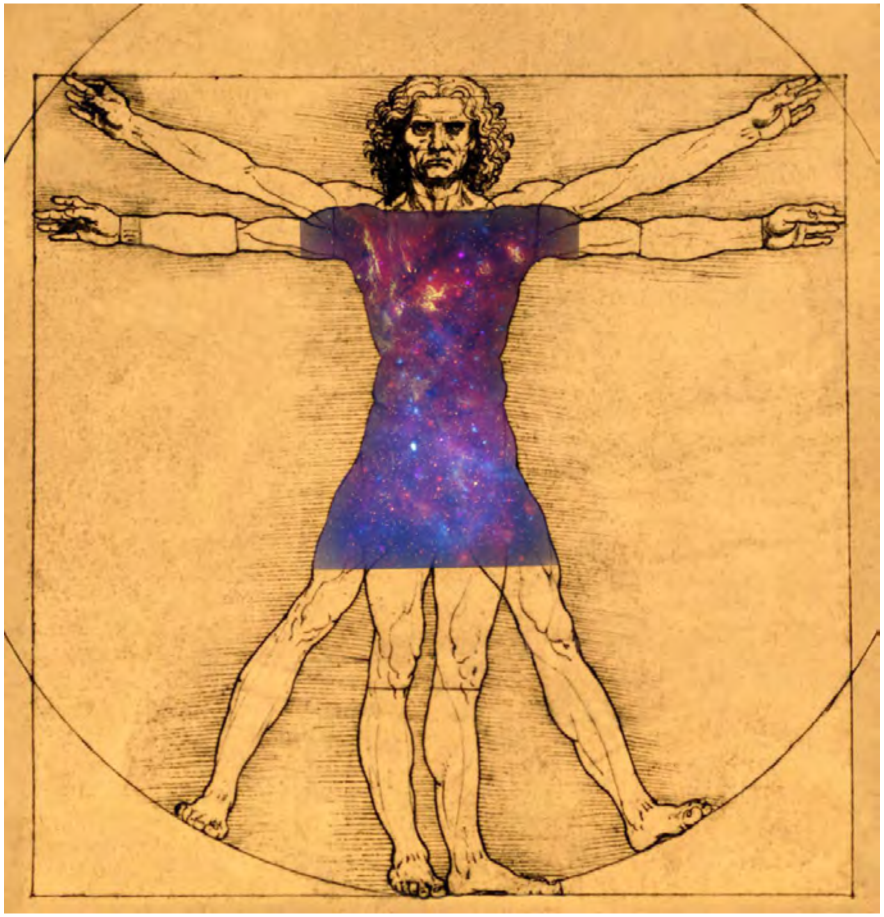
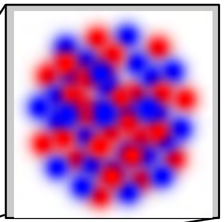
Michigan State University's FRIB Project
Where Do the Atoms in Your Body Come From?



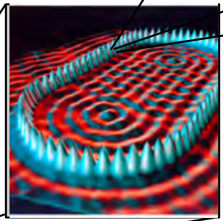
Wolfgang Bauer
Department of Physics and Astronomy
Michigan State University

Power of 100,000

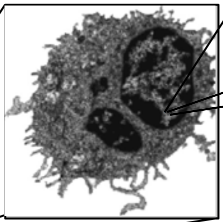
10^{-15} m scale: Nuclei



10^{-10} m scale: Atoms



10^{-5} m scale: Cells



1 m scale: People

10^{5} m scale: Large City

10^{10} m scale: Earth + Moon system

Distance Moon-Earth = $3.8 \cdot 10^{8}$ m, distance Sun-Earth = $1.5 \cdot 10^{11}$ m

All matter is made of atoms!

- 118 known elements
- Hydrogen, Helium, Lithium, …, Copernicium, + 6 more yet to be named
- Each atom is characterized by its charge number = number of electrons
- The nucleus of the atom consists of protons and neutrons and contains almost all of the mass (electrons contribute ~1 part in 2000)
- # protons = # electrons; atoms electrically neutral

All matter is made of atoms!

Solid / Liquid / Gas } at room temperature

Artificially produced

Dmitri Mendeleev (1869)
Periodic Table

Period	Group: 1	2															3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																															2 He
2	3 Li	4 Be																									5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg																									13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	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
5	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
6	55 Cs	56 Ba	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	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
7	87 Fr	88 Ra	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	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113	114	115	116	117	118

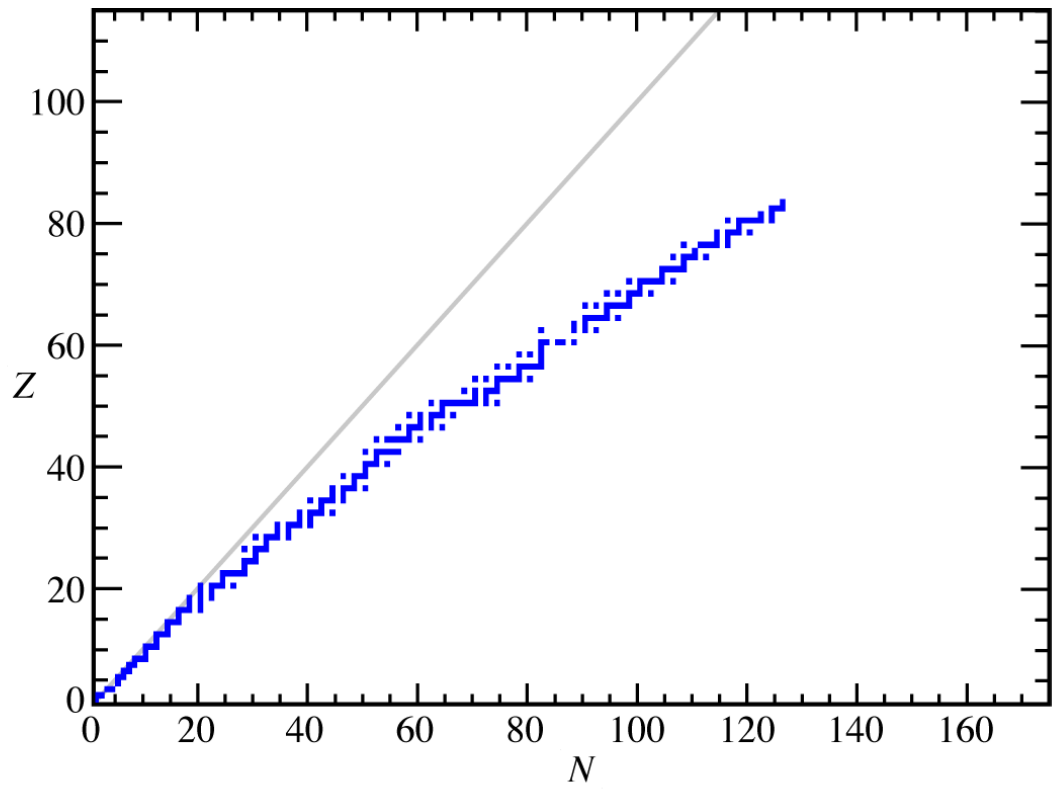
Lanthanides (4f): 57–70

s: groups 1–2; Actinides (5f): 89–102; d: groups 3–12; p: groups 13–18

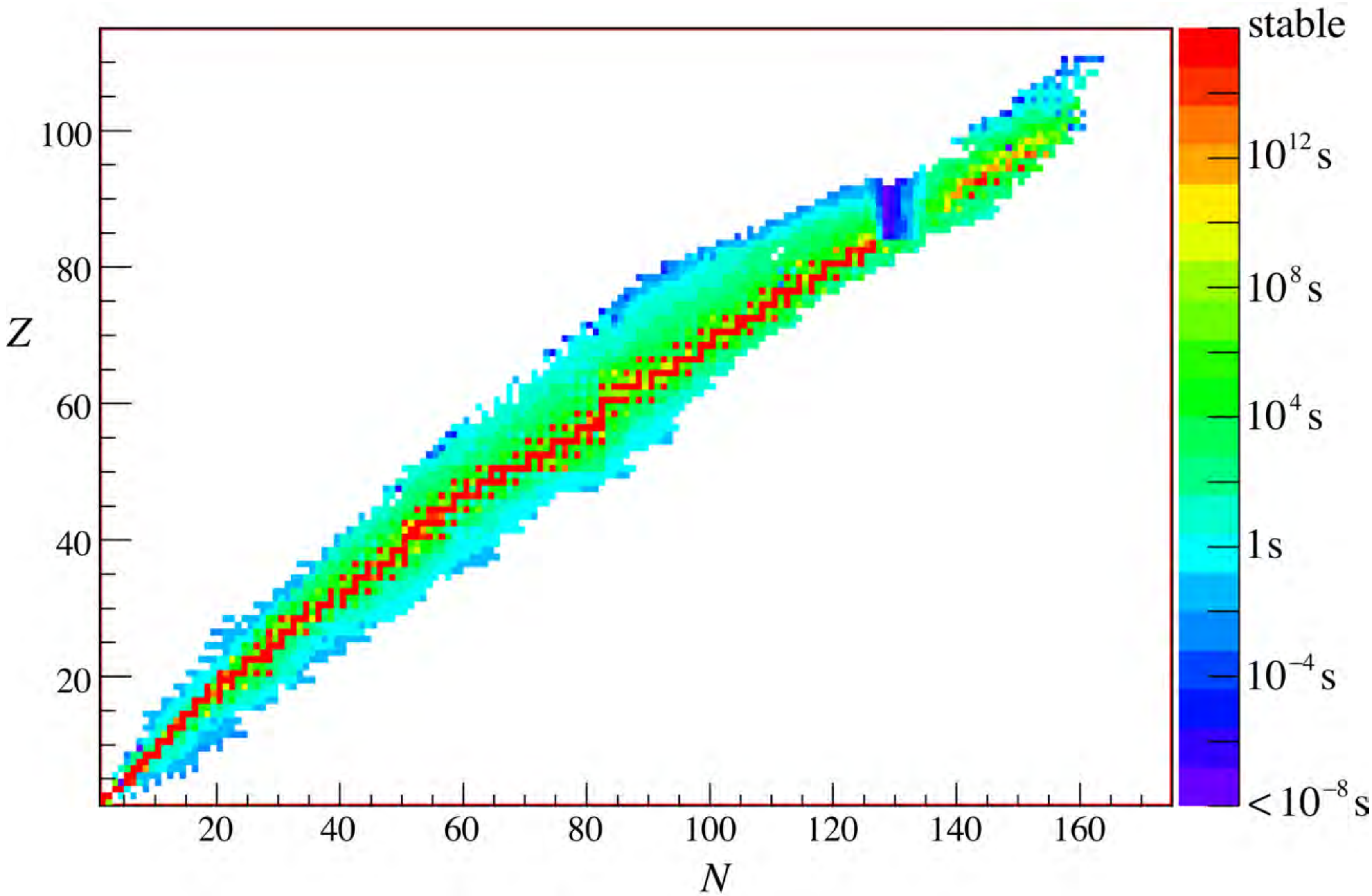
Electrons arranged in shells. Electrons in outer shell(s) determine chemical properties.

Atomic Nuclei

- Nucleus is 10,000 to 100,000 times smaller than atom, but contains almost all mass
- Isotopes of a nucleus are distinguished by different number of neutrons
- 251 known **stable** isotopes (none for Z=43 technetium, Z=61 promethium, Z>83)

