James Webb Telescope
December 2023

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University of Notre Dame
Nuclear Astrophysics 1

What is Nuclear Astrophysics?

Role of Astrophysics in the Manhattan Project

Element distributions and Nuclear Astrophysics

- Birth of Stars
- Stellar Evolution
- Death of Stars

Open challenges and Experimental Tools

A new James Webb Space Telescope image of stars being formed in the Rho Ophiuchi cloud complex. NASA, ESA, CSA, STScI, Klaus Pontoppidan (STScI)

What is the origin of Nuclear Astrophysics?

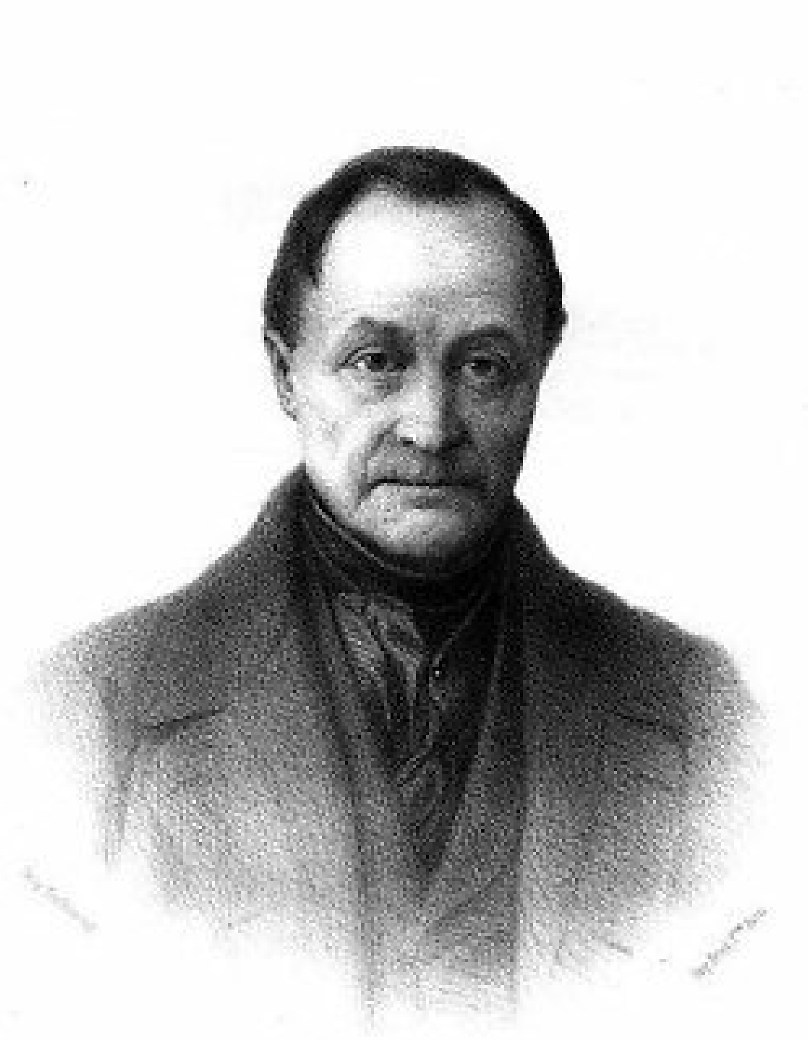
Astronomy
Astrophysics
Nuclear Physics

Astronomy

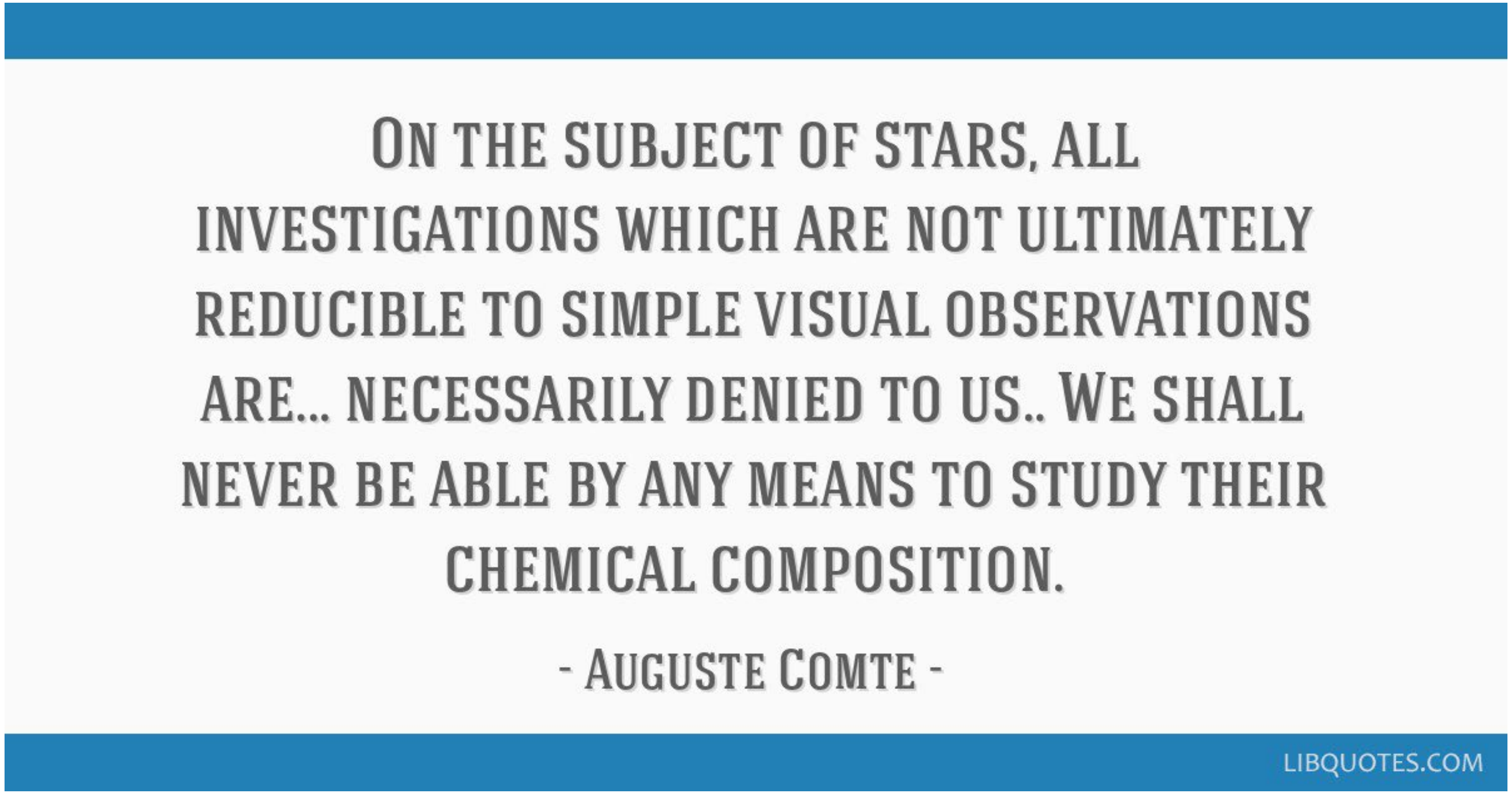
Babylonian stone tablet of Shamash, the Sun-god, dated early 9th century BC. From Sippar, southern Iraq.

The first documented records of systematic astronomical observations date back to the Assyro-Babylonians around 1000 BCE in Mesopotamia.

Oldest Geocentric model of solar system
Armenia , 11-12 th century BCE

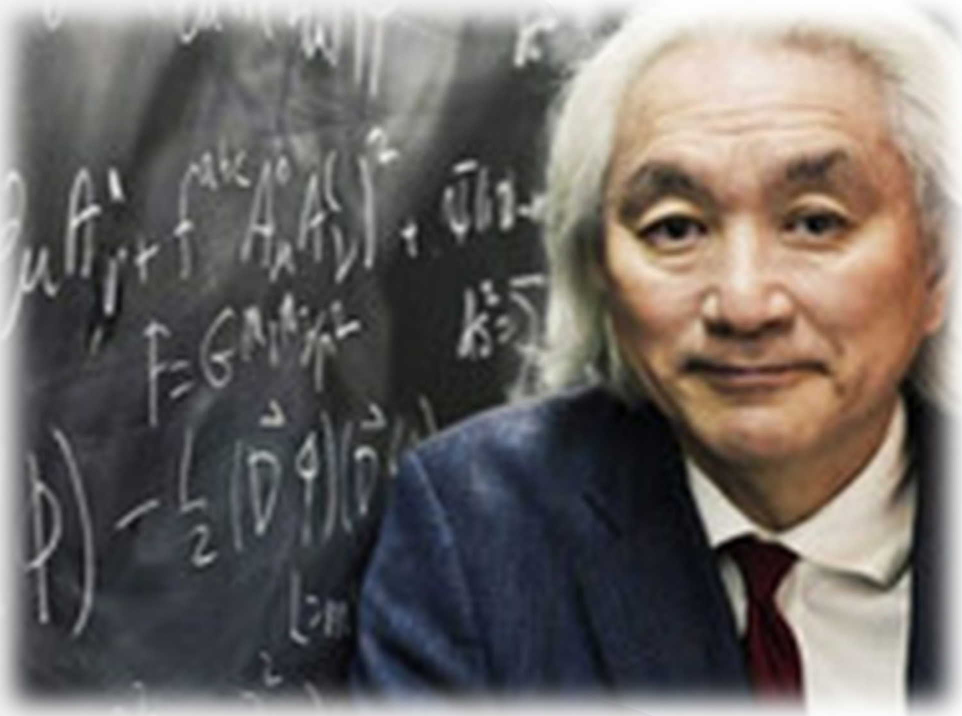


January 19, 1798- September 5, 1857



ON THE SUBJECT OF STARS, ALL INVESTIGATIONS WHICH ARE NOT ULTIMATELY REDUCIBLE TO SIMPLE VISUAL OBSERVATIONS ARE... NECESSARILY DENIED TO US.. WE SHALL NEVER BE ABLE BY ANY MEANS TO STUDY THEIR CHEMICAL COMPOSITION.

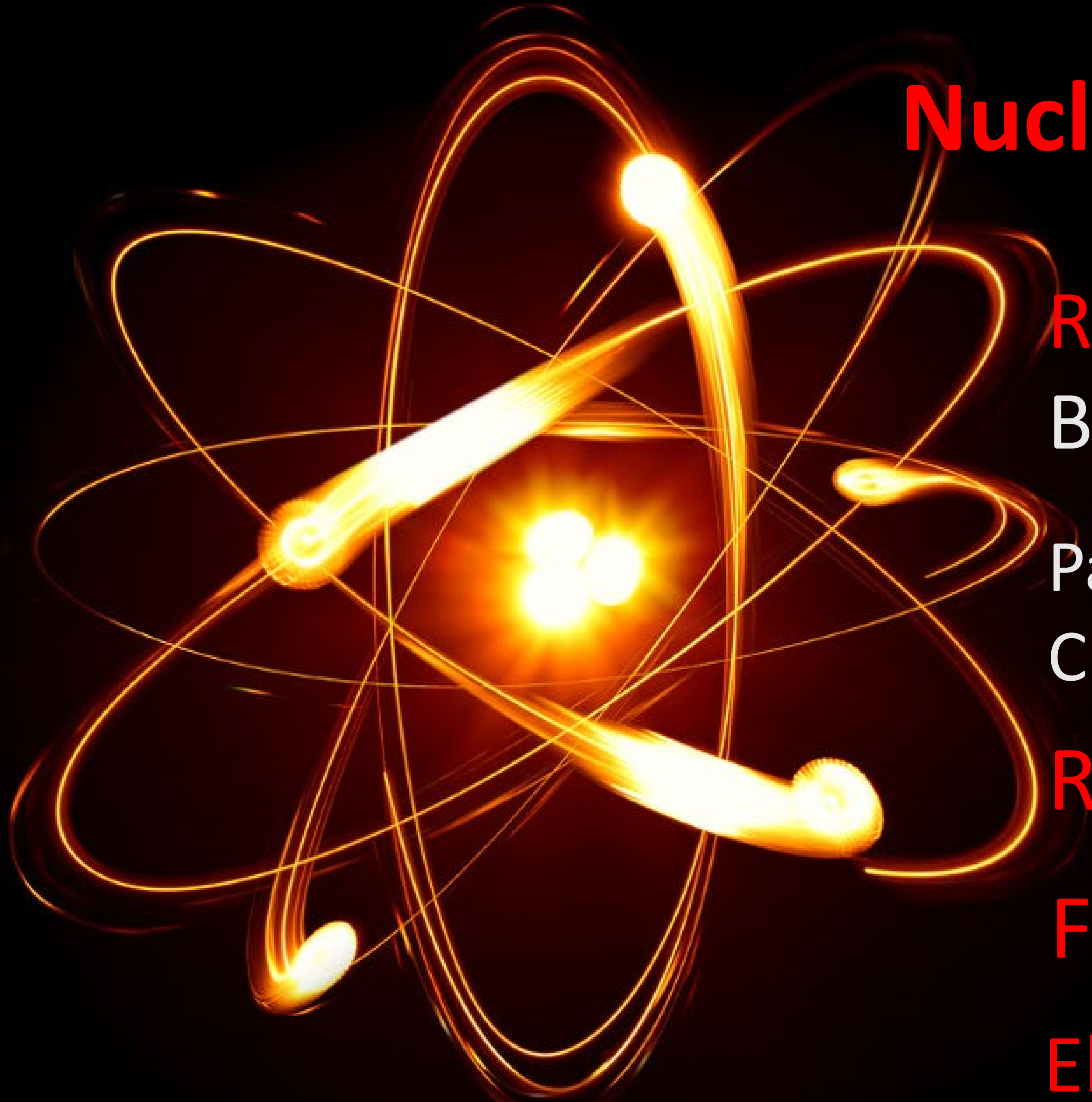
- AUGUSTE COMTE -



> “A hundred years ago, Auguste Comte, … a great philosopher, said that humans will never be able to visit the stars, that we will never know what stars are made out of, that that's the one thing that science will never ever understand, because they're so far away. And then, just a few years later, scientists took starlight, ran it through a prism, looked at the rainbow coming from the starlight, and said: "Hydrogen!" Just a few years after this very rational, very reasonable, very scientific prediction was made, that we'll never know what stars are made of.”

- Michio Kaku

Thousands upon thousands of stars illuminate this breathtaking image of star cluster Liller 1, imaged with Hubble’s Wide Field Camera 3. This stellar system, located 30,000 light-years from Earth, formed stars over 11 billion years….



Nuclear Physics Discoveries

Radioactivity:

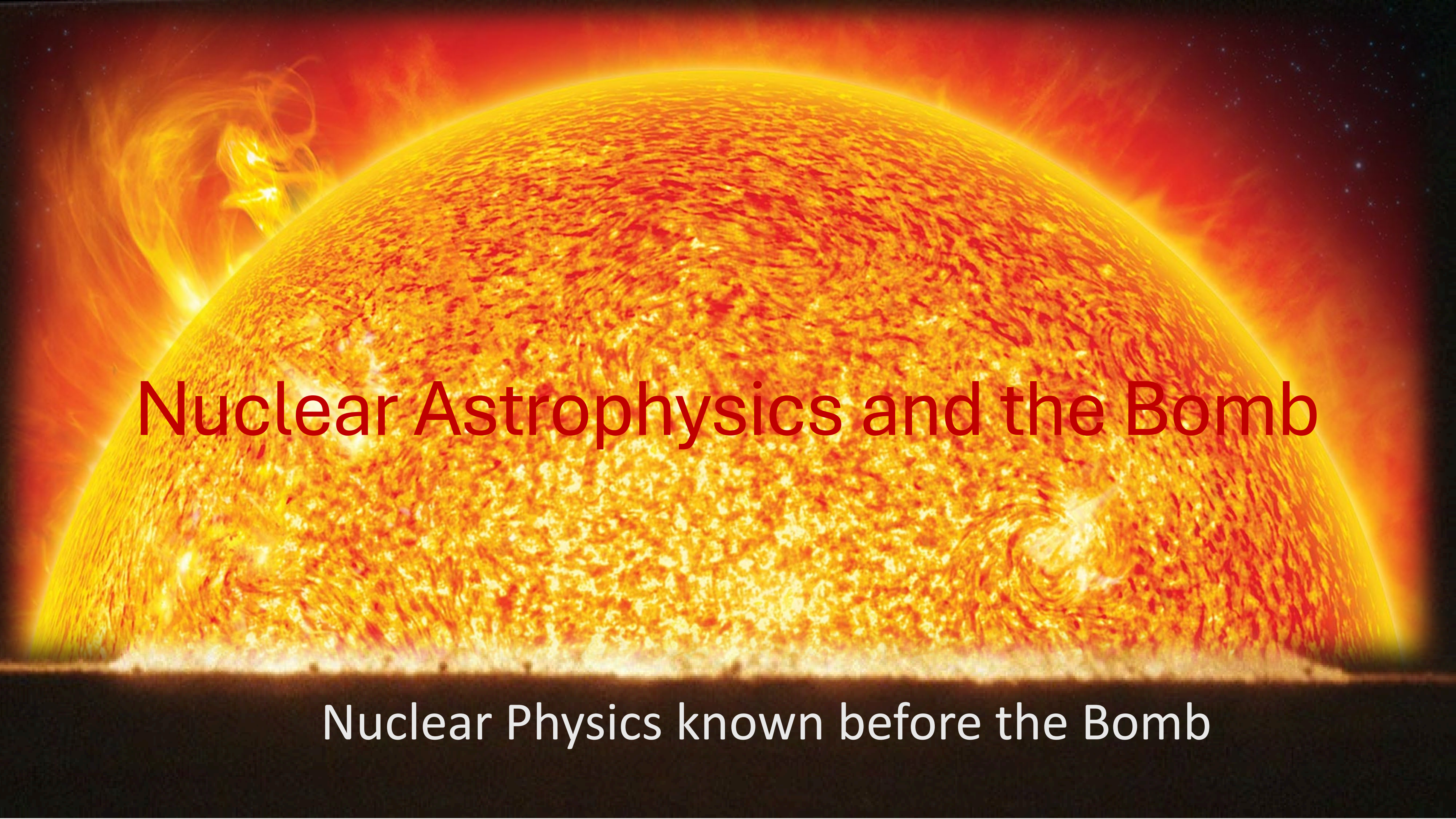
Bequerel, Rutherford, Thomson

Pauli, Fermi, Gamow. Landau,
Chandrasekar, Bethe

Reaction Rates:

Fission:

Elemental Abundances:



Nuclear Astrophysics and the Bomb

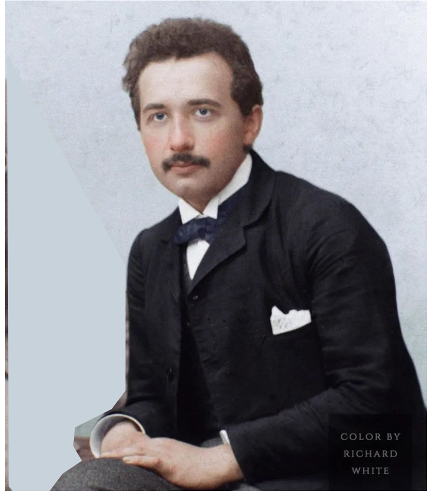
Nuclear Physics known before the Bomb

The Scientific Basis – Two Formulas

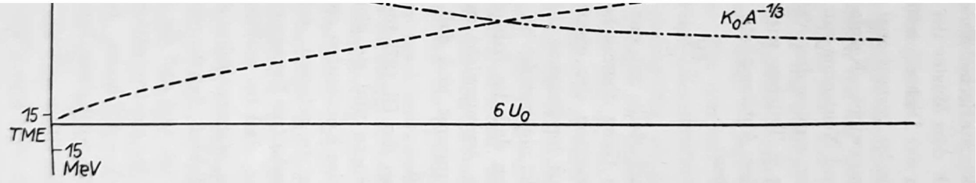
for the energy generation in bomb and stars

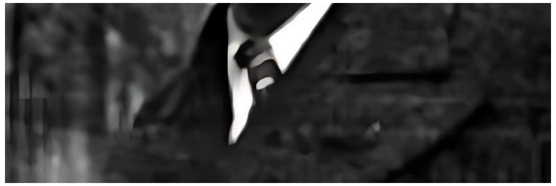
$$E = m \cdot c^2$$

Albert Einstein 1904



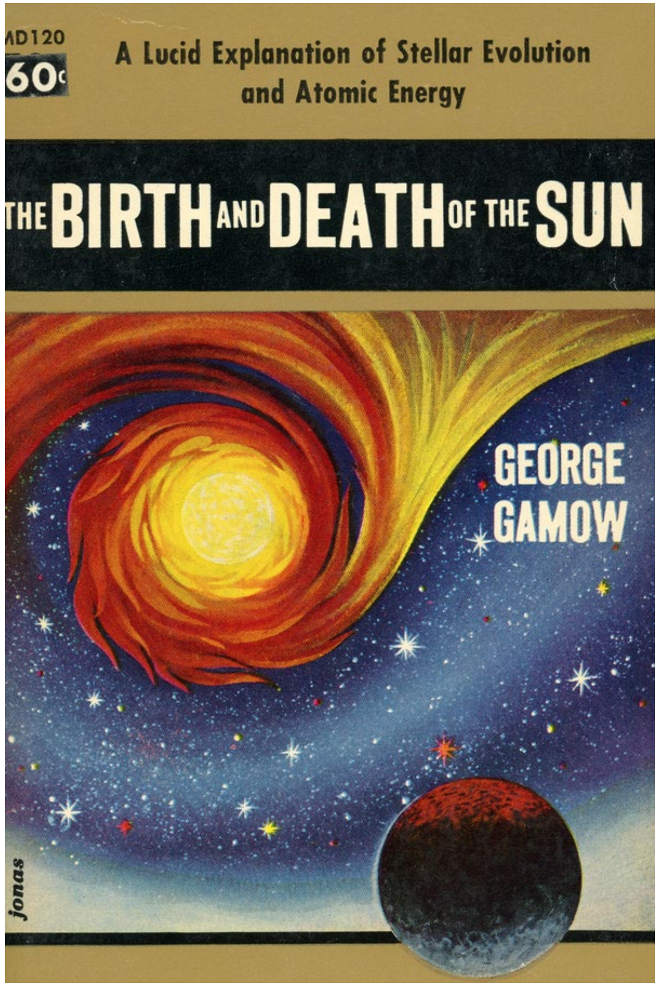
$$E_b^{even-odd} \approx \underbrace{(15.75 MeV) A}_{\text{Volume term}} - \underbrace{(17.8 MeV) A^{2/3}}_{\text{Surface term}} - \underbrace{\frac{(0.711 MeV) Z^2}{A^{1/3}}}_{\text{Coulomb term}} - \underbrace{\frac{(23.7 MeV)(A-2Z)^2}{A}}_{\text{Pauli term}}$$





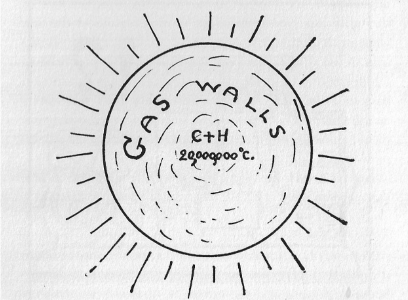
von Weizsäcker
1934
Mass Formula

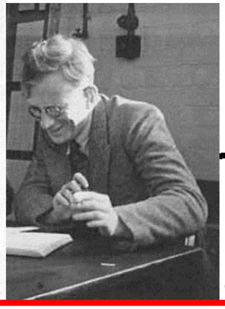
The energy source of the Sun and other stars

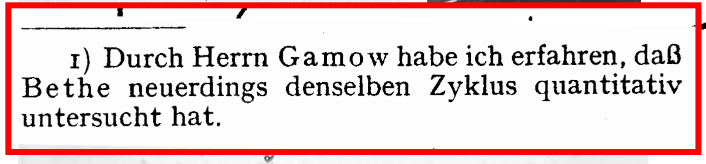


Stars are driven by the release of nuclear energy

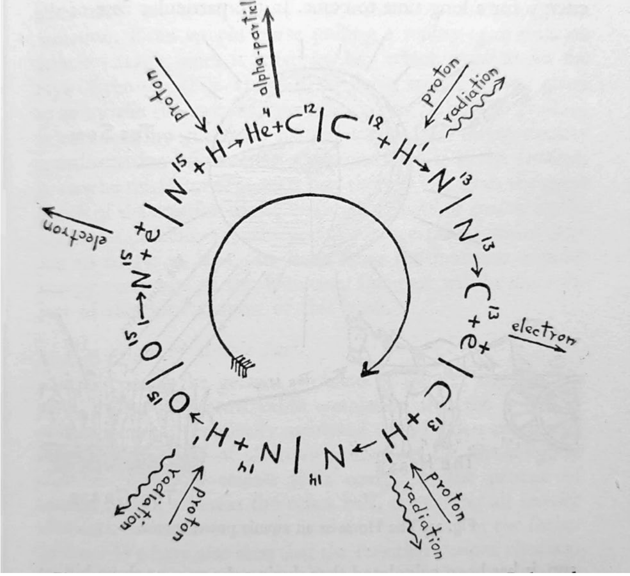
G. Gamow and E. Teller, “The Rate of Selective Thermonuclear Reactions,” *Phys. Rev.* 53 (1938): 608-609.







1) Durch Herrn Gamow habe ich erfahren, daß Bethe neuerdings denselben Zyklus quantitativ untersucht hat.

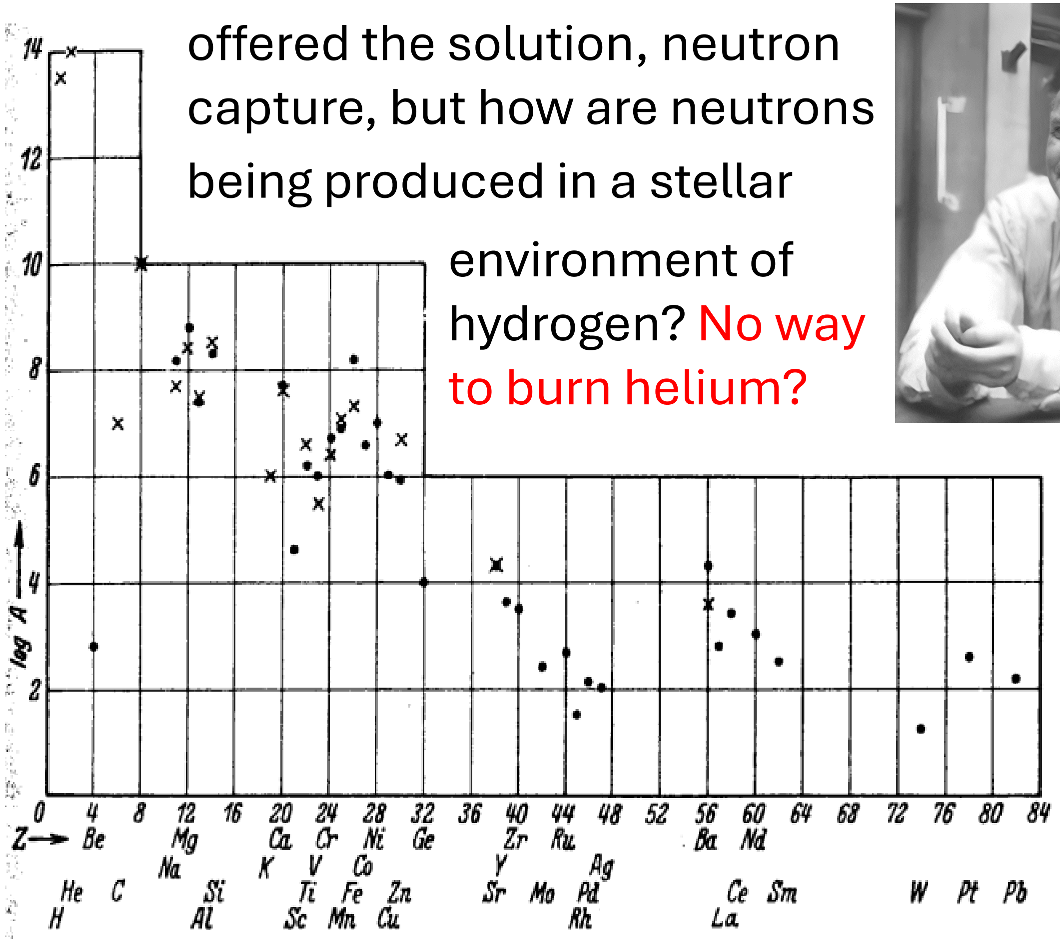


Two seminal papers in 1938 discussed the energy generation in the sun and the origin of the elements in our universe!

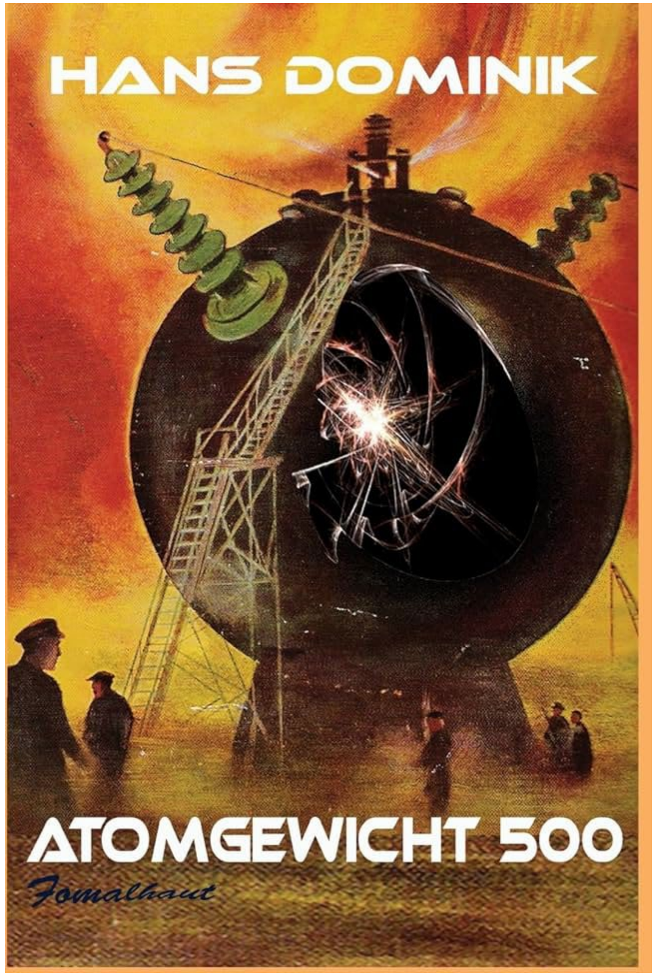
Neutrons for superheavy element production

Observation of heavy elements in 1920-1930
How are heavy elements been produced???

The discovery of the neutron in 1932 by James Chadwick offered the solution, neutron capture, but how are neutrons being produced in a stellar environment of hydrogen? No way to burn helium?



Continuous neutron capture would lead to the formation of ever heavier elements, a source of energy through radioactive decay!



