JUNA progress： underground nuclear astrophysics

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中国科学技术大学

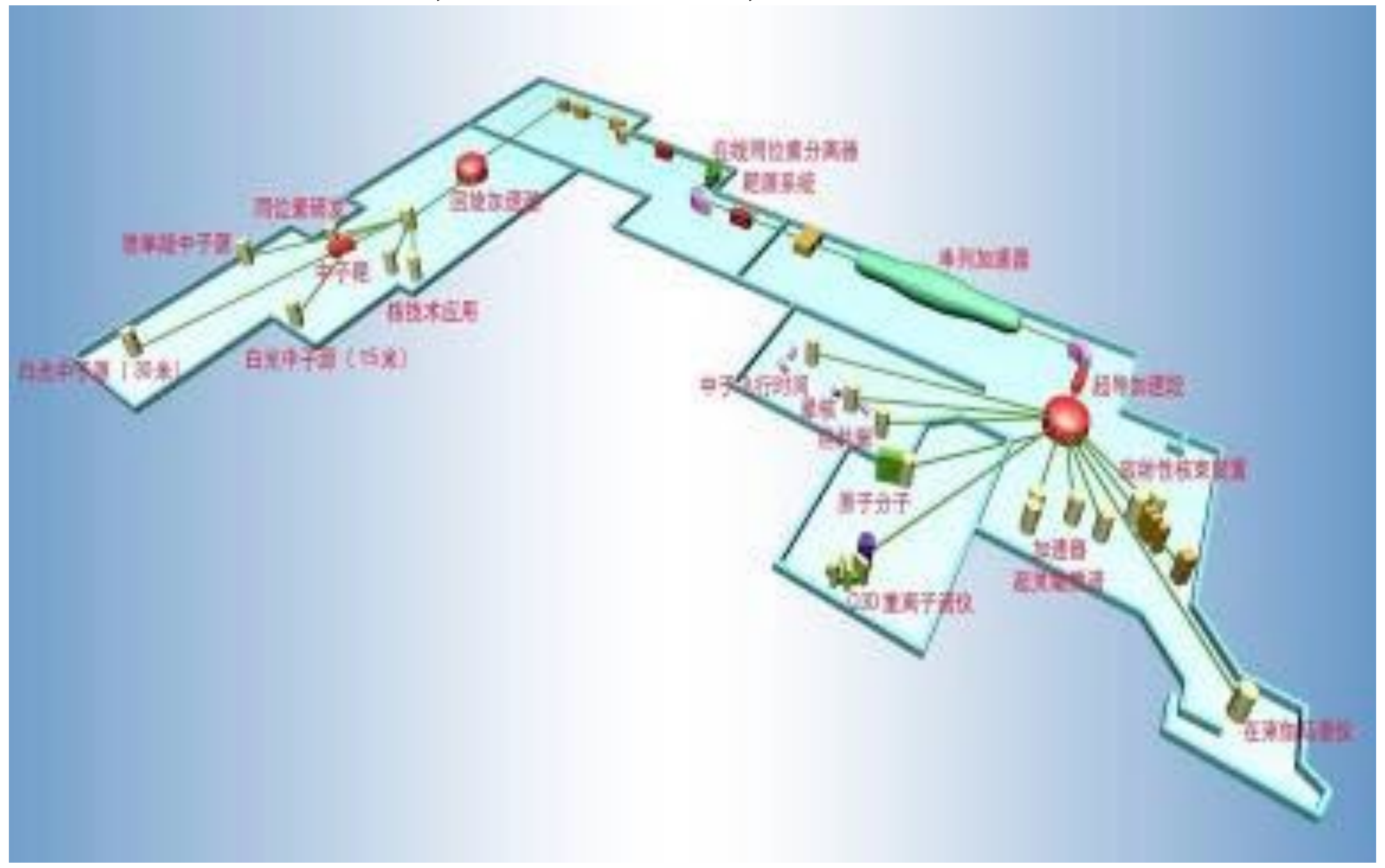
Thanks NSFC, Yalong power, THU, CAS and CNNC

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 DEVELEPOMENT COMPANY, LTD.
南方科技大学 SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY
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
清華大學

中国原子能科学研究院

China Experimental Fast Reactor,
CEFR, 65 MW, 2011

China Advanced Research Reactor,
CARR, 60 MW, 2012



Tandem upgrading project,
BRIF,2014

Radio Chemistry Re-processing lab,
CRARL, 2012

- 核科学诞生地
- 1950年成立
- 3200员工
- 700 高级研究人员

核基础研究
先进核能
核技术应用

核物理
核化学
反应堆物理
核安全
核技术

钱三强
王淦昌
朱光亚

发展沿革 南方科技大学的成长历程

SUSTech

2009 朱清时院士出任创校校长

2010 教育部同意筹建南科大

2012 教育部正式批准南科大成立

2015 陈十一院士出任第二任校长

2018 获批4个博士学位一级学科点(本硕博)，成为历史上最快获批国务院学位办新增博士授权单位

2020 薛其坤院士出任第三任校长

2022 南方科技大学及数学学科入选“双一流”建设高校及建设学科名单

南方科技大学
物理系
Department of Physics
SUSTech

物理系发展历程

Timeline

2011
2月
物理系设立，唐叔贤院士出任创系系主任

2014
2月
本科物理学专业获教育部备案

2015
1月
何佳清教授出任第二届系主任
2月
物理系首届教改班10人顺利毕业

2016
2月
本科应用物理学专业获教育部备案
4月
获物理学学士学位授予权
12月
物理学入选广东省攀峰重点学科

2017
9月
首篇南科大本科生为一作的PRL发表
10月
首个南科大为第一完成单位的教育部优秀成果奖

2018
5月
获得物理学博士、硕士学位授权点
6月
获应用物理学学士学位授予权
11月
物理学入选广东省高等教育“冲补强”重点建设学科

2019
12月
物理学专业入选国家级一流本科专业建设点
10月
获批物理学博士后科研流动站
5月
首篇南科大作为第一单位《自然》期刊文章

2020
10月
《基础物理实验》入选“双万计划”首批省级一流本科课程
10月
《量子力学》入选首批国家一流本科课程

2021
2月
卢海舟教授课题组“拓扑物质的电子输运”项目获深圳市自然科学奖一等奖
2月
物理系连续以第一单位，在《科学》和《自然》发表2篇原创成果

2022
3月
南科大物理学科进入ESI全球前1%
7月
物理系以第一单位在《科学》发表优秀成果
12月
范靖云教授课题组“复数的根本地位”的研究成果入选2022年国际物理学十大进展

CNAP建设思路

核物理与天体物理
国际顶级研究中心

国际科学前沿，形成国际中心

顶级研究团队，继续保持国际领先

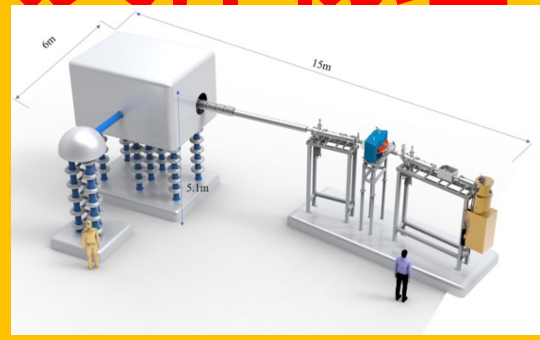
首席，柳卫平

理论，实验，

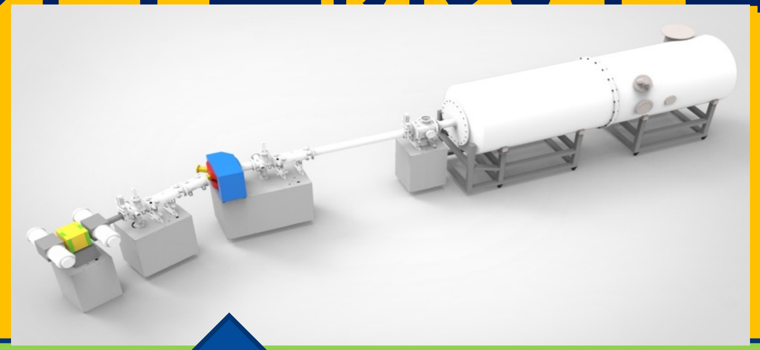
形成成果转化，助力深圳发展

顶级研究平台，南科大学科交叉

锦屏深地核天体物理Super-JUNA



校外中型研究平台



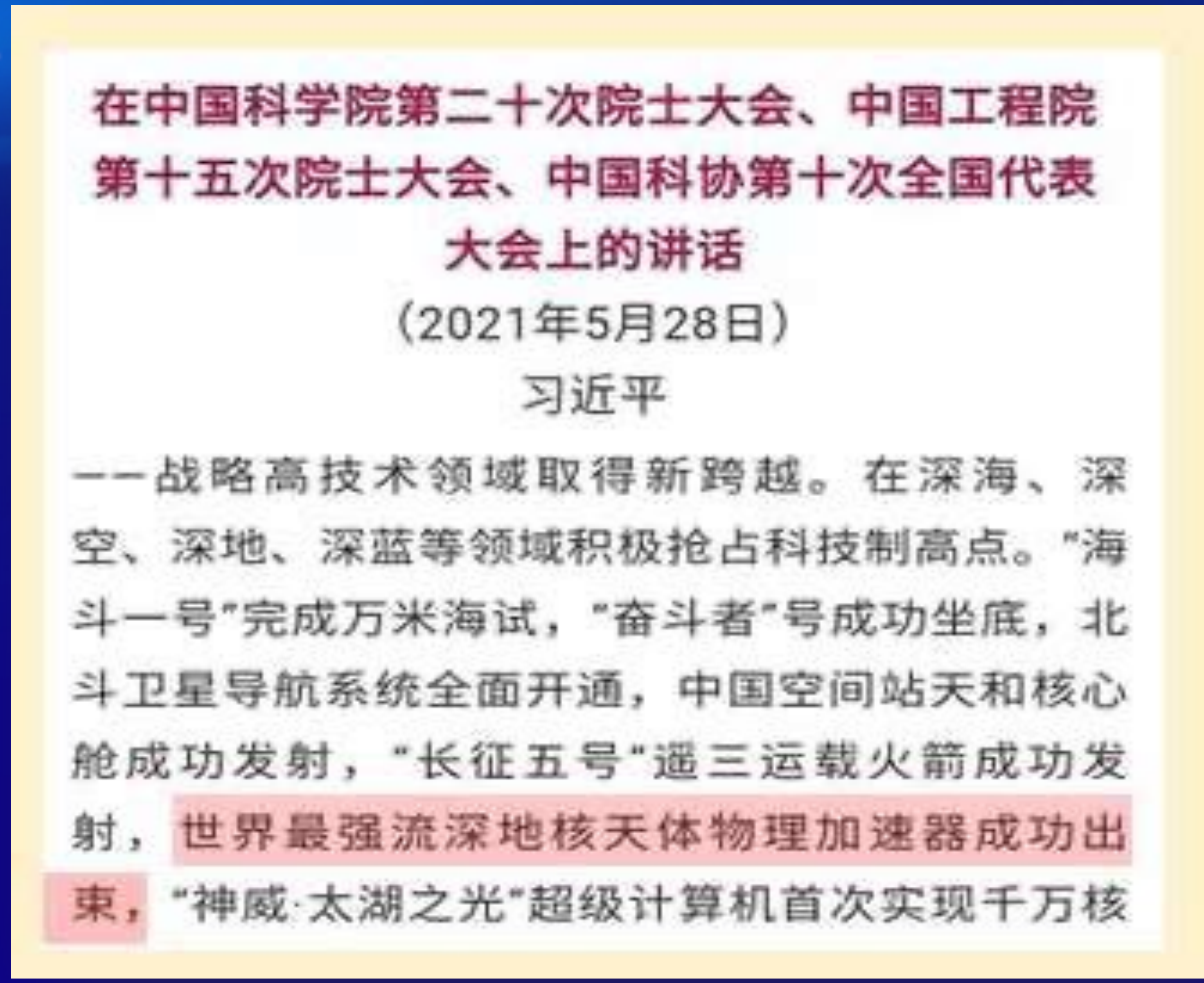
校内小型研究平台

提升国家能力，助力大湾区发展

顶级研究设施，南科大平台矩阵共振

我国大科学平台，FEL，HIAF, JUNO, CSNS, BRIF, CSR

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
One of the ten high tech progress mentioned in the academician conference 2021



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
JUNA first beam

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

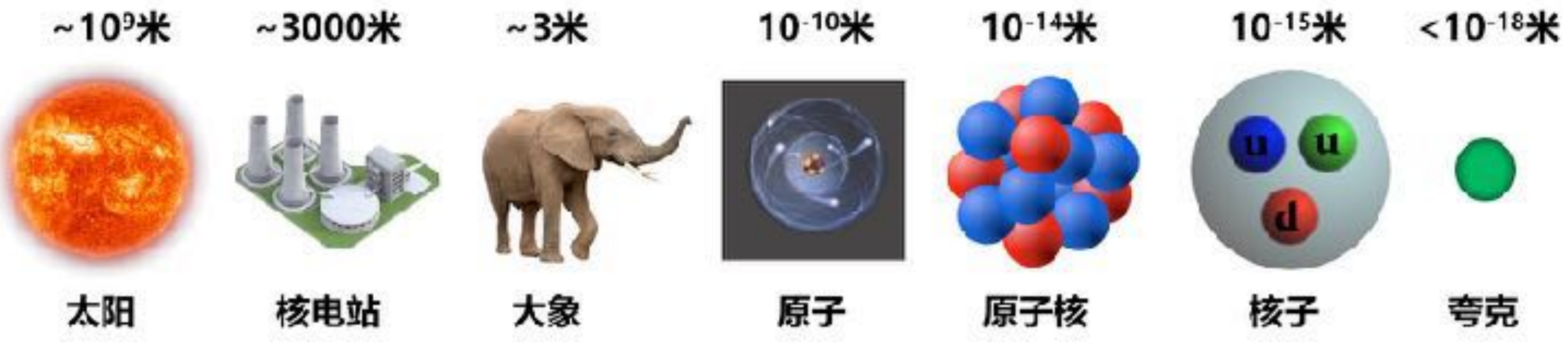
天鲲号
试航成功

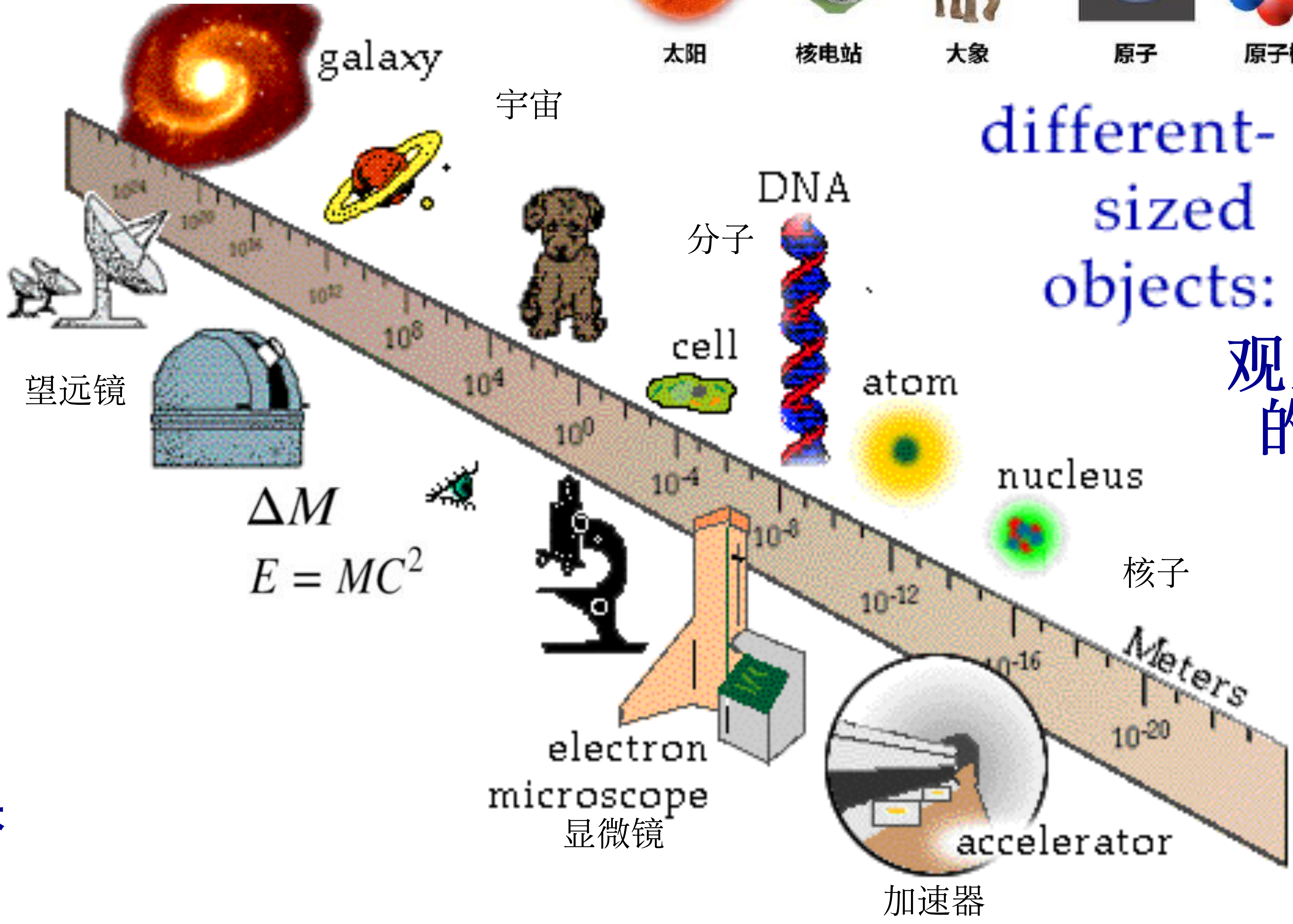
华龙三代
核电技术

太湖超级计算机


2022
BREAKTHROUGH OF THE YEAR

Micro to Cosmic





ΔM

$E = MC^2$

different-sized objects:

观察不同尺度的物质世界

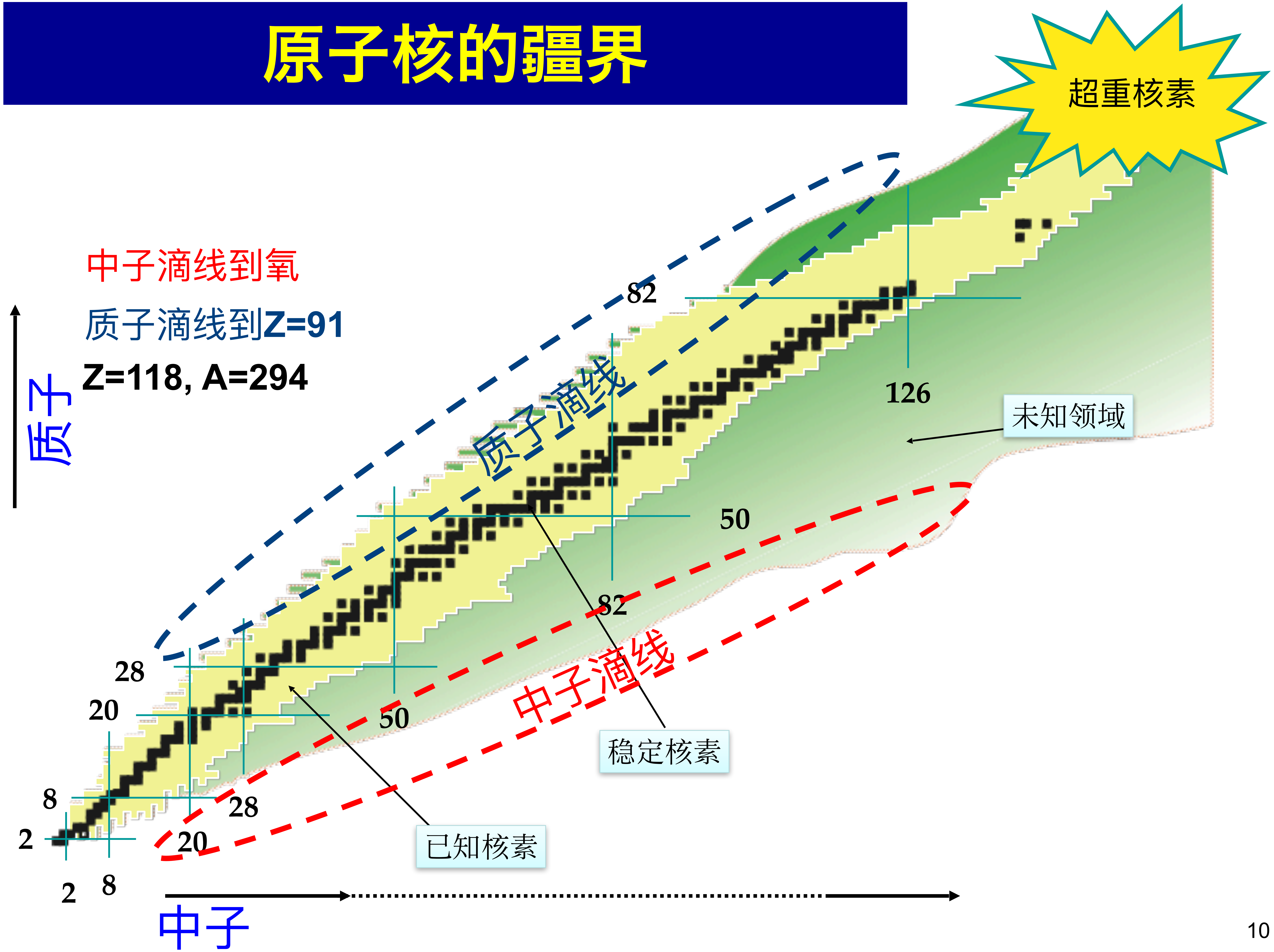
- 质量亏损
- 质能公式
- 原子炉
- 宇宙的大锅
- 射线的照相术

原子核的疆界

中子滴线到氧

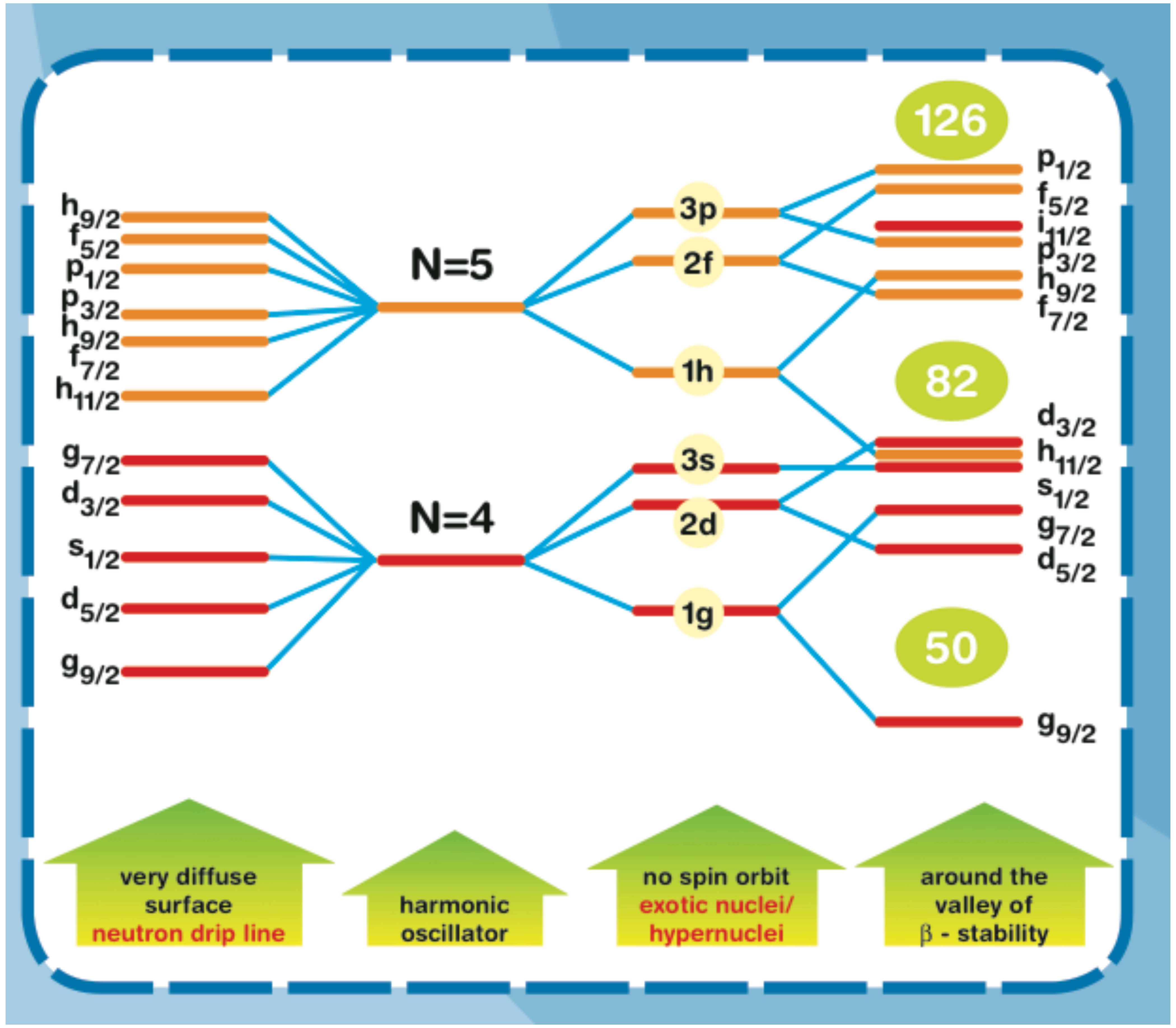
质子滴线到**Z=91**

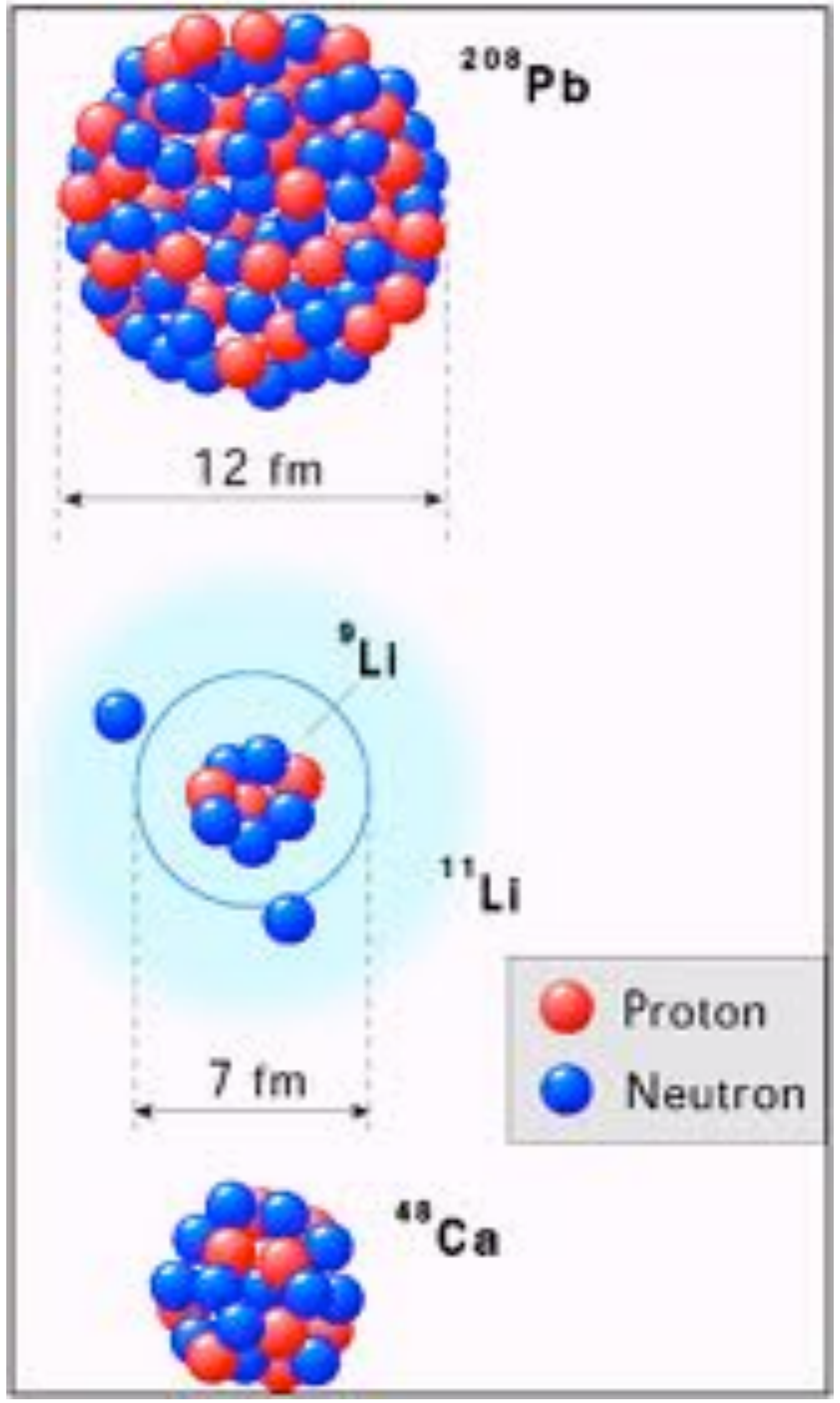
Z=118, A=294



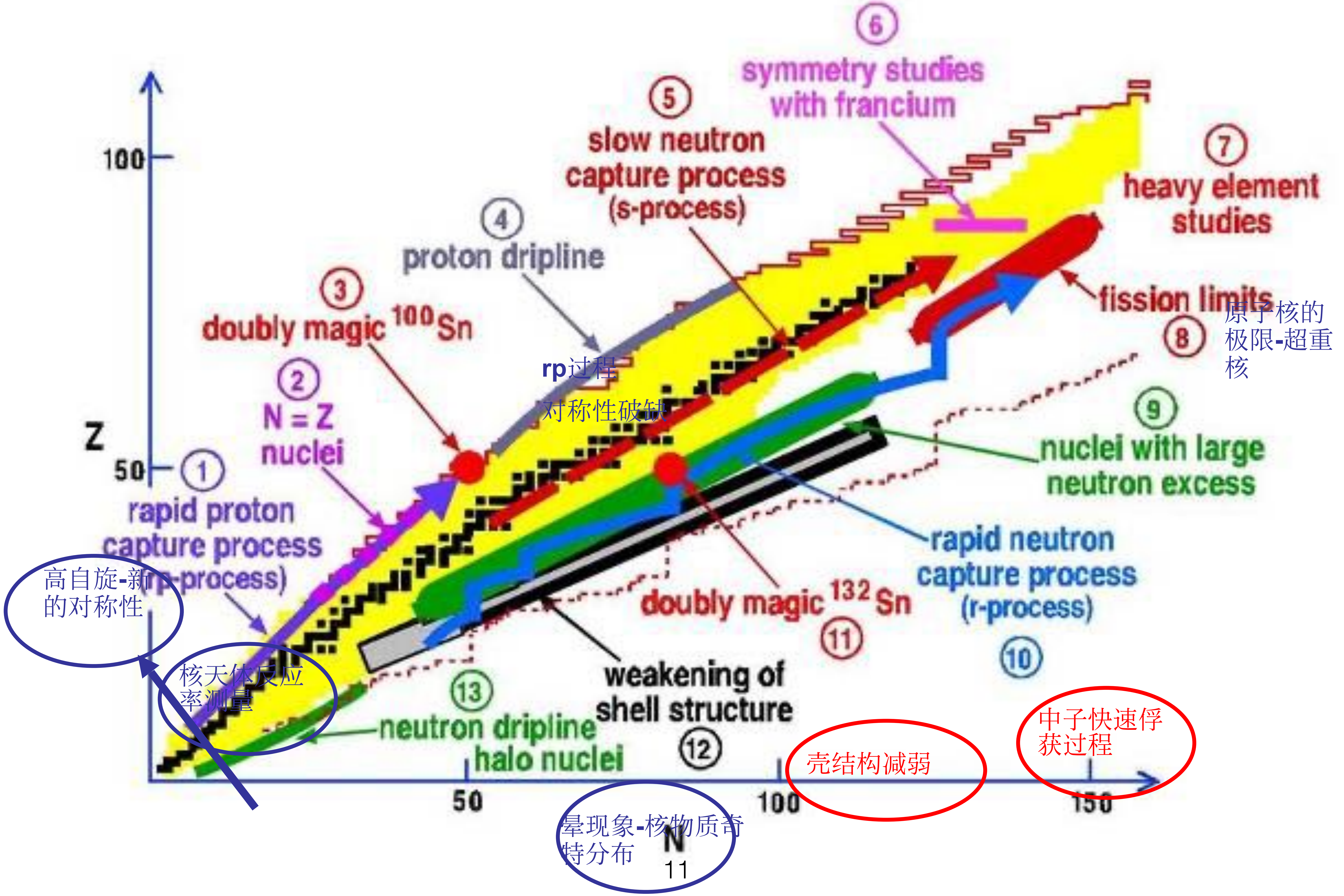
奇异的不稳定核

- 超级松软： ^{11}Li=^{208}Pb
- 规律破坏：新的幻数和简并



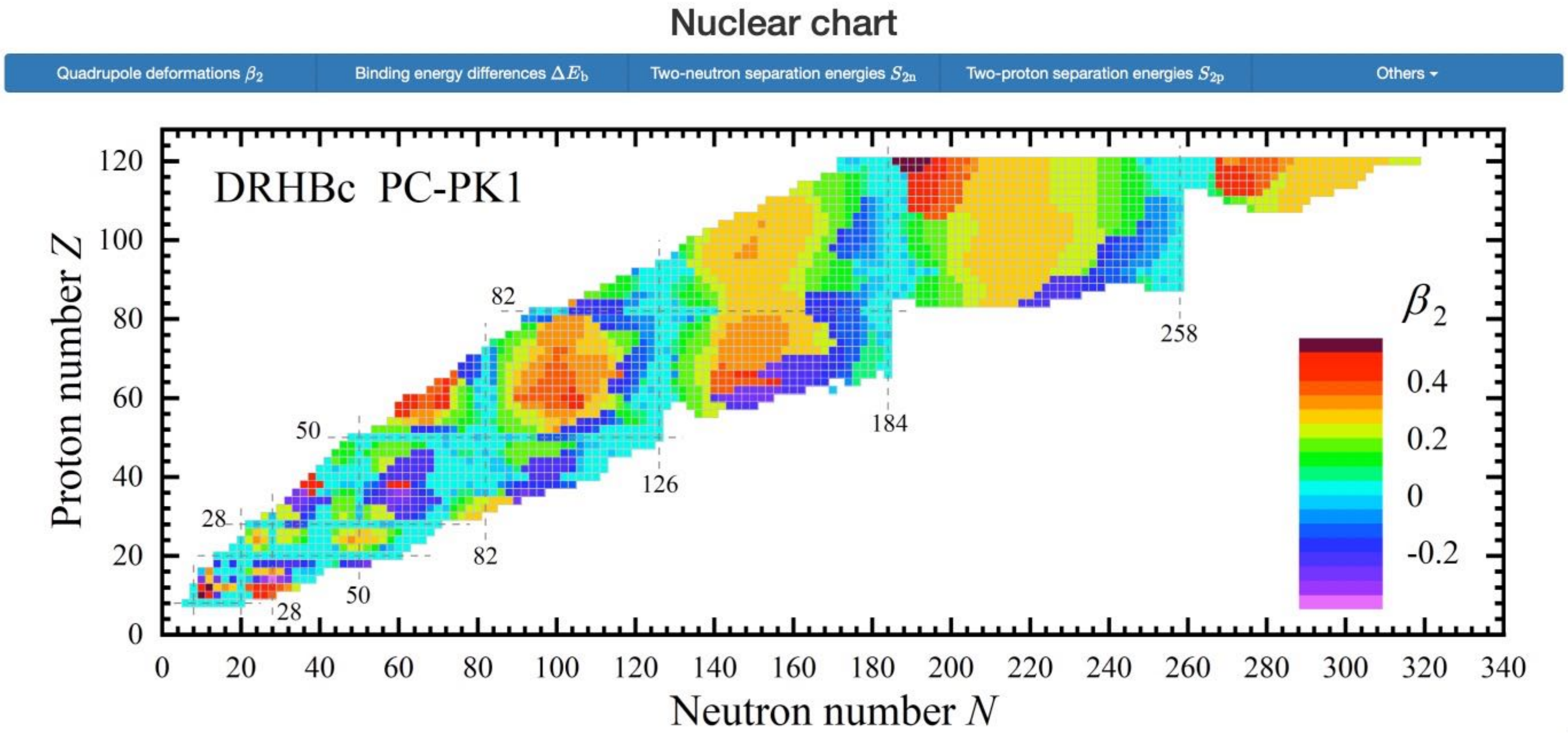


未开垦的处女地

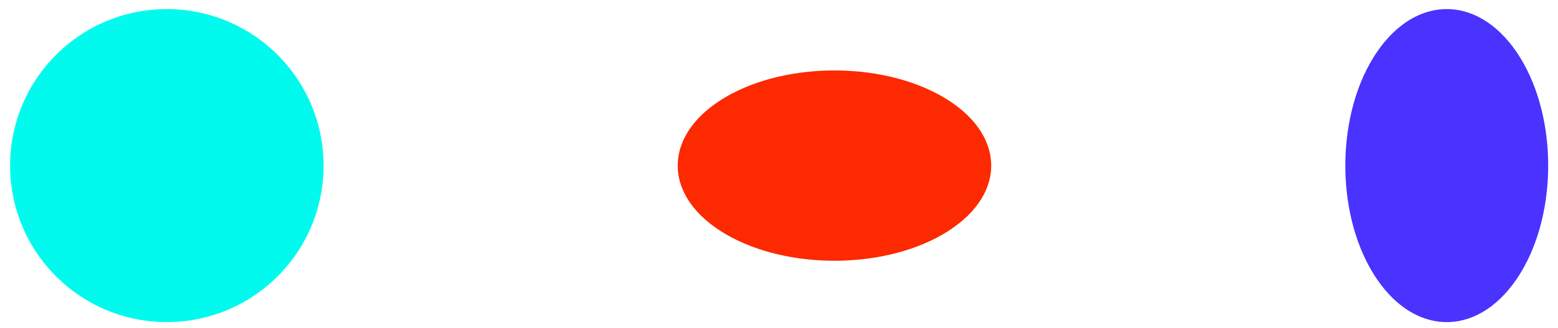


symmetry studies with francium
⑥
⑤
slow neutron capture process (s-process)
⑦
heavy element studies
④
proton dripline
③
doubly magic 100Sn
fission limits
原子核的极限-超重核
⑧
rp过程
②
N = Z nuclei
对称性破缺
Z
100
50
①
rapid proton capture process (rp-process)
⑨
nuclei with large neutron excess
rapid neutron capture process (r-process)
高自旋-新的对称性
doubly magic 132Sn
⑪
⑩
核天体反应率测量
weakening of shell structure
⑬
neutron dripline
halo nuclei
⑫
壳结构减弱
中子快速俘获过程
50
100
150
晕现象-核物质奇特分布
N
11

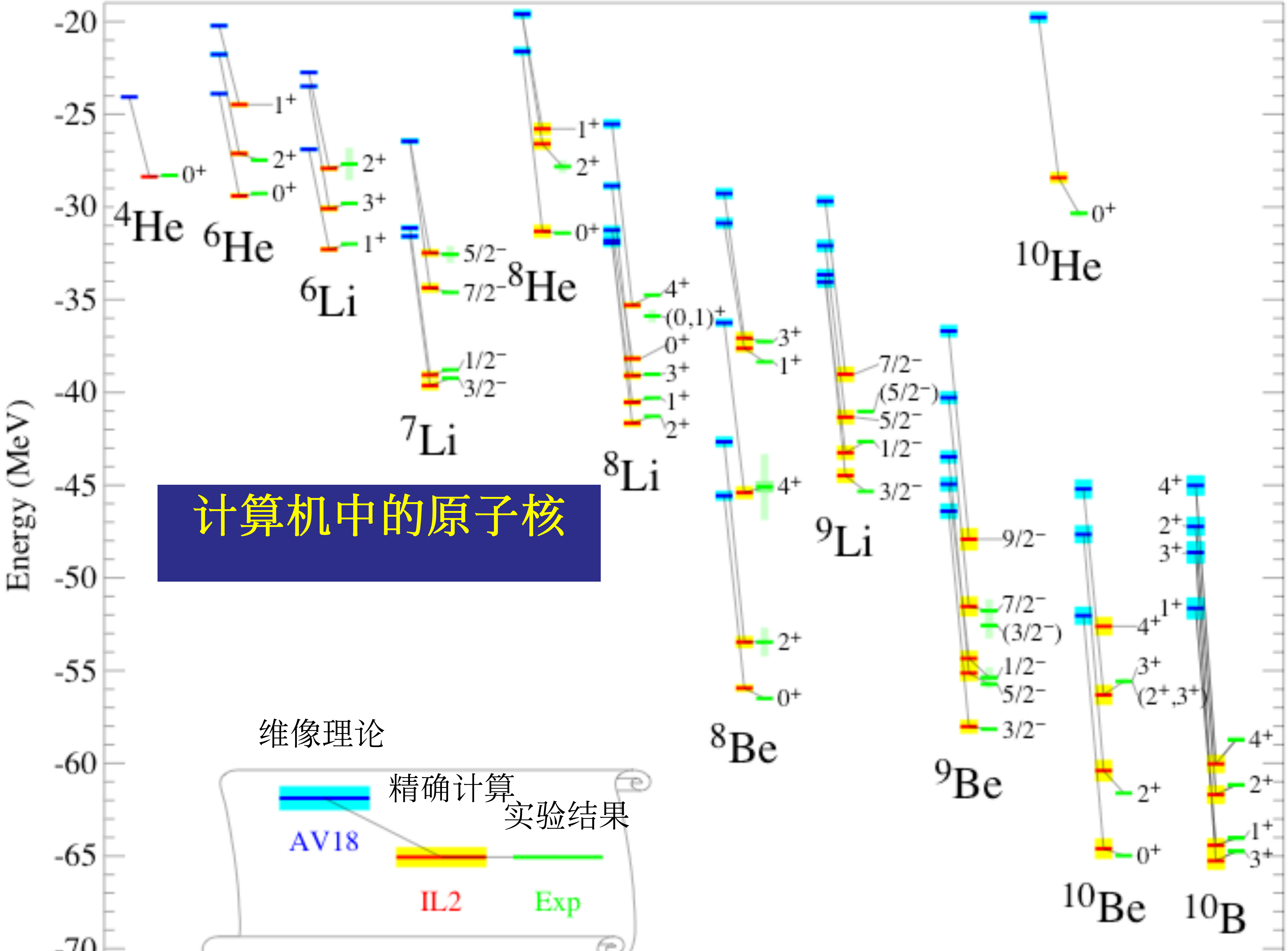
核素形状大观园



Nuclear chart
Quadrupole deformations β_2
Binding energy differences ΔE_b
Two-neutron separation energies S_{2n}
Two-proton separation energies S_{2p}
Others
DRHBc PC-PK1
β_2
0.4
0.2
0
-0.2
Proton number Z
Neutron number N
28
50
82
126
184
258

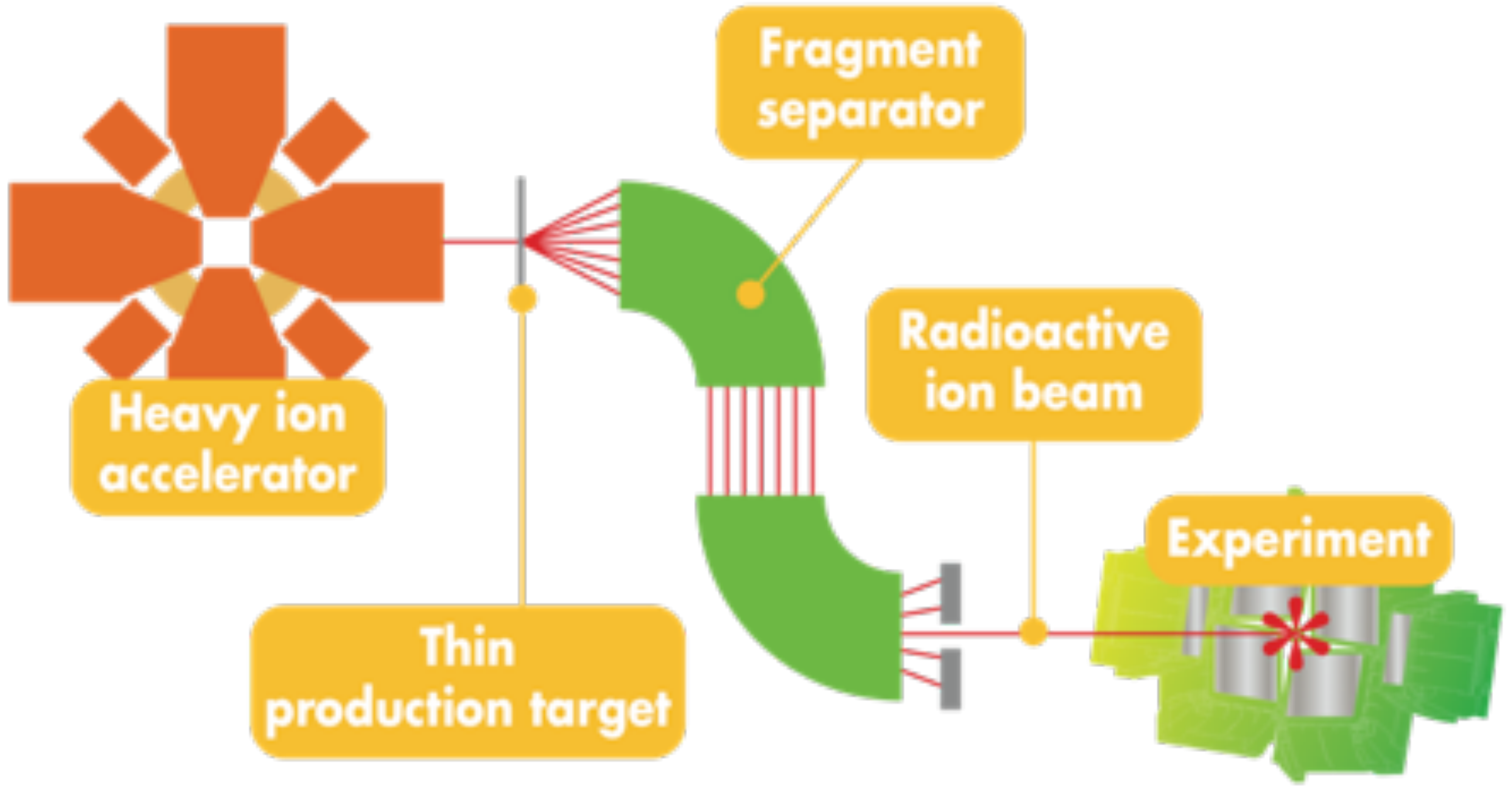


计算机中的原子核

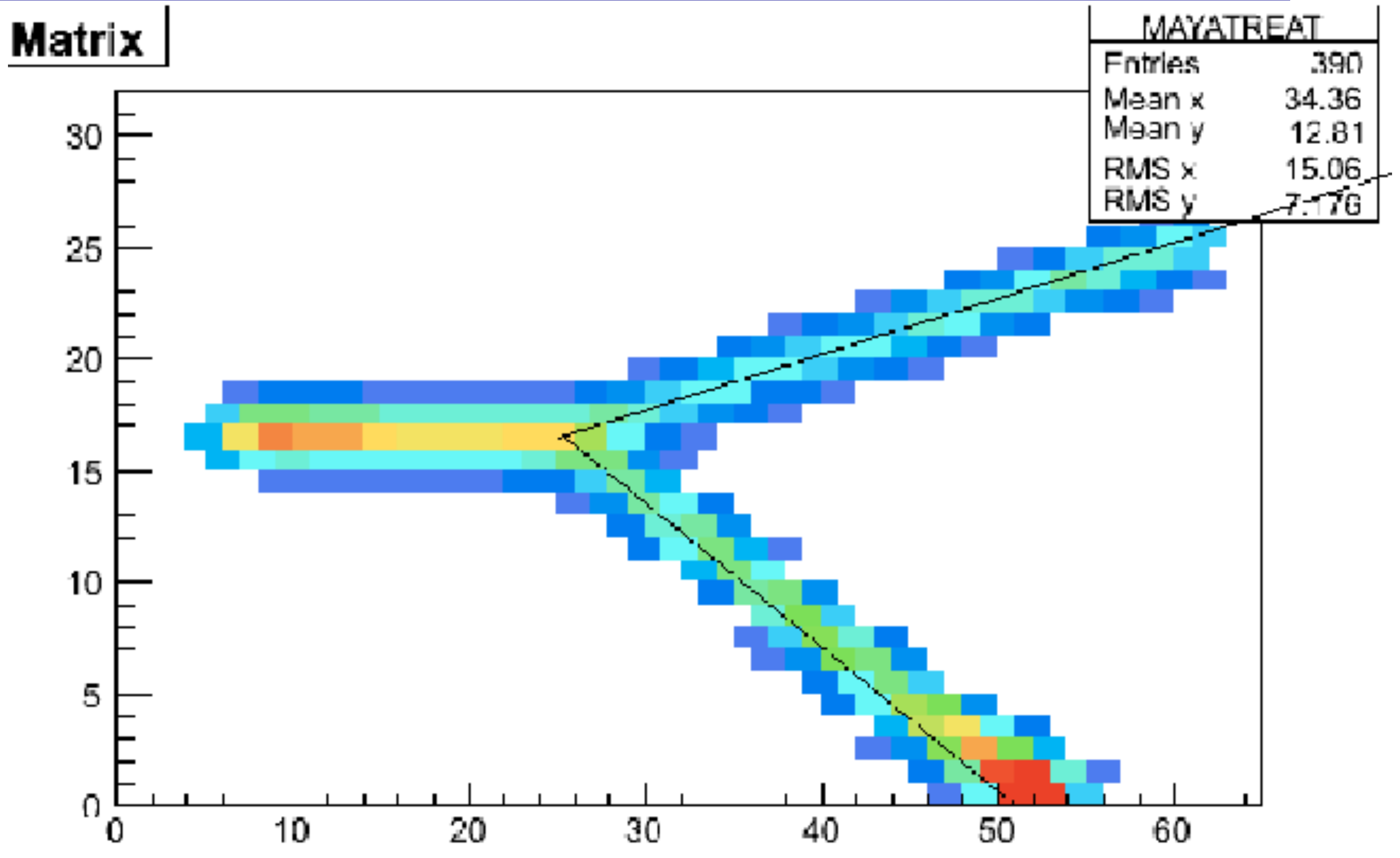


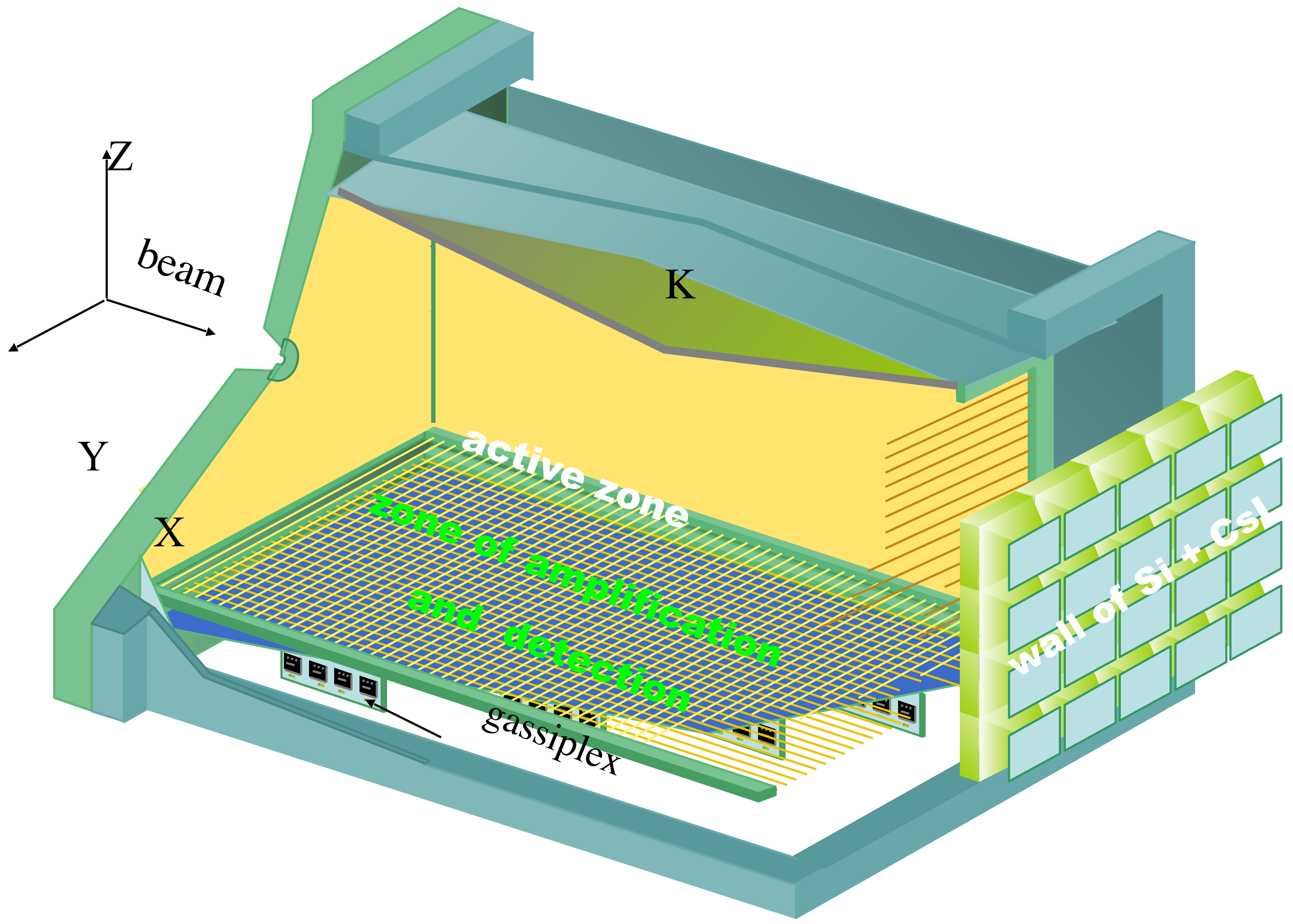
S.C. Pieper / Nuclear Physics A 751 (2005) 516c–532c

