JUNA
(Jinping Underground Nuclear Astrophysics experiment)

Direct measurement of $^{13}C(\alpha, n)^{16}O$ in the Gamow windows of s- and r-processes

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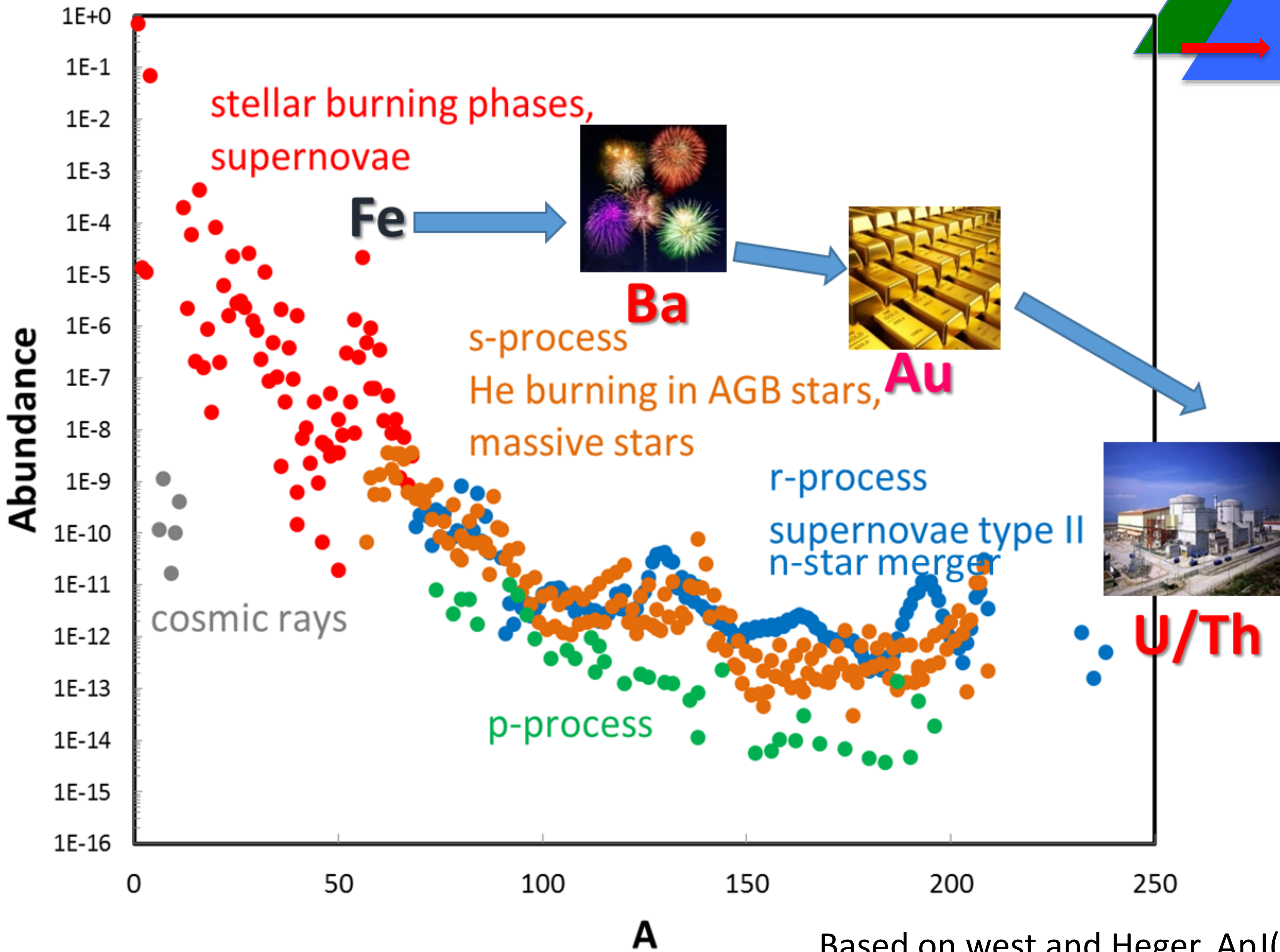
JUNA Collaboration

Origin of Heavy elements



Based on west and Heger, ApJ(2013)

Pioneering works

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ORIGIN OF ANOMALOUS ABUNDANCES OF THE ELEMENTS IN GIANT STARS

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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.

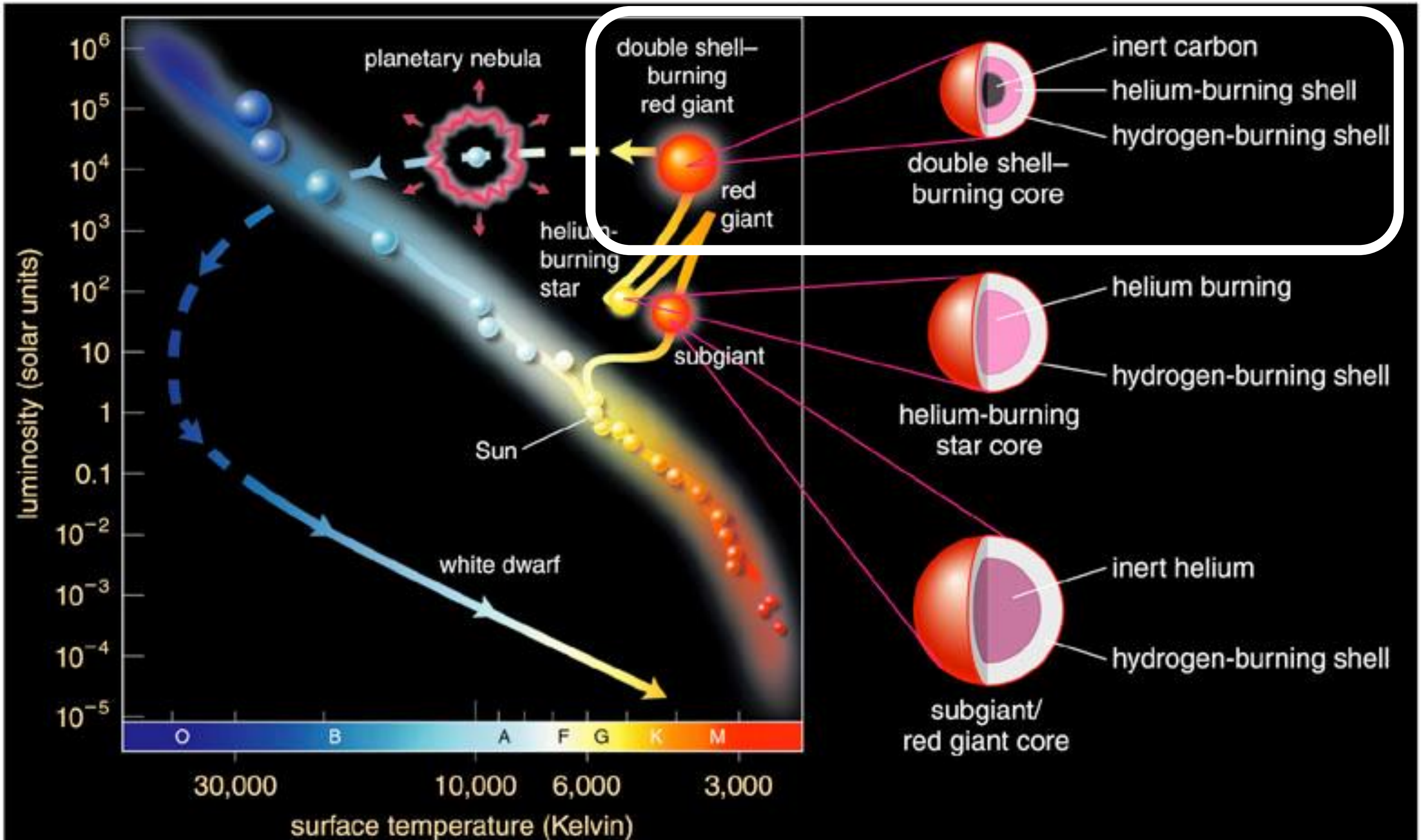
The first stellar neutron source was proposed by Greenstein (Gr54) and by Cameron (Ca54, Ca55), namely the *exothermic* reaction:

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

B2FH(1957)

S factor =3.9x10^3 MeV*barn

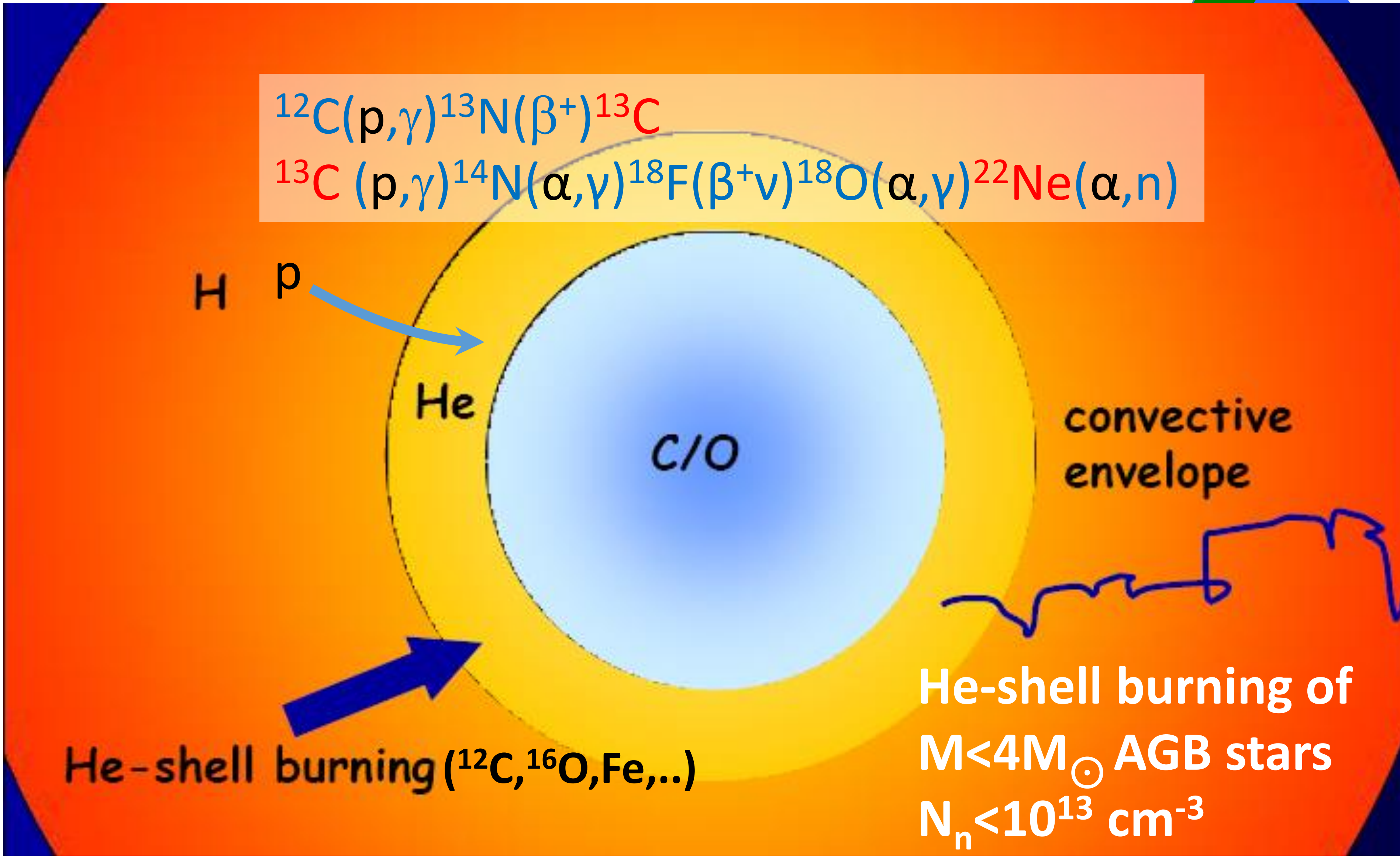
Asymptotic Giant Branch star



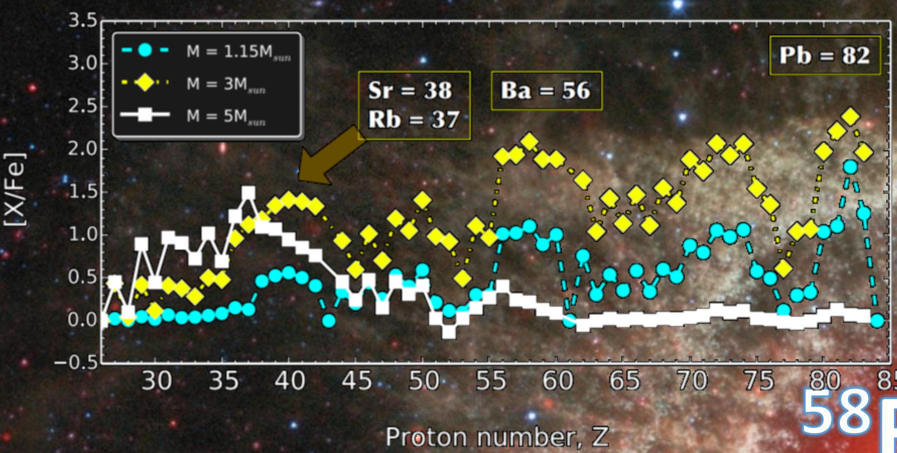
Stars with <10 solar mass go through the asymptotic giant branch (AGB) before becoming white dwarfs.

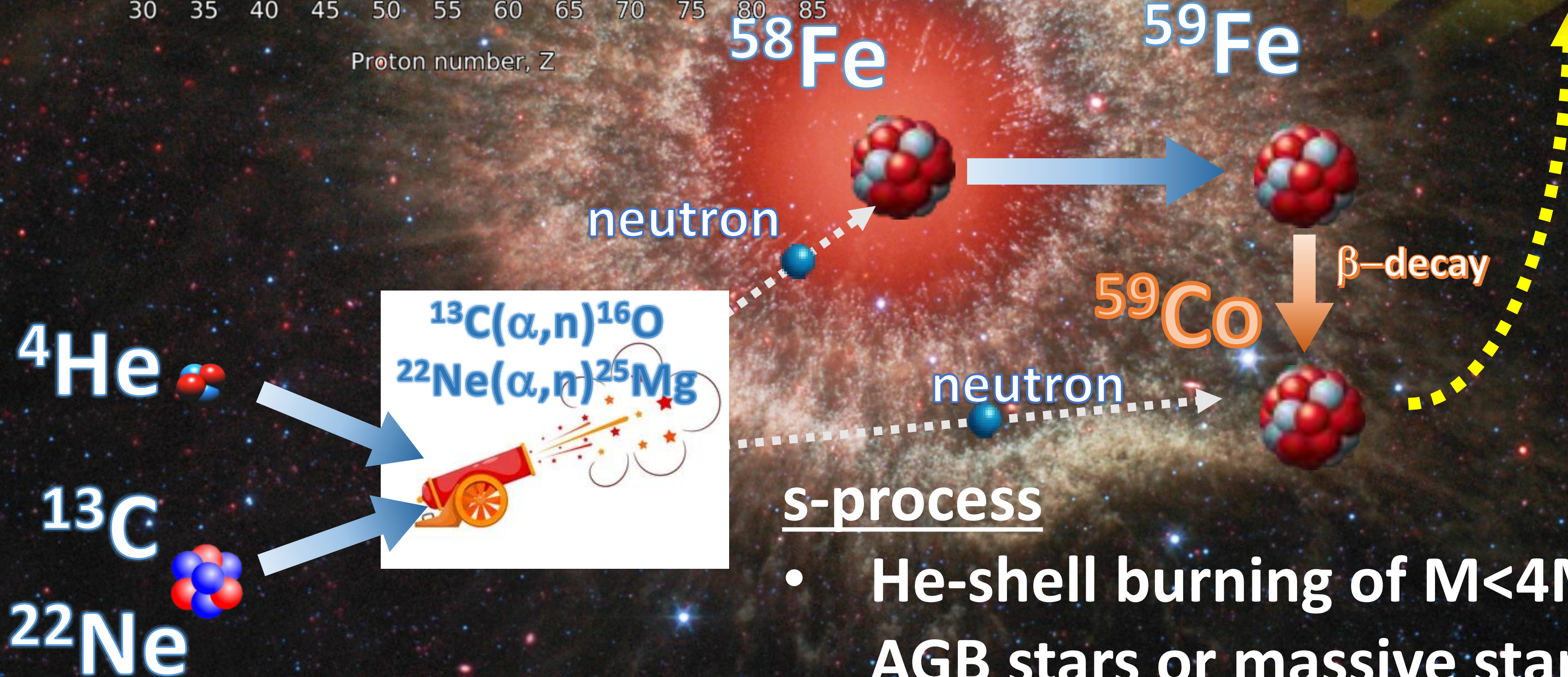
Taken from Lugaro's lecture

Neutrons in Asymptotic Giant Branch



Neutron: Magic Bullet





s-process

- He-shell burning of $M<4M_\odot$ AGB stars or massive stars
- $N_n<10^{13}$ cm^{-3}

S-process stars

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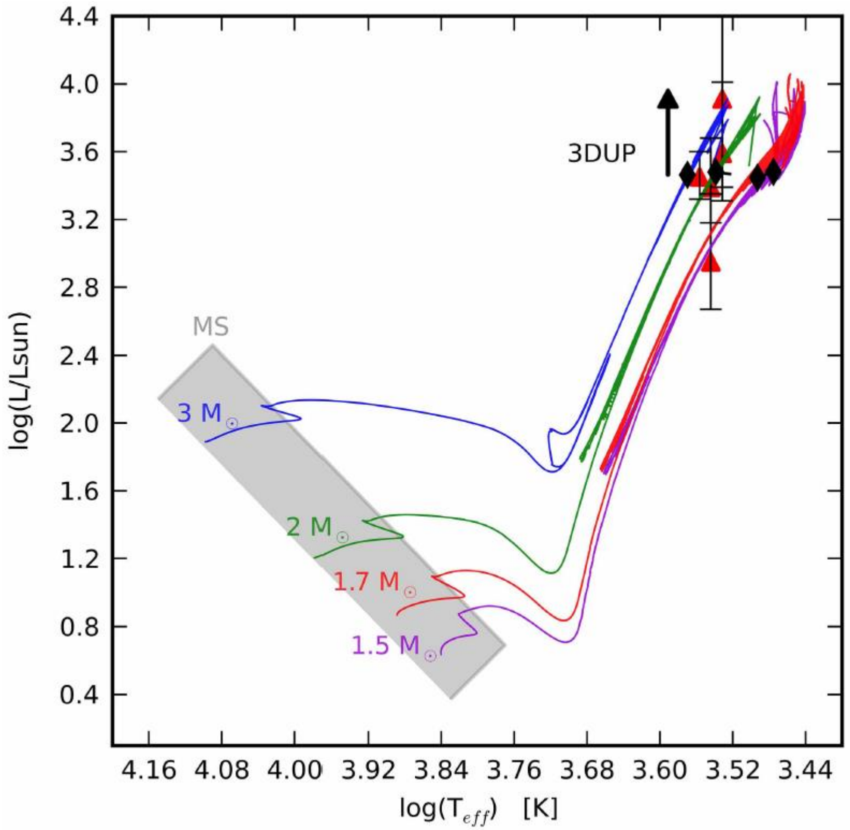
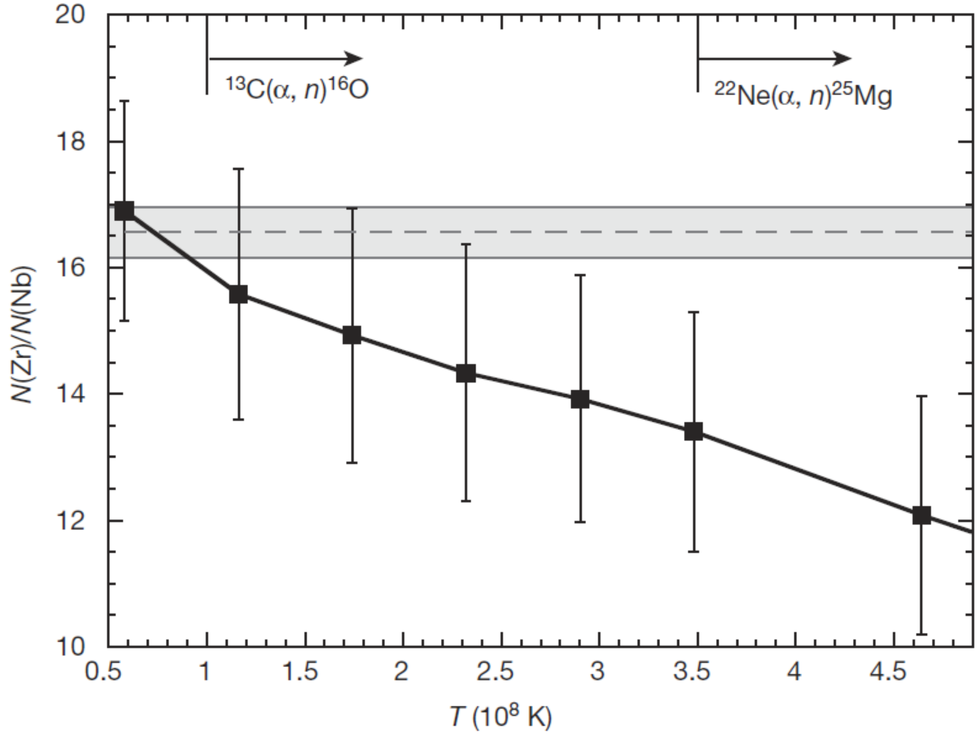


