

Progress of Underground Nuclear Astrophysics experiment JUNA, dark matter, and neutrino physics in China



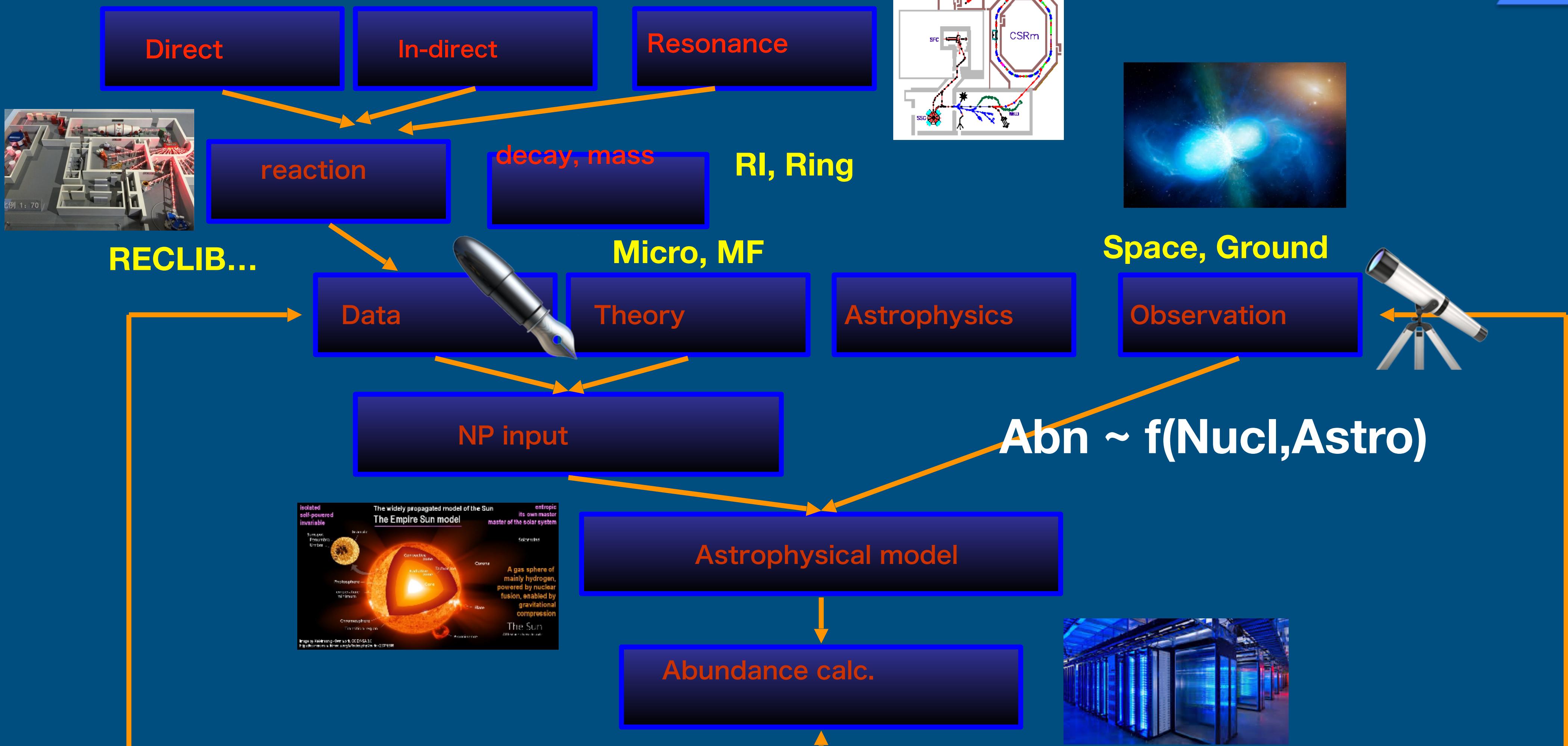
Lanzhou summer school, 2019
August 14, 2019, Lanzhou

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

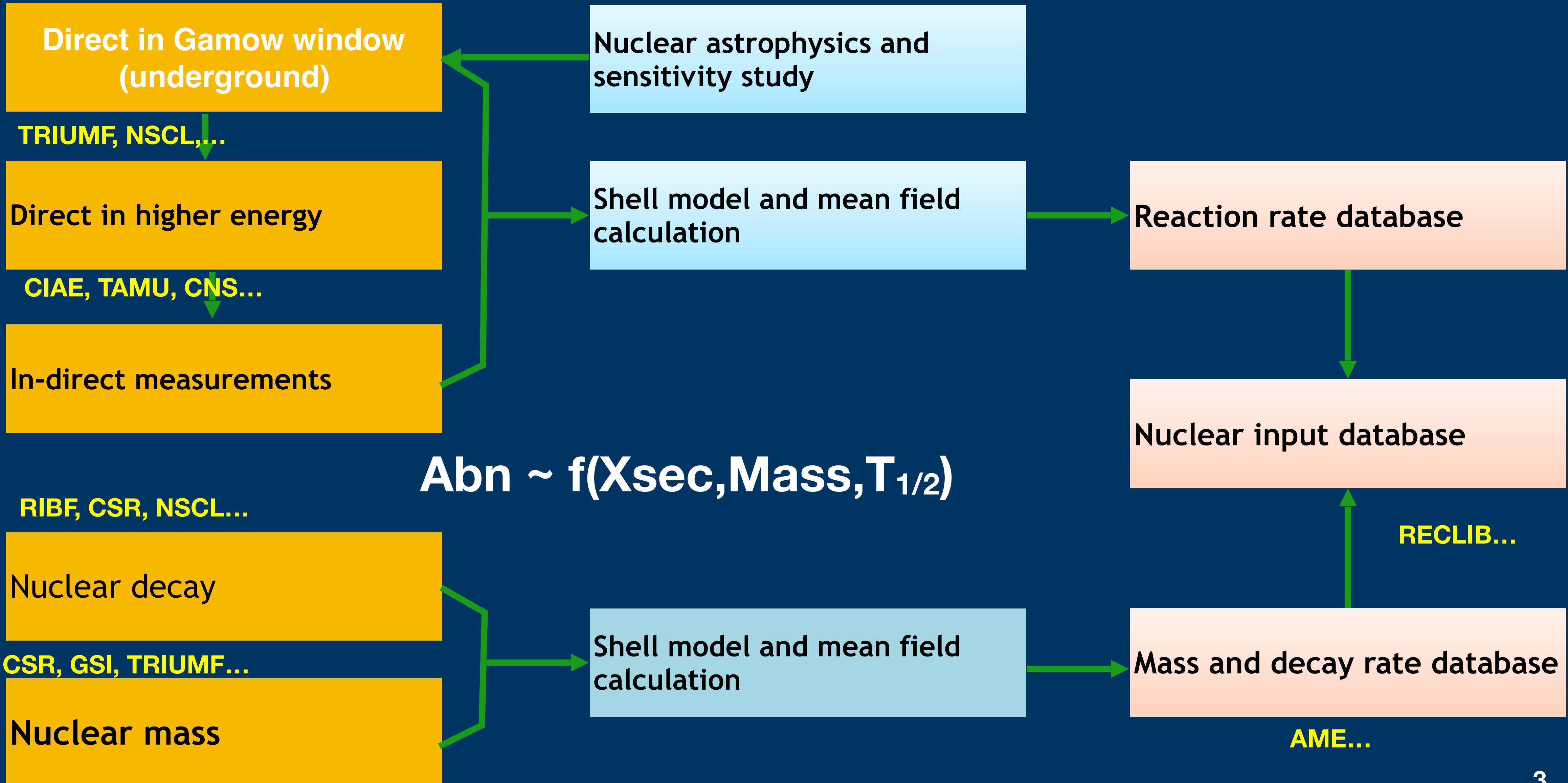
Nuclear Astrophysics roadmap

Ground, Underground



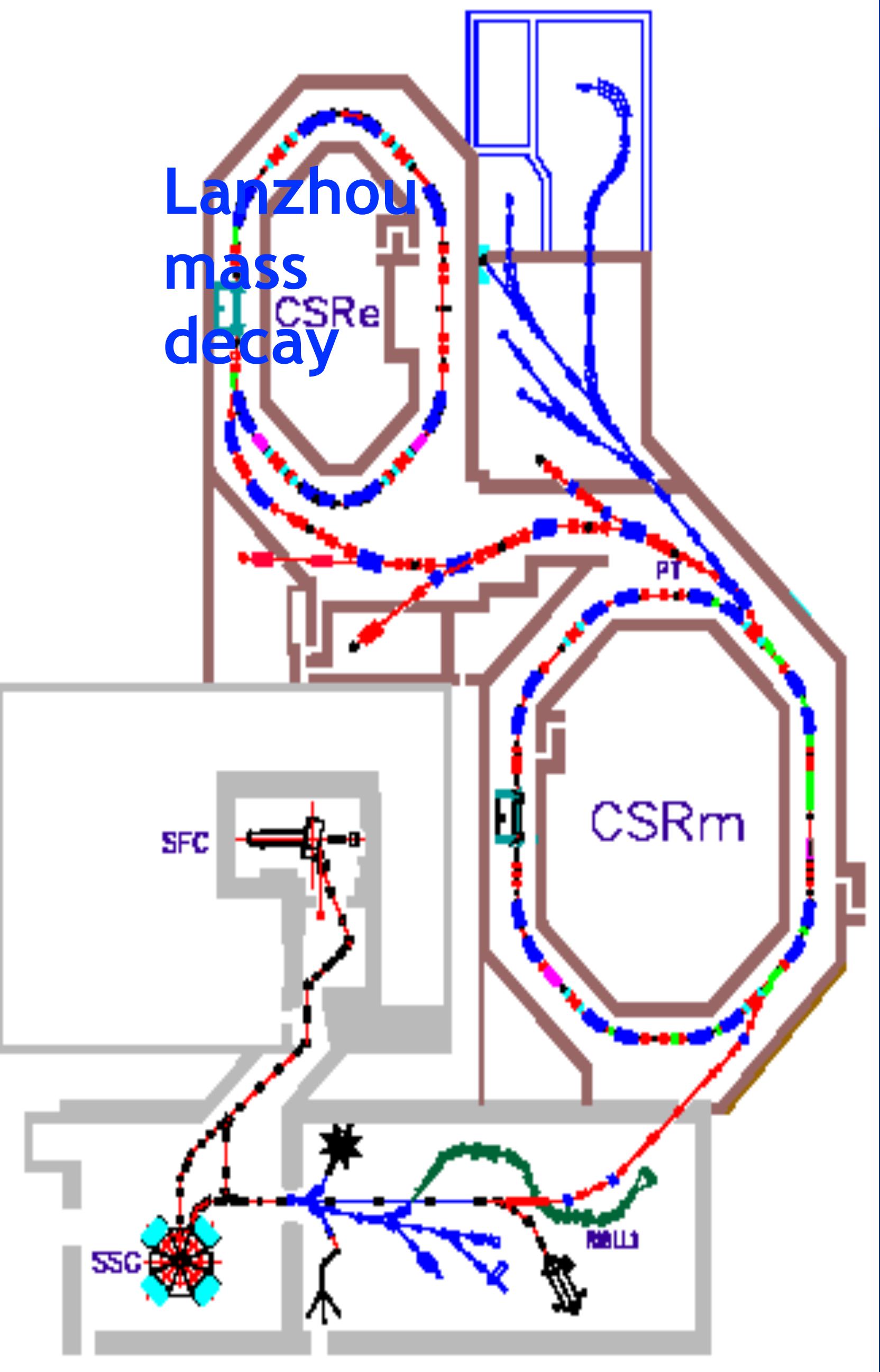
Joint efforts

LUNA, JUNA...

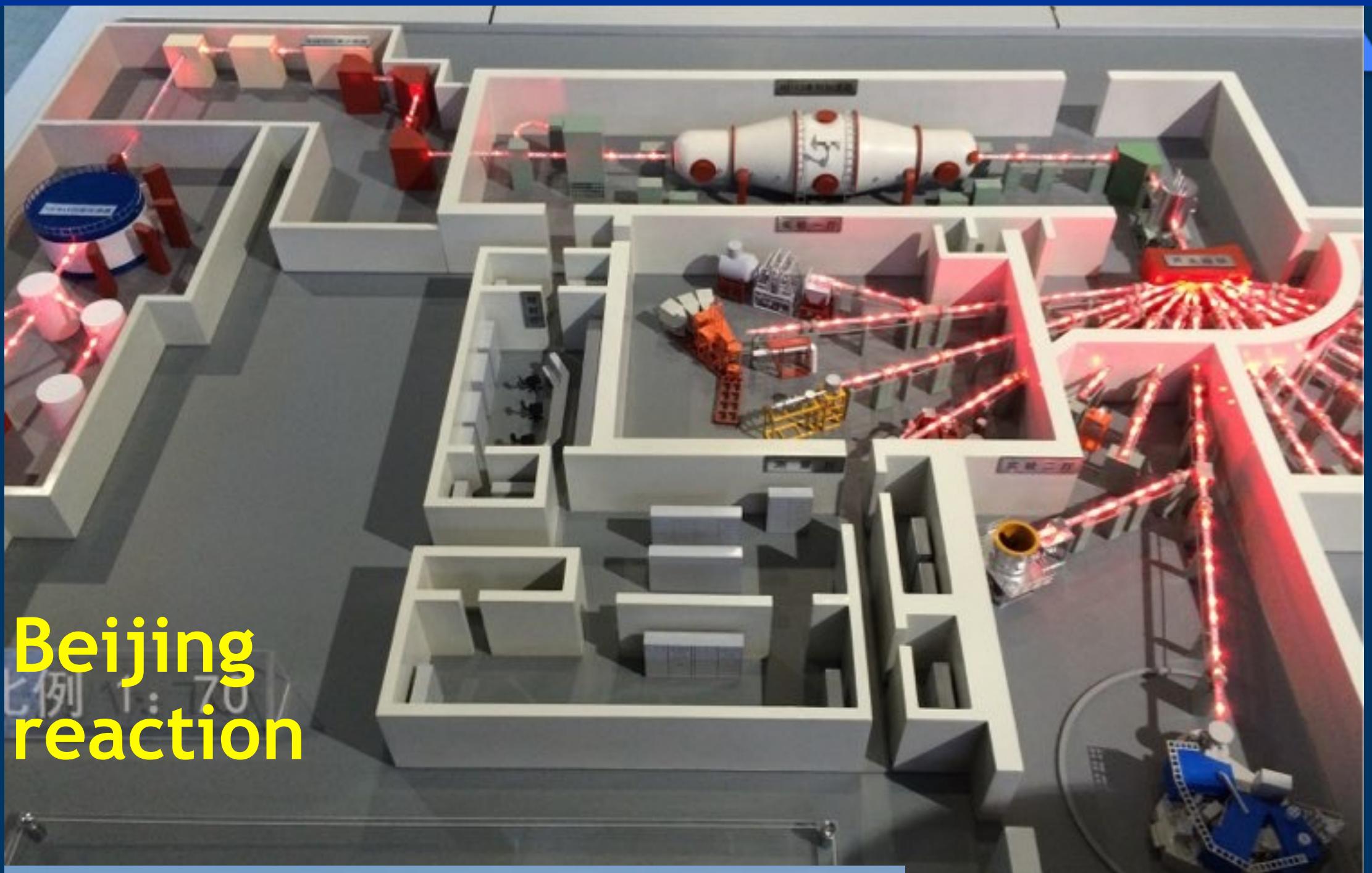


Major facilities in China

Lanzhou
mass
decay



Beijing
reaction



LAMOST
observation



Milestones of NA in China

1993, first RI beam line in China

2005, in-direct extended to ${}^8\text{Li}(n, \gamma){}^9\text{Li}$

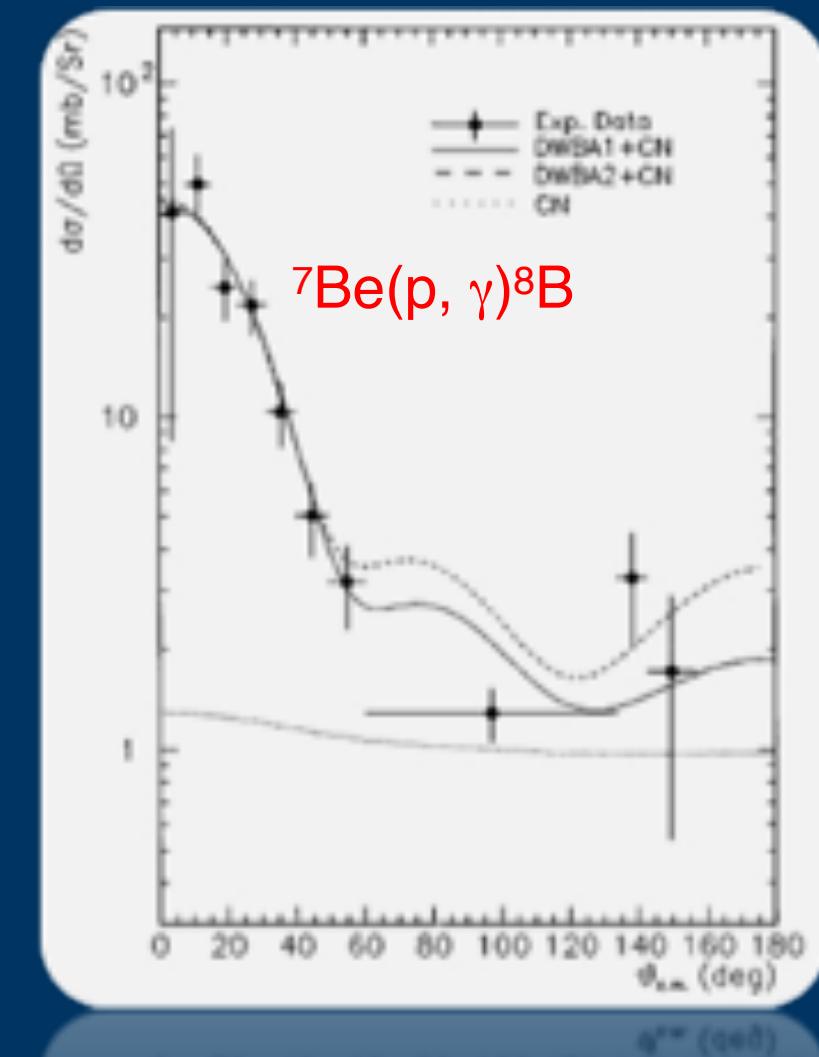
2011, NSFC group fund for Nucl. Astrophys.

