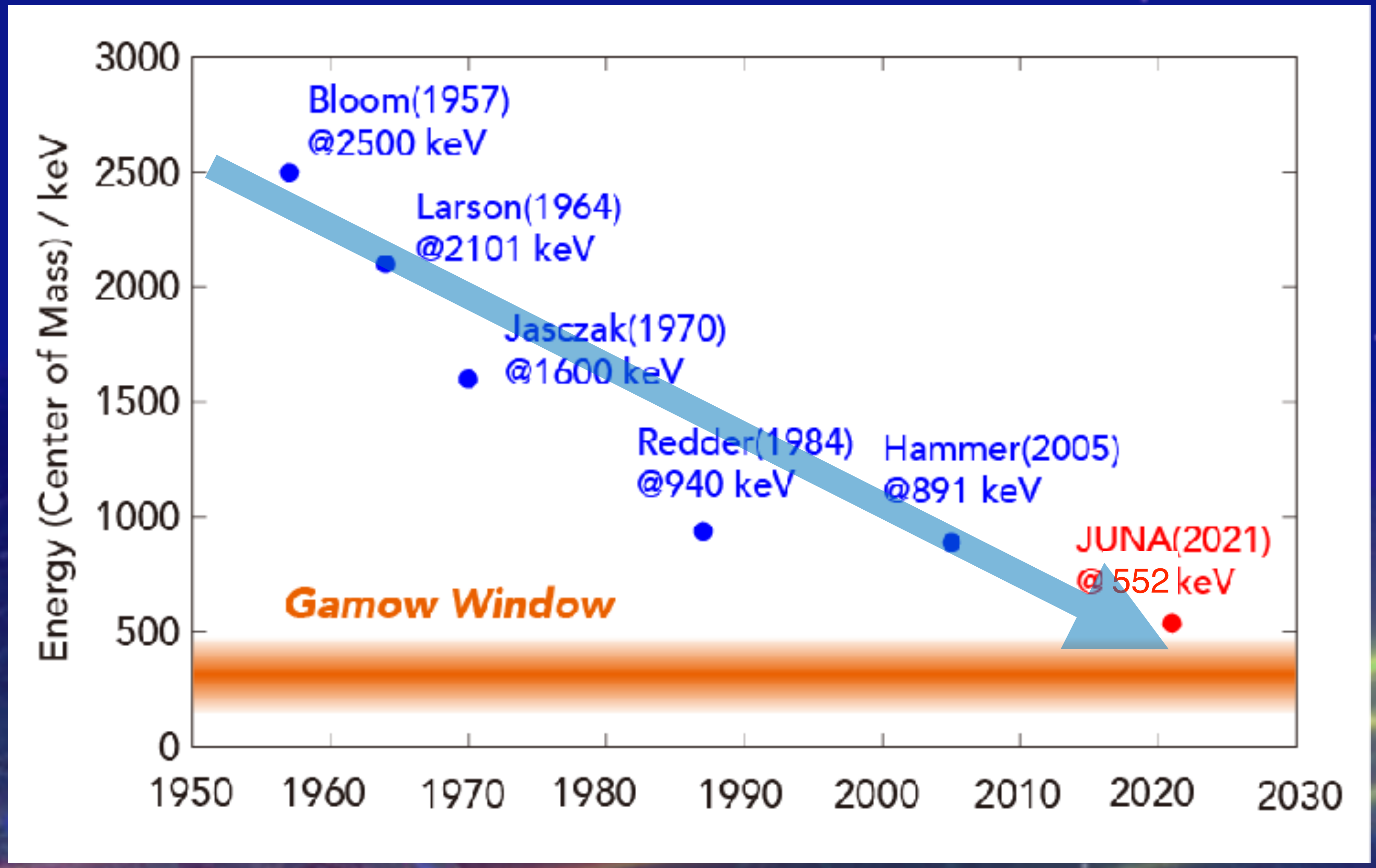


612 keV, 200 C









激发国际深地核天体物理发展 simulating effect

锦屏深地核天体物理实验

Jinping Underground Nuclear Astrophysics Experiment

JUNA and Super JUNA coverage

H burning

$^{7}Be(p,\gamma)^{8}B$

$^{12}C(p,\gamma)^{13}N$

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

$^{15}N(p,\gamma),(p,\alpha)^{16}O,^{12}C$

$^{17}O(p,\gamma),(p,\alpha)^{18}F,^{14}N$

$^{18}O(p,\gamma),(p,\alpha)^{19}F,^{15}N$

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

He burning

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

$^{16}O(\alpha,\gamma)^{20}Ne$

$^{20}Ne(\alpha,\gamma)^{24}Mg$

$^{18}O(\alpha,\gamma)^{22}Ne$

$^{22}Ne(\alpha,\gamma)^{26}Mg$

$^{24}Mg(\alpha,\gamma)^{28}Si$

N source

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

$^{22}Ne(\alpha,n)^{25}Mg$

