JUNA progress

Weiping Liu
JUNA chief scientist
China Institute of Atomic Energy (CIAE)

August 26, 2022

清华大学物理系复系40周年“核物理前沿与交叉”研讨会

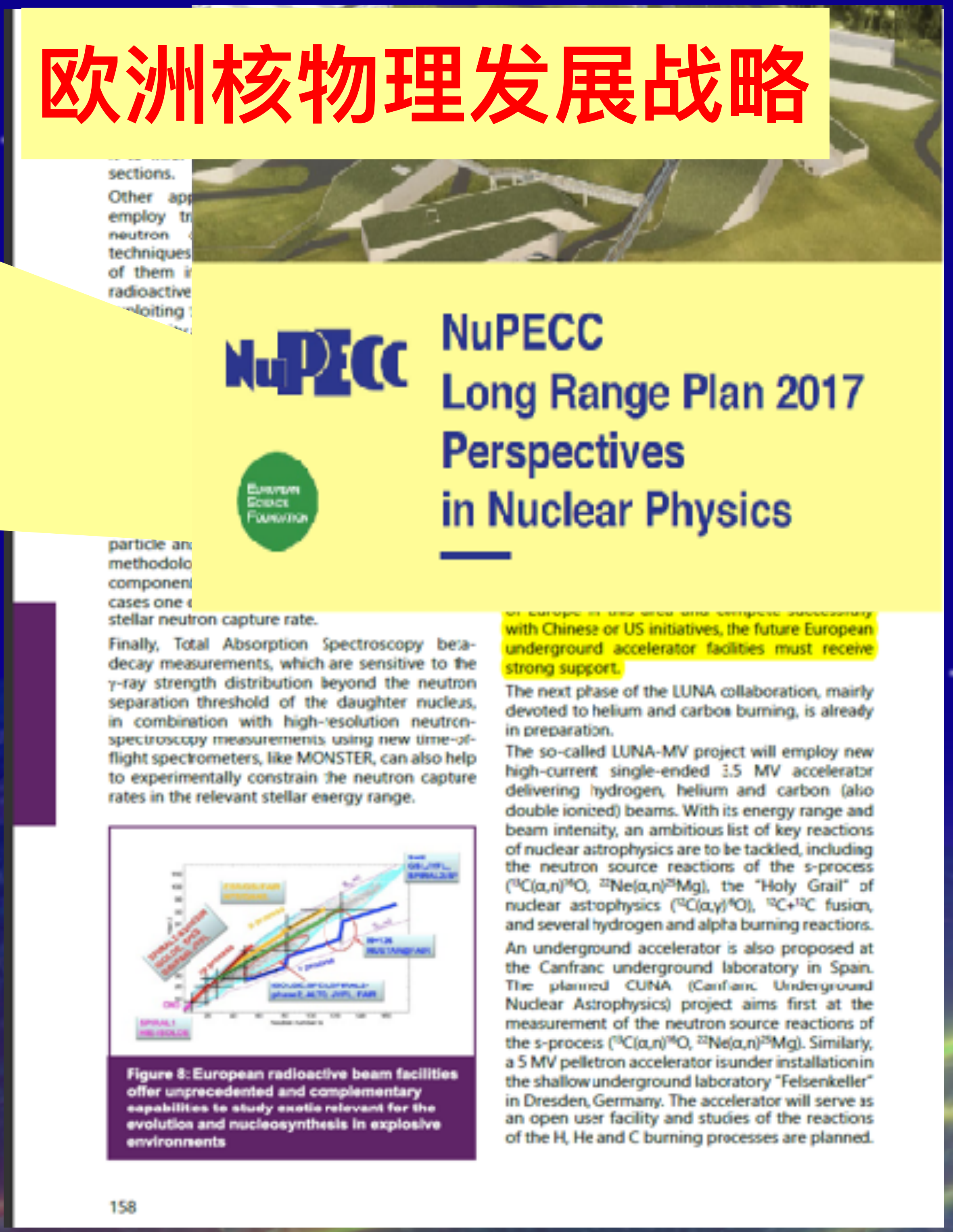
Thanks NSFC, Yalong power, THU, CAS and CNNC

北京师范大学 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 DEVELEFOMENT COMPANY, LTD.
清華大學
上海交通大学 SHANGHAI JIAO TONG UNIVERSITY
山东大学 SHANDONG UNIVERSITY
四川大学 SICHUAN UNIVERSITY
深圳大学 SHENZHEN UNIVERSITY
中山大學 SUN YAT-SEN UNIVERSITY

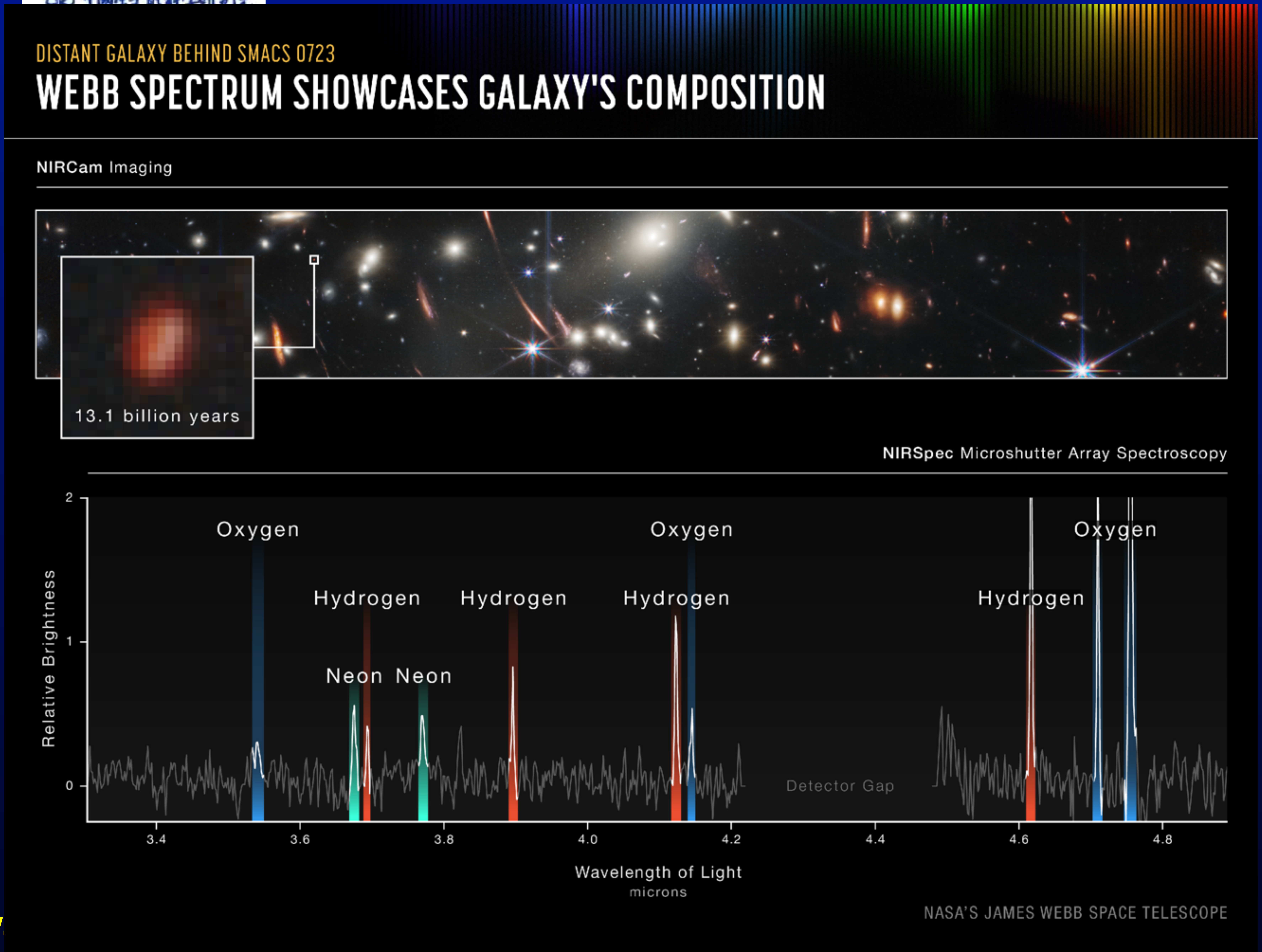
项目领域

- 深海、深地、深空、深蓝是《“十三五”国家科技创新规划》的战略高技术领域，本项目属于深地高科技
- 核天体物理是核物理分支学科，是核物理与天体物理融合的交叉学科，通过加速器测量恒星中核反应，探索星系演化和宇宙元素起源，中美欧核物理长程战略均建议为重点发展领域，面临激烈竞争

为保持欧洲在这一领域的世界领先地位，为成功与中国或美国的计划竞争，未来的欧洲地下加速器设施必须得到强有力支持。



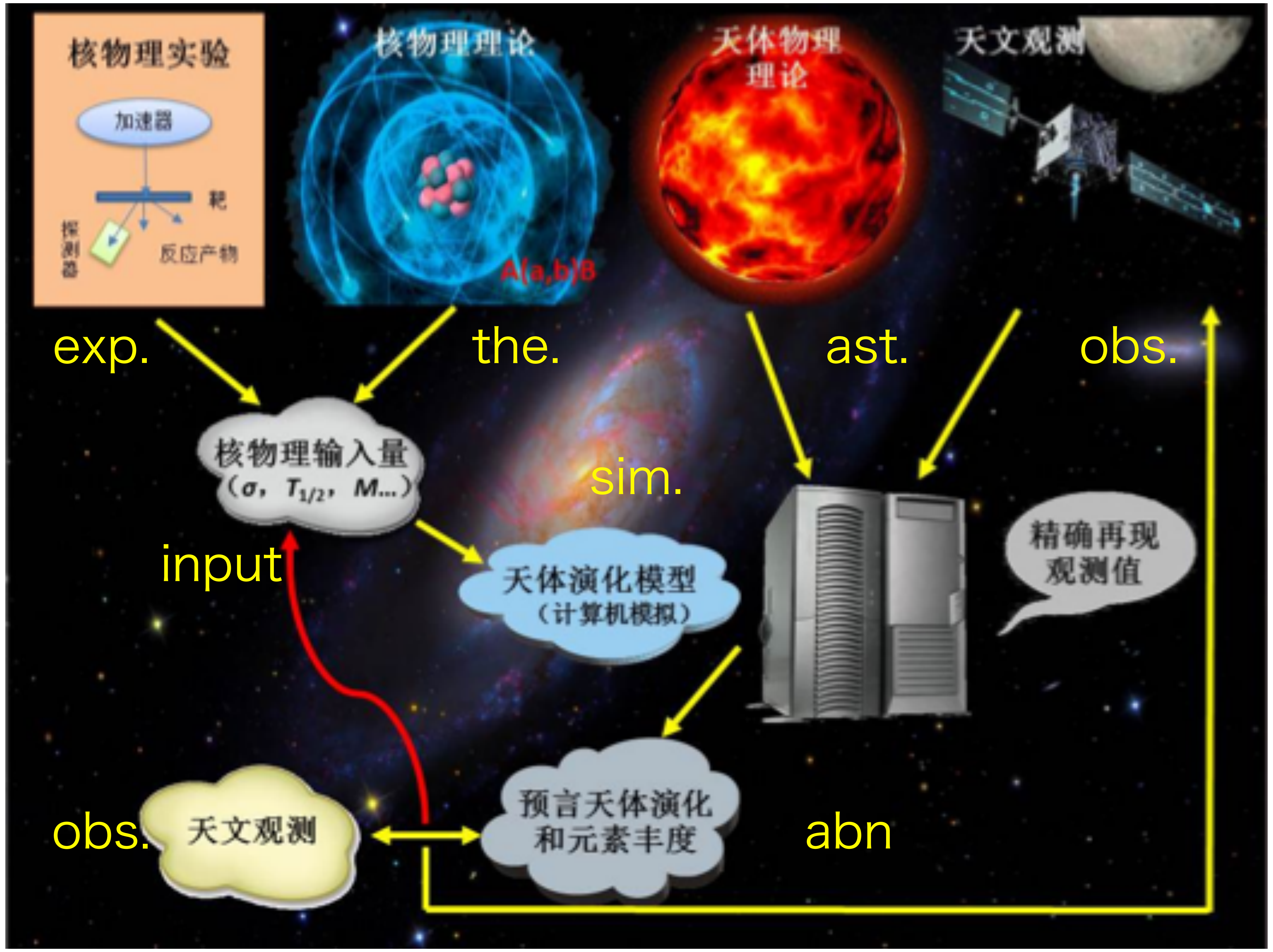
韦布发现的131亿岁的星云



- **Distant Galaxy in SMACS 0723, Webb Spectrum**
- **Thin horizontal section of a galaxy cluster**
- **The pull-out image shows a red pixelated blob**
- **Image is labeled 13.1 billion years to indicate the age of the light shown**
- **Below the images is a spectrum Iplotted as a line graph of brightness vs. wavelength**

Features of nuclear astrophysics research

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



科学前沿

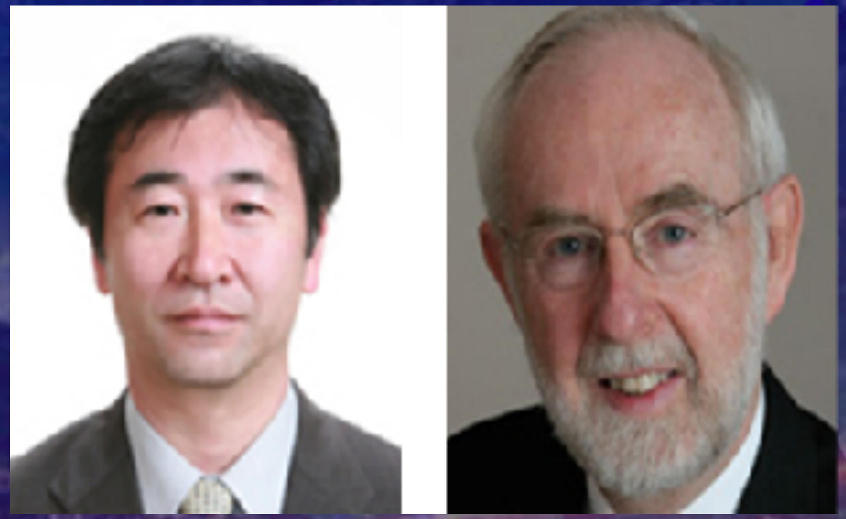
- 国际基础科学若干未解之谜中有：暗物质、中微子、核天体物理，本项目是在深地从事核天体物理研究

1983
威廉·福勒
核反应与元素起源

2006
约翰·马瑟，乔治·斯穆特
CMB黑体形式和各向异性

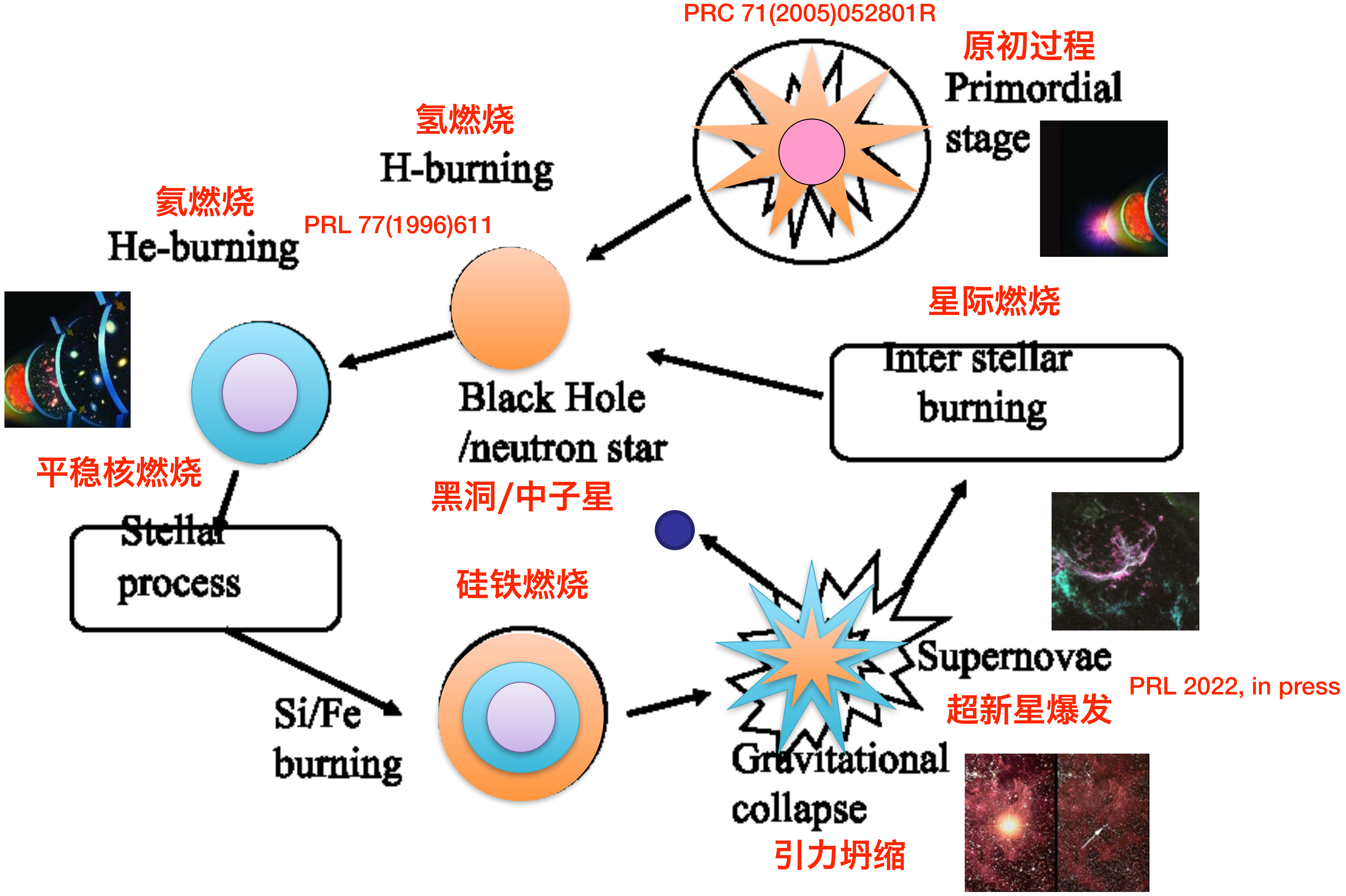
三个未解之谜

2002
雷蒙德·戴维斯
小柴昌俊
宇宙中微子探测



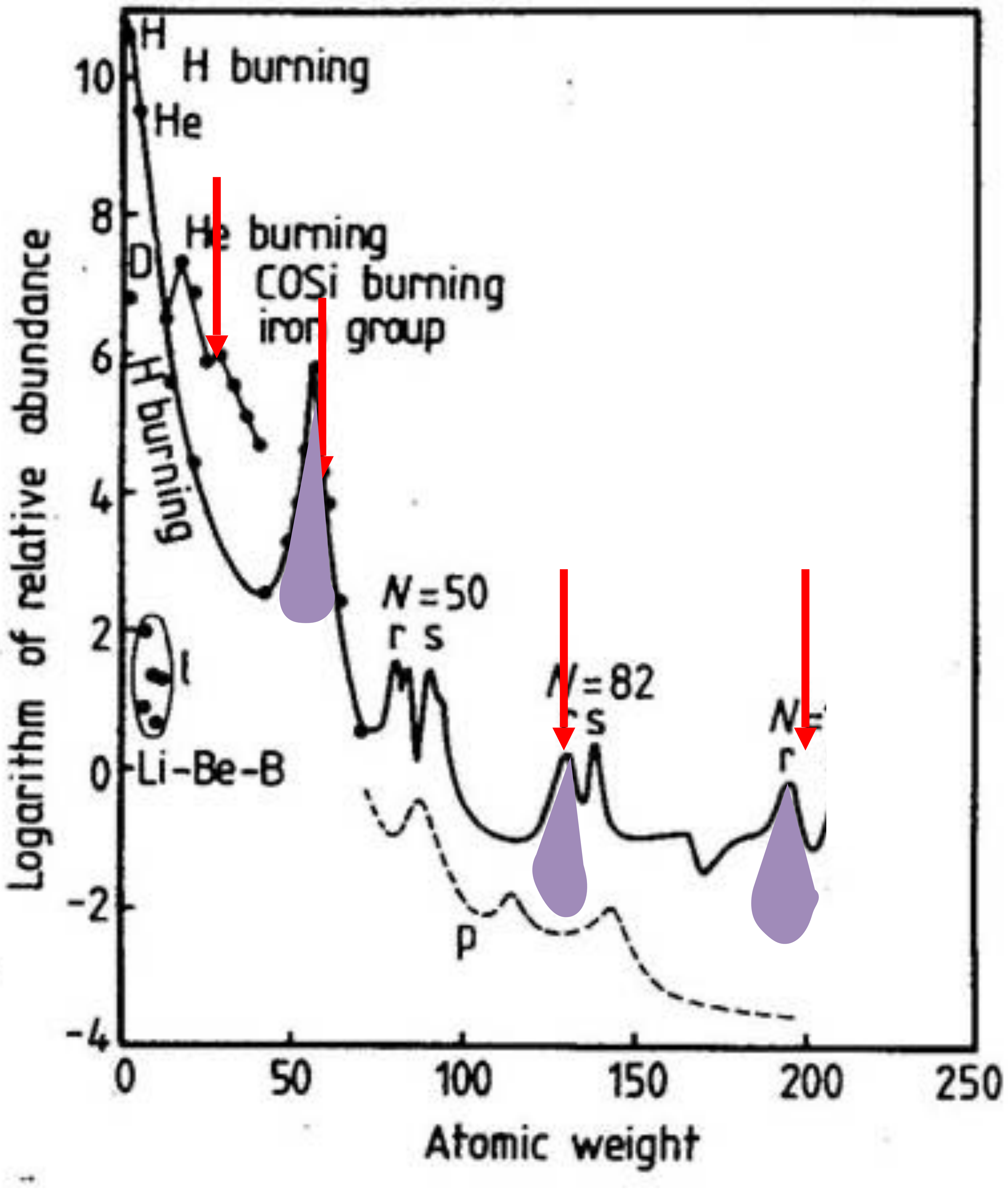
2015
梶田隆章
阿瑟·麦克唐纳
发现中微子震荡

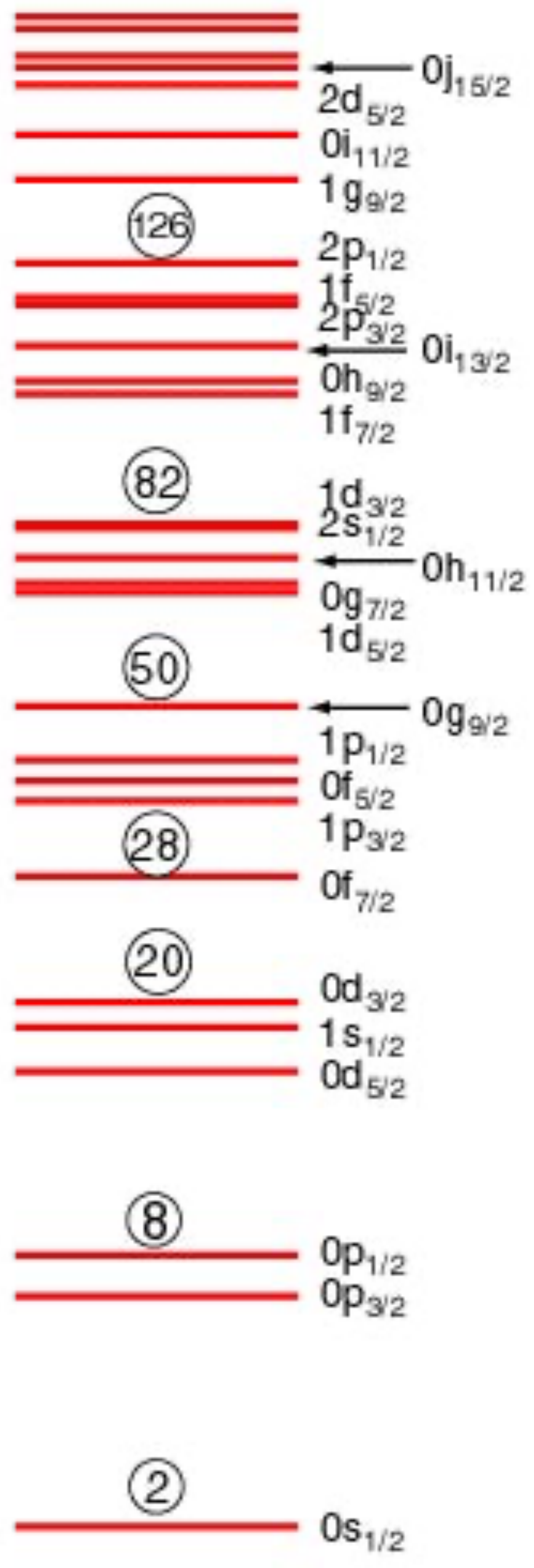
Life of star


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

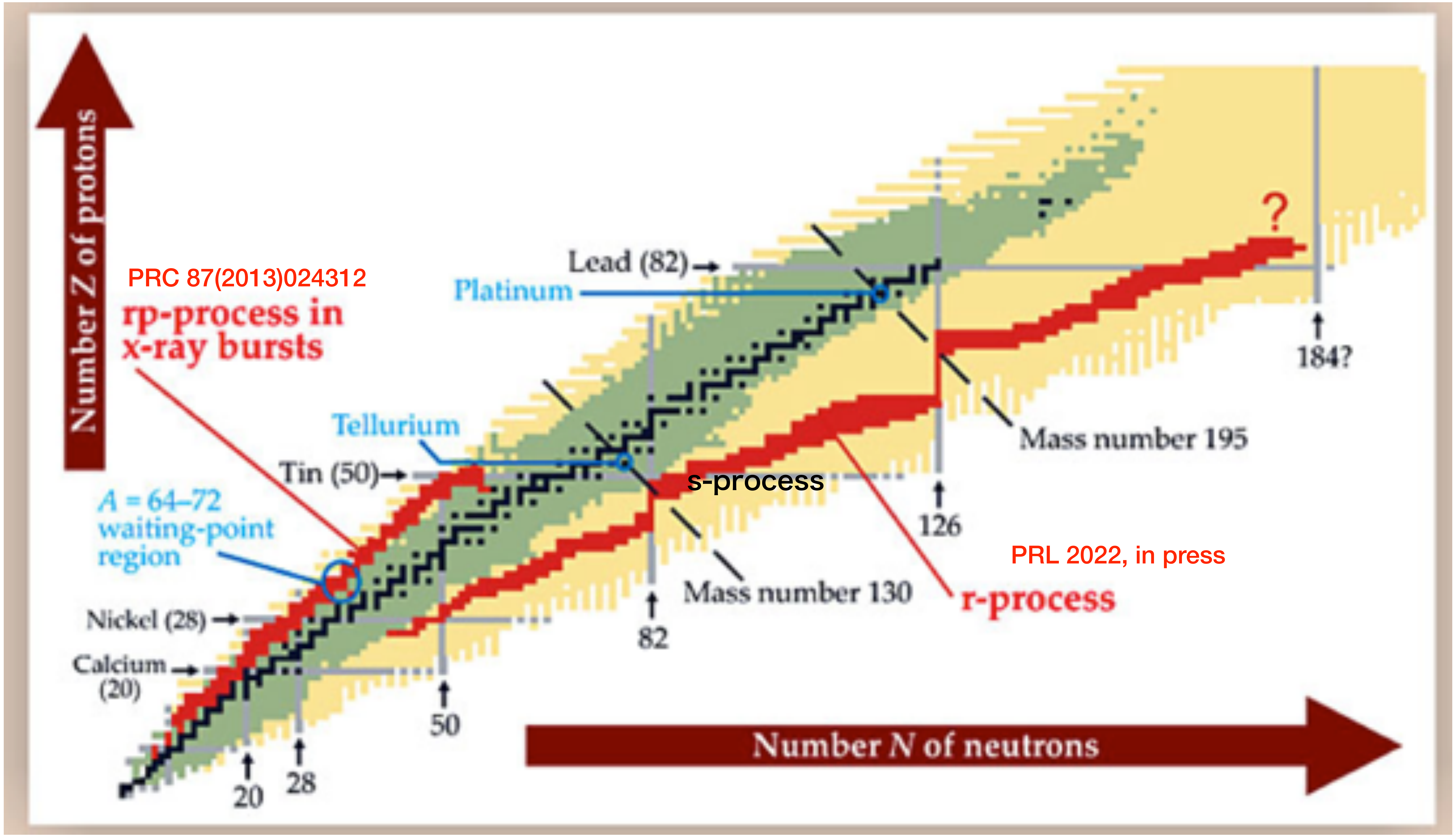
Peaks are the birthmark of nuclear physics: the magic number of the nuclear shell model



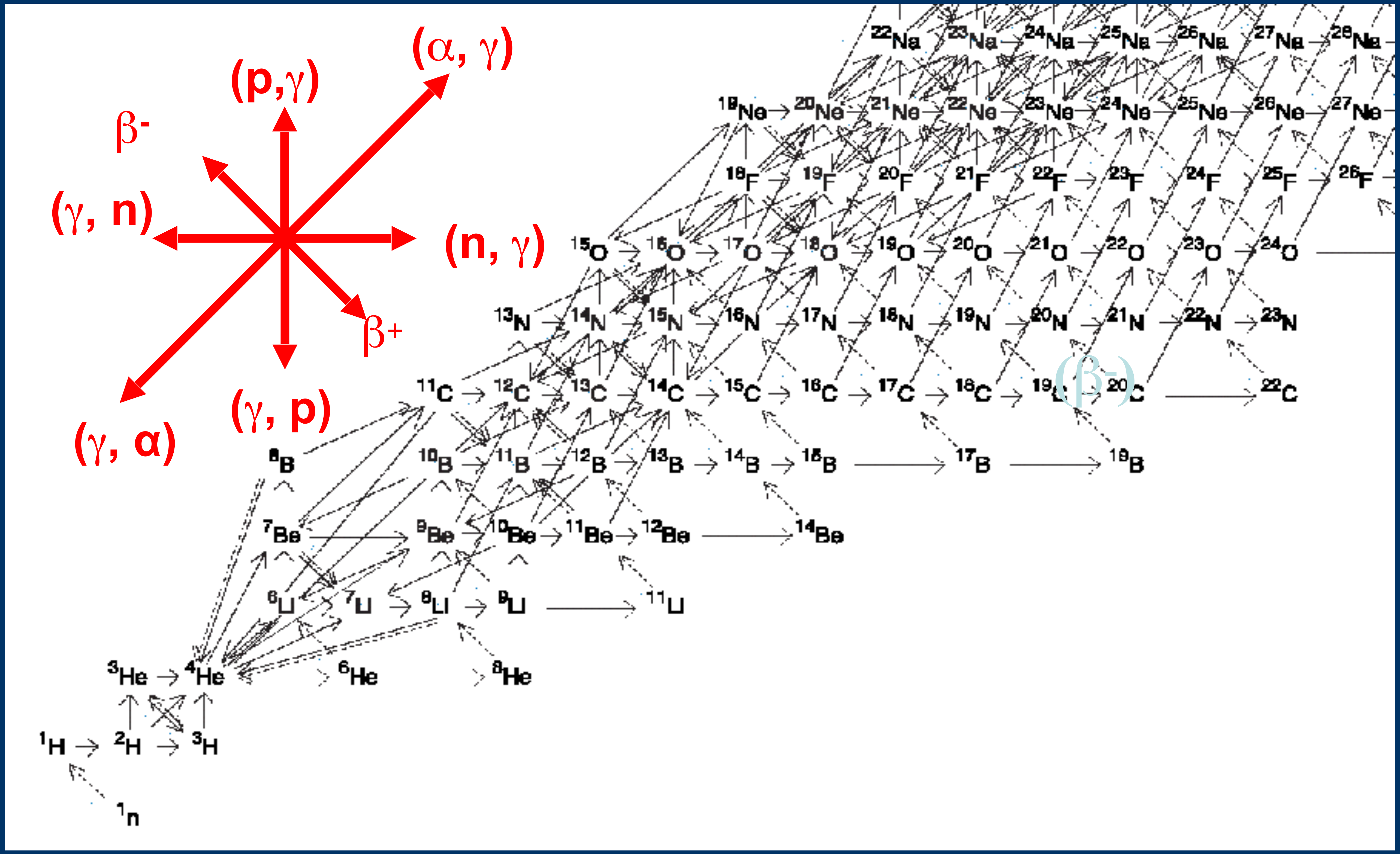


Shell Model of Nuclei

Elemental synthesis in nuclear chart



Element synthesis network



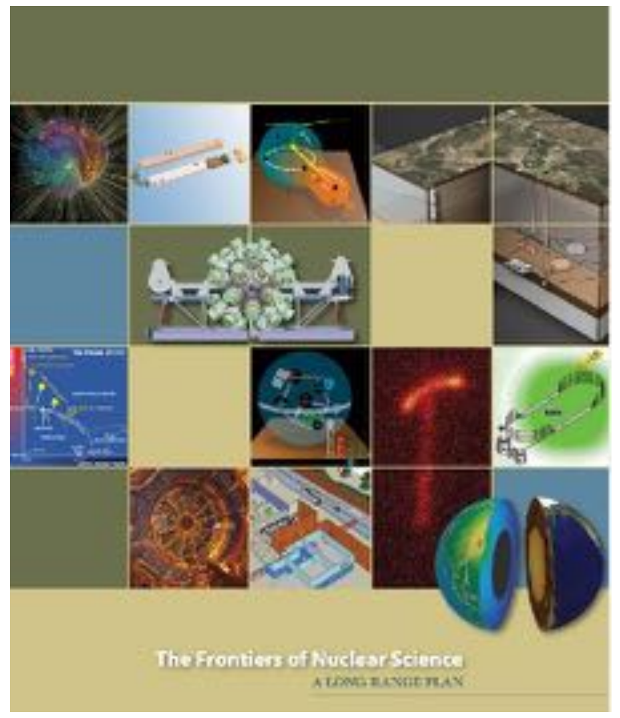
Cross section

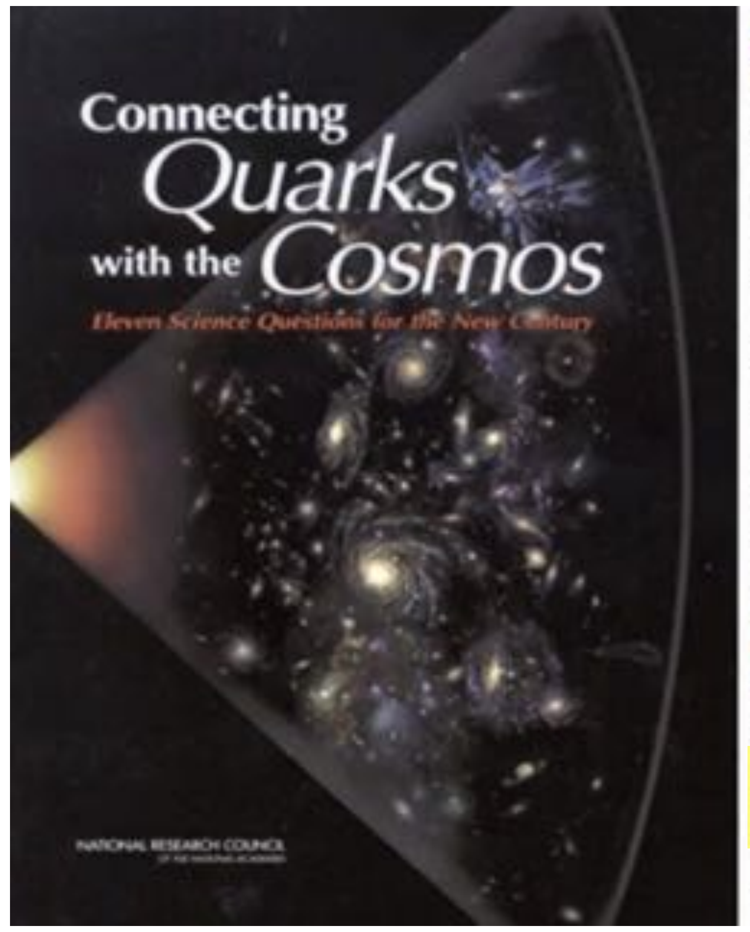
$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho N_A < \sigma V >_{jk,i} Y_j Y_k + \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A{}^2 < \sigma V >_{jkl,i} Y_j Y_k Y_l$$

Decay half-life

Nuclear astrophysics as frontier science

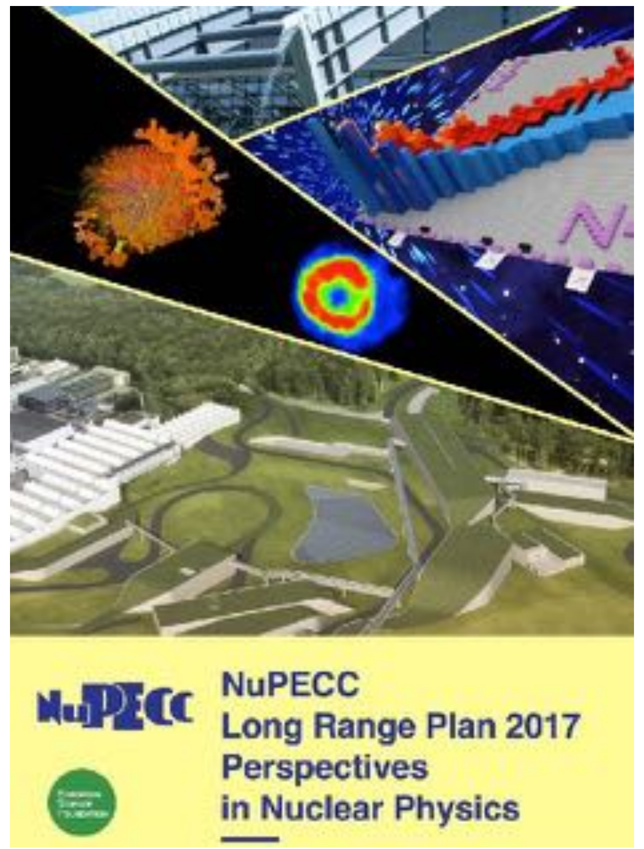
- 基金委数理科学13个优先领域中
  - 恒星的形成、演化与太阳活动
  - 极端条件下的核物理和核天体物理
- 美国DOE核科学中长期规划中
  - What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
  - What is the origin of simple patterns in complex nuclei?
  - What is the nature of neutron stars and dense nuclear matter?
  - What is the origin of the elements in the cosmos?元素起源
  - What are the nuclear reactions that drive stars and stellar explosions?驱动恒星演化和爆发的核反应



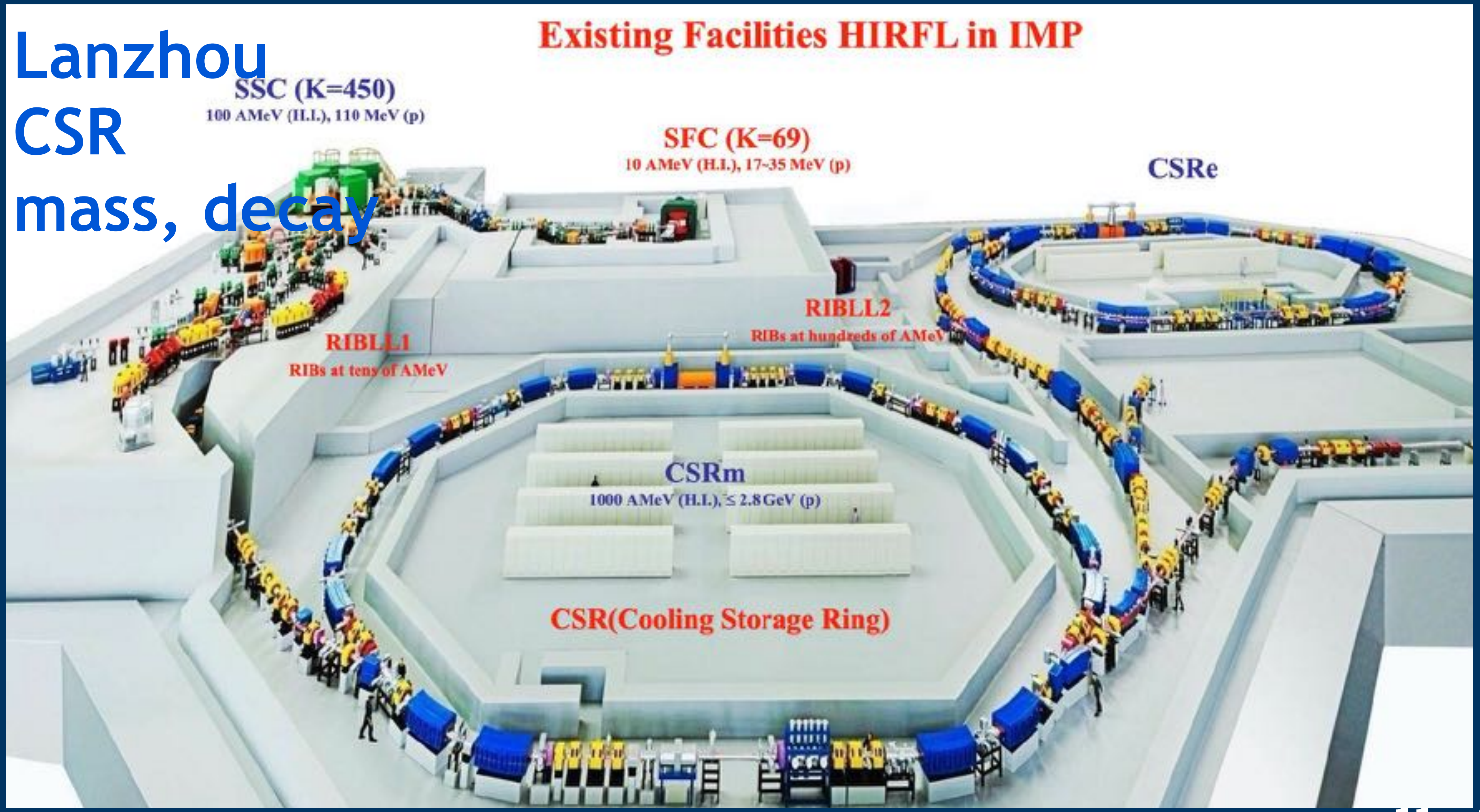


THE ELEVEN QUESTIONS IN 21st CENTURY

What Is Dark Matter?
What Is the Nature of the Dark Energy?
How Did the Universe Begin?
Did Einstein Have the Last Word on Gravity?
What Are the Masses of the Neutrinos and
How Have They Shaped the Evolution of the Universe?
How Do Cosmic Accelerators Work and What Are They Accelerating?
Are Protons Unstable?
What Are the New States of Matter at Exceedingly High Density and Temperature?
Are There Additional Space-Time Dimensions?
How Were the Elements from Iron to Uranium Made?
Is a New Theory of Matter and Light Needed at the Highest Energies?



