Progress of Nuclear Astrophysics and neutrino physics

IAU S350

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July 1-6, 2019, Kyoto

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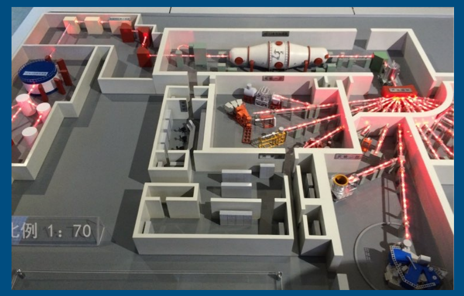
Supported by the National Natural Science Foundation of China, Grant No. 11490560, 2015

Nuclear Astrophysics roadmap

Ground, Underground

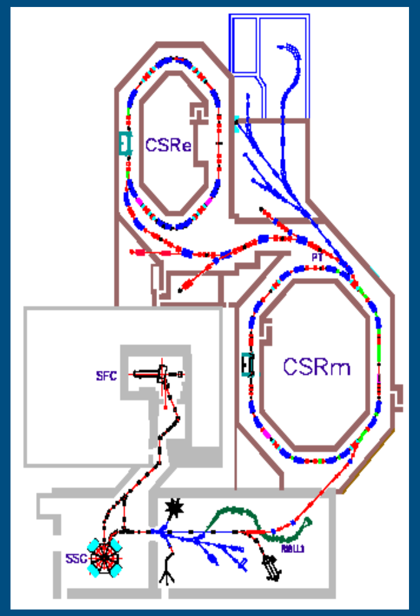
Direct | In-direct | Resonance



reaction

decay, mass

RI, Ring



RECLIB…

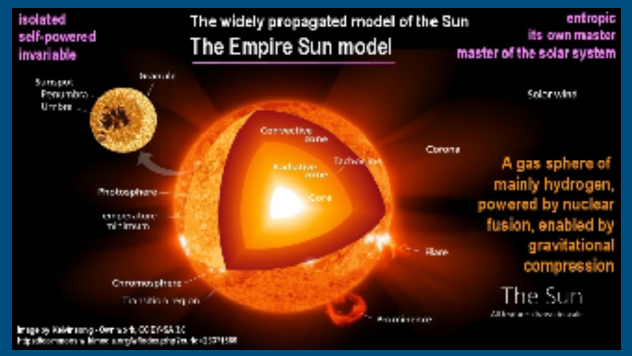
Micro, MF

Space, Ground

Data | Theory | Astrophysics | Observation

NP input

Abn ~ f(Nucl,Astro)

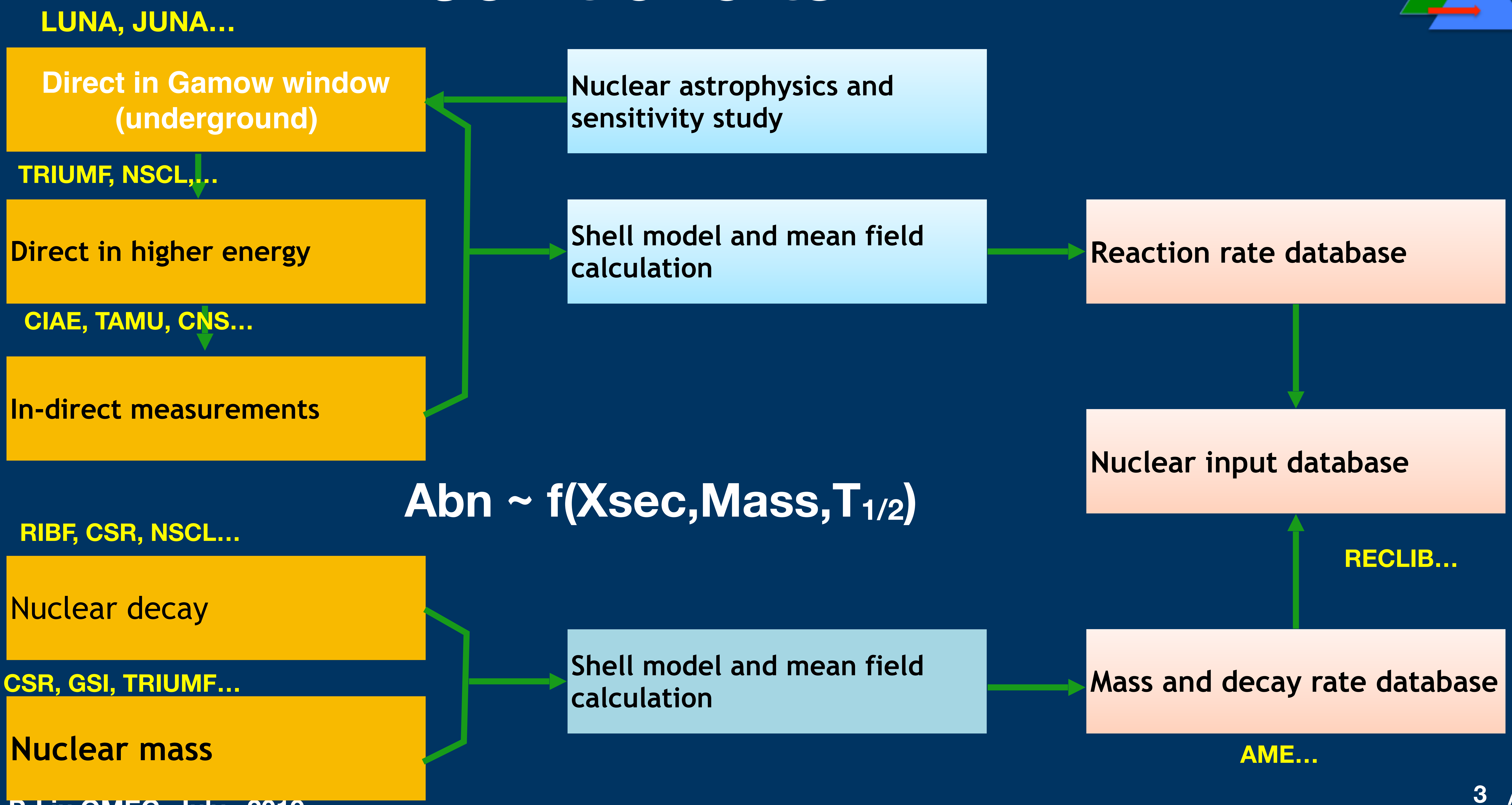


Astrophysical model

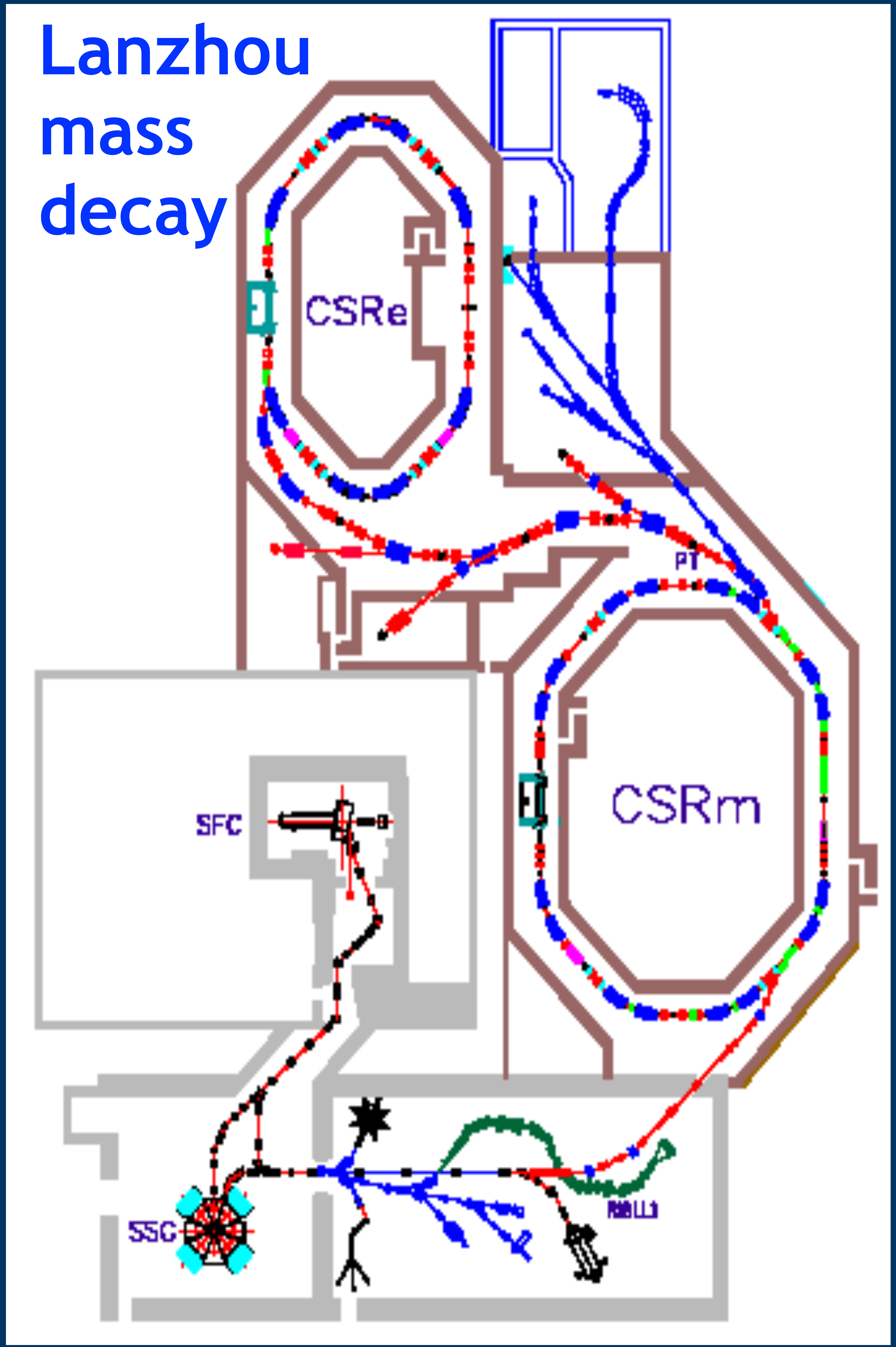
Abundance calc.

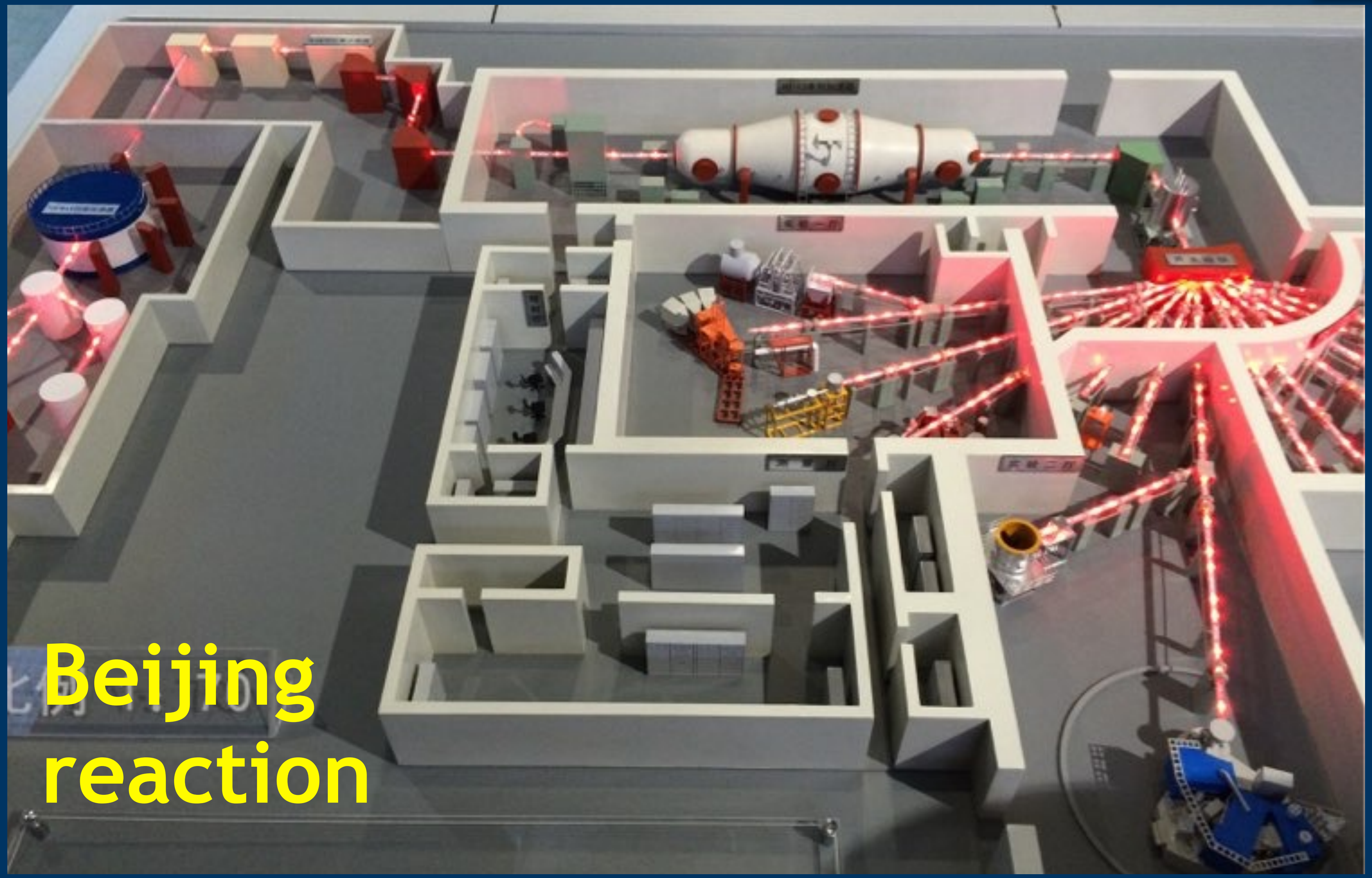
Abundance observation

Joint efforts



Major facilities in China





Milestones of NA in China

1993, first RI beam line in China

2005, in-direct extended to ^{8}Li(n,γ)^{9}Li

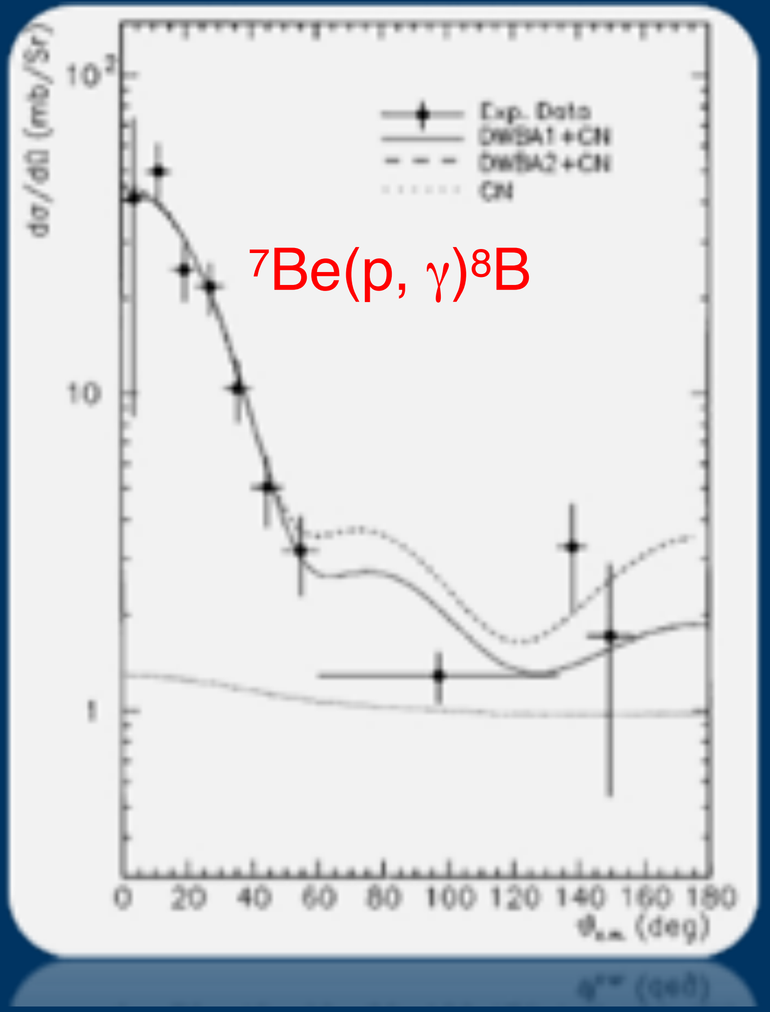
2011, NSFC group fund for Nucl. Astrophys.

2013, direct ^{6}Li(p, γ)^{7}Be in PLB

2015-, NSFC fund JUNA, and MOsT C+C IMME…

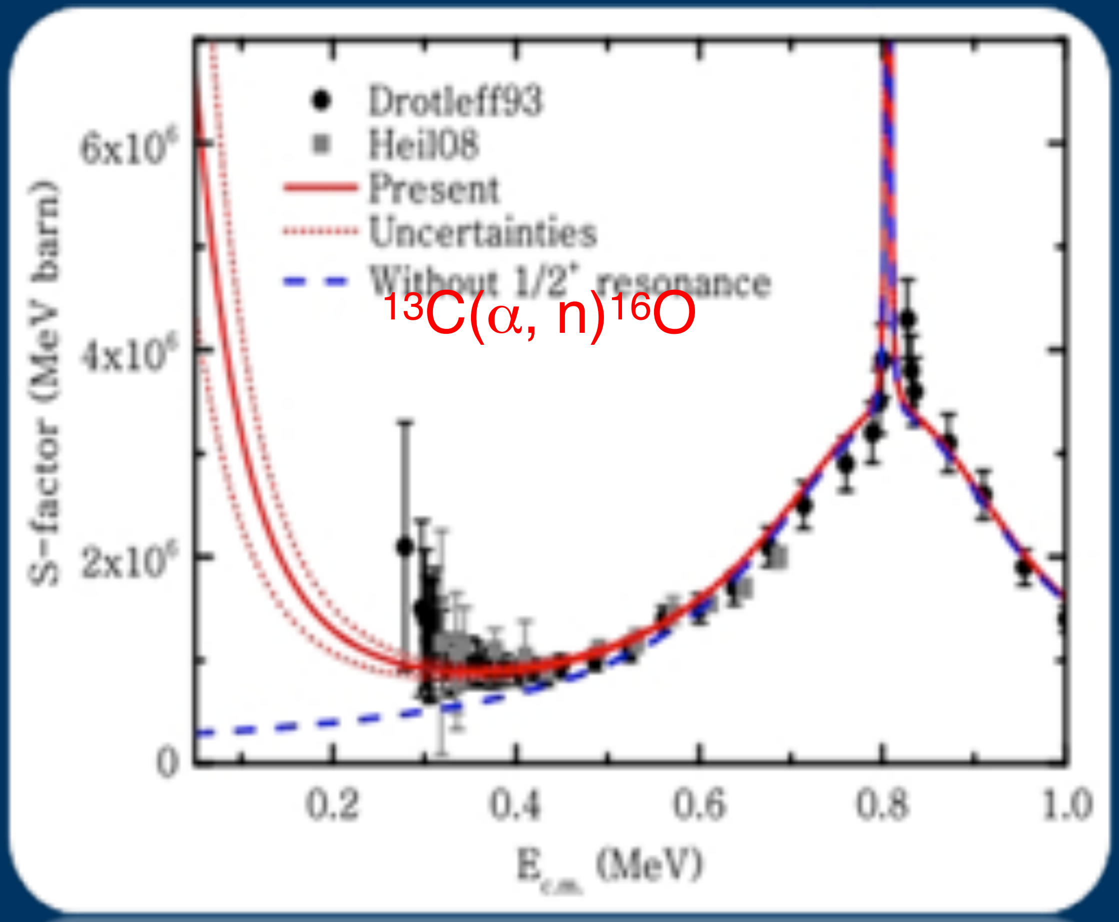
1993 | 1996 | 2005 | 2010 | 2012 | 2014 | 2015

1996, ^{7}Be(p, γ)^{8}B in-direct in PRL



2011, rp mass PRL, APJ

2012, ^{13}C(α, n)^{16}O in-direct in APJ

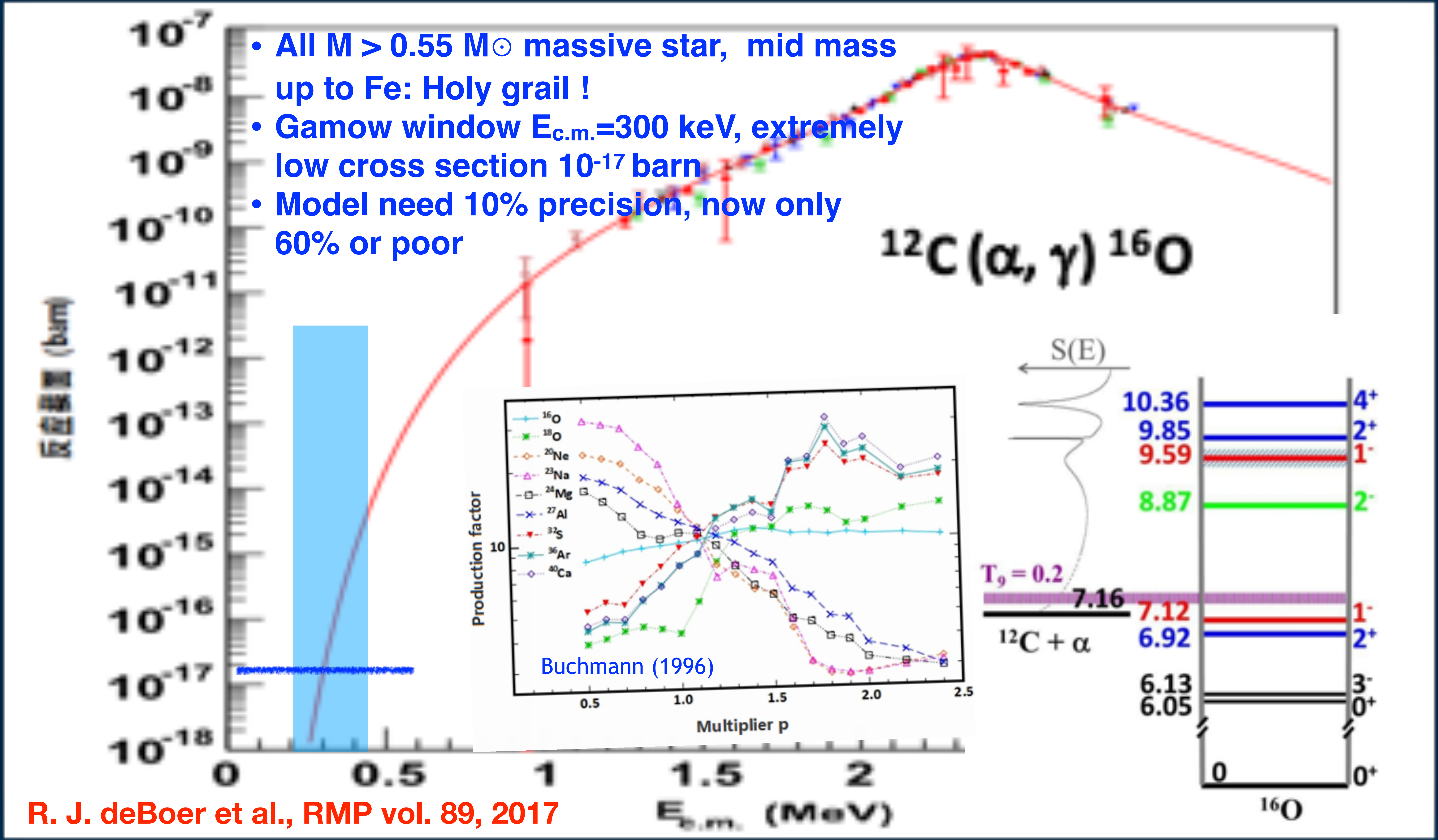


B. Guo, Z. H. Li, M. Lugaro et al., , Astrophys. J. 756, 193 (2012)

Big question, big impact, big challenge

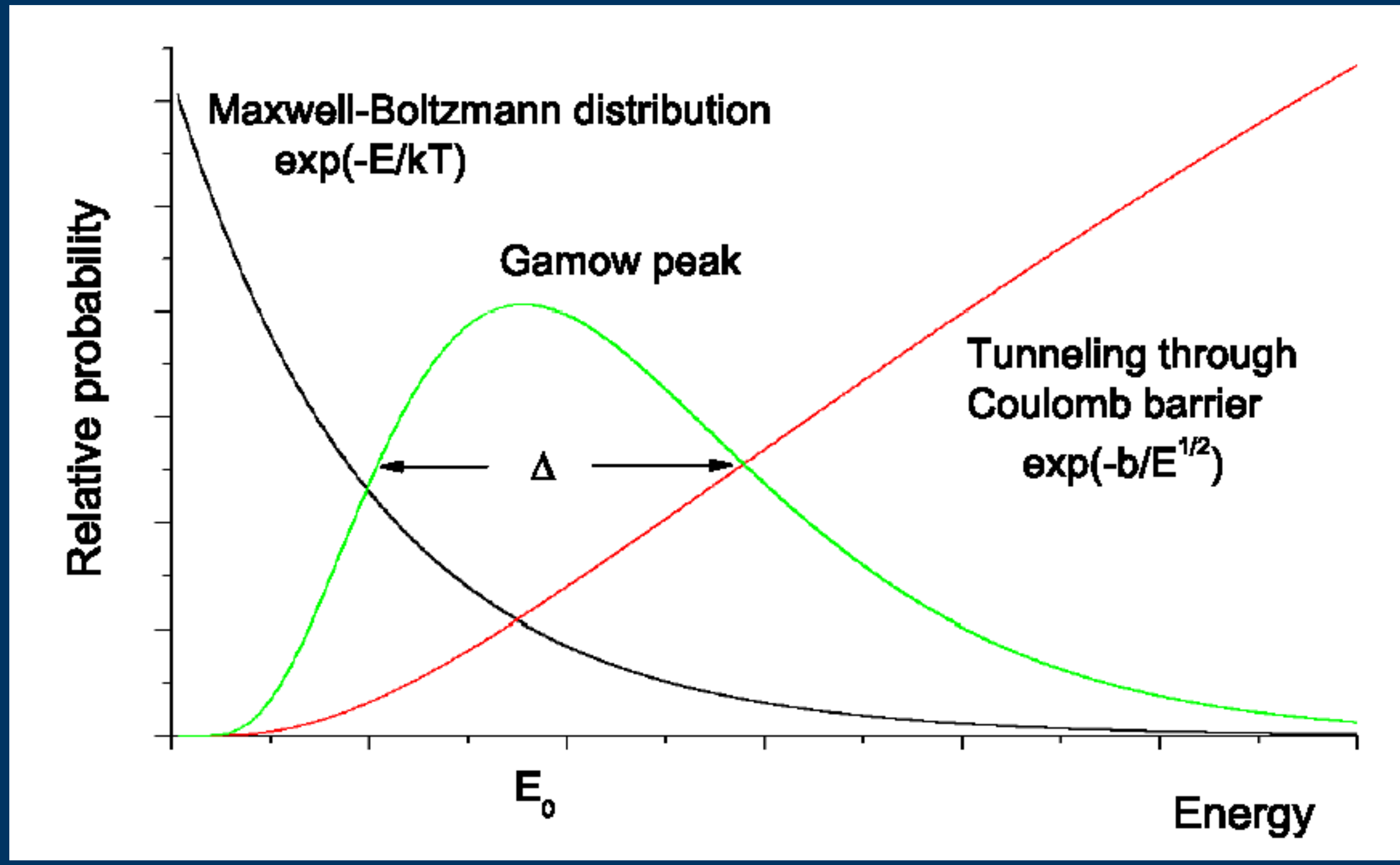
JUNA

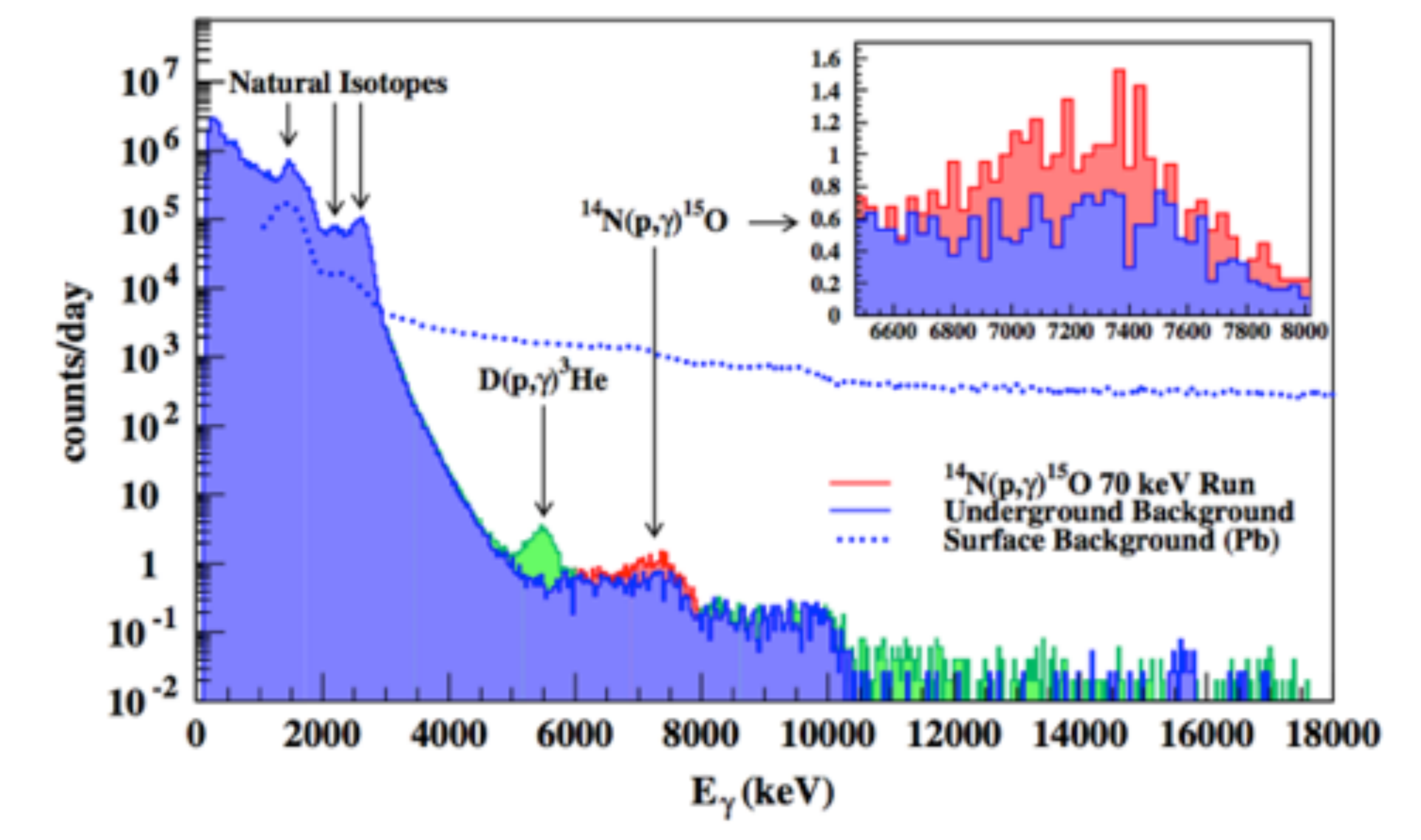
- All M > 0.55 M⊙ massive star, mid mass up to Fe: Holy grail !
- Gamow window $E_{c.m.}$=300 keV, extremely low cross section 10^{-17} barn
- Model need 10% precision, now only 60% or poor