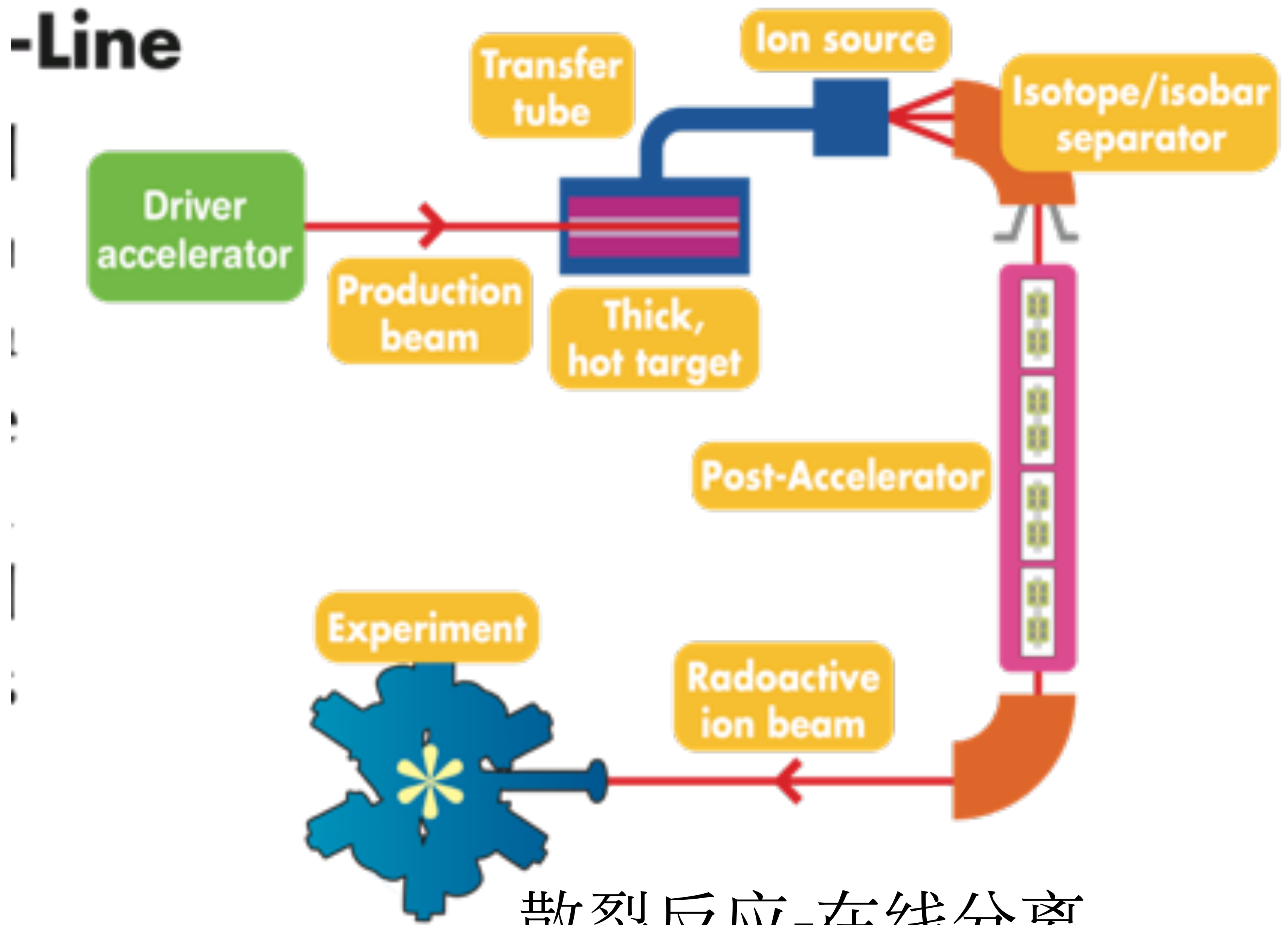
看到每一个原子核的飞行



炮弹碎裂-飞行中分离

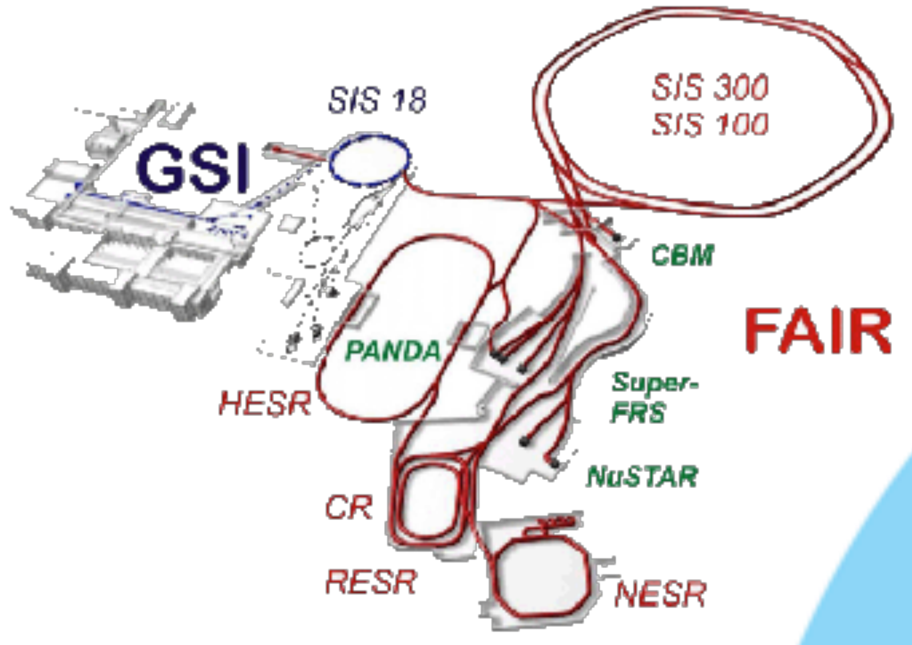


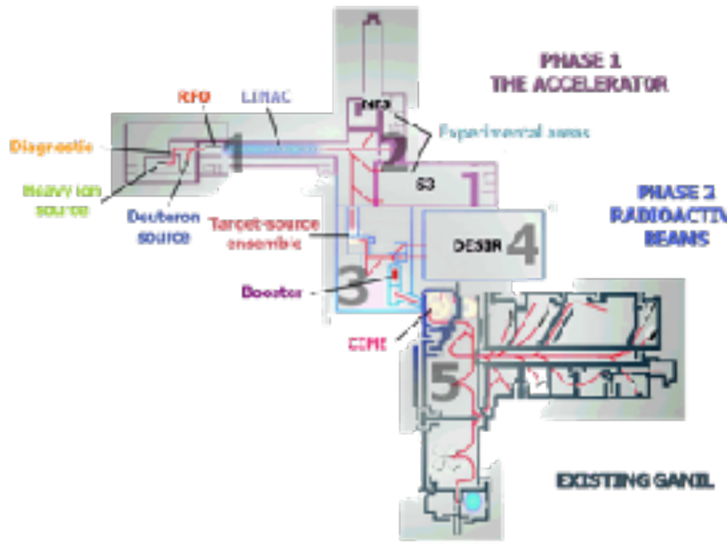


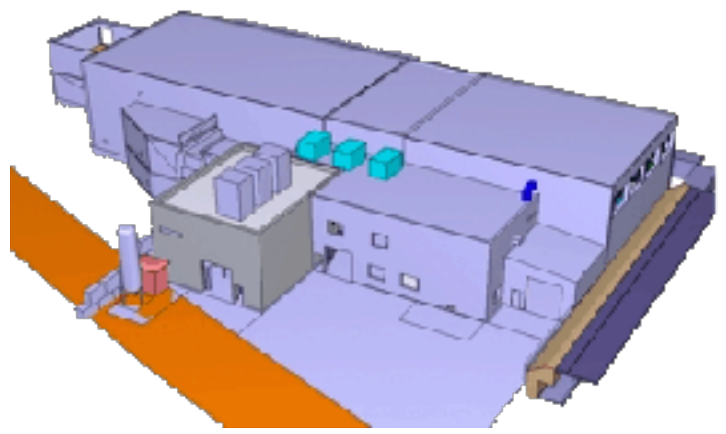


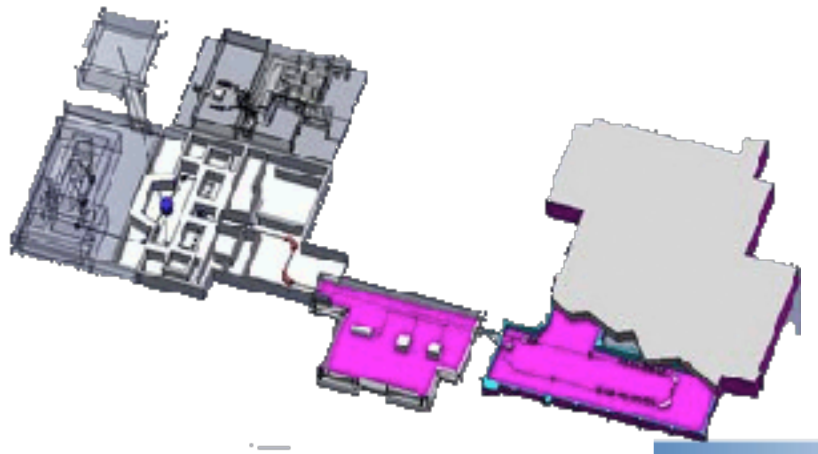
散裂反应-在线分离

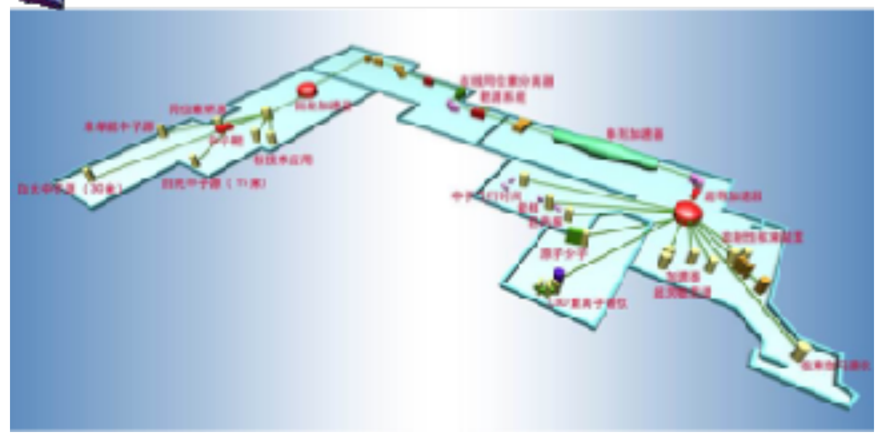
核物理的大观园

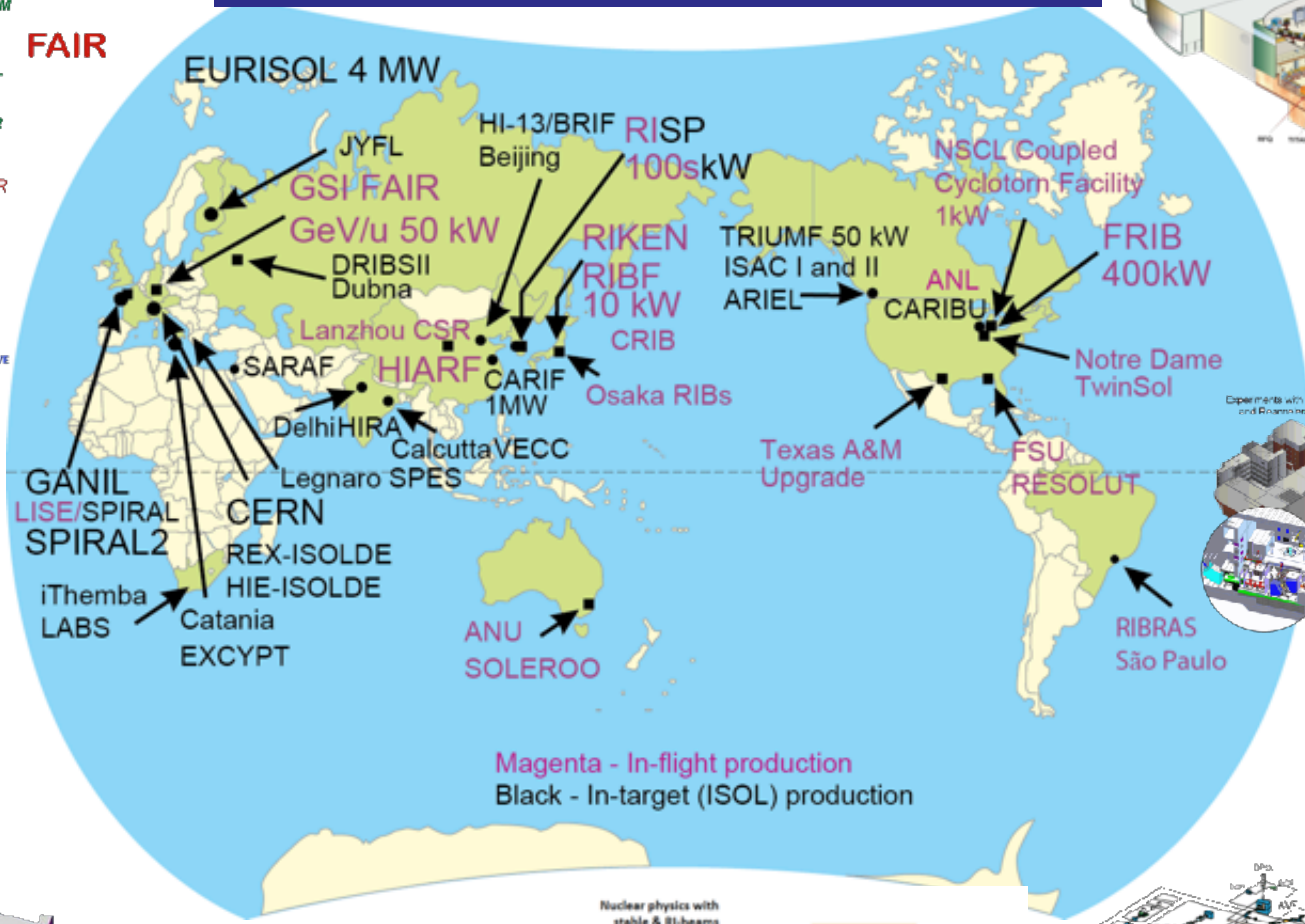


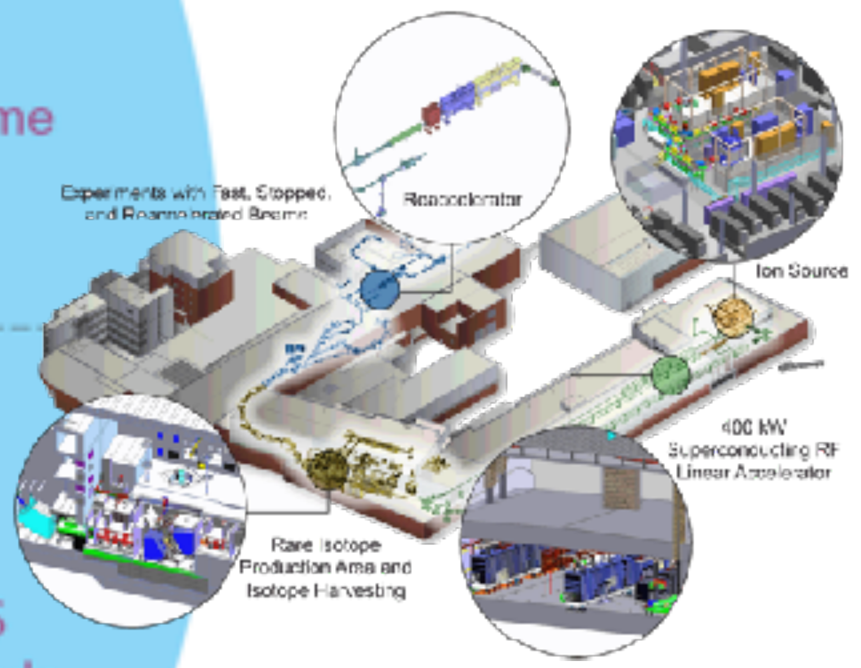


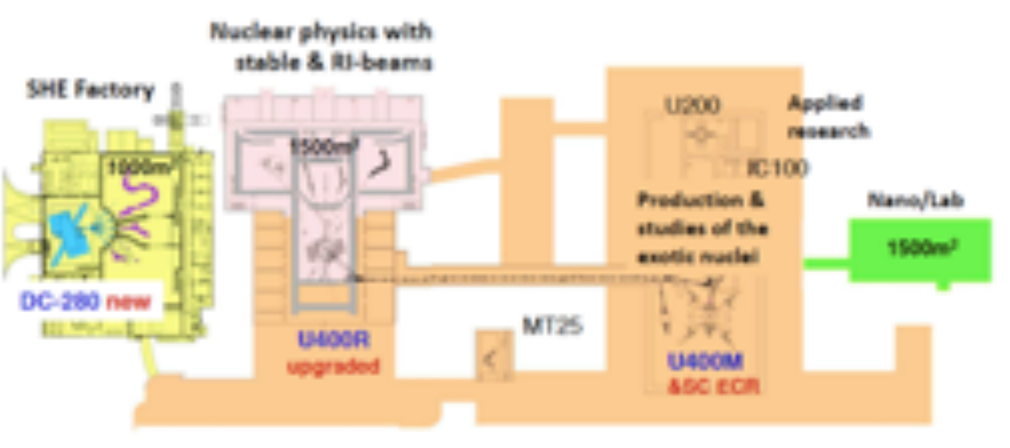




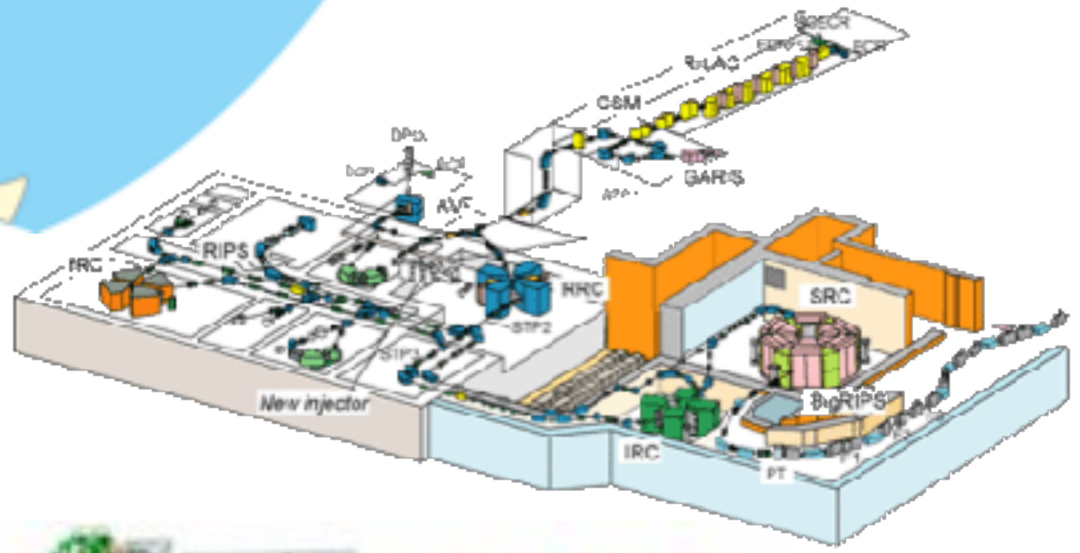








U400M-U400R Accelerator Complex



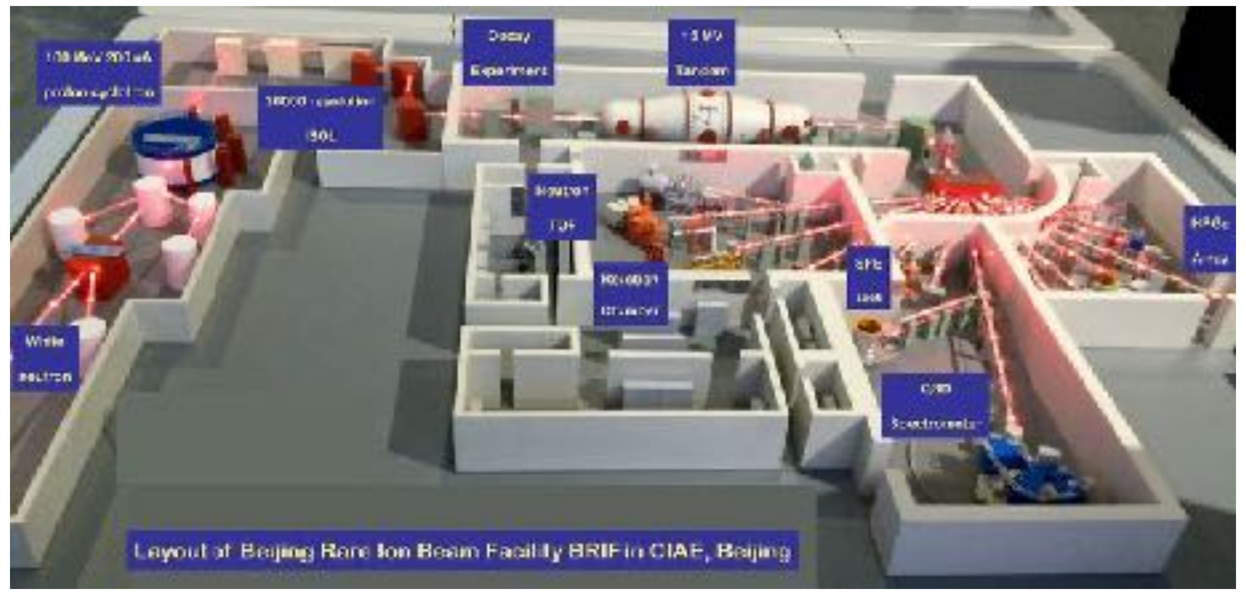
我国的发展路线图

1986 HI-13

1988 SSC

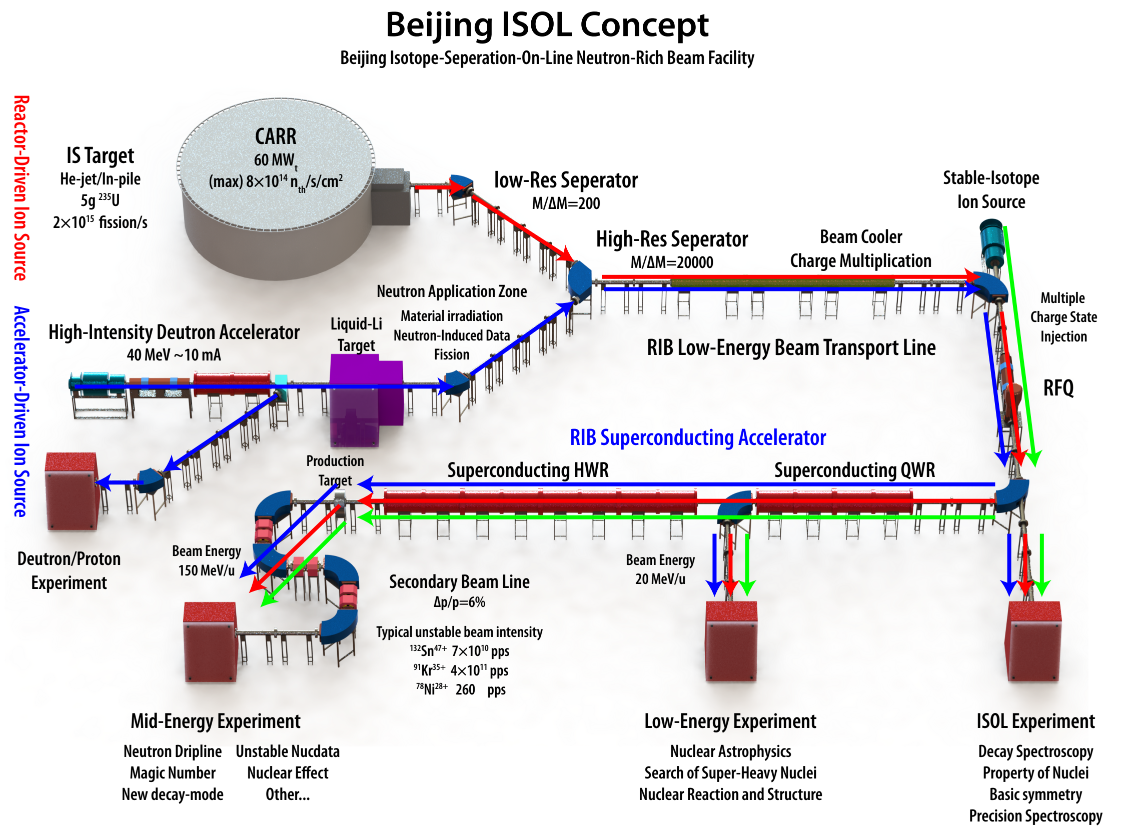
2008 CSR

2014 BRIF



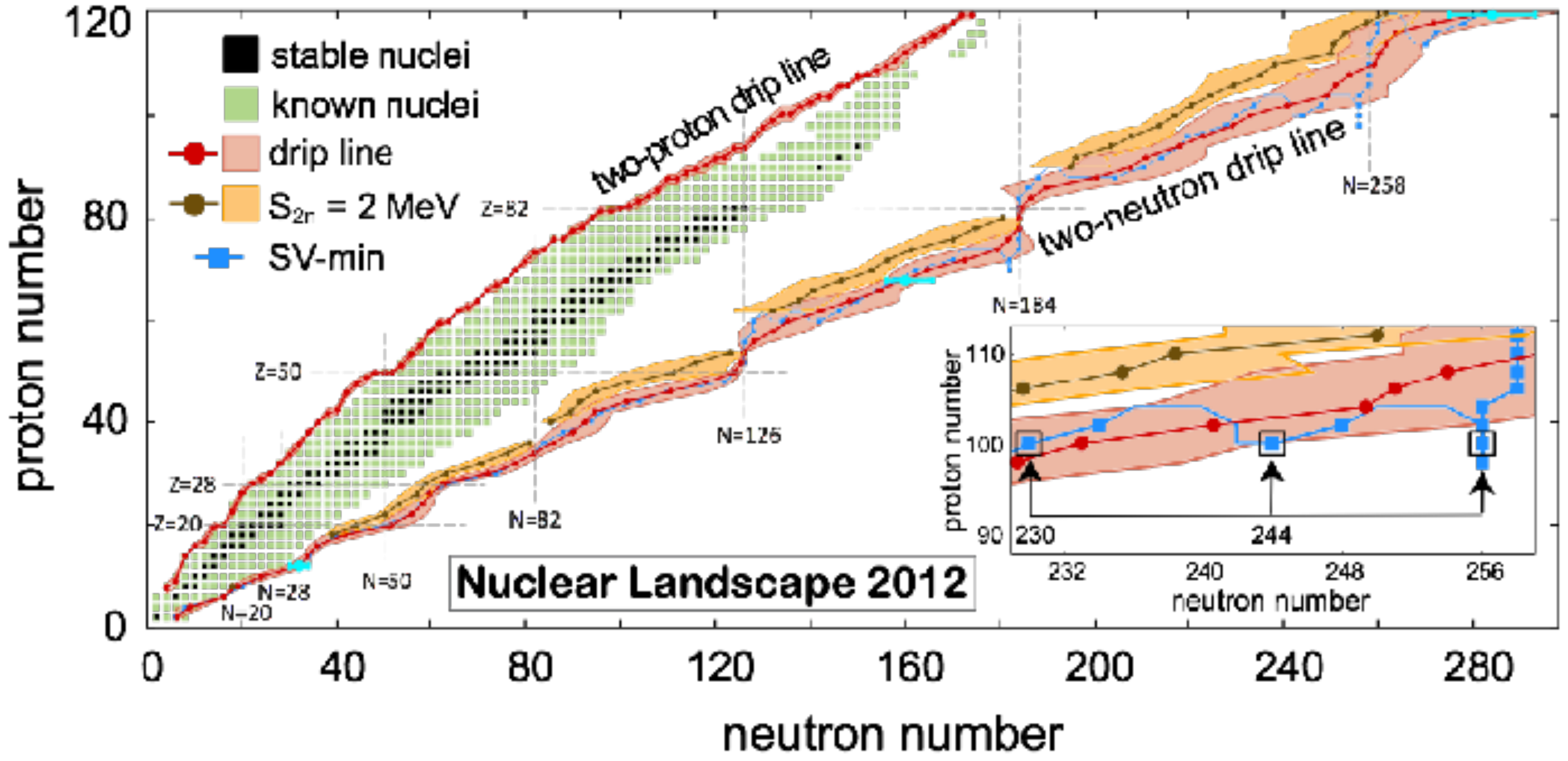
2025 HIAF

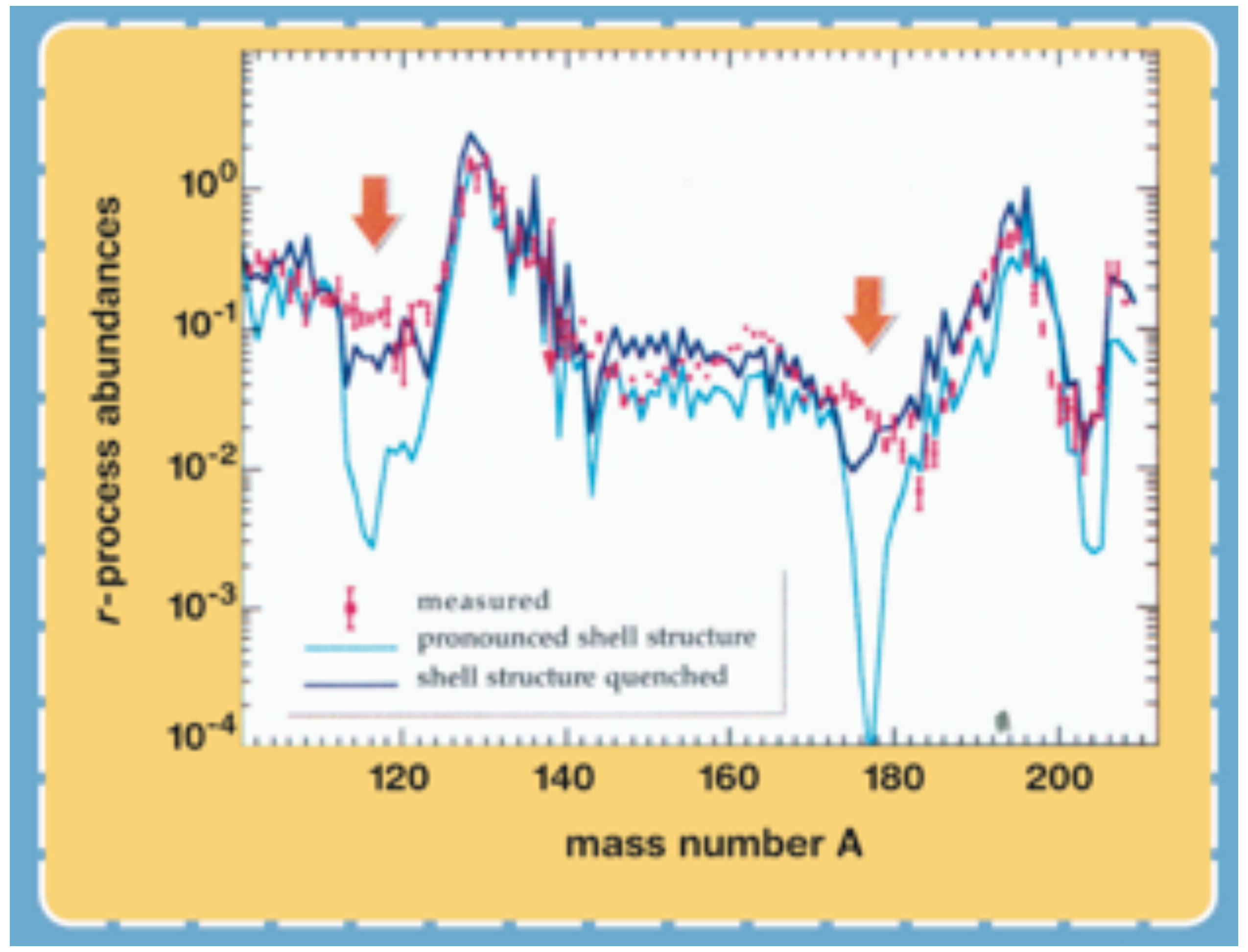
2028 BISOL



核物理的成绩单

- 实验发现核物理教科书的知识需要更新，壳模型的20，28和32的丰中子幻数，因为三体和张量力在丰中子区的存在，出现破缺。
- 发现114到118号超重元素，说明我们正在向超重岛挺近。
- 在大片的r过程丰中子区，实现了精确的质量测量。
- 对大爆炸和太阳内部的核反应率的地面和深地测量，可以使我们解释元素的丰度和中微子通量。
- 实现了对核反应和核结构到达中等质量区的从头计算。





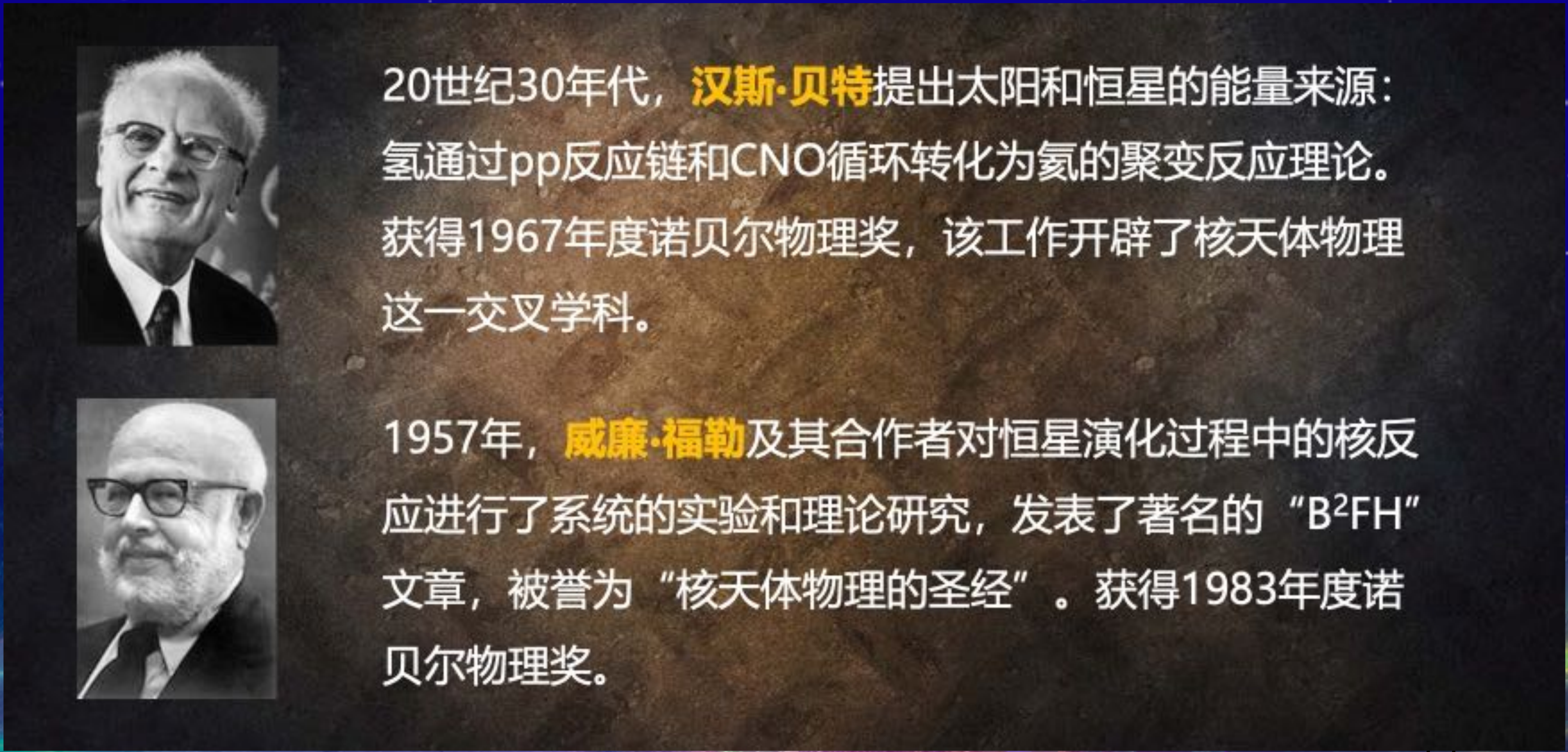
未来20年的发展预测

- 了解r过程的场所
- 具备高强丰中子束流的研究平台
- 了解中子星的条件
- 了解滴线的新作用
- 了解滴线和超重的位置
- 找到超重岛
- 弄清结团和多体现象
- 形成结构和反应统一的理论
- 机器学习的广泛应用
- 了解中子星的状态方程

核天体物理的诞生

1920年，英国物理学家亚瑟.爱丁顿第一个提出恒星的能量来源于核聚变。
1938年，汉斯·贝特提出pp链核合成理论，成功解决了太阳能量来源问题。
1948 年，乔治·伽莫夫提出大爆炸宇宙学模型。
1957年著名的**B²FH**论文发表，勾勒了元素在宇宙中的核合成路径。

Text book reference：
Nuclear Physics in Stars, Christian Ilidadis
科普介绍
核天体物理，郭冰，柳卫平，李志宏，原子能出版社



宇宙中的炼金术师

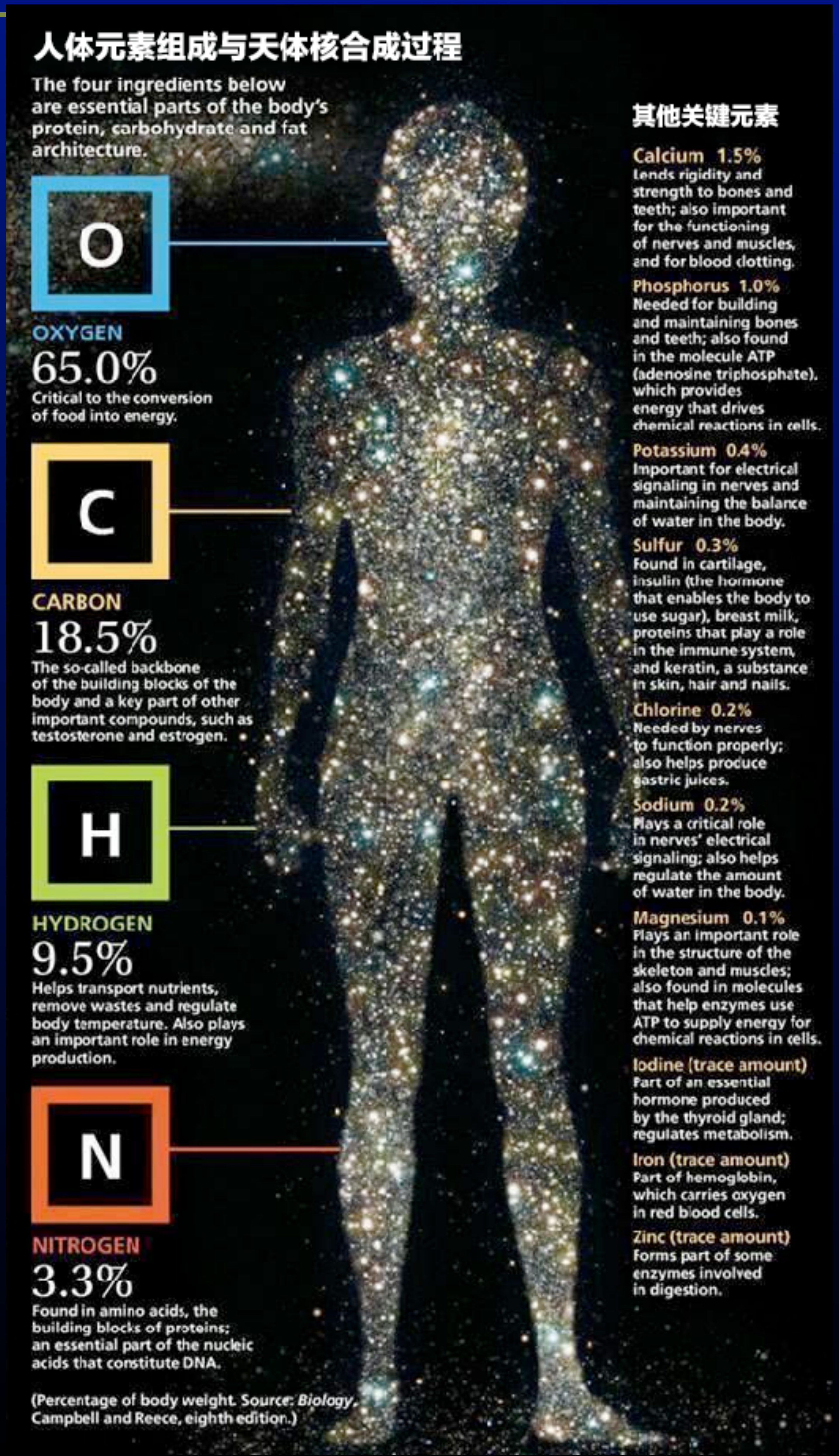
“宇宙就在我们身体里面，我们来自于星际尘埃”—— 卡尔·萨根

Massive stars:
Core Collapse SN
(He Burning)

Low-mass stars:
Giant Star winds
(He Burning)

Big Bang

Every star:
Winds and Explosions
(H Burning)



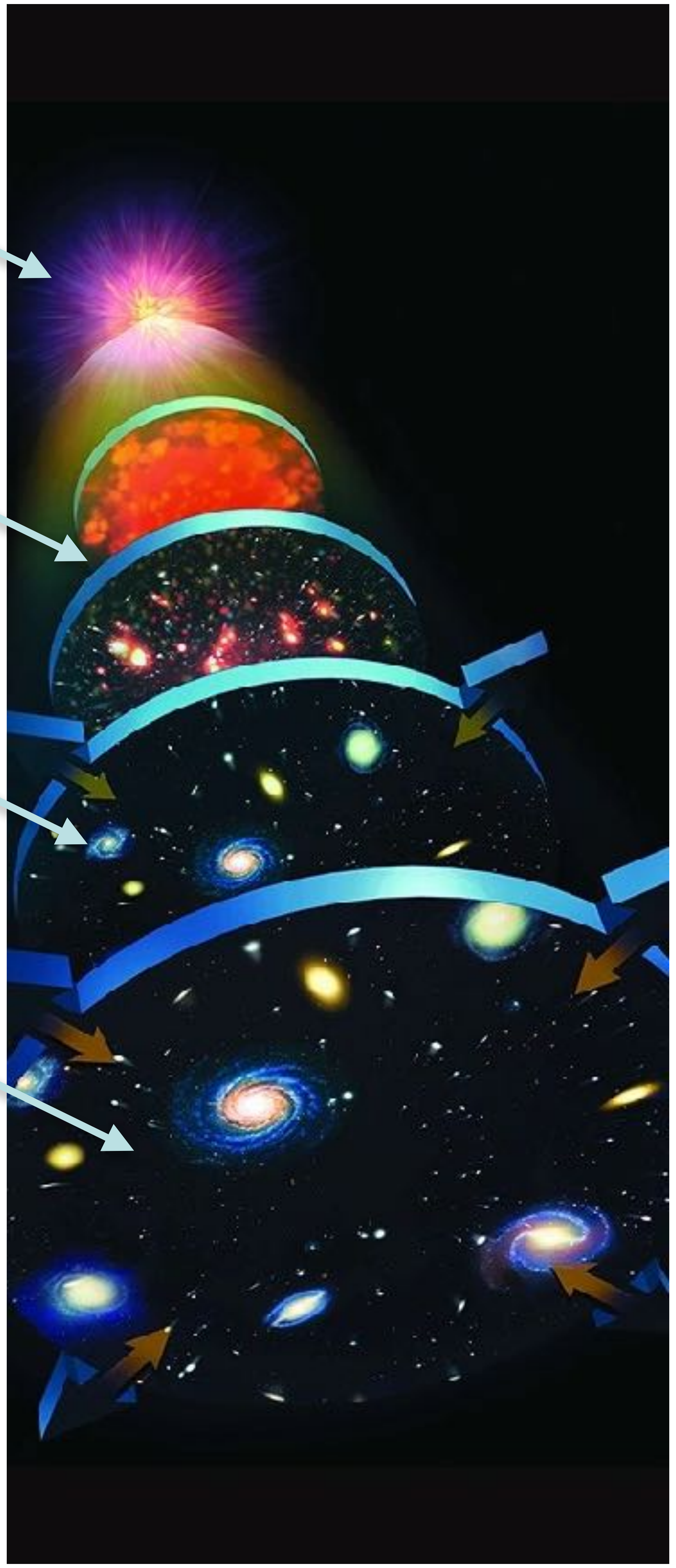
Ca, P, K, S, Cl, Na,Mg
massive stars:
Core Collapse SN
(C, Ne, O burning)

Fe, Zn, …
White Dwarf
Supernovae
(NSE process)

Heavy elements (like I)
(s-,r-,i-process etc)

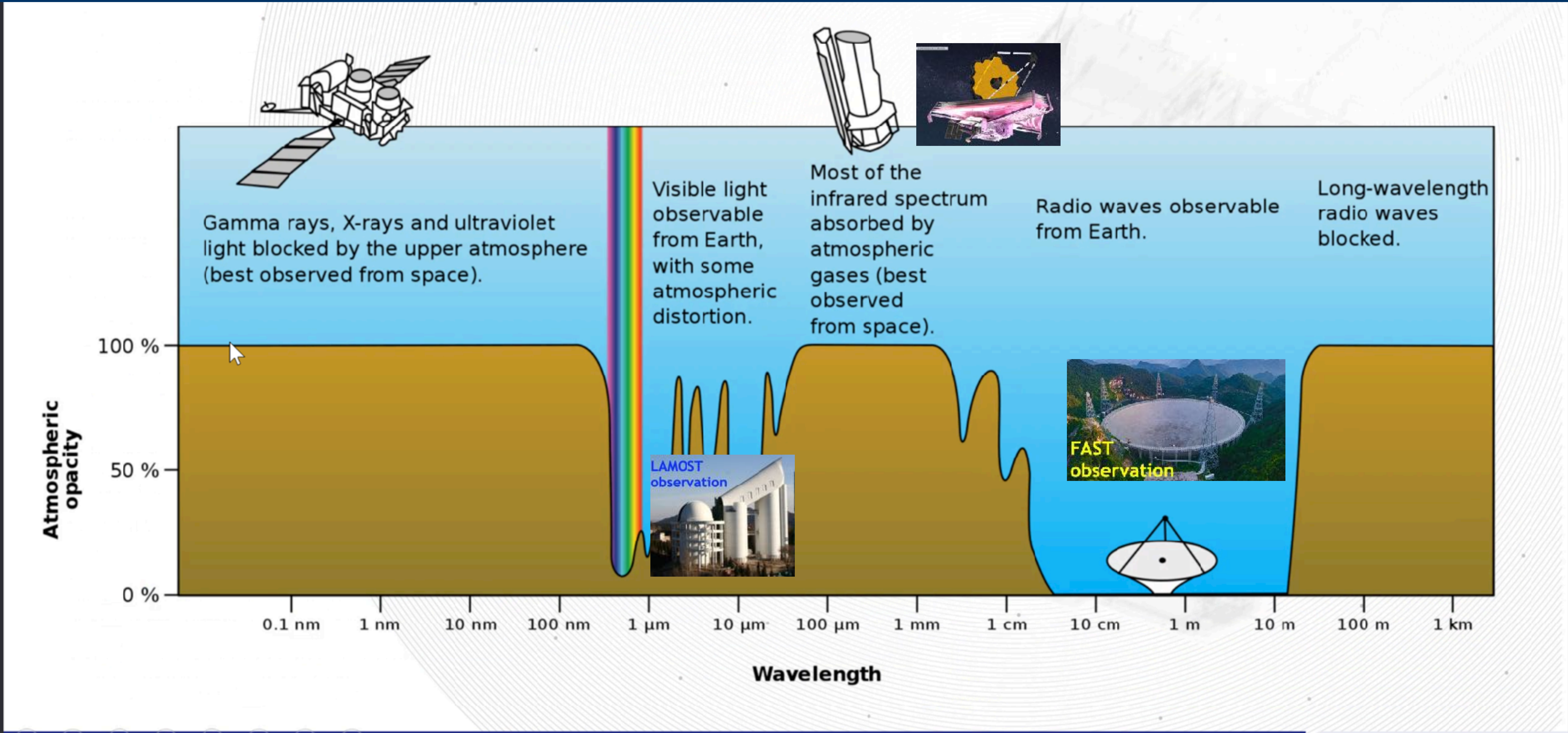
Important discoveries in nuclear astrophysics

- 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



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

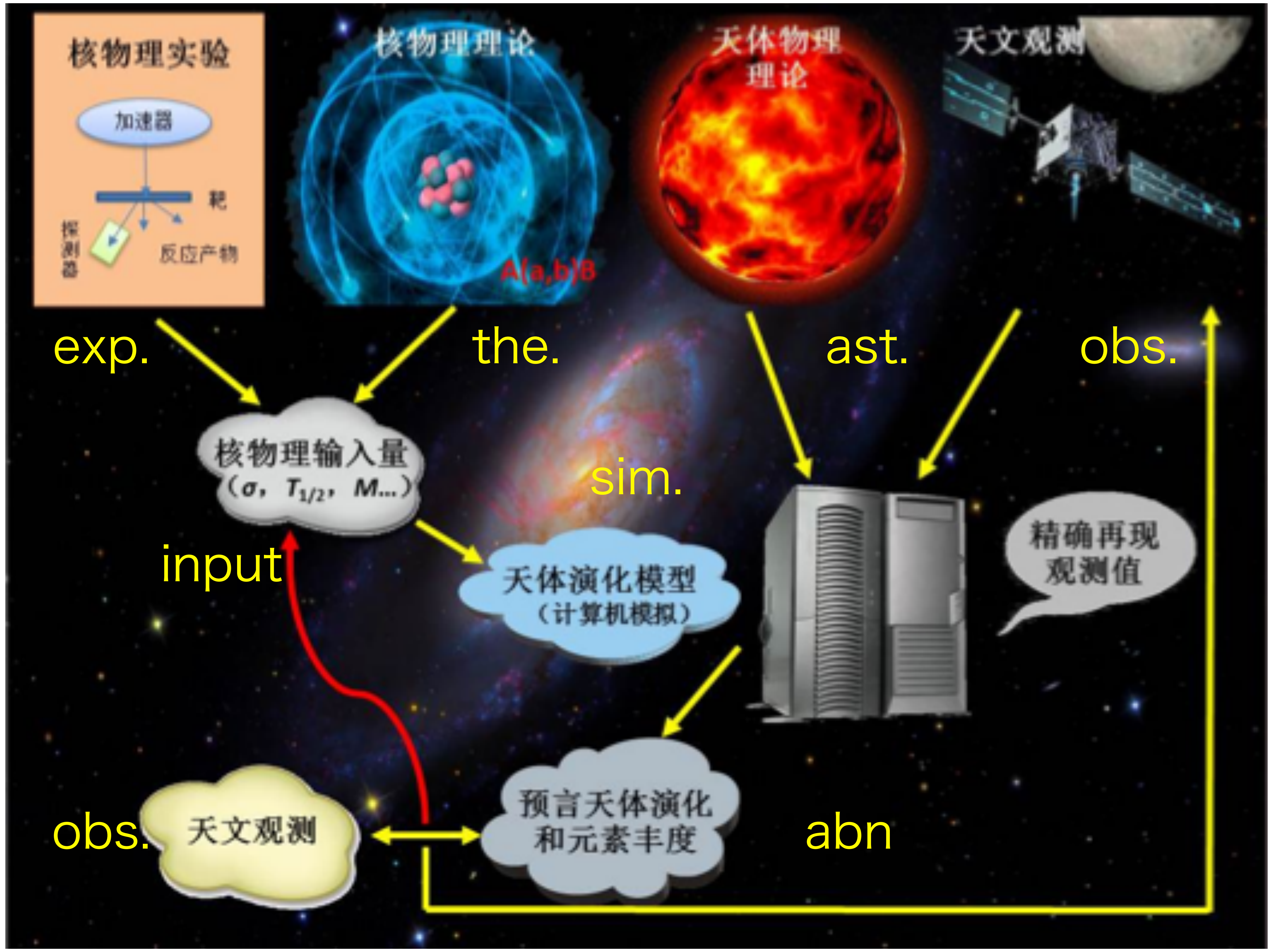
我们所能看到的



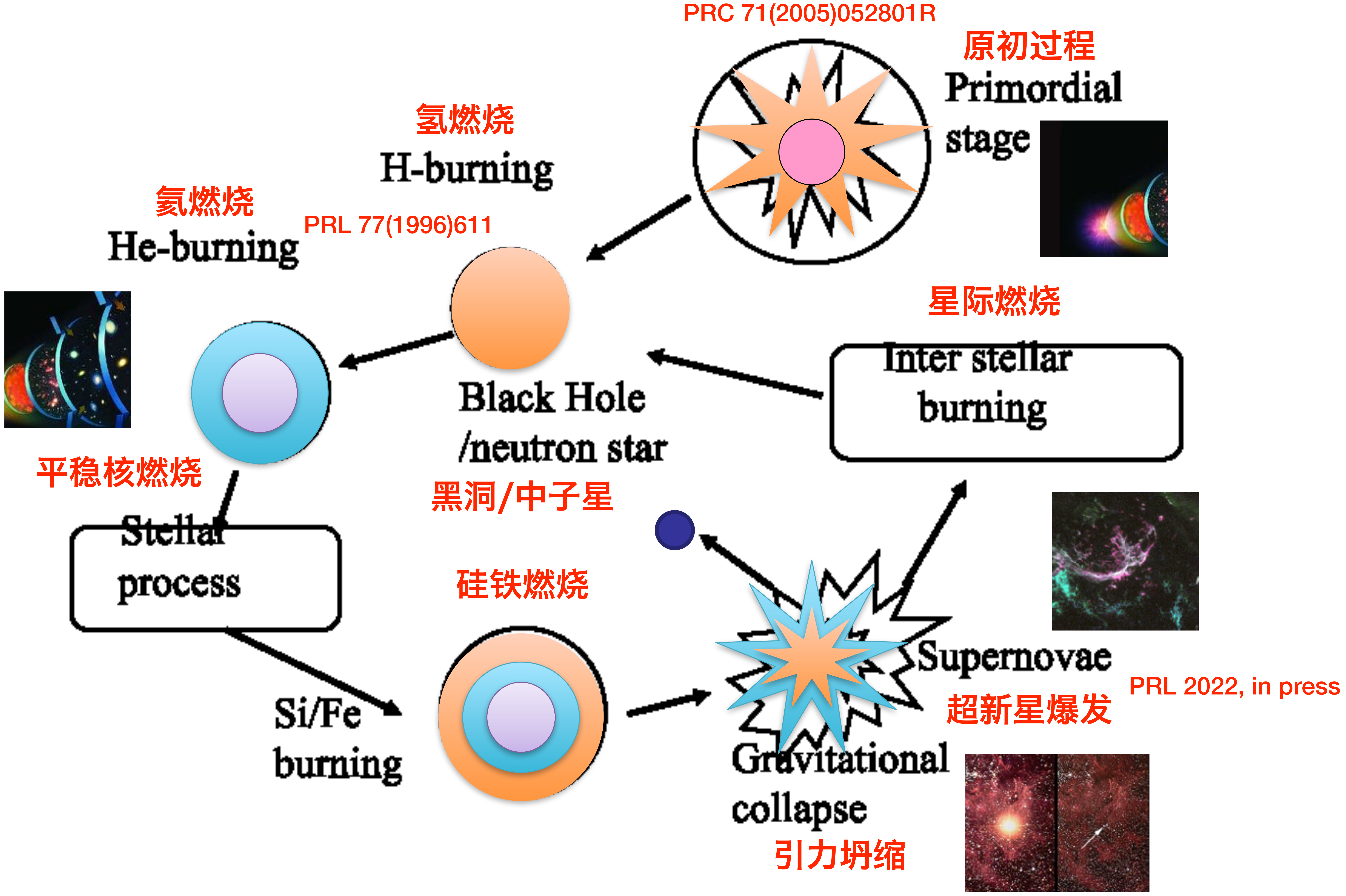
Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gases (best observed from space).
Radio waves observable from Earth.
Long-wavelength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



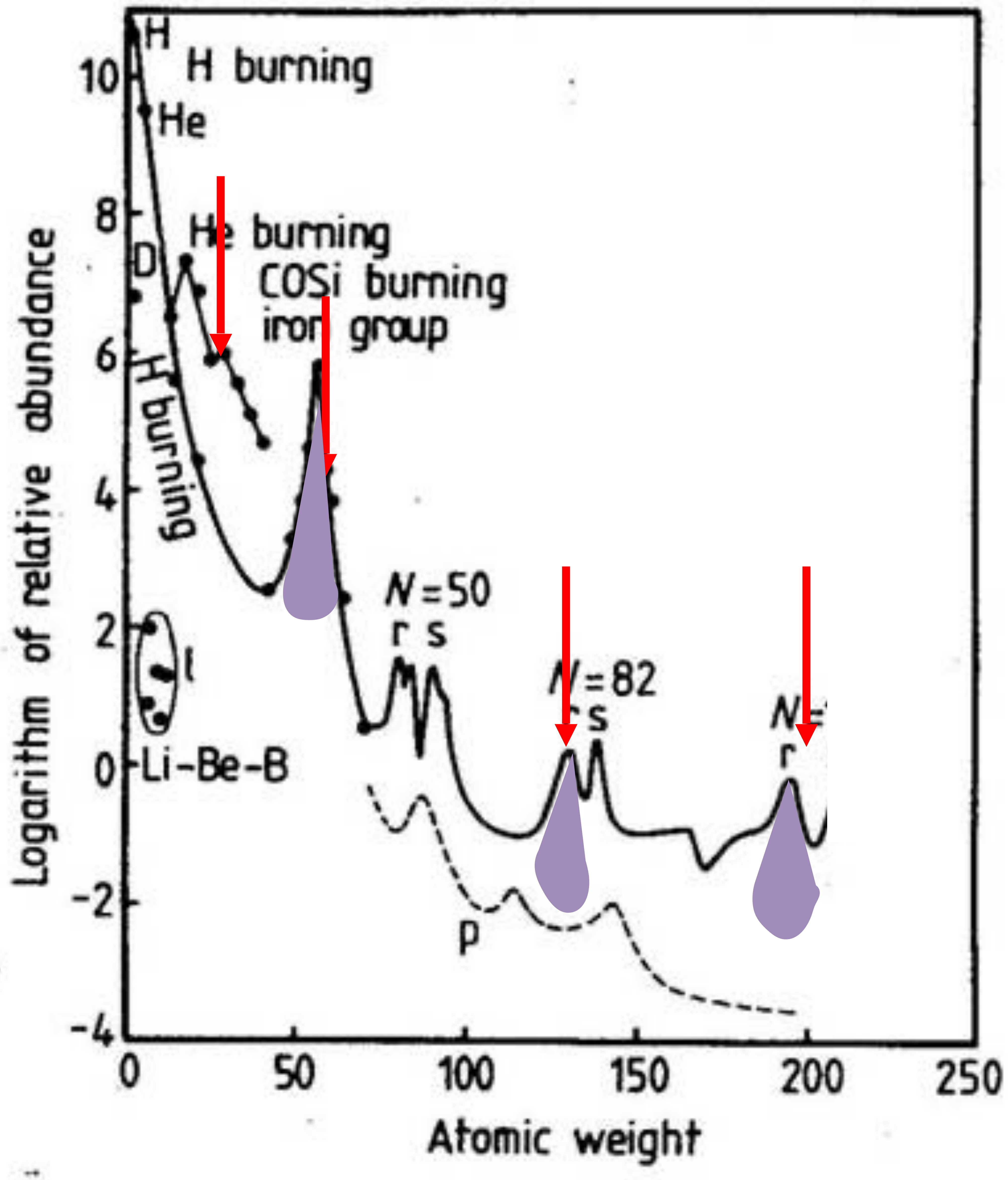
Life of star

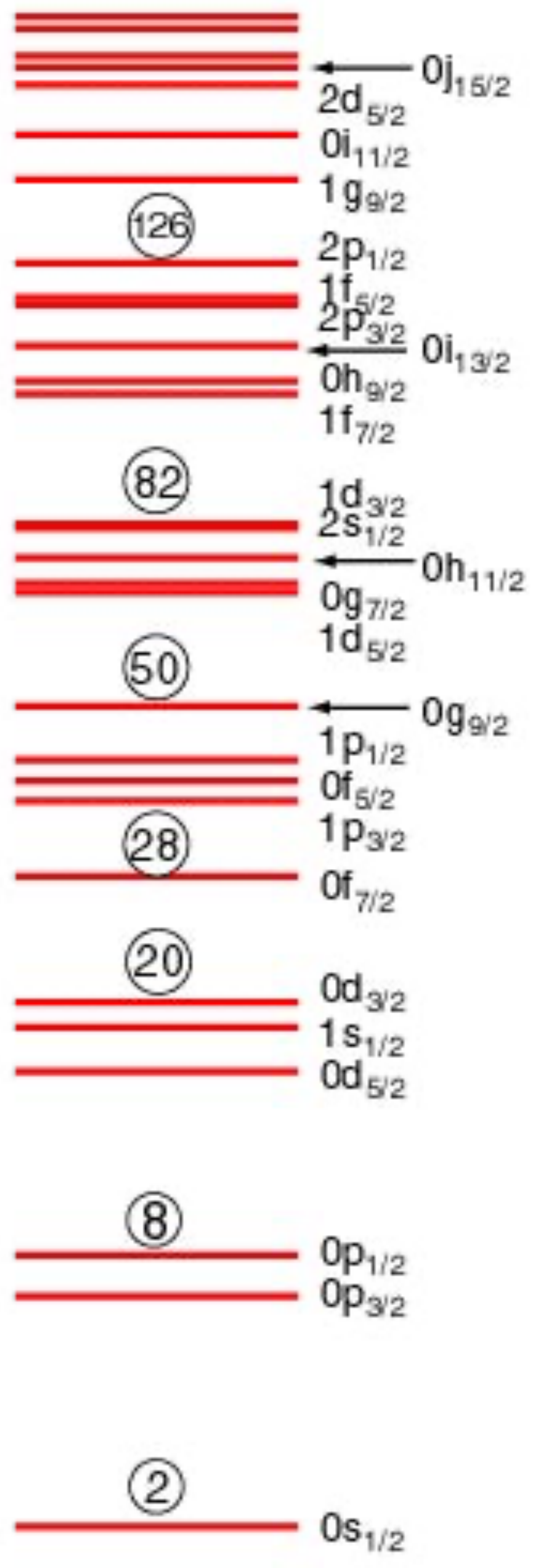


PRC 71(2005)052801R
原初过程
Primordial
stage
氢燃烧
H-burning
氦燃烧
He-burning
PRL 77(1996)611
星际燃烧
Inter stellar
burning
Black Hole
/neutron star
黑洞/中子星
平稳核燃烧
Stellar
process
硅铁燃烧
Si/Fe
burning
Supernovae
超新星爆发
PRL 2022, in press
Gravitational
collapse
引力坍缩

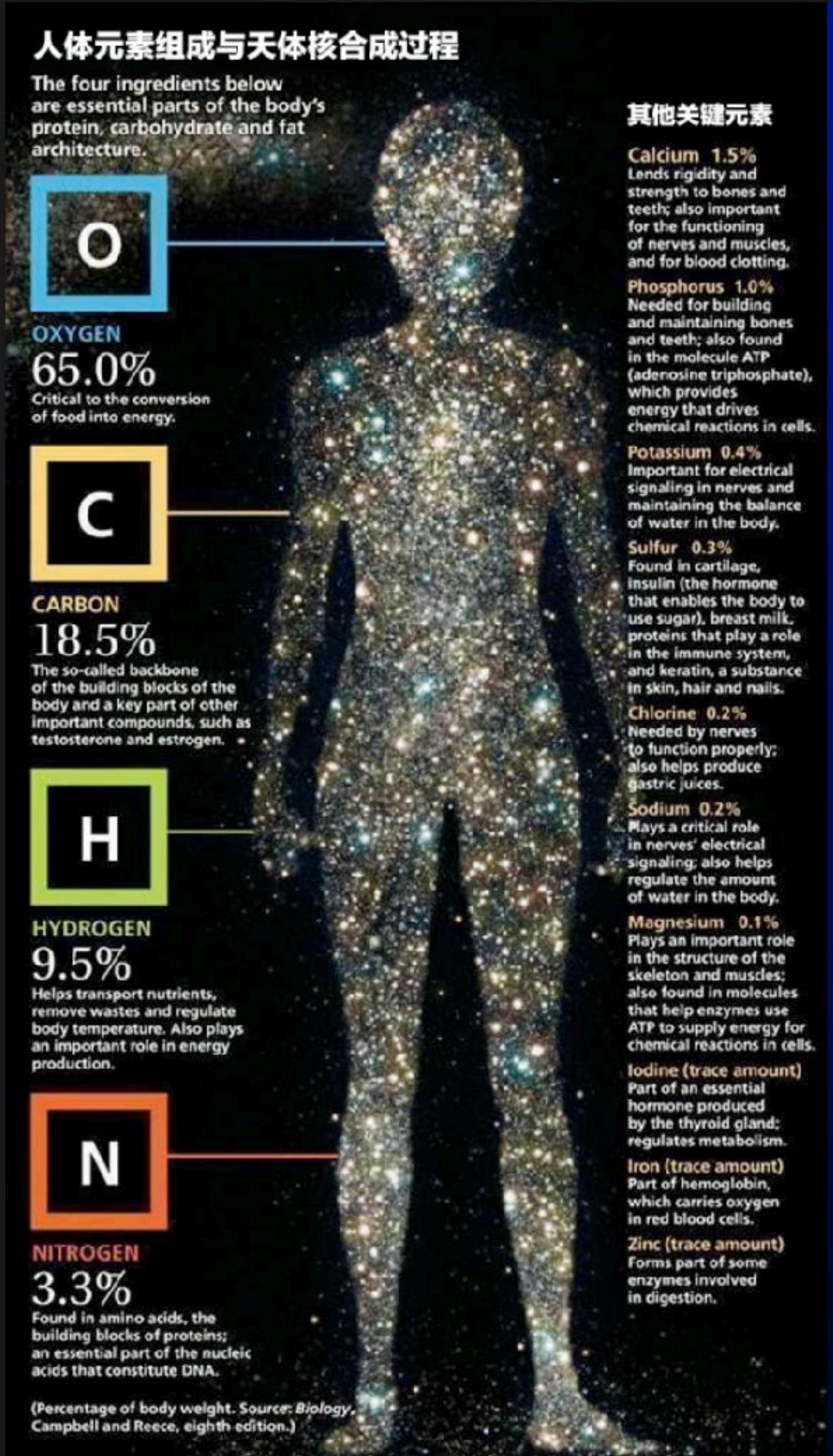
Nuclear Reactions: Alchemists in the Universe