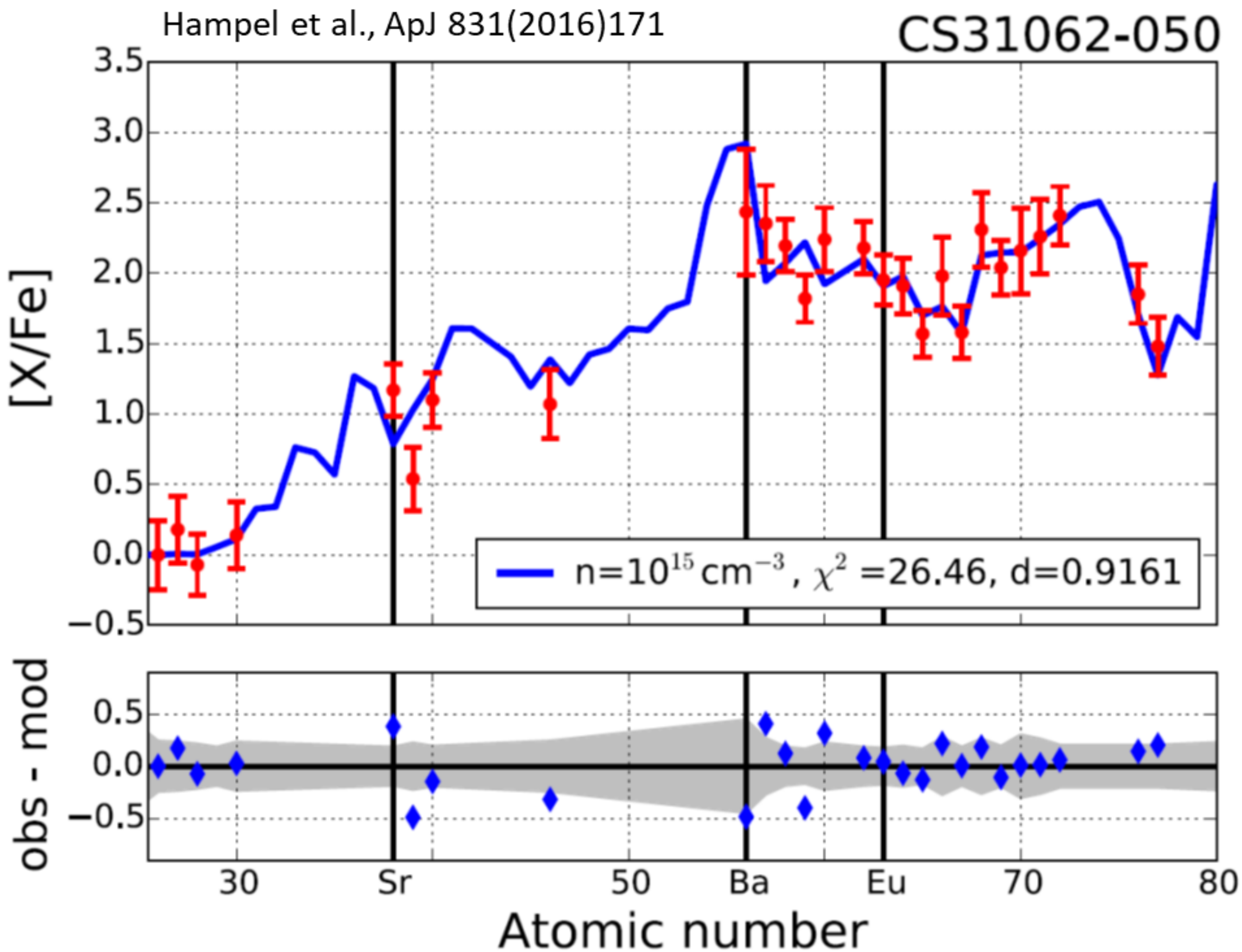


Determine the s-process temperature using Zr and Nb abundances

The derived temperature supports ^{13}C as the s-process neutron source

Neyskens et al. (2015)

Carbon-Enhanced Metal-Poor(CEMP) stars



- R-process: ~10^{20} cm^{-3} S-process: <10^{13} cm^{-3}
- **Intermediate-process (i-process): 10^{14}-10^{16} cm^{-3}**
- **$^{13}C(\alpha,n)^{16}O$ is the neutron source (AGB? Metal-poor star?...)**

Impact on Galactic Chemical Evolution

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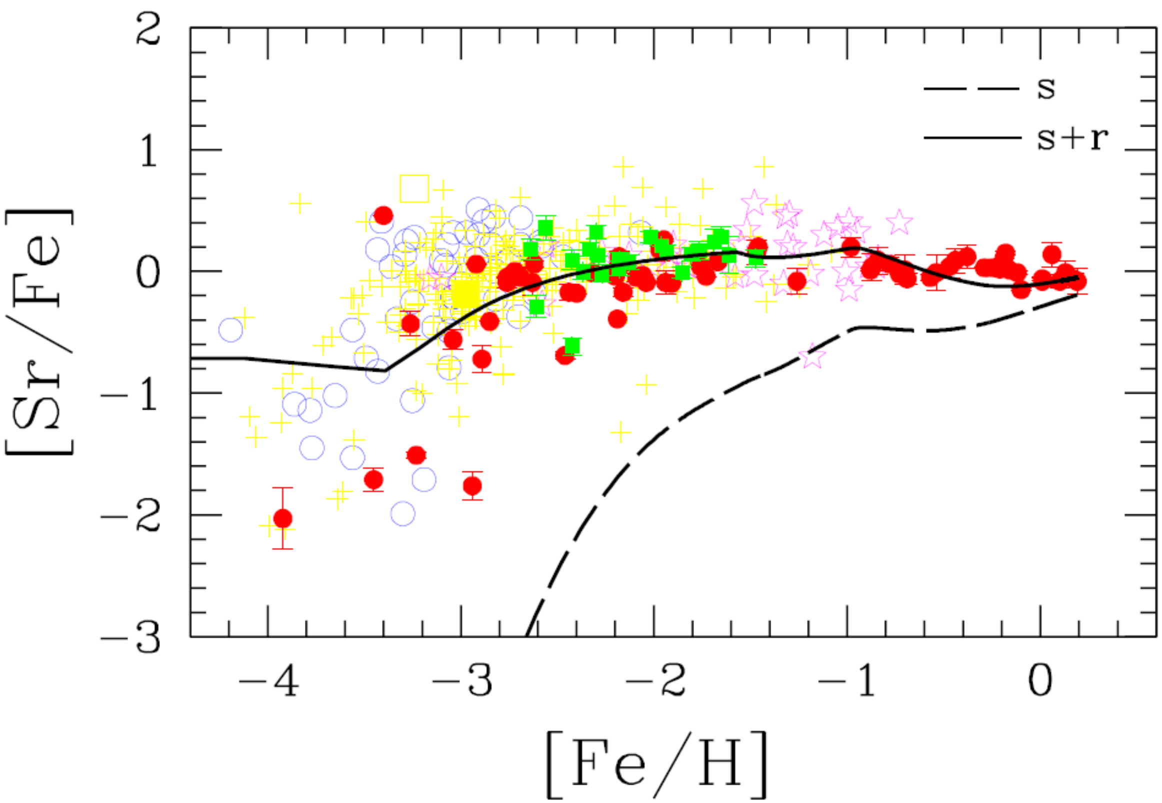


From Kobayashi, Karakas & Lugaro (2020)

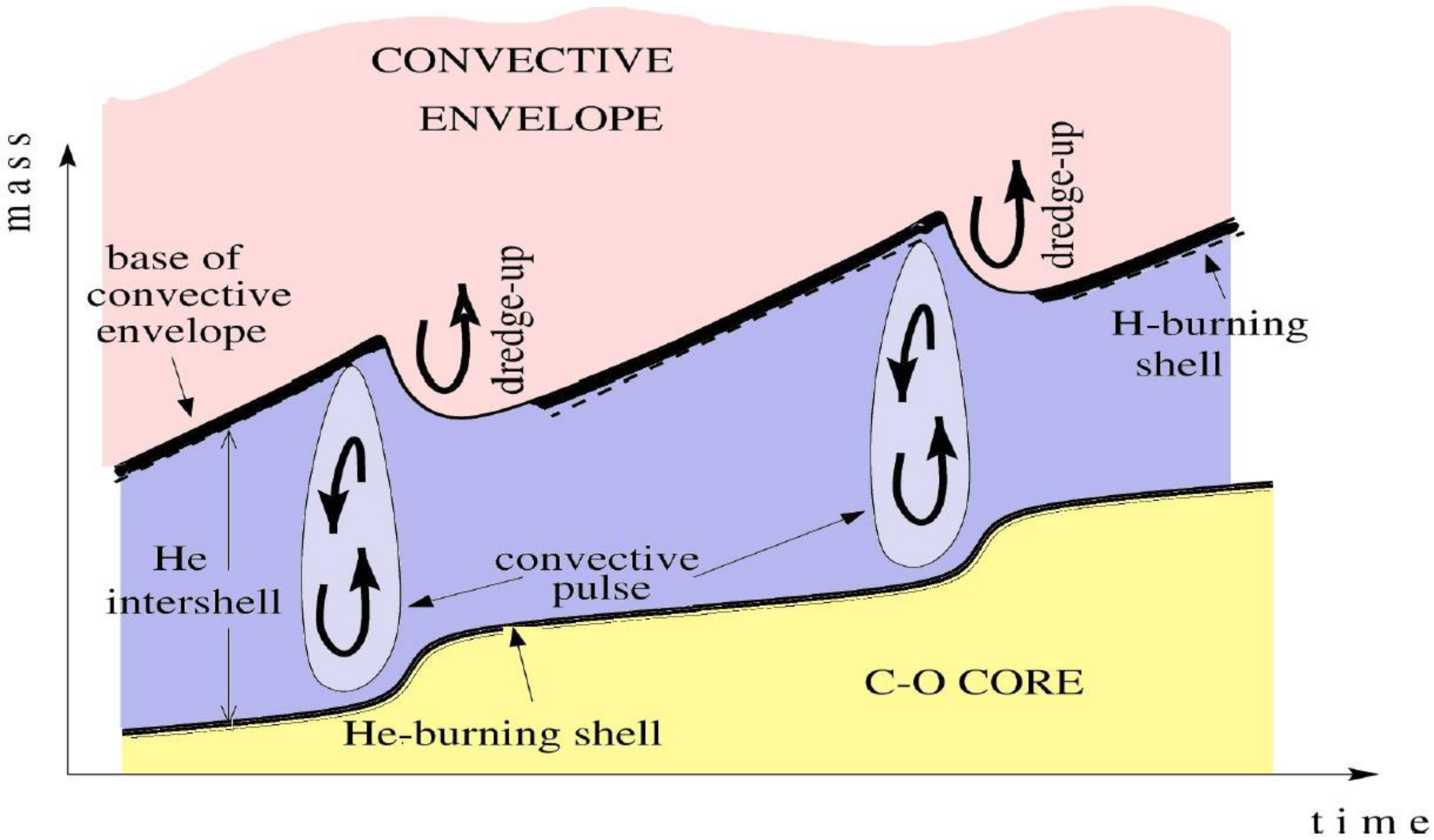
This model matches the solar composition of Sr with yields from s- and r-processes alone.

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)

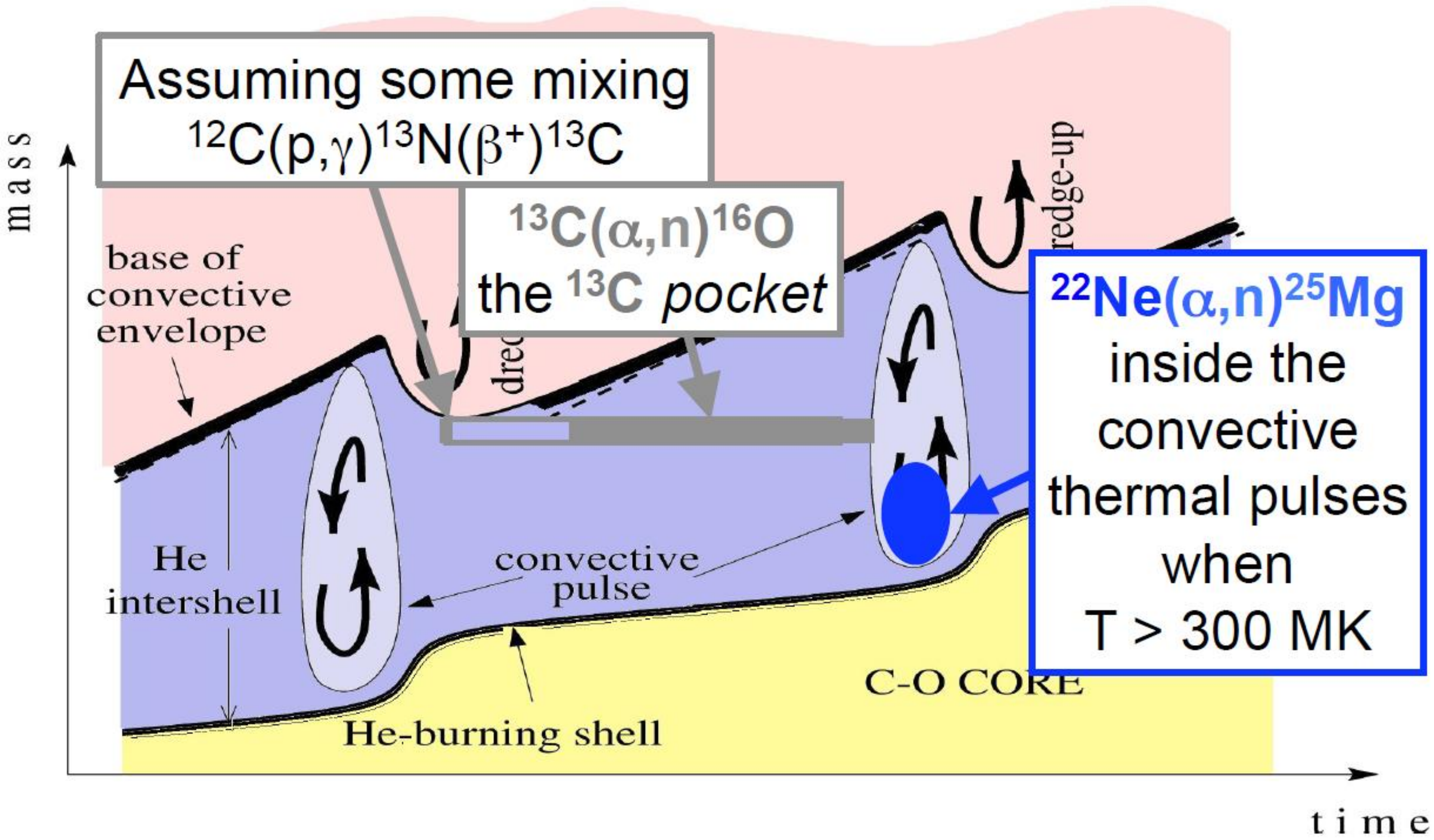
Taken from Karakas's lecture. 16th NIC school
https://indico.ihep.ac.cn/event/15049/overview

The neutron sources



Taken from Lugaro's lecture

The neutron sources



Taken from Lugaro's lecture

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

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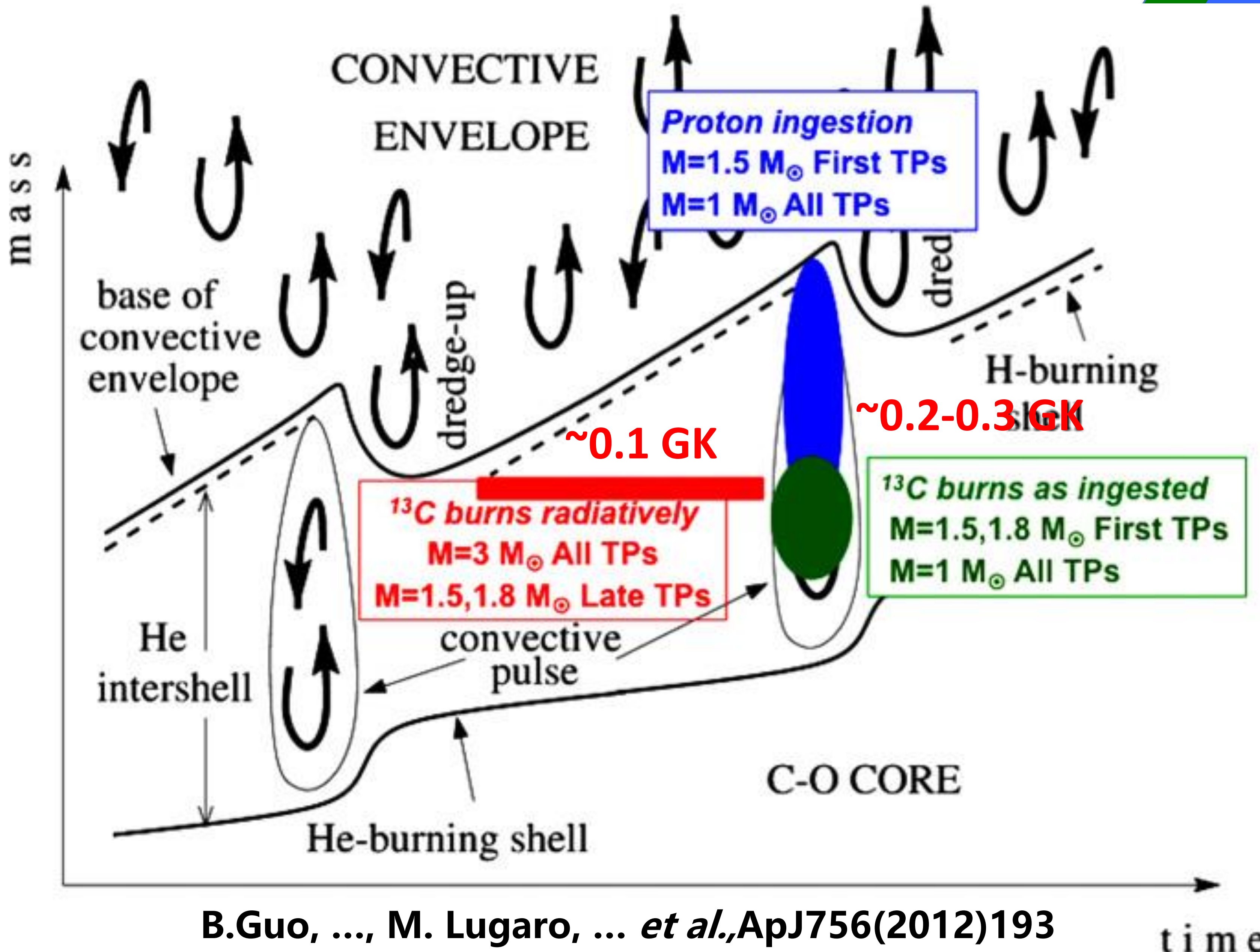
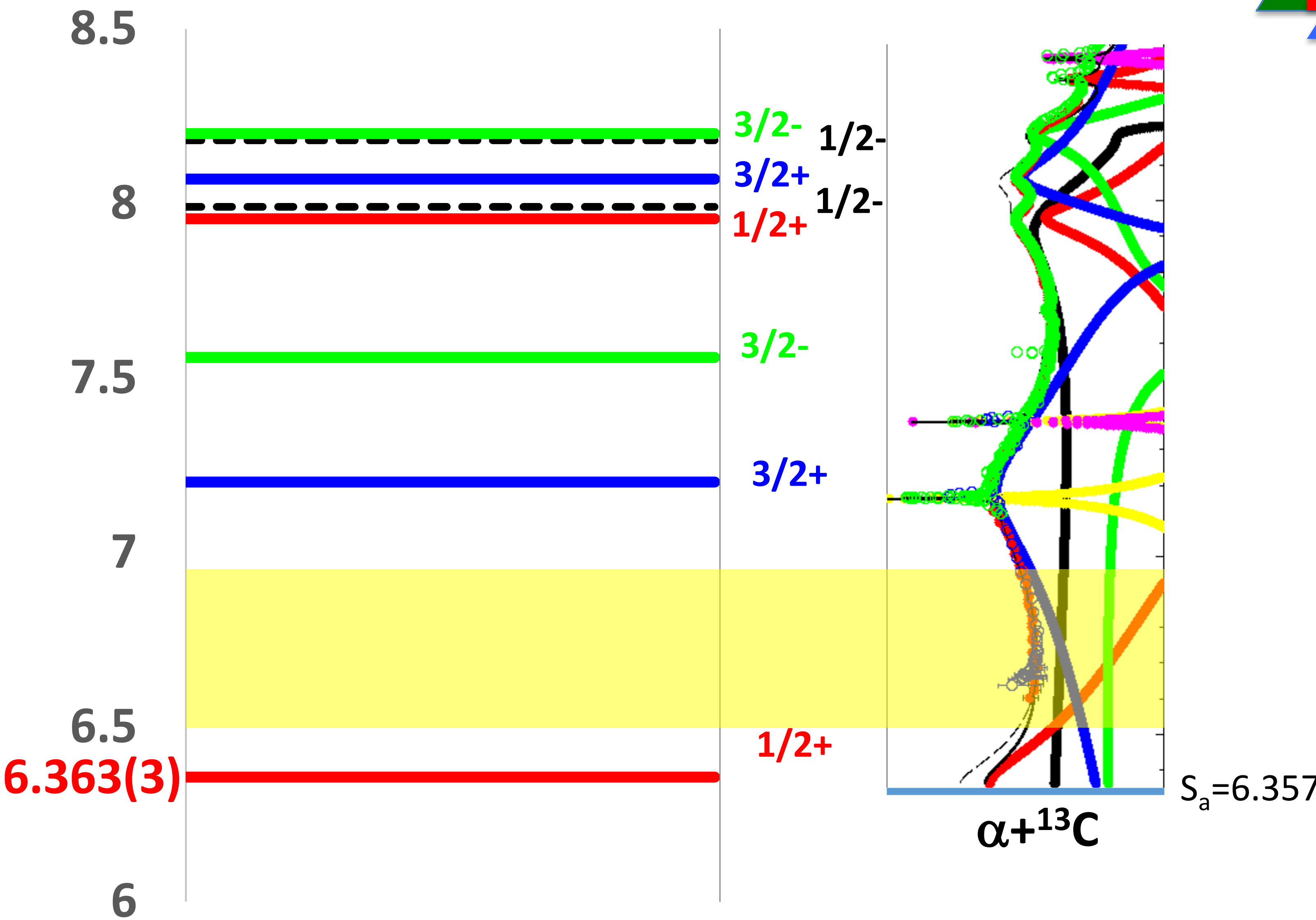


