Astrophysical Relevance of Clustering in Low Density Nuclear Matter

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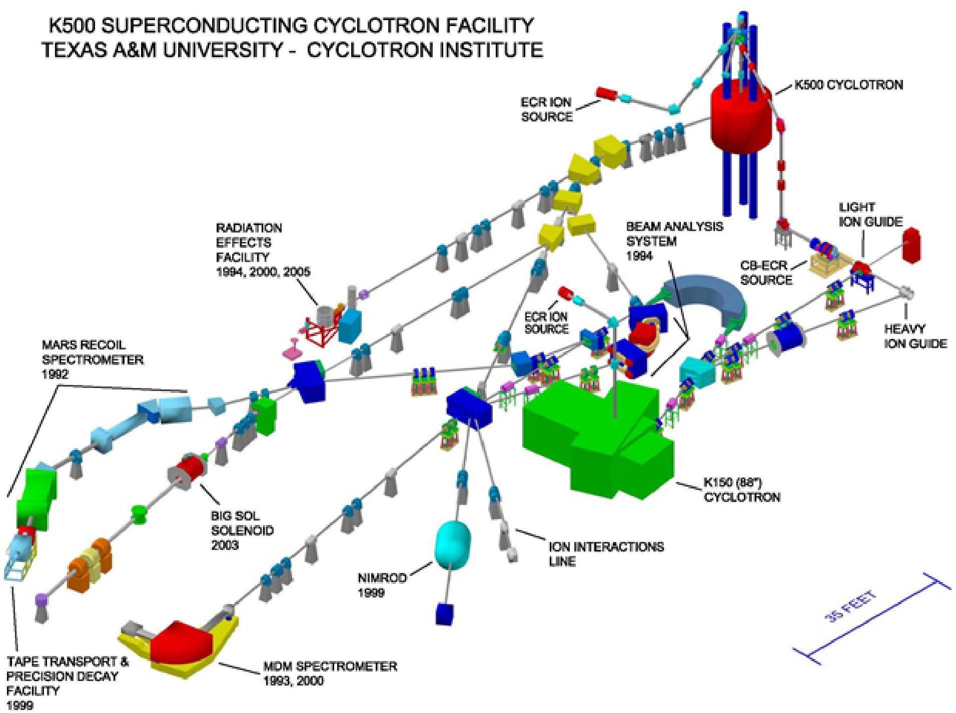
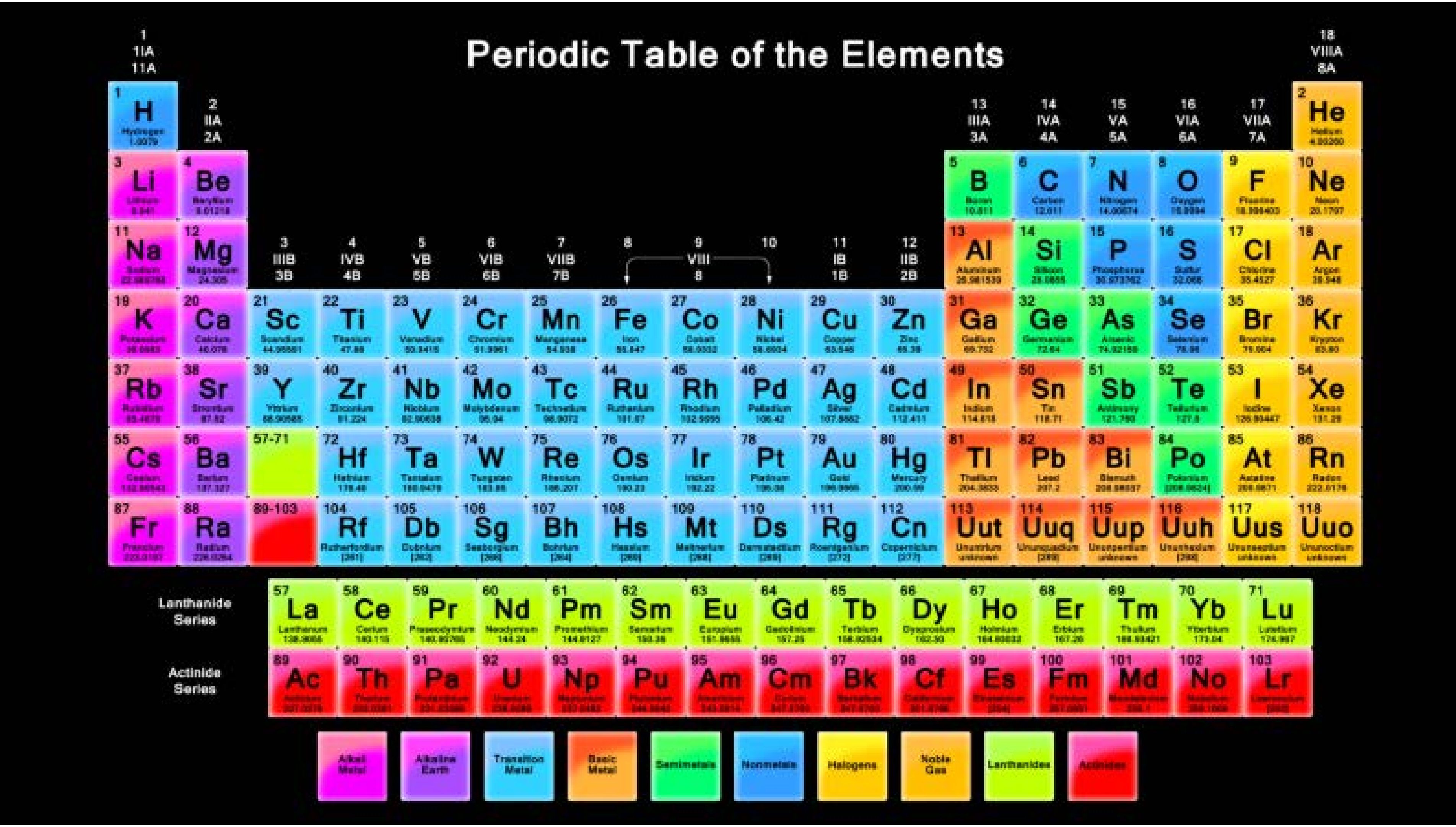


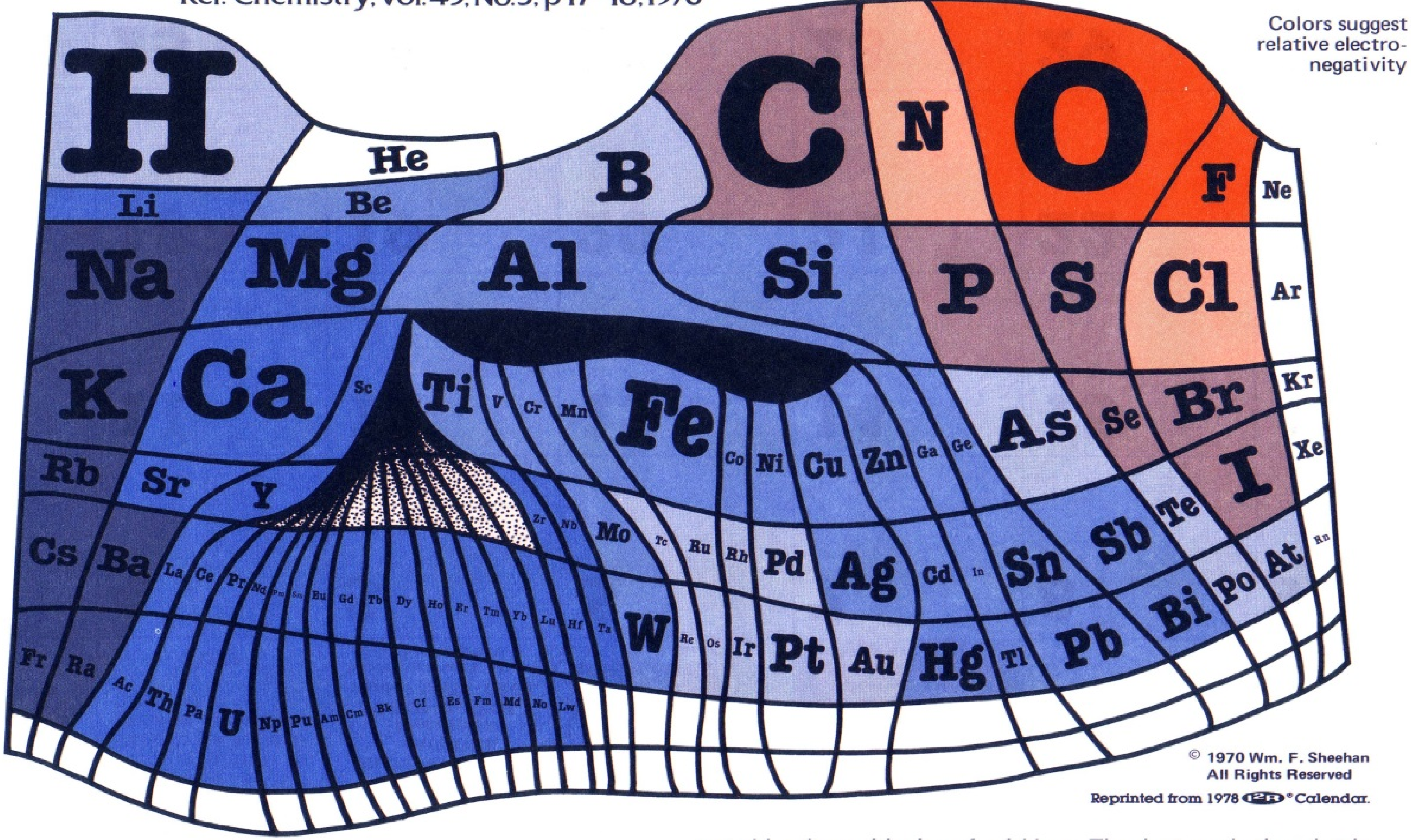


Periodic Table of the Elements
1 1IA 11A
2 IIA 2A
13 IIIA 3A
14 IVA 4A
15 VA 5A
16 VIA 6A
17 VIIA 7A
18 VIIIA 8A
3 IIIB 3B
4 IVB 4B
5 VB 5B
6 VIB 6B
7 VIIB 7B
8 9 10 VIII 8
11 IB 1B
12 IIB 2B
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
57-71
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
89-103
104 Rf
105 Db
106 Sg
107 Bh
108 Hs
109 Mt
110 Ds
111 Rg
112 Cn
113 Uut
114 Uuq
115 Uup
116 Uuh
117 Uus
118 Uuo
Lanthanide Series
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
Actinide Series
89 Ac
90 Th
91 Pa
92 U
93 Np
94 Pu
95 Am
96 Cm
97 Bk
98 Cf
99 Es
100 Fm
101 Md
102 No
103 Lr
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetals
Nonmetals
Halogens
Noble Gas
Lanthanides
Actinides

The Elements According to Relative Abundance

A Periodic Chart by Prof. Wm. F. Sheehan, University of Santa Clara, CA 95053

Ref. Chemistry, Vol. 49, No. 3, p 17–18, 1976



Reprinted from 1978 Calendar.

Roughly, the size of an element's own niche ("I almost wrote square") is proportioned to its abundance on Earth's surface, and in addition, certain chemical similarities (e.g., Be and Al, or B and Si) are suggested by the positioning of neighbors. The chart emphasizes that in real life a chemist will probably meet O, Si, Al, . . . and that he better do something about it. Periodic tables based upon elemental abundance would, of course, vary from planet to planet. . . **W.F.S.**

NOTE: TO ACCOMMODATE ALL ELEMENTS SOME DISTORTIONS WERE NECESSARY, FOR EXAMPLE SOME ELEMENTS DO NOT OCCUR NATURALLY.

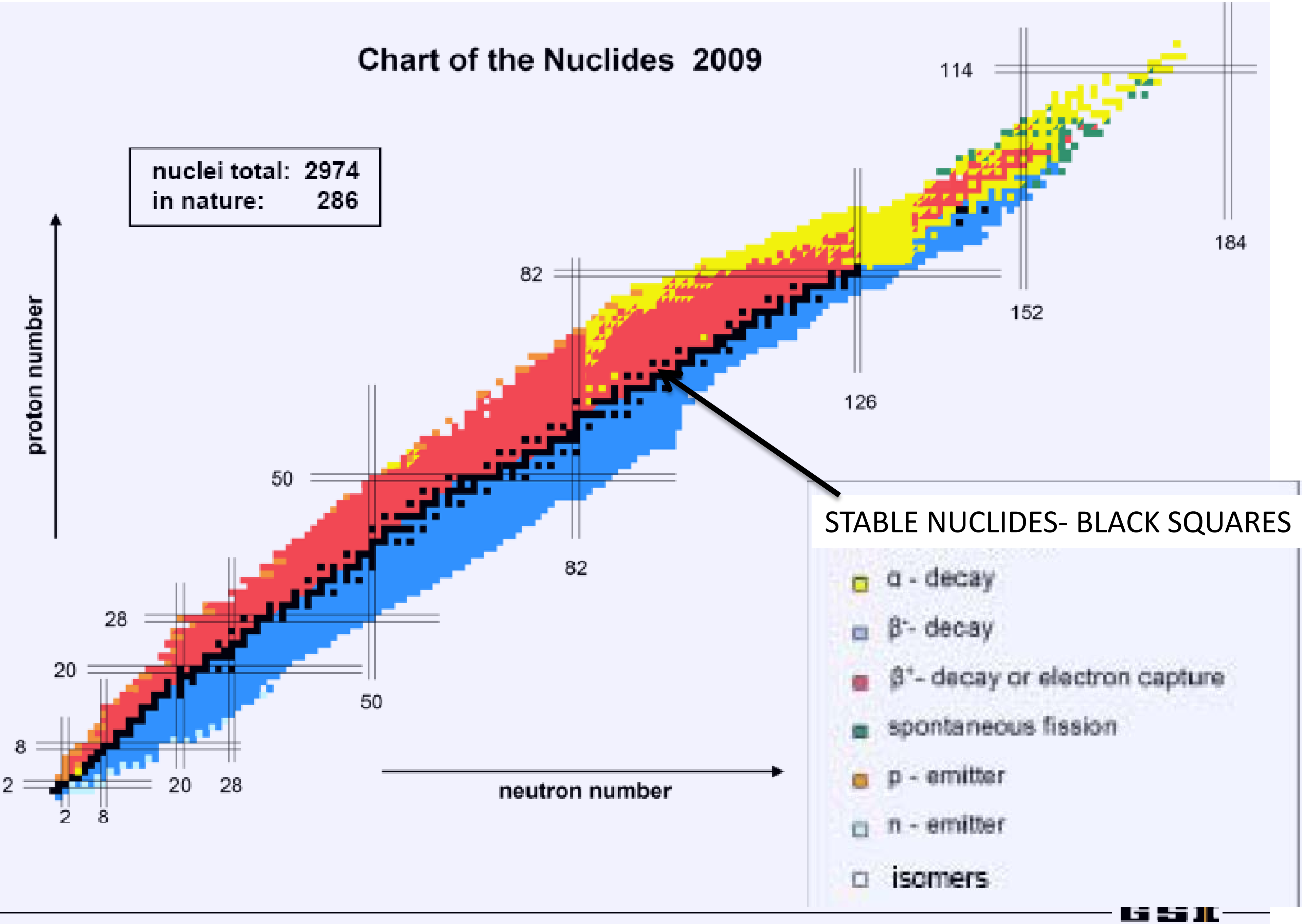


Chart of the Nuclides 2009
nuclei total: 2974
in nature: 286
proton number
neutron number
2
8
20
28
50
82
114
126
152
184
STABLE NUCLIDES- BLACK SQUARES
α - decay
β⁻- decay
β⁺- decay or electron capture
spontaneous fission
p - emitter
n - emitter
isomers

The Liquid Drop Model

The Semi-Empirical Mass Formula

$m(Z,N) = [Z \cdot m_H + N \cdot m_n] - B(Z,N)/c^2 ; \quad B > 0$ neglect e- binding

Original: Weizsacker, Z. Physik 96,431(1935)

$$B(Z,N) = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_a \frac{(A-2Z)^2}{A} - \delta A^{-1/2}$$

Wapstra, Handb. Physik, XXXVIII

INFINITE NUCLEAR MATTER →

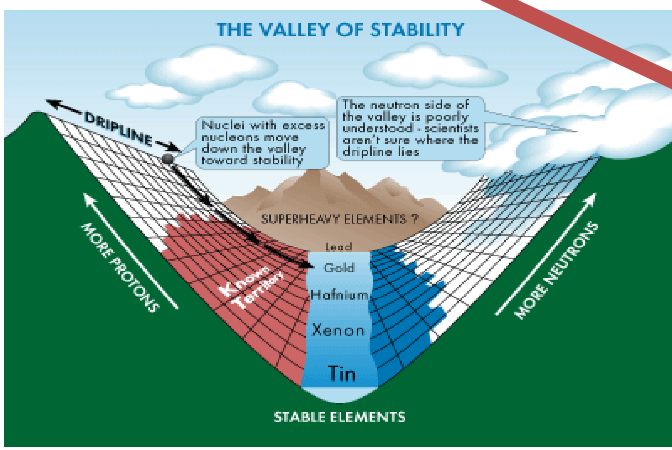
$= 15.835\ MeV$

$a_S = 18.33\ MeV$

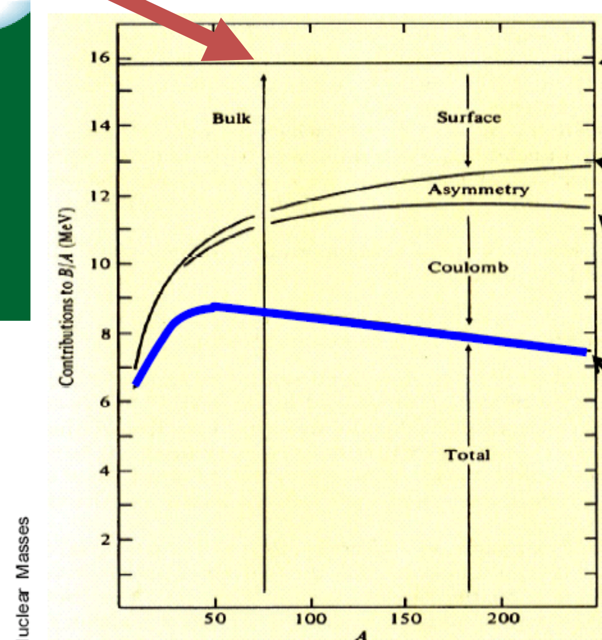
$a_C = 0.714\ MeV$

$a_a = 23.20\ MeV$

$$\delta = \begin{cases} +11.2\ MeV\ for\ \ o-o\ nuclei \\ 0\ MeV\ for\ odd-A\ nuclei \\ -11.2\ MeV\ for\ \ e-e\ nuclei \end{cases}$$