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

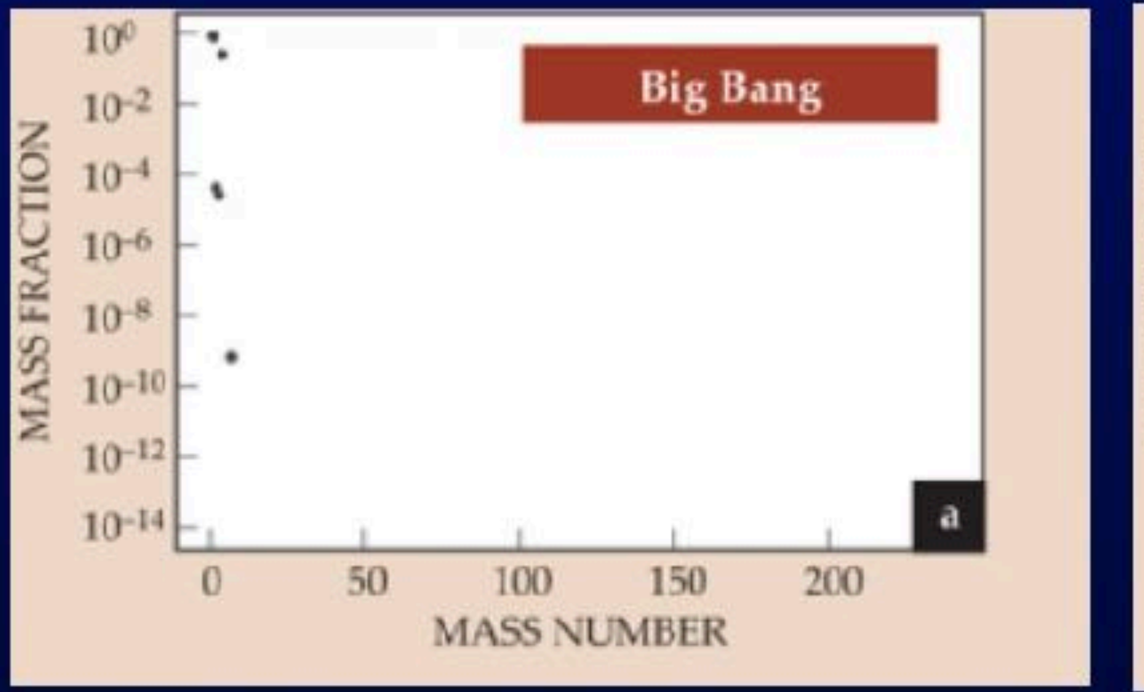


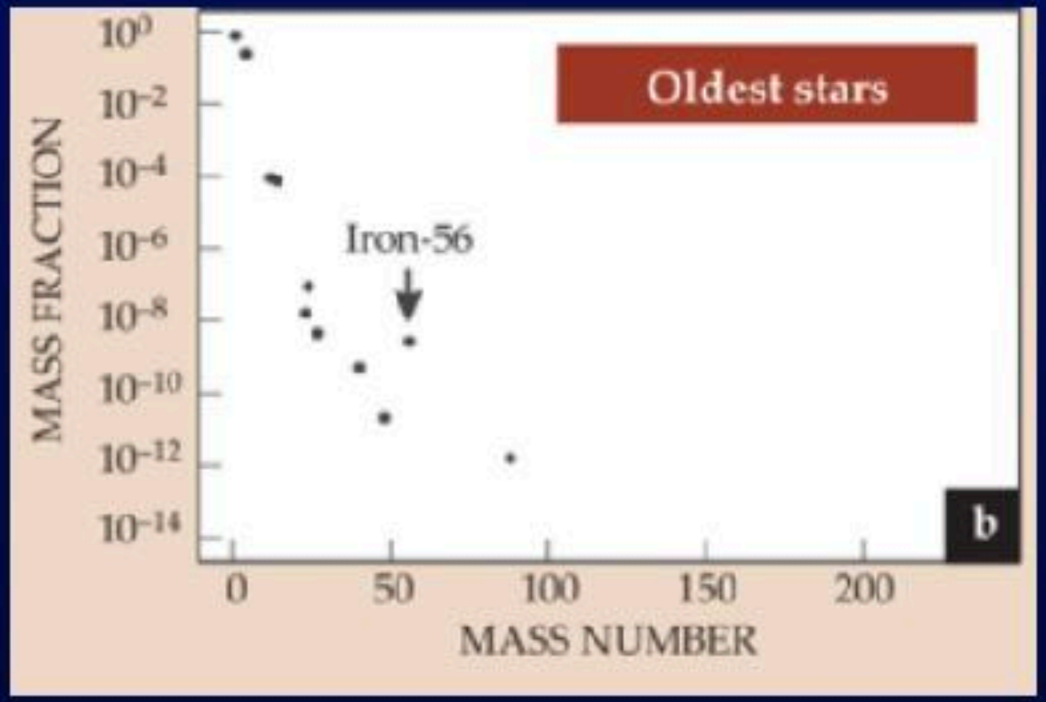


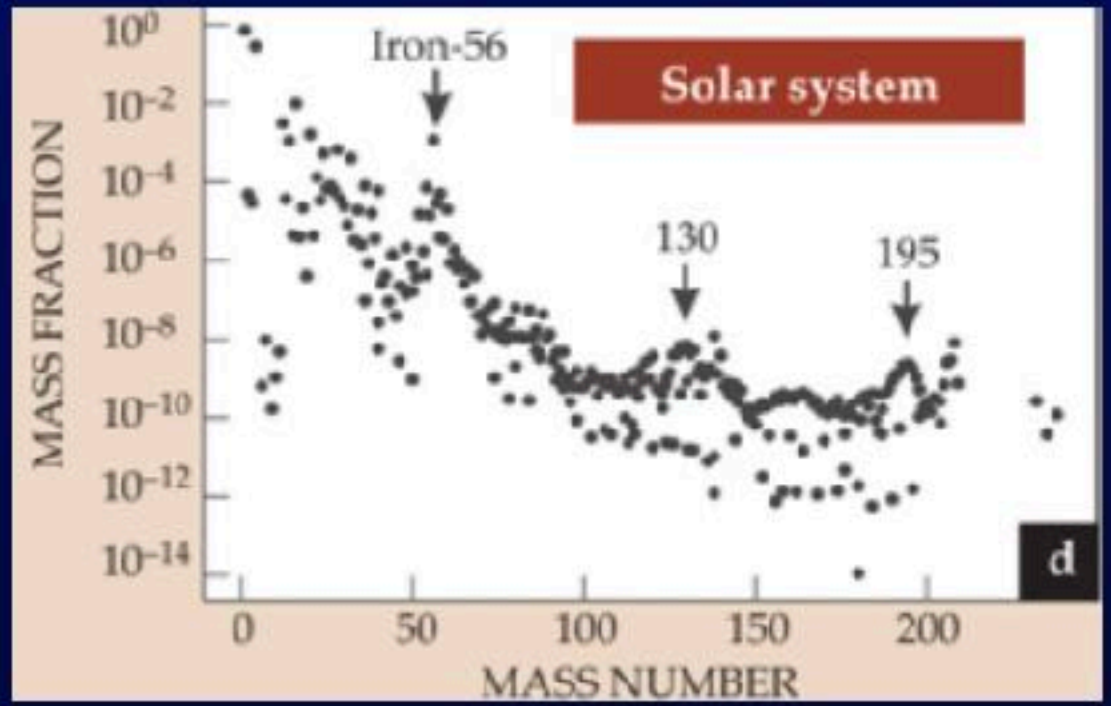
Shell Model of Nuclei



我们从哪里来，到哪里去？Where







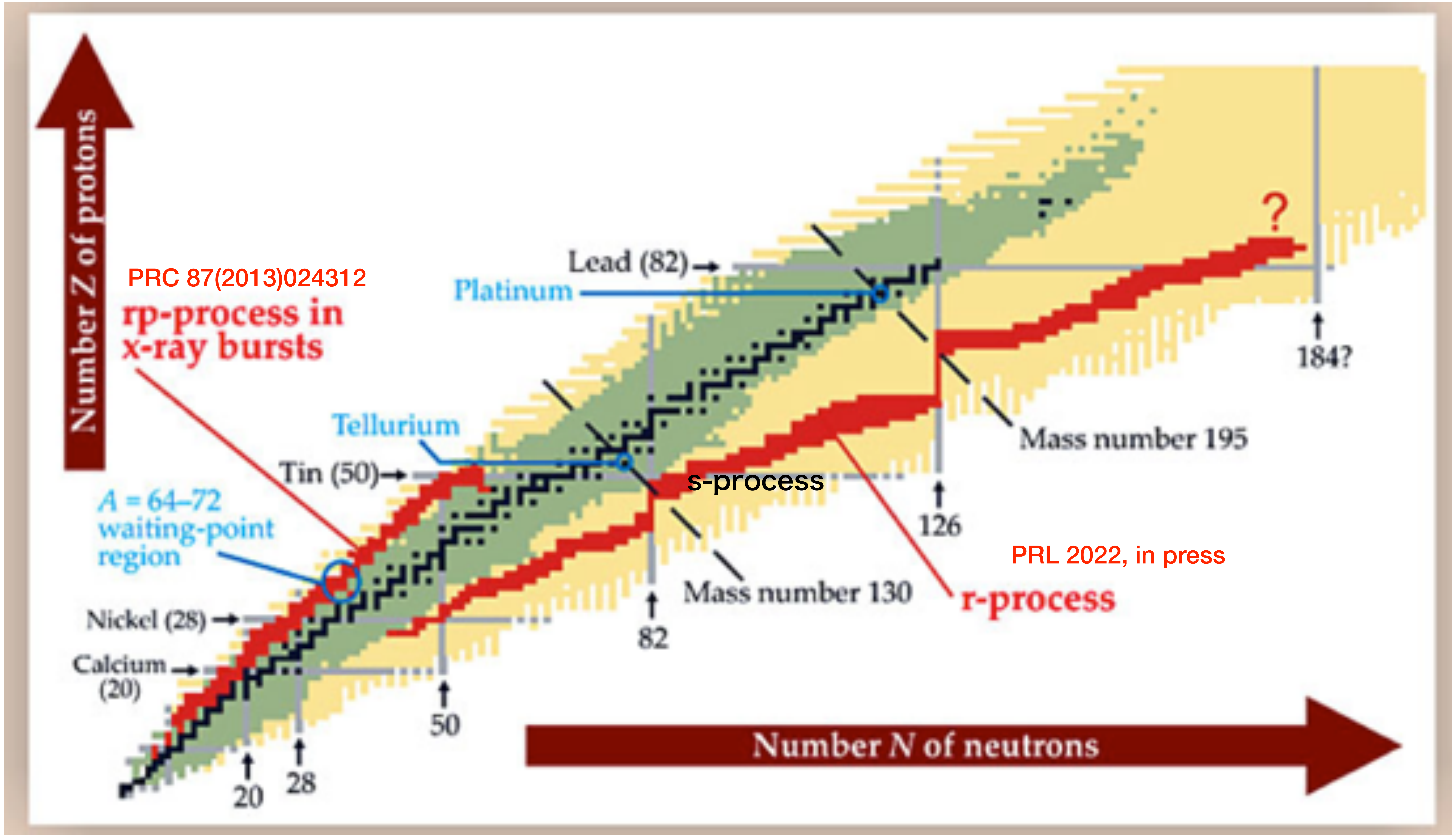
$^{12}C(\alpha,\gamma)^{16}O$

桥梁

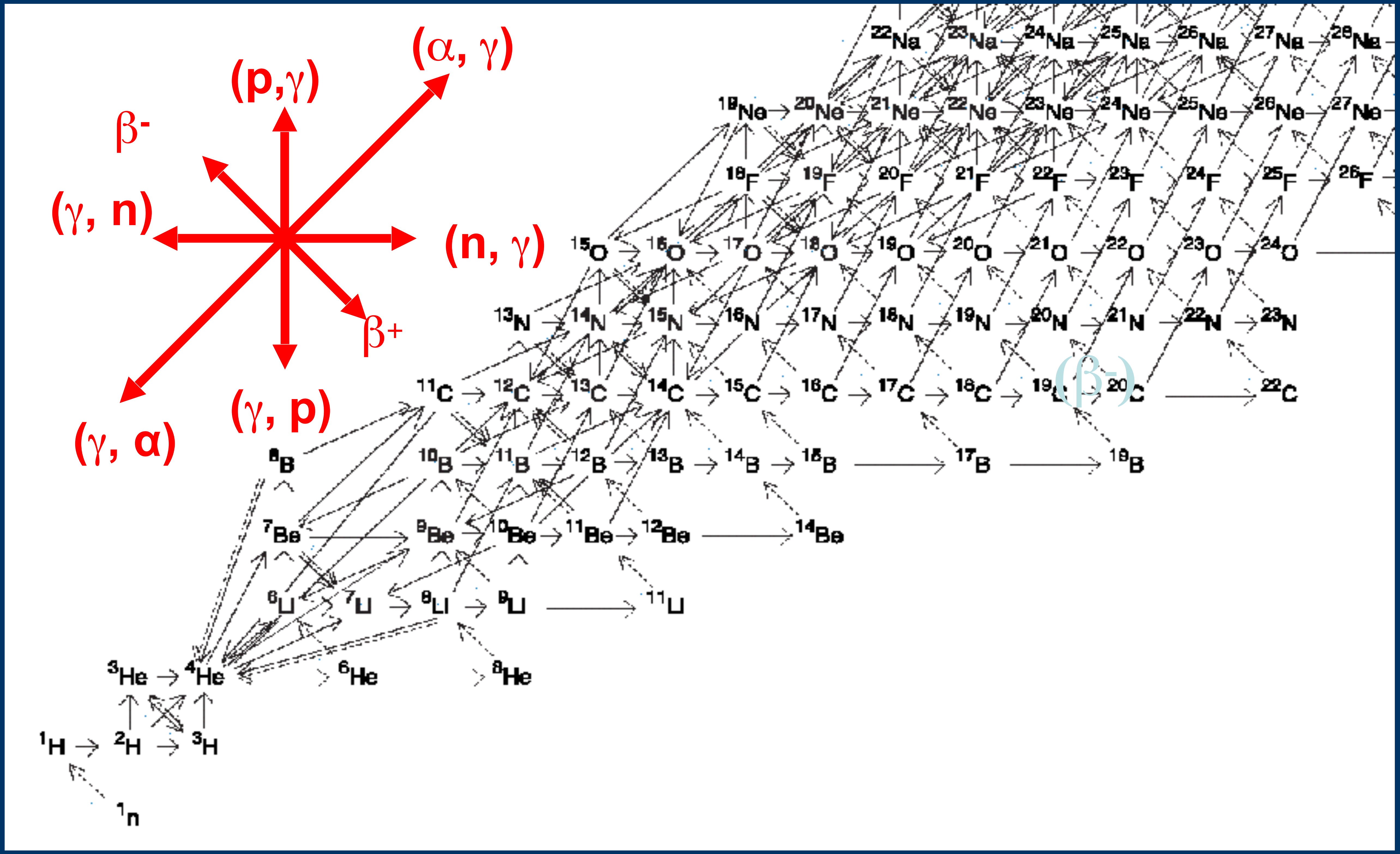
$^{13}C(\alpha,n)^{16}O$

粮食

Elemental synthesis in nuclear chart



Element synthesis network

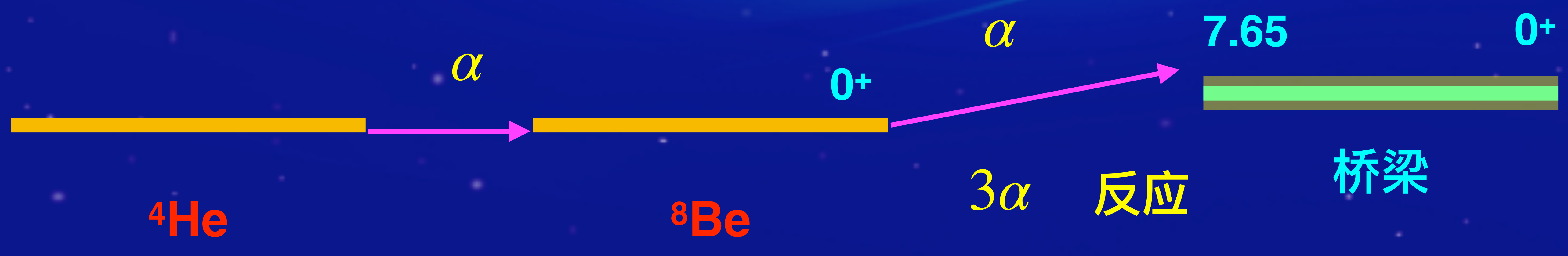


Cross section

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

Decay half-life

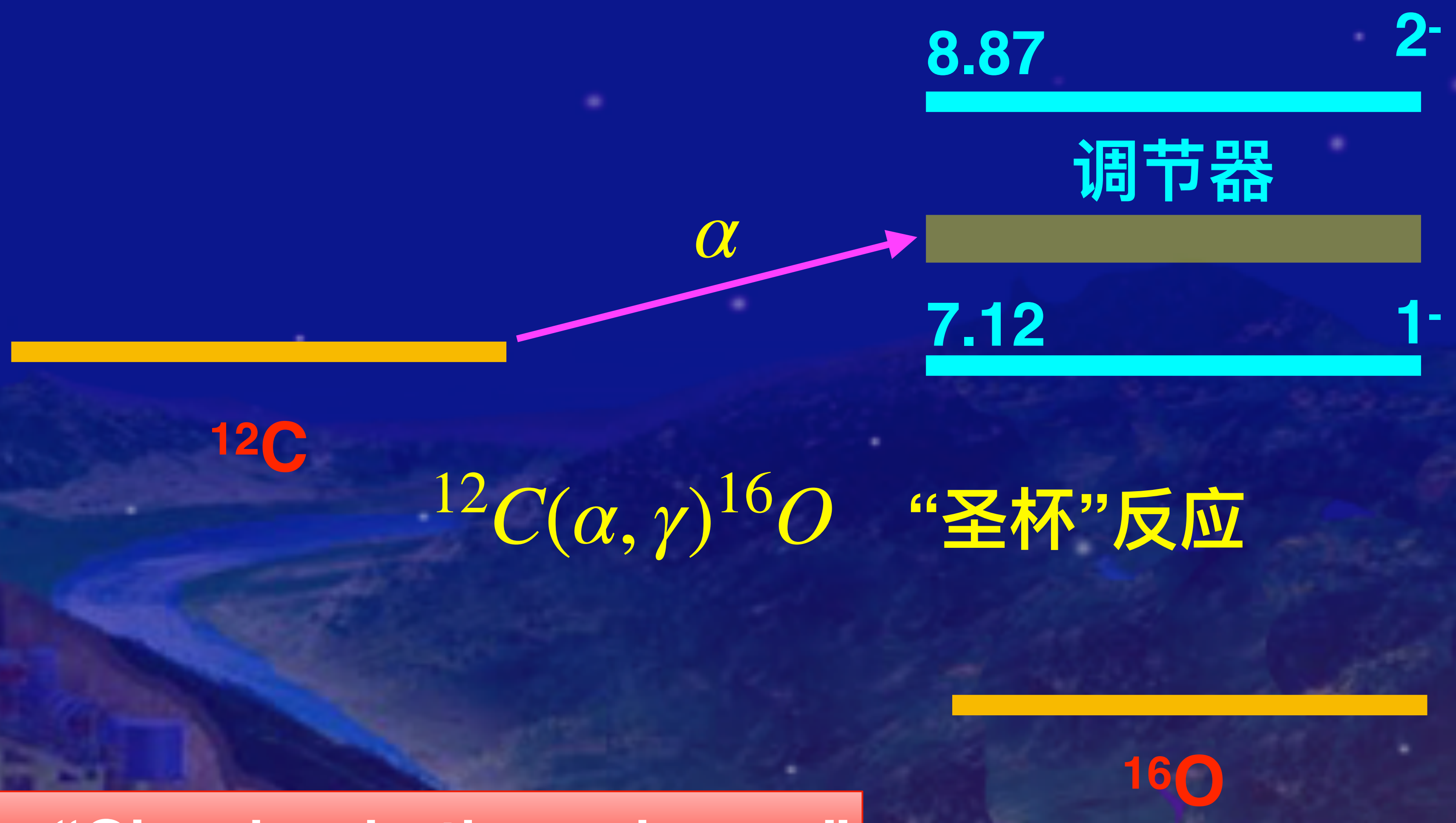
几个原子核的能级决定了宇宙和人类的命运！



1954, Hoyle态，很舒服，
有了碳基生命

Fred Hoyle (1915-2001)

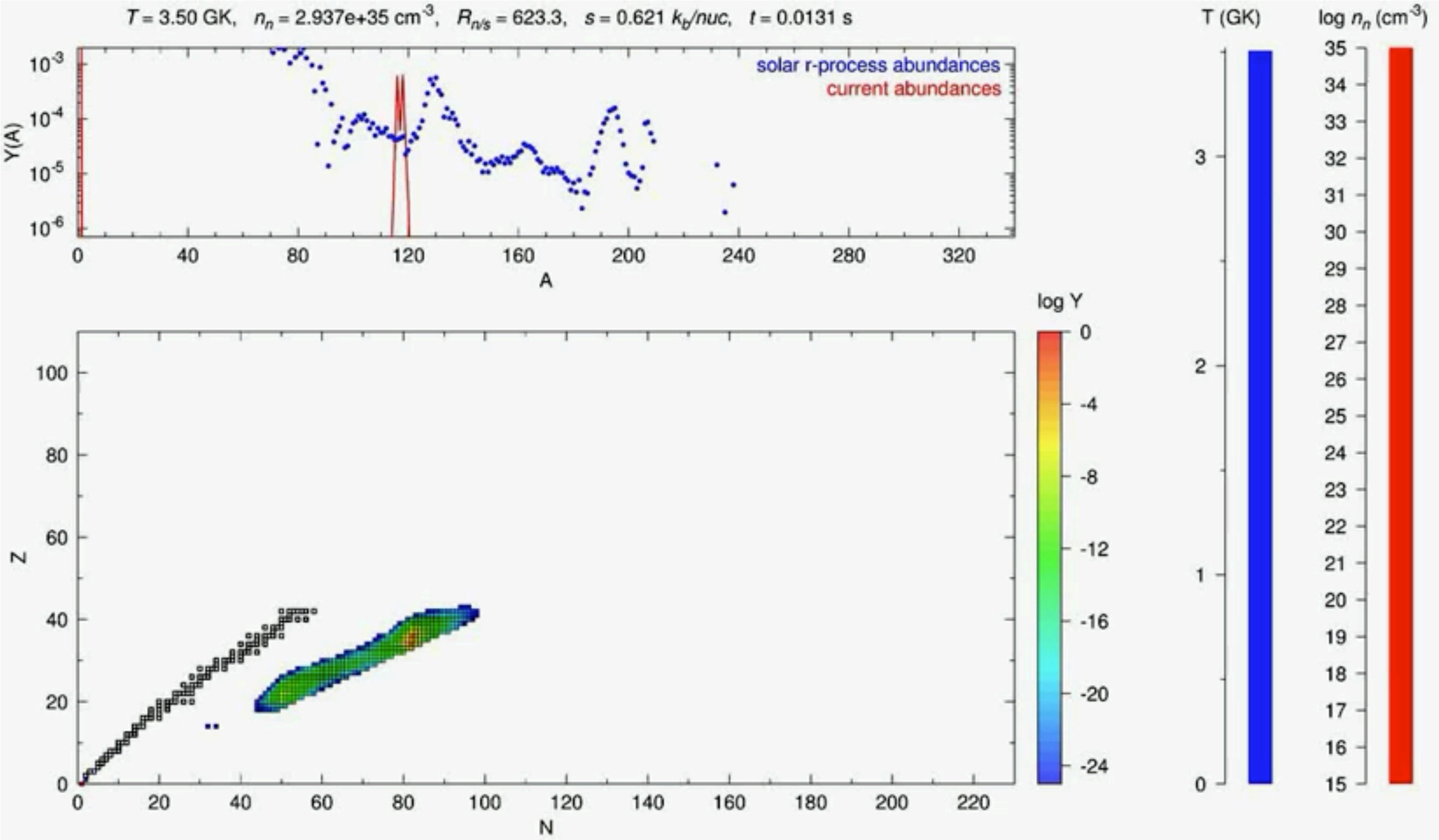
William A. Fowler (1911–1995)



很合适，太阳可以燃烧
数亿年；我们也有足够
氧气呼吸

from “Claudon in the universe”

重元素合成快速中子俘获r过程数值模拟



Nuclear Astrophysics roadmap 路线图

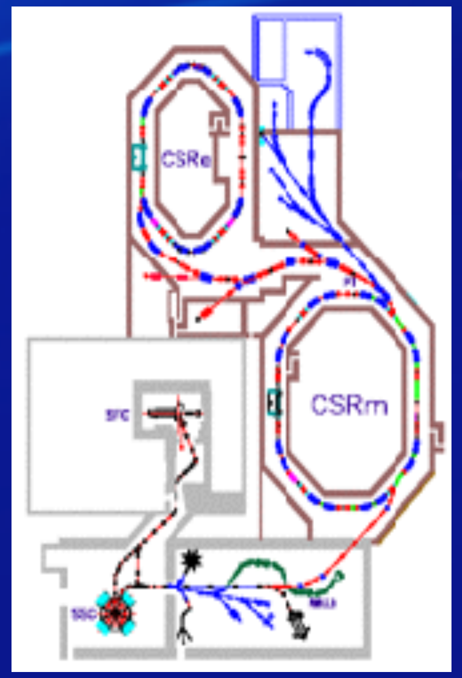
Ground, underground

Direct | In-direct | Resonance

reaction

RI, Ring

decay, mass



RECLIB…

Micro, MF

Space, Ground

Data | Theory | Astrophysics | Observation

NP input

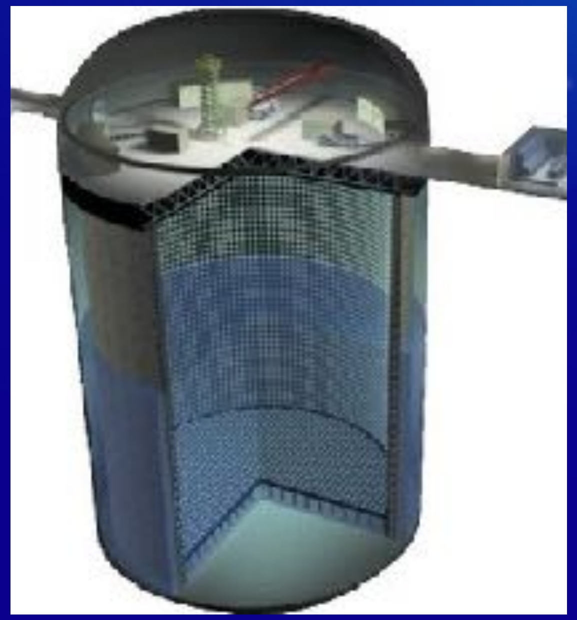
Astrophysical model

Abundance simulation

Abundance observation

Solar neutrino：From question to discovery

Theory



Reaction reduce 2/3?

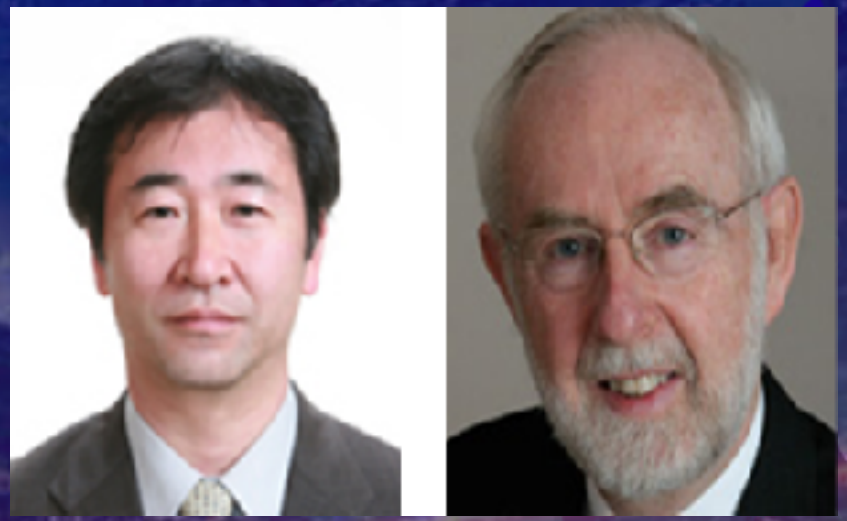
Nuclear data is correct!

Observation

Neutrino to others by 2/3?

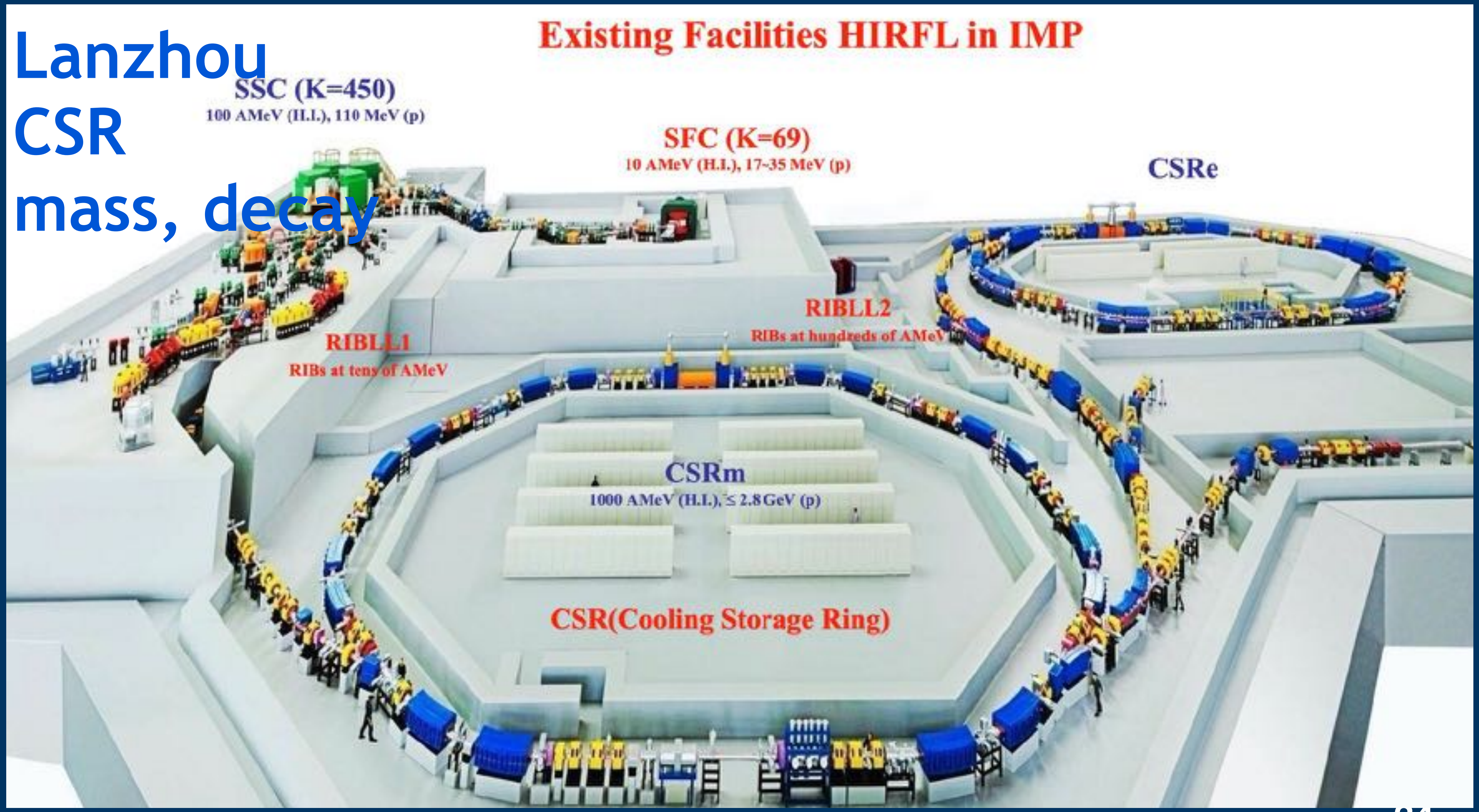
Neutrino has mass!

2002
Davis
Koshiba
Neutrino detection



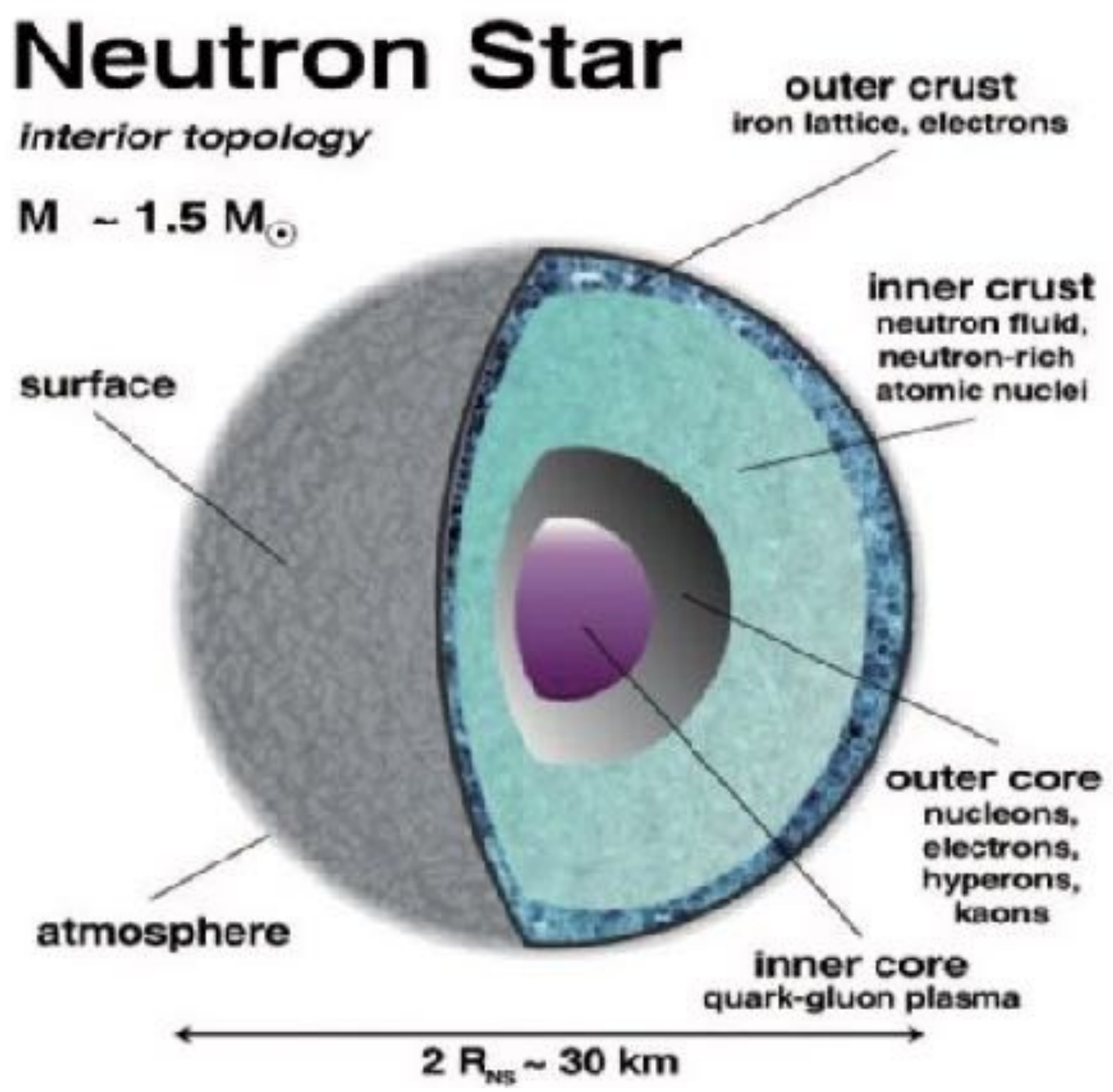
2015
Fujita
McDonald
Neutrino oscillation

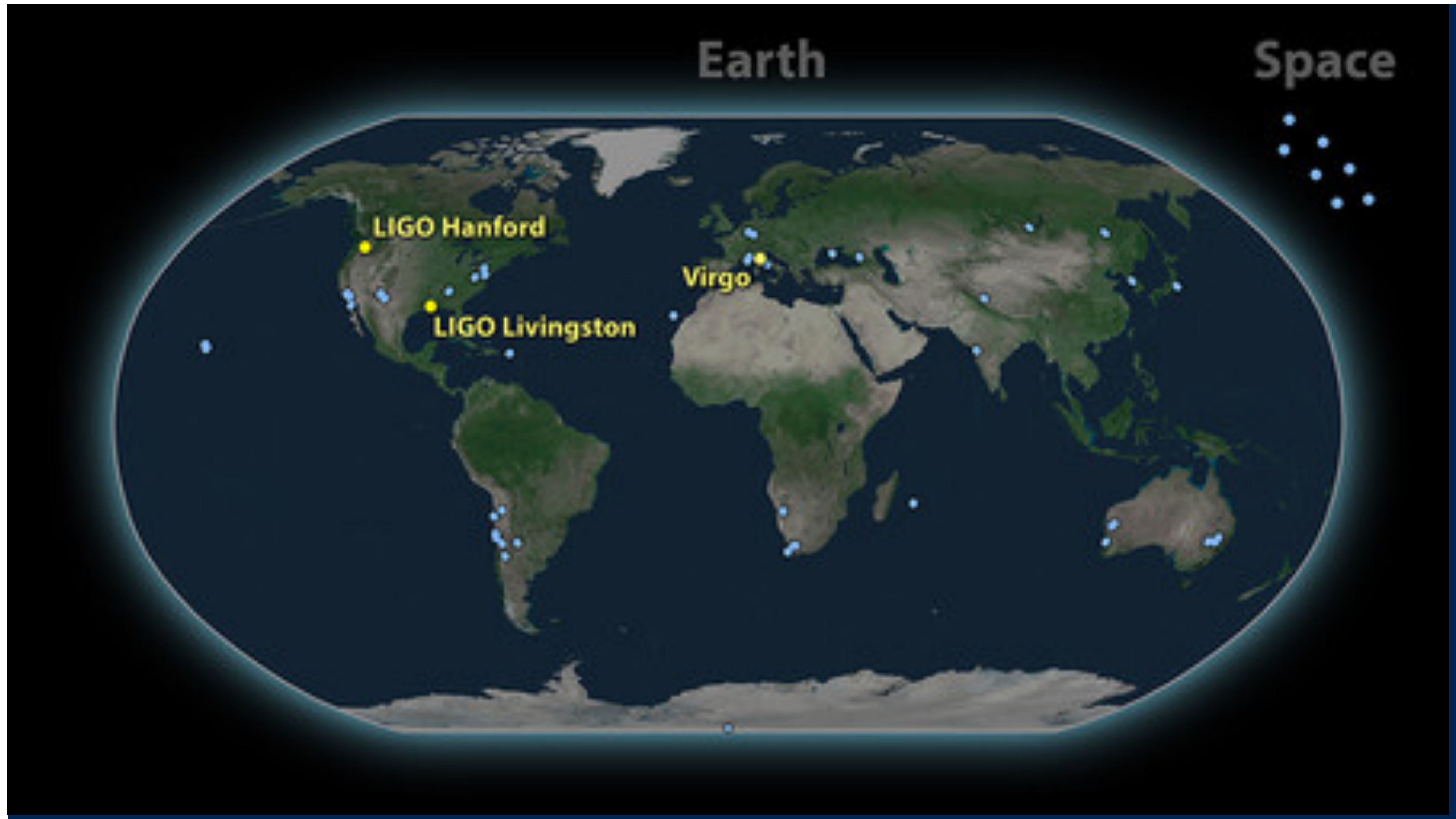
Major facilities in China

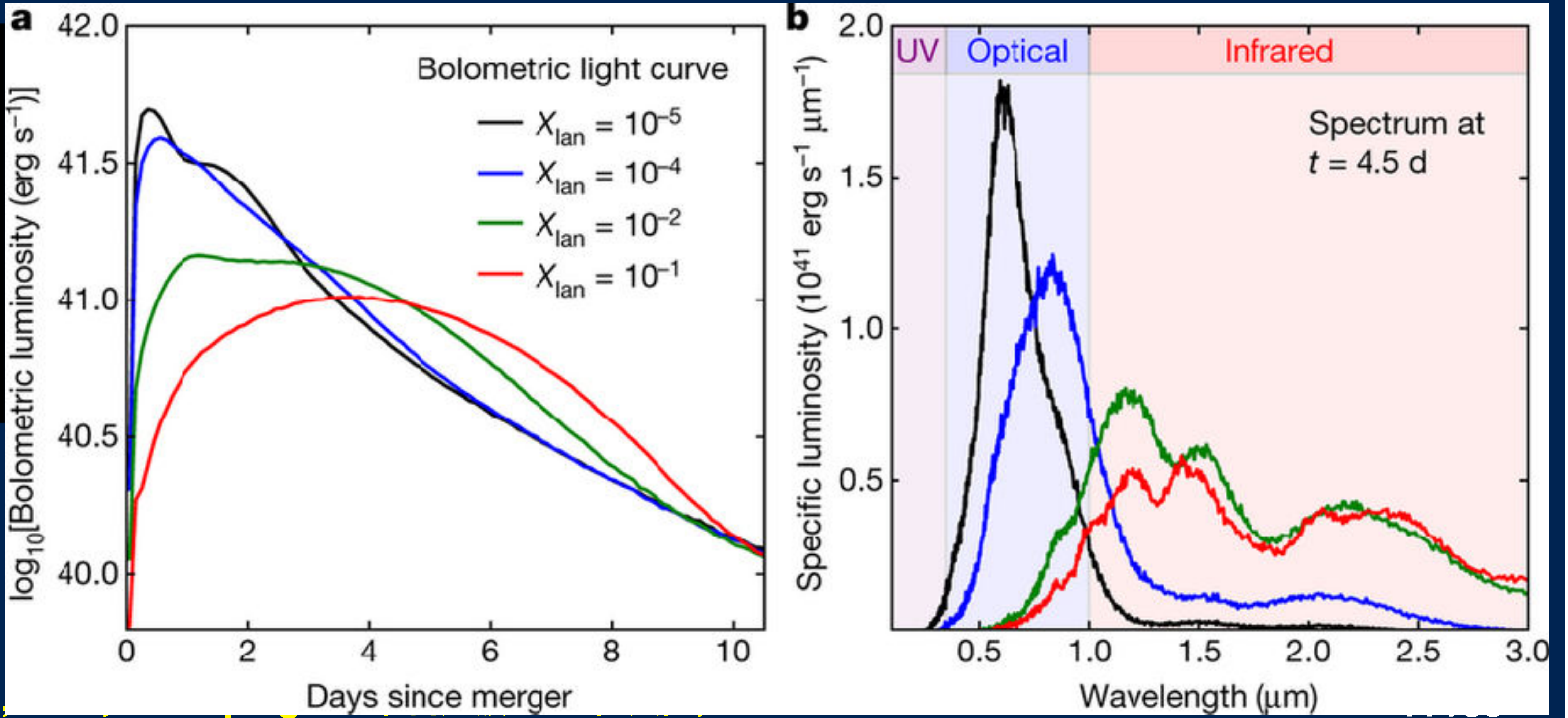


W. P. Liu, 2022, NuSYS

NSM and r process heavy element generation

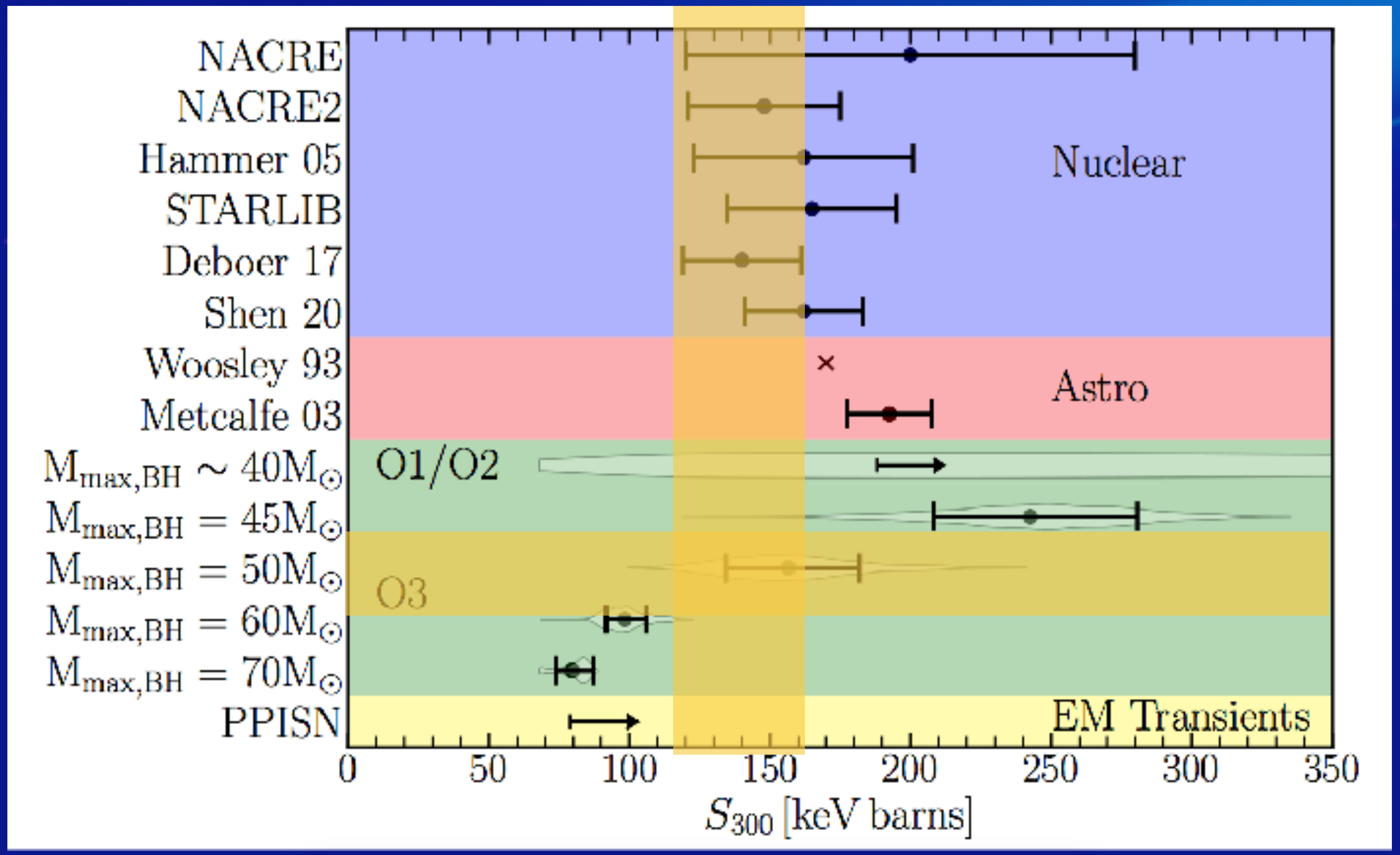


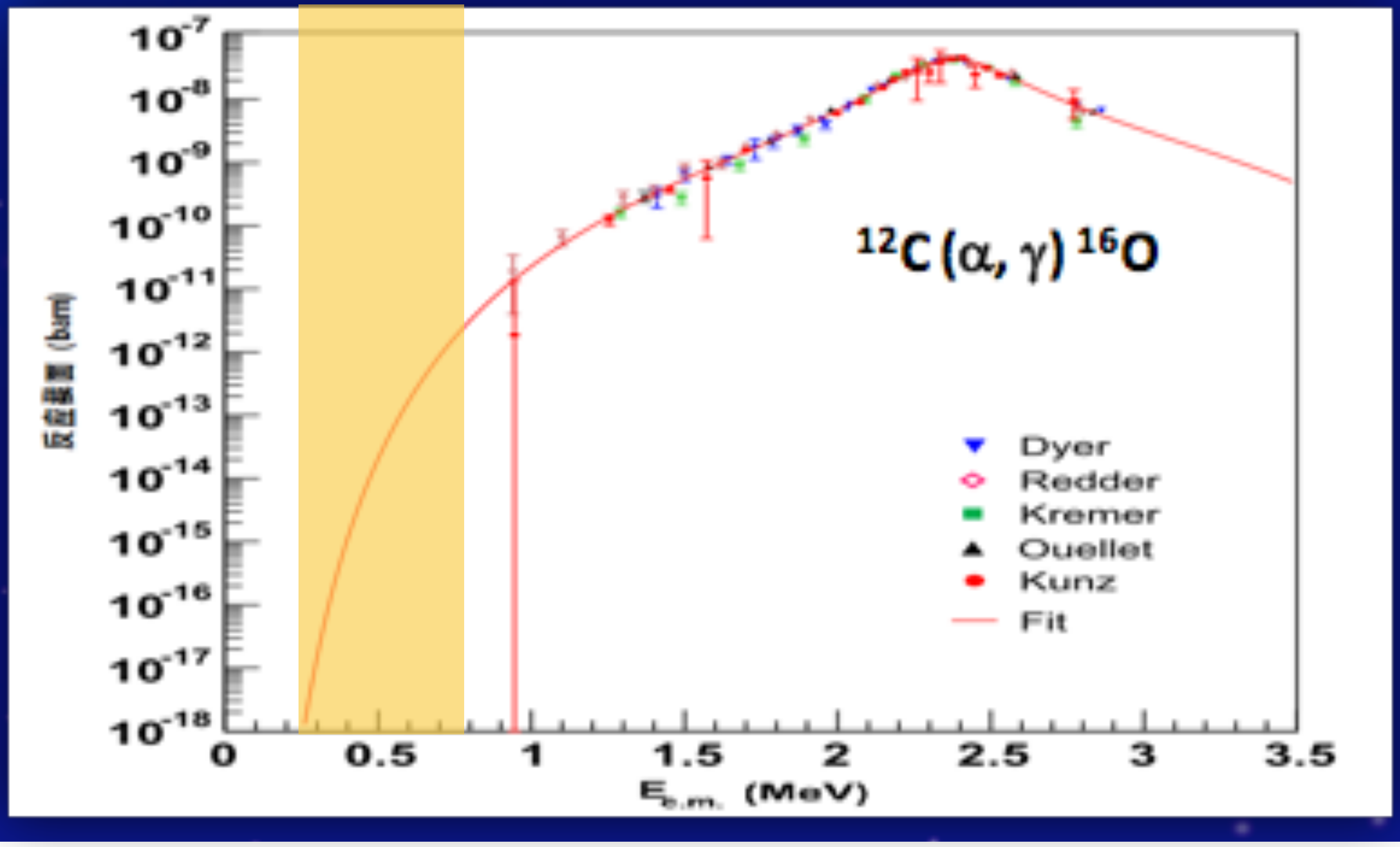


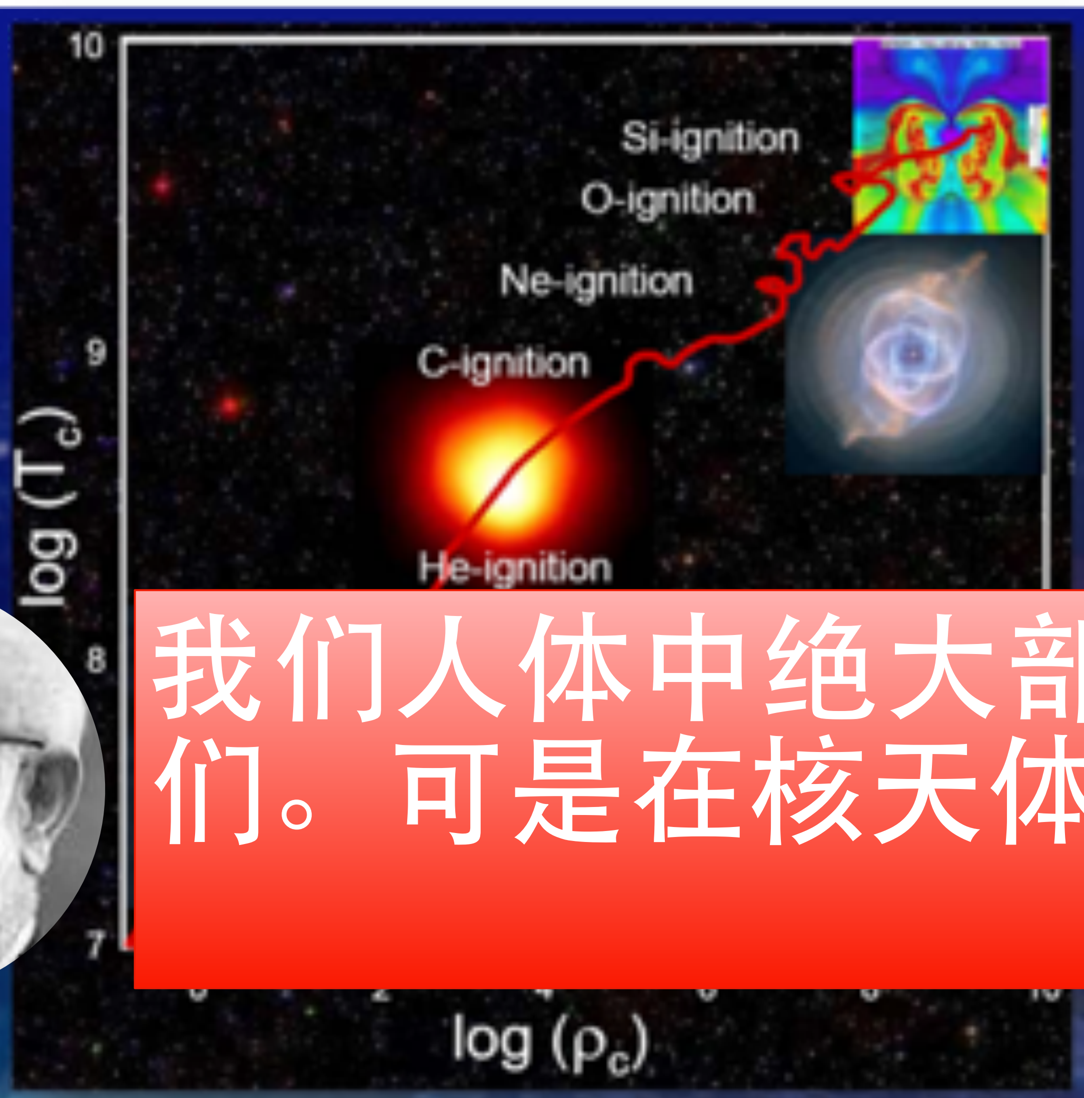


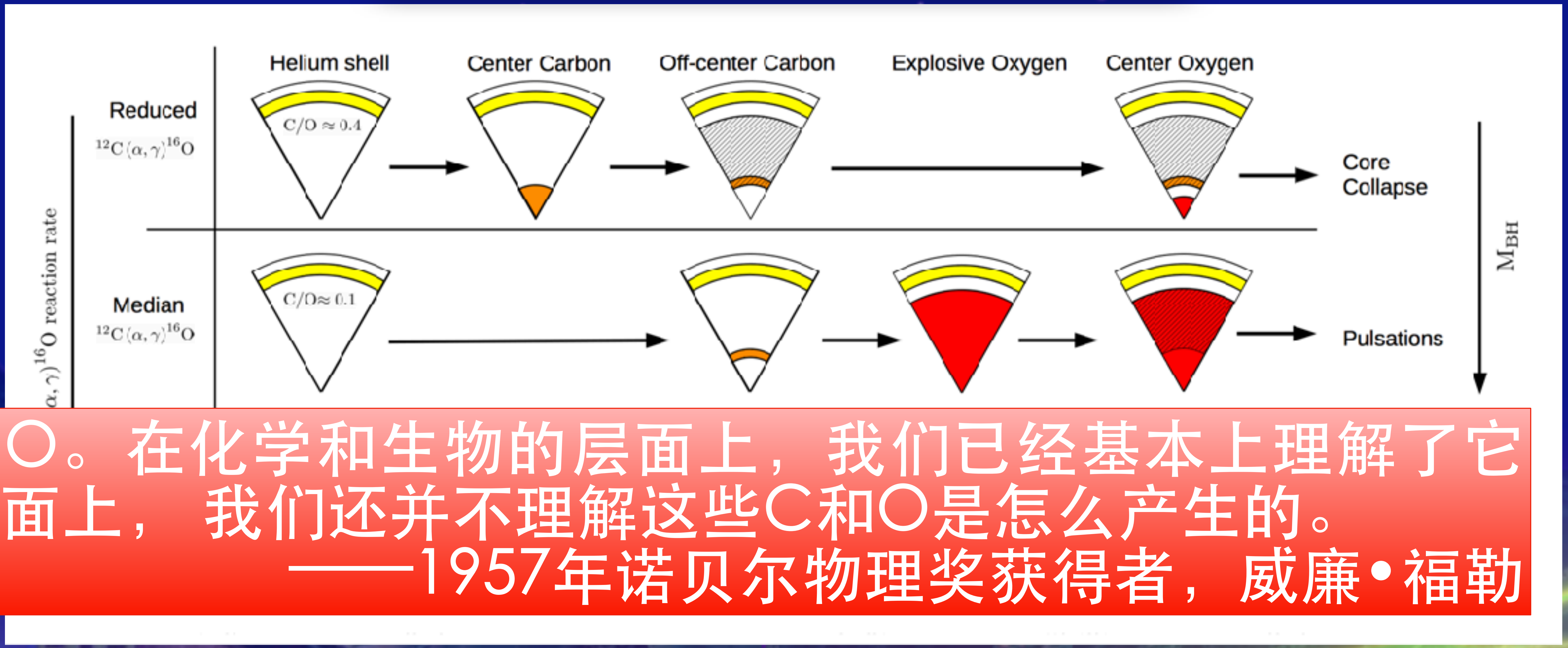
W. P. Liu,

圣杯反应是定海神针 Holy Grail





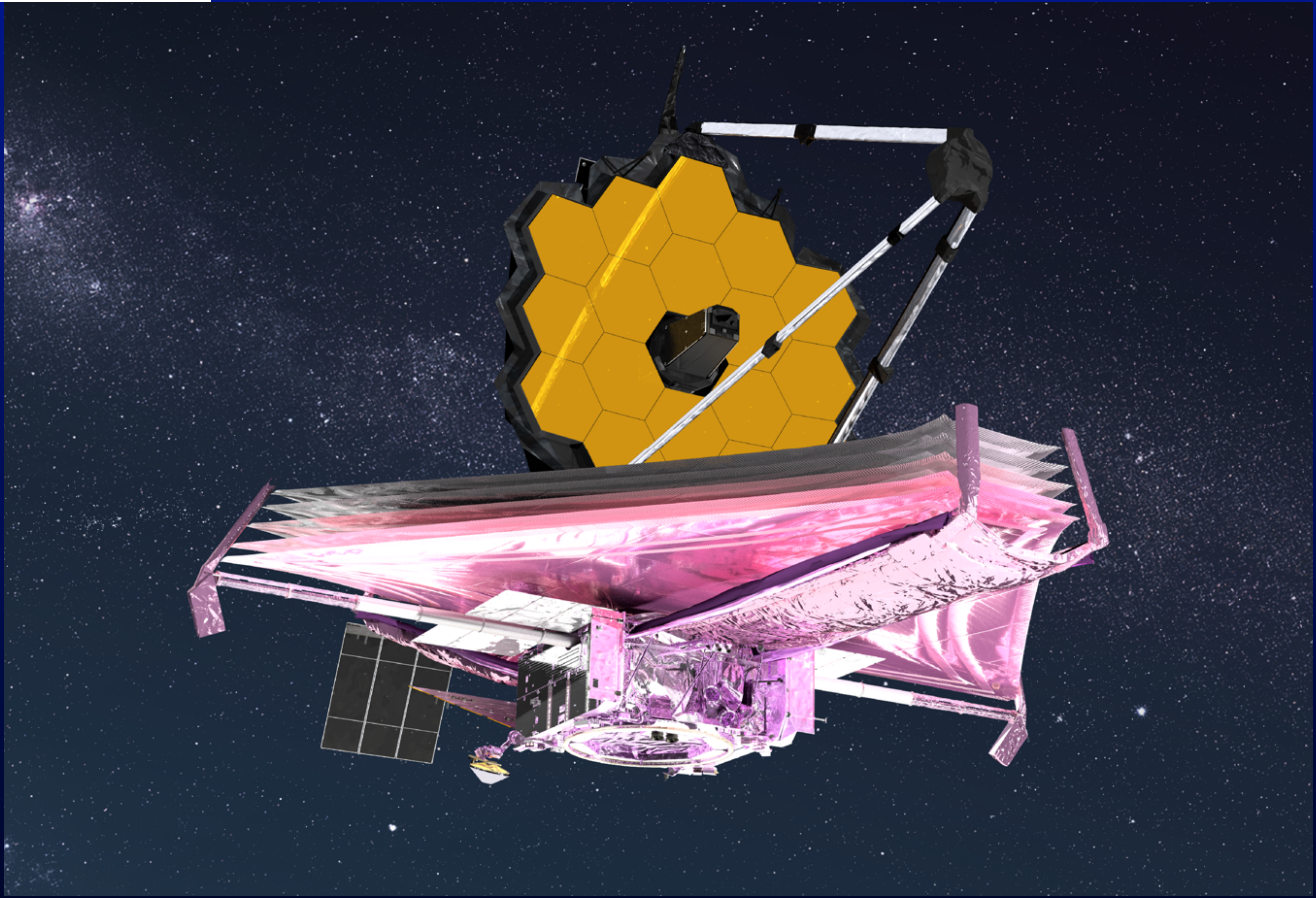




我们人体中绝大部分是C和O。在化学和生物的层面上，我们已经基本上理解了它们。可是在核天体物理的层面上，我们还并不理解这些C和O是怎么产生的。

——1957年诺贝尔物理奖获得者，威廉•福勒

从韦布天文望远镜说起



- JWST
- Lunch
  25 December
  2021
- 1st image 11
  July 2022
- Cost ~$10 B
- ~20 years R&D
- 10-20 years
  operation

First photo JWST

- Deep-field photograph
- Captured Near-Infrared Camera (NIRCam)
- Southern Hemisphere, centered on SMACS 0723
- Galaxy cluster in the constellation of Volans. Thousands of galaxies are visible
- Some as old as 13 billion years
- Highest-resolution image of the early universe

韦布望远镜的科学目标

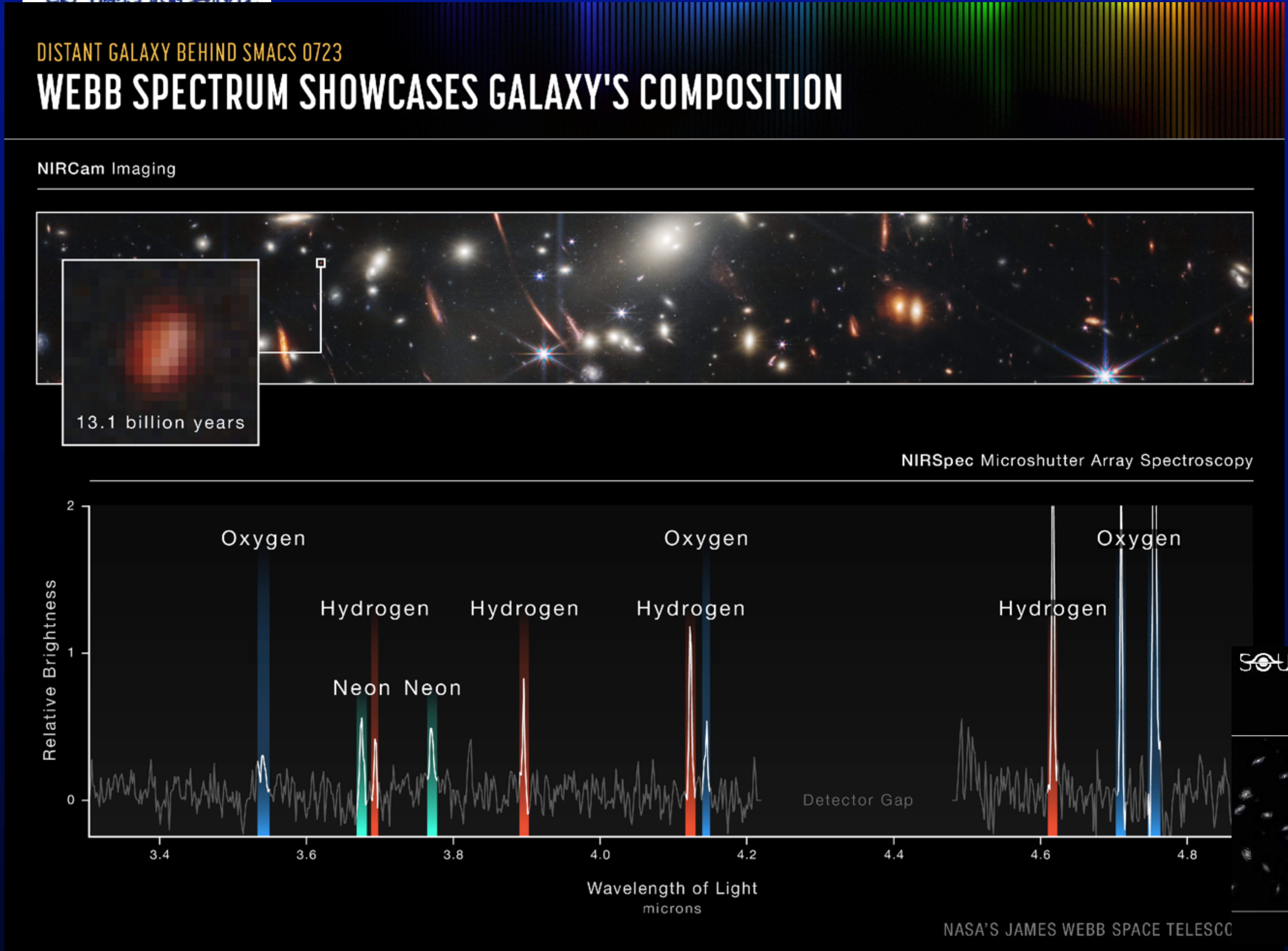
黑暗时代的结束：JWST将是一台具有红外探测能力的强大时光机，将追溯到135亿年前，看到从早期宇宙的黑暗中形成的第一批恒星和星系。

