NIC XVII school 2023, Sep 10 – 15, 2023
Institute for Basic Science, Daejeon, Korea

Experimental nuclear astrophysics (stable beam experiments and underground)

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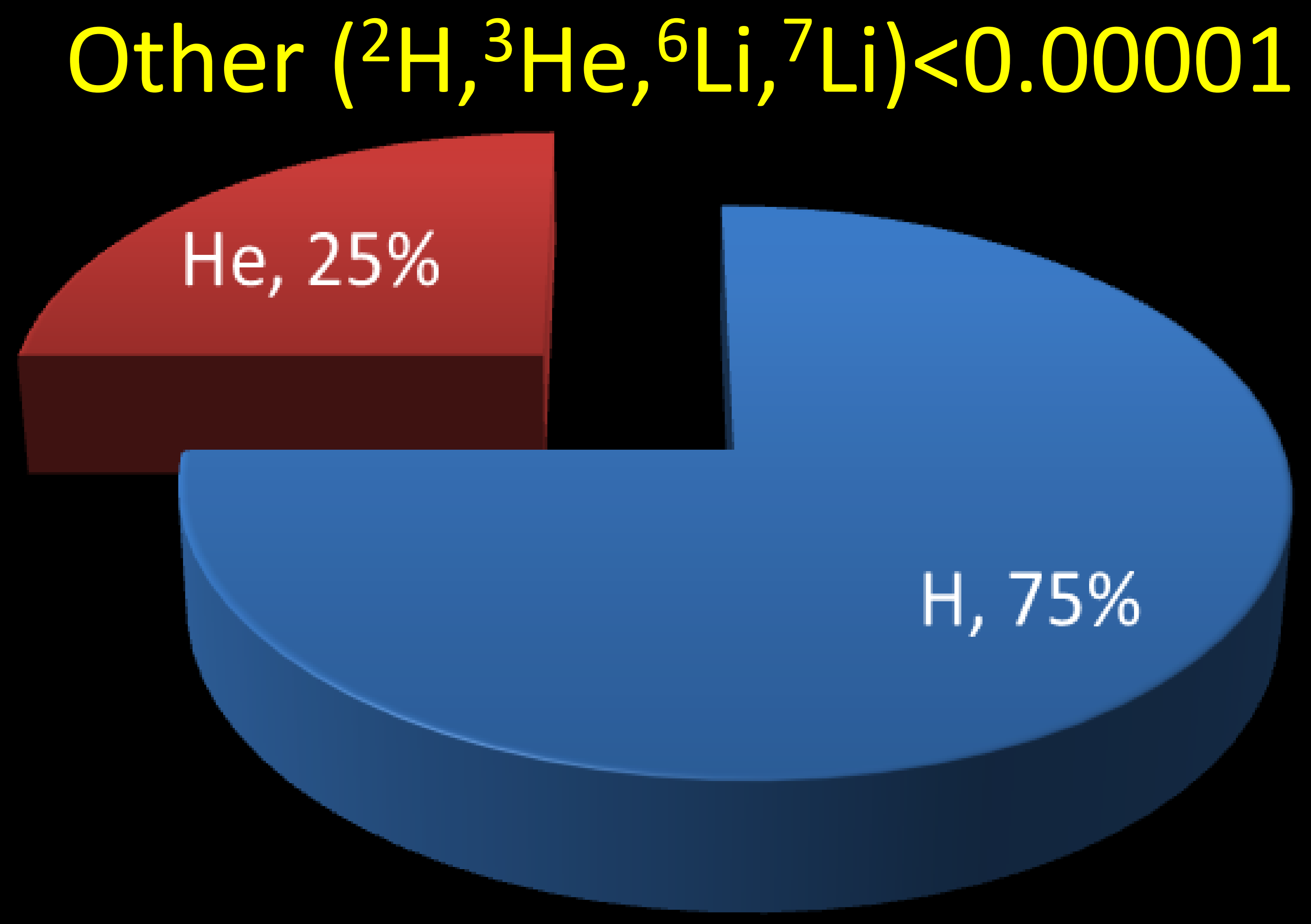
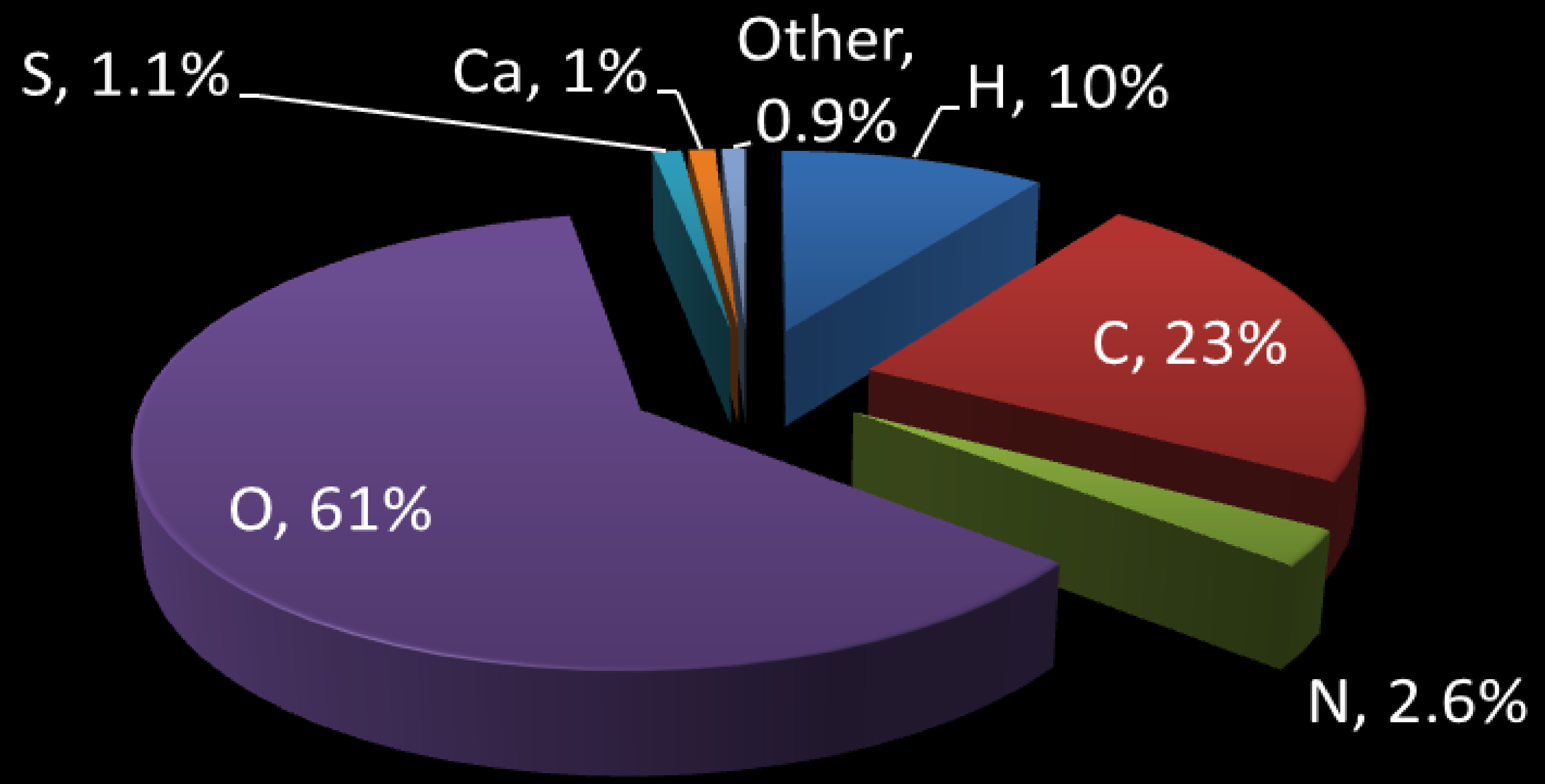
Origin of Elements



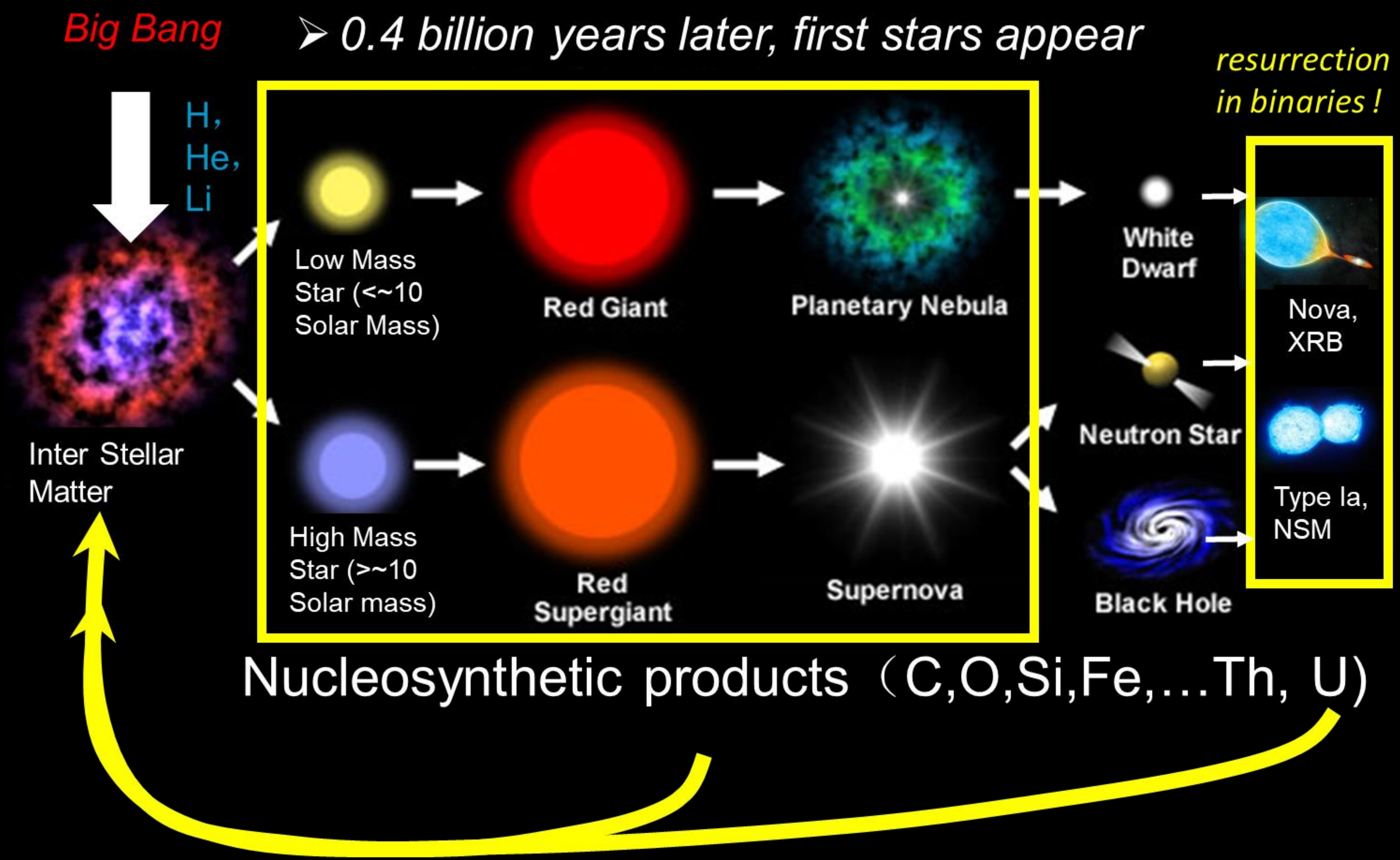
3 mins after Big Bang



13.7 billion years later

Chemical Element Enrichment

- *0.4 billion years later, first stars appear*



Big Bang

H,
He,
Li

Inter Stellar
Matter

Low Mass
Star (<~10
Solar Mass)

Red Giant

Planetary Nebula

White Dwarf

High Mass
Star (>~10
Solar mass)

Red Supergiant

Supernova

Neutron Star

Black Hole

resurrection in binaries !

Nova,
XRB

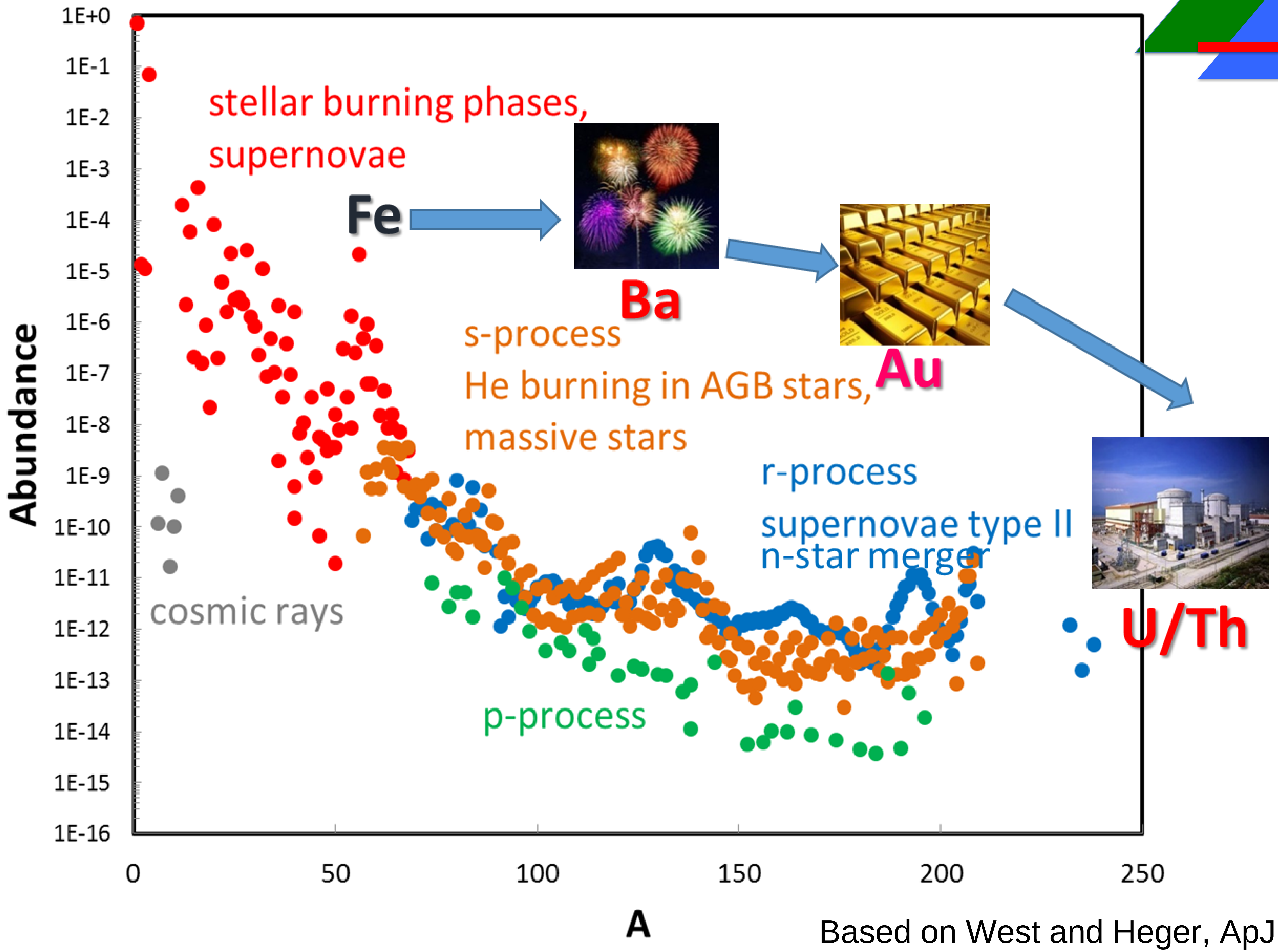
Type Ia,
NSM

Nucleosynthetic products（C,O,Si,Fe,…Th, U)

Origin of elements

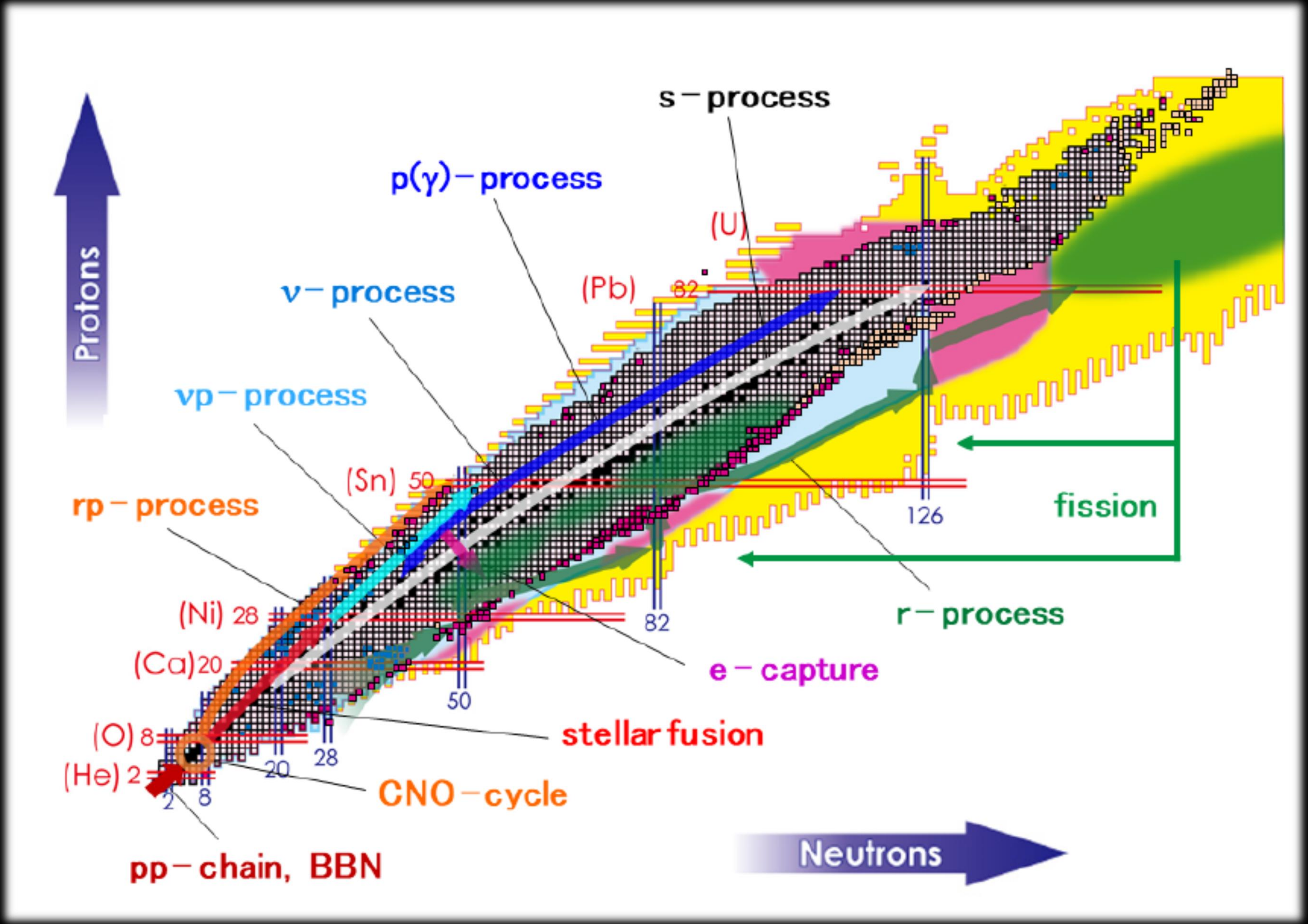
JUNA

The total number of primordial nuclides is then 251 (the stable nuclides) plus the 35 radioactive primordial nuclides, for a total of 286 primordial nuclides.



Based on West and Heger, ApJ(2013)

Nucleosynthesis in stars



1) Big bang

2) Stellar quiescent burning

(pp-chain, stellar fusion, s-process)

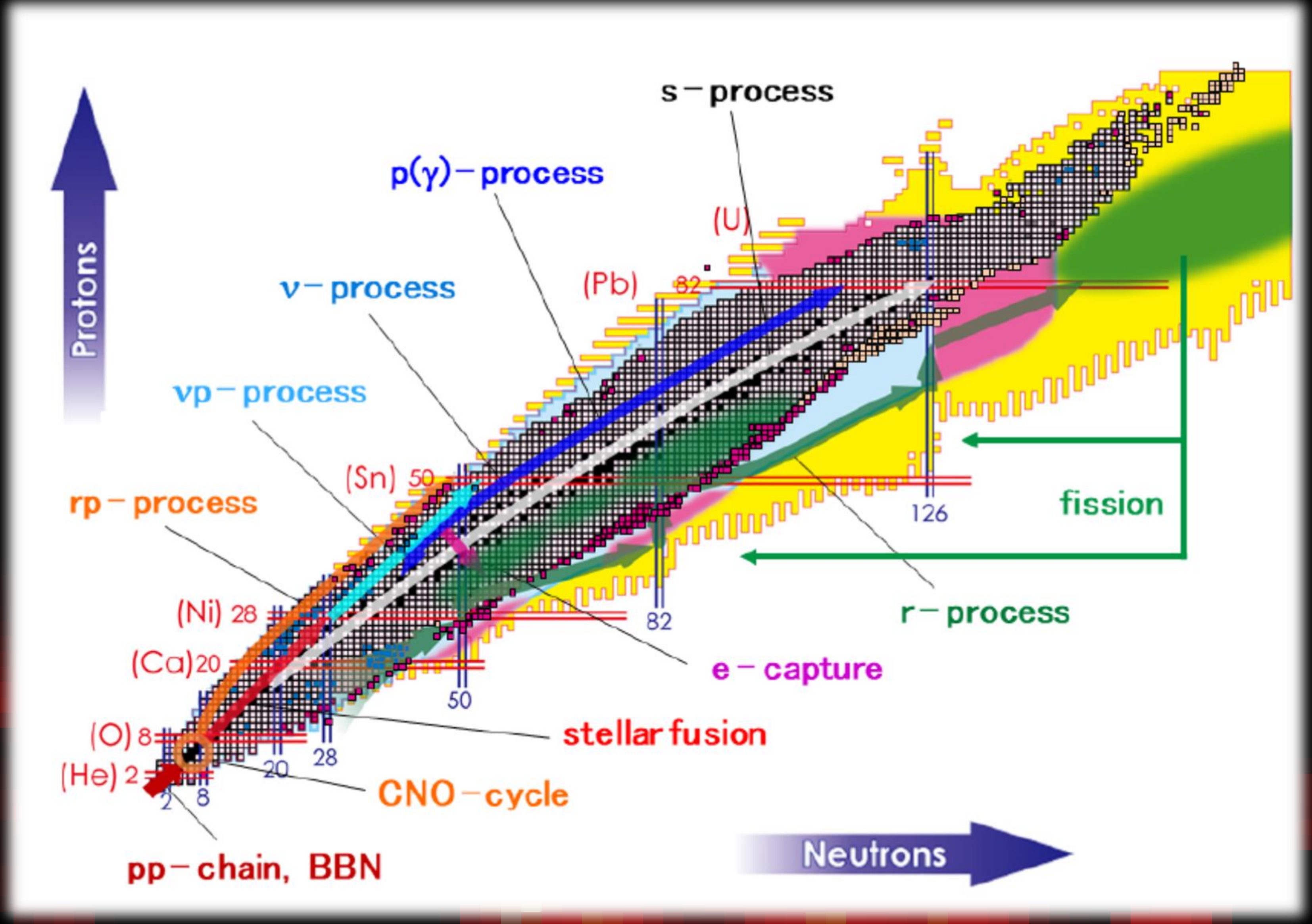
3) Stellar explosive burning

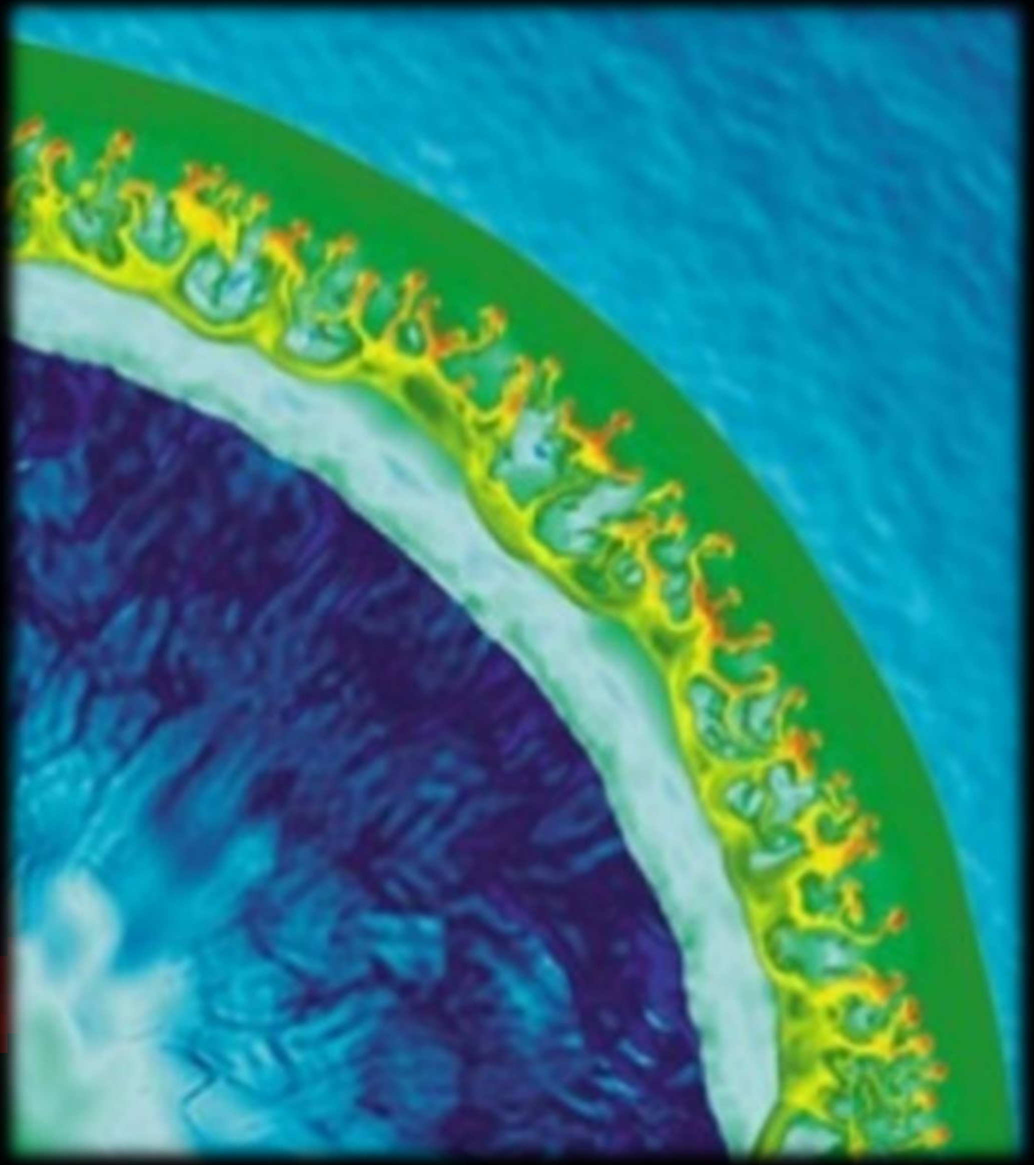
(r-, νp-, ν-, p-, rp-processes)

4) Cosmic Ray spallation

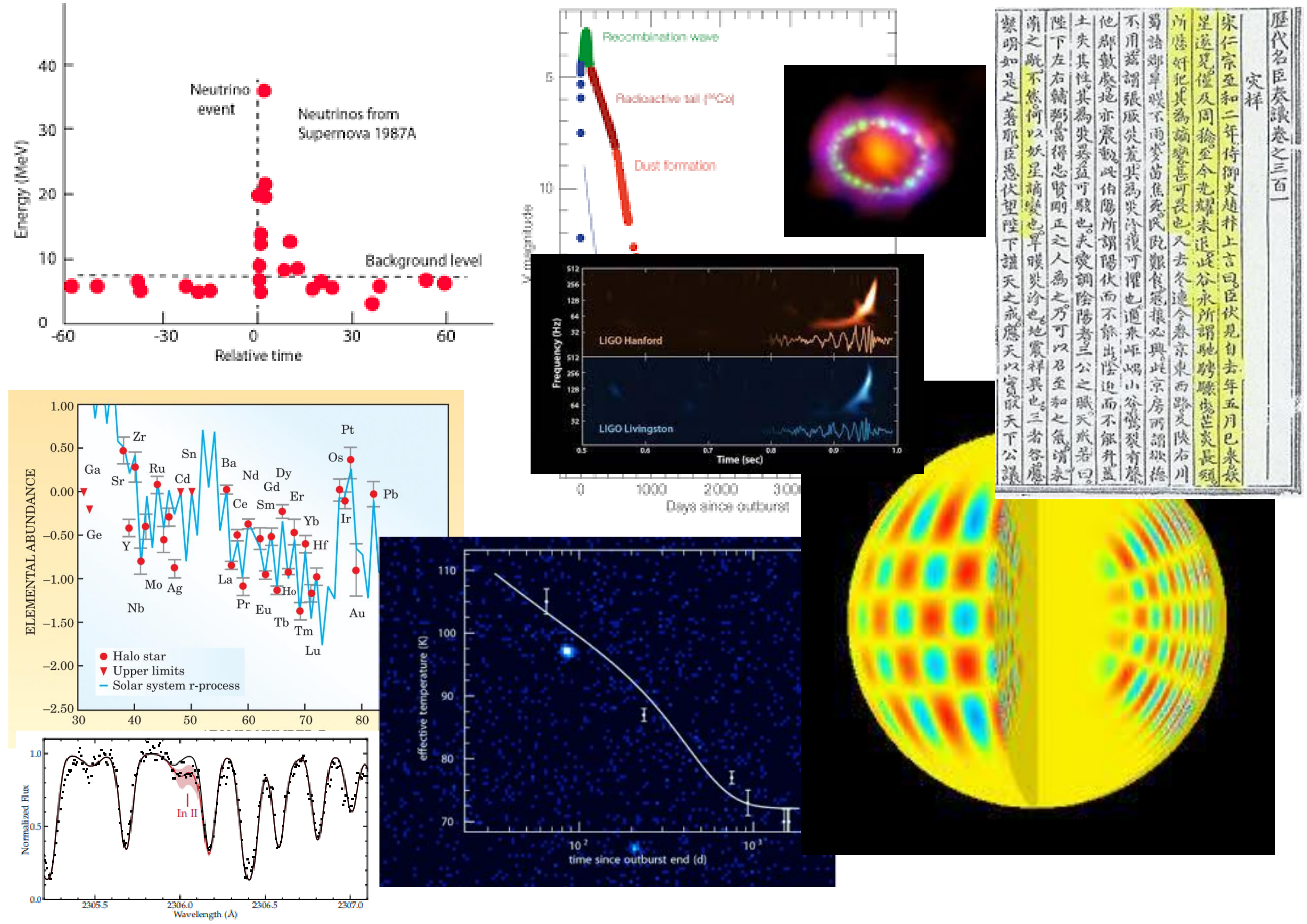
- **What is the origin of the elements in the cosmos?**
- **What are the nuclear reactions that drive the evolution of stars and stellar explosions?**

"Progress in Nuclear Astrophysics of East and Southeast Asia", AAPPS bulletin(2021) 31:18





We are building the nuclear engines to drive the stellar evolution and explosion



How to correctly decipher the messages?

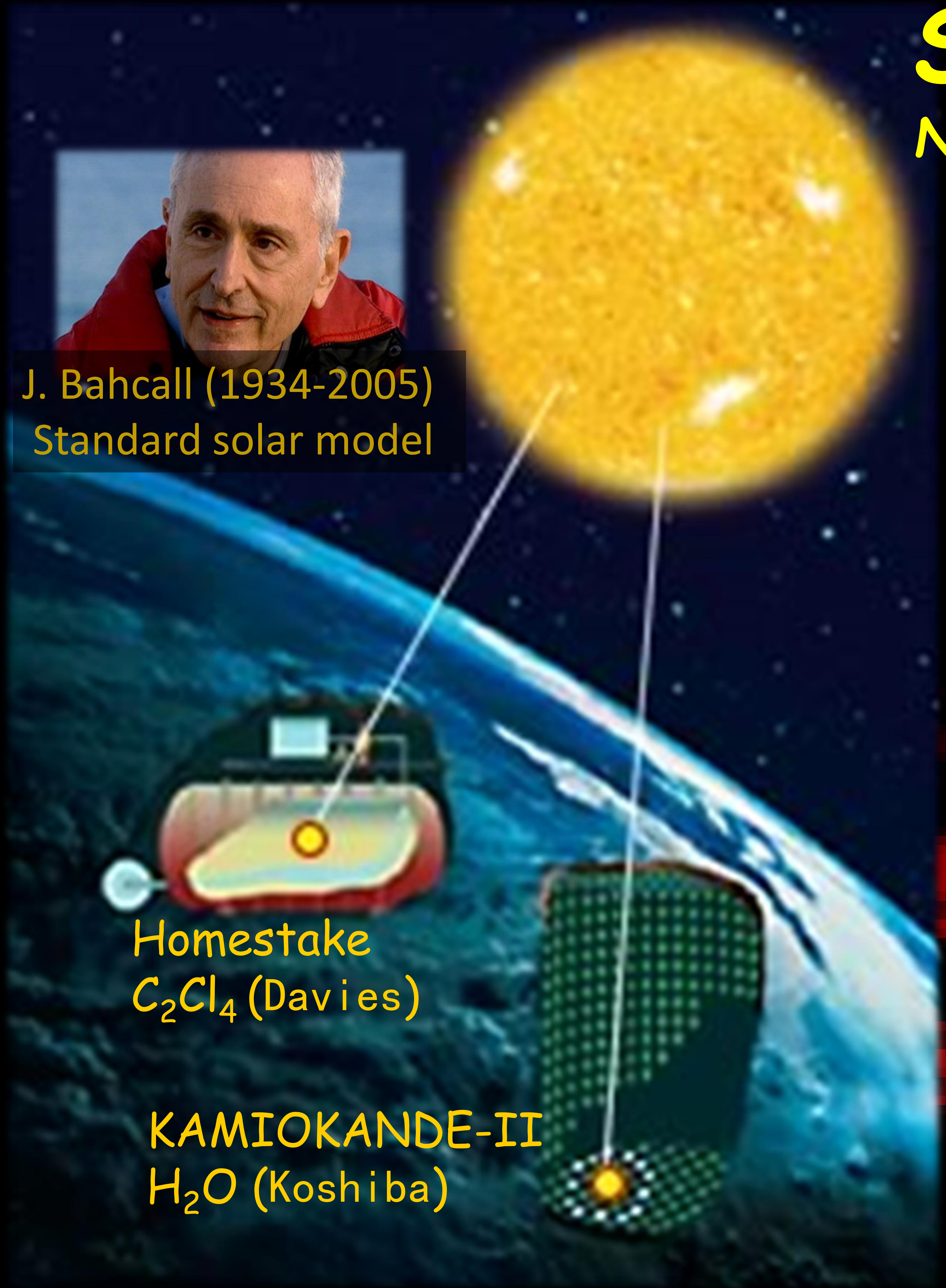
Multi-Messenger

(Visible light, X-ray, Neutrino, Gravitational wave etc.)

Precise knowledge of the critical nuclear physics inputs and reliable stellar models are urgently needed to decipher the encoded messages correctly.

Solar Neutrino “Problem”

New discovery beyond standard model in particle physics

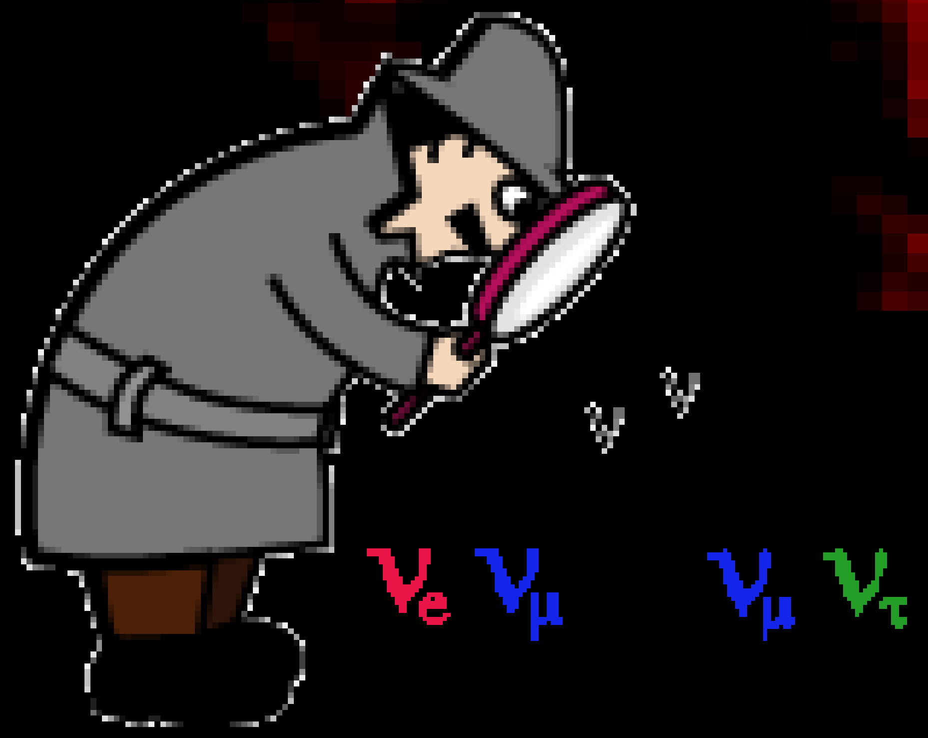


Experiment	Detector medium	Observation /prediction
Homestake	^{37}Cl	0.33 ± 0.03
Kamiokande	water	0.57 ± 0.07

2002 Nobel prize in physics
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos“

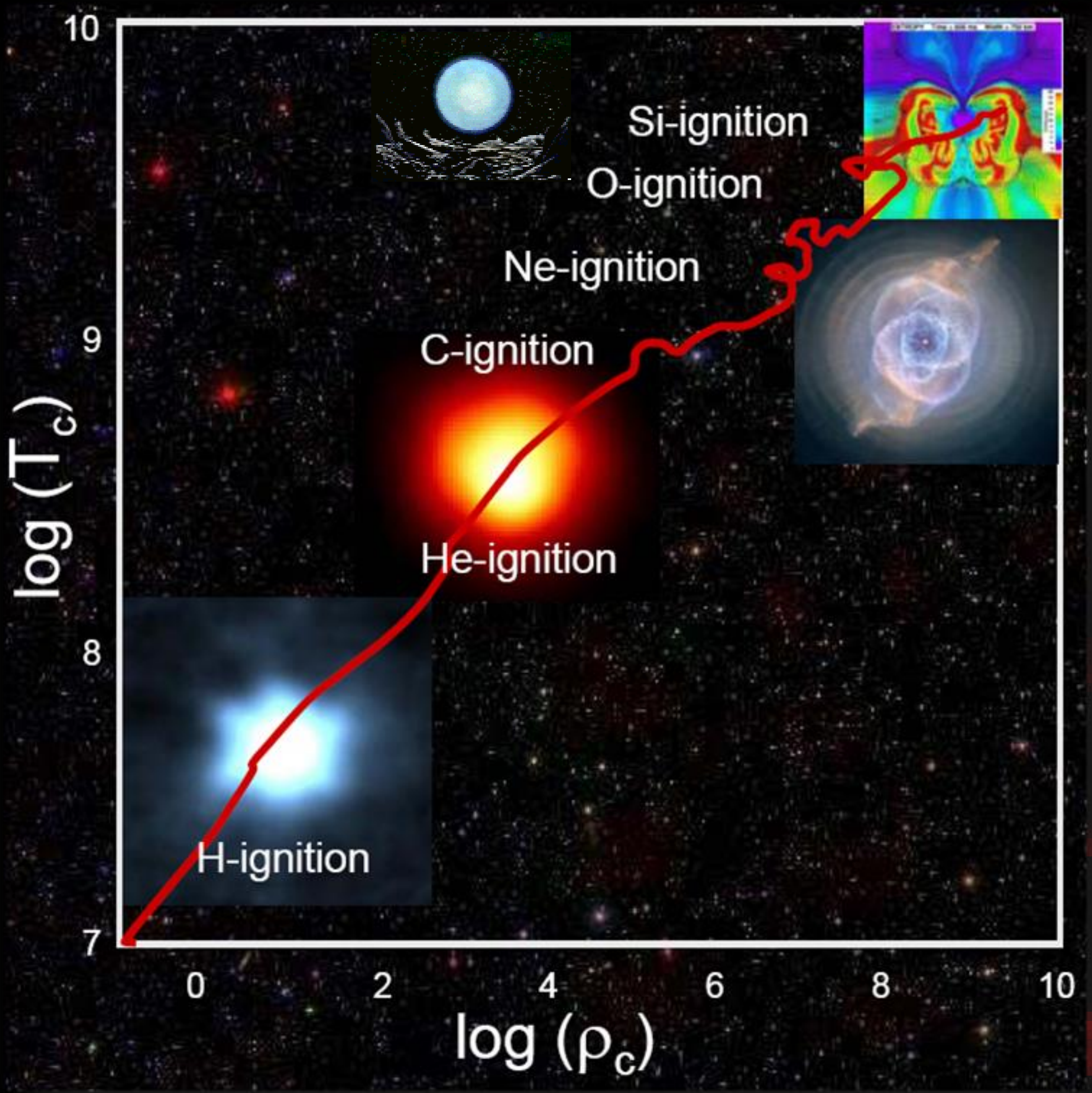
Solar Neutrino “Problem“

- Solar model
- Important cross sections: $^{3}He(^{3}He,2p)^{4}He$, $^{3}He(^{4}He,\gamma)^{7}Be$, $^{7}Be(p,\gamma)^{8}B$
- Unknown neutrino physics - neutrino oscillation???

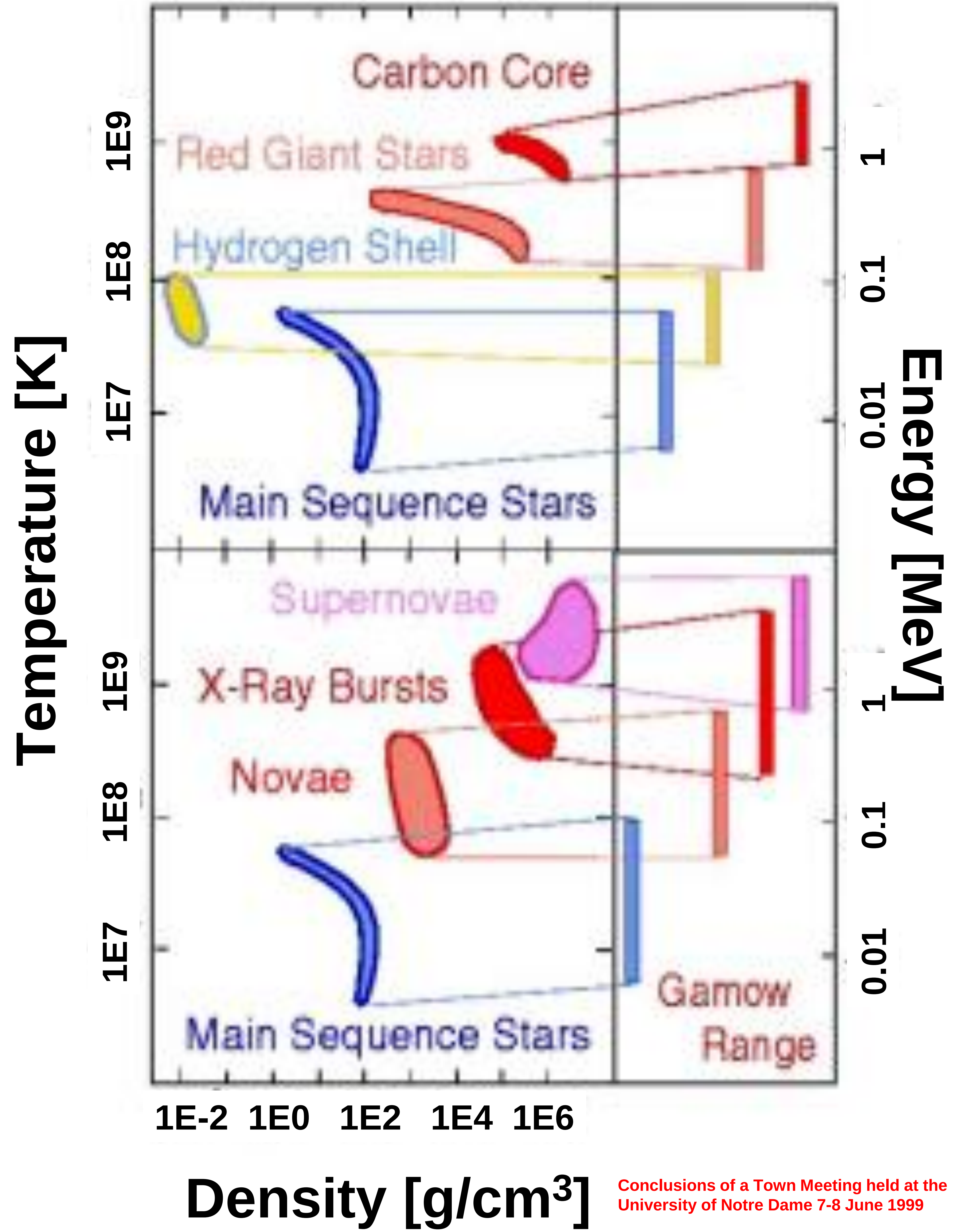


"Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^{8}B neutrinos to within a factor of 2 or 3…"

Howard Georgi and Michael Luke (1990)

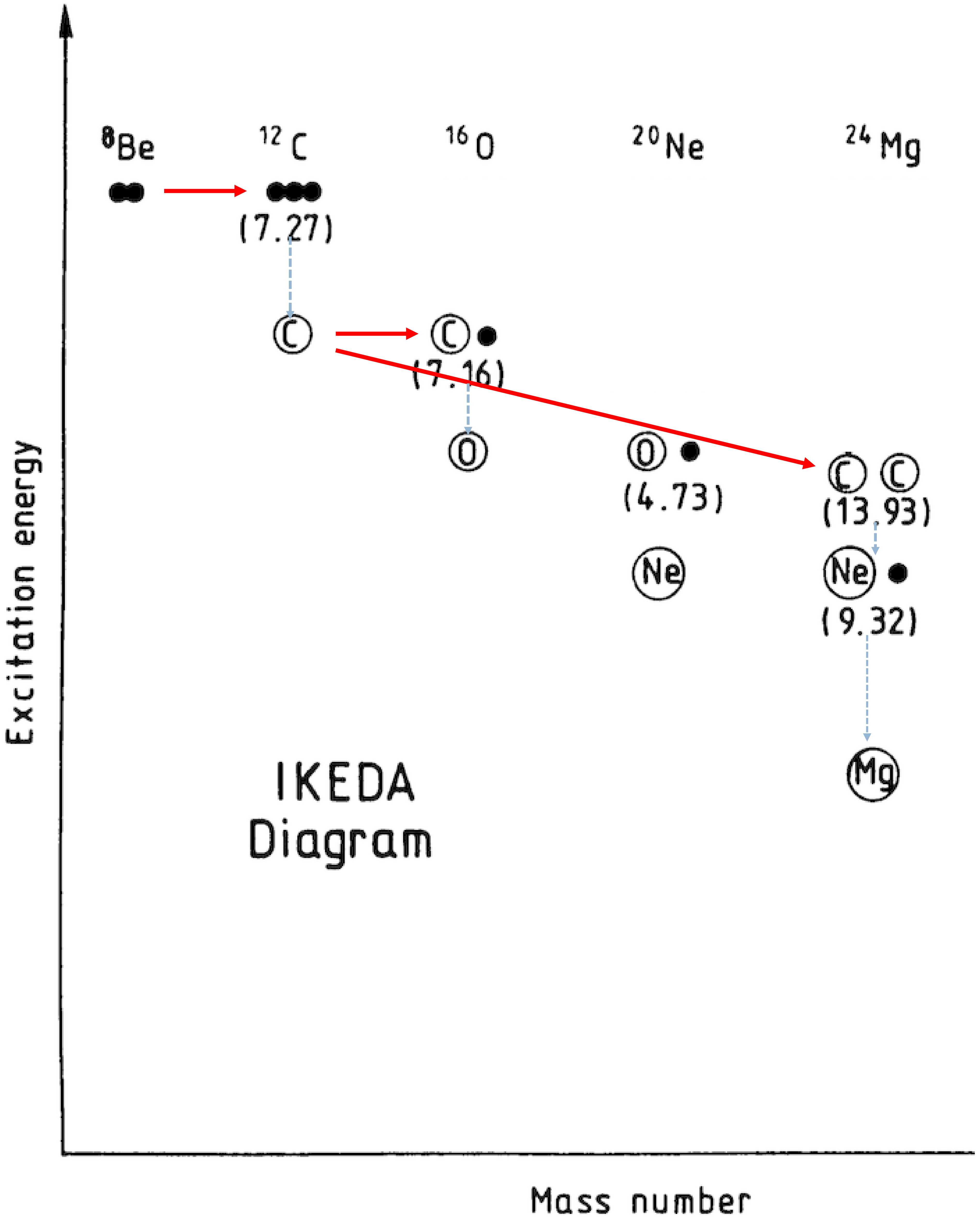


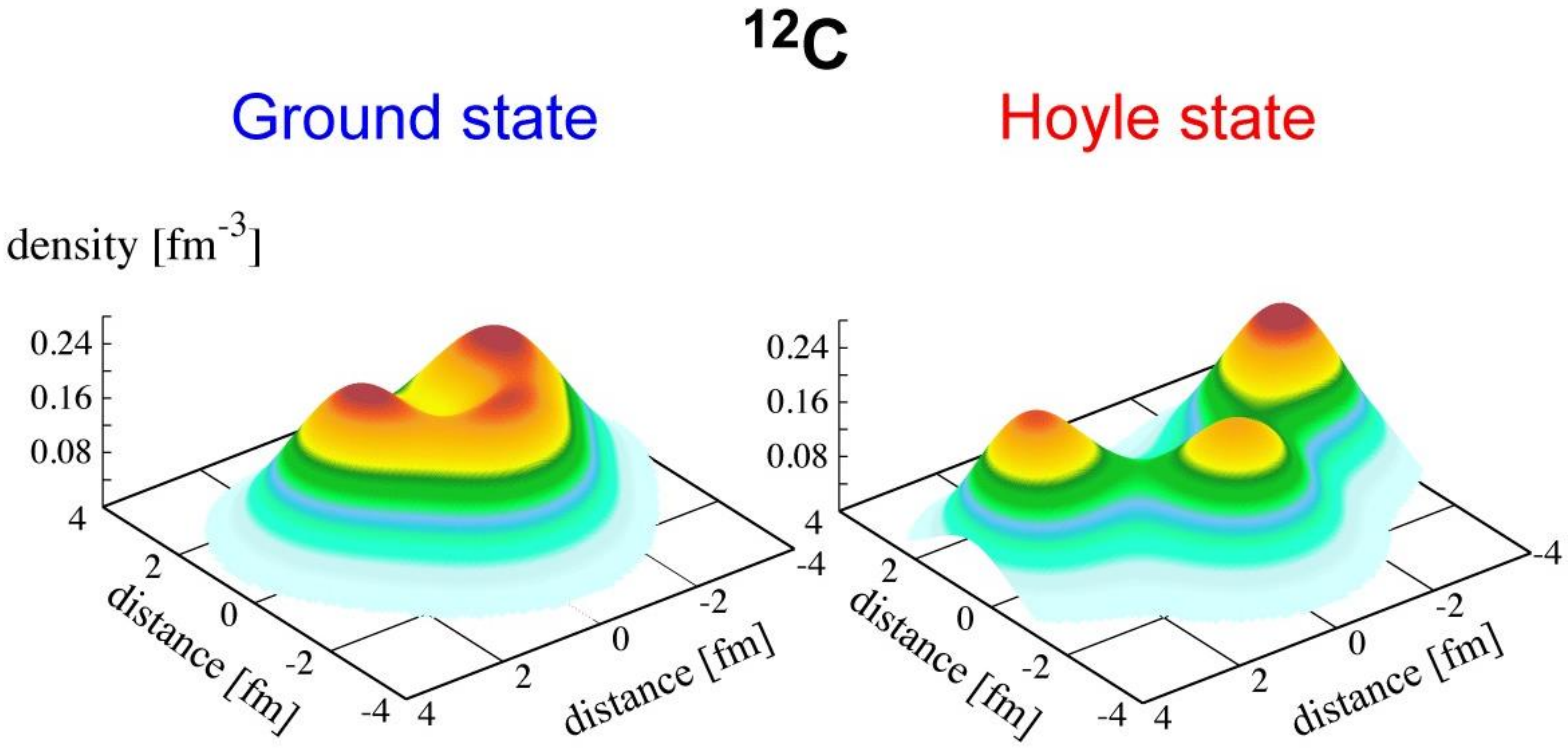
Woosley, Heger, and Weaver, Evolution and explosion of massive stars, Rev. Mod. Phys. (2002)



Conclusions of a Town Meeting held at the University of Notre Dame 7-8 June 1999

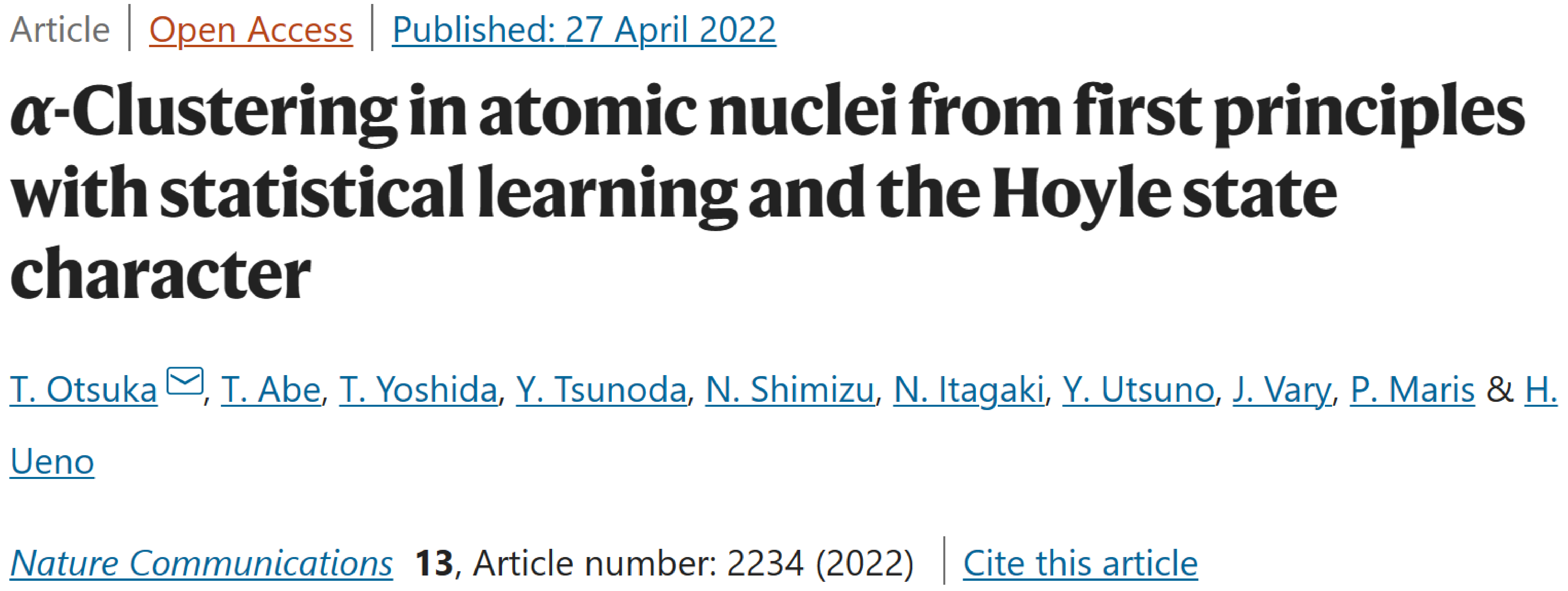
Nuclear clusters as stepping stones in stars




^{12}C

Ground state

Hoyle state


Article | Open Access | Published: 27 April 2022

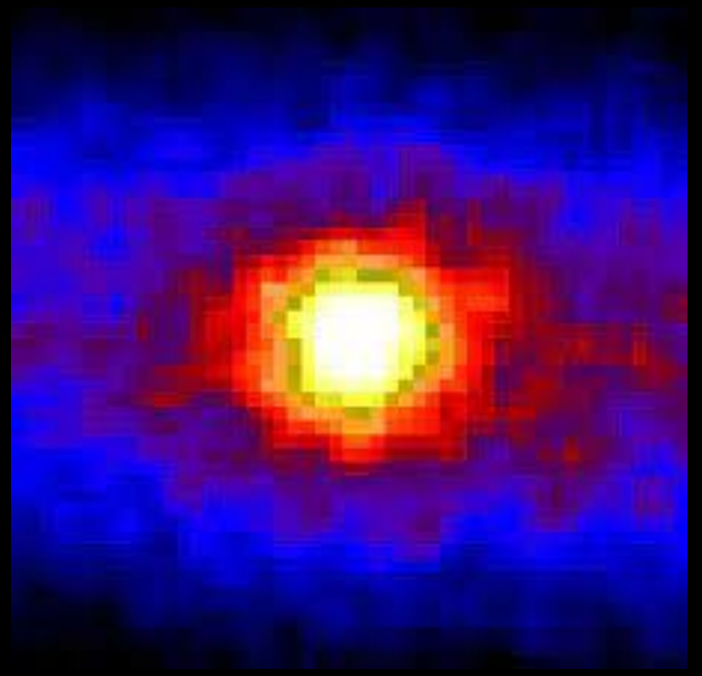
α-Clustering in atomic nuclei from first principles with statistical learning and the Hoyle state character

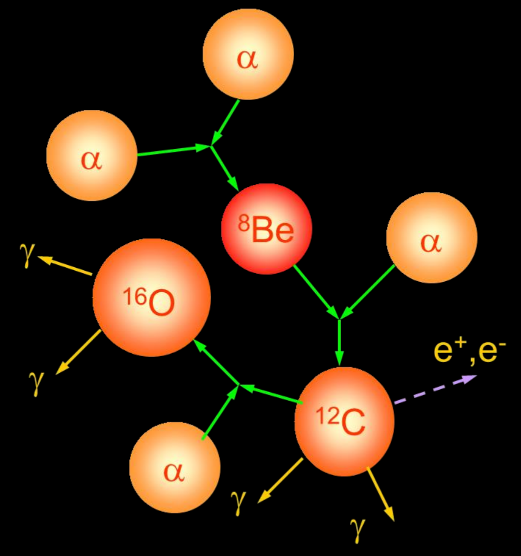
T. Otsuka, T. Abe, T. Yoshida, Y. Tsunoda, N. Shimizu, N. Itagaki, Y. Utsuno, J. Vary, P. Maris & H. Ueno

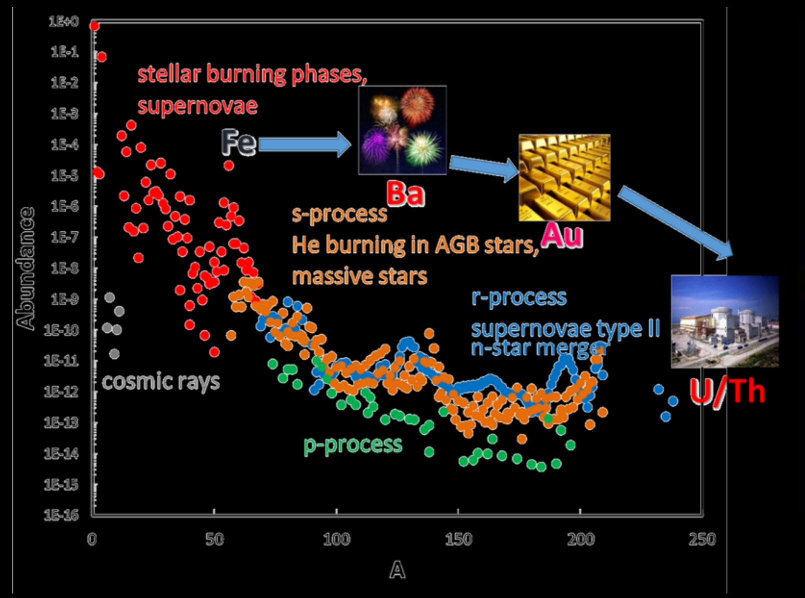
Nature Communications **13**, Article number: 2234 (2022) | Cite this article

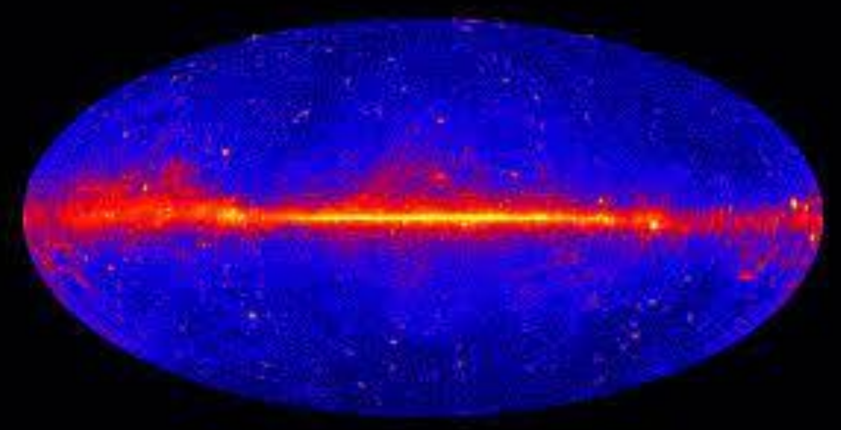
My journey as a nuclear alchemist

- ^{7}Be(p,γ)^{8}B: "Solar neutrino problem"
- ^{11}C(p,γ)^{12}N: Production of carbon in first stars
- ^{59}Fe stellar decay rate: gamma ray astronomy
- ^{16}N decay (^{12}C(α,γ)^{16}O): Origin of carbon and oxygen
- ^{13}C(α,n)^{16}O: Neutron source of heavy element nucleosynthesis
- Carbon fusion reaction (^{12}C+^{12}C): Evolution of massive star, ignition of Type Ia supernova and Superburst

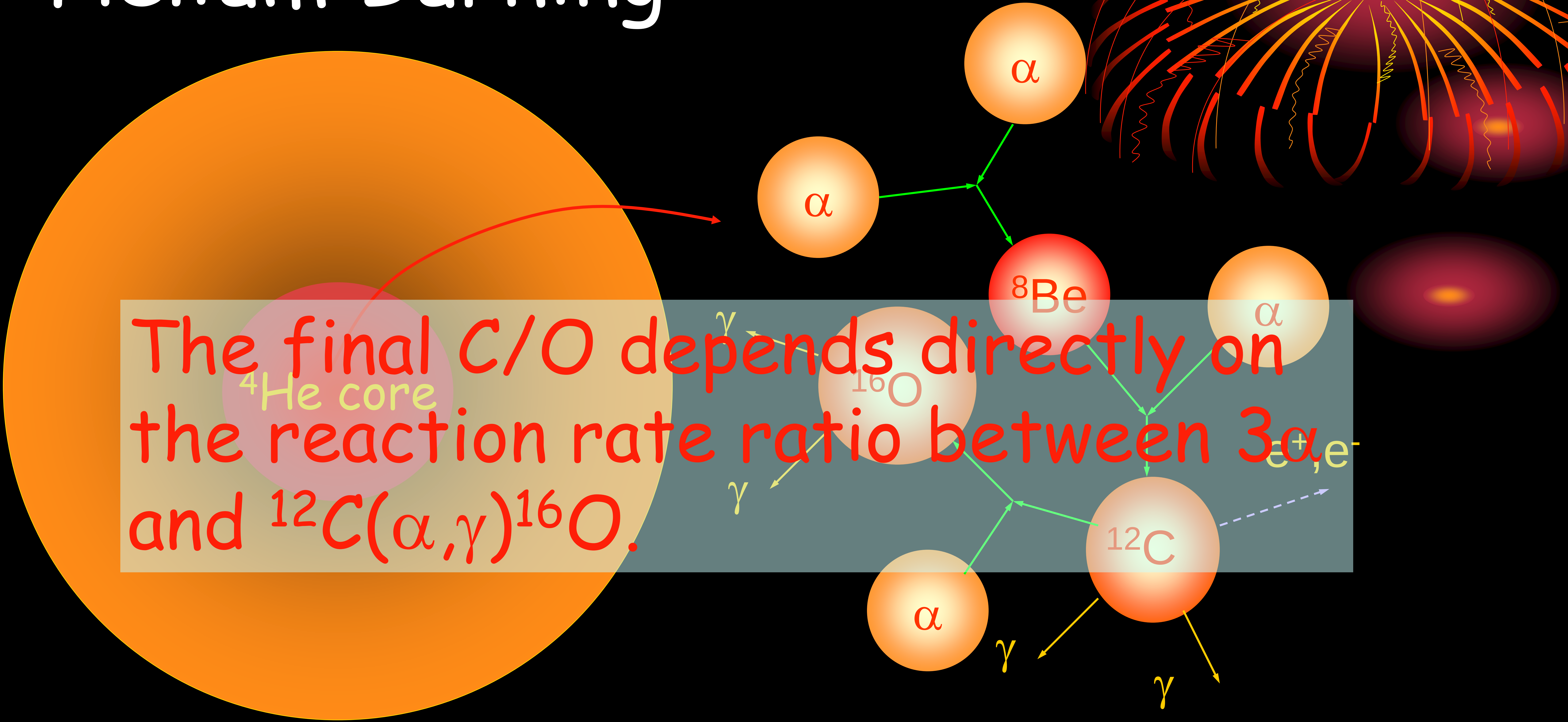








Helium Burning



The final C/O depends directly on the reaction rate ratio between 3α and $^{12}C(\alpha,\gamma)^{16}O$.

