



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

Ewha Womans University / CENS, IBS
Chaeyeon Park

Part 1. What is Nuclear Astrophysics?

Periodic Table of Elements

GROUP																		18	
PERIOD	1	2											13	14	15	16	17	18	
	1 H Hydrogen 1.008												5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 He Helium 4.003	
	3 Li Lithium 6.94	4 Be Beryllium 9.012											13 Al Aluminium 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.95	
	11 Na Sodium 22.99	12 Mg Magnesium 24.31	21 Sc Scandium 44.96	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 52.00	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.64	33 As Arsenic 74.92	34 Se Selenium 78.96	35 Br Bromine 79.90	36 Kr Krypton 83.79	
	37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.96	43 Tc Technetium (98)	44 Ru Ruthenium 101.1	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3	
	55 Cs Caesium 132.9	56 Ba Barium 137.3	57-71 Lanthanides	72 Hf Hafnium 178.5	73 Ta Tantalum 180.9	74 W Tungsten 183.9	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.5	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)	
	87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinides	104 Rf Rutherfordium (261)	105 Db Dubnium (268)	106 Sg Seaborgium (271)	107 Bh Bohrium (270)	108 Hs Hassium (277)	109 Mt Meitnerium (276)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (280)	112 Cn Copernicium (285)	113 Nh Nihonium (284)	114 Fl Flerovium (289)	115 Mc Moscovium (288)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)	

Alkali Metals

Alkaline Earth Metals

Transition Metals

Other Metals

Metalloids

Non-metals

Halogens

Noble Gases

Lanthanides

Actinides

78

Pt

Platinum

195.1

Atomic Number

Symbol

Name

Average Atomic Mass

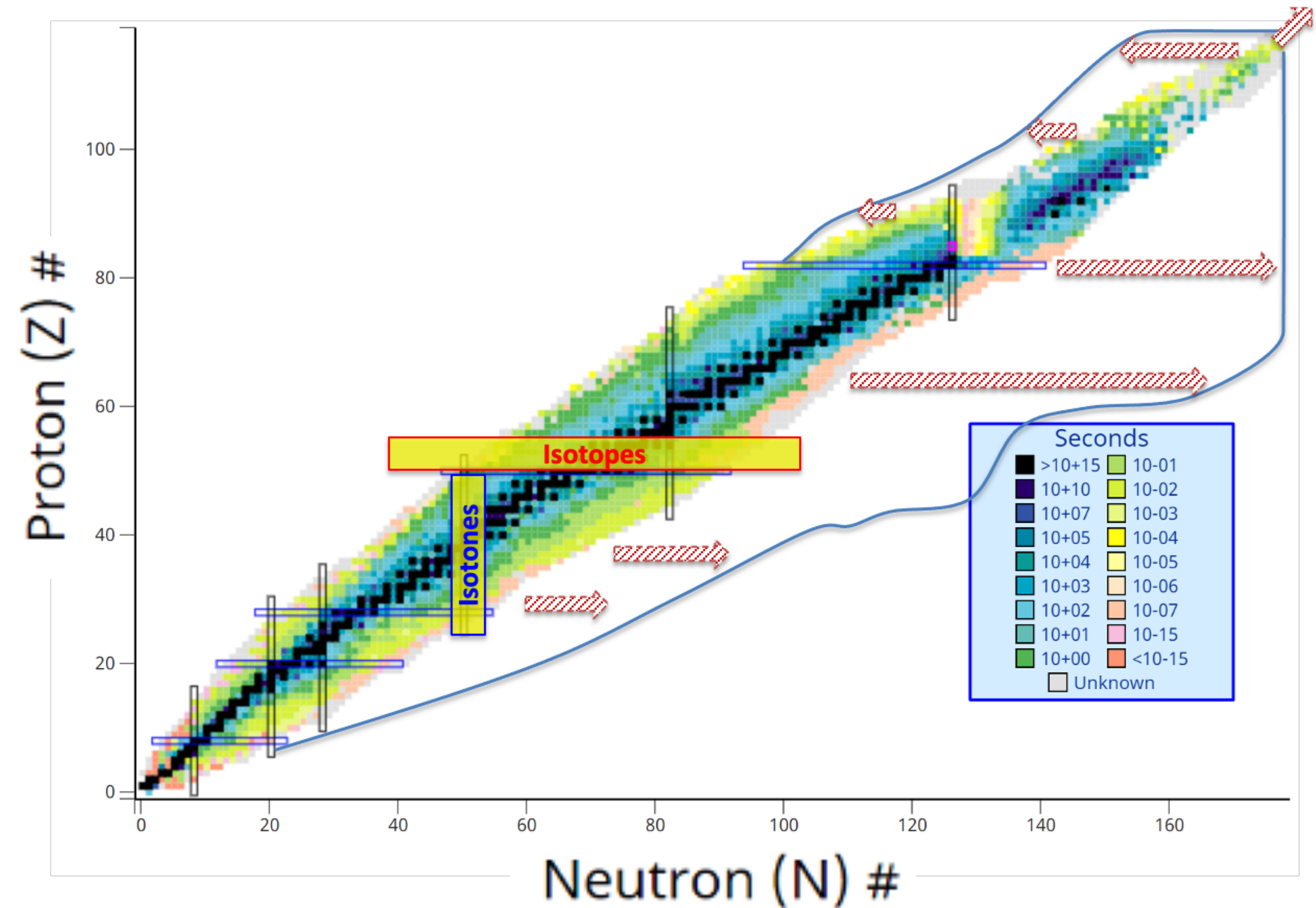
57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La Lanthanum 138.9	Ce Cerium 140.1	Pr Praseodymium 140.9	Nd Neodymium 144.2	Pm Promethium (145)	Sm Samarium 150.4	Eu Europium 152.0	Gd Gadolinium 157.2	Tb Terbium 158.9	Dy Dysprosium 162.5	Ho Holmium 164.9	Er Erbium 167.3	Tm Thulium 168.9	Yb Ytterbium 173.0	Lu Lutetium 175.0
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac Actinium (227)	Th Thorium 232.0	Pa Protactinium 231.0	U Uranium 238.0	Np Neptunium (237)	Pu Plutonium (244)	Am Americium (243)	Cm Curium (247)	Bk Berkelium (247)	Cf Californium (251)	Es Einsteinium (252)	Fm Fermium (257)	Md Mendelevium (258)	No Nobelium (259)	Lr Lawrencium (262)

Chart of Nuclides

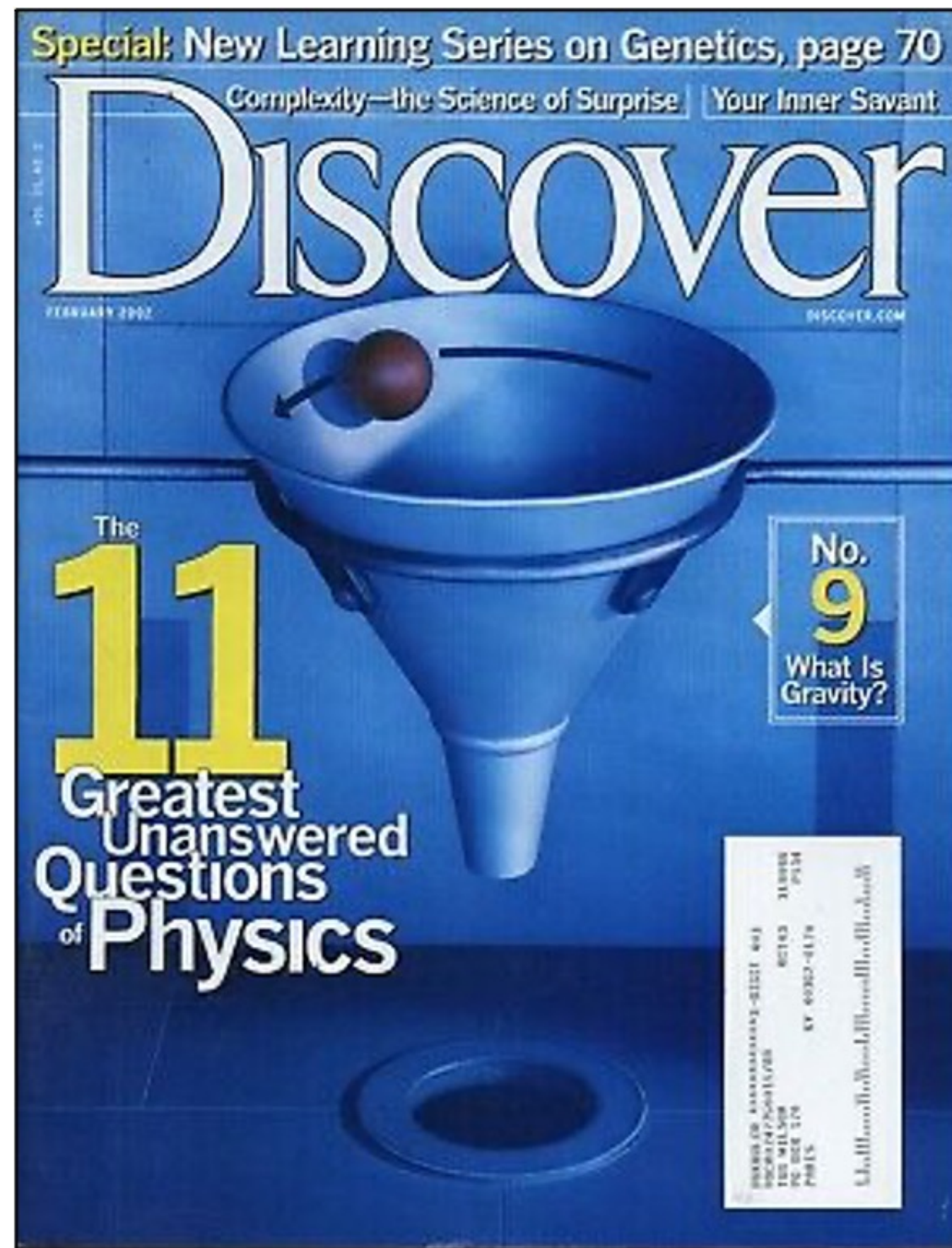
- Only 288 nuclei forms the valley of stability.
- About 3,000 nuclei are known.
- Nuclear theorists estimate about 6,900 nuclei are bound.
- Nuclei away from stability are short lived (down to usec).

* 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?