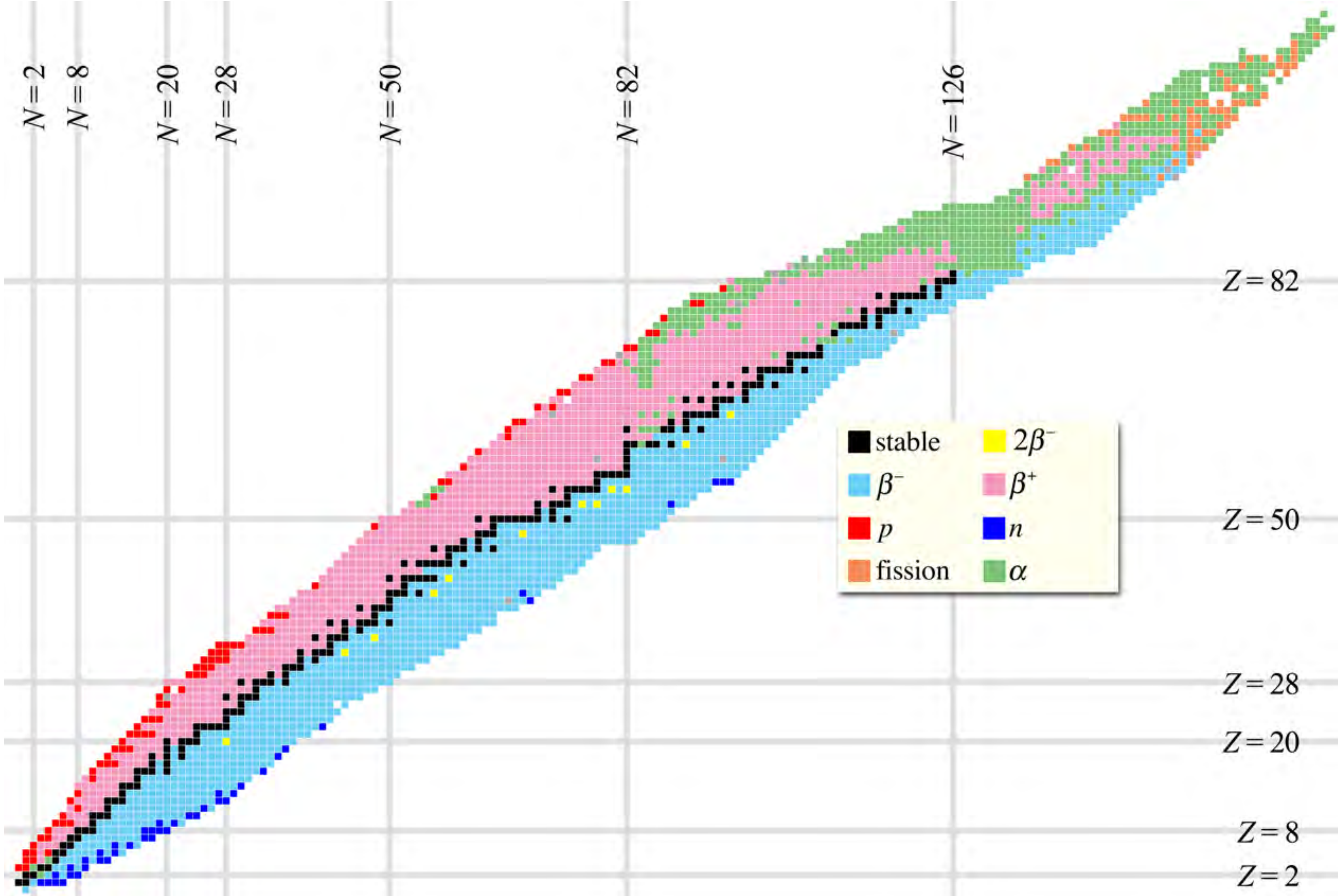


Lifetimes

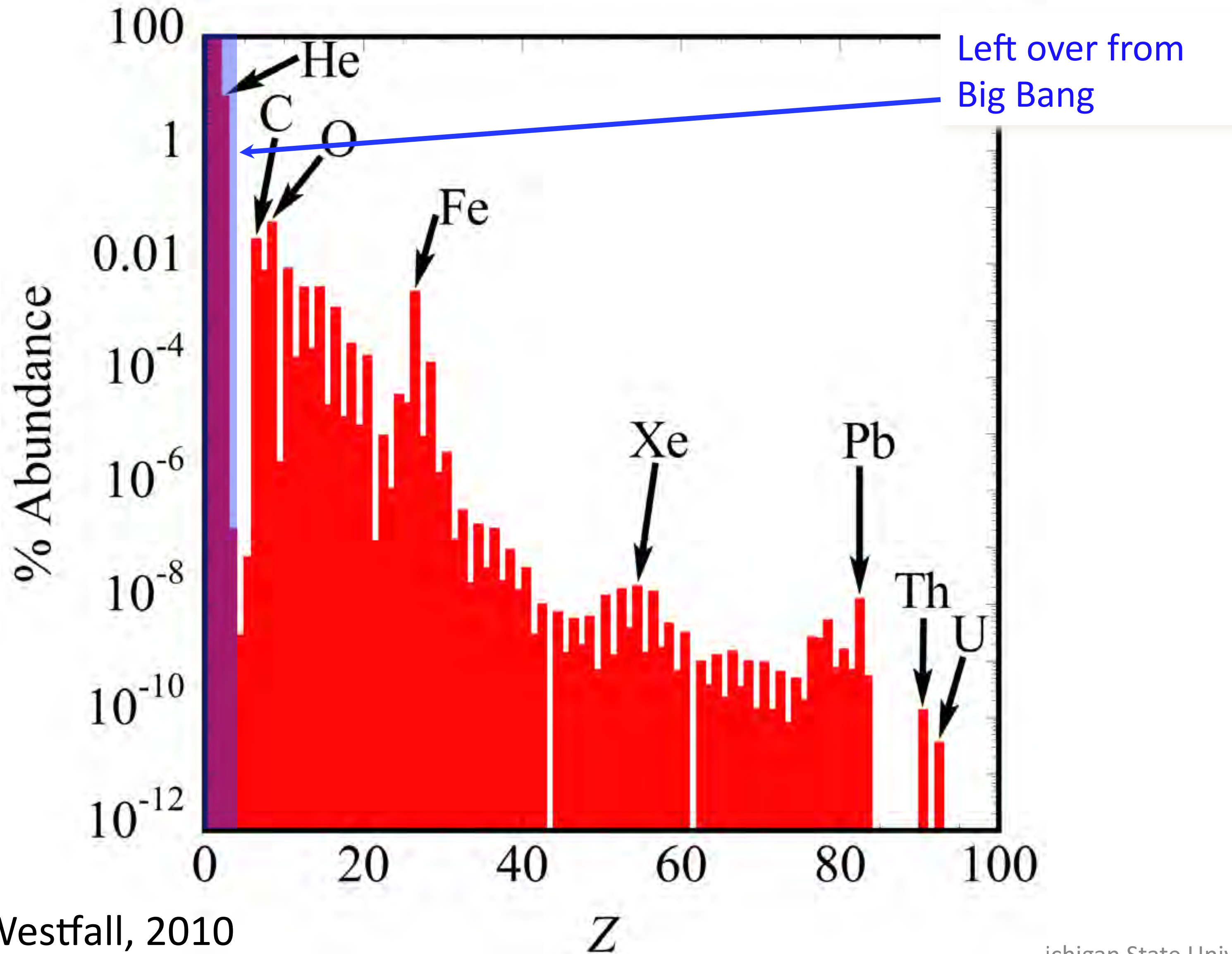


stable
10^{12} s
10^{8} s
10^{4} s
1 s
10^{-4} s
$< 10^{-8}$ s
Z
100
80
60
40
20
N
20
40
60
80
100
120
140
160

Decays


N = 2
N = 8
N = 20
N = 28
N = 50
N = 82
N = 126
Z = 82
Z = 50
Z = 28
Z = 20
Z = 8
Z = 2
stable
2β⁻
β⁻
β⁺
p
n
fission
α

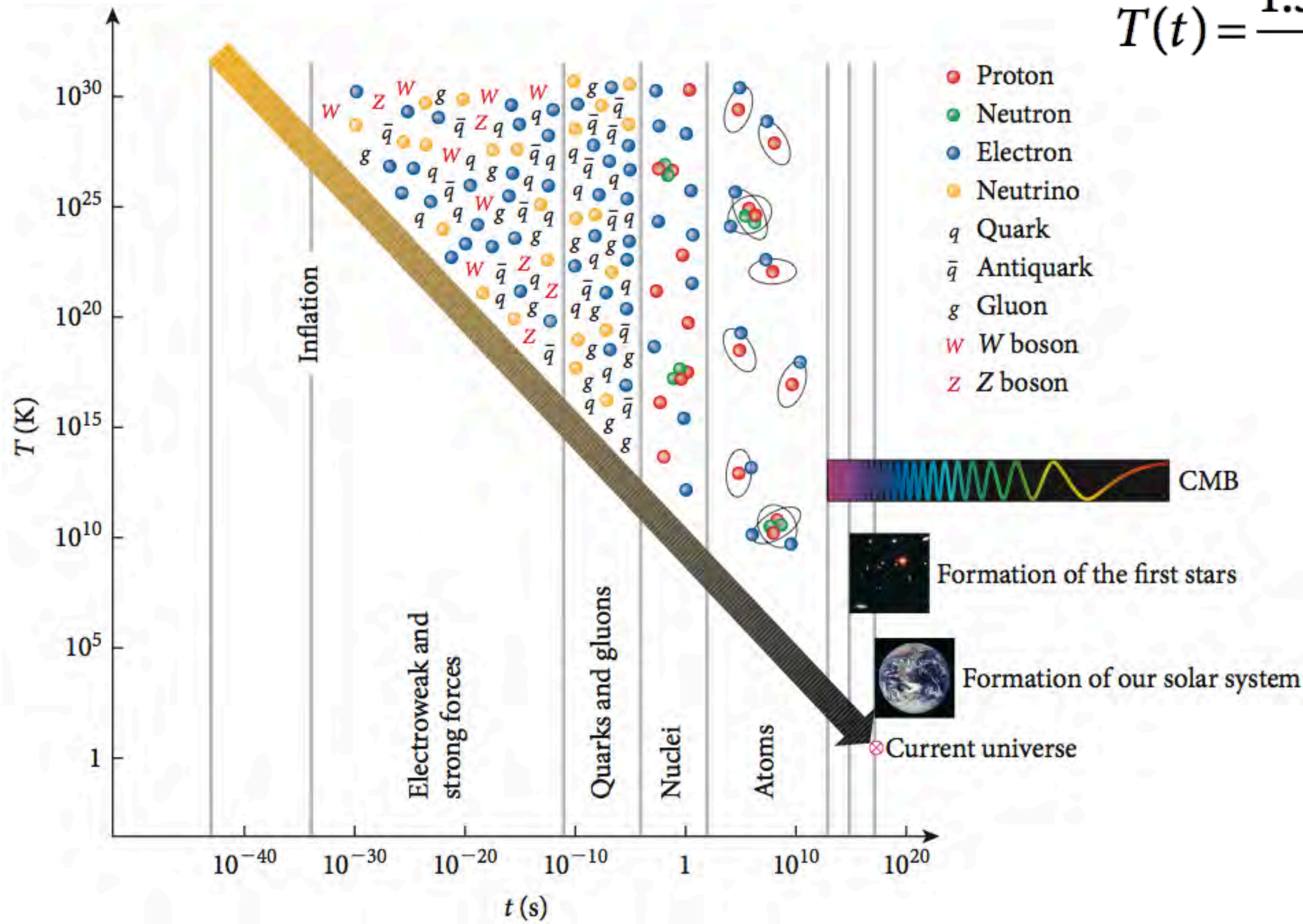
Element Abundances



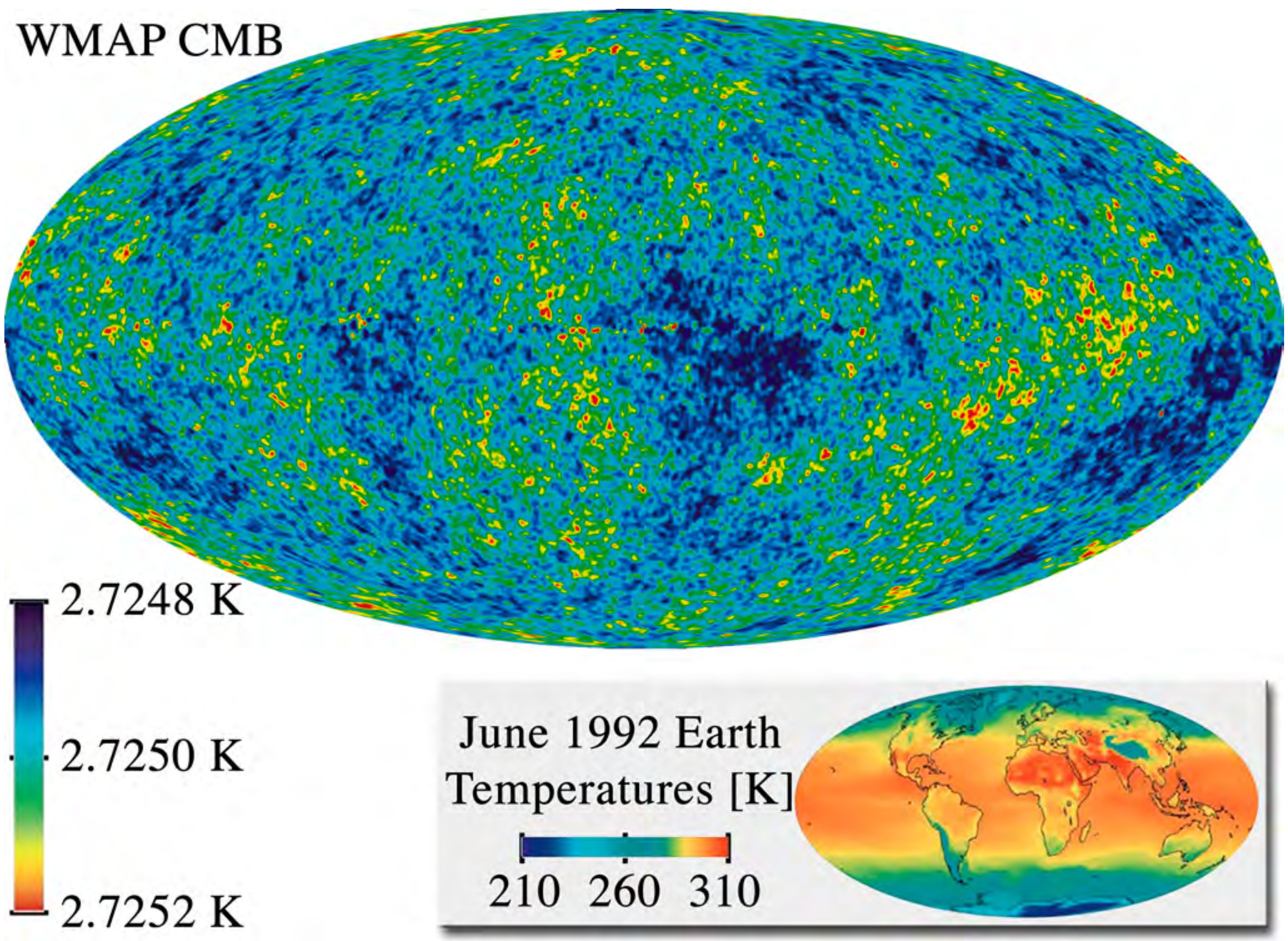
Bauer & Westfall, 2010

Big Bang

$$T(t) = \frac{1.5 \cdot 10^{10}\ \mathrm{K\,s}^{1/2}}{\sqrt{t}}$$



Big Bang Afterglow



He/H ratio from Big Bang

- Coming out of QGP, $T \sim 10^{11}$ K (~10 MeV)
- p and n in equilibrium

$$n + \nu_e \rightleftarrows p + e^-$$

$$n + e^+ \rightleftarrows p + \bar{\nu}_e$$

- Number of p and n determined by Boltzmann factors

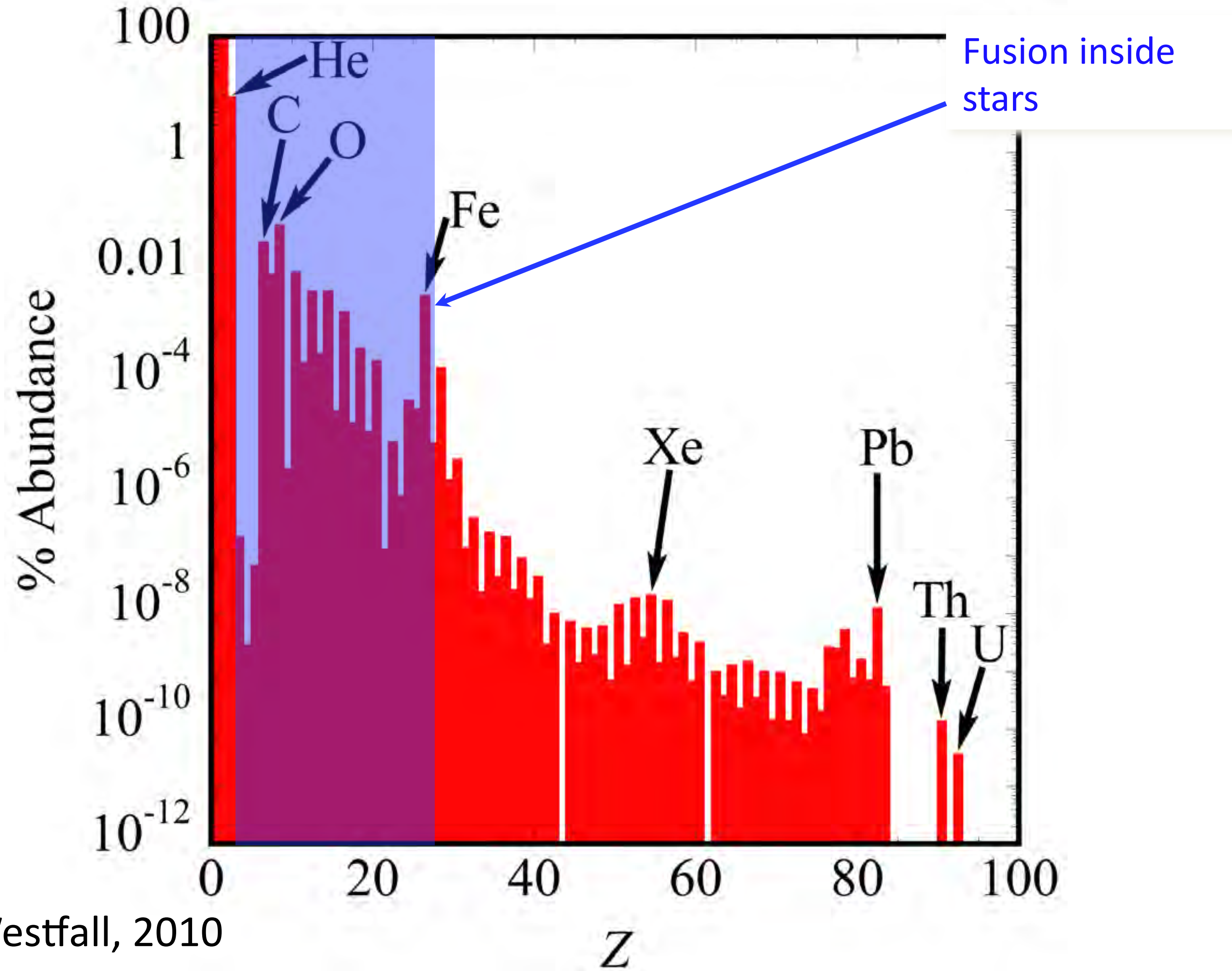
$$\frac{n_\mathrm{n}}{n_\mathrm{p}} = e^{(m_\mathrm{n}c^2 - m_\mathrm{p}c^2)/k_\mathrm{B}T}$$

- T~0.86 MeV: weak reactions too slow to maintain equilibrium
- Ratio freezes out at $e^{-1.293/0.86} = 0.222$

He/H ratio from Big Bang

- So far (t = 1 s): 22 n for every 100 p, T still too high for nuclei to form
- t = 100 s: $T \sim 10^9$ K, nuclei (alpha particles) can form
  - Due to *n* beta decay (half life 15 min), only ~16 *n* are left for every 100 *p*
- All free n can get trapped in alphas:
  - 16 *n* and 16 *p* can form 8 alphas
  - Mass fraction of alphas (= nuclei of helium) is then $4 \cdot 8/(100+16) = 27\%$
  - Close to observed value of 23%
  - Big success for early Big Bang cosmology!