T ~ 0.2 billion Kelvin

Core He Burning

- Helium burns into ^{12}C via triple alpha:

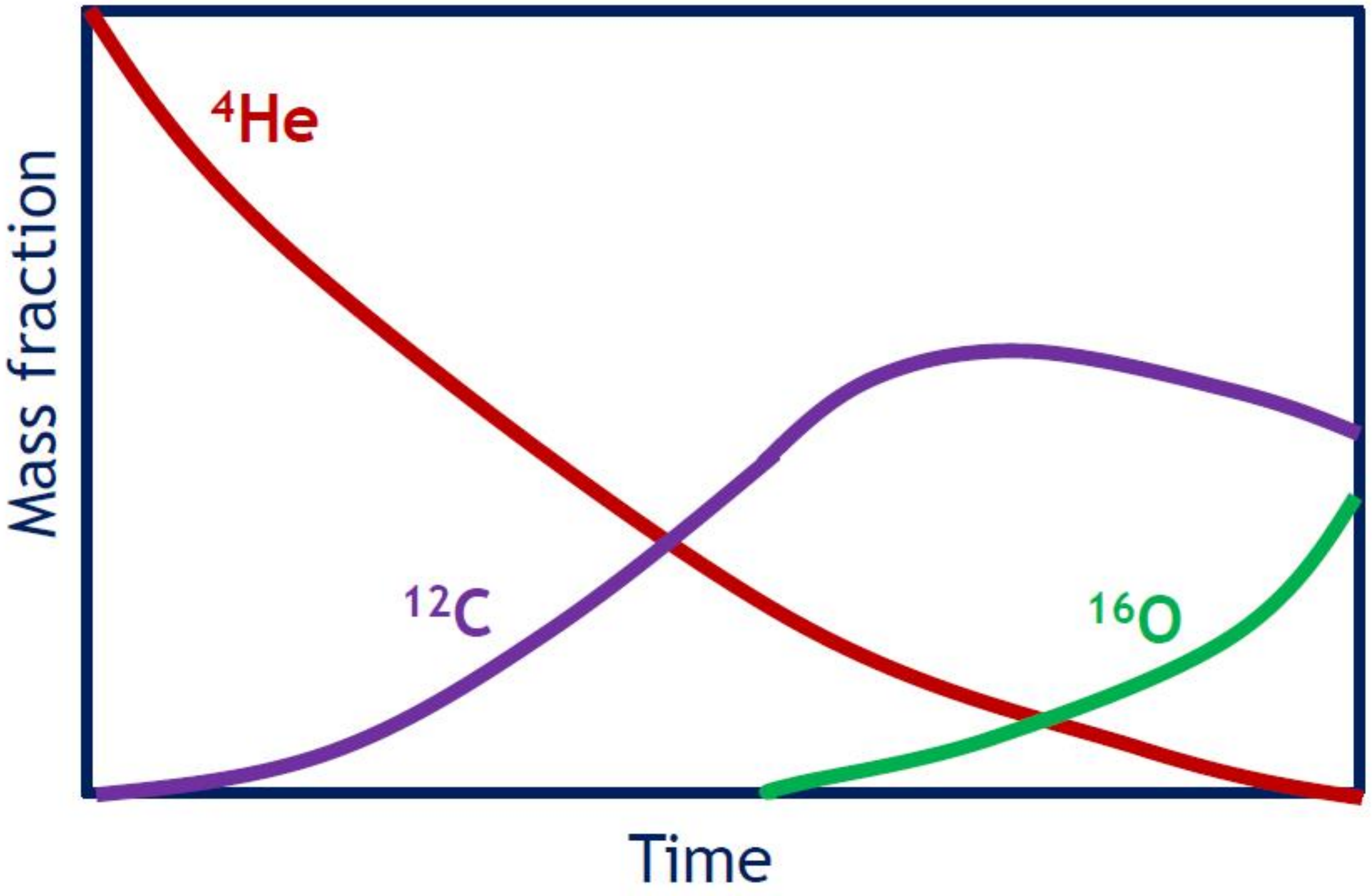
$$3\ ^{4}He \rightarrow {}^{12}C + \gamma$$

- But ^{4}He can also fuse with ^{12}C:

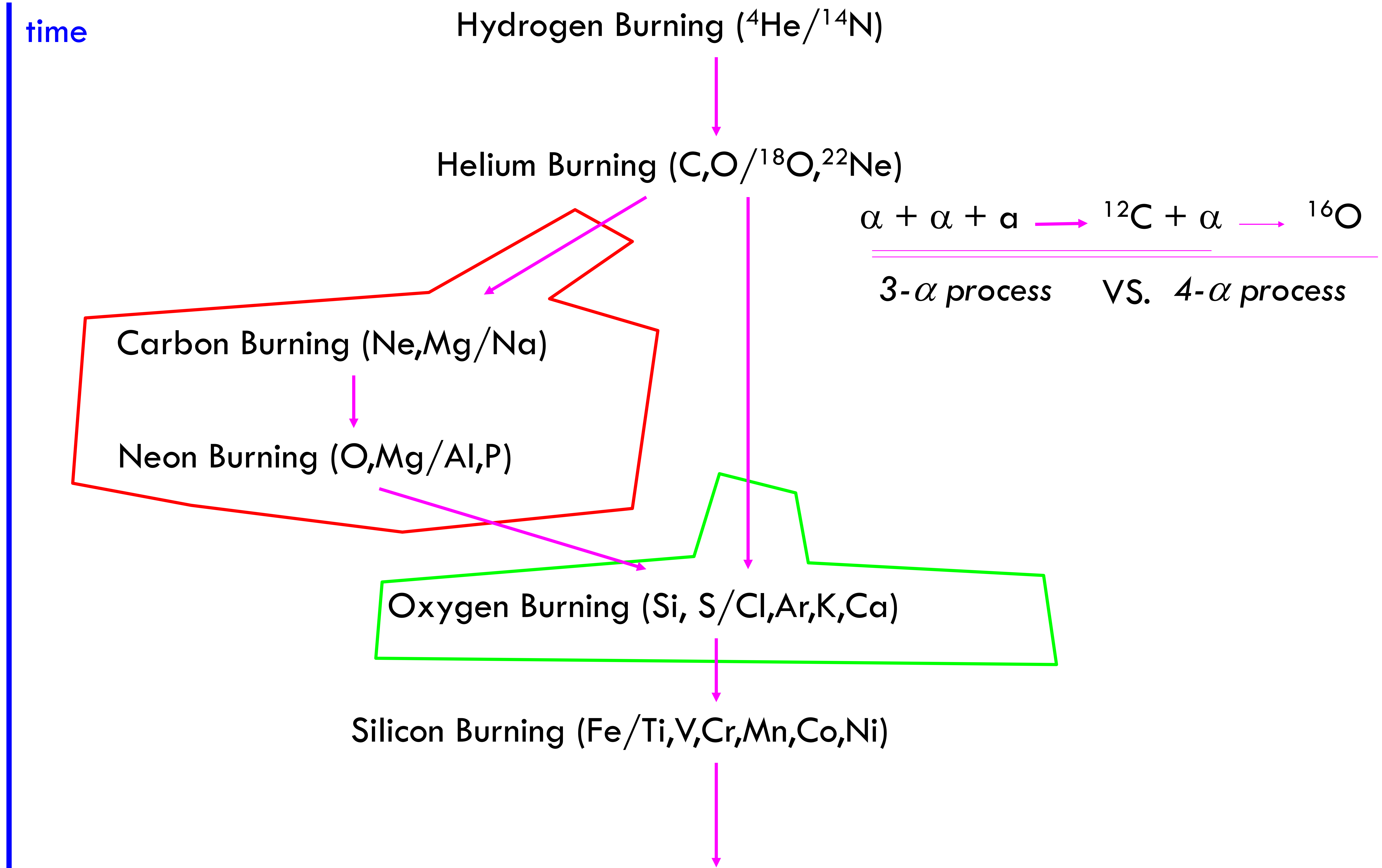
$$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma$$

- So **He decreases** and **C increases**..
- ..until **C decreases and O increases**…
- Final C/O depends on the rate of the $^{12}C + \alpha$ reaction.

AND density! (WHY)



Taken from Karakas's lecture



time

Hydrogen Burning (^{4}He/^{14}N)

Helium Burning (C,O/^{18}O,^{22}Ne)

$\alpha + \alpha + a \rightarrow {}^{12}C + \alpha \rightarrow {}^{16}O$

3-α process VS. *4-α process*

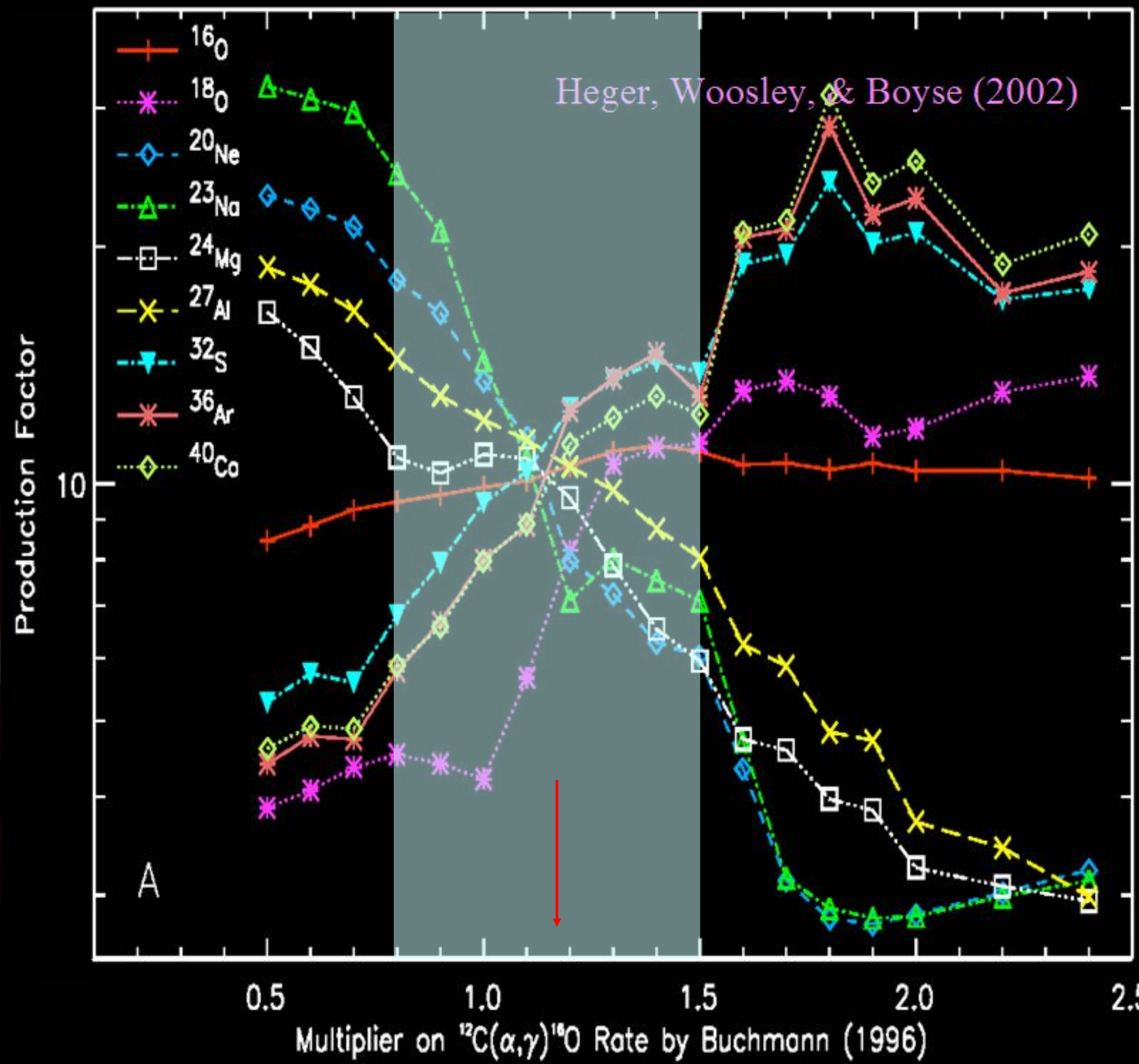
Carbon Burning (Ne,Mg/Na)

Neon Burning (O,Mg/Al,P)

Oxygen Burning (Si, S/Cl,Ar,K,Ca)

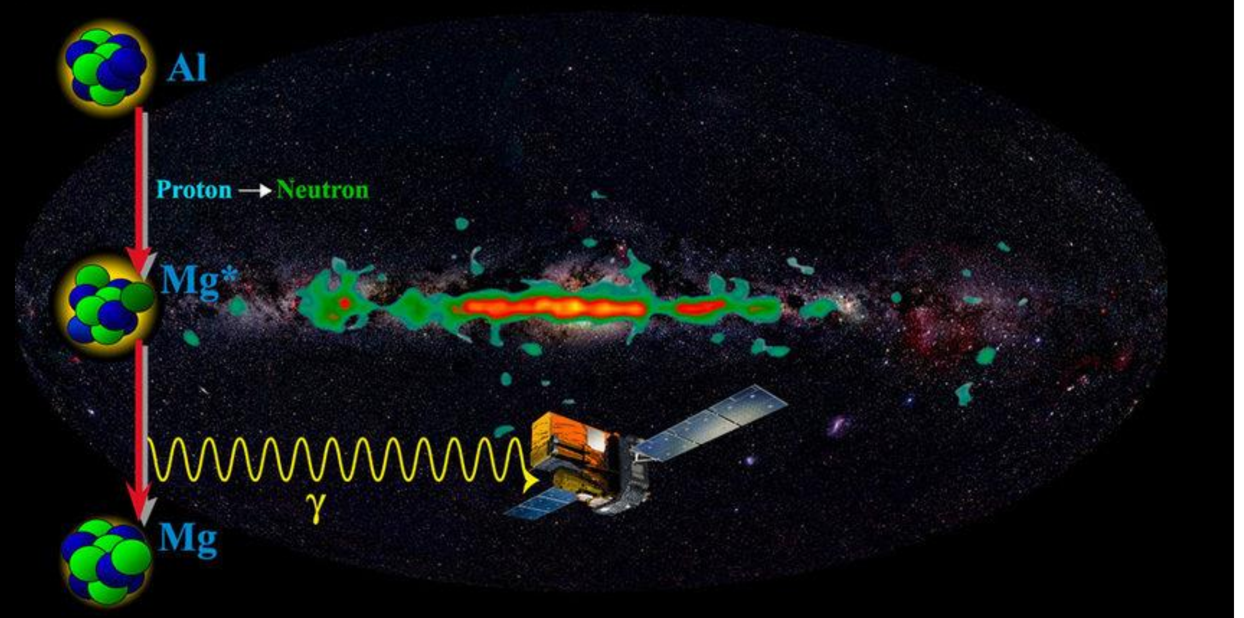
Silicon Burning (Fe/Ti,V,Cr,Mn,Co,Ni)

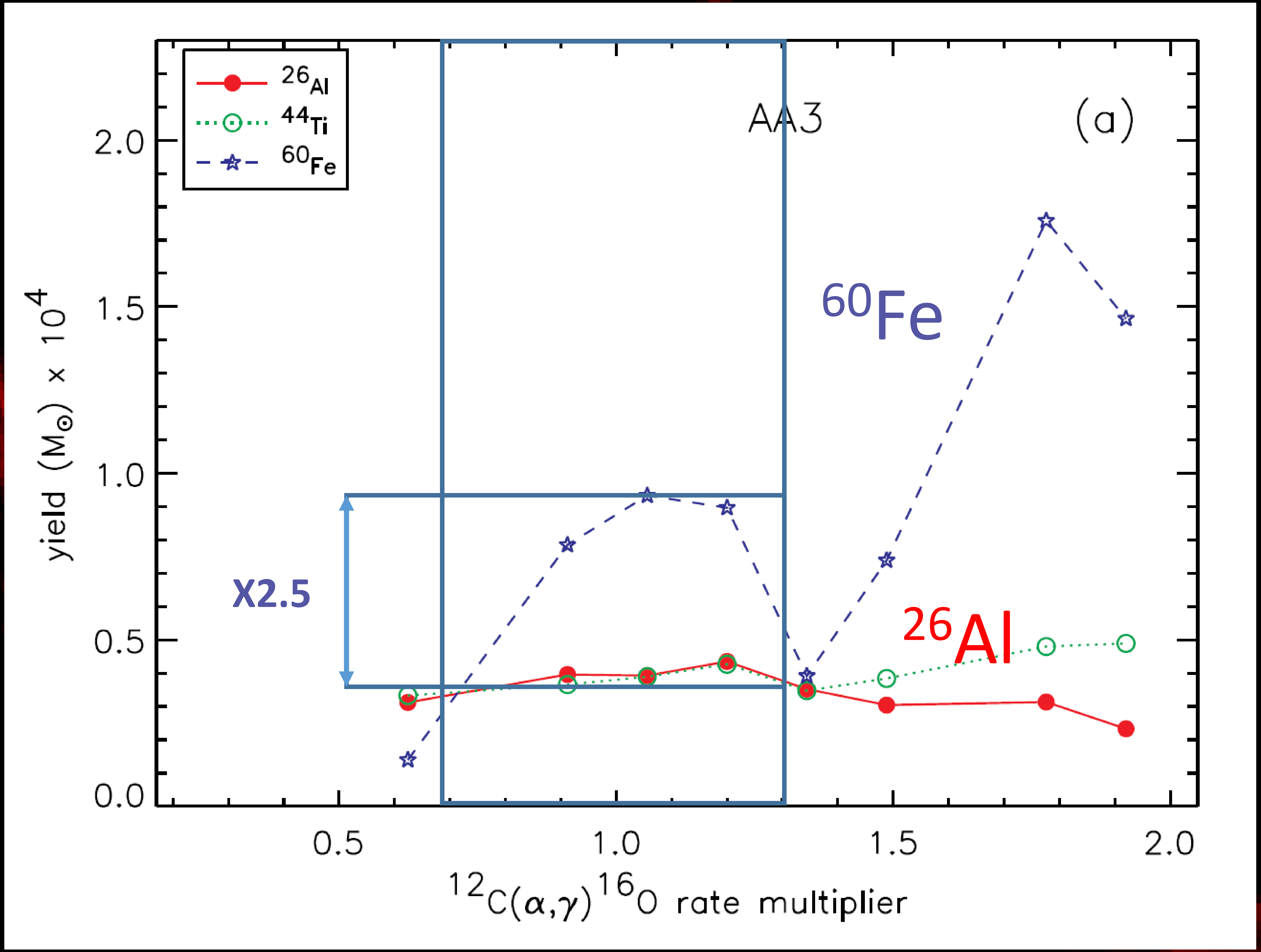
Impact on nucleosynthesis



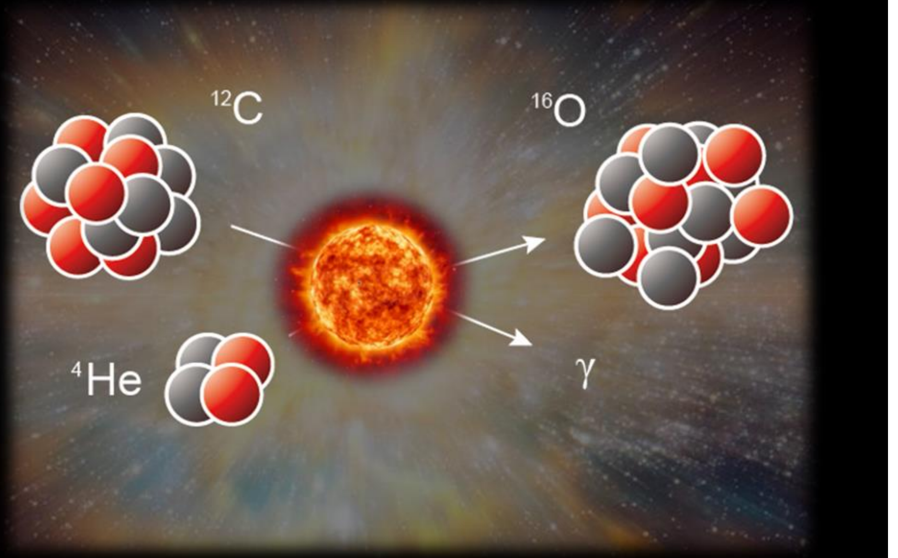
S(300)=170 keVb

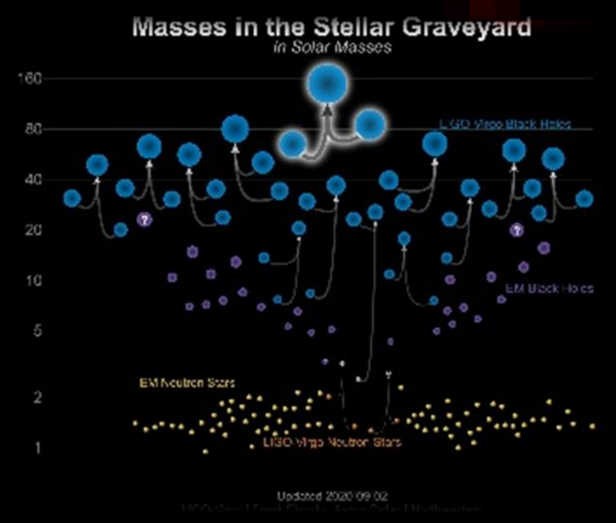
Impact on production of galactic radioactivity

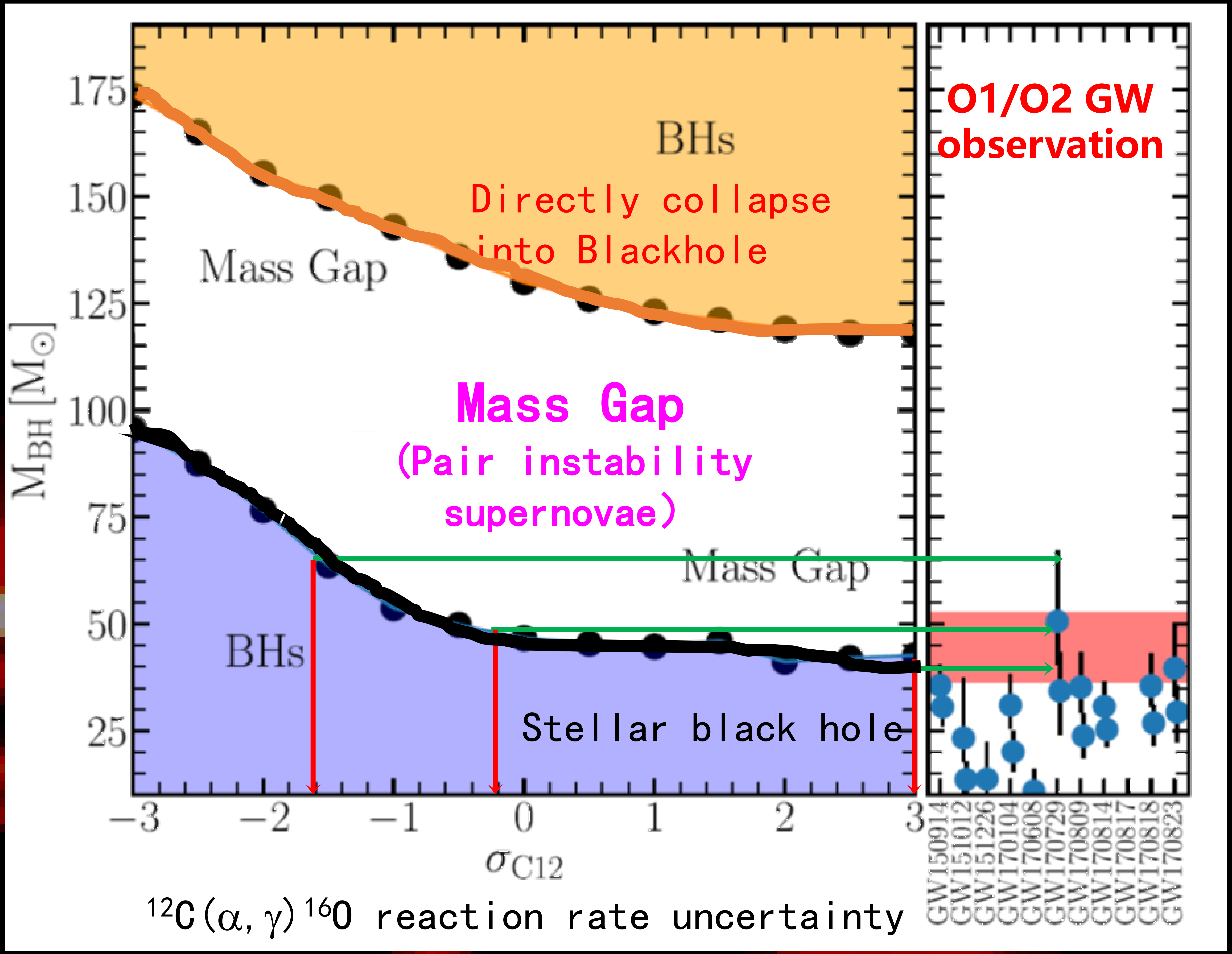




Uncertainty Limits Prediction on Mass Gap of Black holes

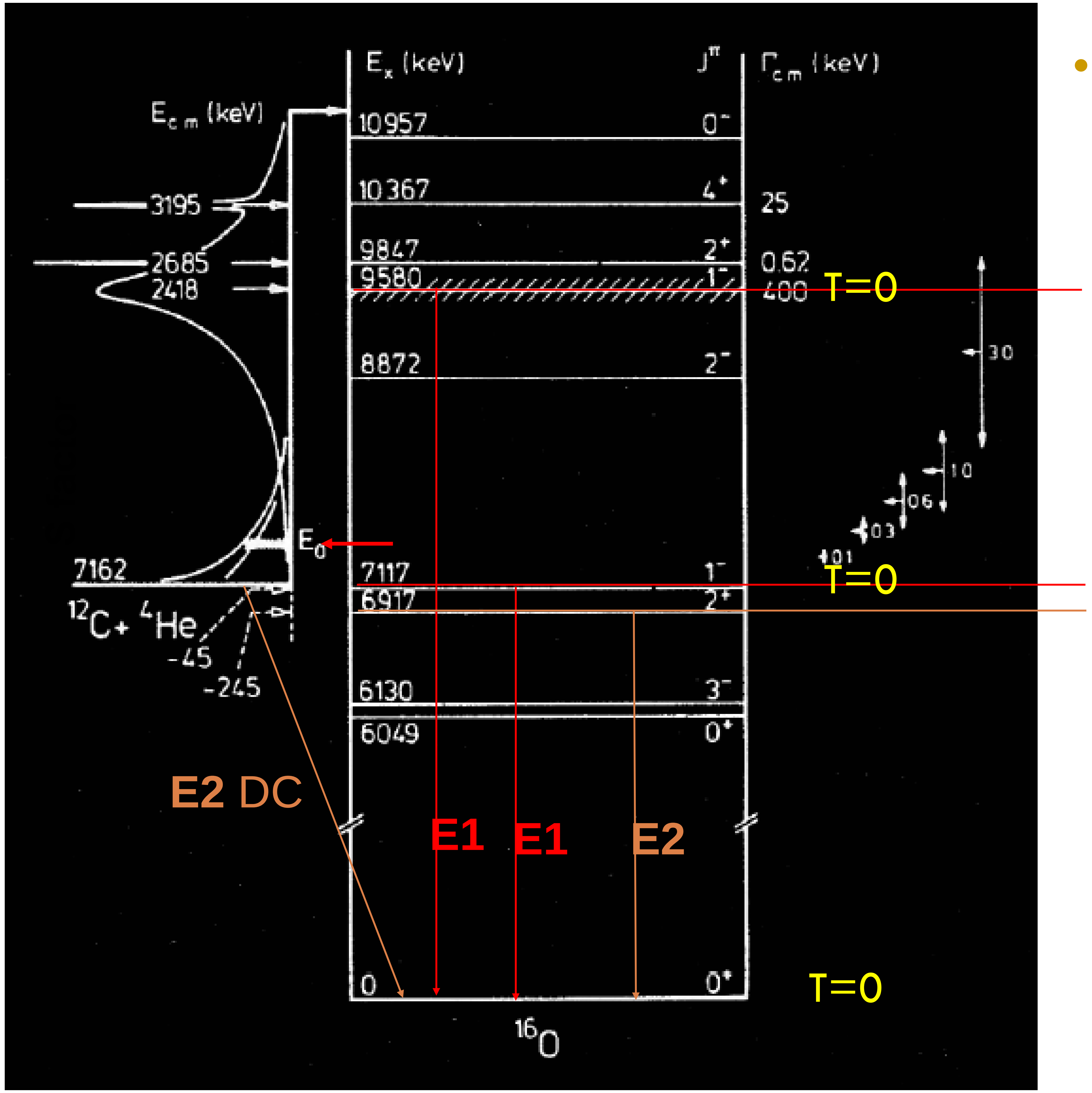






Farmer et al., ApJ 902:L36(2020)

Complicated reaction mechanism



- **3 resonances**

  1 direct capture

resonance
(high lying)

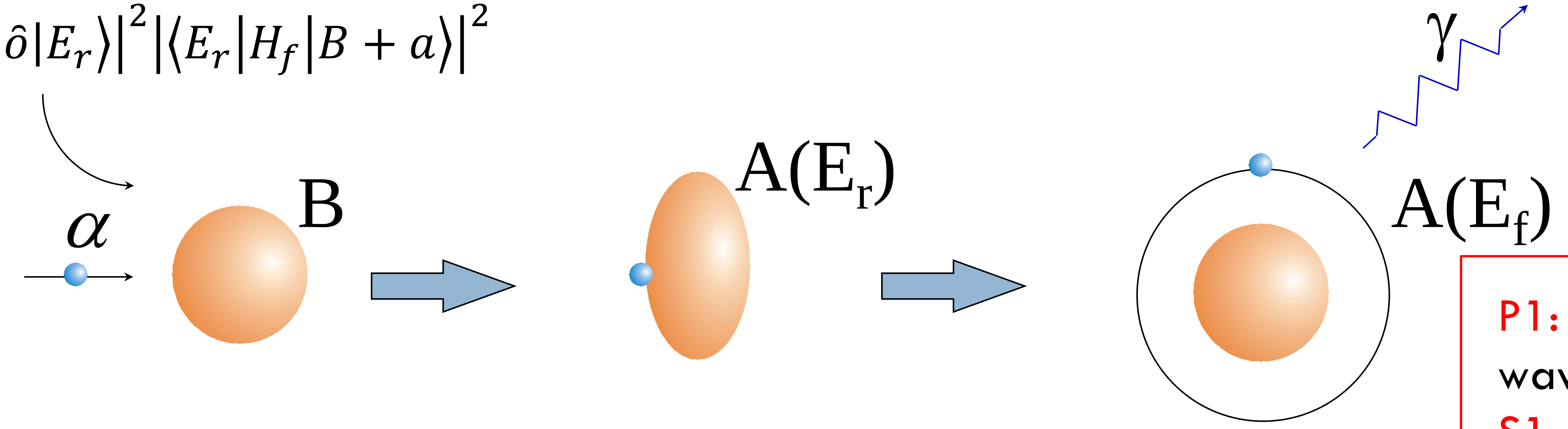
resonance
(sub threshold)

resonance
(sub threshold)

Isospin selection rules suppress the E1 component of the ground state cross section, creating a unique situation where the E1 and E2 contributions are of nearly equal amplitudes.

Resonant Radiative capture

$$\sigma_\gamma \propto \left|\langle E_f|\hat{o}|E_r\rangle\right|^2 \left|\langle E_r|H_f|B+a\rangle\right|^2$$



$$\sigma_{E1}(E) = \frac{6\pi}{k_\alpha^2} P_1 \left| \frac{\sum_{\lambda=1}^{q_1} \frac{\gamma_{\lambda 1}\Gamma_{\lambda\gamma}^{1/2}}{E_{\lambda 1}-E}}{1-(S_1-B_1+iP_1)R_1} \right|^2$$

P1: Penetration factor of p-wave

S1: Shift function of p-wave

B1: Boundary condition of p-wave

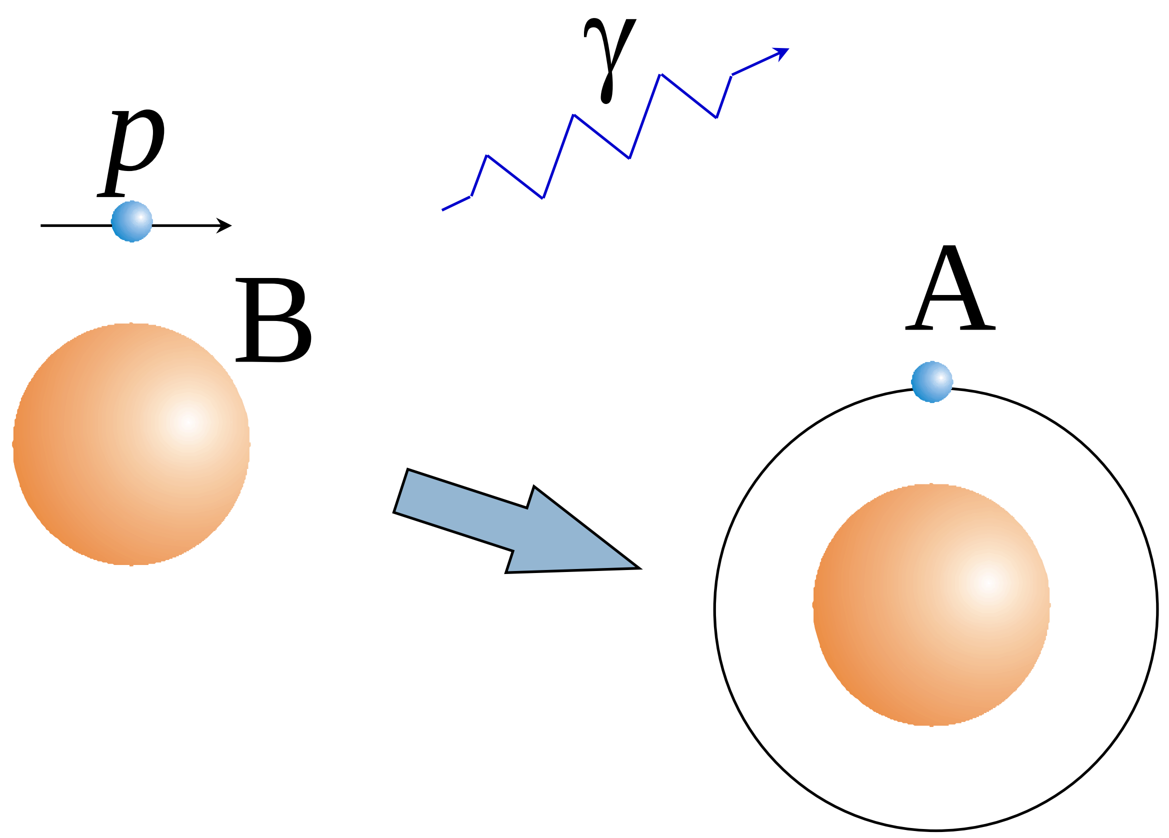
P1, S1 and B1 can be calculated with Coulomb wave function at channel radius (a)

$$R_\ell(E) = \sum_{\lambda=1}^{q_\ell} \frac{\gamma_{\lambda\ell}^2}{E_{\lambda\ell}-E}$$

For sub-threshold states:

- Γ_γ **is measured by gamma spectroscopy**
- **Particle width** $\gamma_\alpha^2 = \frac{\hbar^2 R_c}{2\mu} S_\alpha \phi(R_c)^2 = \frac{\hbar^2}{2\mu R_c} \tilde{C}^2 \tilde{W}(R_c)^2,$ Asymptotic Normalization Coefficient (ANC)

Direct Radiative proton capture



$\sigma_\gamma \propto |\langle A|\hat{o}|B+p\rangle|^2$

$$\sigma \propto |M|^2 \qquad [S(E) = Ee^{2\pi\eta}\sigma]$$

M is: $$M = \left\langle \phi_A(\xi_B, \xi_p, \xi_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \phi_B(\xi_B)\phi_p(\xi_p)\psi_i^{(+)}(r_{Bp}) \right\rangle$$

Integrate over ξ: $$M = \left\langle I_{Bp}^{A}(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

Initial scattering state:
Hard spere wave function

Low B.E.: $$I_{Bp}^{A}(r_{Bp}) \overset{r_B > R_N}{\approx} C_{Bp}^{A} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

Find: $$\sigma_{capture} \propto (C_{Bp}^{A})^2$$

Asymptotic Normalization
Coefficient (ANC)

R-Matrix with Asymptotic Normalization Coefficient

$$\sigma \propto \left| M_{DC} \pm i e^{-i\phi} \frac{\Gamma_p^{1/2}\Gamma_\gamma^{1/2}}{(E-E_R)+i\Gamma/2} \right|^2$$

$$M_{DC} \propto C_{lj} \qquad \Gamma_p \propto \left(C_{lj}\right)^2$$

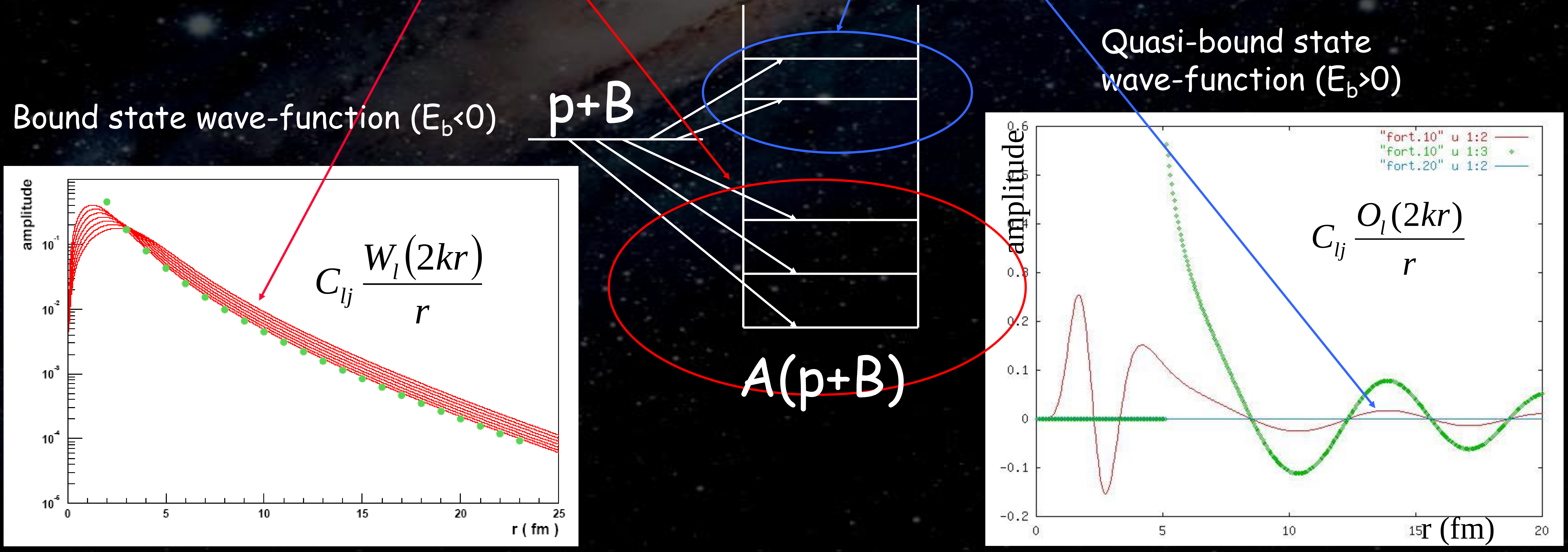
???

Nucleus interior

For narrow resonance:

$\Gamma_p << \Gamma_\gamma$, $\omega\gamma = \omega\Gamma_p$

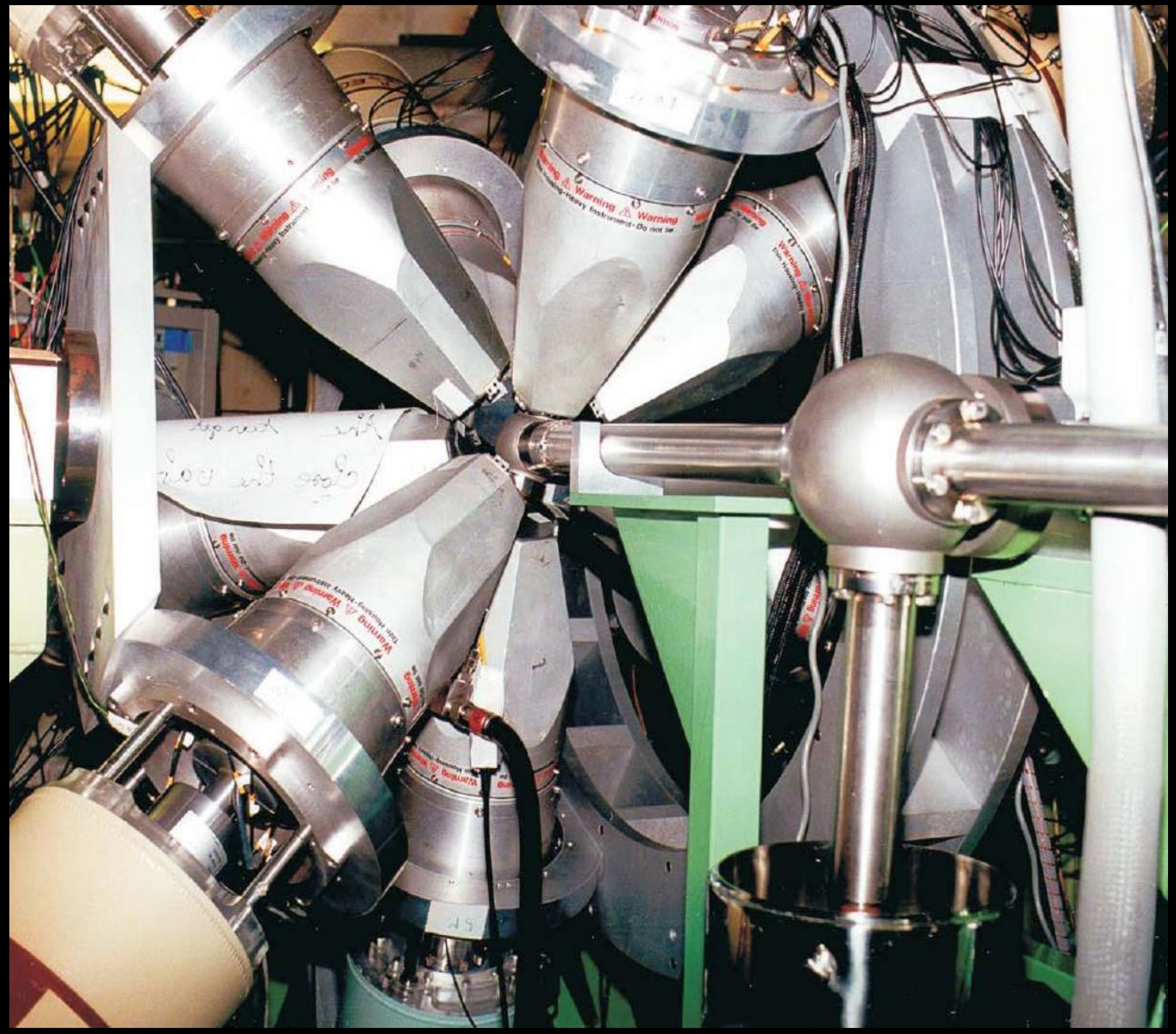
$\Gamma_\gamma << \Gamma_p$, $\omega\gamma = \omega\Gamma_\gamma$



Bound state wave-function ($E_b<0$)

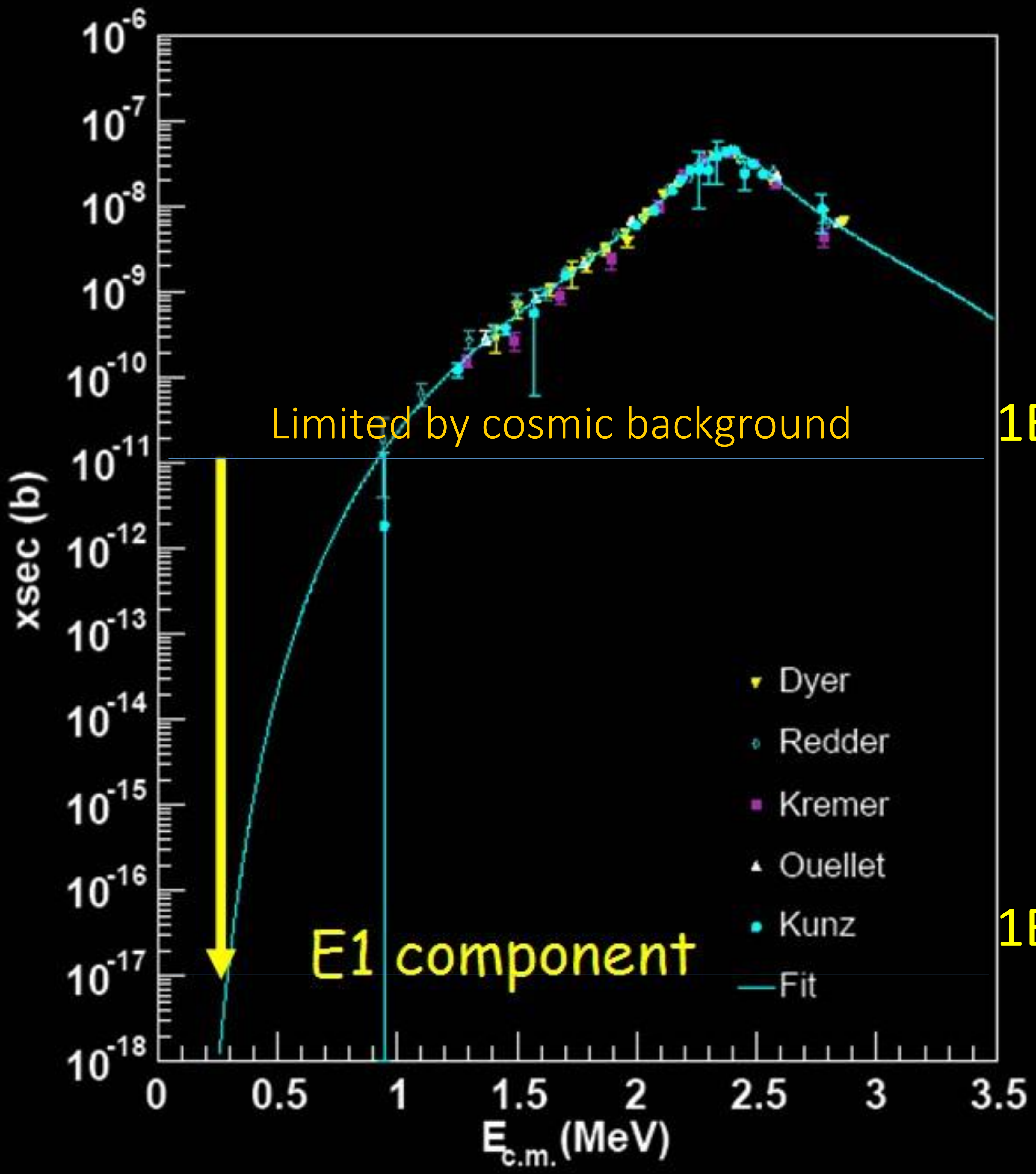
Quasi-bound state wave-function ($E_b>0$)

Direct measurement of $^{12}C(\alpha,\gamma)^{16}O$(1974-)



Setup at University of Stuggart

From Dr. Hammer



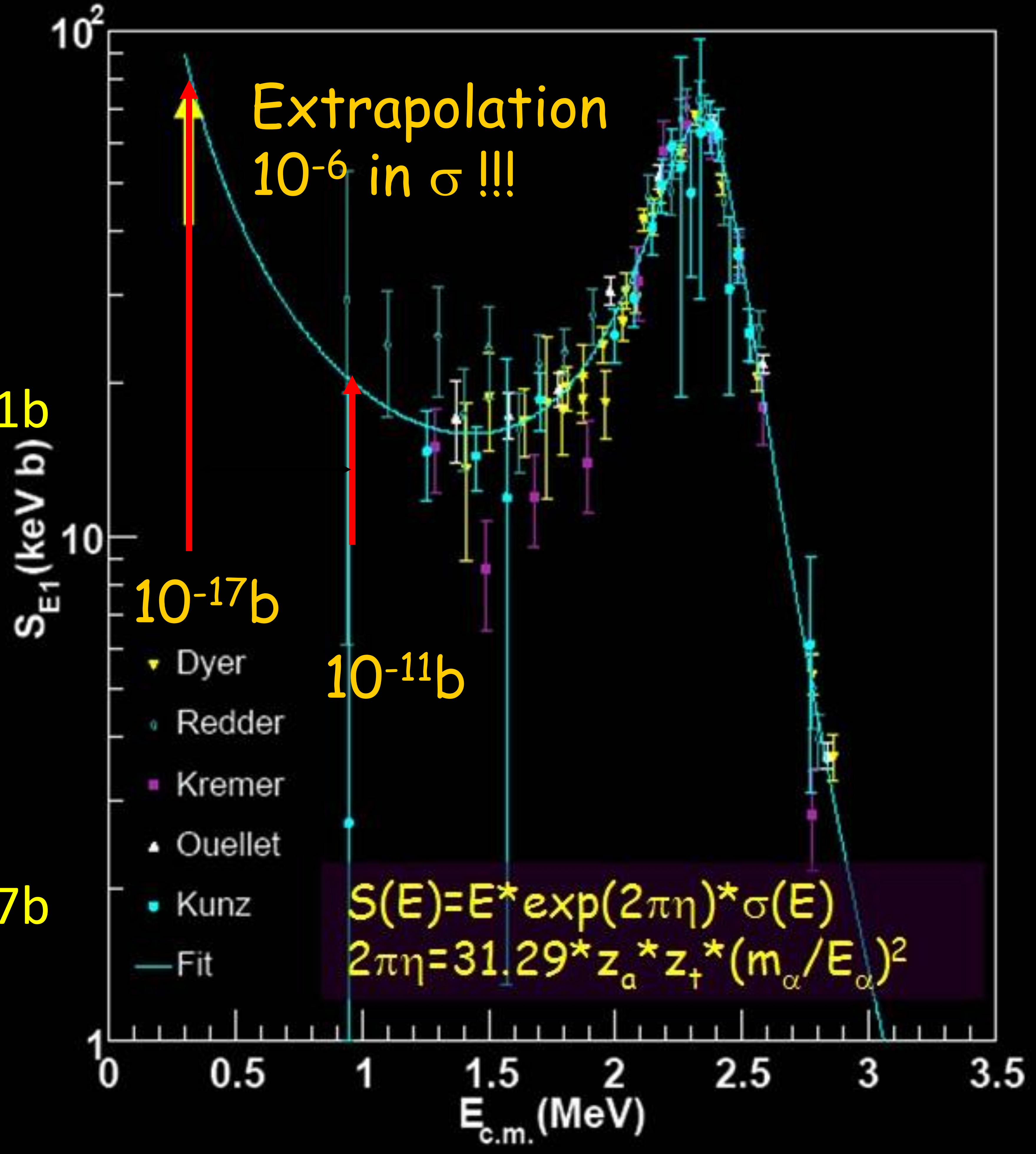
Limited by cosmic background

1E-11b

E1 component

1E-17b

1 barn=10^{-24} cm^2

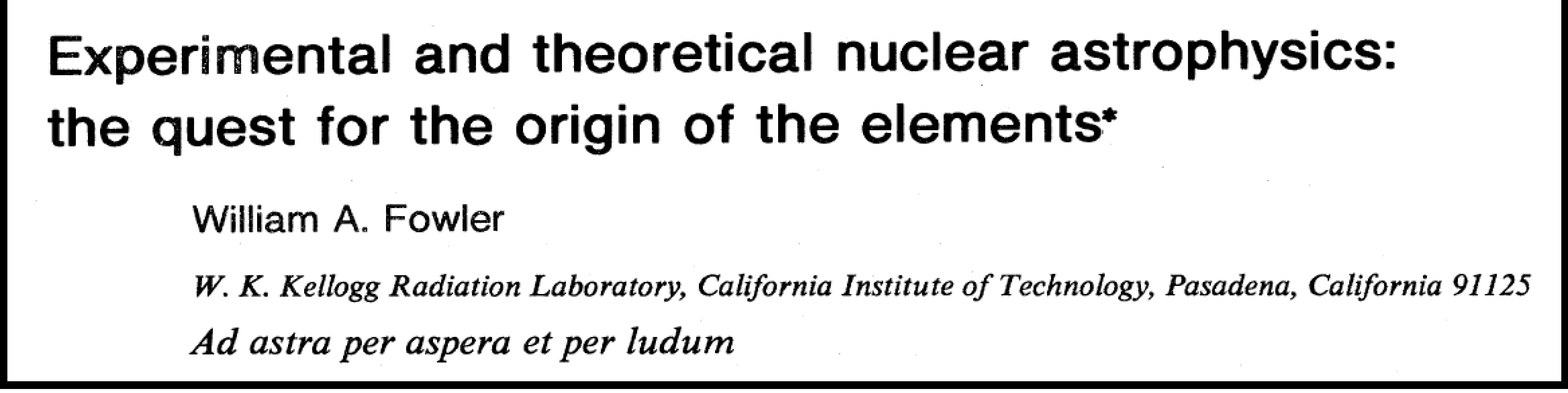


Extrapolation
10^{-6} in σ !!!