$^{25}Mg(\alpha,n)^{28}Si$

$^{26}Mg(\alpha,n)^{29}Si$

C\O burning

$^{12}C+^{12}C$

$^{12}C+^{16}O$

$^{16}O+^{16}O$

γ天文学

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

$^{26}Al(p,\gamma)^{27}Si$

JUNA achieved

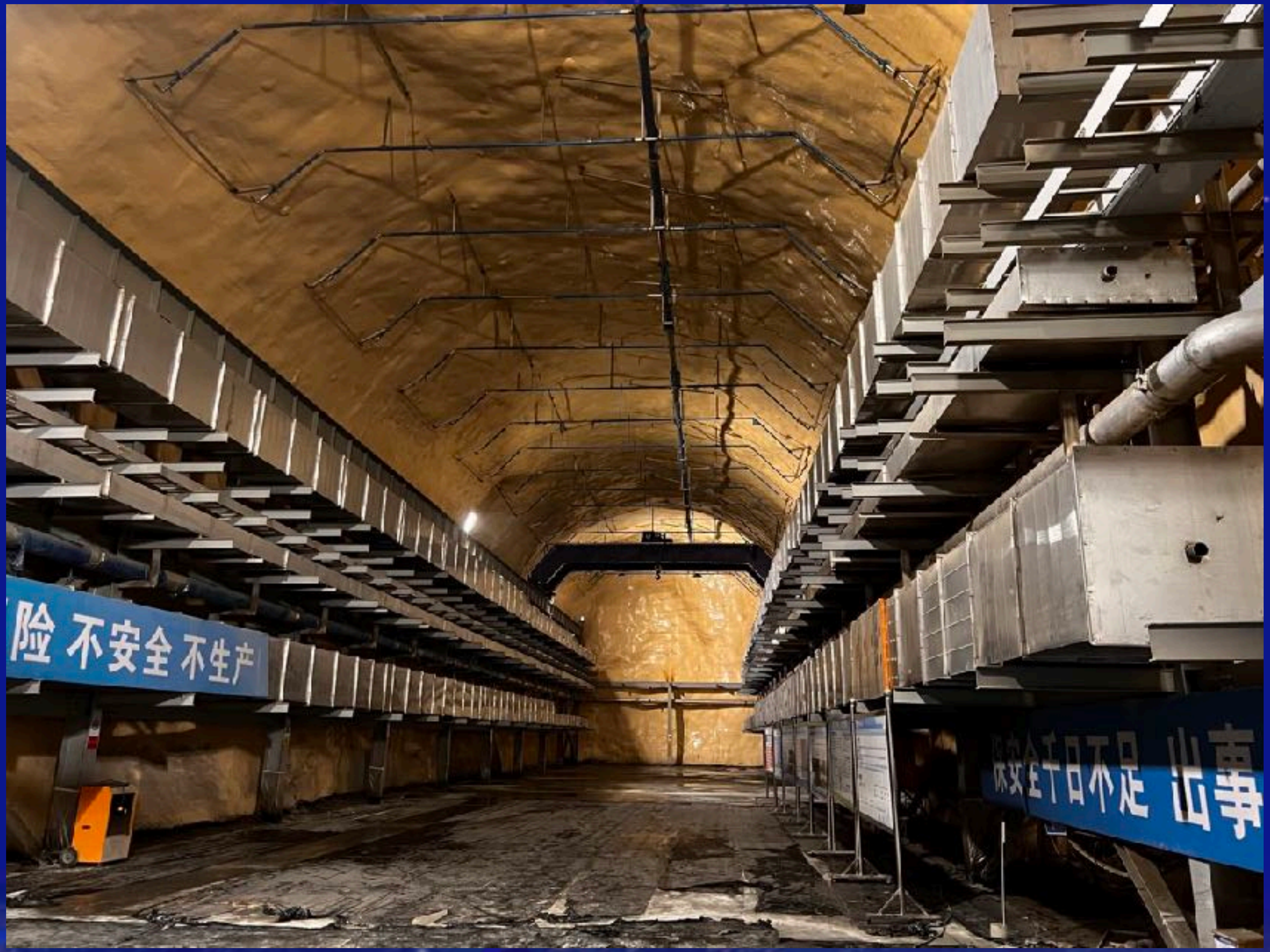
Super JUNA proposed

2025-2030 JUNA 和 Super-JUNA 5年计划

	JUNA	Super-JUNA	JUNA 实验	Super-JUNA 实验
2025	运行	项目支持，部件完成，离子源地面出束	(a,n) 核 (a,g)气体靶实验	
2026	运行	组装，离子源深地出束	正常实验	
2027	升级	加速器深地出束	升级后实验	(p,g) 测试实验
2028	运行	全面运行	正常实验	(a,g), (a,n) 实验
2029	运行	全面运行	正常实验	(a,g), (a,n) 实验
2030	运行	全面运行	正常实验	(a,g), (a,n) 实验

希望和兄弟院校合作的科学问题

- 垒下极低能量辐射俘获反应的理论计算
- 高密度高耐辐射同位素反应靶研发
- 高效率高分辨中子和伽马探测技术
- 元素丰度数值模拟计算



CJPL-II A1 for JUNA: June 28, 2023

JUNA summary 研究成果总结

- 天体物理伽莫夫能量下的核反应概率极低，对其精确测量是制约恒星重元素合成研究的重大科学问题。

- JUNA团队攻克强流带电粒子高效传输和永磁电子回旋共振离子源等关键技术，建成强流低本底JUNA平台，JUNA平台建成使我国成为国际第三个具备开展深地核物理实验能力的国家，入选2021年两院院士大会“战略高技术领域取得新跨越”成果