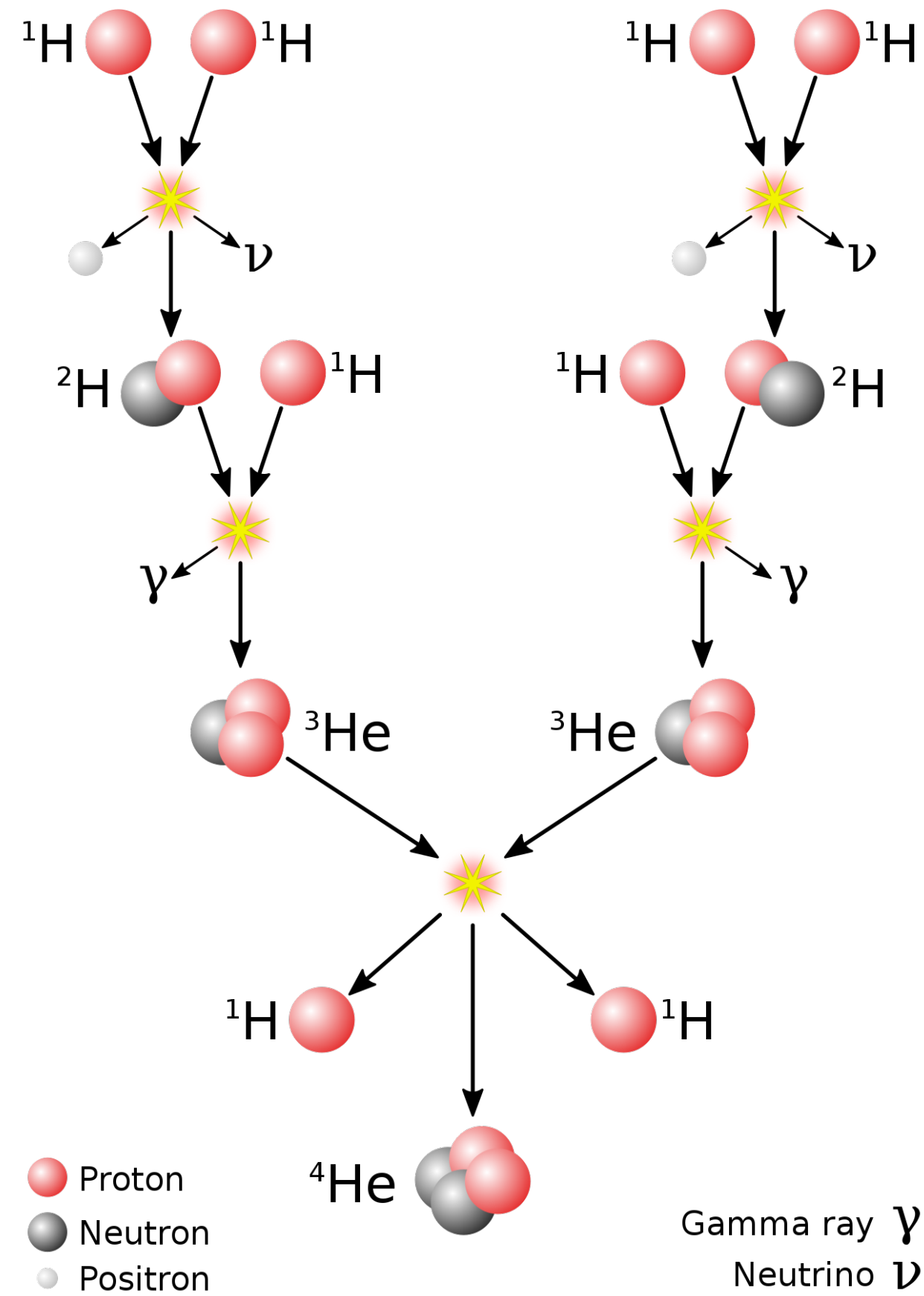
Question 8. Are protons unstable?

Question 9. What is gravity?

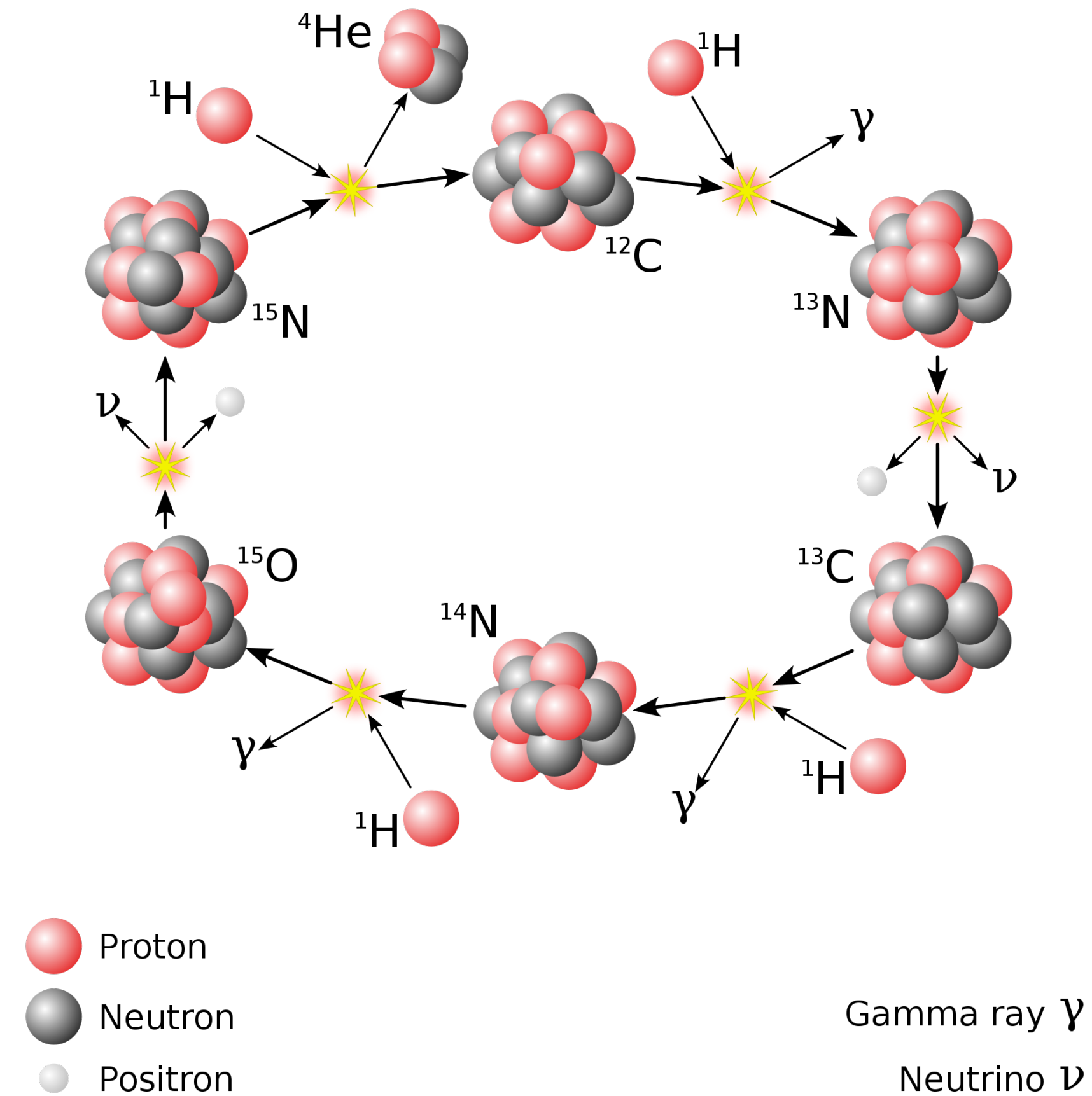
Question 10. Are there additional dimensions?

Question 11. How did the universe begin?