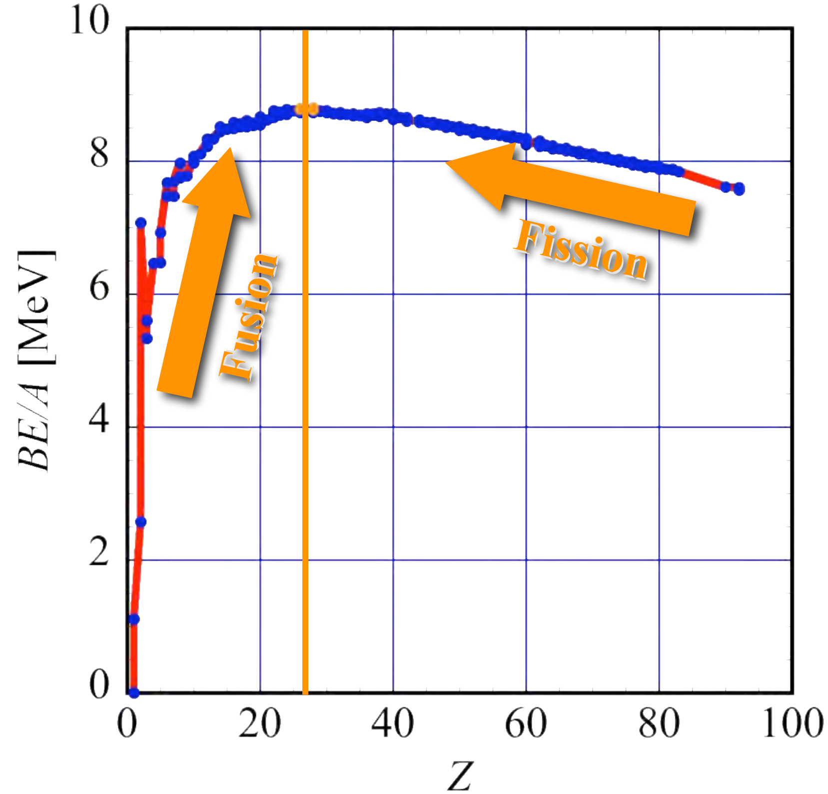
Element Abundances



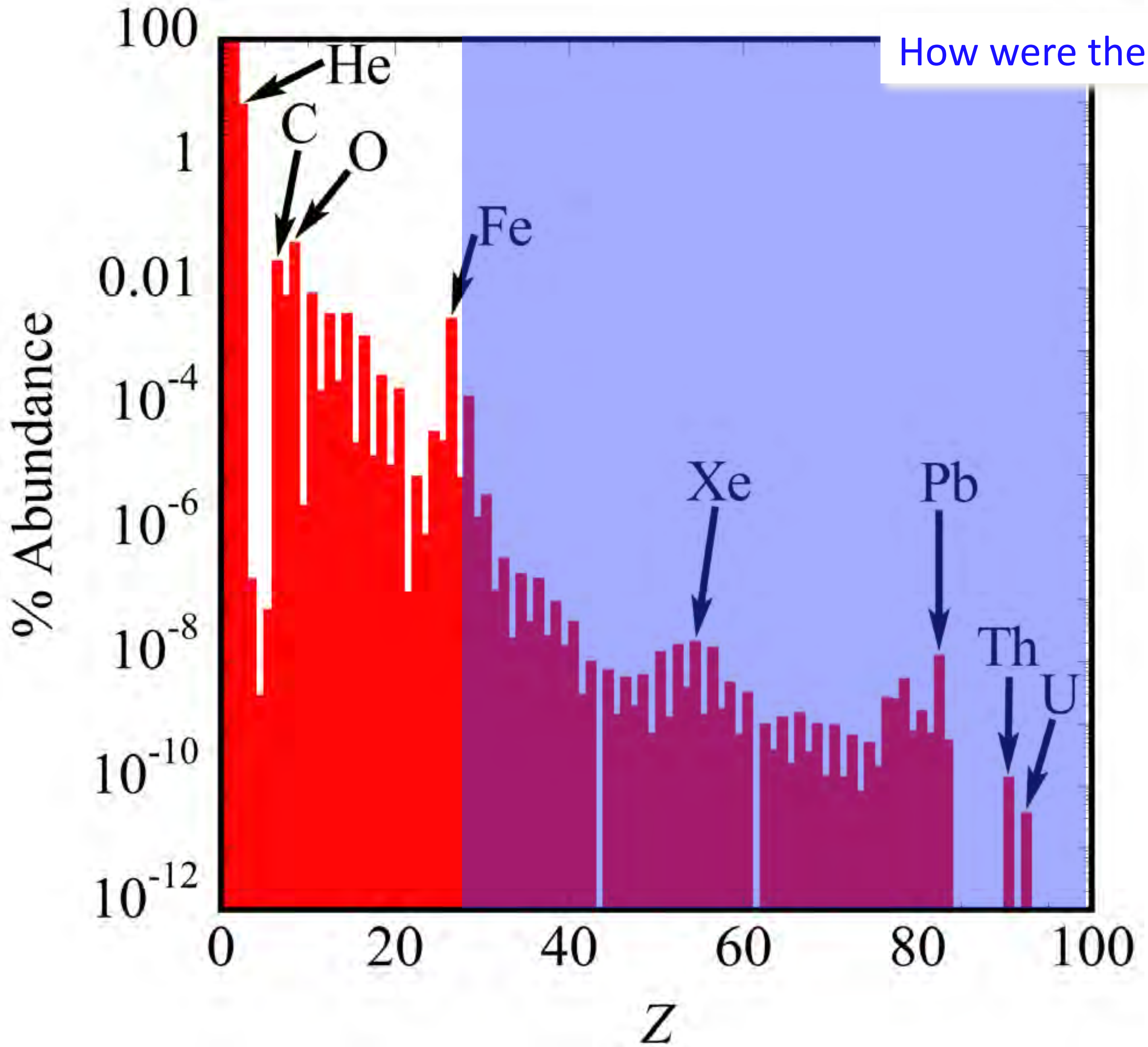
Bauer & Westfall, 2010

Fusion

- In the Sun, hydrogen nuclei fuse into helium (and release a lot of energy)
- Once most hydrogen is used up, the helium fuses to carbon, oxygen, neon, …, iron
- Once the stellar core is all iron, fusion stops, and the star dies
- Nothing heavier than iron can be made inside a star!



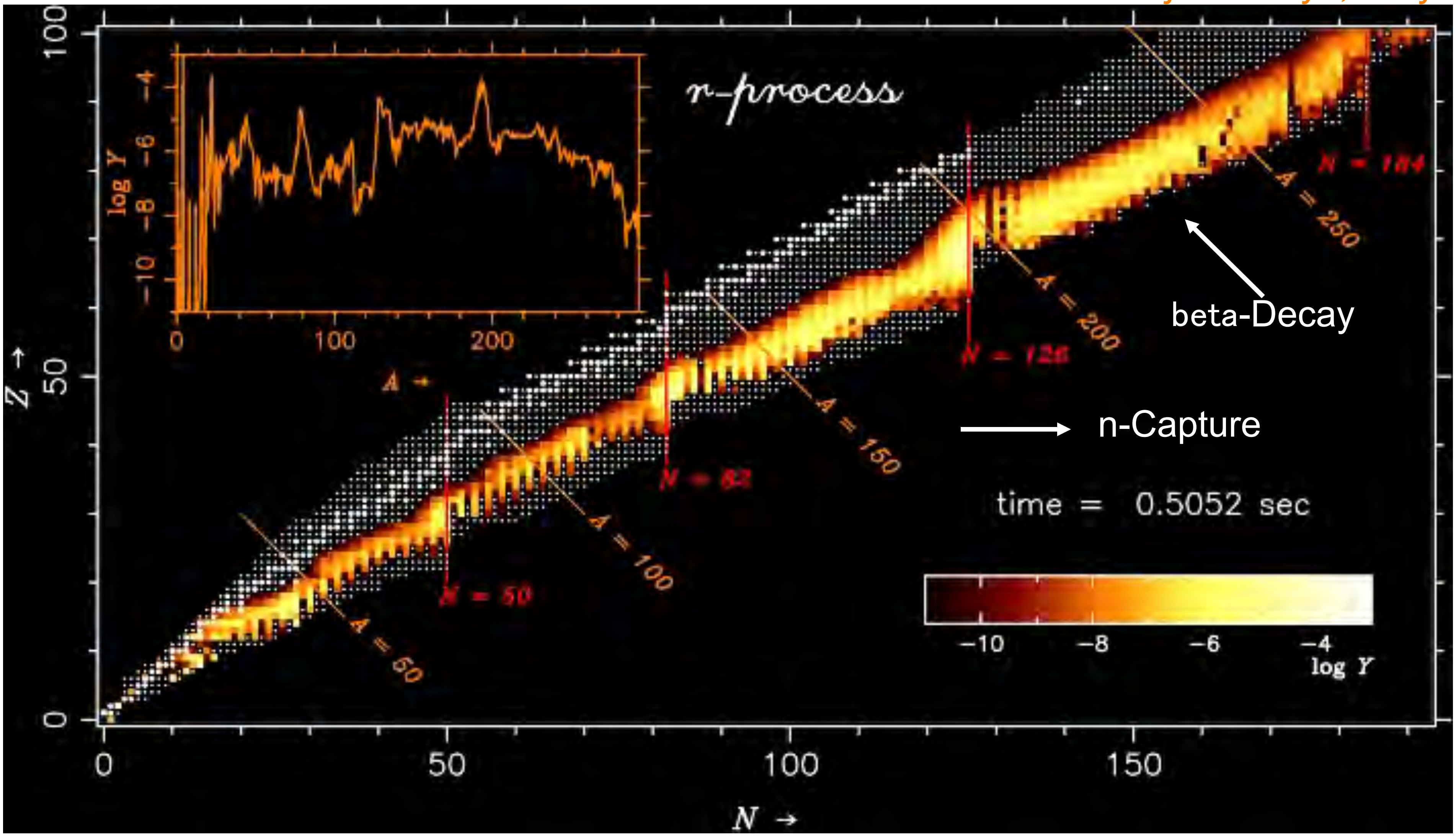
Element Abundances



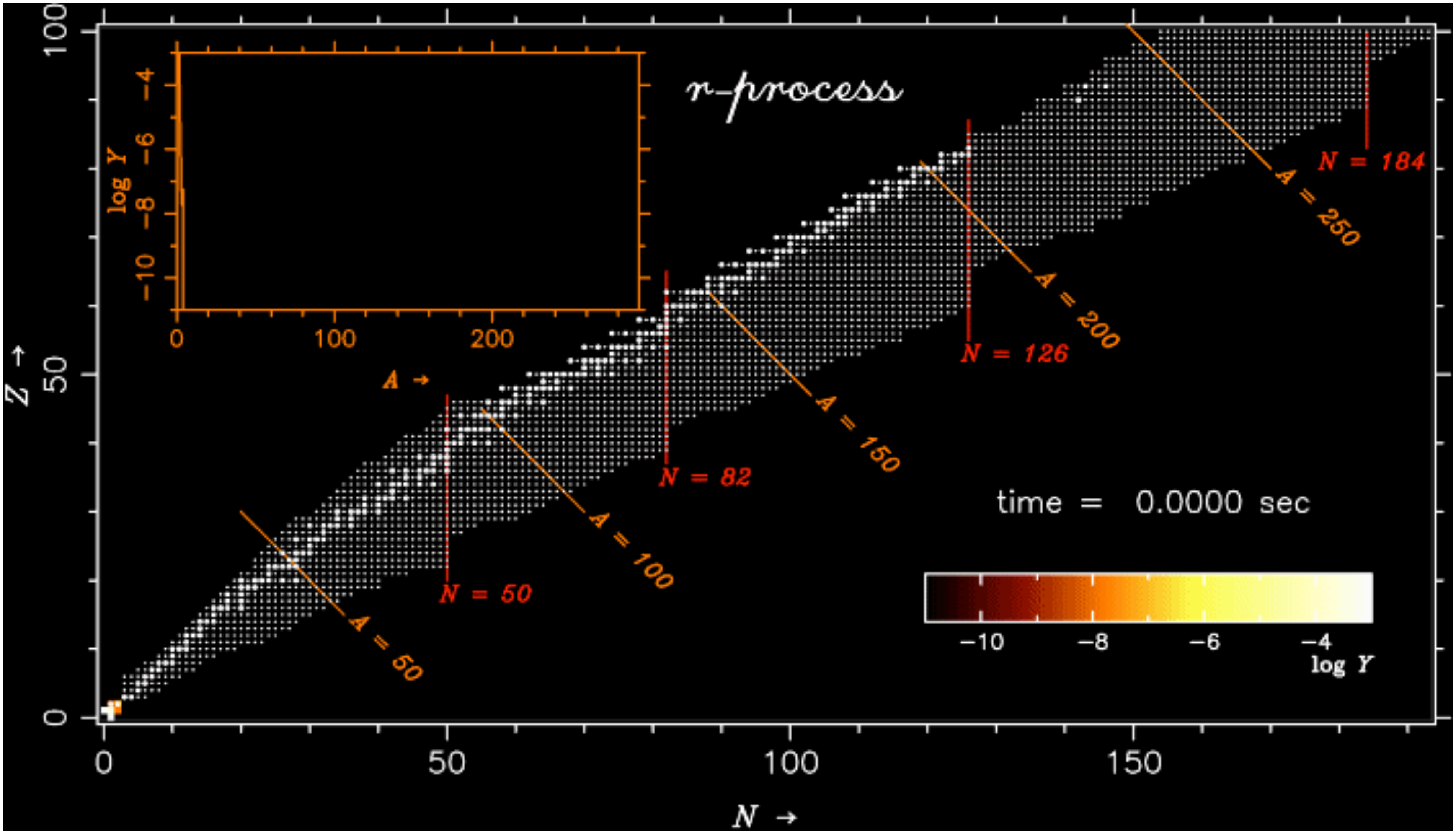
How were these created?