- 通过极低本底伽莫夫窗口精密能量扫描，首次发现碳氮氧循环突破反应$^{19}F(p,\gamma)^{20}Ne$在225 keV存在共振，这导致该反应率较国际NACRE评价数据提高6倍，从而解释了最古老恒星钙丰度超出之谜，成果在Nature上发表并入选该刊亮点文章，为该刊首次刊登我国中低能核物理装置成果

- 通过高精度基态分支比和能级宽度测量，使$^{25}Mg(p,\gamma)^{26}Al$ 伽马射线反应达到最高精度，入选Sci. Bull.封面文章；首次在伽莫夫窗口精确测量$^{19}F(p,\alpha\gamma)^{16}O$氟丰度反应，排除了该反应导致氟超丰可能，入选PRL编辑推荐和APS重要论文；通过深地多电荷态束流和地下与地面双加速器组合，使恒星中子源反应$^{13}C(\alpha,n)^{16}O$首次覆盖天体物理i过程能区，澄清了国际30多年的分歧；天体物理圣杯$^{12}C(\alpha,\gamma)^{16}O$反应达到国际最低能区，灵敏度提高了一个量级。

- 通过JUNA的继续运行和Super-JUNA的建设，我国核天体物理深地直接测量将可以继续保持国际领先地位

JUNA团队 Team

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- 四川大学：安竹，黄宁，罗小兵，王鹏
- 山东大学：王硕
- 深圳大学：李二涛，甘林
- 中山大学：方晓，安振东

- 澳大利亚莫纳什大学：Alexander Heger
- 日本大阪大学: 谷畑 勇夫
- 日本理化学研究所：久保野 茂
- 匈牙利科学院：Maria Lugaro
- 美国南达科他大学: 梅东明
- 美国明尼苏达大学：钱永中
- 美国圣母大学：谭万鹏