Relative Contributions to Nuclear Mass



$R \propto A^{1/3} \rightarrow V_{nucleus} \approx A$
const. contribution from each nucleon→ "saturated" force

fewer interactions on surface → reduce contribution from each surface nucleon $S \propto A^{2/3}$

different interactions between like and unlike nucleons (Fermion statistics, isospin)→ depends on |N-Z|, reduces B

Coulomb self energy becomes large for large Z, heavy nuclei, makes nucleus unstable reduces B

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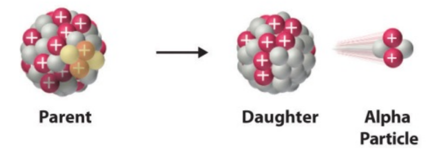
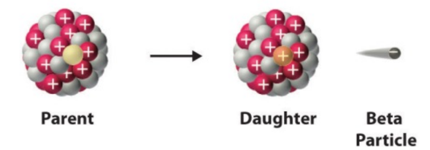
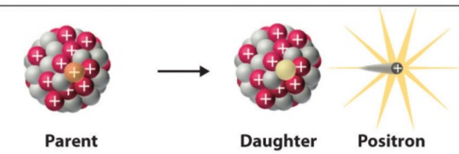
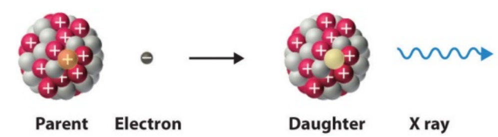
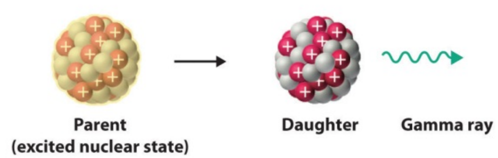
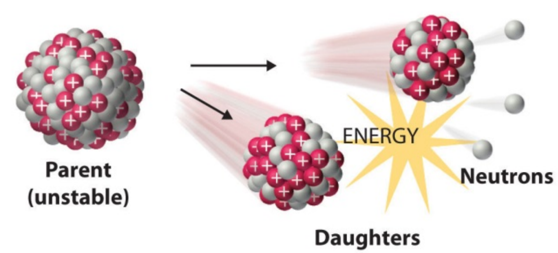
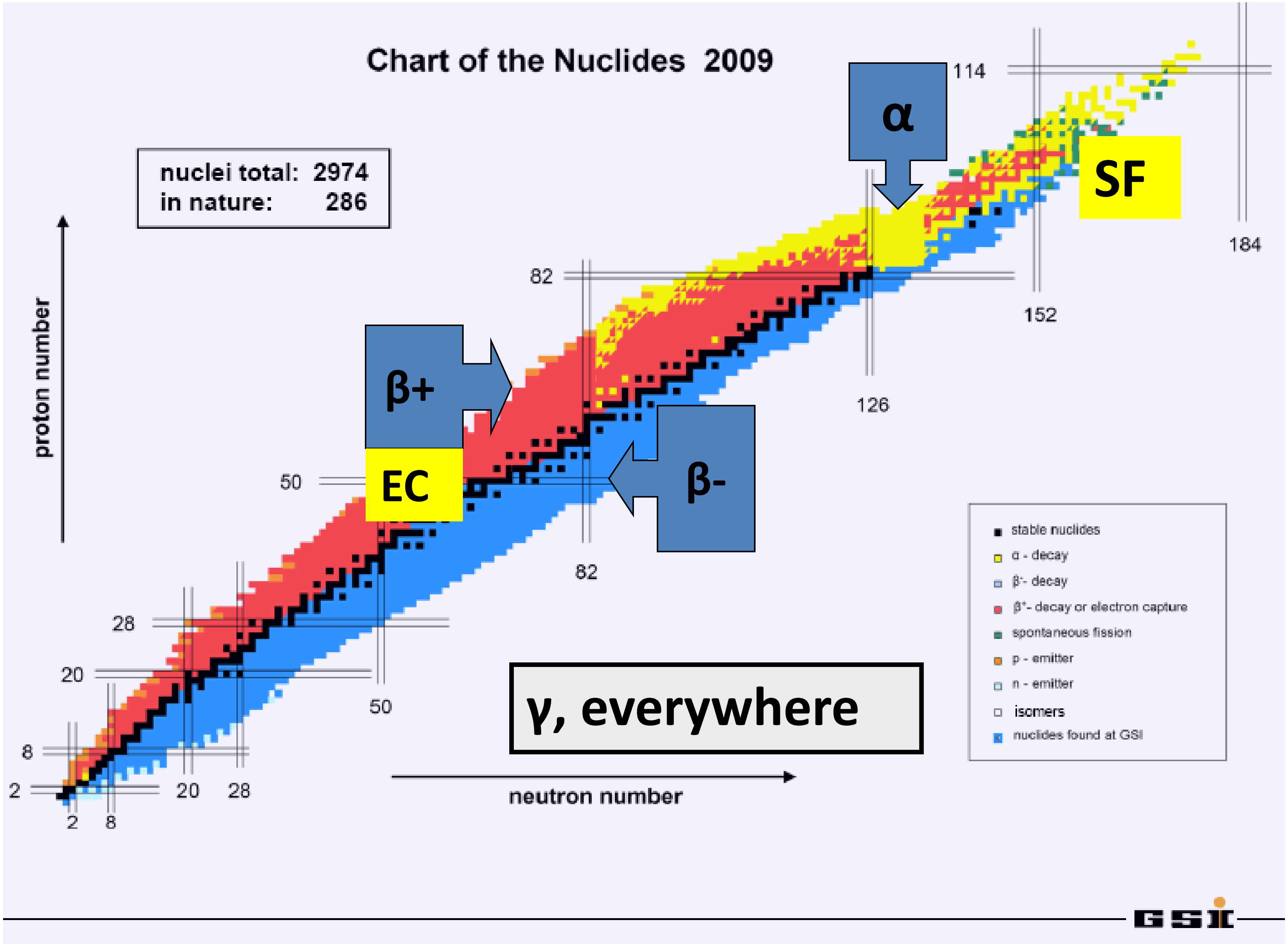
Note:
In these three, neutrinos are also emitted

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	${}^{A}_{Z}X + {}^{0}_{-1}e \longrightarrow {}^{A}_{Z-1}X' + \text{X ray}$	
Gamma emission	${}^{0}_{0}\gamma$	${}^{A}_{Z}X^{*} \xrightarrow{\text{Relaxation}} {}^{A}_{Z}X' + {}^{0}_{0}\gamma$	
Spontaneous fission	Neutrons	${}^{A+B+C}_{Z+Y}X \longrightarrow {}^{A}_{Z}X' + {}^{B}_{Y}X' + C\,{}^{1}_{0}n$	

Most Isotopes are Radioactive



Reversing the Trend --Nuclear Reactions

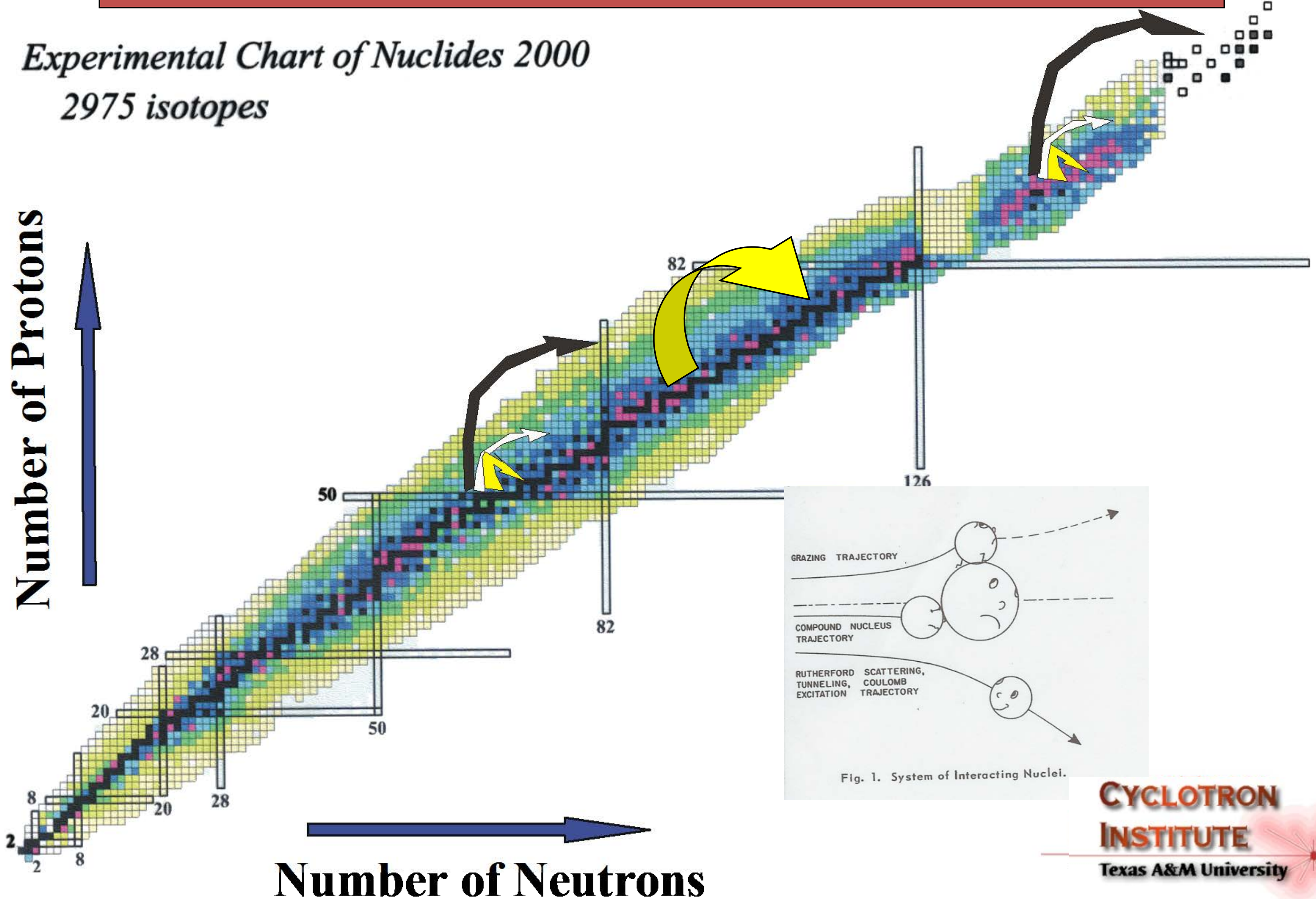


Fig. 1. System of Interacting Nuclei.

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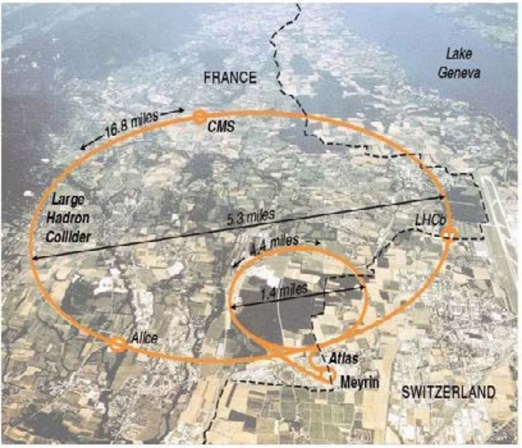
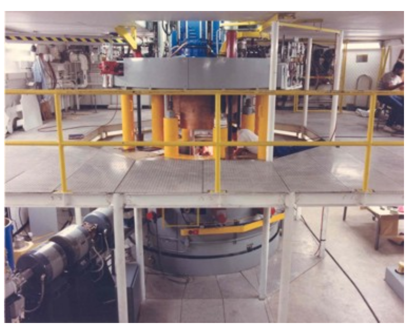
ACCELERATORS

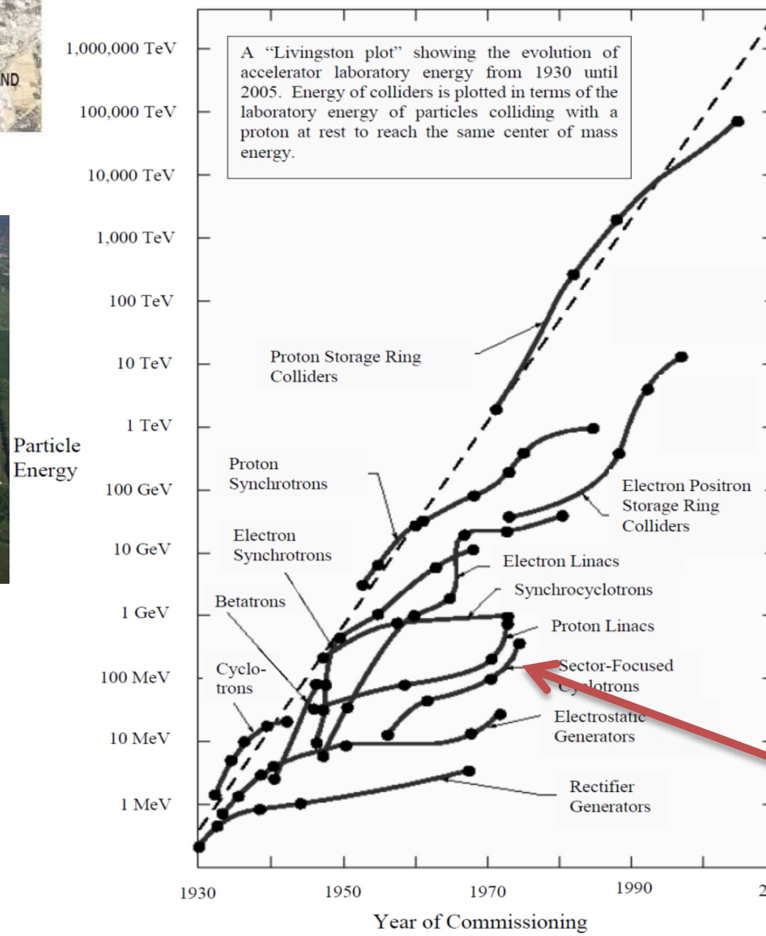


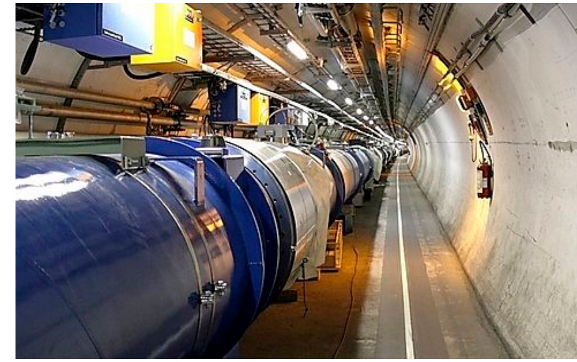
LHC

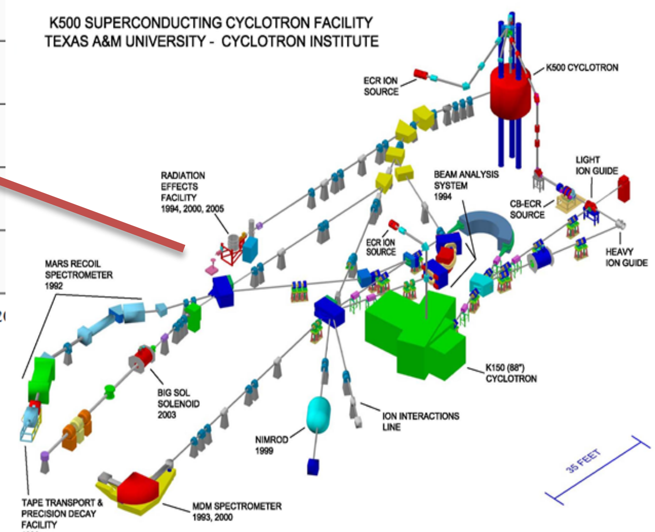
RHIC



TAMU







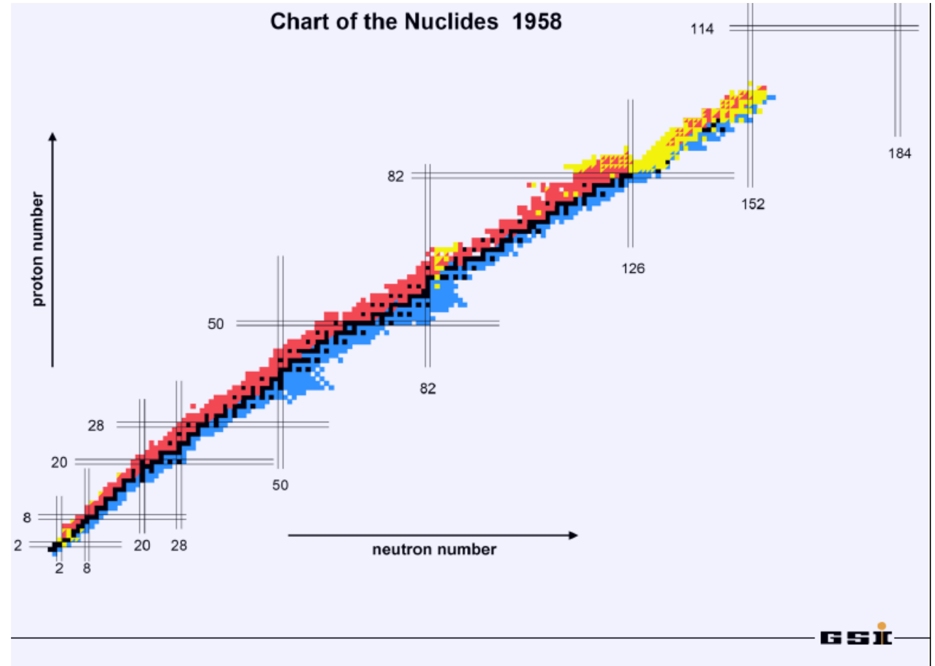
1958-My first course in nuclear chemistry