星系的聚集：JWST前所未有的红外灵敏度将帮助天文学家将最暗的、最早的星系与今天的大螺漩涡和椭圆星系进行比较，帮助我们了解星系如何在数十亿年内聚集在一起。

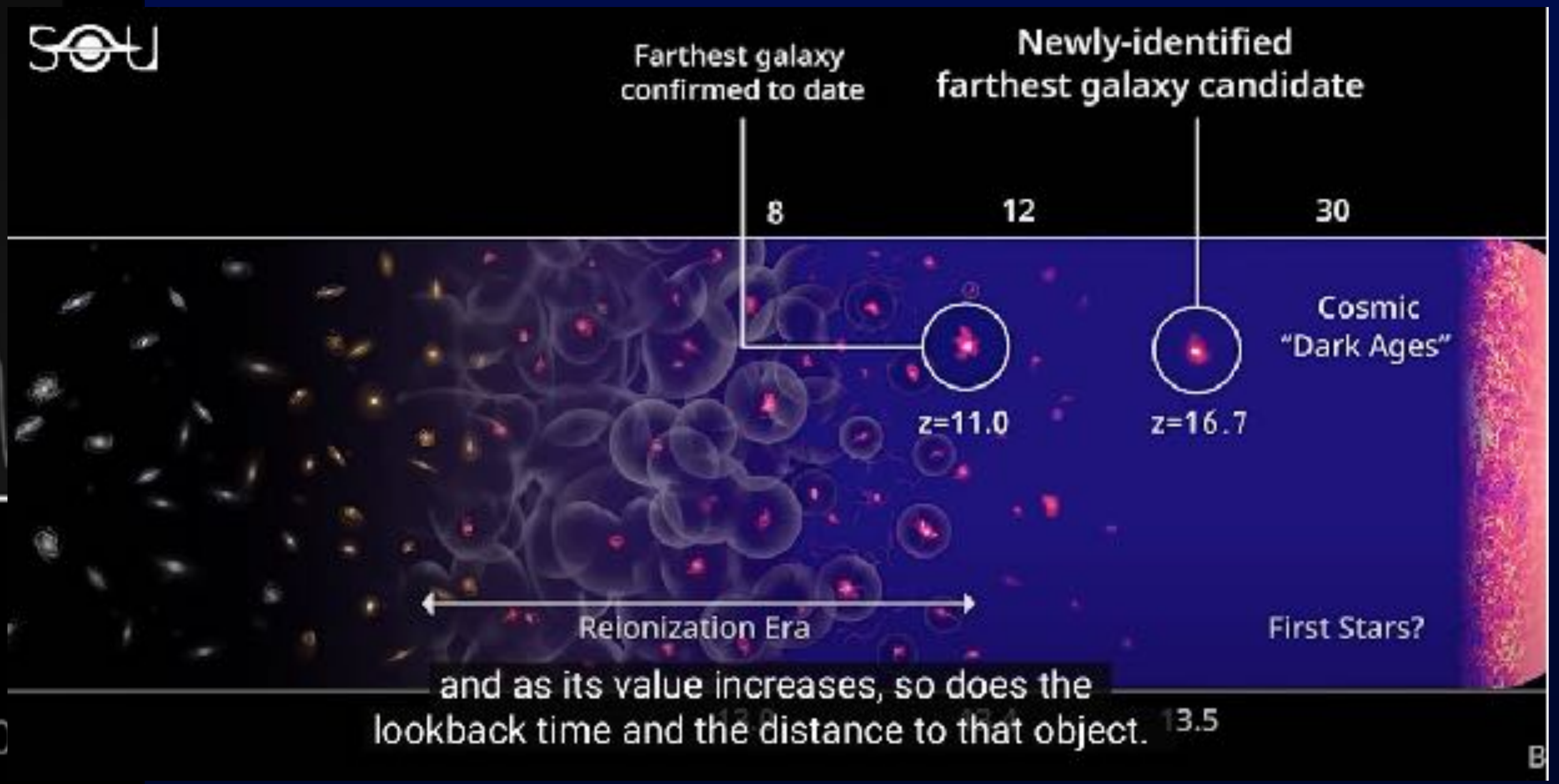
恒星和原行星系统的诞生：JWST将能够直接看到巨大的尘埃云，这些尘埃云对于像哈勃这样的可见光天文台来说是不透明的，哈勃是恒星和行星系统的诞生地。

行星系统和生命起源：JWST将告诉我们更多关于太阳系外行星的大气，甚至可能在宇宙其他地方找到生命的基石。除了其他行星系统外，JWST还将研究我们太阳系内的天体。

Star cloud of 13.1 B Yr old from JWST



- 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



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

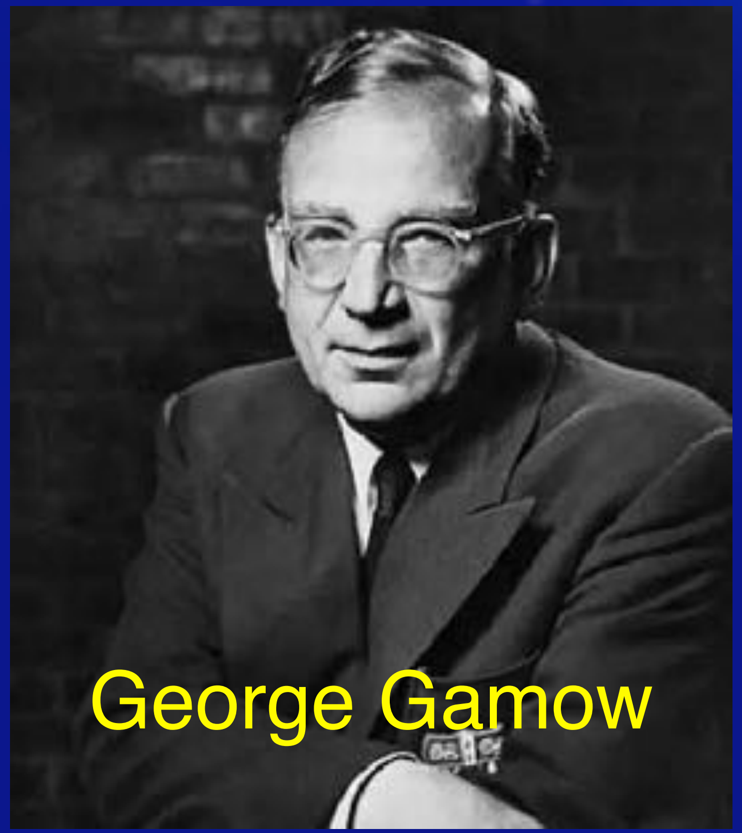
RECLIB…

Nuclear input database

AME…

Mass and decay rate database

需要超大曝光 High exposure



coulomb term

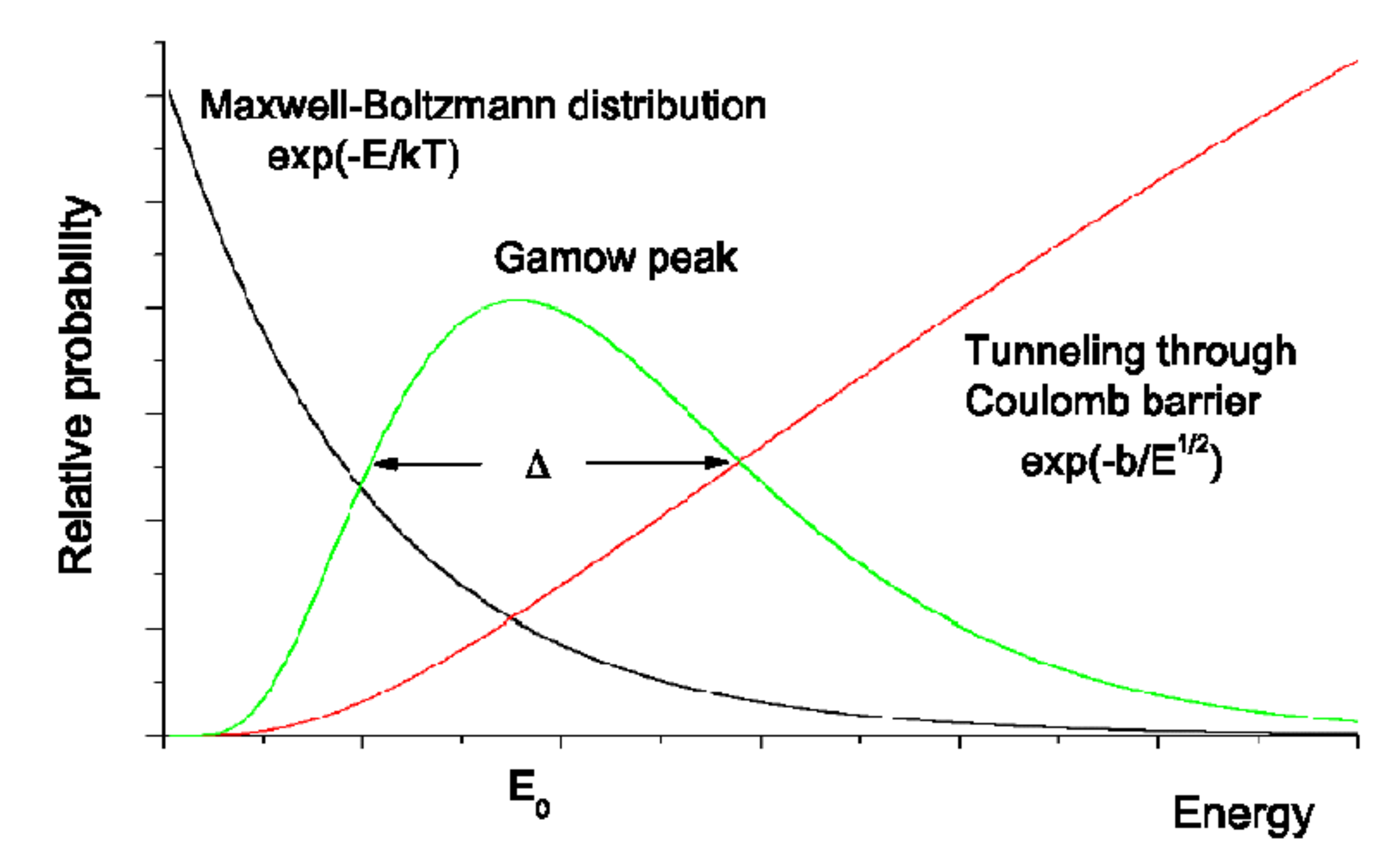
$$\sigma(E) = S(E)e^{-2\pi\eta}\frac{1}{E}$$

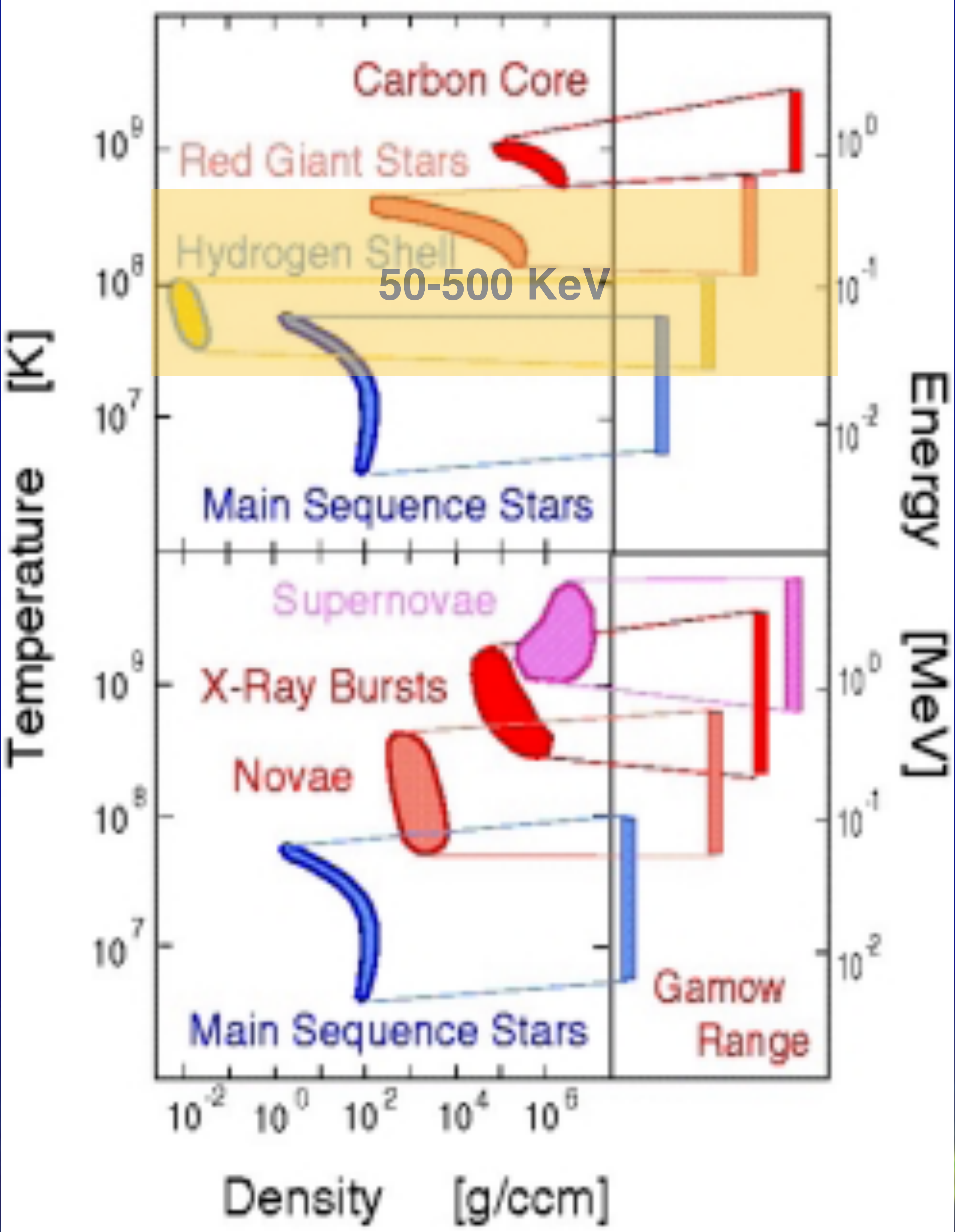
astrophysical s factor

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

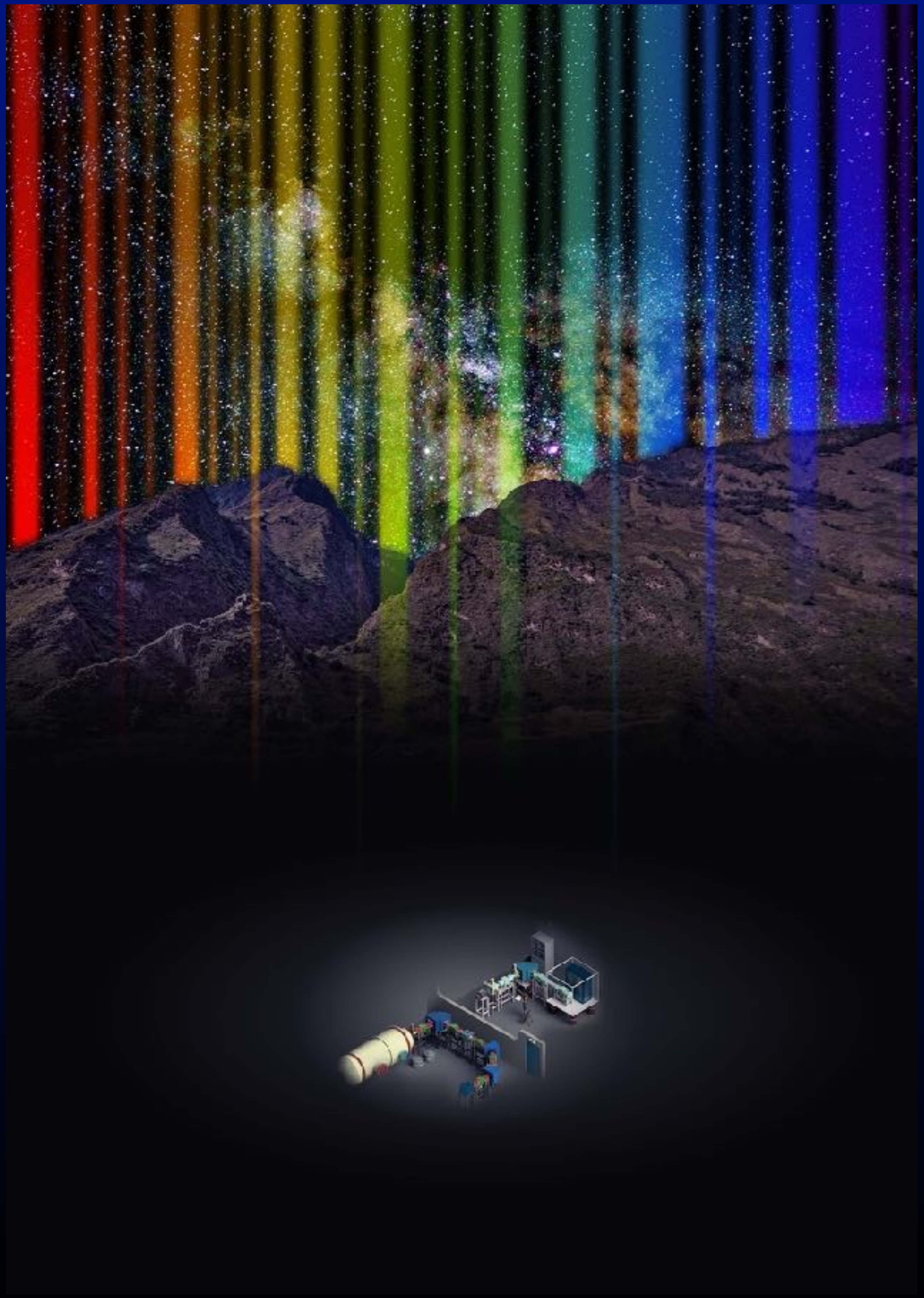
$$E_0 = 1.22(Z_1^2 Z_2^2 M T_6^2)^{1/3}\mathrm{keV}$$

Gamow window



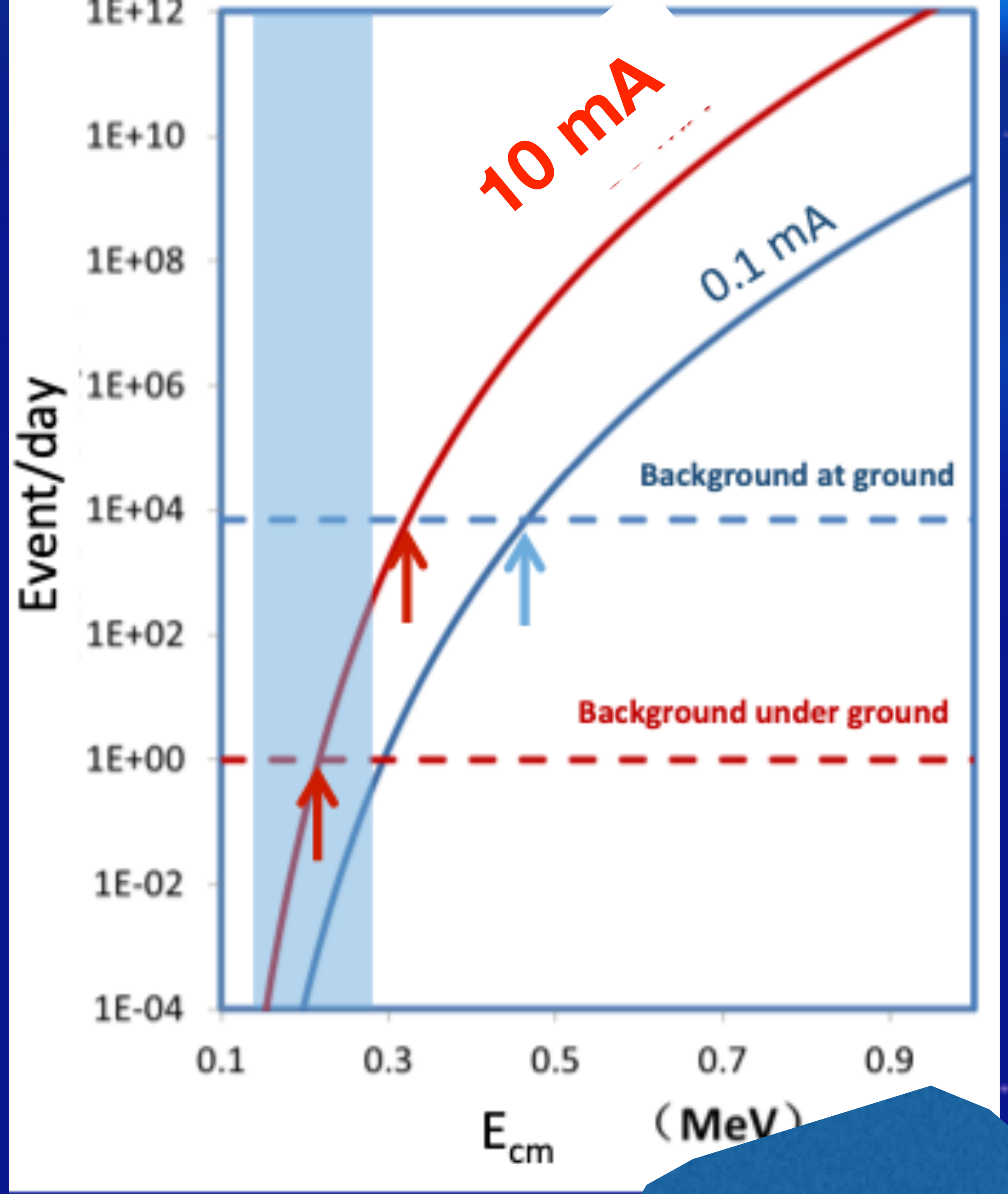


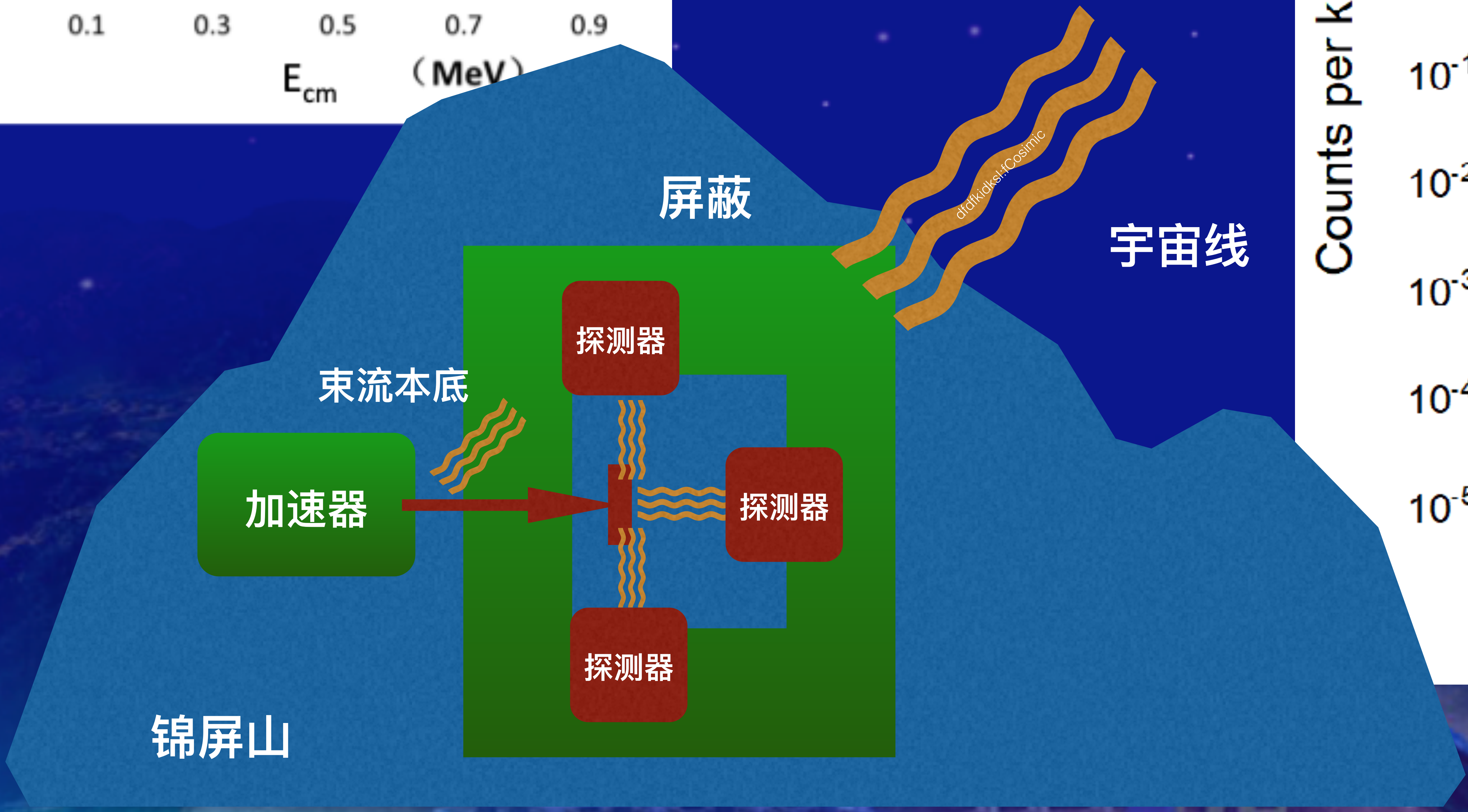
实验场所——从地面到地下

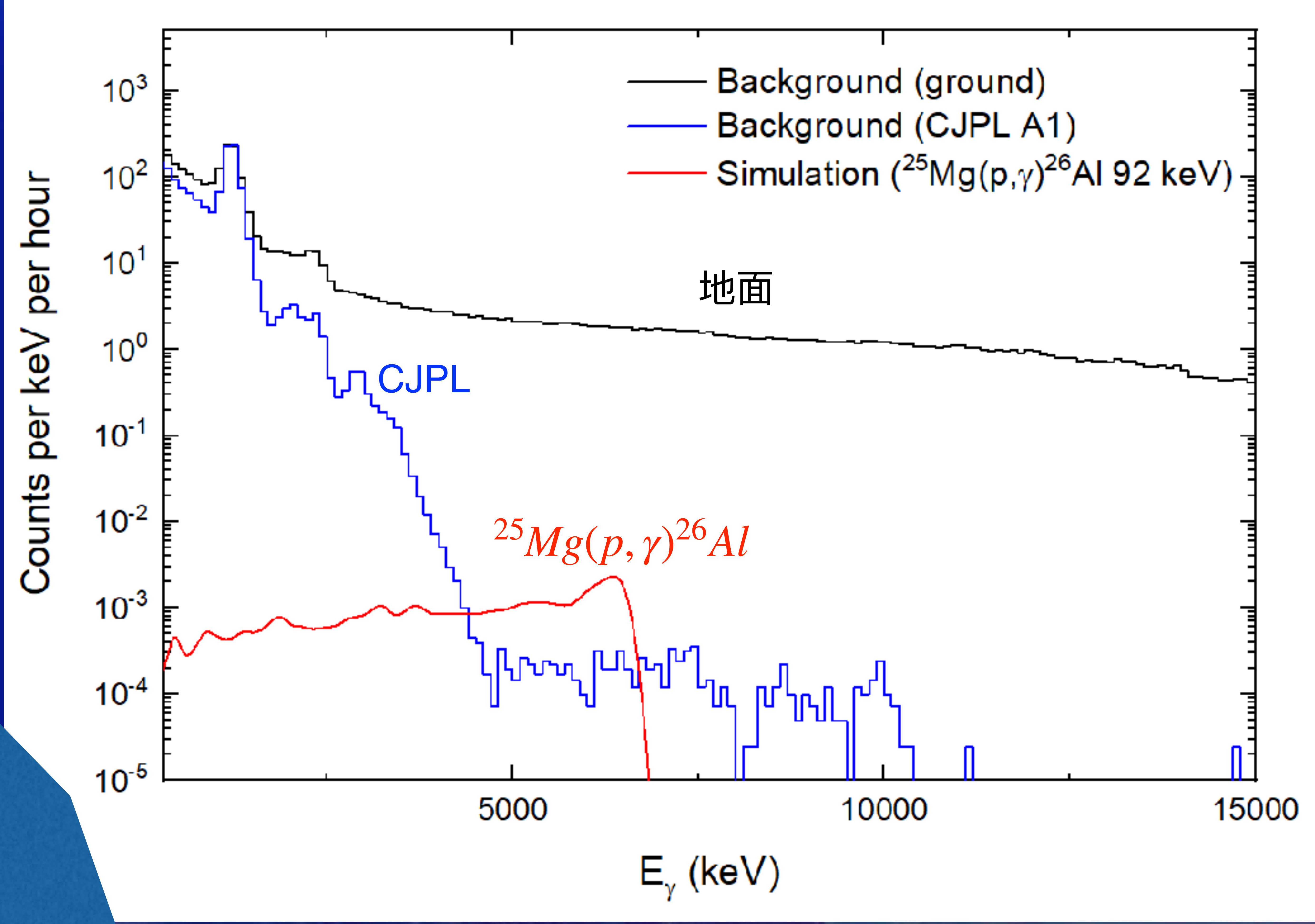


- 来自宇宙的高能射线会在实验仪器上留下大量的痕迹，如同刺耳的噪声，将真实的声音完全掩盖。
- 增加信号，降低噪声（深地实验）

需要大海捞针 Why underground





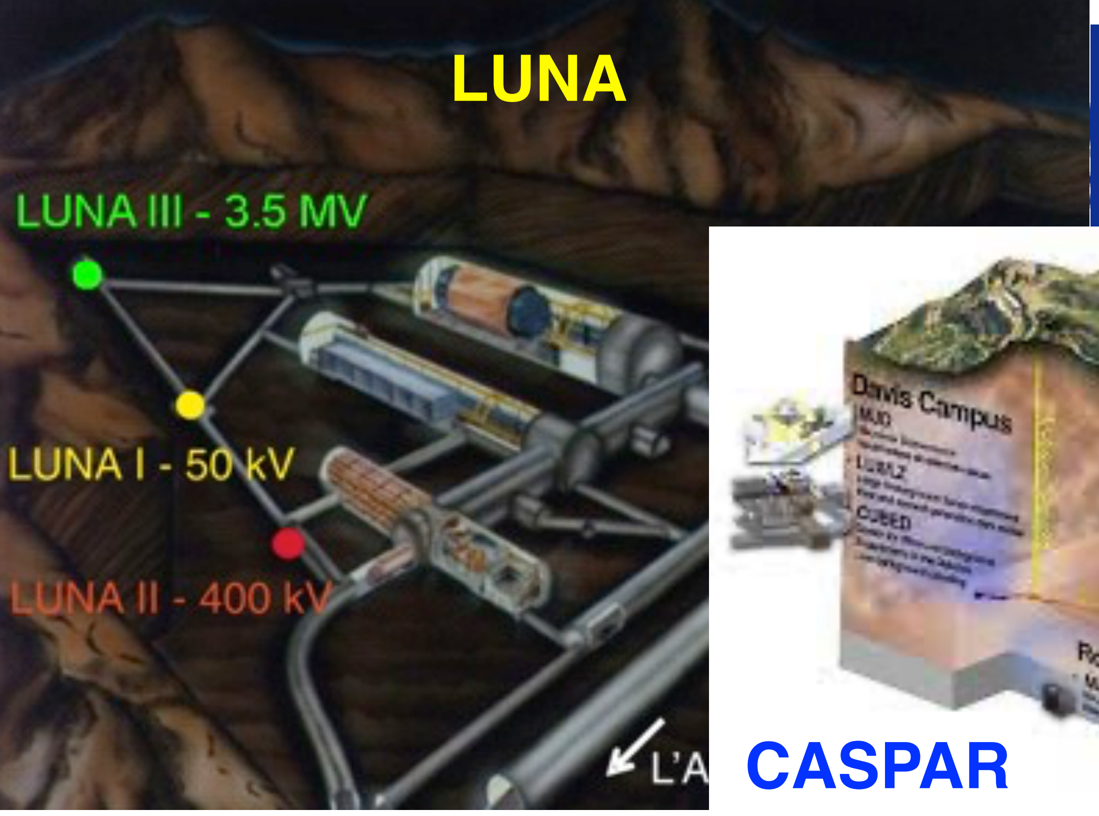


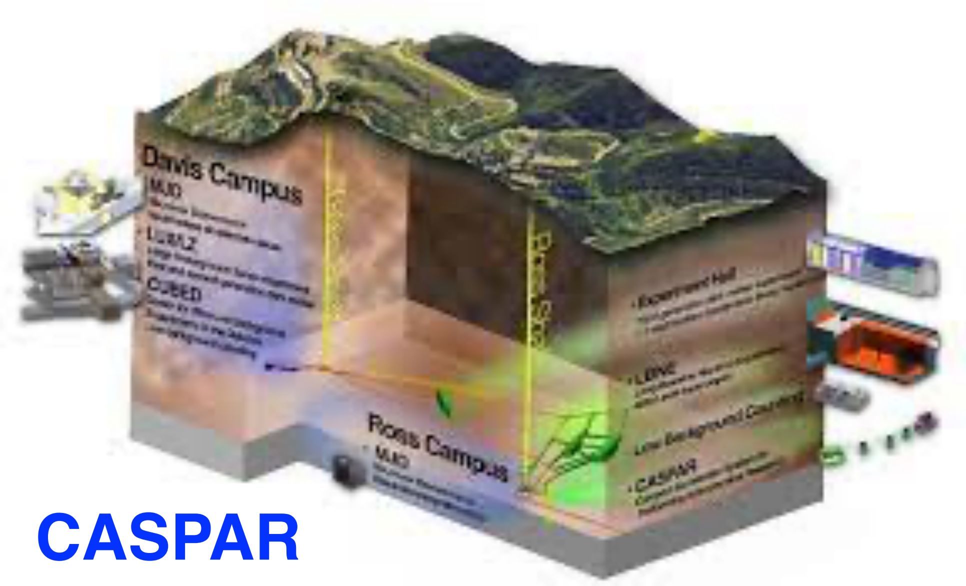
WPL et al., Sci. China 59(2016)2

简单的算术题：圣杯反应$^{12}C(\alpha,\gamma)^{16}O$

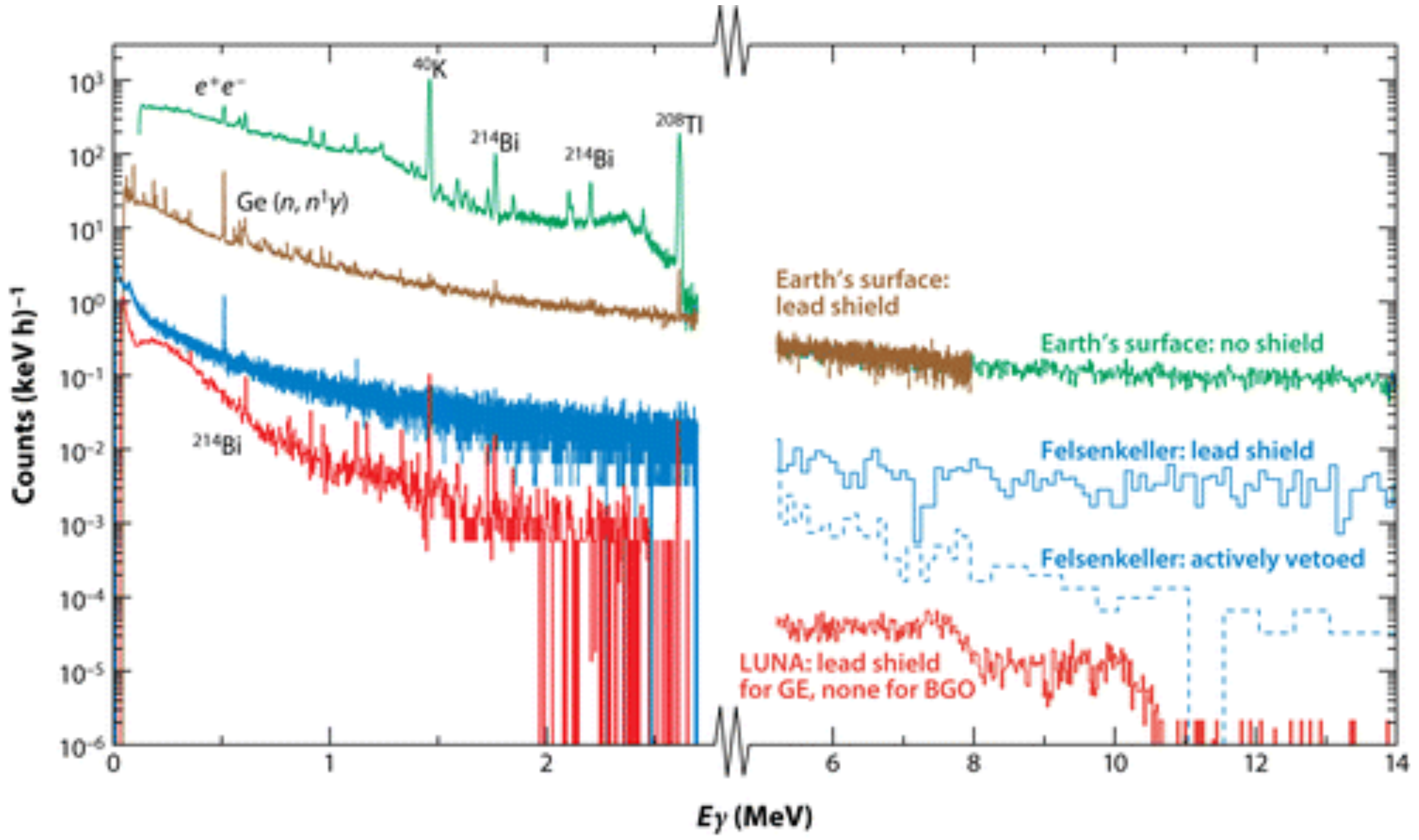
- 离子束流强度1毫安：$10^{-3} \times 10^{19} = 10^{16}$，每秒1亿亿个离子打到反应靶上
- 反应靶的厚度：10^{18}个碳原子核每平方厘米（12克 ^{12}C所含的原子（核）数量：6×10^{23}个）
- 反应的概率：10^{-12}靶恩=10^{-36}核反应每次碰撞
- 探测器的效率：10%
- 每秒钟的核反应数：$10^{16} \times 10^{18} \times 10^{-36} \times 0.1 = 0.001$次
- 每天观测到的核反应数：～100个 （10^{-21}克氧）
- 每天地面的宇宙射线数：~10 万个
- 每天锦屏的剩余本底数：~10 个

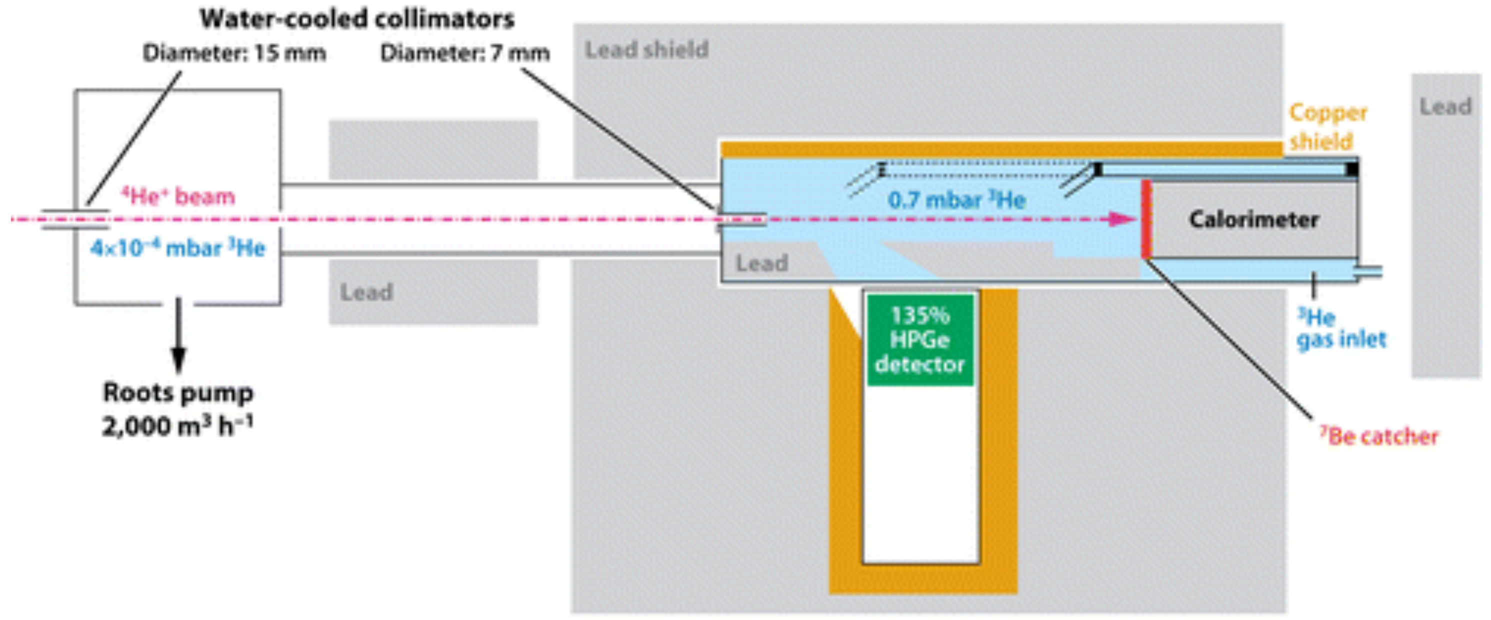
LUNA and CASPAR nuclear astrophysics



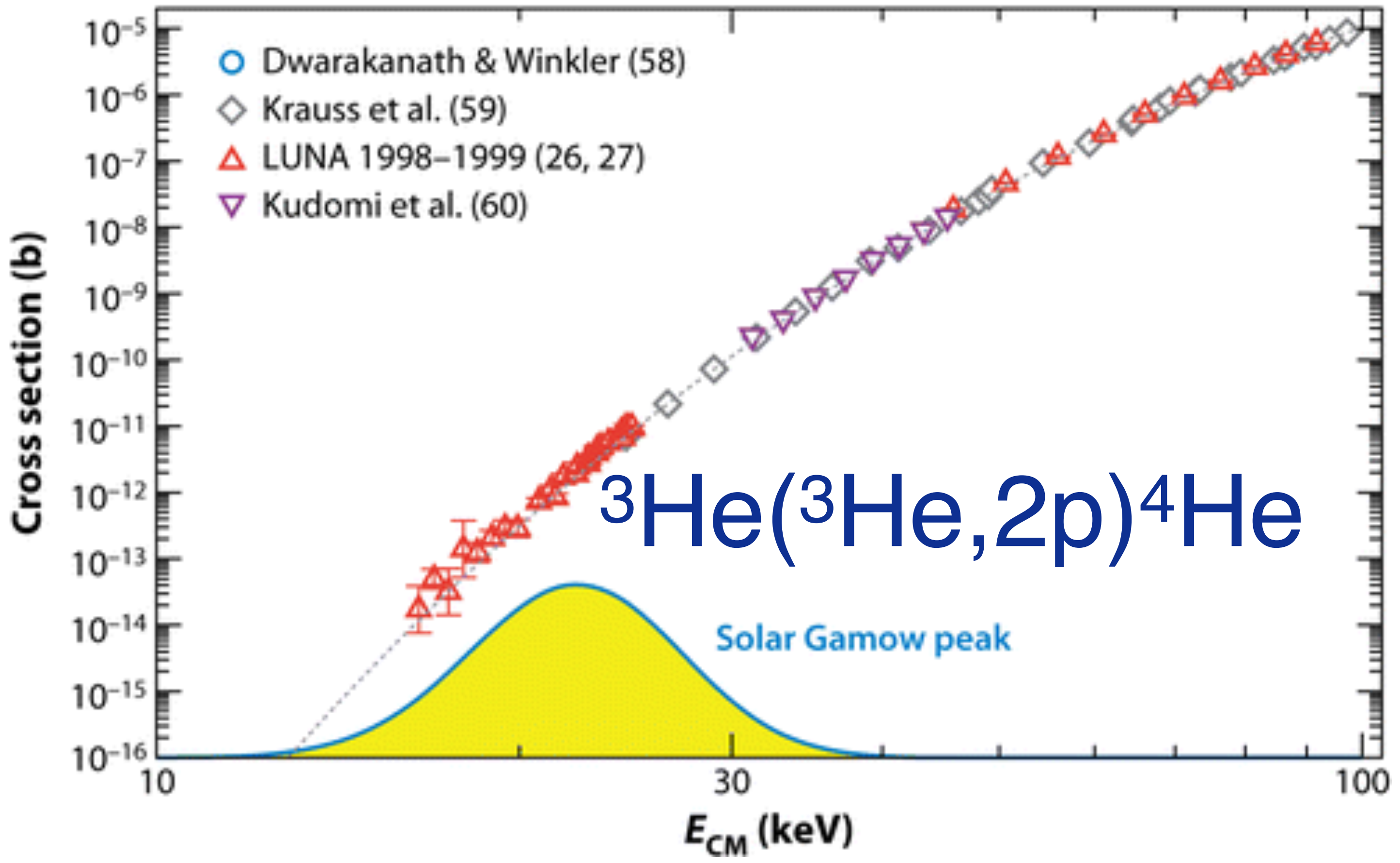


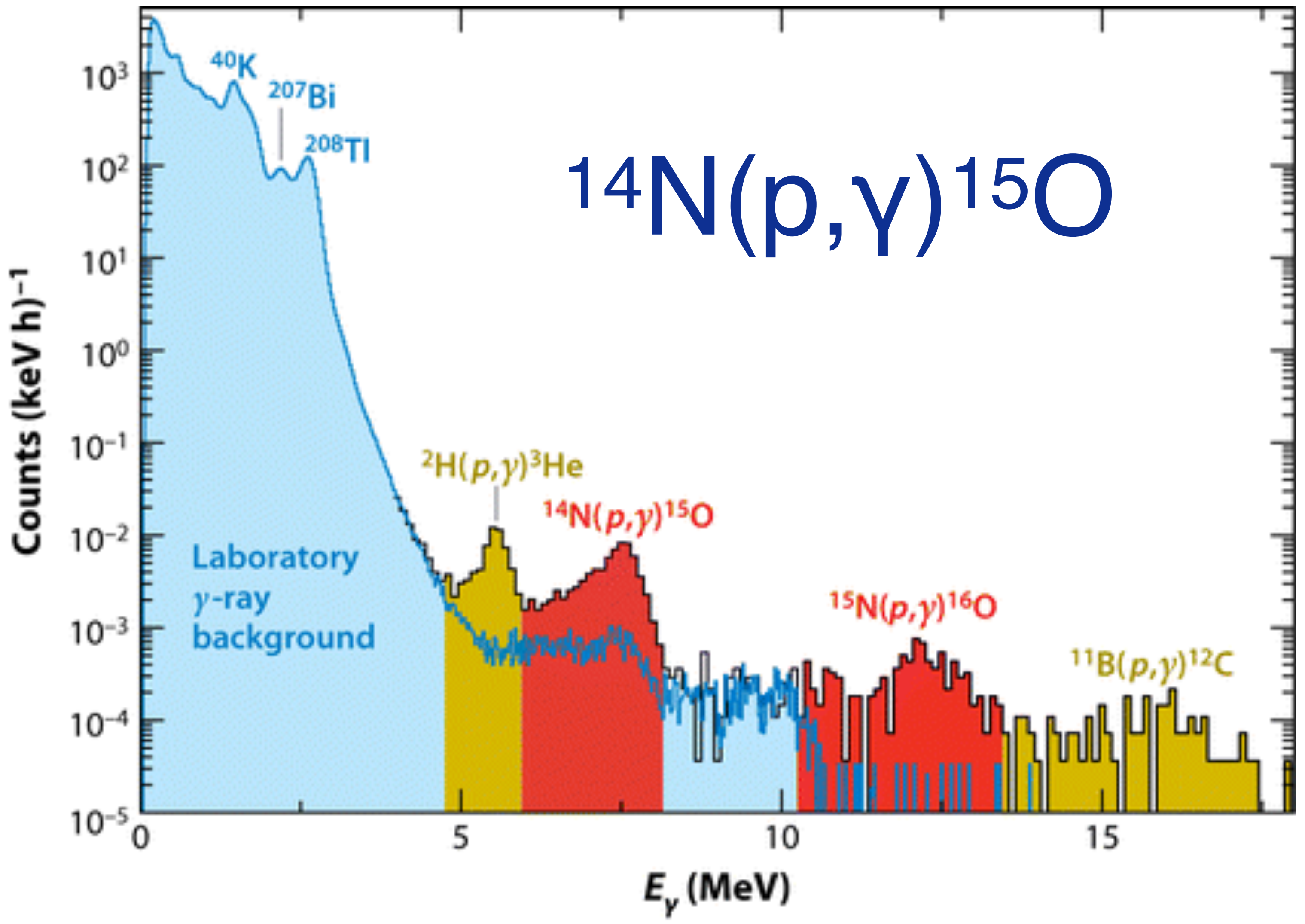
F. Cavanna et al., PRL 115(2015)252501, $^{22}Ne(p,\gamma)^{23}Na$.
F. Ciani et al. PRL 127(2021)152701, $^{13}C(\alpha,n)^{16}O$
V. Mossa et al., Nature 587(2020)210 , $D(p,\gamma)^{3}He$
A. C. Dombos et al., PRL 128(2022)162701, $^{18}O(\alpha,\gamma)^{22}Ne$





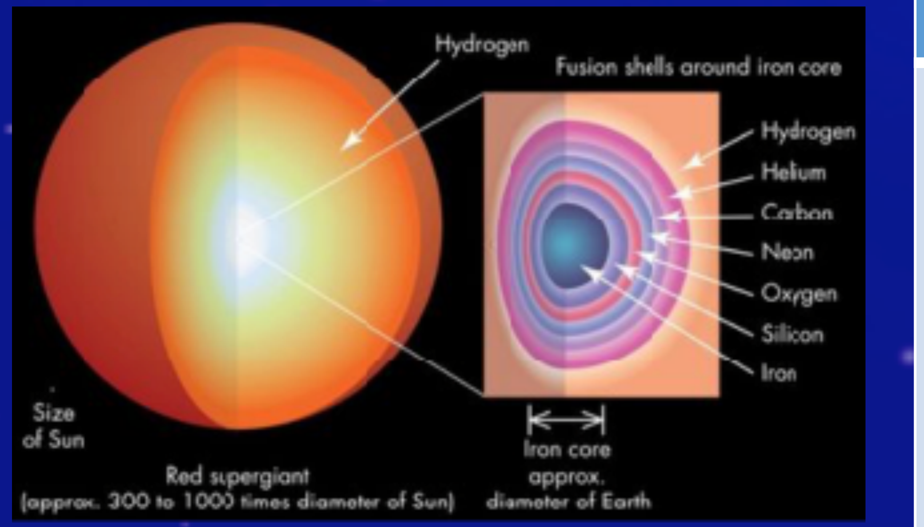
Broggini C, et al. 2010.
Annu. Rev. Nucl. Part. Sci. 60:53–73

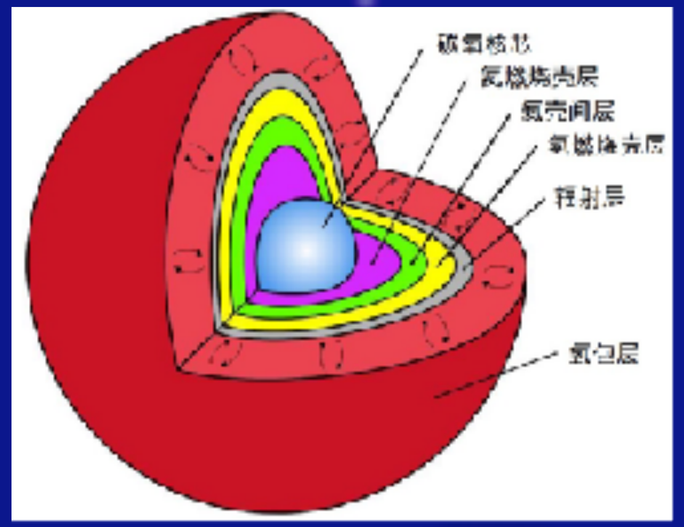


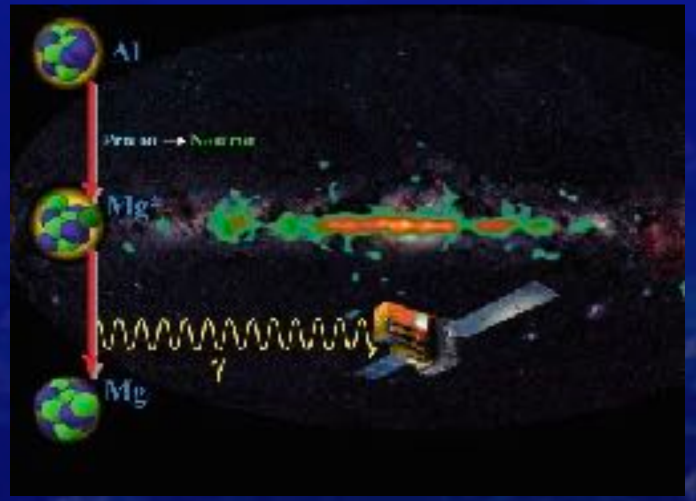


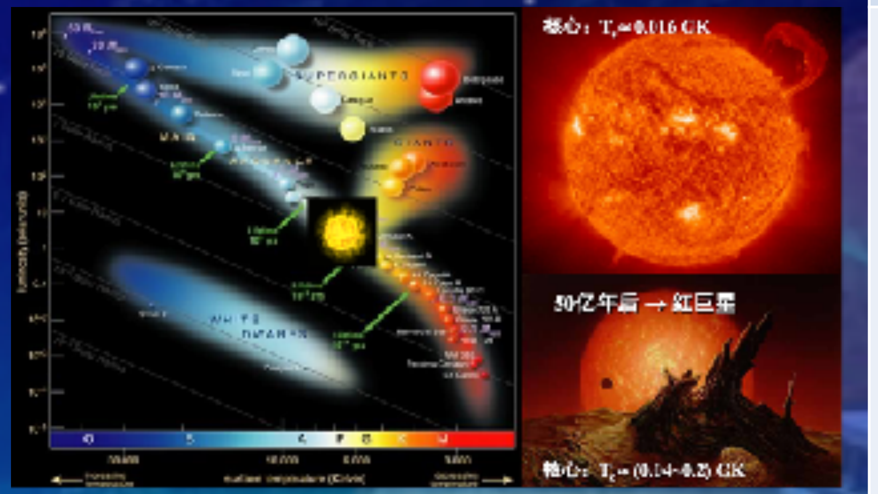
$^{3}He(^{3}He,2p)^{4}He$
PRL82(1999)5205
$^{2}H(^{3}He,p)^{4}He$
PLB482(2000)43
$^{2}H(p,\gamma)^{3}He$
NPA 706(2002)203
$^{3}He(\alpha,\gamma)^{7}Be$
PRL 97(2006)122502
$^{14}N(p,\gamma)^{15}O$
PLB 591(2004)61
$^{15}N(p,\gamma)^{16}O$
PRC82, 055804(2010)
$^{17}O(p,\gamma)^{18}F$
PRL 109, 202601(2012)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

Uncertainty remained for key reactions 天时

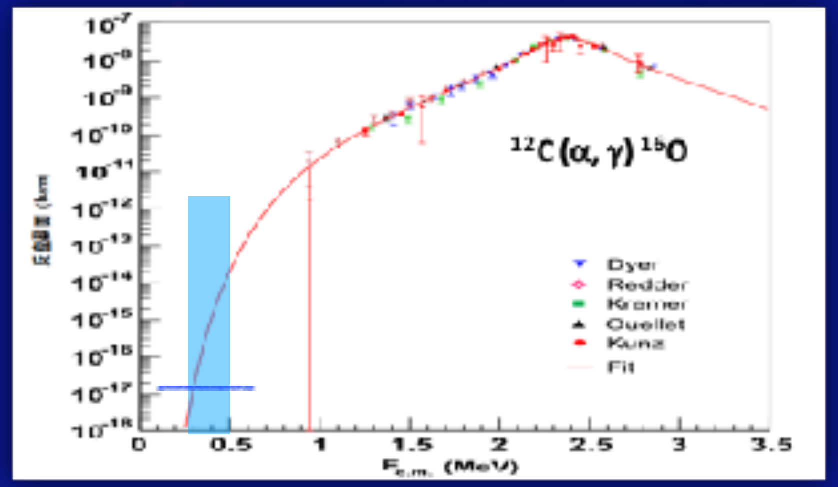




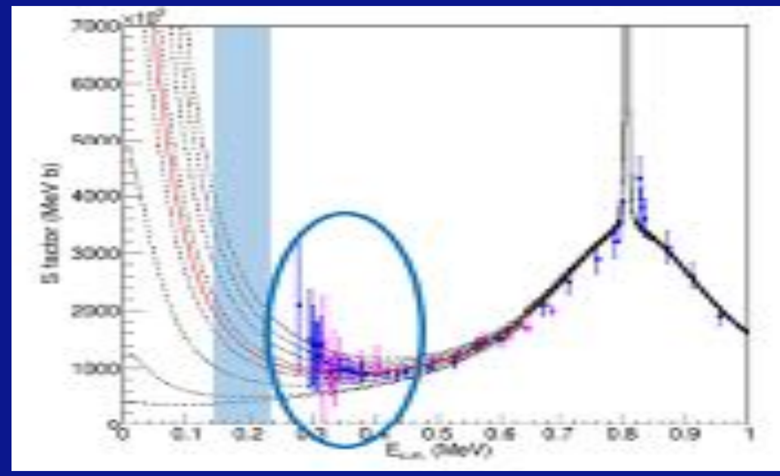




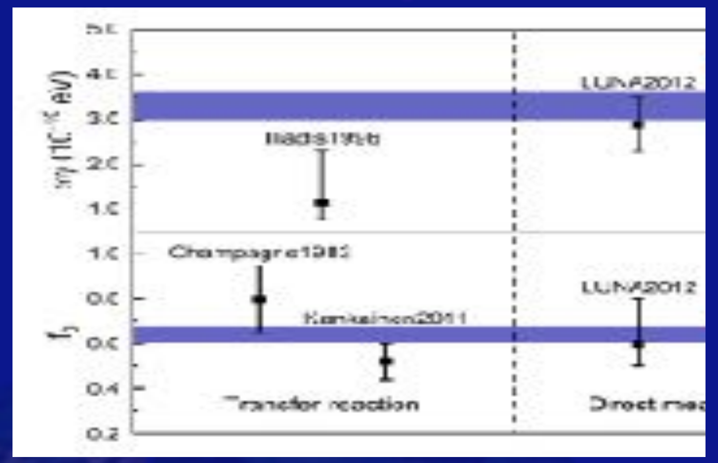
Physics	Reaction	Current	Desired
Massive star	$^{12}C(\alpha,\gamma)^{16}O$	60% 890 keV	20% 220-380 keV
s-process neutron source	$^{13}C(\alpha,n)^{16}O$	60% 230 keV	10% 140-230 keV
Galaxy ^{26}Al source	$^{25}Mg(p,\gamma)^{26}Al$	20% 92 keV	5% 50-300 keV
F aboundace	$^{19}F(p,\alpha)^{16}O$	80 % 189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



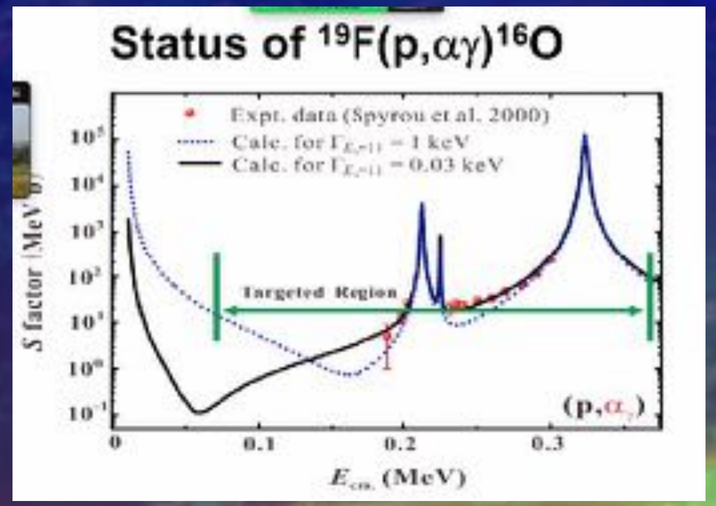
R. J. deBoer et al., RMP vol. 89, 2017



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



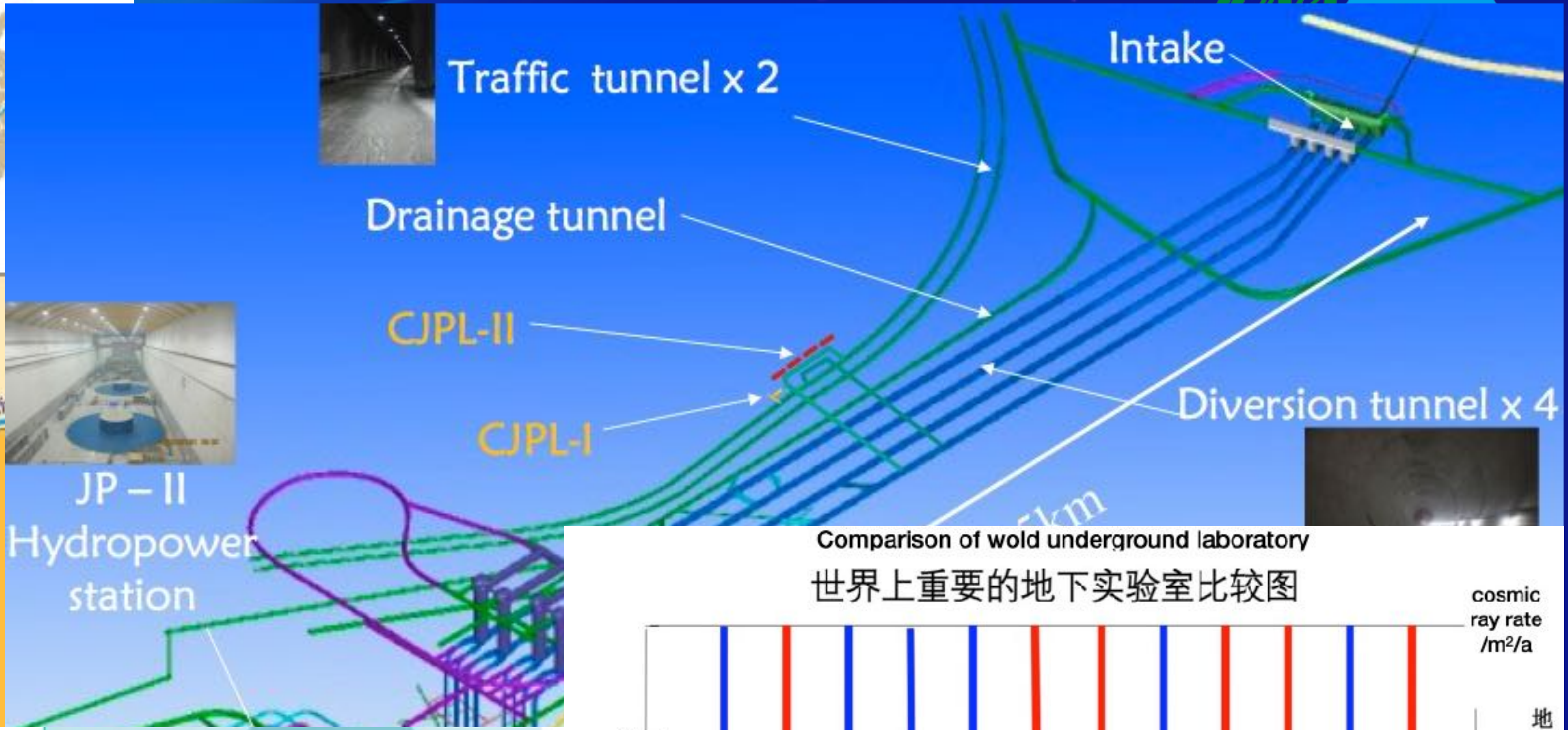
G.F. Ciani et al. PRL 127(2021)152701

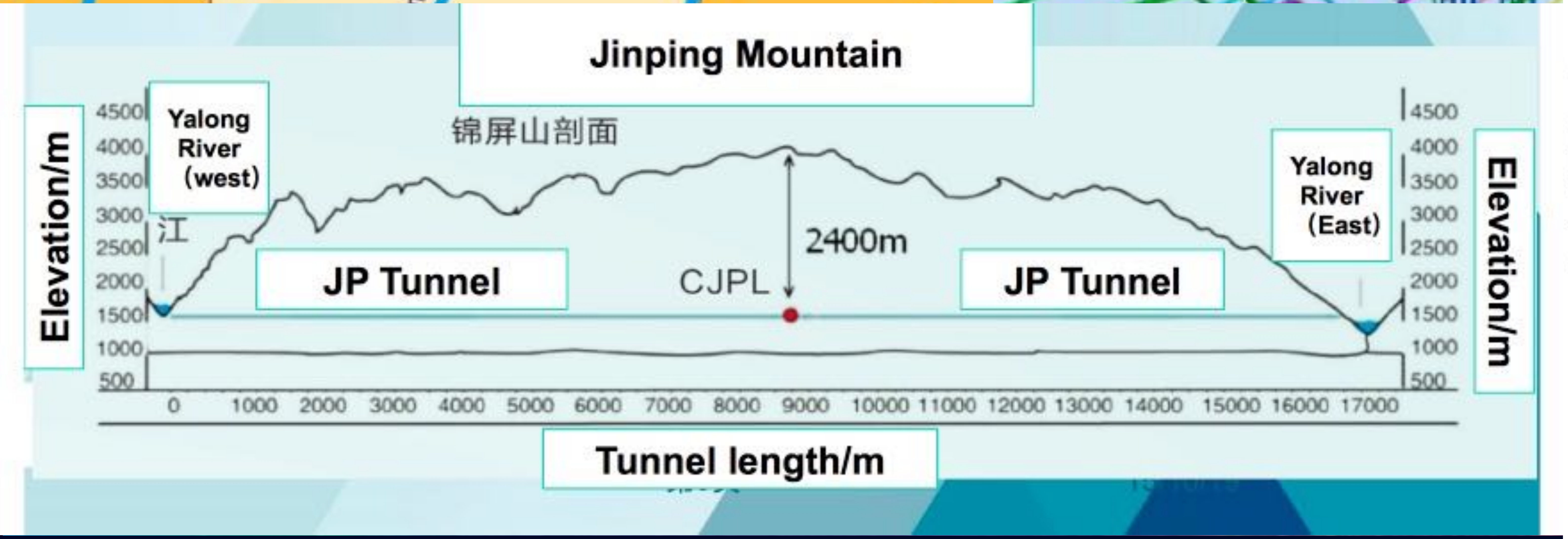


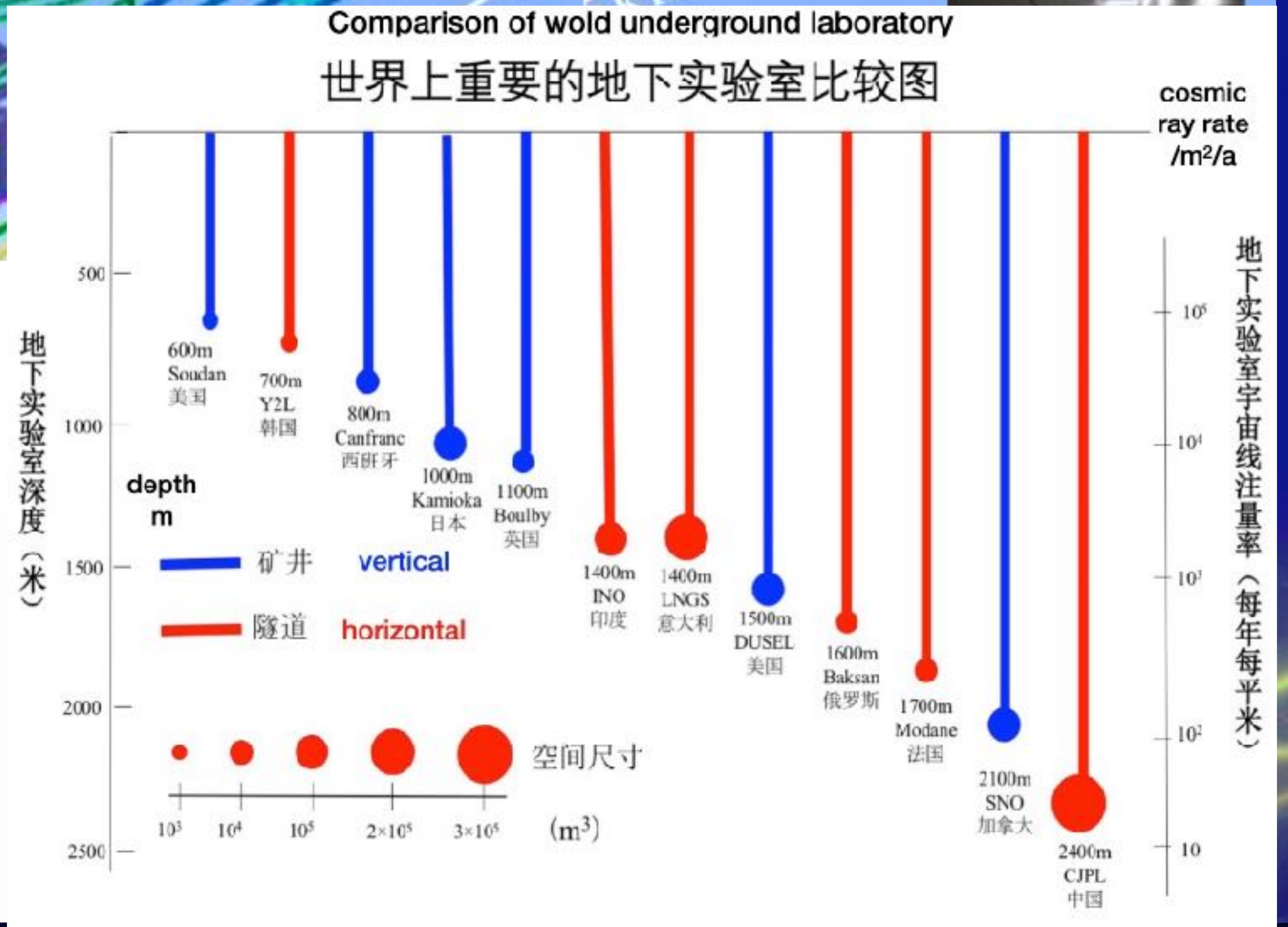
J. J. He et al., Sci. China Phys 59 (2016) 652001