Synthesis of the Light Elements

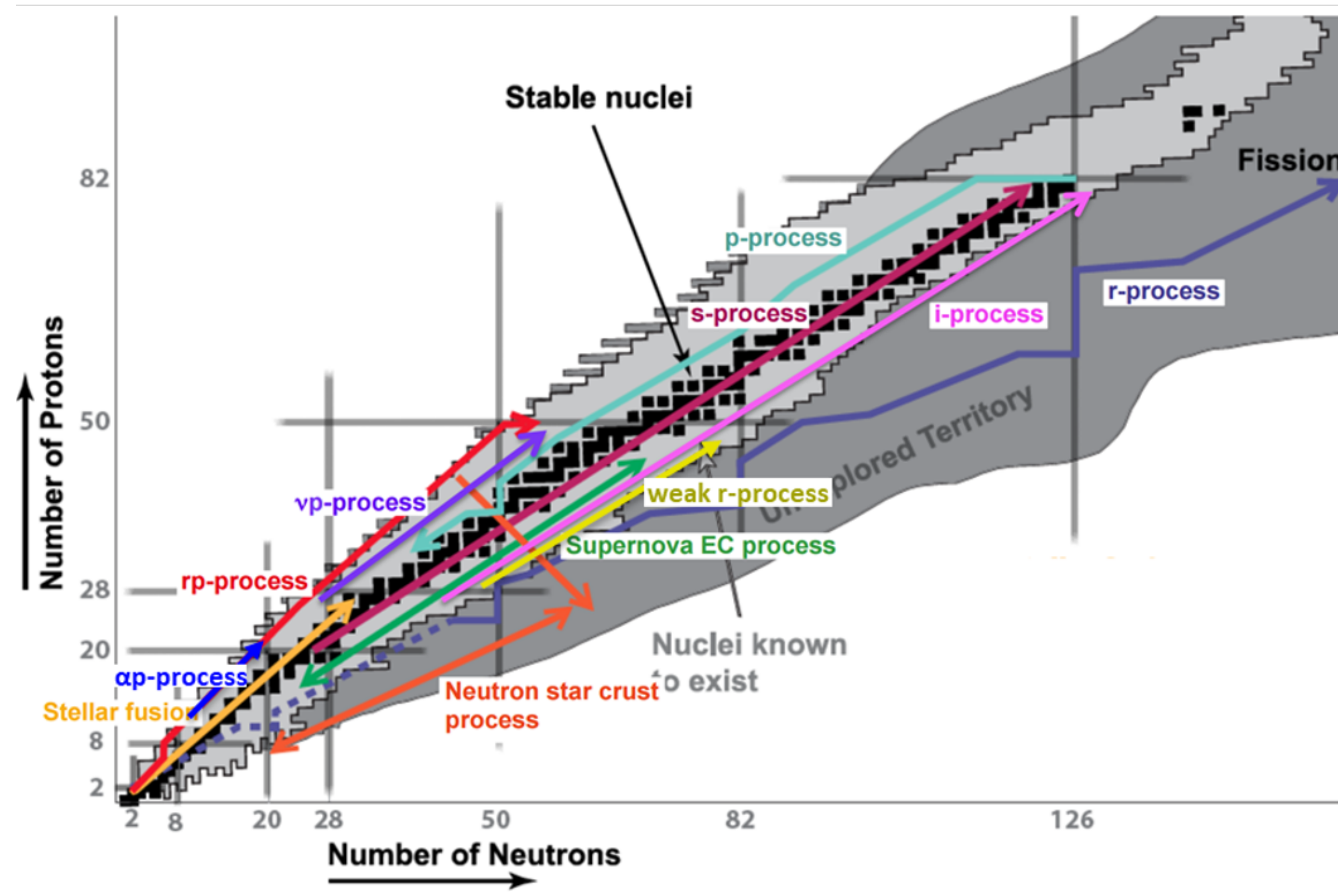


Proton-proton chain



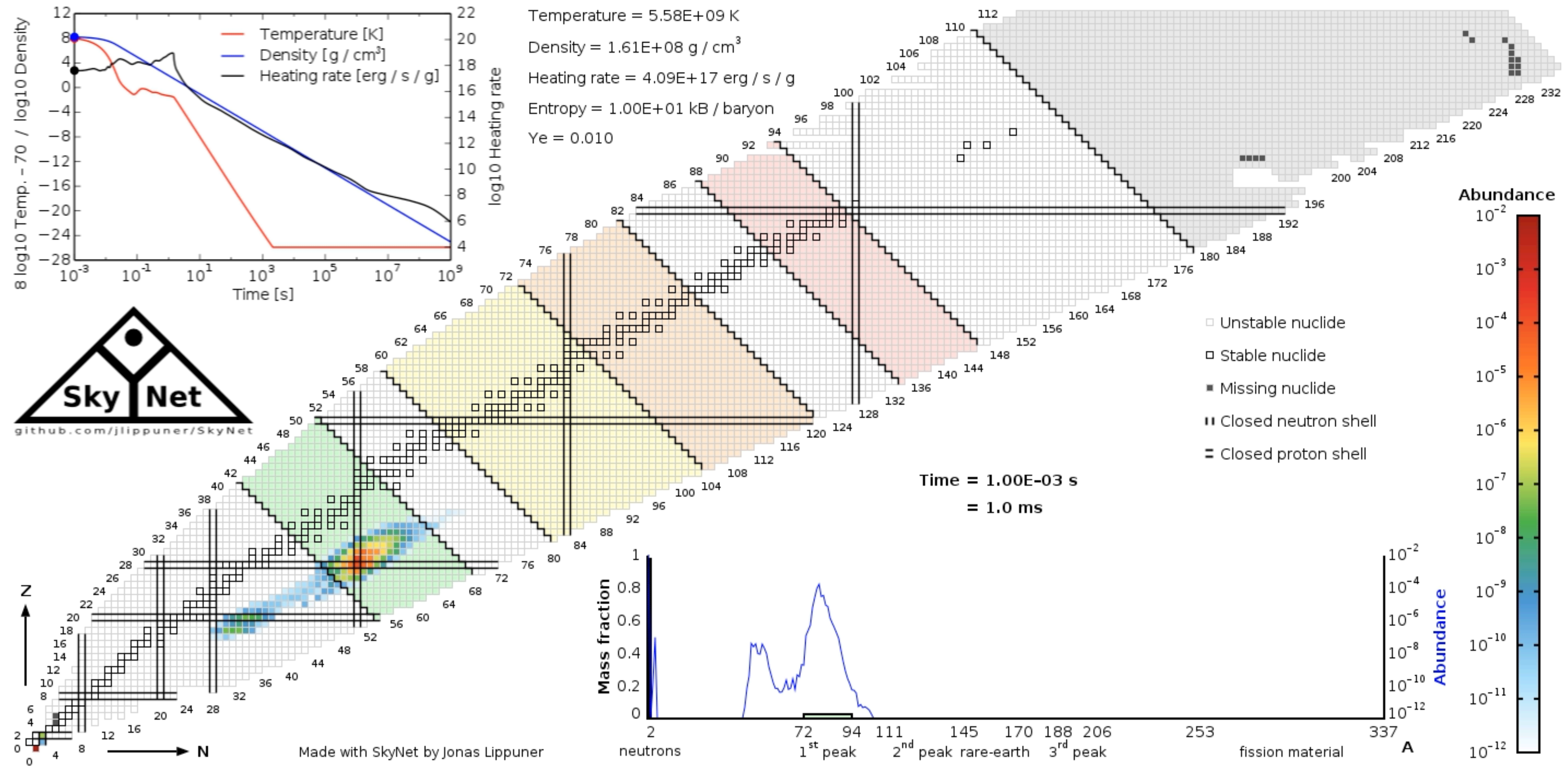
CNO cycle

Nucleosynthesis Processes

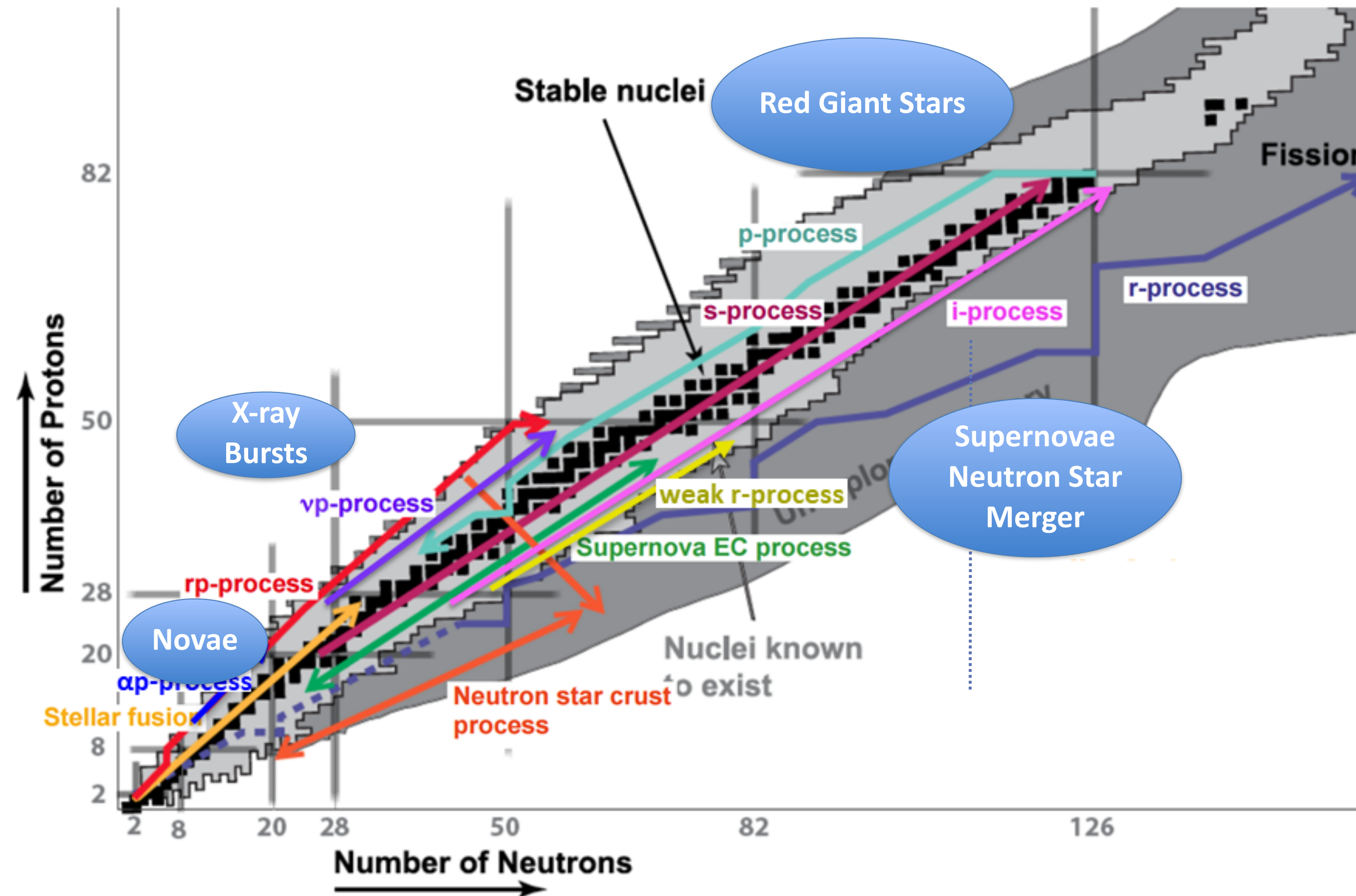


H. Schatz. (2016).

r-process Simulation

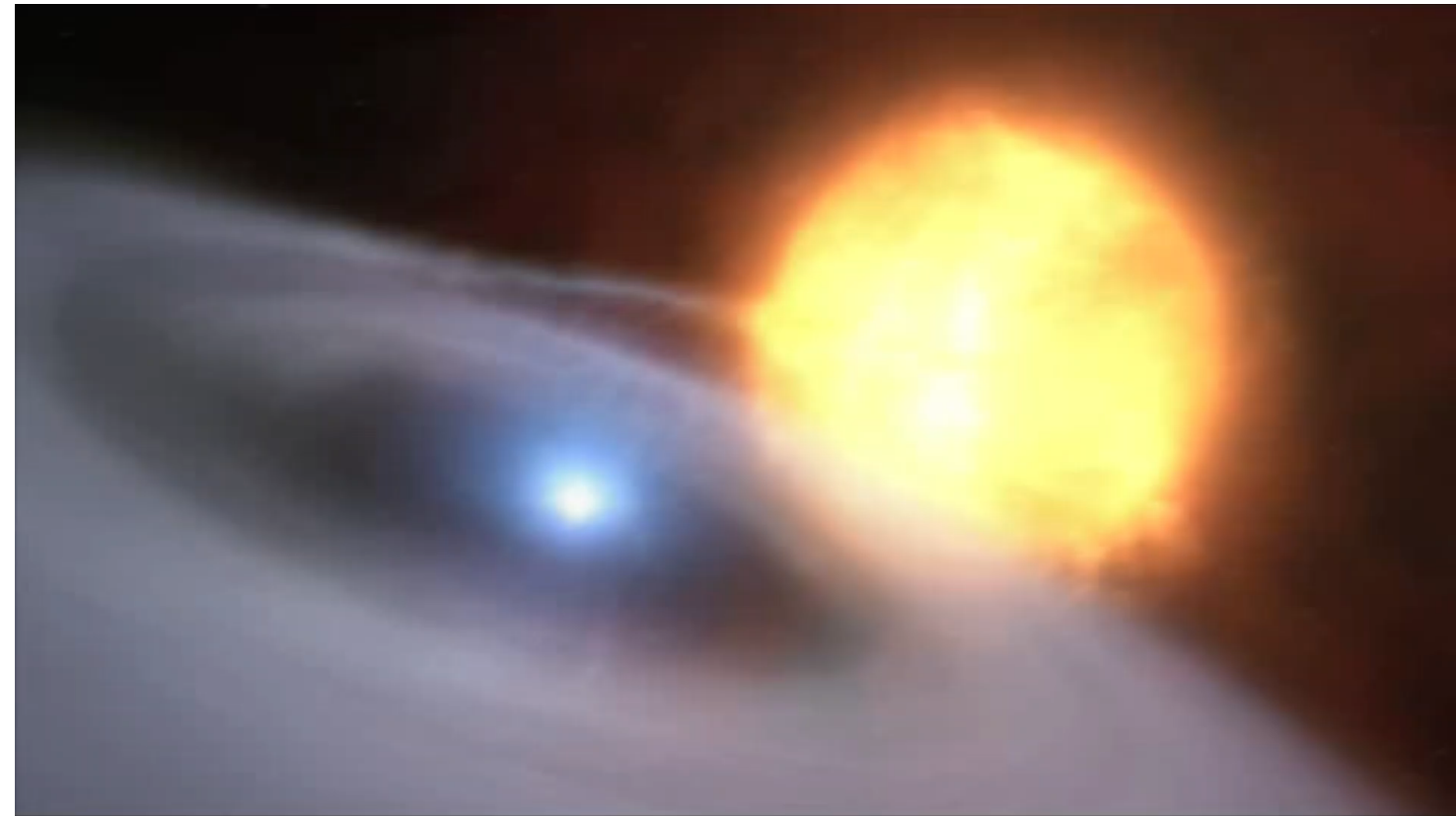


Nucleosynthesis Processes

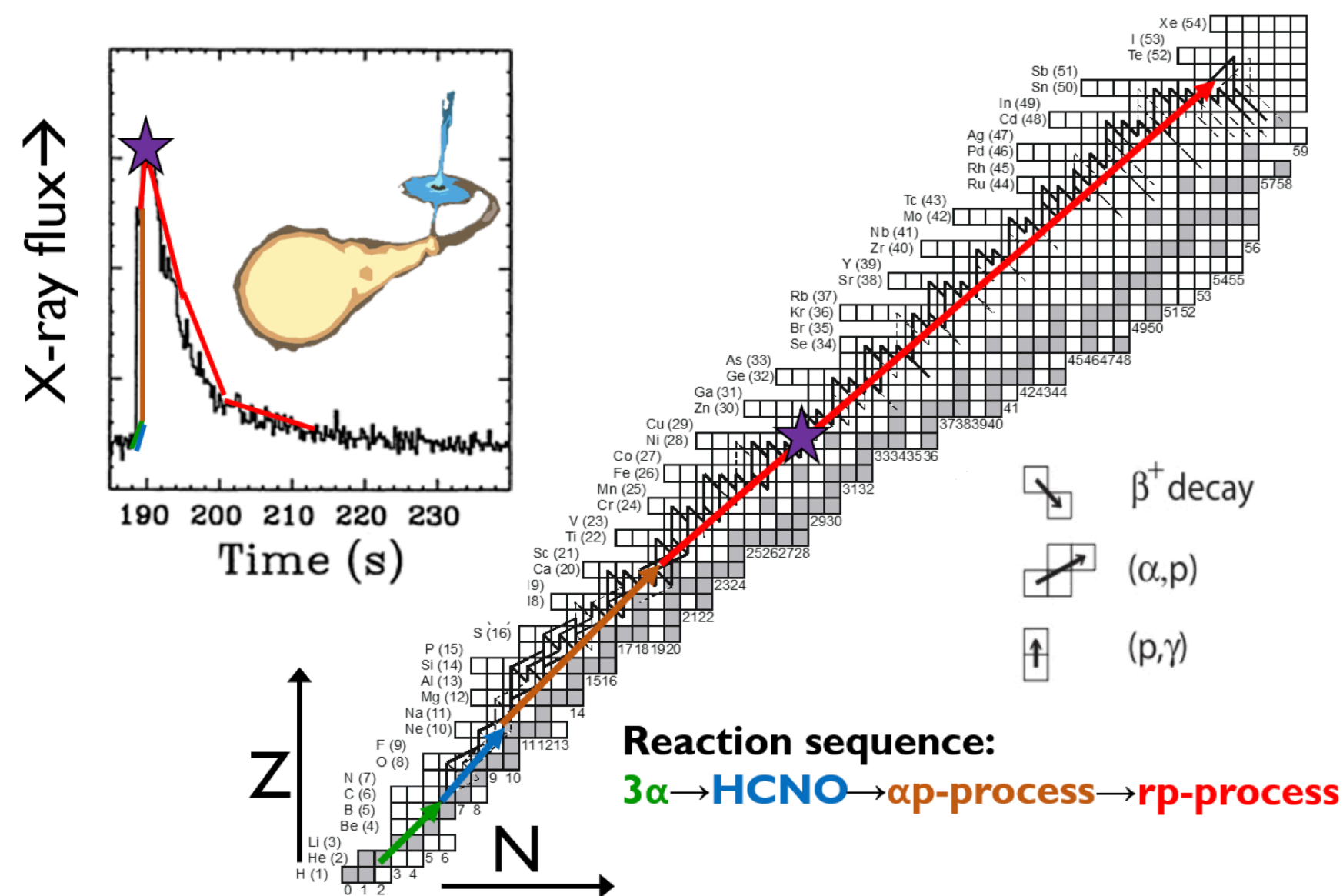


H. Schatz. (2016).

X-Ray Bursts