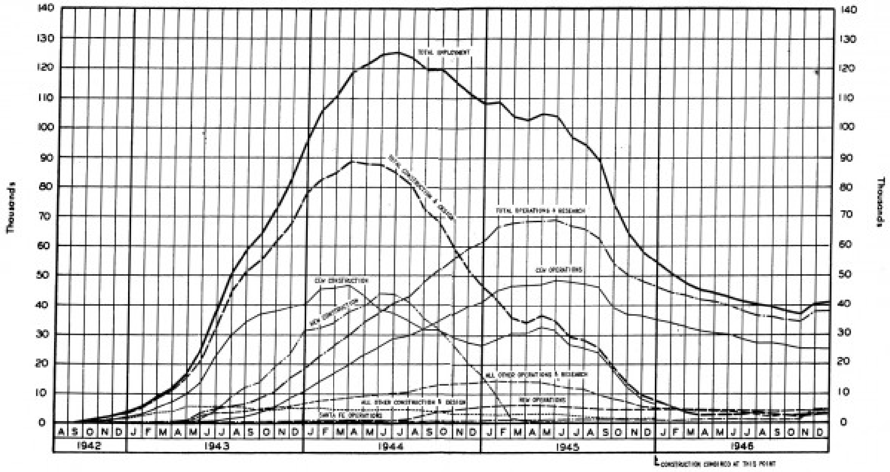
Leaders of the Manhattan Project: USA

J. Robert Oppenheimer: theoretical physicist in Berkeley and Caltech, focusing on the study of quantum physics and the structure of neutron stars and black holes!

Hans A. Bethe: Trained in Germany by Sommerfeld, he quickly emerged as a rising star in nuclear physics at Cornell, interest in light ion fusion processes stars!

Enrico Fermi: an Italian physicist, wo used the opportunity of his Nobel prize in 1936 to leave Fascist Italy for the United States. He was essential for the understanding of neutrons and their role in fission.

Edward Teller: Hungarian firebrand, worked with Heisenberg in Germany before emigrating to the United States in 1933. At George Washington University he became an expert in light ion fusion reactions and a vehement spokesperson for the h



Plus more than 125,000 scientists, technicians, administrators, military people involved in the project!

What was known…

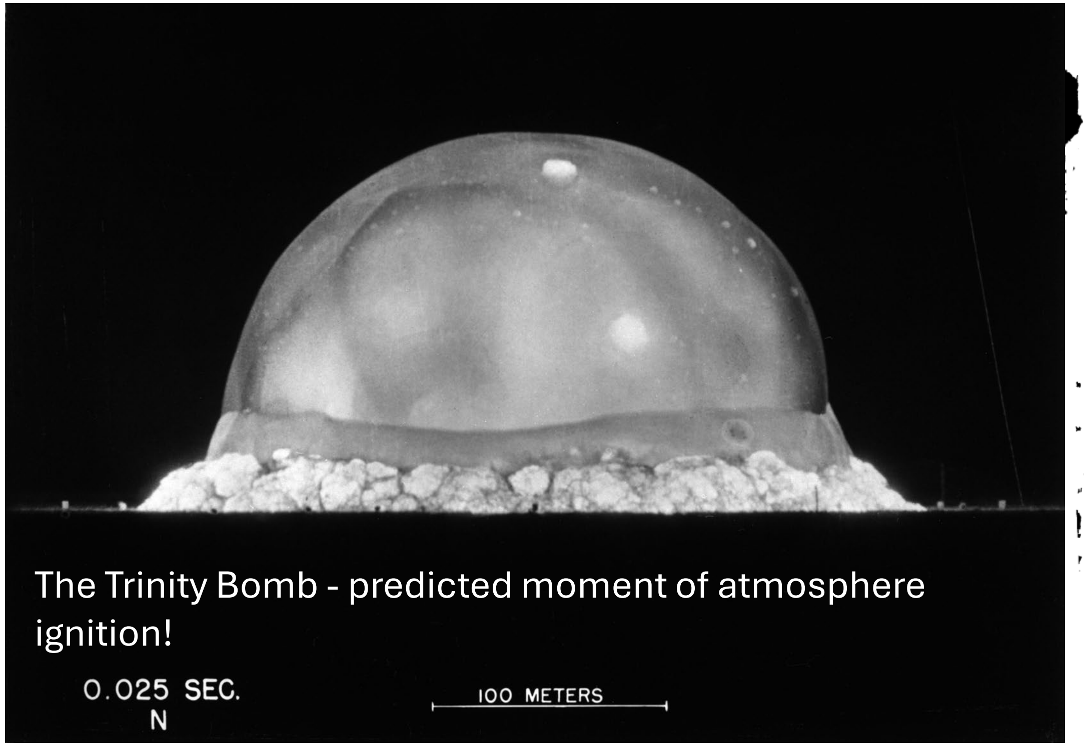
Fission
Energy in matter
Nuclear Reaction cross sections
Relative distributions of some elements

Unknown….

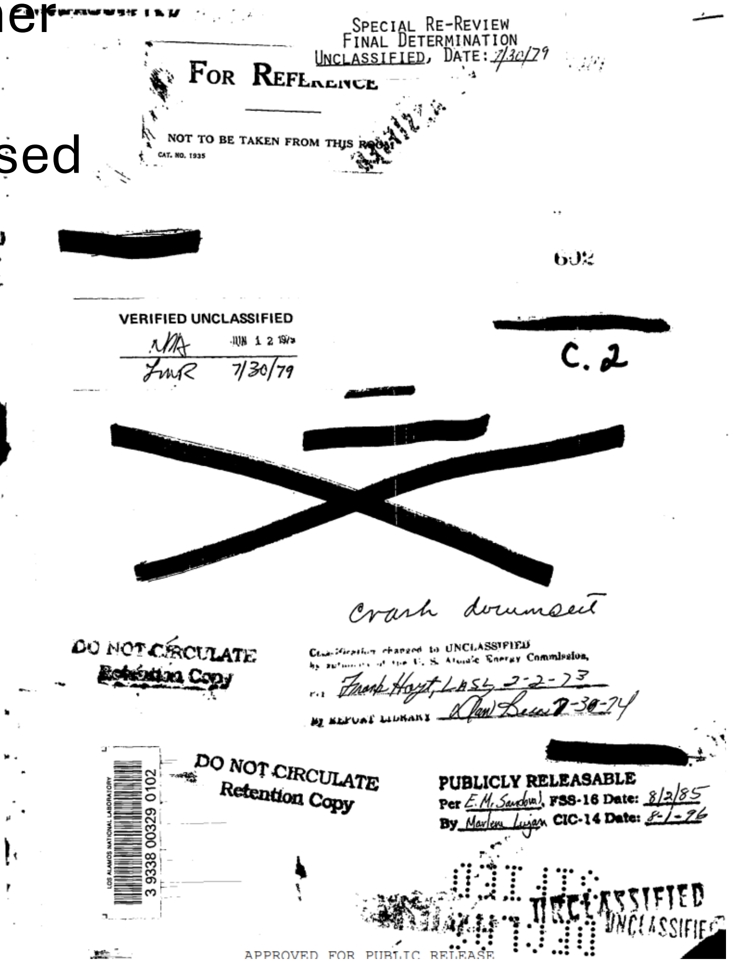
Fusion of Nitrogen and Hydrogen, and Oxygen

$^{14}N+^{14}N$, $^{14}N+^{1}H$. $^{16}O+^{16}O$ in the hotspot of the explosion

Bethe dismissed the idea, but Oppenheimer traveled by train to Chicago to discuss the radiation cooling, compensating the released heat from the bomb with Arthur Compton. Classified report by Edward Teller in 1946!



The Trinity Bomb - predicted moment of atmosphere ignition!



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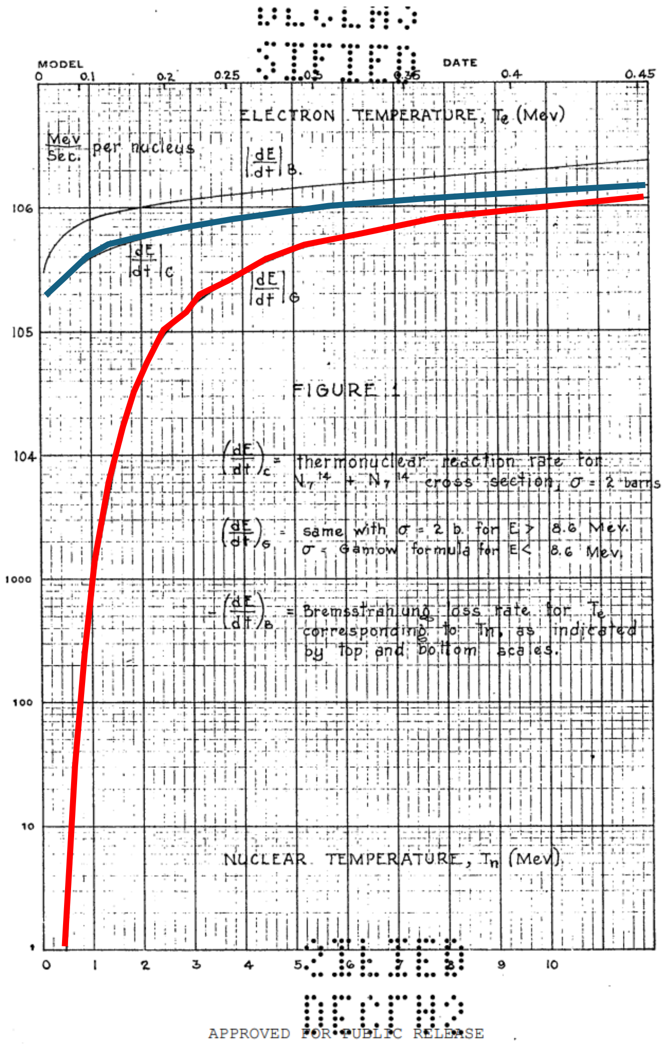

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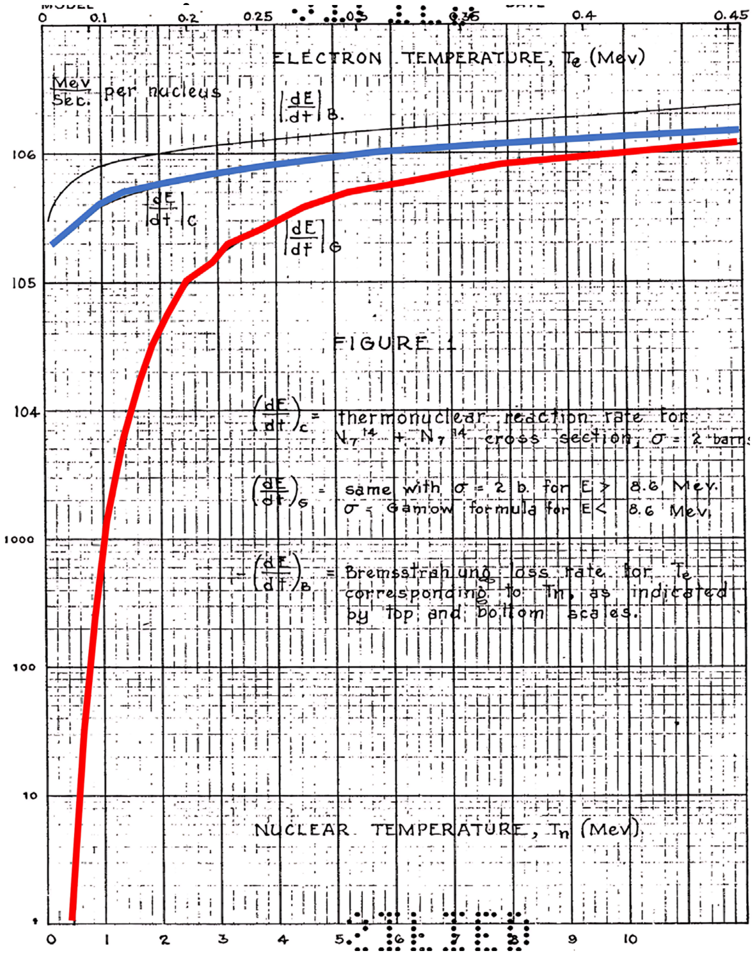
The Fear of Bigger Bombs – the Super

The Ulam-Teller design was based on the original Teller idea, that the heat would be generated by a fission bomb to create the conditions for fusion. Instead of nitrogen, deuterium and tritium would be the fuel, the latter produced at Hanford via the ^{6}Li(n,t)^{4}He



The Ulam-Teller design boosted the yield from the 20 kton to the 20 Mton range, raising again concerns about atmosphere ignition, will radiation cooling be sufficient???

The disquieting feature is that the ‘safety factor’, i.e. the ratio of losses to gains of energy, decreases rapidly with initial temperature, and descends to a value of only about 1.6 beyond a 10-MeV temperature. It is impossible to reach such temperature unless fission bombs or thermonuclear bombs are used which greatly exceed the bombs now under consideration.

https://youtu.be/uYPbbksJxIg?si=dPXzwgf9JTVTeRrP

“Manhattan Project Astrophysics”

By Michael Wiescher and Karlheinz Langanke

Physics Today March 2024

Nuclear Astrophysics
is
the Engine of the Universe

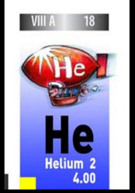
Nuclear Astrophysics Today

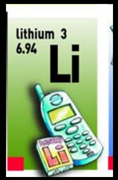
. complex

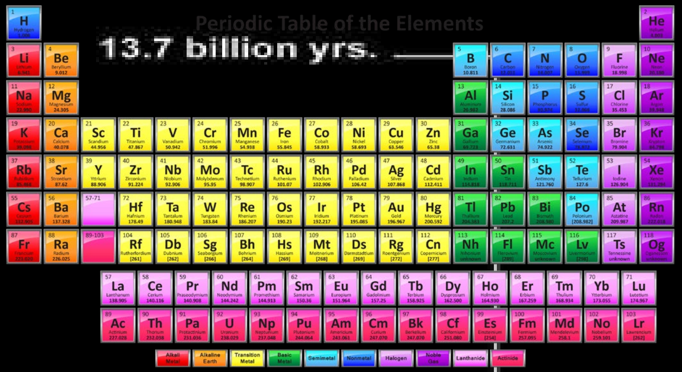
. multi-disciplinary

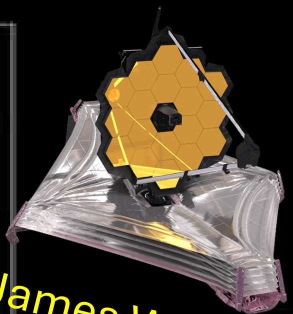
  Thermodynamics
  Atomic
  Nuclear
  HE
  Solid State
  Astronomy
  Astrophysics

. multi-messenger









13.7 billion yrs.

3 billion yrs.

1 billion yrs.

300 million yrs.

300,000 yrs.

100 sec.

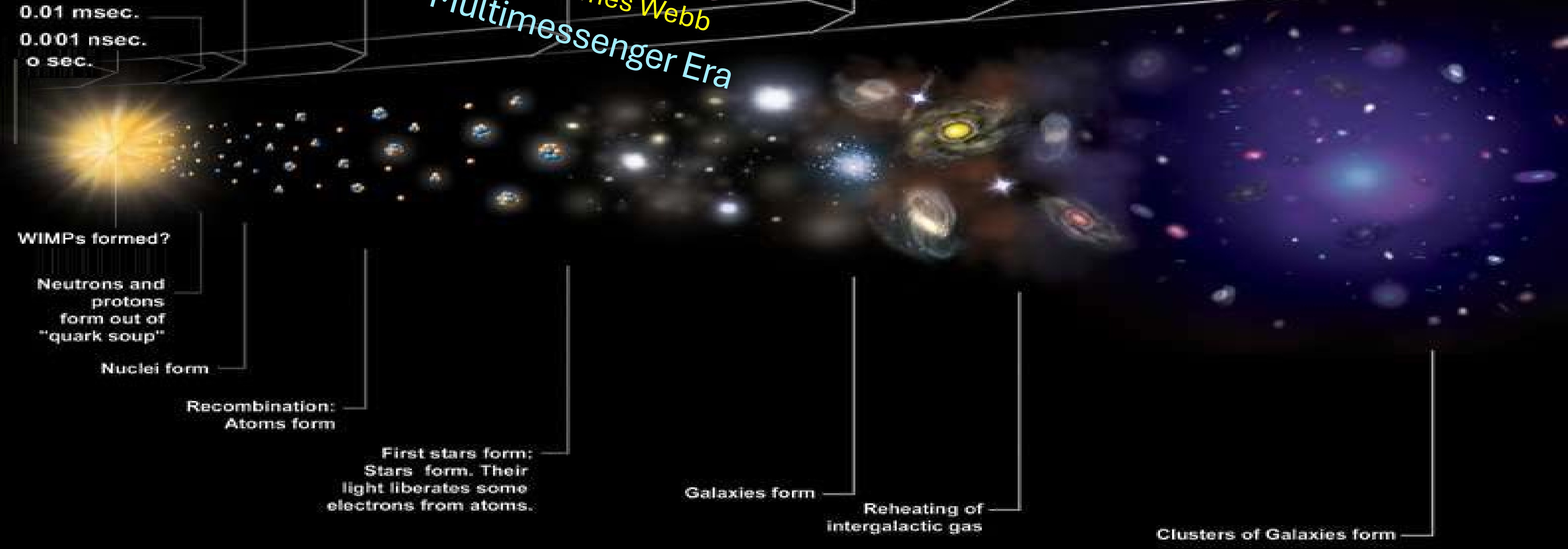
0.01 msec.

0.001 nsec.

0 sec.

James Webb

Multimessenger Era



WIMPs formed?

Neutrons and protons form out of "quark soup"

Nuclei form

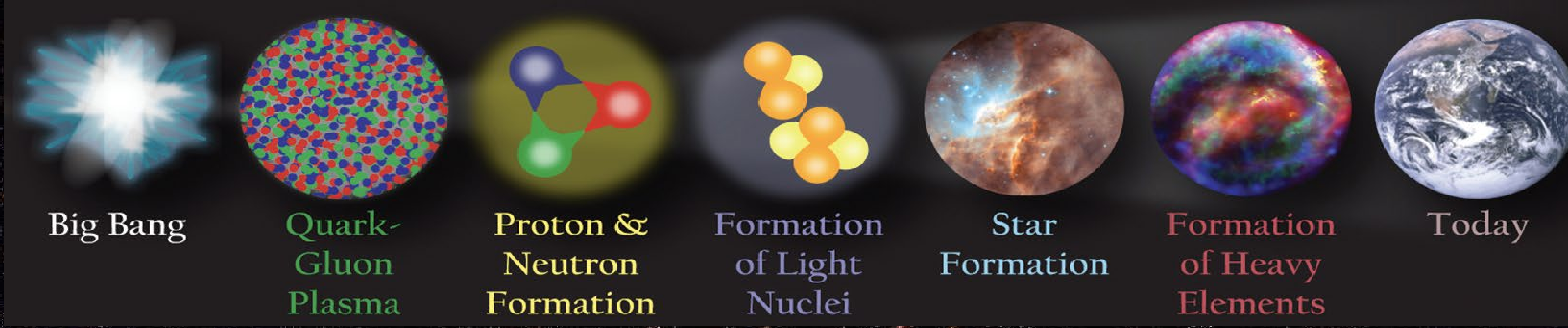
Recombination: Atoms form

First stars form: Stars form. Their light liberates some electrons from atoms.

Galaxies form

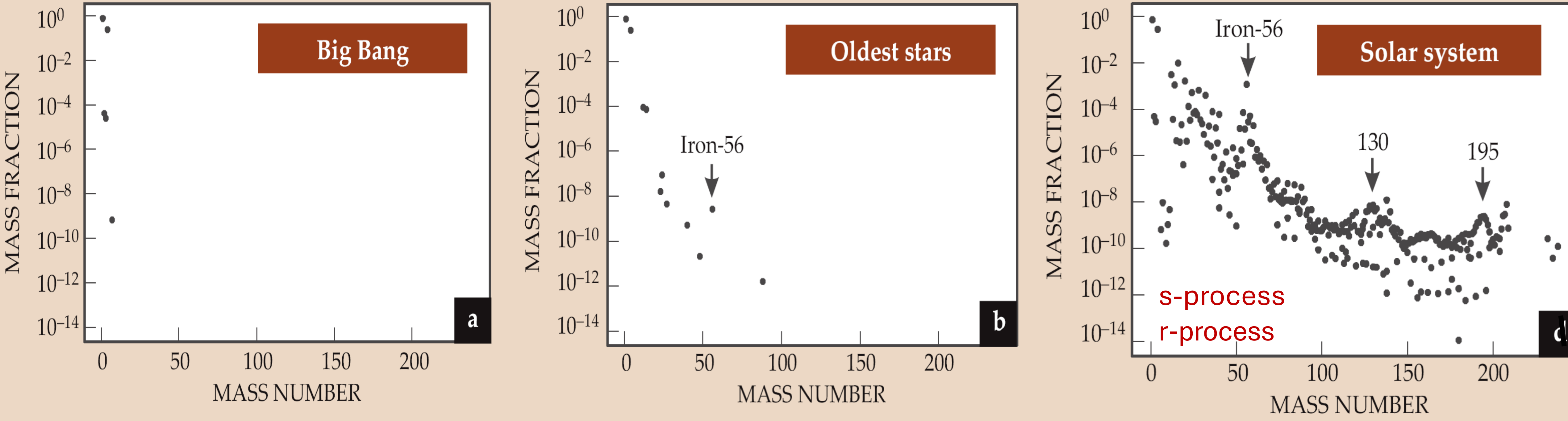
Reheating of intergalactic gas

Clusters of Galaxies form

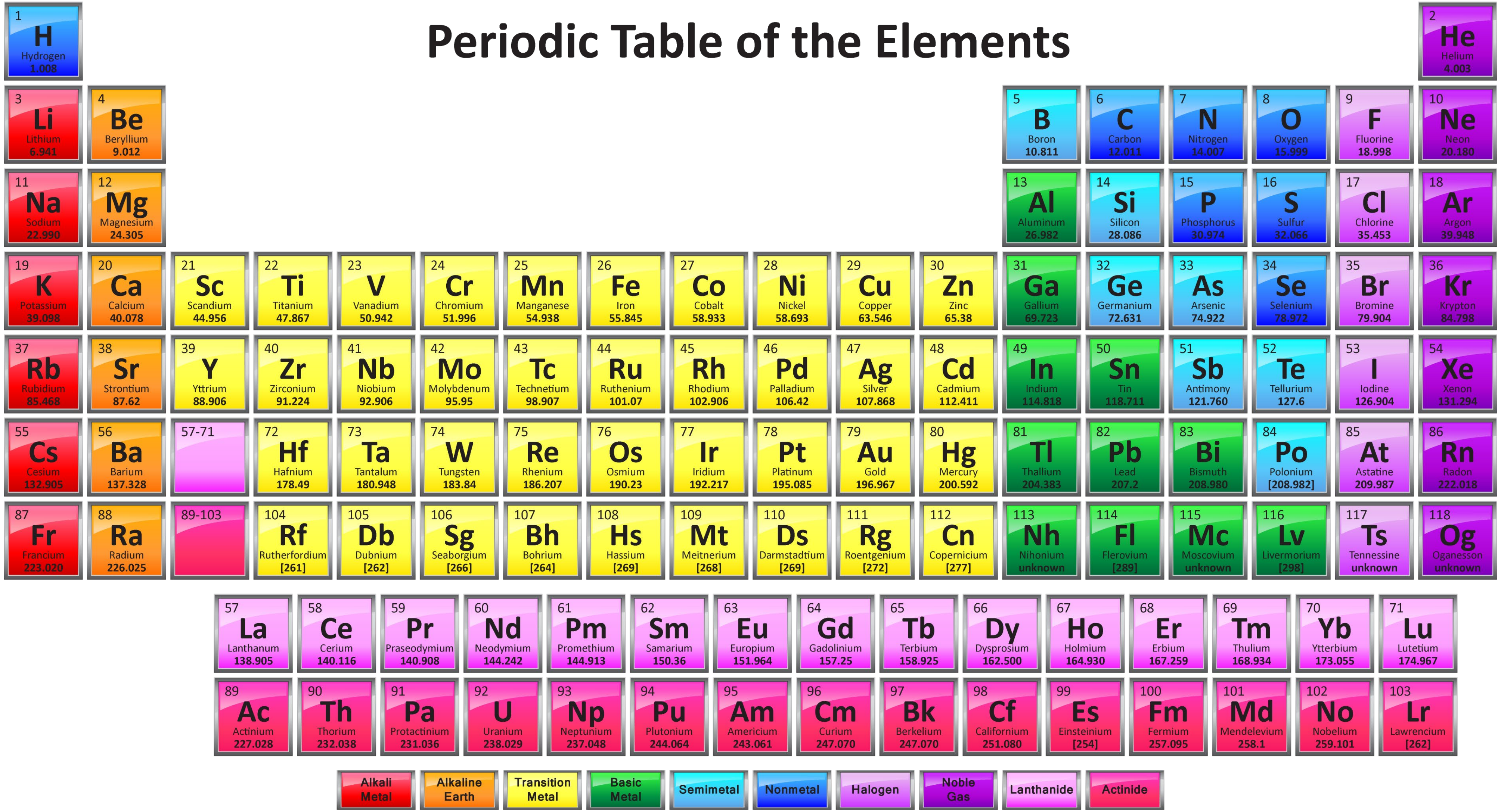


- How were elements Fe to U made?

Wiescher
Schatz



Periodic Table of the Elements



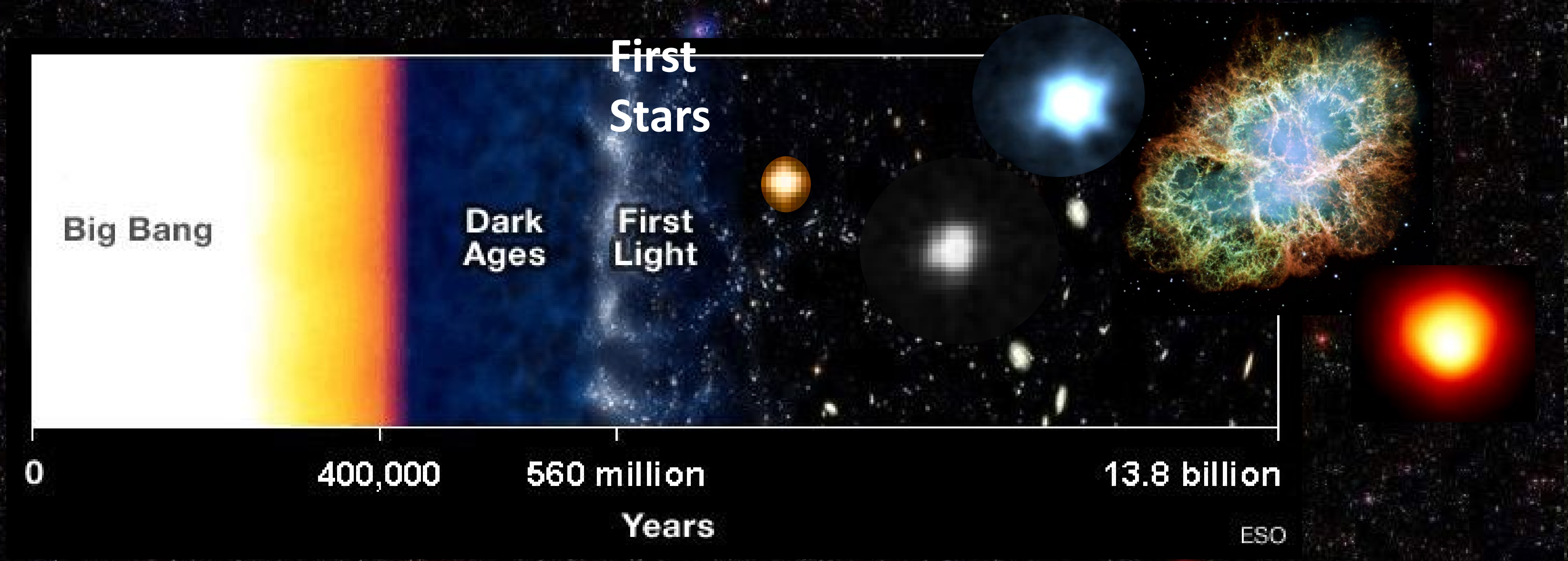
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Mc Moscovium unknown	116 Lv Livermorium [298]	117 Ts Tennessine unknown	118 Og Oganesson unknown

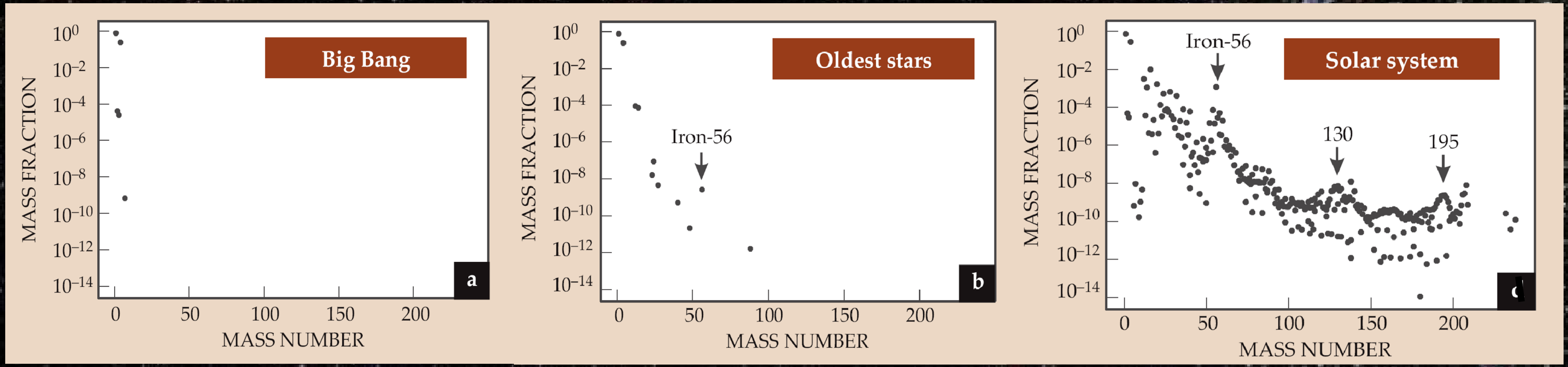
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetal | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

Are there more elements?