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

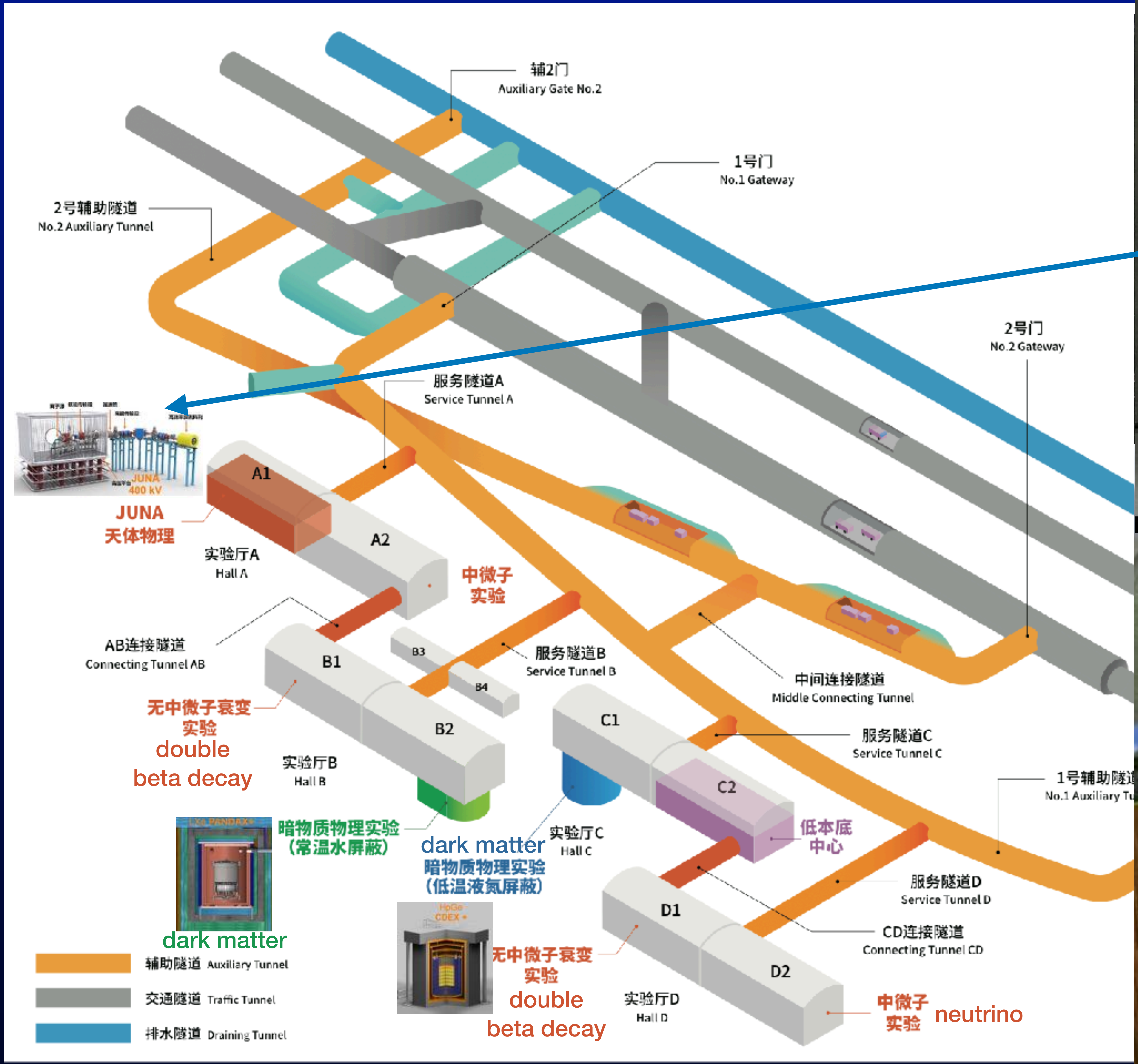
China Jinping: CJPL







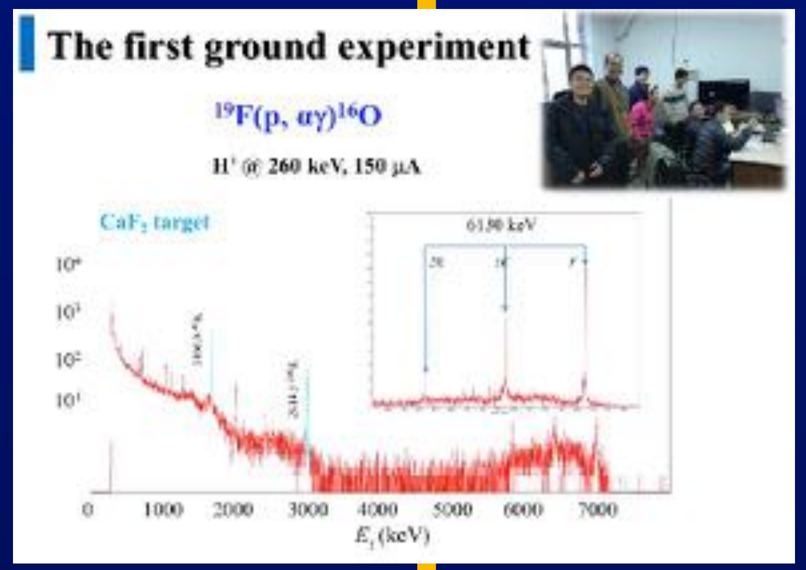
Most silent location: CJPL



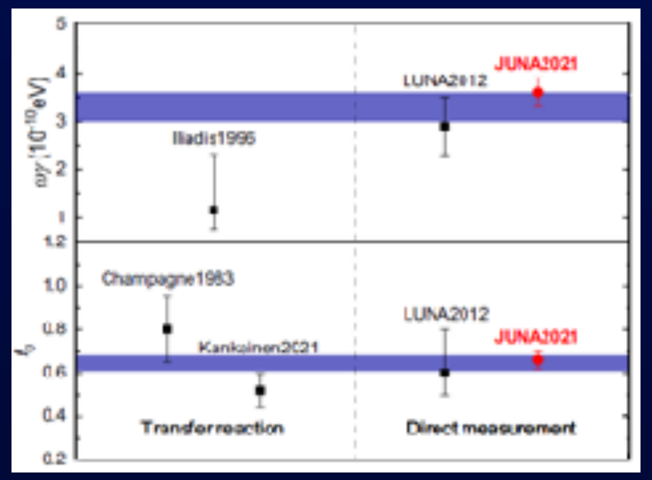
JUNA accelerator setup 火神山速度

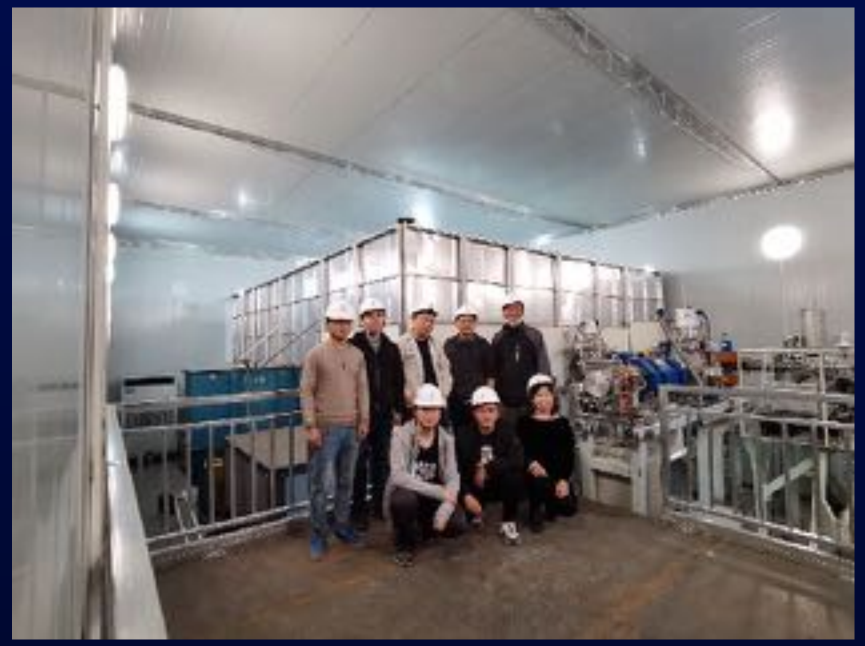
JUNA Milestone

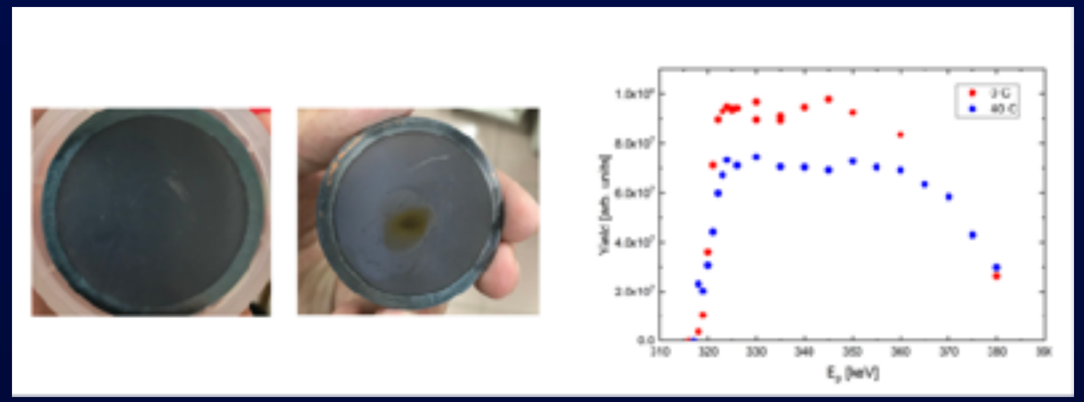
Aug. 2013 Startup meeting → **Jan. 2015** Project inauguration → **Mar. 2016** On site start → **May 2017** Beam on ground → **Dec. 2017** 3 mA on ground

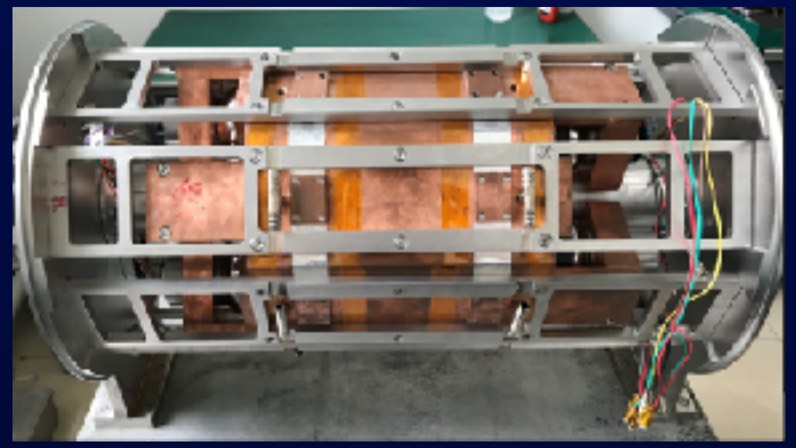


Dec. 2018 Der. Ready Beam 10 mA → **April 2019** Target ready Acc. Ready → **Dec. 2020** Beam underground → **May 2021** ^{25}Mg, ^{19}F, ^{13}C and ^{12}C data ready → **Dec. 2021** Project commission



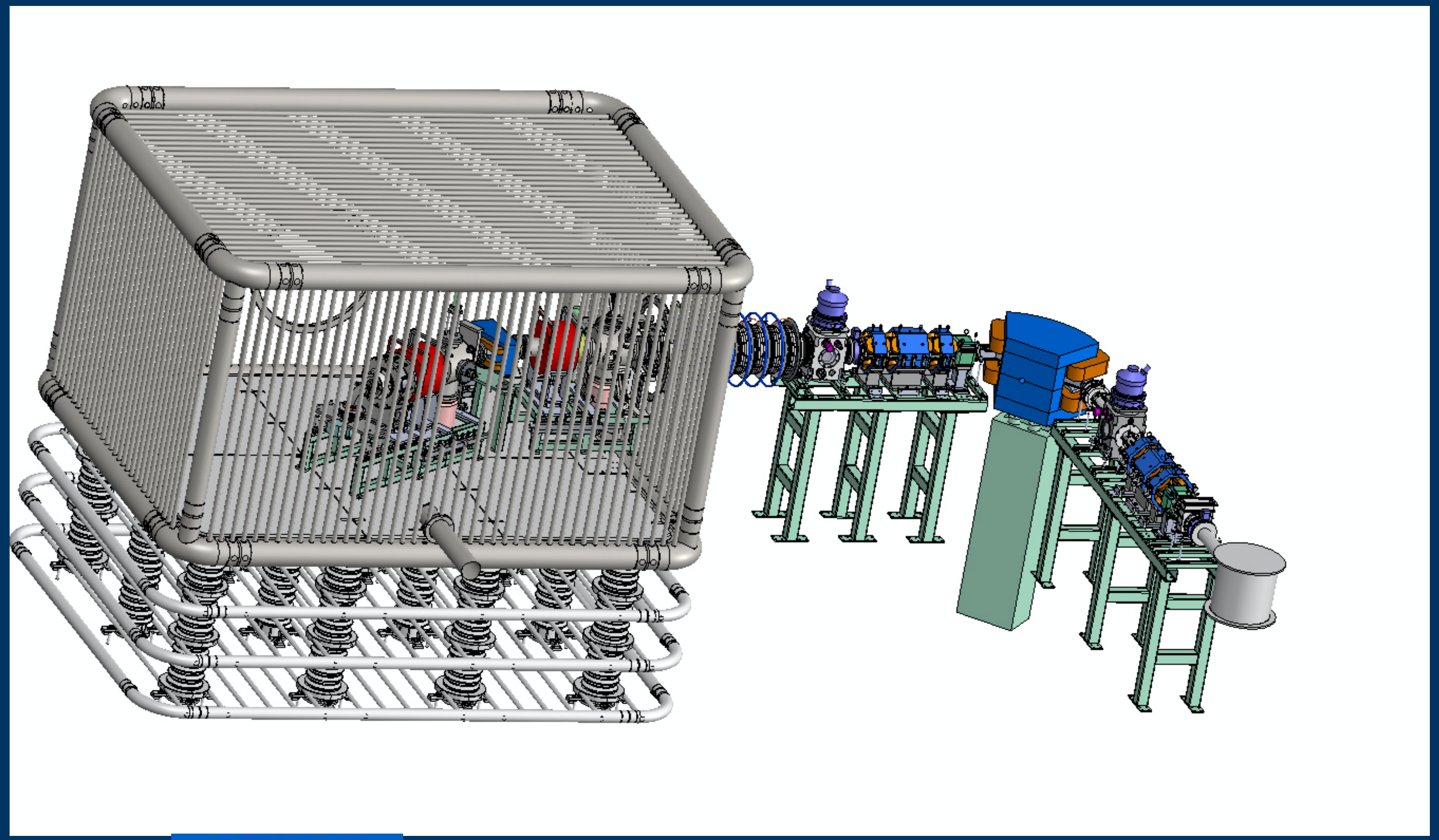






WPL et al., Sci. China 59(2016)2

JUNA dream team



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

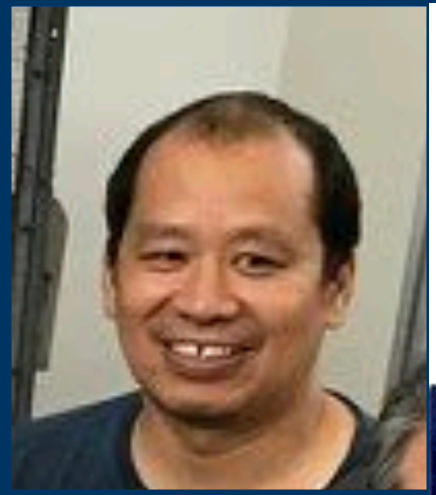
Shuo Wang
$^{14}N(p,\gamma)^{15}O$
SDU

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

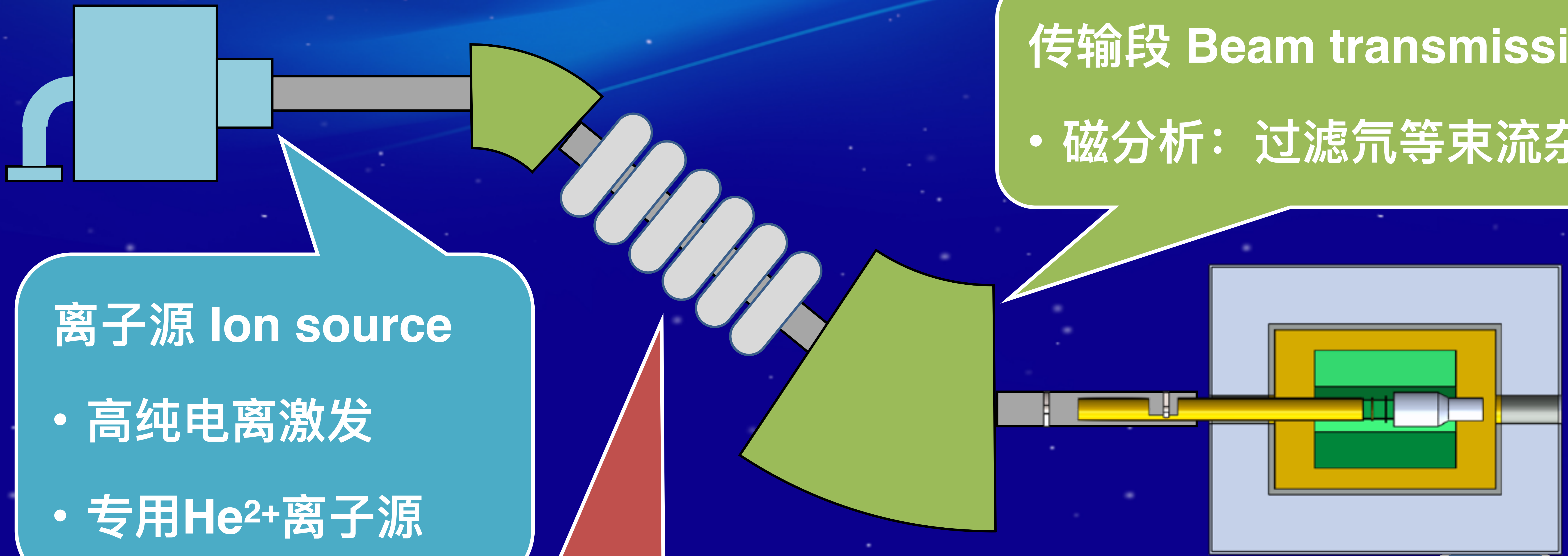
中国科学院
CHINESE ACADEMY OF SCIENCES

中核集团
CNNC

Need to apply for JUNA II and welcome international contribution

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

加速段 Accelerator tube
- 选用低本底材料
- 提高传输效率（>90%）

传输段 Beam transmission
- 磁分析：过滤氘等束流杂质

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

强流加速器技术 High intensity accelarator

离子源 Ion source

PI: L. T. Sun, IMP

实验需求		技术突破
地下空间小	→	紧凑永磁结构
毫安级高流强	→	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 Acc. tube

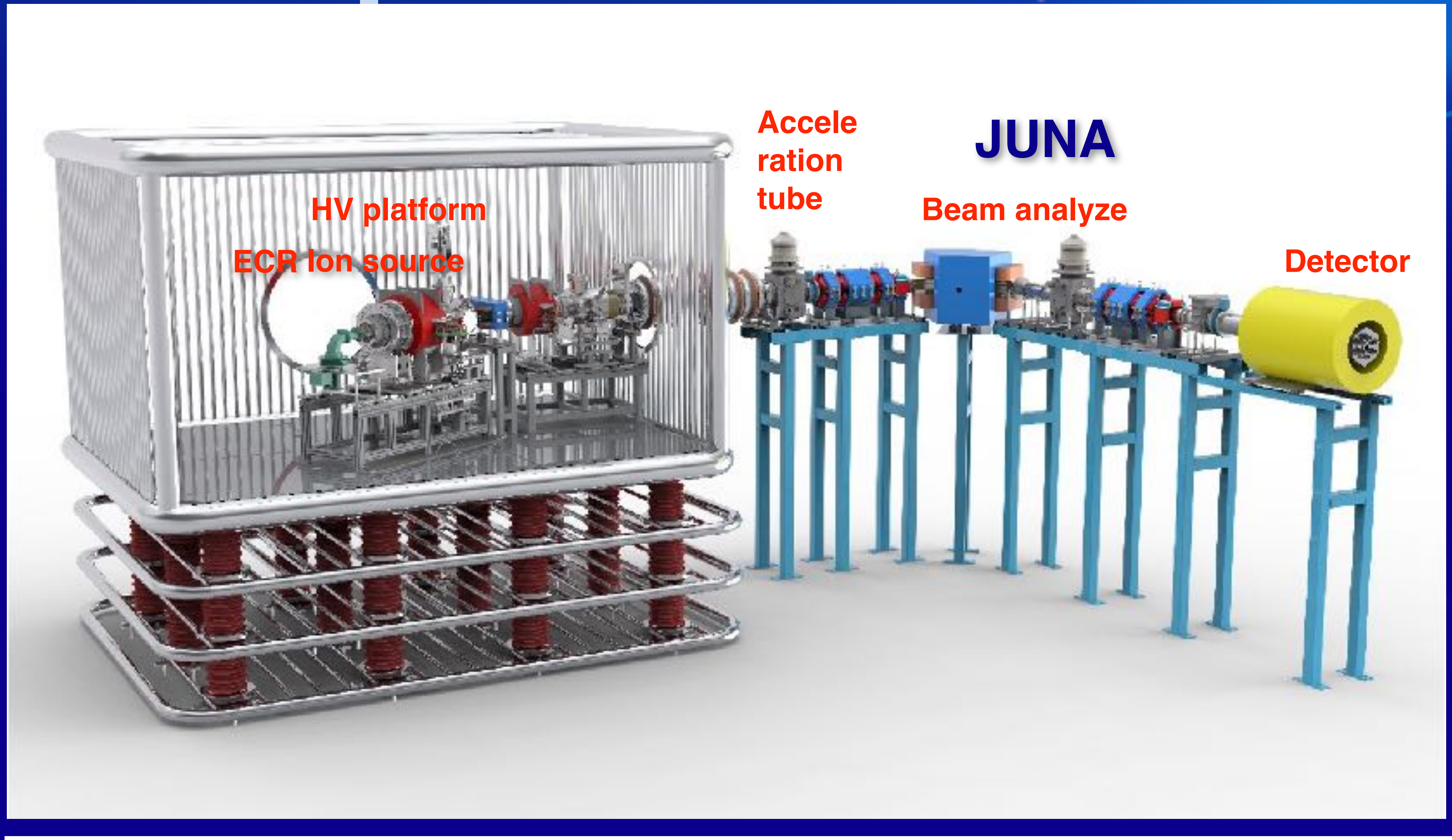
PI: B. Q. Cui, CIAE

实验需求		技术突破
克服空间电荷效应	→	短间隙大孔径加速
能量精确可调	→	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

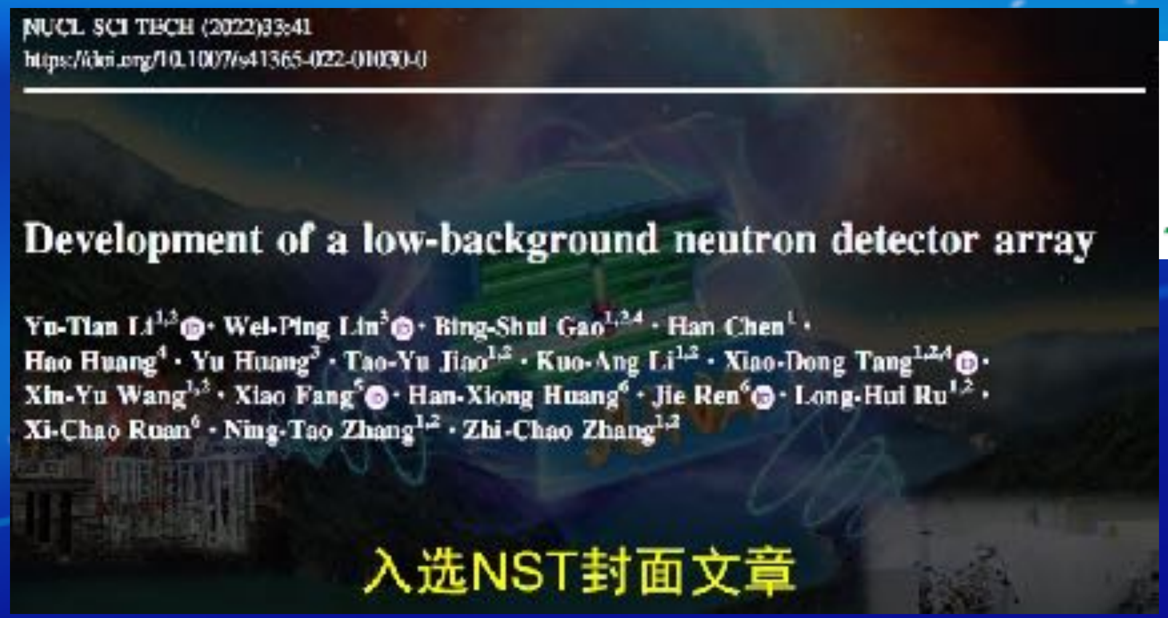
锦屏深地核天体物理实验
Jinping Underground Nuclear Astrophysics Experiment



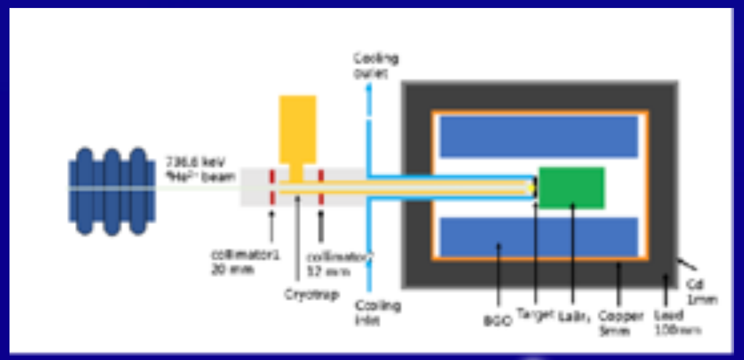
	cosmic μ bkg ($cm^{-2}\,s^{-1}$)	beam energy （keV）			beam intensity （emA）			energy stability
		H^+	He^+	He^{2+}	H^+	He^+	He^{2+}	
LUNA	2×10^{-8}	50-400	50-400	---	0.3~1	0.3~0.8	---	0.05%
CASPAR	4.4×10^{-9}	100-1000	100-1000	---	0.1	0.1	---	0.05%
JUNA	2×10^{-10}	50-400	50-400	100-800	10	10	2	0.04%

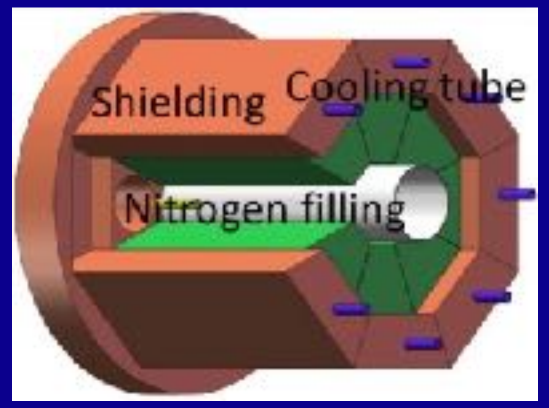
WPL et al., Sci. China 59(2016)2

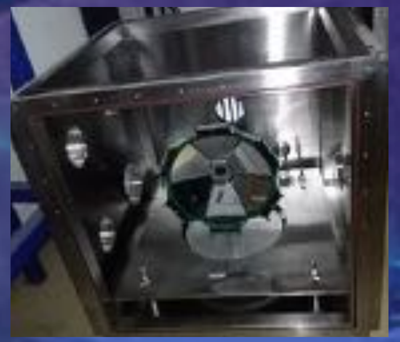
先进探测器技术
Detector tech.



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







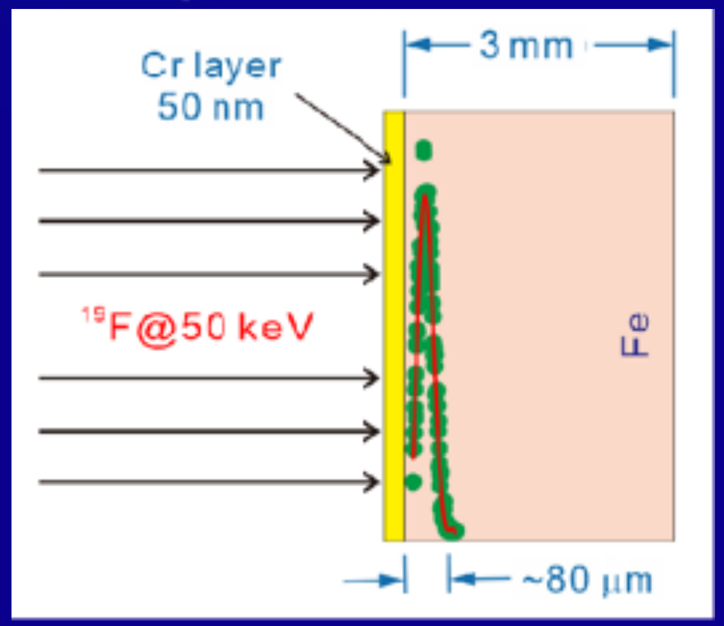
核反应 reaction	采用技术 technology	发表文章 publication	国外记录 world best	我们达到 JUNA
^{12}C	BGO+LaBr		down to 891 keV	down to 552 keV
^{25}Mg	BGO array X8	Atomic ST 52(2018)140	resolution17 %	11 %
^{13}C	^{3}He array X24	NST33(2022) 41, cover story	Exptripolation	Self consisitent
^{19}F	Charged particle array		170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

耐辐照反应靶技术 High durability target

耐辐照性是国际同类最好水平的3-10倍 3-10 times better than previous targets

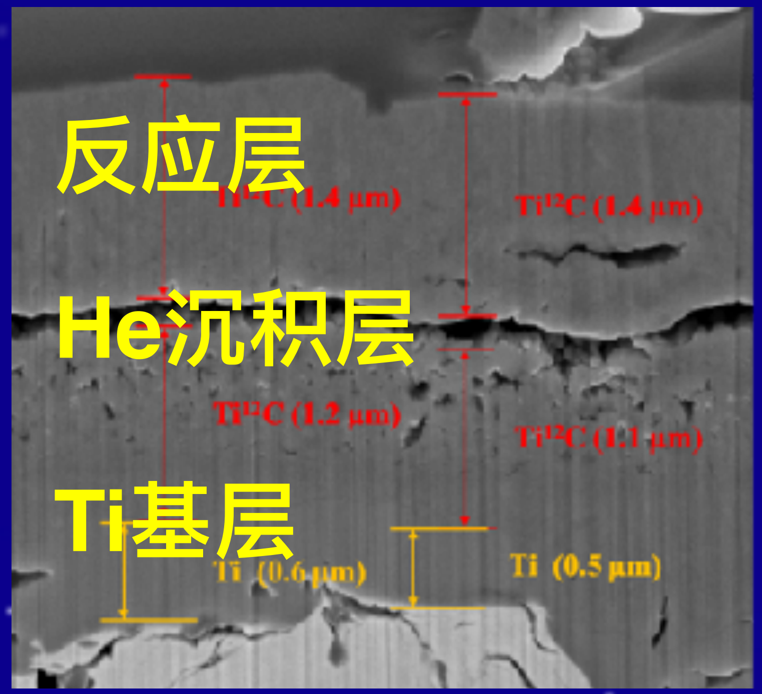
^{19}F注入靶技术 Implantation

- 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 Deposit target

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

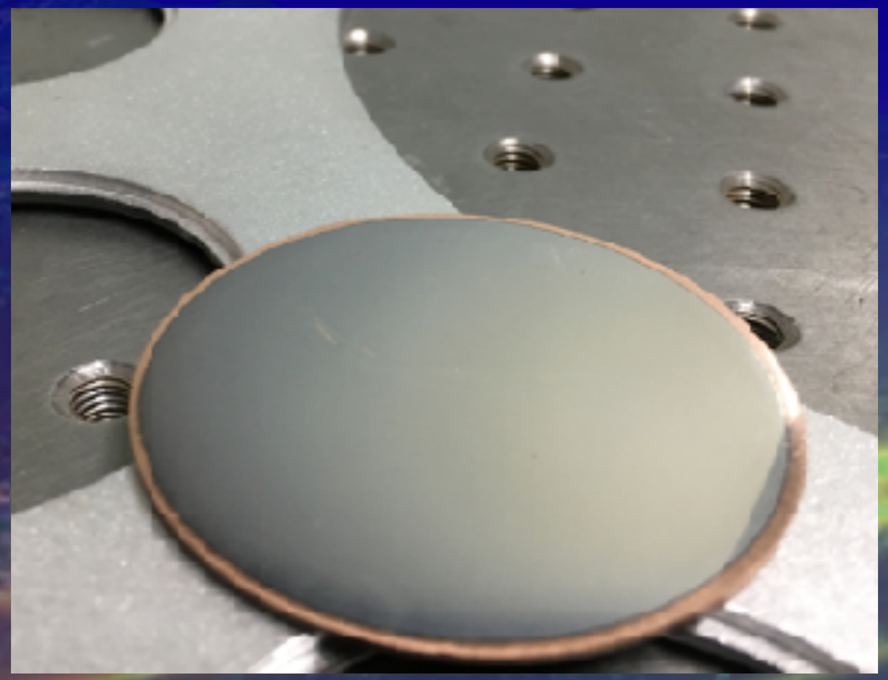


^{13}C同位素厚靶 Thick target

- 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 Hybrid layers

- Cr+Mg+Cr三明治结构
- 旋转蒸镀技术
- 耐辐照达300库仑



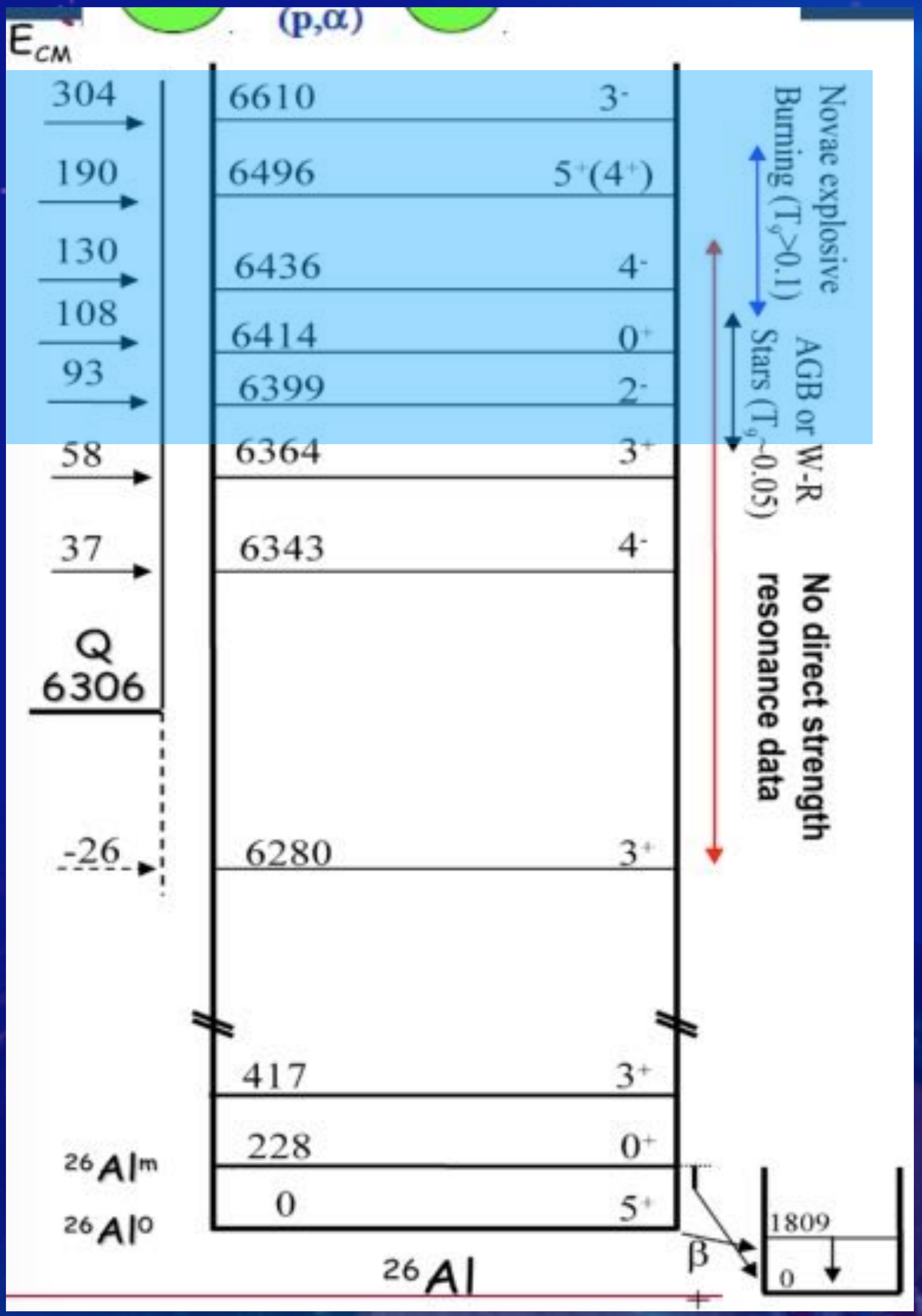
2020年12月26日， 锦屏地下实验室A1实验厅

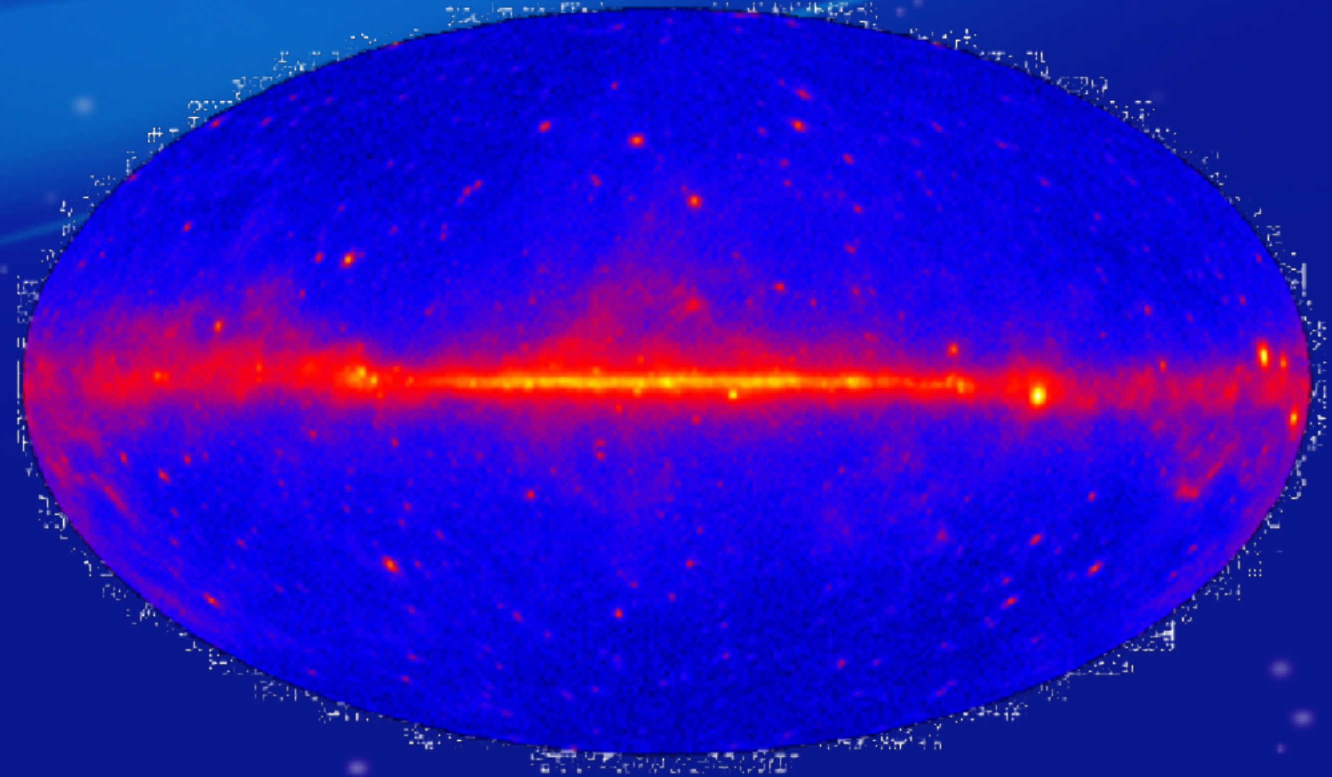
$^{25}Mg(p,\gamma)^{26}Al$ physics 伽马天文反应