10^{-17}b

10^{-11}b

$S(E)=E*\exp(2\pi\eta)*\sigma(E)$
$2\pi\eta=31.29*z_a*z_t*(m_\alpha/E_\alpha)^2$



Experimental and theoretical nuclear astrophysics: the quest for the origin of the elements*

William A. Fowler

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

Ad astra per aspera et per ludum

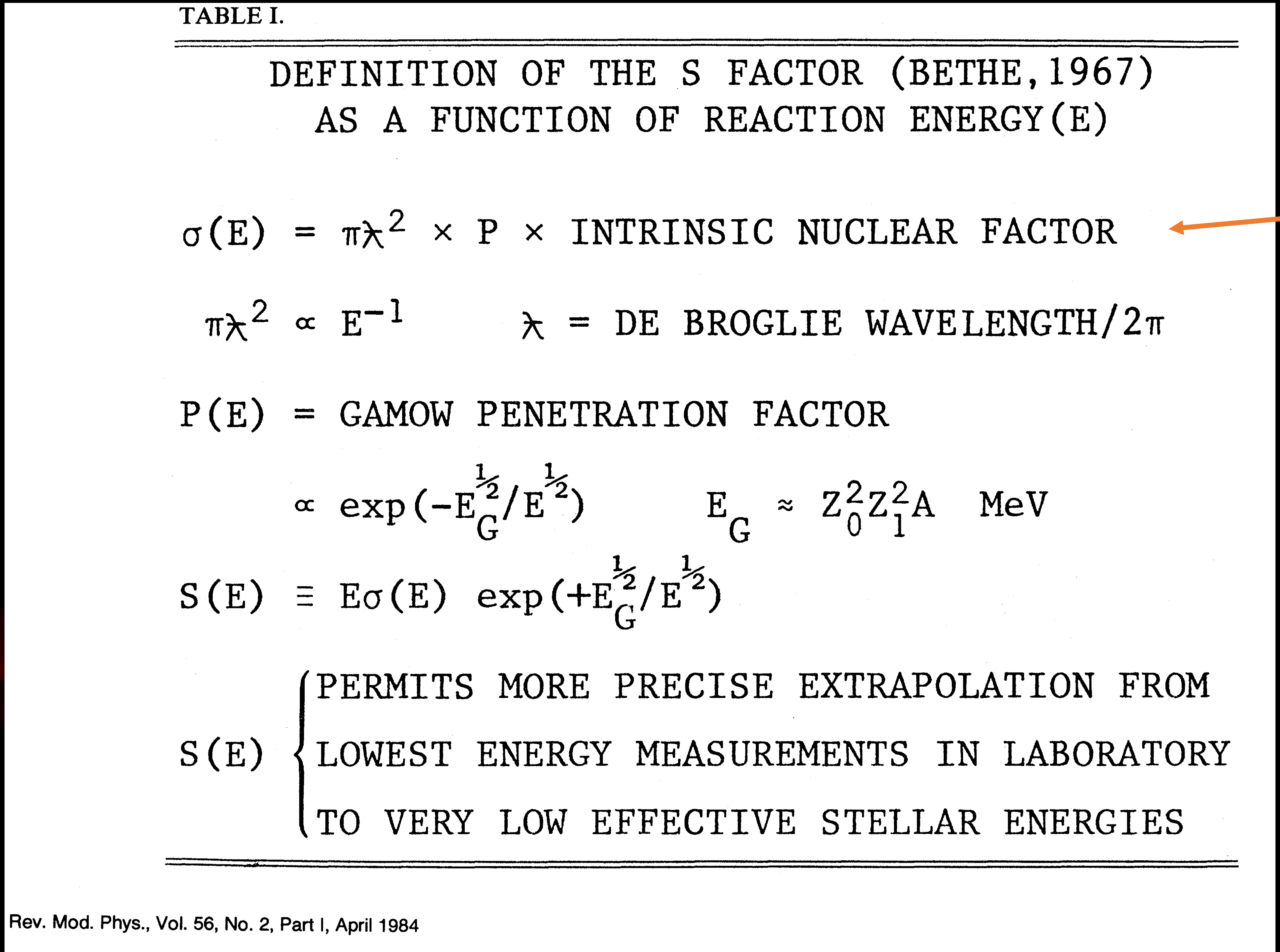


TABLE I.

DEFINITION OF THE S FACTOR (BETHE, 1967)
AS A FUNCTION OF REACTION ENERGY (E)

$$\sigma(E) = \pi\lambdabar^2 \times P \times \text{INTRINSIC NUCLEAR FACTOR}$$

$\pi\lambdabar^2 \propto E^{-1}$ $\lambdabar$ = DE BROGLIE WAVELENGTH/2π

P(E) = GAMOW PENETRATION FACTOR

$\propto \exp(-E_G^{1/2}/E^{1/2})$ $E_G \approx Z_0^2 Z_1^2 A$ MeV

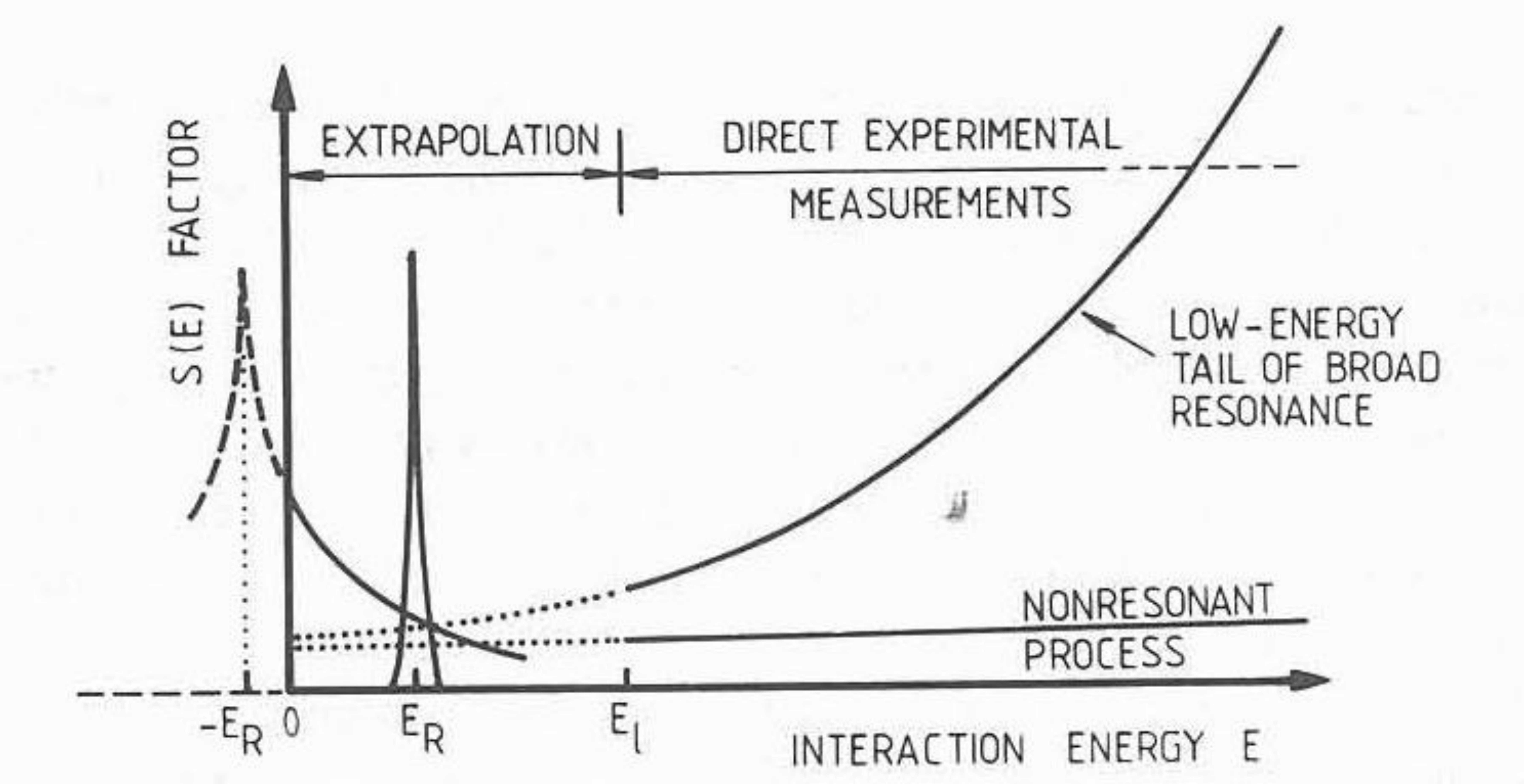
$$S(E) \equiv E\sigma(E)\ \exp(+E_G^{1/2}/E^{1/2})$$

S(E) { PERMITS MORE PRECISE EXTRAPOLATION FROM
LOWEST ENERGY MEASUREMENTS IN LABORATORY
TO VERY LOW EFFECTIVE STELLAR ENERGIES

Rev. Mod. Phys., Vol. 56, No. 2, Part I, April 1984

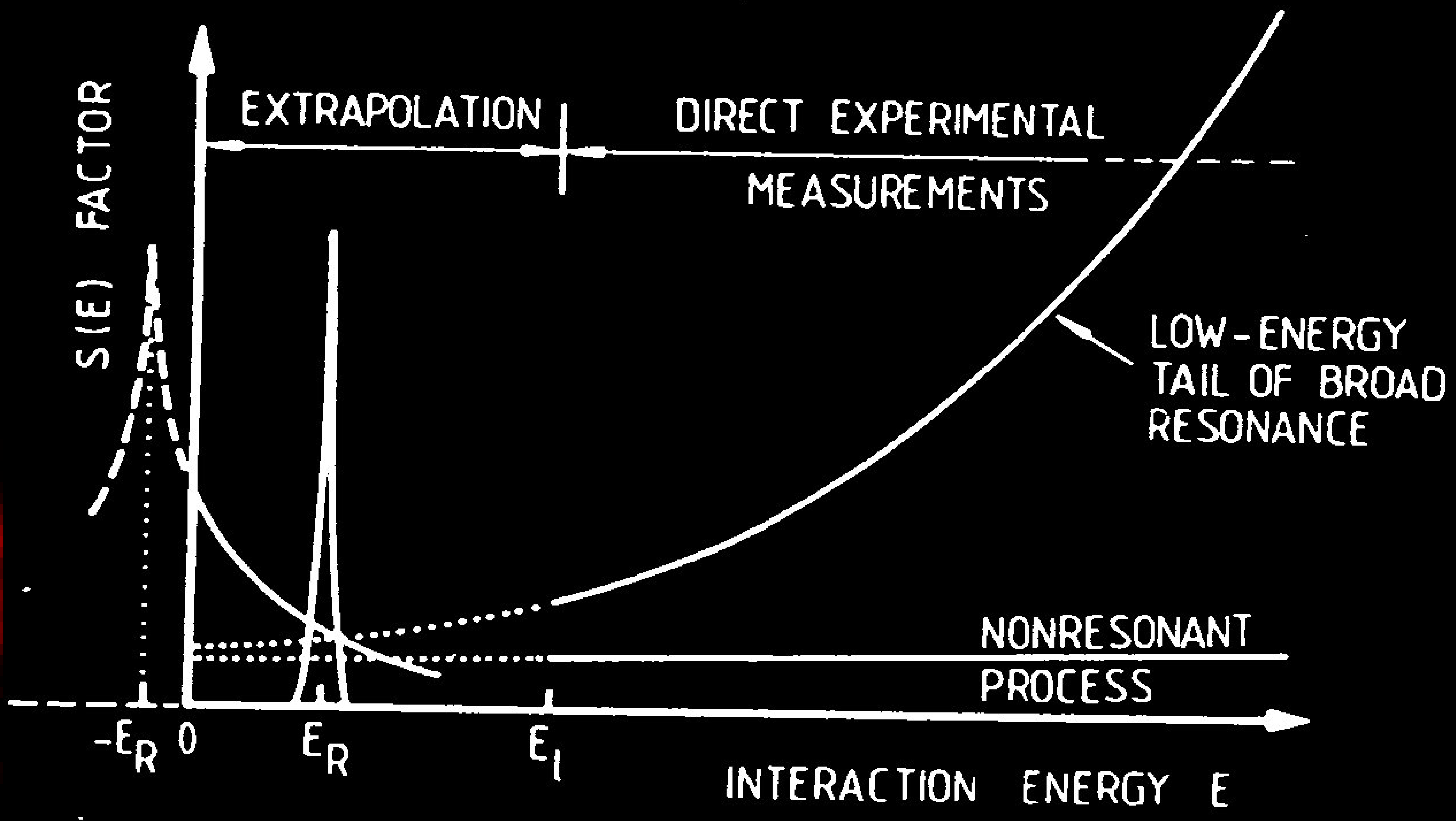
s-wave !

Challenging extrapolation



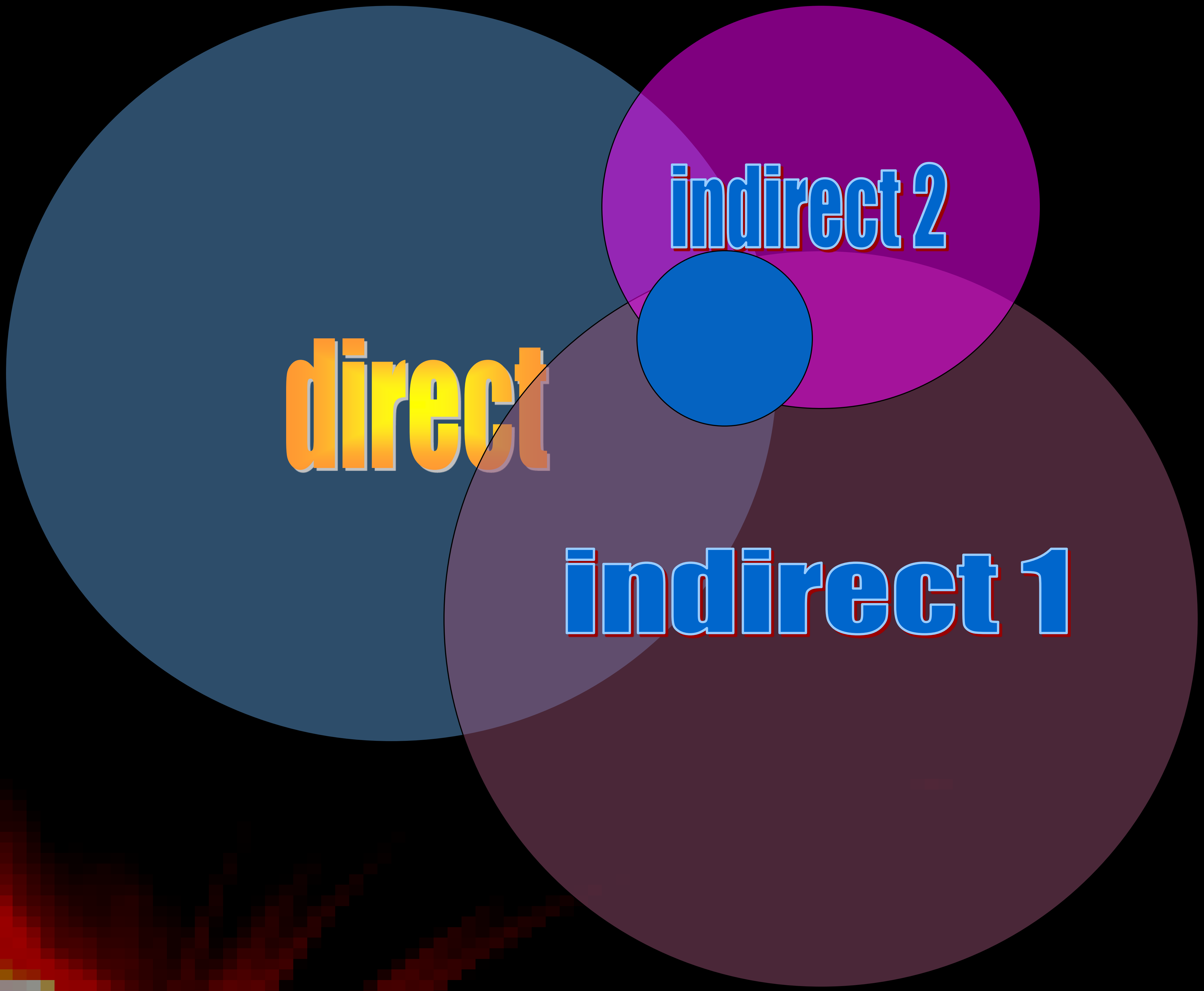
Rolfs and Rodney, Cauldrons in the cosmos, (1988)

Approaching the stellar energies



- Better experimental technologies, lower energies
- Hard to reach stellar energy regions, especially for RNB
- Extrapolation is inevitable for most cases

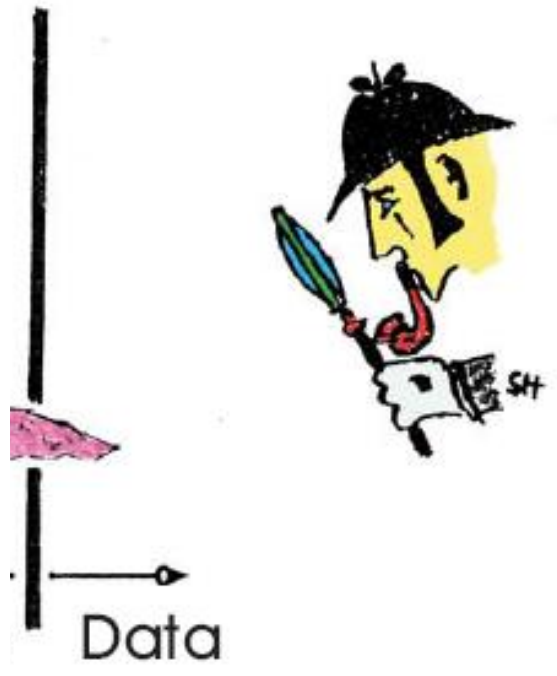
Direct + Indirect

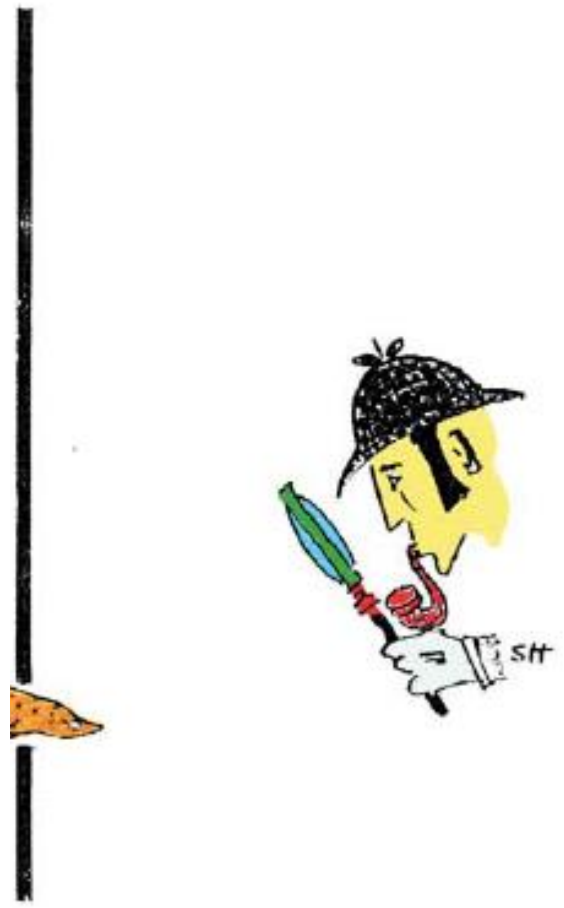


Reduce the overall uncertainty by combining various approaches, with assurance that systematic uncertainties are independent.

The case of subthreshold resonances:

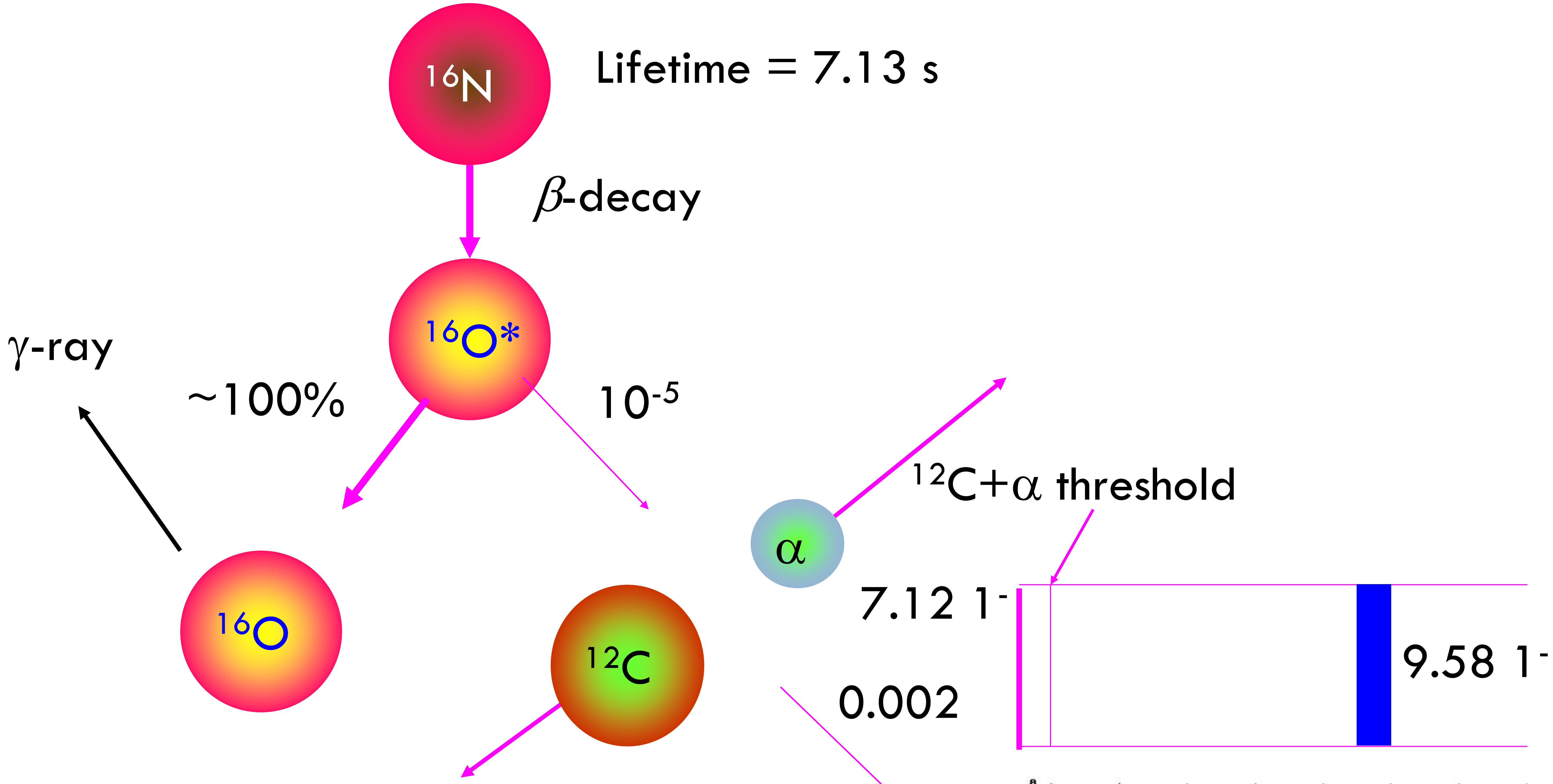
detective
work





By C. Rolf

^{16}N β-delayed α decay



^{16}N

Lifetime = 7.13 s

β-decay

^{16}O*

γ-ray

~100%

10^{-5}

^{16}O

^{12}C

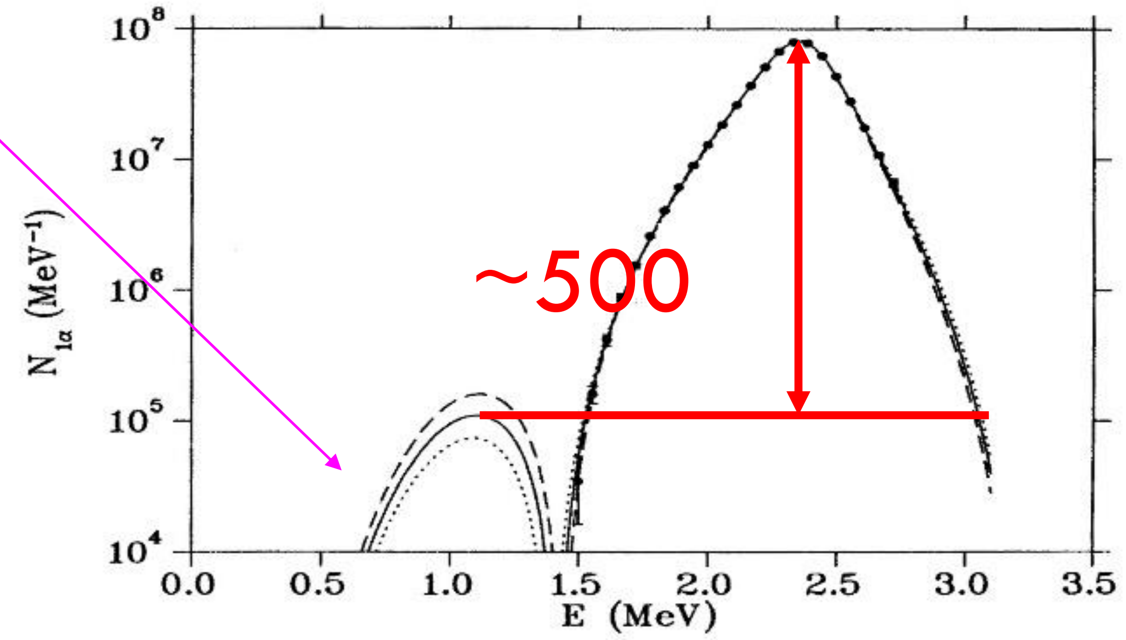
α

^{12}C+α threshold

7.12 1^-

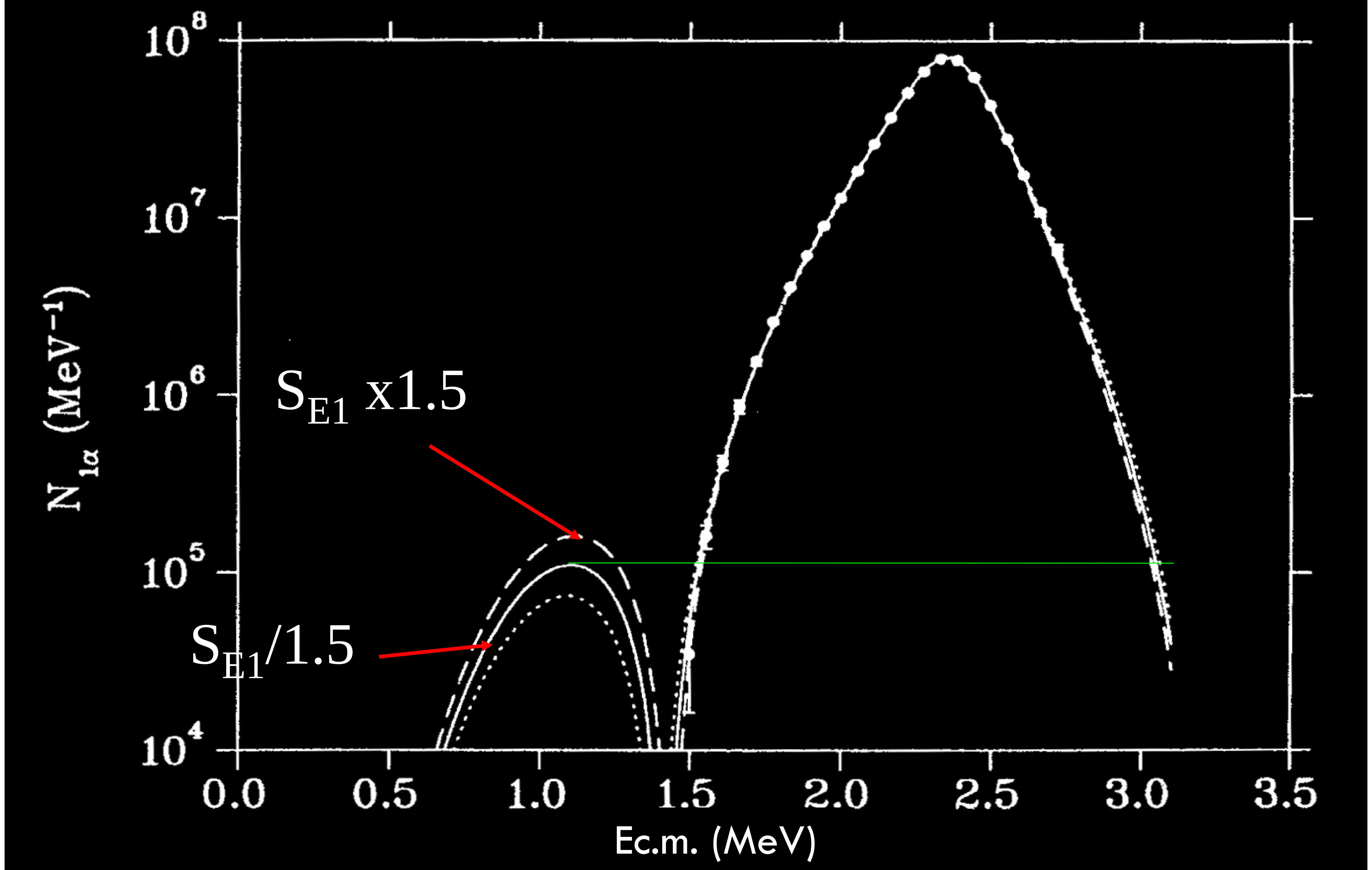
9.58 1^-

0.002

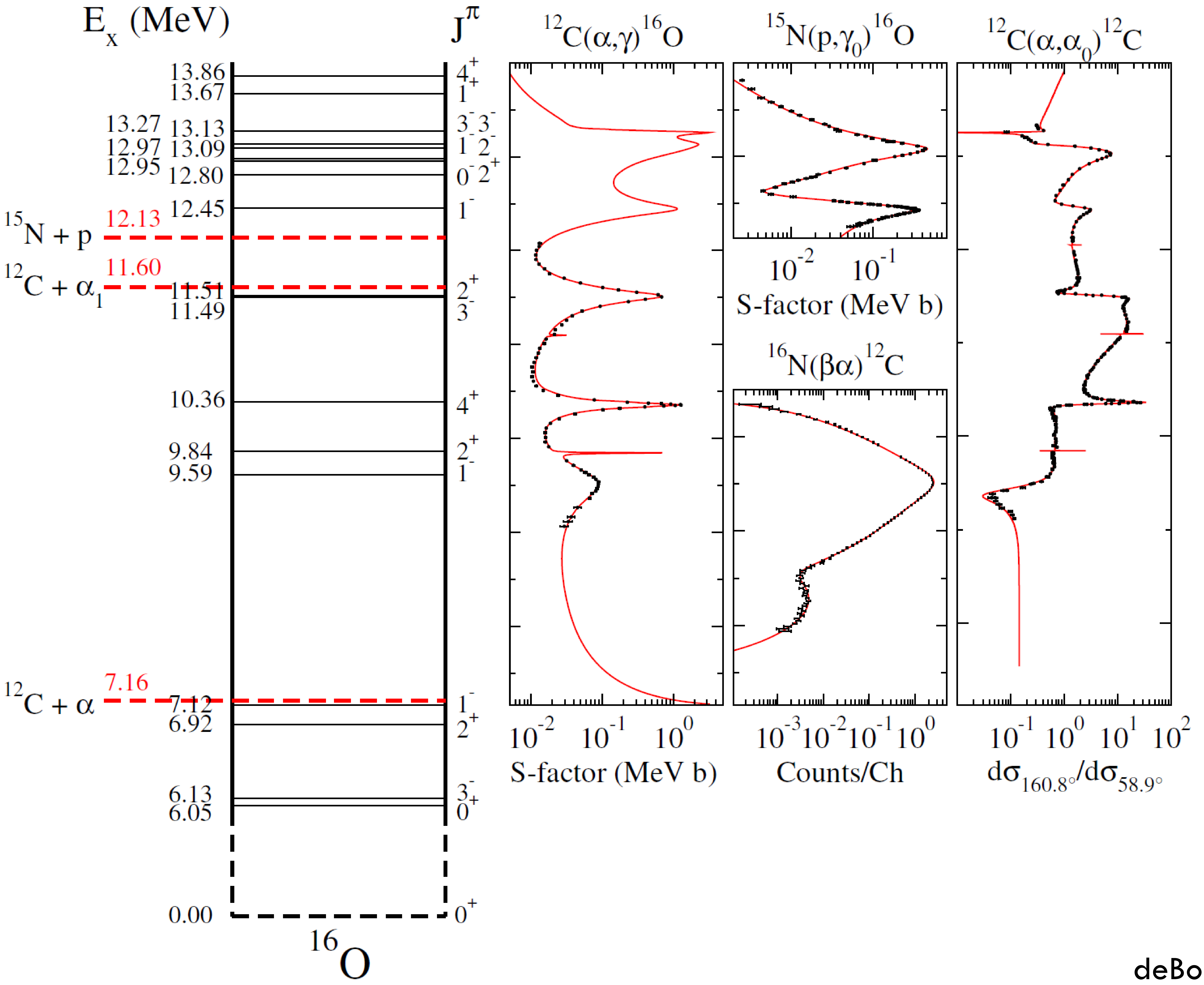


Baye & Descouvemont predicted the interference peak in 1988 !!!
NPA458(1988)445

Interference between the allowed and subthreshold 1^- states in the ^{16}N β delayed α decay. [$^{16}N(\beta^-)^{16}O \rightarrow {}^{12}C + \alpha$]



J. Humblet et al., Phys. Rev. C44, 2530(1991)

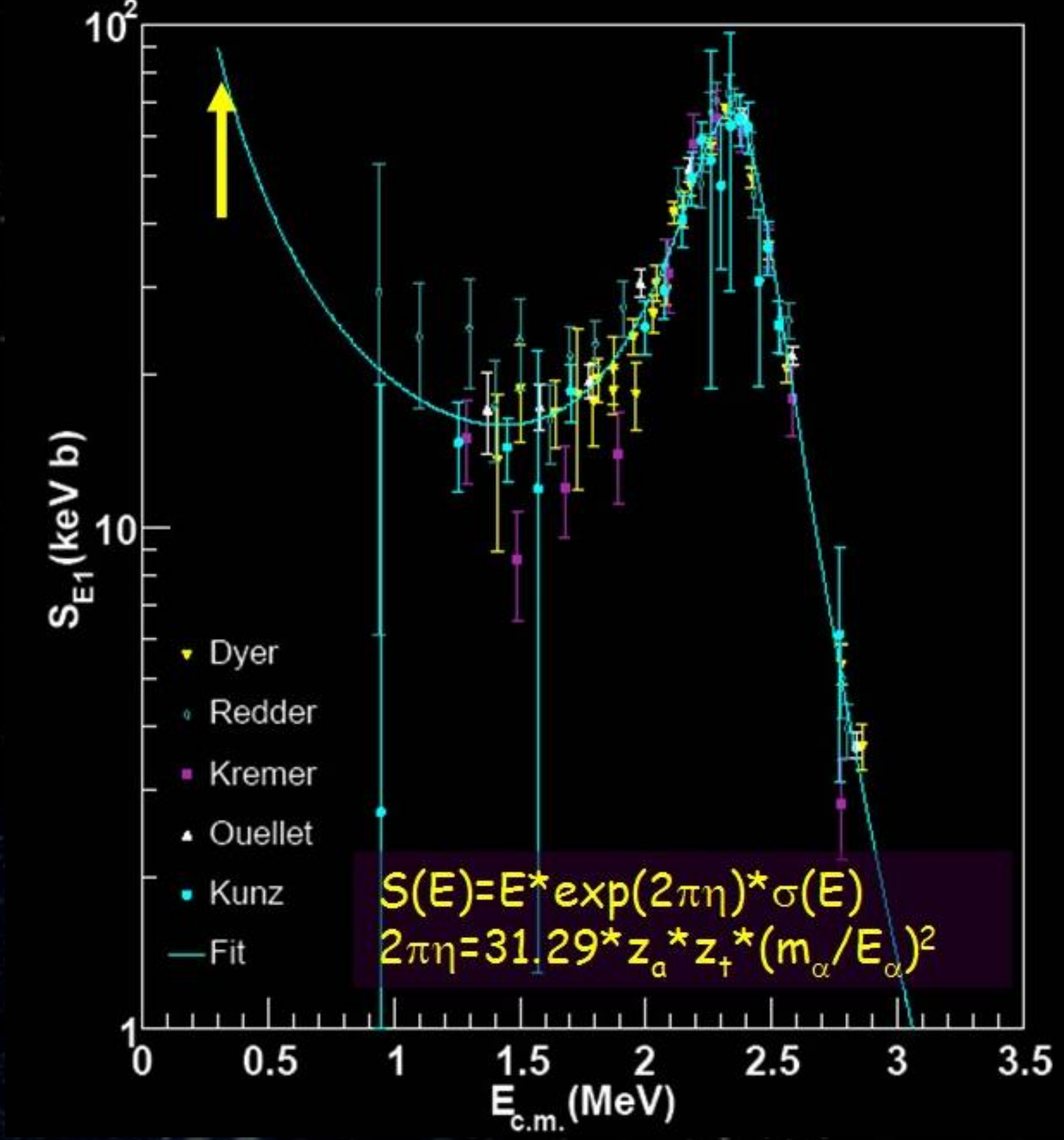


deBoer et al., RMP(2017)

Subthreshold resonance:

From $^{12}C(^{6}Li,d)^{16}O$ to $^{12}C(\alpha,\gamma)^{16}O$

$$C_i^2 = \frac{2\mu a}{\hbar^2 W^2(a)} \left(\frac{\gamma_i^2}{1 + \gamma_i^2 \frac{dS}{dE}} \right),$$



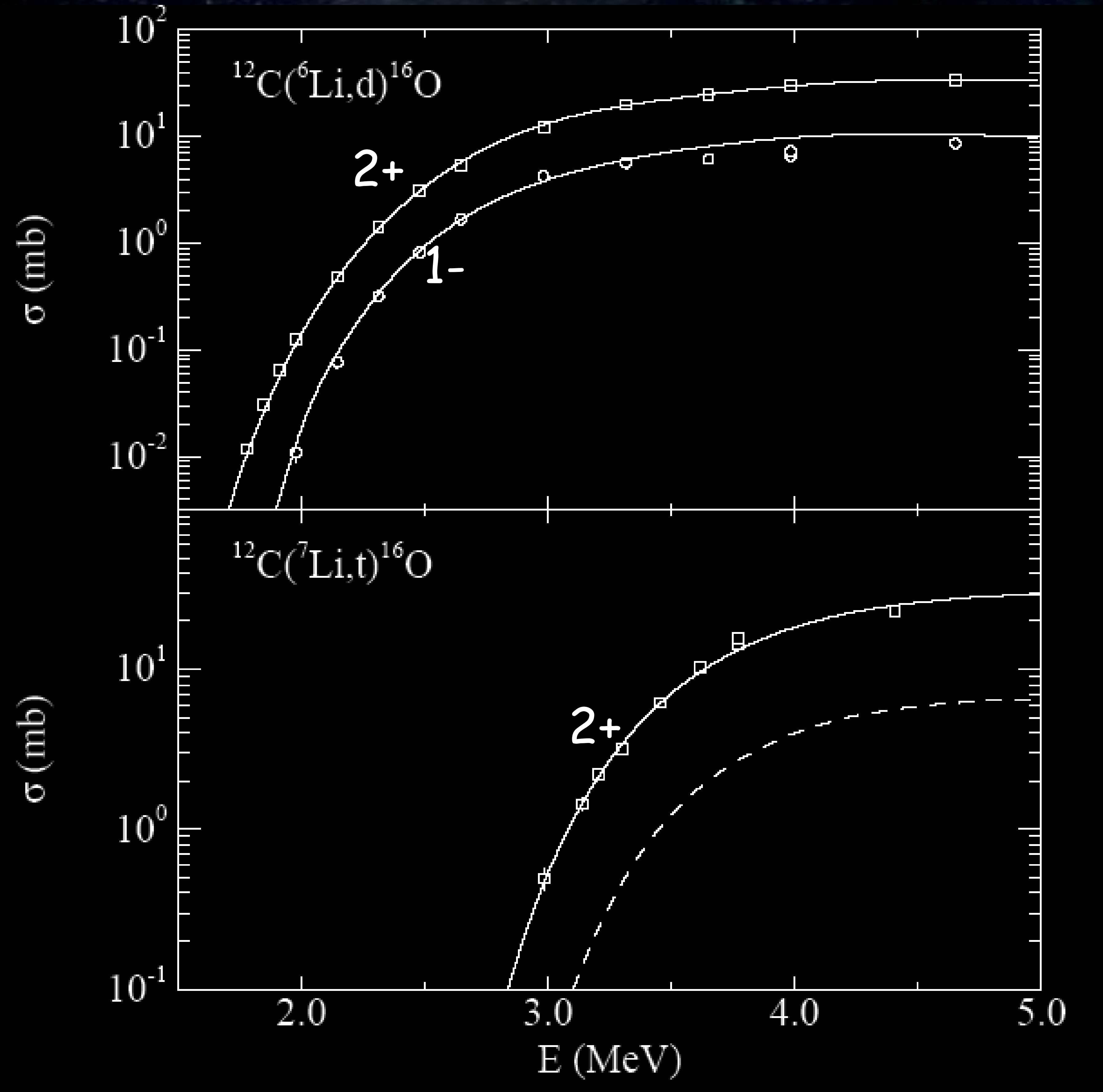
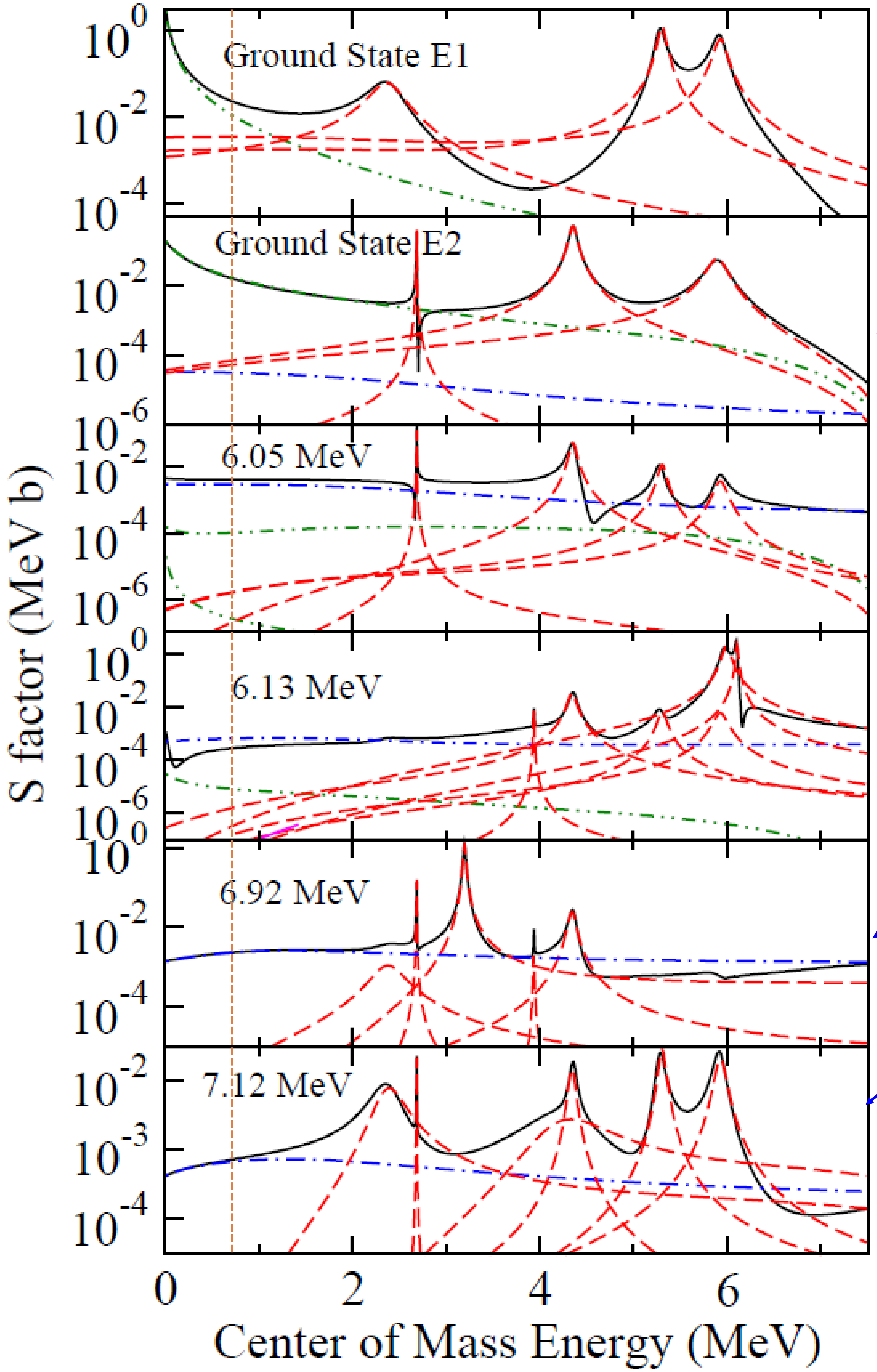


FIG. 2. Total cross sections measured using ^{6}Li (upper panel) and ^{7}Li (lower panel) beams for the 6.92-MeV 2^+ state of ^{16}O (□) and the 7.12-MeV 1^- state (○, ^{6}Li beam only). The solid curves are DWBA calculations normalized to the data; the dashed curve is described in the text.

