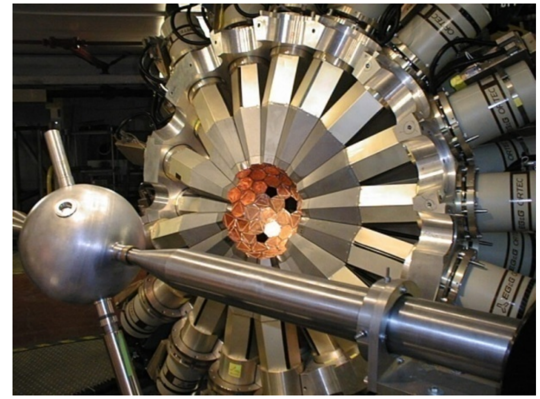
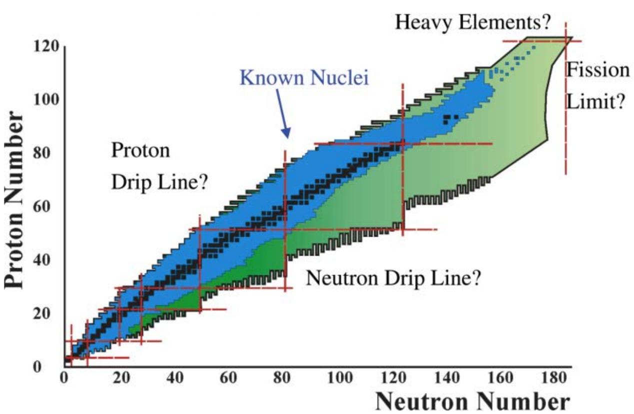
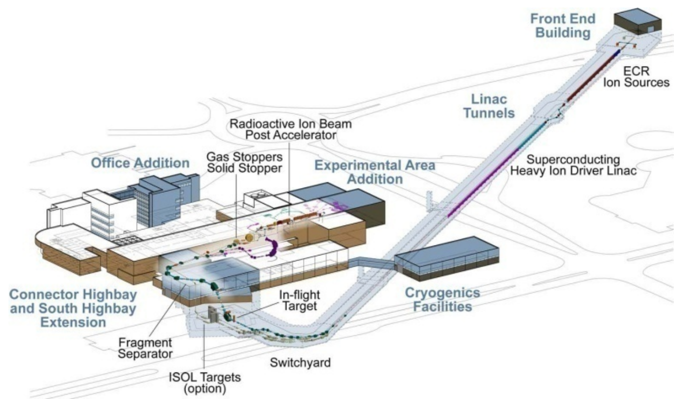
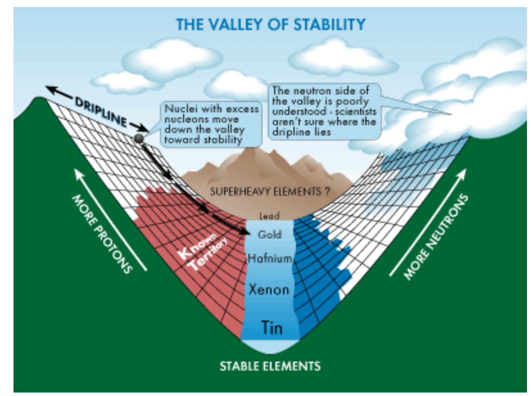
# Gamma-Rays: The Key to Unlocking the Mysteries of the Atomic Nucleus

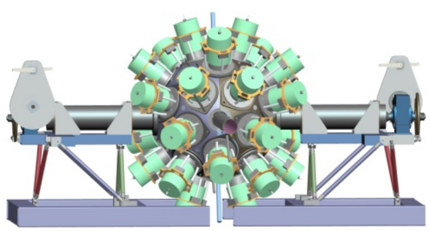





## Mark Riley (Florida State University)



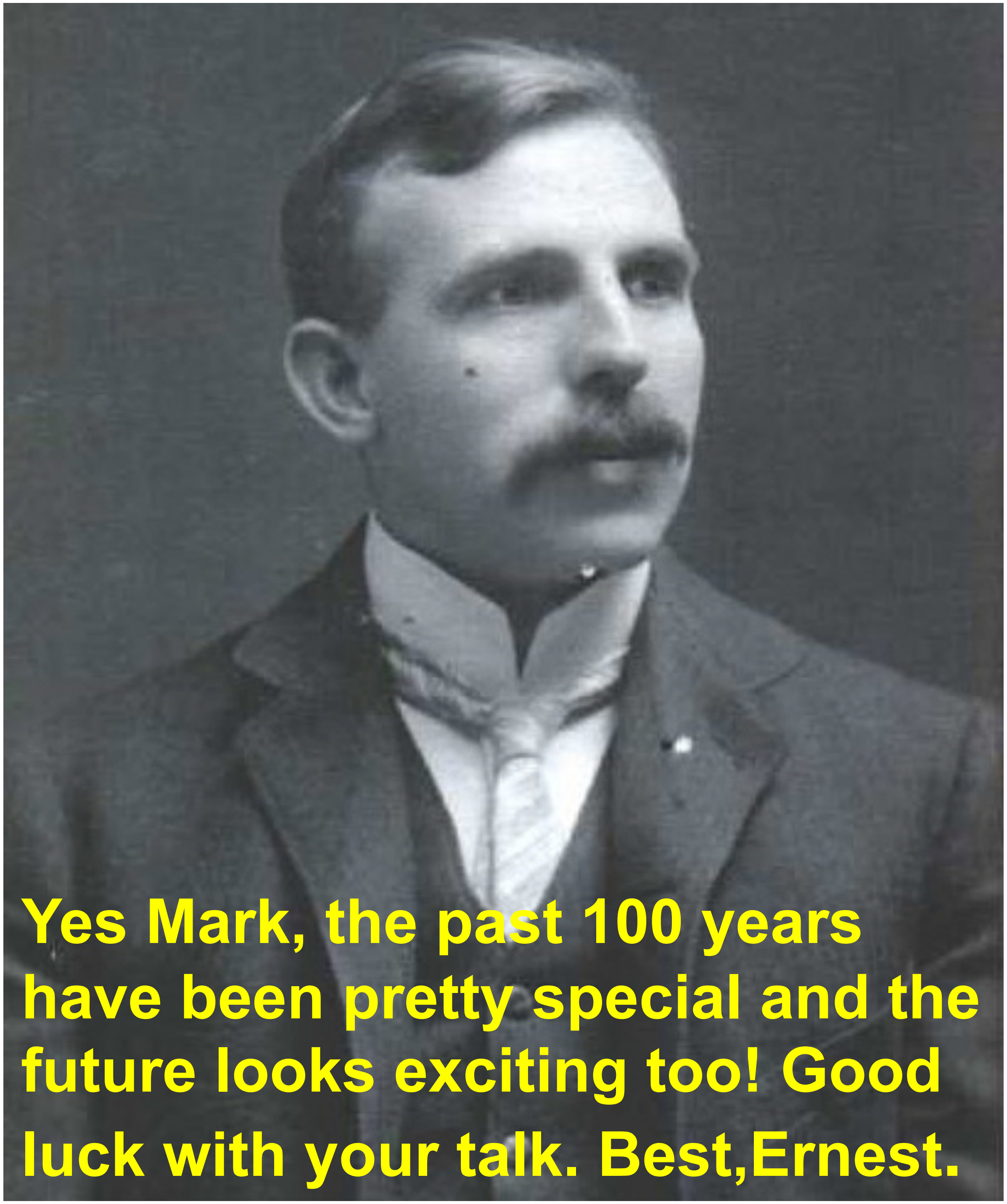
# Understanding our Universe?

What pieces of the puzzle are we missing?

These are very exciting times indeed!

**The Scattering of α and β Particles by Matter and the Structure of the Atom**
E. Rutherford, F.R.S.*
*Philosophical Magazine*
Series 6, vol. 21
May 1911, p. 669-688

"It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter…. the atom must be a seat of an intense electric field.."