Galactic Chemical Evolution





Primordial Stars

1. Origin and mass distribution of First Stars
2. Abundance distribution in old stars
3. The cluster structure of light nuclei
4. Nuclear clusters as stepping-stones across the mass gap.
5. The timing conditions for bridging the mass gap

Credit: NSF

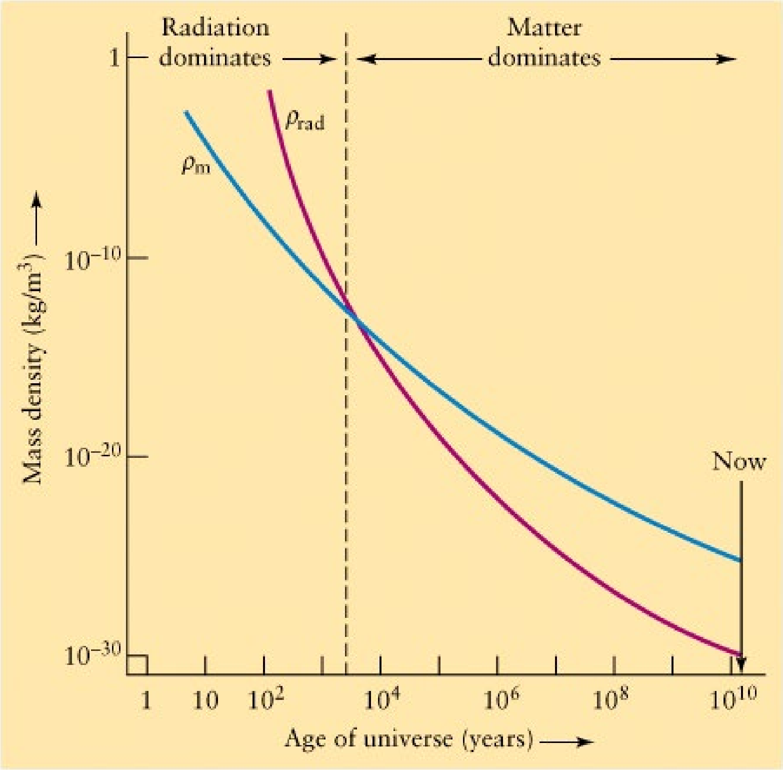
The Dark Ages

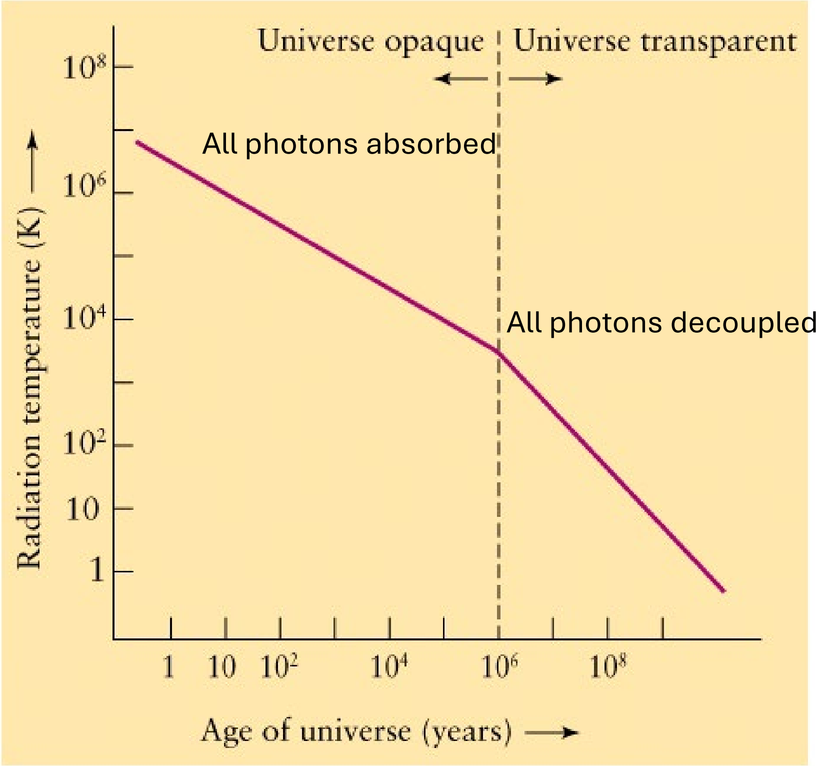
The expansion and cooling of the universe pushed the Planck distribution of the primordial photon flux below the wavelength range of visible and infra-red light and heat. The universe grew dark and cold – the Dark Ages

Temperature and Density Development in an Expanding Universe

$$t_{exp} = \frac{1}{H} = \sqrt{\frac{3c^2}{8\pi G\rho}}\rho_\gamma$$

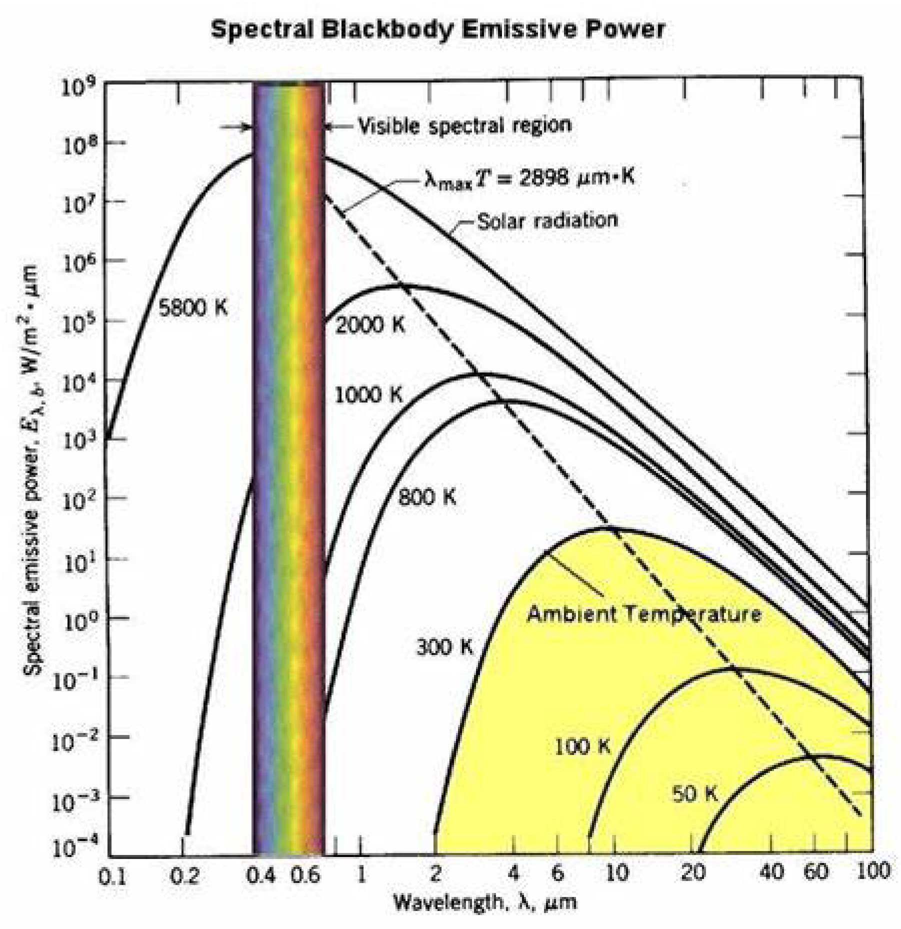
The early universe was radiation dominated: $\rho_\gamma(t) > \rho_m(t)$; transition from radiation to matter dominated universe: $\rho_\gamma(t) = \rho_m(t)$ with $\rho_\gamma(t) = \rho_m(t)$; $\rho_\gamma(T) = \frac{4}{c}\sigma \cdot T^4$

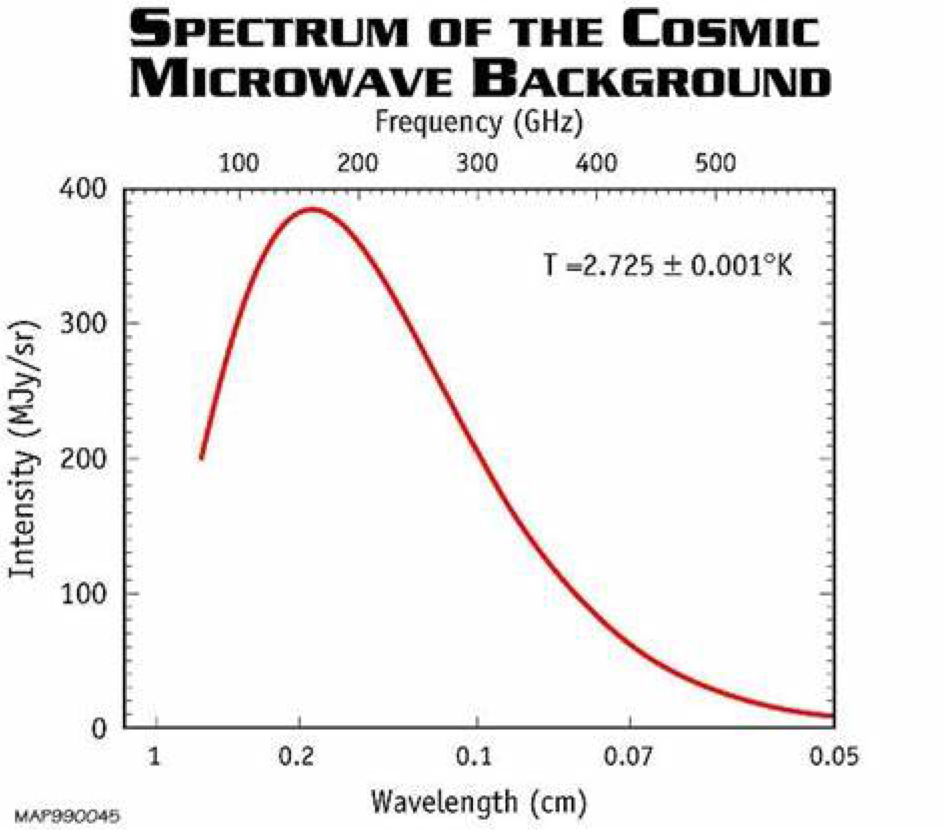




The Planck Distribution in an Expanding and Cooling Universe

Wavelength shift from $\lambda \approx 0.09$ μm X-rays, ionizing hydrogen, to $\lambda \approx 0.5$ μm of visible light to Cosmic microwave background of $\lambda \approx 1600$ μm. **It became dark!**



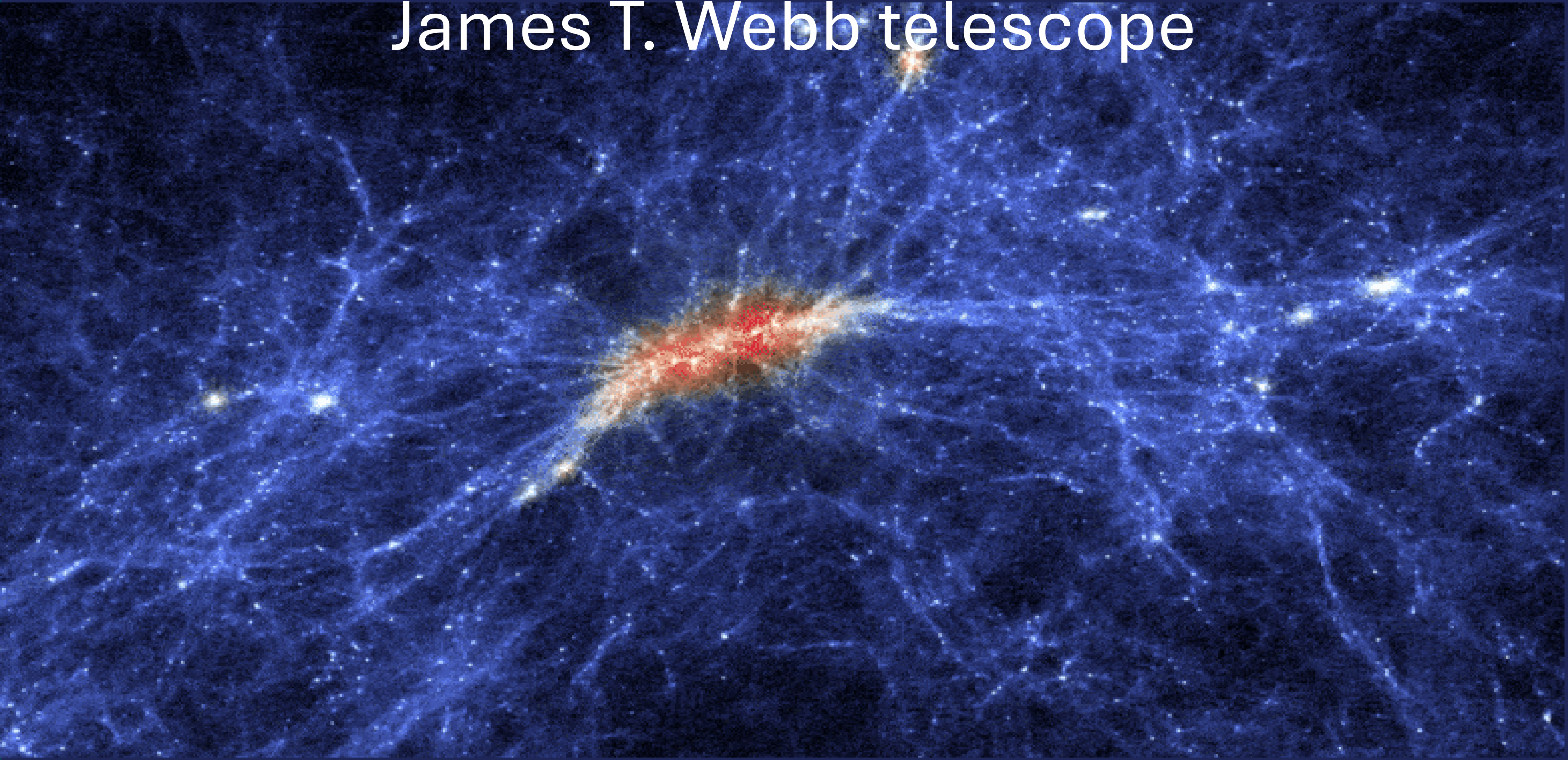


The End of the Dark Ages

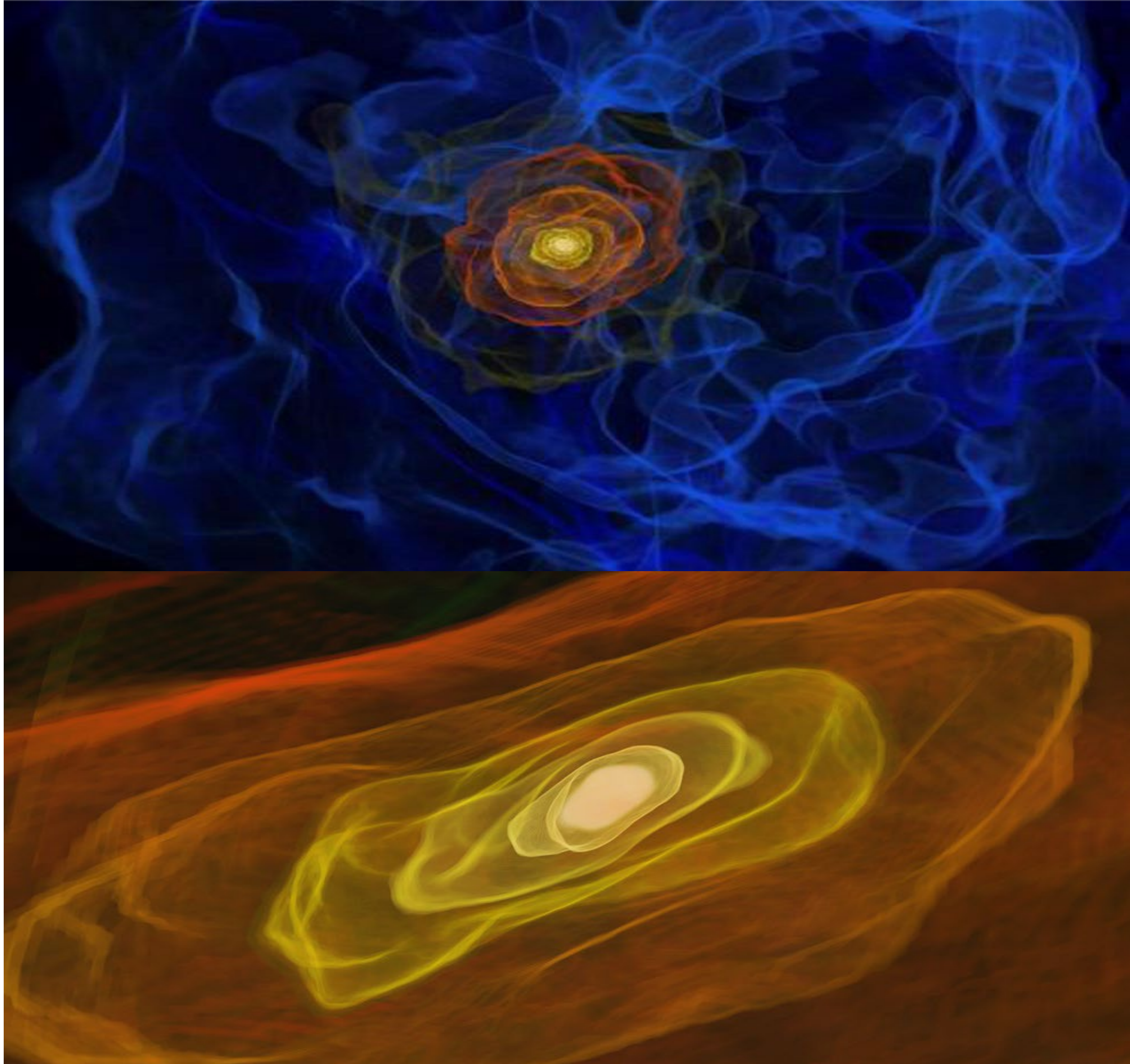
The Dark Age is the period between the time when the cosmic photon background wavelength grew beyond λ ≥ 2 μm and the time when the evolution of structure in the universe led to the gravitational collapse of objects, in which the first stars were formed generating radiation energy, starting the reionization of matter.

The universe became light again and the first stars emerged as the eldest light sources!

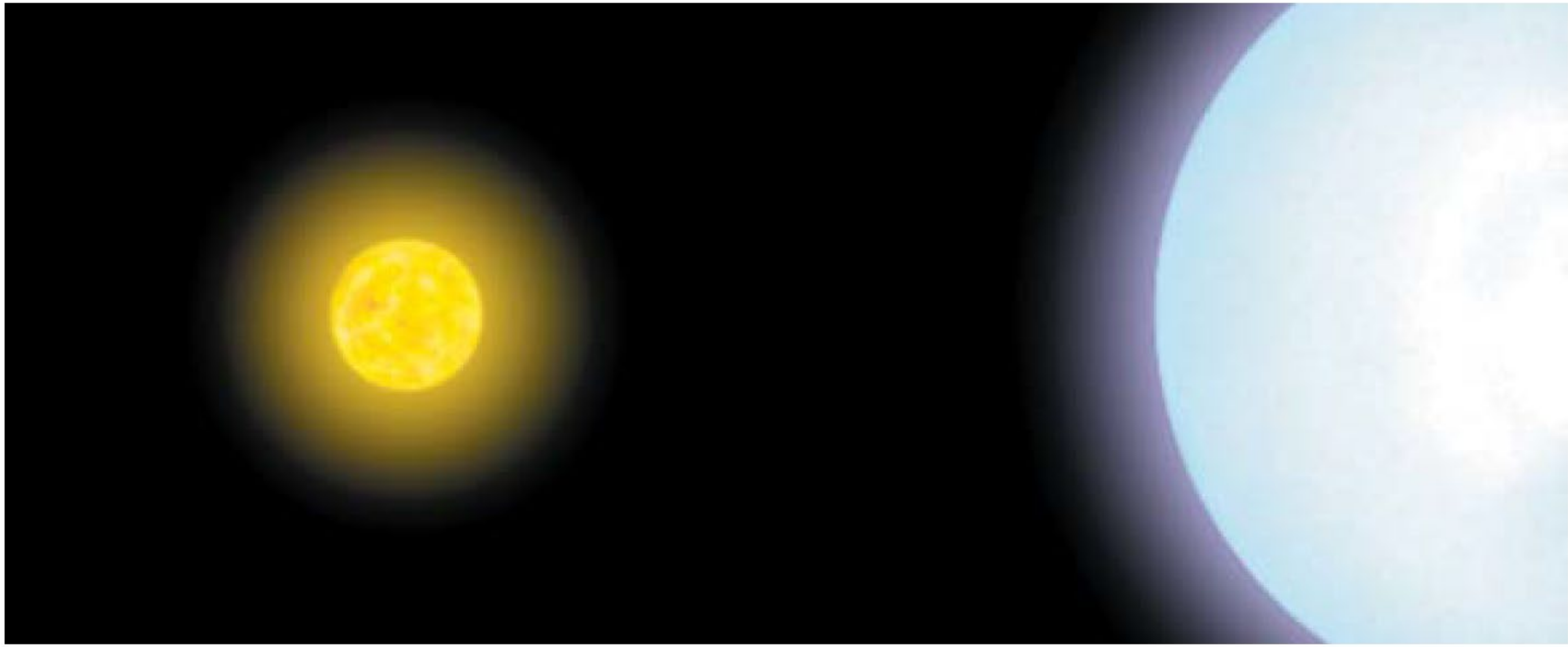
The view towards the early stars and galaxies in the Universe with the James T. Webb telescope



First Star formation from inhomogeneities in the mass distribution of the early universe



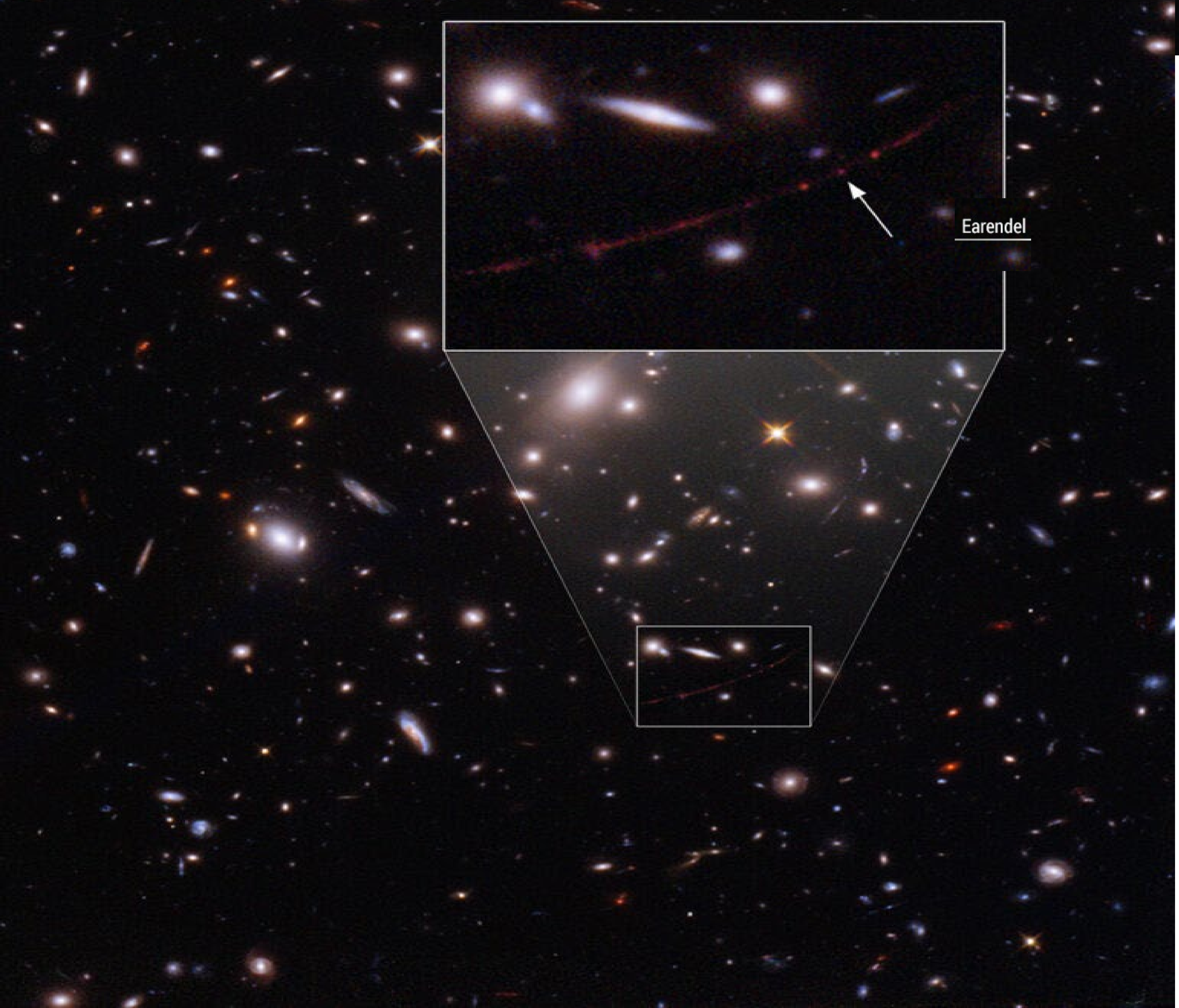
The Mass Distribution of First Stars

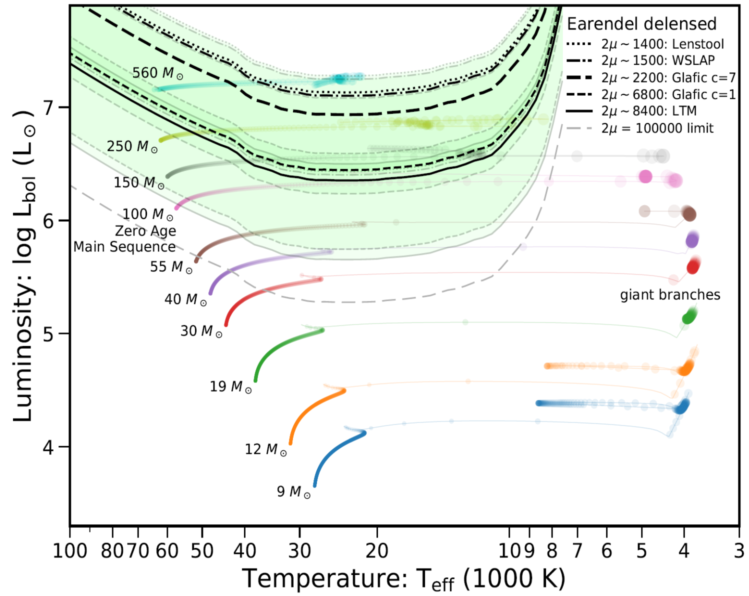


SUN
MASS: 1.989×10^{30} kilograms
RADIUS: 696,000 kilometers
LUMINOSITY: 3.85×10^{23} kilowatts
SURFACE TEMPERATURE: 5,780 kelvins
LIFETIME: 10 billion years

FIRST STARS
MASS: 100 to 1,000 solar masses
RADIUS: 4 to 14 solar radii
LUMINOSITY: 1 million to 30 million solar units
SURFACE TEMPERATURE: 100,000 to 110,000 kelvins
LIFETIME: 3 million years

Earendel, the Oldest Star Observed





Earendel is distant star at a redshift 900 million years after the Big Bang. This star is magnified by a factor of thousands by the foreground galaxy cluster lens WHL0137-08. The absolute UV magnitude, -10 ± 2, is consistent with a star of 50 to 500 solar masses.

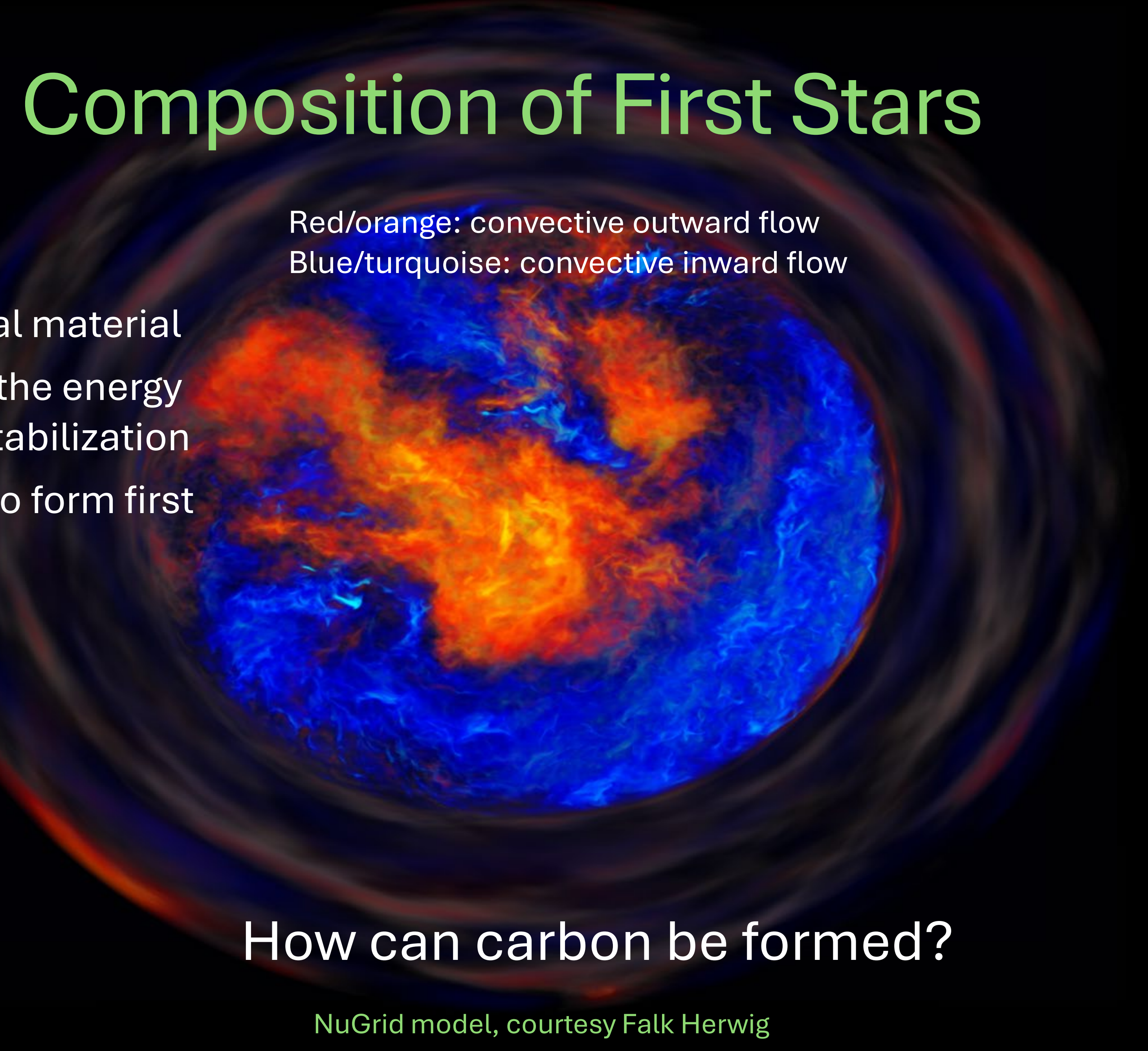
12.9 Billion yrs: Hubble observation, 2022

James Webb observation:

Methuselah is located in the constellation Libra, close to the Milky Way galaxy's Ophiuchus border, and around 190 light-years away from the Earth.
14.5 +/-0.8 Billion years old

The Structure and Composition of First Stars

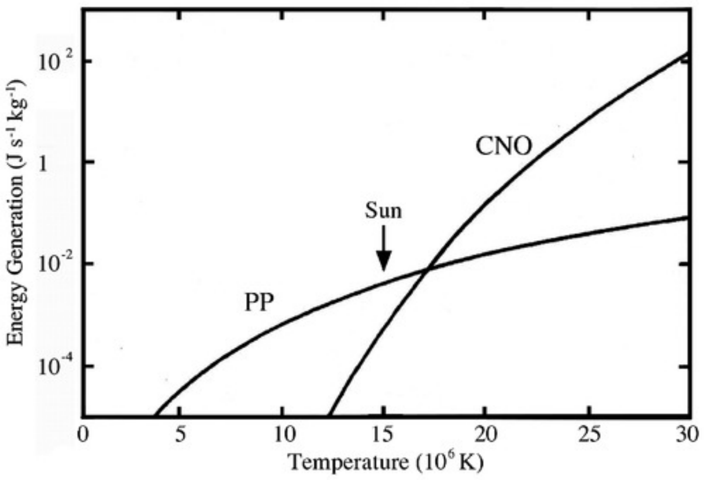
- They are made of primordial material
- No CNO cycle to generate the energy and internal pressure for stabilization
- Contraction and collapse to form first supernovae



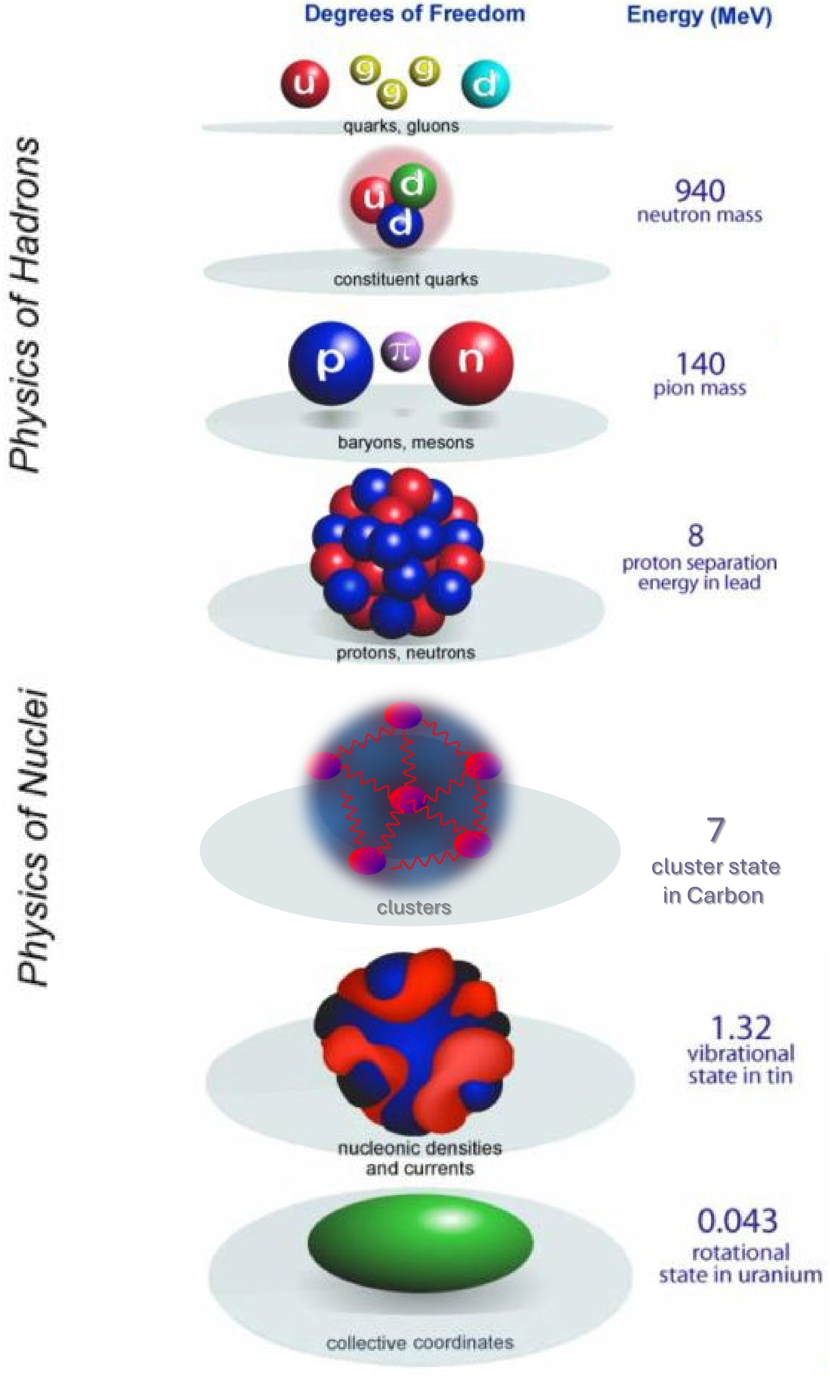
Red/orange: convective outward flow
Blue/turquoise: convective inward flow

How can carbon be formed?

