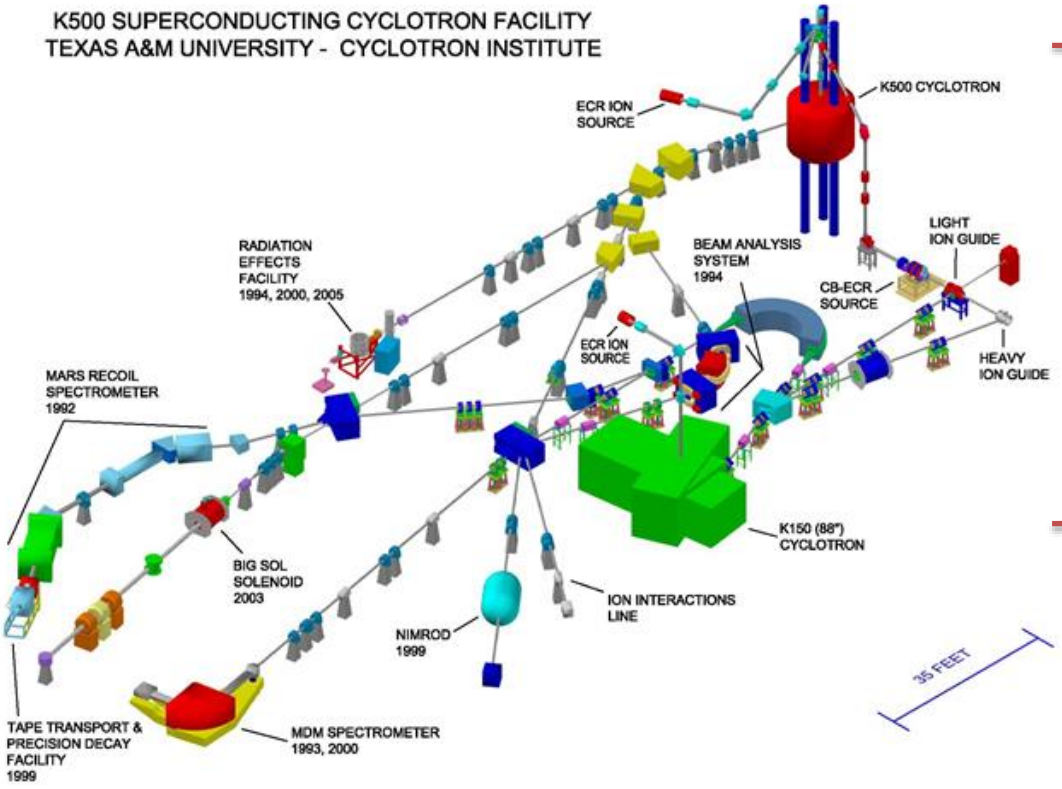
Nuclear Reactions
Where Would We Be Without Them?

J. Natowitz



T-REX

[TAMU **Re**accelerated **EX**otics]

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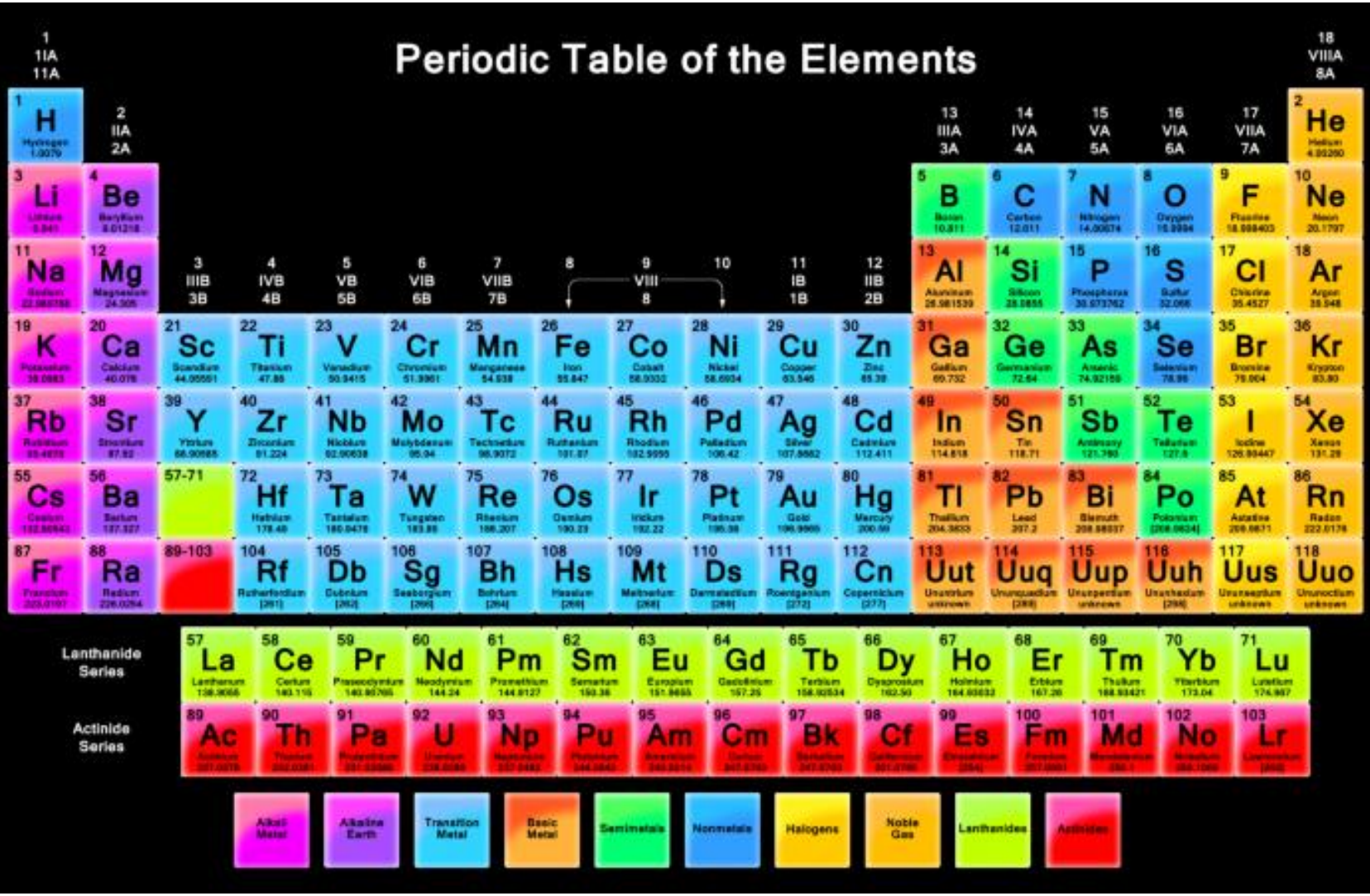
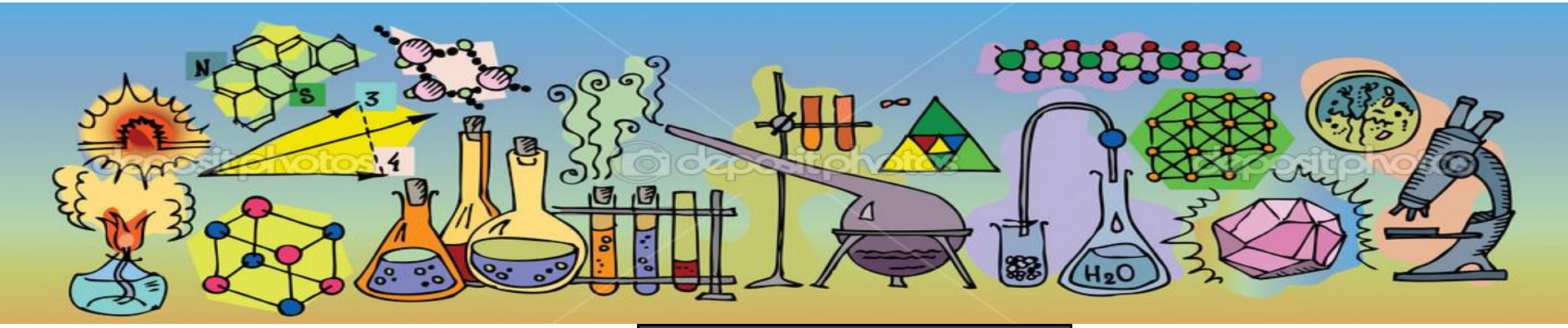
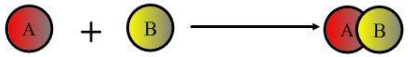
T-REX


Periodic Table of the Elements
1 1IA 11A
2 IIA 2A
3 IIIB 3B
4 IVB 4B
5 VB 5B
6 VIB 6B
7 VIIB 7B
8 9 VIII 8 10
11 IB 1B
12 IIB 2B
13 IIIA 3A
14 IVA 4A
15 VA 5A
16 VIA 6A
17 VIIA 7A
18 VIIIA 8A
H Hydrogen 1.0079
He Helium 4.00260
Li Lithium 6.941
Be Beryllium 9.01218
B Boron 10.811
C Carbon 12.011
N Nitrogen 14.00674
O Oxygen 15.9994
F Fluorine 18.998403
Ne Neon 20.1797
Na Sodium 22.989769
Mg Magnesium 24.305
Al Aluminum 26.981539
Si Silicon 28.0855
P Phosphorus 30.973762
S Sulfur 32.066
Cl Chlorine 35.4527
Ar Argon 39.948
K Potassium 39.0983
Ca Calcium 40.078
Sc Scandium 44.95591
Ti Titanium 47.88
V Vanadium 50.9415
Cr Chromium 51.9961
Mn Manganese 54.938
Fe Iron 55.847
Co Cobalt 58.9332
Ni Nickel 58.6934
Cu Copper 63.546
Zn Zinc 65.39
Ga Gallium 69.732
Ge Germanium 72.64
As Arsenic 74.92159
Se Selenium 78.96
Br Bromine 79.904
Kr Krypton 83.80
Rb Rubidium 85.4678
Sr Strontium 87.62
Y Yttrium 88.90585
Zr Zirconium 91.224
Nb Niobium 92.90638
Mo Molybdenum 95.94
Tc Technetium 98.9072
Ru Ruthenium 101.07
Rh Rhodium 102.9055
Pd Palladium 106.42
Ag Silver 107.8682
Cd Cadmium 112.411
In Indium 114.818
Sn Tin 118.71
Sb Antimony 121.760
Te Tellurium 127.6
I Iodine 126.90447
Xe Xenon 131.29
Cs Cesium 132.90543
Ba Barium 137.327
57-71
Hf Hafnium 178.49
Ta Tantalum 180.9479
W Tungsten 183.85
Re Rhenium 186.207
Os Osmium 190.23
Ir Iridium 192.22
Pt Platinum 195.08
Au Gold 196.9665
Hg Mercury 200.59
Tl Thallium 204.3833
Pb Lead 207.2
Bi Bismuth 208.98037
Po Polonium [208.9824]
At Astatine 209.9871
Rn Radon 222.0176
Fr Francium 223.0197
Ra Radium 226.0254
89-103
Rf Rutherfordium [261]
Db Dubnium [262]
Sg Seaborgium [266]
Bh Bohrium [264]
Hs Hassium [269]
Mt Meitnerium [268]
Ds Darmstadtium [269]
Rg Roentgenium [272]
Cn Copernicium [277]
Uut Ununtrium unknown
Uuq Ununquadium [289]
Uup Ununpentium unknown
Uuh Ununhexium [293]
Uus Ununseptium unknown
Uuo Ununoctium unknown
Lanthanide Series
La Lanthanum 138.9055
Ce Cerium 140.116
Pr Praseodymium 140.90765
Nd Neodymium 144.24
Pm Promethium 144.9127
Sm Samarium 150.36
Eu Europium 151.9655
Gd Gadolinium 157.25
Tb Terbium 158.92534
Dy Dysprosium 162.50
Ho Holmium 164.93032
Er Erbium 167.26
Tm Thulium 168.93421
Yb Ytterbium 173.04
Lu Lutetium 174.967
Actinide Series
Ac Actinium 227.0278
Th Thorium 232.0381
Pa Protactinium 231.03588
U Uranium 238.0289
Np Neptunium 237.0482
Pu Plutonium 244.0642
Am Americium 243.0614
Cm Curium 247.0703
Bk Berkelium 247.0703
Cf Californium 251.0796
Es Einsteinium [254]
Fm Fermium 257.0951
Md Mendelevium [258]
No Nobelium [259.1009]
Lr Lawrencium [262]
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetals
Nonmetals
Halogens
Noble Gas
Lanthanides
Actinides

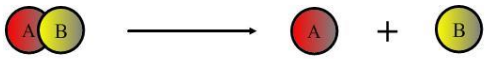


Types of Chemical Reactions

A) Synthesis Reactions: two reactants combine to make a larger product

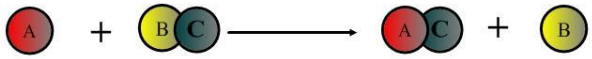


B) Decomposition Reactions: larger reactant breaks down to form 2 or more simple products



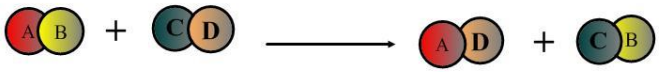
C) Single Displacement Reactions:

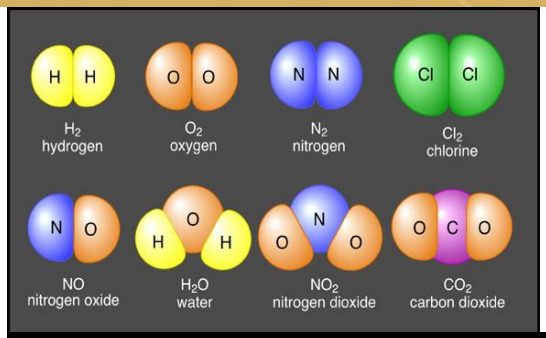
one element displaces or replaces an element in a compound

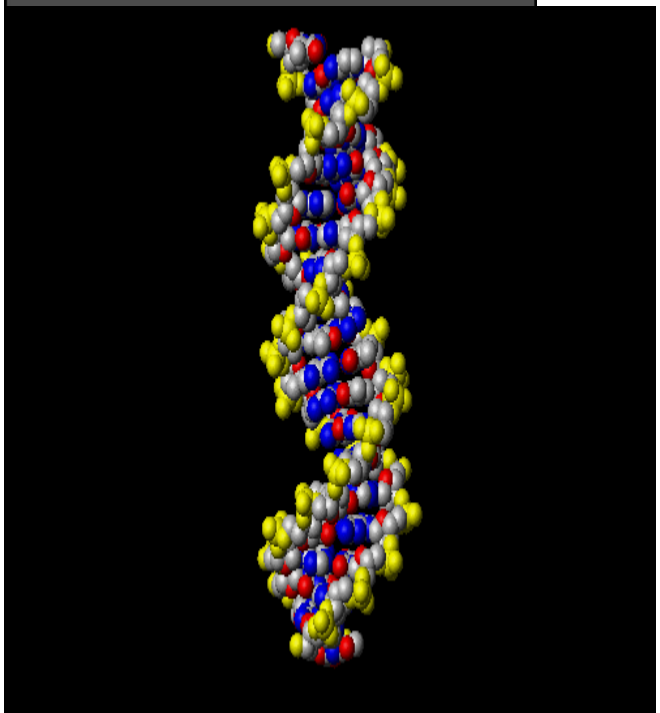


D) Double Displacement Reactions:

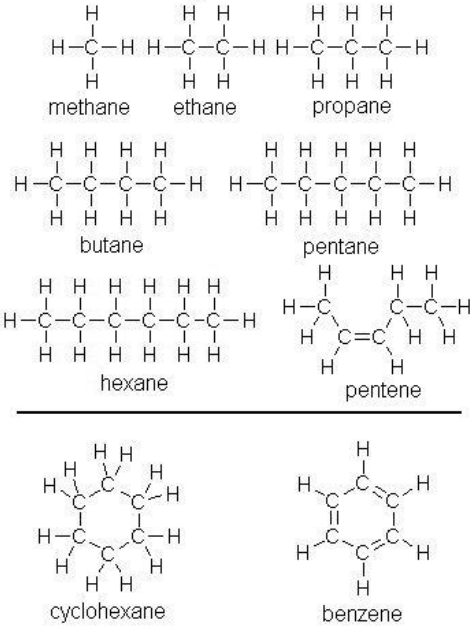
two elements in different compounds trade places