2013, direct ${}^6\text{Li}(p, \gamma){}^7\text{Be}$ in PLB

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

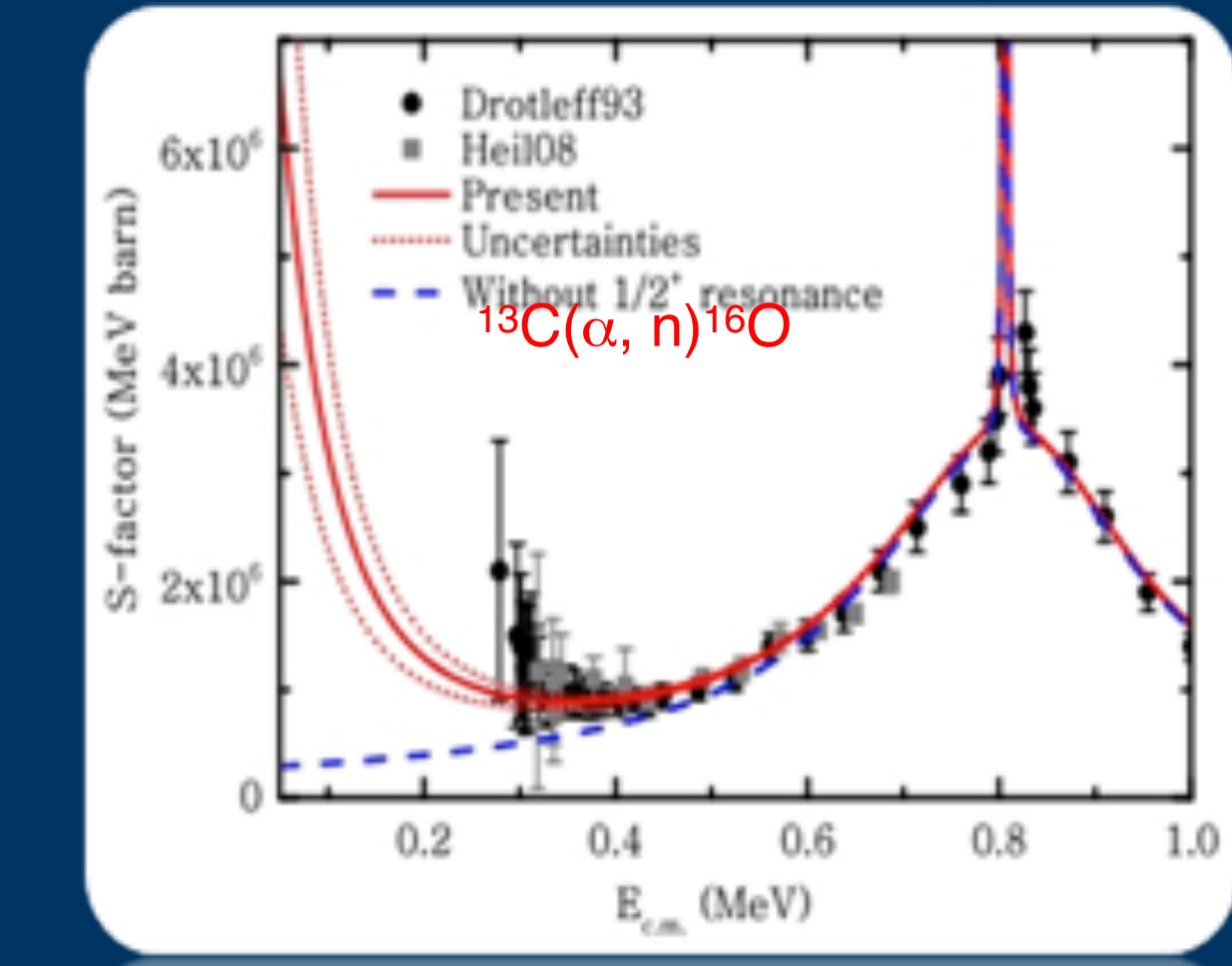


1996,
 ${}^7\text{Be}(p, \gamma){}^8\text{B}$ in-direct
in PRL



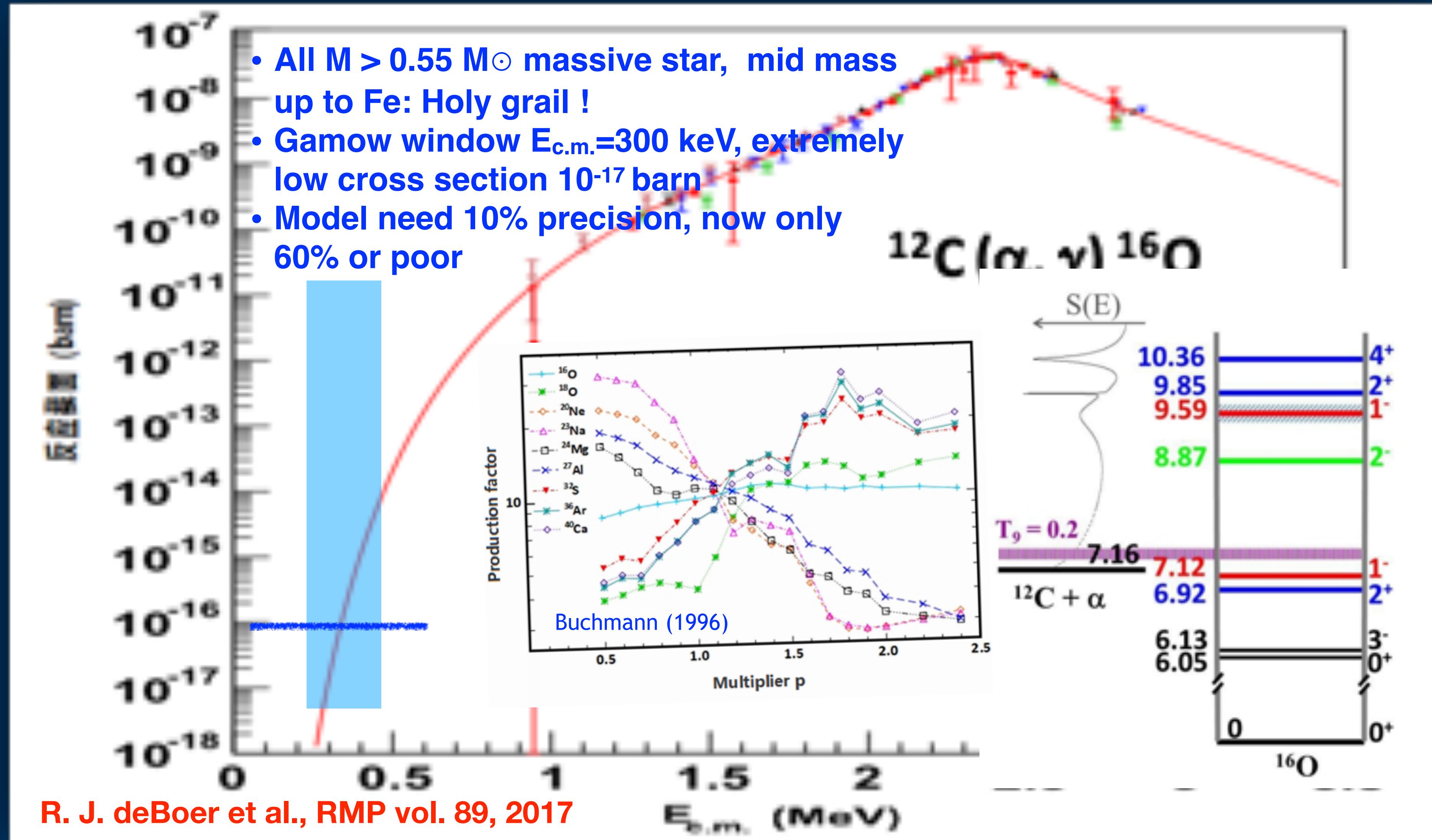
2011,
rp mass
PRL, APJ

2012,
 ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ in-
direct in APJ

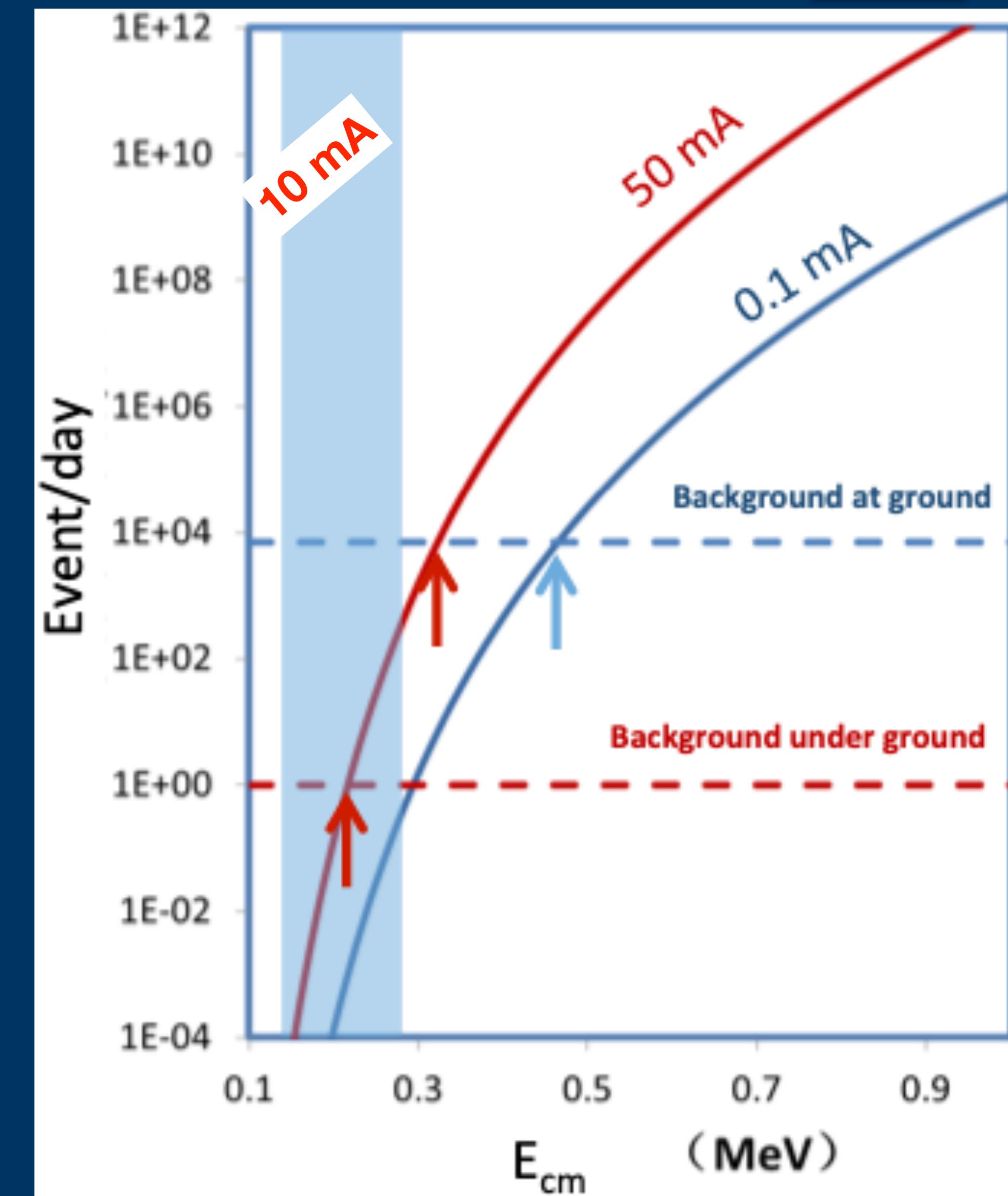
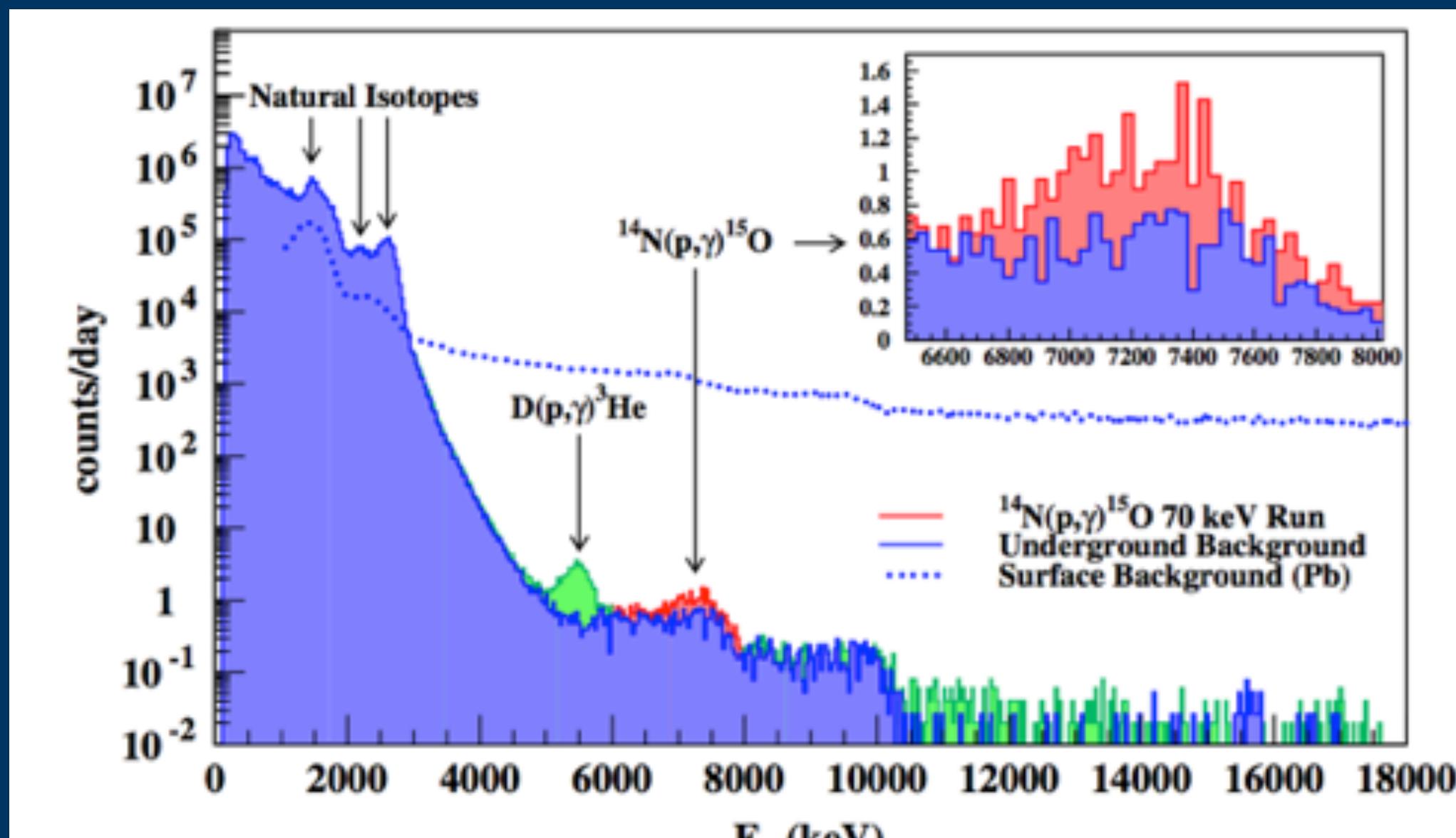
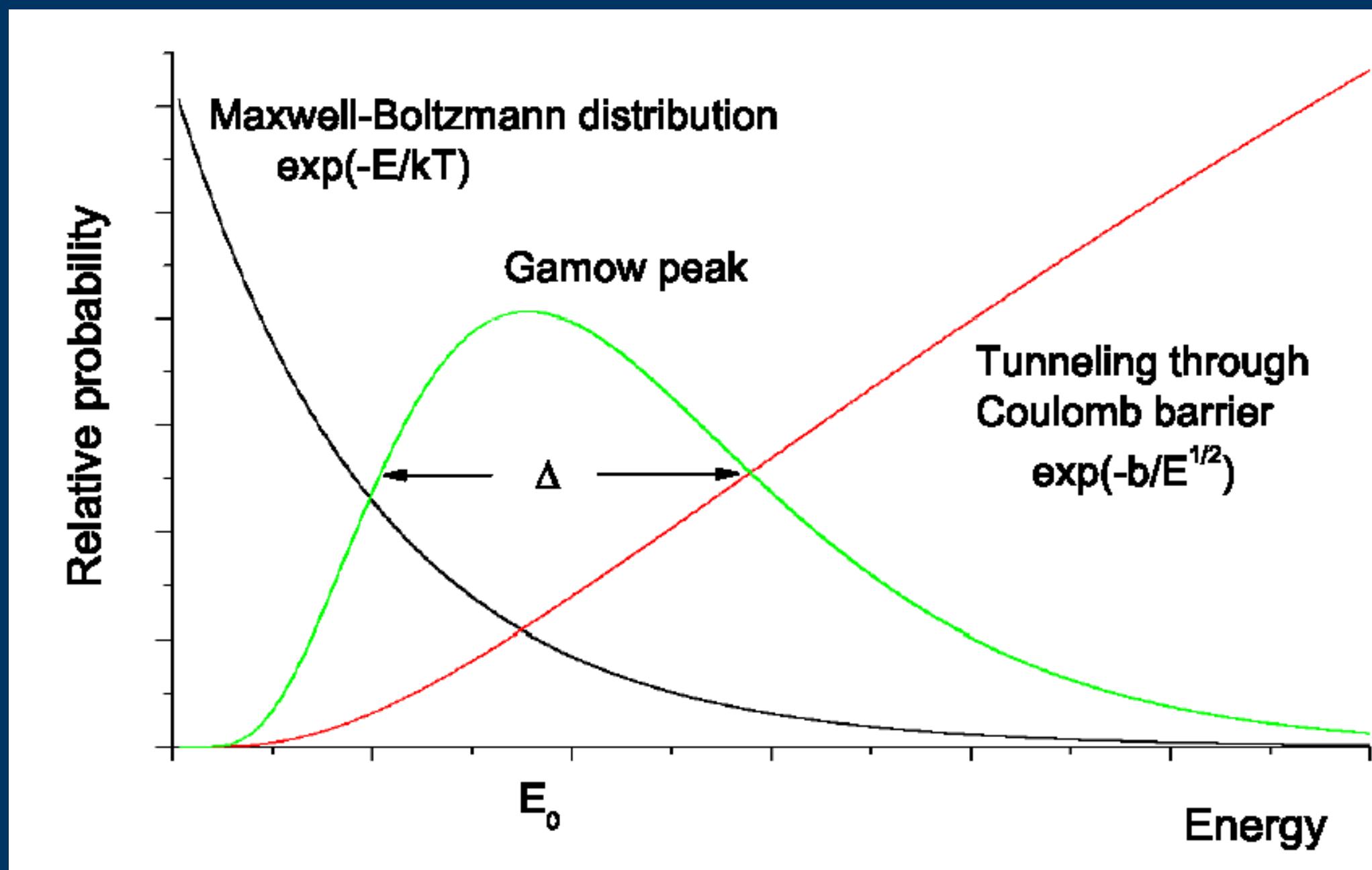


Big question, and JUNA

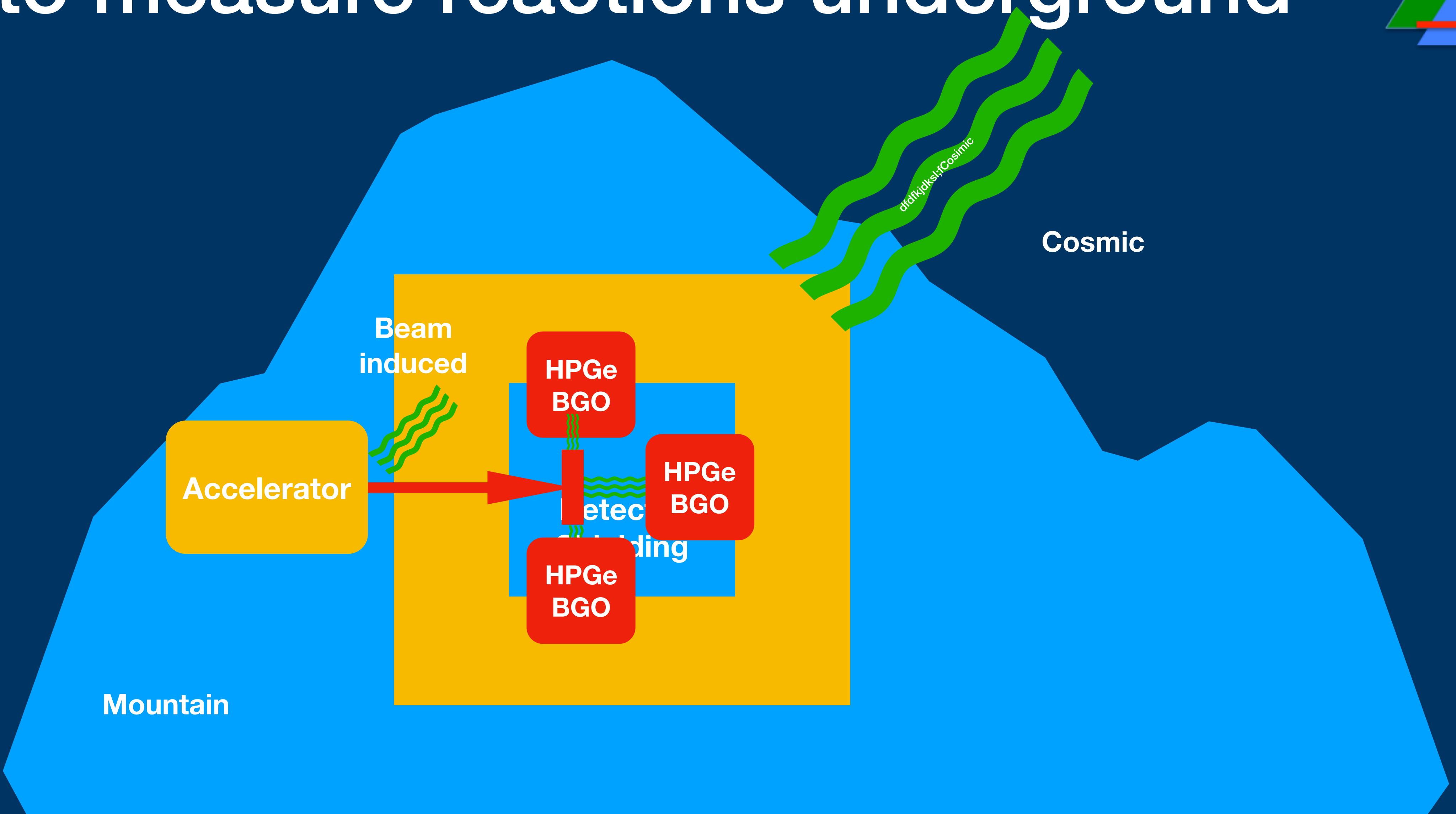
Jinping Underground nuclear astrophysics experiment



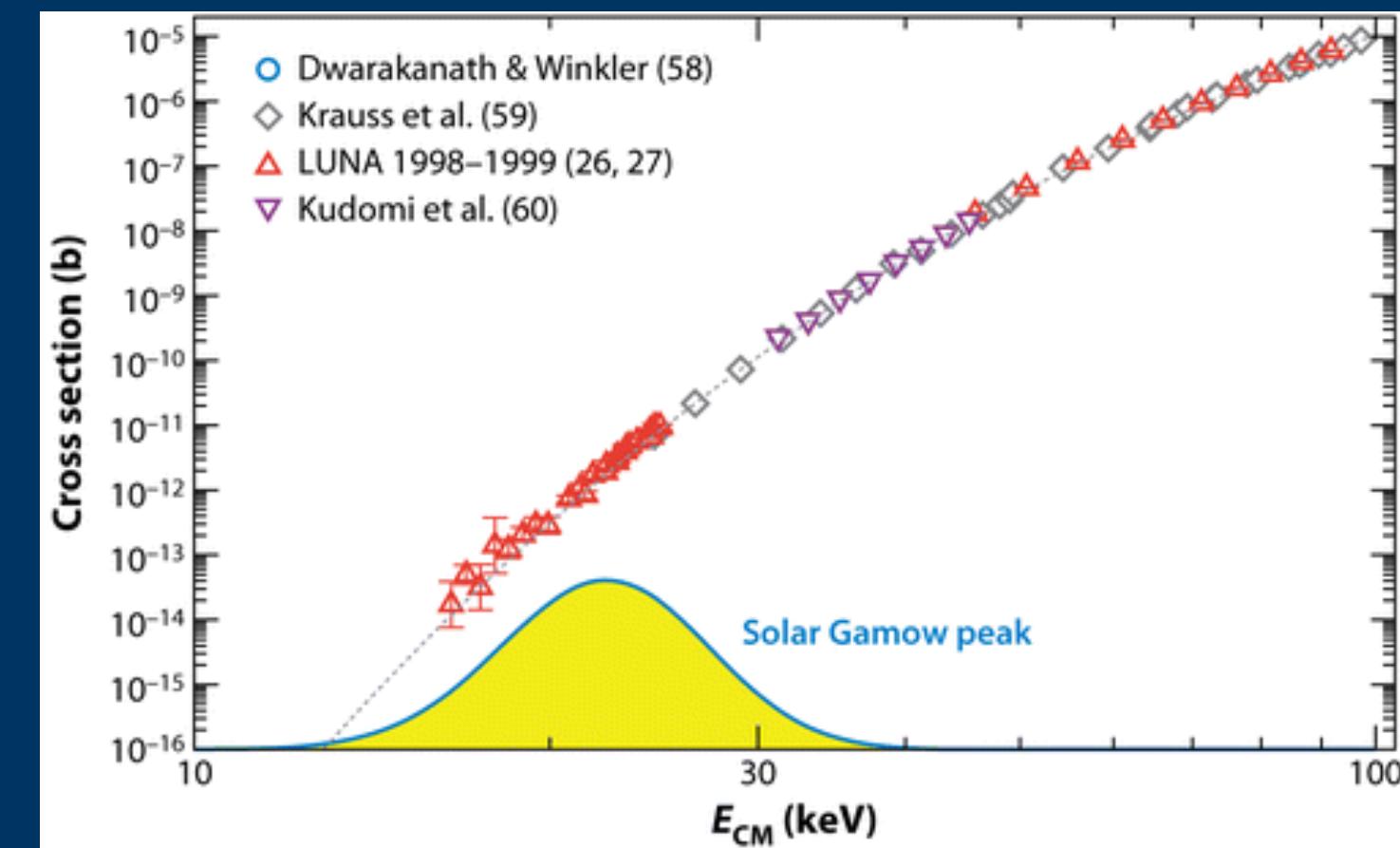
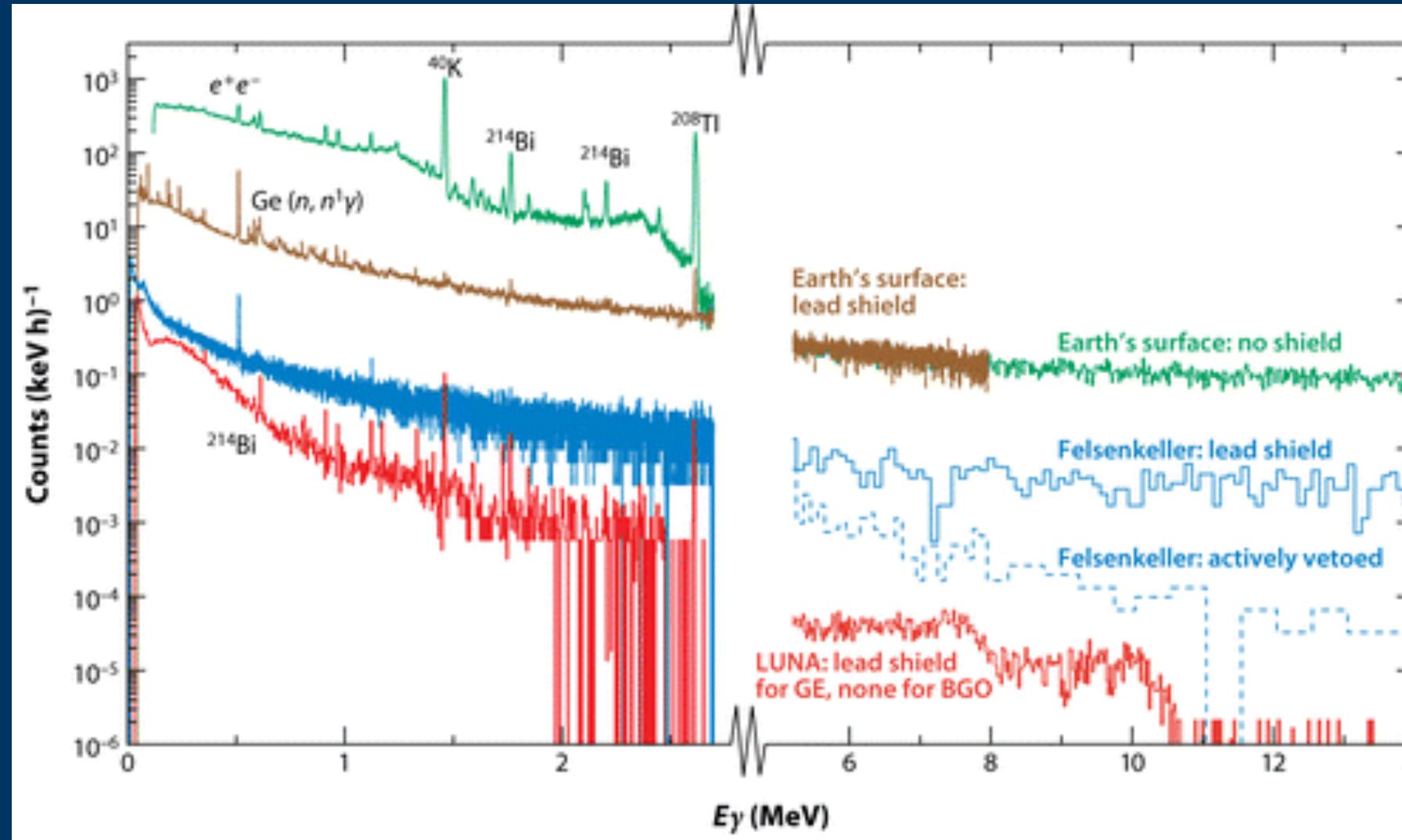
Underground advantage and key to success



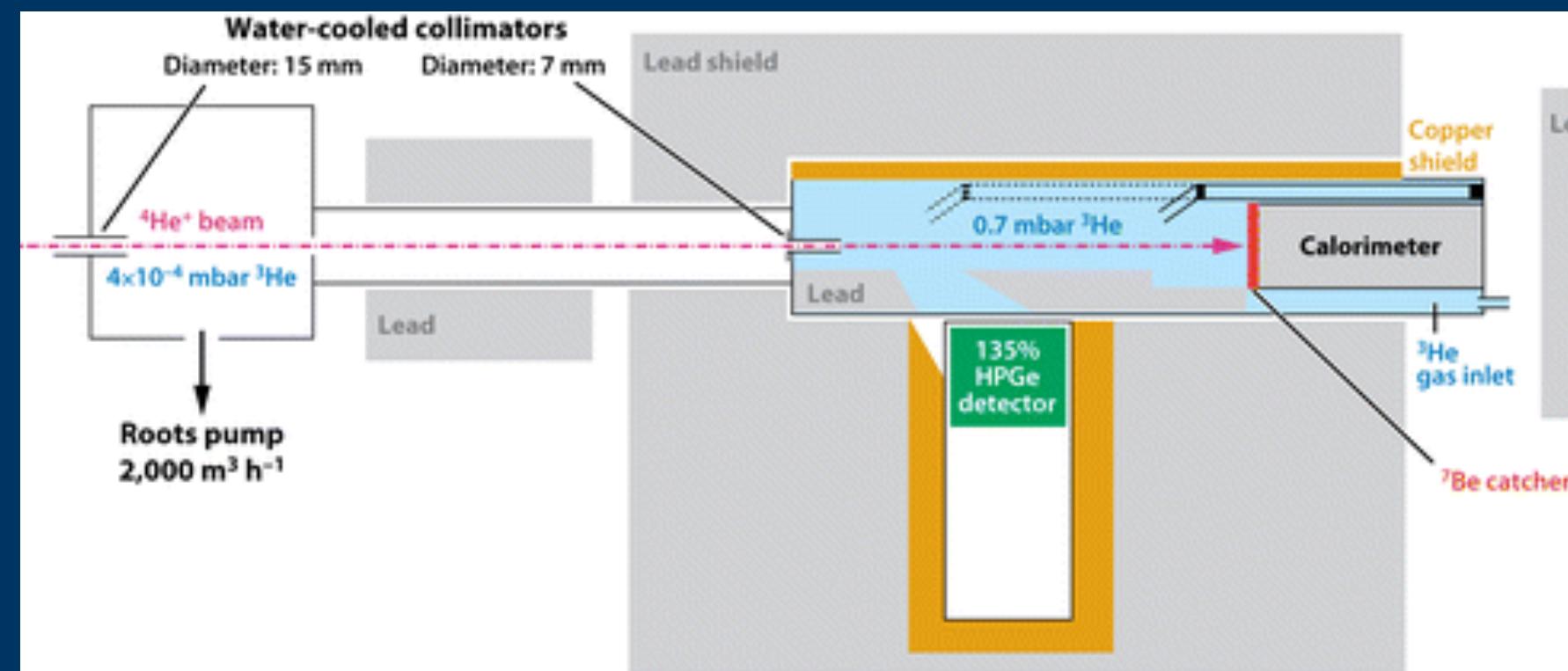
How to measure reactions underground



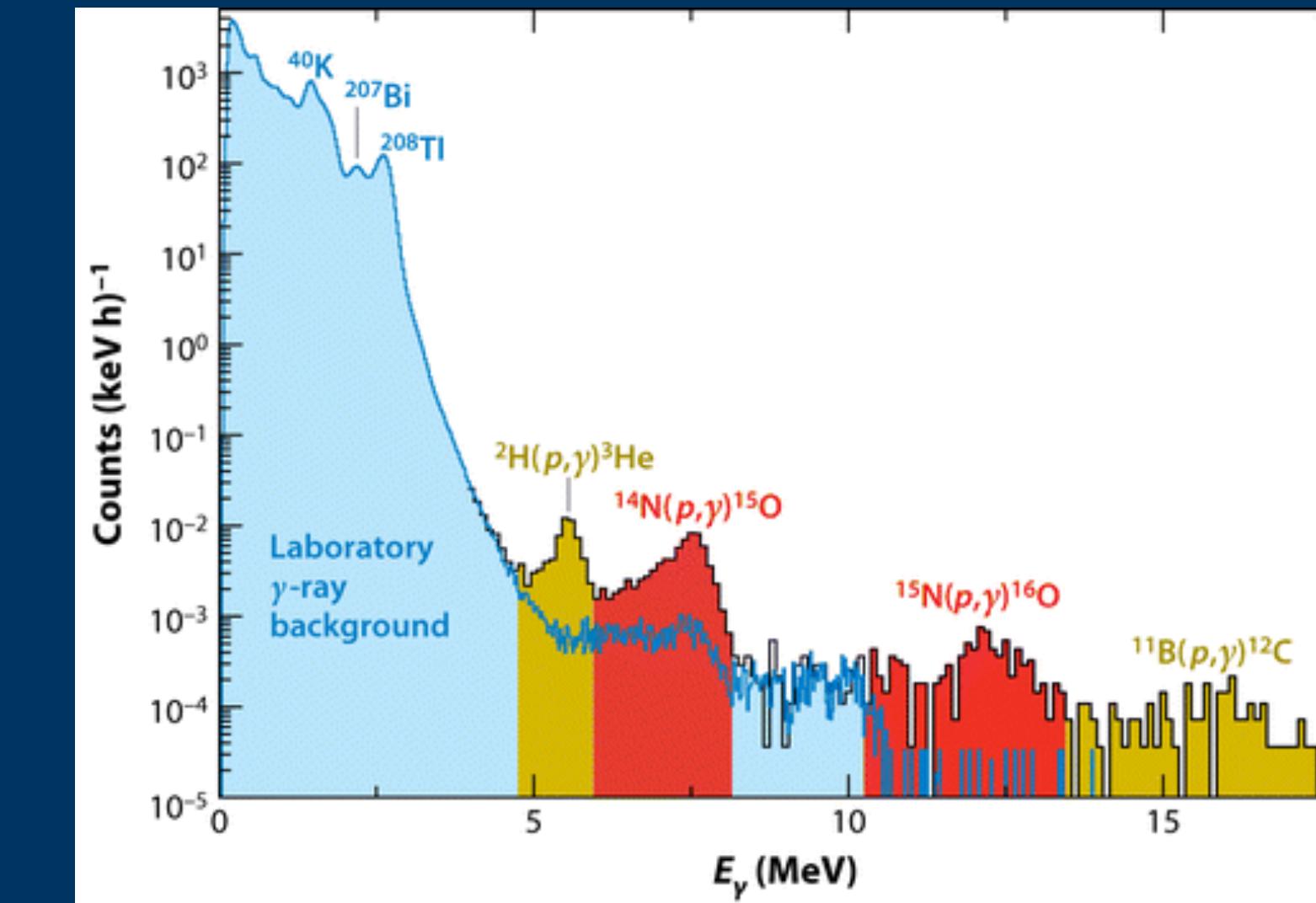
LUNA nuclear astrophysics



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



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



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

$^3\text{He}(^3\text{He}, 2\text{p})^4\text{He}$
PRL 82(1999)5205

$^2\text{H}(^3\text{He}, \text{p})^4\text{He}$
PLB 482(2000)43

$^2\text{H}(\text{p}, \gamma)^3\text{He}$
NPA 706(2002)203

$^3\text{He}(\alpha, \gamma)^7\text{Be}$
PRL 97(2006)122502

$^{14}\text{N}(\text{p}, \gamma)^{15}\text{O}$
PLB 591(2004)61

$^{15}\text{N}(\text{p}, \gamma)^{16}\text{O}$
PRC 82, 055804(2010)

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

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

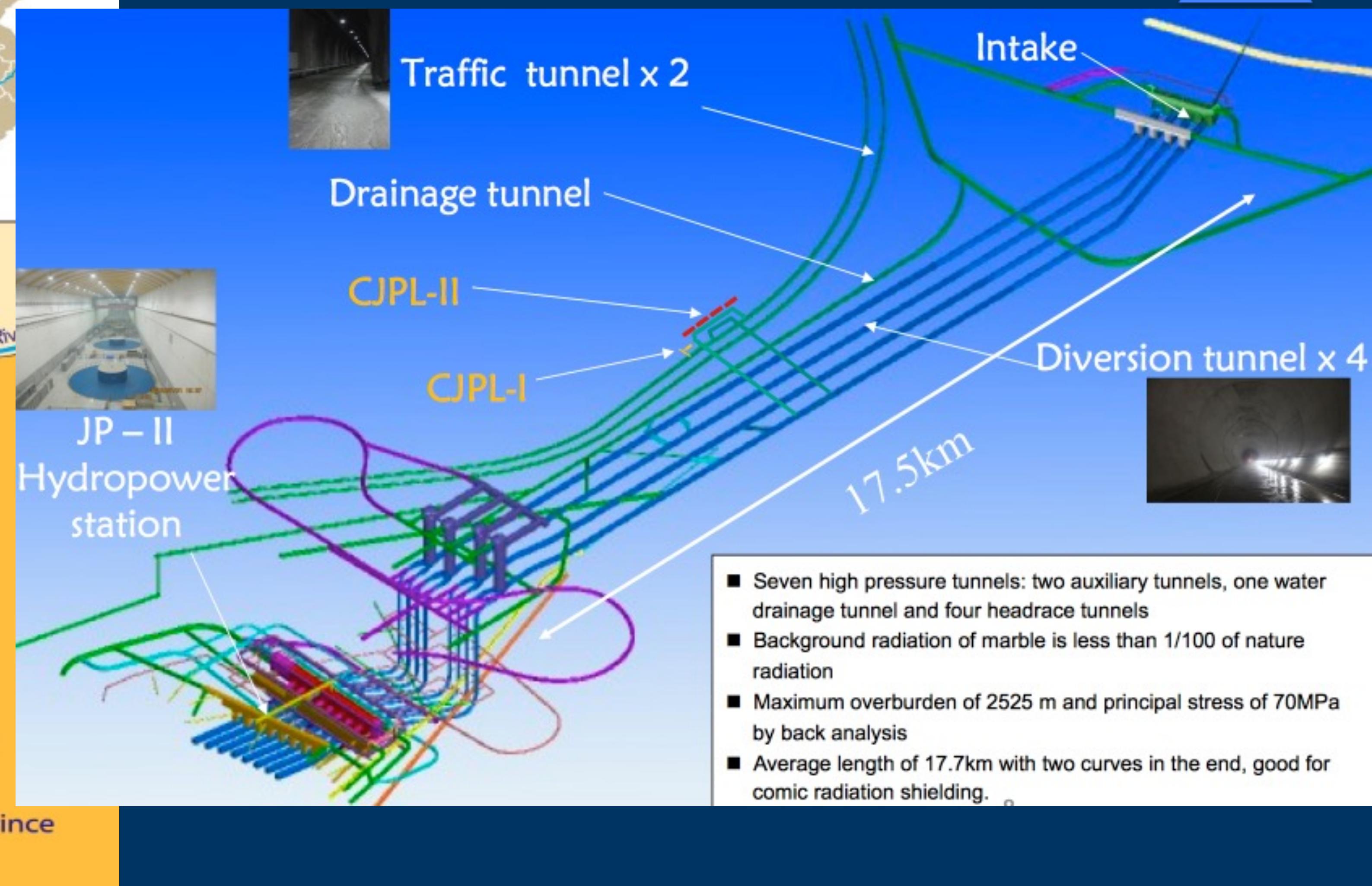
Uncertainty remained for key reactions

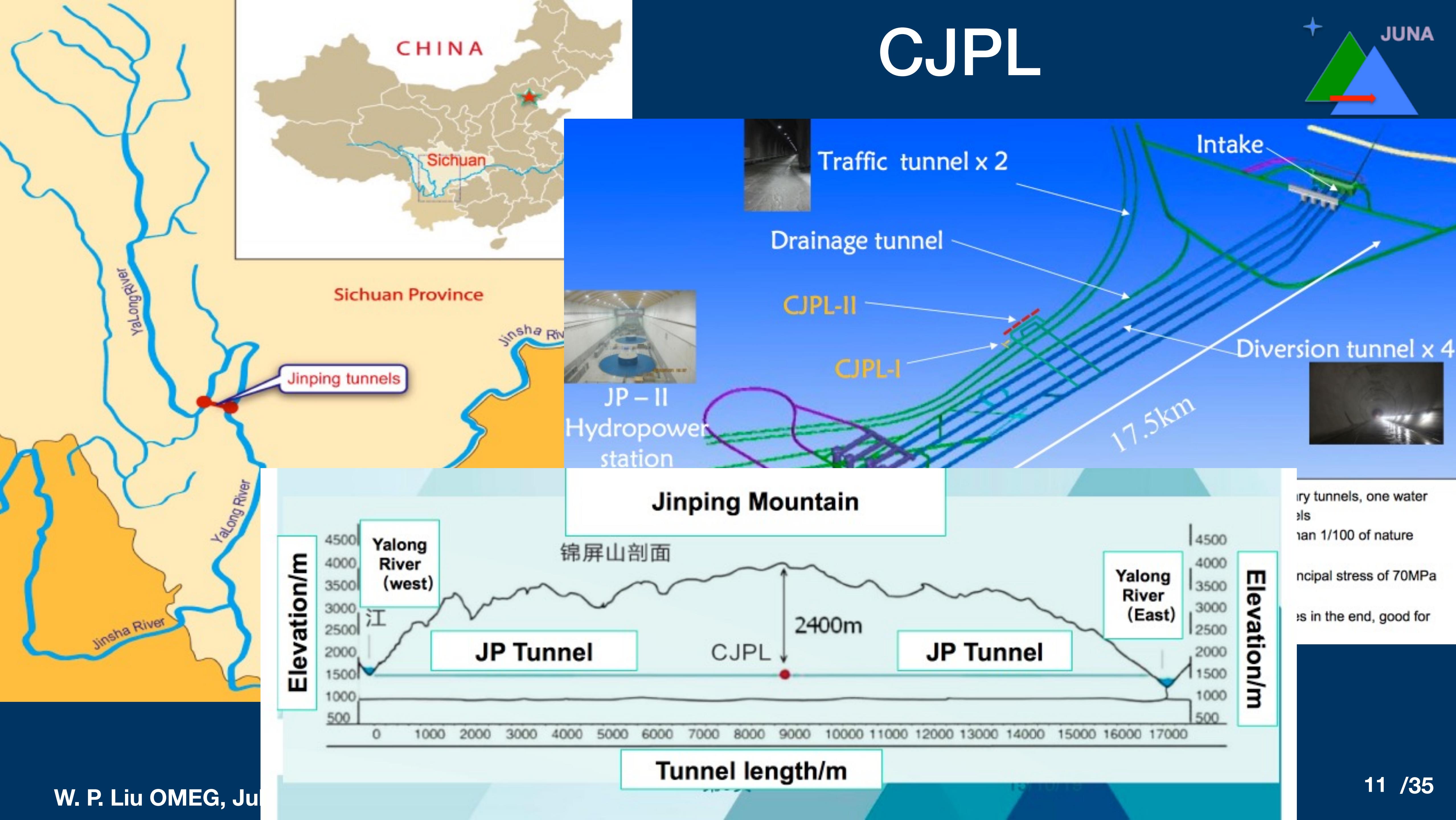
Physics	Reaction	Current	Desired
Massive star	$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$	60% 890 keV	20% 220-380 keV
s-process neutron source	$^{13}\text{C}(\alpha, n)^{16}\text{O}$	60% 279 keV	10% 140-230 keV
Galaxy ^{26}Al source	$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$	20% 92 keV	5% 50-300 keV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