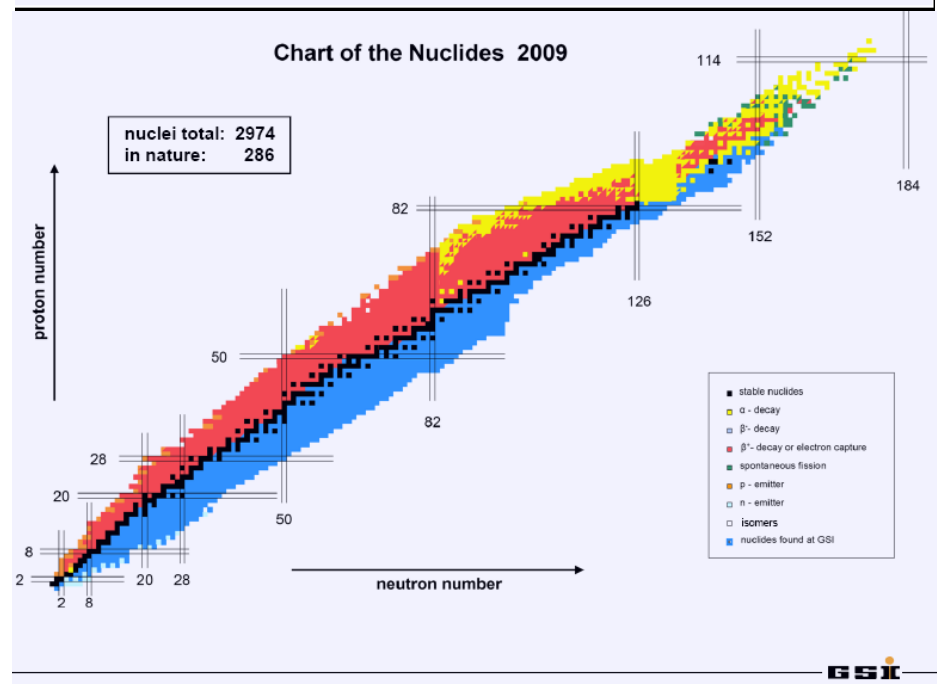
- With such reactions new isotopes

  and

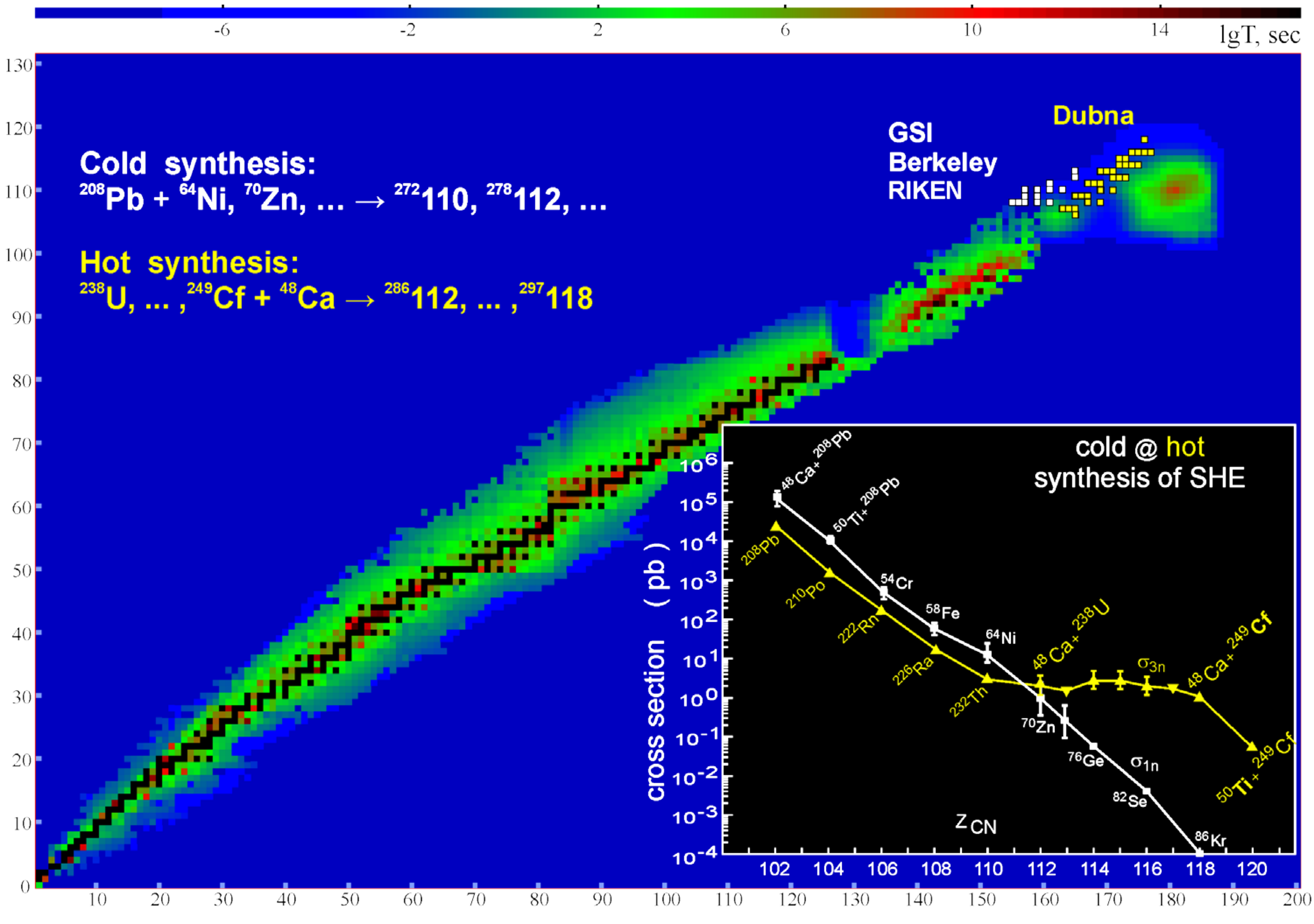
  new elements

  can be made

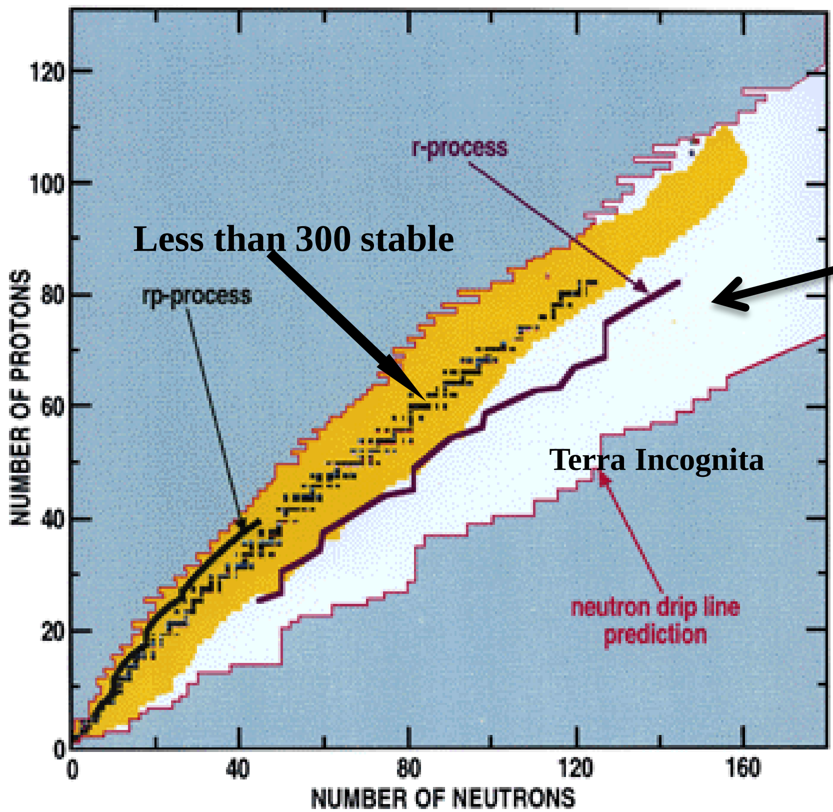




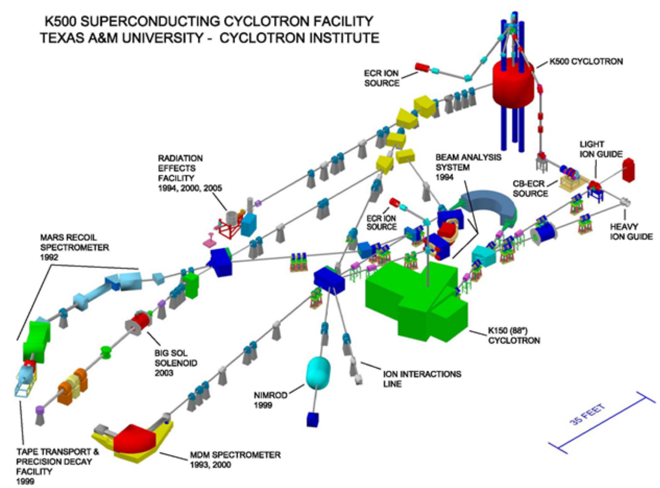
Synthesis of superheavy elements (cold and hot fusion)



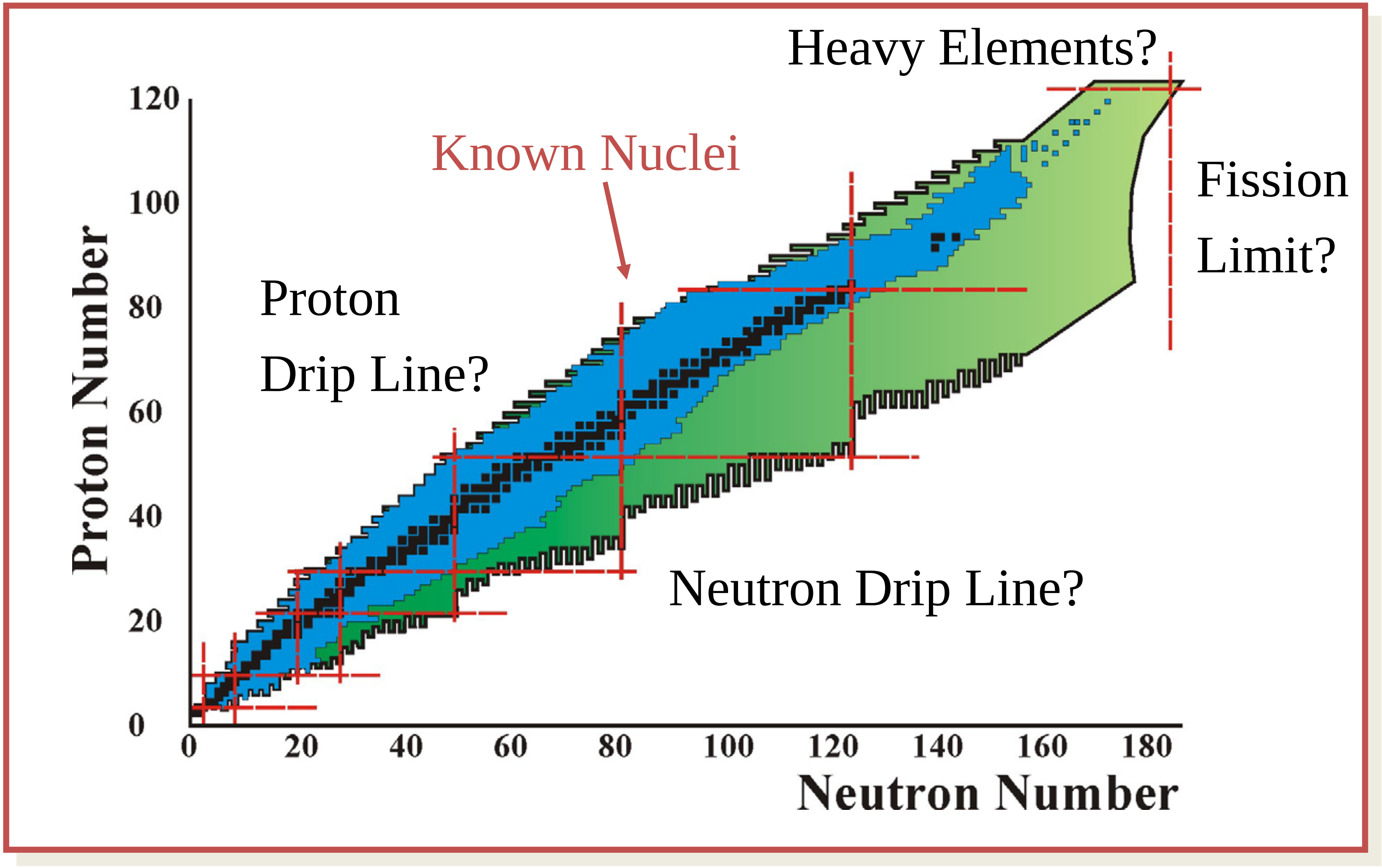
Theoretical Limits to the Existence of Nuclei



- 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



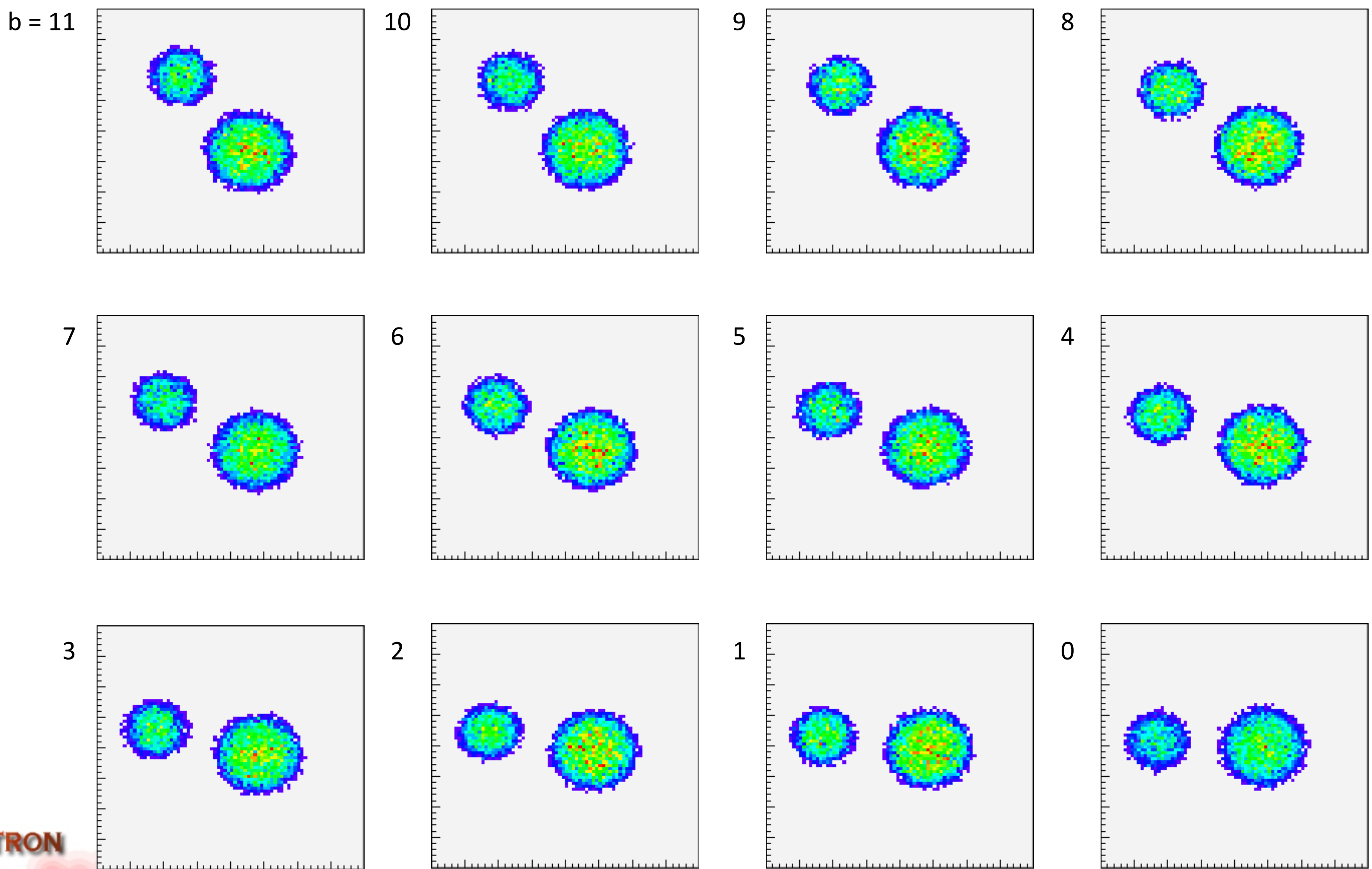
Limits of Stability



Higher Energy Reactions

Time (fm/c) = 1

32 MeV/nucleon $^{48}Ca + ^{124}Sn$



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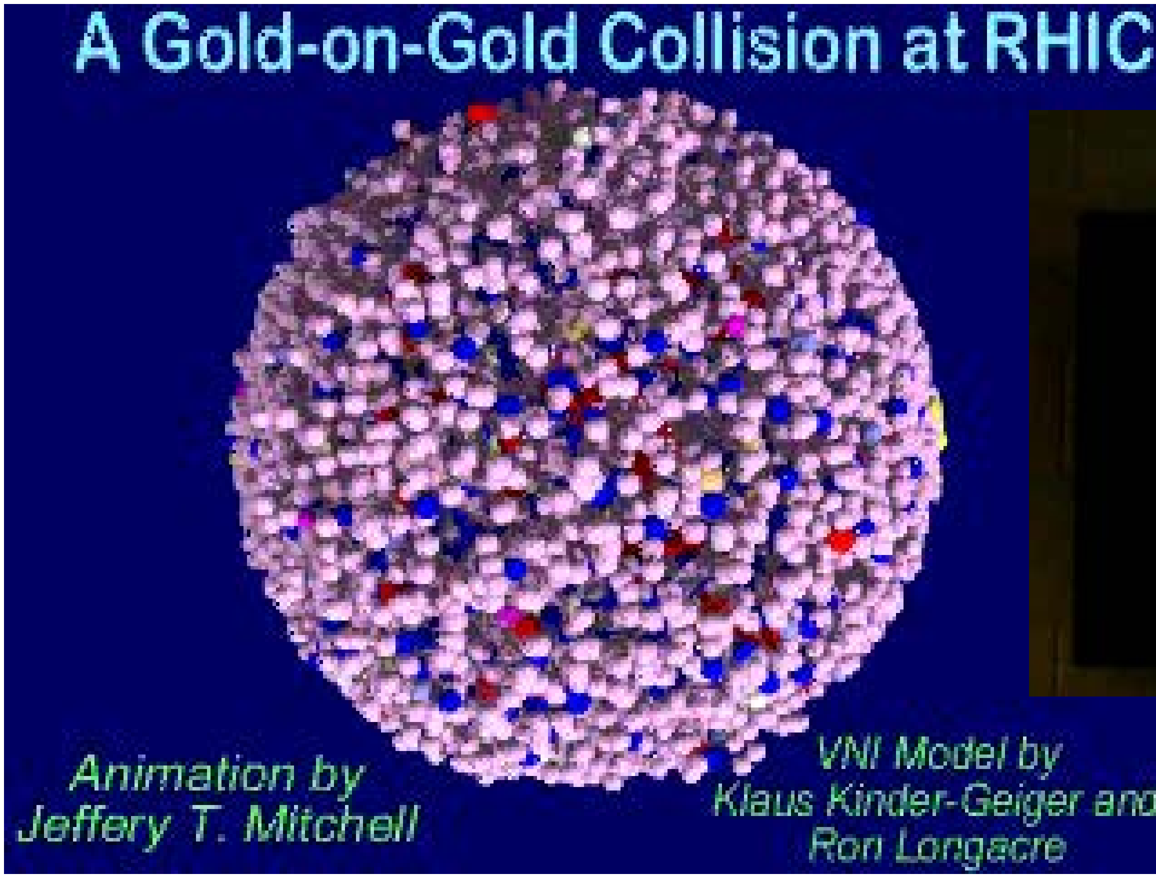
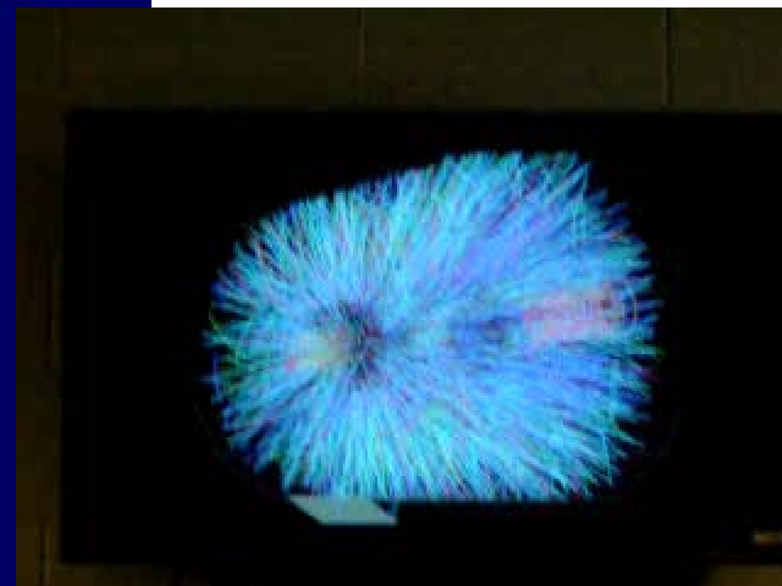
[13] A.L. Keksis, thesis, Texas A&M University, 2007