# Rutherford's Lab in Manchester ~1910

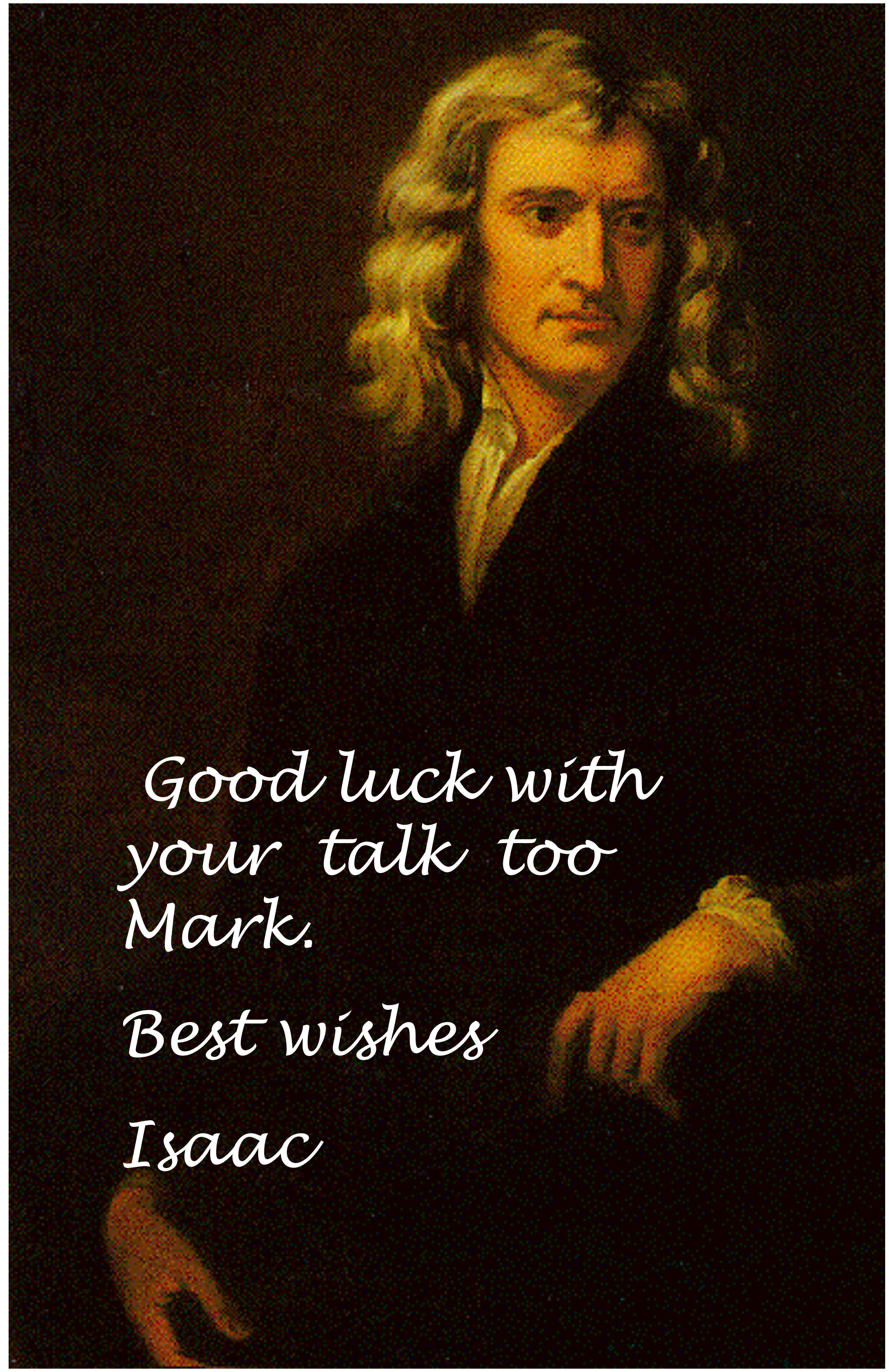

# Rutherford’s Lab in Manchester ~1911

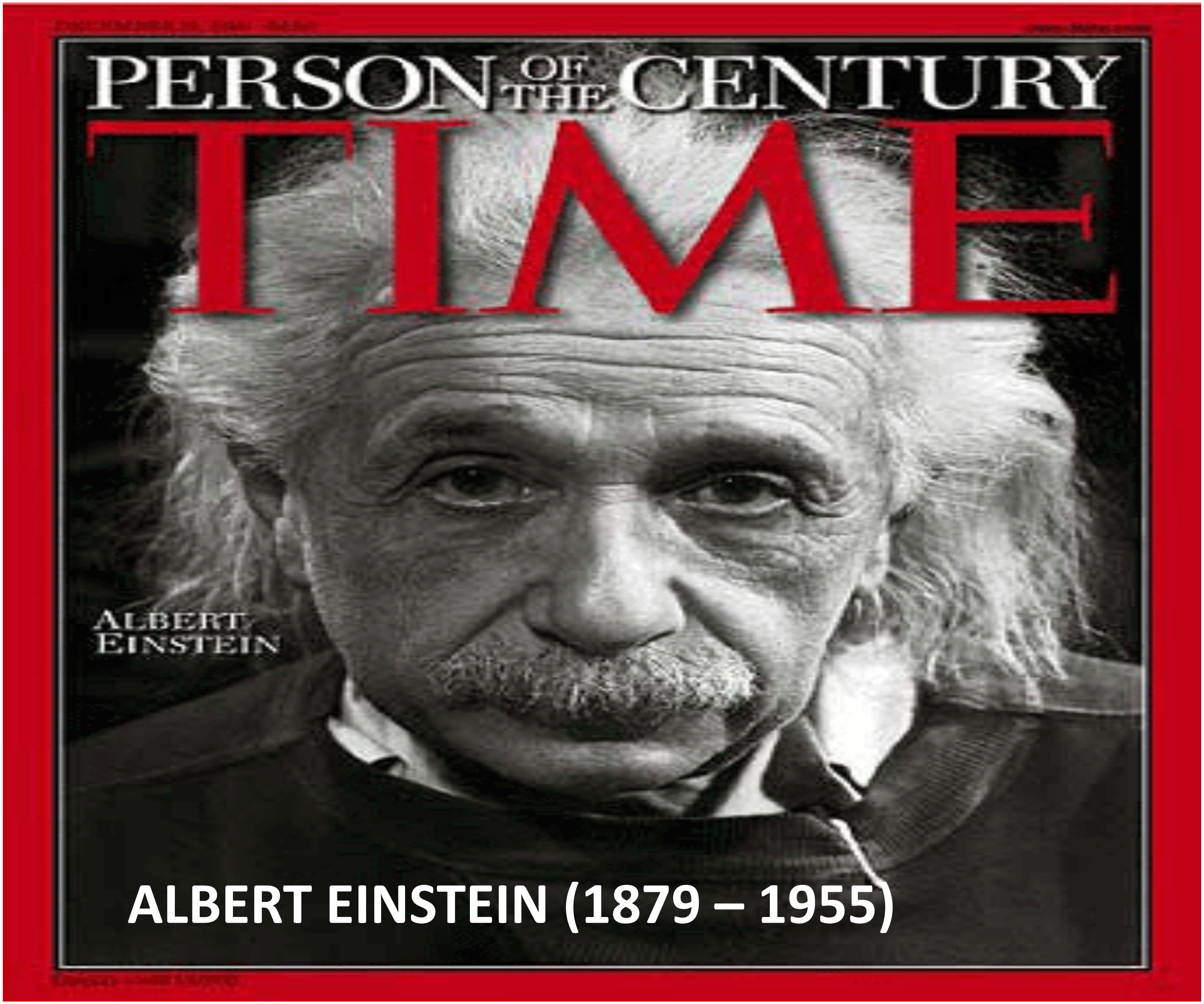

# Niels Bohr at Manchester

**“While at Manchester University, Bohr adapted Rutherford's nuclear structure to Max Planck's quantum theory and so obtained a model of atomic structure (1913).”**

# Heroes

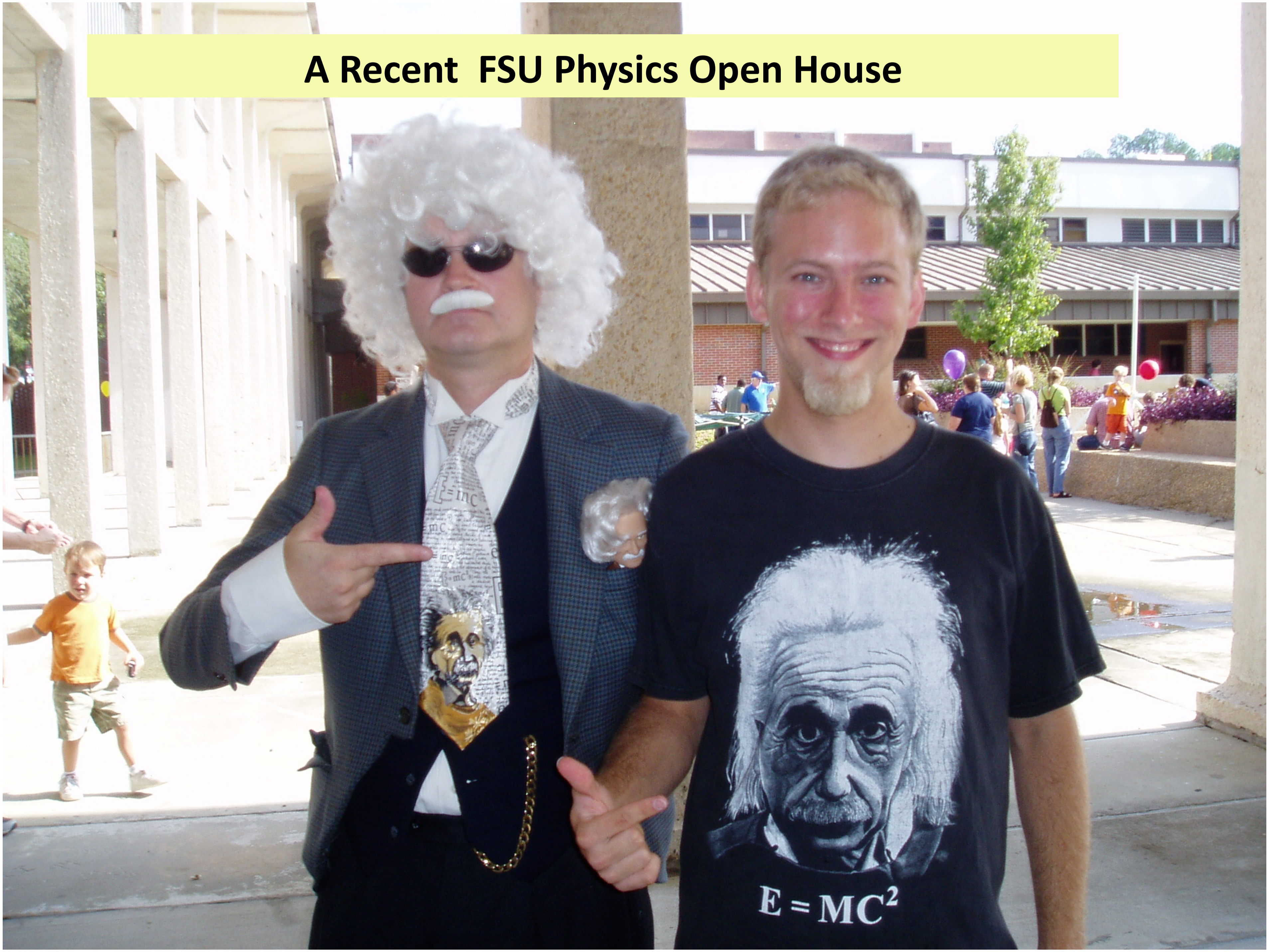
Isaac Newton
(1642 – 1727)






ALBERT EINSTEIN (1879 – 1955)

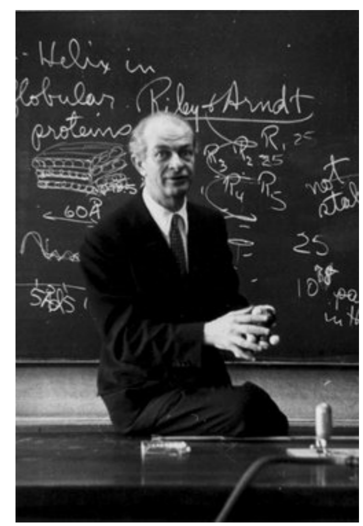
# A Recent FSU Physics Open House



Einstein in his 20's …. YOUR AGE!
When he did all his best work!
And had his best haircut.

# Linus Pauling:
# Two Times Nobel Prize Winner
# (Chemistry and Peace)

- **The world progresses, year by year, century by century, as the members of the younger generation find out what was wrong among the things their elders said. So you must always remain skeptical – always think for yourself.**

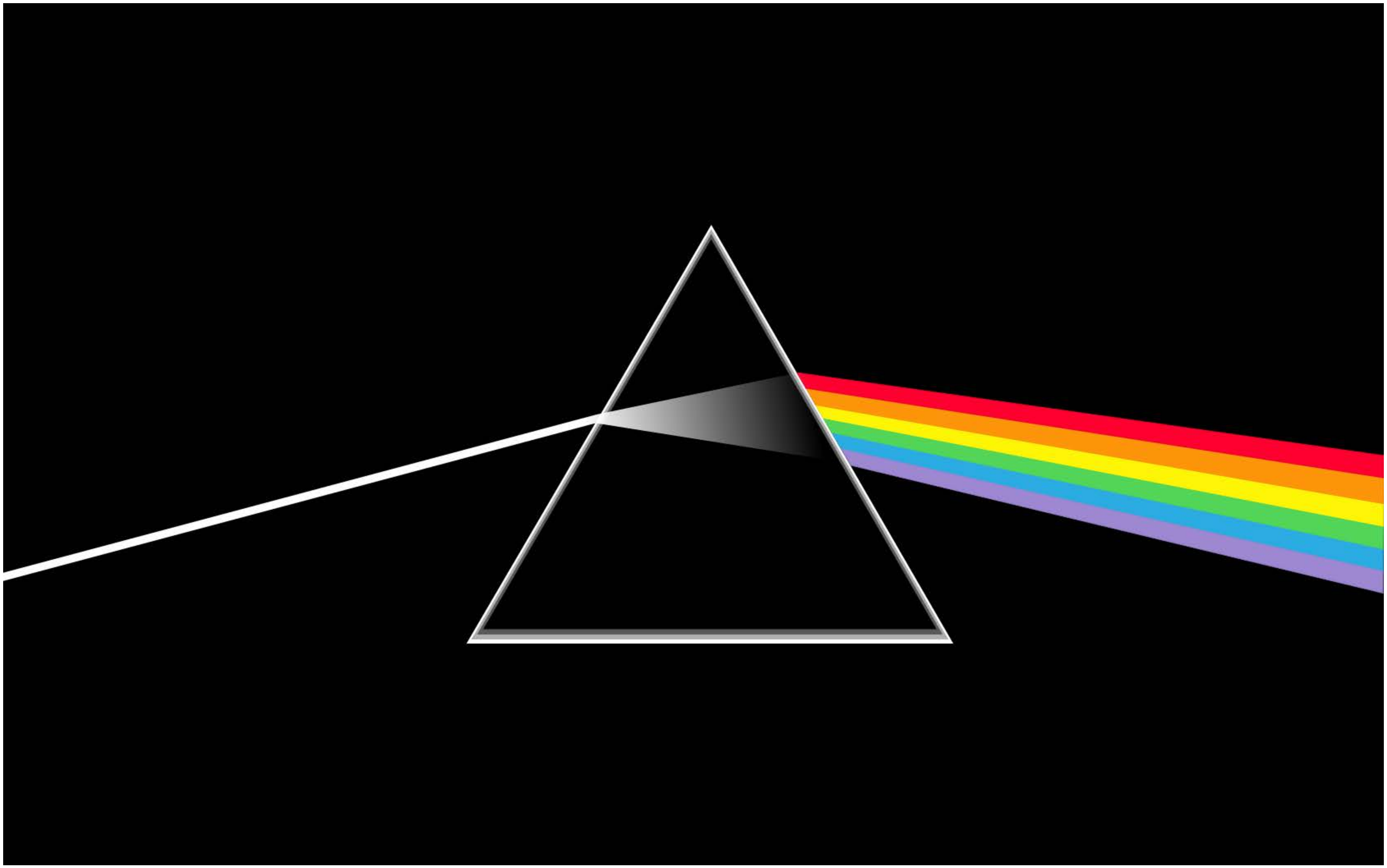


**And now for something completely different …….**

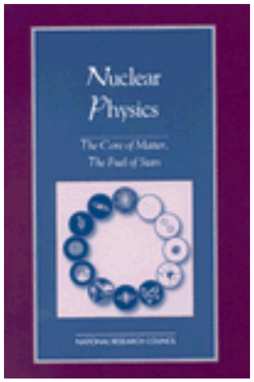
**My third hero at college**

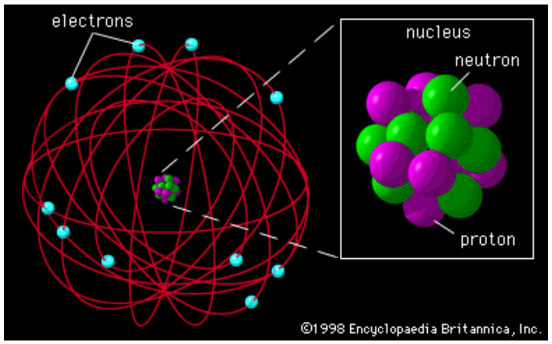
# Monty Python!

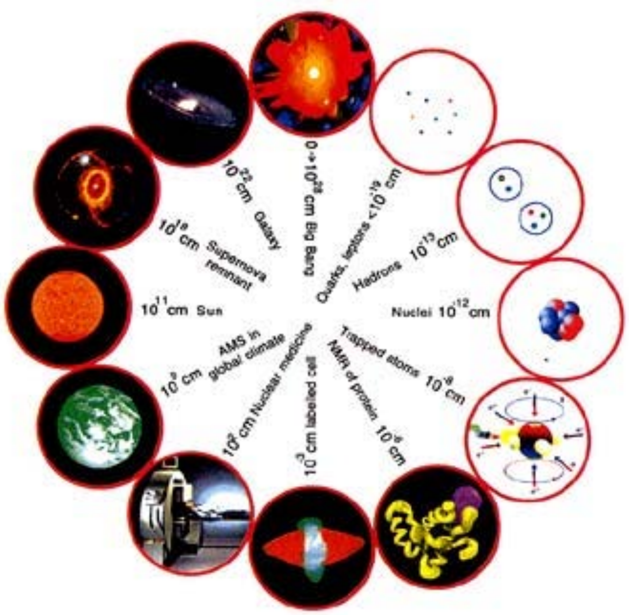
# Music heroes too!