NuGrid model, courtesy Falk Herwig



Nuclear Structure



Single particle configurations

Cluster – molecular configurations

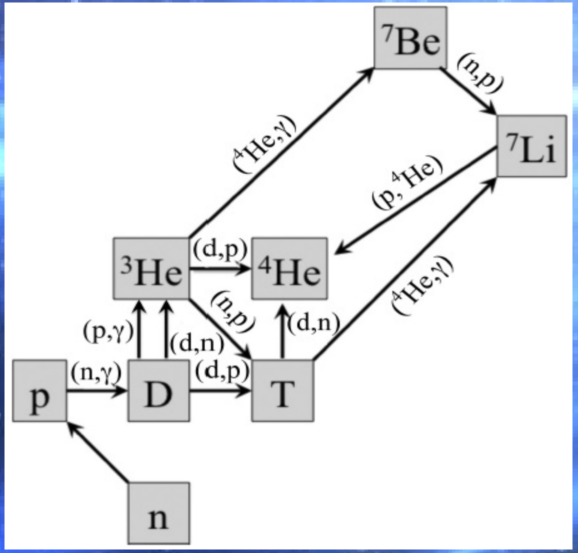
Nuclear Structure

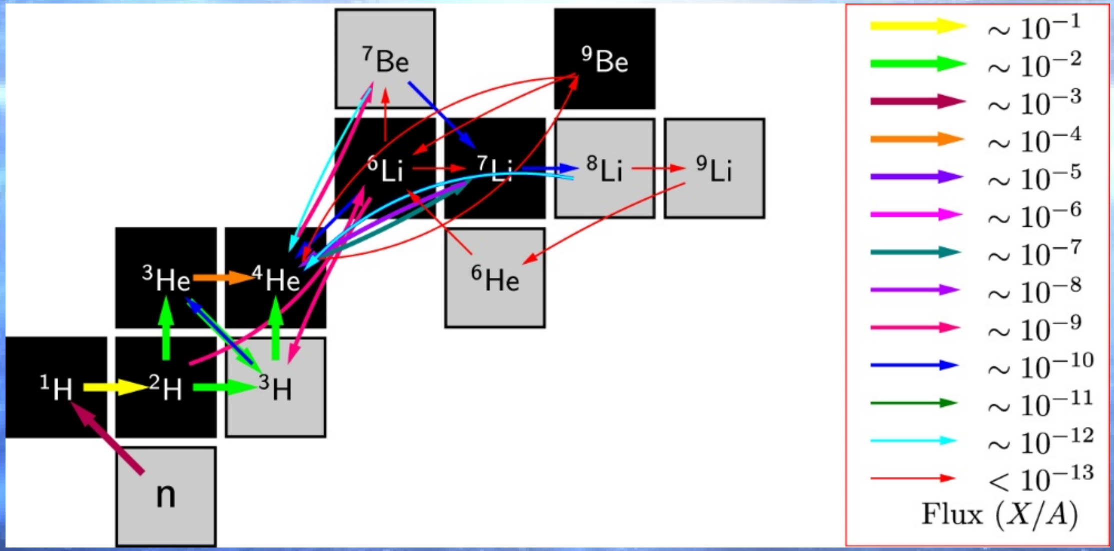
Collective vibrational configurations

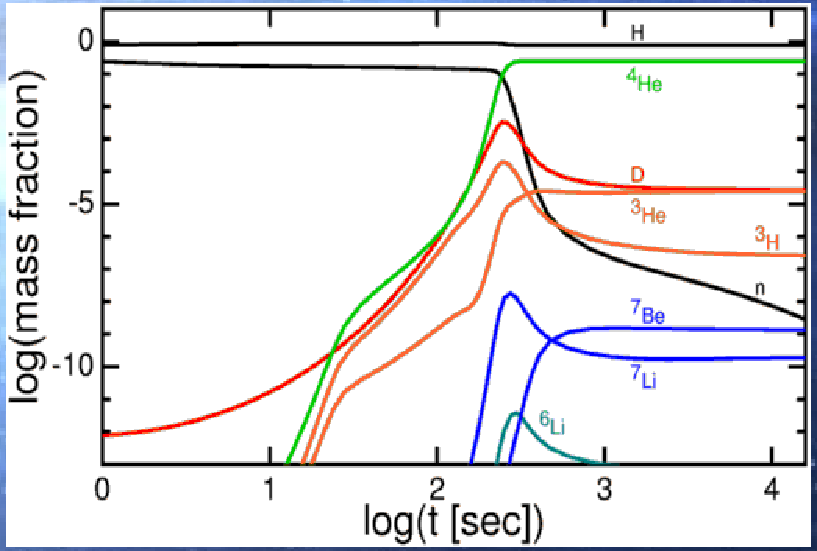
Collective rotational configurations

Big Bang Nucleosynthesis

The origin of the primordial elements: H, He, Li

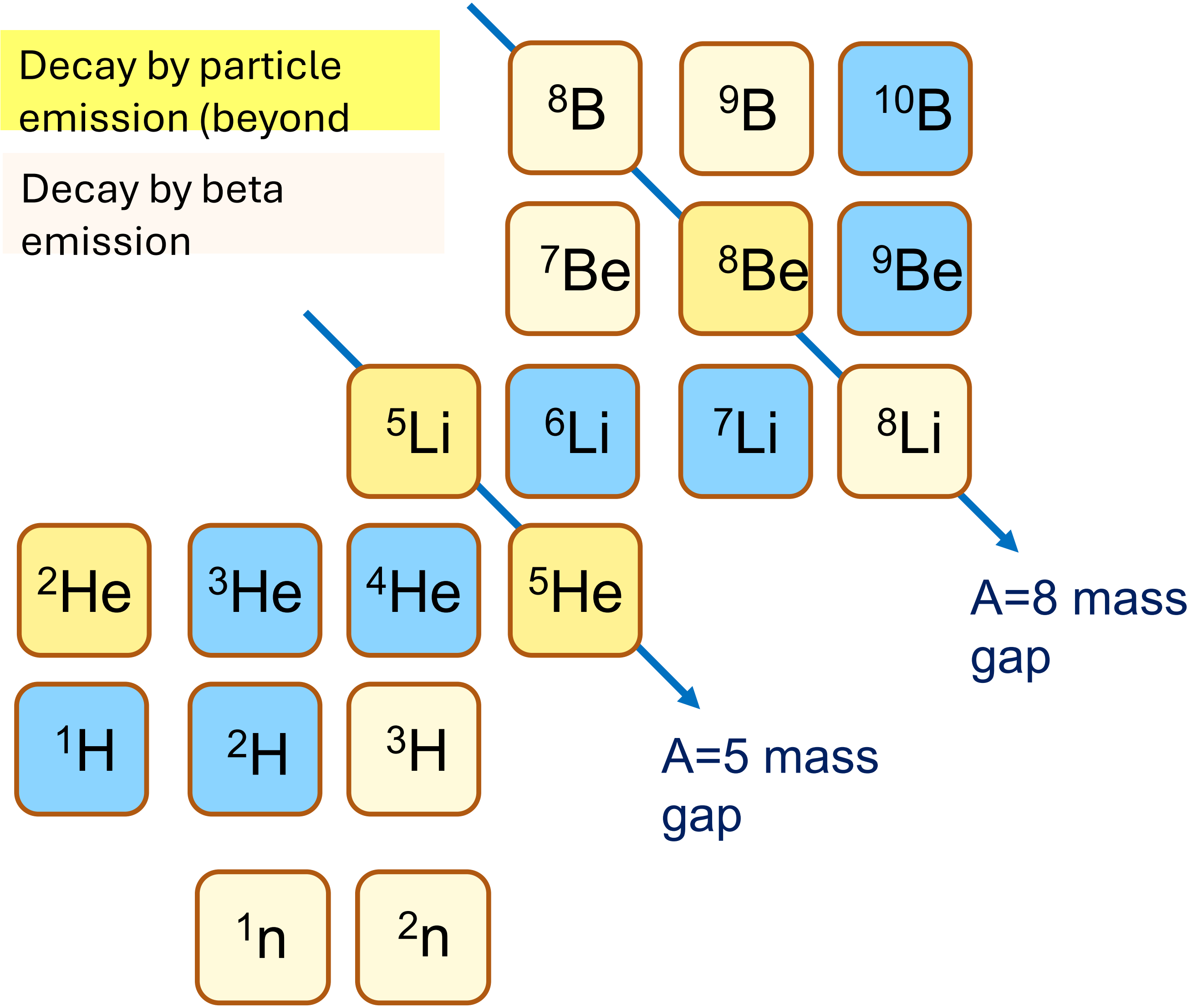






The mass A=5 gap prohibits the production of substantial amounts of lithium and beryllium.
The mass A=8 gap prohibits the production of heavier elements such as boron, carbon, and beyond!

The Mass A=5 and A=8 Mass Gap



There are no stable nuclei with mass A=5 and mass A=8 in the universe!

The formation of heavier nuclei requires sufficient to jump these two gaps by nuclear reaction processes!

This is a challenge in the rapidly expanding hydrogen and helium environments associated with the Big Bang, Neutrino driven shocks, or merging neutron stars.

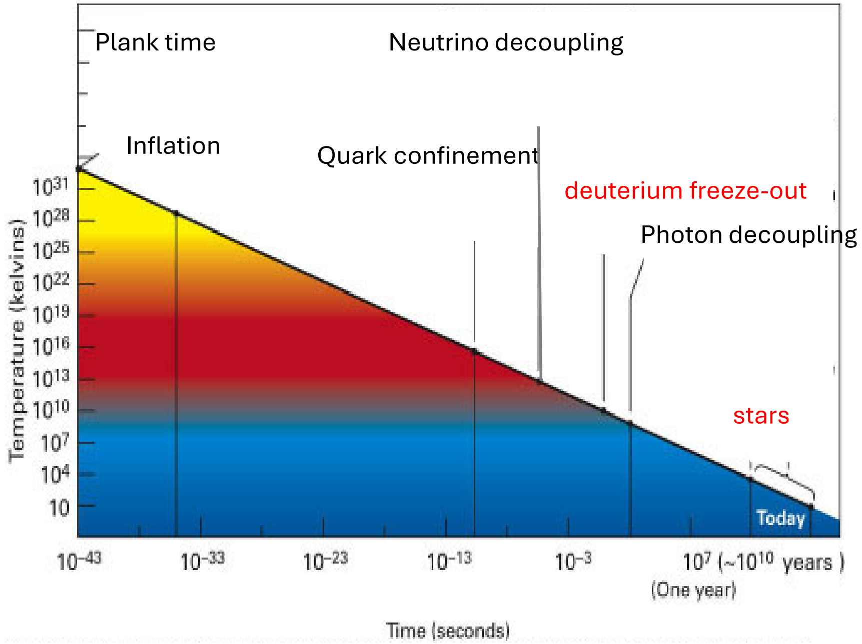
H, n, He Environments

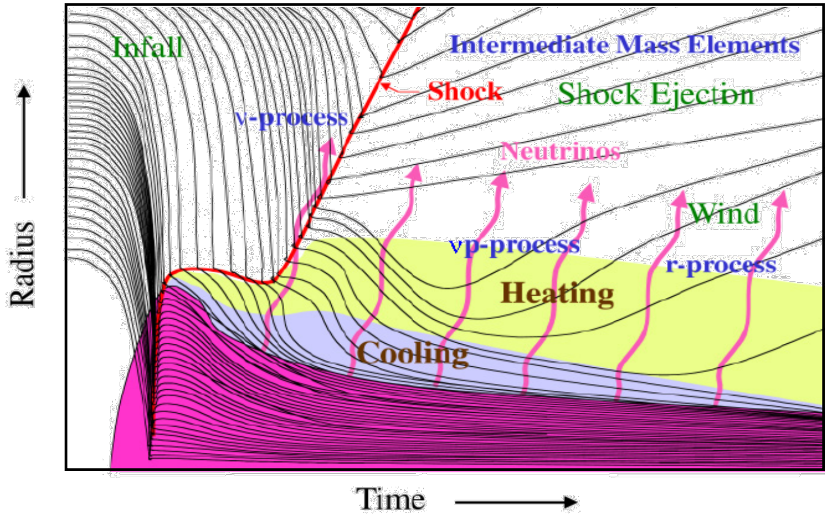
- Produced in Big Bang within the first three minutes by expansion creating non equilibrium conditions for nuclear reactions. The decoupling of weak interaction forms p, n dominated abundance distribution, which is converted to α.

Can it go beyond ^{4}He?

- Produced in core collapse SN or on merging neutron star by nuclear-statistical equilibrium (NSE), which indicates full chemical equilibrium among all of the involved nuclear reactions. For high temperature and density conditions the equilibrium shifts to p, n, and α dominated abundance distribution.

How does it bridge the mass gap?

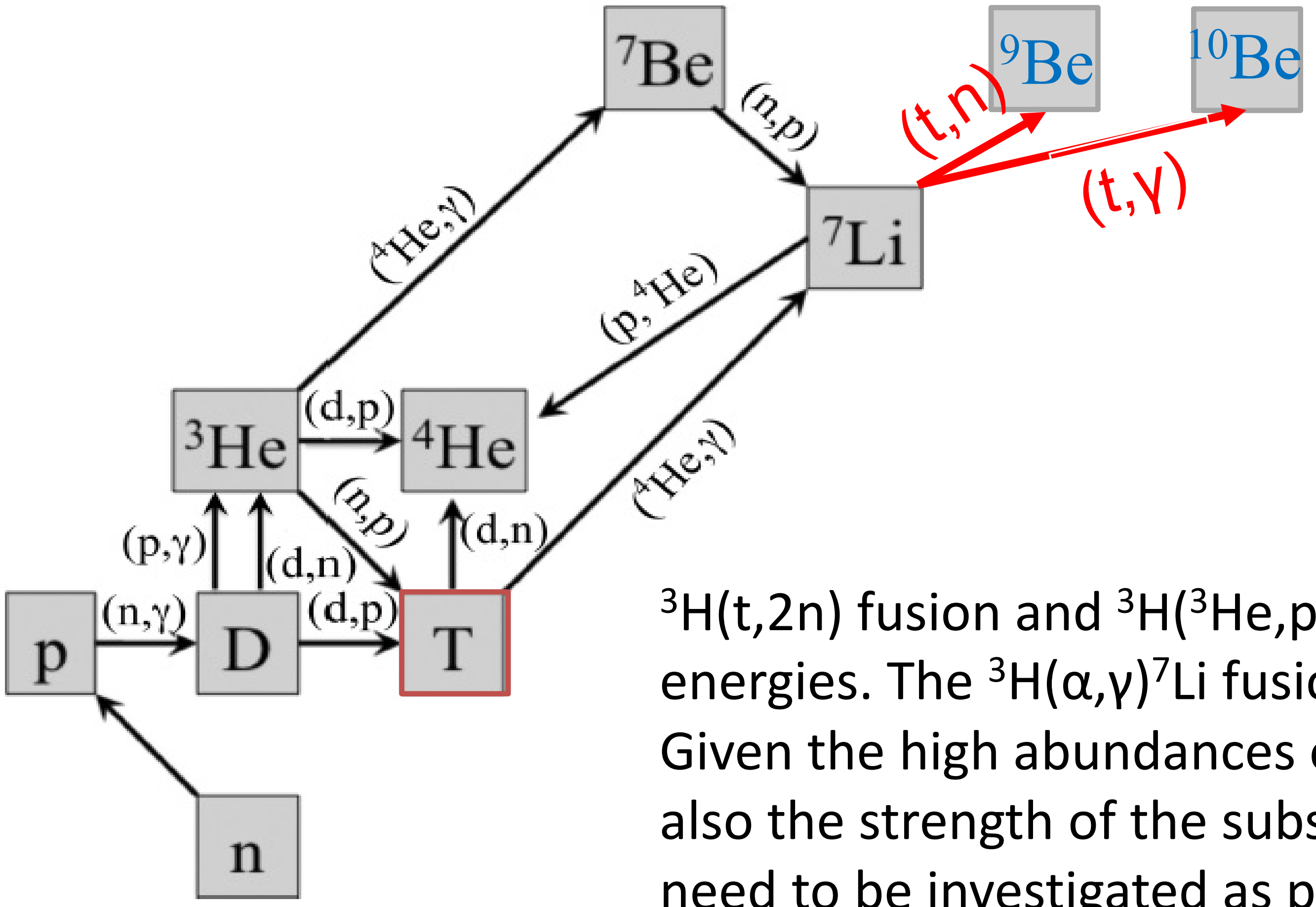




Bridging the mass 5 and 8 gap with tritium

- Big Bang Nucleosynthesis
- Neutrino Driven Supernova Shock
- Merging Neutron Stars

Open questions: tritium reaction studies

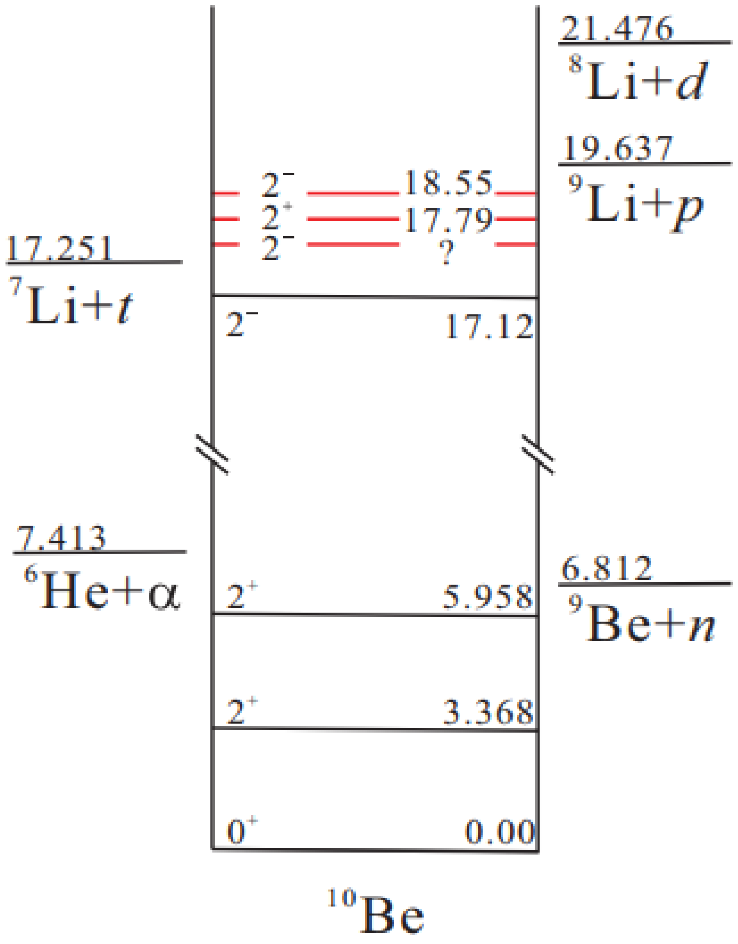


The neglect of these tritium reactions may explain why the observed ^{7}Li abundance is three times lower than predicted!

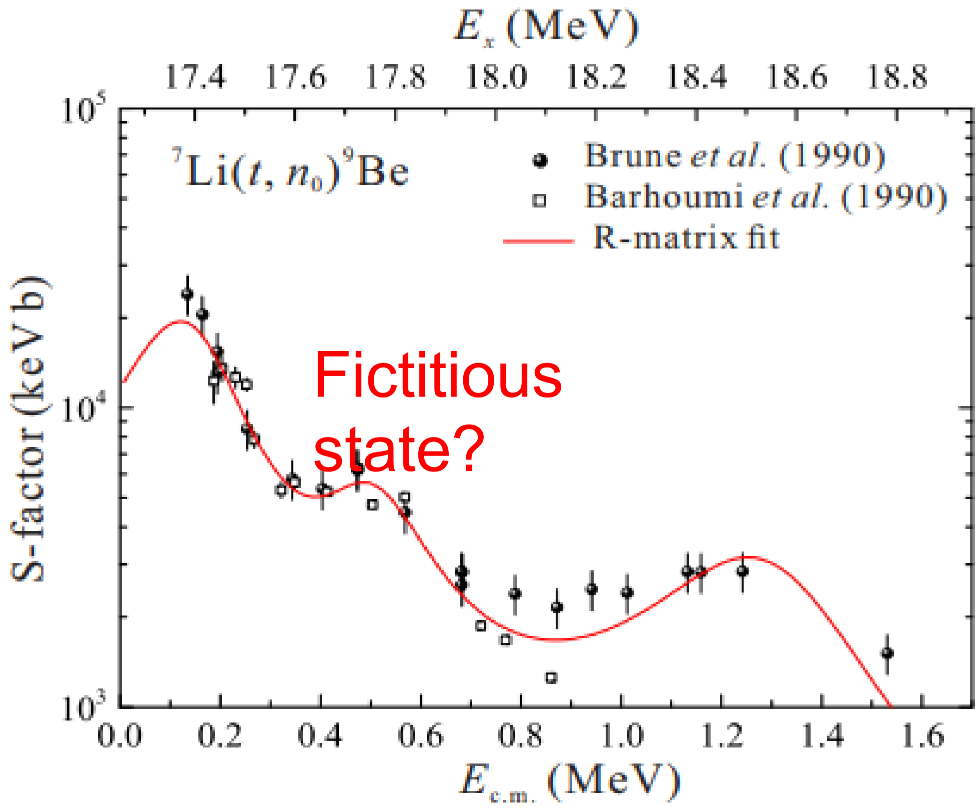
Subsequent ^{9}Be(α,n)^{12}C may generate neutrons and ^{12}C.

^{3}H(t,2n) fusion and ^{3}H(^{3}He,pn) fusion require further studies at low energies. The ^{3}H(α,γ)^{7}Li fusion studies show pronounced discrepancies. Given the high abundances of tritium in the early Big Bang environment also the strength of the subsequent ^{7}Li(t,γ)^{10}Be and ^{7}Li(t,n)^{9}Be reactions need to be investigated as possible solution of Lithium problem.

Impact of threshold states

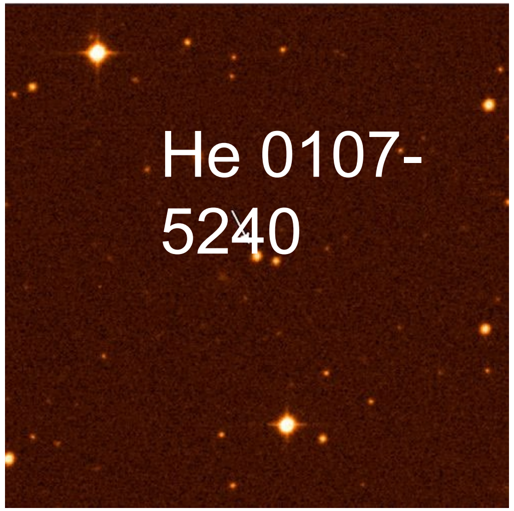


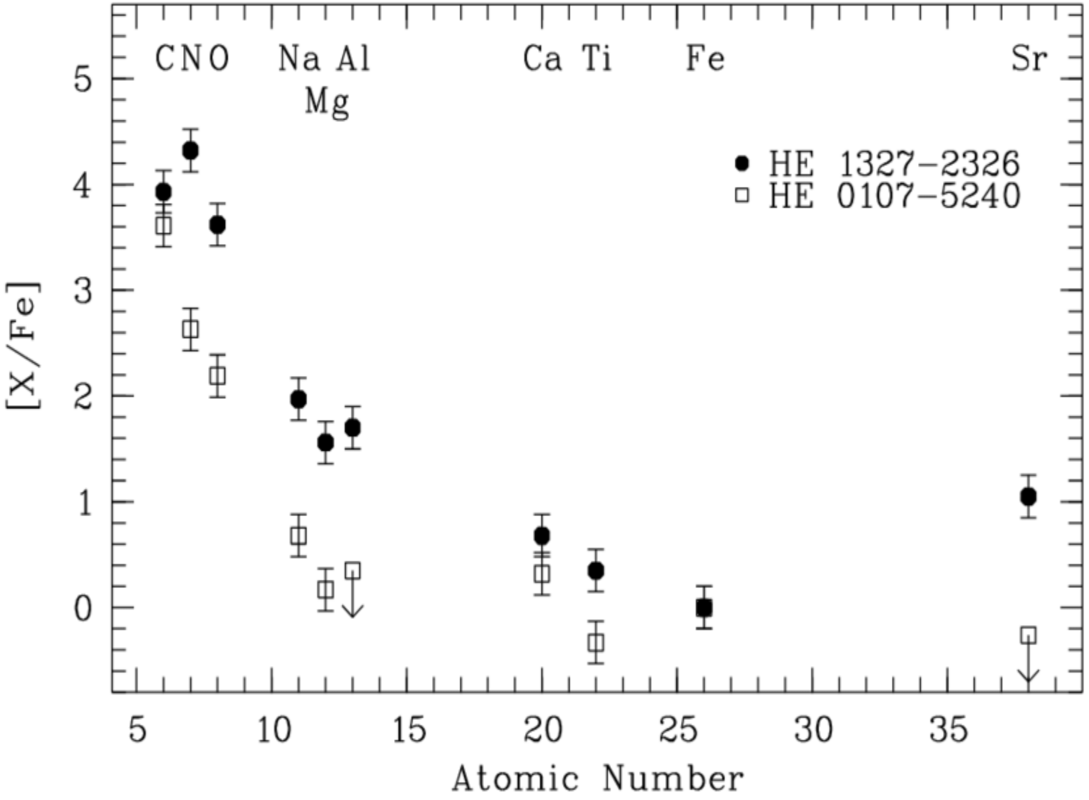
Impact of near threshold s-wave resonance states may cause order of magnitude increase in reaction rate!



Fictitious state?

Element Distributions in very old Stars





How are the CNO elements being formed and what are the nuclear reactions towards Ca and beyond in the nucleo-chemistry in first stars?