200 GeV/nucleon



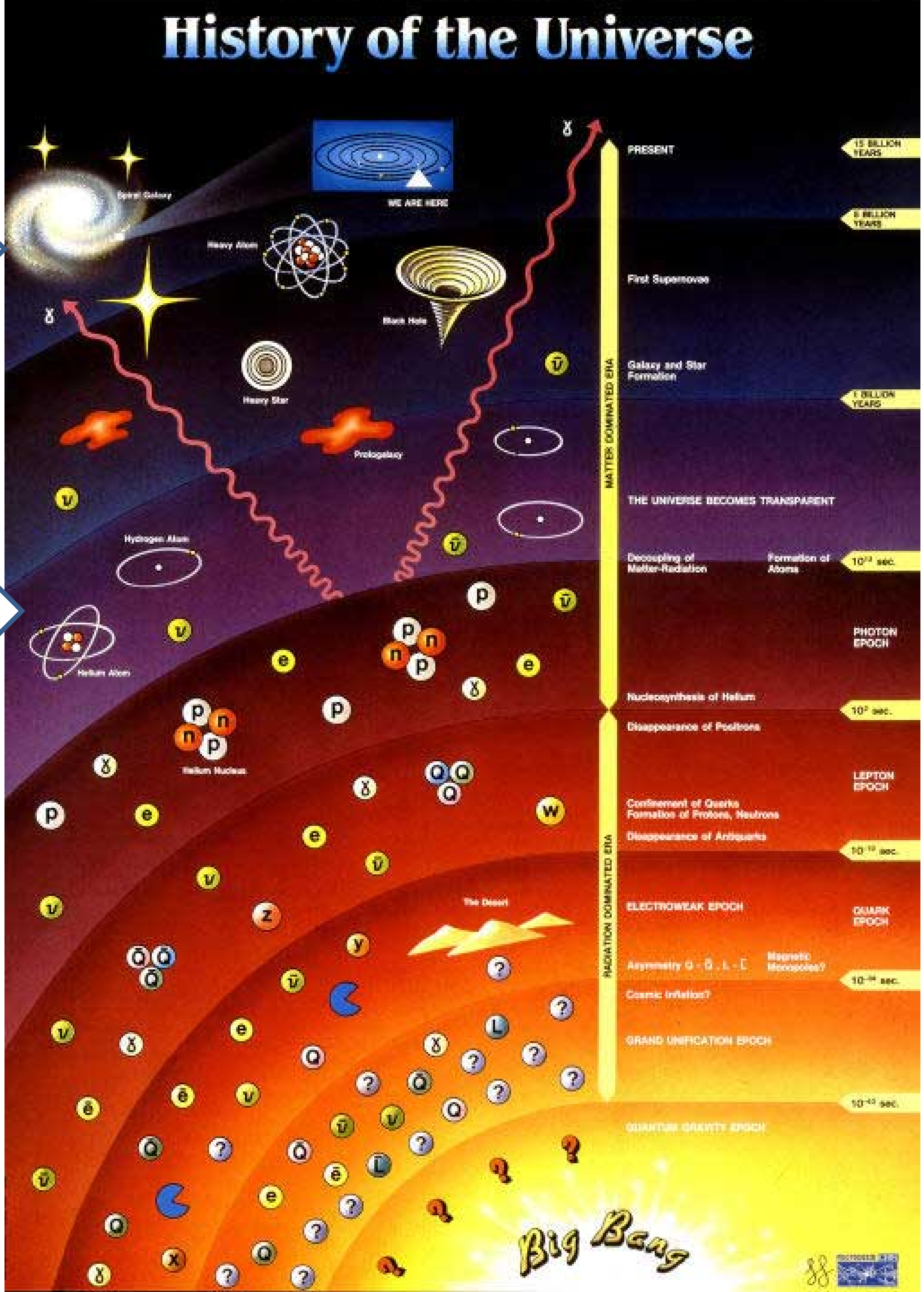


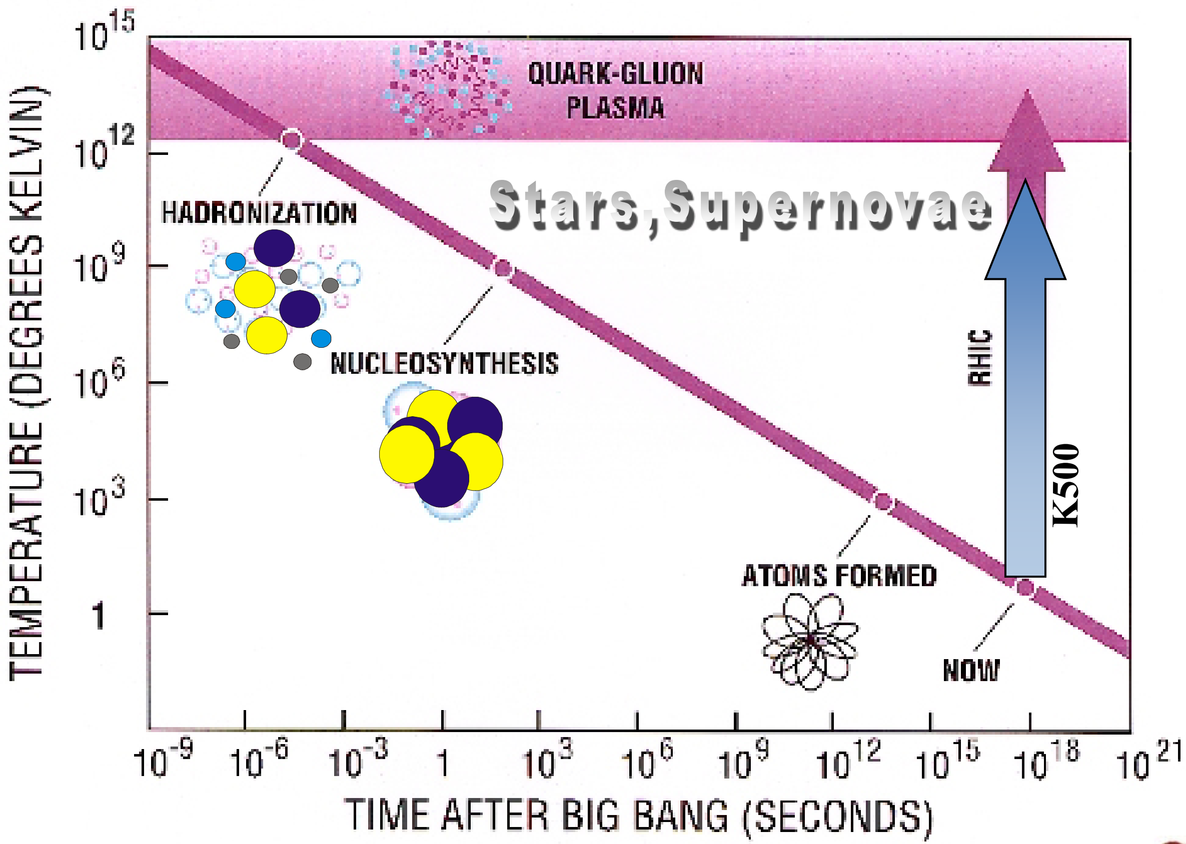
The Little Bang

The Big Bang

Heavier Elements

First Atoms, H and He





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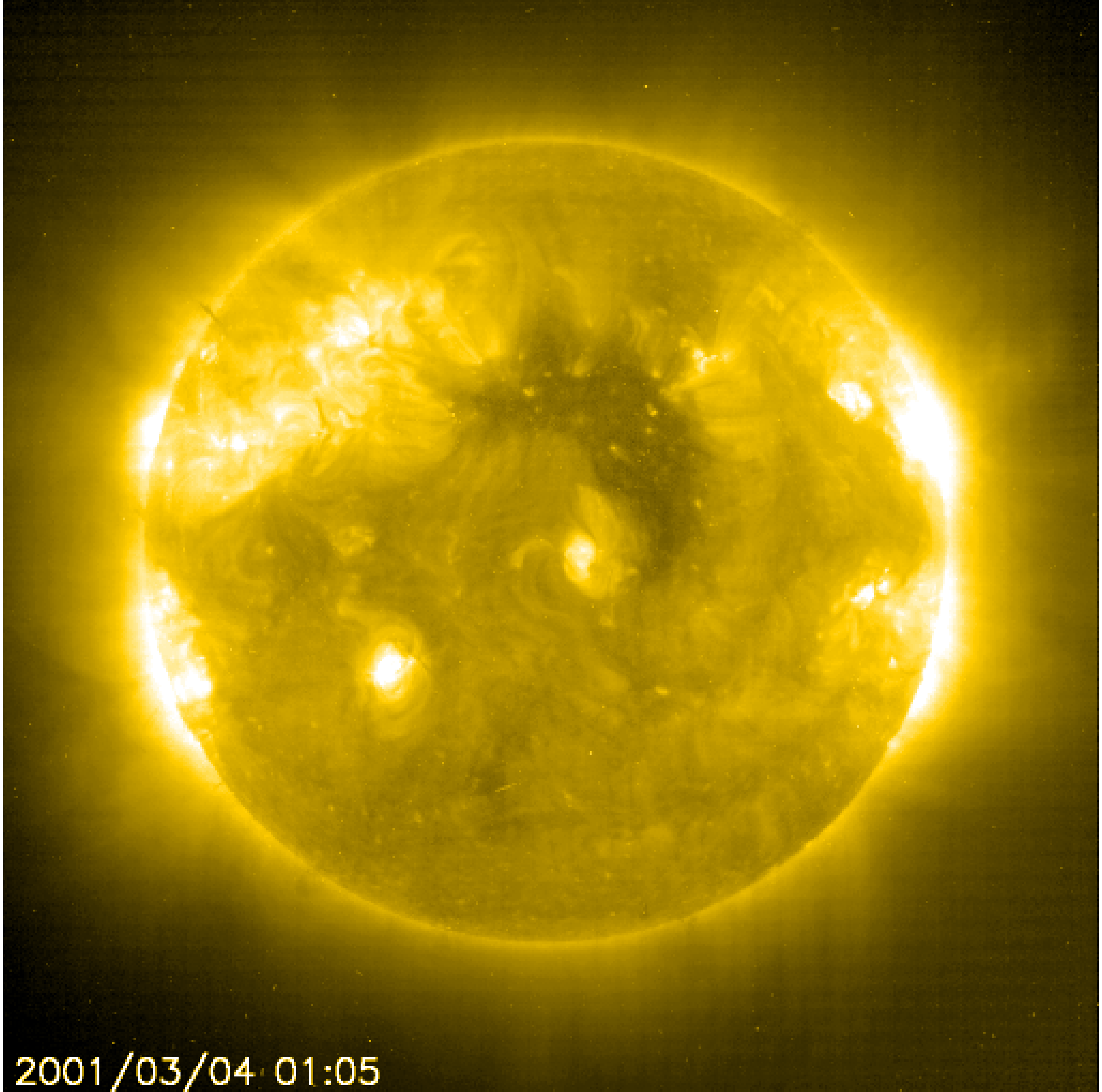
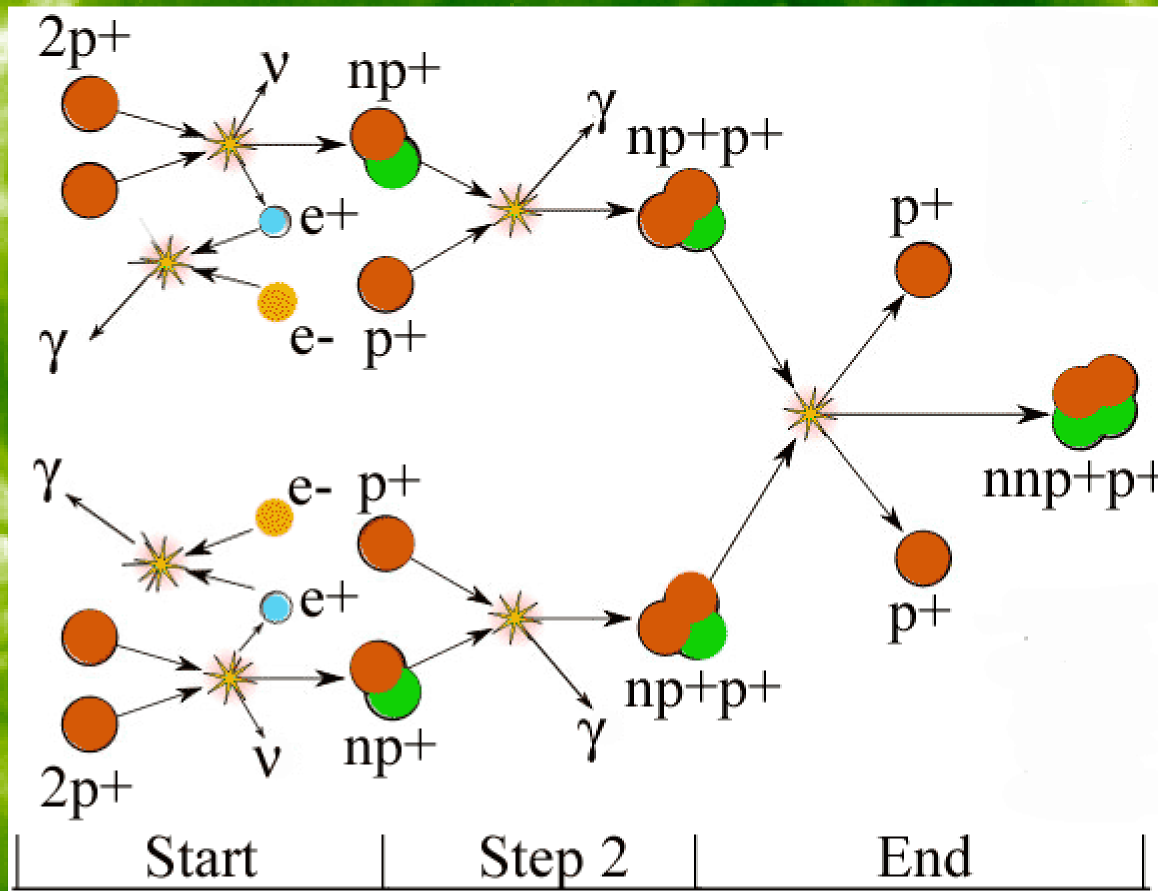

2001/03/04 01:05

OUR SUN



10,000,000 DEGREES

NEUTRINO ASTROPHYSICS

W. C. Haxton
Institute for Nuclear Theory and Department of Physics
Box 351550 University of Washington, Seattle, WA 98195
email: Haxton@phys.washington.edu

Figure 1: The Homestake Mine's chlorine detector, which Ray Davis Jr. and colleagues operated for over three decades.

