Progress of nuclear astrophysics and JUNA project

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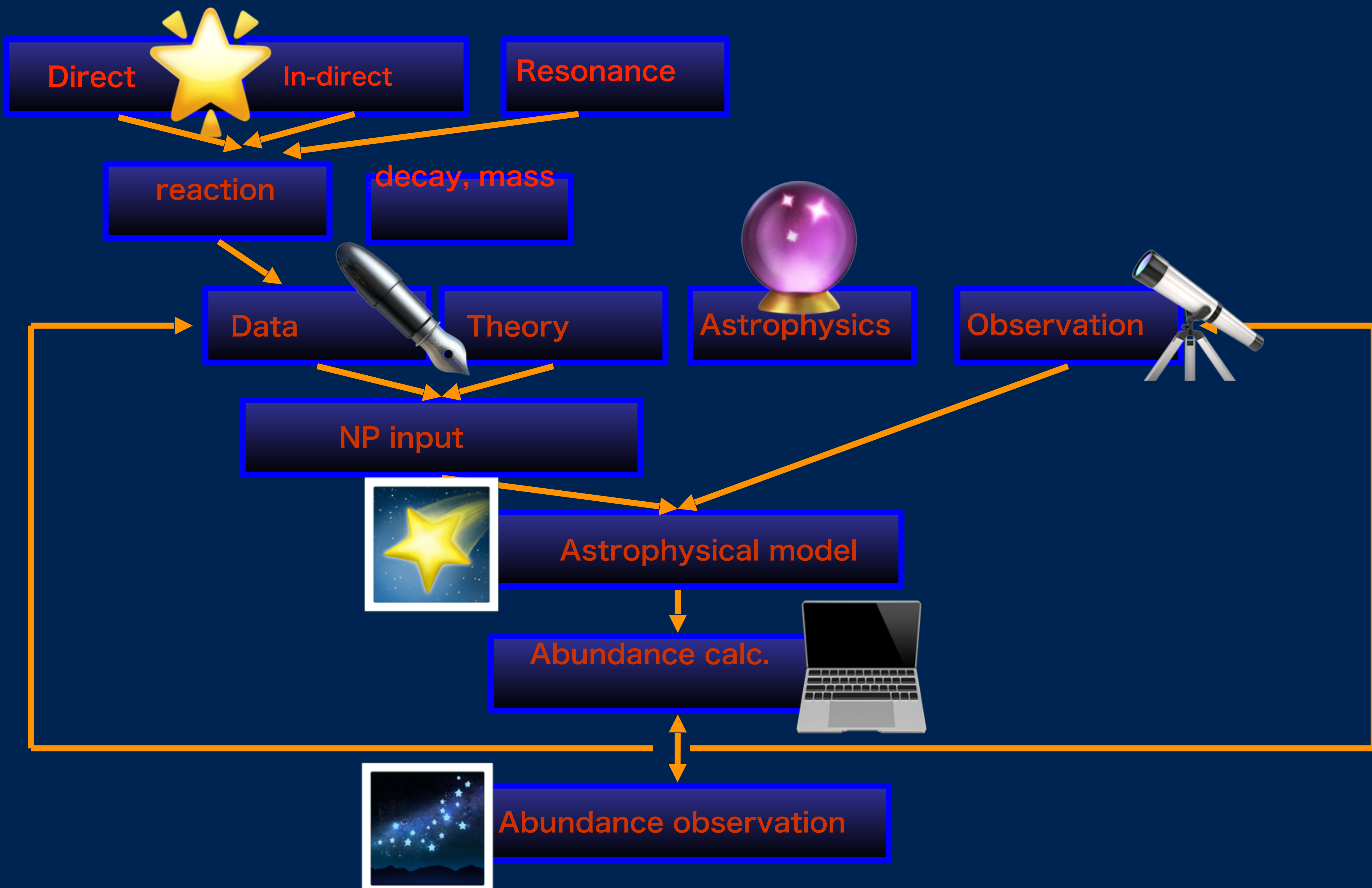
Nuclear Astrophysics roadmap



What is Nuclear Astrophysics

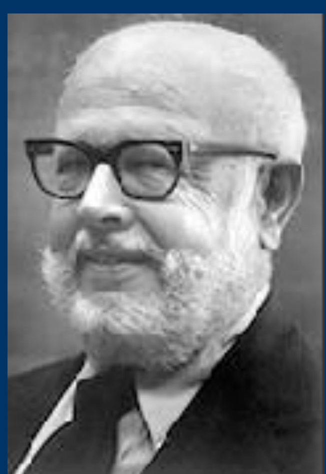
- Extending between macro and micro world: nuclear physics and astrophysics
- Application of nuclear physics in energy production and element synthesis in star
- Determining time scales of evolution, star environment, isotope abundance
- In combination with astrophysical model and observation
- Using nuclear mass, cross section, half-life as input
- Difficulty: low cross section due to low energy and high isospin, many reactions and decays

Some of the great discovery of astrophysics

- 3K microwave background radiation,1965, experimental support for Big-Bang theory
- Detection of solar neutrino, 1960, gave the hints of neutrino oscillation
- Detection of ^{26}Al γ-ray, 1980, direct support of explosive nuclear synthesis, and triggering γ-ray astronomy
- Detection of SN1987A supernova explosion,1987
- Experimental explanation of solar neutrino missing, 2003

Contribution of nuclear physicist, Nobel prize of physics winner

- 1930, Hans Bethe, pp chain, CNO cycle, 1967

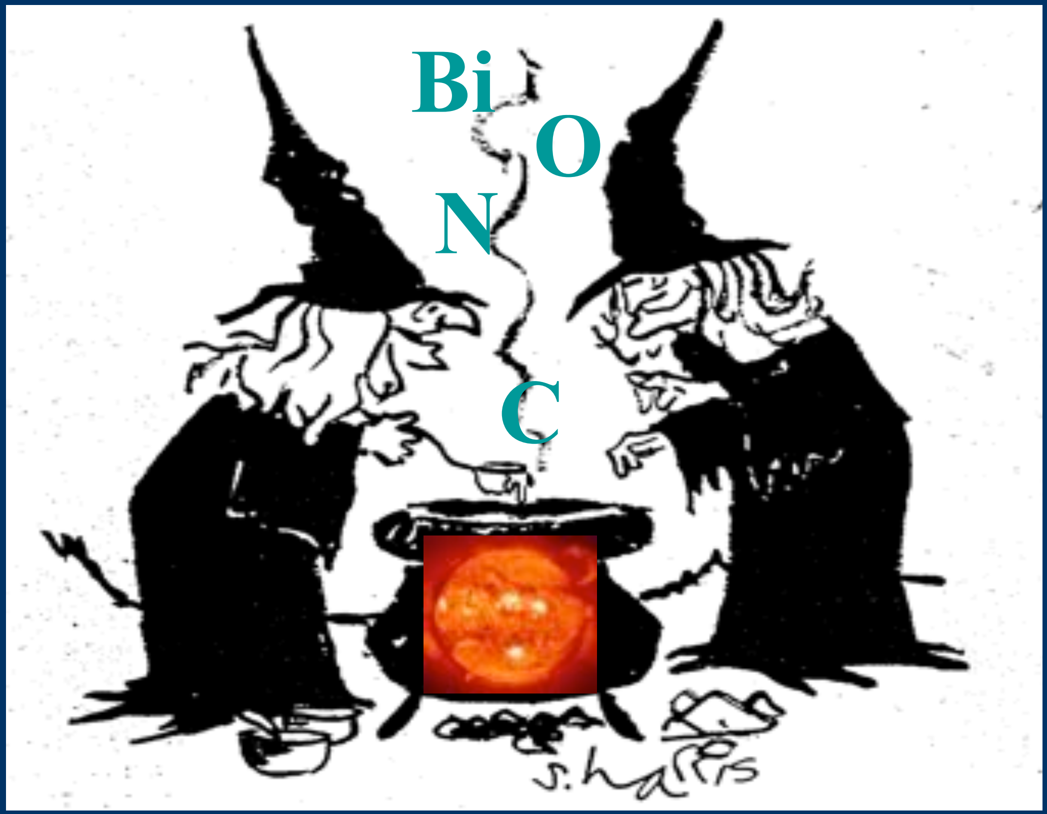


- 1957, William Fowler, star evolution, B^2FH, 1983

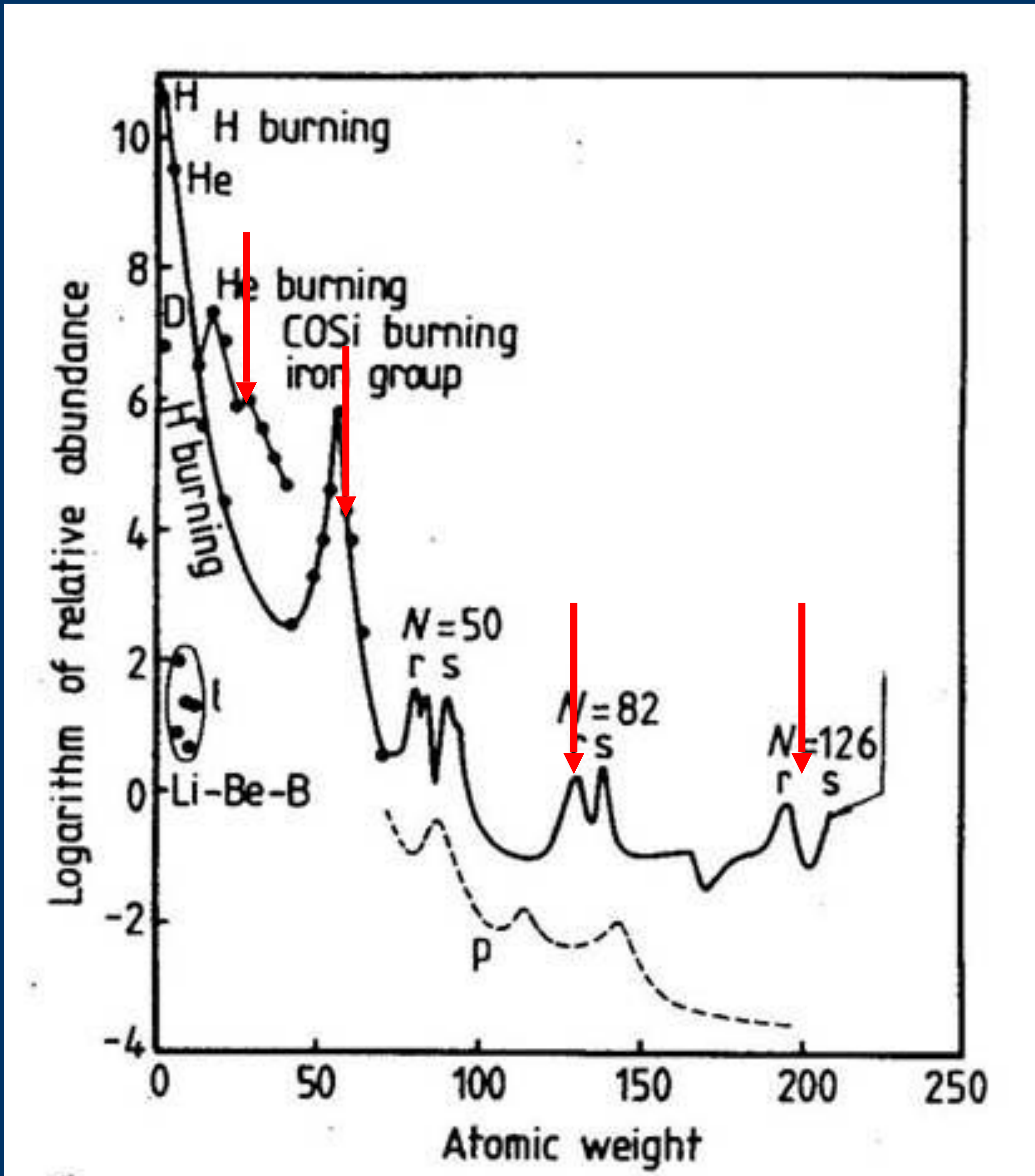
- 1960, Raymond Davis and Masatoshi Koshiba, neutrino detection, 2002

We are made of star staffs

- Abundance curve in star rock and our bone are the same, except for Si
- Mixing of many cycles and explosions
- Some reaction would change the world and ourselves completely, like $^{12}C(\alpha,\gamma)^{16}O$

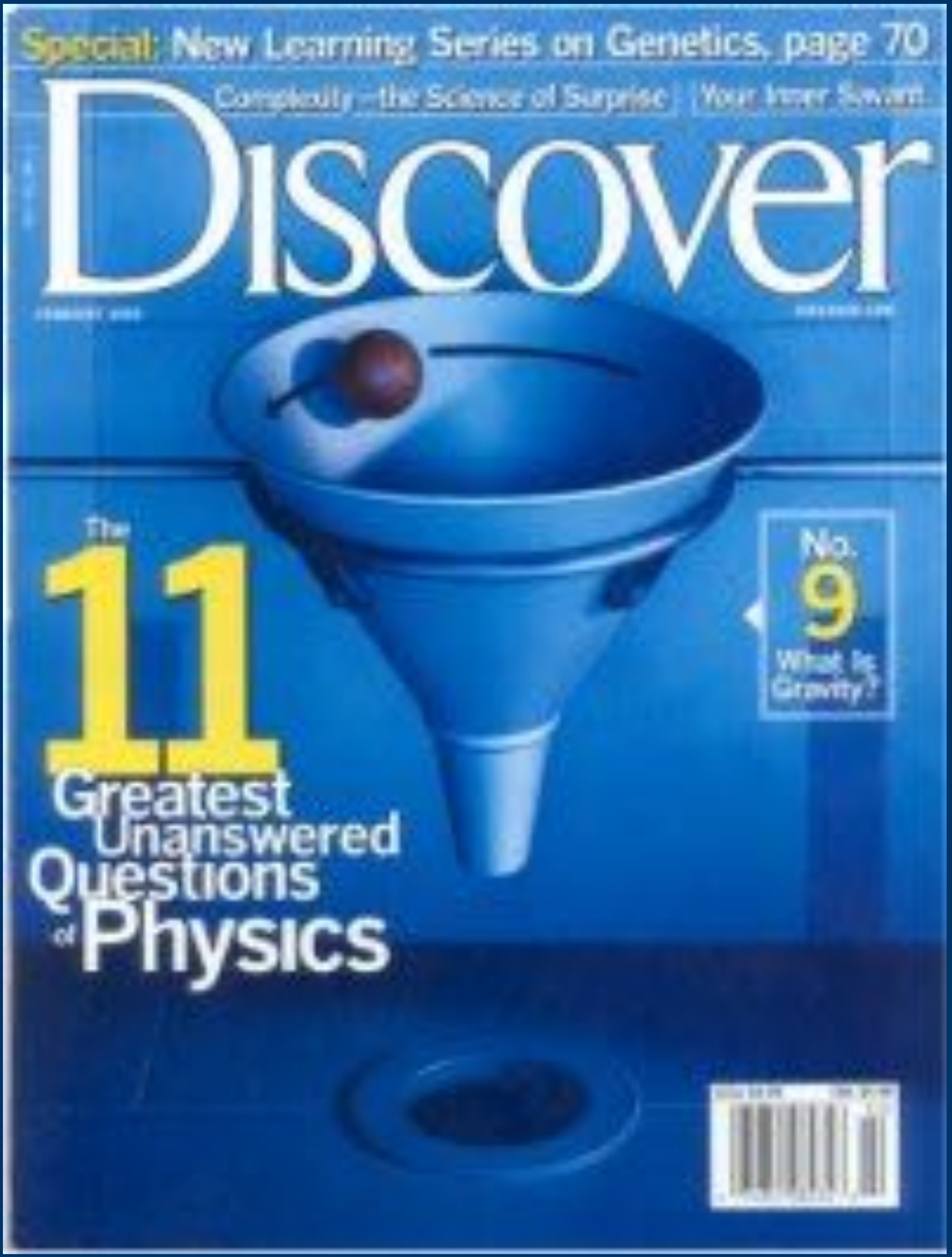


Nuclear reaction: alchemist in universe



Peak: finger print of nuclear physics: Shell model magic number

Nuclear astrophysics as frontier



- **Greatest unanswered question of physics**
- **How were the heavy elements from iron to uranium made?**

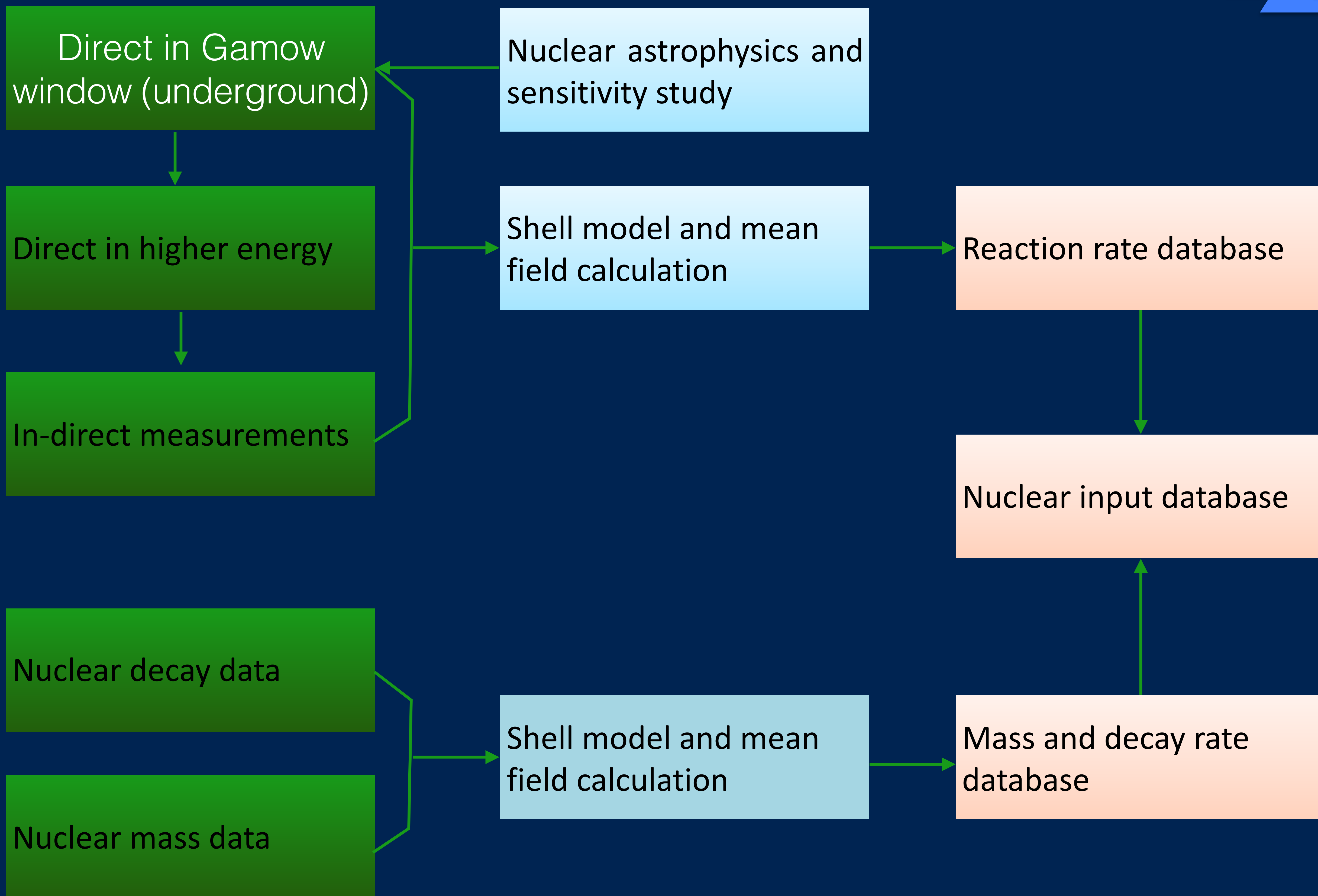
- NSAC

  What is the origin of the elements in the cosmos?
  What are the nuclear reactions that drive stars and stellar explosions?

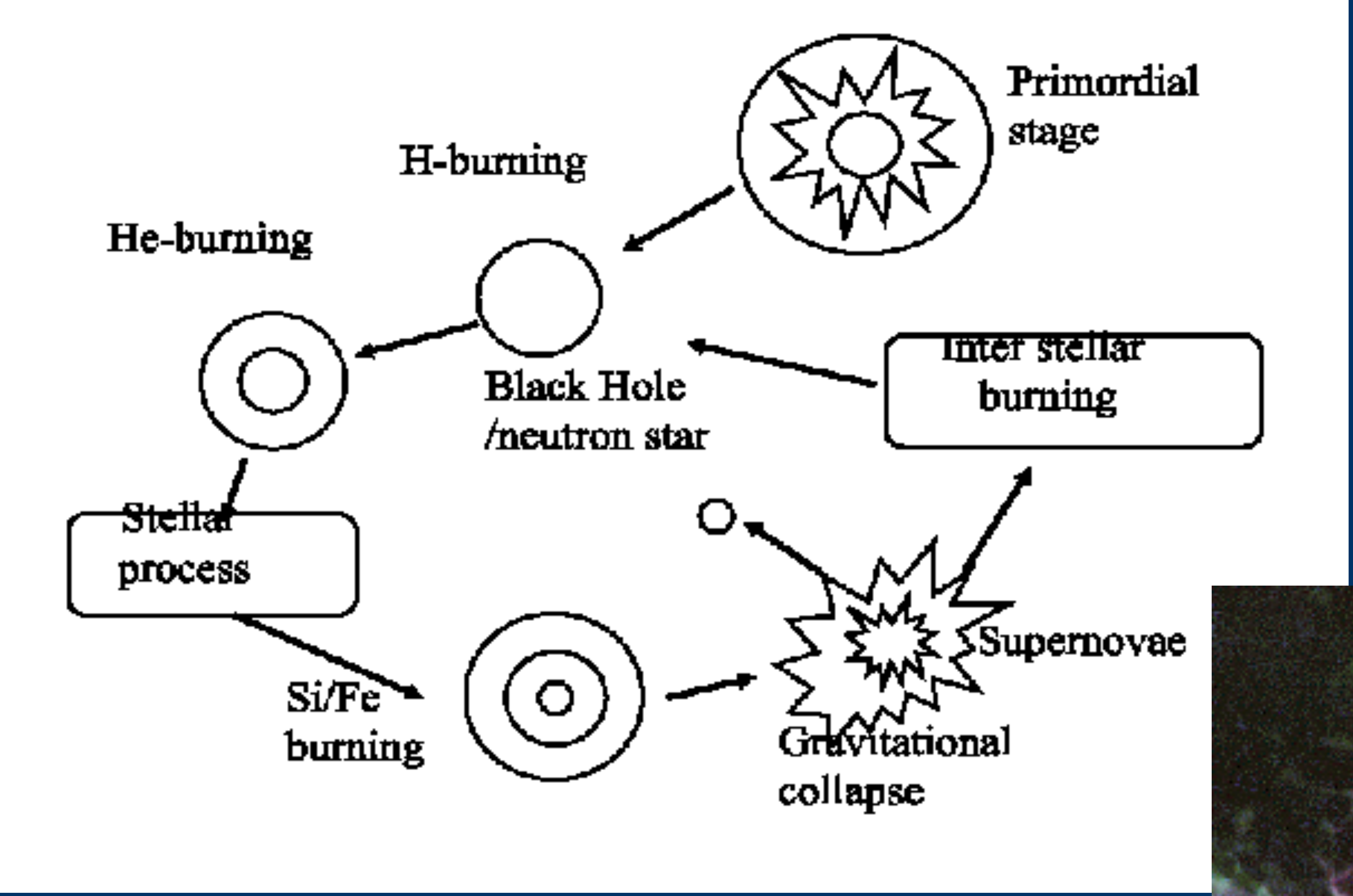
- NUPPEC

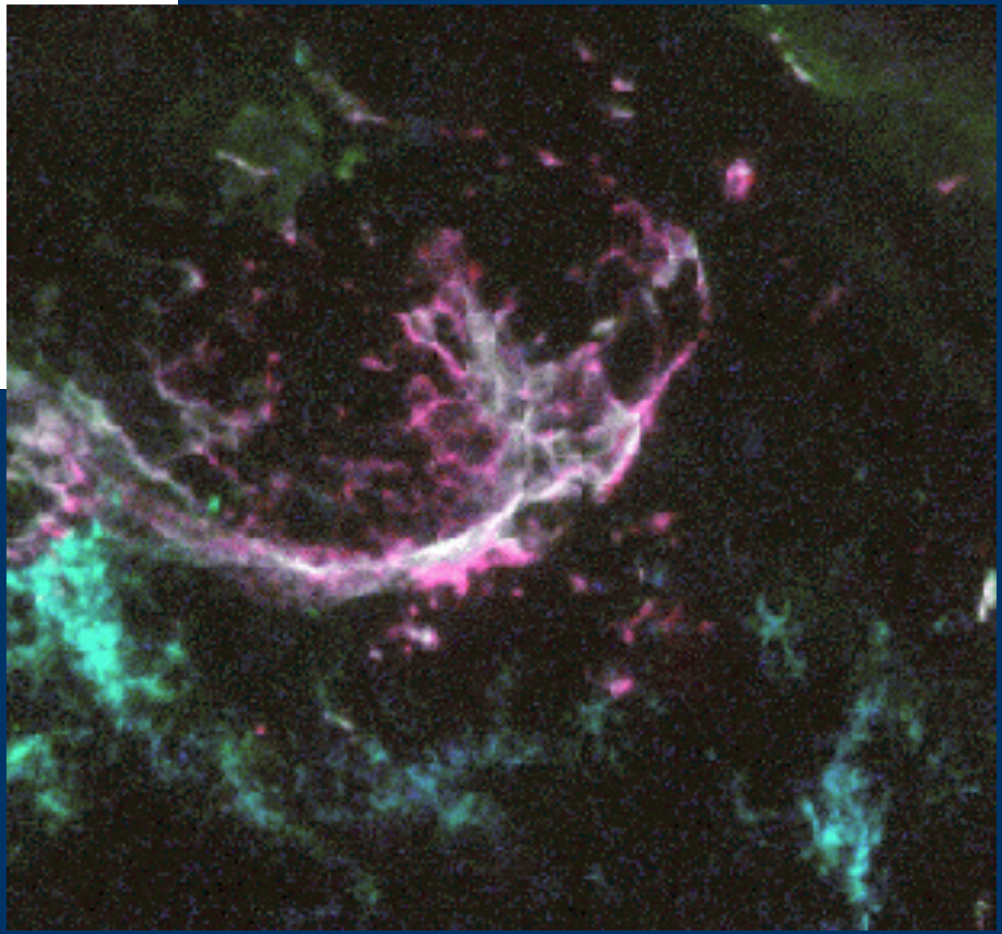
  How and where the elements are made?
  Can we recreate on Earth, and understand, the critical reactions that drive the energy generation and the associated synthesis of new elements in the stars?

Methodology



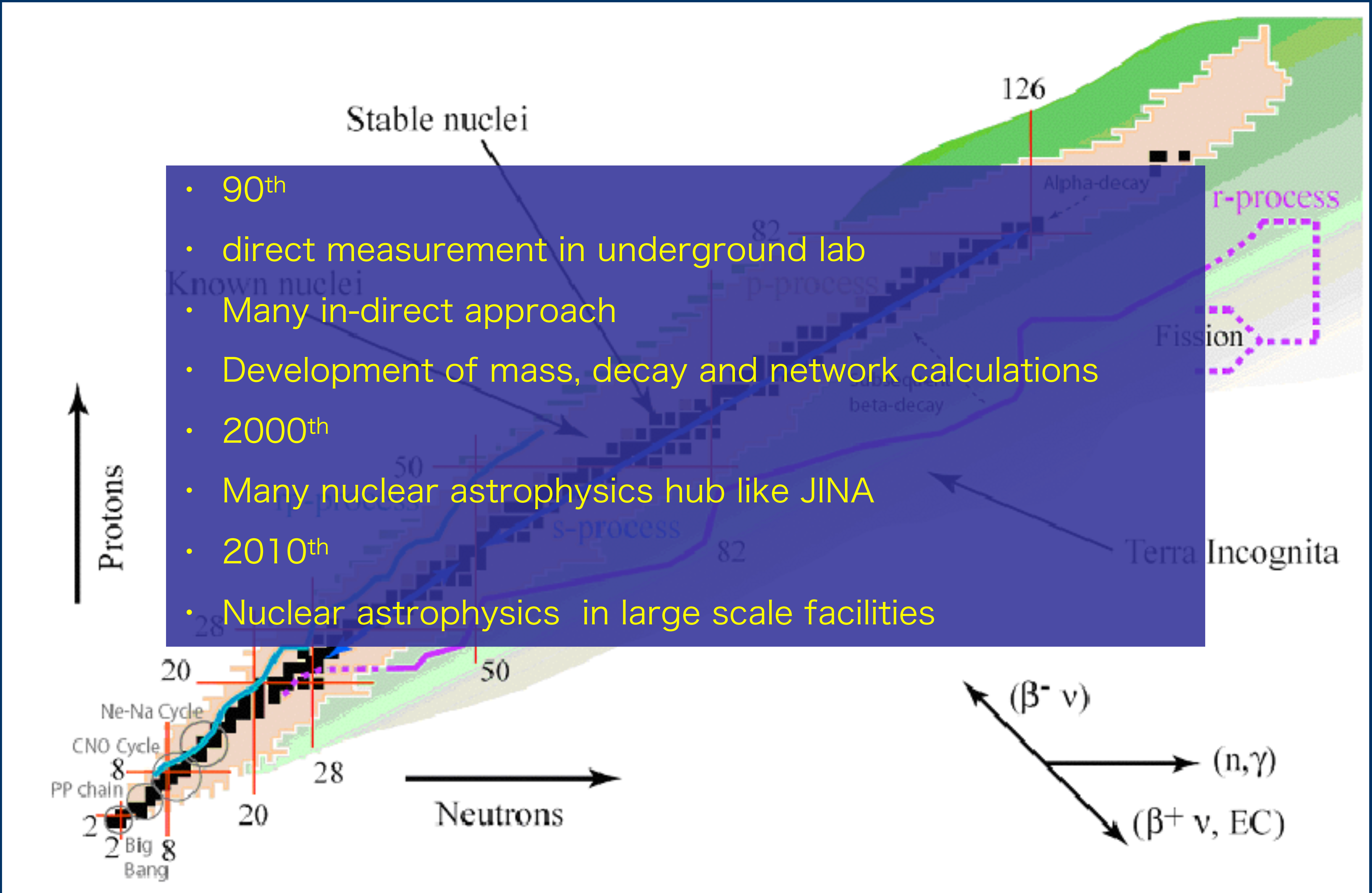
Primordial and stellar elements syntheses



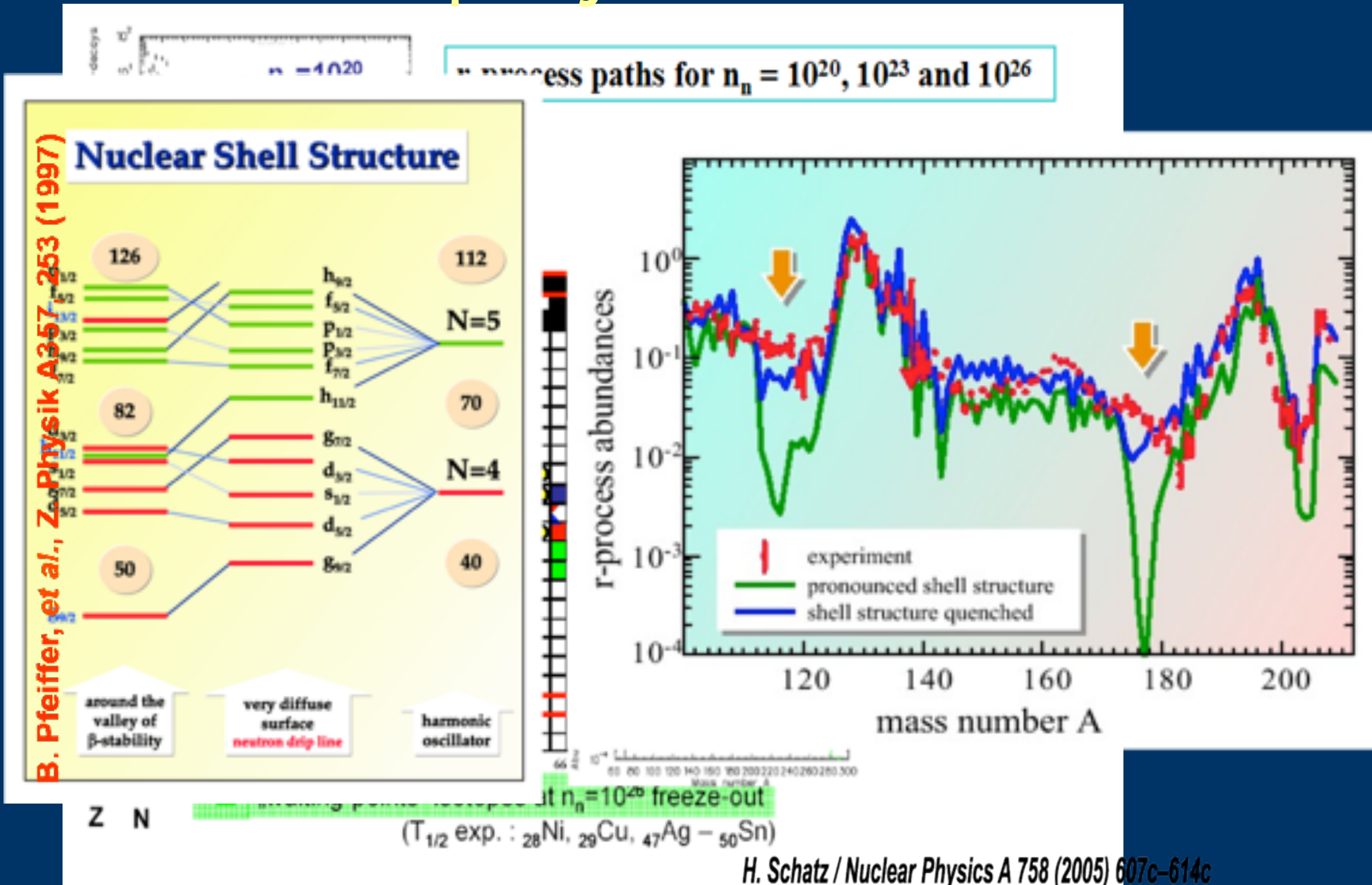


Astrophysical process in chart of nuclei

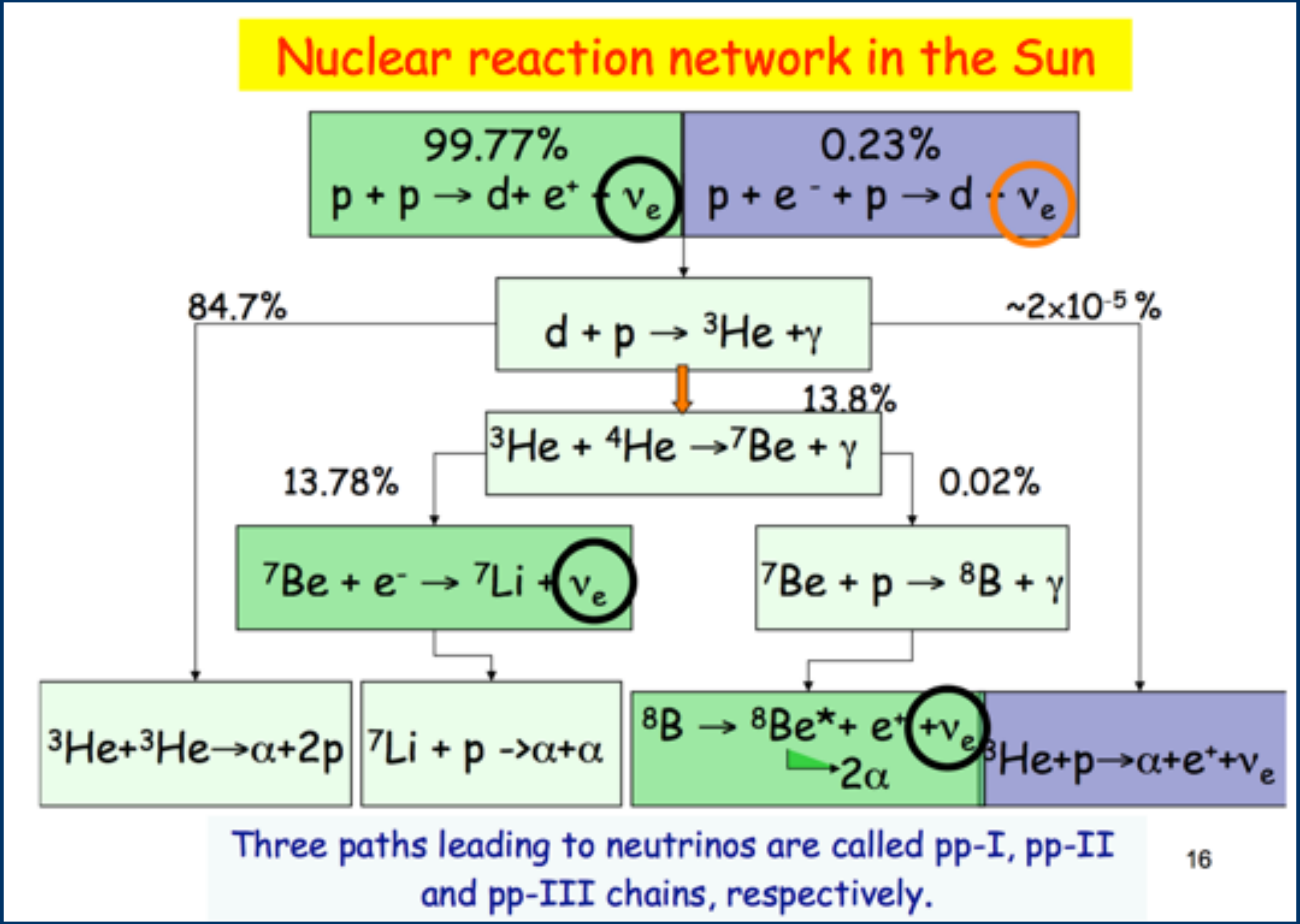
- 90^{th}
- direct measurement in underground lab
- Many in-direct approach
- Development of mass, decay and network calculations
- 2000^{th}
- Many nuclear astrophysics hub like JINA
- 2010^{th}
- Nuclear astrophysics in large scale facilities



