Overview of Nuclear Astrophysics
: In Search of the Origin of Elements

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69TH WORKSHOP ON GRAVITATIONAL WAVES AND NUMERICAL RELATIVITY

Part 1. What is Nuclear Astrophysics?

Periodic Table of Elements

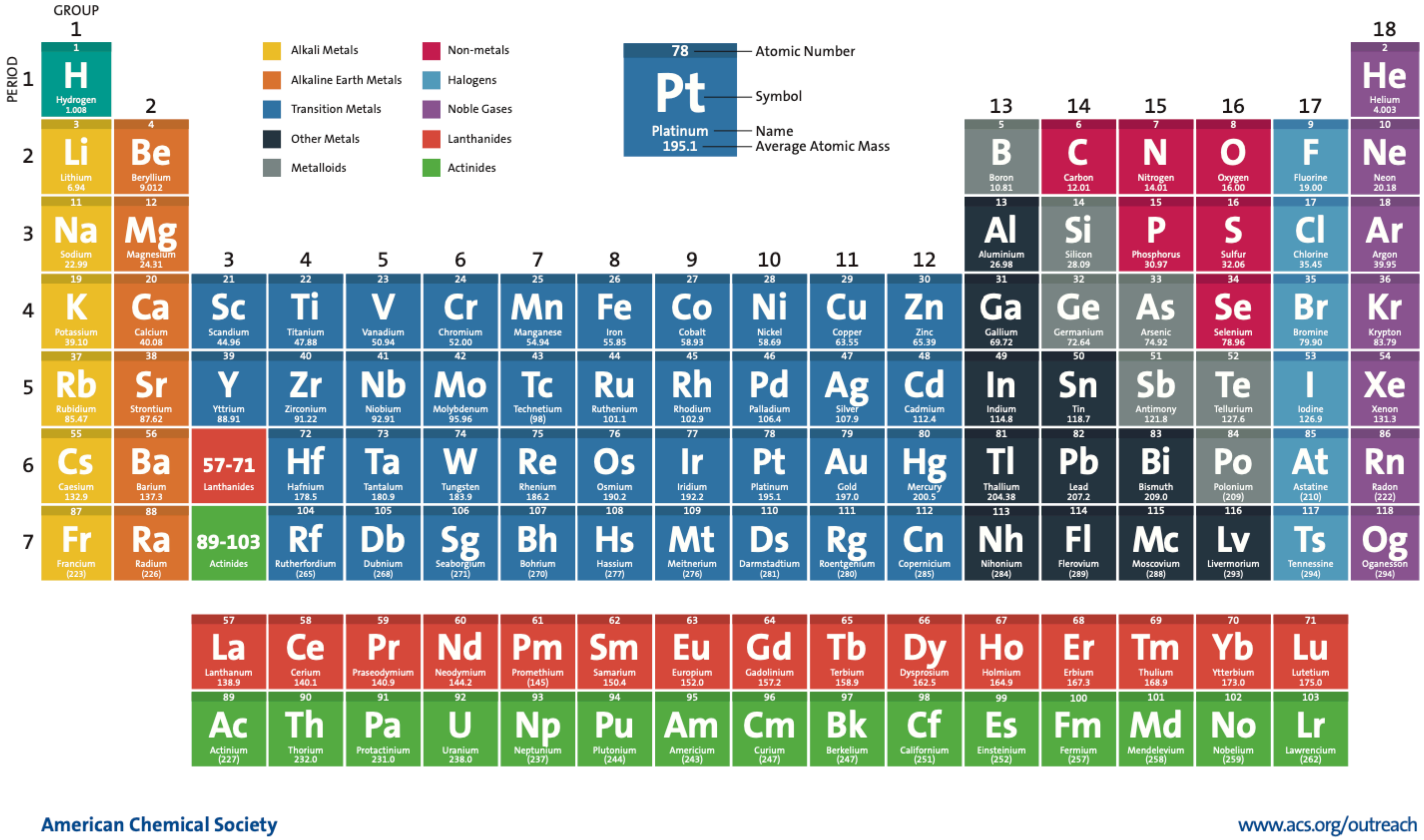
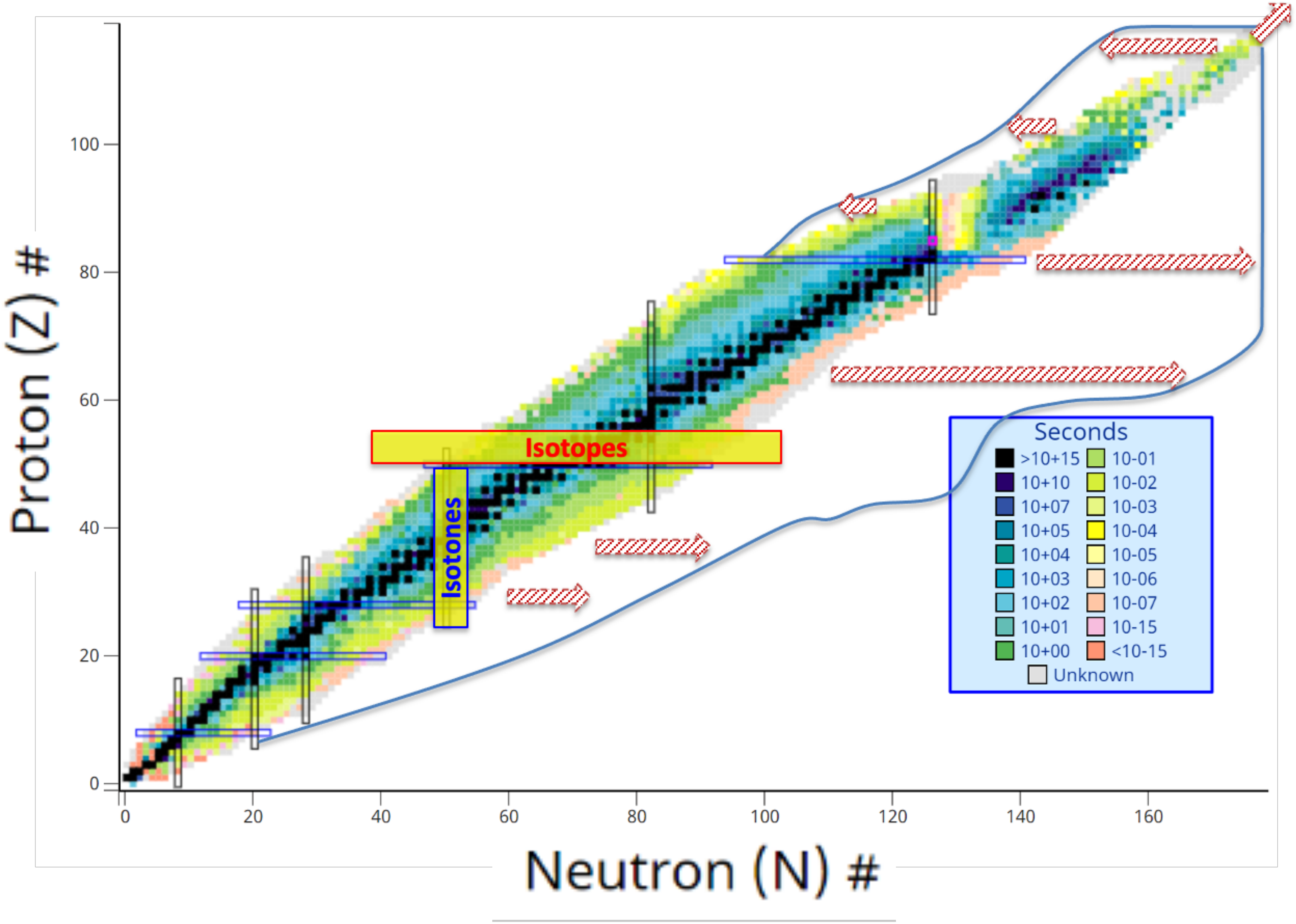


Chart of Nuclides

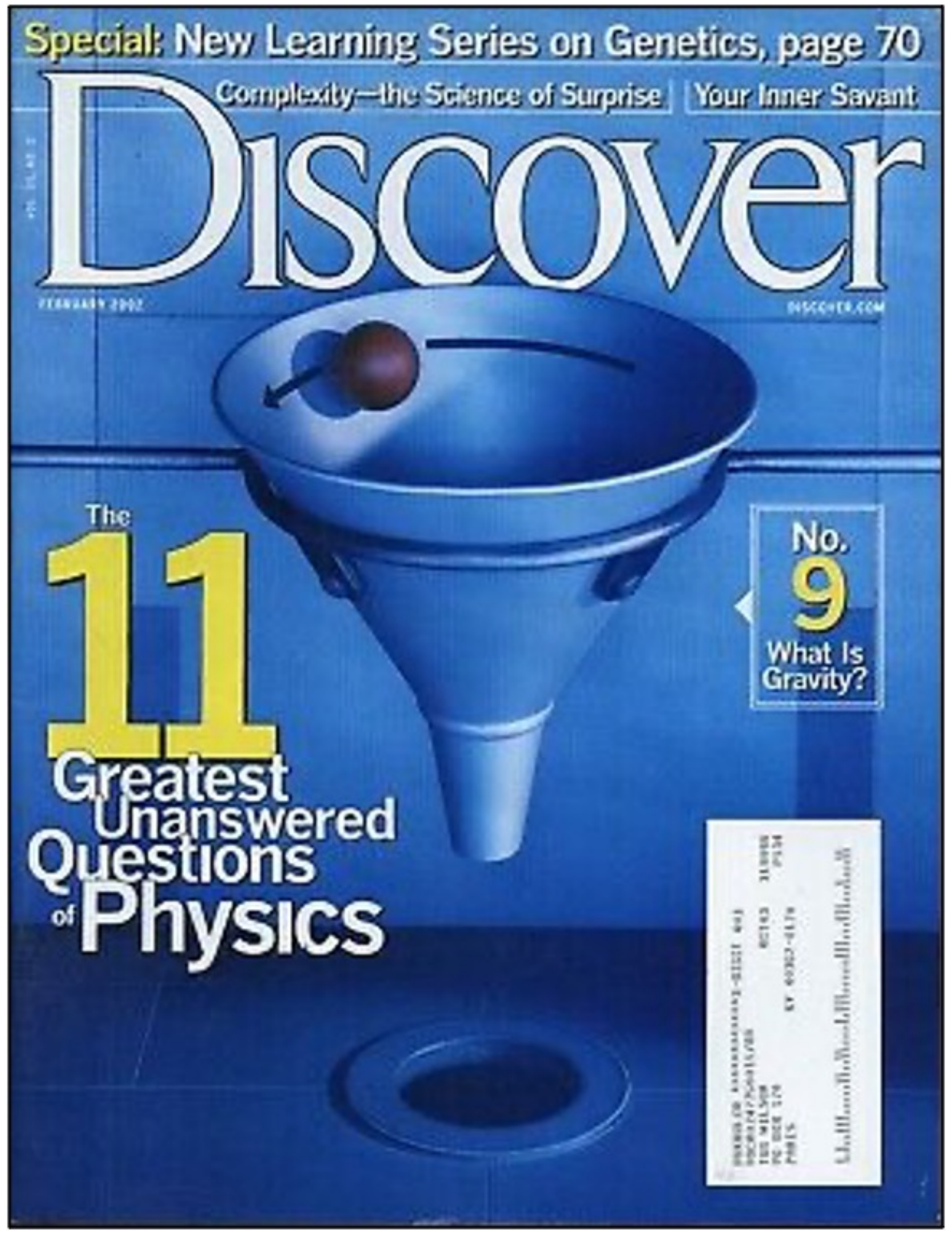
- Only 288 nuclei forms the valley of stability.
- About 3,000 nuclei are known.
- Nuclear theorists estimate about 6,900 nuclei are bound.
- Nuclei away from stability are short lived (down to usec).

* FYI

- Nuclear [adj]
  : of or relating to the nucleus of an atom
- Nucleus
  : the central part of an atom that is made up of protons and neutrons
- Nuclei: the plural form of nucleus
- Nucleon: a proton or neutron
- Nuclide
  : a distinct kind of atom or nucleus characterized by a specific number of protons and neutrons



The 11 Greatest Questions of Physics



Question 1. What is dark matter?

Question 2. What is dark energy?

Question 3. How were the heavy elements from iron to uranium made?

Question 4. Do neutrinos have mass?

Question 5. Where do ultrahigh-energy particles come from?

Question 6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?

Question 7. Are there new states of matter at ultrahigh temperatures and densities?