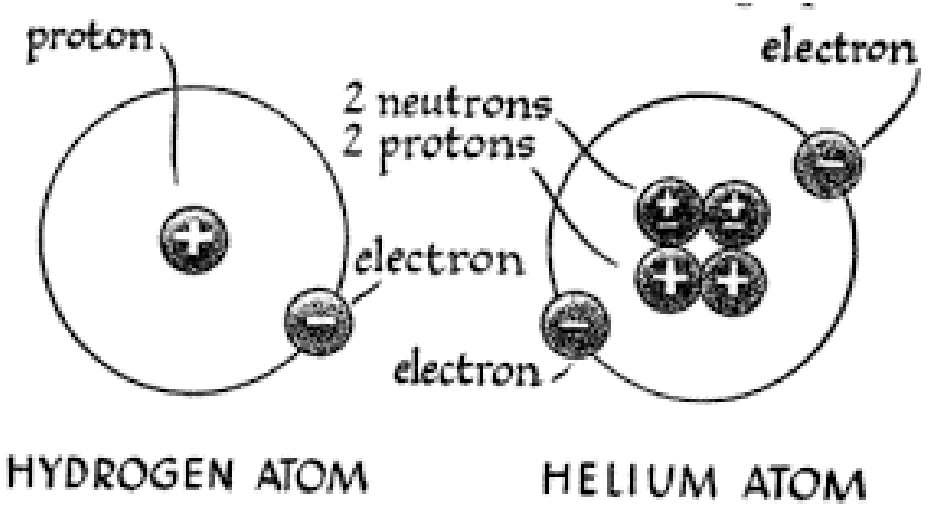




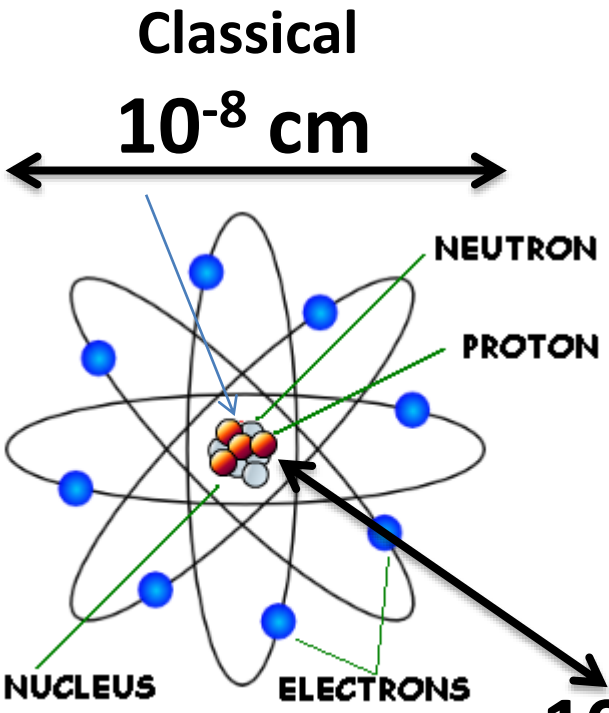


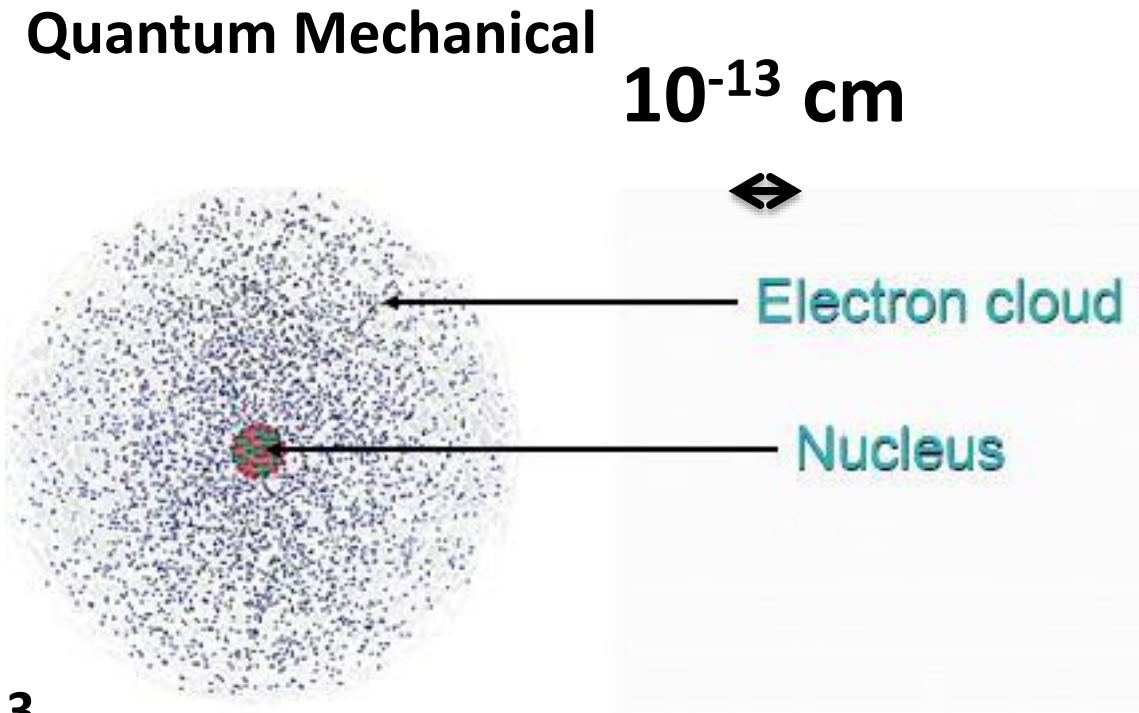
Some Organic Molecules



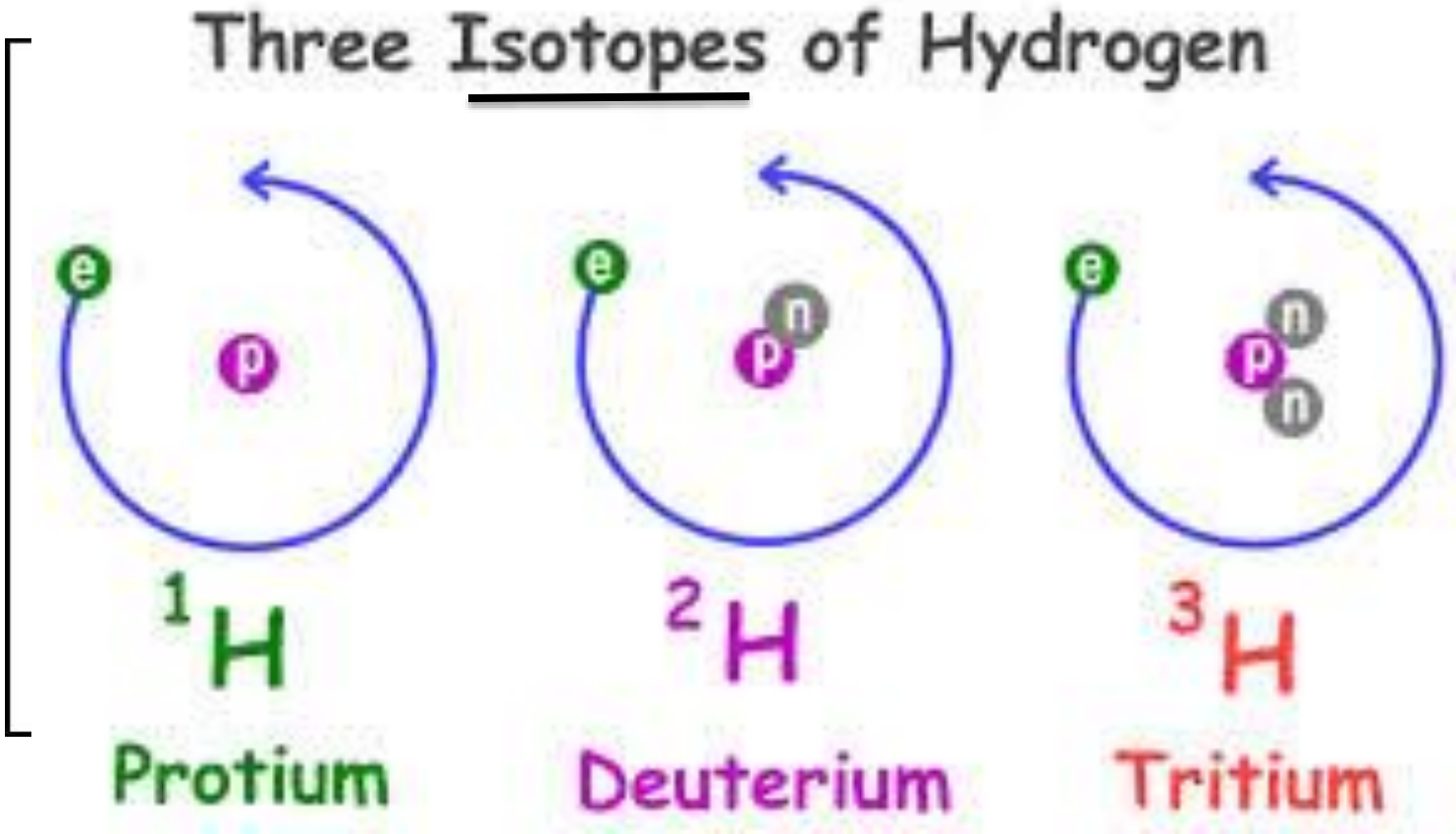

proton
electron
2 neutrons
2 protons
electron
electron
HYDROGEN ATOM
HELIUM ATOM

The Atom

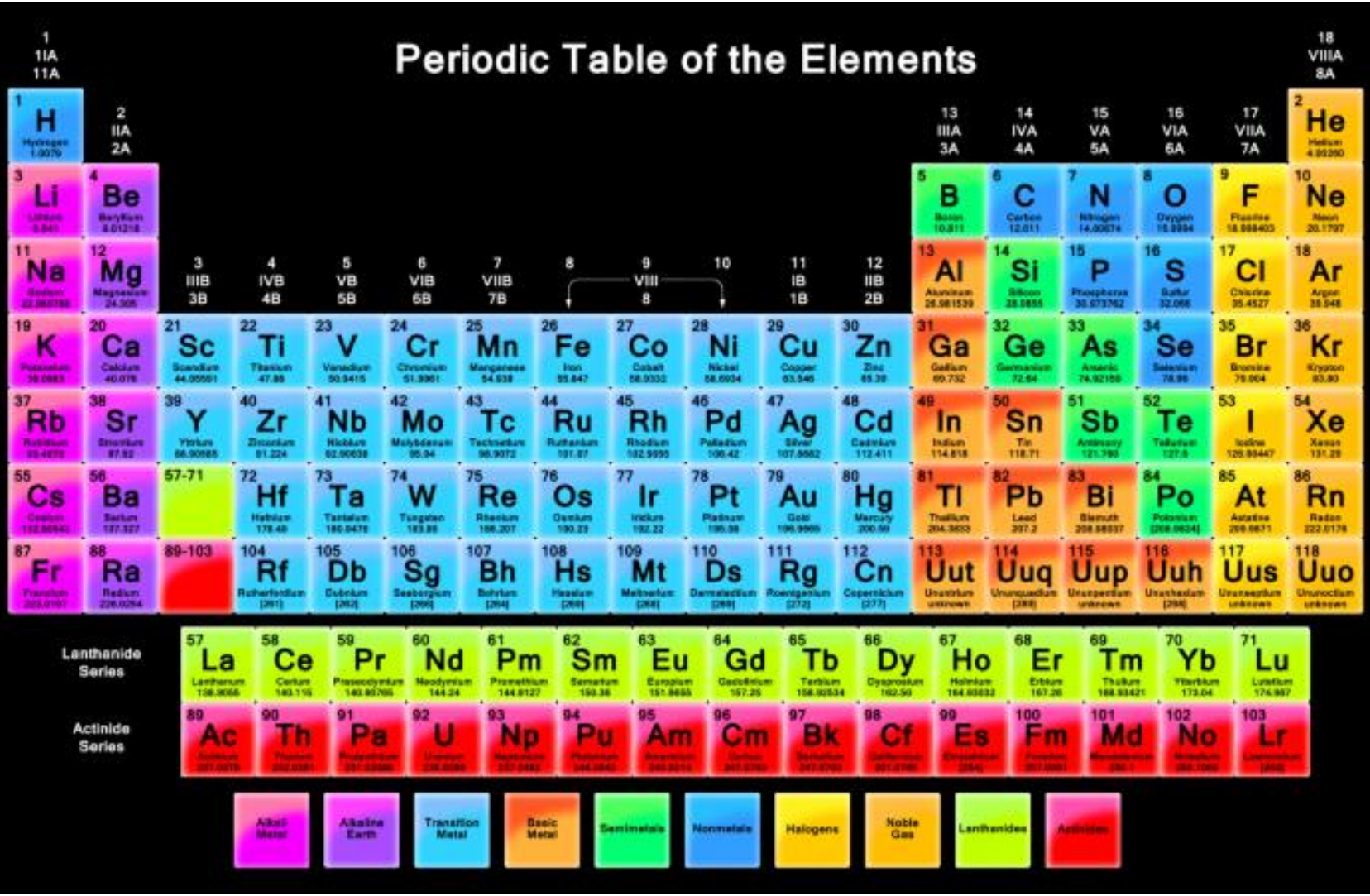

Classical
10^{-8} cm
NEUTRON
PROTON
NUCLEUS
ELECTRONS
10^{-13} cm


Quantum Mechanical
10^{-13} cm
Electron cloud
Nucleus

All Atoms With One Proton in the Nucleus are Hydrogen Atoms



There are many possible isotopes of each element.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Cm Curium 247.0703
Bk Berkelium 247.0703
Cf Californium 251.0796
Es Einsteinium [254]
Fm Fermium 257.0951
Md Mendelevium [258]
No Nobelium [259.1009]
Lr Lawrencium [262]
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetals
Nonmetals
Halogens
Noble Gas
Lanthanides
Actinides

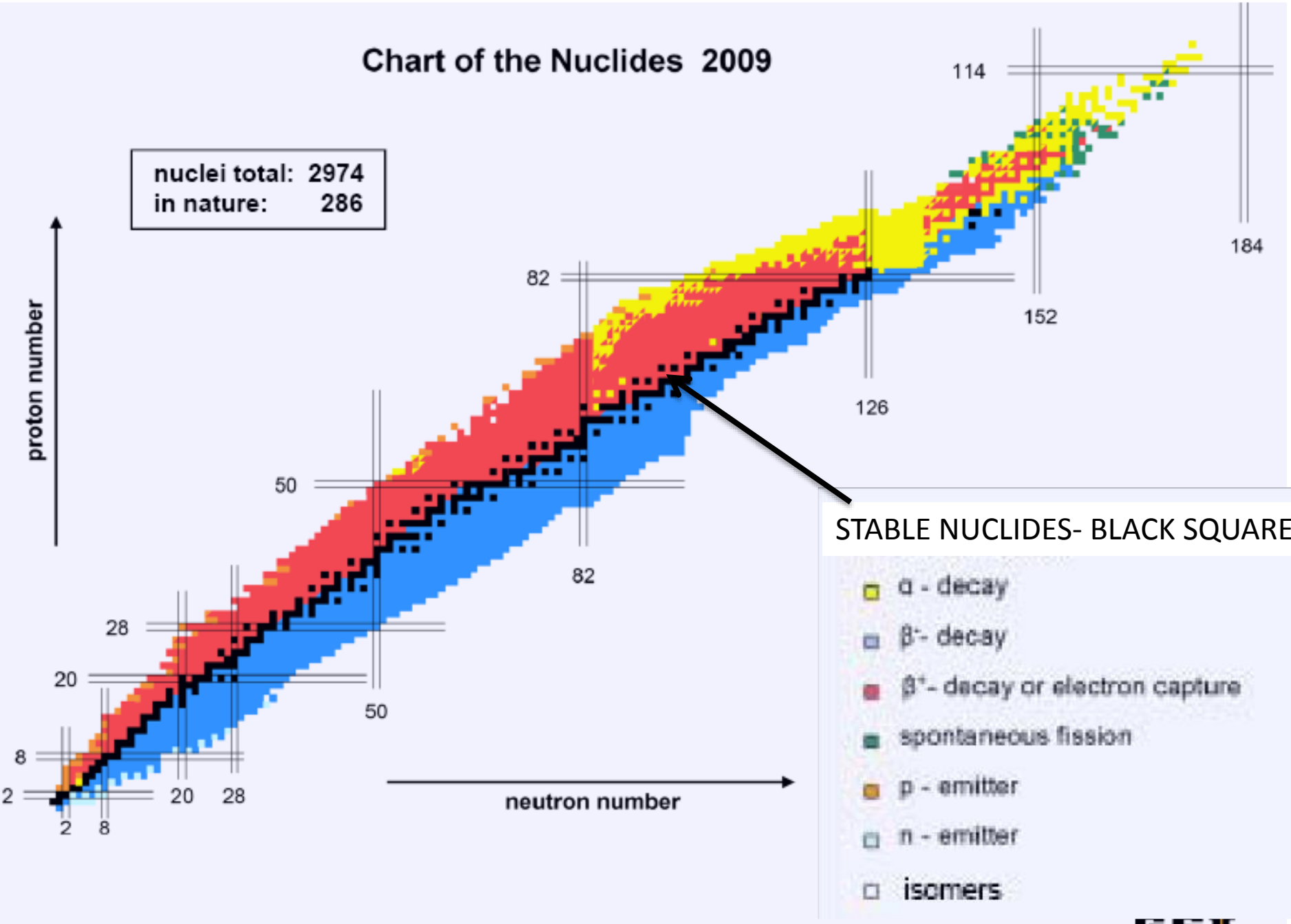


Chart of the Nuclides 2009
nuclei total: 2974
in nature: 286
proton number
neutron number
2
8
20
28
50
82
114
126
152
184
STABLE NUCLIDES- BLACK SQUARES
α - decay
β⁻- decay
β⁺- decay or electron capture
spontaneous fission
p - emitter
n - emitter
isomers

Nuclear Binding Energy

Consider the formation of an atom from its constituents

$$Z \times {}^{1}H + N \times {}^{1}n \rightarrow {}^{A}X_{Z}$$

- Define binding energy as the mass difference between the sum of the mass of free constituents (protons, neutrons, electrons) and the mass of the nucleus

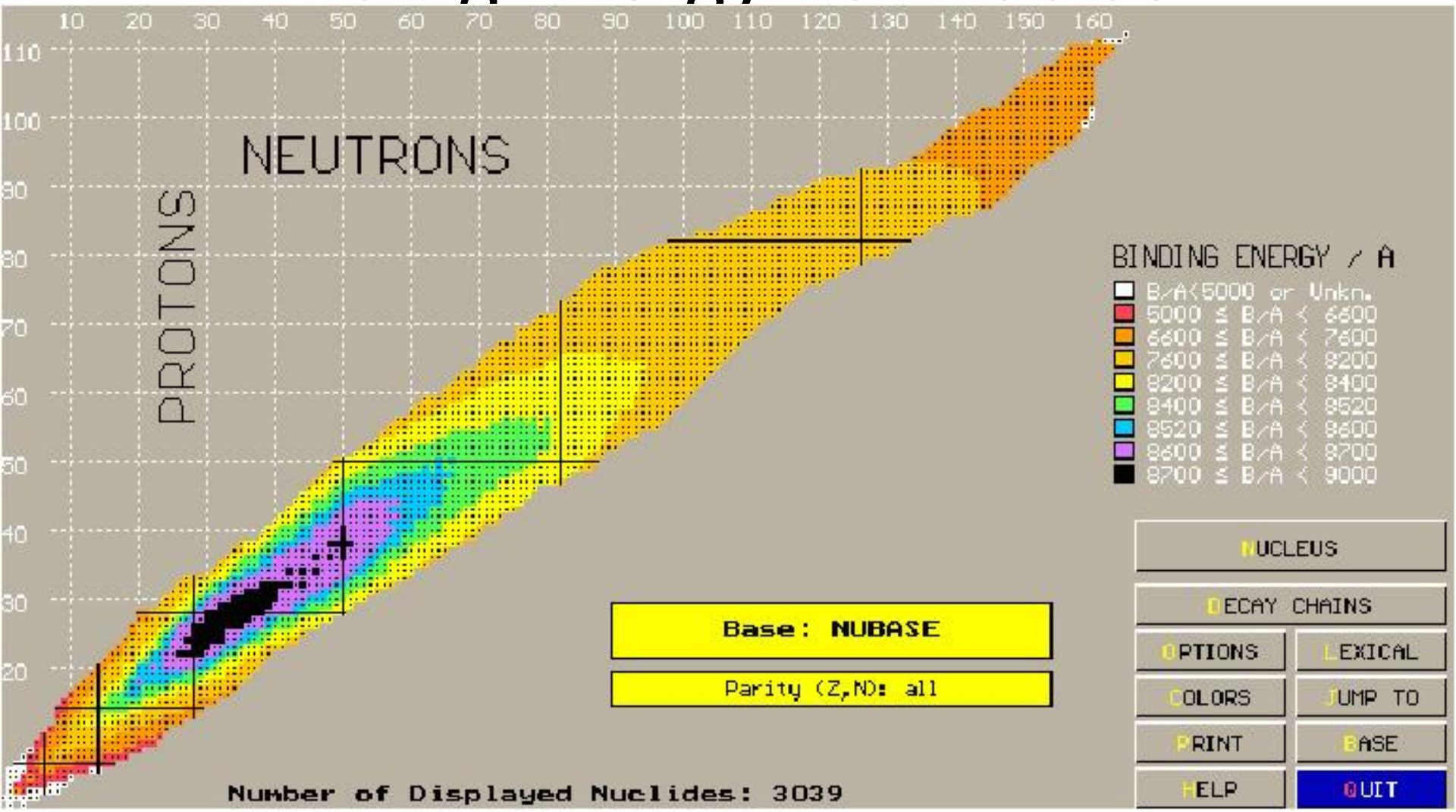
$$E_B = [(Z \times M_H + N \times M_N - M(A,Z)] c^2$$