B.Guo, …, M. Lugaro, … *et al.*,ApJ756(2012)193

Complicated Reaction



Faestermann et al. PRC(2015)

Importance of the threshold state

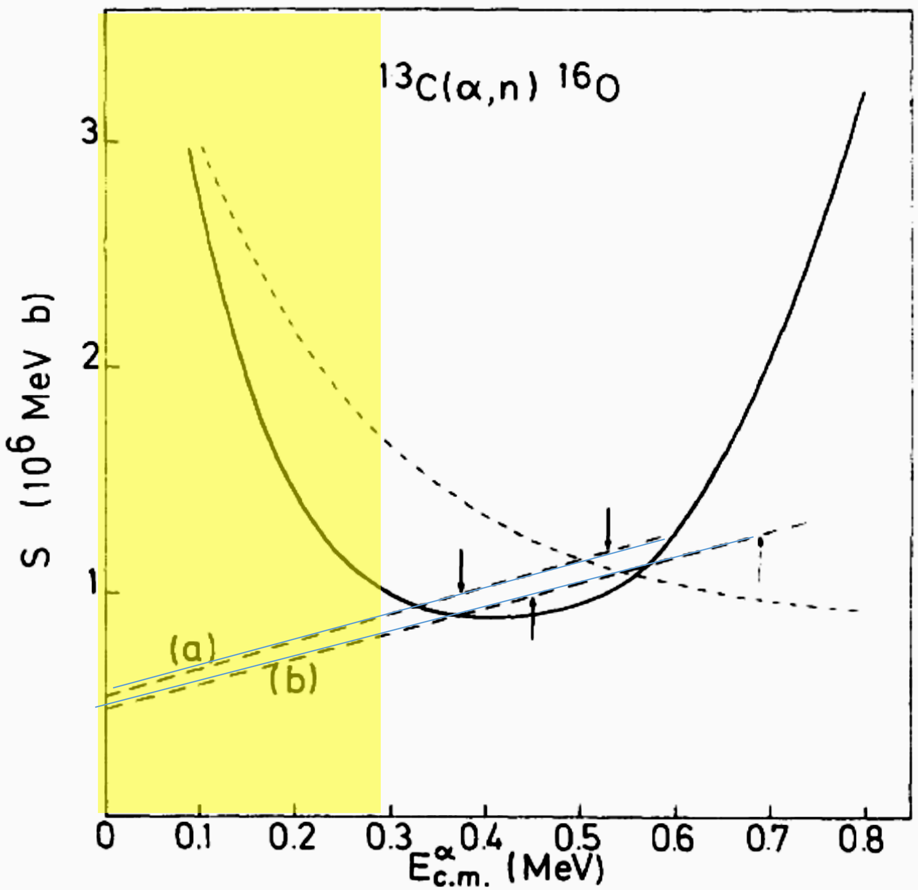
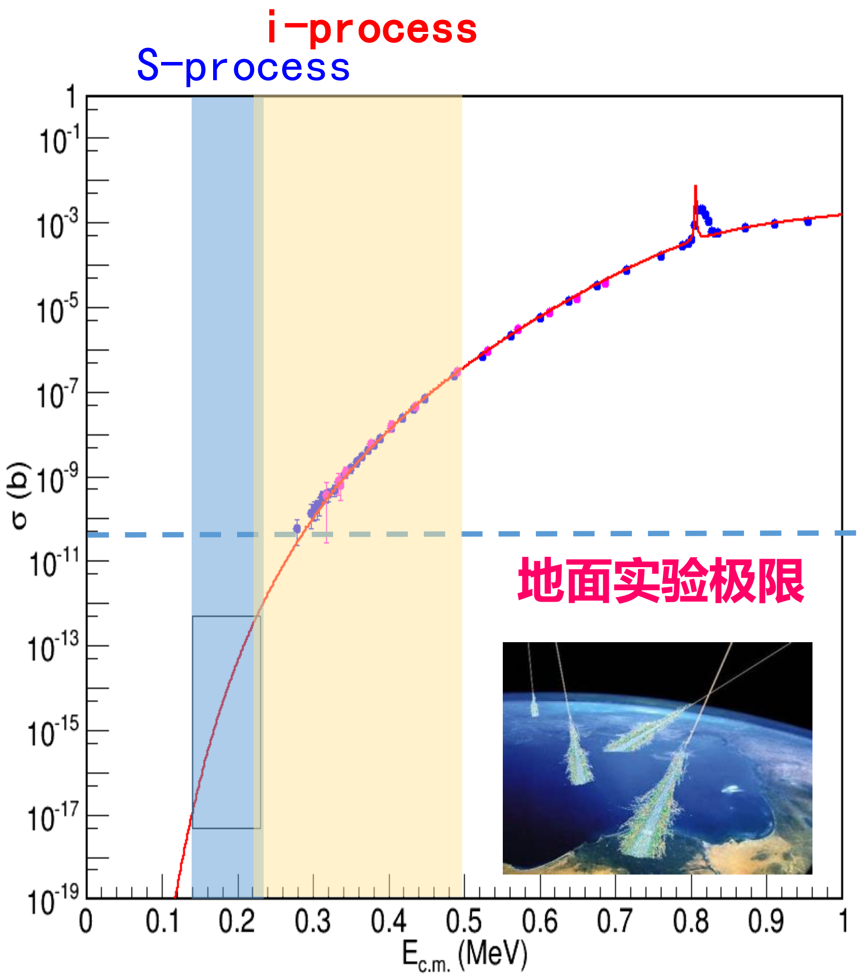
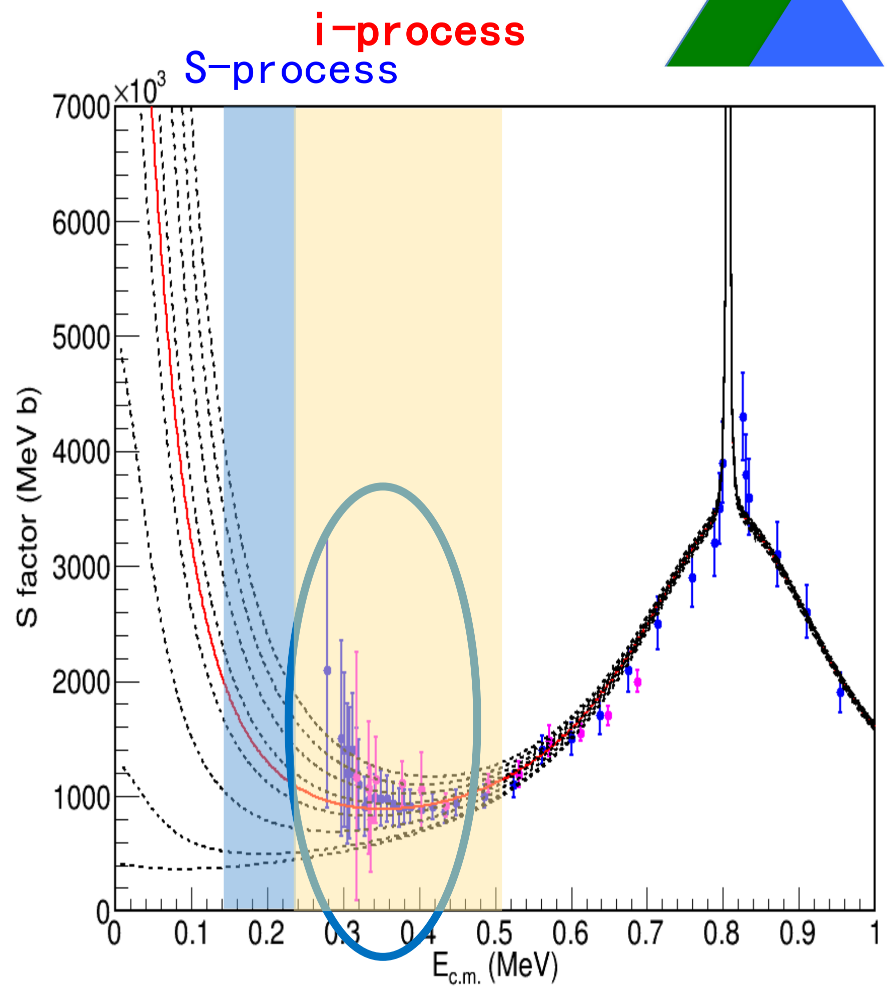


FIG. 6. $^{13}C(\alpha,n)^{16}O$ S factor. The dotted line represents the GCM result; the full line is obtained with the Breit-Wigner parametrization (see text); the dashed lines are the experimental data taken from Ref. 3 (a) and Ref. 4 (b). The arrows indicate the energy range where the experiments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

P. Descouvemont PRC(1987)

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





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

Indirect approaches:

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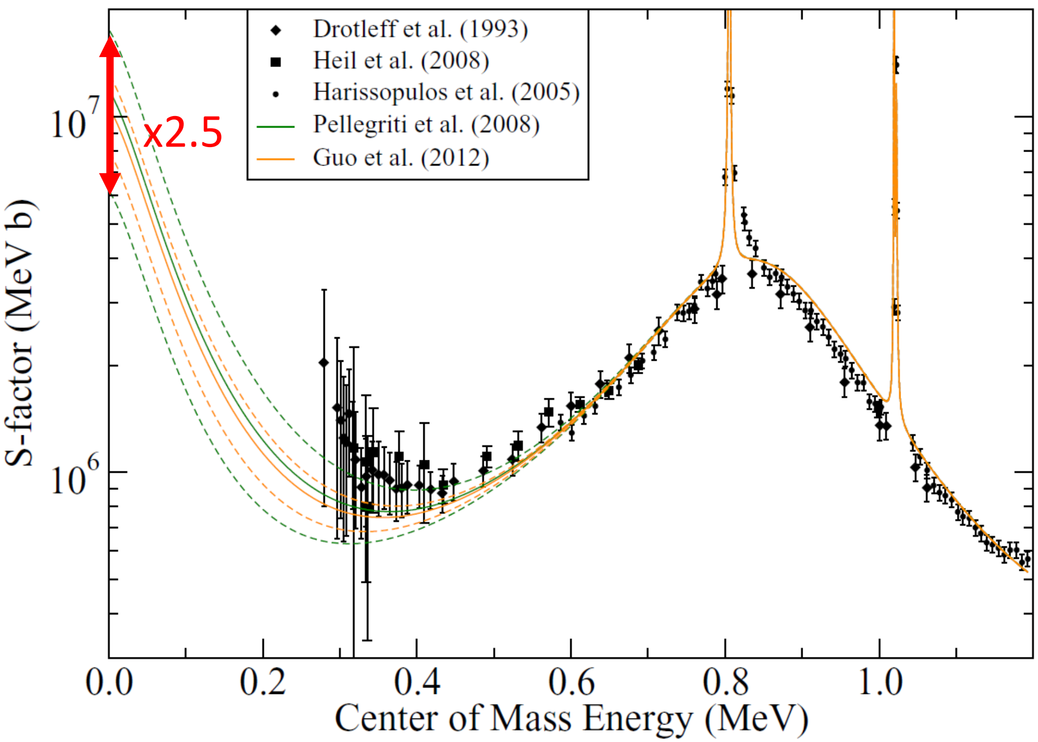
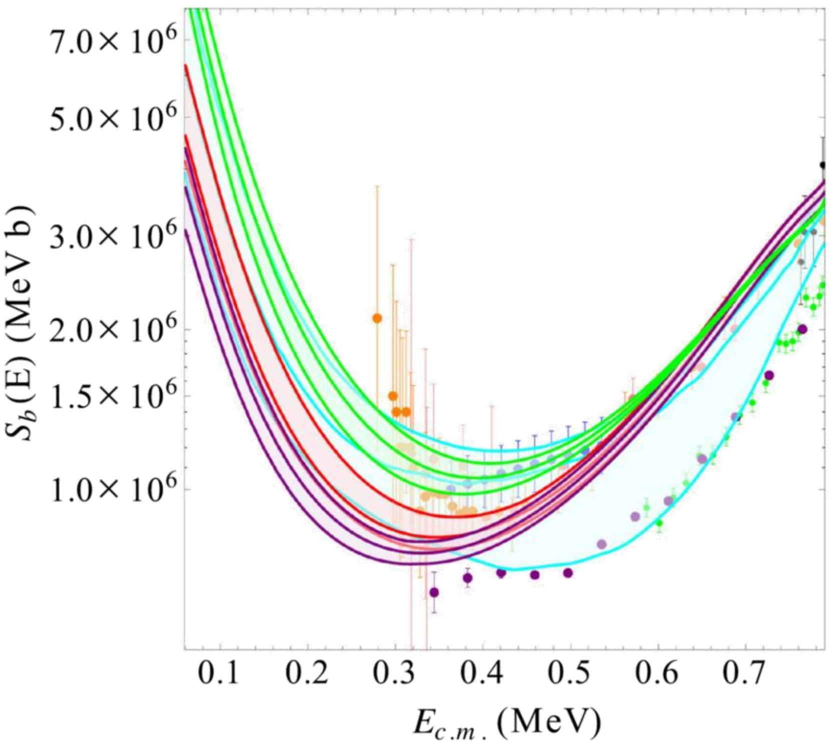




Asymptotic Normalization Coefficient (ANC)

See deBoer (2020) for a summary

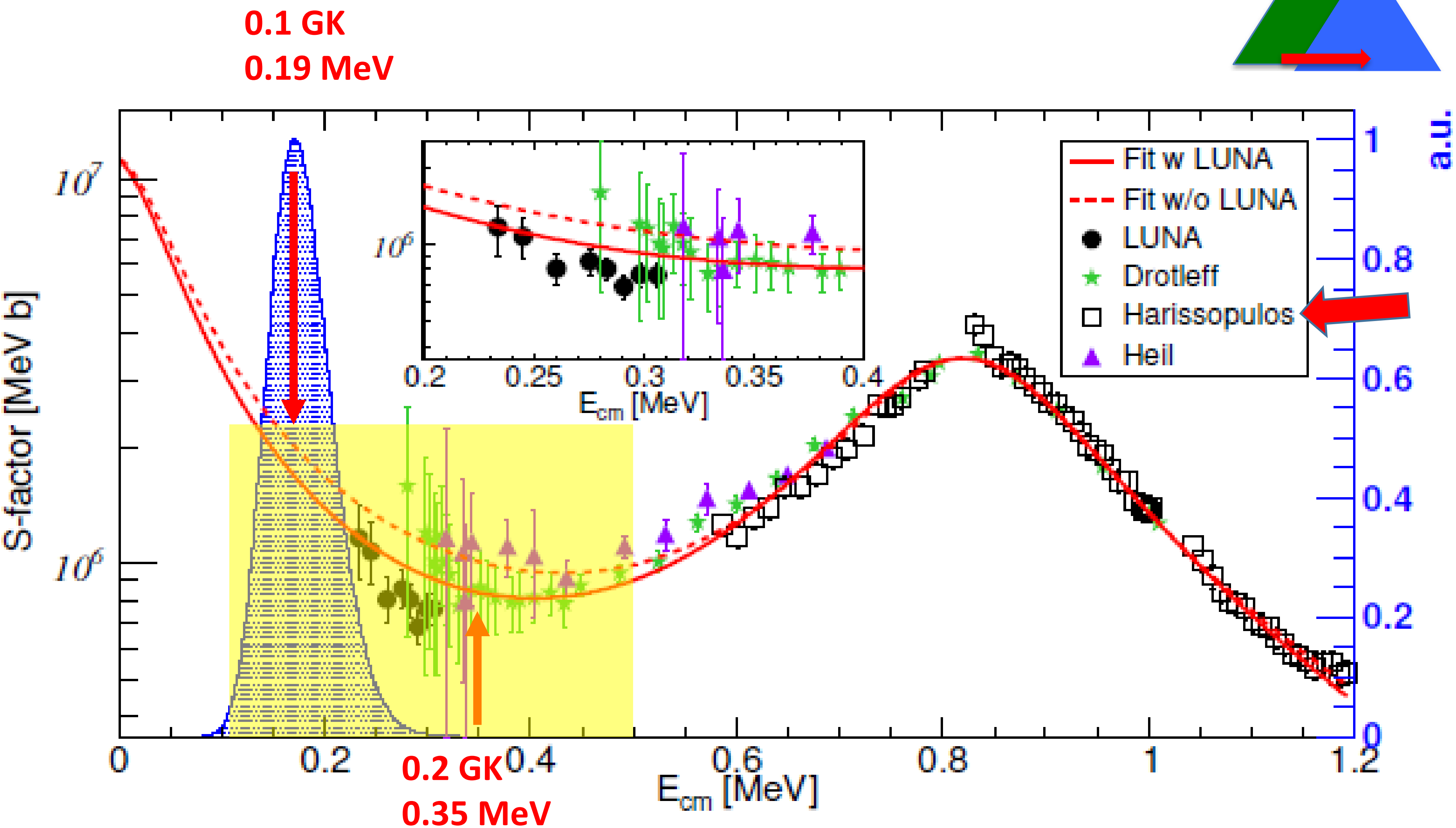
Trojan Horse Methode (THM)

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

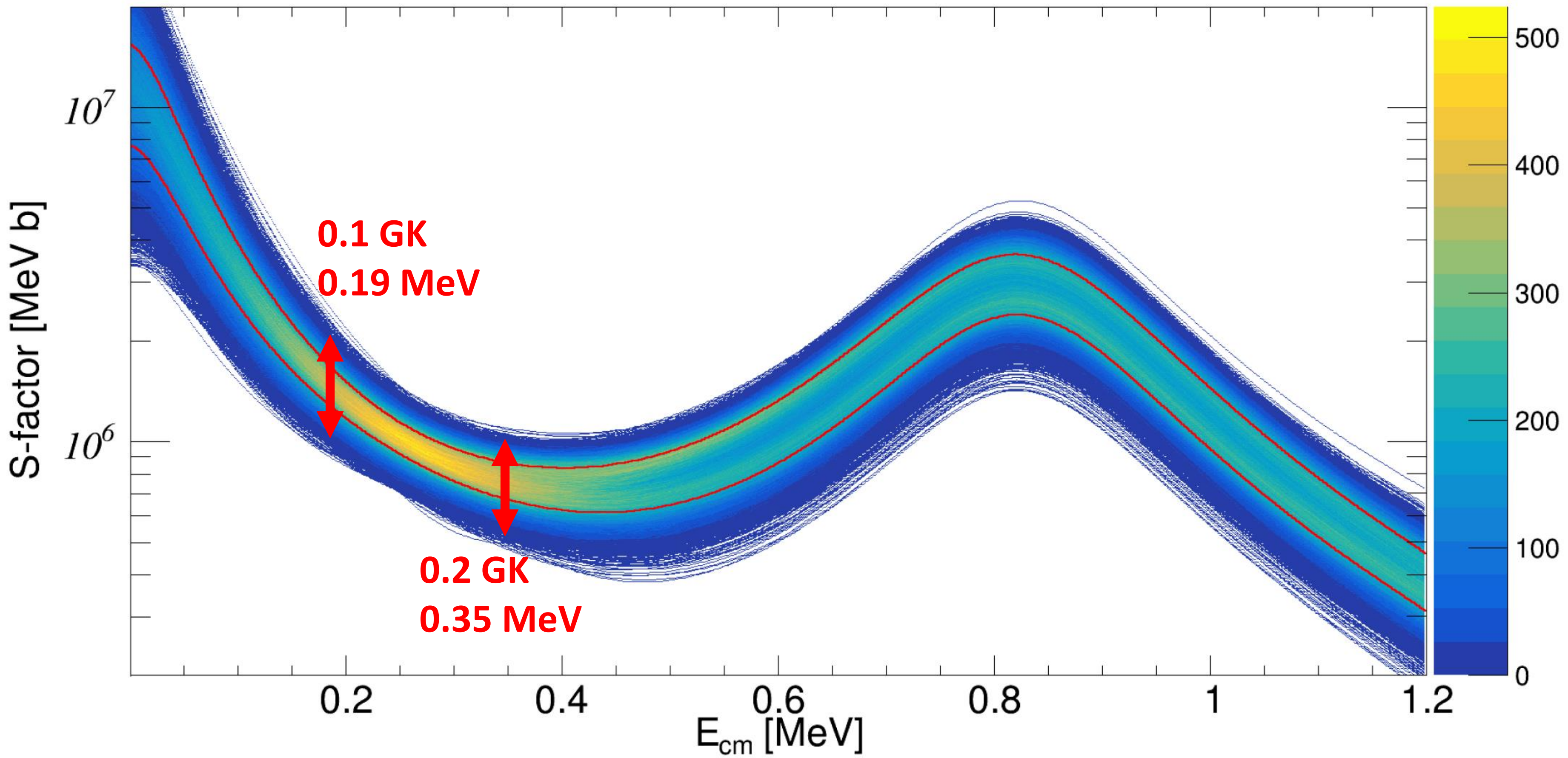
First Underground Measurement



- **First measurement of the higher energy part of the Gamow window of s-process**
- **Max. 150 pμA beam on > 100 targets**