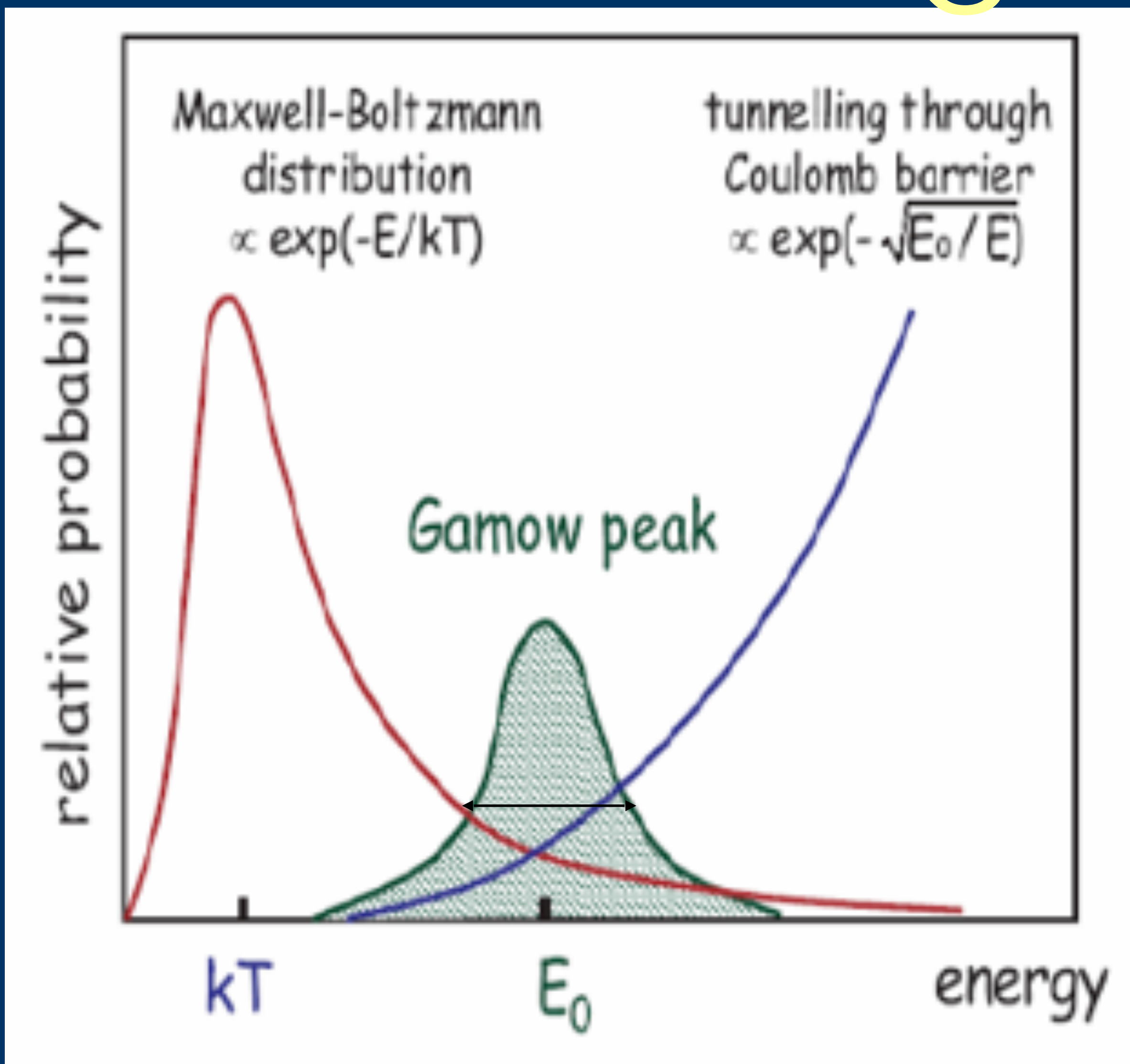
Interplay of frontier

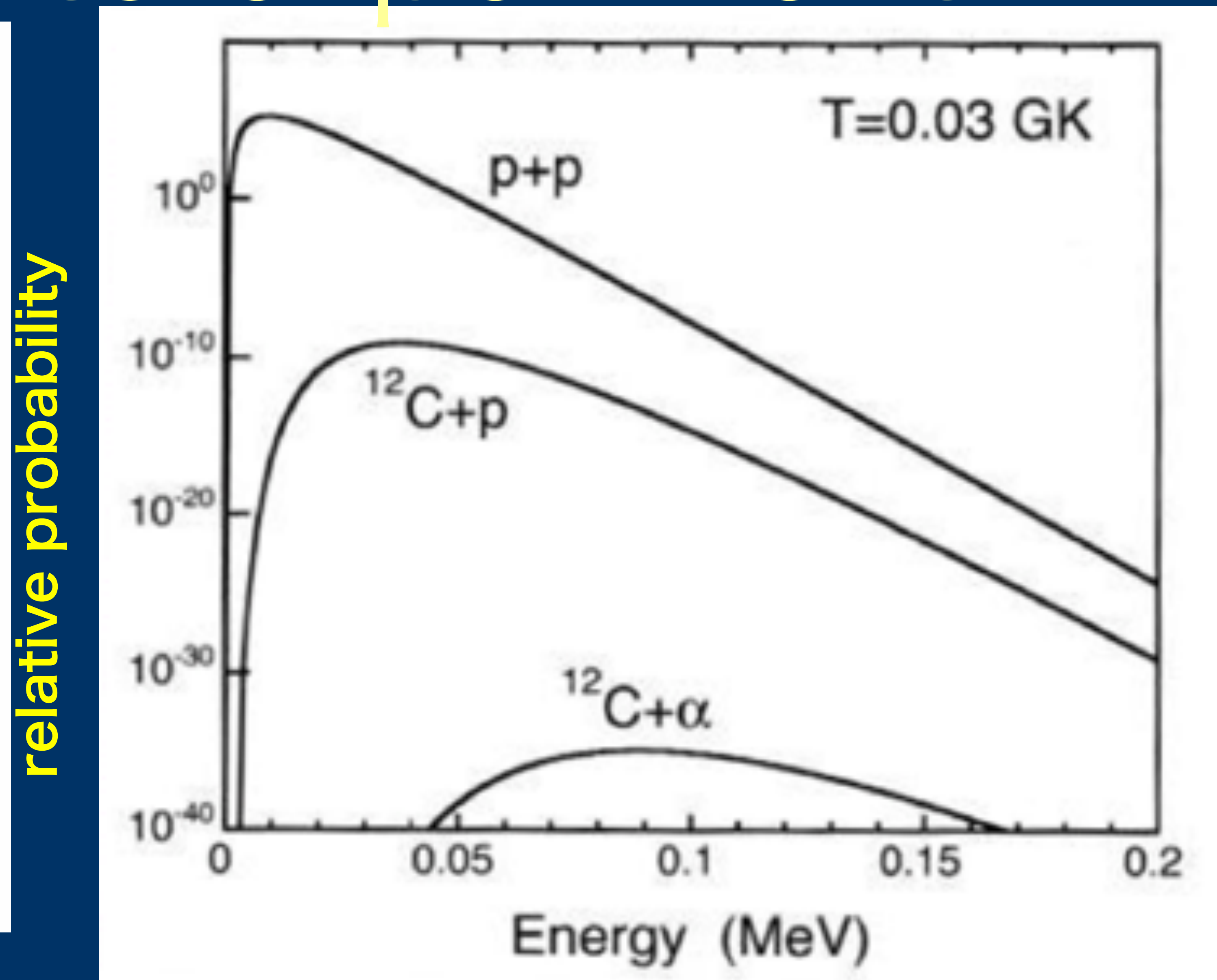


Nuclear burning inside sun



Challenge to experiment





- **Ultra low cross section**
- **Many times, in-direct approach**
- **Low background underground direct measurements**

Key scientific topics

- Direct measurements of cross sections for reactions in hydrostatic stellar burning
- Reliable extrapolation of high-energy charged-particle reaction cross sections to domains of astrophysical interest
- Indirect measurements of nuclear reaction cross sections critical to the explosive rp- and r-processes
- Measurements of masses, decay and resonance-state properties of nuclei involved in the rp- and r-processes
- Theoretical calculations of nuclear decay properties and reaction rates, including those for neutrino-nucleus interaction
- Effects of neutrino oscillations and neutrino-nucleus interaction on stellar explosion and nucleosynthesis
- Buildup of databases and network codes
- Observations of element abundances in stars and implications for the sites and mechanisms for nucleosynthesis.

Distribution of task force

(GSI, German; U. Tokyo, Japan; U. Paris, France; LBNL; JINA)

UNIVERSE Excellence Center
(TU München; MPI Garching; Sternwarte München; ANL; JINA)

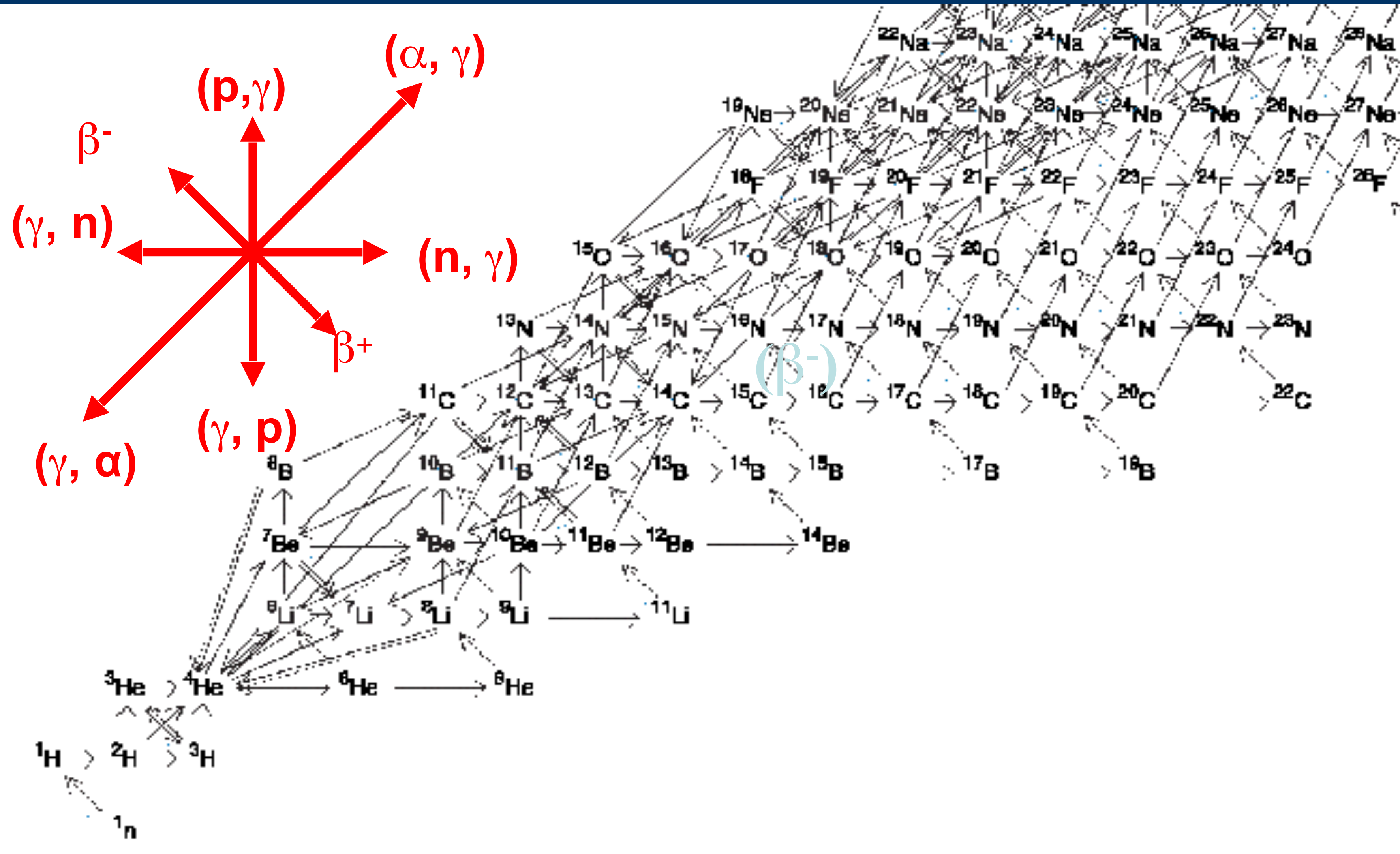
Chinese Nuclear Astrophysics
(CIAE, Lanzhou, SJTU; CJPL, LAMOST)

Saha/INO (FRENA 3MV accelerator laboratory)
(SAHA Institute, Kolkata, India; NSL/ND)

Institute for Advanced Studies (IEA) of the University of Sao Paulo, Brazil
(University of Sao Paulo, Brazil, University of Rio; JINA)

Australian Center for Nuclear Astrophysics
(ANU; Monash; Siding Springs; SkyMapper; JINA)
- Host of Nuclei in the Cosmos 2012 -

Element synthesis network



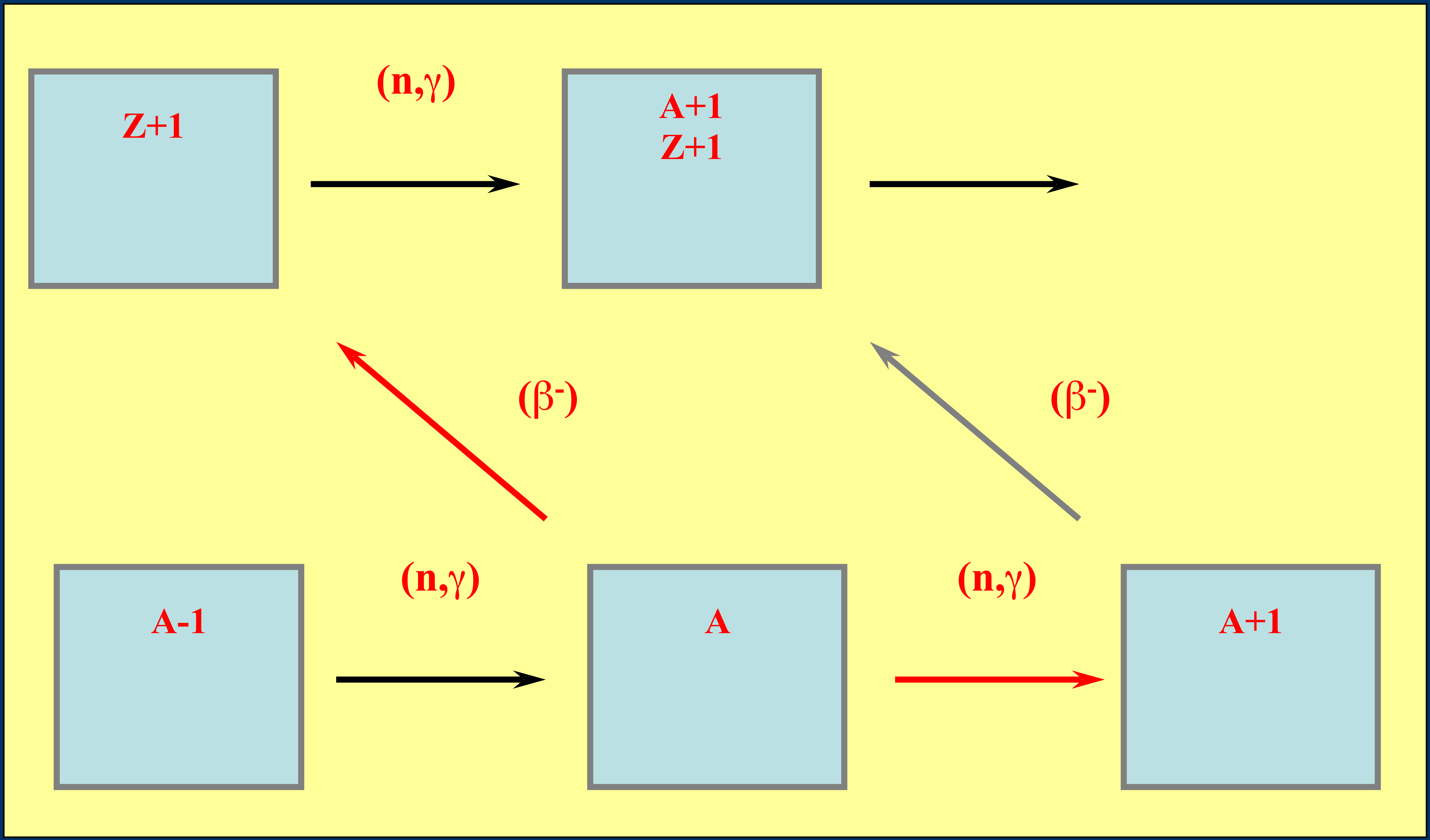
Cross section

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

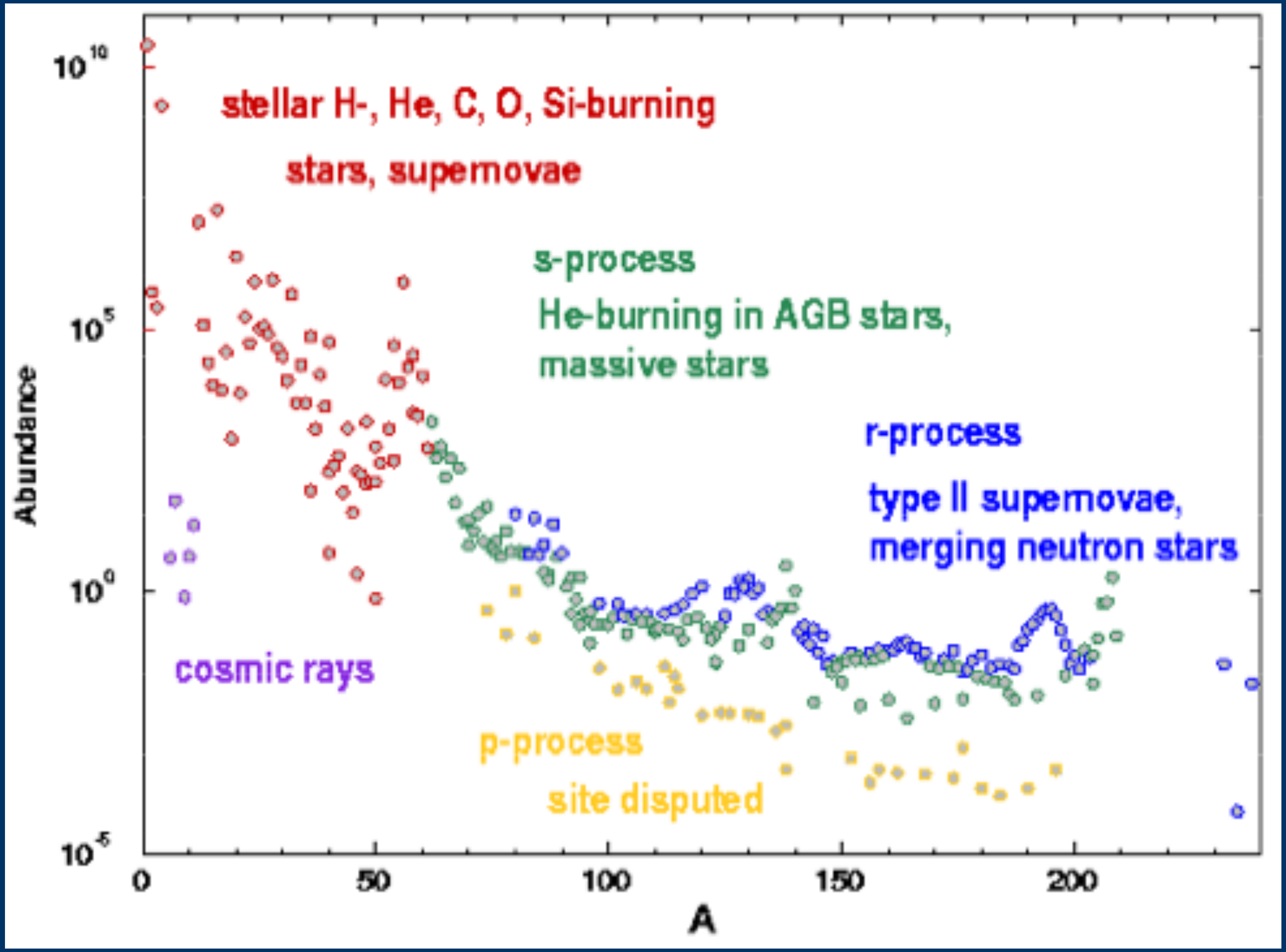
$$+ \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A{}^2 < \sigma V >_{jkl,i} Y_j Y_k Y_l$$

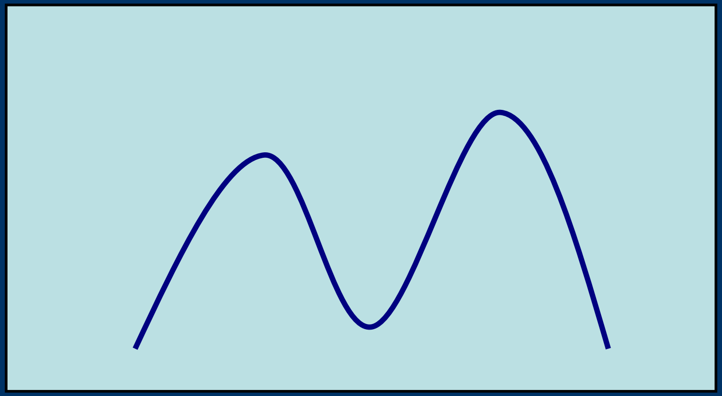
Decay half-life

How elements become heavier



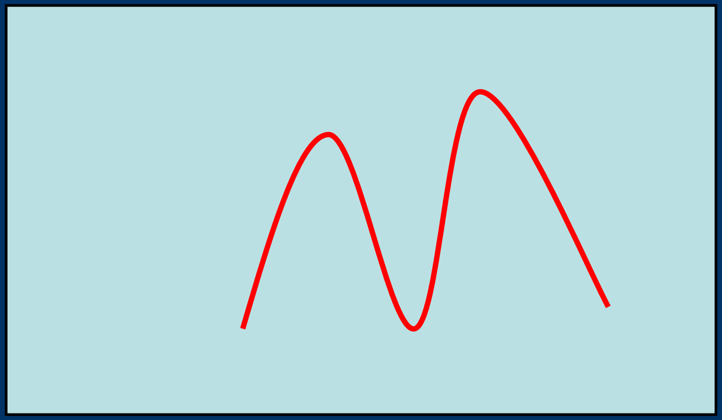
Abundance curve





Light curve

$\downarrow$ $/\sigma_{\text{atomic transition}}$



Abundance curve

The importance of one and more experiments

- Key reaction, most difficult, like $^{12}C(\alpha,\gamma)^{16}O$, $^{7}Be(p,\gamma)^{8}B$
- Supporting reaction, large numbers, like $^{11}C(p,\gamma)$, $^{8}Li(\alpha,n)$
- Importance of international collaboration, data evaluation and compilation
- Importance of theoretical calculation, fill the impossible

Status in China

- Theoretical (Network, neutron star, …)
- Observation (LAMOST, Yangbajing, Daya Bay)
- Nuclear physics experiments (Beijing, Lanzhou)
- Major research project MOST funds and group funds (RNB & astrophysics)
- Network calculation (Exp + The)
- International collaboration (TRIUMF, Bochum, JINA, RIKEN, GSI, MSU…)

Important nuclear physics data

- S-factor, focus on NP, down to astrophysics energies
- Reaction rates, direct input to network calculation
- Direct capture, direct reactions
- Resonance, level scheme, level width, and partial width
- Mass and decay half-life and branching ratio

Reaction rates

$$< \sigma v >= \int_0^\infty \phi(v)\sigma(v)v dv. \quad (1)$$

Maxwell-Boltzmann speed distribution is

$$\phi(v) = 4\pi v^2 (\frac{\mu}{2\pi kT})^{3/2} \exp(-\frac{\mu v^2}{2kT}), \quad (2)$$

In which, μ, k and T is reduced mass Boltzmann constant and star temperature respectively. It can be simplified into,

$$N_A < \sigma v >= 3.7313 \times 10^{10} \mu^{-1/2} T_9^{-3/2} \int_0^\infty \sigma(E) E \exp(-11.605 E/T_9) dE, \quad (3)$$

Where the reation rate $N_A < \sigma v >$ is in the unit of $\mathrm{cm^3 mol^{-1} s^{-1}}$ and center of mass energy E and corss section σ are in the unit of MeV and b.

C.E. Rolfs and W.S. Rodney, Cauldron in the Cosmos, The University of Chicago Press, (1988).

Astrophysical S-factor

The reaction cross section can be re-scaled into astrophysical S-factor,

$$\sigma(E) = S(E)\exp(-2\pi\eta)\frac{1}{E}, \tag{4}$$

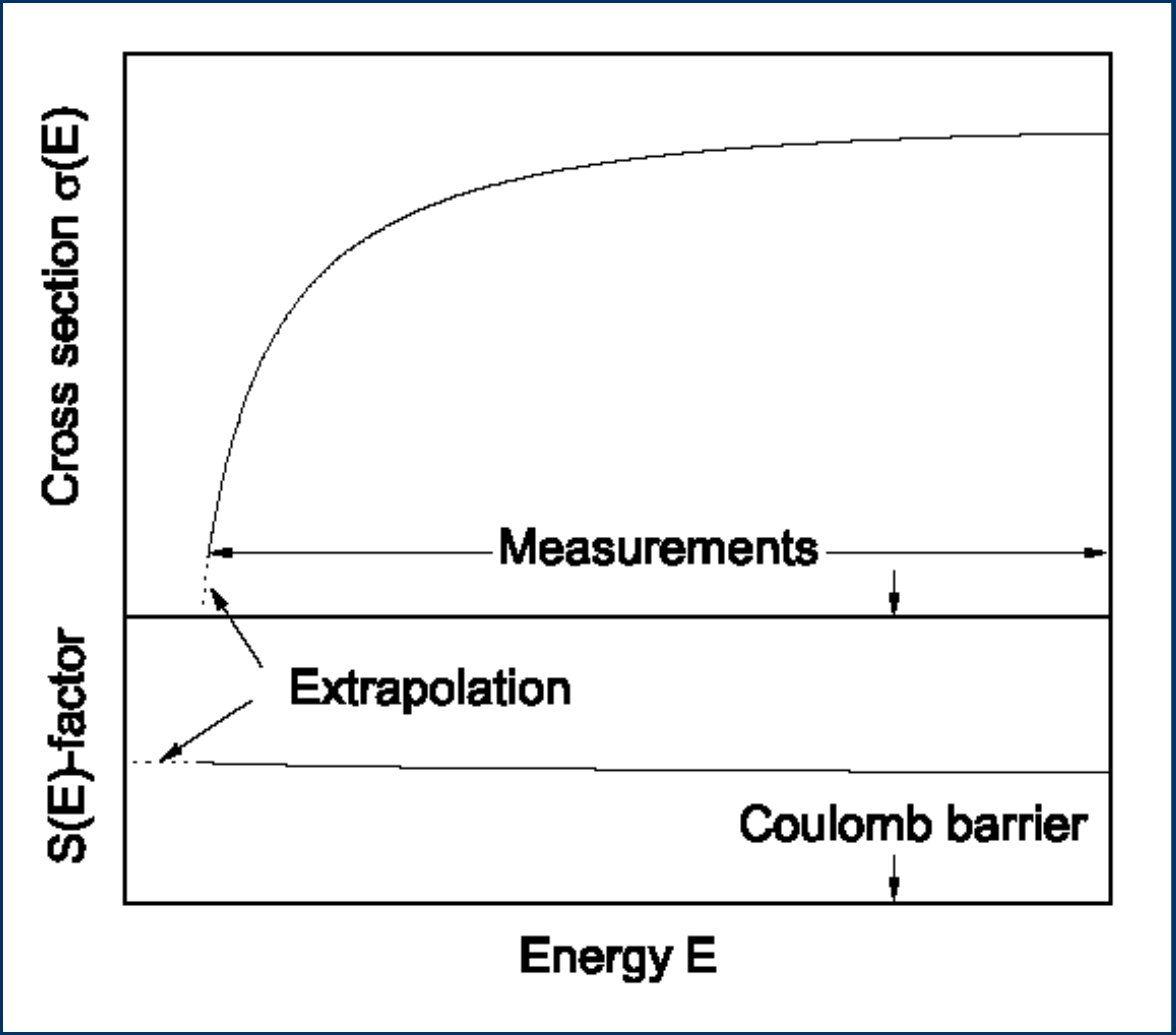
Where η is Sommerfeld constant,

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v} = 0.1575 Z_1 Z_2 (\frac{\mu}{E})^{1/2}, \tag{5}$$

Where $\hbar$ is reduced Plank constant, Z_1 and Z_2 are atomic number, E is the center of mass energy in MeV.

C.E. Rolfs and W.S. Rodney, Cauldron in the Cosmos, The University of Chicago Press, (1988).

Energy dependence of cross section and astrophysical S-factor



Gamow window

$$N_A < \sigma v >= N_A(\frac{8}{\pi\mu})^{1/2}\frac{1}{(kT)^{3/2}}\int_0^{\infty} S(E)\exp(-\frac{E}{kT}-\frac{b}{E^{1/2}})dE, \quad (6)$$

b come from Coulomb penetration

$$b = (2\mu)^{1/2}\pi e^2 Z_1 Z_2/\hbar = 0.989 Z_1 Z_2 \mu^{1/2}(\mathrm{MeV})^{1/2}. \quad (7)$$

Its square is so called Gamow energy E_G.

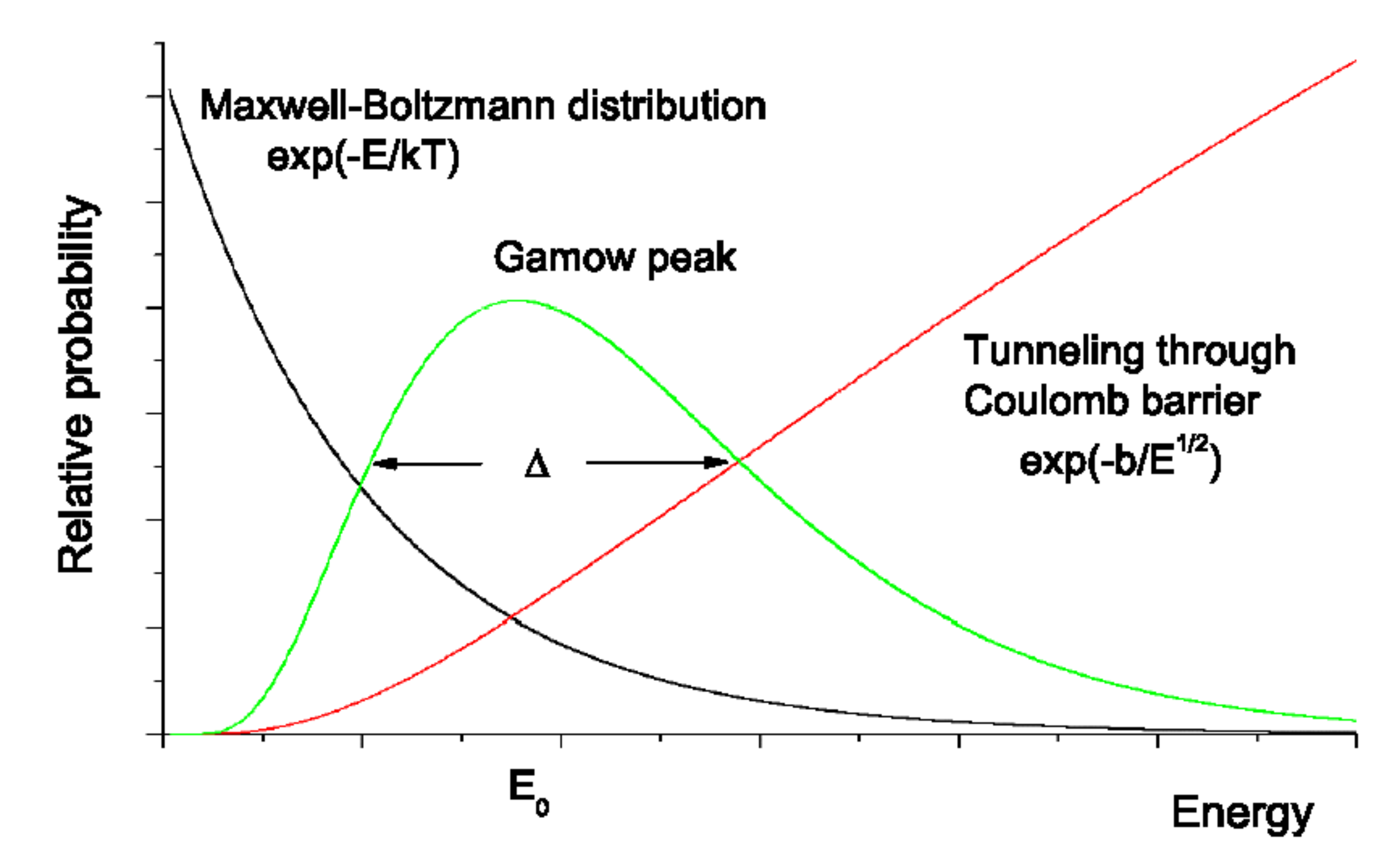
In exponential part of Equ. 6, the first term come from Maxwell-Boltzmann velocity distribution, the second term is Coulomb term, the interplay of two terms reach a maximum in E_0, as shown in Fig. 4. Where the effective mean energy E_0 can be expressed as:

$$E_0 = (bKT/2)^{2/3} = 1.22(Z_2^1 Z_2^2$$

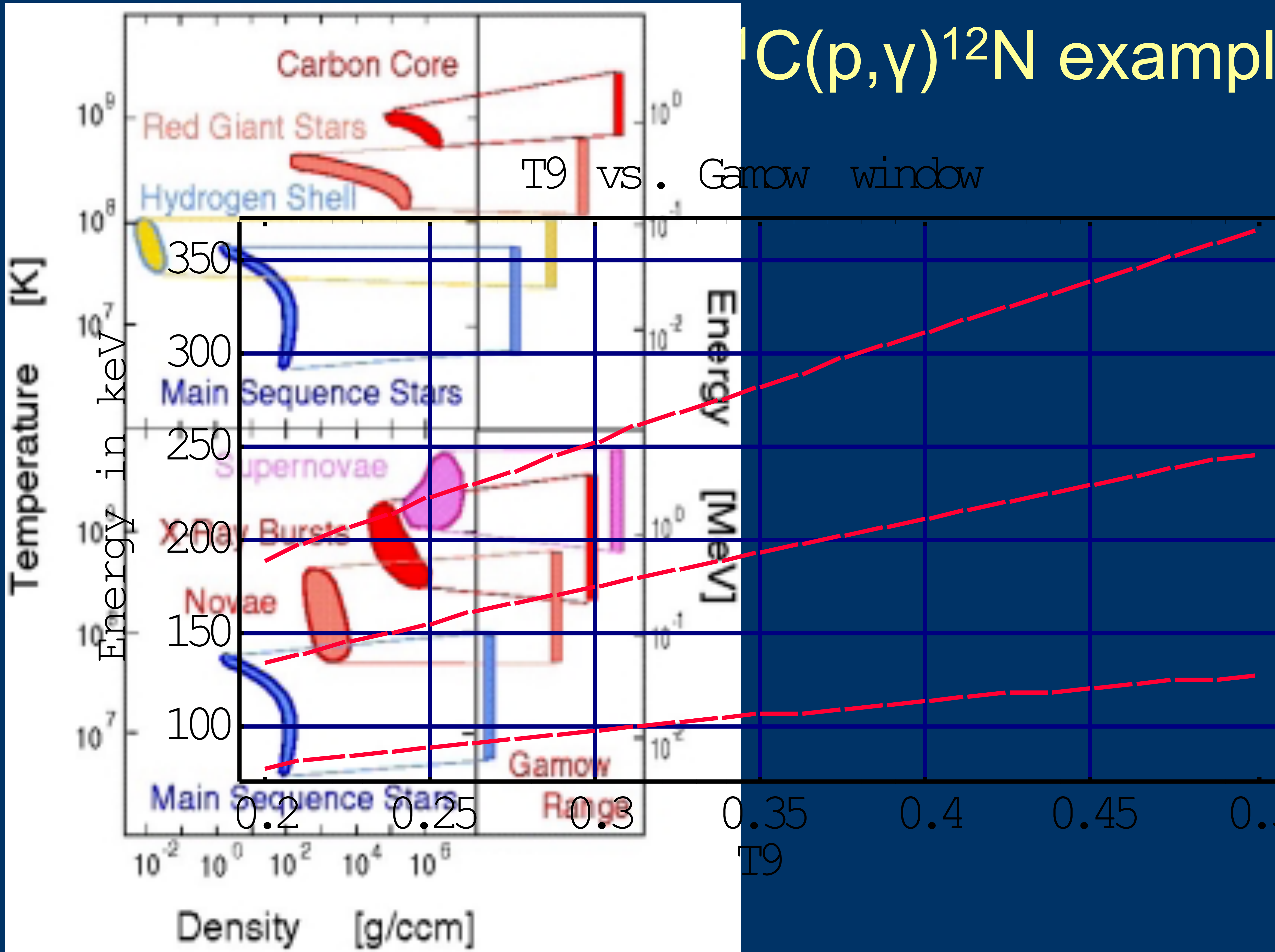
$\mu \mathrm{T}_6^2)^{1/3} keV(8)$

It is E_0 that is most important parameter for experimentalists to reach directly or in-directly. For system p+p, , for sun T_6=15, E_0 is only 5.9 keV!