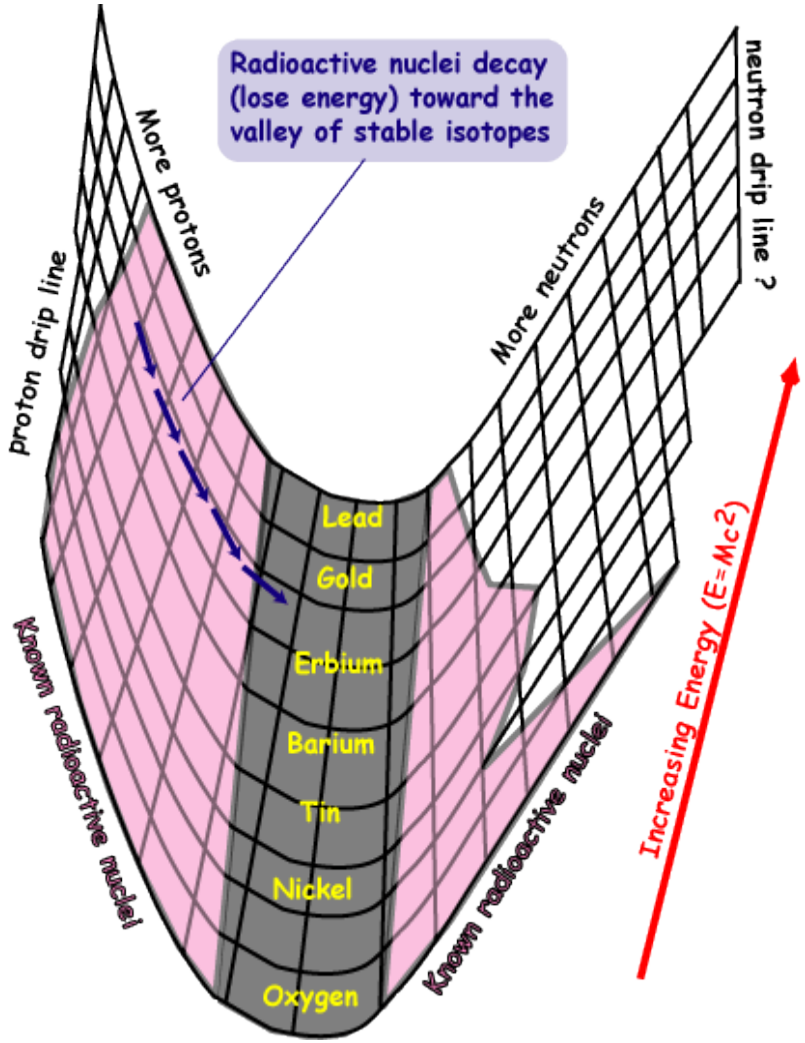
$C^2 = 931.5$ MeV/u

- **Binding Energy**
  - The difference in mass between the constituent protons, electrons and neutrons and that of the isotope formed converted into energy, usually in MeV.
  - **For ^{208}Pb BE = 1636 MeV**

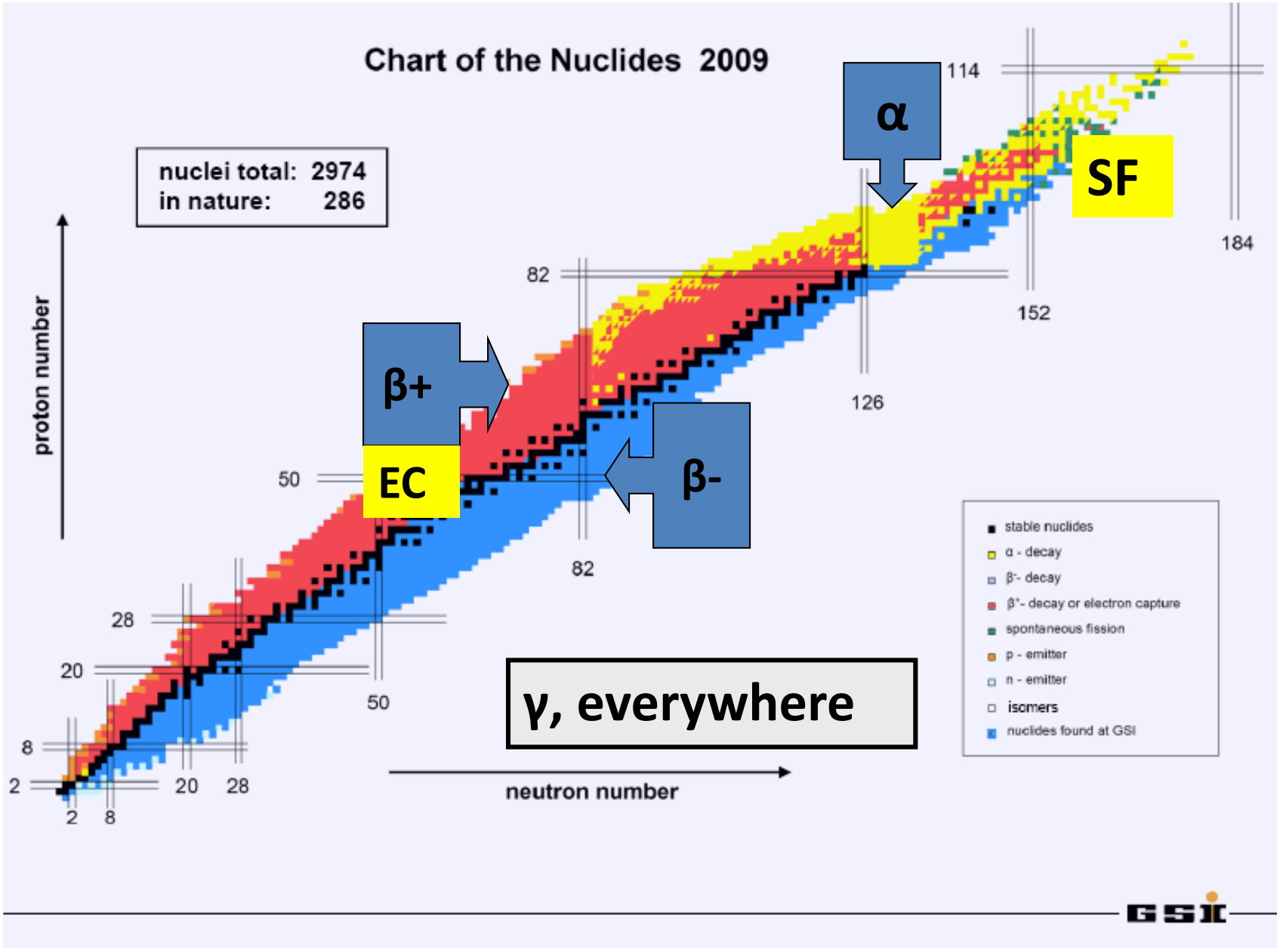
- **Binding Energy per Nucleon**
  - The Binding energy divided by A, the total number of nucleons.
  - **For ^{208}Pb BE = 1636/208 = 7.87 MeV/nucleon**

Binding Energy Per Nucleon

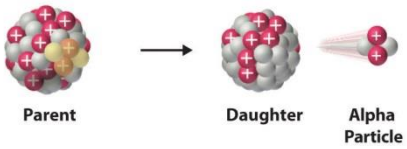
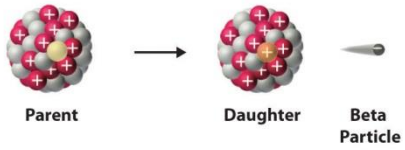
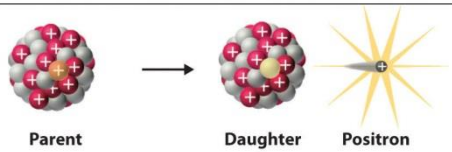
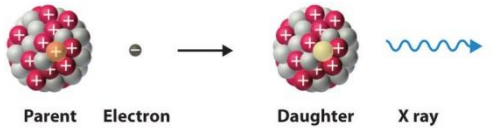
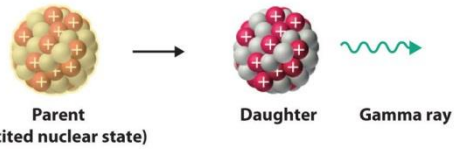
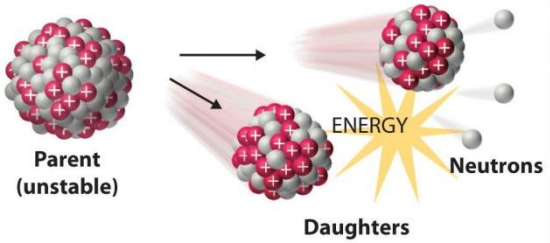



Radioactive nuclei decay (lose energy) toward the valley of stable isotopes
More protons
More neutrons
proton drip line
neutron drip line ?
Lead
Gold
Erbium
Barium
Tin
Nickel
Oxygen
Known radioactive nuclei
Known radioactive nuclei
Increasing Energy (E=Mc2)

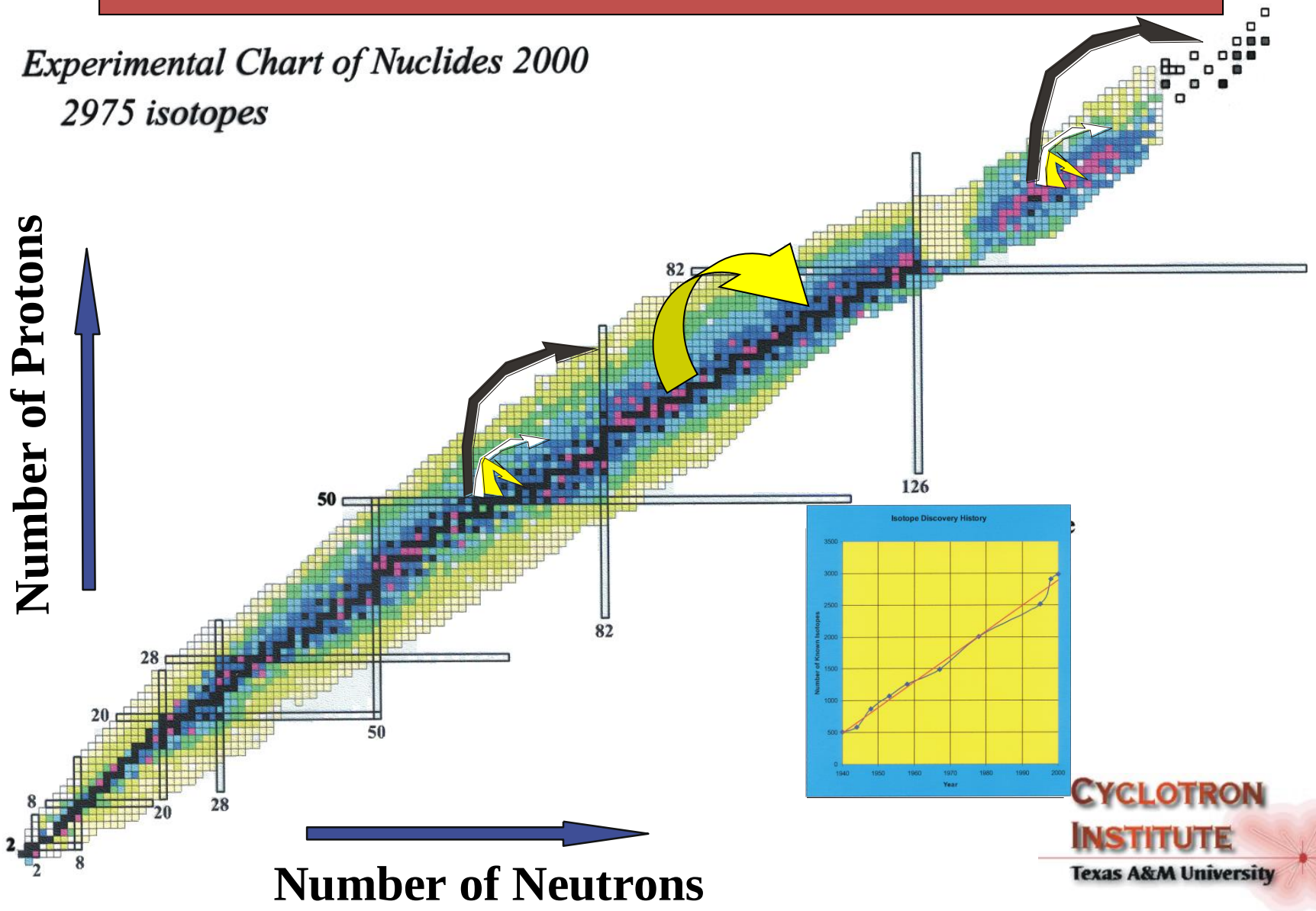
Most Isotopes are Radioactive



Note:
In these three, neutrinos are also emitted

Decay Type	Radiation Emitted	Generic Equation	Model
Alpha decay	${}^{4}_{2}\alpha$	${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}\alpha$	
Beta decay	${}^{0}_{-1}\beta$	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}X' + {}^{0}_{-1}\beta$	
Positron emission	${}^{0}_{+1}\beta$	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}X' + {}^{0}_{+1}\beta$	
Electron capture	X rays	${}^{A}_{Z}X + {}^{0}_{-1}e \longrightarrow {}^{A}_{Z-1}X' + X\text{ ray}$	
Gamma emission	${}^{0}_{0}\gamma$	${}^{A}_{Z}X^{*} \xrightarrow{\text{Relaxation}} {}^{A}_{Z}X' + {}^{0}_{0}\gamma$	
Spontaneous fission	Neutrons	${}^{A+B+C}_{Z+Y}X \longrightarrow {}^{A}_{Z}X' + {}^{B}_{Y}X' + C\,{}^{1}_{0}n$	

Reversing the Trend --Nuclear Reactions



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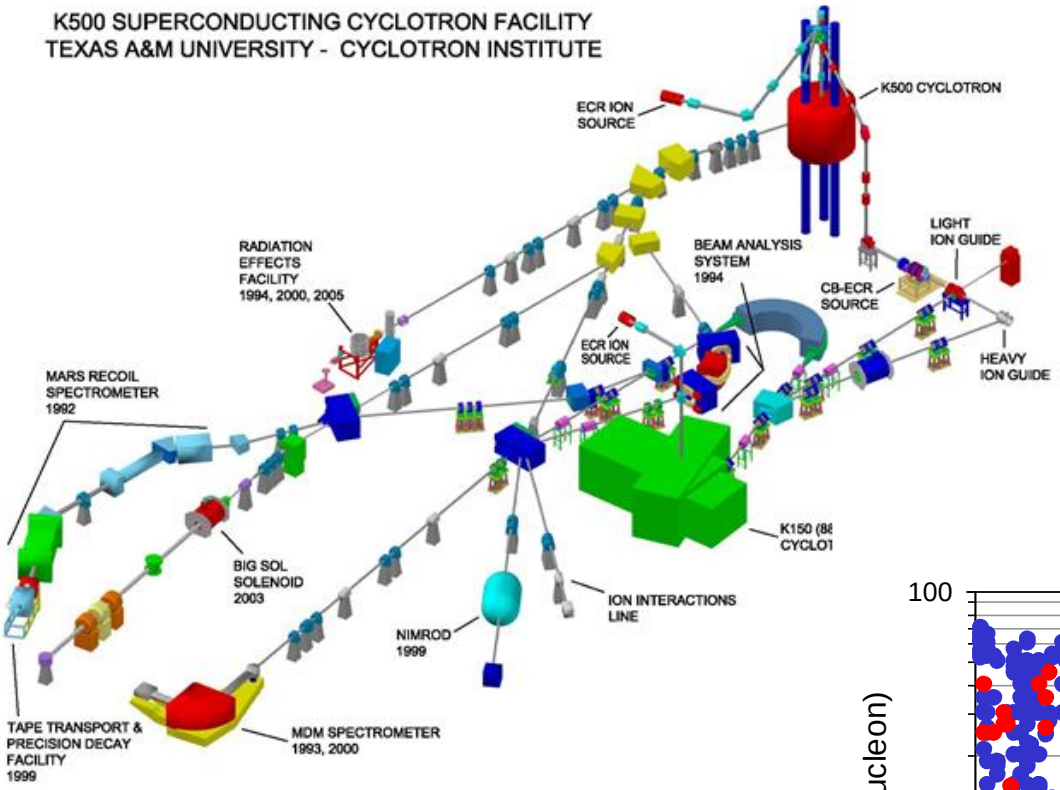
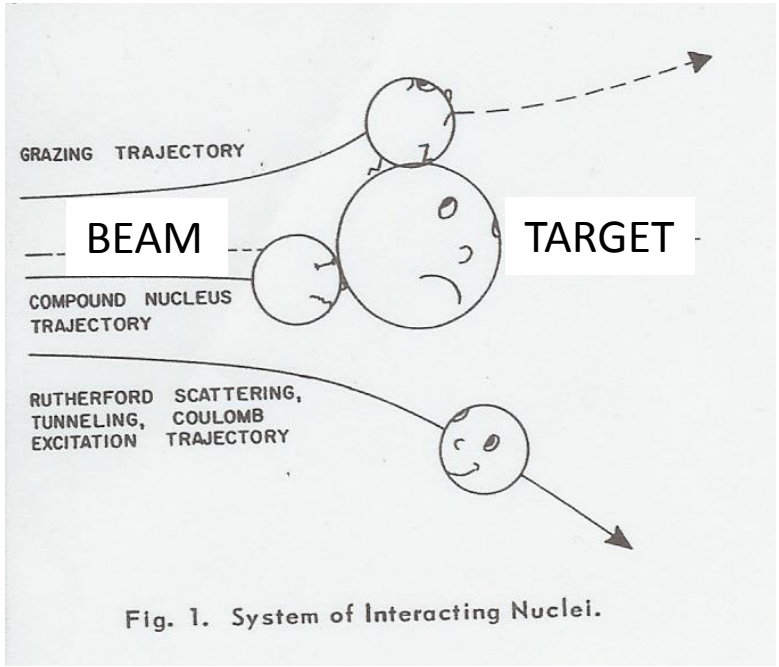
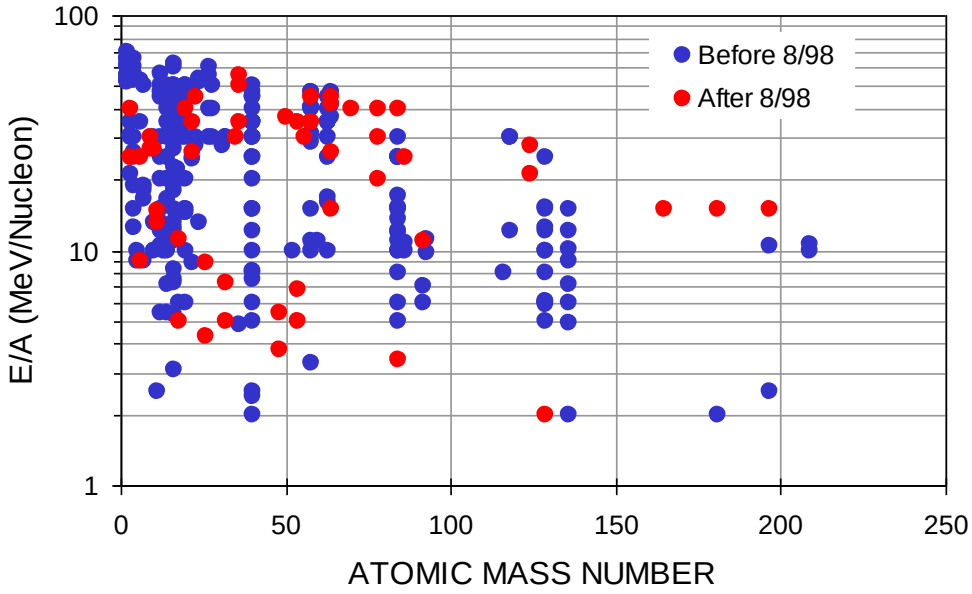
Texas A&M University