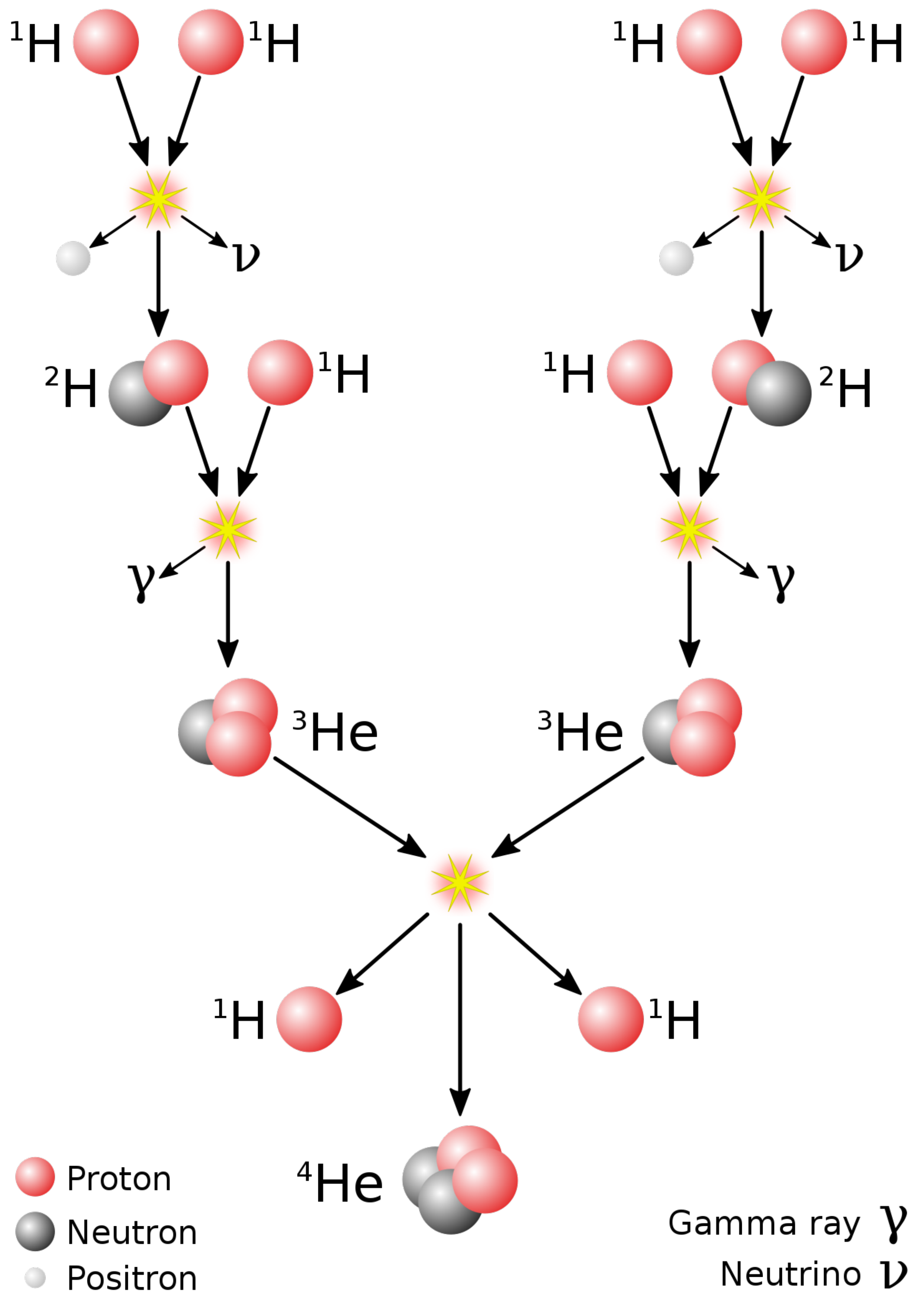
Question 8. Are protons unstable?

Question 9. What is gravity?

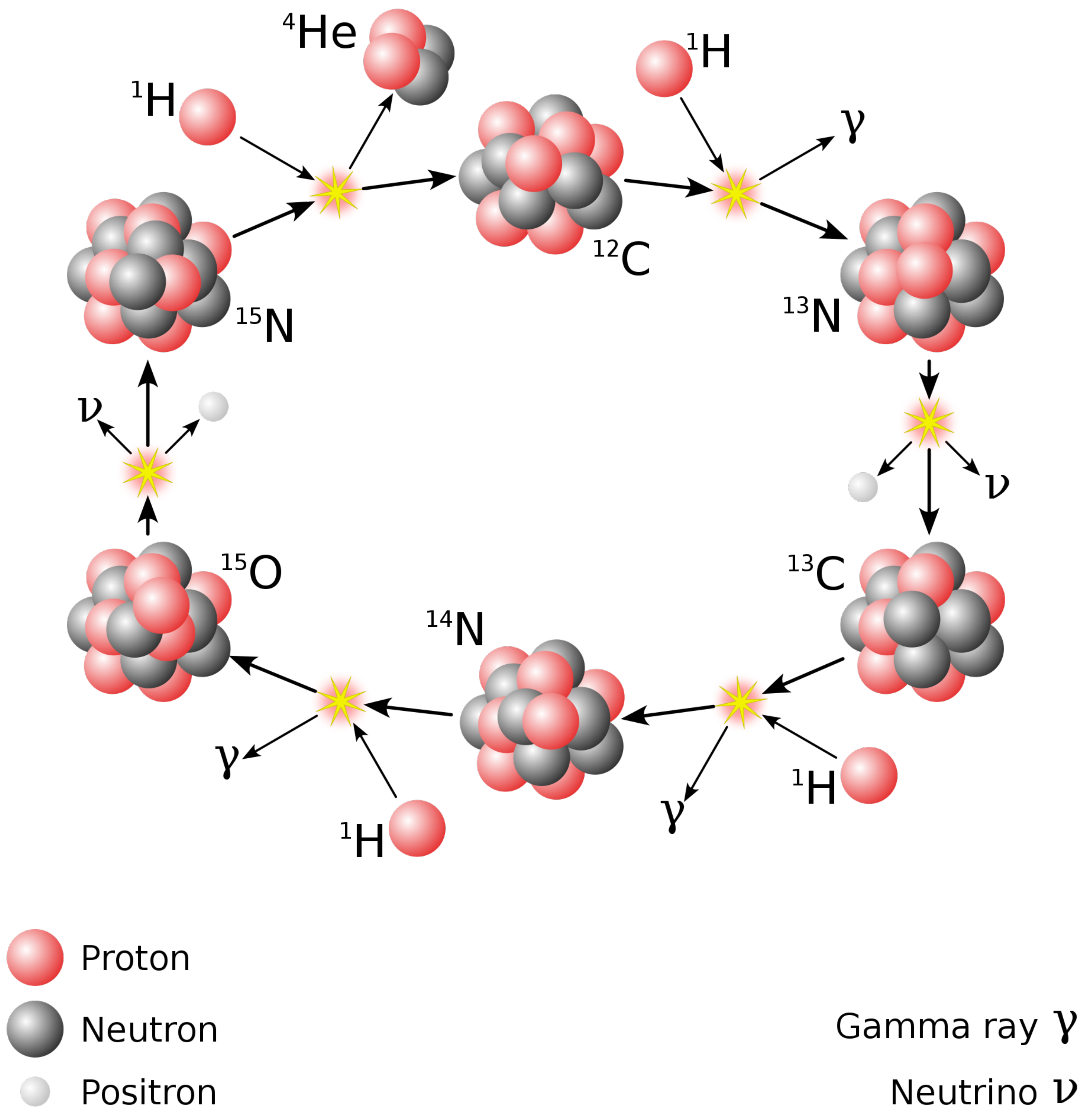
Question 10. Are there additional dimensions?

Question 11. How did the universe begin?