The Gamow window



^{1}C(p,γ)^{12}N example

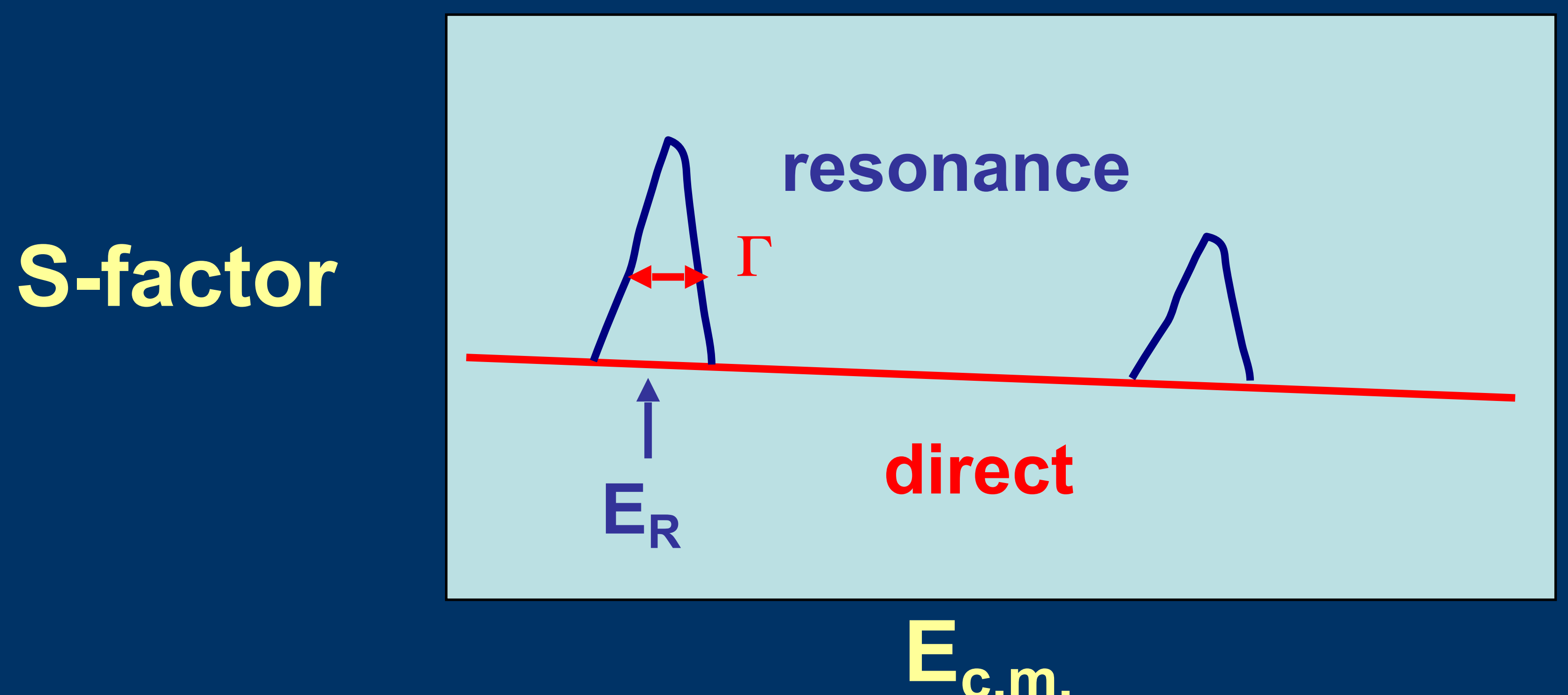


Resonance capture

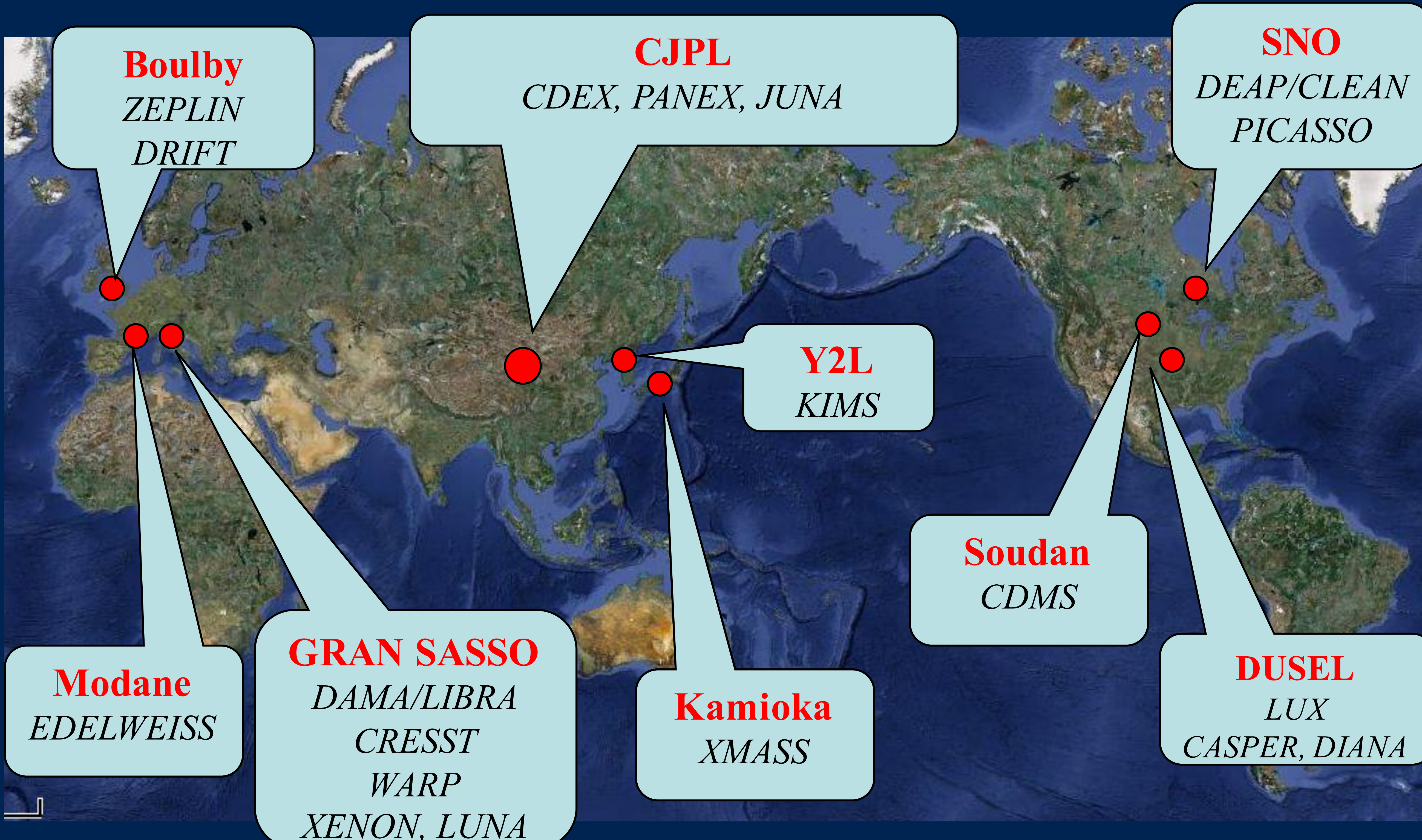
The resonance capture reaction cross section can be expressed by Breit-Wigner formula [17],

$$\sigma_{BW}(E) = \pi \frac{\hbar^2}{2\mu E} \frac{2J_R + 1}{(2J_1 + 1)(2J_2 + 1)} \frac{\Gamma_{in}(E)\Gamma_{out}(E)}{(E - E_R)^2 + (\Gamma_{tot}/2)^2}, \quad (9)$$

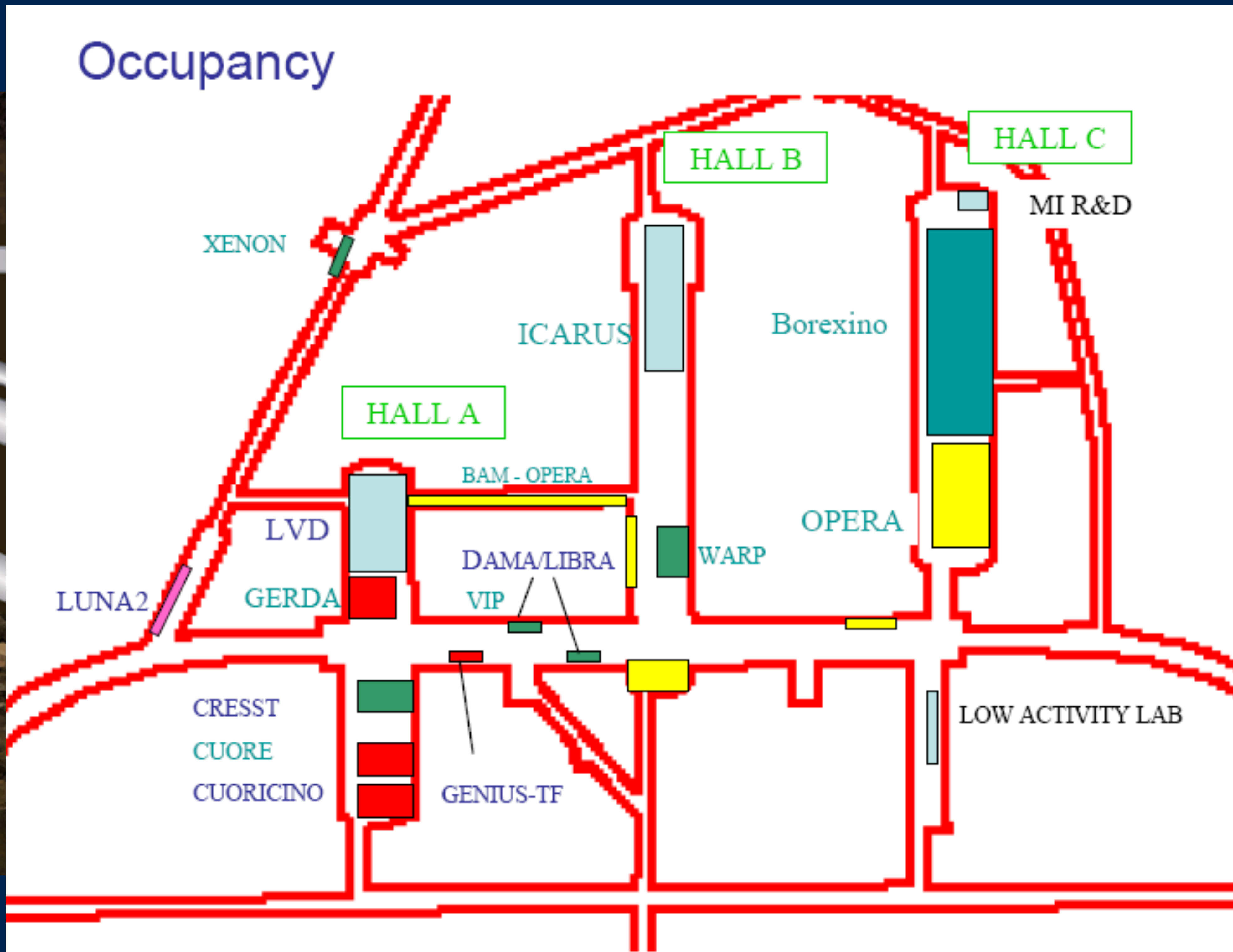
Where J_1, J_2, J_R is the spin of beam, target and compound state respectively, Γ_{in}, Γ_{out} are entrance channel partial width, Γ_{tot} is the total width.



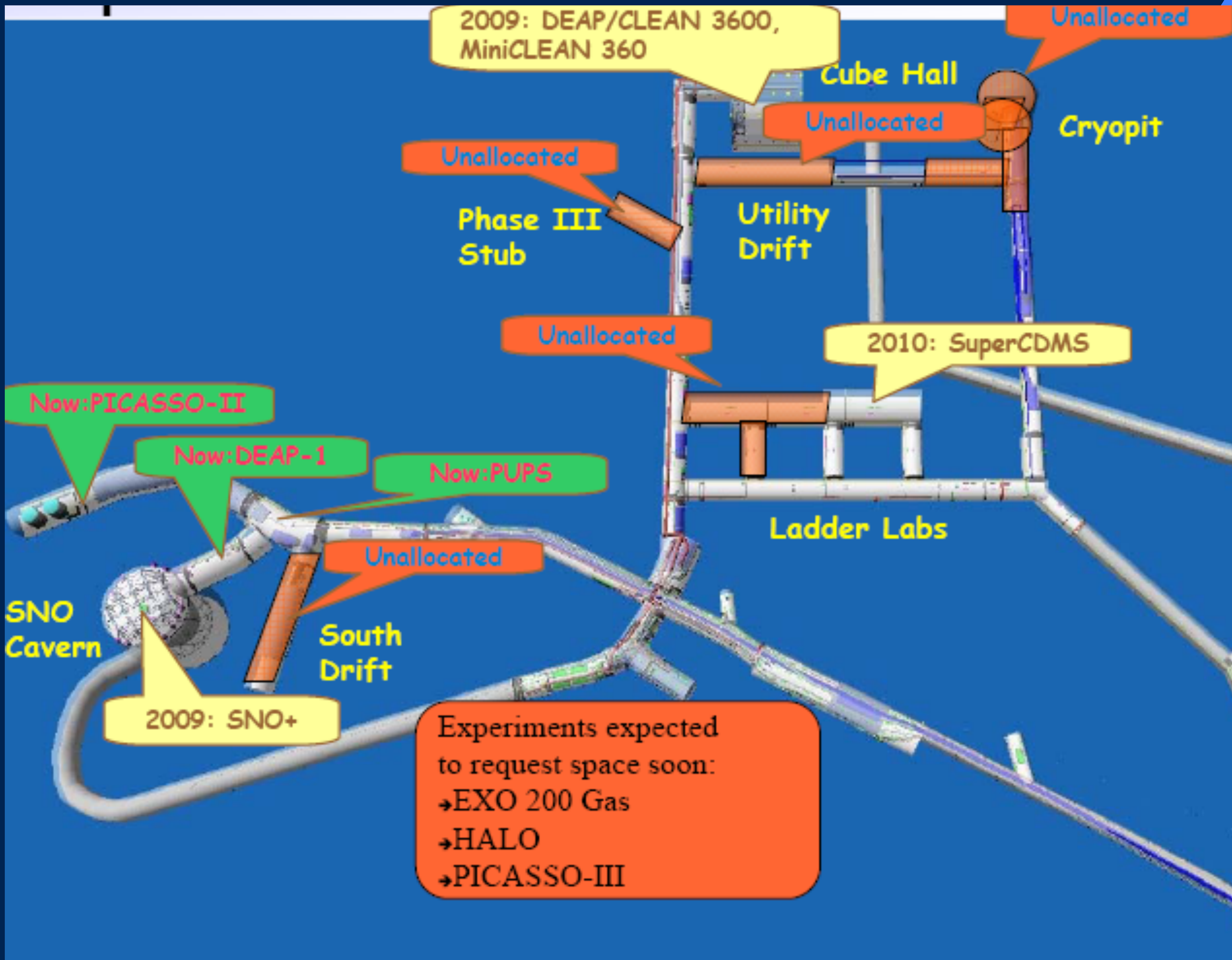
World underground labs



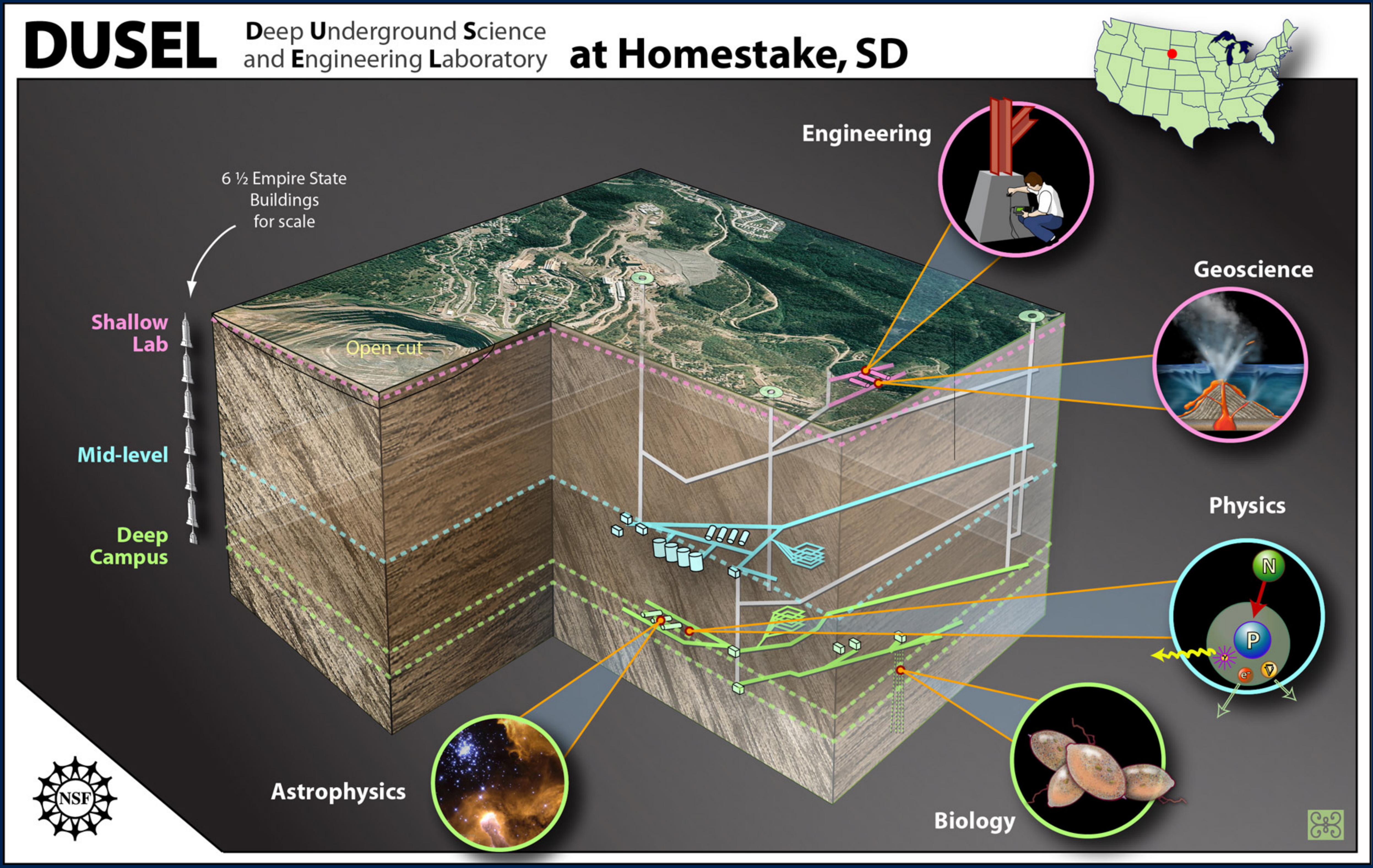
GRAN SASSO


Occupancy
HALL A
HALL B
HALL C
MI R&D
XENON
ICARUS
Borexino
BAM - OPERA
LVD
DAMA/LIBRA
WARP
OPERA
LUNA2
GERDA
VIP
CRESST
CUORE
CUORICINO
GENIUS-TF
LOW ACTIVITY LAB

SNO lab

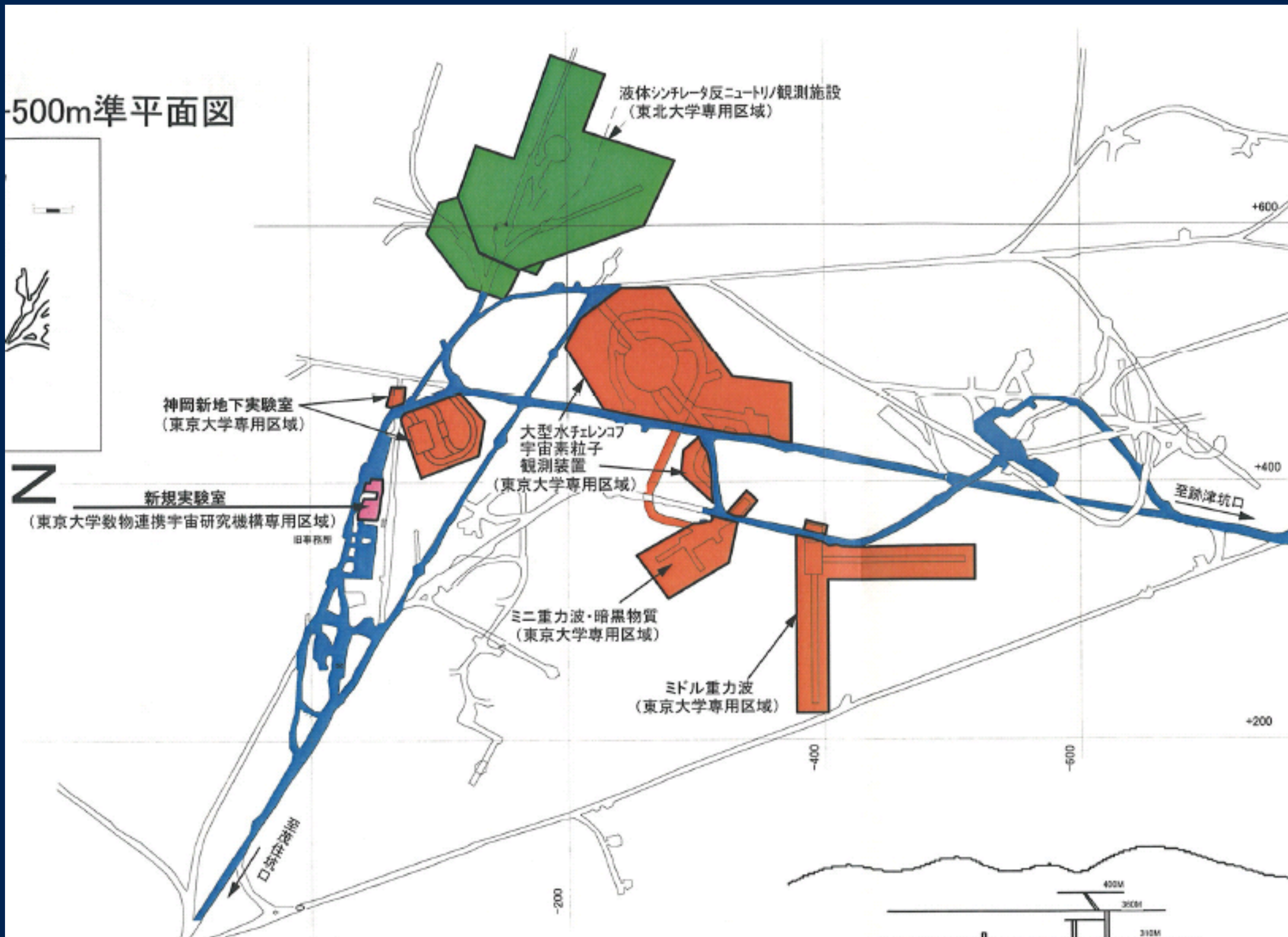

2009: DEAP/CLEAN 3600,
MiniCLEAN 360
Unallocated
Cube Hall
Unallocated
Cryopit
Unallocated
Phase III
Stub
Utility
Drift
Unallocated
2010: SuperCDMS
Now:PICASSO-II
Now:DEAP-1
Now:PUPS
Ladder Labs
Unallocated
SNO
Cavern
South
Drift
2009: SNO+
Experiments expected
to request space soon:
EXO 200 Gas
HALO
PICASSO-III

DUSEL


DUSEL Deep Underground Science and Engineering Laboratory at Homestake, SD
6 ½ Empire State Buildings for scale
Shallow Lab
Mid-level
Deep Campus
Open cut
Engineering
Geoscience
Physics
N
P
Astrophysics
Biology
NSF

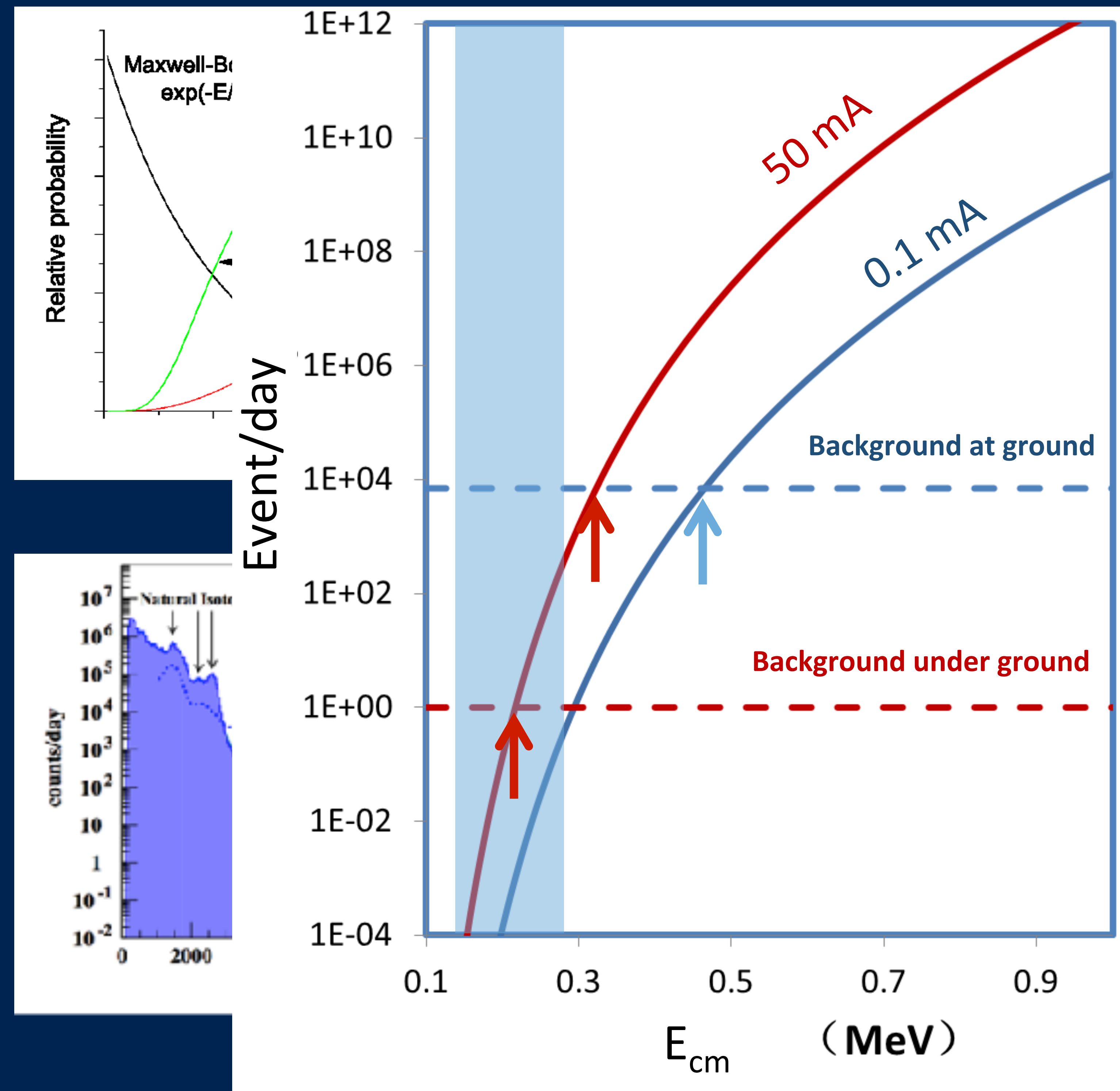
JUNA

KAMIOKA



Underground nuclear astrophysics

- Direct is the way to get rid of model dependence
- Direct in Gamow window have to go underground
- Underground is list in top priority
- Many world lab planned, with LUNA operational



From X. D. Tang

The importance

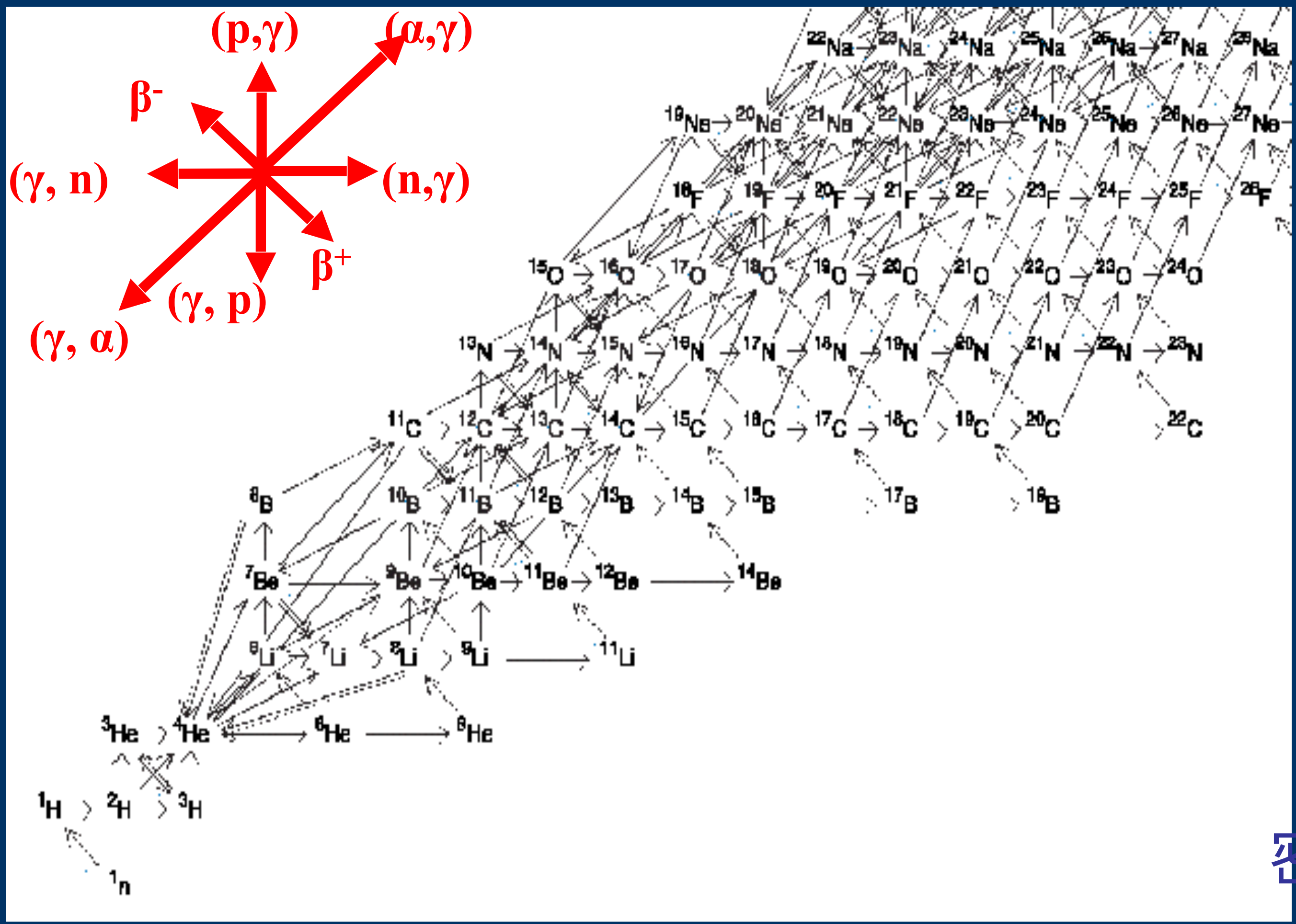
JUNA

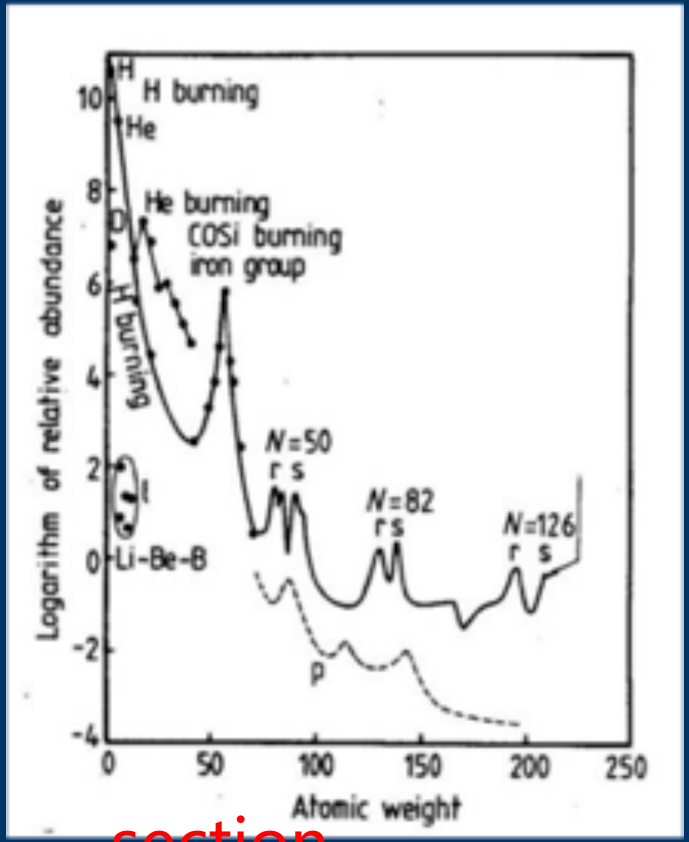
- NuPPEC

Over the last decade our understanding has progressed tremendously due not least to significant experimental advances connected to the use of the Gran Sasso deep underground accelerator … Providing an underground multi-MV accelerator facility is a high priority. There are a number of proposals being developed in Europe and it is vital that construction of one or more facilities starts as soon as possible.