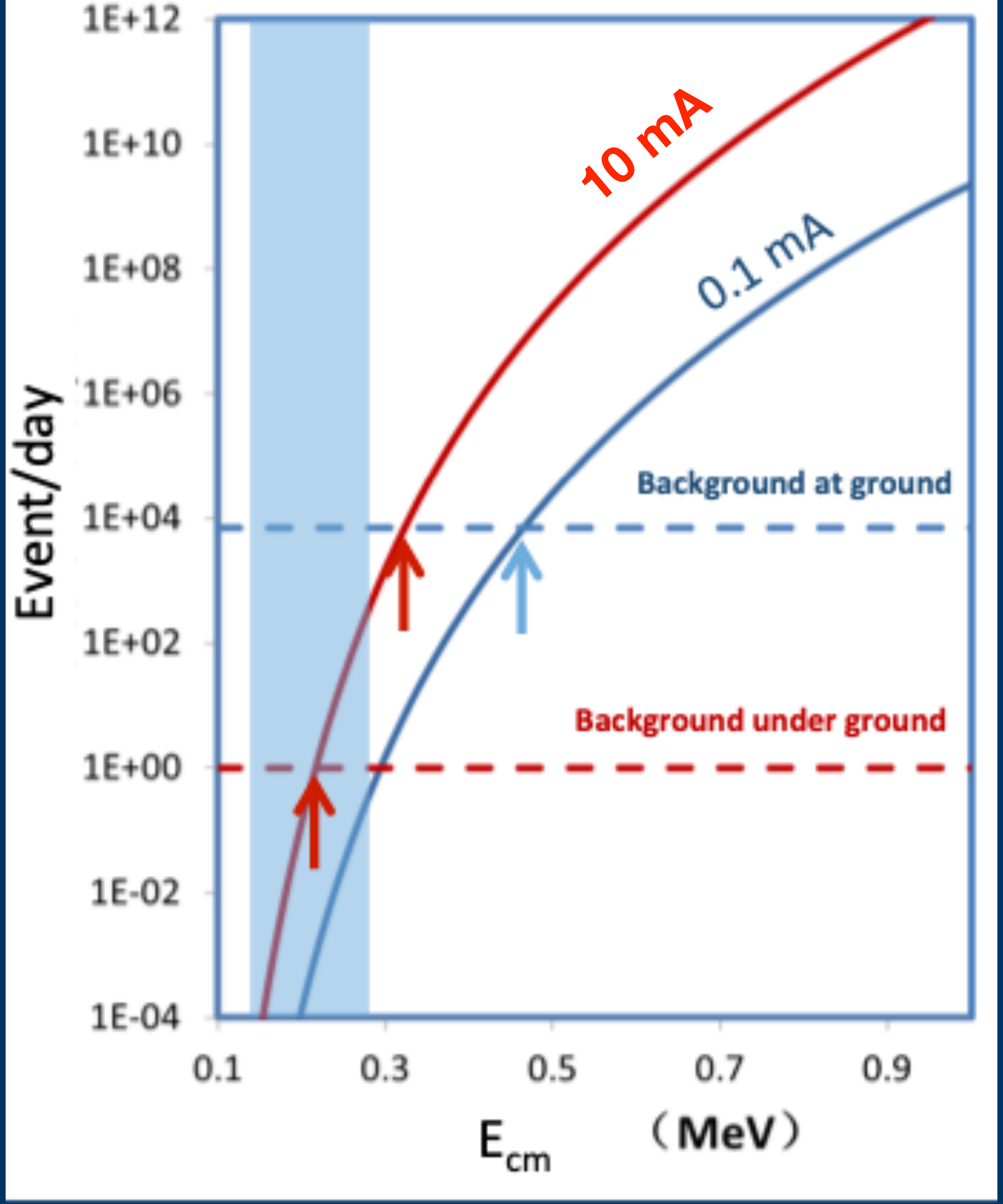


R. J. deBoer et al., RMP vol. 89, 2017

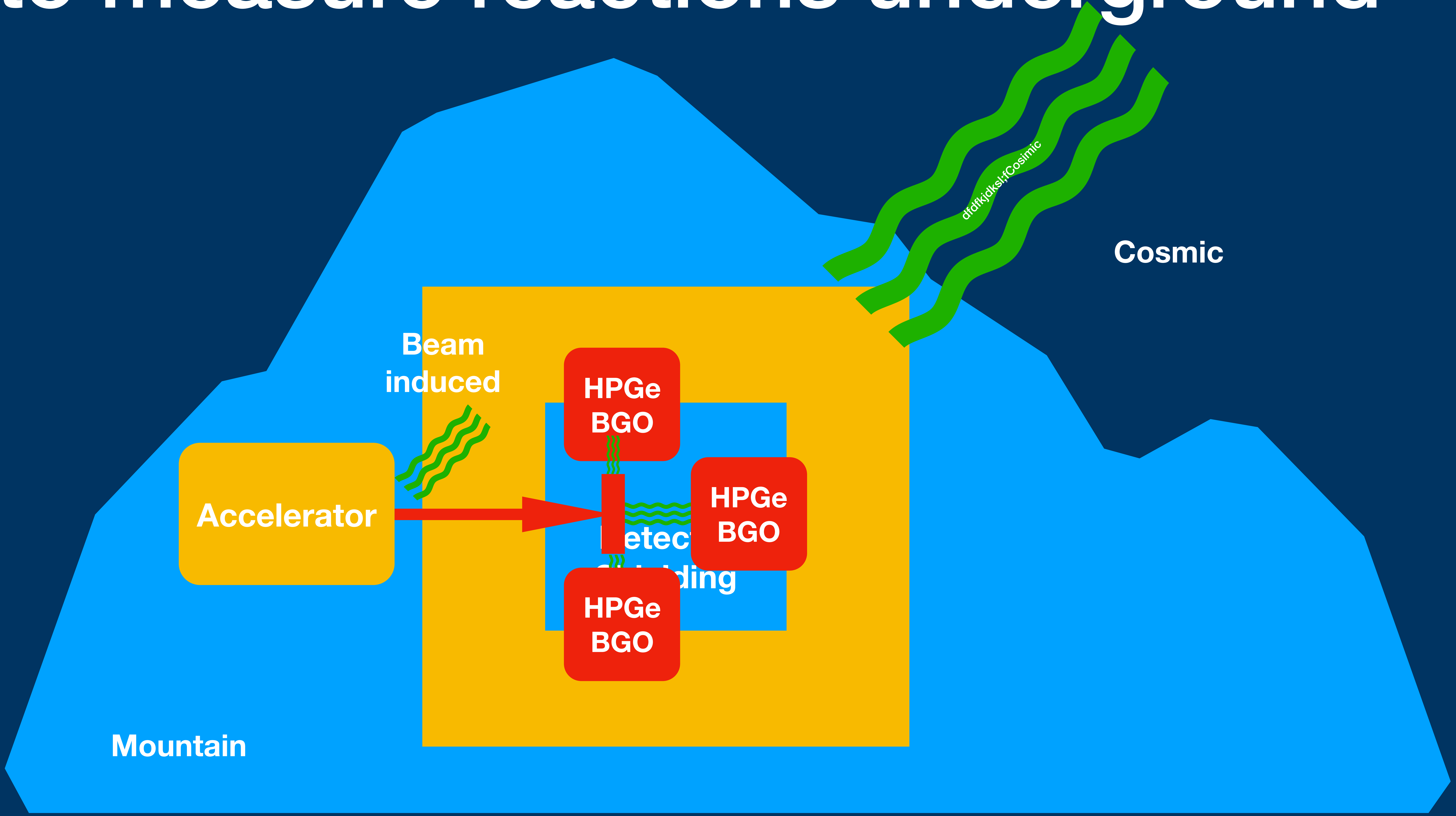
Underground advantage and key to success



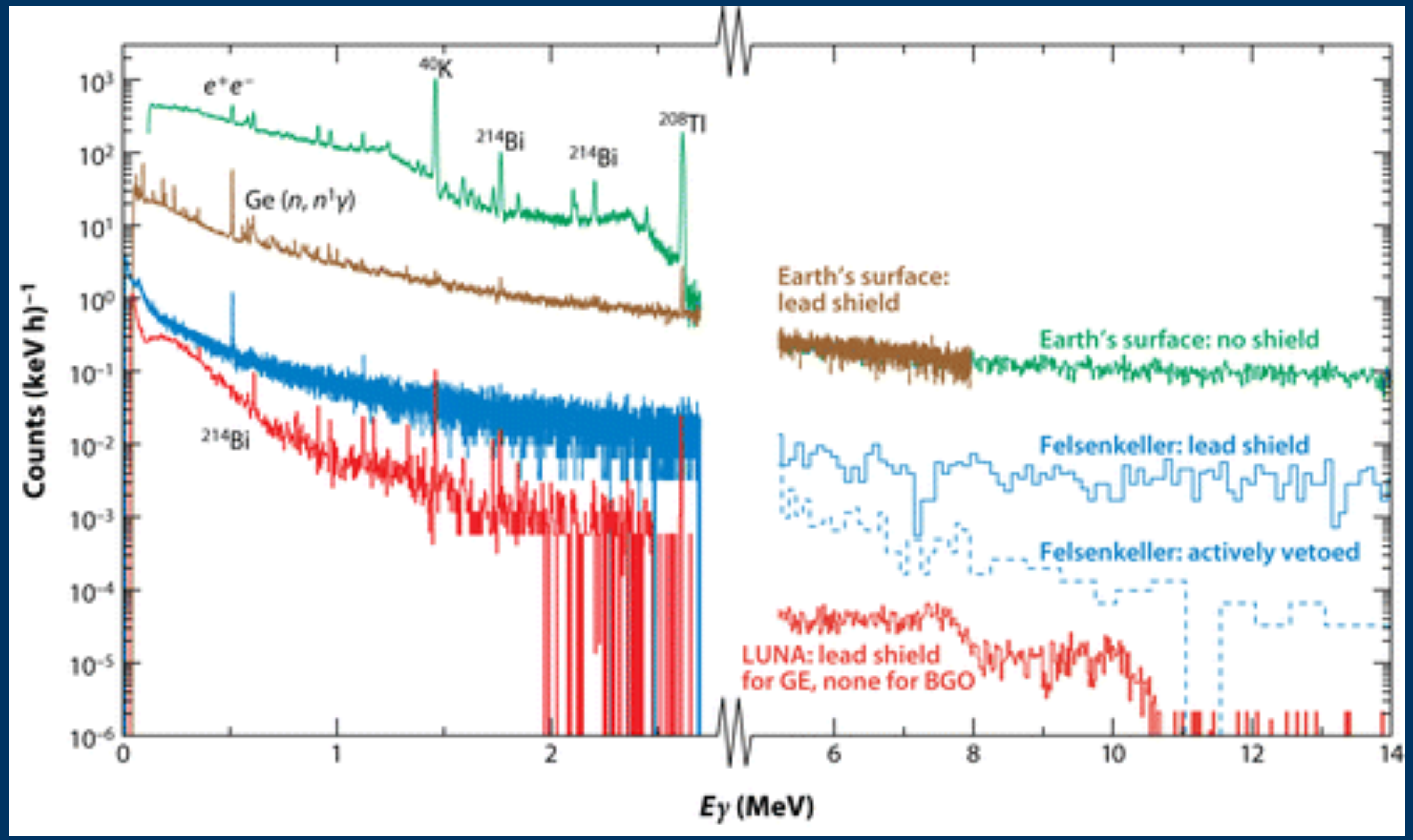


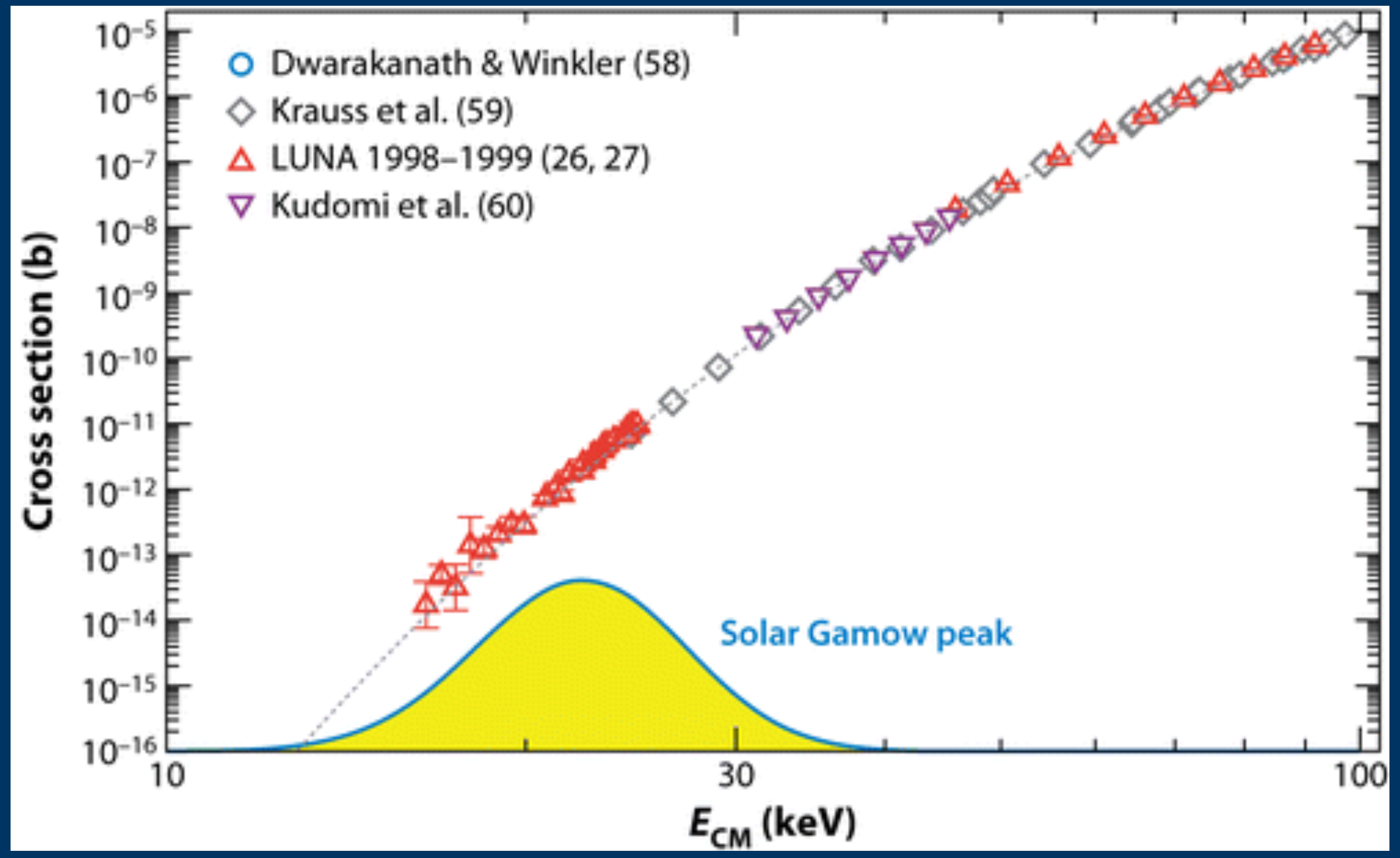


How to measure reactions underground

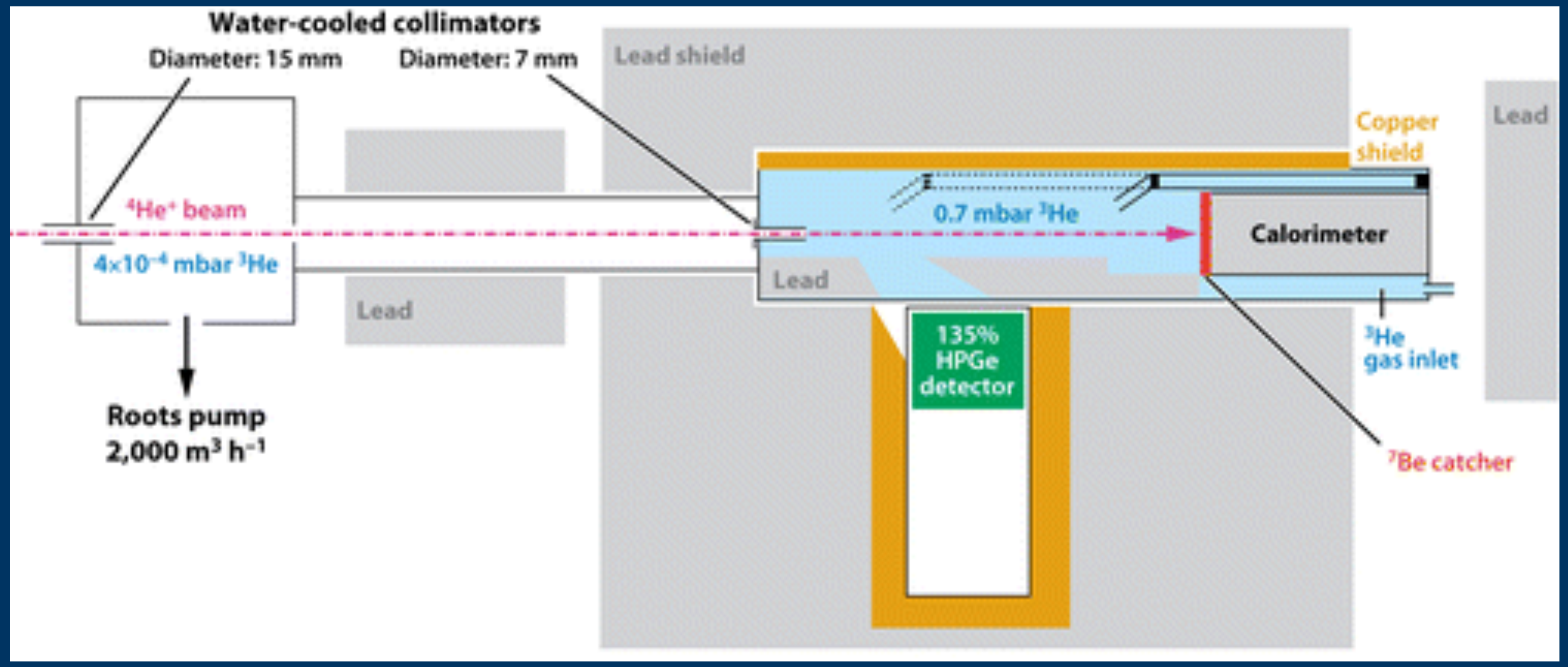


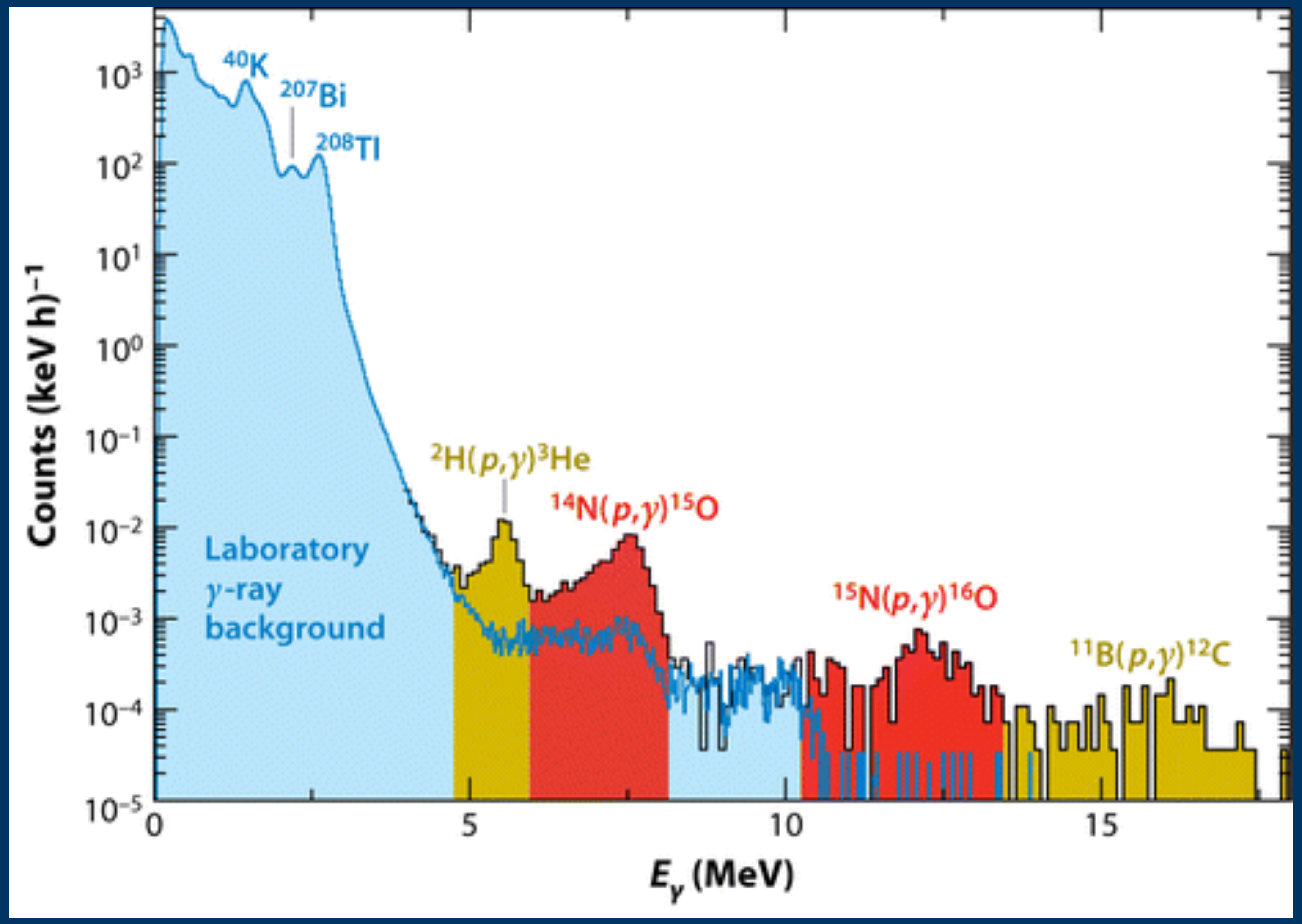
LUNA nuclear astrophysics





^{3}He(^{3}He,2p)^{4}He





^{14}N(p,γ)^{15}O

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,γ)^{3}He
NPA 706(2002)203

^{3}He(α,γ)^{7}Be
PRL 97(2006)122502

^{14}N(p,γ)^{15}O
PLB 591(2004)61

^{15}N(p,γ)^{16}O
PRC82, 055804(2010)

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

^{25}Mg(p,γ)^{26}Al
PLB 707(2012) 60

Uncertainty remained for key reactions

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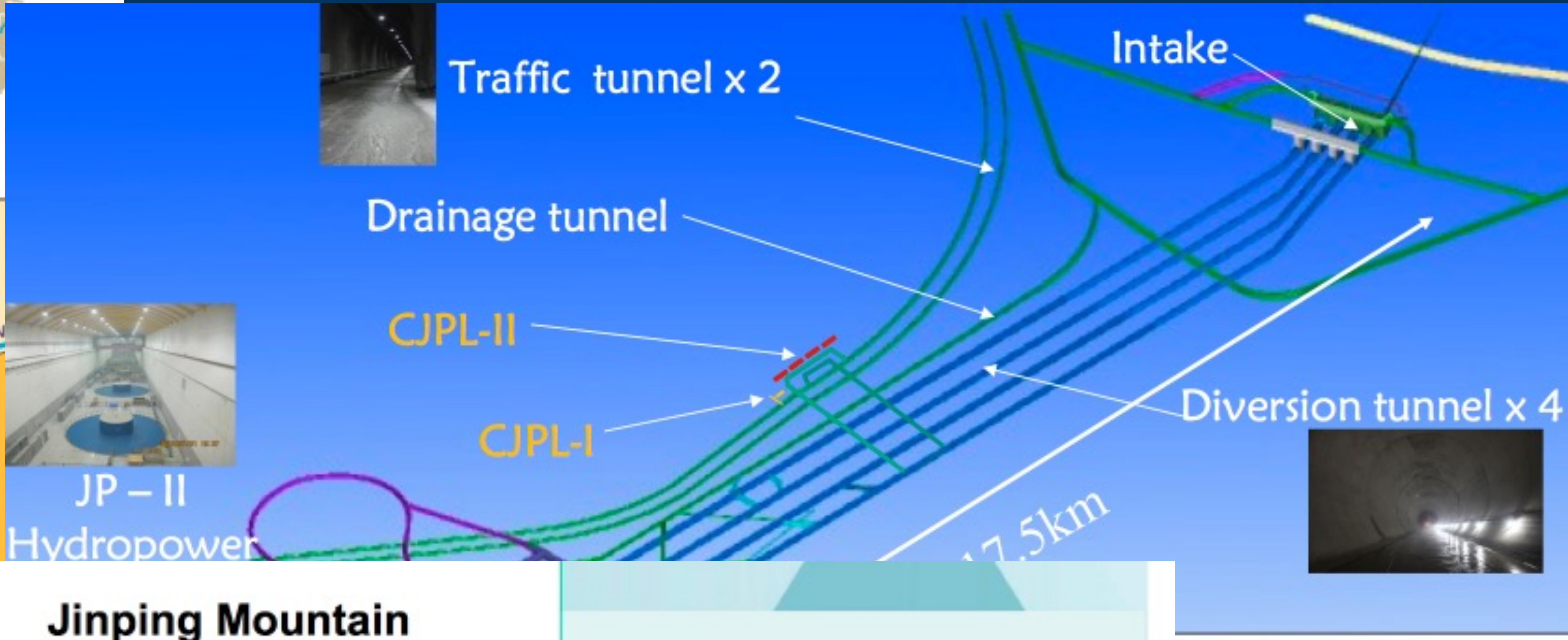
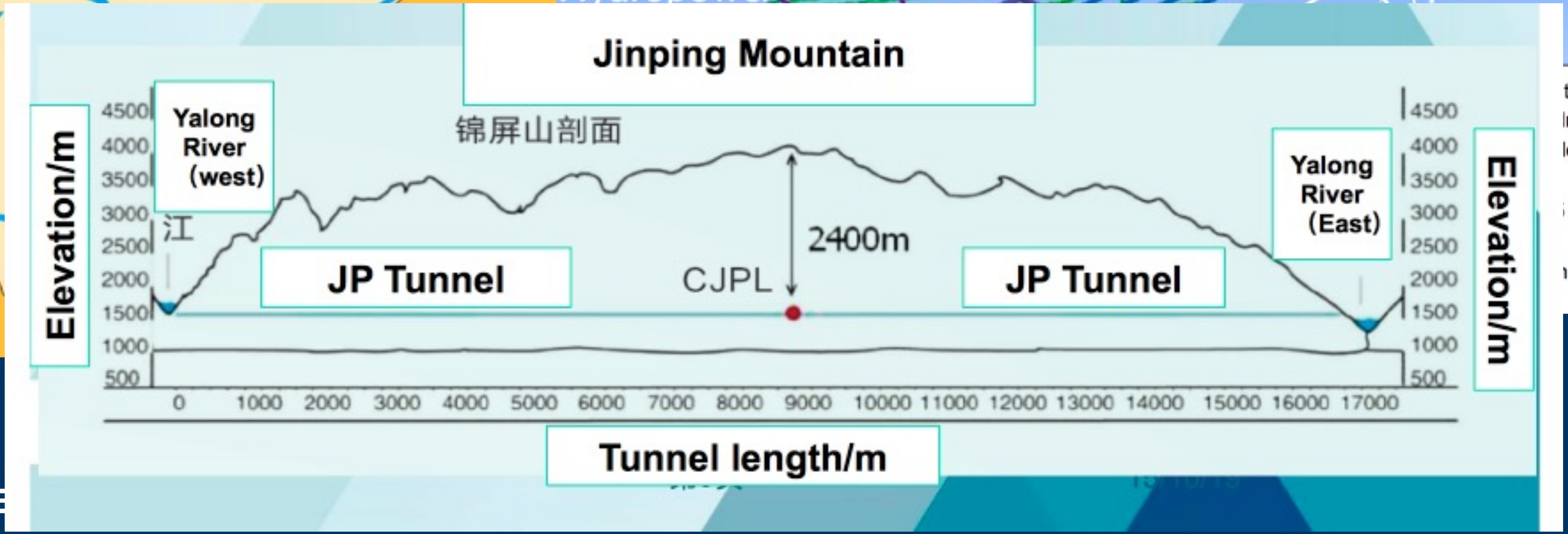
Physics	Reaction	Current	Desired
Massive star	$^{12}C(\alpha,\gamma)^{16}O$	60% 890 keV	20% 220-380 keV
s-process neutron source	$^{13}C(\alpha,n)^{16}O$	60% 279 keV	10% 140-230 keV
Galaxy ^{26}Al source	$^{25}Mg(p,\gamma)^{26}Al$	20% 92 keV	5% 50-300 keV
F aboundace	$^{19}F(p,\alpha)^{16}O$	80 % 189 keV	5 % 50-250 keV