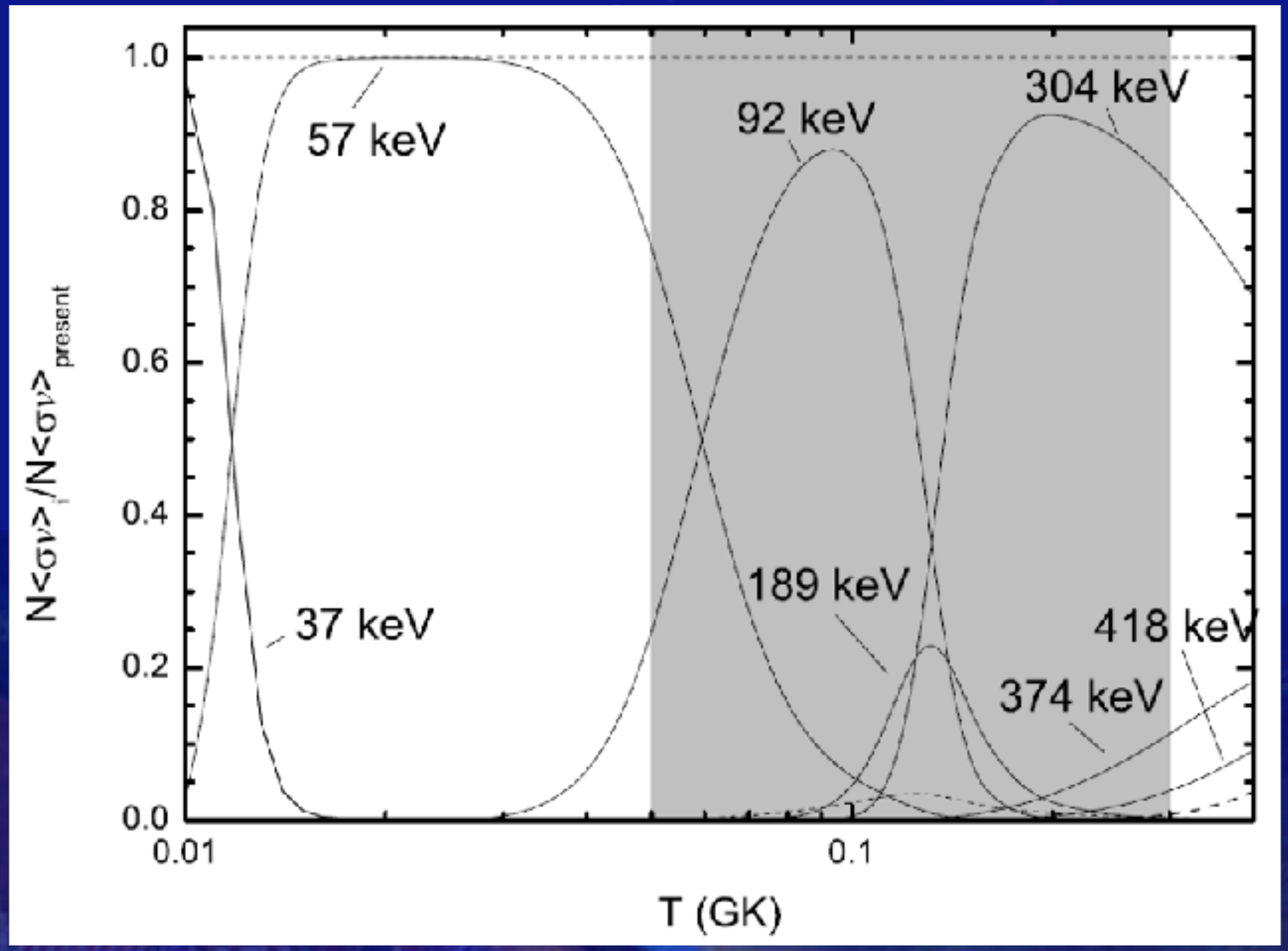
Exp.: Jan. 1-15, 2021

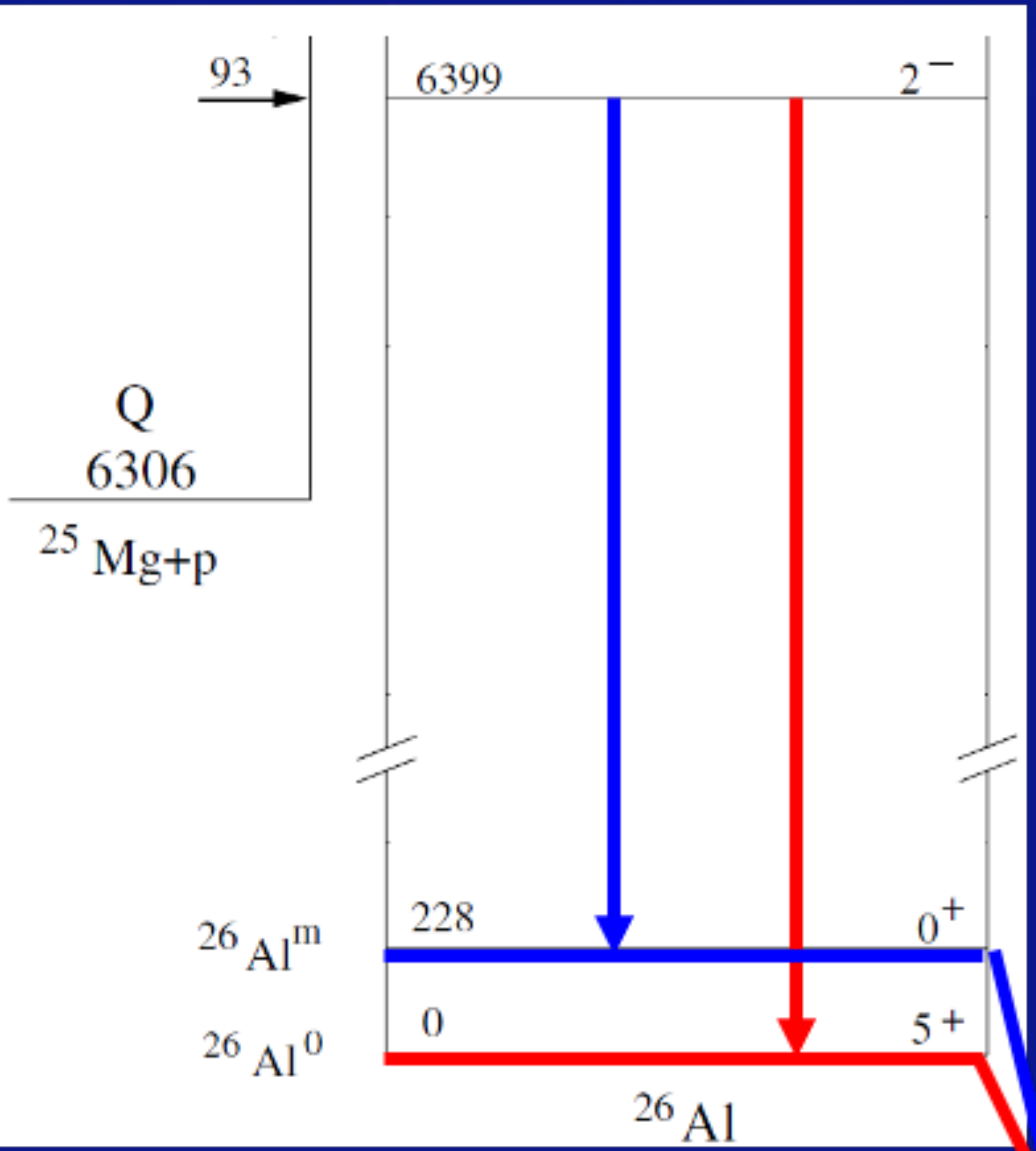
PI: Z. H. Li, CIAE

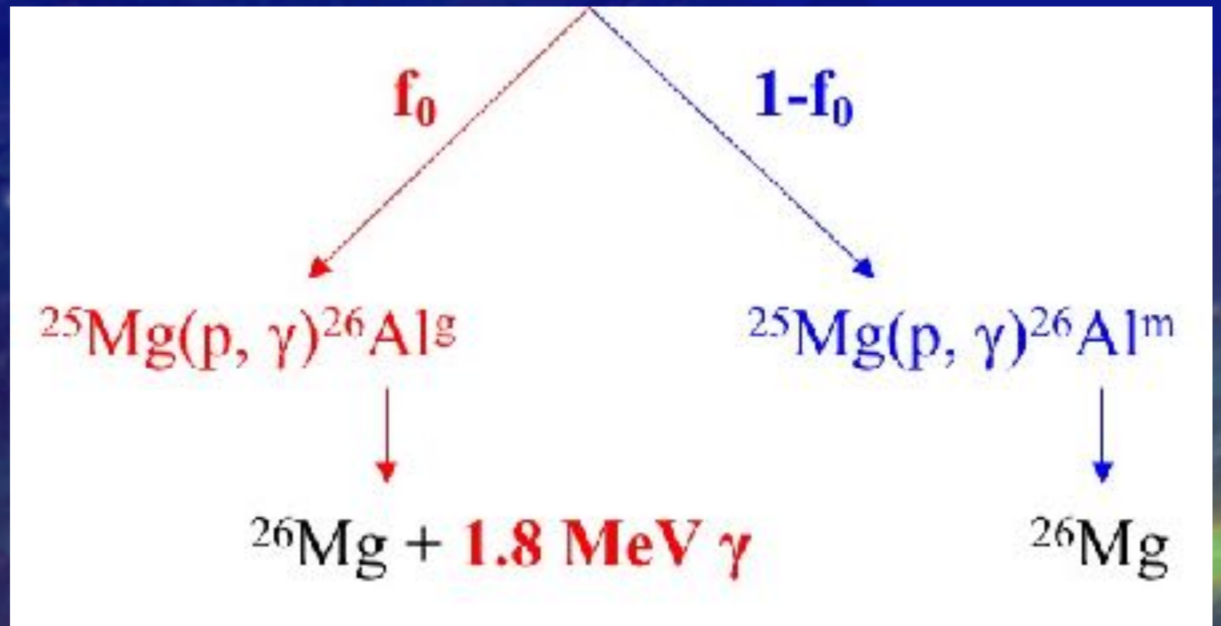
J. Su, CIAE/BNU







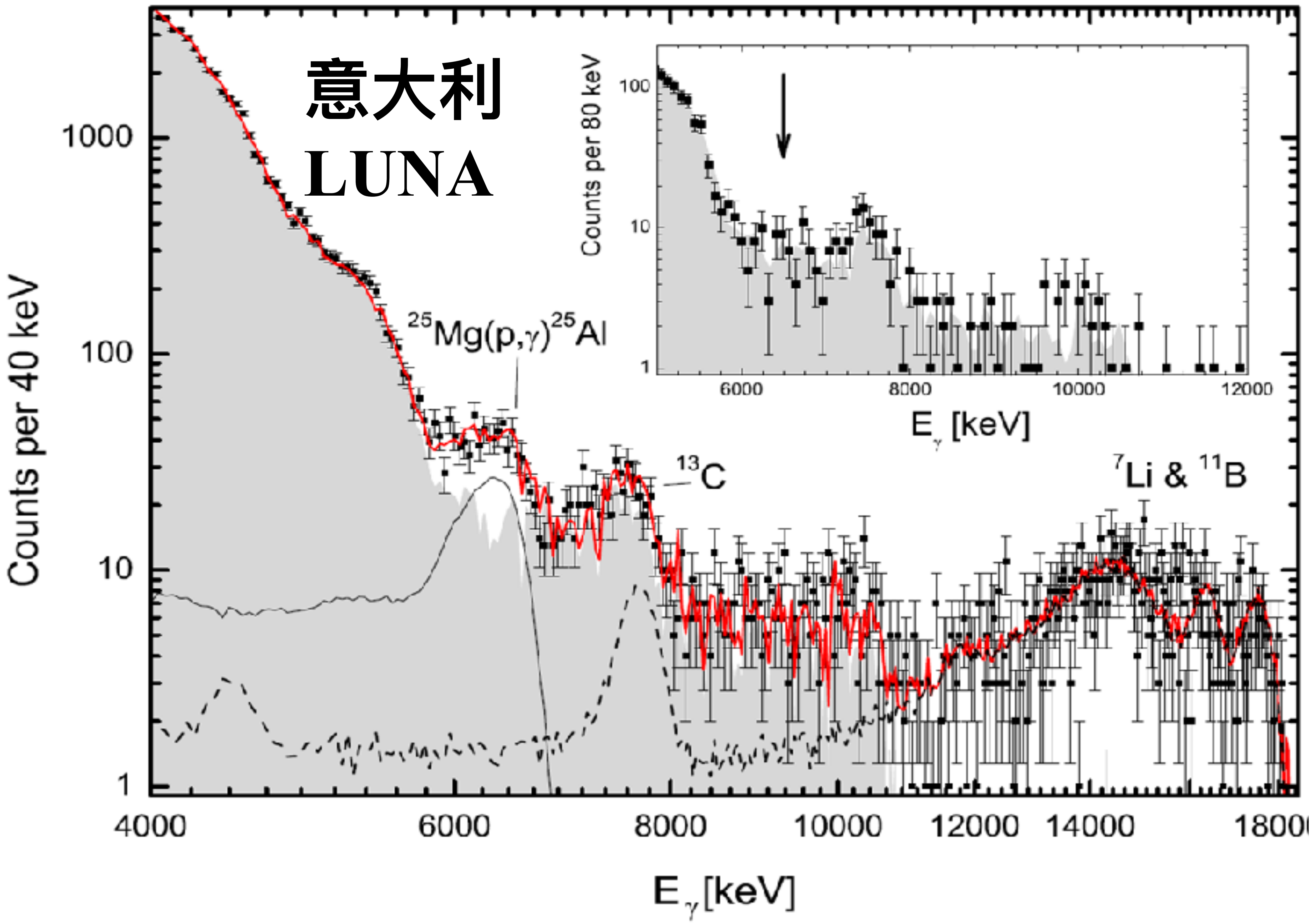


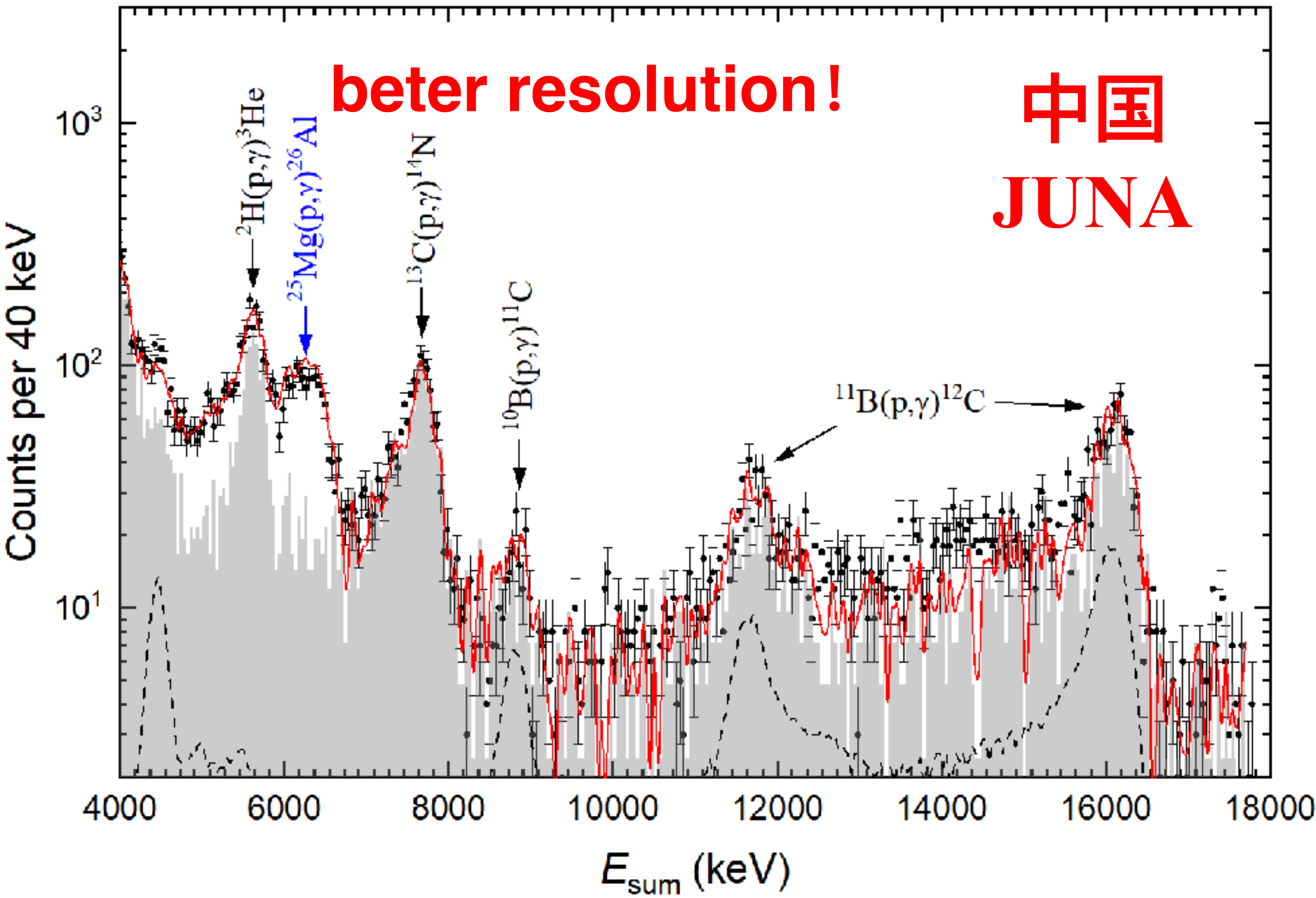


Z. H. Li et al., Sci. China Phys 58. 082002(2015), J. Su et al., Science Bulletin, 67(2022)2（封面文章）

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±0.6×10-10 eV

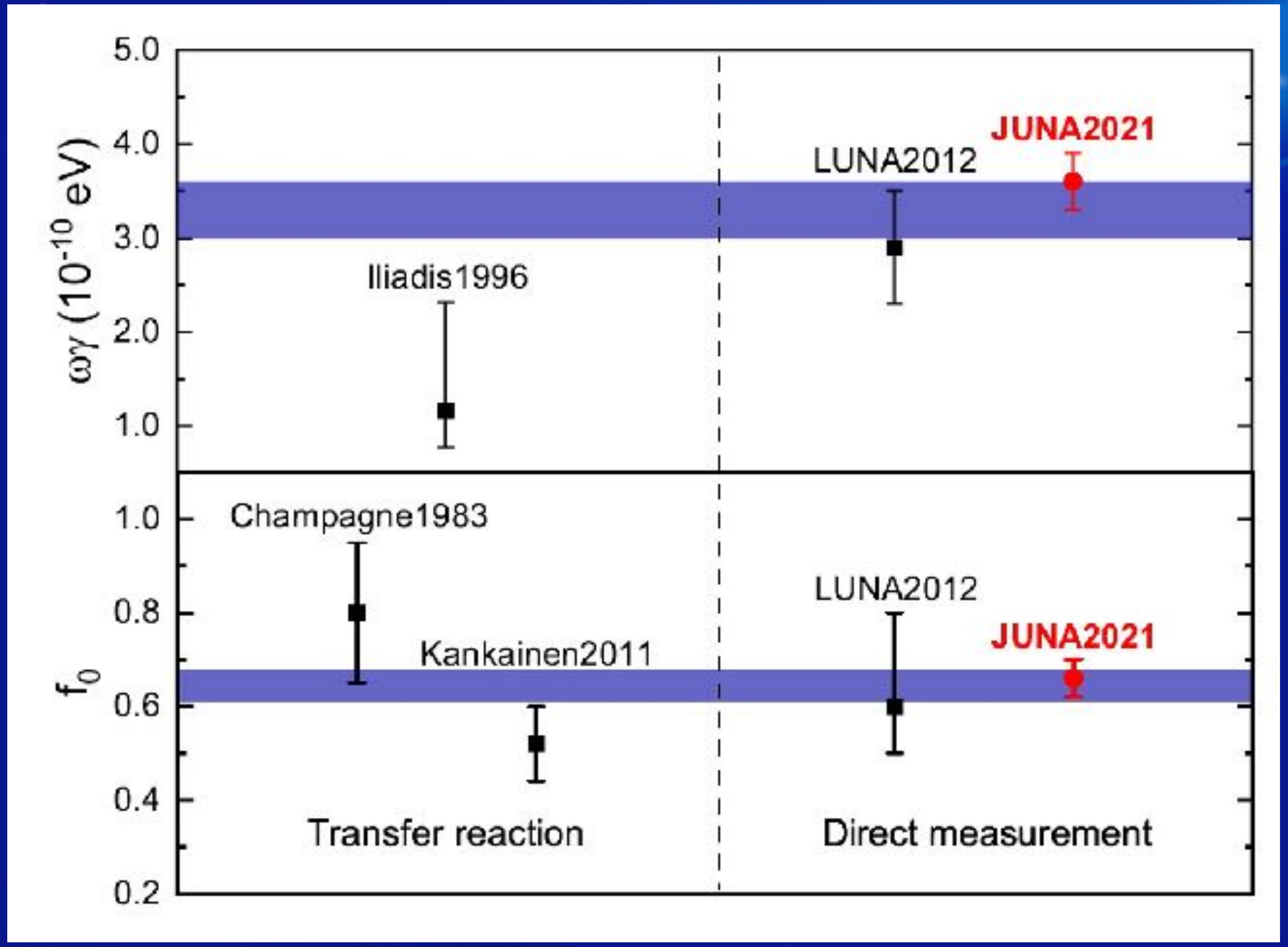
15days(S+N)，1008 C

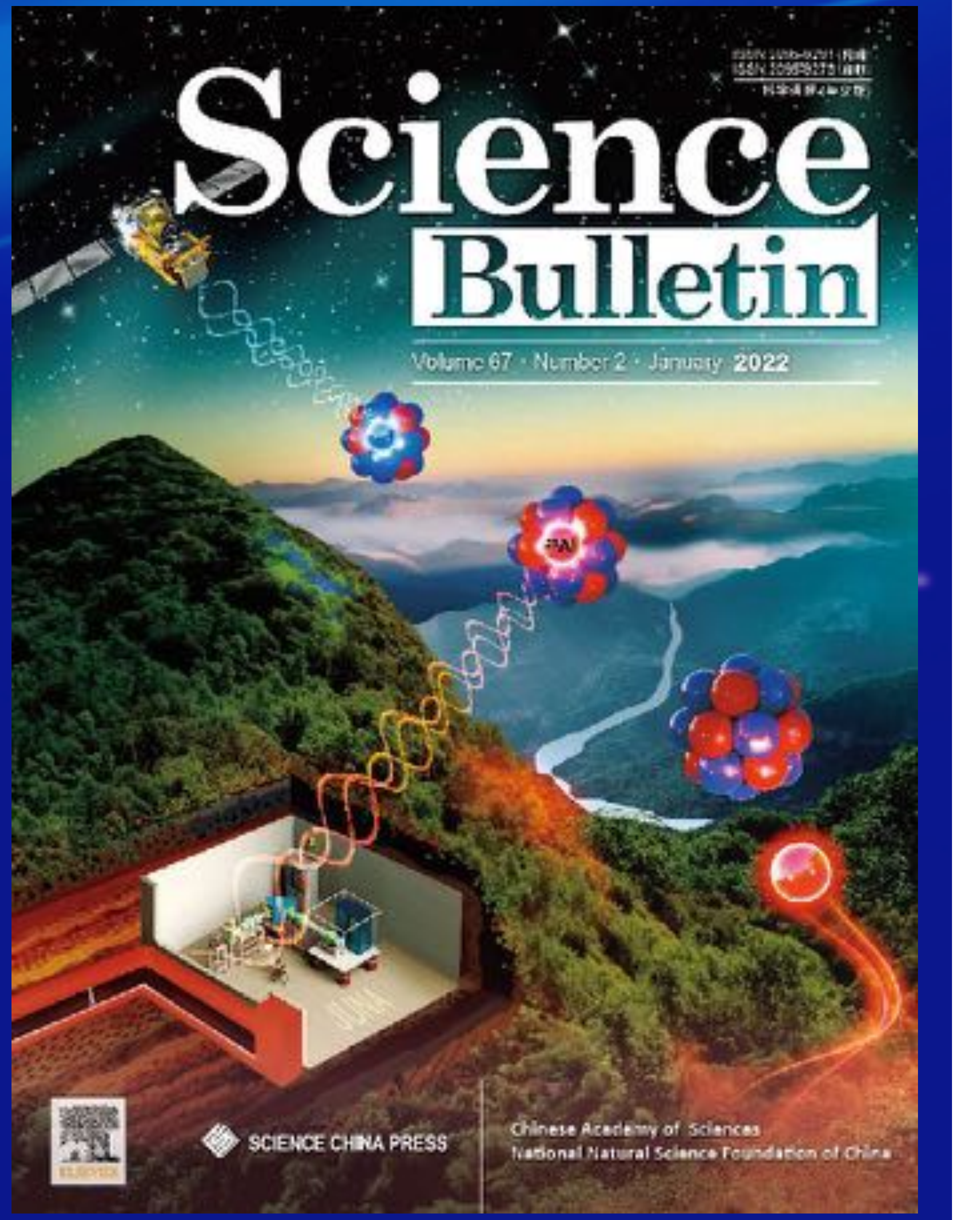
signal：1225

strength：3.8±0.4×10-10 eV

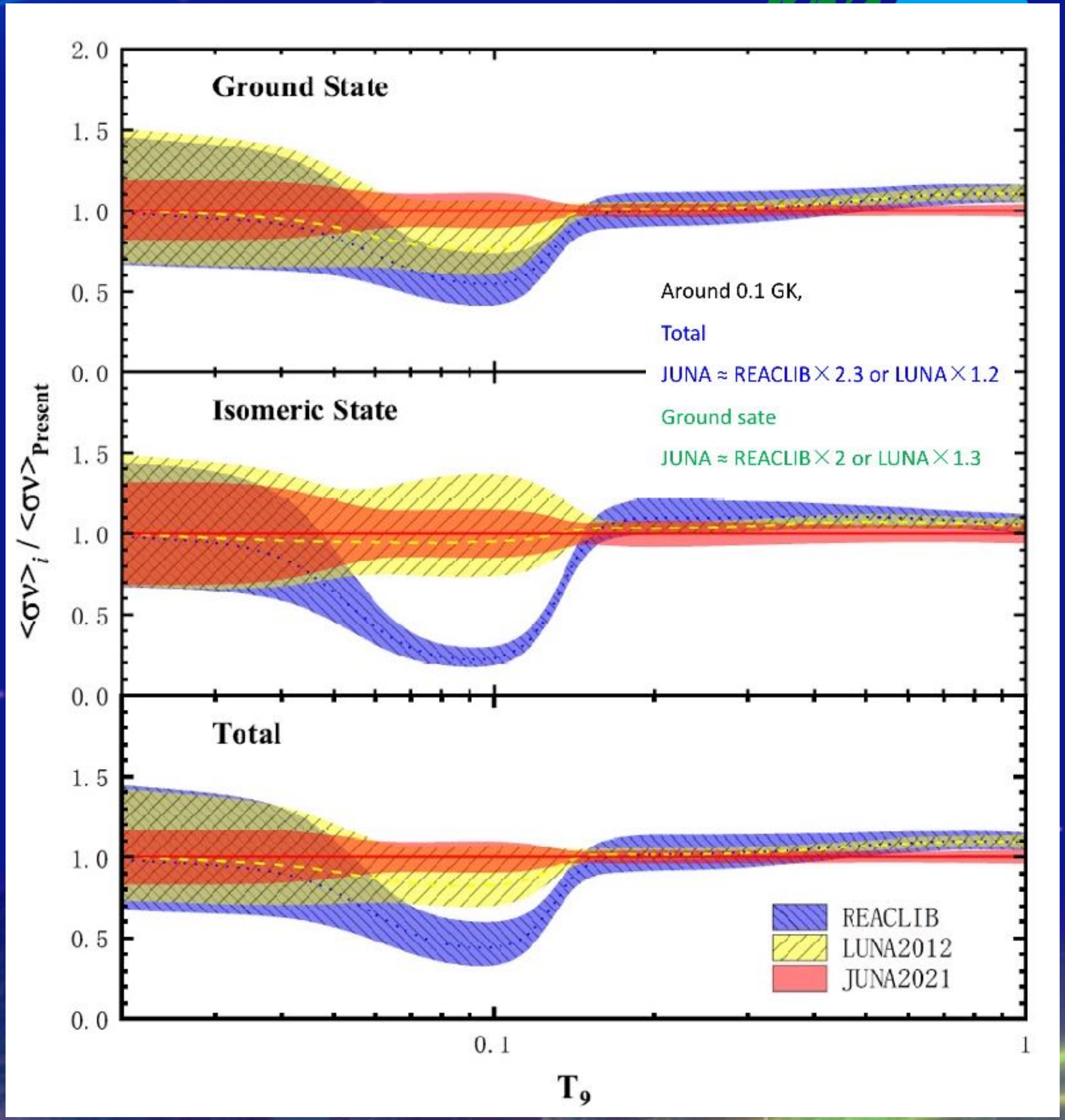
J. Su, Z. H. Li*,…., WPL*, Science Bulletin, 67(2022)2, cover paper

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

PI: J. J. He, BNU

L.Y. Zhang, BNU

key reaction for F in star

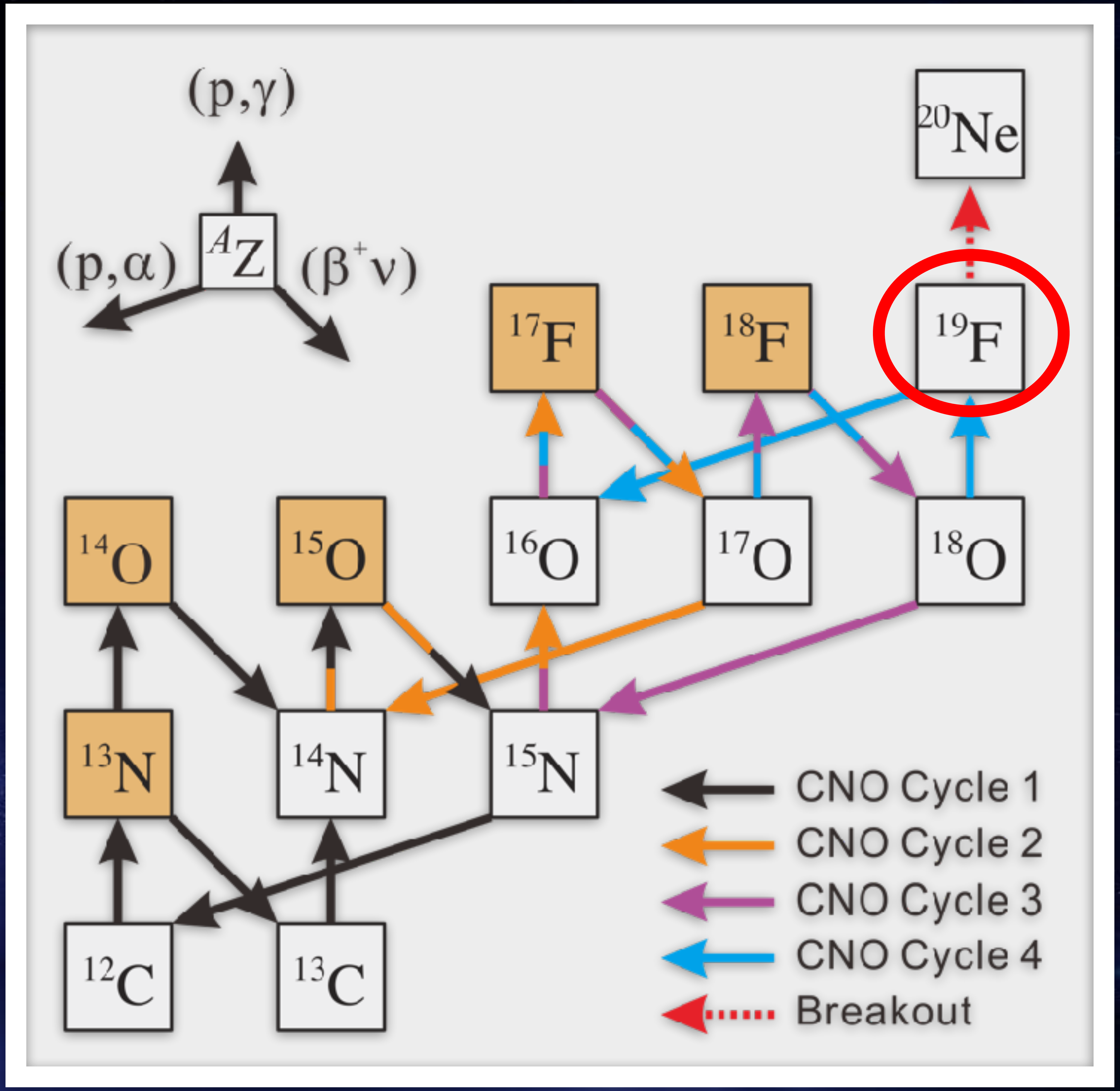
Exp.: Jan. 16-25, 2021

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：

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

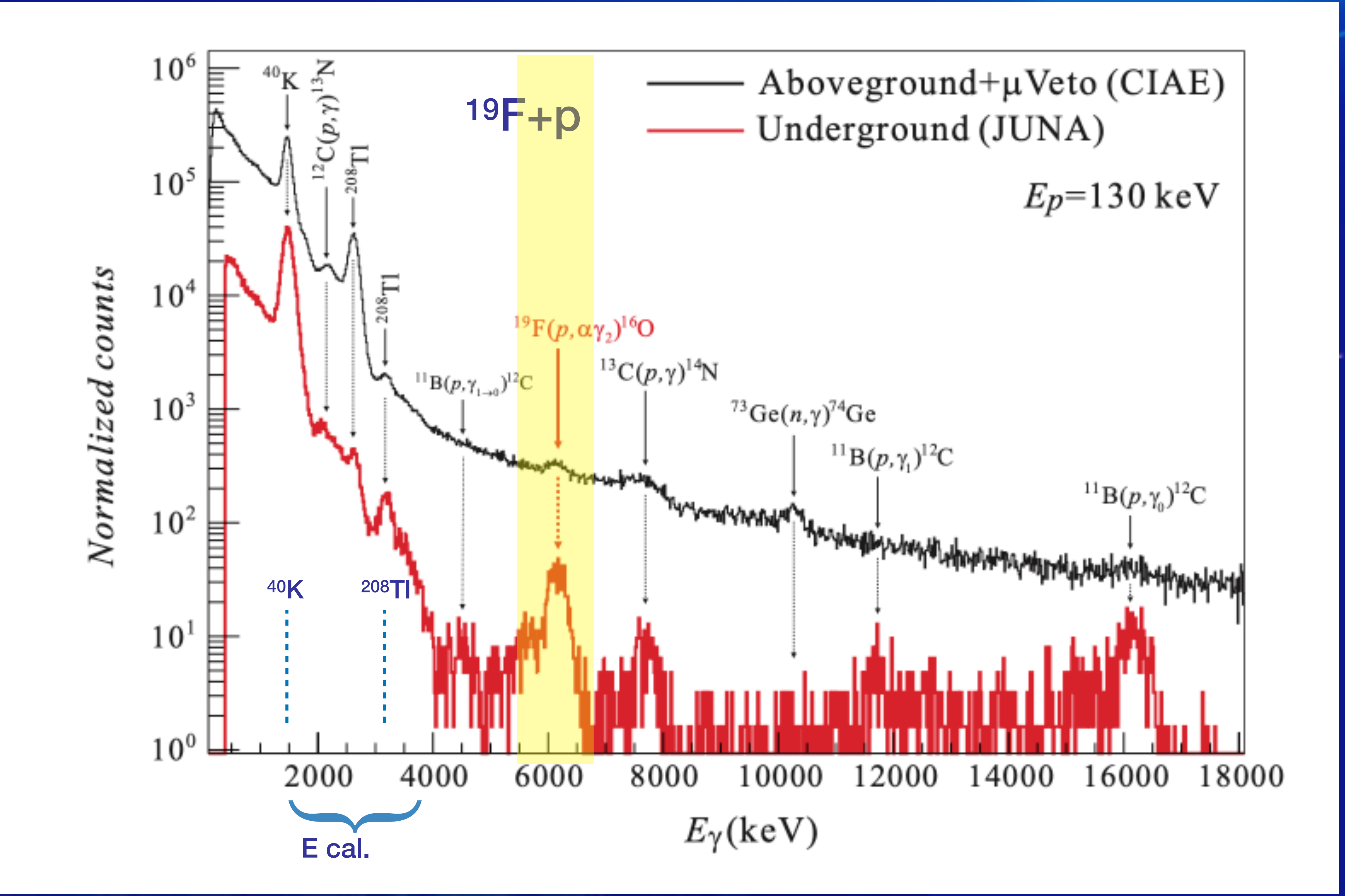


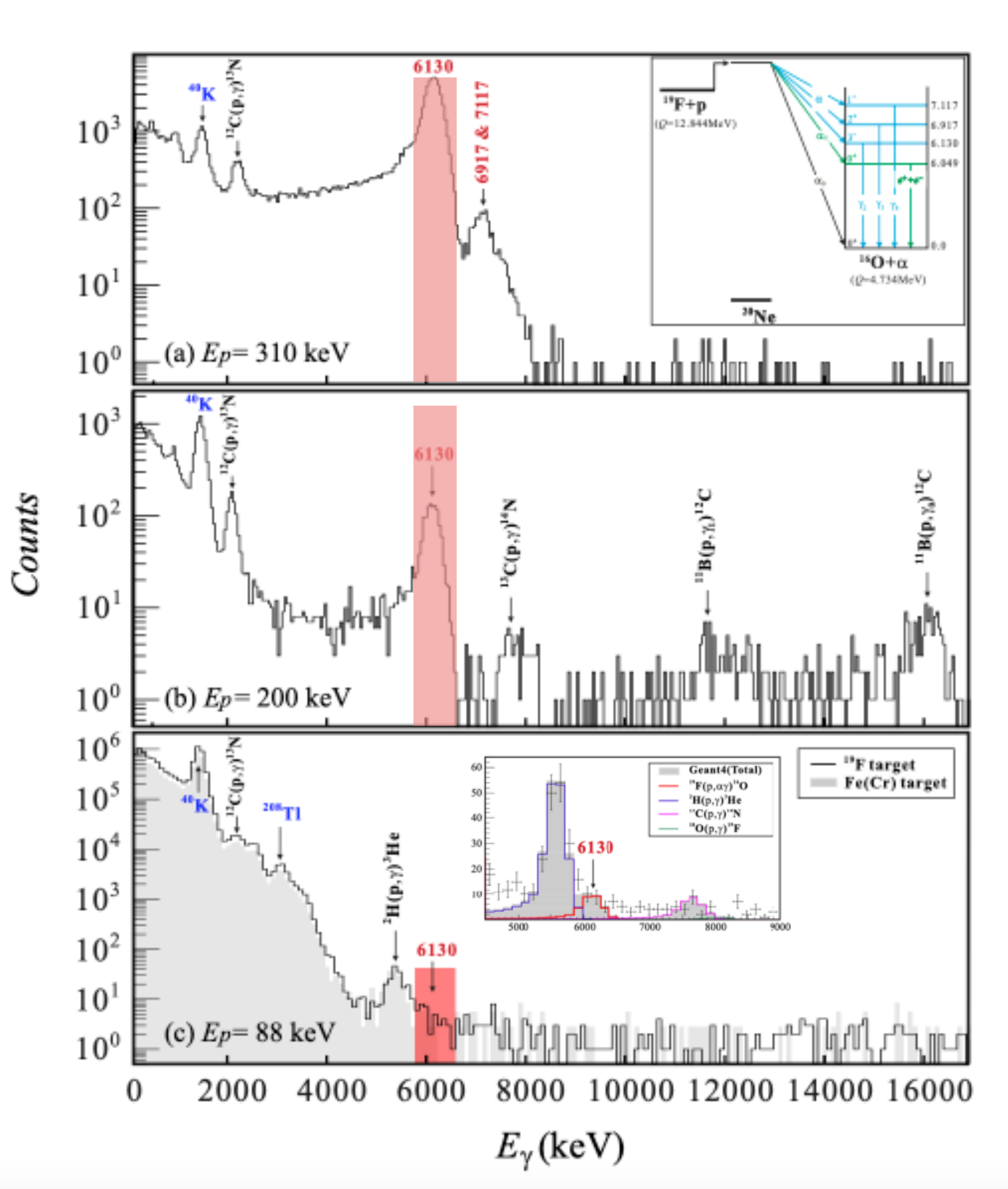
J.J. He *et al.*, Sci. China-Phys. Mech. Astron. 59 (2016) 652001

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

北京師範大學 BEIJING NORMAL UNIVERSITY

^{19}F(p,αγ)^{16}O data

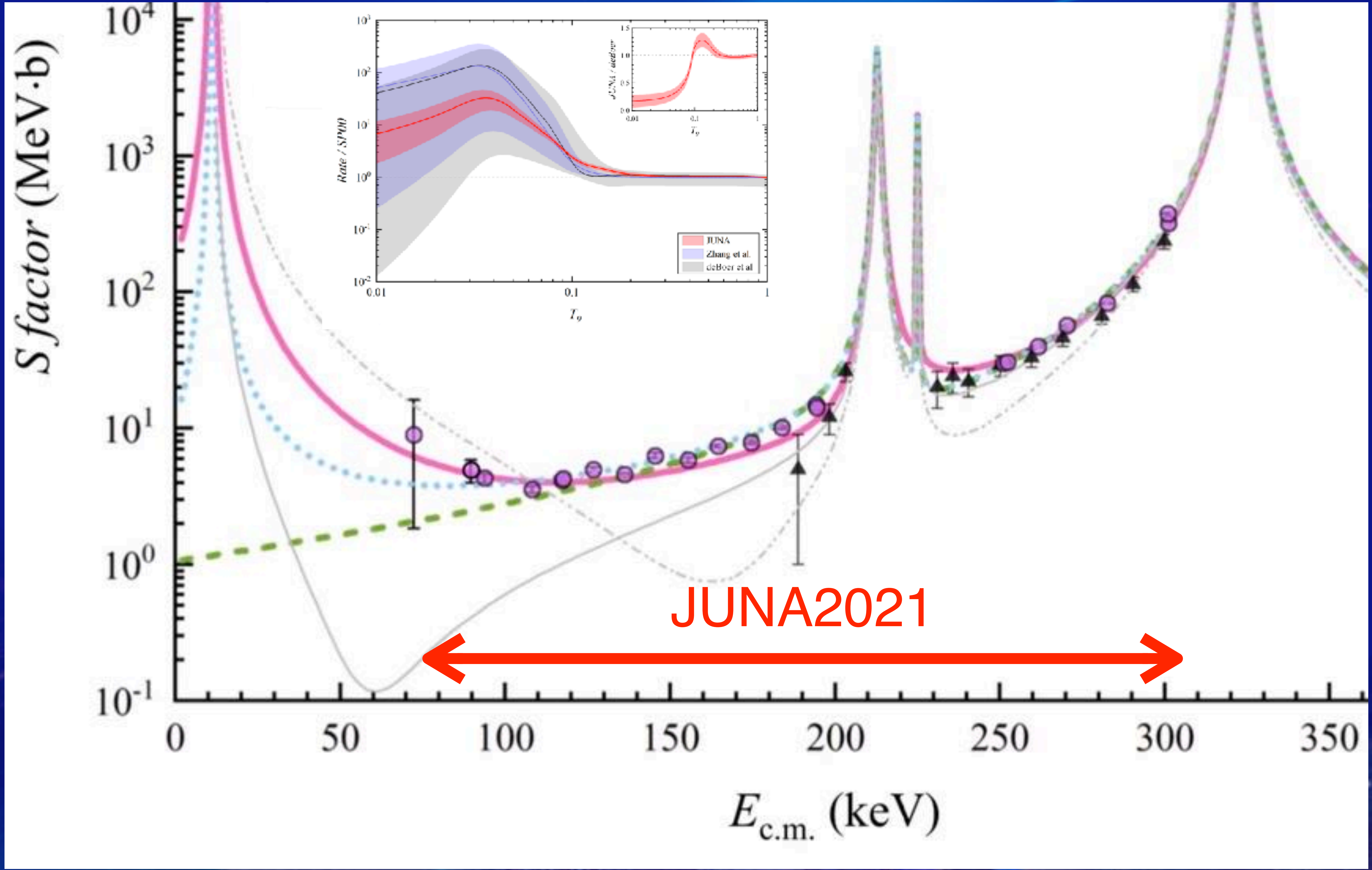




- ^{19}F implatation+ Cr coding, long durabilty with 2 mA
- L.Y. Zhang, Y.J. Chen, J.J. He* et al., Nucl. Instr. Meth. B 496(2021)9

L.Y. Zhang, J. Su, J. J. He*, …, WPL*, ^{19}F(p,αγ)^{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,†] 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,†]

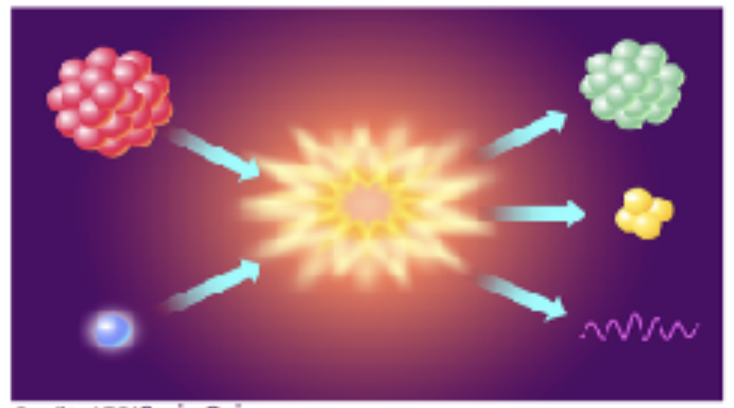
Physics — SYNOPSIS

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 1.23×10^{-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).

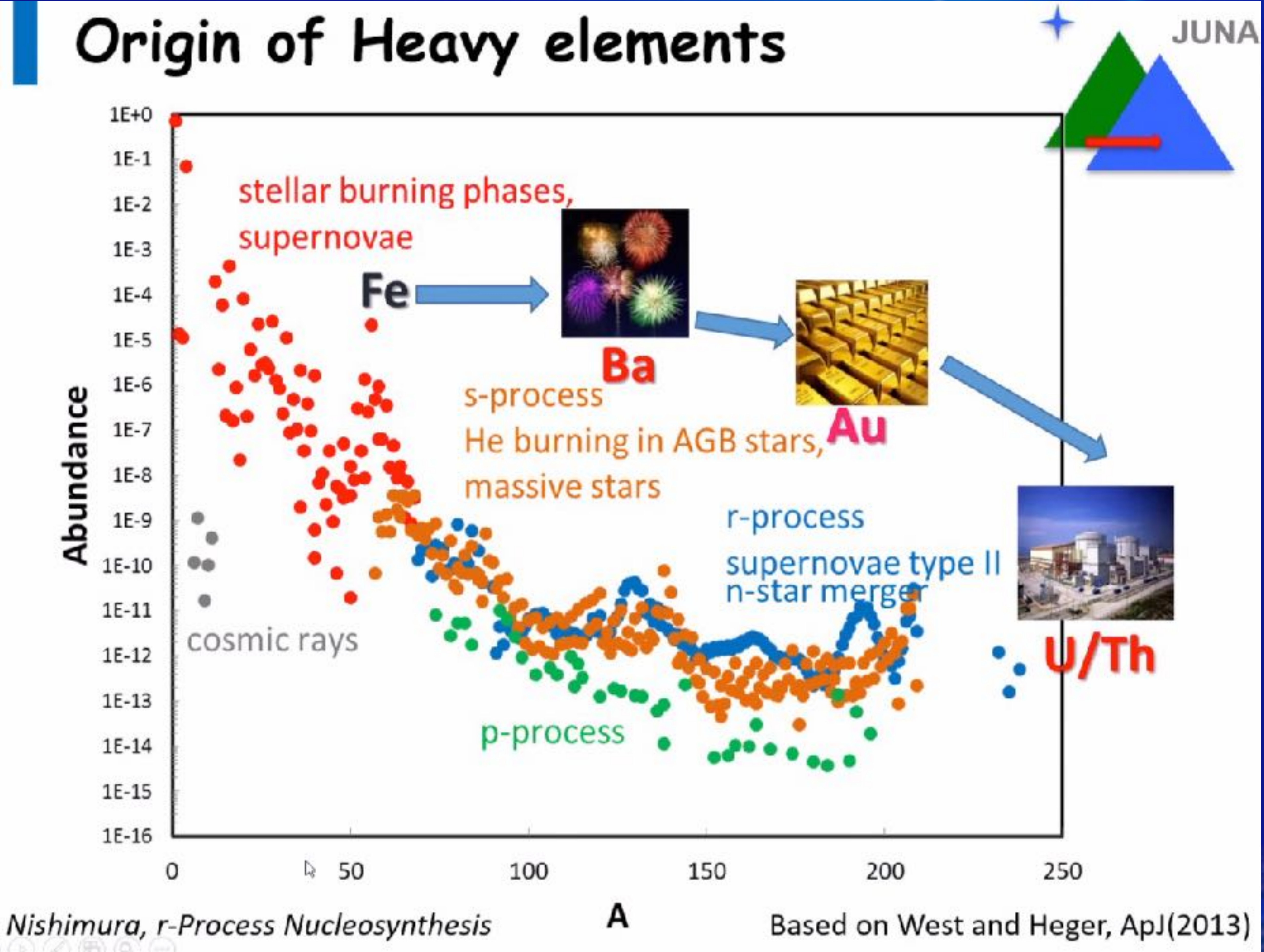
L.Y. Zhang, J. Su, J. J. He*, …, WPL*, $^{19}F(p,\alpha\gamma)^{16}O$, PRL 127(2021)152702. editor suggestions

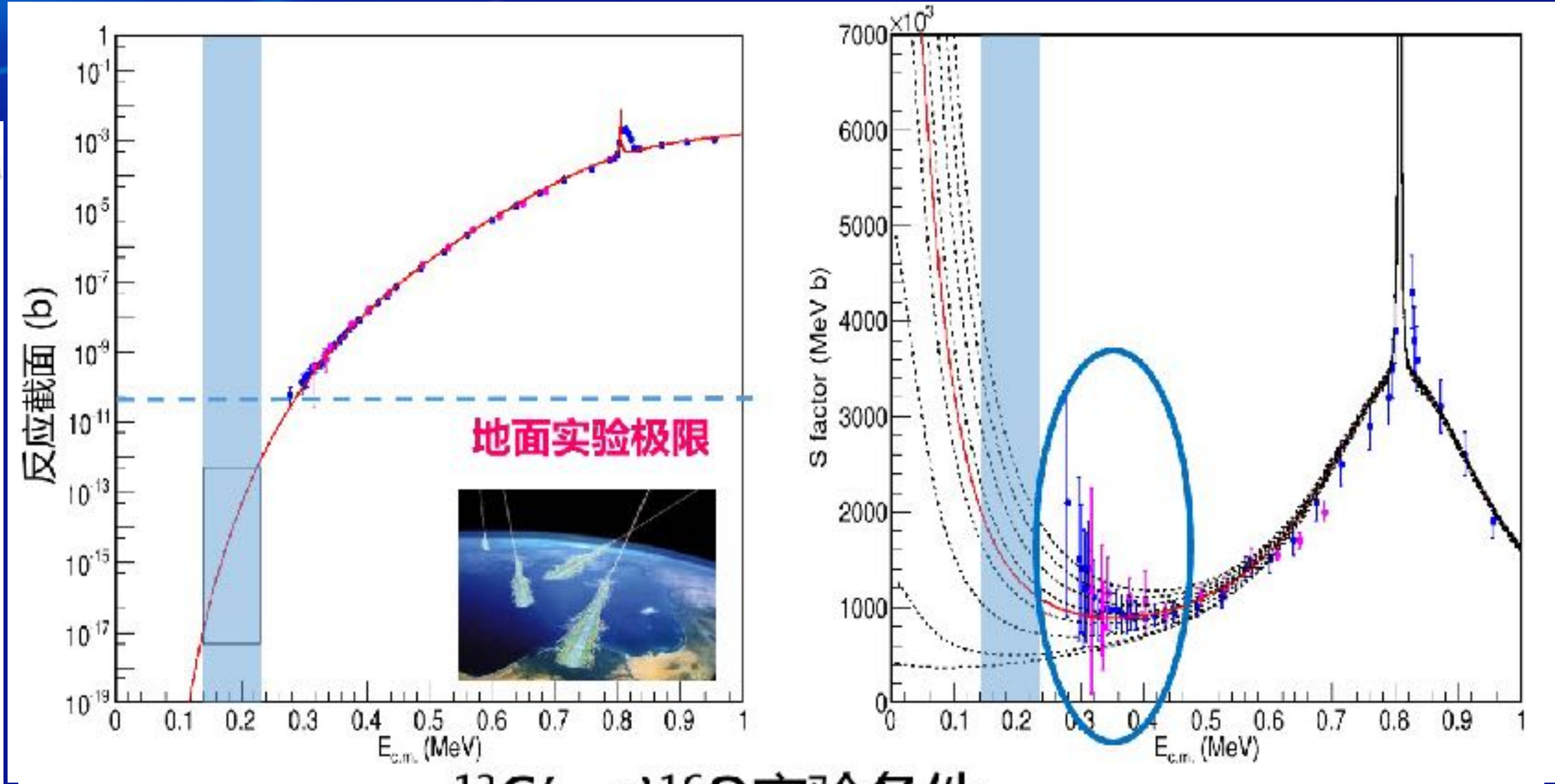
$^{13}C(a,n)^{16}O$中子源反应 neutron source reaction

PI: X. D. Tang, IMP

B. Gao, IMP

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





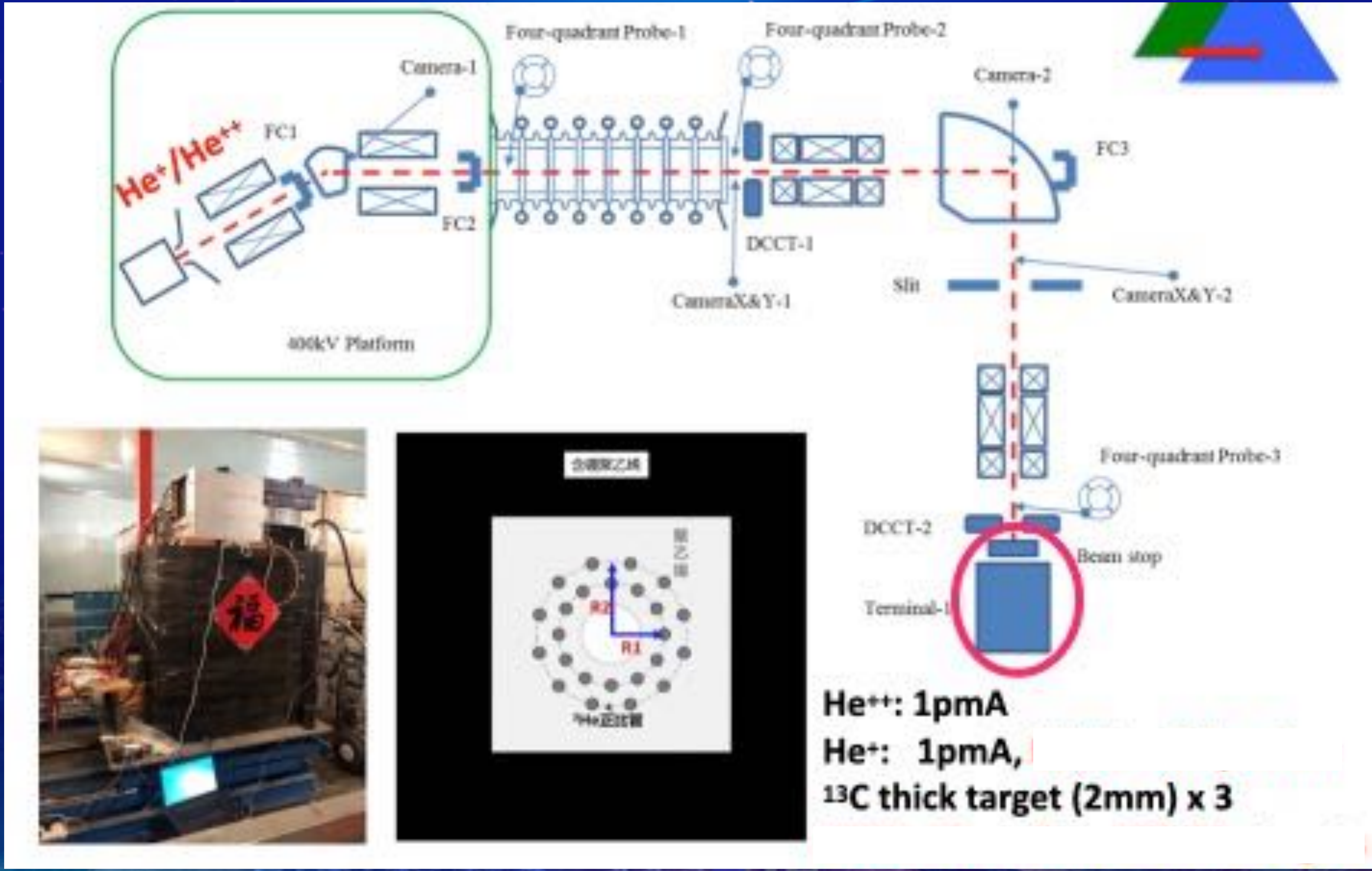
$^{13}C(\alpha,n)^{16}O$实验条件

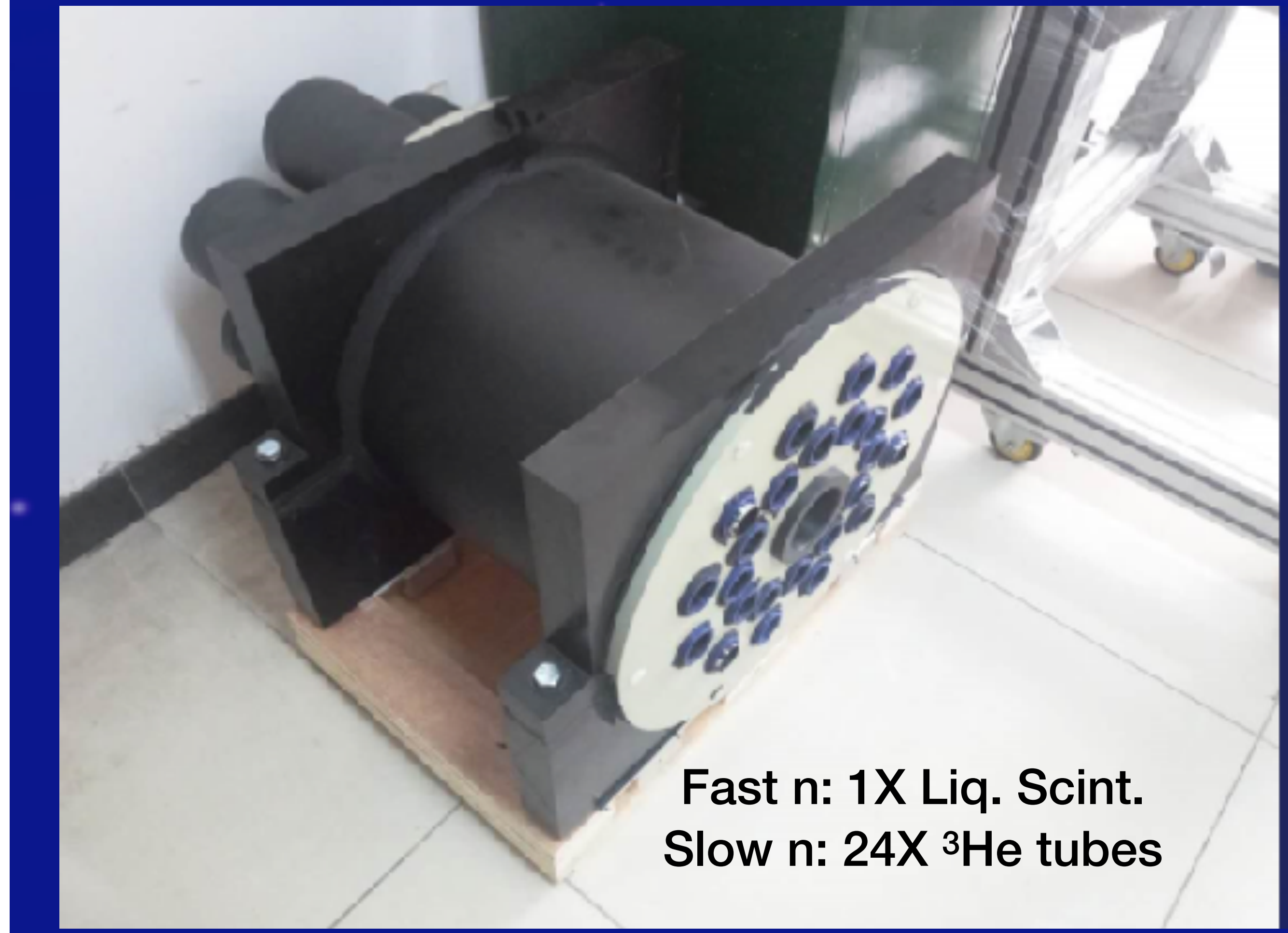
指标	LUNA (意大利)	JUNA (中国)
束流强度 beam (粒子毫安)	~0.15	~2
靶数目 target	>100	3
能区 (MeV) energy	0.23-0.31	0.24-1.2
束流时间（天）	240	14

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（0.24-1.2MeV）提供基准数据

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

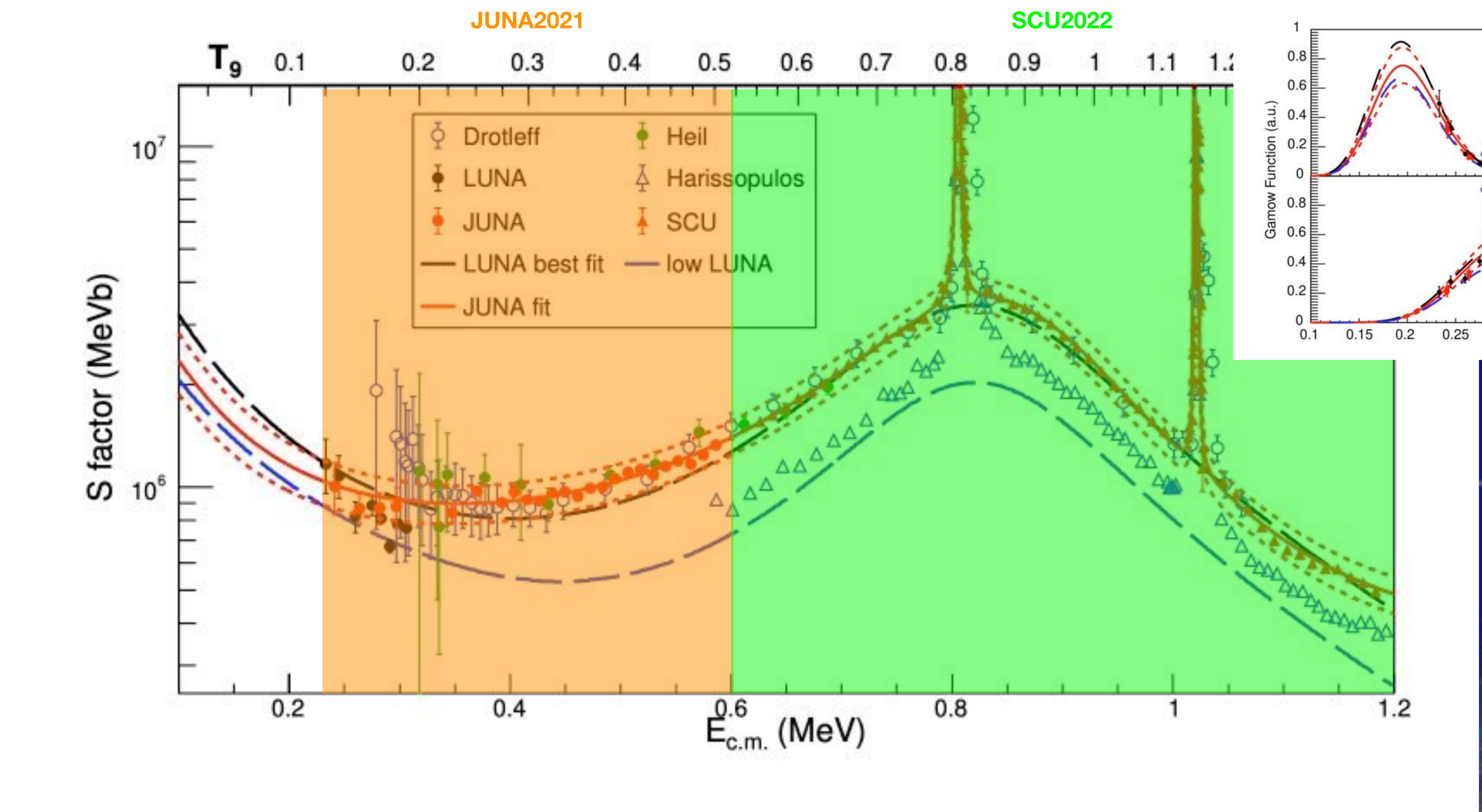
$^{13}C(\alpha,n)^{16}O$ status

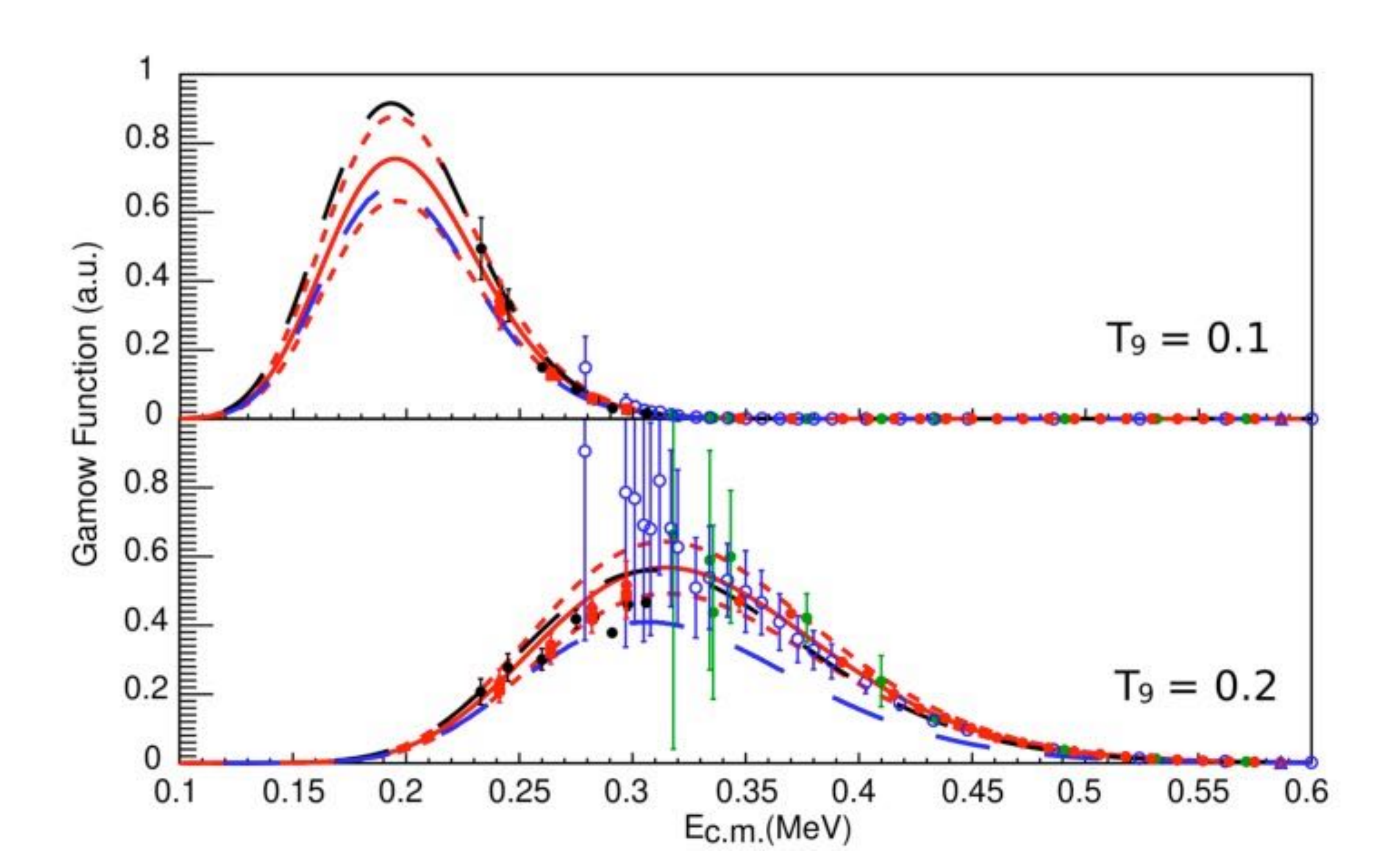




B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(\alpha,n)^{16}O$, PRL 129(2022)132701

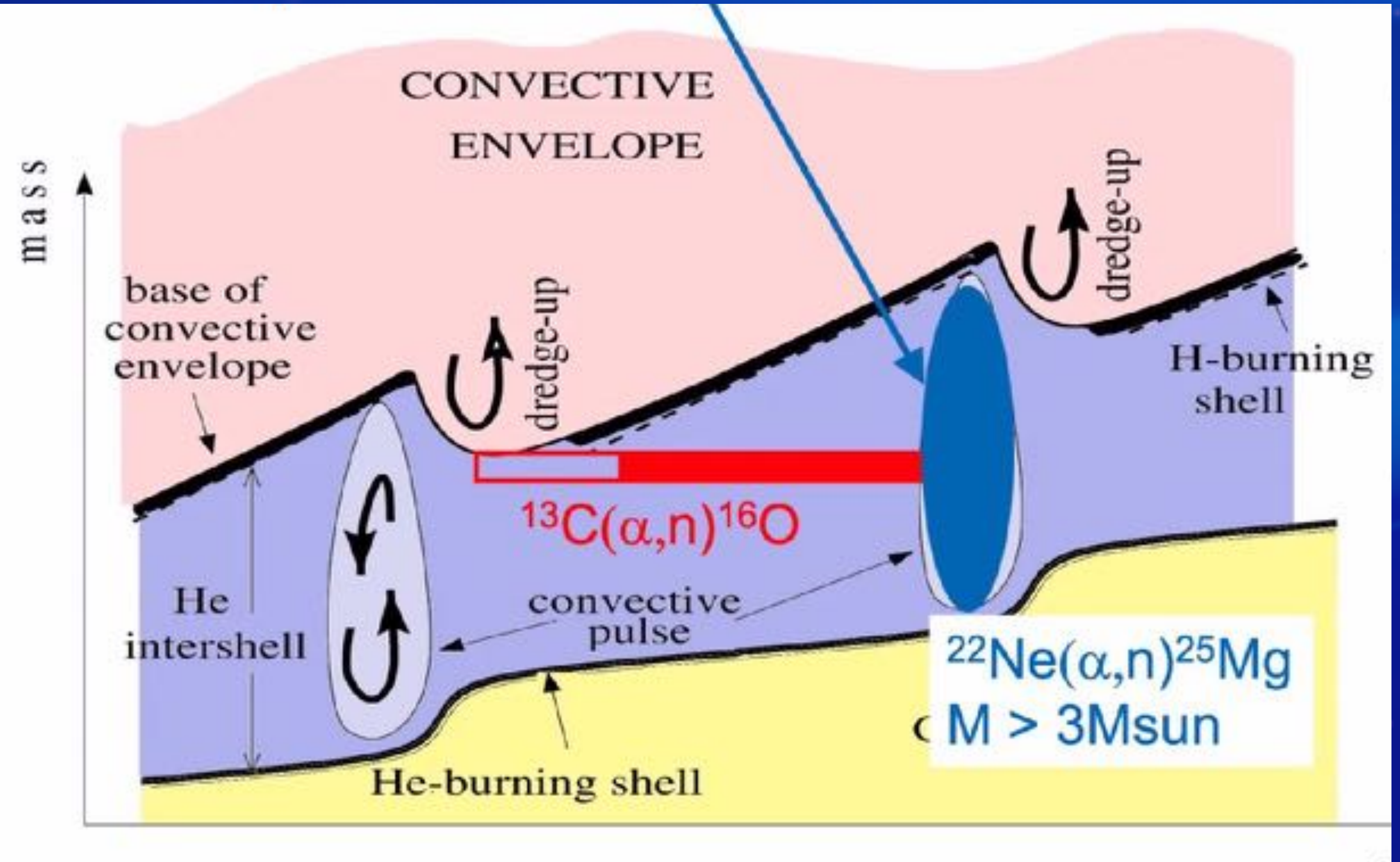
$^{13}C(\alpha,n)^{16}O$: solve the uncertainty





- 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

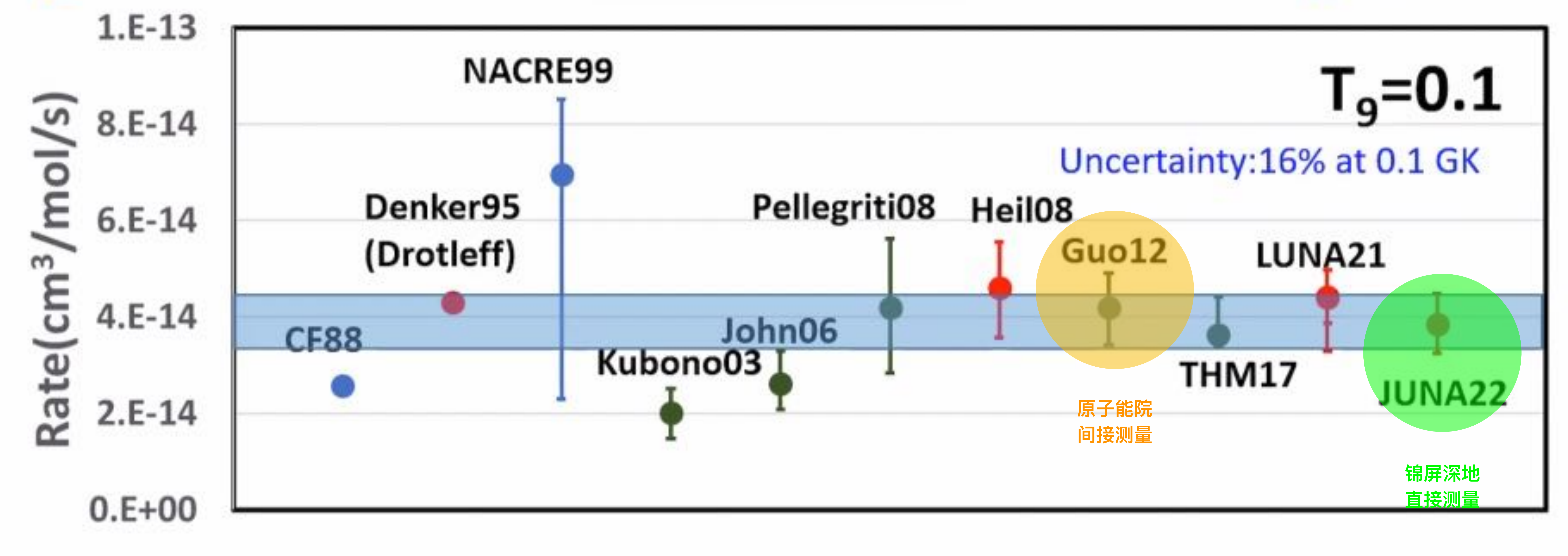
B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(\alpha,n)^{16}O$, PRL 129(2022)132701



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 …

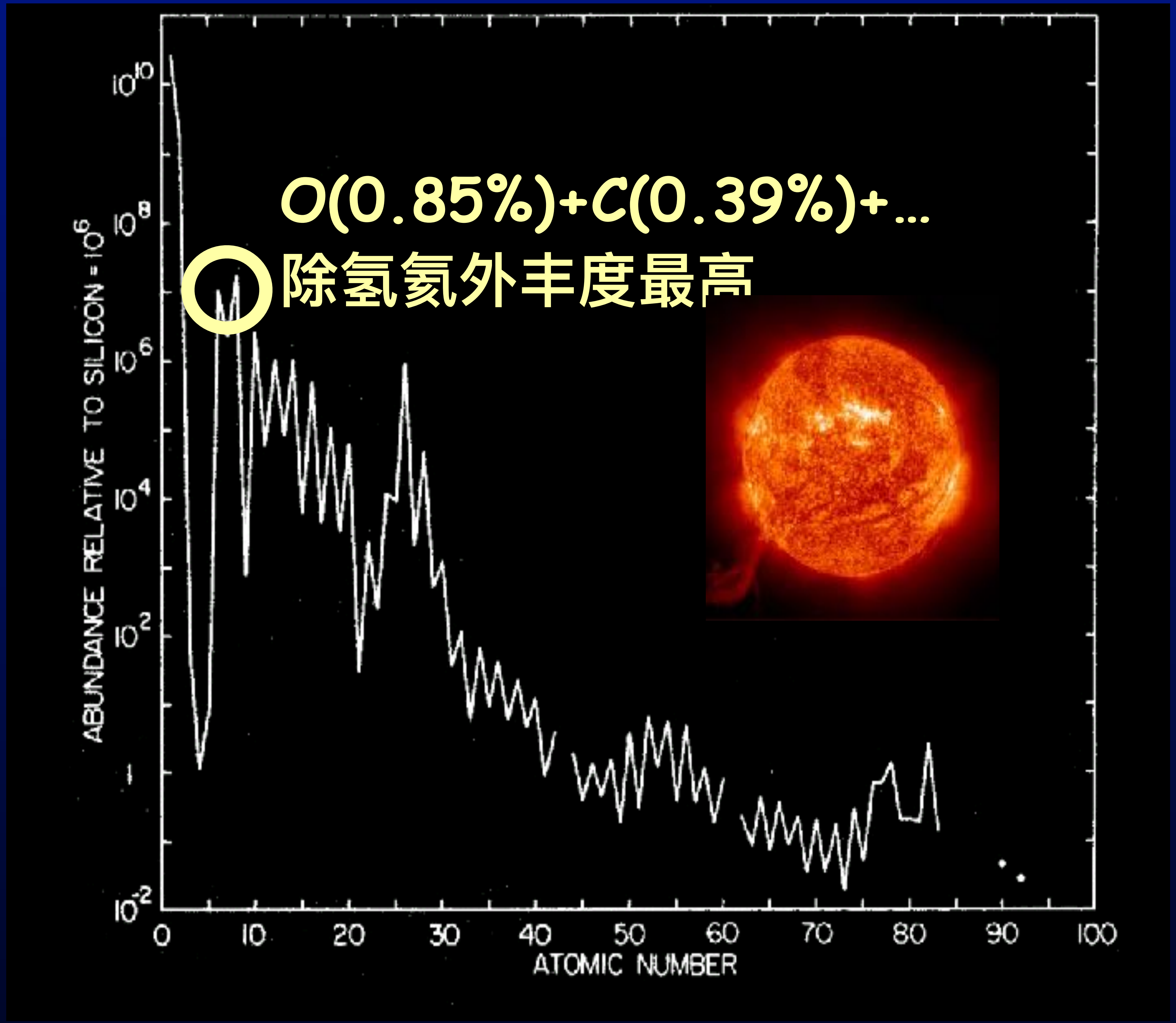
the new underground and new above ground measurements are smoothly continuous over a large energy range, thereby providing a much improved and more precise s-factor than previously available



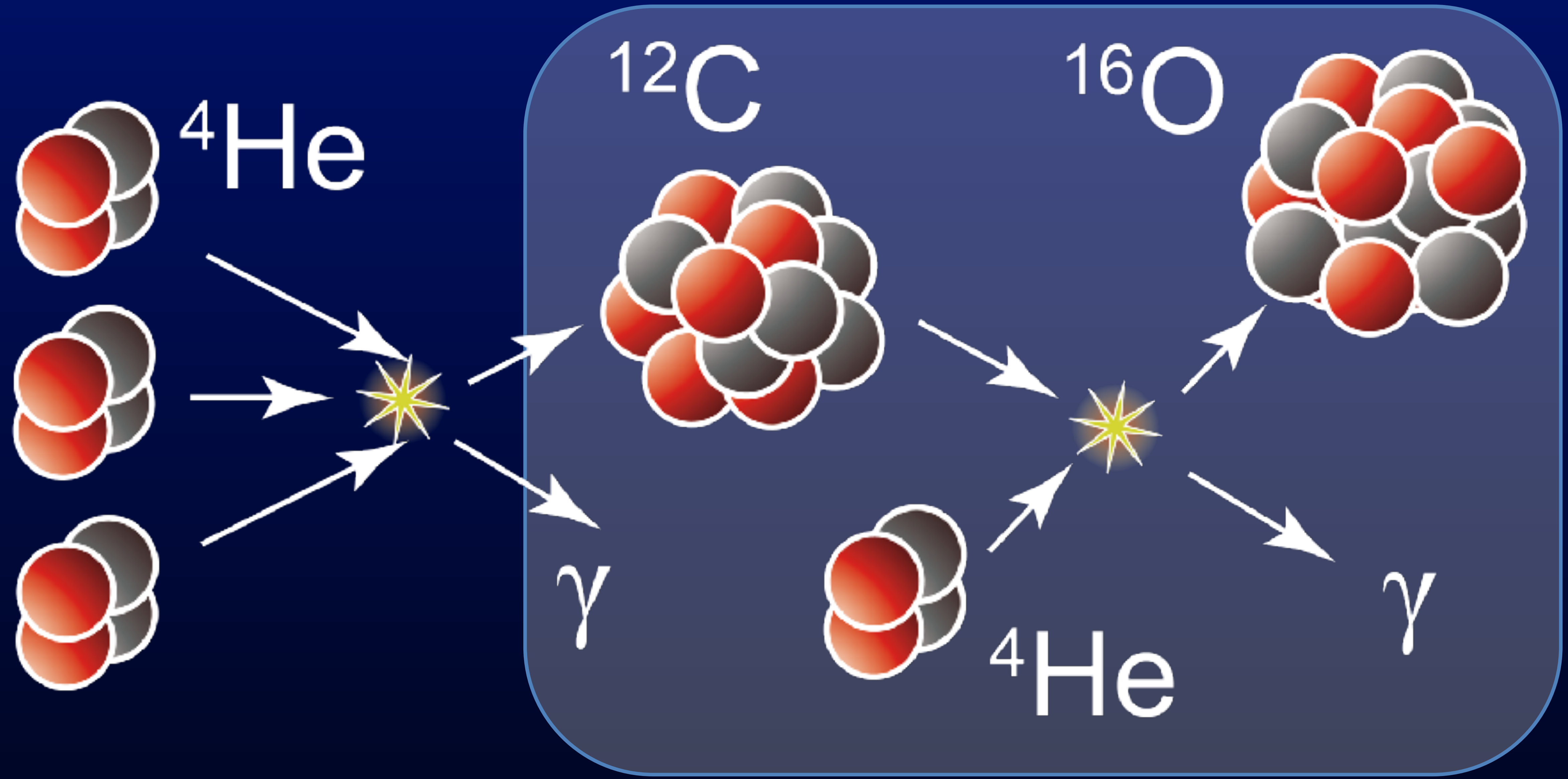
B. Gao, …, Y. D. Tang*,…, WPL*, $^{13}C(\alpha,n)^{16}O$, PRL 129(2022)132701
B. Guo*, Z. H. Li,…, WPL*, Astrophys. J. 756(2012)193.