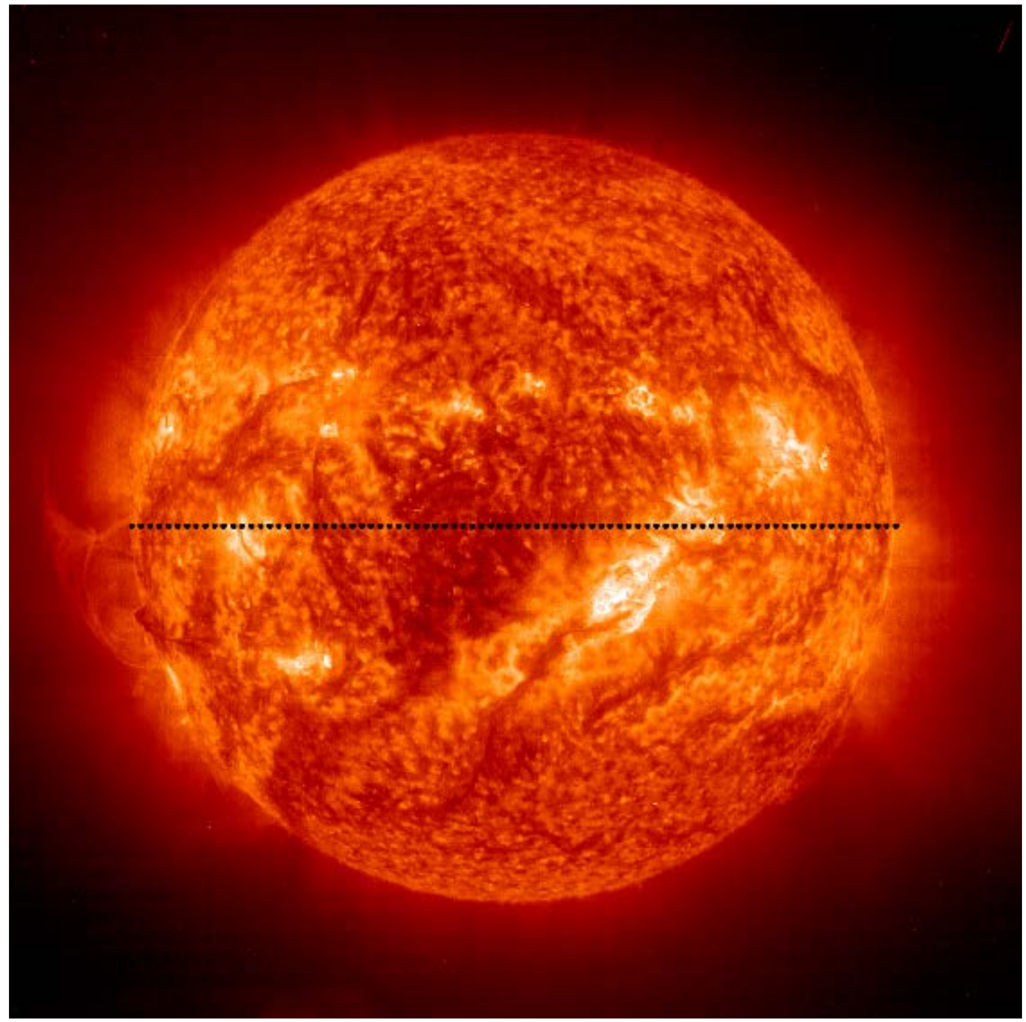


# Nuclear Physics: The Core of Matter, The Fuel of Stars. (NRC "Schiffer" Report)



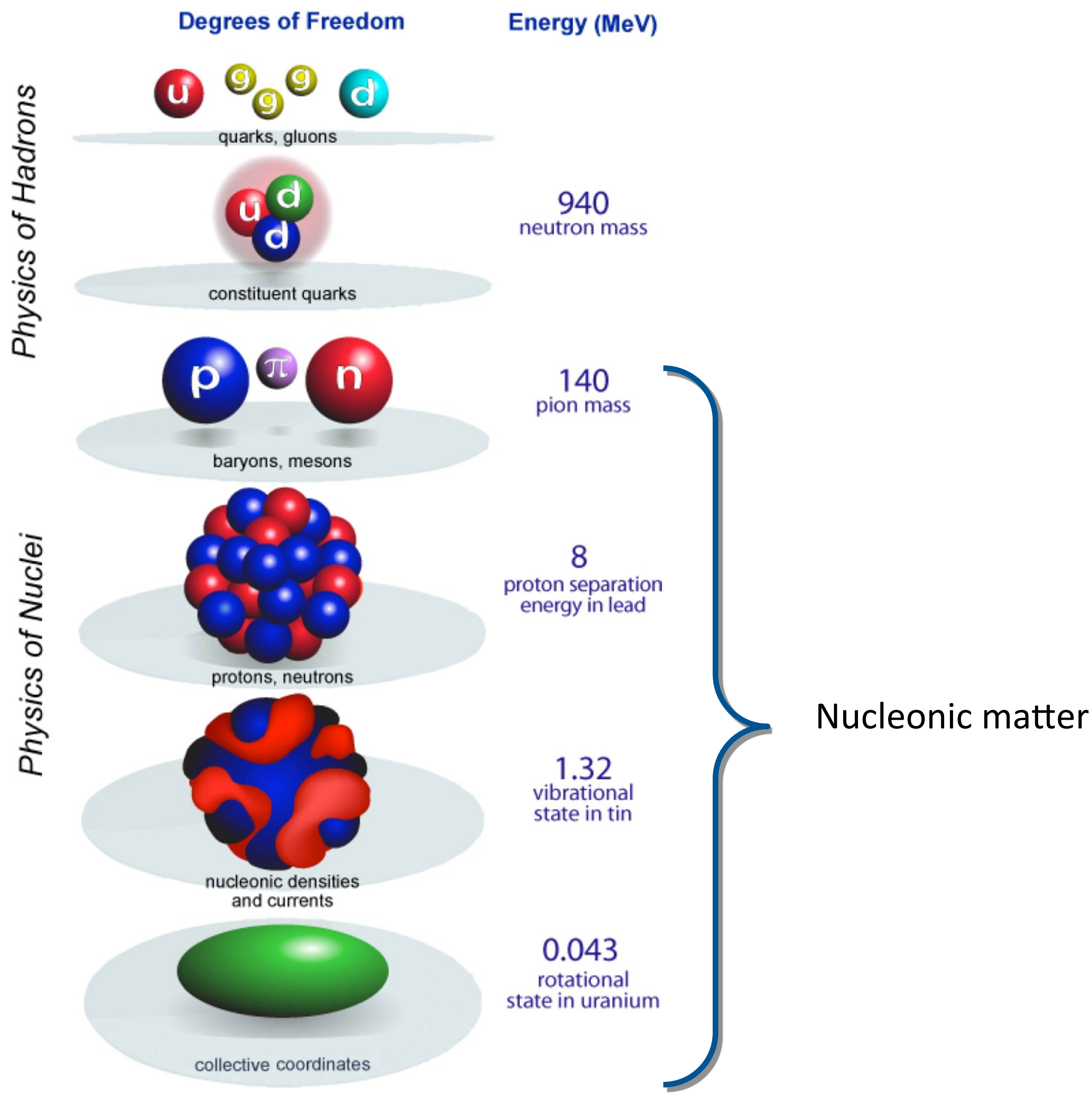




# Nuclear Physics: Exploring the Heart of Matter
## June 2012

- Nuclear physics today is a diverse field, encompassing research that spans dimensions from a tiny fraction of the volume of neutrons and protons to the enormous scales of astrophysical objects in the cosmos. As described in this decadal survey from the National Research Council (NRC) of the National Academies, **nuclear science is a thriving enterprise; its accomplishments and major discoveries since the last decadal survey are causing a revision of our view of the cosmos, its beginnings, and the structure of matter within it**. Further, the report describes how its **techniques and instruments are being used to address major societal issues in a number of areas, including medicine, national security, energy technology, and climate research**. The survey concludes by presenting a global context for the field and proposing a framework **for progress though 2020 and beyond**.

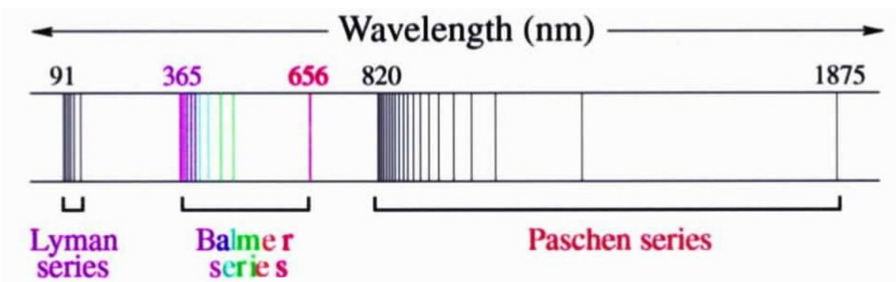
http://www.nap.edu/catalog.php?record_id=13438


Degrees of Freedom
Energy (MeV)
Physics of Hadrons
quarks, gluons
constituent quarks
940
neutron mass
baryons, mesons
140
pion mass
Physics of Nuclei
protons, neutrons
8
proton separation
energy in lead
nucleonic densities
and currents
1.32
vibrational
state in tin
collective coordinates
0.043
rotational
state in uranium
Nucleonic matter

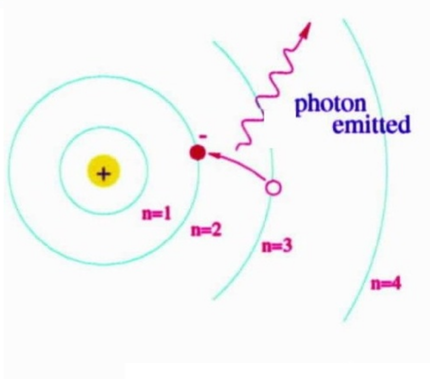
•In 1937 Bohr and Kalckar proposed that we could learn about the structure of nuclei by detecting their gamma-ray emissions.

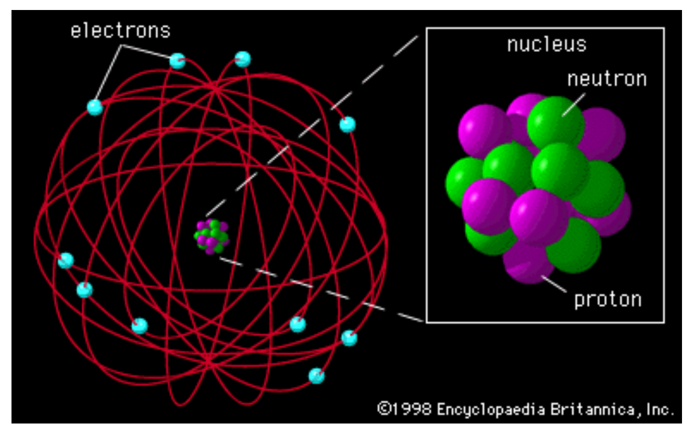
•The picture of the atomic nucleus that has emerged since this pioneering suggestion is extremely rich, displaying a wealth of static and dynamical facets. It continues to amaze and fascinate!

•The number of nucleons is sufficient in this strongly interacting multi-fermion system (<300) to allow correlations but yet finite.