CJPL





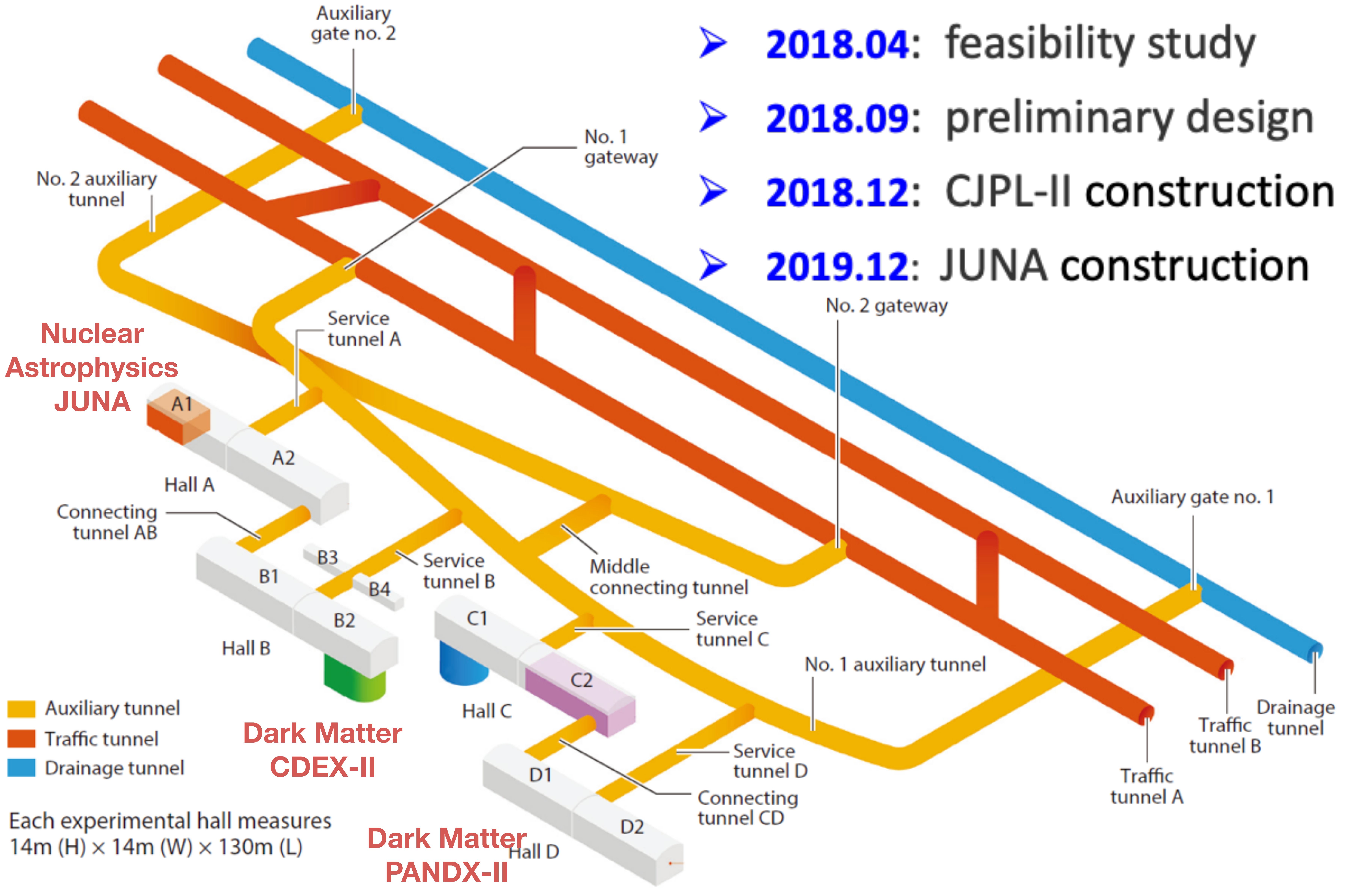
two auxiliary tunnels, one water
lrace tunnels
le is less than 1/100 of nature

m and principal stress of 70MPa

two curves in the end, good for

CJPL-II milestone

- **2018.04**: feasibility study
- **2018.09**: preliminary design
- **2018.12**: CJPL-II construction
- **2019.12**: JUNA construction



CJPL-II status 2016-2018

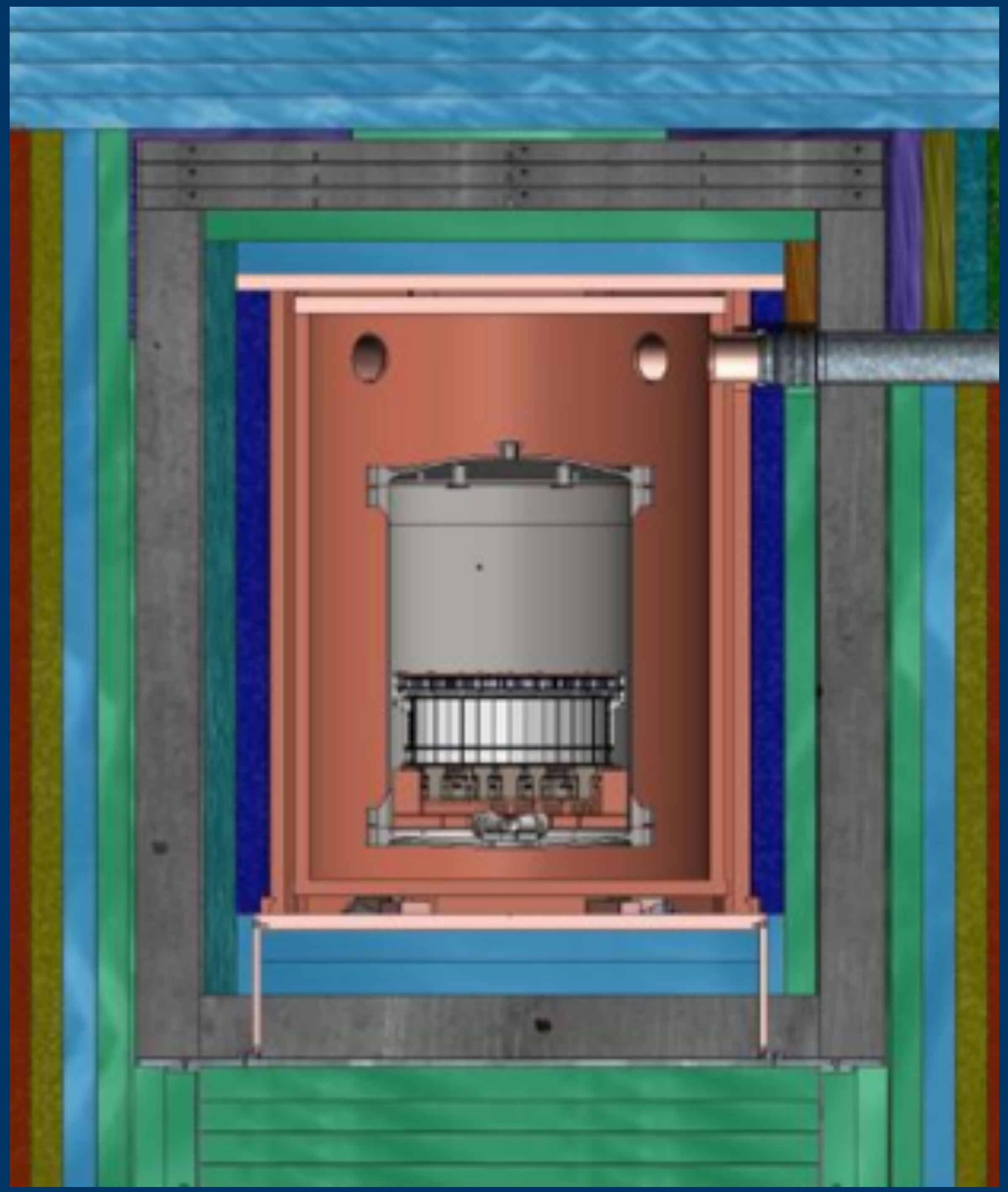

Under construction


Transport tunnel


B2 for CDEX-II

JUNA inauguration
Mar. 1, 2016

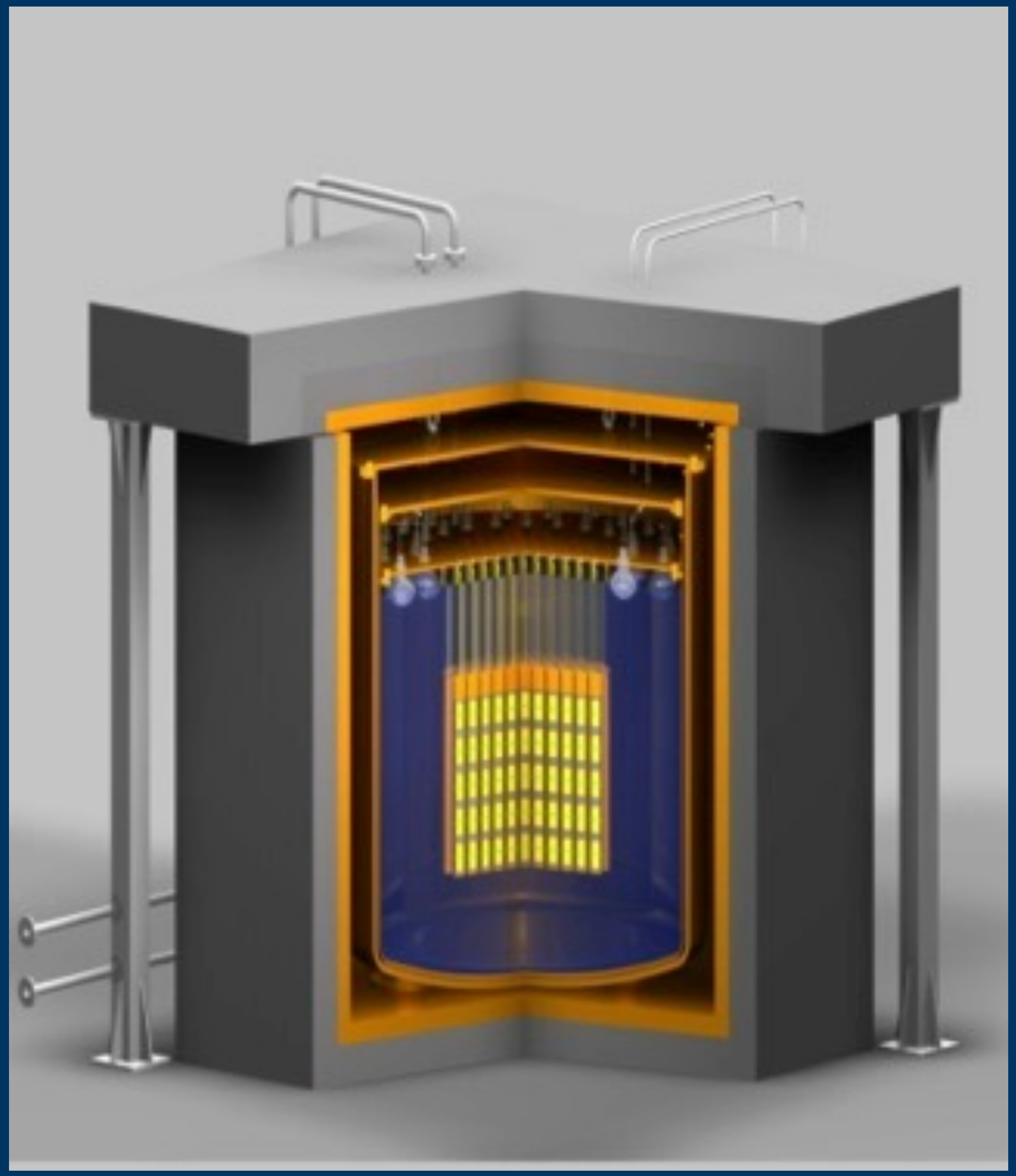
CJPL-II experiments



LXe **PANDAX+**

Nuclear
Astrophysics
JUNA
400 kV

More
experiments…



HpGe
CDEX +

JUNA team

Group leader

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

中国原子能科学研究院
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Institute of Modern Physics, Chinese Academy of Sciences

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

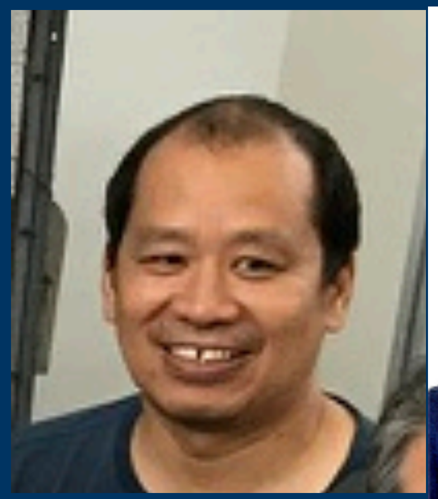
PI

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

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

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

Gang Lian
Lab. exp. sup,

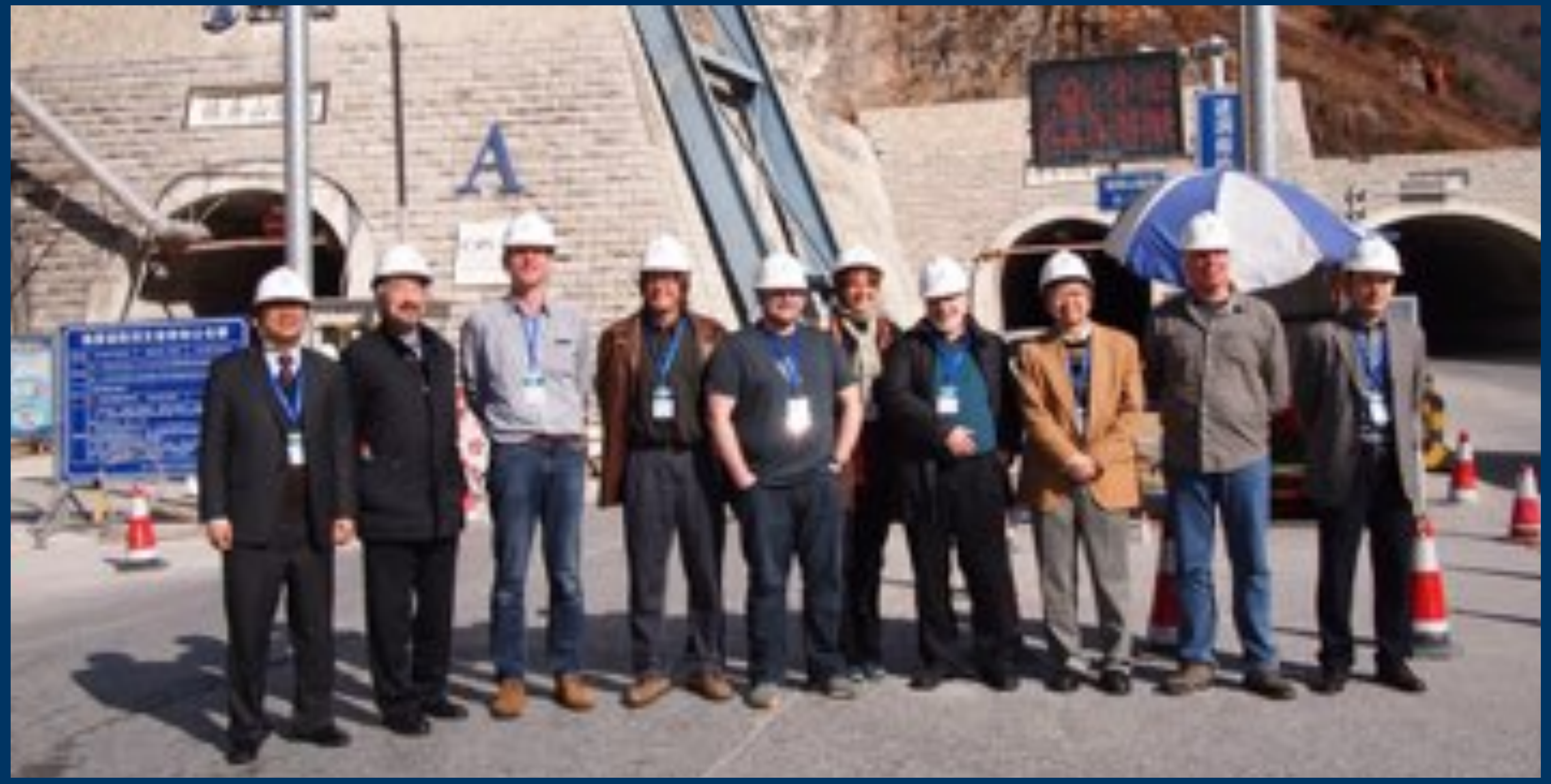


Bao Quncui, Liangting Sun
Ion source and acc.

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

JUNA IAC

M. Wiescher	UND
T. Motobayashi	RIKEN
H. Wang	TCAS
C. Brune	Ohio
M. Junker	INFN
D. Robertson	UND
F. Strieder	SDSMT
D. Leitner	LBL
Q. Yue	THU



IAC, CJPL, Mar. 1, 2016

Mini IAC, Shanghai, Sept. 19, 2017

1st meeting July 2015, 1st formal IAC meeting March, 2016, 2nd mini meeting Sept. 2017

JUNA funding

JUNA

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

CJPL-II / Tsinghua ~$3+M

Detectors（NSFC $1.3M）

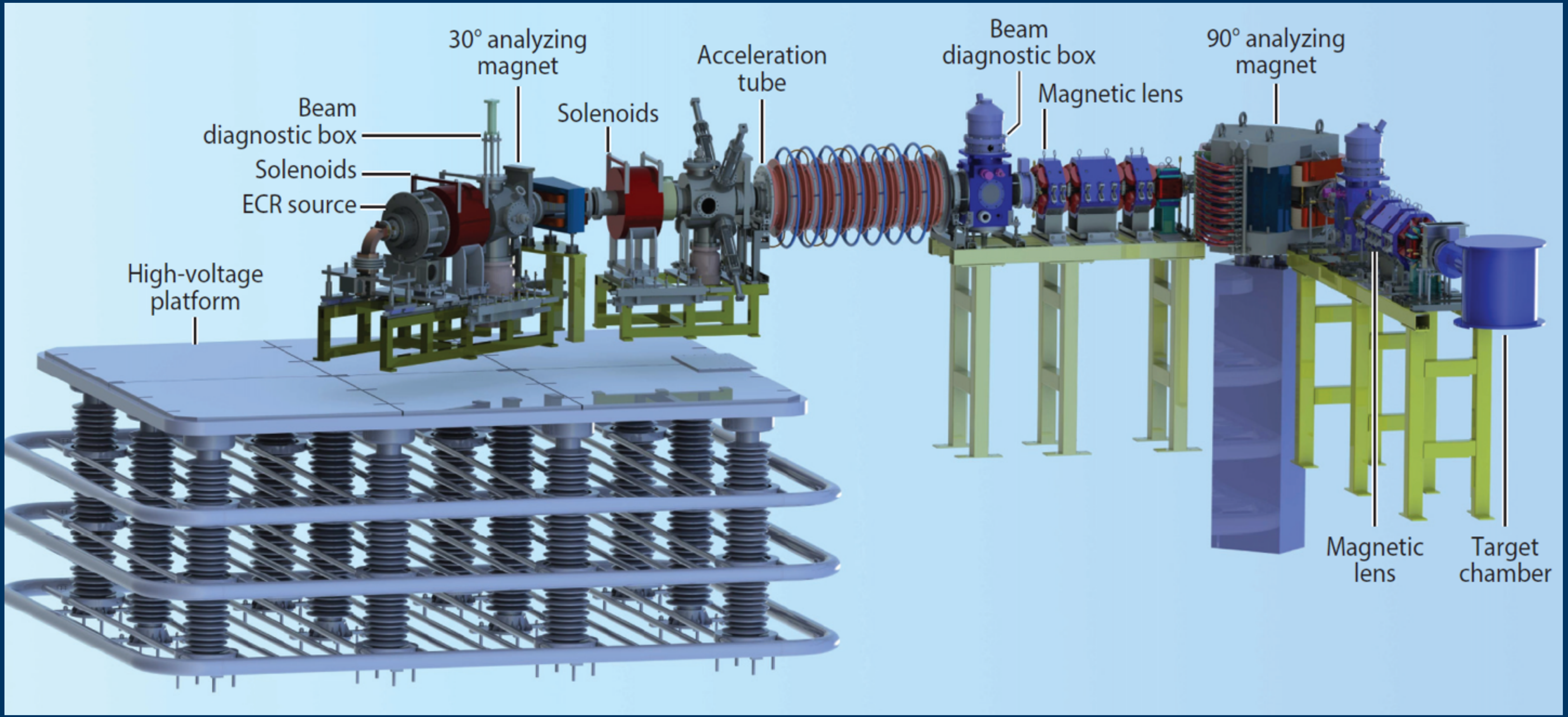
Electronics, shielding (NSFC $1.0M)

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

Lab CJPL II（CNNC, Tsinghua，NSFC $3+M）

total $8+ M

JUNA Accelarator



Goal

Beam	Intensity, mA	Energy,keV
H+	10	70-400
He+	10	70-400
He++	2	140-800

Achieved

Beam	Intensity, mA	Energy,keV
H+	12	350
He+	2.5	350

reaction	physics	current limit (keV)	precision (%)	ref.	JUNA limit (keV)	Gamow energy (keV)
$^{12}C(\alpha,\gamma)^{16}O$	Massive star	890	60	[17]	380	220-380
$^{13}C(\alpha,n)^{16}O$	HI synthesis	279	60	[18]	200	140-230
$^{25}Mg(p,\gamma)^{26}Al$	Galaxy ^{26}Al	92	20	[13]	58	50-300
$^{19}F(p,\alpha)^{16}O$	F abundance	189	80	[19]	100	50-350

See: L. H. Chen, Poster No.13

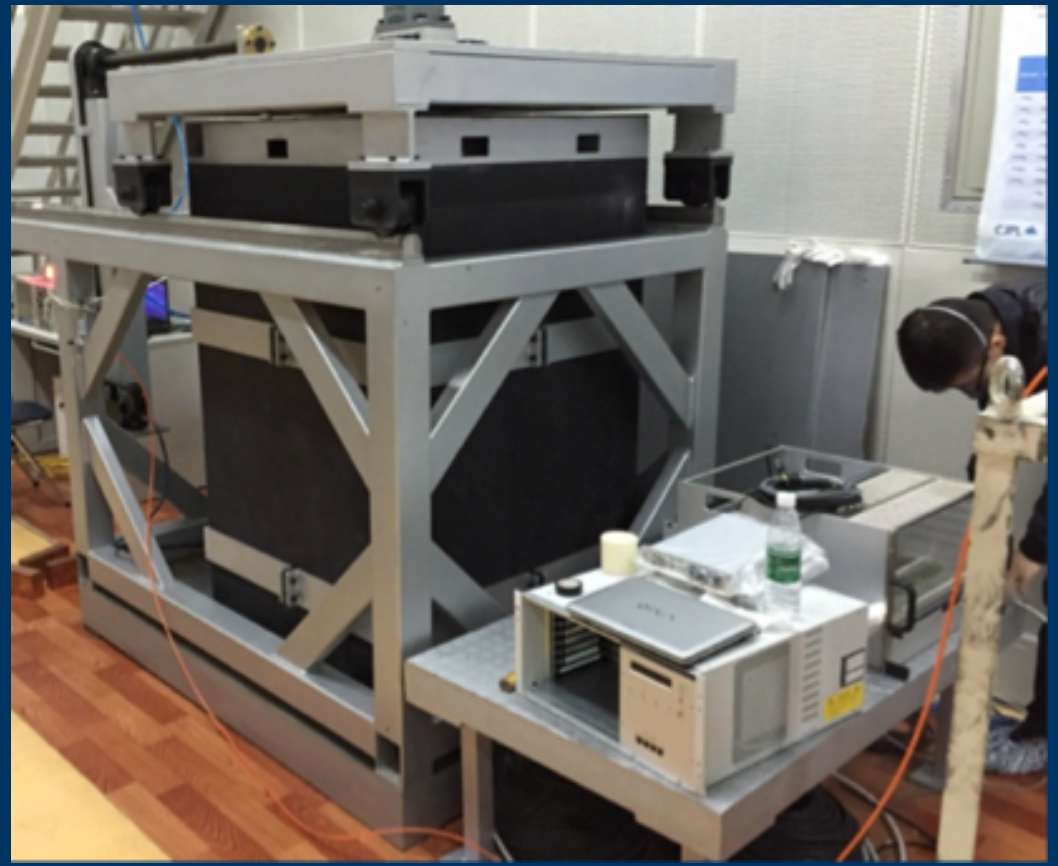
JUNA expertise

JUNA

Superconducting ECR

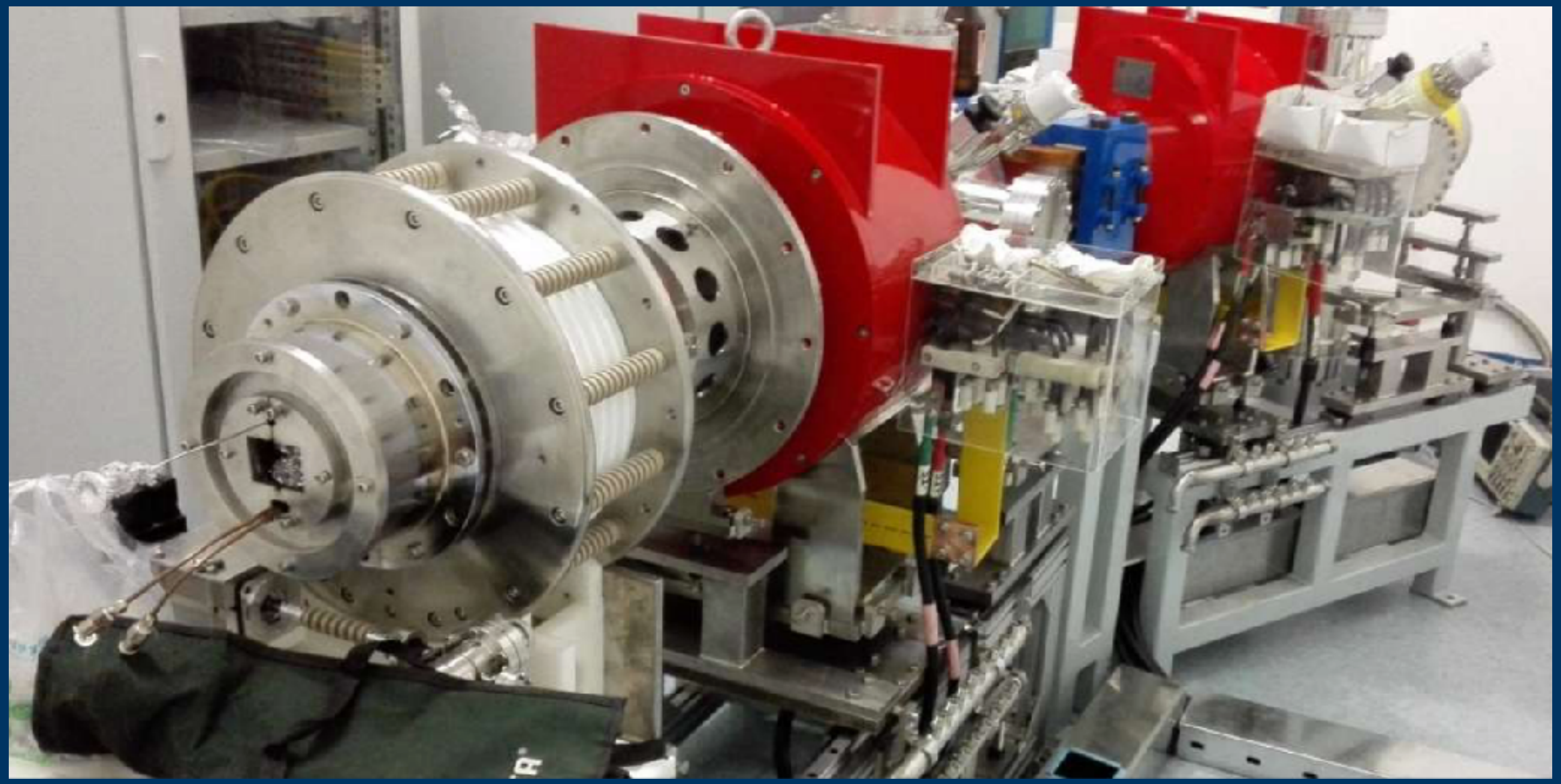
Tandem for test experiment

solid and gas detector and electronics



CJPL low background facility

Ion source and accelerator status



Ion source installed, 1 mA tested; 7/31/16, reach 16 mA in Oct.