Ciani et al. (2021)

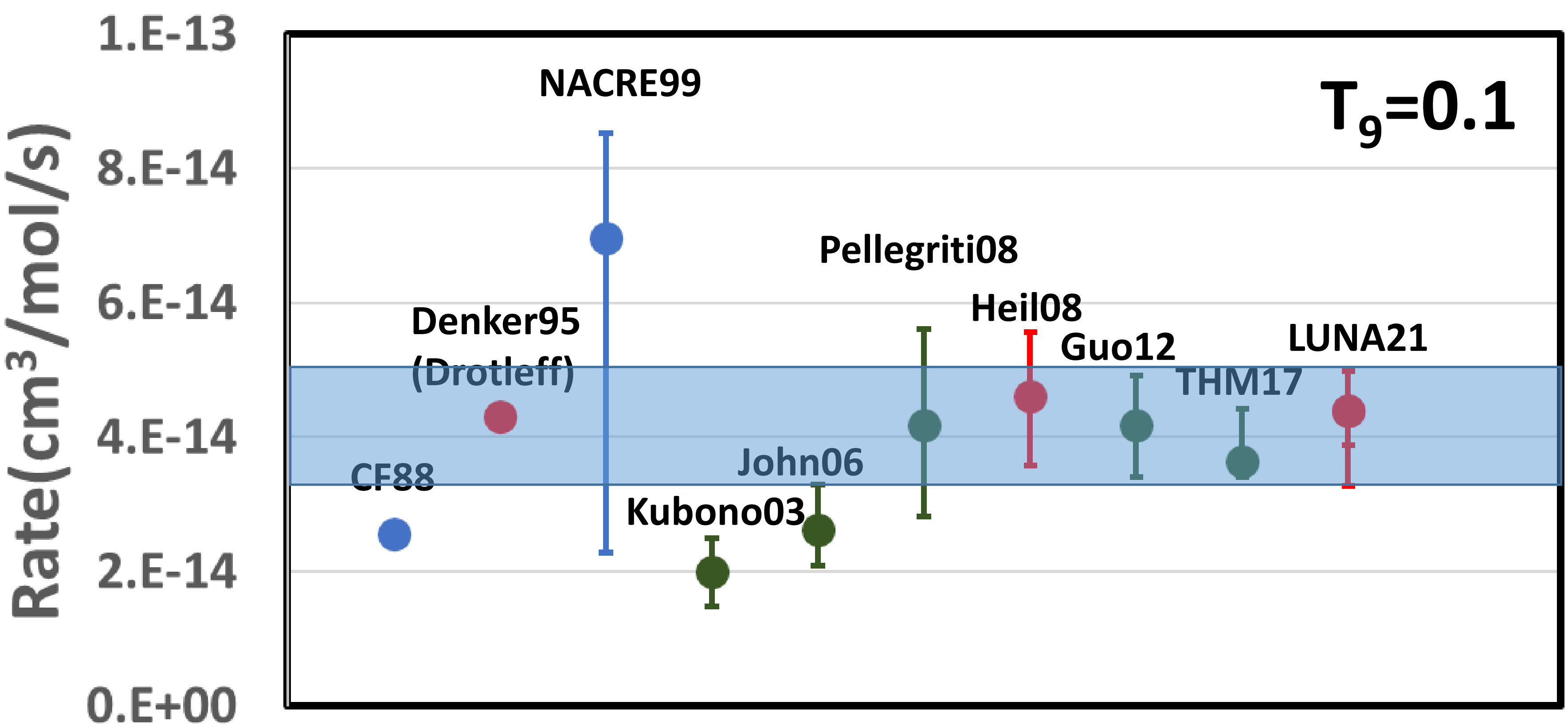
First Measurement in the Gamow window of s-process



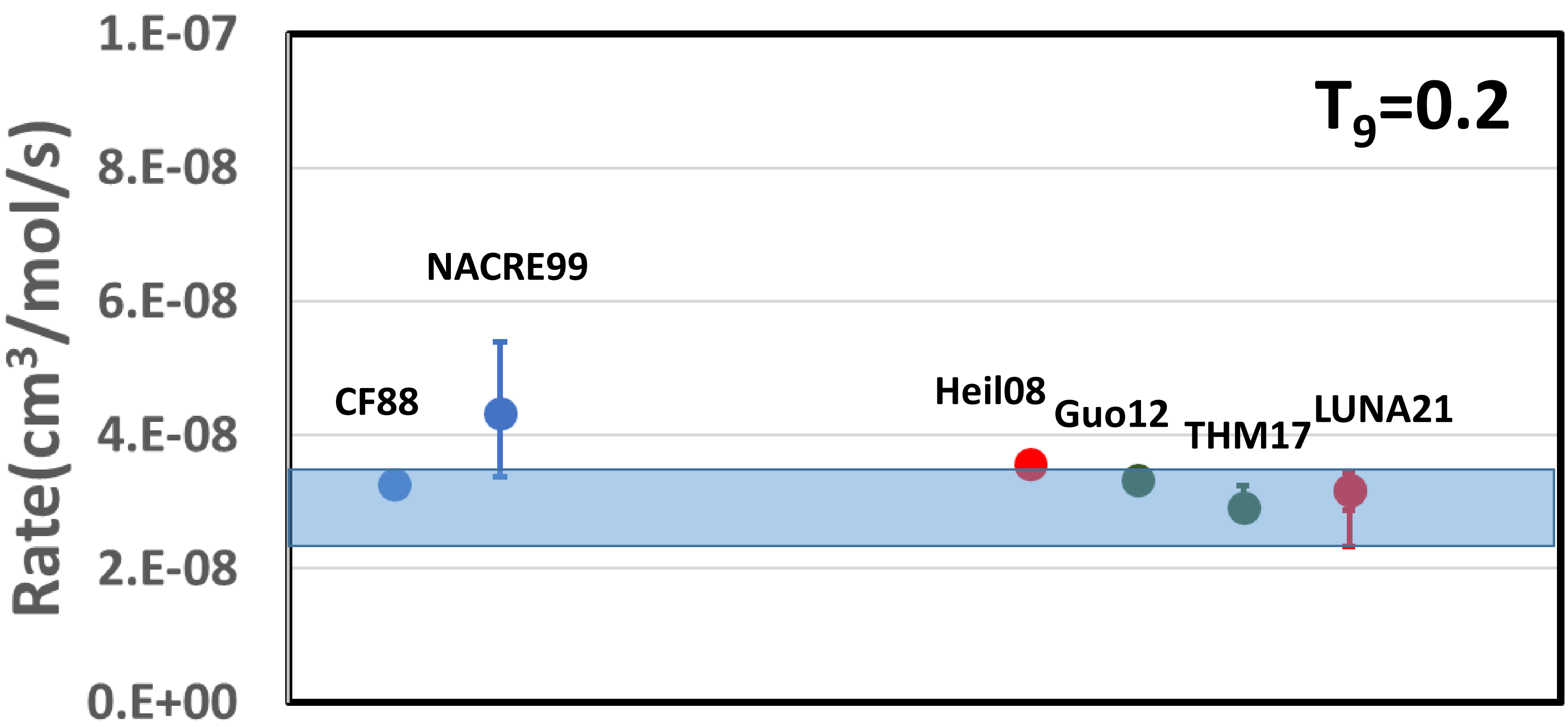
- Extrapolation needs ANC of the threshold state and higher energy data
- Inconsistency among the data sets is the major systematic uncertainty

Ciani et al. (2021)

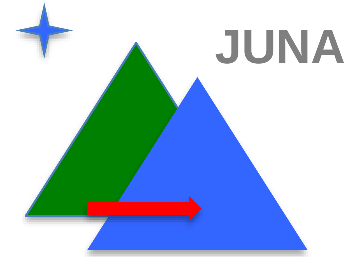
Reaction Rate Uncertainty

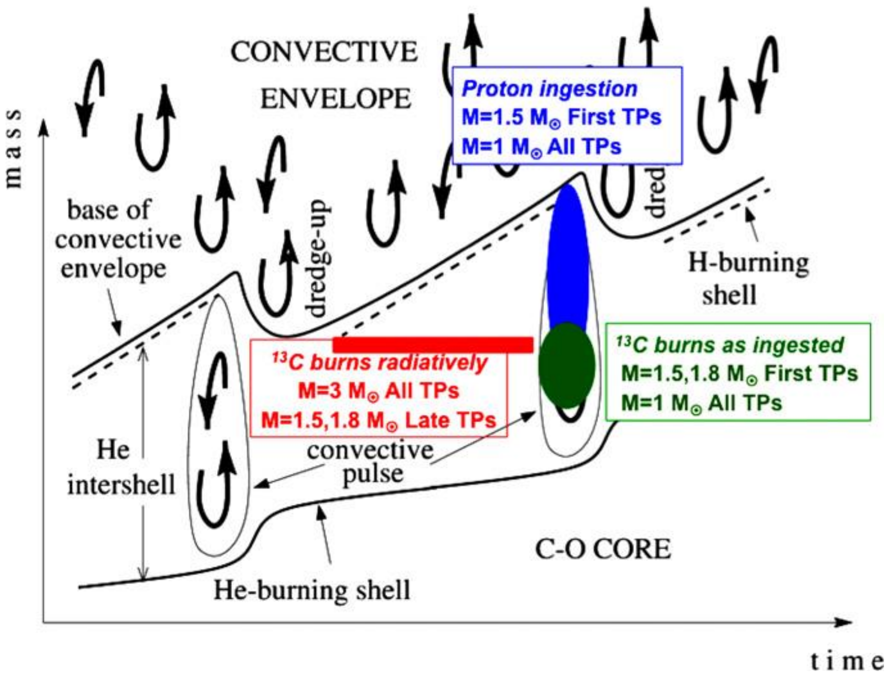


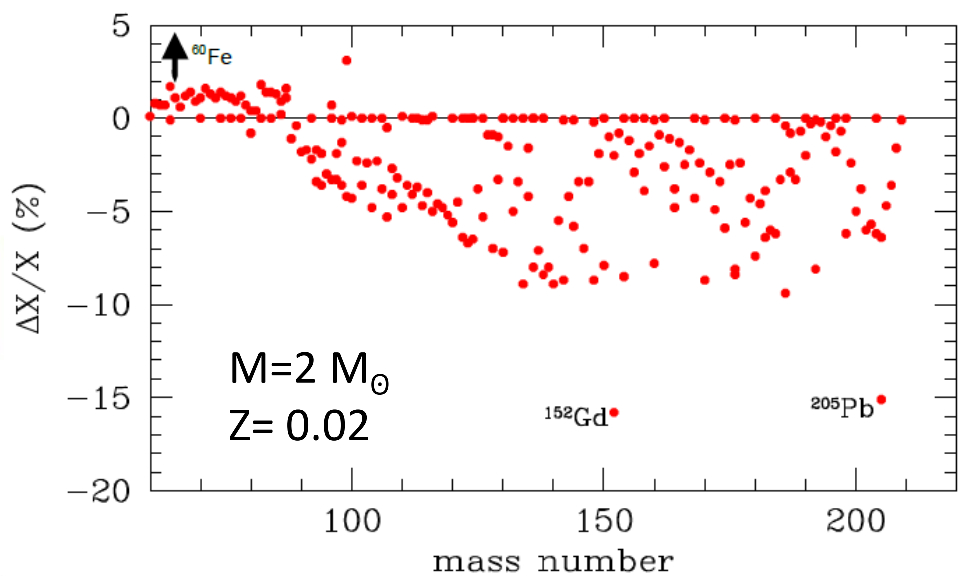
Reaction Rate Uncertainty



Impact to s process nucleosynthesis

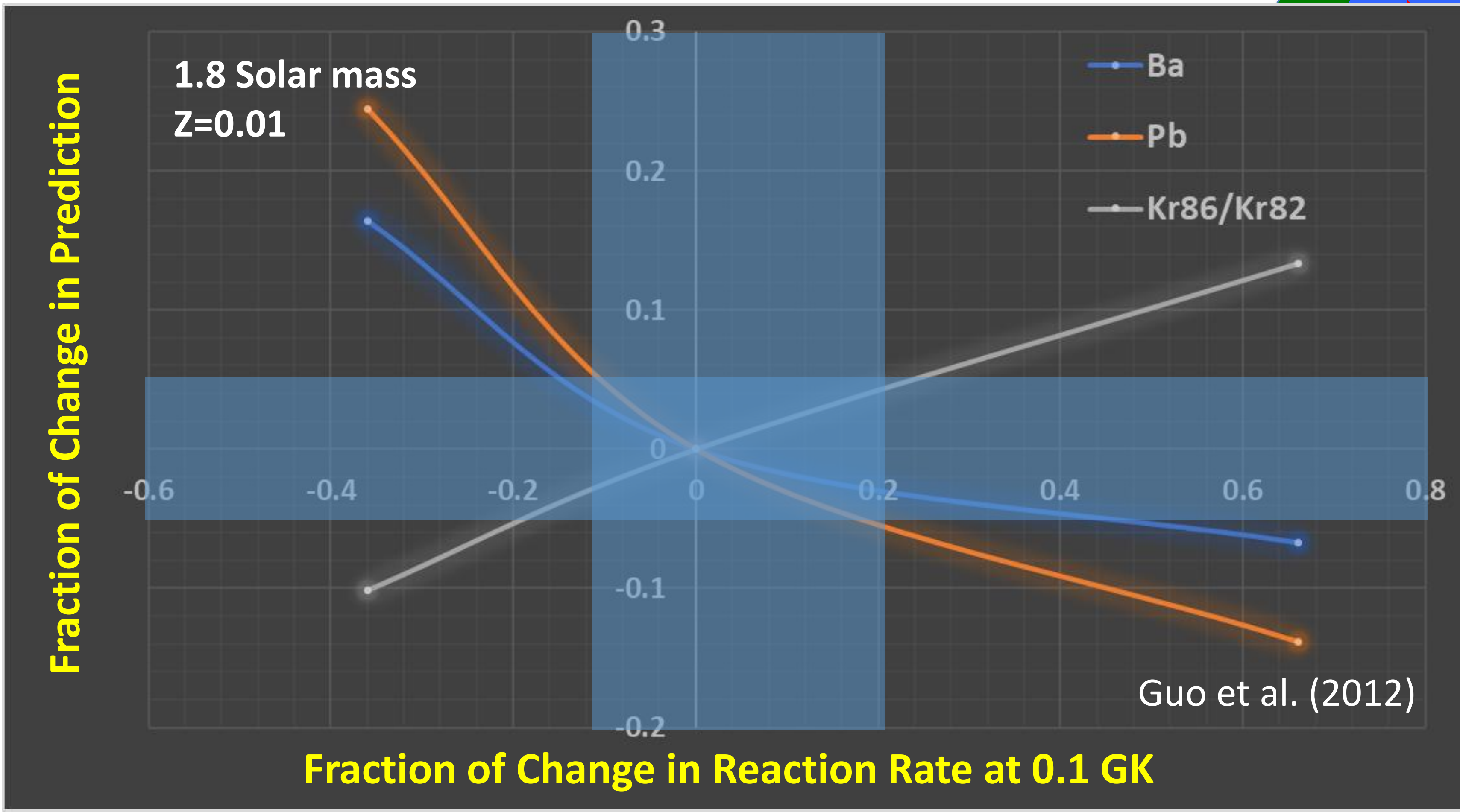






- Low-LUNA rate favors more ^{13}C surviving in the ^{13}C-pocket (0.1GK)
- The leftover ^{13}C provides extra neutrons from $^{13}C(\alpha,n)^{16}O$ during the following thermal pulse (0.2 GK), affecting ^{60}Fe, ^{205}Pb, and ^{152}Gd

Impact on s-process nucleosynthesis



+20%/−12% in Reaction Rate at 0.1GK requires
+/− 5% in the s−process yield→could be large for r−process yield

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

Impact on s/i-process nucleosynthesis

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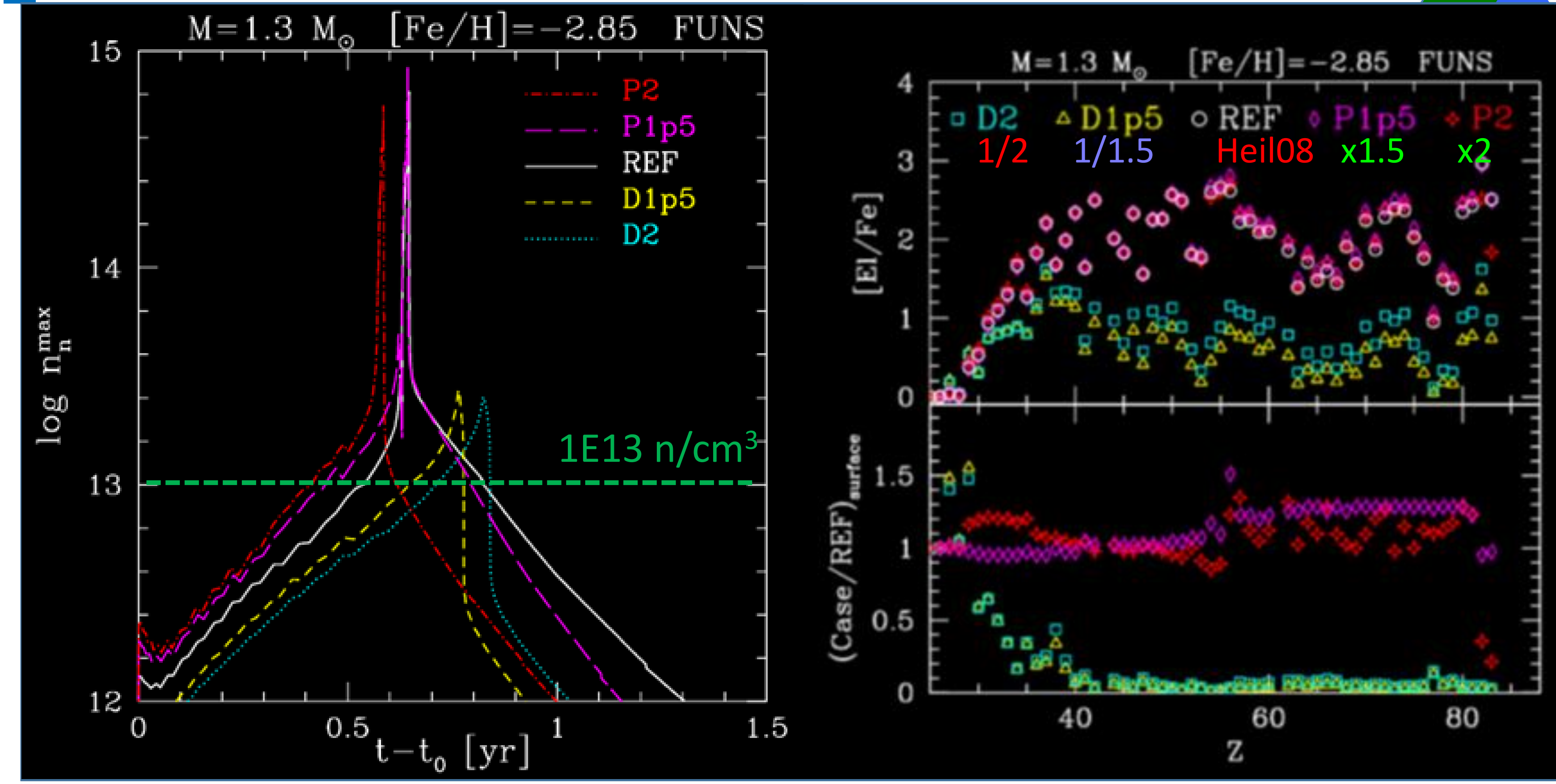