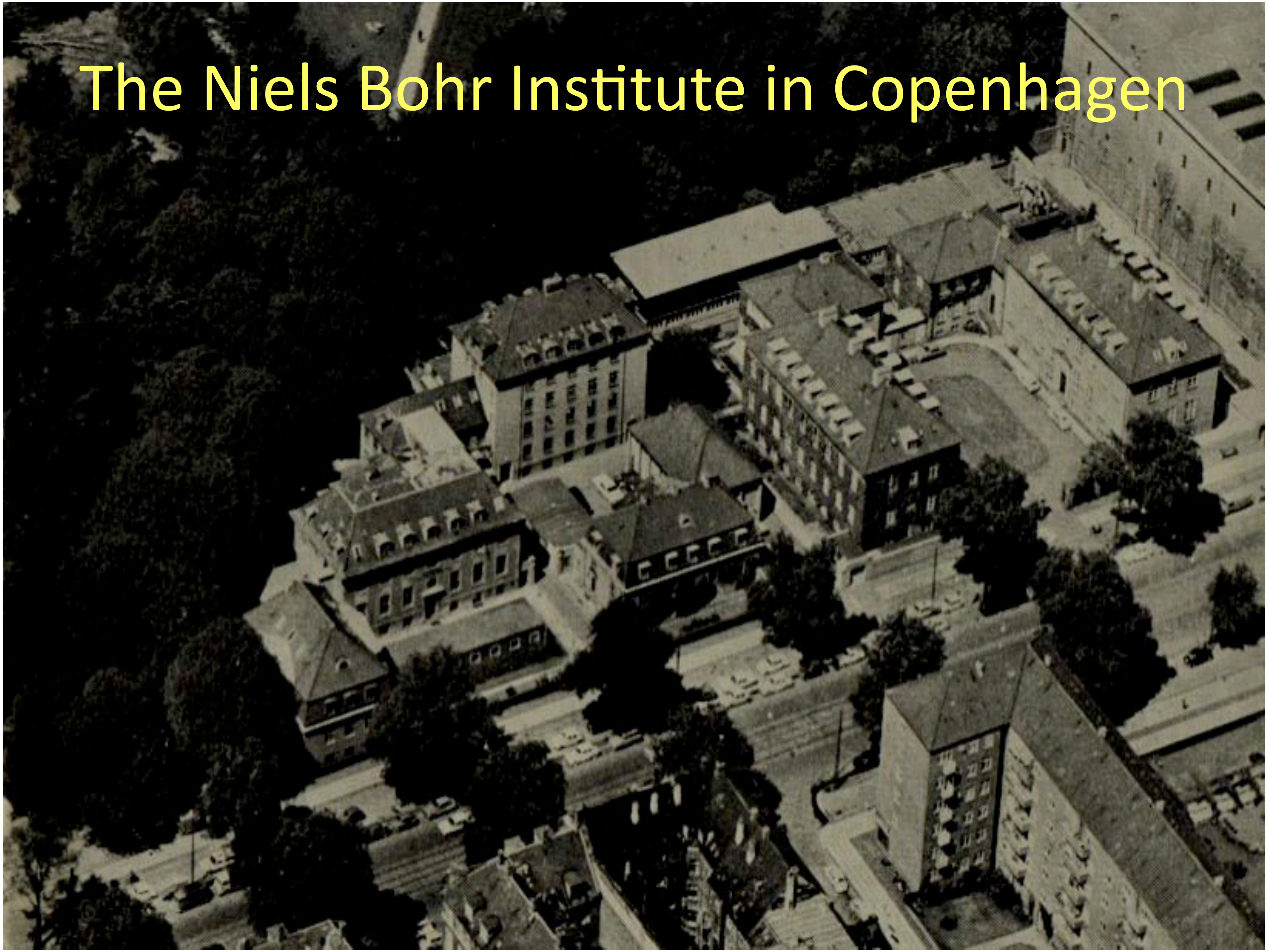



Bohr Atom



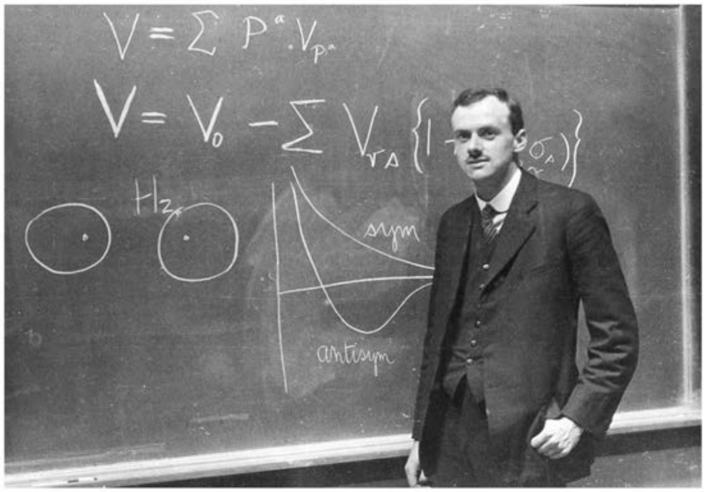



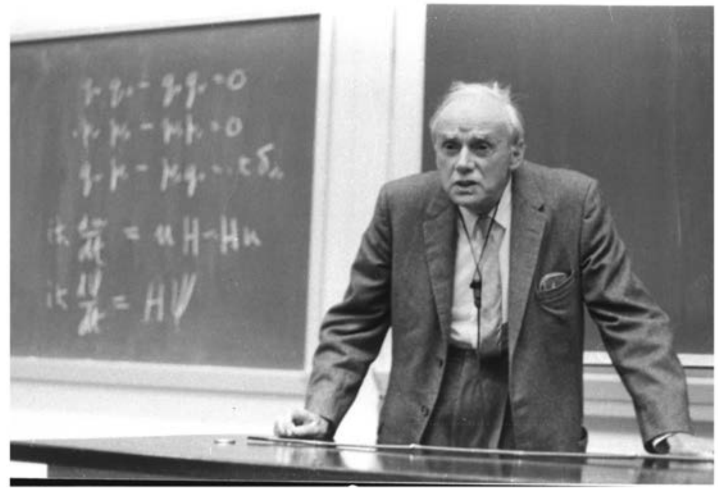
# The Niels Bohr Institute in Copenhagen

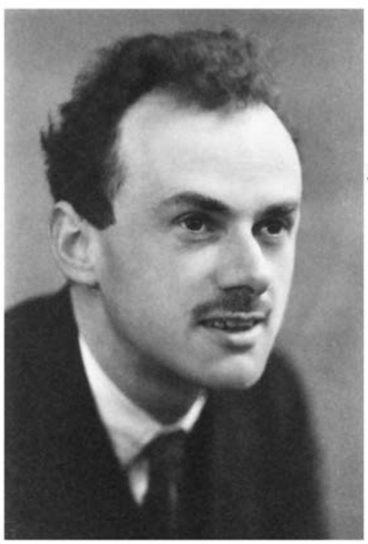


# The Niels Bohr Institute in Copenhagen

# Paul Dirac at Cambridge and FSU



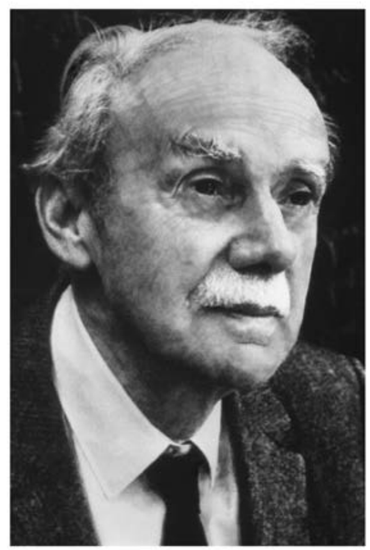




*Paul Adrien Maurice Dirac*

*(August 8, 1902 – October 20, 1984)*

*Paul Dirac was a British theoretical physicist. Dirac made fundamental contributions to the early development of both quantum mechanics and quantum electrodynamics. He held the Lucasian Chair of Mathematics at the University of Cambridge.*



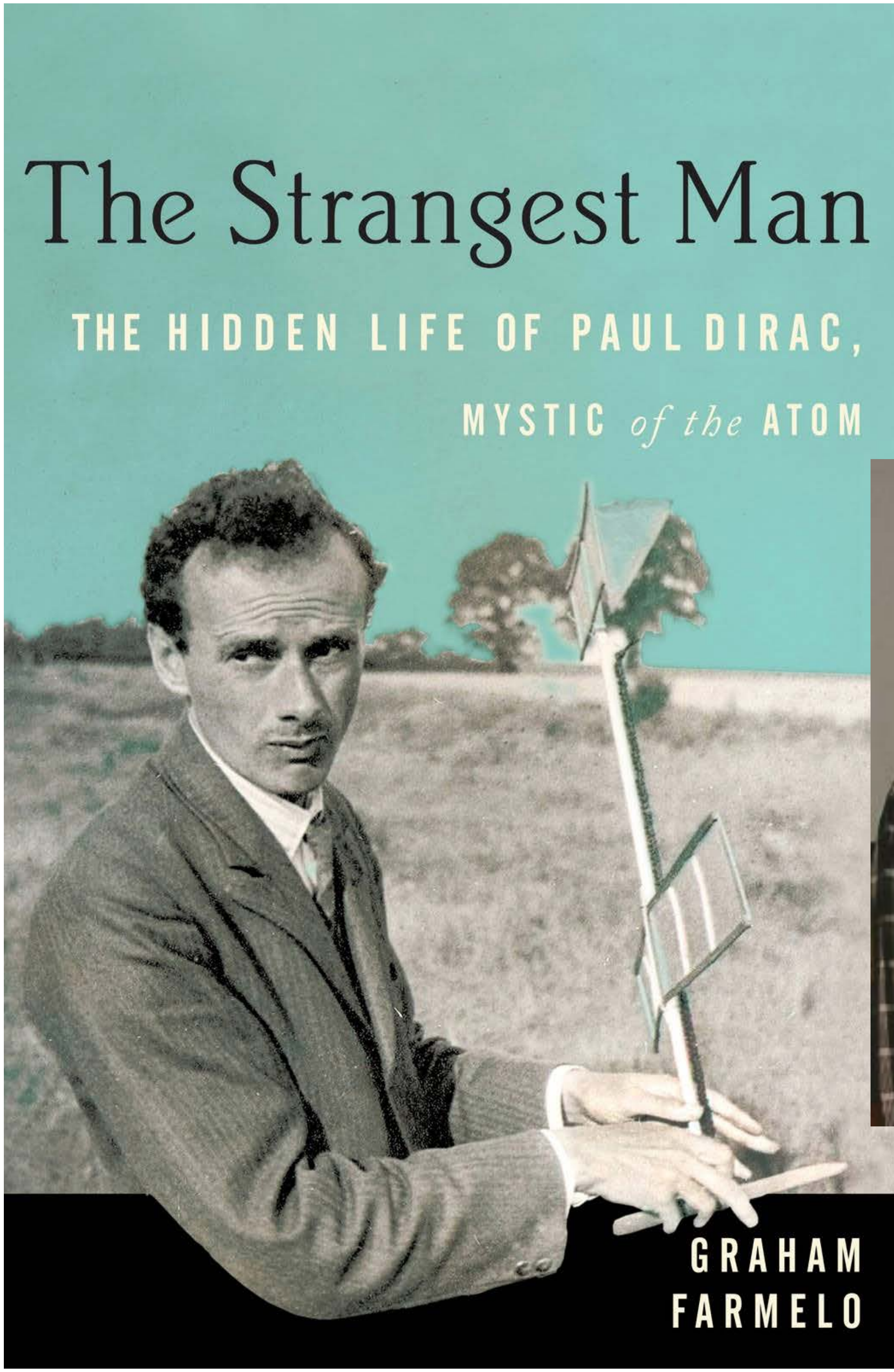
*Paul Adrien Maurice Dirac*

*(August 8, 1902 – October 20, 1984)*

*Among other discoveries, he formulated the Dirac equation, which describes the behavior of fermions and which led to the prediction of the existence of antimatter.*

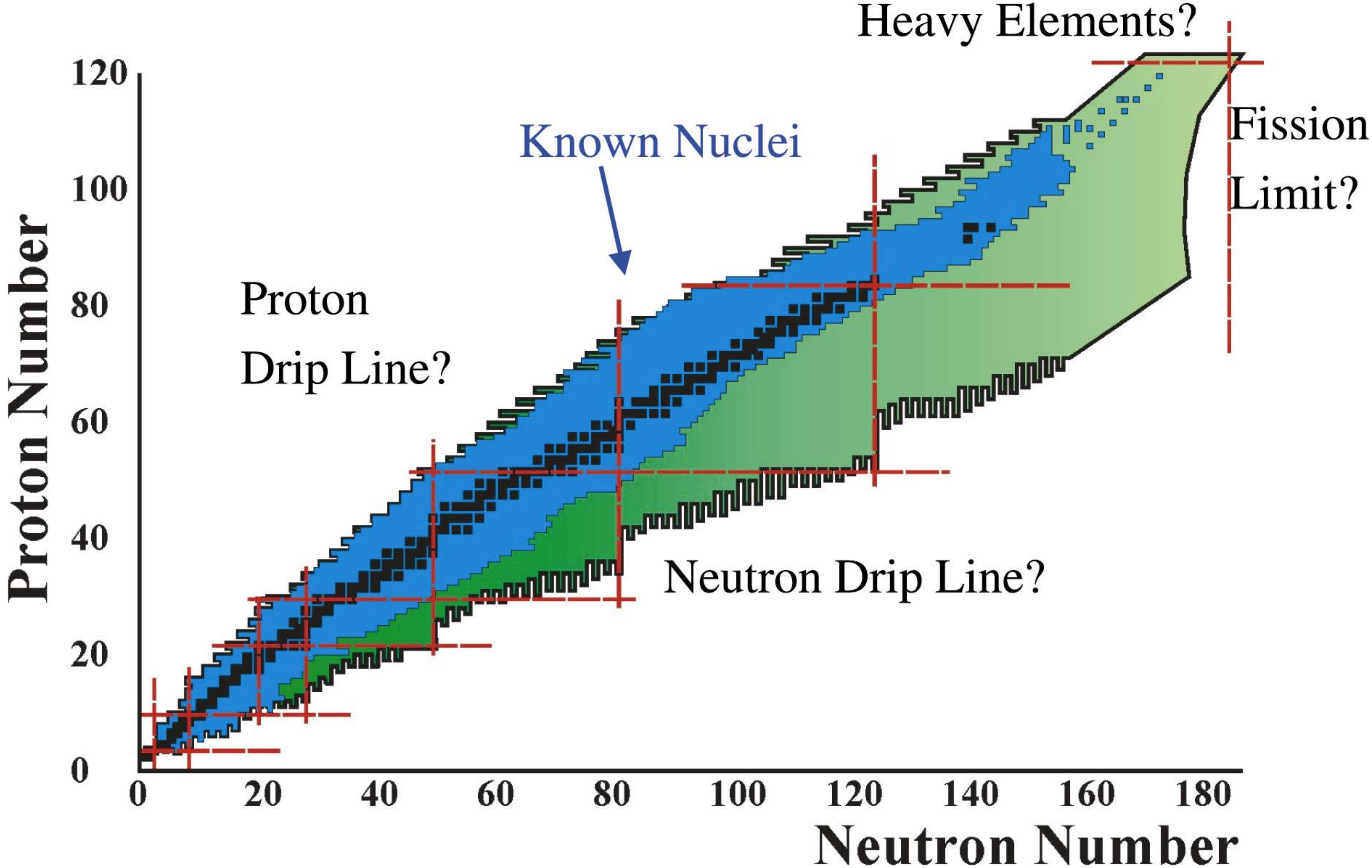
*Dirac shared the Nobel Prize in physics for 1933 with Erwin Schrödinger, "for the discovery of new productive forms of atomic theory."*