Why underground

JUNA





section

temp

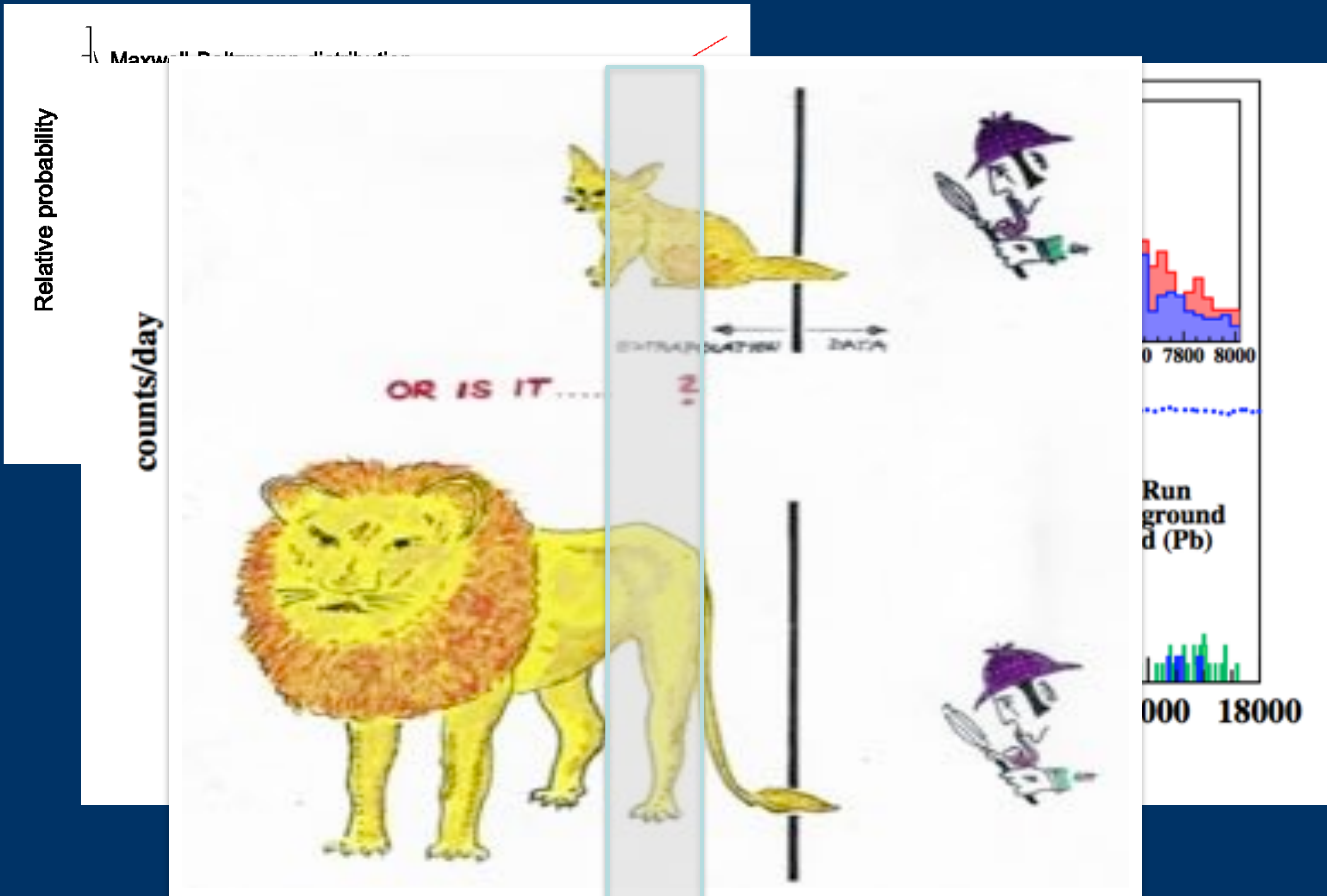
密度

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

rate

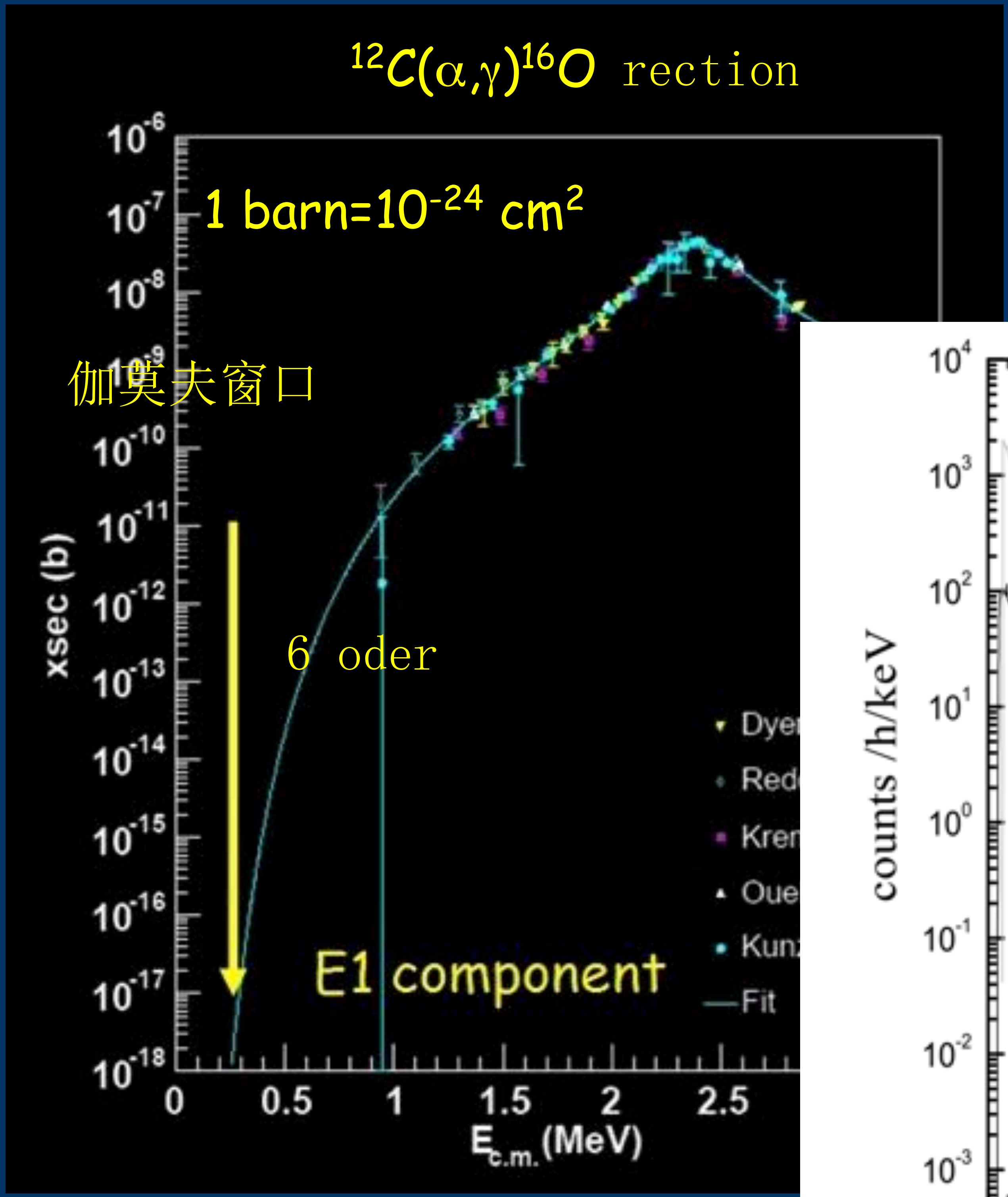
Direct→in-direct→theory→network：direct is essnetial

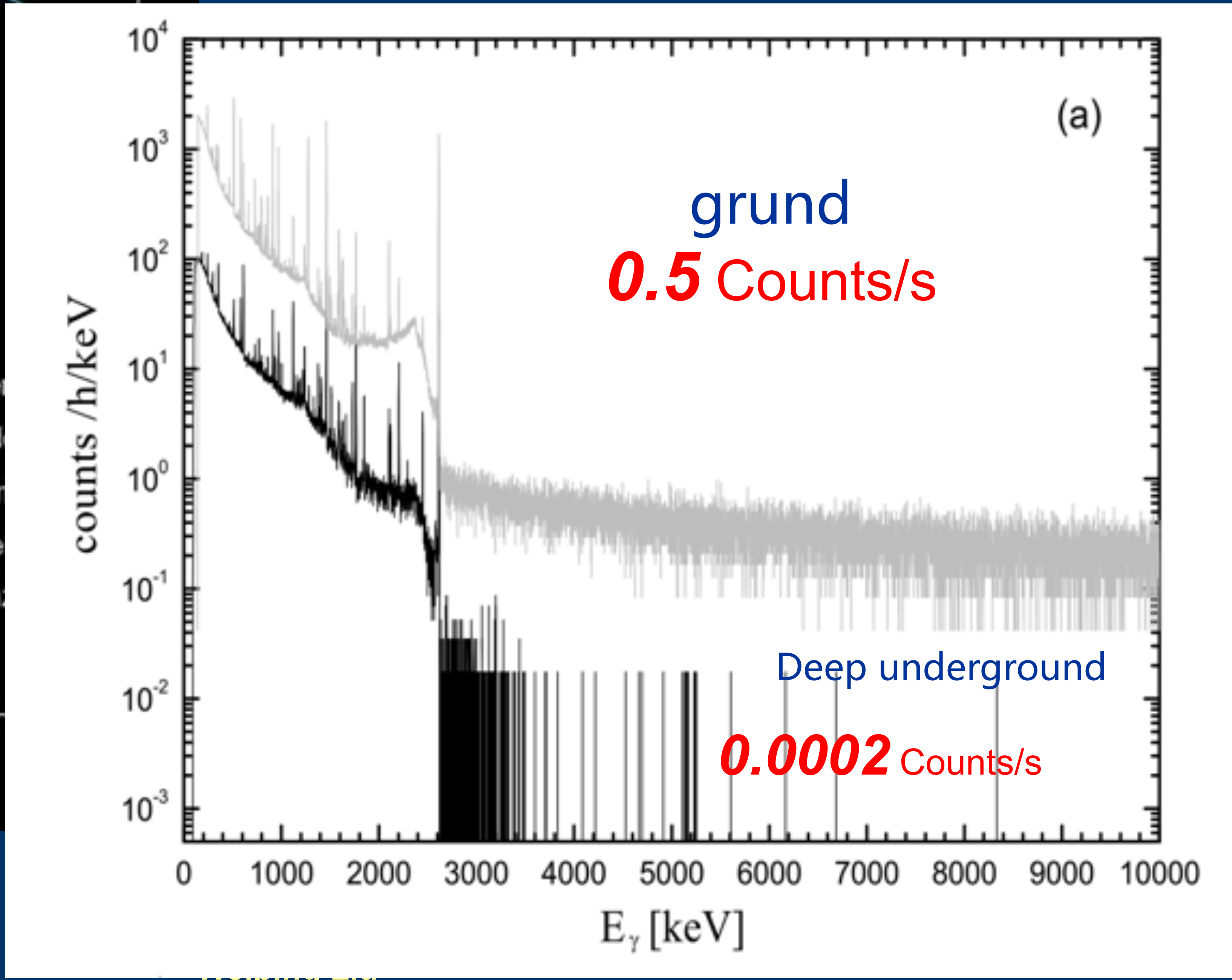
Why underground

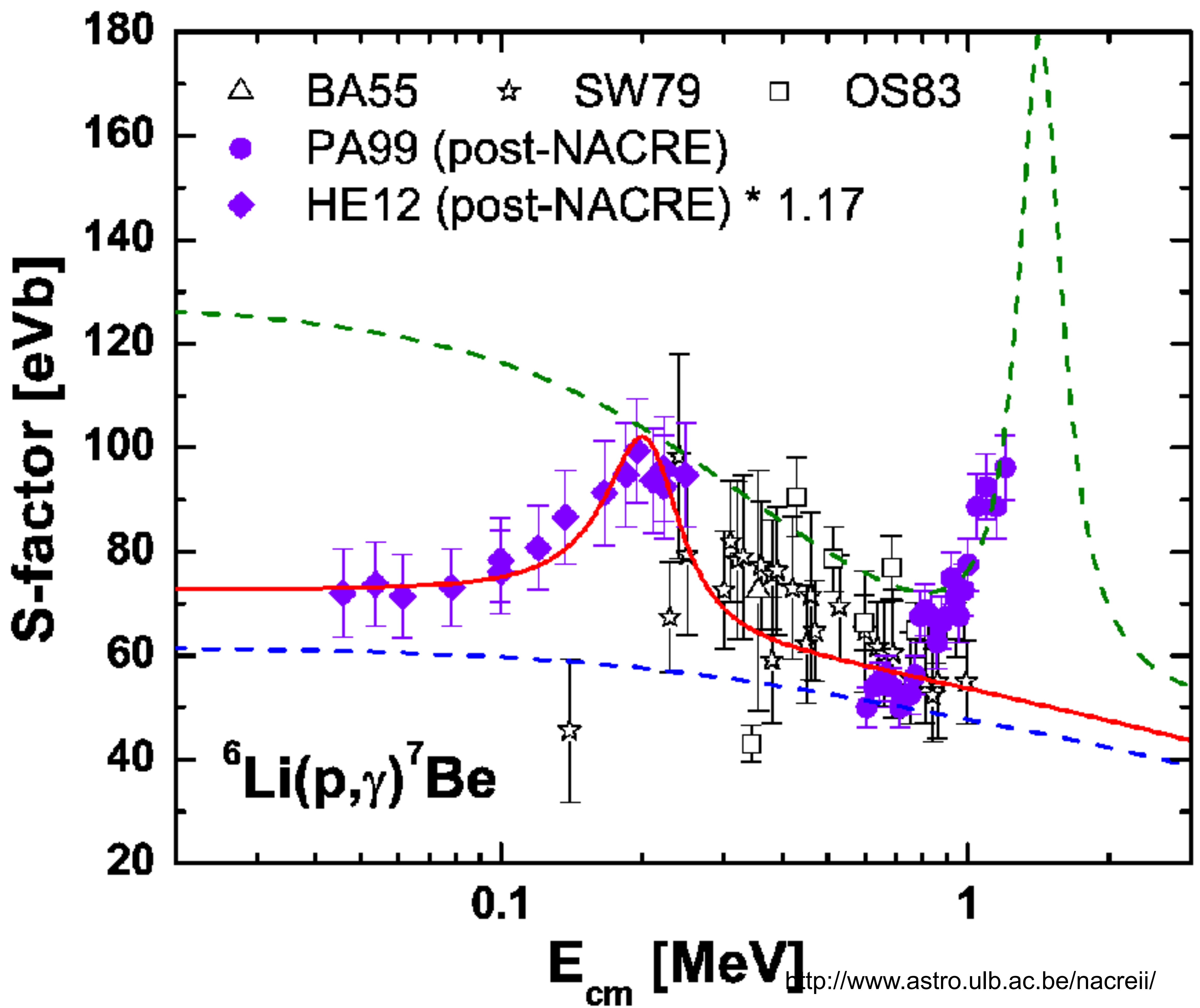


Nuclear astrophysics direct

JUNA



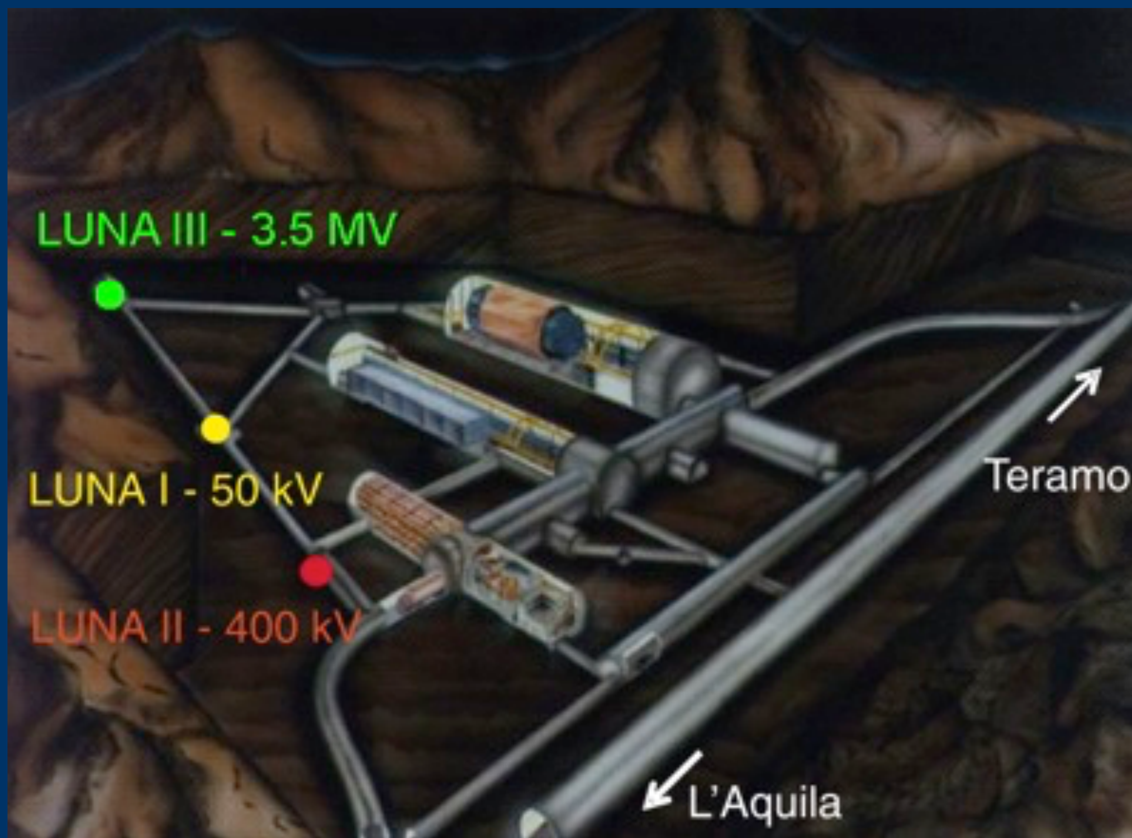


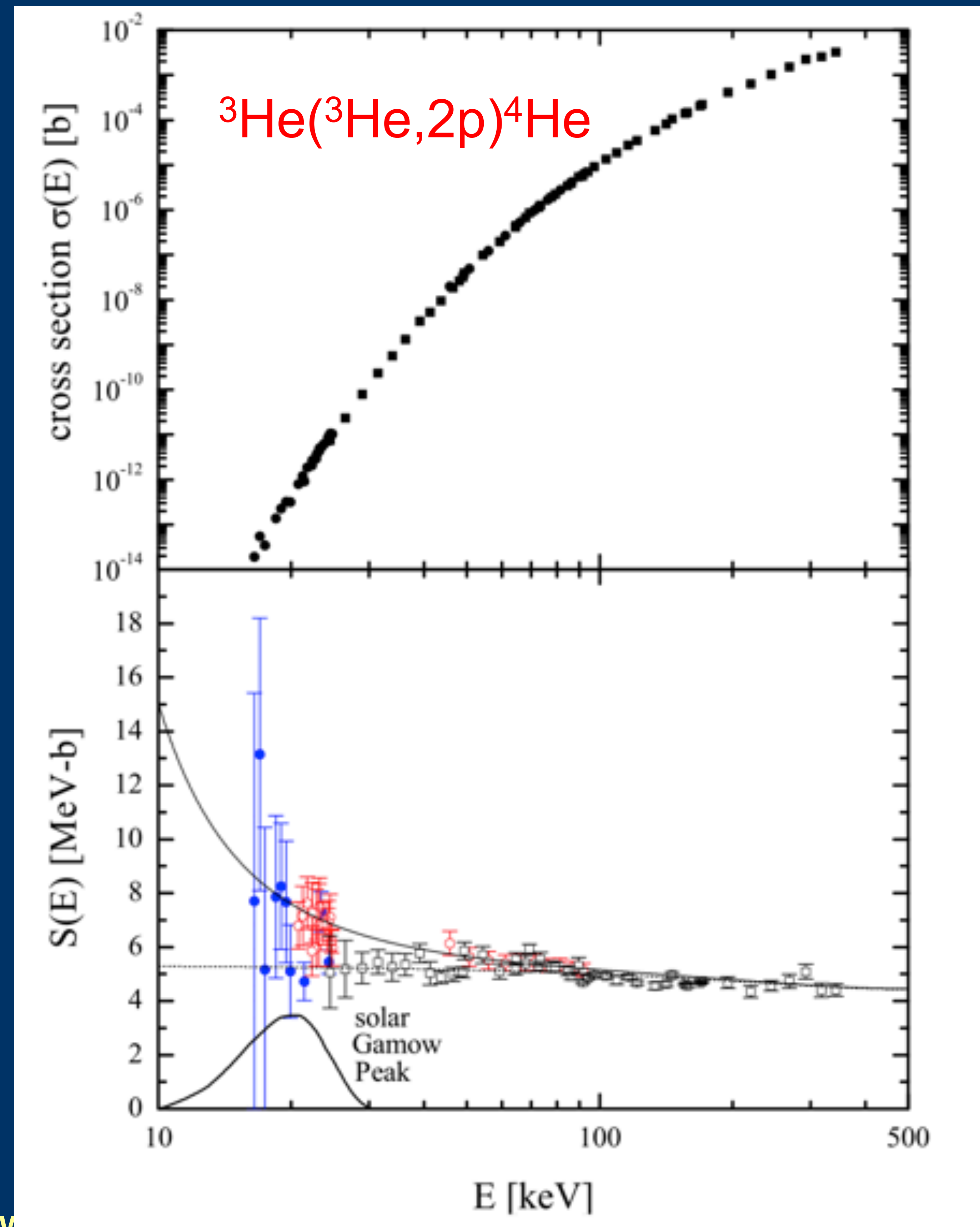


http://www.astro.ulb.ac.be/nacreii/

LUNA progress

JUNA





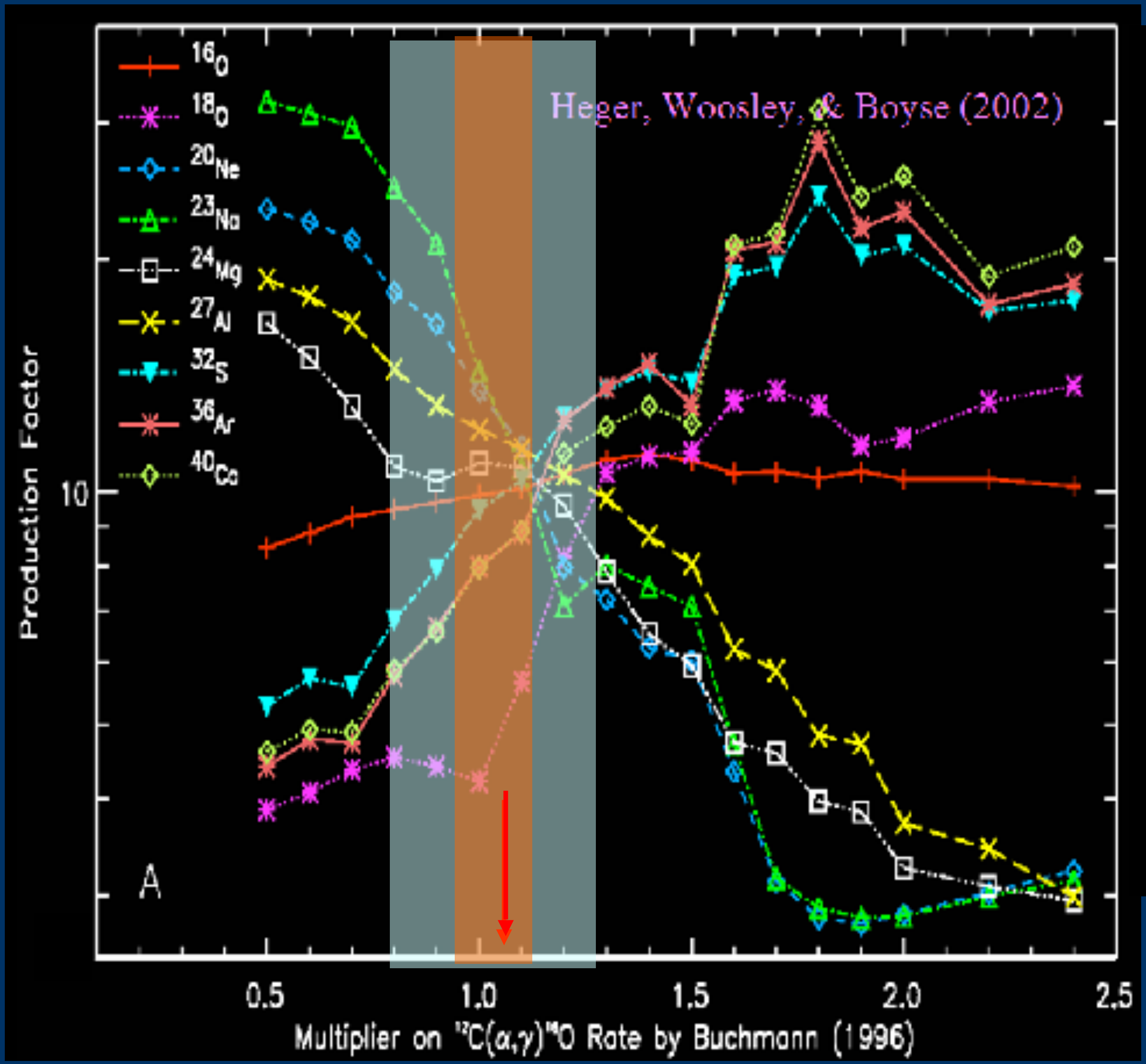
- LUNA
- Only Nuclear astrophysics under ground
- 50 kV and 400 kV

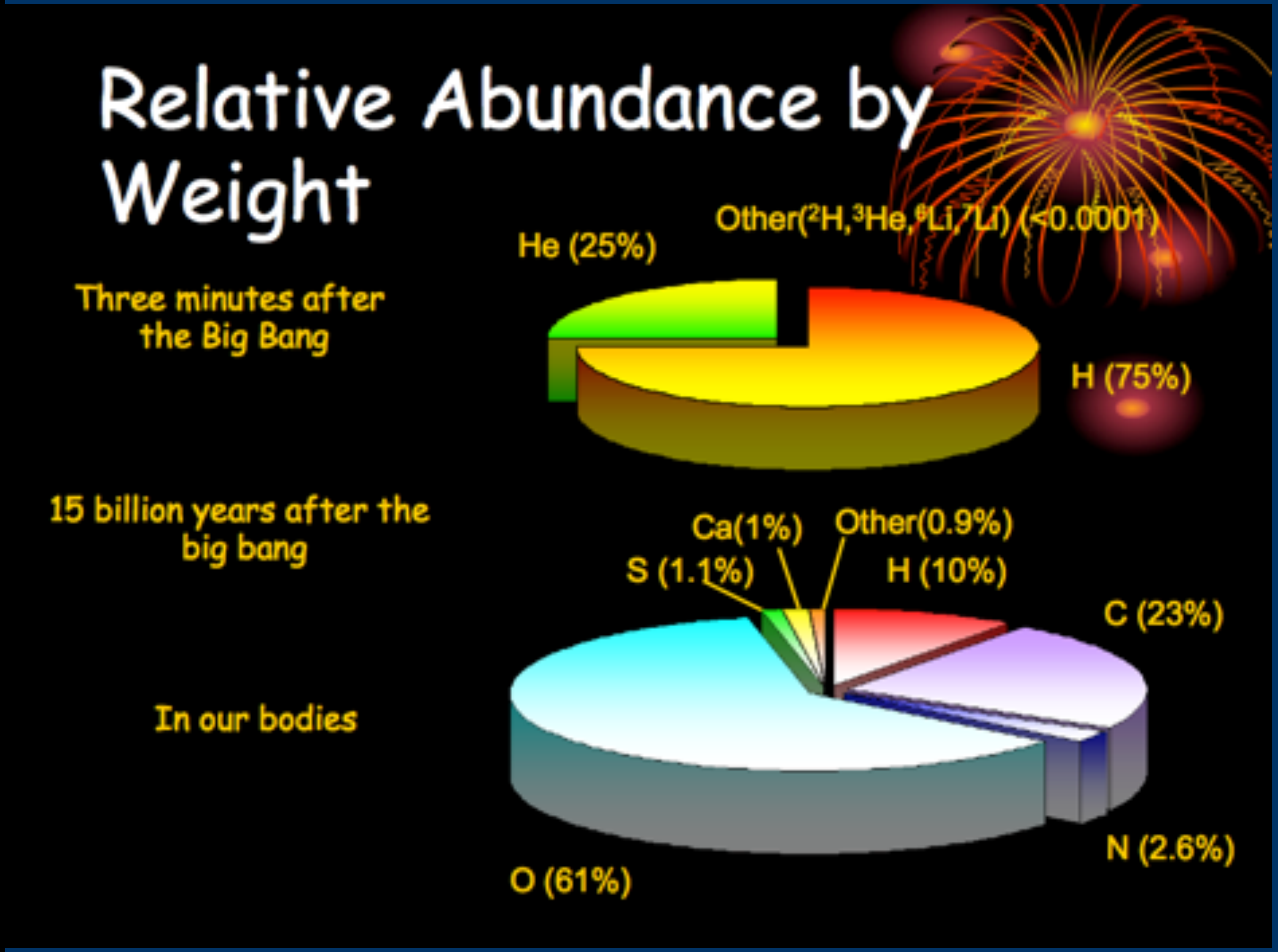
How to deal with low rate

SITE	INT	BG	CTS	XSEC
ground	1 mA	1800/hour	20/hour	10^{-12} b
LUNA	1 mA	20/day	1/day	10^{-15} b
JUNA	10 mA	6/month	10/month	10^{-16} b

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

JUNA





The determination of the ratio C/O produced in helium burning is a problem of paramount importance in Nuclear Astrophysics. *W. Fowler, Nobel lecture, 1983*

The fusion of ^{4}He and ^{12}C nuclei to ^{16}O is the most important nuclear reaction in the development of massive stars. *NuPECC Long Range Plan 2004*

世界上最先进的深地低能加速器装置

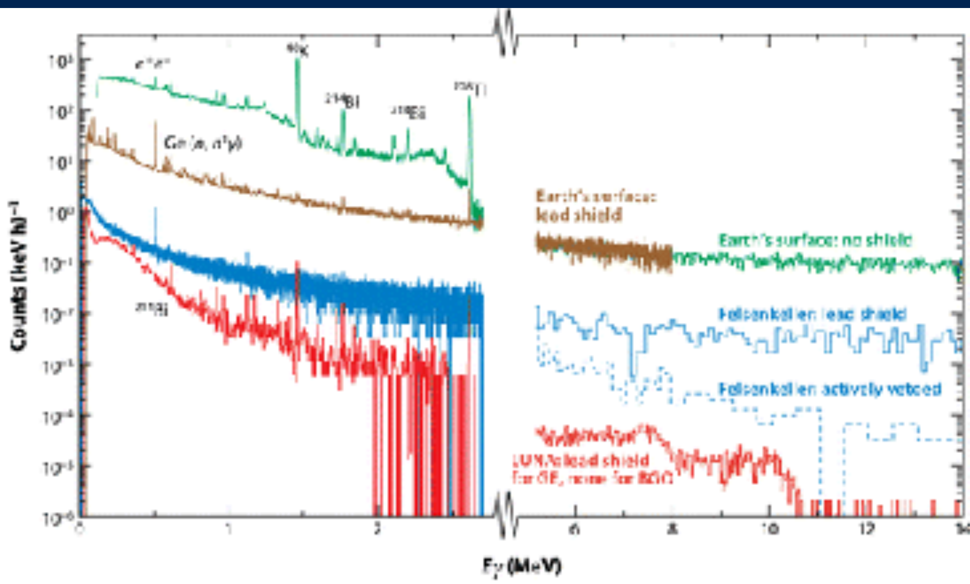
JUNA

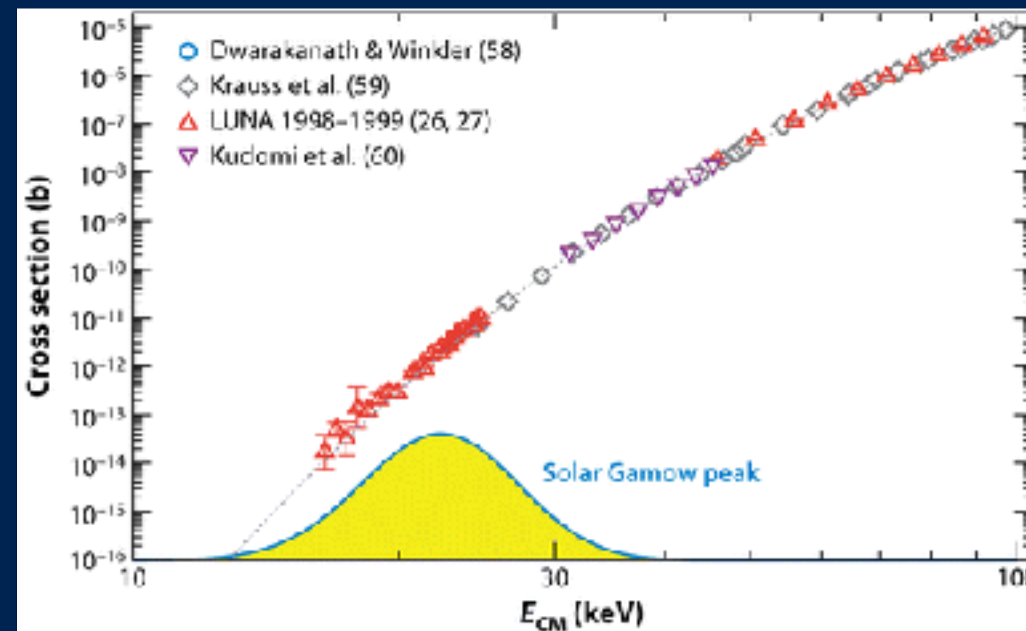
		束流, mA	能量范围, keV
加速离子	H^+	~10 (0.5)	50~400 (400)
	He^+	~10 (0.3)	50~400
	He^{2+}	~5 (无)	100~800 （无）