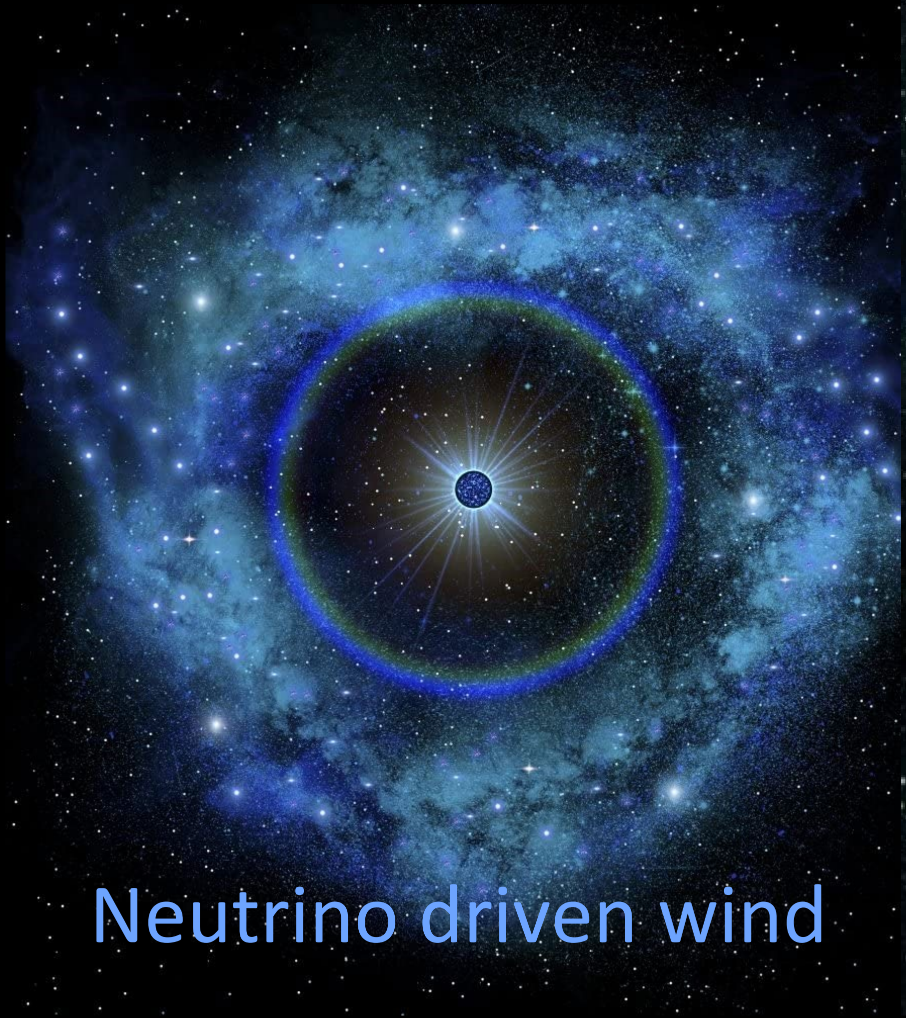
Emergence of early stars with carbon and neutron products

Primordial Elements
First Star Nucleosynthesis
Experimental Needs & Tools
First Model Results

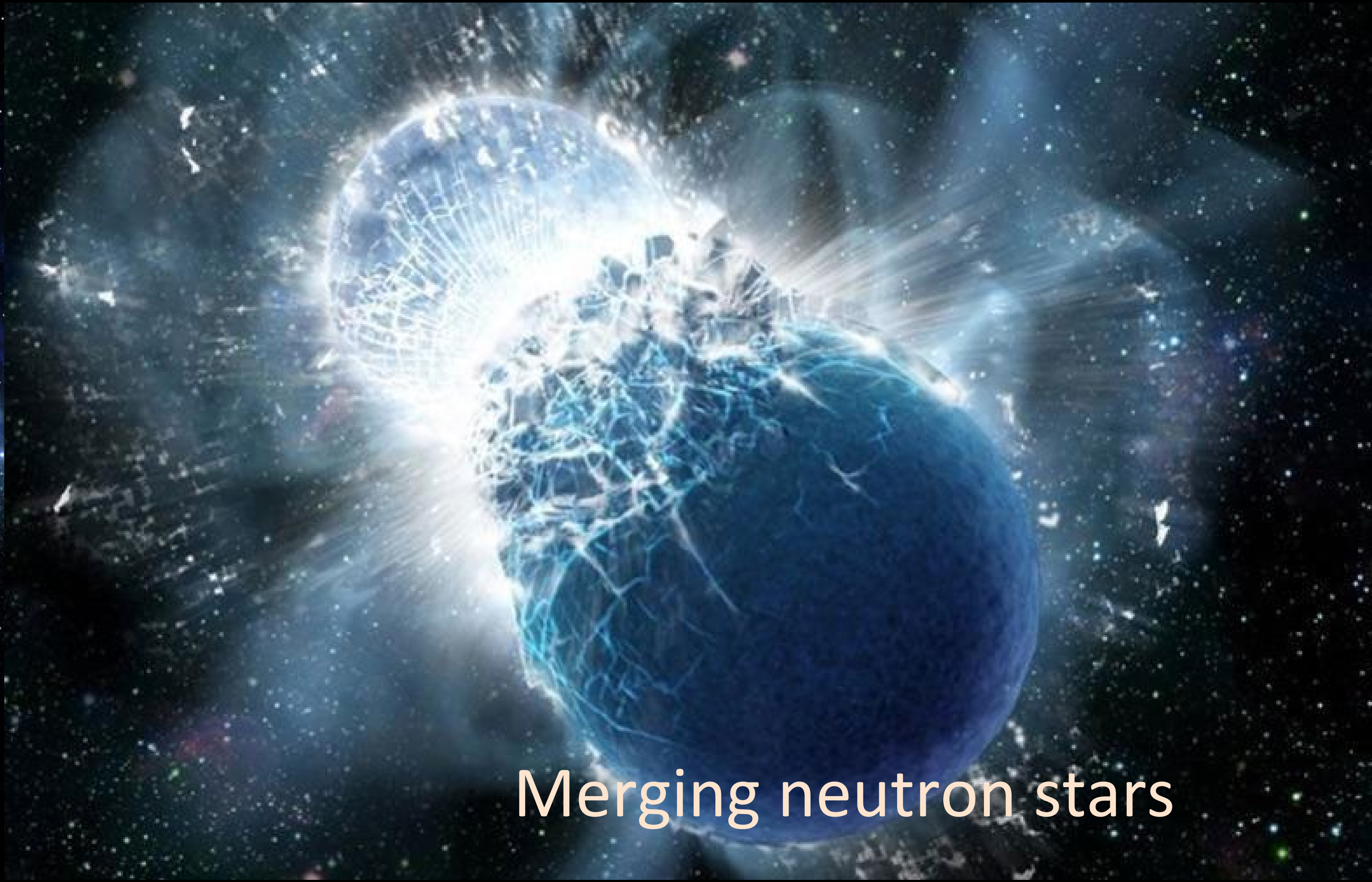
H, n, He at extreme matter conditions?

Onset of supernova or merging neutron stars!

Dissociation of elements at high temperature and density conditions?



Neutrino driven wind



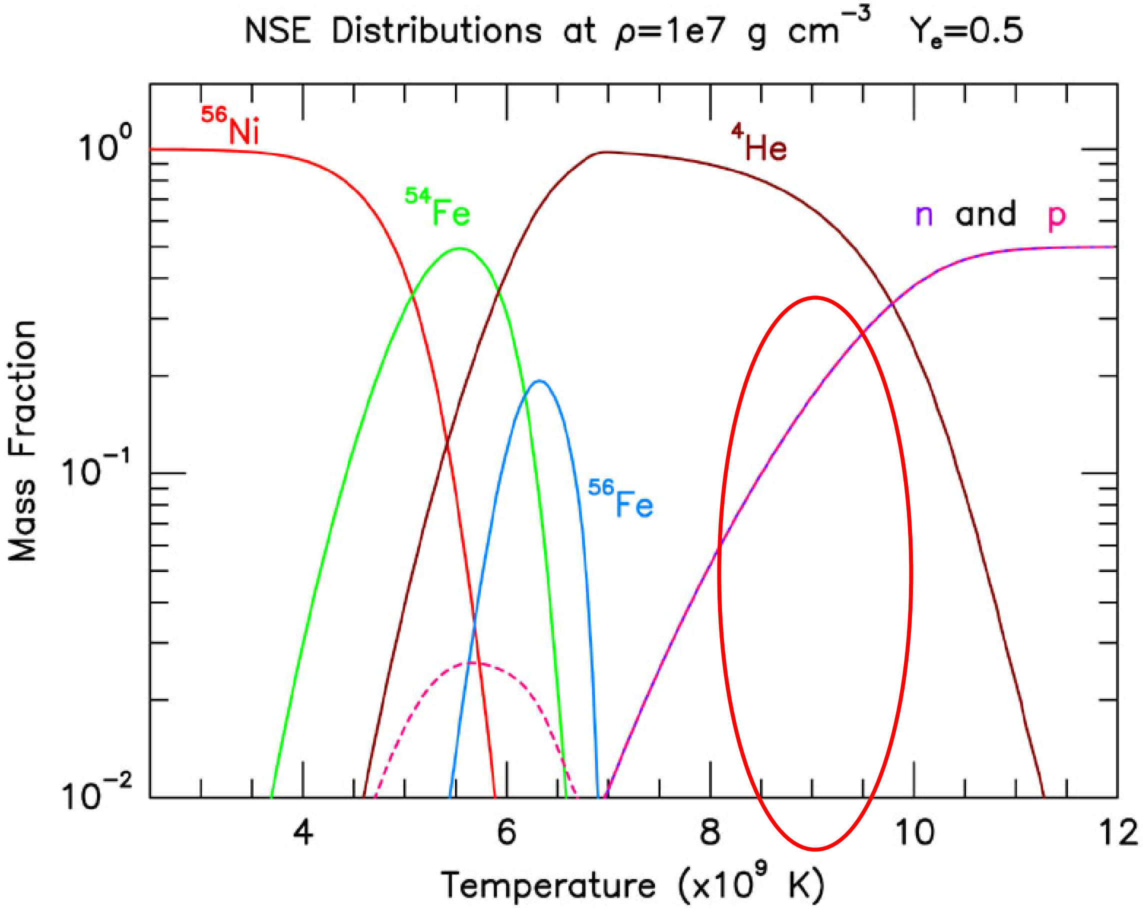
Merging neutron stars

Chemical Equilibrium at high Densities and Temperatures

$$Y_{Z,N} = G_{Z,N} \cdot (\rho \cdot N_A)^{A-1} \cdot \left(\frac{2\pi \cdot \hbar^2}{m_u \cdot kT} \right)^{\frac{3}{2}\cdot(A-1)} \cdot e^{\frac{B_{Z,N}}{kT}} \cdot Y_n^N \cdot Y_p^Z$$

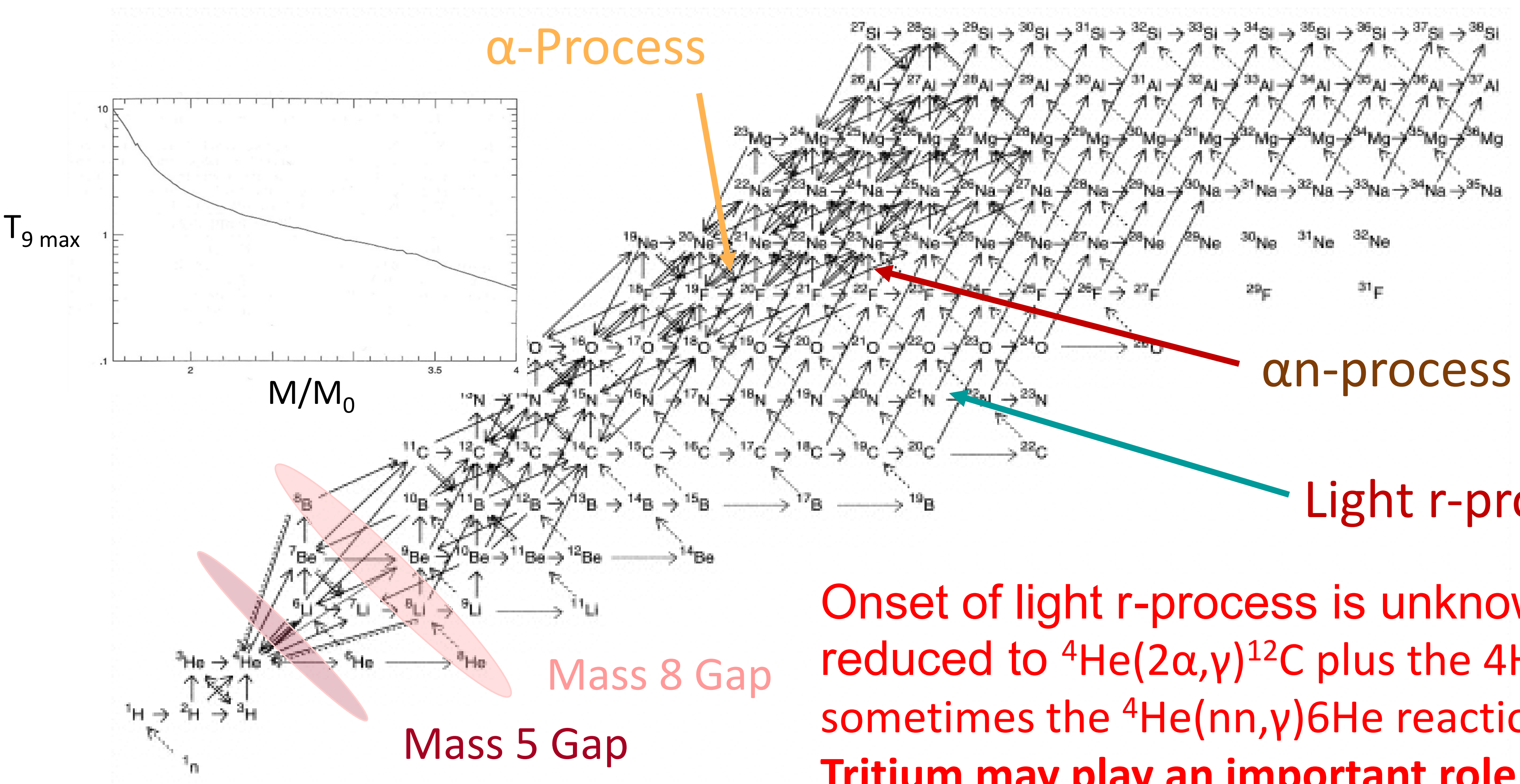
High ρ: Massive nuclei
High T: Light nuclei
Median T: Tightly bound nuclei.

With the expansion of the shock follows a gradual change in abundance distribution on a timescale determined by assembling, the n, p, α nuclei to heavier nuclei. That timing depends on the associated rates.



Neutron Star Mergers and Nucleosynthesis of Heavy Elements
F.-K. Thielemann, M. Eichler, I.V. Panov, and B. Wehmeyer.
Annual Review of Nuclear and Particle Science 67 (2017) 253-274.

Dynamical Reaction Network bridging the gap



α-Process

αn-process

Light r-process ?

Mass 8 Gap

Mass 5 Gap

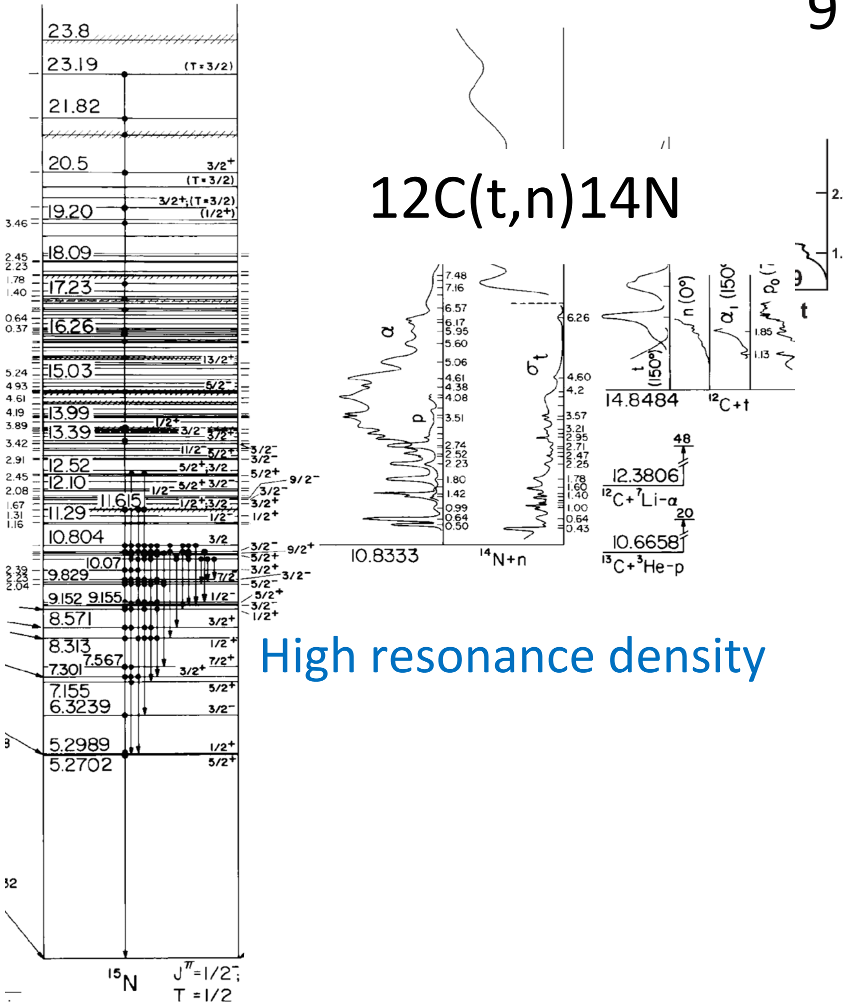
Onset of light r-process is unknown – usually reduced to ^{4}He(2α,γ)^{12}C plus the 4He(αn,γ)^{9}Be and sometimes the ^{4}He(nn,γ)6He reactions.

Tritium may play an important role!

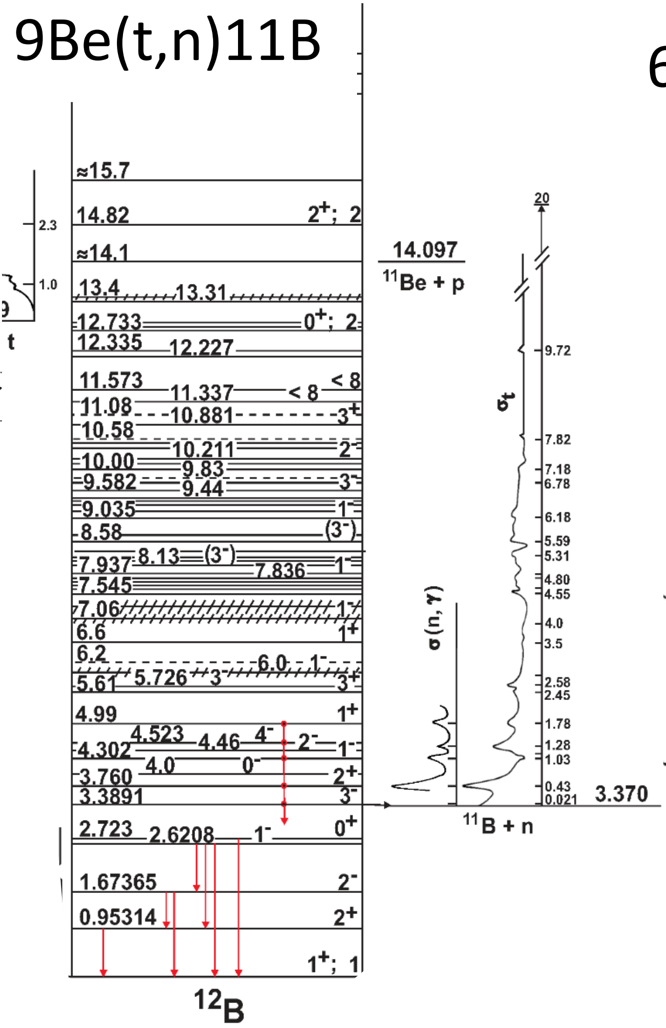
Double neutron capture on hydrogen will form tritium, triggering tritium induced reactions in a rapidly expanding supernova shock. Tritium interactions with rapidly formed light isotopes along the alpha chain but also along the light r-process path should be investigated.

12C(t,n)14N

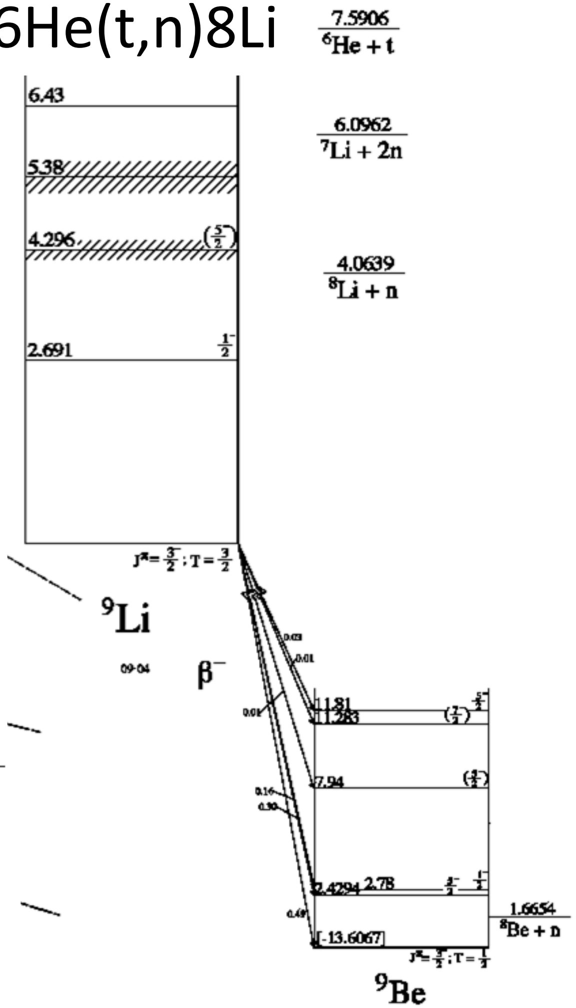
High resonance density



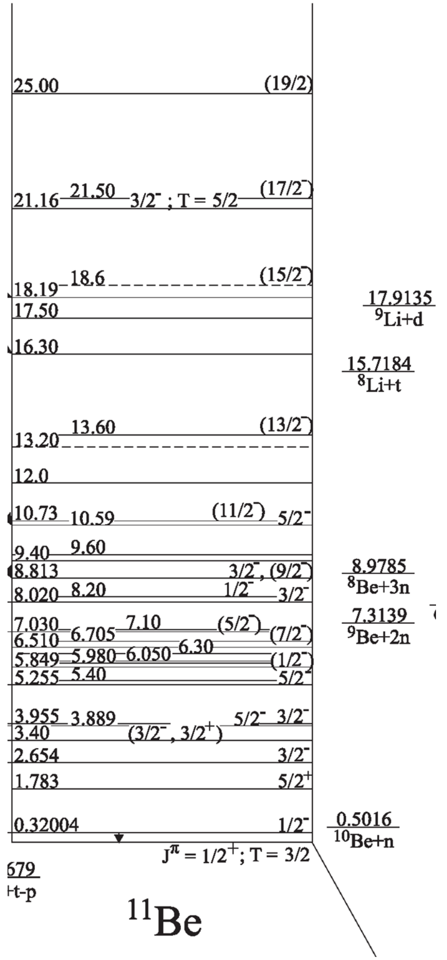
9Be(t,n)11B



6He(t,n)8Li



8Li(t,2n)9Be



Subsequent (α,n) reactions would boost the r-process

Experimental Challenge

$$E_0 = \left(\frac{\pi e^2 Z_1 Z_2}{\hbar} \sqrt{\frac{\mu}{2}} kT \right)^{2/3}$$

$$E_0 = 1.22 \cdot \left(Z_1^2 Z_2^2 \mu T_6^2 \right)^{1/3} \ [keV]$$

$$E_0 = 0.122 \cdot \left(Z_1^2 Z_2^2 \mu T_9^2 \right)^{1/3} [MeV]$$

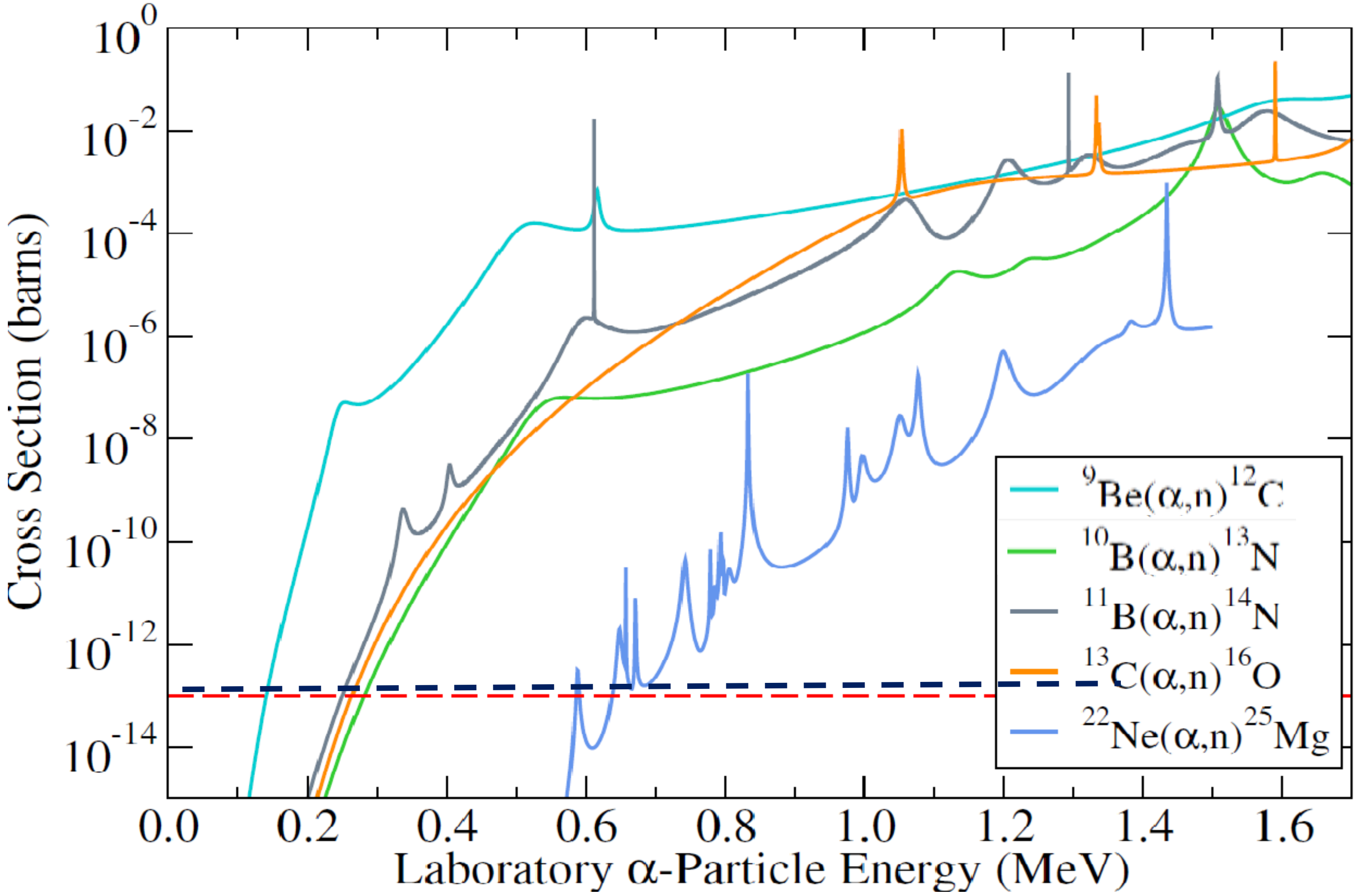
Gamow range

$$\Delta E = \frac{4}{\sqrt{3}} \left(E_0 kT \right)^{1/2}$$

$$= 0.748 \cdot \left(Z_1^2 Z_2^2 \mu T_6^5 \right)^{1/6} \quad [keV]$$

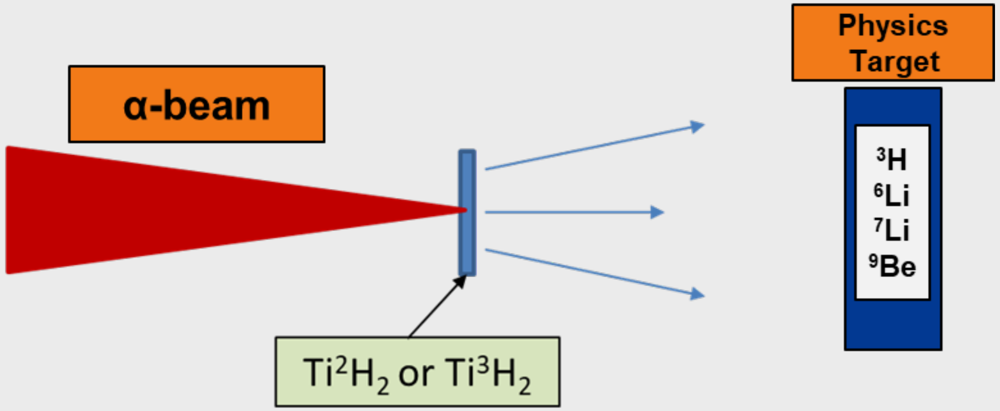
$$= 0.236 \cdot \left(Z_1^2 Z_2^2 \mu T_9^5 \right)^{1/6} \quad [MeV]$$

$\mu = \frac{m_1 m_2}{m_1 + m_2}$ in amu



Two Laser-Driven Nuclear Physics (LDNP) flagship experiments have been identified for the EP-OPAL Laser Facility under development at the University of Rochester

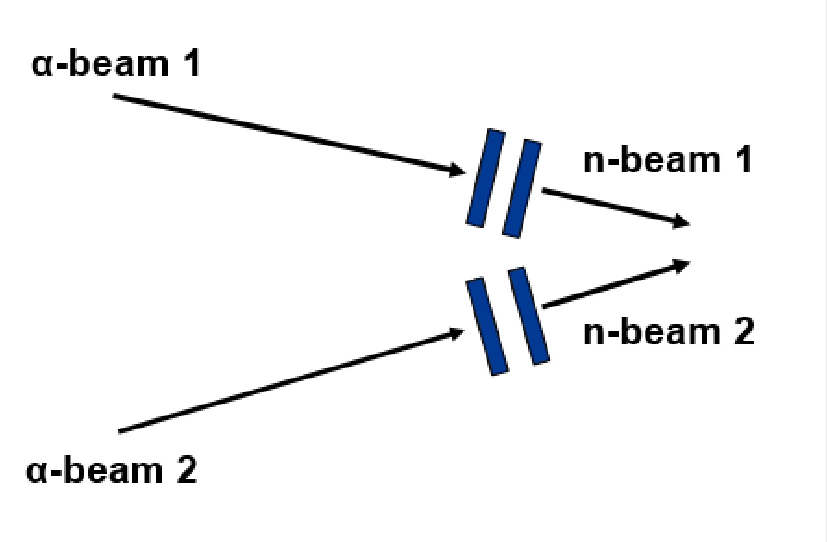
Flagship #1



Tritium Induced Nuclear Experiments Platform

- Investigate the nuclear structure of light nuclei.
- first measurements of cross-sections at low energy (~MeV).

Flagship #2

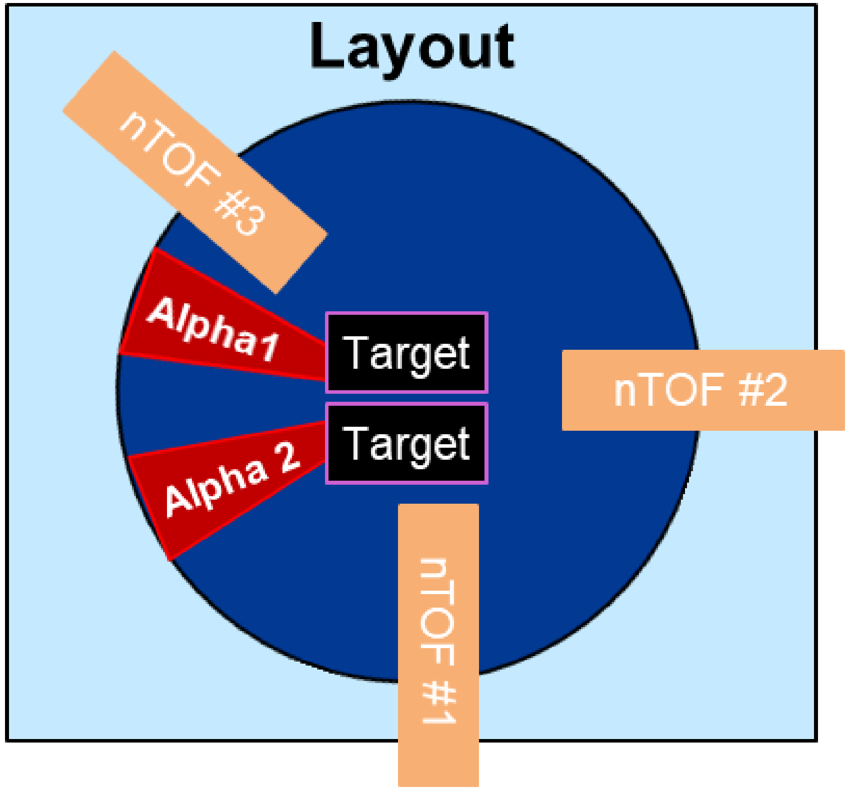


Neutron-Neutron Scattering Platform

- directly test nuclear charge symmetry.
- essential to understand the structure and dynamics of neutron stars.