Synthesis of the Light Elements

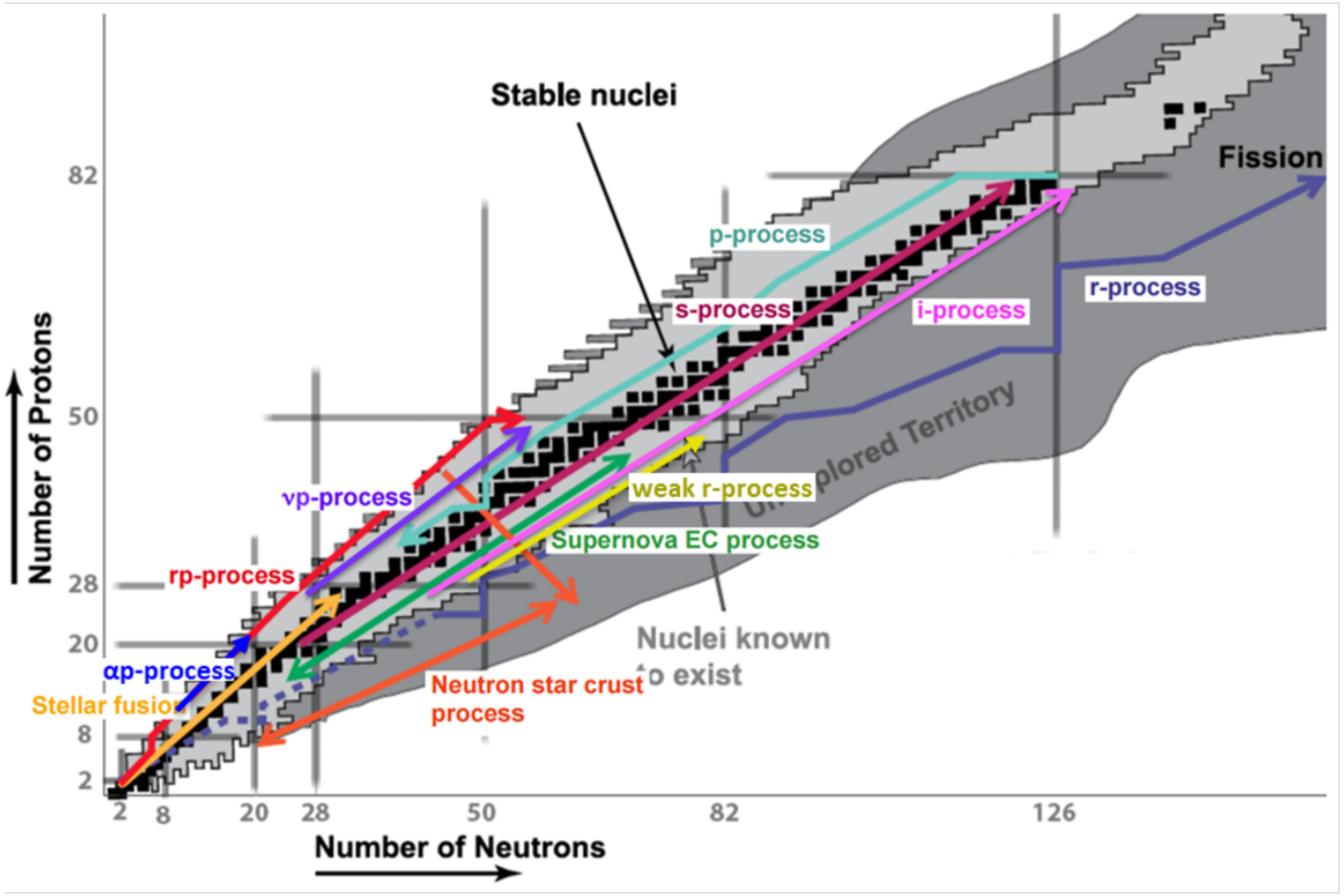


Proton-proton chain



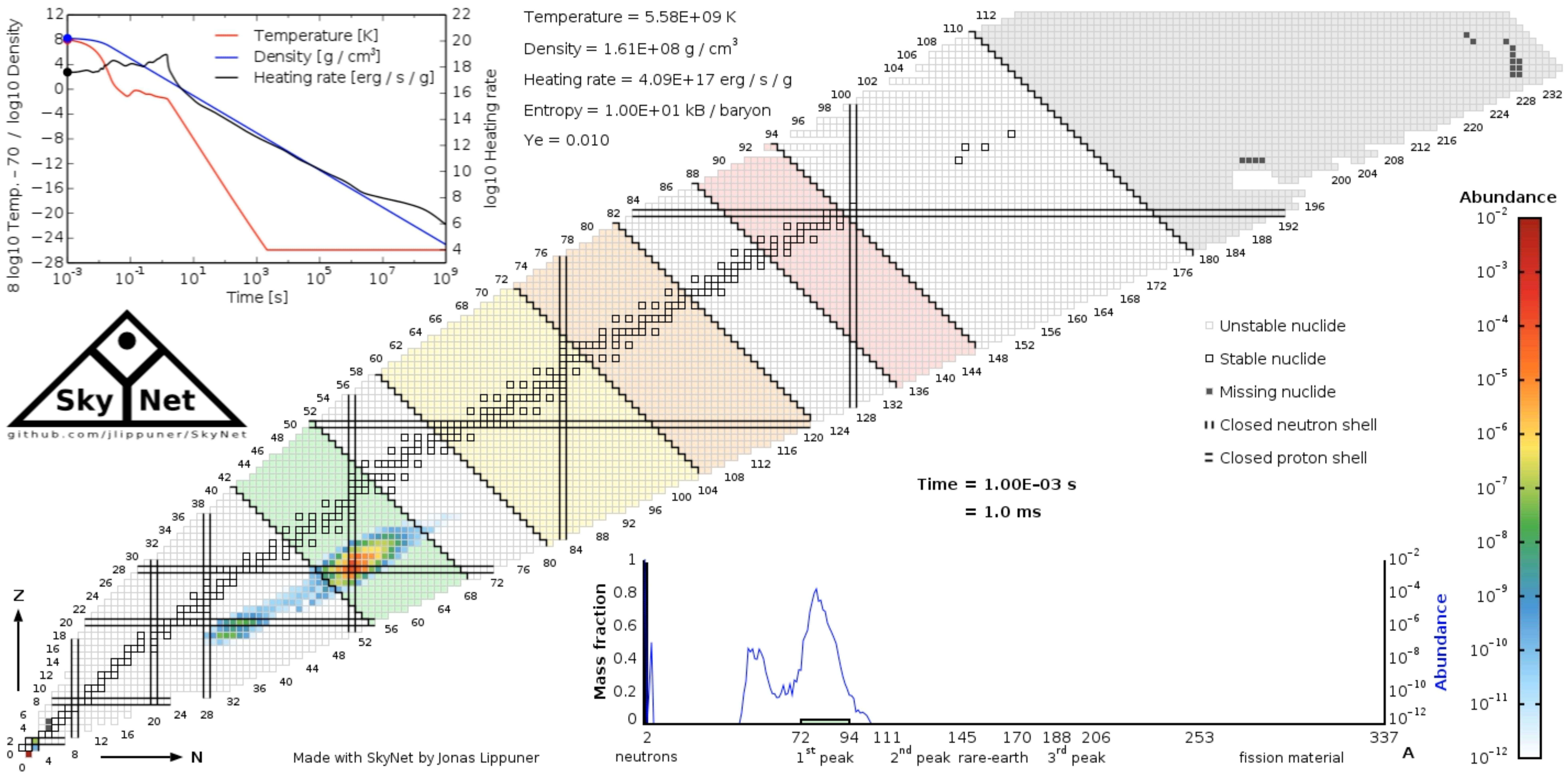
CNO cycle

Nucleosynthesis Processes

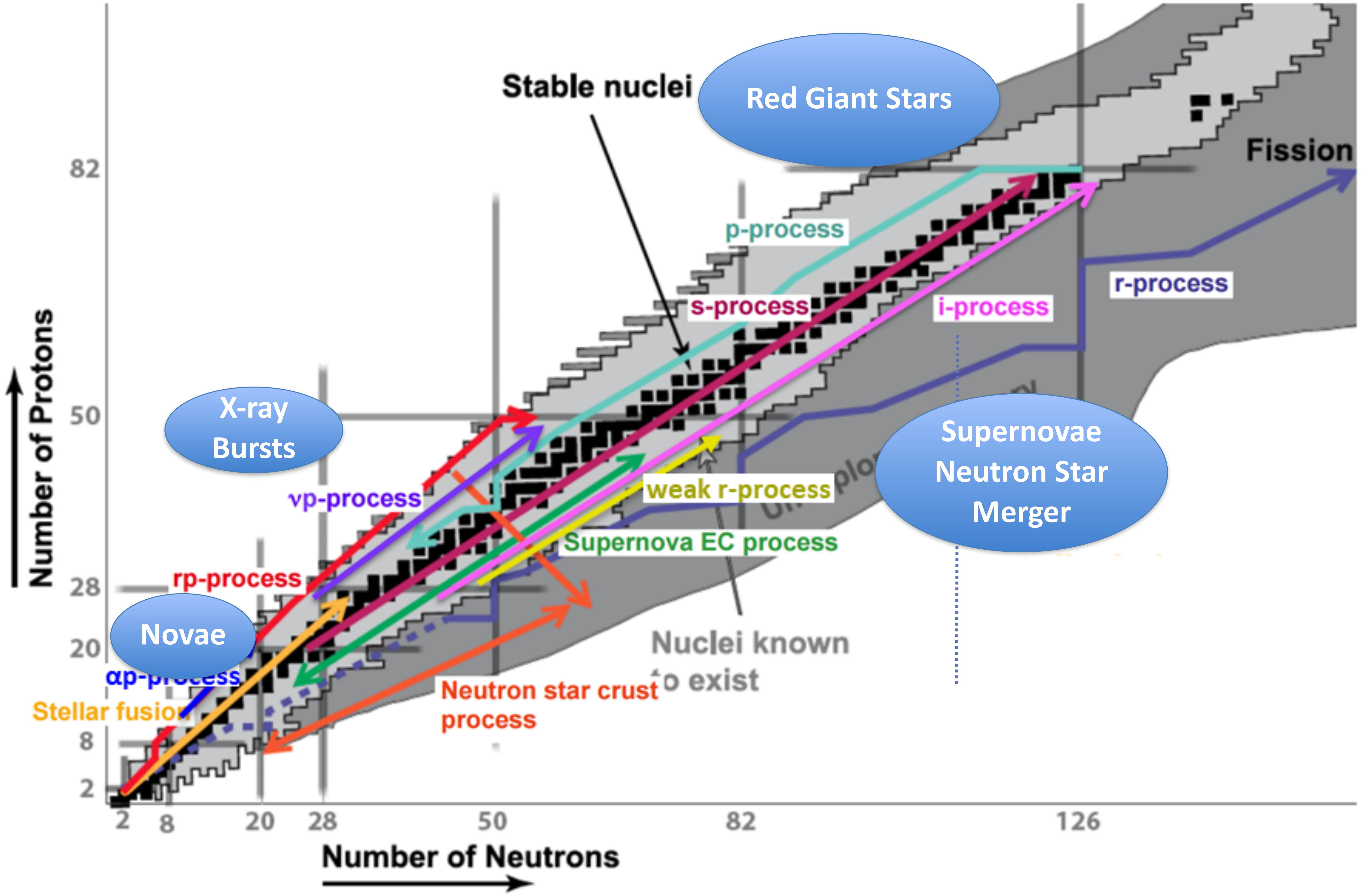


H. Schatz. (2016).

r-process Simulation

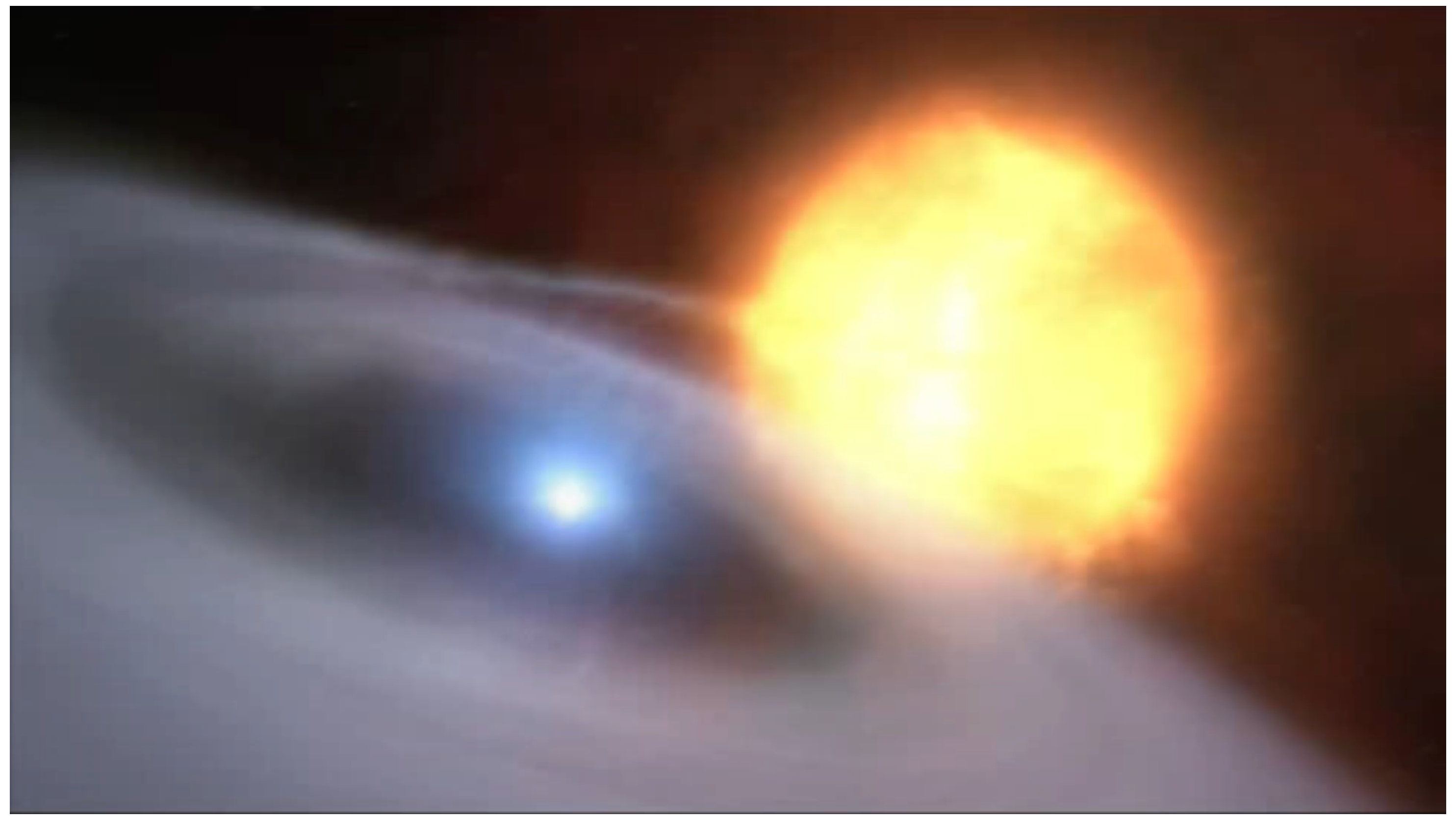


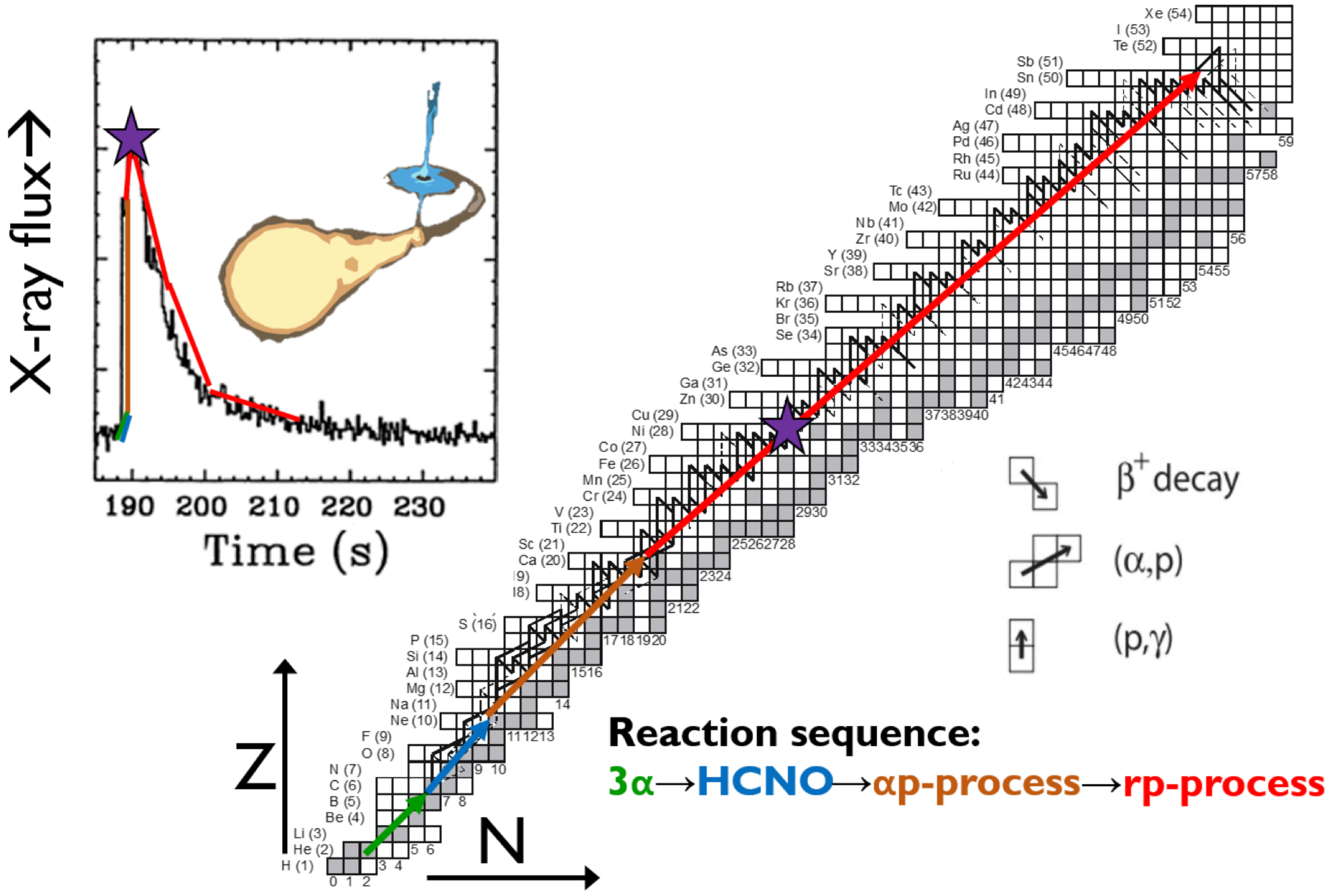
Nucleosynthesis Processes



H. Schatz. (2016).

X-Ray Bursts



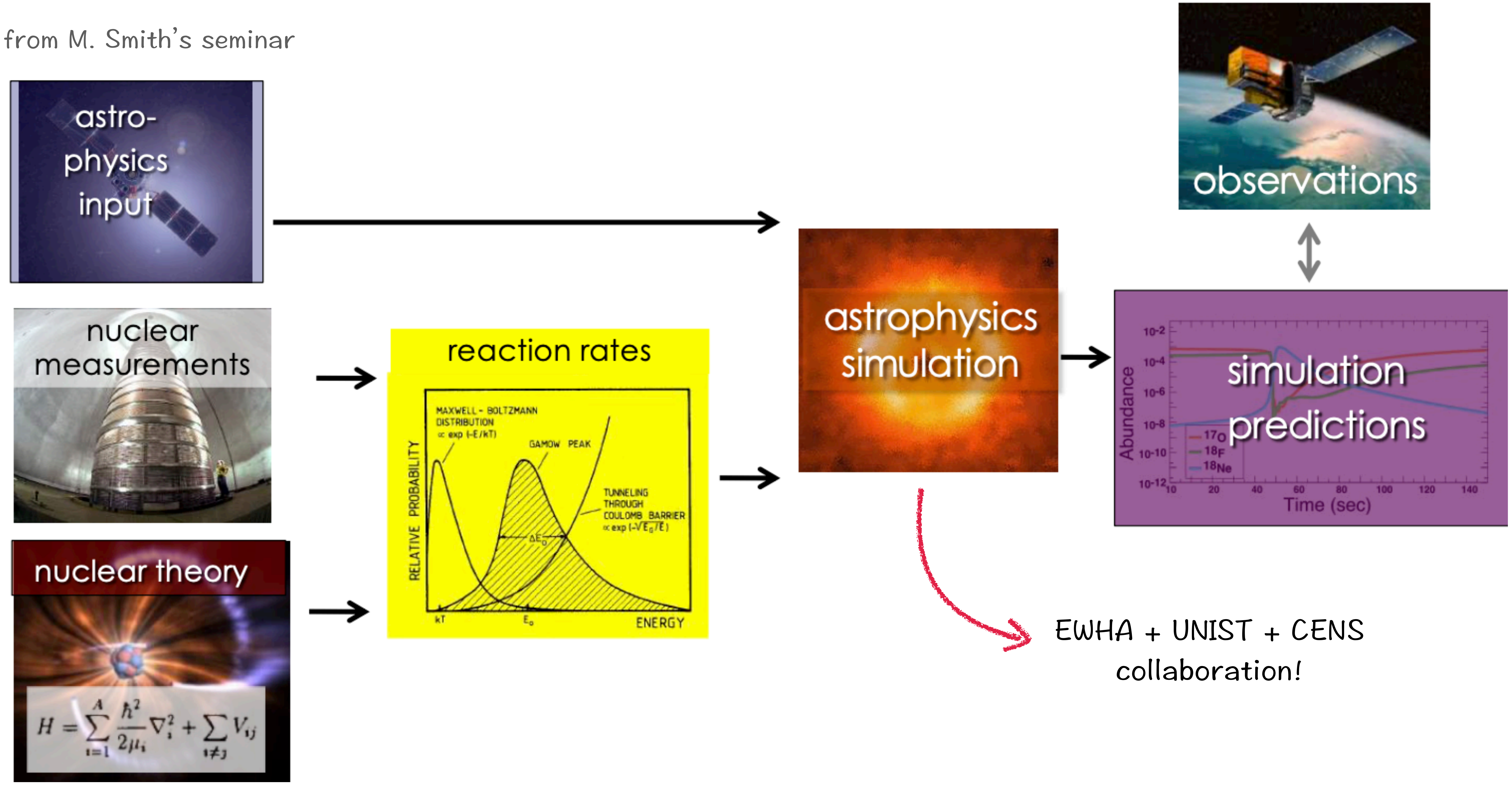


Z. Meisel et al. (2018).

- Binary star composed of:
  - an accreting compact object (commonly neutron star)
  - a main sequence companion 'donor' star
- ^{4}He capture reactions process (ap-process):
  - $^{15}O + {}^{4}He \rightarrow {}^{18}Ne + \gamma \rightarrow {}^{18}Ne + {}^{4}He \rightarrow {}^{21}Na + p$
  - $^{14}O + {}^{4}He \rightarrow {}^{18}Ne \rightarrow {}^{17}F + p$
- Rapid proton capture process (rp-process):
  - $^{13}N + p \rightarrow {}^{14}O + \gamma$
  - $^{17}F + p \rightarrow {}^{18}Ne + \gamma$
  - Proton captures by Ne, Mg, Na and so on