（LUNA参数）

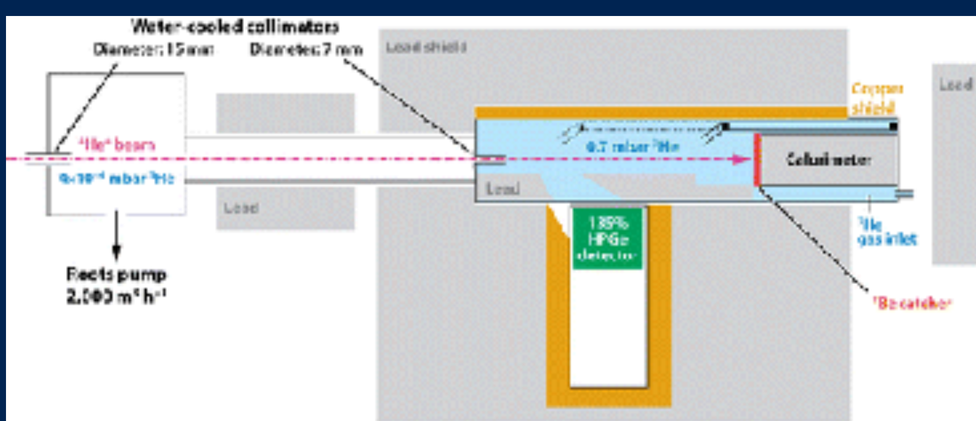
JUNA

LUNA experiments

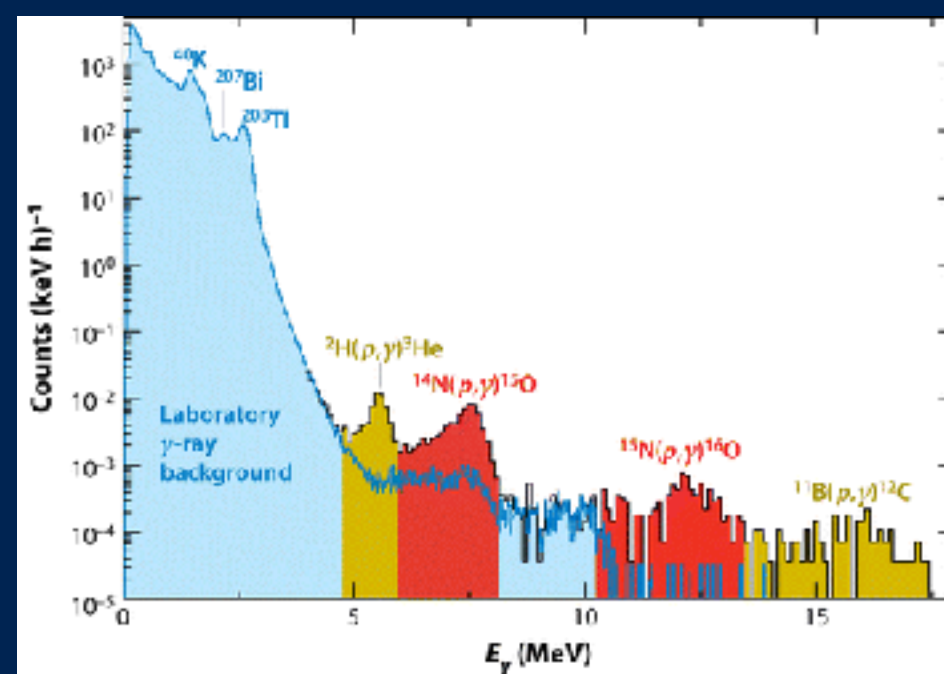




$^3He(^3He,2p)^4He$



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



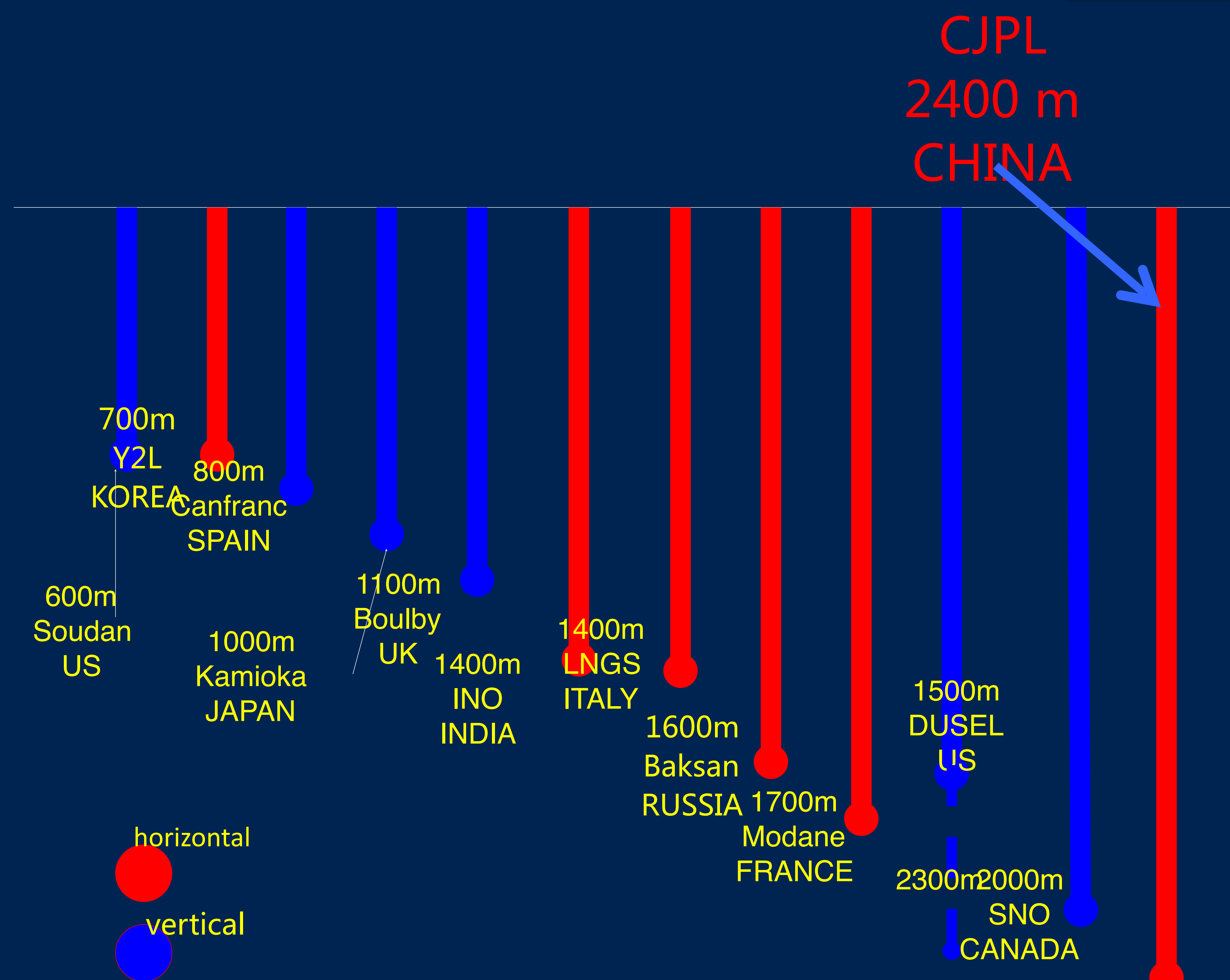
$^{14}N(p,\gamma)^{15}O$

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

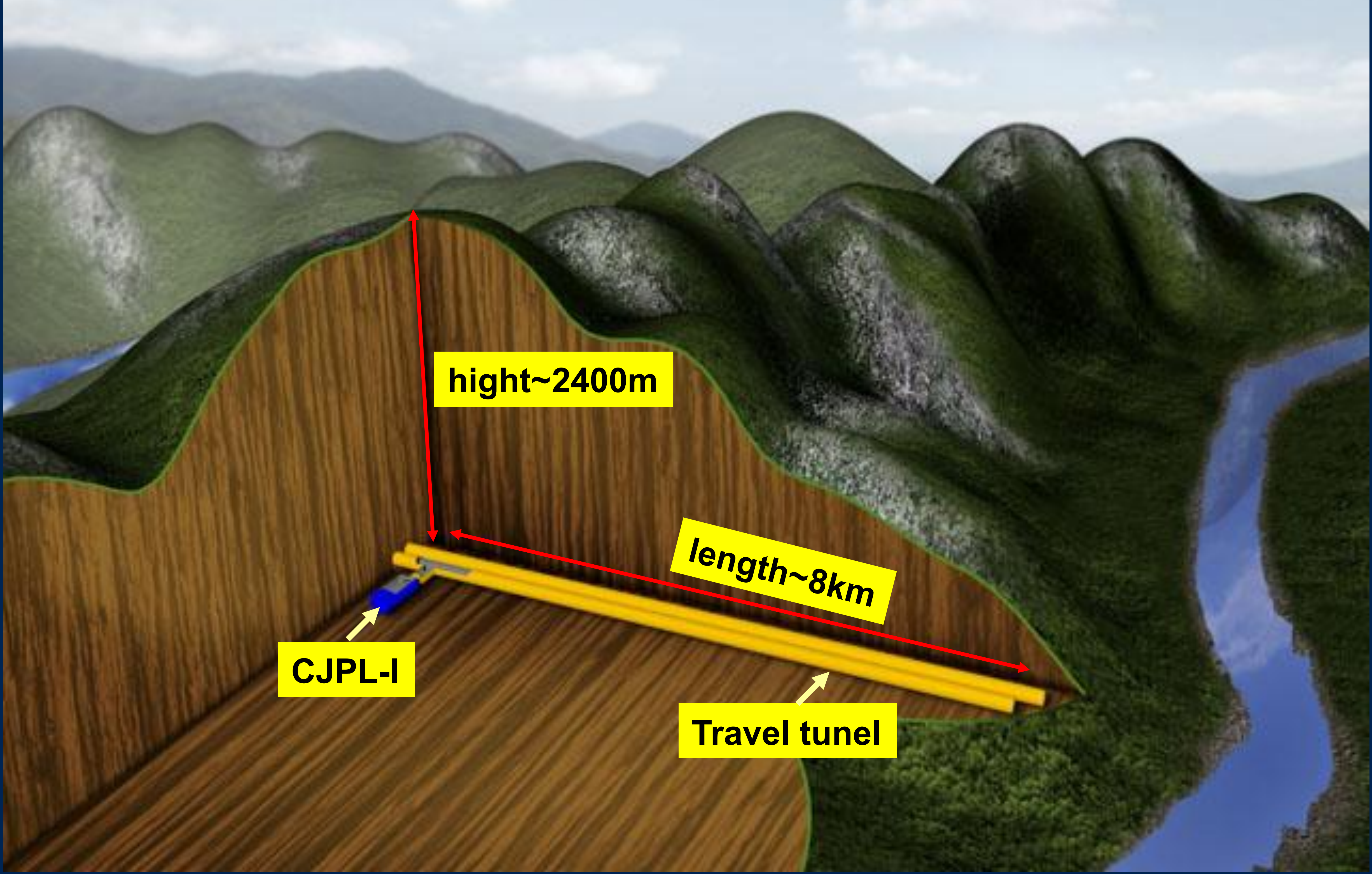
Physics focused

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 underground laboratory

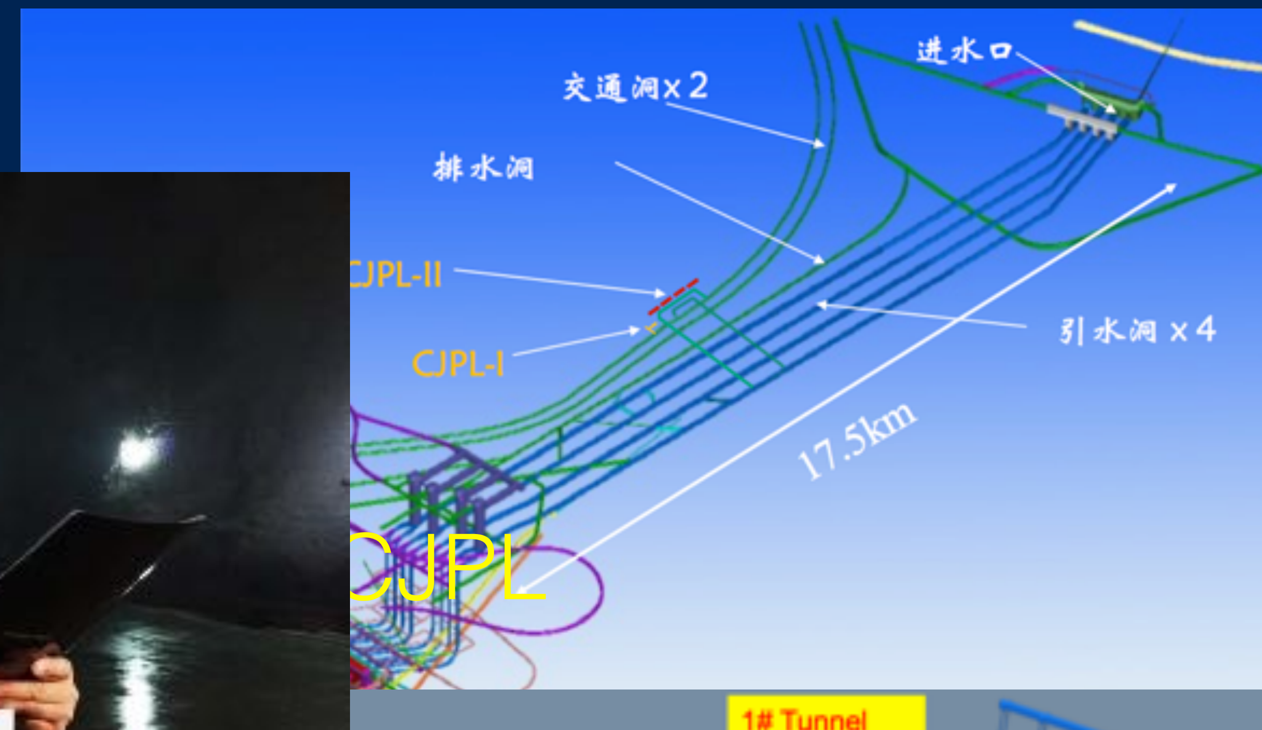


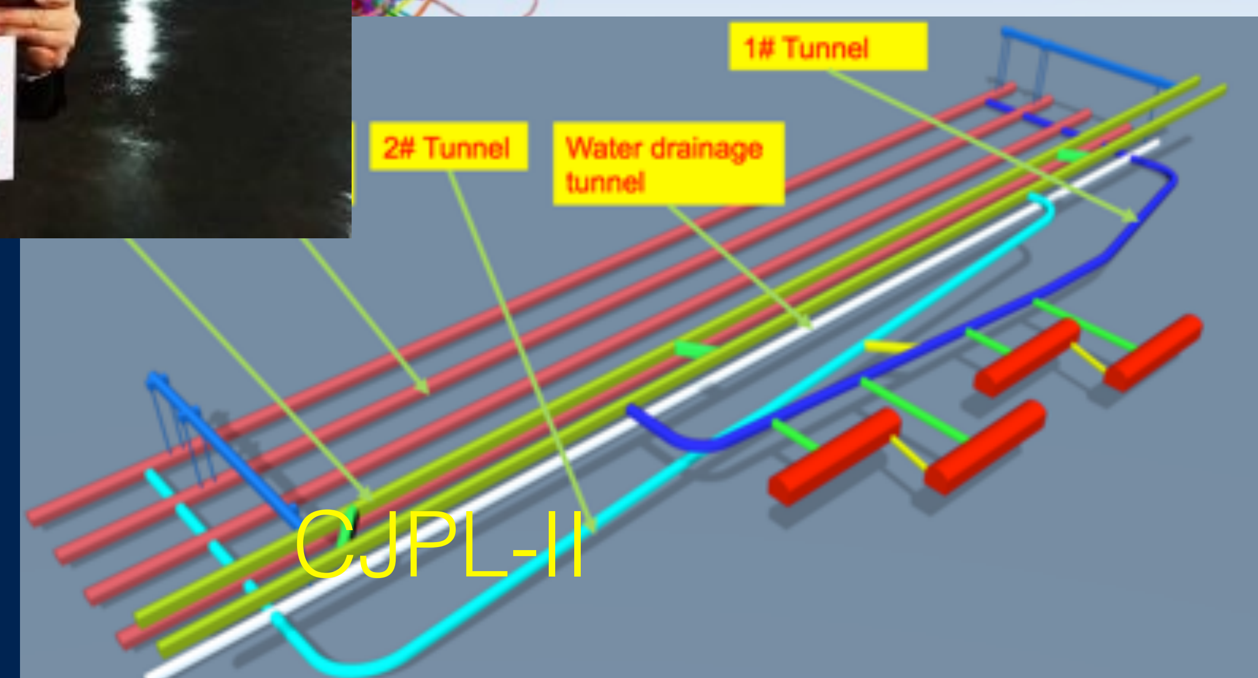
China Jinping underground lab（CJPL）



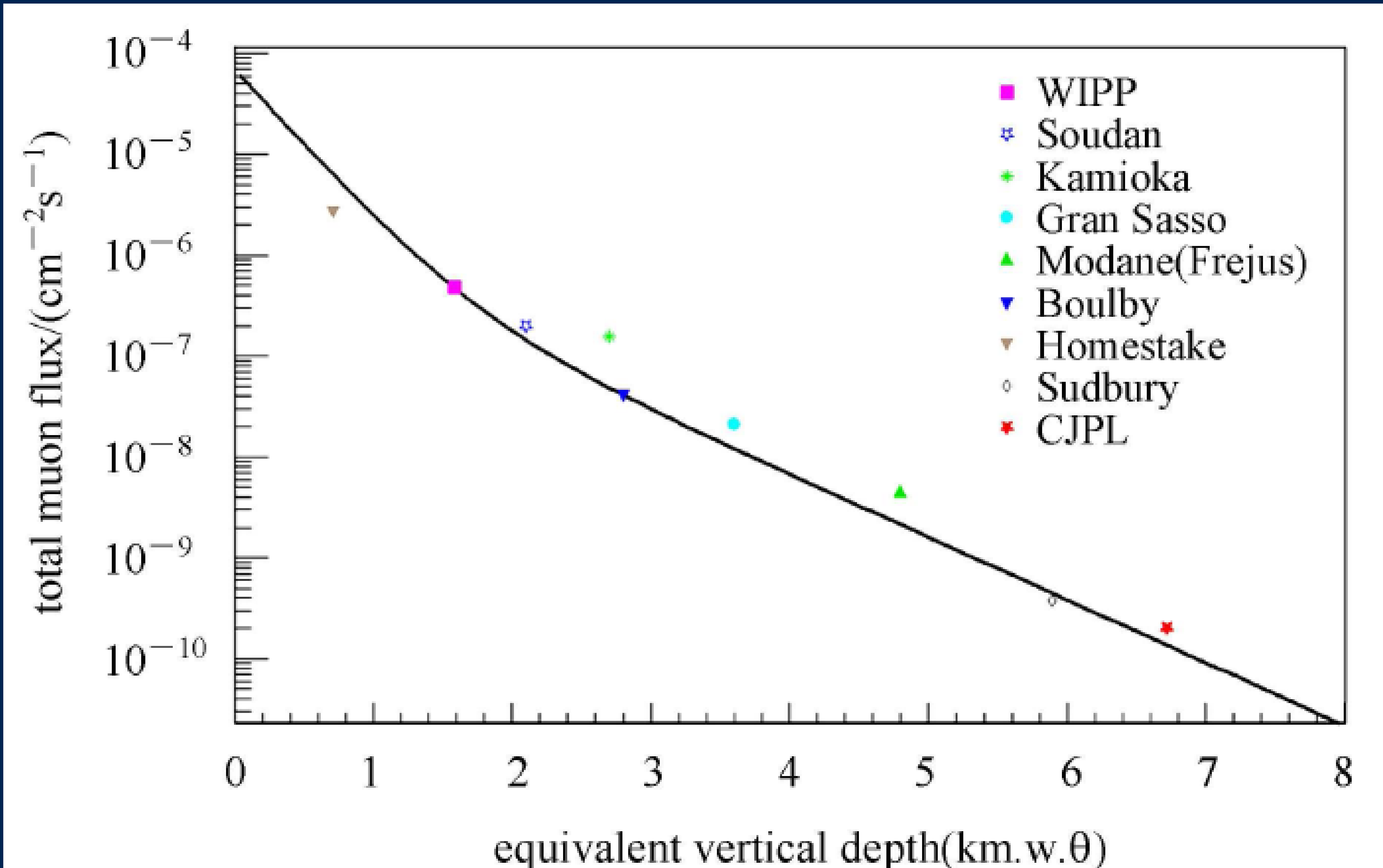
CJPL and CJPL-II

2014

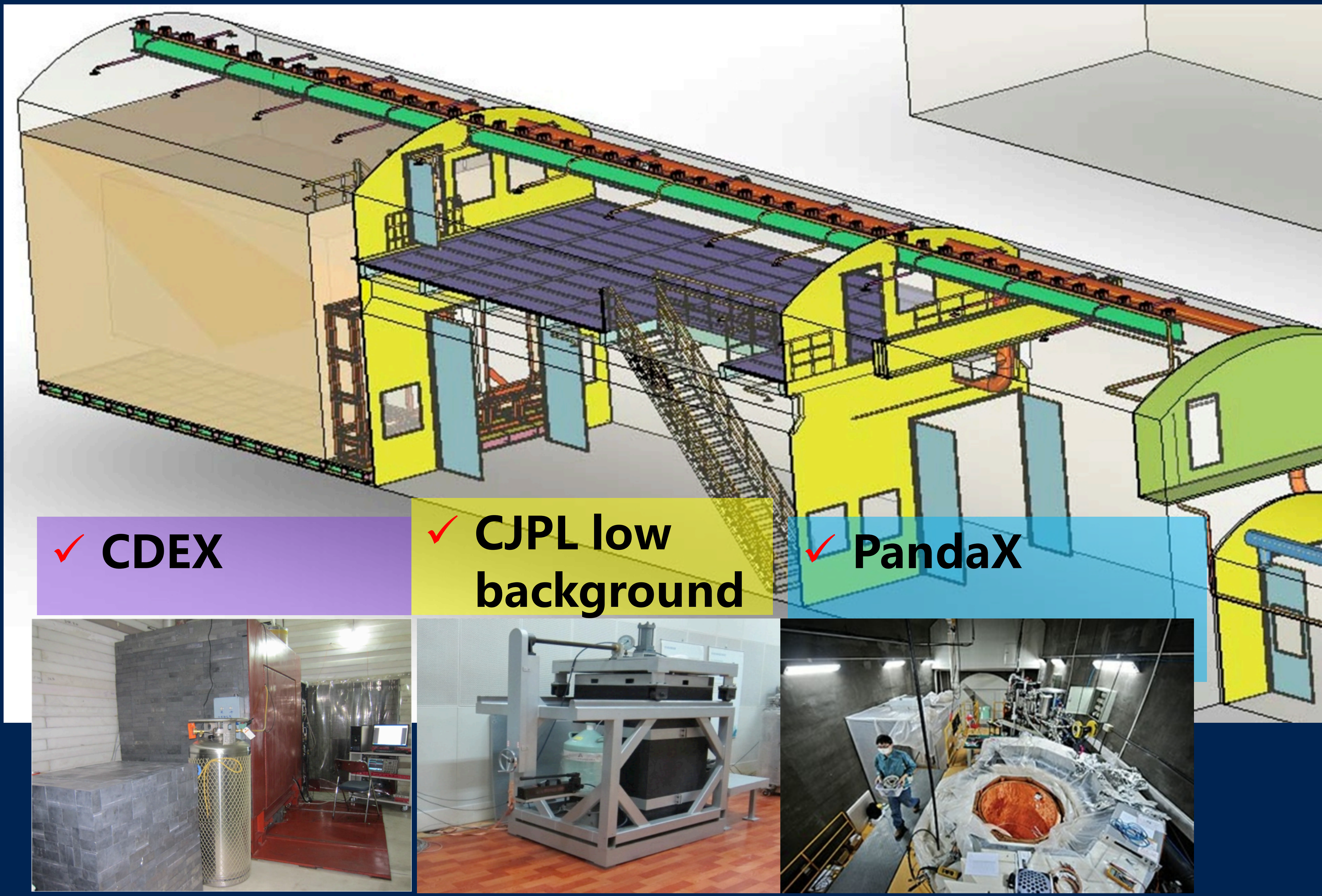




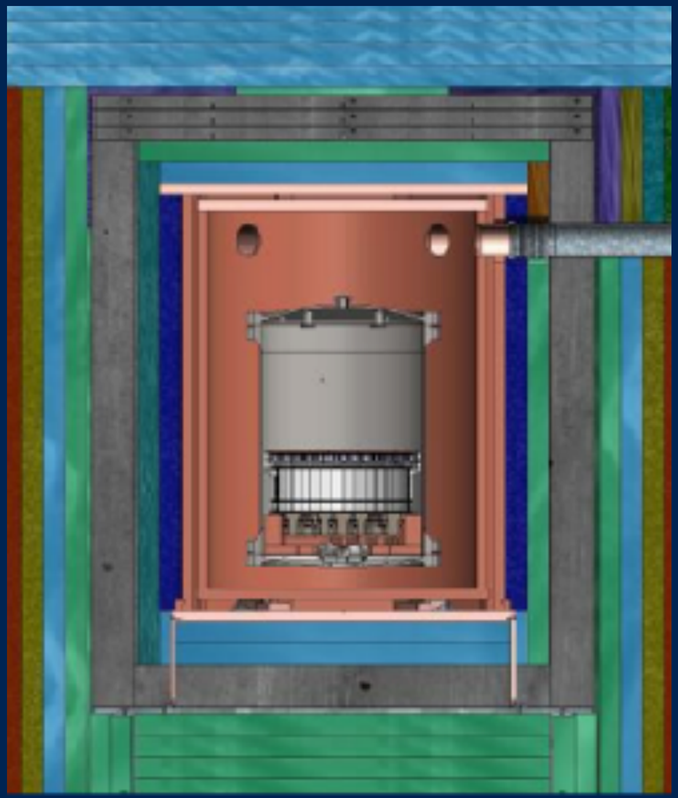
CJPL advantage



CJPL-I experiments



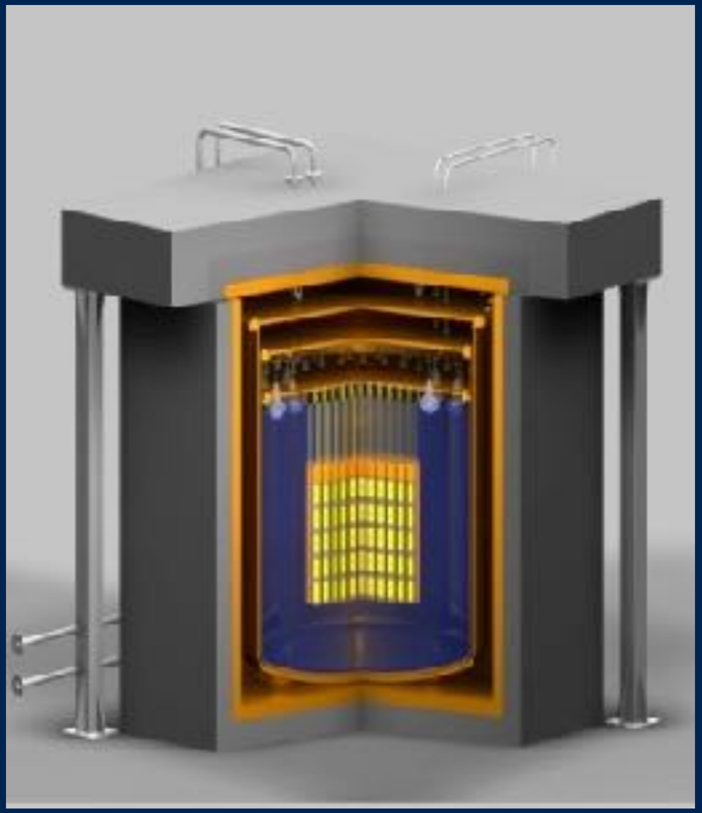
CJPL-II experiments



LXe
PANDAX+

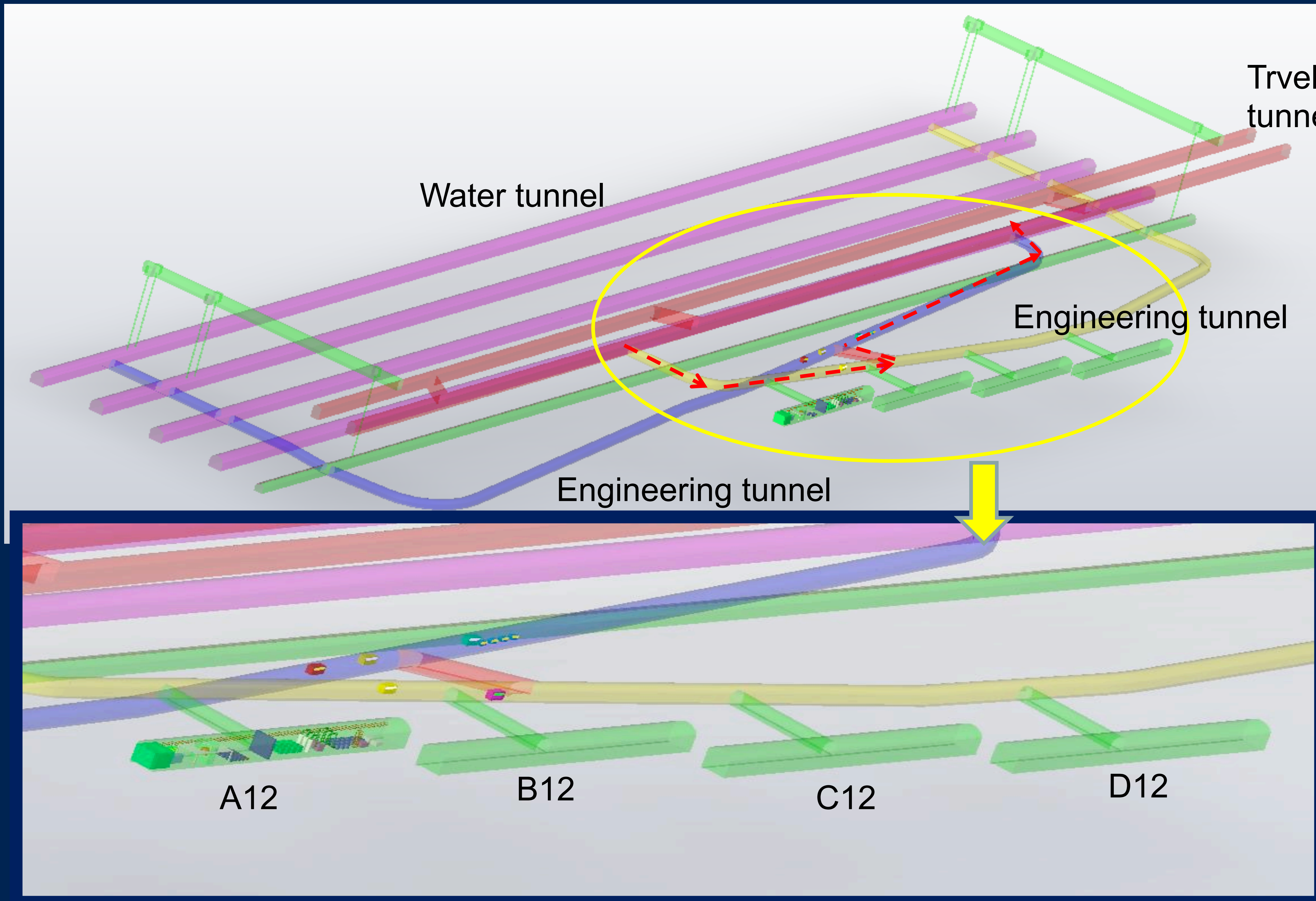
Nuclear
Astrophysics
JUNA
400 kV

More
experiments…

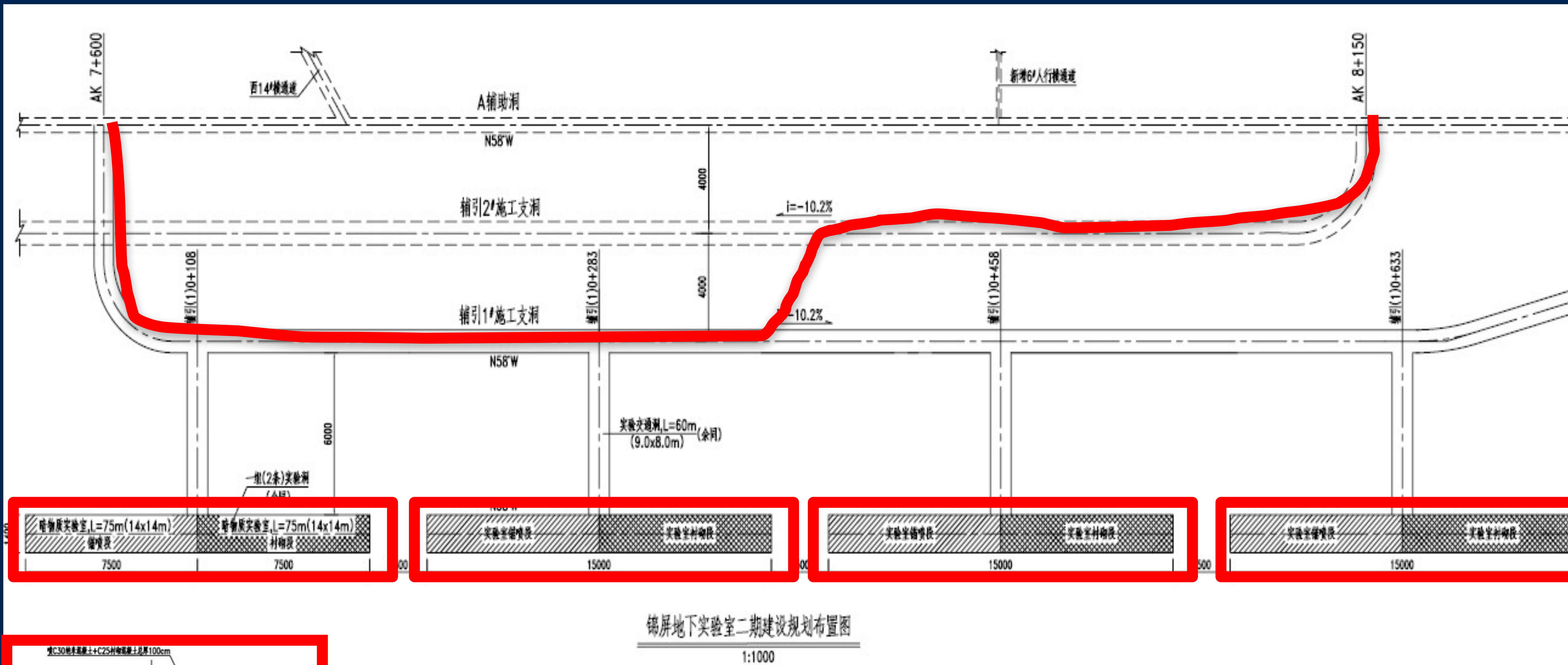


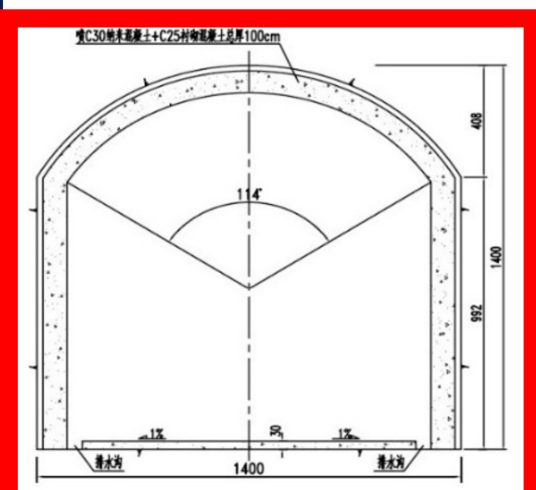
HpGe
CDEX +

CJPL-II structure



CJPL-II floor plan





CJPL-II 100k m3，8X12m*12m*150m

JUNA **PI introduction**

CIAE
IMP
THU
SJTU
SCU
SDU
SZU
...

Group leader

Weiping Liu[1], Zhihong Li[1], Jianjun He[2], Xiaodong Tang[2], Gang Lian[1], Zhu An[4], Qinghao Chen[3], Xiongjun Chen[1], Yangping Chen[1], Zhijun Chen[2], Baoqun Cui[1], Xianchao Du[1], Changbo Fu[5], Lin Gan[1], Bing Guo[1], Guozhu He[1], Alexander Heger[6], Suqing Hou[2], Hanxiong Huang[1], Ning Huang[4], Baolu Jia[2], Liyang Jiang[1], Shigeru Kubono[7], Jianmin Li[3], Kuoang Li[2], Tao Li[2], Yunju Li[1], Maria Lugaro[8], Xiaobing Luo[4], Shaobo Ma[2], Dongming Mei[9], Yongzhong Qian[10], Jiuchang Qin[1], Jie Ren[1], Jun Su[1], Liangting Sun[2], Wanpeng Tan[11], Isao Tanihata[12], Peng Wang[4], Shuo Wang[13], Youbao Wang[1], Qi Wu[2], Shiwei Xu[2], Shengquan Yan[1], Litao Yang[3], Xiangqing Yu[2], Qian Yue[3], Sheng Zeng[1], Huanyu Zhang[1], Hui Zhang[3], Liyong Zhang[2], Ningtao Zhang2, Qiwei Zhang[1], Tao Zhang[5], Xiaopeng Zhang[5], Xuezhen Zhang[2], Zimin Zhang[2], Wei Zhao[3], Zuo Zhao[1], Chao Zhou[1]

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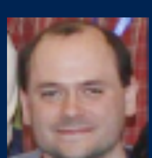
[13]Shangdong University, Beihai , China

Xiaoc
^{13}C(
Ion

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 entrance

IAC+JUNA, CJPL-II-8

IAC, 305 m high dam

1st meeting July 2015, 1st formal IAC meeting March, 2016

JUNA funding

Detectors（NSFC $1.3M）

Electronics, shielding (NSFC $1.0M）

Ion source (CAS $0.8M), accelerator (CNNC $1.0M)

Lab CJPL II（CNNC, Tsinghua，NSFC $1.2M）

total $4.8+ M

Do step by step

High energy test in ground base, setup the basic feasibility

↓

Middle energy test in CJPL-II site, compare with measured data, setup underground reference

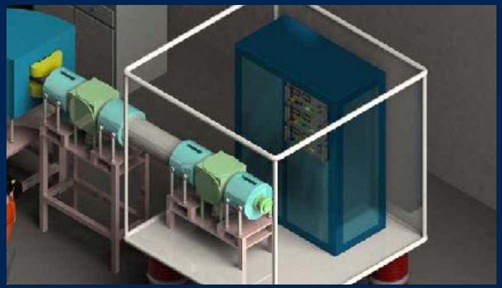
↓

Low energy hunting for long time, aiming at signal higher than background, or upper limit is unfortunate cases

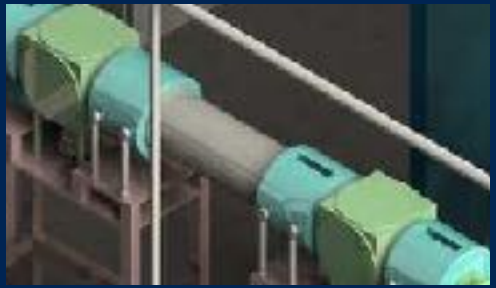
JUNA plan

CJPL-II c

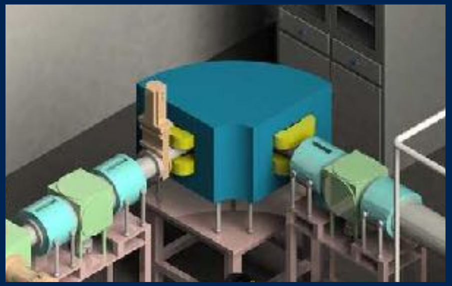
JUNA



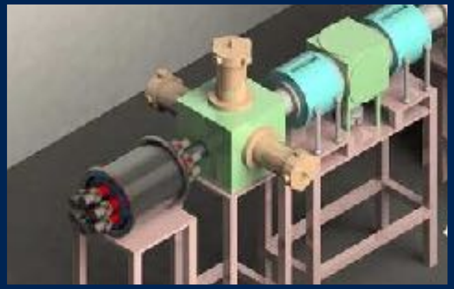
ECR source



Acceleration



Magnet

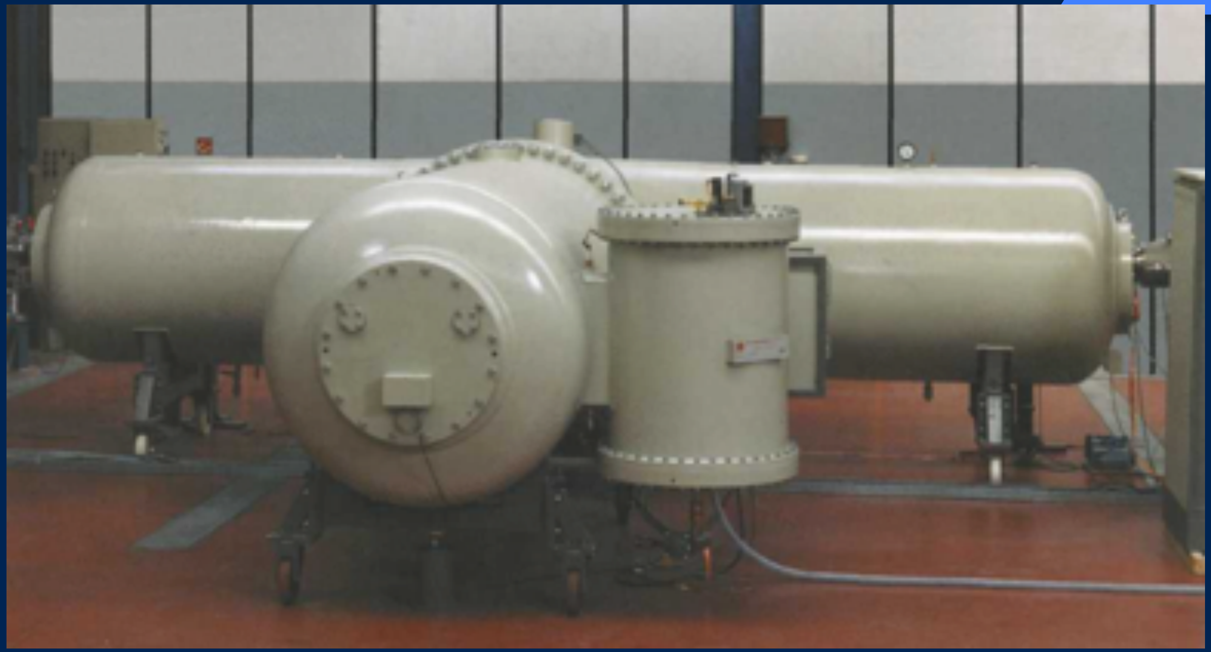


Detectors

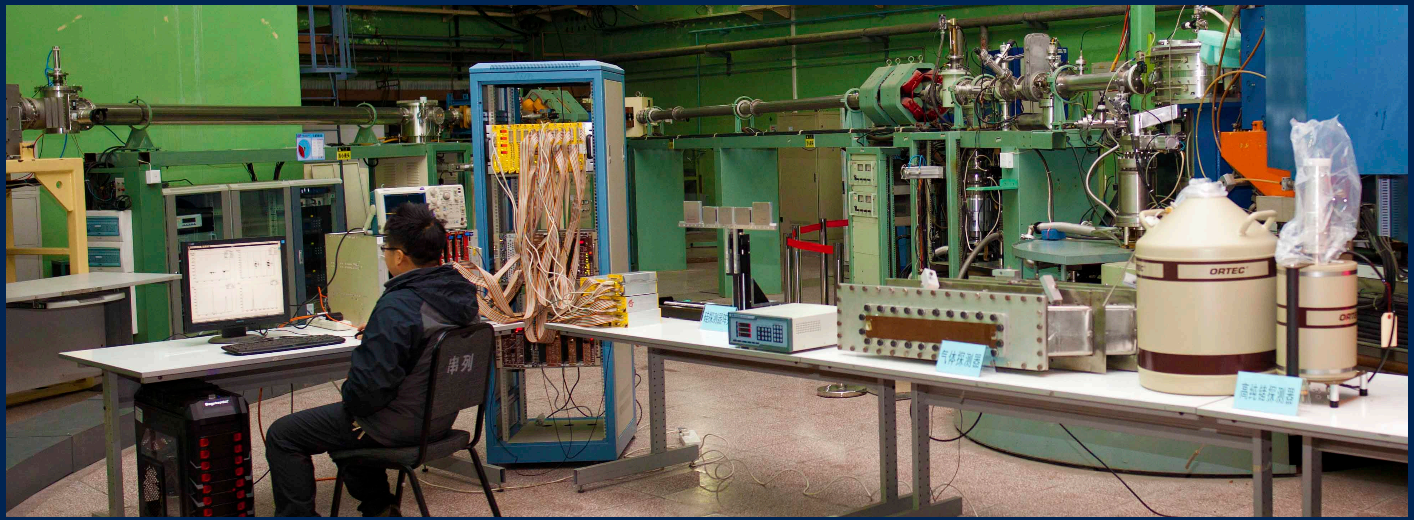
Beam	Intensity, mA	Energy,keV
H^+	10	70-400
He^+	10	70-400
He^{++}	2	140-800