r(apid)-Process

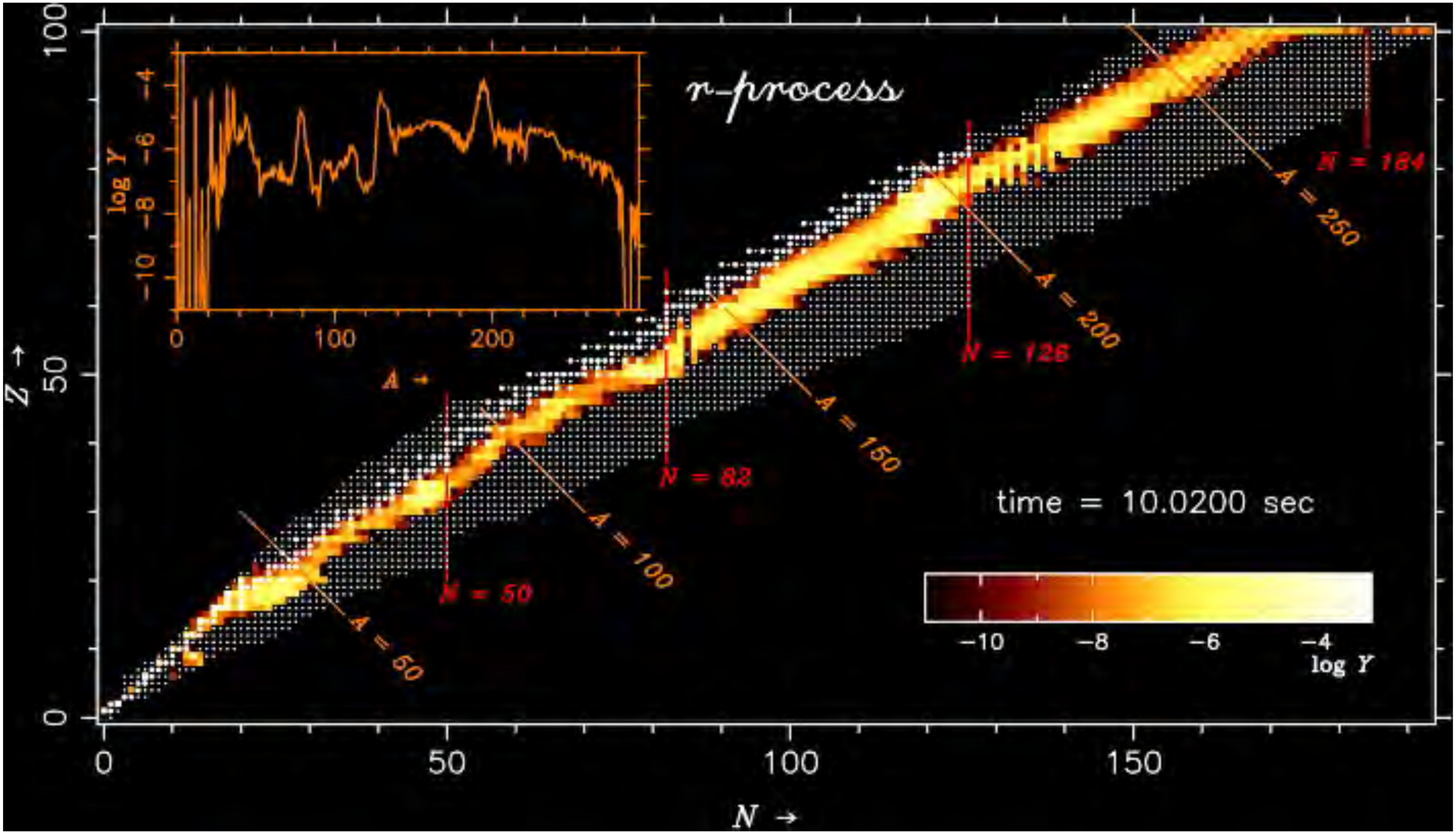
Calculation: Shinja Wanayo, Tokyo



r(apid)-Process - the movie

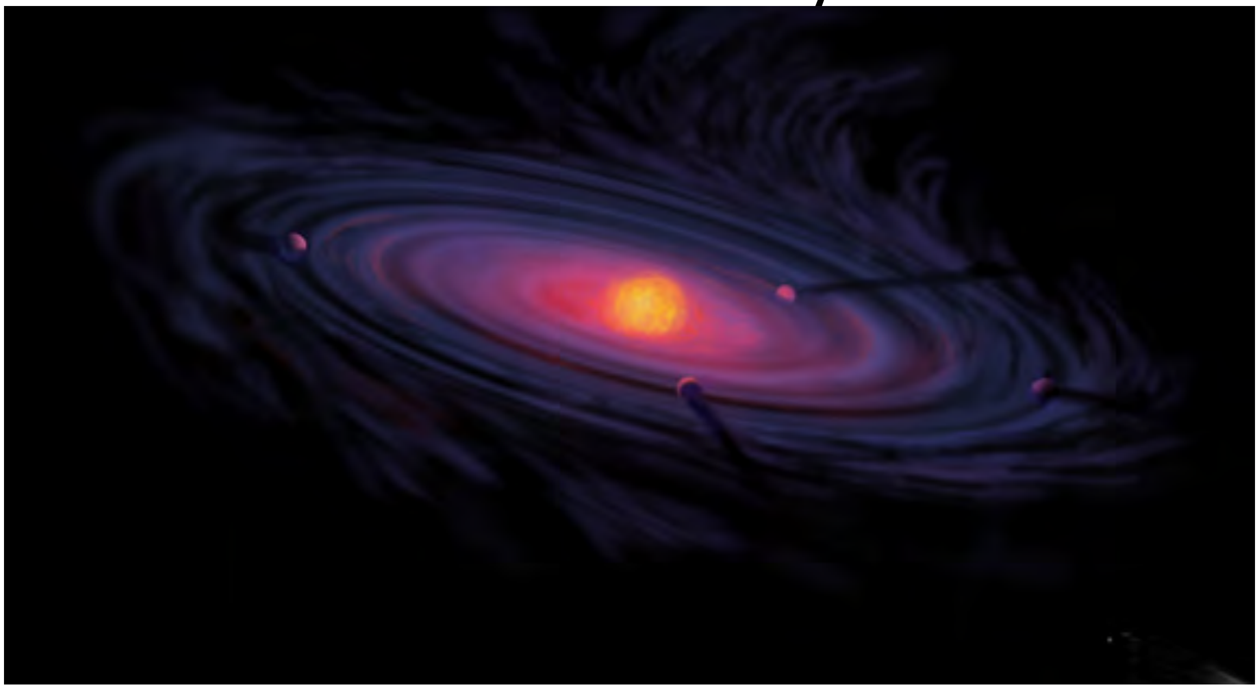


r(apid)-Process - the movie



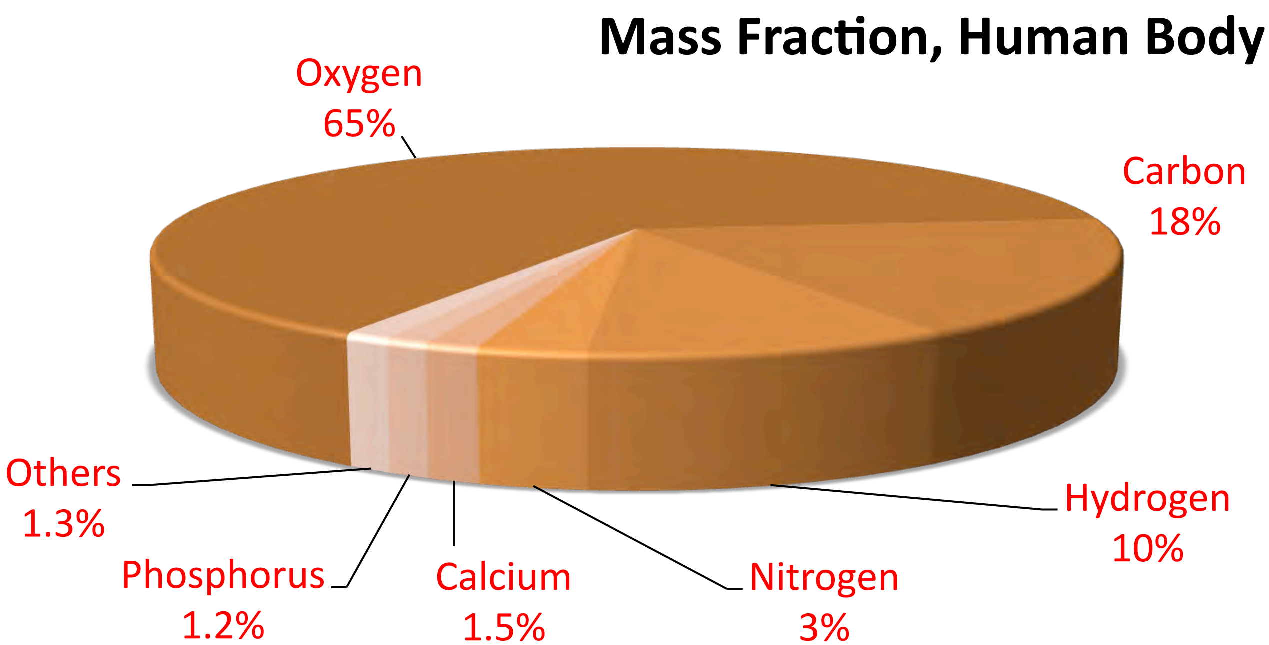
How old are Atoms on Earth?

- Solar system formed 4.6 billion years ago from interstellar dust cloud via gravitational collapse
  - Dust cloud generated from previous supernova explosion
- Most atoms on Earth > 4.6 billion years old



All matter is made of atoms!

This includes us: We are made from the ashes of a dying star!



Others: Sulfur, chlorine, sodium, magnesium, iron, cobalt, zinc, iodine, selenium, fluorine, …

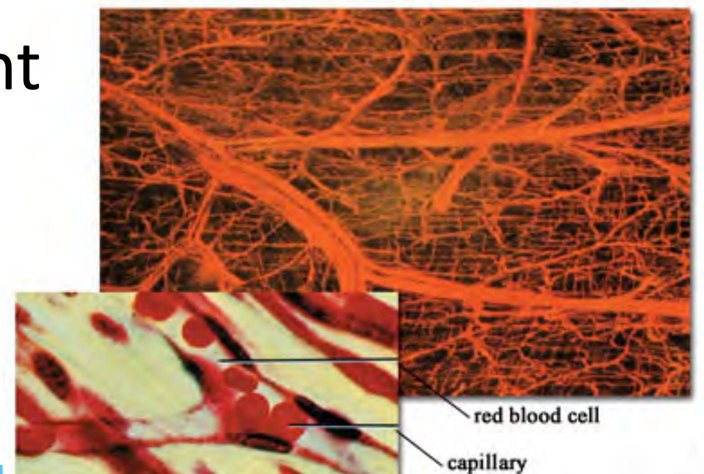
How Many Atoms Inside of Us?

- Assume a mass of 70 kg (~155 lb)
- Approximately $6.7 \cdot 10^{27}$ atoms
- 6,700,000,000,000,000,000,000,000,000

Stack 10 million atoms on top of each other: Thickness of a fingernail

Atom Exchange

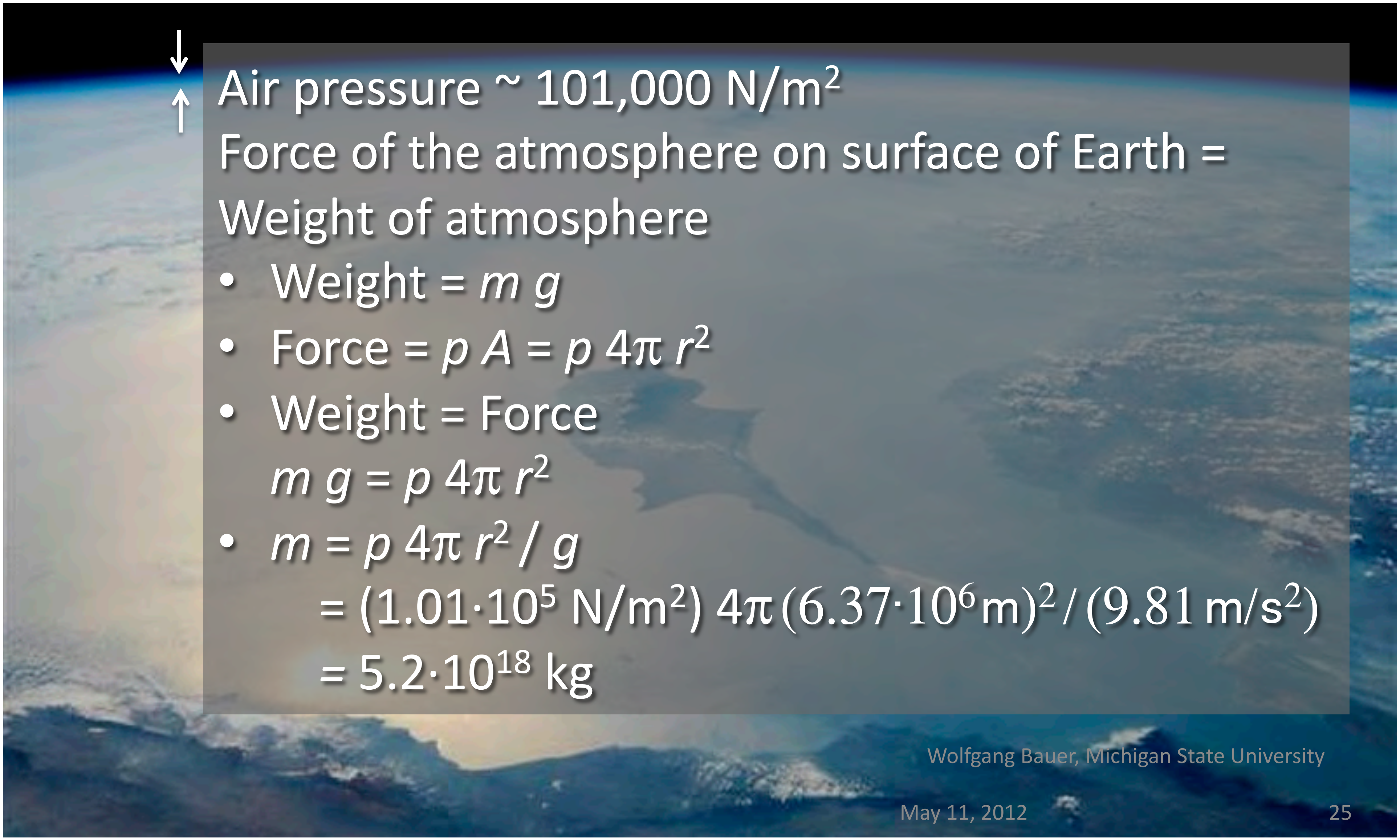
- Our bodies constantly exchange atoms with environment
  - Breathing (produces ~1 kg of CO_2/day)
  - Eating, drinking
  - Transported to each of our ~100 trillion cells via blood vessel network of ~100,000 km total length
- Exchange >10 times our body weight with biosphere each year
  - ~50,000 kg during average life time



Where do Exchanged Atoms go?