*Paul Dirac spent the last fourteen years of his life at Florida State University.*

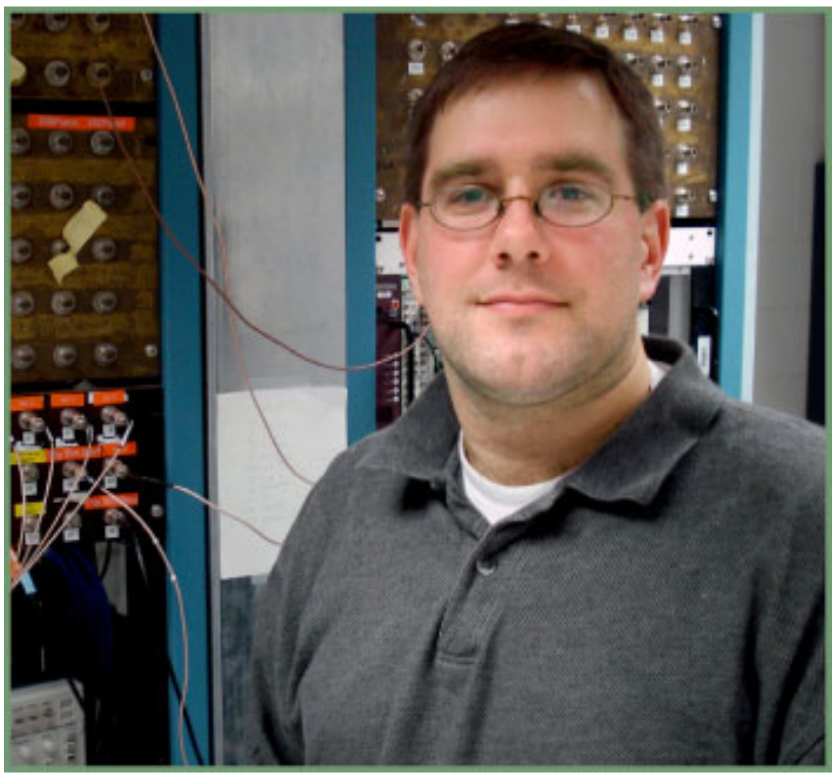


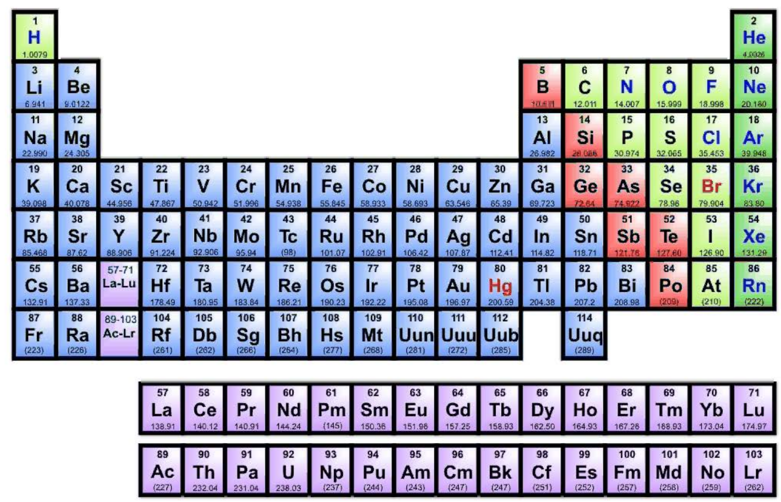

Bob Schrieffer and
yours truly plus
“The Backbender”!
… more of this later

# The Chart of the Nuclides



# Periodic Table to Nuclear Chart in 1 min
# Sean Liddick (MSU)



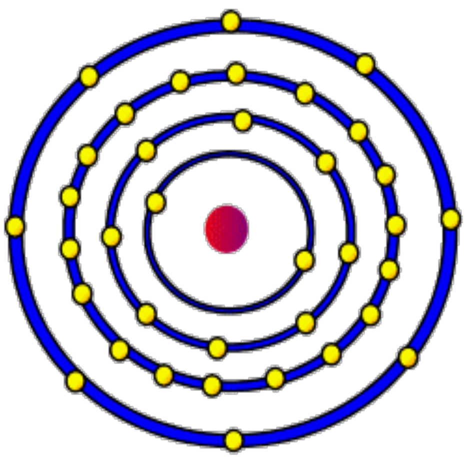


| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H 1.0079 | | | | | | | | | | | | | | | | | 2 He 4.0026 |
| 3 Li 6.941 | 4 Be 9.0122 | | | | | | | | | | | 5 B [illegible] | 6 C 12.011 | 7 N 14.007 | 8 O 15.999 | 9 F 18.998 | 10 Ne 20.180 |
| 11 Na 22.990 | 12 Mg 24.305 | | | | | | | | | | | 13 Al 26.982 | 14 Si 28.086 | 15 P 30.974 | 16 S 32.065 | 17 Cl 35.453 | 18 Ar 39.948 |
| 19 K 39.098 | 20 Ca 40.078 | 21 Sc 44.956 | 22 Ti 47.867 | 23 V 50.942 | 24 Cr 51.996 | 25 Mn 54.938 | 26 Fe 55.845 | 27 Co 58.933 | 28 Ni 58.693 | 29 Cu 63.546 | 30 Zn 65.39 | 31 Ga 69.723 | 32 Ge 72.64 | 33 As 74.922 | 34 Se 78.96 | 35 Br 79.904 | 36 Kr 83.80 |
| 37 Rb 85.468 | 38 Sr 87.62 | 39 Y 88.906 | 40 Zr 91.224 | 41 Nb 92.906 | 42 Mo 95.94 | 43 Tc (98) | 44 Ru 101.07 | 45 Rh 102.91 | 46 Pd 106.42 | 47 Ag 107.87 | 48 Cd 112.41 | 49 In 114.82 | 50 Sn 118.71 | 51 Sb 121.76 | 52 Te 127.60 | 53 I 126.90 | 54 Xe 131.29 |
| 55 Cs 132.91 | 56 Ba 137.33 | 57-71 La-Lu | 72 Hf 178.49 | 73 Ta 180.95 | 74 W 183.84 | 75 Re 186.21 | 76 Os 190.23 | 77 Ir 192.22 | 78 Pt 195.08 | 79 Au 196.97 | 80 Hg 200.59 | 81 Tl 204.38 | 82 Pb 207.2 | 83 Bi 208.98 | 84 Po (209) | 85 At (210) | 86 Rn (222) |
| 87 Fr (223) | 88 Ra (226) | 89-103 Ac-Lr | 104 Rf (261) | 105 Db (262) | 106 Sg (266) | 107 Bh (264) | 108 Hs (277) | 109 Mt (268) | 110 Uun (281) | 111 Uuu (272) | 112 Uub (285) | | 114 Uuq (289) | | | | |

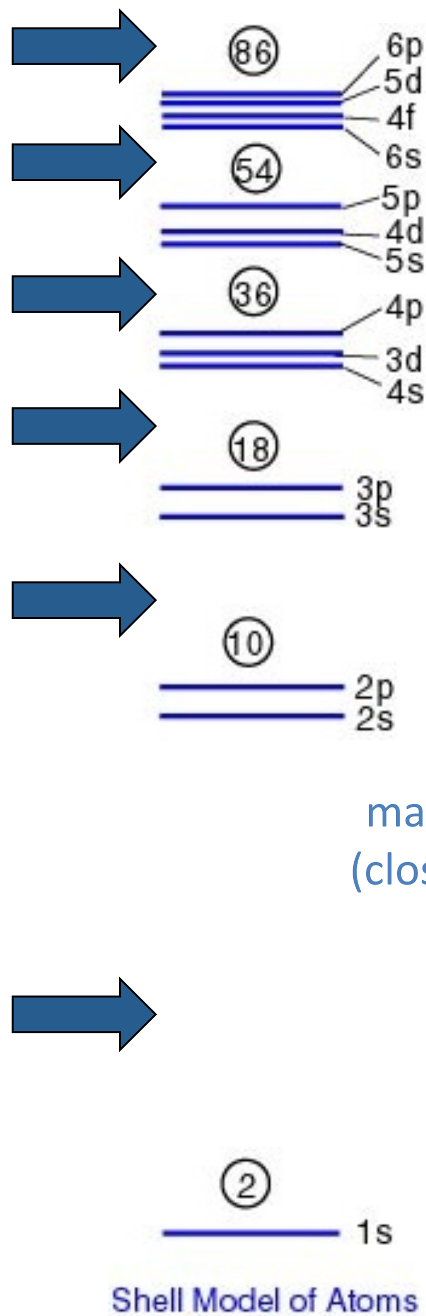
| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 57 La 138.91 | 58 Ce 140.12 | 59 Pr 140.91 | 60 Nd 144.24 | 61 Pm (145) | 62 Sm 150.36 | 63 Eu 151.96 | 64 Gd 157.25 | 65 Tb 158.93 | 66 Dy 162.50 | 67 Ho 164.93 | 68 Er 167.26 | 69 Tm 168.93 | 70 Yb 173.04 | 71 Lu 174.97 |
| 89 Ac (227) | 90 Th 232.04 | 91 Pa 231.04 | 92 U 238.03 | 93 Np (237) | 94 Pu (244) | 95 Am (243) | 96 Cm (247) | 97 Bk (247) | 98 Cf (251) | 99 Es (252) | 100 Fm (257) | 101 Md (258) | 102 No (259) | 103 Lr (262) |

Atom:
electron shells

noble gases
(closed shells)

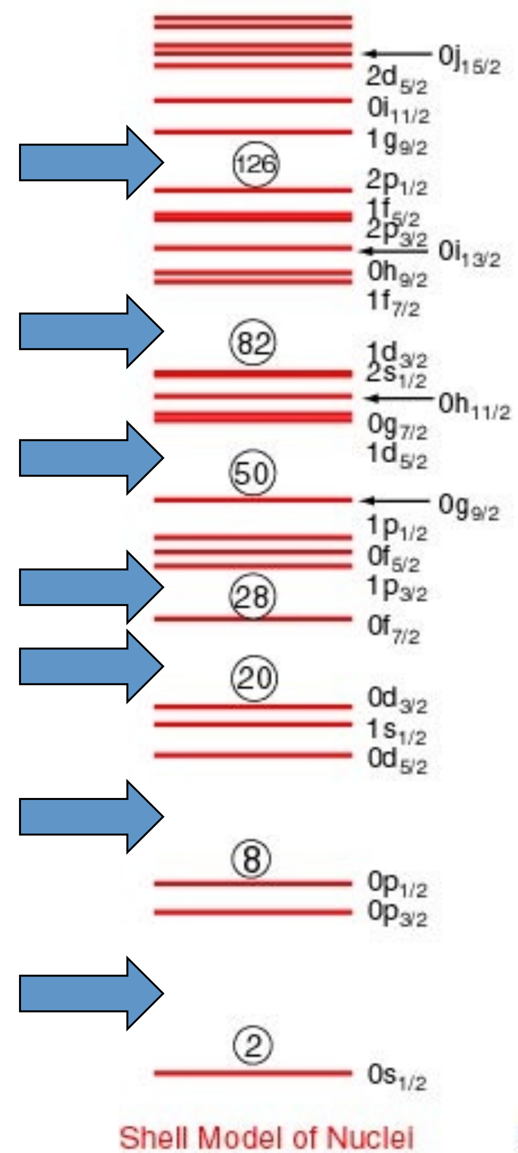


Krypton Atom




magic nuclei
(closed shells)