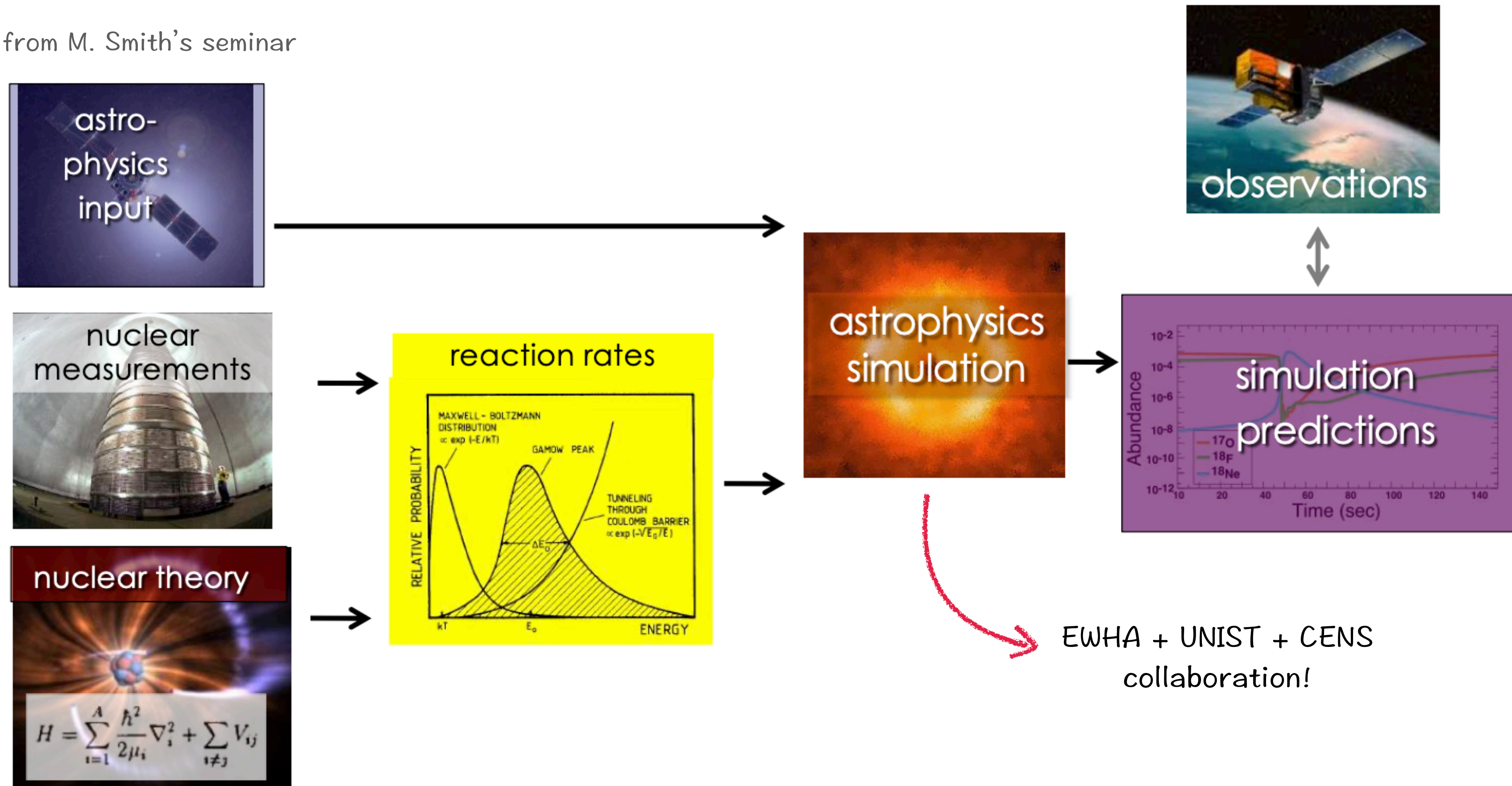


- Binary star composed of:
 - an accreting compact object (commonly neutron star)
 - a main sequence companion 'donor' star
- ^4He capture reactions process (ap-process):
 - $^{15}\text{O} + ^4\text{He} \rightarrow ^{18}\text{Ne} + \gamma \rightarrow ^{18}\text{Ne} + ^4\text{He} \rightarrow ^{21}\text{Na}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