- Majority of atoms expelled from body are contained in CO_2 and H_2O
  - CO_2 enters atmosphere
  - H_2O distributed in biosphere
- Rapid (order of days to years) mixing with other atoms and distribution throughout the biosphere

Weight of the Atmosphere



Air pressure ~ 101,000 N/m^2

Force of the atmosphere on surface of Earth = Weight of atmosphere

- Weight = $m\,g$
- Force = $p\,A = p\,4\pi\,r^2$
- Weight = Force

  $m\,g = p\,4\pi\,r^2$
- $m = p\,4\pi\,r^2 / g$

  $= (1.01\cdot10^5\ \mathrm{N/m^2})\ 4\pi\,(6.37\cdot10^6\,\mathrm{m})^2 / (9.81\,\mathrm{m/s^2})$

  $= 5.2\cdot10^{18}$ kg

Size of the Biosphere

Atmosphere: ~100 km thick, $m = 5.2 \cdot 10^{18}$ kg

- equivalent 10 m water depth

Biosphere:

- Oceans of average depth ~ 3 km
- Land mass with soil, plants, animals
- Factor ~10^2 more mass than atmosphere

Total mass of biosphere ~ **$5 \cdot 10^{20}$ kg**

How many atoms do you have from …?

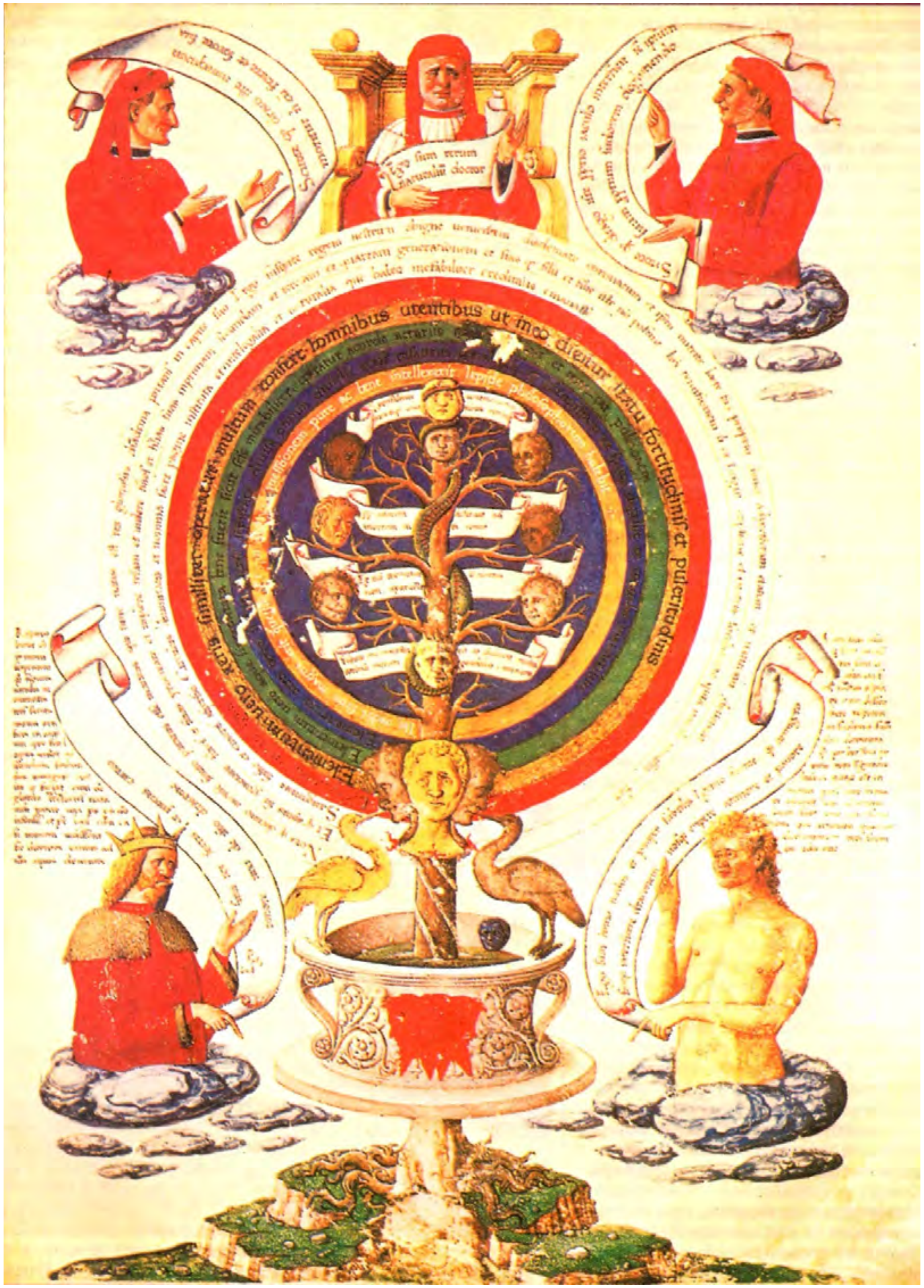
- Probability that a given atom has been part of the body of a given person (historical figure)

$$p = \frac{50{,}000\ \text{kg}}{5 \cdot 10^{20}\ \text{kg}} = 1 \cdot 10^{-16}$$

- Number of atoms in your body right now that once belonged to <*fill in the blank*>

$$N = p \cdot N_{\text{atoms}} = (7 \cdot 10^{27})(1 \cdot 10^{-16}) = 7 \cdot 10^{11}$$

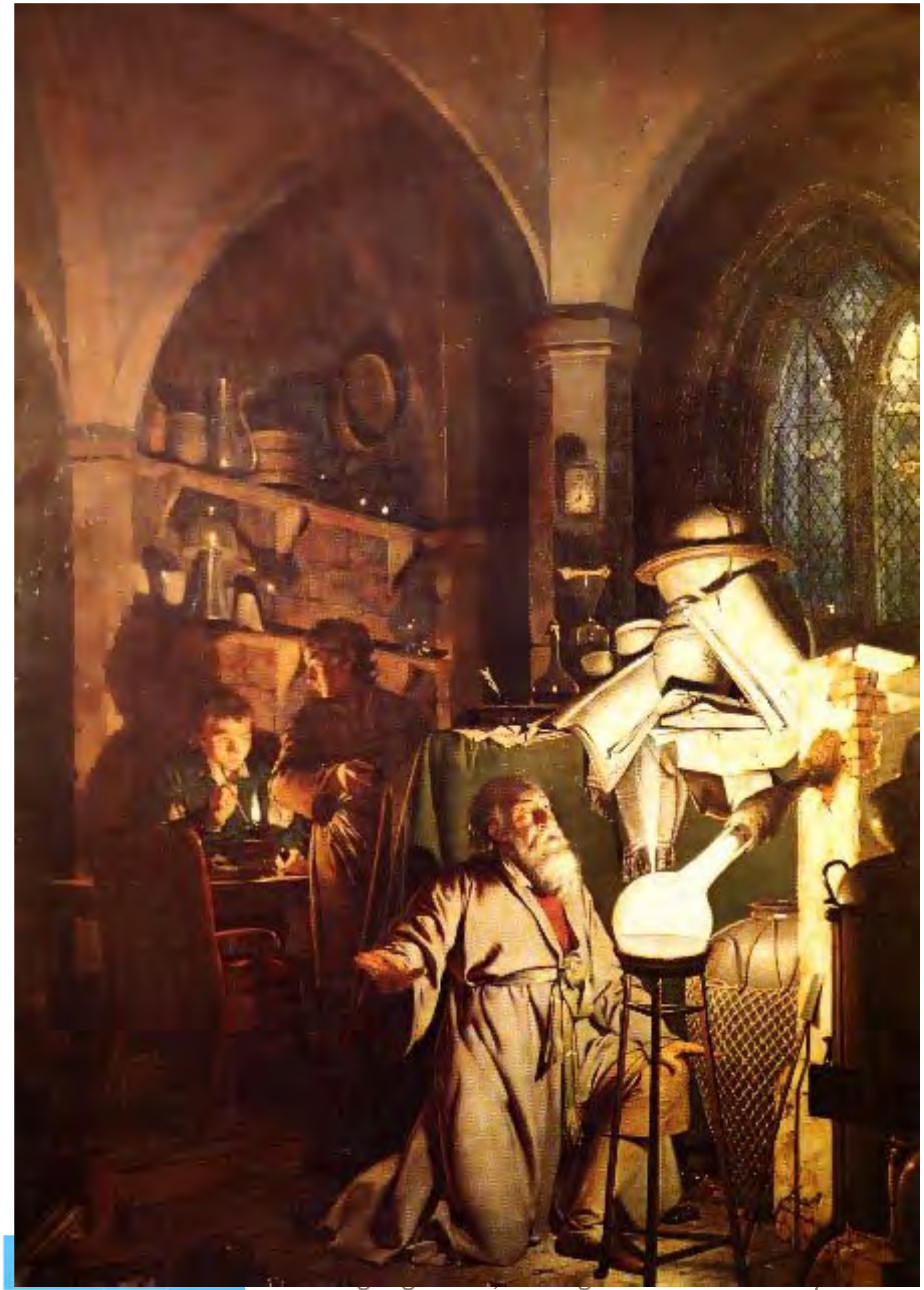
Approximately a **trillion** atoms!!!



Alchemy

Alchemy

- Primary Objective:
  - (Re)Creation of the Philosopher's Stone
  - ="Magnum Opus"
- Philosopher's Stone
  - Turns common metals (lead, iron) into silver or gold
  - Elixir of life
- Attempted for many centuries



Success in the 20th Century

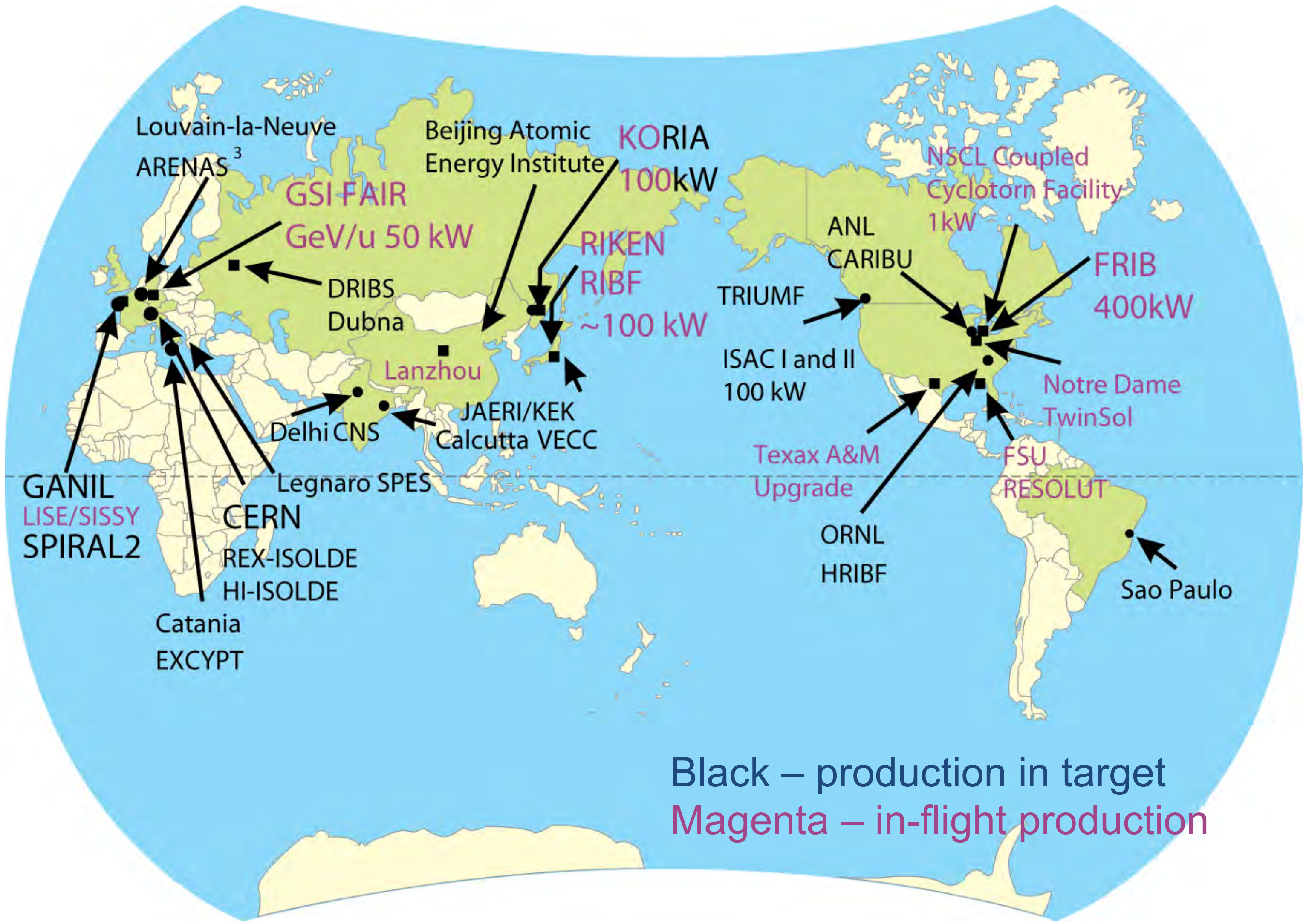
- "Gold can be extracted from mercury, but mercury cannot be transmuted into gold." *1924 Editors of Scientific American*
- "It was not until **1941** that gold was actually prepared from a base metal. By bombarding mercury with fast neutrons, Sherr, Bainbridge, and Anderson obtained three radioactive isotopes of gold. Even that did not fulfill the dream of the alchemists; the gold was radioactive and the process did not produce wealth; it consumed it." *A Philatelic Ramble Through Chemistry* (Heilbronner and Miller; Verlag 1998)

THE
PHYSICAL REVIEW
A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893
VOL. 60, NO. 7 OCTOBER 1, 1941 SECOND SERIES