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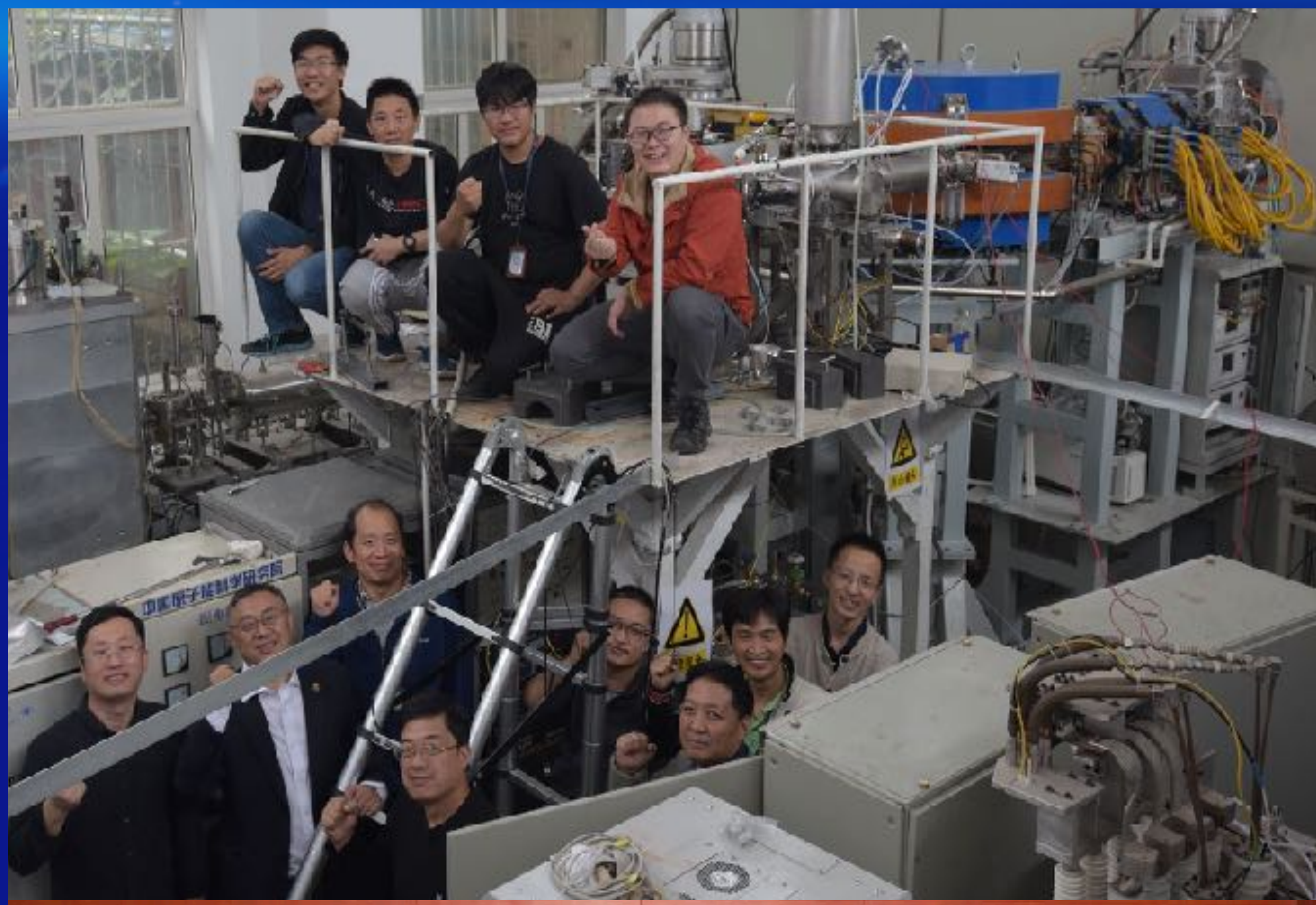
D. Robertson （圣母大学）

F. Strieder （南达科达矿业理工学院）

D. Leitner （加州大学伯克利分校）

岳骞 （清华大学）



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雅砻江流域水电开发有限公司，锦屏水力发电厂、锦屏地下实验室管理局，清华大学，北京师范大学

Thank you for your attention, welcome to collaborate with JUNA！