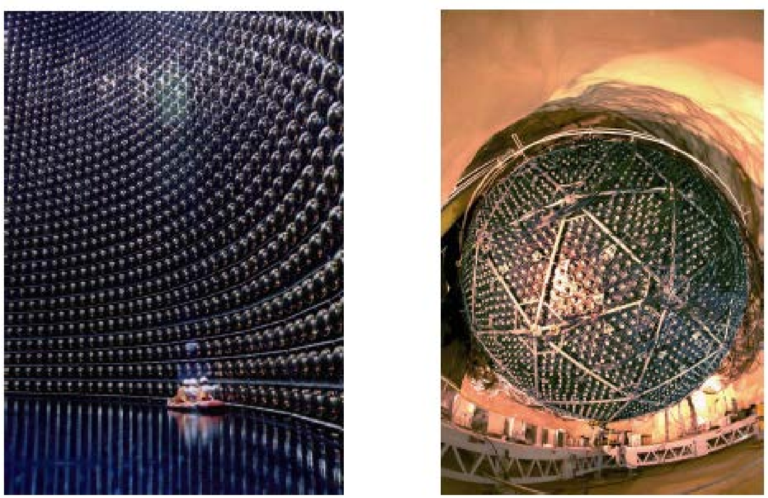
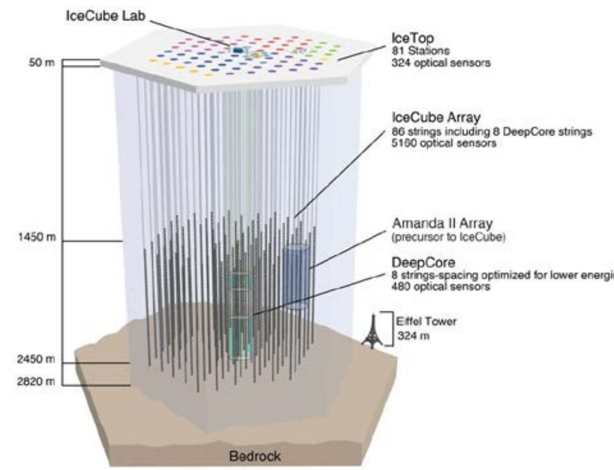
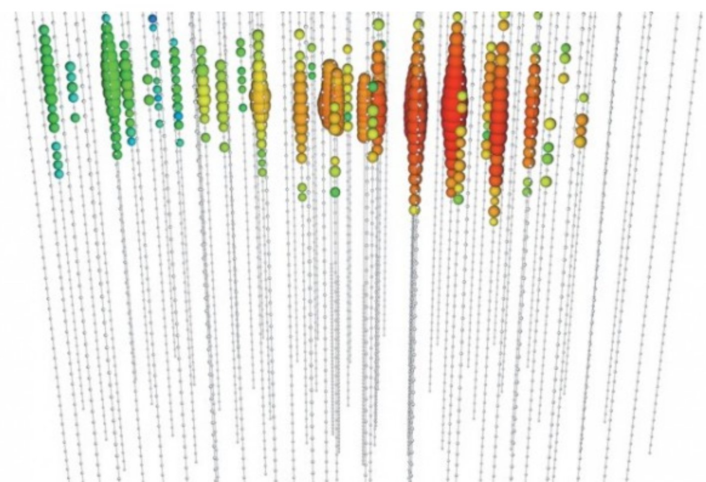
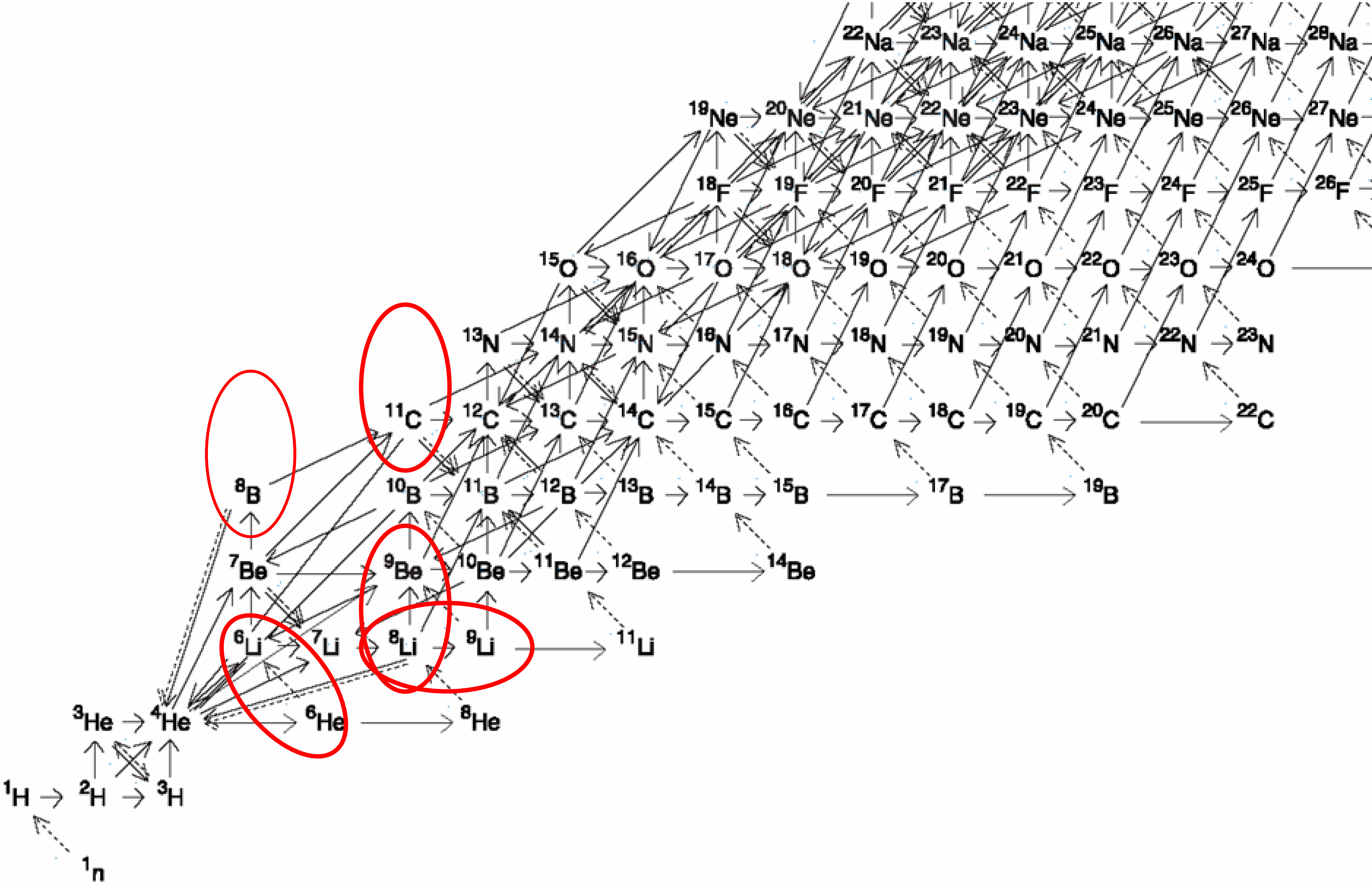


Figure 3: The left panel shows the Super-Kamiokande detector during filling, with scientists cleaning PMT surfaces as the water rises. The right panel is a fish-eye photo of the SNO detector and cavity, showing the PMTs and support structure prior to cavity and detector filling.



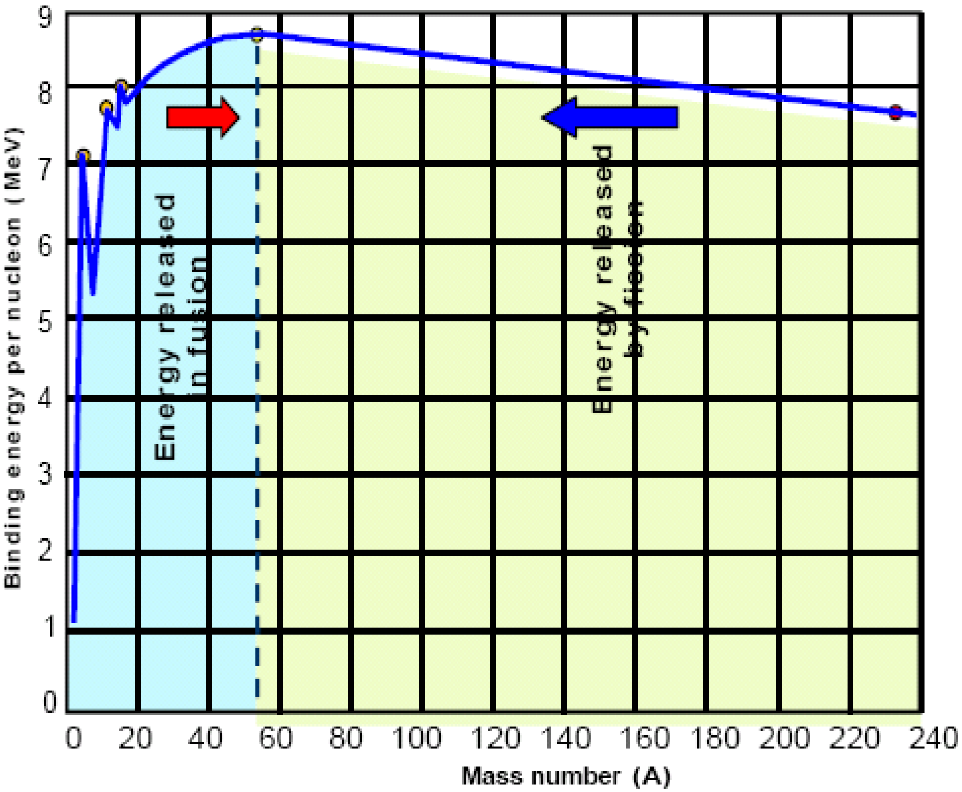


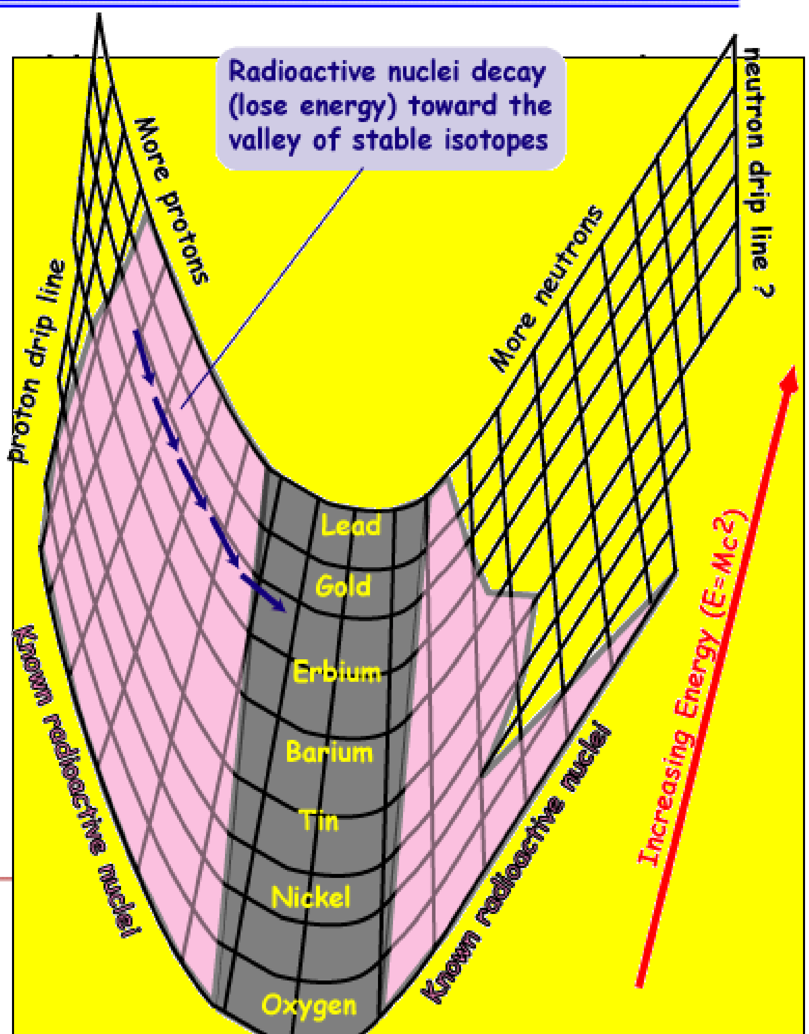
Origin of the Lighter Elements



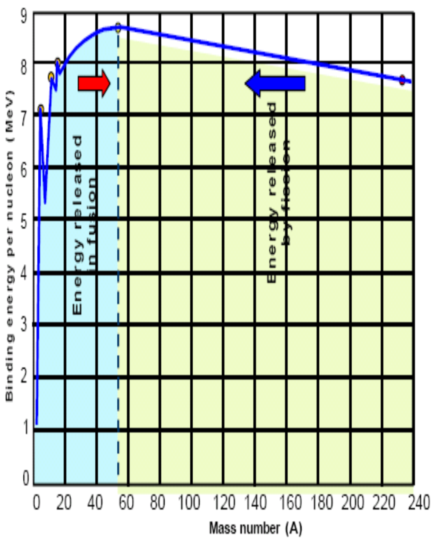
Floor of Binding Energy Valley is Not Flat

Energetics of Transmutation

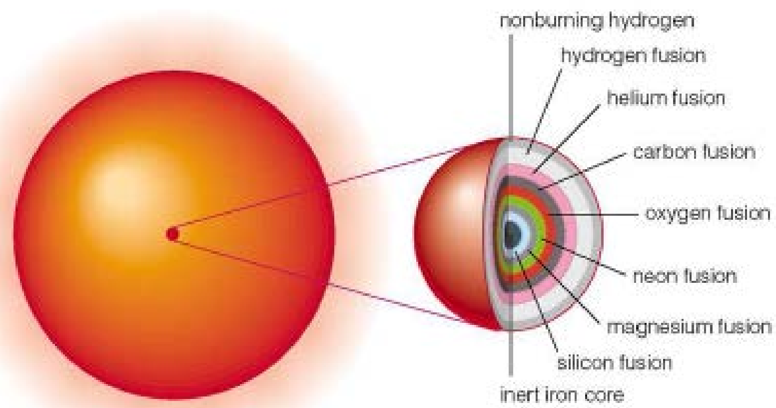


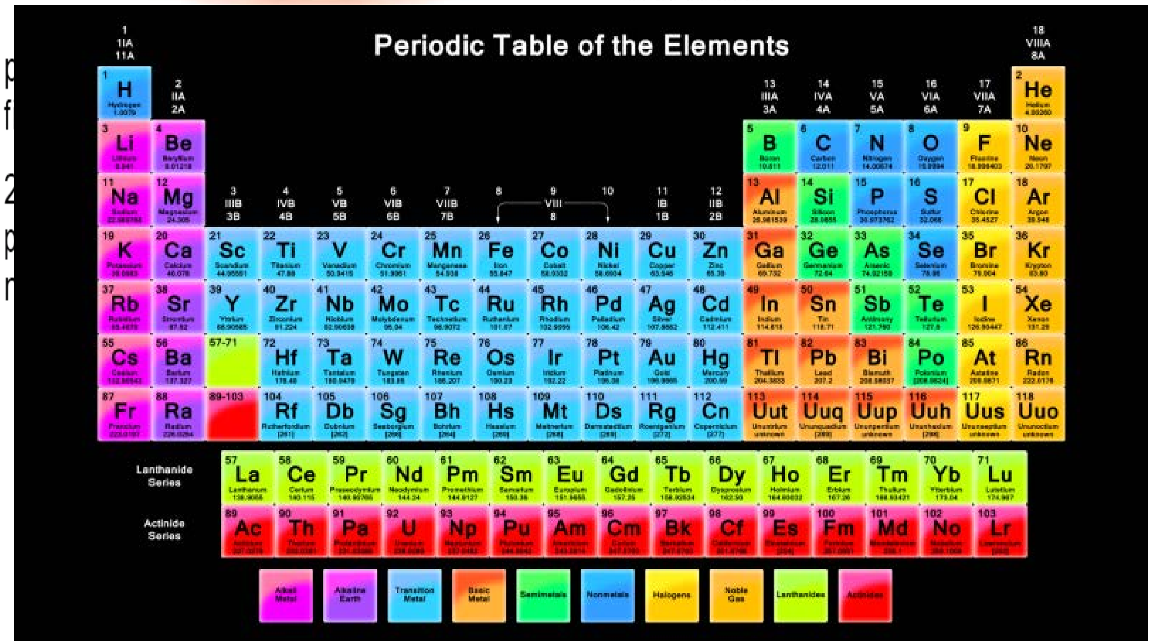


Energetics of Transmutation



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

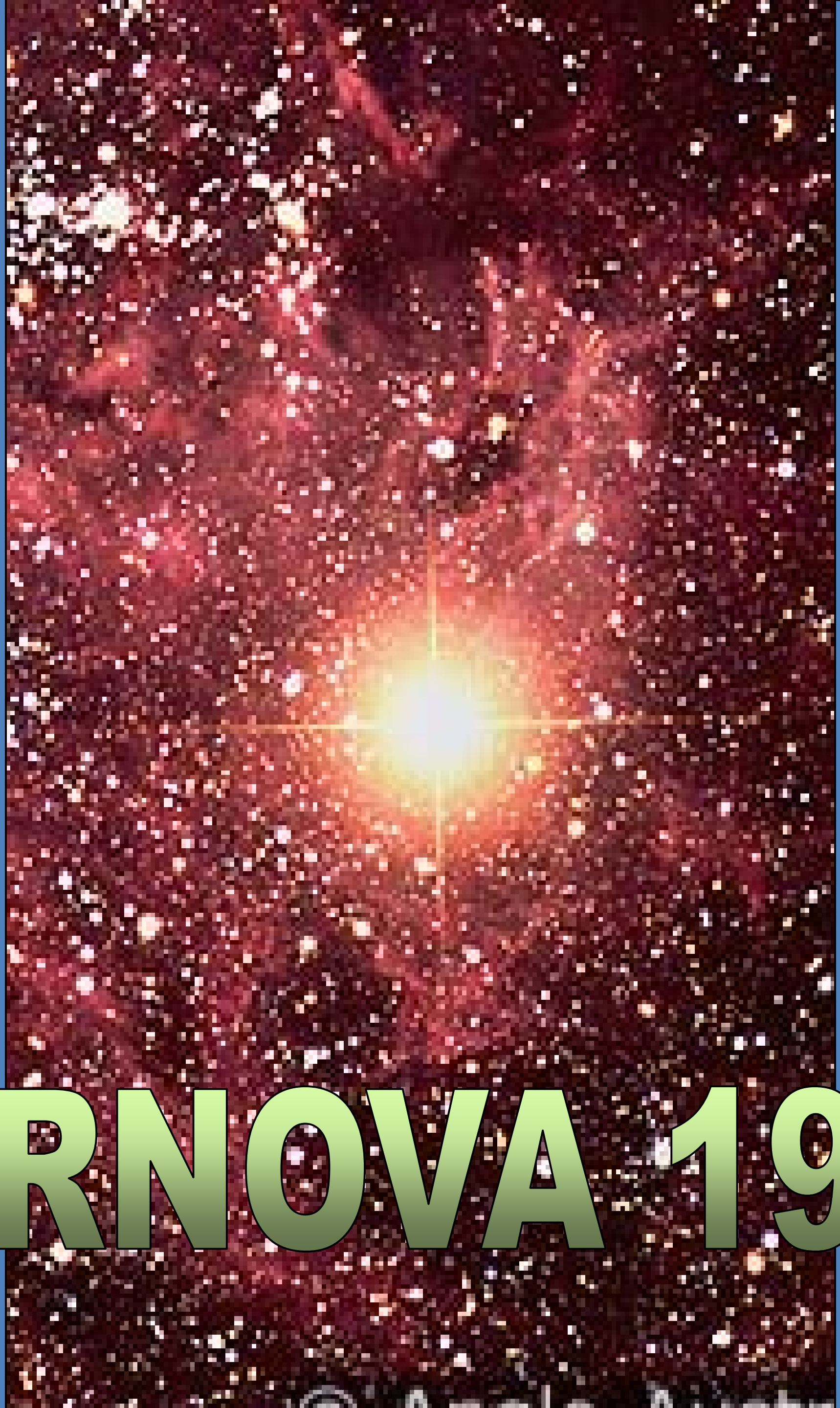




HOW ARE THE HEAVIER ELEMENTS PRODUCED ?

23 February 1987

SUPERNOVA 1987A



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

CORE COLLAPSE SUPERNOVAE

DID 1987A EXPLODE IN 1987 ?

NO!

It was 9.87 x 10^{17} MILES Away ! The light took 168, 000 years to reach us.

