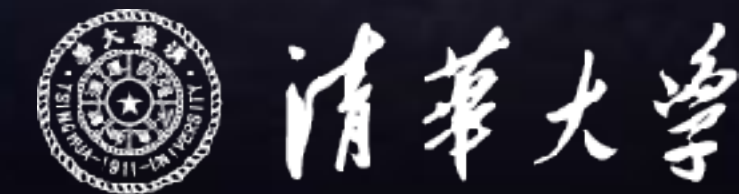
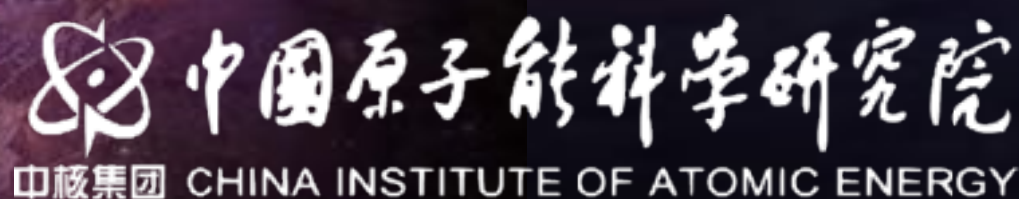


Progress of underground nuclear astrophysics experiment (JUNA)

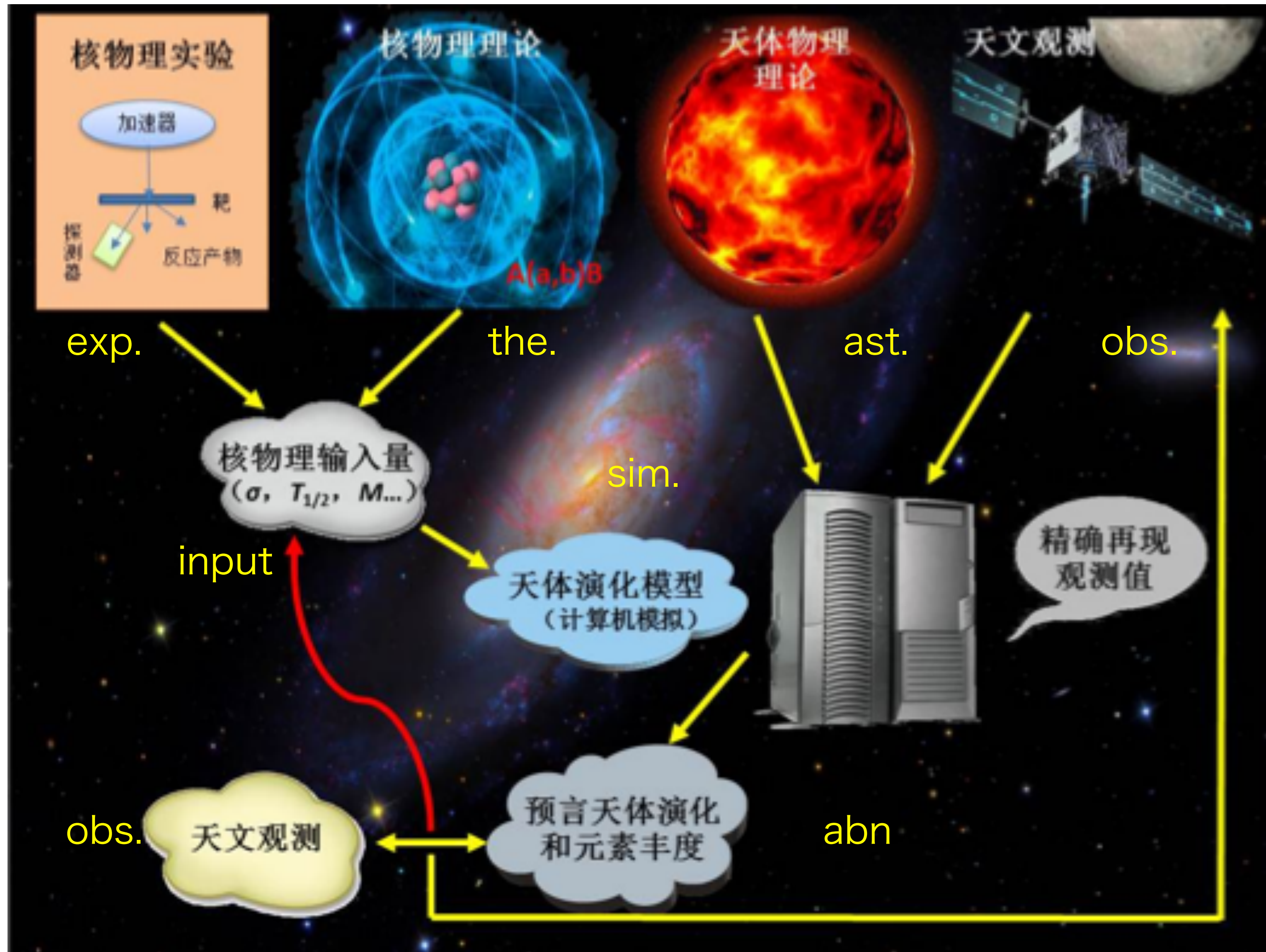
Weiping Liu
JUNA chief scientist
CIAE/SUSTech

The 17th International Symposium on Origin of Matter
and Evolution of Galaxies
Chengdu, China
September 8-11, 2024

Thanks NSFC, Yalong power, THU, CAS and CNNC



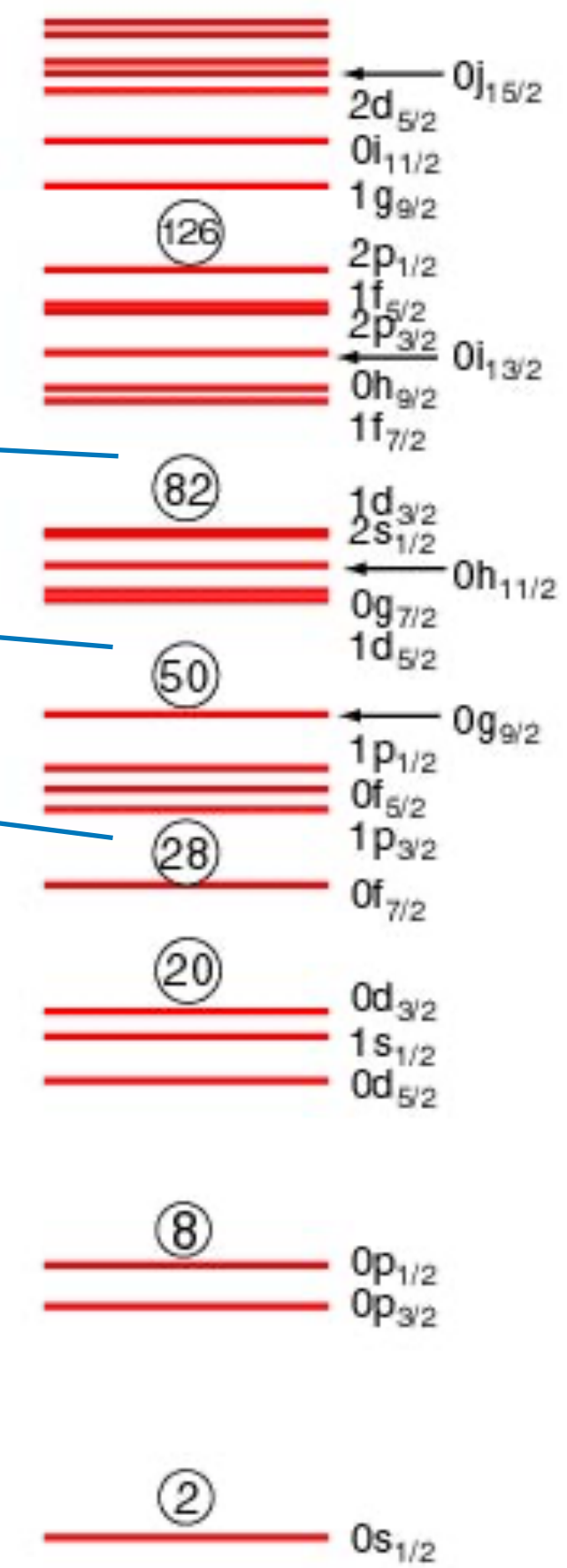
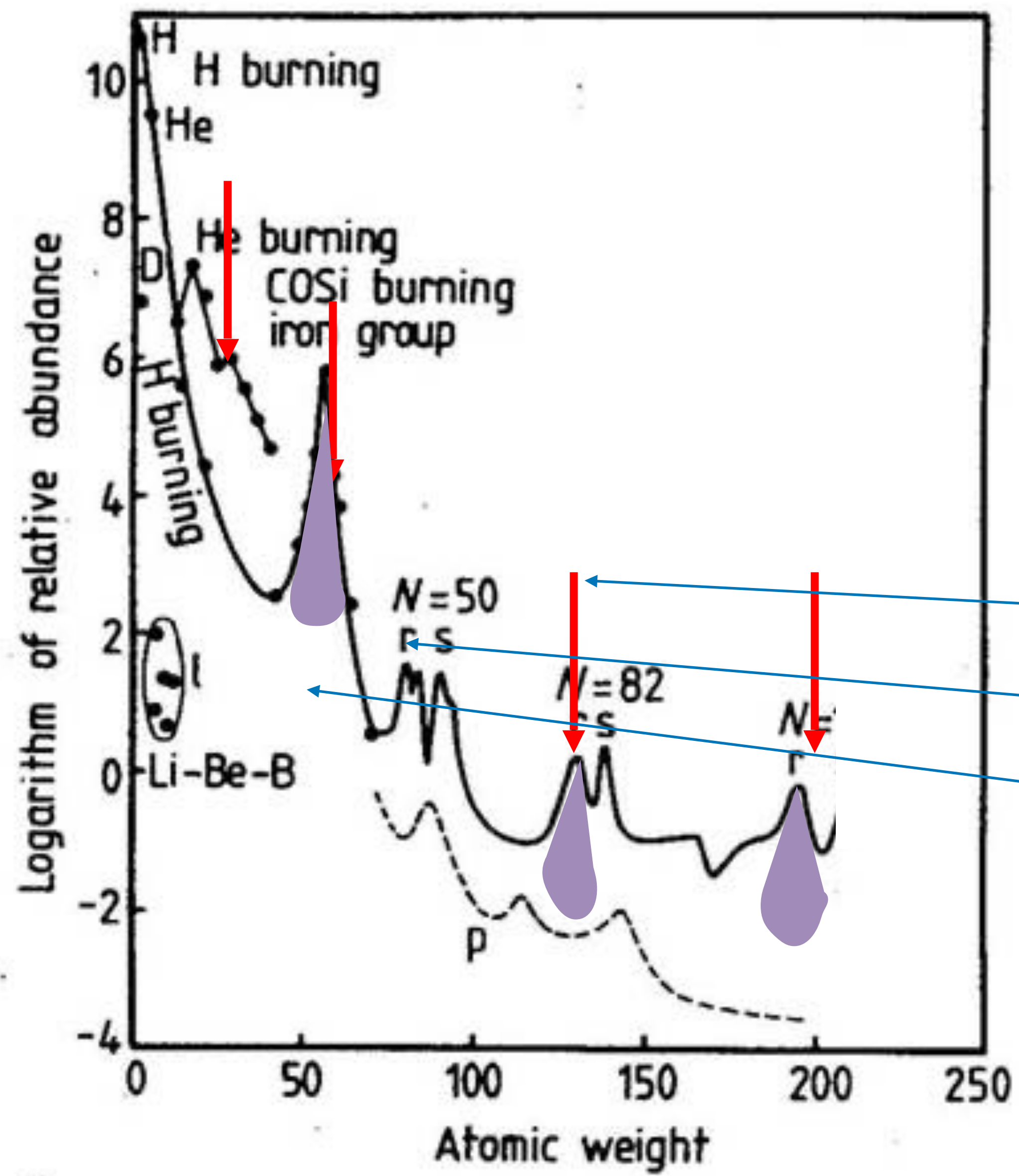
nuclear astrophysics



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

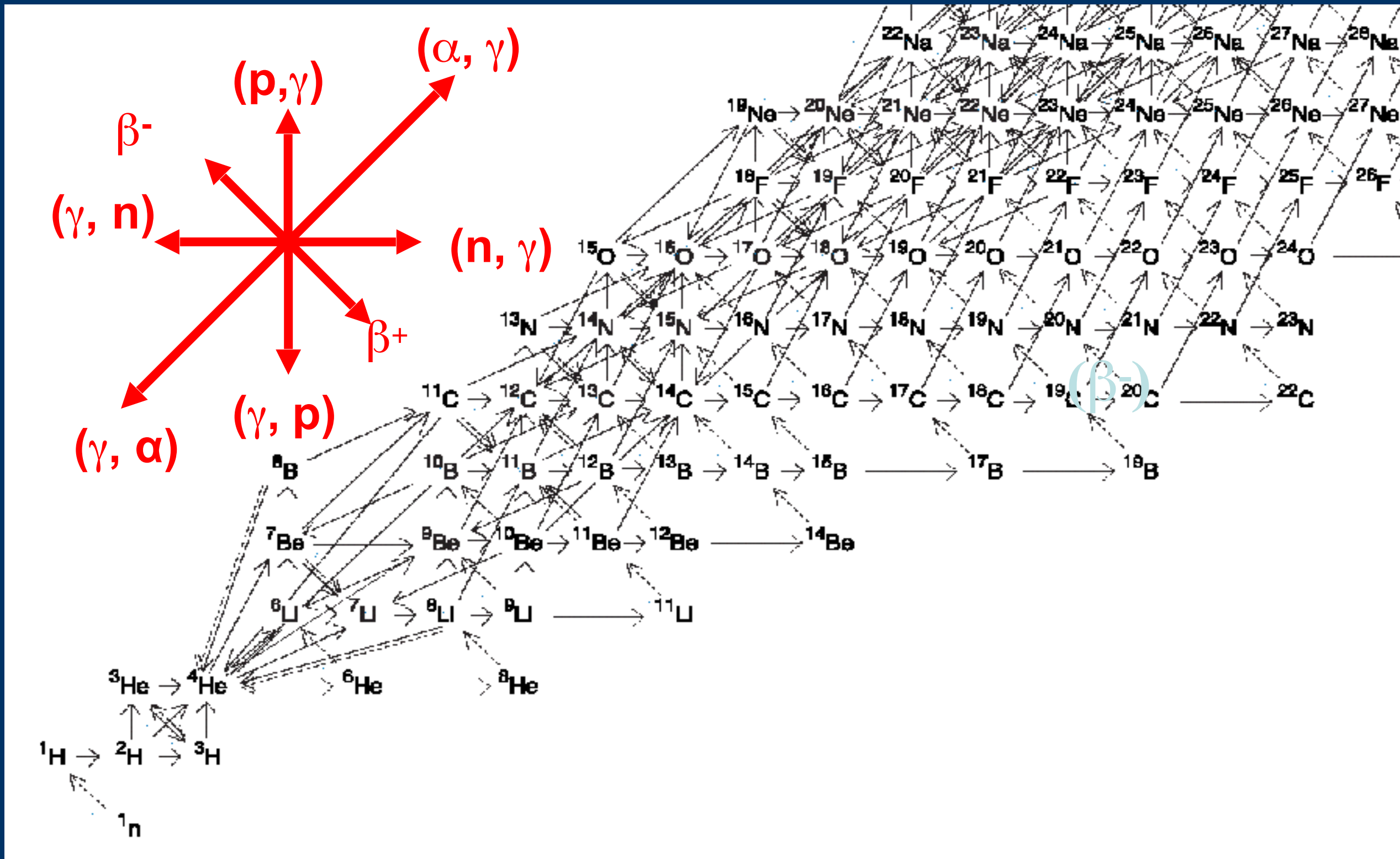
Nuclear Reactions: Alchemists in the Universe

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



Shell Model of Nuclei

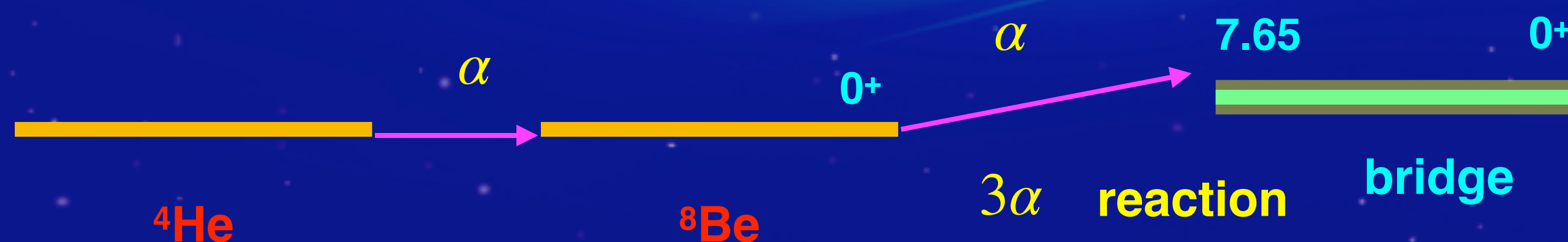
Element synthesis network



Cross section

$$\frac{dY_i}{dt} = \sum_j N_j^i \lambda_j Y_j + \sum_{j,k} N_{j,k}^i \rho N_A \langle \sigma V \rangle_{jk,i} Y_j Y_k + \sum_{j,k,l} N_{j,k,l}^i \rho^2 N_A^2 \langle \sigma V \rangle_{jkl,i} Y_j Y_k Y_l$$

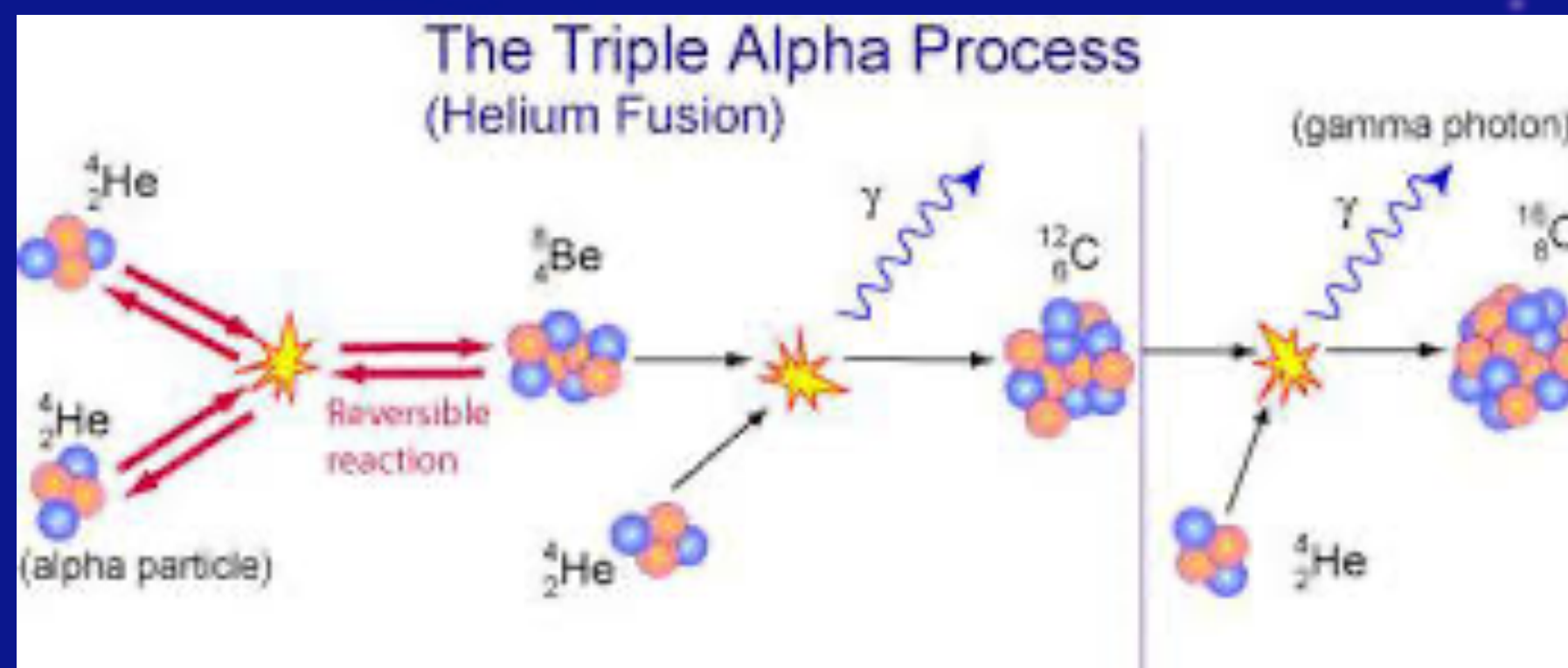
State of nuclei, fate of star



1954, Hoyle state, large amount of Carbon



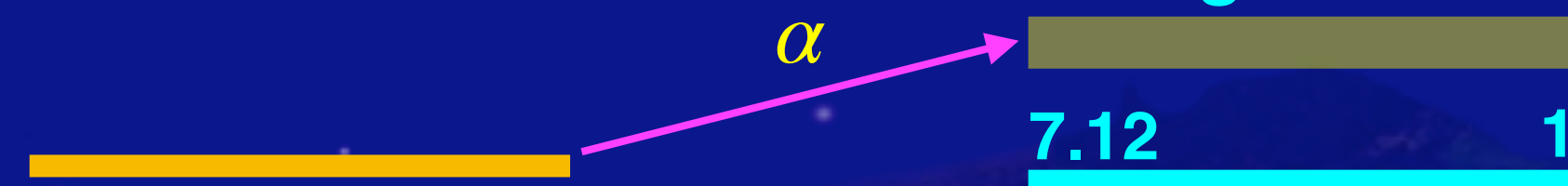
Fred Hoyle (1915-2001)
APJS 1(1954)121



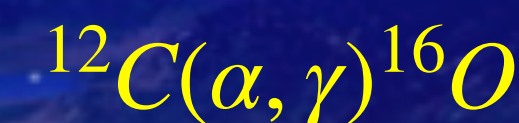
William A. Fowler (1911–1995)
Rev.Mod.Phys. 56 (1984) 149-179

8.87 2-
regulator

Adequate amount: for sun burn long, for human live



¹²C



Holy grail reaction

¹⁶O

from "Cladon in the universe"

Nuclear astrophysics in China



JUNA experiment

Direct in Gamow window
(underground)

RIBLL and LEAF experiment

Direct in higher energy

CIAE experiment

In-direct measurements

BRIF, CSR experiment

Nuclear decay

CSR experiment

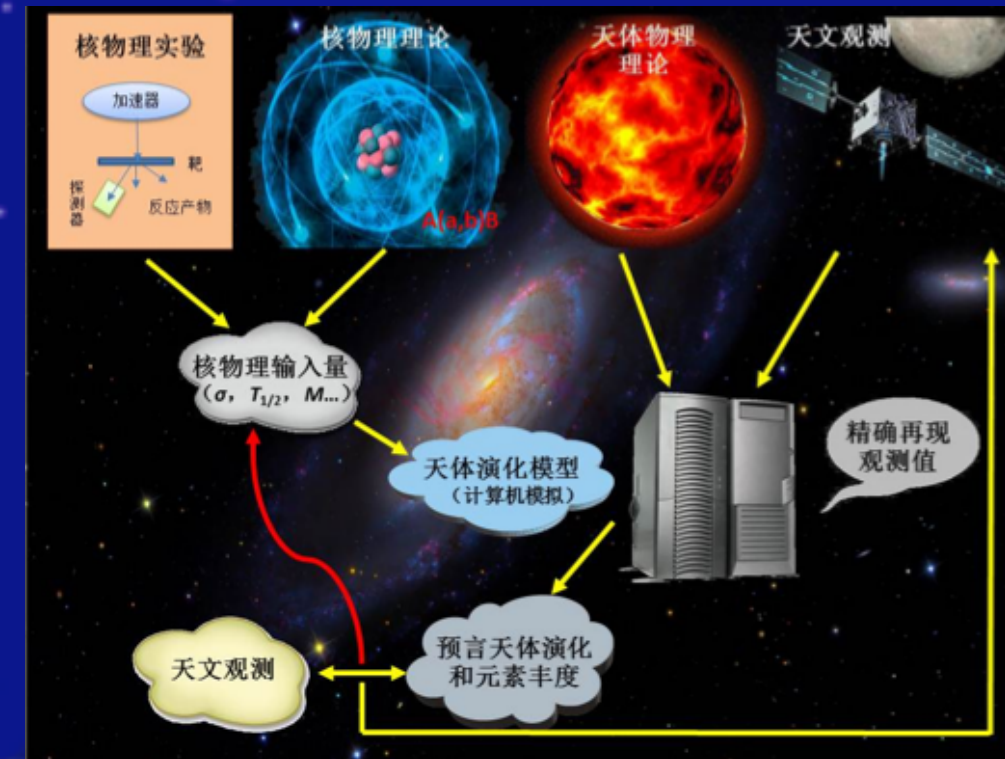
Nuclear mass

theoretical study

Nuclear astrophysics and sensitivity study

theoretical study

Shell model and mean field calculation



theoretical study

Shell model and mean field calculation

theoretical study

Nuclear astrophysics network calculation

Reaction rate database

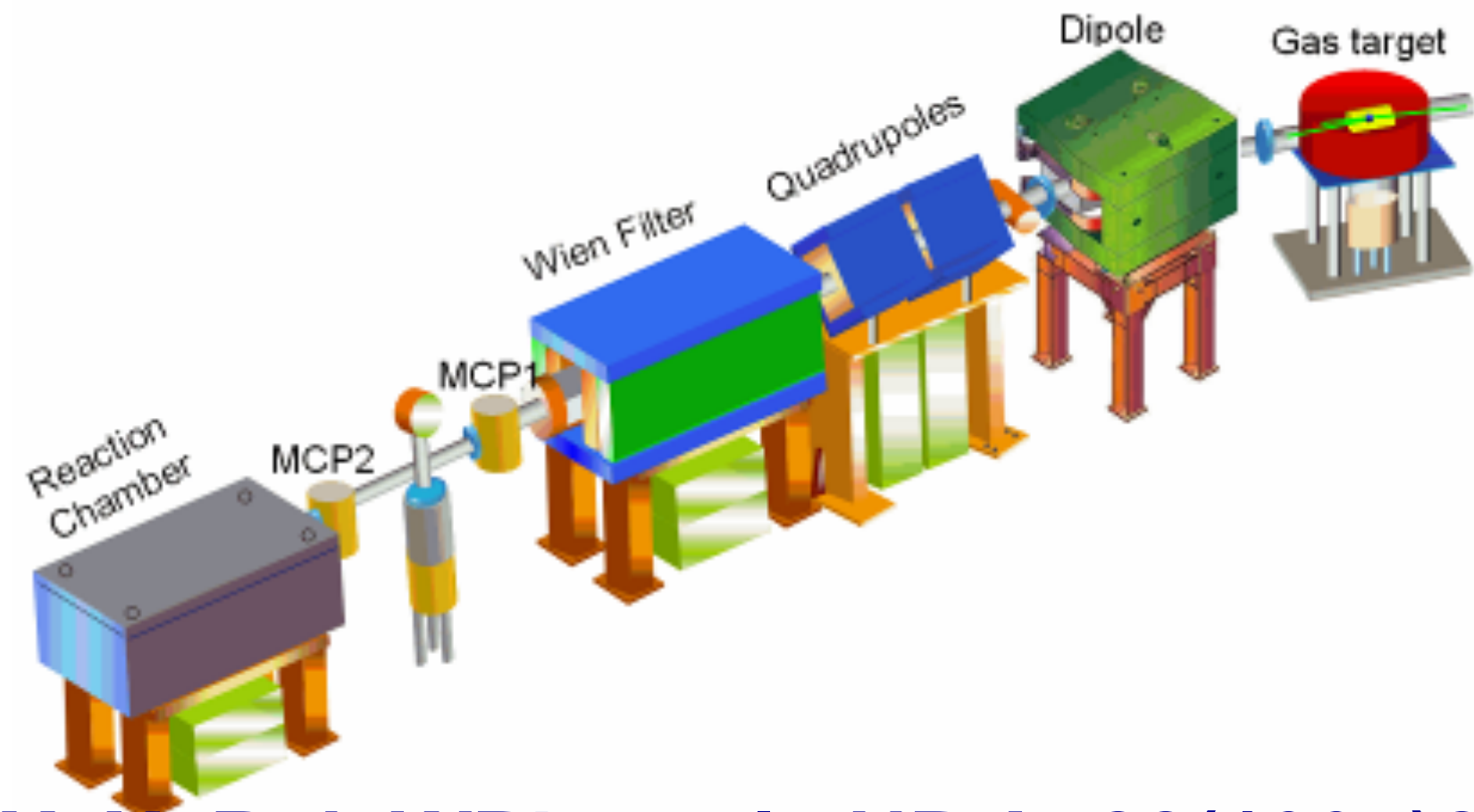
Nuclear input database

Mass data compilation in China

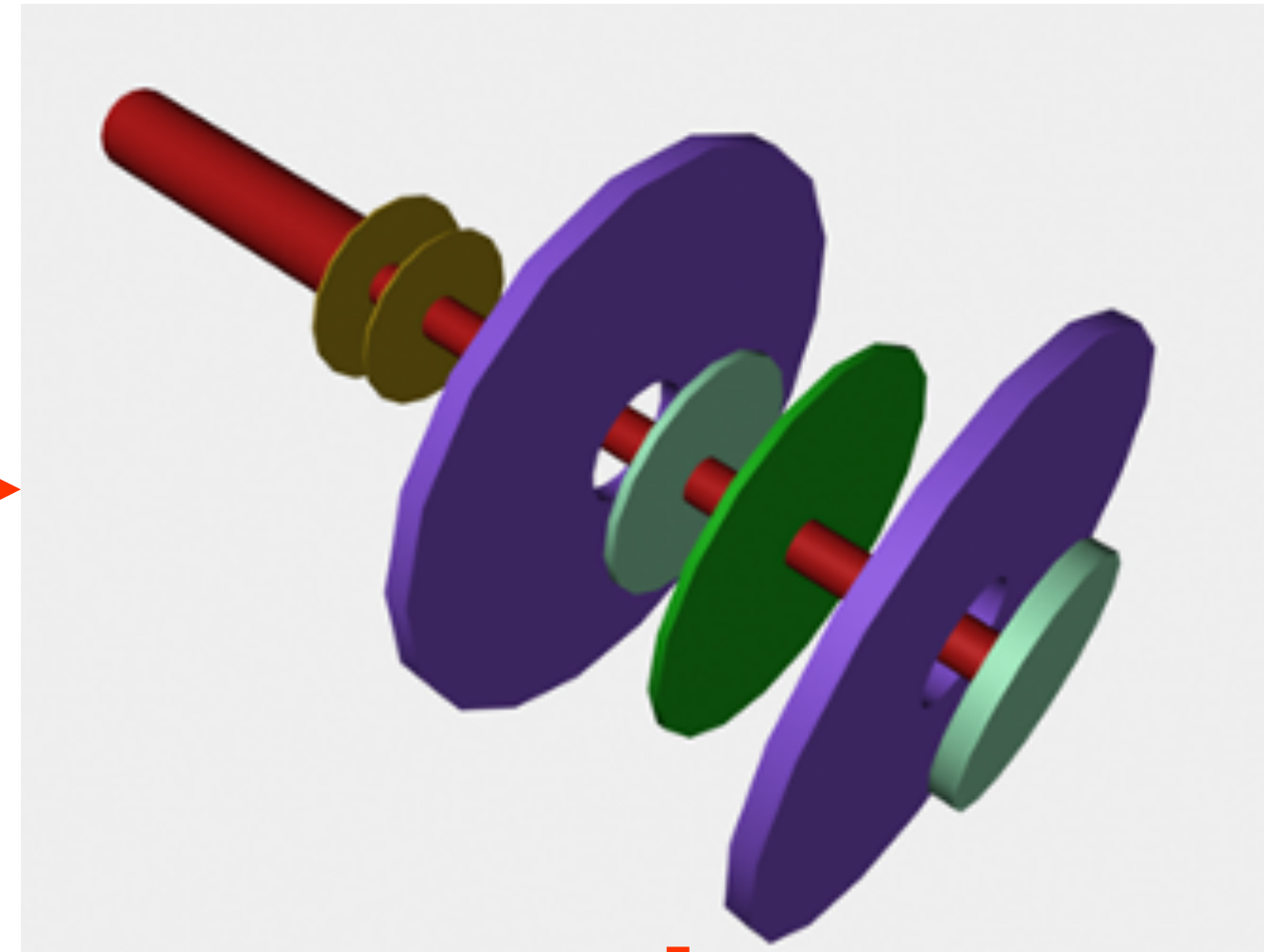
Mass and decay rate database

1996: new method for ^8B solar neutrino cross section

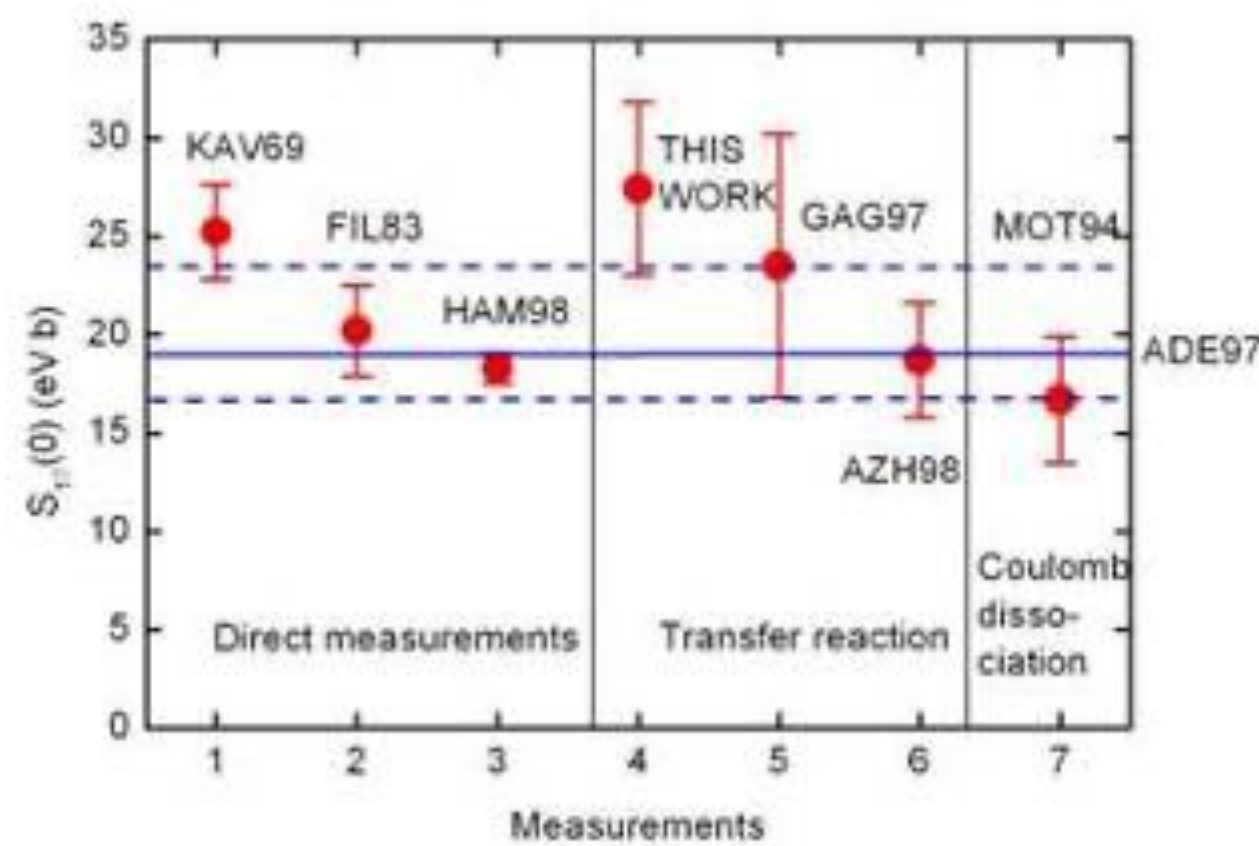
RIB production



(d,n) or (d,p) measurement



X. X. Bai, WPL et al., NP A588(1995)273c



Astrophysical reaction rates

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} - \left(\frac{d\sigma}{d\Omega}\right)_{\text{CN}} = \sum_{j_i j_f} (C_{l_i j_i}^d)^2 (C_{l_f j_f}^{12\text{N}})^2 \frac{d\sigma_{l_f j_f l_i j_i}^{\text{DW}}}{b_{l_i j_i}^2 b_{l_f j_f}^2}$$

$$\sigma_t = \frac{16\pi}{9} \left(\frac{E_\gamma}{\hbar c}\right)^3 \frac{1}{\hbar v} \frac{e_{\text{eff}}^2}{k^2} \frac{(2j_f + 1)}{(2I_1 + 1)(2I_2 + 1)} C_{l_f j_f}^2 \times \left| \int_{R_N}^{\infty} r^2 dr f_{l_j}(kr) W_{\eta, l_f + 1/2}(2kr) \right|^2$$

ANC or Spec factor

This paper describes an excellent experiment, one of the first examples where a radioactive ion beam has been used in inverse transfer reaction studies.

The topic is sufficient important that this paper should see timely and widespread exposure to the physics community in order to stimulate a board-based dialog.