NEED AN ACCELERATOR





K500 CYCLOTRON + ECR



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Texas A&M University

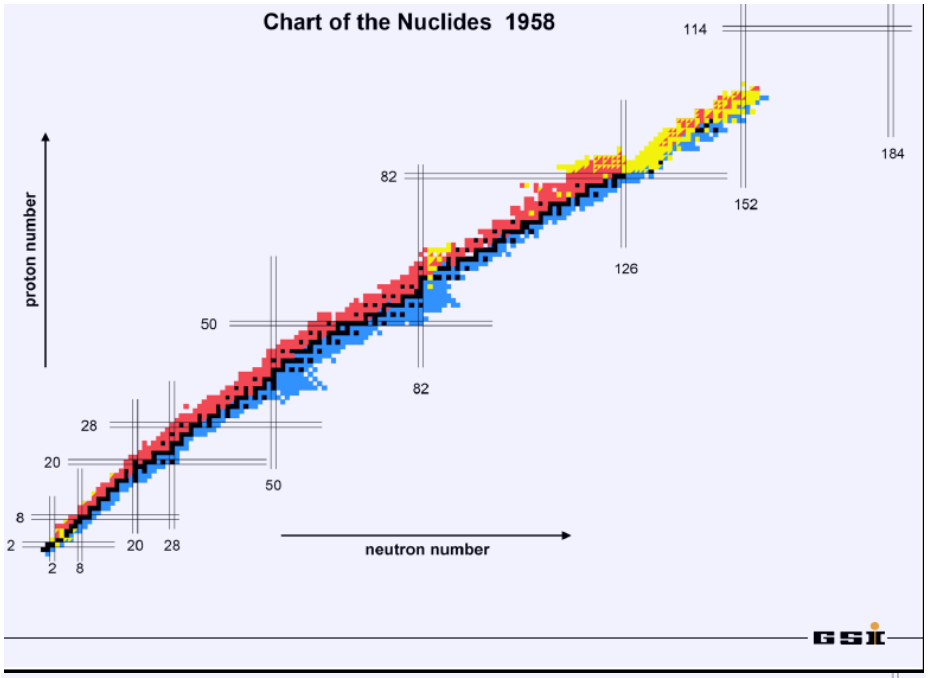
1958-My first course in nuclear chemistry

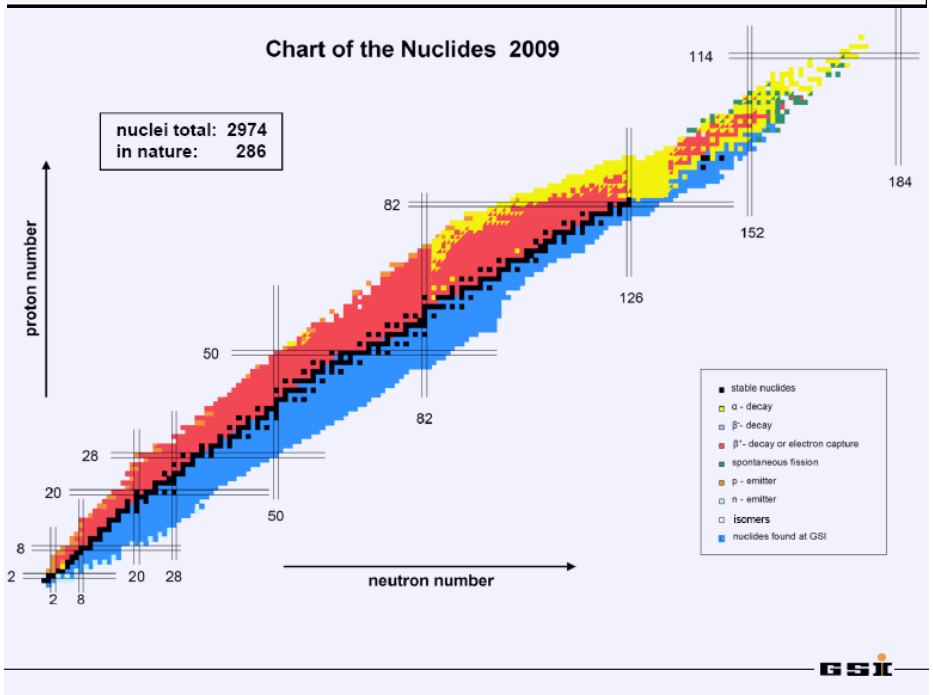
- With such reactions new isotopes

  and

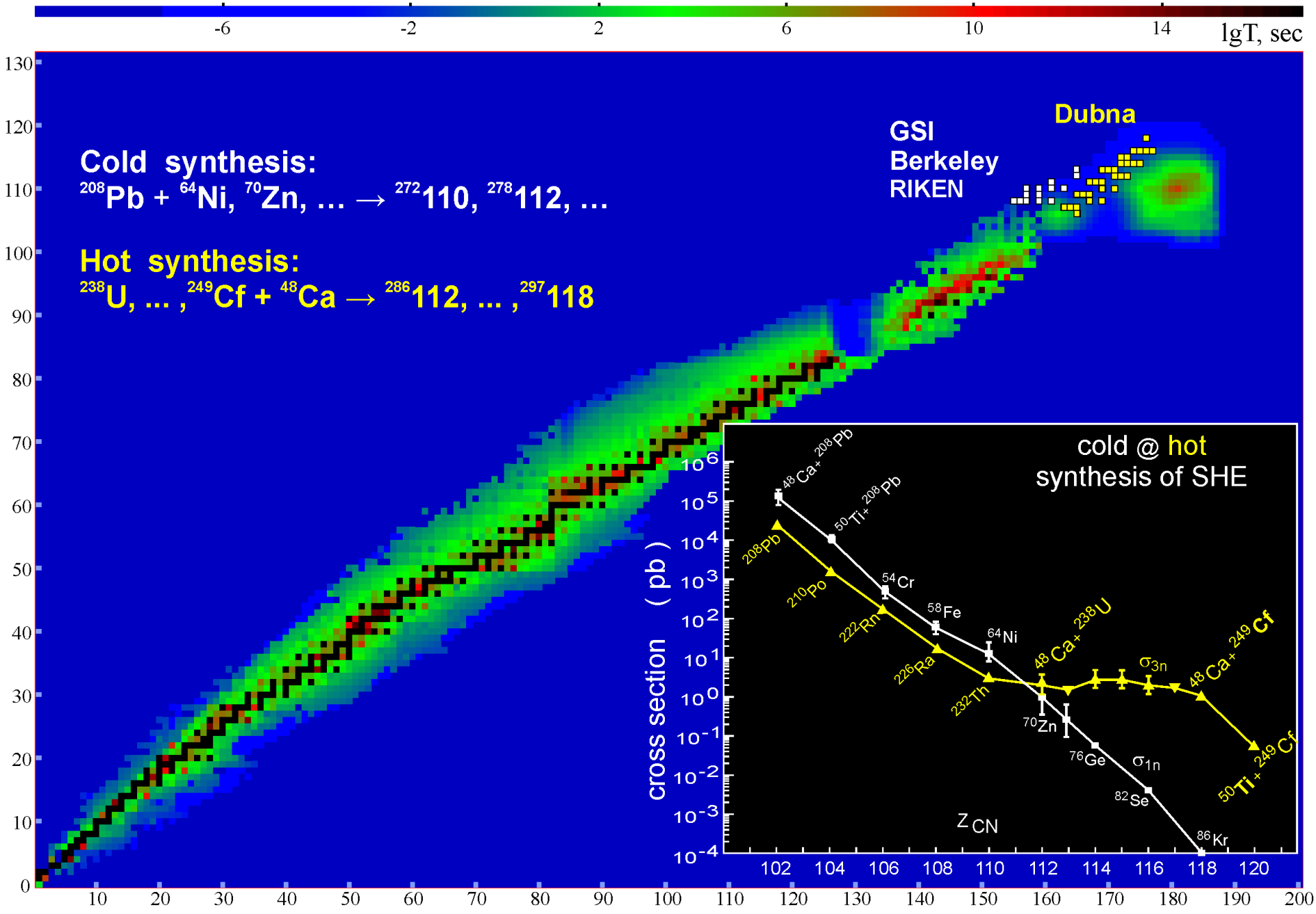
  new elements

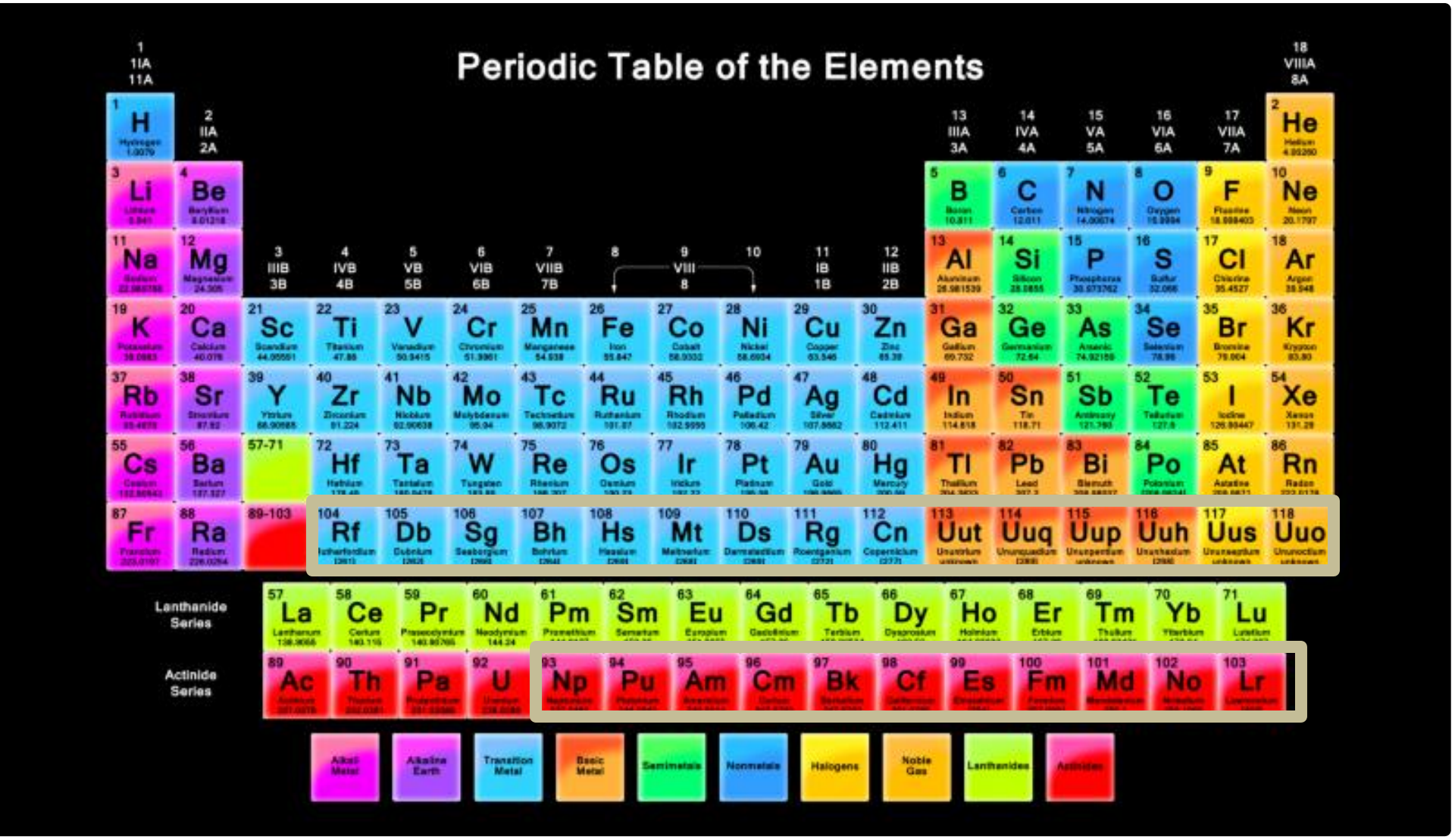
  can be made





Synthesis of superheavy elements (cold and hot fusion)

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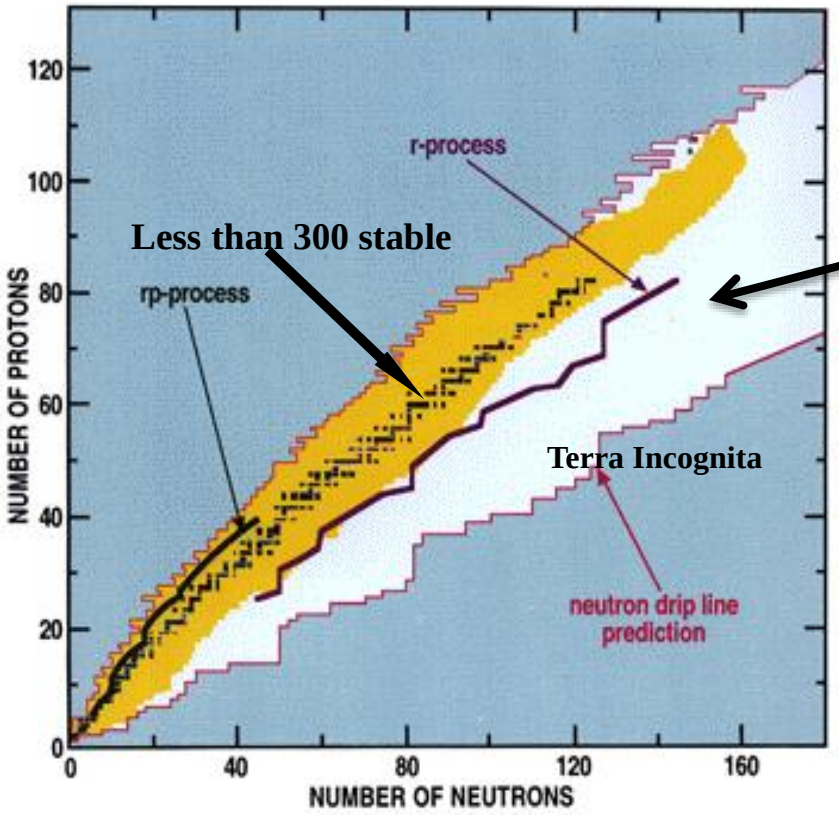
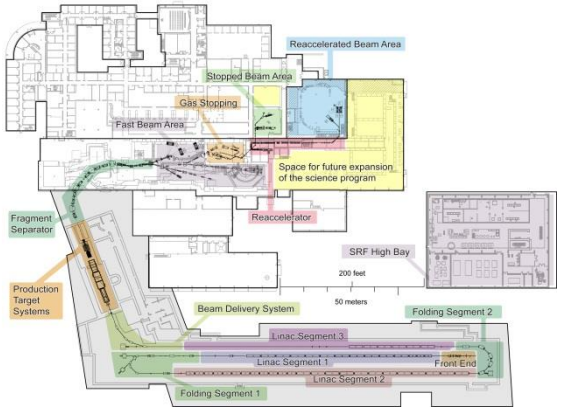
H Hydrogen 1.0079
He Helium 4.00260
Li Lithium 6.941
Be Beryllium 9.01218
B Boron 10.811
C Carbon 12.011
N Nitrogen 14.00674
O Oxygen 15.9994
F Fluorine 18.9984403
Ne Neon 20.1797
Na Sodium 22.989768
Mg Magnesium 24.305
Al Aluminum 26.981539
Si Silicon 28.0855
P Phosphorus 30.973762
S Sulfur 32.066
Cl Chlorine 35.4527
Ar Argon 39.948
K Potassium 39.0983
Ca Calcium 40.078
Sc Scandium 44.95591
Ti Titanium 47.88
V Vanadium 50.9415
Cr Chromium 51.9961
Mn Manganese 54.938
Fe Iron 55.847
Co Cobalt 58.9332
Ni Nickel 58.6934
Cu Copper 63.546
Zn Zinc 65.39
Ga Gallium 69.732
Ge Germanium 72.64
As Arsenic 74.92159
Se Selenium 78.96
Br Bromine 79.904
Kr Krypton 83.80
Rb Rubidium 85.4678
Sr Strontium 87.62
Y Yttrium 88.90585
Zr Zirconium 91.224
Nb Niobium 92.90638
Mo Molybdenum 95.94
Tc Technetium 98.9072
Ru Ruthenium 101.07
Rh Rhodium 102.9055
Pd Palladium 106.42
Ag Silver 107.8682
Cd Cadmium 112.411
In Indium 114.818
Sn Tin 118.71
Sb Antimony 121.760
Te Tellurium 127.6
I Iodine 126.90447
Xe Xenon 131.29
Cs Cesium 132.90543
Ba Barium 137.327
57-71
Hf Hafnium 178.49
Ta Tantalum 180.9479
W Tungsten 183.85
Re Rhenium 186.207
Os Osmium 190.23
Ir Iridium 192.22
Pt Platinum 195.08
Au Gold 196.9665
Hg Mercury 200.59
Tl Thallium 204.3833
Pb Lead 207.2
Bi Bismuth 208.98037
Po Polonium [209]
At Astatine [210]
Rn Radon [222]
Fr Francium [223]
Ra Radium 226.0254
89-103
Rf Rutherfordium [261]
Db Dubnium [262]
Sg Seaborgium [266]
Bh Bohrium [264]
Hs Hassium [269]
Mt Meitnerium [268]
Ds Darmstadtium [281]
Rg Roentgenium [272]
Cn Copernicium [277]
Uut Ununtrium unknown
Uuq Ununquadium [289]
Uup Ununpentium unknown
Uuh Ununhexium [292]
Uus Ununseptium unknown
Uuo Ununoctium unknown
Lanthanide Series
La Lanthanum 138.9055
Ce Cerium 140.116
Pr Praseodymium 140.90765
Nd Neodymium 144.24
Pm Promethium [145]
Sm Samarium 150.36
Eu Europium 151.965
Gd Gadolinium 157.25
Tb Terbium 158.92534
Dy Dysprosium 162.50
Ho Holmium 164.93032
Er Erbium 167.26
Tm Thulium 168.93421
Yb Ytterbium 173.04
Lu Lutetium 174.967
Actinide Series
Ac Actinium [227]
Th Thorium 232.0381
Pa Protactinium 231.03588
U Uranium 238.0289
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]
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetals
Nonmetals
Halogens
Noble Gas
Lanthanides
Actinides

Theoretical Limits to the Existence of Nuclei

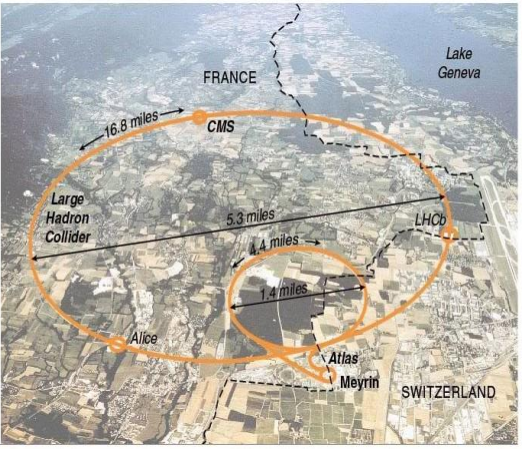


- **Only a fraction of the theoretically possible isotopes have been produced and studied.**
- **A new generation of accelerators being constructed will accelerate radioactive ions and probe the region of unknown isotopes**



Layout of the accelerator, experimental systems and the experimental areas of the Facility for Rare Isotope Beams.