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

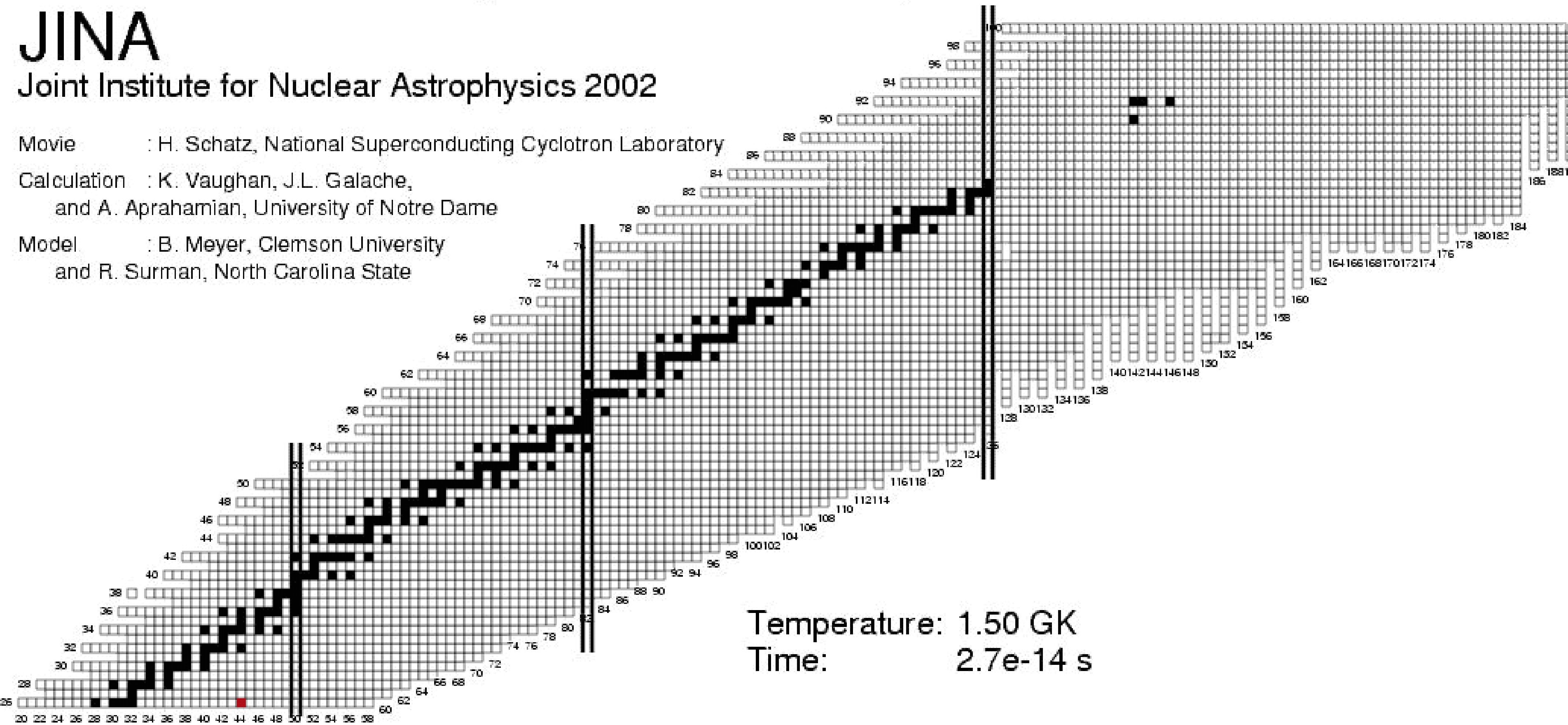
Nucleosynthesis in the r-process

JINA
Joint Institute for Nuclear Astrophysics 2002

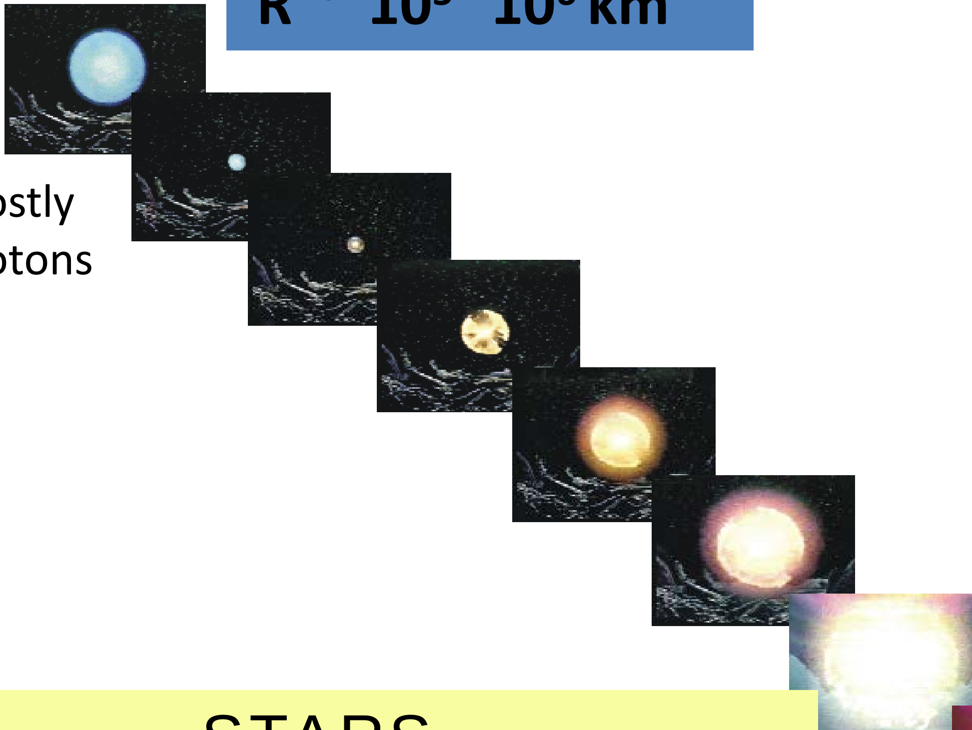
Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache, and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University and R. Surman, North Carolina State

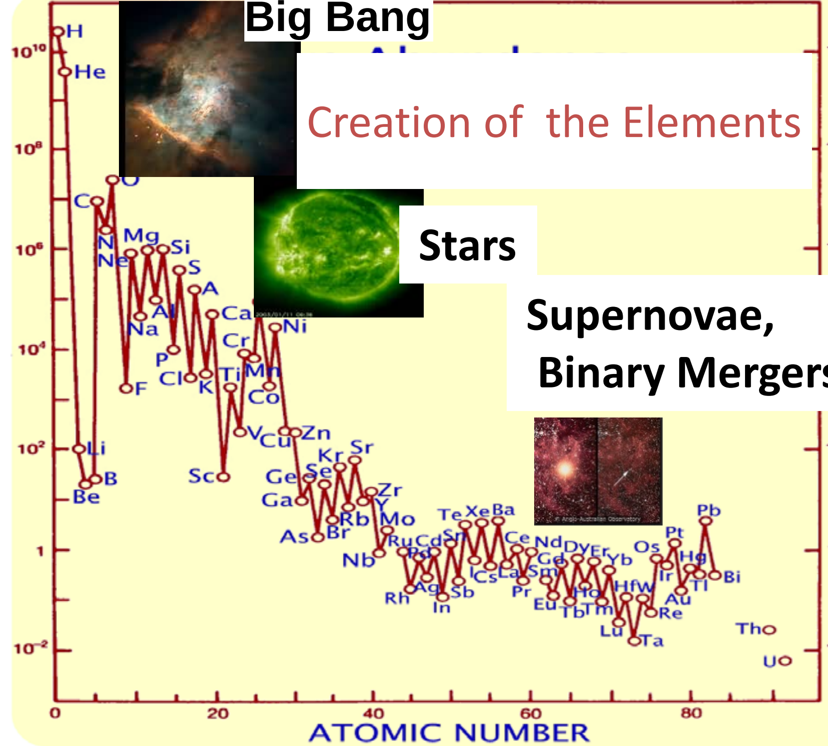


R ~ 10^{5}- 10^{6} km



Mostly protons

Big Bang



Creation of the Elements

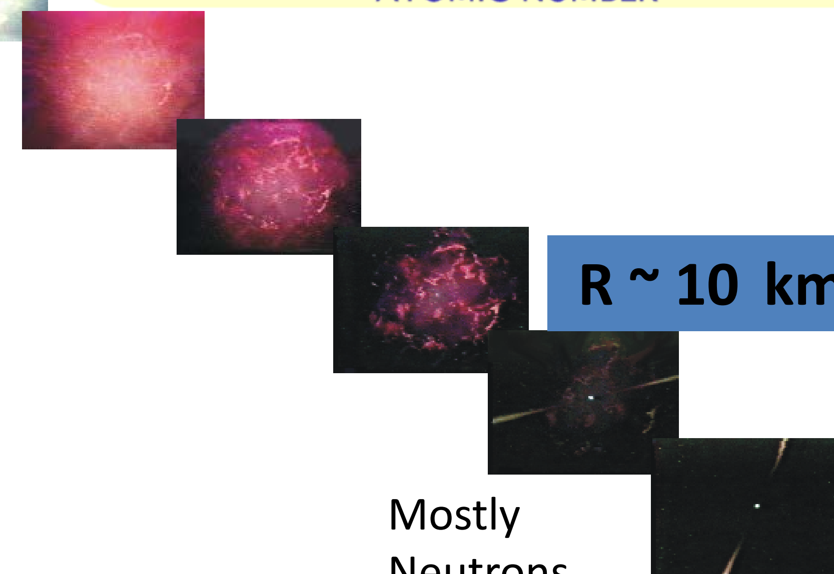
Stars

Supernovae, Binary Mergers

STARS

Giant Nuclei And Sites of Nucleosynthesis

Large Changes in Temperature, Density, Proton/Neutron content

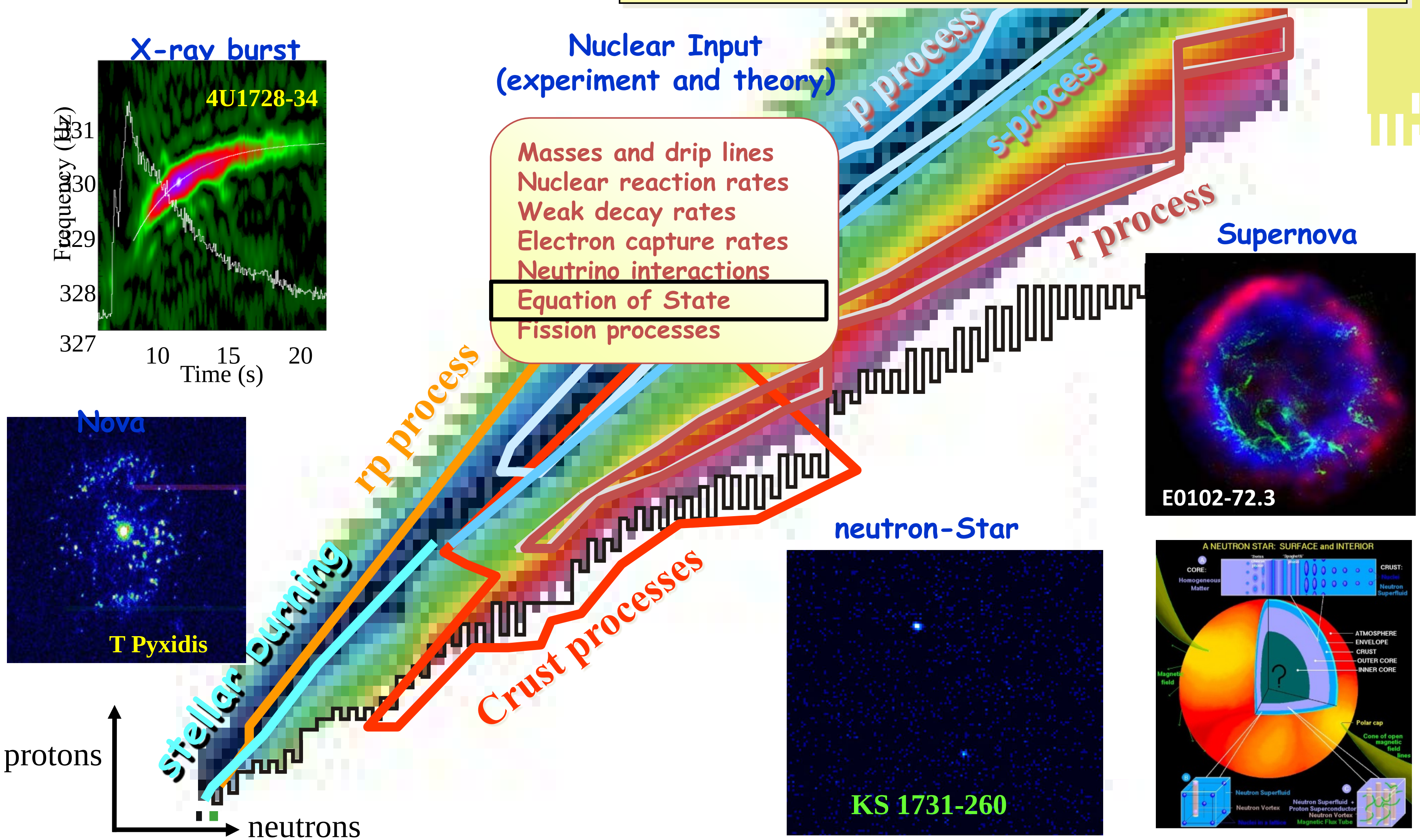


R ~ 10 km

Mostly Neutrons

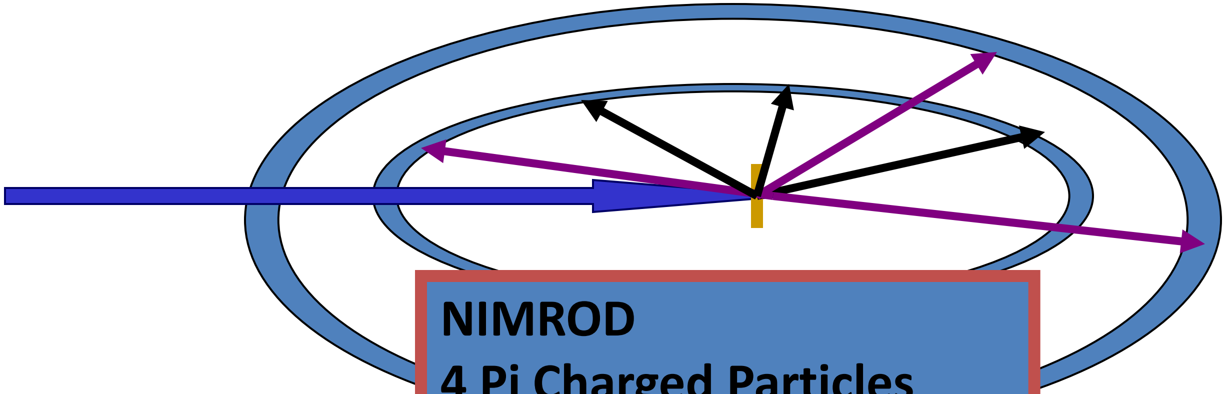
How does the physics of nuclei impact the physical universe?

- What is the origin of elements heavier than iron?
- How do stars burn and explode?
- What is the nucleonic structure of neutron stars?

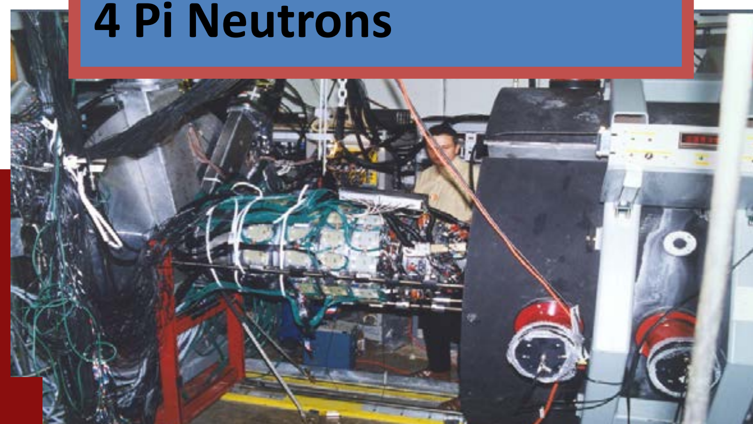


- Relevance of heavy ion collisions to core collapse supernovae
  - Allow probing different densities in the lab
  - Comparisons of heavy ion data to supernovae calculations may help discriminate between different models.
- Clusters appear in shock heated nuclear matter
  - Clusters Role on the explosion dynamics and the subsequent cooling and compression of the proto-neutron star is not yet fully understood
  - Valid treatment of the correlations and clusterization in low density matter is a vital ingredient of astrophysical models
- Equation of state (EOS)
  - Many fundamental connections between the equation of state and neutrino interactions
  - Crucial input for understanding proto-neutron star evolution

Light Charged Particle Emission Studies



NIMROD
4 Pi Charged Particles
4 Pi Neutrons



Reaction System List

- *4He + 112Sn and 124Sn*
- *10B + 112Sn and 124Sn*
- *20Ne + 112Sn and 124Sn*
- *40Ar + 112Sn and 124Sn*
- *64Zn+ 112Sn and 124Sn*