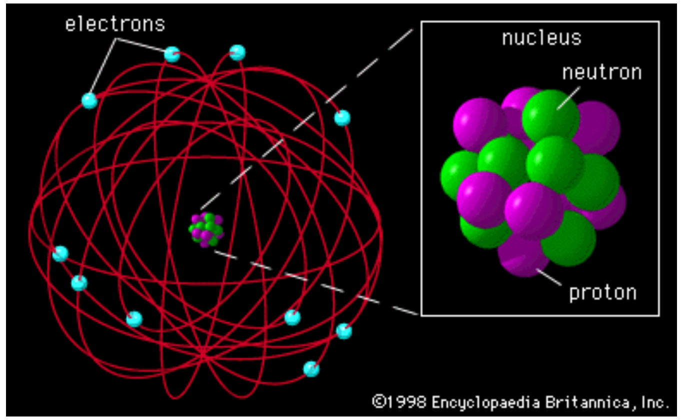
Nucleus:
proton/neutron shells



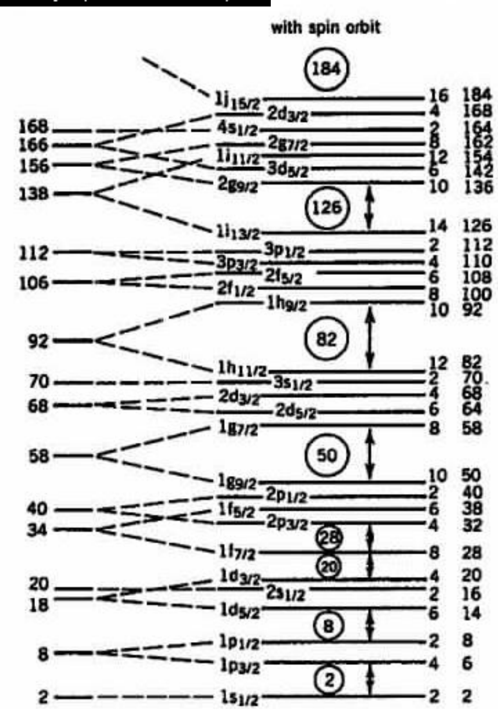
# Shell Structure

Atomic

Nuclear

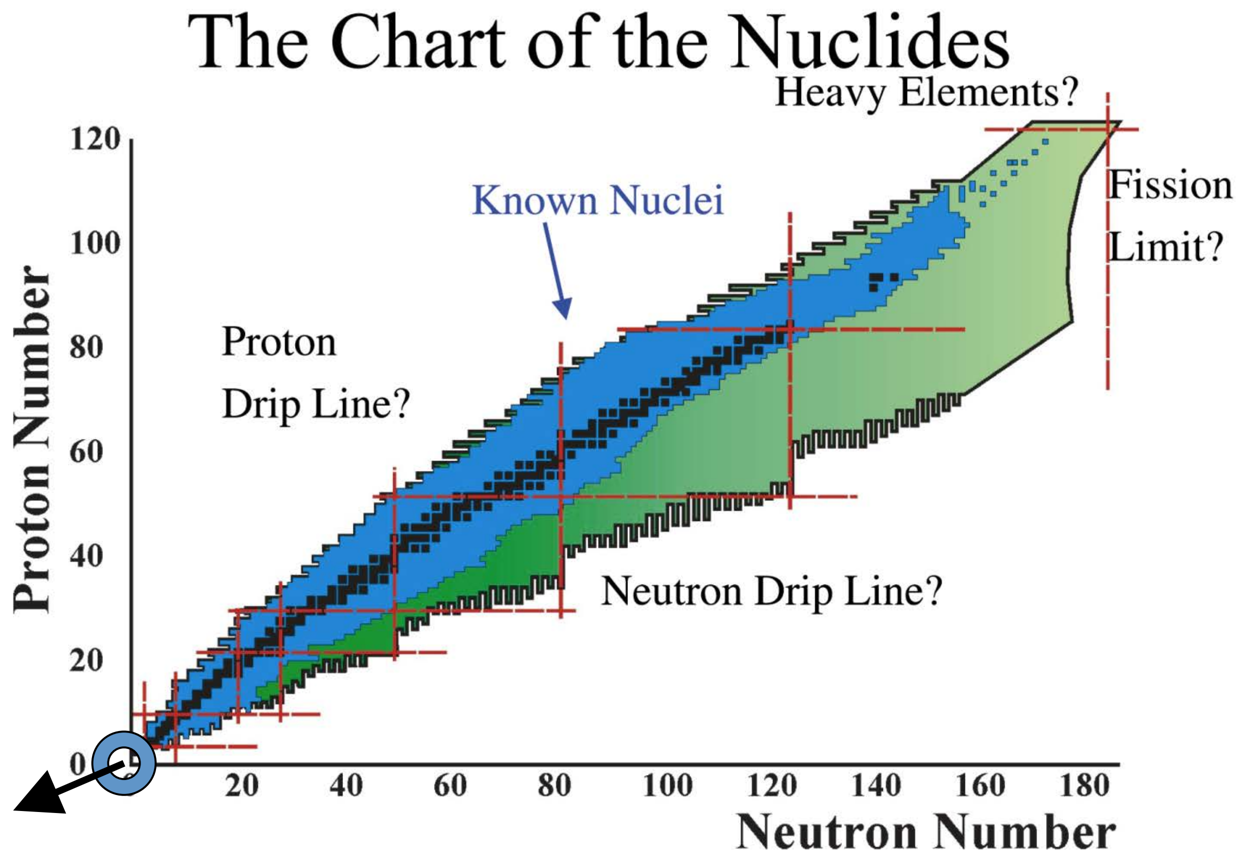



Nucleons



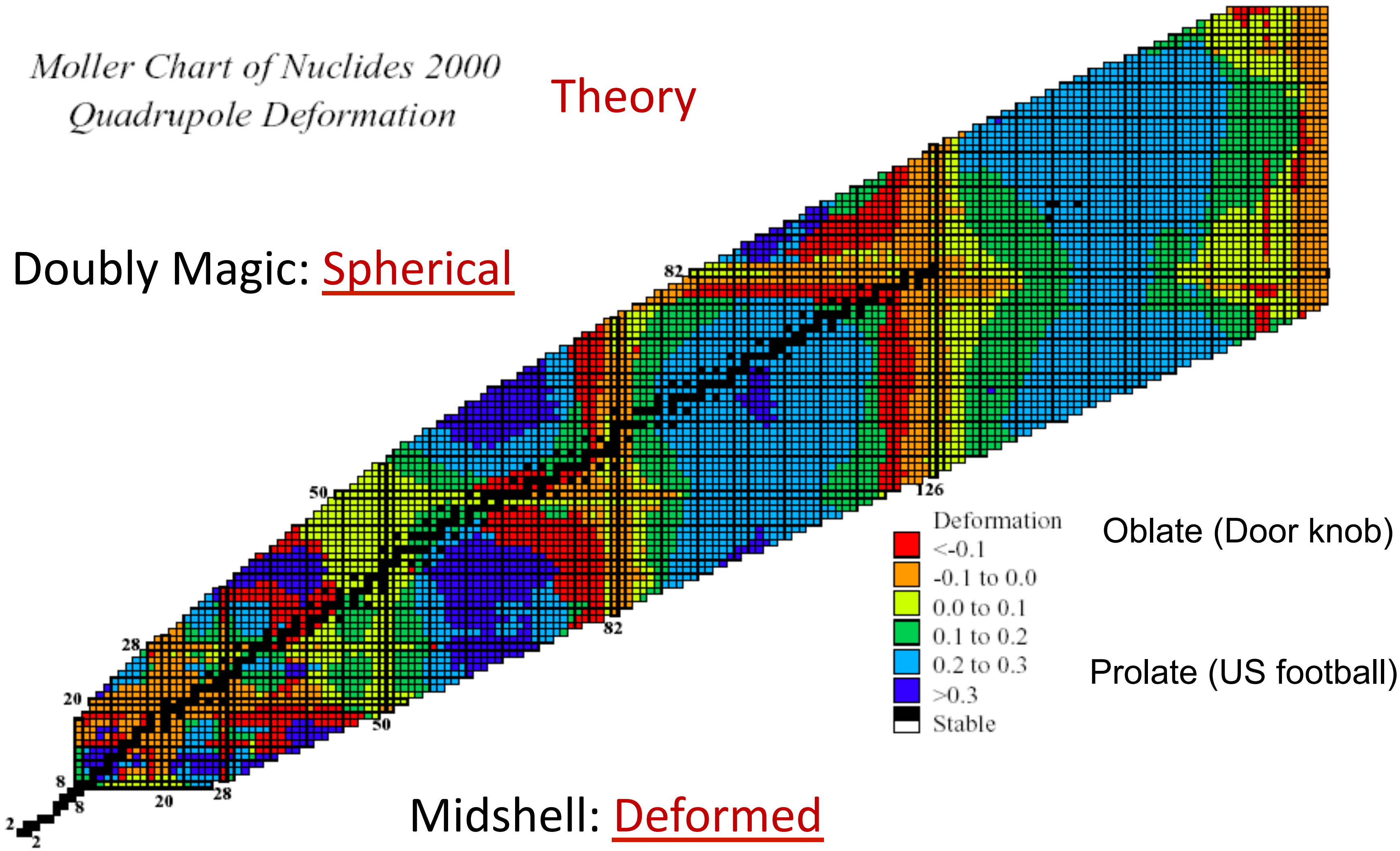

We still have a long way to go before we can say we understand the nucleus. It is a wild and mysterious place!

# We want to know where are the limits and what happens on the way?




**Increasing Angular Momentum and Excitation Energy:** **An excellent way to investigate nuclear structure, especially to see what the intruder orbitals are doing.**