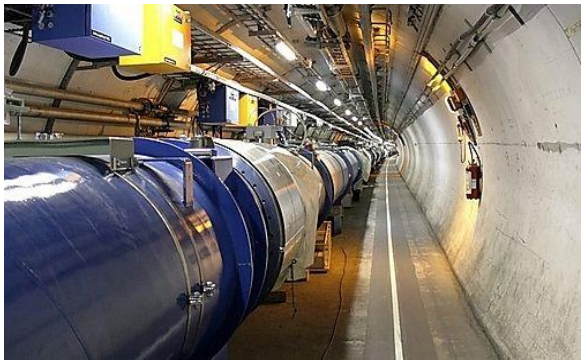
ACCELERATORS

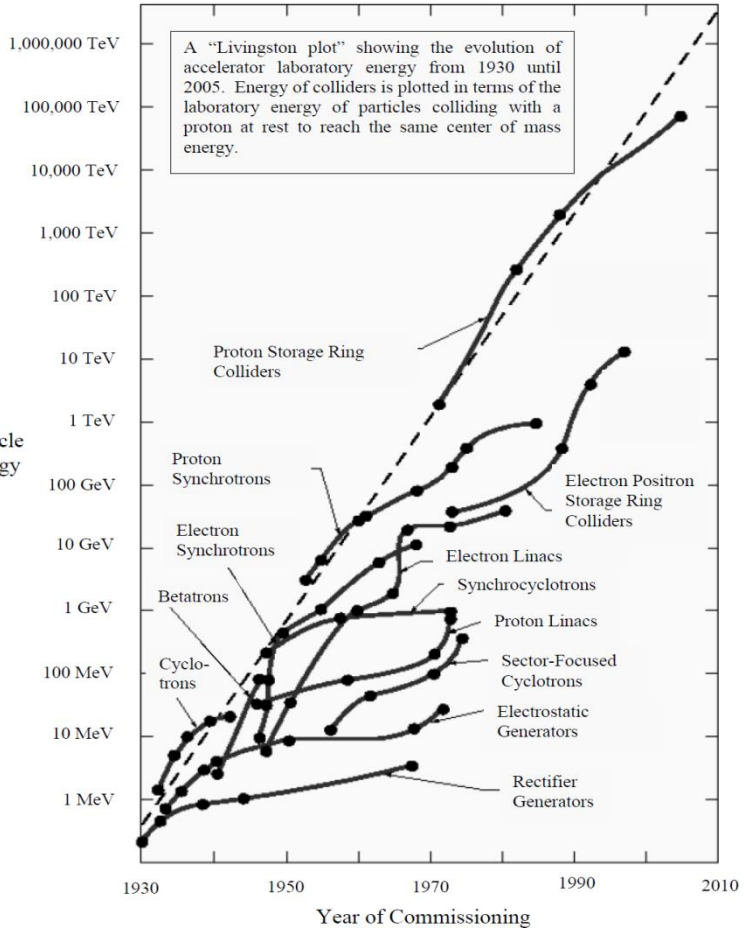


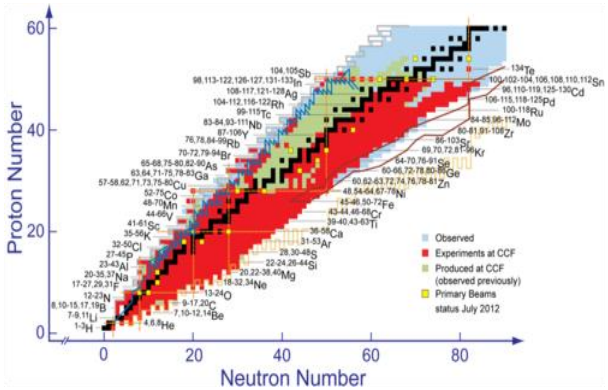
LHC

RHIC

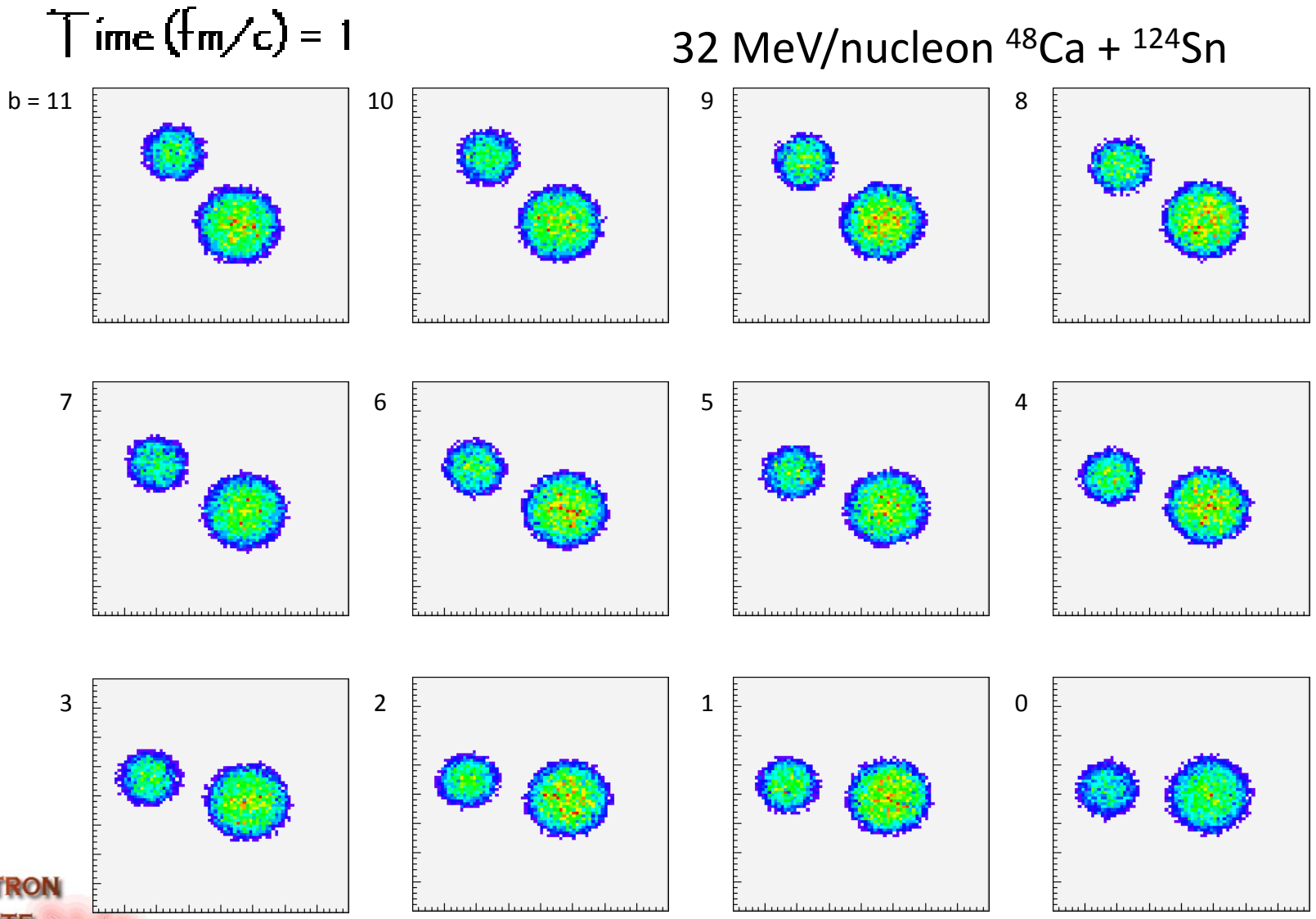
TAMU



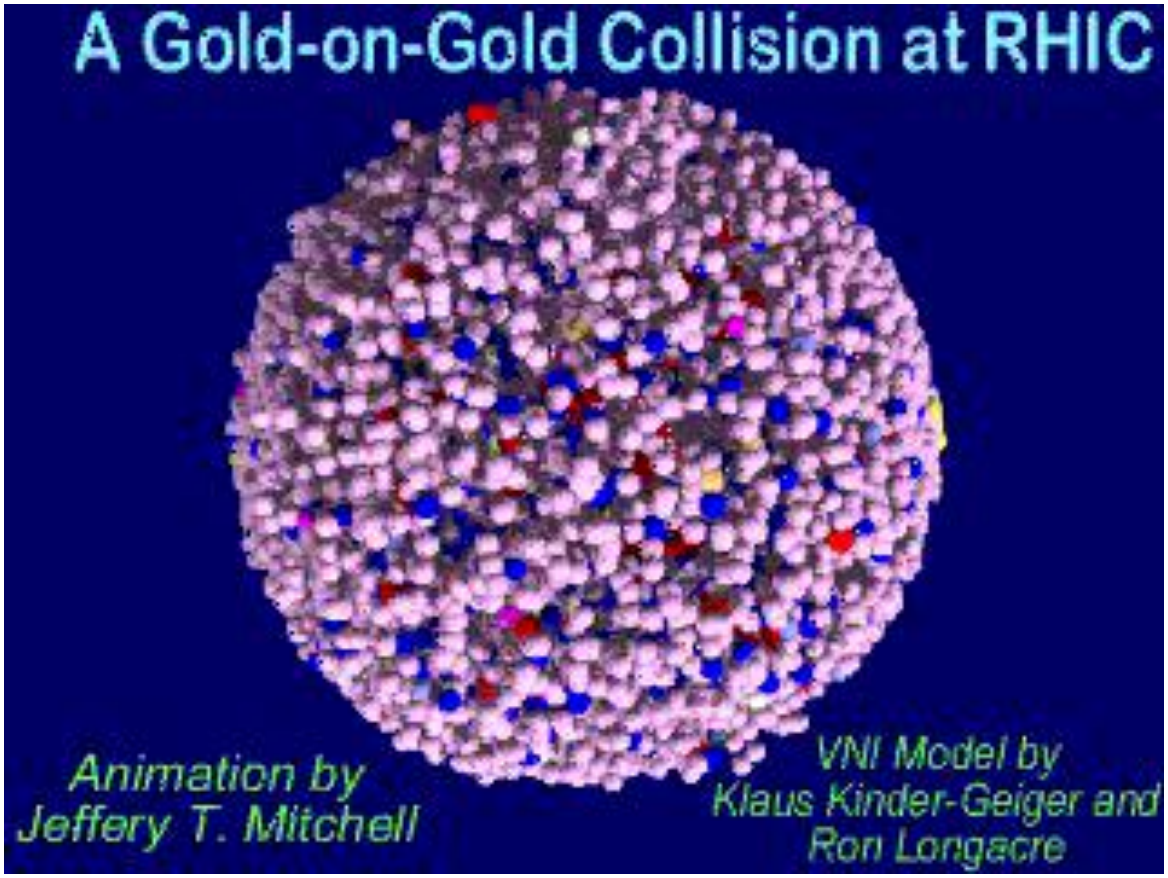




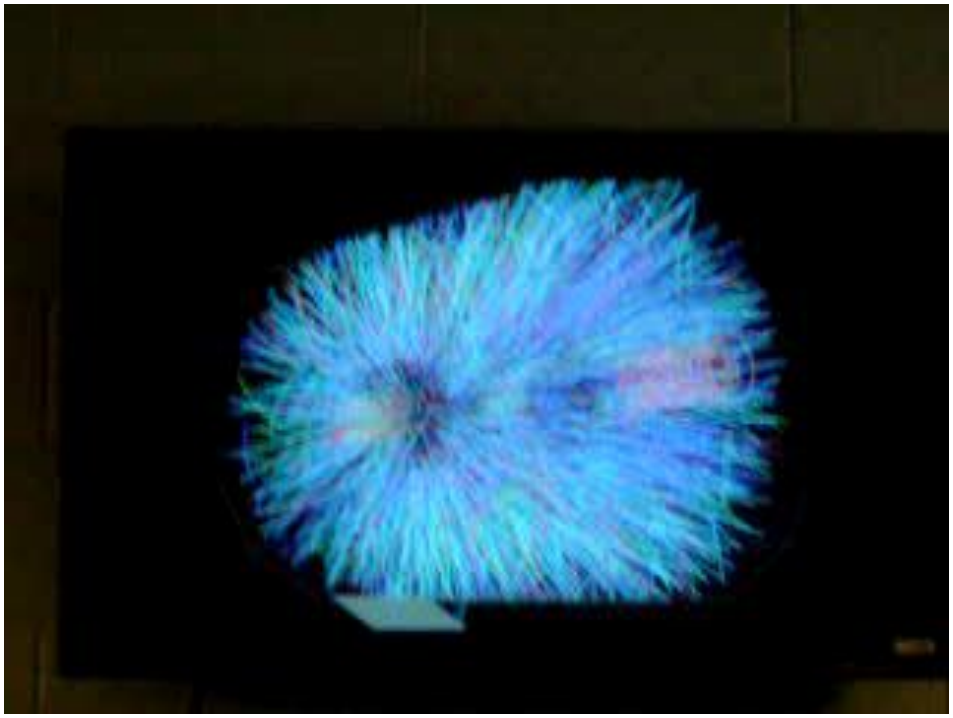
Higher Energy Reactions



[13] A.L. Keksis, thesis, Texas A&M University, 2007

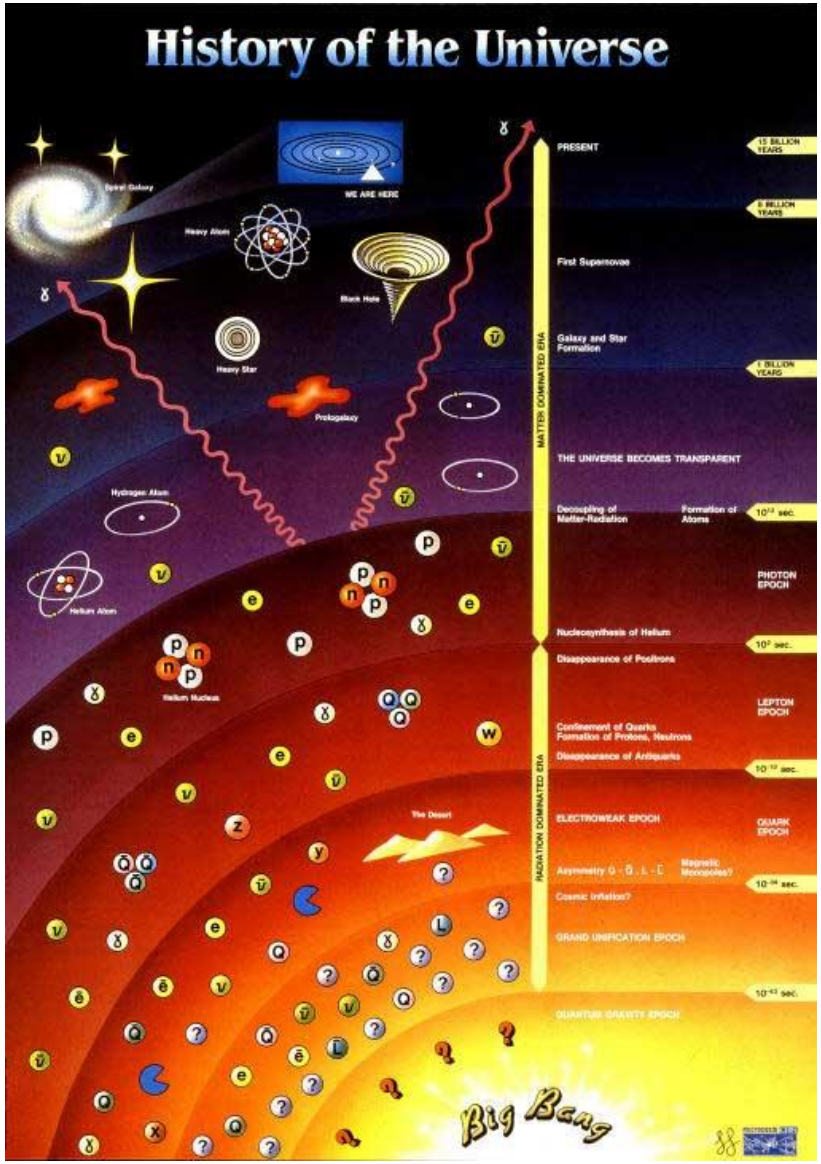

A Gold-on-Gold Collision at RHIC
Animation by
Jeffery T. Mitchell
VNI Model by
Klaus Kinder-Geiger and
Ron Longacre

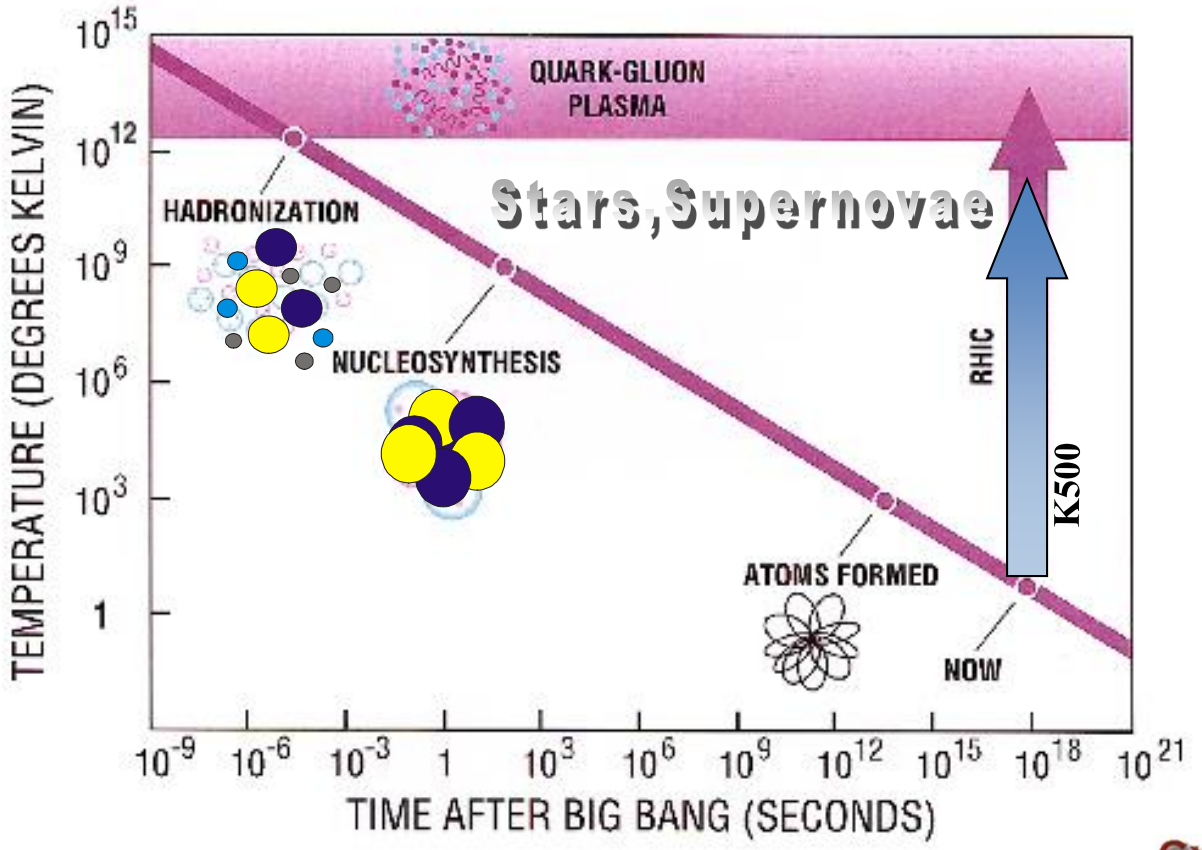
The Little Bang



The Big Bang

The Big Bang

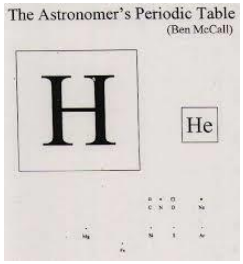

History of the Universe
WE ARE HERE
Spiral Galaxy
Heavy Atom
Black Hole
Heavy Star
Protogalaxy
Hydrogen Atom
Helium Atom
Helium Nucleus
The Desert
PRESENT
15 BILLION YEARS
8 BILLION YEARS
First Supernovae
Galaxy and Star Formation
1 BILLION YEARS
THE UNIVERSE BECOMES TRANSPARENT
Decoupling of Matter-Radiation
Formation of Atoms
PHOTON EPOCH
Nucleosynthesis of Helium
Disappearance of Positrons
LEPTON EPOCH
Confinement of Quarks
Formation of Protons, Neutrons
Disappearance of Antiquarks
ELECTROWEAK EPOCH
QUARK EPOCH
Asymmetry Q - Q , L - L
Magnetic Monopoles?
Cosmic Inflation?
GRAND UNIFICATION EPOCH
QUANTUM GRAVITY EPOCH
MATTER DOMINATED ERA
RADIATION DOMINATED ERA
Big Bang