Major facilities in China



W. P. Liu, 2022, NuSYS

Joint efforts 方法论

LUNA, 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

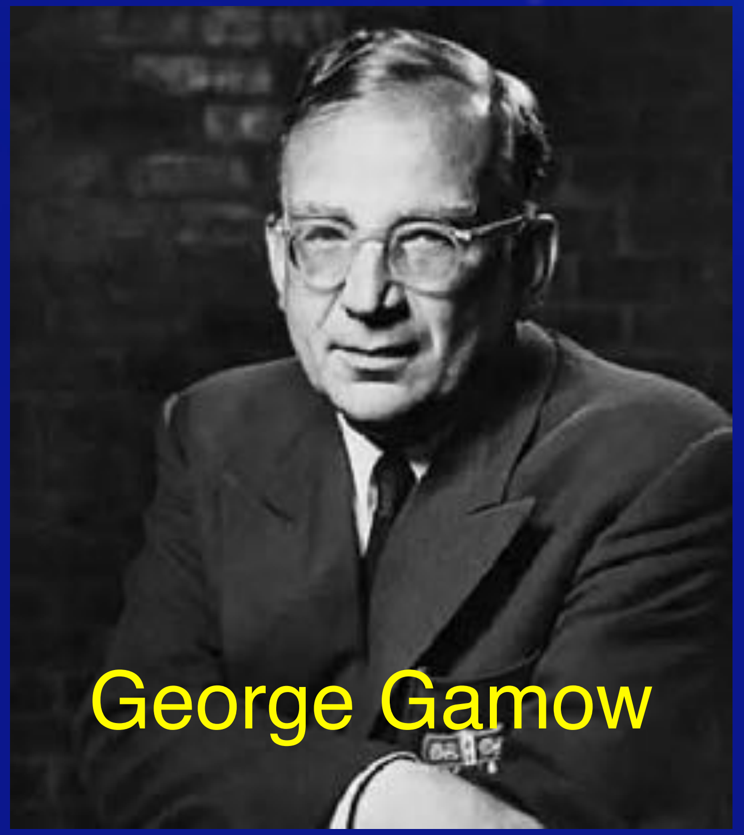
RECLIB…

Nuclear input database

AME…

Mass and decay rate database

需要超大曝光 High exposure



coulomb term

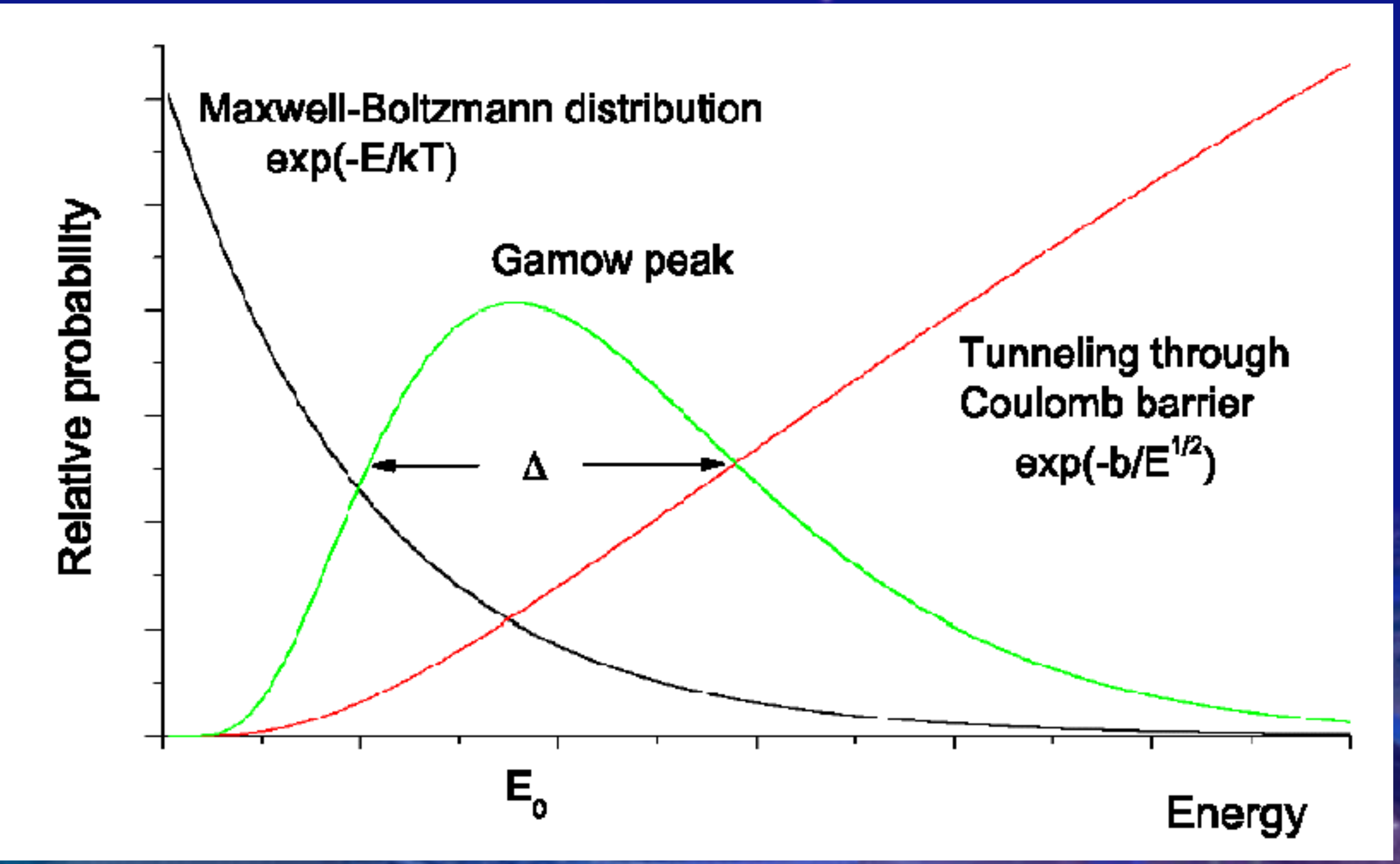
$$\sigma(E) = S(E)e^{-2\pi\eta}\frac{1}{E}$$

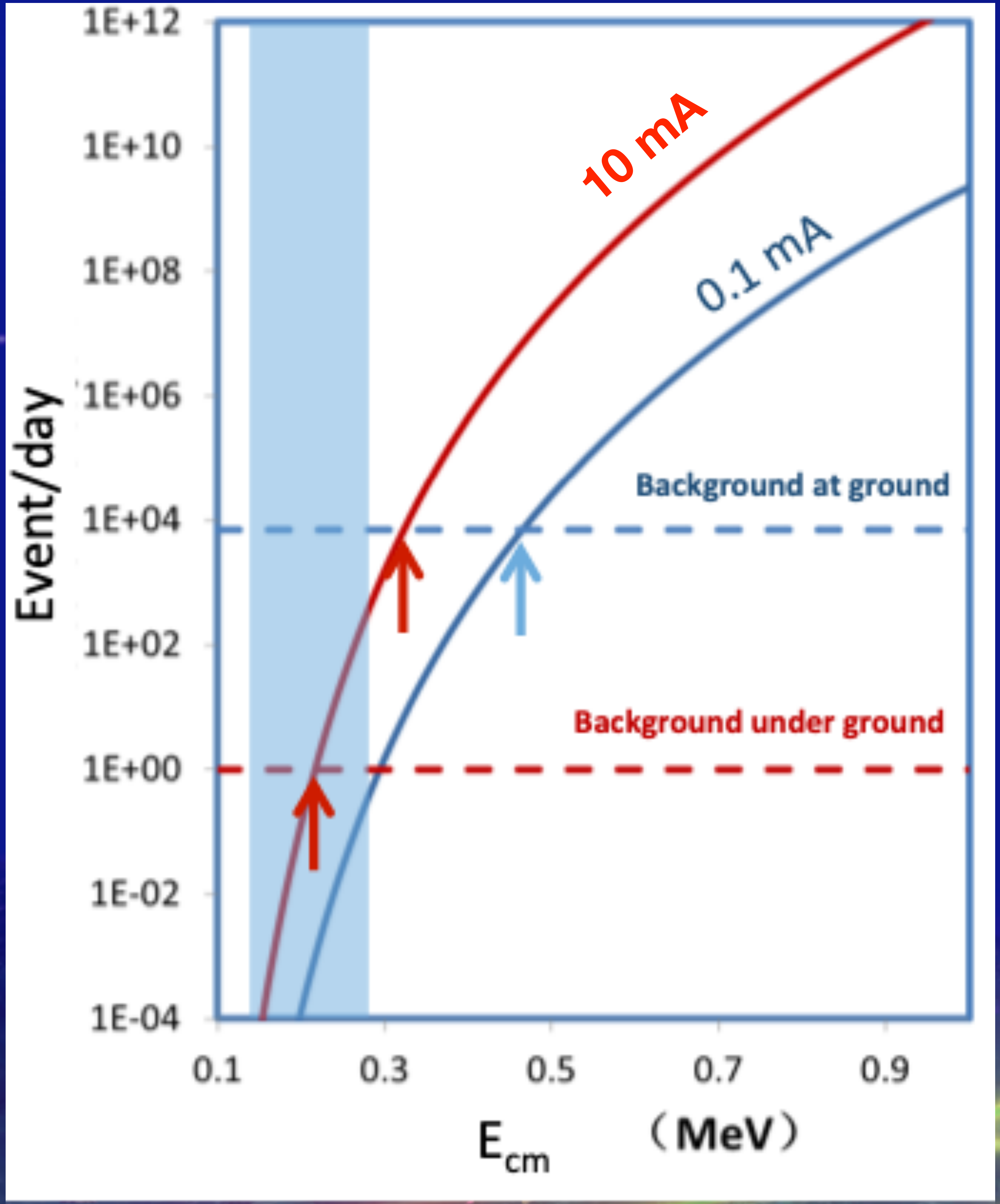
astrophysical s factor

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

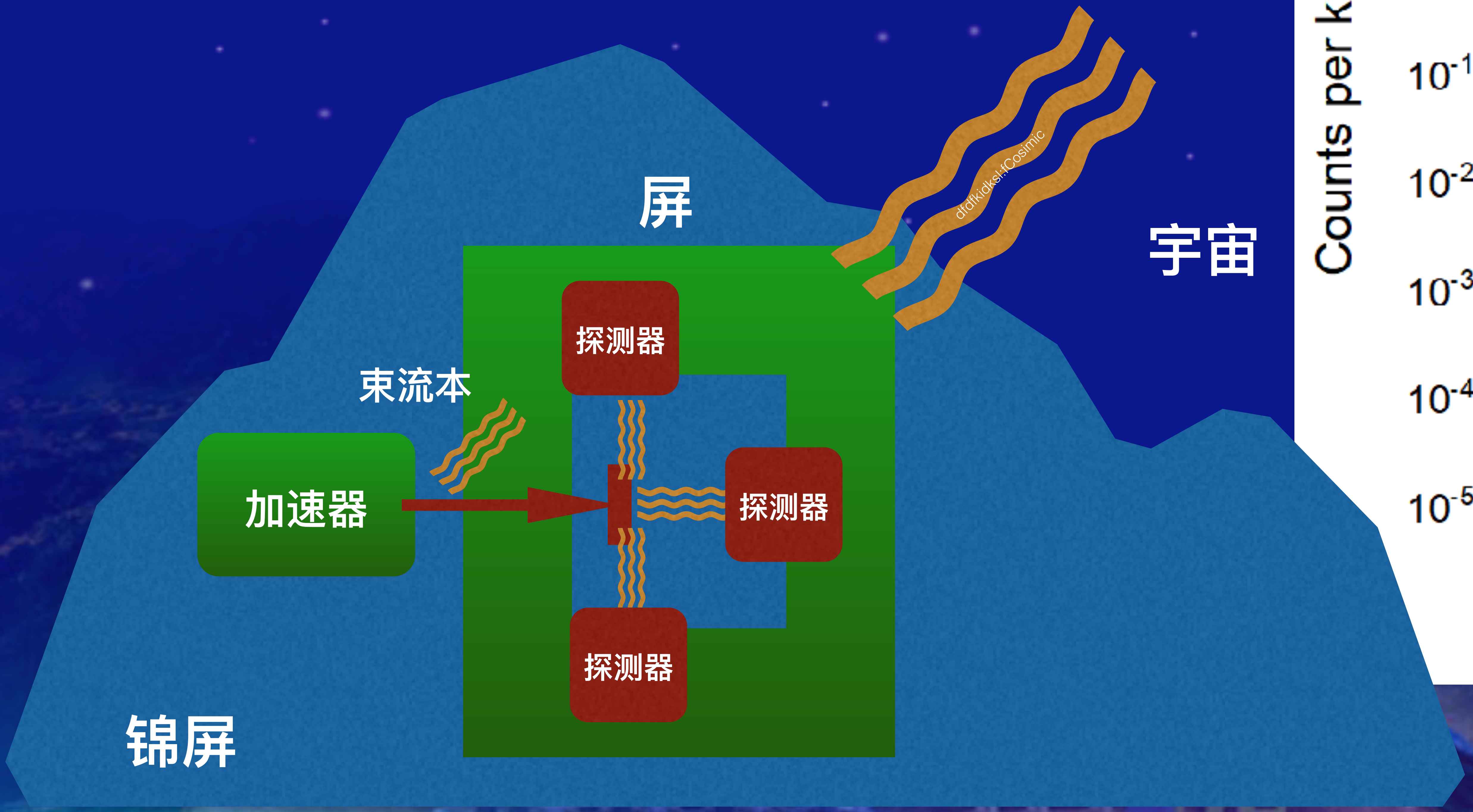
$$E_0 = 1.22(Z_1^2 Z_2^2 M T_6^2)^{1/3}\text{keV}$$

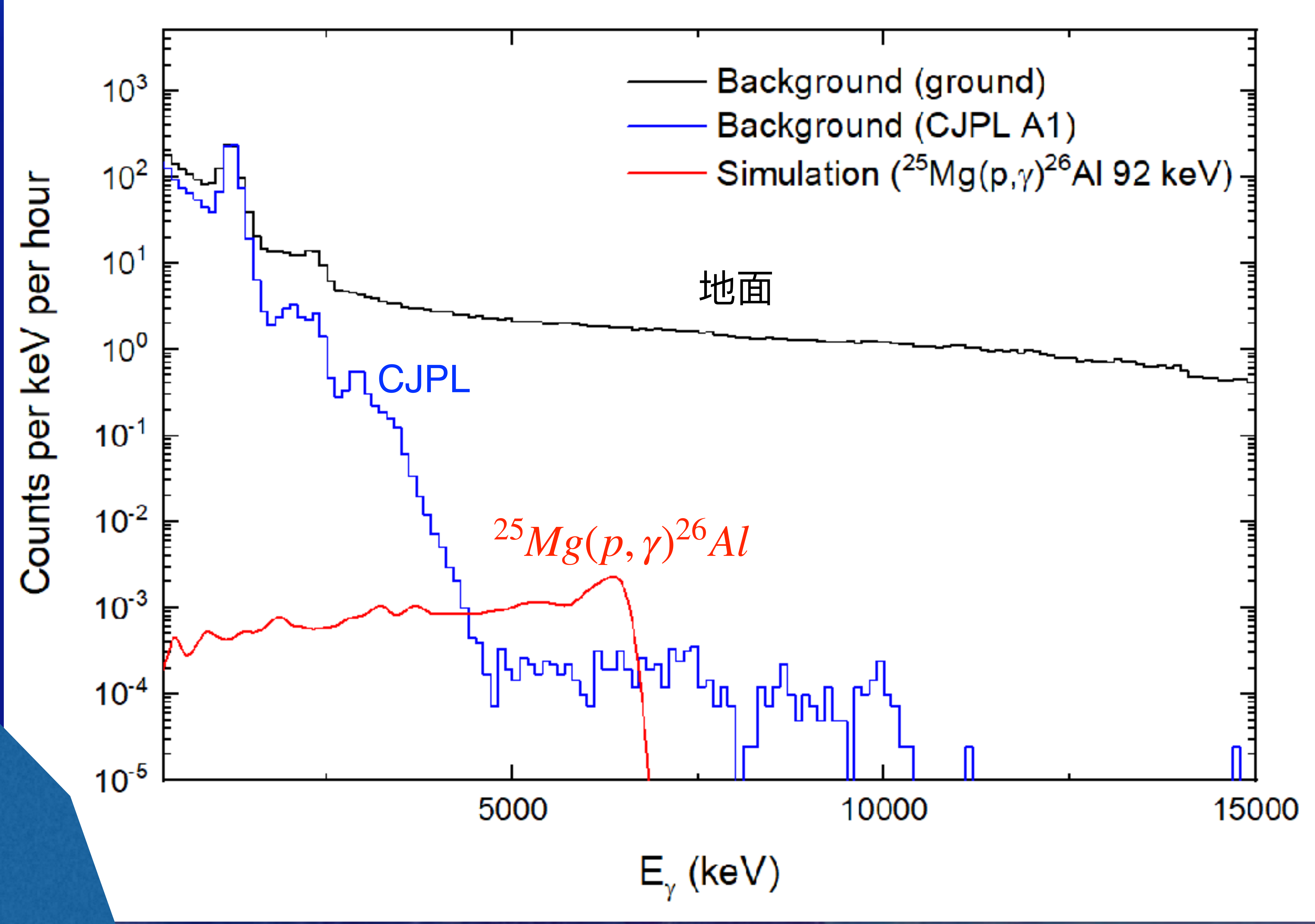
Gamow window





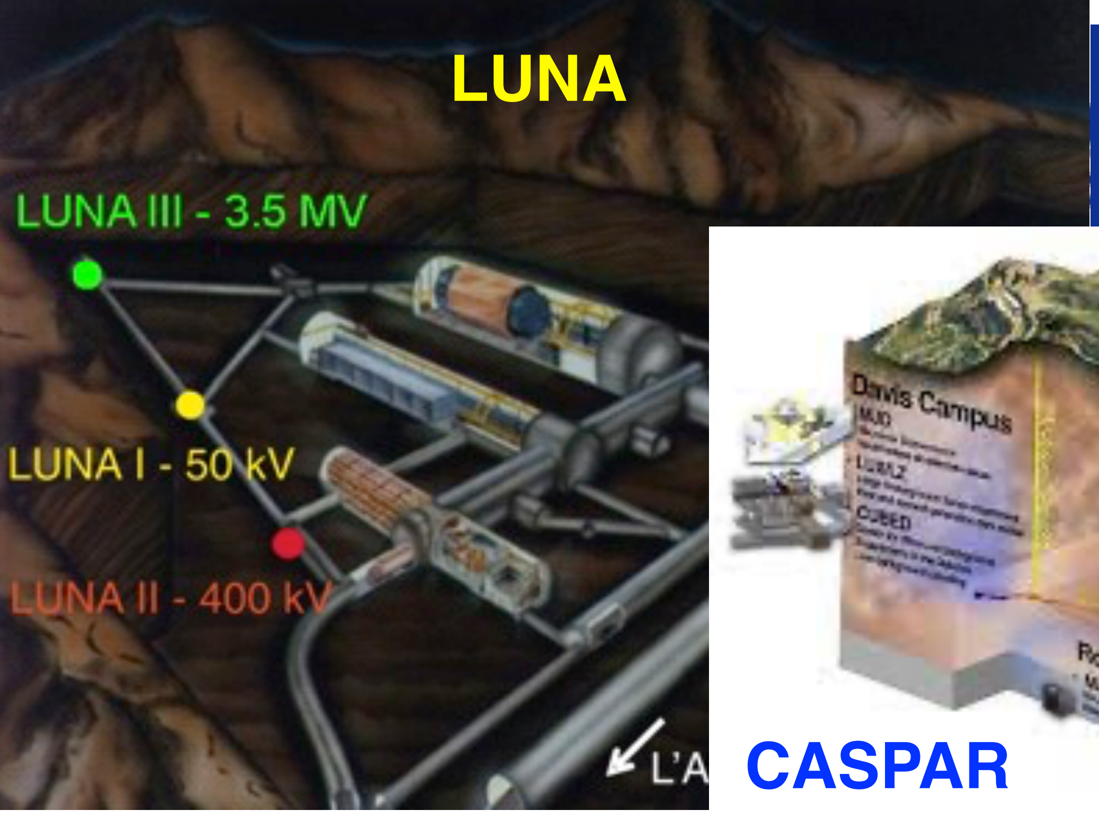
需要大海捞针 Underground

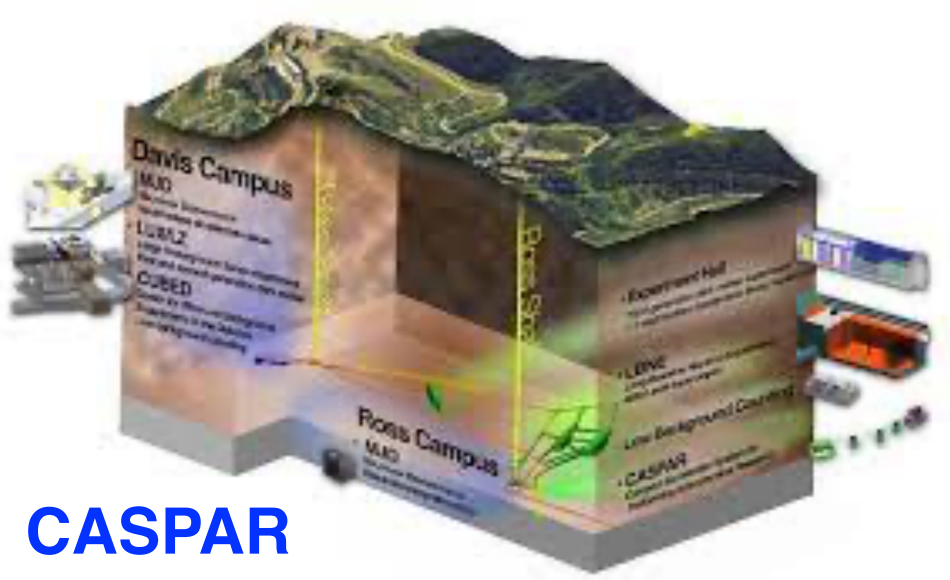




WPL et al., Sci. China 59(2016)2

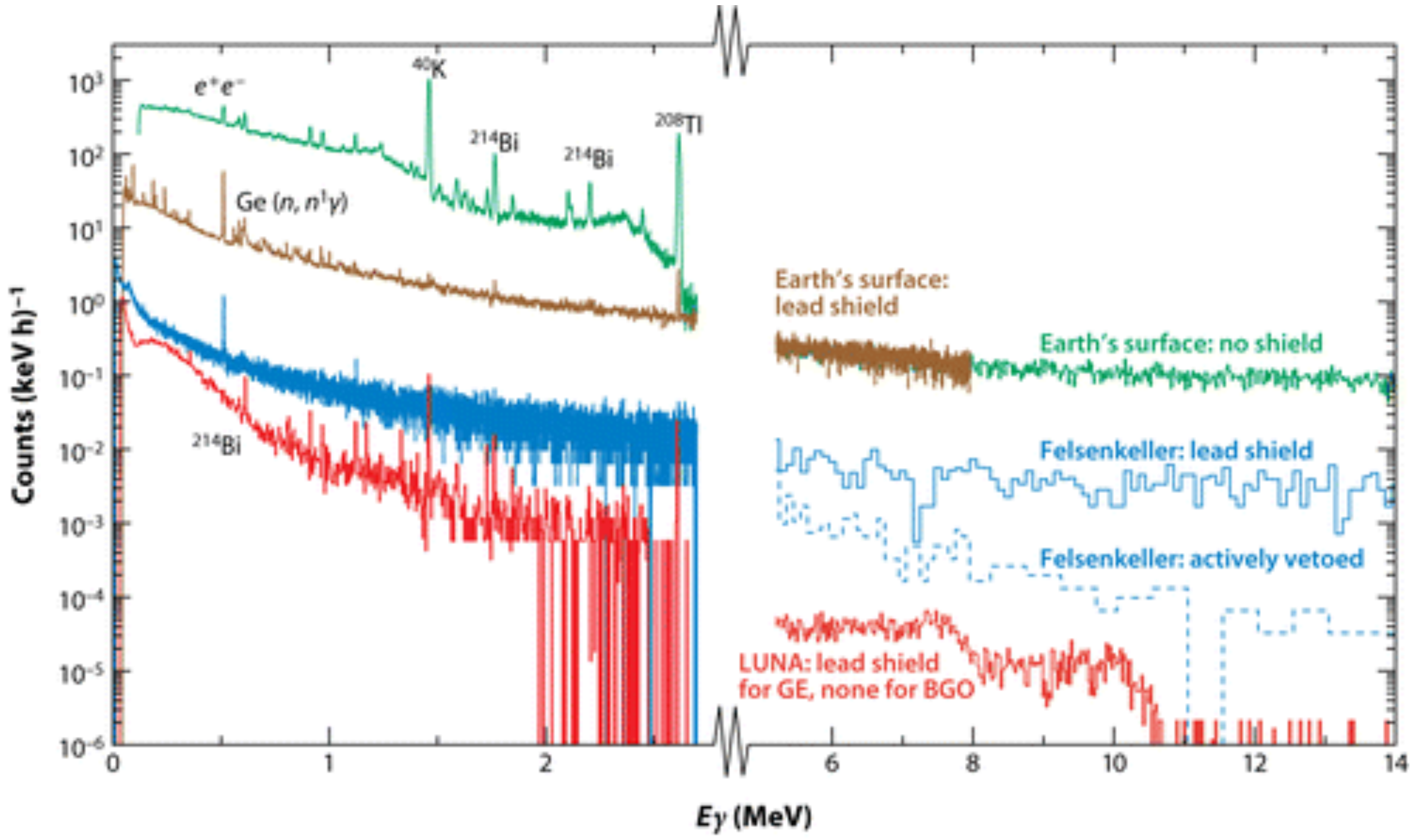
LUNA and CASPAR nuclear astrophysics

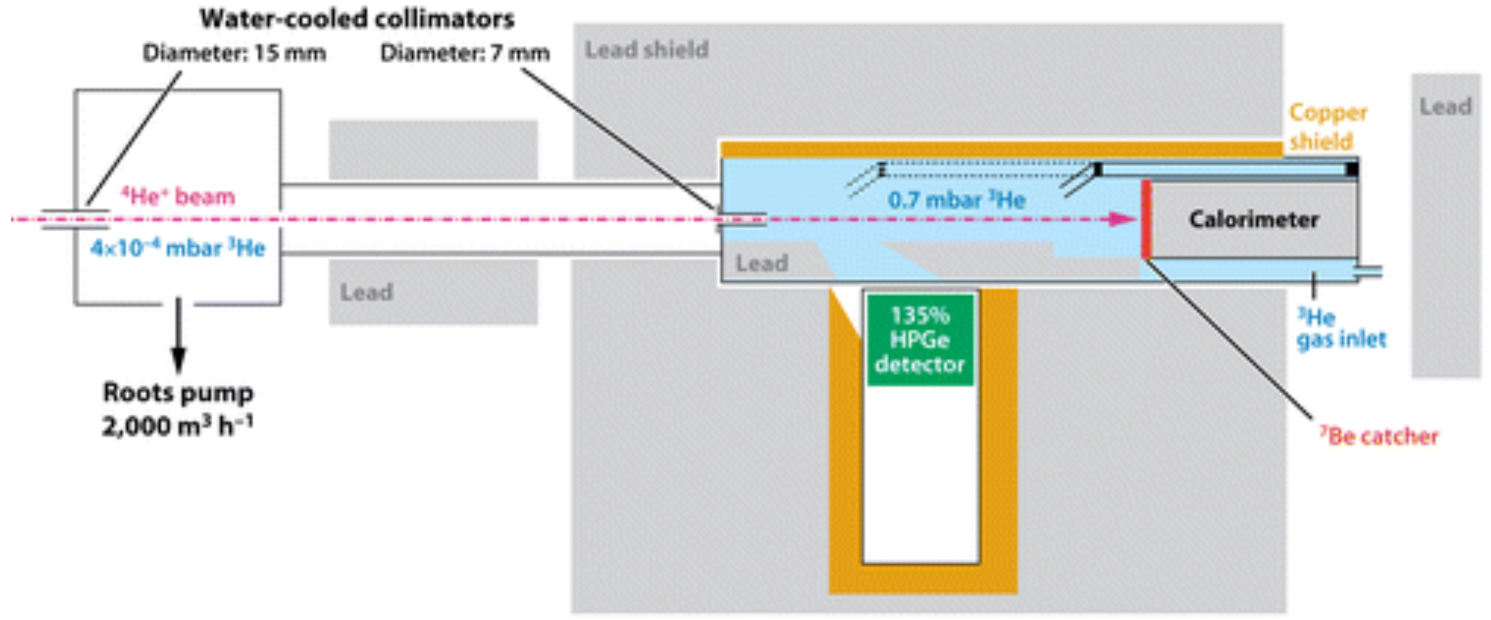




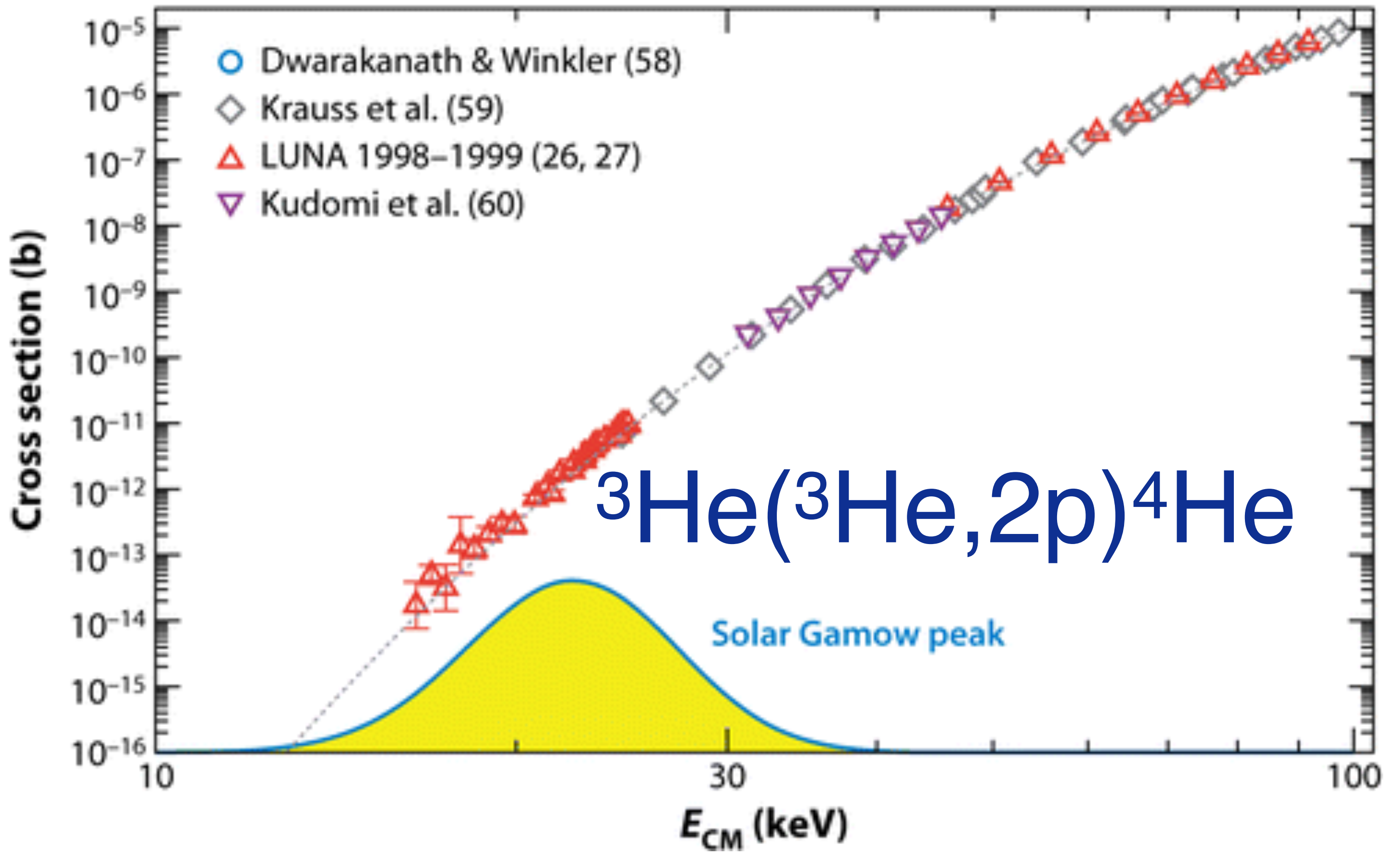
CASPAR

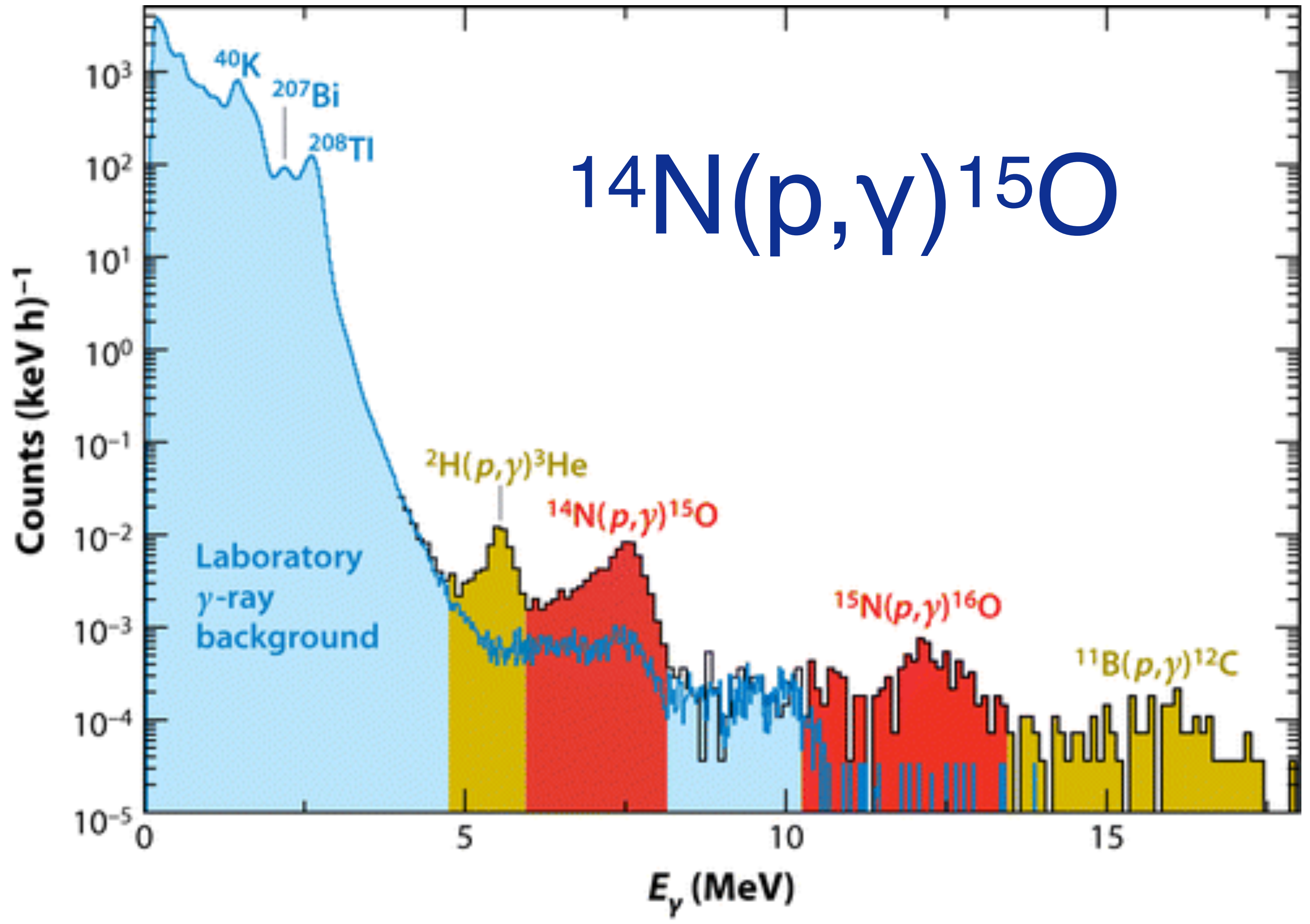
F. Cavanna et al., PRL 115(2015)252501, $^{22}Ne(p,\gamma)^{23}Na$.
F. Ciani et al. PRL 127(2021)152701, $^{13}C(\alpha,n)^{16}O$
V. Mossa et al., Nature 587(2020)210 , $D(p,\gamma)^{3}He$
A. C. Dombos et al., PRL 128(2022)162701, $^{18}O(\alpha,\gamma)^{22}Ne$





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

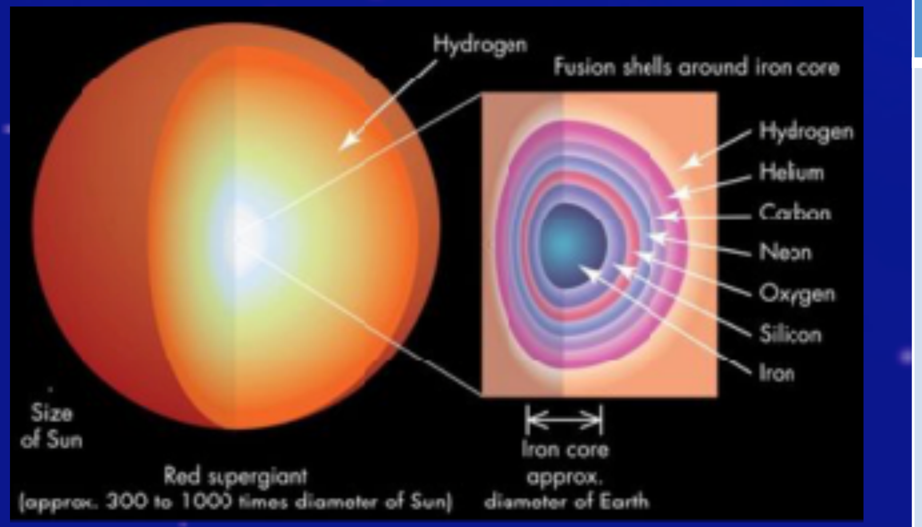
$^{15}N(p,\gamma)^{16}O$
PRC82, 055804(2010)

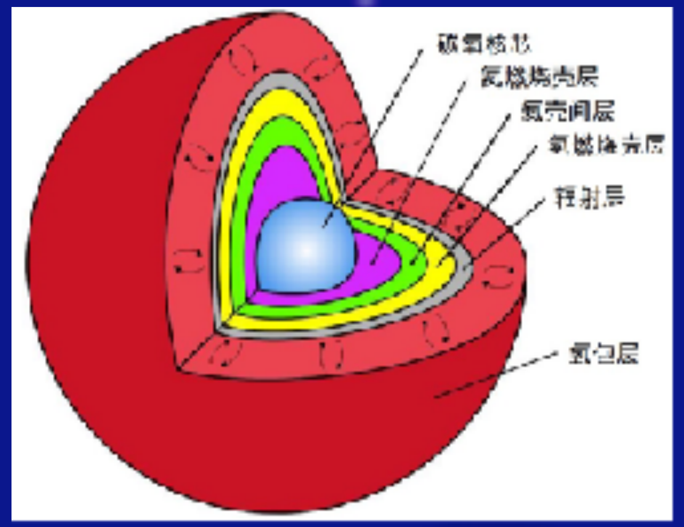
$^{17}O(p,\gamma)^{18}F$
PRL 109, 202601(2012)