First beam of proton with 260 keV and 3 mA on May 27, 2017

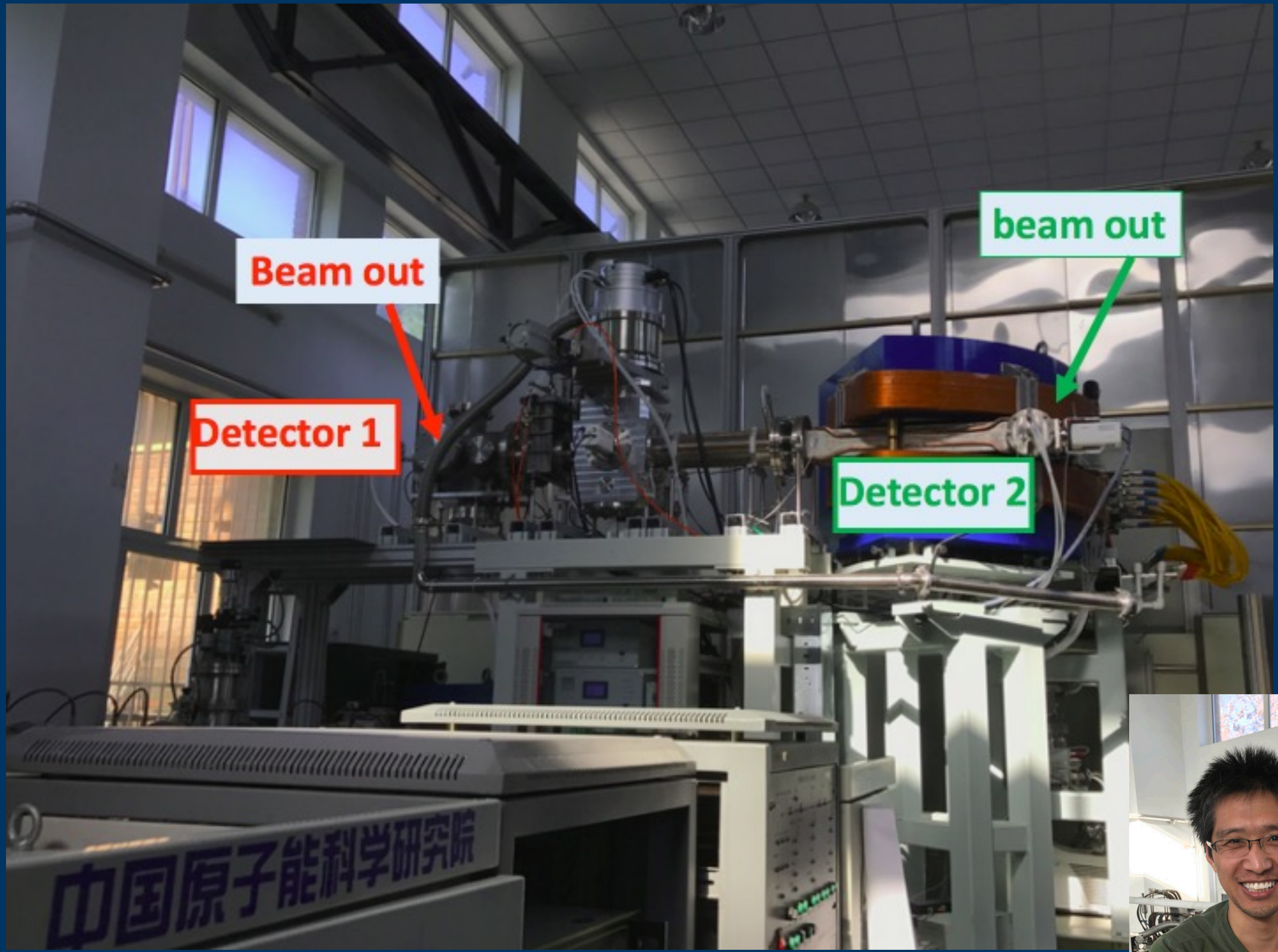
Accelerator tank established 8/30/16

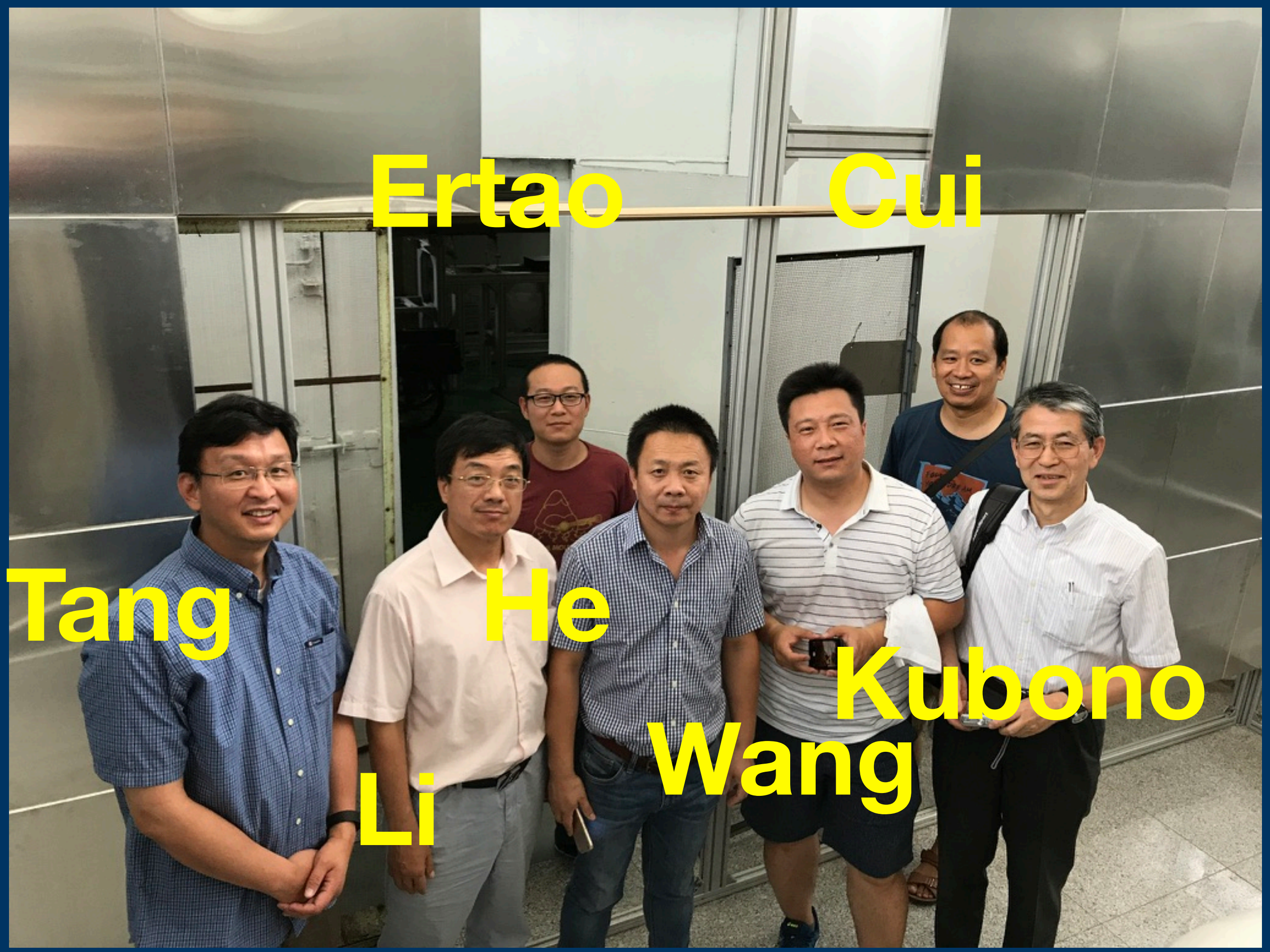
Beam line

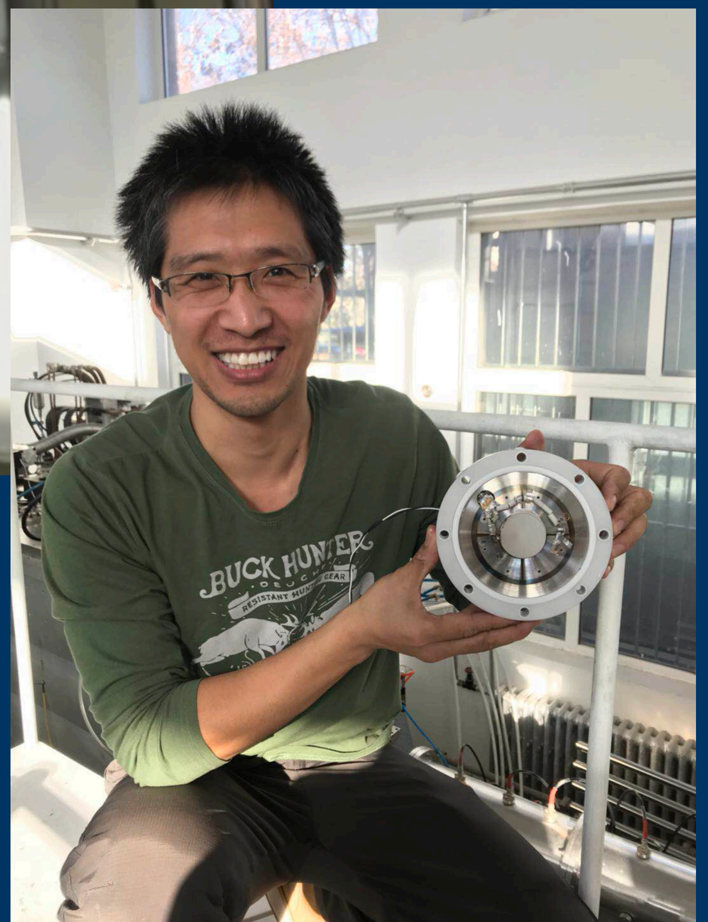
Beam dignostics

Ground test experiment

Content	Detector	Beam	Energy(keV)	Intensity
Energy calibration	HPGe (35%)	H^+	150-250	100 uA
Target of ^{25}Mg	HPGe (35%)	H^+	230	100 uA
$^{25}Mg(p, \gamma)^{26}Al$	HPGe (175%)	H^+	210-330	0.1-1 mA
$^{25}Mg(p, \gamma)^{26}Al$	BGO	H^+	210-330	0.1-1 mA
$^{19}F(p, \alpha\gamma)^{16}O$	BGO	H^+	150-300	10-100 uA
Target of ^{13}C	----	He^+	400	6 mA
Target of ^{12}C	----	He^+	400	2 mA

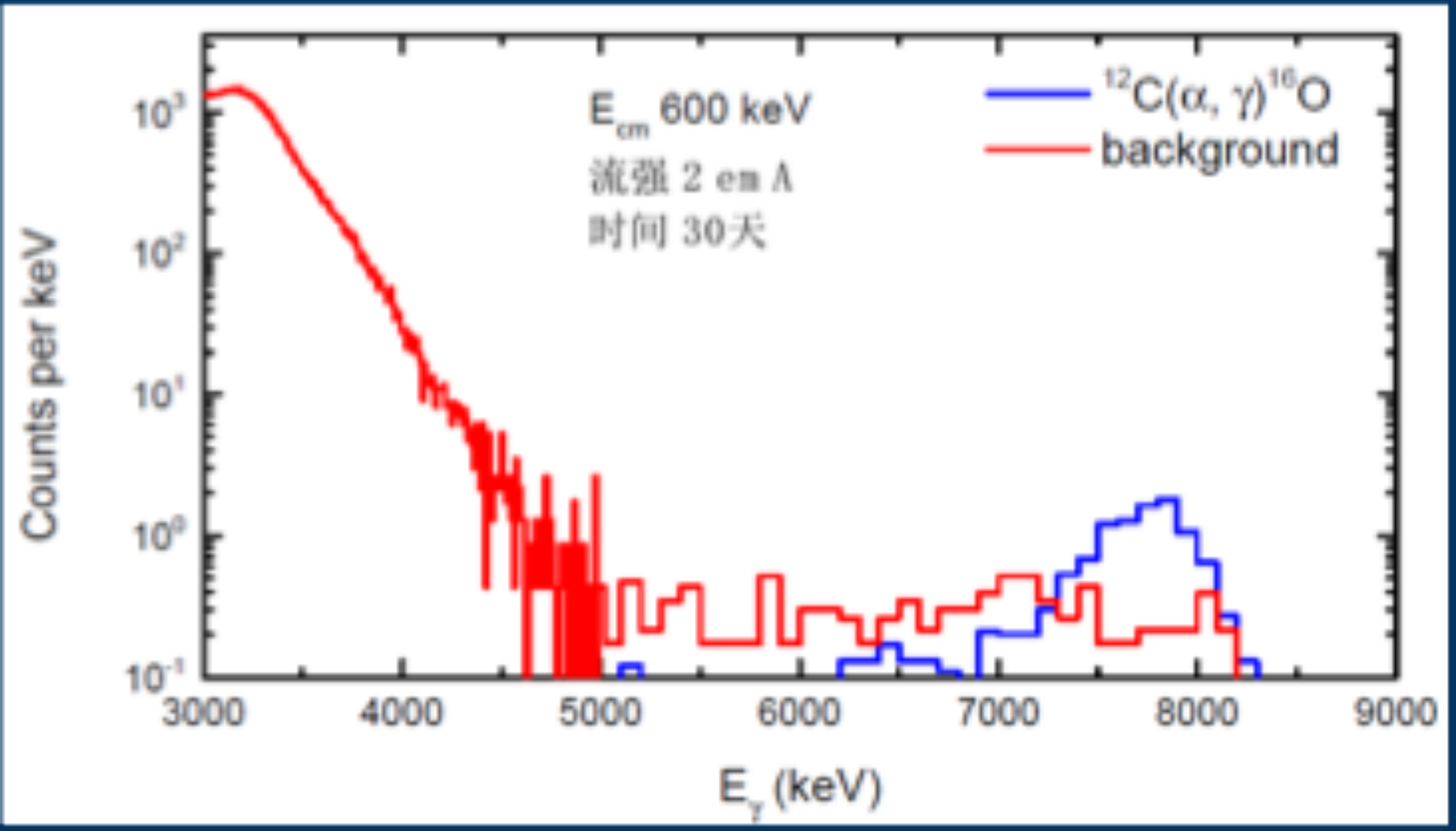




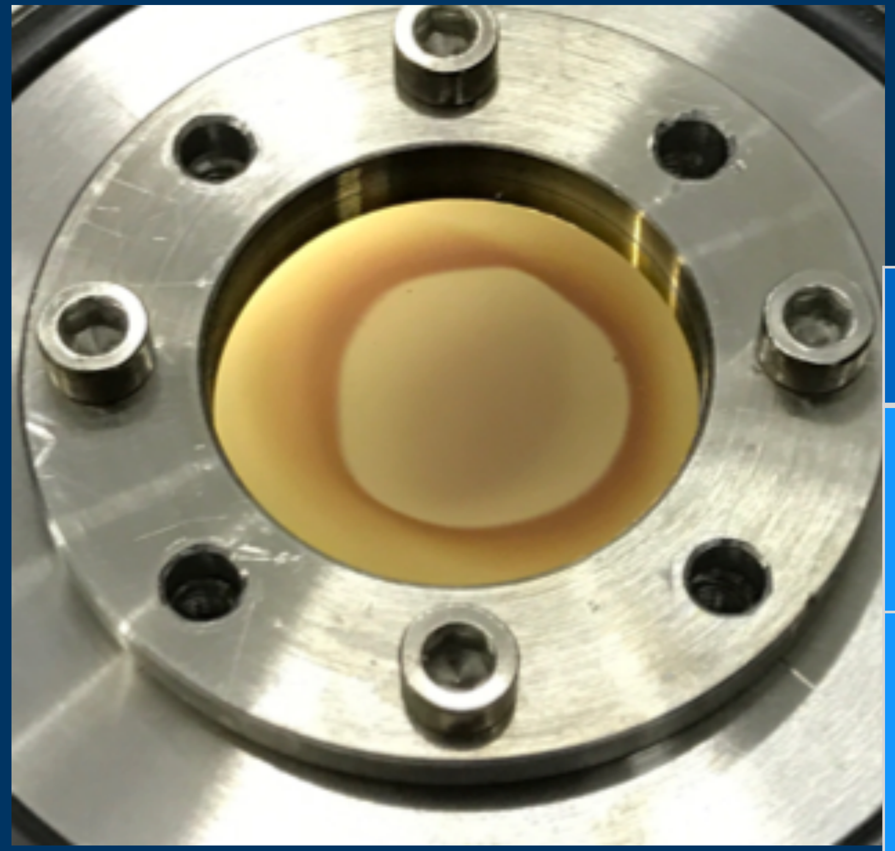


W. P. Liu OMEG, July , 2019

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

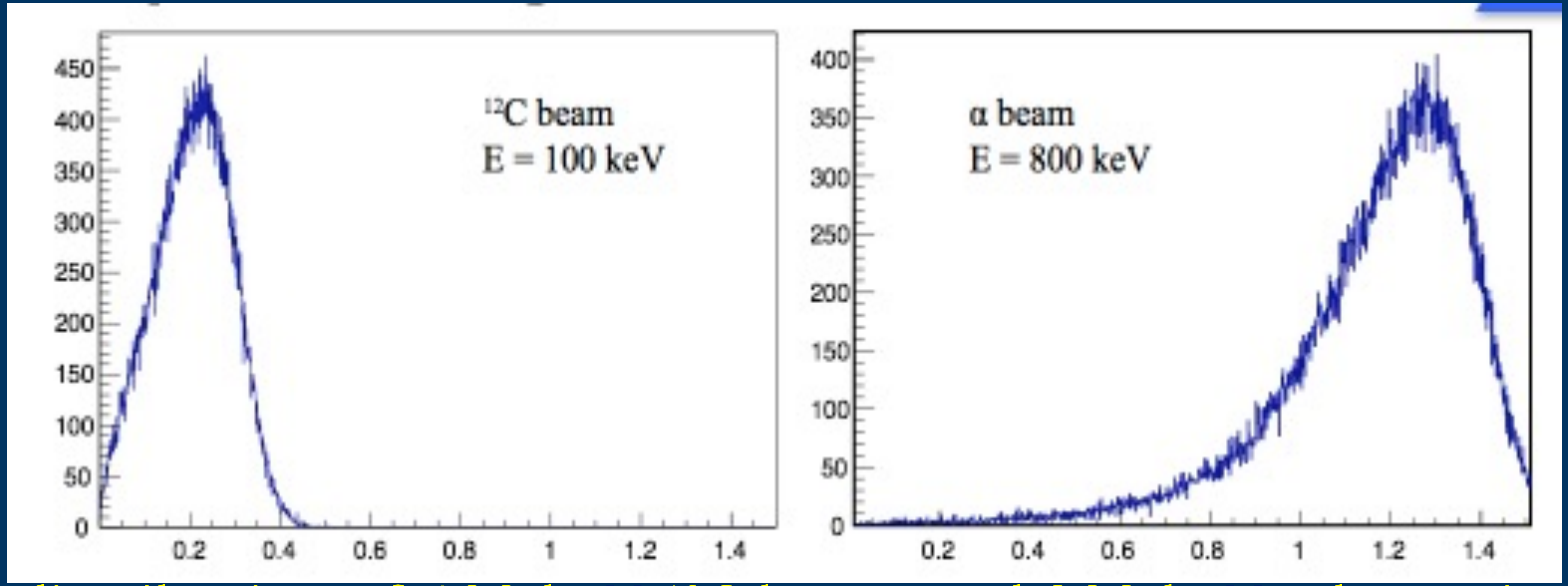


Simulation for BGO

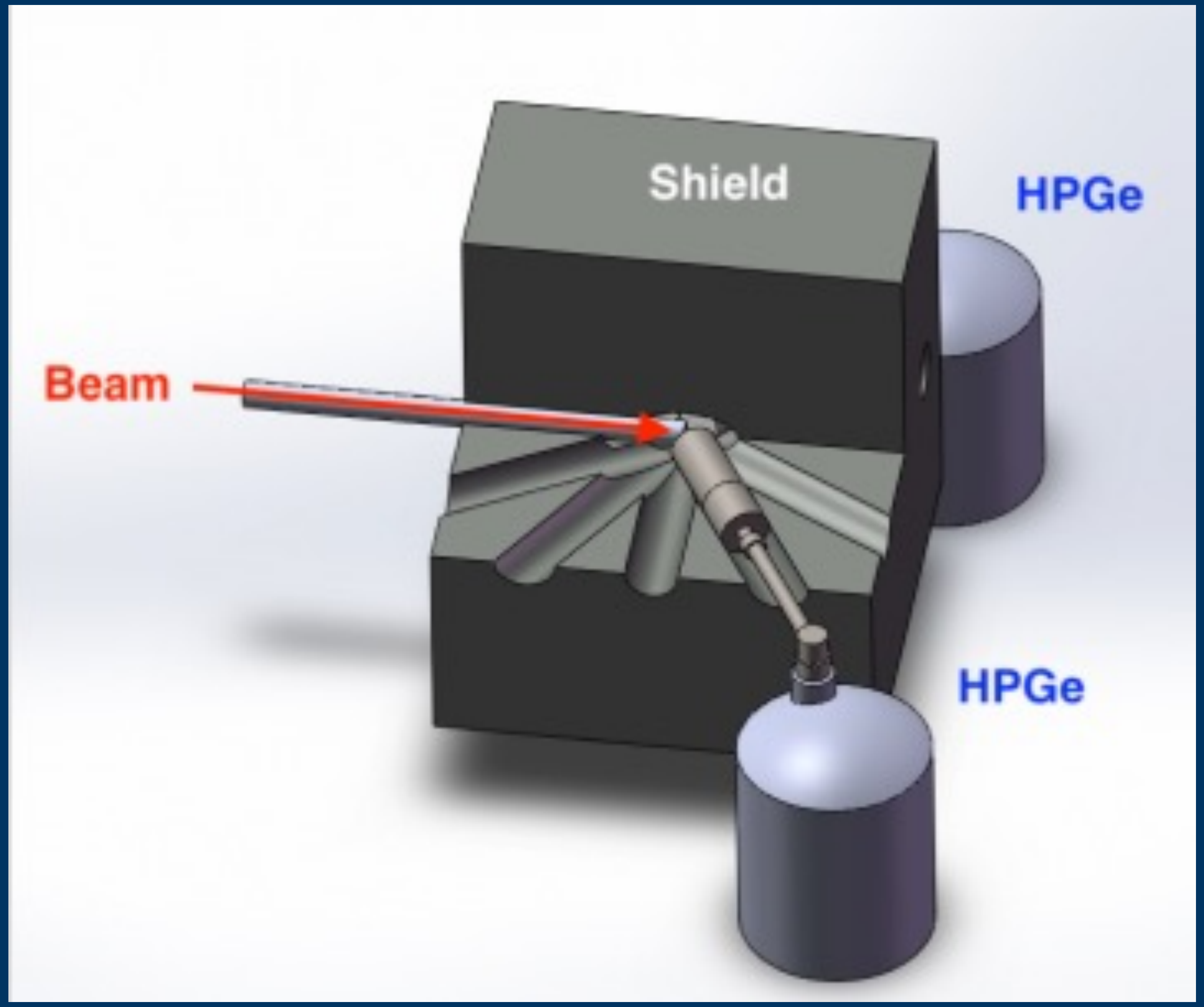


^{12}C implantation target in Lanzhou

	Det	E, kev	σ, b	ε, %	C/B/day
$d\sigma/d\Omega$	HPGe	600	10^{-13}	1.4	1/0.04
σ_{tot}	BGO	450	10^{-15}	60	1/1



distribution of 100 keV ^{12}C beam and 800 keV α beam in coated gold



High energy point for $^{12}C(\alpha,\gamma)^{16}O$

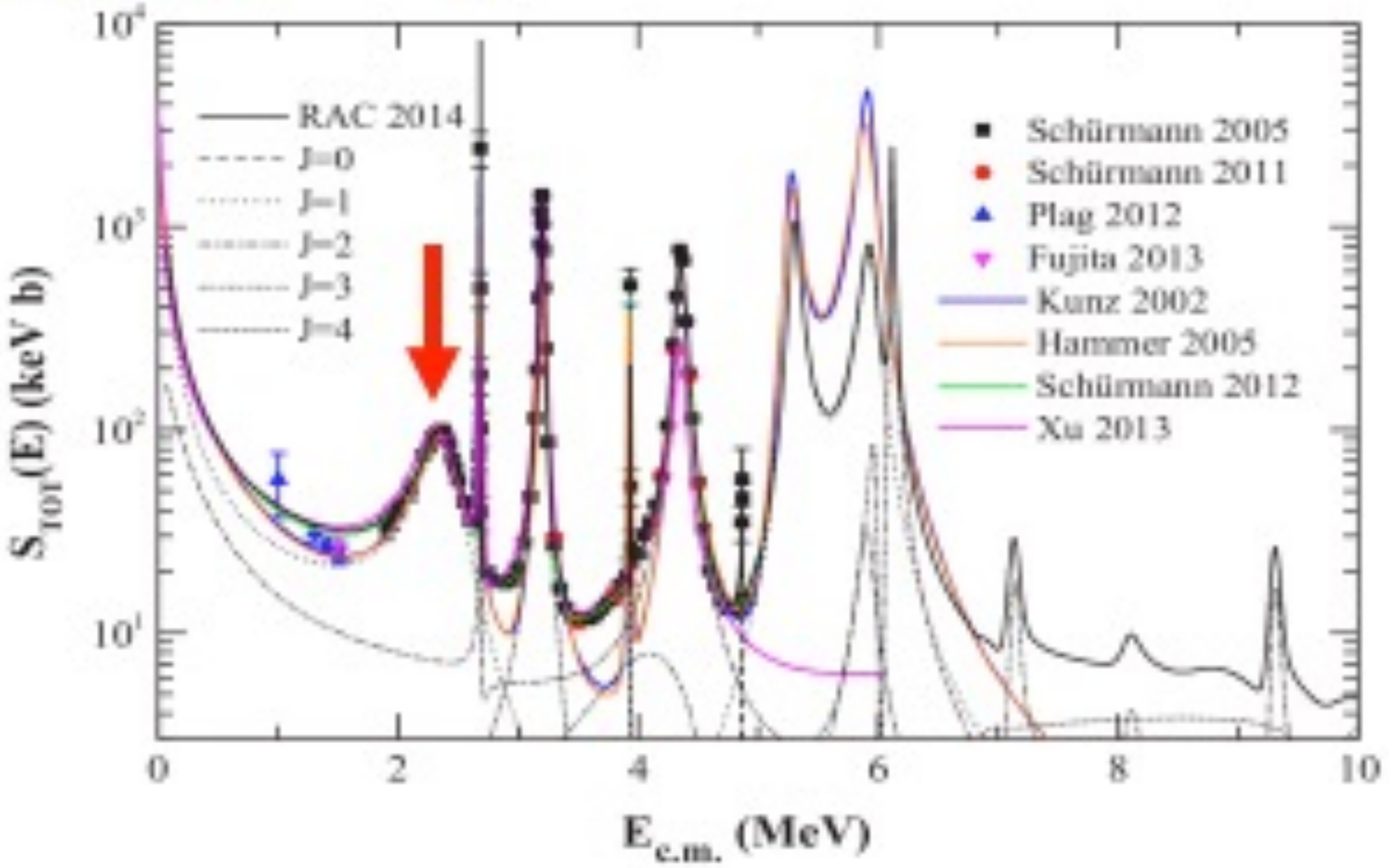
JUNA

Direct Measurement of $^{12}C(\alpha,\gamma)^{16}O$ at high energy points 2017.10