Nuclear Physics - Astrophysics Connection

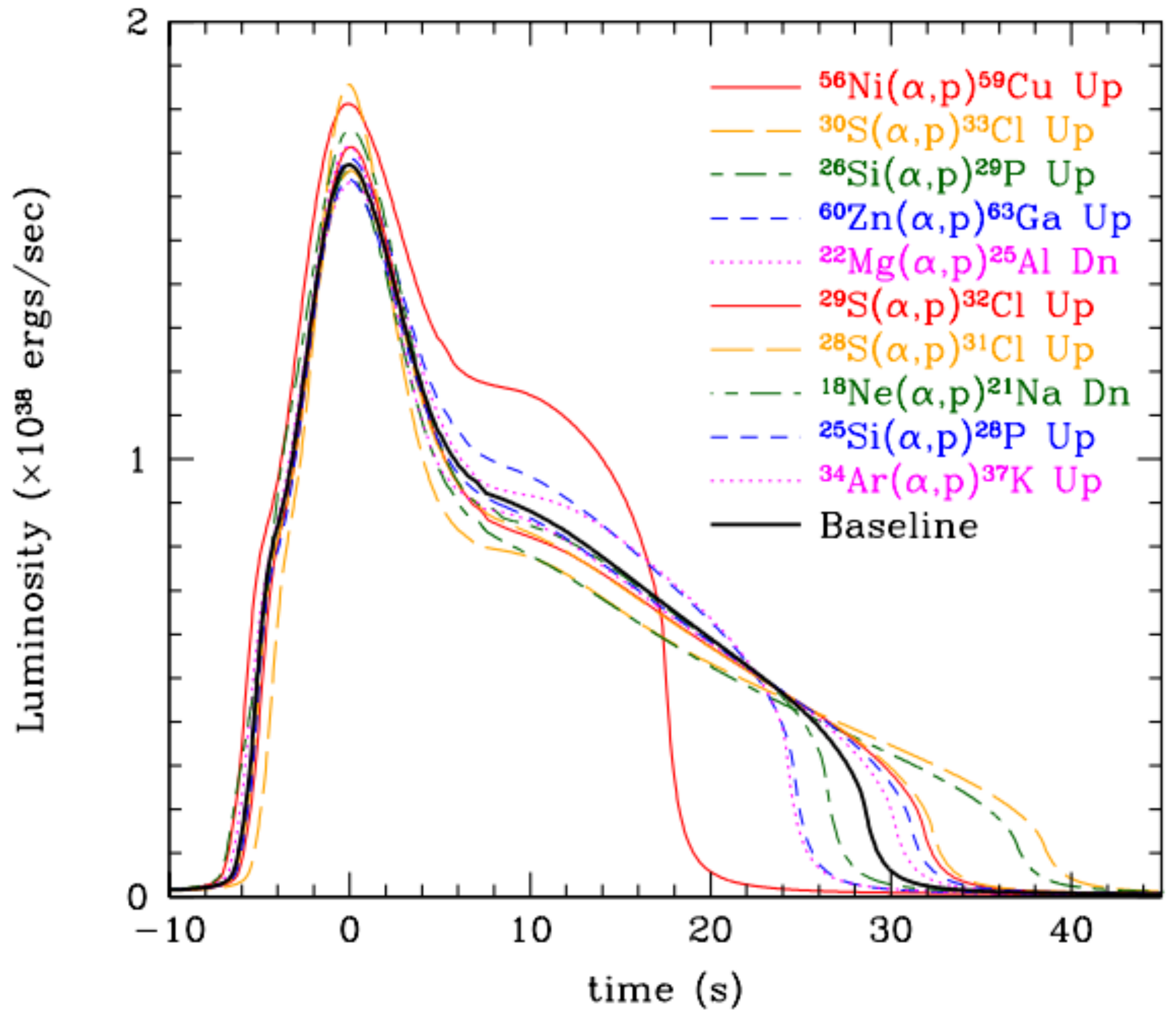
from M. Smith's seminar



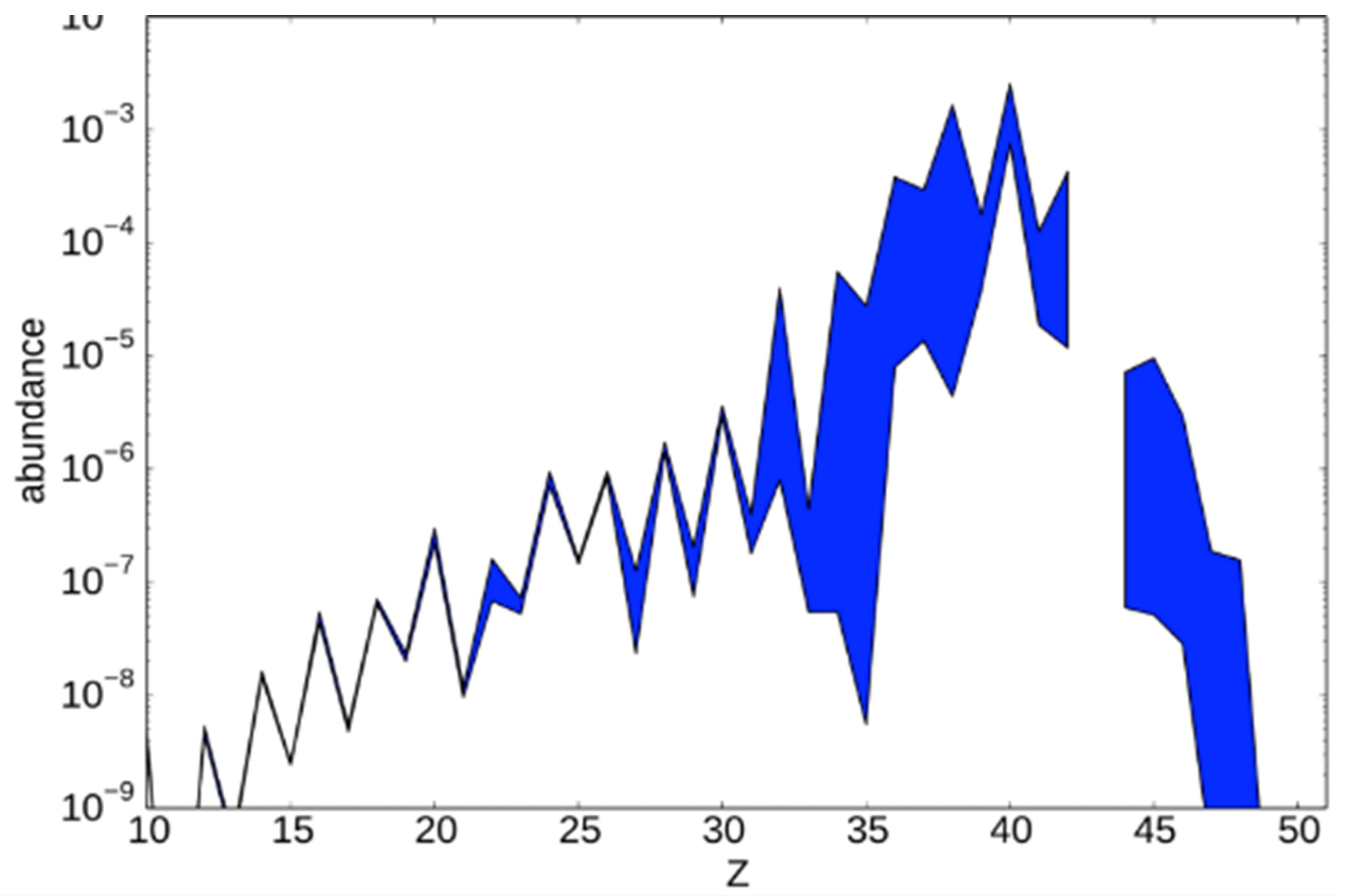
EWHA + UNIST + CENS
collaboration!

Role of Nuclear Physics

- Nucleosynthesis process can explain the observation.
  - → Nuclear Physics plays an important role!
  - → mass, Q-value, $T_{1/2}$, level densities and reaction rates ← Uncertainties of nuclear properties are huge!



Calculated light curves of X-ray burst within a factor of 100
R. H. Cyburt *et al.*, 2016

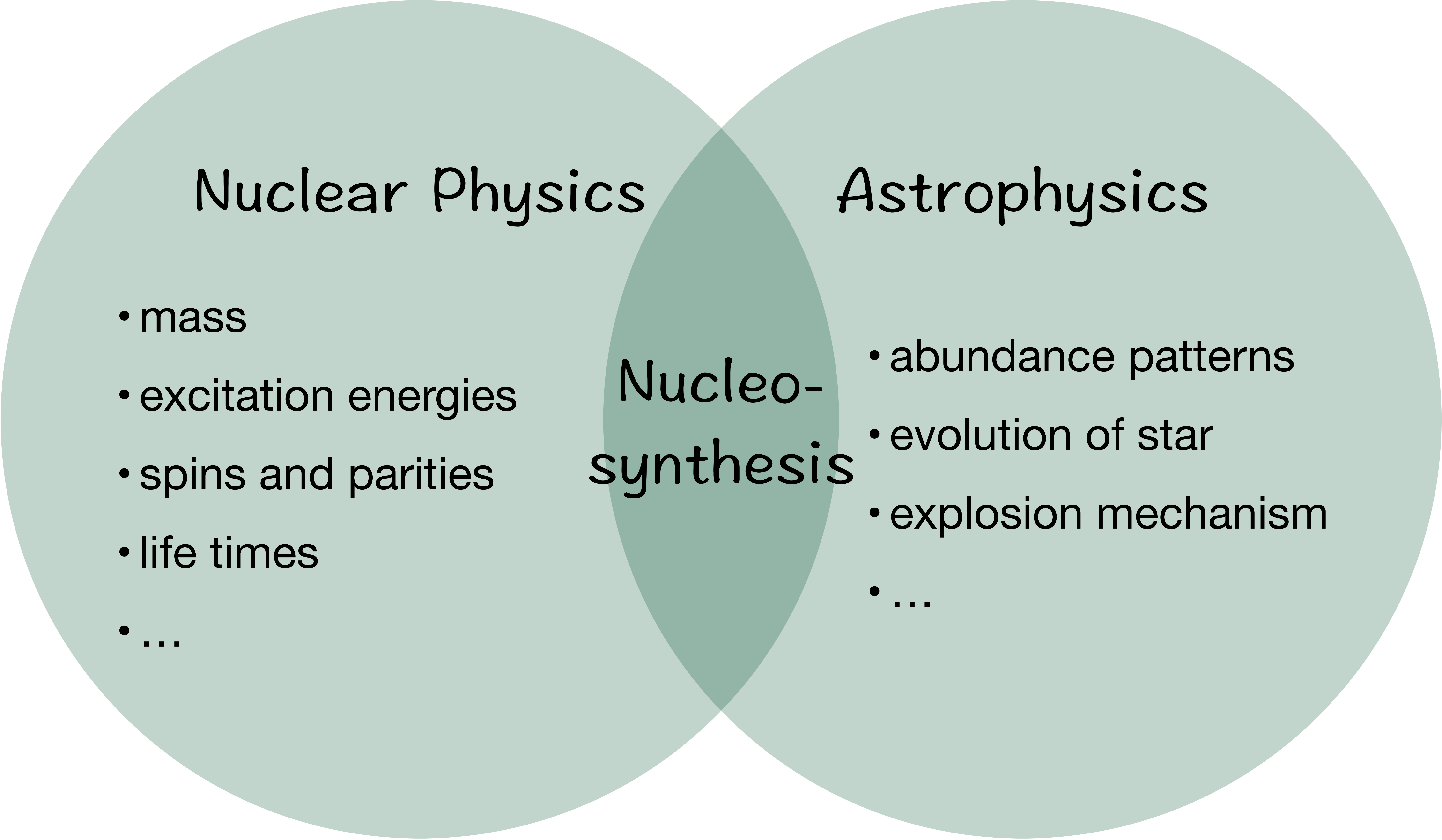


Monte-Carlo variations of (*α,n*) rates within a factor 100
Bliss *et al.*

Atomic Mass (A)

Nuclear Astrophysics

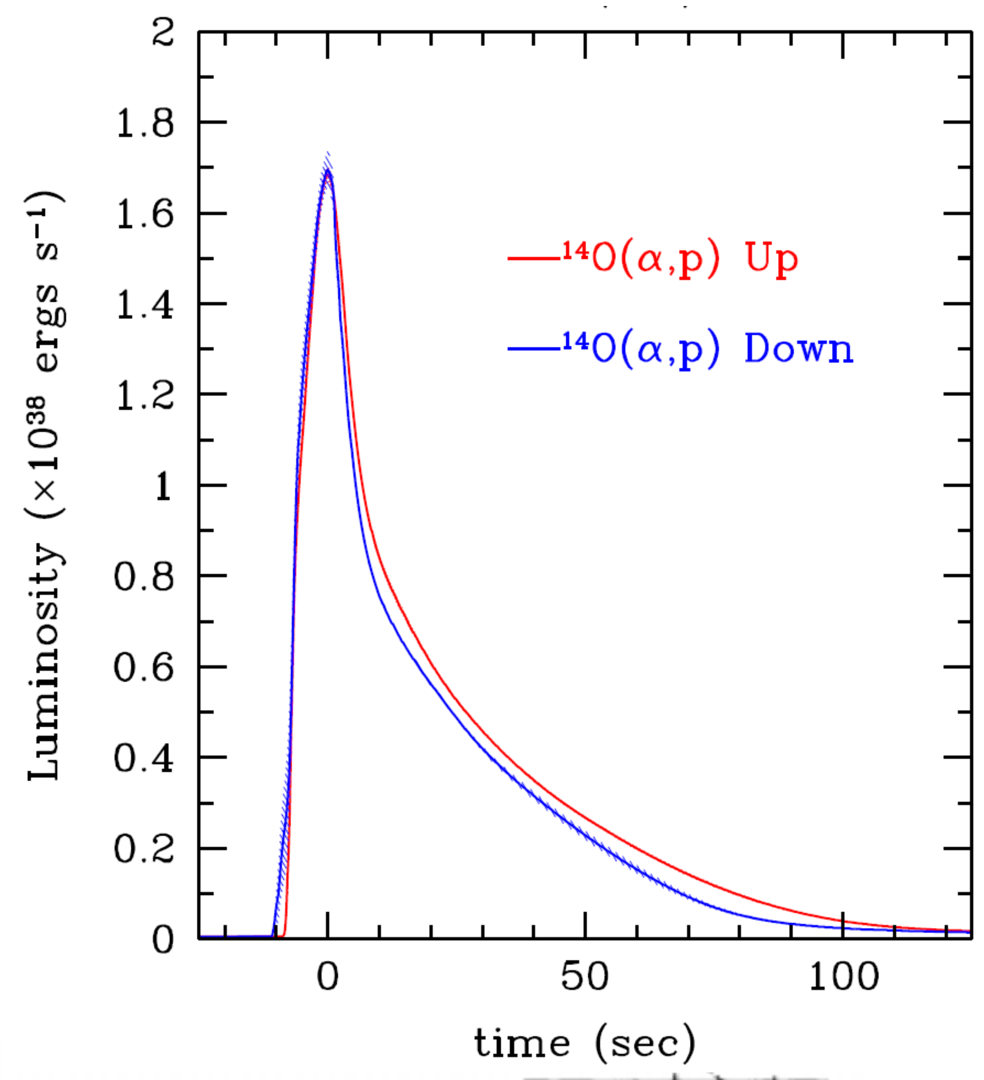
Tries to find the origin of elements



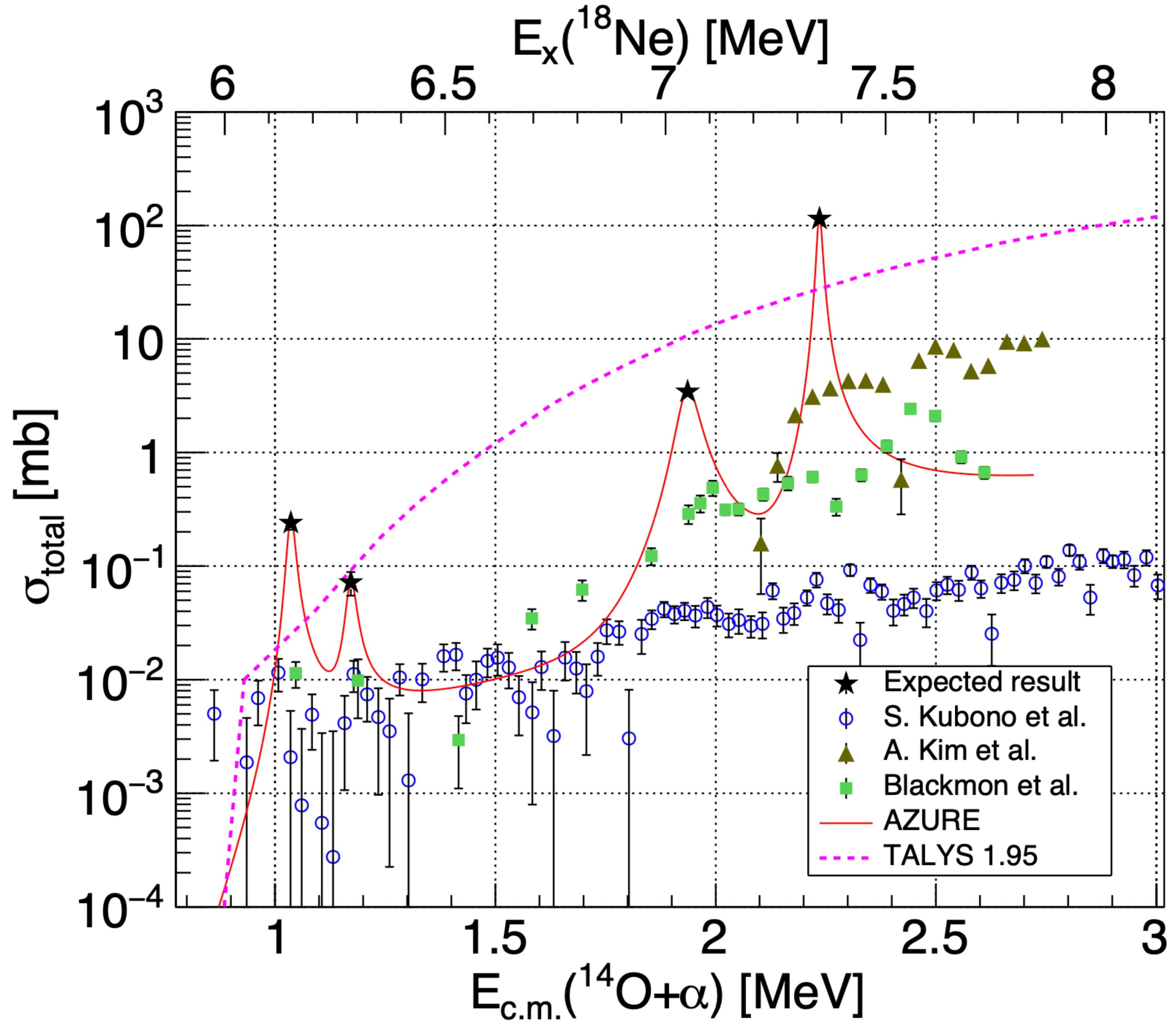
Part 2. The $^{14}O(\alpha,p)^{17}F$ Experiment