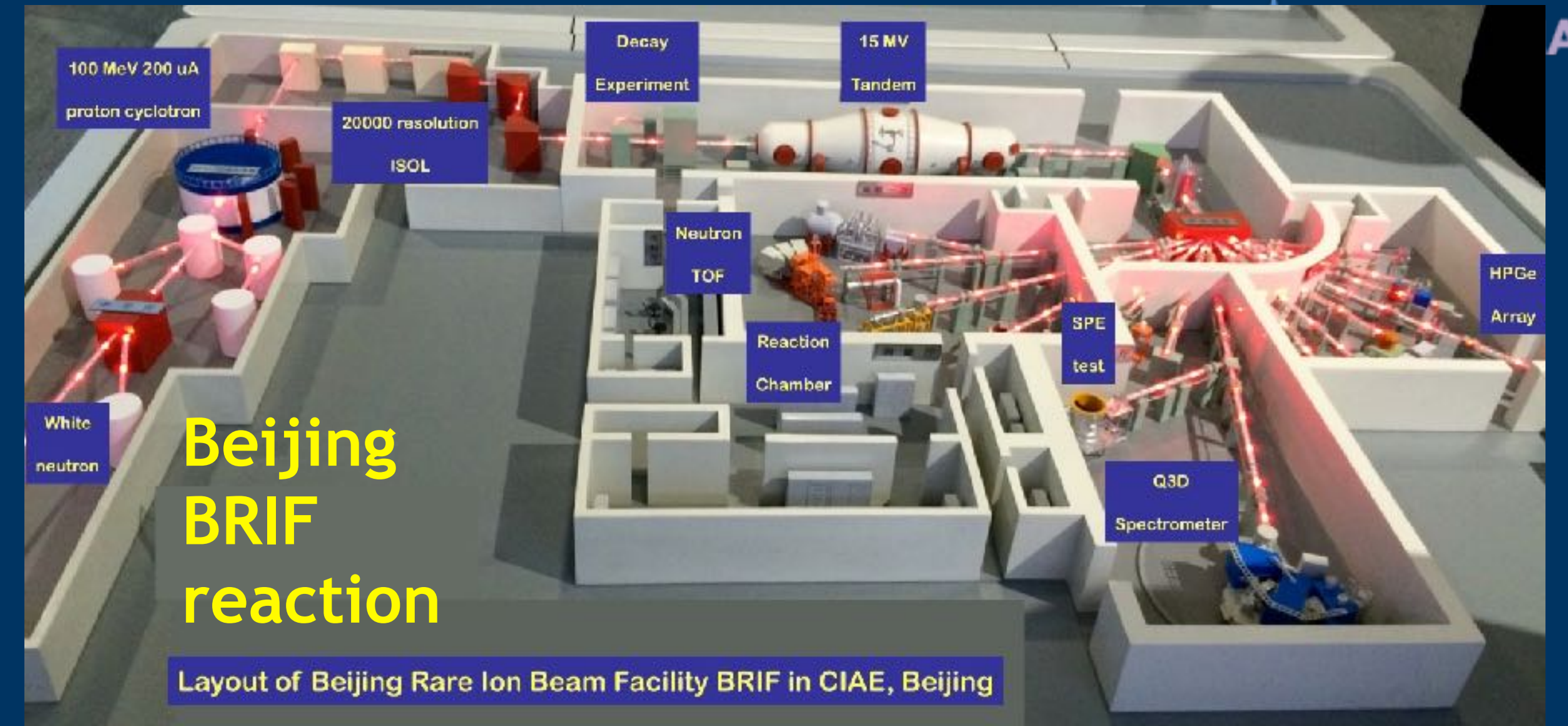
WPL et al.,
PRL77(1996)611, 1st NP
exp. paper in PRL in
China

Major facilities in China

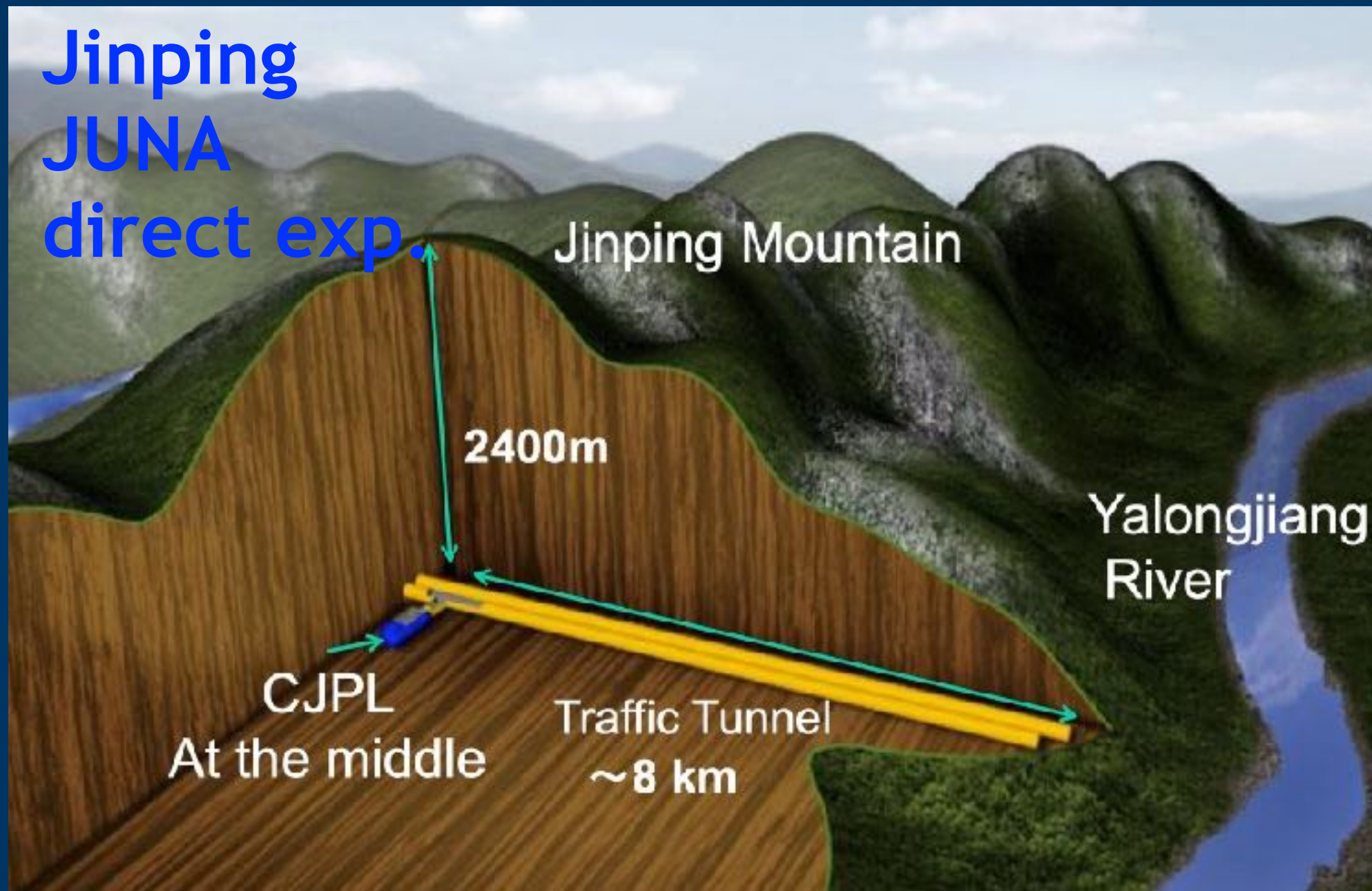
LAMOST
observation



FAST
observation



Jinping
JUNA
direct exp.



Lanzhou
CSR
mass, decay



Gamow window



George Gamow

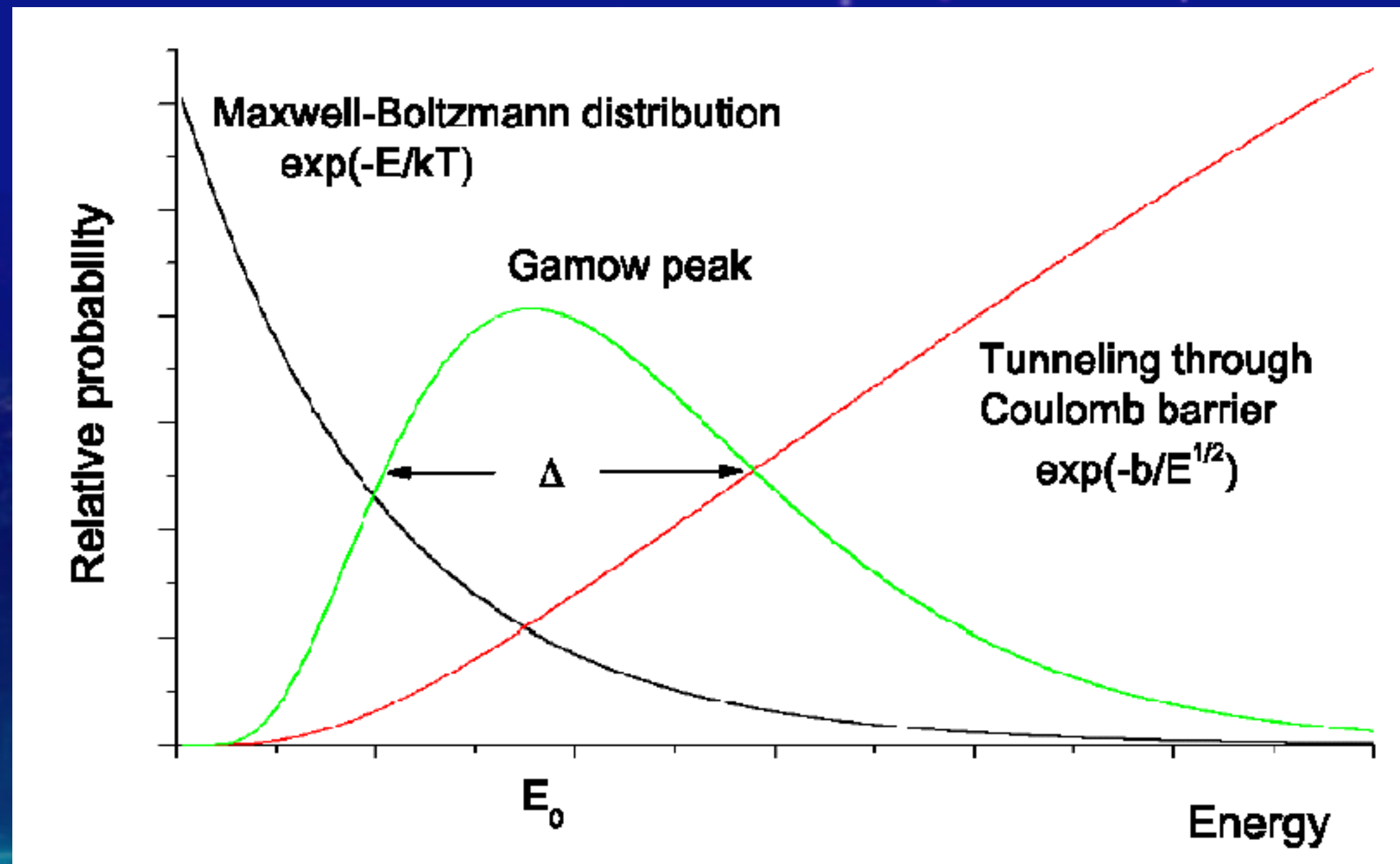
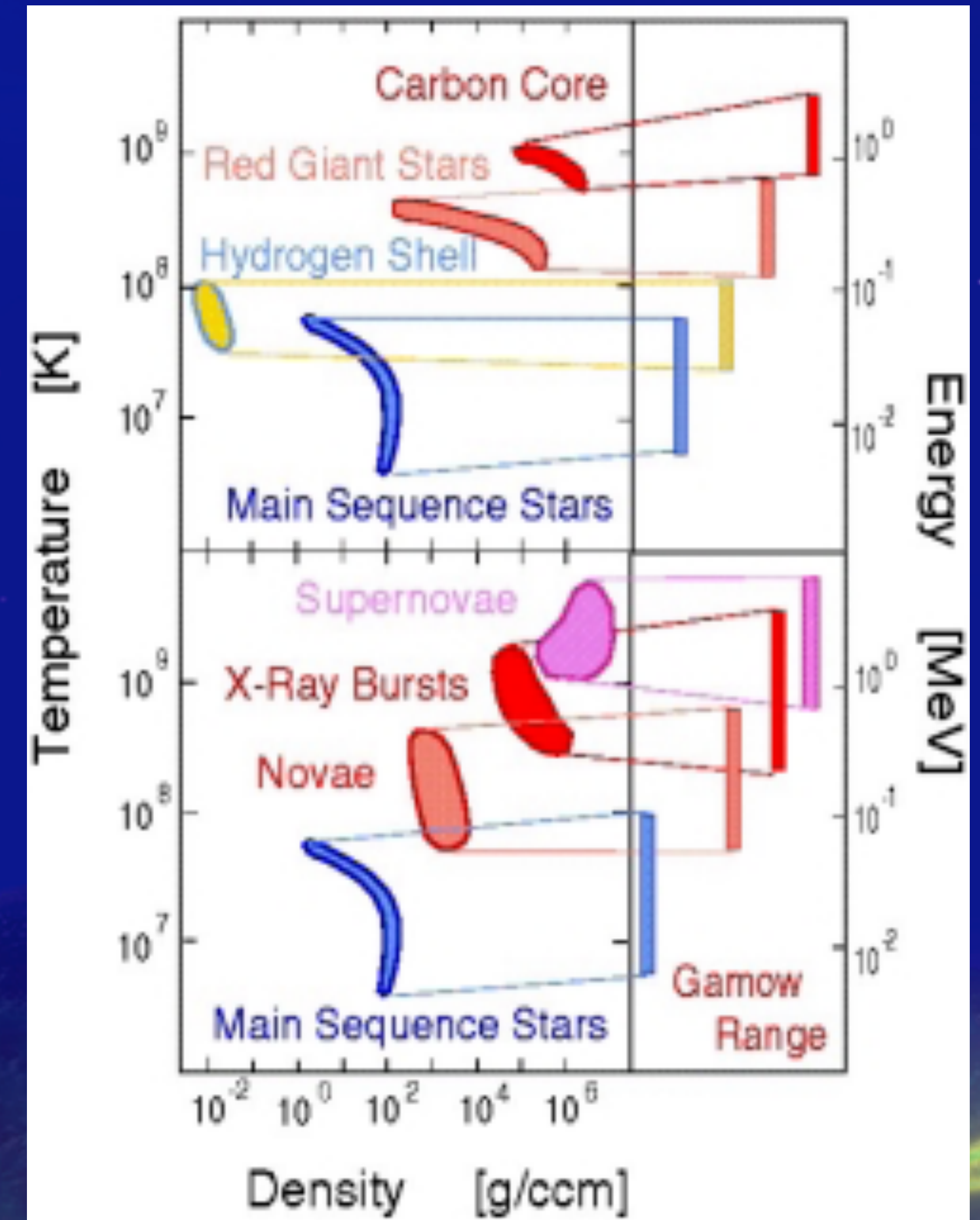
$$\sigma(E) = S(E) e^{-2\pi\eta} \frac{1}{E}$$

astrophysical s factor

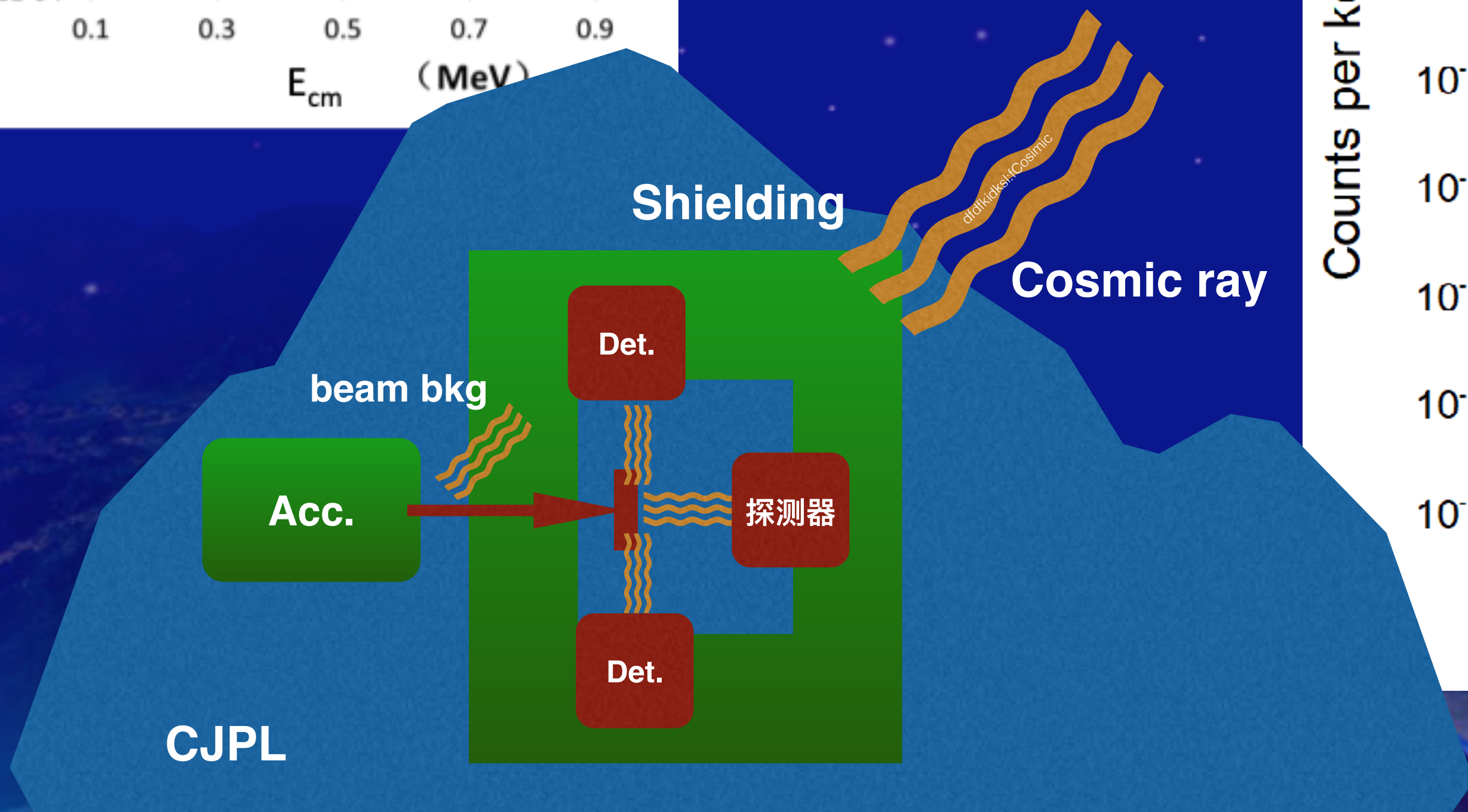
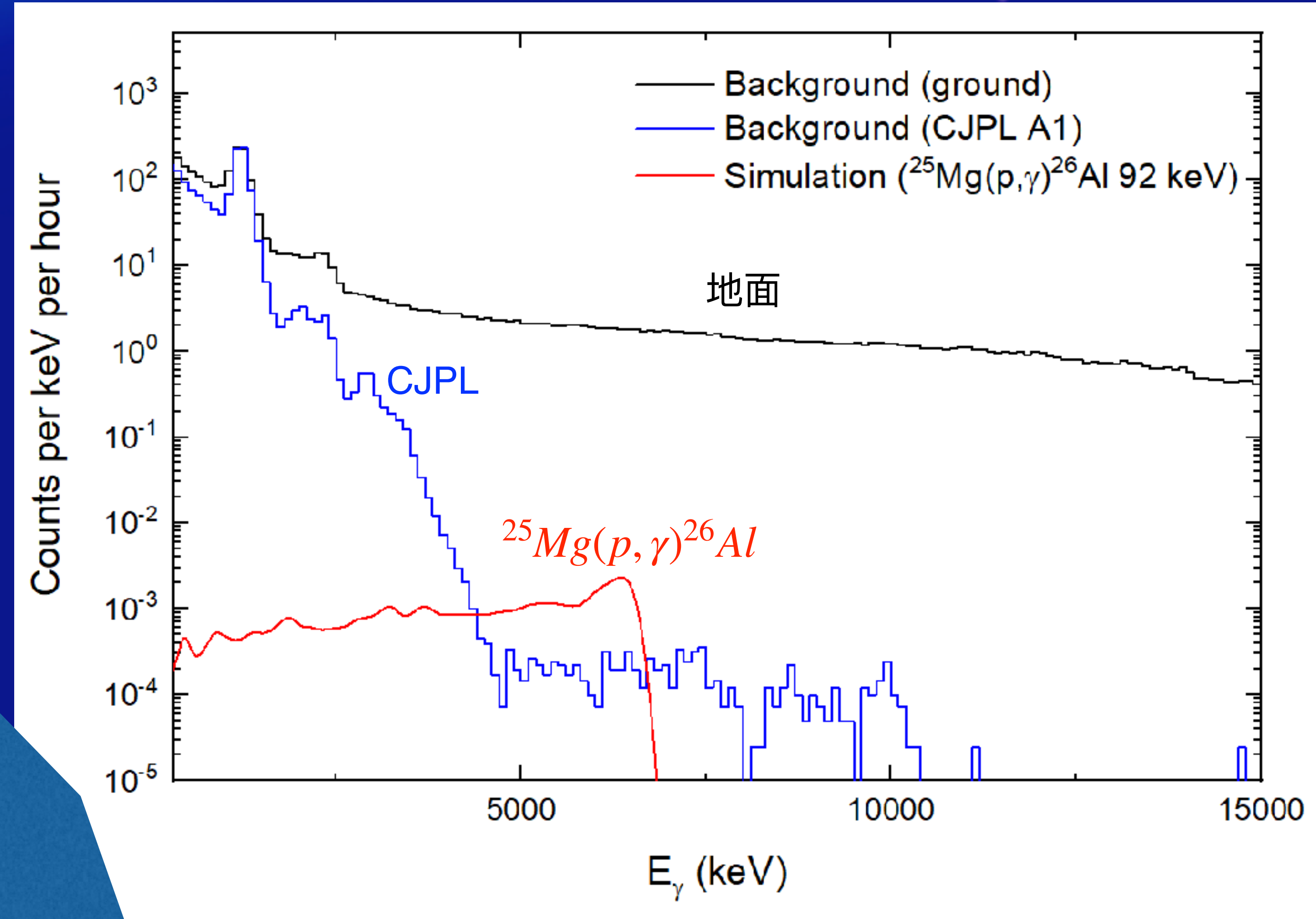
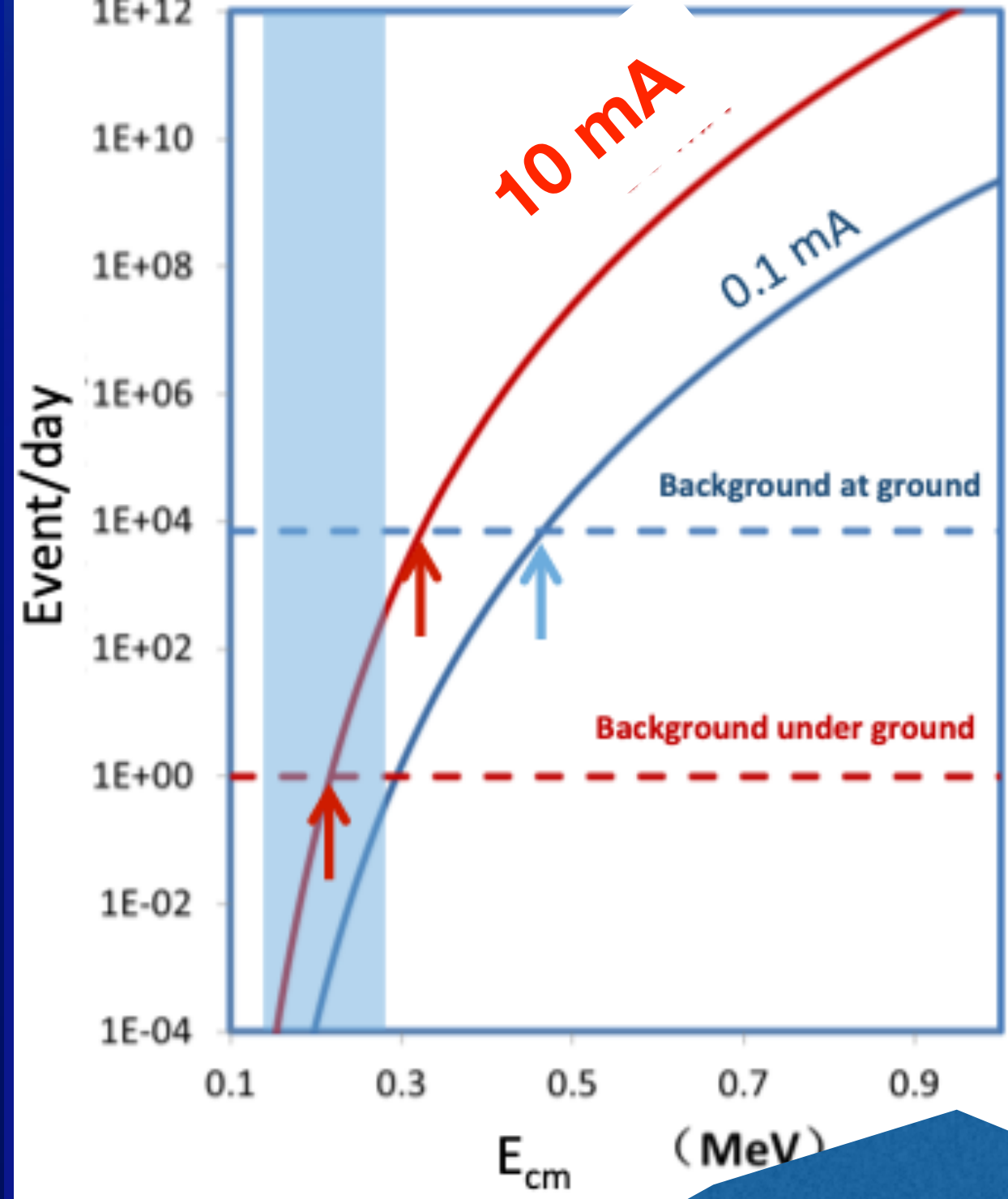
coulomb term

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

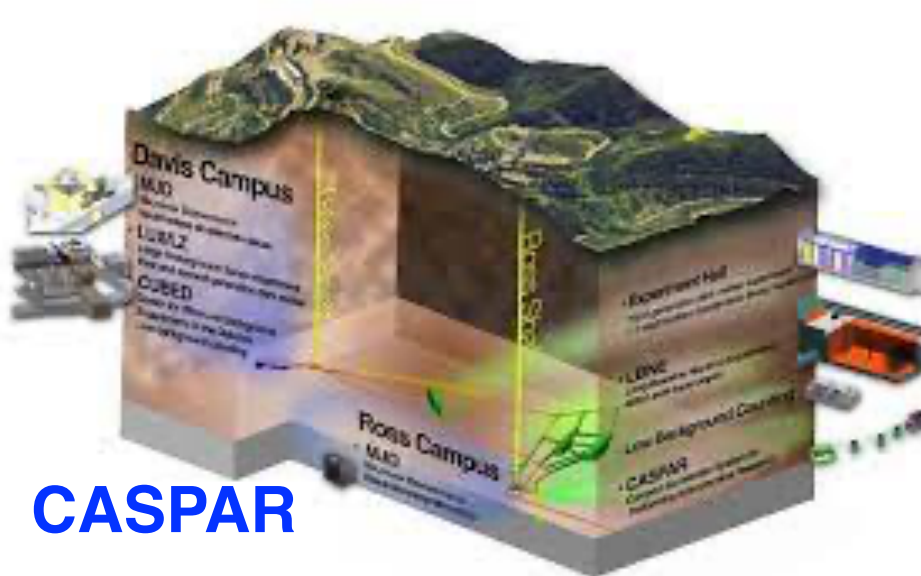
$$E_0 = 1.22 (Z_1^2 Z_2^2 M T_6^2)^{1/3} \text{keV} \quad \text{Gamow window}$$



low bkg+high intensity



LUNA, CASPAR and Felsenkeller

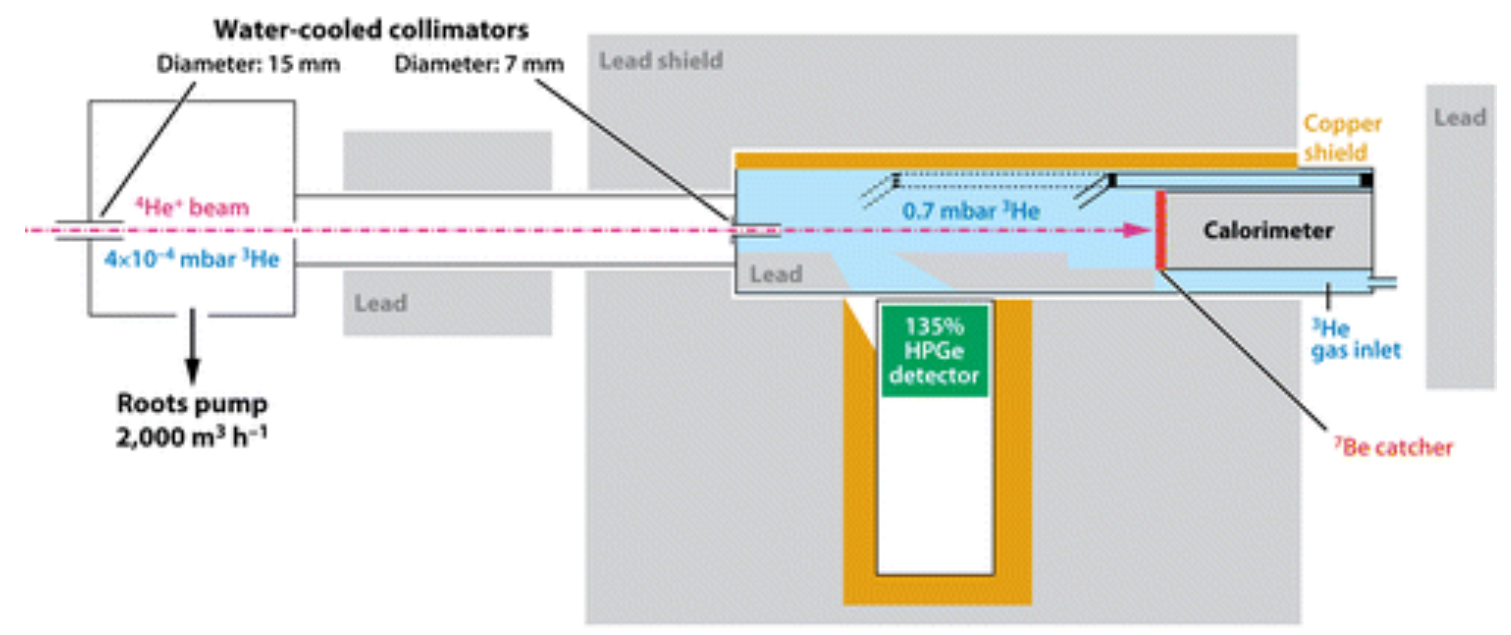
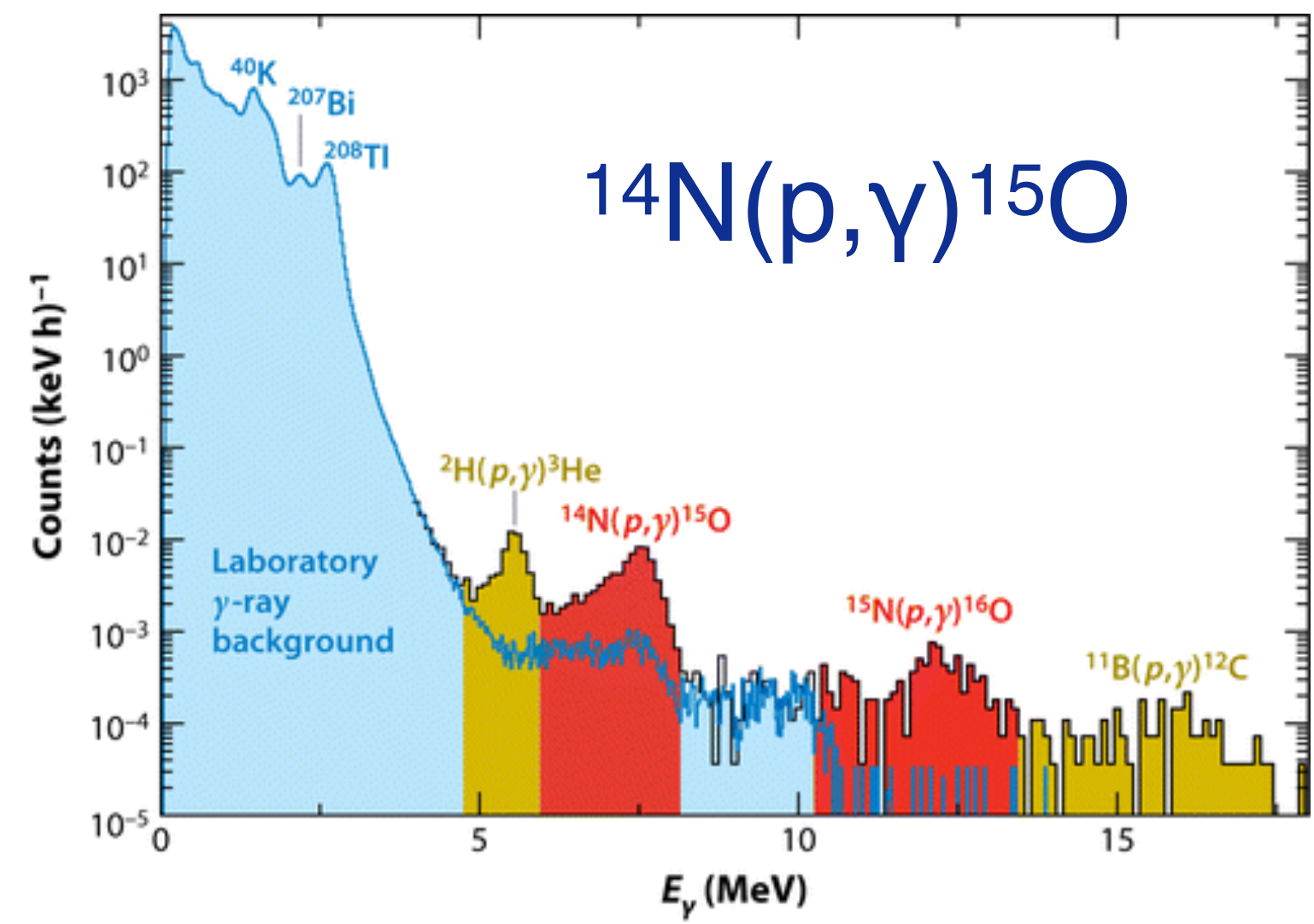
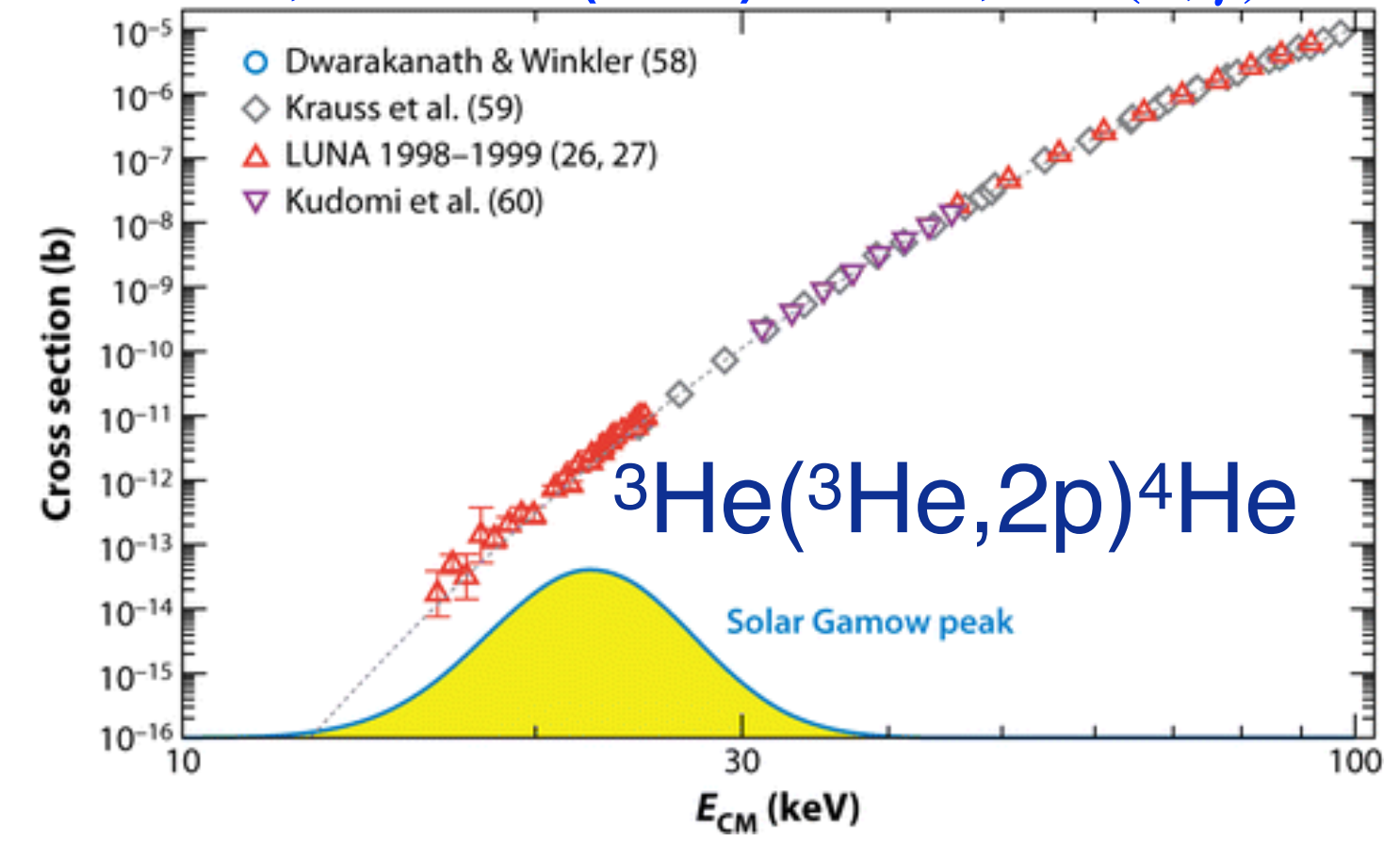
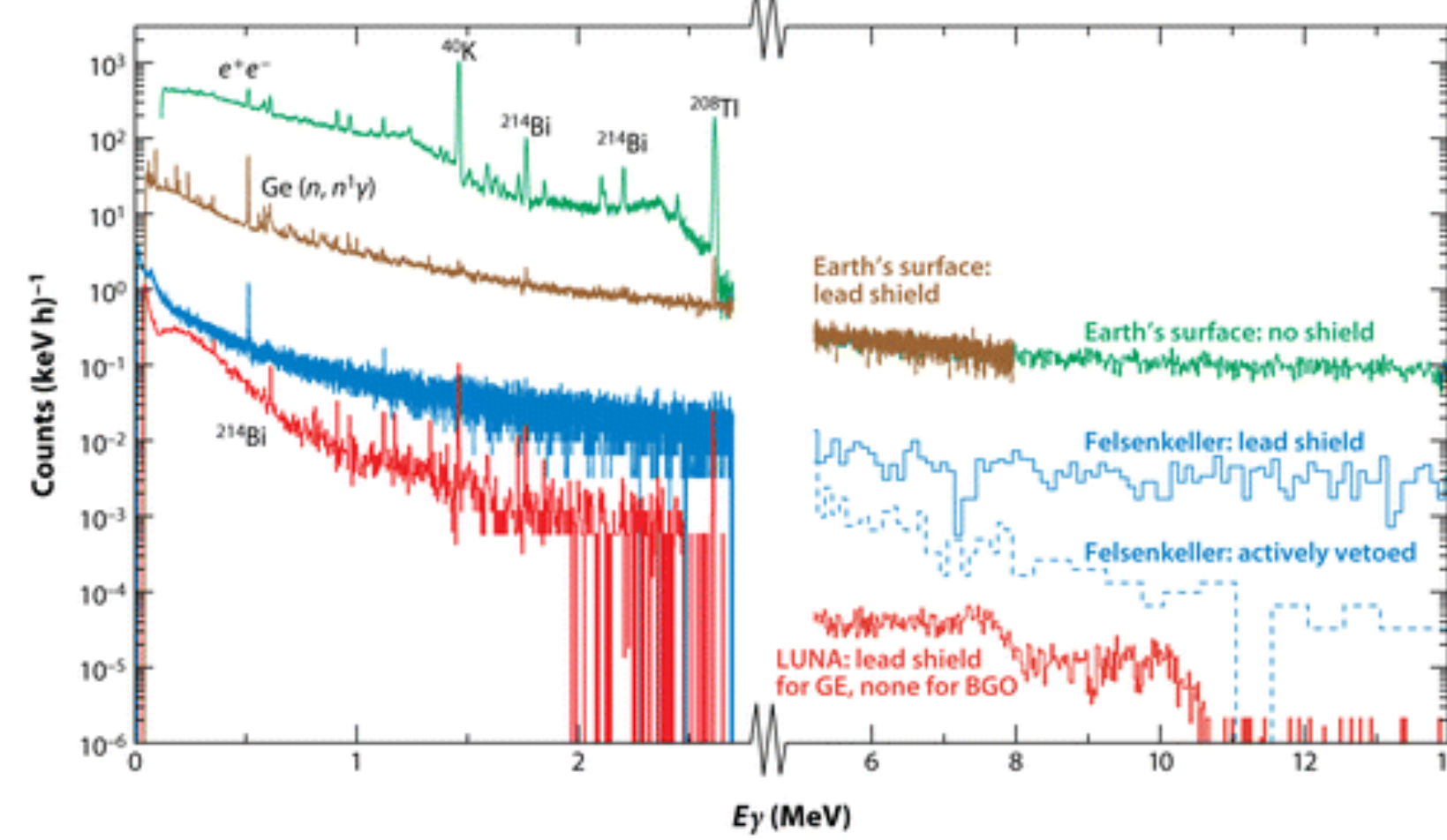