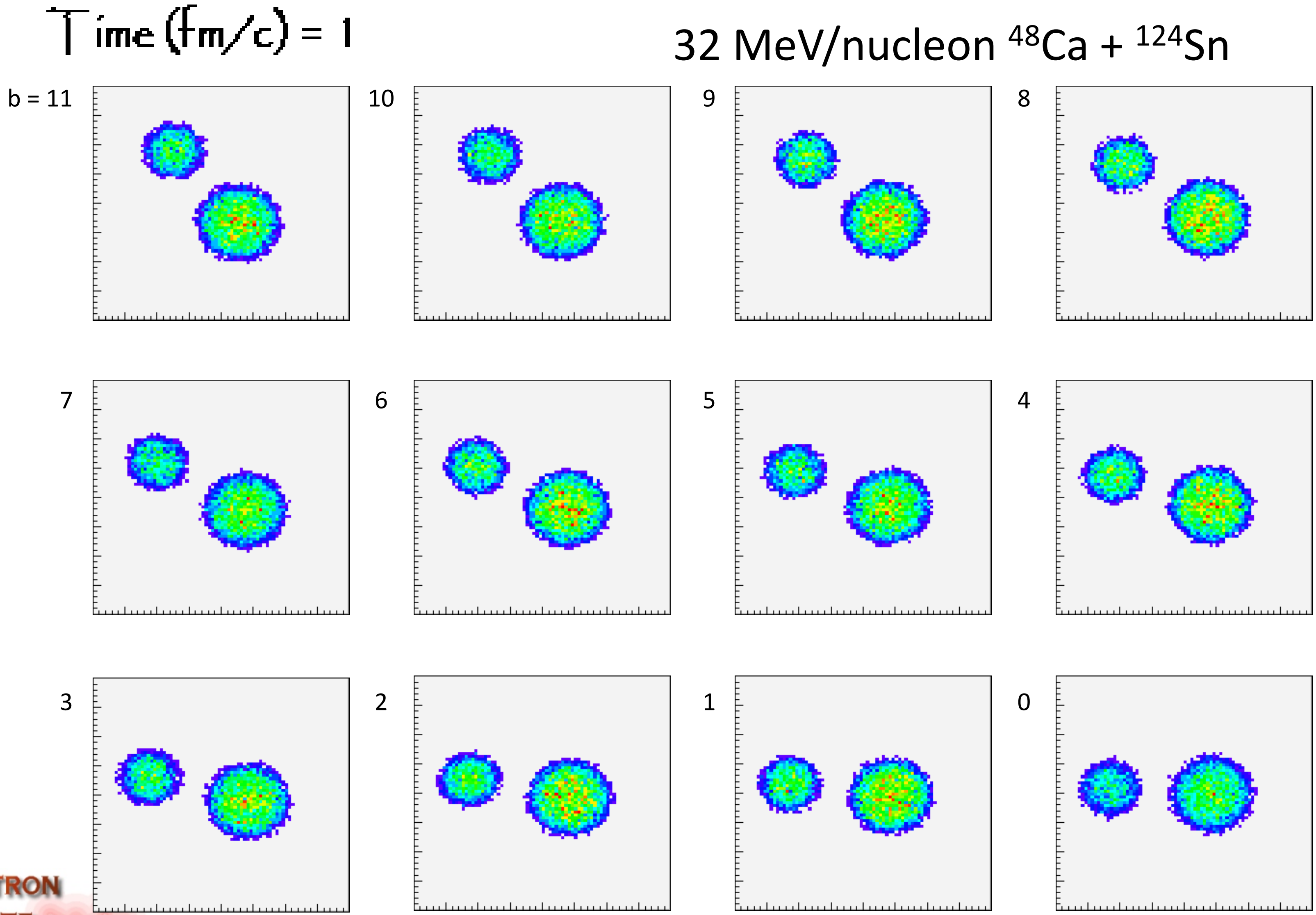
- *Projectile Energy - 47A MeV*

Thesis – L. Qin
TAMU- 2008

TEXAS A&M UNIVERSITY

Higher Energy Reactions

32 MeV/nucleon $^{48}Ca + ^{124}Sn$



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

Velocity Plots

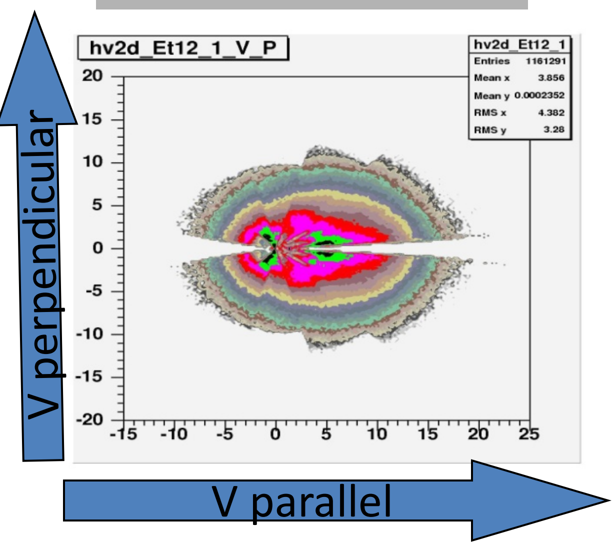
Light Charged Particles- Most Violent Collisions

From Fitting

Velocity Plot Protons

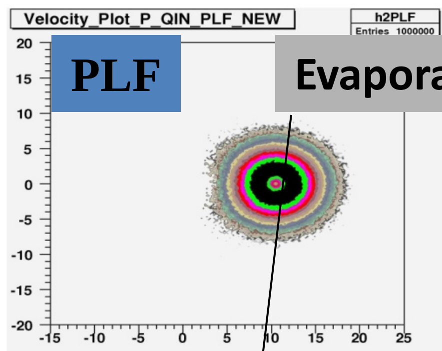
$^{40}Ar+^{124}Sn$

Experiment



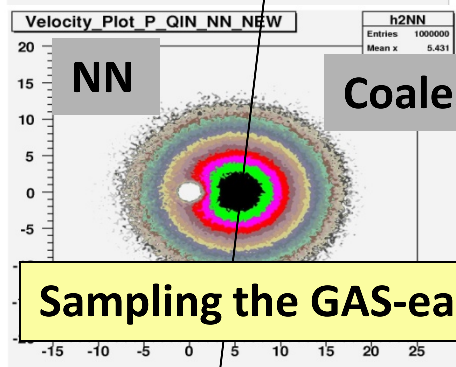
PLF

Evaporation-like



NN

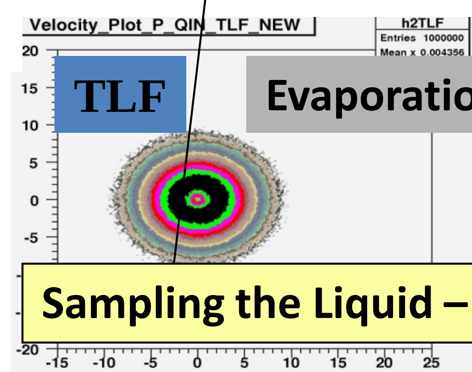
Coalescence-like



Sampling the GAS-early emission

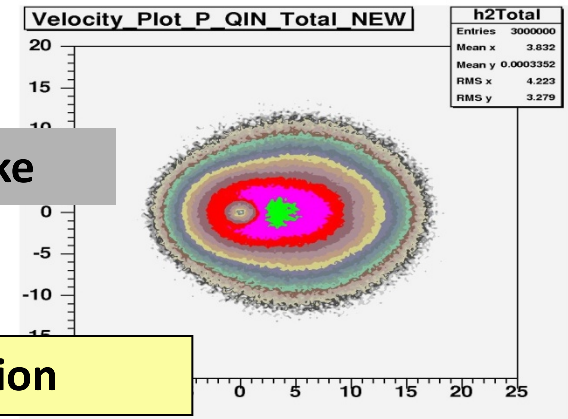
TLF

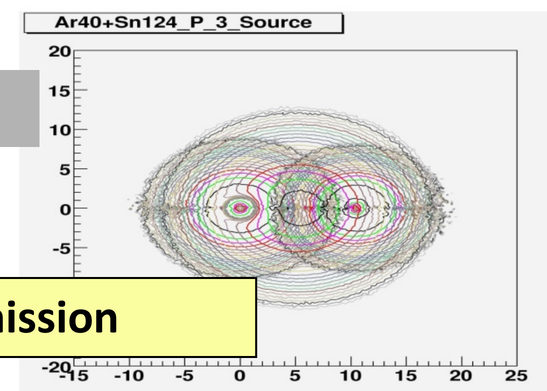
Evaporation-like

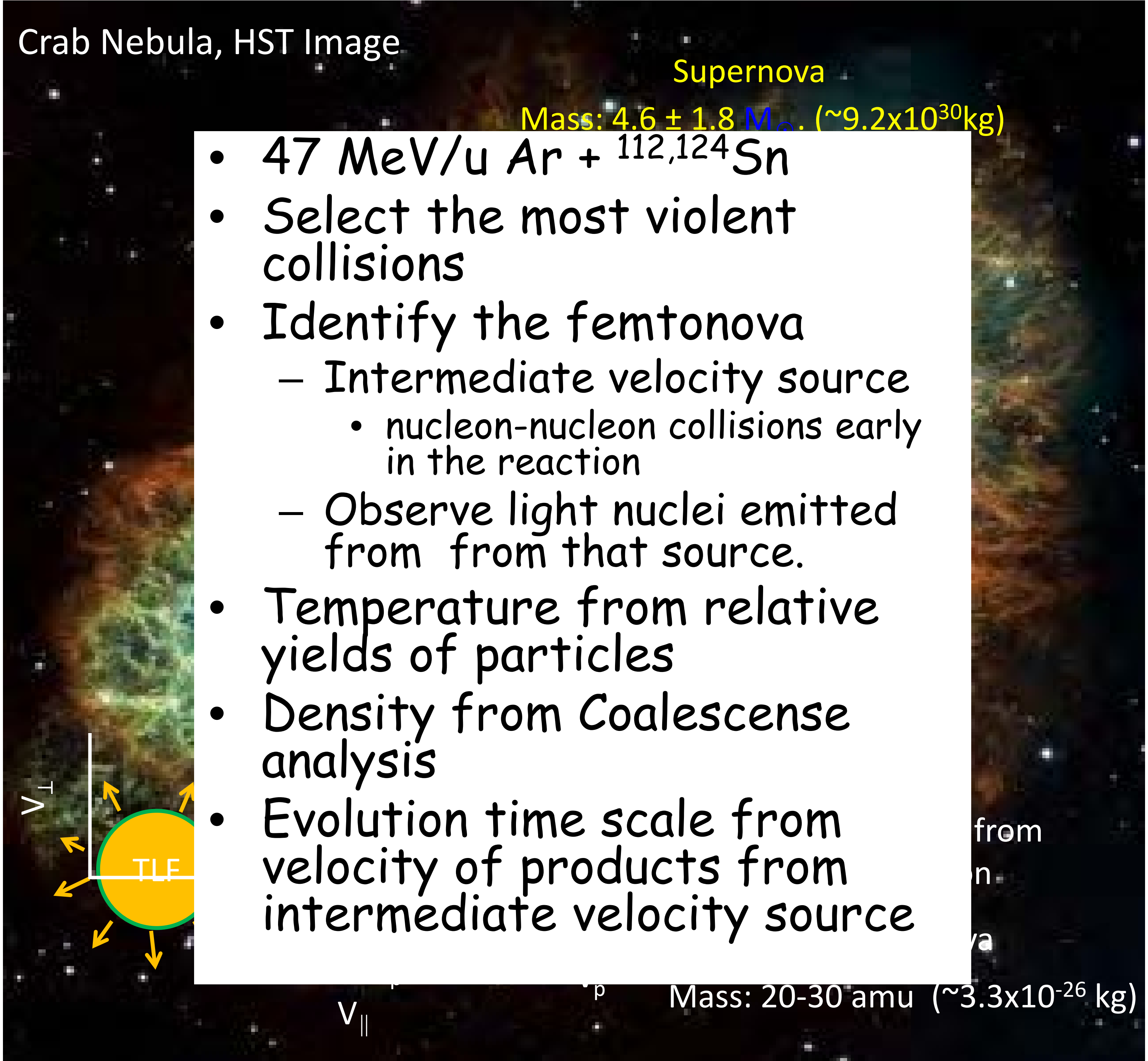


Sampling the Liquid – late emission

Sum of Source Fits







- 47 MeV/u Ar + ^{112,124}Sn
- Select the most violent collisions
- Identify the femtonova
  - Intermediate velocity source
    - nucleon-nucleon collisions early in the reaction
  - Observe light nuclei emitted from from that source.
- Temperature from relative yields of particles
- Density from Coalescense analysis
- Evolution time scale from velocity of products from intermediate velocity source

CLUSTER FORMATION Modifies Nuclear EOS

Astrophysical Implications, e.g., Core-collapse Supernovae

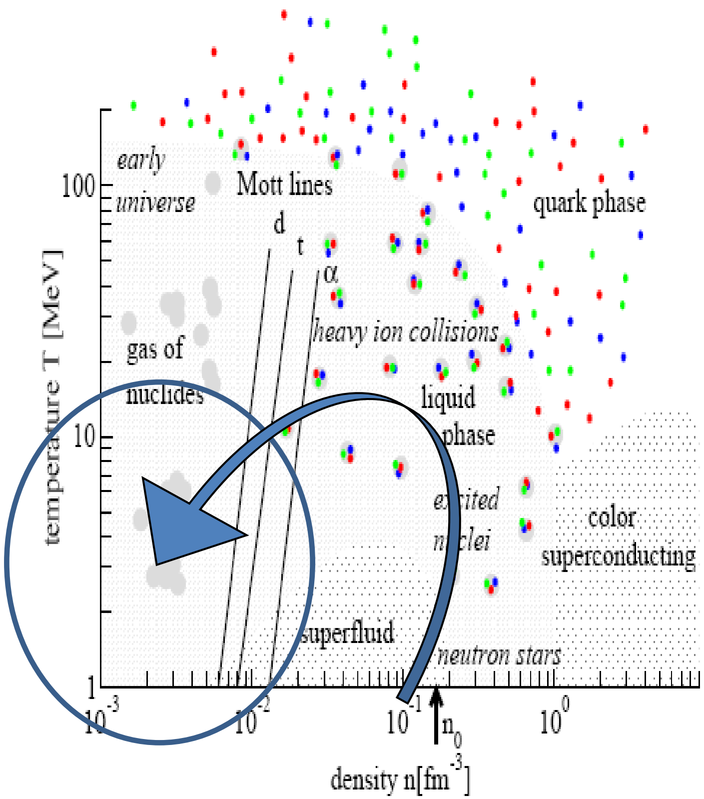
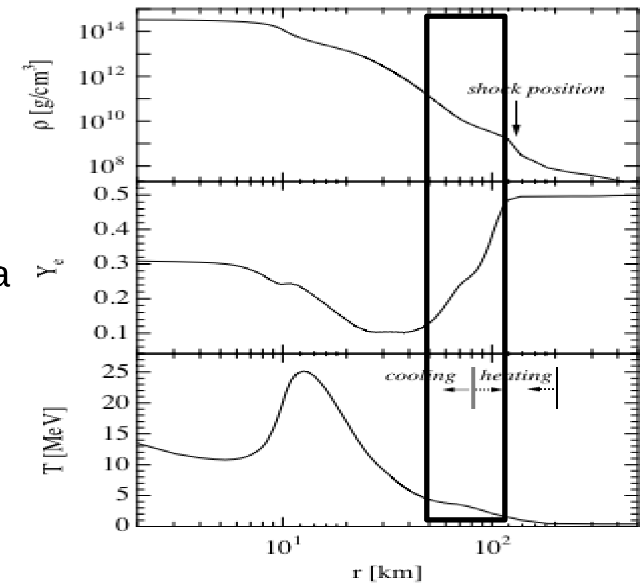


Figure 1. Schematic view of the phase diagram of nuclear matter. The phase diagram is empirical accessible by heavy ion collisions, excited nuclei, observation of neutron stars and the early universe as indicated in the diagram. New plans at GSI aim at exploring the color superconducting phase as well.

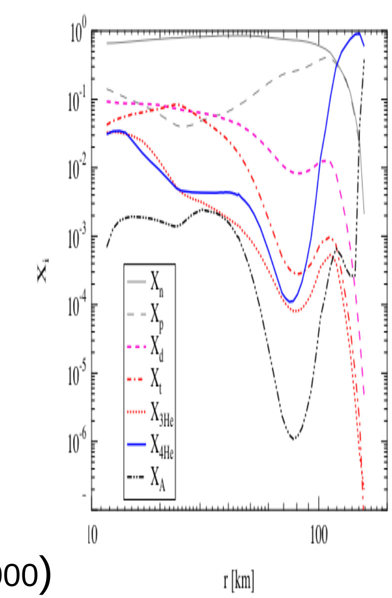
K.Sumiyoshi et al., Astrophys.J. **629**, 922 (2005)

Density. electron fraction, and temperature profileof a 15 solar mass supernova at 150 ms after core bounce --as function of the radius.



K.Sumiyoshi, G. Roepke PRC 77, 055804 (2008)

cluster formation Influences neutrino flux



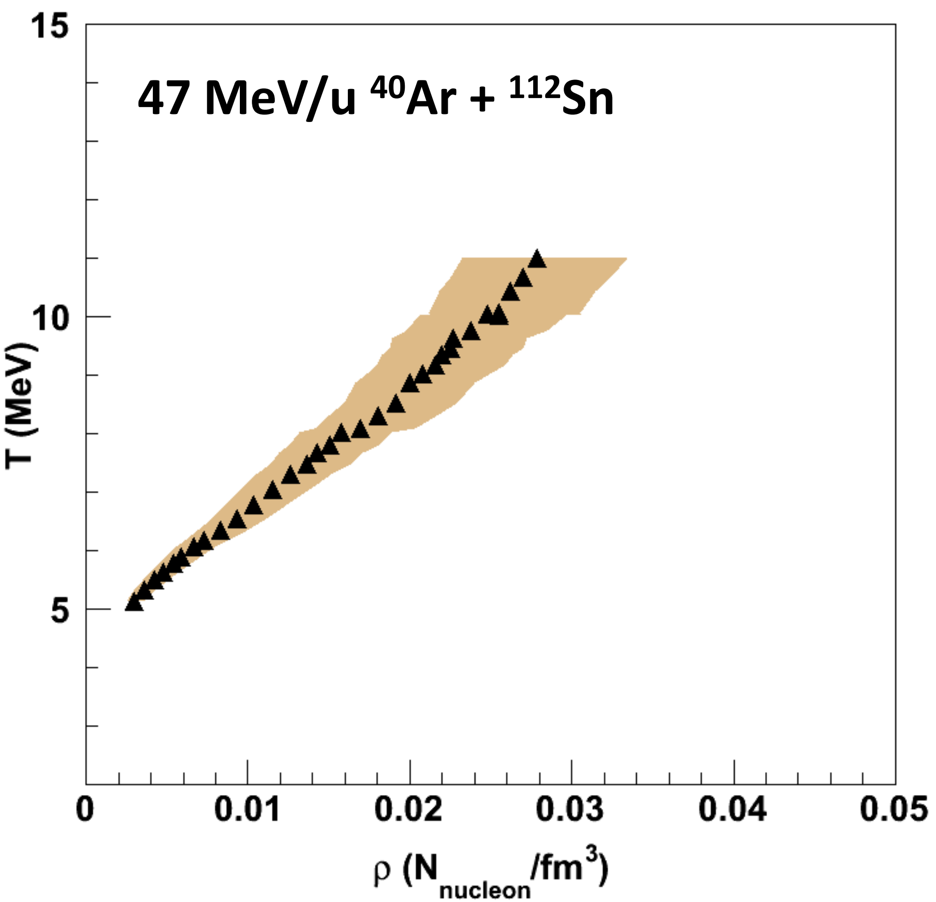
INSTITUTE
Texas A&M University

S. Typel, et al., ArXiv 0908.234 August 2009

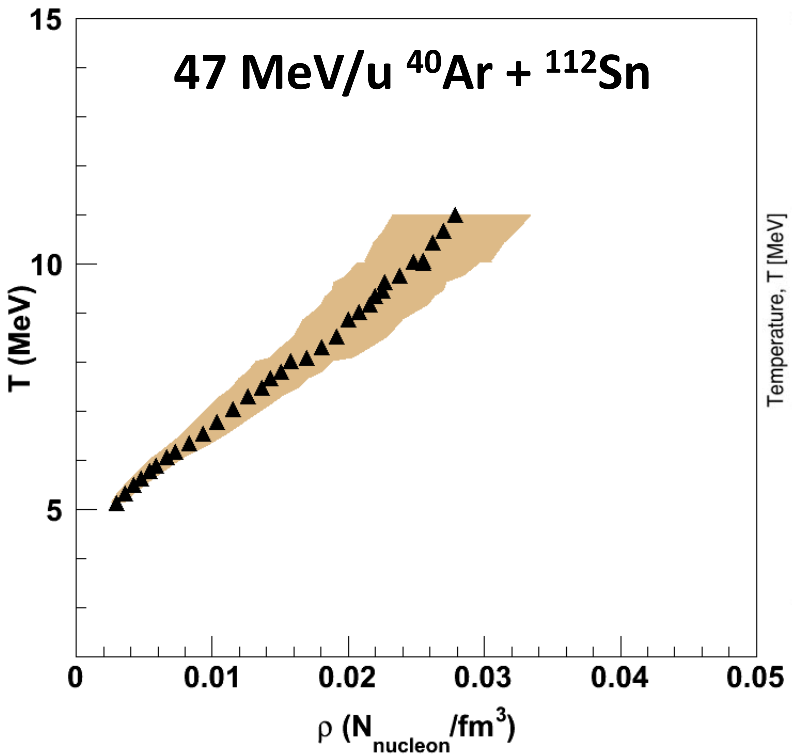
M. Beyer et al., Phys.Lett. B488, 247-253 (2000)