C. R. Brune *et al.*, Phys. Rev. Lett. **83**, 4025 (1999).



Critical alpha widths (or ANCs) below the thresholds

J^π	E_x (MeV)	Γ_α (keV) / ANC ($\mathrm{fm}^{-1/2}$)	$\Gamma_{\gamma 0}$ (meV)
0^+	0	58	
0^+	6.05	1560	
2^+	6.92	1.14×10^5	97
1^-	7.12	2.08×10^{14}	55
1^-	9.586	382	-15
2^+	11.5055	83	-490

- 6.05 MeV, 6.13 MeV, 6.92 MeV, 7.12 MeV:

Sub-barrier transfer reaction: (6Li,d), (7Li,t) [Brune 1999, Avila 2015]

- 7.12 MeV:

^{16}N beta delayed alpha decay: [Azuma 1994, Zhao 1993, Tang2010]

- Ground state:

Above-barrier transfer reaction: (11B,7Li) [Y.P. Shen 2021]

Red dashed lines: individual resonance contributions

blue dashed-dot lines: direct capture

Green dashed-dot-dot lines: subthreshold contributions

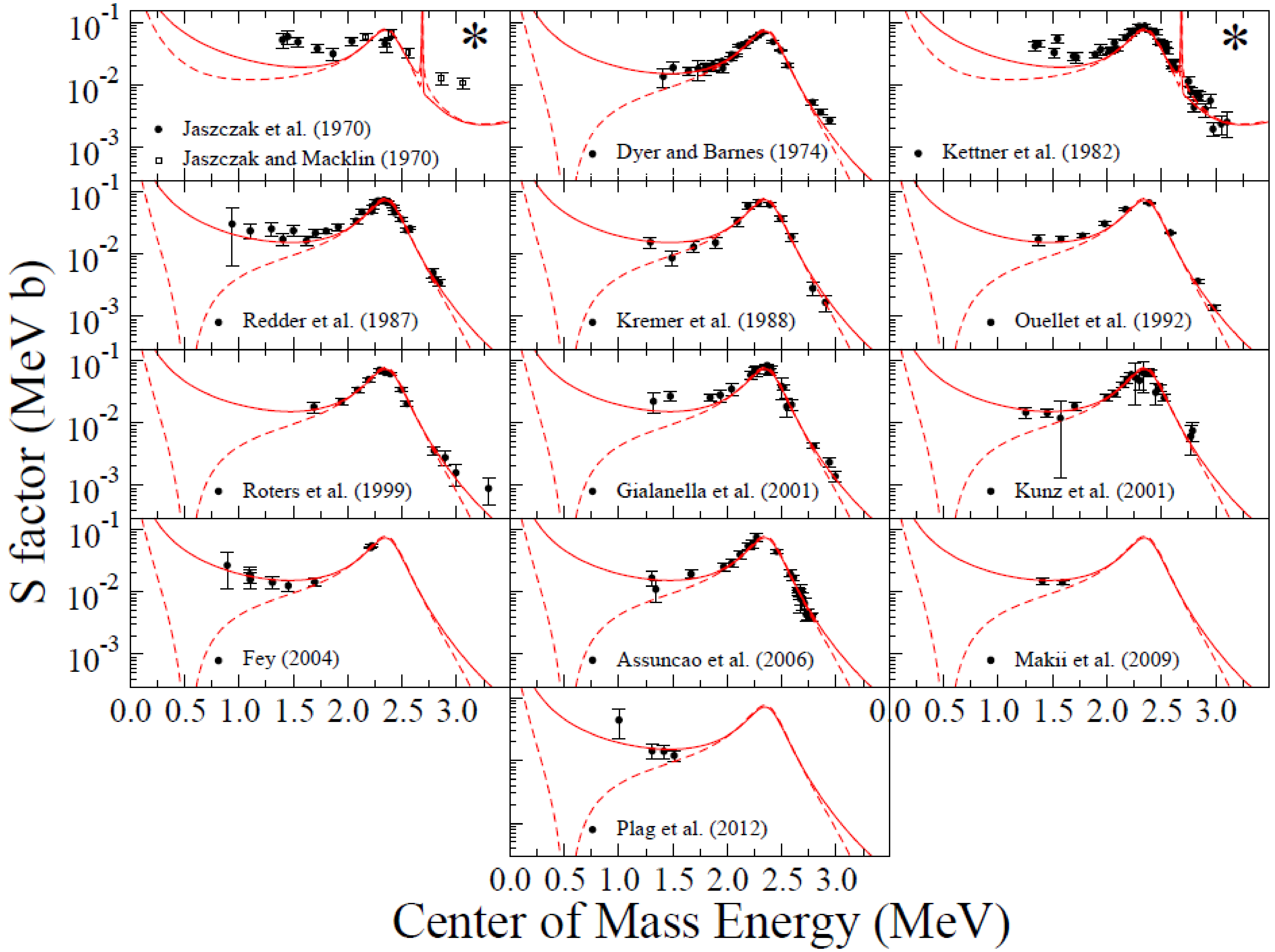
Solid black lines: the total with interferences included

deBoer et al., RMP(2017)

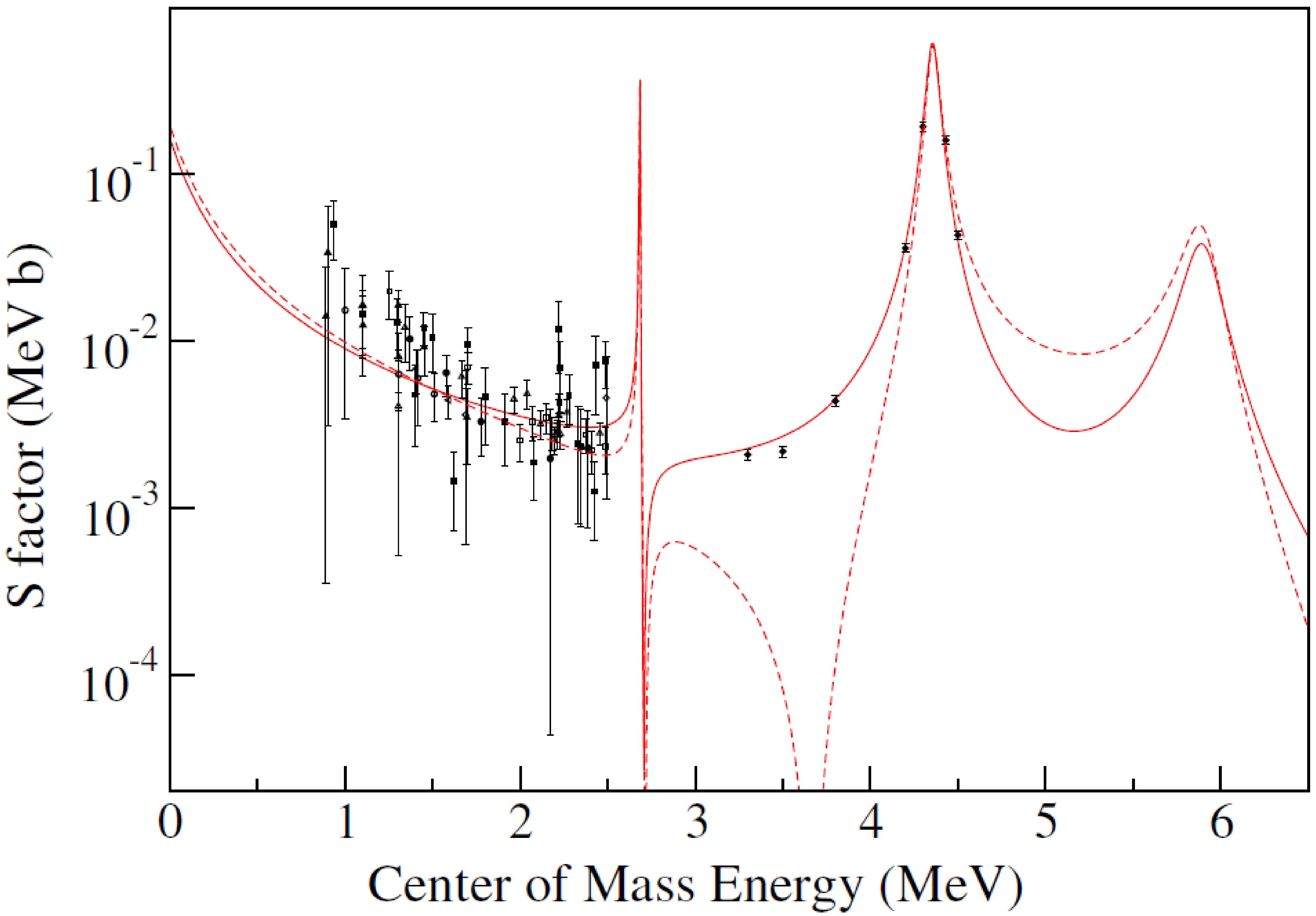
Another complication: Interference

$$\sigma_{E1}(E) = \frac{6\pi}{k_\alpha^2} P_1 \left| \frac{\boxed{\sum_{\lambda=1}^{q_1} \frac{\gamma_{\lambda 1}\Gamma_{\lambda\gamma}^{1/2}}{E_{\lambda 1}-E}}}{1-(S_1-B_1+iP_1)R_1} \right|^2$$

E1

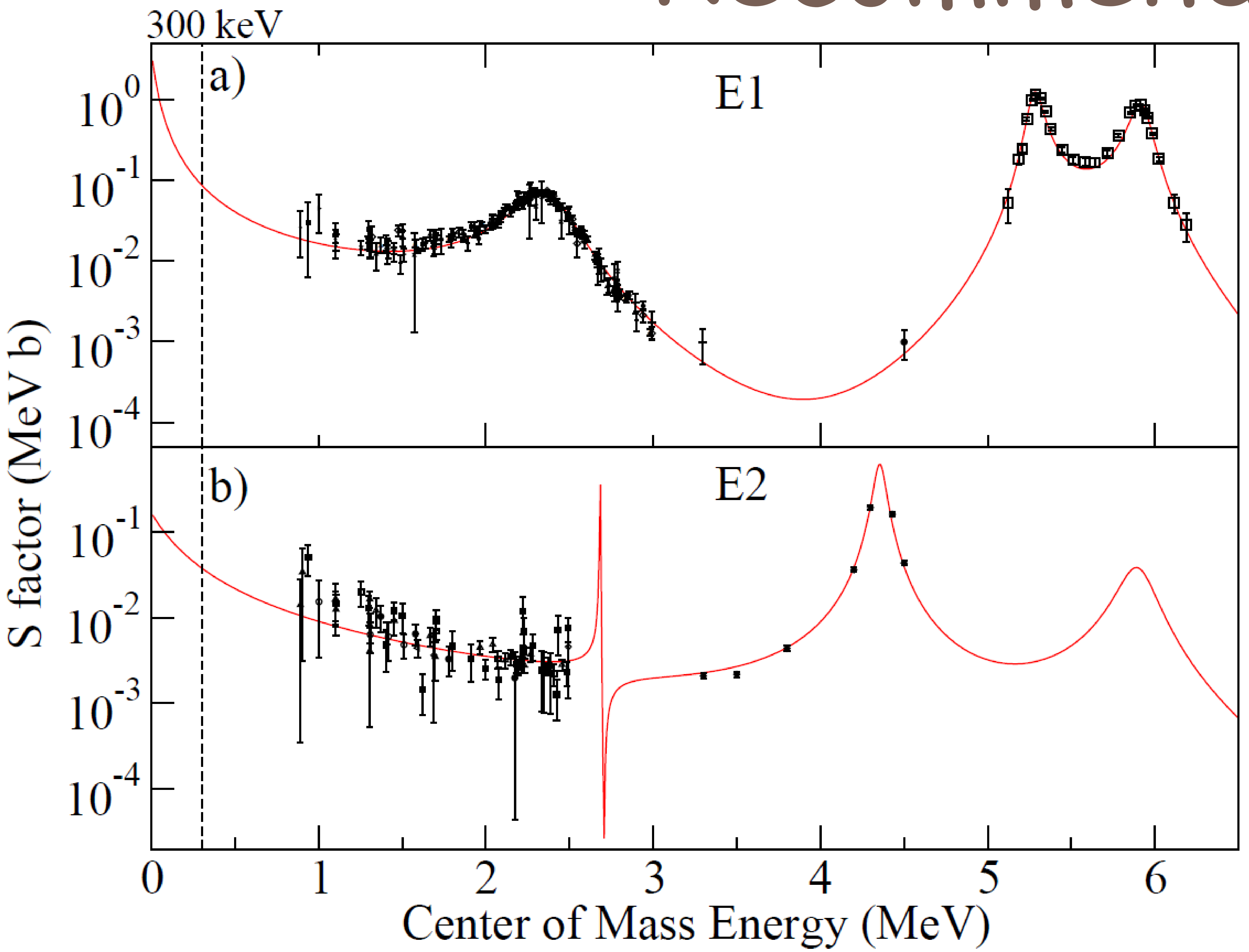


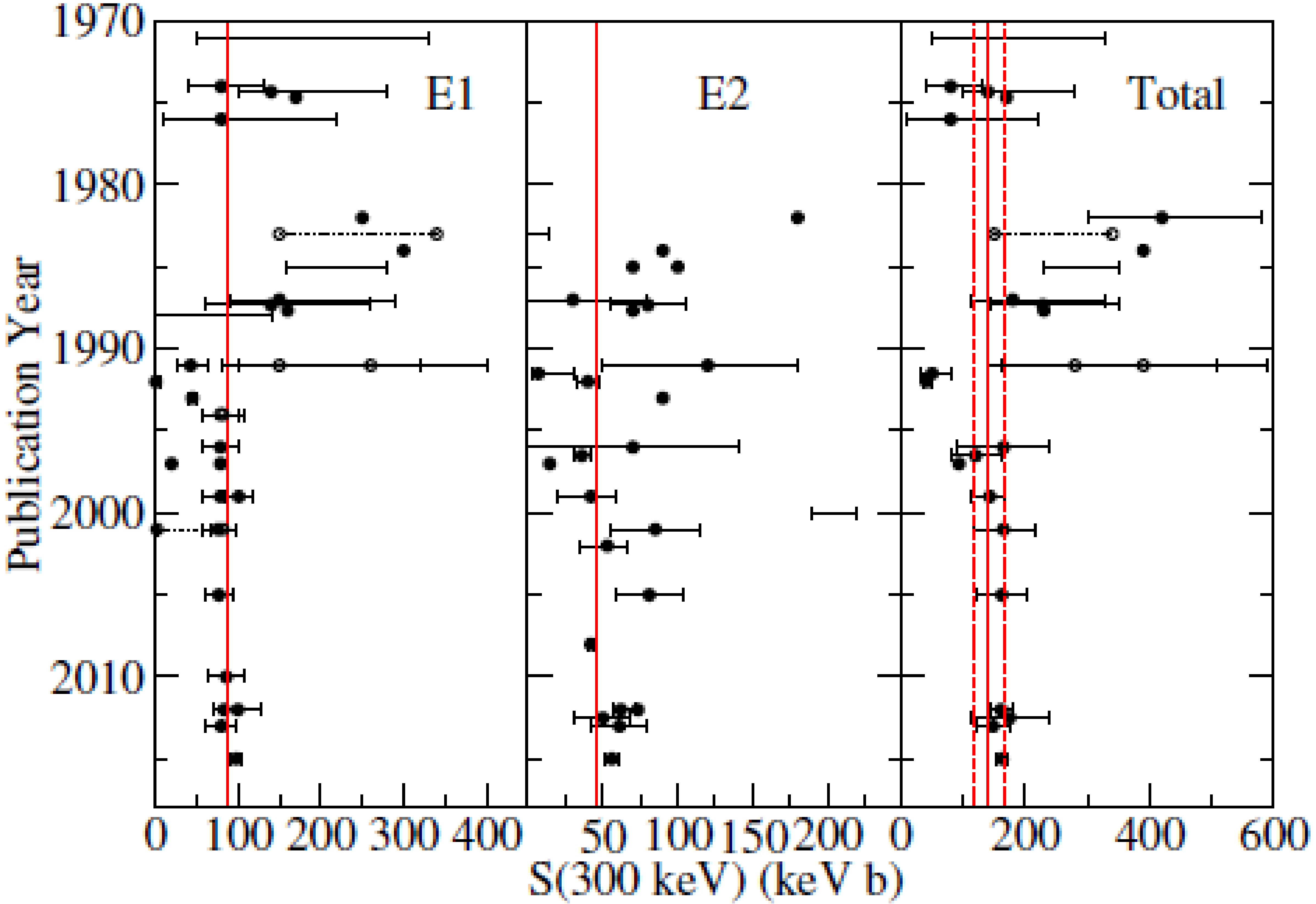
E2



deBoer et al., RMP(2017)

Recommended S factor



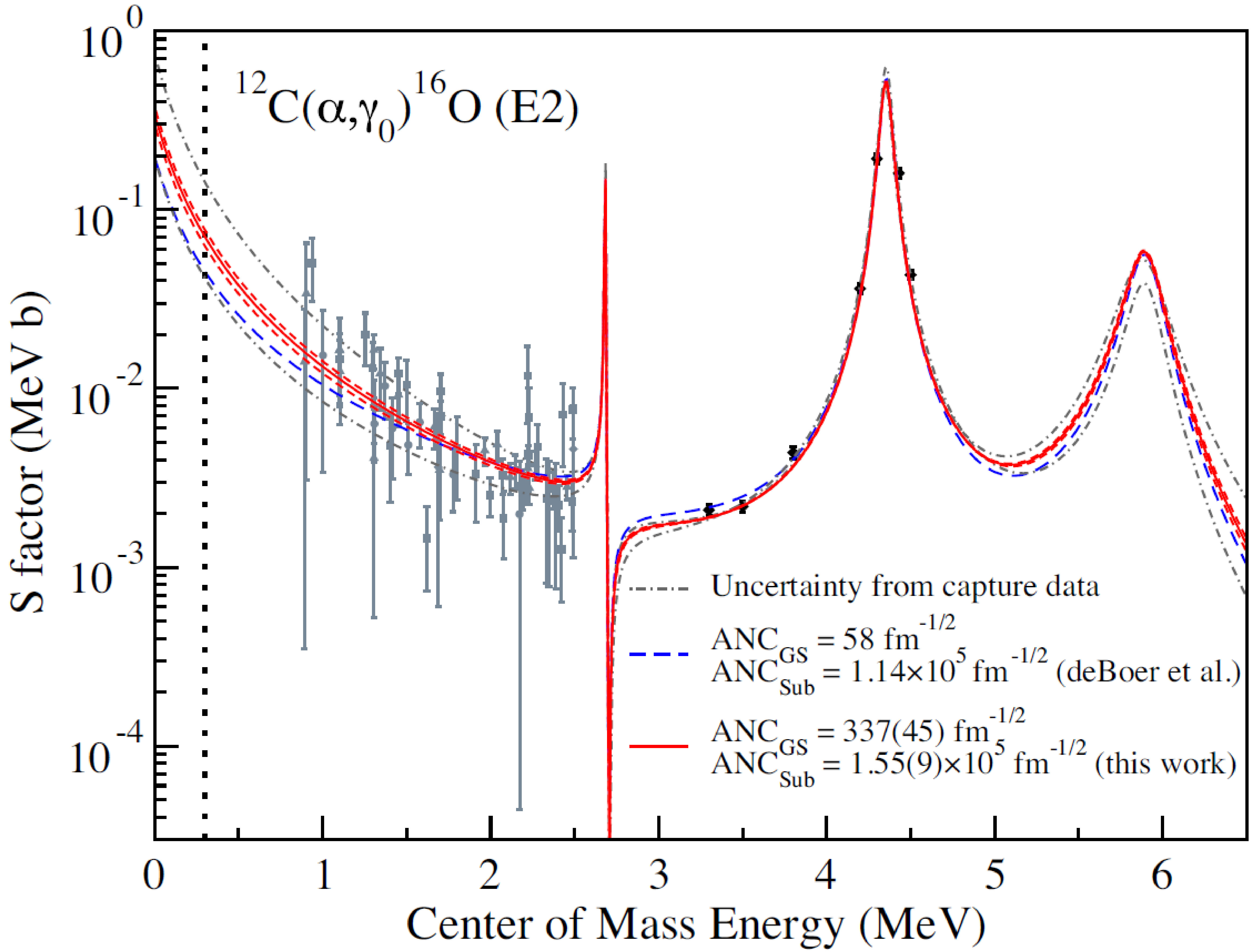


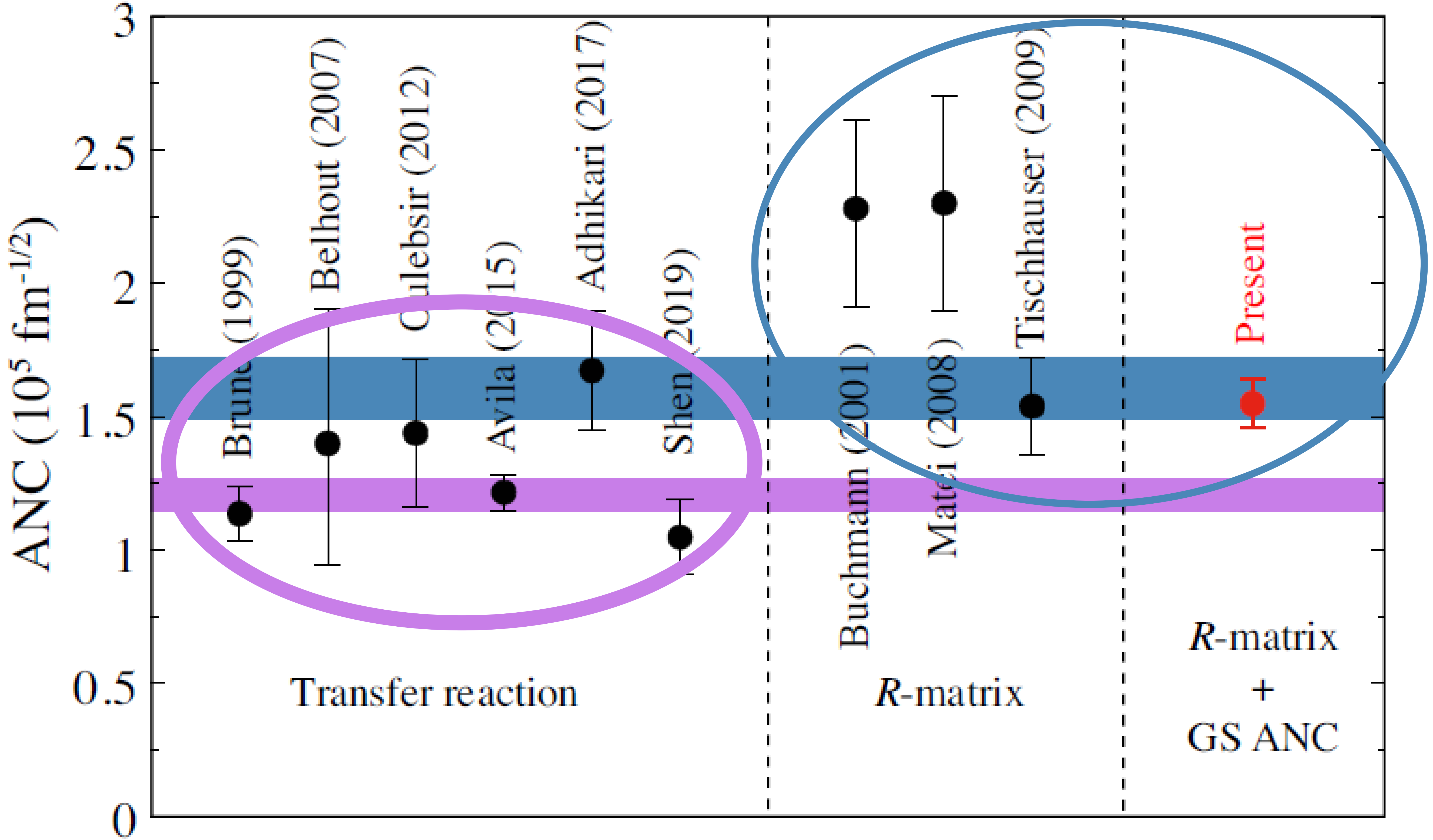
S(E1)=86.3 keVb; S(E2)=45.3 keVb; S(cascade)=7 keVb

Total S factor = $140 \pm 21_{(\mathrm{MC})}\,{}^{+18}_{-11(\mathrm{model})}$ keV b.

deBoer et al., RMP(2017)

Growing discrepancy between sub-barrier transfer reaction and other approaches



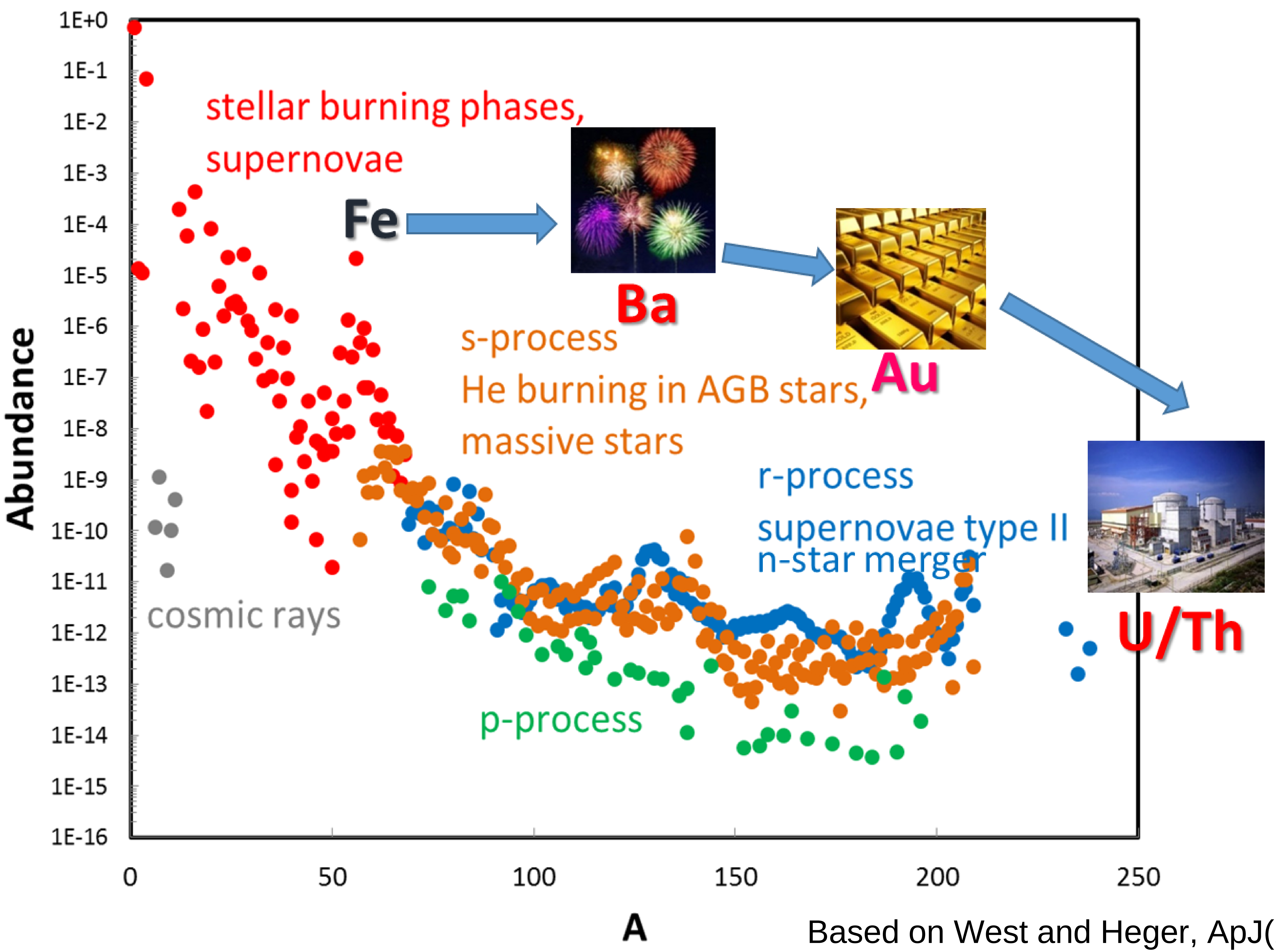


Y.P. Shen et al., PRL(2021)

- ANCs of 6.92 MeV(2$^+$) and the ground state (GS) correlate with each other (degenerated solutions with direct measurements)
- ^{12}C(^{11}B,^{7}Li)^{16}O at energies above barrier increases the ANC of G.S., increasing ANC of 6.92 MeV(2$^+$) from 1.14E5 to 1.55E5 fm$^{-1/2}$→tension between transfer and R-matrix (Problem of E2 measurement or systematic error of transfer?)
- S(E2) increases from 45 keVb to 70±7 keVb→Total S factor = 162 keVb agreeing with 170+/-20 keVb by Woosley

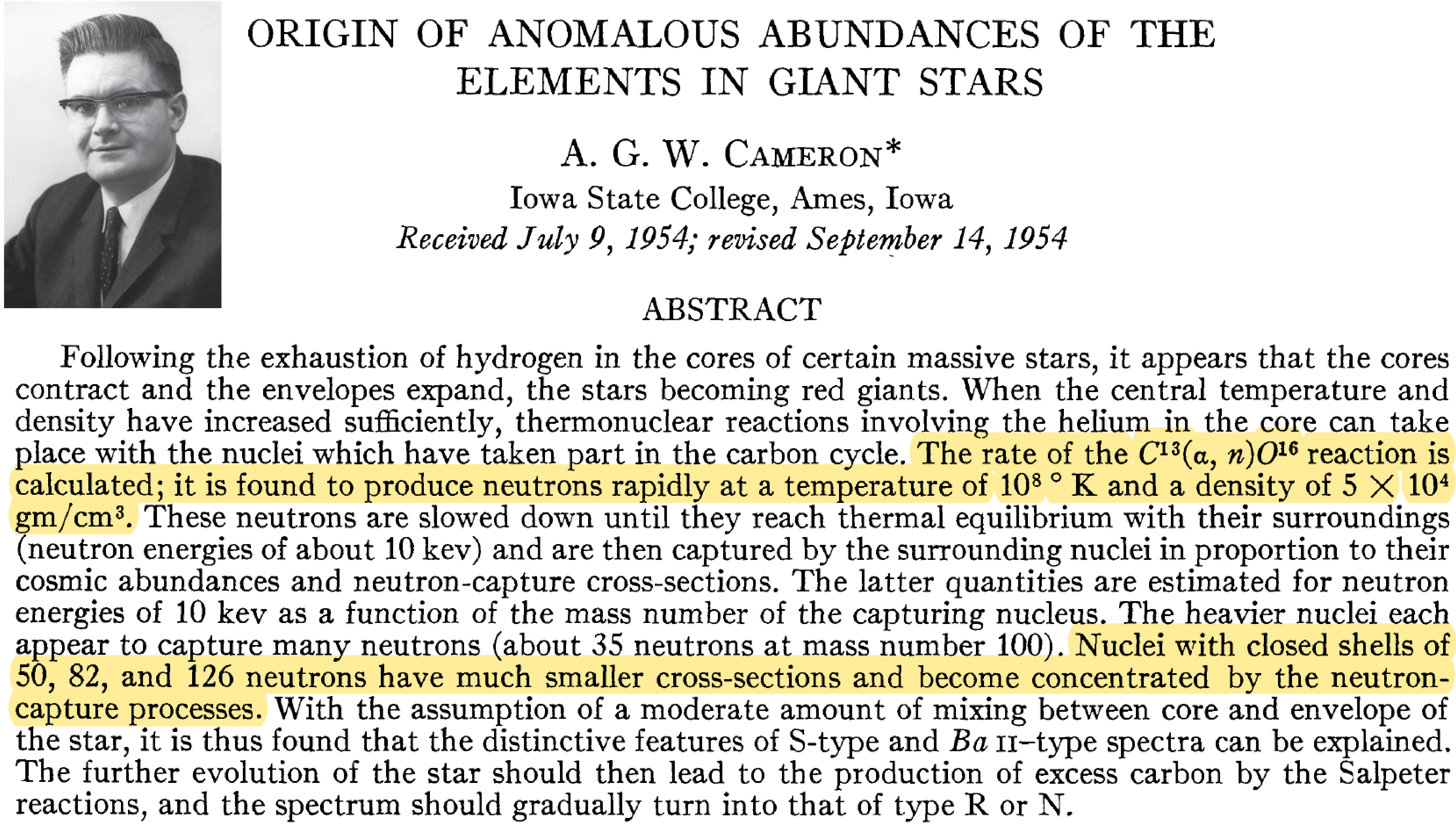
Origin of Heavy elements

JUNA



Based on West and Heger, ApJ(2013)

Pioneering works



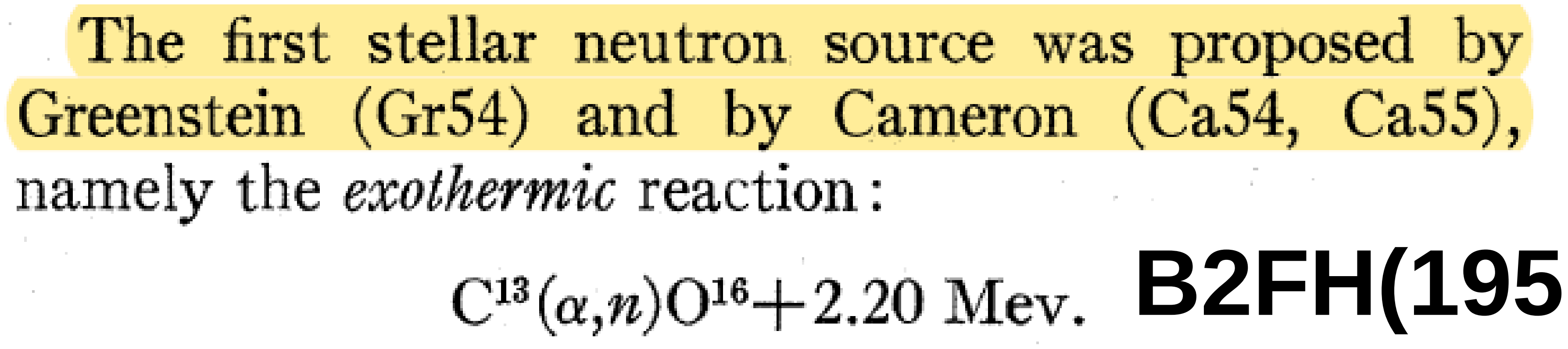
ORIGIN OF ANOMALOUS ABUNDANCES OF THE ELEMENTS IN GIANT STARS

A. G. W. Cameron*
Iowa State College, Ames, Iowa

Received July 9, 1954; revised September 14, 1954

ABSTRACT

Following the exhaustion of hydrogen in the cores of certain massive stars, it appears that the cores contract and the envelopes expand, the stars becoming red giants. When the central temperature and density have increased sufficiently, thermonuclear reactions involving the helium in the core can take place with the nuclei which have taken part in the carbon cycle. The rate of the $C^{13}(\alpha, n)O^{16}$ reaction is calculated; it is found to produce neutrons rapidly at a temperature of 10^8 ° K and a density of 5×10^4 gm/cm^3. These neutrons are slowed down until they reach thermal equilibrium with their surroundings (neutron energies of about 10 kev) and are then captured by the surrounding nuclei in proportion to their cosmic abundances and neutron-capture cross-sections. The latter quantities are estimated for neutron energies of 10 kev as a function of the mass number of the capturing nucleus. The heavier nuclei each appear to capture many neutrons (about 35 neutrons at mass number 100). Nuclei with closed shells of 50, 82, and 126 neutrons have much smaller cross-sections and become concentrated by the neutron-capture processes. With the assumption of a moderate amount of mixing between core and envelope of the star, it is thus found that the distinctive features of S-type and *Ba* II–type spectra can be explained. The further evolution of the star should then lead to the production of excess carbon by the Salpeter reactions, and the spectrum should gradually turn into that of type R or N.



The first stellar neutron source was proposed by Greenstein (Gr54) and by Cameron (Ca54, Ca55), namely the *exothermic* reaction:

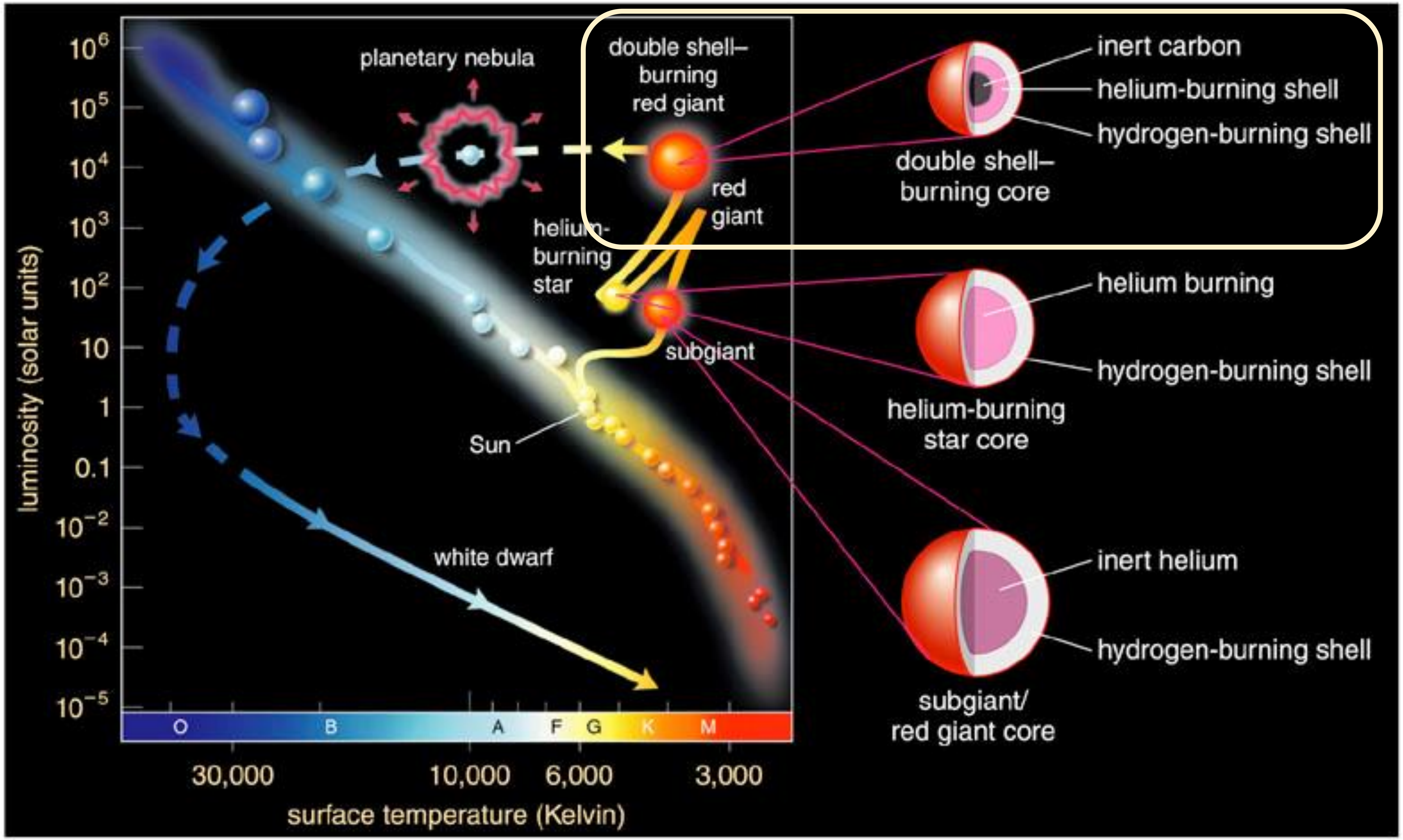
$$C^{13}(\alpha,n)O^{16}+2.20 \text{ Mev.}$$

B2FH(1957)

S factor =3.9x10^3 MeV*barn

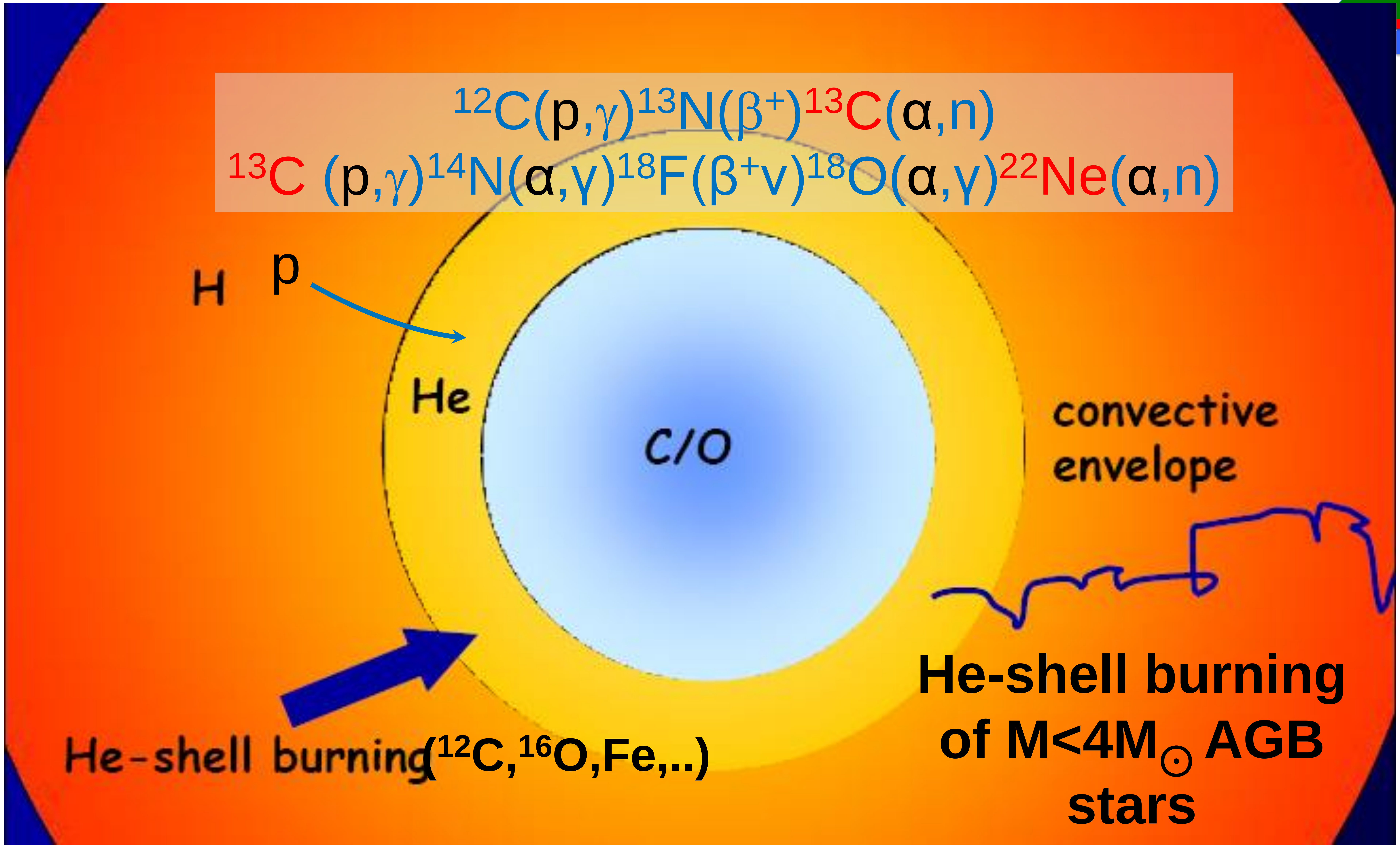
~1/1000 of the present value

Asymptotic Giant Branch star



Stars with <10 solar mass go through the asymptotic giant branch (AGB) before becoming white dwarfs. *Taken from Lugaro's lecture*

Neutrons in Asymptotic Giant Branch



$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)$

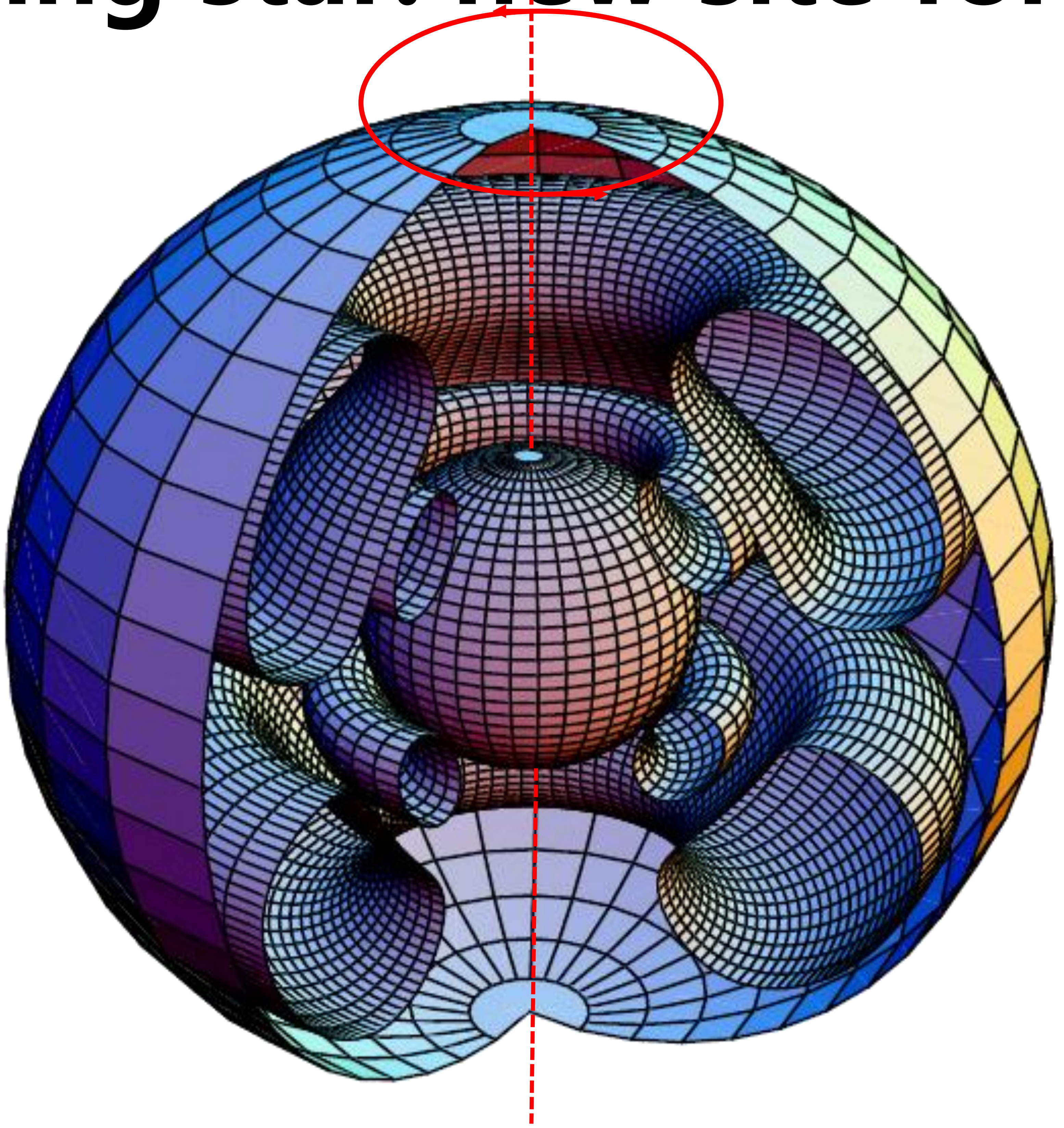
$^{13}C\ (p,\gamma)^{14}N(\alpha,\gamma)^{18}F(\beta^+v)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)$

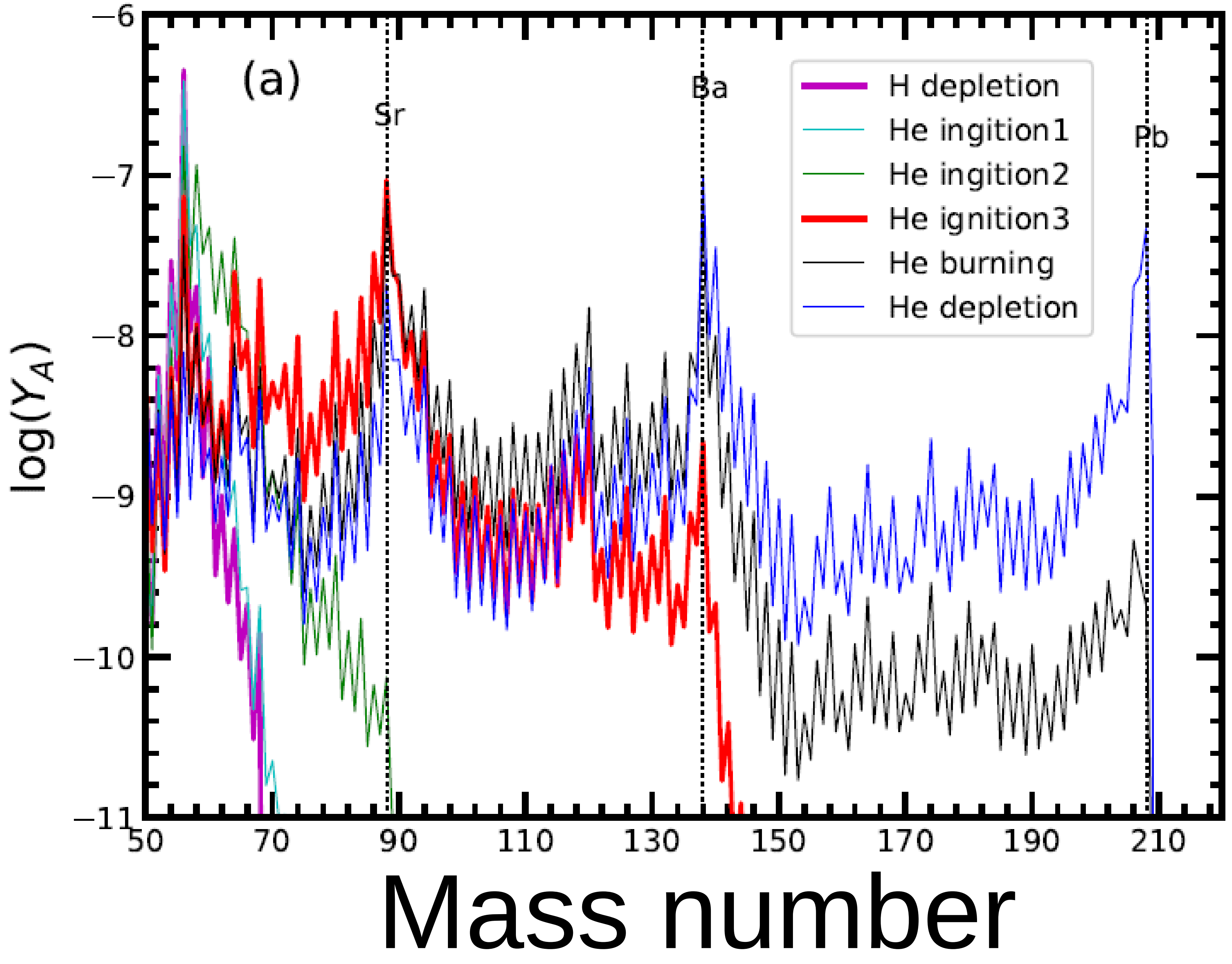
(^{12}C,^{16}O,Fe,..)

He-shell burning of $M<4M_{\odot}$ AGB stars

$N_n<10^9$ cm^{-3}

Rotating star: new site for s-process

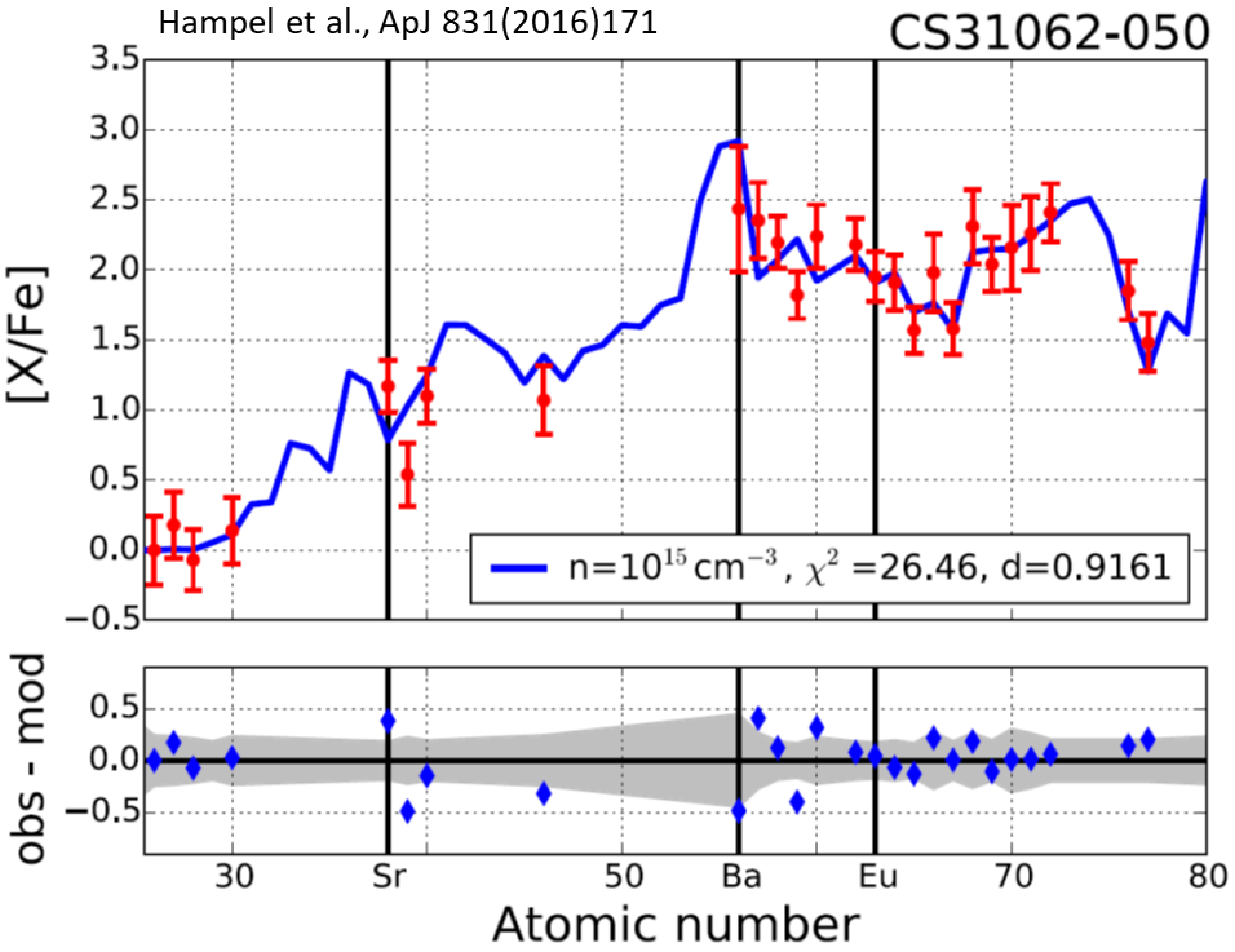




- Stars more massive than about 1.5 $M_\odot$ rotate fast but “standard model” ignores the rotation
- Rotation-induced mixing results in primary production of ^{13}C, which subsequently makes neutrons via $^{13}C(\alpha,n)^{16}O$ during core He burning
- New site for the main s-process: **rotating metal-poor massive stars**

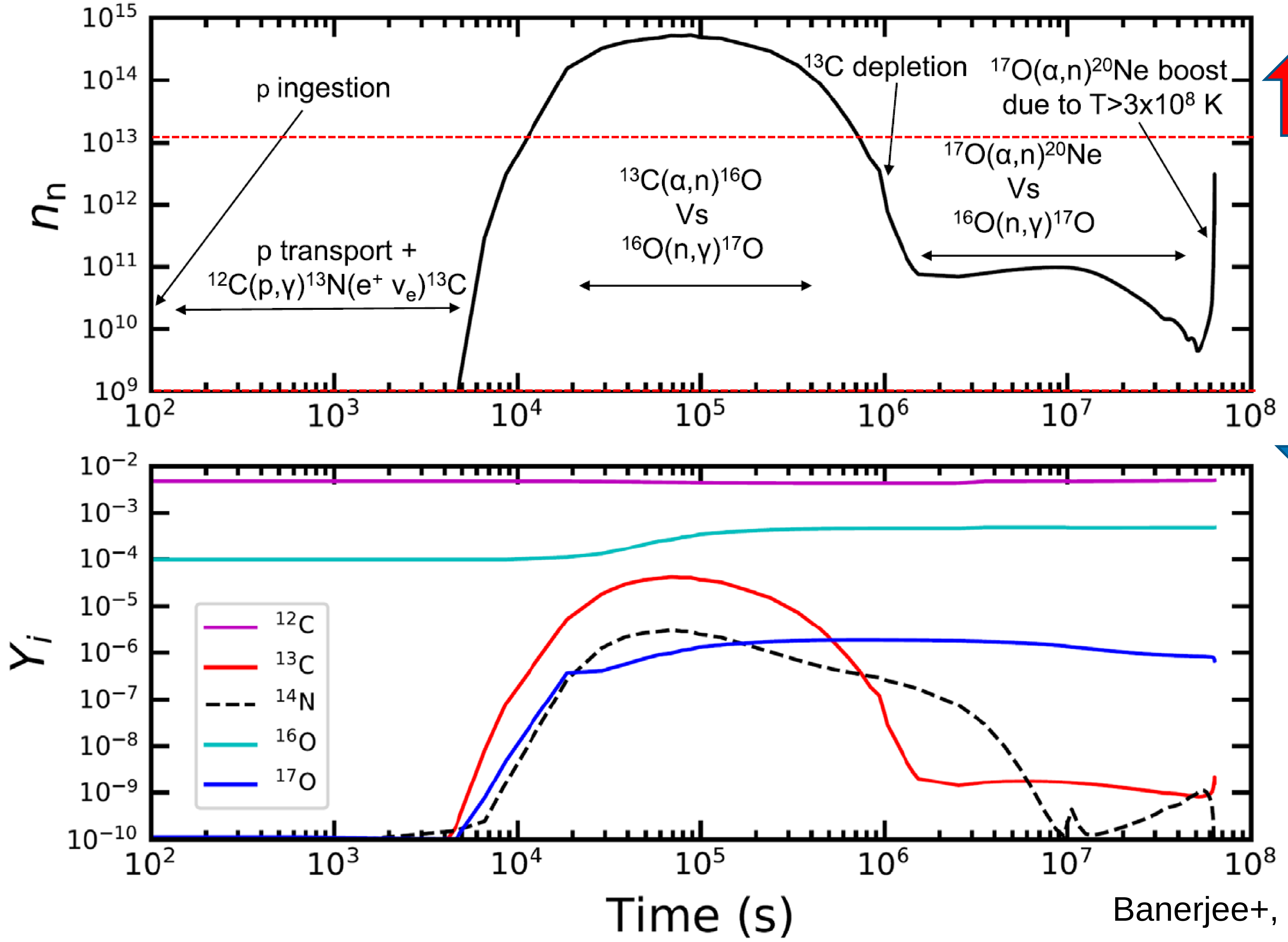
Langer+, (1999), Meynet & Maeder, (2002), Prantzos+, (2018), Banerjee, Heger and Qian, (2019)

Carbon-Enhanced Metal-Poor(CEMP) stars



- R-process: ~10^{20} cm^{-3} S-process: <10^{9} cm^{-3}
- **Intermediate-process (i-process): 10^{13}-10^{16} cm^{-3}**
- **$^{13}C(\alpha,n)^{16}O$ is the neutron source (AGB? Metal-poor star?...)**

Proton Ingestion in Pop-III and Pop-II



Banerjee+, (2018); Cristallo+, (2018)

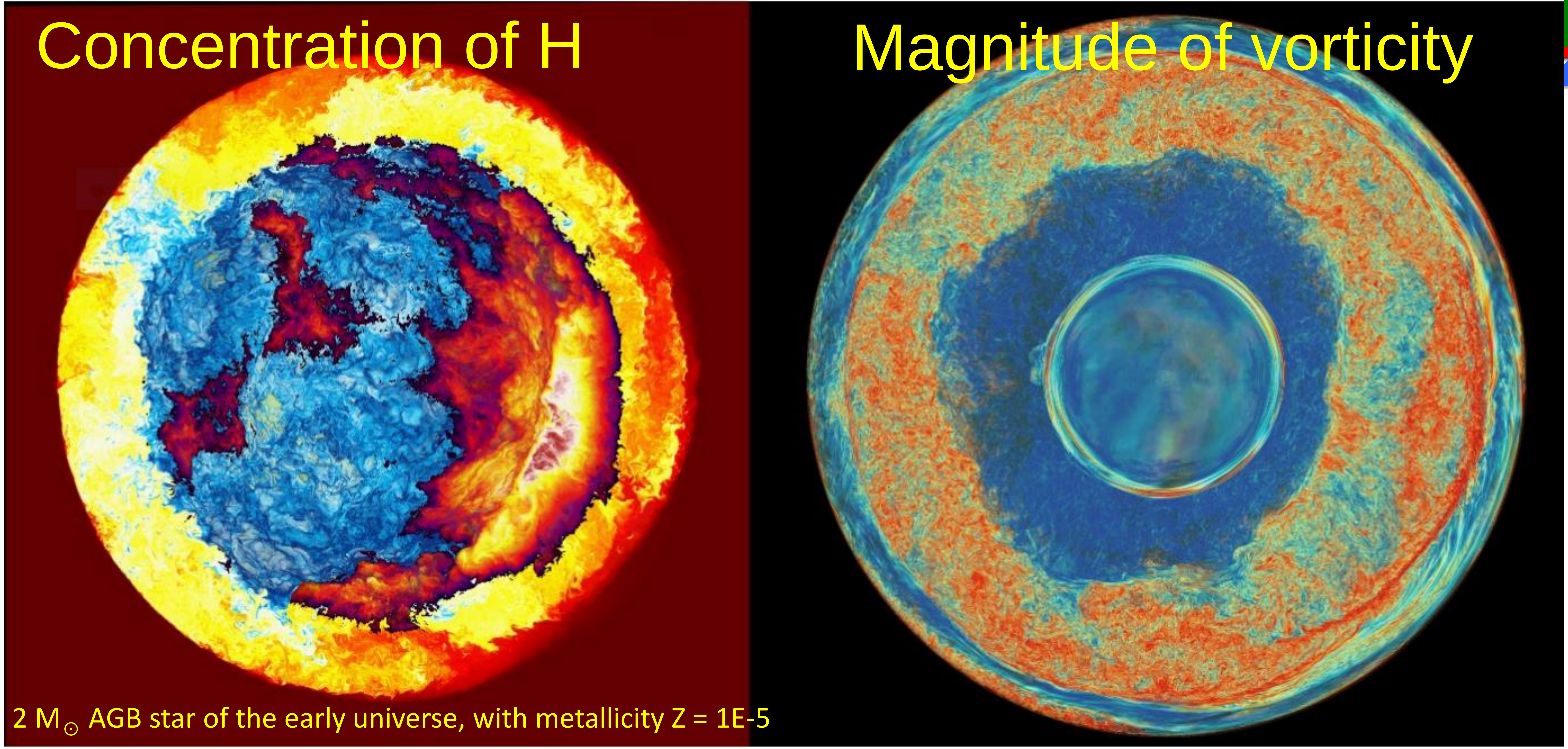
i-process

s-process

T_9~0.27 GK

- Accurate 3D modeling of proton ingestion and subsequent mixing in He shells of metal-free and metal-poor massive stars
- Accurate nuclear physics cross sections: $^{13}C(\alpha,n)^{16}O(n,\gamma)^{17}O(\alpha,n)$

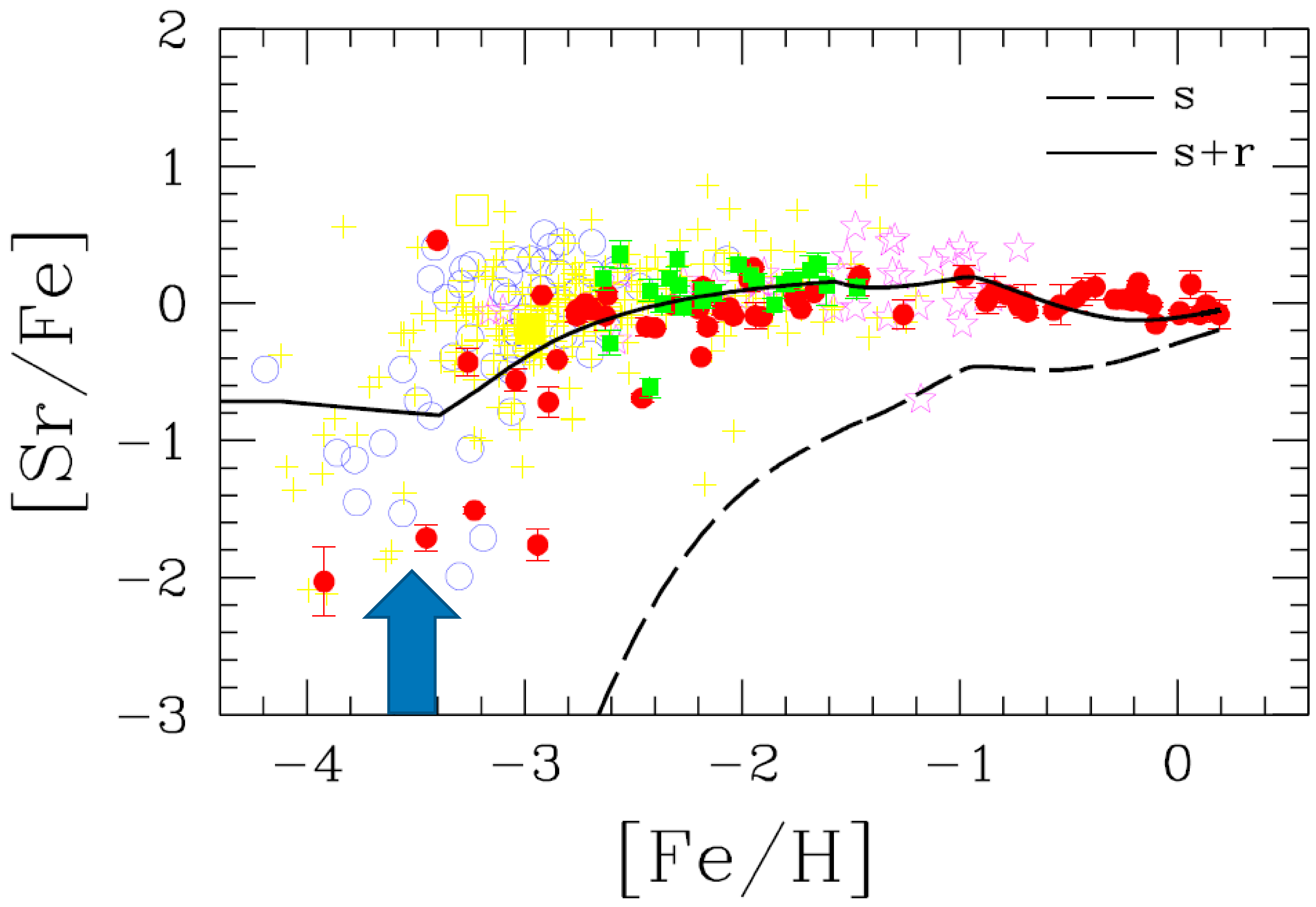
Proton Ingestion in Pop-III and Pop-II



Credit: Woodward, Herwig, Wetherbee

- Accurate 3D modeling of proton ingestion and subsequent mixing in He shells of metal-free and metal-poor massive stars
- Accurate nuclear physics cross sections: $^{13}C(\alpha,n)^{16}O(n,\gamma)^{17}O(\alpha,n)$

Impact on Galactic Chemical Evolution



From Kobayashi, Karakas & Lugaro (2020)

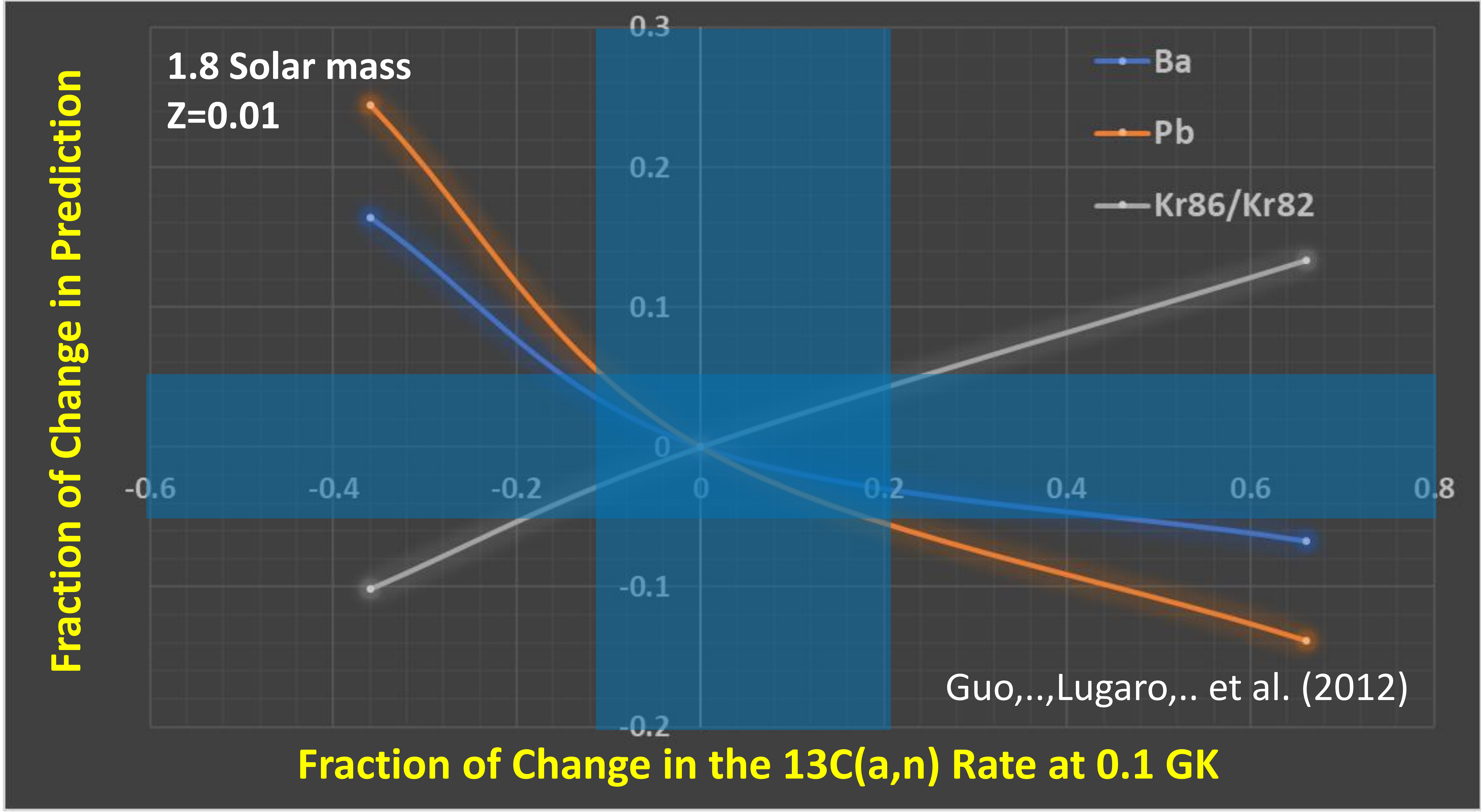
This model matches the solar composition of Sr with yields from s- and r-processes alone.