Transmutation of Mercury by Fast Neutrons

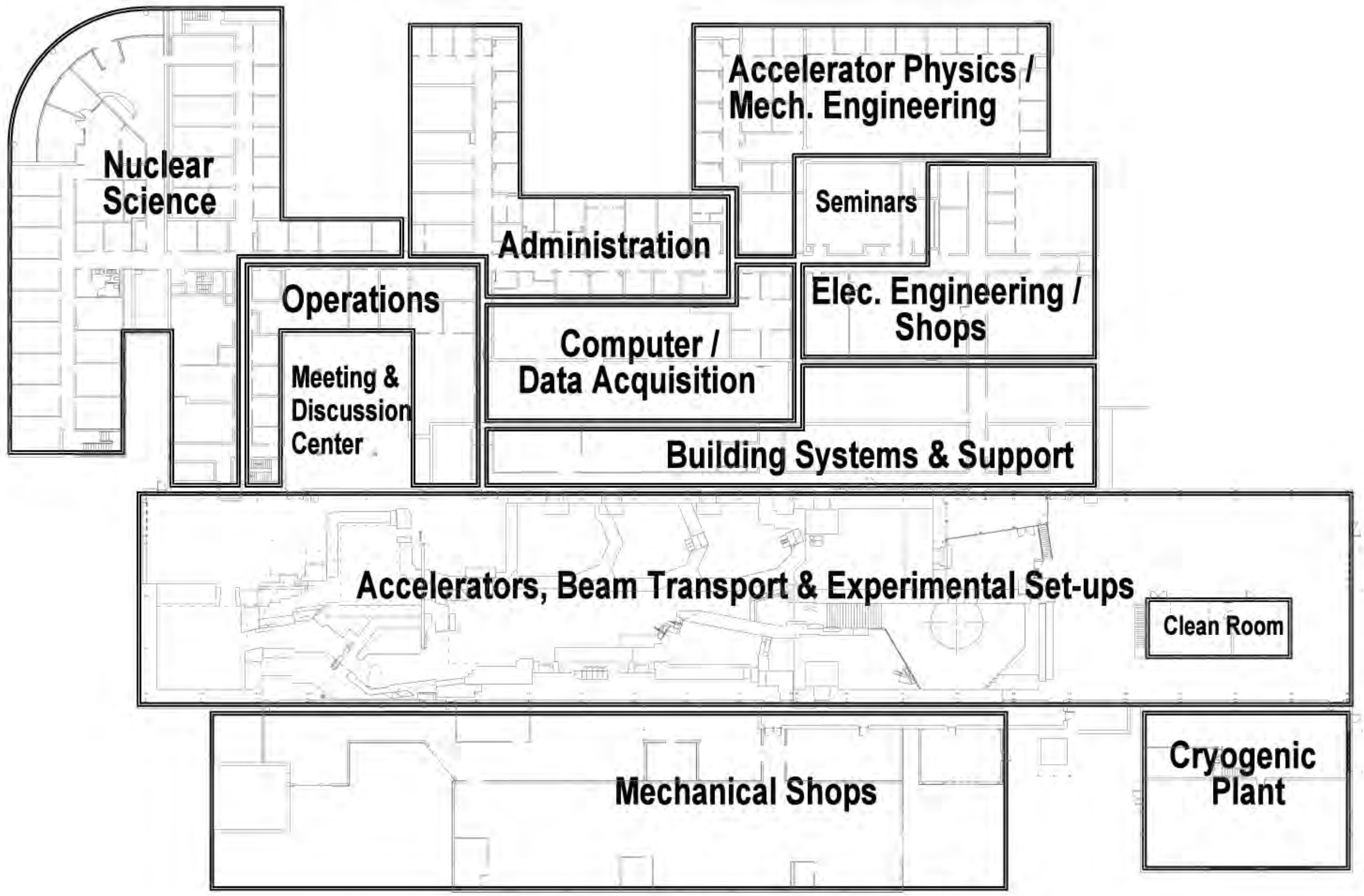
R. SHERR AND K. T. BAINBRIDGE, *Research Laboratory of Physics, Harvard University, Cambridge, Massachusetts*
AND
H. H. ANDERSON, *Mallinckrodt Laboratory, Department of Chemistry, Harvard University, Cambridge, Massachusetts*
(Received August 13, 1941)

Rare Isotope Facilities

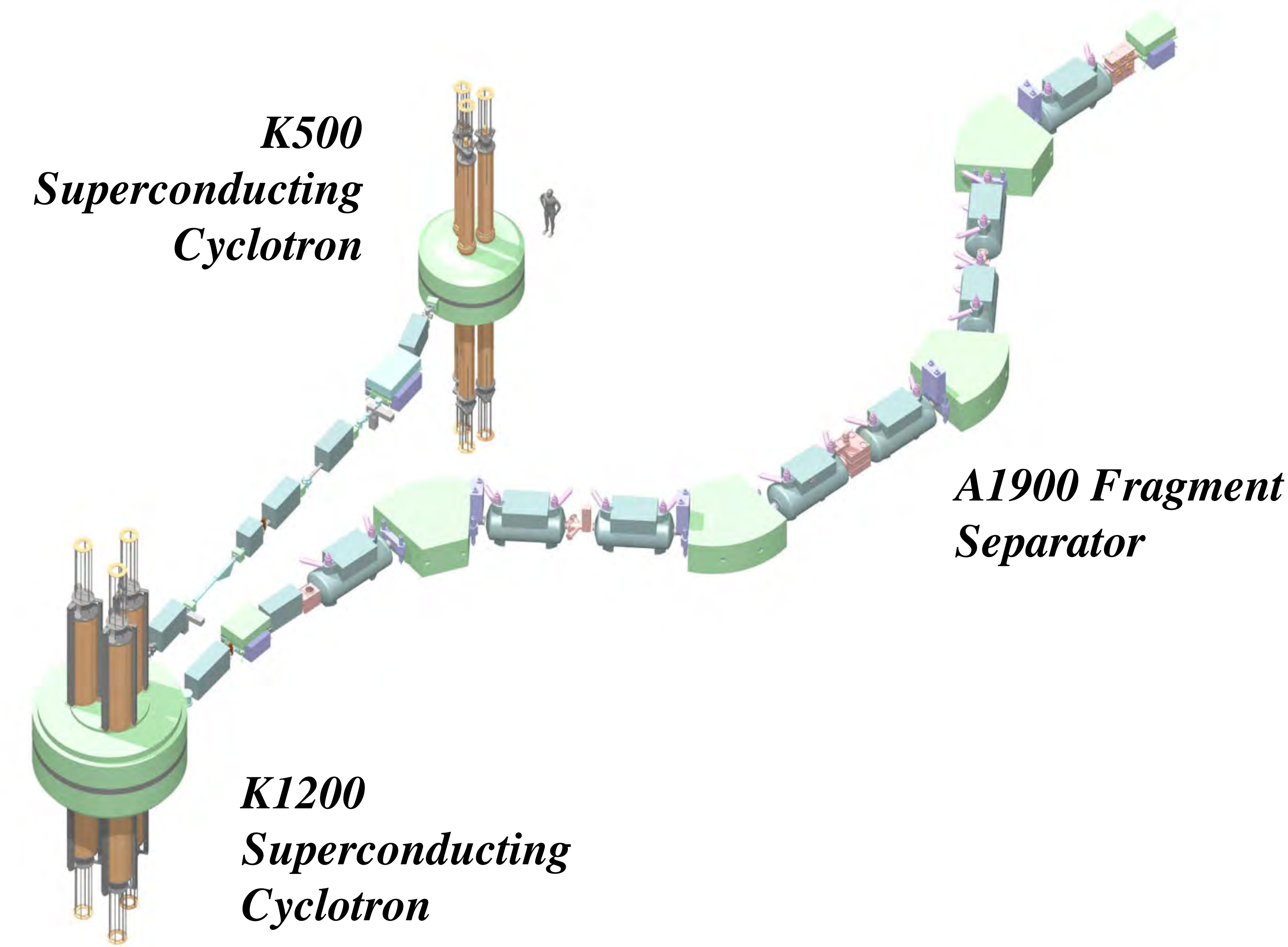


NSCL, National Superconducting Cyclotron Laboratory

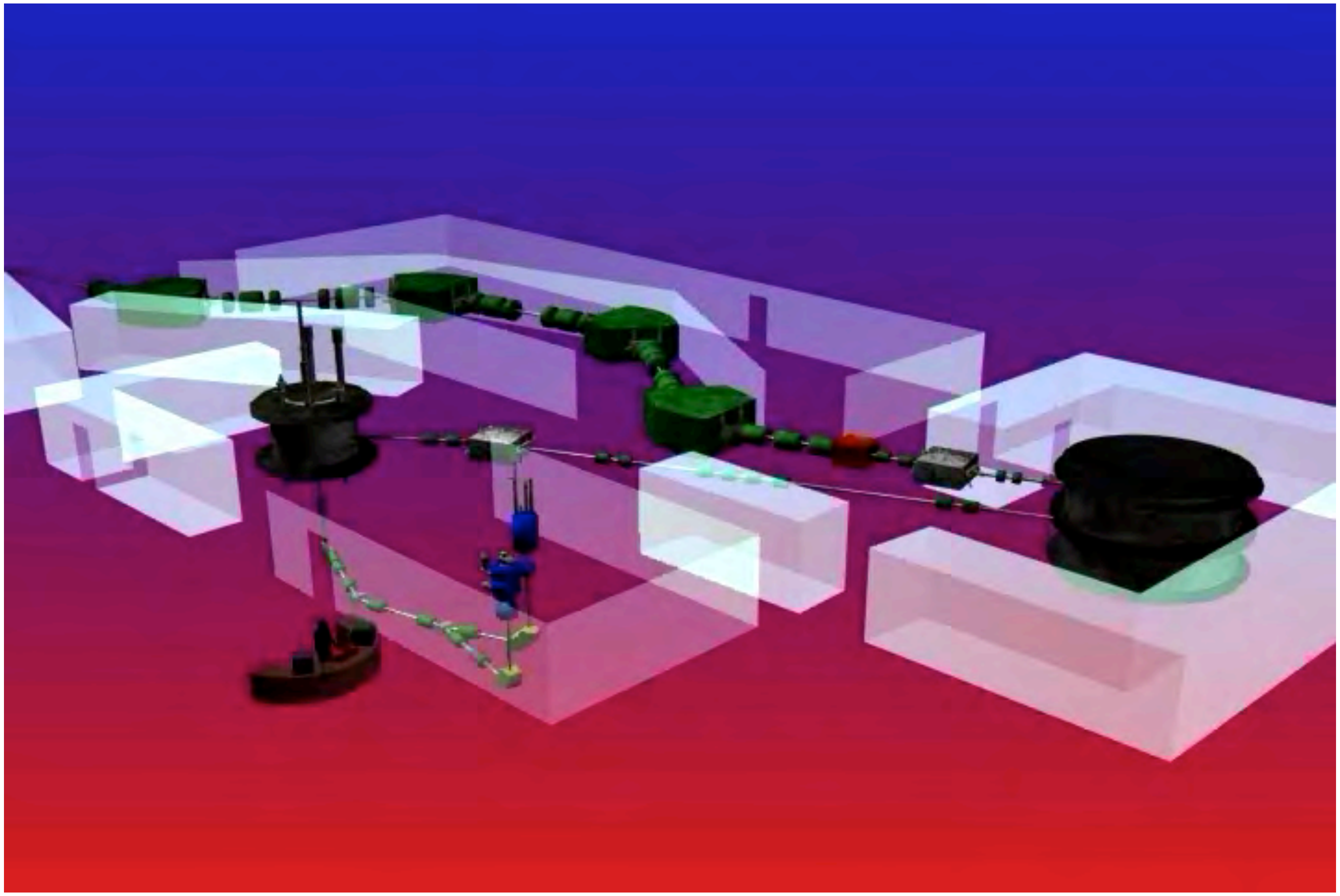
Layout of NSCL



Overview of Coupled Cyclotrons



Fly-by of NSCL Coupled Cyclotron Facility



Wolfgang Bauer, Department of Physics and Astronomy
Biomedical and Physical

The next step: FRIB

FACILITY FOR
RARE ISOTOPE BEAMS

MSU Project Management Team

The MSU FRIB Project Management Team designs and establishes FRIB as a Department of Energy Office of Science national user facility to support the mission of the Office of Nuclear Physics. Once FRIB is completed the FRIB Project will cease to exist and the MSU FRIB Laboratory will operate FRIB as a national user facility.

Thomas Glasmacher

Project Manager

Donna Donovan

Deputy Project Manager

Al Zeller

Associate Project Manager

Jie Wei

Accelerator Systems Division Director

Georg Bollen

Experimental Systems Division Director

Brad Bull

Conventional Facilities Division Director

Peter Grivins

Environmental, Safety, Health, and Quality Manager

Robert Lowrie

Environmental, Safety, and Health Deputy Manager

Dan Stout

Project Chief Engineer

The MSU FRIB Laboratory will operate FRIB as a national user facility once the FRIB Project is complete. During design and establishment of FRIB, the FRIB Laboratory interacts with the scientific community on MSU's behalf.