Ground facilities

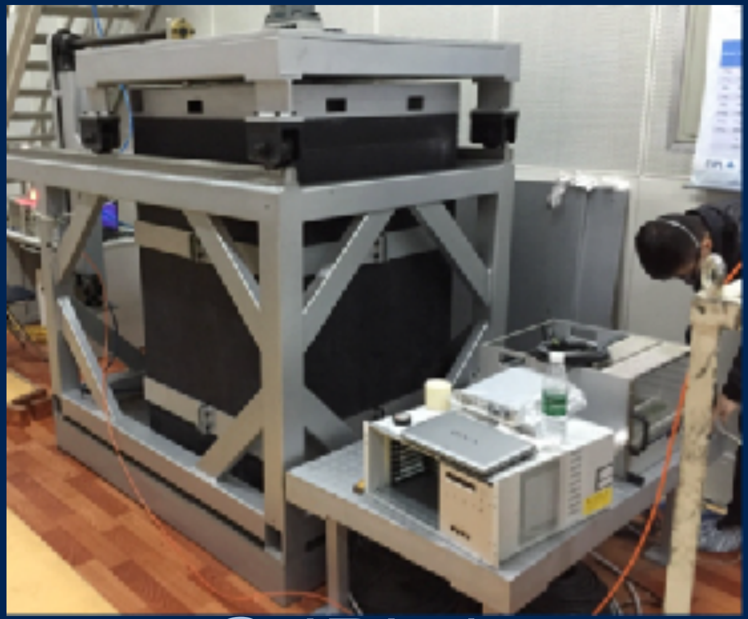
beam with 40 KV and 20 mA



Tandem of implantation target

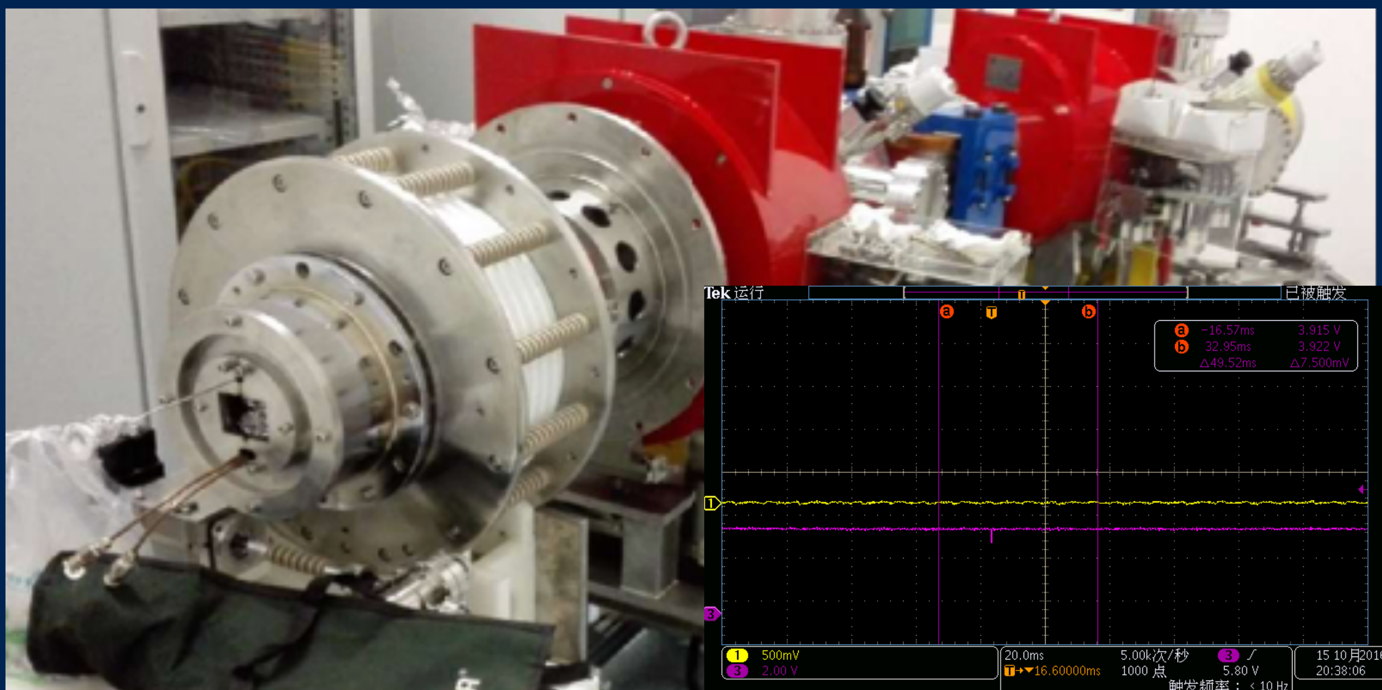


solid and gas detector and electronics

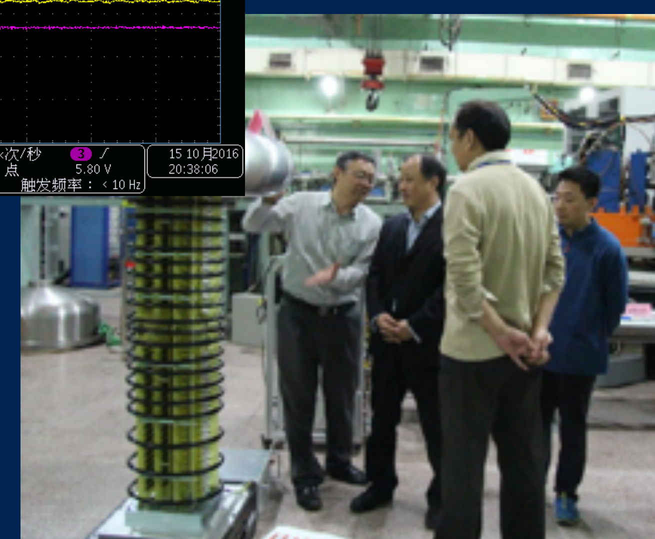


CJPL low background station

Ion source and accelerator



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



Accelerator tube
check by NSFC

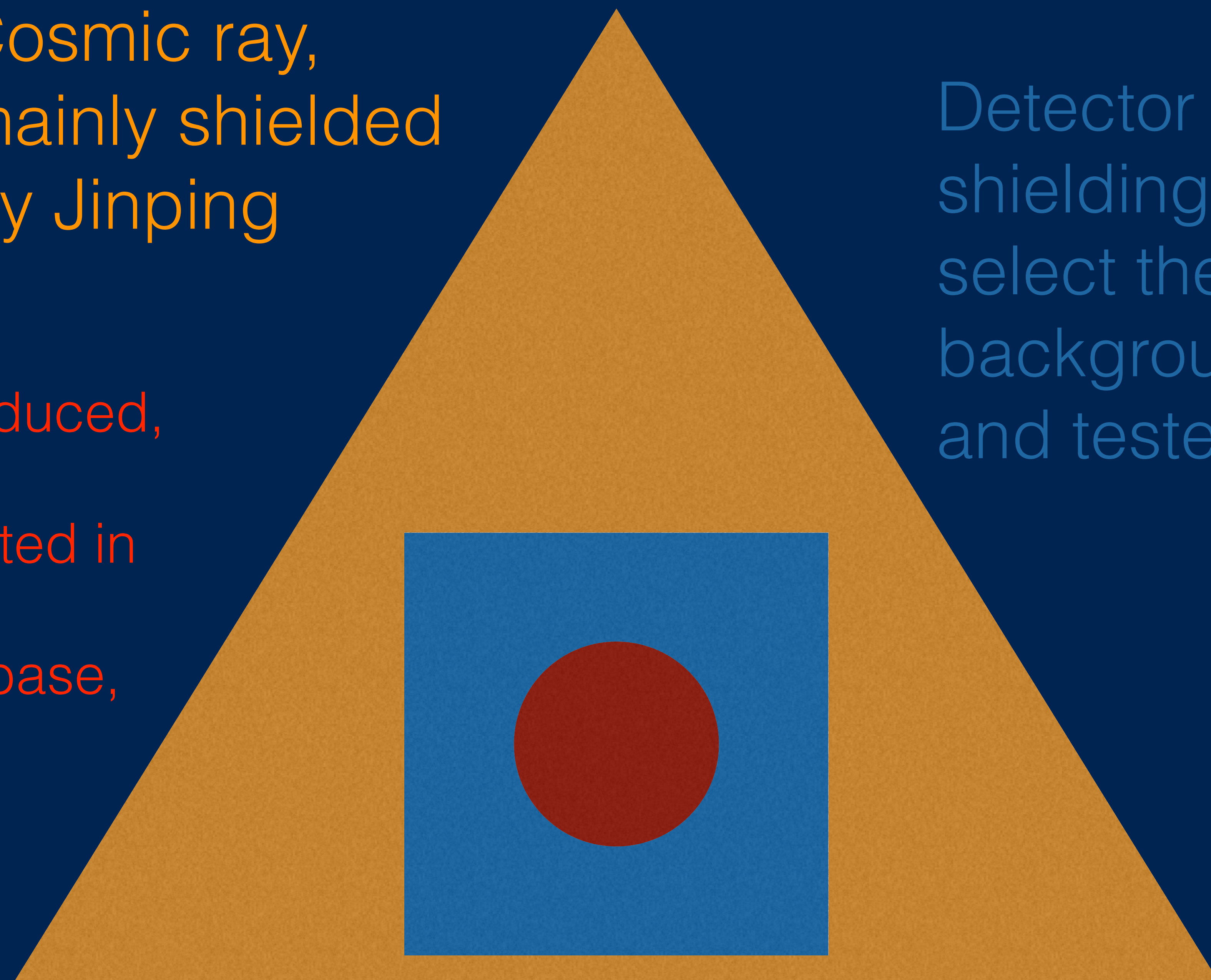
Accelerator tank
established 8/30/16

Type of background

Cosmic ray, mainly shielded by Jinping

Detector and shielding material, select the low background material and tested in CJPL-I

Accelerator induced, estimated by simulation, tested in ground and underground base, improve the emittance and transmission



Way to do underground experiment

JUNA

On site tuning in low intensity and short time

↓

Long time exposure for data taking, with remote monitoring

↓

Change target periodically, with carefully radiation dose monitoring

↓

Change detector and shielding for another experiment

For four experiments

^{19}F, most cross section, push to lower and higher precision, with good help of ground experience, day one

↓

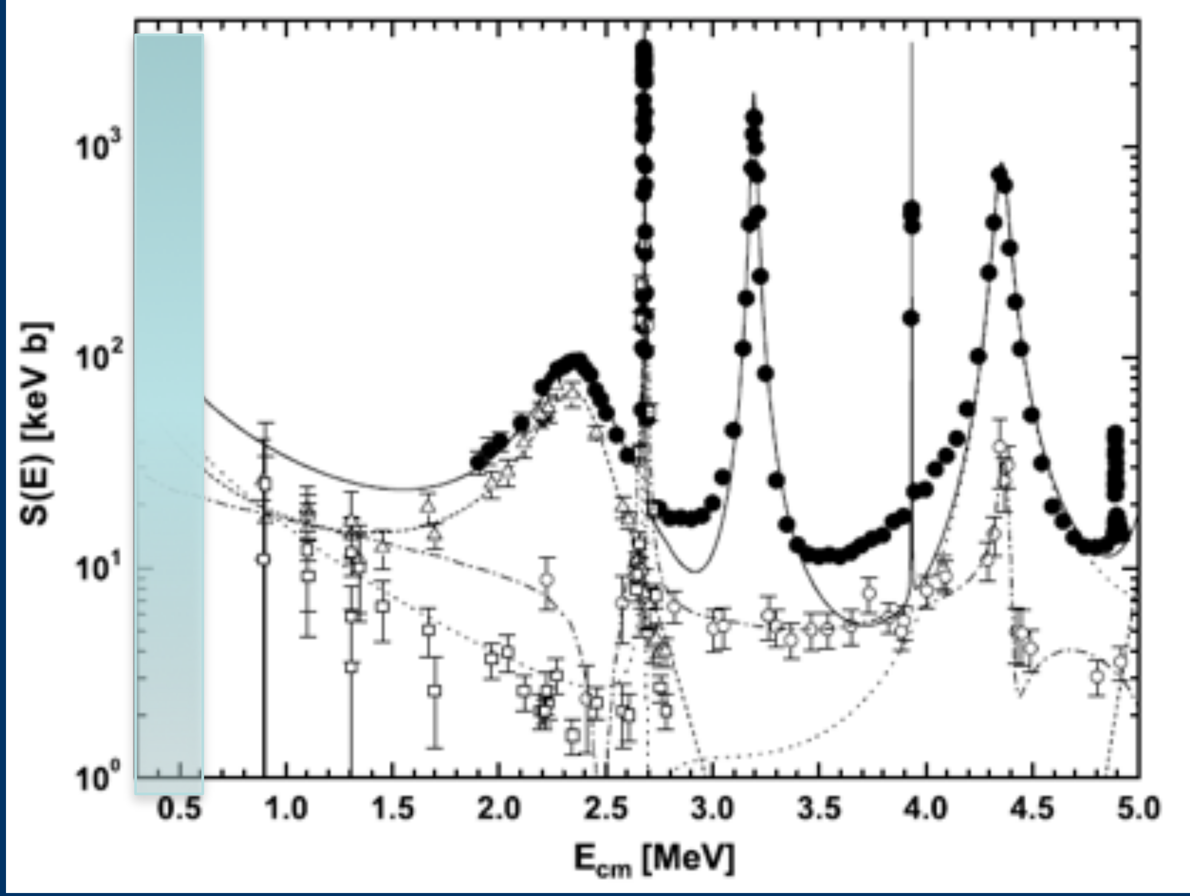
^{25}Mg, aiming at 92 keV resonance at first, compare with LUNA with HpGe, then down to 58 keV run, with BGO, then HpGe

↓

^{13}C, set good separation of neutron group, and wait for effect neutrons, estimated with the rate from in-direct data, wish for He 2^+

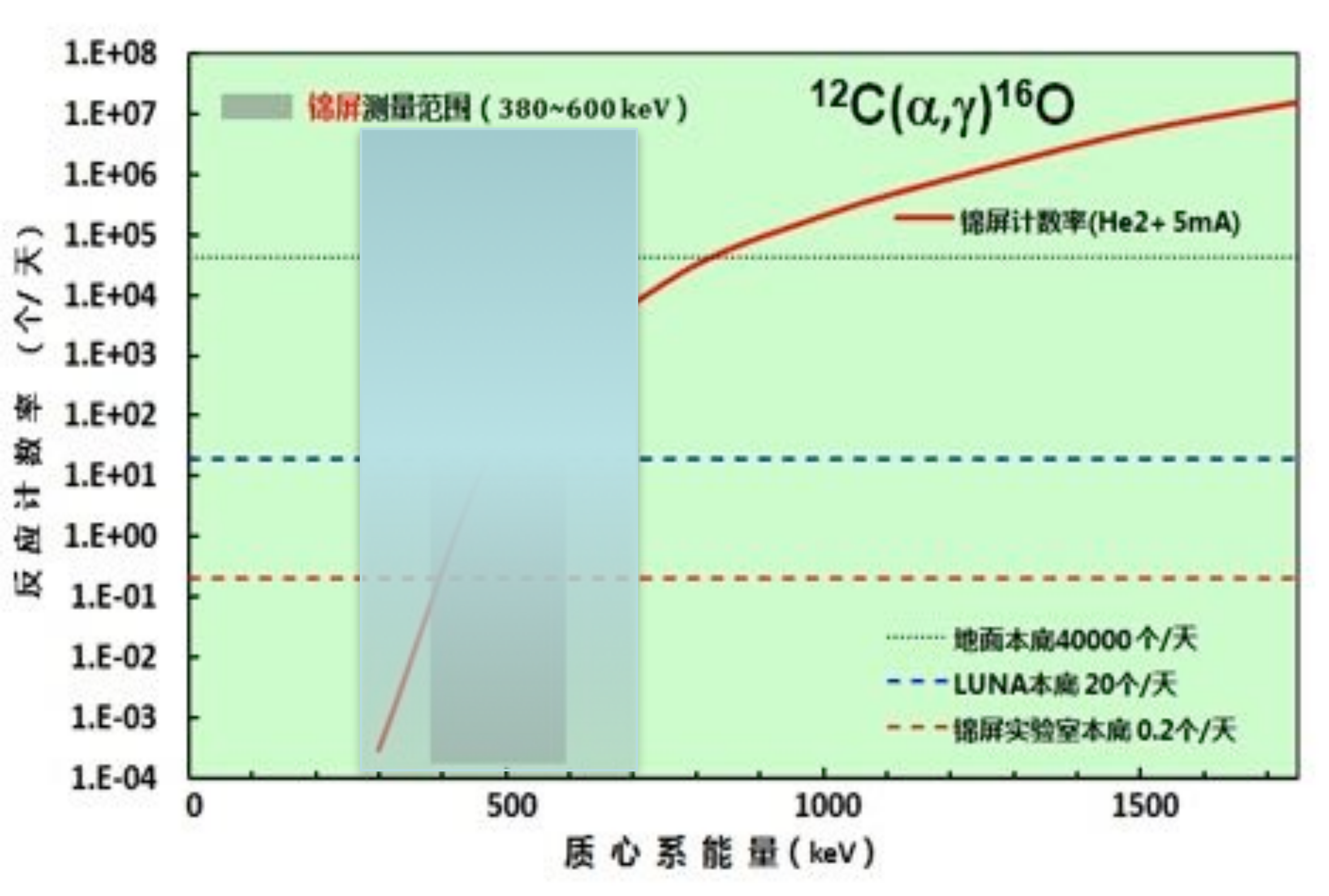
↓

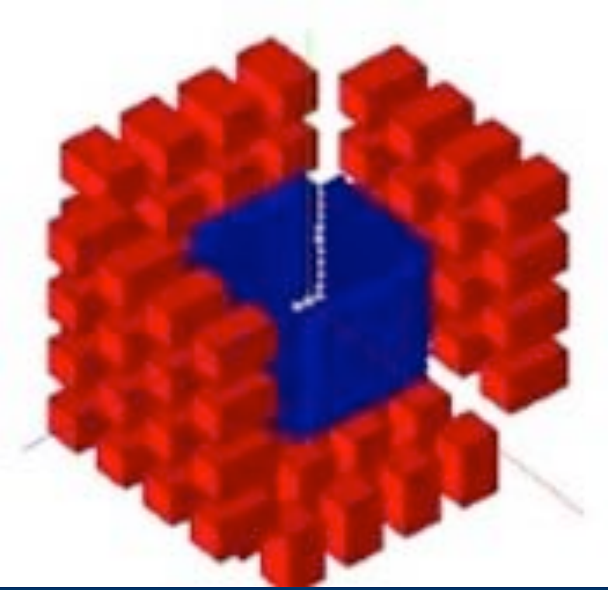
^{12}C, the most challenging part, started with higher energy 600 keV $E_{c.m.}$ with HpGe, then BGO, followed by test run of 380 keV $E_{c.m.}$ with BGO, He 2^+ must be provided



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

JUNA





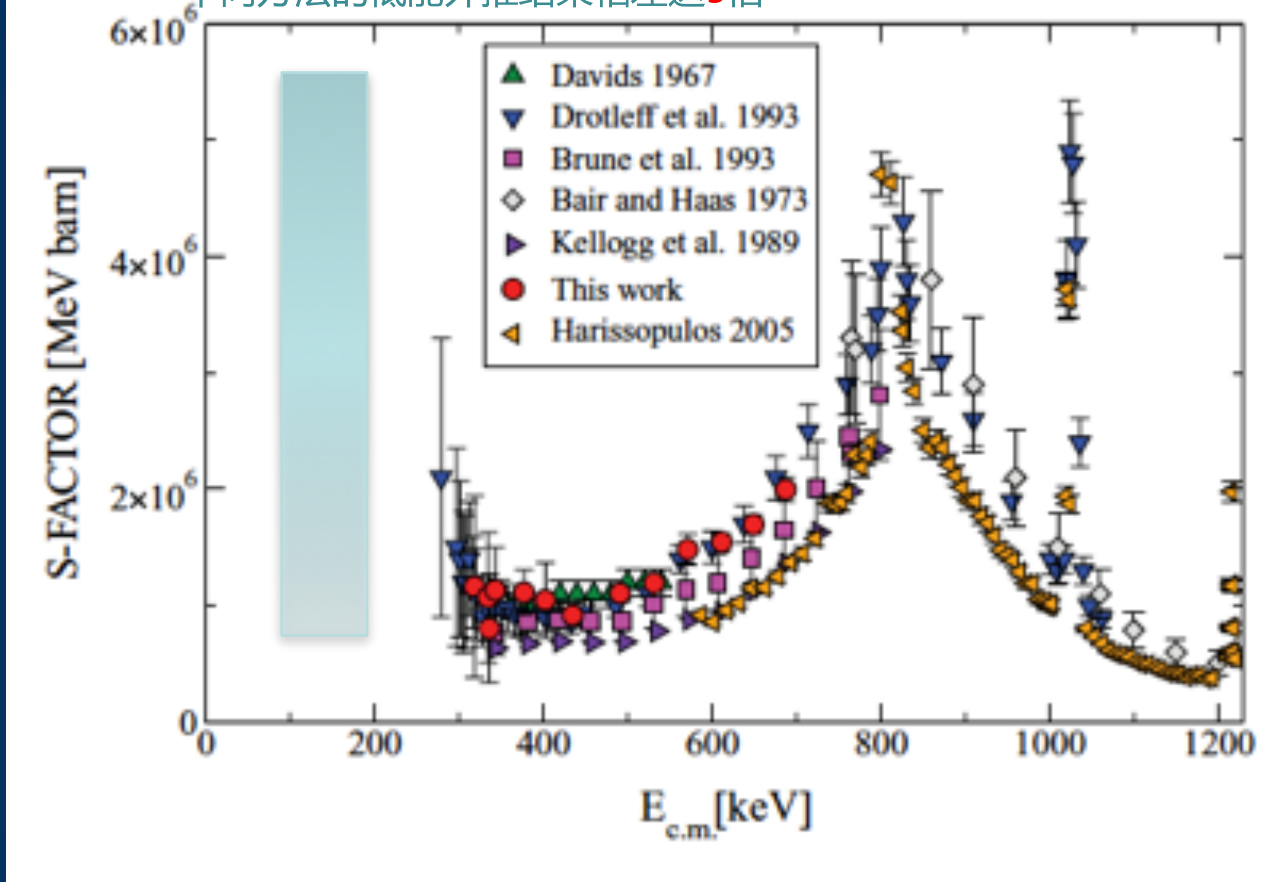
($LaBr_3$ + CsI)

Goal: push 300 keV down to Gamow, precision from 30% down to 10%; clarify extrapolation, test Weaver and Woosely star evolution model, Phys. Rep. 227(1993)65

Method: He intensity, γ effciency, background, ^{12}C implantation, R-matrix

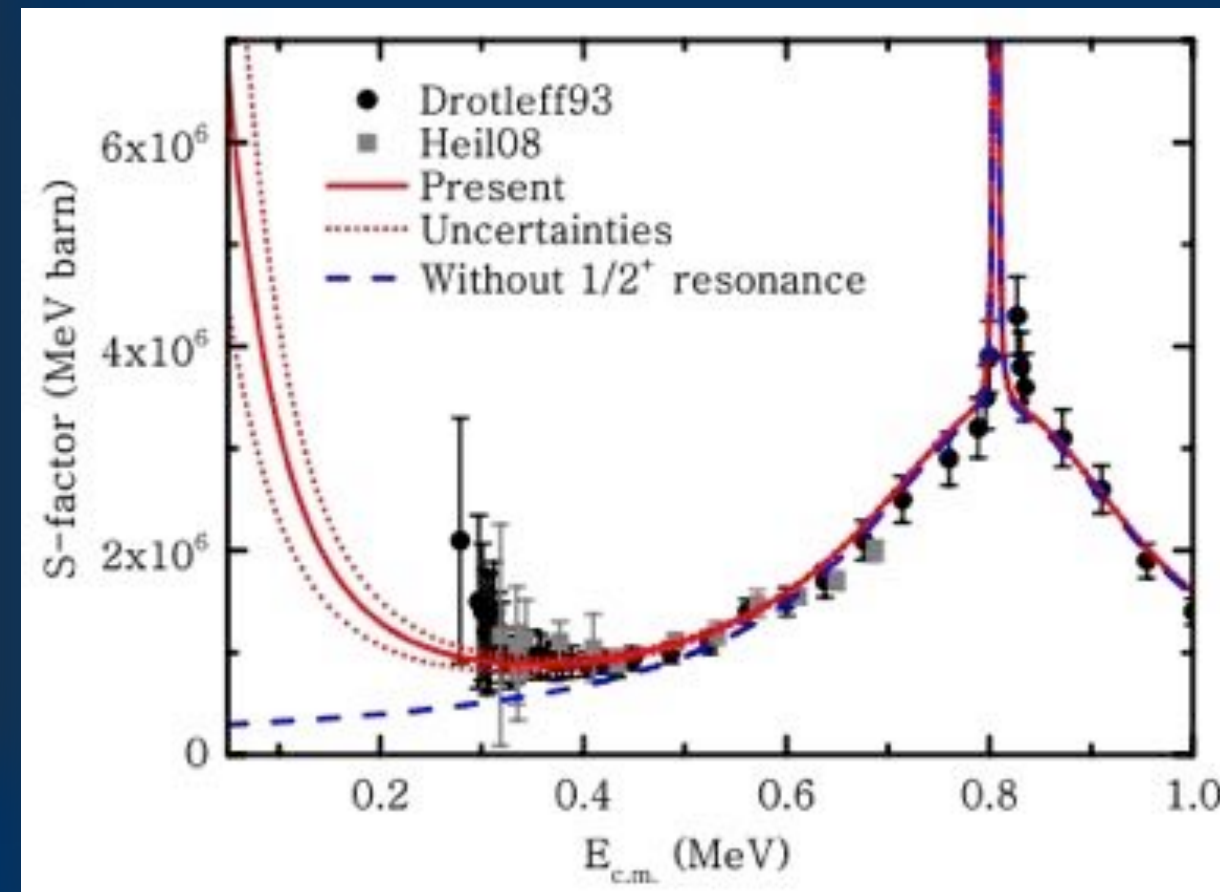
$^{13}C(\alpha,n)^{16}O$

不同方法的低能外推结果相差达5倍



- CIAE $^{13}C(\alpha, n)^{16}O$ in-direct , IMP 300keV exp. plan

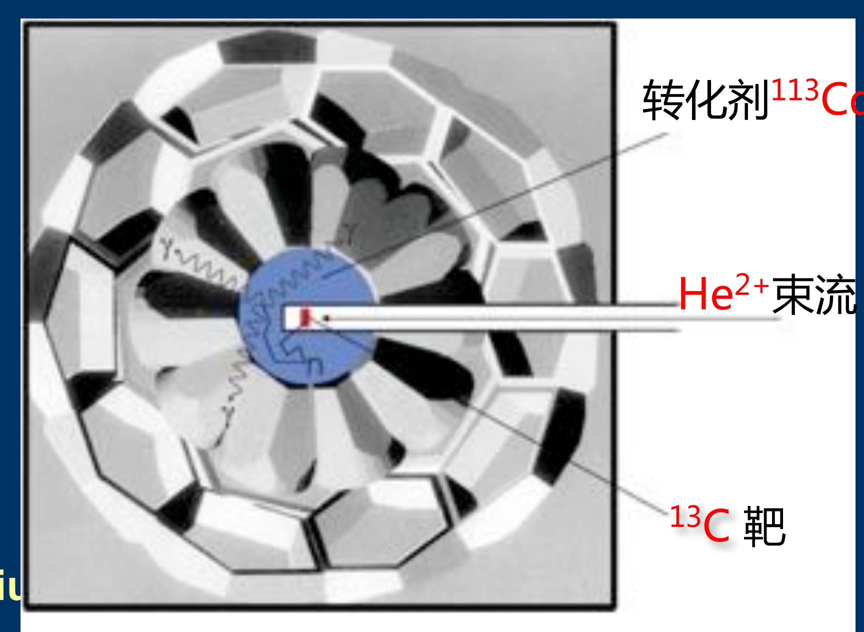
JUNA



B.Guo *et al.*,ApJ756(2012)193

Goal: push 270 keV down to Gamow, precision from 50% down to 20%; clarify resonance, pin down n source rate