# Deformation Systematics

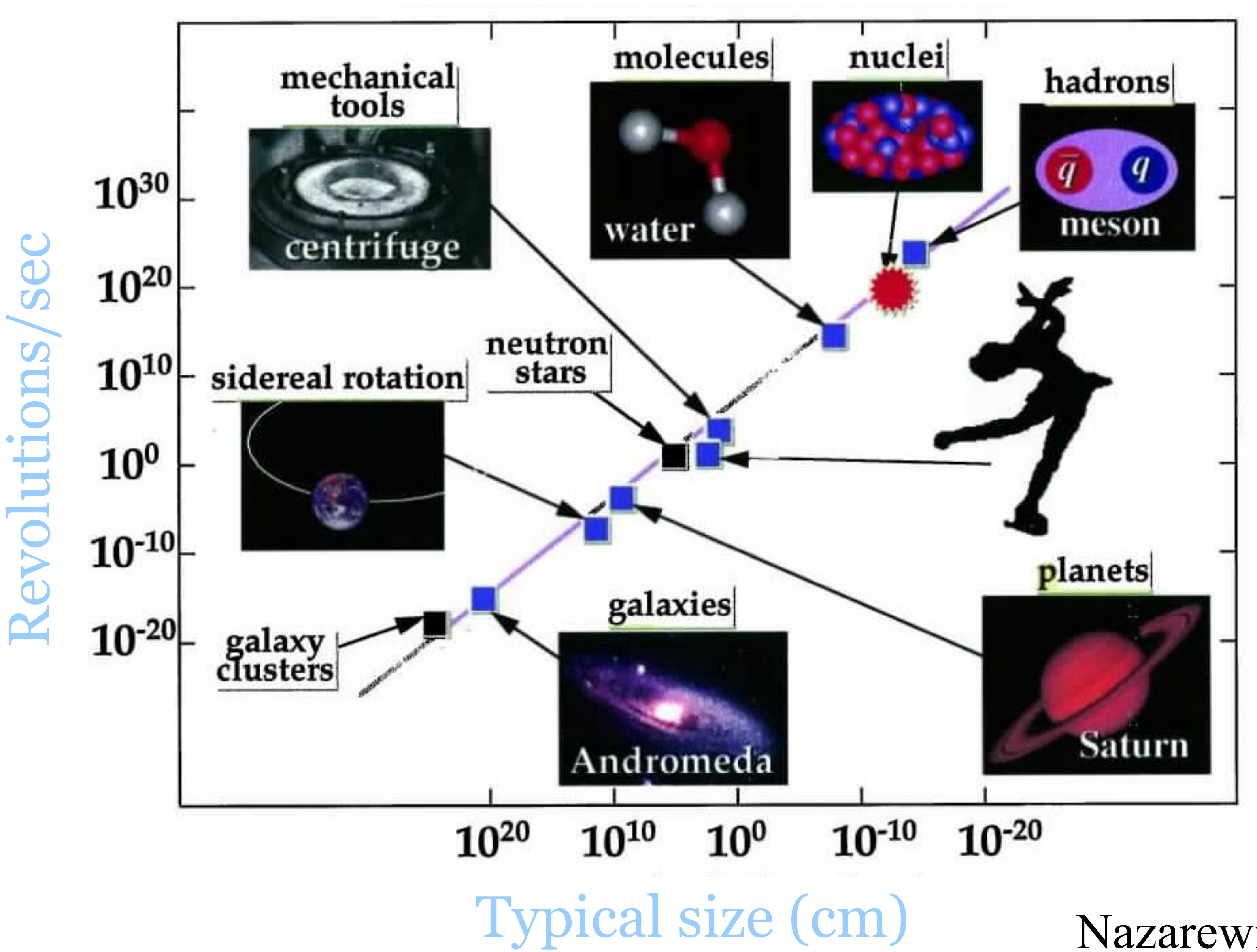


# Rotation can reveal information about the internal structure!

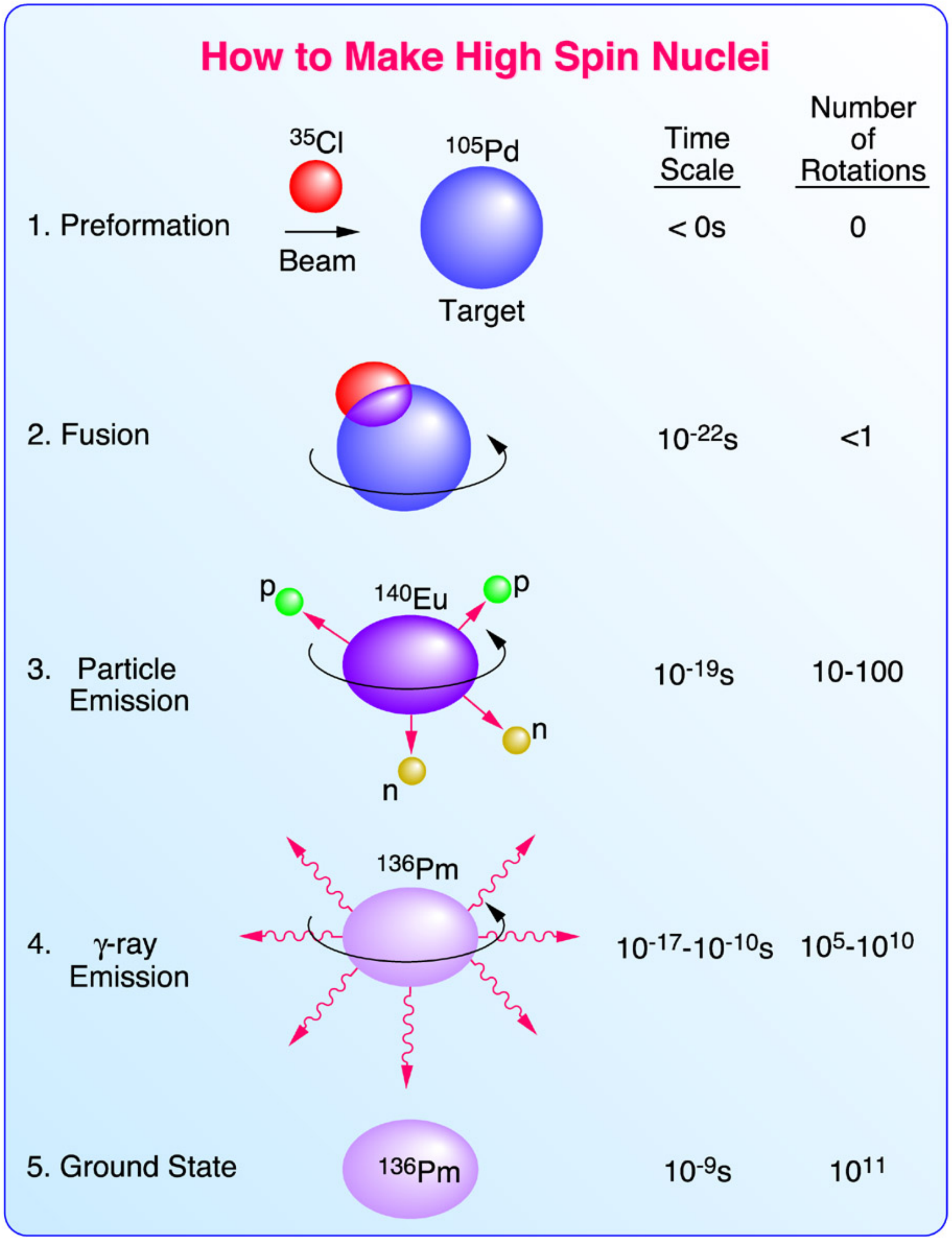
- Hard boiled and soft boiled egg experiment.

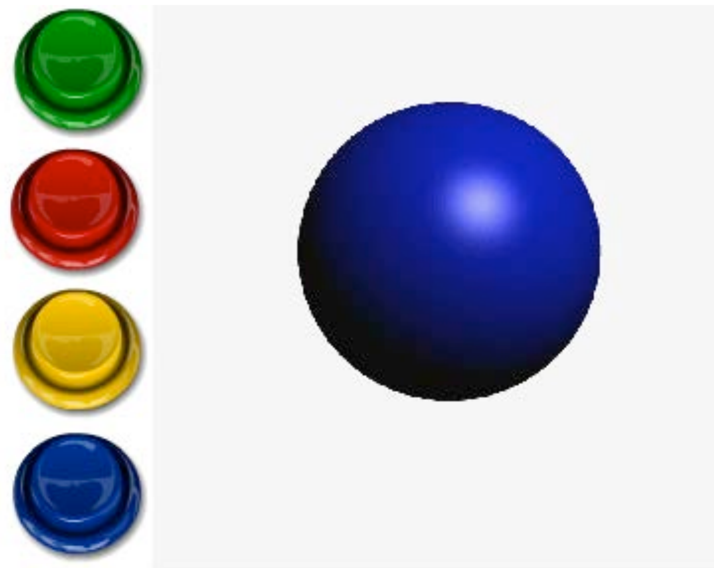
# Spinning things is fun!

# Rotations in the Universe




Nazarewicz



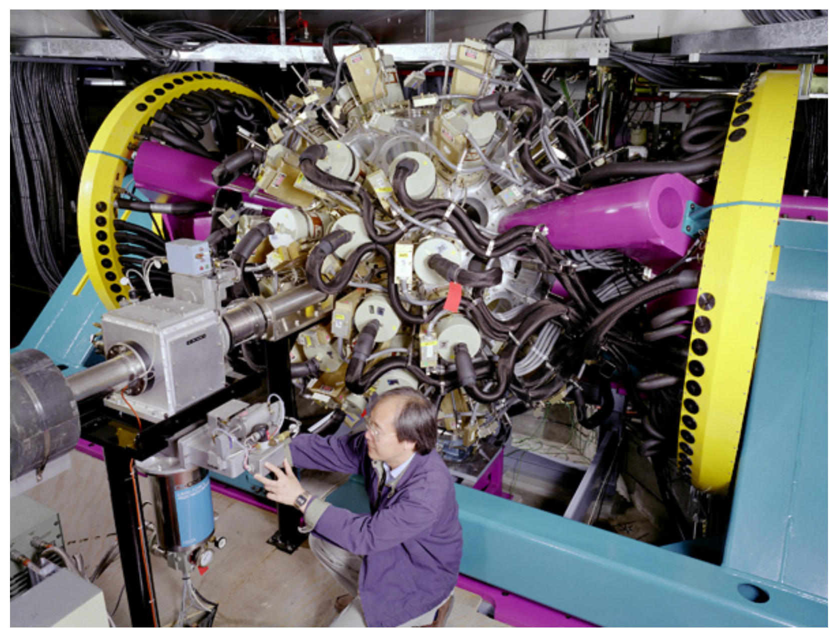



- Need to catch as many of the γ rays in each cascade as possible.

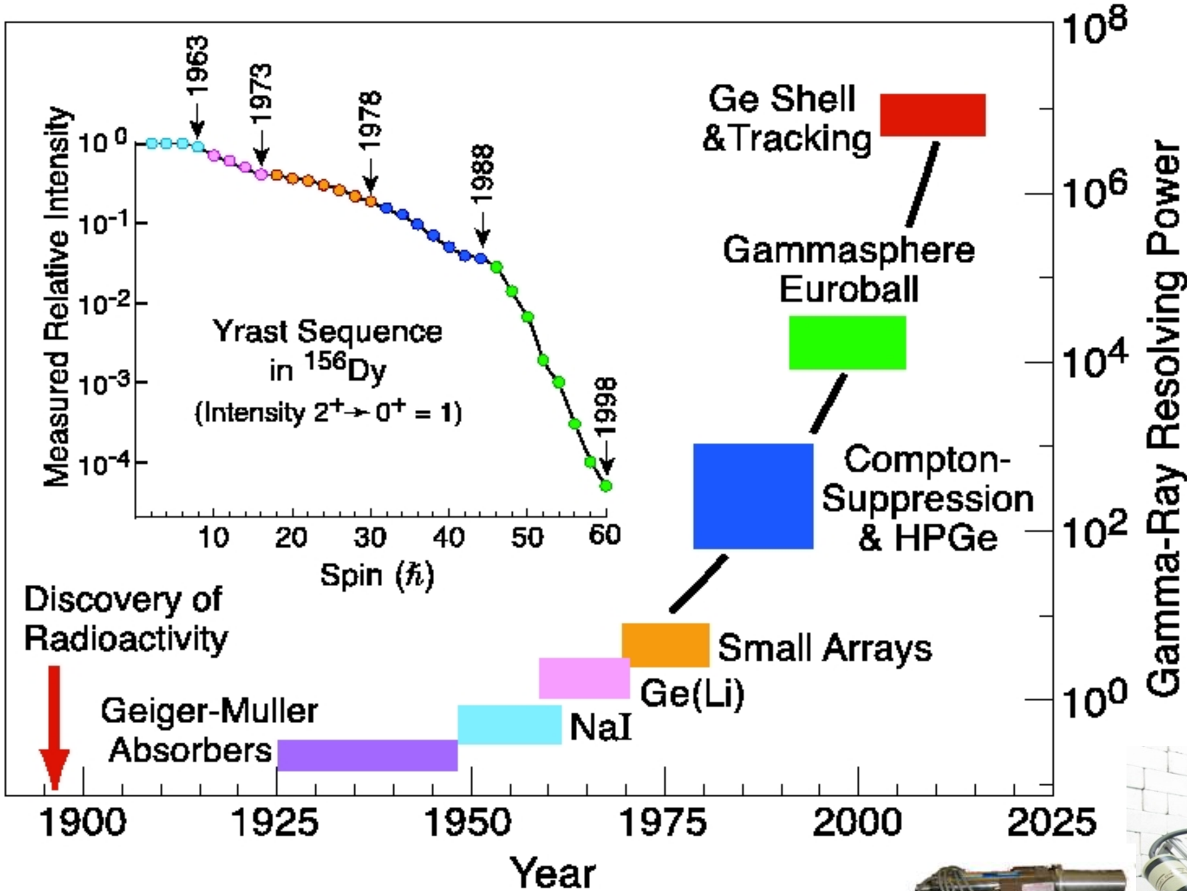
- Need efficient detector systems!

- In nuclear reactions, eg, fusion evaporation, when we create our hot, excited, rapidly rotating nuclei we need to catch as many of the $\gamma$ rays emitted in each cascade or flash as possible.

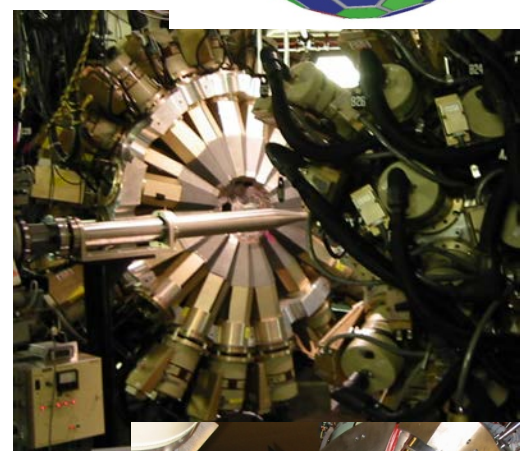
- Need efficient detector systems!