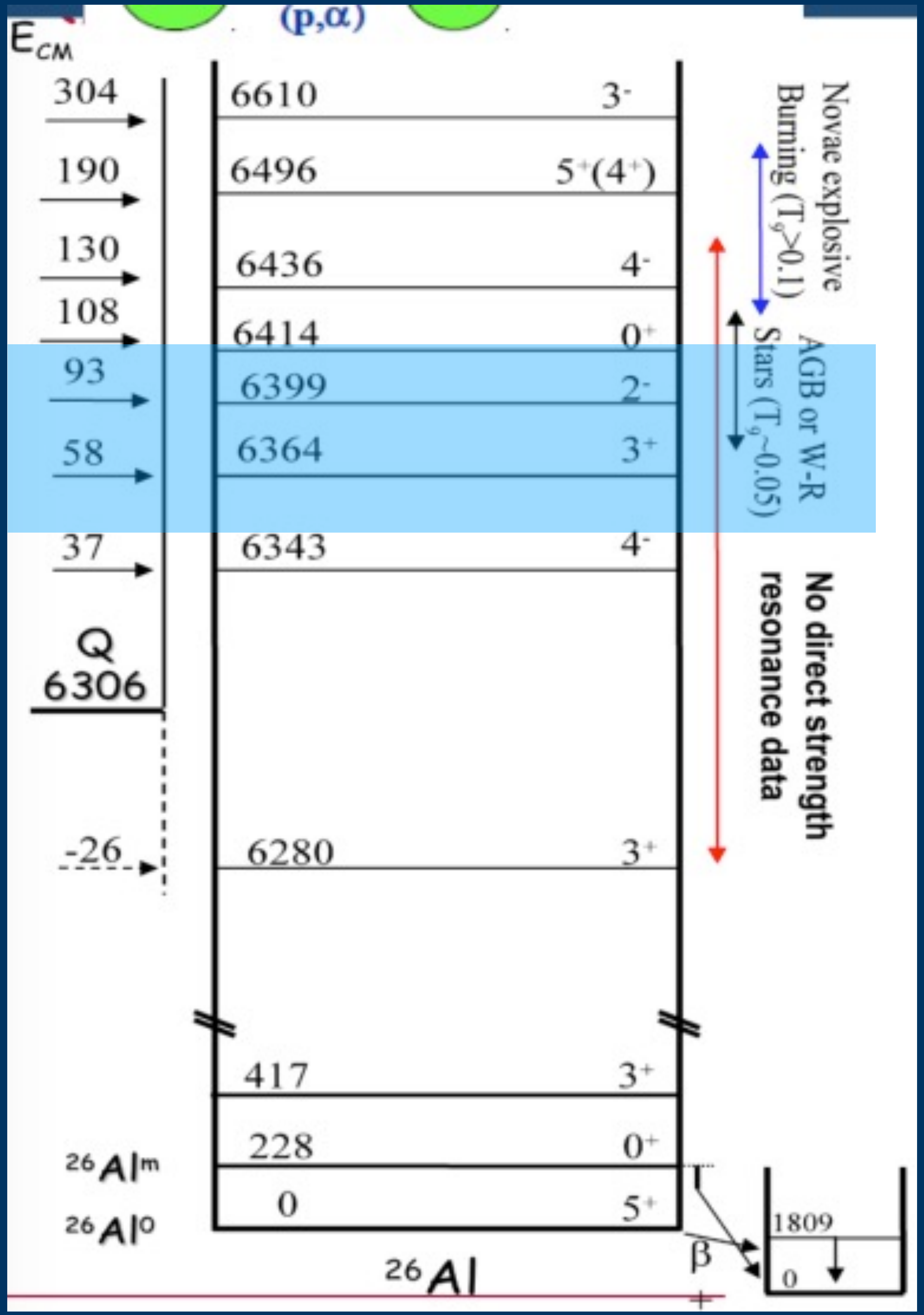
3 MV accelerator in SCU

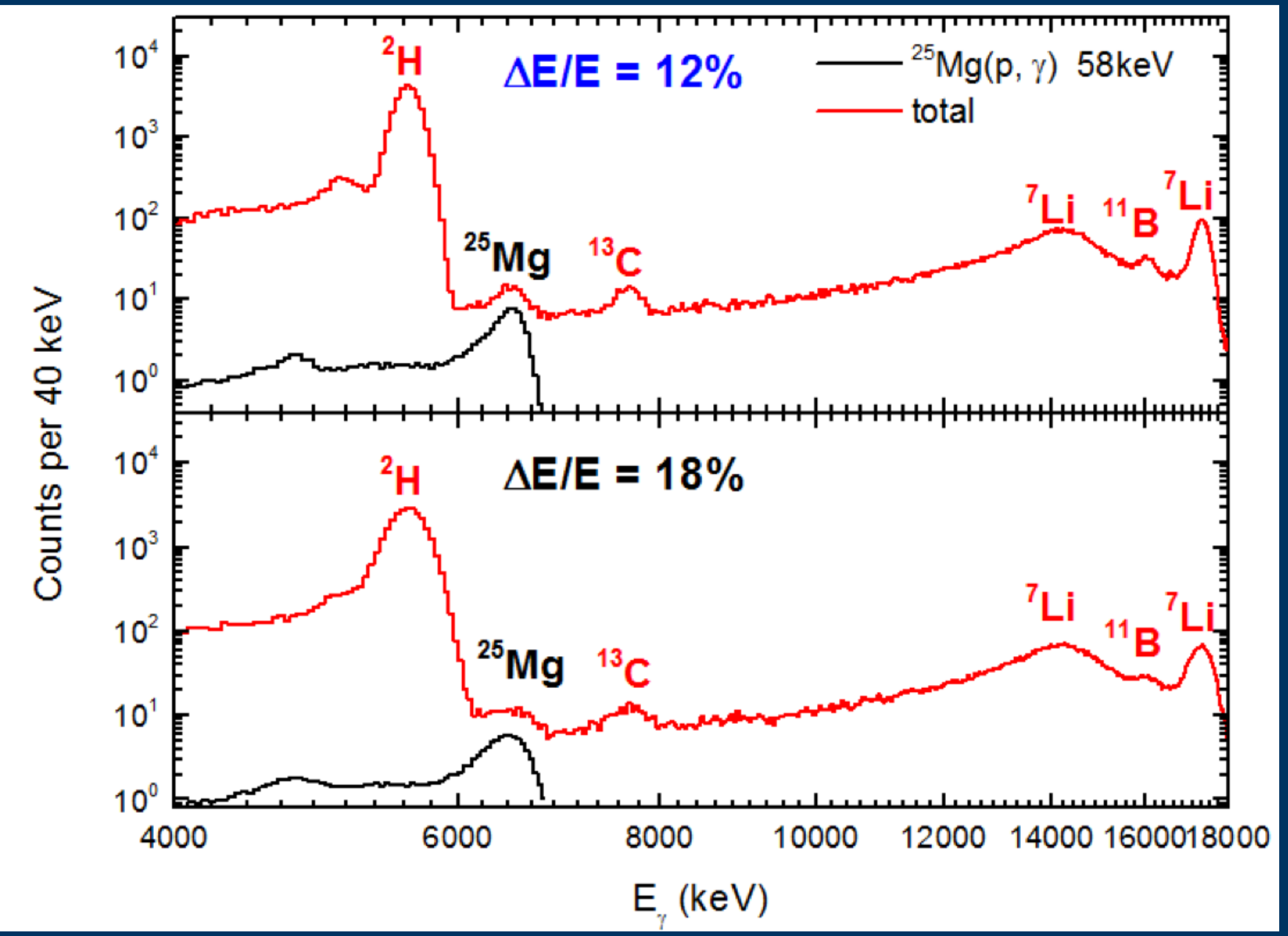
beam : He^{2+} , 5 euA

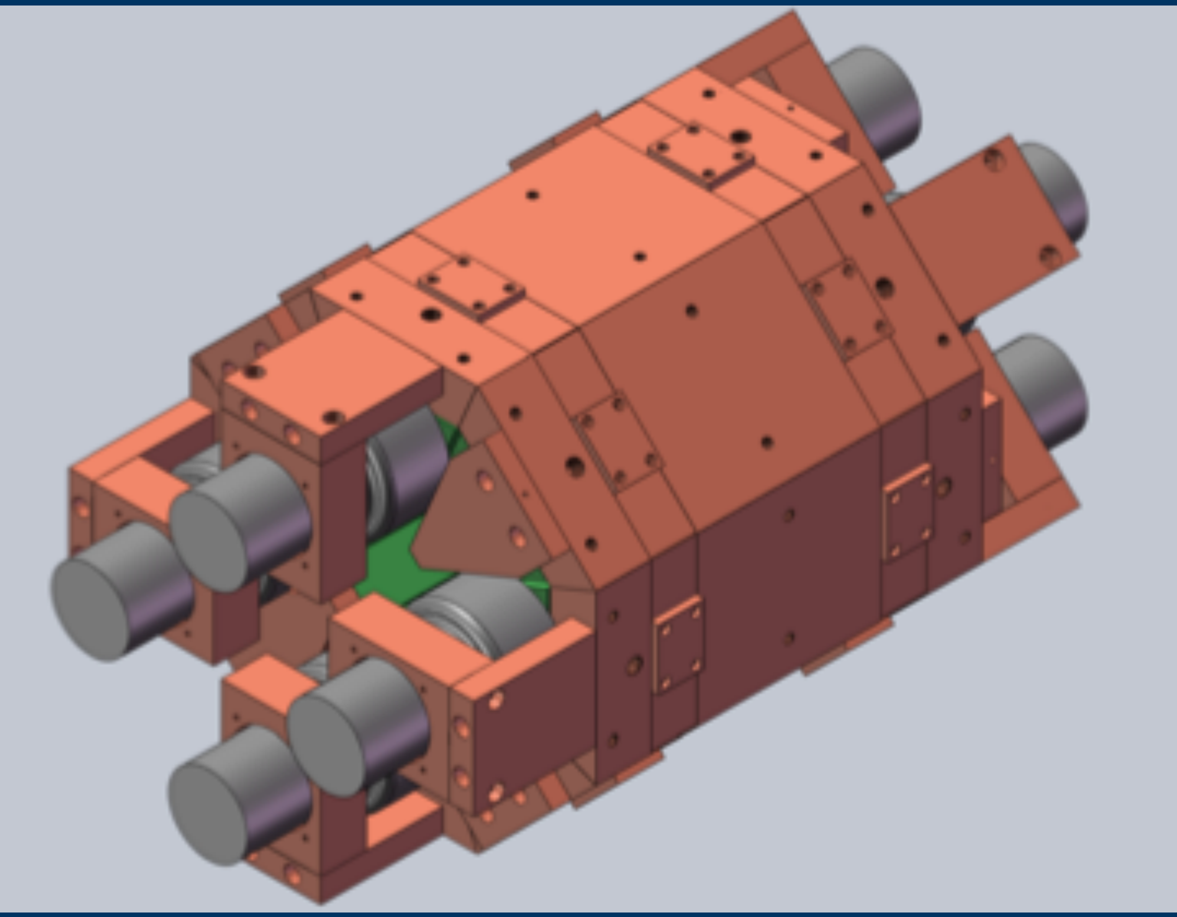
- two 175% rel. HPGe detector
- ^{12}C implanted target: thickness 1×10^{18} atoms/cm^2
- $E_{c.m.}$=2.42 MeV (3.23 MeV) E1 resonance (420 keV) , reaction rate 1 s^{-1}
- $E_{c.m.}$=2.69 MeV (3.59 MeV) E2 resonance (0.62 keV) , reaction rate 10 s^{-1}



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

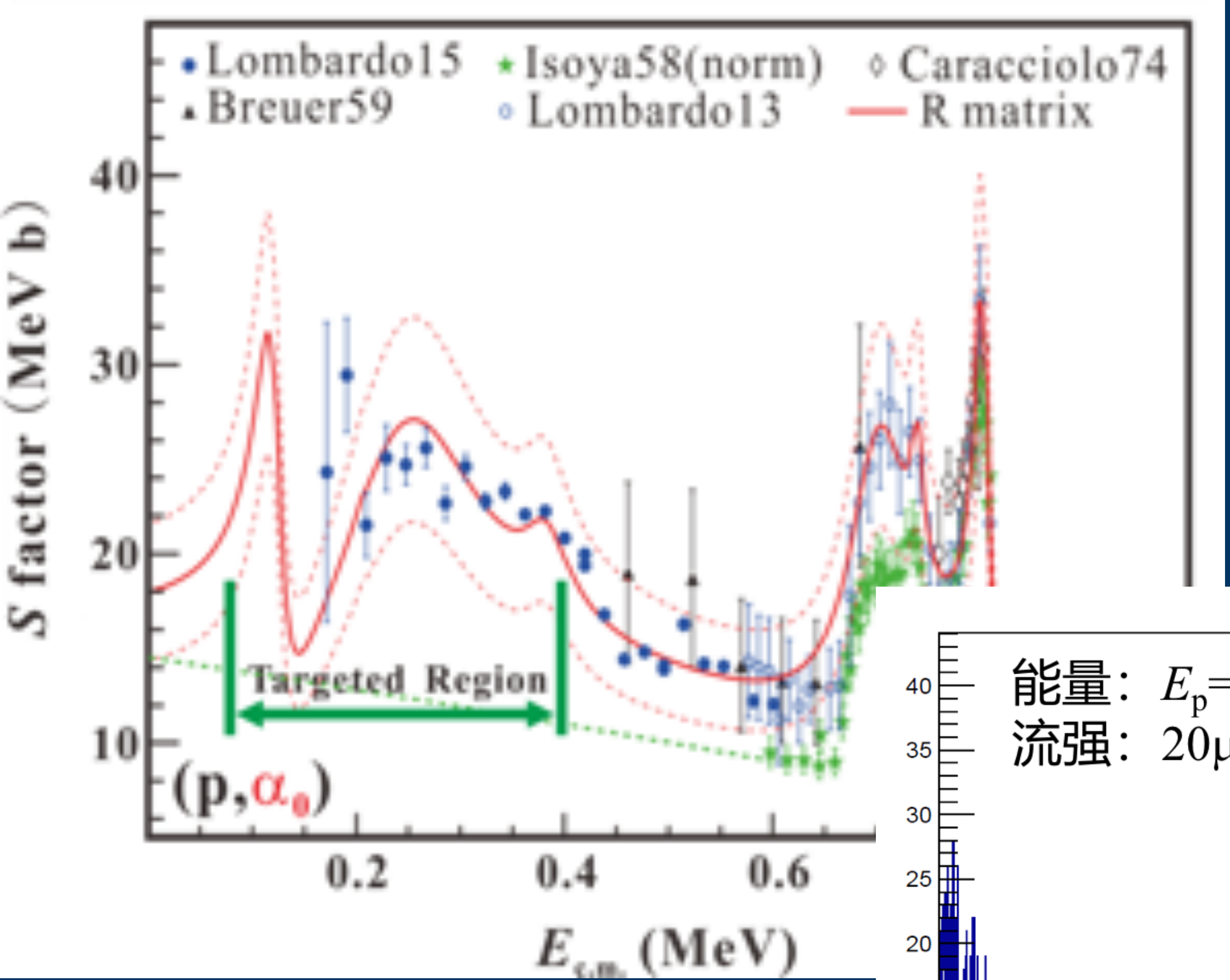


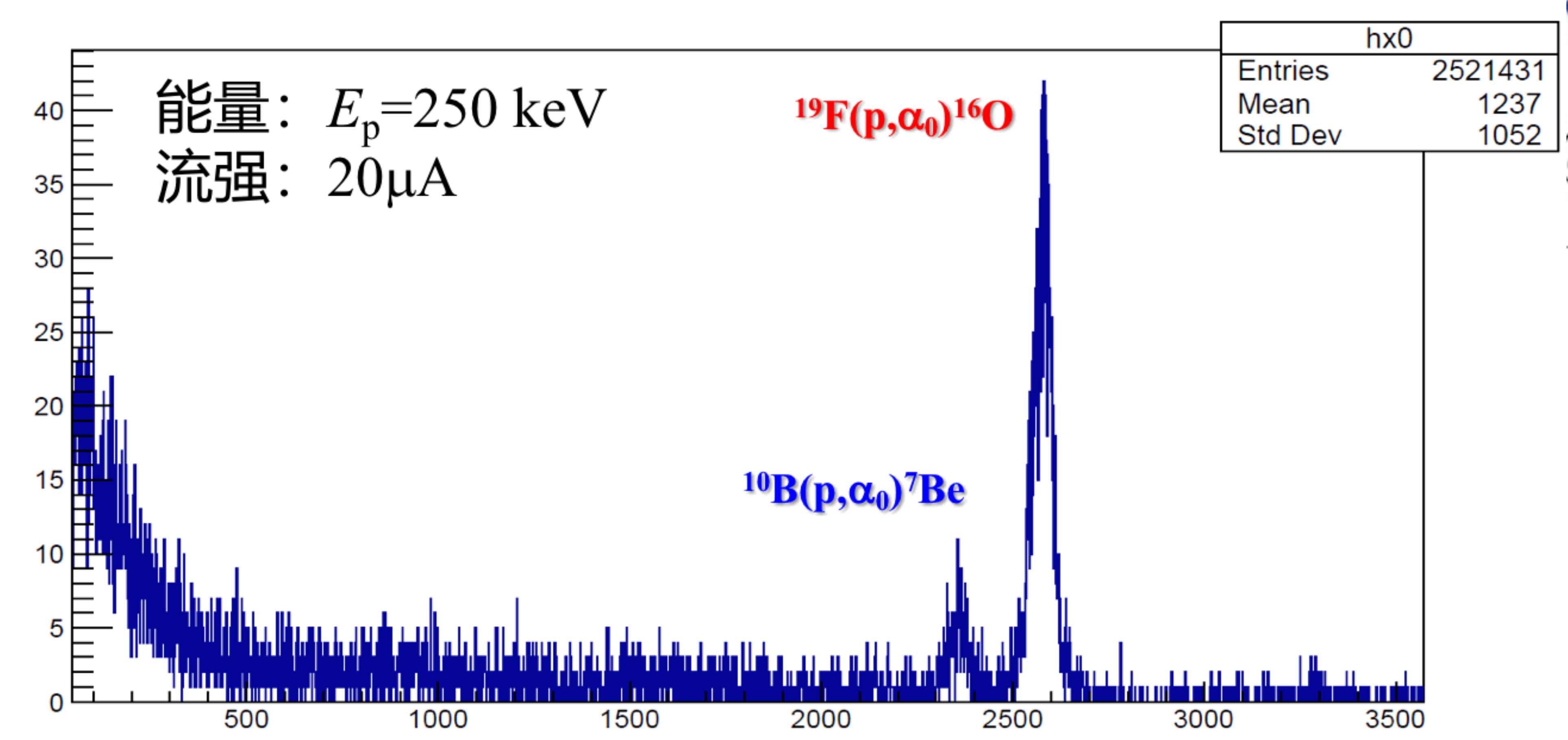


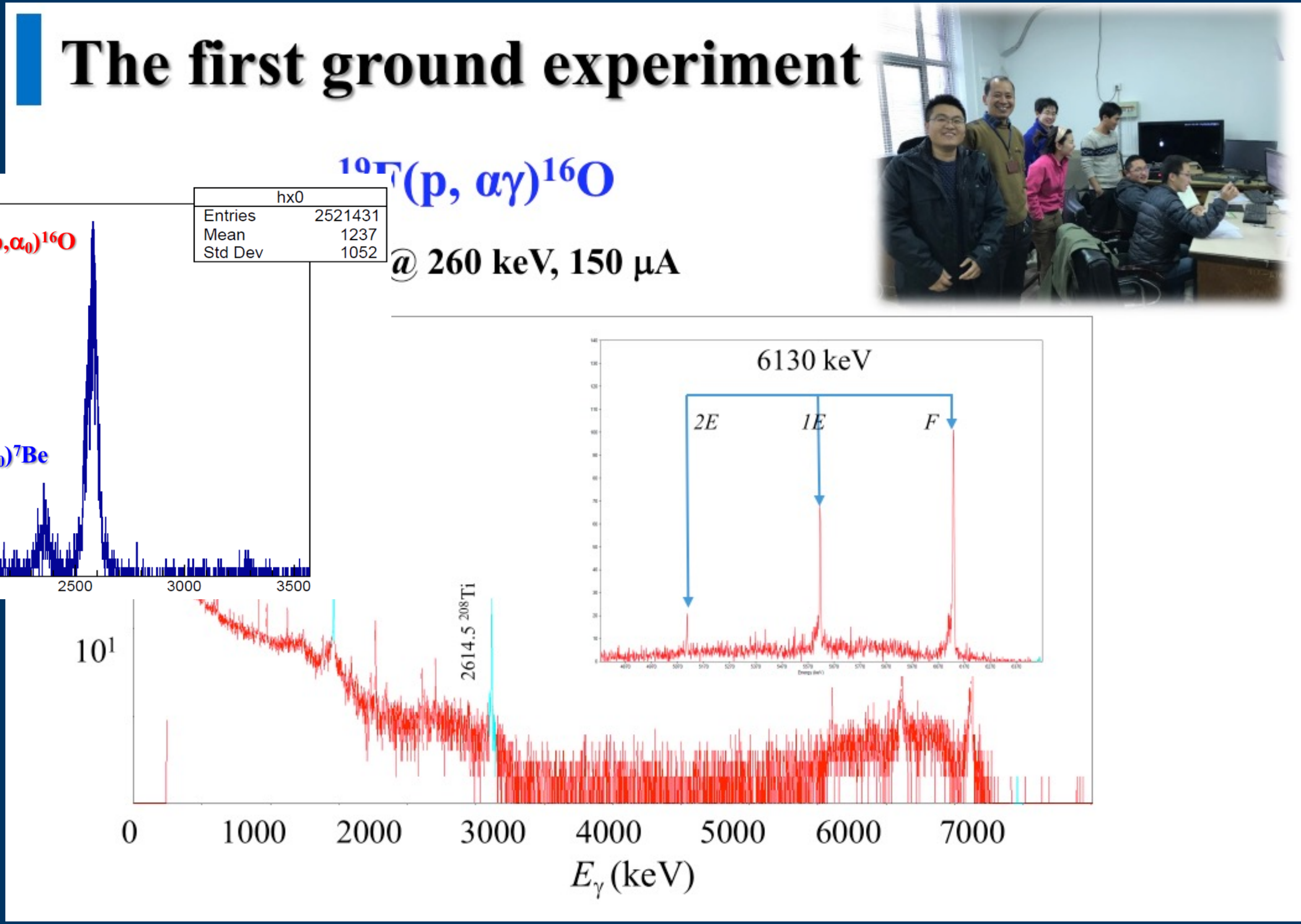


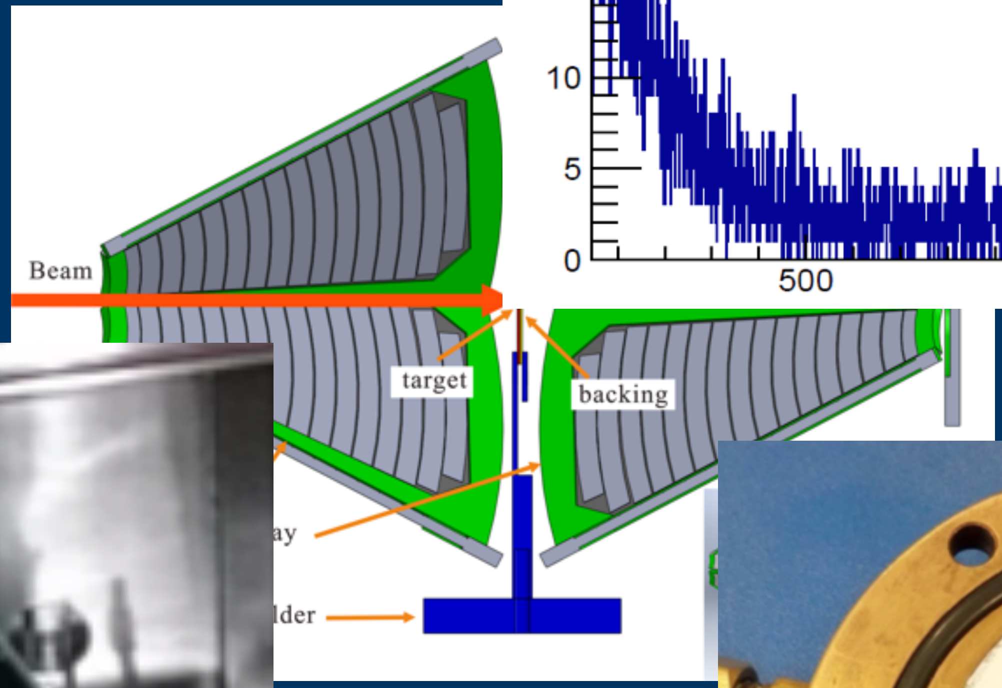
Z. H. Li et al., Sci. China Phys 58. 082002(2015).

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

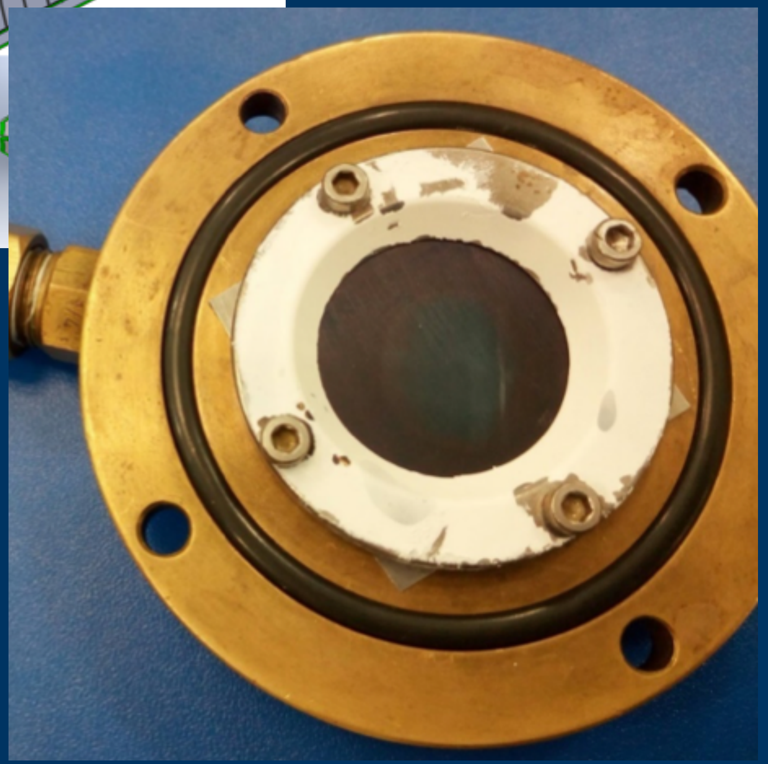








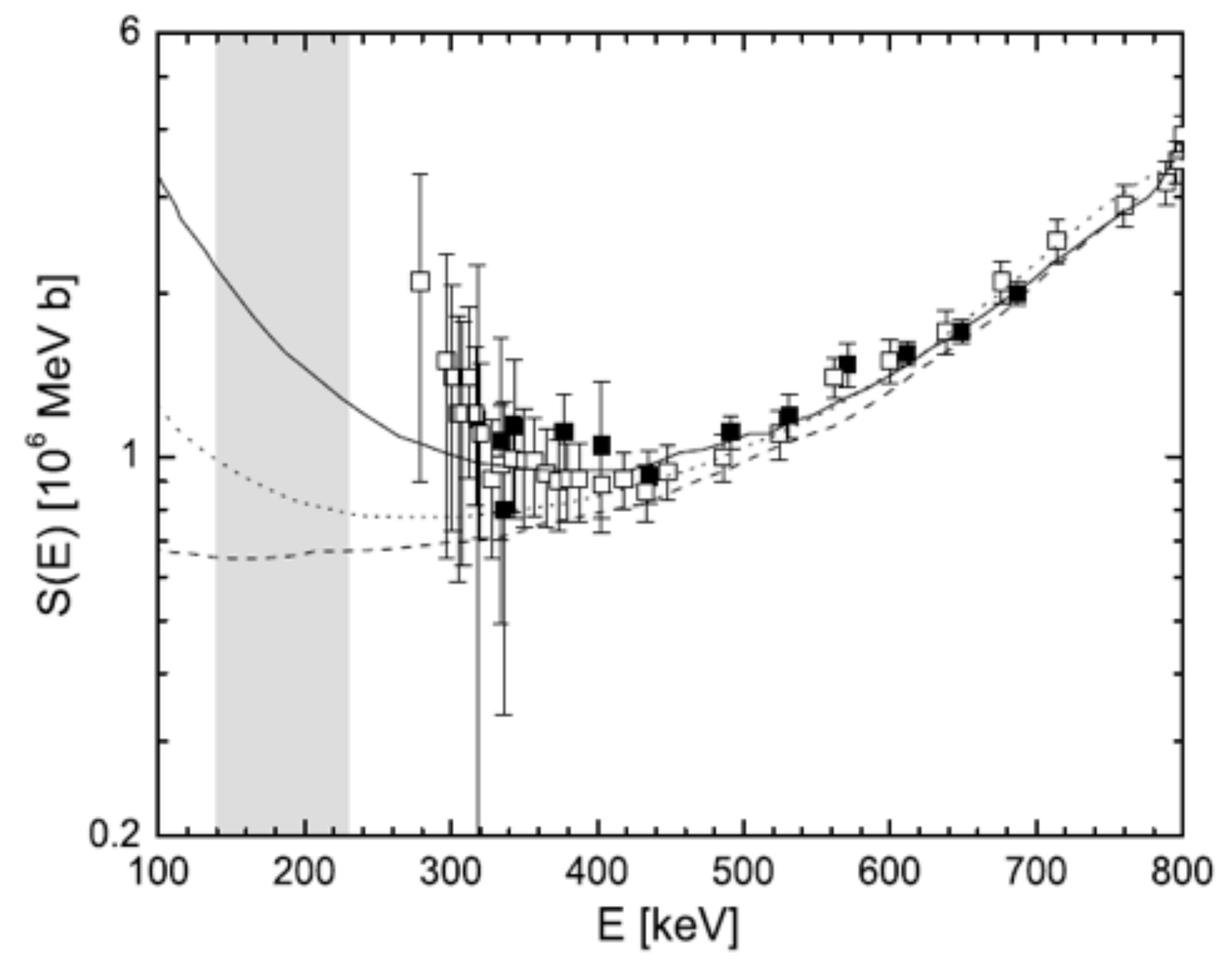
$^{19}F(p,\alpha_0)$ channel: Silicon Detectors