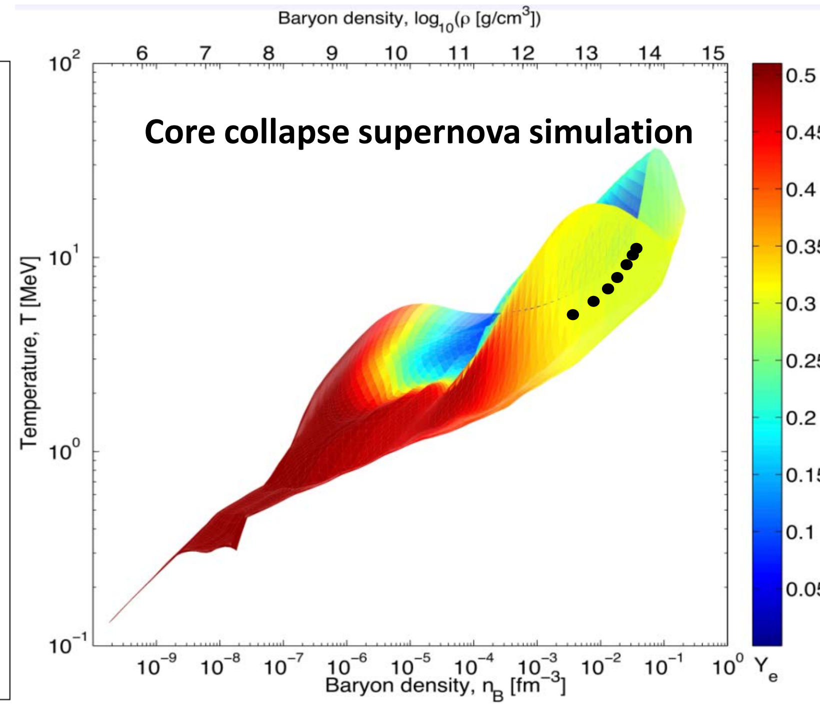
Temperatures and Densities Are Correlated

- System starts hot
- As it cools, it expands



Temperatures and Densities





- SN are "infinite", but HIC are finite
- The "infinite" matter in SN is charge neutral, but HIC has a net charge
- Proton fraction, Y_p can differ
- Composition of nuclear matter in calculations
  - Different calculations include different species

	Supernova	Heavy Ion Nuclear reaction
Density (nuc/fm³)	$10^{-10} < \rho < 2$	$2\times10^{-3} < \rho < 3\times10^{-2}$
Temperature (MeV)	$\sim 0 < T < 100$	$5 < T < 11$
Electron fraction	$0 < Y_p < 0.6$	$Y_p \sim 0.41$

From Wikipedia, the free encyclopedia

The **equilibrium constant** of a chemical reaction

$$\alpha A + \beta B ... \rightleftharpoons \rho R + \sigma S ...$$

is the value of the reaction quotient when the reaction has reached equilibrium.

For a general chemical equilibriumthe thermodynamic equilibrium constant can be defined such that, at equilibrium,[1][2]

$$K^{\ominus} = \frac{\{R\}^{\rho}\{S\}^{\sigma}...}{\{A\}^{\alpha}\{B\}^{\beta}...}$$

where curly brackets denote the thermodynamic activities** of the chemical species. The right-hand side of this equation corresponds to the reaction quotient Q for arbitrary values of the activities. The reaction coefficient becomes the equilibrium constant as shown when the reaction reaches equilibrium.

An equilibrium constant value is independent of the analytical concentrations of the reactant and product species in a mixture, but depends on temperature and on ionic strength. Known equilibrium constant values can be used to determine the composition of a system at equilibrium.

The equilibrium constant is related to the standard Gibbs free energy change for the reaction.

$$\Delta G^{\ominus} = -RT \ln K^{\ominus}$$

If deviations from ideal behavior are neglected, the activities of solutes may be replaced by concentrations, [*A*], and the activity quotient becomes a concentration quotient, K_c.

$$K_c = \frac{[R]^{\rho}[S]^{\sigma}...}{[A]^{\alpha}[B]^{\beta}...}$$

K_c is defined in an equivalent way to the thermodynamic equilibrium constant but with concentrations of reactants and products instead of activities. (K_c appears here to have units of concentration raised to some power while K is dimensionless; however the concentration factors in K_c are properly divided by a standard concentration so that K_c is dimensionless also.

Assuming ideal behavior, the activity of a solvent may be replaced by its mole fraction, (approximately by 1 in dilute solution). The activity of a pure liquid or solid phase is exactly 1. The activity of a species in an ideal gas phase may be replaced by its partial pressure.

** In chemical thermodynamics, **activity**) is a measure of the "effective concentration" of a species in a mixture. The species' chemical potential depends on the activity Activity depends on temperature, pressure and composition of the mixture, among other things. The difference between activity and other measures of composition arises because molecules in non-ideal gases or solutions interact with each other, either to attract or to repel each other.

Constraining supernova equations of state with equilibrium constants from heavy-ion collisions

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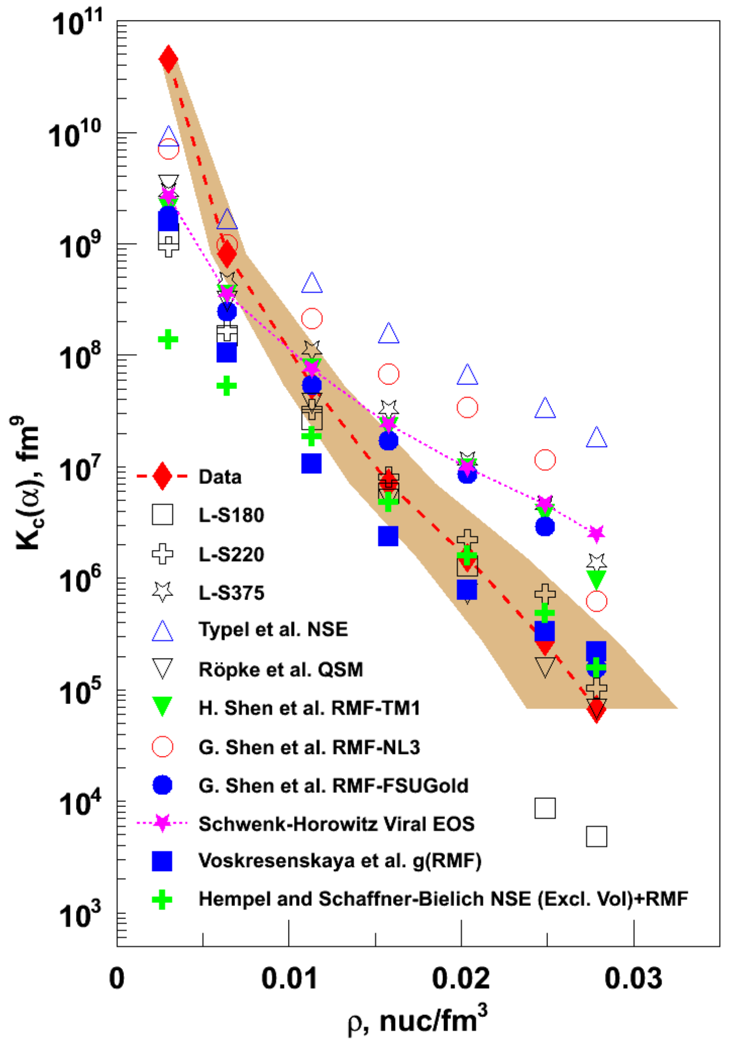
Joseph Natowitz, Kris Hagel, Stefan Typel, and Gerd Röpke
(Dated: January 29, 2015)

- M. Hempel et al., Phys. Rev. C **91**, 045805 (2015).
- Dependence of Equilibrium constants on various quantities
  - Asymmetry of system
  - Coulomb effects
  - Particle degrees of freedom
- Include comparison where possible to other particle types observed in experiment (d, t, ^{3}He)
- Other EOS models

Equilibrium constants for α-particles

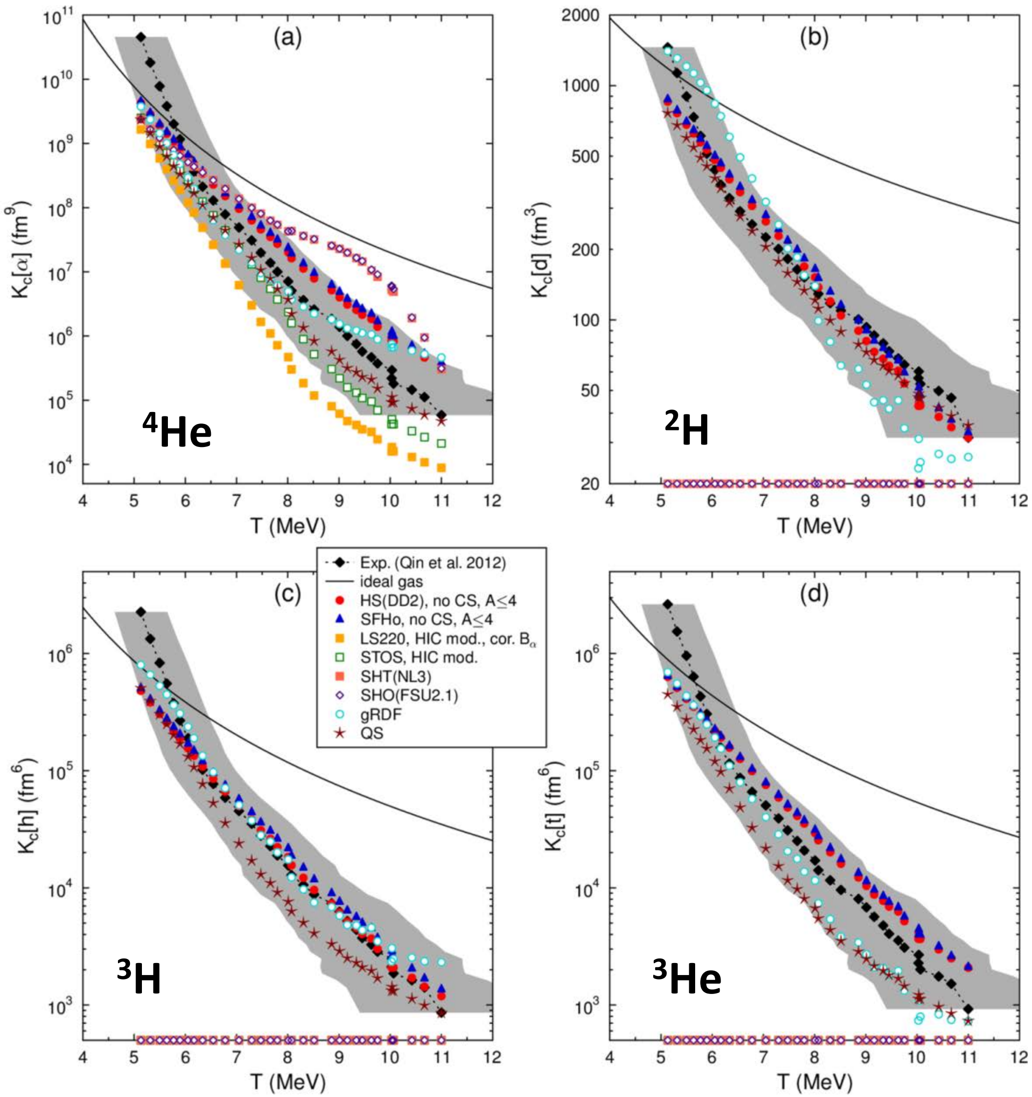
$$K_c(A,Z) = \frac{\rho(A,Z)}{\rho_p^Z \rho_n^{(A-Z)}}$$

- Many tests of EOS are done using mass fractions and various calculations include various different competing species.
- If any relevant species are not included, mass fractions are not accurate.
- Equilibrium constants should be more robust with respect to the choice of competing species assumed in a particular model if interactions are the same
- Differences in the equilibrium constants may offer the possibility to study the interactions
- Models converge at lowest densities, but are significantly below data

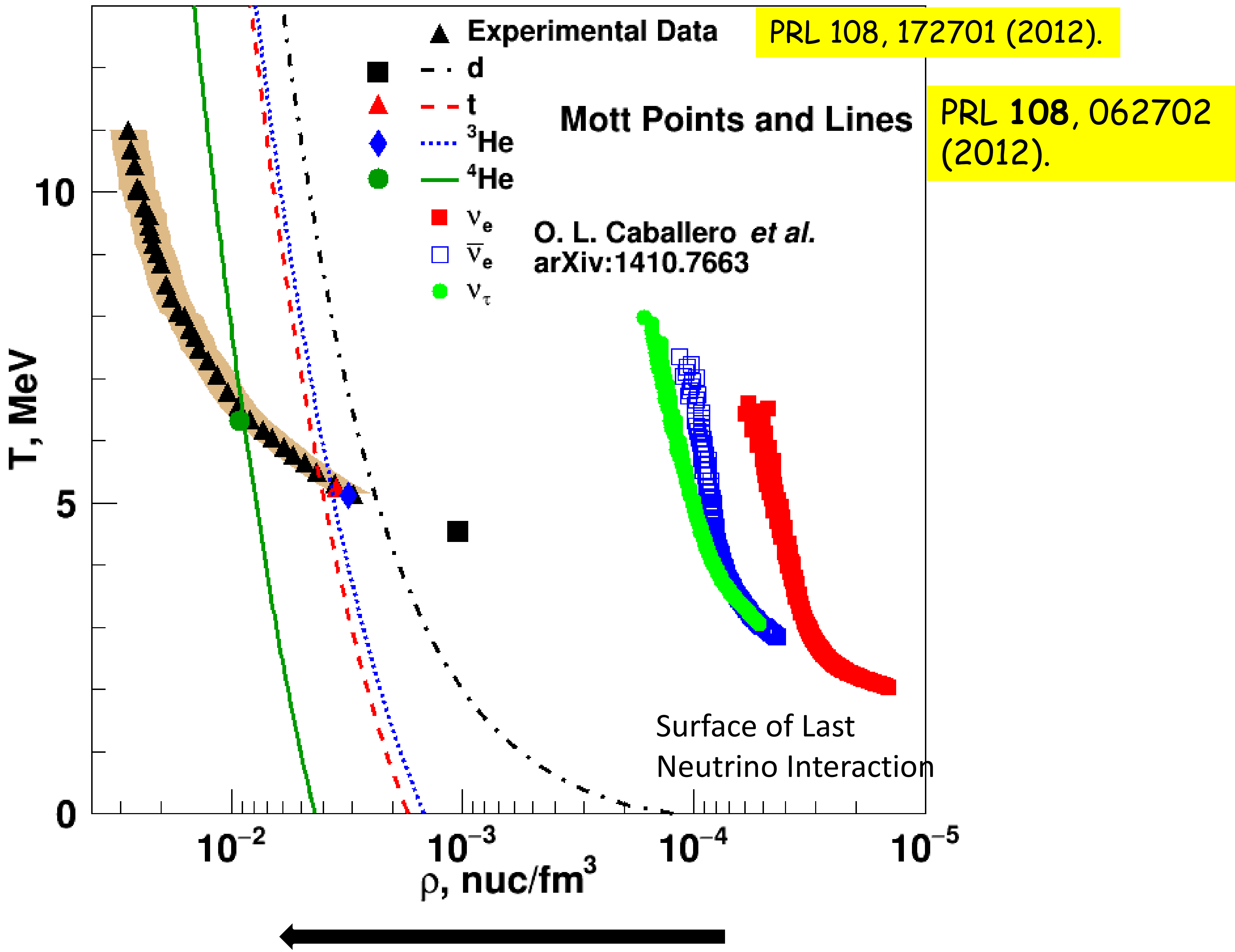


PRL **108** (2012) 172701.

$K_{eq}(T)$



- Keq(T)
- Uncertainity in temperature measurement including at low density
- Ideal gas Keq is function of T only.



Experimental Data
d
t
^{3}He
^{4}He
ν_e
$\bar{\nu}_e$
ν_τ
PRL 108, 172701 (2012).
Mott Points and Lines
PRL **108**, 062702 (2012).
O. L. Caballero *et al.*
arXiv:1410.7663
T, MeV
10
5
0
10^{-2}
10^{-3}
10^{-4}
10^{-5}
ρ, nuc/fm^3
Surface of Last
Neutrino Interaction

- Core-collapse supernovae (SN)
  - Explosions of massive stars that radiate 99% of their energy in neutrinos
  - Birth places of neutron stars
  - Wide range of densities ranging from much lower than normal nuclear density to much higher are sampled

- Core Collapse Supernovae dynamics and the observed neutrino signals are sensitive to the details of neutrino interactions with low density nuclear matter at the *Neutrinosphere*
  - Last scattering site of neutrinos in proto-neutron star: ~10^{12} g/cm^3 (~6×10^{-4} fm^{-3}), T~5 MeV
  - A thermal surface from which around 10^{53} ergs (10^{37} MeV) are emitted in all neutrino species during the explosion

  - The neutrino interactions determine the nucleosynthesis conditions in the so-called neutrino-driven wind

  - Detailed information on the composition and other thermodynamic properties of matter in the neutrinosphere region is important to evaluate role of neutrino scattering.

THANK YOU !