Nuclear Physics - Astrophysics Connection

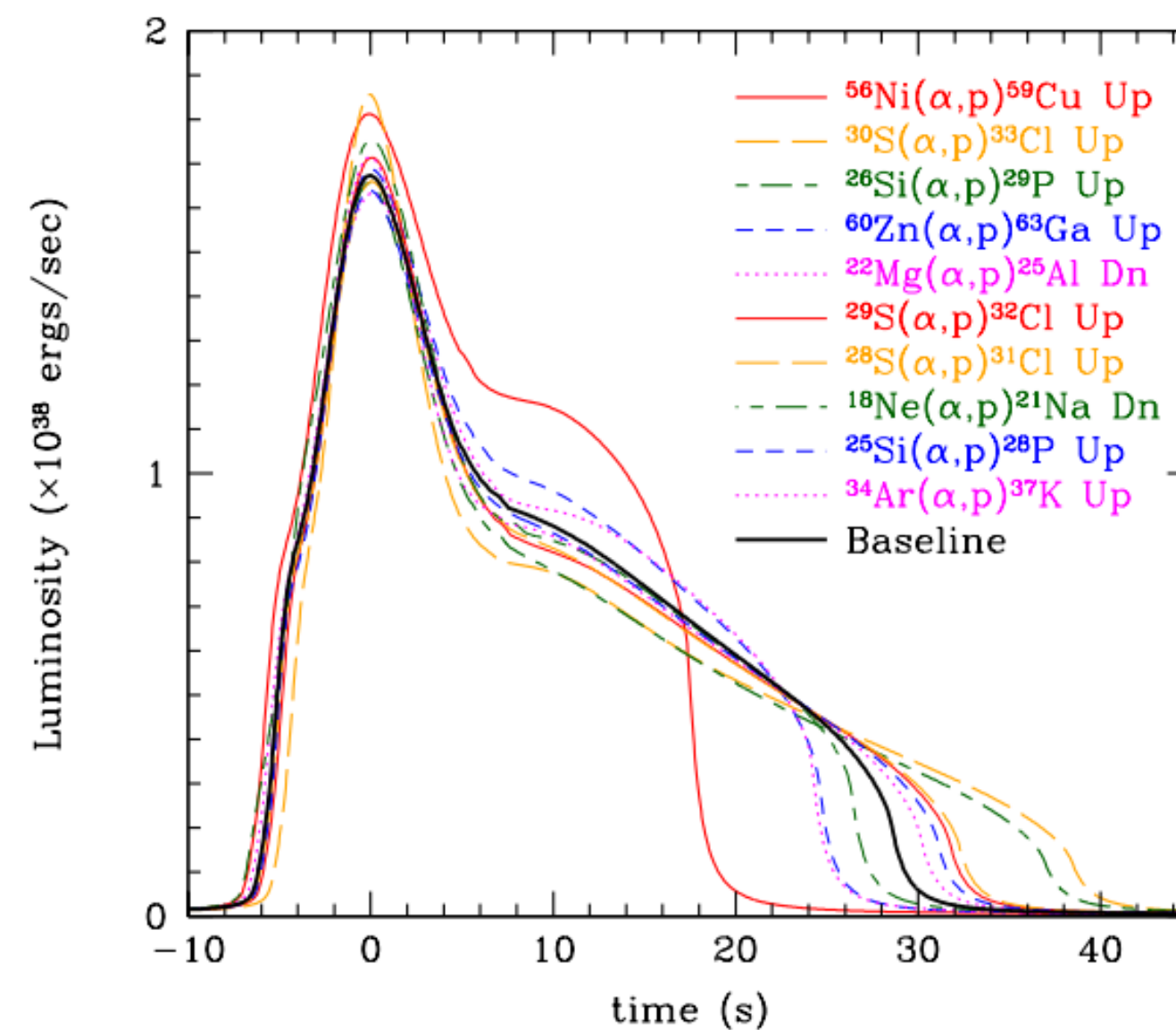
from M. Smith's seminar



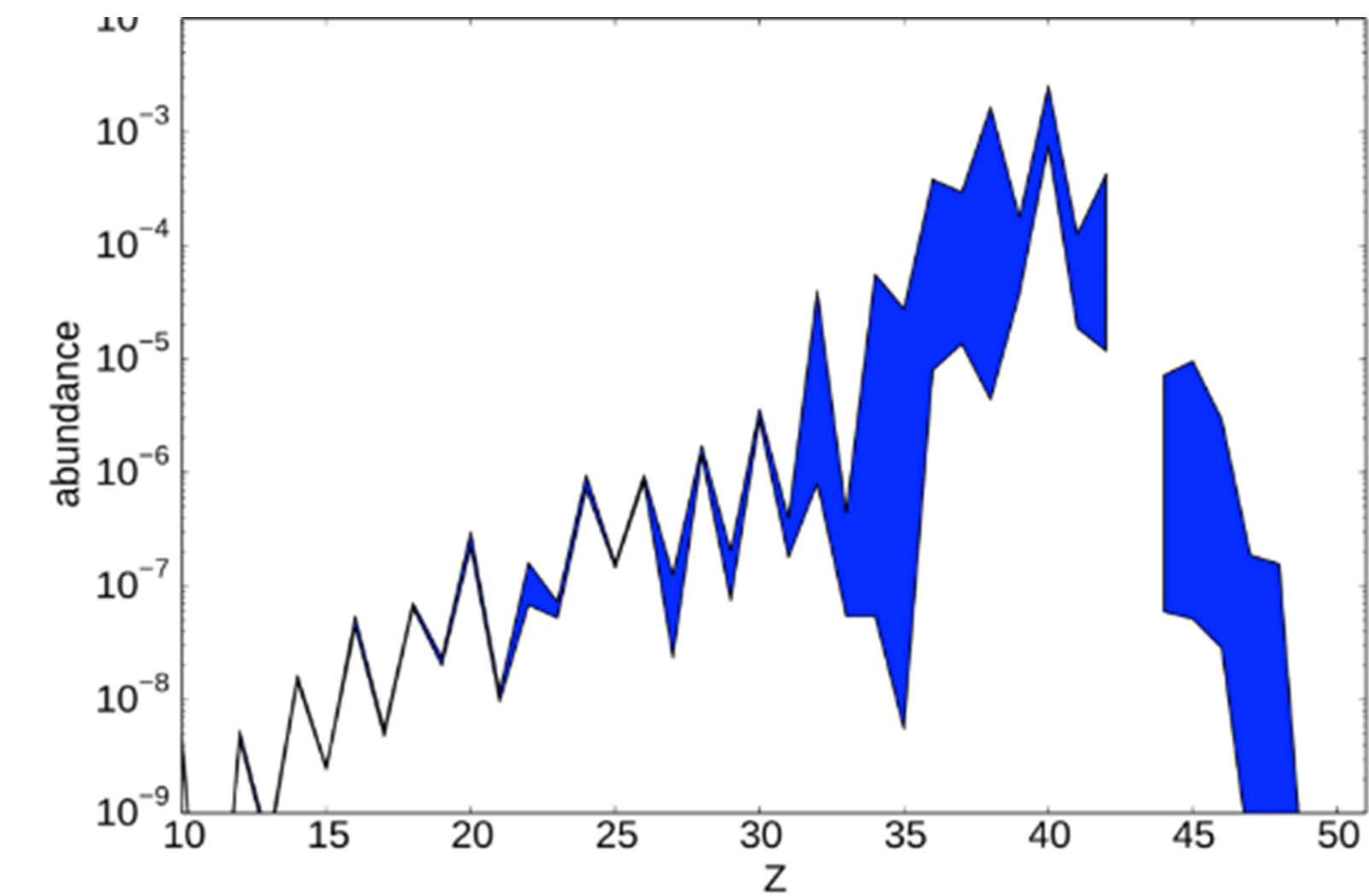
Role of Nuclear Physics

- 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!



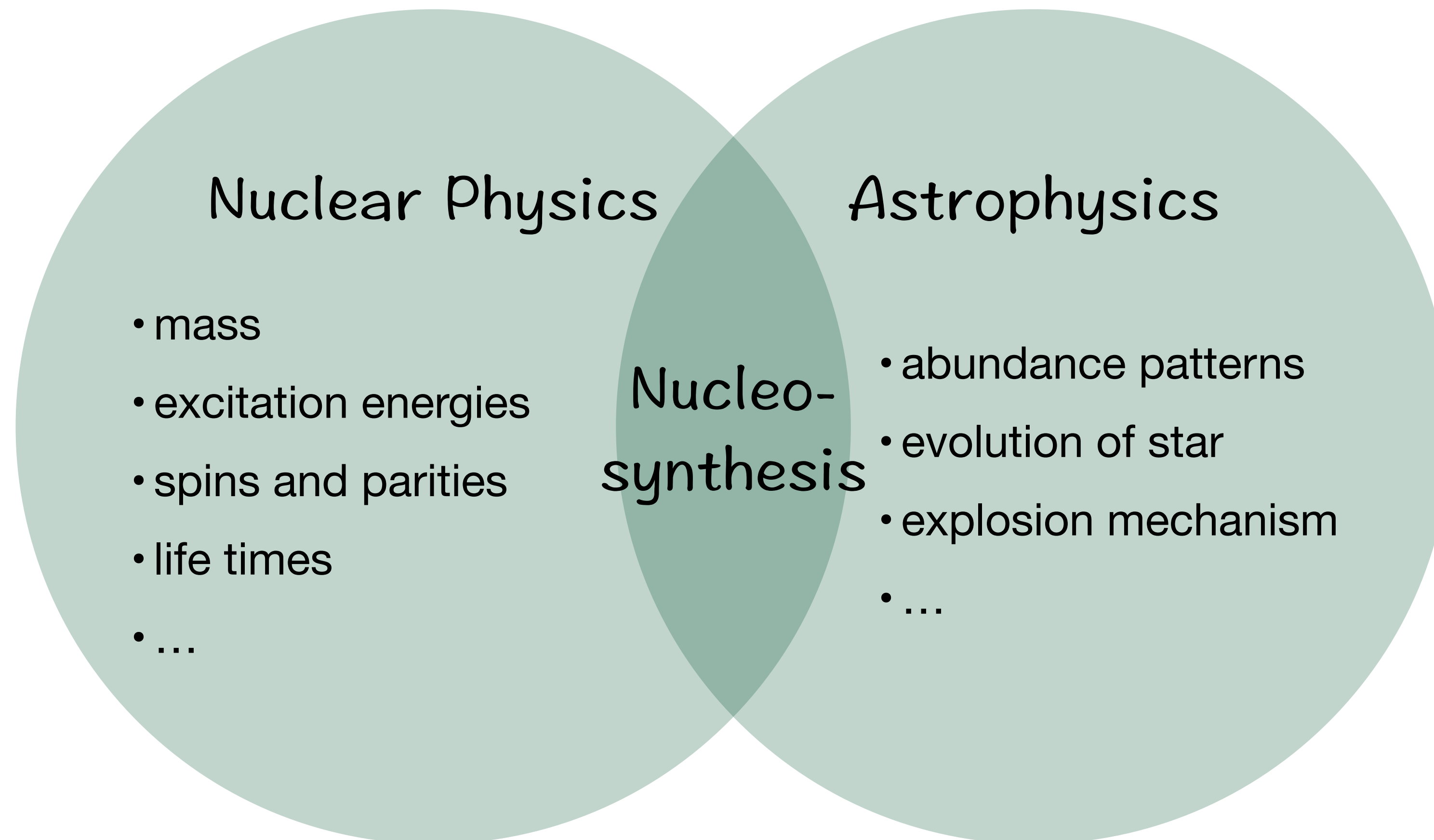
Calculated light curves of X-ray burst within a factor of 100
R. H. Cyburt *et al.*, 2016