CASPAR

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

LUNA

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



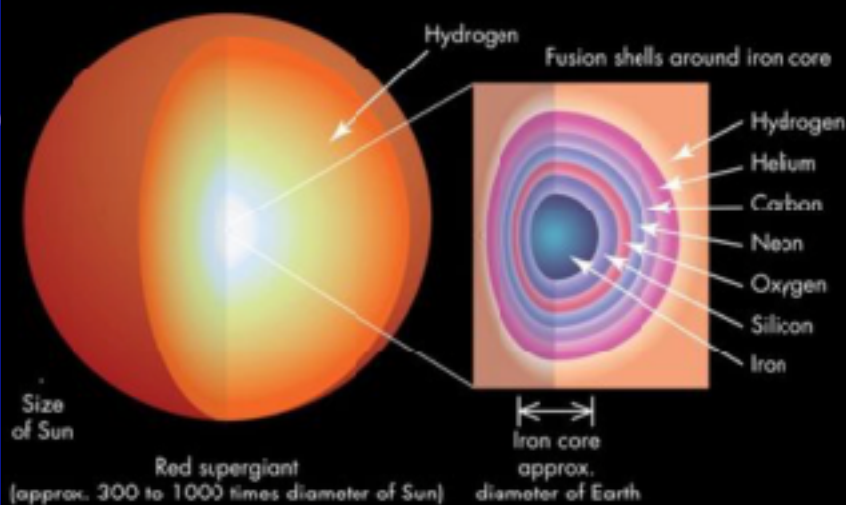
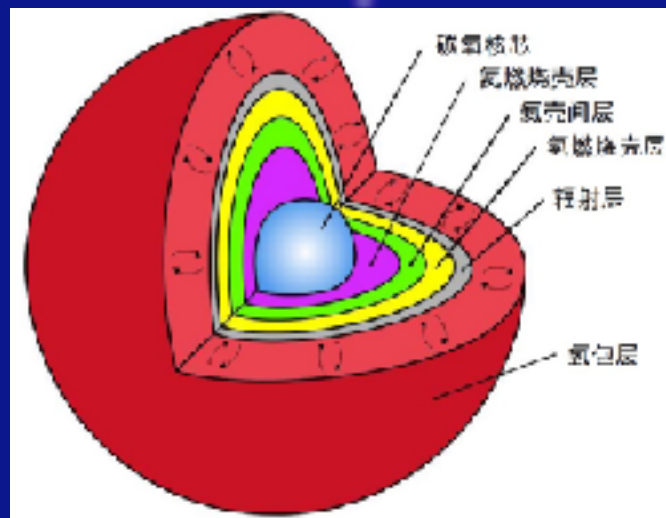
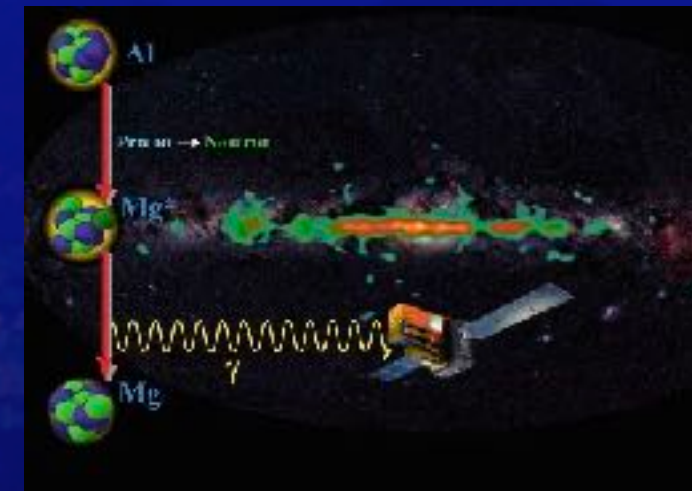
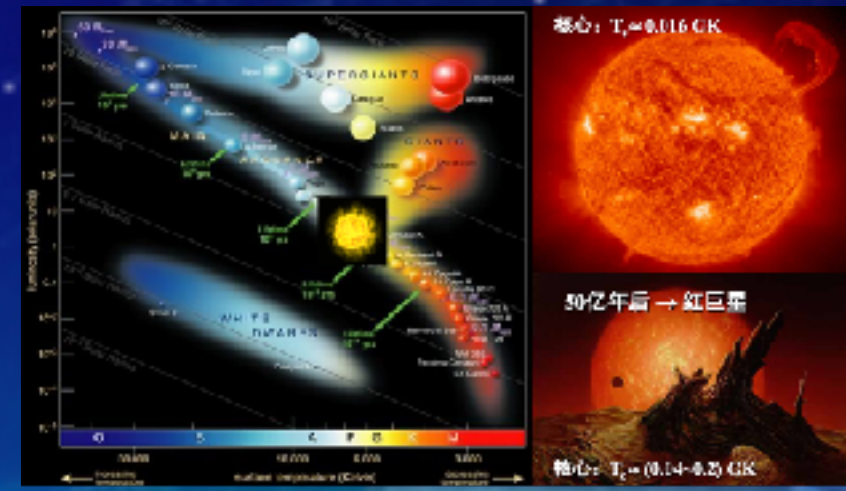
R. M. Gesuè et al., PRL 133(2024)052701, $^{17}\text{O}(p, \gamma)^{18}\text{F}$

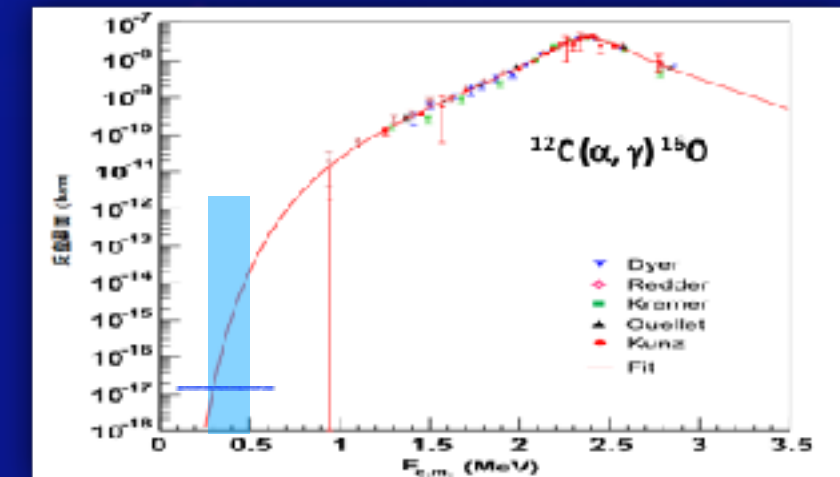
Felsenkeller

- $^3\text{He}(\alpha, \gamma)^7\text{Be}$, progress
- $^2\text{H}(p, \gamma)^3\text{He}$, progress
- $^{12}\text{C}(p, \gamma)^{13}\text{N}$, progress
- $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$, plan

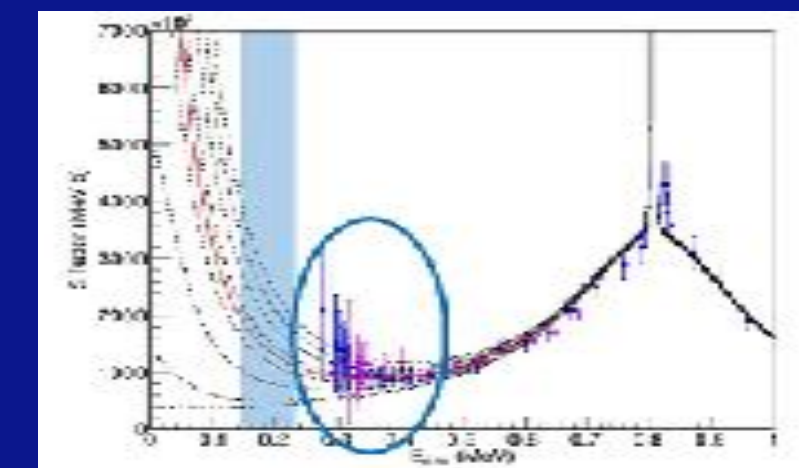
Uncertainty remained for key reactions



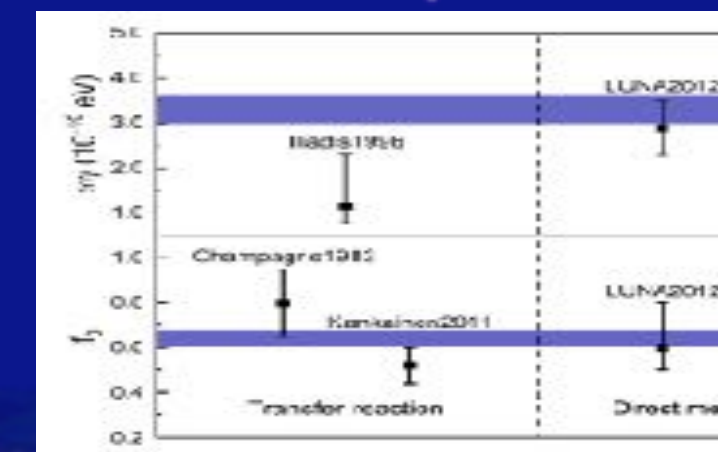
Physics	Reaction	Current	Desired
 <p>Massive star</p>	$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$	60% 890 keV	20% 220-380 keV
 <p>s-process neutron source</p>	$^{13}\text{C}(\alpha, n)^{16}\text{O}$	60% 230 keV	10% 140-230 keV
 <p>Galaxy ^{26}Al source</p>	$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$	20%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



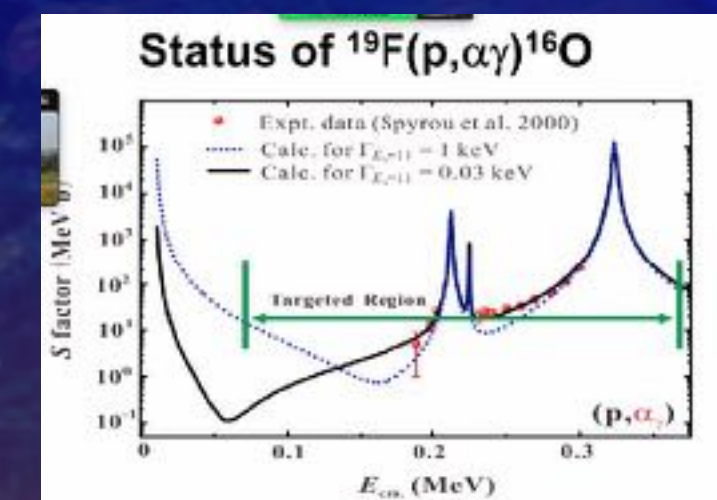
R. J. deBoer et al., RMP vol. 89, 2017



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

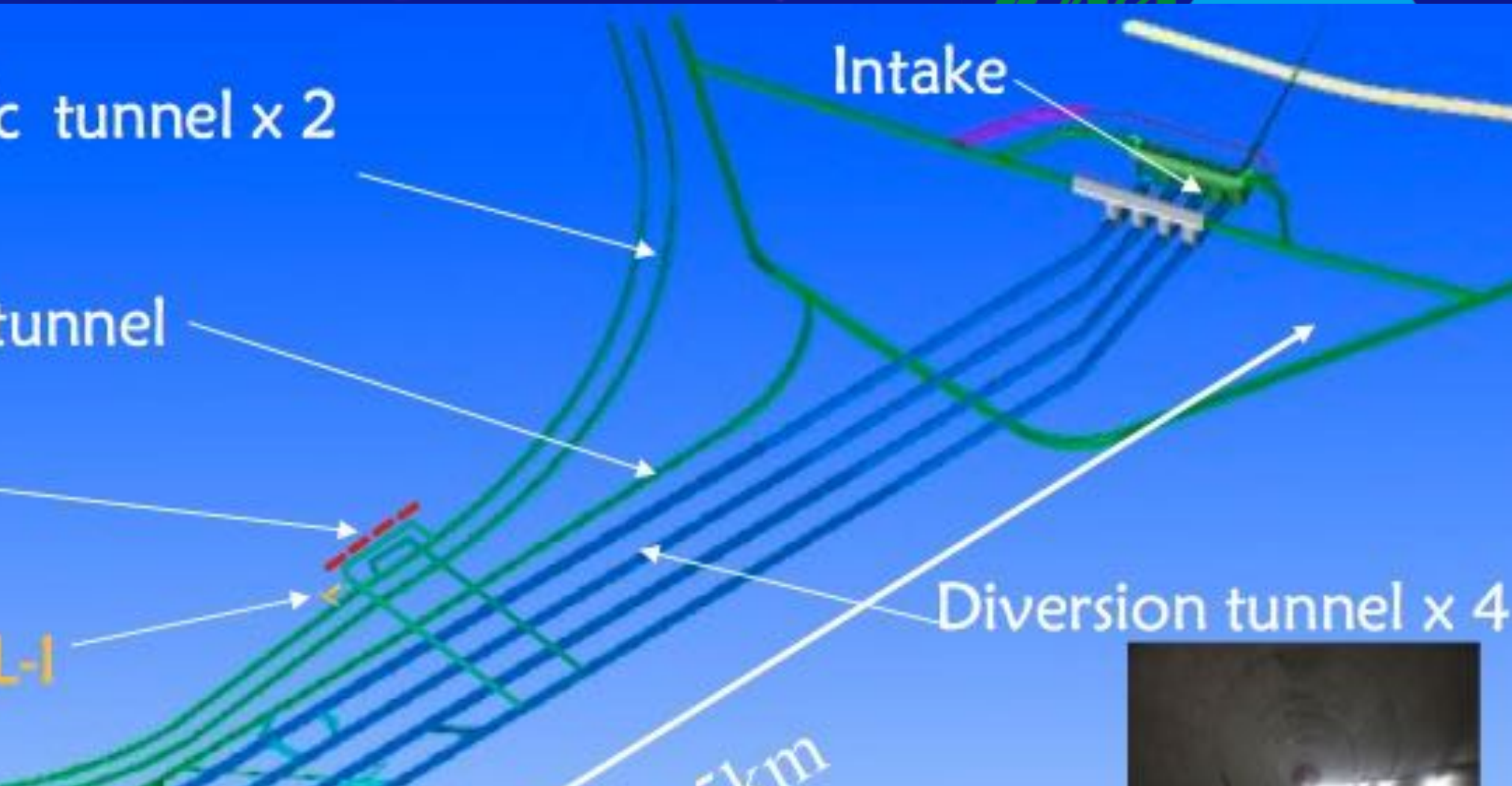
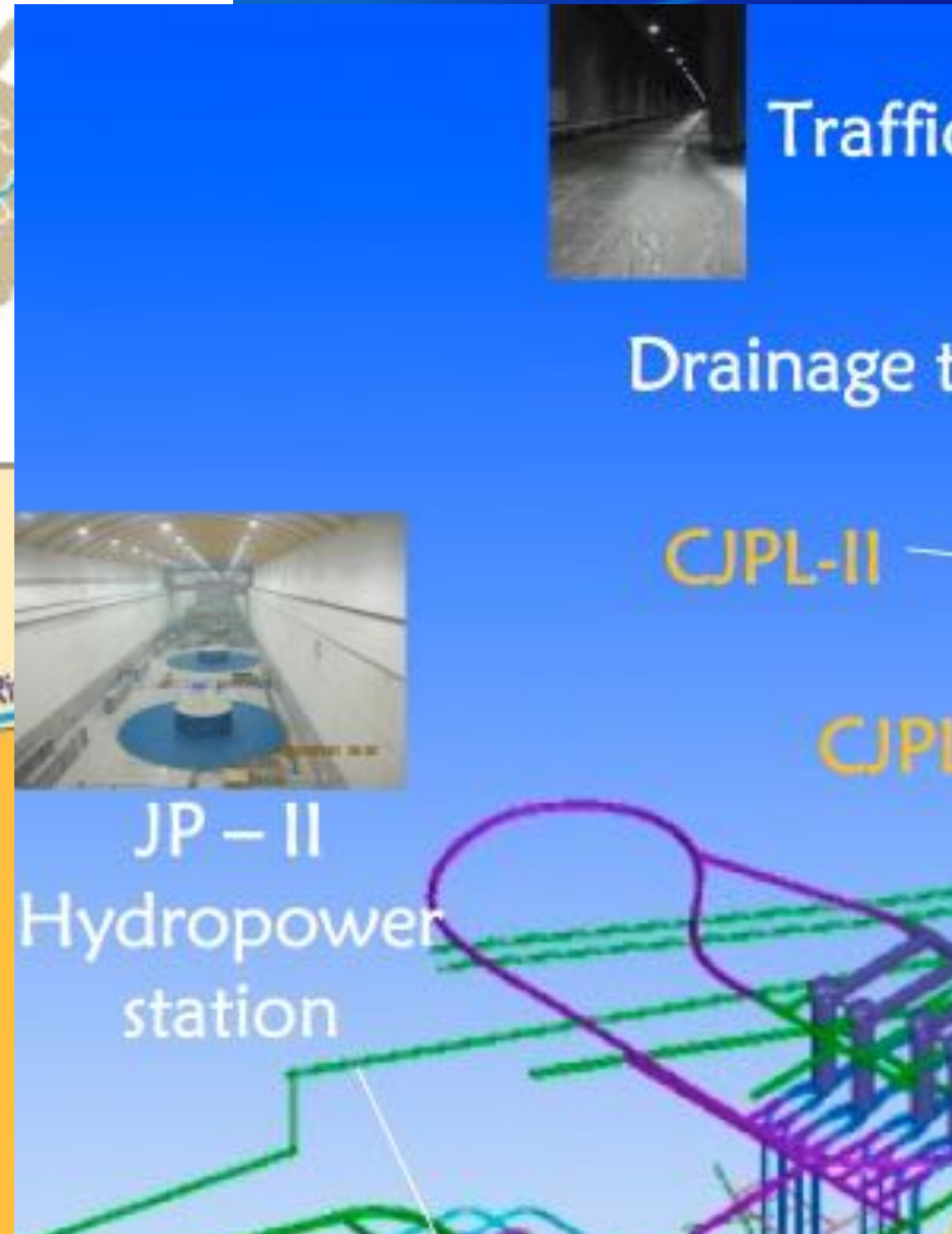


G.F. Ciani et al. PRL 127(2021)152701

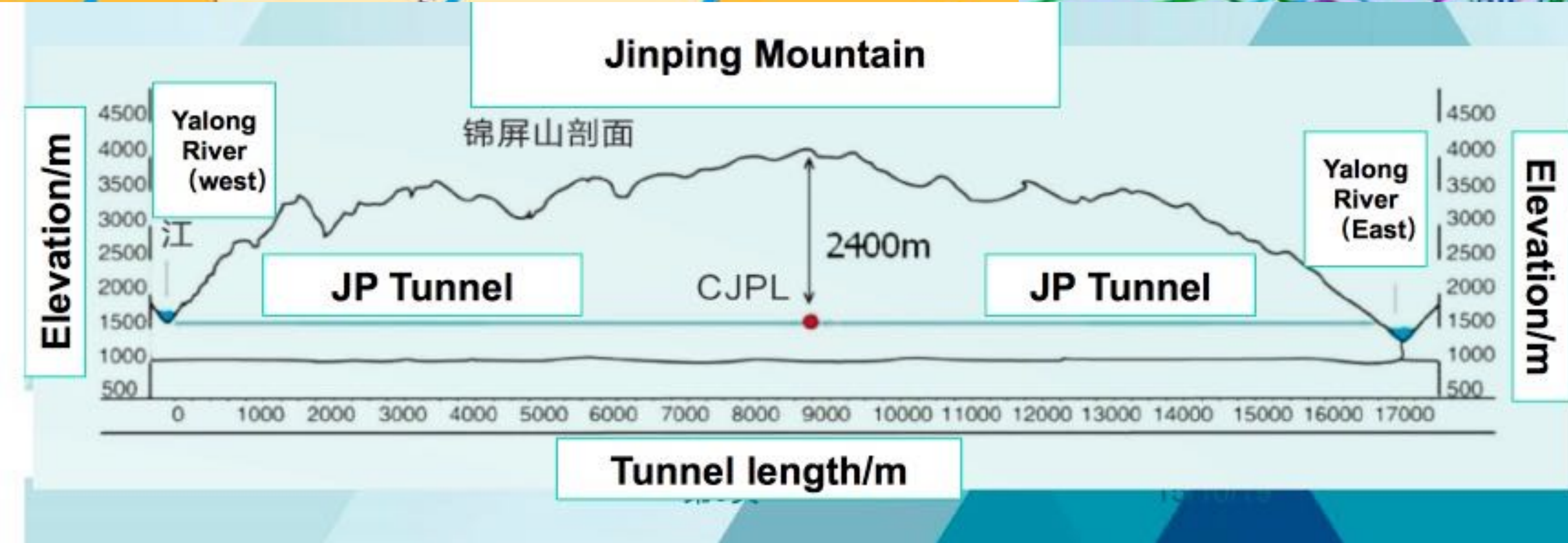
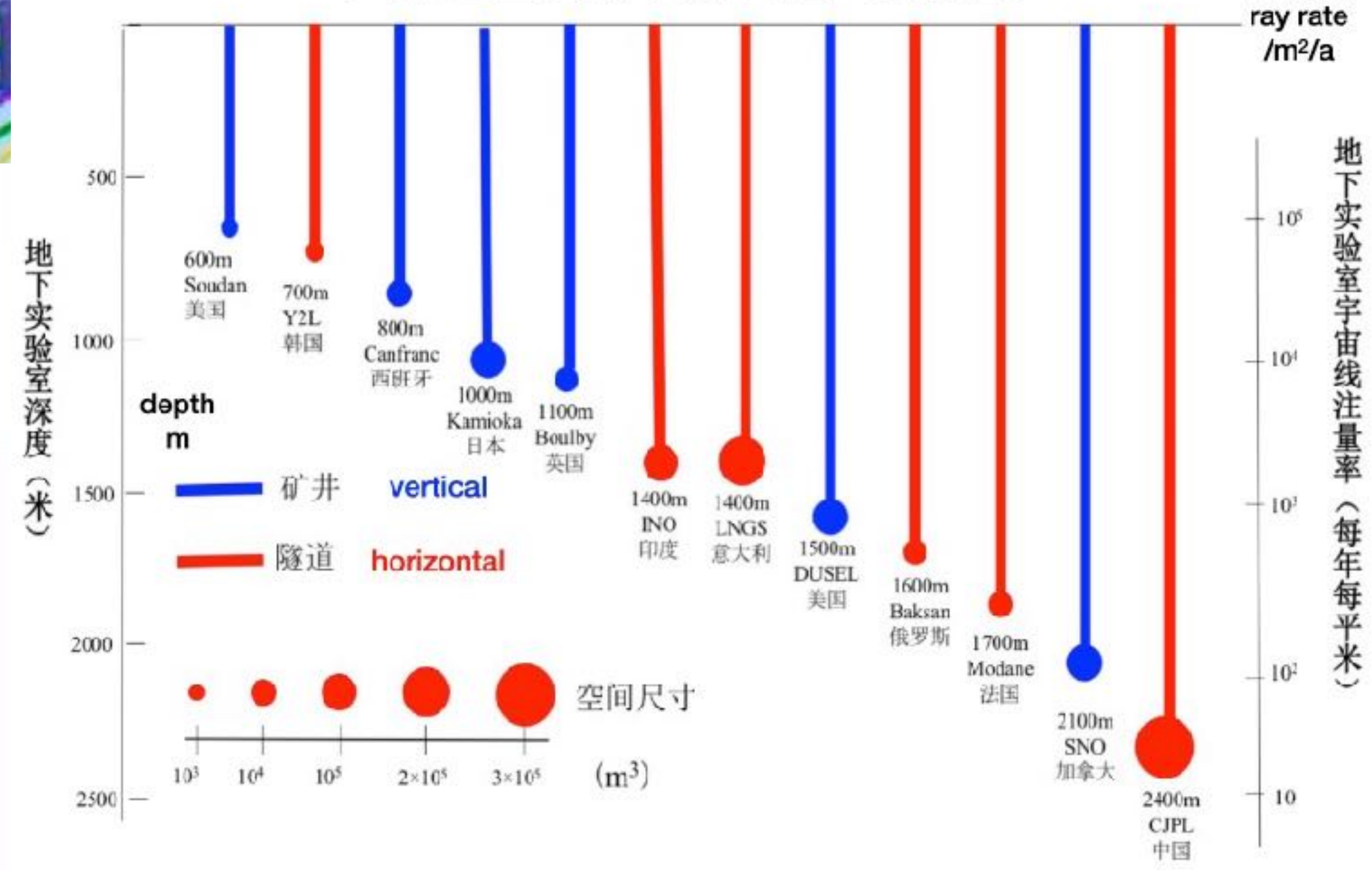


J. J. He et al., Sci. China Phys 59 (2016) 652001

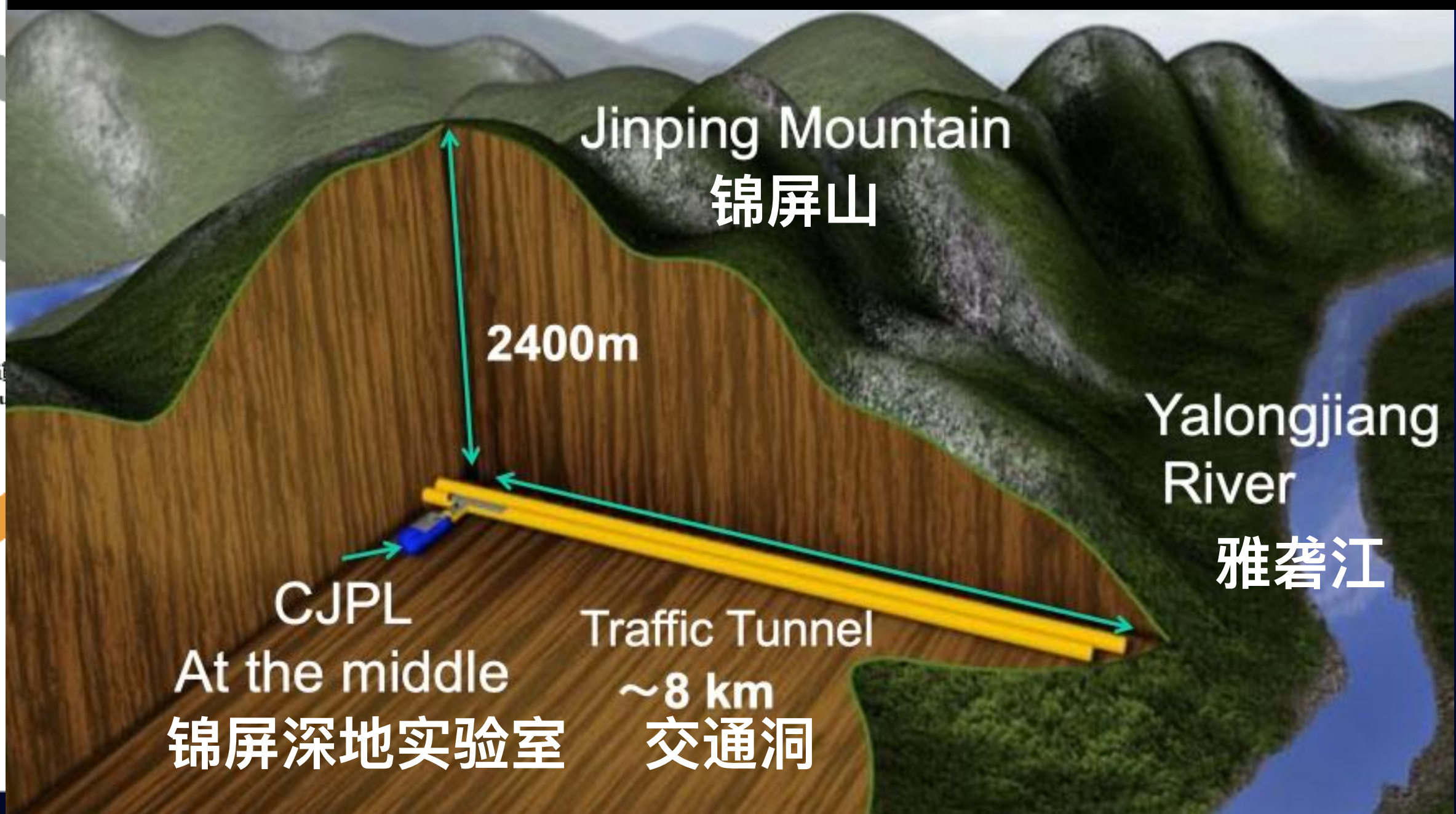
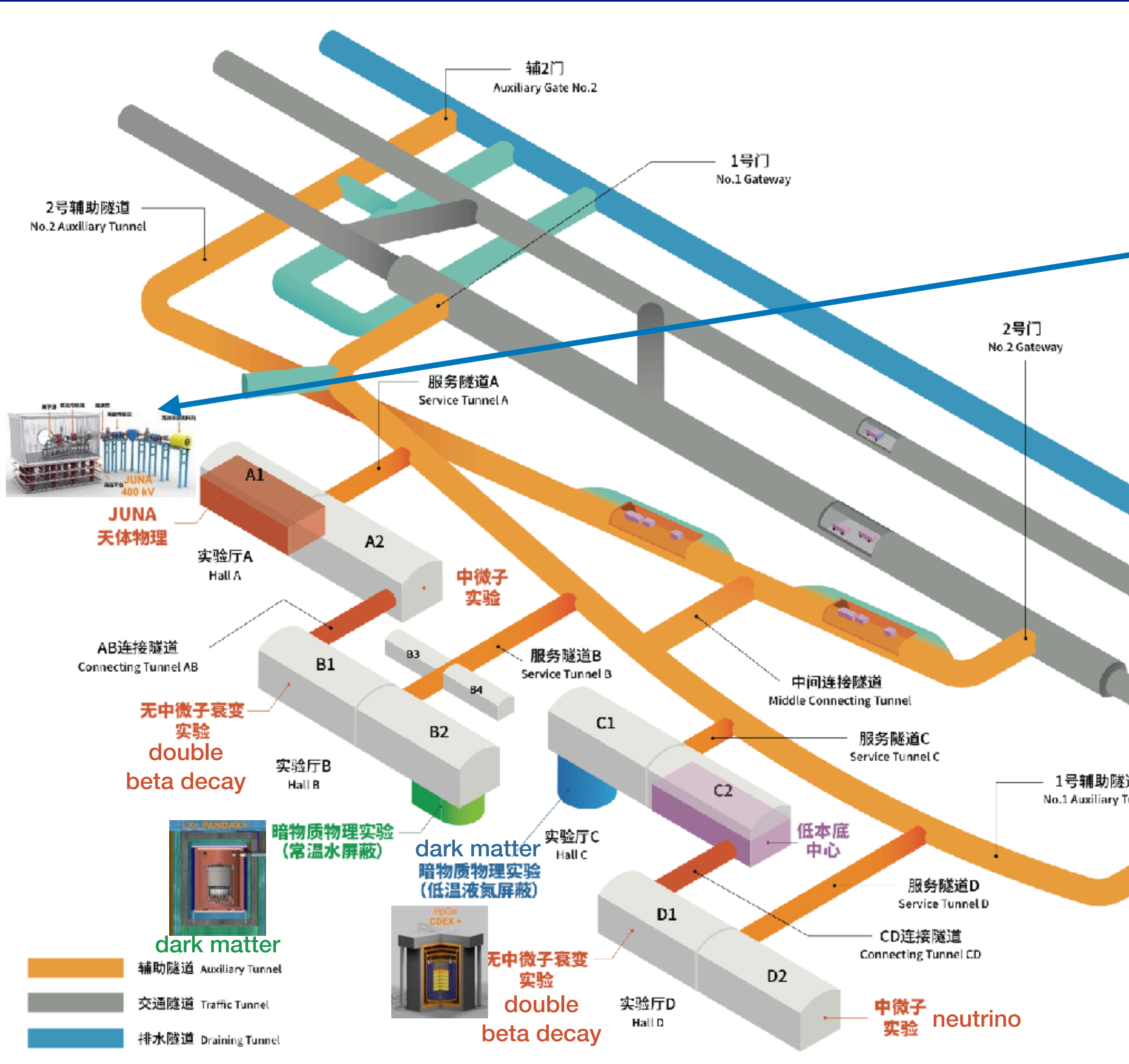
China Jinping: CJPL



Comparison of world underground laboratory
世界上重要的地下实验室比较图

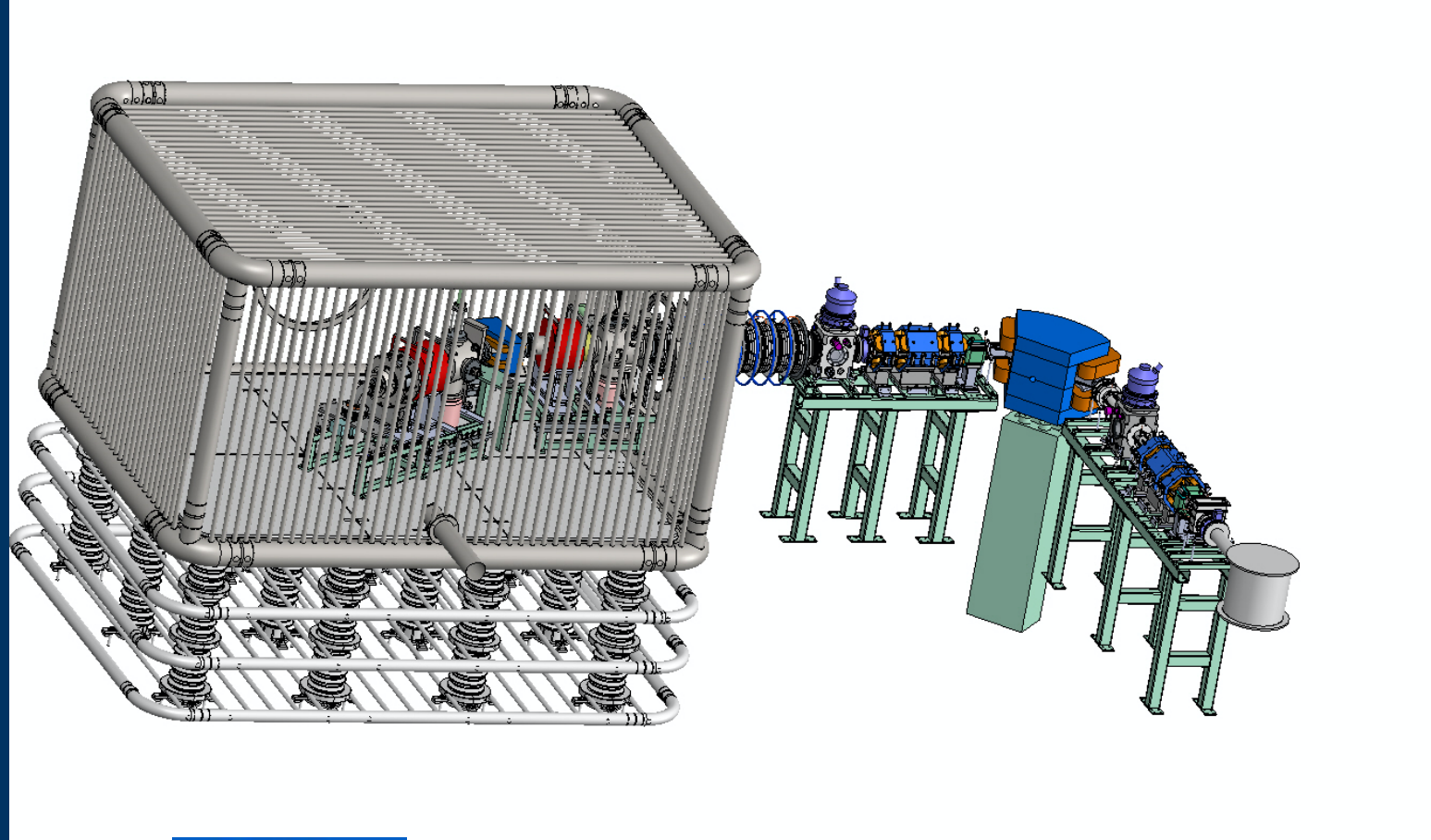


Most silent location: CJPL



JUNA dream team

Group leader



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



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



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



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



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



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



Gang Lian
Lab. exp. sup.
CIAE



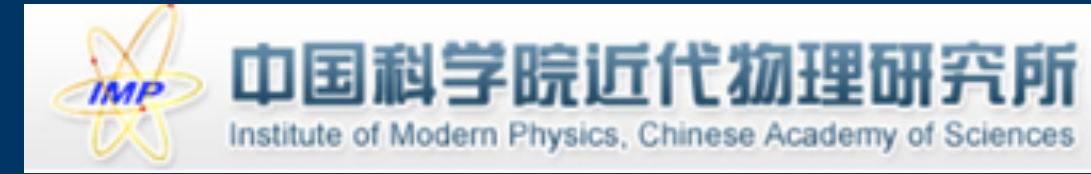
Bao Quncui, CIAE
Liangting Sun, IMP
Ion source and acc.