Flagship #1 – Tritium Induced Nuclear Experiments Platform

The high intensity laser being proposed (NSF-OPAL) is required to generate the required neutron production to achieve a n-n scattering measurement

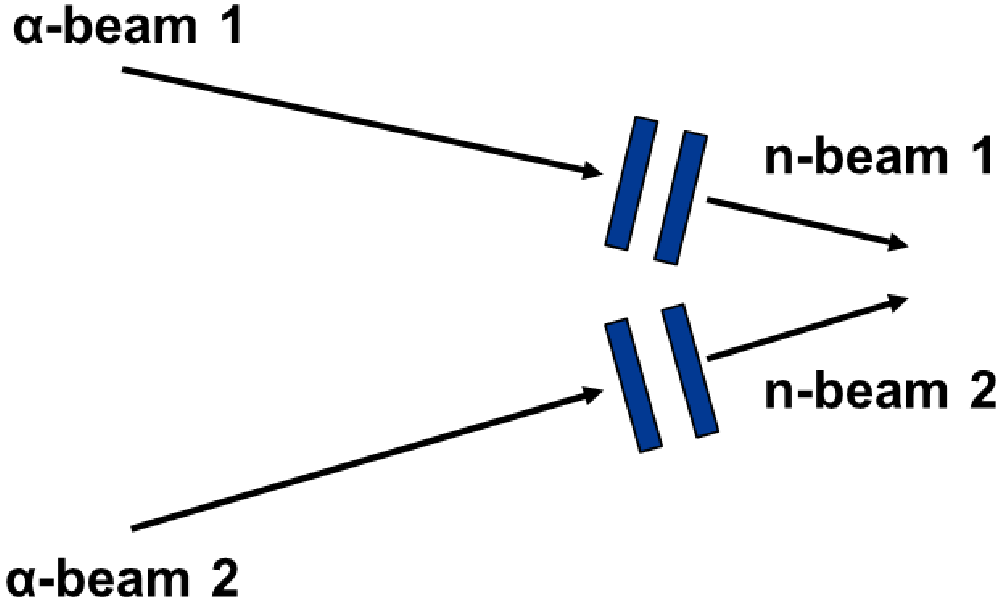


Flagship requirements

- **Two different configuration of alpha-beams at directly opposing to nearly parallel:**
  - **to investigate angular interactions**
- **Development of liquid (frozen) hydrogen isotope planar targets.**
- **Several highly-collimated lines-of-sight at ~20 meters from target chamber center.**
- **Develop model to simulate n-n scattering to optimize diagnostics.**
  - **presently, there is no deterministic code (i.e. MCNP) with the capability to model n-n scattering**

Flagship #2 – Neutron-Neutron Scattering Platform

The neutron-neutron scattering length is a quantity of fundamental importance in nuclear and particle physics that has not been directly measured



- **Neutron-neutron scattering parameters (a_{nn})**
  - **directly test nuclear charge symmetry[*,**]**
  - **critical to understanding neutron stars**
- **Dual TNSA configurations are required with the ability to overlap the neutron beams.**
- **Success in this platform will enable measurements that:**
  - **Are free from the effects of coulombic interactions.**
  - **Evaluate energy and angular dependence of n-n scattering.**
  - **Essential to understand the structure and dynamics of neutron stars.**

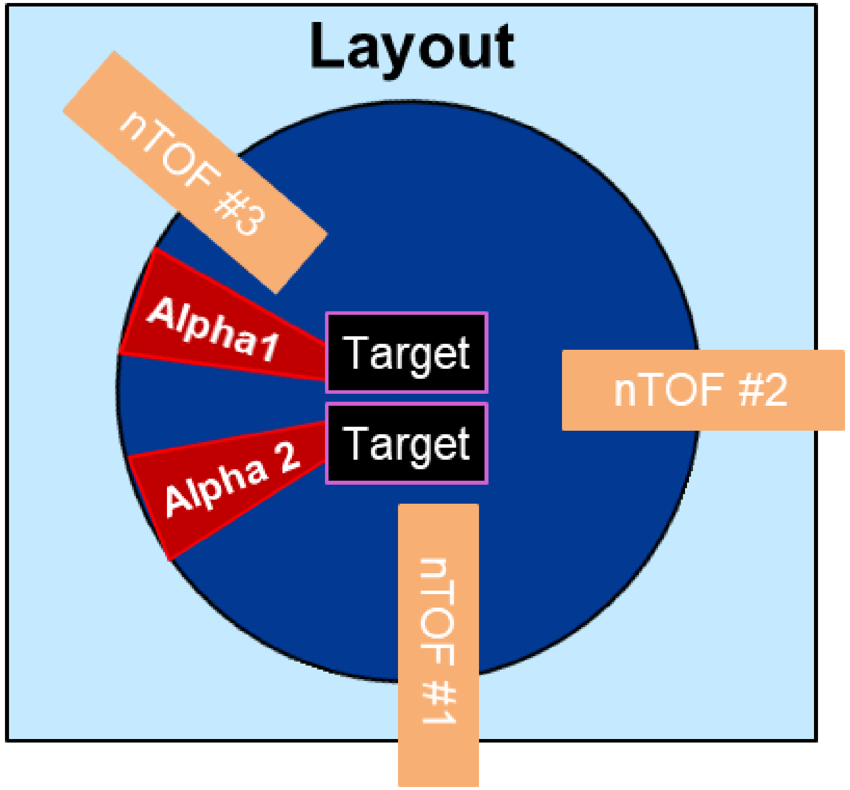
---

[*] M J. Moravcsik, Phys. Rev. Letter 136 3B (1964)

[**] D.W. Glasgow *et. al.*, Radiation Effects, 1986, Vol. 94 1-4, pp. 239-244

Flagship #2 – Neutron-Neutron

The high intensity laser being proposed (NSF-OPAL) is required to generate the required neutron production to achieve a n-n scattering measurement



Flagship requirements

- **Two different configuration of alpha-beams at directly opposing to nearly parallel:**
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- **Develop model to simulate n-n scattering to optimize diagnostics.**
  - **presently, there is no deterministic code (i.e. MCNP) with the capability to model n-n scattering**

Proof-of-principle experiments are underway and is required for transformational science on the NSF-OPAL Laser Facility

Laser Pre-Pulse Testing (FY24-25)

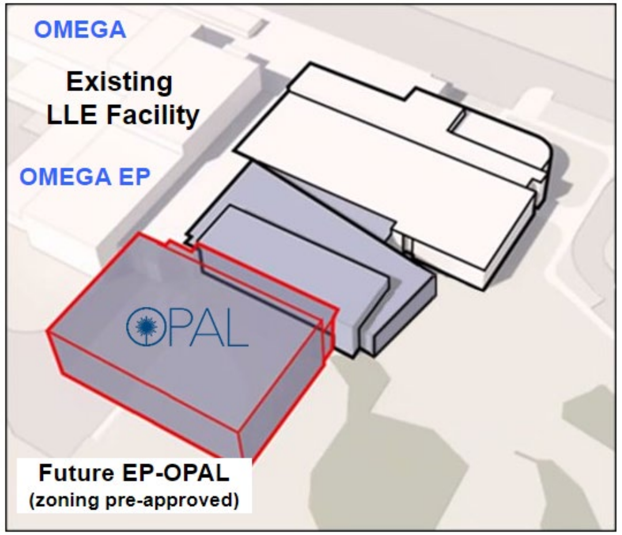
Novel Target Design Testing (FY25-26)

Phoswich Detector Development (FY26)

Cryogenic Target Design Testing (FY27)

<u>Planned experiment for subset of outstanding goals in LDNP</u>

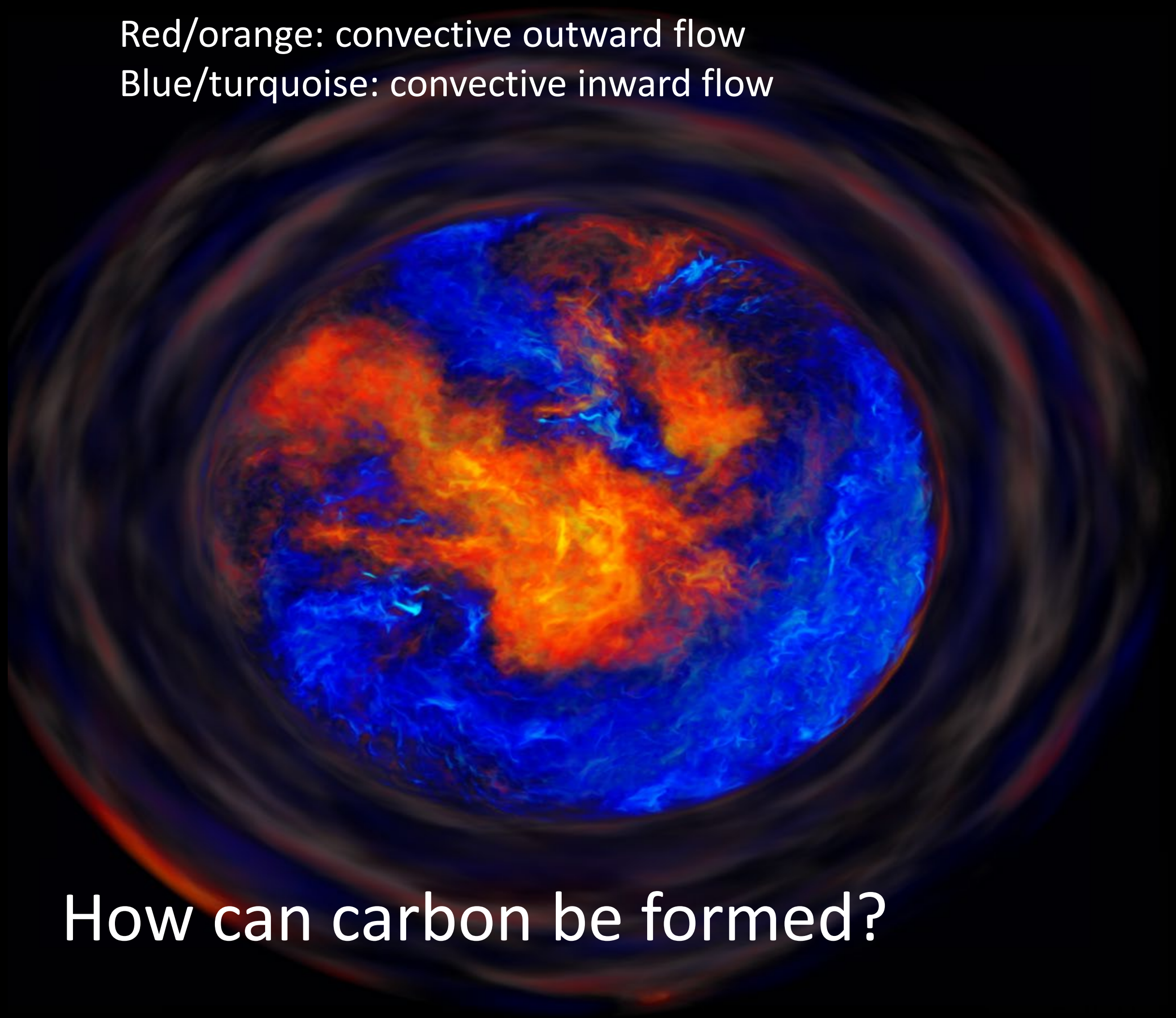
- Monoenergetic ion energy spectrum
- Optimization of ion acceleration from metal foils
- Detector development for new cross-section measurements
- Development of cryogenic hydrogen isotope targets



JINA–CEE

First generation stars

- They are made of primordial material
- They are very massive (10-100-1000 $M_{\odot}$)
- They contract under gravitational force
- No CNO cycle to generate the energy release and internal pressure for stabilization
- Collapse to form first supernovae



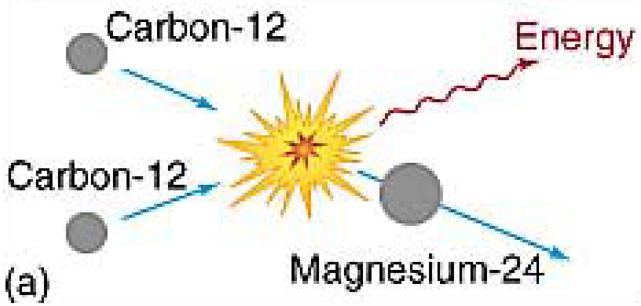
Red/orange: convective outward flow
Blue/turquoise: convective inward flow

How can carbon be formed?

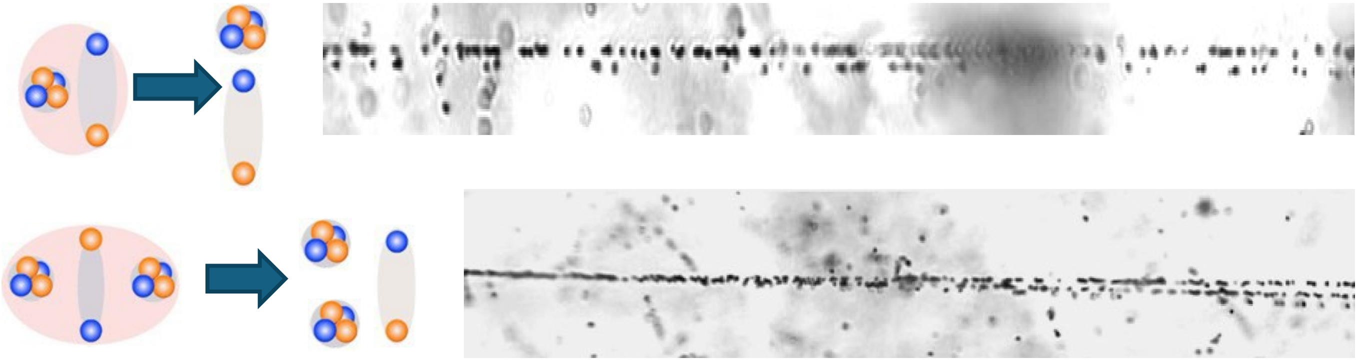
Fusion Reactions in Stars

- First stars: fusion for mid-mass elements

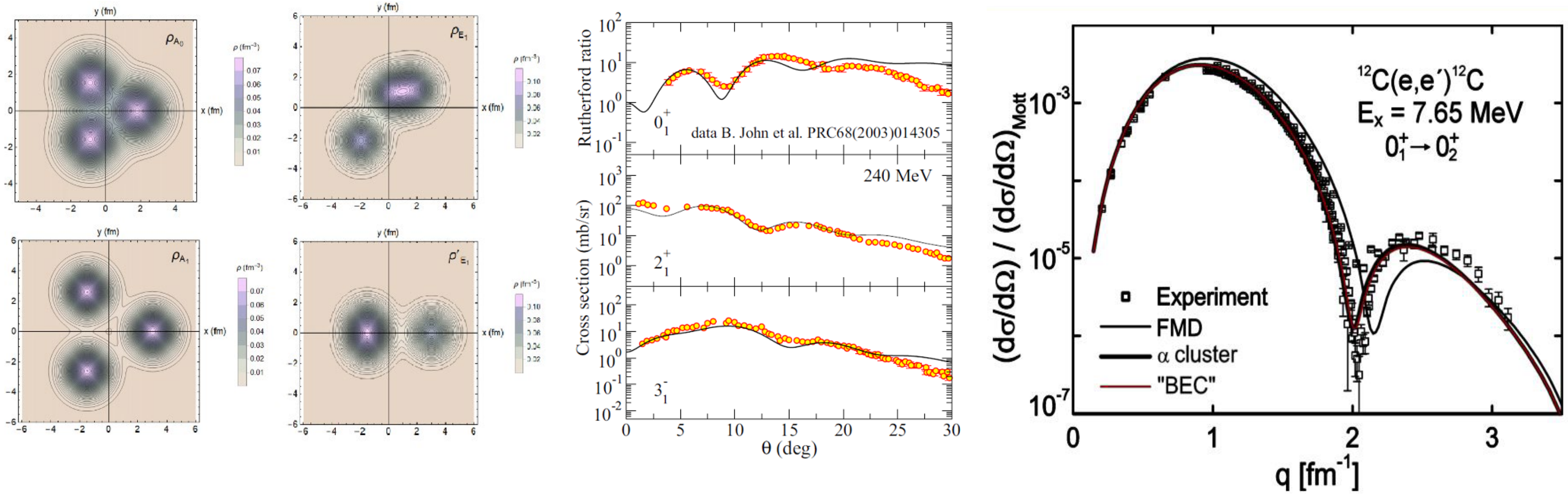
- Late stars: post-red-giant stellar evolution, carbon and oxygen burning
- Ignition of type Ia supernovae
- Ignition of superbursts



Observation of cluster configurations

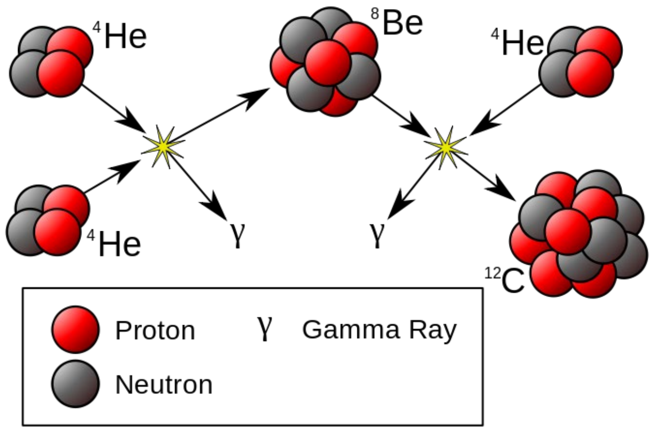


^{6}Li and ^{10}B Cosmic Ray Dissociation into d+^{4}He clusters



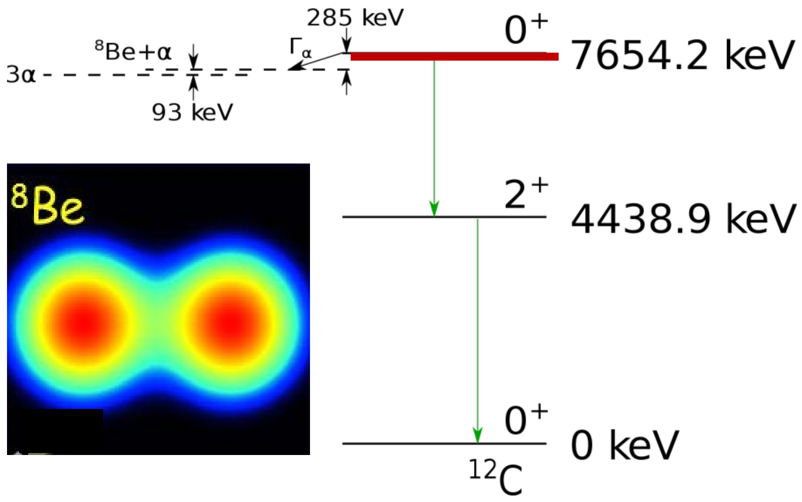
Cluster model-based cross-sections for ^{12}C(α,α’) inelastic scattering, and inelastic ^{12}C(e,e’) electron scattering data matching the alpha cluster model!

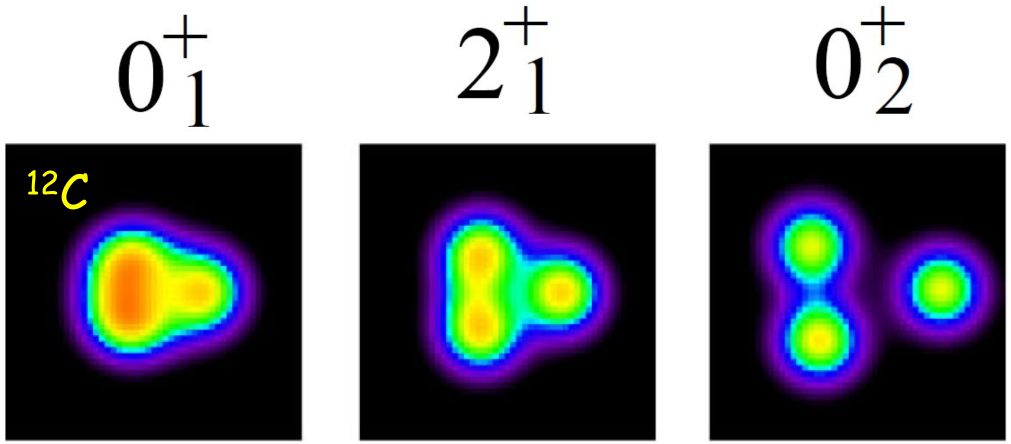
The triple-alpha-process



Three particle fusion that may occur by different reaction pathways:

- Single step process (more likely for high density environments
- Two step sequence (handicap is short-lived ^{8}Be in equilibrium abundance)
- Unbound 0^+ alpha-cluster state in ^{12}C (Hoyle state) saves the day since it adds a resonant component.

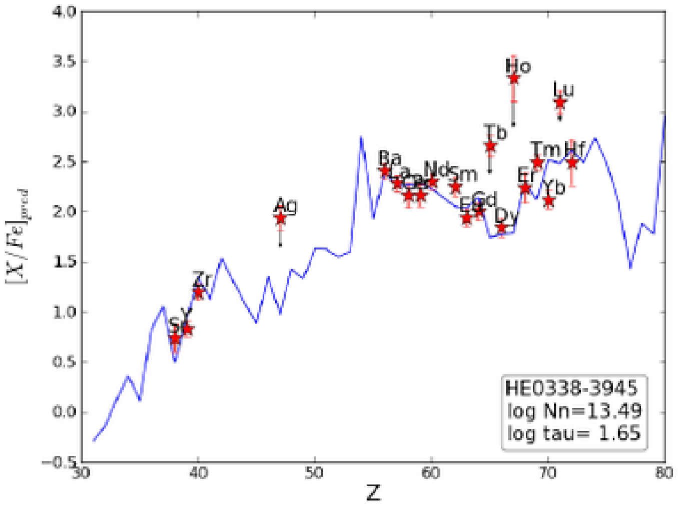


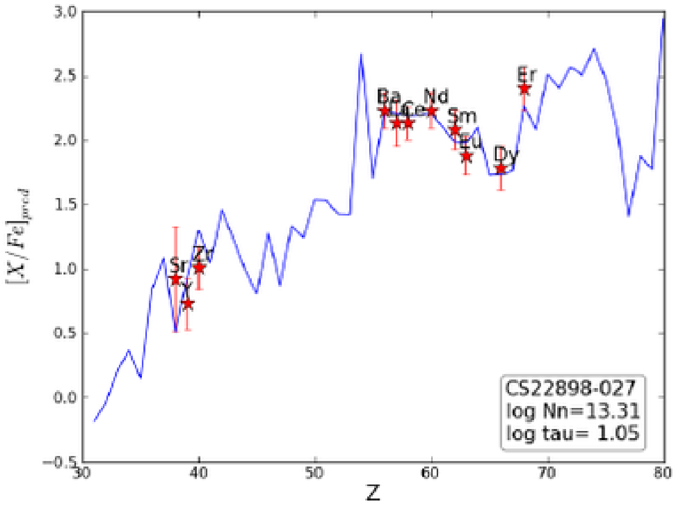


Structure simulations by Kanada En’yo and co-workers

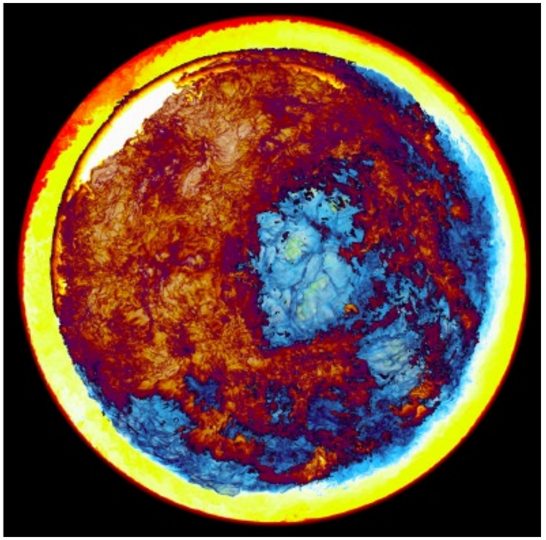
i-process simulations in early star environments

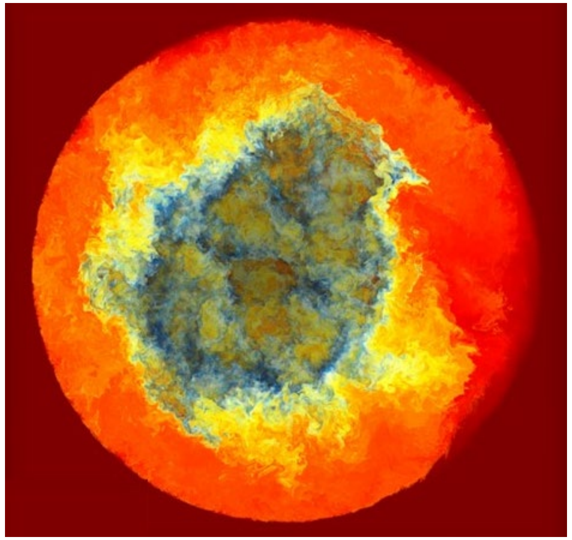
(relying on special $^{12}C(p,\gamma)^{13}N(\beta^{+})^{13}C(\alpha,n)$ neutron source driven by convective processes – see later chapters.)





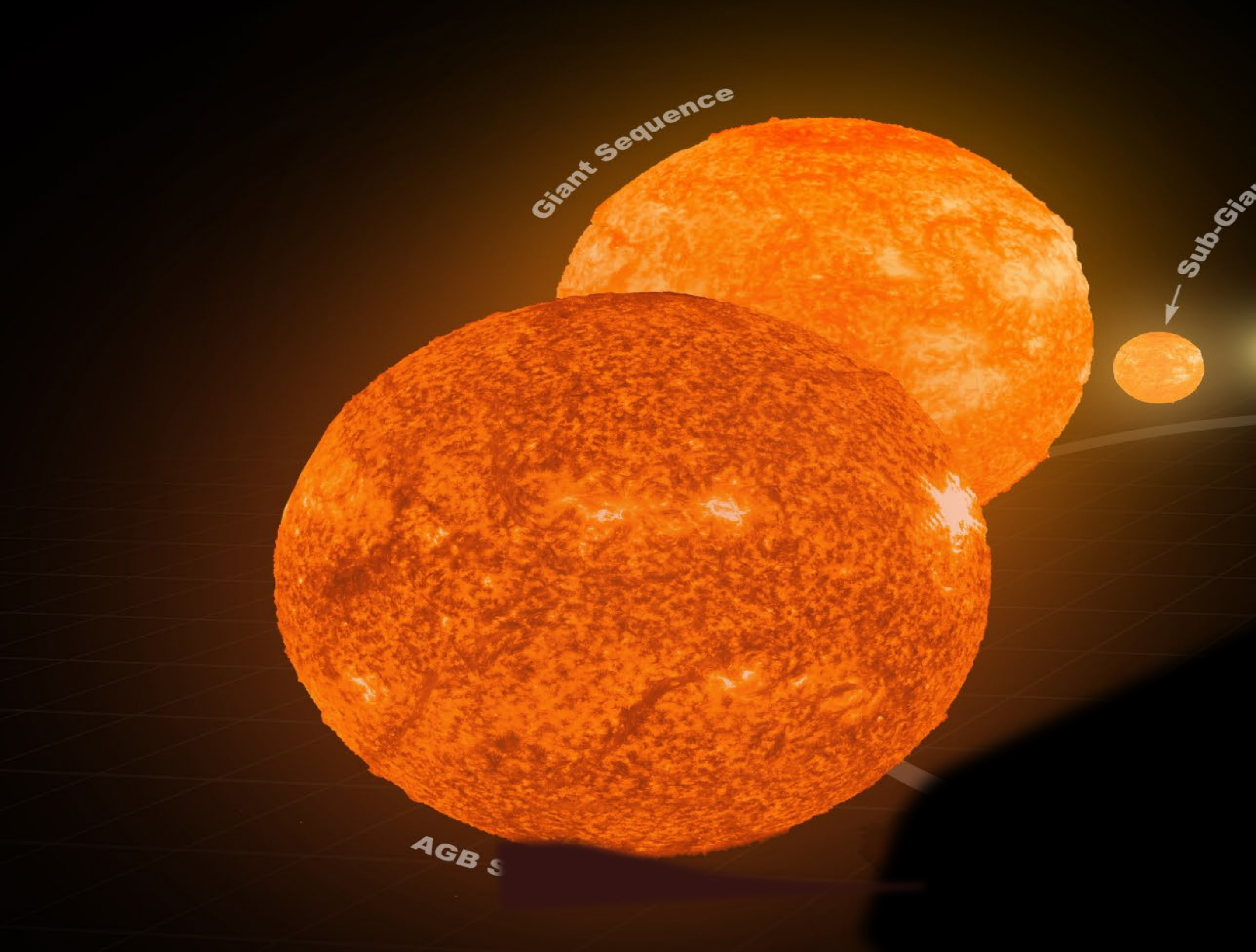
CEMP star environment with mixtures of H-rich gas and He+C-rich gas. The energy release rate from the burning of ingested H is shown in very dark blue, yellow, and white.

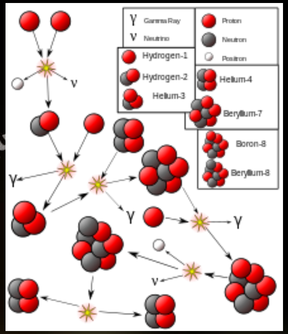


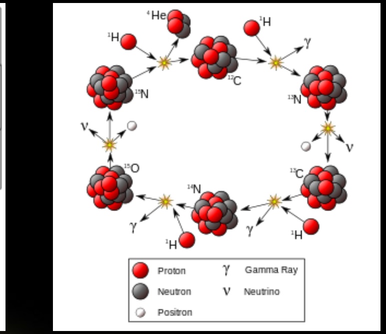


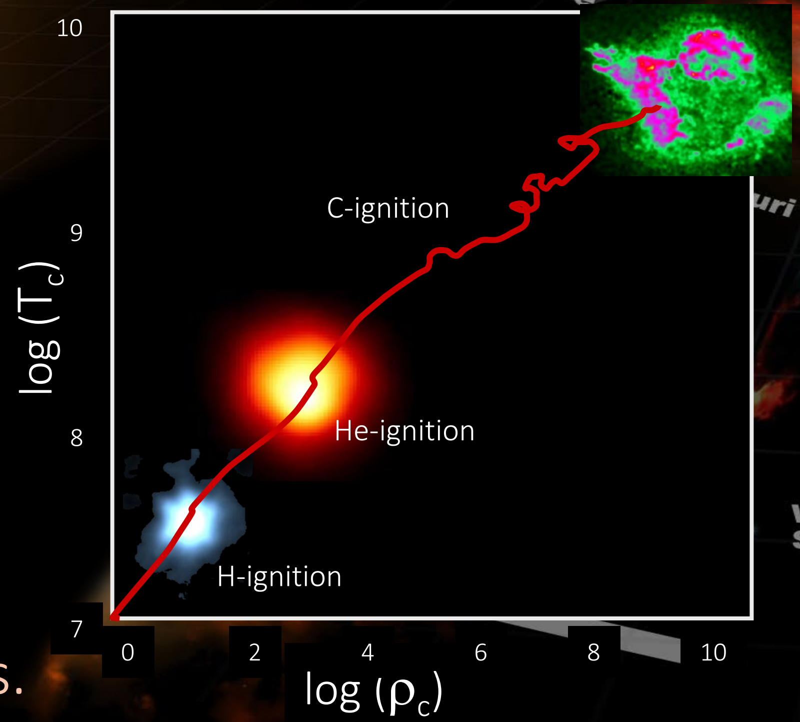
H-rich material (red-yellow- blue) concentration in a 3D hydro simulation of H ingestion into the He- shell flash convection of an accreting white dwarf.

From Hydrogen to Helium Burning.









Ashes of hydrogen burning: ^{4}He from the pp-chains and ^{4}He and ^{14}N from CNO cycles.