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

Nuclear Astrophysics

Tries to find the origin of elements

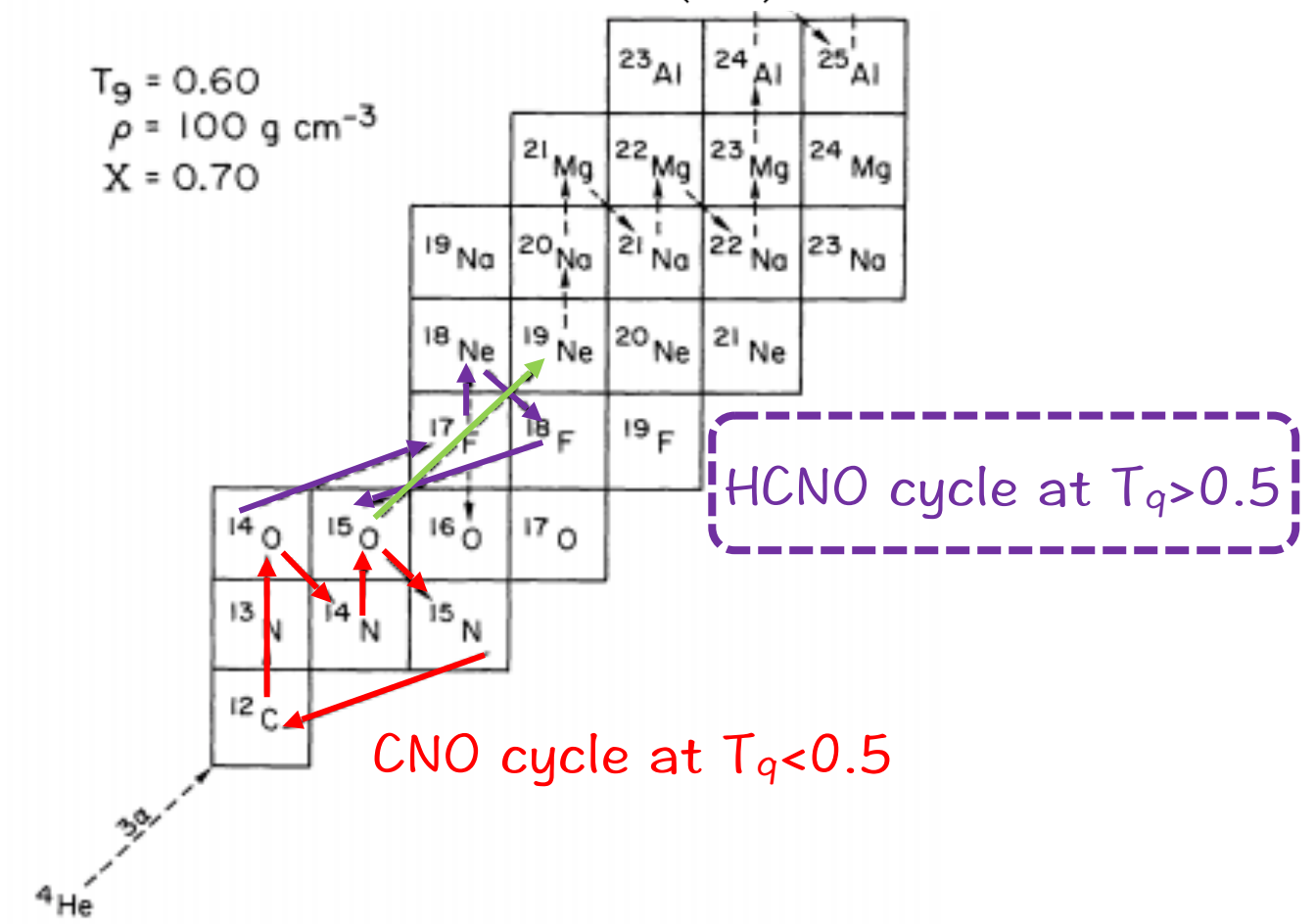
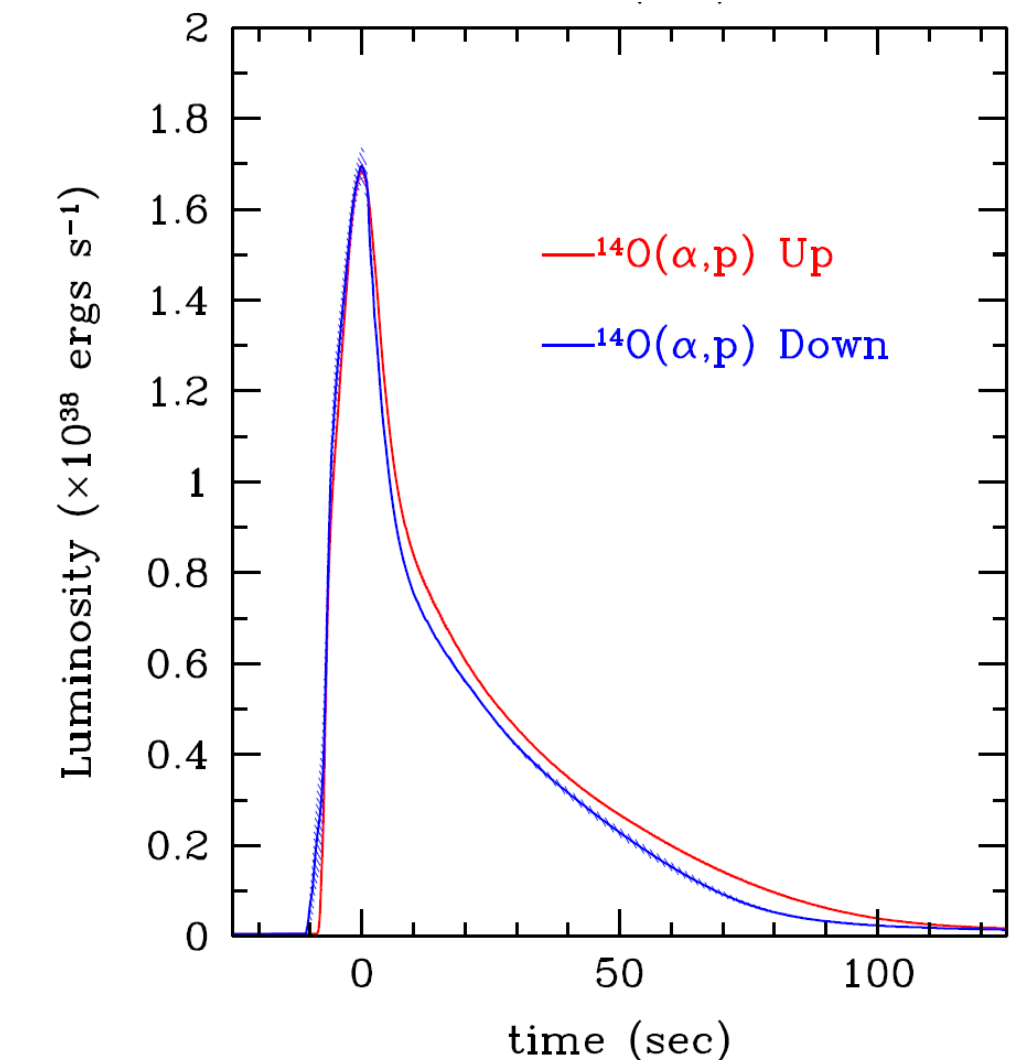
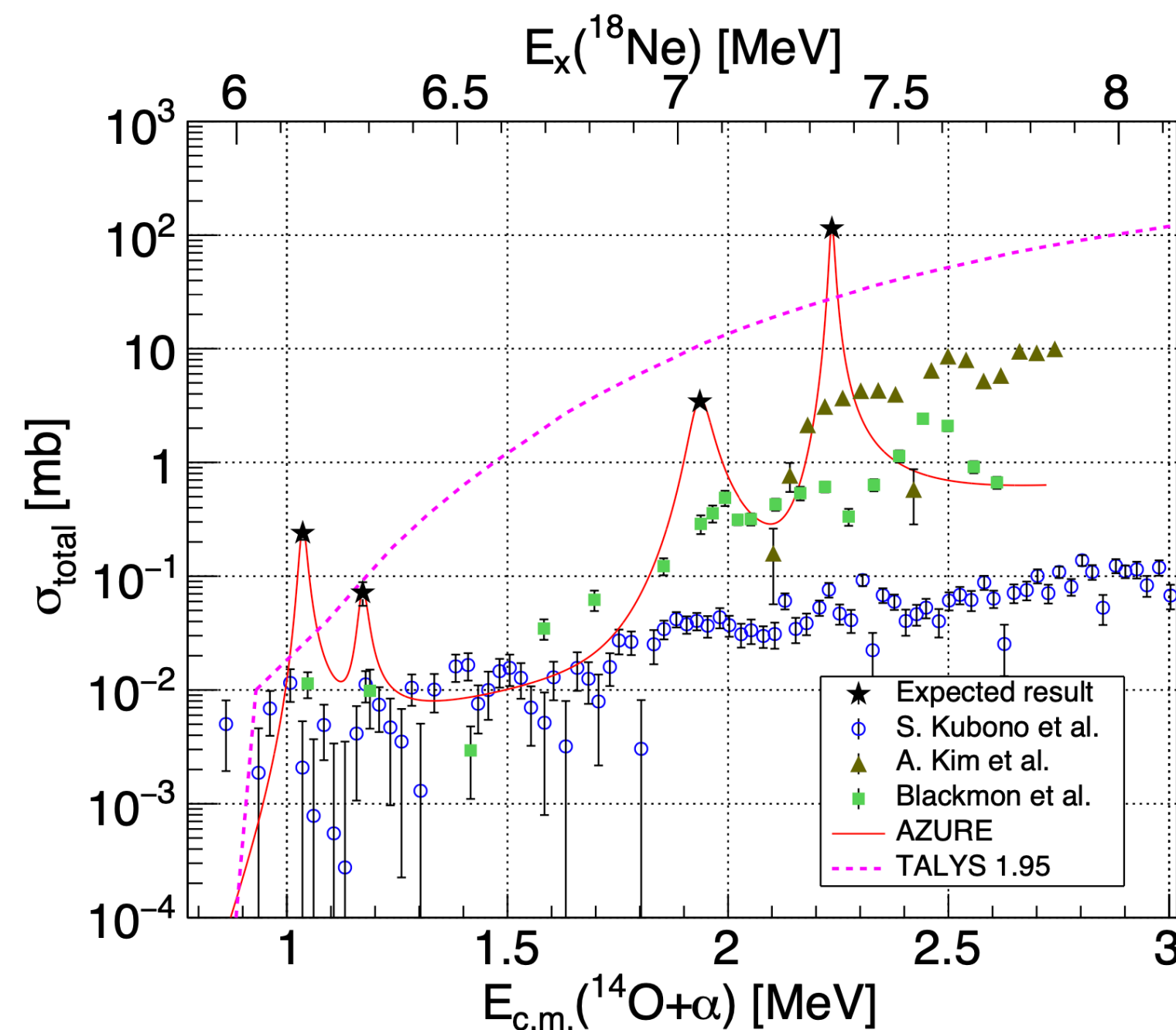


Part 2. The $^{14}\text{O}(\alpha, p)^{17}\text{F}$ Experiment

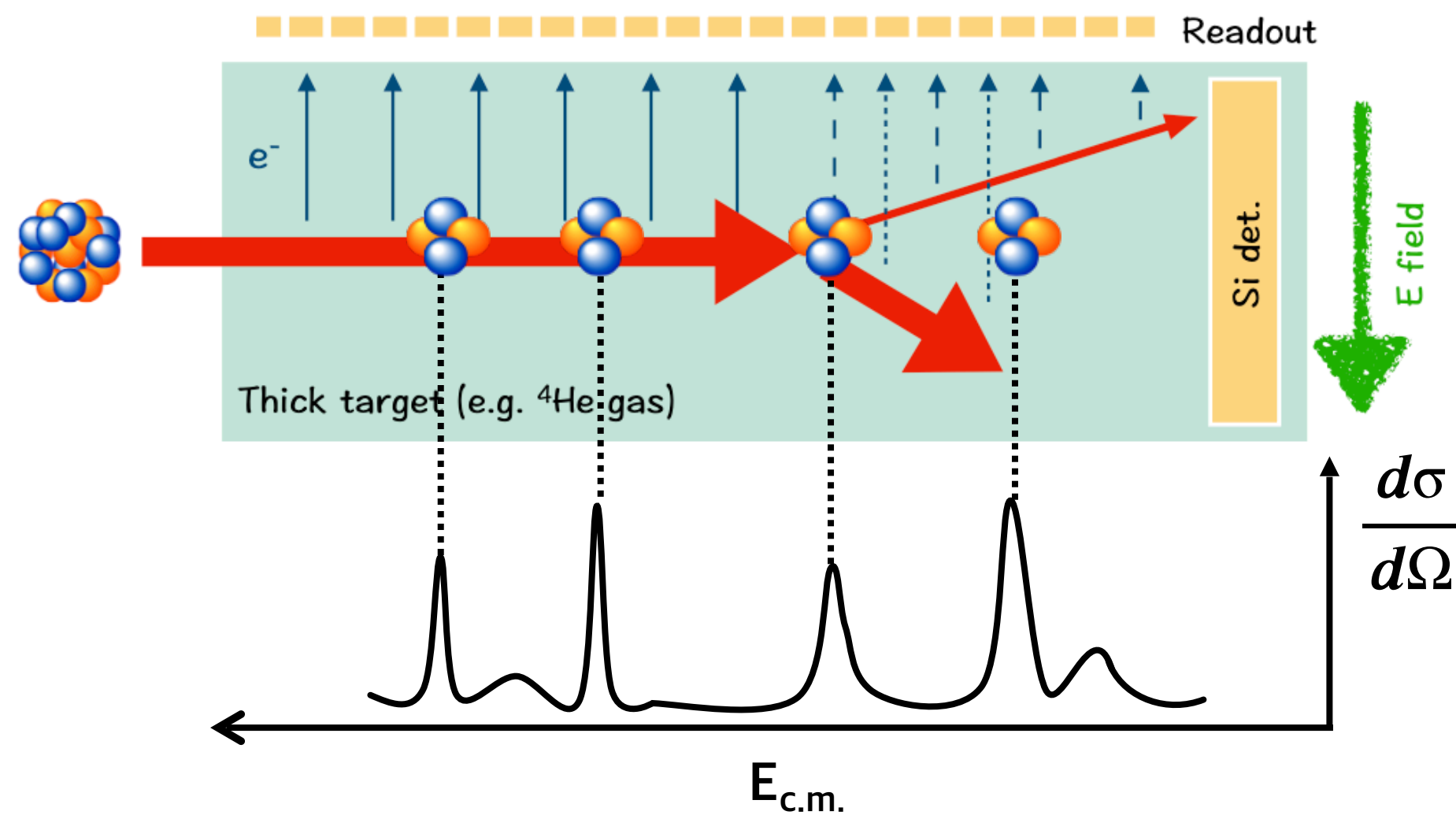
Motivation

- 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).