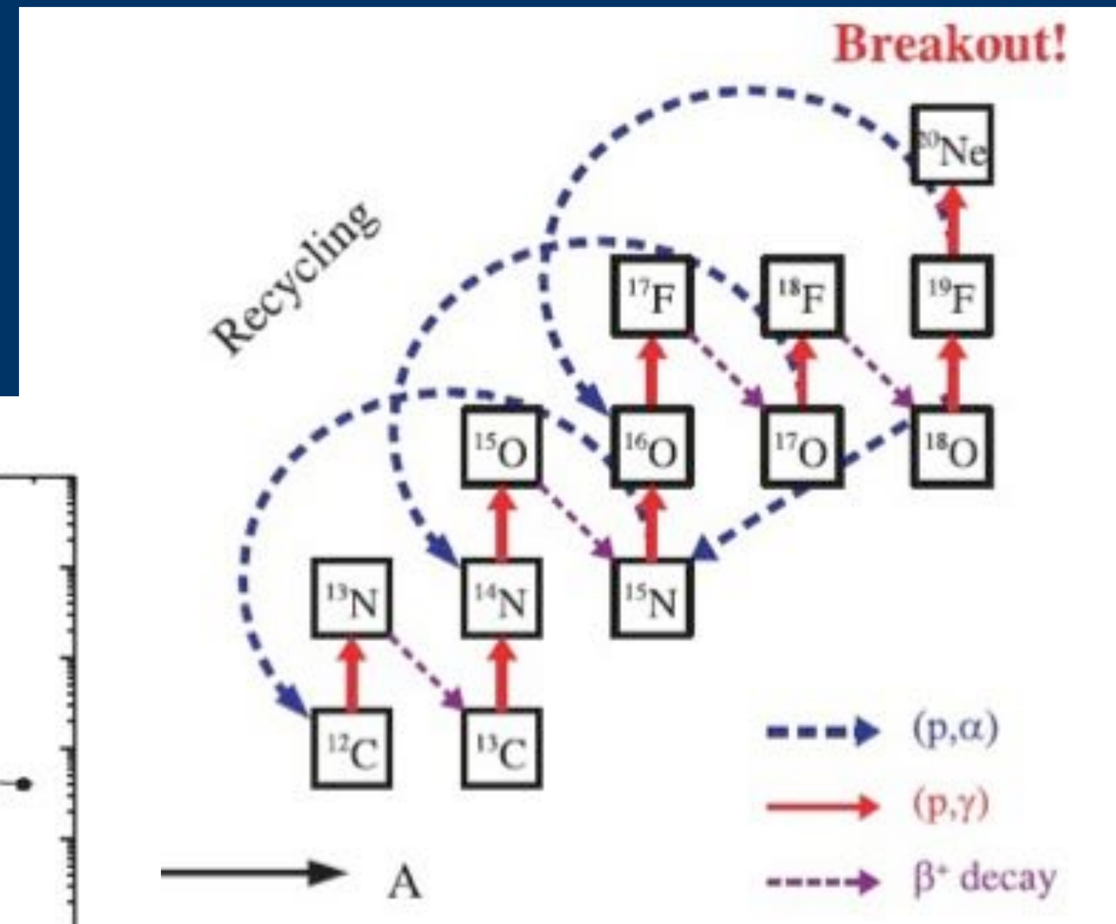
Method: n conversion, γ effciency

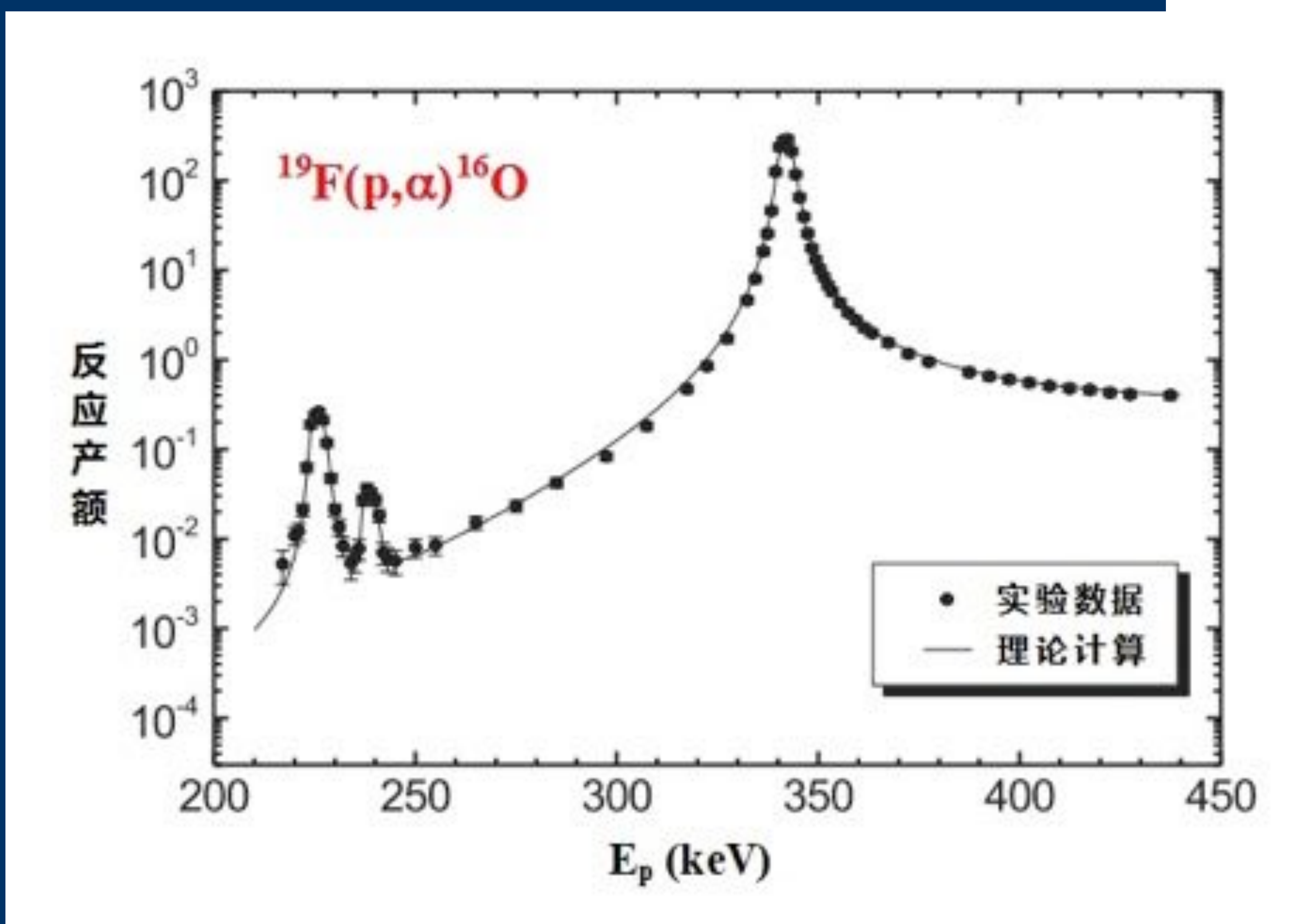


$^{19}F(p,\alpha)^{16}O$

JUNA

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





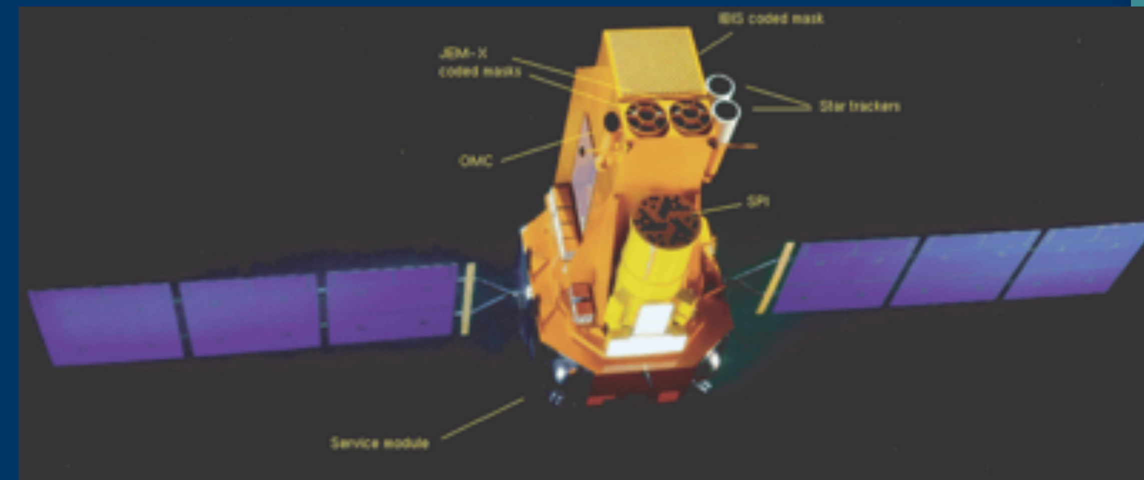
K. Spyrou *et al.,EPJA 7 (2000)79*

$^{19}F(p,\alpha)^{16}O$ to （$E_{c.m.}$= 27~300 keV）

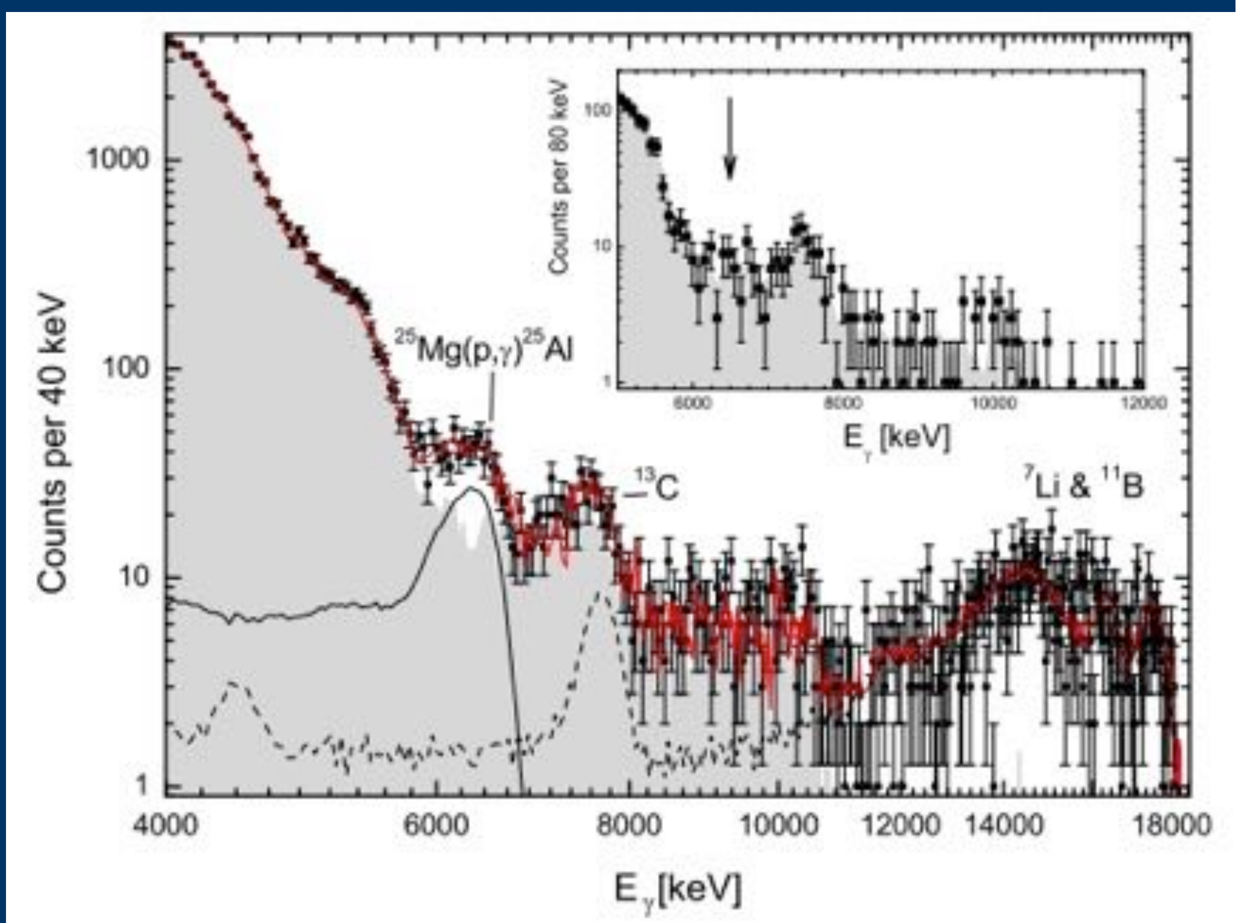
^{25}Mg(p, γ)^{26}Al

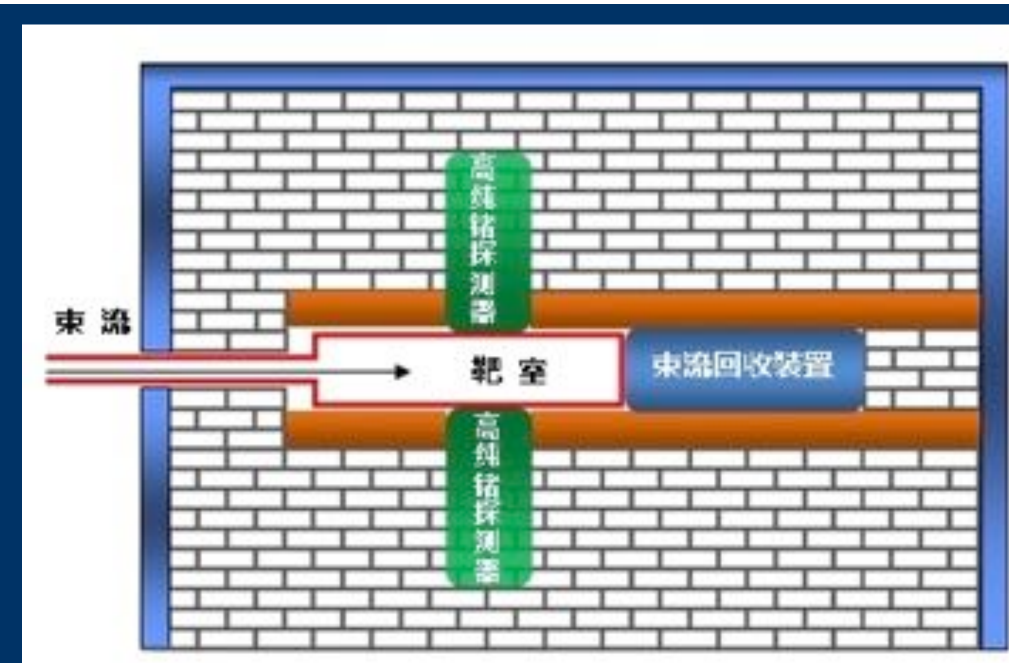
J UNA

^{6}Al- β decay ^{26}Mg1809 keV γ



E [keV][a]	ωγ [eV]
304.0	$(3.08 \pm 0.13) \times 10^{-2}$ [b]
189.5	$(9.0 \pm 0.6) \times 10^{-7}$
130.0	$< 2.5 \times 10^{-10}$
92.2	$(2.9 \pm 0.6) \times 10^{-10}$



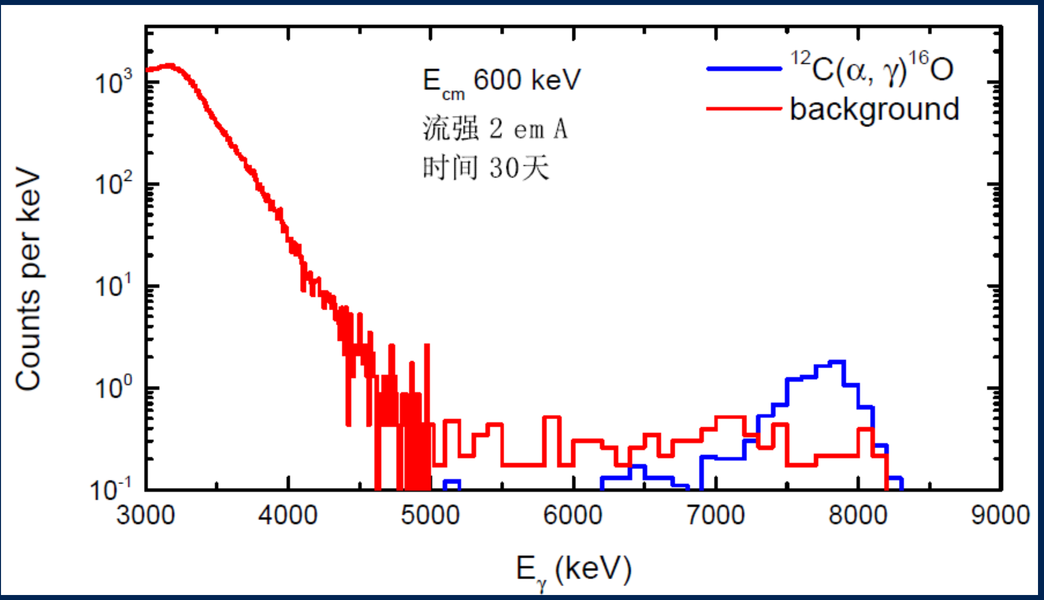


92keV 20% to 5%，and measure 58 keV

13/27

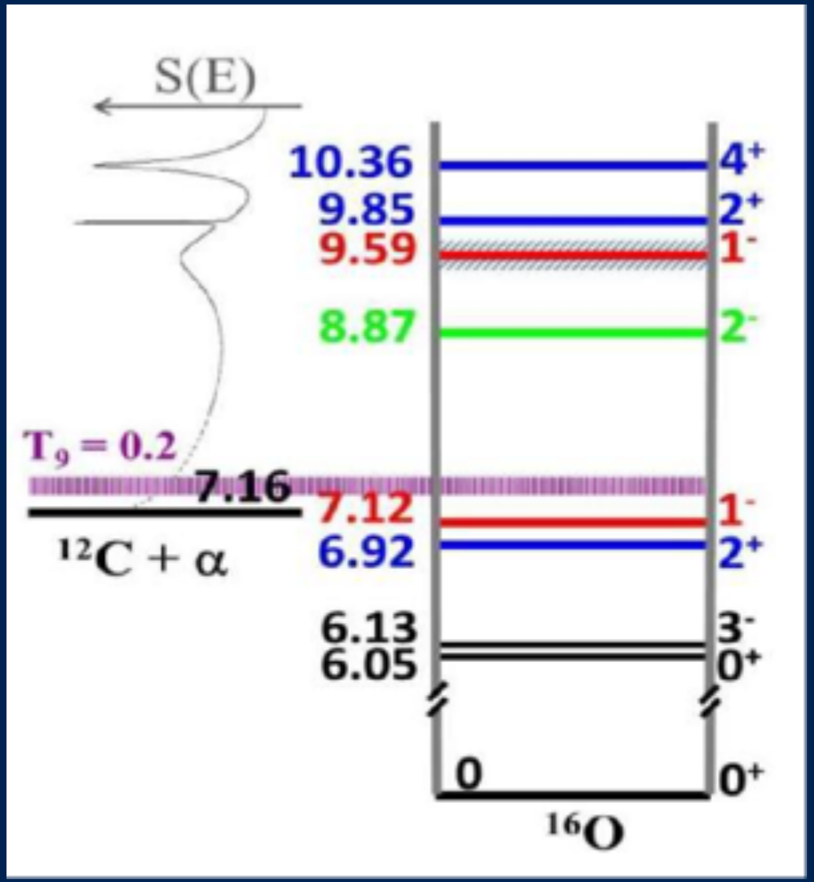
^{12}C progress

JUNA



Simulation fro BGO

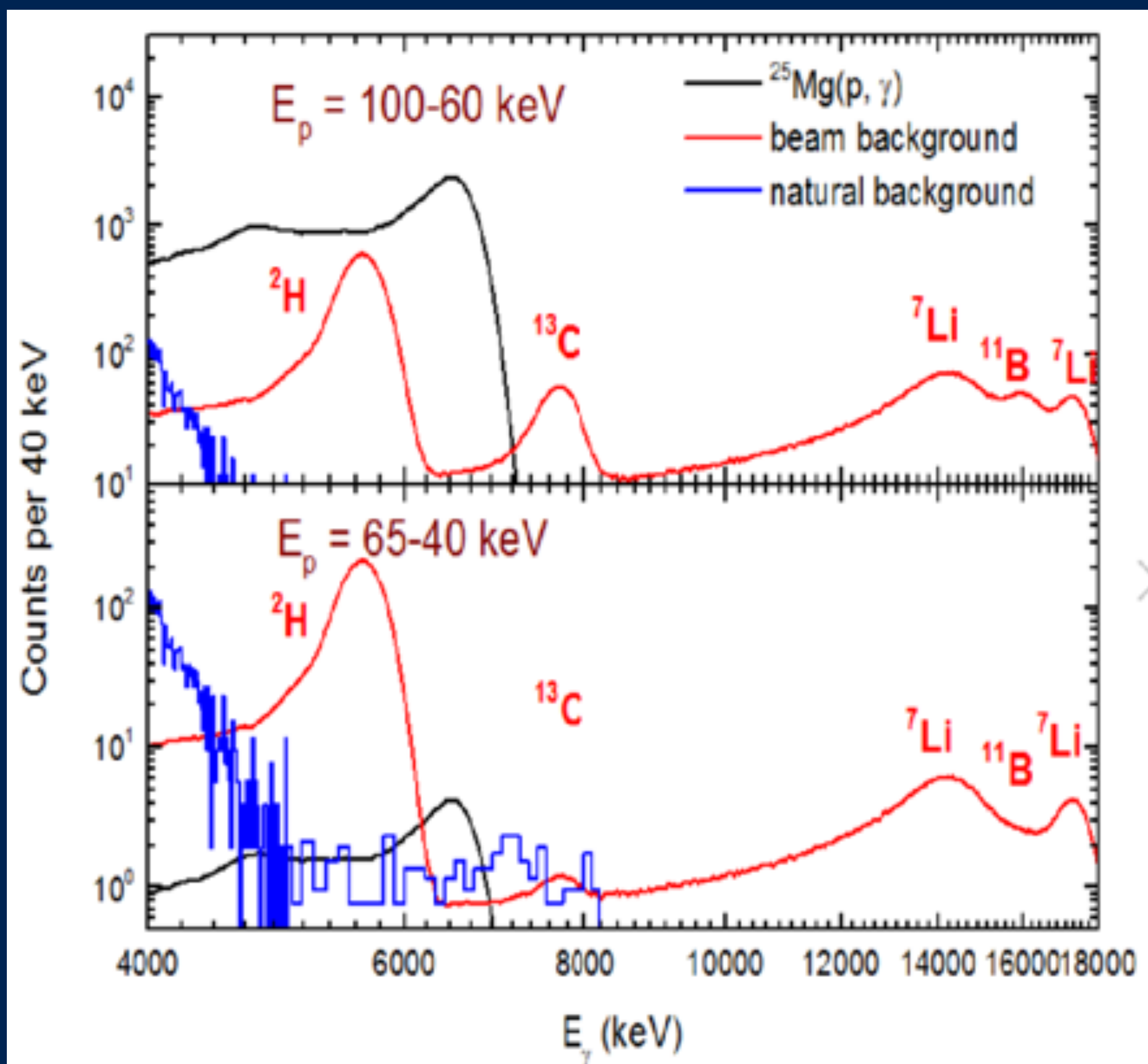
^{12}C implantation target tested 30/8/16