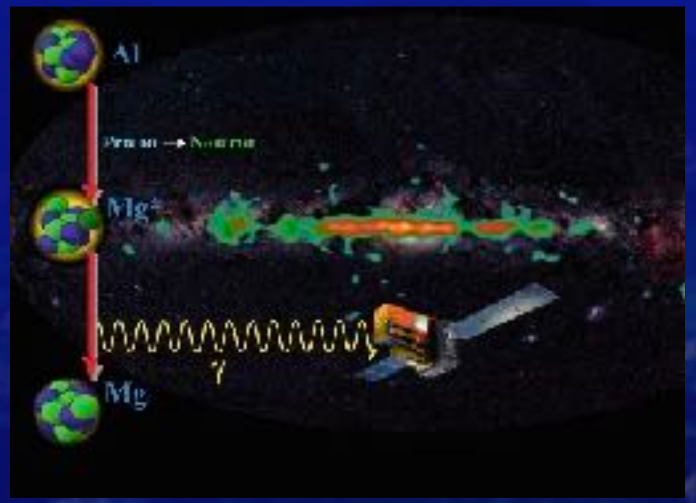
$^{25}Mg(p,\gamma)^{26}Al$
PLB 707(2012) 60

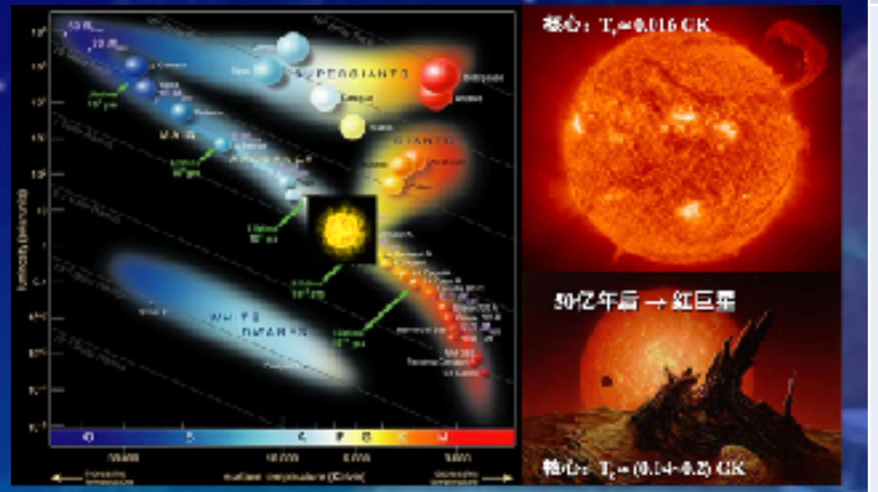
Uncertainty remained for key reactions 天时

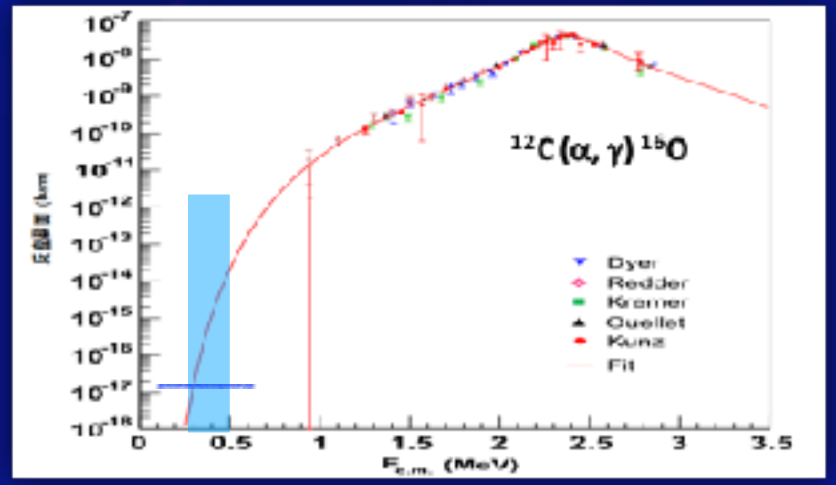
Physics	Reaction	Current	Desired
Massive star	$^{12}C(\alpha,\gamma)^{16}O$	60% 890 keV	20% 220-380 keV
s-process neutron source	$^{13}C(\alpha,n)^{16}O$	60% 230 keV	10% 140-230 keV
Galaxy ^{26}Al source	$^{25}Mg(p,\gamma)^{26}Al$	20% 92 keV	5% 50-300 keV
F aboundace	$^{19}F(p,\alpha)^{16}O$	80 % 189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



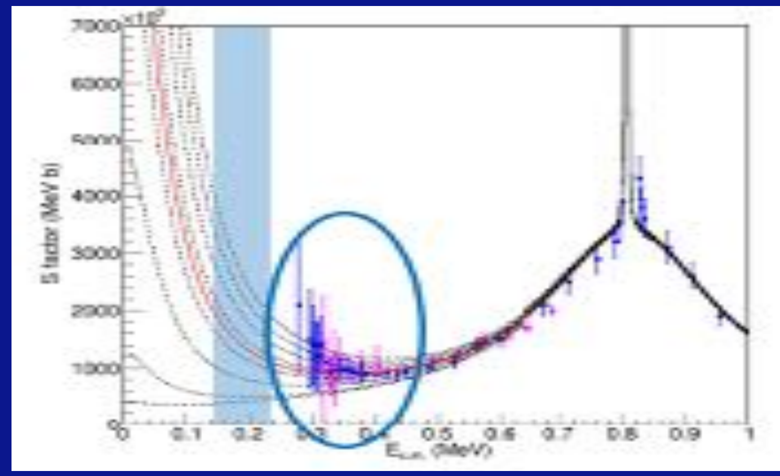




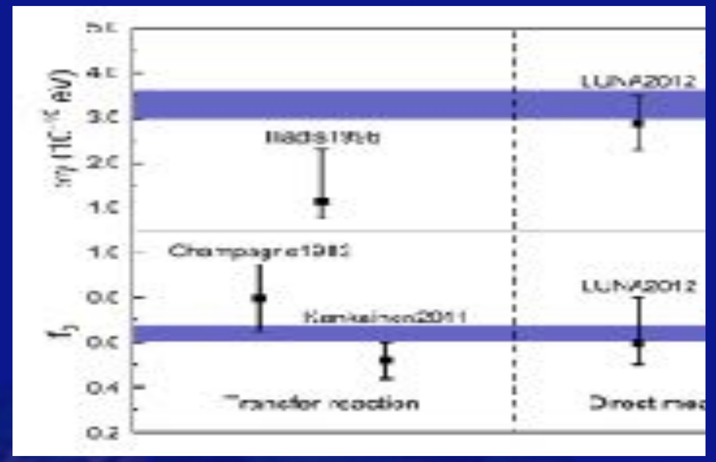




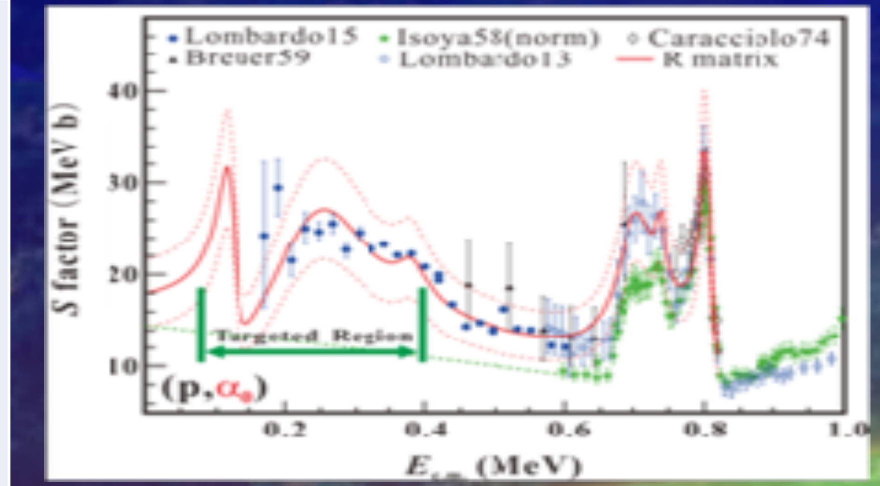
R. J. deBoer et al., RMP vol. 89, 2017



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



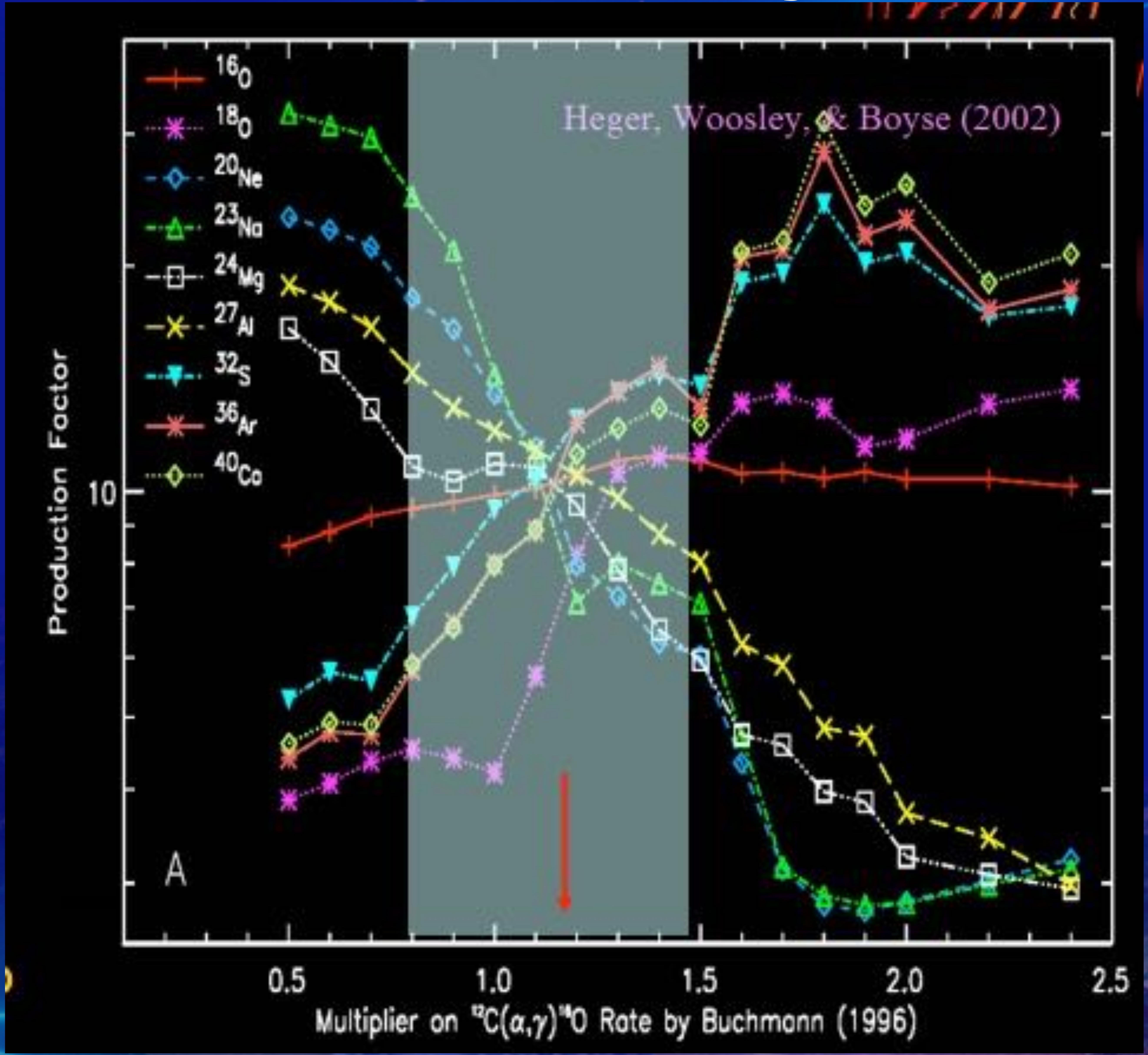
G.F. Ciani et al. PRL 127(2021)152701

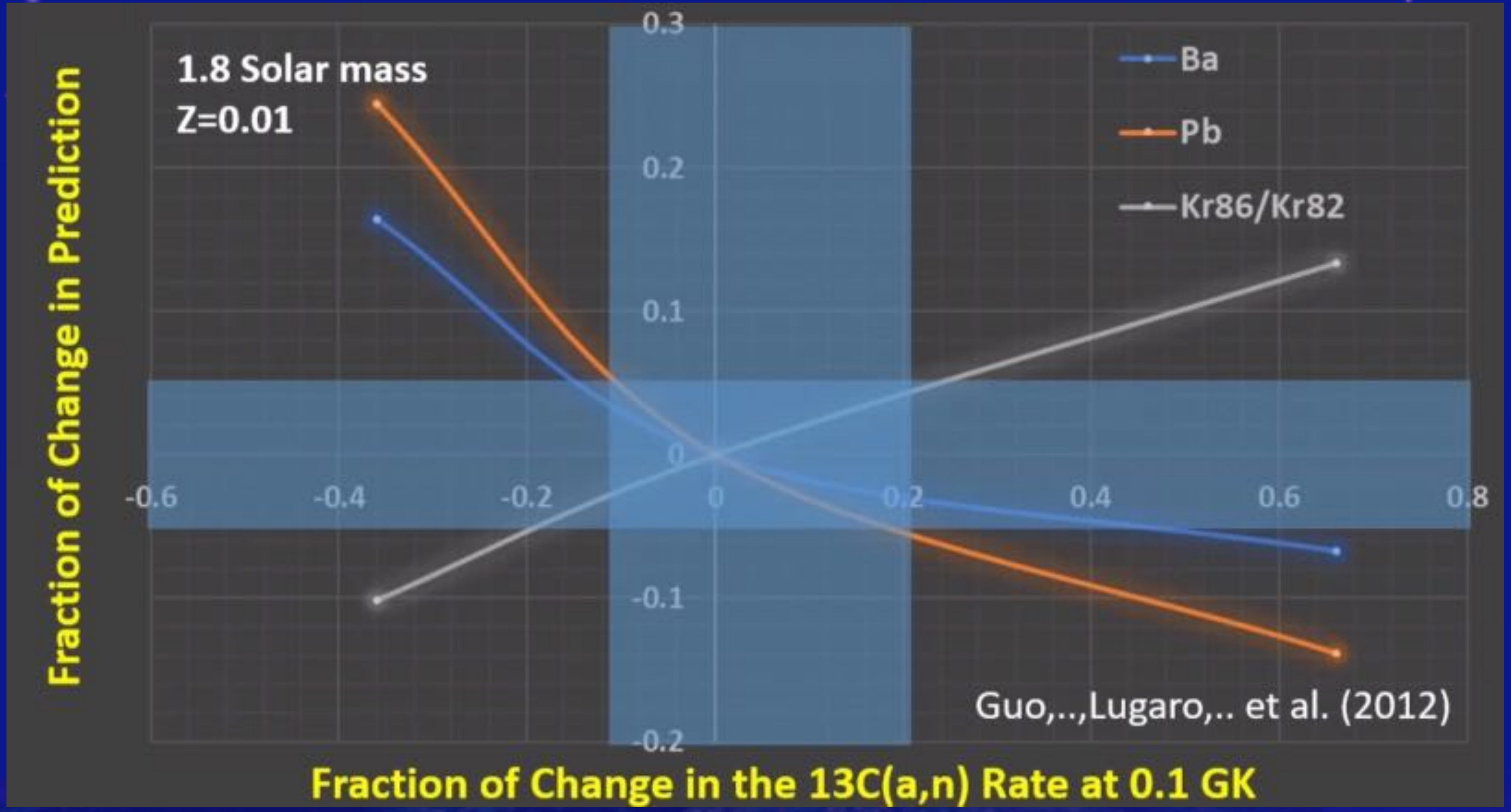


J. J. He et al., Sci. China Phys 59（2016）652001

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

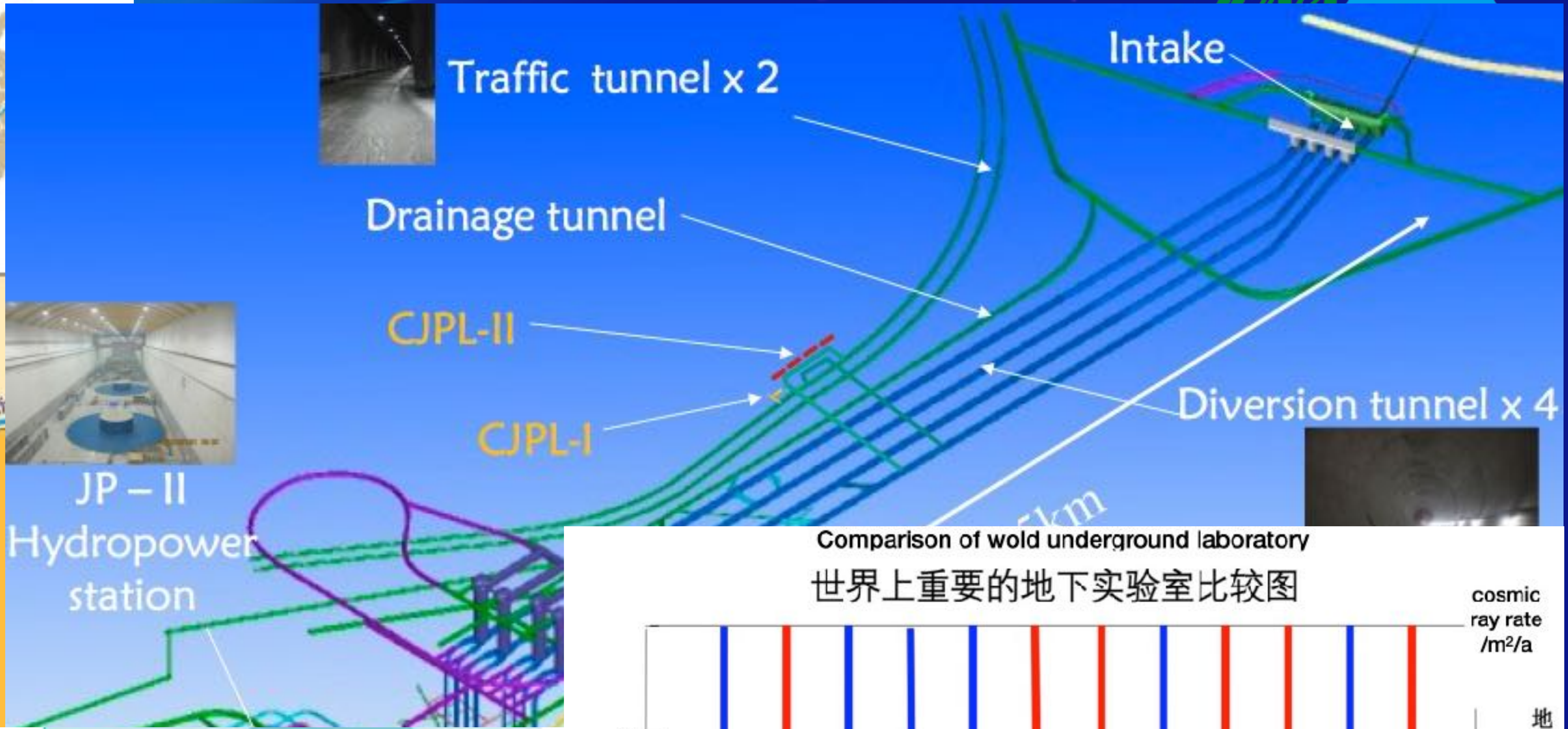
Uncertainty and abundance

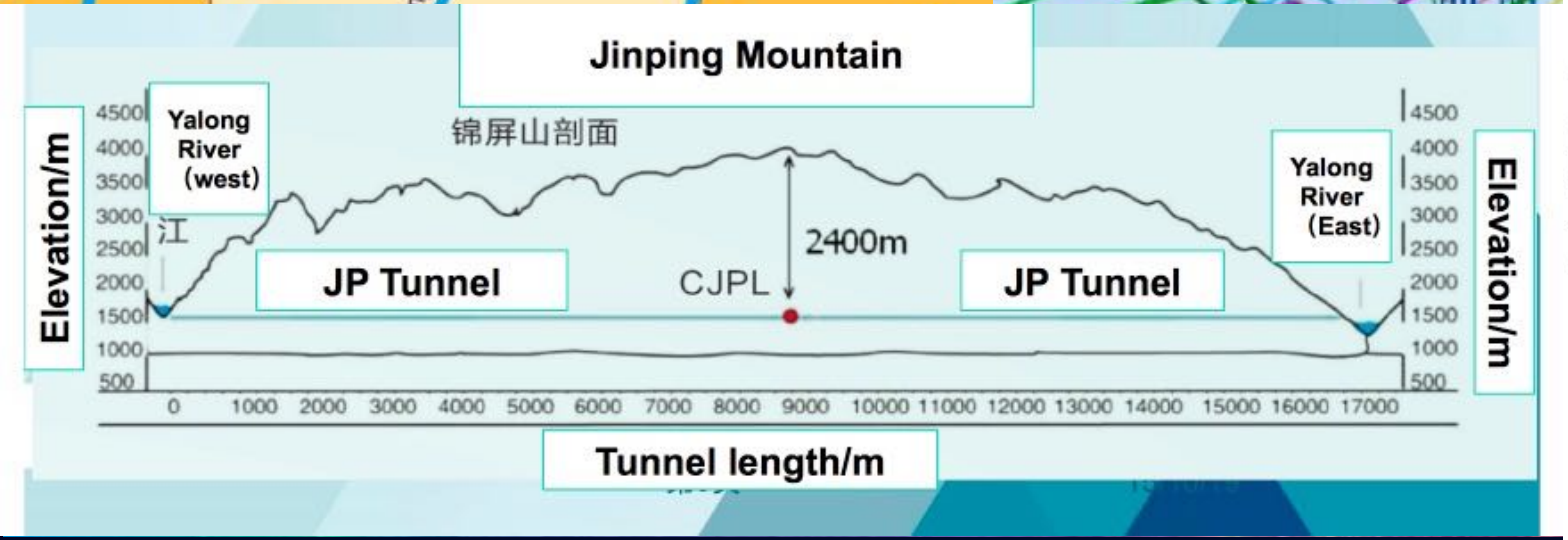


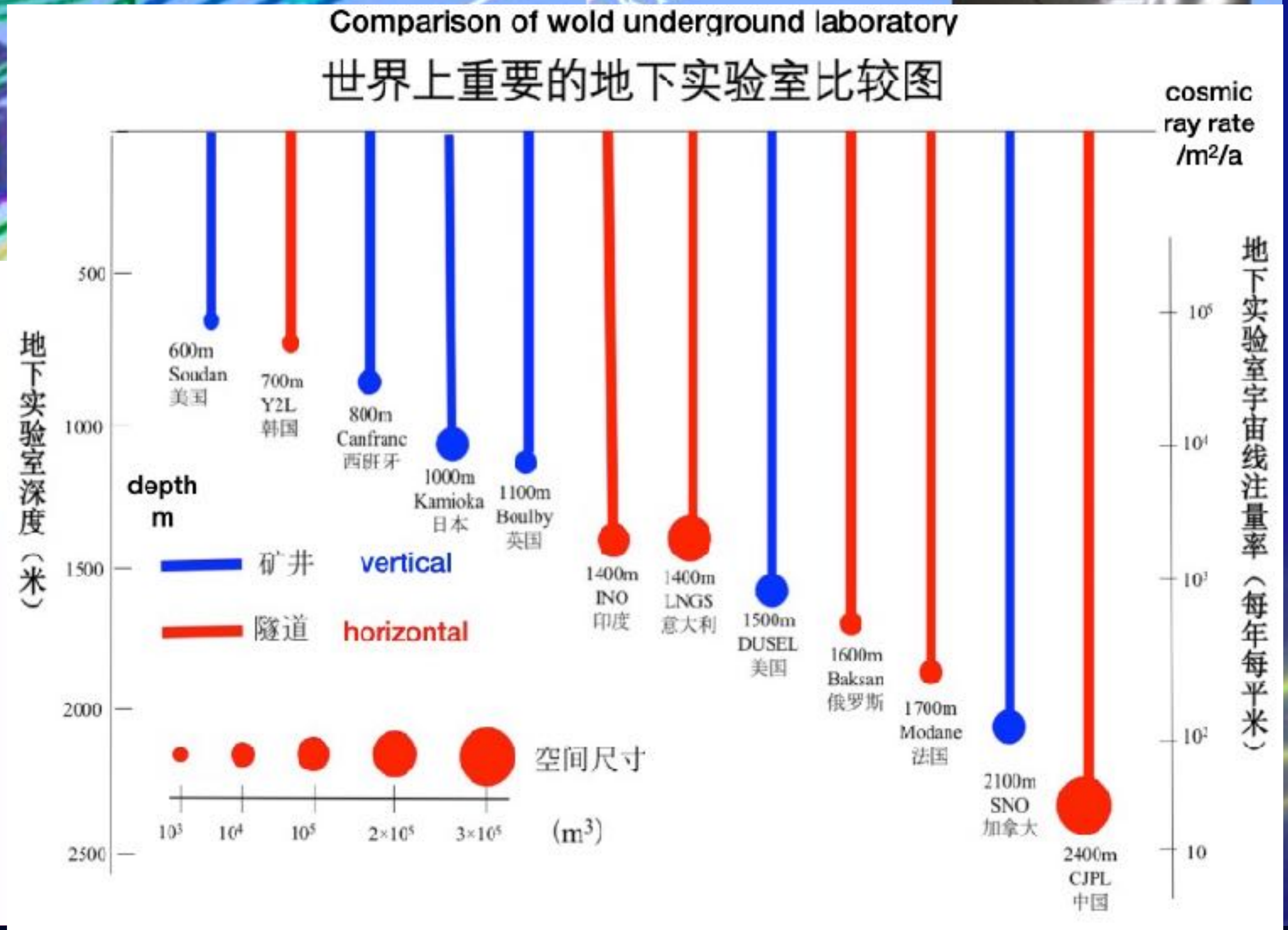


CJPL

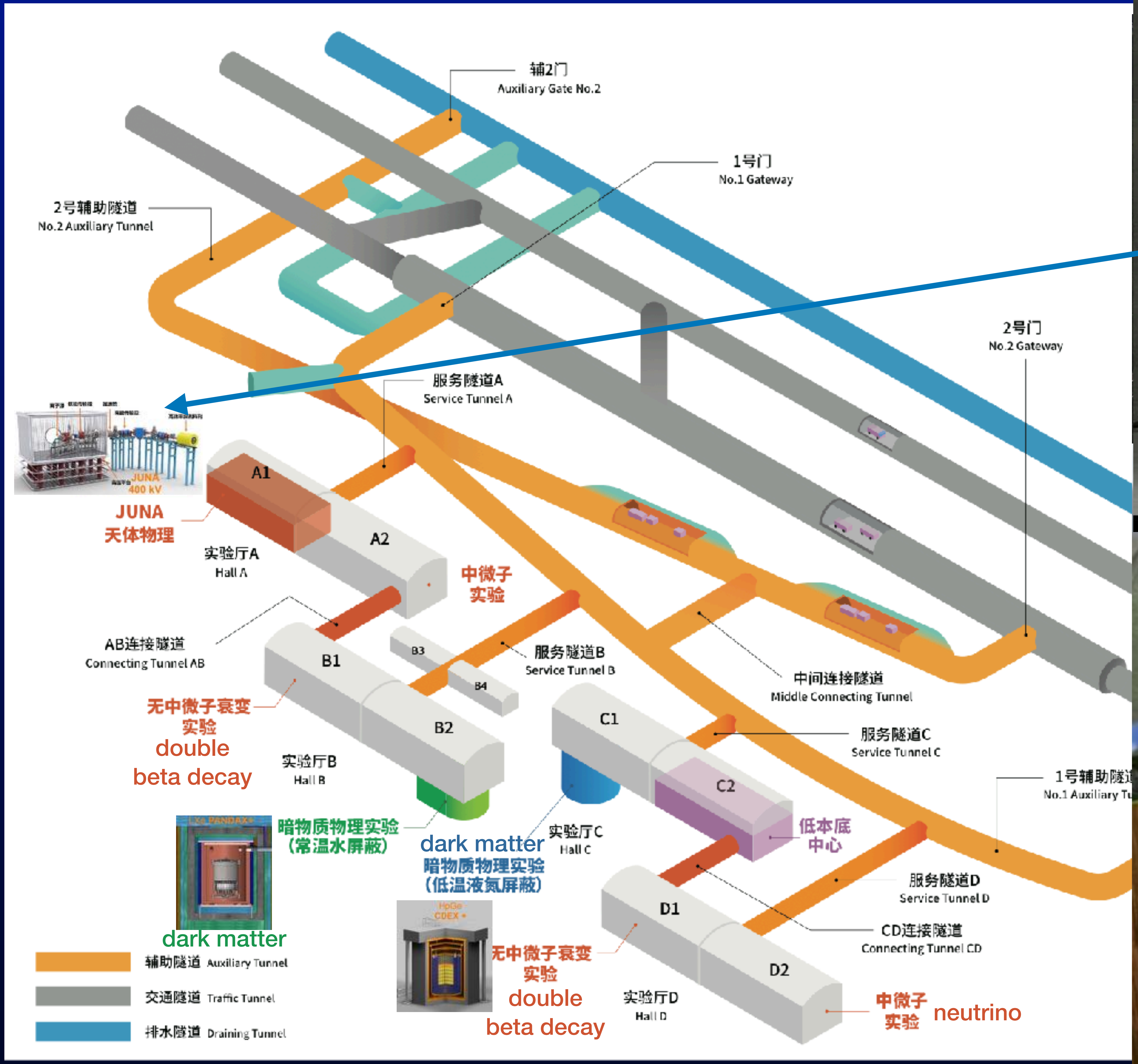

CHINA
Sichuan
Sichuan Province
YaLongRiver
Jinsha Ri
Jinping tunnels


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


Jinping Mountain
锦屏山剖面
Elevation/m
Yalong
River
(west)
Yalong
River
(East)
JP Tunnel
CJPL
2400m
JP Tunnel
Elevation/m
4500
4000
3500
3000
2500
2000
1500
1000
500
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）
地下实验室宇宙线注量率（每年每平米）
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
(m³)

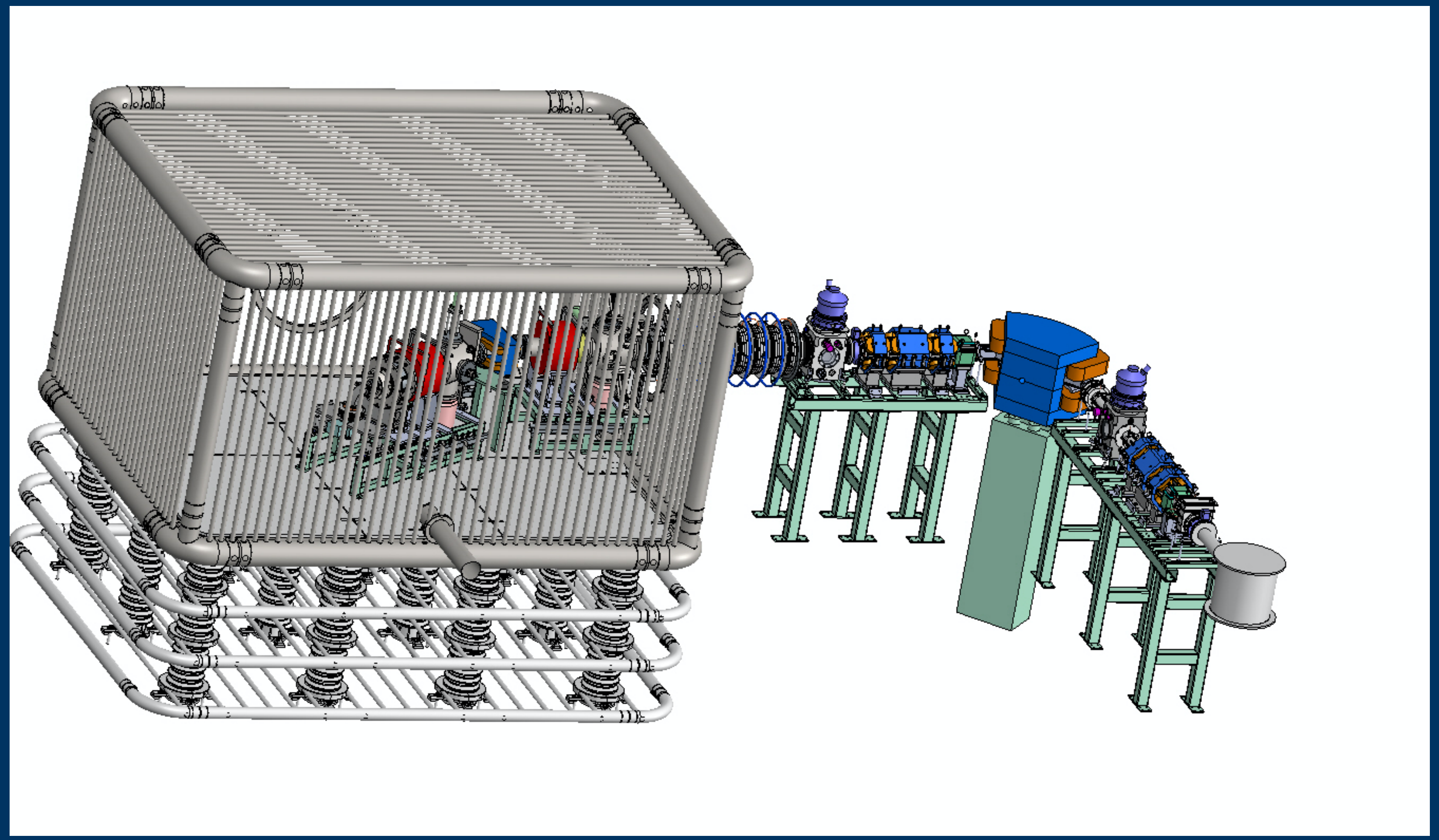
Most silent location: CJPL



JUNA dream team

JUNA

Group leader



Weiping Liu
$^{12}C(\alpha,\gamma)^{16}O$
Yangping Shen, CIAE
Jun Su, BNU
PI

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

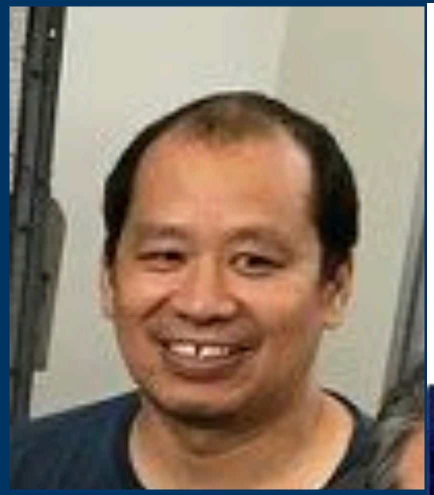
Shuo Wang
$^{14}N(p,\gamma)^{15}O$
SDU

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 funding 经费

NSFC $2.9+M	CAS $0.65M	CNNC $1.6 M

CJPL-II / Tsinghua ~$3+M

Detectors（NSFC $1.3M）

Electronics, shielding (NSFC $1.0M)

Ion source (CAS $0.65M), accelerator (CNNC $1.6M)

Lab CJPL II（CNNC, Tsinghua，NSFC $3+M）

total $8+ M

国家自然科学基金委员会
National Natural Science Foundation of China

中国科学院
CHINESE ACADEMY OF SCIENCES

中核集团
CNNC

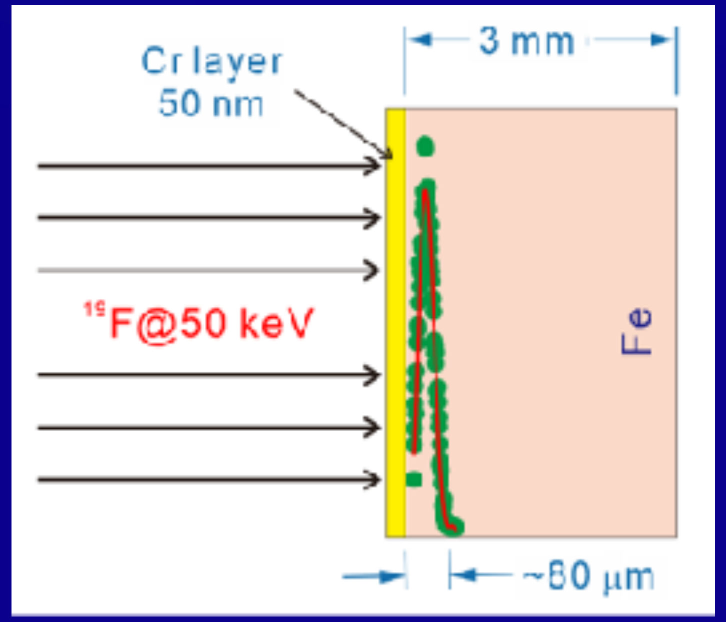
Need to apply for JUNA II and welcome international contribution

耐辐照反应靶技术

耐辐照性是国际同类最好水平的3-10倍

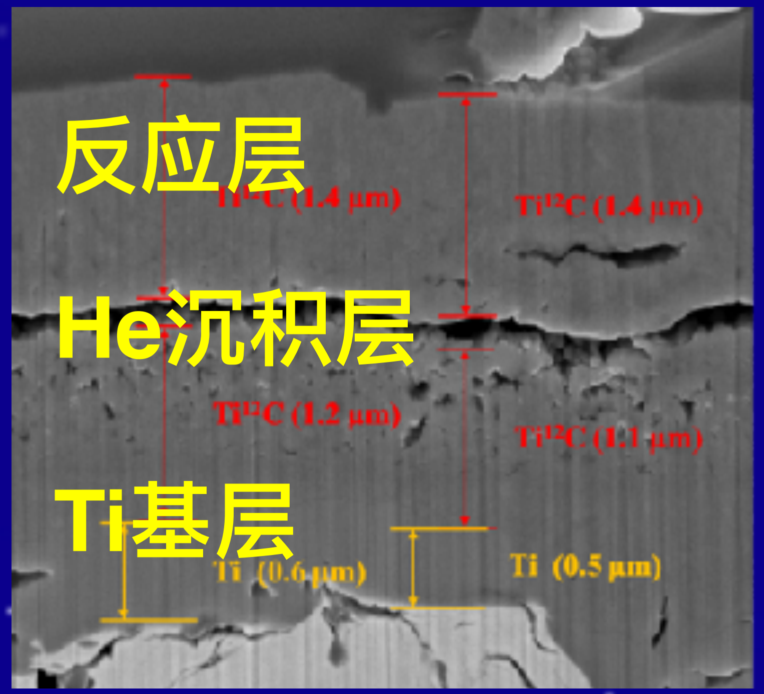
^{19}F注入靶技术

- 高纯度铁衬底
- 磁控镀铬提高稳定性
- 耐辐照能力比传统氟化钙靶提高10倍(10库仑→100库仑)



^{12}C离子沉积靶

- FCVA离子沉积致密成膜
- ^{12}C富集99.99%
- 耐辐照达400库仑

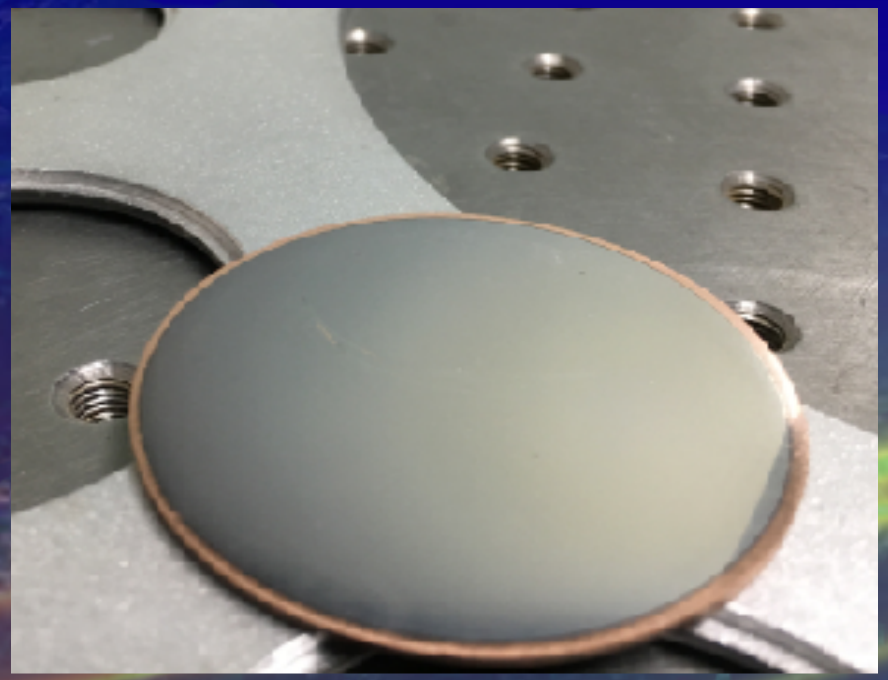


^{13}C同位素厚靶

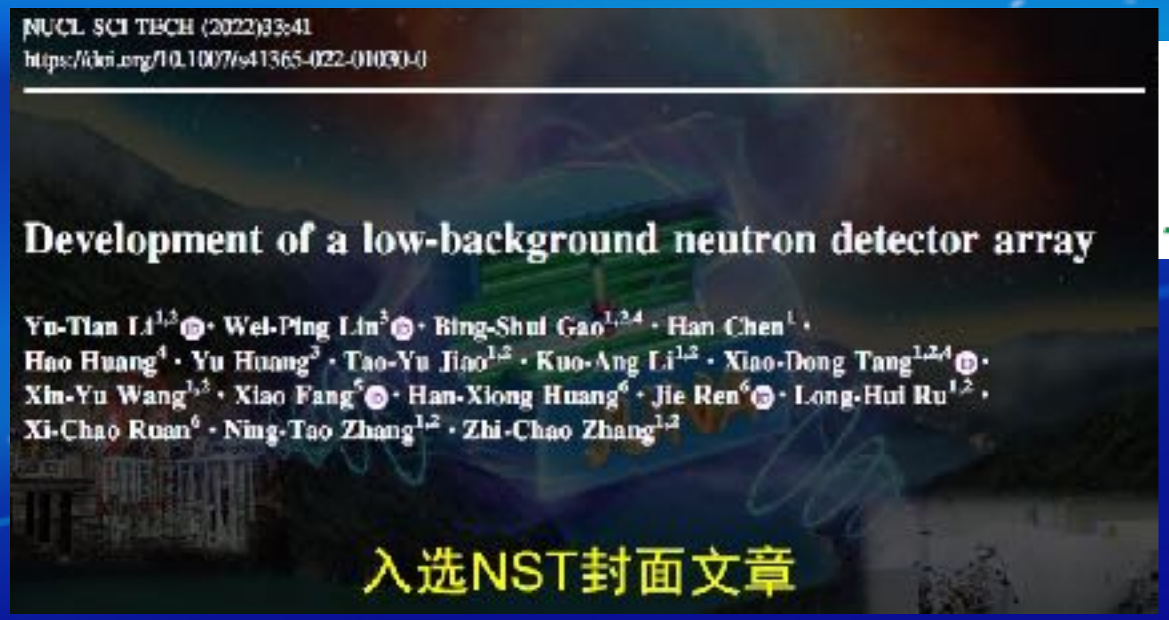
- 高温高压烧结
- 最高耐热3550°C
- 热流密度0.5kW/cm^2
- 耐辐照达400库仑

^{25}Mg多层复合靶

- Cr+Mg+Cr三明治结构
- 旋转蒸镀技术
- 耐辐照达300库仑



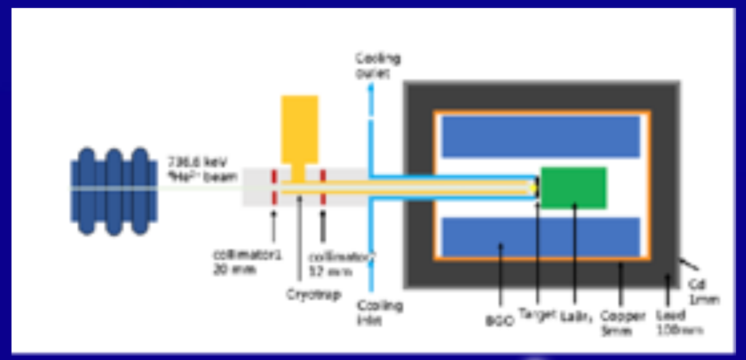
先进探测器技术
Detector tech.