CJPL



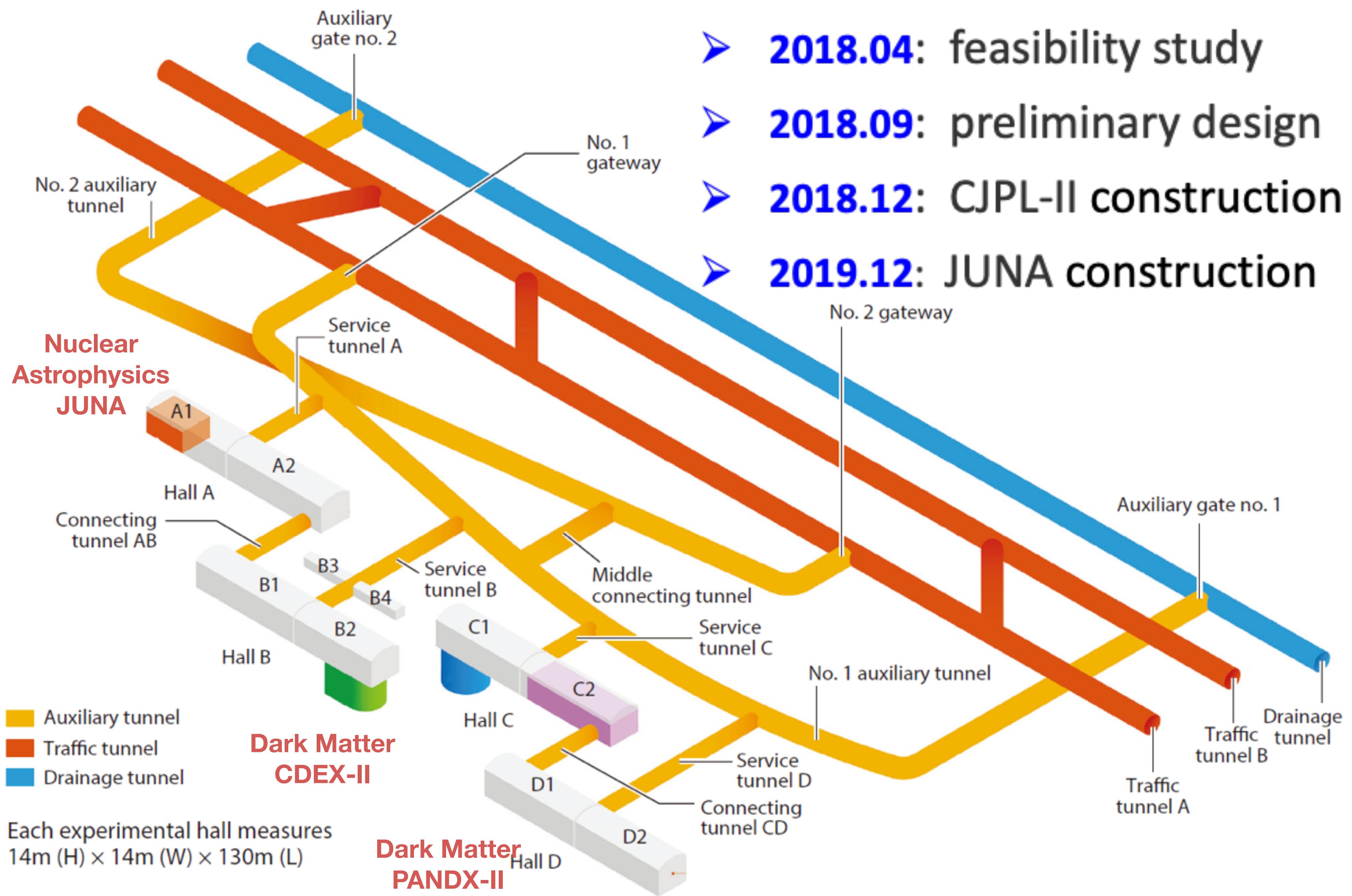
CJPL



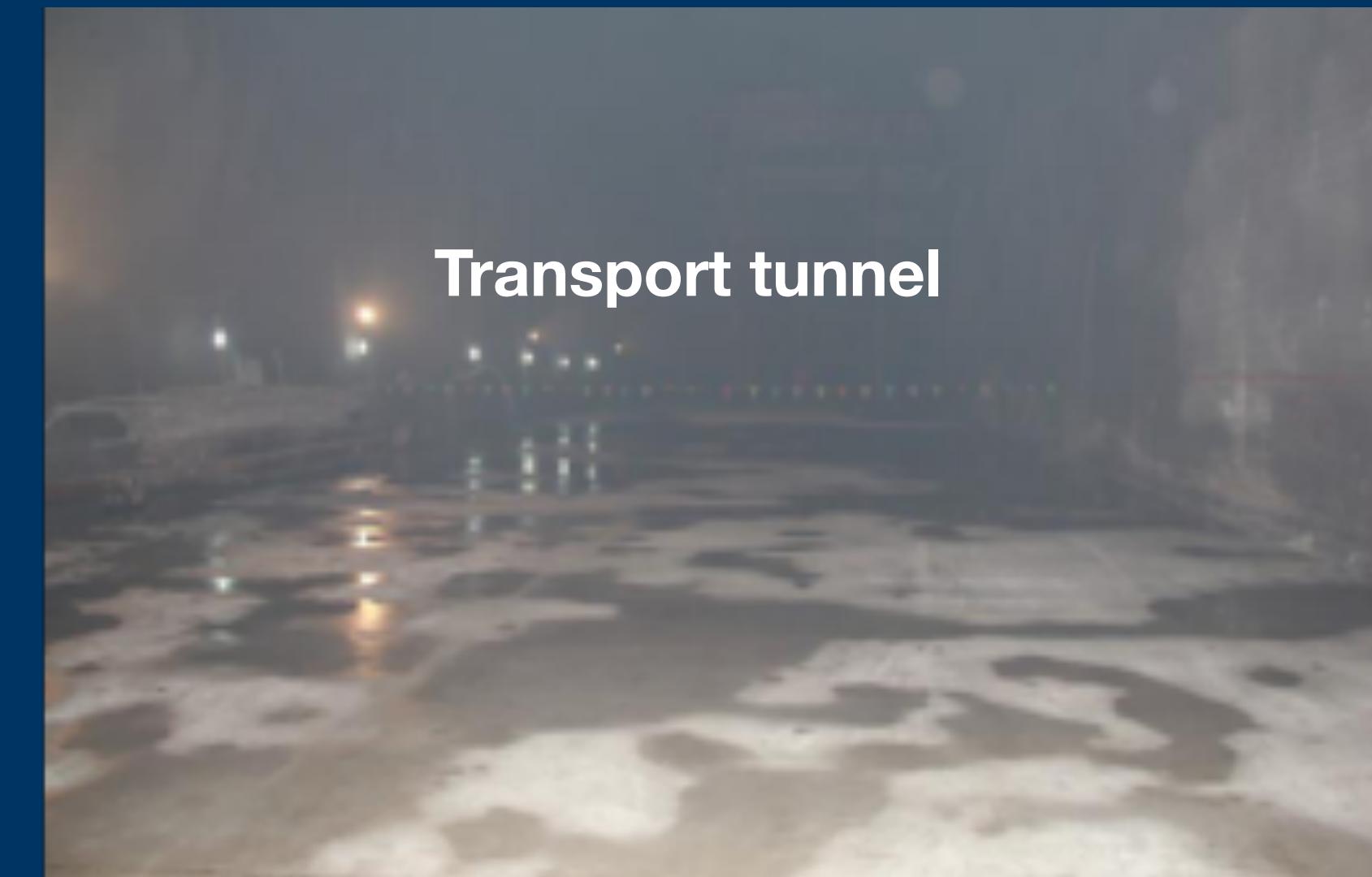


CJPL-II milestone

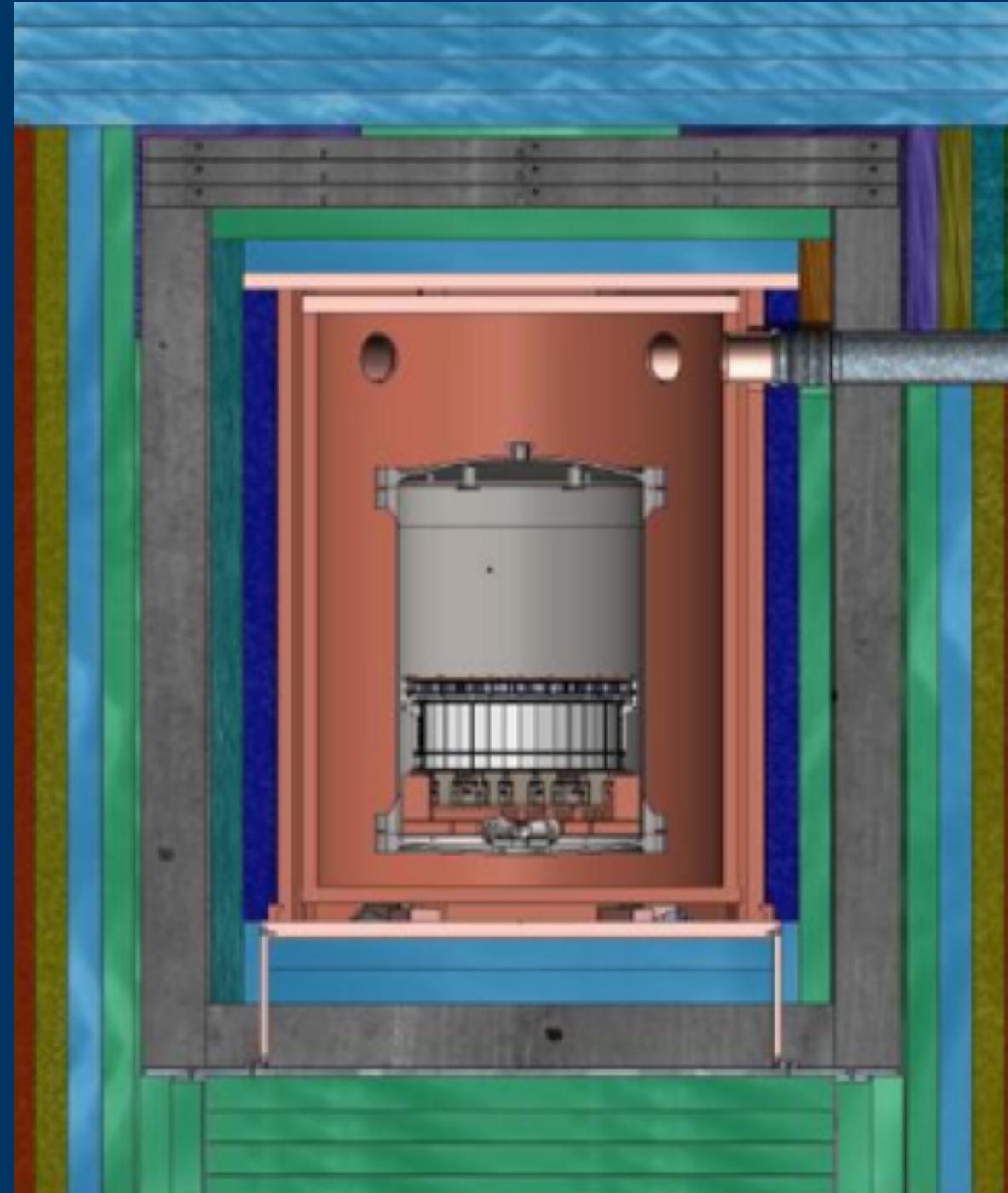
JUNA



CJPL-II status 2016-2018

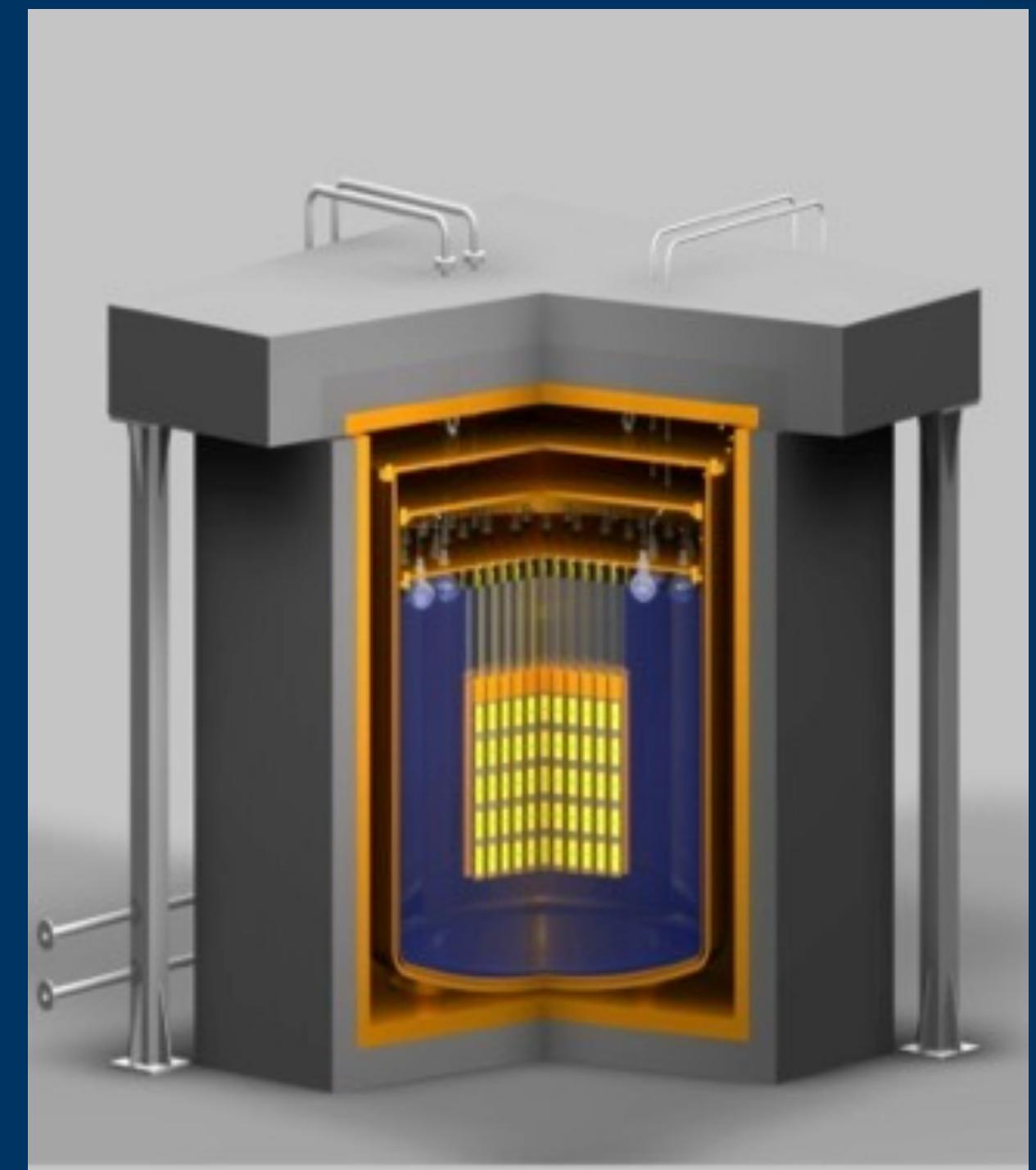


CJPL-II experiments



LXe **PANDAX+**

Nuclear
Astrophysics
JUNA
400 kV



HpGe
CDEX +

More
experiments...

JUNA team

Group leader



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

PI



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



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



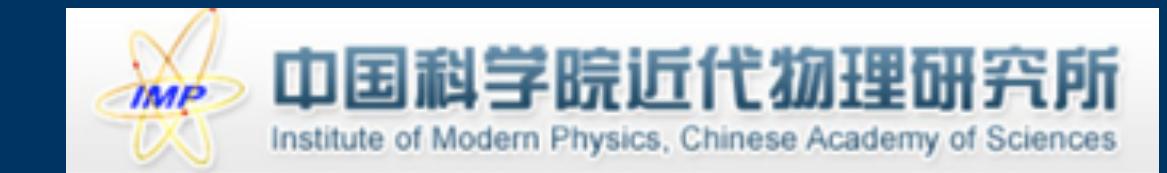
Jianjun He
 $^{19}\text{F}(p, \alpha)^{16}\text{O}$
Lab. exp. sup,



Gang Lian
Lab. exp. sup,



Bao Quncui,
Liangting
Sun
Ion source
and acc.





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 IAC

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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



NSFC \$2.9+M

CAS \$0.65M

CNNC \$1.6 M

CJPL-II / Tsinghua ~\$3+M

Detectors (NSFC \$1.3M)

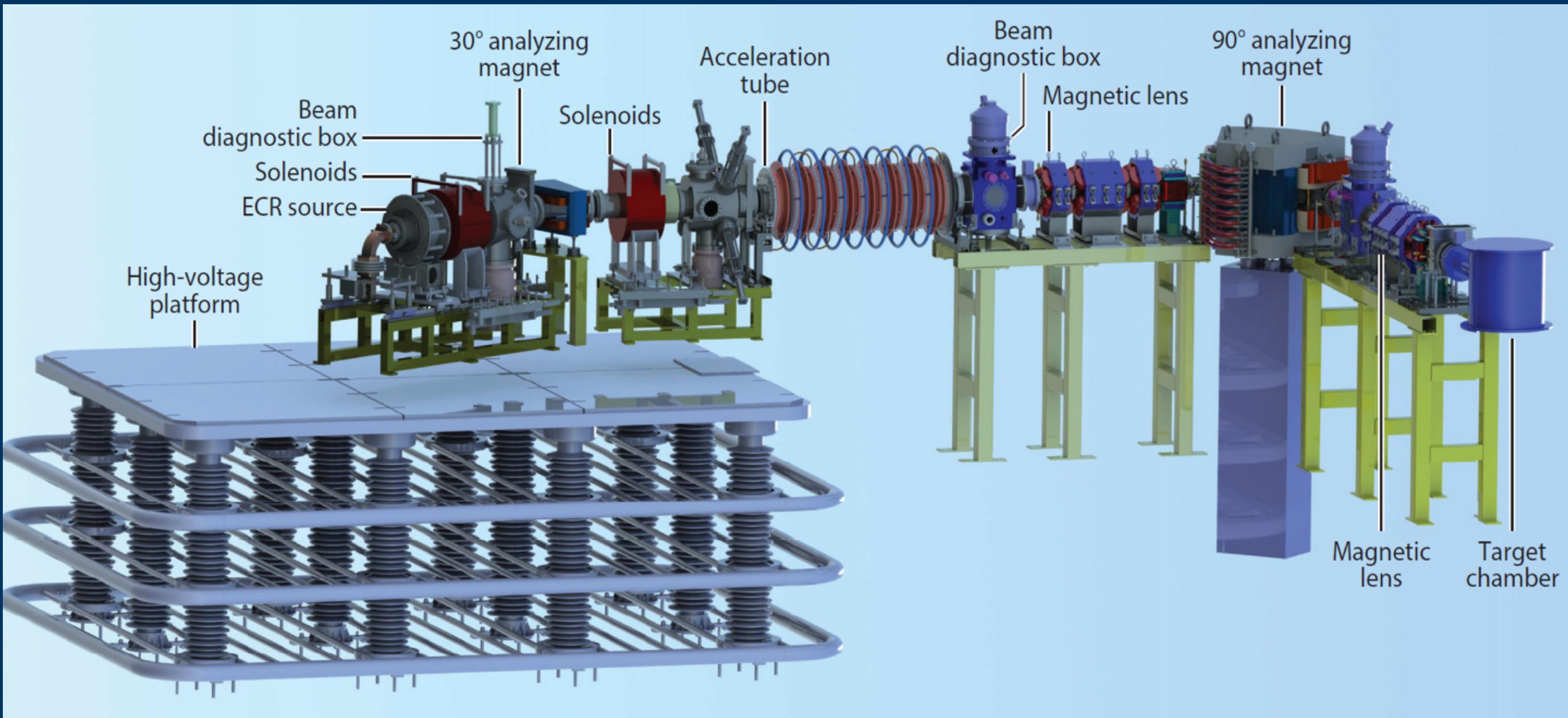
Electronics, shielding (NSFC \$1.0M)

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

Lab CJPL II (CNNC, Tsinghua, NSFC \$3+M)

total \$8+ M

JUNA Accelerator



Goal		
Beam	Intensity, mA	Energy, keV
H ⁺	10	70-400
He ⁺	10	70-400
He ⁺⁺	2	140-80
Achieved		0
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(α,γ) ¹⁶ O	Massive star	890	60	[17]	380	220-380
¹³ C(α,n) ¹⁶ O	HI synthesis	279	60	[18]	200	140-230
²⁵ Mg(p,γ) ²⁶ Al	Galaxy ²⁶ Al	92	20	[13]	58	50-300
¹⁹ F(p,α) ¹⁶ O	F abundance	189	80	[19]	100	50-350