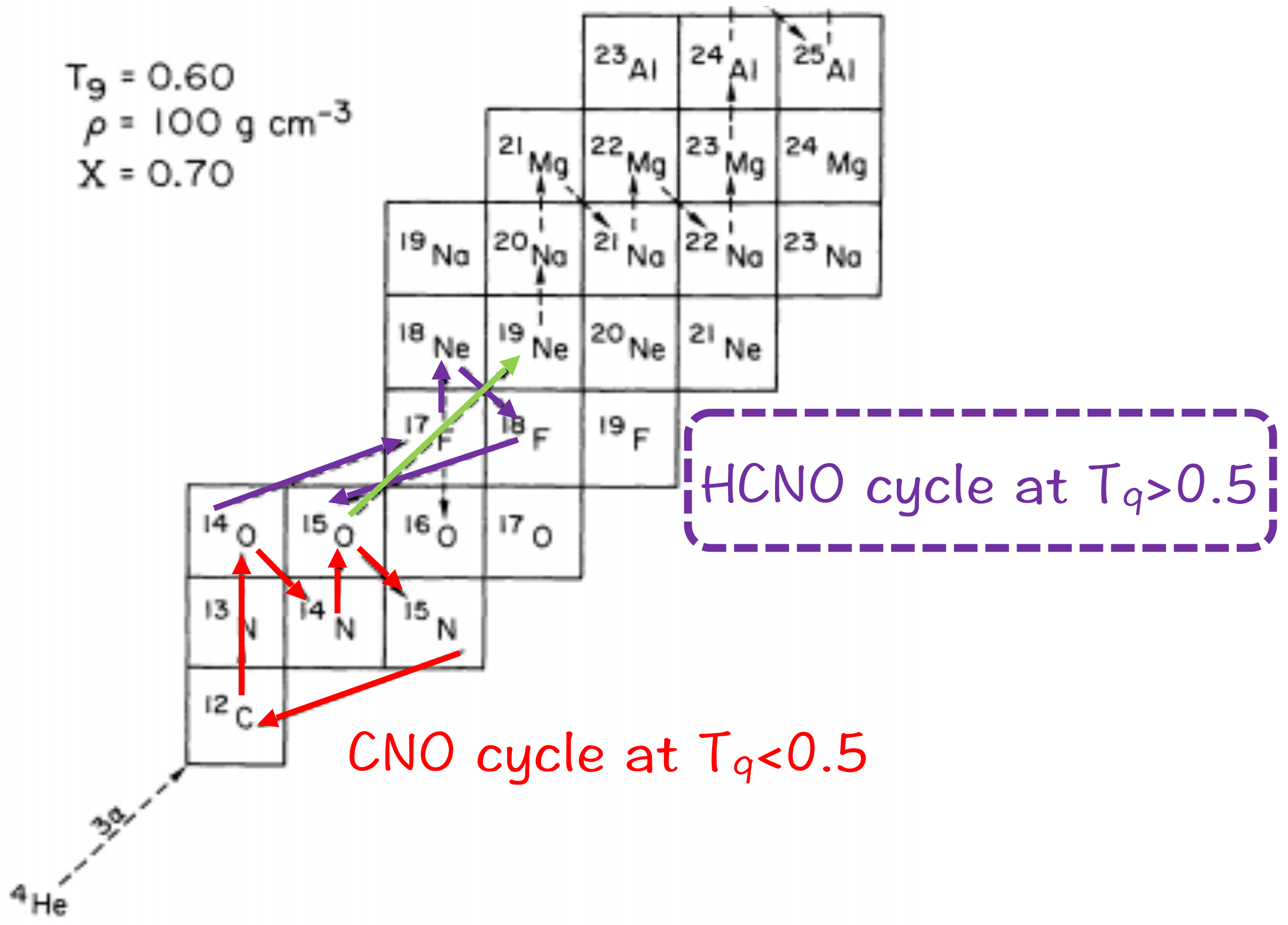
Motivation

- One of the most important (α,p) cross sections in X-ray bursts
- Alternate break-out path from the hot CNO cycle to the rapid proton burning (rp-process).

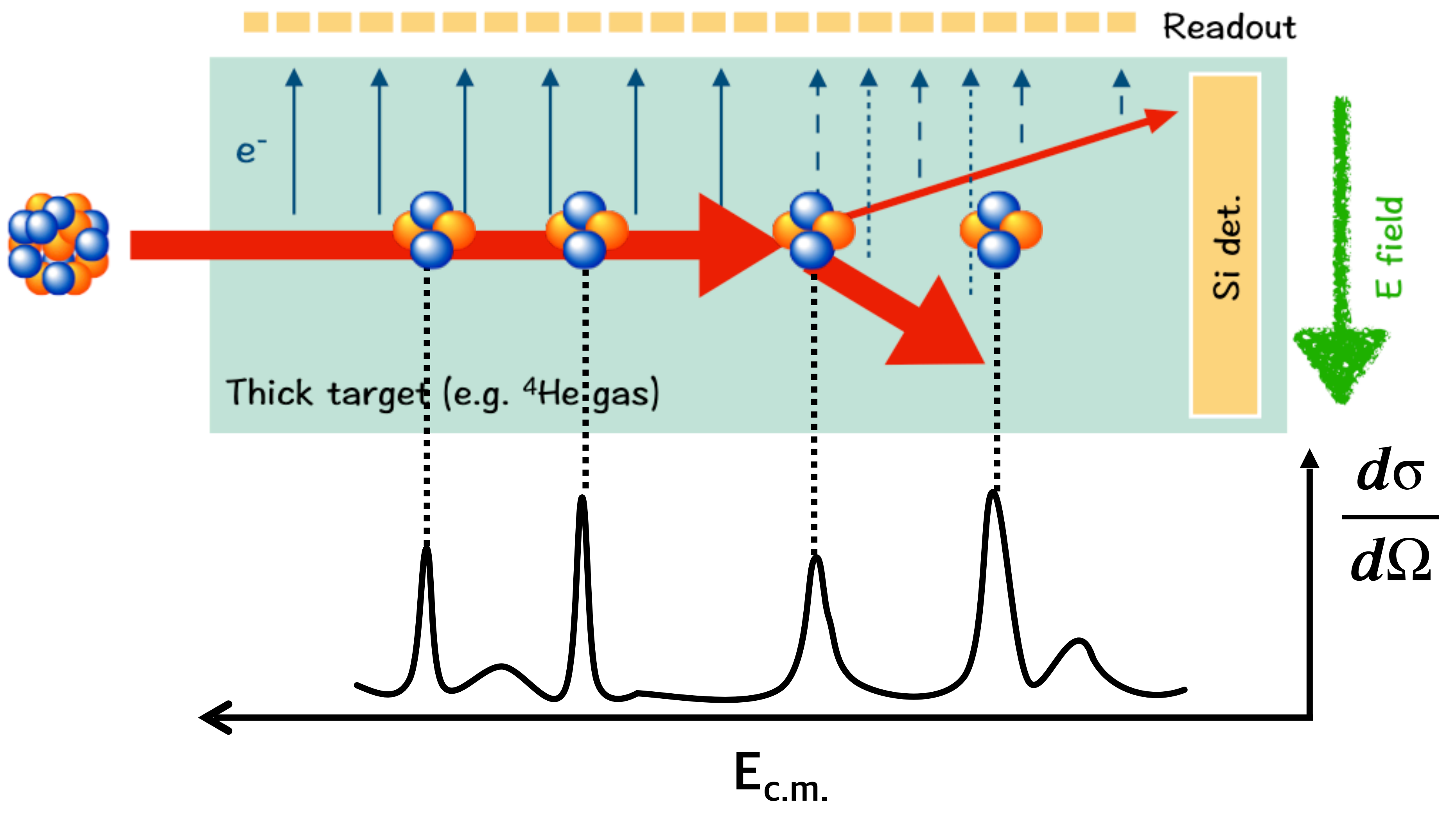


- Large uncertainty
  - Previous cross section measurements at high energy range (2 MeV ≤ E_{cm} ≤ 2.8 MeV) show large disagreements.
  - Results at low energy range (1 MeV ≤ E_{cm} ≤ 1.5 MeV) with large error bars have to be confirmed from another study.