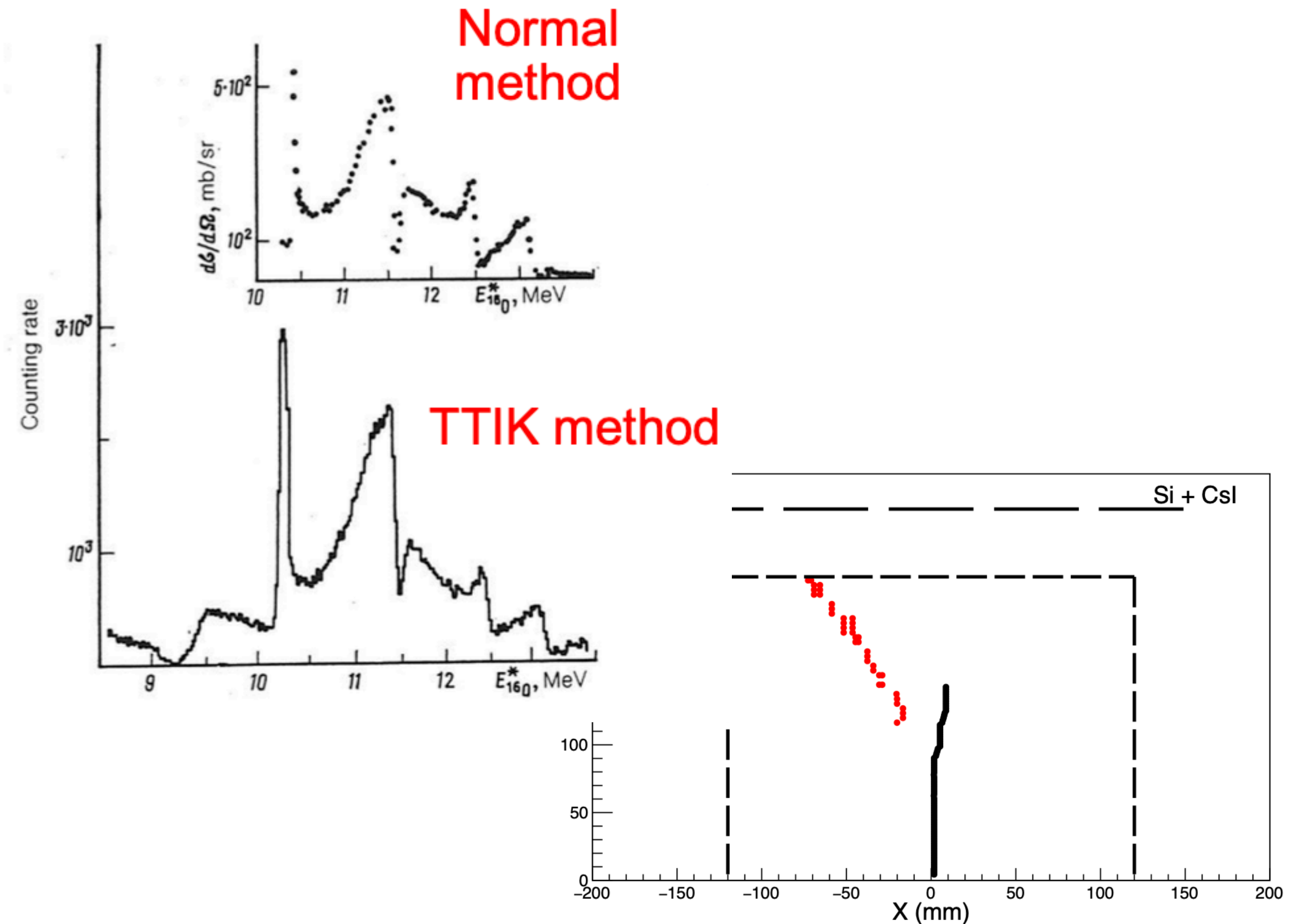
- Large uncertainty
 - Previous cross section measurements at high energy range ($2 \text{ MeV} \leq E_{\text{cm}} \leq 2.8 \text{ MeV}$) show large disagreements.
 - Results at low energy range ($1 \text{ MeV} \leq E_{\text{cm}} \leq 1.5 \text{ MeV}$) with large error bars have to be confirmed from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



Active Target Time Projection Chamber (AT-TPC)

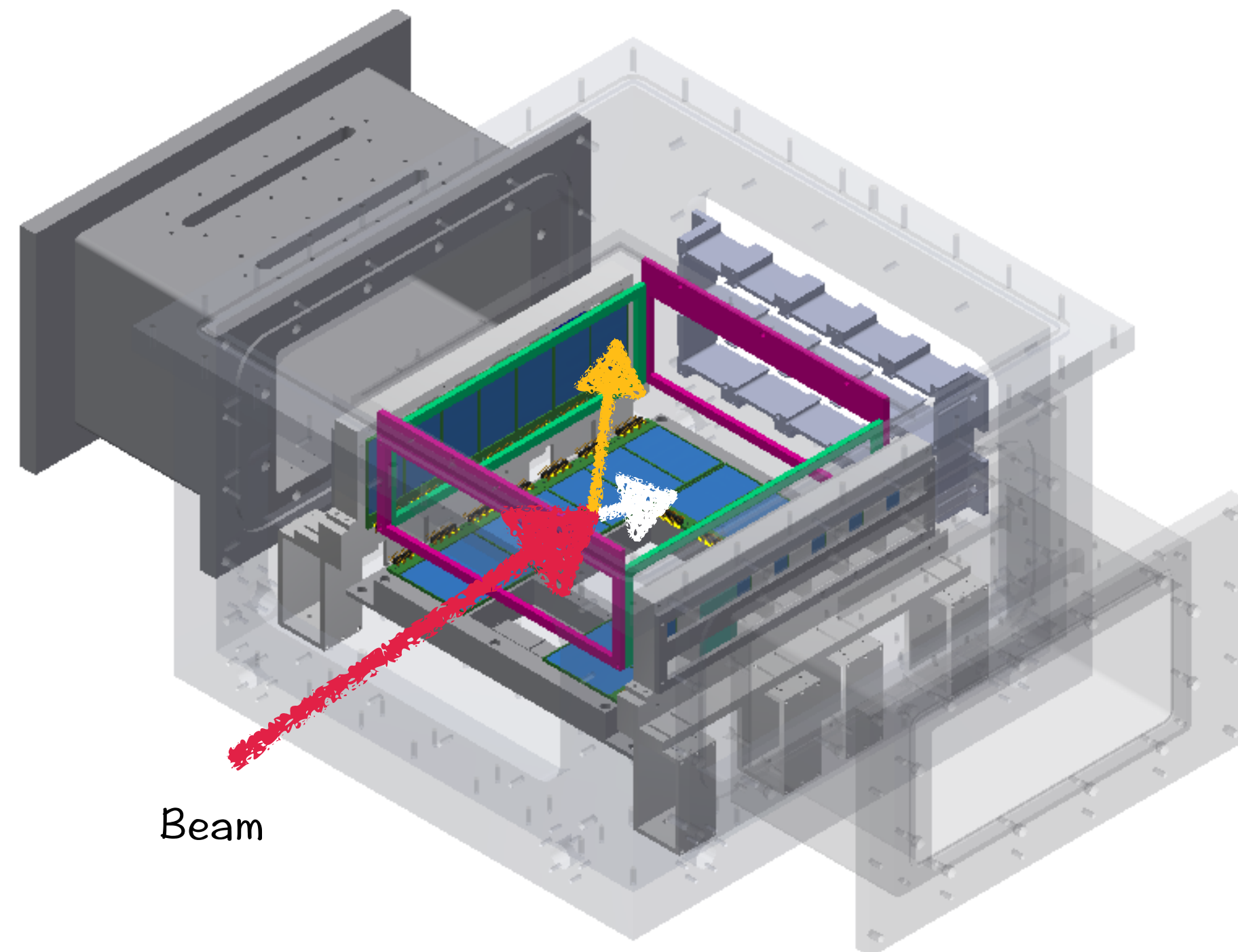


- Thick target inverse kinematics
- Tracking charged particles: vertex point, energy, angle
→ excitation function