Do we even need an i-process? Maybe, at low metallicities?

Côté et al. 2018 suggests important for the first s-process peak (Sr, Y, Zr)

Taken from Karakas's lecture. 16th NIC school
https://indico.ihep.ac.cn/event/15049/overview

Sensitivity study on s-process in AGB



1.8 Solar mass
Z=0.01

Guo,..,Lugaro,.. et al. (2012)

- +20%/-12% in Reaction Rate at 0.1GK requires
- +/- 5% in the s-process yield→could be large for r-process yield
- Should consider both uncertainties: ^{22}Ne(a, n) and ^{13}C(a, n)

Observed solar abundance = s-process + r-process + p-process

Complicated Reaction

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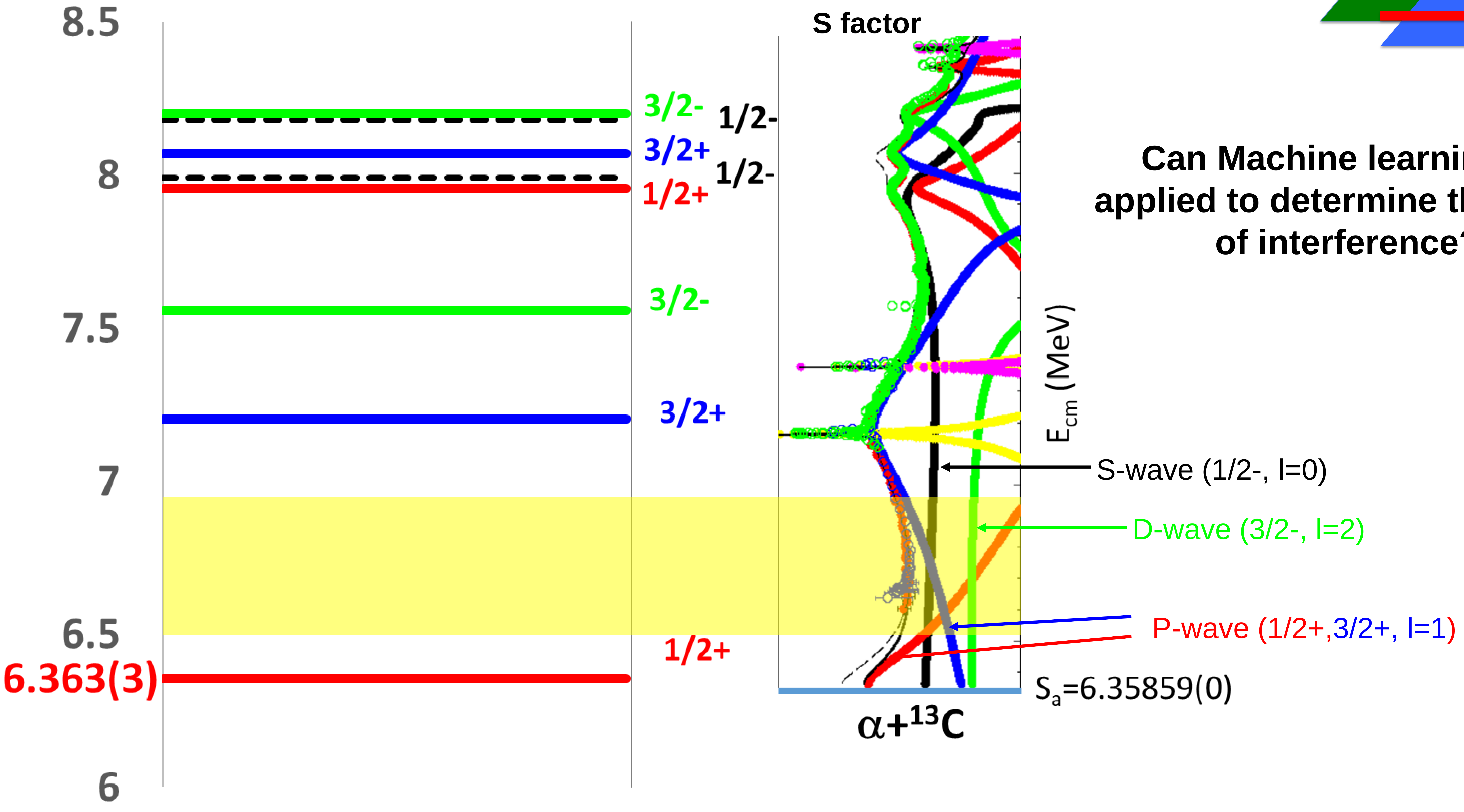
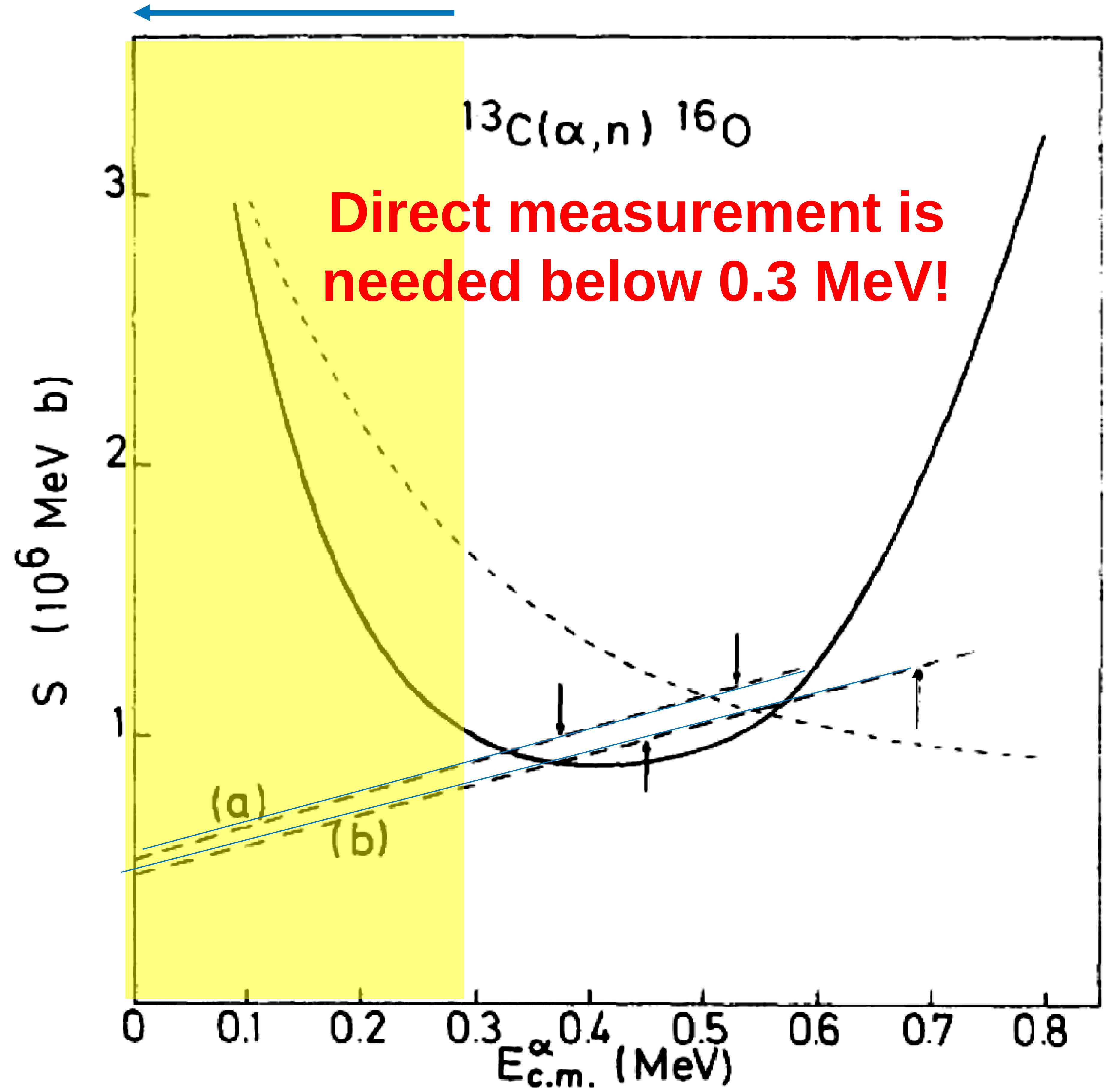
Need consistent measurements in a wide energy range



Can Machine learning be applied to determine the signs of interference?

Faestermann et al. PRC(2015)

Importance of the threshold state



Direct measurement is needed below 0.3 MeV!

FIG. 6. $^{13}C(\alpha,n)^{16}O$ S factor. The dotted line represents the GCM result; the full line is obtained with the Breit-Wigner parametrization (see text); the dashed lines are the experimental data taken from Ref. 3 (a) and Ref. 4 (b). The arrows indicate the energy range where the experiments are carried out.

P. Descouvemont PRC(1987)

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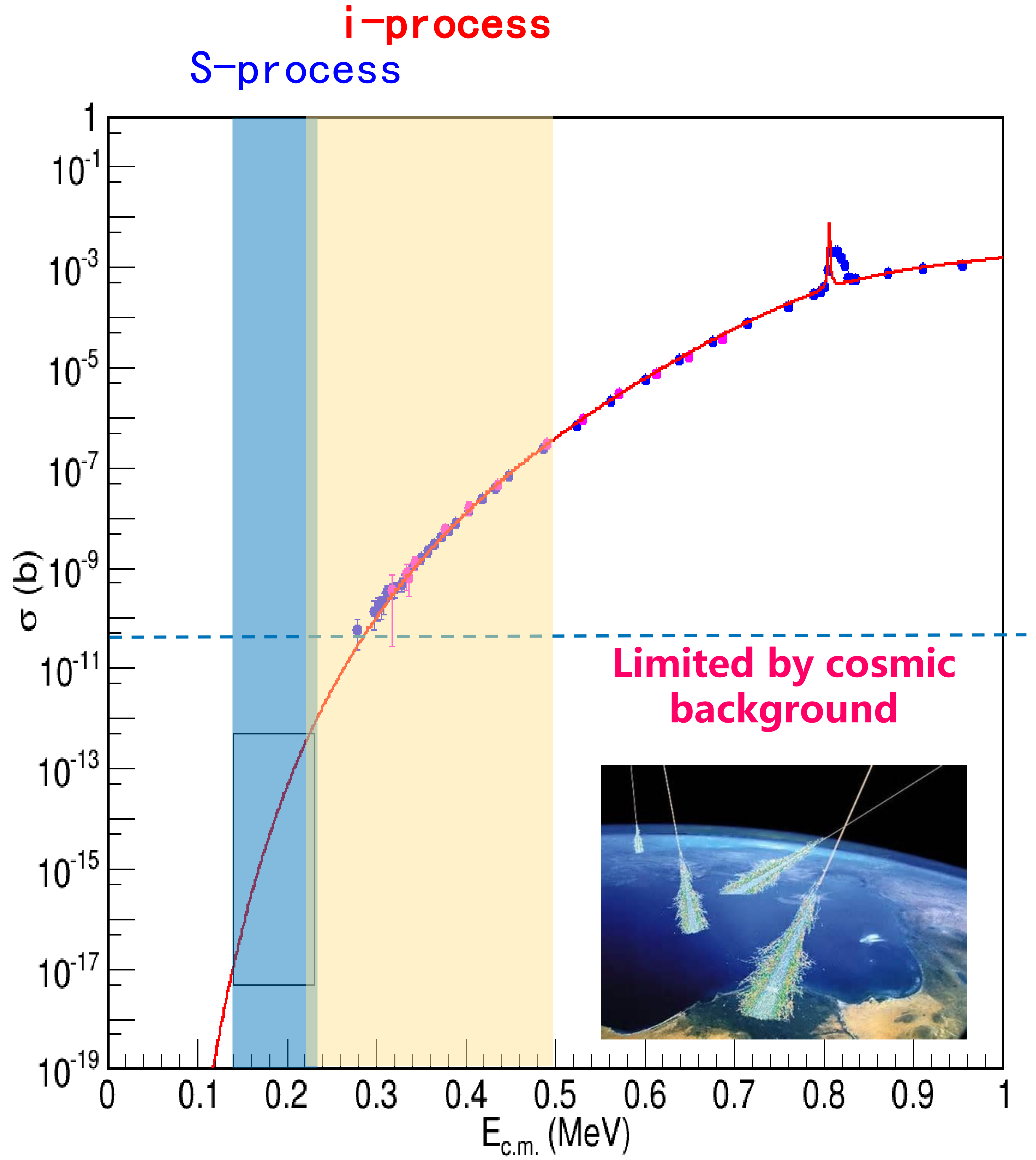
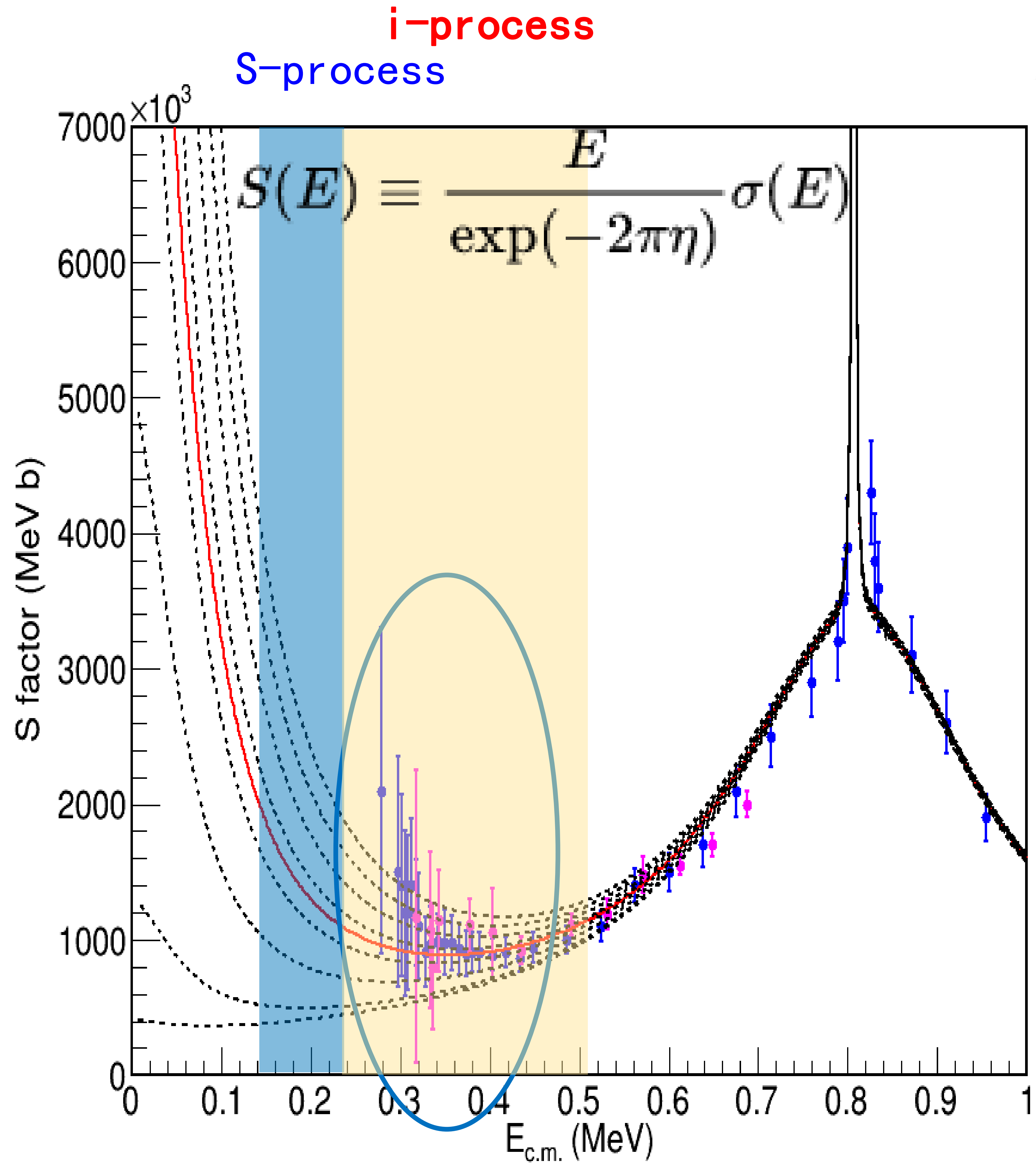
$^{13}C(\alpha,n)^{16}O$ measurements



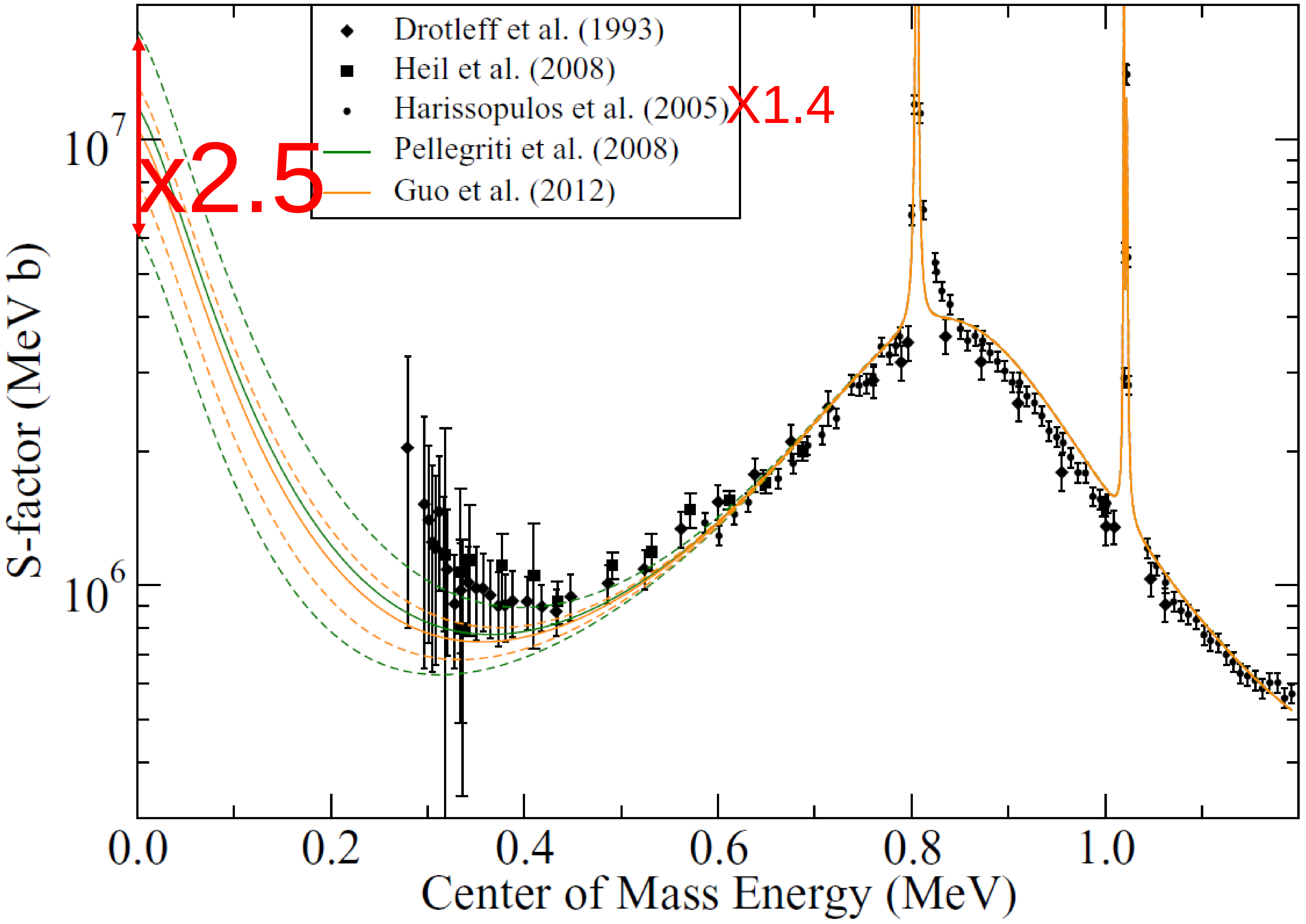
Limited by cosmic background

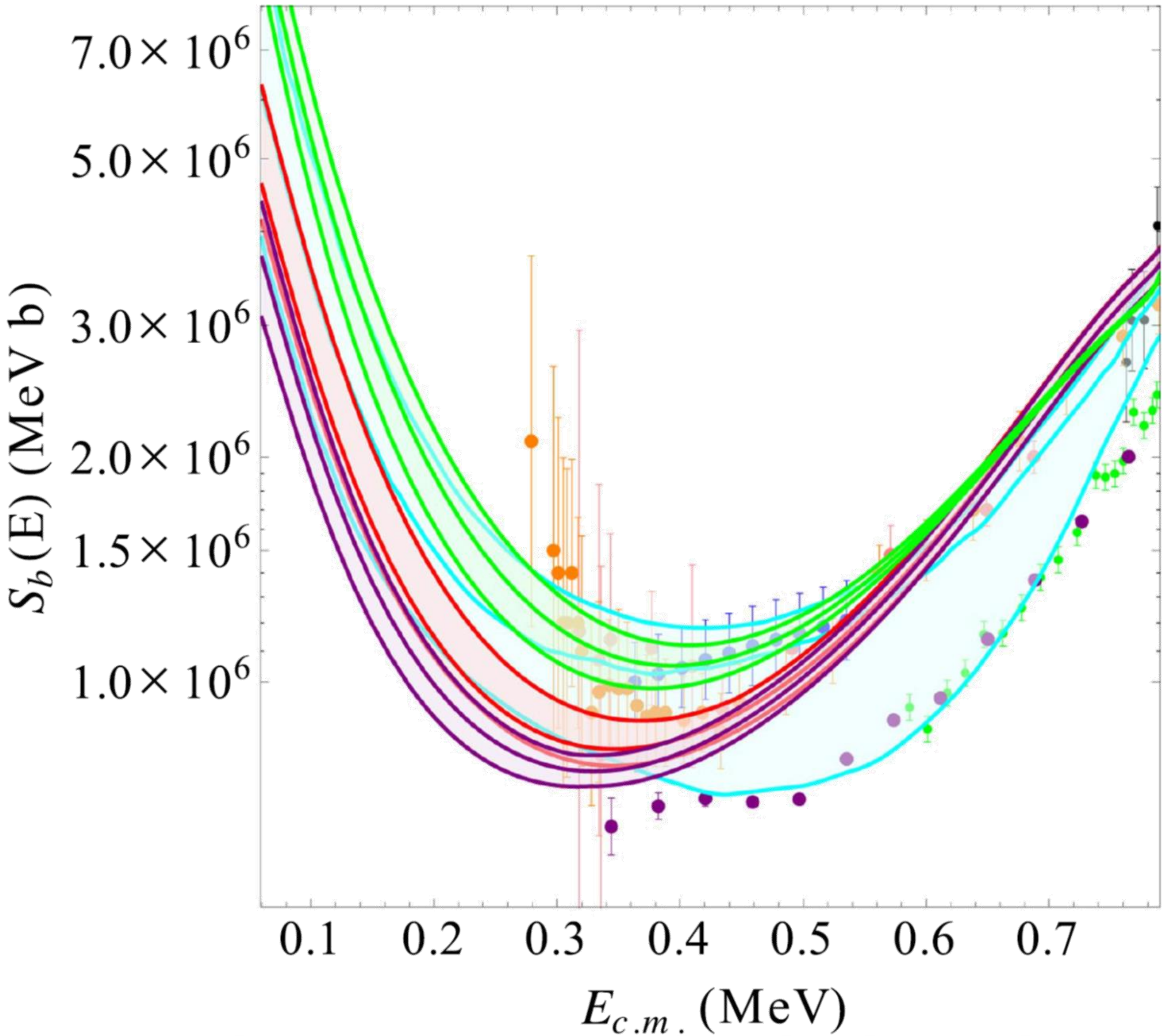


$$S(E) \equiv \frac{E}{\exp(-2\pi\eta)}\sigma(E)$$

- **Ground based experiments are limited by cosmic rays**
- **Errors (~70%) are too large to constrain contribution of threshold state**

Indirect approaches





Asymptotic Normalization Coefficient (ANC)

See deBoer (2020) for a summary

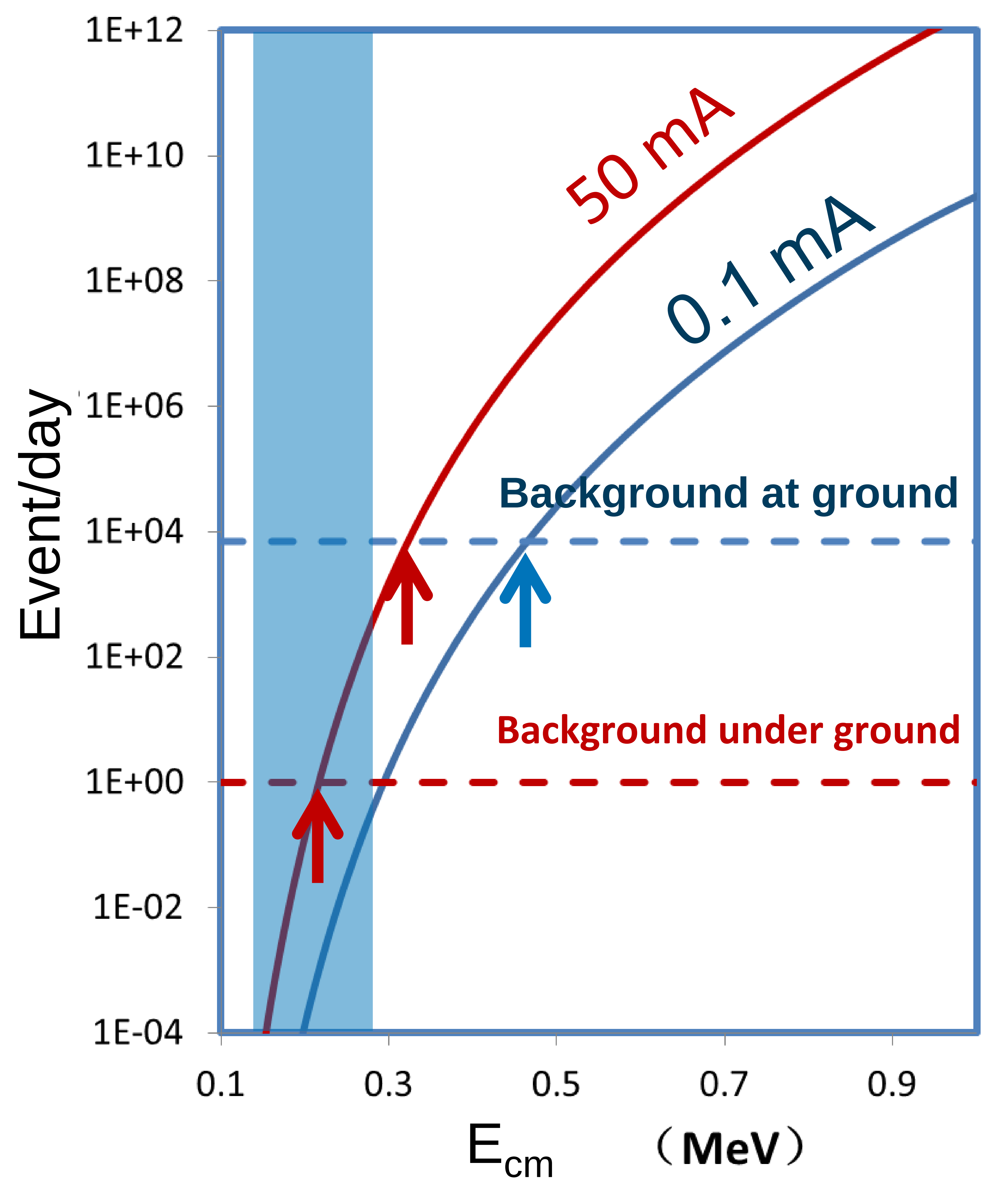
Trojan Horse Methode (THM)

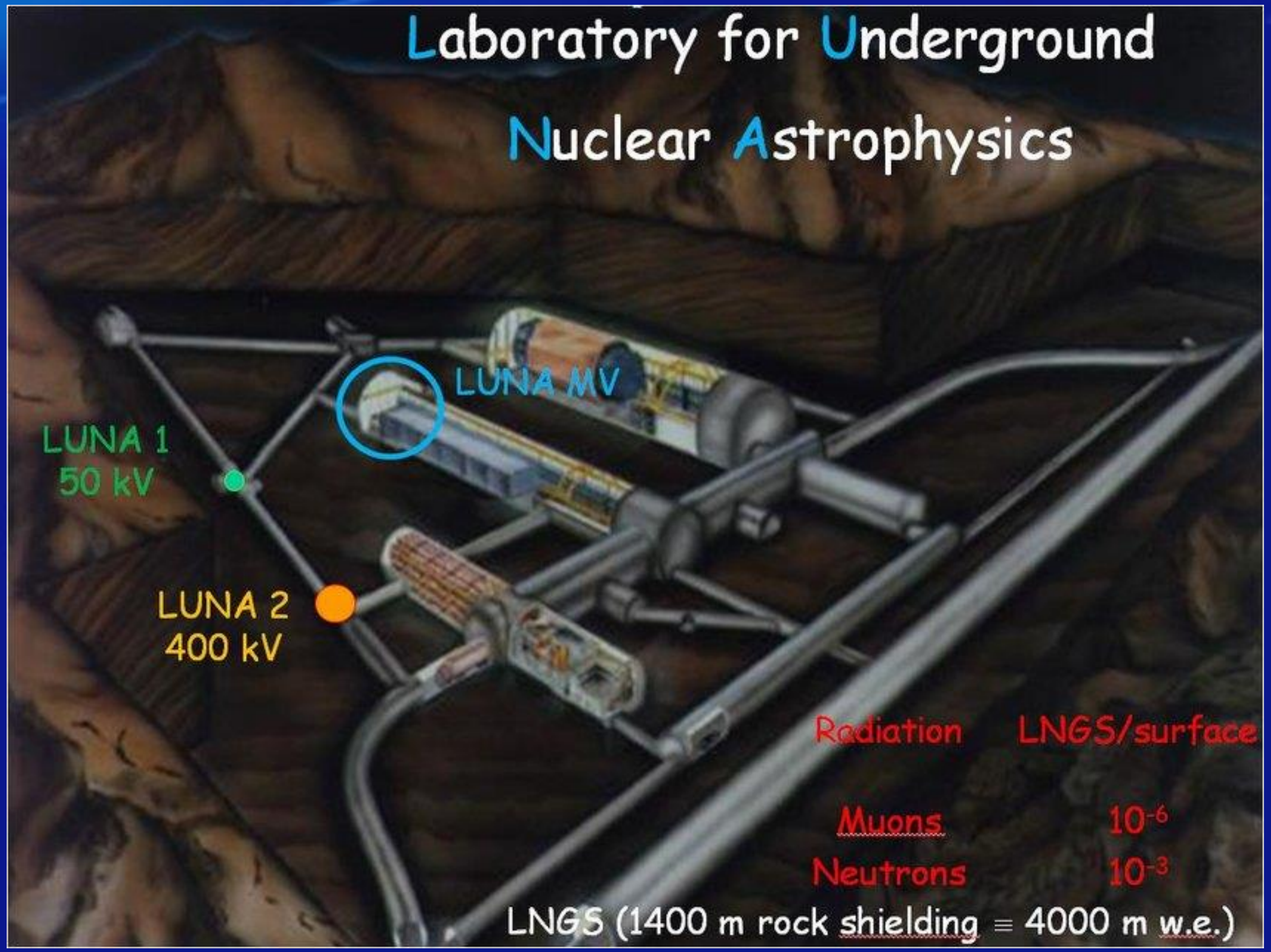
Trippella & Cognata (2017)

Mukhamedzhanov et al (2017)

- Systematic error is difficult to be correctly evaluated
- Inconsistency of direct measurements limits the precision of extrapolation
- Need direct measurement at low energies to validate the results

Challenging the tiny cross sections

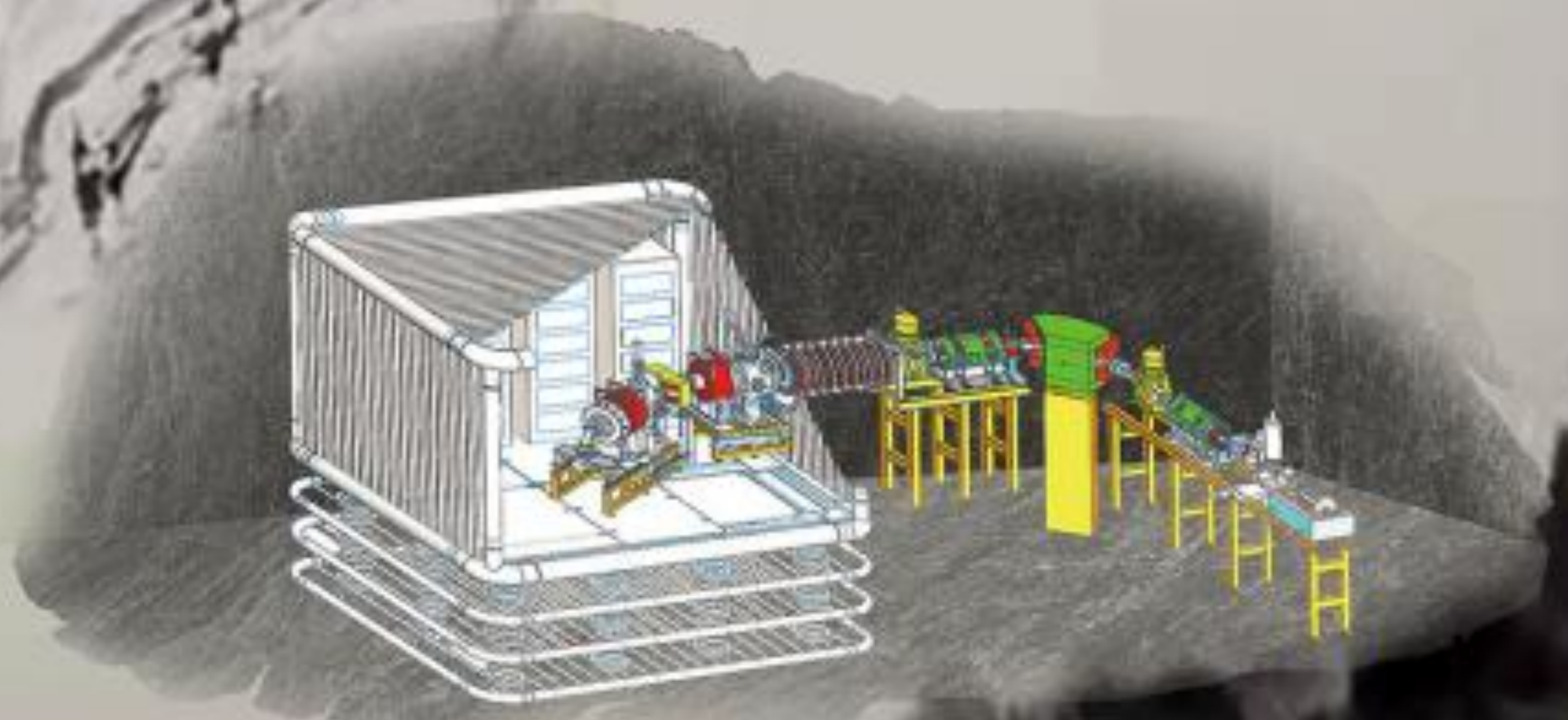





CASPAR (1480 m rock shielding)

Complemented with indirect approaches

Jinping Underground Nuclear Astrophysics experiment

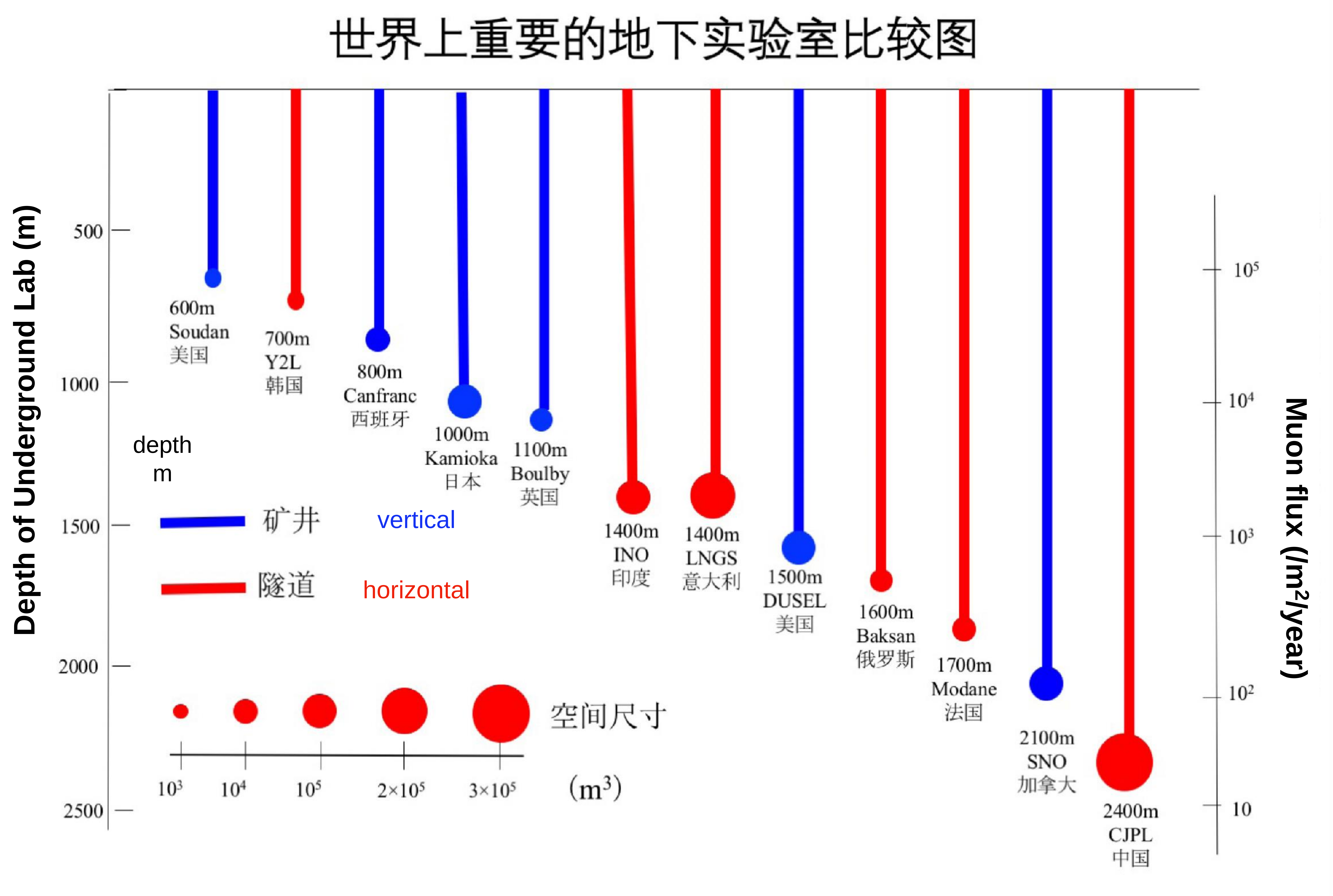


China Jinping Underground Laboratory(CJPL)

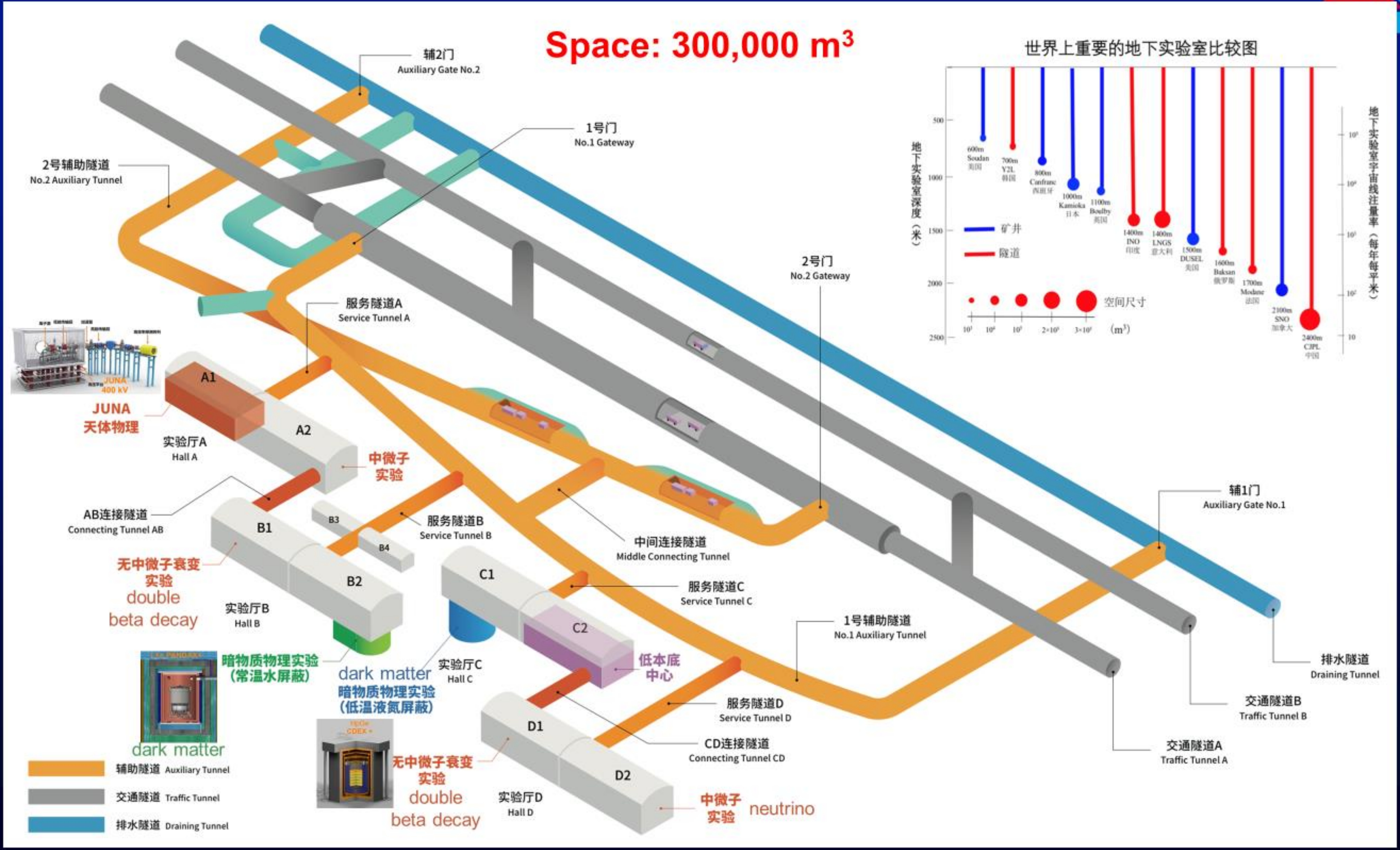

A
出口
入口

Major underground laboratories

Comparison of wold underground laboratory

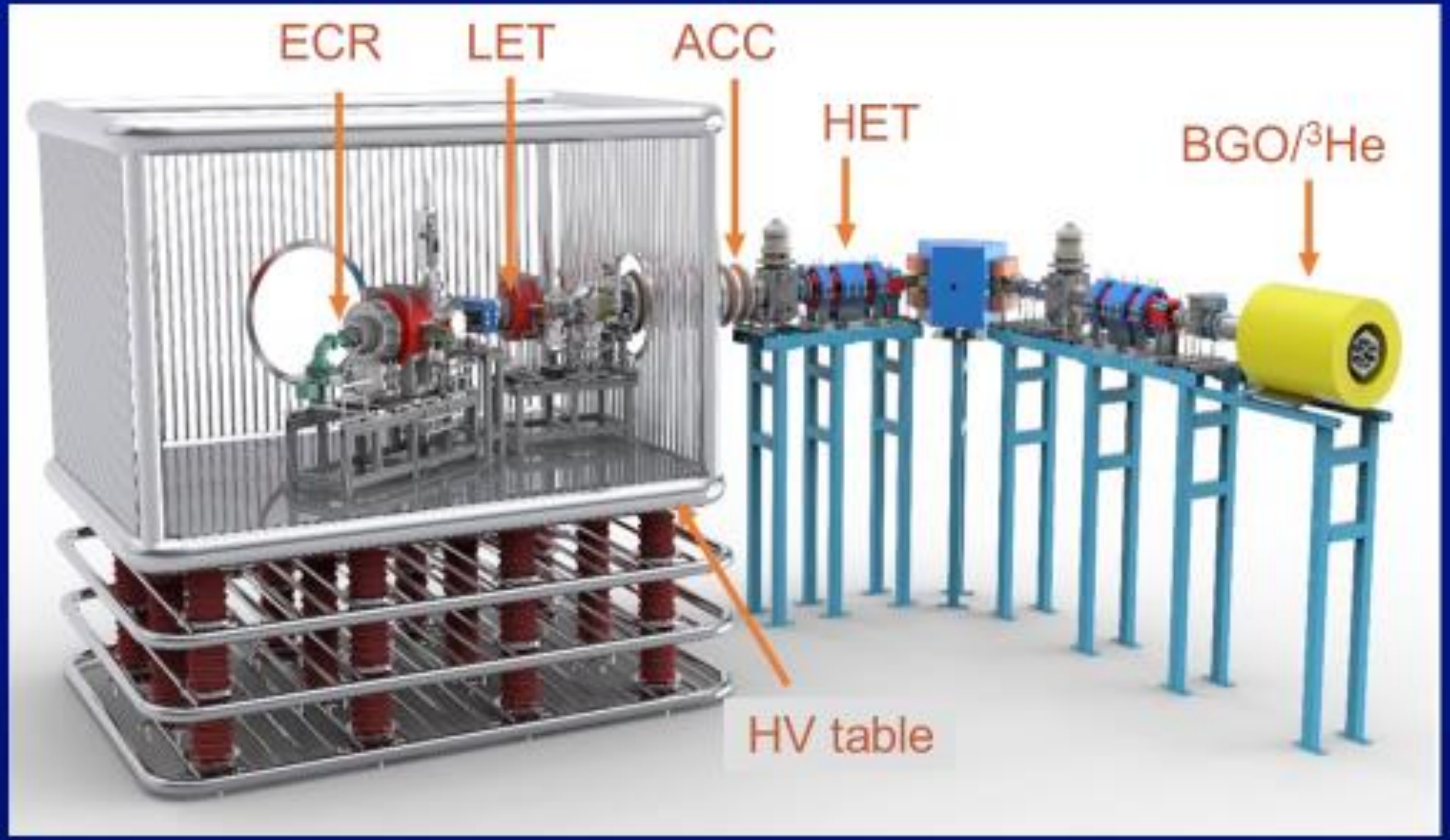


CJPL-II


Space: 300,000 m³
辅2门
Auxiliary Gate No.2
1号门
No.1 Gateway
2号辅助隧道
No.2 Auxiliary Tunnel
2号门
No.2 Gateway
服务隧道A
Service Tunnel A
JUNA 400 kV
A1
A2
JUNA
天体物理
实验厅A
Hall A
中微子
实验
AB连接隧道
Connecting Tunnel AB
B1
B2
B3
B4
服务隧道B
Service Tunnel B
中间连接隧道
Middle Connecting Tunnel
无中微子衰变
实验
double
beta decay
实验厅B
Hall B
C1
C2
服务隧道C
Service Tunnel C
辅1门
Auxiliary Gate No.1
1号辅助隧道
No.1 Auxiliary Tunnel
排水隧道
Draining Tunnel
交通隧道B
Traffic Tunnel B
交通隧道A
Traffic Tunnel A
PANDAX
暗物质物理实验
(常温水屏蔽)
dark matter
dark matter
暗物质物理实验
(低温液氮屏蔽)
实验厅C
Hall C
低本底
中心
服务隧道D
Service Tunnel D
CD连接隧道
Connecting Tunnel CD
CDEX
D1
D2
无中微子衰变
实验
double
beta decay
实验厅D
Hall D
中微子
实验
neutrino
辅助隧道 Auxiliary Tunnel
交通隧道 Traffic Tunnel
排水隧道 Draining Tunnel
世界上重要的地下实验室比较图
地下实验室深度（米）
500
1000
1500
2000
2500
600m Soudan 美国
700m Y2L 韩国
800m Canfranc 西班牙
1000m Kamioka 日本
1100m Boulby 英国
1400m INO 印度
1400m LNGS 意大利
1500m DUSEL 美国
1600m Baksan 俄罗斯
1700m Modane 法国
2100m SNO 加拿大
2400m CJPL 中国
矿井
隧道
空间尺寸
10³
10⁴
10⁵
2×10⁵
3×10⁵
(m³)
地下实验室宇宙线注量率（每年每平米）
10⁵
10⁴
10³
10²
10

JUNA Management

Group leader



Weiping Liu **PI**

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

Yangping Shen, CIAE

Jun Su, BNU

中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

SDIC 国投集团 SDIC GROUP

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

Acc. installation
Aijun Li

A1 construction
Hongwei Yang

Site support
Xiaopan Cheng

Acc. operation
Long Zhang

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

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

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

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

Jun Su, BNU

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

Gang Lian
Lab. exp. sup.
CIAE

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

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

JUNA funding

JUNA

NSFC $2.9+M

CAS $0.65M

CNNC $1.6 M

CJPL-II / Tsinghua ~$3+M

国家自然科学基金委员会
National Natural Science Foundation of China

中国科学院
CHINESE ACADEMY OF SCIENCES

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)

中核集团
CNNC

total $8+ M

Will apply for SUPER JUNA and international collaborations are warmly welcome!