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

JUNA合作组
谌阳平、苏俊、连钢、柳卫平等

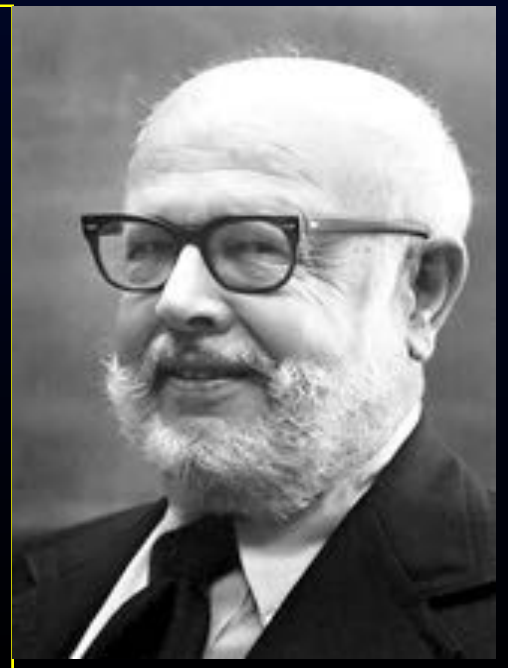


- $^{12}C(\alpha,\gamma)^{16}O$决定**碳氧比例**
- 影响恒星演化和几乎全部核素丰度
- 被称为“**圣杯反应**”



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

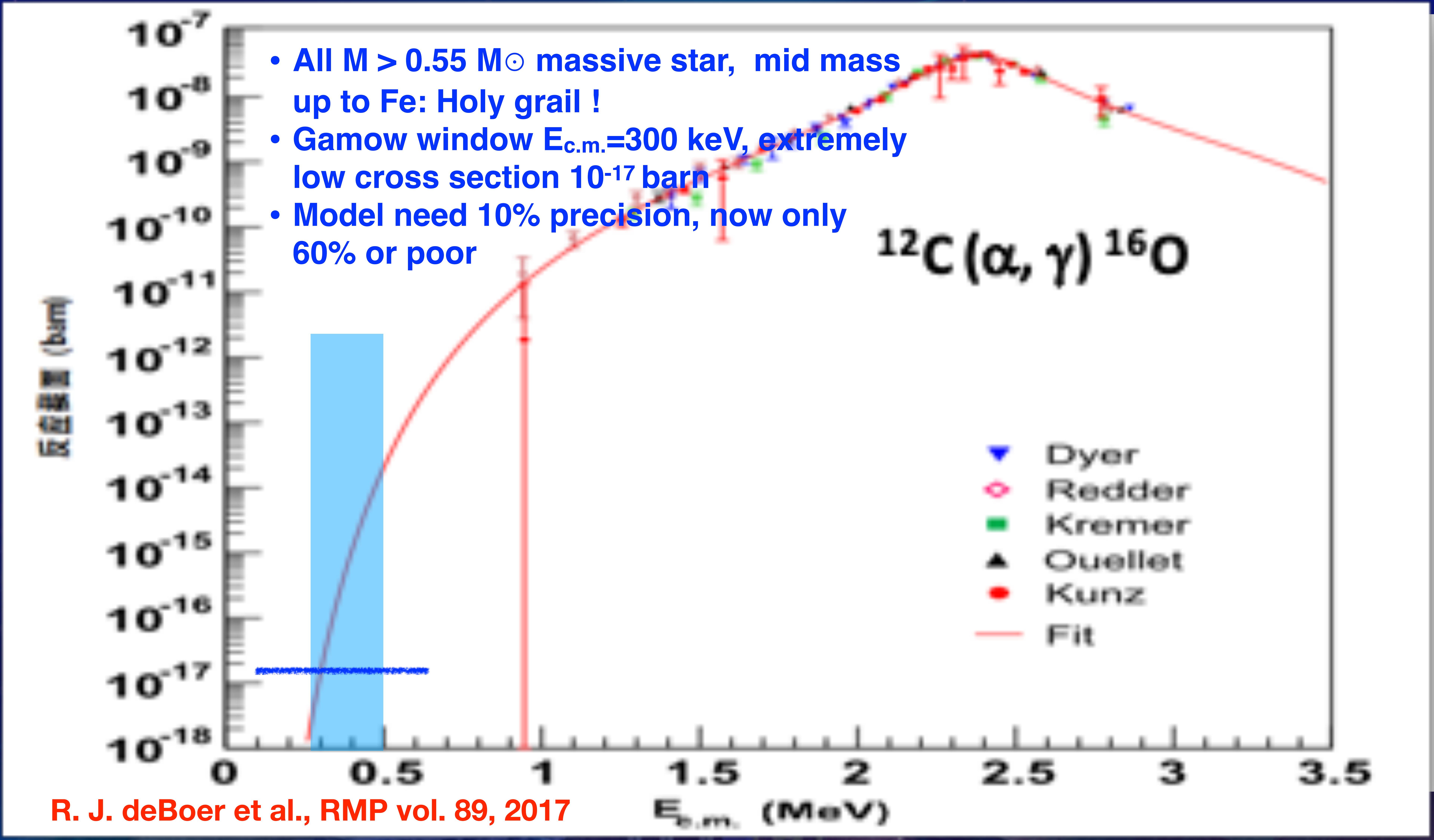


Big question, big impact, big challenge 圣杯

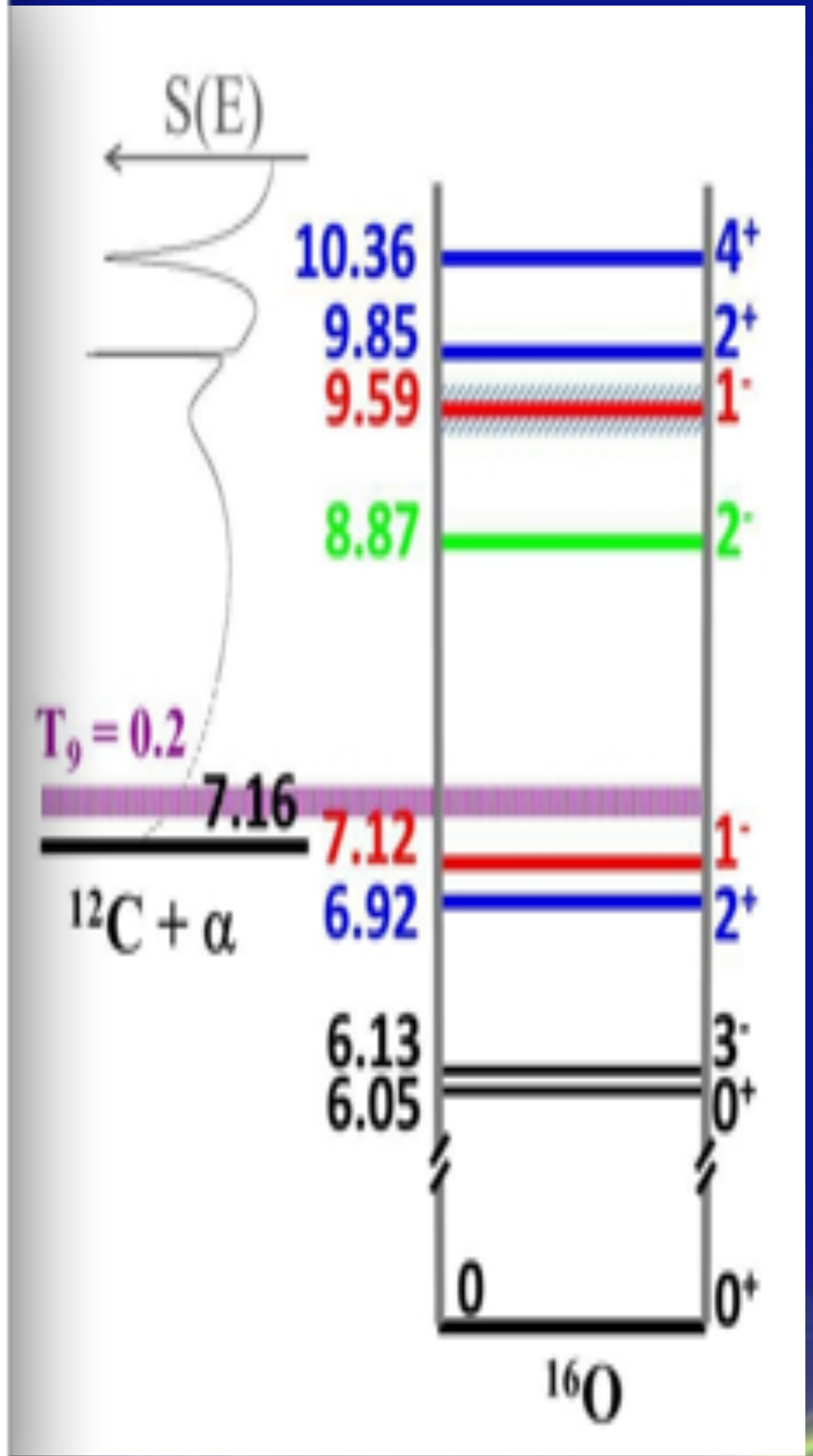
PI: WPL/Y. P. Shen, CIAE

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)

Current Status

Dozens of Works, Hundreds of Data Points

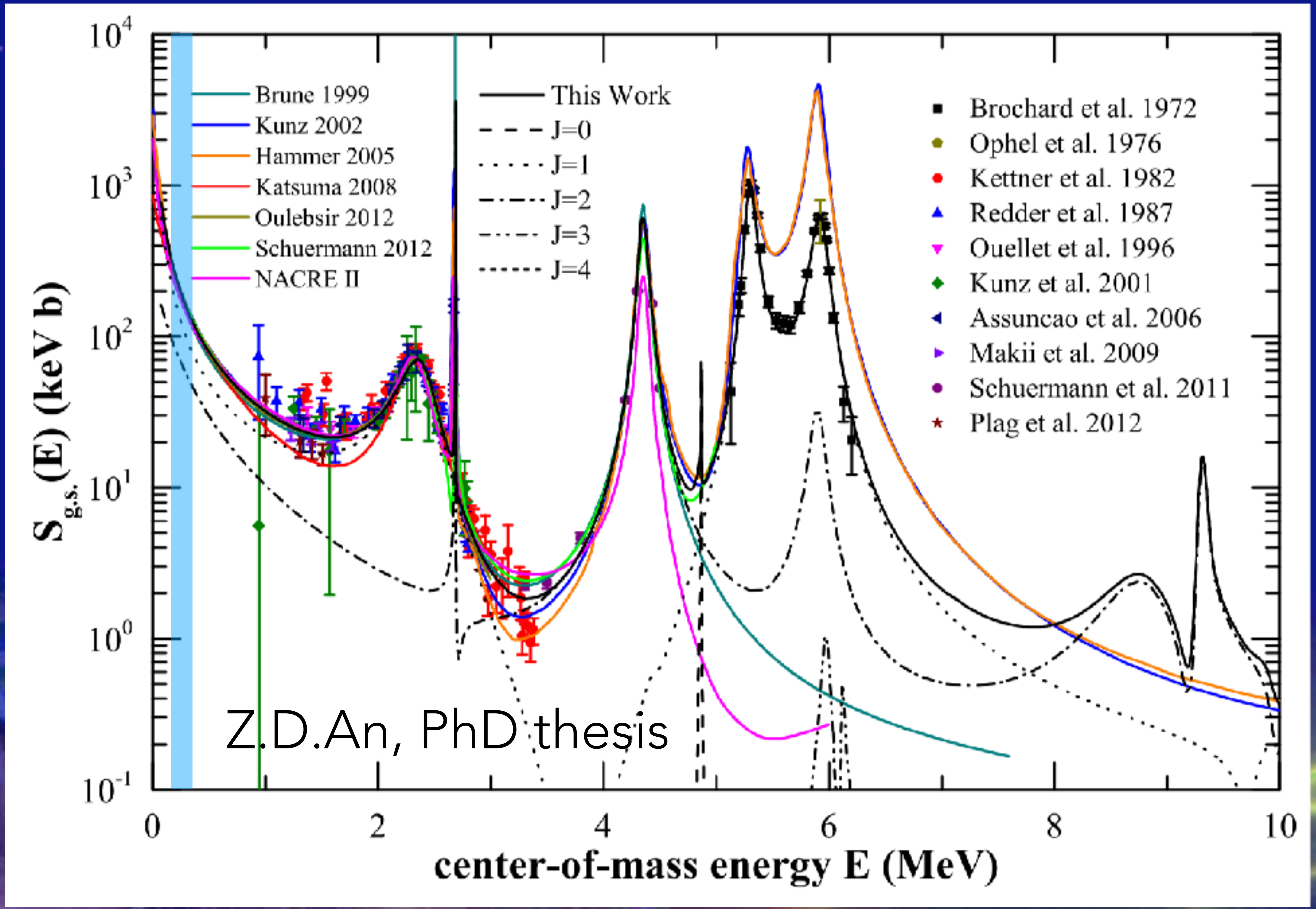
Still Far from Gamow Window

TABLE IV. Extrapolations of the $^{12}C(\alpha,\gamma)^{16}O$ S factor to $E_{c.m.} = 300$ keV categorized by either cluster model calculations are phenomenological fits. The abbreviations used below are for the generalized coordinate method (GCM) and potential model (PM) for the theoretical works and Breit-Wigner (BW), R matrix (R), and K matrix (K) for the phenomenological calculations. Hybrid R-matrix (HR) models have also been used in an effort to connect the phenomenological calculations more closely to more fundamental theory.

			S(300 keV) (keV b)		
Reference	$E1$	$E2$	Cascades	Total	Model
Cluster models					
Descouvemont, Baye, and Heenen (1984)	300	90			GCM
Langanke and Koonin (1985)	160–280	70	< 10[a]	230–350	HR & PM
Funck, Langanke, and Weiguny (1985)		100			PM
Redder *et al.* (1987)	140^{+120}_{-80}	80 ± 25	7 ± 3[a] $1.3^{+0.5}_{-1.0}$[b]		R & PM
Descouvemont and Baye (1987)	160	70			GCM
Ouellet *et al.* (1992)	1^{+6}_{-1}	40 ± 7			R & PM
Descouvemont (1993)		90			GCM
Ouellet *et al.* (1996)	79 ± 16	36 ± 6		120 ± 40	R, K, PM
Dufour and Descouvemont (2008)		42 ± 2			GCM
Katsuma (2012)	≈ 3	150^{+41}_{-17}	18.0 ± 4.5[c]	171^{+46}_{-22}	PM
Xu *et al.* (2013) (NACRE2)	80 ± 18	61 ± 19	$6.5^{+4.7}_{-2.2}$[c]	148 ± 27	PM
Burbidge *et al.* (1957)	340			340	BW
Barker (1971)	50–330			50–330	R
Koonin, Tombrello, and Fox (1974)	80^{+50}_{-40}			80^{+50}_{-40}	HR
Dyer and Barnes (1974)	140^{+140}_{-40}			140^{+140}_{-40}	R & HR
Weisser, Morgan, and Thompson (1974)	170			170	R
Humblet, Dyer, and Zimmerman (1976)	80^{+140}_{-70}			80^{+140}_{-70}	K
Kettner *et al.* (1982)	250	180	12(2)[a,b]	420^{+160}_{-120}	BW
Langanke and Koonin (1983)	150 or 340	< 4% of $E1$		150 or 340	HR
Barker (1987)	150^{+140}_{-60}	30^{+50}_{-30}			R
Kremer *et al.* (1988)	0–140				R & HR
Filippone, Humblet, and Langanke (1989)	0–170	5–28		0–170	K
Barker and Kajino (1991)	150^{+170}_{-70} or 260^{+140}_{-160}	120^{+60}_{-70}	10[a] 1–2[b]	280^{+230}_{-140} or 390^{+200}_{-230}	R
Humblet, Filippone, and Koonin (1991)	43^{+20}_{-15}	7^{+24}_{-5}		50^{+30}_{-20}	K
Humblet, Filippone, and Koonin (1993)	45^{+5}_{-6}				K
Azuma *et al.* (1994)	79 ± 21 or 82 ± 26				R & K
Buchmann *et al.* (1996)	79 ± 21	70 ± 70	16 ± 16[a,b,d]	165 ± 75	R & K
Hale (1997)	20				R
Trautvetter *et al.* (1997)	79	14.5			BW
Brune *et al.* (1999)	101 ± 17	42^{+16}_{-23}			R
Roters *et al.* (1999)	79 ± 21				R
Angulo and Descouvemont (2000)		190–220			R
Gialanella *et al.* (2001)	82 ± 16 or 2.4 ± 1.0				R
Kunz *et al.* (2001)	76 ± 20	85 ± 30	4 ± 4[c]	165 ± 50	R
Tischhauser *et al.* (2002)		53^{+13}_{-18}			R
Hammer *et al.* (2005b)	77 ± 17	81 ± 22		162 ± 39	R
Buchmann and Barnes (2006)			$5^{+7}_{-4.5}$[d] 7^{+13}_{-4}[e]		R
Matei *et al.* (2006)			25^{+16}_{-15}[d]		R
Matei, Brune, and Massey (2008)			7.1 ± 1.6[e]		R
Tang *et al.* (2010)	86 ± 22				R
Schürmann *et al.* (2011)			< 1[d]		R
Schürmann *et al.* (2012)	83.4	73.4	4.4[c]	$161 \pm 19_{(stat)}{}^{+8}_{-2}{}_{(syst)}$	R
Oulebsir *et al.* (2012)	100 ± 28	50 ± 19		175^{+63}_{-62}	R
Sayre *et al.* (2012)		62^{+9}_{-6}			R
Avila *et al.* (2015)			1.96 ± 0.30 or 4.36 ± 0.45[d] 0.12 ± 0.04 or 1.44 ± 0.12[e]		R
An *et al.* (2015)	98.0 ± 7.0	56 ± 4.1	8.7 ± 1.8[c]	162.7 ± 7.3	R
This work	86.3	45.3	7[c]	$140 \pm 21_{(MC)}{}^{+18}_{-11}{}_{(model)}$	R

[a]6.92 MeV transition.
[b]7.12 MeV transition.
[c]Sum of all cascade transitions.
[d]6.05 MeV transition.
[e]6.13 MeV transition.

deBoer+RMP2017



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

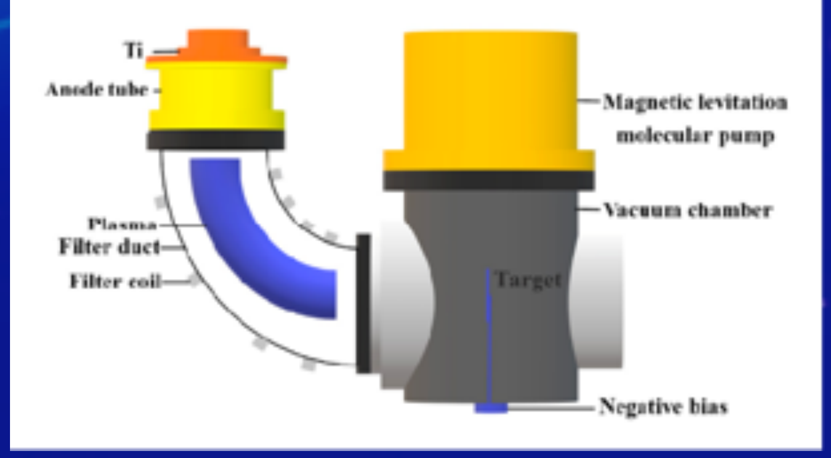

Contents lists available at ScienceDirect

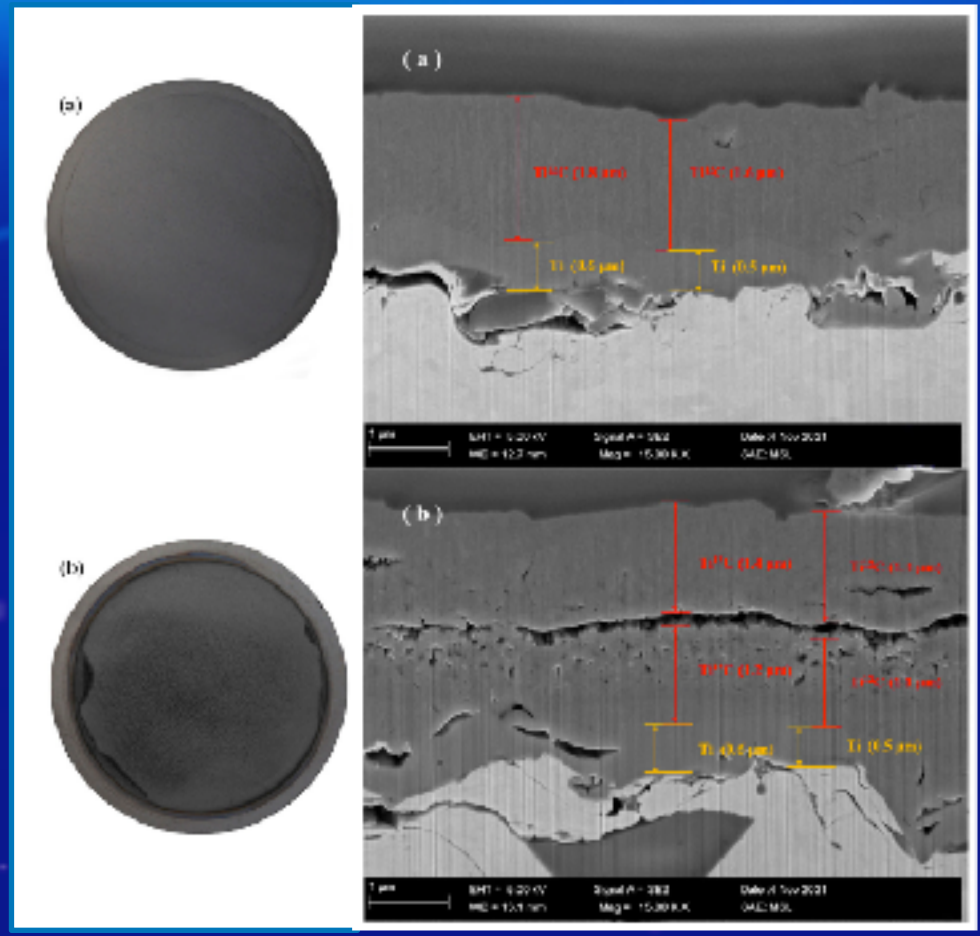
Nuclear Inst. and Methods in Physics Research, B

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,d], W.P. Liu[c]





	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)

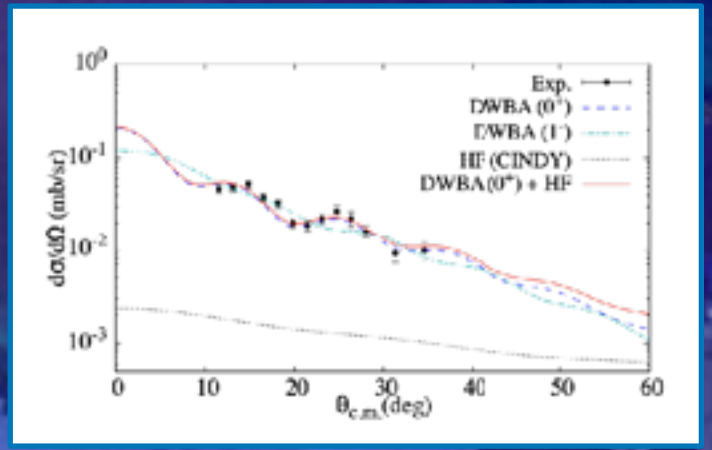
高耐辐照^{12}C高纯同位素靶研发

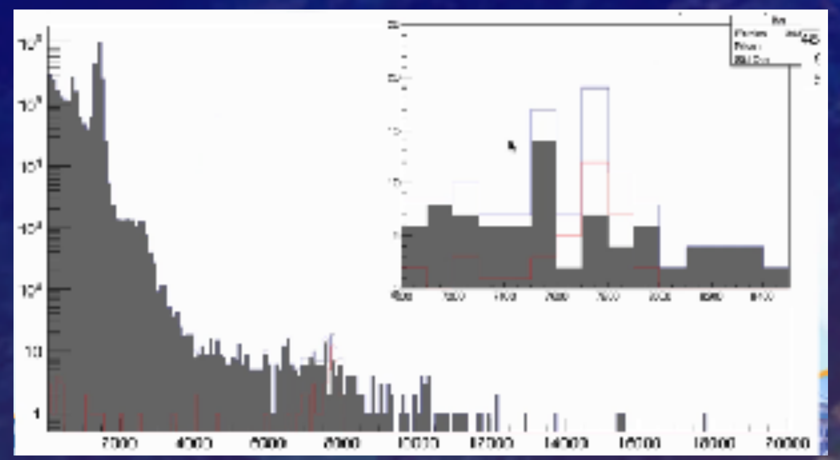
Target procedure

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

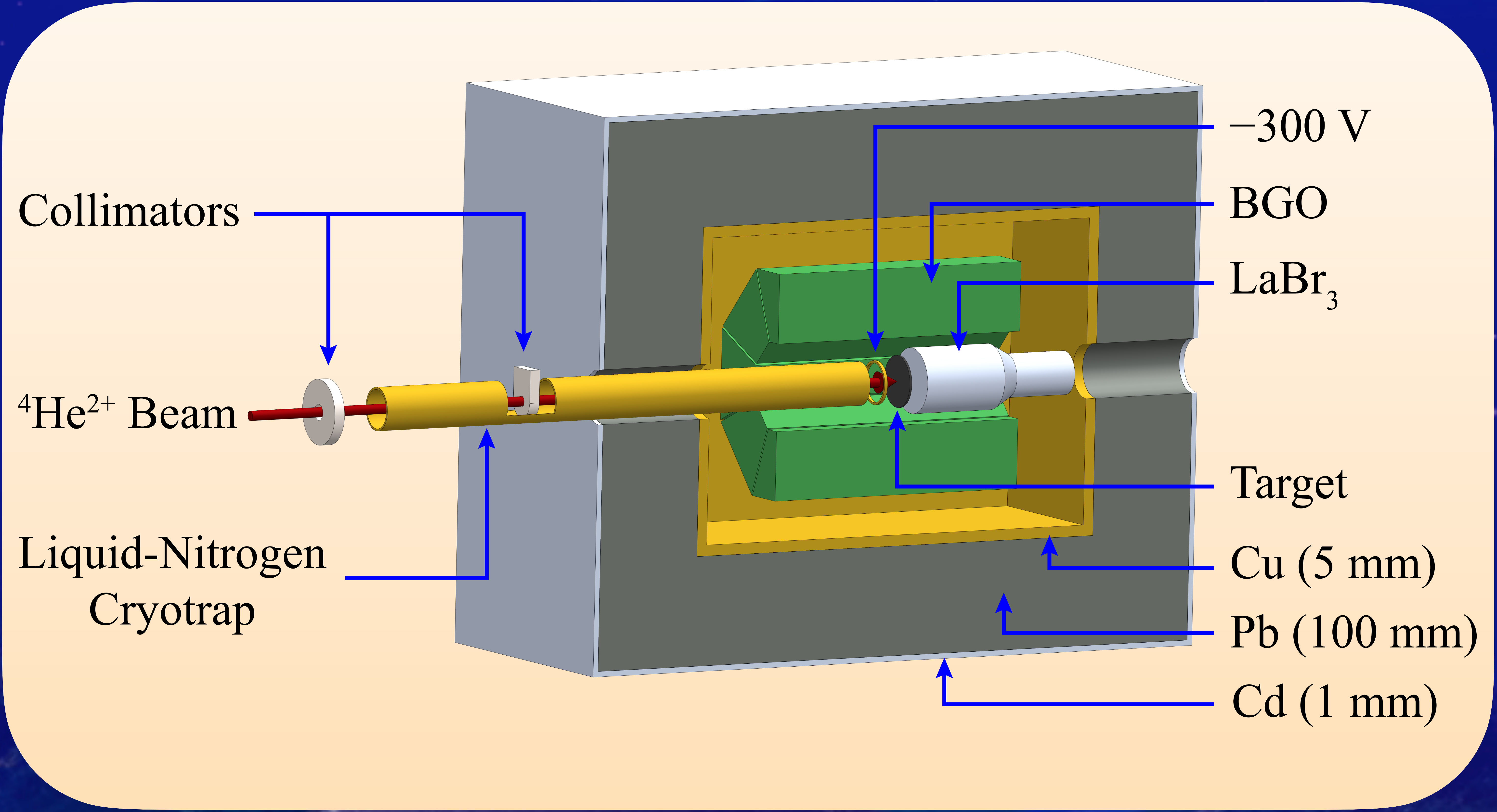
Indirect measurement → Ground high energy direct test → Underground background by C_{nat} target → Underground data taking





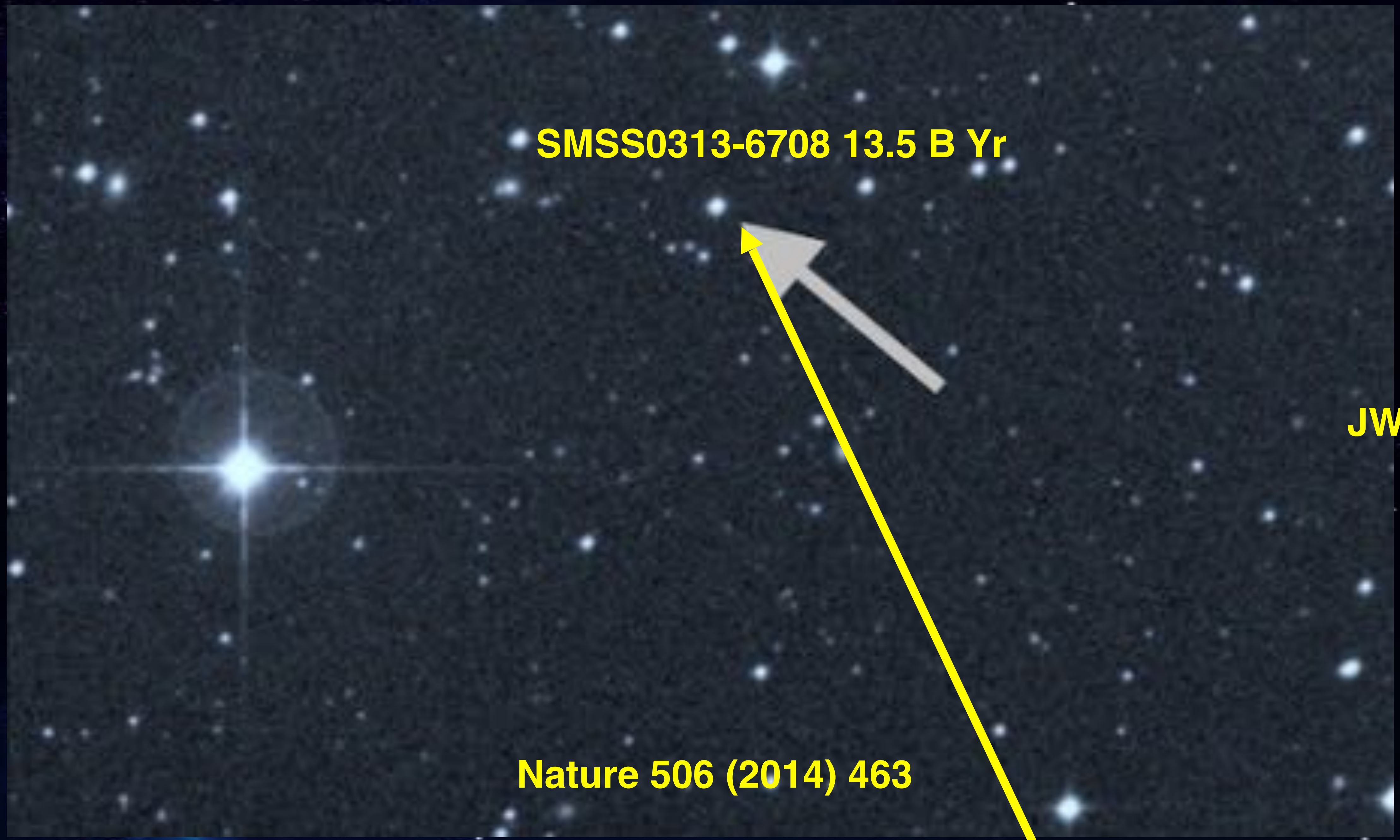
L. H. Wang et al., enriched ^{12}C targets, NIMB, 2021, accepted

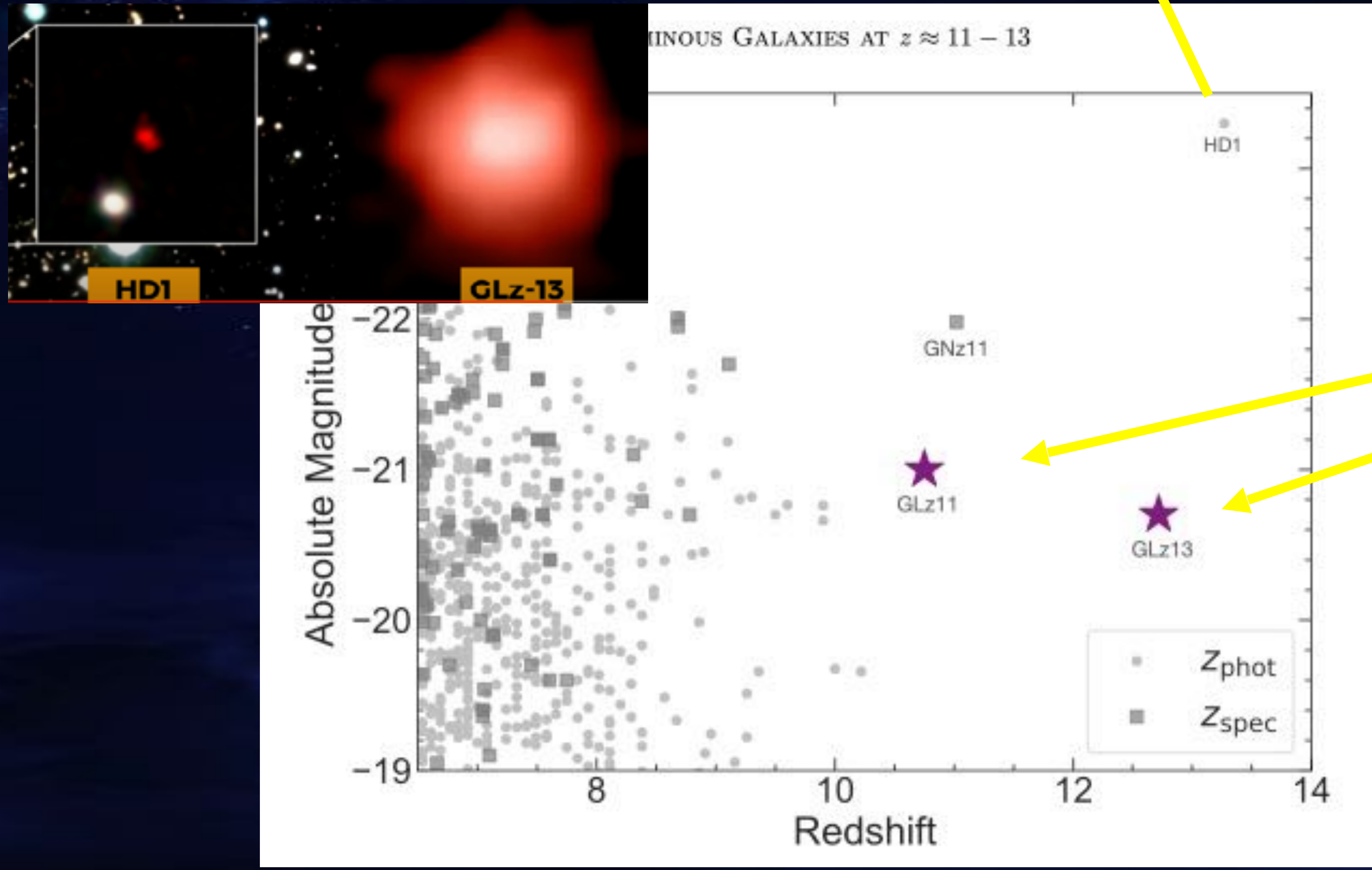
$^{12}C(\alpha,\gamma)^{16}O$ ： more sensitivity 最灵敏



- 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

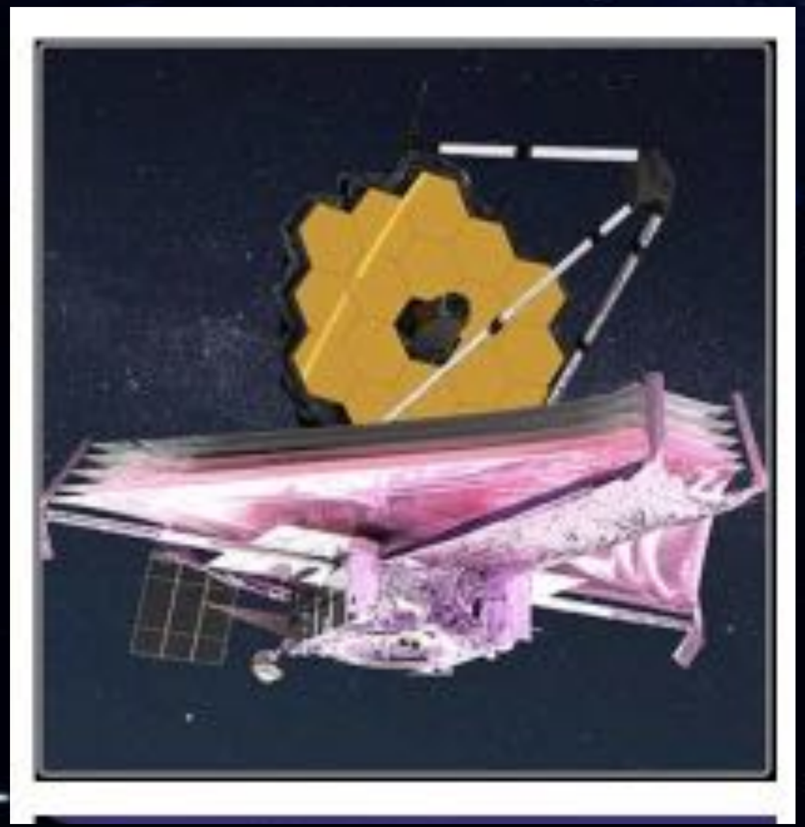
New excitement from JUNA $^{19}F(p,\gamma)^{18}Ne$: CNO break out, explain Ca in oldest known star

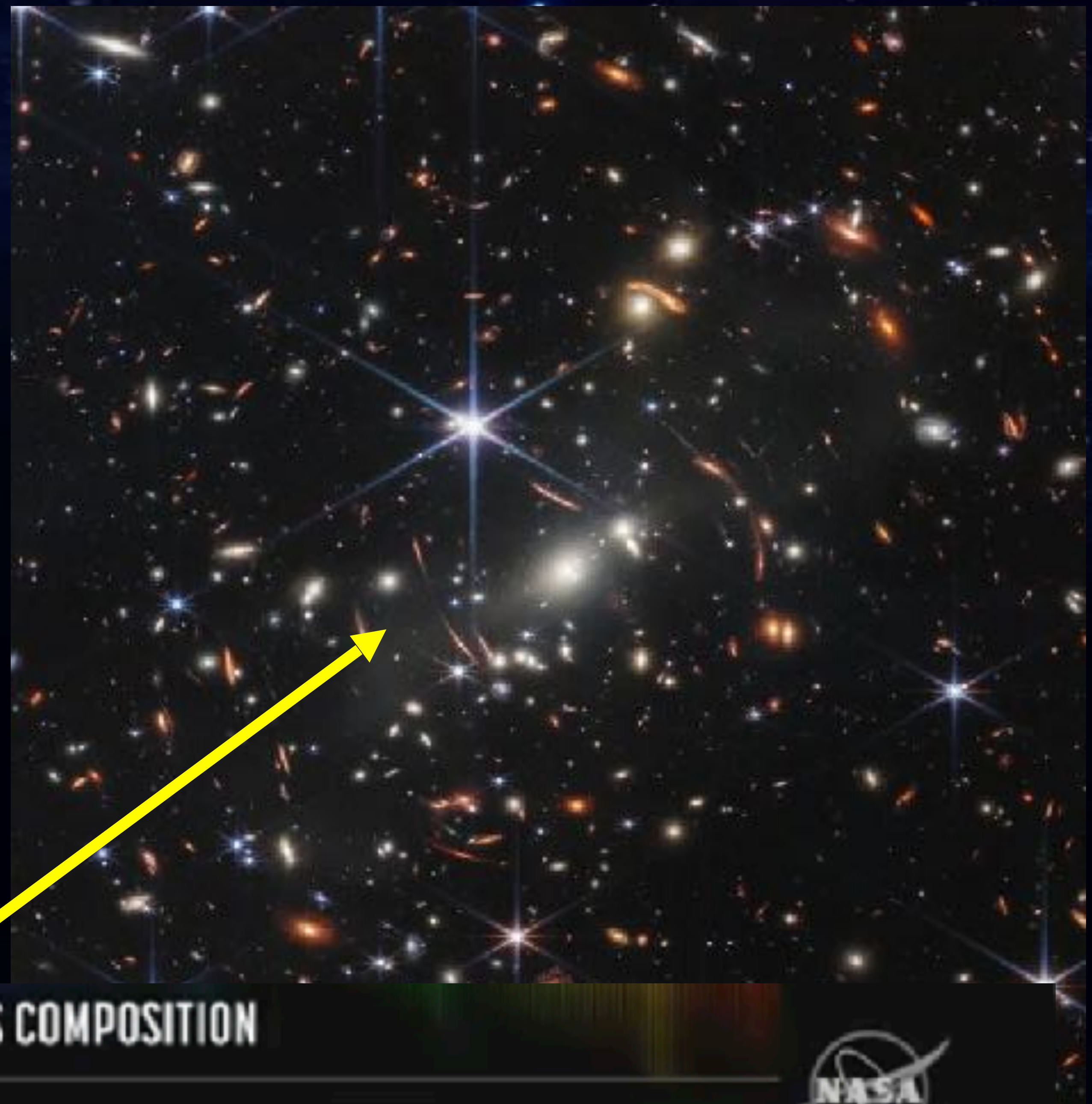


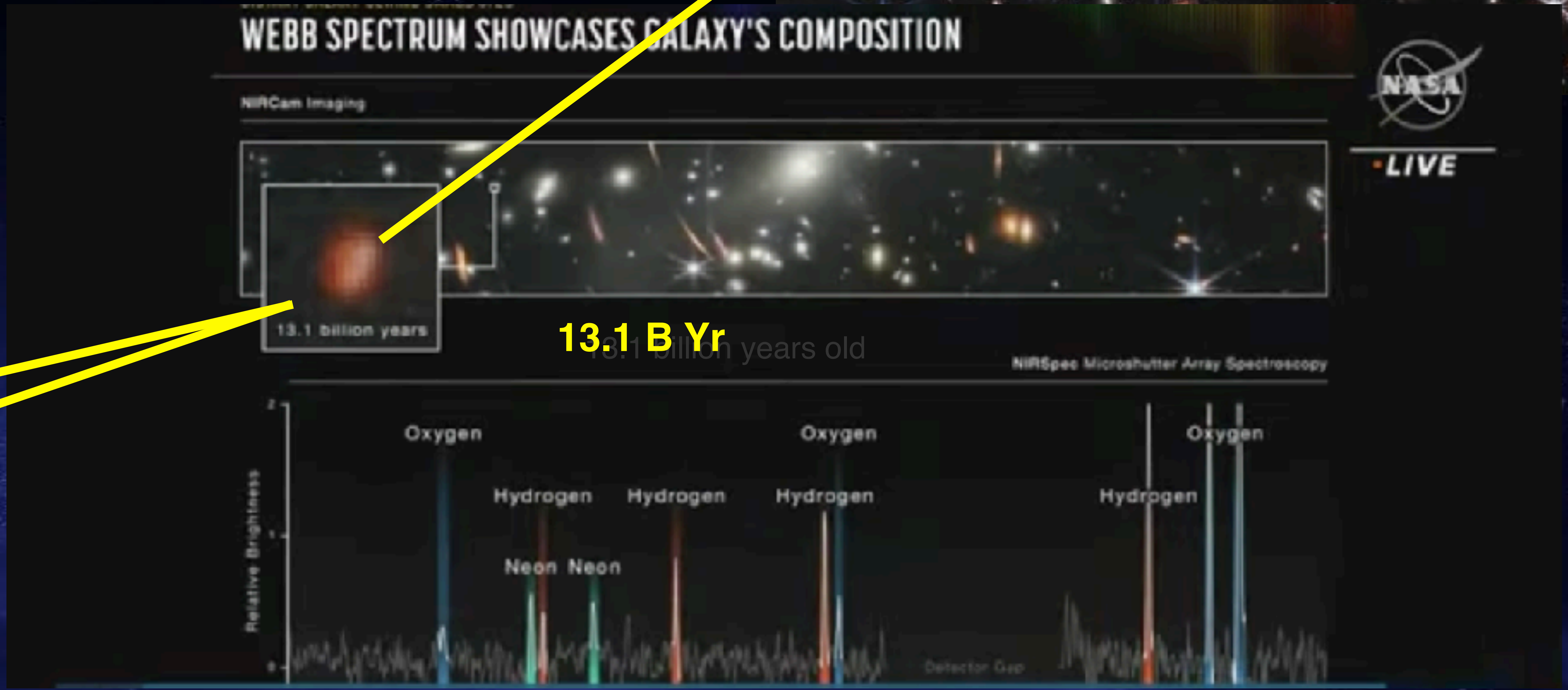


Rohan P. Naidu et. al., arXiv:2207.09434v1, July 2022

JWST

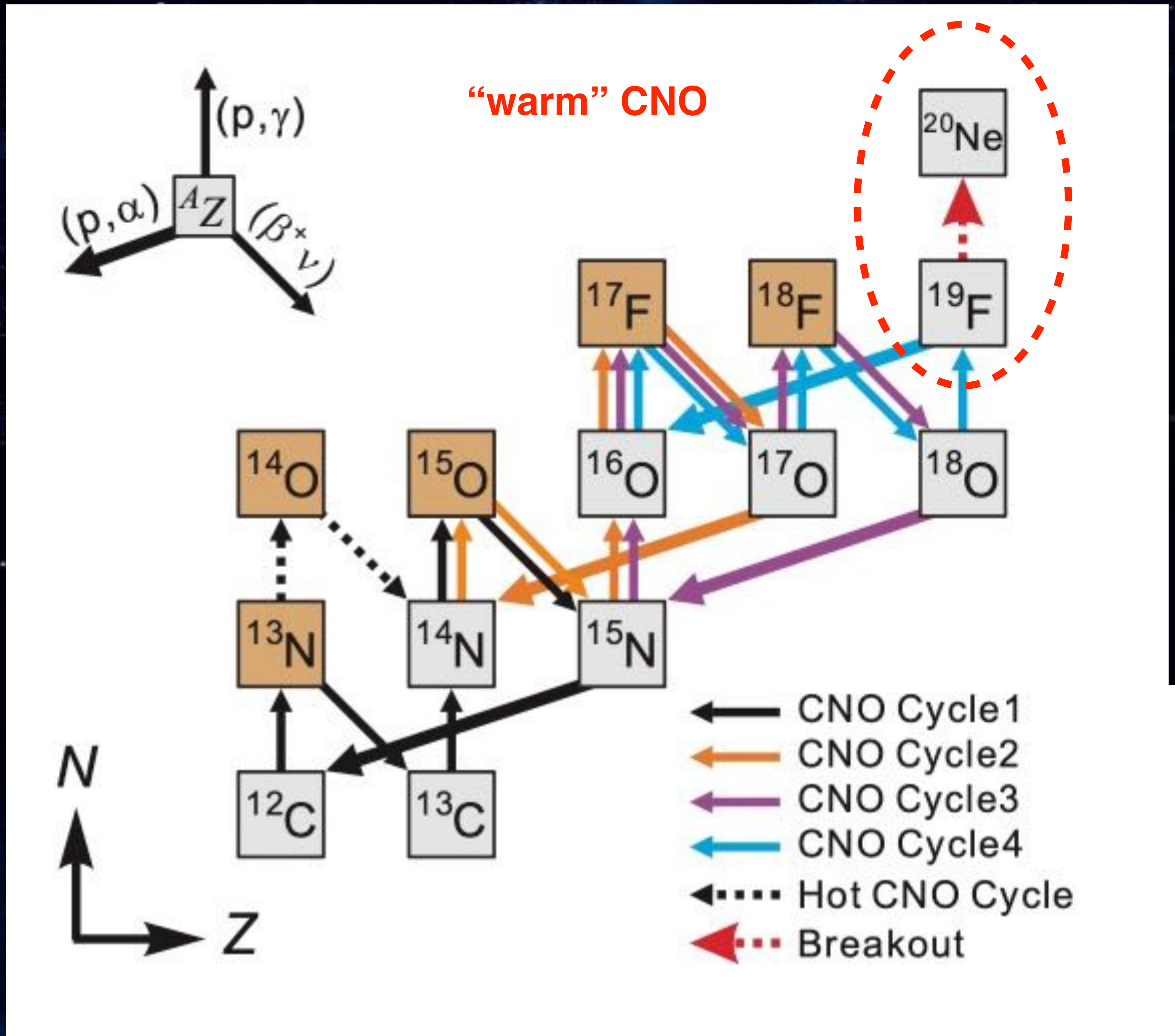


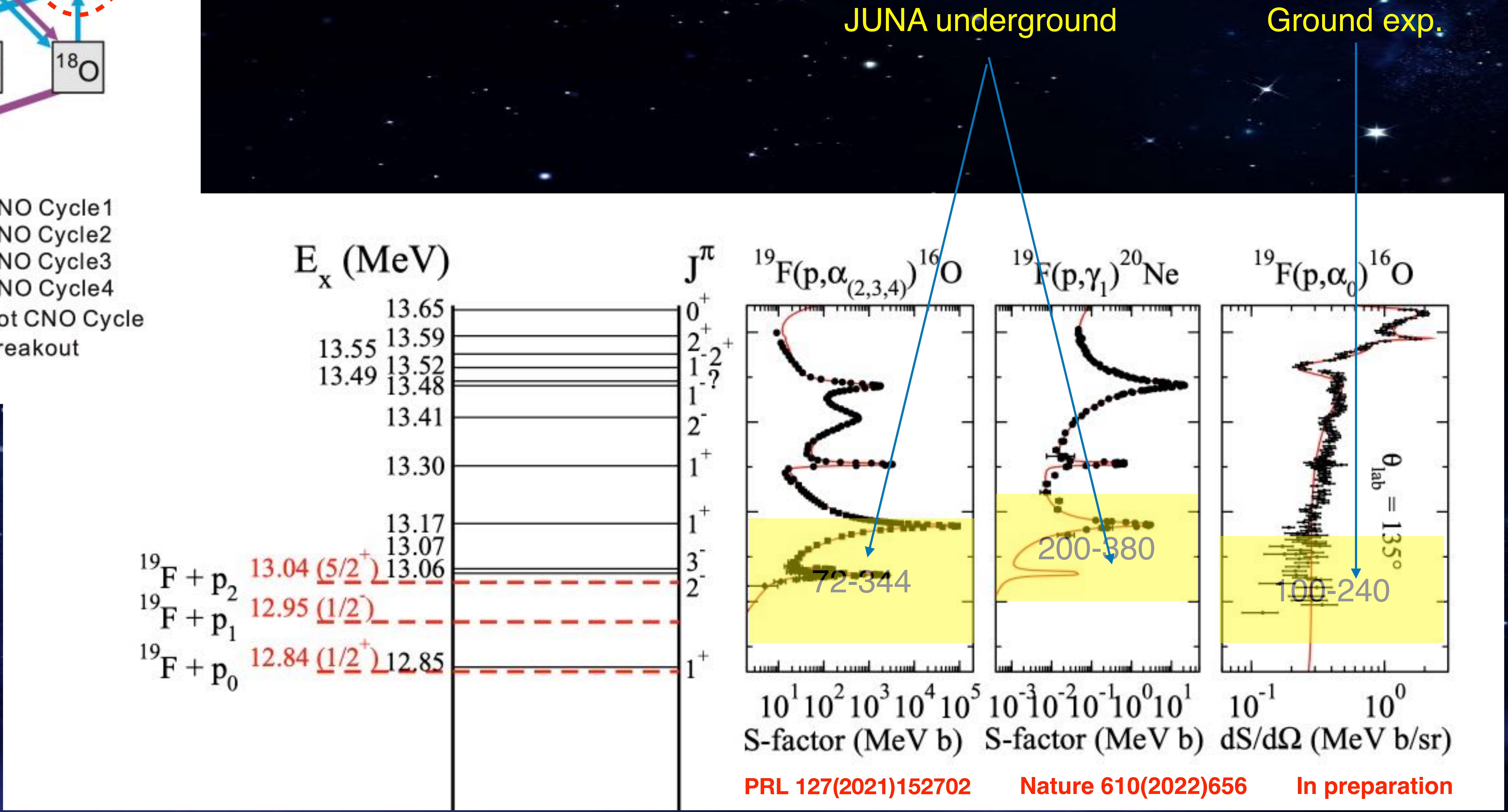




How to explain Ca “over” abundance in oldest known star: nuclear physics? astrophysics?