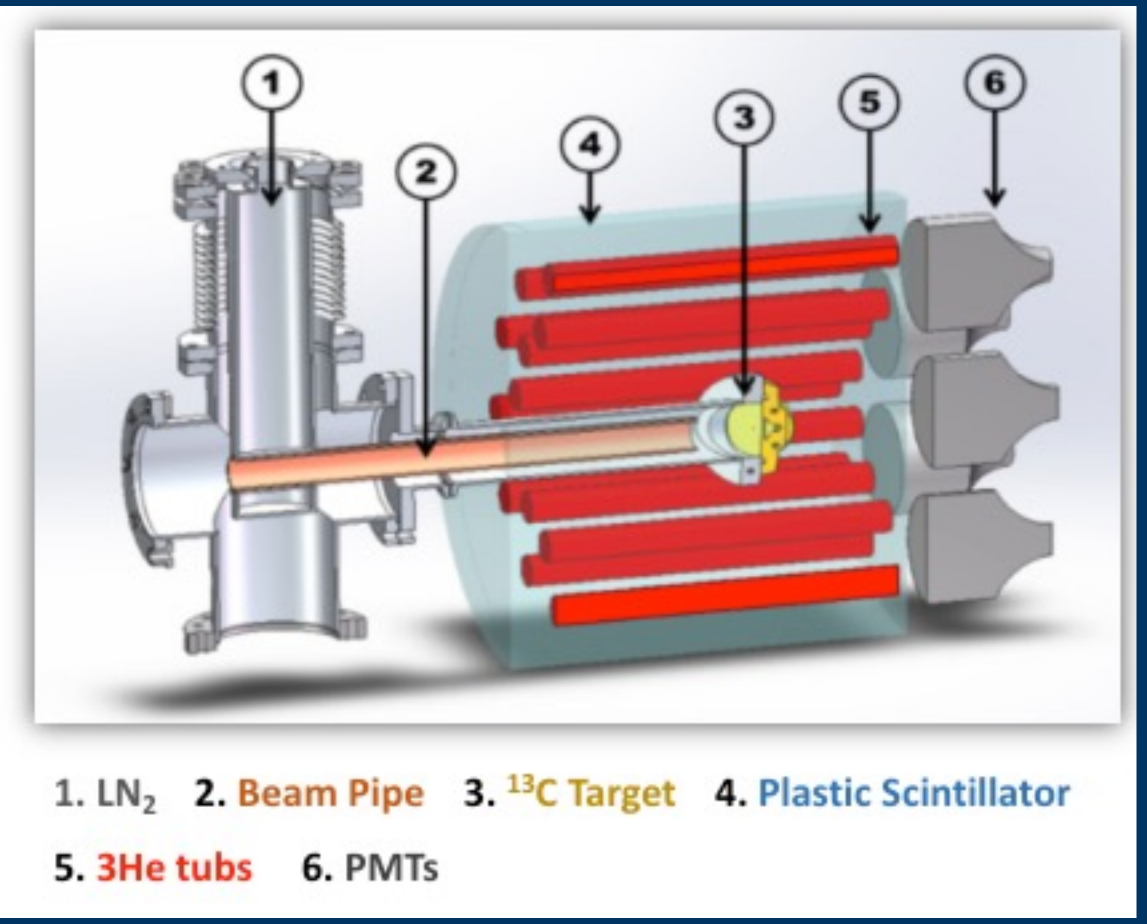


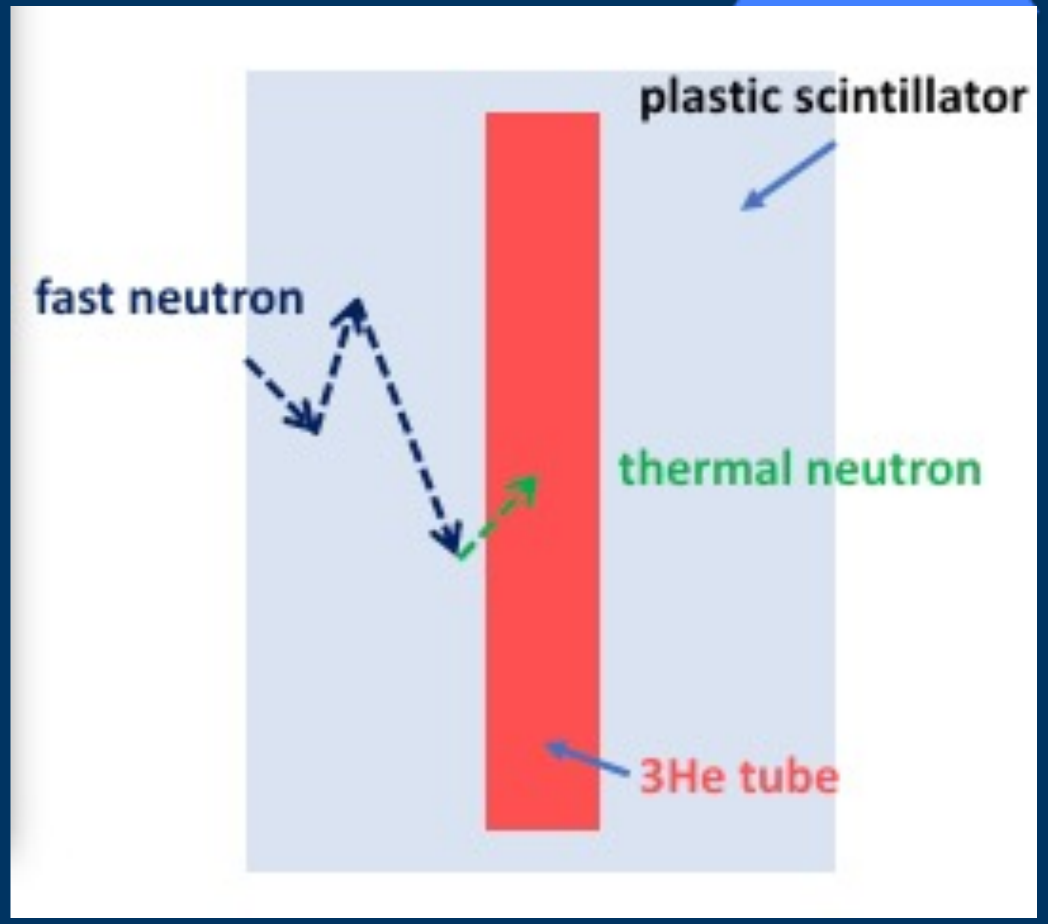
Stable under 1.5 C bombardment !

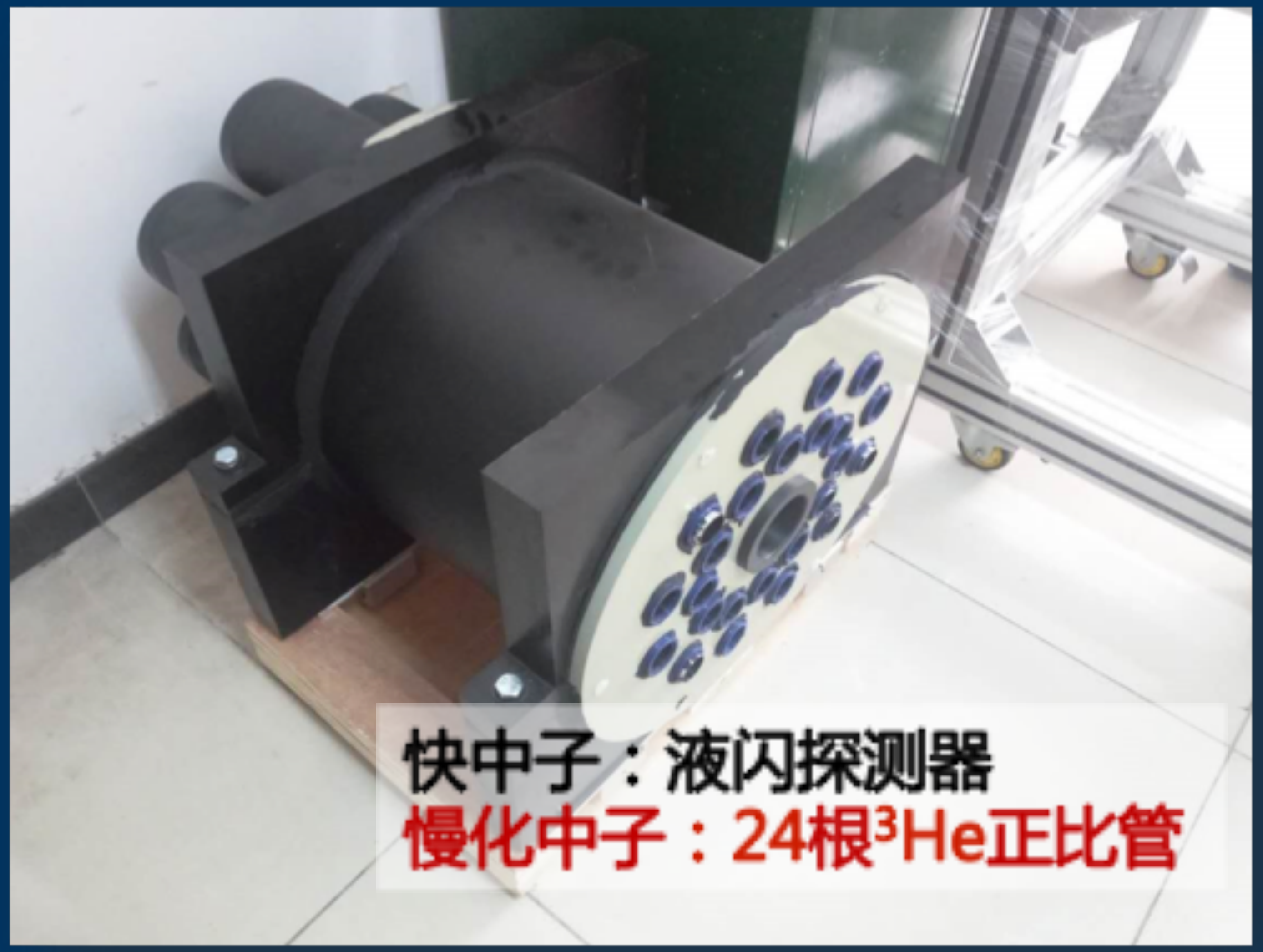
J. J. He et al., Sci. China Phys 59. 652001(2016