JUNA expertise



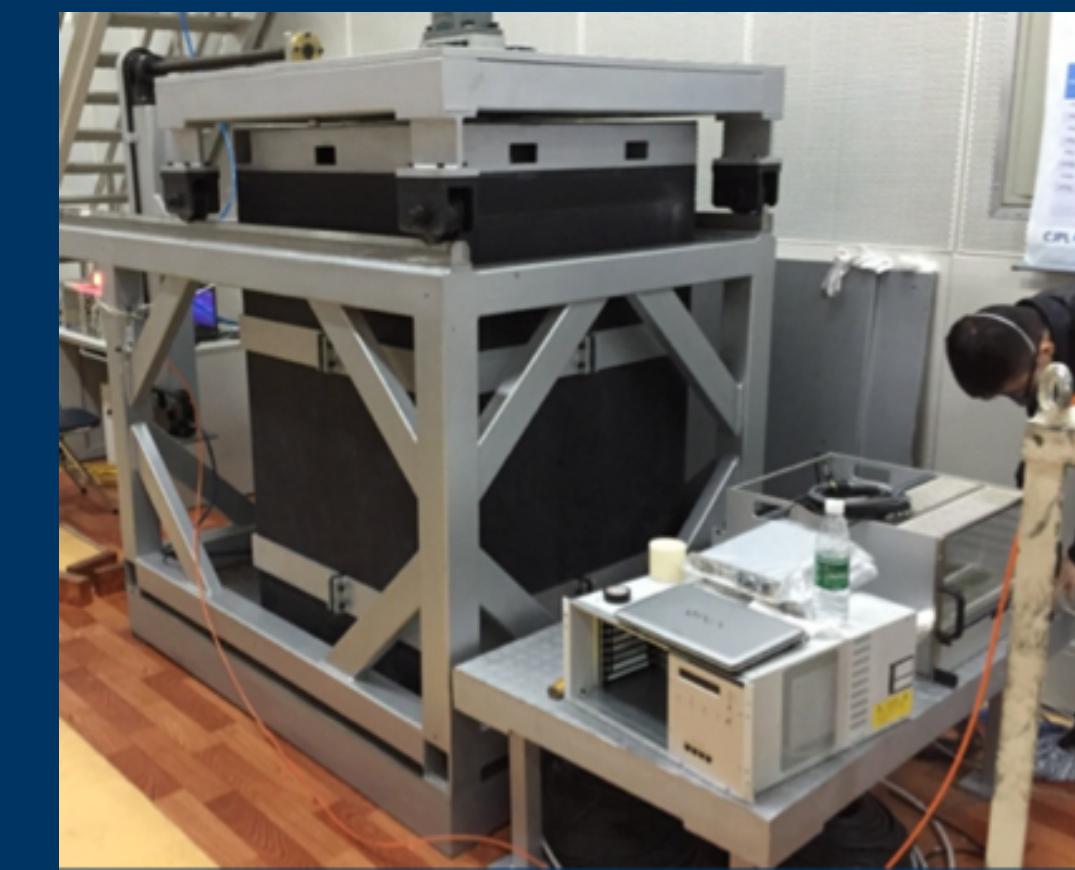
Superconducting ECR



Tandem for test experiment

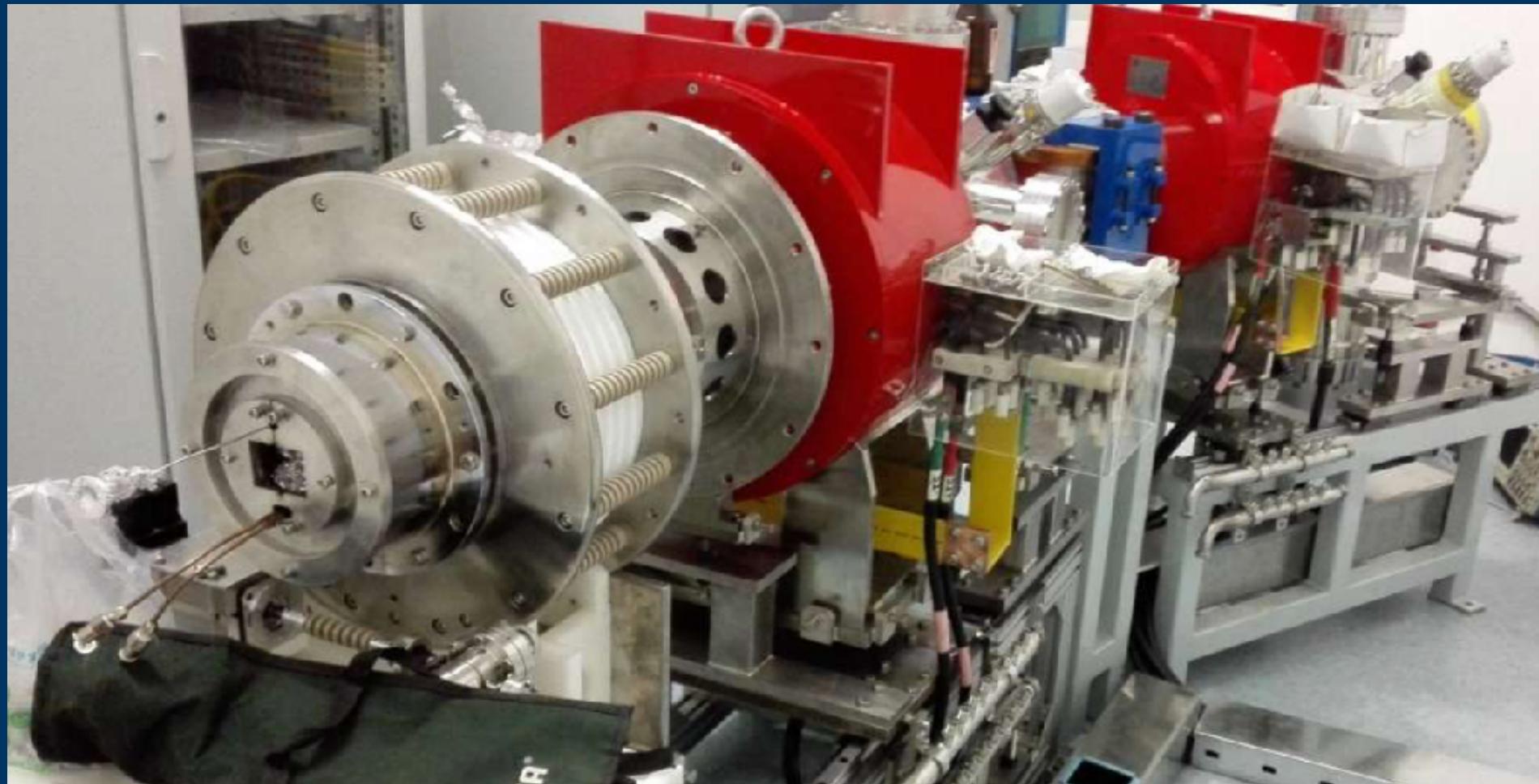


solid and gas detector and electronics



CJPL low background facility

Ion source and accelerator status



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

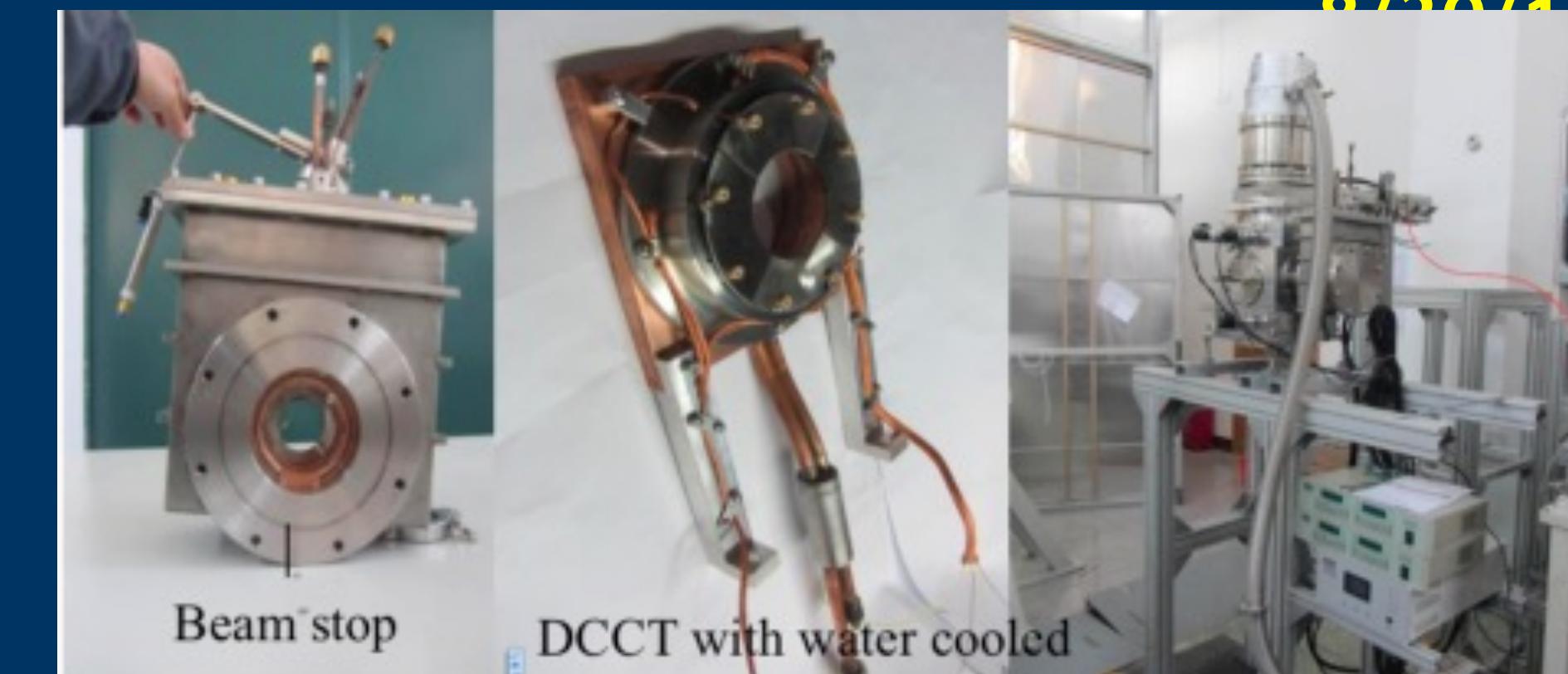


Beam line

W. P. Liu OMEG, July , 2019



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



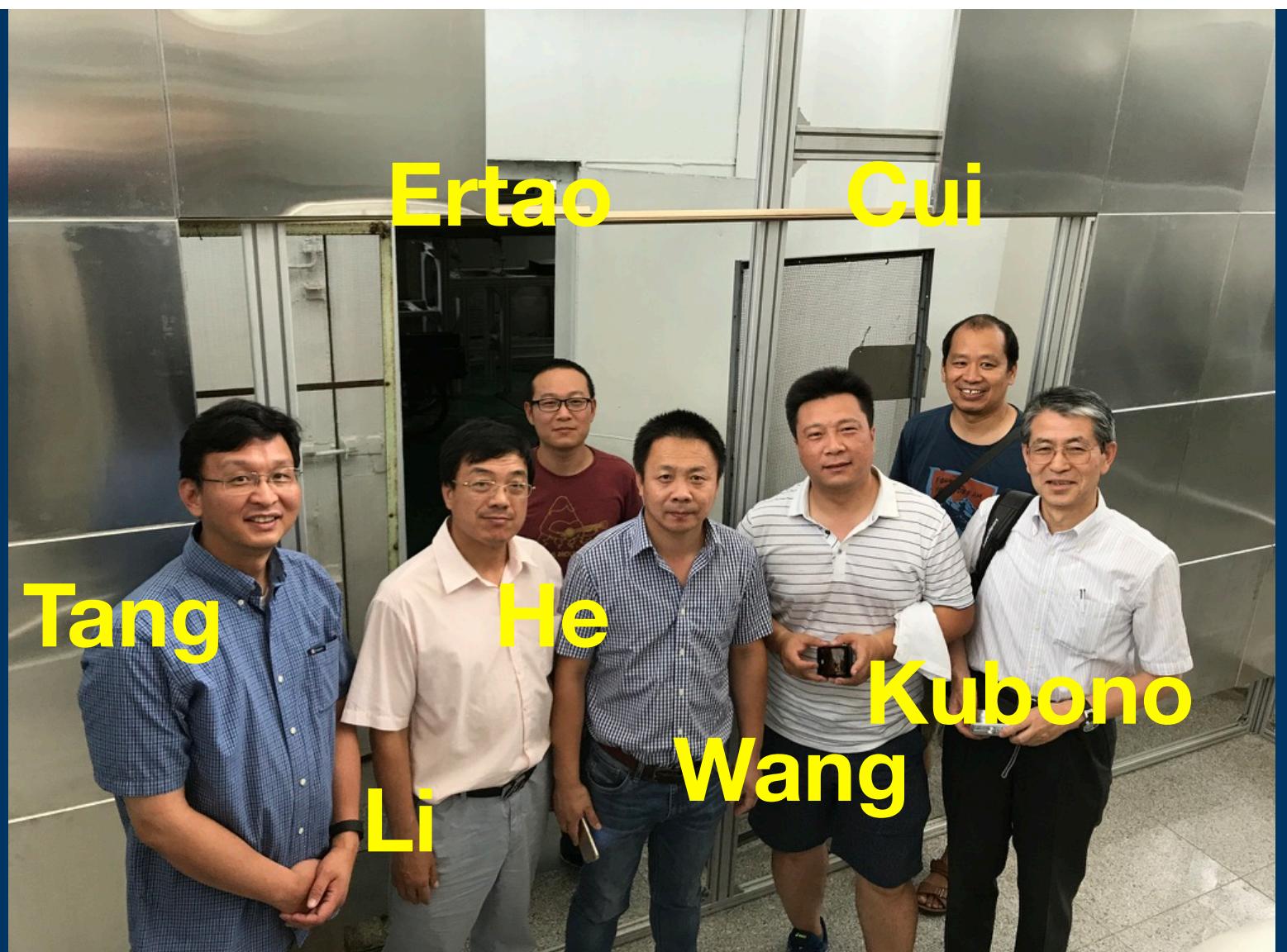
Beam diagnostics



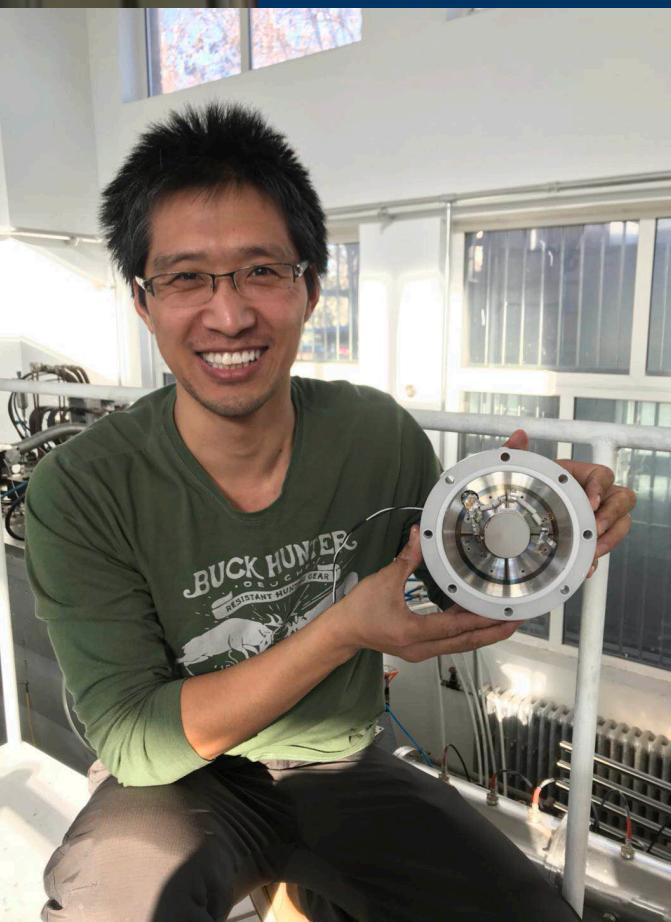
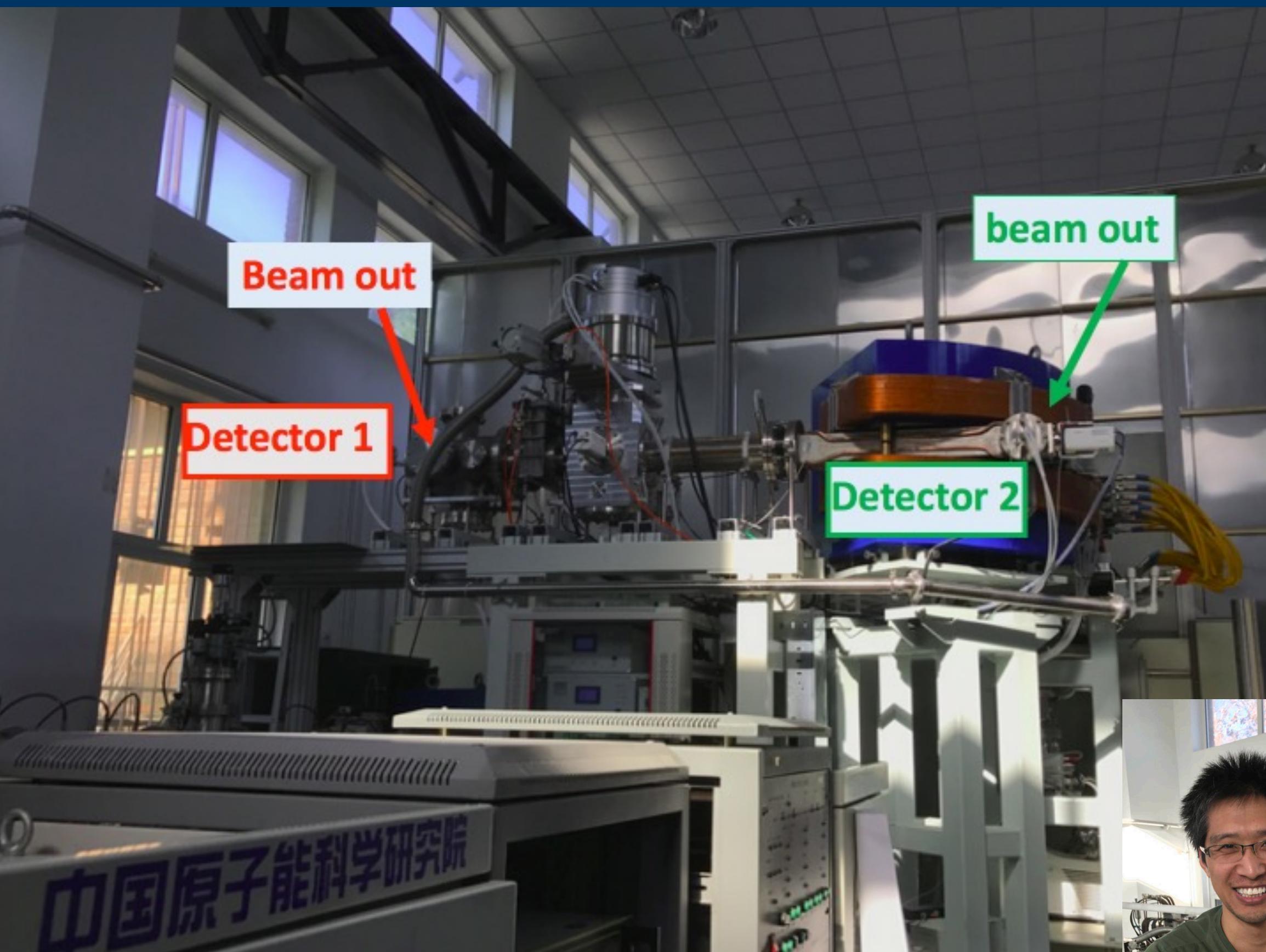
**Accelerator tank
established
8/20/16**

Ground test experiment

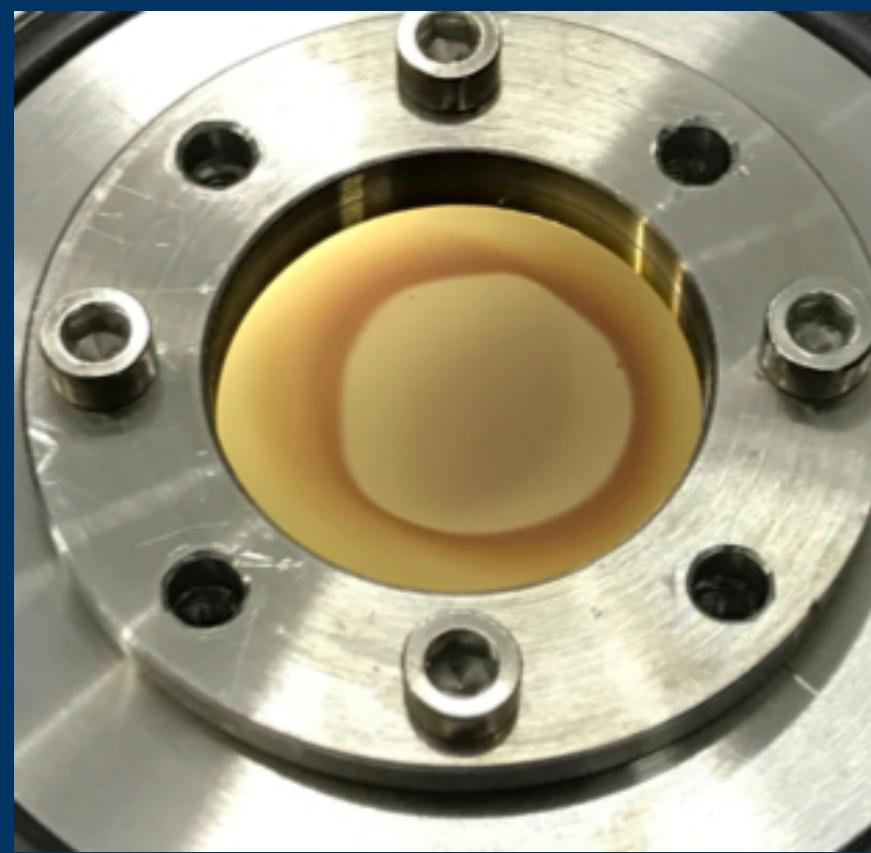
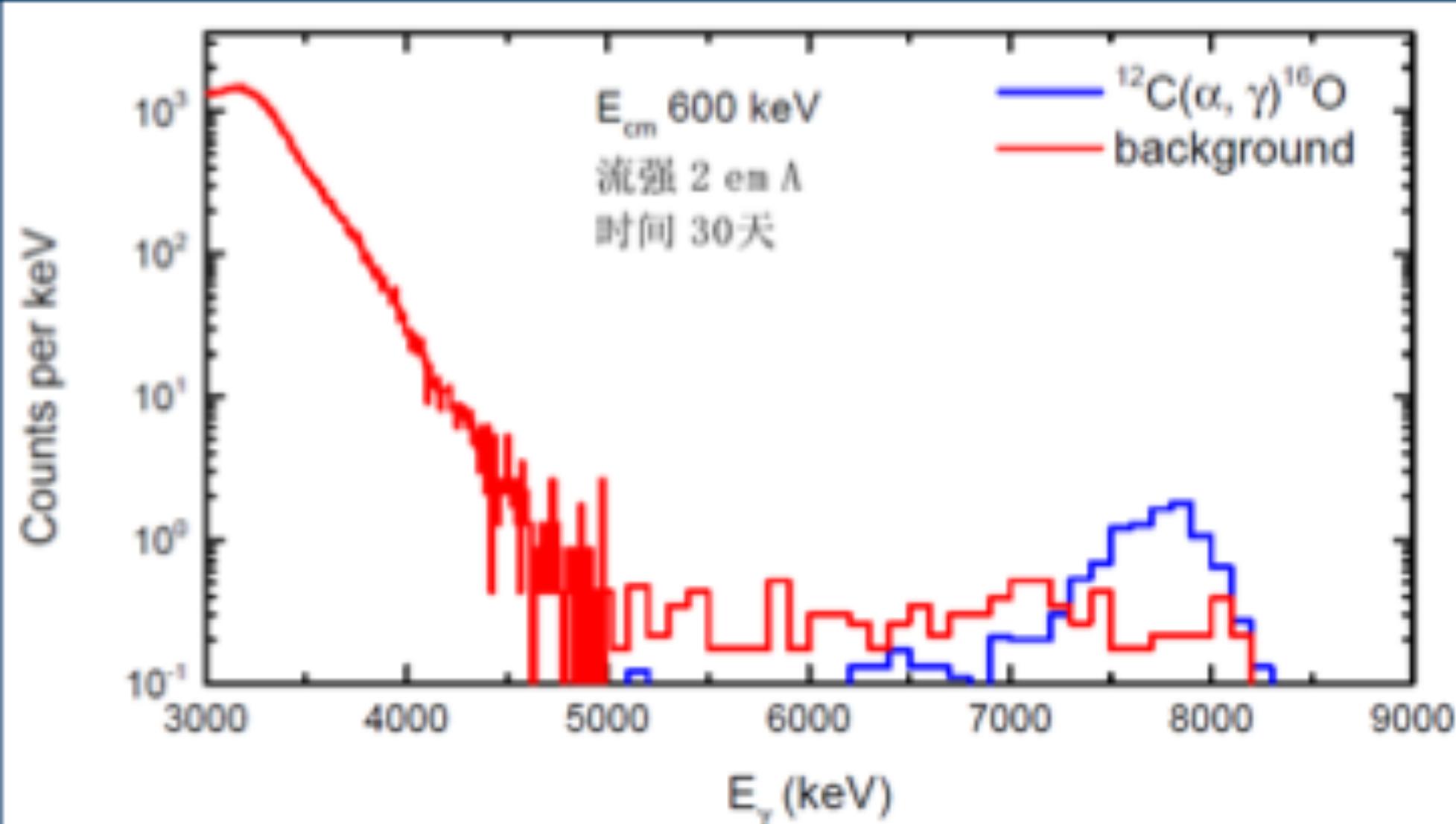
Content	Detector	Beam	Energy(keV)	Intensity
Energy calibration	HPGe (35%)	H ⁺	150-250	100 uA
Target of ²⁵ Mg	HPGe (35%)	H ⁺	230	100 uA
²⁵ Mg(p, γ) ²⁶ Al	HPGe (175%)	H ⁺	210-330	0.1-1 mA
²⁵ Mg(p, γ) ²⁶ Al	BGO	H ⁺	210-330	0.1-1 mA
¹⁹ F(p, $\alpha\gamma$) ¹⁶ O	BGO	H ⁺	150-300	10-100 uA
Target of ¹³ C	----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



W. P. Liu OMEG, July , 2019

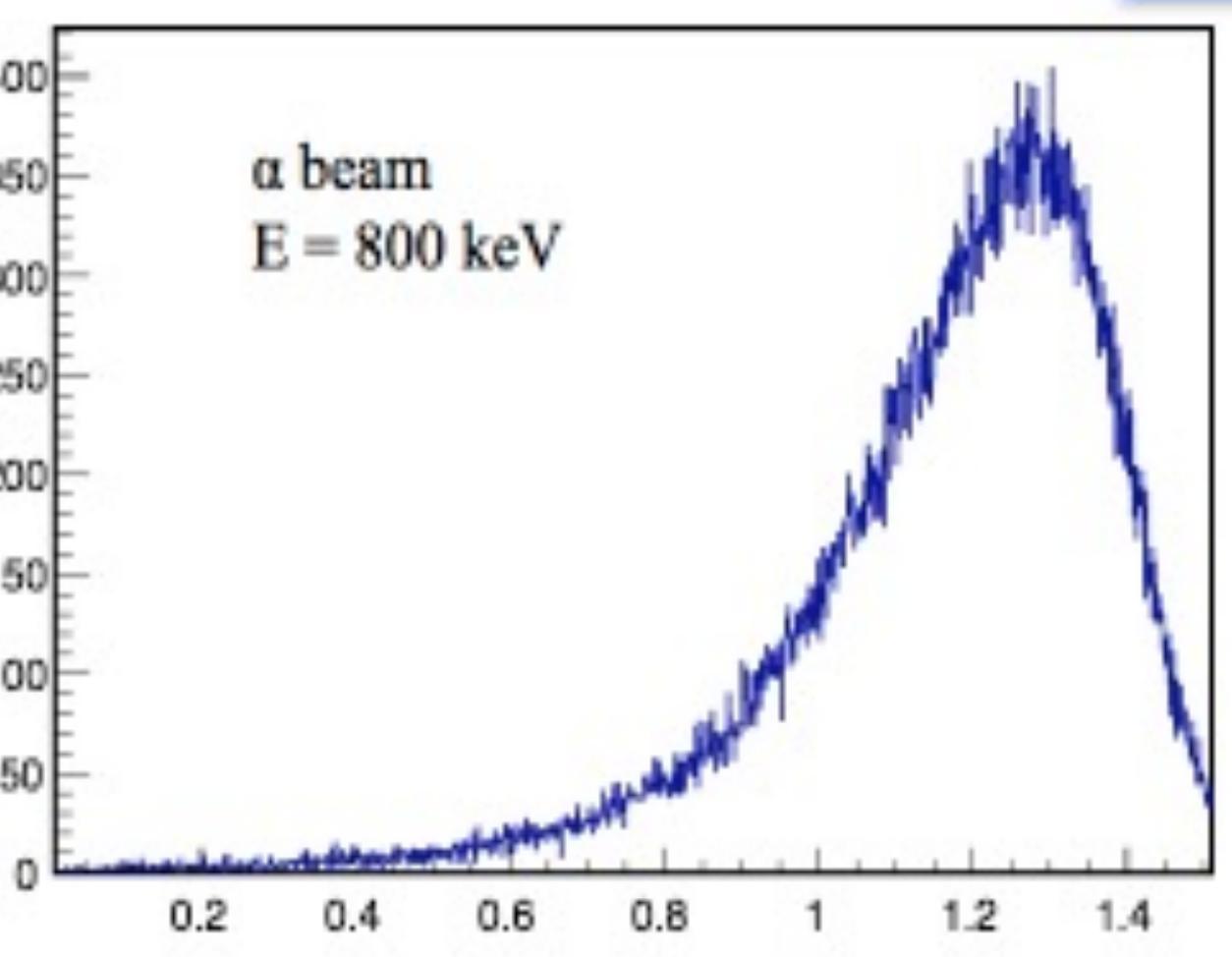
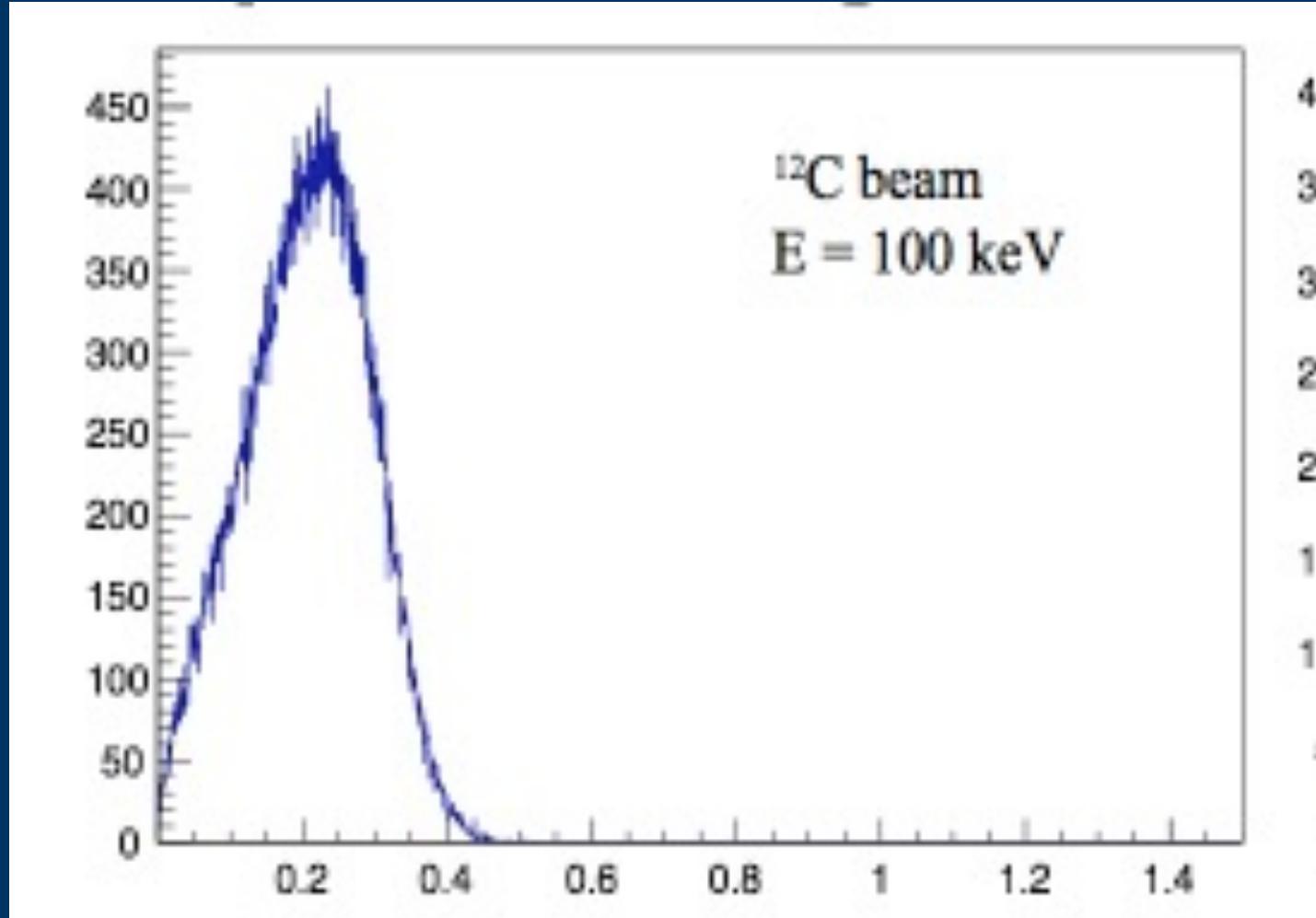


$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ status



	Det	E, kev	σ, b	$\epsilon, \%$	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

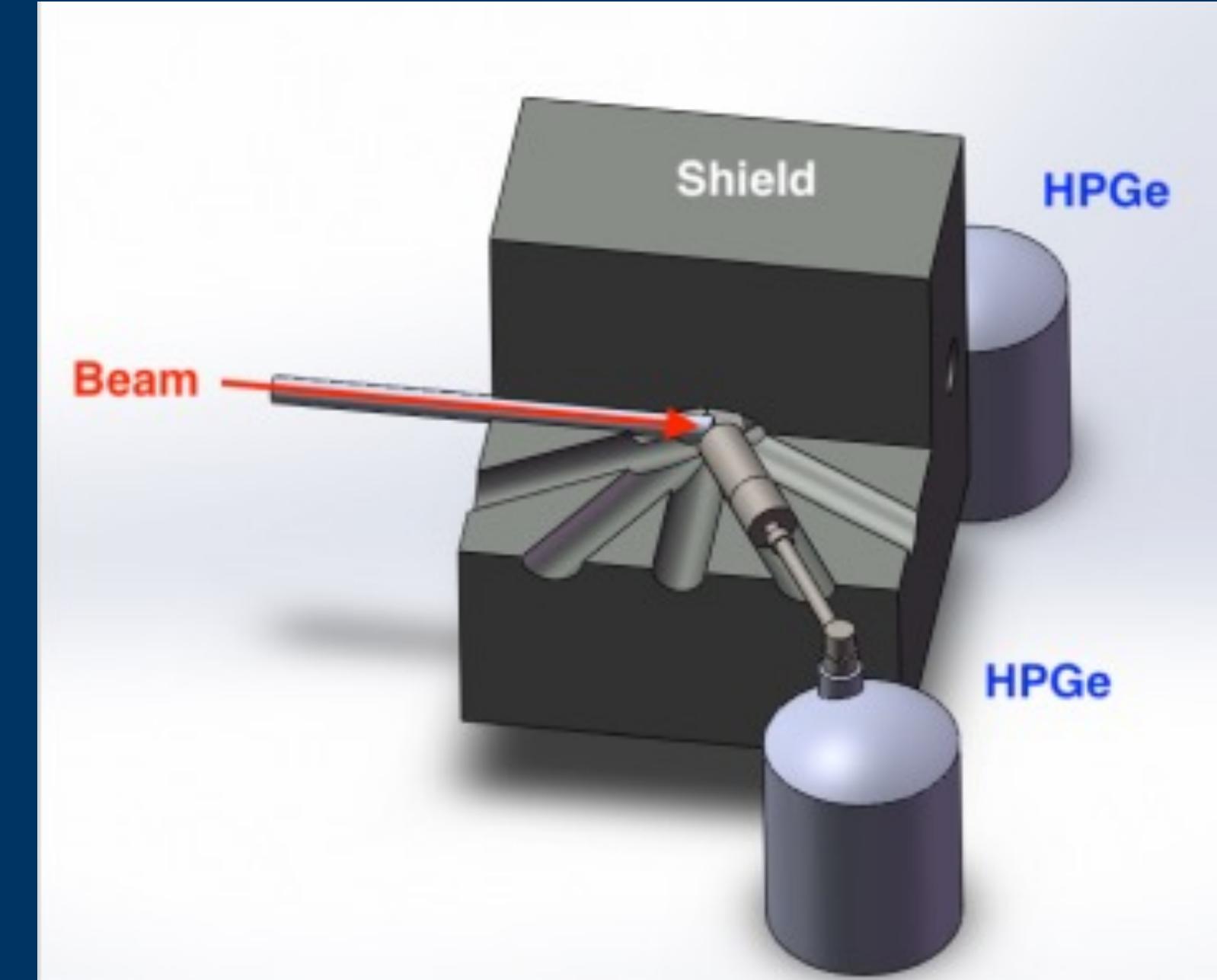
Simulation for BGO



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

W. P. Liu OMEG, July , 2019

^{12}C implantation target in Lanzhou



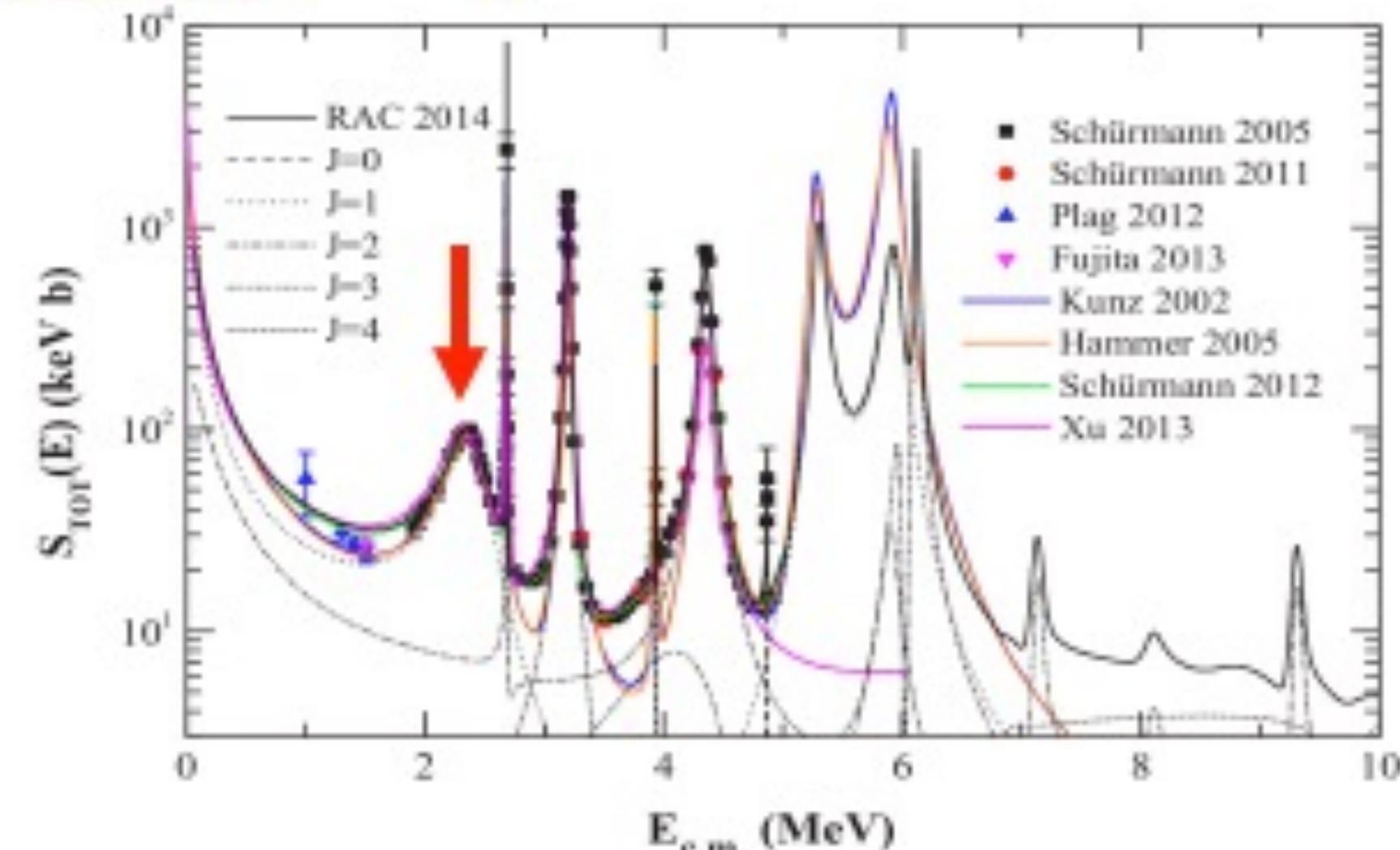
High energy point for $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$