J. Hooker et al. (2020).

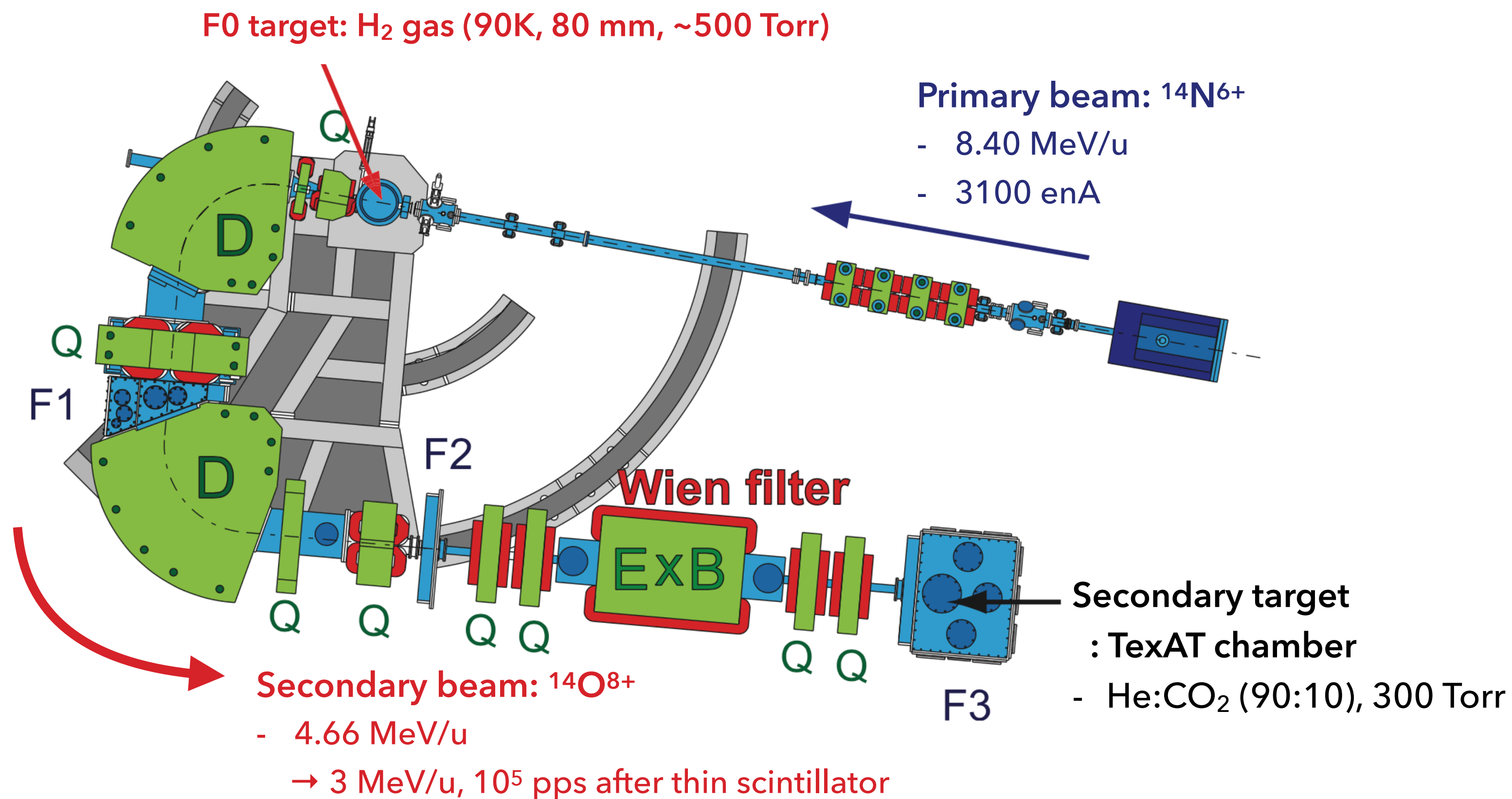
Texas Active Target TPC ver 2 (TexAT_v2)



- 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

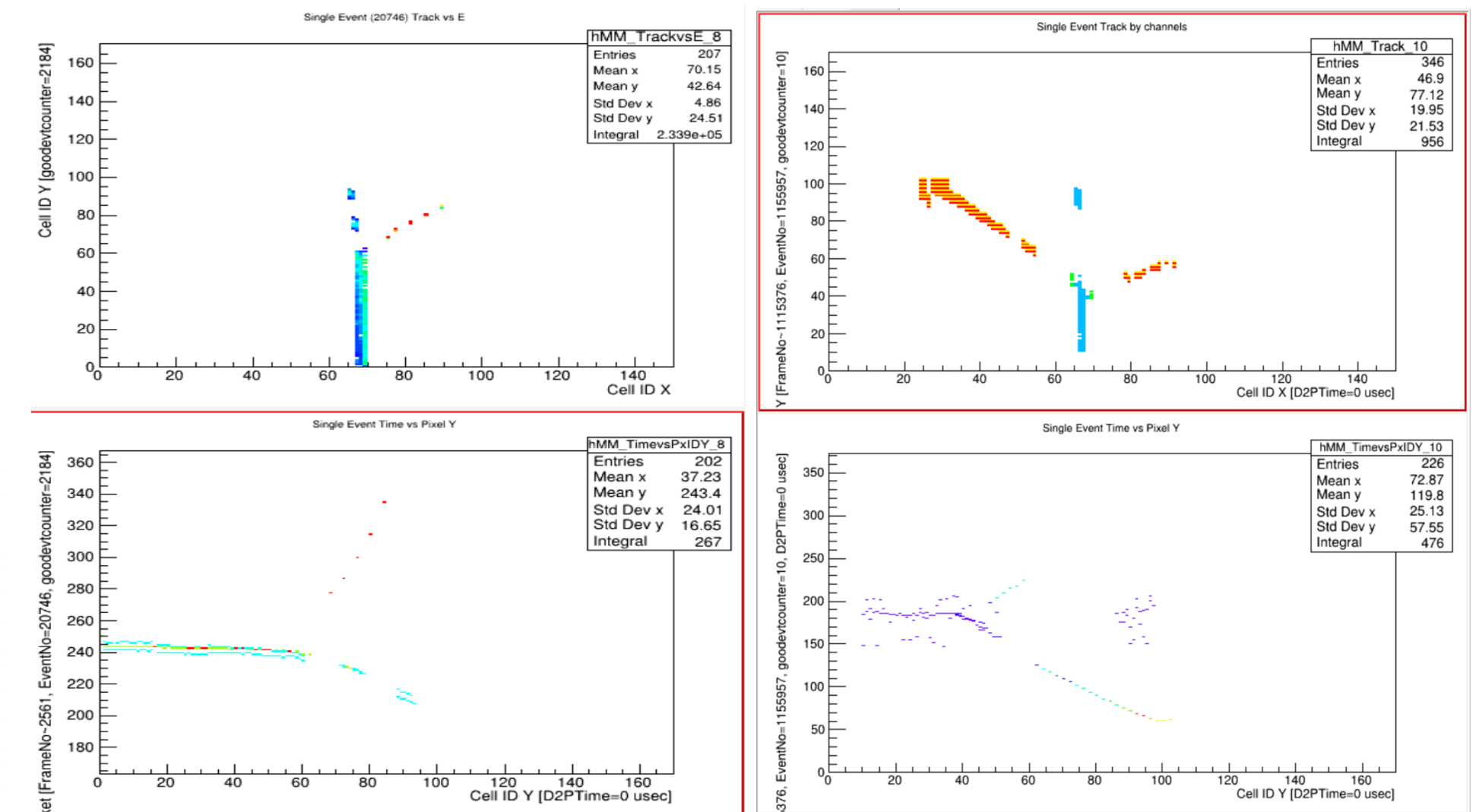
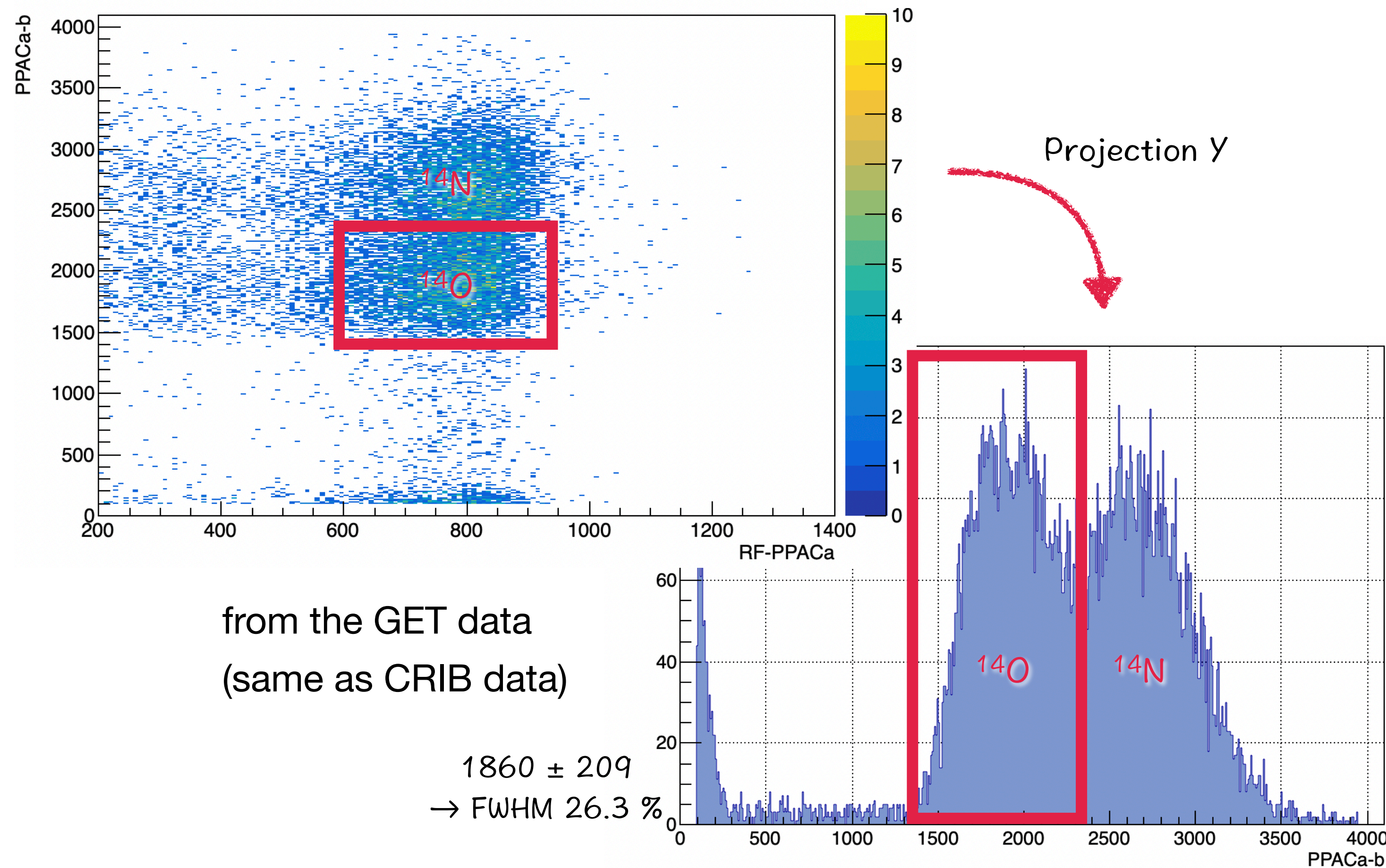


TexAT chamber



Preliminary Results

RF-PPaCa vs PPaCa-b



Analysis on going ...

Outlook

- The experiment measuring the cross section of astrophysical important reaction, $^{14}\text{O}(\alpha, p)^{17}\text{F}$, 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			
CNS	T. W. Chillery, S. Hayakawa, N. Imai, N. Kitamura, K. Okawa, H. Yamaguchi, Q. Zhang			
TAMU	M. Barbui, J. Bishop, E. Koshchiy, C. E. Parker, G. V. Rogachev, M. Roosa			
SKKU	K.Y. Chae, G.M. Gu, M.J. Kim, S.H. Kim, C.H. Kim		Ewha Womans University	C. Kim
Korea University	S. Do, B. Hong, A. Kim		TITech	H. Lee, T. Nakamura
RIKEN Nishina Center	S. Kubono, M. Sasano	ANL	M. L. Avila	Université Libre de Bruxelles M. Sferrazza
University of Notre Dame	D. W. Bardayan	McMaster University	A. Chen	Tohoku University N. Iwasa
INFN	M. La Cognata	Van Lang University	N. N. Duy	TUNL A. Psaltis

Thank you

2023.06.14 - 15 Chaeyeon Park