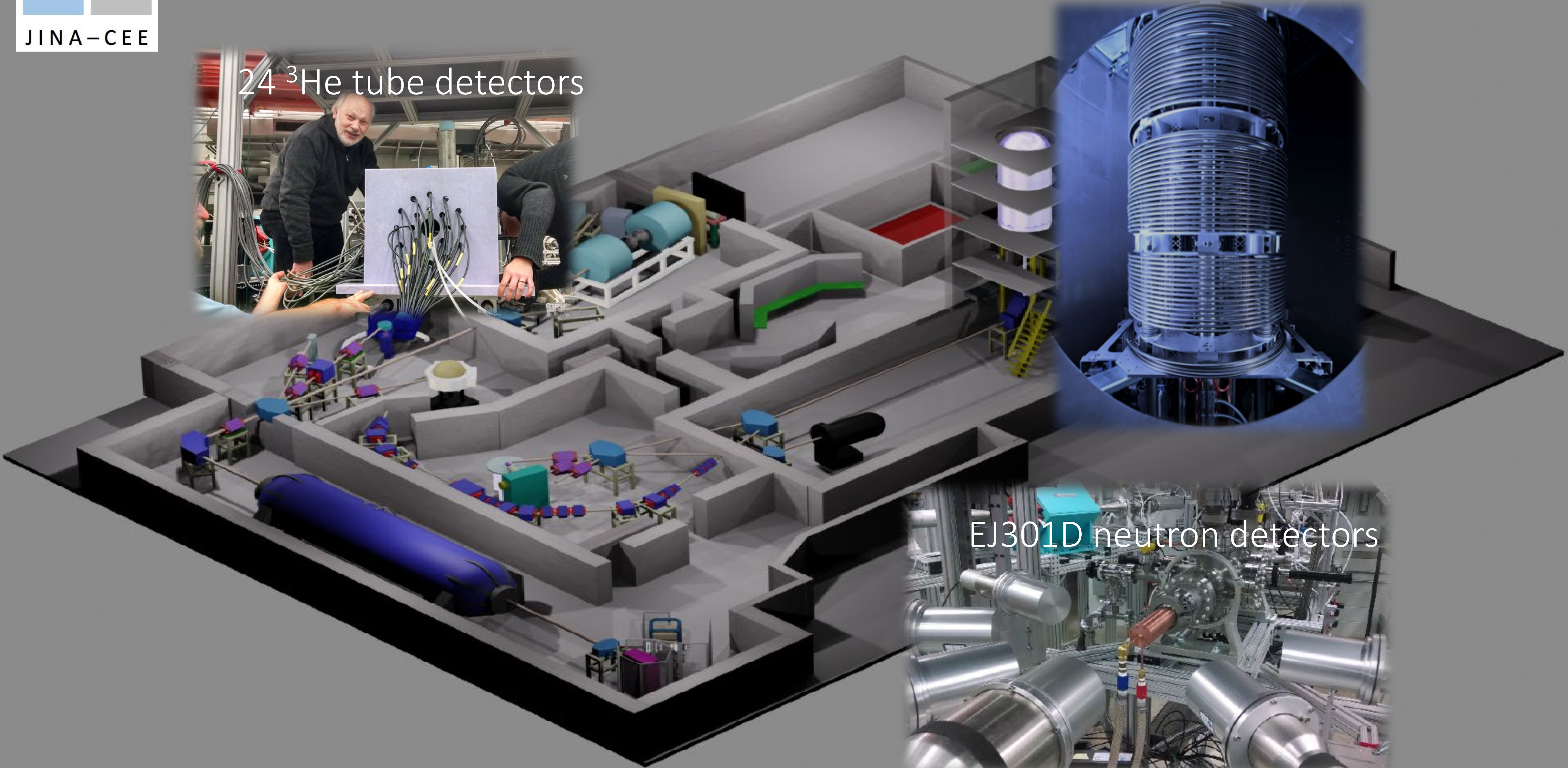
The Stellar Helium Burning

In Betelgeuse

The energy is generated by burning the ^{4}He fuel through the triple α process and the subsequent $^{12}C(\alpha,\gamma)^{16}O$ reaction.

The ^{14}N ashes of the CNO cycles is converted into neutrons and ^{25}Mg via the $^{14}N\ (\alpha,\gamma)^{18}F(\beta\nu^{+})^{18}O\ (\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ reaction sequence!

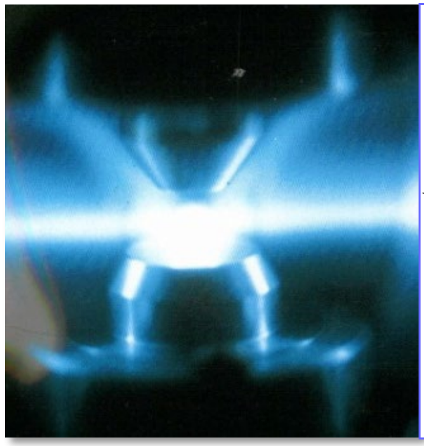
Experimental facilities at Notre Dame

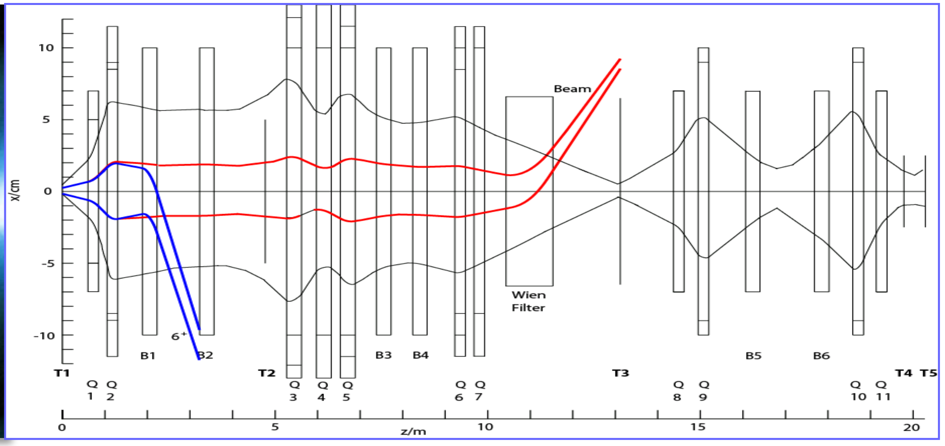


24 ^{3}He tube detectors

EJ301D neutron detectors

Counting with Separators

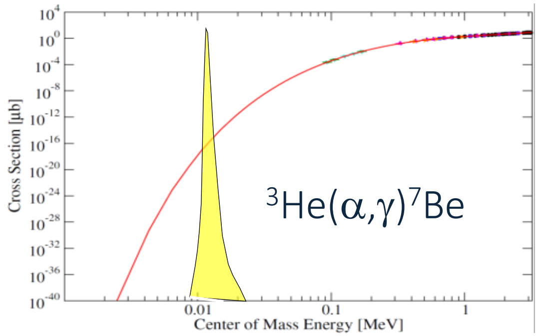


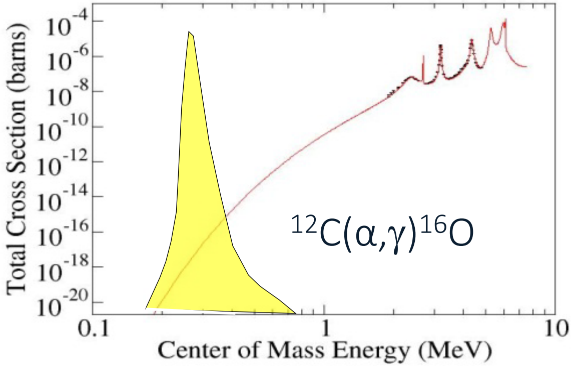


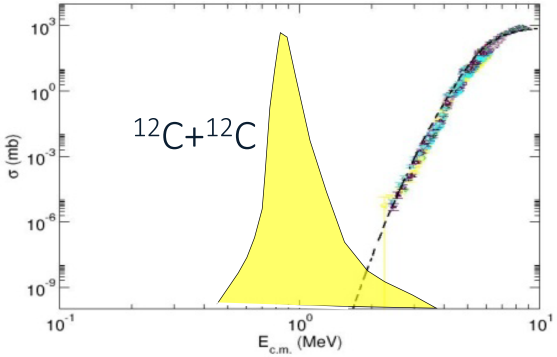
Separation ratio of reaction products to primary beam 10^{-18} !

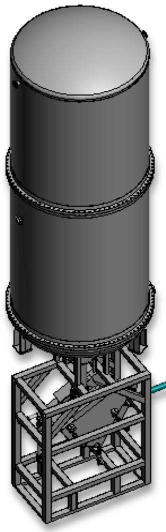
Strong **G**radient **E**lectro-magnetic **O**nline **R**ecoil separator for capture **G**amma ray **E**xperiments

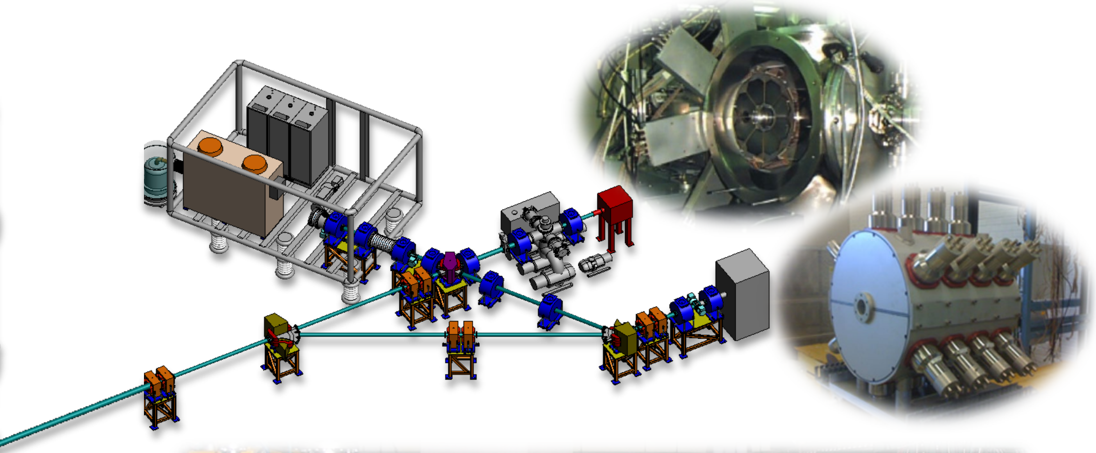
Experiments with Charged Particles

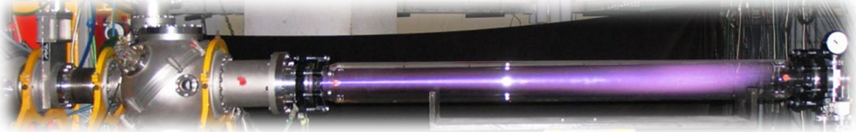




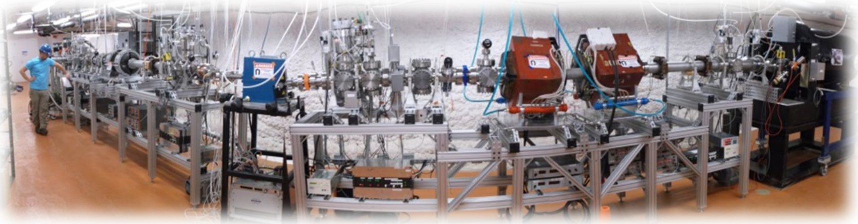




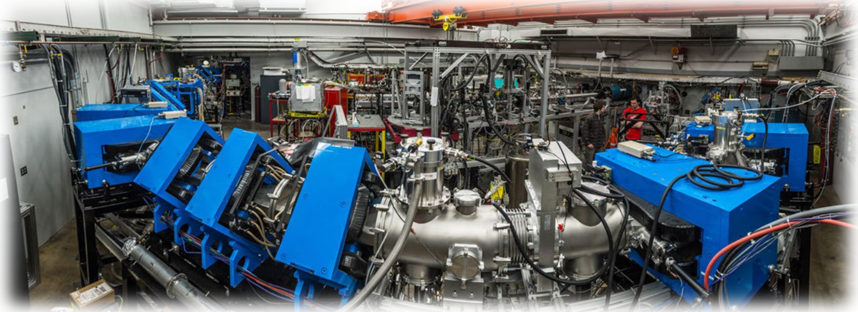




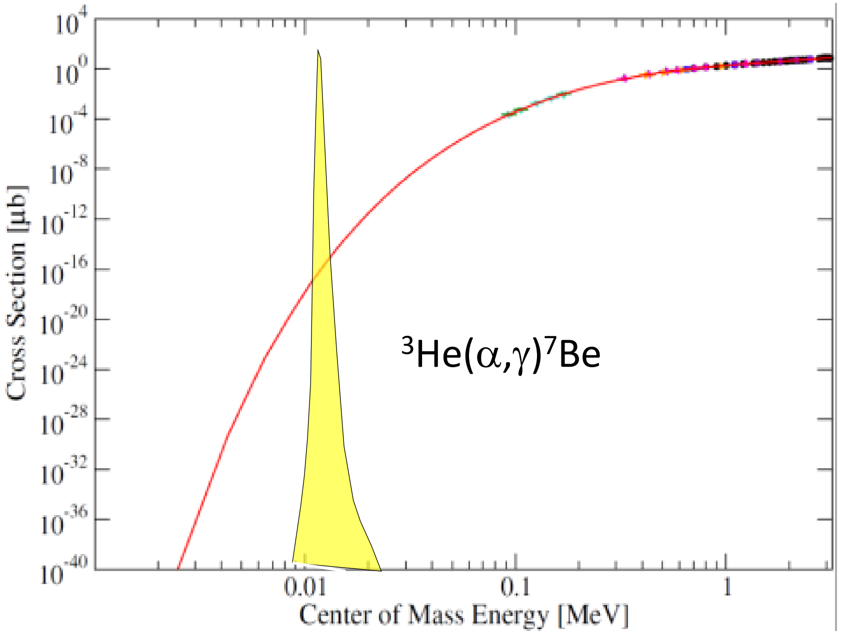
Forward kinematics underground with radiation detection

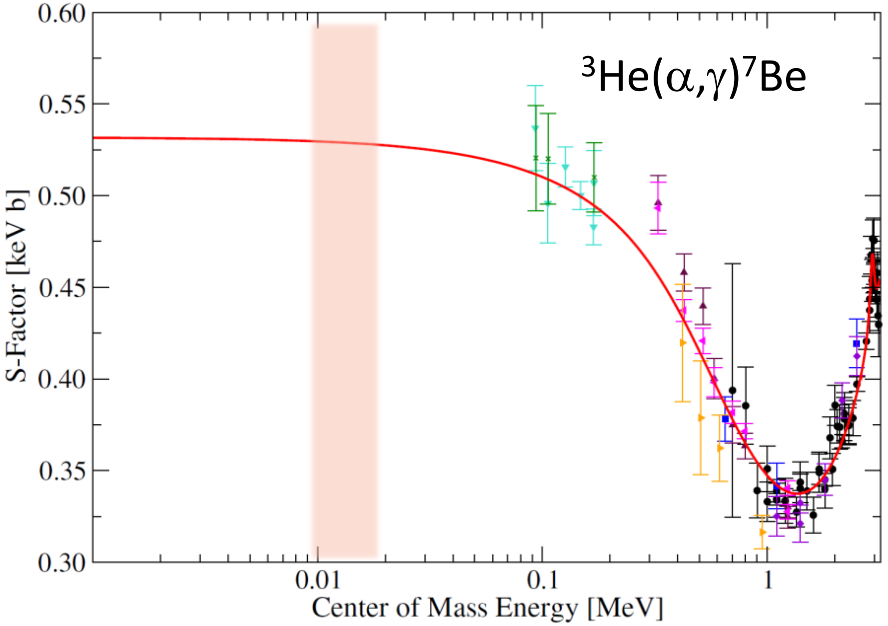


inverse kinematics with recoil separation and detection



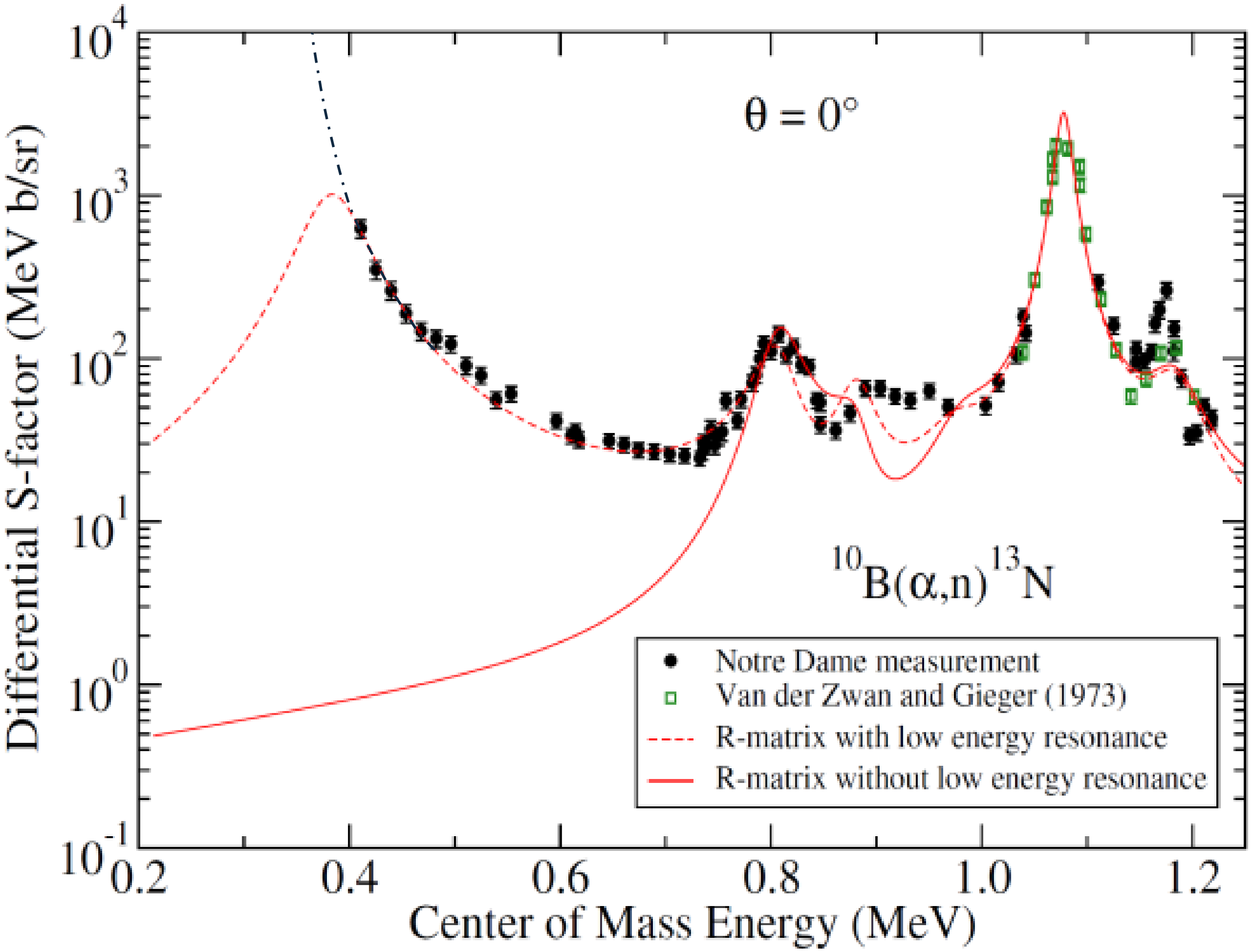
Nuclear reactions in context





A direct measurement of a charged particle cross section for stellar burning is more than unlikely! A comprehensive analysis of the reaction rate at stellar energies, requires a full understanding of the reaction mechanism and the reaction components to be fully integrated into the extrapolation process. First principle nuclear models are limited, phenomenological models (R-matrix) are limited, but multi-channel approach with a wide-range of data seem promising!

First experimental results $^{10}B(\alpha,n)^{13}N$



Further studies towards lower energies scheduled for late March 2019!

Neutron background sources are:

Cosmogenic neutrons

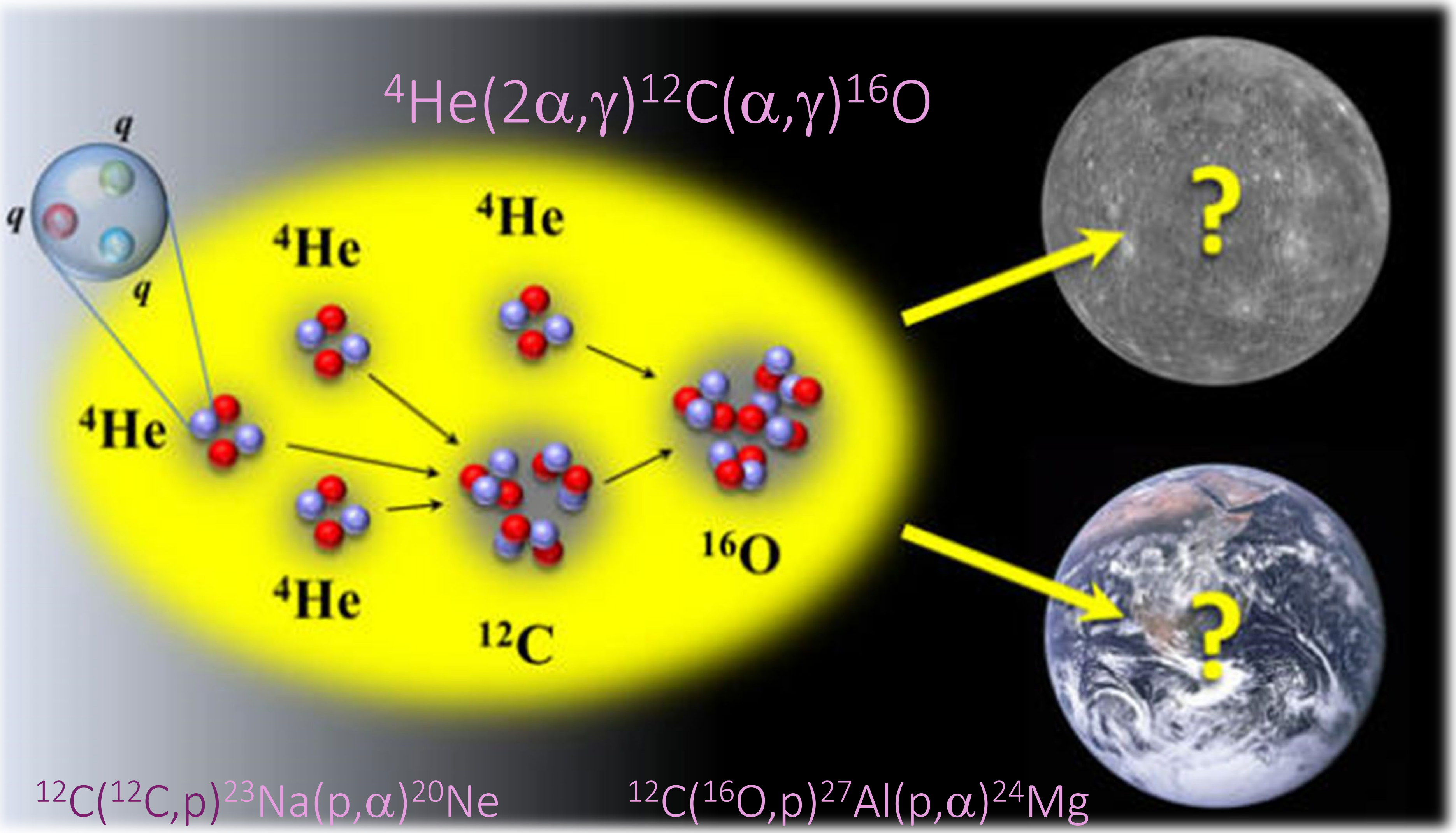
Radiogenic neutrons

Beam induced neutrons

Other reactions presently under investigation: $^{11}B(\alpha.n)$, $^{10}B(\alpha,d)$, $^{7}Li(\alpha,\gamma)$, $^{6}Li(\alpha,\gamma)$

As well as back-processing reactions: $^{10}B(p,\alpha)$

Helium Burning: The Cosmo-Chemistry of Carbon and Oxygen



$^{4}He(2\alpha,\gamma)^{12}C(\alpha,\gamma)^{16}O$

$^{12}C(^{12}C,p)^{23}Na(p,\alpha)^{20}Ne$

$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{16}O,p)^{27}Al(p,\alpha)^{24}Mg$

$^{12}C(^{16}O,\alpha)^{24}Mg$

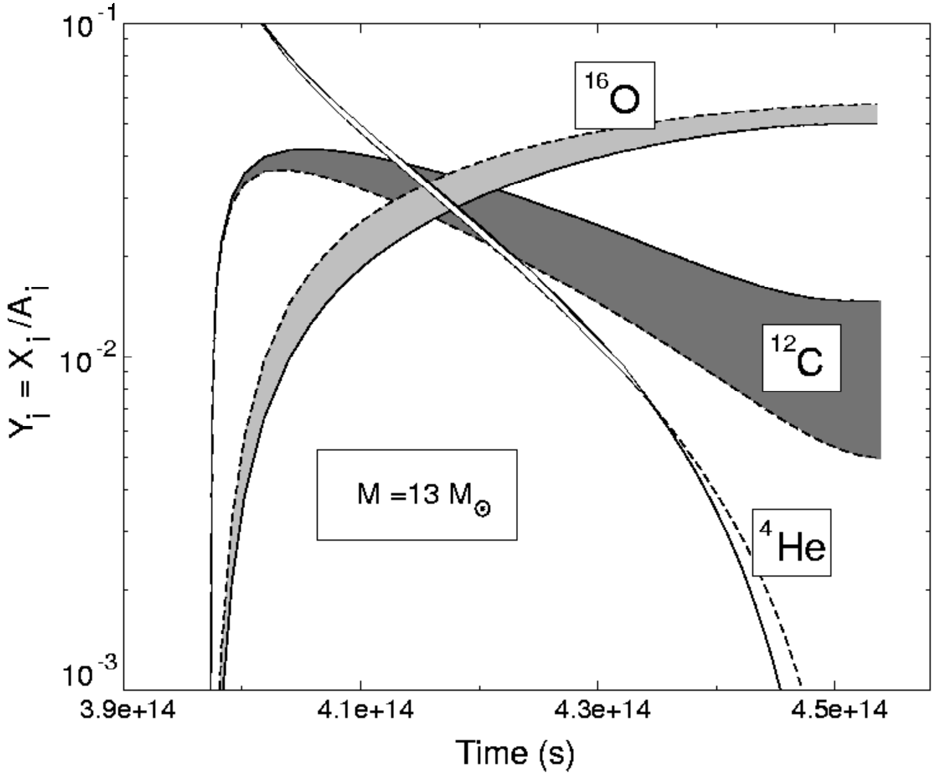
JINA–CEE

The “holy Grail”

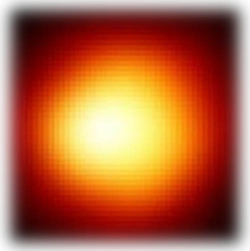
The step after carbon is being formed in a high temperature density environment:

$^{12}C(p,\gamma)^{13}N$ triggering the CNO cycle leading to **^{14}N**

$^{12}C(\alpha,\gamma)^{16}O$ determining the early **$^{12}C/^{16}O$** ratio



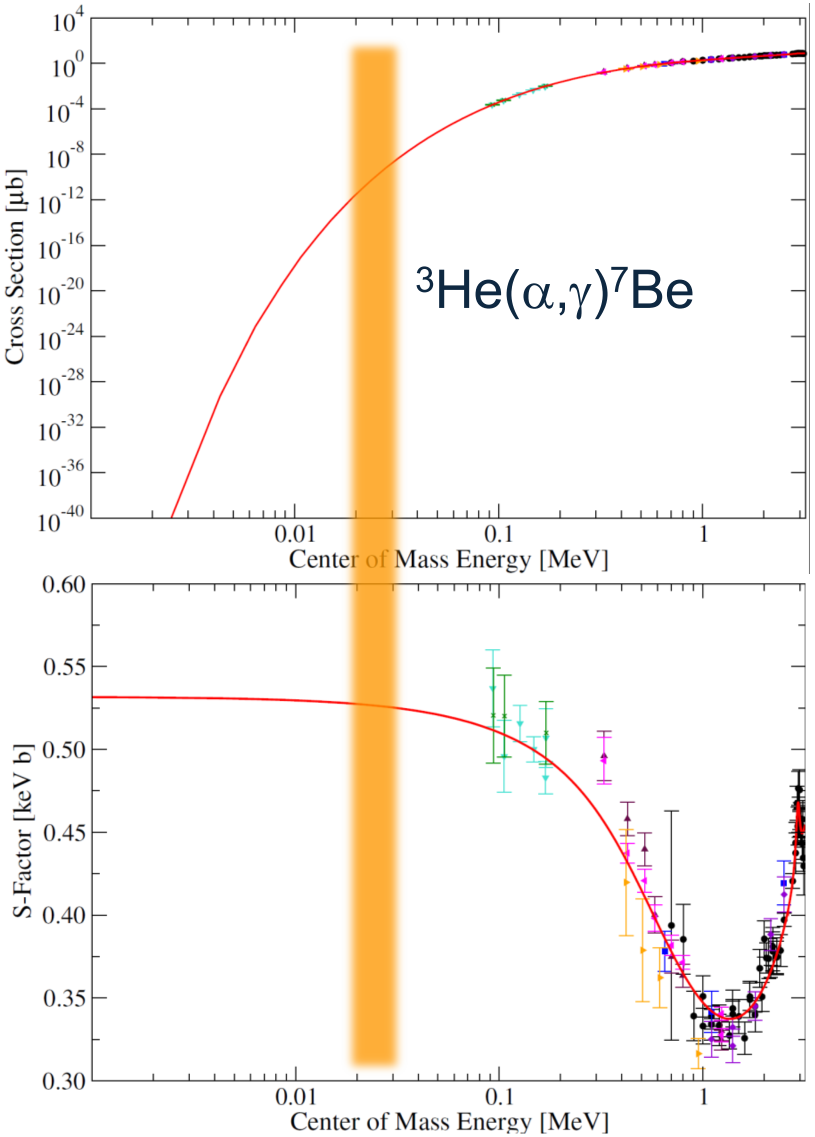
- ➢ Late Stellar Evolution
  determines Carbon and/or Oxygen phase