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

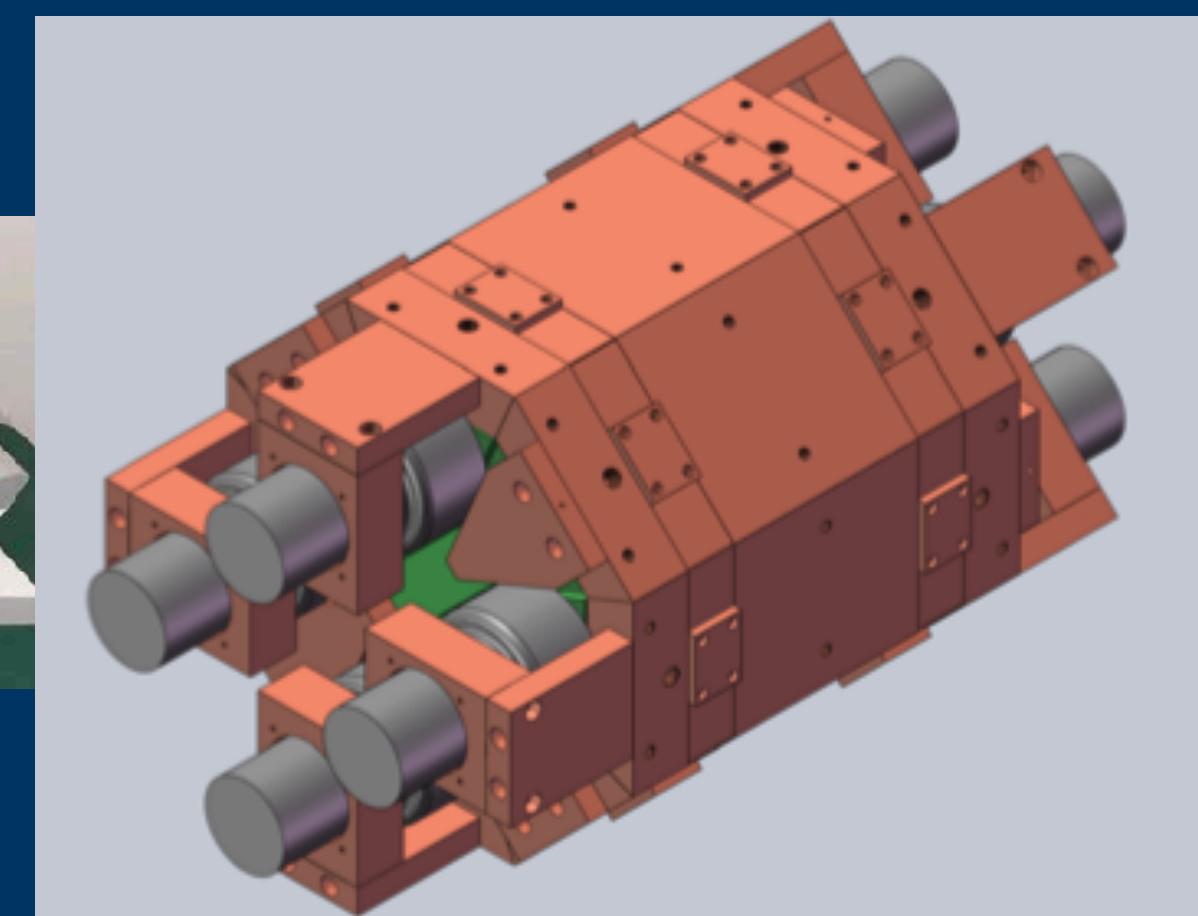
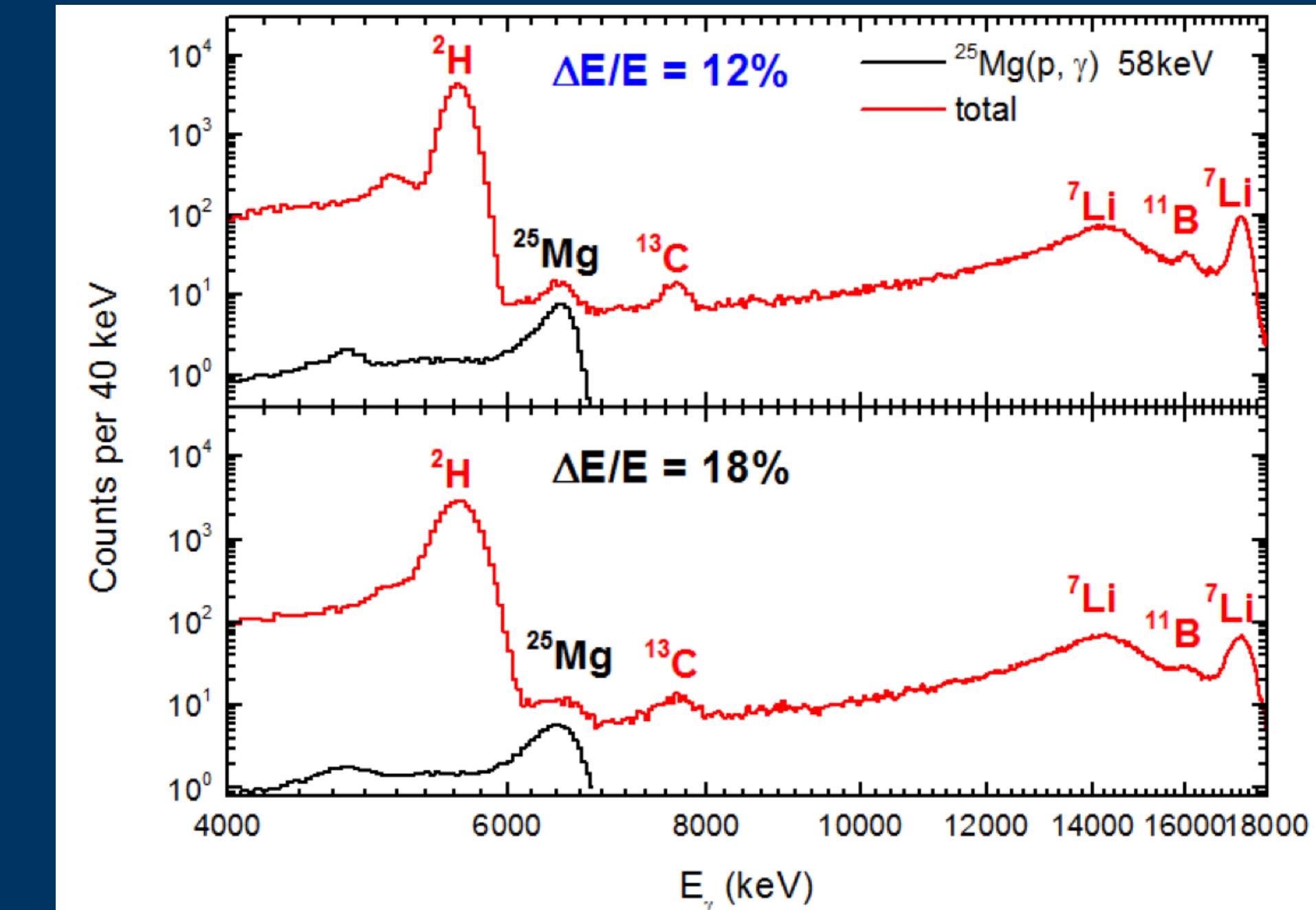
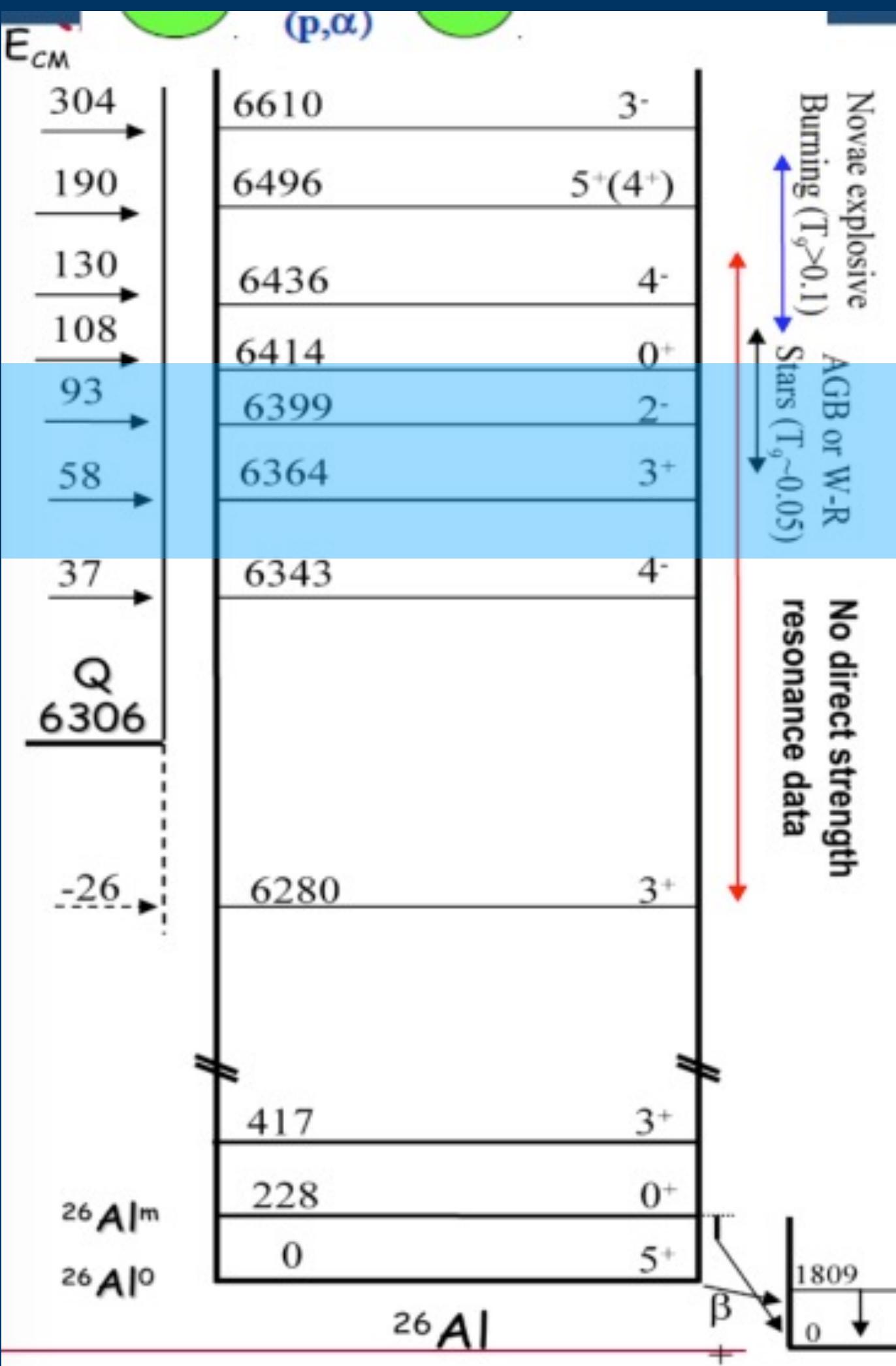
3 MV accelerator in SCU

beam : He^{2+} , 5 μA

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



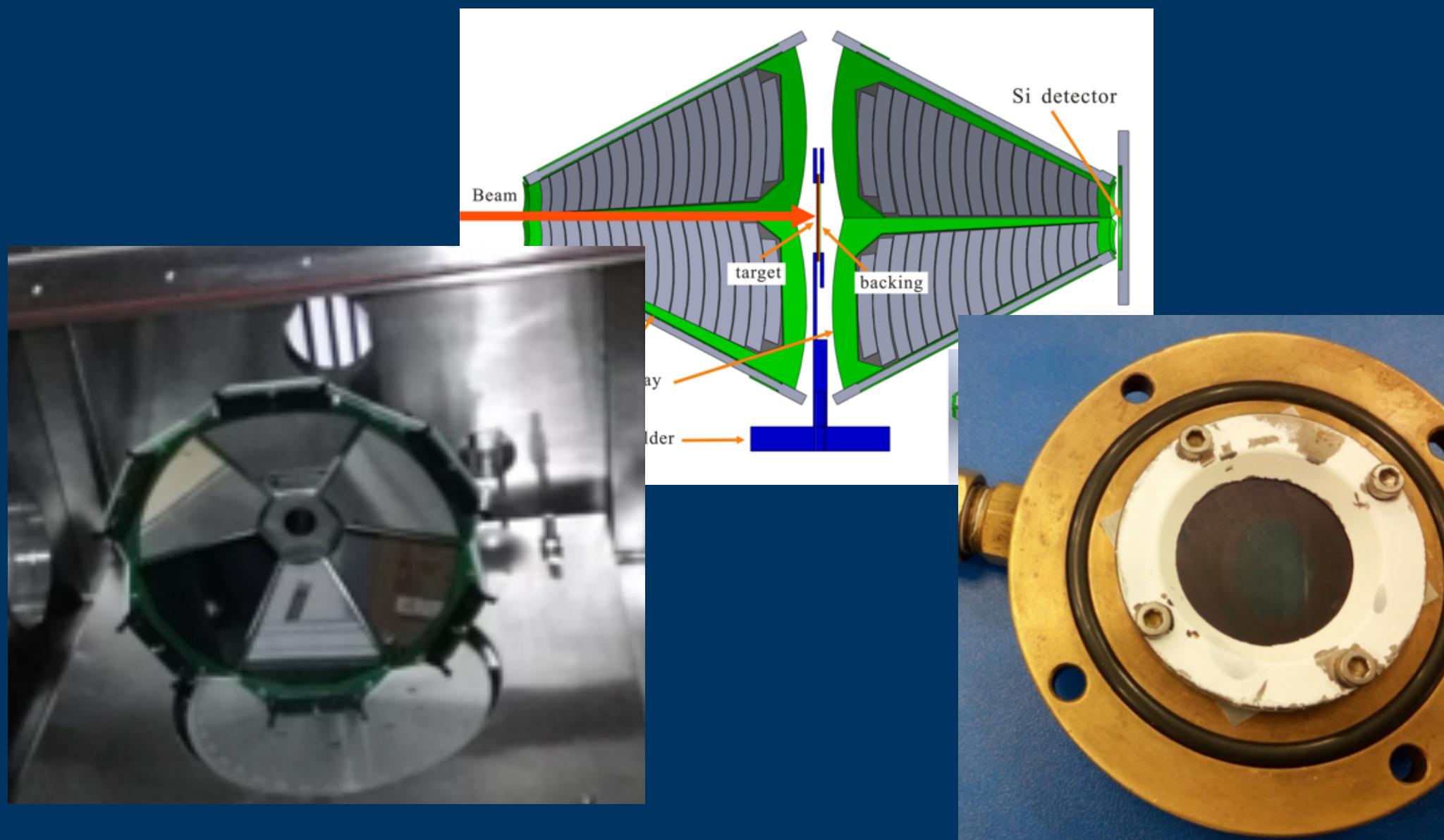
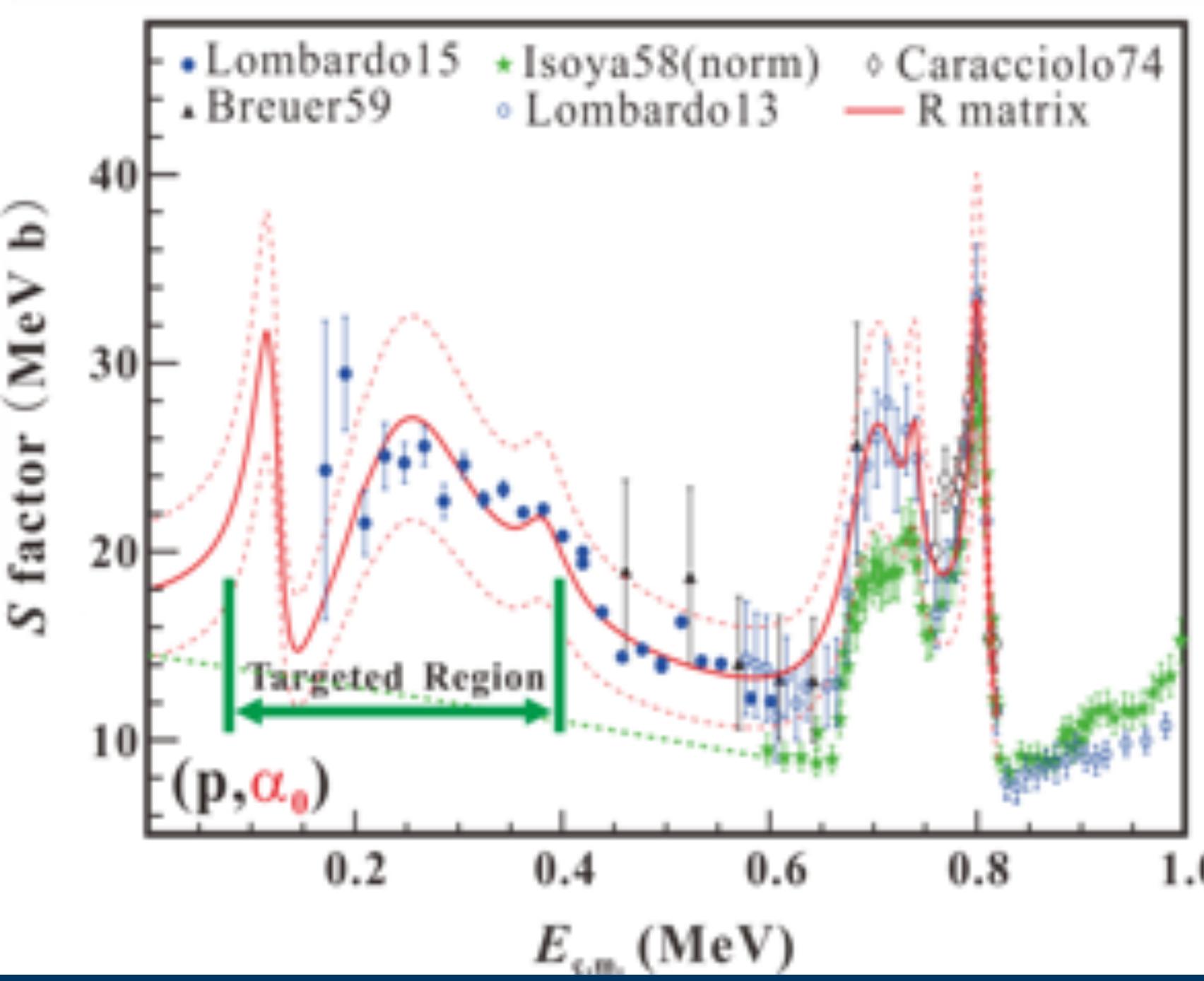
$^{25}\text{Mg}(\text{p},\gamma)^{26}\text{Al}$ status



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

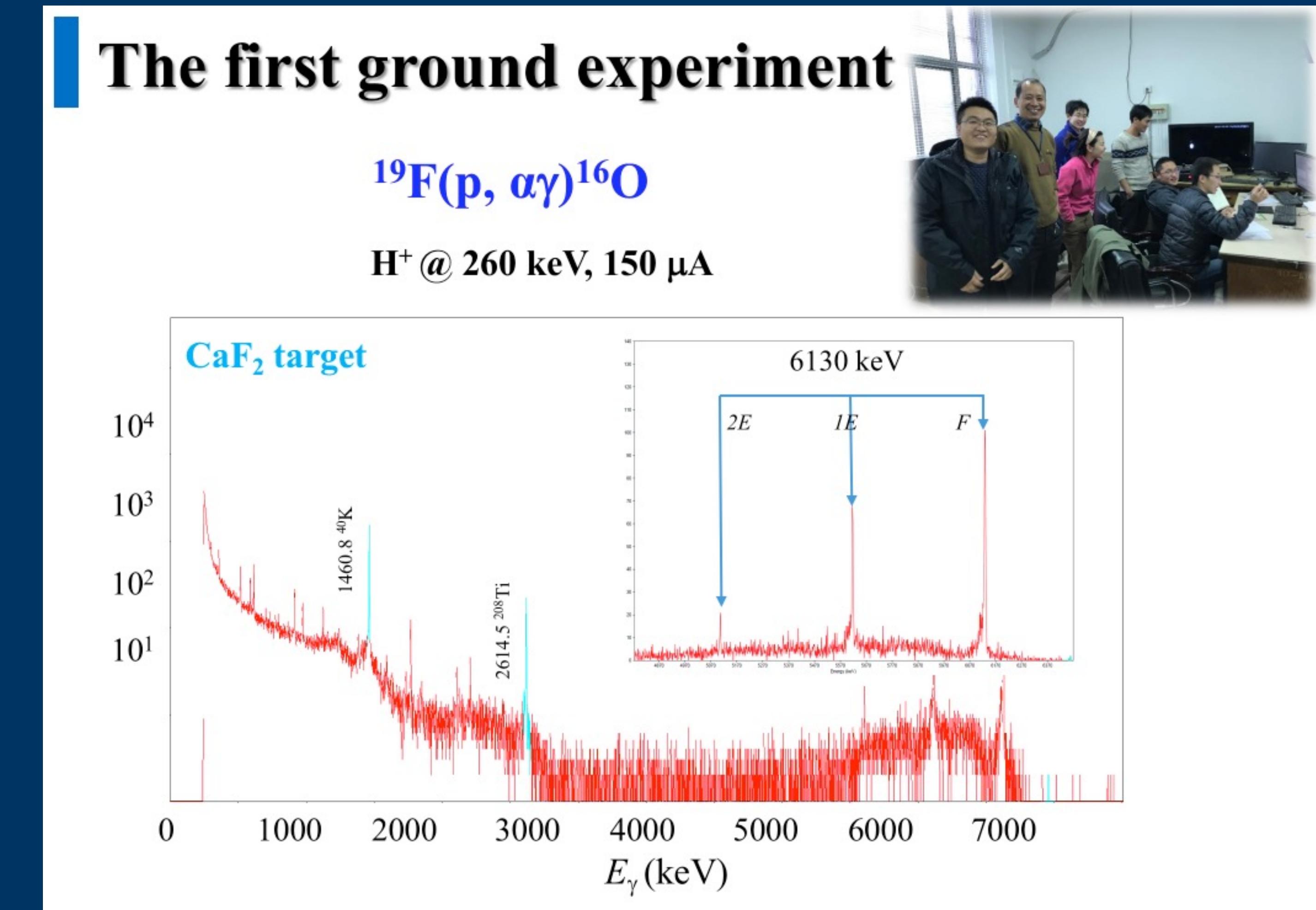
W. P. Liu OMEG, July , 2019

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



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

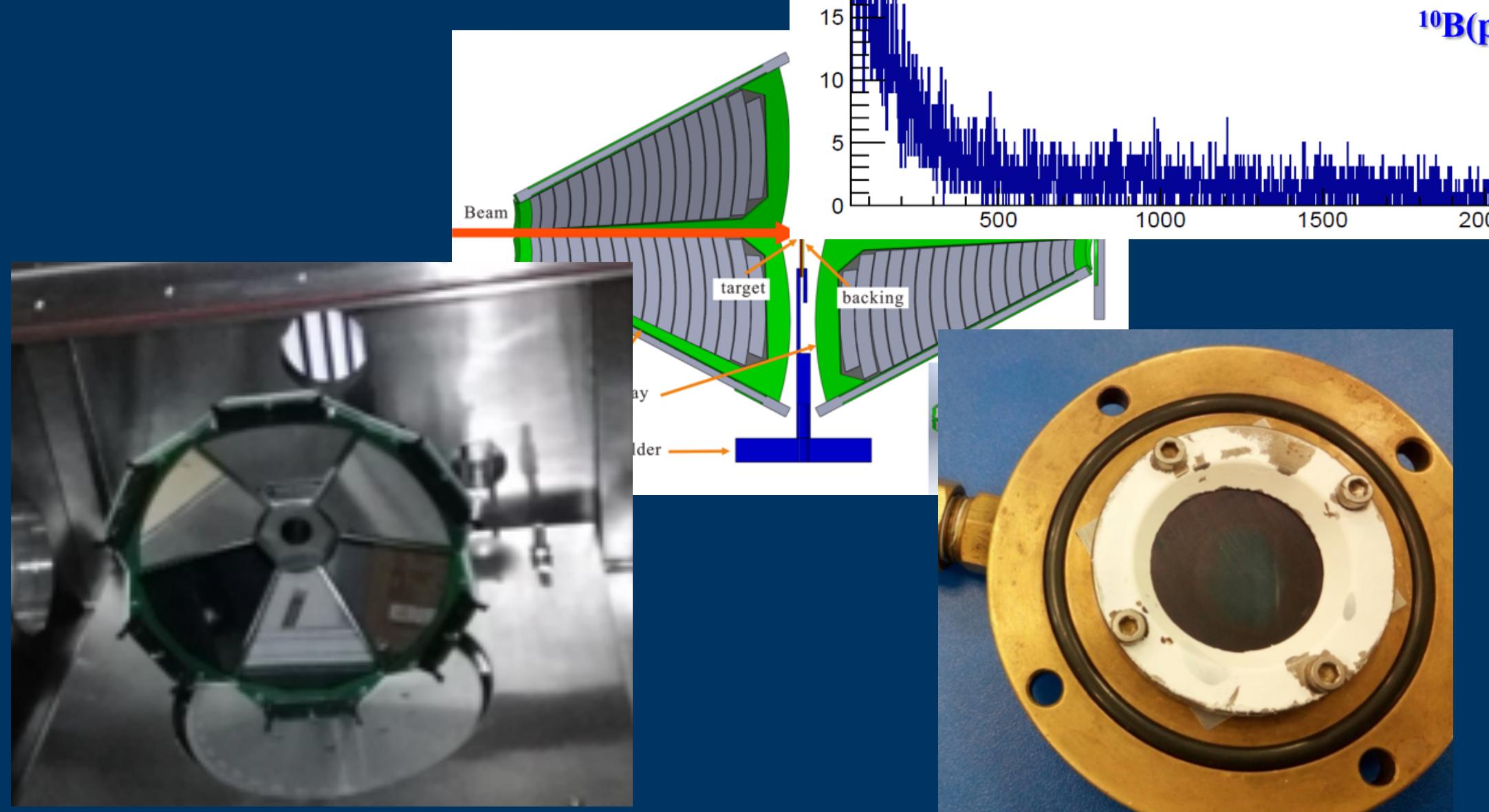
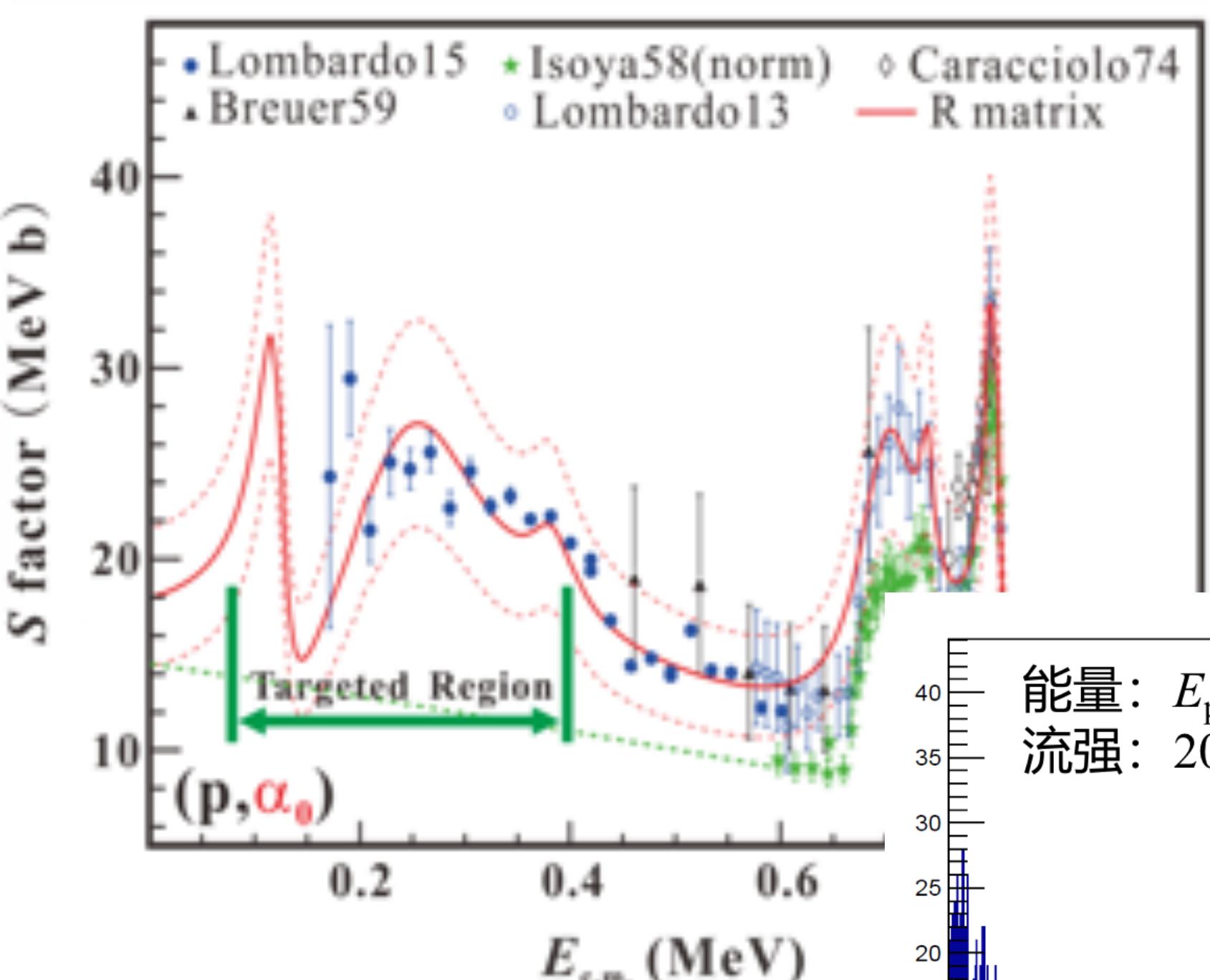
W. P. Liu OMEG, July , 2019



Stable under 1.5 C bombardment !