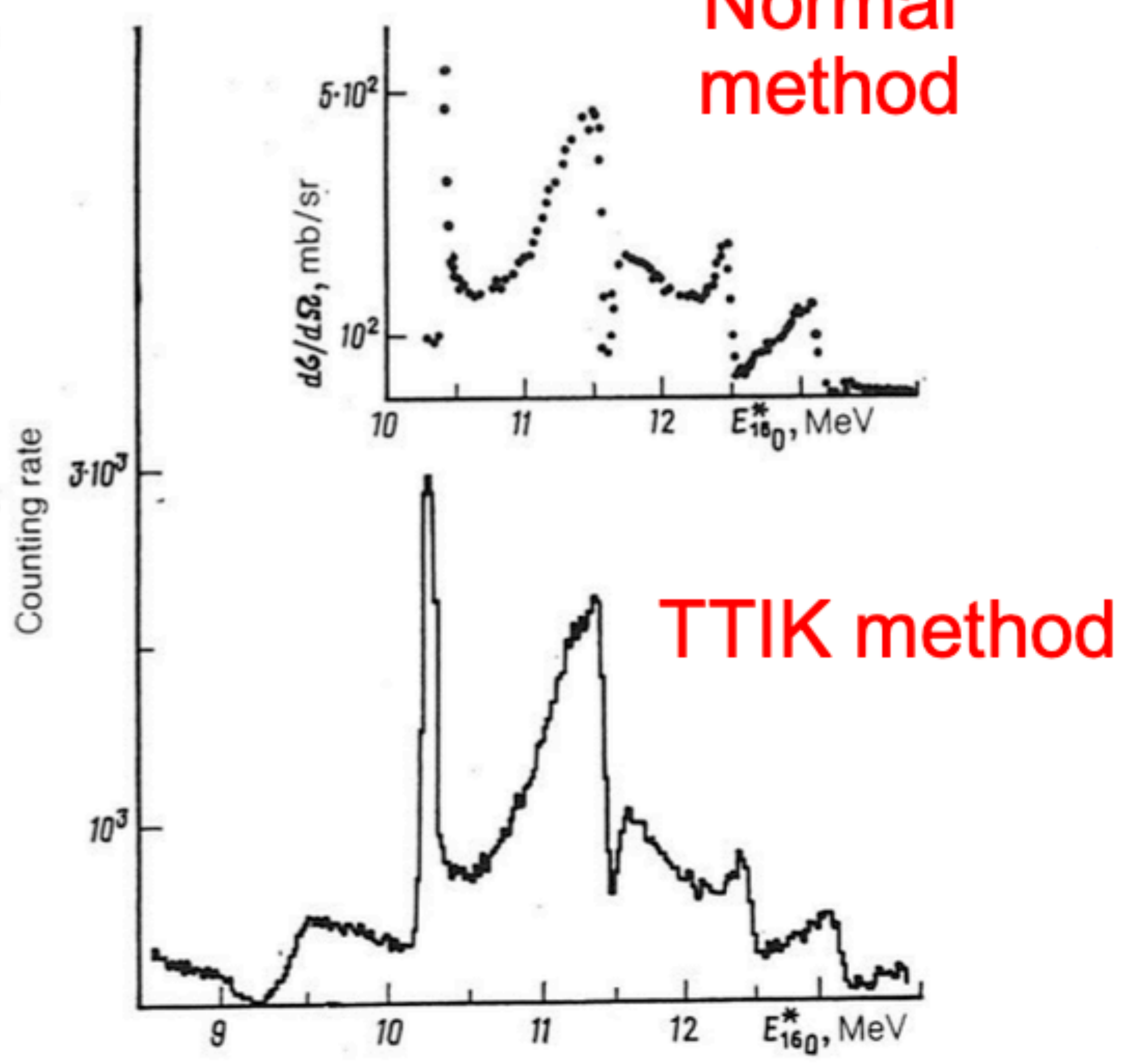


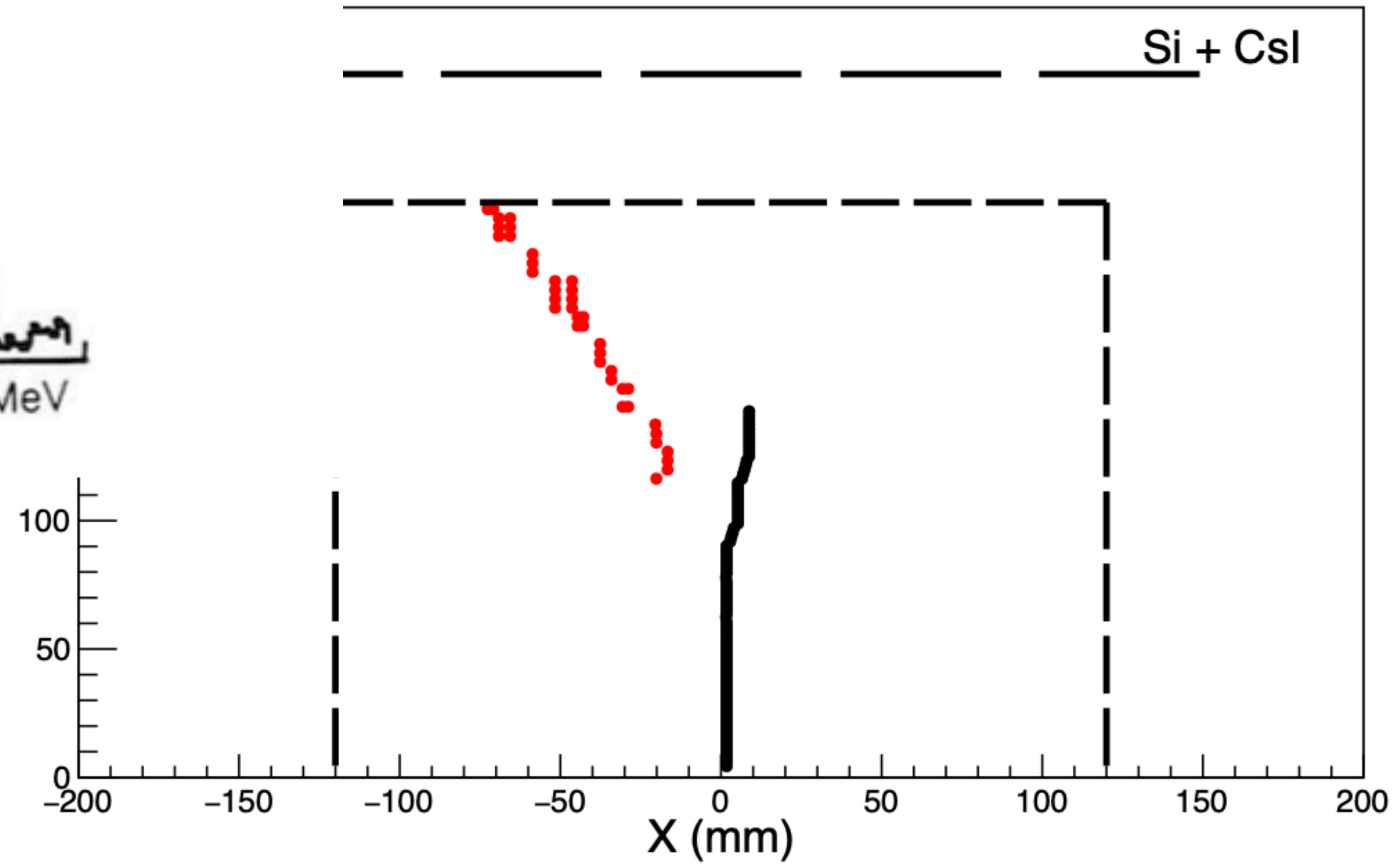


Active Target Time Projection Chamber (AT-TPC)



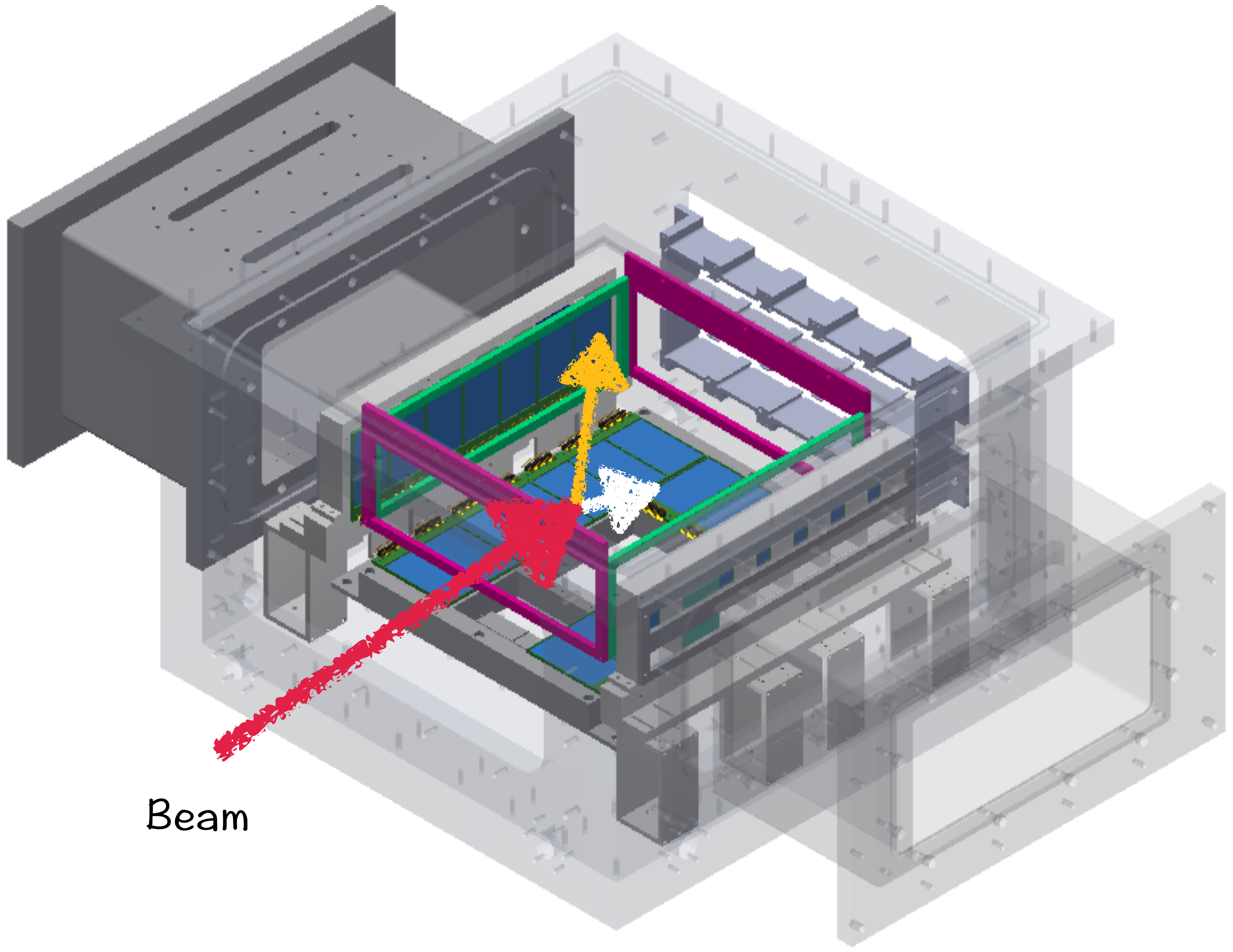
- Thick target inverse kinematics
- Tracking charged particles: vertex point, energy, angle
  → excitation function





J. Hooker et al. (2020).

Texas Active Target TPC ver 2 (TexAT_v2)

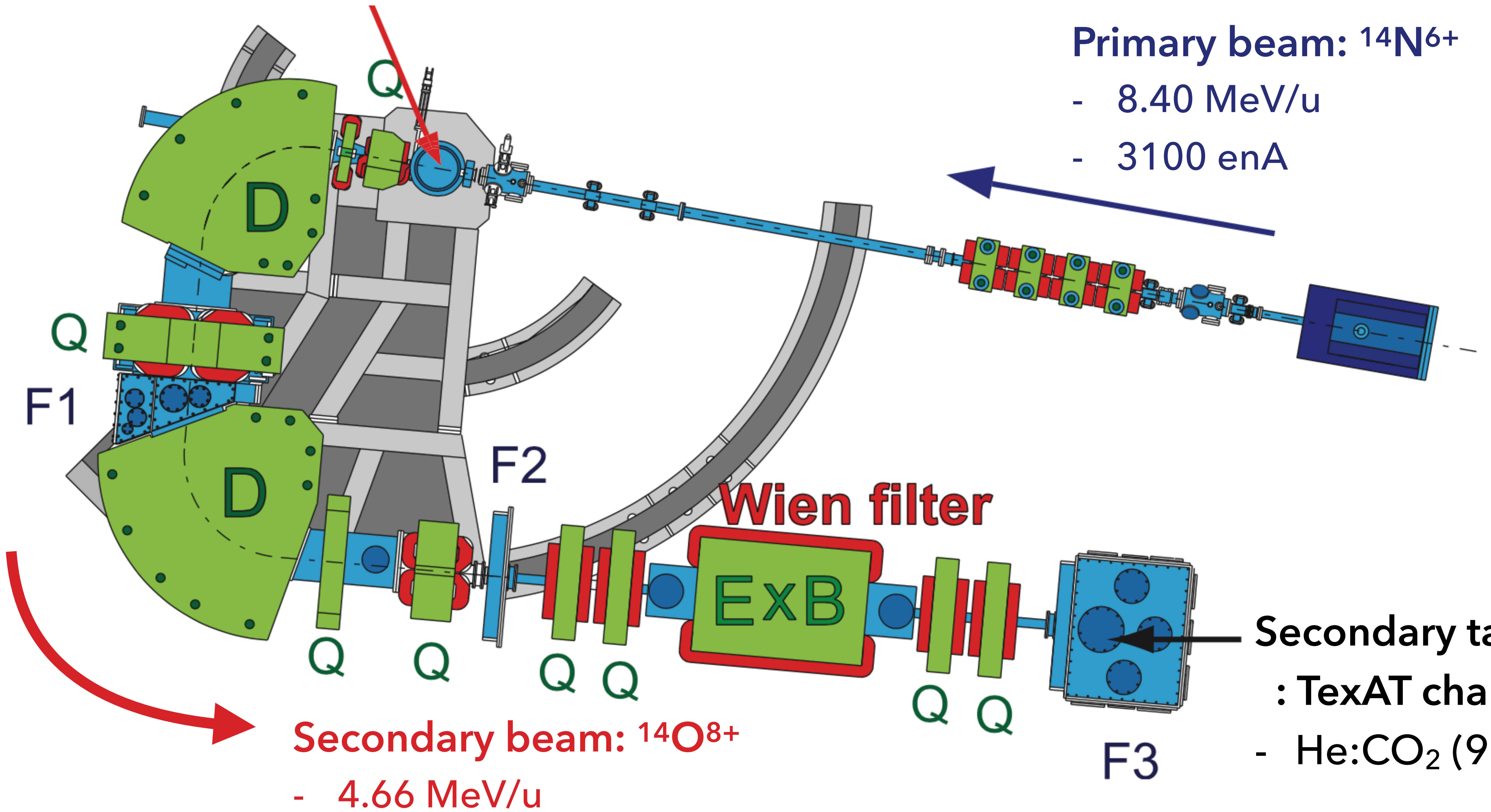


- Originally build from Texas A&M University
- Consist of …
  - Solid detector arrays for measuring energy
    : Si + CsI(Tl) with PIN diode
    X6 + CsI(Tl) with SiPM
  - Micromegas + GEM for tracking
  - Field cage for applying uniform electric field
  - Beam monitor
  - Wing chamber
  - Data acquisition system
- Can handle beam intensity up to 10^5 pps (tested)