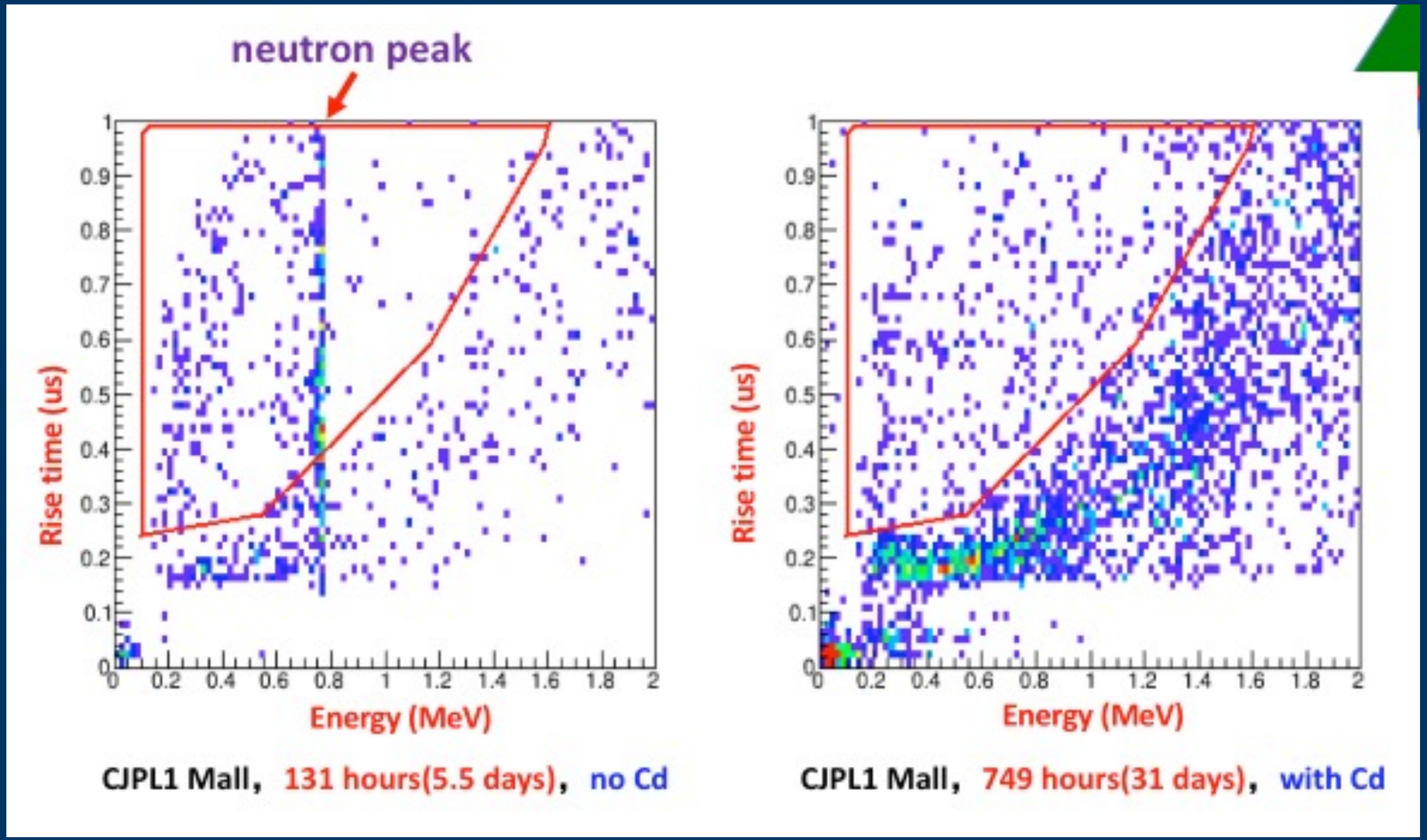
$^{13}C(\alpha,n)^{16}O$ status,





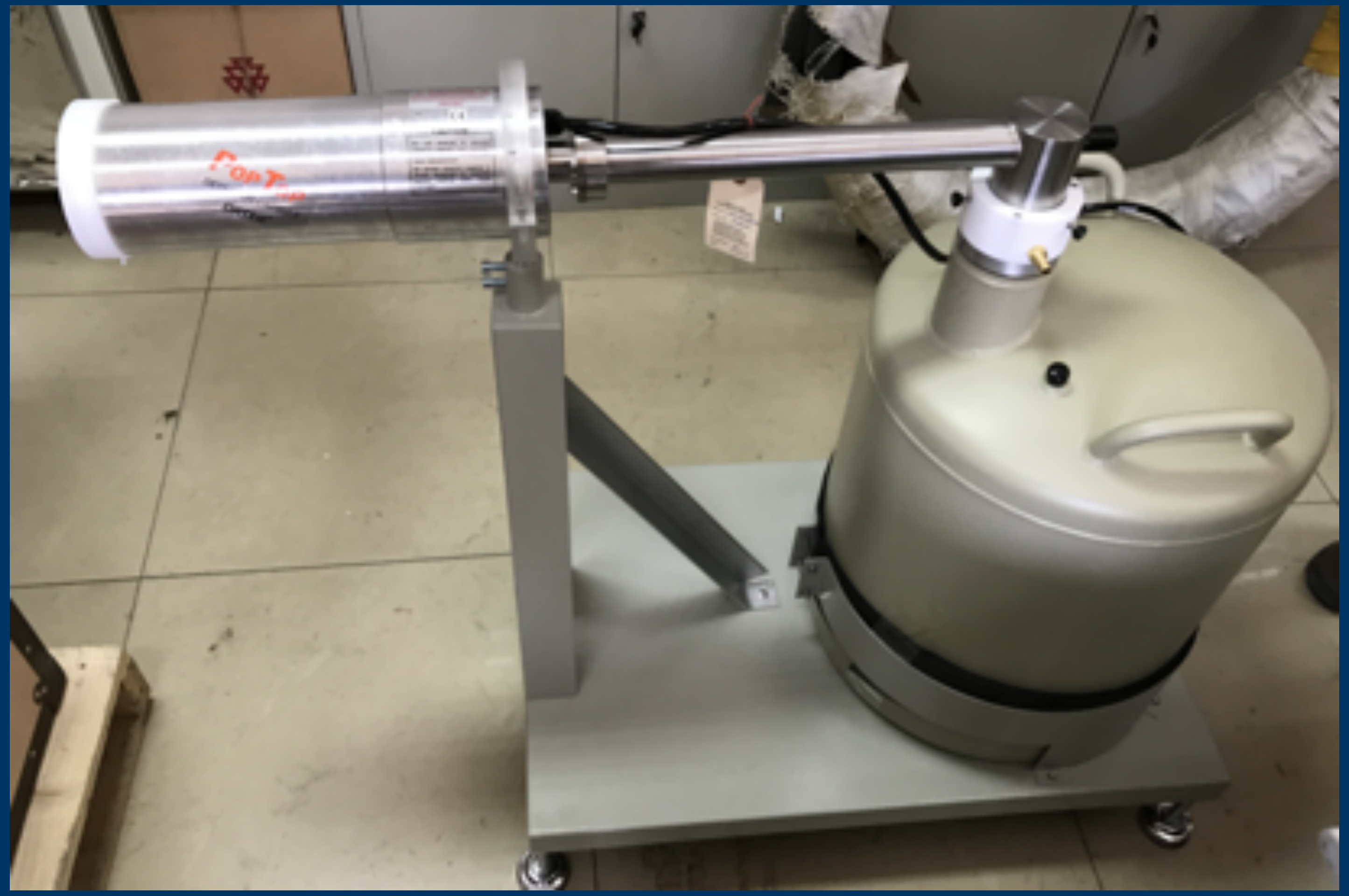


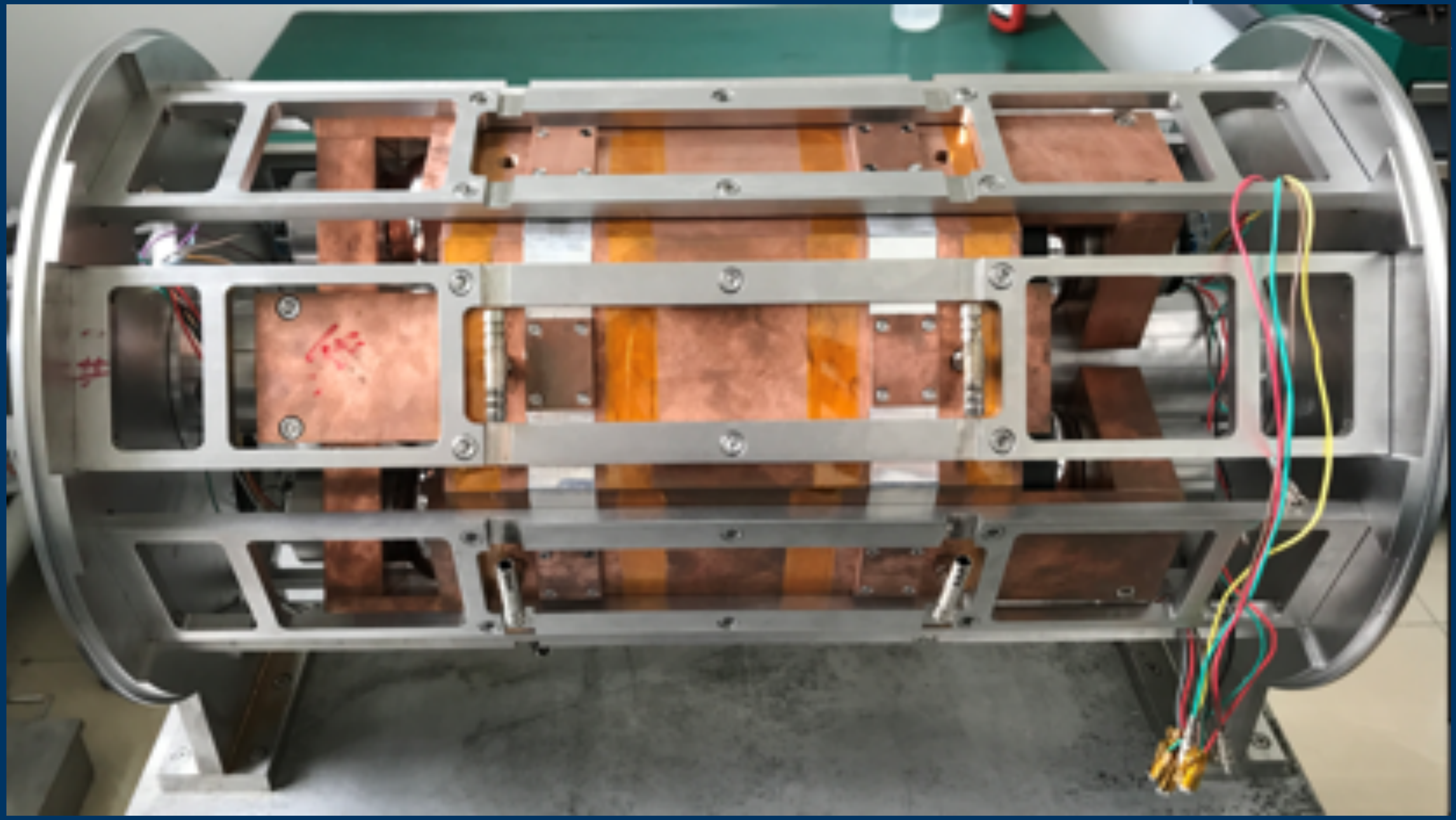




X. D. Tang

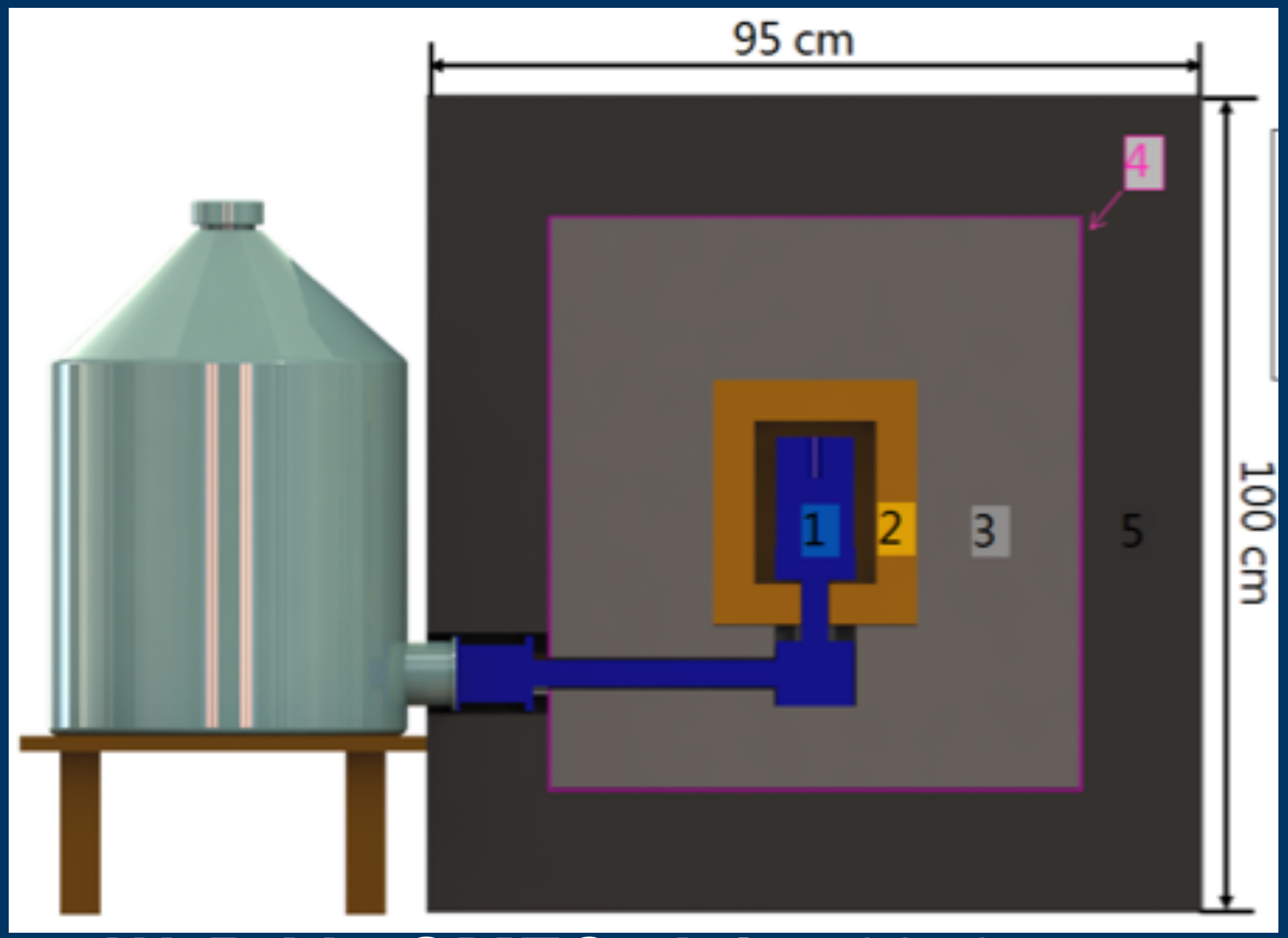
Detector status



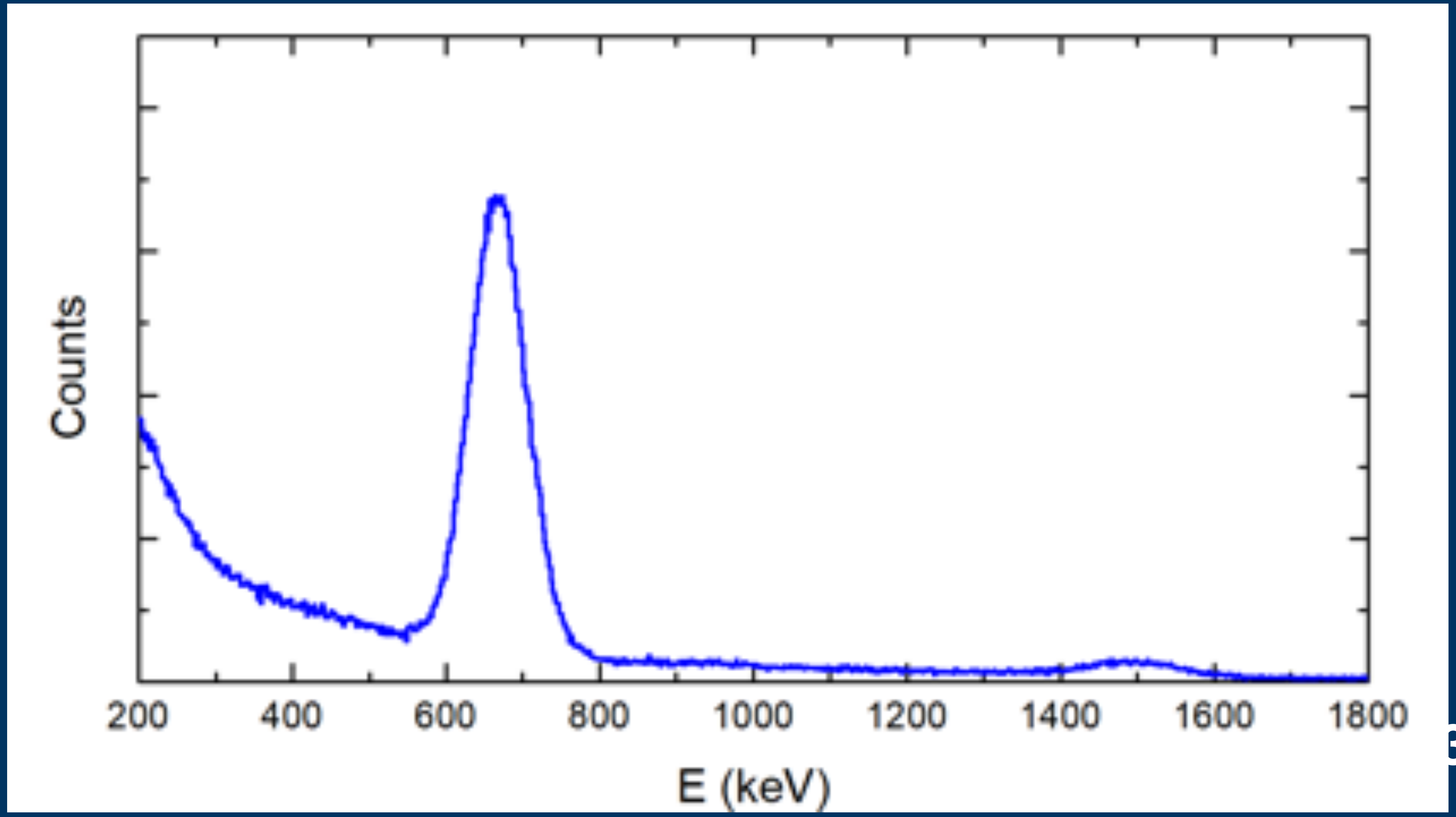


HPGe, ΔE = 2 keV@1332 keV;
ε = 0.8 % @7 MeV

BGO, ΔE/E = 13%@662 keV; ε = 60%@ 7 MeV

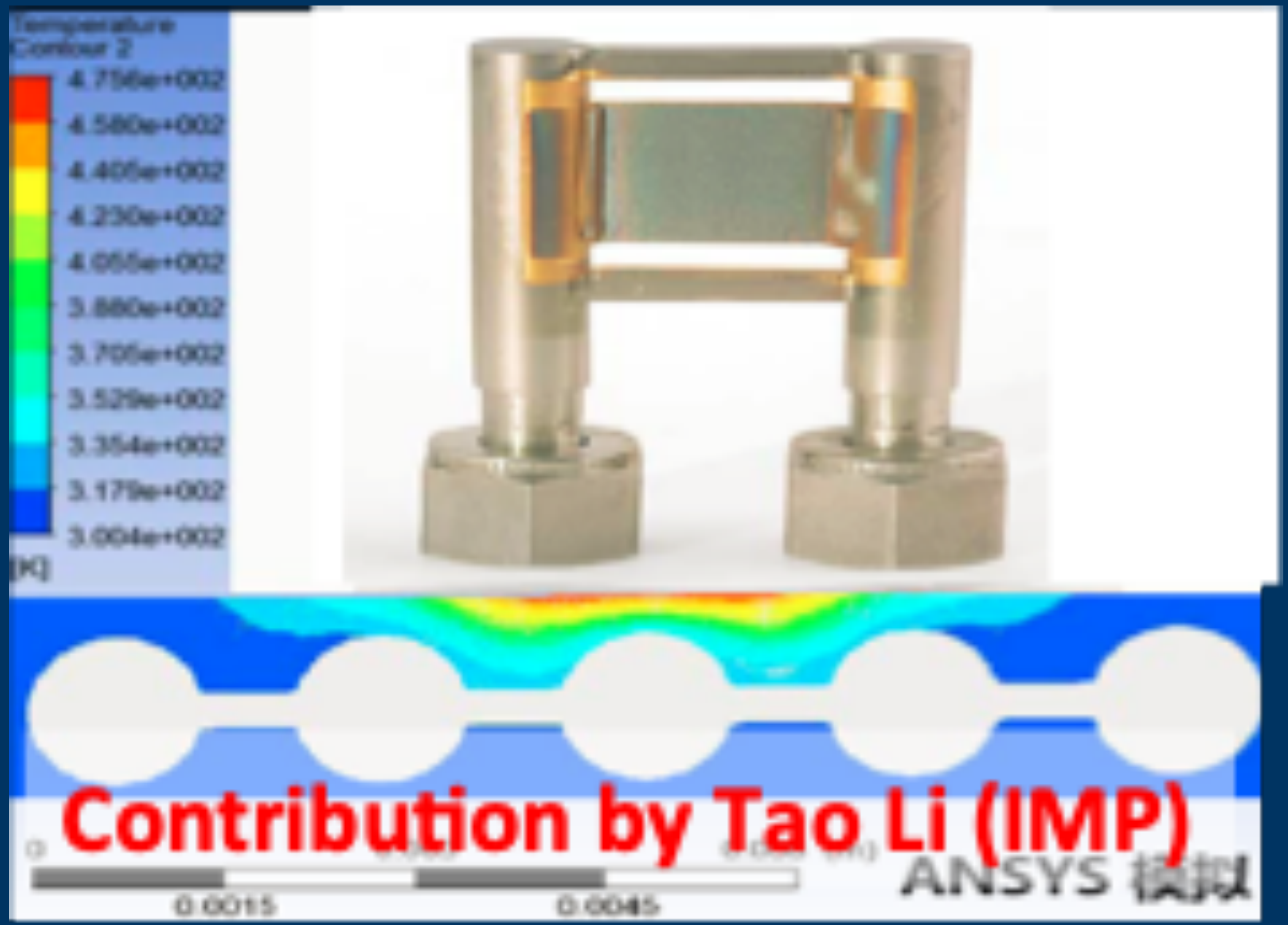


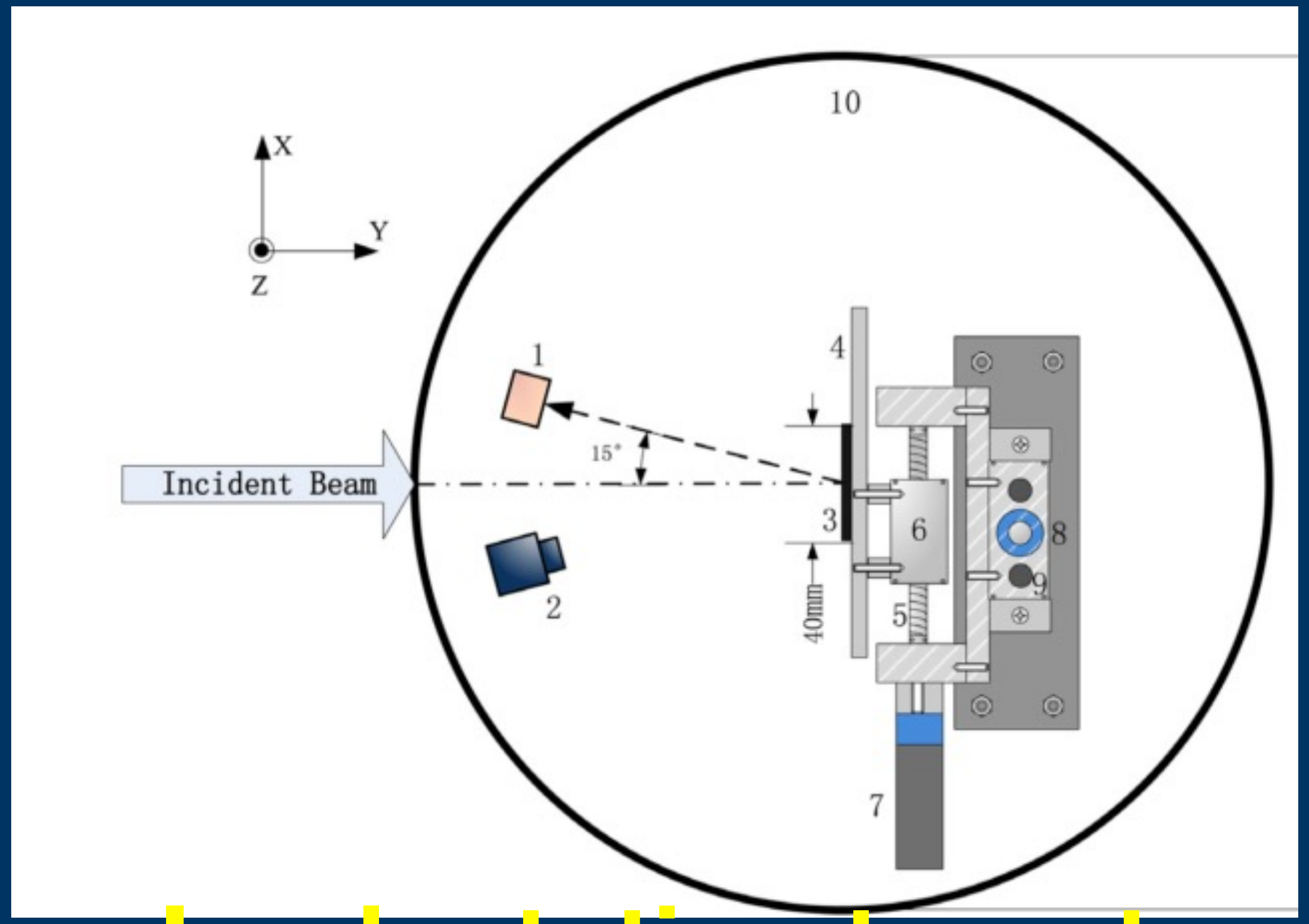
1. GWL-300-15
2. 5 cm oxygen-free copper
3. 20 cm lead
4. 1 mm Cr
5. 15 cm boron-doping polyethylene



Target and shielding,

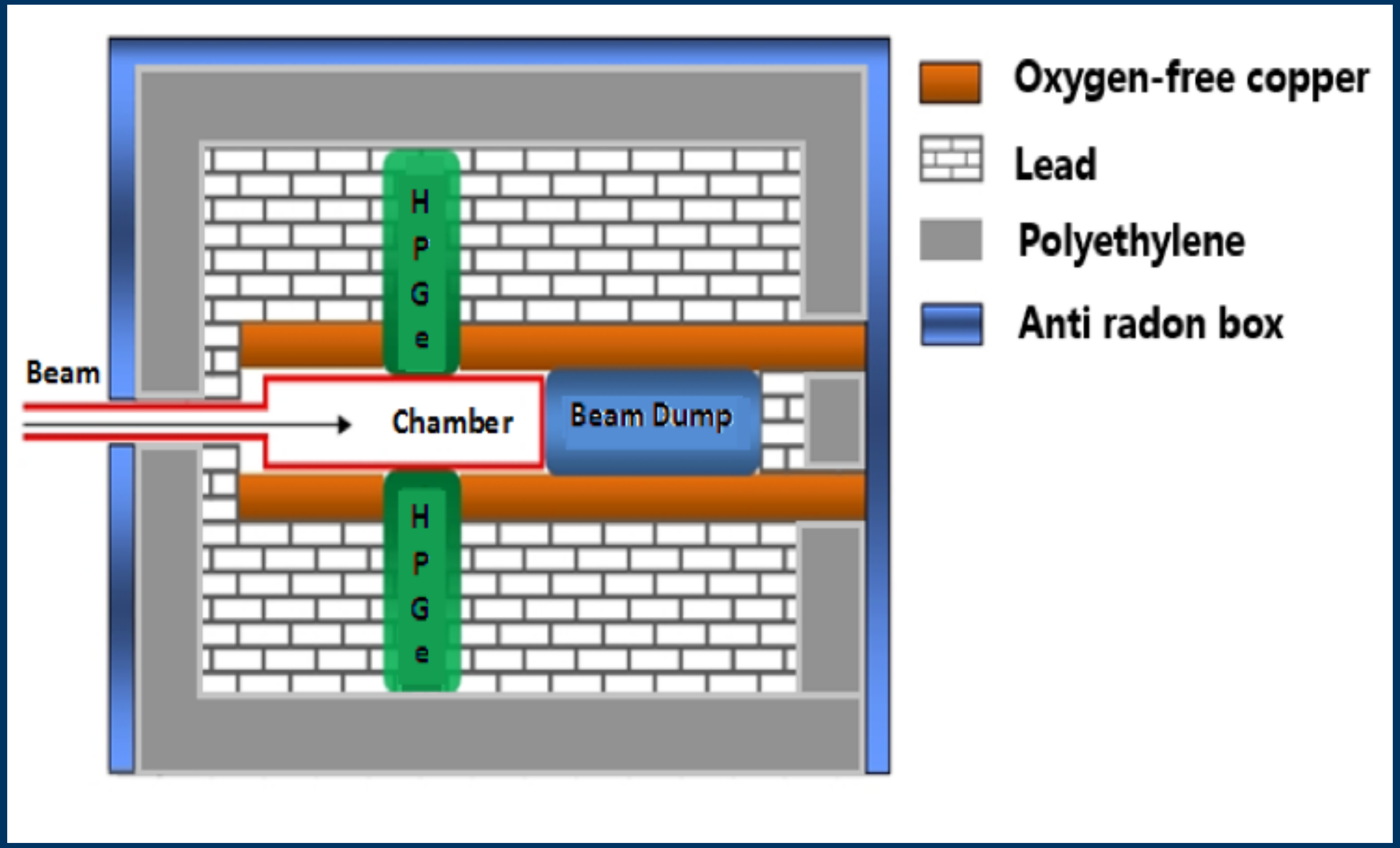
Y. J. Li

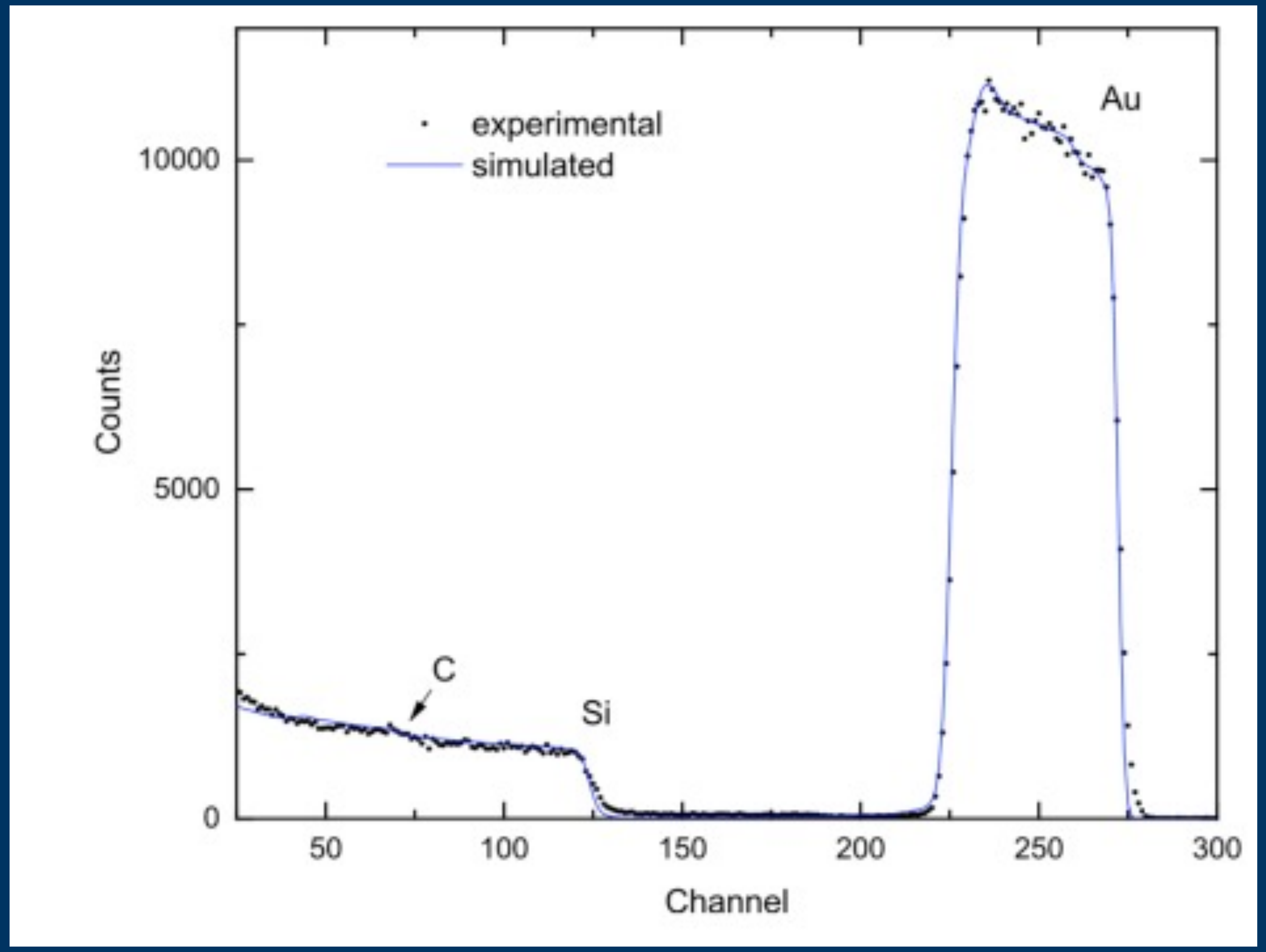




Implantation target analysis

Rotation target tested 30/8/16



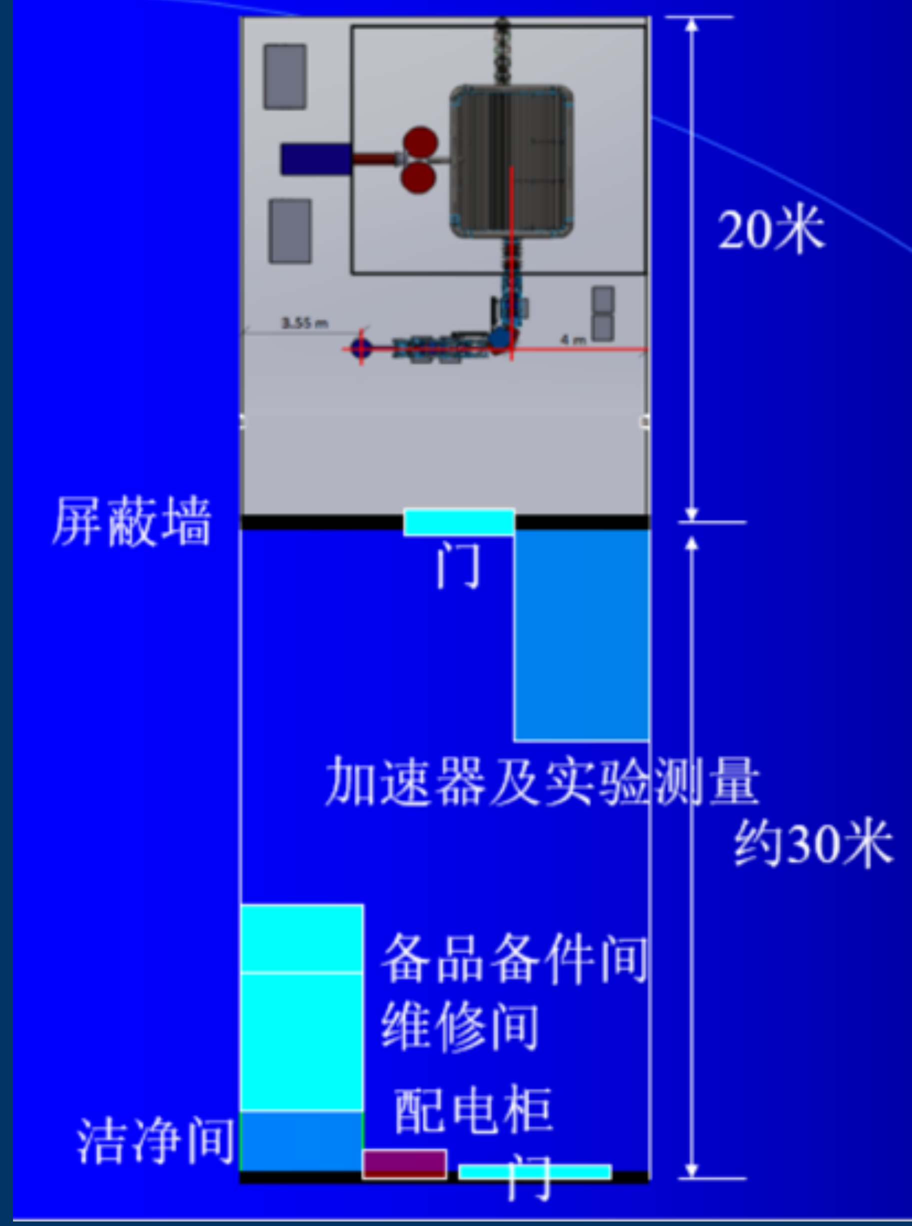


W. P. Liu OMEG, July , 2019

P. Wang et al., NIM A 902 (2018) 88–94

Lab construction

3D layout



特 急

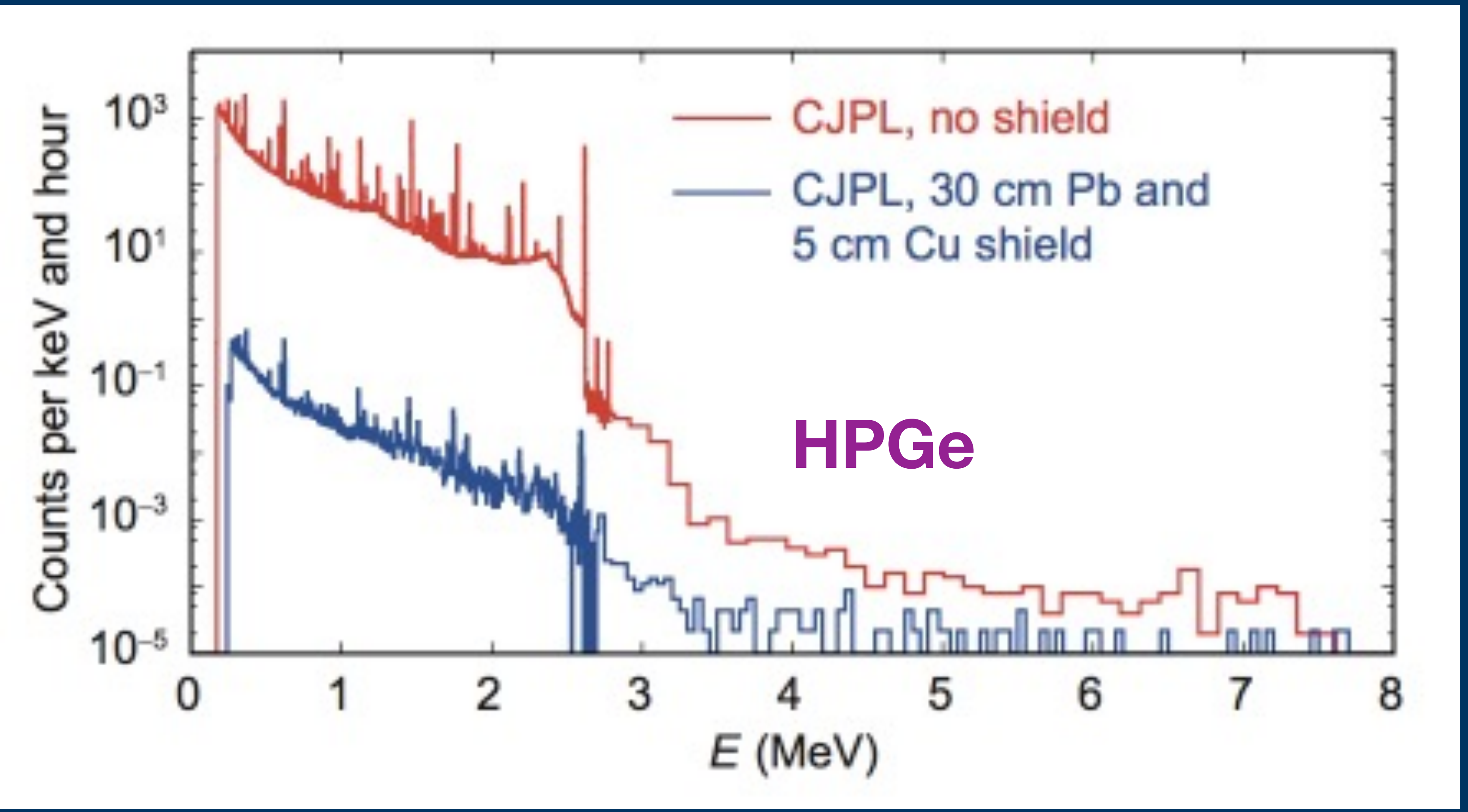
国家发展和改革委员会
教育部
科学技术部
财政部
中国科学院
中国工程院
国家自然科学基金委员会
国家国防科技工业局
中央军委装备发展部
文件

件成熟、前期准备工作充分的重大科技基础设施建设项目。"十三五"期间，优先项目包括：空间环境地基监测网（子午工程二期），大型光学红外望远镜，极深地下极低辐射本底前沿物理实验设施，大型地震工程模拟研究设施，聚变堆主机关键系统综合研究设施，高能同步辐射光源，硬 X 射线自由电子激光装置，多模态跨尺度生物医学成像设施，超重力离心模拟与实验装置，高精度地基授时系统。

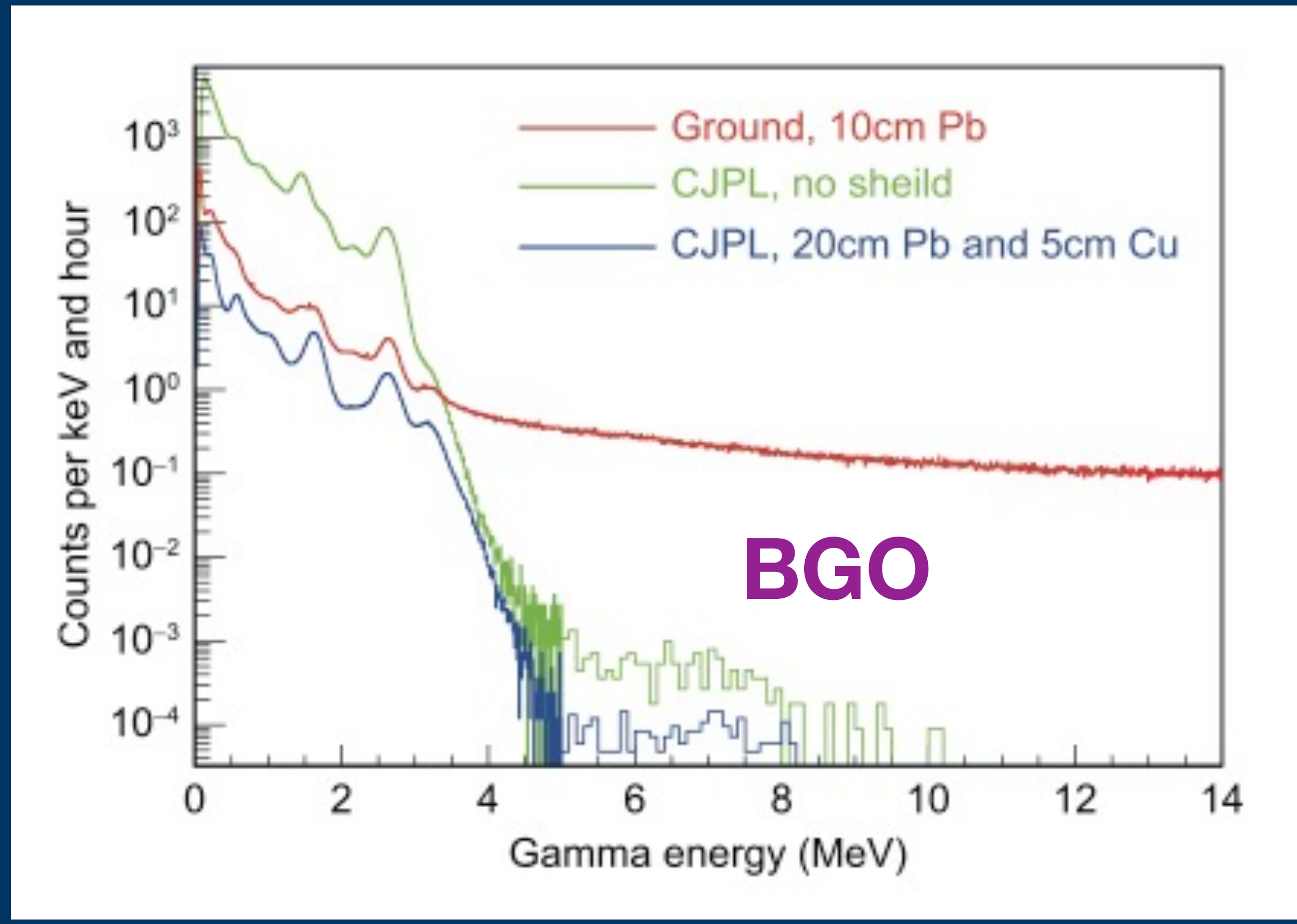
Nov. 11, 2017, MOU with Yalong Co.