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

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

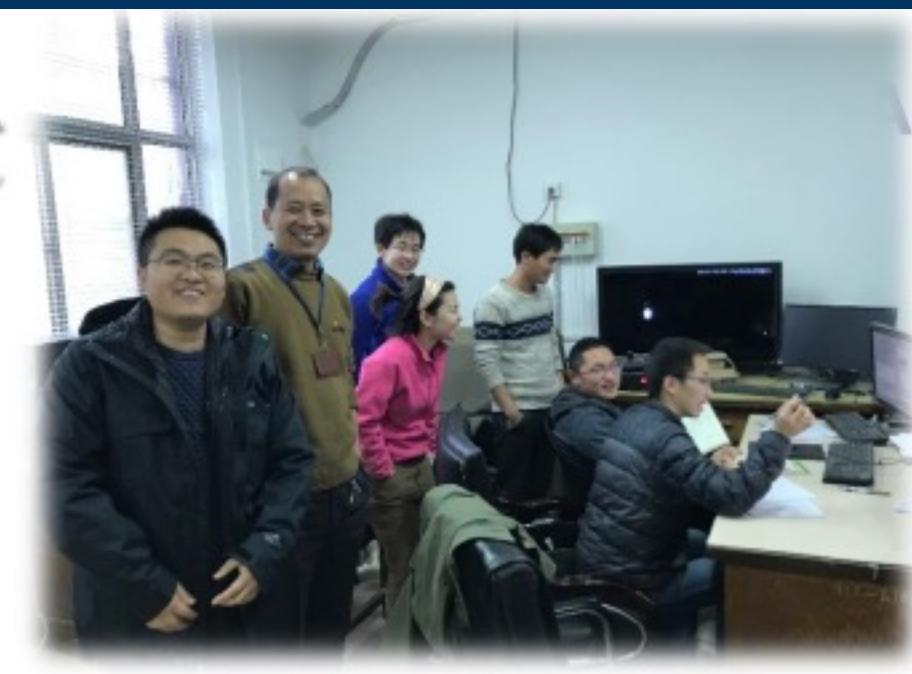
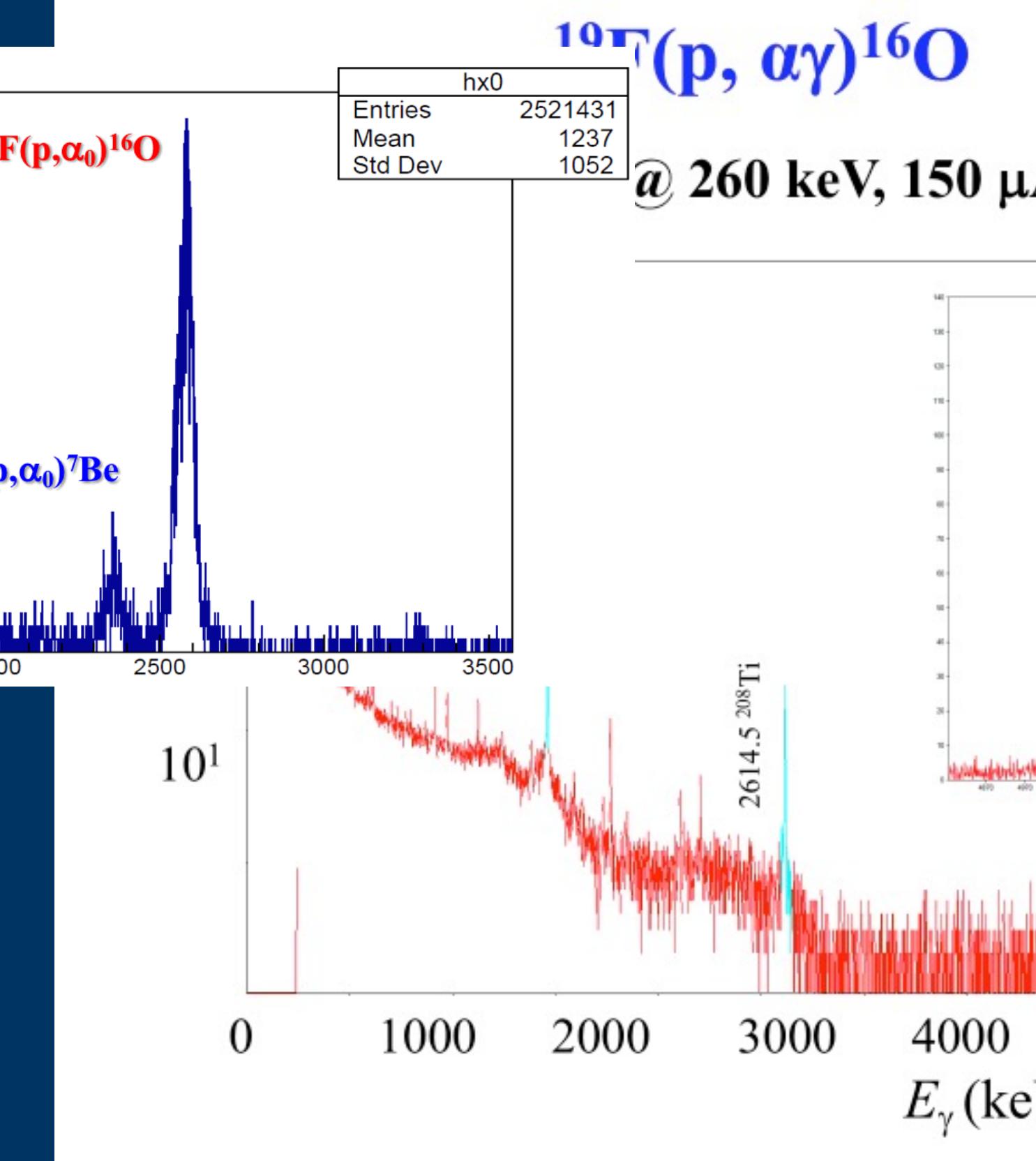


$^{19}\text{F}(\text{p},\alpha_0)$ channel: Silicon Detectors

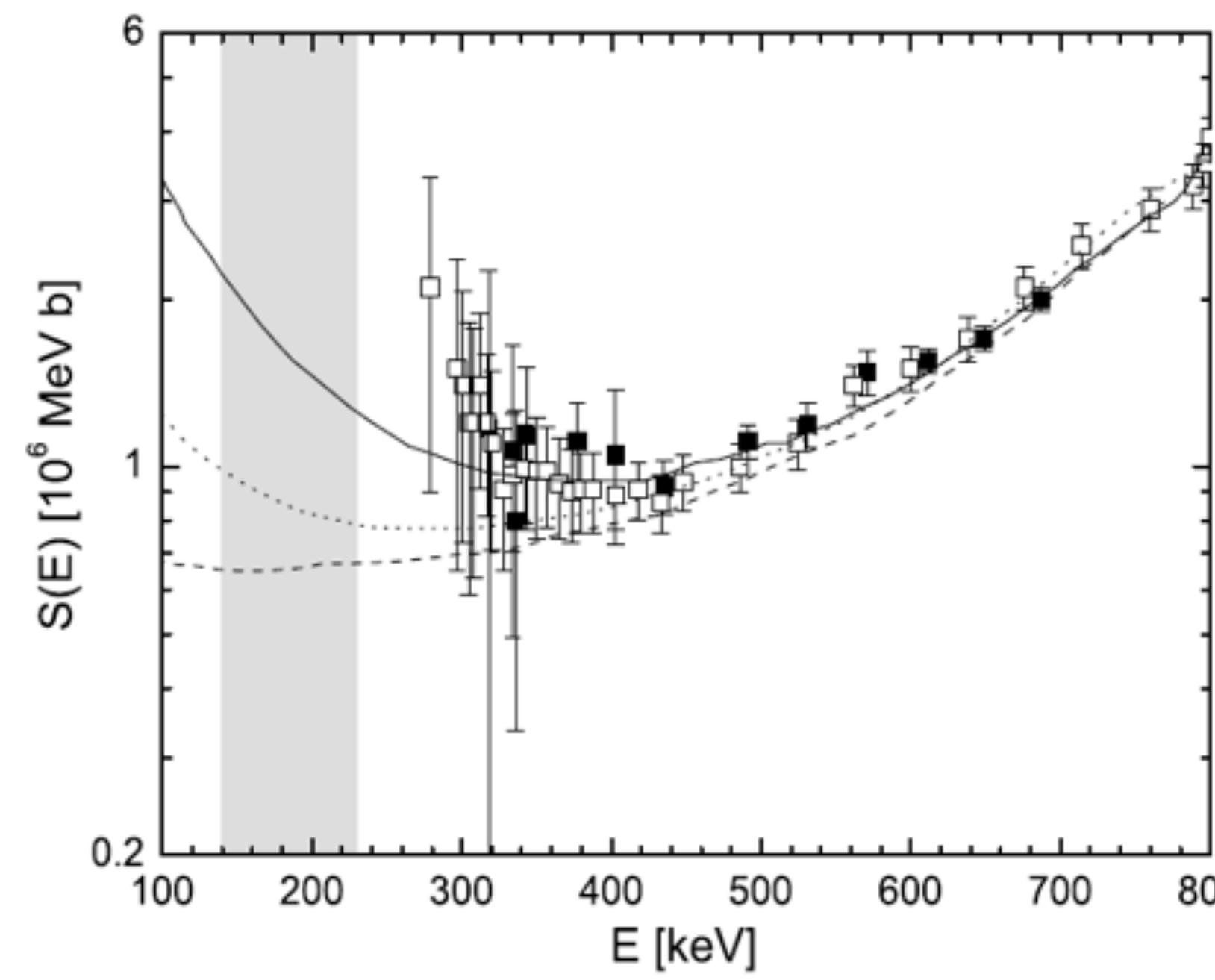
W. P. Liu OMEG, July , 2019

Stable under 1.5 C bombardment !

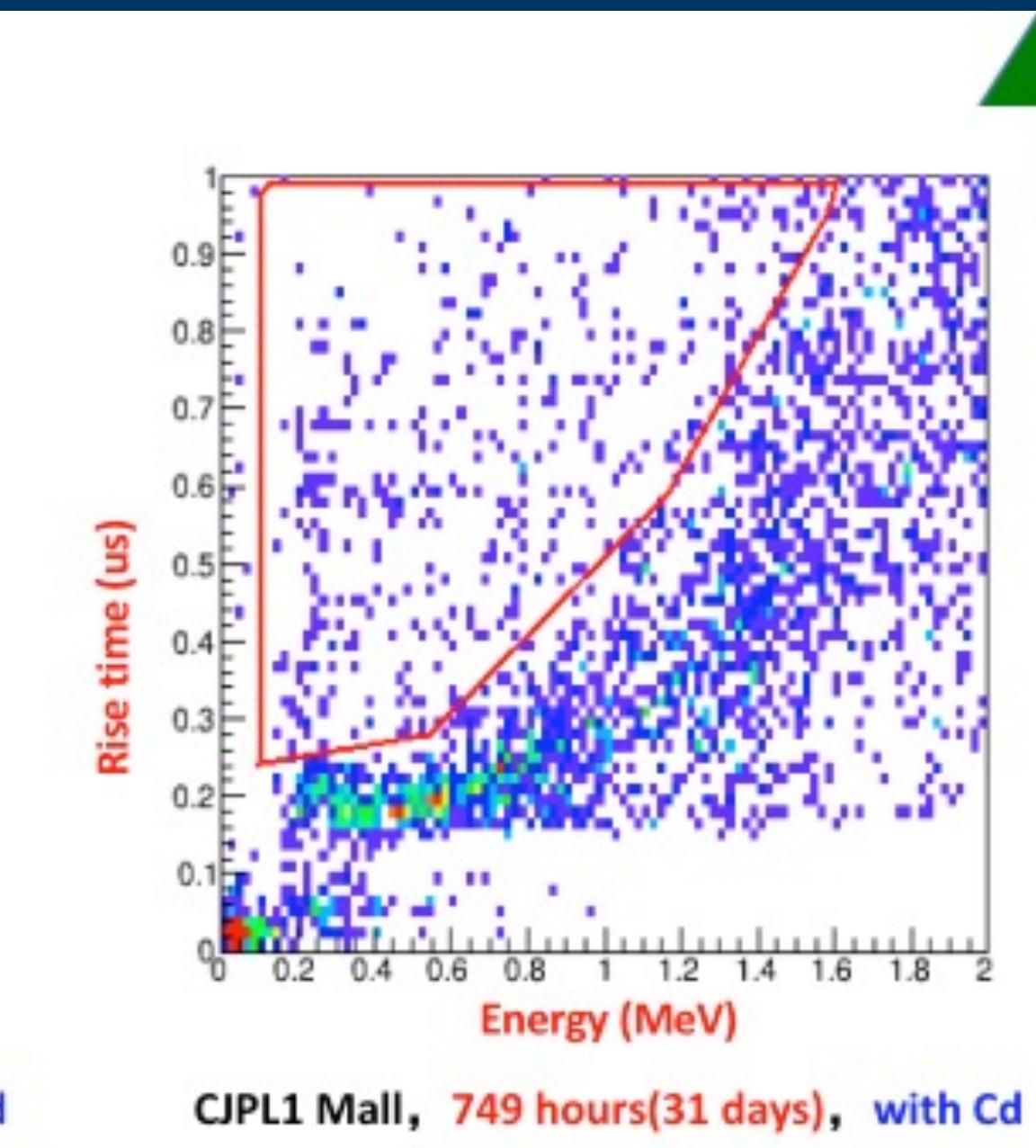
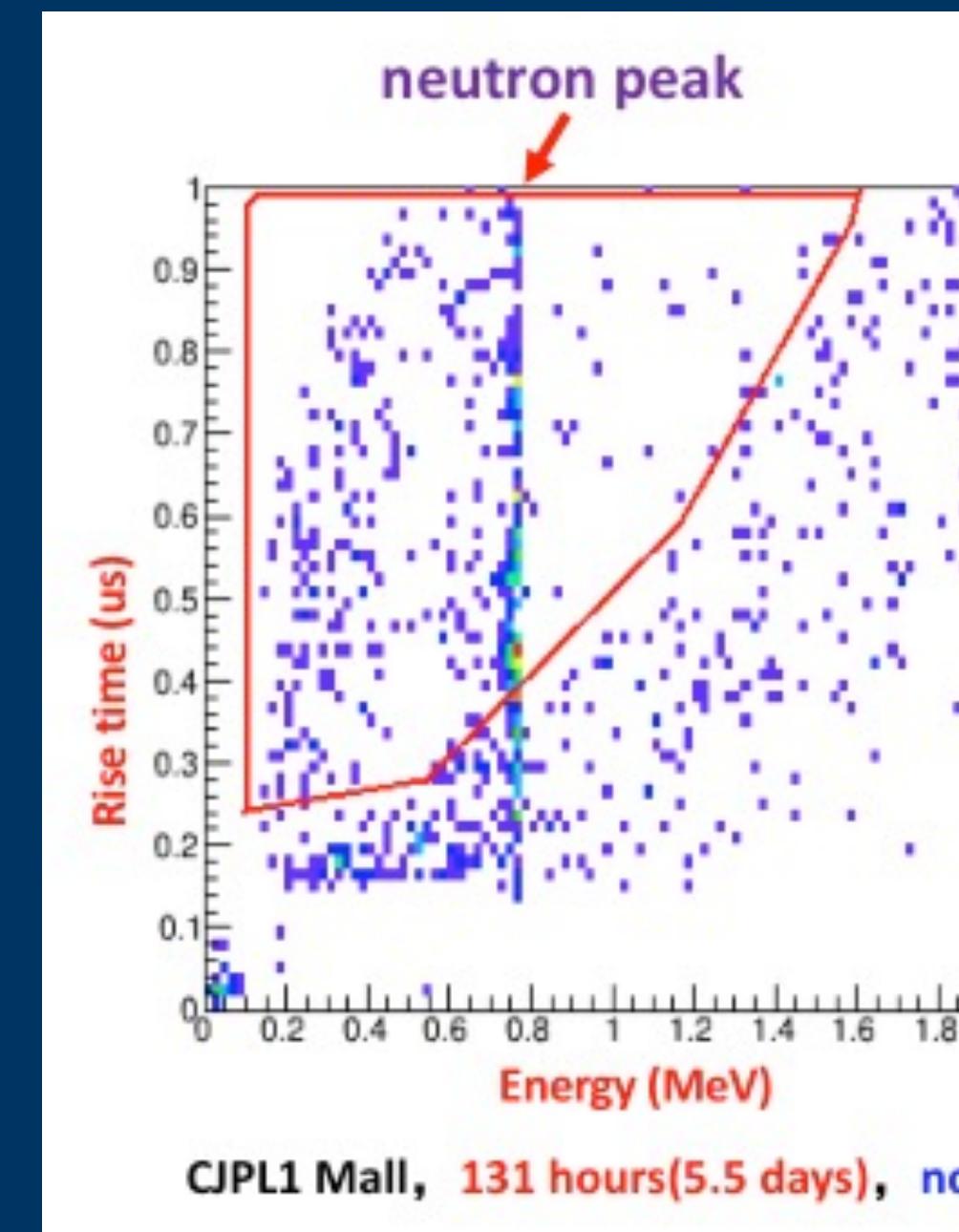
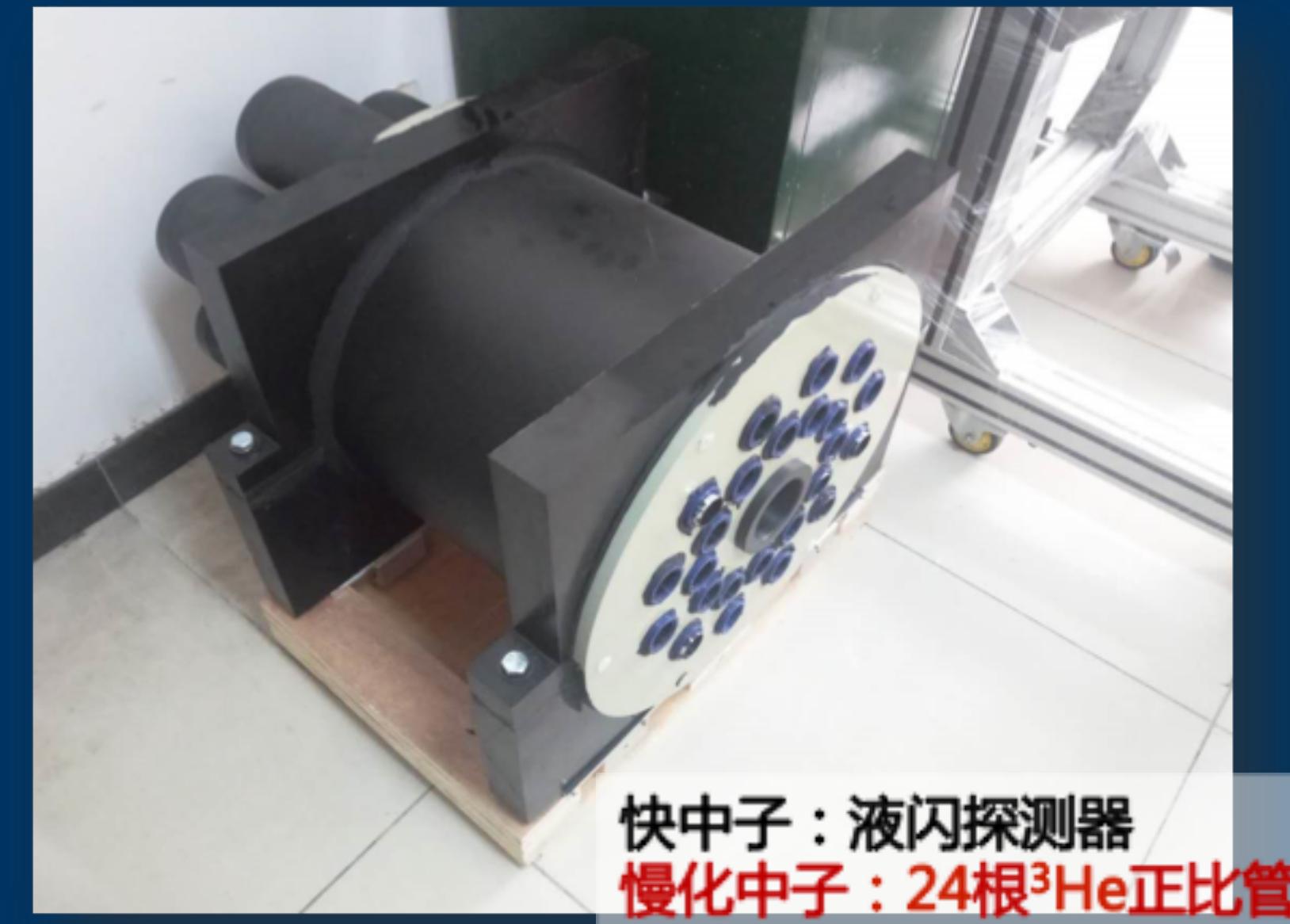
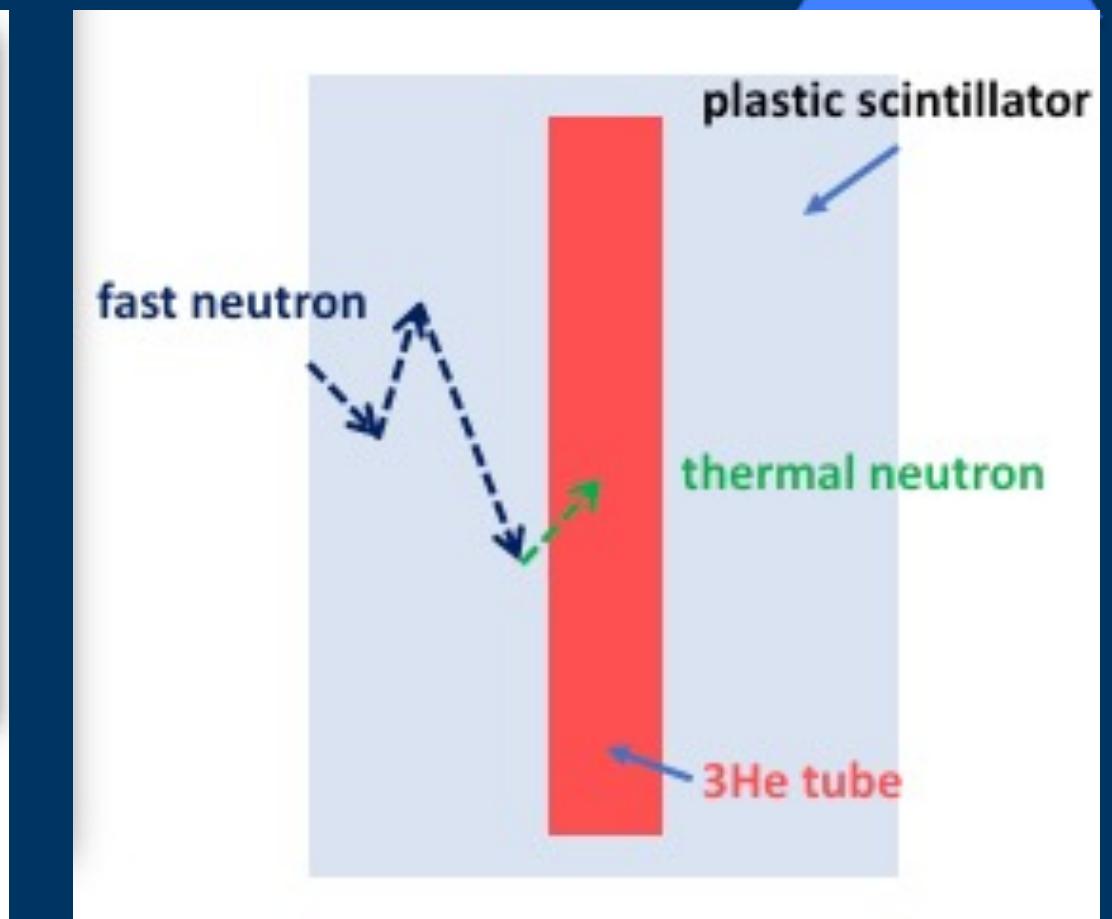
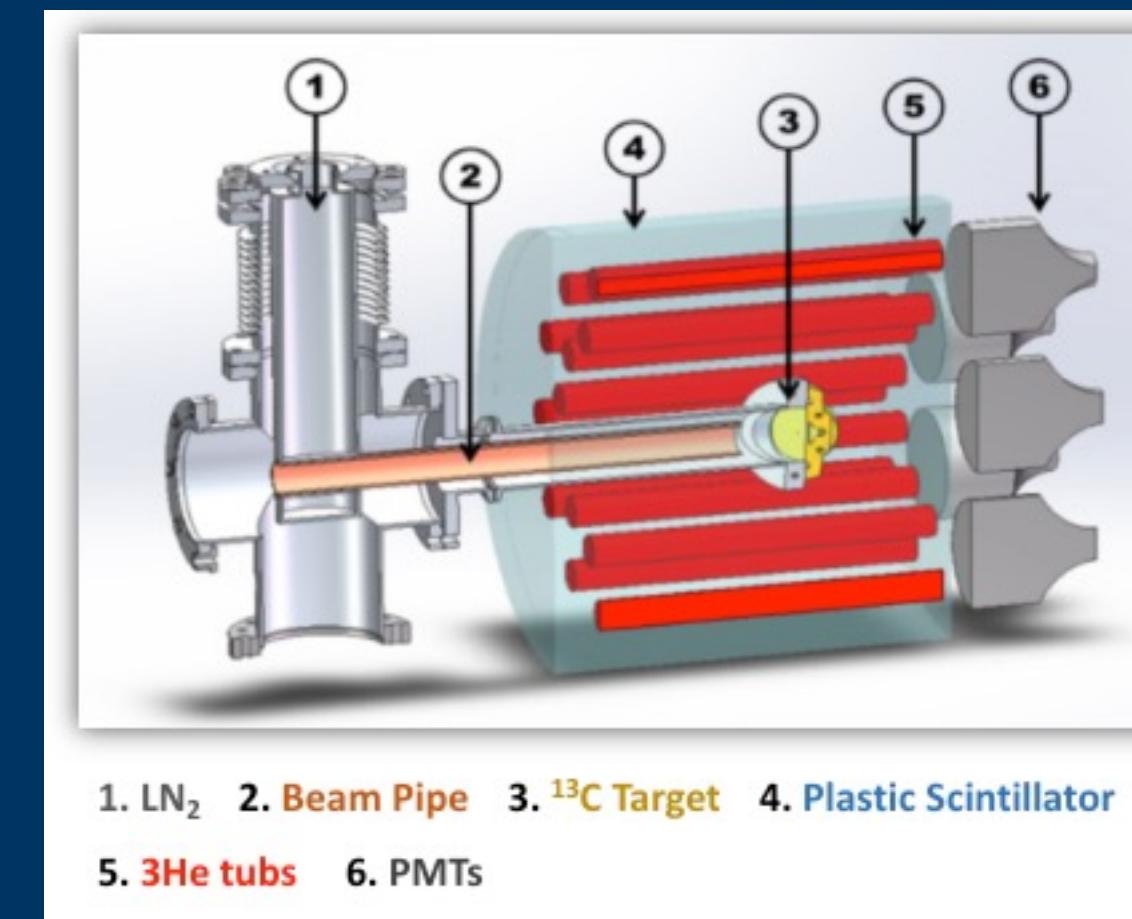
The first ground experiment



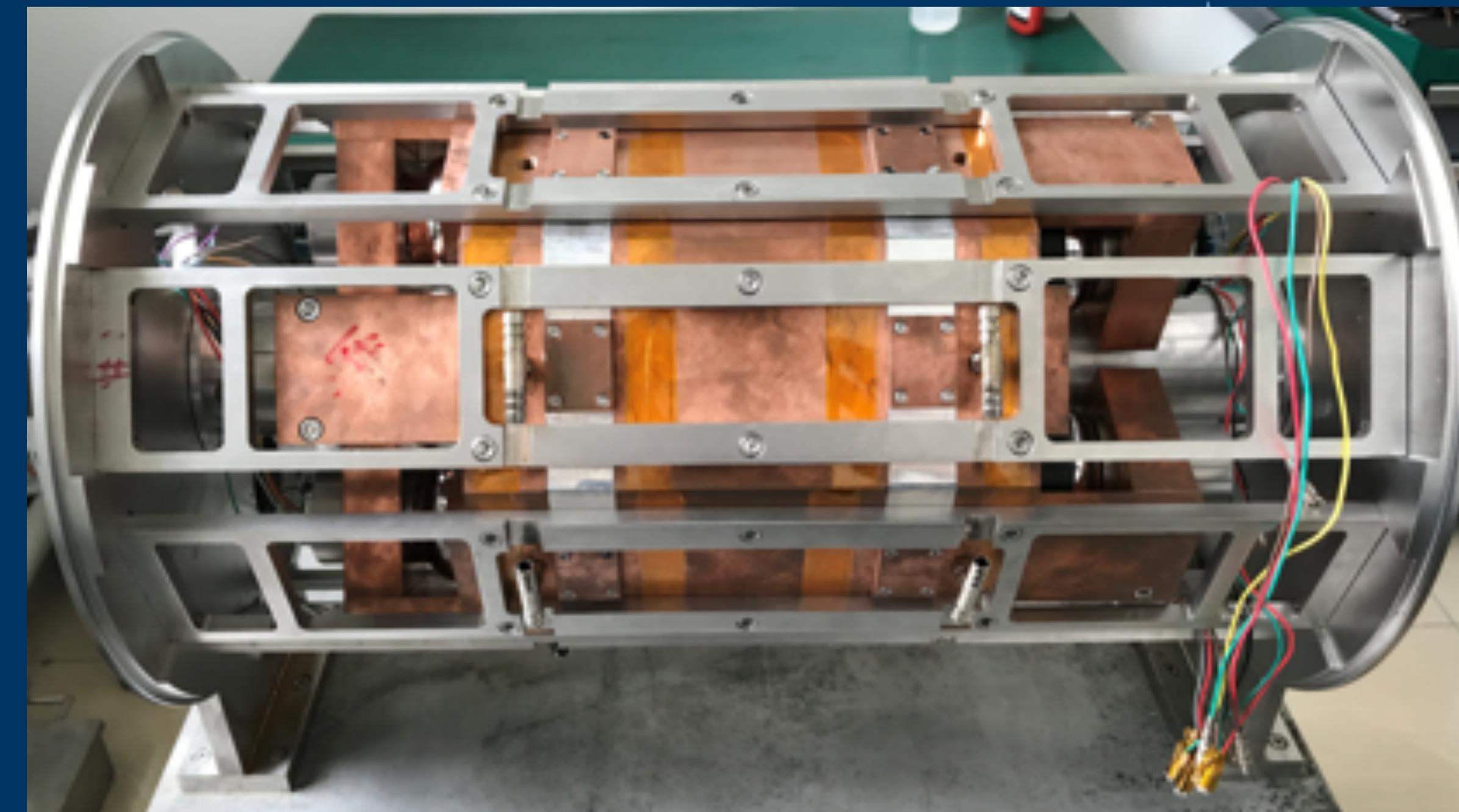
J. J. He et al., Sci. China Phys 59. 652001(2016)