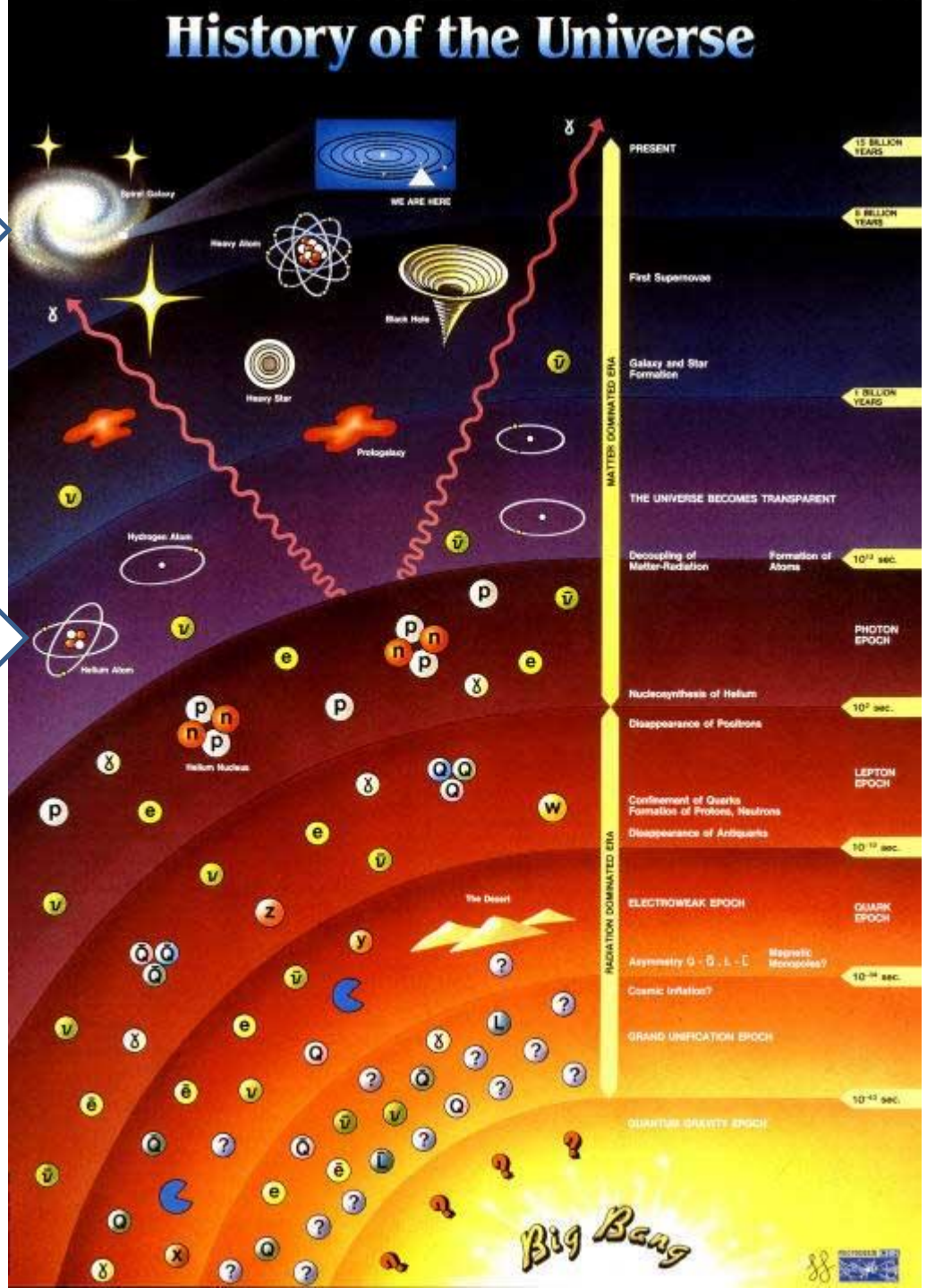


CYCLOTRON INSTITUTE
Texas A&M University

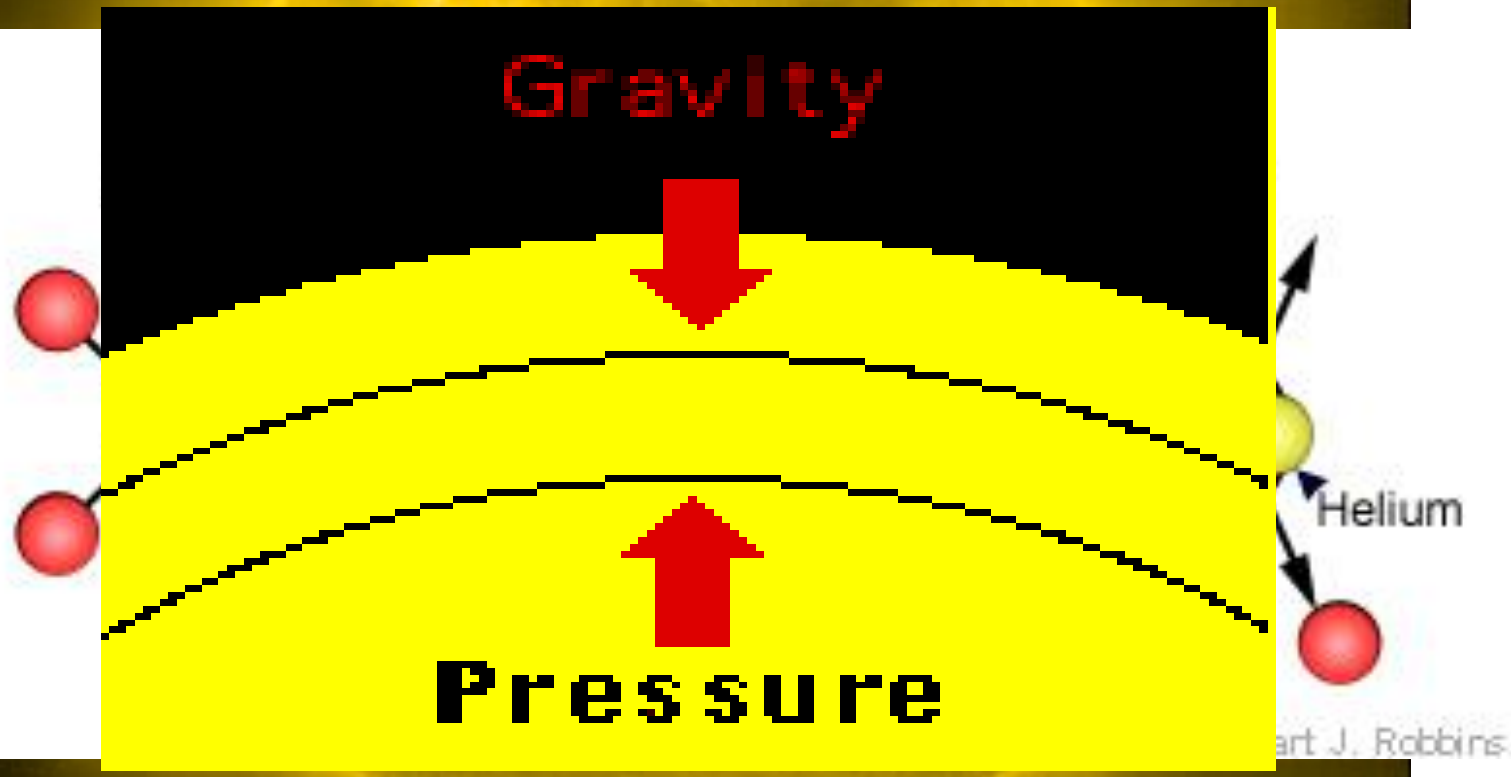
Heavier Elements

First Atoms, H and He



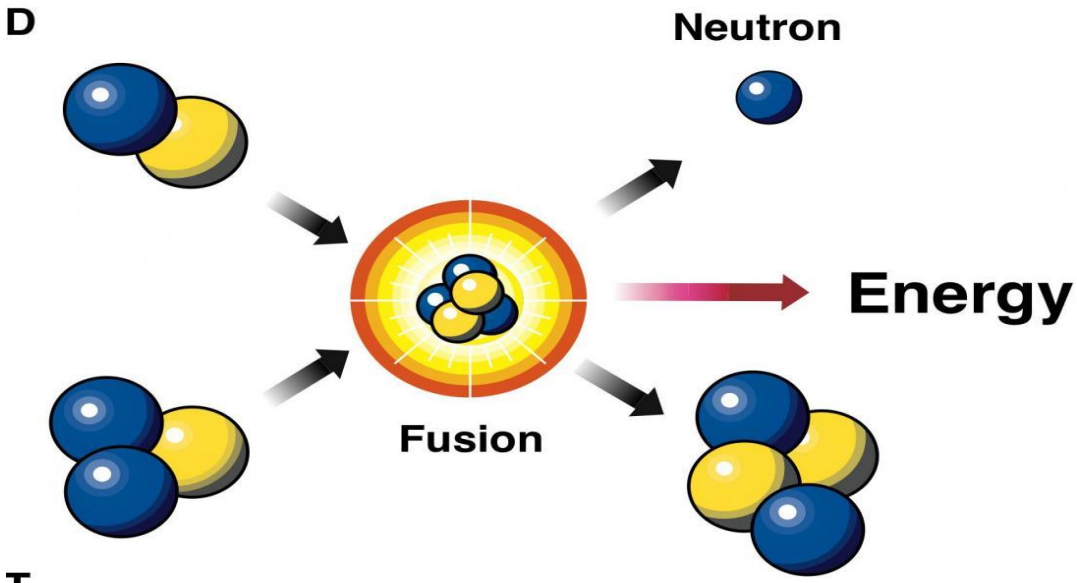


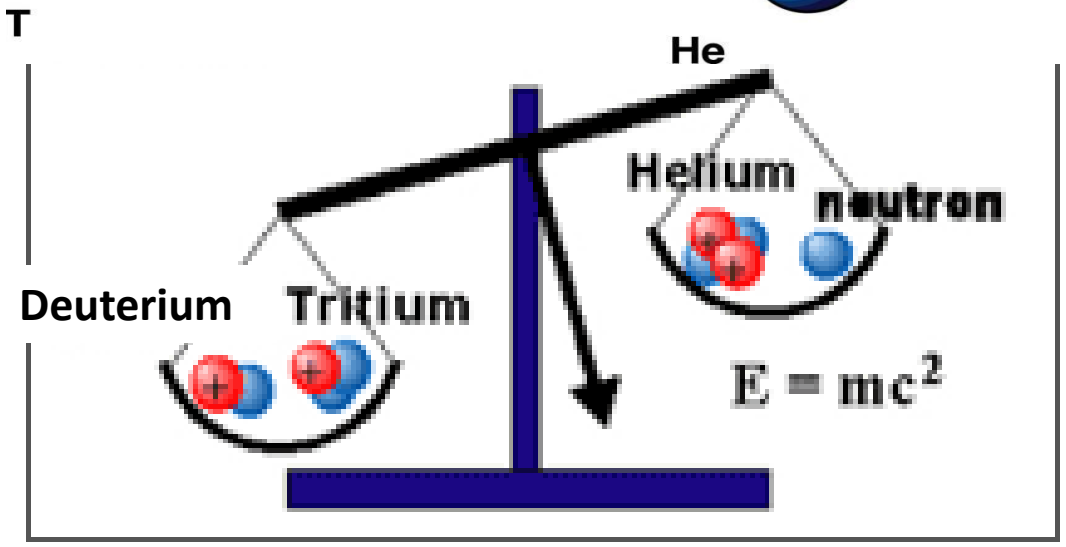
OUR SUN
A Ball of Hydrogen



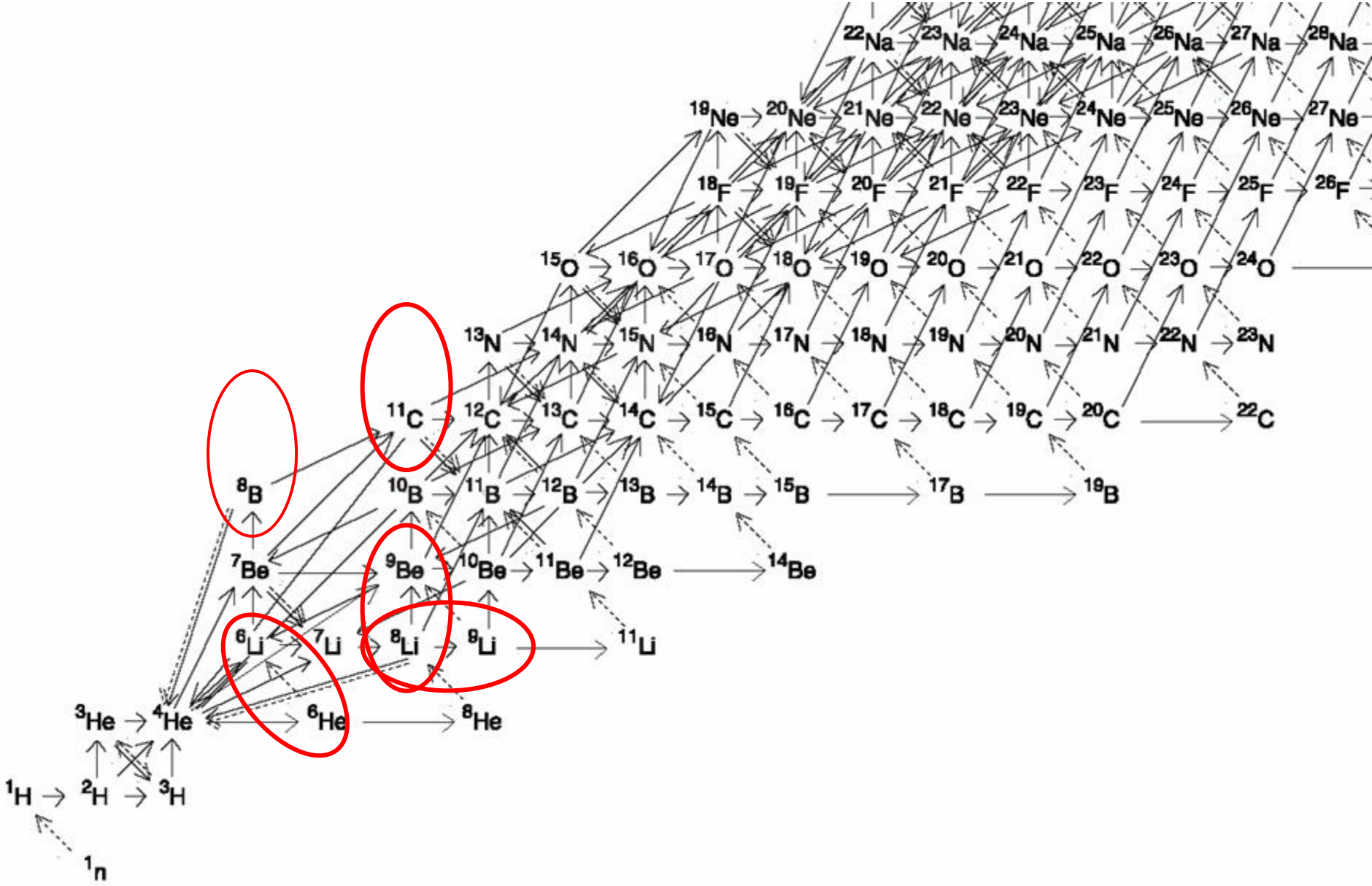
10,000,000 DEGREES KELVIN

2001/03/04 01:05

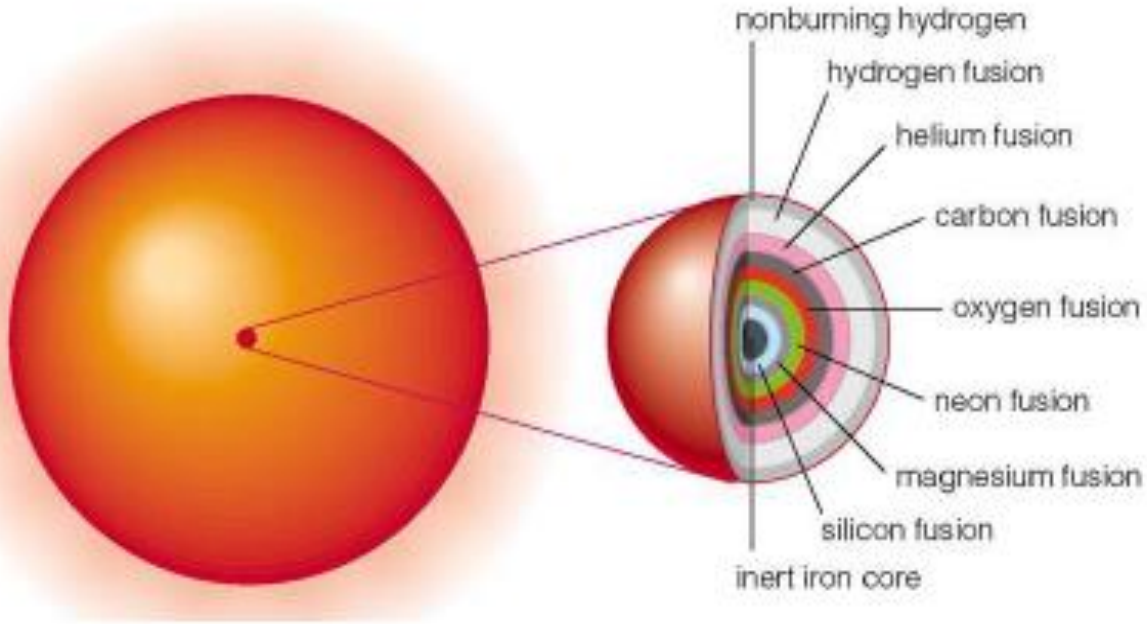

D
Neutron
Energy
Fusion


T
He
Helium
neutron
Deuterium
Tritium
$E = mc^2$

Origin of the Lighter Elements

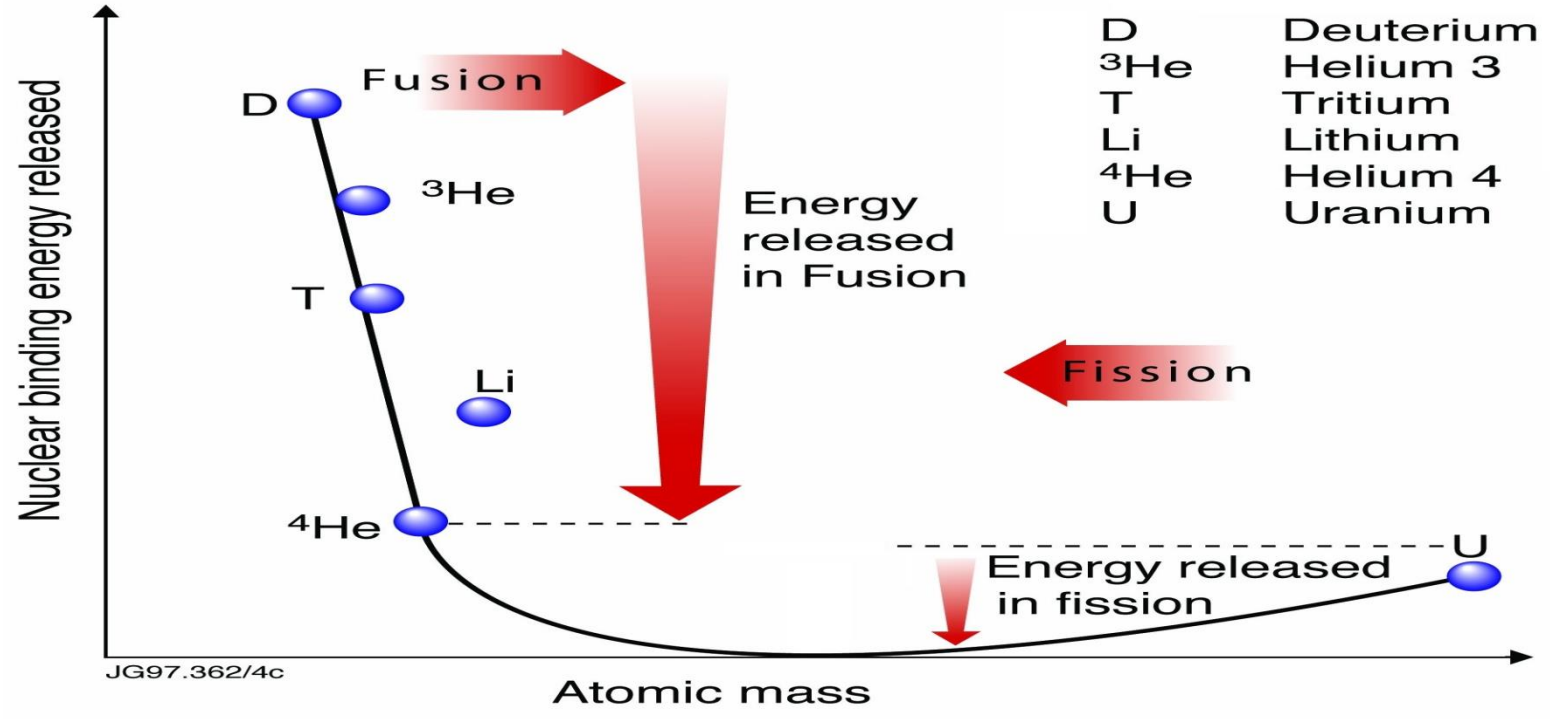


A massive star near the end of its lifetime has "onion ring" structure



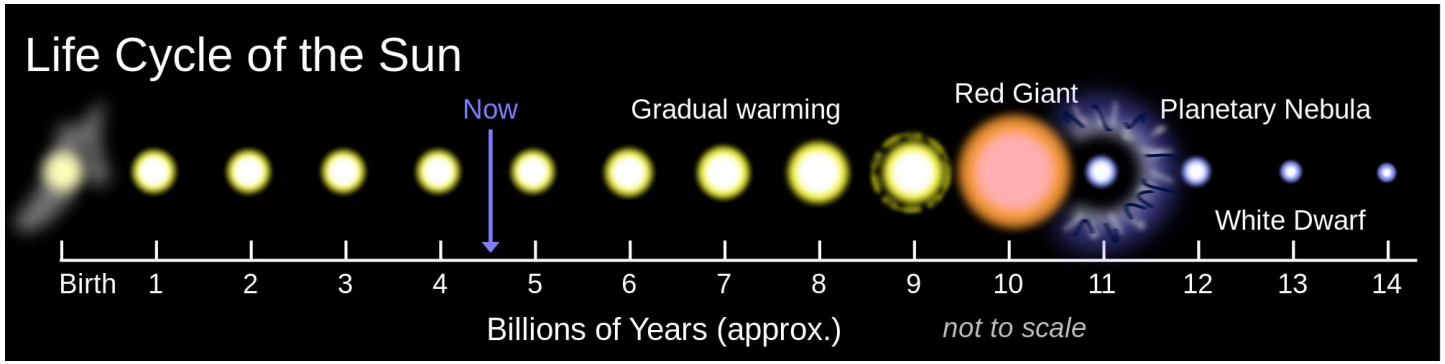
WHY?