Large variations (up x50) are found in low-mass low-metallicity models, if protons are mixed and burnt at very high temperatures

$$[x/y] = \log_{10}\left(N(x)/N(y)\right)_{star} - \log_{10}\left(N(x)/N(y)\right)_{sun}$$

Cristallo et al., (2018)

Jinping Underground Nuclear Astrophysics

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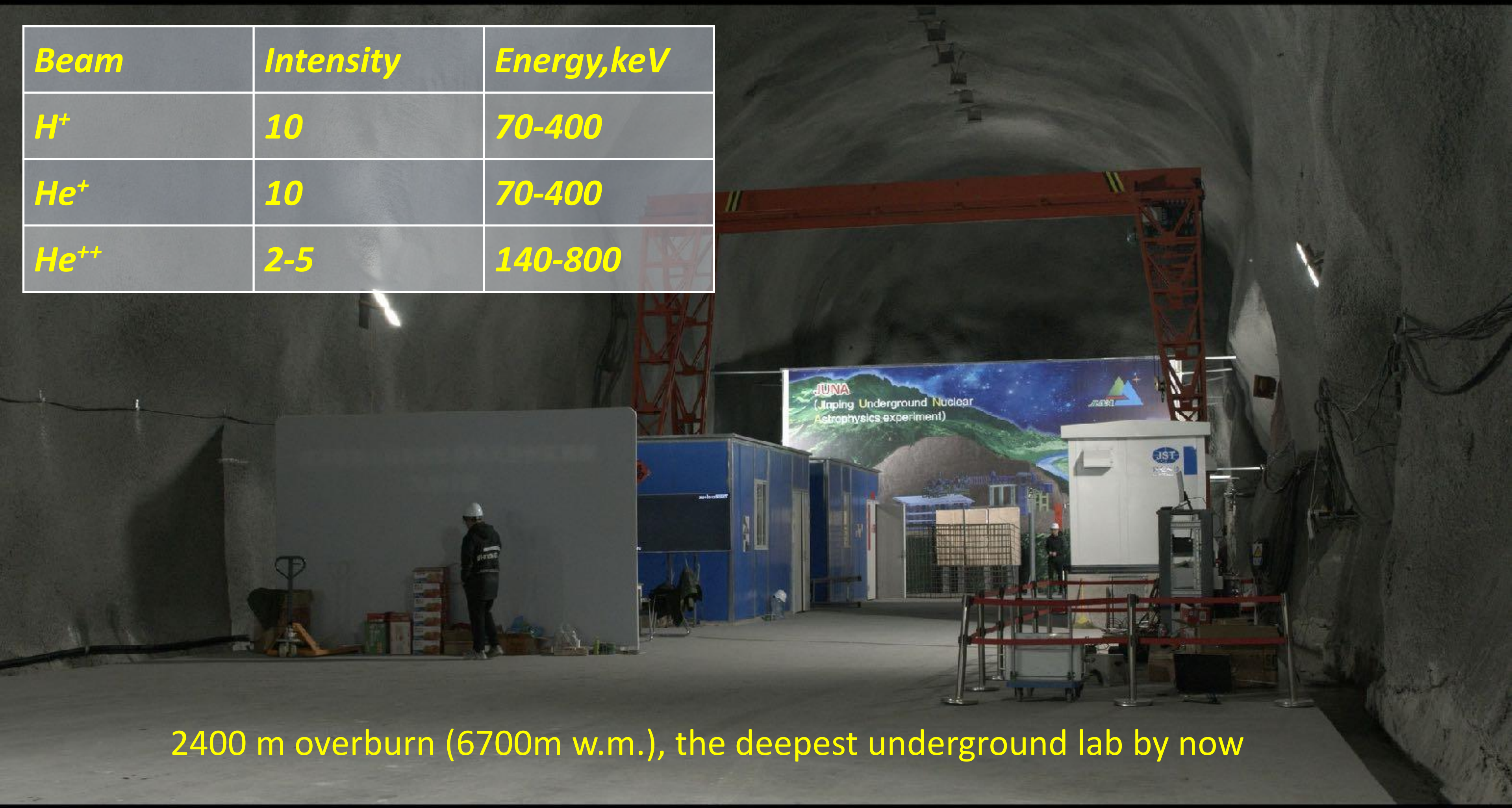


Beam	*Intensity*	*Energy,keV*
H^+	*10*	*70-400*
He^+	*10*	*70-400*
He^{++}	*2-5*	*140-800*

2400 m overburn (6700m w.m.), the deepest underground lab by now

JUNA projects (2015-2021)

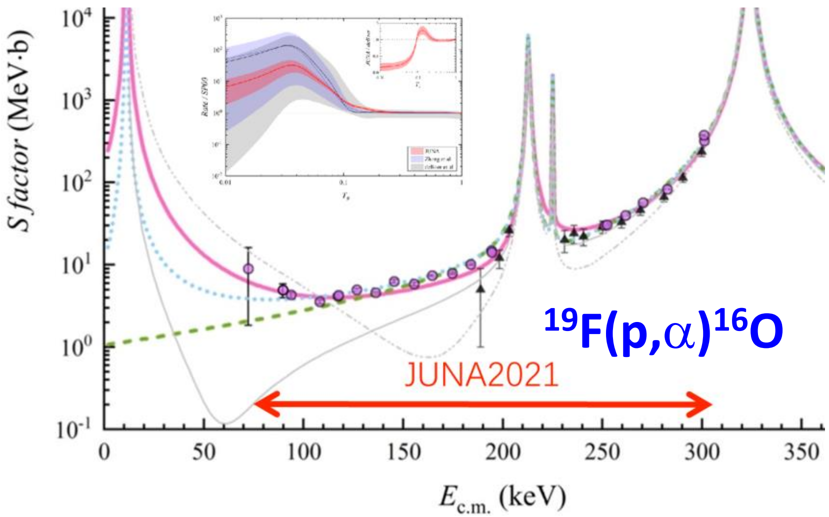
CIAE， W.P. Liu
$^{12}C(\alpha,\gamma)^{16}O$

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

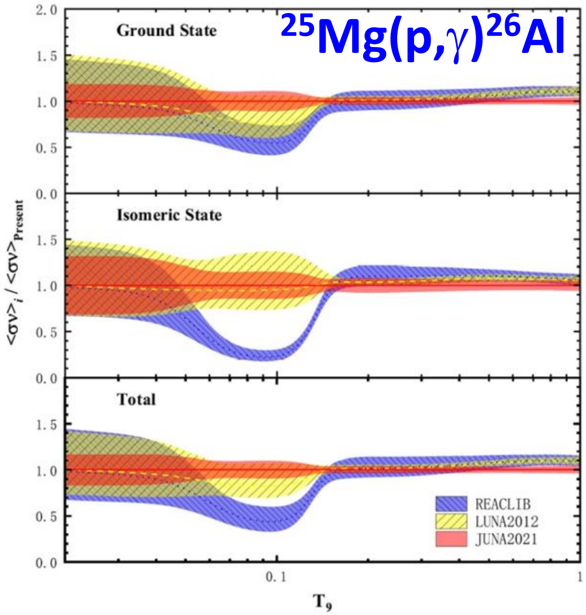
CIAE, Z.H. Li
$^{25}Mg(p,\gamma)^{26}Al$

IMP, X.D. Tang
$^{13}C(\alpha,n)^{16}O$

CIAE, G. Lian
Accelerator and Infrastructure



L.Y. Zhang et al, PRL127(2021)152702



J. Su et al., Science Bulletin, 67(2022)2

Ion source and accelerator status

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

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

Accelerator tank installed in Aug. 2016

Beam line and ECR

Beam diagnostics

Courtesy from W.P.Liu

Underground progress Sept. 2020-Apr. 2021

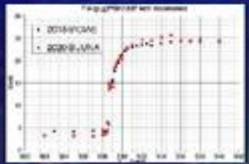
Sept. 2020 | Oct. | Nov. | Dec. | Jan. 2021 | Feb.-Apr.

- Team arrive
- Exp. room Dis. Acc.
- Acc. sent
- Power ready Acc. arrive
- Acc. setup
- Acc. room Water ready
- ECR beam
- Exp. Cal. Acc. beam
- Beam on show
- Exp. ready
- ^{25}Mg exp.
- ^{19}F exp.
- ^{13}C exp.
- ^{12}C exp.



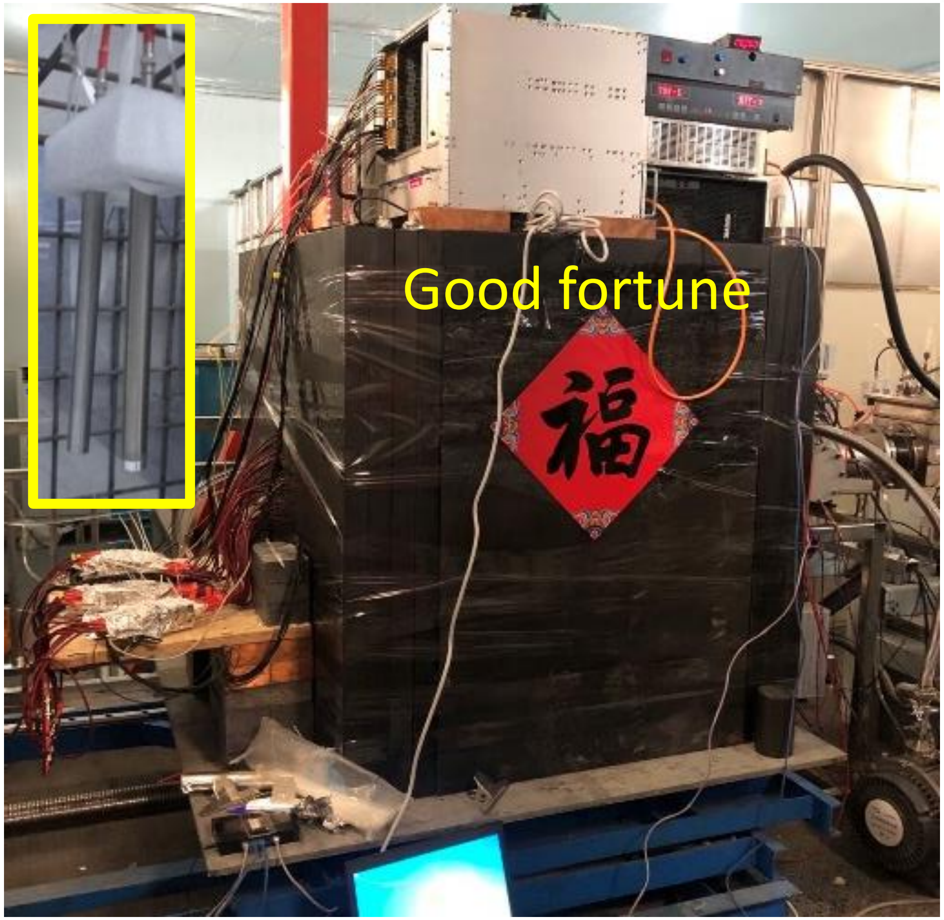


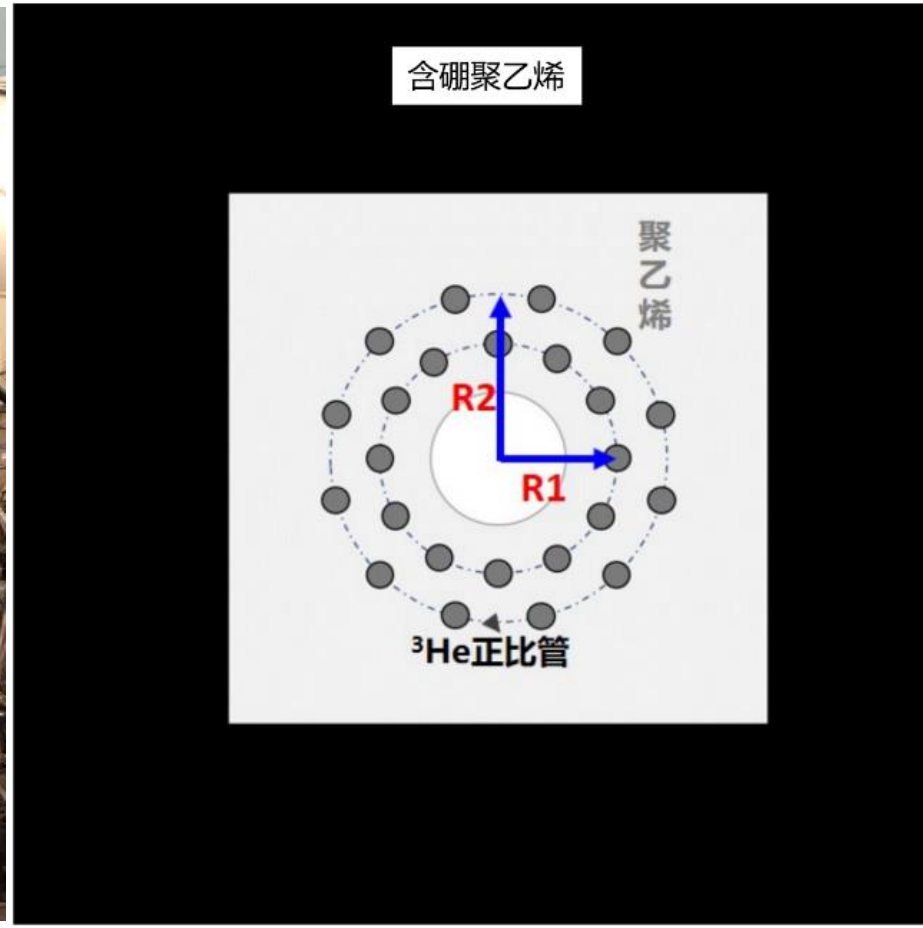




Courtesy from W.P.Liu

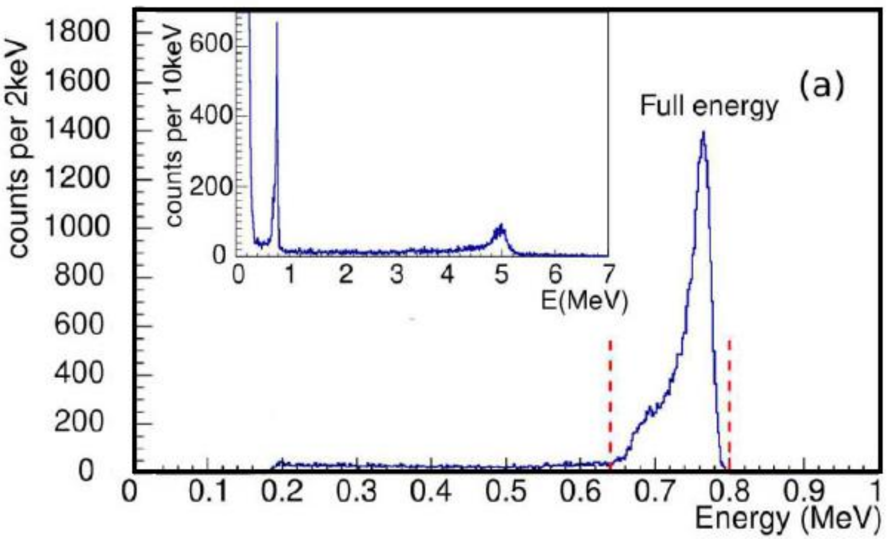
Low background neutron detector

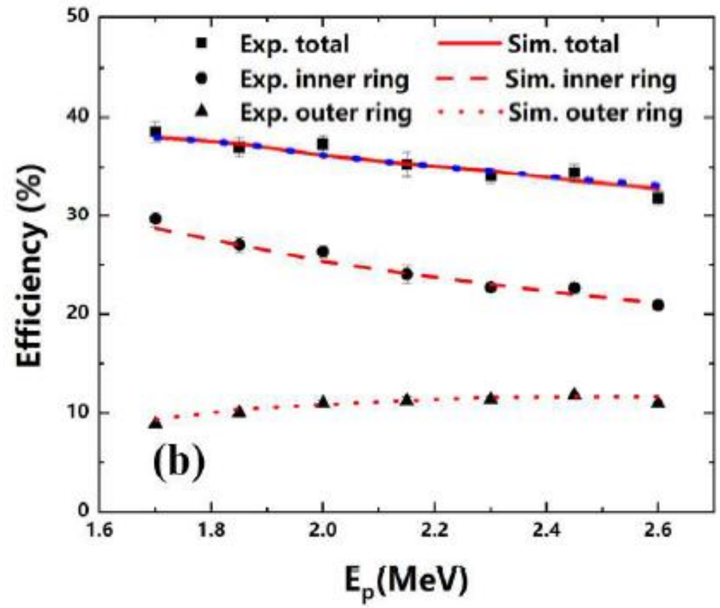


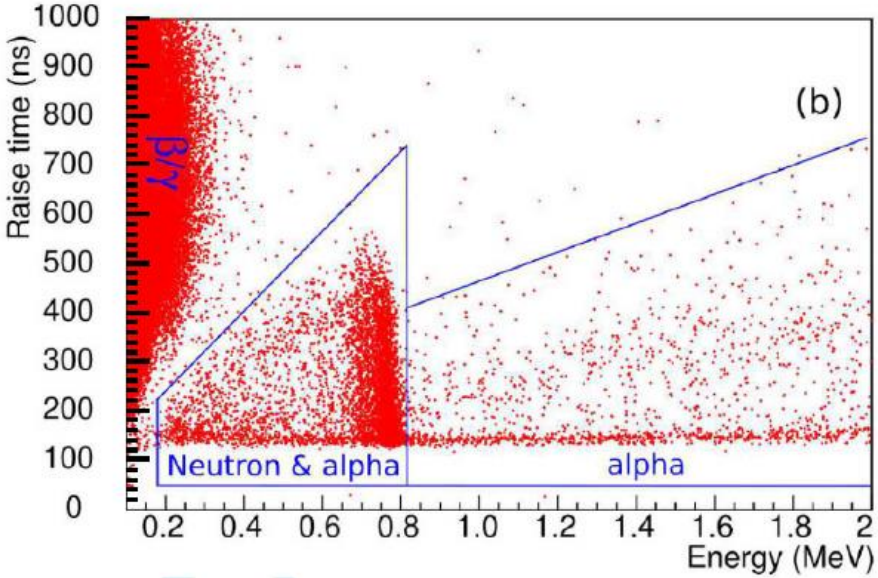


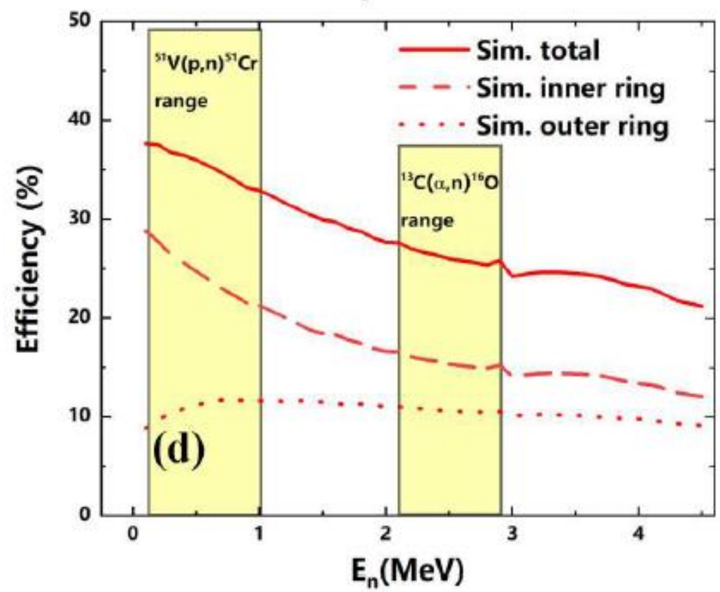
24x^{3}He counter + High Density PE + Borated PE