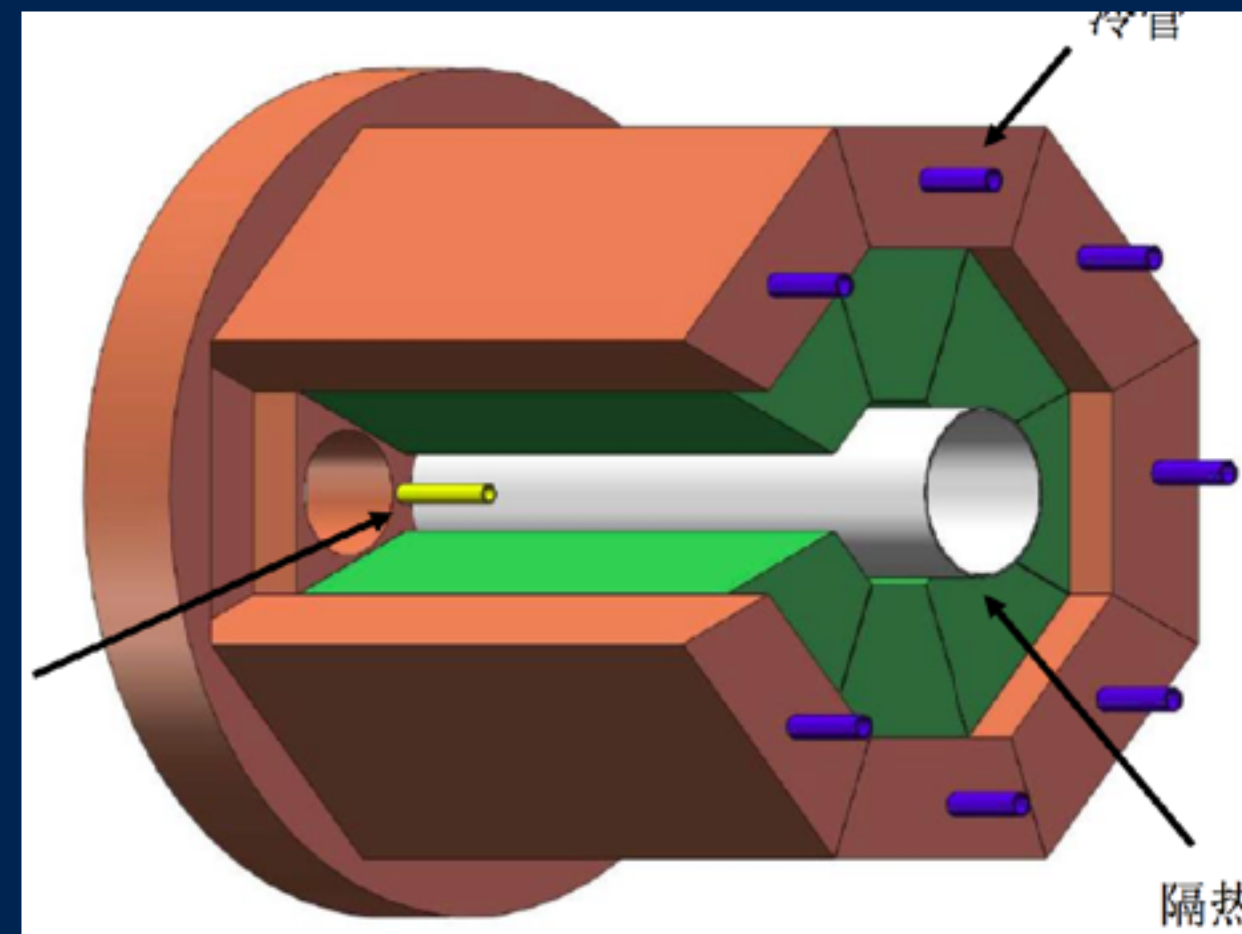


Test exp. SCU 12/16

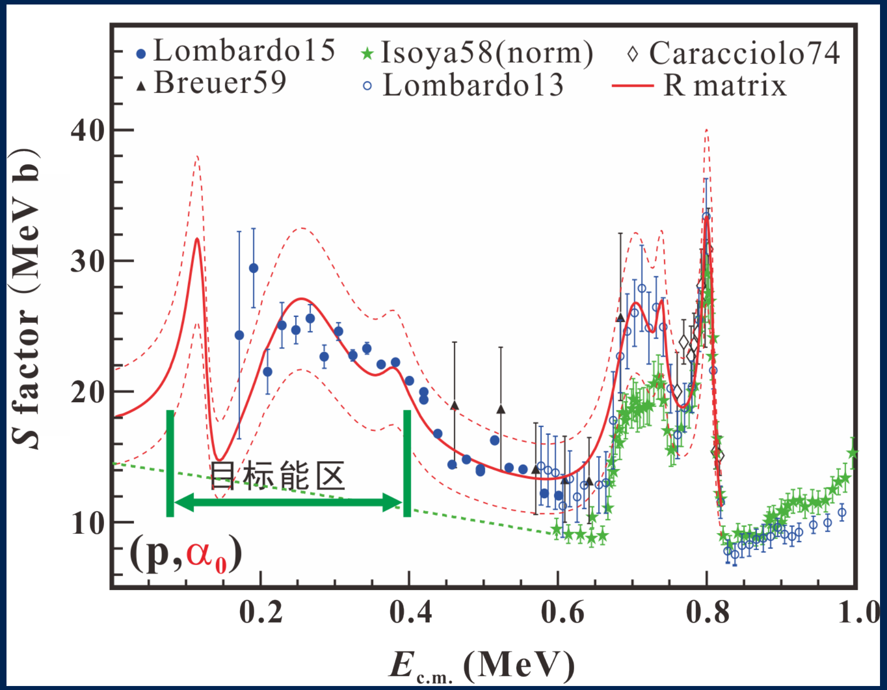
G. Lian

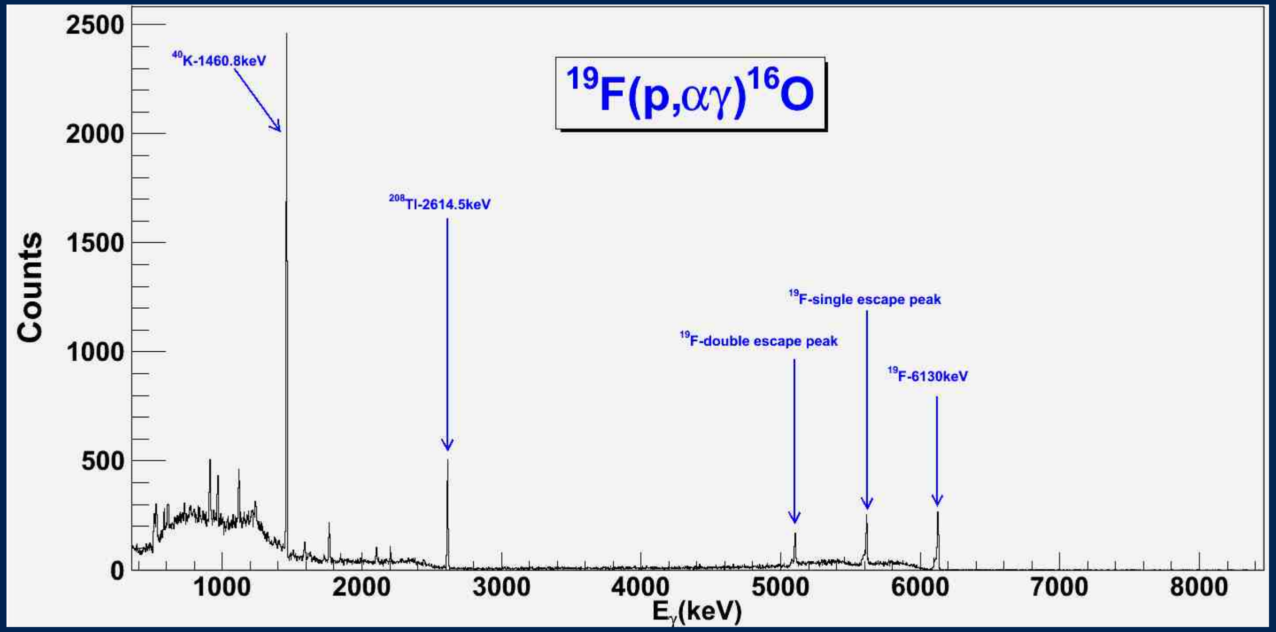
^{25}Mg progress

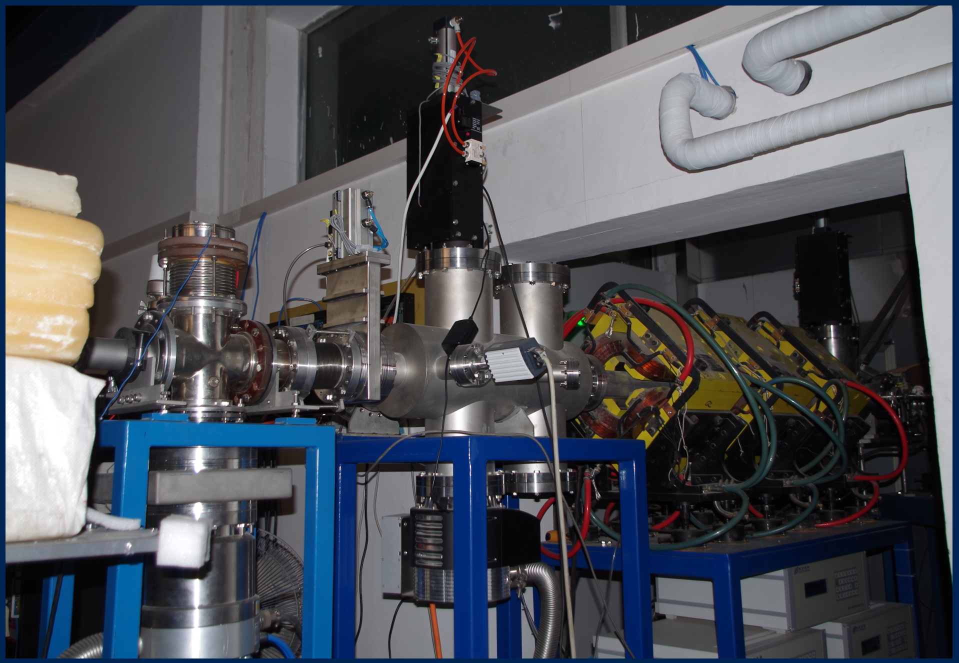




^{19}F progress

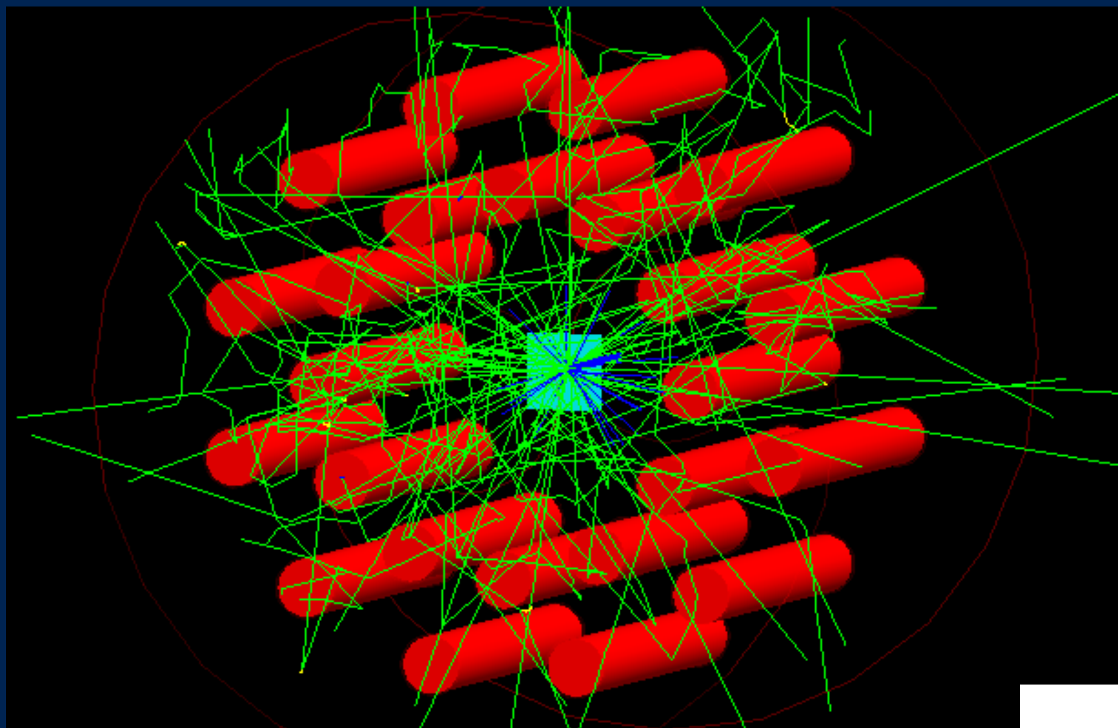


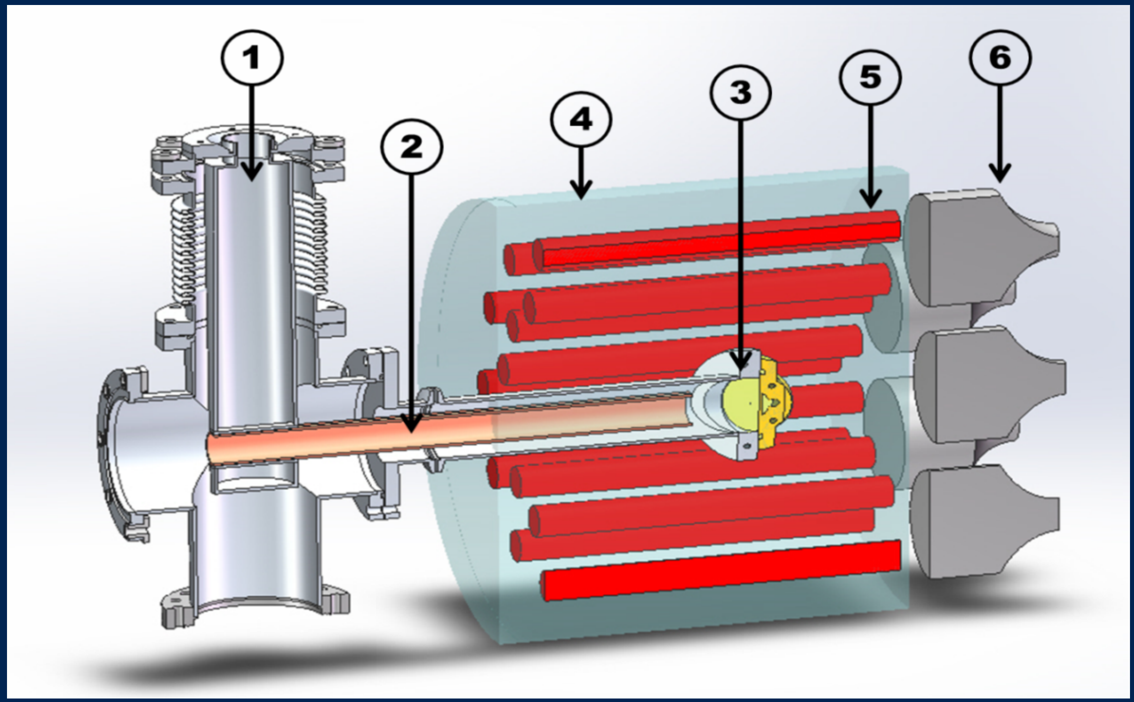




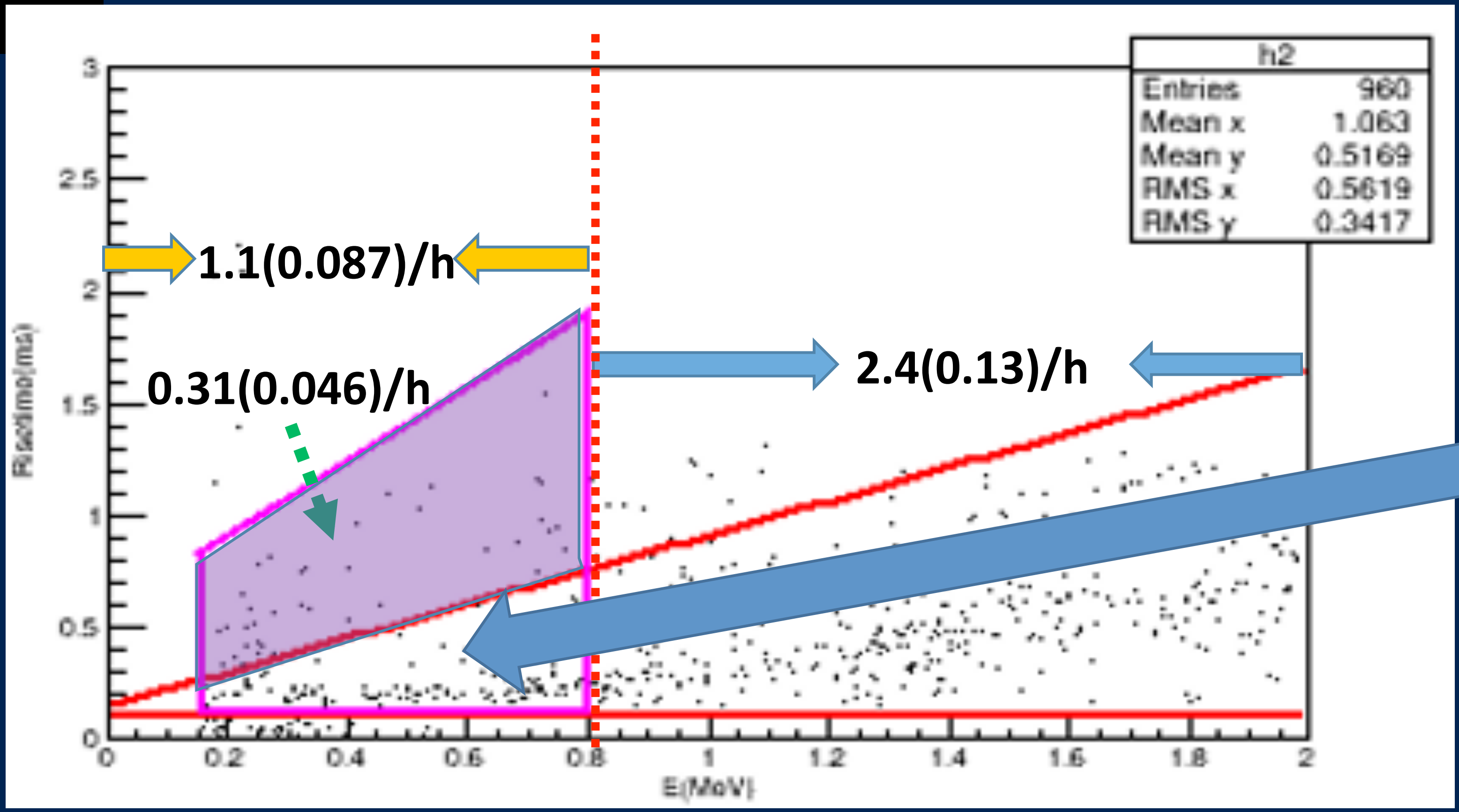
J. J. He

^{13}C progress



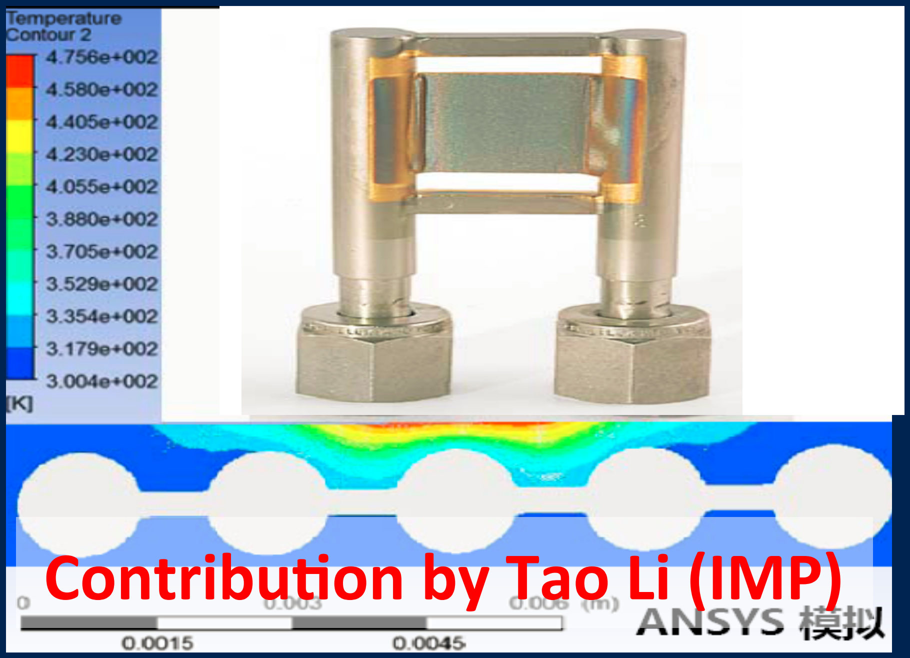


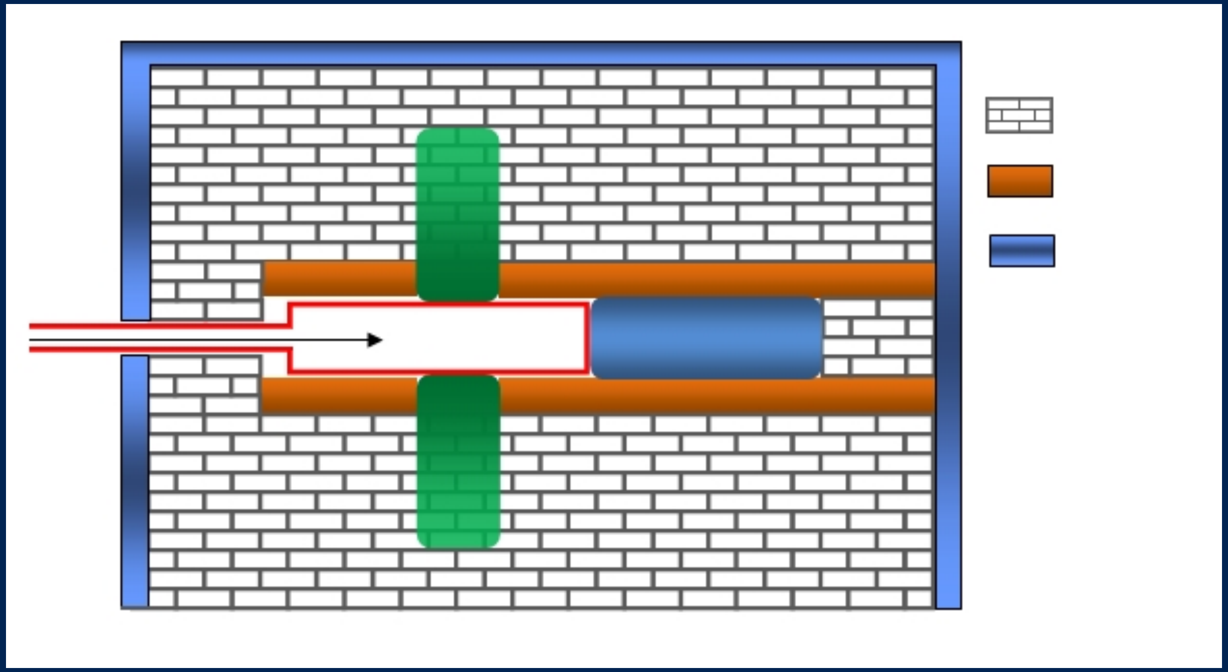
快中子：液闪探测器
慢化中子：24根^{3}He正比管



X. D. Tang

Target and shielding

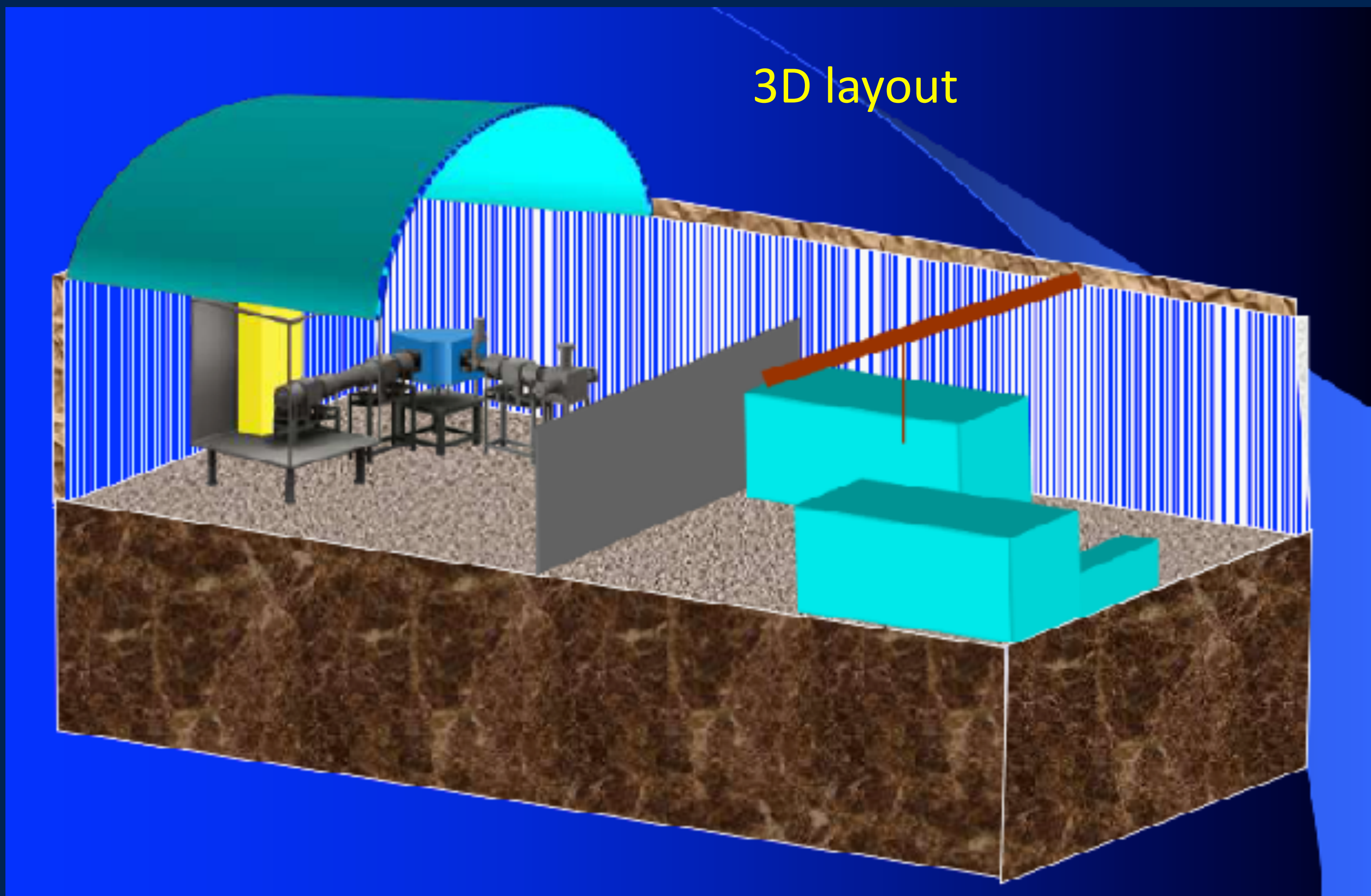


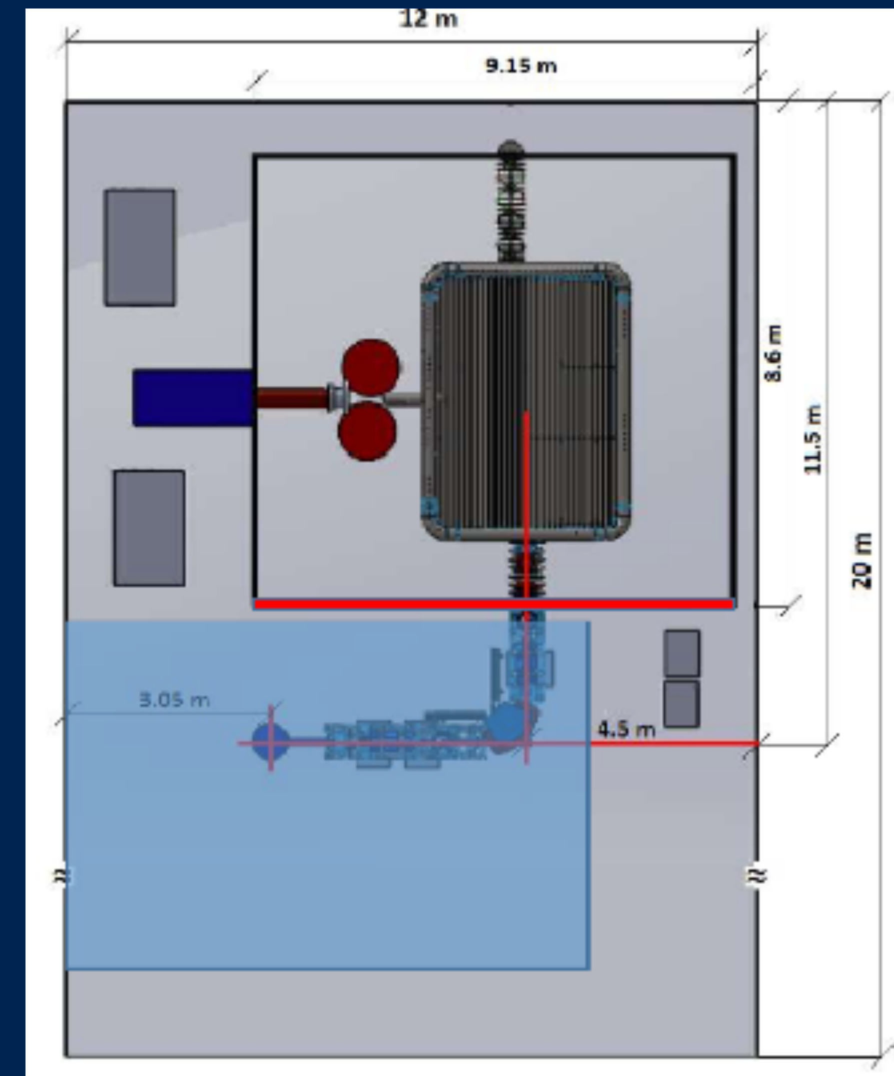


Rotation target tested 30/8/16

Y. J. Li

Lab construction

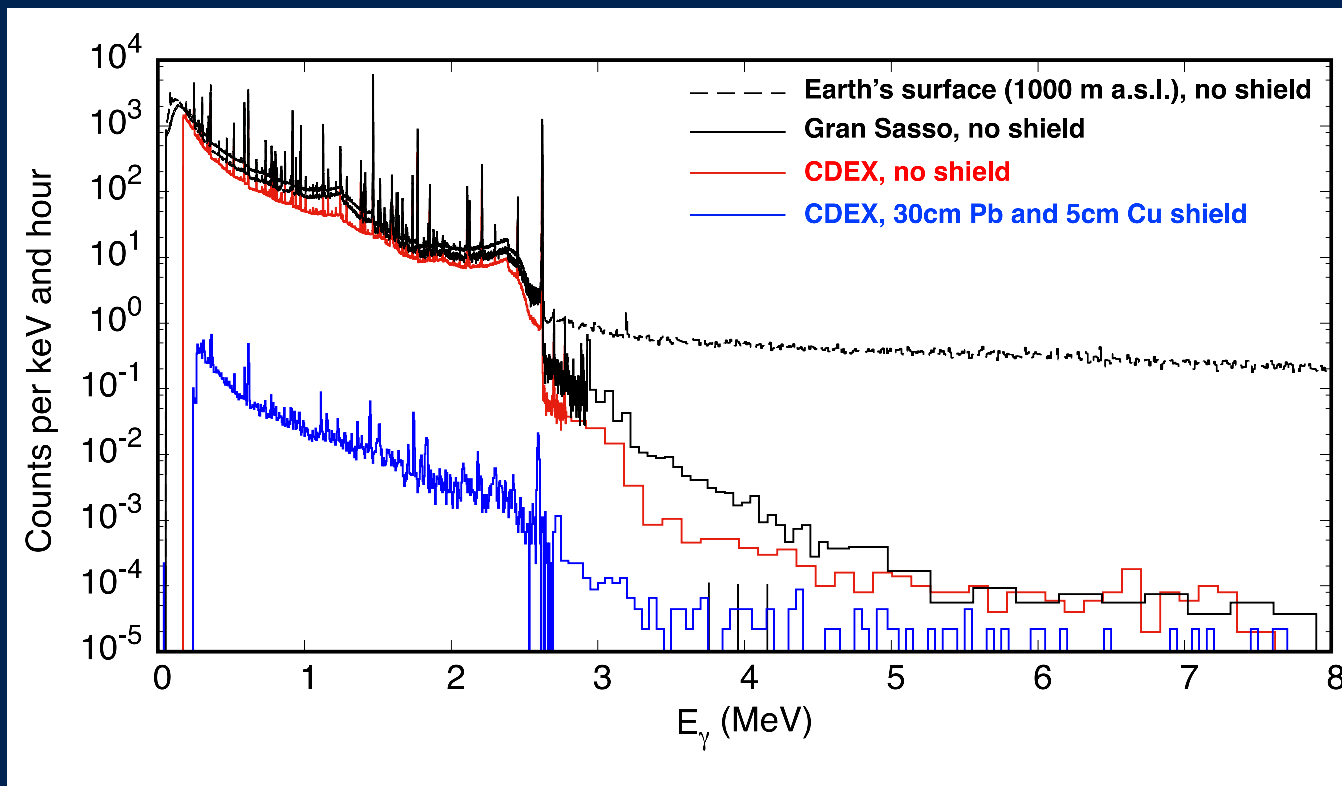




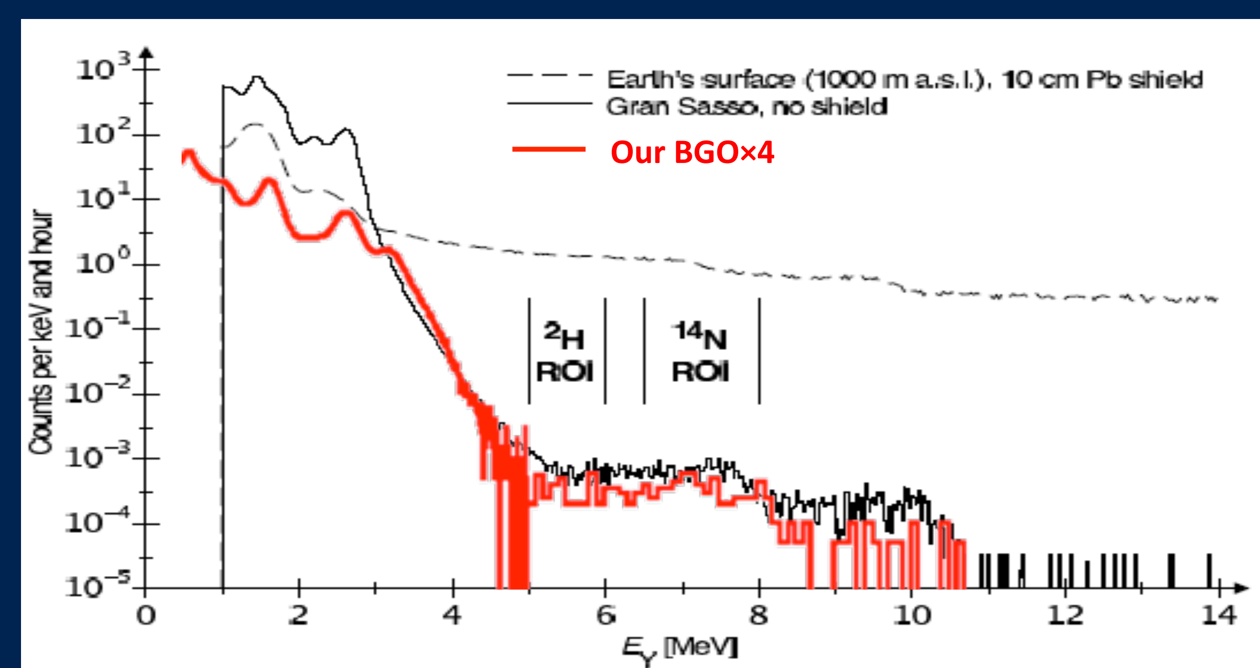
Accelerator floor plan

- **Start design, will construction 2017 Jan.-June, very tight schedule**
- **Need to start CJPL-II JUNA lab construction, need formal confirmation of A1 space from management committee ASAP**

HPGe and BGO background in CJPL-I



Duration	Contents
Mar. - May	*Gamma*
May - July	*Gamma with shielding*
Aug. - Oct.	*BGO*
Oct. - Dec.	*Neutron*



Detailed 5 year time table

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	construction	fabrication
2017 Q3-Q4	on site tuning	fine tuning	ground test
2018 Q1-Q2	He 2^{+} develop	shedding setup	$^{19}F(p,a)^{16}O$, $^{25}Mg(p,g)^{26}Al$
2018 Q3-Q4		new detector layout	$^{13}C(a,n)^{16}O$
2019 Q1-Q2			$^{13}C(a,n)^{16}O$, $^{12}C(a,g)^{16}O$
2019 Q3-Q4			$^{12}C(a,g)^{16}O$

JUNA expectation

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

Background 2015 | **Fabrication 2016** | **Installation 2017** | **Experiment 2018-2019**

Summary

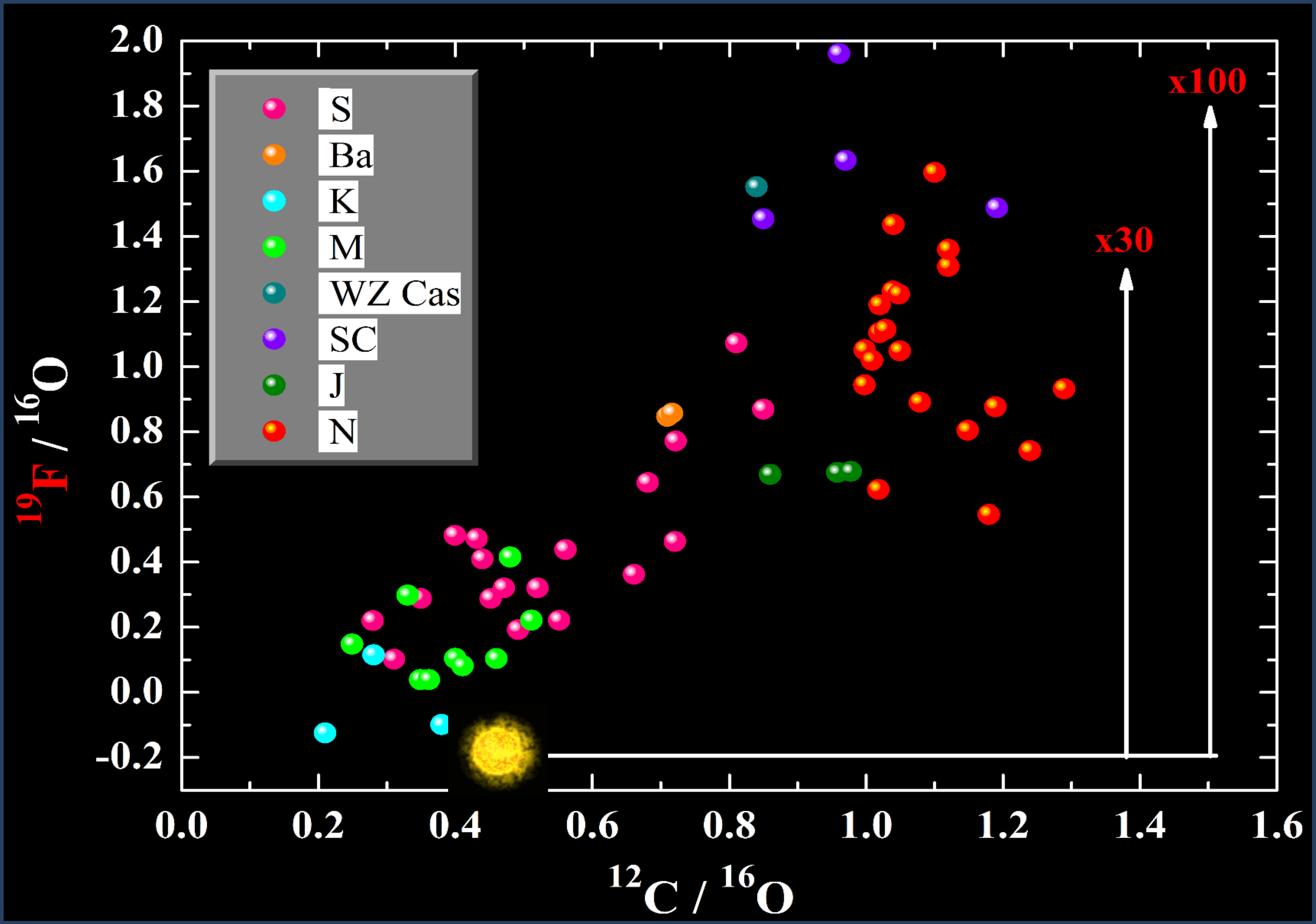
JUNA

- Nuclear astrophysics in good progress in China
- Direct measurement is a key data
- Underground JUNA is in progress, scheduled ground tuning 2016, and site turning 2017, hopefully start experiment in 2018
- Need to start CJPL-II JUNA lab construction, need formal confirmation of A1 space from management committee ASAP
- JUNA collaboration needed to tackle key experimental and technique challenges
- Welcome you to join JUNA!

Q&A: physics

- light curve and abundance curve
  - with time, half life and mass
  - with integral, abundance
- importance of $^{12}C(a,g)^{16}O$ reaction
  - how well do we know the rate: 60 %
  - the impact of higher precision: same with 3a, need for 10%, better for massive star
- importance of 19F(p,a) reaction
  - rule out the uncertainty of F abundance from NP
- importance of 25Mg(p,g)26Al reaction
  - see slides
- The JUNA-II plan
  - with MV machine and gas target and recoil meter see slides

F-overabundance in AGB stars



Standard AGB models cannot explain the observed F-overabundance phenomenon. Nucleosynthesis model needs precise cross section data relevant to ^{19}F production and destruction reactions.

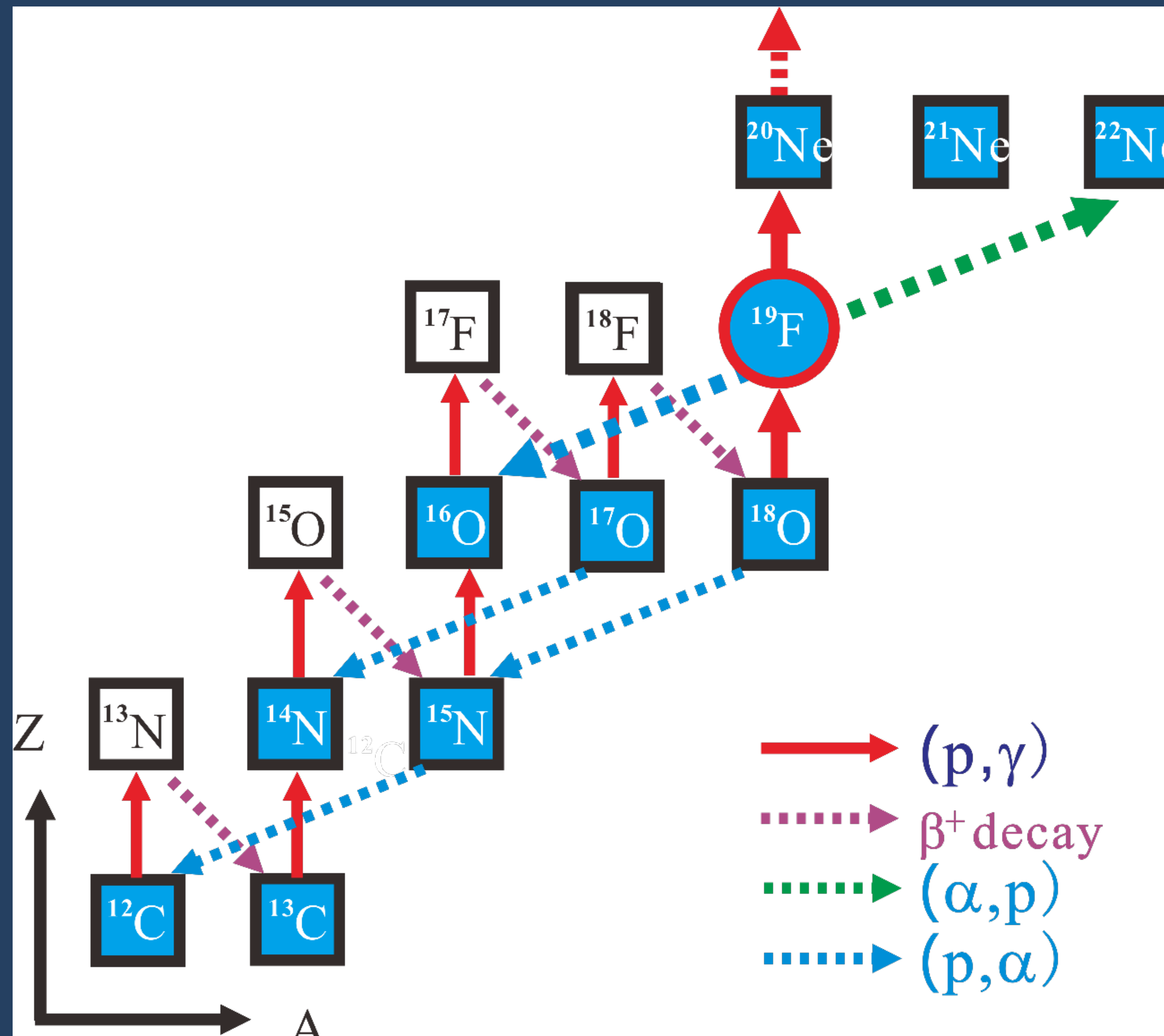
F-overabundance in AGB stars

Destruction:

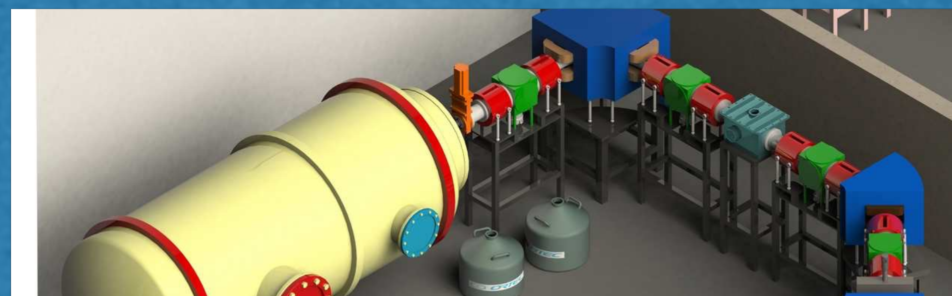
- [x] $^{18}O(p,\gamma)^{19}F$
- [x] $^{15}N(\alpha,\gamma)^{19}F$
- [ ] $^{14}C(\alpha,\gamma)^{18}O$

Production:

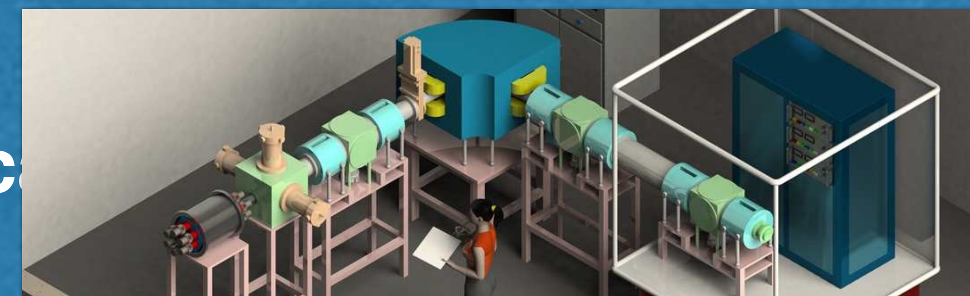
- [ ] **$^{19}F(p,\alpha)^{16}O$**
- [ ] $^{19}F(\alpha,p)^{22}Ne$
- [ ] $^{19}F(p,\gamma)^{20}Ne$
- [ ] $^{19}F(\alpha,\gamma)^{23}Na$



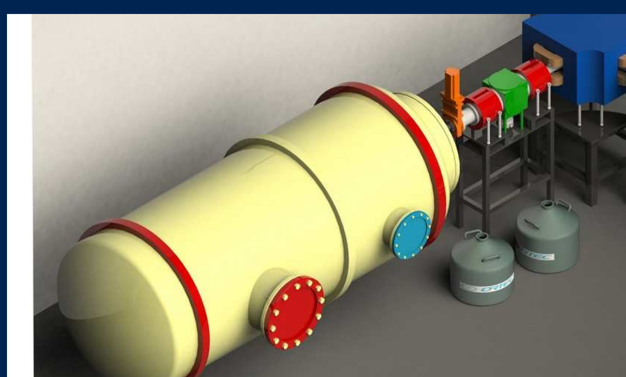
JUNA-II 二期计划



JUNA-II

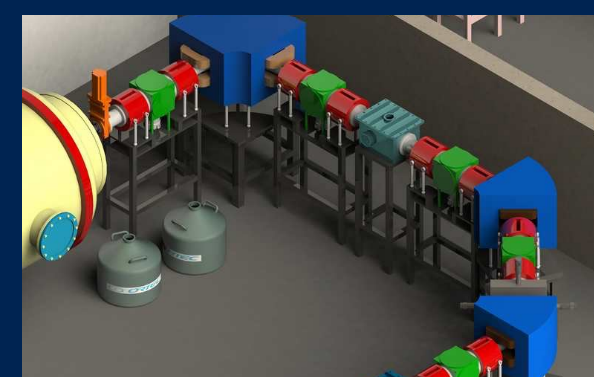


JUNA-I

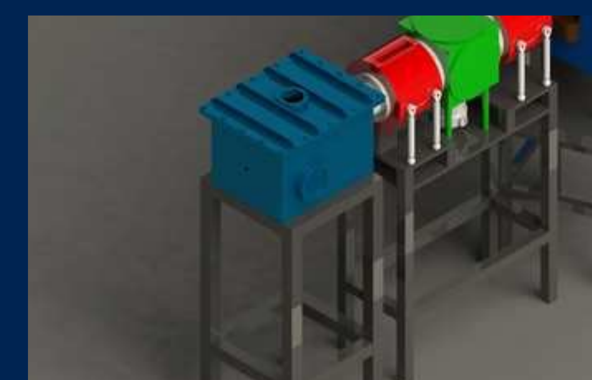


4MV accelerator

Windowless target



RMS



Detectors

JUNA-II计划纳入国家重点基础研究锦屏实验室项目

JUNA 时间表 time table

- 2014, 项目得到NSFC批准
- 2015, 实验方案设计， 探测器建造
- 2016-2017, 加速器、离子源和探测器安装和调试
- 2018, $^{25}Mg(p,\gamma)^{26}Al$, $^{19}F(p,a)^{16}O$实验测量, JUNAII 启动
- 2019, $^{13}C(\alpha,n)^{16}O$实验测量， $^{12}C(\alpha,\gamma)^{16}O$实验测量
- 2021, JUNAII 完成
- 2021-, $^{12}C(\alpha,\gamma)^{16}O$使用$^{12}C$ 束流… $^{12}C+^{12}C$, $^{12}C+^{16}O$,

JUNA 的蓝图

JUNA

H burning

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

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

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

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

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

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

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

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

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

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

He burning

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

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

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

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

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

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

C, O burning

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

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

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

n source

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

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

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

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

γ astronomy

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

JUNA-I

JUNA-II

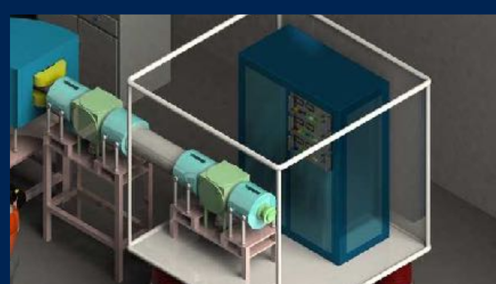
Q&A: technical

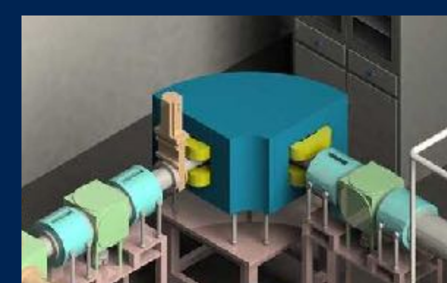
- JUNA targets for 10 emA
  - rotation, new material, like nano material
- background vs. depth
  - cosmic ray: yes
  - rock: no
  - accelerator and detector: no
- Energy and ion source of JUNA
  - see slides
- How more accuracy (cross sections) achieved compared with other experiments?
  - higher beam intensity: mA vs. 100 less uA
  - better detector: large BGO vs. HPGe
- Way to shield background
  - complex around target and detector and coincidence
- Detailed experimental setup
  - see slides
- Way of measuring cross section (with faraday cup)
  - No, FC can not give identification, with particle, gamma and neutron detectors

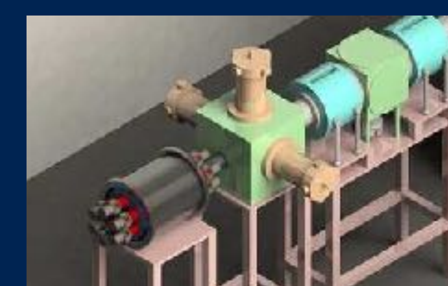
JUNA plan

CJPL-II c

JUNA



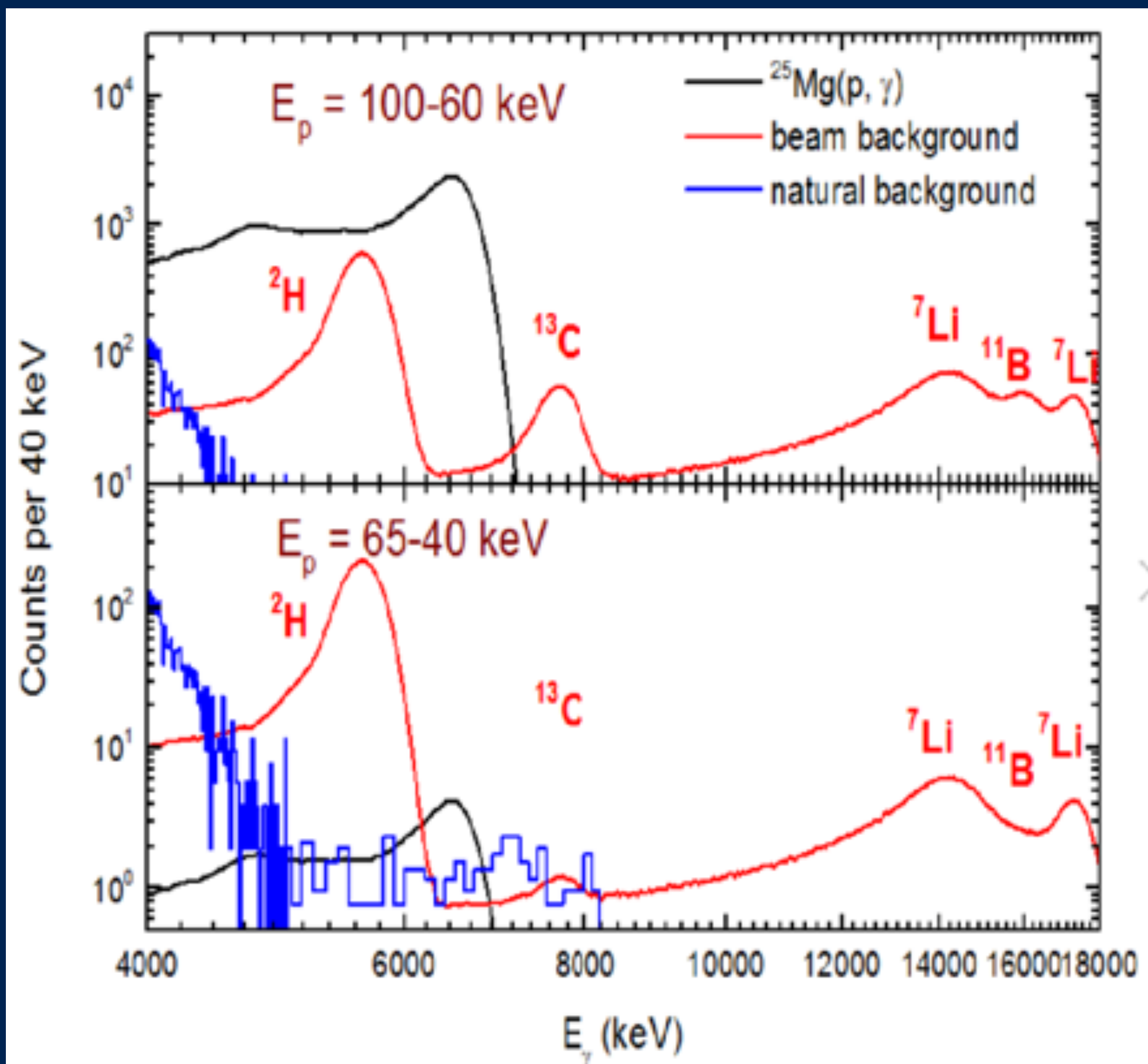


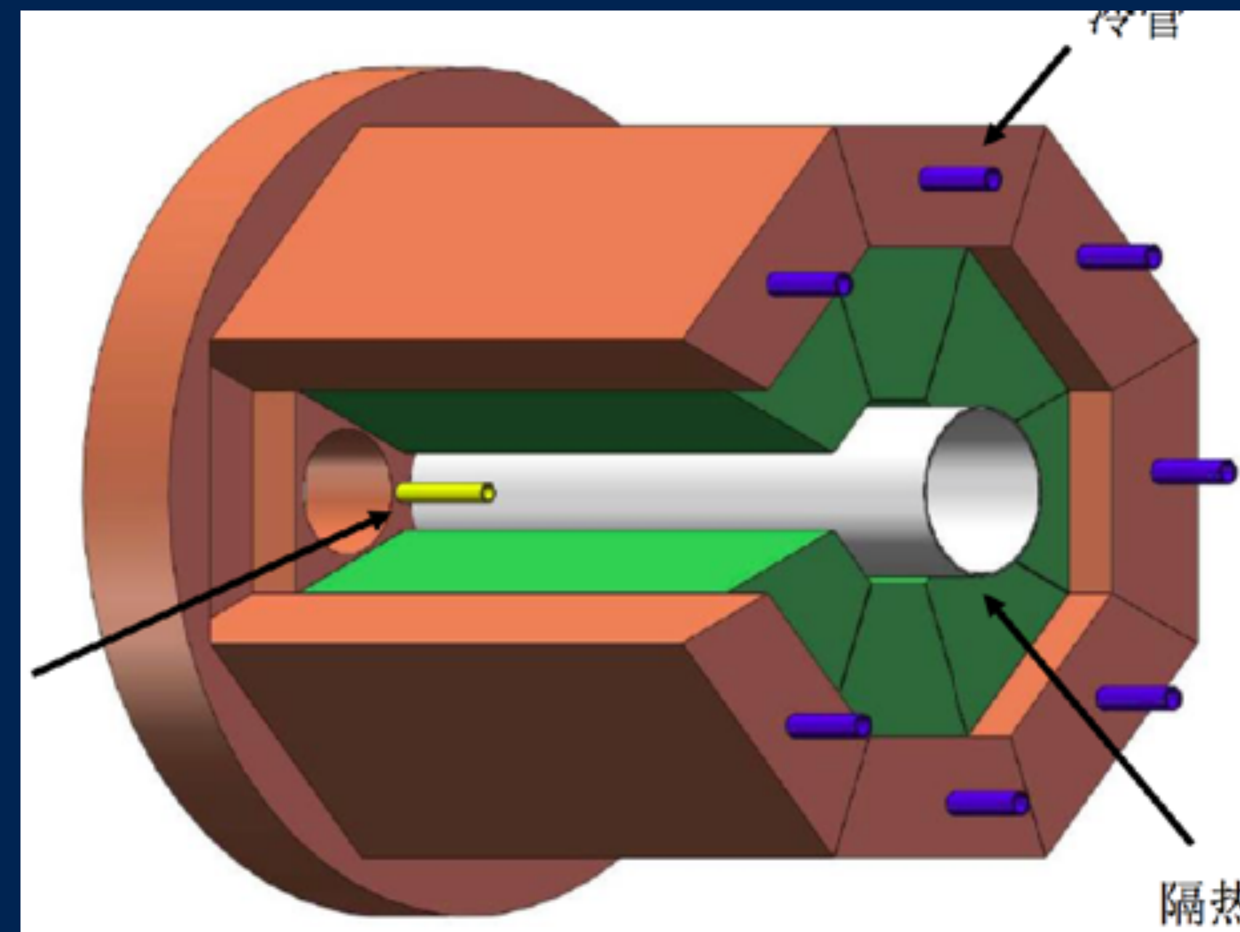


ECR source **Acceleration** **Magnet** **Detectors**

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

^{25}Mg progress





Z. H. Li

Q&A 3: MISC

- element made by earth?
  - Yes, by reactor and accelerator

More reference

- Lecture notes (nuclear astrophysics and physics of unstable physics.)