Because Floor of Binding Energy Valley is Not Flat

For A Given Number of Nucleons, An Increase in Binding Energy per Nucleon Means that Energy Will Be Released

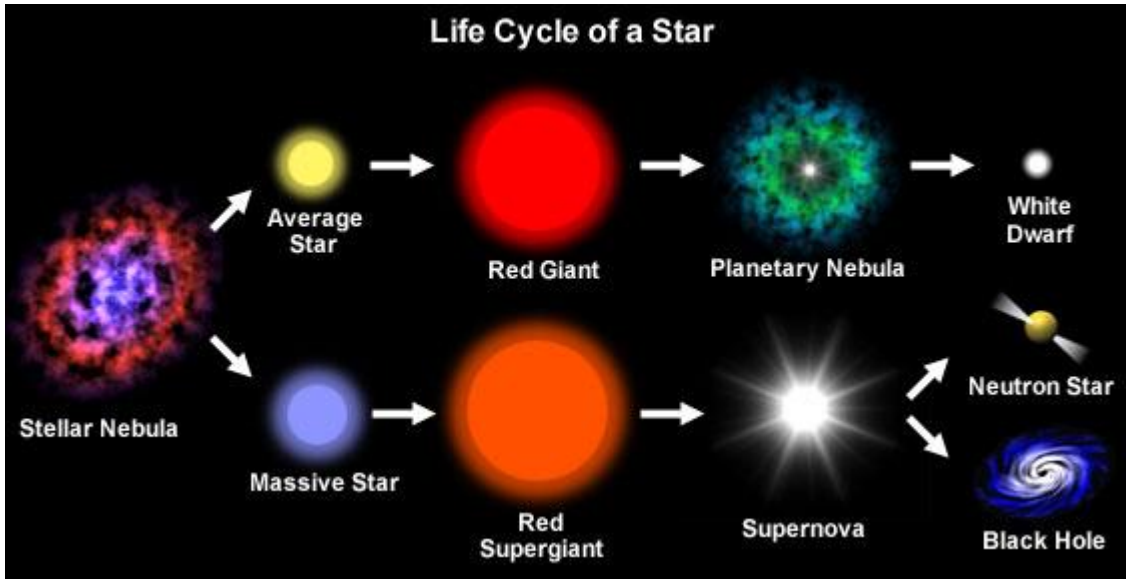


For Small Numbers of Nucleons, i.e., Nuclei Much Lighter Than Iron, Energy is Released If Nuclei Fuse (FUSION)

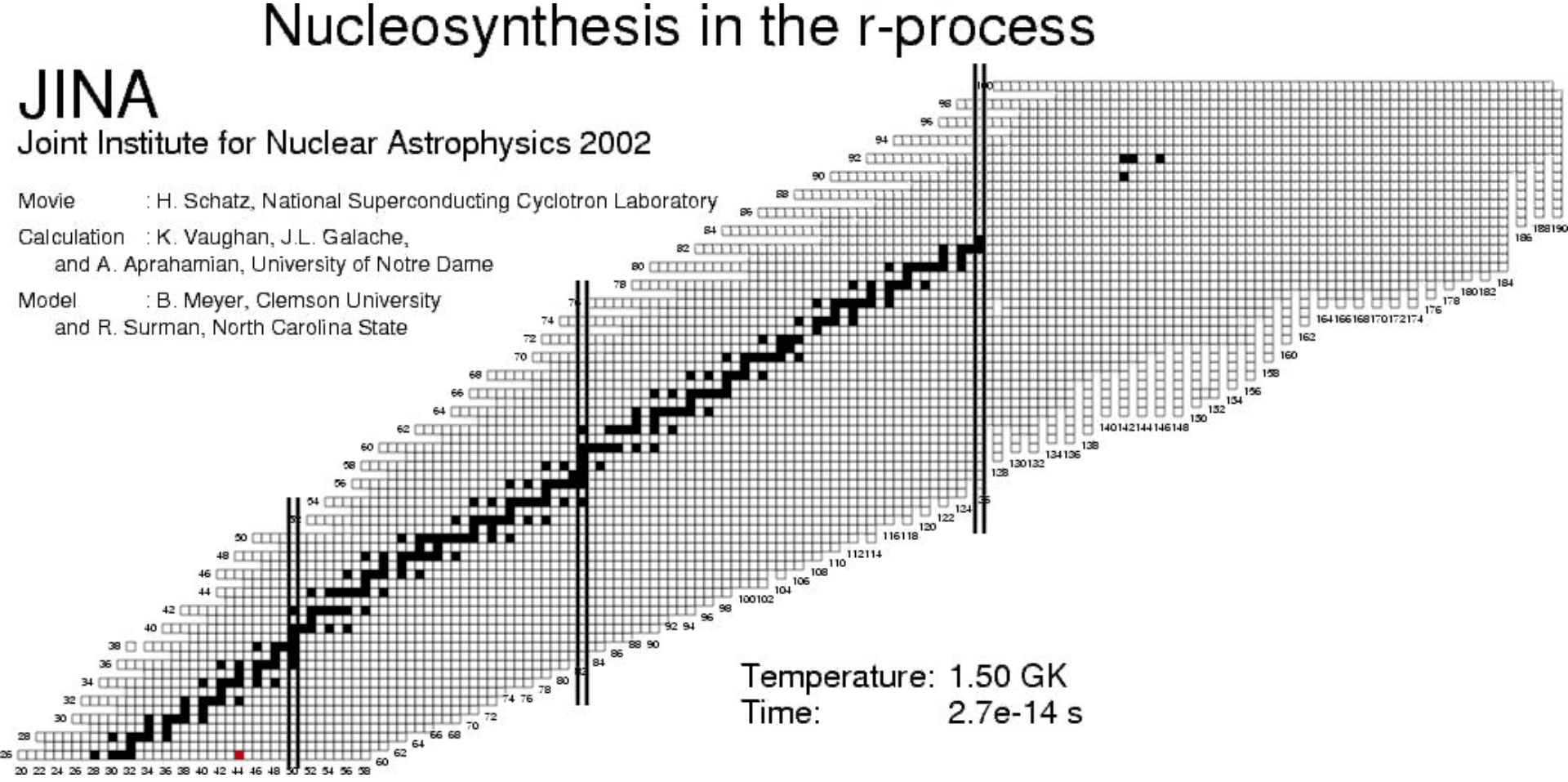
For Large Numbers of Nucleons i.e., Nuclei Much Heavier Than Iron, Energy is Released If the Nuclei Split (FISSION)

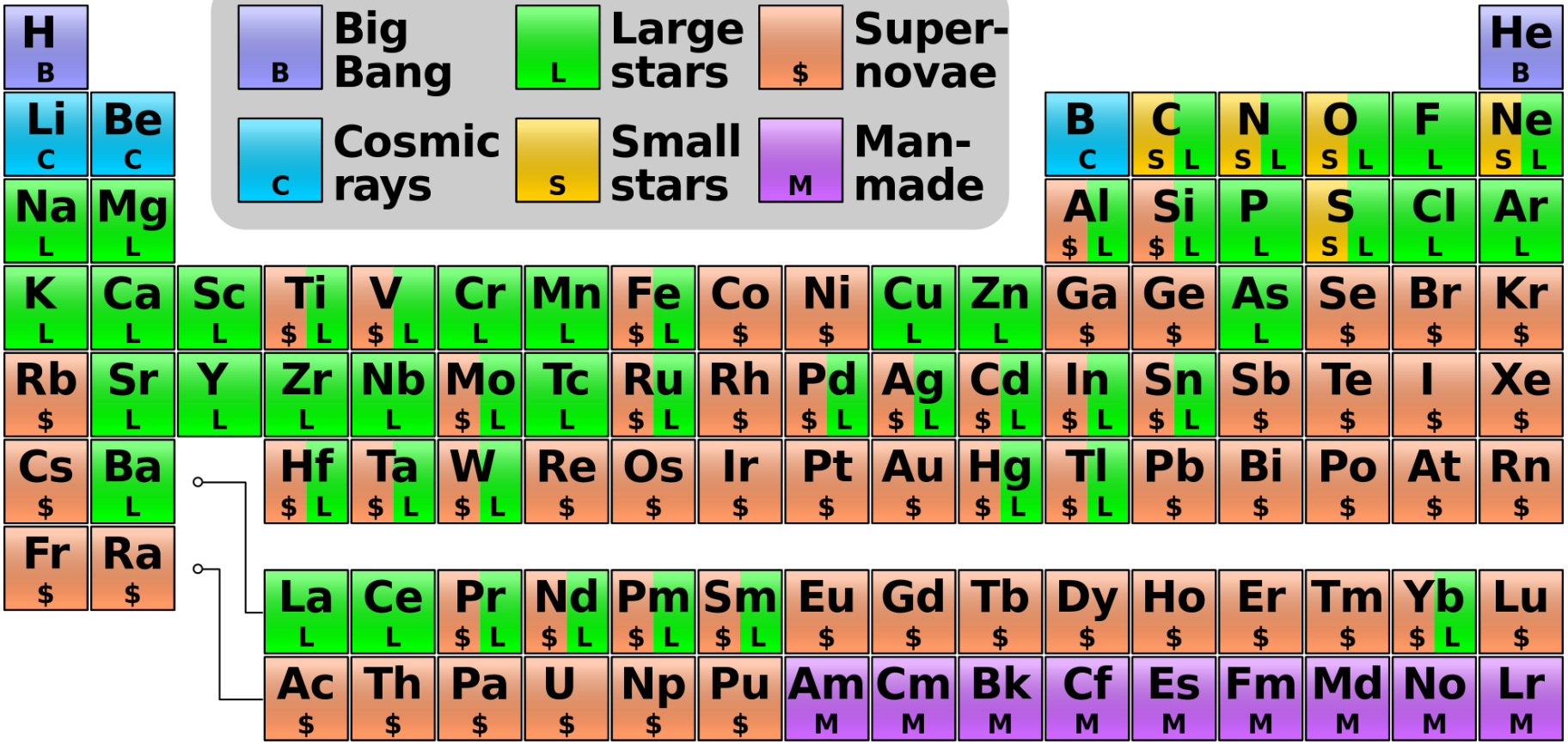


HOW ARE THE HEAVIER ELEMENTS PRODUCED ?

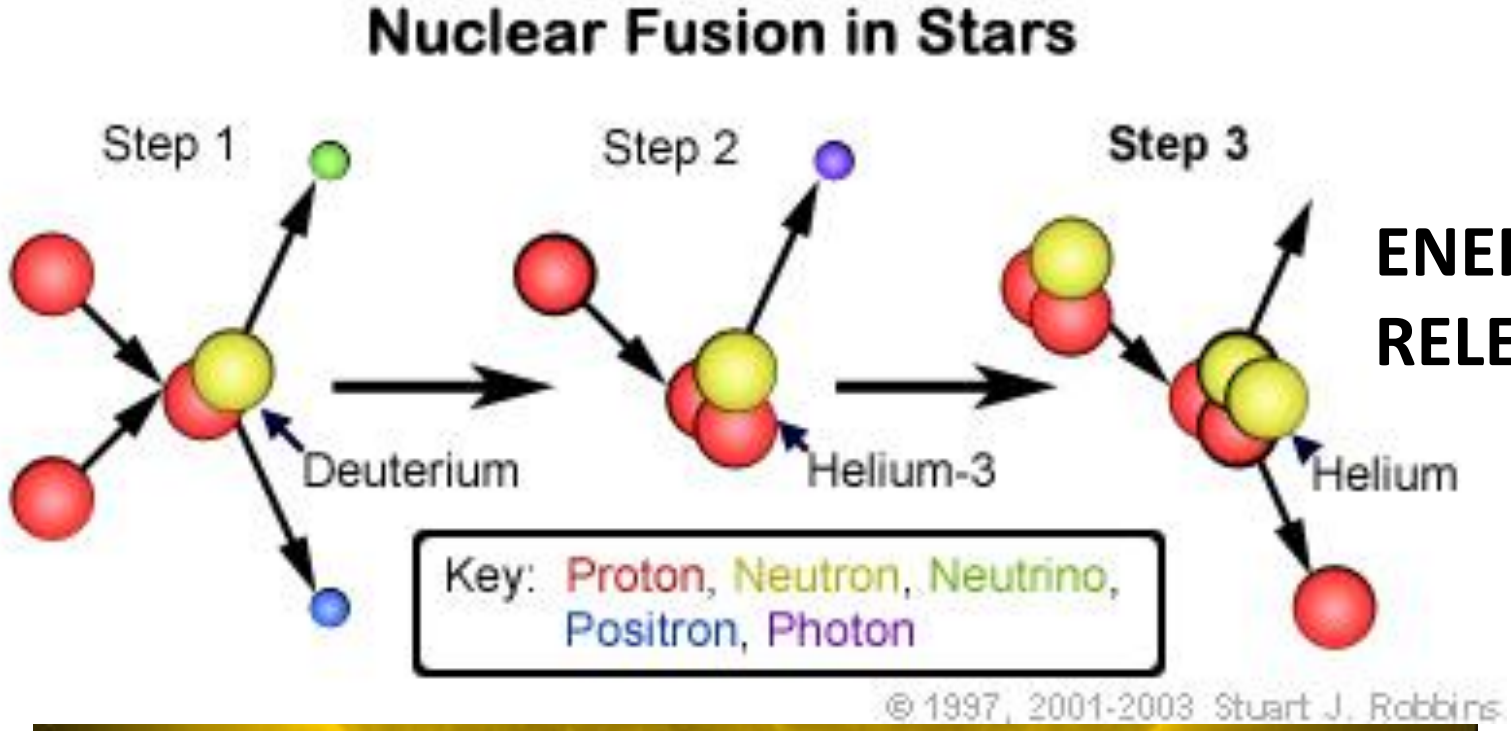


One Important Source for Generation of THE ELEMENTS BEYOND IRON Is EXPLOSIONS of SUCH STARS