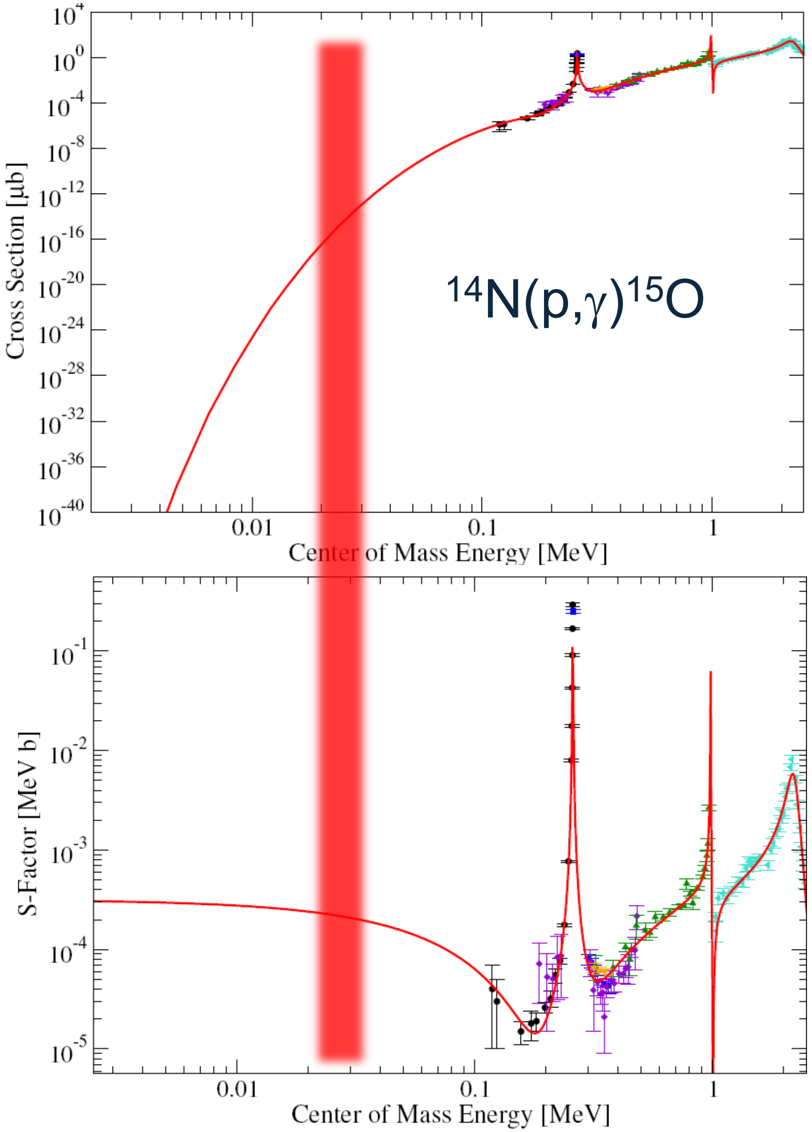


- ➢ Type Ia Supernova
  central carbon burning of C/O white dwarf

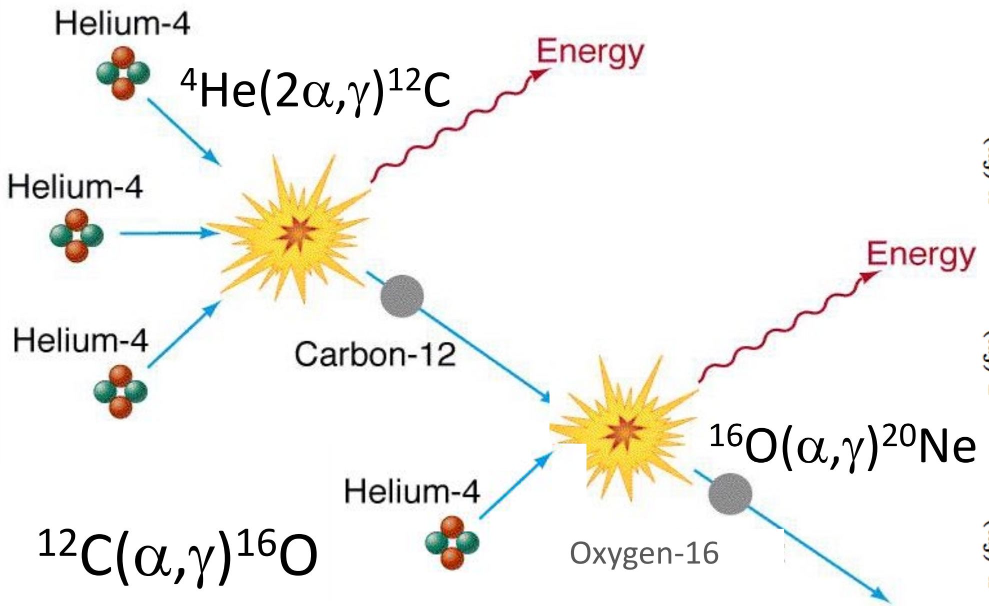
- ➢ Type II Supernova
  shock-front nucleosynthesis in C and He shells of pre-supernova star

The two most critical rates





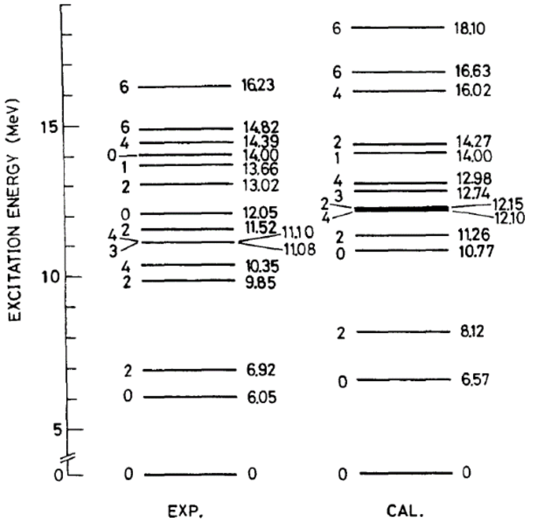
Cluster Structure of ^{16}O

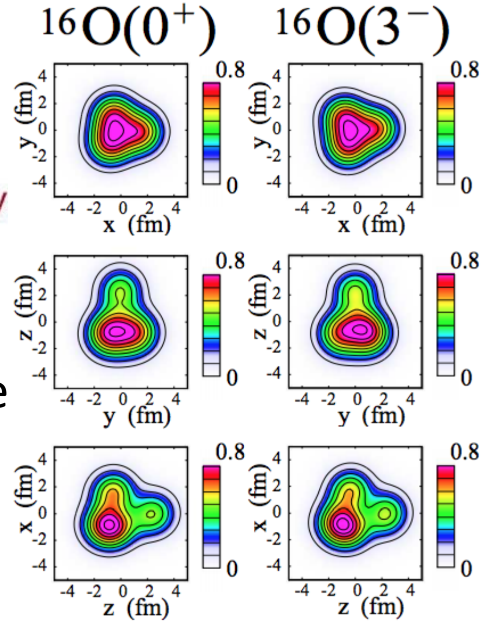


$^{4}He(2\alpha,\gamma)^{12}C$

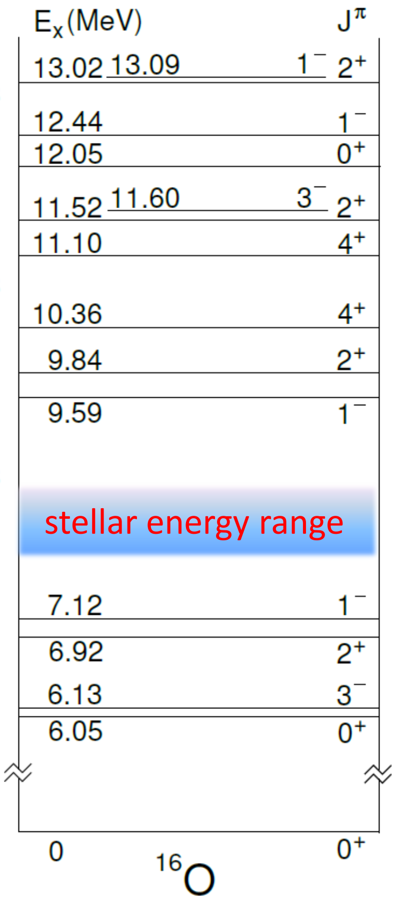
$^{16}O(\alpha,\gamma)^{20}Ne$

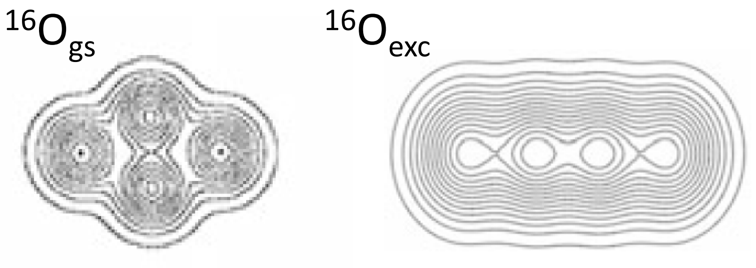
$^{12}C(\alpha,\gamma)^{16}O$





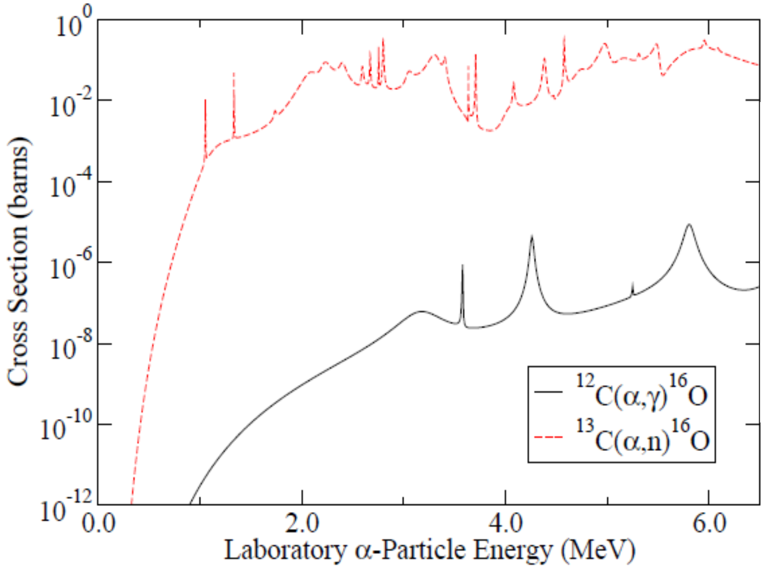
Structure simulations by Kanada En'yo et al.



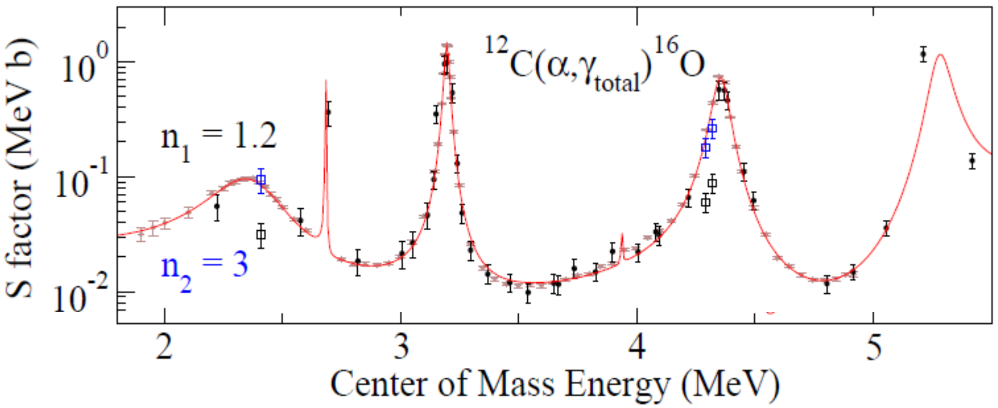


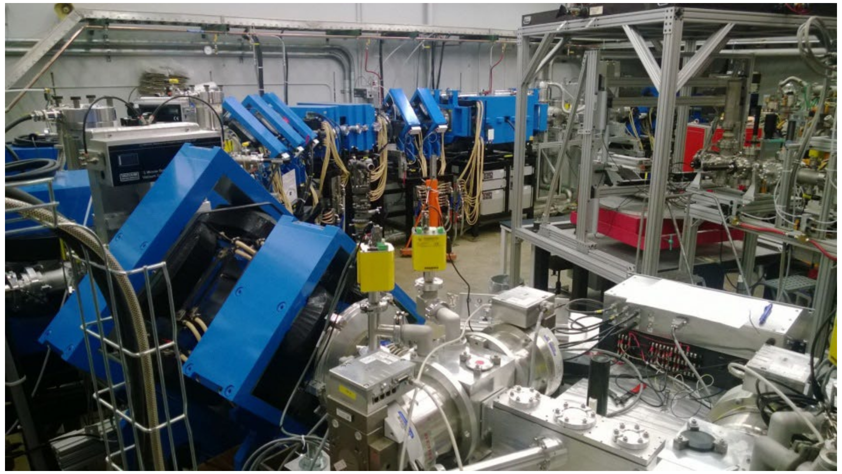
Alpha cluster structure configurations in ^{16}O

Experimental Efforts > 50 yrs

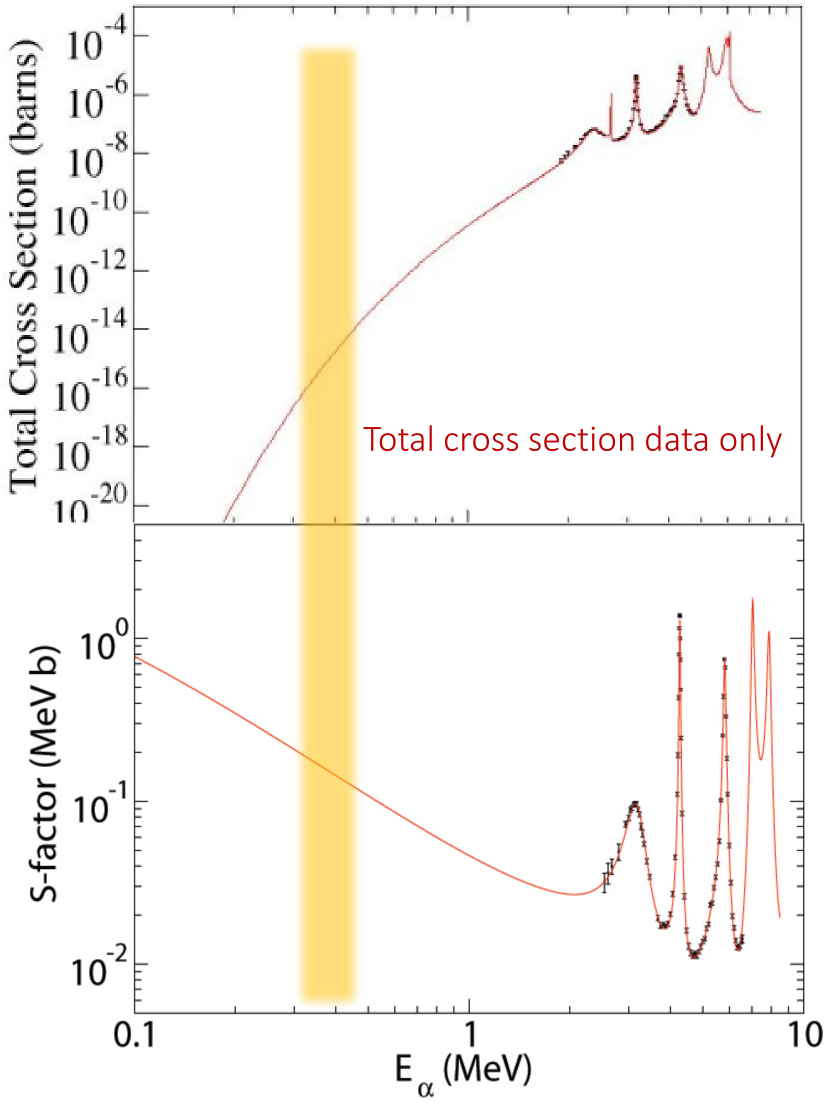


Conversion of cross section data to S-factor

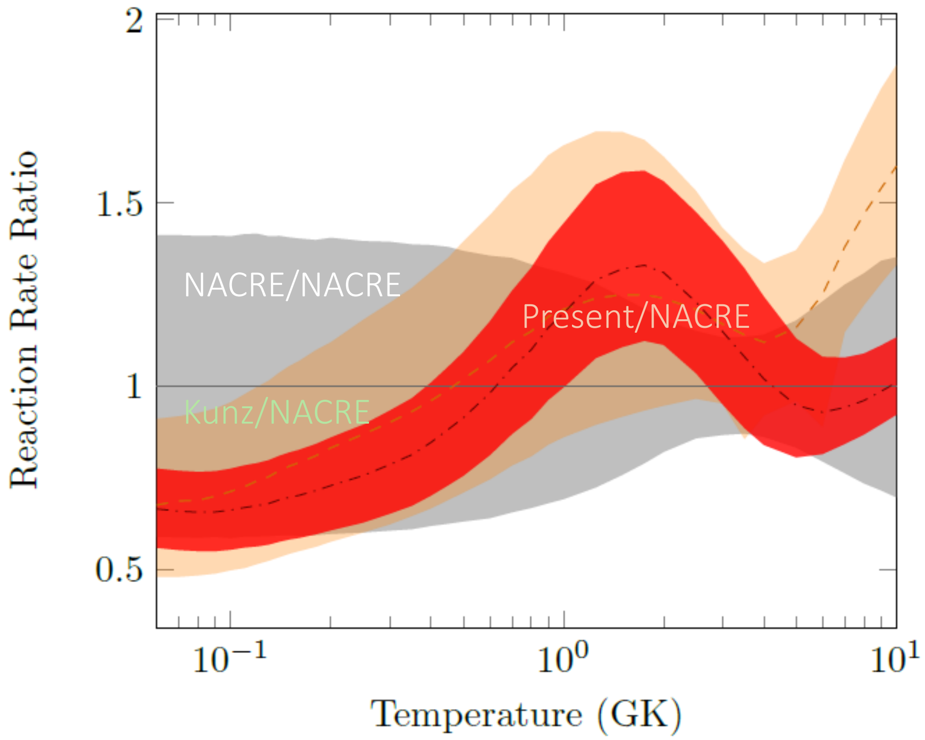




R-Matrix Analysis phenomenology, but …

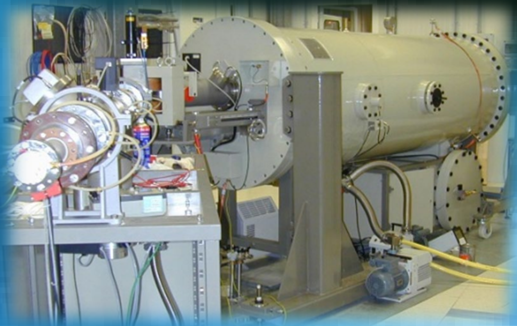


Total cross section data only



R-matrix (AZURE) based cross section extrapolation on the basis of all existing reaction data through ^{16}O compound nucleus give 15%-20% uncertainty in reaction rate extrapolation.

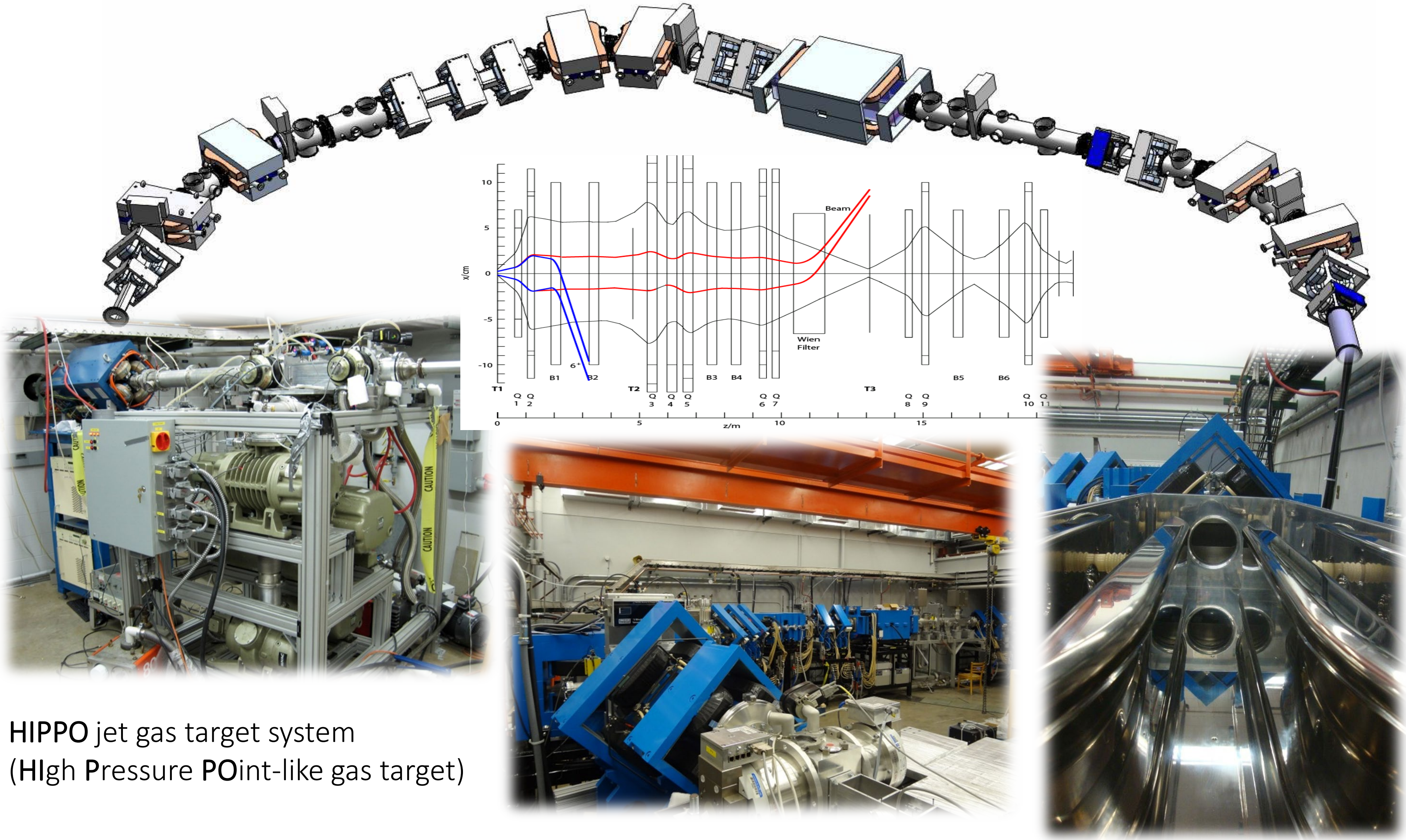
Experimental Techniques



Laboratory based nucleosynthesis

St. George Separator

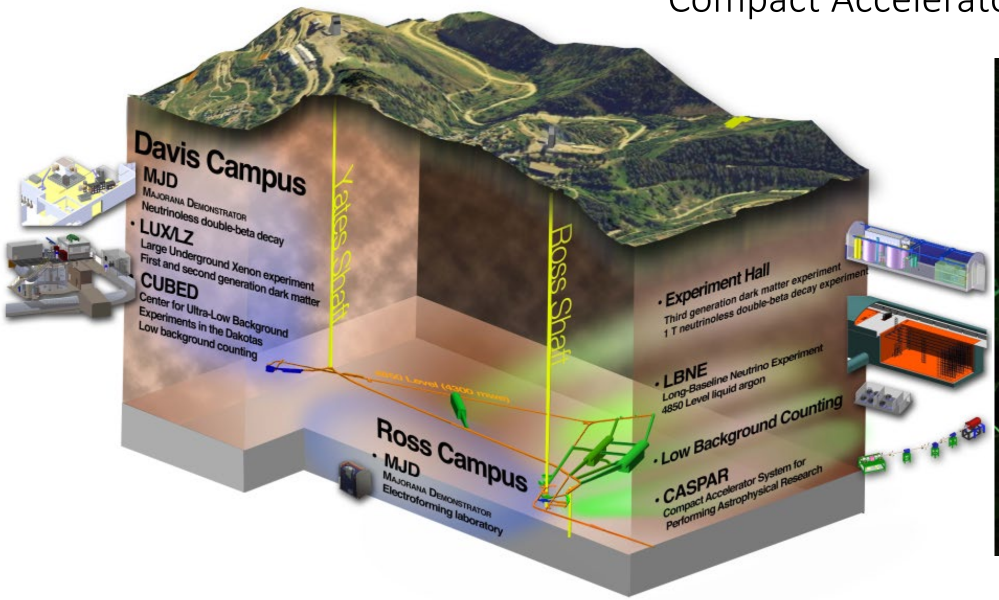
Strong **G**radient **E**lectro-magnetic **O**nline **R**ecoil separator for capture **G**amma ray **E**xperiments

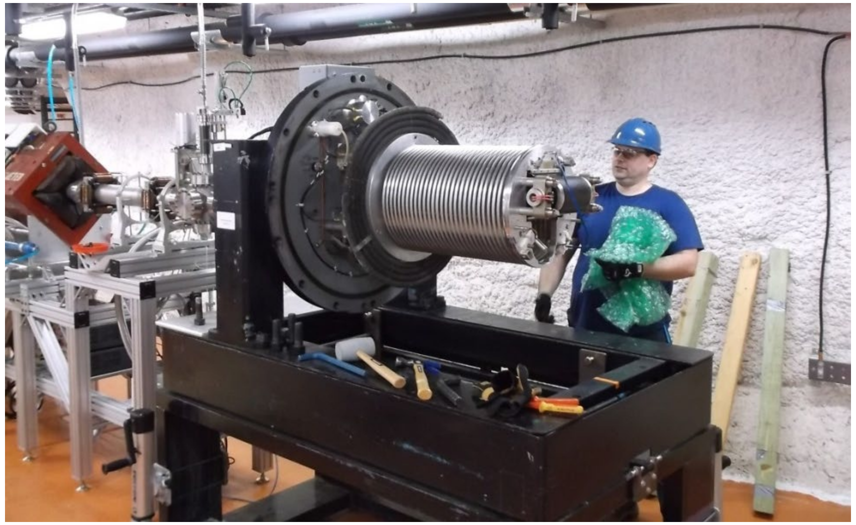


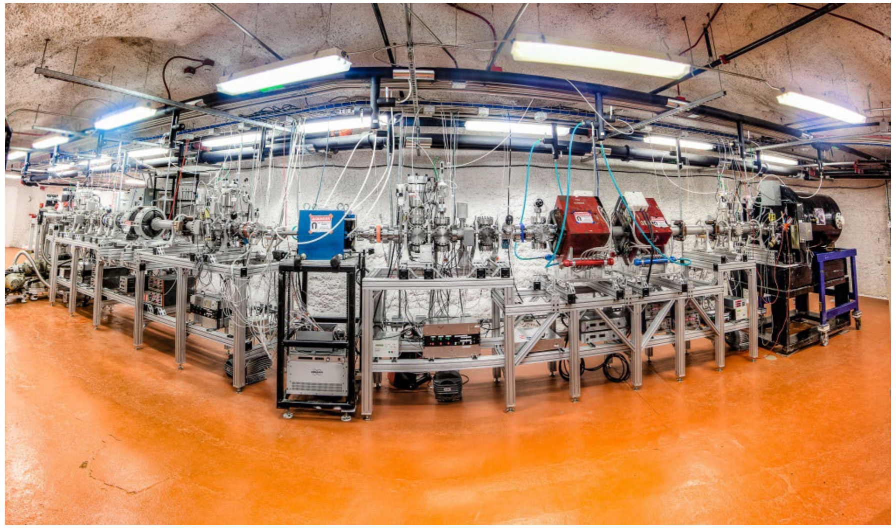
HIPPO jet gas target system
(**HI**gh **P**ressure **PO**int-like gas target)

CASPAR underground accelerator

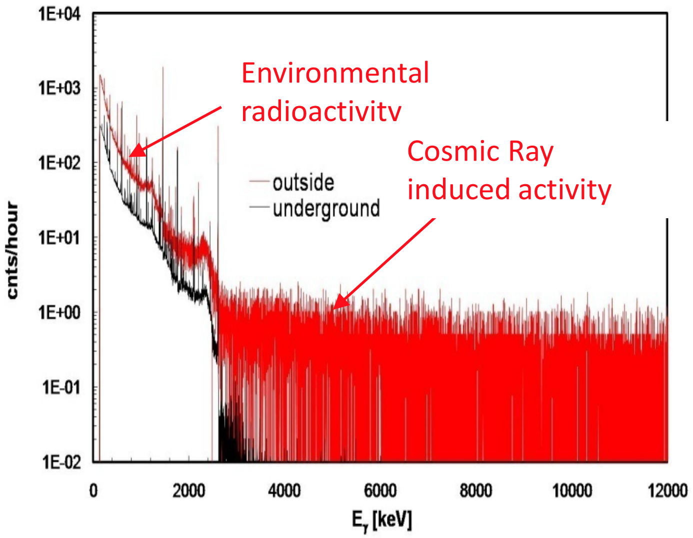
Compact Accelerator for Performing Astrophysical Research





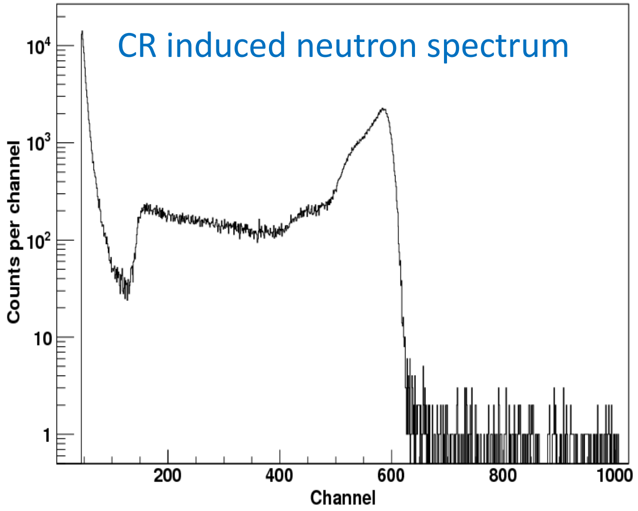


Advantage of underground physics

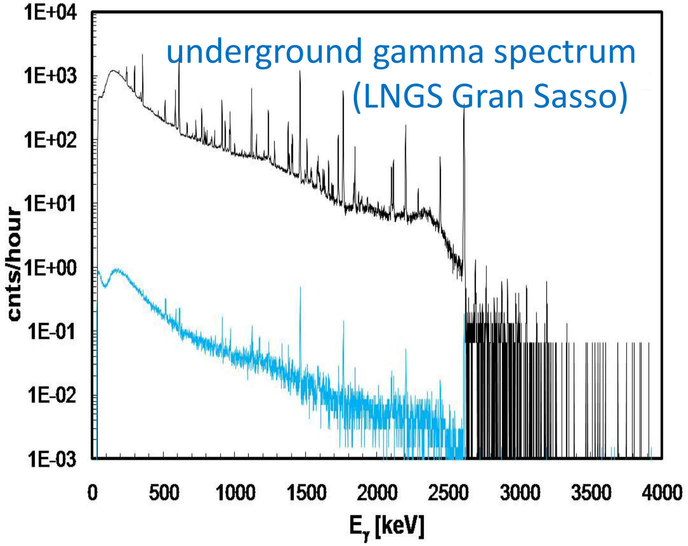


Environmental radioactivity

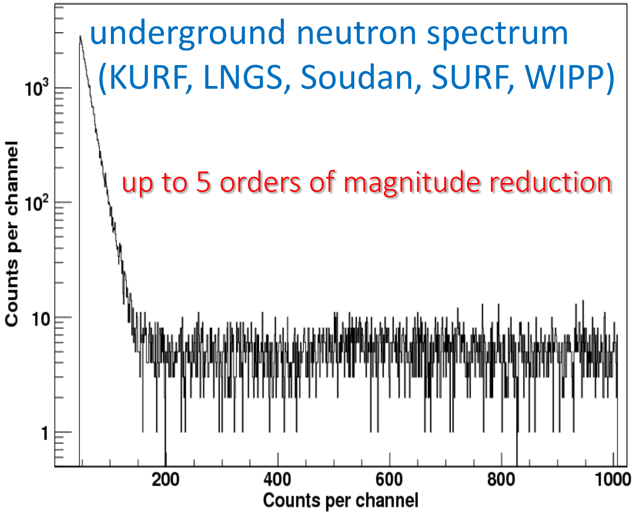
Cosmic Ray induced activity



CR induced neutron spectrum



underground gamma spectrum (LNGS Gran Sasso)



underground neutron spectrum (KURF, LNGS, Soudan, SURF, WIPP)

up to 5 orders of magnitude reduction

Summary

- Improvements in astronomical and cosmo-chemical observation techniques drive field
- Nuclear reaction rates remain a dominant uncertainty for reliable model predictions
- Cluster structure configurations dictate helium burning reaction strength
- Alternative indirect experimental techniques from ANC to THM measurements should be utilized.
- New experimental initiatives using either recoil techniques or background free deep underground facilities open new opportunities