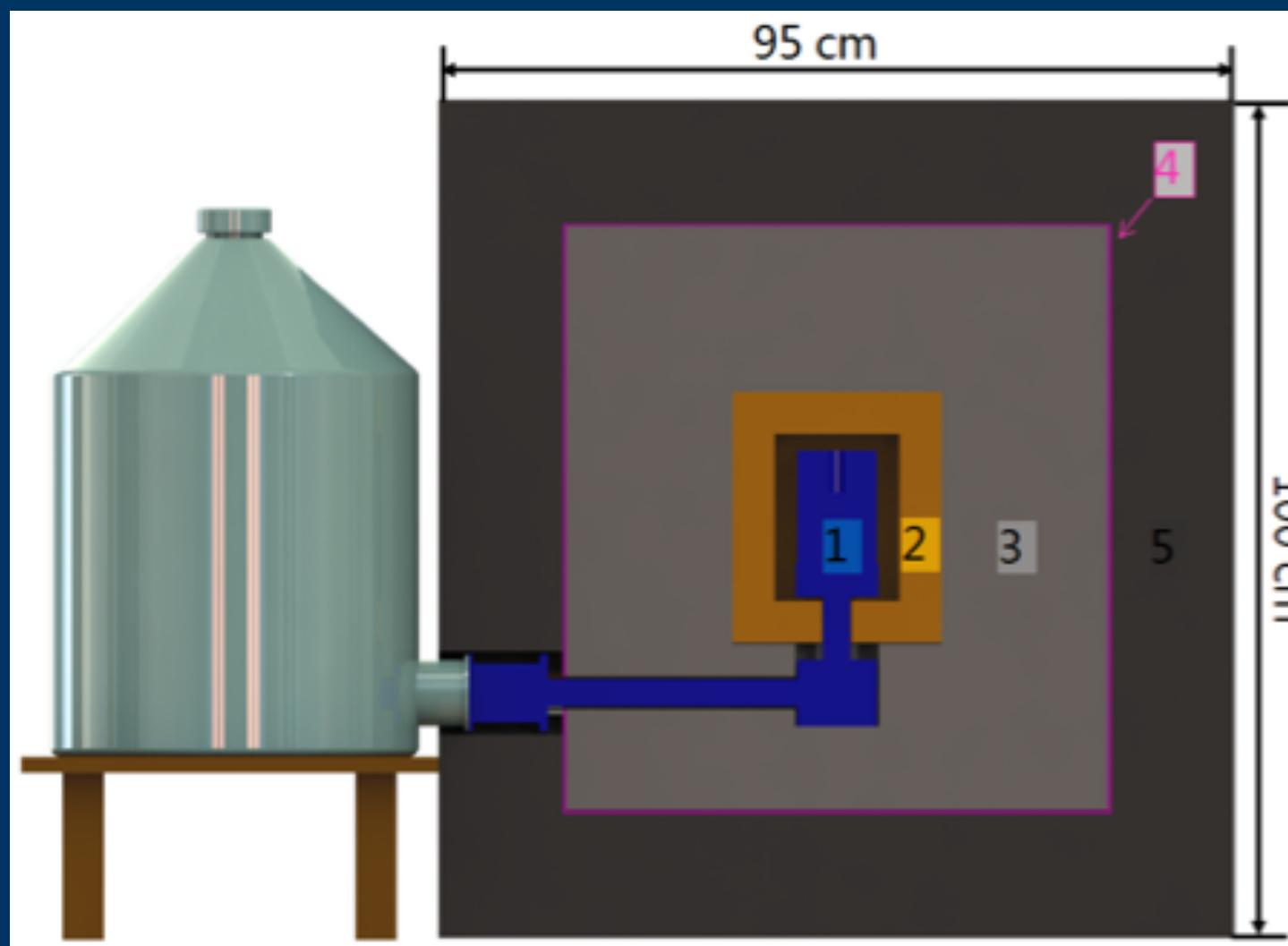
$^{13}\text{C}(\text{a},\text{n})^{16}\text{O}$ status,



Detector status

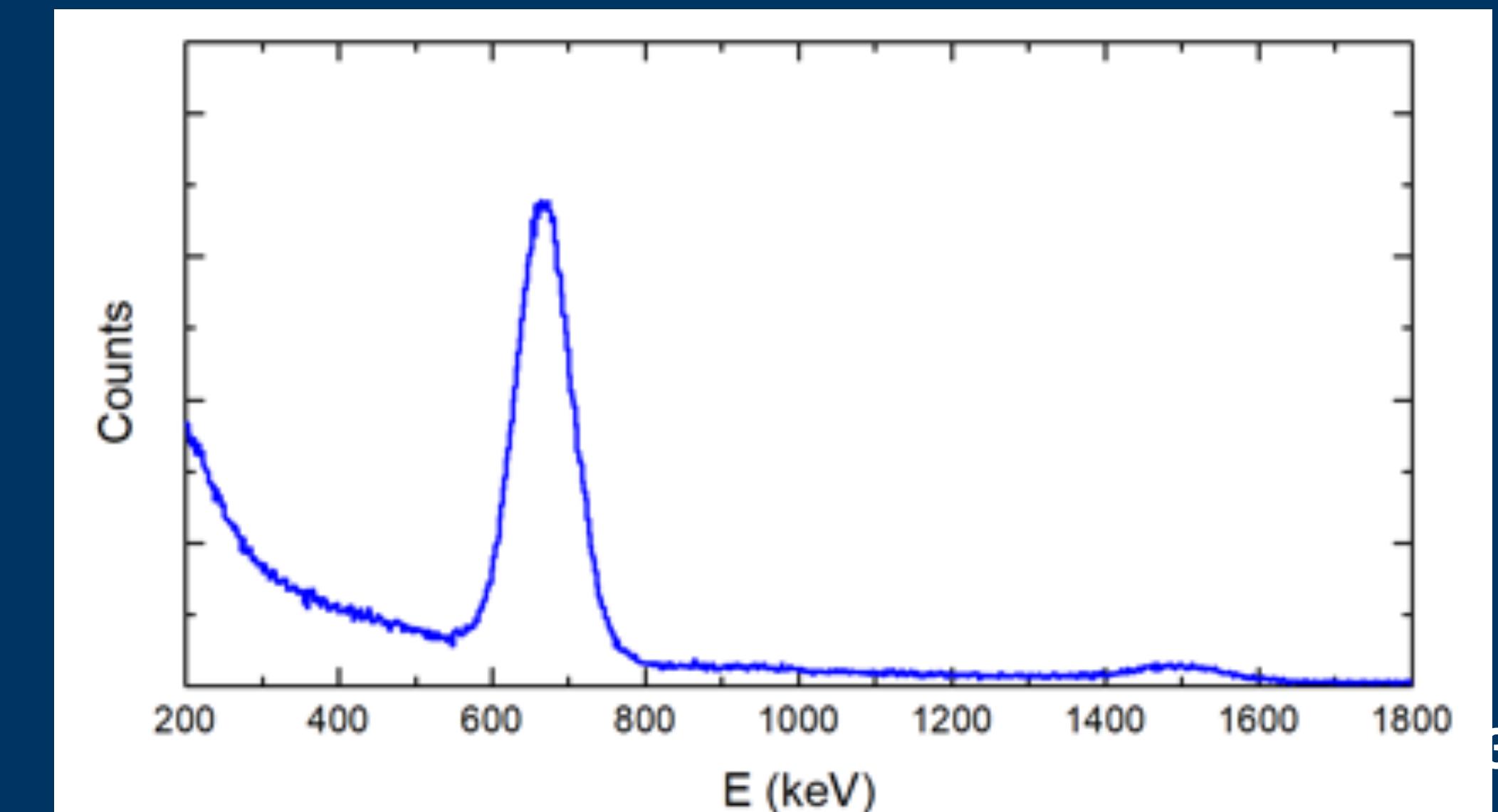


HPGe, $\Delta E = 2 \text{ keV@1332 keV}$;
 $\varepsilon = 0.8 \% @7 \text{ MeV}$



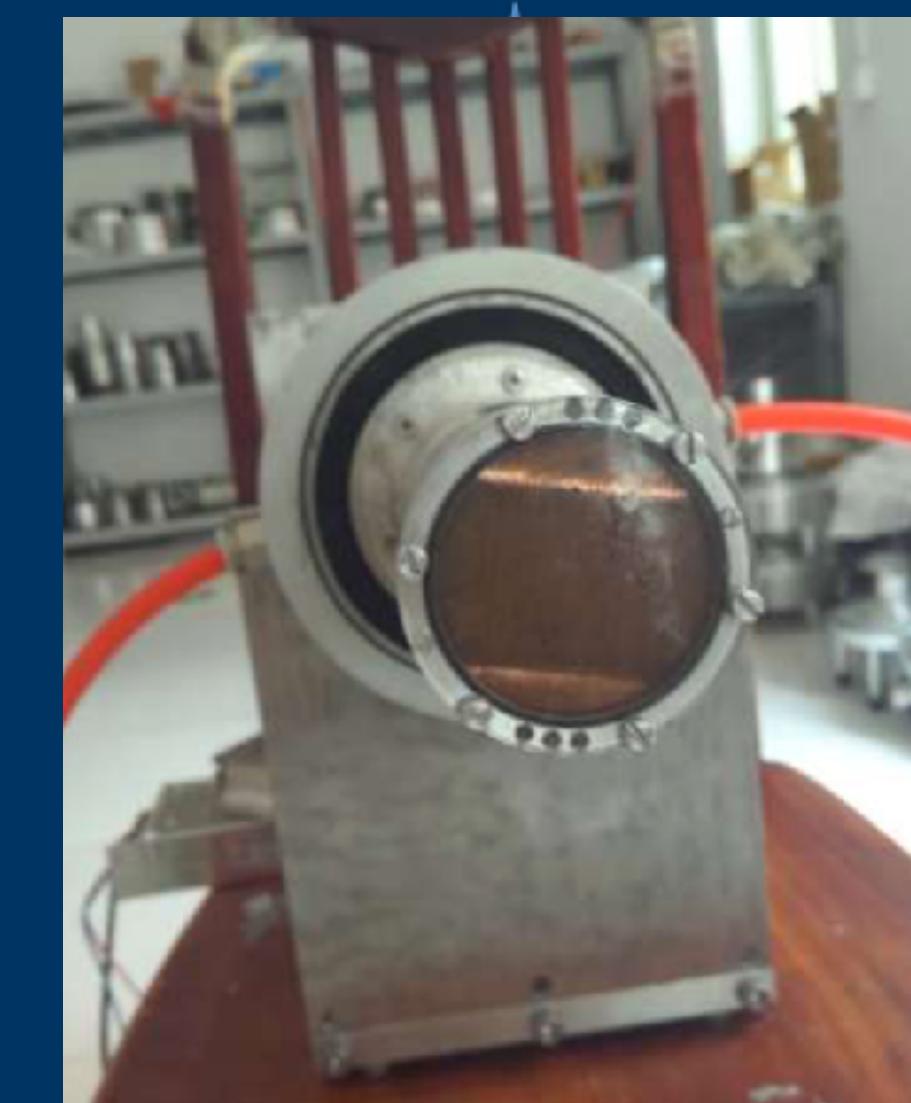
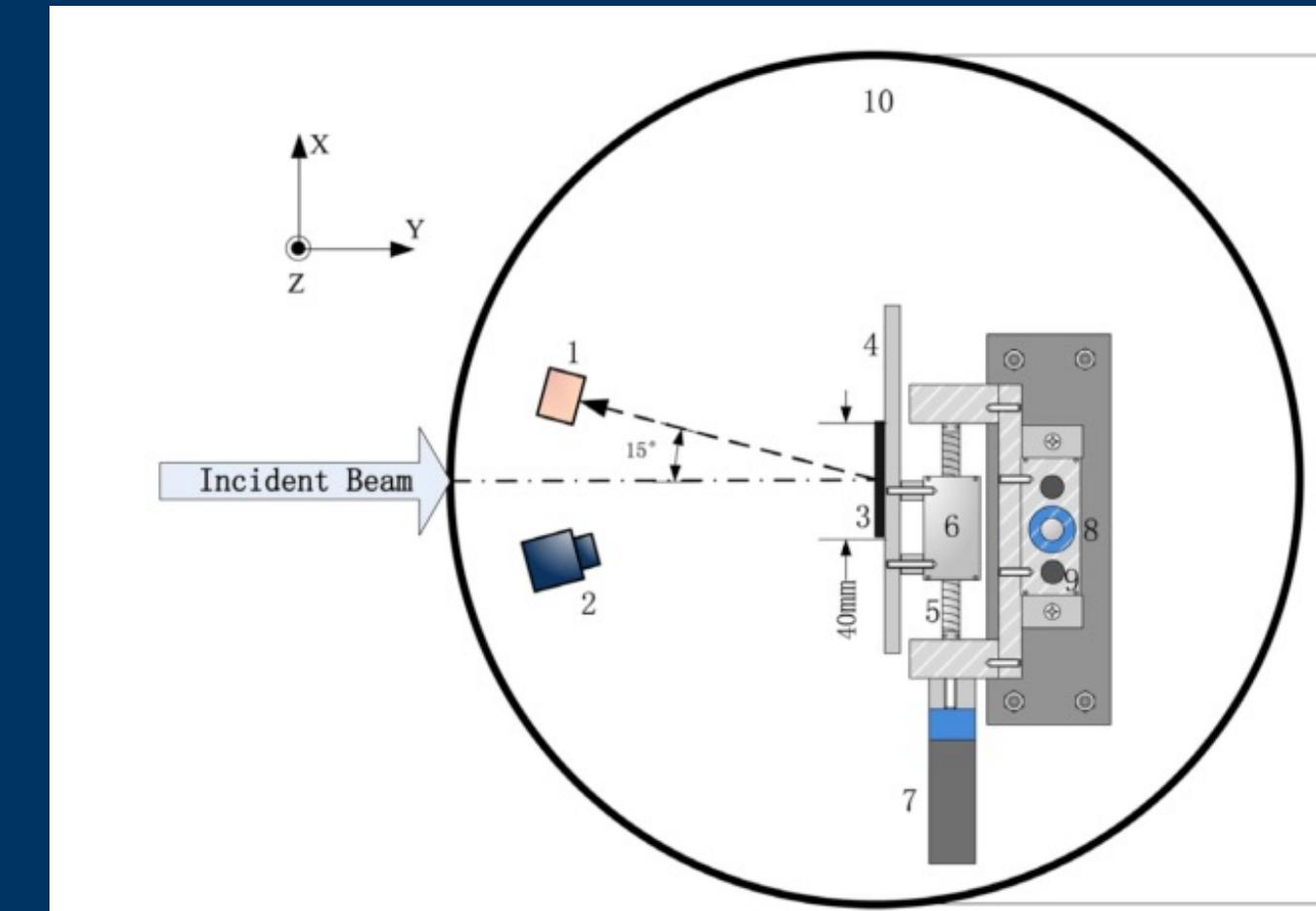
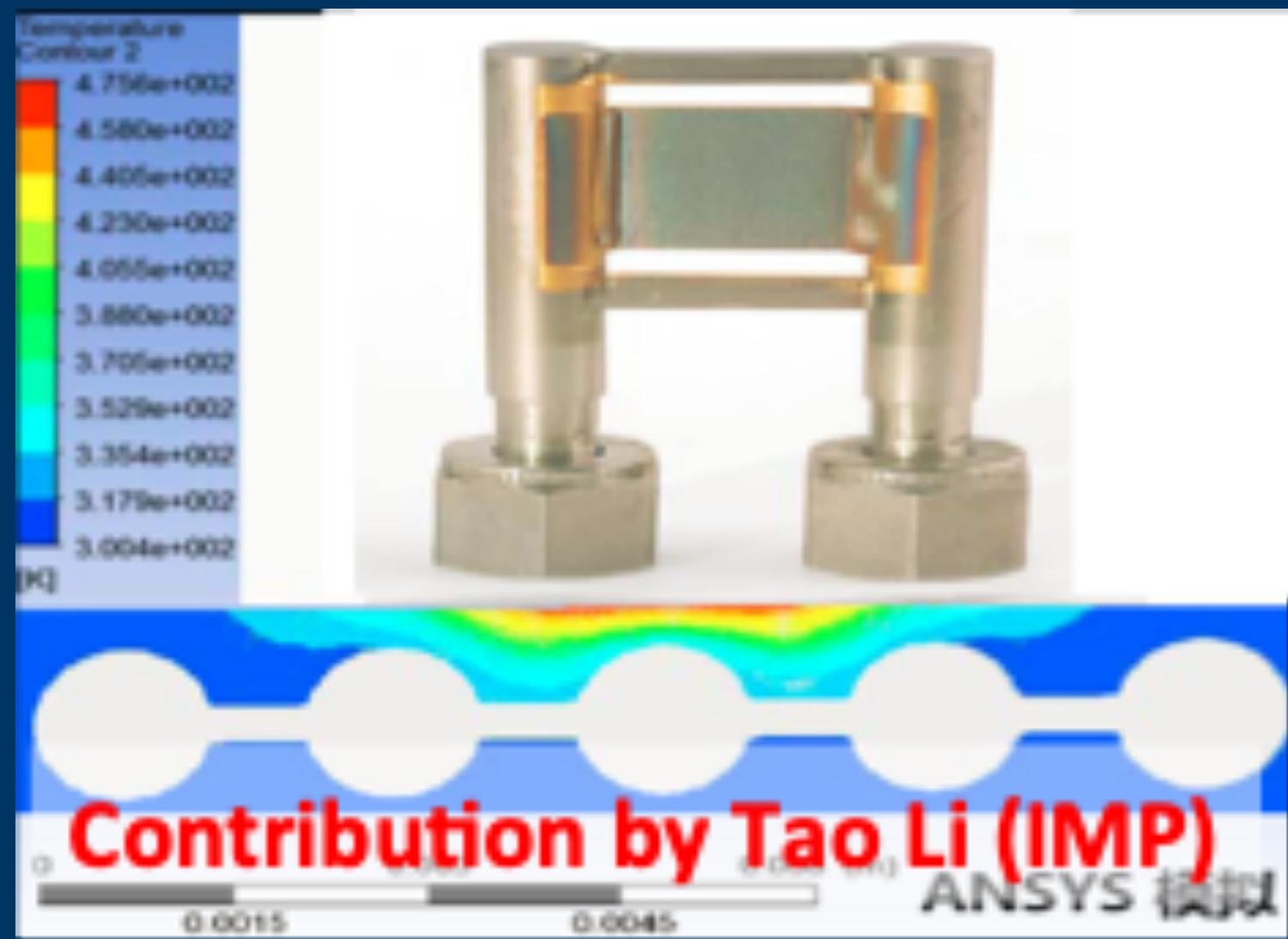
1. GWL-300-15
2. 5 cm oxygen-free copper
3. 20 cm lead
4. 1 mm Cr
5. 15 cm boron-doping polyethylene

BGO, $\Delta E/E = 13\% @662 \text{ keV}$; $\varepsilon = 60\% @ 7 \text{ MeV}$



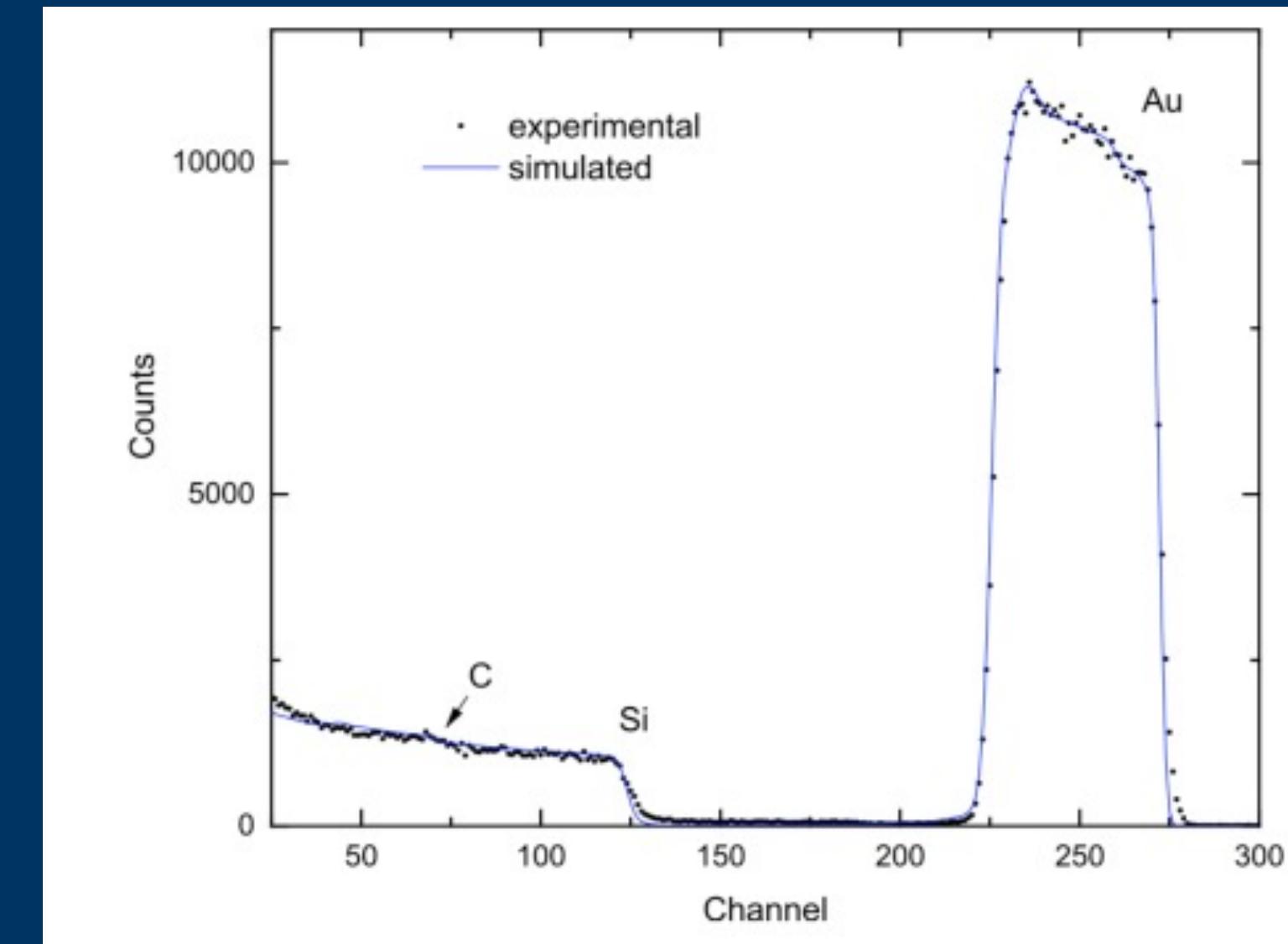
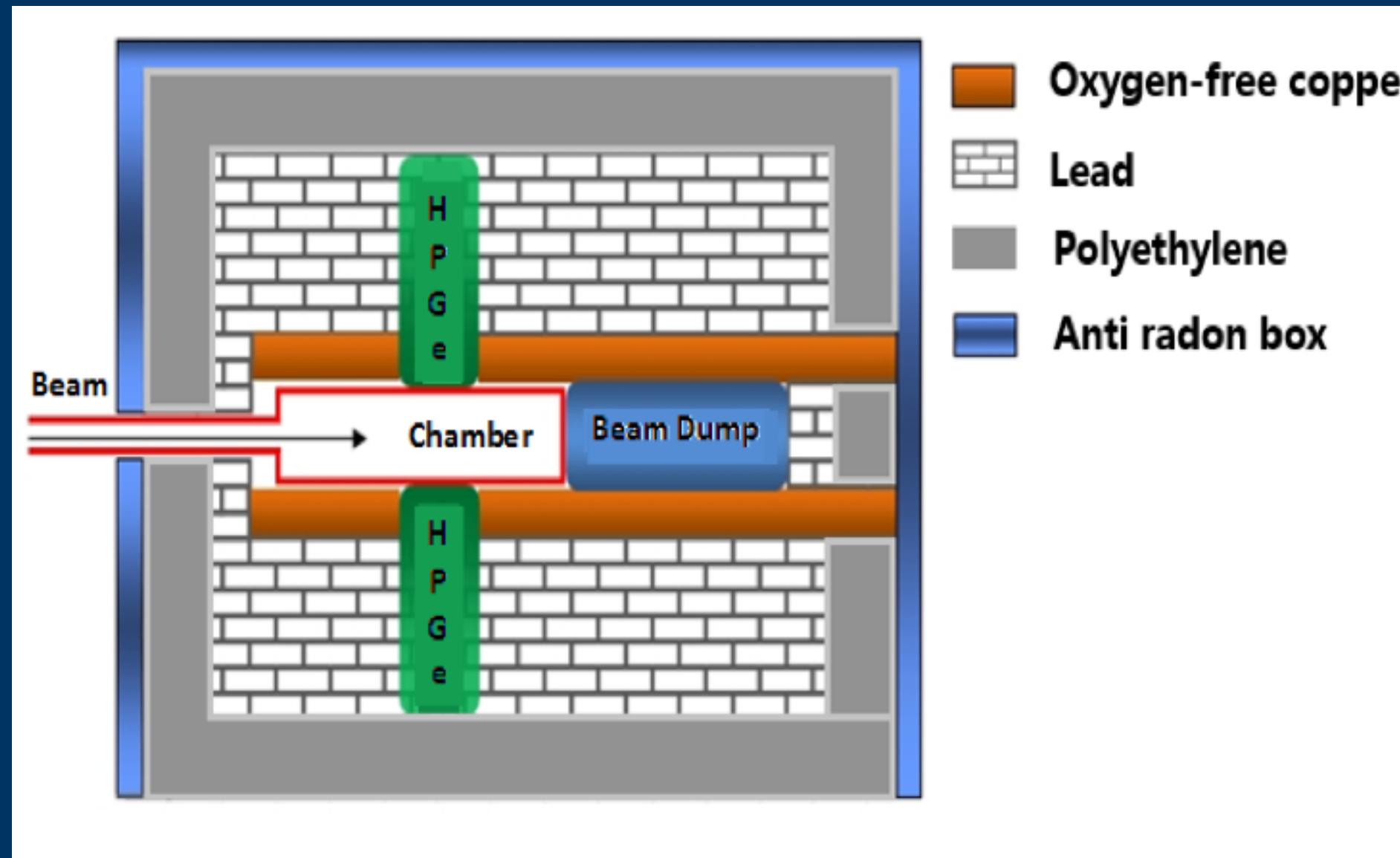
Target and shielding,

Y. J. Li



Rotation target
tested 30/8/16

Implantation target analysis



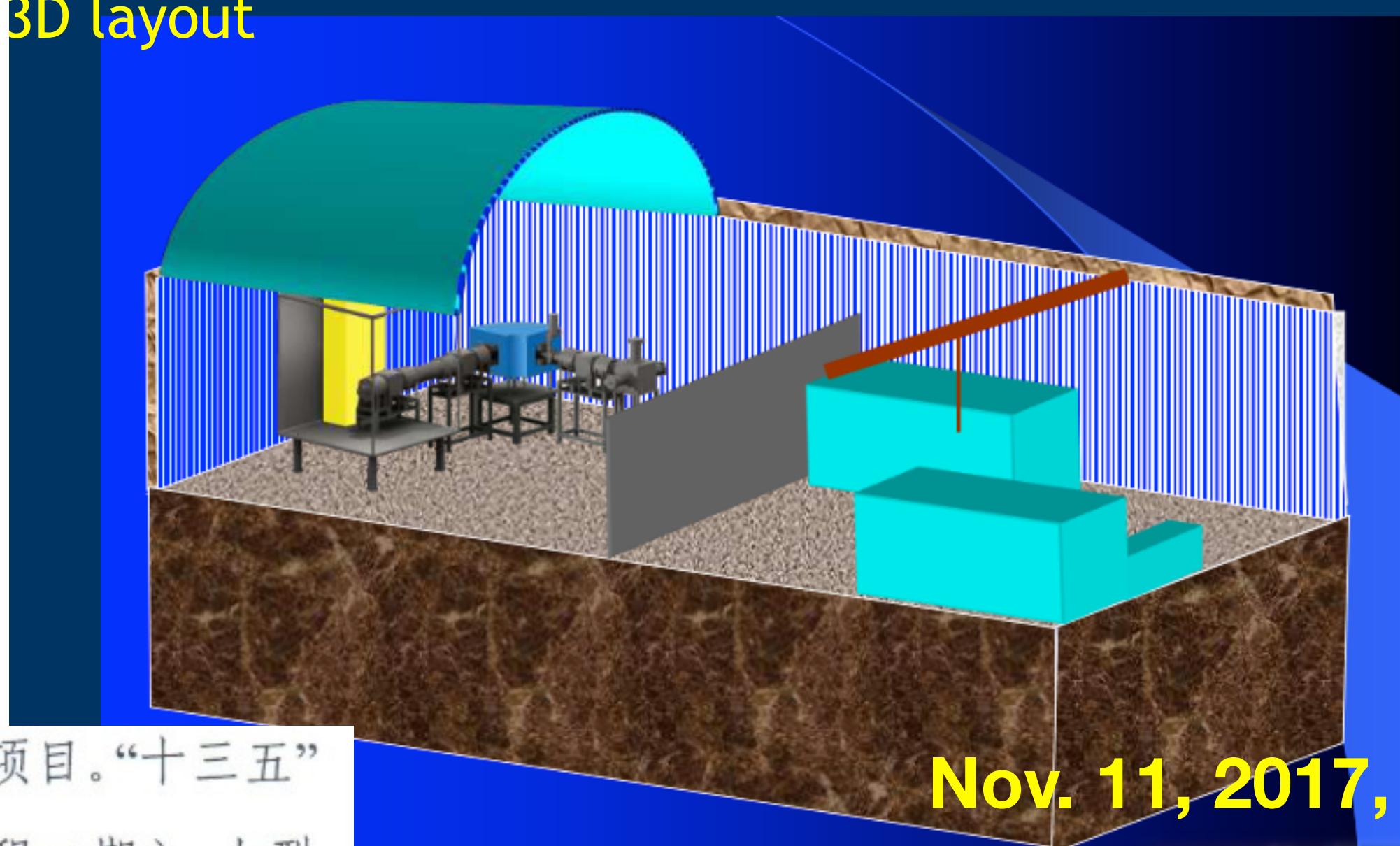
Lab construction

特急

国家发展和改革委员会
教育部
科技部
财政部
中科院
中国工程院
国家自然科学基金委员会
国家国防科工局
中央军委装备发展部

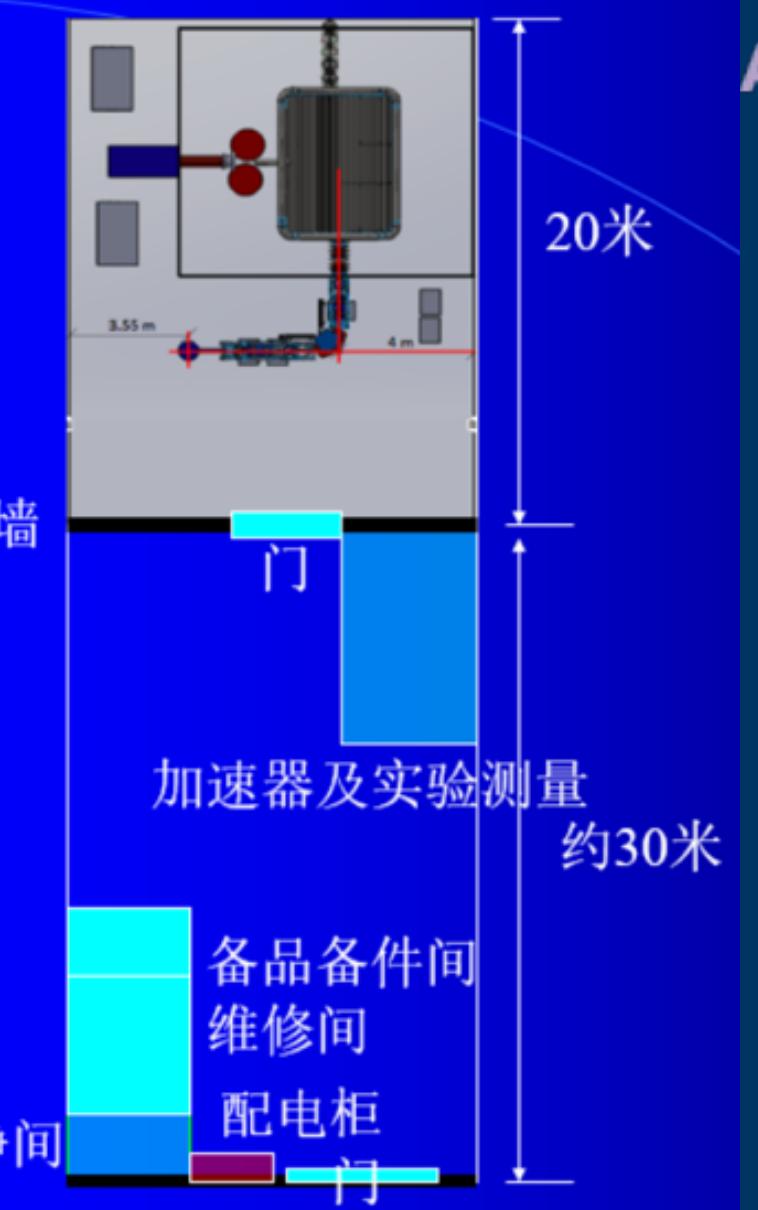
文件

3D layout



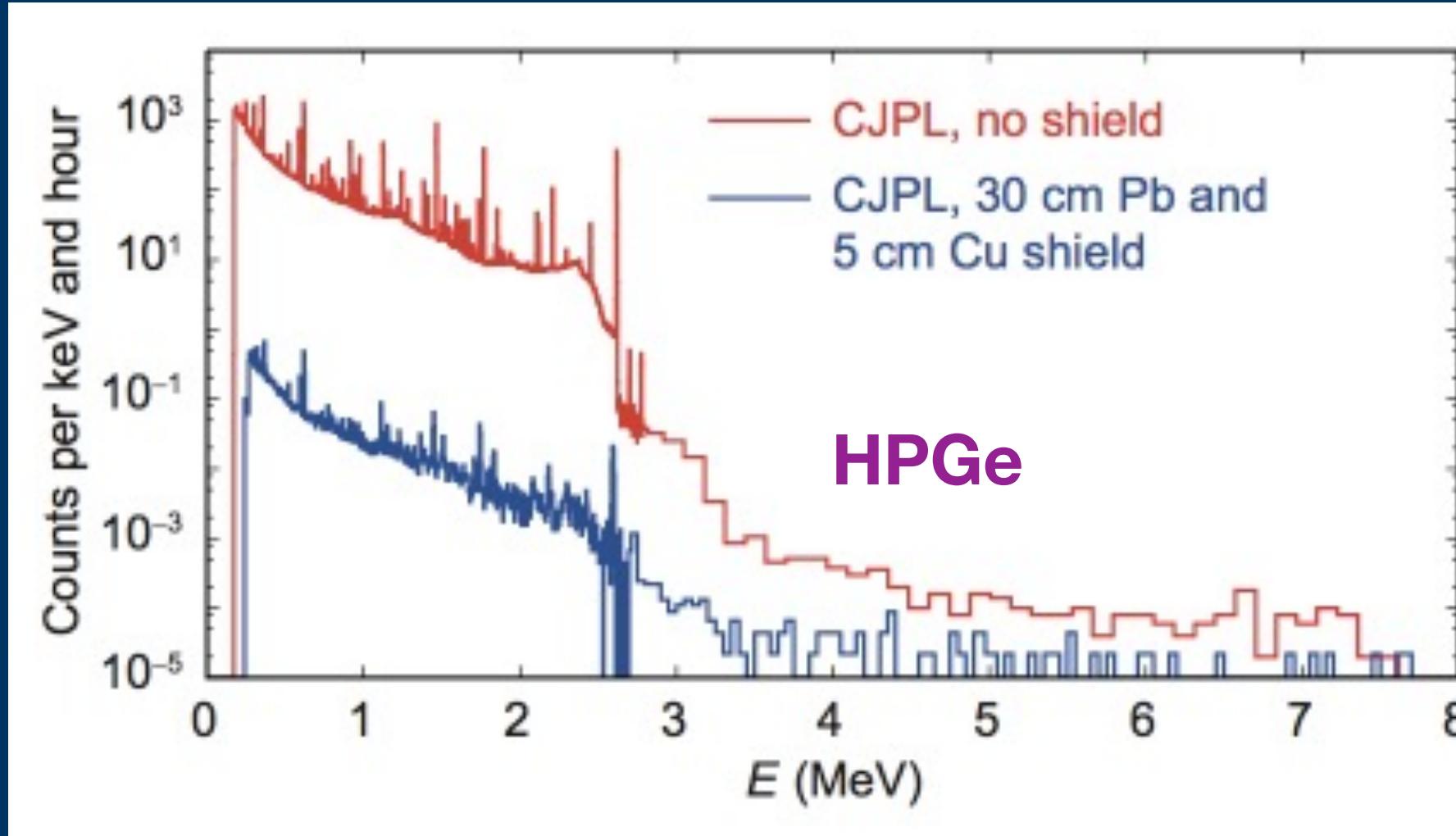
Nov. 11, 2017, MOU with Yalong Co.