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



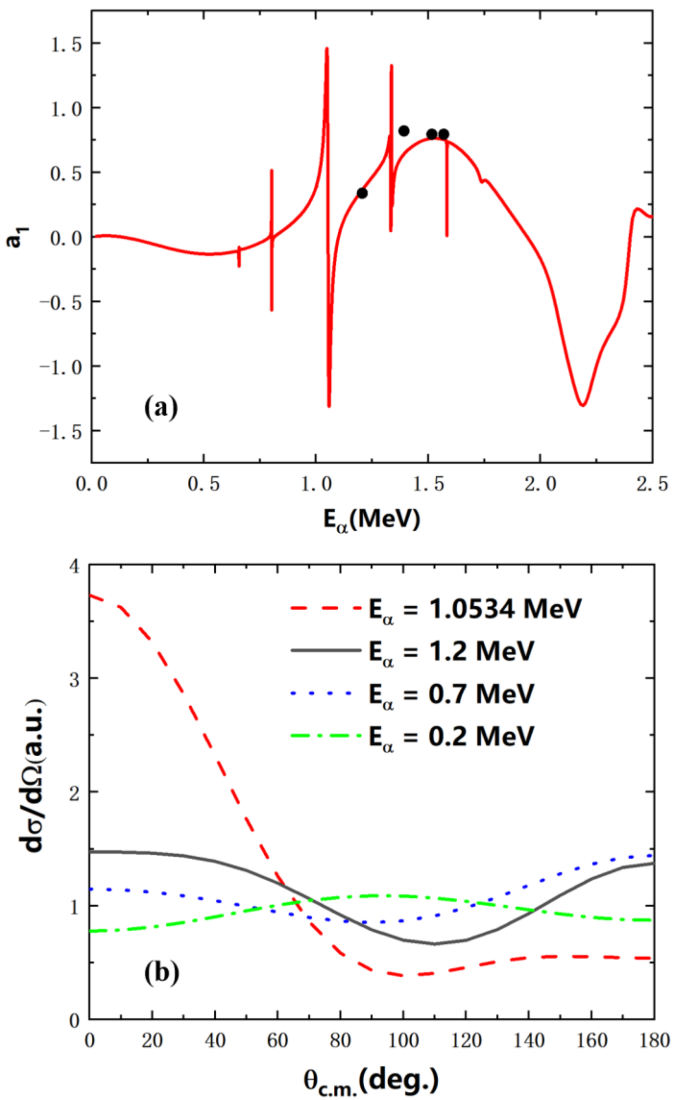


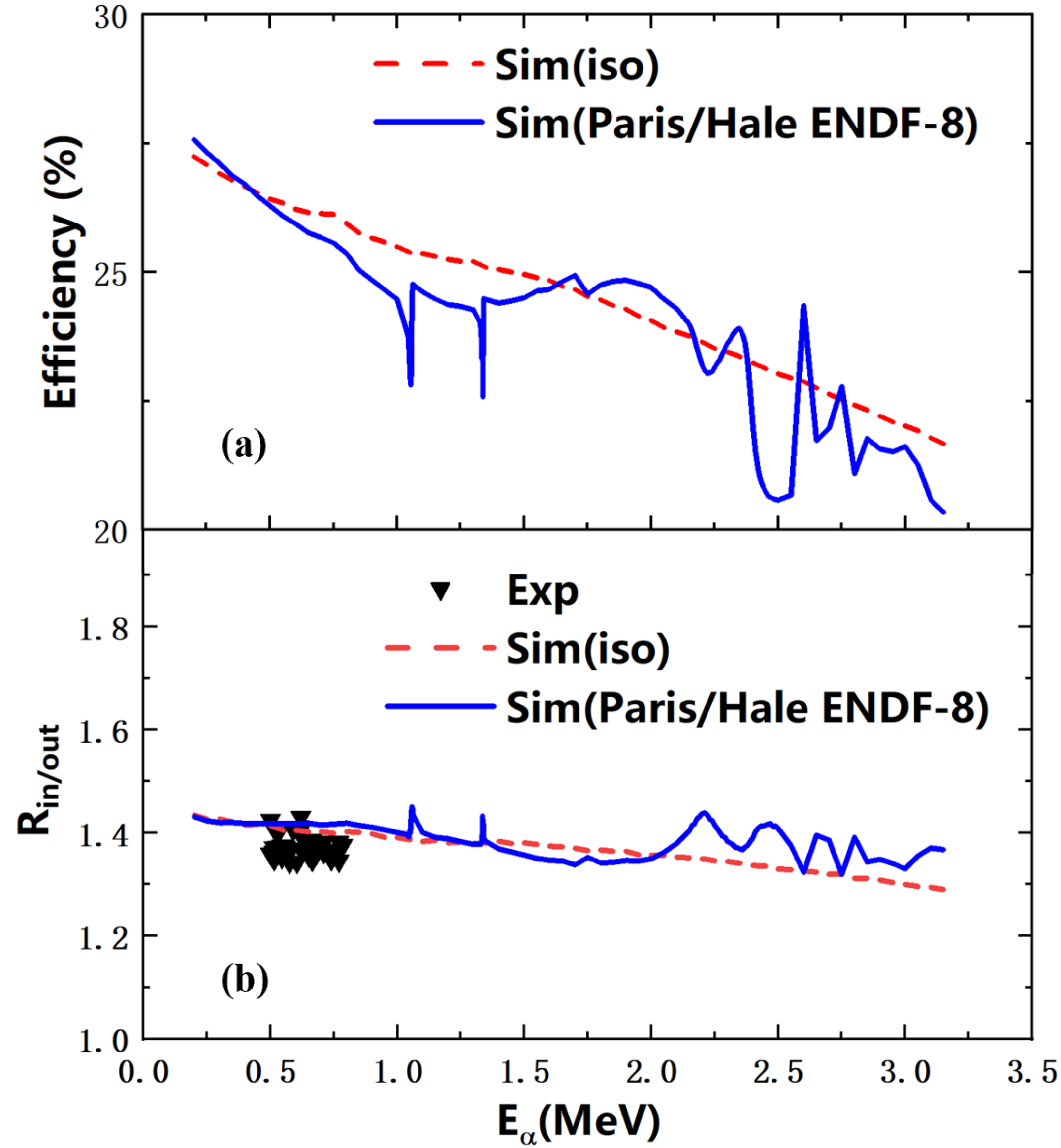




JUNA, Y.T. Li, T.Y.Jiao, B.S. Gao, W.P.Lin et al. arXiv:2111.12552, accepted by NST

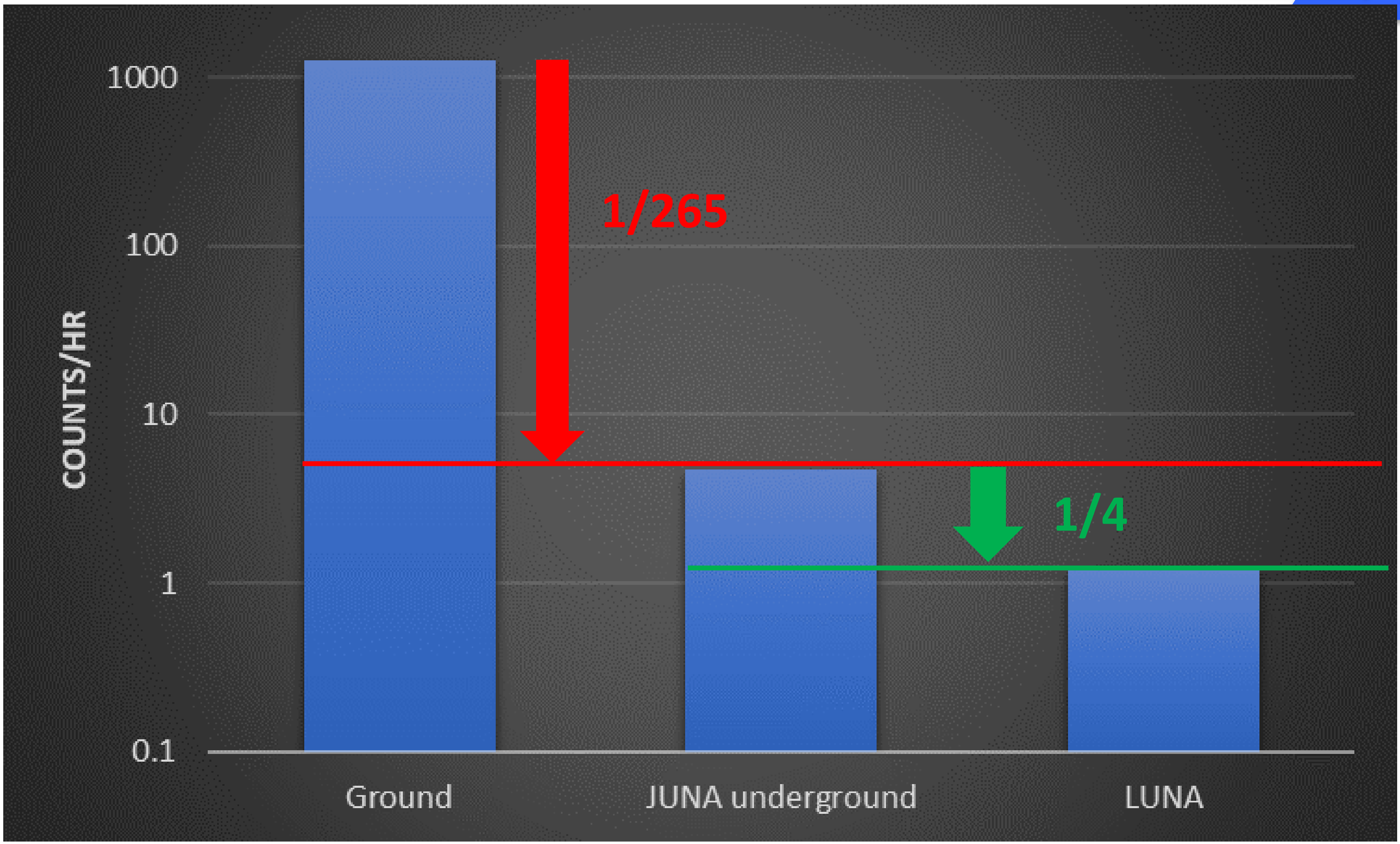
Effect of angular distribution





JUNA, Y.T. Li, T.y.Jiao, B.S. Gao, W.P.Lin et al. arXiv:2111.12552, accepted by NST

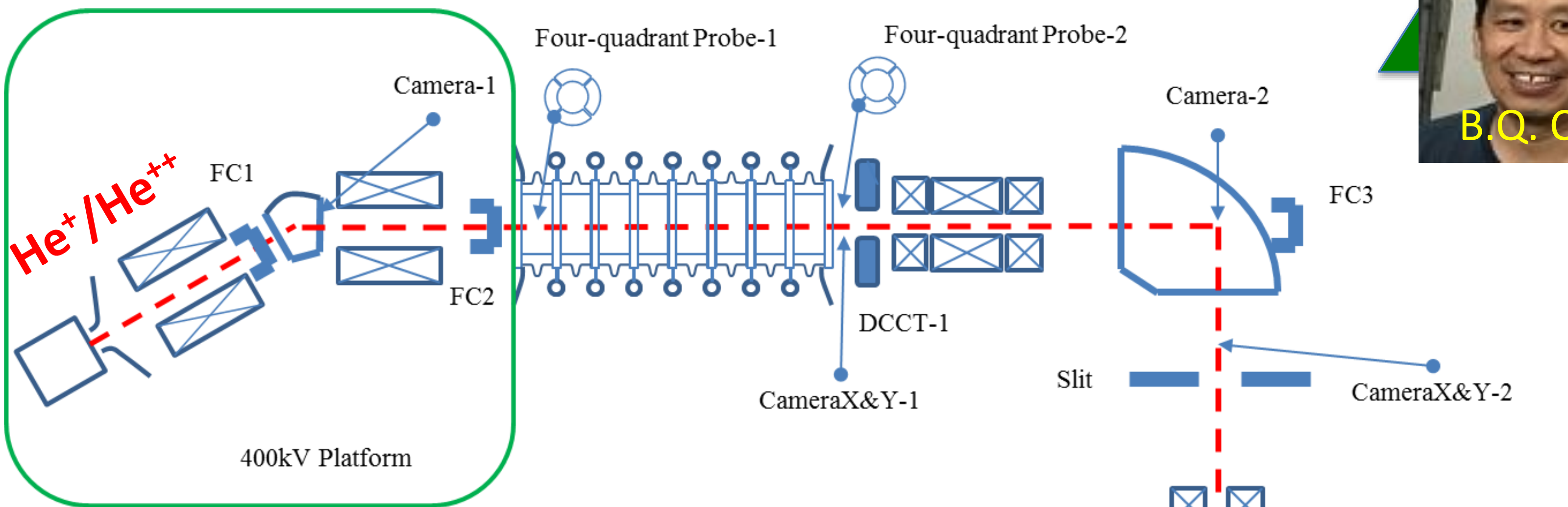
Natural background

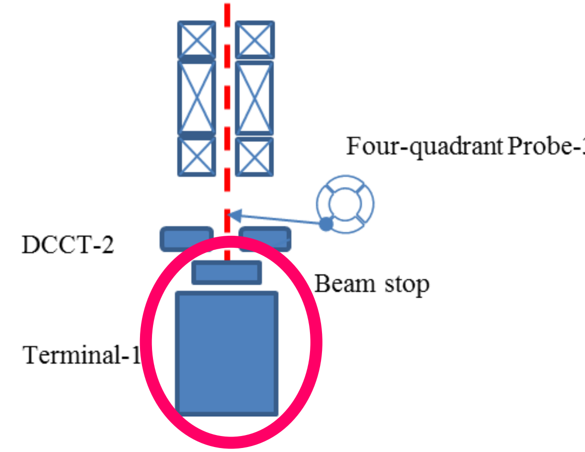


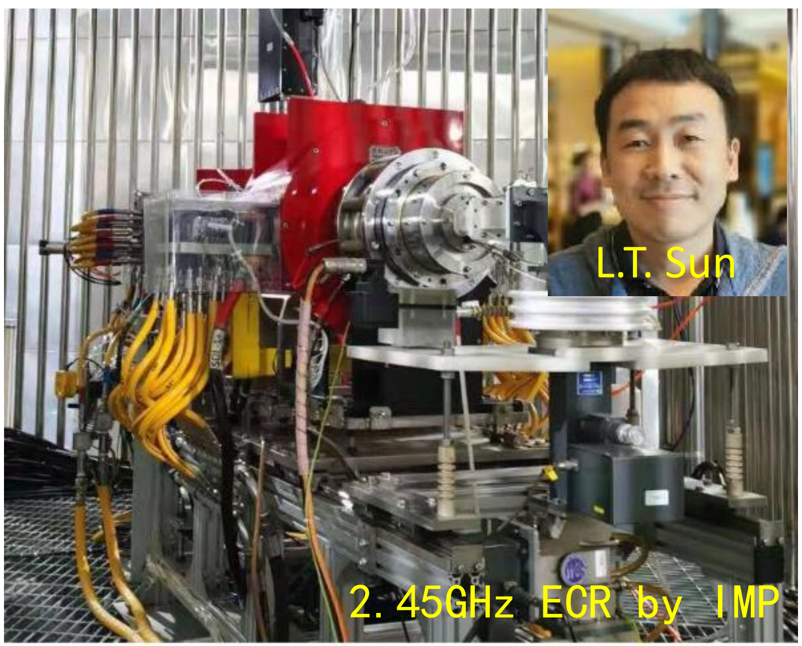
LUNA, Csedreki NIMA (2021)

JUNA, Y.T. Li, T.y.Jiao, B.S. Gao, W.P.Lin et al. arXiv:2111.12552, accepted by NST

JUNA high intensity accelerator



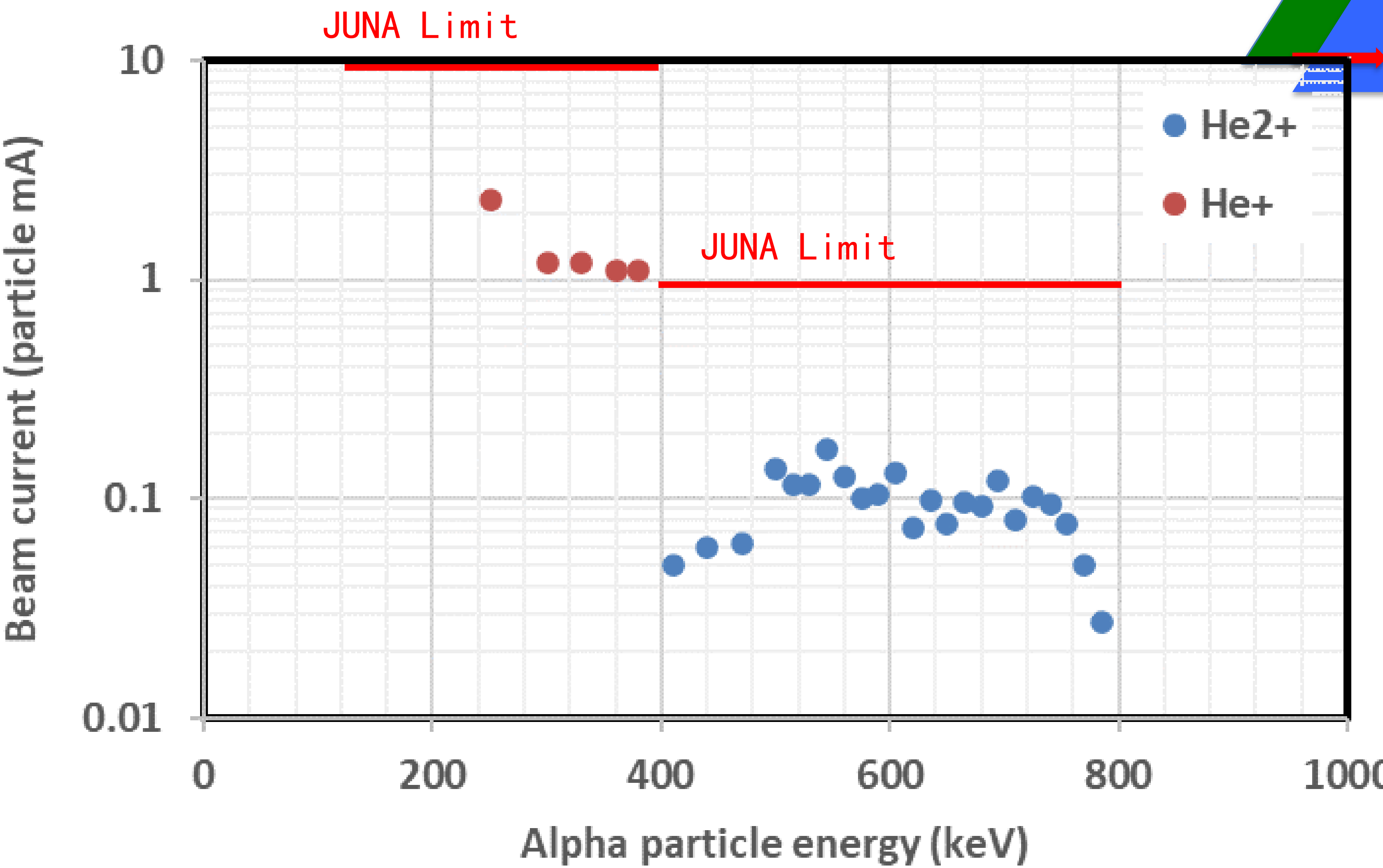




14.5 GHz ECR: 1 pmA He^{++}

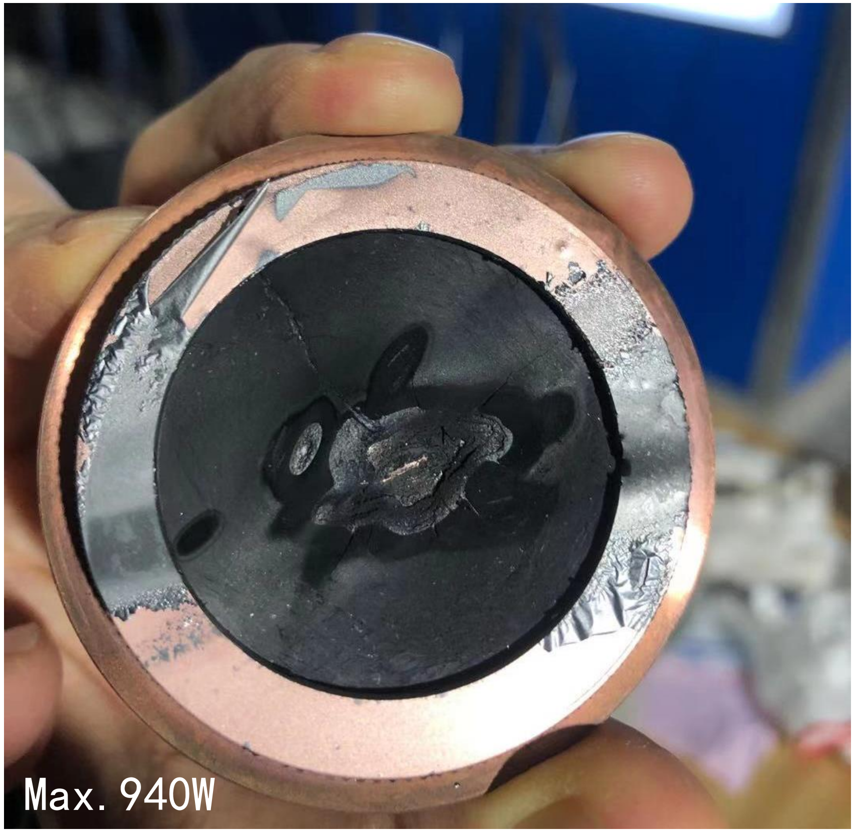
2.45 GHz ECR: 10 pmA He^{+}

Highest beam current



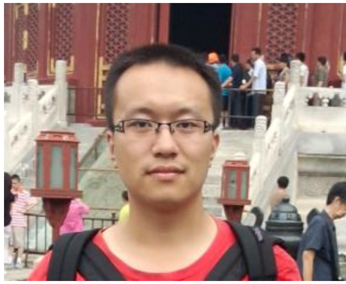
Preparation + Beam time: Feb. 27 to Mar. 16, 2021