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

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

W. P. Liu, 2022, NuSYS



Acc. installation
Arjun Li

A1 construction
Hongwei Yang

Site support
Xiaopan Cheng

Acc. operation
Long Zhang

JUNA Milestone



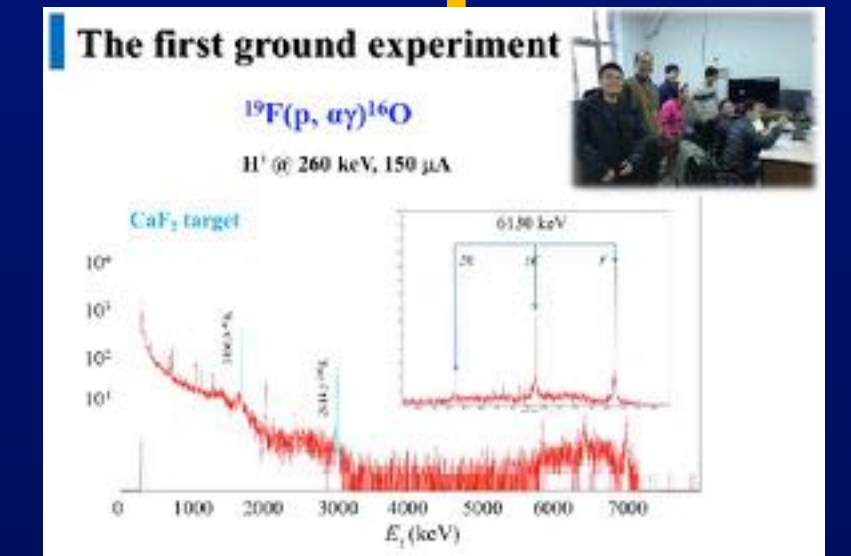
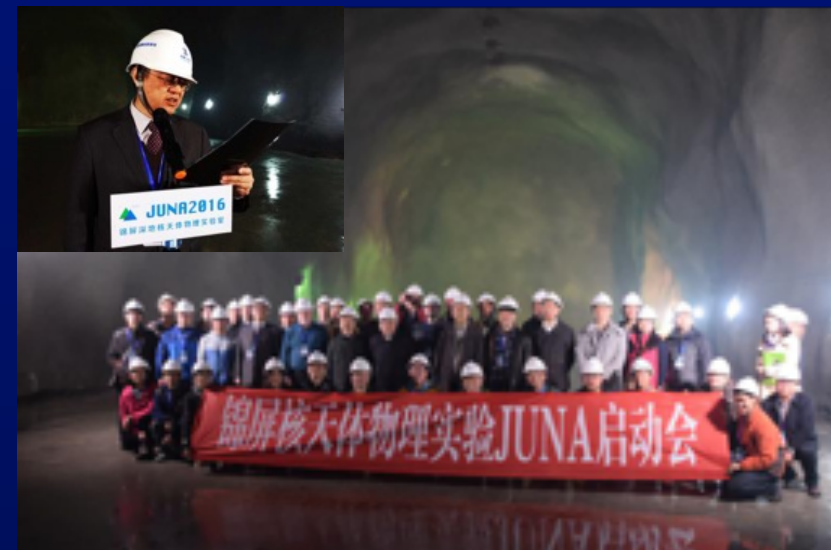
Aug. 2013
Startup
meeting

Jan. 2015
Project
inauguration

Mar. 2016
On site start

May 2017
Beam on
ground

Dec. 2017
3 mA on ground



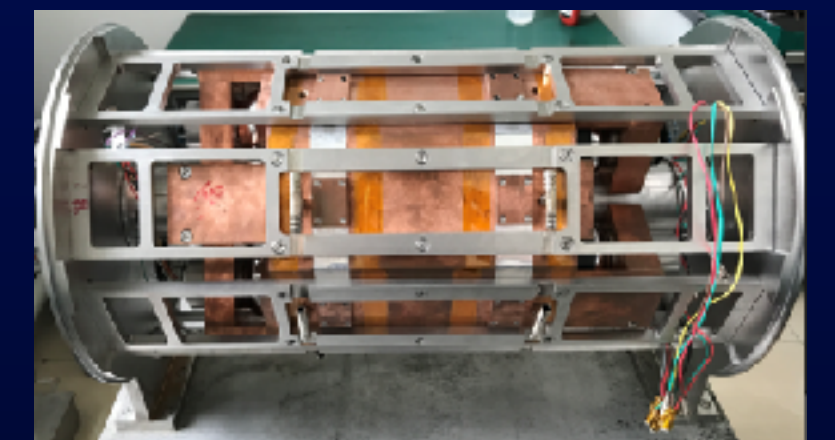
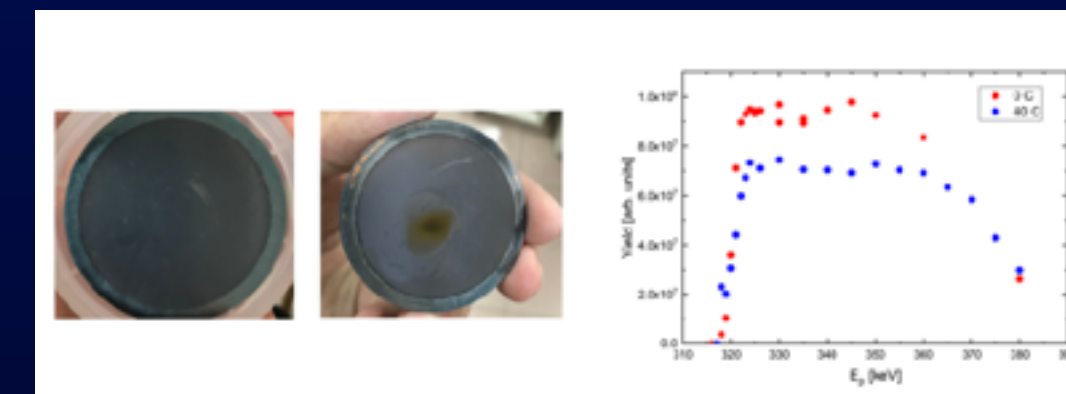
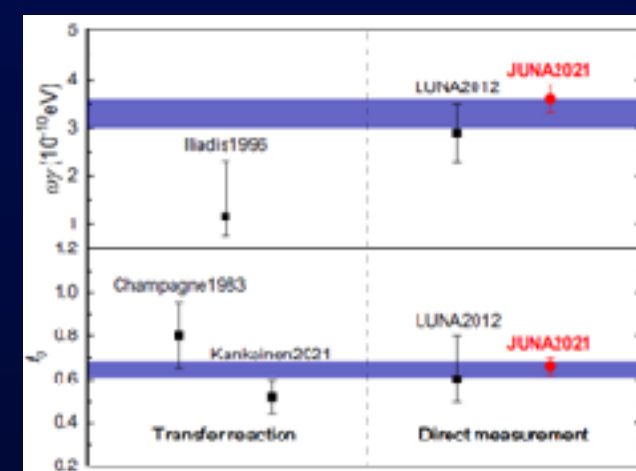
Dec. 2021
Project
commission

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

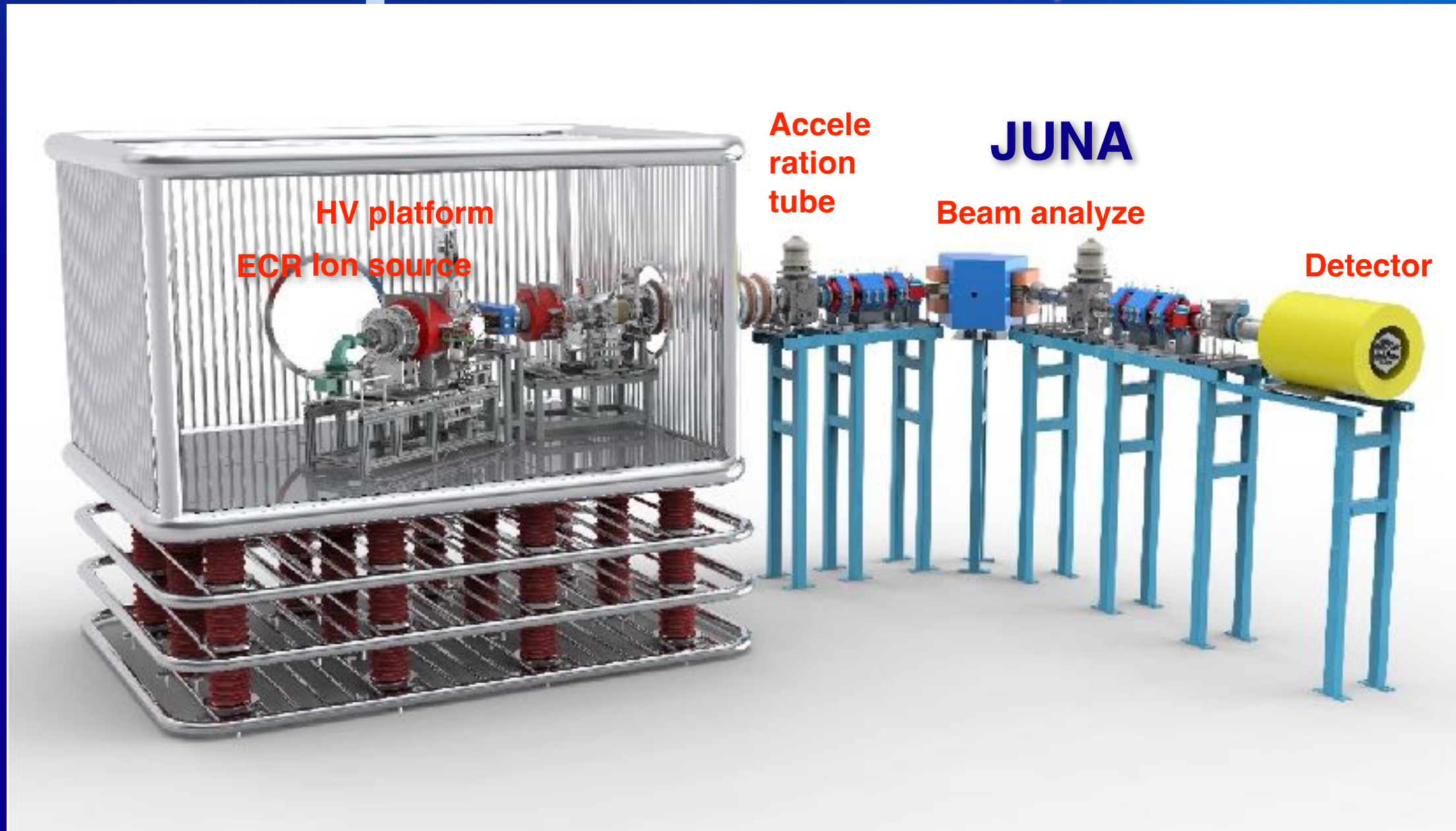
Dec. 2020
Beam
underground

April 2019
Target ready
Acc. Ready

Dec. 2018
Der. Ready
Beam 10 mA

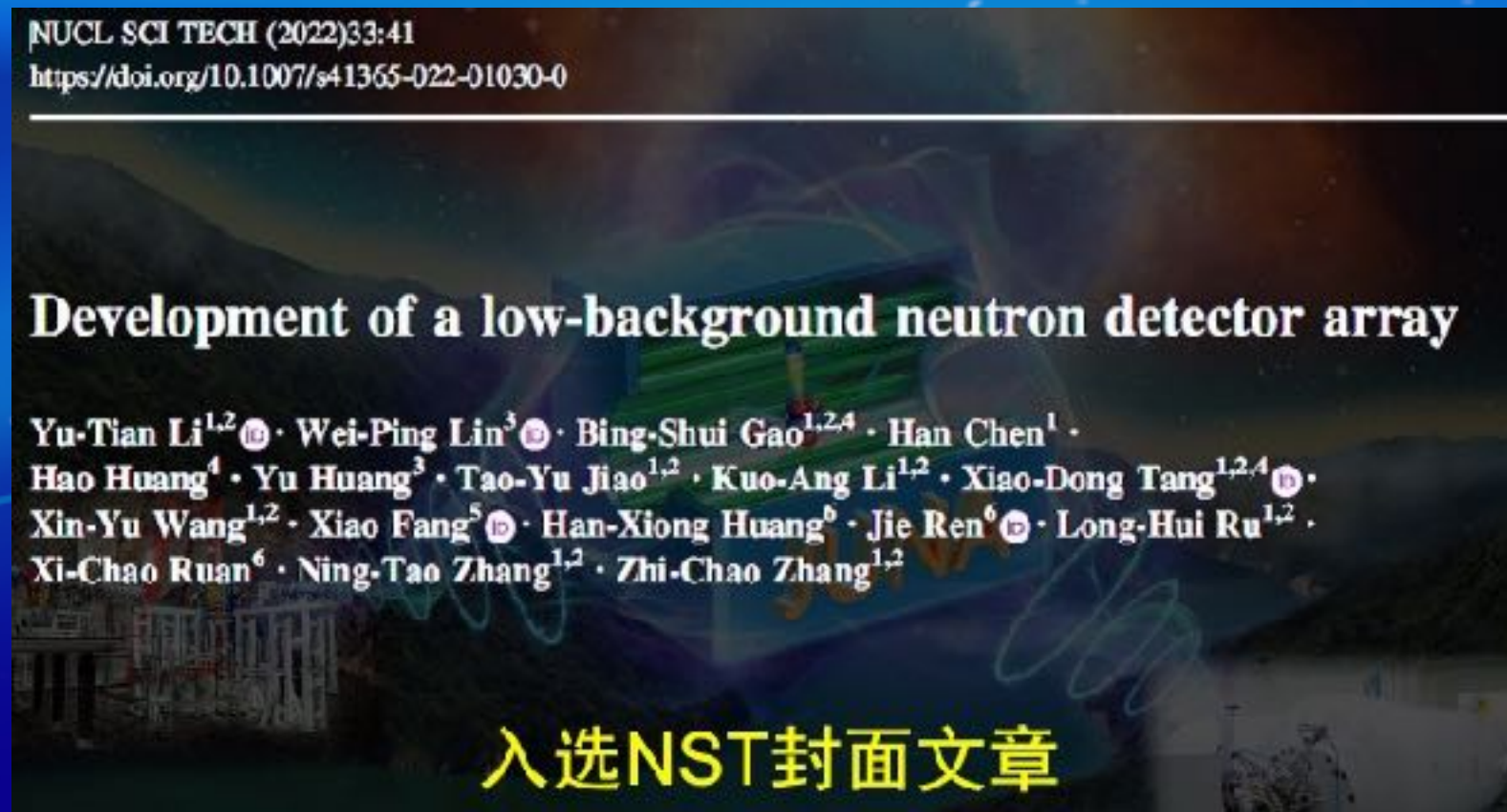


JUNA accelerator

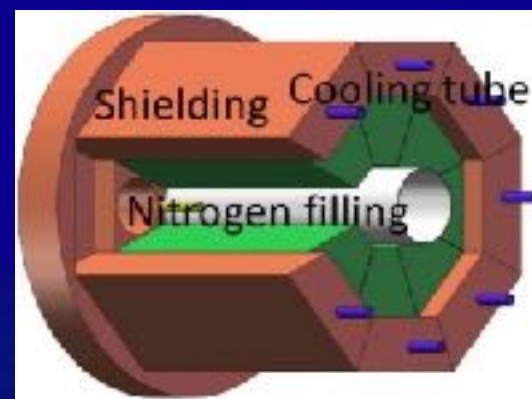
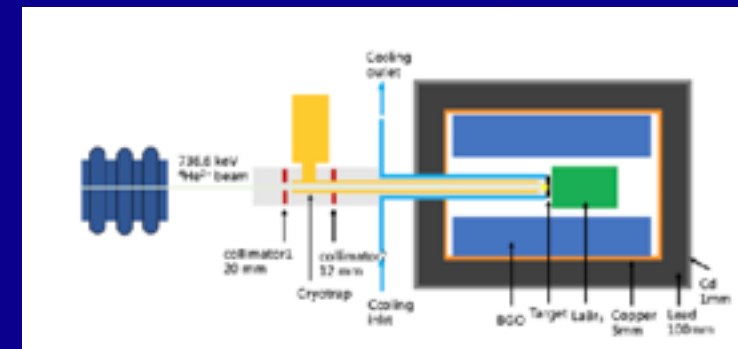


	lab depth m	cosmic μ bkg ($\text{cm}^{-2} \text{s}^{-1}$)	beam energy (keV)			beam intensity (emA)			energy stability
			H ⁺	He ⁺	He ²⁺	H ⁺	He ⁺	He ²⁺	
LUNA	1400	2×10^{-8}	50-400	50-400	3.5 MV	0.3~1	0.3~0.8	---	0.05%
CASPAR	1500	4×10^{-9}	100-1000	100-1000	1 MV	0.1	0.1	---	0.05%
JUNA	2400	2×10^{-10}	50-400	50-400	100-800	2-10	2-10	1-2	0.04%
Felsenkeller	45	$\sim 10^{-7}$			5 MV		30 μ A		

Detector tech.



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



JUNA2022

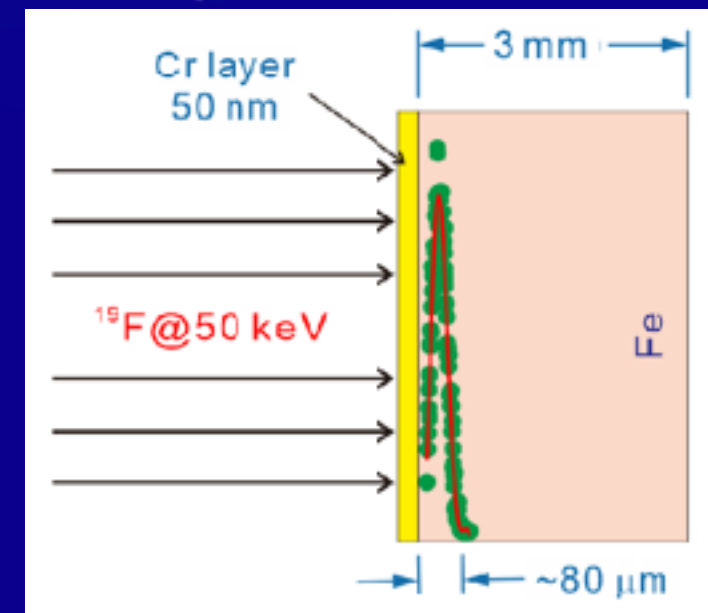
reaction	technology	publication	world best	JUNA
^{12}C	BGO+LaBr		down to 891 keV	down to 552 keV
^{25}Mg	BGO array X8	Atomic ST 52(2018)140	resolution 17 %	11 %
^{13}C	^3He array X24	NST33(2022) 41, cover story	Extrapolation	Self consistent
^{19}F	Charged particle array		170 keV	down to 100 keV

High durability target

3-10 times better than previous targets

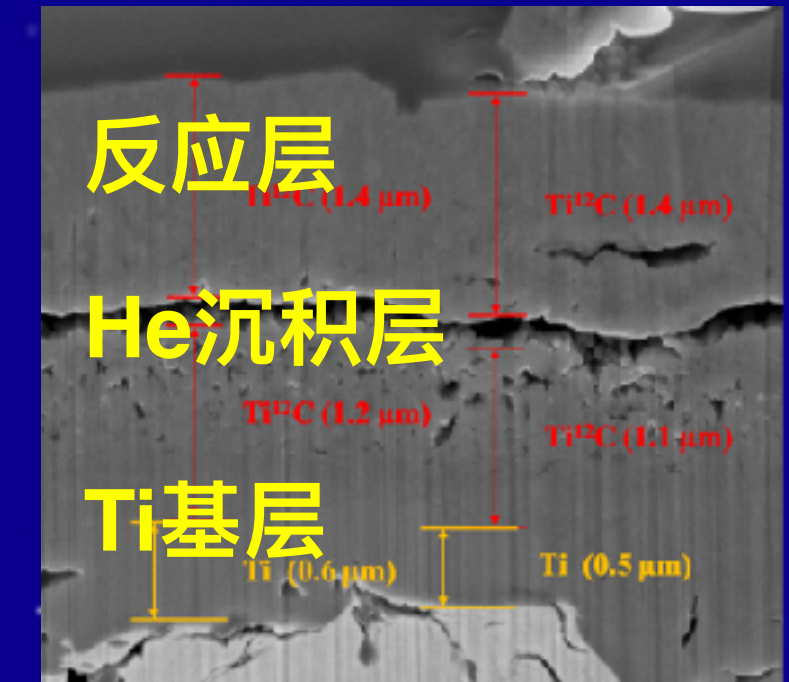
^{19}F Implantation

- High-purity iron substrate
- Magnetron chrome plating
- 100 C



^{12}C Deposit target

- FCVA
- ^{12}C 99.99%
- 400 C



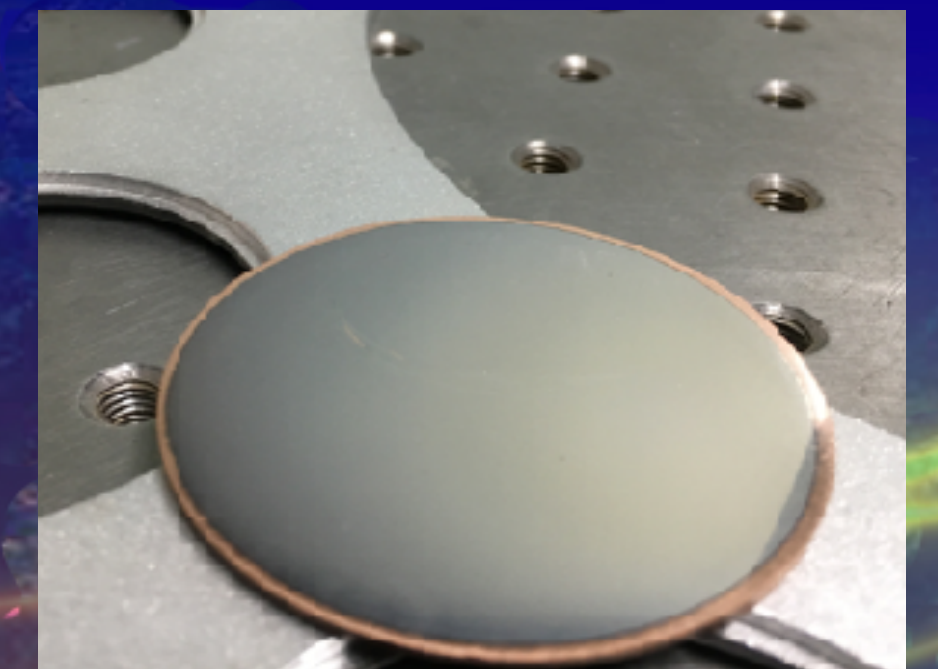
^{13}C Thick target

- High-temperature and high-pressure sintering
- 3550°C
- 0.5kW/cm²



^{25}Mg Hybrid layers

- Cr+Mg+Cr
- rotating coating
- 300 C





JUNA in DOE long range plan 2023



9 FACILITIES

experimental complex that uses secondary beams to perform precision measurements on hyper-nuclear spectroscopy, Λ -nucleon scattering, Λ -nuclei, and other topics of interest in QCD. J-PARC also houses a vibrant fundamental symmetries physics program that is searching for the ν DM and a neutron lifetime measurement. The Belle II experiment at SuperKEKB, an asymmetric energy electron-positron Super B factory located in Japan, will play an important and complementary role in the study of QCD alongside experiments involving hadron beams and/or hadron targets, as demonstrated by the previous Belle experiment at the High-Energy Accelerator Research Organization (KEK, Japan), the BaBar experiment at SLAC, and the ongoing BES-III experiment at BEPC II in China. The large Belle II dataset anticipated will enable the precise determination of complex correlations in the hadronization process, which are necessary for a detailed mapping of the QCD dynamics at play.

At the LHC, all four detectors (ALICE, ATLAS, CMS and LHCb) have significant heavy-ion programs with strong US participation. Before Run 3, the LHCb collaboration has completed the first of a series of detector upgrades, Upgrade 1. Before Run 4, LHCb will implement Upgrade 1b, which will include new tracking detectors. For Run 4, both ATLAS and CMS are planning major upgrades that will directly benefit the heavy-ion physics program. Both ATLAS and CMS will have upgraded trackers. CMS is also planning a new timing detector, which can make measurements with identified hadrons. ALICE has just completed several major upgrades, for which the US component of the ALICE collaboration (ALICE-USA) has made vital contributions to the new Inner Tracking System and Time Projection Chamber readout. ALICE-USA will now utilize these upgrades for a comprehensive physics program in the ALICE 2 phase that also provides a unique opportunity for hot and cold QCD studies between the expected times when RHIC discontinues collecting data in 2025 and when the EIC begins collecting data around 2028. ALICE-USA is one of the key proponents of the Forward Calorimeter (FoCal), which will collect data in Run 4. The development, installation, and operation of the FoCal will occur during the 2023 Long Range Plan timeframe and before the EIC begins collecting data. ALICE-USA fully supports the ALICE 3 detector, a next generation detector that is designed to operate in Runs 5 and 6 (2026 and beyond). On the same timescale as the ALICE 3 detector, LHCb is planning Upgrade II to make measurements over the full centrality range of heavy-ion collisions for the first time.

The Facility for Antiproton and Ion Research (FAIR) in Europe, under construction at GSI Darmstadt, is a

top-priority flagship facility for nuclear physics in Europe. US participation in the international collaboration of the Compressed Baryonic Matter experiment at this facility, driven by unprecedented beams from the superconducting heavy-ion synchrotron SIS100, will allow the US nuclear physics program to build on its successful exploration of the QCD phase diagram, use the expertise gained at RHIC to make complementary measurements, and contribute to achieving the scientific goals of the BES program. SIS100 and the FAIR Super Fragment Separator will enable the Nuclear Structure, Astrophysics, and Reactions (NUSSTAR) program at FAIR. NUSSTAR will have RIBs with the highest energies (>1 GeV/nucleon) and will provide opportunities for unique experiments not possible at other facilities. The University of Mainz in Germany is currently constructing the Mainz Energy Recovery Superconducting Accelerator (MESA); first electron beam is expected in 2024 for scientists to explore the limits of Standard Model physics. Among key experiments currently under development, the Mainz Gas Injection Target Experiment (MAGIX) is a multipurpose spectrometer for a precise determination of the proton charge radius and dark matter searches. MESA has grown from the expertise gained in operation of the Mainz Microtron accelerator, where US nuclear physicists are actively engaged in electron and photon scattering experiments. The Electron Stretcher Accelerator (ELSA) is operated by the University of Bonn in Germany. ELSA delivers a beam of polarized or unpolarized electrons with variable energies up to 3.5 GeV with main research topics in hadron physics.

US nuclear physicists are also actively conducting experiments in proton charge radius and fundamental symmetries studies at the Paul Scherrer Institut (PSI) in Switzerland and in hadron structure studies with the Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) experiment at CERN, exploiting unique beam capabilities not available in the United States. International facilities are also critical to efforts in fundamental symmetries, in particular the search for neutrinoless double beta decay. Two main laboratories will provide the locations necessary for these low-background, rare-event searches: SNOLAB in Sudbury, Ontario, Canada, and LNGS near L'Aquila, Italy. SNOLAB is a world-class science facility located deep underground in the operational Vale Creighton nickel mine, near Sudbury, Ontario, in Canada. At a depth of 2 km, SNOLAB is the deepest cleanest laboratory in the world. It is an expansion of the facilities constructed for the Sudbury Neutrino Observatory (SNO) solar neutrino experiment and has 5,000 m³ of clean space underground for experiments and supporting infrastructure. A staff of over 100 support the science, providing busi-

ness processes, engineering design, construction, installation, technical support, and operations. LNGS is the largest underground laboratory in the world devoted to neutrino, astroparticle physics and nuclear physics located between L'Aquila and Teramo, Italy.

One of the technologies discussed in Chapter 6 for neutrinoless double beta decay, CUPID, will be sited at LNGS; the nEXO detector will be hosted by SNO-LAB. LEGEND-1000, the ton-scale germanium-based system, can be hosted by either laboratory.

Various experimental facilities in Asia are involved in all areas of experimental nuclear physics, including those under construction. These facilities include the new Yemilab underground laboratory and the Rare Isotope Accelerator Complex for Online Experiment (RAON) in Korea; the Stawell Underground Physics Laboratory (SUPL) in Australia; and the Jinping Underground Laboratory for Nuclear Astrophysics (JUNA) facility, the Beijing Radioactive Ion Beam Facility (BRIF), the Heavy Ion Accelerator Facility (HAIF), and CJPL-II Underground Laboratory in China. All these international facilities are shown in Figure 9.8.

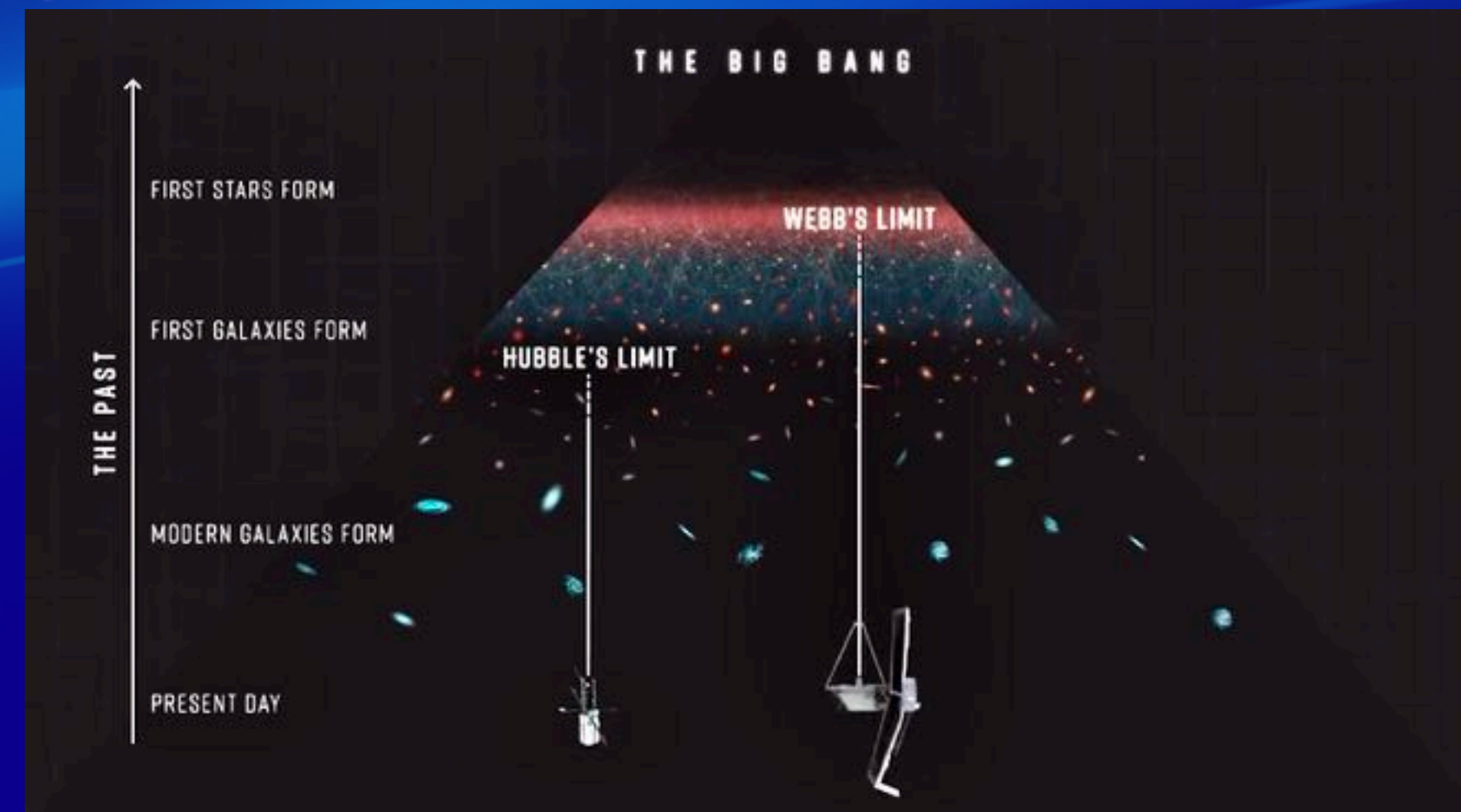


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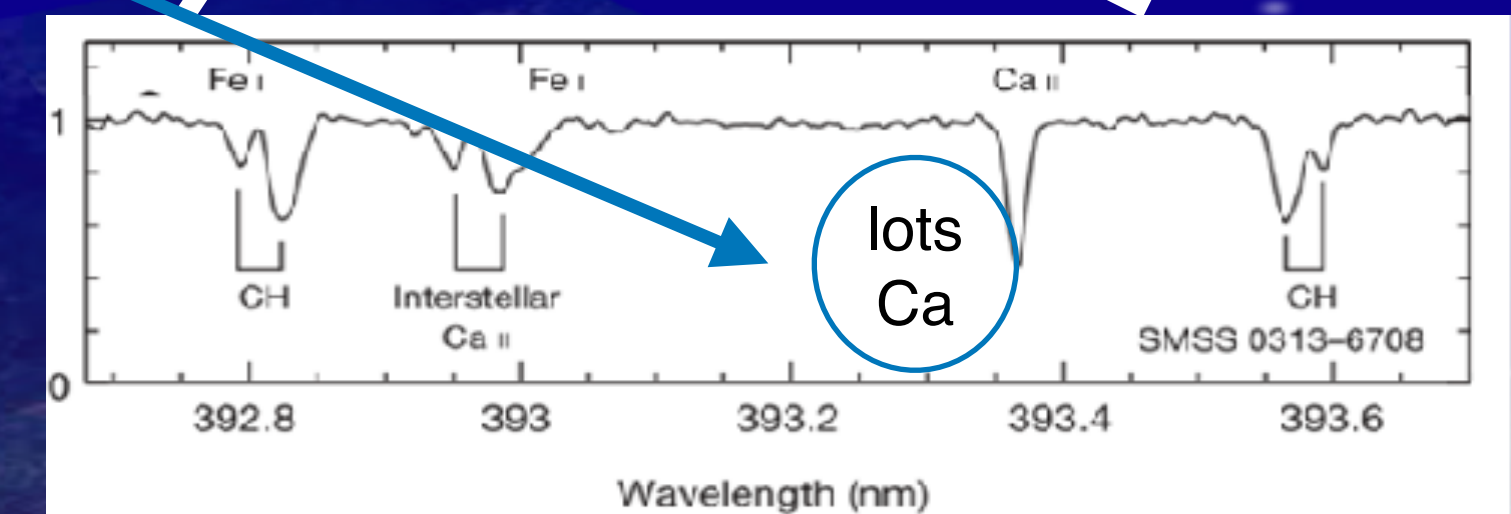
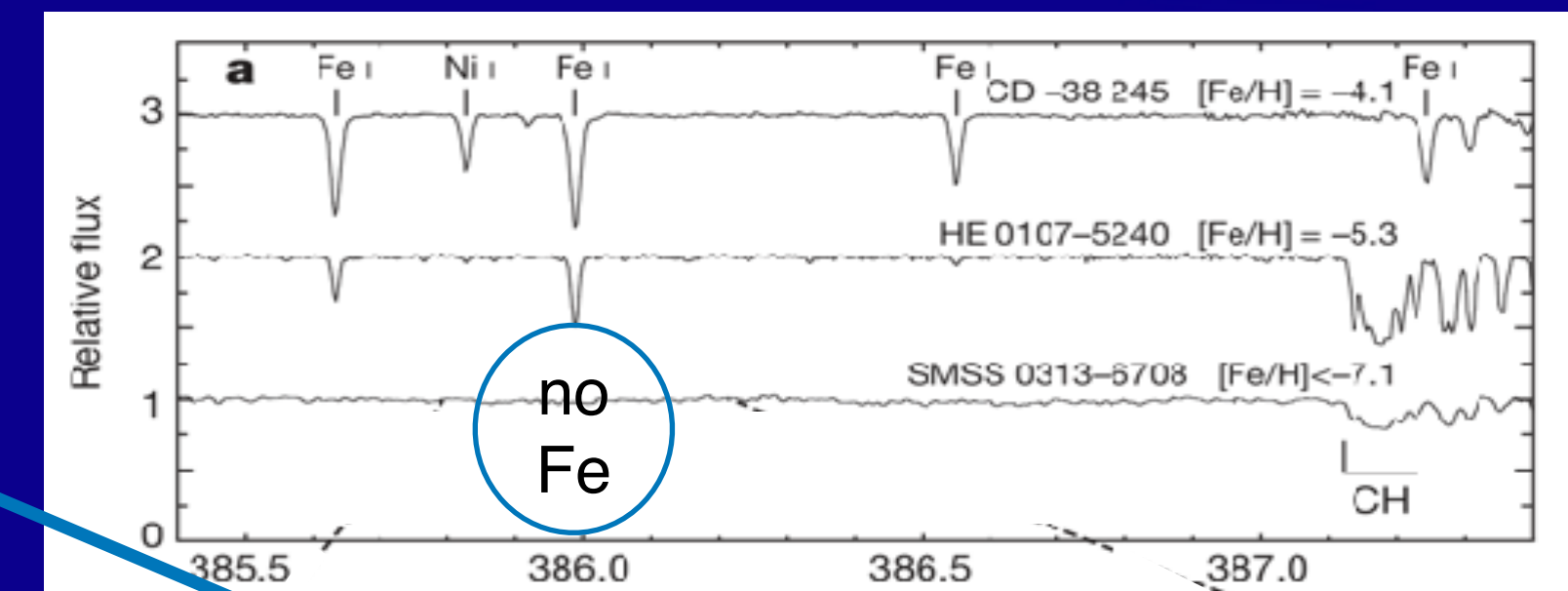
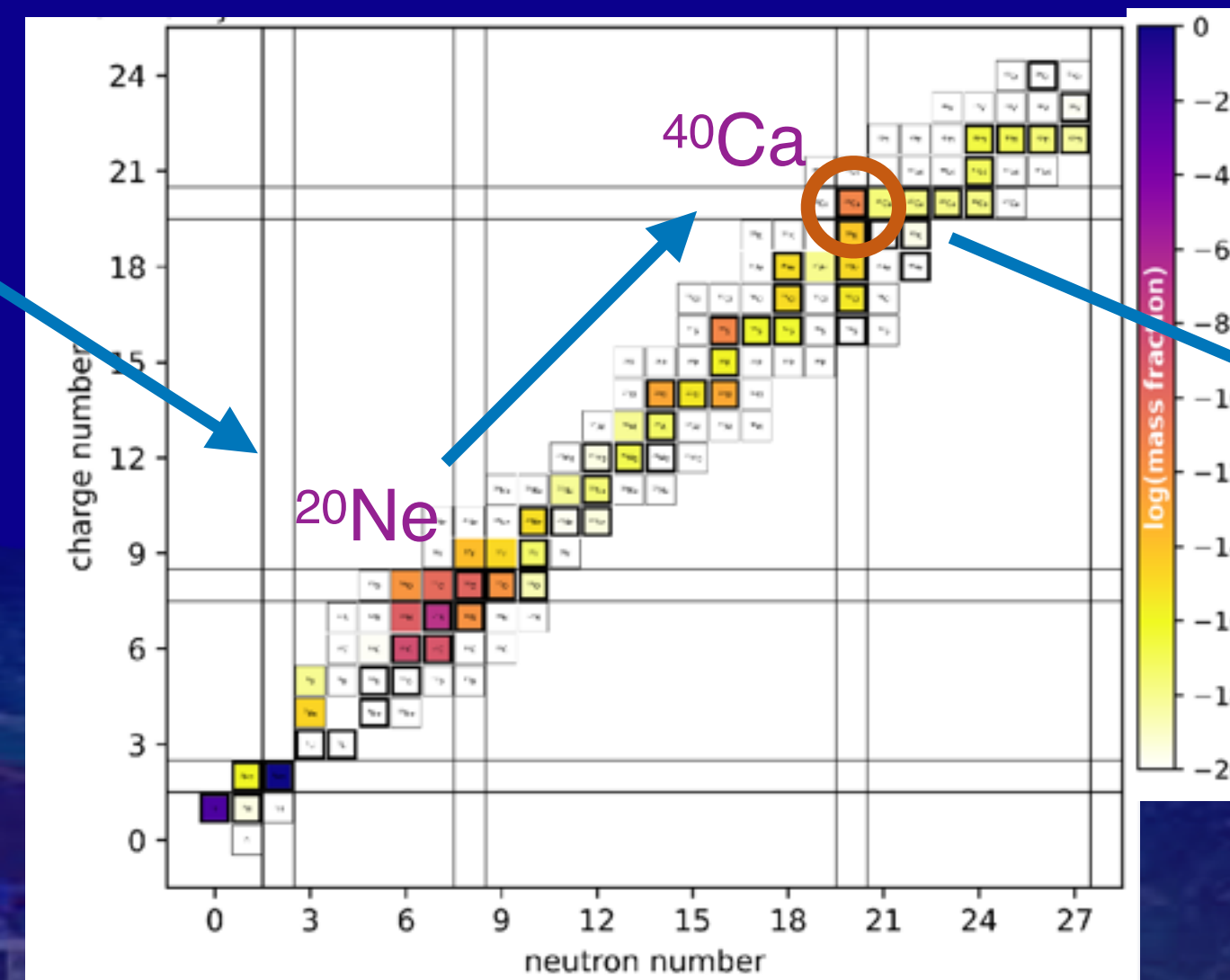
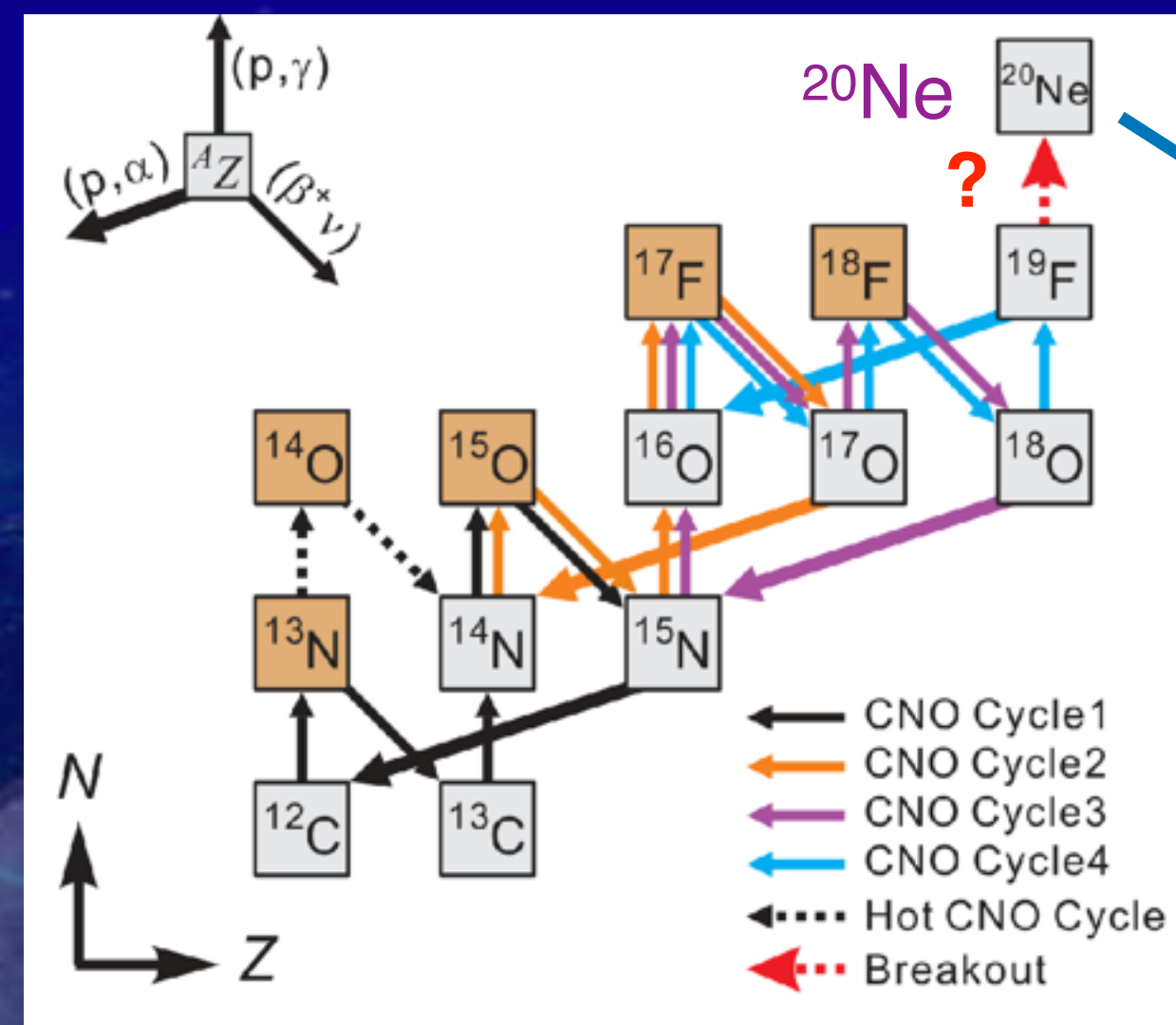
$^{19}\text{F}(p,\gamma)^{20}\text{Ne}$: confirm CNO break, explain Ca in oldest star



JWST



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



Solution: $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$ rate one order large?