JUNA Team

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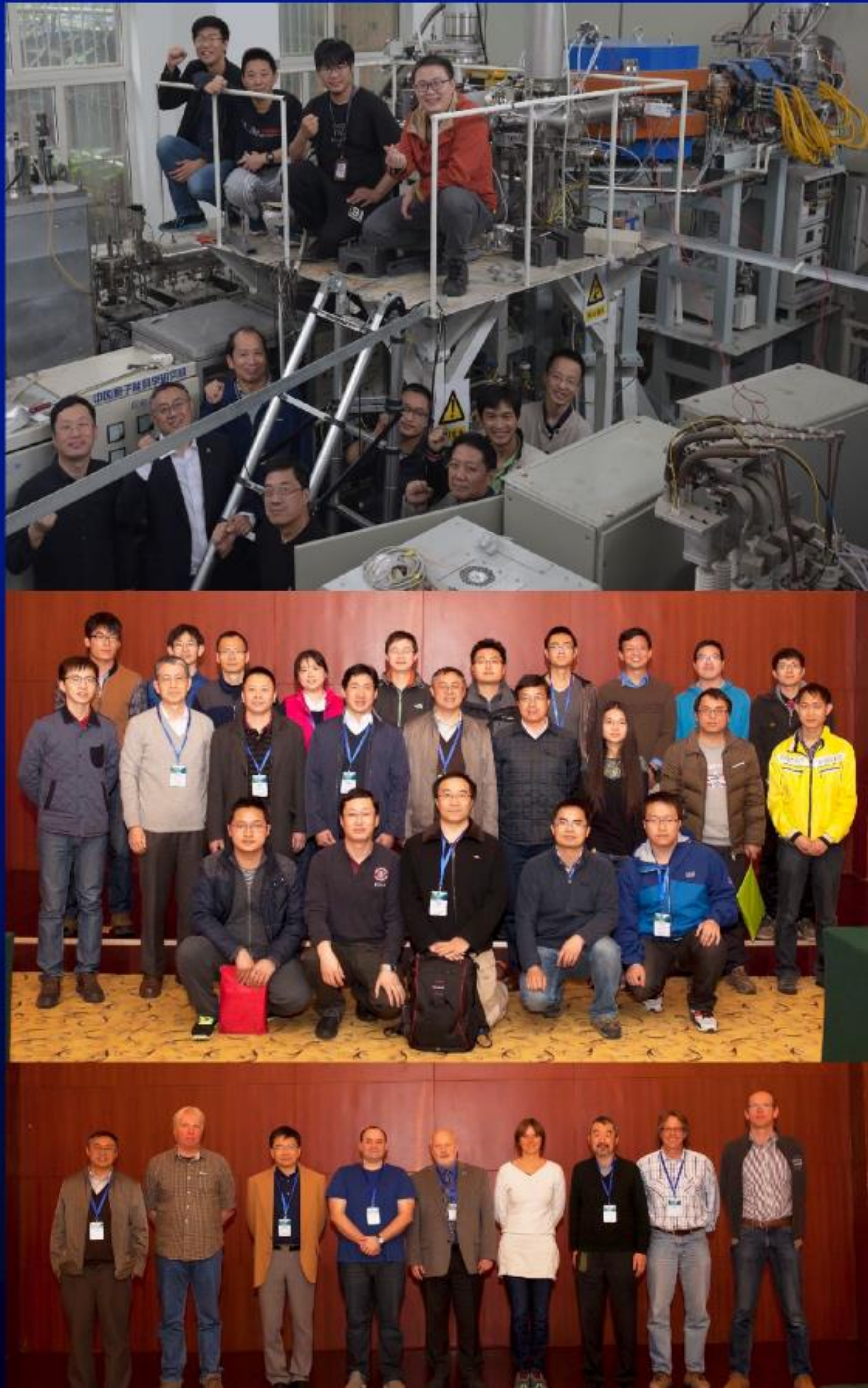


JUNA IAC

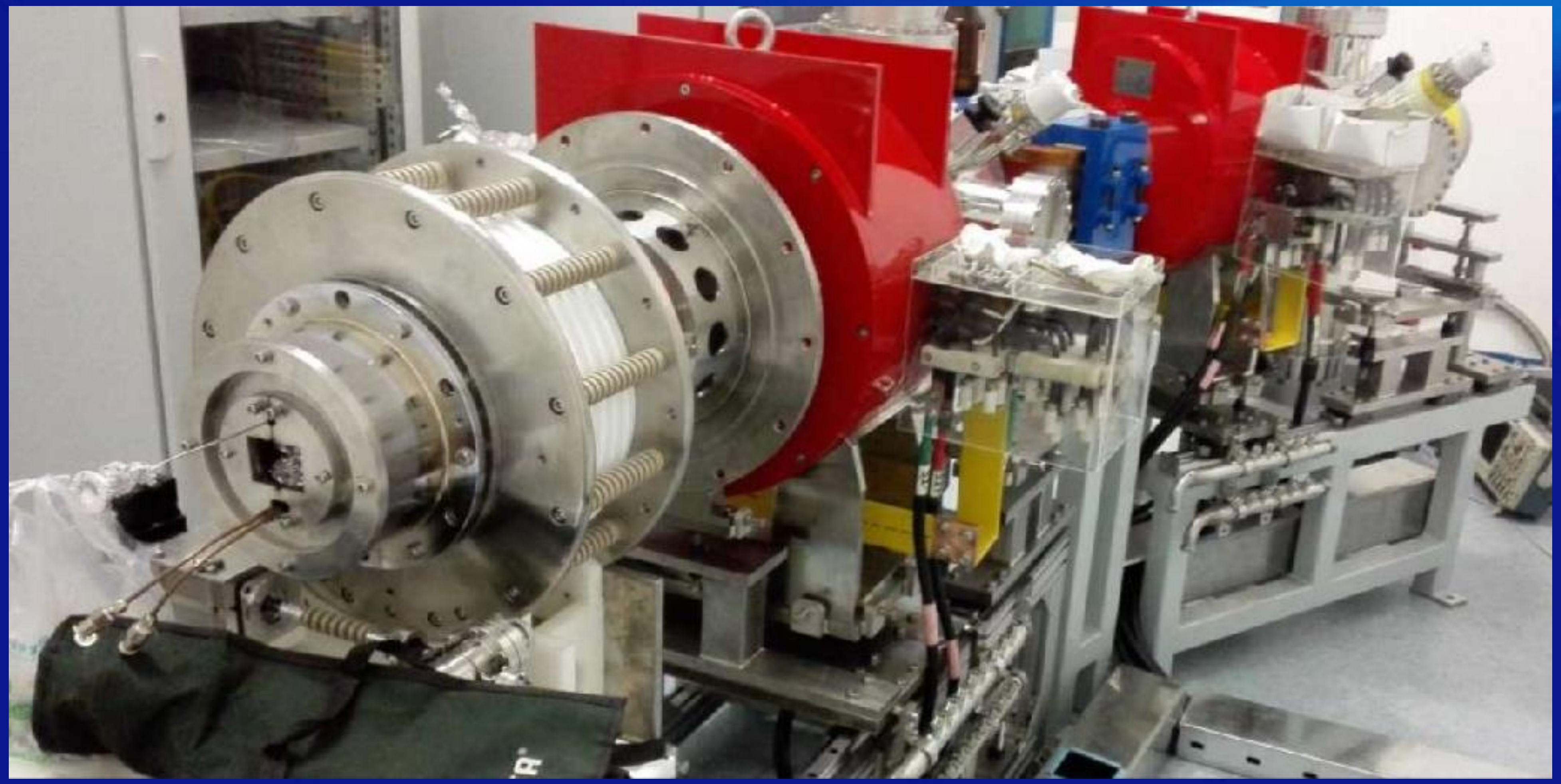
M. Wiescher	UND
T. Motobayashi	RIKEN
H. Wang	TCAS
C. Brune	Ohio
M. Junker	INFN
D. Robertson	UND
F. Strieder	SDSMT
D. Leitner	LBL
Q. Yue	THU

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

Ion source and accelerator



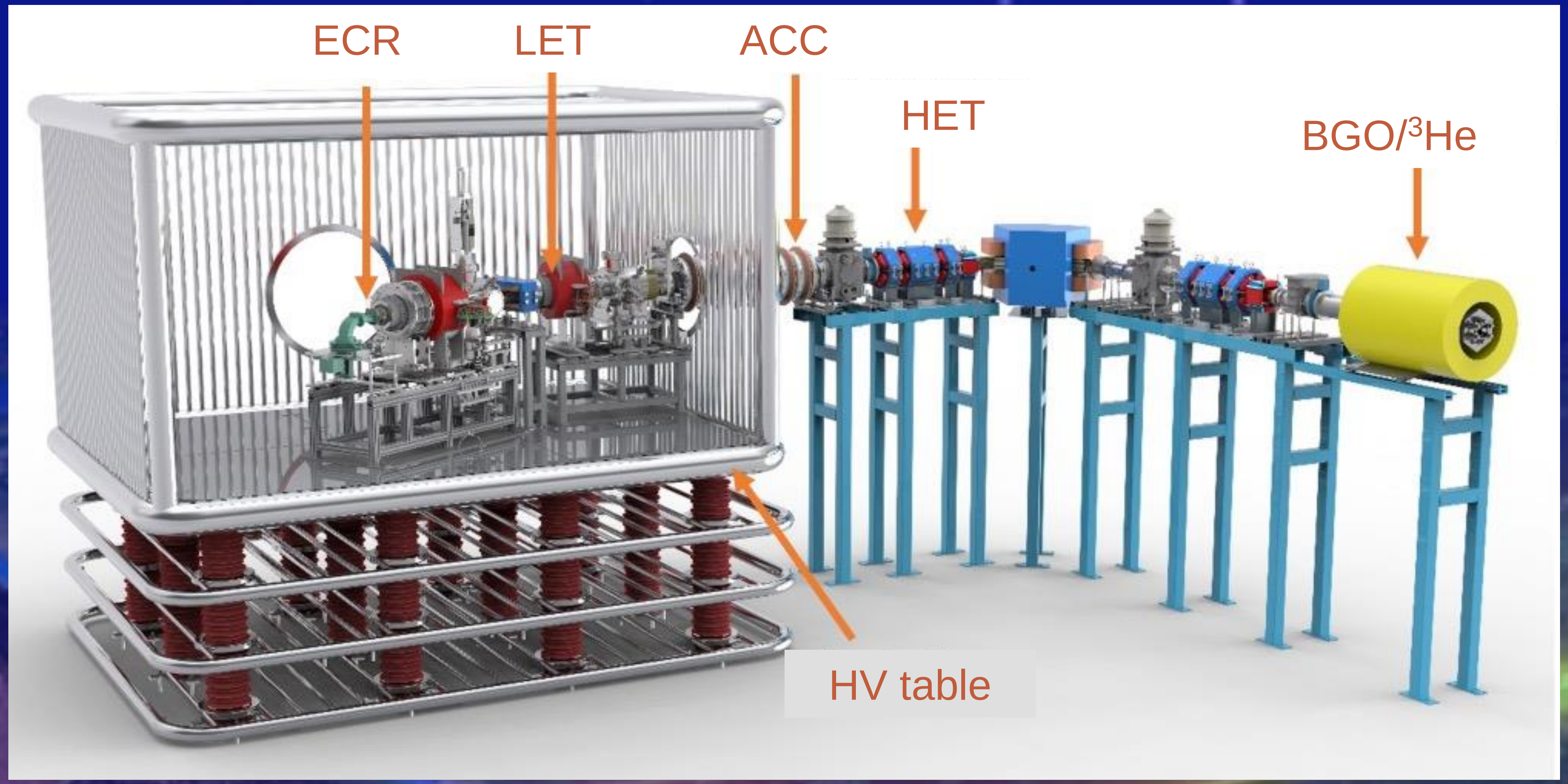
Ion source 1 mA in Jul. 2016, 16 mA in Oct.

Accelerator HV platform installed in Aug. 2016

First proton beam of 260 keV and 3 mA in May 2017

Beam	Intensity pmA	Energy keV	ECR GHz
H^+	12	400	2.45
He^+	10	400	2.45
He^{++}	1	800	14.5

WPL et al., Sci China 59 (2016) 642001

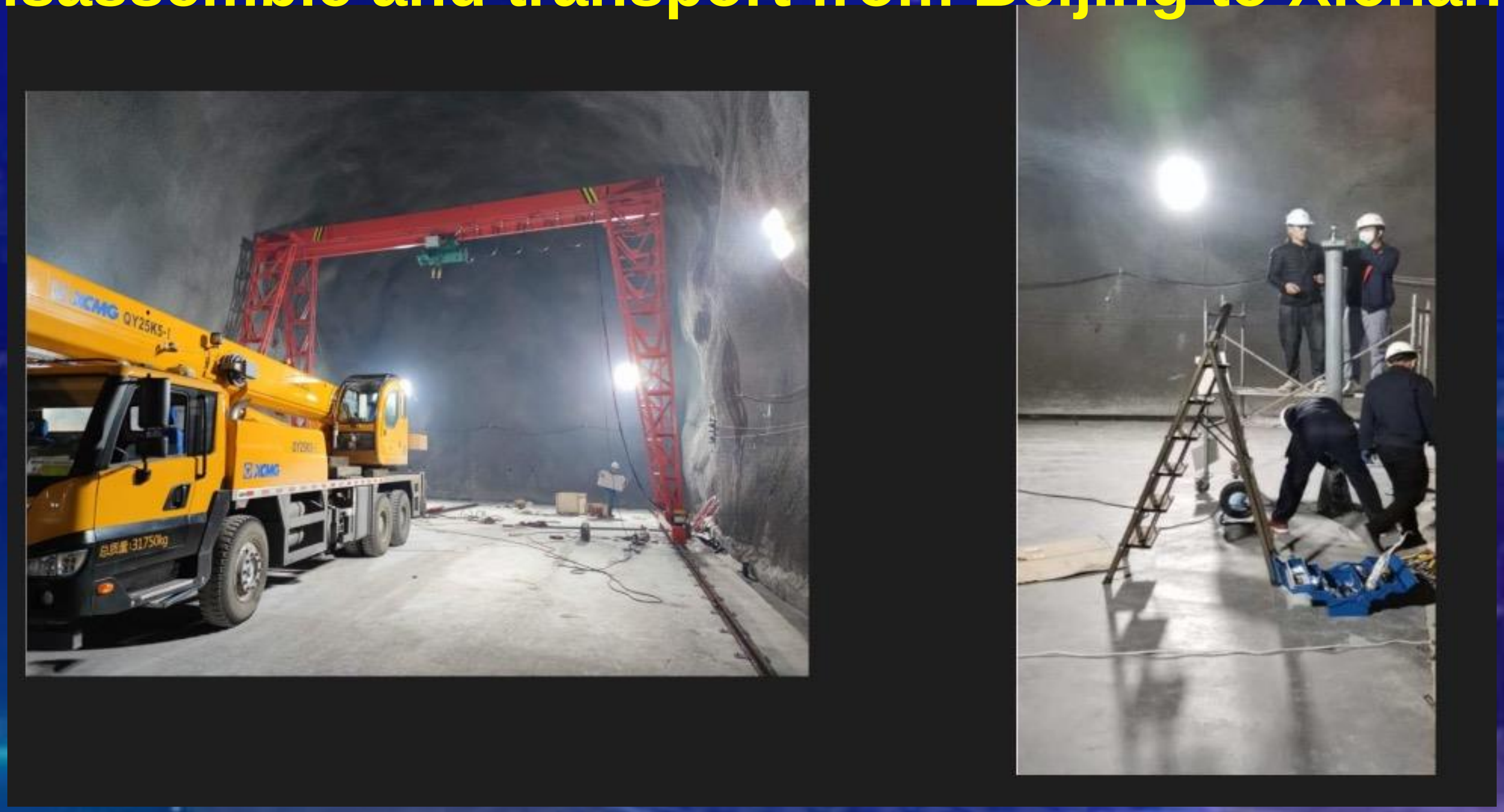


2020.10-2020.12

WPL et al., Sci China 59 (2016) 642001

farewell party above ground

disassemble and transport from Beijing to Xichang



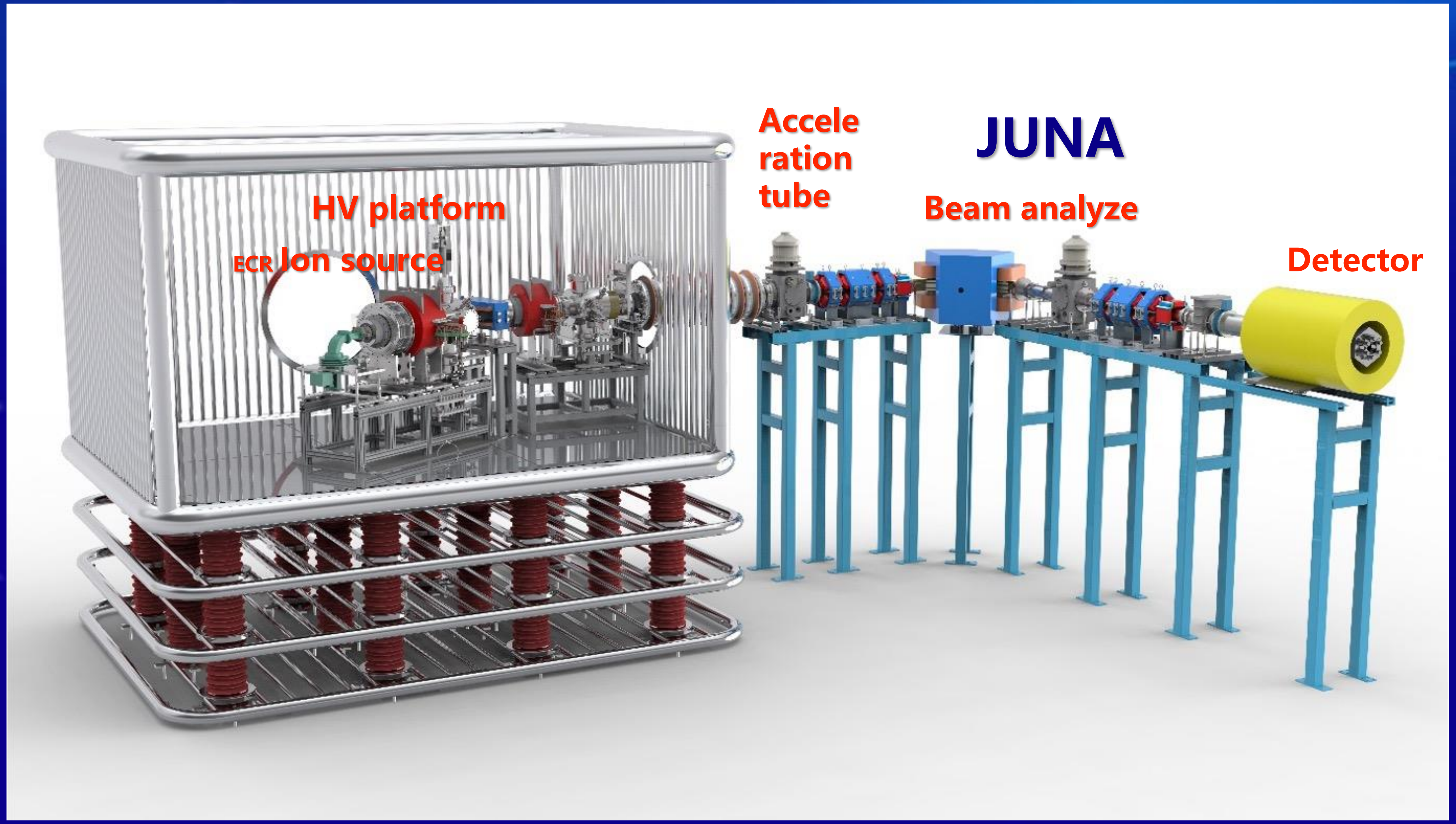
setup JUNA lab in CJPL II A1

ECR source and acceleration tube

beam transport and detector

Unique capabilities

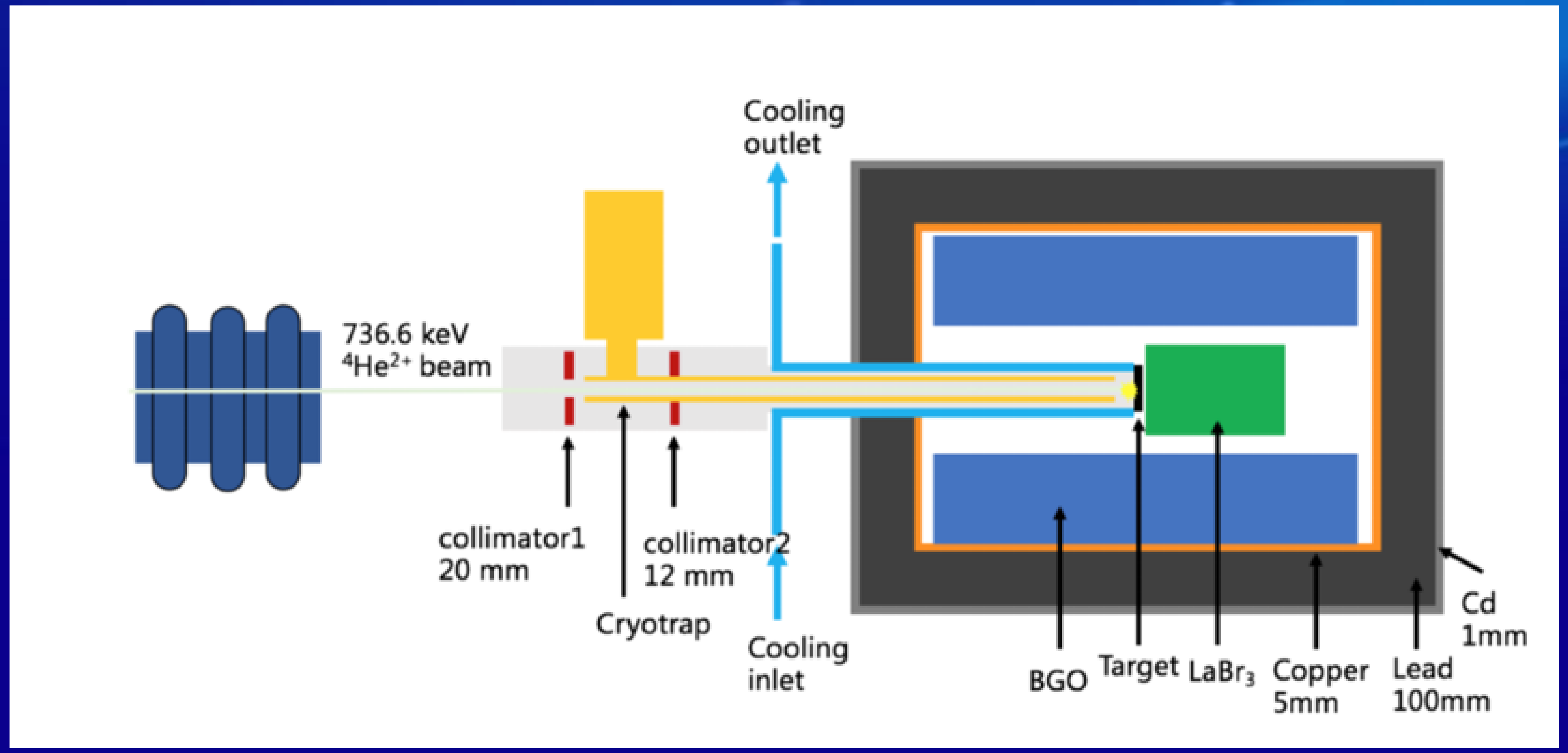
锦屏深地核天体物理实验
Jinping Underground Nuclear Astrophysics Experiment



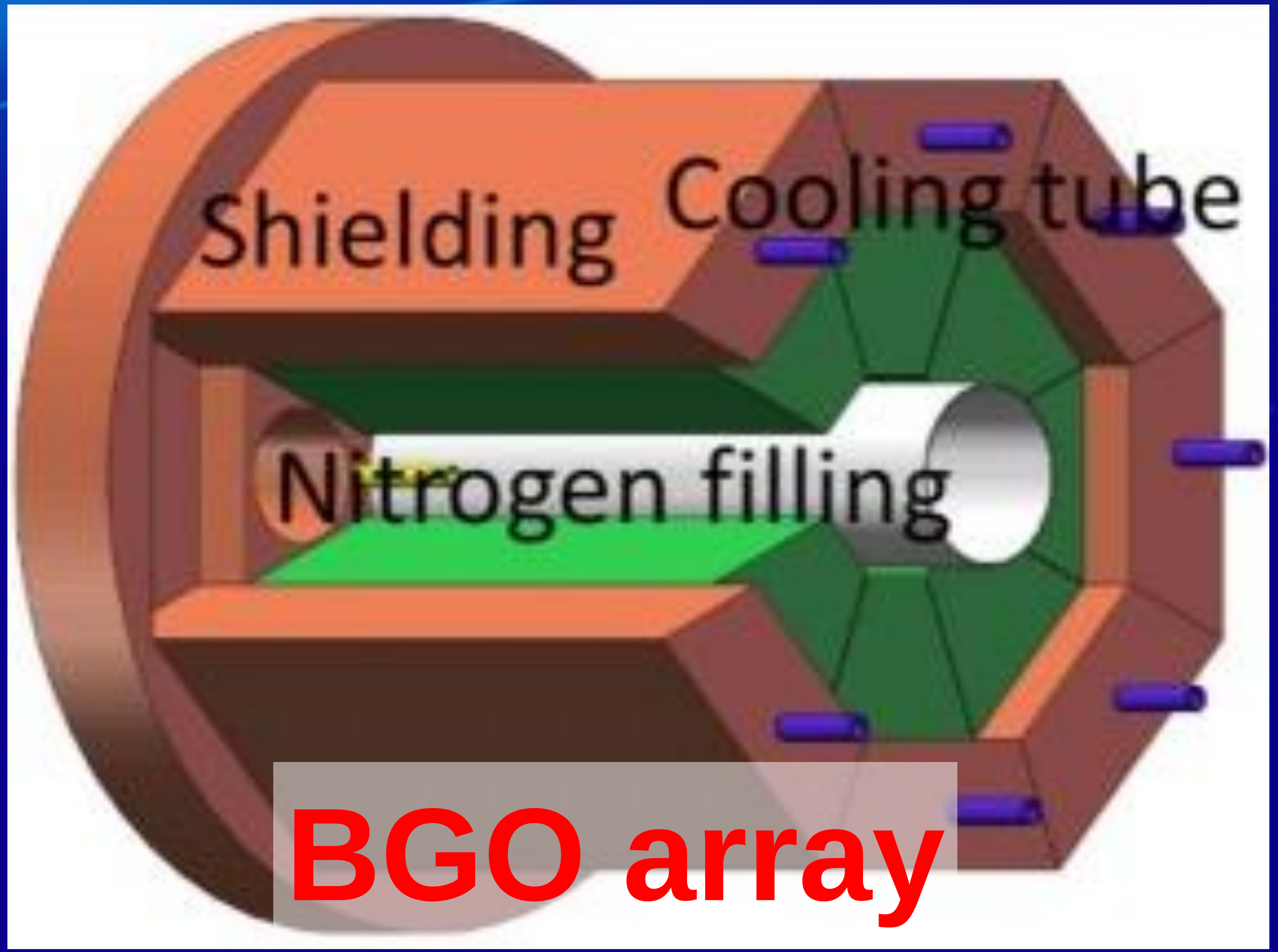
	cosmic muon bkg ($cm^{-2}\,s^{-1}$)	beam energy (keV)			beam intensity (emA)			energy stability
		H^+	He^+	He^{2+}	H^+	He^+	He^{2+}	
LUNA	2×10^{-8}	50-400	50-400	---	0.3~1	0.3~0.8	---	0.05%
CASPAR	4.4×10^{-9}	100-1000	100-1000	---	0.1	0.1	---	0.05%
JUNA	**2×10^{-10}**	50-400	50-400	**100-800**	**10**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

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

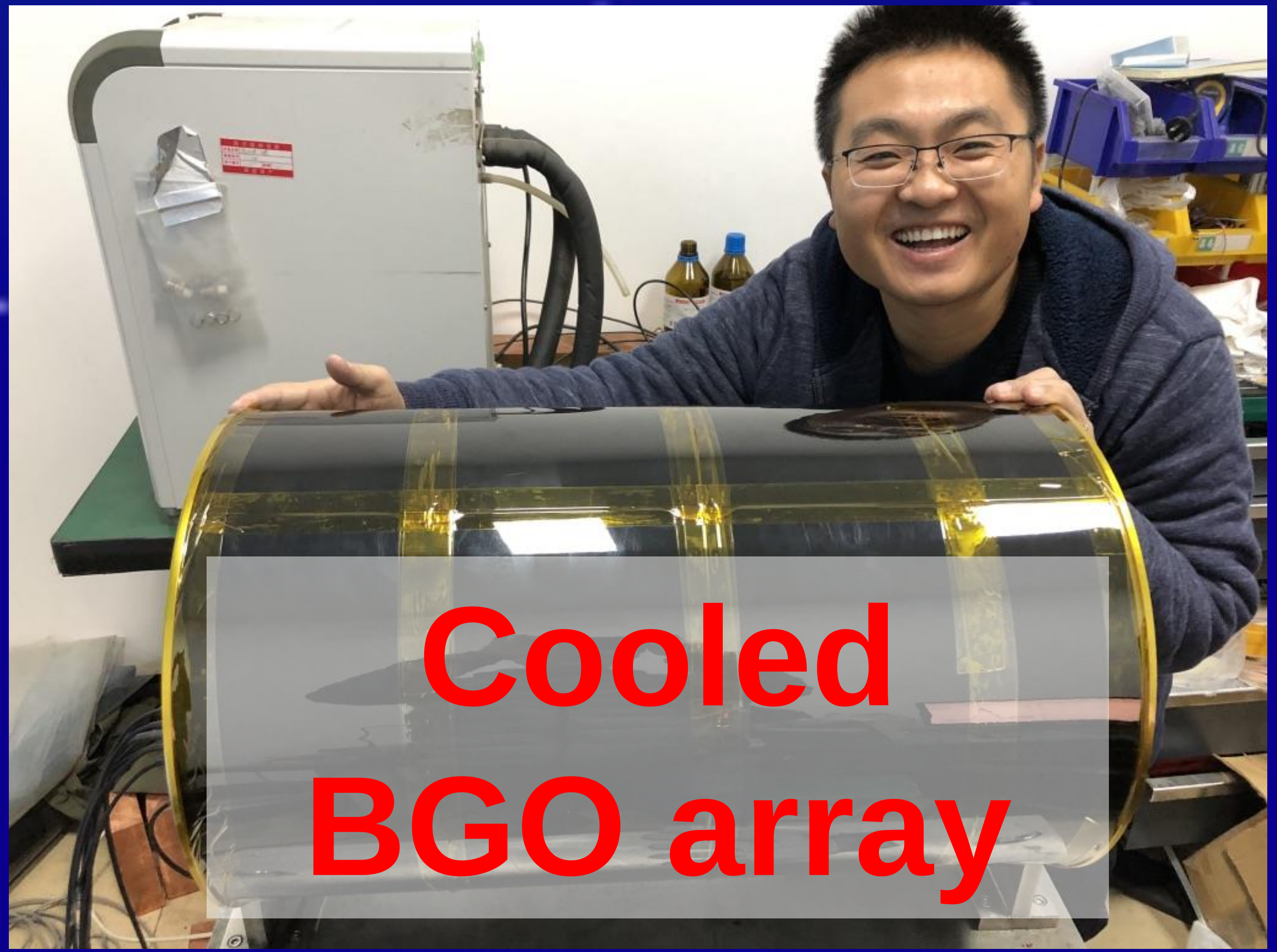
Detection systems



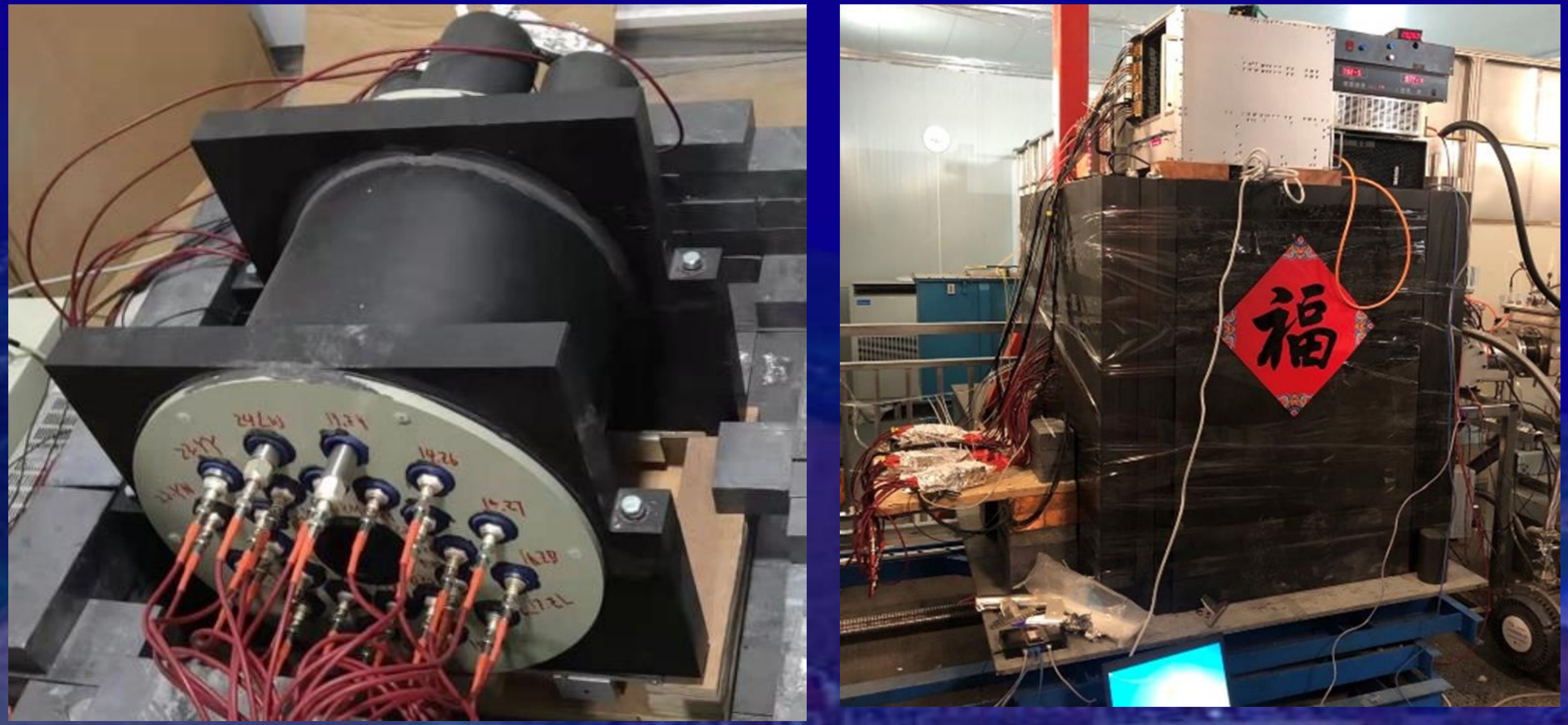
LaBr$_3$+BGO array



BGO array



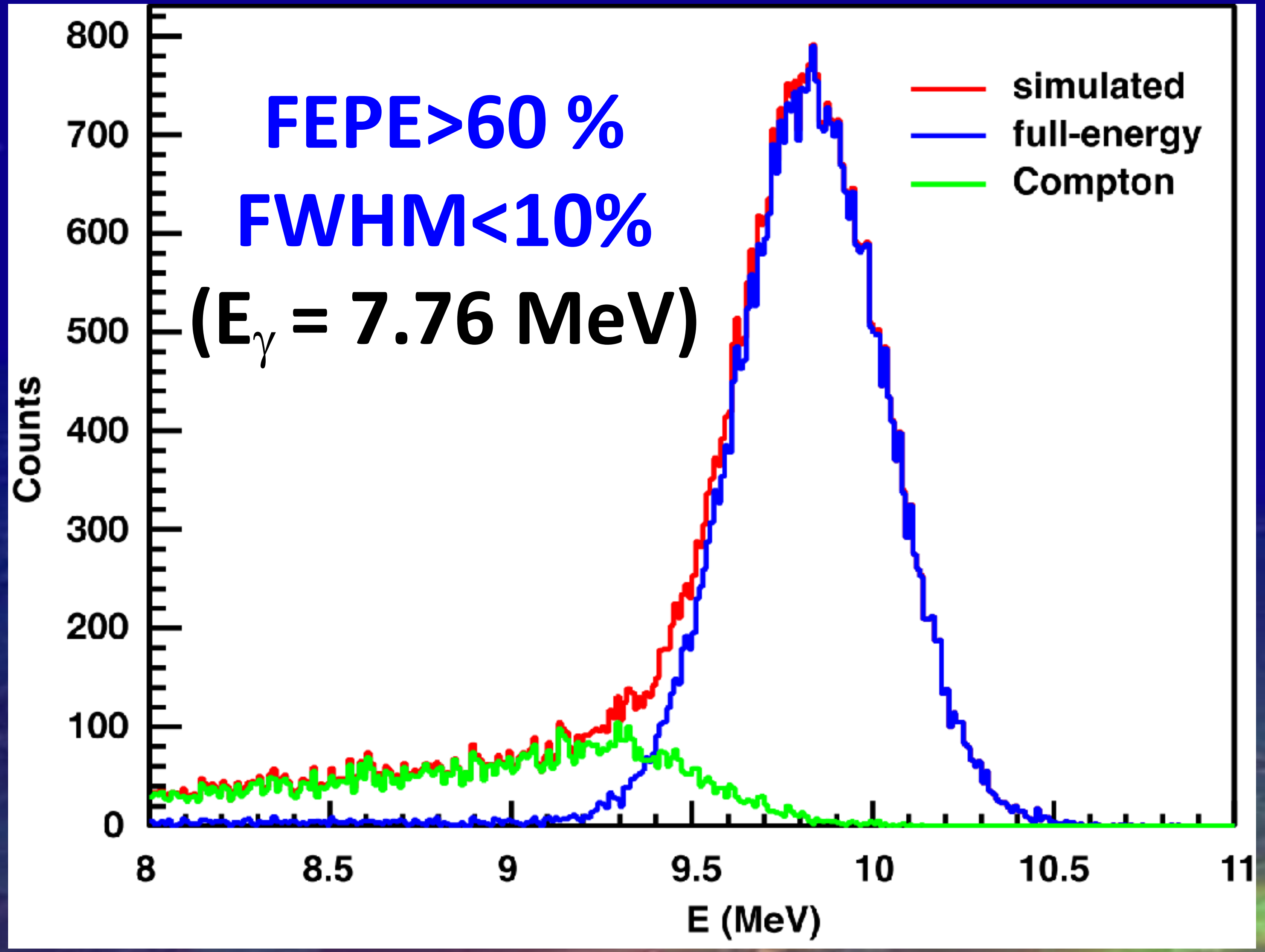
Cooled BGO array



^{3}He detector array

26%@2.5MeV neutron

Silicon array

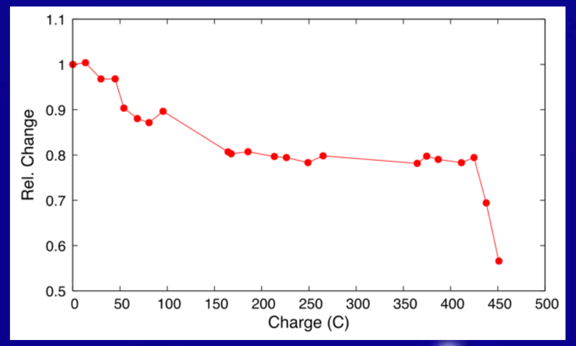


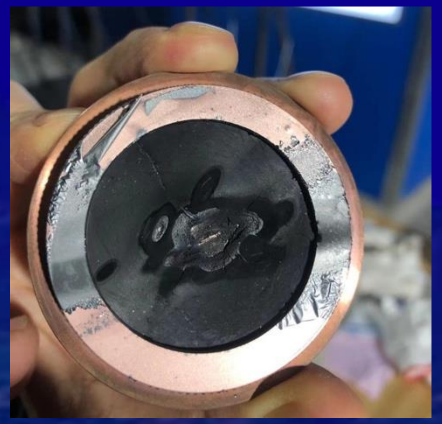
FEPE>60 %

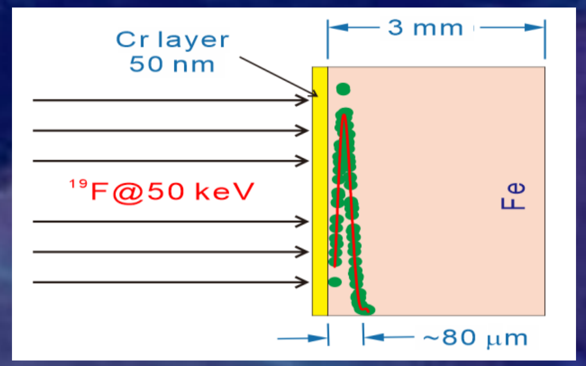
FWHM<10%

(E_γ = 7.76 MeV)

Target technologies

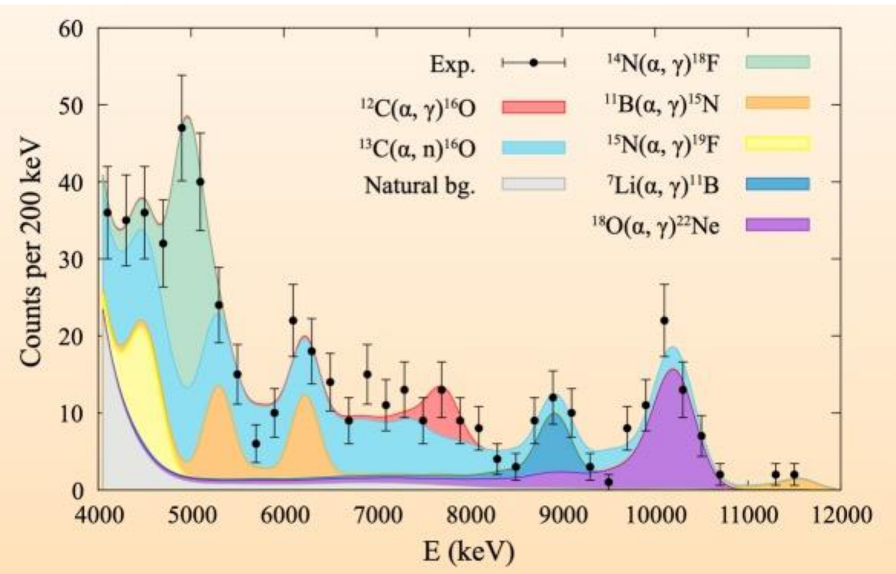


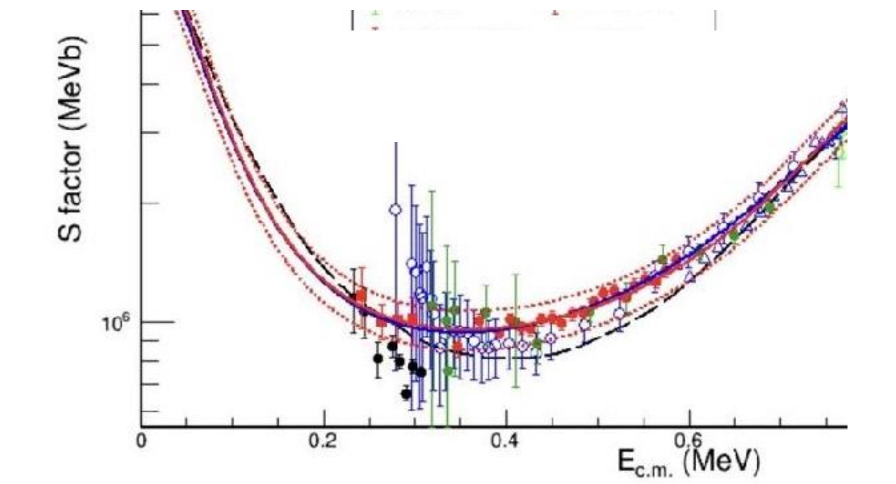


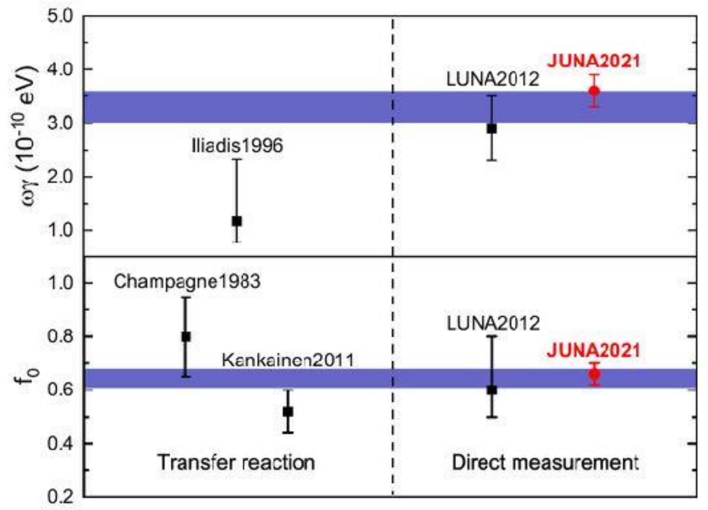


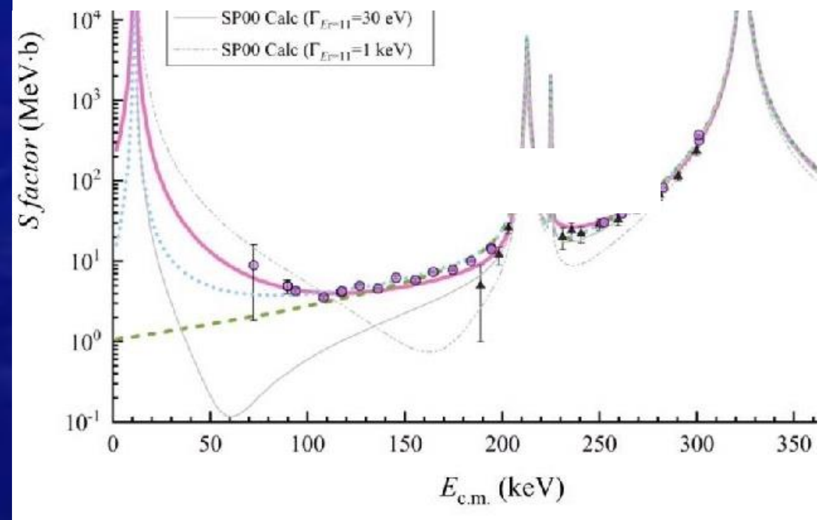
Target	Technology	Publication	Previous record	JUNA
^{12}C	Filter cathodic vacuum arc FCVA	1 patent	100 C	400 C
^{25}Mg	rotation+ Cr coating	NST31(2020)91	20 C	300 C
^{13}C	Enriched thick	In preparation	>100 targets	3 targets ~500 W
^{19}F	Implantation+ Cr coating	NIMB 438(2019)48 496(2012)9	0.02 mA	1 mA

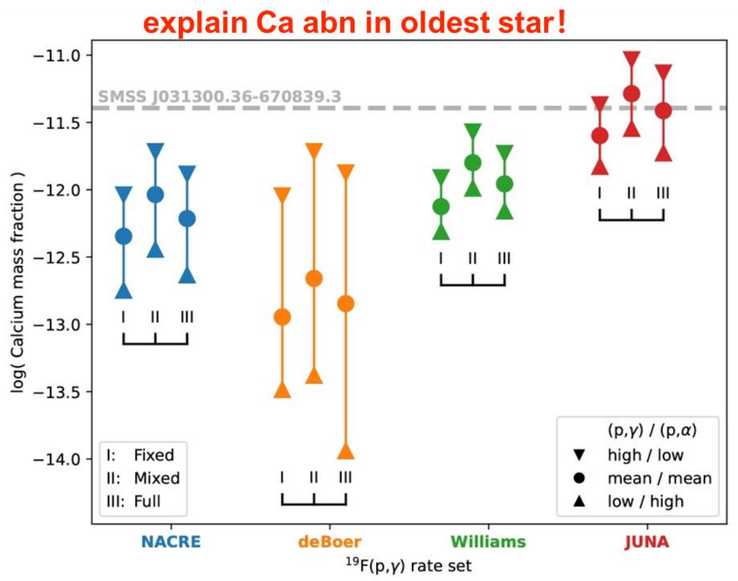
Summary of first campaign (2022.1-2022.4)





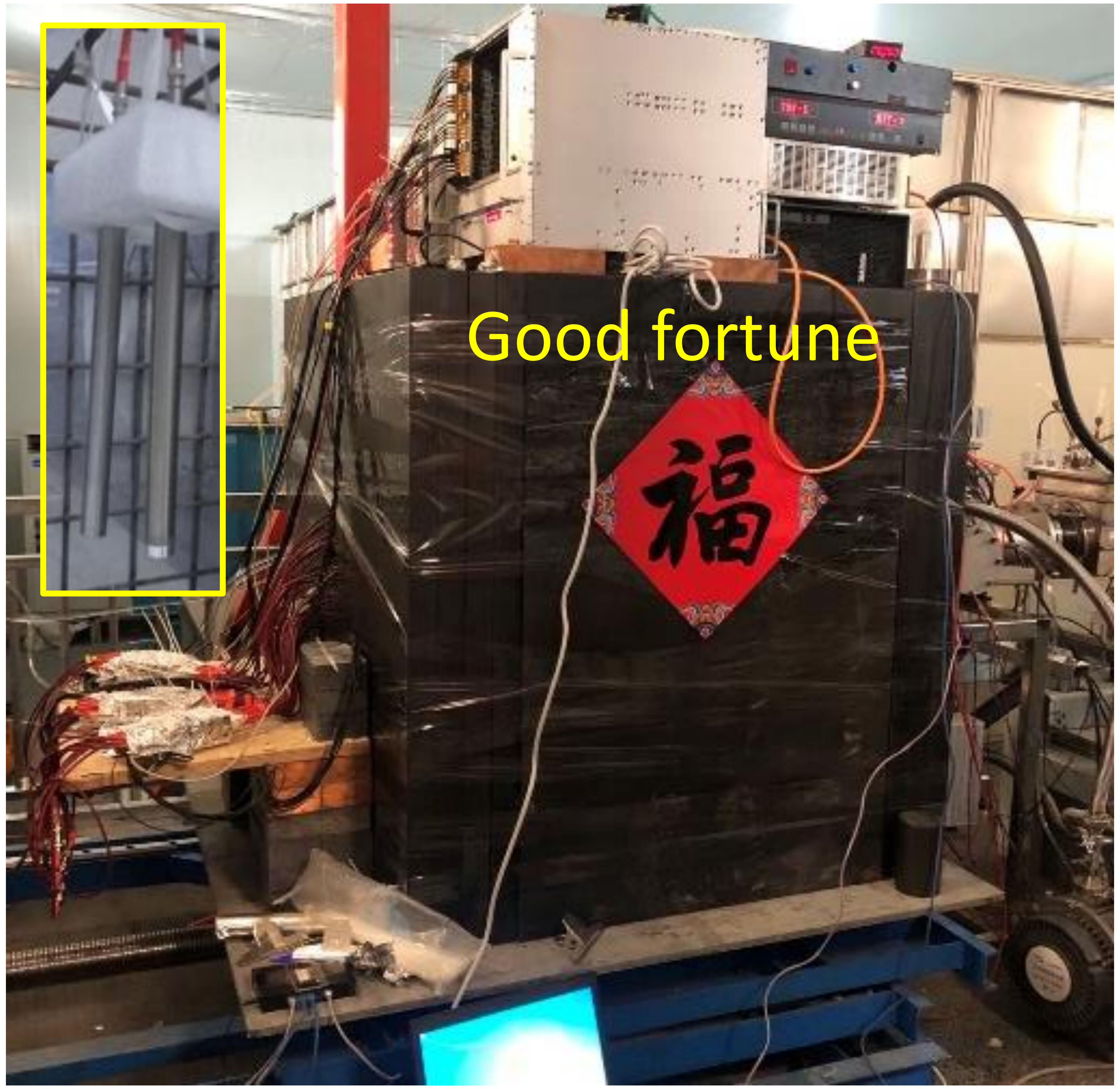


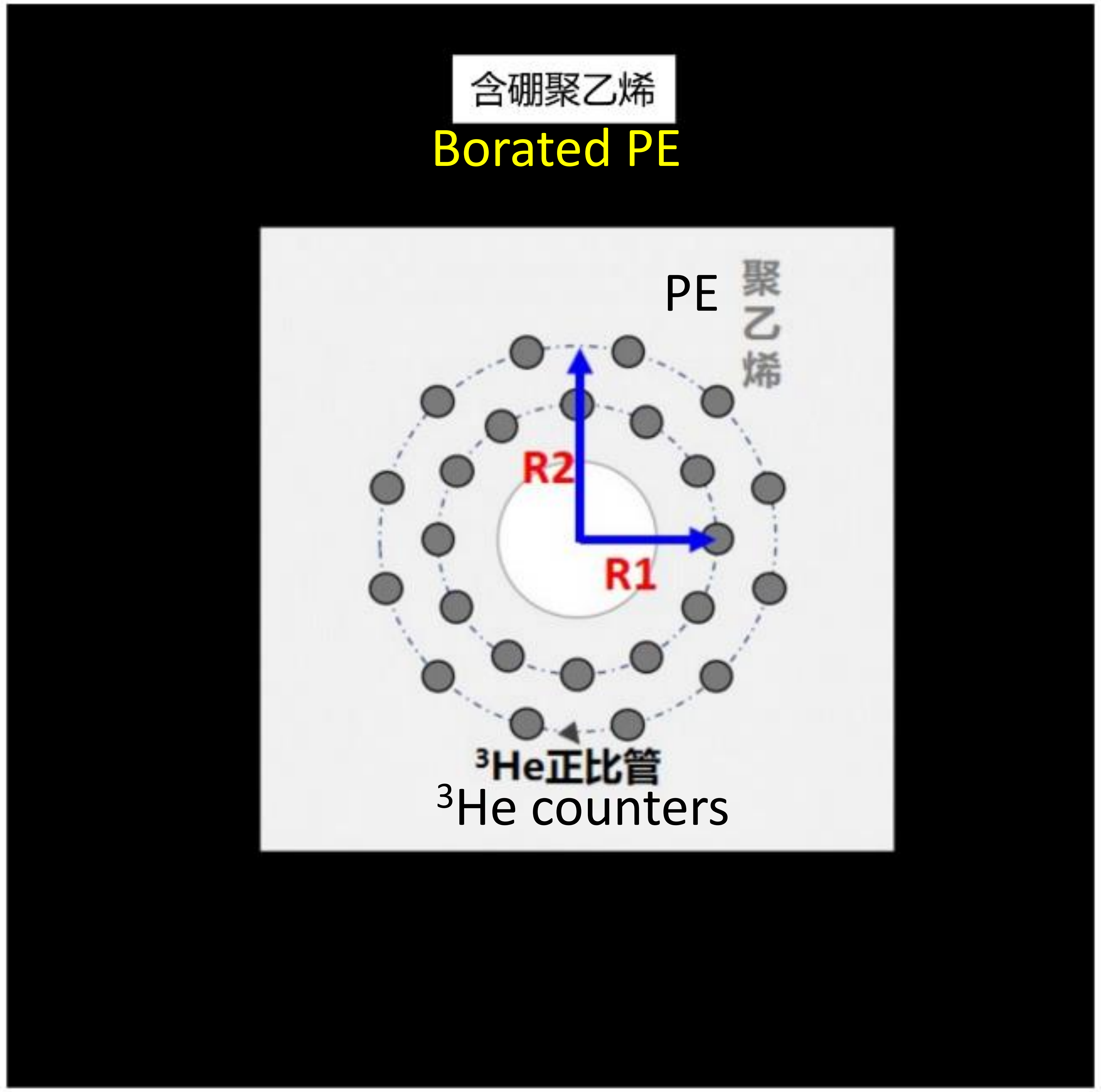




reaction	previous status	JUNA results	exposure C	intensity, mA
^{12}C(α,γ)^{16}O (^{18}O(a,γ)^{22}Ne, PRL 130(2023)092701)	60% 890 keV ~10^{-11} b	Upper limit 552 keV ~10^{-12} b	1034	1.0
^{13}C(α,n)^{16}O PRL 129, 132701 (2022)	60% 230-300 keV	~15% 240-1900 keV	350	0.5-2.0
^{25}Mg(p,γ)^{26}Al Sci Bull, 67(2022)125	21% 92 keV	8% 92 keV	1225	1.5
^{19}F(p,αγ)^{16}O *^{19}F(p,γ)^{20}Ne Nature (2022)* PRL 127(2021)152702	80 % 189 keV *300 keV*	5 % 72 keV *200 keV*		1.0