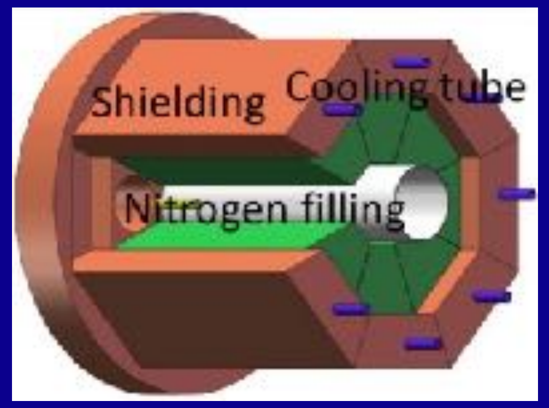

NUCL. SCI TECH (2022)33:41
https://doi.org/10.1007/s41365-022-01030-0

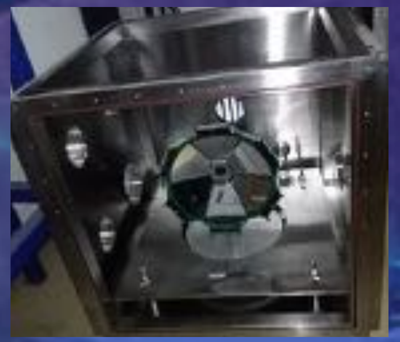
Development of a low-background neutron detector array

Yu-Tian Li · Wei-Ping Lin · Bing-Shui Gao · Han Chen · Hao Huang · Yu Huang · Tao-Yu Jiao · Kuo-Ang Li · Xiao-Dong Tang · Xin-Yu Wang · Xiao Fang · Han-Xiong Huang · Jie Ren · Long-Hui Ru · Xi-Chao Ruan · Ning-Tao Zhang · Zhi-Chao Zhang

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

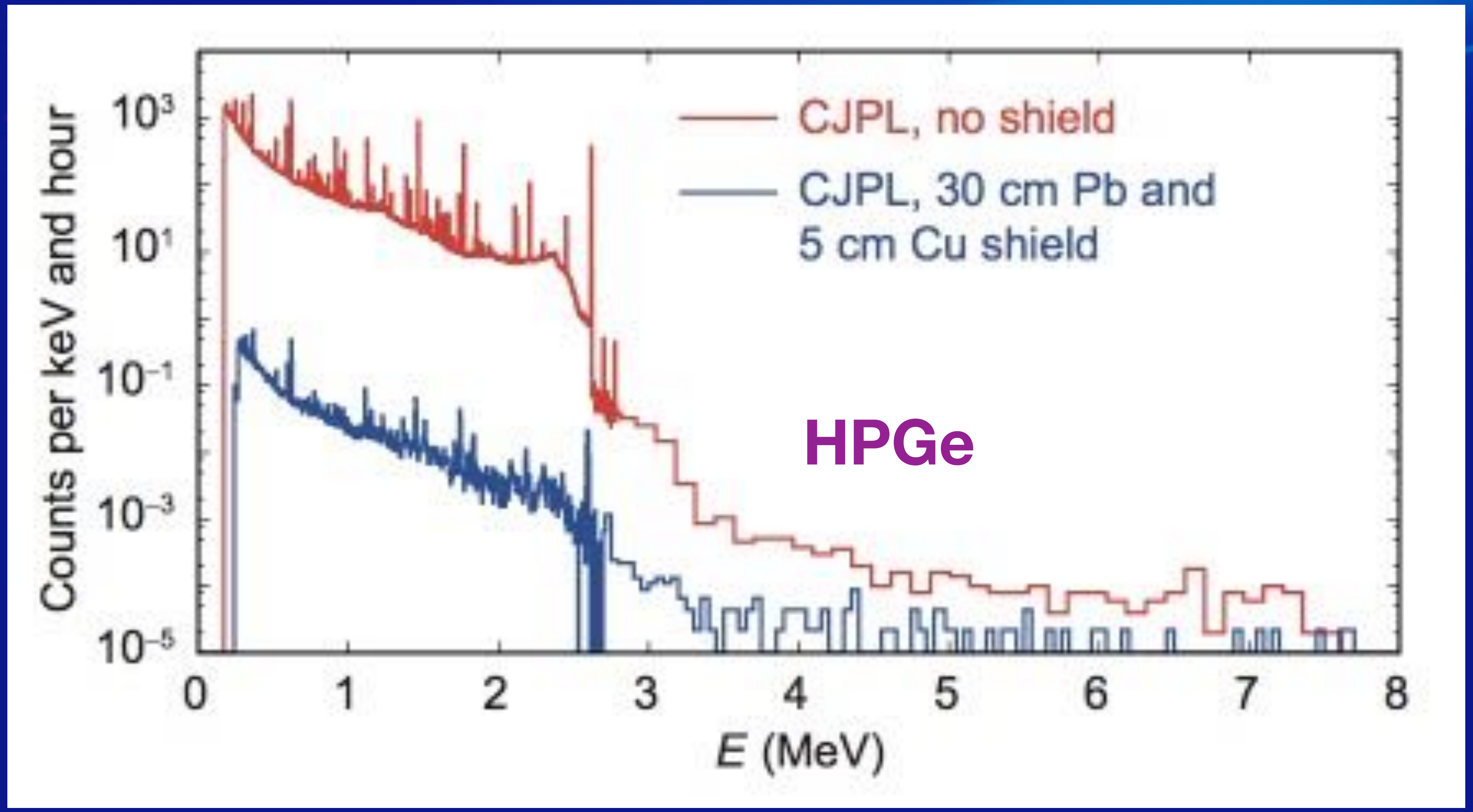




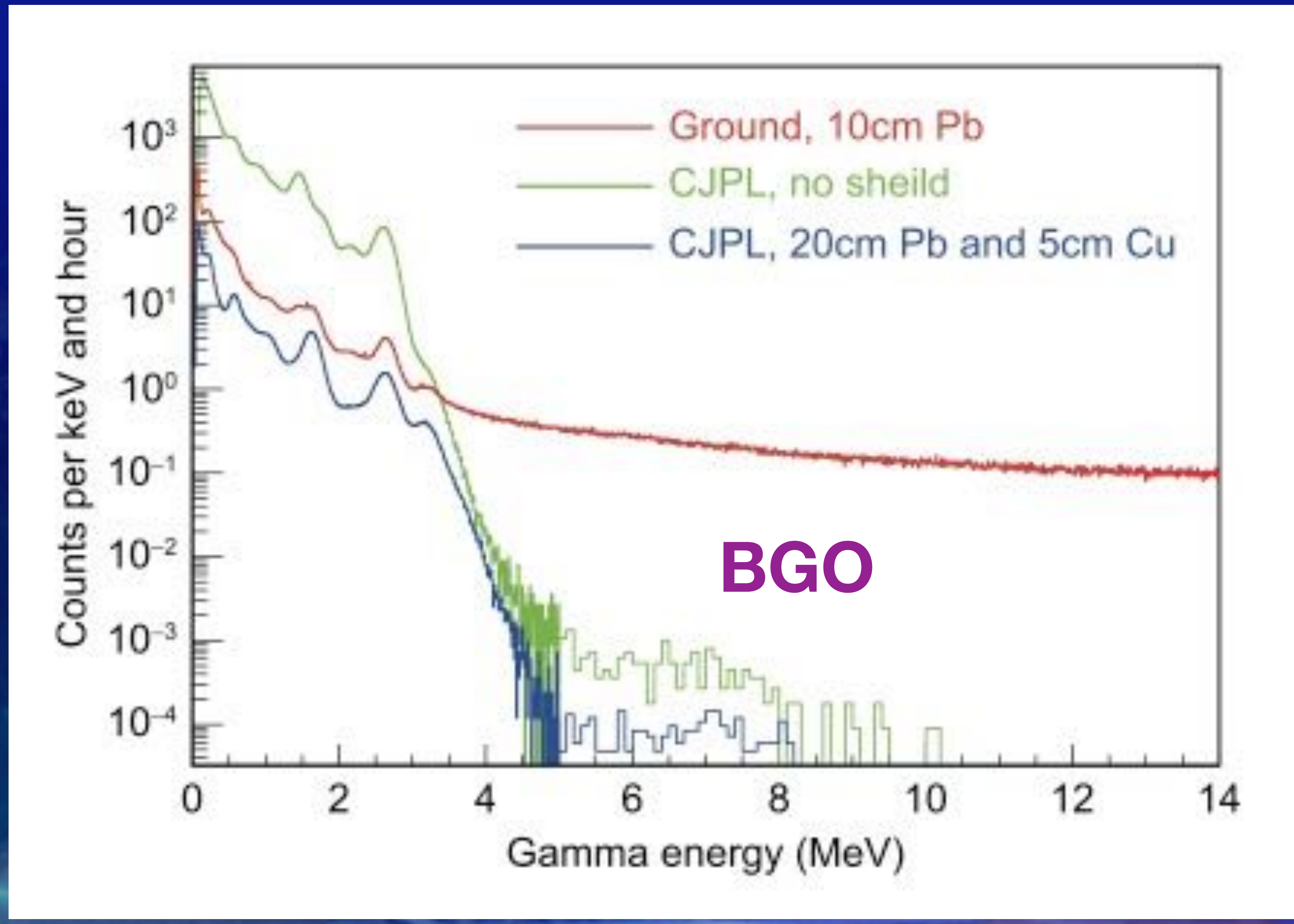


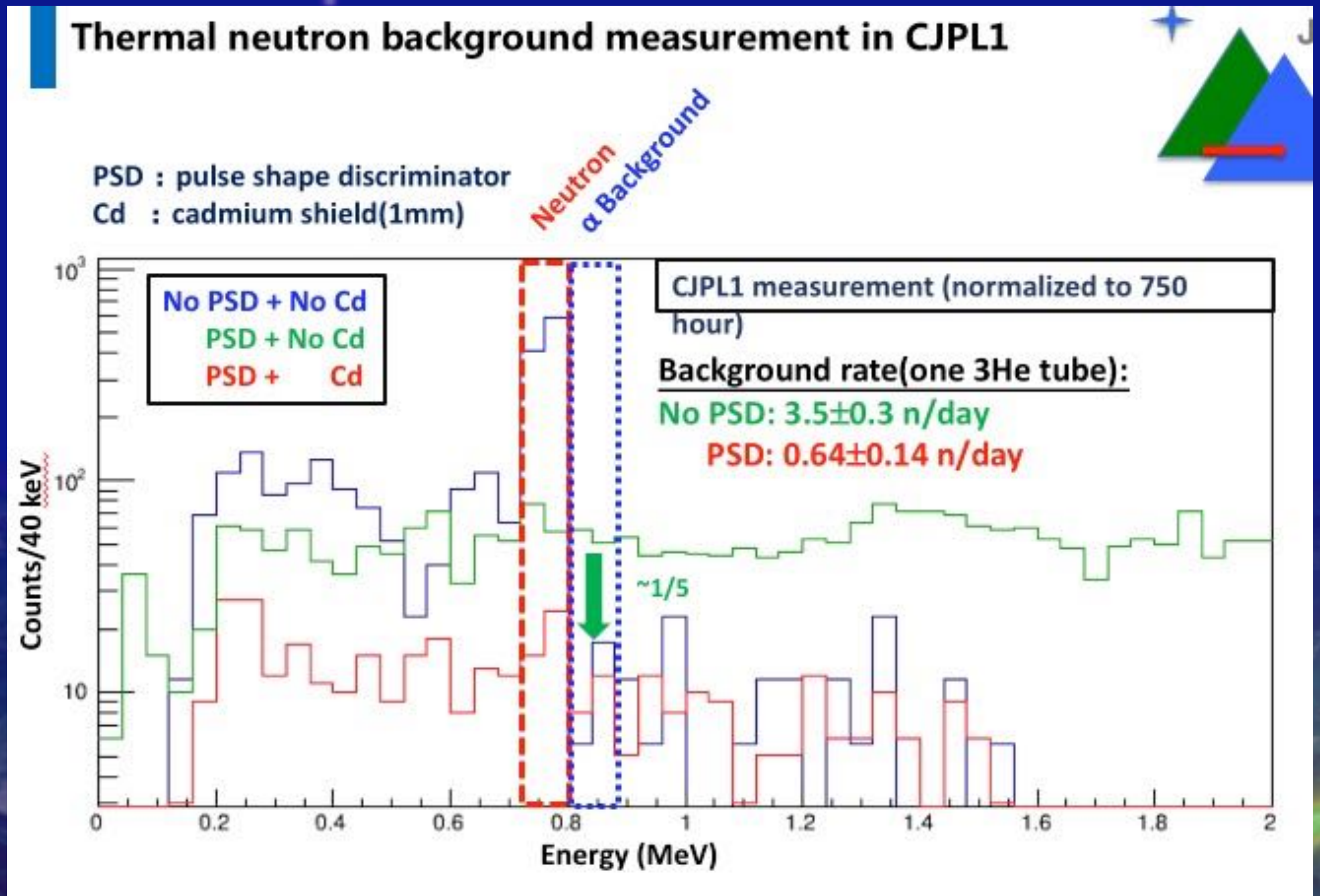
核反应 reaction	采用技术 technology	发表文章 publication	国外记录 world best	我们达到 JUNA
^{12}C	BGO+LaBr		down to 891 keV	down to 552 keV
^{25}Mg	BGO array X8	Atomic ST 52(2018)140	resolution17 %	11 %
^{13}C	^{3}He array X24	NST33(2022) 41, cover story	Exptripolation	Self consisitent
^{19}F	Charged particle array		170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

HPGe and BGO background in CJPL-I 2016-2019 本底测量



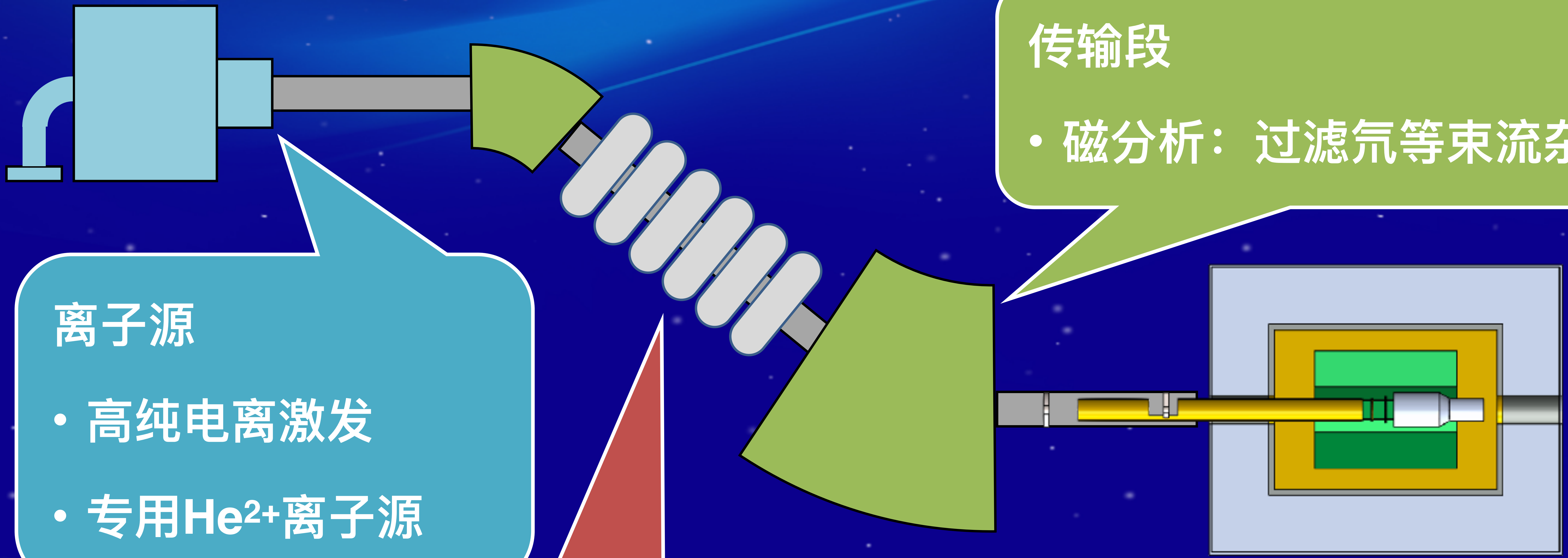
Duration	*Contents*
15, Mar. - May	*Gamma*
May - July	*Gamma with shielding*
Aug. - Oct.	*BGO*
Oct. - Dec.	*Neutron*
16, Nov.-17. Jan.	*BGO, LaBr*
17-19	*Neutron*





Y. P. Chen, J. Su et al., Sci. China Phys 60. (2017)

极低本底获得——全面的本底控制



传输段

- 磁分析：过滤氘等束流杂质

离子源

- 高纯电离激发
- 专用He^{2+}离子源

加速段

- 选用低本底材料
- 提高传输效率（>90%）

实验终端

- 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

强流加速器技术

离子源

实验需求

地下空间小

毫安级高流强

…

技术突破

紧凑永磁结构

微波耦合高效电离激发

…

- 国际深地**最强流离子源**
- 国际重离子加速器大会**特邀报告**

加速段

实验需求

克服空间电荷效应

能量精确可调

…

技术突破

短间隙大孔径加速

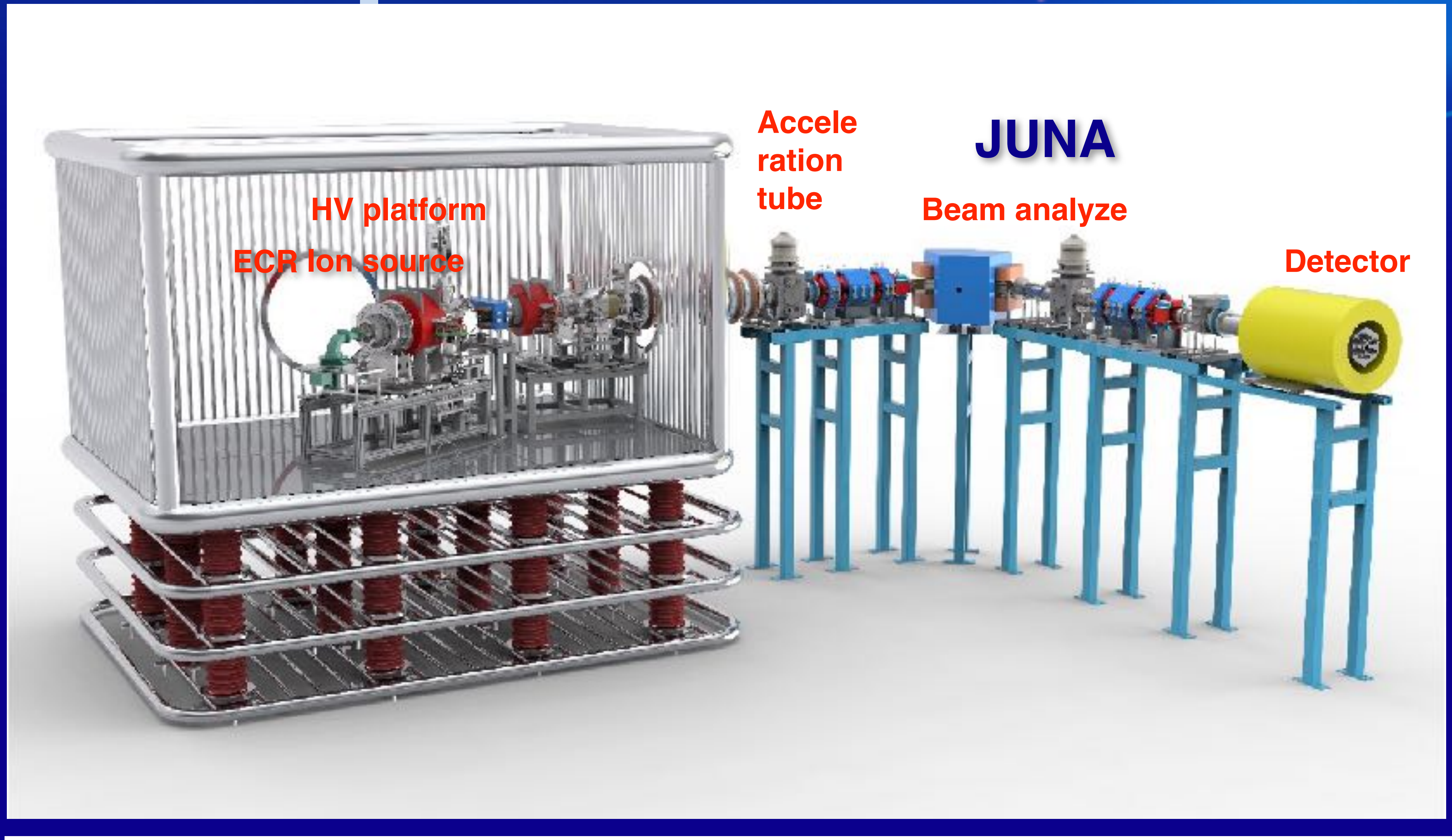
高稳定高压供给

…

- 束流强度 10 mA，传输效率 90%
- **“世界最强流深地加速器”**

国际最强流深地核天体物理JUNA experiment

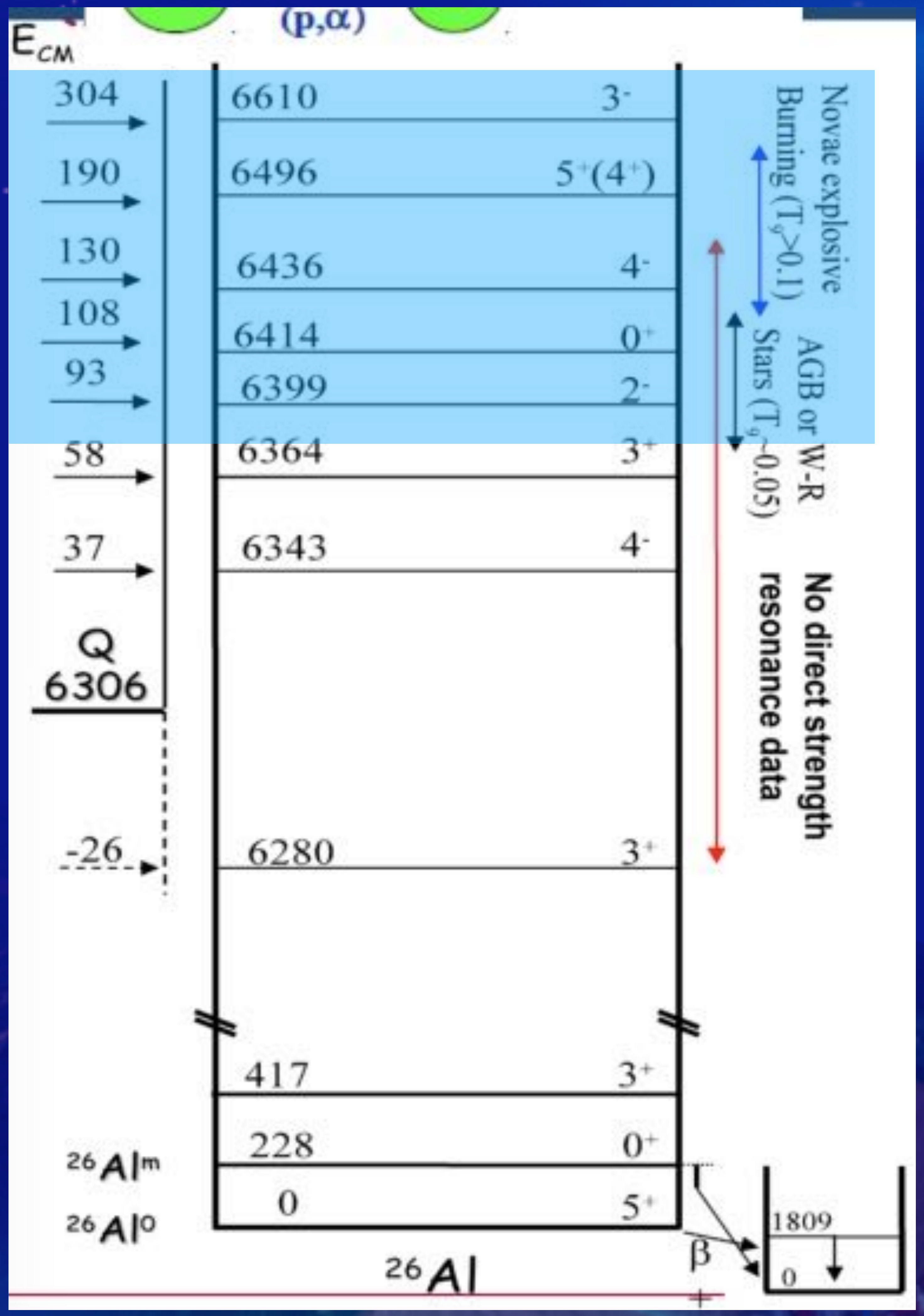
锦屏深地核天体物理实验
Jinping Underground Nuclear Astrophysics Experiment

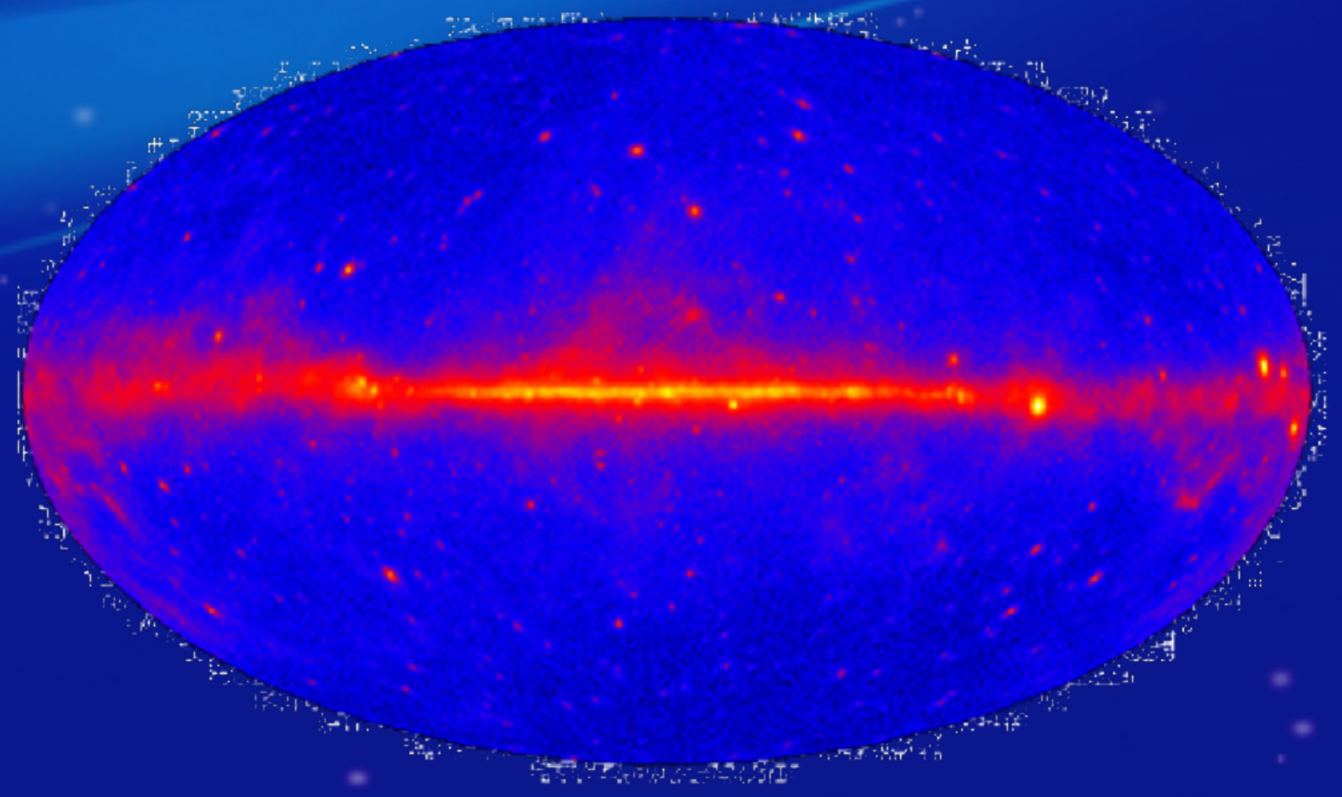


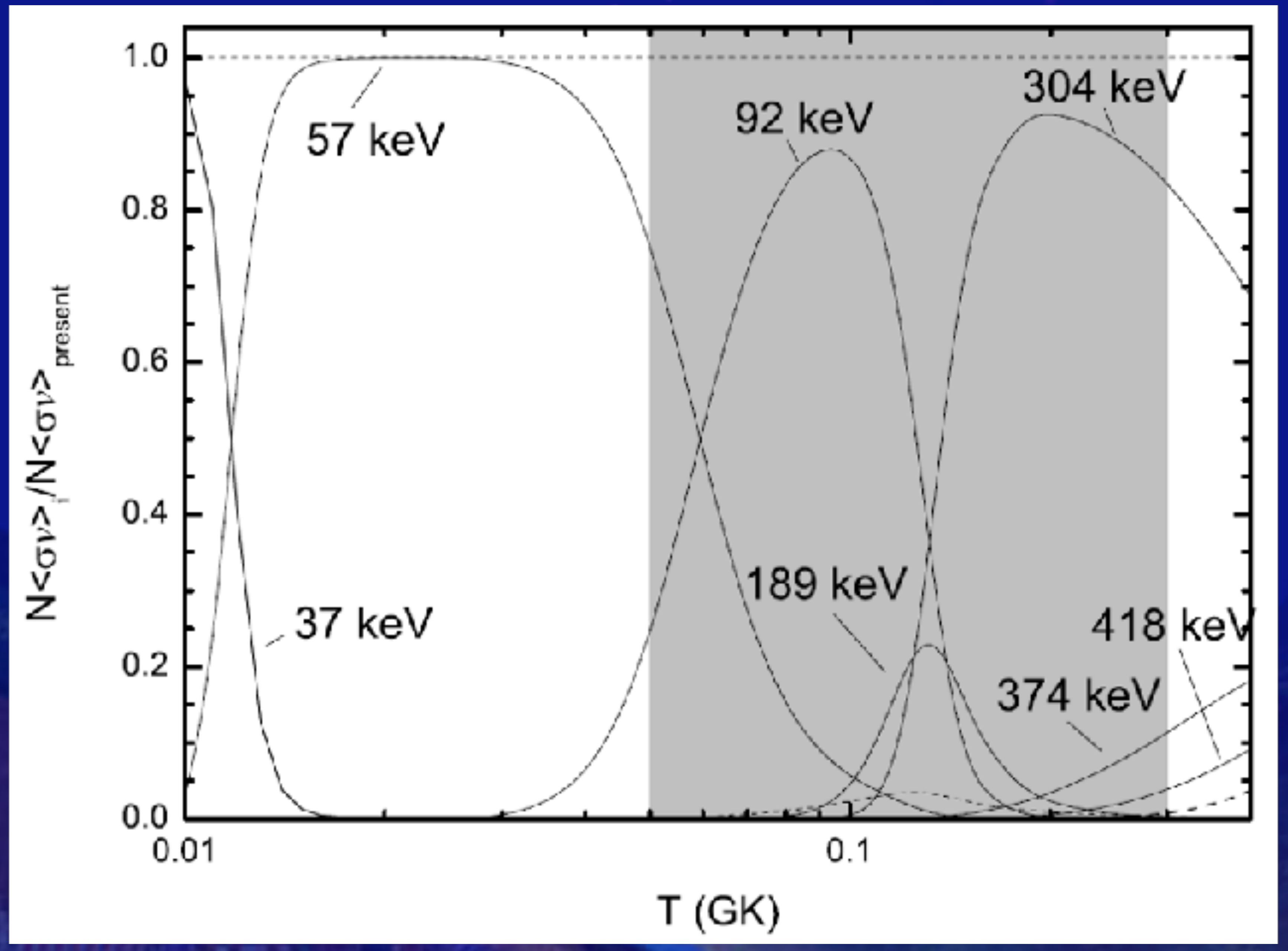
	cosmic μ bkg (cm^{-2} s^{-1})	beam energy（keV）			beam intensity（emA）			energy stability
		H^+	He^+	He^{2+}	H^+	He^+	He^{2+}	
LUNA	2×10^{-8}	50-400	50-400	---	0.3~1	0.3~0.8	---	0.05%
CASPAR	4.4×10^{-9}	100-1000	100-1000	---	0.1	0.1	---	0.05%
JUNA	2×10^{-10}	50-400	50-400	100-800	10	10	2	0.04%