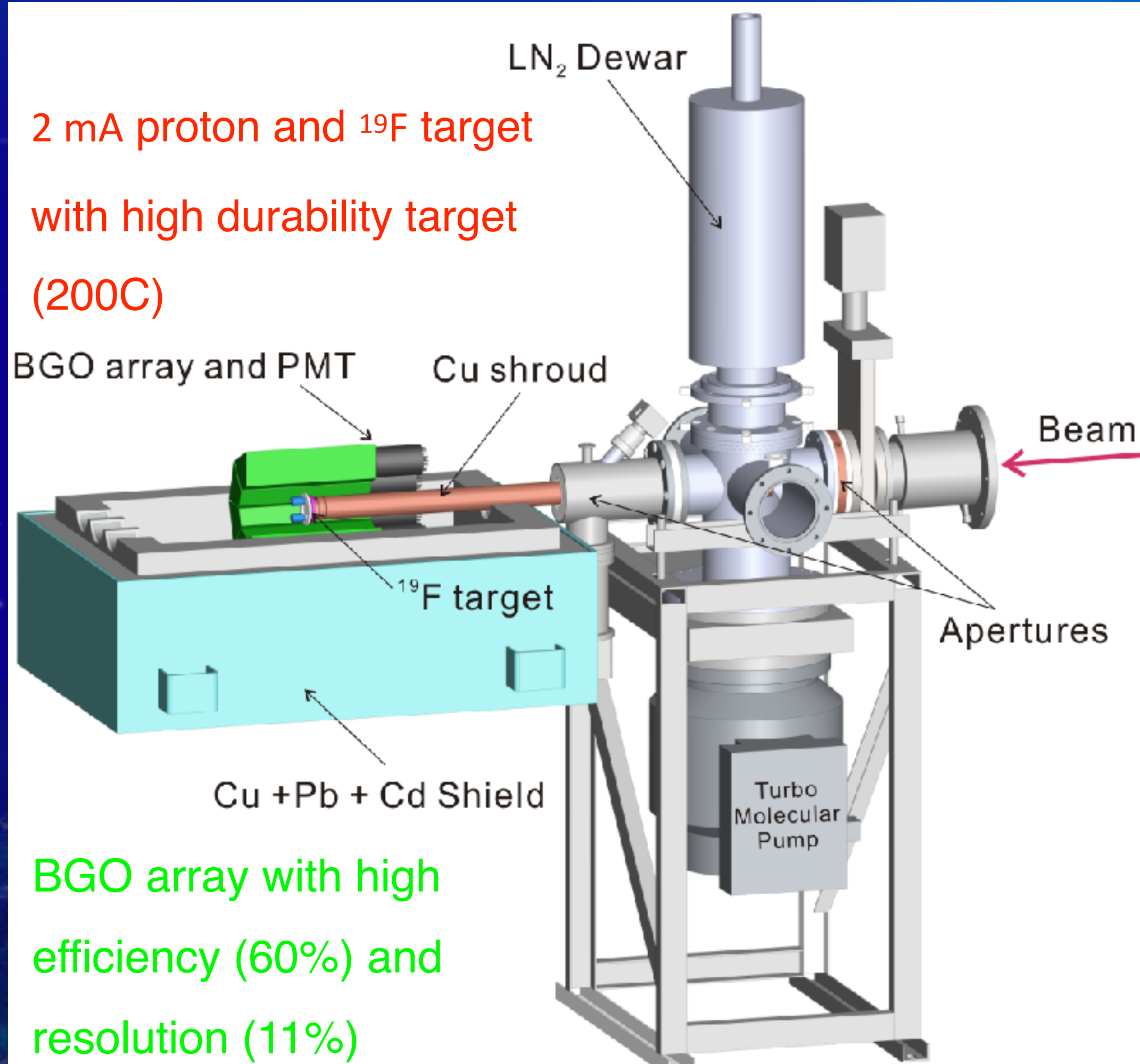
SMSS 0313-6708: lots of Ca, but no Fe?

Experiment setup

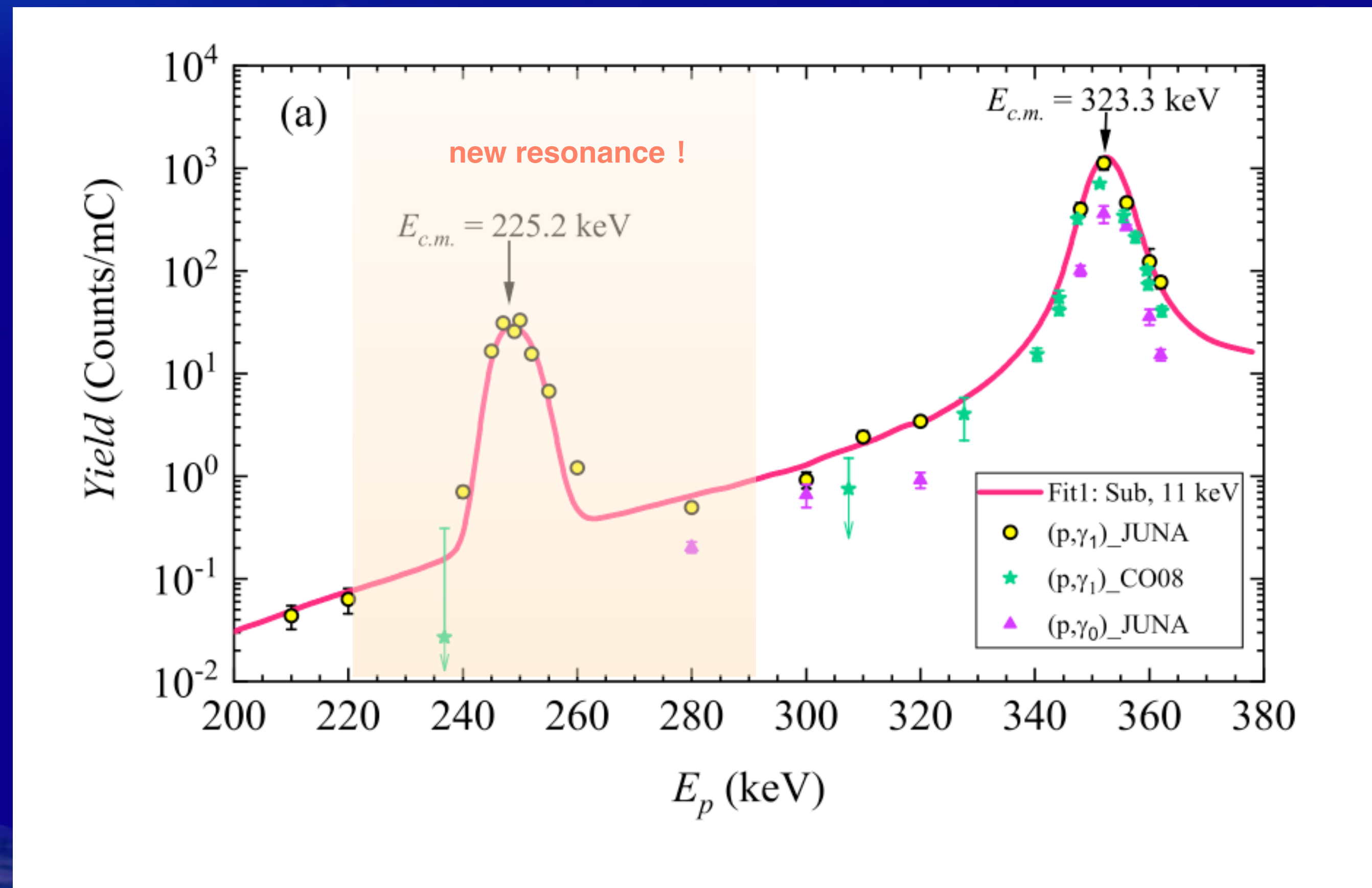


PI: J. J. He, BNU
with L. Y. Zhang, BNU

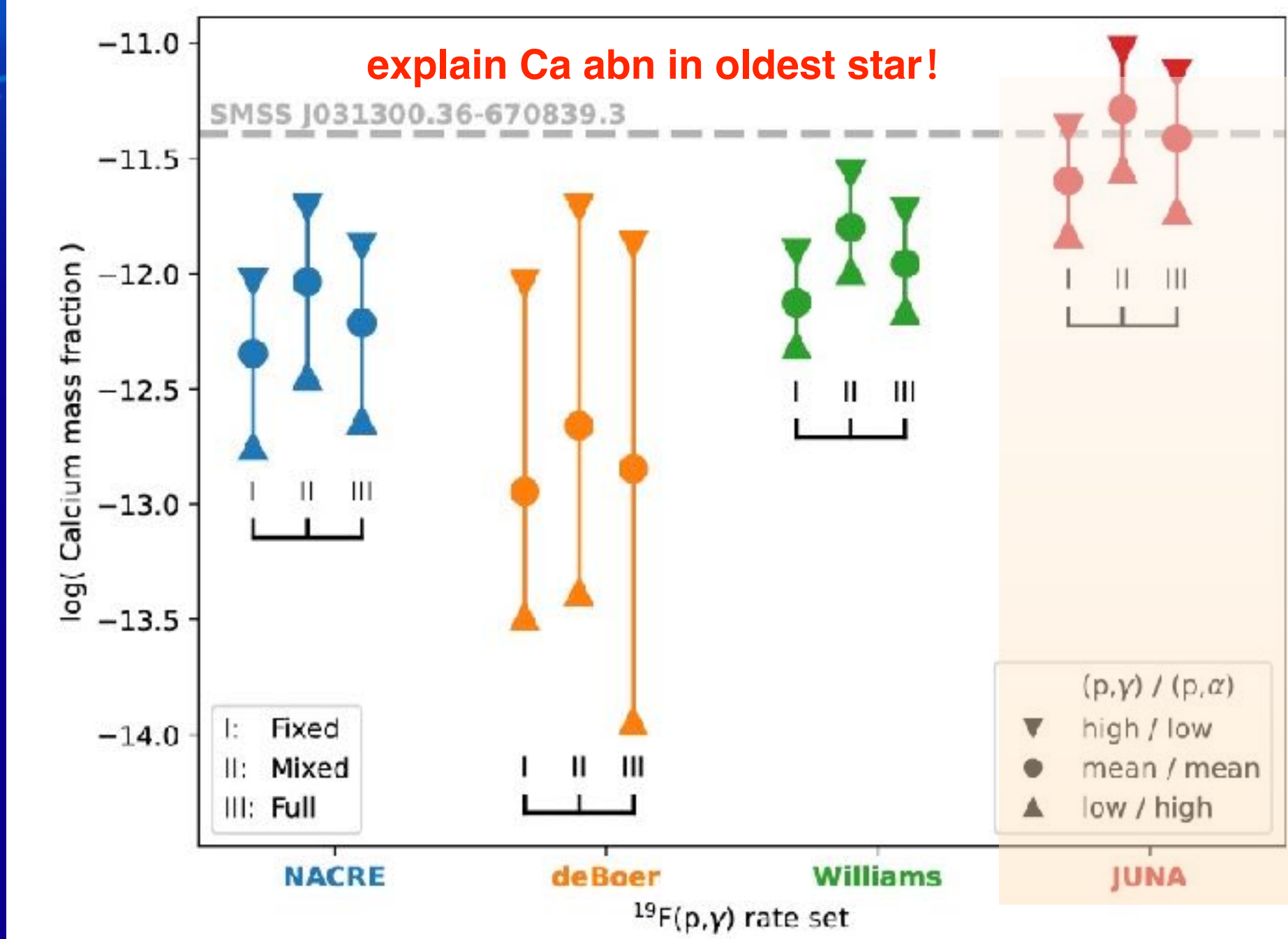
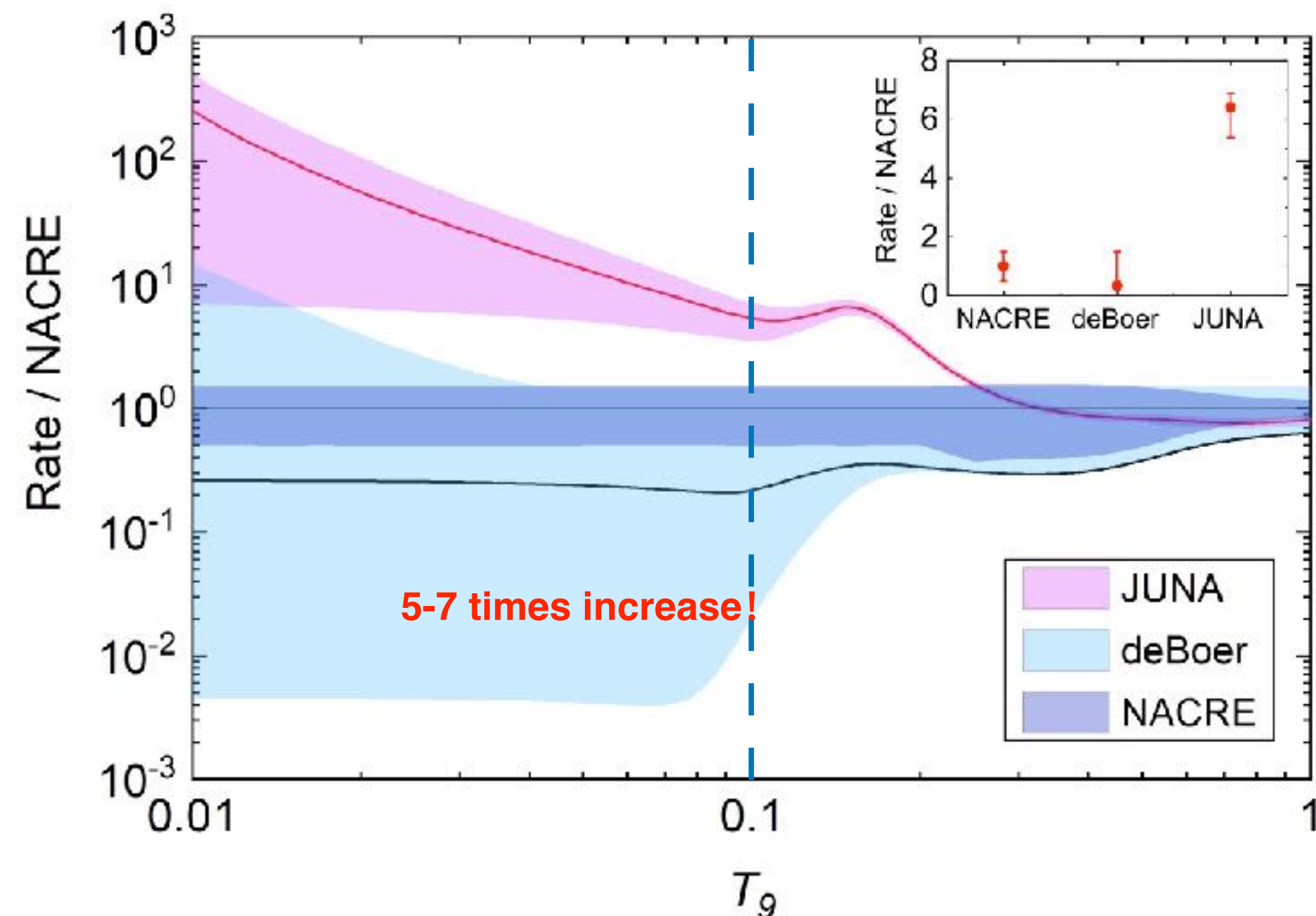
2 mA proton and ^{19}F target
with high durability target
(200C)



BGO array with high
efficiency (60%) and
resolution (11%)



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



Article

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

<https://doi.org/10.1038/s41586-022-05230-x>

Received: 28 February 2022

Accepted: 11 August 2022

Check for updates

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Nuclear astrophysics

Underground route to grasping the oldest stars

Marco Pignatari & Athanasios Psaltis

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. See p.656

L. Y. Zhang, J. J. He*, ..., WPL*, Nature 610(2022)656, Selected as news and views

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

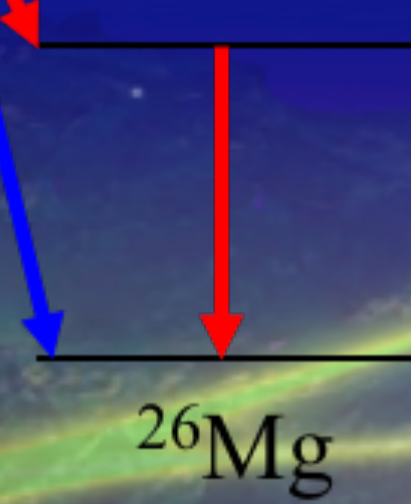
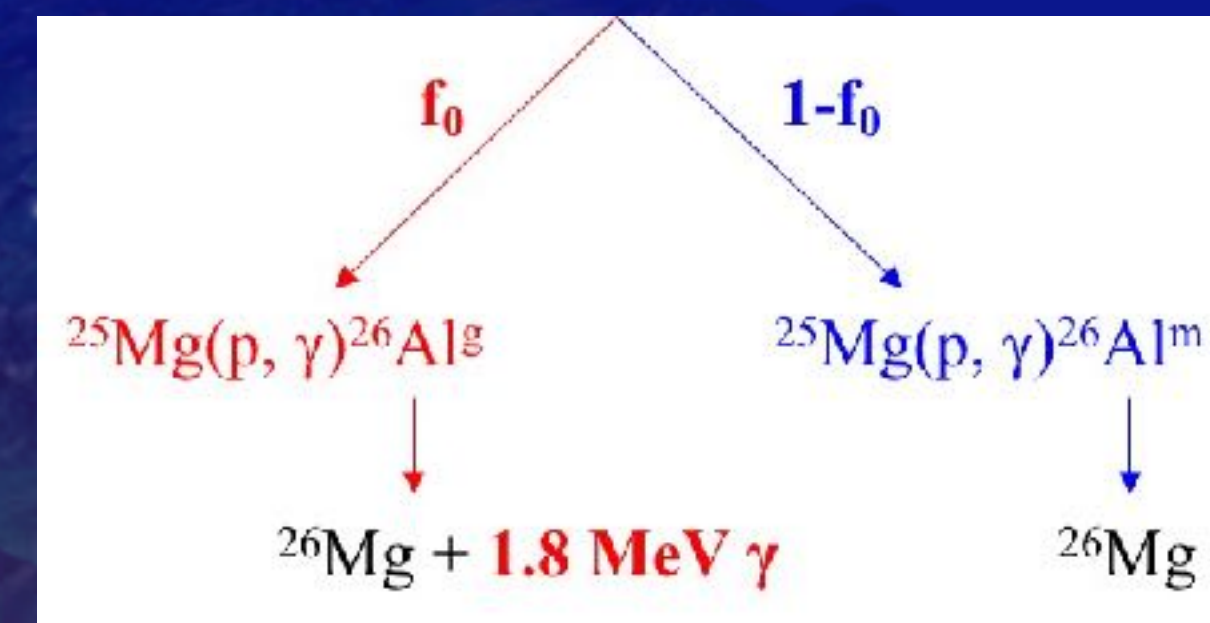
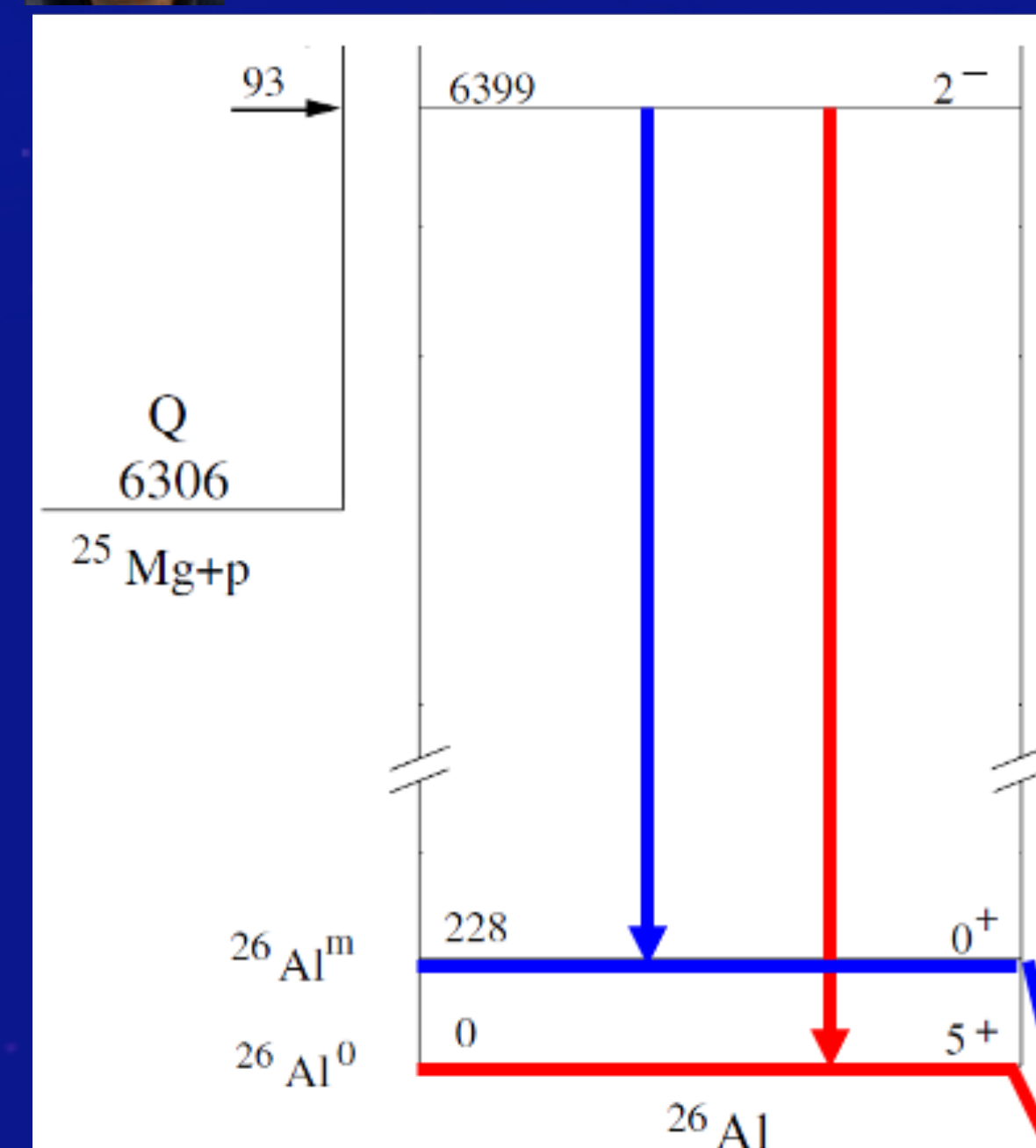
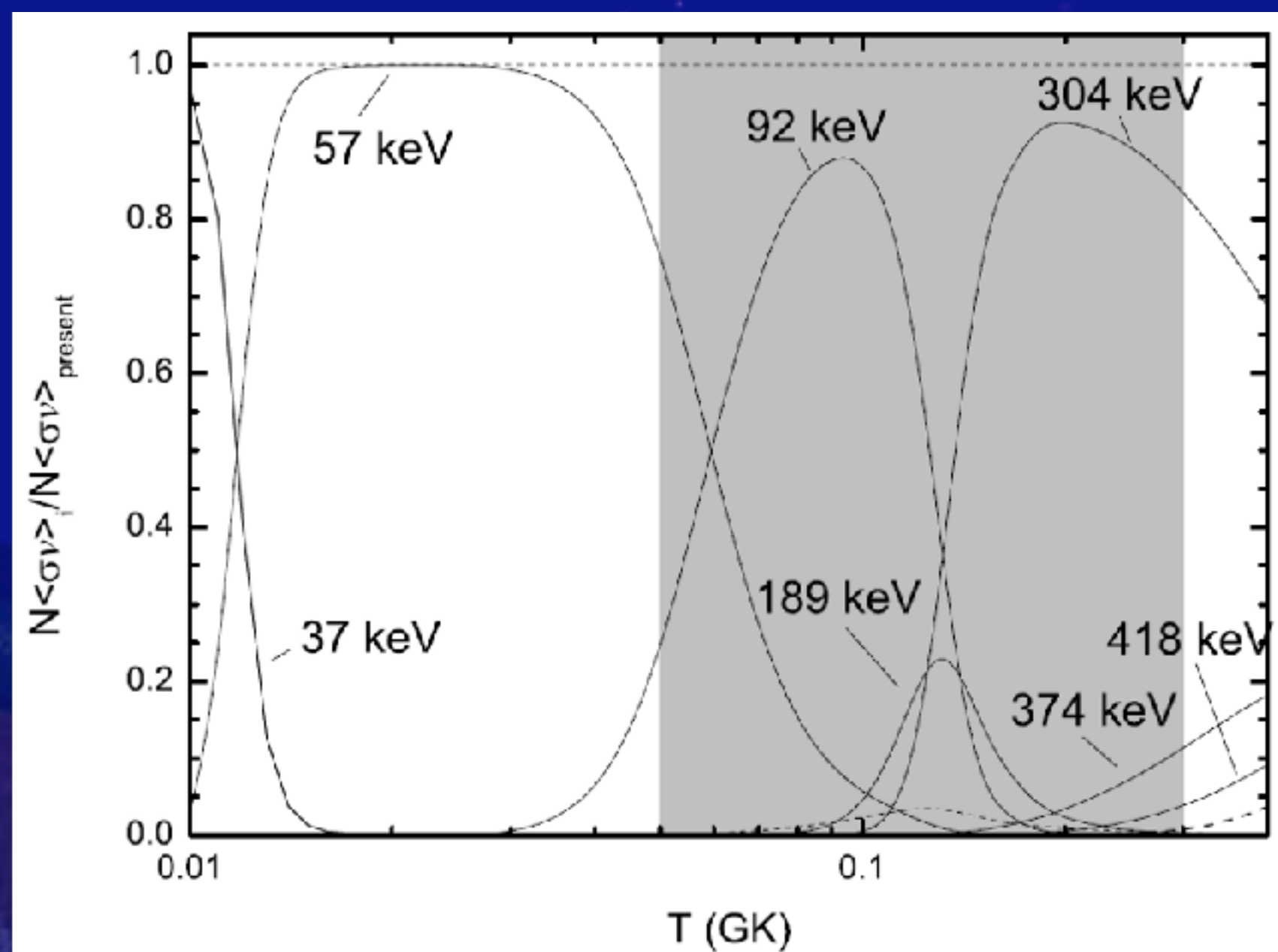
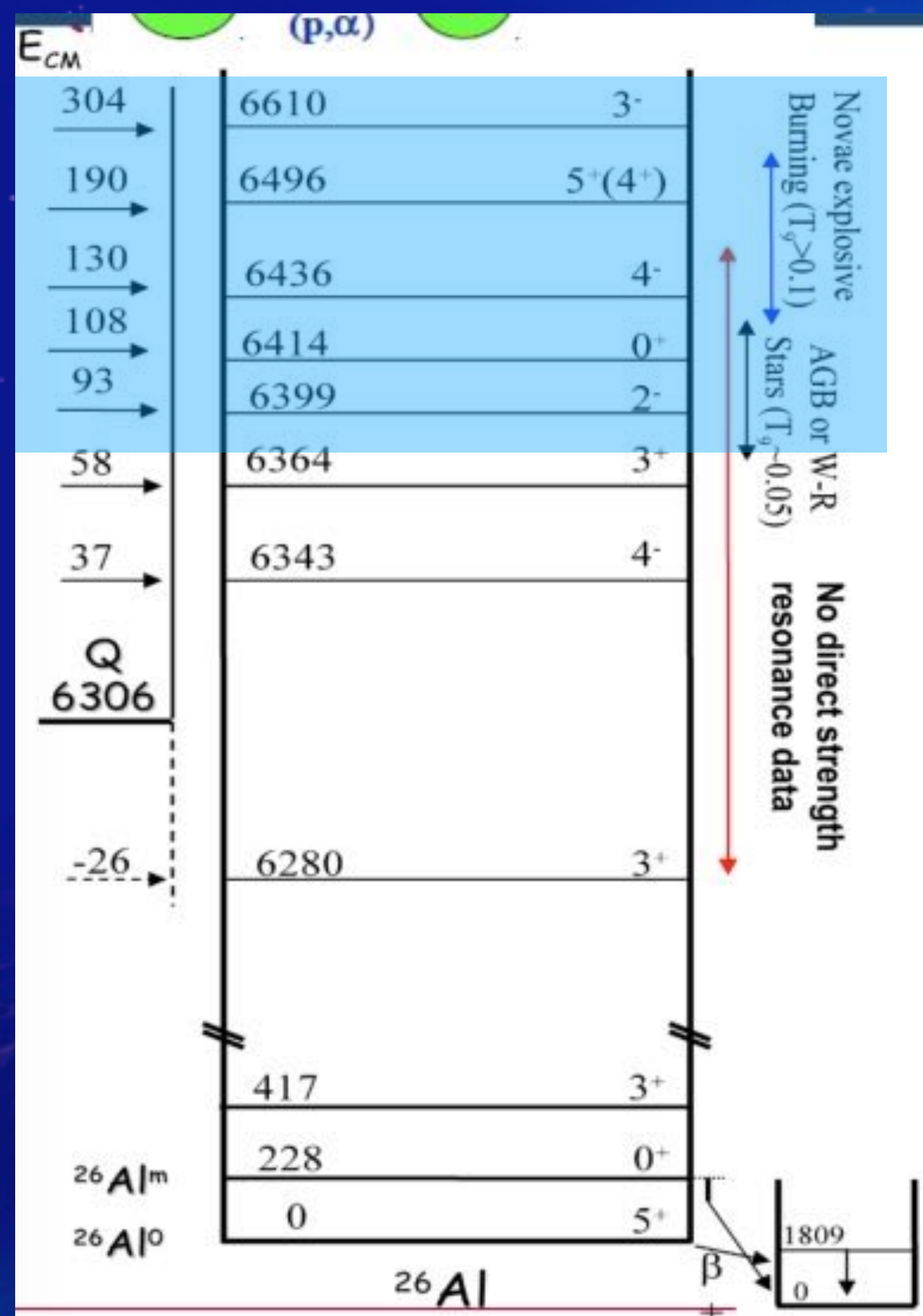
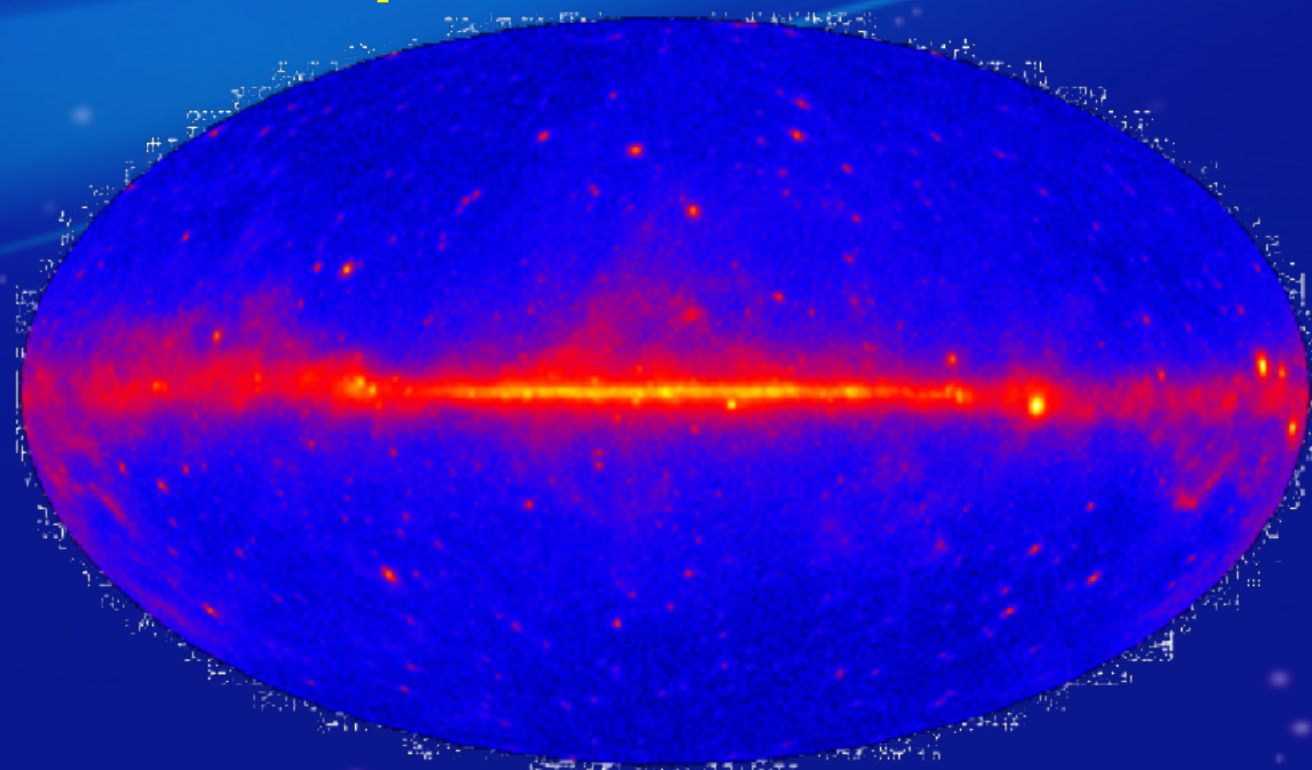
Exp.: Jan. 1-15, 2021