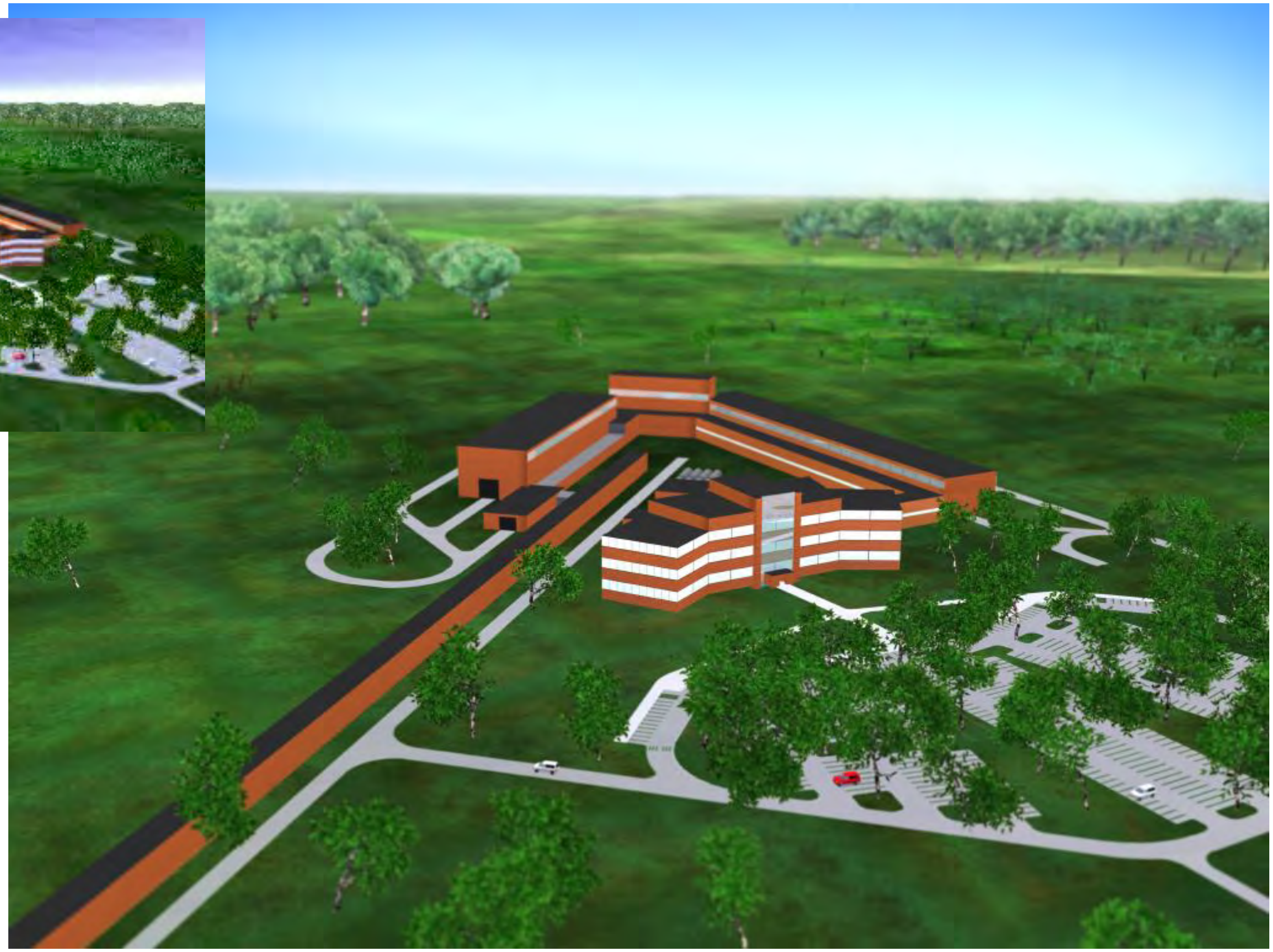
Konrad Gelbke

FRIB Laboratory Director

Bradley Sherrill

FRIB Chief Scientist

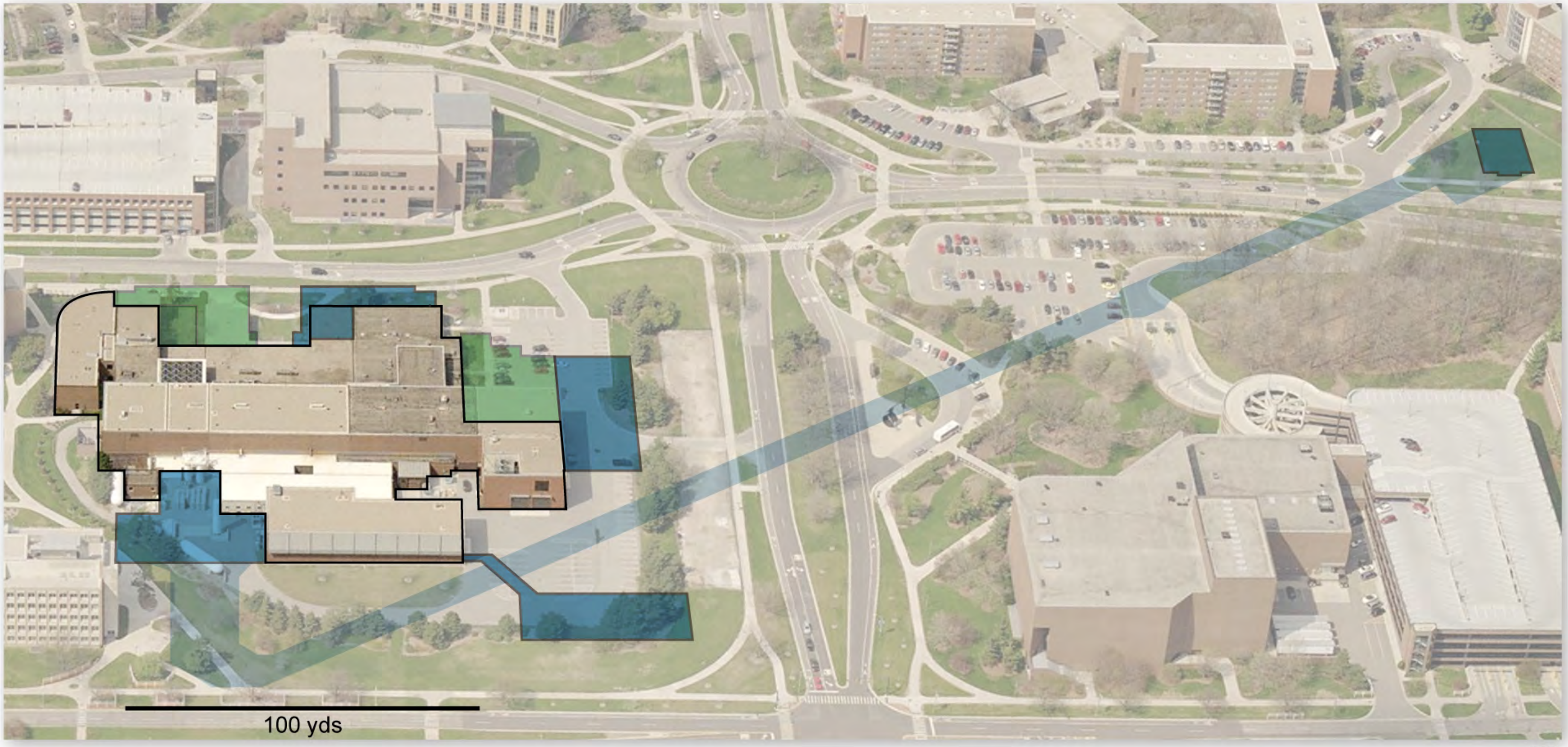
RIA at MSU Projected Site



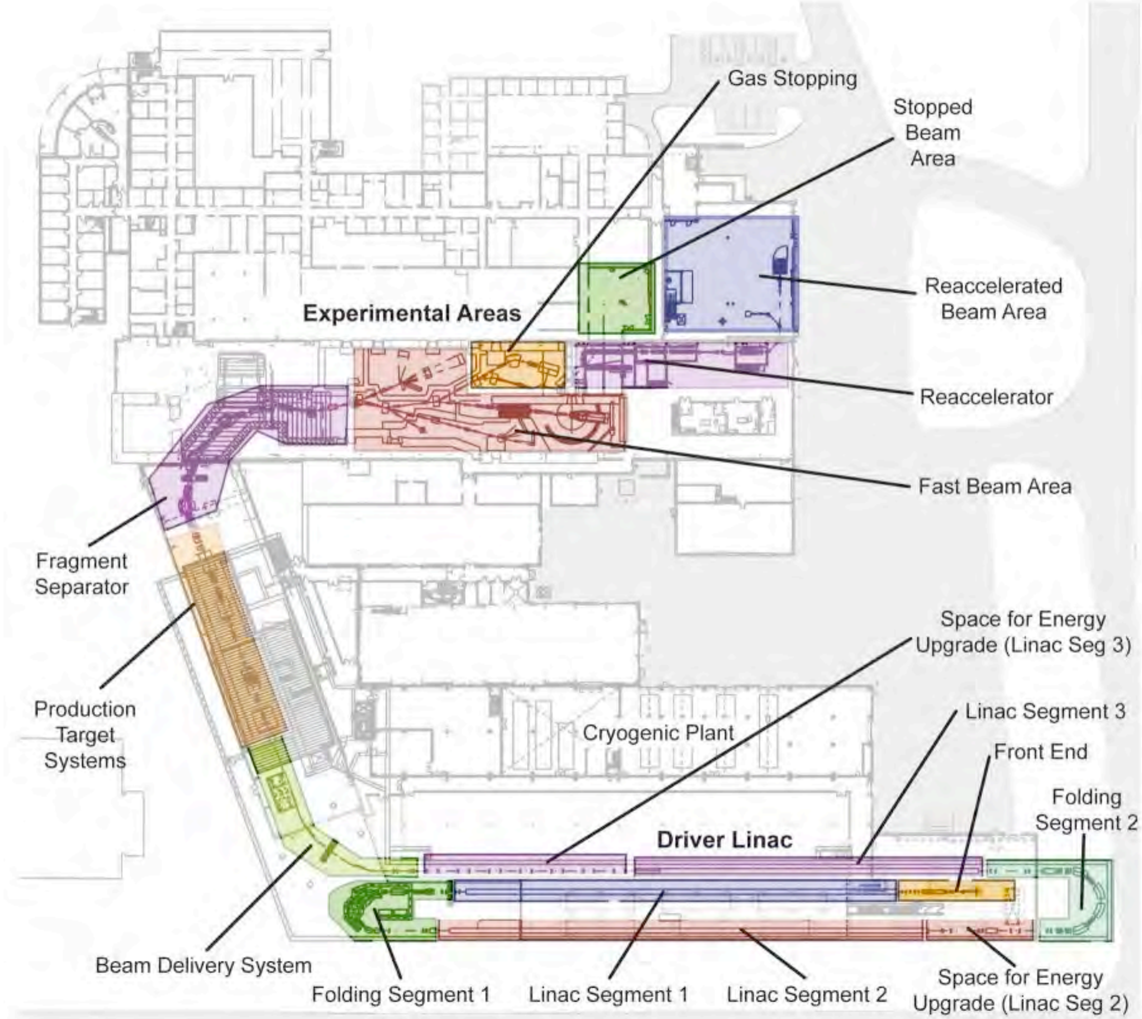
RIA is the 900 million dollar Rare Isotope Accelerator being pursued by MSU

A decade-long battle for a Mega-Project in Michigan: status as of 2009

FRIB: Preliminary Design

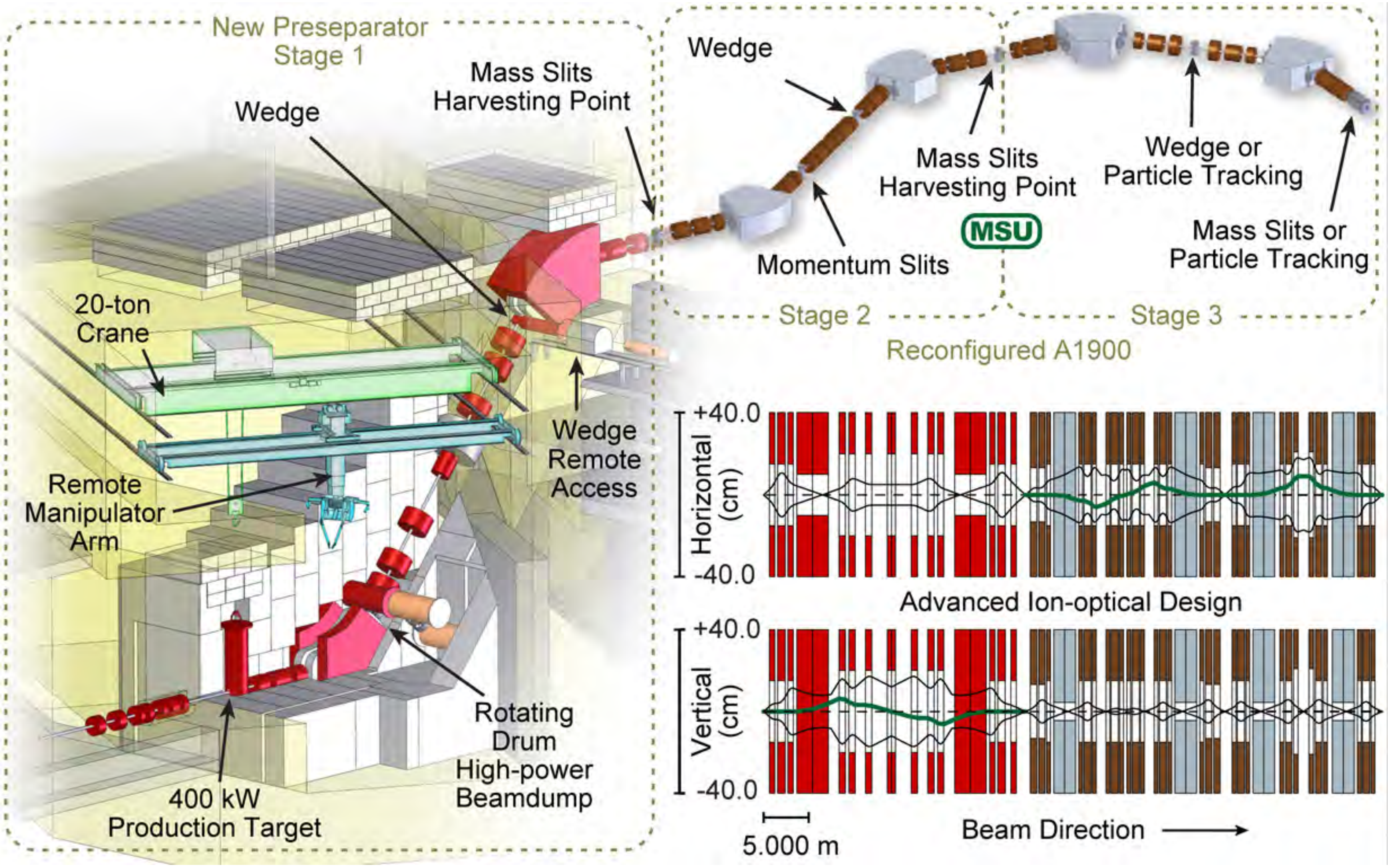


FRIB Final Design: Cutaway Drawing



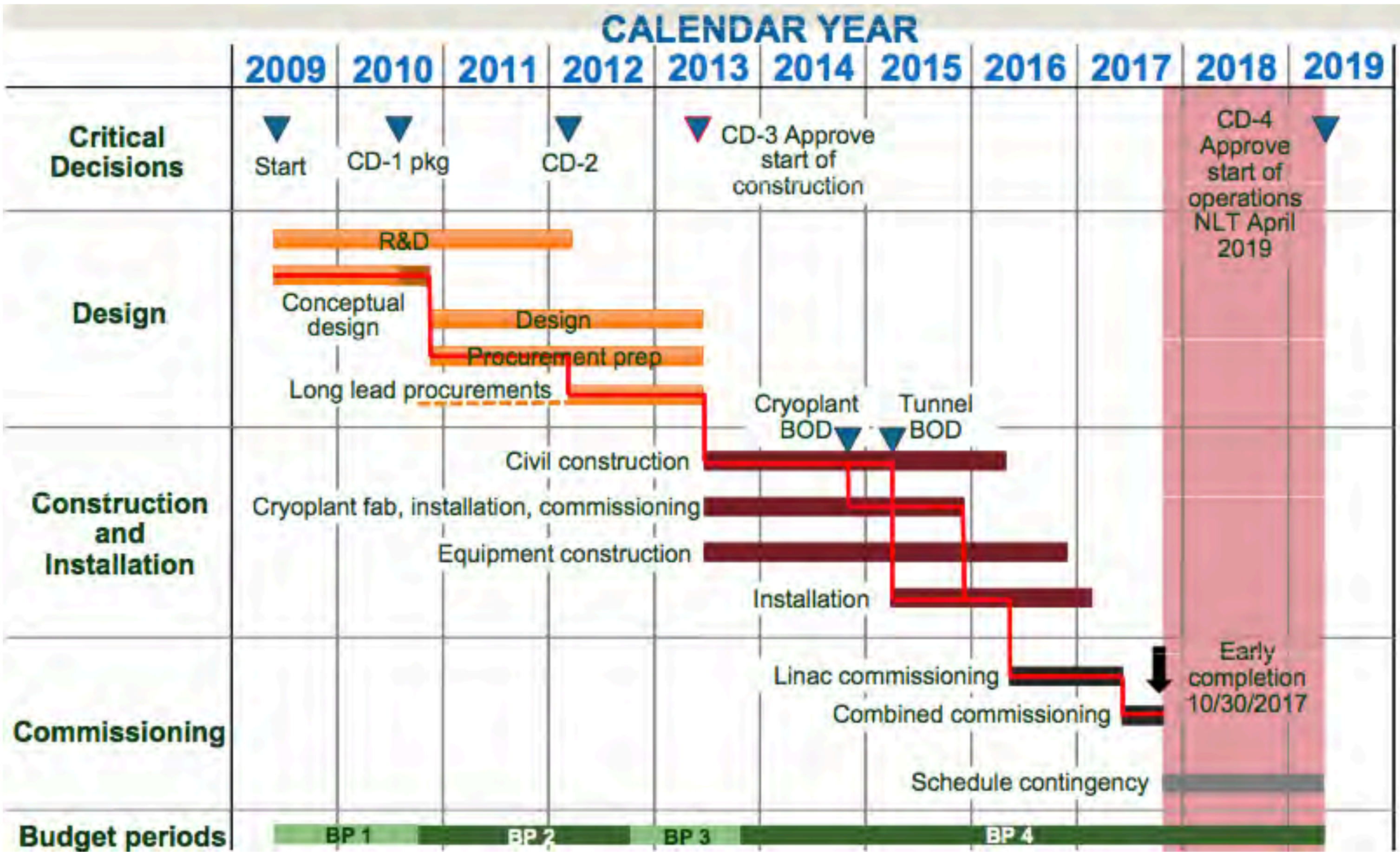
FRIB: Proposed Experiment Areas

FRIB 3-Stage Fragment Separator



Timeline for FRIB

- FRIB timeline is dependent on funding by Congress and approval by Department of Energy