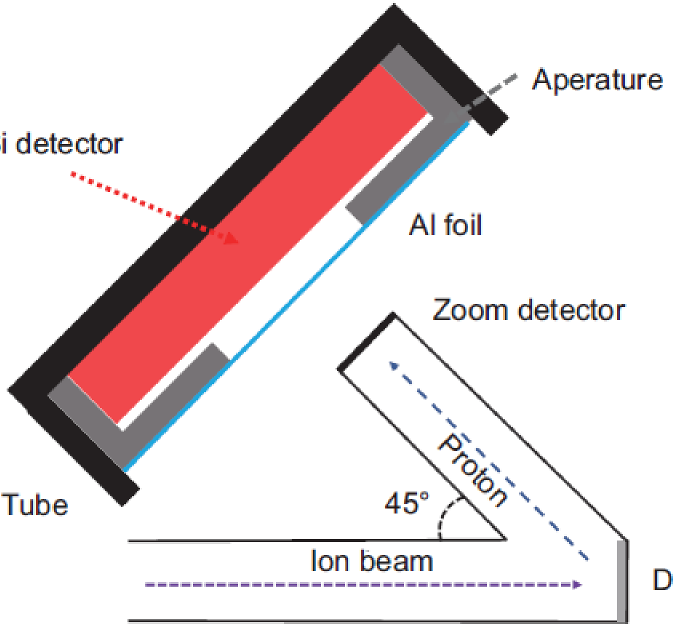
^{13}C-enriched thick target

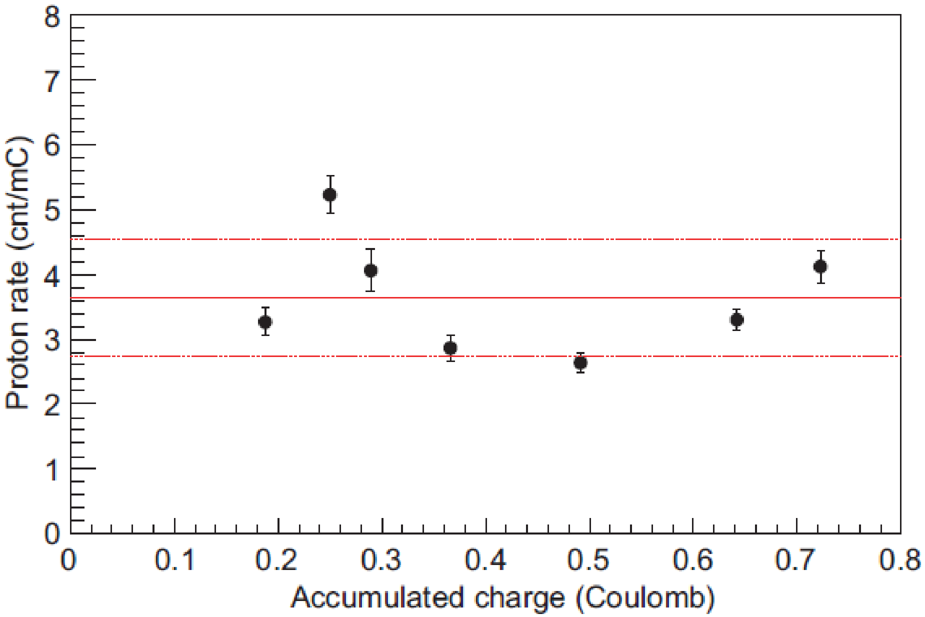


- **2mm-thick, max. power ~500W**
- **Will use beam wobbler to reduce the beam power density**

Deuterium impurity in the He^{2+} beam





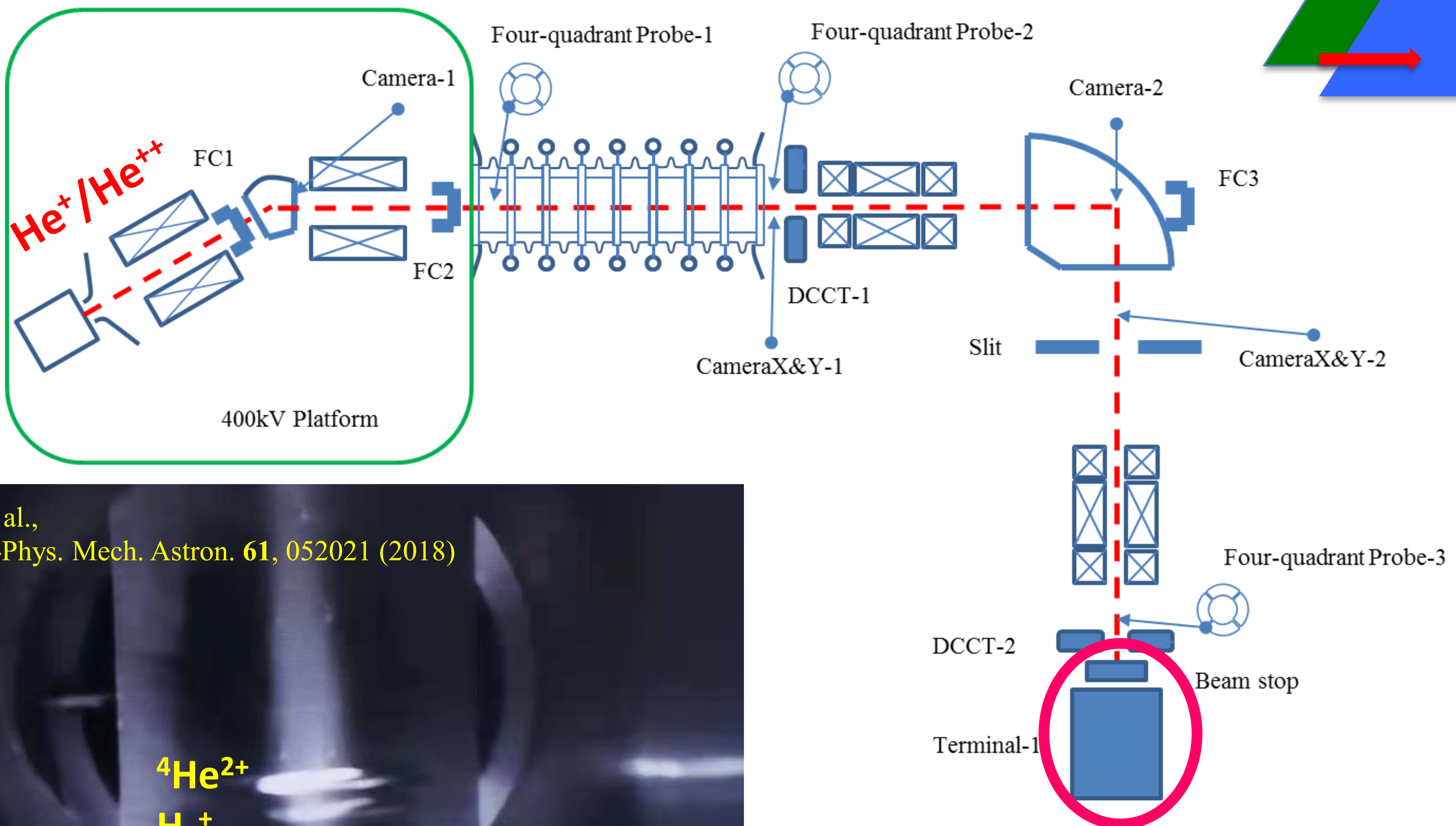


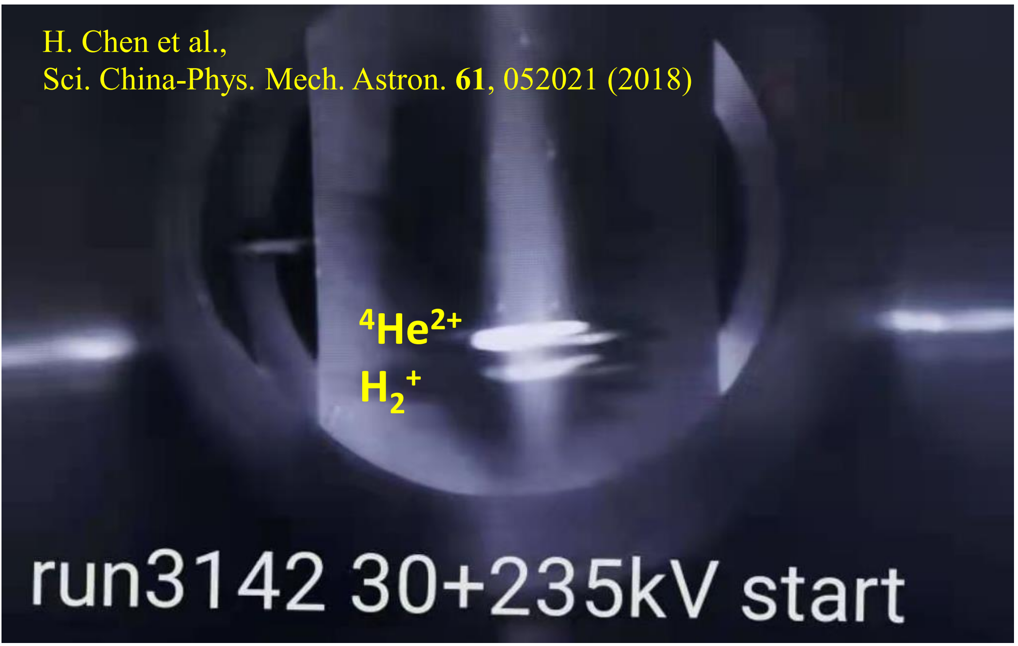
- Impurity analysis Using D(d,p)t reaction : $\frac{I_{D^+}}{I_{He^{2+}}}=(7.1\pm0.7)\times10^{-6}$

  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





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

2.45 GHz ECR: 5-10 pmA He^{+}

Beam induced background

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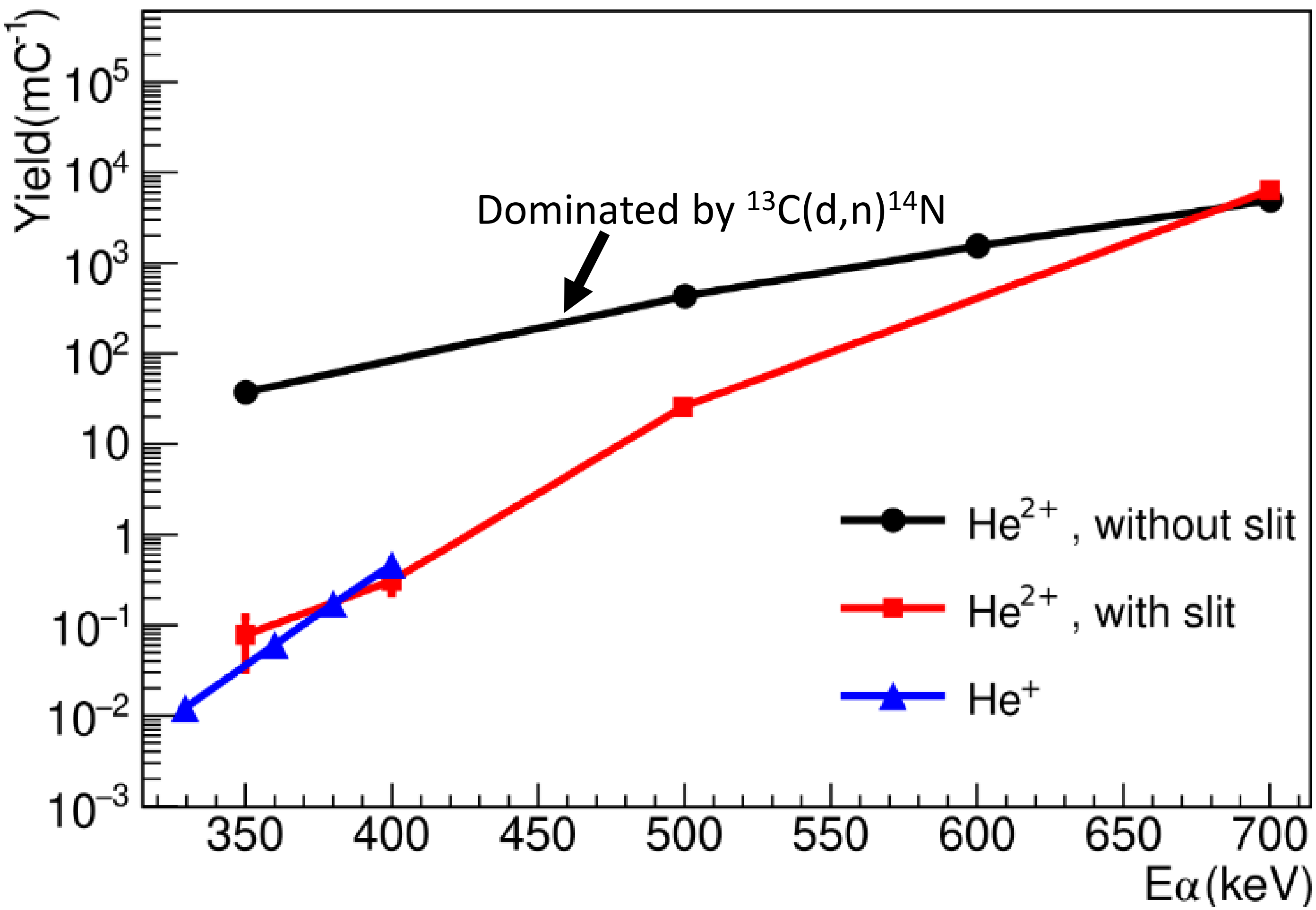
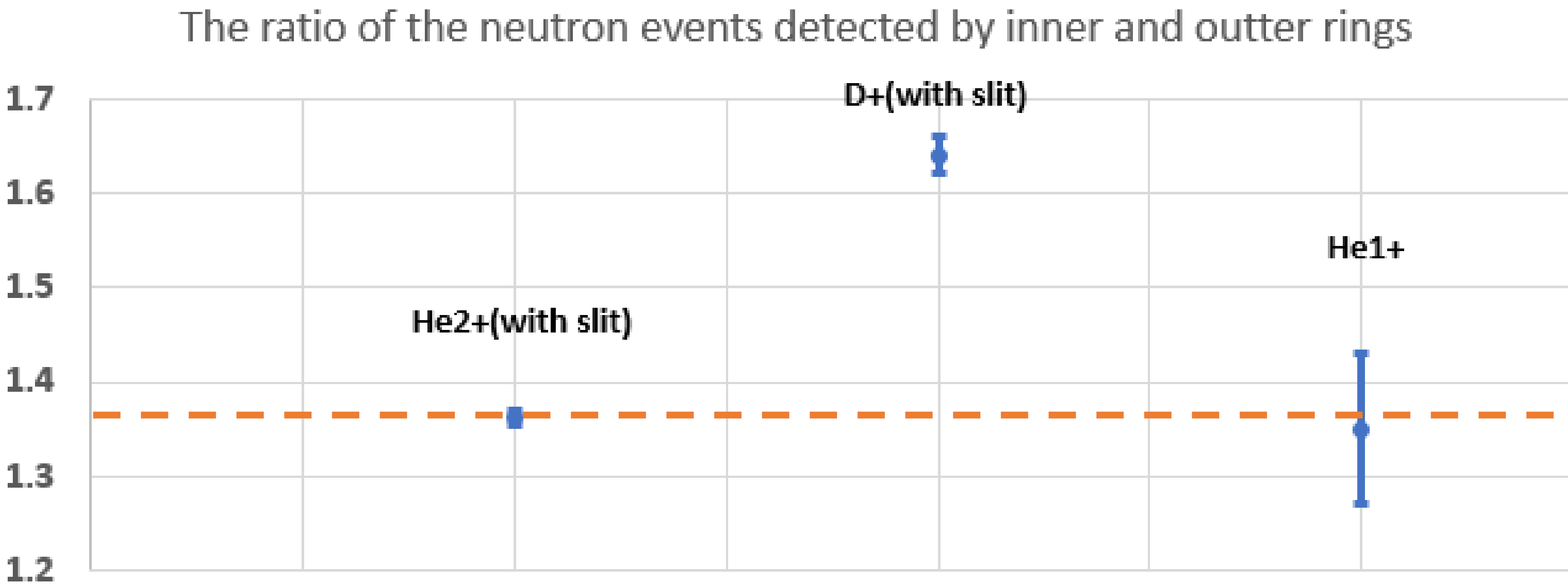


Yield at Ea=250 keV using He^{+} is 0.05(8) cnts/Coulomb, being consistent with the zero

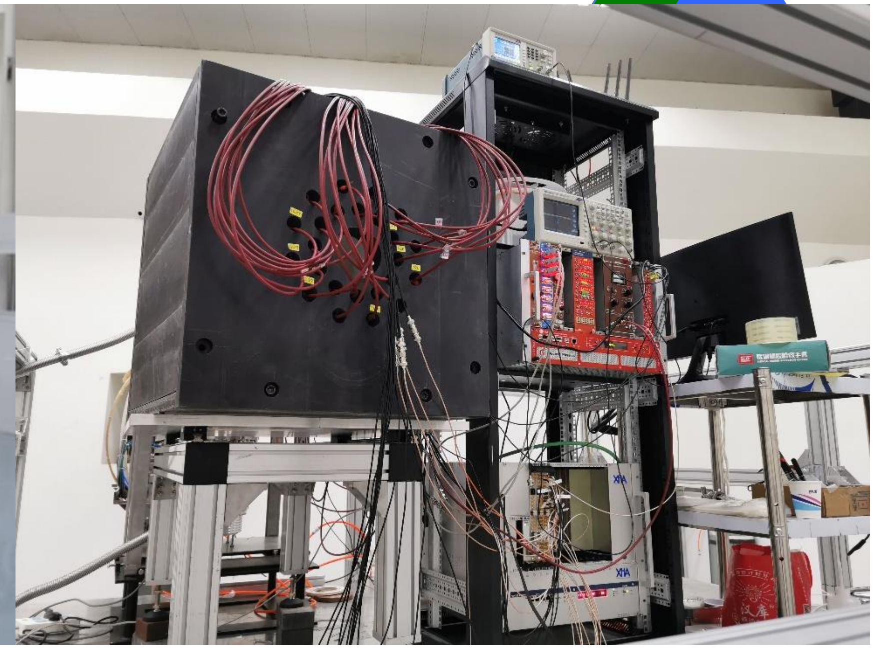
Ratio of the counts of inner to outer rings



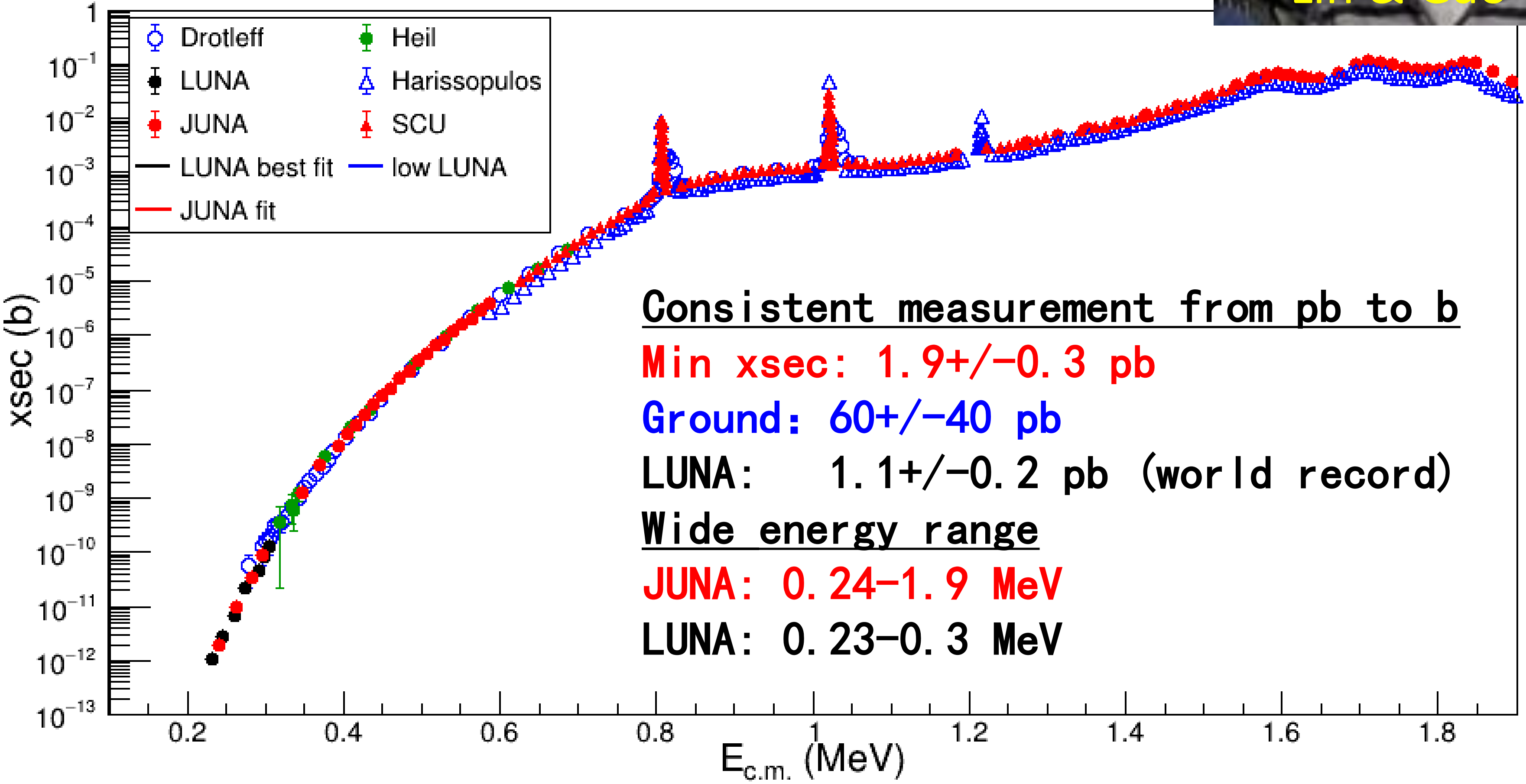
- Beam on ^{13}C target
- Ratio of inner-ring counts/outer-ring counter is sensitive to energy and angular distribution
- He^{2+} w slit agrees with He^{1+}, which is nearly free of Deuterium