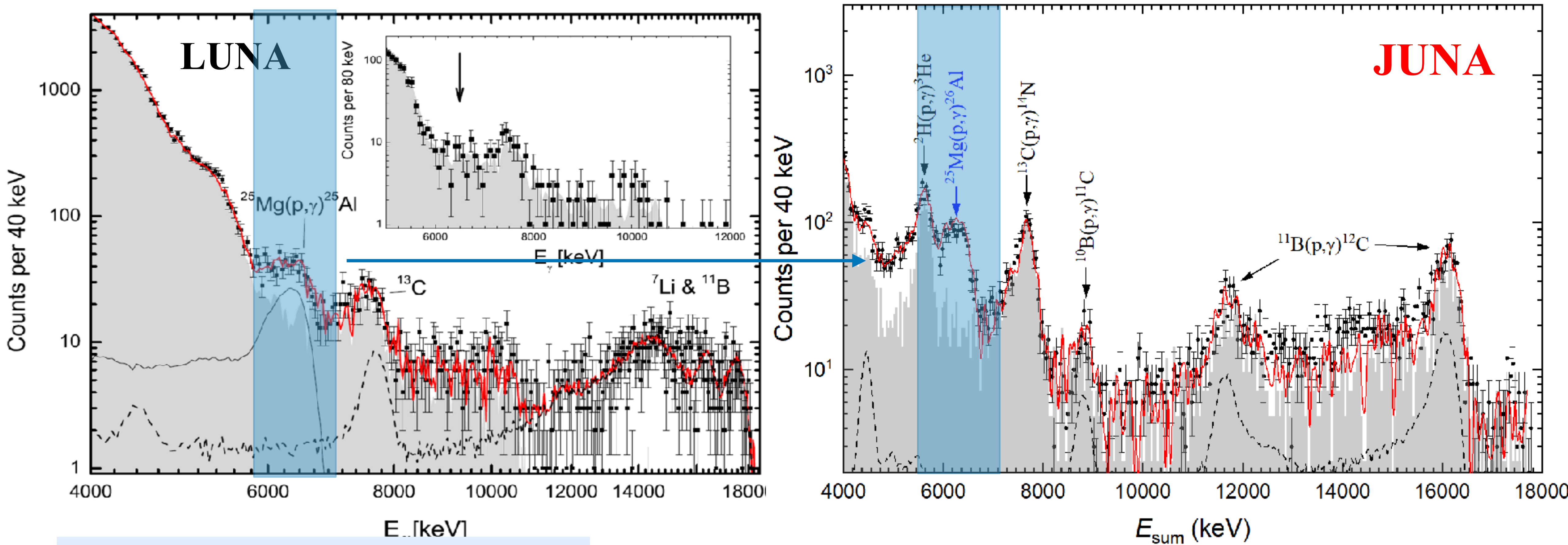
PI: Z. H. Li, CIAE



J. Su, CIAE/BNU



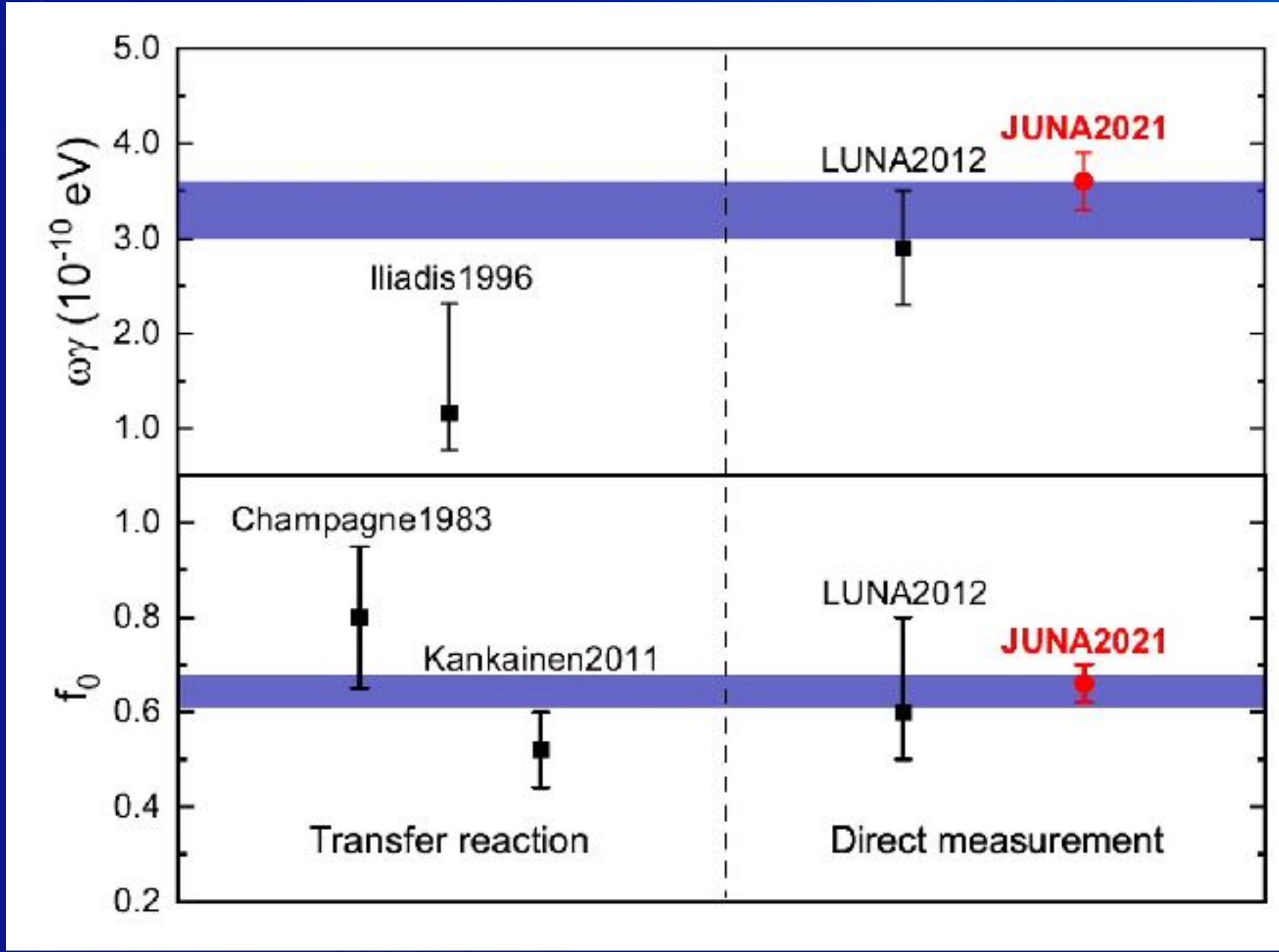
JUNA vs. LUNA



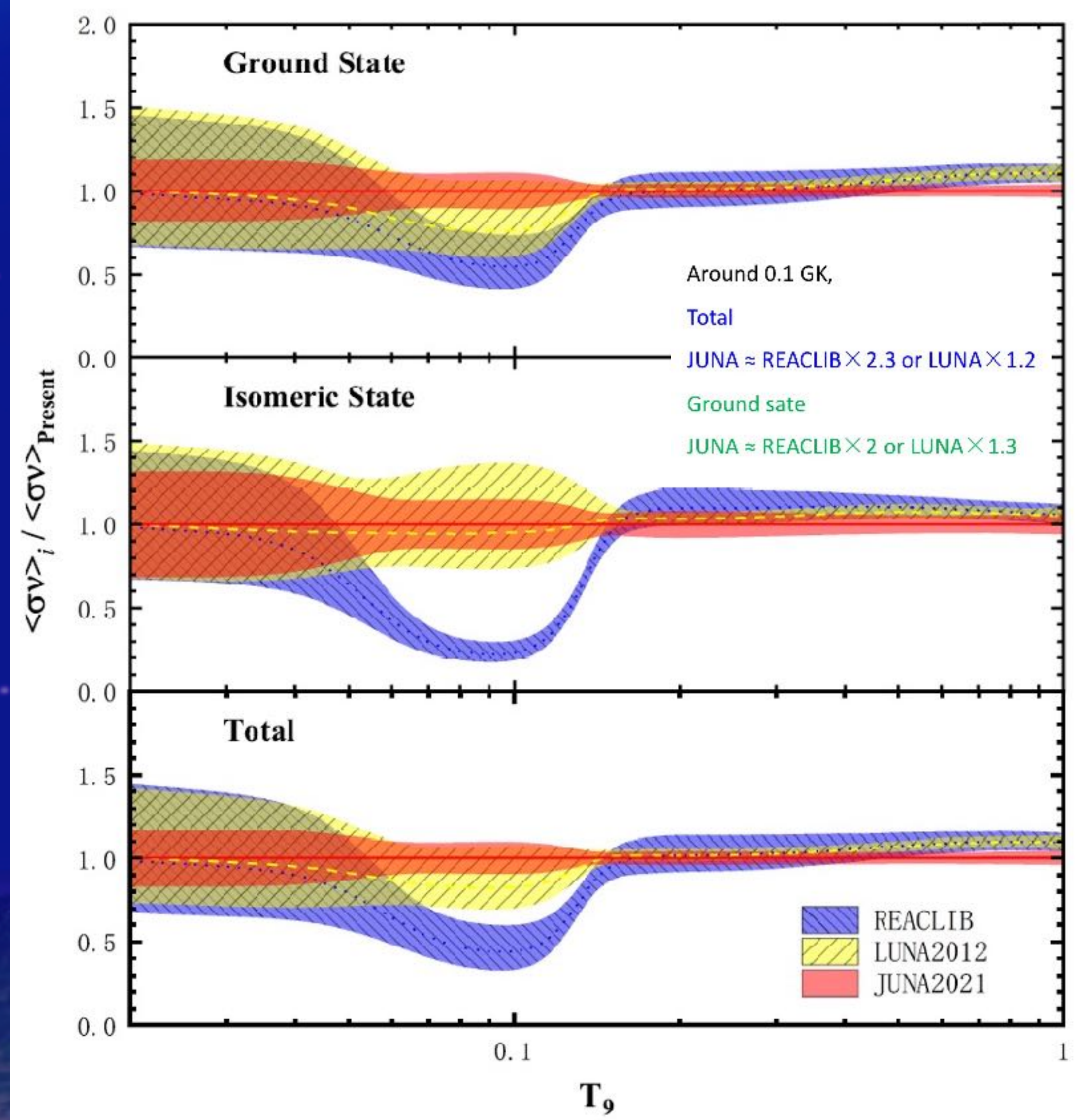
52 days, 370 C
signal: 410
strength: $2.9 \pm 0.6 \times 10^{-10}$ eV

15 days, 1008 C
signal: 1225
strength: $3.8 \pm 0.4 \times 10^{-10}$ eV

JUNA result of $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$



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

JUNA underground

JUNA ground

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

$^{13}\text{C}(\alpha, n)^{16}\text{O}$ neutron source reaction for heavy elements



PI: X. D. Tang, IMP



B. Gao, IMP

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

Main s-process $\sim 90 < A < 210$

TP-AGB stars

shell H-burning

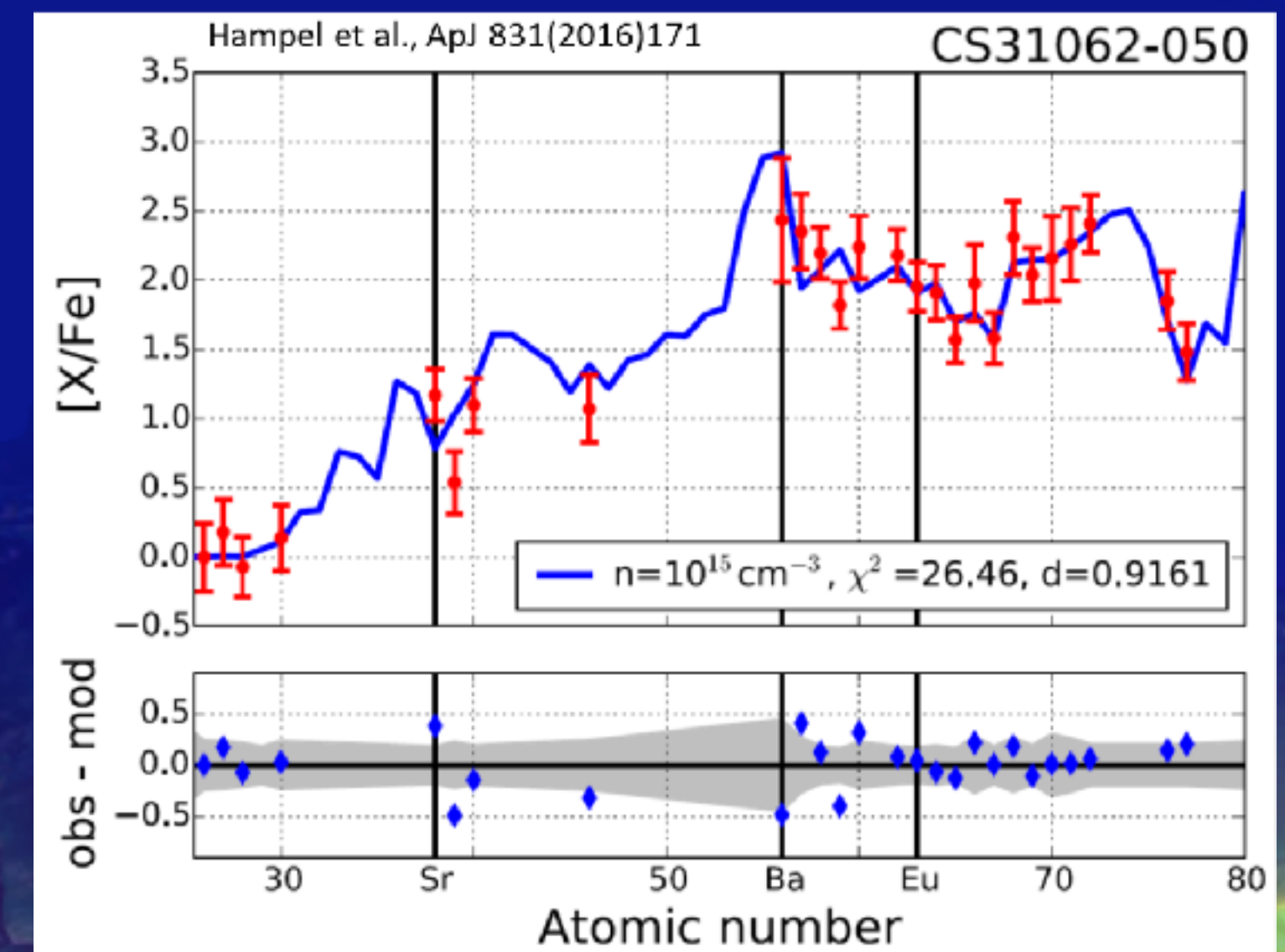
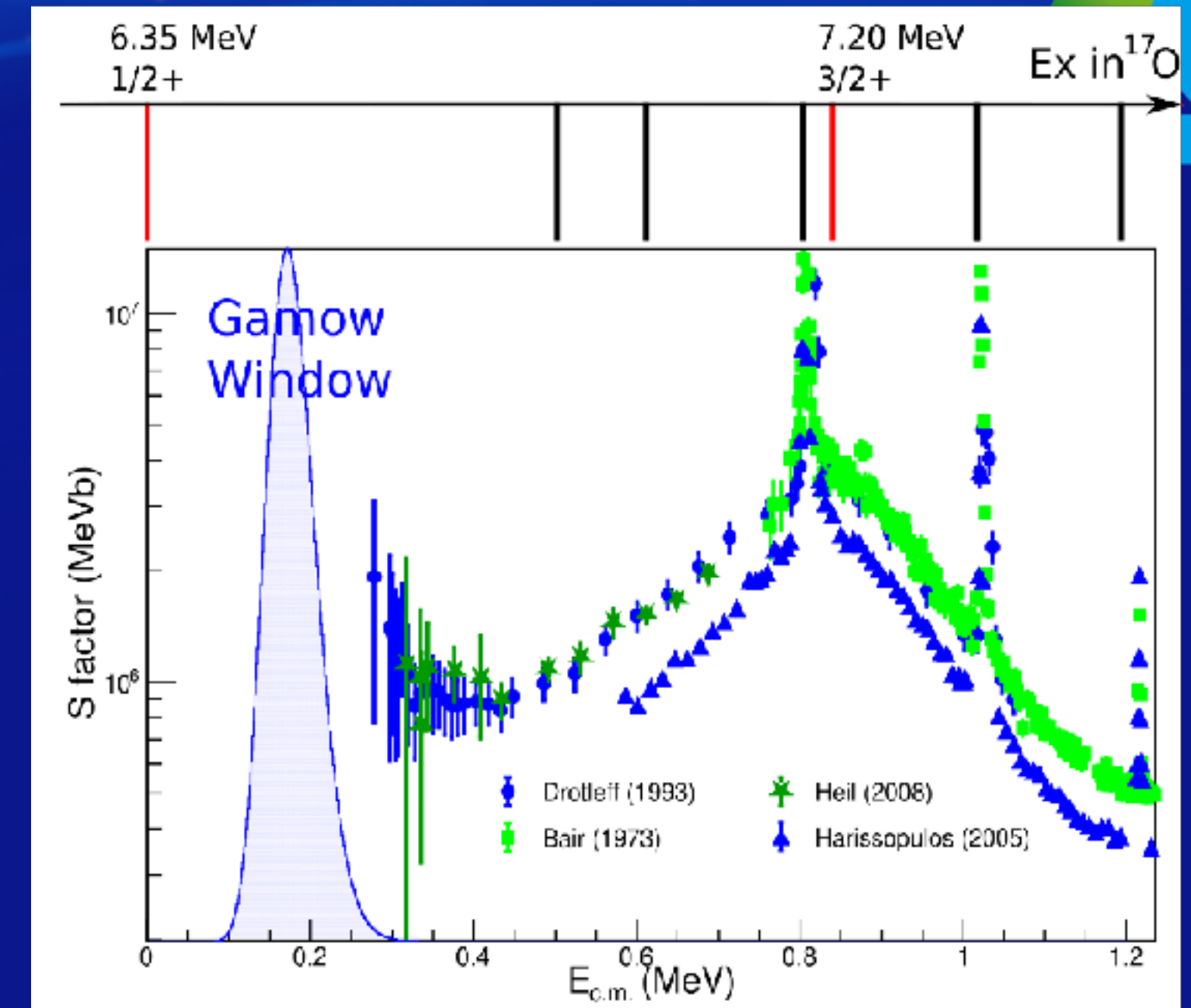
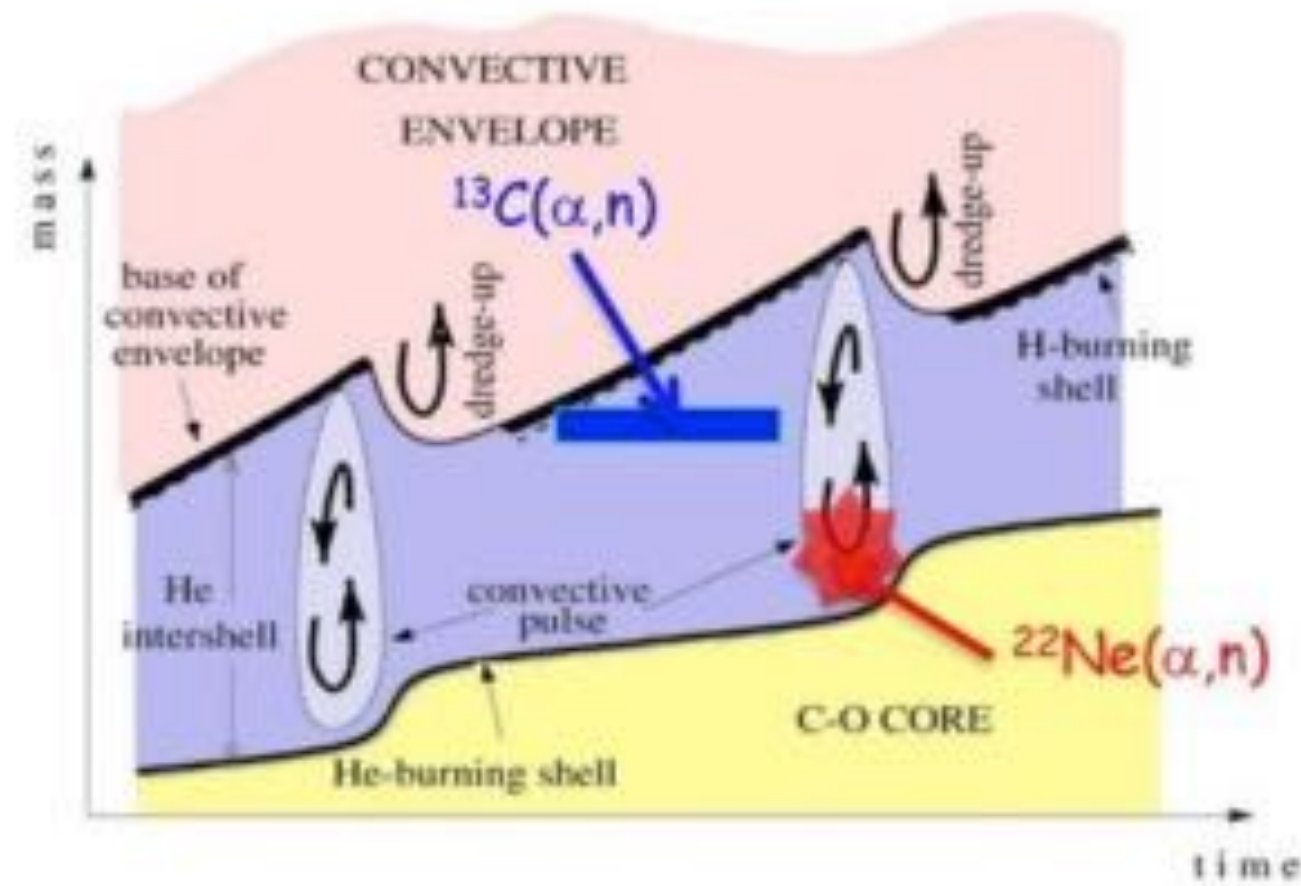
$T_9 \sim 0.1 \text{ K}$
 $10^7 - 10^8 \text{ cm}^{-3}$

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

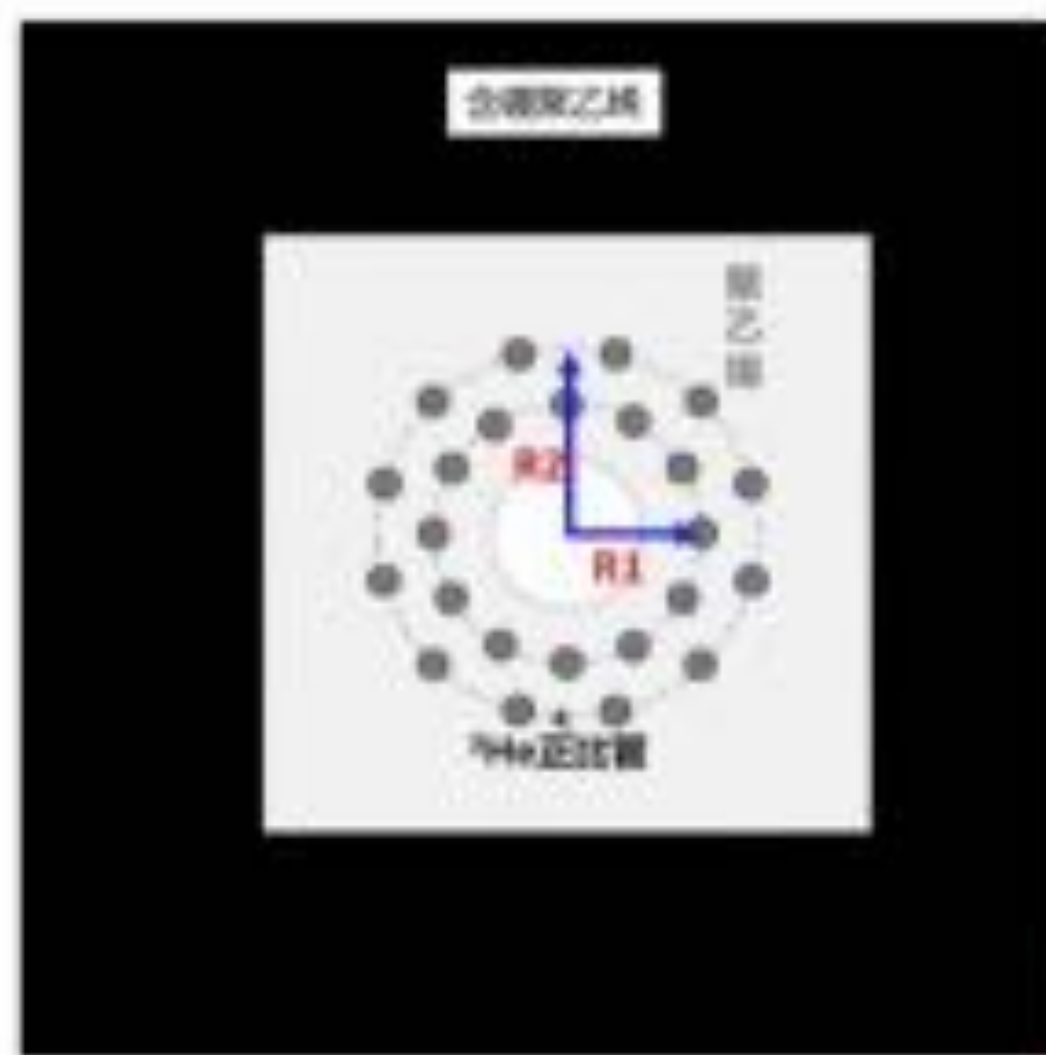
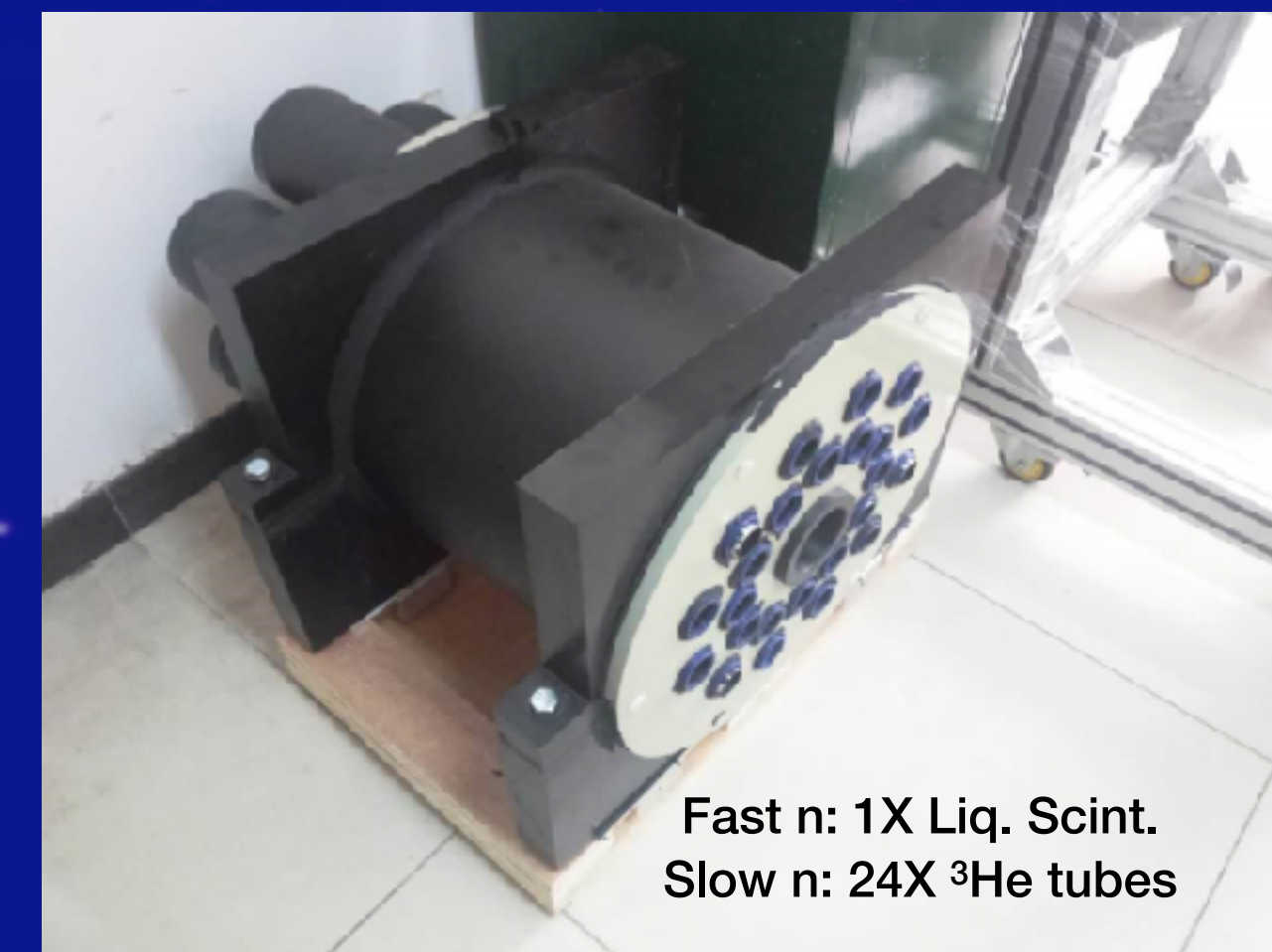
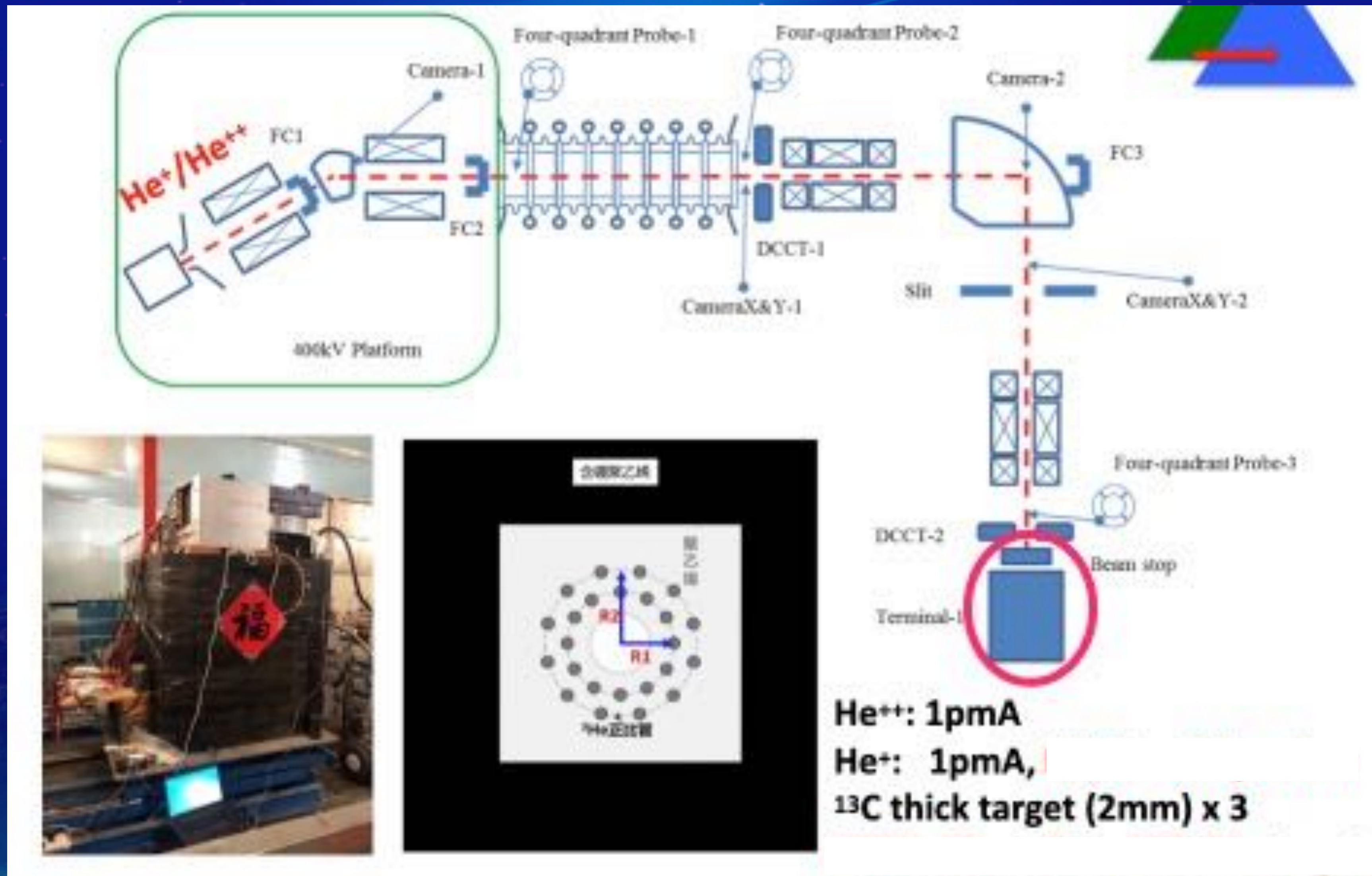
He-flash

$0.25 \leq T_9 \sim 0.4 \text{ K}$
 $10^{10} - 10^{11} \text{ cm}^{-3}$

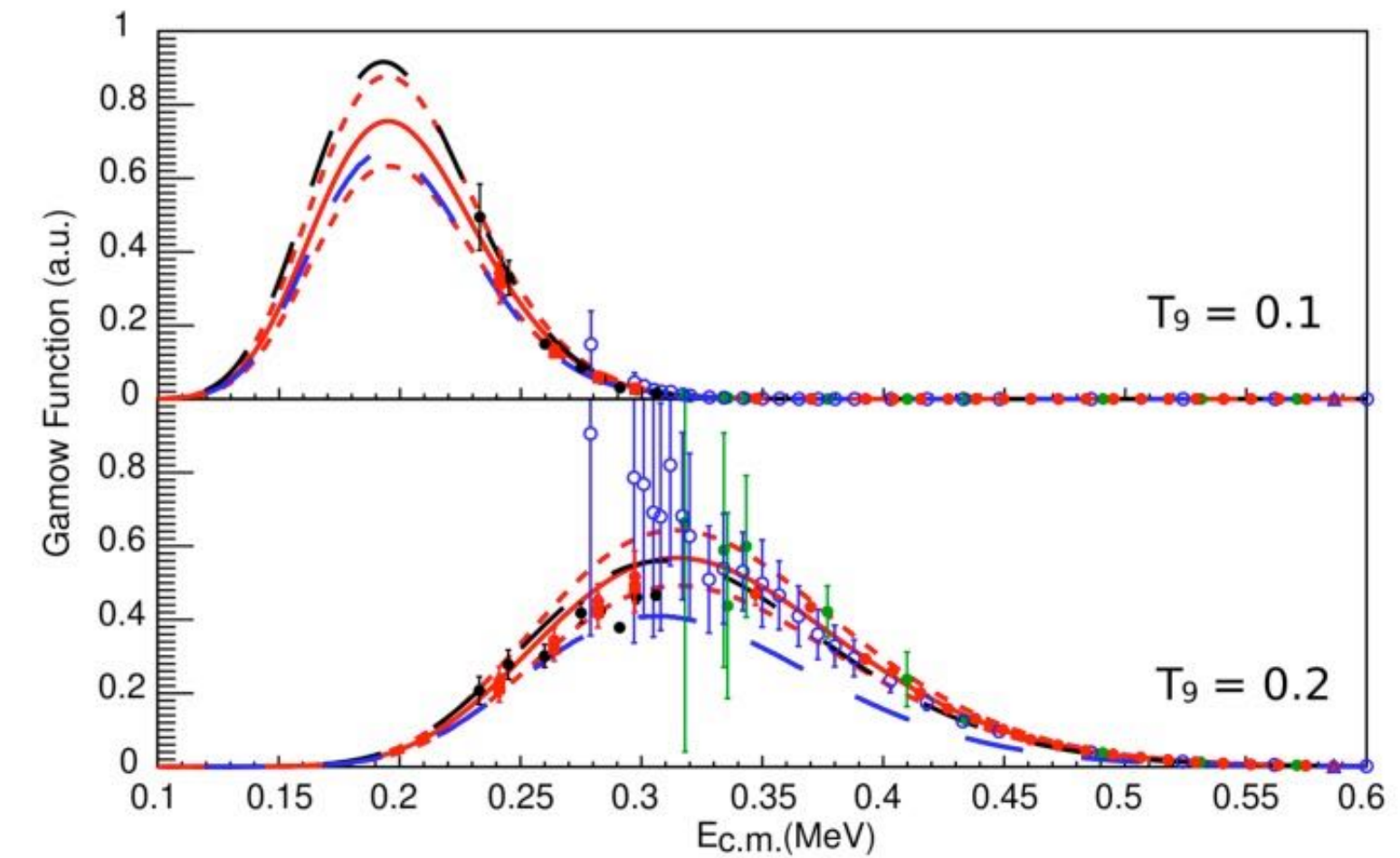
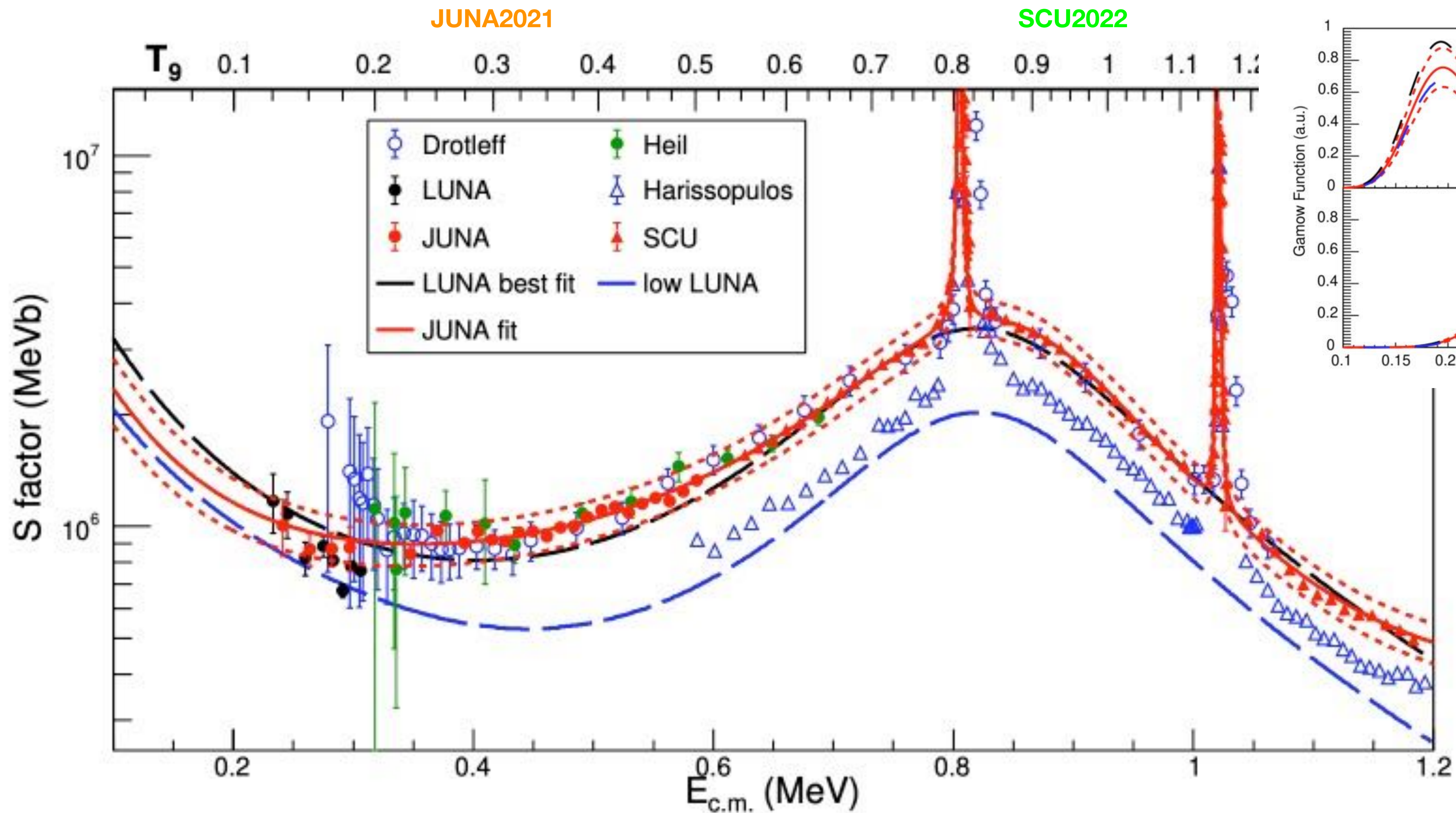
$^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$