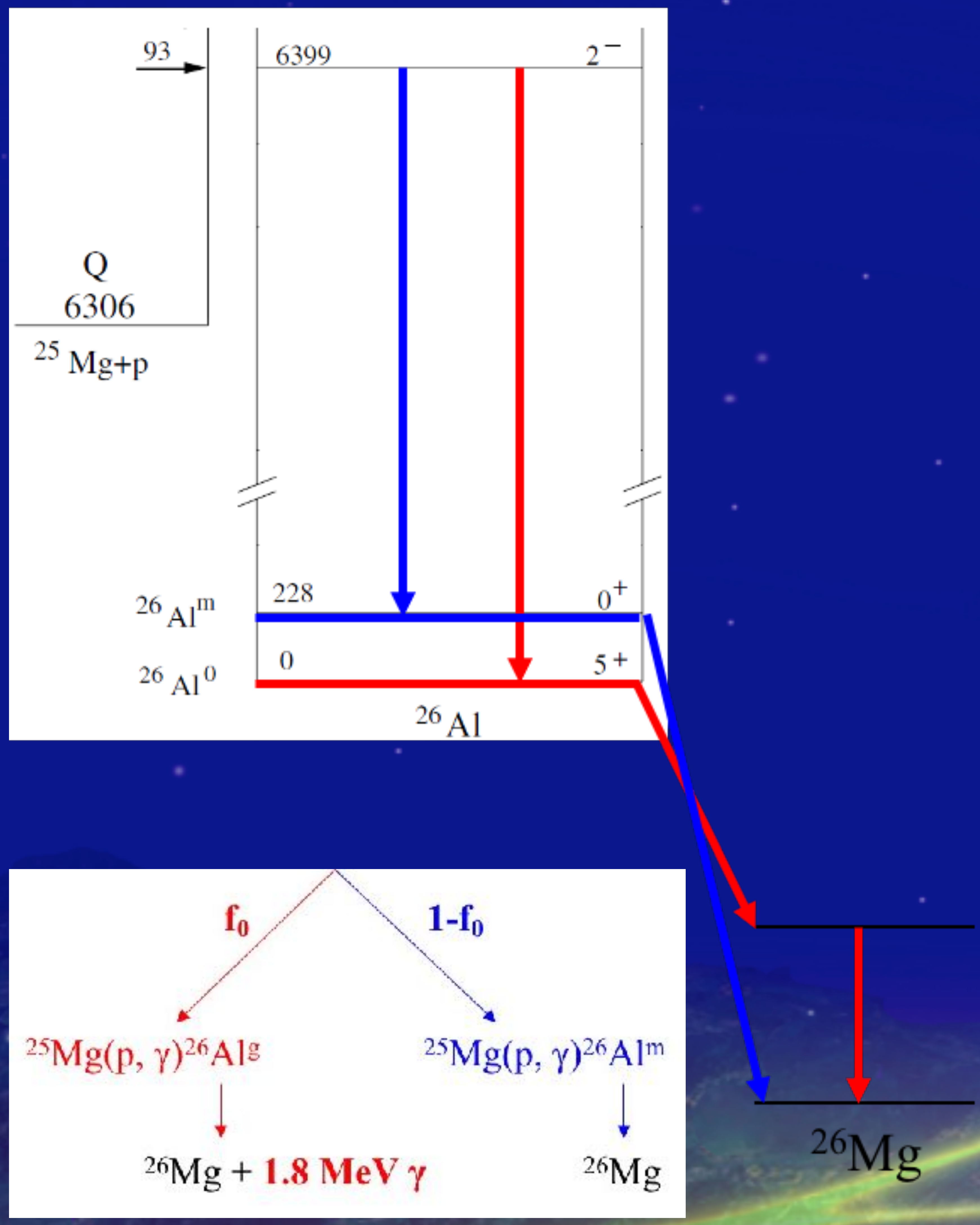
WPL et al., Sci. China 59(2016)2

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





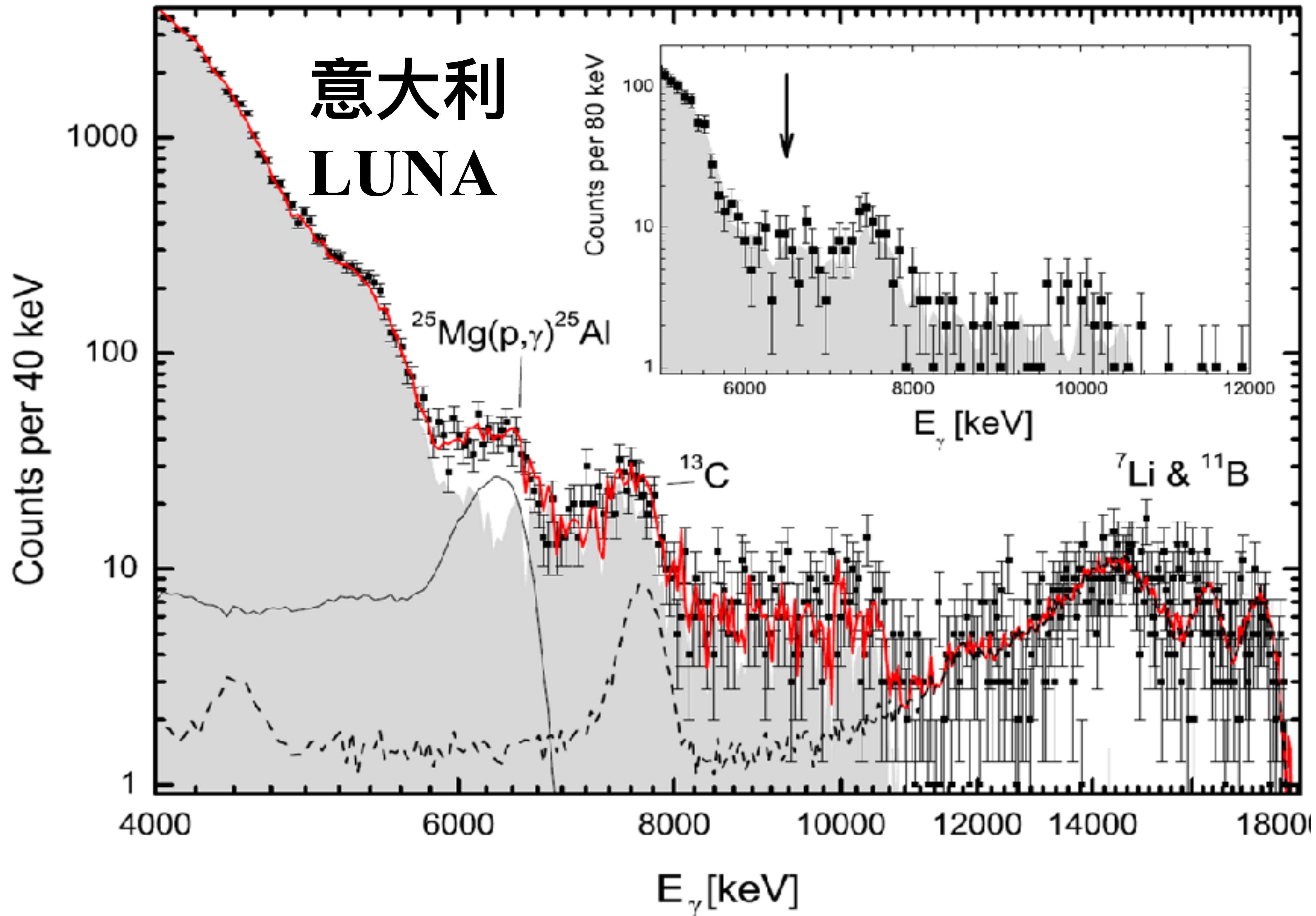


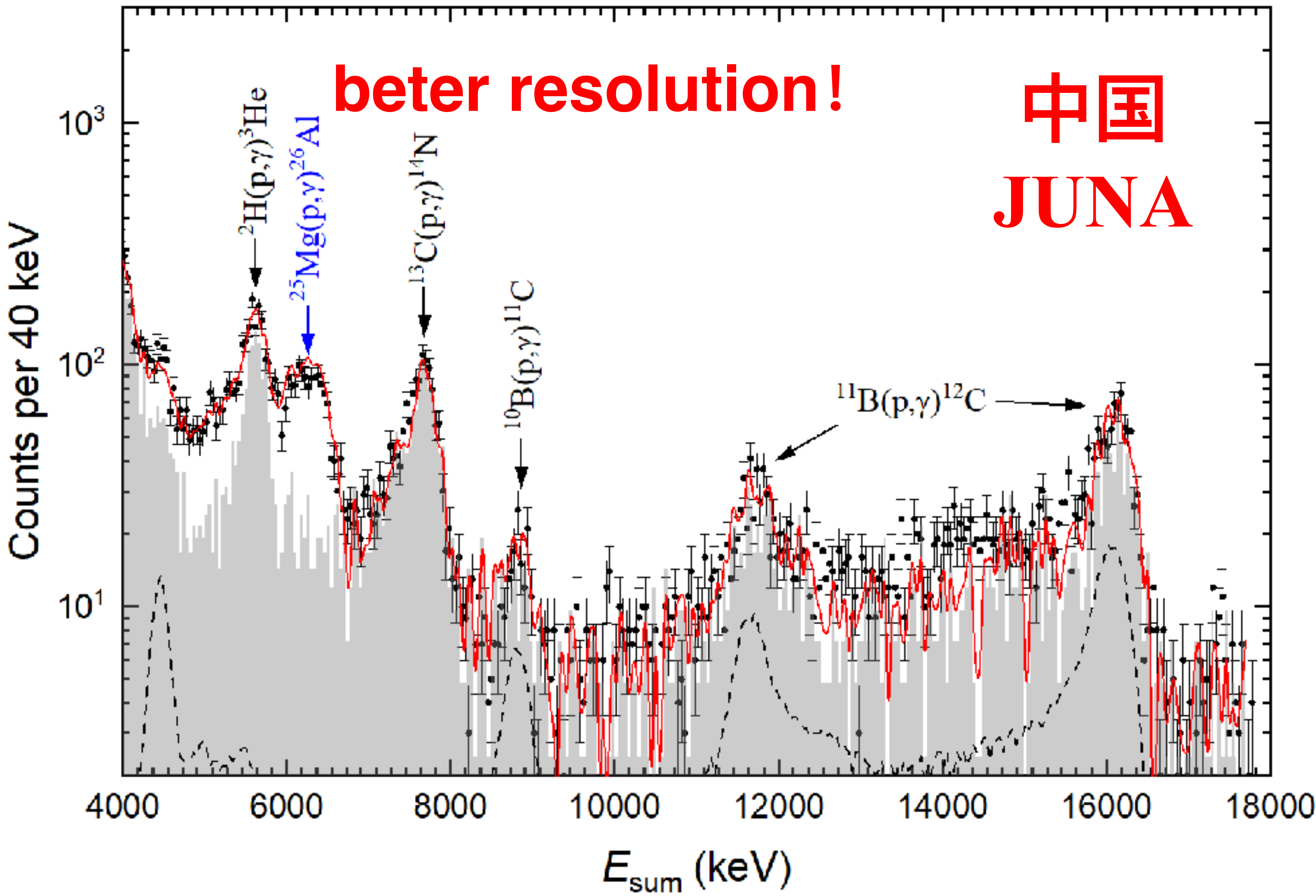


Z. H. Li et al., Sci. China Phys 58. 082002(2015), J. Su et al., Science Bulletin, 67(2022)2

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

JUNA vs. LUNA





52 days (S+N)， 370 C

signal： 410

strength： $2.9\pm0.6\times10^{-10}$ eV

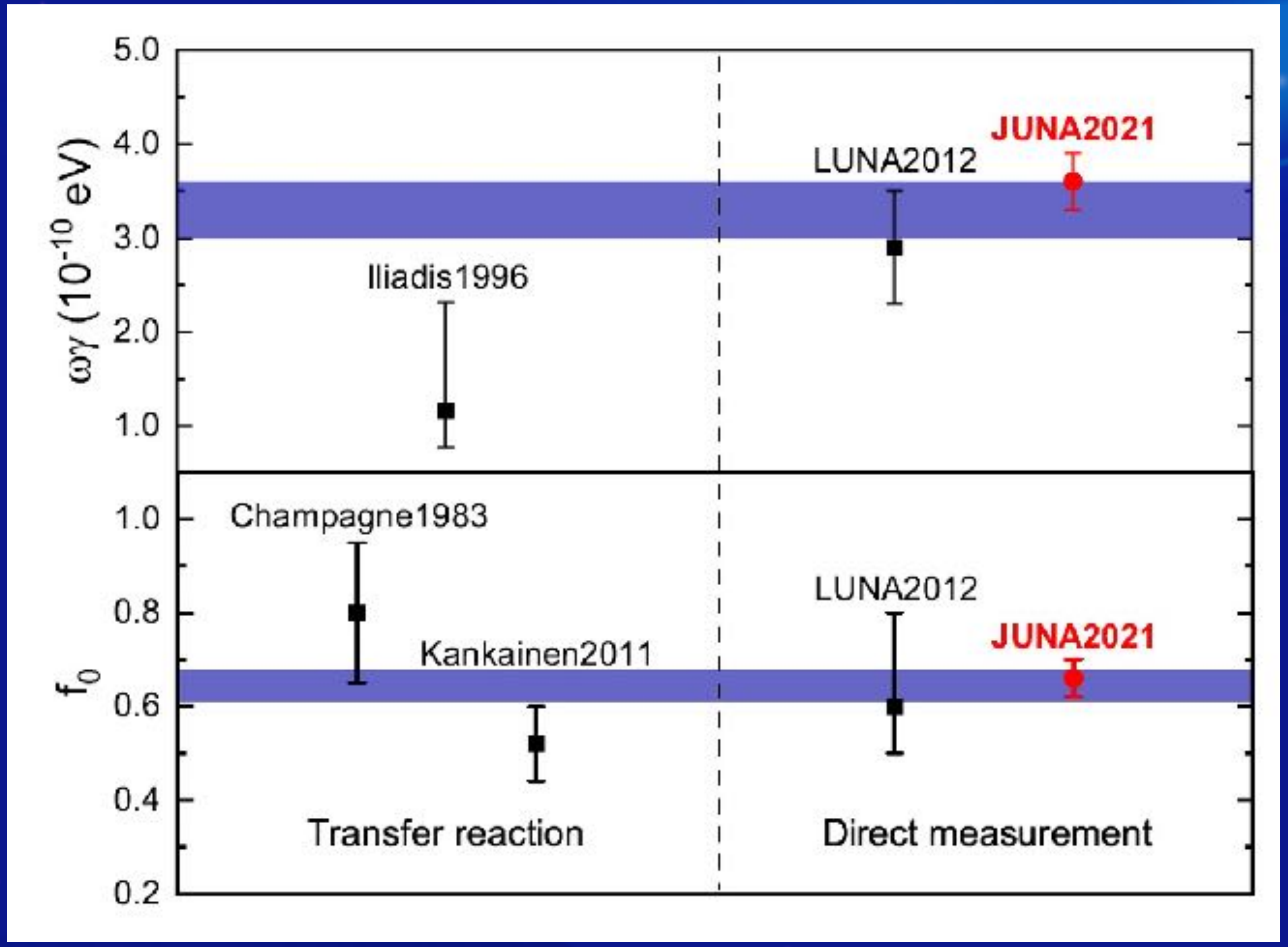
15days(S+N)， 1008 C

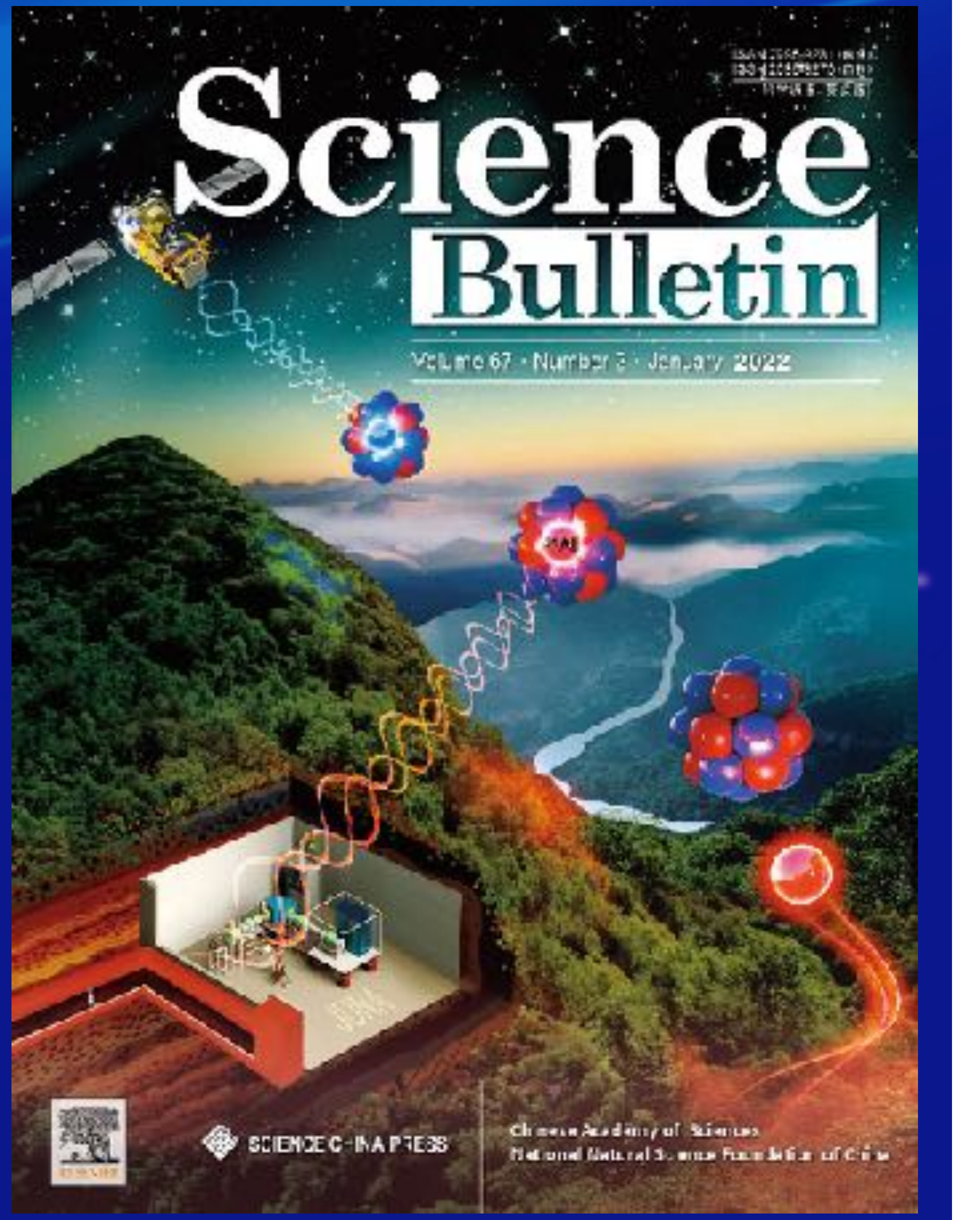
signal： 1225

strength： $3.8\pm0.4\times10^{-10}$ eV

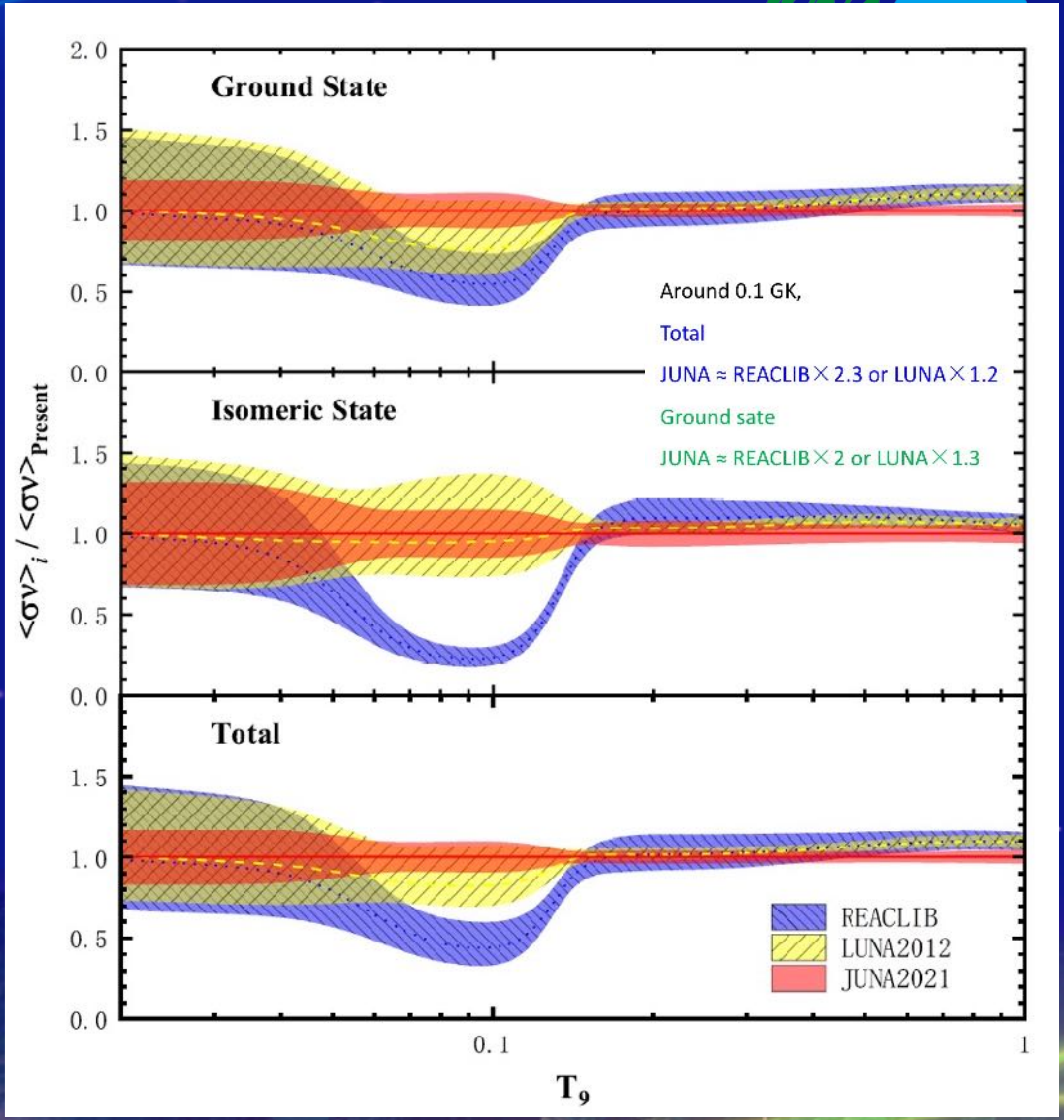
J. Su, Z. H. Li*,…., WPL*, Science Bulletin, 67(2022)2, cover paper

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

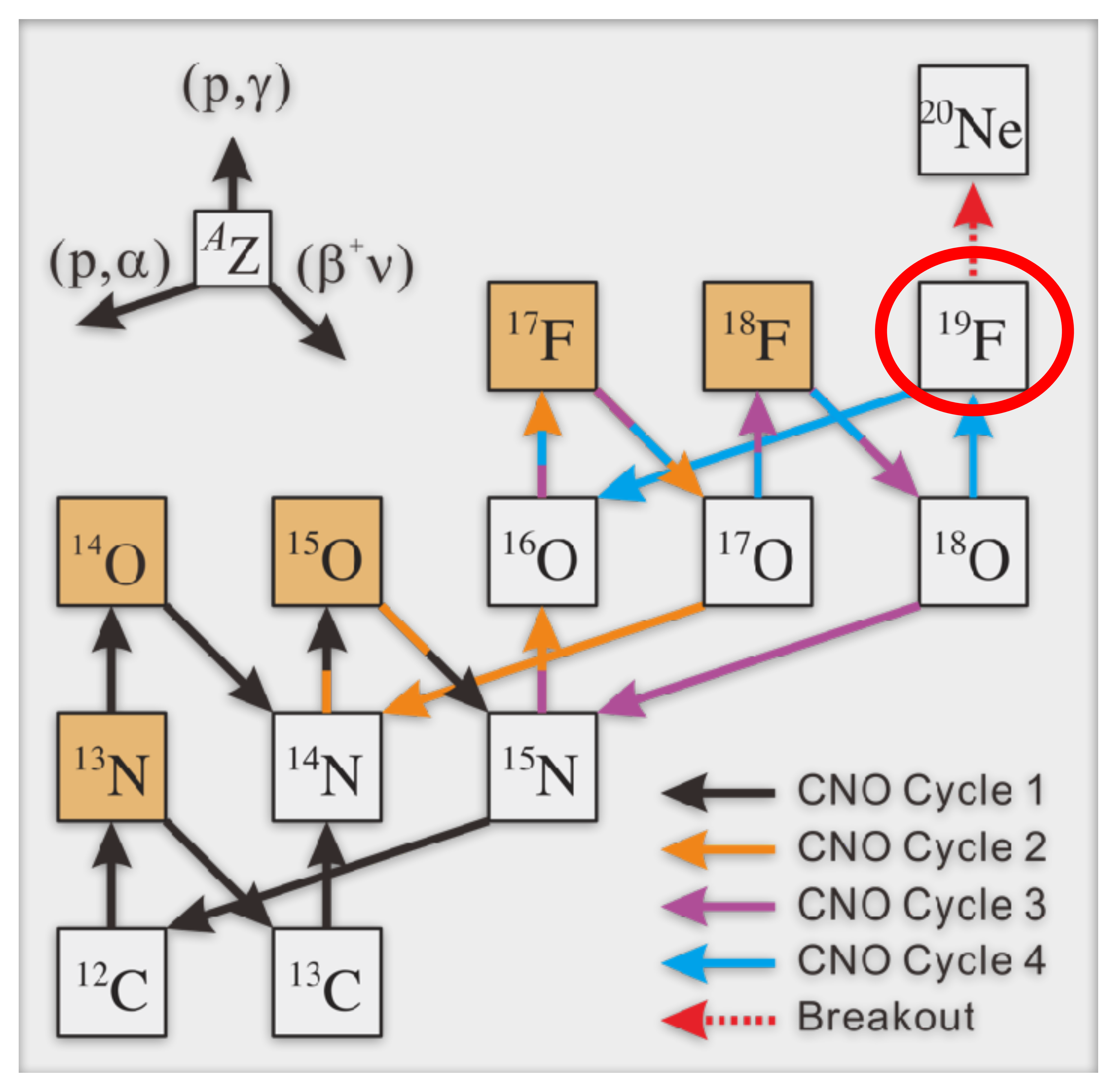
key reaction for F in star

destroy：

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

production：

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

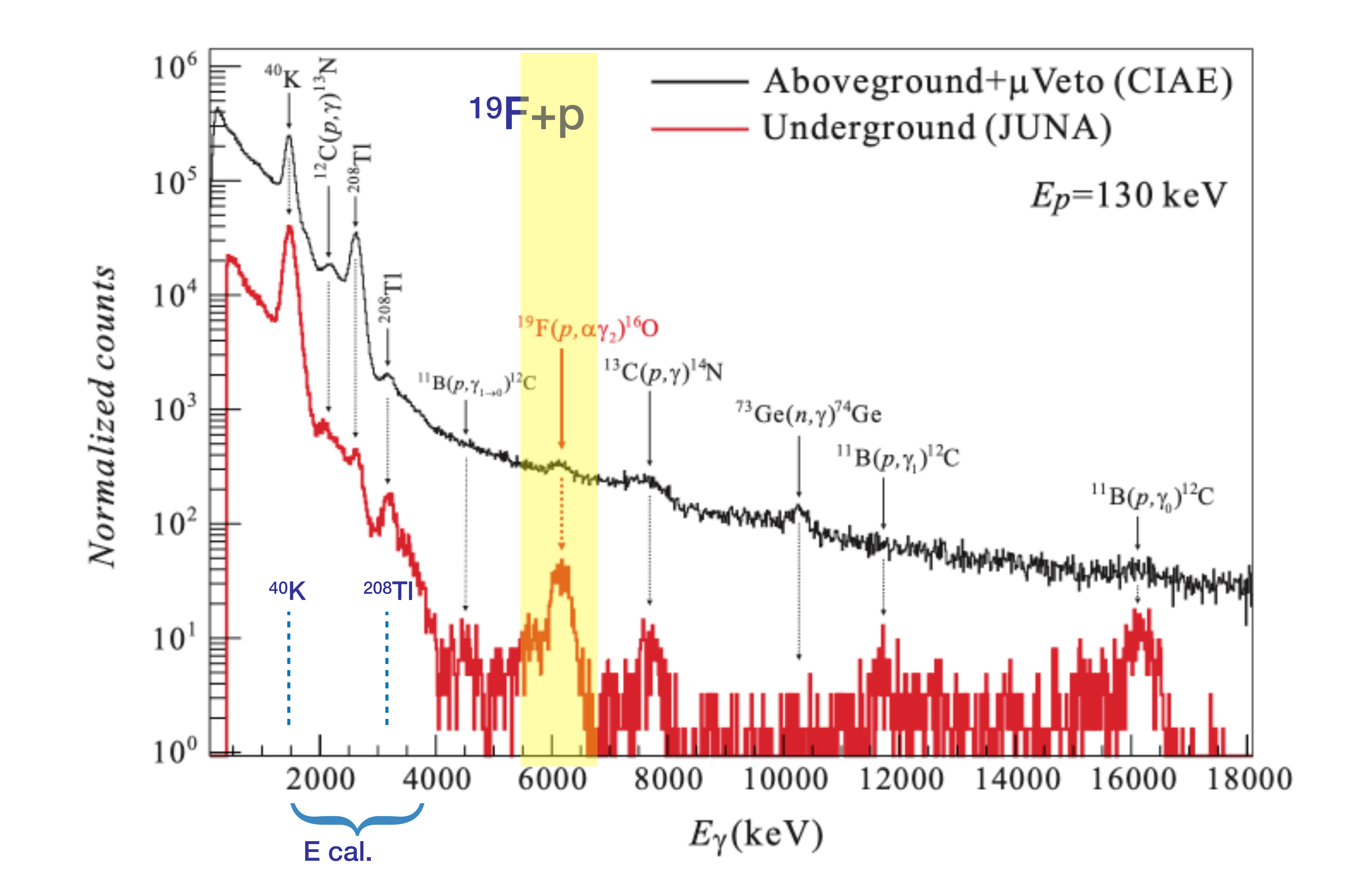


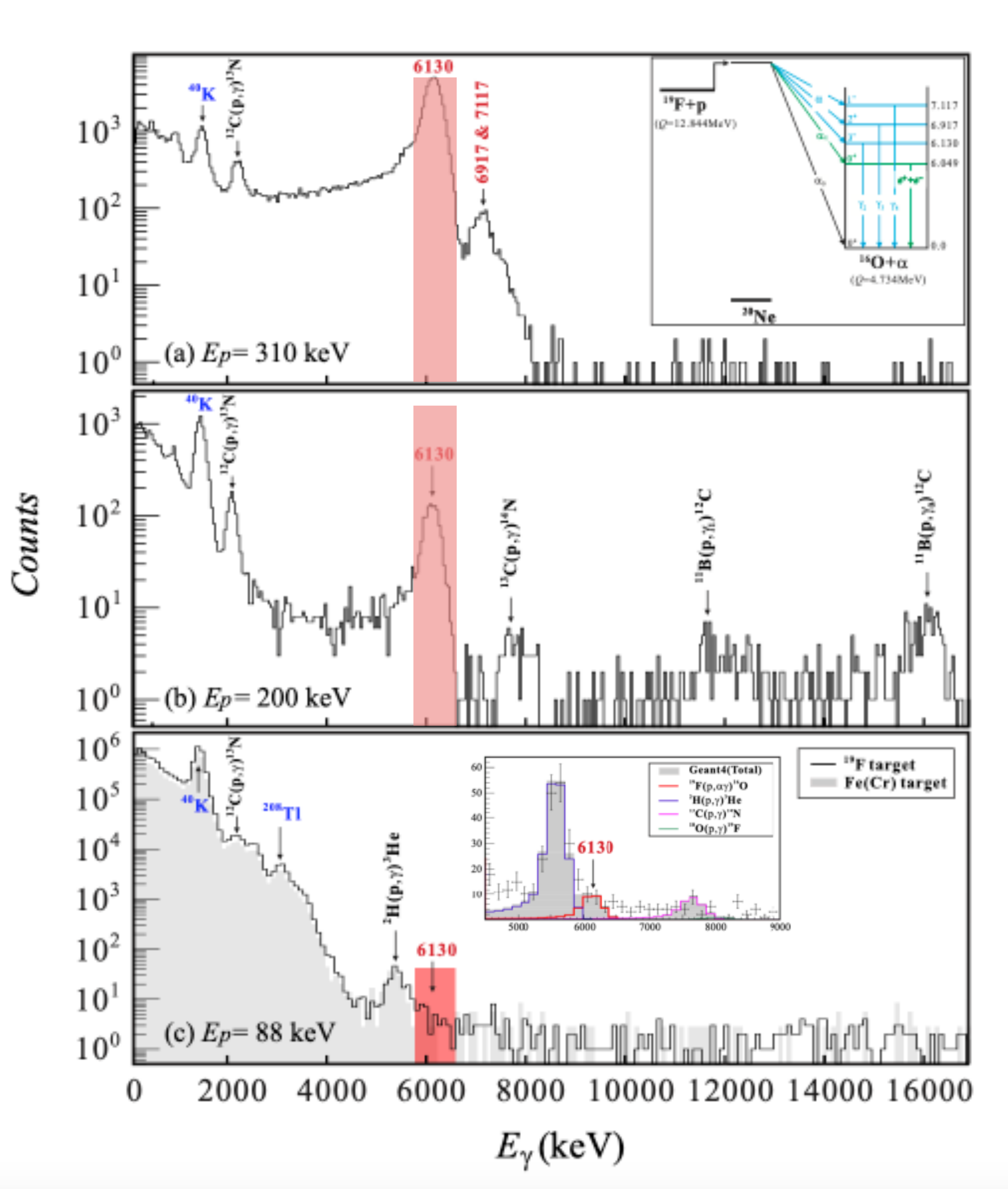
J.J. He *et al.*, Sci. China-Phys. Mech. Astron. 59 (2016) 652001

L.Y. Zhang, J. Su, J. J. He*, …, WPL*, $^{19}F(p,\alpha\gamma)^{16}O$, PRL127(2021)152702. editor suggestion

北京师范大学 BEIJING NORMAL UNIVERSITY

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

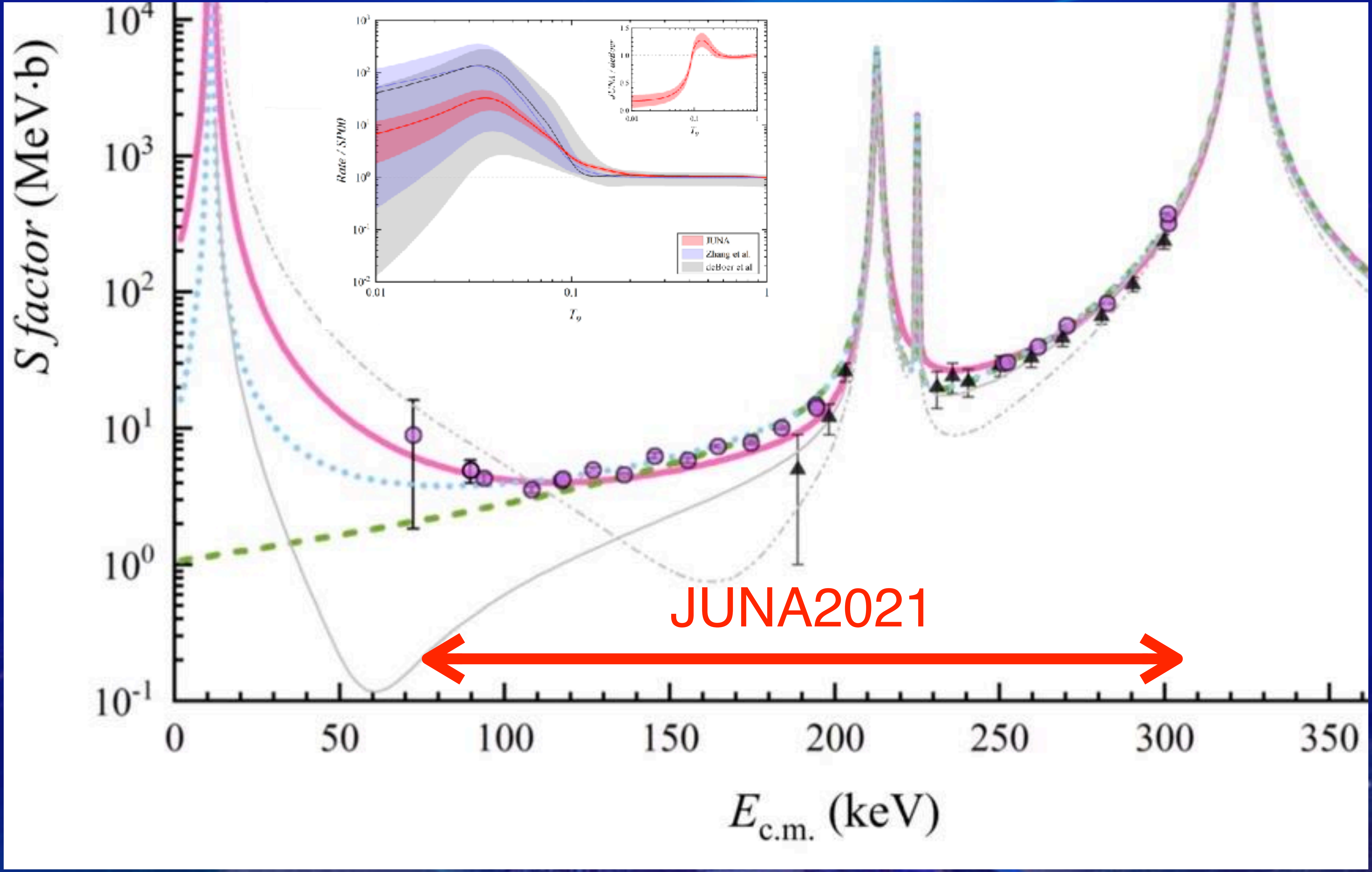




- ^{19}F implatation+ Cr coding，long durabilty with 2 mA
- L.Y. Zhang, Y.J. Chen, J.J. He* et al., Nucl. Instr. Meth. B 496(2021)9

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,αγ)^{16}O reaches Gamow window



PHYSICAL REVIEW LETTERS 127, 152702 (2021)

Editors' Suggestion | Featured in Physics

Direct Measurement of the Astrophysical ^{19}F(p,αγ)^{16}O Reaction in the Deepest Operational Underground Laboratory

L. Y. Zhang, J. Su, J. J. He, M. Wiescher, R. J. deBoer, D. Kahl, Y. J. Chen, X. Y. Li, J. G. Wang, L. Zhang, F. Q. Cao, H. Zhang, Z. C. Zhang, T. Y. Jiao, Y. D. Sheng, L. H. Wang, L. Y. Song, X. Z. Jiang, Z. M. Li, E. T. Li, S. Wang, G. Lian, Z. H. Li, X. D. Tang, H. W. Zhao, L. T. Sun, Q. Wu, J. Q. Li, B. Q. Cui, L. H. Chen, R. G. Ma, B. Guo, S. W. Xu, J. Y. Li, N. C. Qi, W. L. Sun, X. Y. Guo, P. Zhang, Y. H. Chen, Y. Zhou, J. F. Zhou, J. R. He, C. S. Shang, M. C. Li, X. H. Zhou, Y. H. Zhang, F. S. Zhang, Z. G. Hu, H. S. Xu, J. P. Chen, and W. P. Liu

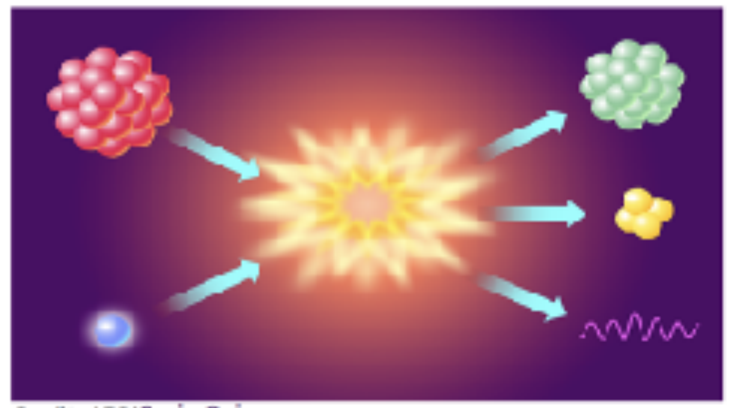
Physics — SYNOPSIS

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 × [illegible] $cm^3 s^{-1} mol^{-1}$ 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.

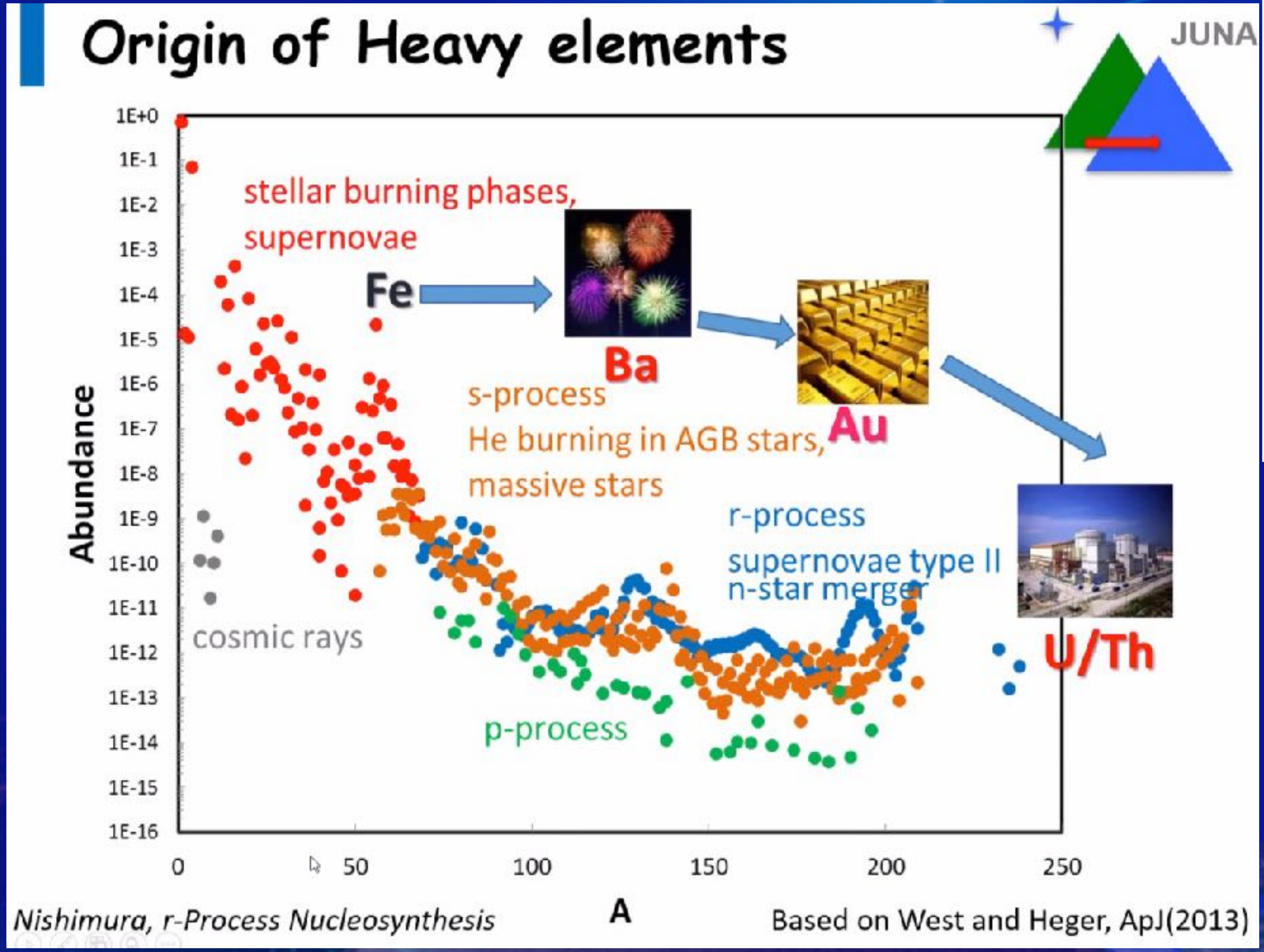
Christopher Crockett is a freelance writer based in Arlington, Virginia.