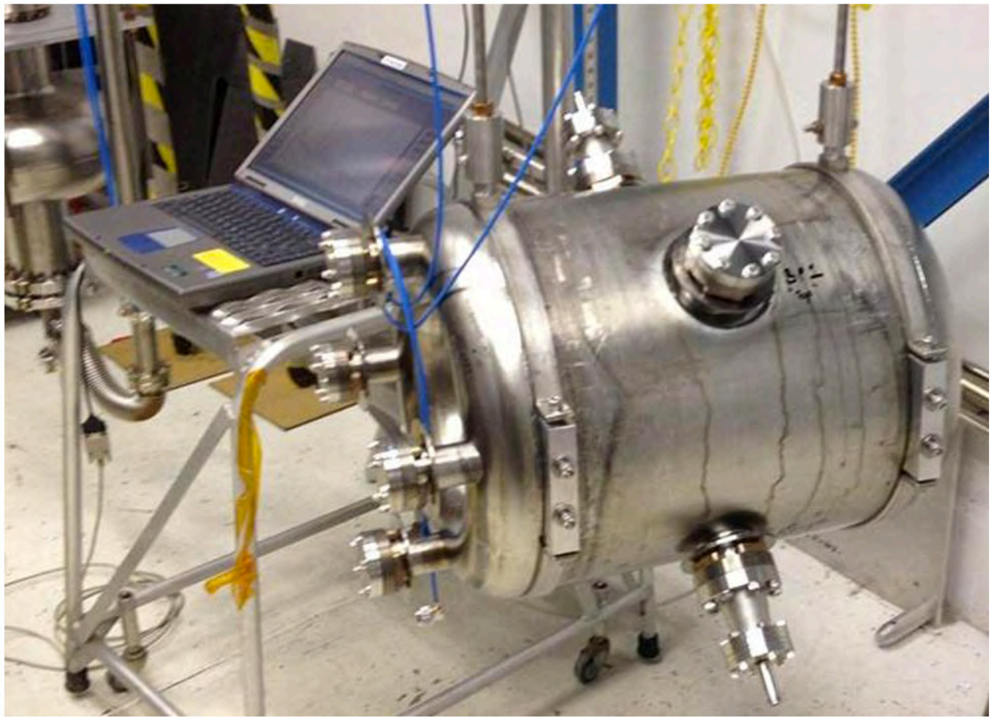
Construction Status

Construction Status

Construction Status

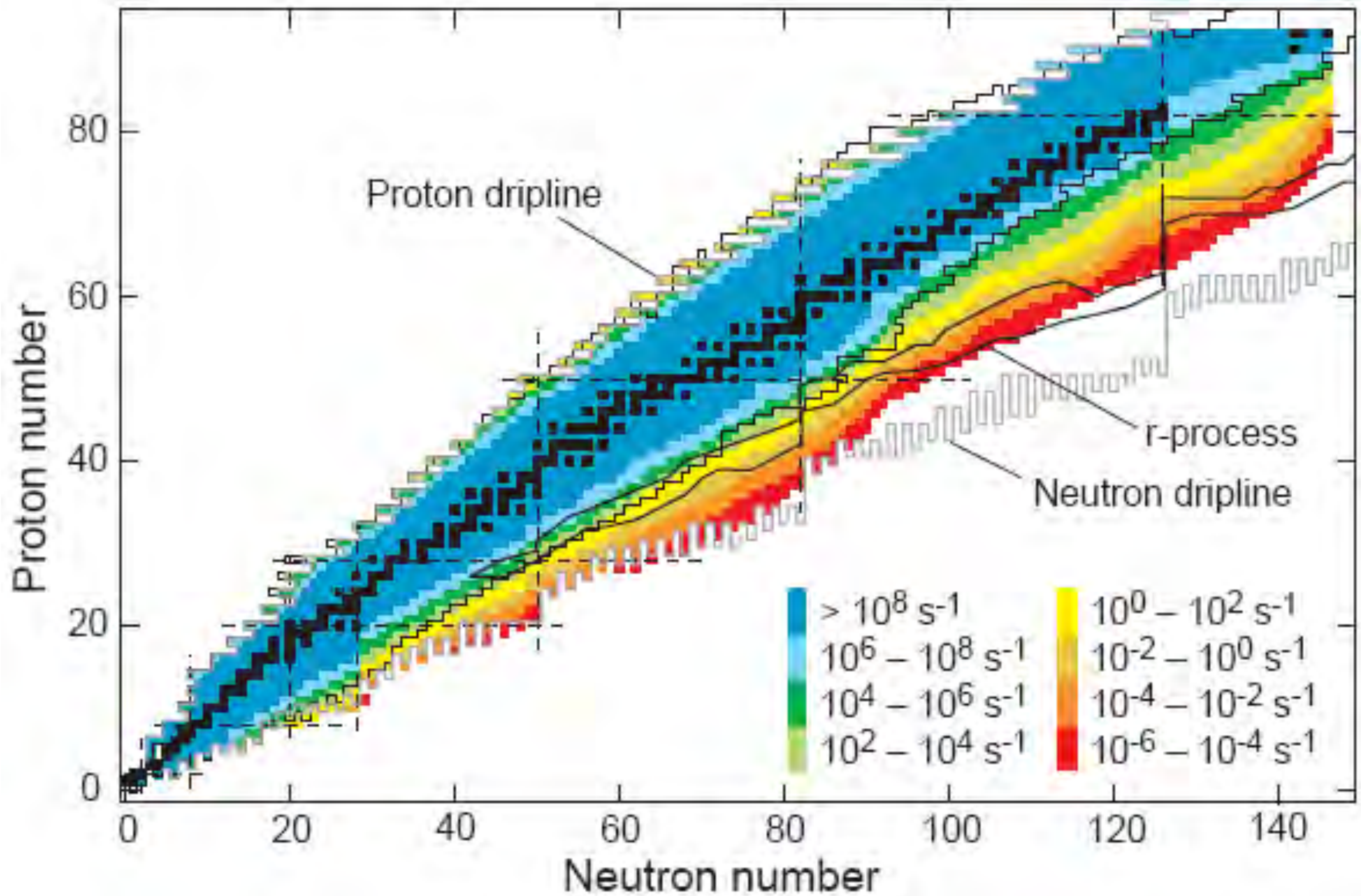
Industrial Partners

- Industry-built superconducting RF cavity
  - Successfully tested at JLAB
  - March 4, 2012



What New Nuclides Will FRIB Produce?
Key: All Produced are Available for Study

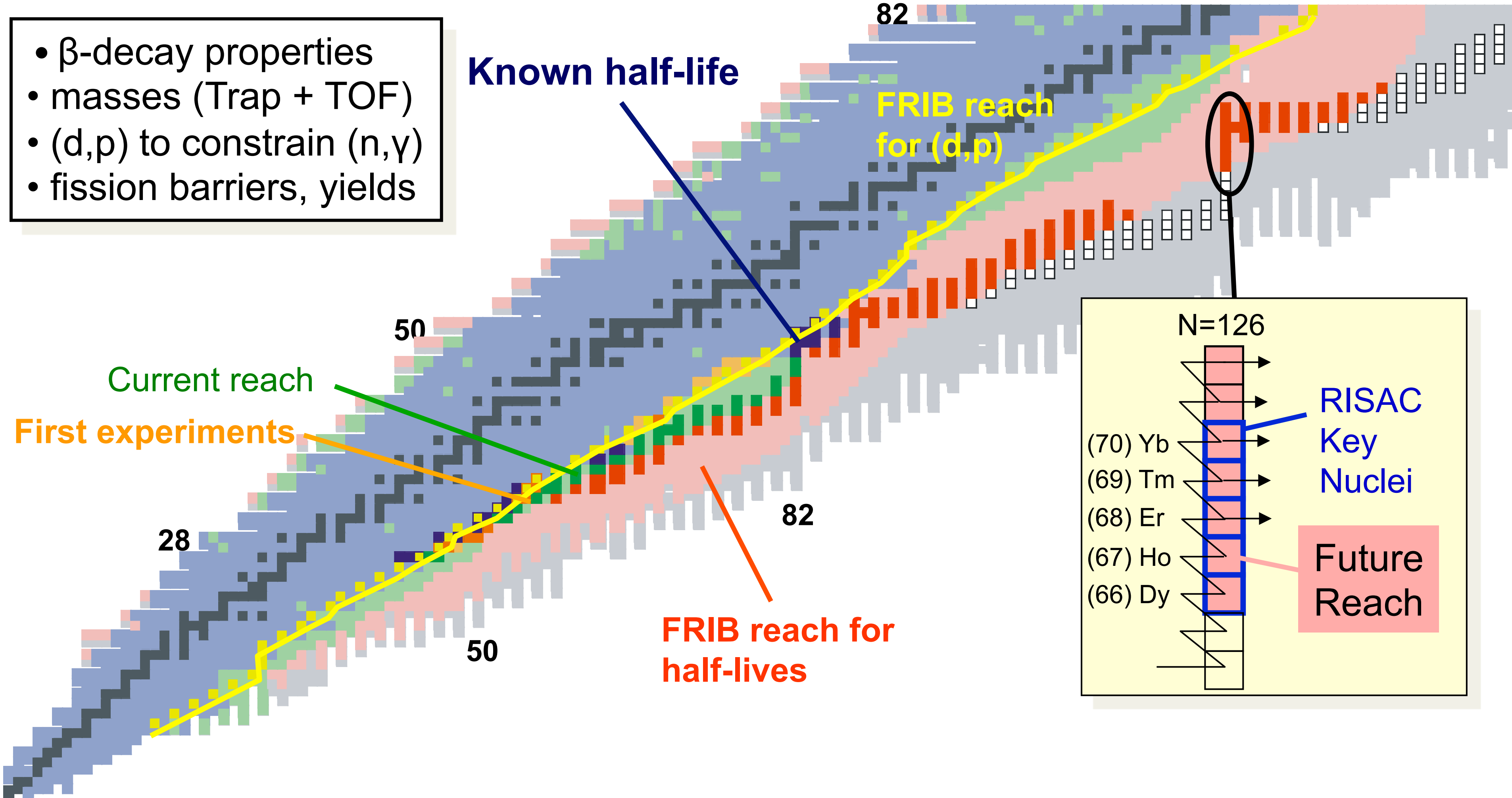
- FRIB will produce more than 1000 NEW isotopes at useful rates
- Interaction with Theory is key to making the right measurements
- Exciting prospects for study of the drip line to mass 120 (compared to 24)
- Production of most of the key nuclei for astrophysical modeling
- Harvesting prospects near stability



Rates are available at http://groups.nscl.msu.edu/frib/rates/

Reach of FRIB: Will Allow Modeling of the r-Process; We will understand the Origin of our Elements!

- β-decay properties
- masses (Trap + TOF)
- (d,p) to constrain (n,γ)
- fission barriers, yields

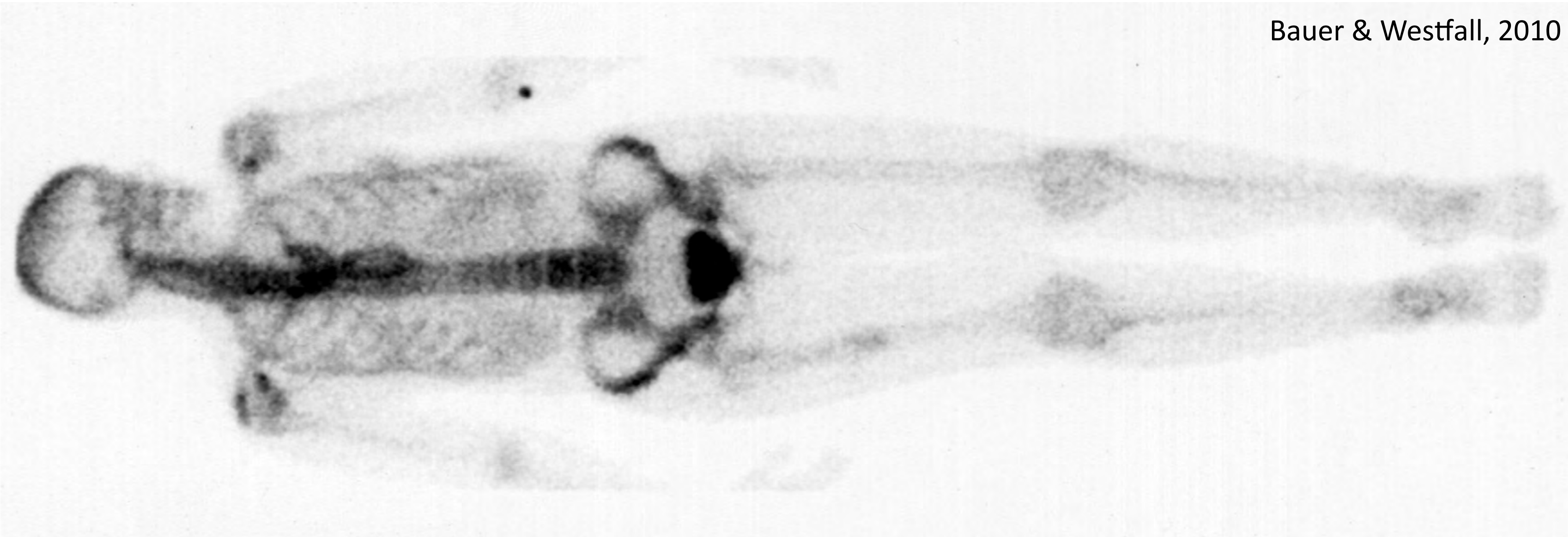


Rare Isotopes For Society

- Isotopes for medical research
  - Examples: ^{47}Sc, ^{62}Zn, ^{64}Cu, ^{67}Cu, ^{68}Ge, ^{149}Tb, ^{153}Gd, ^{168}Ho, ^{177}Lu, ^{188}Re, ^{211}At, ^{212}Bi, ^{213}Bi, ^{223}Ra (DOE Isotope Workshop)
  - γ-emitters ^{149}Tb, ^{211}At: potential treatment of metastatic cancer
  - Example: Ca-isotopes for bone research
- Reaction rates for stockpile stewardship – non-classified research
  - Determination of extremely high neutron fluxes by activation analysis
  - Rare isotope samples for (n,γ), (n,n'), (n,2n), (n,f) e.g. ^{88,89}Zr
    - Same technique important for astrophysics
  - More difficult cases studied via surrogate reactions (d,p), …
- Tracers for Geology, Condensed Matter Physics (^{8}Li), Material Science, Biology …

Isotope harvesting is included in the FRIB scope

Example: Technetium Scan



- Rare isotopes for medical imaging / treatment
- Future isotope use will allow to focus on particular element and allow study of biological processes on different time scales, from milliseconds to years

Summary

- Atoms in our bodies are *immortal*
- We constantly *exchange* atoms with the environment
- ~*trillions* of atoms in our bodies have been in those of historical figures
- We have achieved the alchemists' ultimate goal and can *trans-mutate atoms*
- *Designer isotopes* can be used for fundamental studies and for medical and technical applications
- **FRIB** will be Mid-Michigan's world-leading entry into this field

Final Word

- You can follow my musings on Twitter: http://twitter.com/BauerWestfall
- Email: bauer@pa.msu.edu
- Bring your friends & families
  - NSCL /FRIB tours
    - (Planetarium is next door, too)