Accelerator floor plan

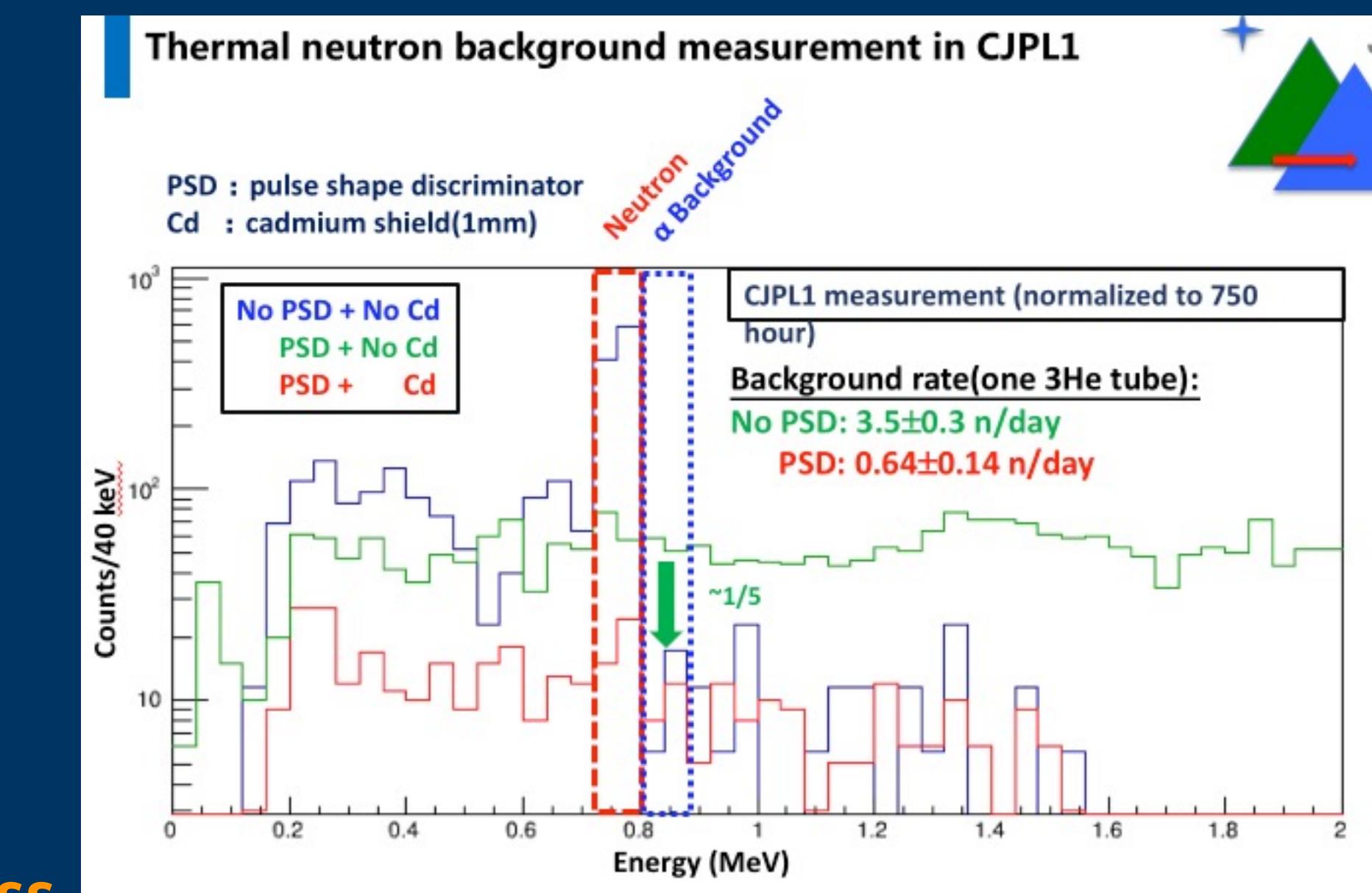
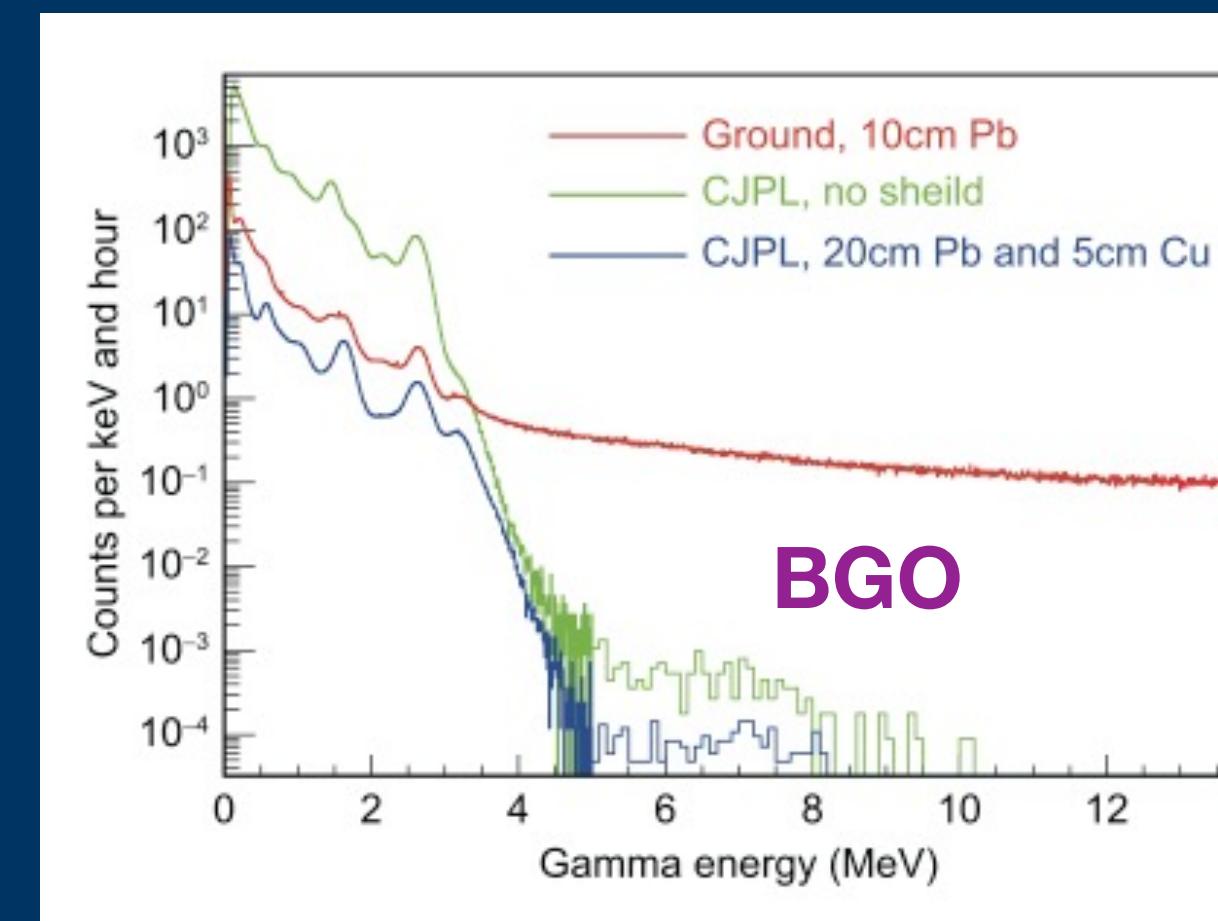


• Under design, start construction end of 2018, part of National science plan

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



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	$^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$, $^{25}\text{Mg}(\text{p},\gamma)^{26}\text{Al}$
2021	^{2+}He ion source		$^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$, $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
2022			$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

Future milestone



	June Ground experiment finished	June Accelerator beam underground	December ^{25}Mg data, ^{13}C start to underground	
2019				
2020		September ^{17}F data & NIC2020		
	December Accelerator to underground			December Project commission
			June ^{13}C data ^{12}C start	

JUNA expectation



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

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

Underground wish list



H burning



He bruning



C, O burning



Neutron source



γ astronomy

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

Underground wish list



H burning



He bruning



C, O burning



Neutron source



γ astronomy



Underground wish list



H burning



He bruning



C, O burning



Neutron source



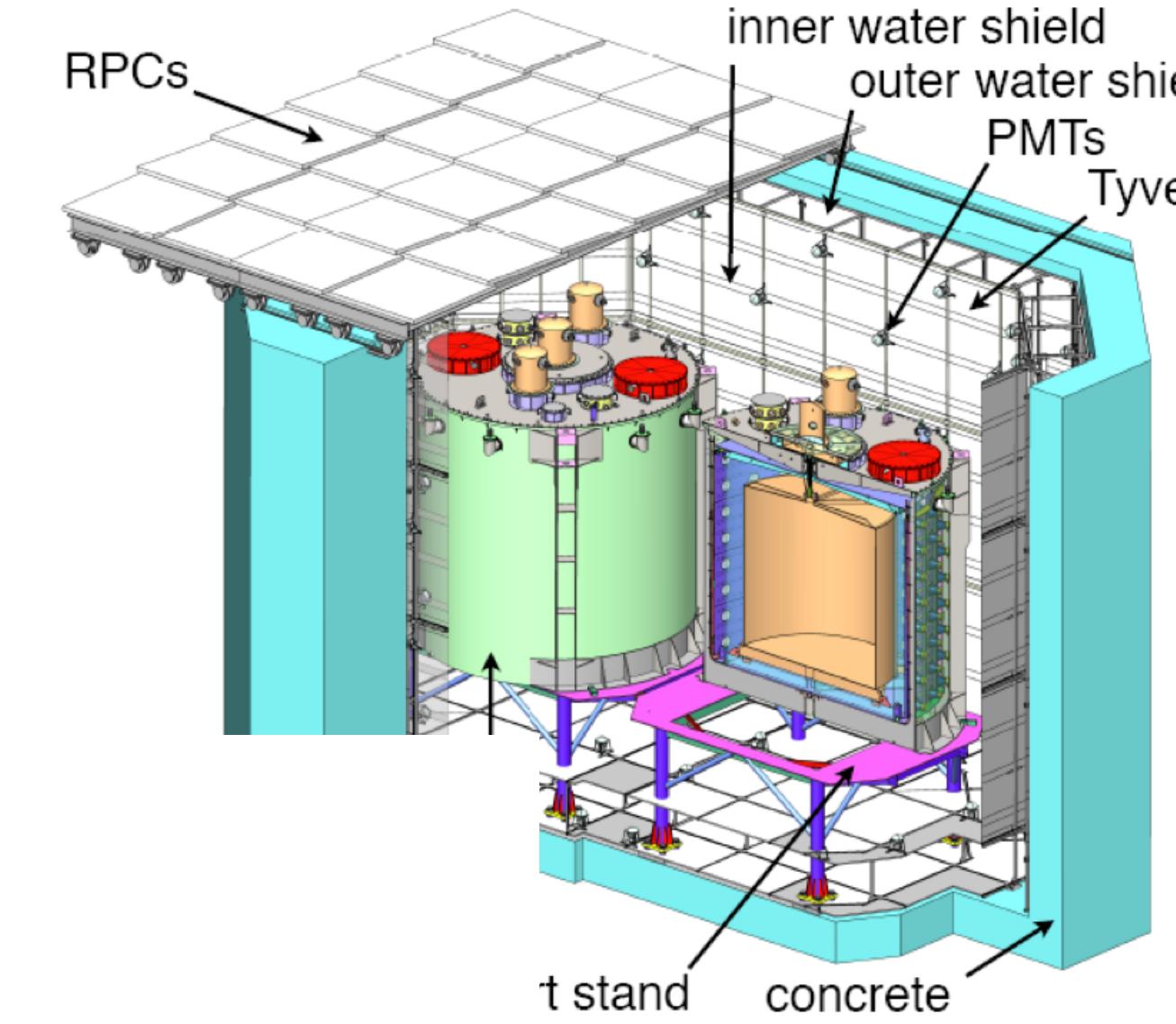
γ astronomy



JUNA-I

JUNA-II

Daya Bay experiment



Summary

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

$$R = 0.940 \pm 0.011 \text{ (stat)} \pm 0.004 \text{ (syst)},$$

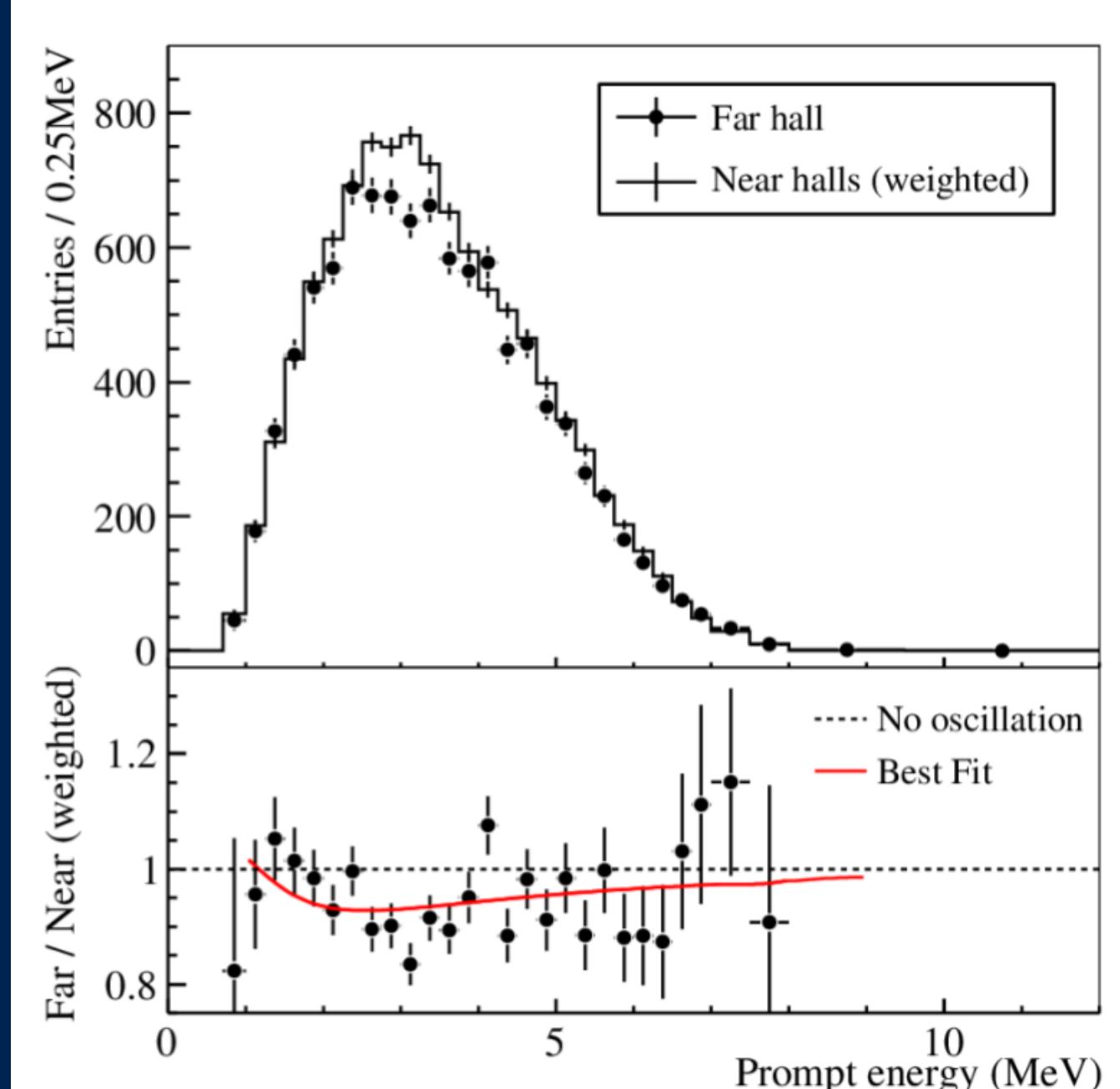
together with a spectral distortion

- ◆ A new type of neutrino oscillation is thus discovered

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)}$$

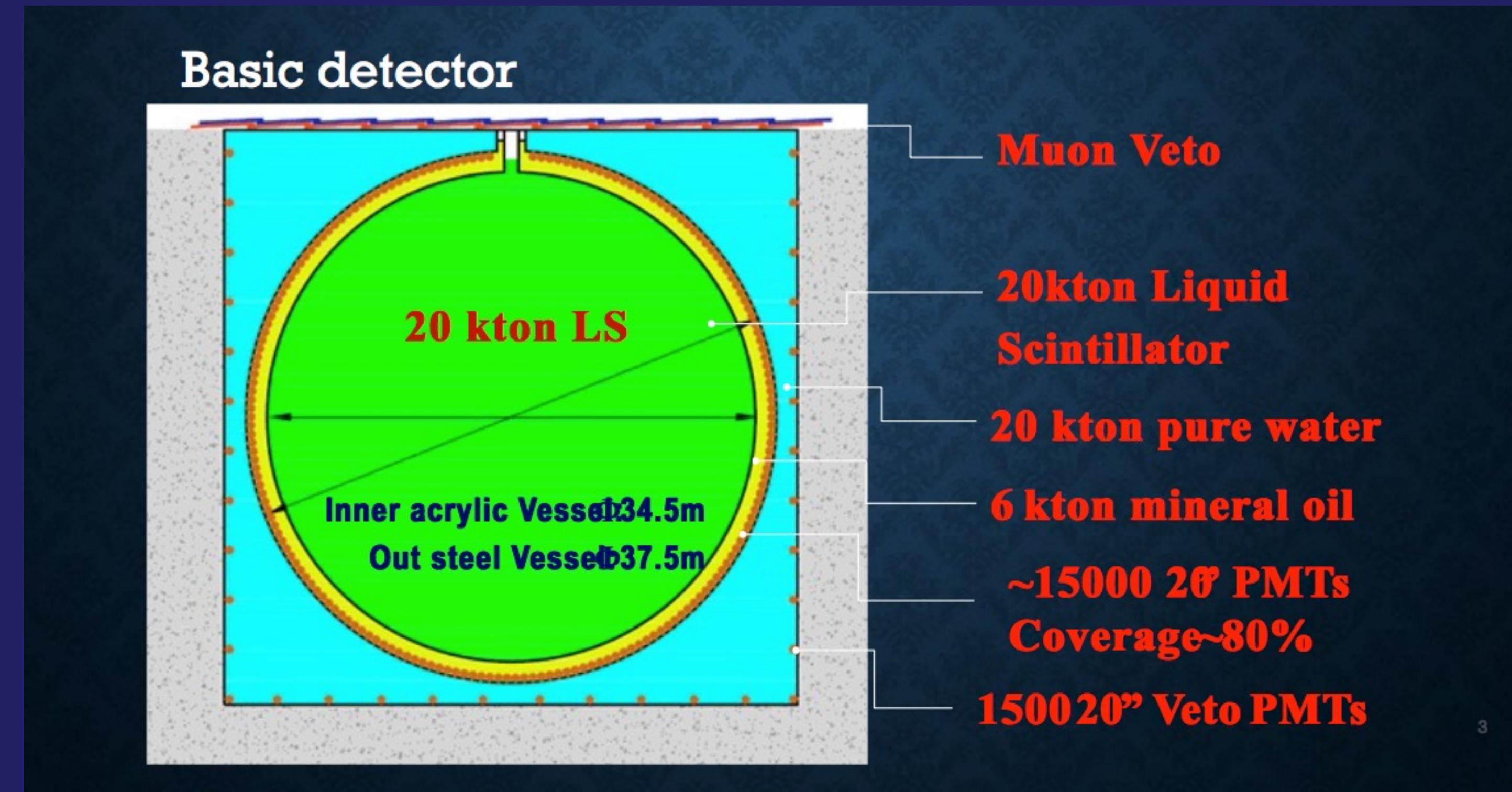
$$\chi^2/\text{NDF} = 4.26/4$$

5.2 σ for non-zero θ_{13}



JUNO experiment

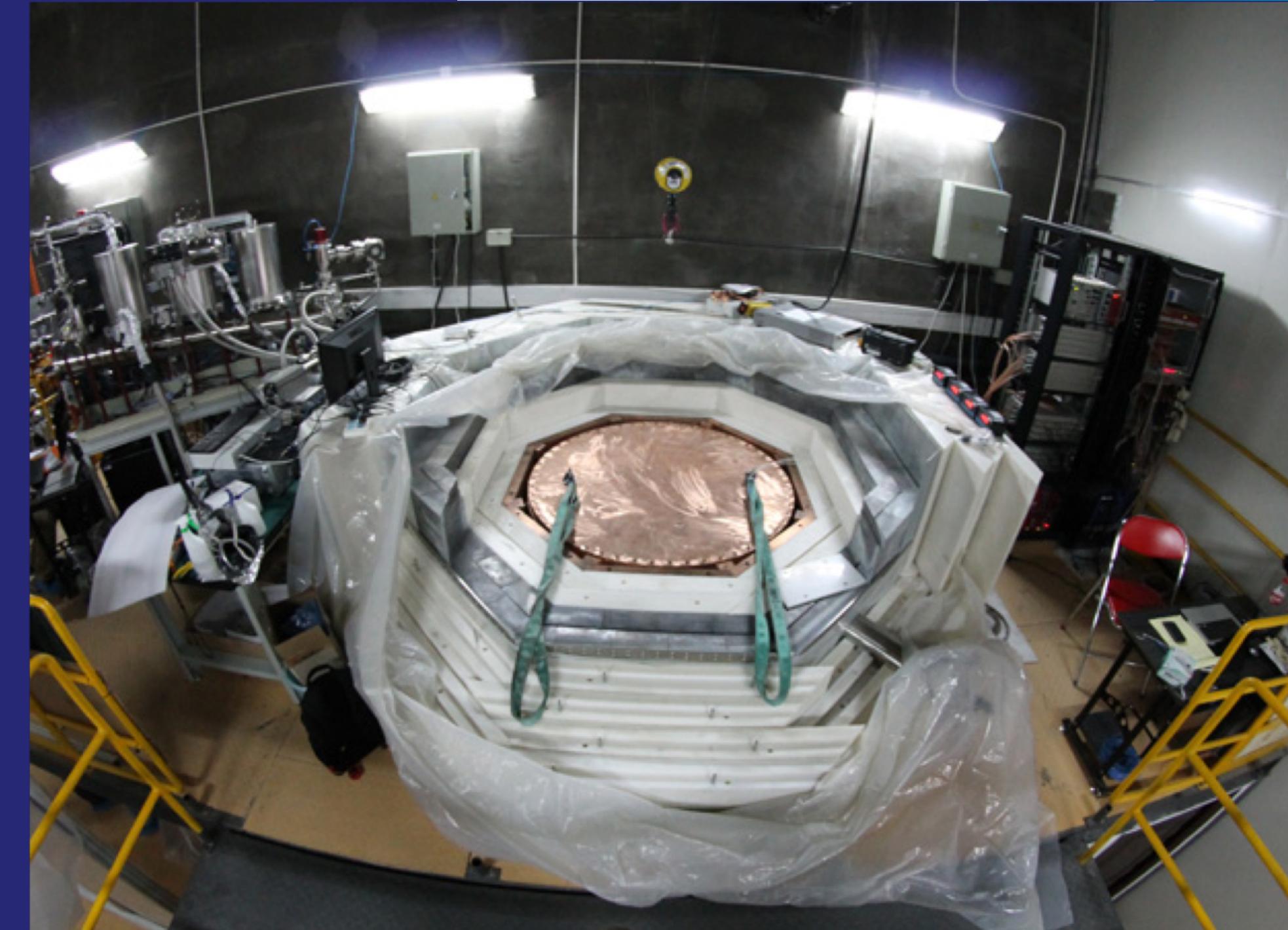
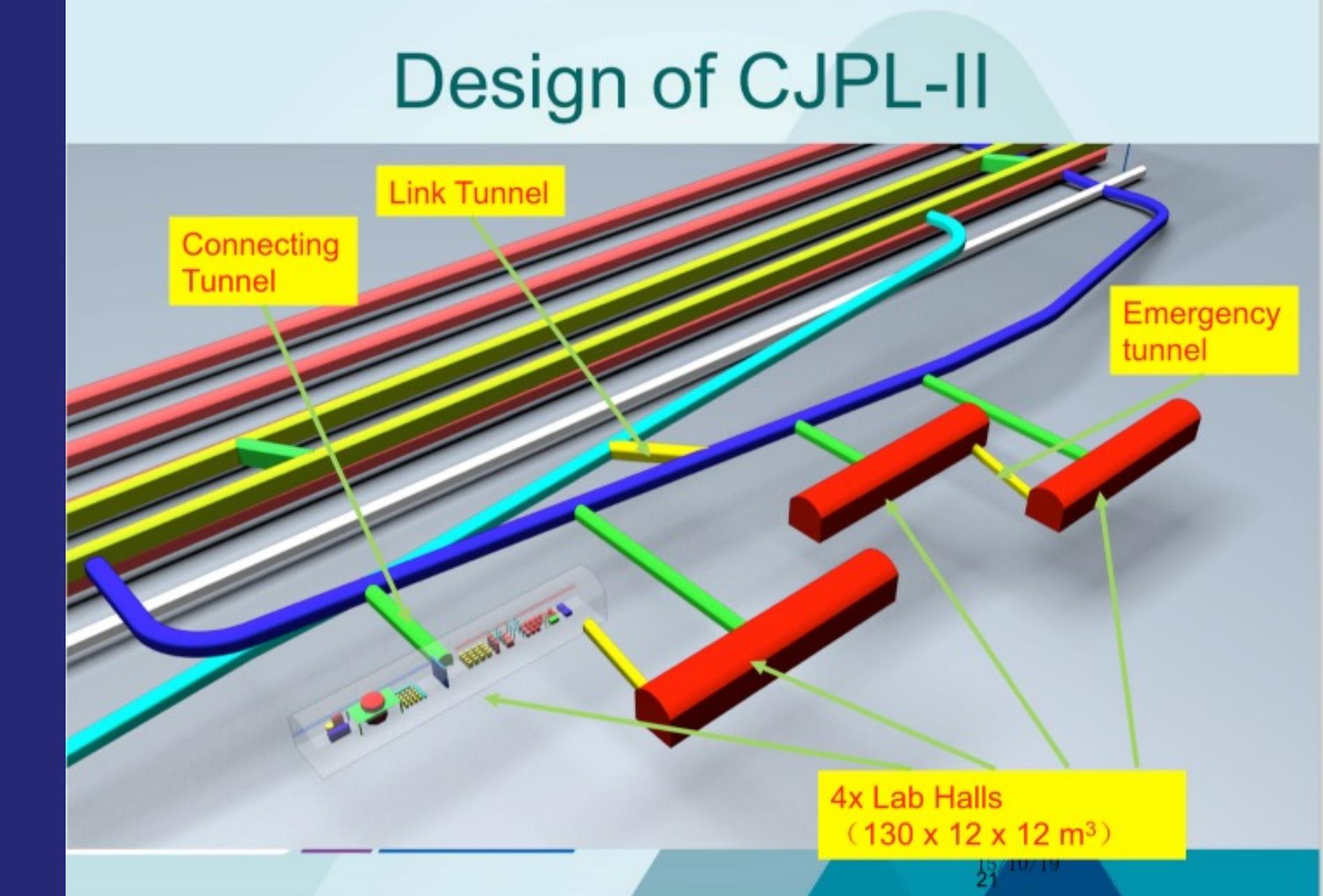
- Jiangmen reactor neutrino observatory JUNO, 2008-2021, 300M\$, 20 kT LS, 700 m underground, Kaiping, Guangdong
- 20 GW+ NP 50 km away. For mass hierarchy (4σ in 6 yr), θ_{12} , Supernovae, Geo-u, etc..
- 6K home made MCP-PMT ready, electronic in progress, tunnel schedule got some delay due to geological complexities.



Jiangmen 20 kT tank

CJPL dark matter exp.

- 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 $8.6 \times 10^{-47} \text{ cm}^2$ @ 40 GeV/c². Ton level PandaX-II near completion, will be in CJPL-II.



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
- Neutrino and dark matter experiment is in well progress, and aiming at leading positions in the world wide research

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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