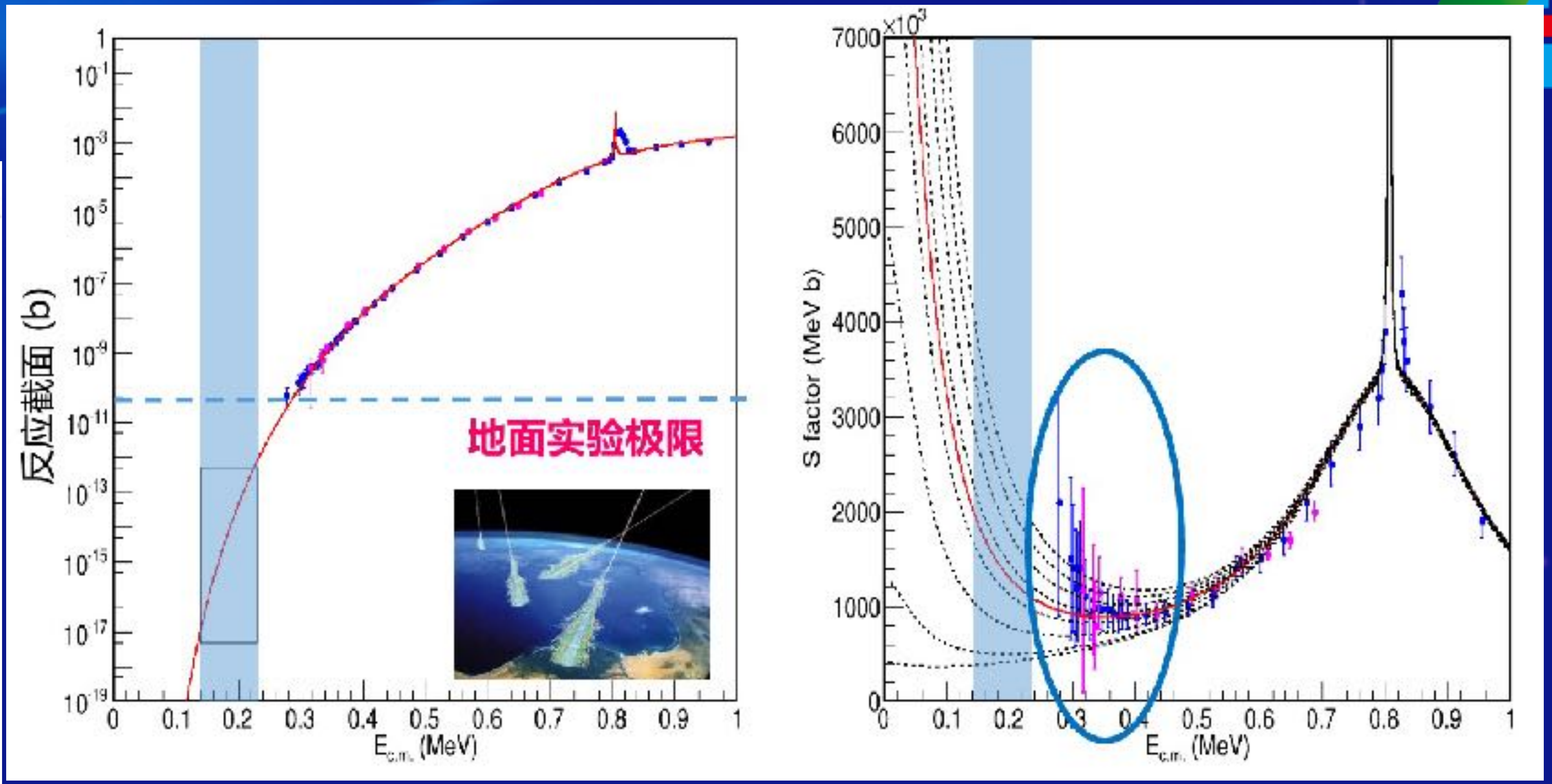
REFERENCES

1. L. Y. Zhang et al., "Direct measurement of the astrophysical ^{19}F(p,αγ)^{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,αγ)^{16}O, PRL 127(2021)152702. editor suggestions

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





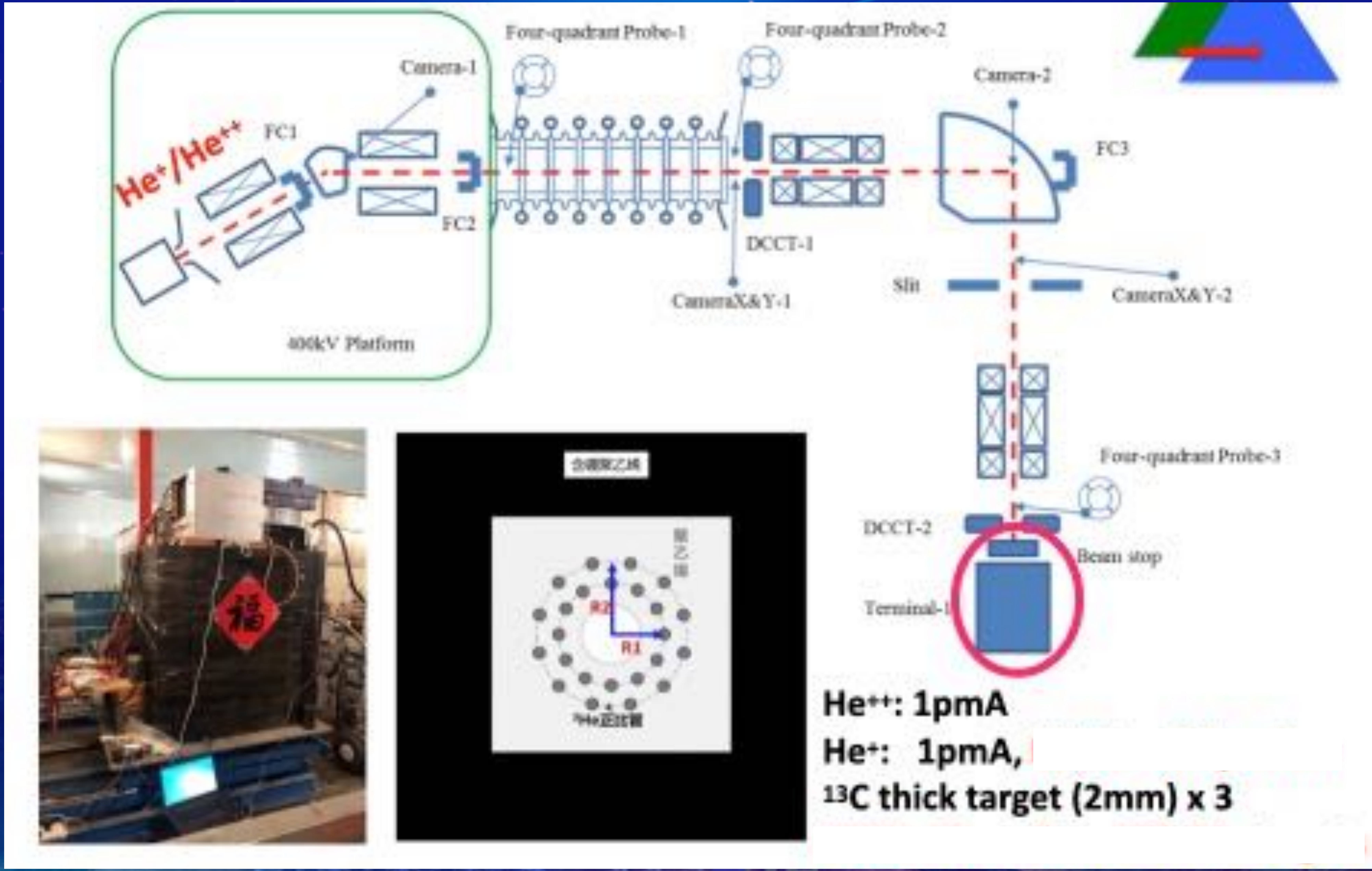
$^{13}C(\alpha,n)^{16}O$实验条件

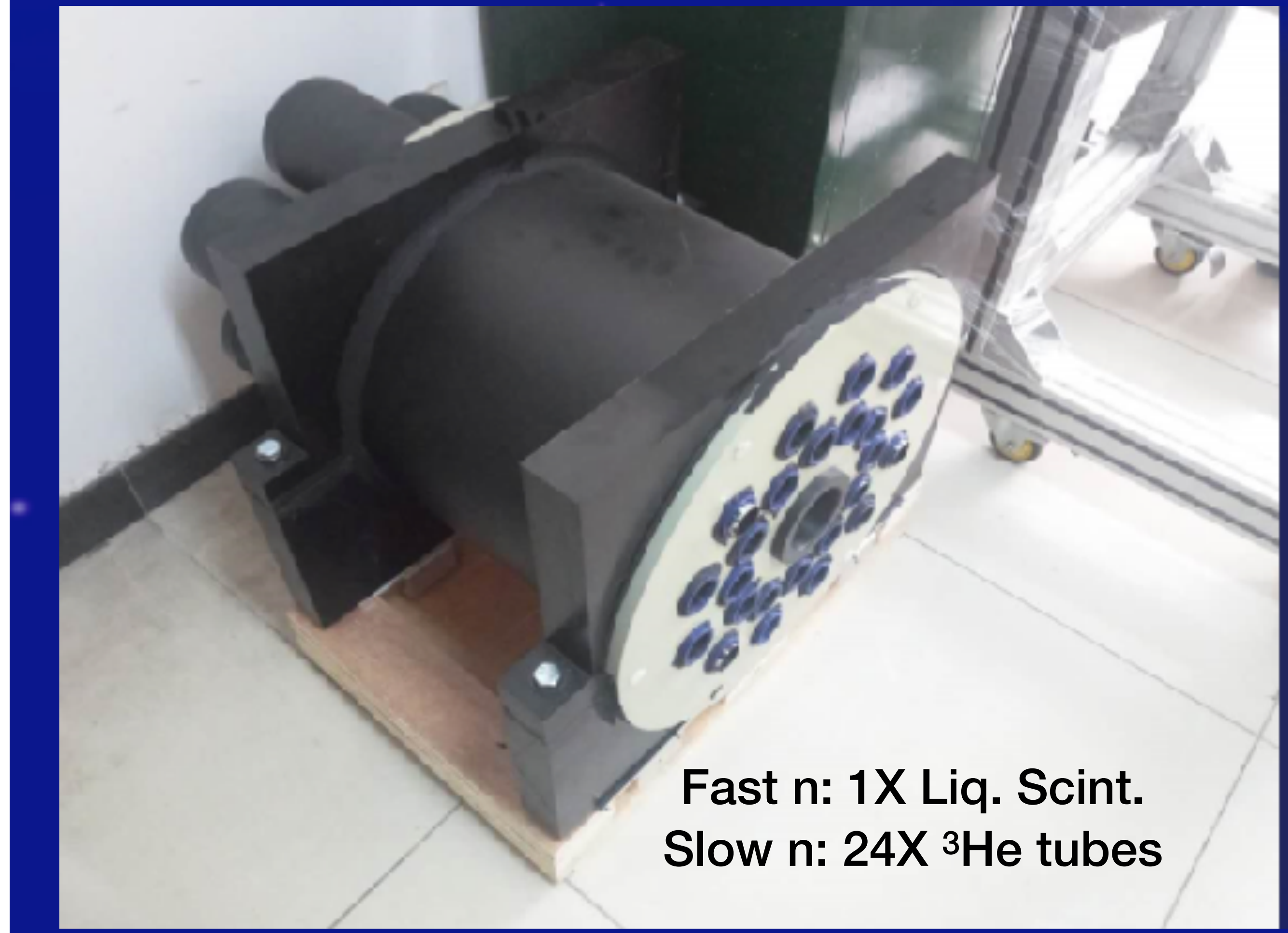
指标	LUNA (意大利)	JUNA (中国)
束流强度beam (粒子毫安)	~0.15	~2
靶数目 target	>100	3
能区 (MeV) energy	0.23-0.31	0.24-1.2
束流时间（天）	240	14

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*, $^{13}C(\alpha,n)^{16}O$, PRL in press, 2022

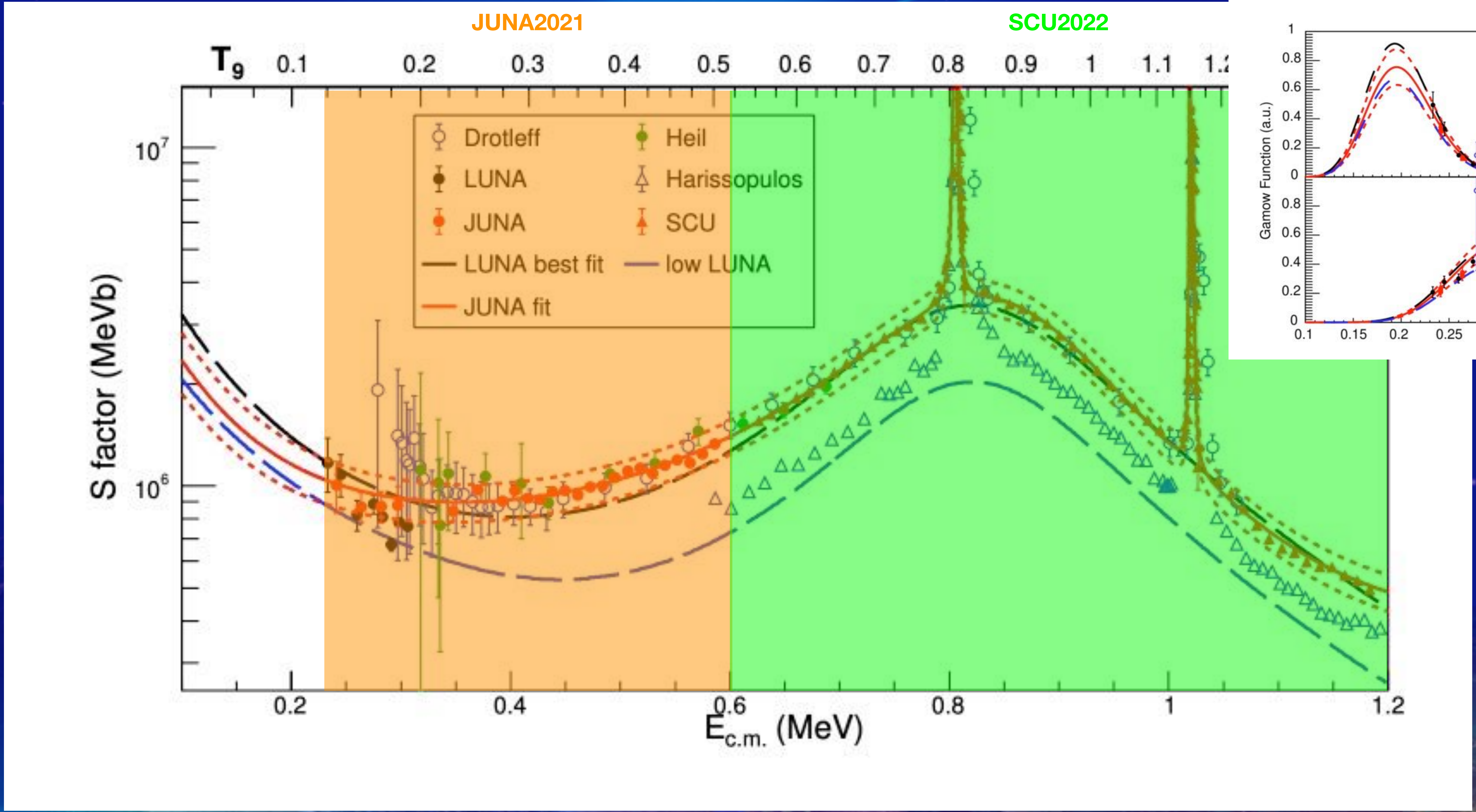
$^{13}C(\alpha,n)^{16}O$ status

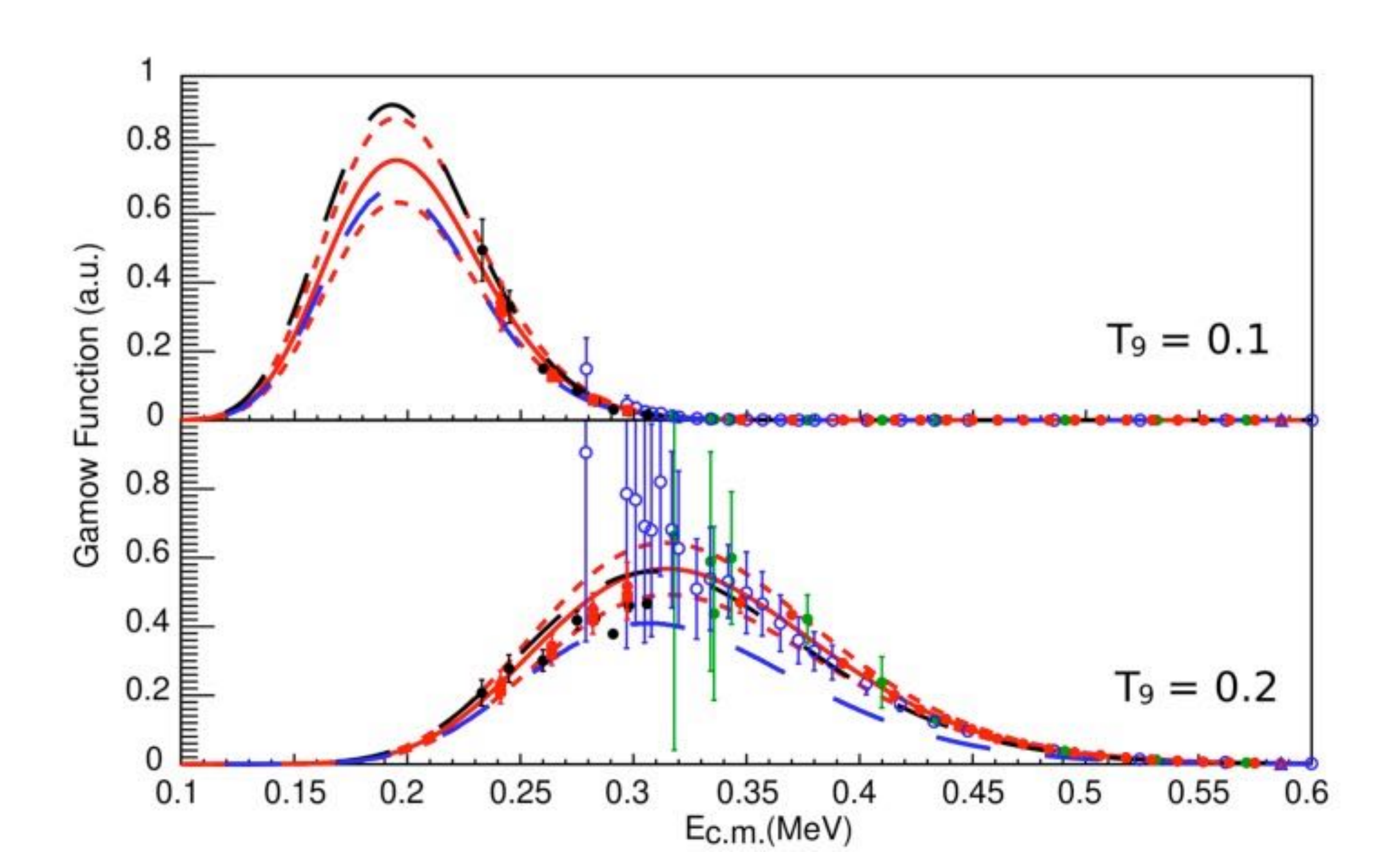




B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(\alpha,n)^{16}O$, PRL in press, 2022

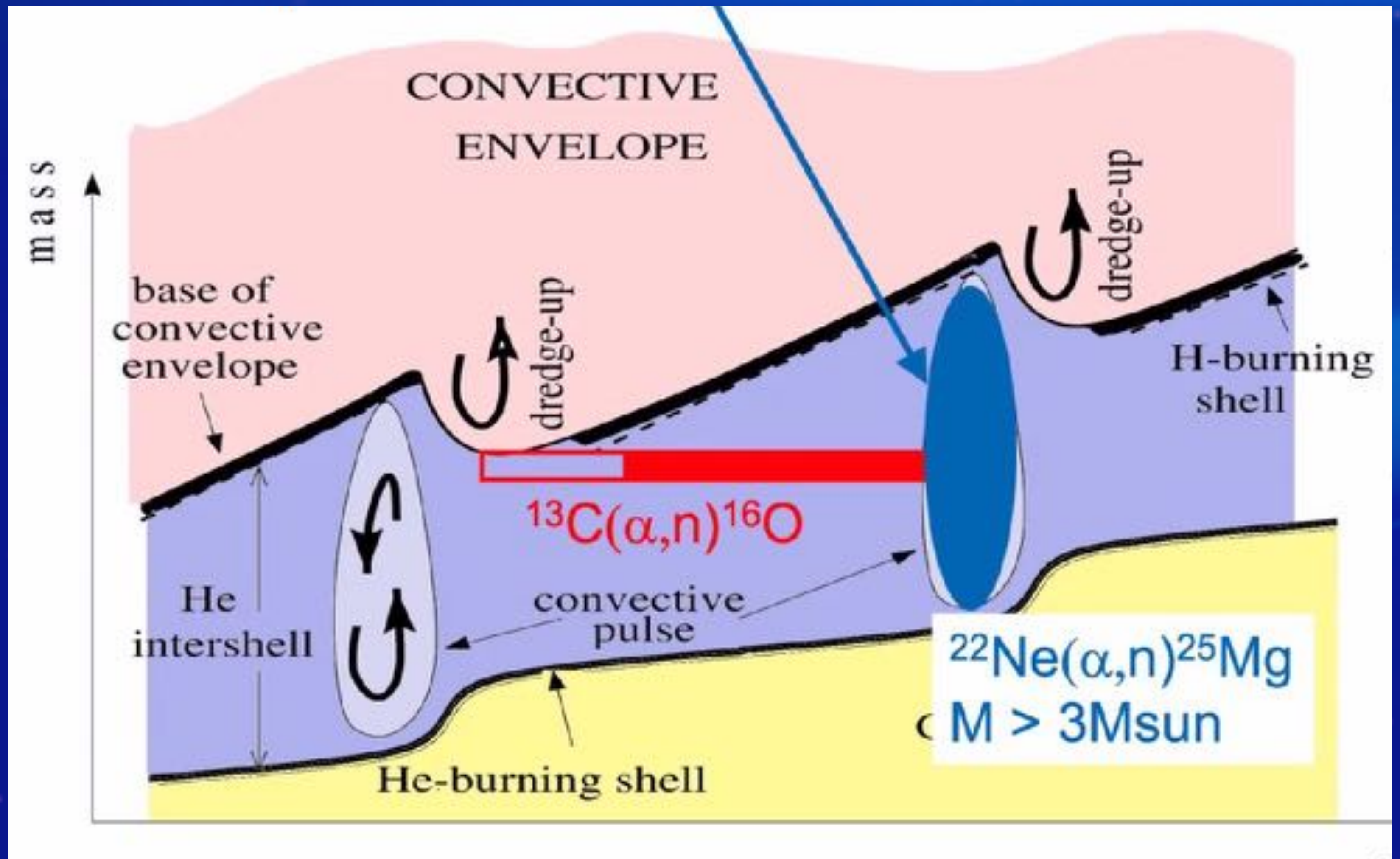
$^{13}C(\alpha,n)^{16}O$: solve the uncertainty





- 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

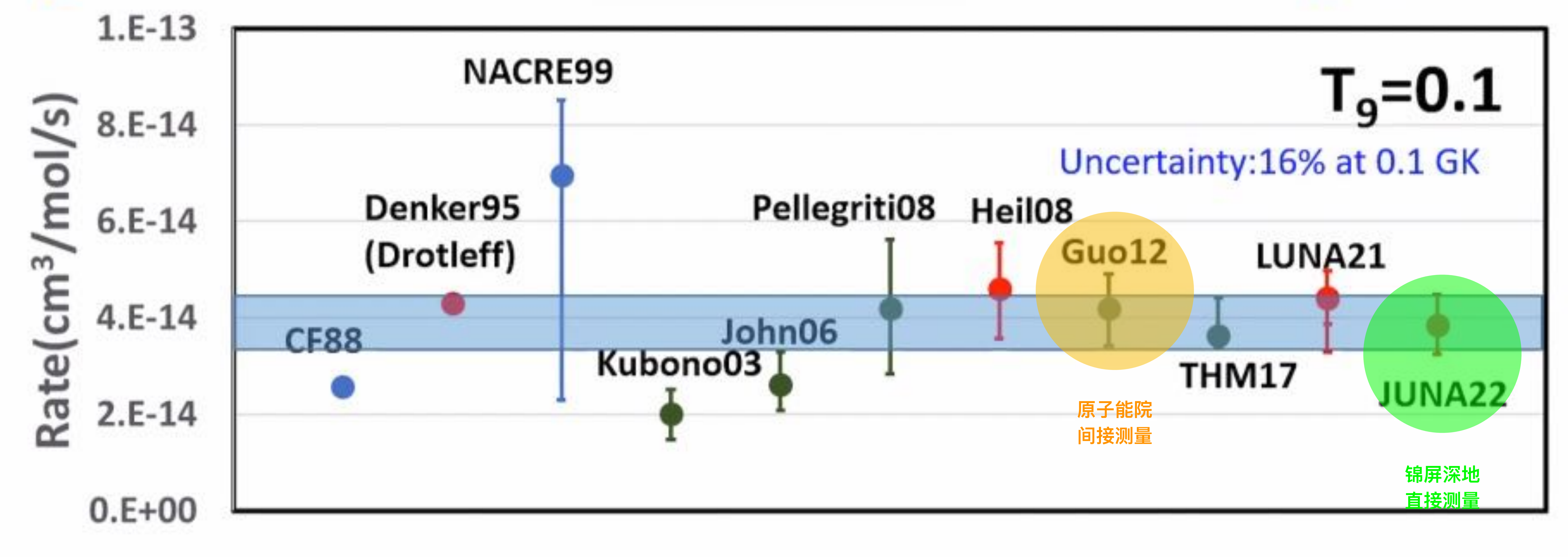
B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(\alpha,n)^{16}O$, PRL in press, 2022



恒星中子源30年探寻30 years research

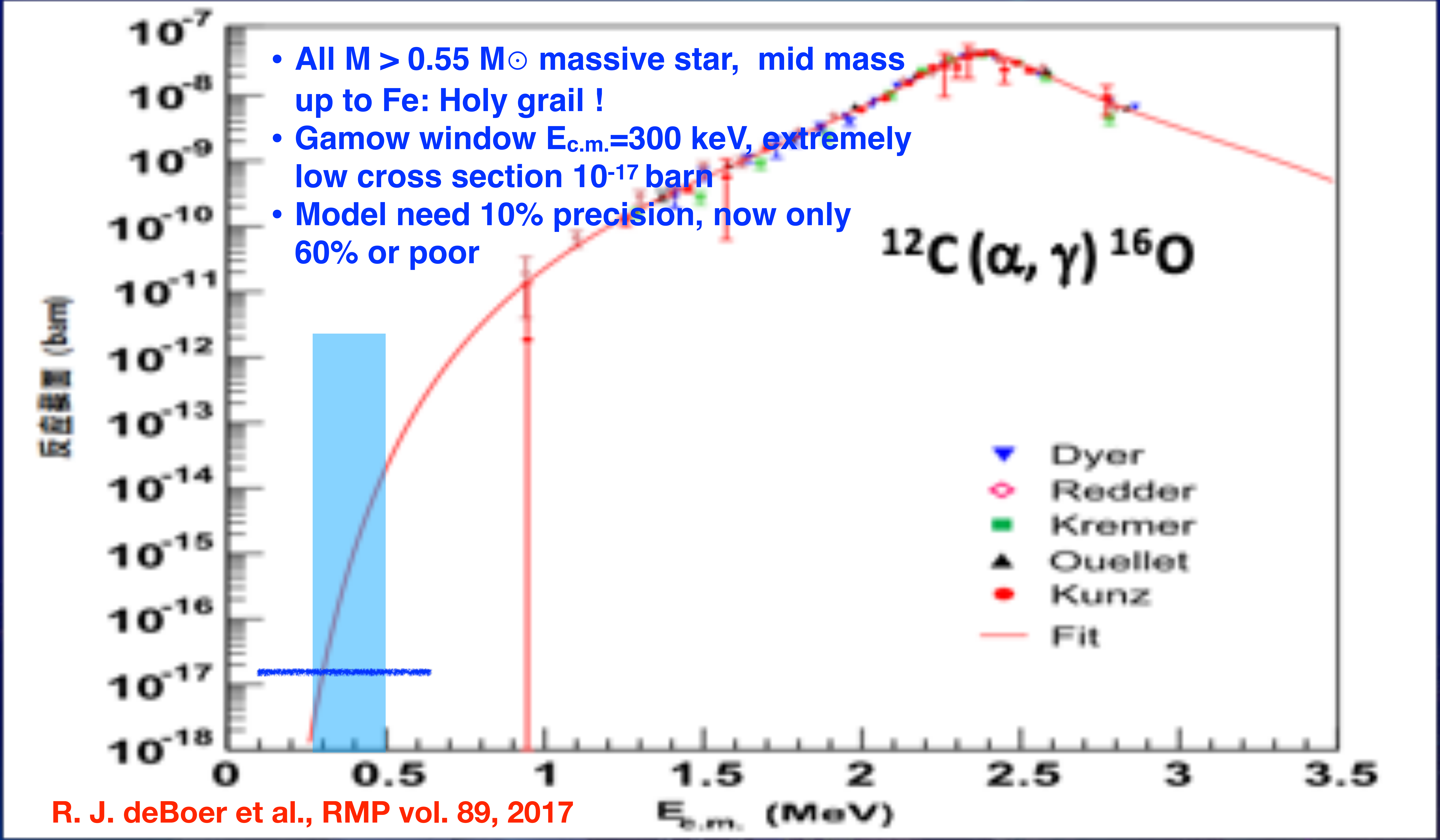
The significant reduction in uncertainty is fantastic. Now I believe that the work is a major achievement in experimental nuclear astrophysics …

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

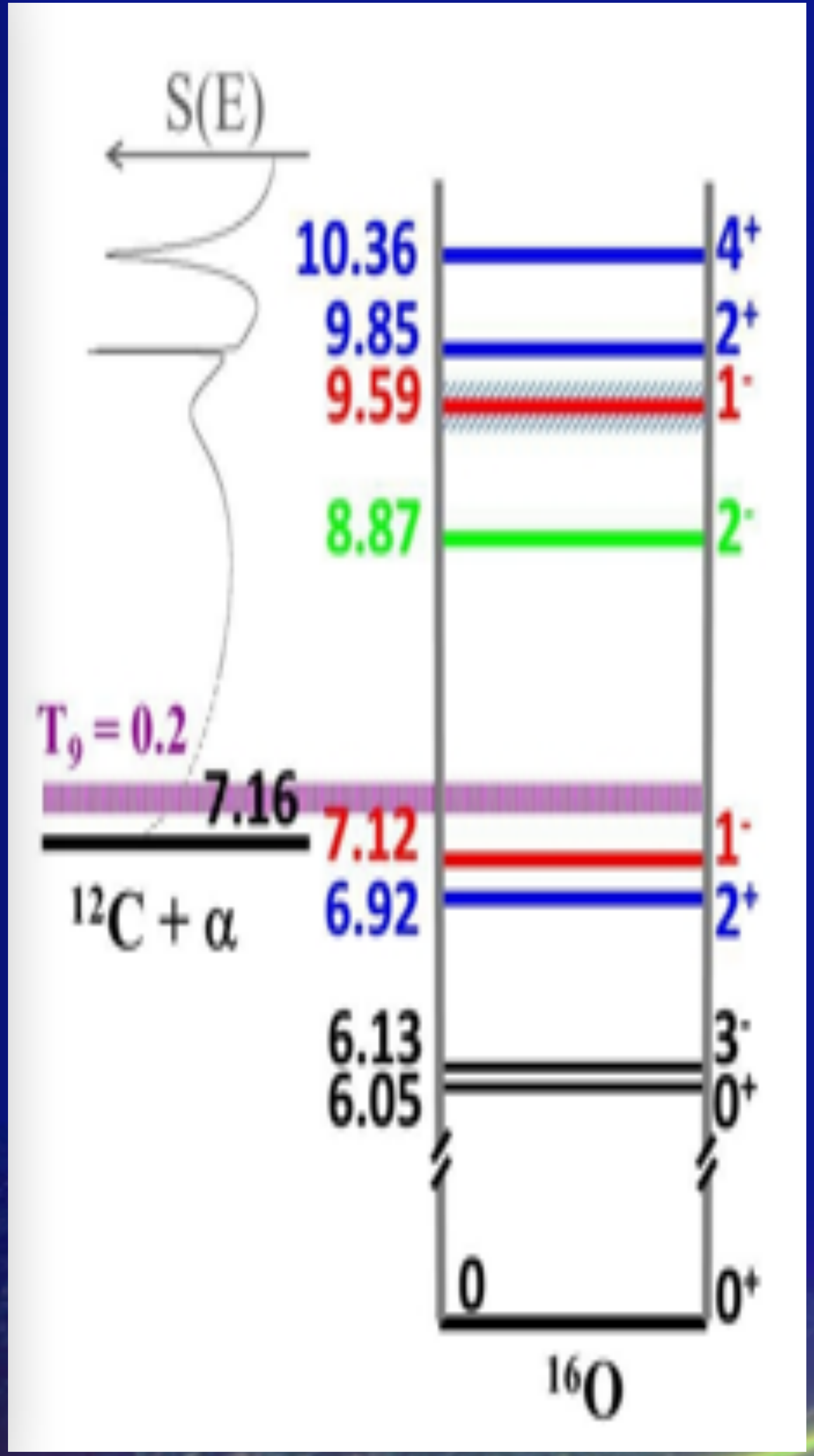


B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(\alpha,n)^{16}O$, PRL in press, 2022
B. Guo*, Z. H. Li,…, WPL*, Astrophys. J. 756, 193 (2012).

Big question, big impact, big challenge 圣杯



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



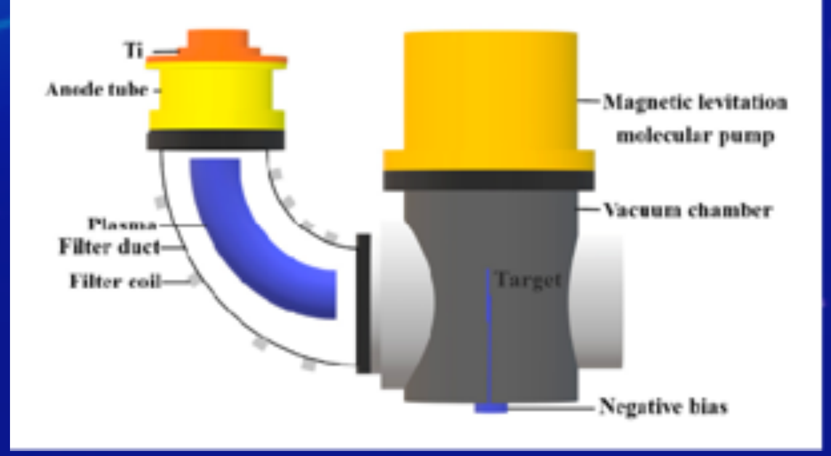
B. Guo, Z. H. Li, …, WPL,, APJ 756, 193 (2012)
Y. P. Shen, B. Guo, …, WPL, PRL 124, 162701(2020)

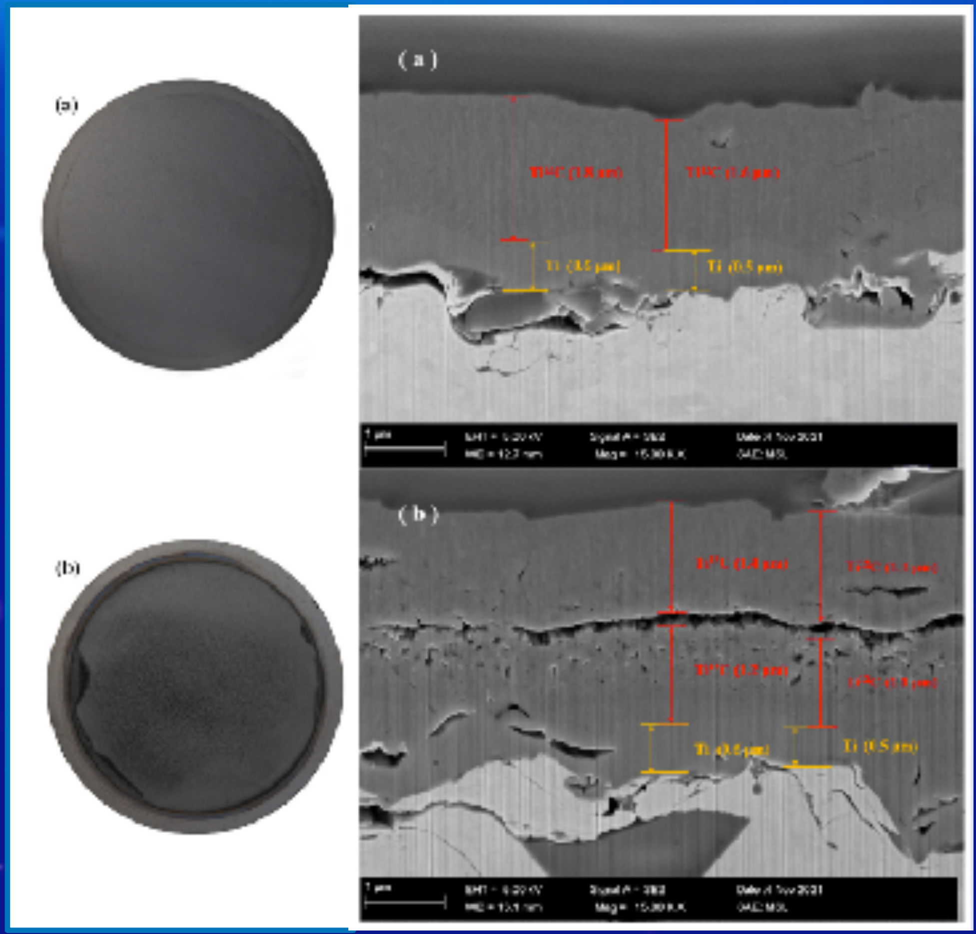
$^{12}C(\alpha,\gamma)^{16}O$ procedure

Contents lists available at ScienceDirect
Nuclear Inst. and Methods in Physics Research, B
journal homepage: www.elsevier.com/locate/nimb

Development of irradiation-resistant enriched ^{12}C targets for astrophysical $^{12}C(\alpha,\gamma)^{16}O$ reaction measurements

L.H. Wang[a], Y.P. Shen[b], J. Su[a,b,*], X.Y. Li[a,**], W.Q. Yan[a], J.J. He[a,b], L.Y. Zhang[a,b], B. Liao[a,b], Y.F. Wu[a], Y.D. Sheng[a], Z.M. Li[a], Y.J. Chen[a], L.Y. Song[a], X.Z. Jiang[a], G. Lian[c], W. Nan[c], W.K. Nan[c], L. Zhang[c], F.Q. Cao[c], C. Chen[c], N. Song[c], H. Zhang[a,c], W.P. Liu[c]
[a] Key Laboratory of Beam Technology of Ministry of Education, College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China
[b] Beijing Radiation Center, Beijing 100875, China
[c] China Institute of Atomic Energy, P.O. Box 275(10), Beijing 102413, China





	Hammer 2005	JUNA 2021
辐照量 C	90.6	280
靶厚衰减 %	20	25
制备方法	离子注入	过滤阴极真空电弧 (FCVA)

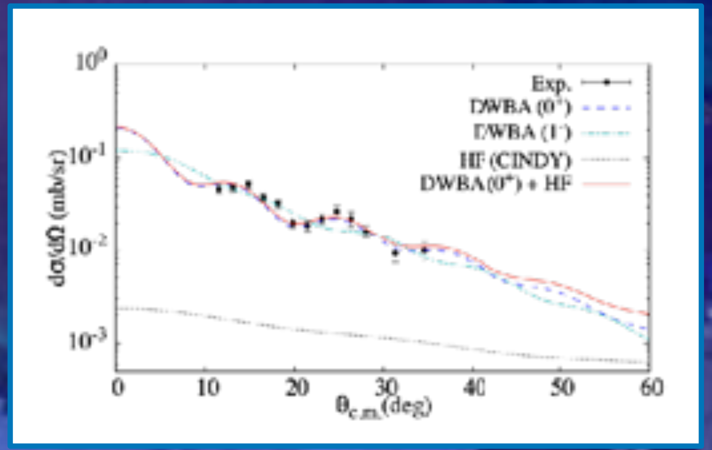
高耐辐照^{12}C高纯同位素靶研发

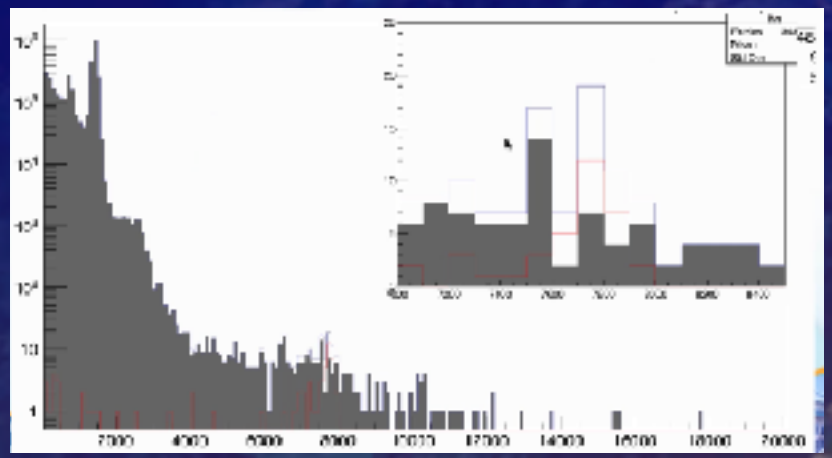
Target procedure

High purity ^{12}C gas → Made FCVA target $\frac{^{13}C}{^{12}C} = 1.1 \times 10^{-4}$ → Beam durability test → For data taking