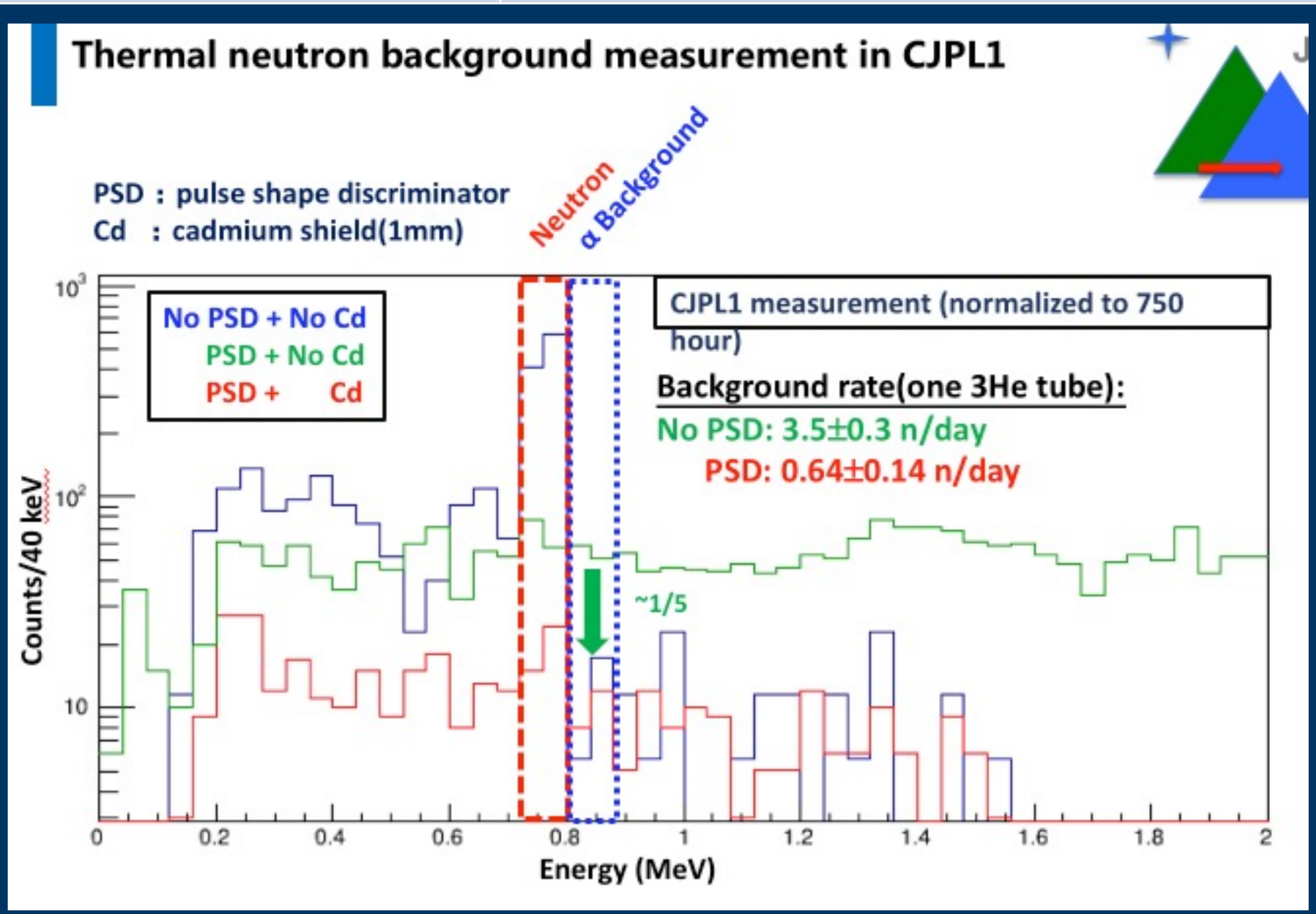
- **Under design, start construction end of 2018, part of National science plan**

HPGe and BGO background in CJPL-I 2016



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





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

JUNA

Period/Task	Accelerator	Laboratory	Experiment
2015 Q1-Q2	design, layout	layout	simulation, physics
2015 Q3-Q4	parts fabrication	on site study	background, test
2016 Q1-Q2	ion source, tube	design	background, prototype
2016 Q3-Q4	assemble	detailed design	target test
2017 Q1-Q2	beam on ground	design	fabrication
2018	ground tuning	construction	ground test
2019	underground	shield setup	ground experiment
2020		new detector layout	^{19}F(p,α)^{16}O, ^{25}Mg(p,γ)^{26}Al
2021	$^{2+}$He ion source		^{13}C(α,n)^{16}O, ^{12}C(α,γ)^{16}O
2022			^{12}C(α,γ)^{16}O

Future milestone

JUNA

2019

June
Ground experiment finished

December
Accelerator to underground

2020

June
Accelerator beam underground

September
^{17}F data & NIC2020

December
^{25}Mg data, ^{13}C start to underground

2021

June
^{13}C data ^{12}C start

December
Project commission

JUNA expectation

reaction	beam	inten. (emA)	Ec.m. (keV)	cross section (mb)	target atoms/cm^2	eff. %	CTS (/day)	BKD (/day)
$^{12}C(\alpha,\gamma)^{16}O$	$^4He^{2+}$	2.5	380	10^{-13}	10^{18}	75	0.7	0.7
$^{13}C(\alpha,n)^{16}O$	$^4He^{1+}$	10	200	10^{-12}	10^{21}	20	7	1
$^{25}Mg(p,\gamma)^{26}Al$	$^1H^{1+}$	10	58	$\omega\gamma$ 2.1×10^{-13} eV	0.6 μg/cm^2	38	1.4	0.7
$^{19}F(p,\alpha)^{16}O$	$^1H^{1+}$	0.1	100	7.2×10^{-9}	4 μg/cm^2	75	27	0.7

reaction	physics	current limit (keV)	precision (%)	ref.	JUNA limit (keV)	Gamow energy (keV)	precision (%)
$^{12}C(\alpha,\gamma)^{16}O$	Massive star	890	60	[17]	380	220-380	test
$^{13}C(\alpha,n)^{16}O$	HI synthesis	279	60	[18]	200	140-230	20
$^{25}Mg(p,\gamma)^{26}Al$	Galaxy ^{26}Al	92	20	[13]	58	50-300	15
$^{19}F(p,\alpha)^{16}O$	F abundance	189	80	[19]	100	50-350	10

JUNA road map

400 kV
p, α, 1-10 pmA
2019-

4 MV
^{12}C, ^{16}O, 0.1-1 mA
2022-

Underground wish list

JUNA

H 燃烧

$^{3}He(\alpha,\gamma)^{7}Be$

$^{2}H(\alpha,\gamma)^{6}Li$

$^{3}He(^{3}He,2p)^{4}He$

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

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

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

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

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

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

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

He 燃烧

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

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

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

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

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

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

中子源

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

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

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

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

C, O 燃烧

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

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

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

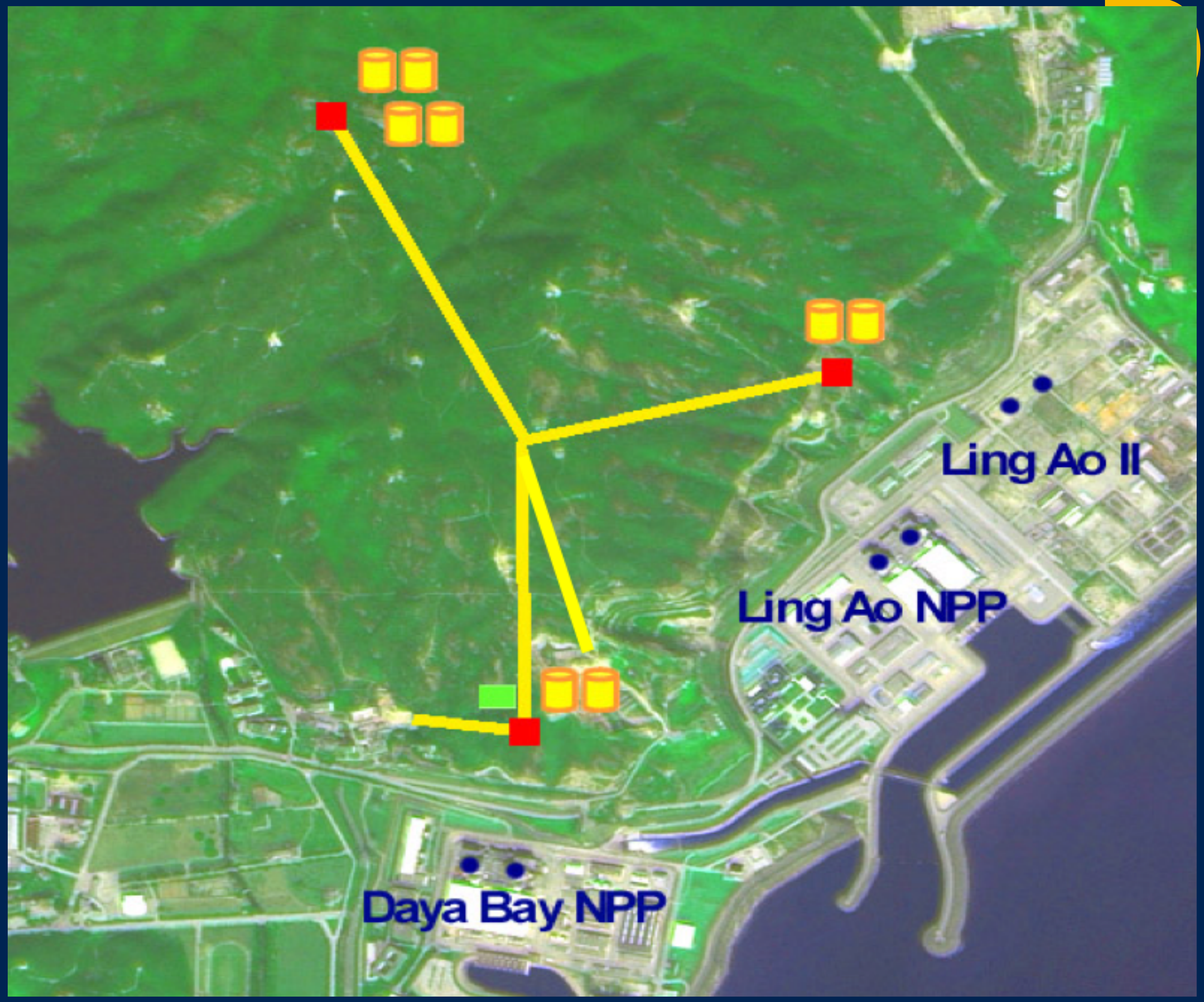
γ 天文学

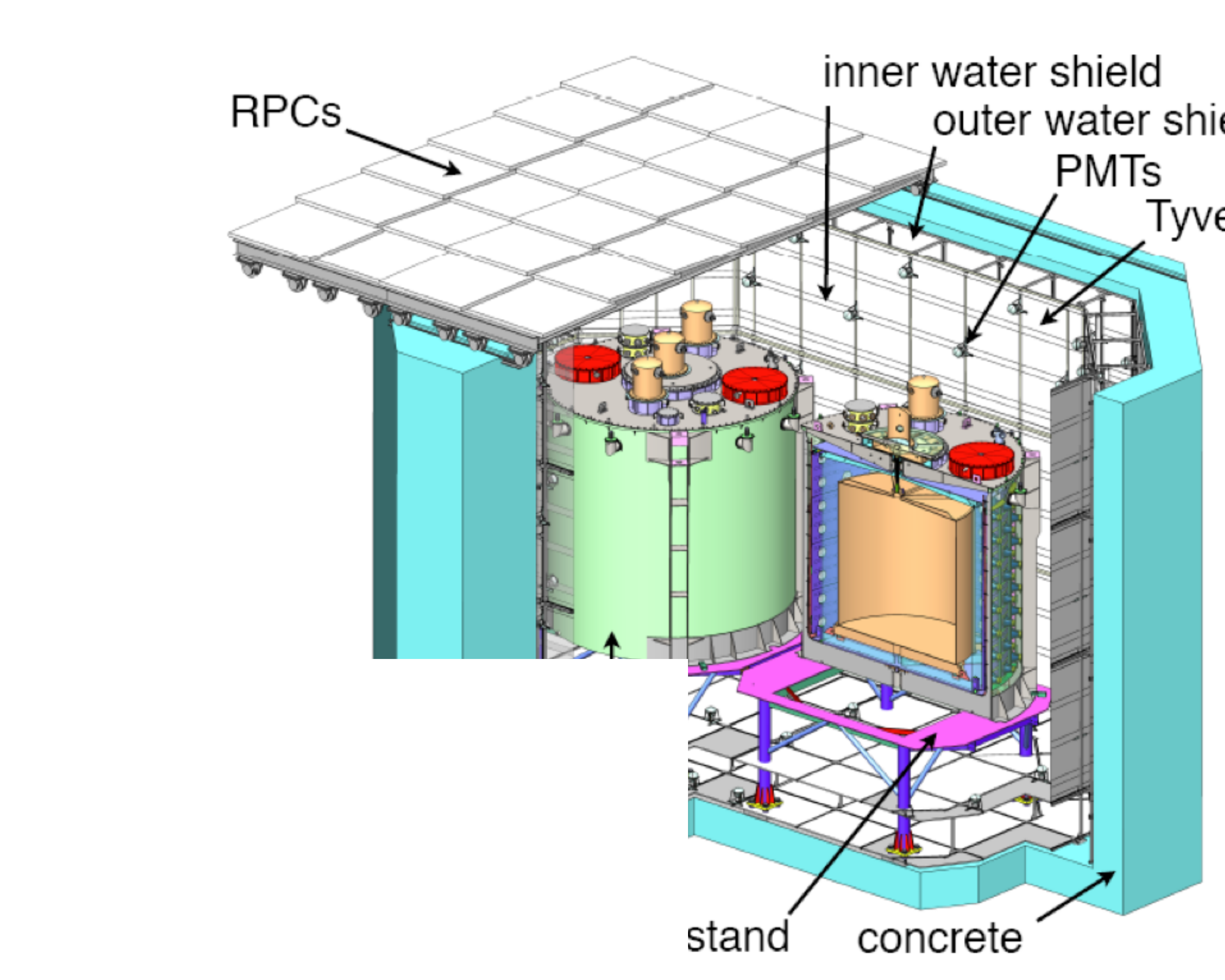
$^{25}Mg(p,\gamma)^{26}Al$ ：

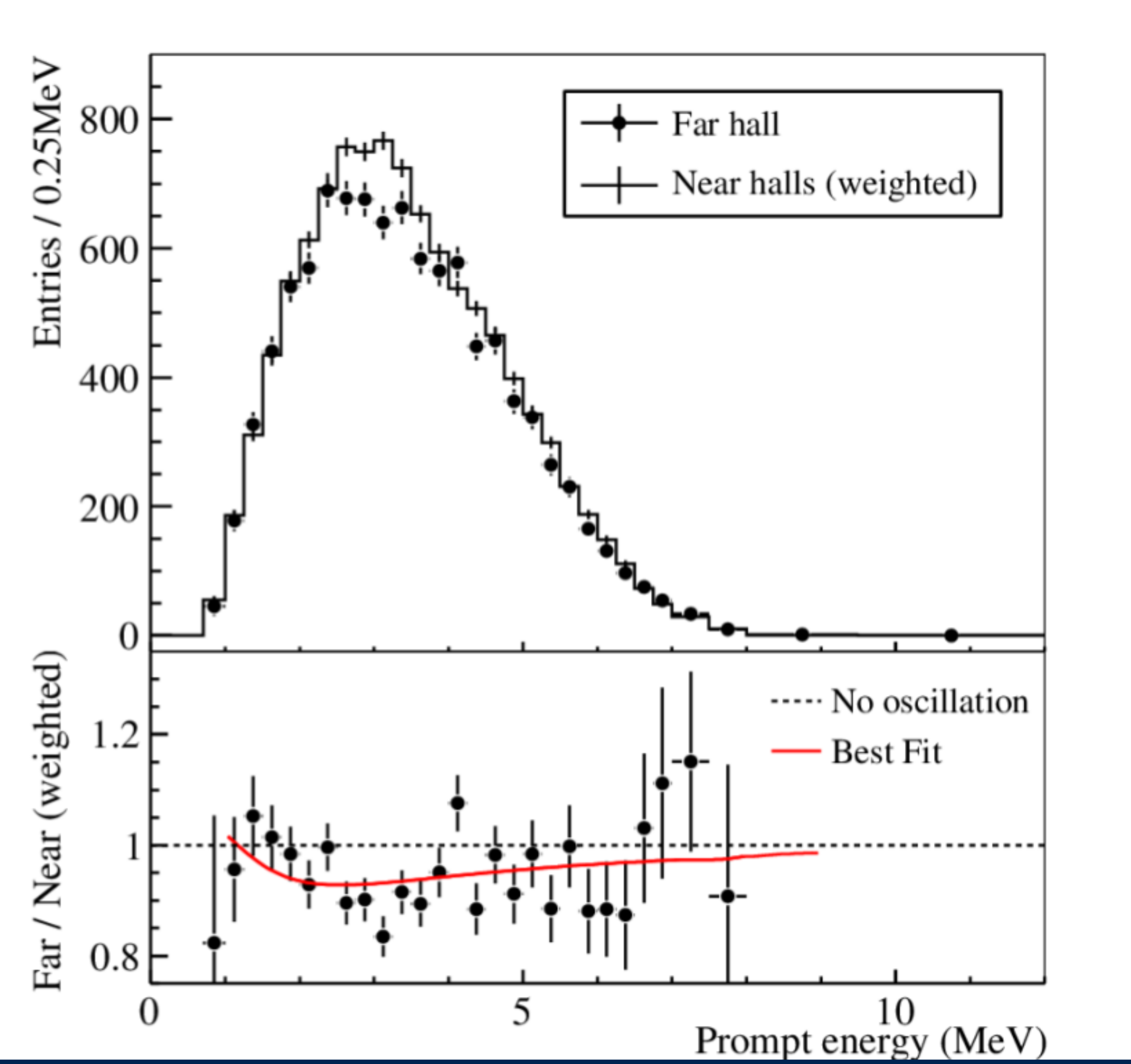
JUNA-I

JUNA-II

Daya Bay experiment







Summary

- Electron anti-neutrino disappearance is observed at Daya Bay,

  R = 0.940 ±0.011 (stat) ±0.004 (syst),

  together with a spectral distortion
- A new type of neutrino oscillation is thus discovered

$\text{Sin}^2 2\theta_{13}$=0.092± 0.016 (stat)±0.005(syst)
χ^2/NDF = 4.26/4
5.2 σ for non-zero θ_{13}

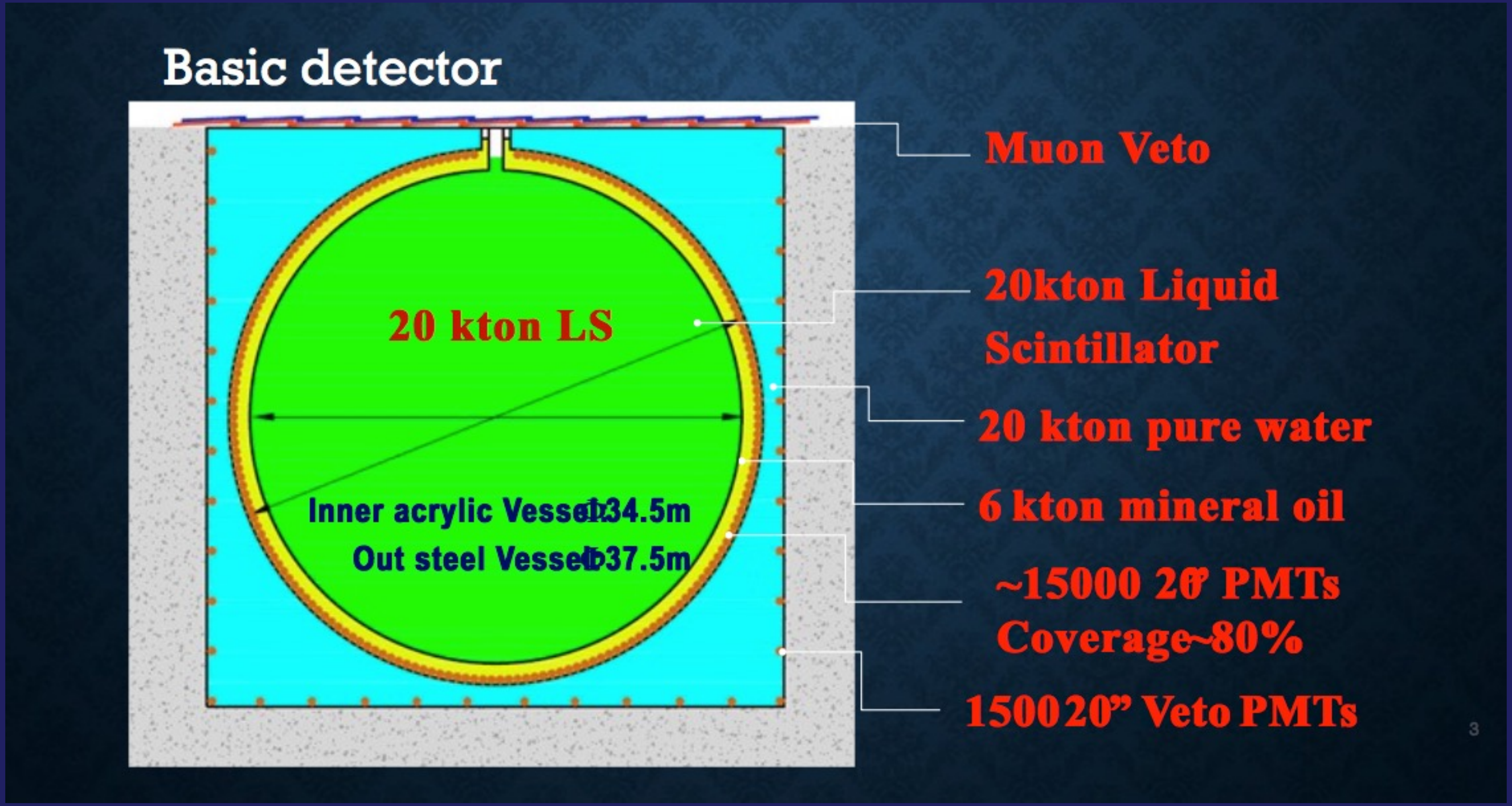
Y. F. Wang

Non-accelerator science

- Jiangmen reactor neutrino observatory JUNO, 2008-2021, 300M$, 20 kT LS, 700 m underground, Kaiping, Guangdong

- 20 GW+ NP 50 km away. For mass hierarchy (4σ in 6 yr), θ_{12}, Supernovae, Geo-ν, etc..

- 6K home made MCP-PMT ready, electronic in progress, tunnel schedule got some delay due to geological complexities.



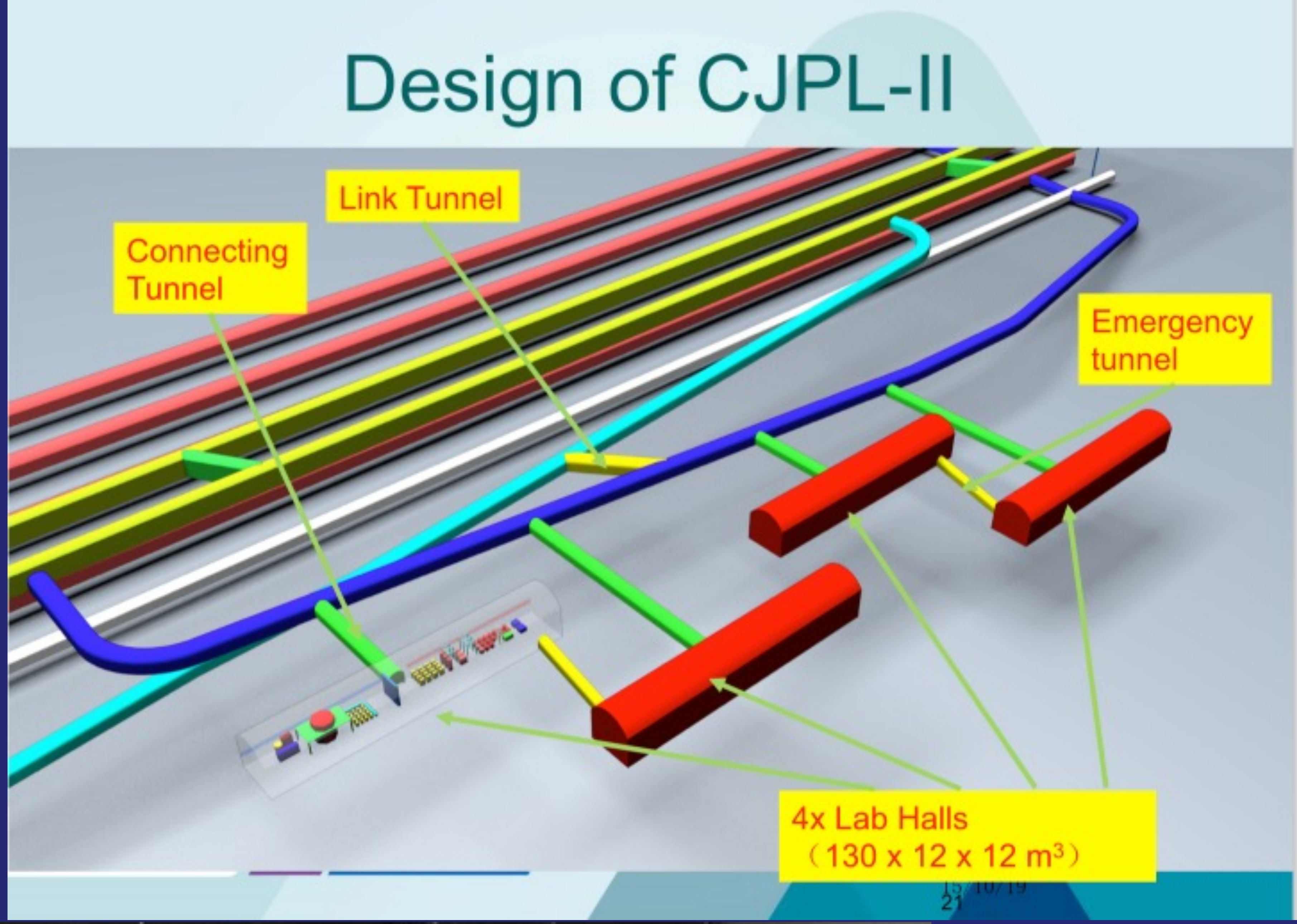
Jiangmen 20 kT tank

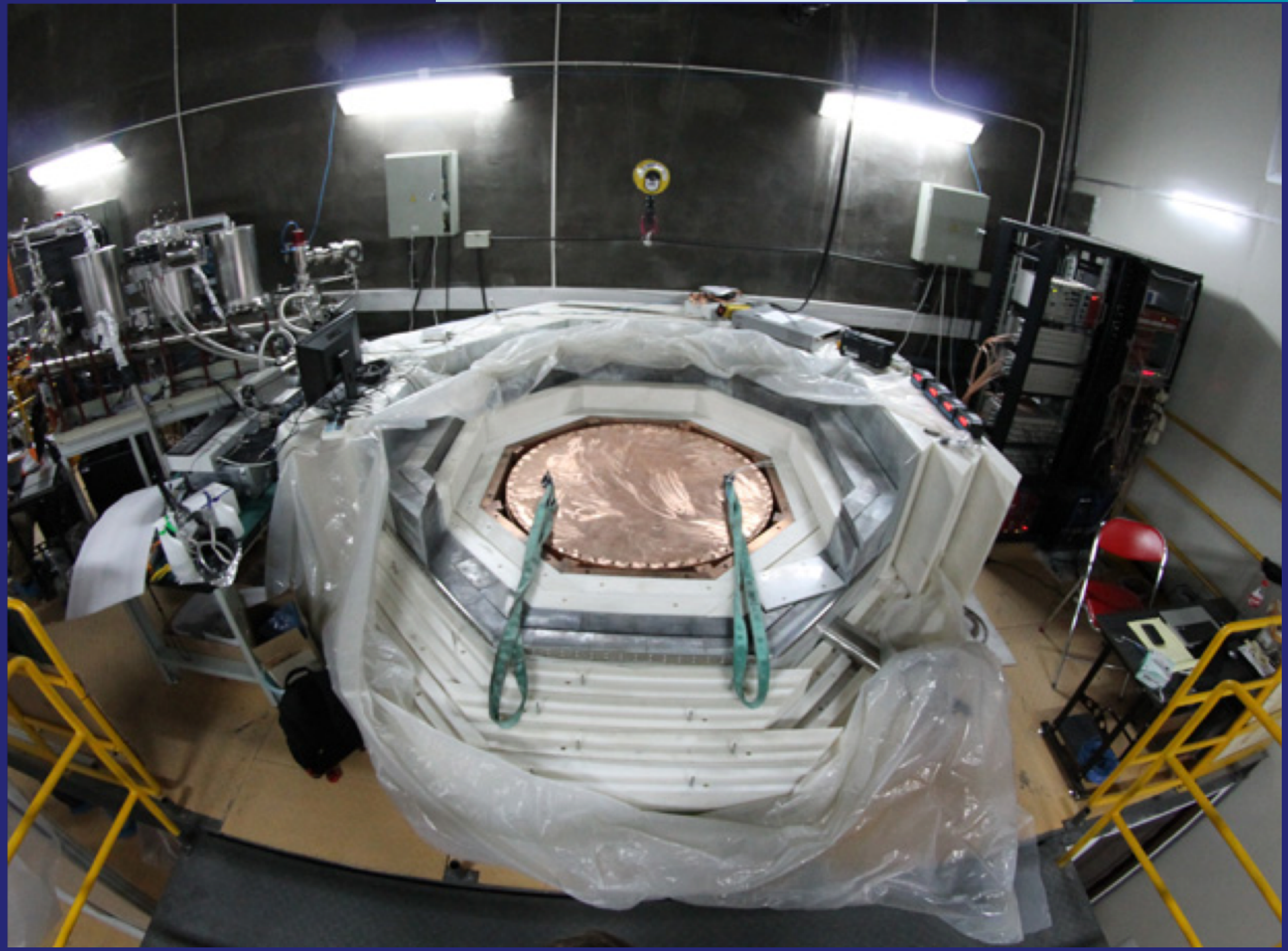
Non-accelerator science project-I

- Jinping underground lab CJPL: CJPL-I 2010 for CDEX and PandaX dark matter experiment get full results

- CJPL-II, 2019-2023 for above expansion and JUNA. With national budget of 1.24 BRMB, initial construction, end 2019 FCD planned, Dec. 2020 test operation expected.

- Jinping underground LXe dark matter experiment PandaX. 2014 120 kg, 2018 580 kg, ton level in future; ~60 T-day exposure, exclusion 8.6×10^{-47} cm^2@ 40 GeV/c^2. Ton level PandaX-II near completion, will be in CJPL-II.





PandaX in CJPL-I

Summary

- Direct measurement is a key data for nuclear astrophysics
- Underground JUNA is in progress, up to now, accelerator get proton beam, detectors near ready, target under development, lab. construction under way, on site detector measurement finished
- JUNA is now under ground tuning, will site turning 2019, hopefully start experiment in 2020
- In near future JUNA and other underground labs will be able to answer to key questions of most important reactions that driving the massive star evolution

W. P. Liu, Z. H. Li, J. J. He, X. D. Tang, G. Lian et al., Sci. China Phys 59. 642001(2016).

JUNA collaboration

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