Low background neutron detector

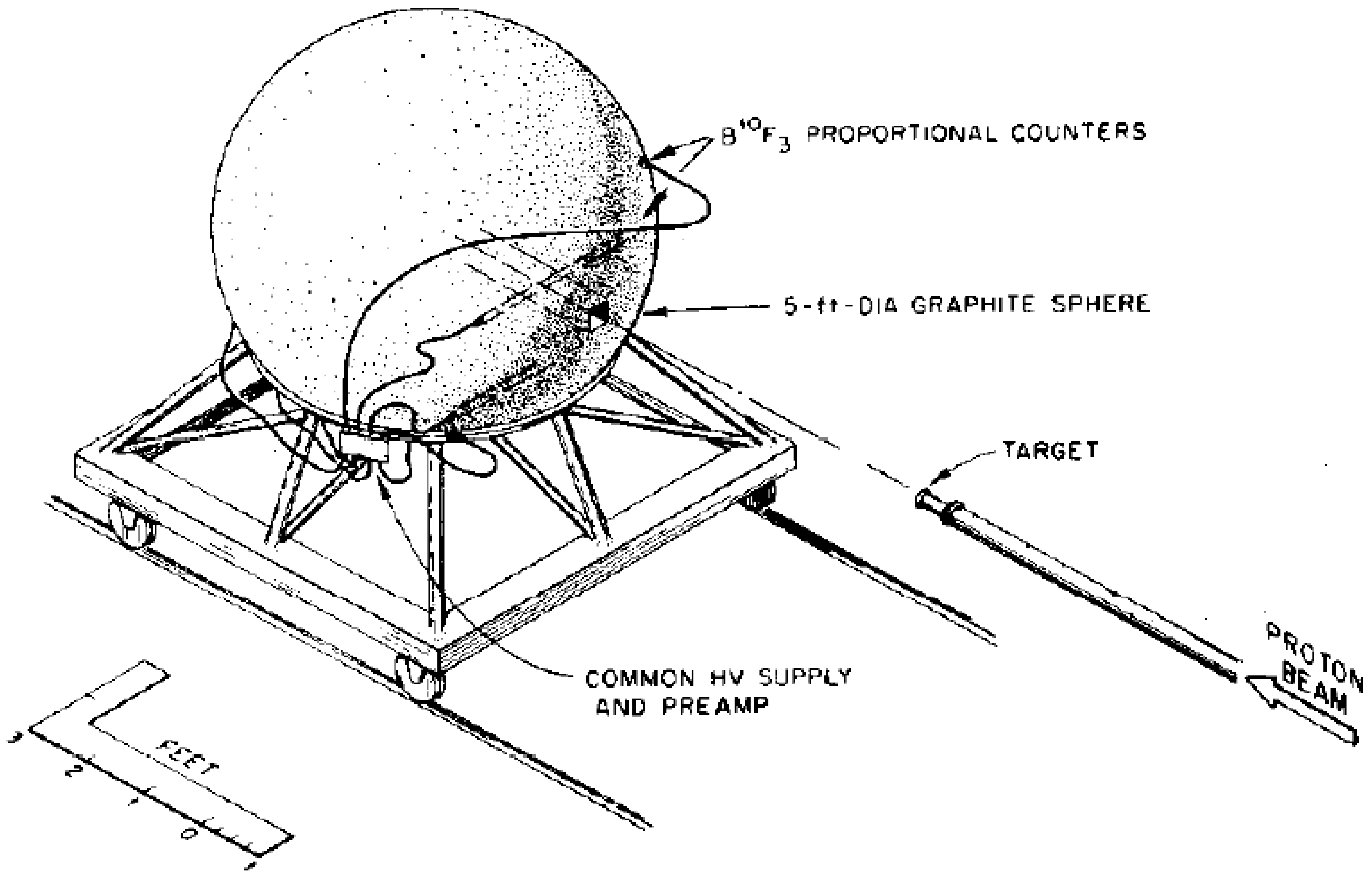


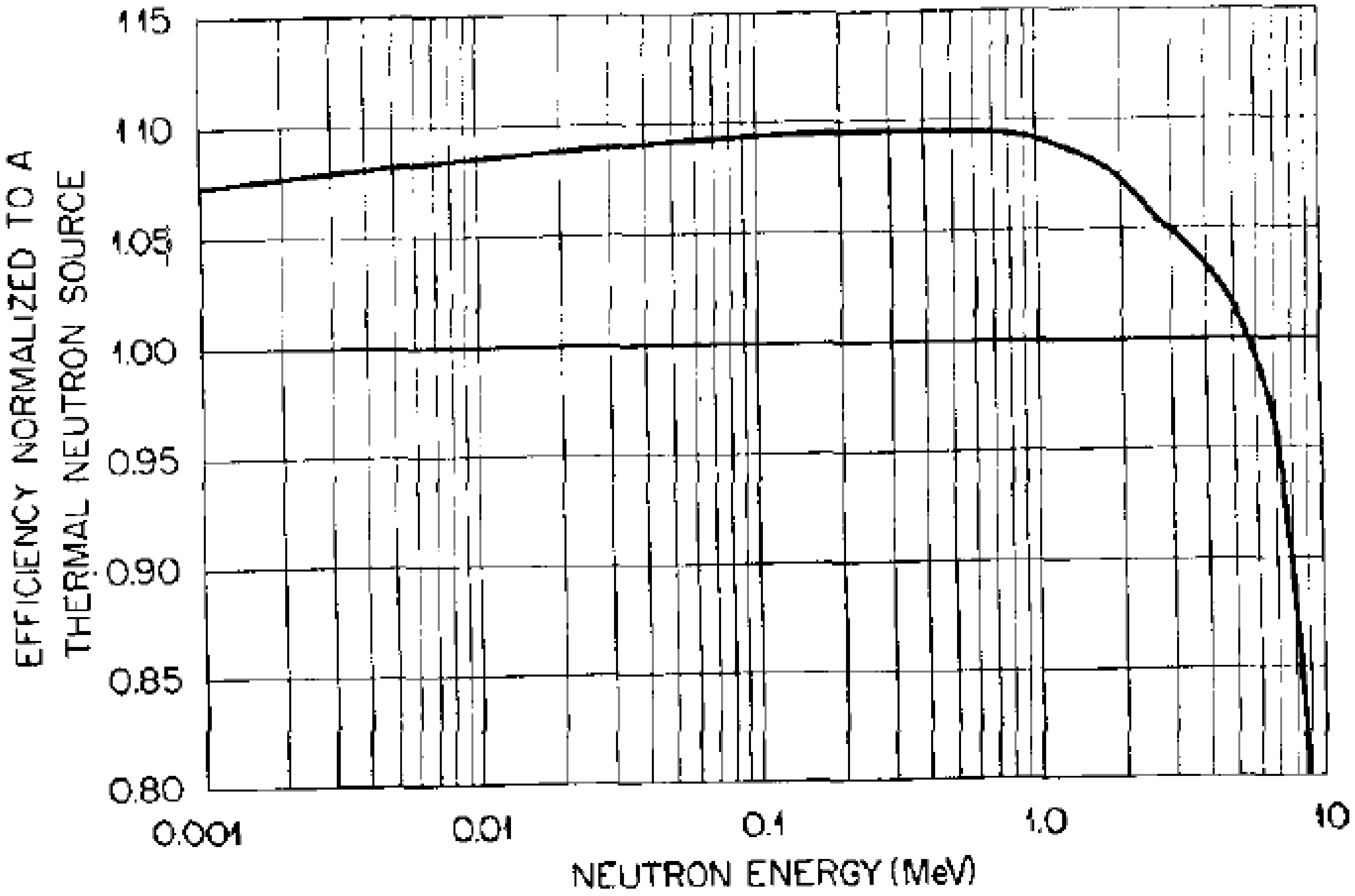


$24 \times {}^3$He counter + High Density PE + Borated PE

Y.T. Li, T.Y.Jiao, B.S. Gao, W.P.Lin et al. arXiv:2111.12552, NST(2022)33:41

GRAPHITE SPHERE NEUTRON DETECTOR



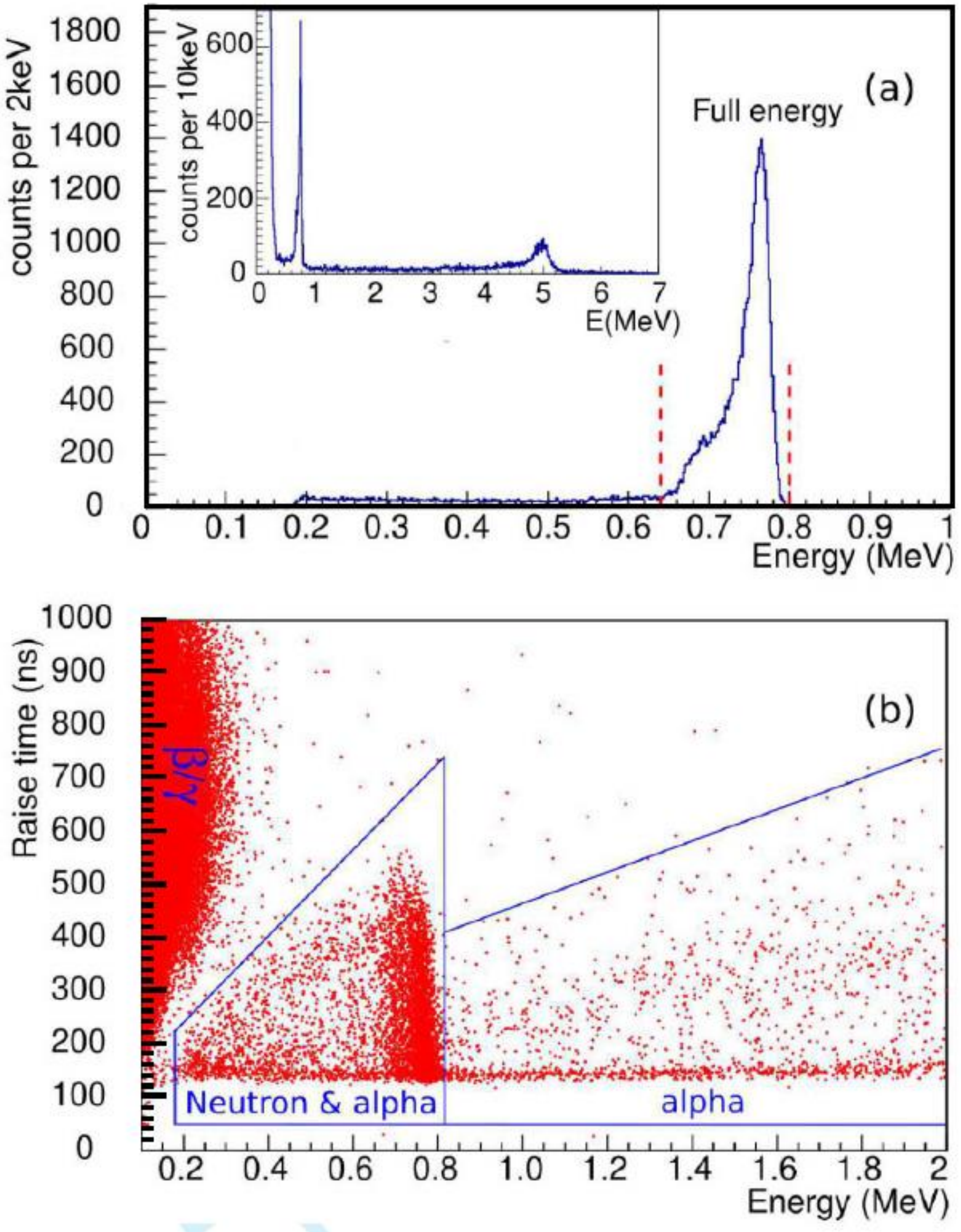


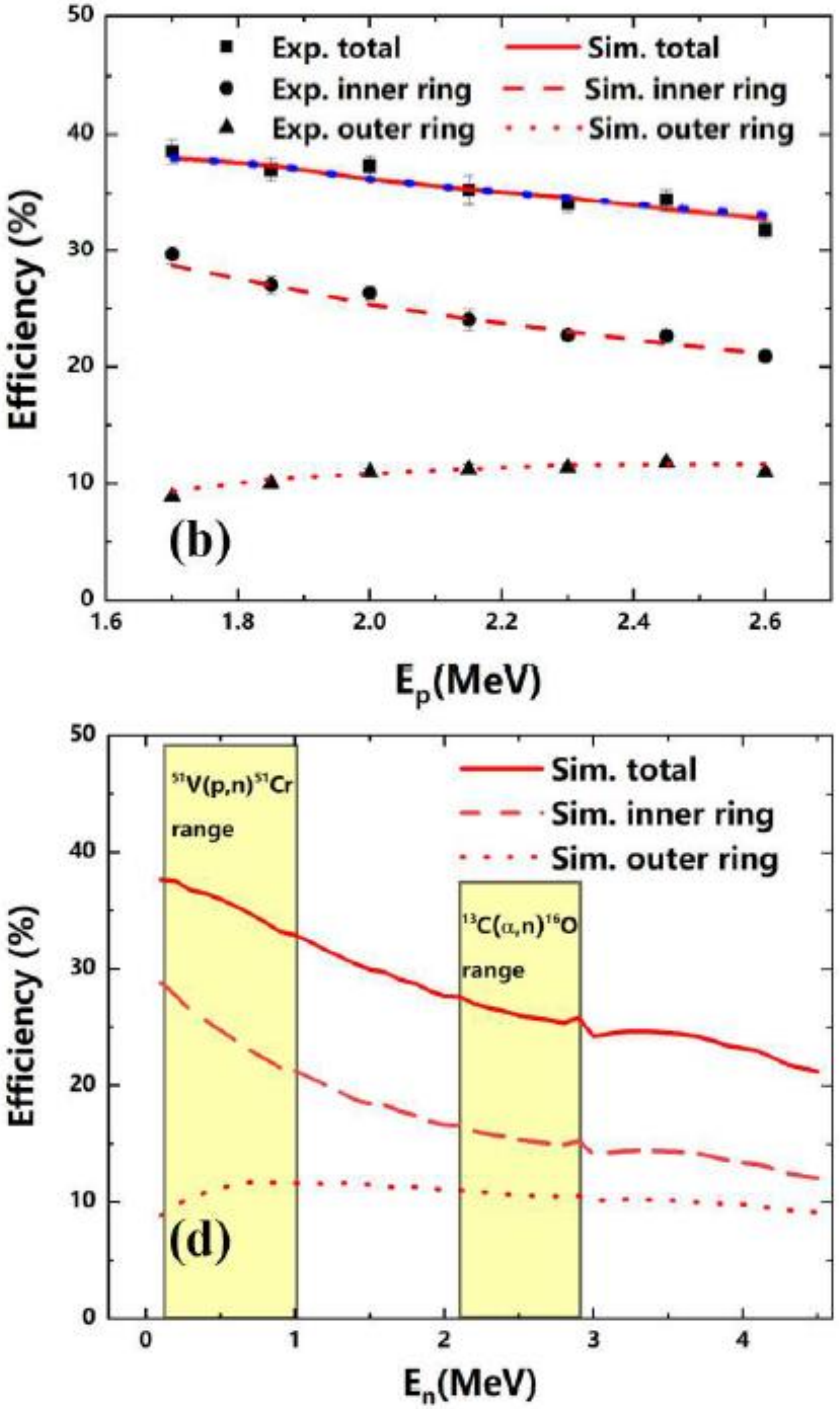
Relative Efficiency of Graphite Sphere with Central Neutron Source. $a = 80.0$ cm; $r = 69.7$ cm; $L = 48.8$ cm; $\rho = 1.652$ g/cm^3

An absolute calibration of a (NBS) standardized Sb-Be neutron source was performed by measuring the exit current of thermal neutrons with a thin wafer of ^{6}LiI(Eu) scintillator.

R. L. MACKLIN, NUCLEAR INSTRUMENTS 1 (1957) 335-339

Efficiency calibration w $^{51}V(p,n)^{51}Cr$



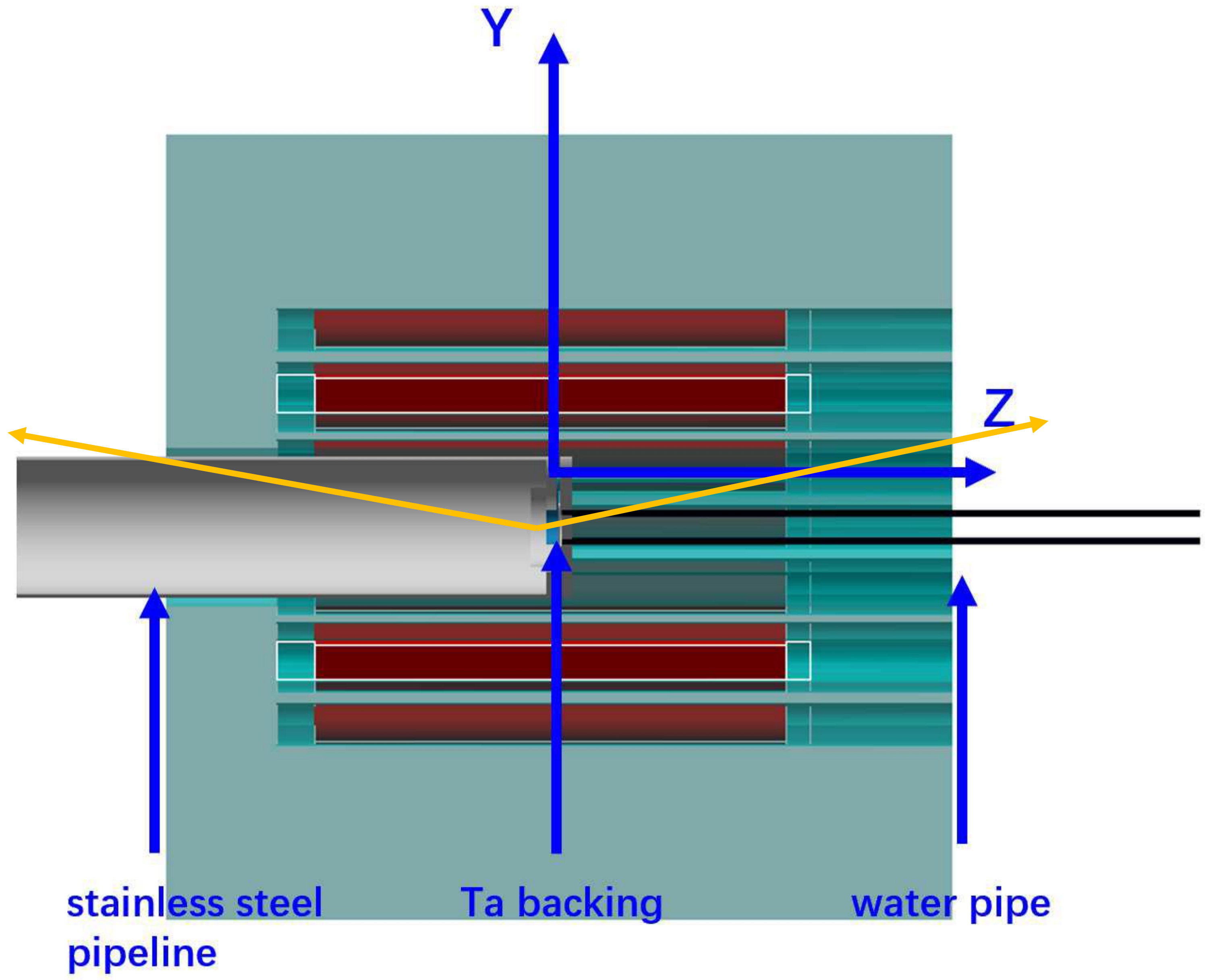


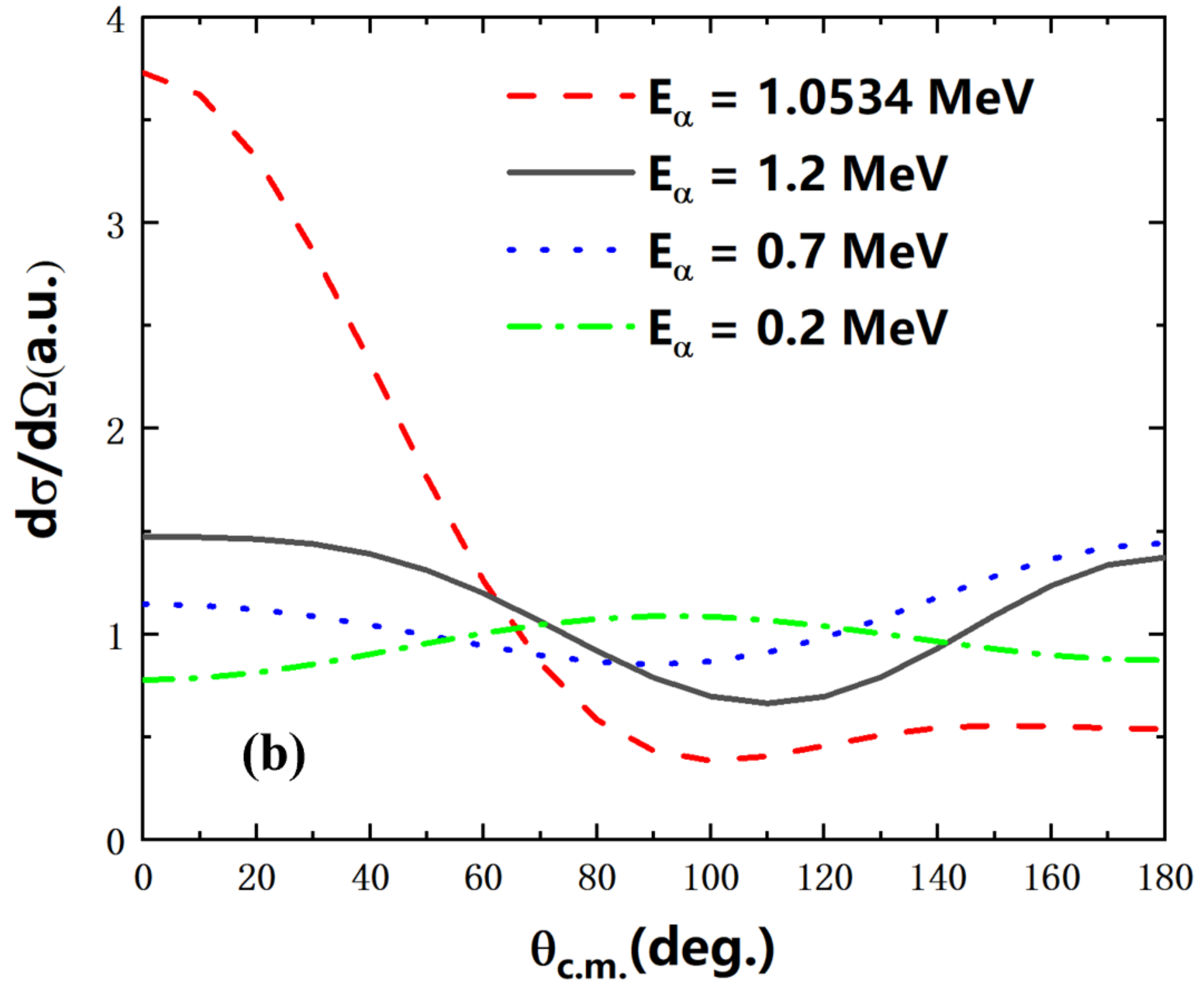
Any information of the angular distribution of $^{51}V(p,n)^{51}Cr$?

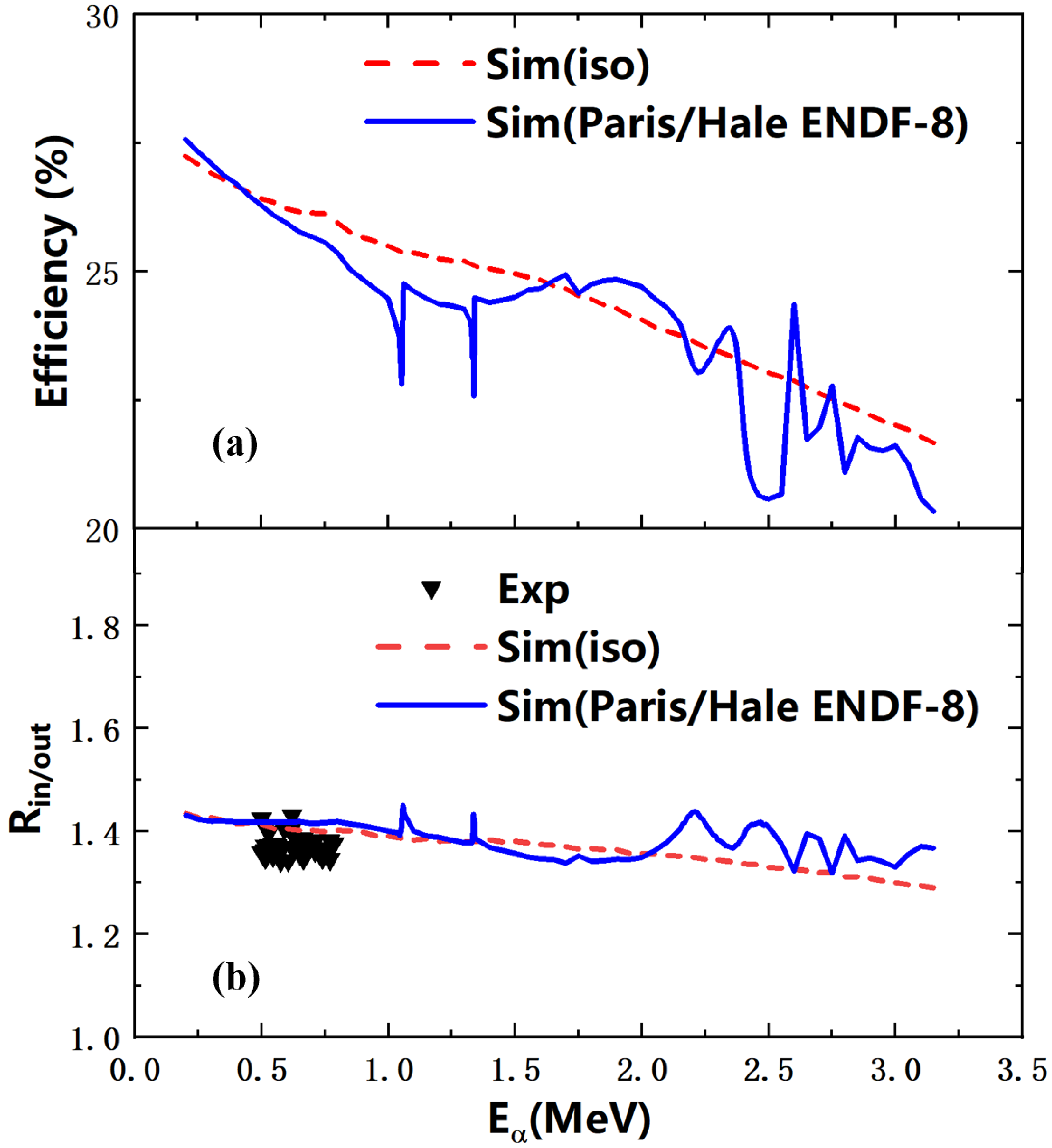
How to estimate the systematic uncertainty of extrapolation based on Geant4?

Y.T. Li, T.Y.Jiao, B.S. Gao, W.P.Lin et al. arXiv:2111.12552, NST(2022) 33:41

Effect of angular distribution

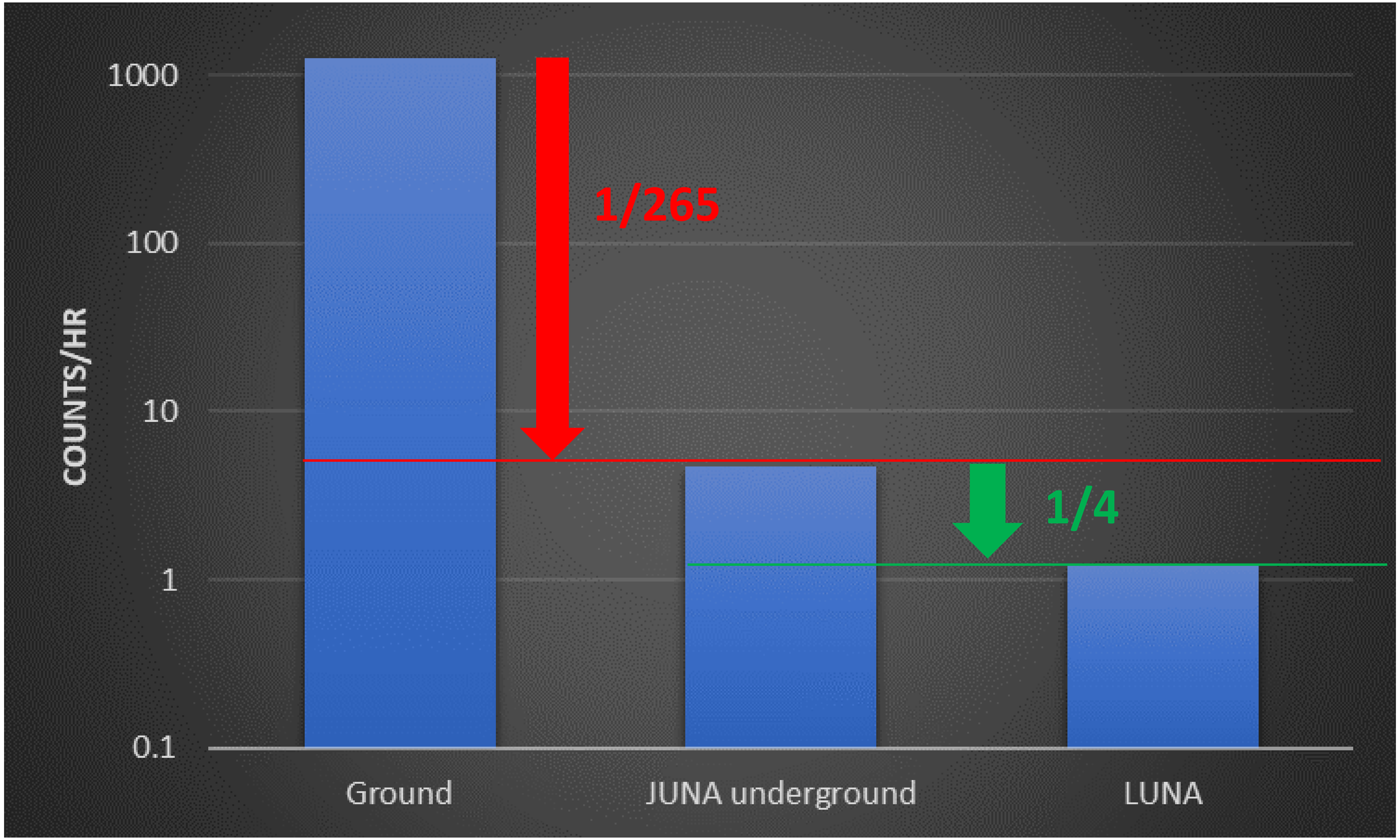






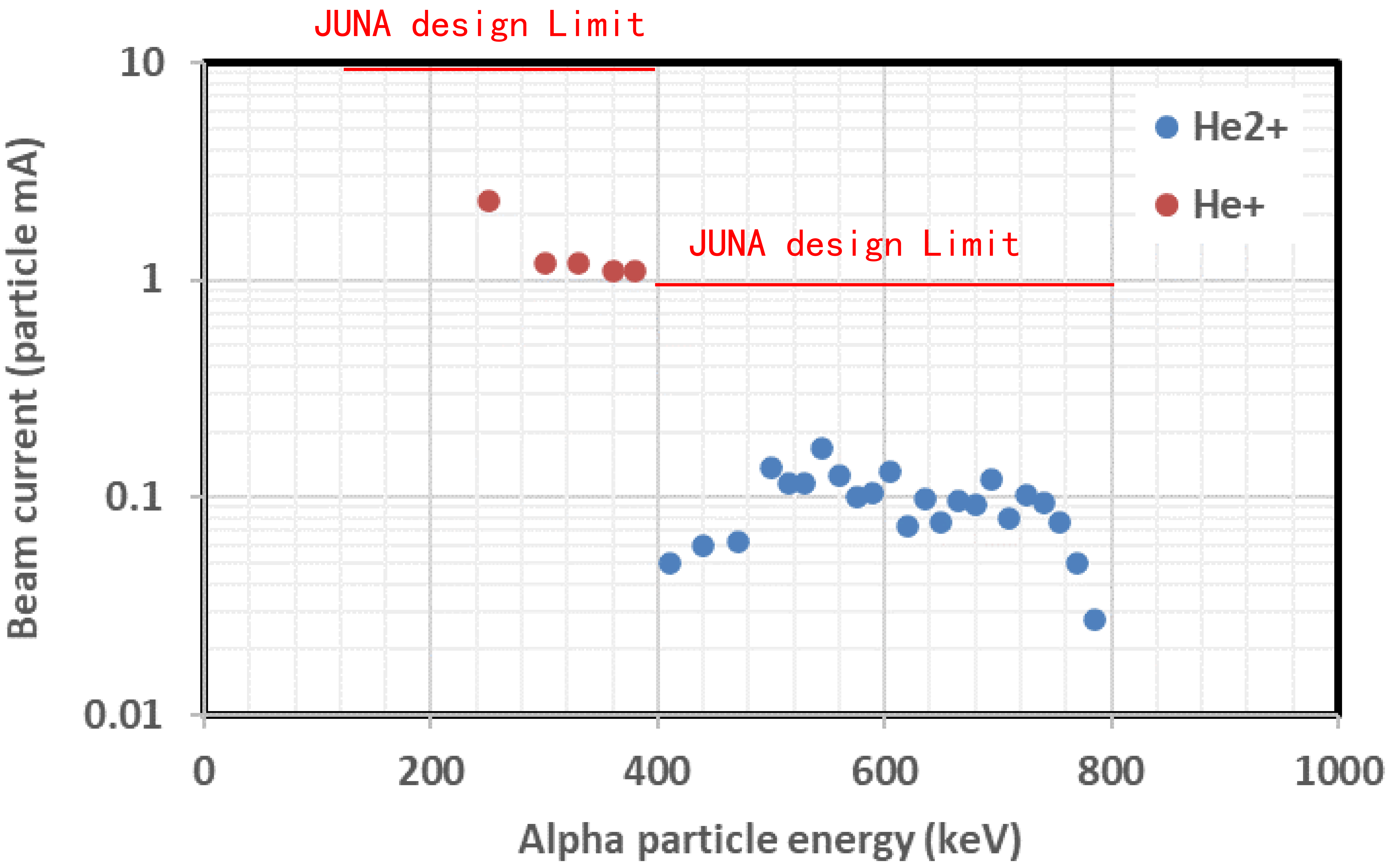
Y.T. Li, T.Y.Jiao, B.S. Gao, W.P.Lin et al. arXiv:2111.12552, NUCL SCI TECH (2022) 33:41

Natural background



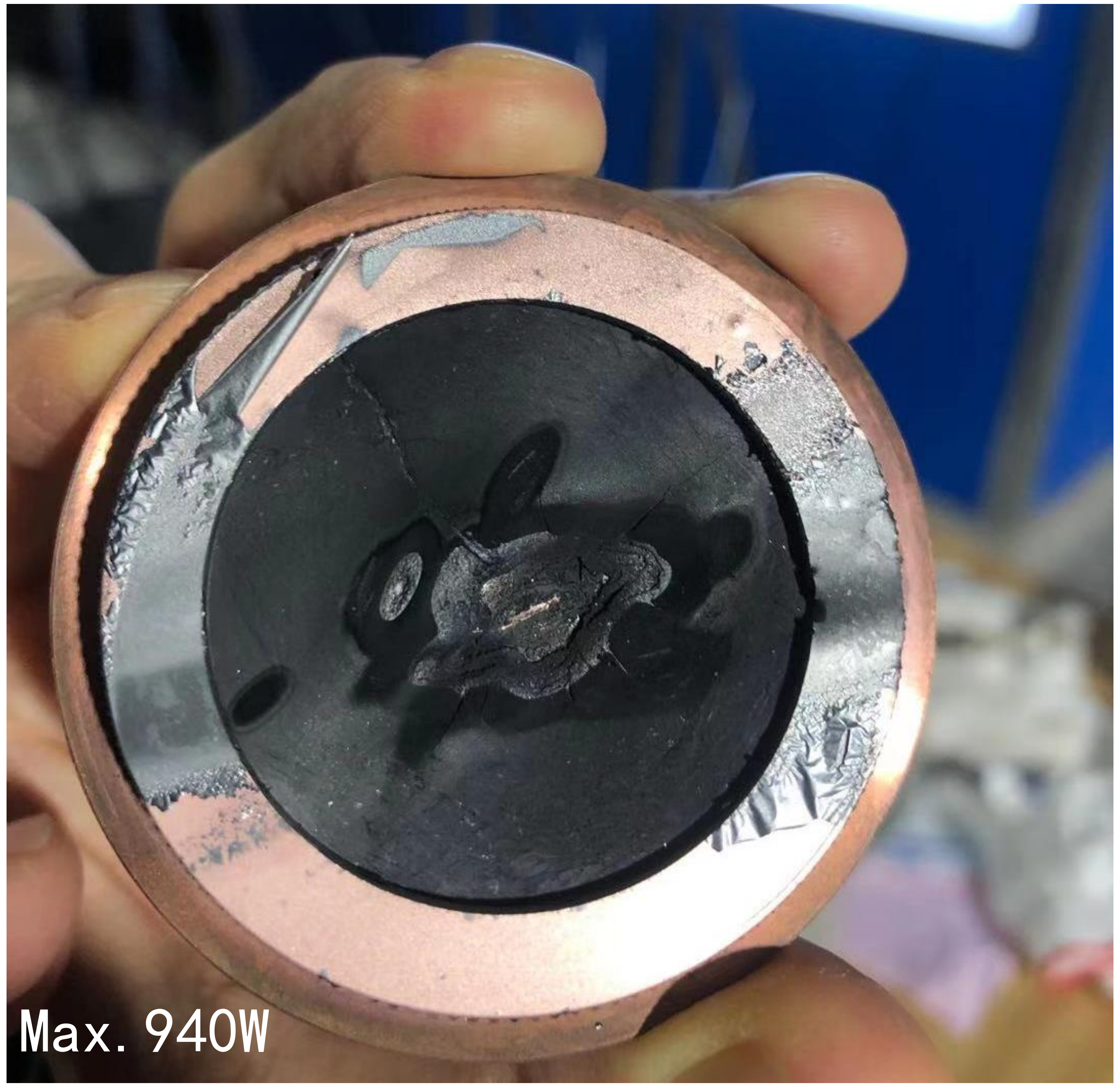
LUNA, Csedreki NIMA (2021)
Y.T. Li, T.Y.Jiao, B.S. Gao, W.P.Lin et al. arXiv:2111.12552, NST(2022) 33:41

Highest beam current



Preparation + Beam time: Jan. 27 to Feb. 16, 2021

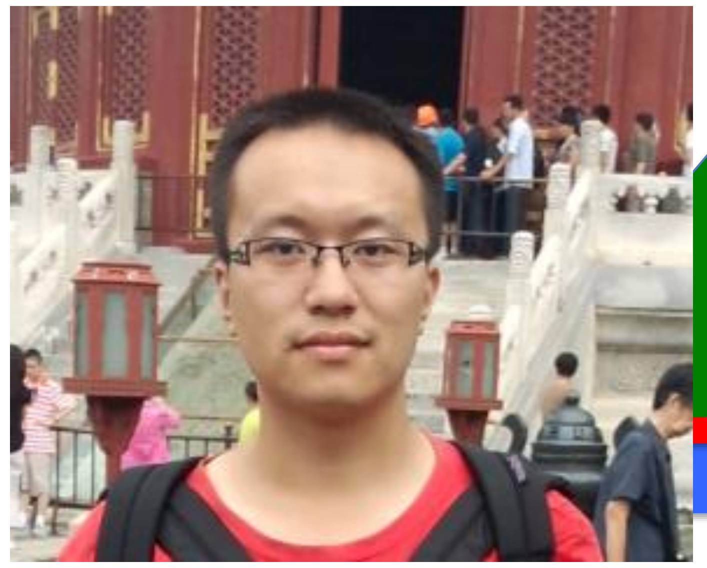
^{13}C-enriched thick target

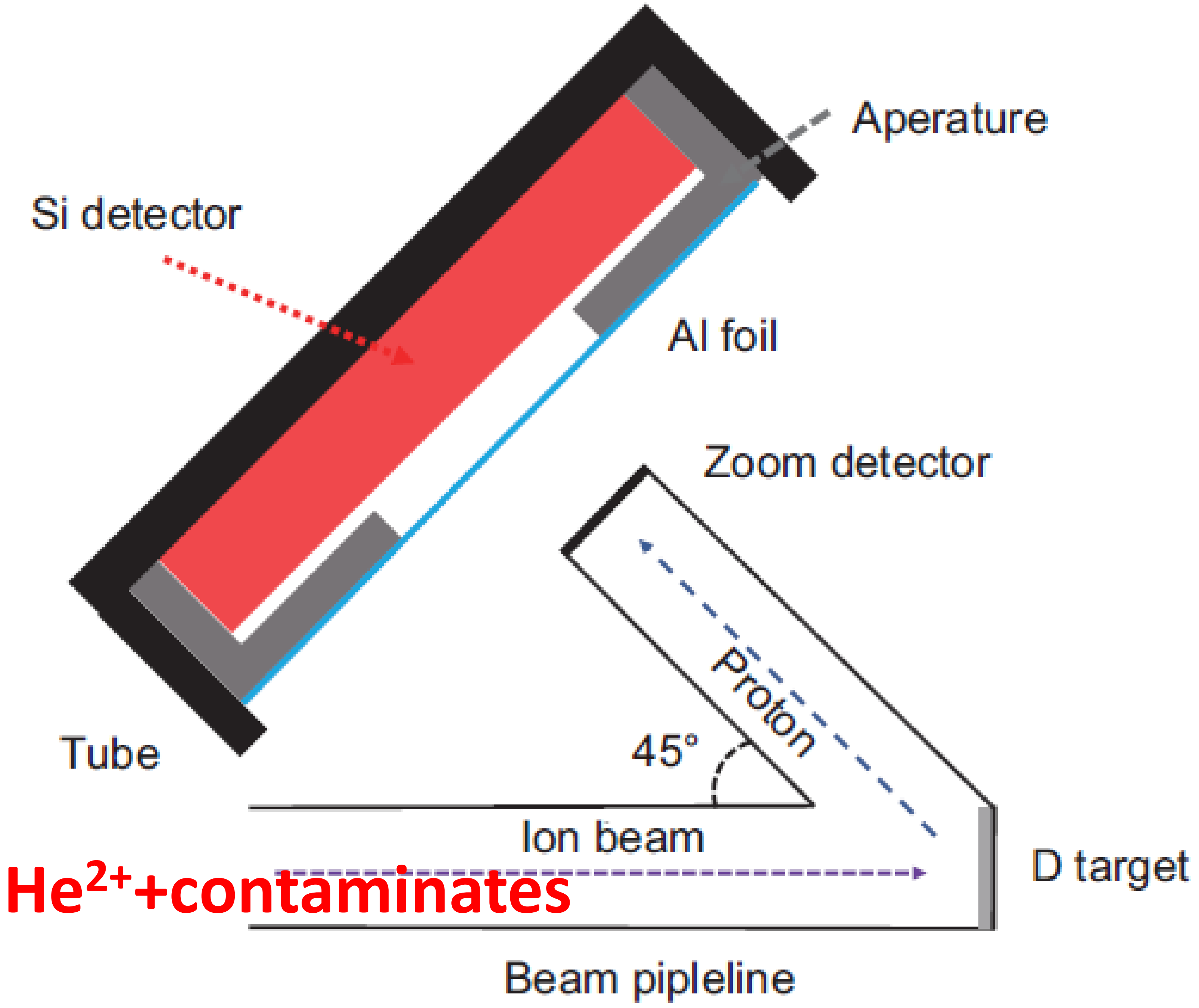


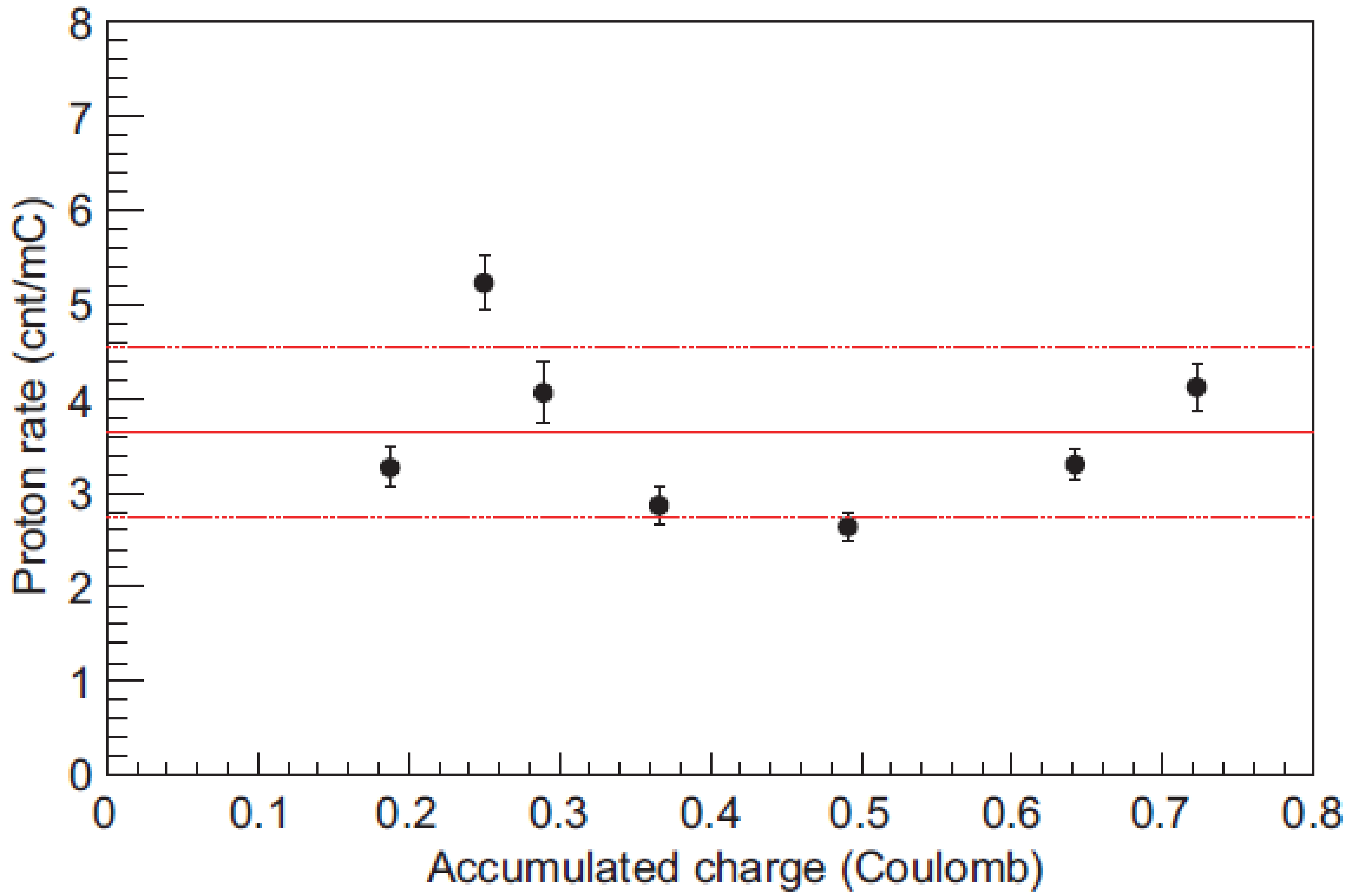
- 2mm-thick, max. power >500W
- Improving the thermal contact
- Will use beam wobbler to reduce the beam power density

JUNA

Deuterium impurity in the He^{2+} beam





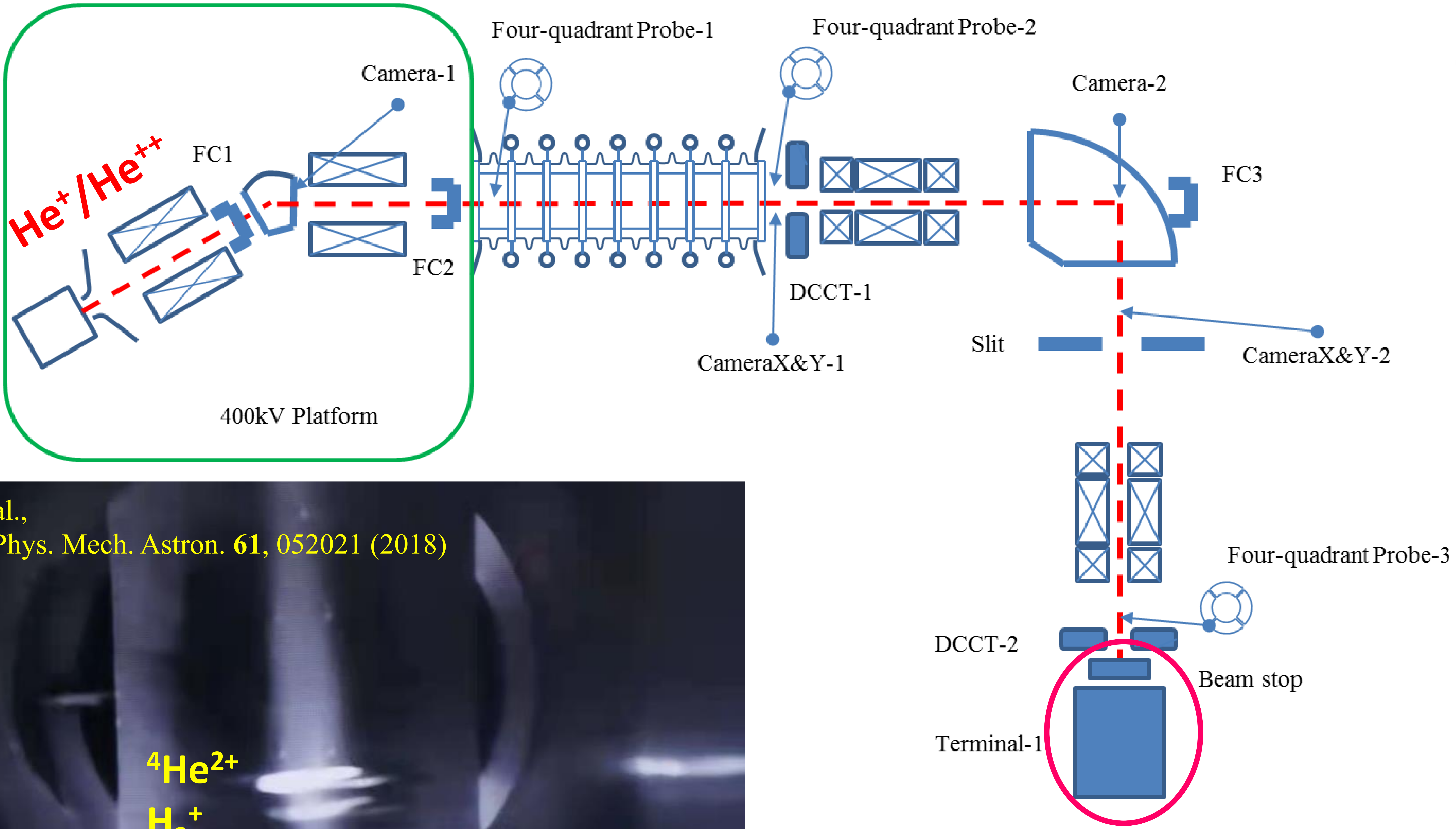


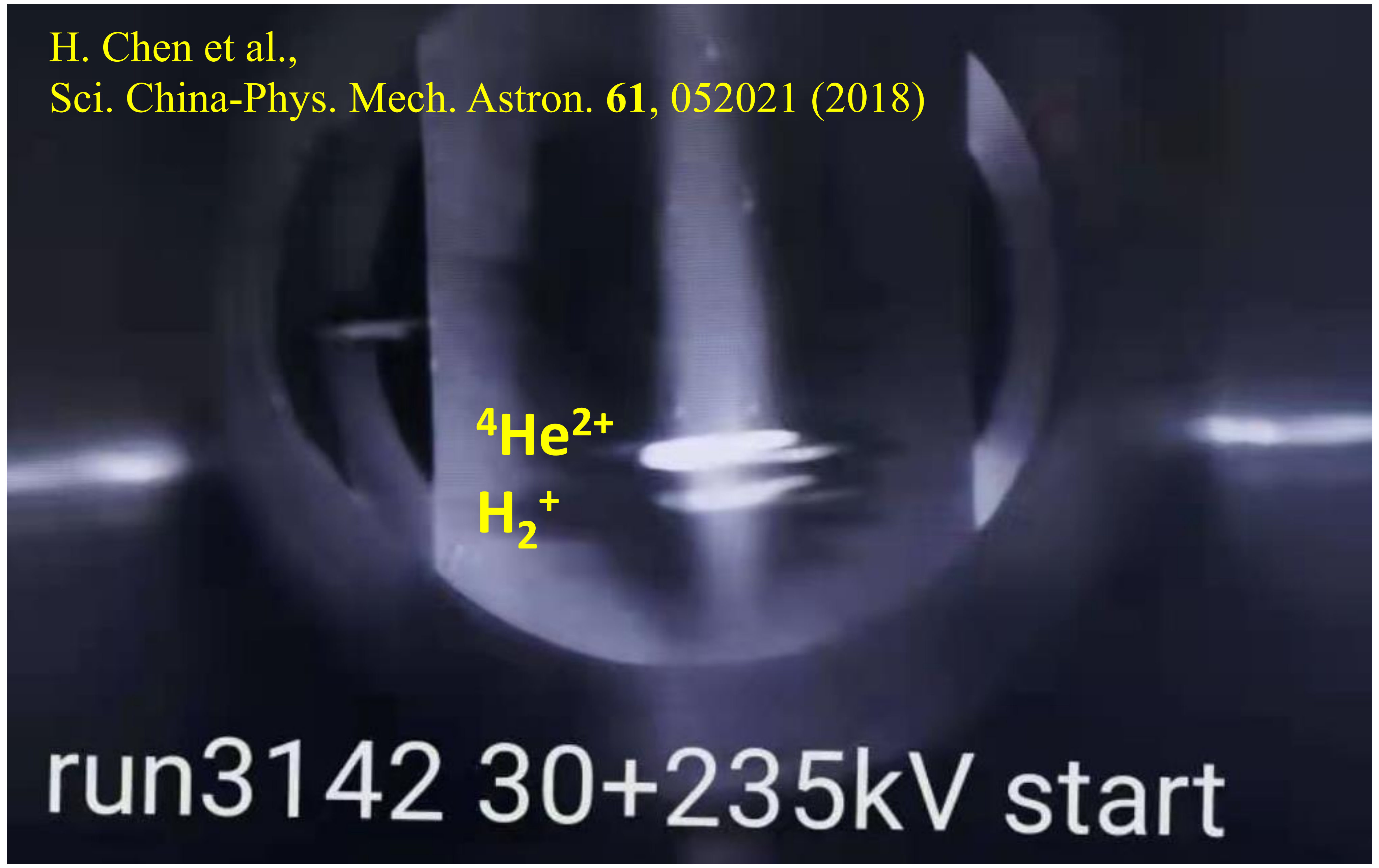
- **Impurity analysis Using D(d,p)t reaction : $\frac{I_{D^+}}{I_{He^{2+}}}$=(7.1±0.7)×$10^{-6}$**

  1.25 emA He^{2+} mixed with 9 pnA of Deuterium
- **Estimating D_2^+ /$^4He^+$ ~ 10^{-9}**