Experiment procedure

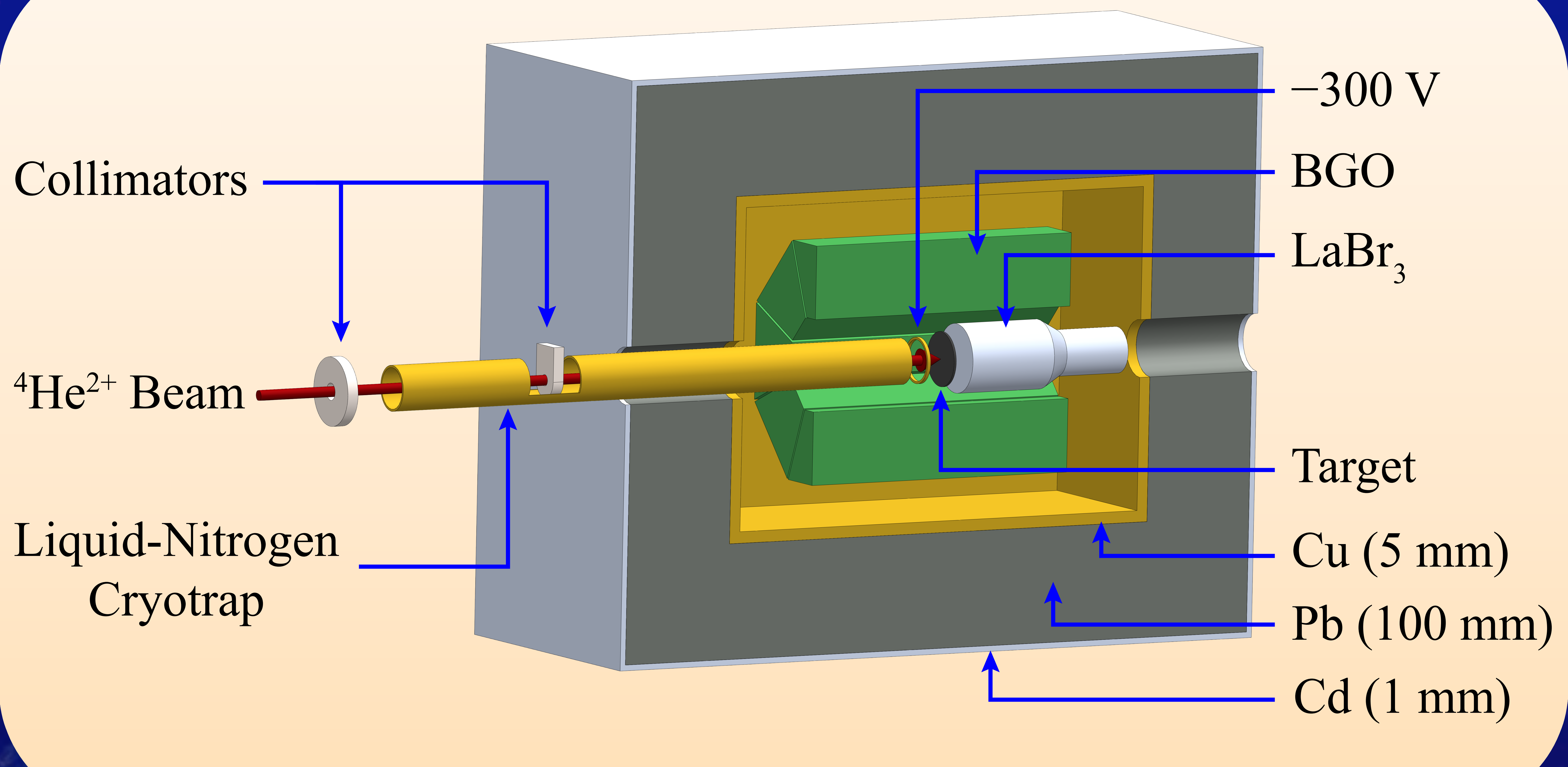
Indirect measurement → Ground high energy direct test → Underground background by C_{nat} target → Underground data taking





L. H. Wang et al., enriched ^{12}C targets, NIMB, 2021, accepted

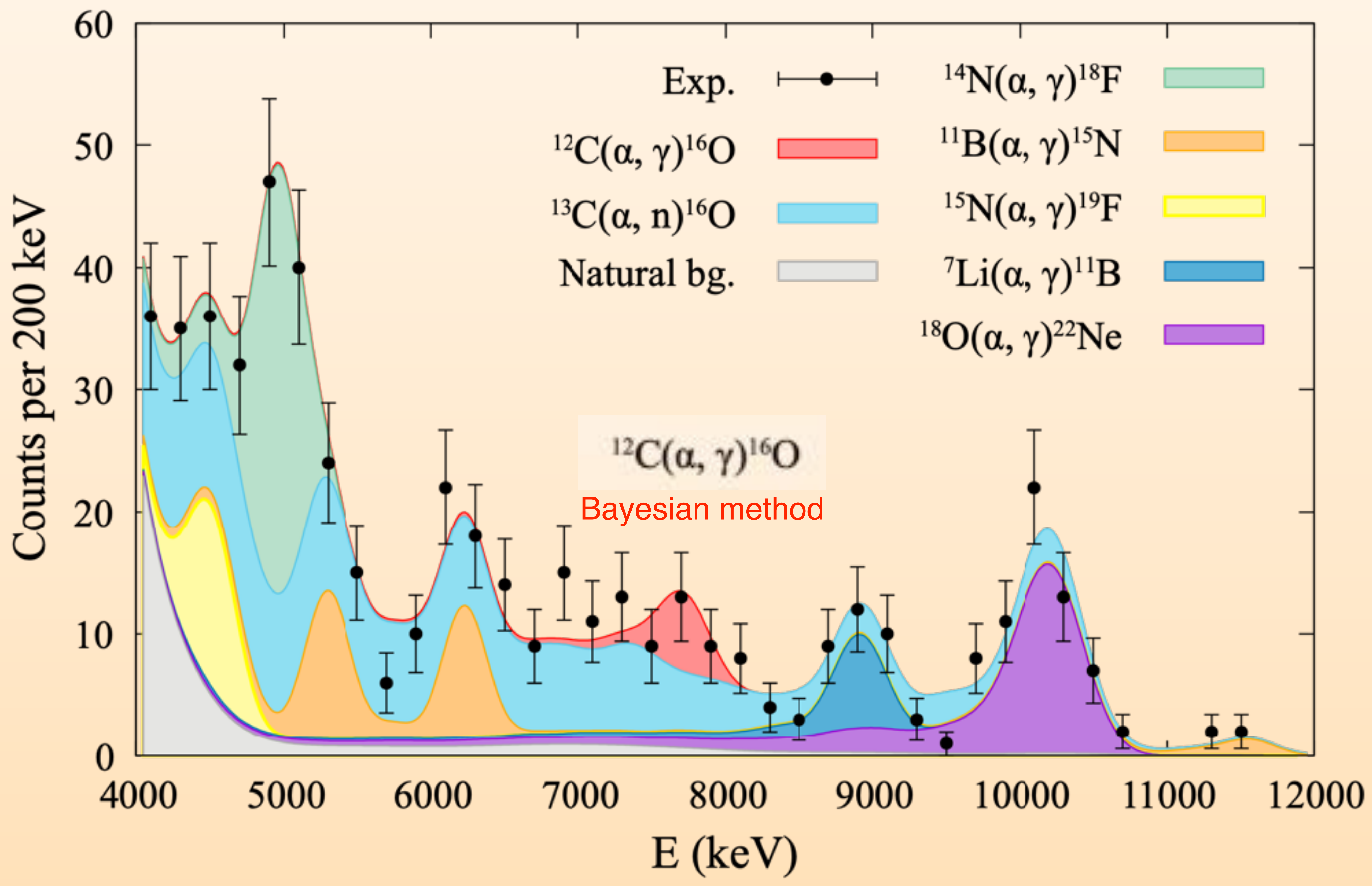
$^{12}C(\alpha,\gamma)^{16}O$ ： more sensitivity 最灵敏

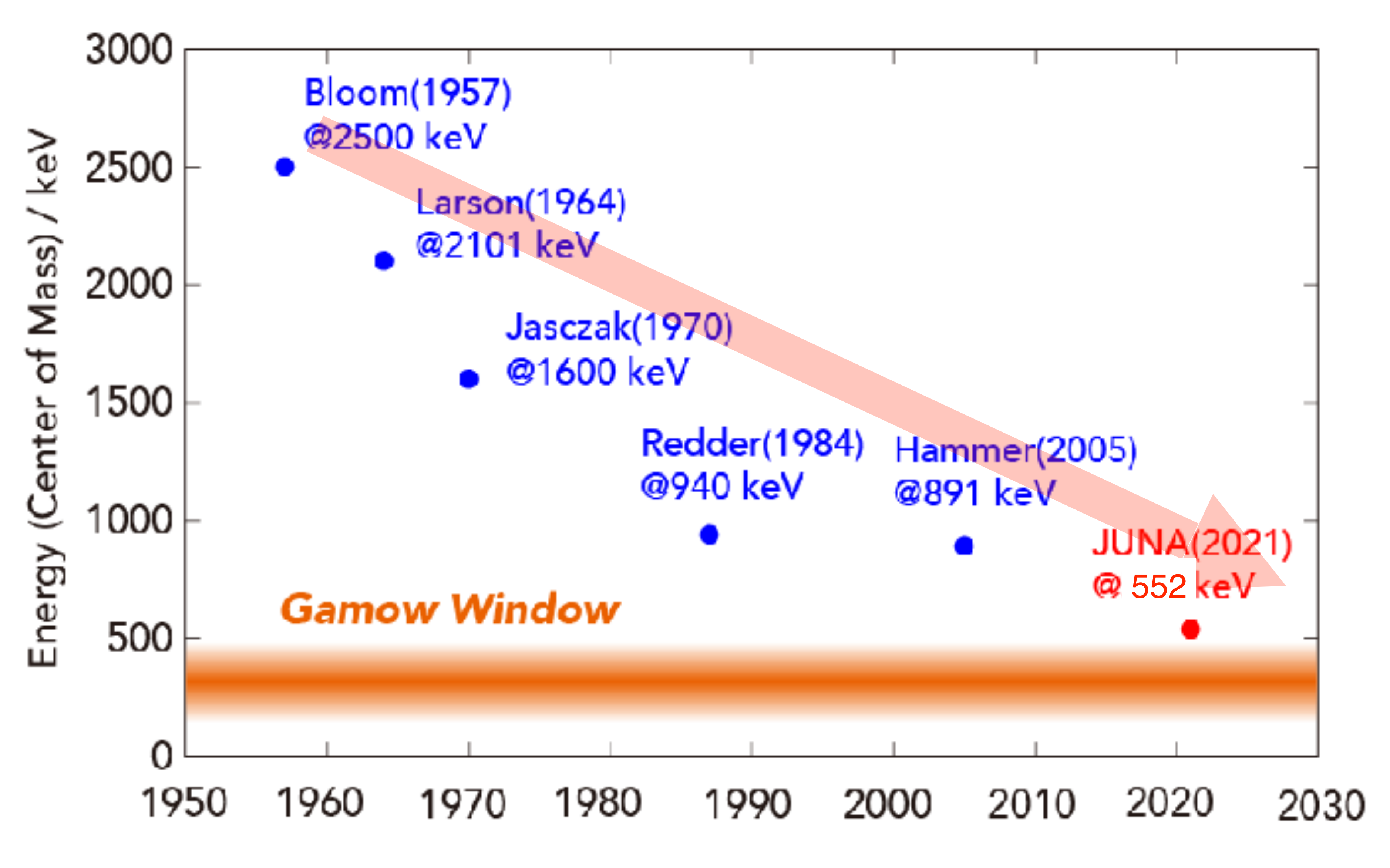


- FCVA implantation CTi thick targets
- durability >280 C @800 keV He^{2+}, with only 25% loss
- BGO+$LaBr_3$ (Lanthanum bromide) veto
- wide energy search for best S/N, 552 keV is best, other suffer from $^{18}O(\alpha,\gamma)^{22}Ne$ contaminations
- sensitivity of 10^{-12} b @$E_{c.m.}$ = 552 keV

$^{12}C(\alpha,\gamma)^{16}O$: more sensitivity, near Gamow window

Preliminary



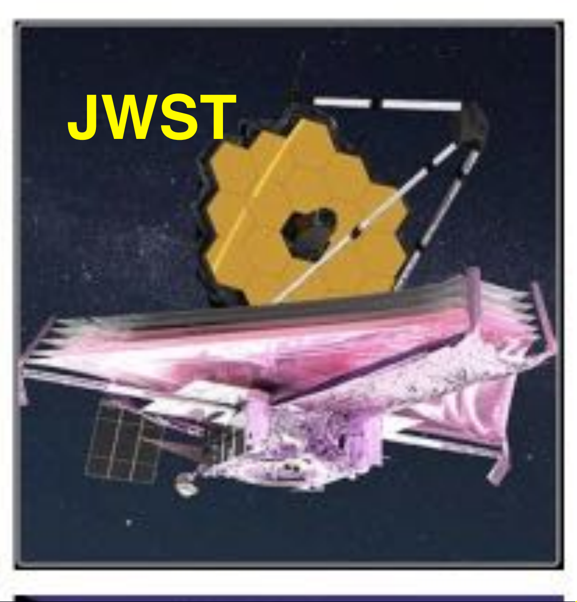


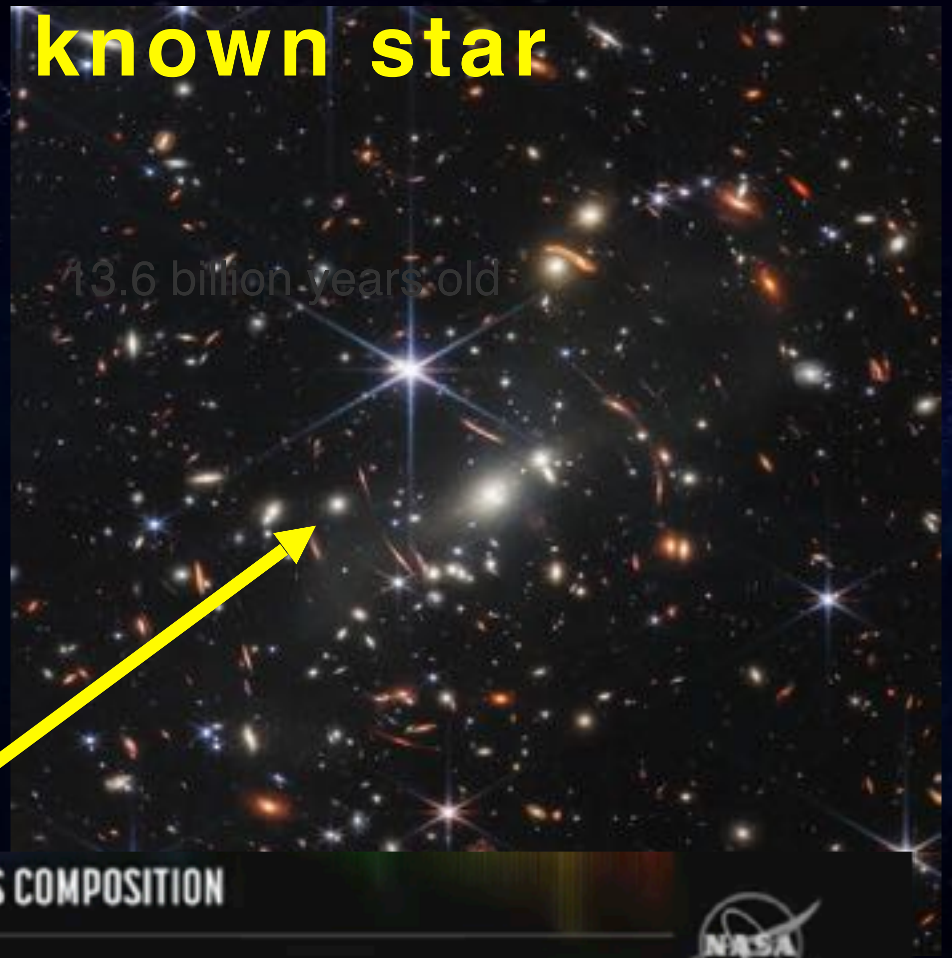
New excitement from JUNA $^{19}F(p,\gamma)^{18}Ne$： CNO break out，explain Ca in oldest known star

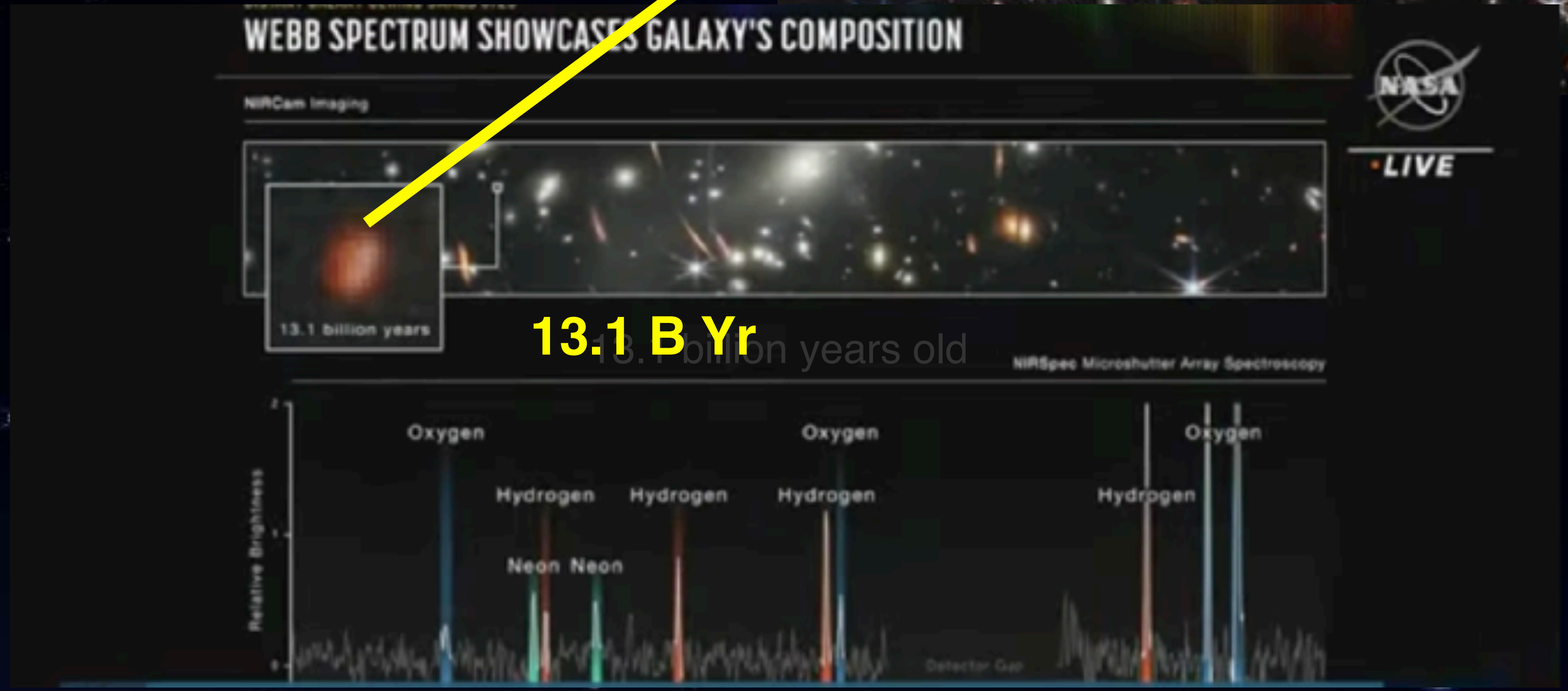
We are delighted to accept your manuscript entitled "Measurement of 19F(p,γ)20Ne reaction suggests CNO break-out in first stars" for publication in Nature. Thank you for choosing to publish your interesting work with us.

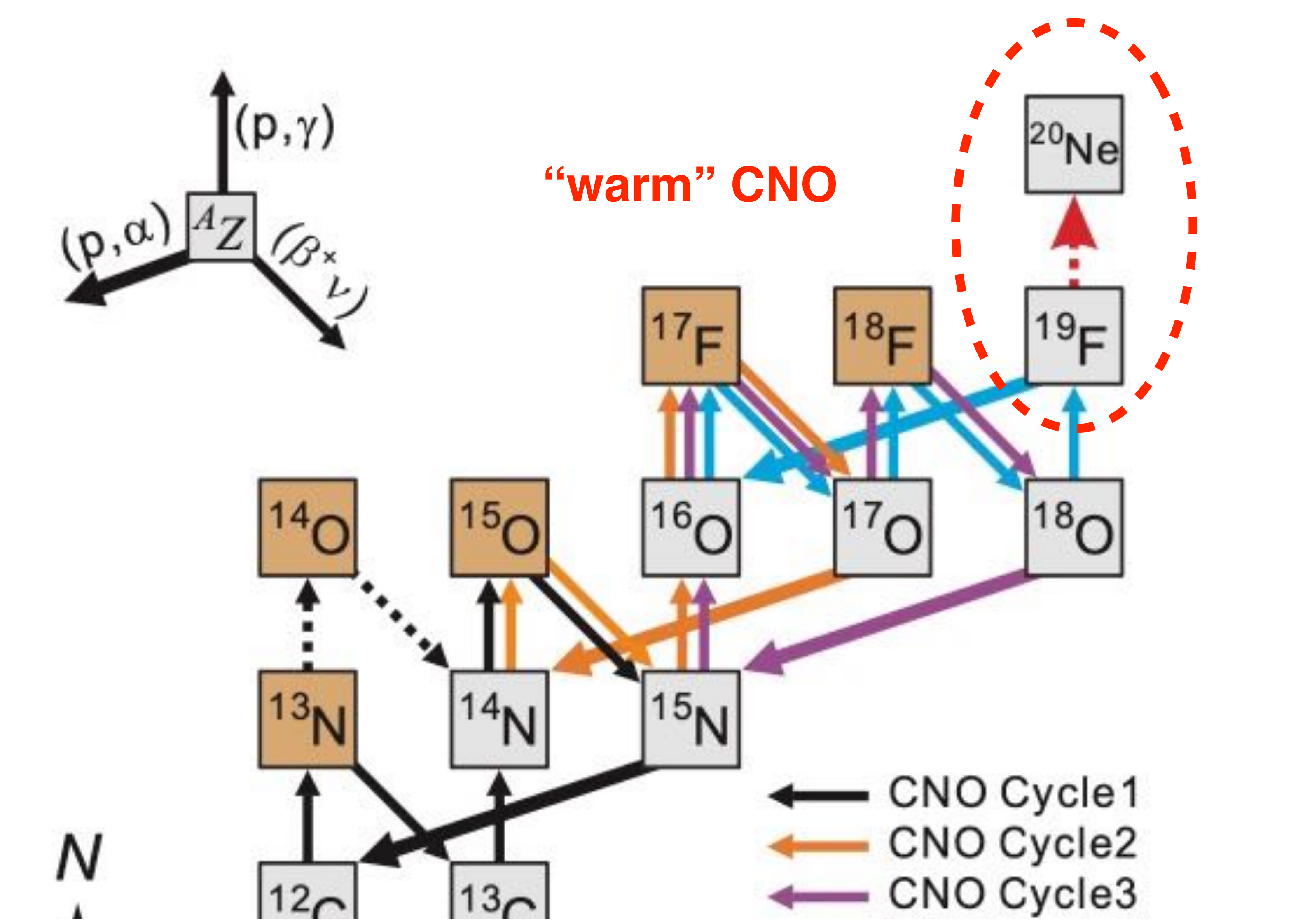
Aug. 11, 2022

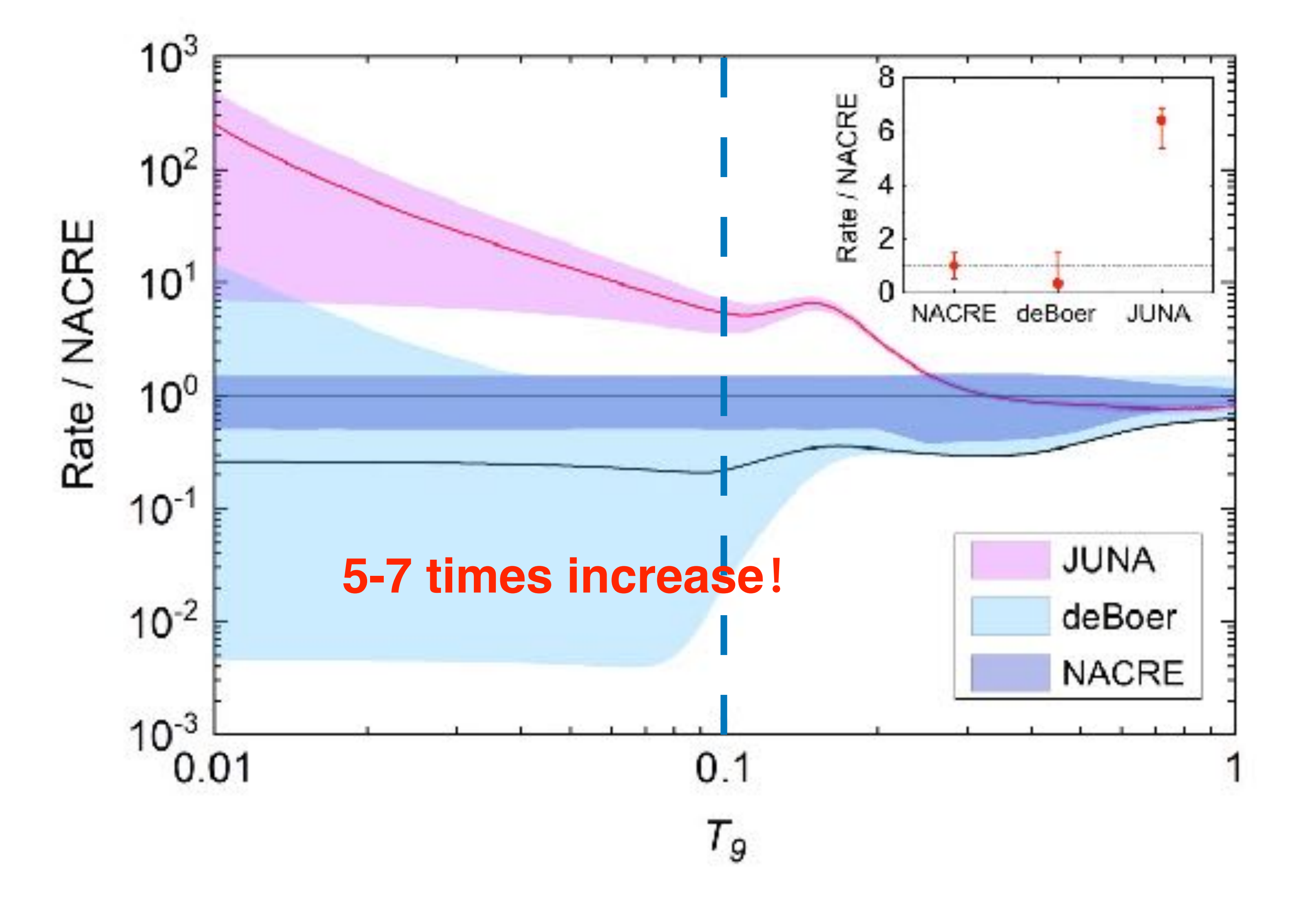
L. Y. Zhang, J. J. He*, ..., WPL*
New study of the key CNO break-out reaction $^{19}F(p,\gamma)^{20}Ne$ in first stars
Nature 2022 accepted

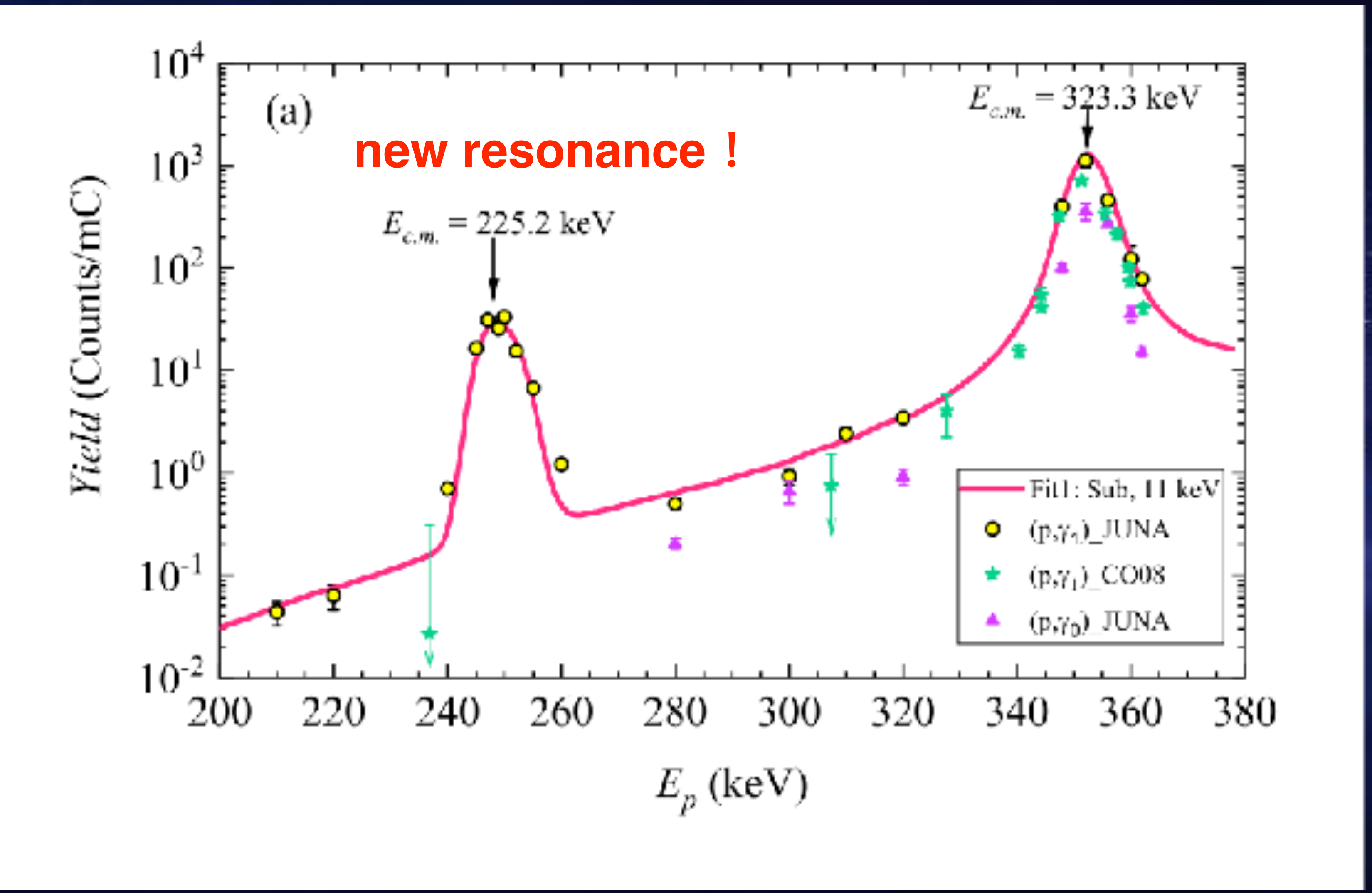


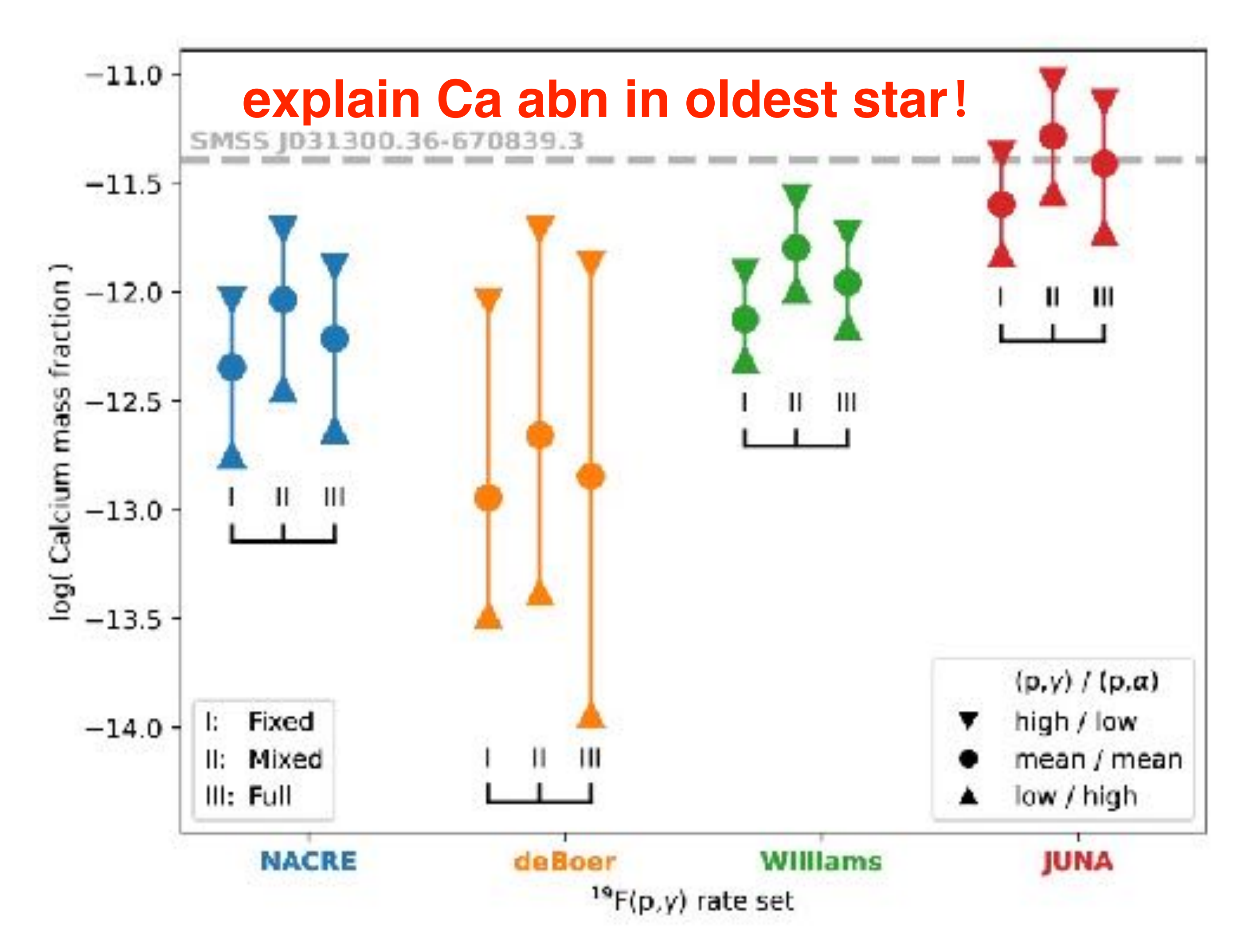












JUNA Milestone

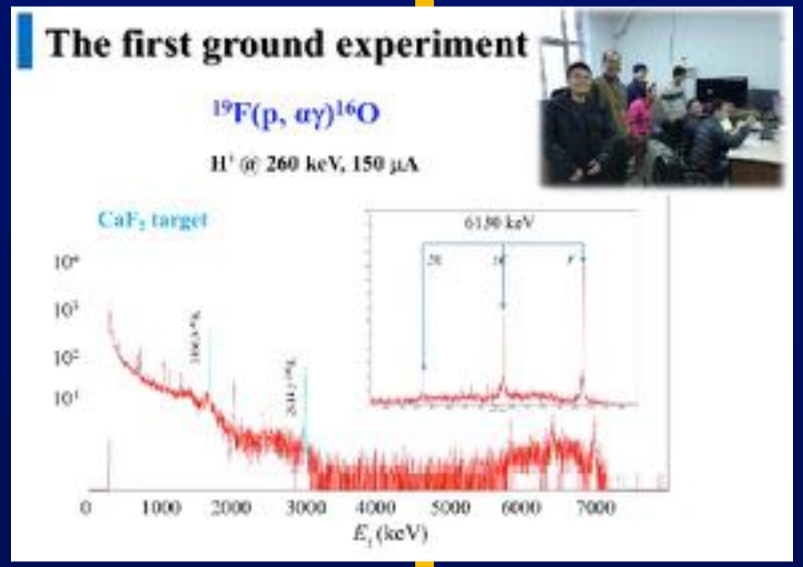
Aug. 2013
Startup meeting

Jan. 2015
Project inauguration

Mar. 2016
On site start

May 2017
Beam on ground

Dec. 2017
3 mA on ground



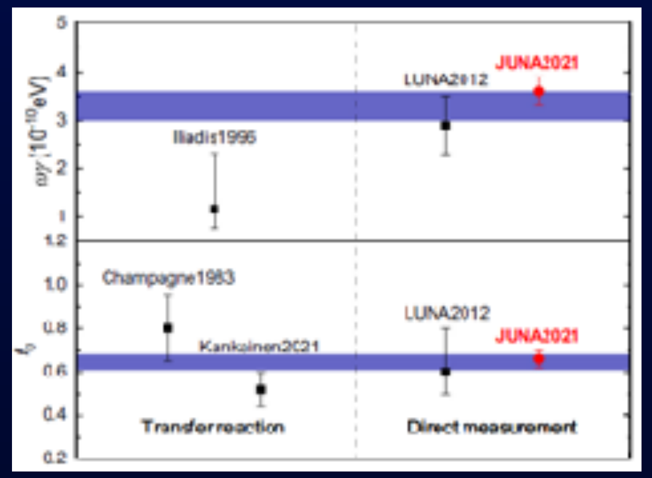
Dec. 2018
Der. Ready
Beam 10 mA

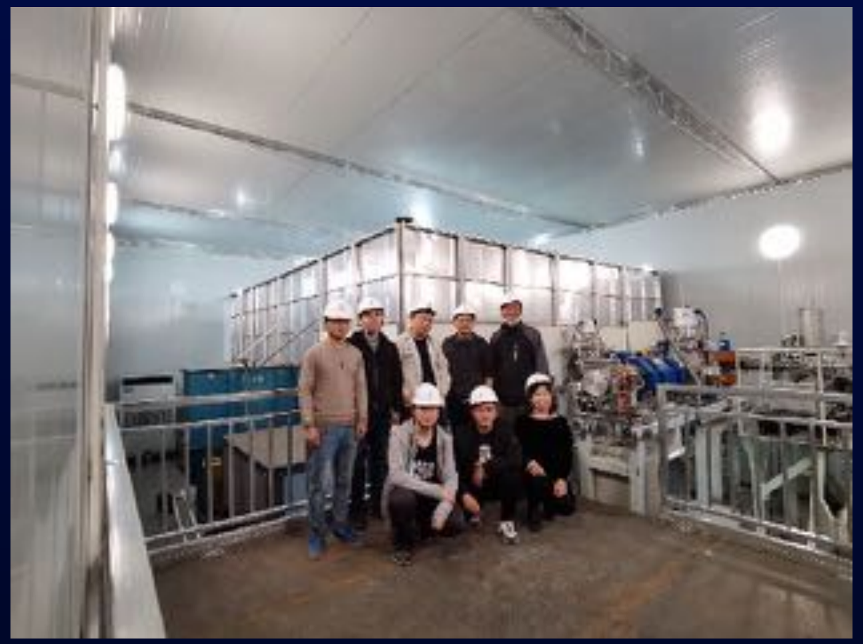
April 2019
Target ready
Acc. Ready

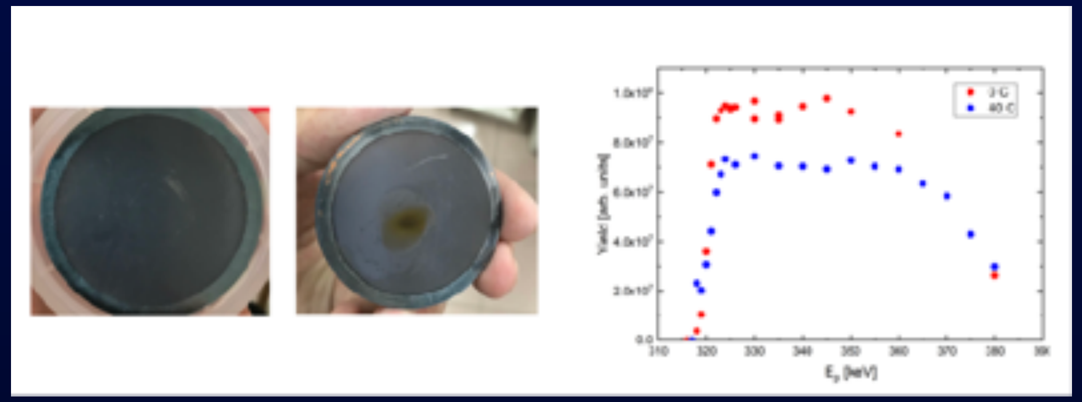
Dec. 2020
Beam underground

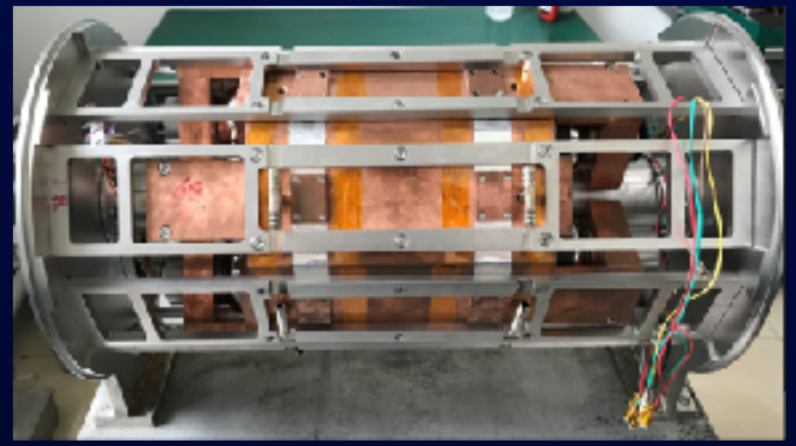
Mar. 2021
^{25}Mg, ^{19}F and ^{13}C data ready