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



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



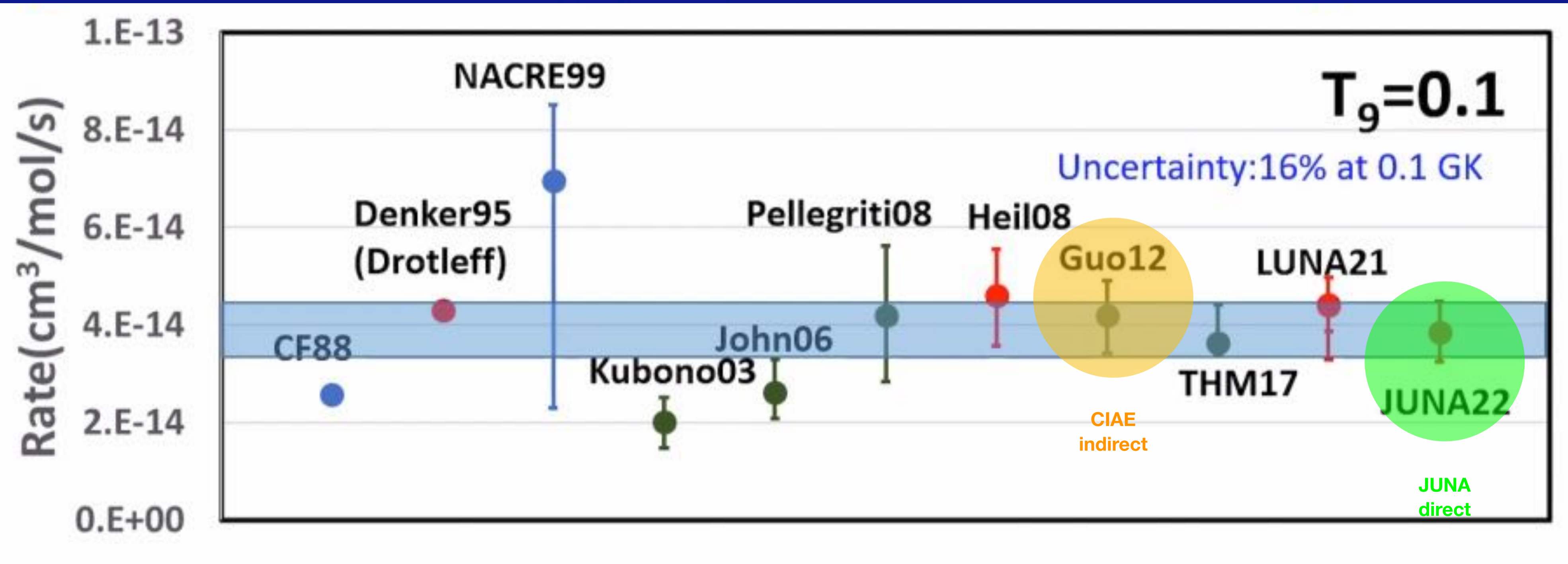
- mA thick target, differential method to pin down thickness
- magnetic removal of He^{2+} , cover 0.4 MeV to 0.8 MeV (JUNA), cover i-process; to 1.2 MeV tandem, calibration of eff., cross check other data
- n background 5/ hour, 2.5 MeV eff. 25%, good S/N

Resolve conflict in 30 years research

Annu. Rev. Nucl. Part. Sci. 2023. 73:315–40



Recent studies of the low-energy range of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction rate at the deep underground accelerator facilities of LUNA in Italy (83) and JUNA in China (84) have removed most of the uncertainties in the extrapolation of the previous higher-energy data [the NACRE II compilation (85)]. The low-energy data match well the prediction of a recent R-matrix analysis (86)



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

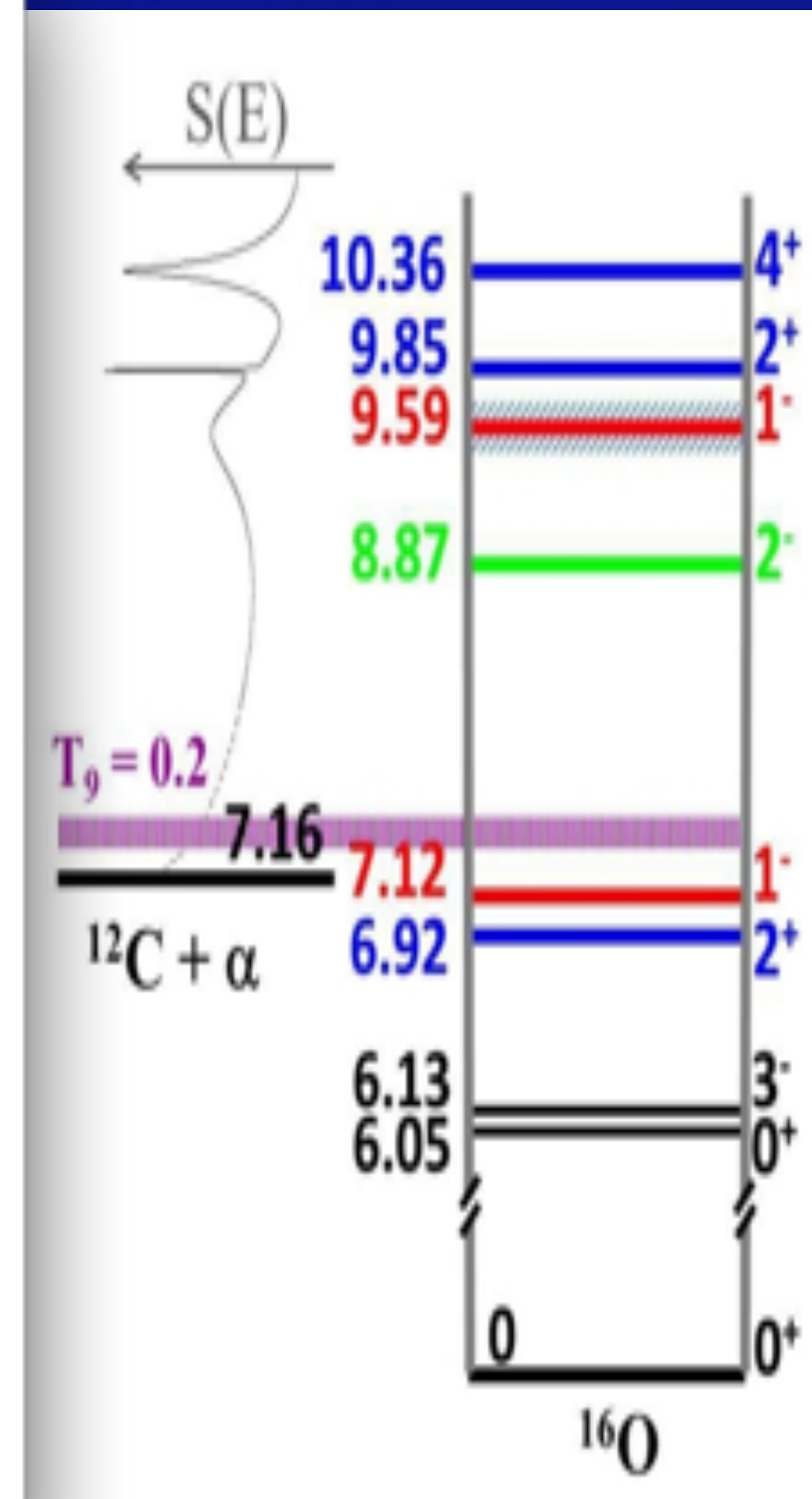
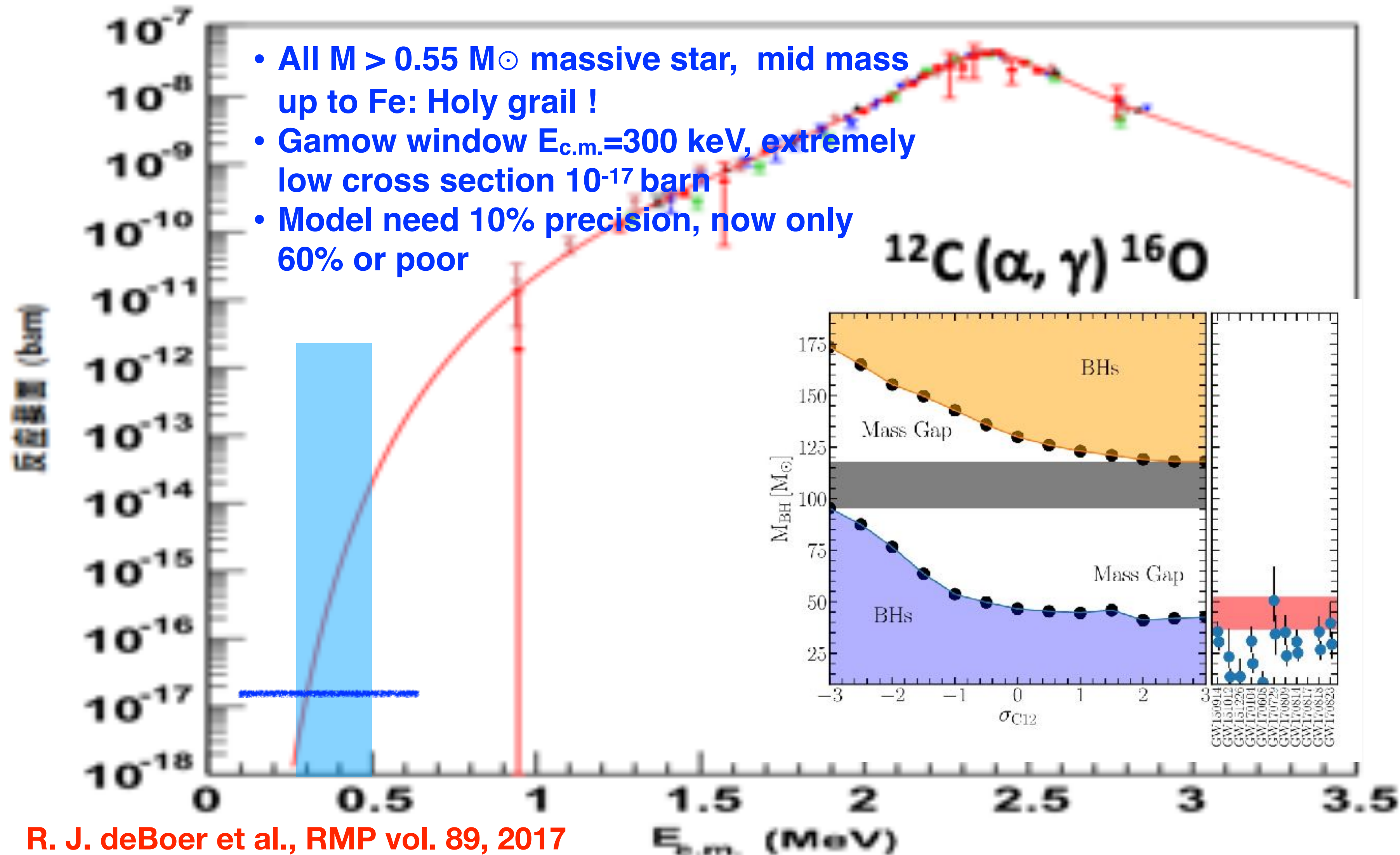
B. Guo*, Z. H. Li, ..., WPL*, Astrophys. J. 756(2012)193.

Big question, big impact, big challenge

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



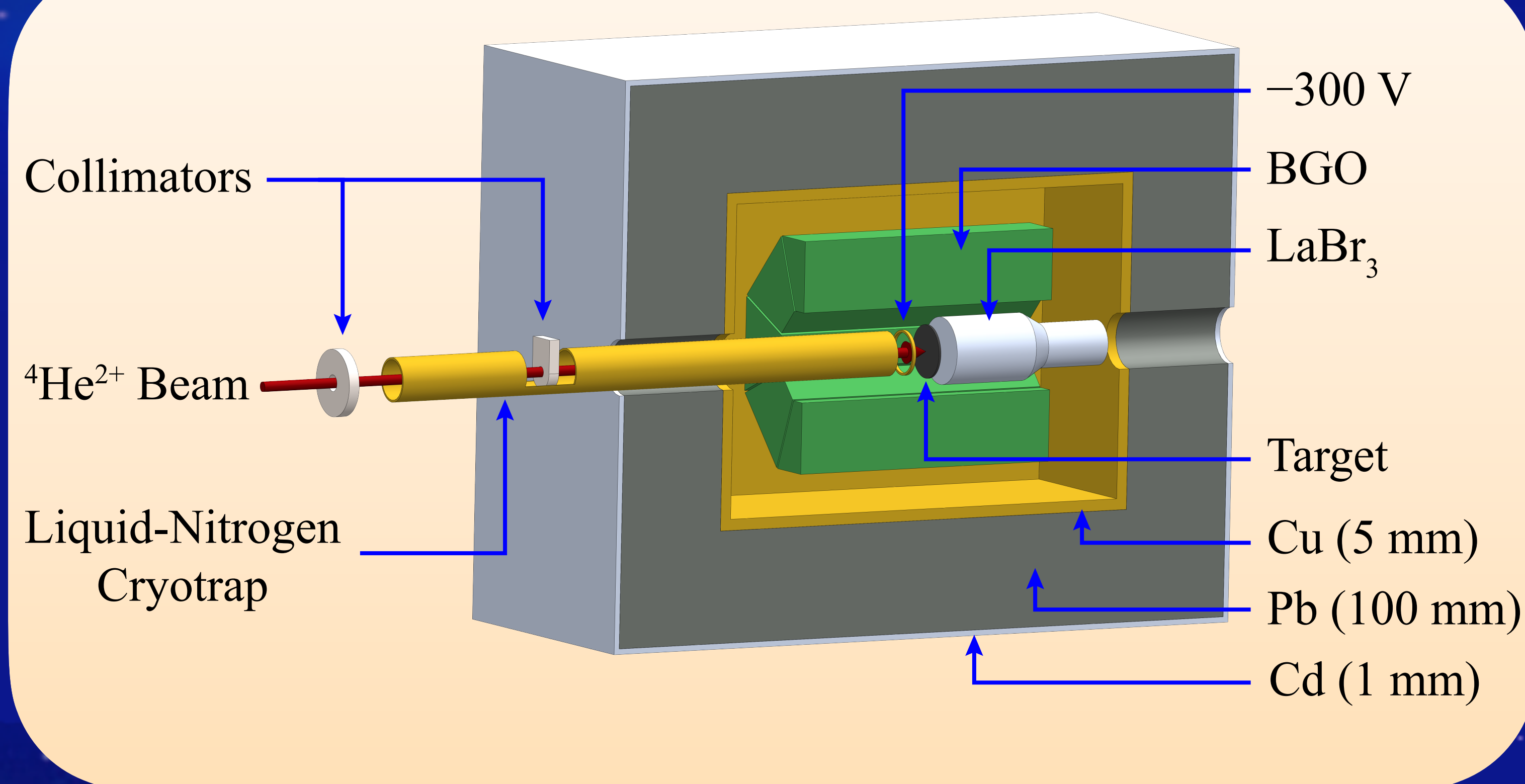
PI: WPL/Y. P. Shen, CIAE



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

R. Farmer^{1,2}, M. Renzo³, S. E. de Mink et al., APJ 902, L36, 2020

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

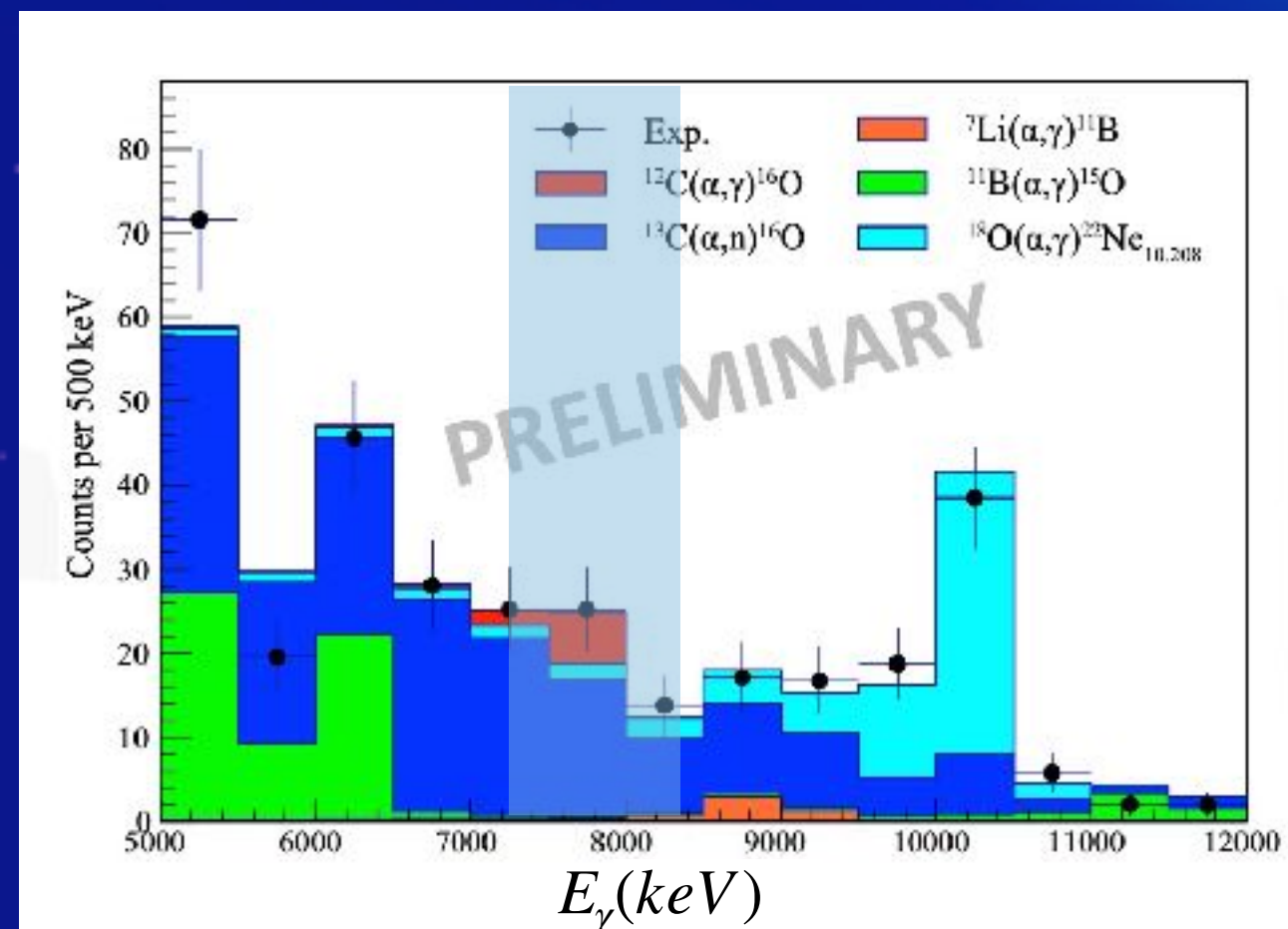


- FCVA implantation CTi thick targets
- durability $>280\text{ C}$ @ 800 keV He^{2+} , with only 25% loss
- BGO+LaBr₃ (Lanthanum bromide) veto
- wide energy search for best S/N, 552 keV is best, other suffer from $^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$ contaminations
- sensitivity of 10^{-12} b @ $E_{\text{c.m.}} = 552\text{ keV}$

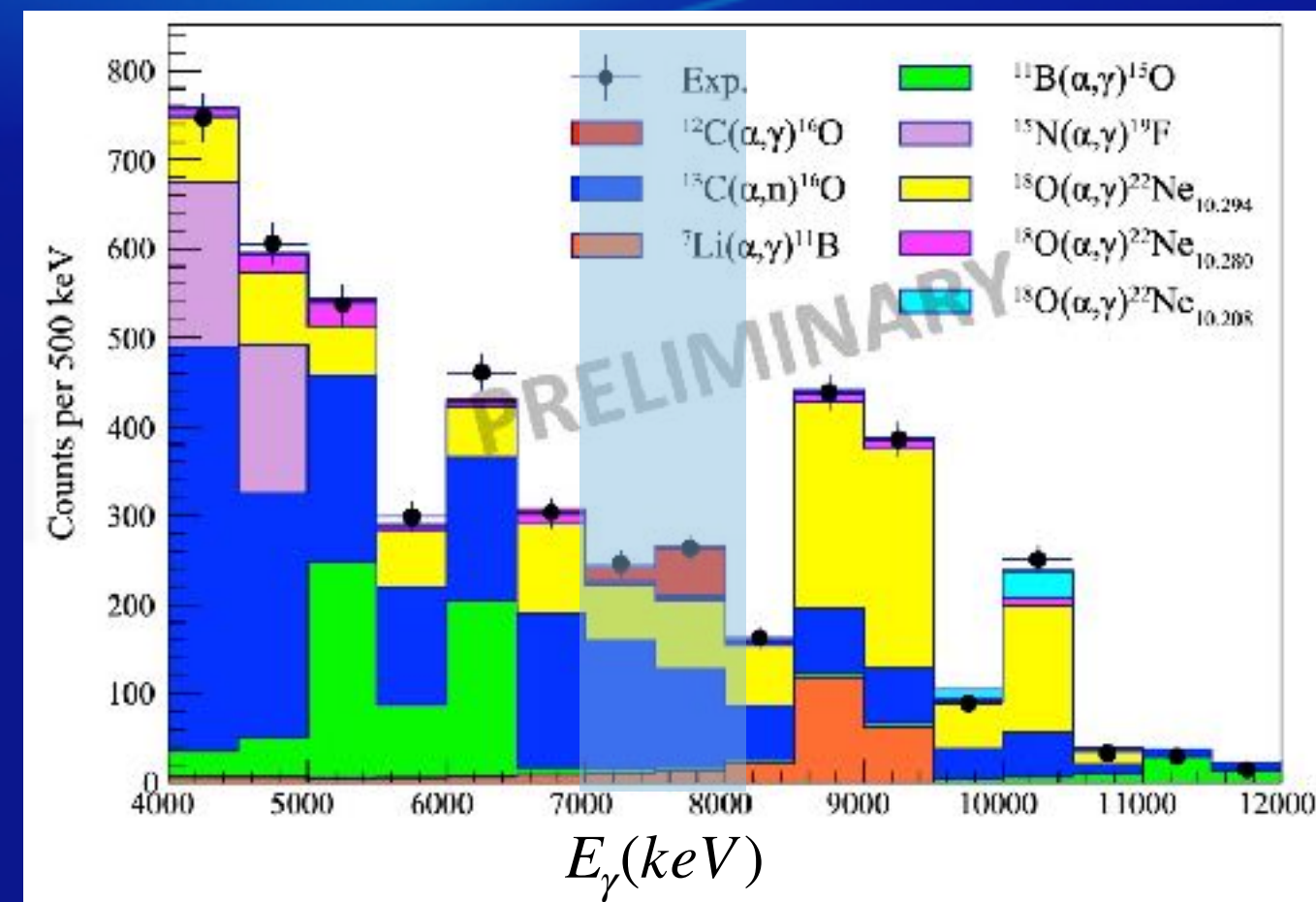
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$: submitted



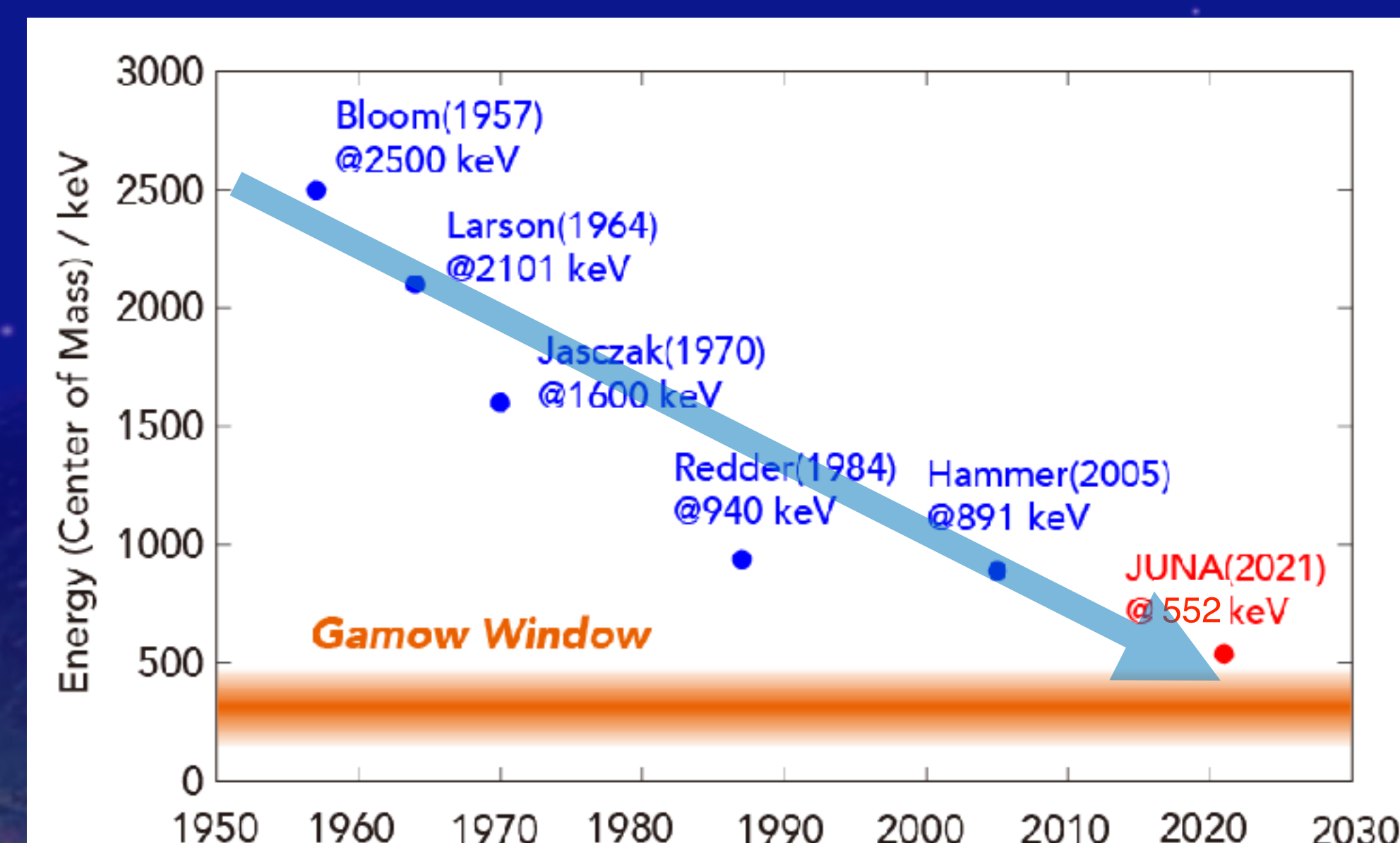
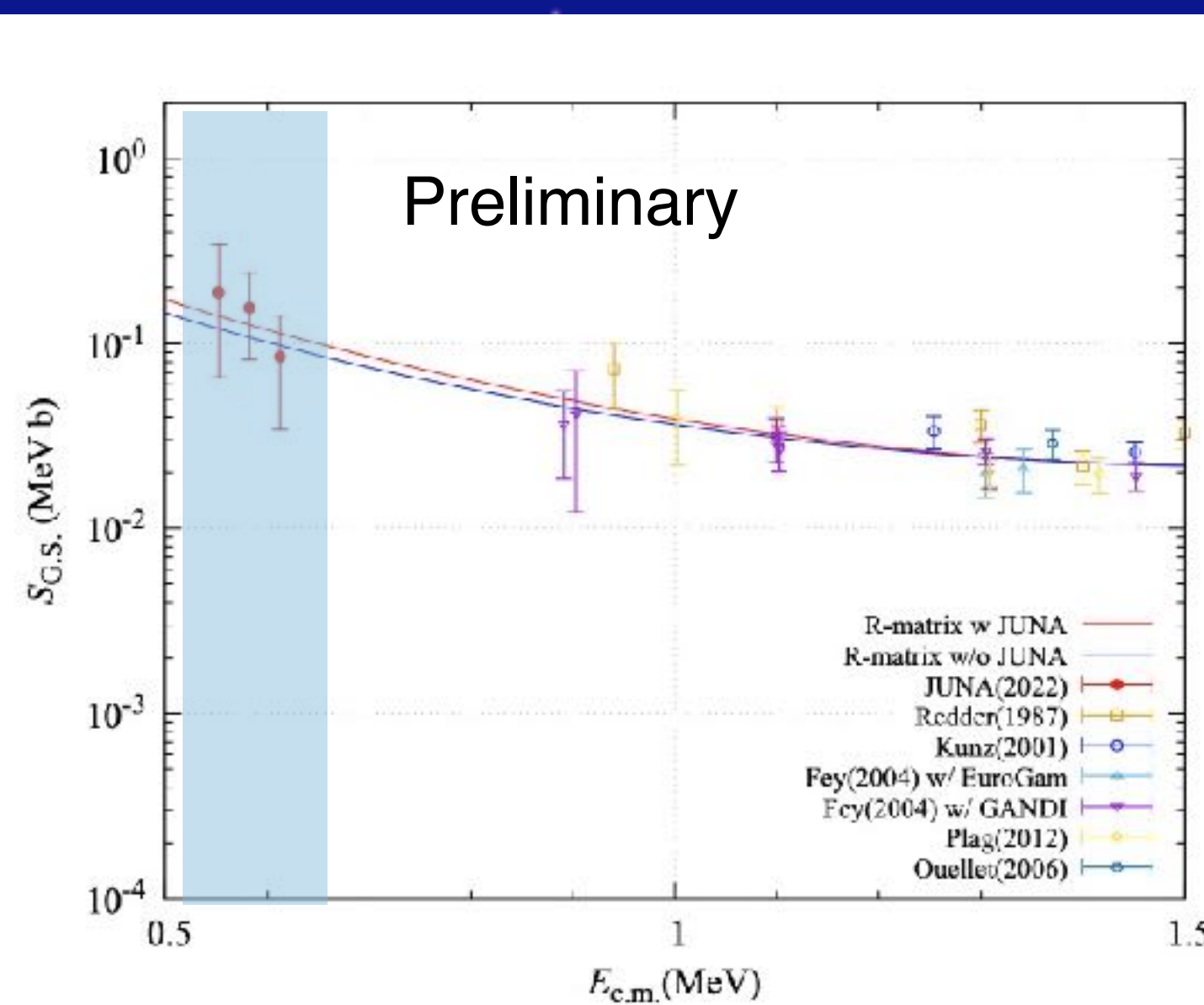
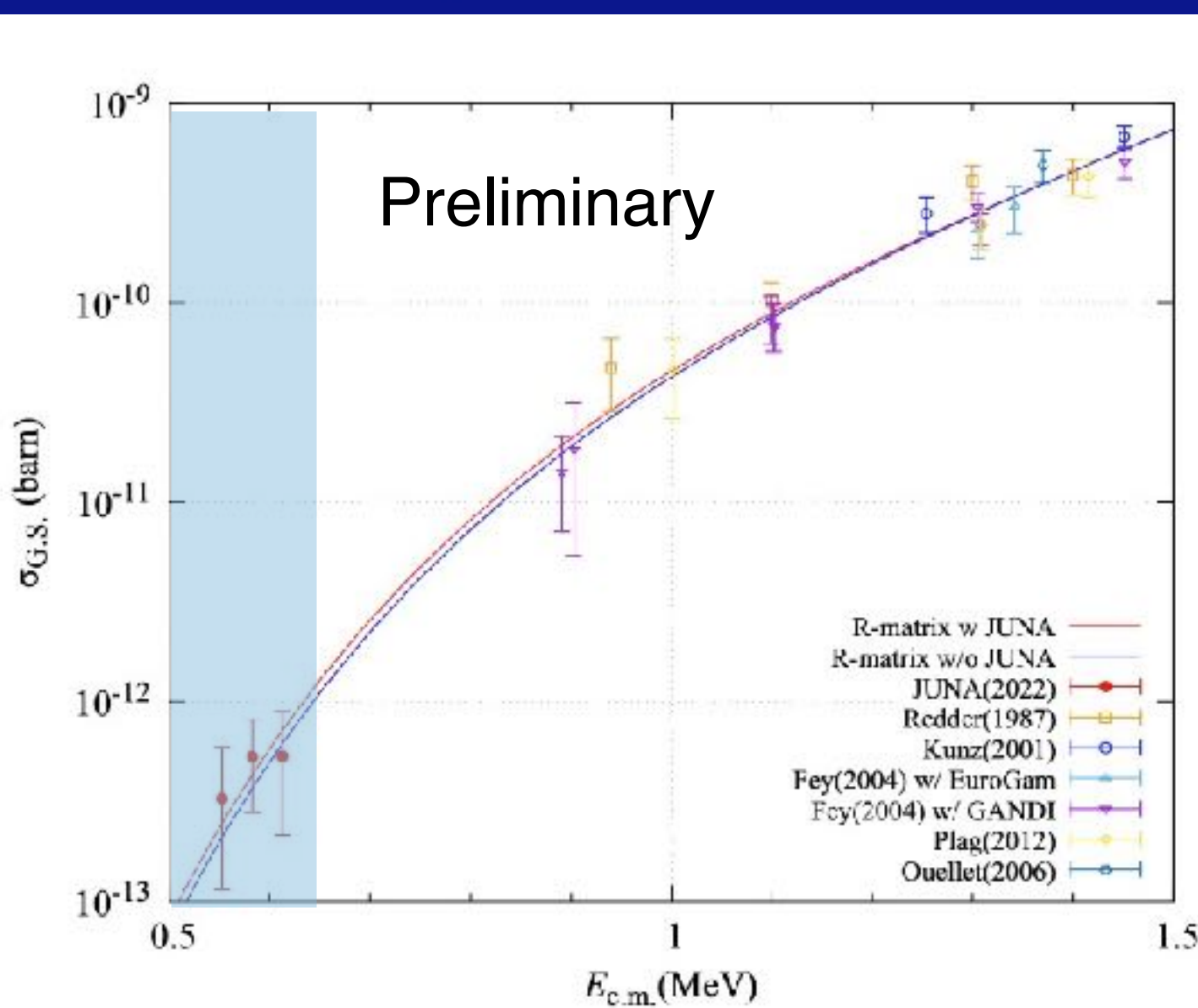
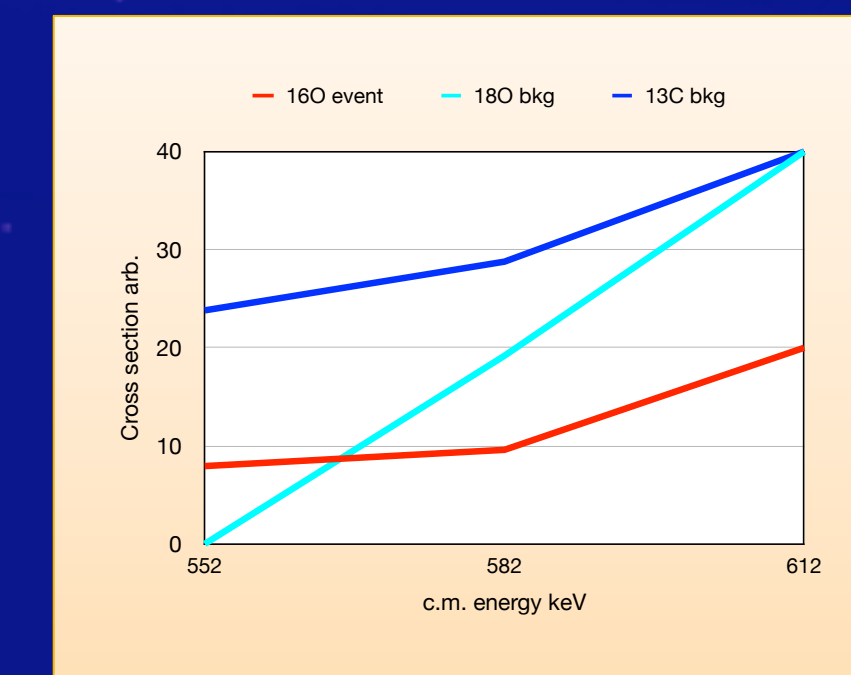
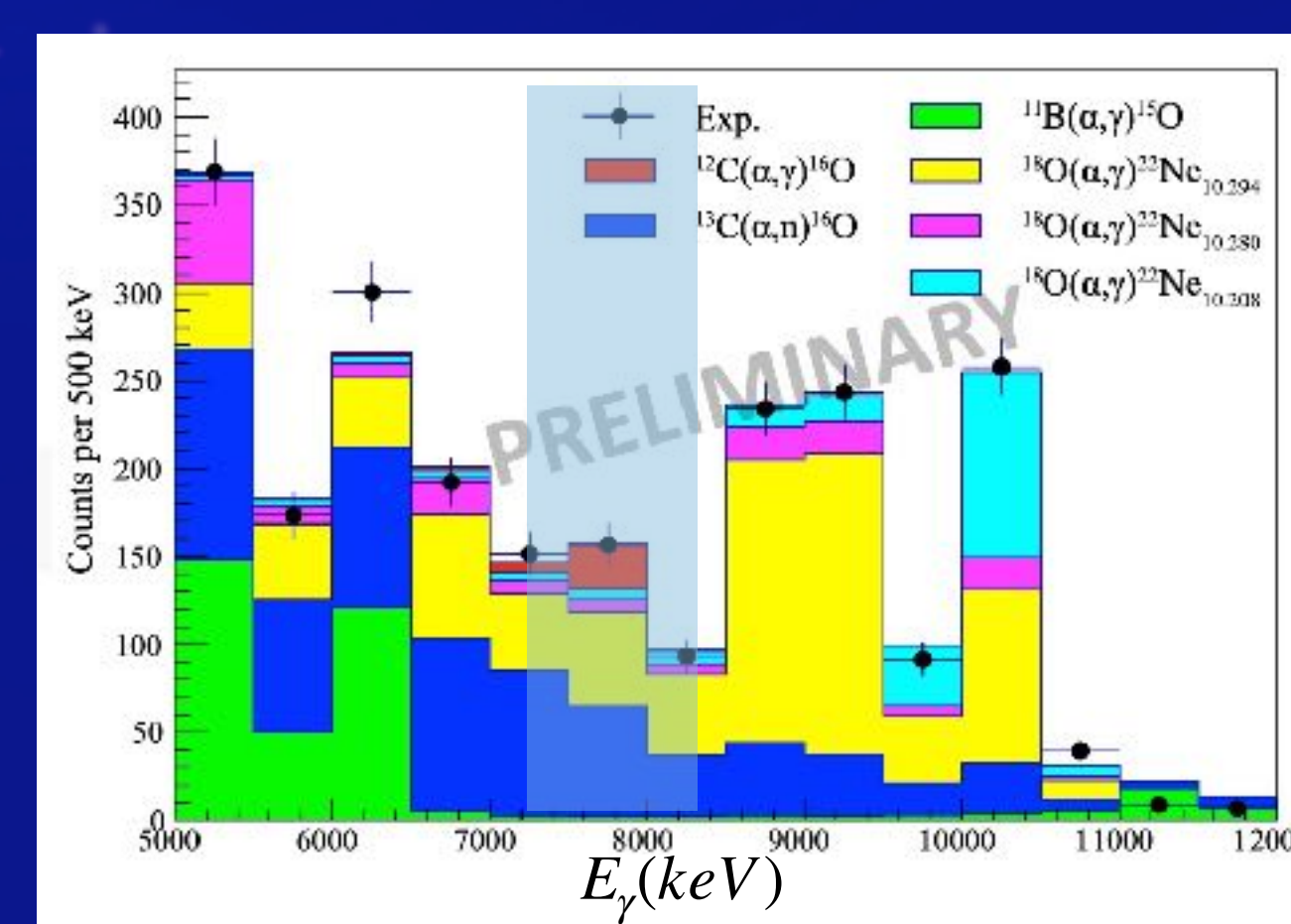
552 keV, 126 C