H. Chen et al., Sci. China-Phys. Mech. Astron. **61**, 052021 (2018)

JUNA accelerator

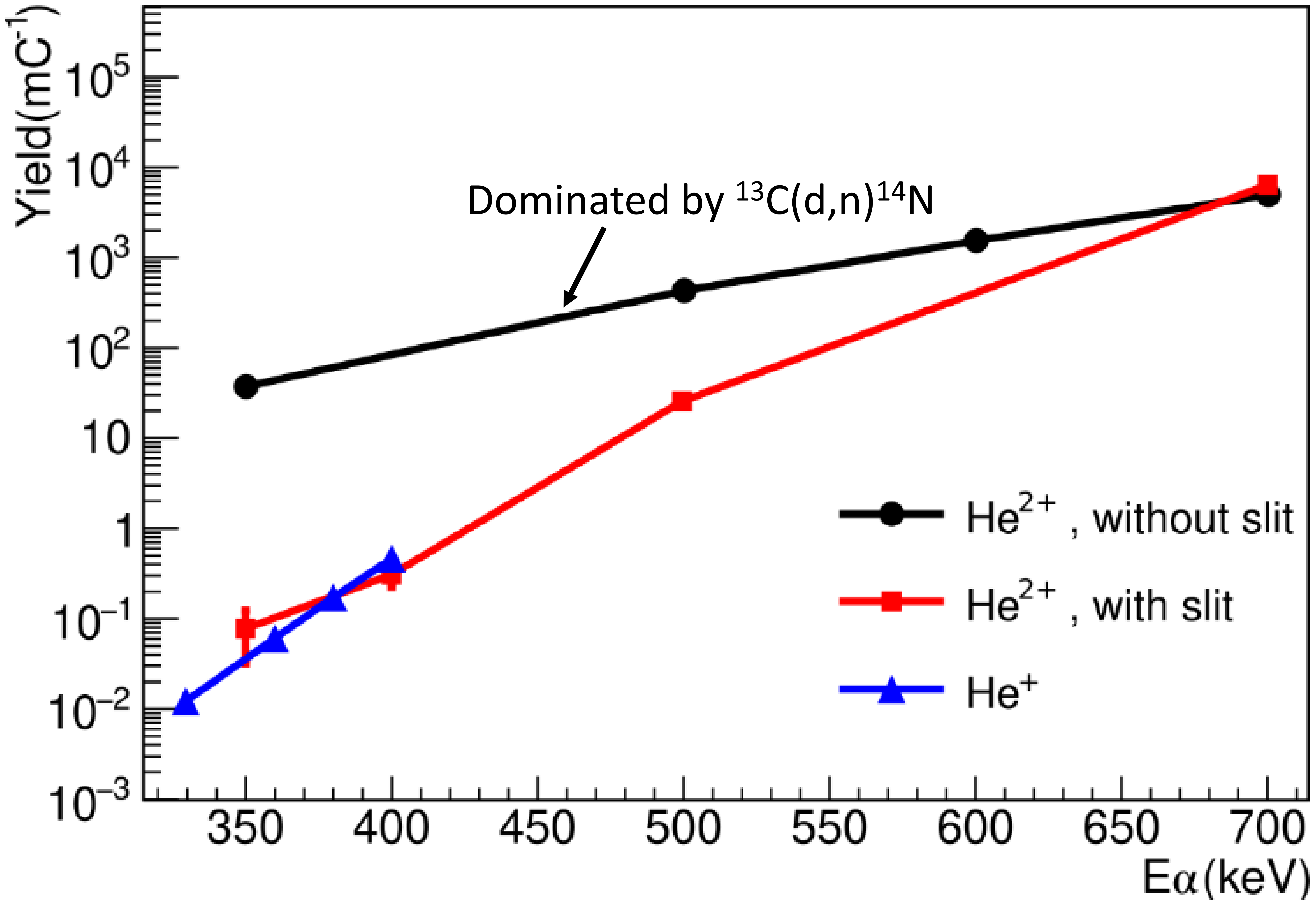



H. Chen et al.,
Sci. China-Phys. Mech. Astron. **61**, 052021 (2018)

14.5 GHz ECR: 1 pmA He^{++}

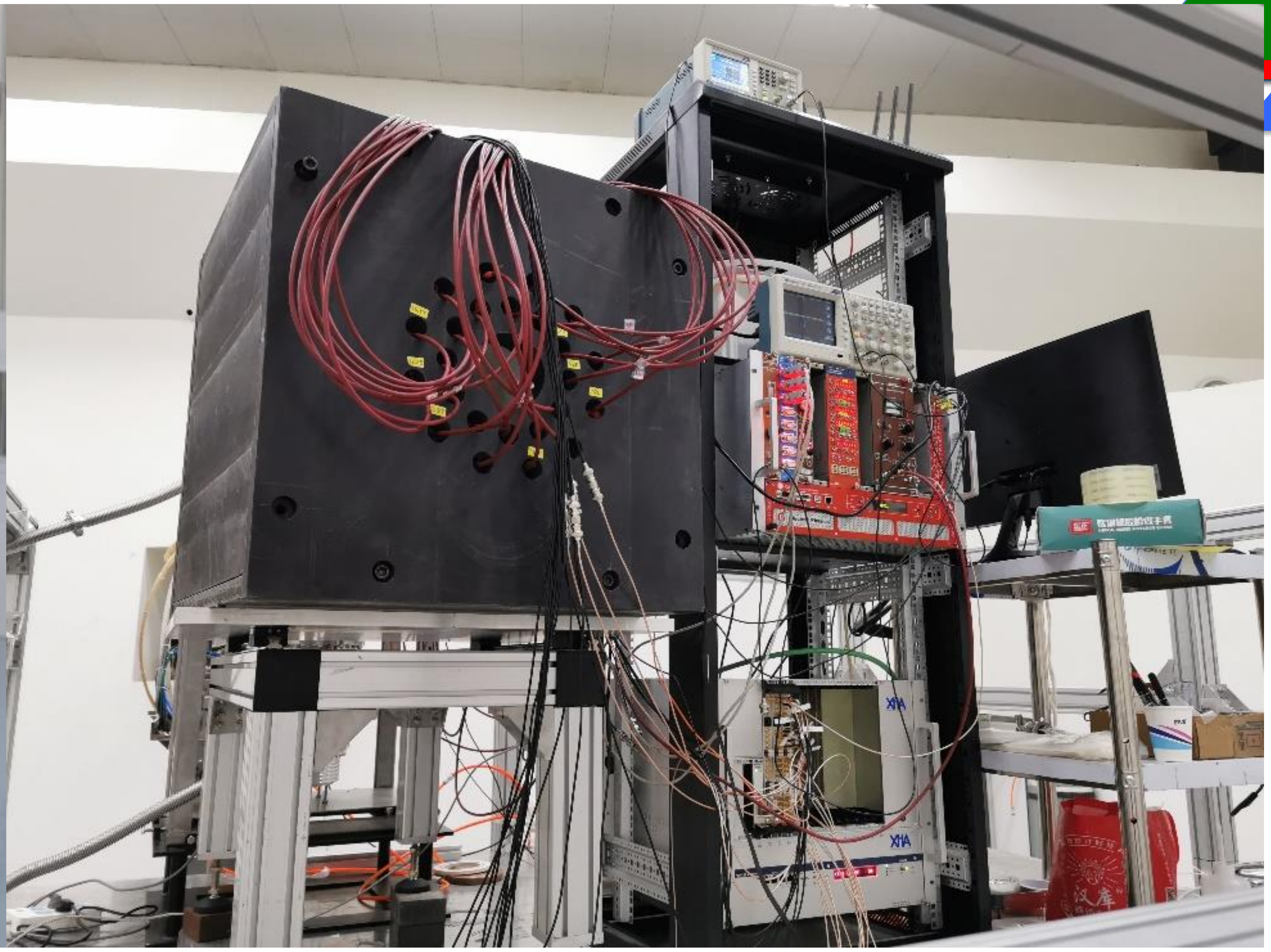
2.45 GHz ECR: 10 pmA He^{+}

Beam induced background

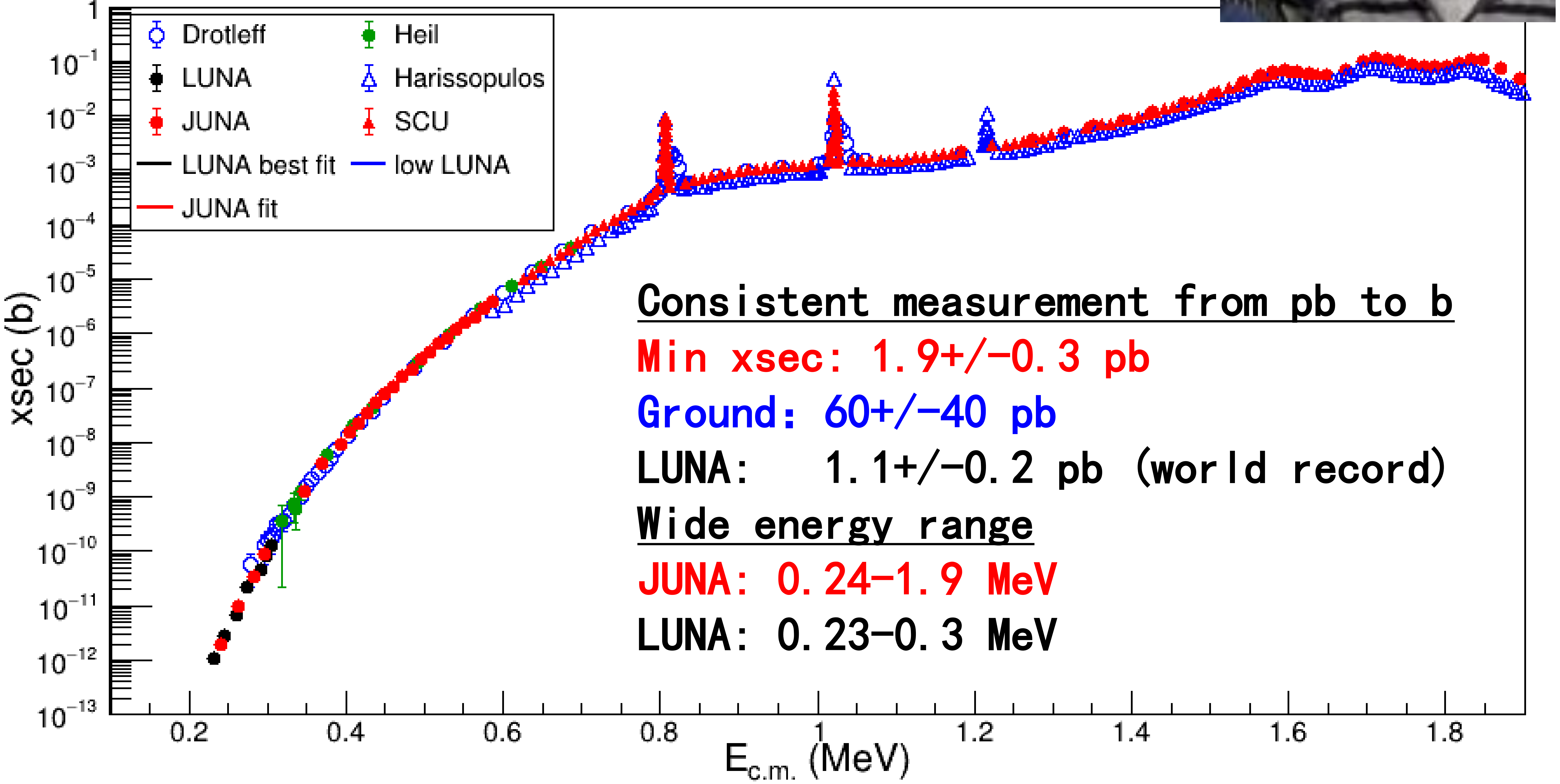


Yield at E_α=250 keV using He$^+$ is 0.05(8) cnts/Coulomb, being consistent with the zero

Consistent measurement at Eα=0.8-2.52 MeV



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



Consistent measurement from pb to b

Min xsec: 1.9+/-0.3 pb

Ground: 60+/-40 pb

LUNA: 1.1+/-0.2 pb (world record)

Wide energy range

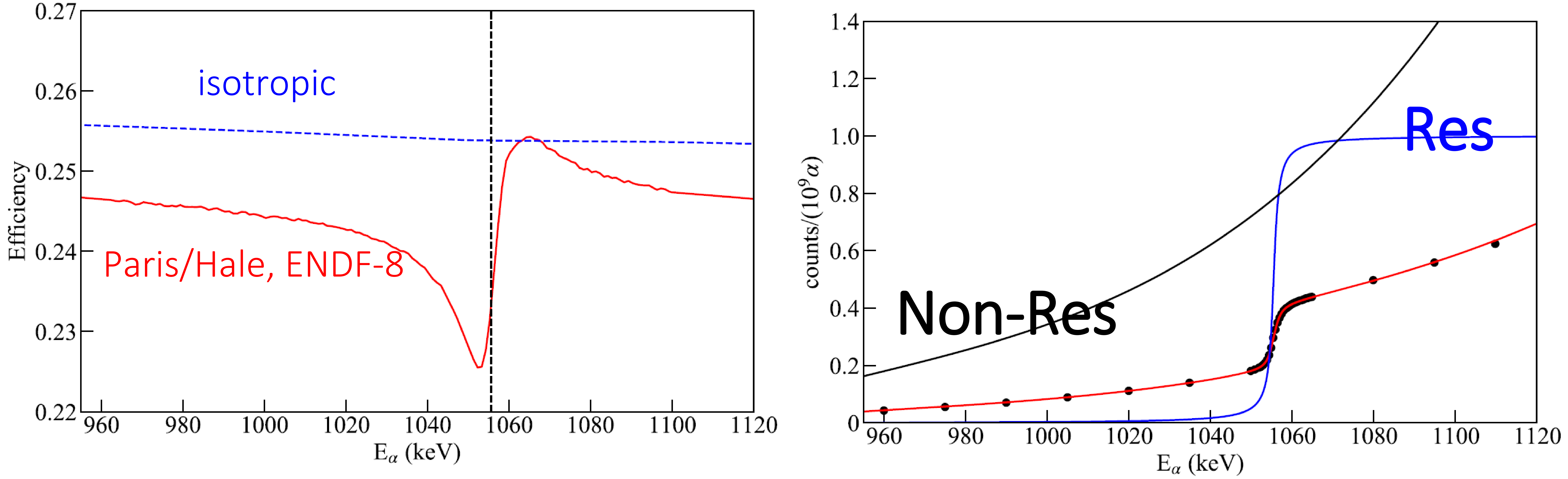
JUNA: 0.24-1.9 MeV

LUNA: 0.23-0.3 MeV

- JUNA data analyzed by B.S. Gao (IMP)
- SCU data analyzed by W.P. Lin(SCU)

Normalization standard #1

Thick target yield of resonance at E_α = 1055.63 keV



- **Pros:** **thick target yield does not depend on target thickness and stopping power**
- **Con: Angular distribution effect needs correction (5%-10%)**

L.H. Ru et al, PHYSICAL REVIEW C 107, 065803 (2023)

Normalization standard #1

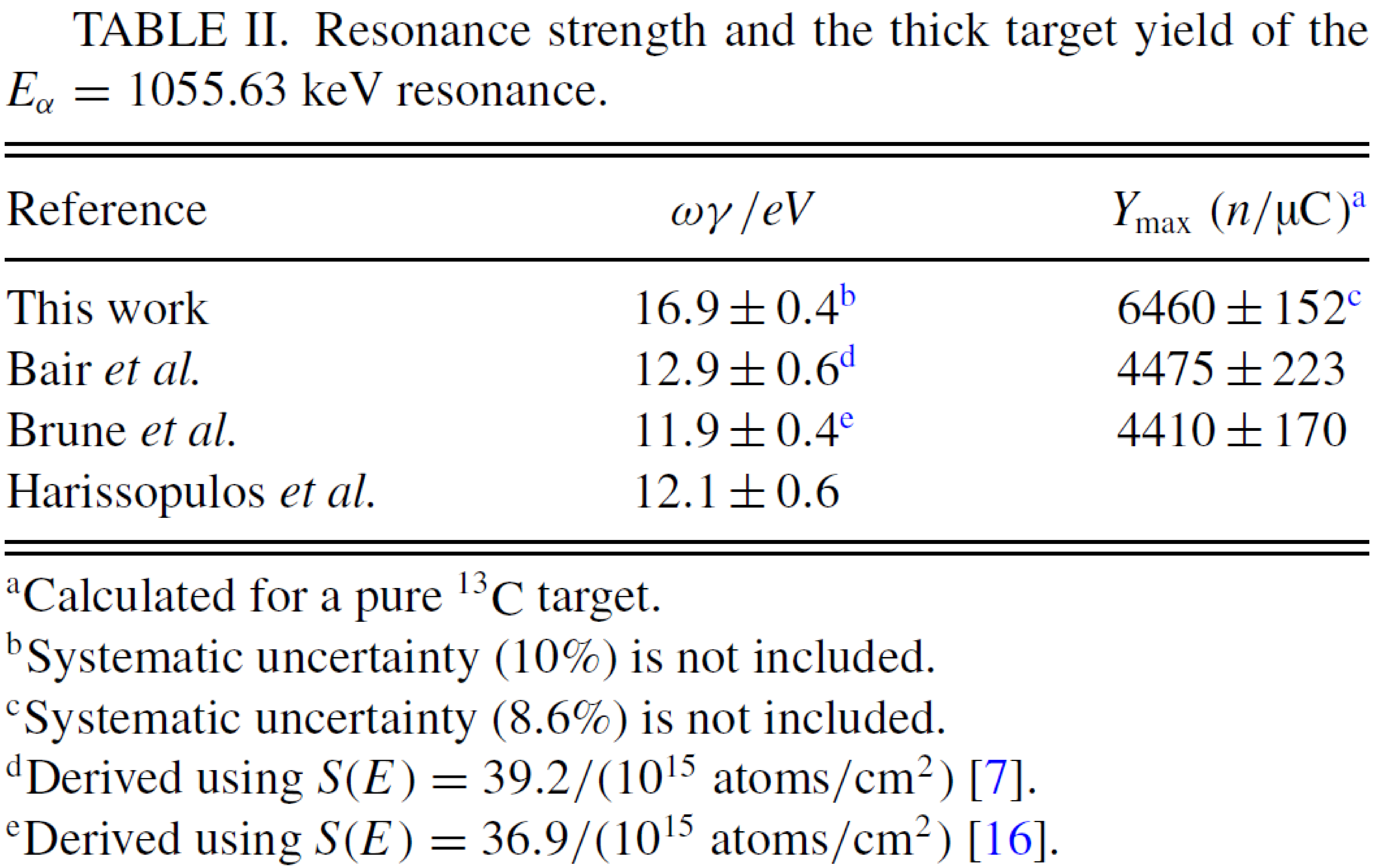


TABLE II. Resonance strength and the thick target yield of the $E_\alpha = 1055.63$ keV resonance.

Reference	$\omega\gamma / eV$	$Y_{\max}$ $(n/\mu C)^a$
This work	16.9 ± 0.4^b	6460 ± 152^c
Bair *et al.*	12.9 ± 0.6^d	4475 ± 223
Brune *et al.*	11.9 ± 0.4^e	4410 ± 170
Harissopulos *et al.*	12.1 ± 0.6	

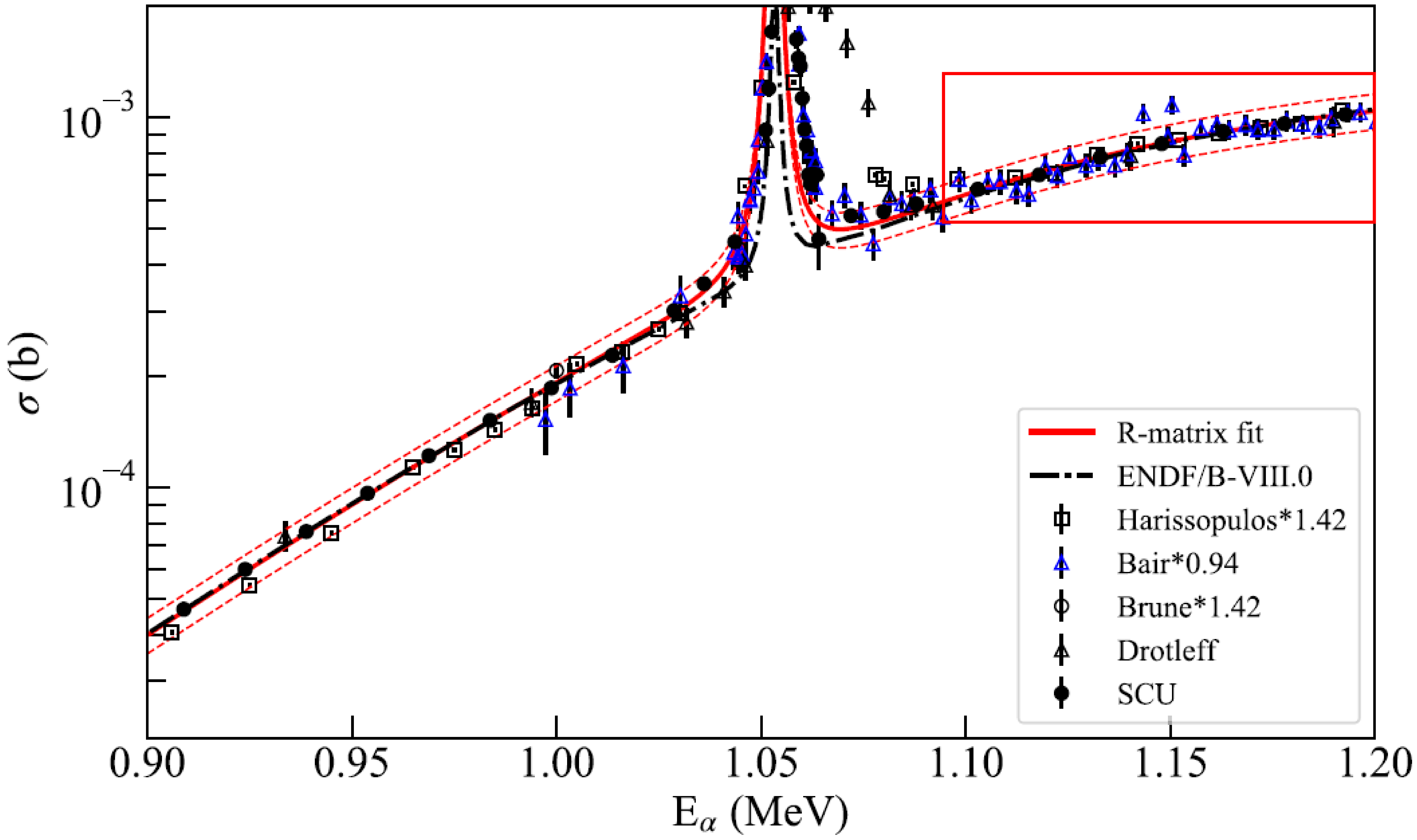
[a] Calculated for a pure ^{13}C target.
[b] Systematic uncertainty (10%) is not included.
[c] Systematic uncertainty (8.6%) is not included.
[d] Derived using $S(E) = 39.2/(10^{15}$ atoms/cm^2) [7].
[e] Derived using $S(E) = 36.9/(10^{15}$ atoms/cm^2) [16].

beam current integration (5%), detection efficiency (7%), and stopping power (5%).

Thick target yield (sys. Err. 8.6%)

Resonance strength/cross section (sys. Err. 10%)

Normalization standard #2



L.H. Ru et al, PHYSICAL REVIEW C 107, 065803 (2023)

Recommendation of normalization

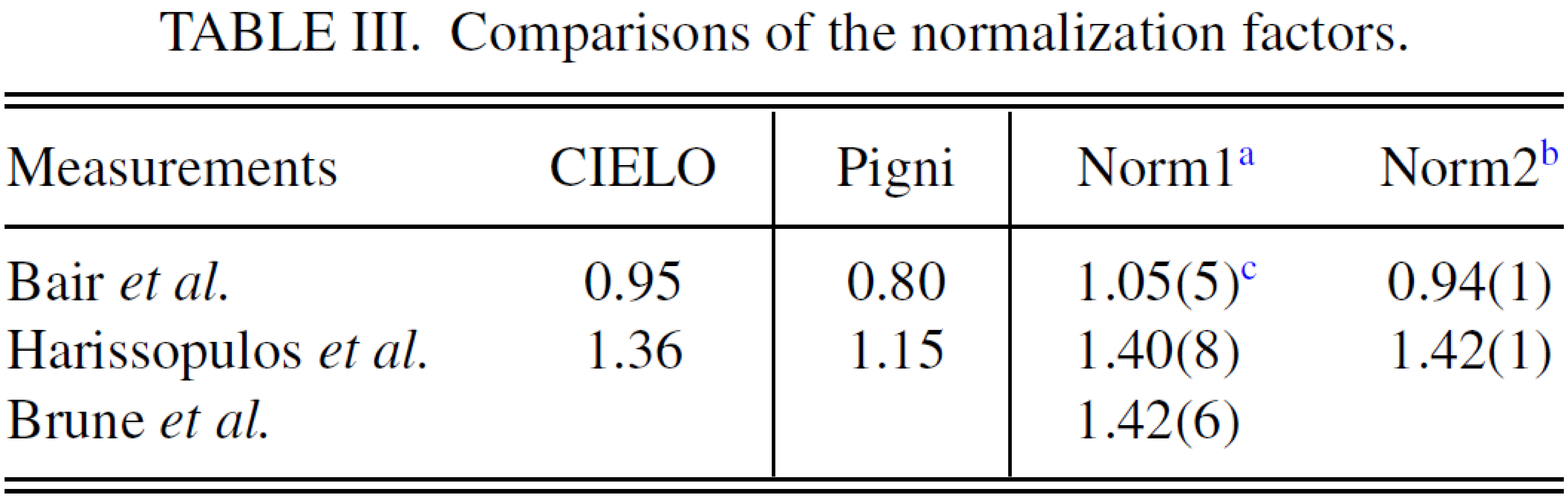


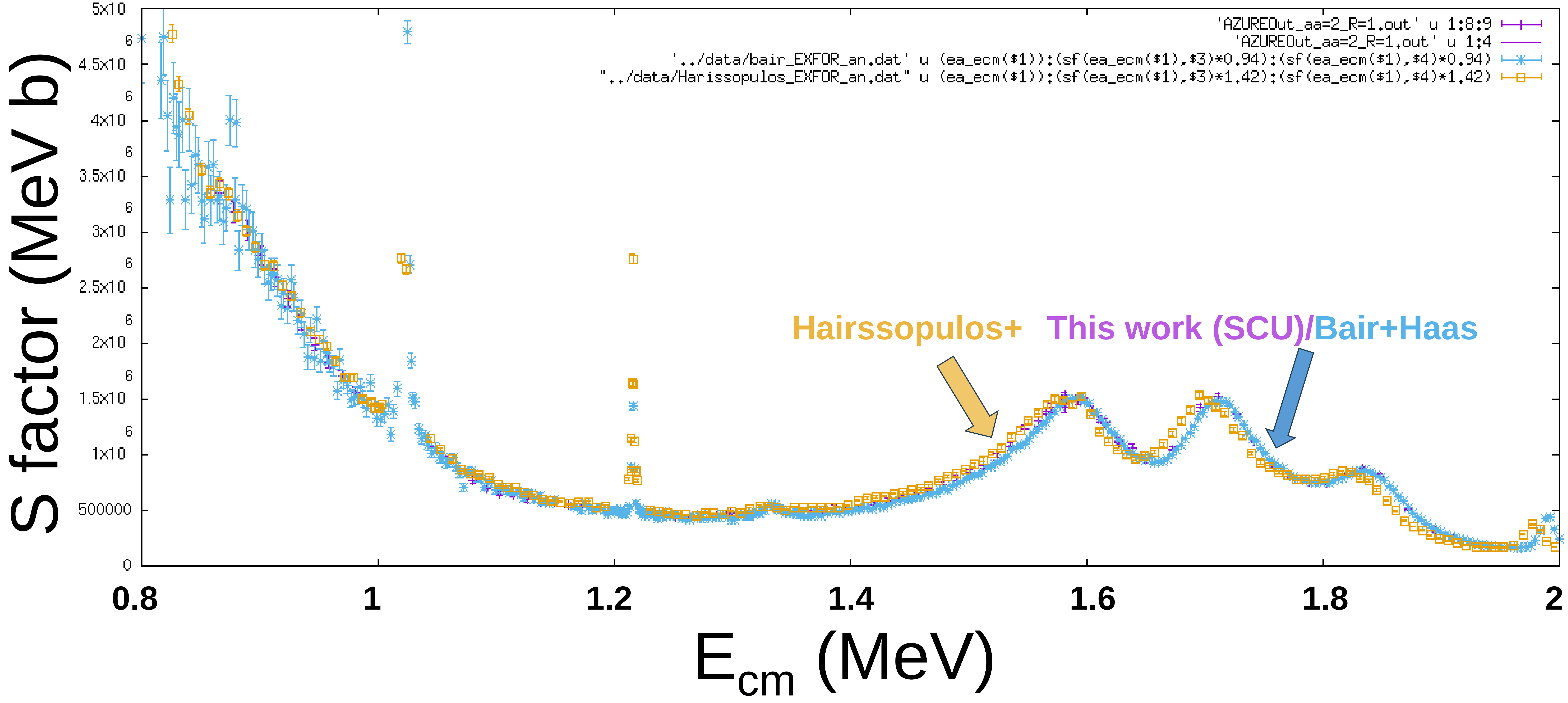
TABLE III. Comparisons of the normalization factors.

Measurements	CIELO	Pigni	Norm1[a]	Norm2[b]
Bair *et al.*	0.95	0.80	1.05(5)[c]	0.94(1)
Harissopulos *et al.*	1.36	1.15	1.40(8)	1.42(1)
Brune *et al.*			1.42(6)	

Our normalization factors agree with the recommendation of the ENDF/B-VIII.0 evaluation and the CIELO project.

L.H. Ru et al, PHYSICAL REVIEW C 107, 065803 (2023)

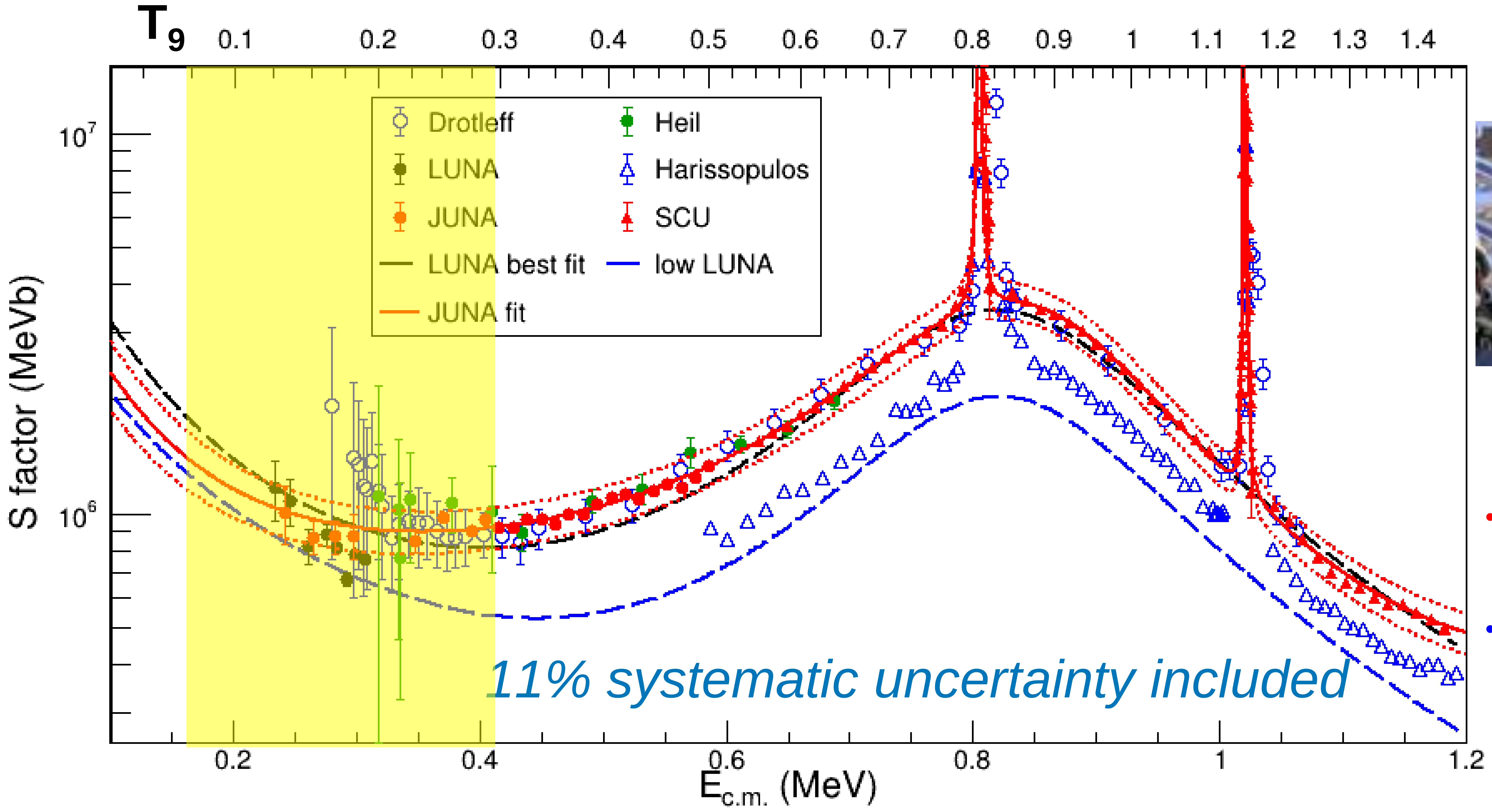
Some other problems remain



- ➢ Energy calibration
- ➢ Target thickness correction
- ➢ Energy dependence of simulated efficiency

$^{13}C(\alpha,n)^{16}O$: neutron source of s- and i- processes

JUNA



11% systematic uncertainty included

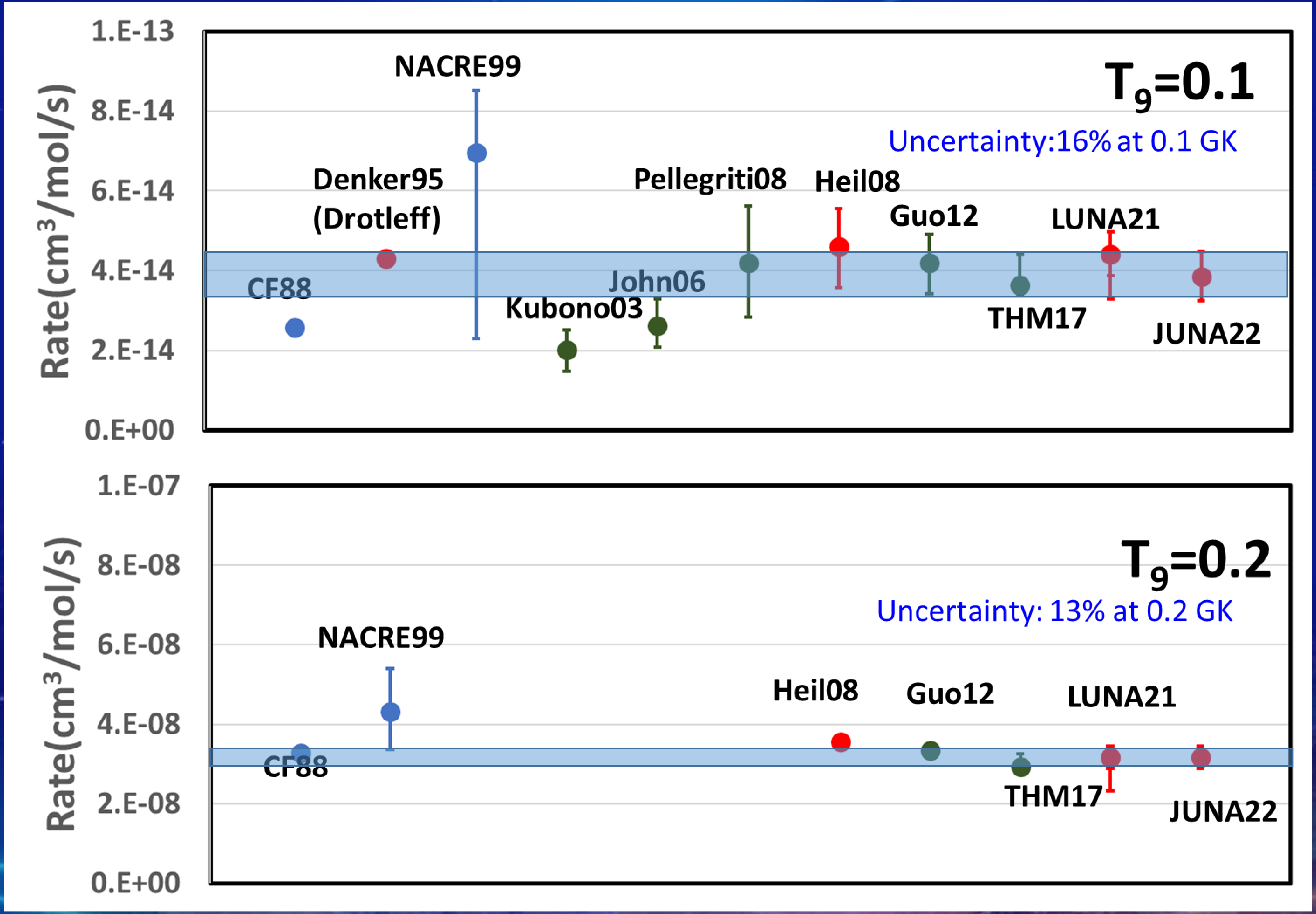
Lin & Gao

- JUNA data analyzed by B.S. Gao (IMP)
- SCU data analyzed by W.P. Lin(SCU)

- **Consistent measurement from 0.24-1.9 MeV resolves the existing discrepancy**
- **Fit with AZURE2 agrees with the best LUNA fit at E_{cm}>0.2 MeV and the “low LUNA” fit at E_{cm}<0.2 MeV**
- **15% systematically higher than the LUNA data**

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

B. S. Gao et al., PRL129(2022) 132701



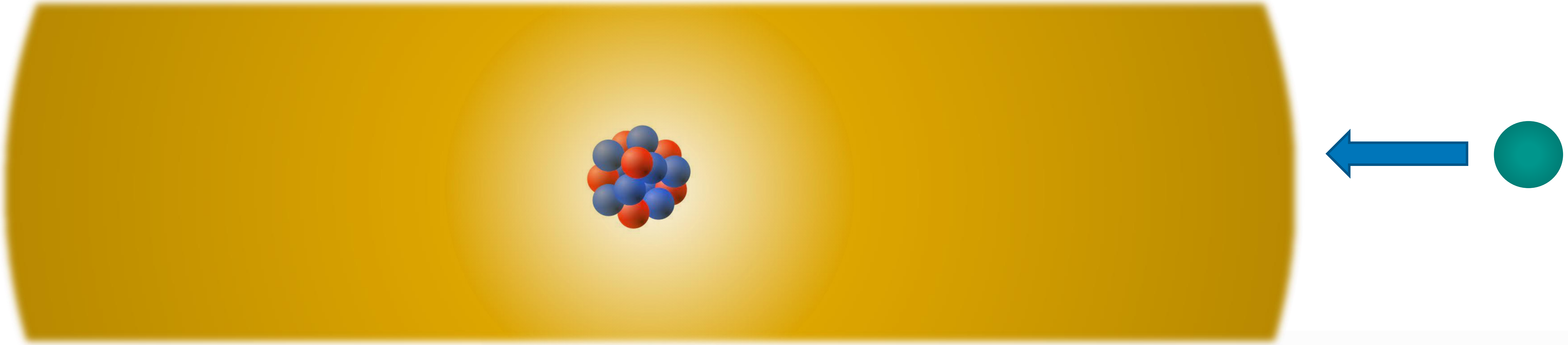
- Indirect measurement in Green
- Direct measurement in Red
- Compilation in Blue

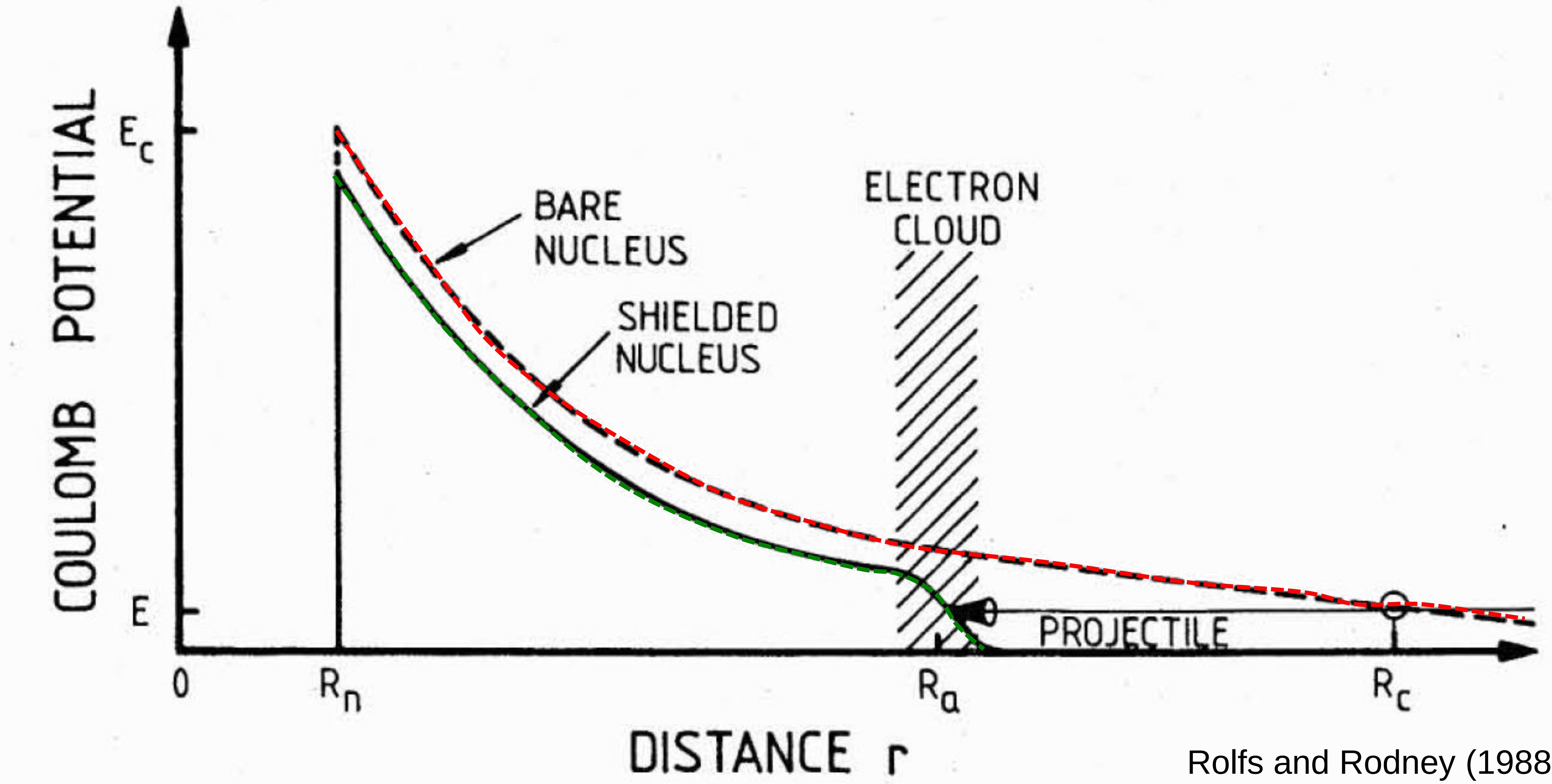
Screening effect

U_e: Screening potential

JUNA

$$f_{\mathrm{lab}}(E)=\sigma_s(E)/\sigma_b(E)\approx\exp(\pi\eta U_e/E)\geq 1$$





Rolfs and Rodney (1988)
Assenbaum, Langanke and Rolfs, Z. Phys. A327, 461 (1987)

Alpha Strength of the Threshold and Screening Potential

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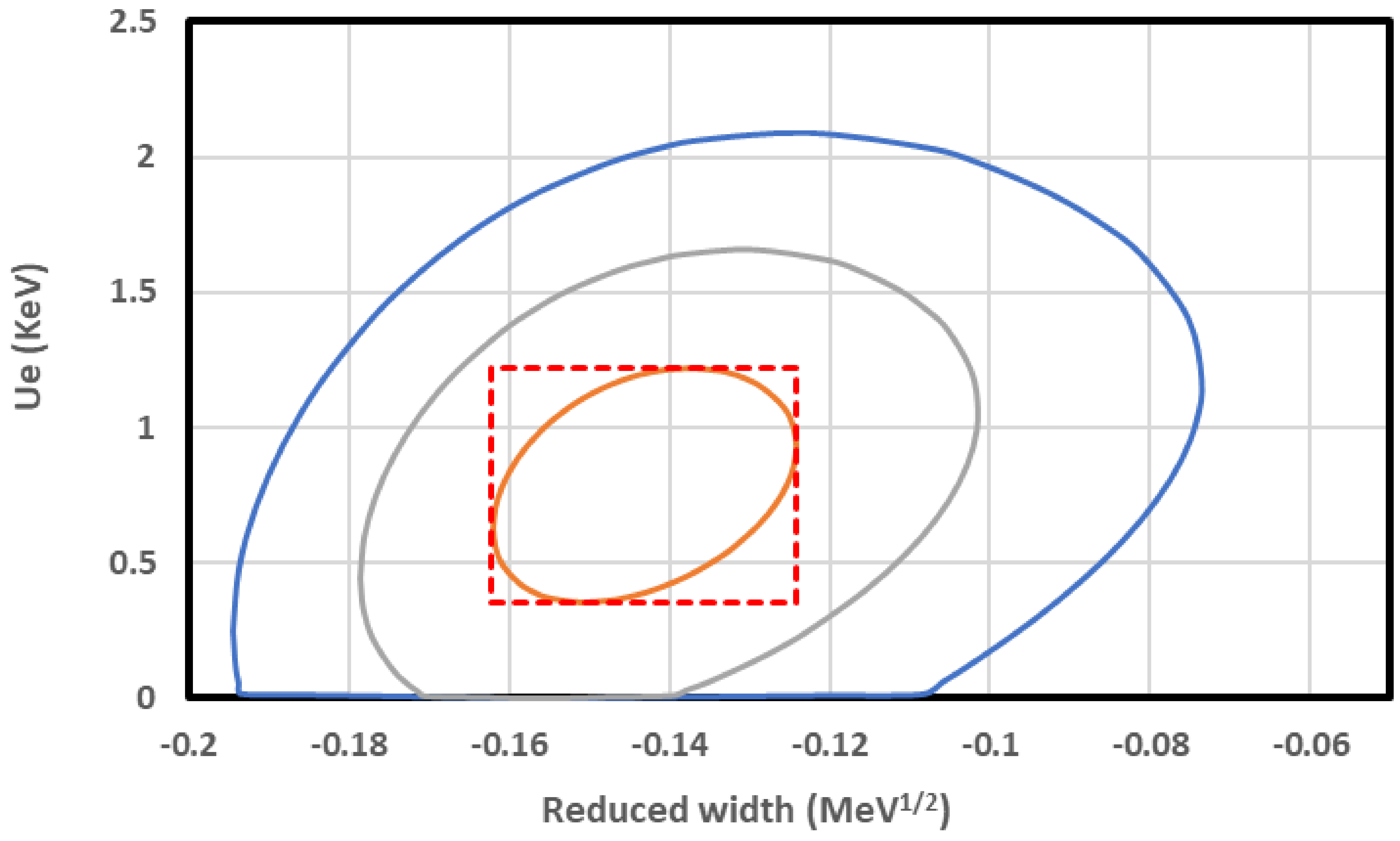
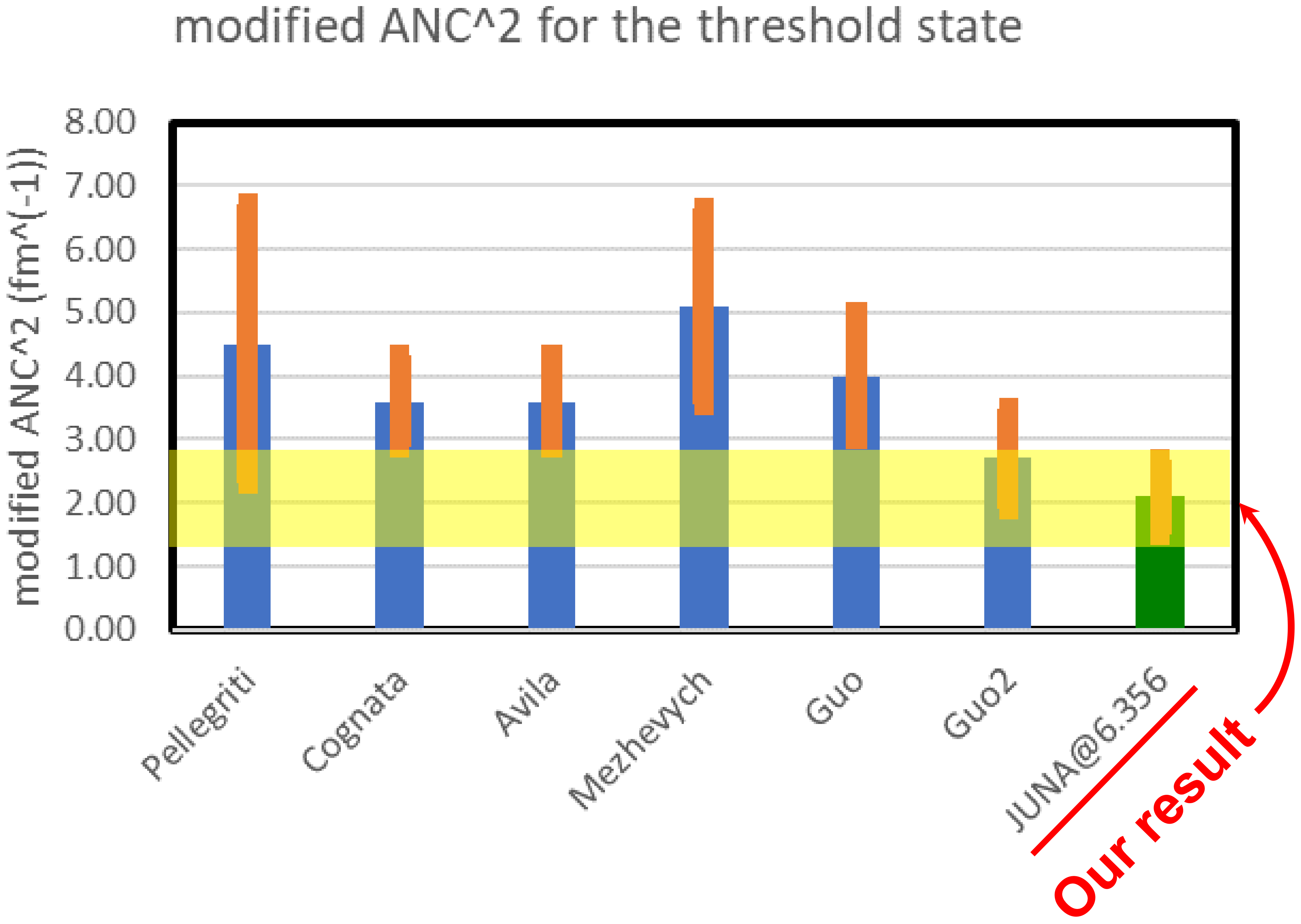


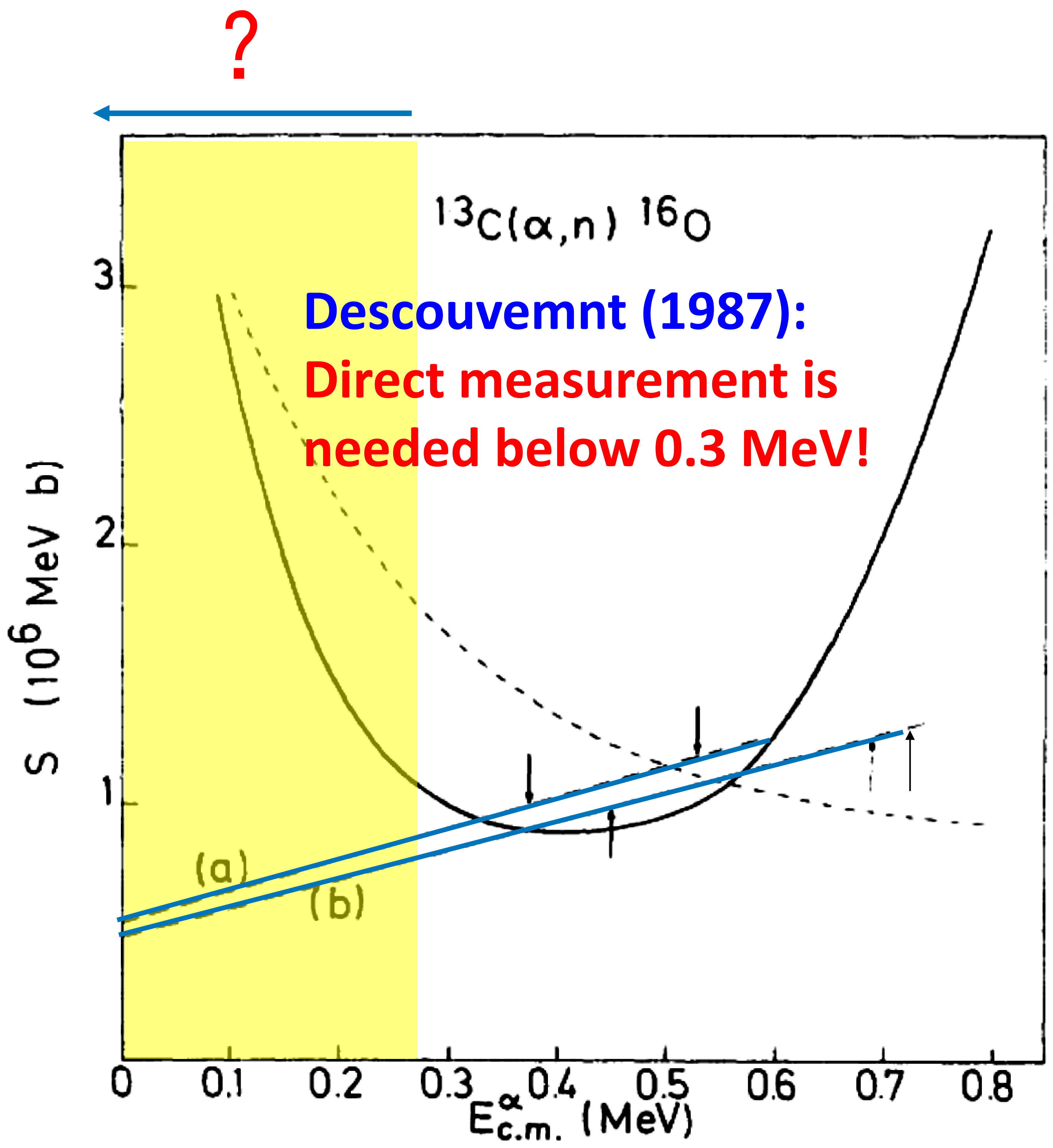


- JUNA reduced width = -0.145+/-0.019 MeV$^{1/2}$ at R=6.684 fm, modified ANC^2=2.1+/-0.6 fm^{-1} with Ex=6.356 MeV
- Ue=0.78+/-0.43 keV agrees with Ue=0.937 keV predicted using the adiabatic limit, rules out other predictions.

Guo2 taken from Shen, Guo et al., PLB(2020)

A journey of 36 years（1987-2023)

JUNA



Descouvemnt (1987):

Direct measurement is needed below 0.3 MeV!

FIG. 6. $^{13}C(\alpha,n)^{16}O$ *S* factor. The dotted line represents the GCM result; the full line is obtained with the Breit-Wigner parametrization (see text); the dashed lines are the experimental data taken from Ref. 3 (a) and Ref. 4 (b). The arrows indicate the energy range where the experiments are carried out.

Phu Quoc, Vietnam,
May 8, 2023


小心低温
RIBF


^{16}O
^{4}He

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

$^{13}C(\alpha,n)^{16}O$ experiment（Feb.27, 2021-March 16, 2021）

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

JUNA

Super JUNA

JUNA and Super JUNA coverage

H burning

^{7}Be(p,γ)^{8}B

^{12}C(p,γ)^{13}N

^{14}N(p,γ)^{15}O

^{15}N(p,γ),(p,α)^{16}O,^{12}C

^{17}O(p,γ),(p,α)^{18}F,^{14}N

^{18}O(p,γ),(p,α)^{19}F,^{15}N

^{19}F(p,α)^{16}O

He burning

^{12}C(α,γ)^{16}O

^{16}O(α,γ)^{20}Ne

^{20}Ne(α,γ)^{24}Mg

^{18}O(α,γ)^{22}Ne

^{22}Ne(α,γ)^{26}Mg

^{24}Mg(α,γ)^{28}Si

N source

^{13}C(α,n)^{16}O

^{22}Ne(α,n)^{25}Mg

^{25}Mg(α,n)^{28}Si

^{26}Mg(α,n)^{29}Si

C\O burning

^{12}C+^{12}C

^{12}C+^{16}O

^{16}O+^{16}O

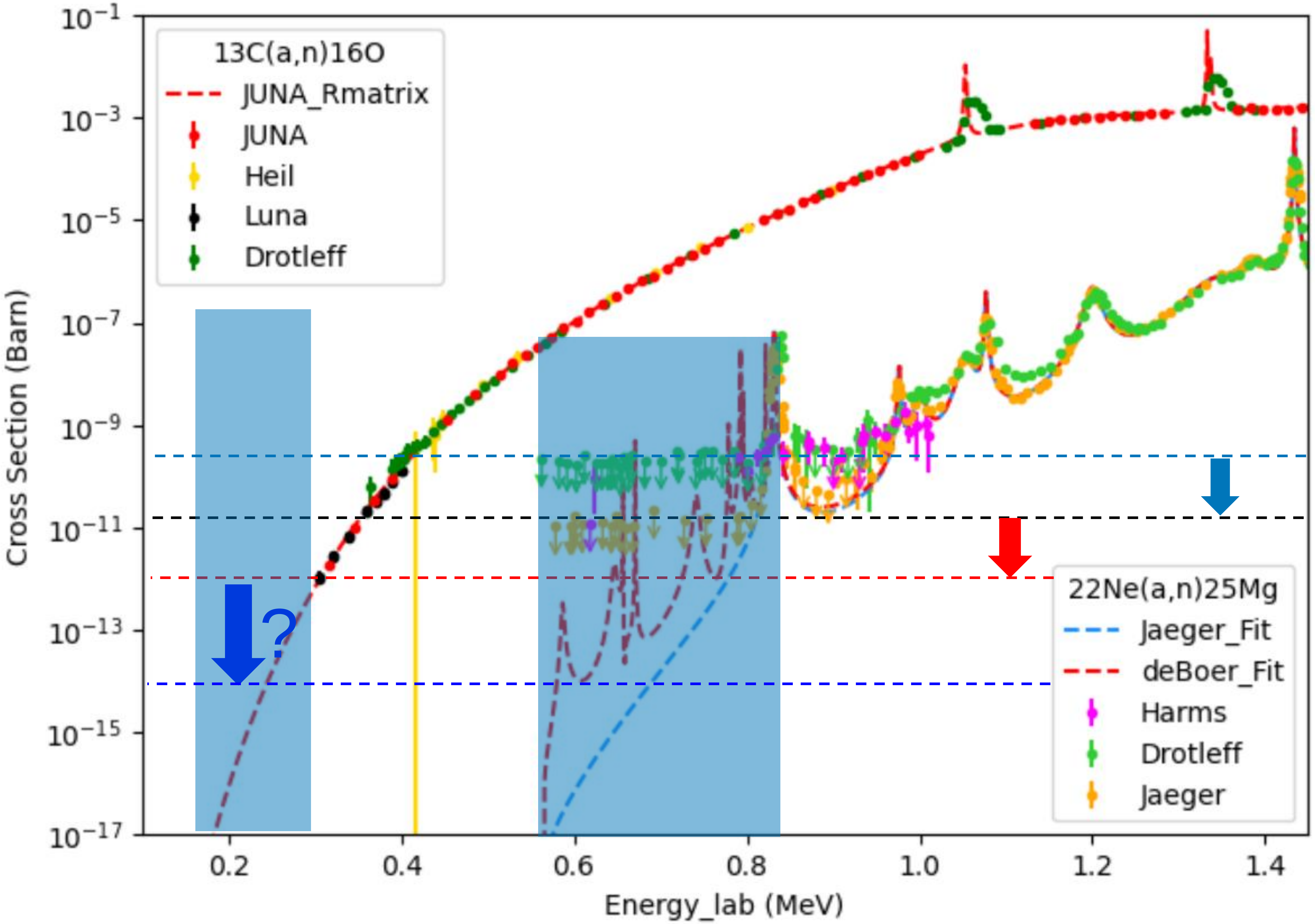
γ astronomy

^{25}Mg(p,γ)^{26}Al

^{26}Al(p,γ)^{27}Si

🟨 **JUNA achieved**

🟥 **Super JUNA proposed**



1993 Drotleff et al.

2001 Jaeger et al.

2021 LUNA+JUNA

Increase intensity
Lower the background

JUNA Team

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Summary

- Nuclear structure near threshold is crucial to the nucleosynthesis inside of stars

- Both direct and indirect approaches are indispensable.

- JUNA is becoming an advanced deep astrophysics platform
  - Gamma-ray astronomical reaction rate has reached the highest precision
  - astrophysical holy grail reaction has achieved the highest sensitivity
  - new resonances revealing the origin of heavy element abundance in the oldest stars in JWST
  - Discrepancies of neutron source reactions was resolved

- There are still questions to be addressed

- Welcome to join JUNA collaboration and submit your proposals deep underground!