Dec. 2021
Project commission







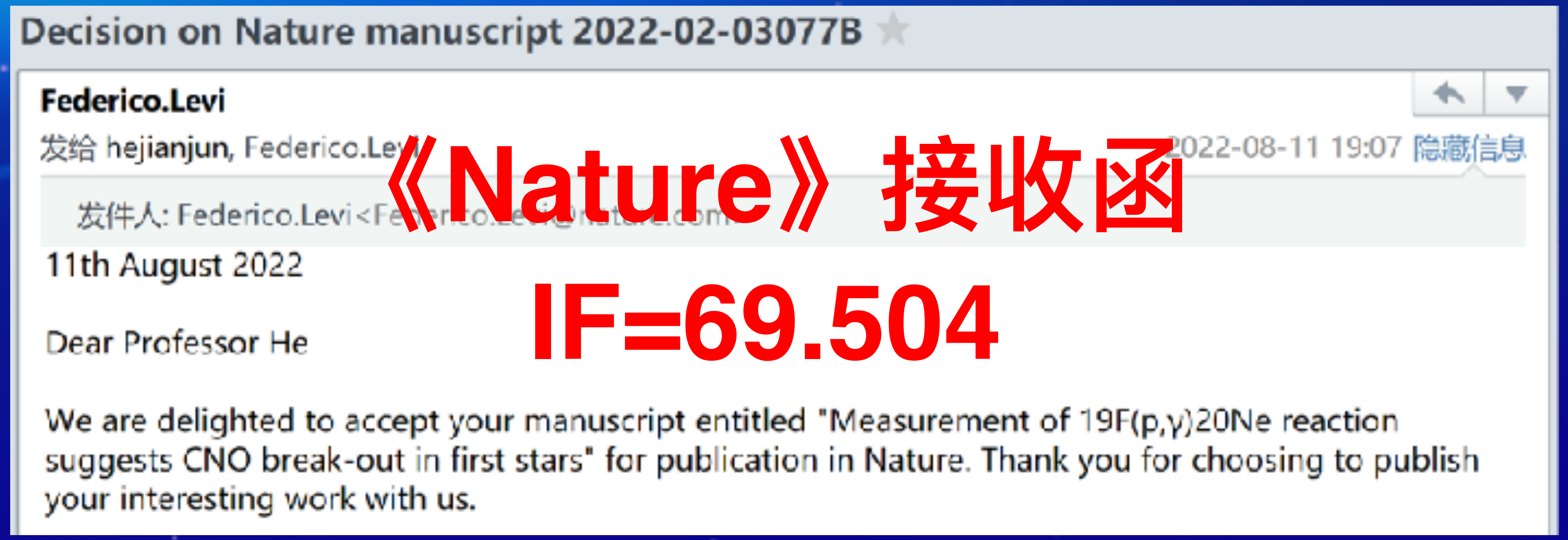


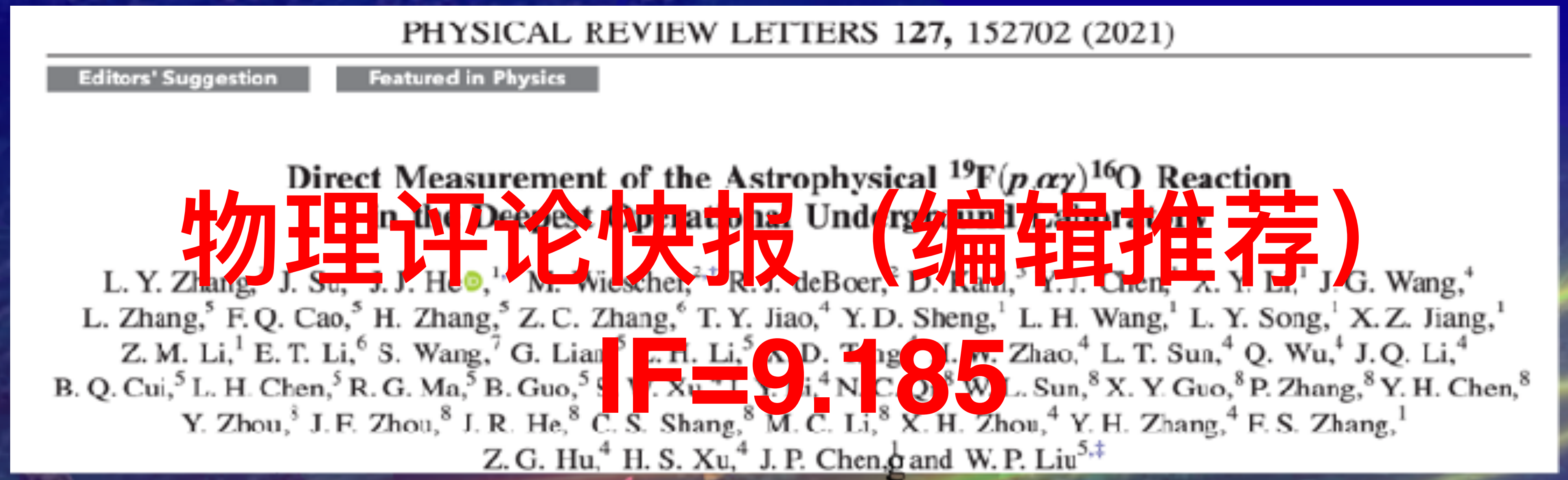
WPL et al., Sci. China 59(2016)2

取得杰出物理成果

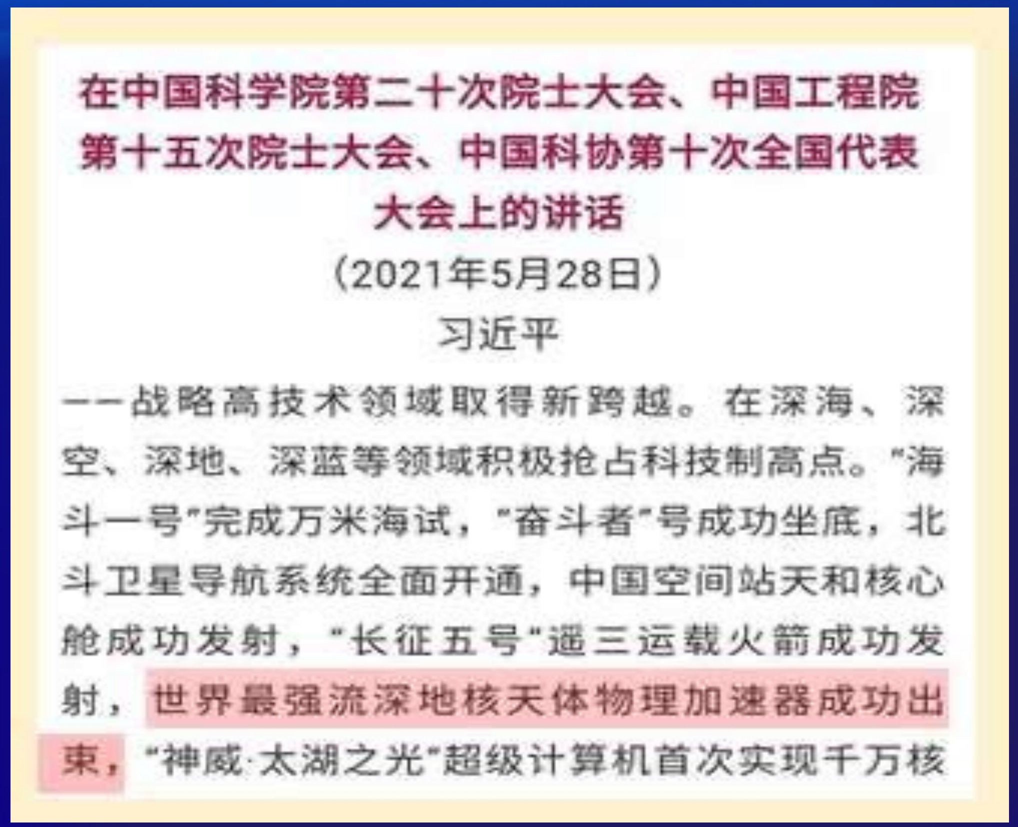
发表四篇国际顶级物理学期刊文章

- $^{19}F(p,\gamma)^{20}Ne$：《Nature》杂志成果：首次解释最古老恒星钙丰度疑难
- $^{19}F(p,\alpha g)^{16}O$：物理评论快报编辑推荐成果：排除氟丰度超出的核物理不确定性
- $^{25}Mg(p,\gamma)^{26}Al$：科学通报封面成果：取得最精确的伽马射线源的产生率
- $^{13}C(\alpha,n)^{16}O$：物理评论快报：解决30多年的中子源强度的分歧
- $^{12}C(\alpha,\gamma)^{16}O$：国际最高灵敏度：70年来首次使圣杯反应接近天体能量窗口
- 成果在国际天文大会、国际核天体物理大会、亚太物理会议报告



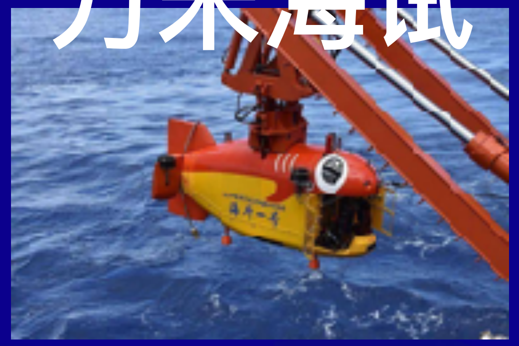


总书记在2021年两院院士大会
表扬的我国十大战略高技术进展


在中国科学院第二十次院士大会、中国工程院第十五次院士大会、中国科协第十次全国代表大会上的讲话
（2021年5月28日）
习近平

——战略高技术领域取得新跨越。在深海、深空、深地、深蓝等领域积极抢占科技制高点。"海斗一号"完成万米海试，"奋斗者"号成功坐底，北斗卫星导航系统全面开通，中国空间站天和核心舱成功发射，"长征五号"遥三运载火箭成功发射，世界最强流深地核天体物理加速器成功出束，"神威·太湖之光"超级计算机首次实现千万核

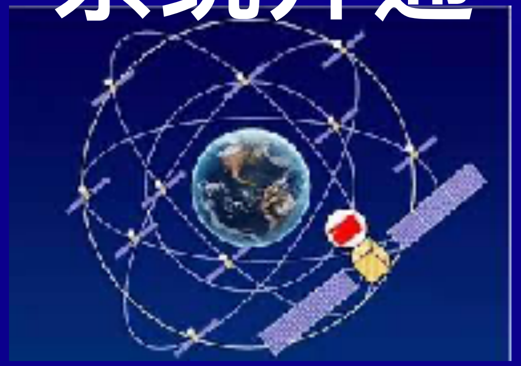
海斗一号
万米海试



奋斗者号
成功坐底

世界最强流深地核天体
物理加速器成功出束

北斗导航
系统开通



中国空间站天
和核心舱发射

长征五号
遥三发射

墨子号
密钥分发

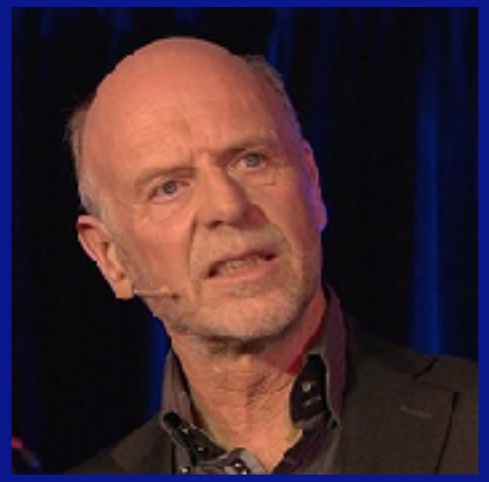
天鲲号
试航成功

华龙三代
核电技术

太湖超级
计算机

International recognition

- J. C. Mather, 2006 Nobel Prize Winner, JWST chief scientist, **"And congratulations on your new measurements; they seem quite important."**

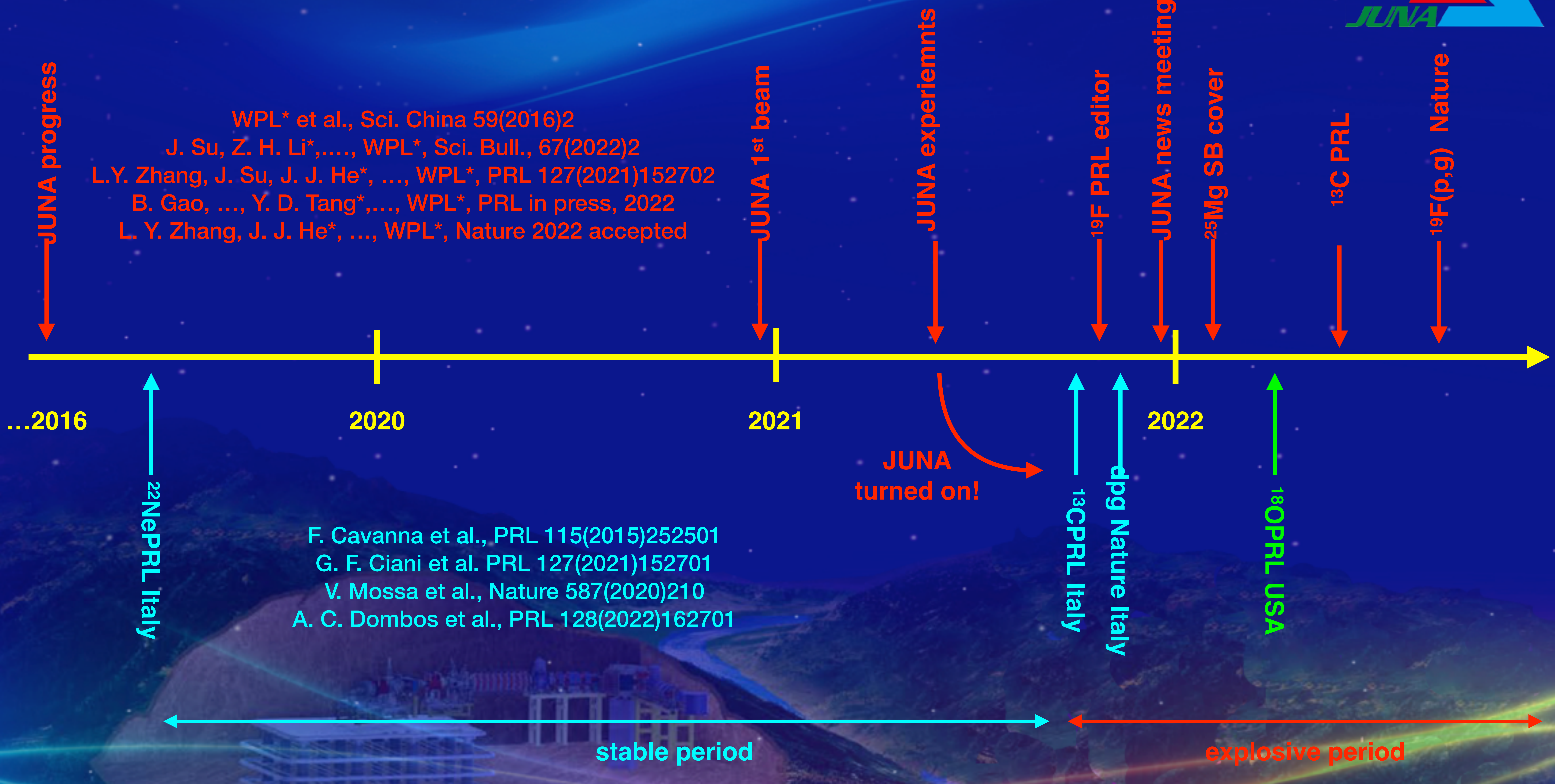


- R. Diehl, INTEGRAL spokes person, **"This is great news and a big achievement: Congratulations!"**

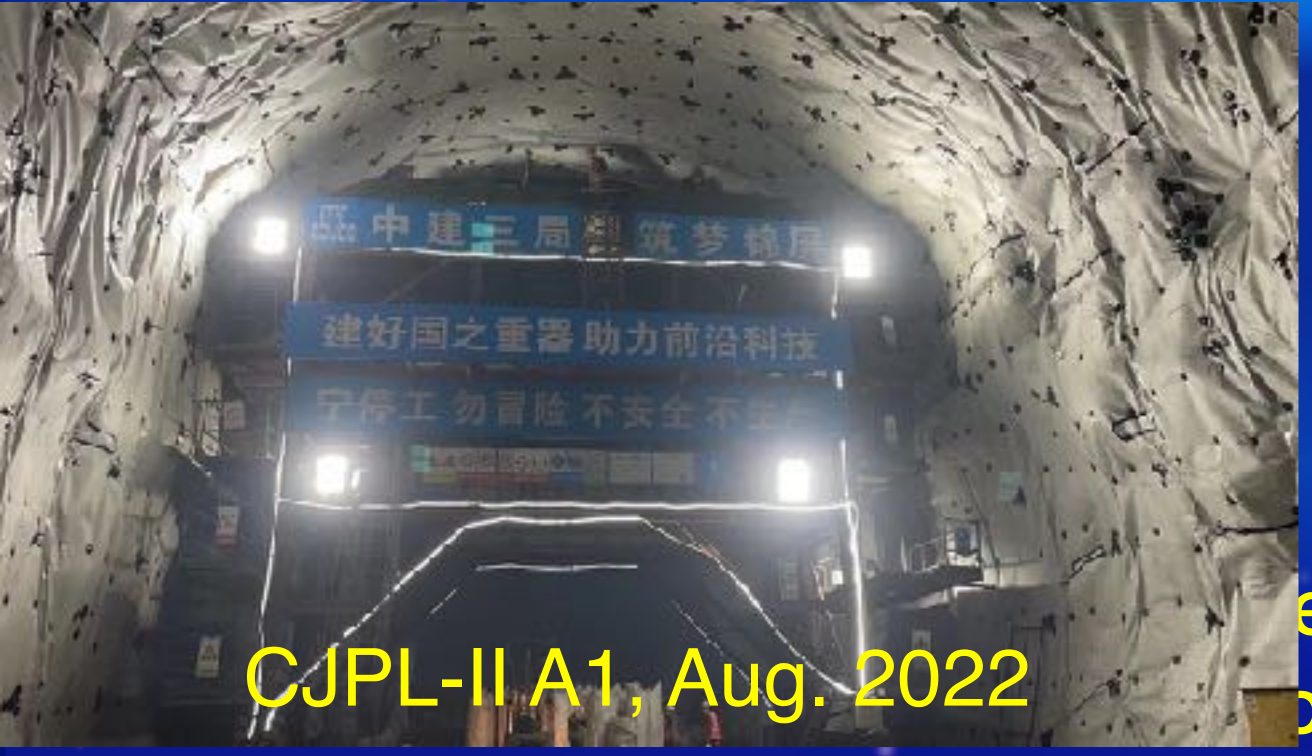
- M. Wiescher, former JINA chair, **"There's no question that you're in the lead."**

- T. Kajino, BUAA/NAOJ professor, **"The JUNA achievement in the first year is really great by producing several important results with the world highest precision."**

激发国际深地核天体物理发展 simulating effect



Future plan from 2023



e
or

Detector
Target

Signal
Background

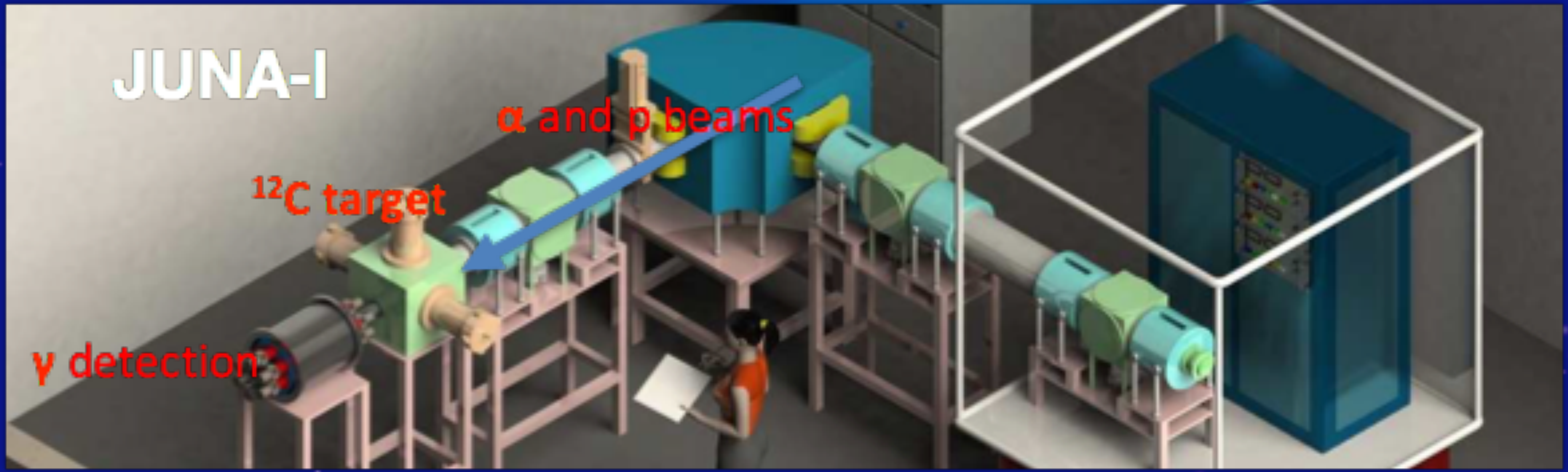
Analysis
Improvement

Jan. 2015 Project start → May 2017 Beam on ground → Dec. 2020 beam underground → April 2021 Exp. Phase 1 → 2023 Exp. Phase 2

Reaction	Achieved with ca. 1 emA beam
$^{12}C(\alpha,\gamma)^{16}O$	1X10^{-12} b limit 552 keV
$^{13}C(\alpha,n)^{16}O$	10%, 10^{-12} b 230-600 keV
$^{25}Mg(p,\gamma)^{26}Al$	5% 92 keV
$^{19}F(p,\alpha\gamma)^{16}O$ $^{19}F(p,\gamma)^{20}Ne$	5 %,72-344 keV, PRL 5 %,188-344 keV

Reaction	Desired with max. 10 emA beam
$^{12}C(\alpha,\gamma)^{16}O$	1X10^{-13} b limit 450 keV
$^{13}C(\alpha,n)^{16}O$	10%, , 10^{-13} b 150 keV
$^{22}Ne(\alpha,n)^{25}Mg$	gas target
$^{14}N(p,\gamma)^{15}O$	

JUNA未来：走向卓越 Future



400 kV
p, α
2020-
one of best

reaction	physics
$^{12}C(\alpha,\gamma)^{16}O$	Massive star
$^{13}C(\alpha,n)^{16}O$	HI synthesis
$^{25}Mg(p,\gamma)^{26}Al$	Galaxy ^{26}Al
$^{19}F(p,\alpha)^{16}O$	F abundance

4 MV
^{12}C, ^{16}O
2023-
top class

H 燃烧

$^{3}He(\alpha,\gamma)^{7}Be$
$^{2}H(\alpha,\gamma)^{6}Li$
$^{3}He(^{3}He,2p)^{4}He$
$^{7}Be(p,\gamma)^{8}B$
$^{12}C(p,\gamma)^{13}N$
$^{14}N(p,\gamma)^{15}O$
$^{15}N(p,\gamma),(p,\alpha)^{16}O,^{12}C$
$^{17}O(p,\gamma),(p,\alpha)^{18}F,^{14}N$
$^{18}O(p,\gamma),(p,\alpha)^{19}F,^{15}N$
$^{19}F(p,\gamma),(p,\alpha)^{20}Ne,^{16}O$

He 燃烧

$^{12}C(\alpha,\gamma)^{16}O$
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{20}Ne(\alpha,\gamma)^{24}Mg$
$^{18}O(\alpha,\gamma)^{22}Ne$
$^{22}Ne(\alpha,\gamma)^{26}Mg$
$^{24}Mg(\alpha,\gamma)^{28}Si$

中子源

$^{13}C(\alpha,n)^{16}O$
$^{22}Ne(\alpha,n)^{25}Mg$
$^{25}Mg(\alpha,n)^{28}Si$
$^{26}Mg(\alpha,n)^{29}Si$

C, O 燃烧

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

γ 天文学

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

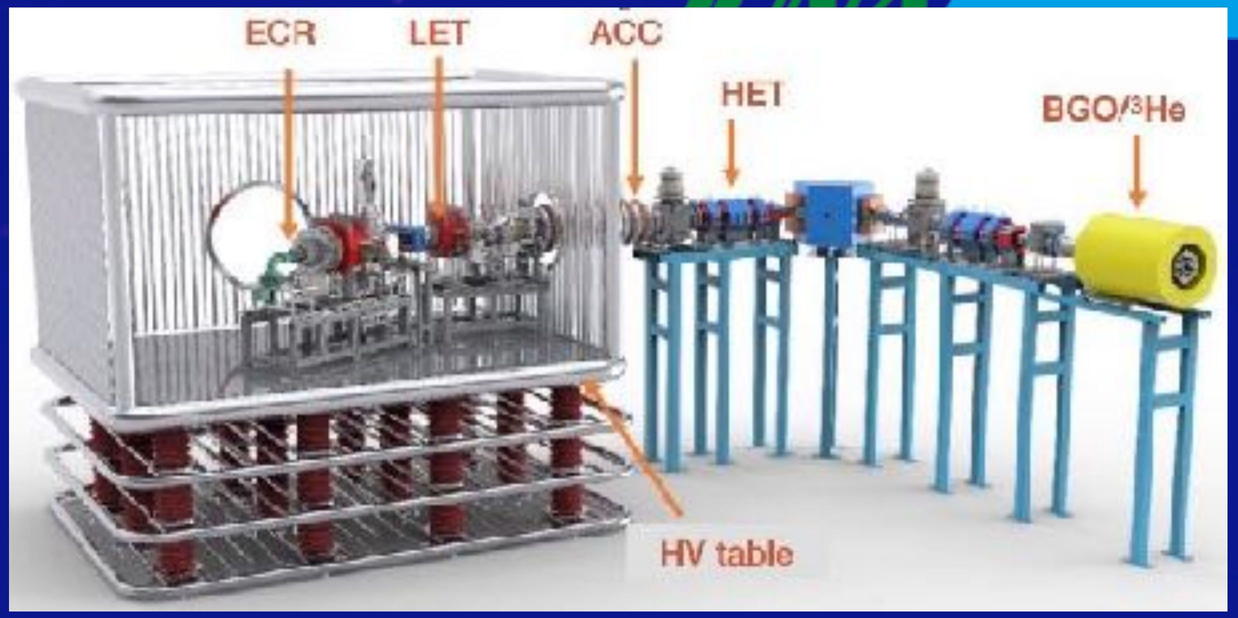
JUNA summary 重大研究成果总结

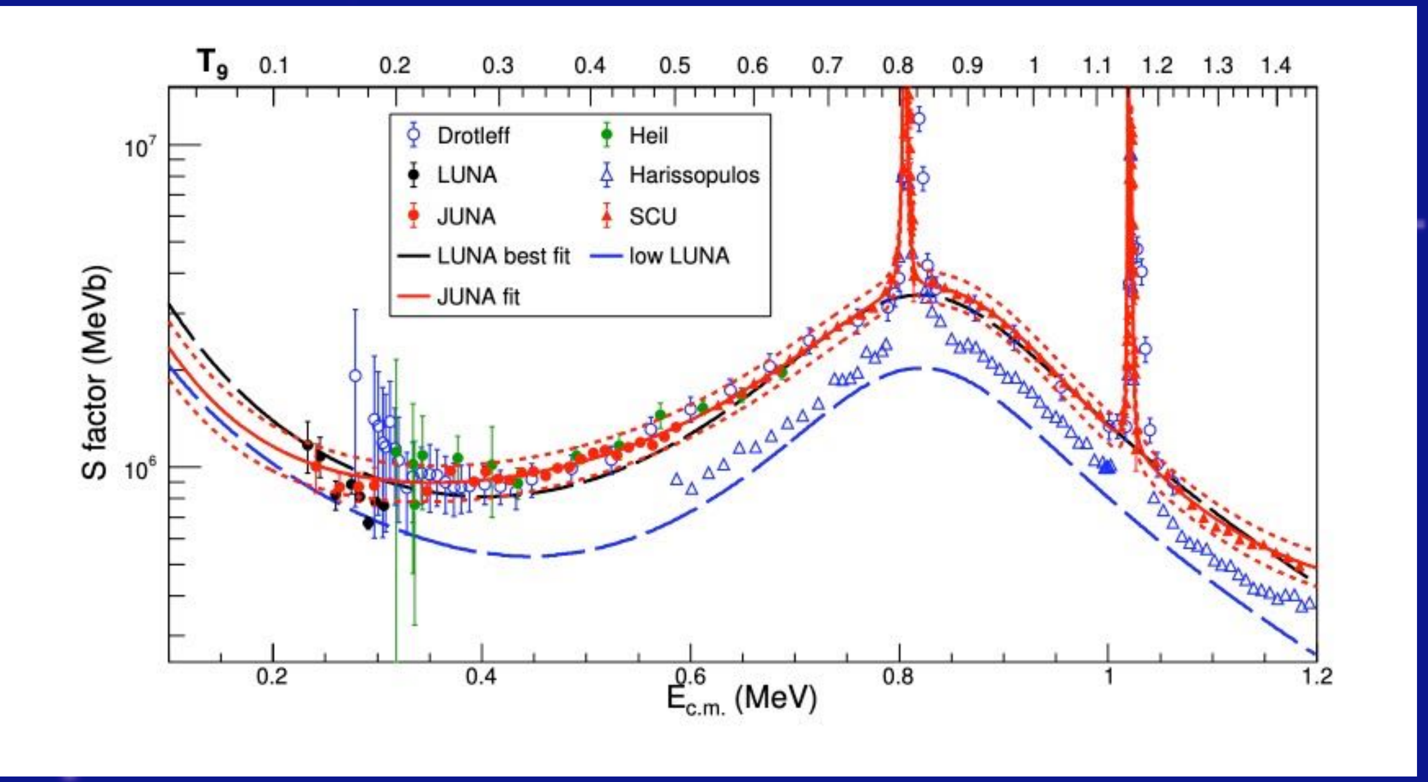
- JUNA is becoming an advanced deep astrophysics platform. China, follow Italy and United States, to be third to carry out direct measurement of deep core astrophysical reactions

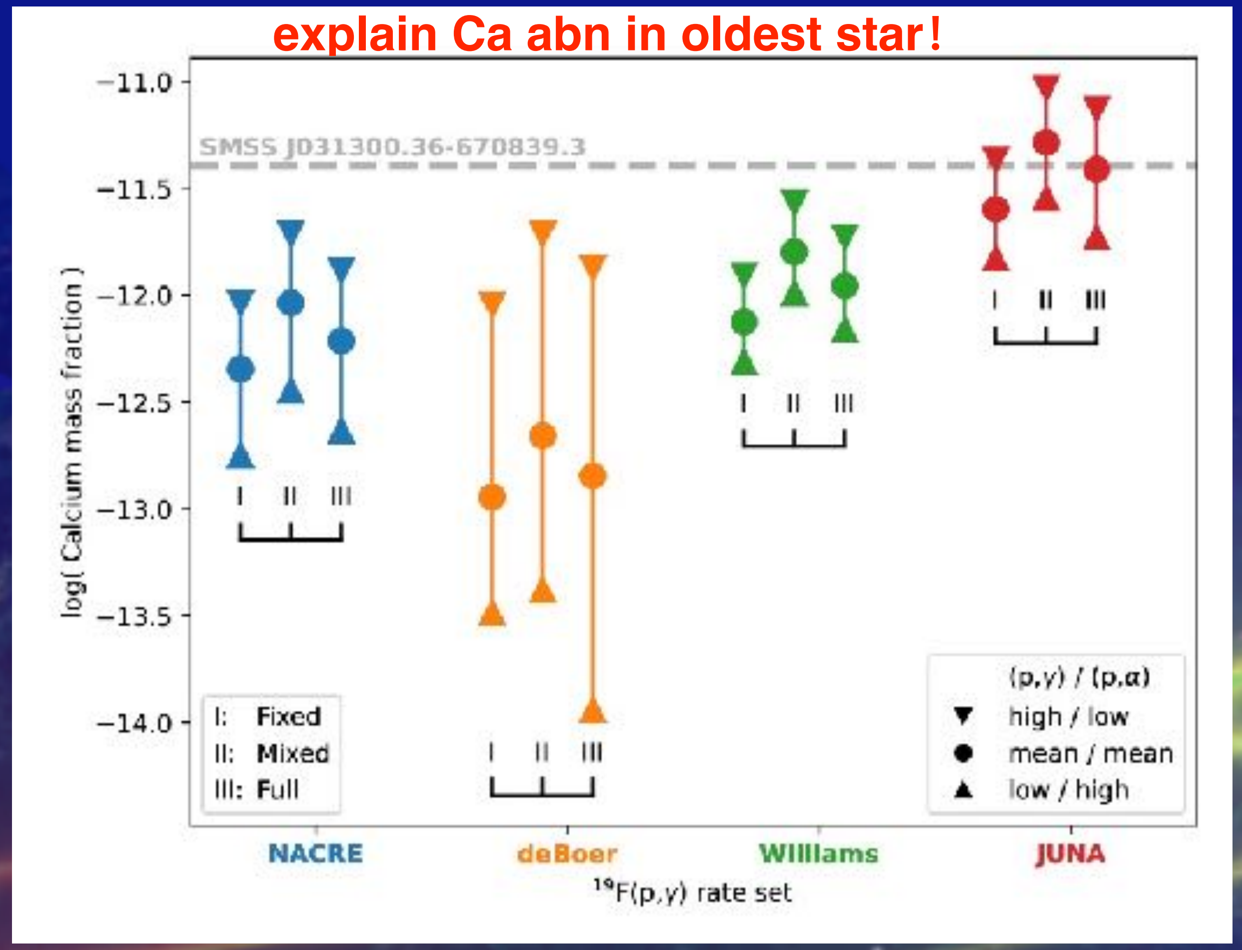
- Accurately measured key nuclear astrophysical reactions. Compared with previous experiment, beam intensity is higher, detector efficiency, target exposure, sensitivity and energy coverage are greatly improved,

- Gamma-ray astronomical reaction has reached the highest precision, and the astrophysical holy grail reaction has achieved the highest sensitivity, new resonances revealing the origin of heavy element abundance in the oldest stars in JWST, and the discrepancies of neutron source reactions was resolved.

- Welcome to join JUNA collaboration and submit your proposals deep underground!



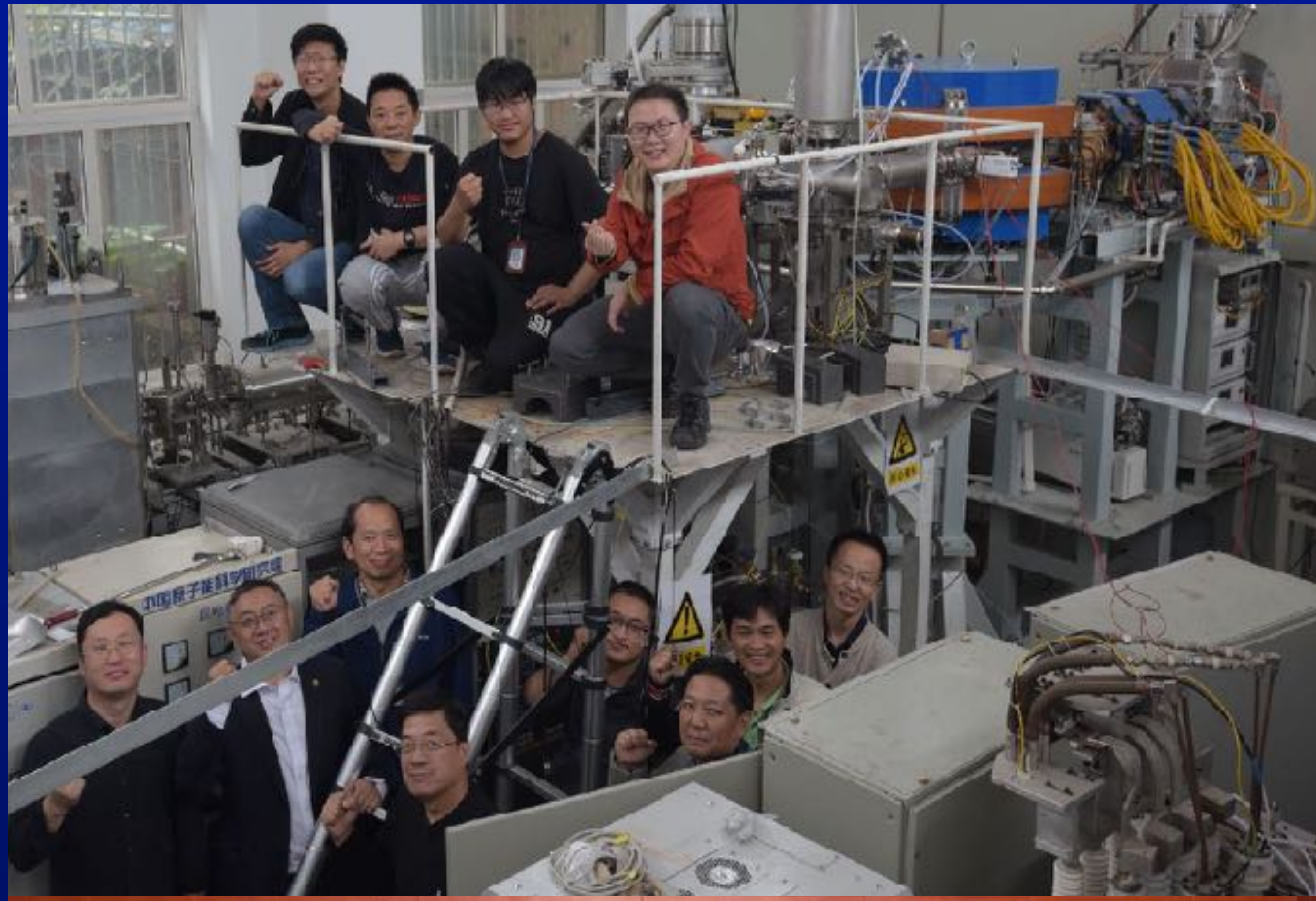




JUNA Team

Weiping Liu[1], Zhihong Li[1], Jianjun He[2], Xiaodong Tang[2], Gang Lian[1], Zhu An[4], Qinghao Chen[3], Xiongjun Chen[1], Yangping Chen[1], Zhijun Chen[2], Baoqun Cui[1], Xianchao Du[1], Changbo Fu[5], Lin Gan[1], Bing Guo[1], Guozhu He[1], Alexander Heger[6], Suqing Hou[2], Hanxiong Huang[1], Ning Huang[4], Baolu Jia[2], Liyang Jiang[1], Shigeru Kubono[7], Jianmin Li[3], Kuoang Li[2], Tao Li[2], Yunju Li[1], Maria Lugaro[8], Xiaobing Luo[4], Shaobo Ma[2], Dongming Mei[9], Yongzhong Qian[10], Jiuchang Qin[1], Jie Ren[1], Jun Su[1], Liangting Sun[2], Wanpeng Tan[11], Isao Tanihata[12], Peng Wang[4], Shuo Wang[13], Youbao Wang[1], Qi Wu[2], Shiwei Xu[2], Shengquan Yan[1], Litao Yang[3], Xiangqing Yu[2], Qian Yue[3], Sheng Zeng[1], Huanyu Zhang[1], Hui Zhang[3], Liyong Zhang[2], Ningtao Zhang[2], Qiwei Zhang[1], Tao Zhang[5], Xiaopeng Zhang[5], Xuezhen Zhang[2], Zimin Zhang[2], Wei Zhao[3], Zuo Zhao[1], Chao Zhou[1]

[1]China Institute of Atomic Energy, Beijing, China,
[2]Institute of Modern Physics, Lanzhou, China
[3]Tsinghua University, Beijing, China,
[4]Sichuan University, Chengdu, China
[5]Shanghai Jiaotong University, Shanghai, China,
[6]Monash University, Melbourne, Victoria, Australia,
[7]RIKEN, Institute of Physical and Chemical Research, Wako, Japan,
[8]Konkoly Observatory of the Hungarian Academy of Sciences, Hungary,
[9]South Dakota State University, Brookings, South Dakota, US
[10]Minnesota University, Minneapolis and Saint Paul, Minnesota, US,
[11]University of Notre Dame, Notre Dame, Indiana, US,
[12]Osaka University, Suita, Osaka, Japan
[13]Shangdong University, Beihai , China




谢谢各位老师！
热烈祝贺清华大学物理系复系40周年！