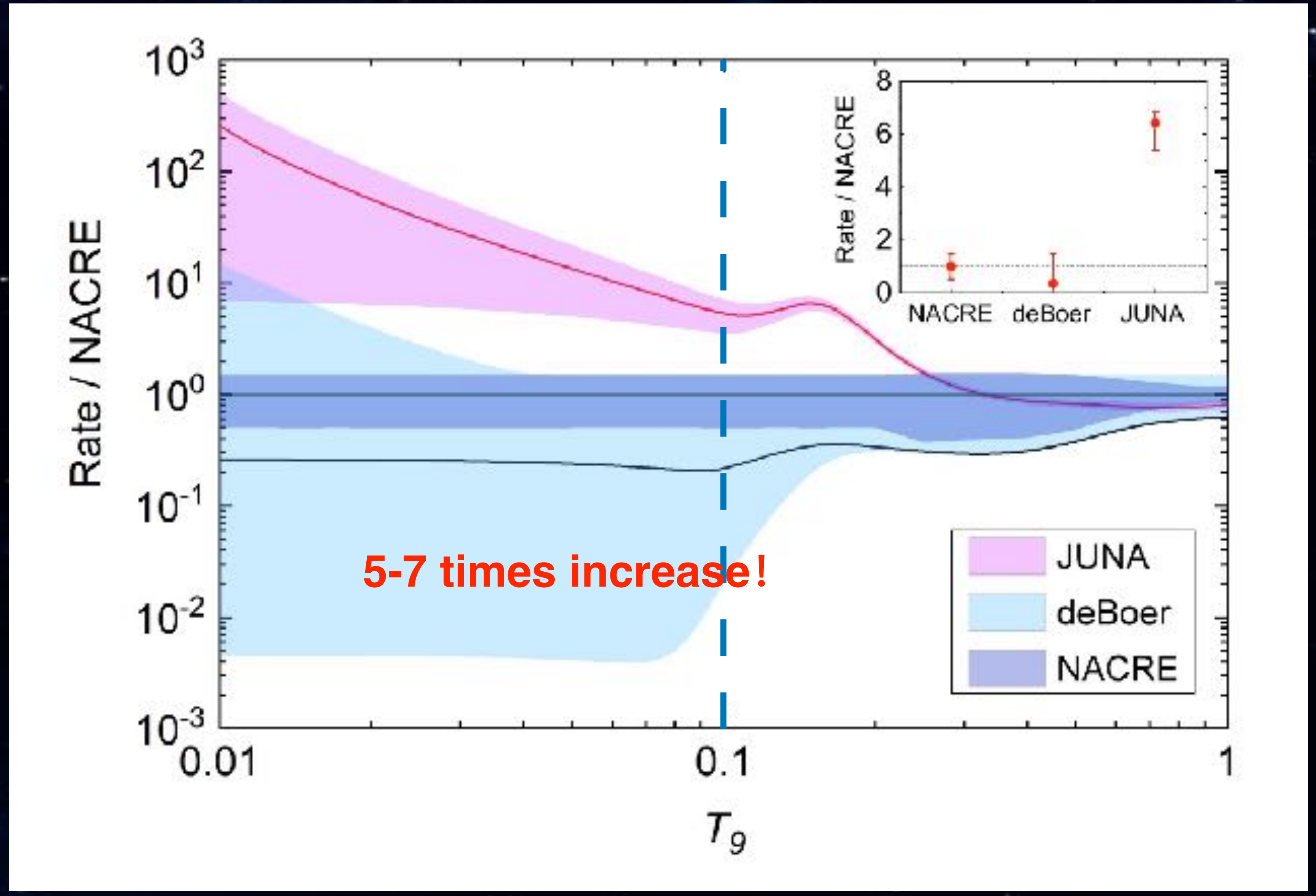
Systematic and simultaneous study of ^{19}F related reactions in Gamow window

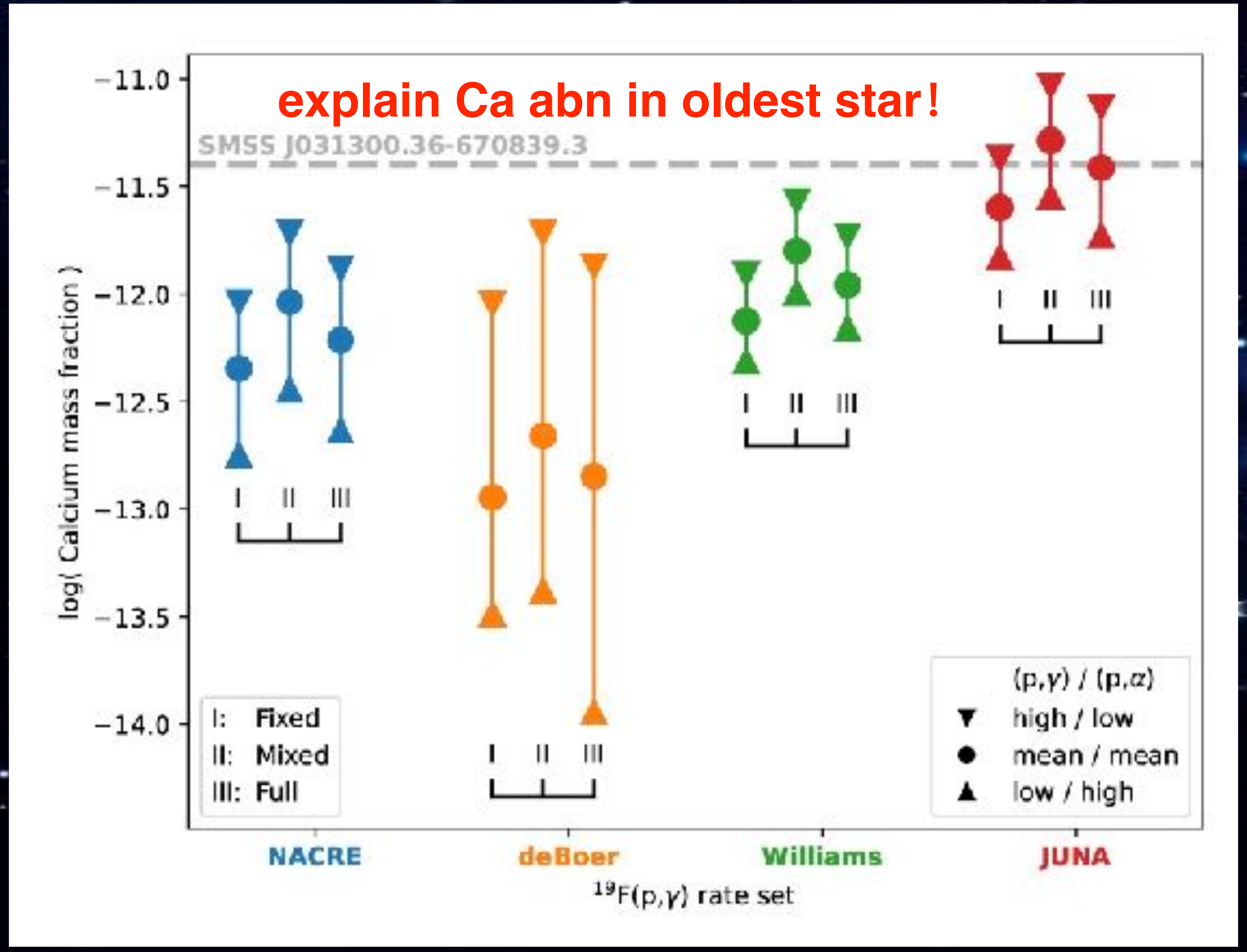




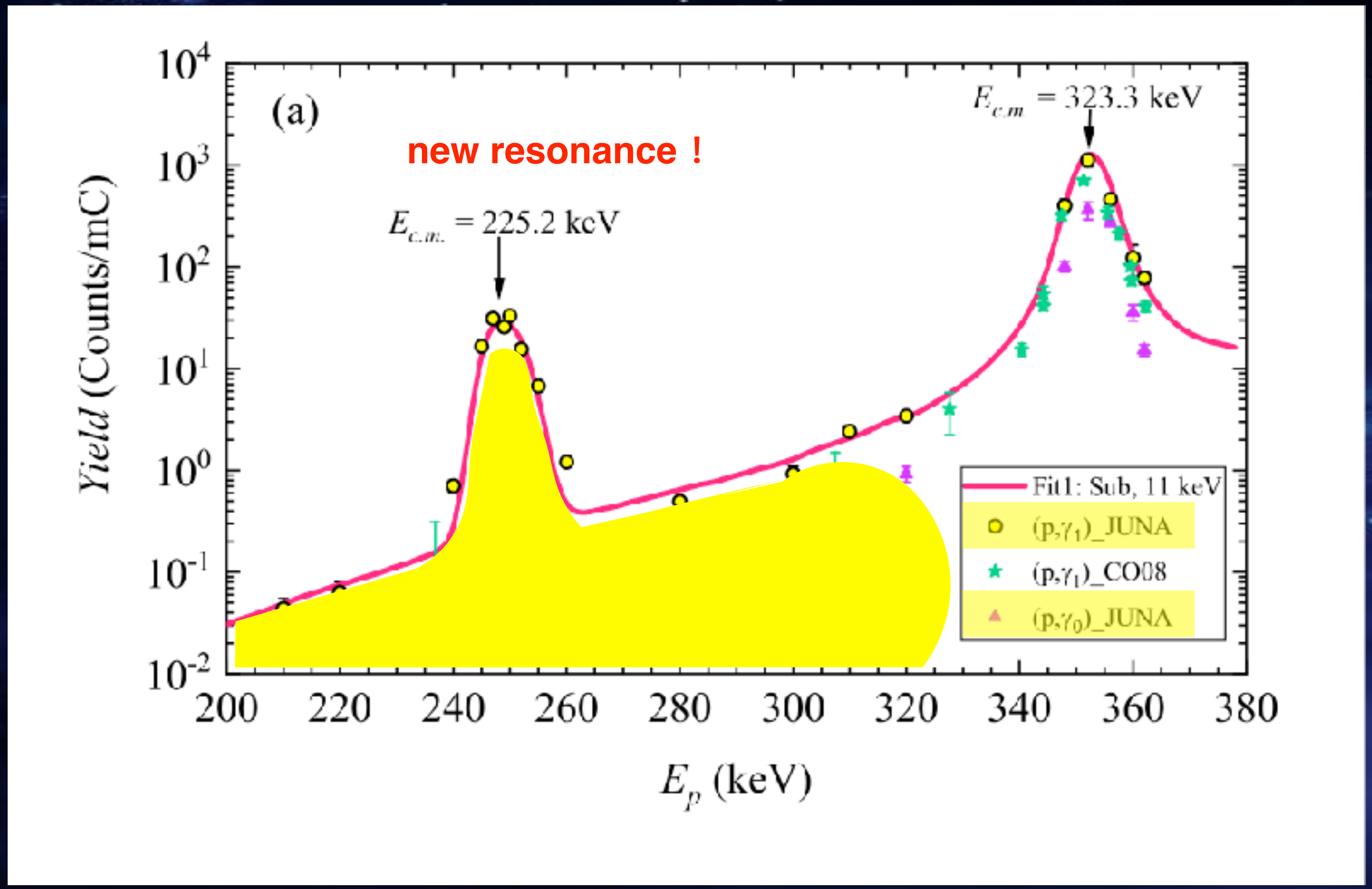
R. J. deBoer et. al., PRC **103**, 055815 (2021)

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

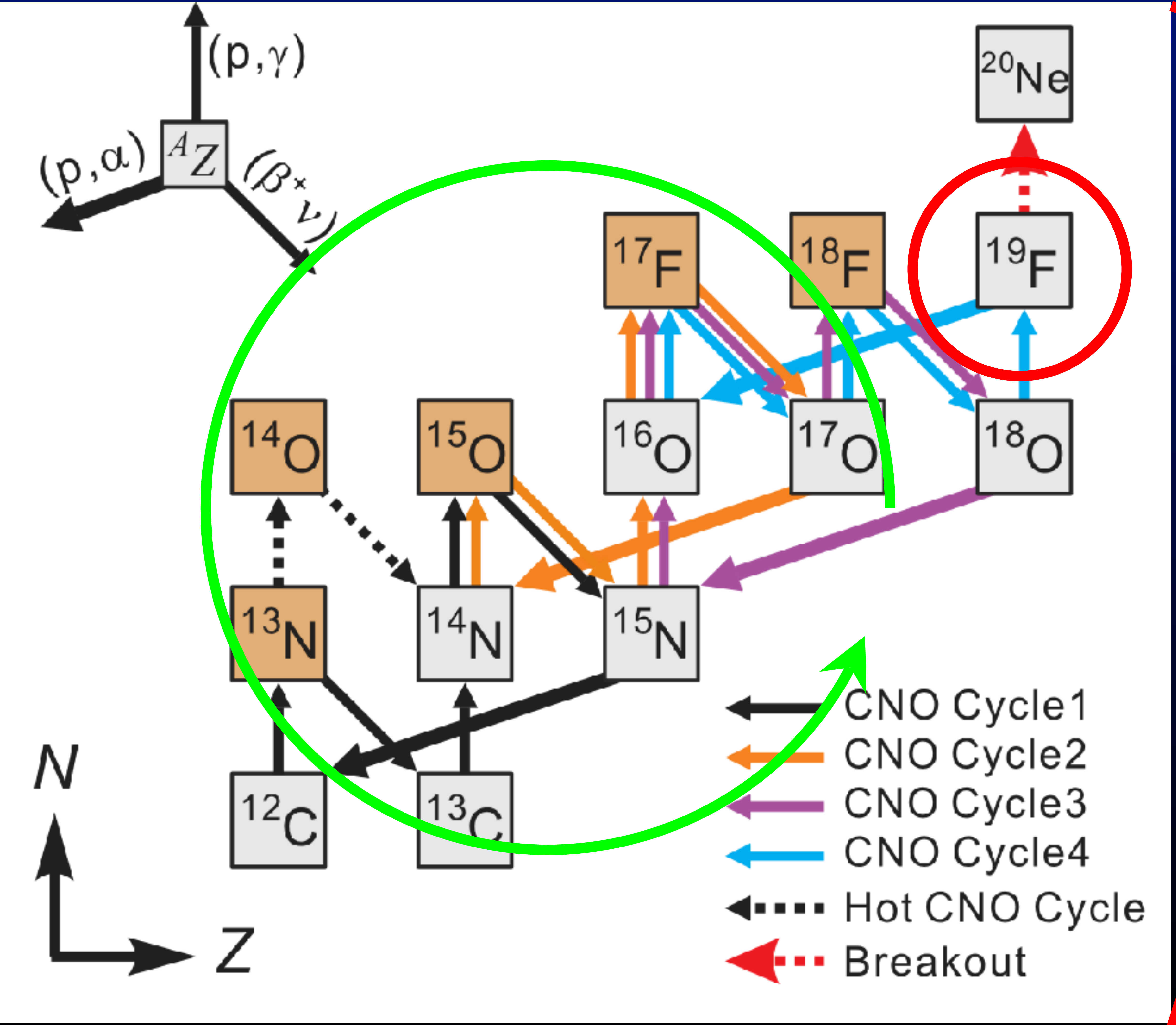
— Show fewer authors

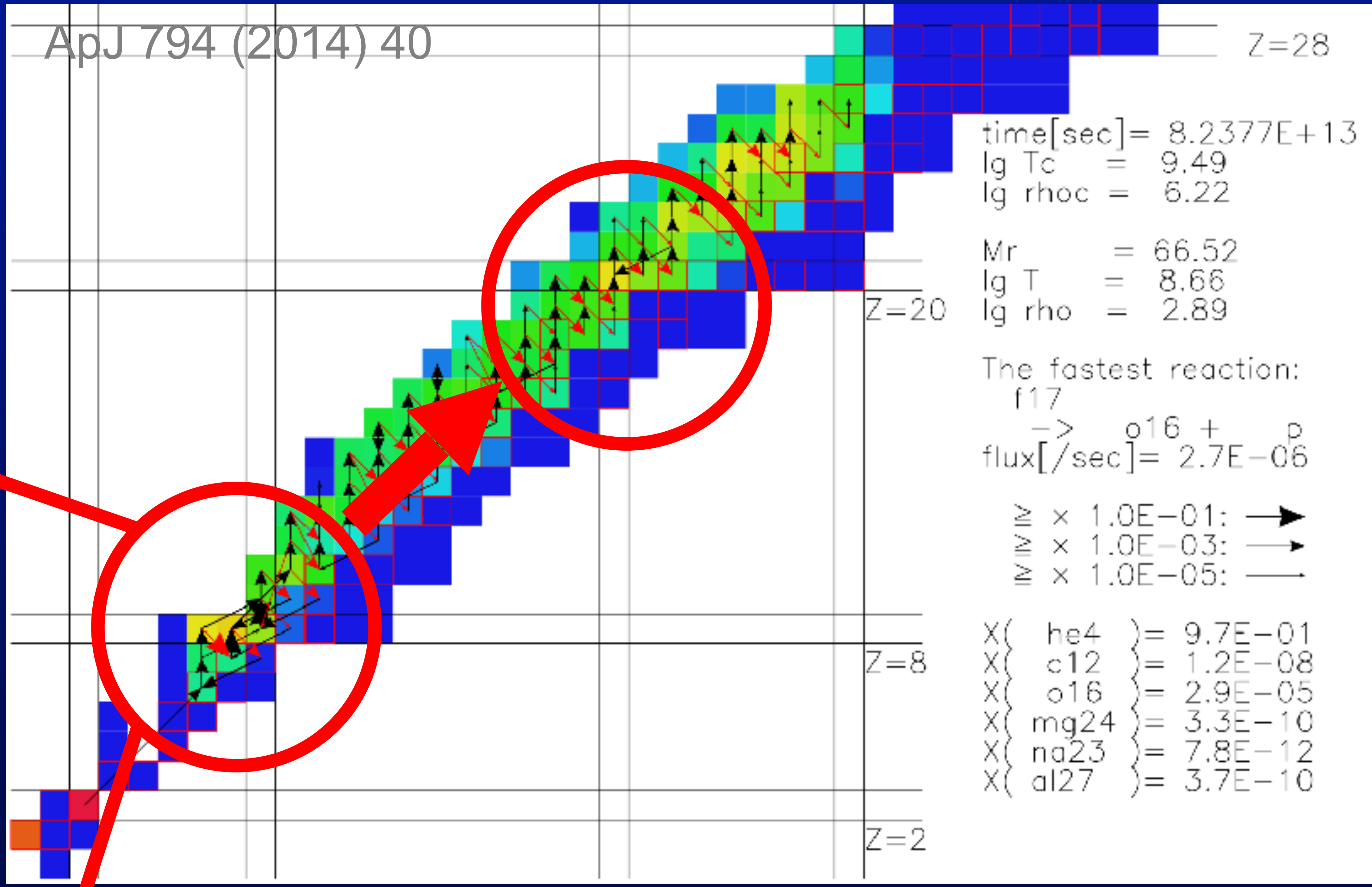
Nature 610, 656–660 (2022) | Cite this article

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

最古老恒星钙元素来源新途径

L.Y. Zhang, et al. (JUNA collaboration), Nature 610, 656-660 (2022)





CNO循环与Ca丰度

- 主要通过(p,α)反馈回CNO循环
- 1/10000 的^{19}F通过(p,γ)突破到A>20核区
- 最终影响双幻核^{40}Ca丰度

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

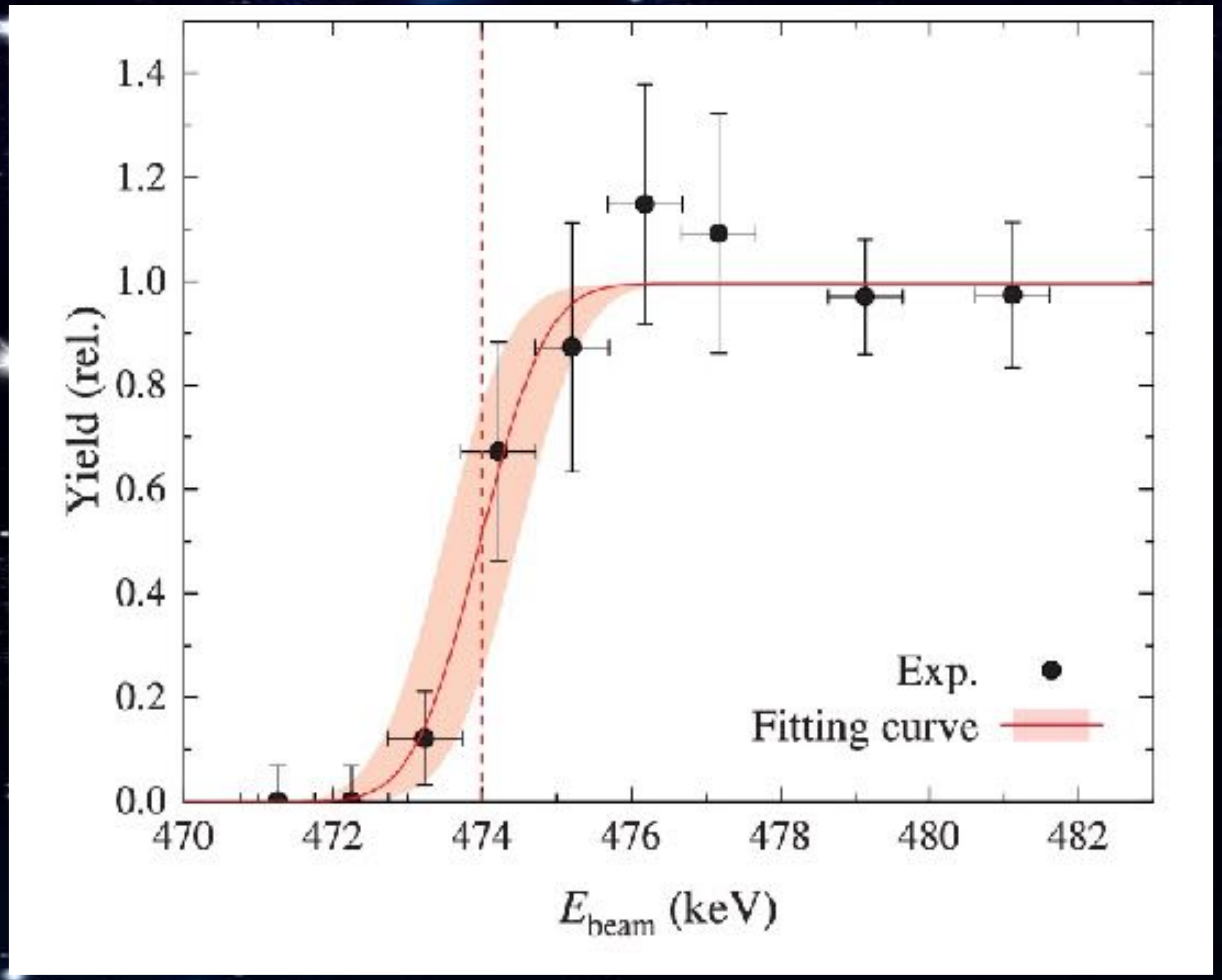
When the first stars in the Milky Way formed around 13 billion years ago, they consisted mainly of hydrogen and helium. But other chemical elements – the heaviest being calcium – have been detected in the atmosphere of one of the oldest-known stars, an amazing object known as SMSS0313-6708 that lies 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.

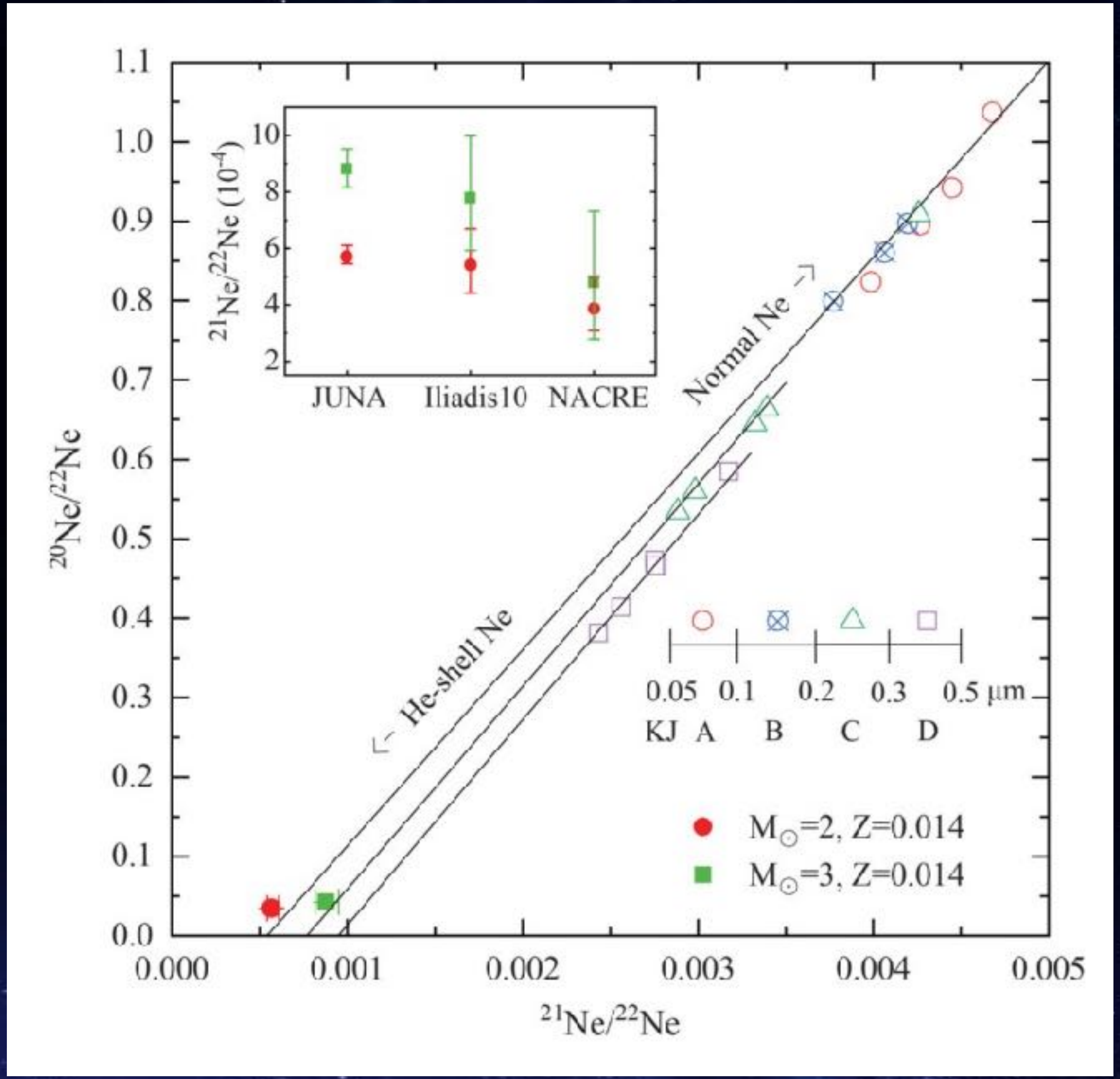
Marco Pignatari

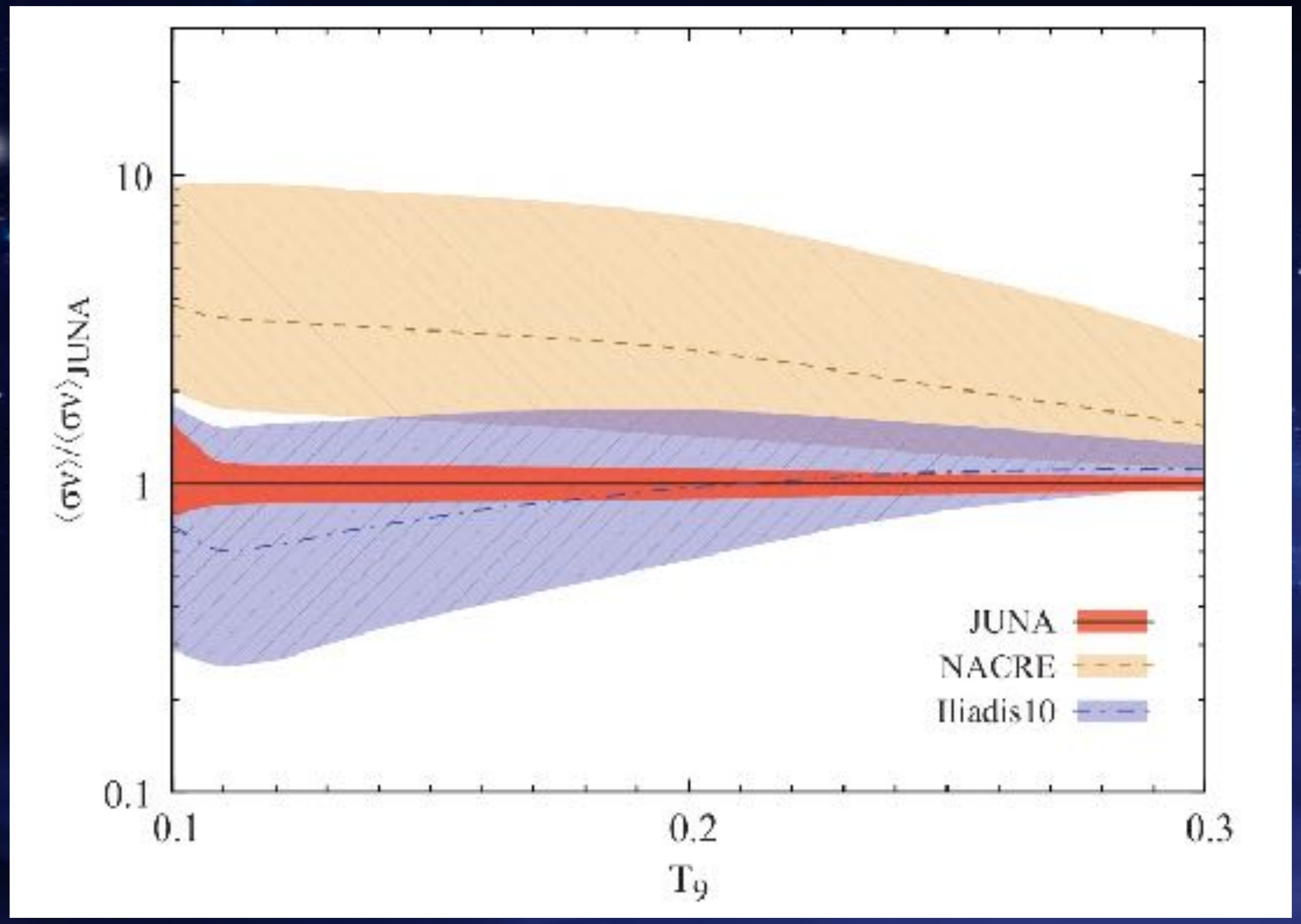
Athanaiscs. Psalits

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.





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

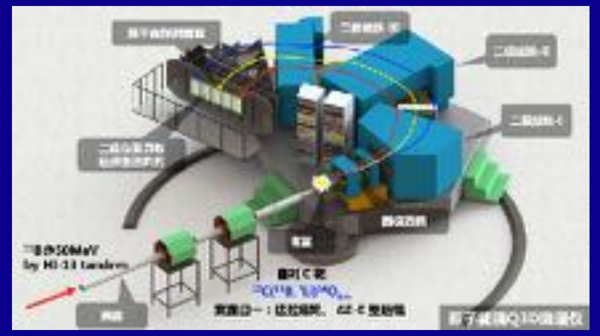
实现重要核天体测量国际最高灵敏度

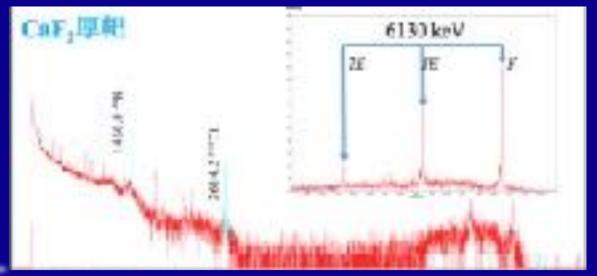
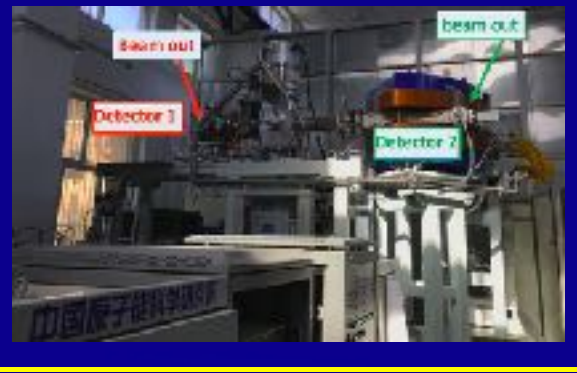
核天体物理反应	关键指标	国际之前实验	中国 JUNA实验	成果发表情况
大质量恒星形成反应 $^{12}C(\alpha,\gamma)^{16}O$	最低能量	891	552	国际最高灵敏度，70年来首次使圣杯反应接近天体能量窗口
	灵敏度 b	10^{-11}	10^{-12}	
重元素中子源反应 $^{13}C(\alpha,n)^{16}O$	能量范围 keV	230-300	240-1900	《物理评论快报》PRL，解决30多年的中子源强度的分歧
	测量精度	50-60%	15-20%	
星际 ^{26}Al 产生反应 $^{25}Mg(p,\gamma)^{26}Al$	测量精度	21%	8%	《科学通报》封面文章，取得最精确的伽马射线源的产生率
	累积束流量	410 库伦	1225 库伦	
F丰度反应 $^{19}F(p,\alpha g)^{16}O$	最低能量	189 keV	72 keV	《物理评论快报》PRL编辑推荐，排除氟丰度超出的核物理不确定性
	测量精度	80%	5%	
CNO 泄露反应 $^{19}F(p,\gamma)^{20}Ne$	最低能量	300 keV	200 keV	《自然》Nature 国内核物理装置首篇，首次解释最古老恒星钙丰度疑难

实现了核天体物理实验地面地下空间有机结合
From ground to underground to space

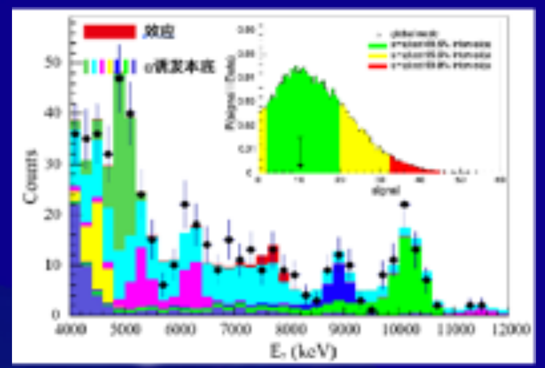
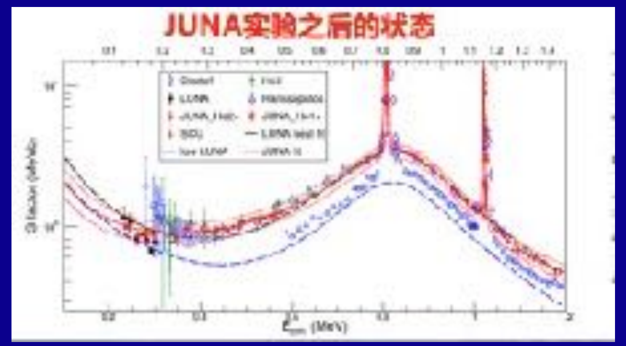
锦屏深地核天体物理实验
Jinping Underground Nuclear Astrophysics Experiment

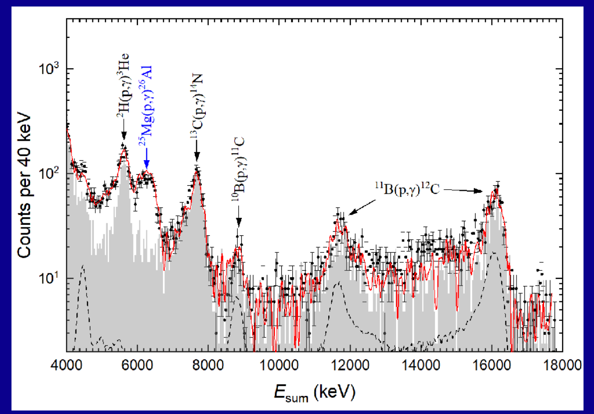
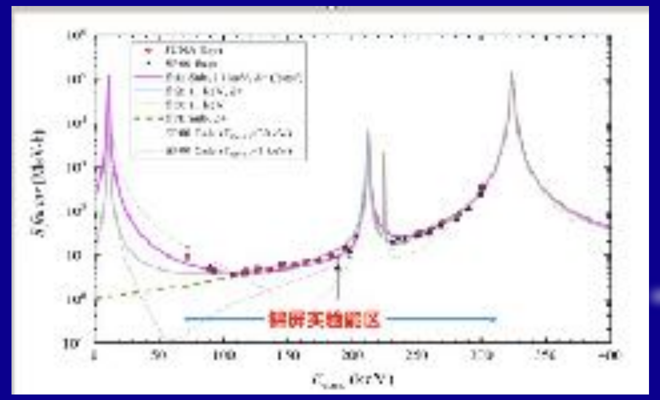
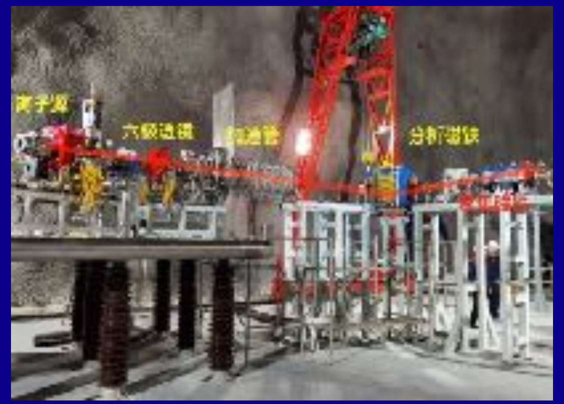
	$^{12}C(\alpha,\gamma)^{16}O$	$^{13}C(\alpha,n)^{16}O$	$^{25}Mg(p,\gamma)^{26}Al$	$^{19}F(p,\alpha\gamma)^{16}O$	JUNA platform
ground	sub-threshold constrain PRL124(2020)16270 CIAE	sub-threshold constrain APJ756(2012)193 CIAE high energy point SCU	58 keV in-direct measurement SC58(2015)082002 CIAE	high energy point CIAE Hefei	high energy test CIAE



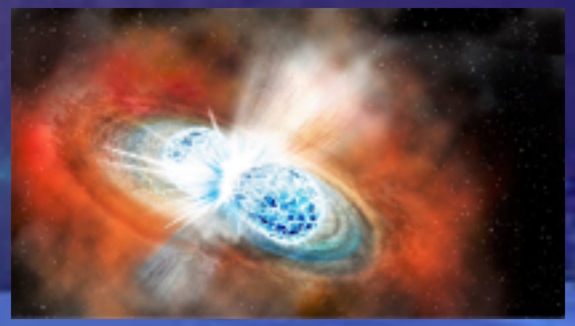
JUNA underground

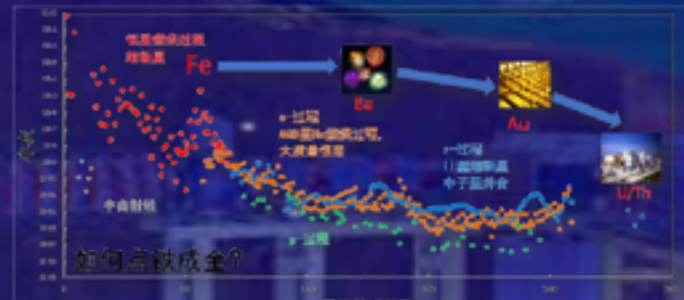



552 keV higher sensitivity	240 keV直接测量 PRL 2022 in press	93 keV precise rate SB 67(2022)125	72 keV cover Gamow window PRL127(2021)152702	underground operation SC59(2016)642001

space


neutron star merger


heavy element synthesis

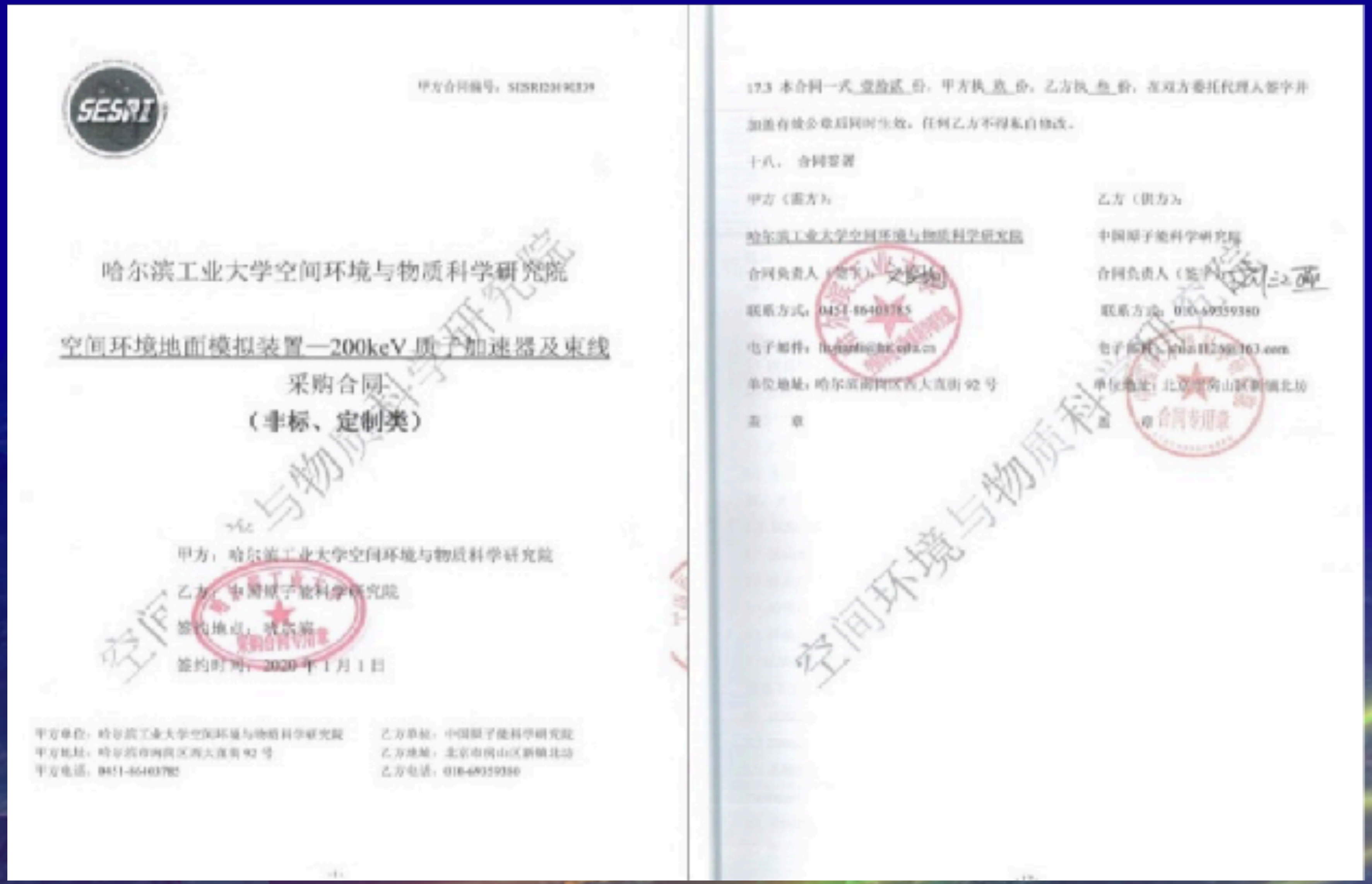
gamma ray astronomy


Jame Webb telescope

JUNA2022

掌握强流高压加速器完全自主知识产权

- **建立最强流深地加速器，取得国际领先的核天体物理研究成果**
- **突破强流高压加速器的技术，**打破国际封锁，在深地核天体物理实验、核心电子元器件研发等方面得到应用
- **发展先进伽马和中子探测器。**用于核天体物理实验和核数据测量
- **取得3项发明专利，**4项实用新型专利
- **满足国际科技前沿探索和国家战略需求，两个面向**



国内外专家的高度评价

- 中国核学会王寿君理事长、科工局刘永德总工、中核集团马文军副总经理、罗琦院士、于俊崇院士亲临现场鉴定
- 詹文龙、高原宁、邹冰松、王赤、黄国俊、赵军、杨大助等院士专家鉴定委员会：**“建成了国际最高灵敏度的锦屏深地核天体物理实验平台”**
- 入选2021年中国核学会和中核集团十大新闻

CCTV朝闻天下
重点报道

中国科学报
头版头条

- 欧洲射线天体物理实验室负责人罗兰·戴尔：**“这是一个重大成就”**
- 美国核天体物理联合会前主席迈克尔·威彻：**“毫无疑问，你们站到了领先地位”**
- 日本国立天文台梶野敏贵教授：**“JUNA设施目前在地下核天体物理学的精确测量方面处于世界前列”**

JUNA团队杰出人才情况 young talent via JUNA （2015-2022）

- 柳卫平，团队/成就奖：Liu Weiping, 2021 Nuclear Society Outstanding Achievement Award；2019 CNSA Innovation Team Award

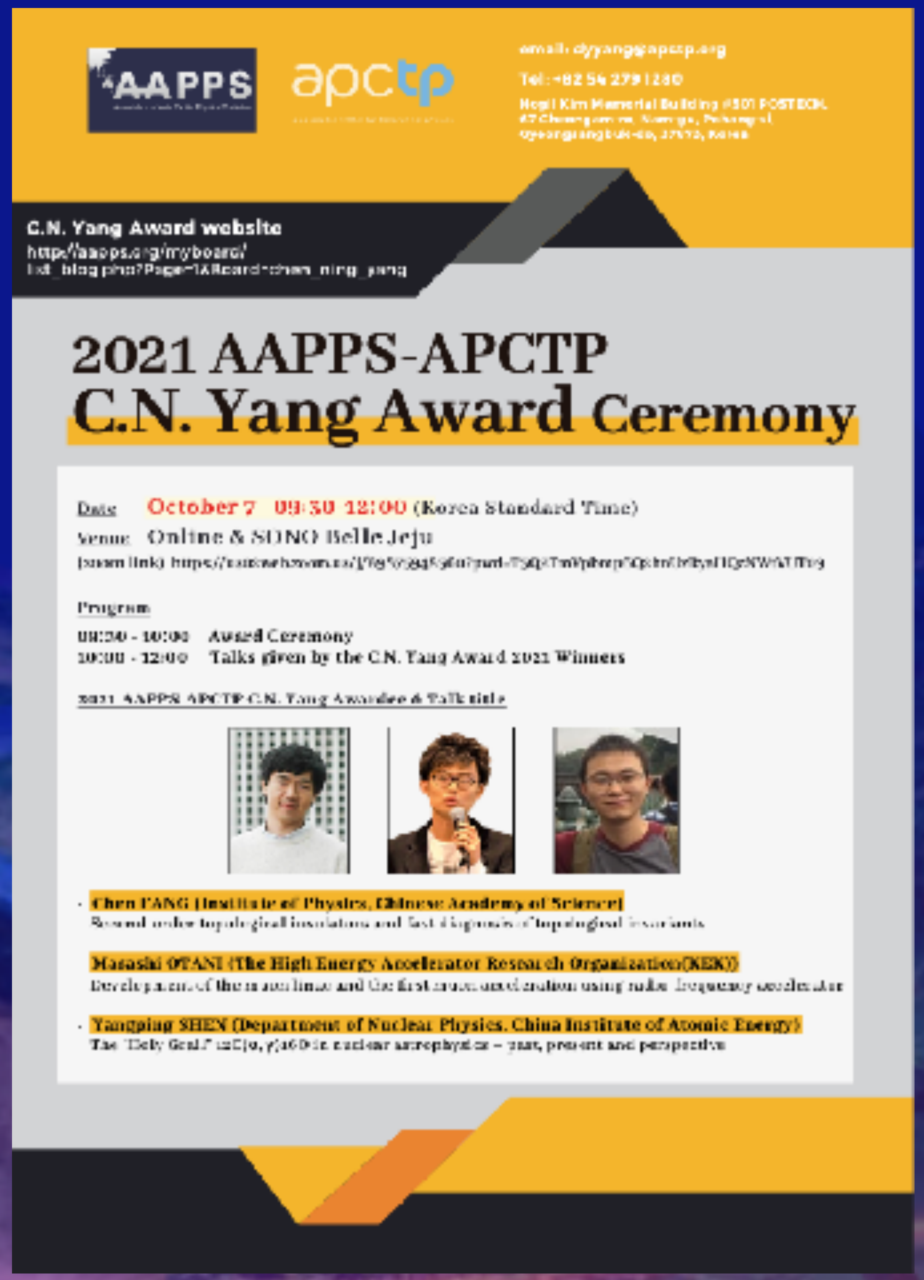
- 郭冰，杰青/吴有训奖：Guo Bing, 2020 Chinese Physical Society Wu Youxun Award；2021, NSFC distinguished Young Scholars

- 何建军，杰青，He Jianjun 2019

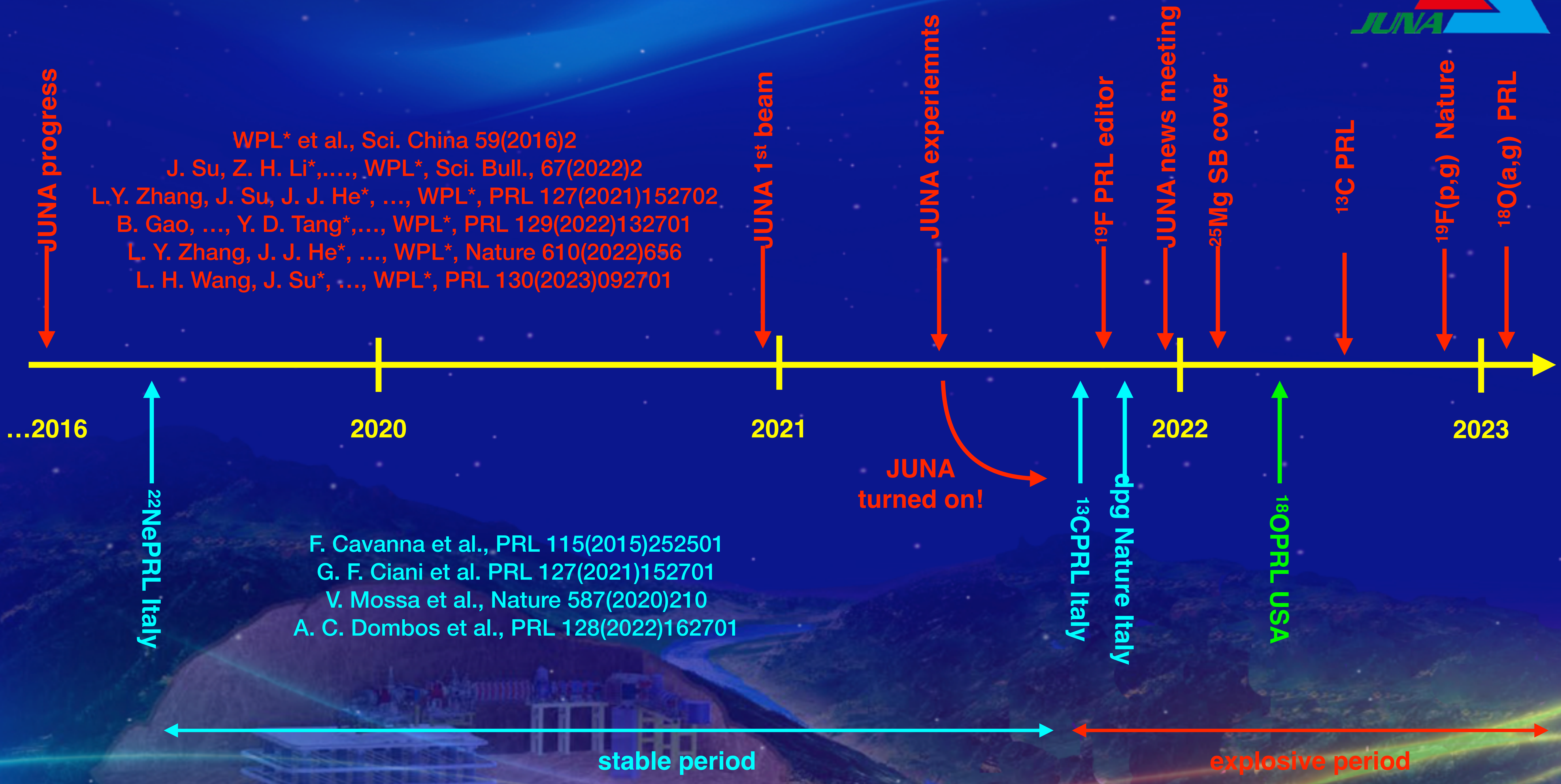
- 孙良亭，杰青：Sun Liangting 2020

- 唐晓东，首席：Tang Xiaodong 2016, Chief Scientist of National Key R&D fund

- 谌阳平，优青/杨振宁奖：Shen Yangping, 2021 Asia-Pacific Physical Society C. N. Yang Award, 2022 Young talent from NSFC



激发国际深地核天体物理发展 simulating effect



国际地位的显著提升，但需要尽快升级方可保持领先

- **M. Wiescher, former JINA chair**

➢ LRP 2015: "A high intensity underground accelerator would be essential for addressing the broad range of experimental questions associated with the nucleosynthesis in stars."

➢ Underground accelerator? **Yes, but the train is leaving the station**, funding for participation in Europe or Asia will help to maintain the scientific role and impact of the US community!

- 高强度加速器是研究恒星元素合成的广泛实验问题的基础条件；深地加速器很必要，但是火车已经出发，如果要保持美国的科学影响力需要经费支持，参加欧洲或亚洲的平台

- 深地加速器的技术创新来保持美国的领先，在短期需要提供经费与欧洲和亚洲合作

➢ **Underground accelerator?** An underground accelerator laboratory of novel design would be necessary to maintain if not regain US leadership. To maintain some scientific role and impact of the US community in the short term, bridge funding for participation in European or Asian efforts are needed!


锦屏深地核天体物理实验
JUNA
Jinping Underground Nuclear Astrophysics Experiment
400 kV
800 kV
6m
15m
5.1m
JUNA
Super JUNA

JUNA and Super JUNA coverage

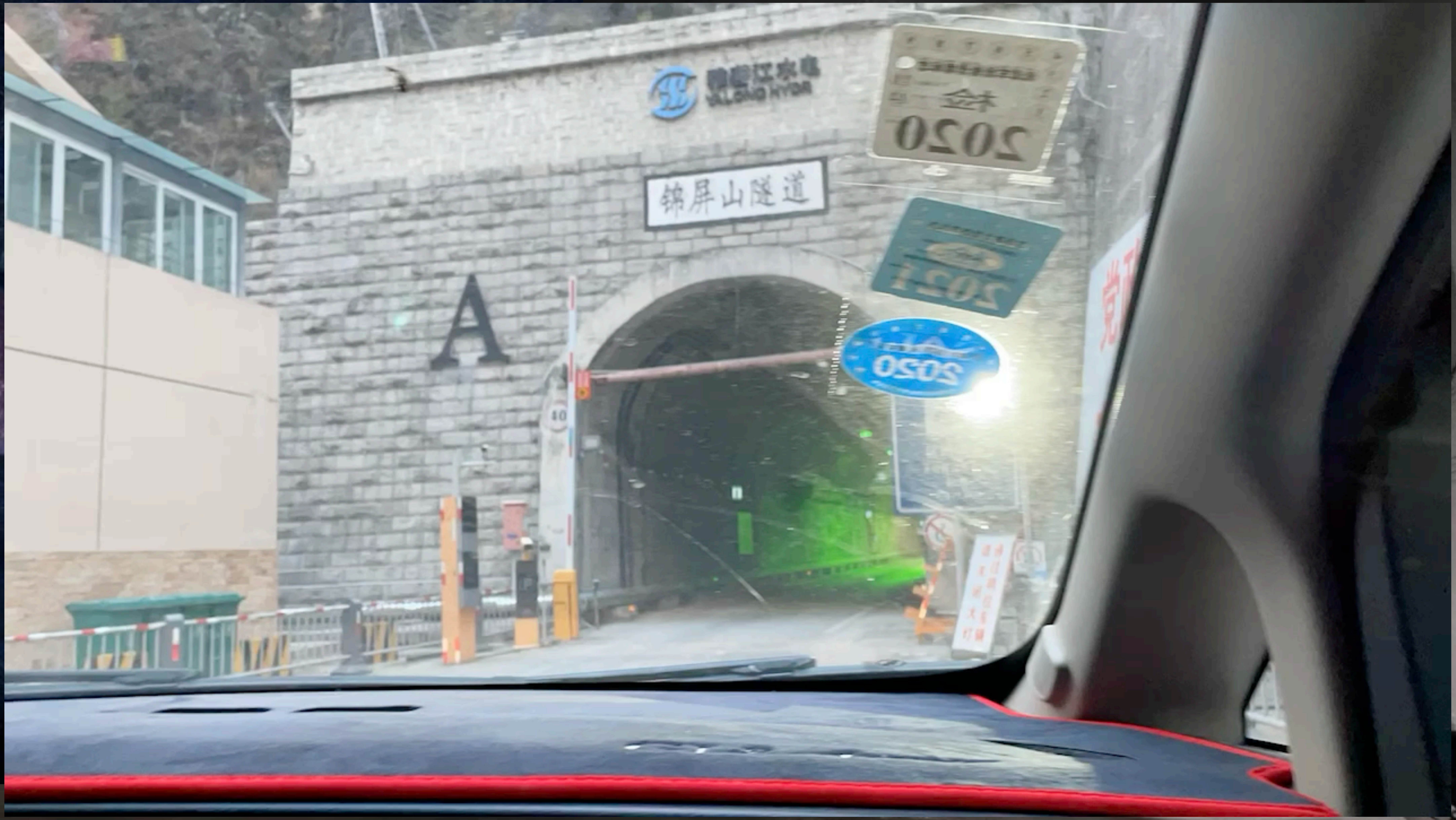
H burning	He burning	N source	C\O burning
$^{7}Be(p,\gamma)^{8}B$	$^{12}C(\alpha,\gamma)^{16}O$	$^{13}C(\alpha,n)^{16}O$	$^{12}C+^{12}C$
$^{12}C(p,\gamma)^{13}N$	$^{16}O(\alpha,\gamma)^{20}Ne$	$^{22}Ne(\alpha,n)^{25}Mg$	$^{12}C+^{16}O$
$^{14}N(p,\gamma)^{15}O$	$^{20}Ne(\alpha,\gamma)^{24}Mg$	$^{25}Mg(\alpha,n)^{28}Si$	$^{16}O+^{16}O$
$^{15}N(p,\gamma),(p,\alpha)^{16}O,^{12}C$	$^{18}O(\alpha,\gamma)^{22}Ne$	$^{26}Mg(\alpha,n)^{29}Si$	γ天文学
$^{17}O(p,\gamma),(p,\alpha)^{18}F,^{14}N$	$^{22}Ne(\alpha,\gamma)^{26}Mg$		$^{25}Mg(p,\gamma)^{26}Al$
$^{18}O(p,\gamma),(p,\alpha)^{19}F,^{15}N$	$^{24}Mg(\alpha,\gamma)^{28}Si$		$^{26}Al(p,\gamma)^{27}Si$
$^{19}F(p,\alpha)^{16}O$			

JUNA achieved

Super JUNA proposed

一起穿越时光隧道，探寻宇宙演化密码

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



总结

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

- **核天体物理是国际前沿交叉学科，深地核天体物理是目前核天体领域的前沿方向，还存在很多未解之谜**
  大量关键反应需要深地低本底环境开展可靠的直接测量，中美欧竞争激烈

- **我国科学家抓住机遇，努力拼搏，把JUNA建成国际先进水平的深地核天体物理实验平台**
  强流加速器，低本底高效率中子、伽马、带电粒子探测阵列，使我国继意大利和美国之后具备了开展深地核天体物理反应直接测量能力。

- **JUNA取得了优异的成果建立深地核天体物理反应直接测量实验技术，精确测量了多个关键核天体物理反应**束流强度、探测器效率、反应靶曝光量、实验的灵敏度和能量覆盖都达到国际最好水平。成果入选Nature亮点文章、PRL编辑推荐文章、Sci. Bull. 封面文章和2020年度中国核学会十大新闻。发表高水平研究论文60余篇，获6项专利授权，基金委重大项目结题评为A级

- **JUNA未来将建设国际领先的深地核天体平台，覆盖更多关键反应，成为中国锦屏地下实验室对外开放的窗口之一，未来可期，希望更多的老师和同学参加的深地核天体物理的行业中来！**

JUNA团队 Team

- 中国原子能科学研究院：柳卫平（南科大），李志宏，连钢，崔保群，郭冰，陈立华，颜胜权，李云居，张龙，曹富强，廖俊辉，曾晟，谌阳平，张昊，陈晨，南巍，南威克，李歌星
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- 中山大学：方晓，安振东

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- 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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F. Strieder （南达科达矿业理工学院）

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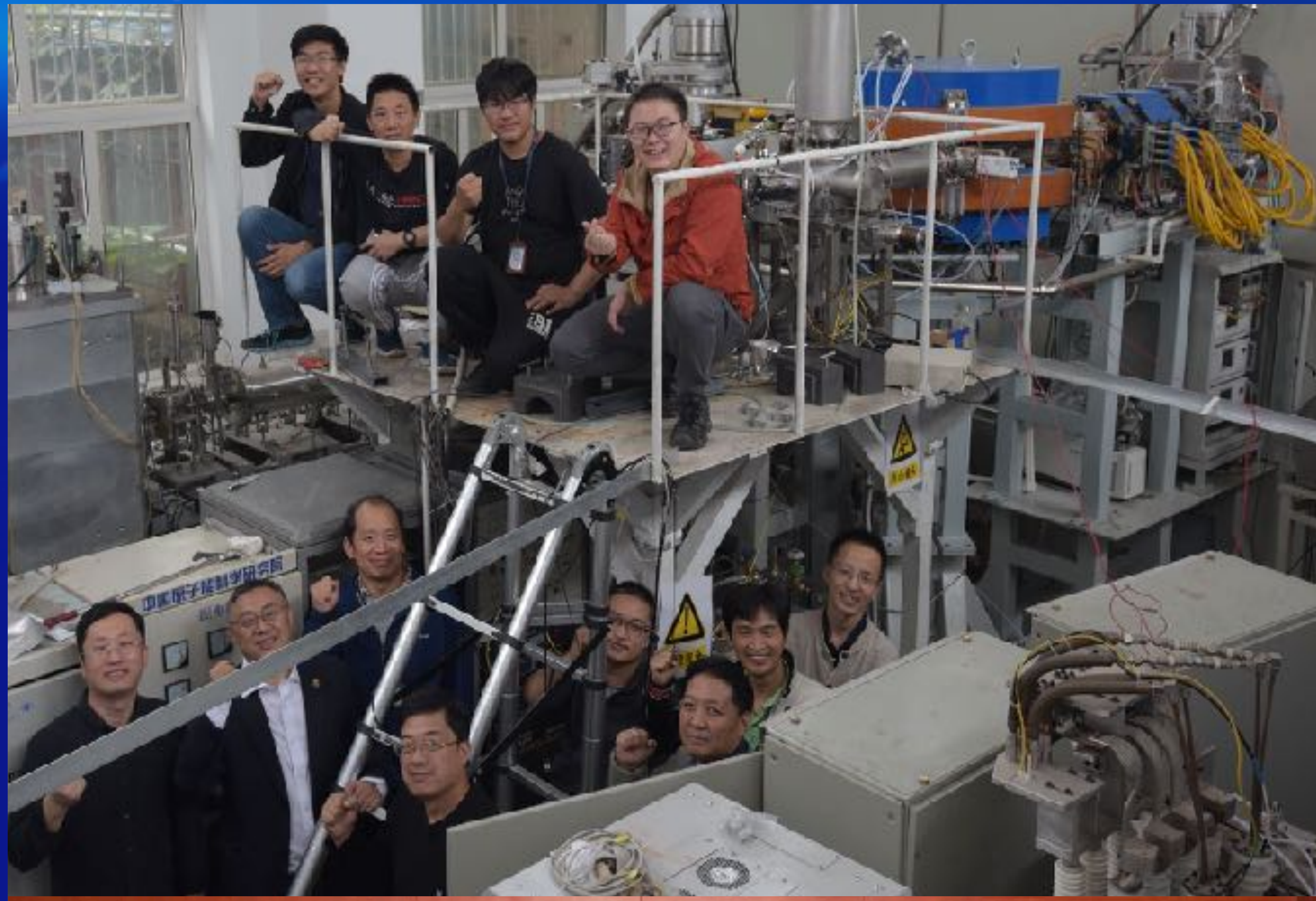
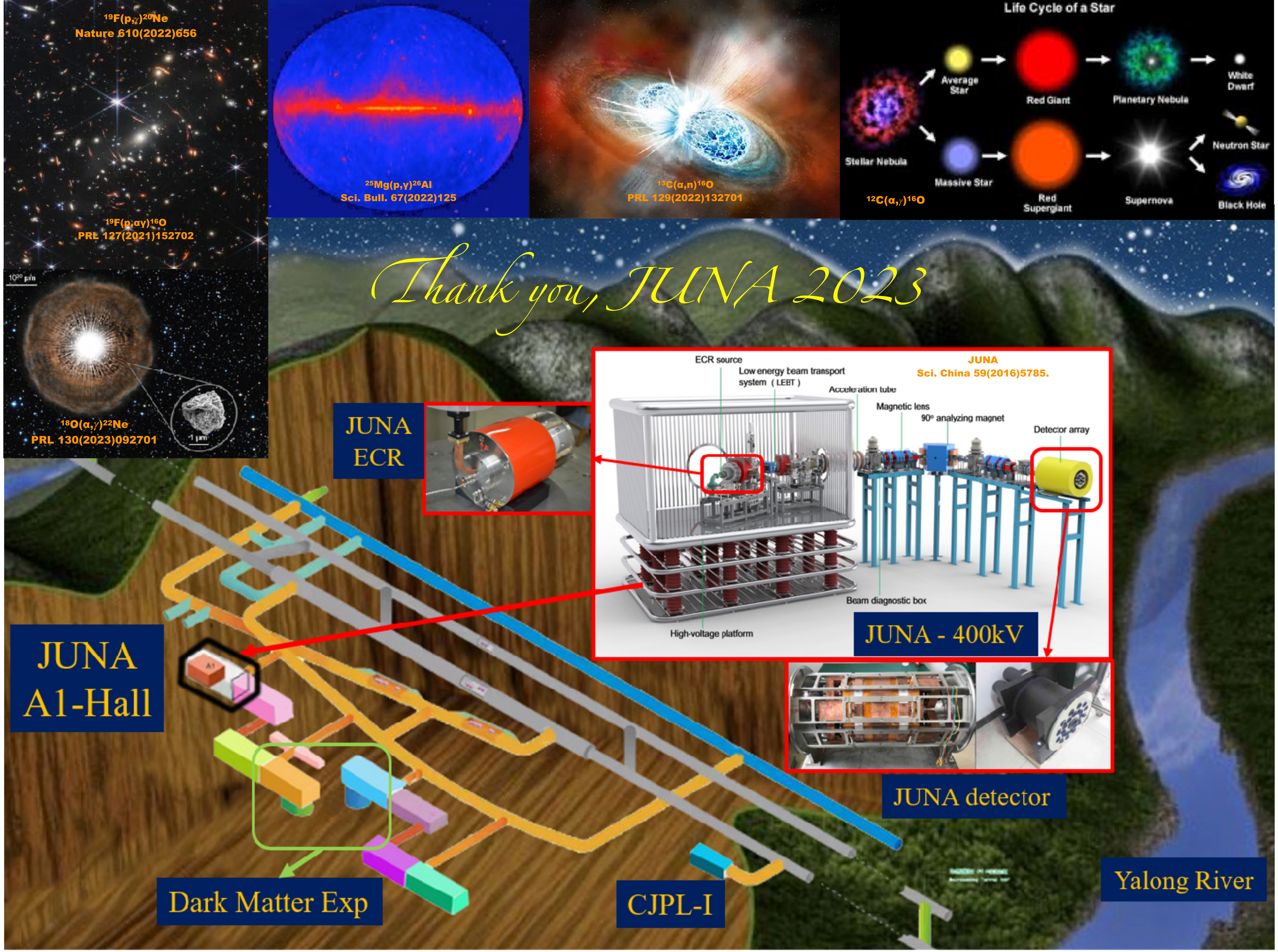
岳骞 （清华大学）



特别致谢：国家自然科学基金委，中国锦屏地下实验室，中国核工业集团公司，中国科学院
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, JUNA 2023
$^{19}F(p,\gamma)^{20}Ne$
Nature 610(2022)656
$^{19}F(p,\alpha\gamma)^{16}O$
PRL 127(2021)152702
$^{25}Mg(p,\gamma)^{26}Al$
Sci. Bull. 67(2022)125
$^{13}C(\alpha,n)^{16}O$
PRL 129(2022)132701
Life Cycle of a Star
Stellar Nebula
Average Star
Red Giant
Planetary Nebula
White Dwarf
Massive Star
Red Supergiant
Supernova
Neutron Star
Black Hole
$^{12}C(\alpha,\gamma)^{16}O$
$^{18}O(\alpha,\gamma)^{22}Ne$
PRL 130(2023)092701
1 μm
JUNA ECR
ECR source
Low energy beam transport system (LEBT)
Acceleration tube
Magnetic lens
90° analyzing magnet
Detector array
JUNA
Sci. China 59(2016)5785.
Beam diagnostic box
High-voltage platform
JUNA - 400kV
JUNA detector
JUNA A1-Hall
Dark Matter Exp
CJPL-I
Yalong River

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