Consistent measurement at Eα=0.8-2.52 MeV

JUNA

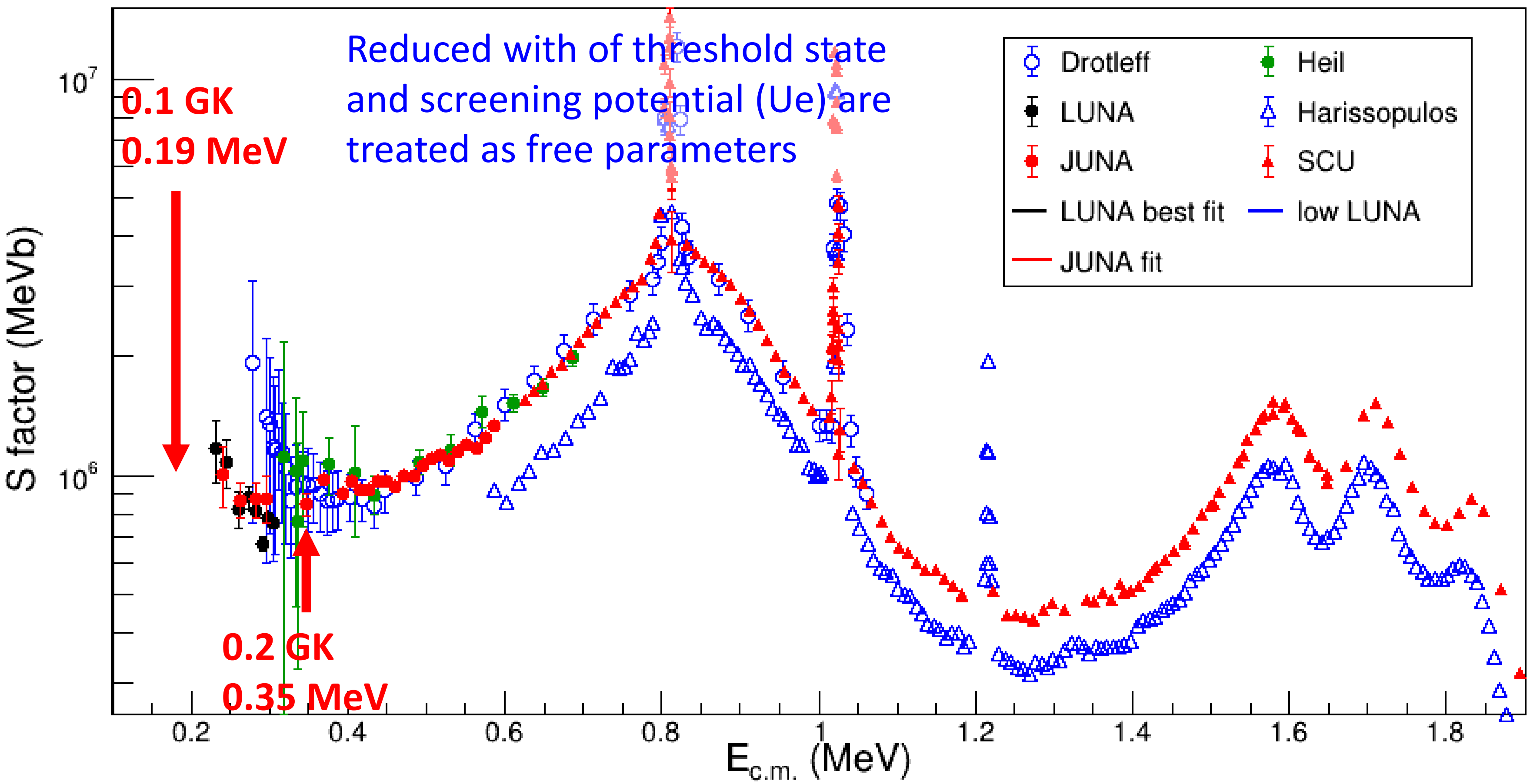


Cross section of $^{13}C(\alpha,n)^{16}O$



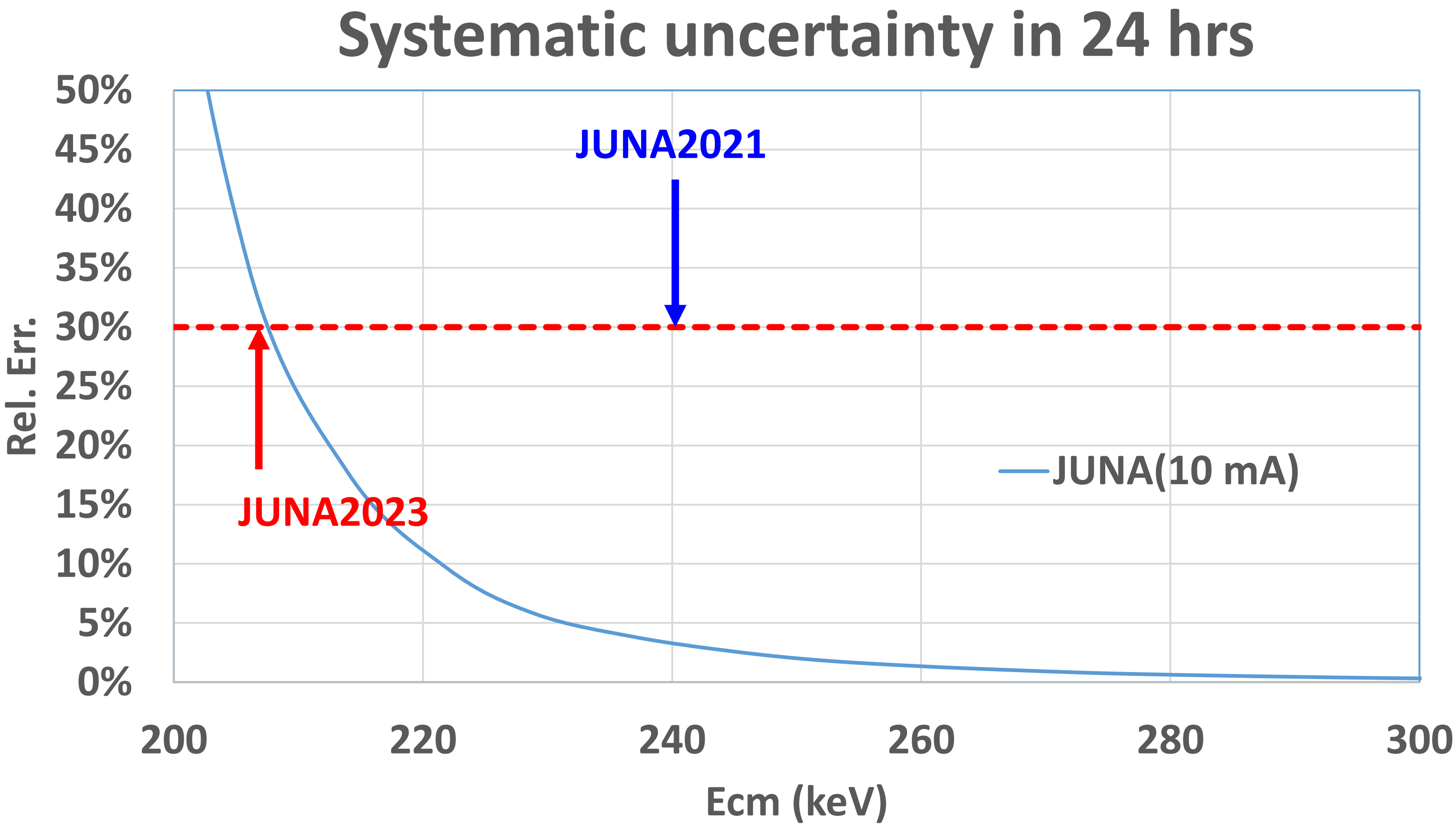
- JUNA data analyzed by B.S. Gao (IMP)
- SCU data analyzed by W.P. Lin(SCU)

S-factor of $^{13}C(\alpha,n)^{16}O$



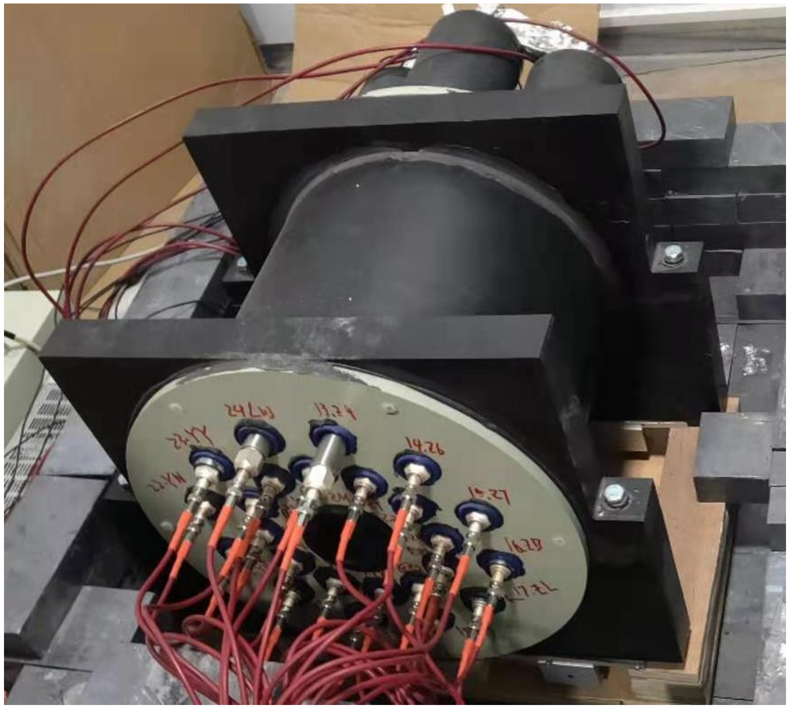
- Cover almost the entire Gamow window for i-processs (0.2-0.3 GK)
- **Extrapolation needed for s-process (0.1 GK)**

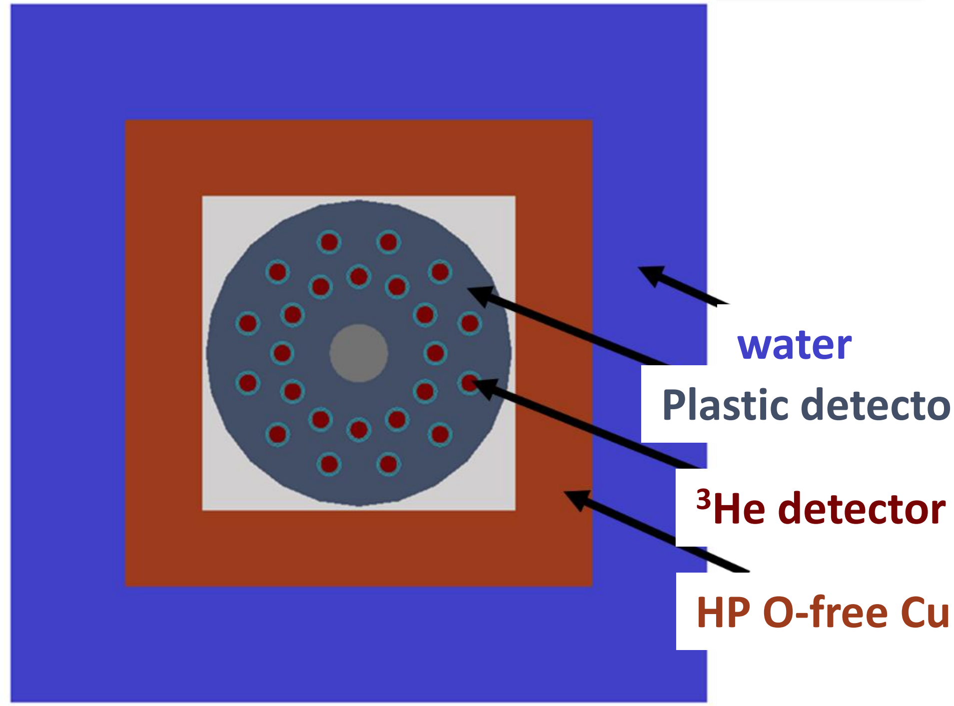
Outlook



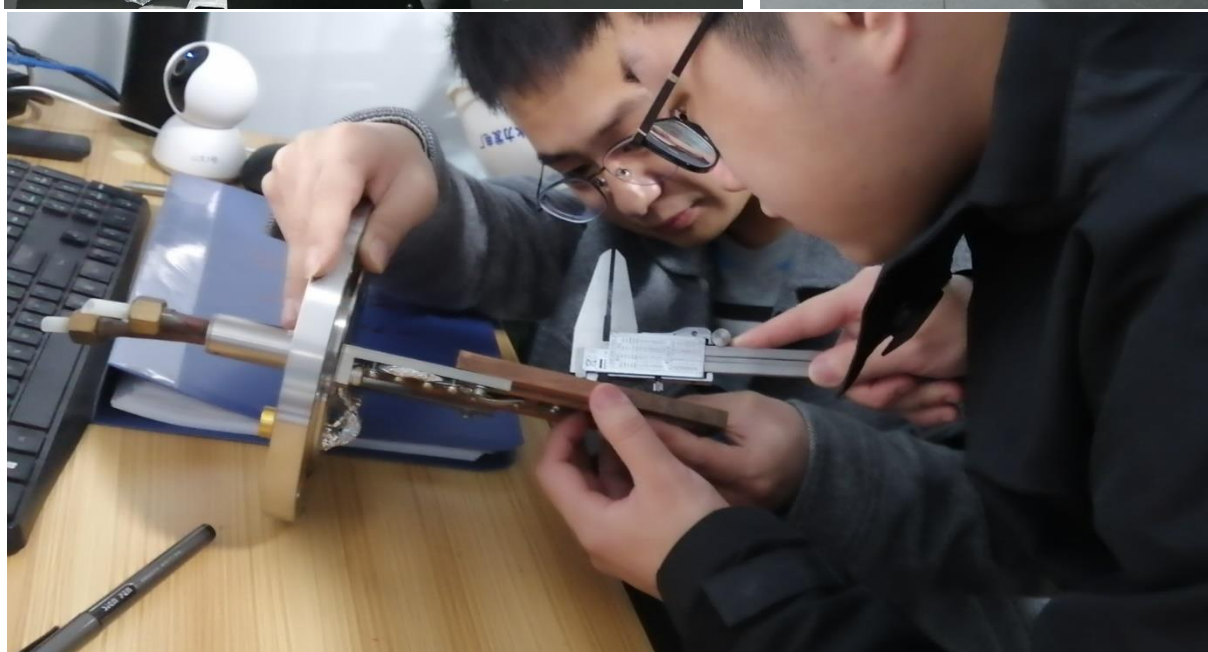
Estimated with a background rate of 2 cnts/hr

Background suppression





- Suppress the alpha background using the coincidence of fast and slow neutron signals
- Suppress the natural neutron background using water
- Suppress the gamma background using Cu
- Drop the background from 4 cnts/hr to 0.4 cnts/hr

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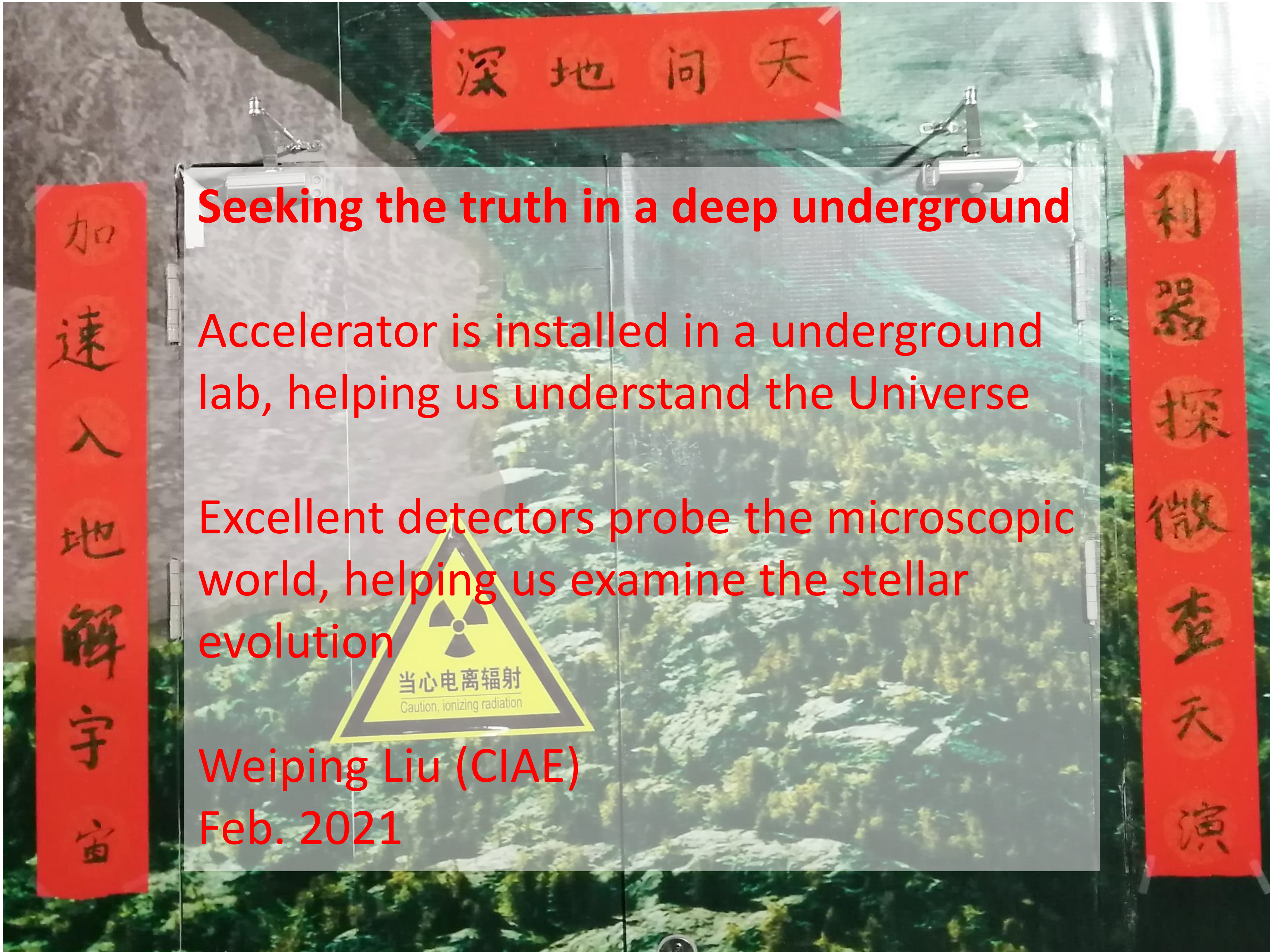

Seeking the truth in a deep underground

Accelerator is installed in a underground lab, helping us understand the Universe

Excellent detectors probe the microscopic world, helping us examine the stellar evolution

Weiping Liu (CIAE)
Feb. 2021

Summary

JUNA

- Consistent direct measurement in E_{cm}=0.24-1.9 MeV cover almost the entire Gamow-window of i-process
- Resolving the inconsistency
- A more reliable reaction rate: 13% at 0.2 GK, 16% at 0.1 GK
- Constraining ANC of threshold state and screening potential
- 2023: continue the measurement of $^{13}C(\alpha,n)^{16}O$ and start other difficult measurement such as $^{22}Ne(\alpha,n)^{25}Mg$

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Jinping Underground Nuclear Astrophysics （JUNA）

$^{13}C(\alpha, n)^{16}O$ experiment
(2/27/2021-3/16/2021）