Experimental Setup

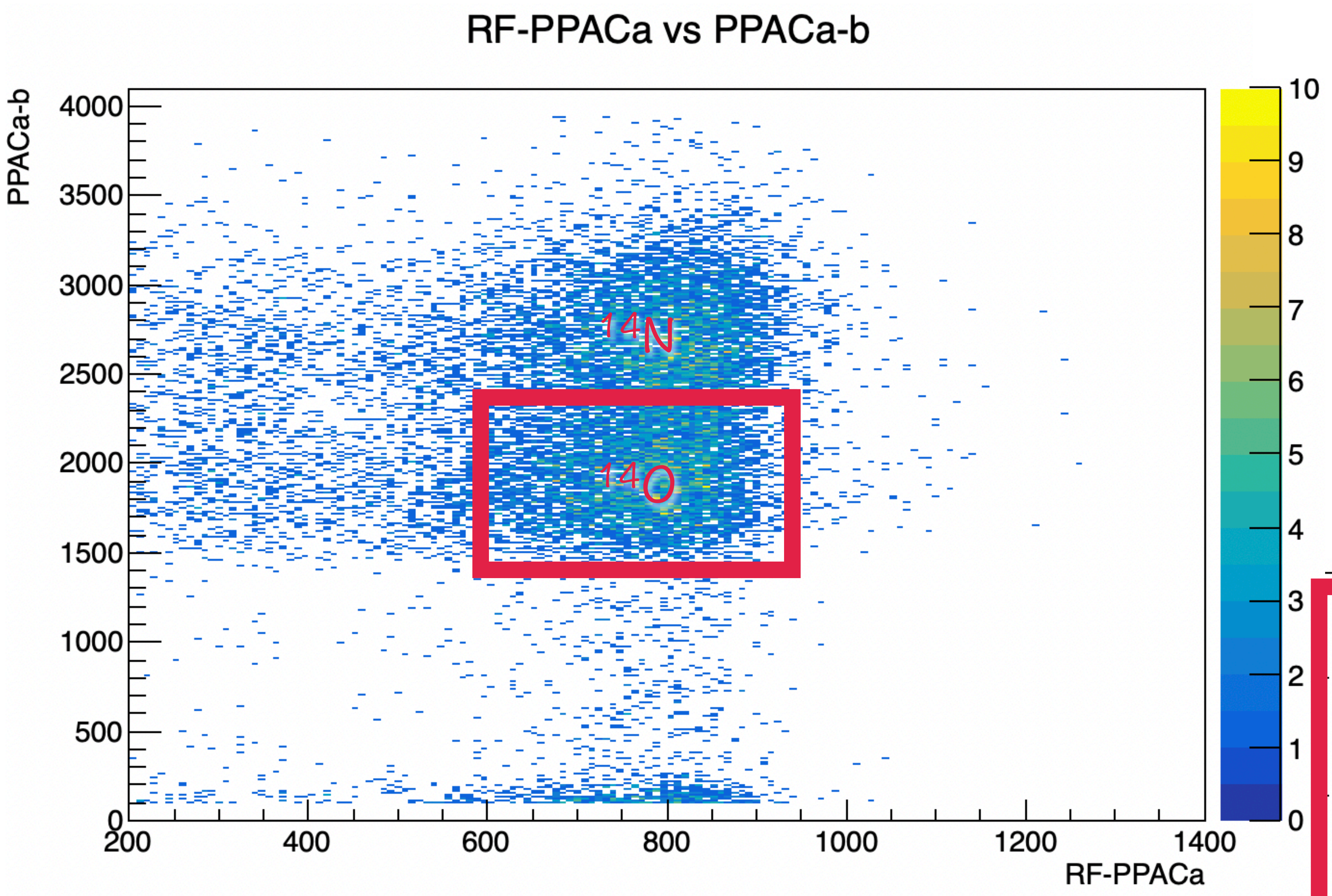
CRIB @ RIKEN, Japan

CNS Radio-Isotope Beam Separator

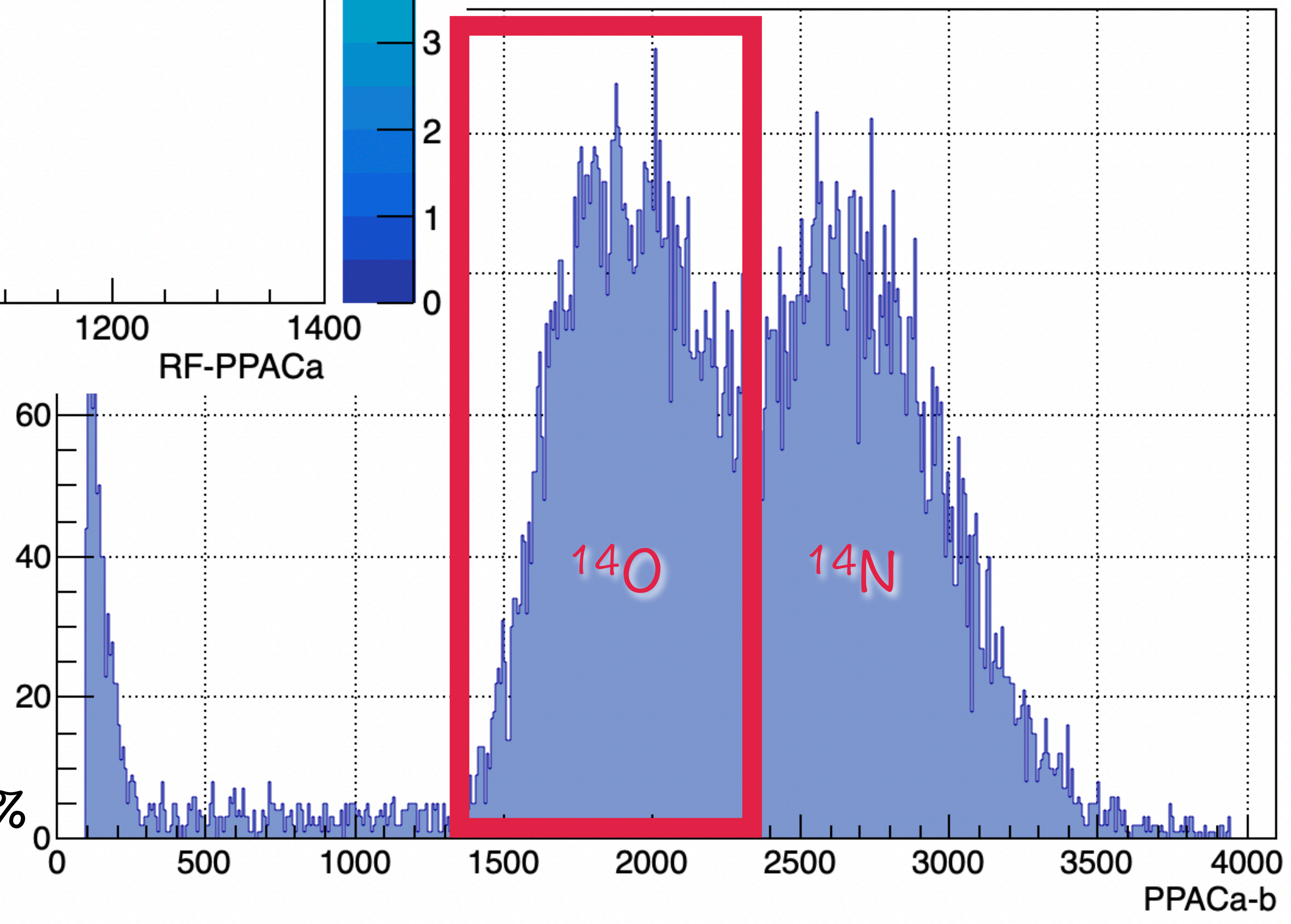


TexAT chamber

Preliminary Results



Projection Y

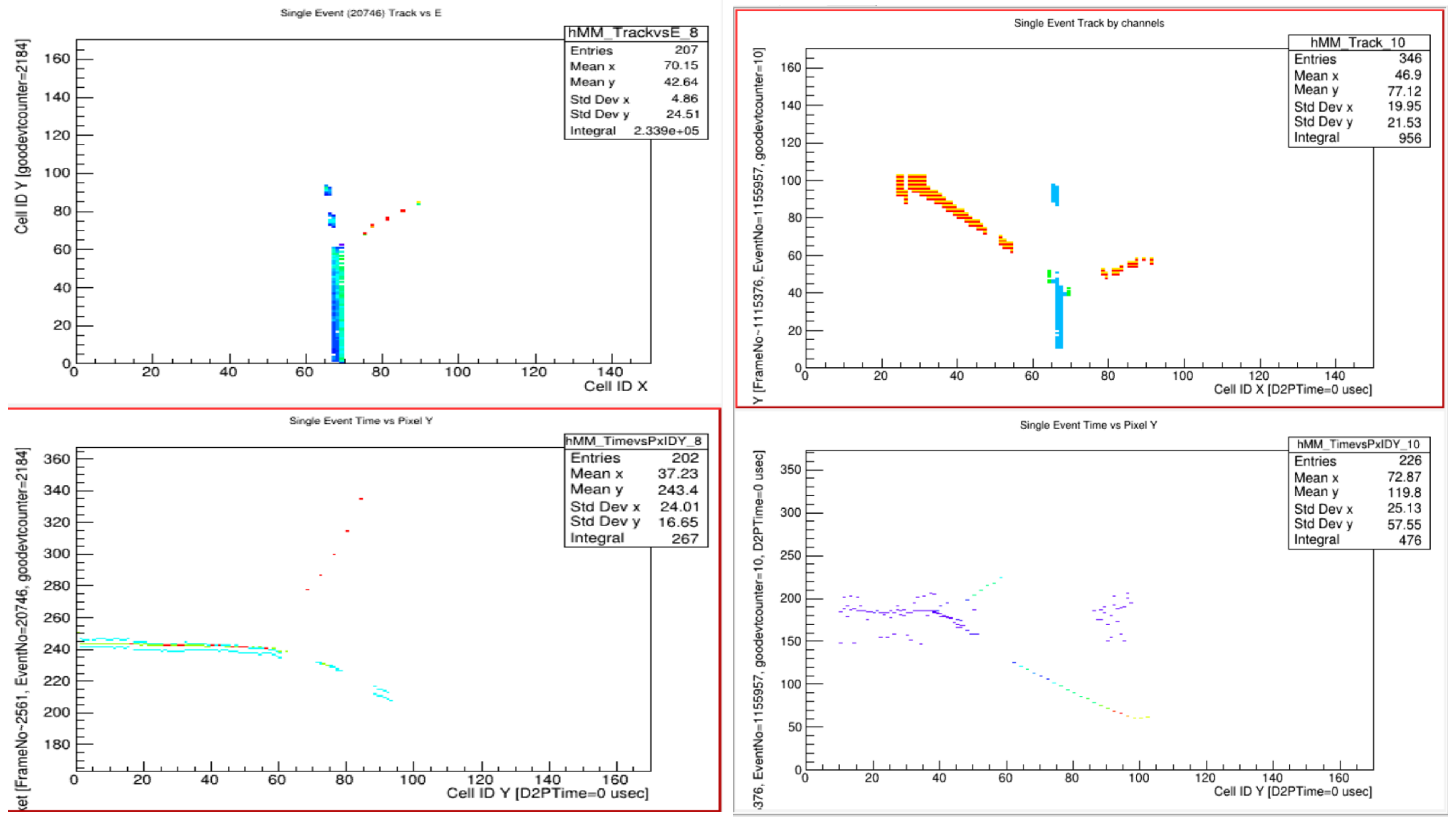


from the GET data

(same as CRIB data)

1860 ± 209

→ FWHM 26.3 %



Analysis on going …

Outlook

- The experiment measuring the cross section of astrophysical important reaction, $^{14}O(\alpha,p)^{17}F$, is performed in CRIB, RIKEN.
  - Data transportation is done. (30 TB!)
- Analysis is on-going.
  - Find the reaction vertex and extract the cross section.
  - Calculate the reaction rate and extrapolate to the full range of Gamow window.
- Study of the impact of reaction rate on astrophysics simulation is going on the other hand.

Collaborator List

CENS, IBS	S. Ahn, S. Bae, S.M. Cha, K. I. Hahn, D. Kim, Y.H. Kim, B. Moon				
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Thank you

2023.06.14 - 15 Chaeyeon Park