582 keV, 417 C



612 keV, 200 C

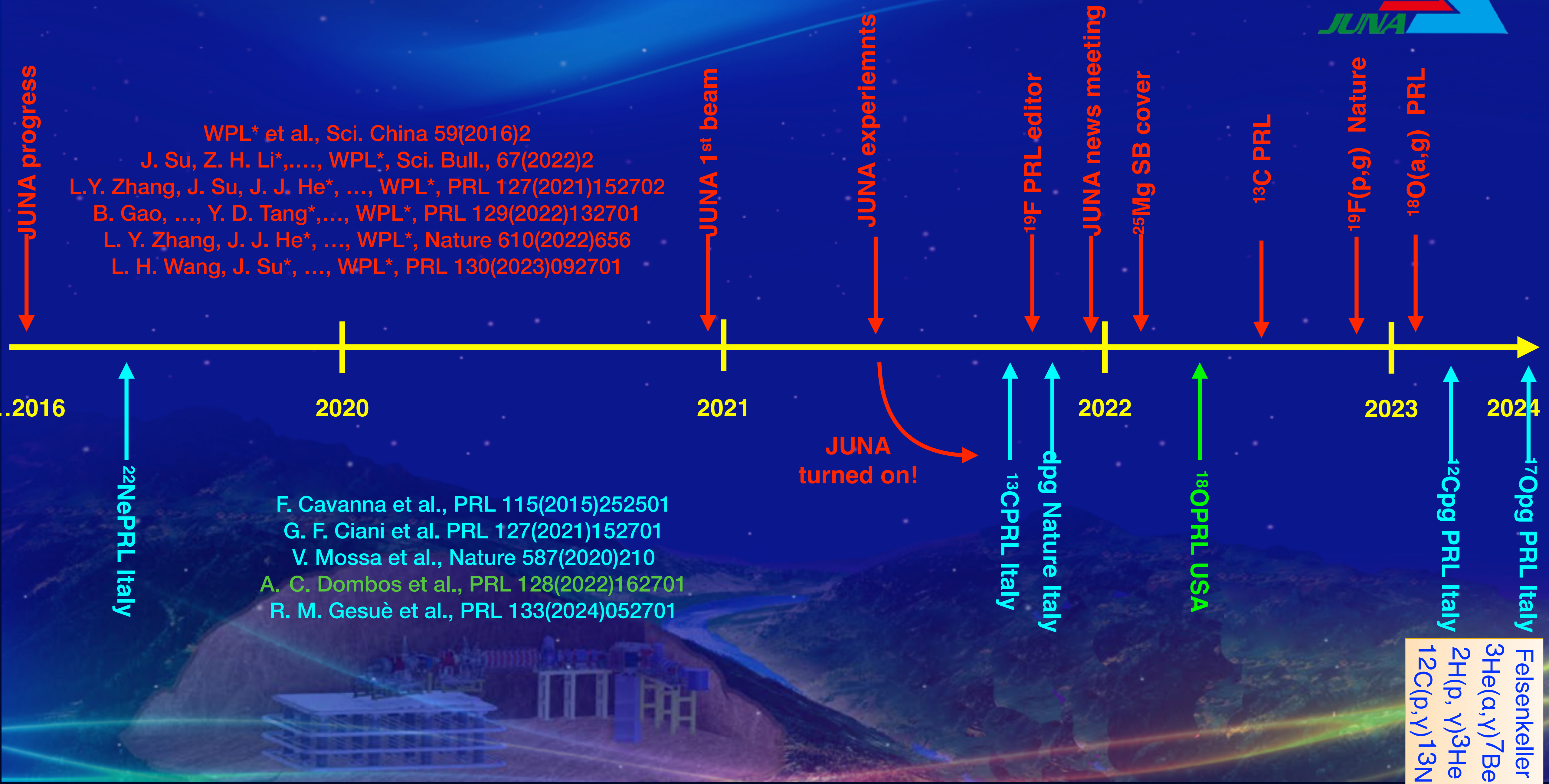


JUNA results from Run-1



Reaction	Quantities	Best data before	JUNA data	Publication
Holy grail $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$	Lowest energy/keV	891	552	In preparation
	Cross section/b	10^{-11}	10^{-12}	
Neutron source $^{13}\text{C}(\alpha, n)^{16}\text{O}$	Energy range/keV	230-300	240-1900	PRL 129(2022)132701
	s-process	50%	20%	
^{26}Al abundance $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$	Uncertainty	21%	8%	Science Bulletin 67(2022)2 cover paper
F abundance $^{19}\text{F}(p, \alpha \gamma)^{16}\text{O}$	Lowest energy/keV	189	72	PRL 127(2021)152702 Editor suggestion
	Uncertainty	80%	5%	
Ne isotope ratio $^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$	Uncertainty	472 ± 18 keV	474.1 ± 1.1 keV	PRL 130(2023)092701
CNO breakout $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$	Lowest energy/keV	300	200	Nature 610(2022)656 news and views

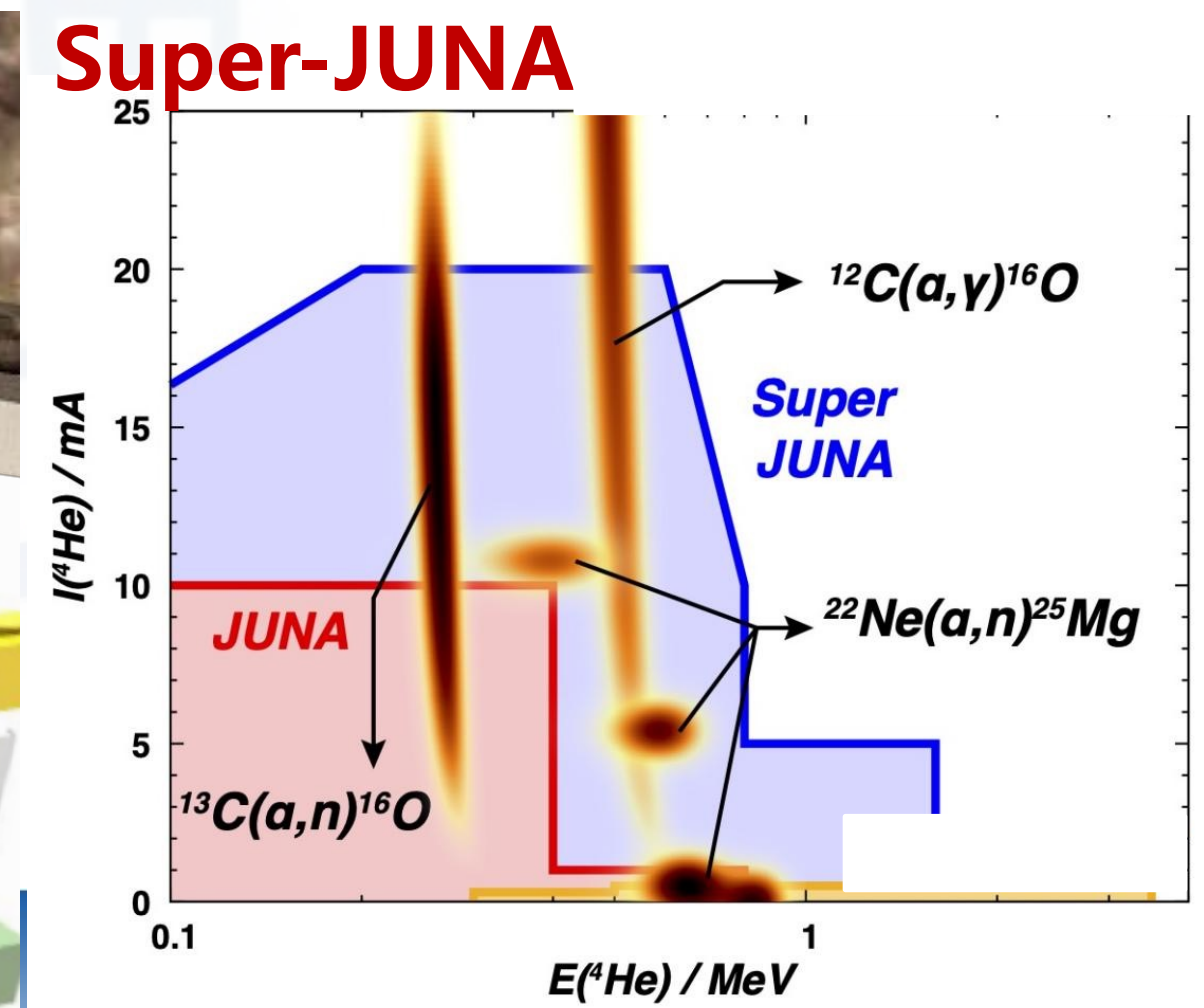
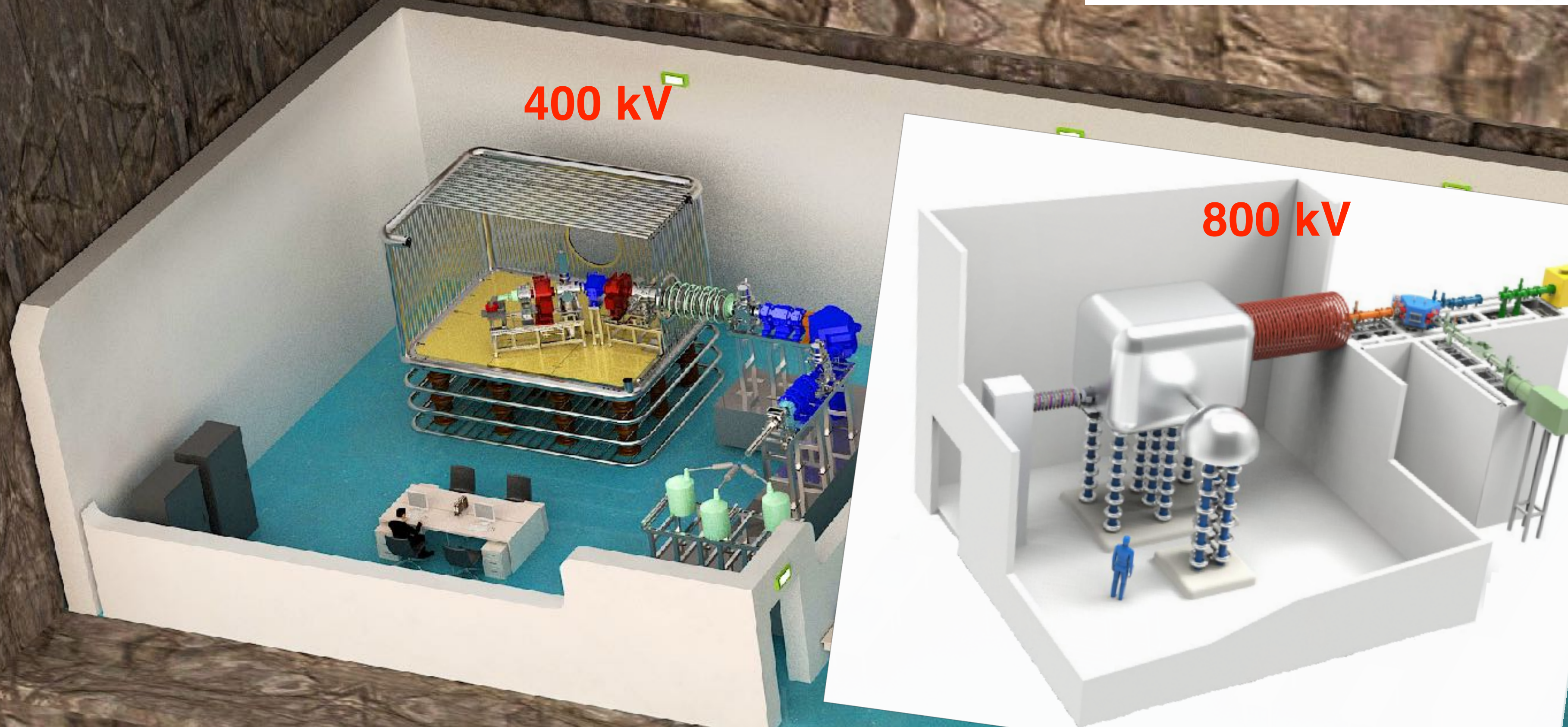
Recent development in underground nuclear astrophysics





锦屏深地核天体物理实验

Jinping Underground Nuclear Astrophysics Experiment



JUNA

Super JUNA



JUNA and Super JUNA coverage

H burning



He burning



N source



C/O burning



γ astronomy



JUNA achieved



JUNA and Super JUNA proposed

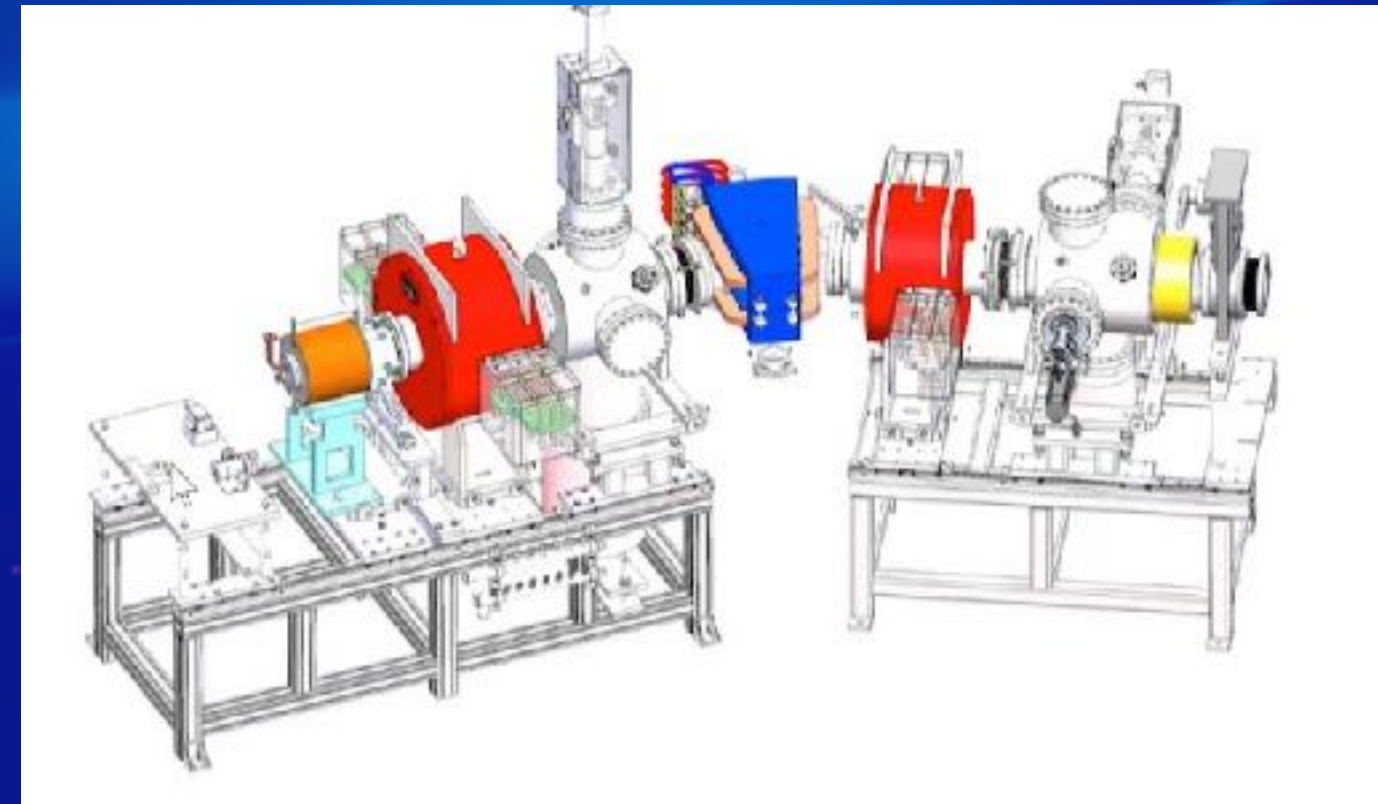
2024-2030 JUNA and Super-JUNA



	JUNA	Super-JUNA	JUNA Exp.	Super-JUNA Exp.
2024	ground test run Run-2 exp.	R&D	(p,g)	
2025	Run-2	Ground test and fabrication	(a,n) and (a,g) gas target	
2026	Run-2	Setup and test	cont.	
2027	Upgrade Run-3 exp.	Test run Run-4 exp.	Test run	(p,g) test
2028	Run-3	Run-4	cont.	(a,g), (a,n) Exp.
2029	Run-3	Run-4	cont.	(a,g), (a,n) Exp.
2030	Run-3	Run-4	cont.	(a,g), (a,n) Exp.

Green lights for JUNA Run-2

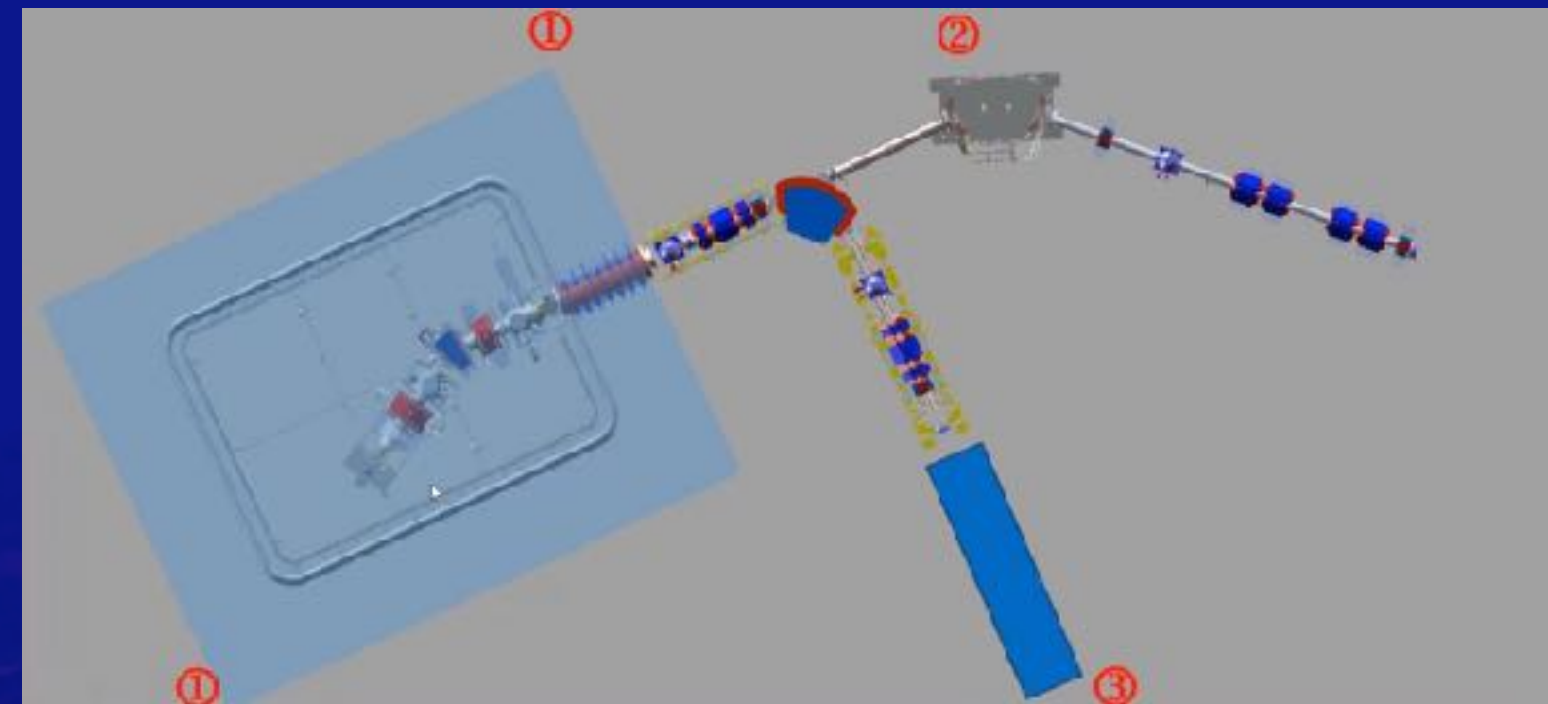
- CJPL IAC highly recommend JUNA and gave green lights for next 5 years and support for A1 fine tuning
- High density radiation hard target and gas target
- High resolution and efficiency neutron and gamma detector



Improved ion source



Run-2 kickoff meeting April 24, 2024



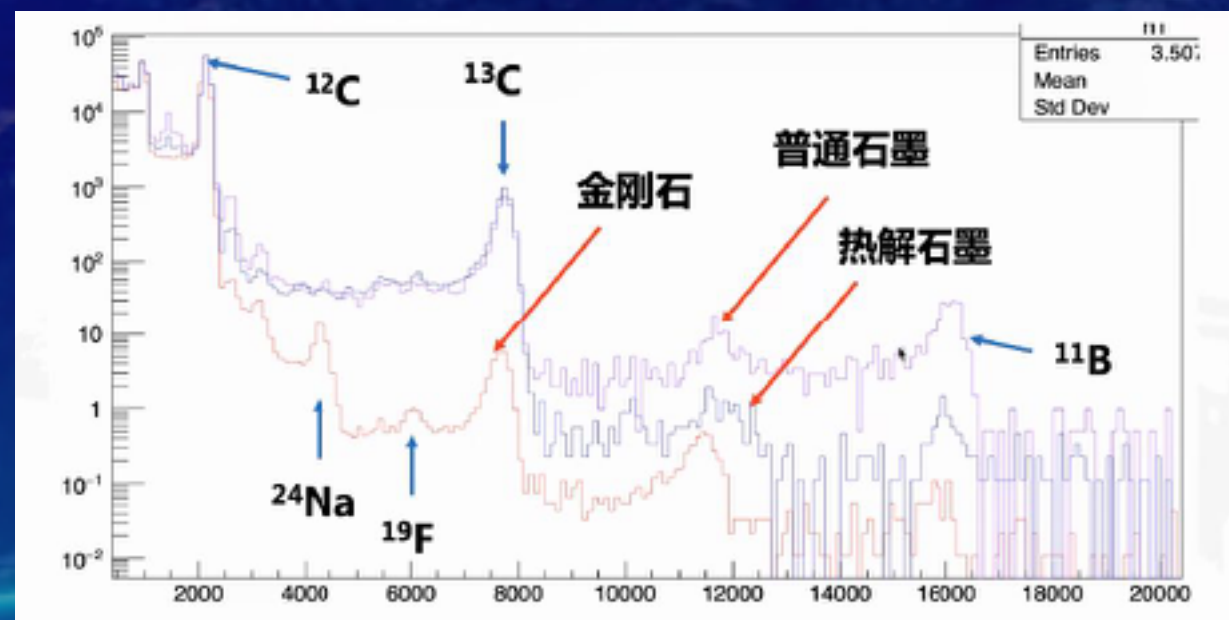
floor plan for JUNA Run-2



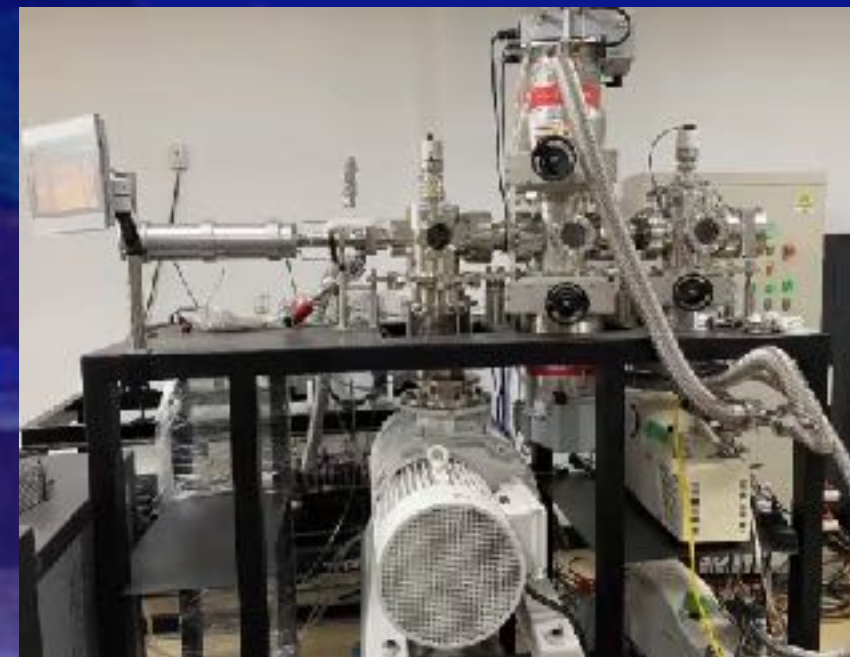
CJPL-II A1 for JUNA: March, 2024

No.	任务名称	2022												2023												2024											
		9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12								
1	项目入驻申请																																				
1.1	入驻申请																																				
1.2	CDR报告评审																																				
1.3	TDR报告评审																																				
1.3	签订入驻协议																																				
2	实验室建设																																				
2.1	协调大设工程																																				
2.2	方案设计																																				
2.3	现场施工																																				
2.3	实验室美化																																				
3	实验平台恢复																																				
3.1	方案设计																																				
3.2	加速器增能																																				
3.3	安装调试																																				
4	实验平台优化																																				
4.1	整体设计																																				
4.2	无窗气体靶																																				
4.3	新增束流线																																				

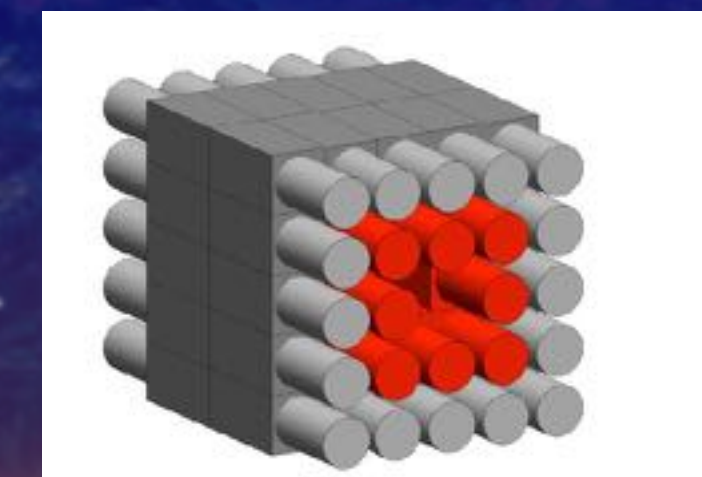
Run-2 schedule April 24, 2024



test result for diamond target



gas jet target



enlarged BGO array

JUNA Run-2 Exp.: 2024-2026

- From Run-1 to lower energy

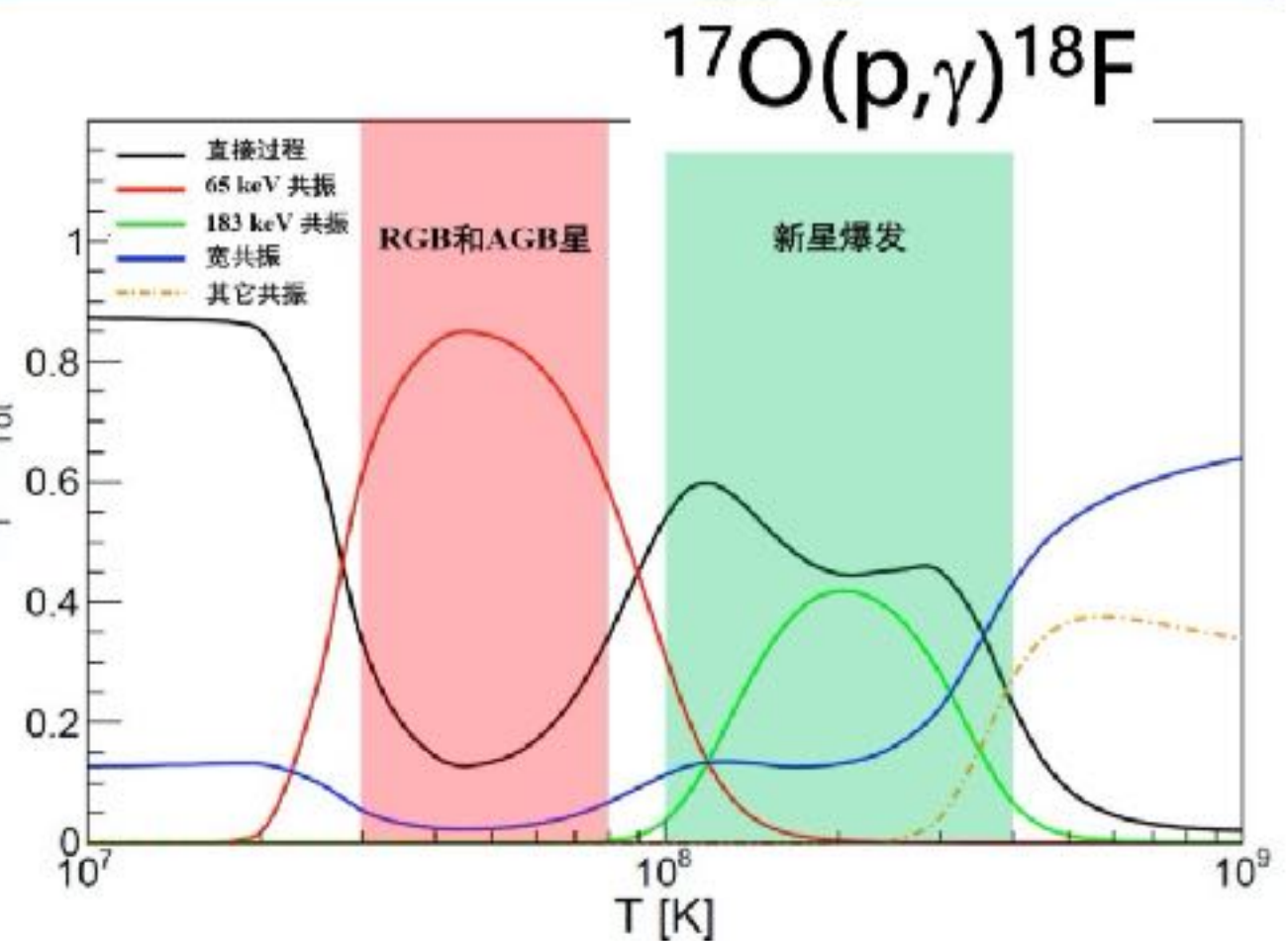
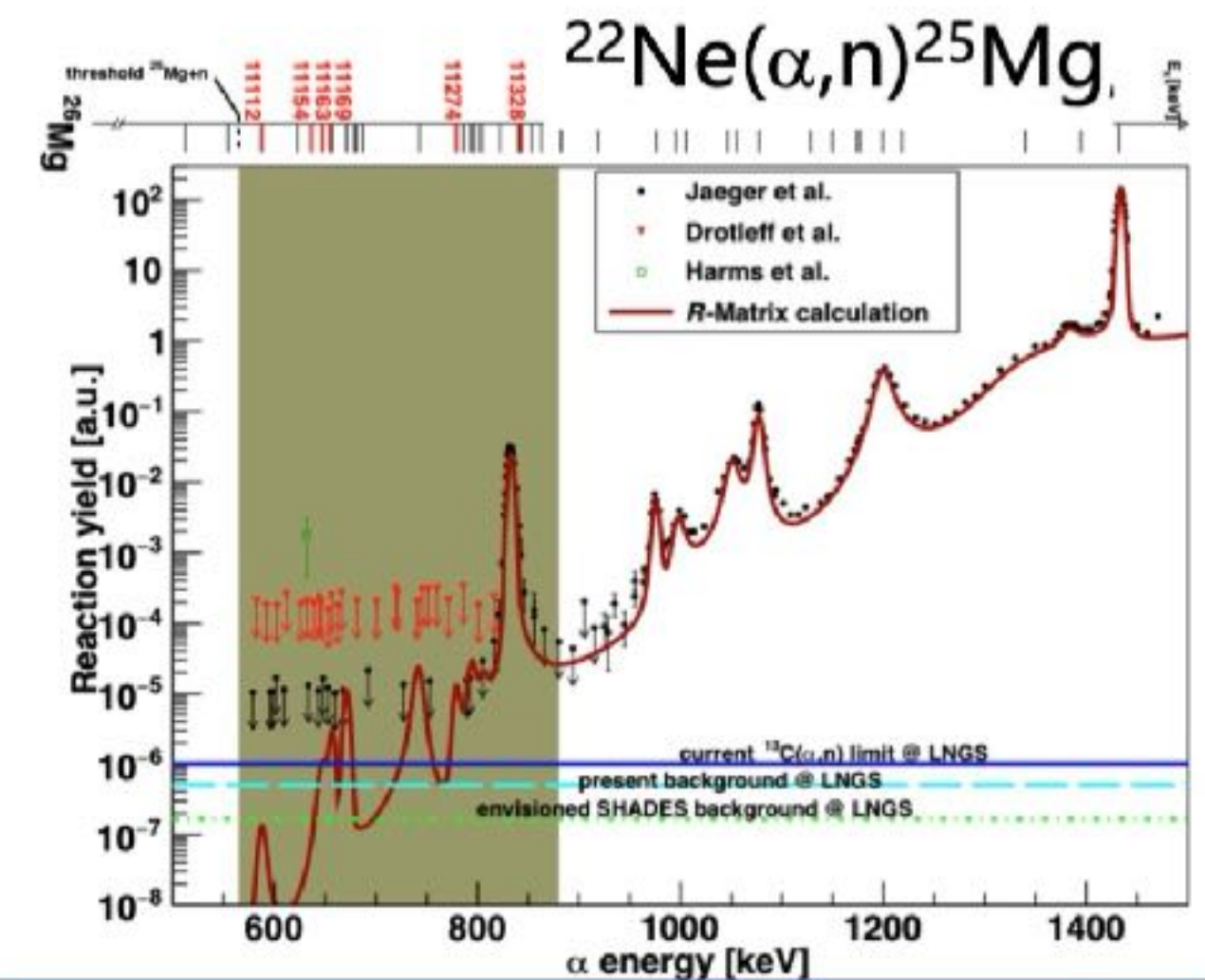
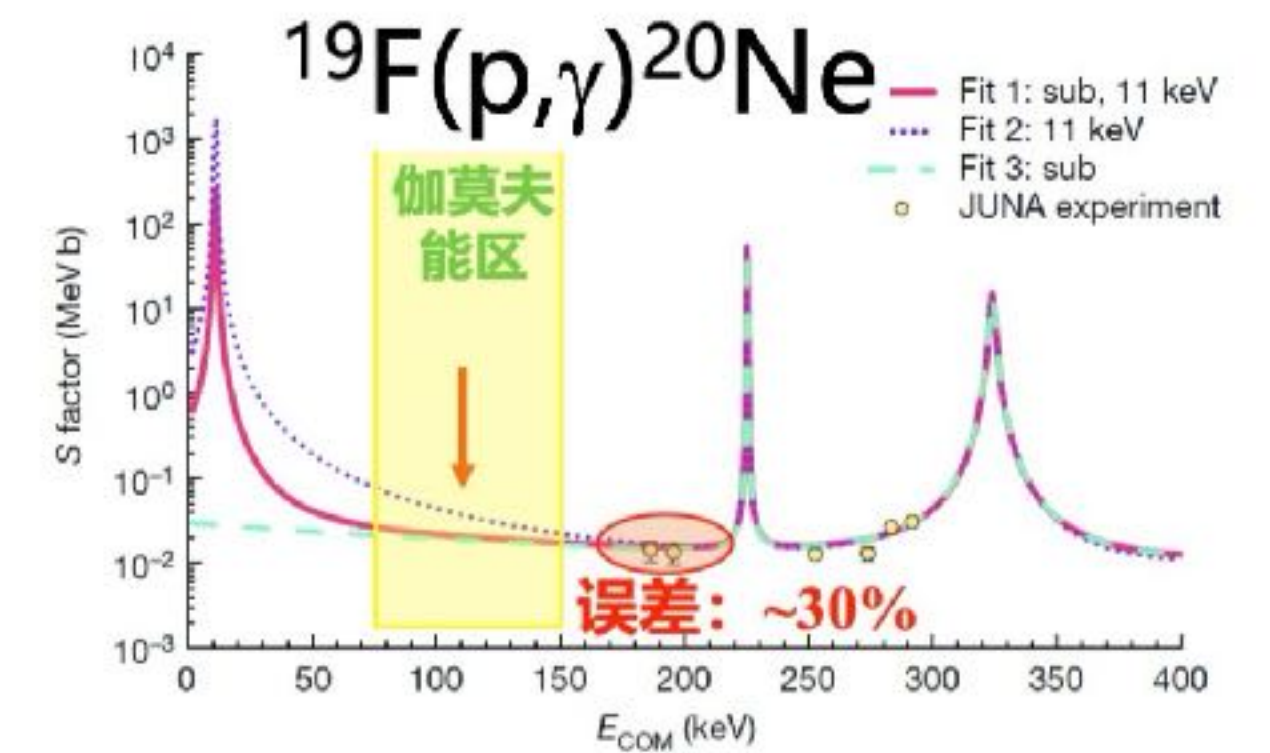
- $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$, precision from 1s to 3s
- $^{13}\text{C}(\alpha, n)^{16}\text{O}$, full coverage of s-process
- $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$, cover 80-150 keV with high precision
- $^{14}\text{N}(p, \gamma)^{15}\text{O}$, Solar neutrino

- Using gas target

- $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$, weak s-process n source
- $^3\text{He}(\alpha, \gamma)^7\text{Be}$, solar neutron, Li problem, 80-380 keV

- Others

- $^{17}\text{O}(p, \alpha)^{14}\text{N}$, ^{17}O over abundance
- $^{17}\text{O}(p, \gamma)^{18}\text{F}$, H isotope ratio, 65 keV resonance
- $^{26}\text{Al}(p, \gamma)^{27}\text{Si}$, BRIF ISOL ^{26}Al implantation target
- $^{10}\text{B}(\alpha, n)^{13}\text{N}$, search for new resonance



JUNA summary



- **JUNA is an advanced deep astrophysics platform. China, follow Italy and United States and others, started to carry out direct measurement of key astrophysical reactions, which leading the nuclear astrophysics to the stage of precision numerical simulation stage**
- **JUNA 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**
- **From JUNA Run-1, 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, and the discrepancies of neutron source reactions was resolved**
- **JUNA Run-2 will start by the end of 2024, welcome to join JUNA collaboration and submit your proposals deep underground!**

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