B Big Bang
L Large stars
$ Super-novae
C Cosmic rays
S Small stars
M Man-made
H B
He B
Li C
Be C
B C
C S L
N S L
O S L
F L
Ne S L
Na L
Mg L
Al $ L
Si $ L
P L
S S L
Cl L
Ar L
K L
Ca L
Sc L
Ti $ L
V $ L
Cr L
Mn L
Fe $ L
Co $
Ni $
Cu L
Zn L
Ga $
Ge $
As L
Se $
Br $
Kr $
Rb $
Sr L
Y L
Zr L
Nb L
Mo $ L
Tc L
Ru $ L
Rh $
Pd $ L
Ag $ L
Cd $ L
In $ L
Sn $ L
Sb $
Te $
I $
Xe $
Cs $
Ba L
Hf $ L
Ta $ L
W $ L
Re $
Os $
Ir $
Pt $
Au $
Hg $ L
Tl $ L
Pb $
Bi $
Po $
At $
Rn $
Fr $
Ra $
La L
Ce L
Pr $ L
Nd $ L
Pm $ L
Sm $ L
Eu $
Gd $
Tb $
Dy $
Ho $
Er $
Tm $
Yb $ L
Lu $
Ac $
Th $
Pa $
U $
Np $
Pu $
Am M
Cm M
Bk M
Cf M
Es M
Fm M
Md M
No M
Lr M

OUR SUN



ENERGY IS RELEASED

10,000,000 DEGREES KELVIN

2001/03/04 01:05

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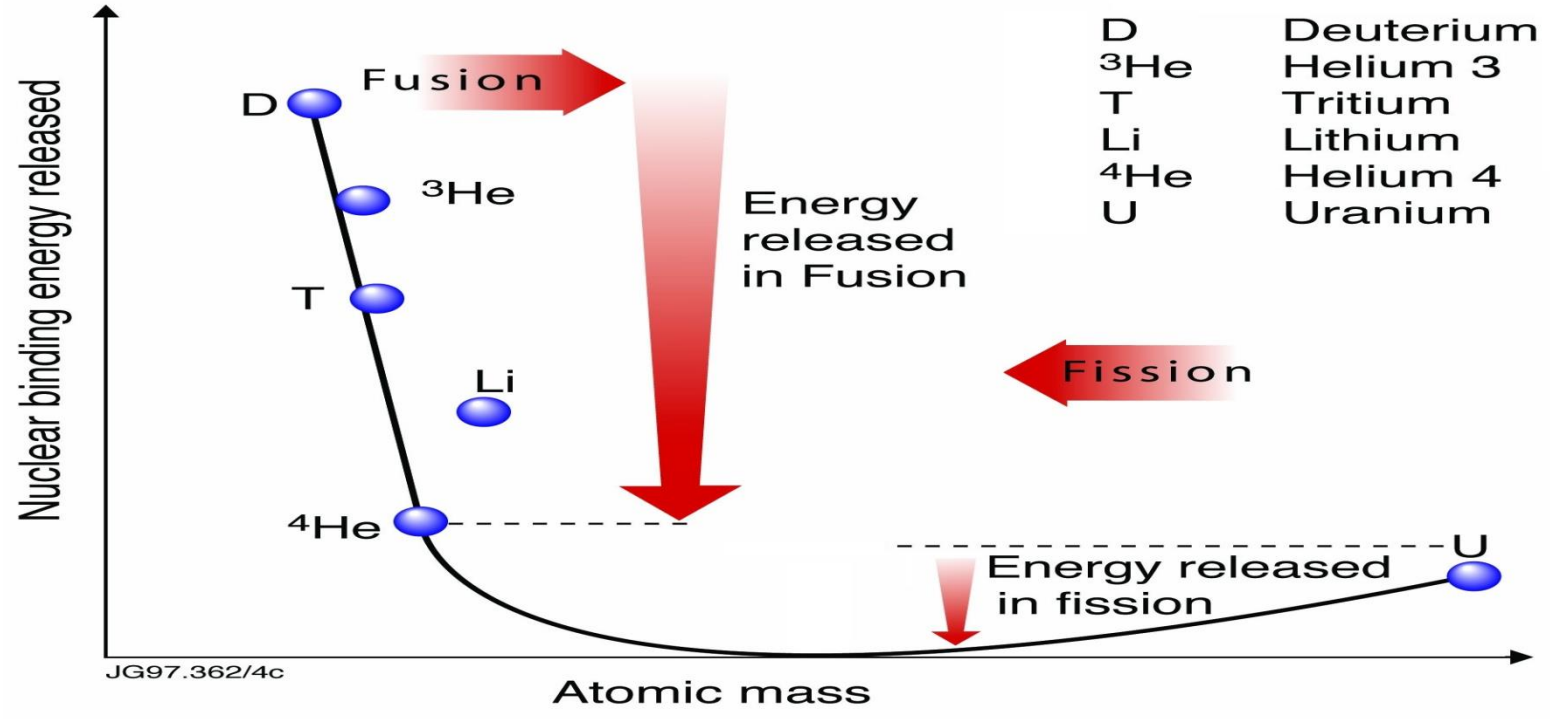

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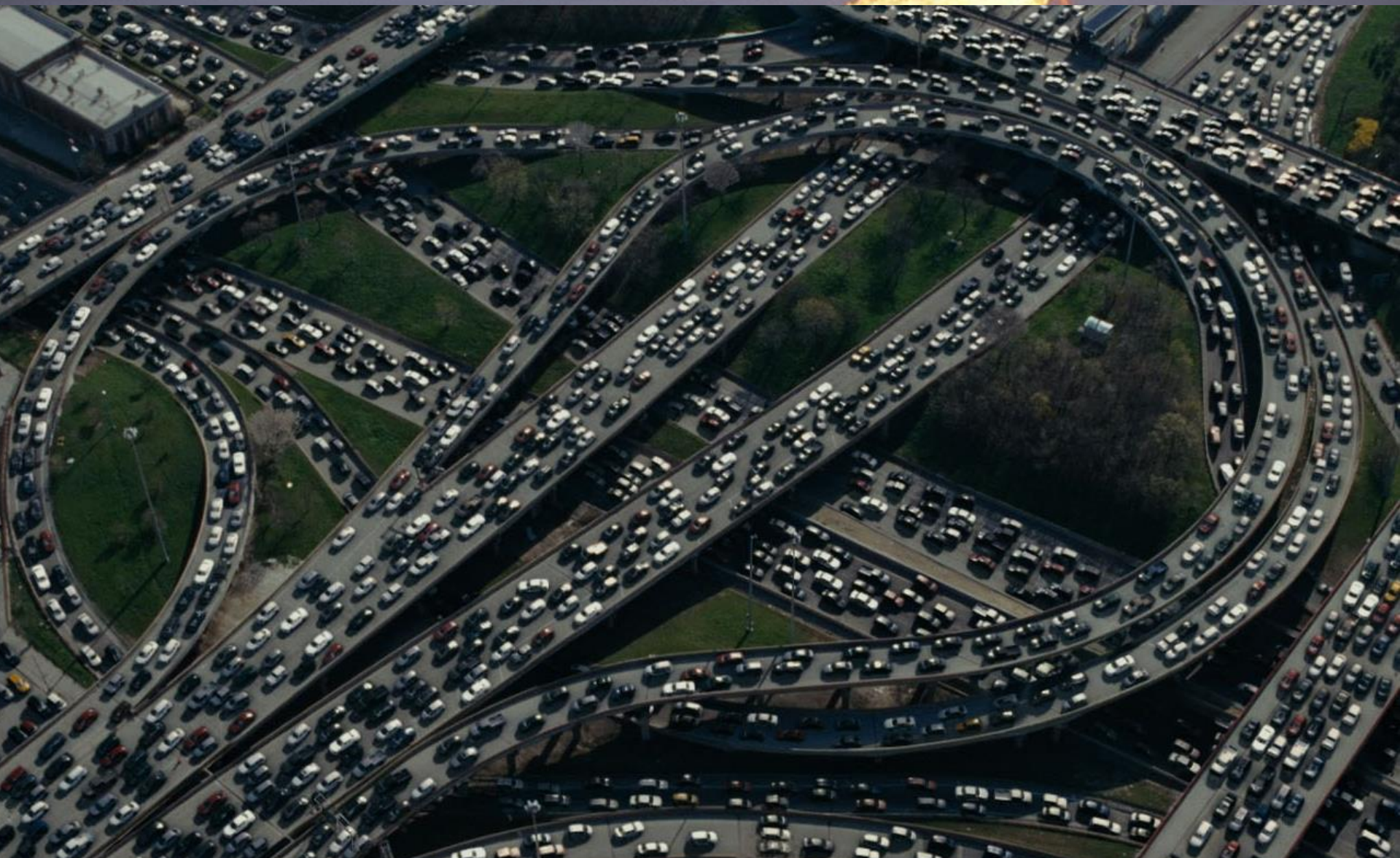
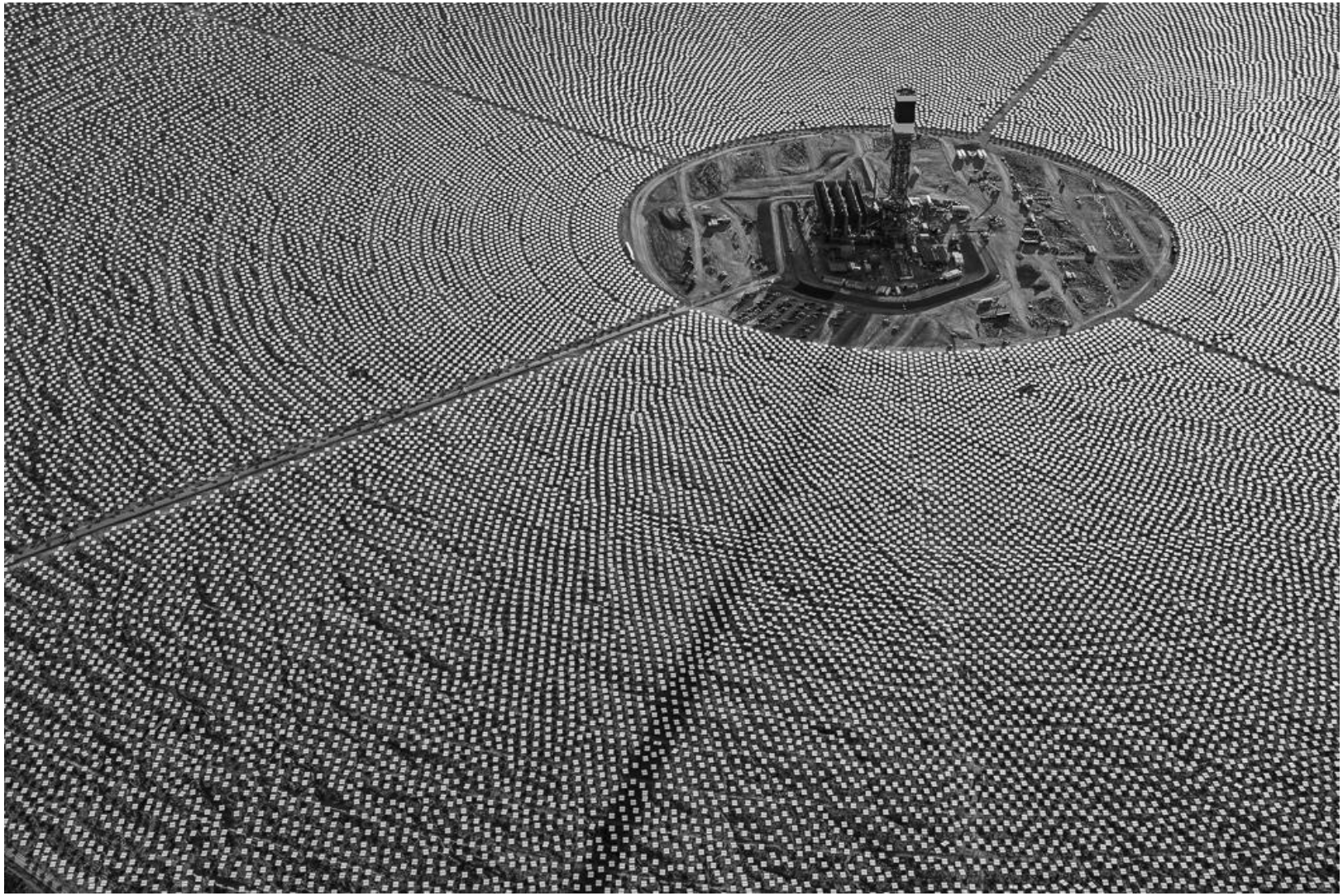
Using Fossil Fuels is Indirectly Harvesting Solar Energy For Energy Production

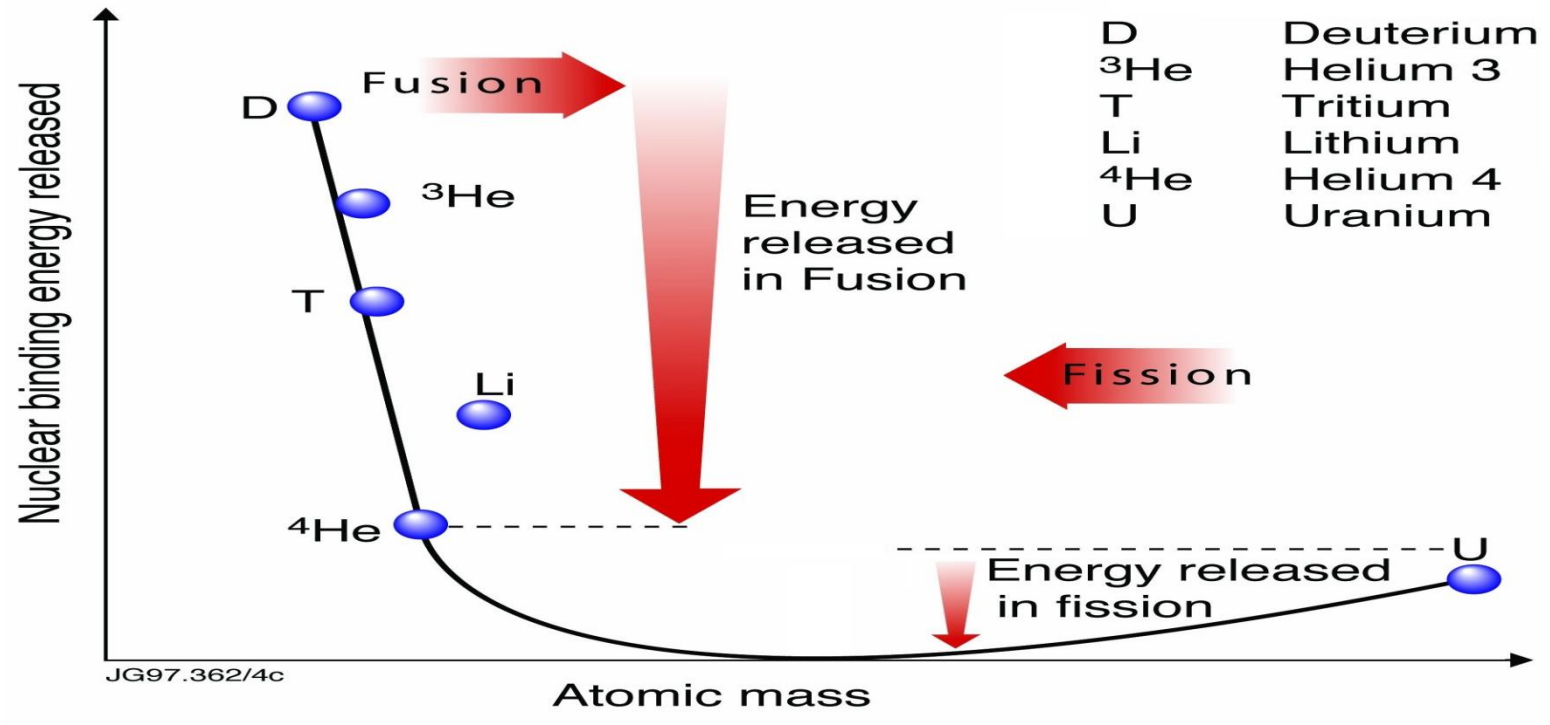


Directly Harvesting Solar Energy For Energy Production



Harnessing Nuclear Reactions For Energy Production

For A Given Number of Nucleons, An Increase in Binding Energy per Nucleon Means that Energy Will Be Released



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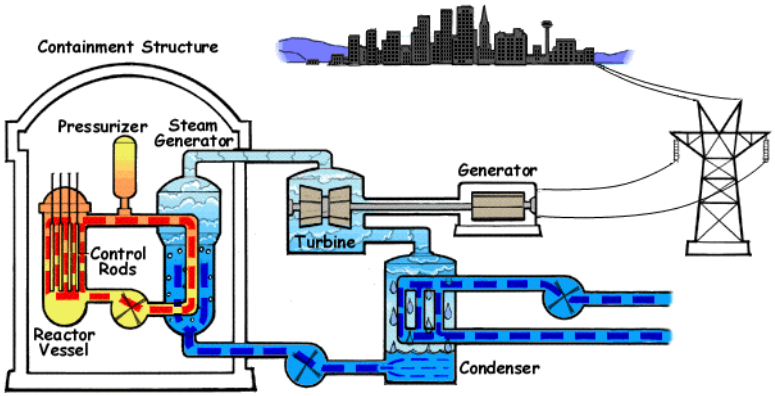
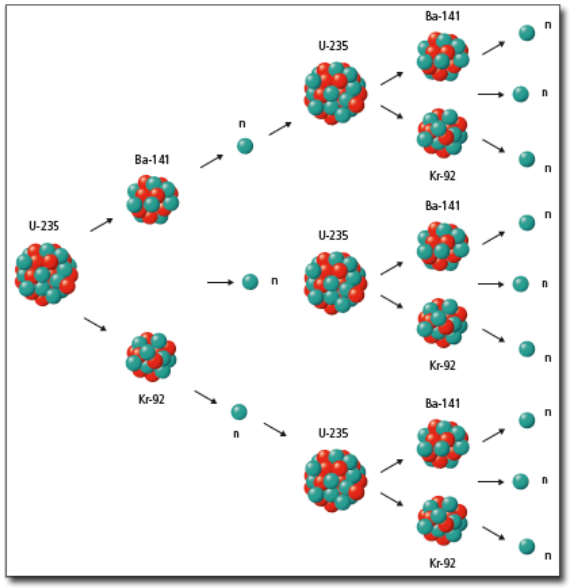
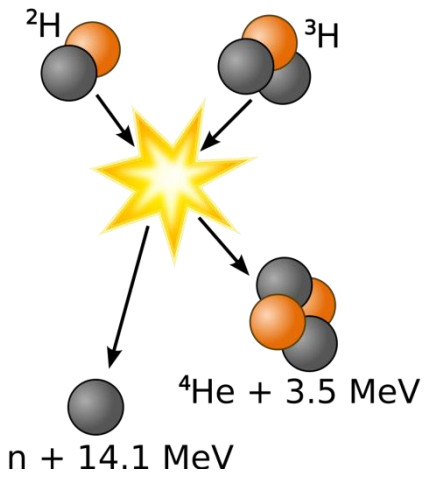
FISSION REACTOR
Harnessing the Heavy Elements
NOW





FUSION REACTOR
Harnessing the Light Elements
Still in the future



Nuclear Reactions
Where Would We Be Without Them?

"There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy. "

Shakespeare

- *Hamlet* (1.5.167-8), Hamlet to Horatio