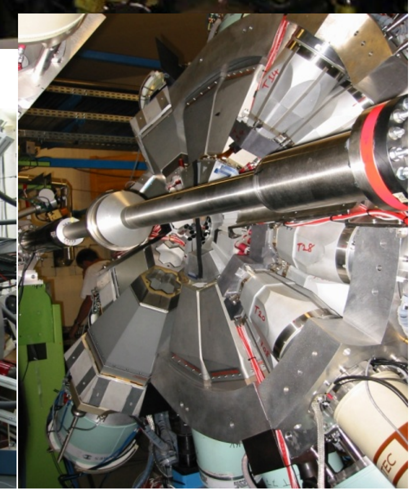


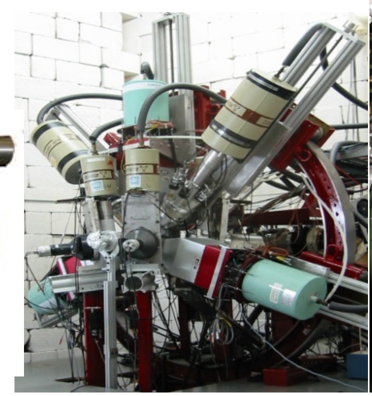
# Gamma-Ray Detection Evolution



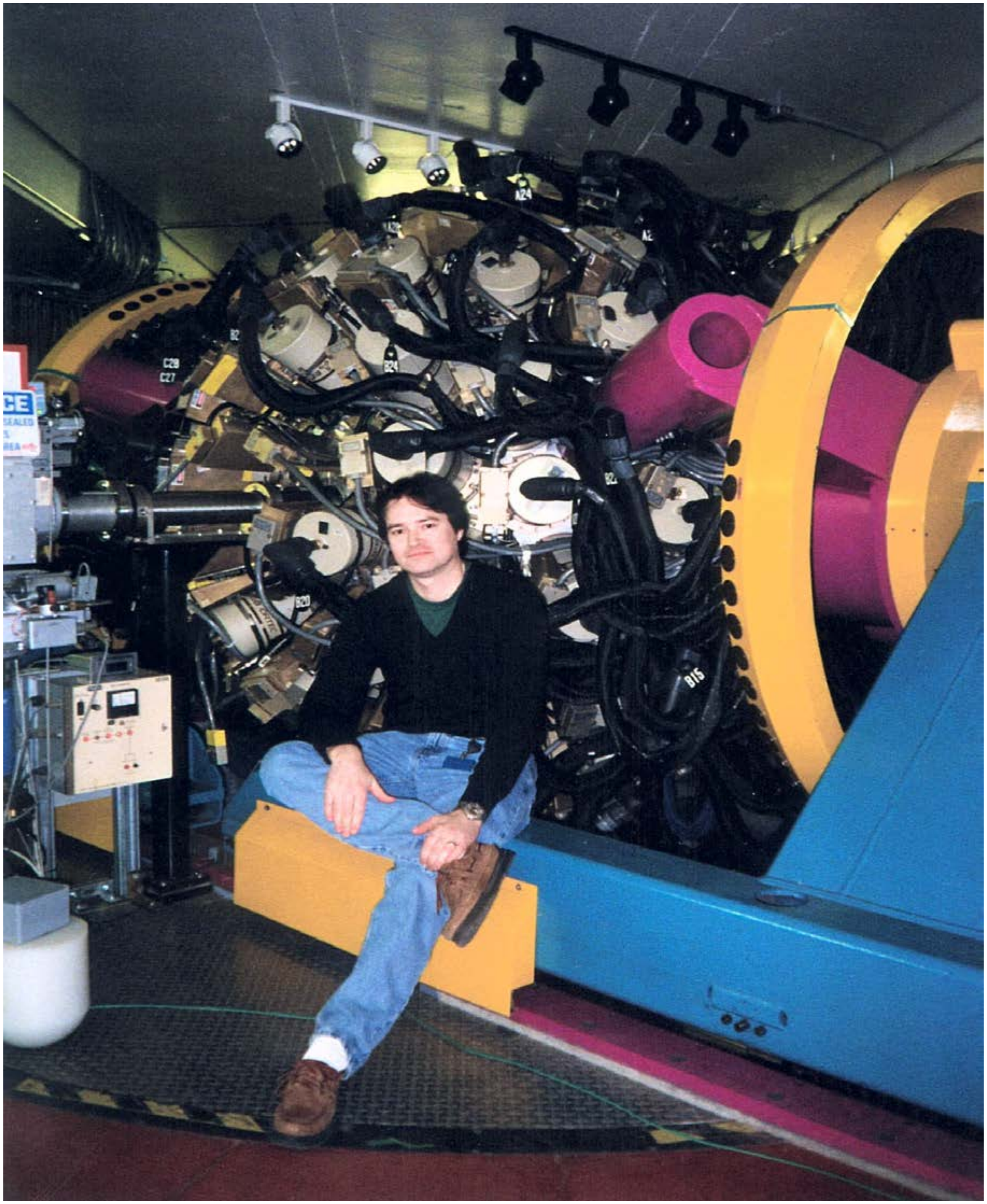








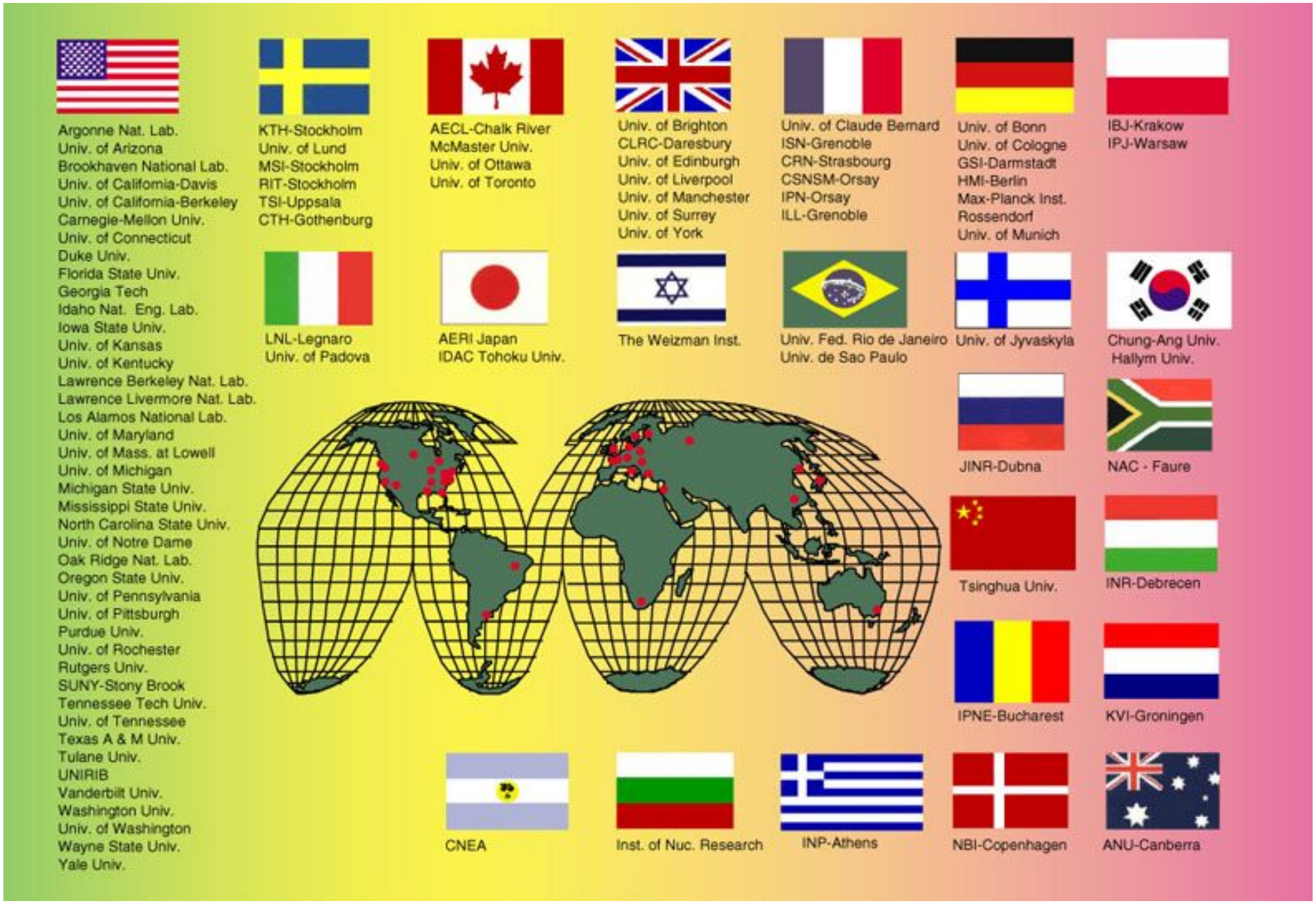

# Gammasphere:
# The most powerful
# Gamma-Ray Spectrometer
# for nuclear structure studies
# in the world!


A24
C29
C27
B15

**Universal Pictures presents The Hulk, directed by Ang Lee, opening June 20, 2003.**

Credit: ILM/Universal

# The GAMMASPHERE Collaboration

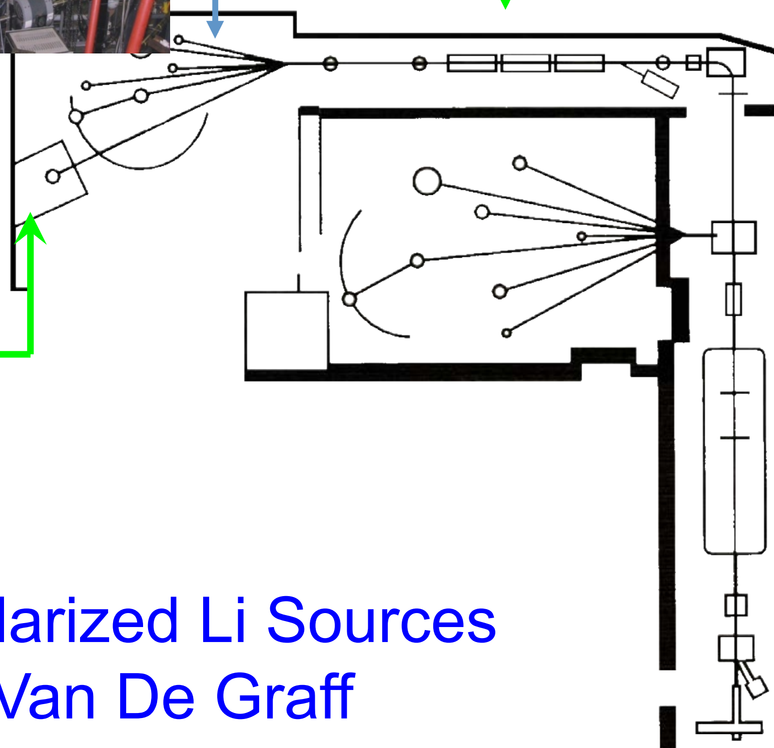



**~100 institutions, ~25 nations**

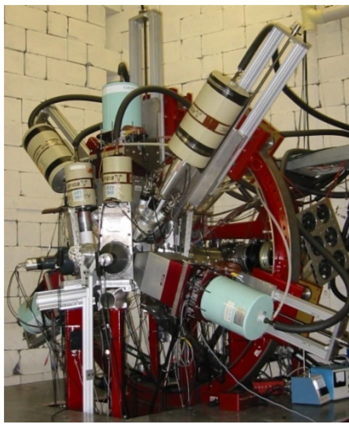
# Experimental Nuclear Facilities

## John D Fox Superconducting Accelerator Laboratory


Resolut



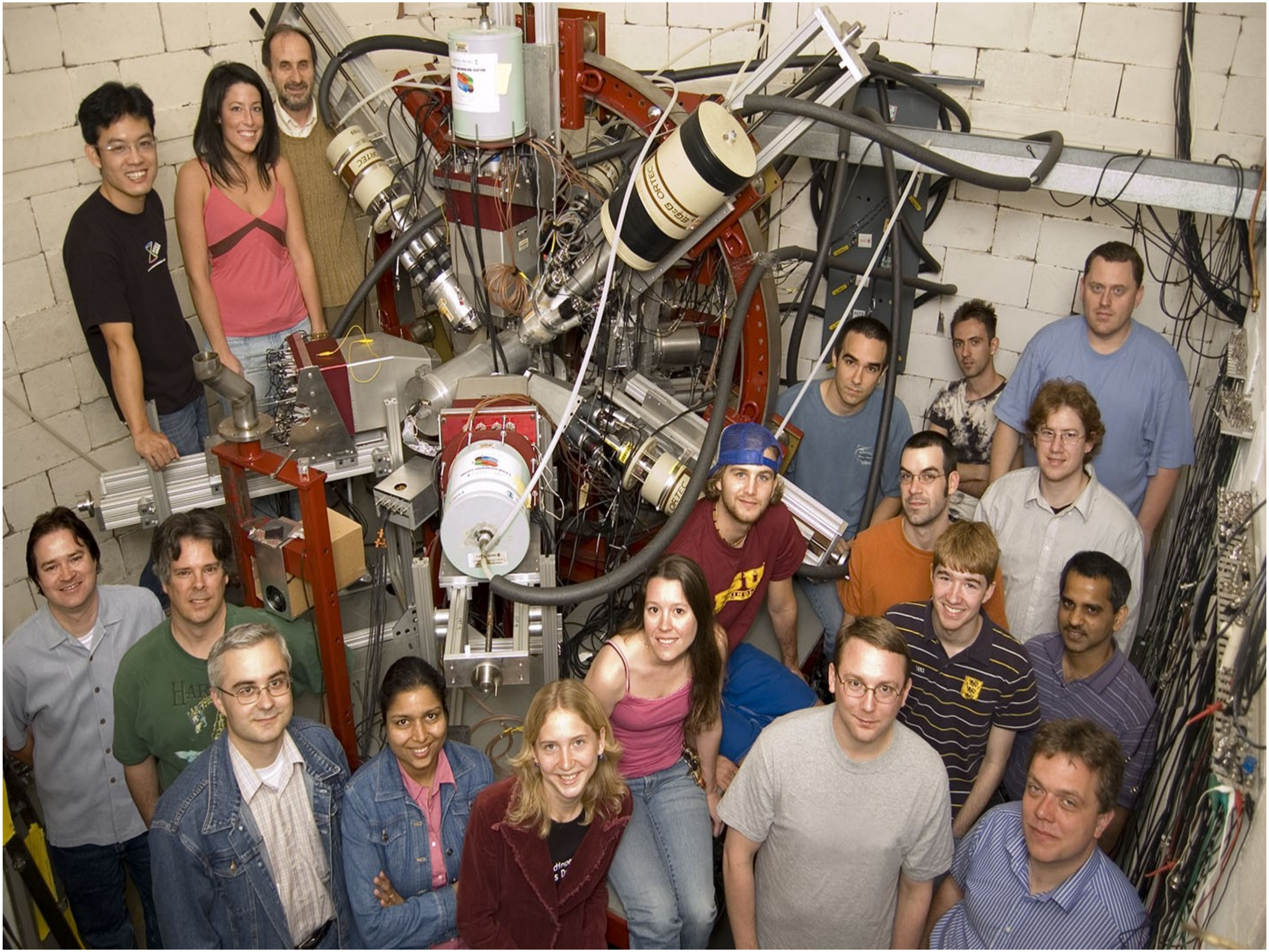
LINAC



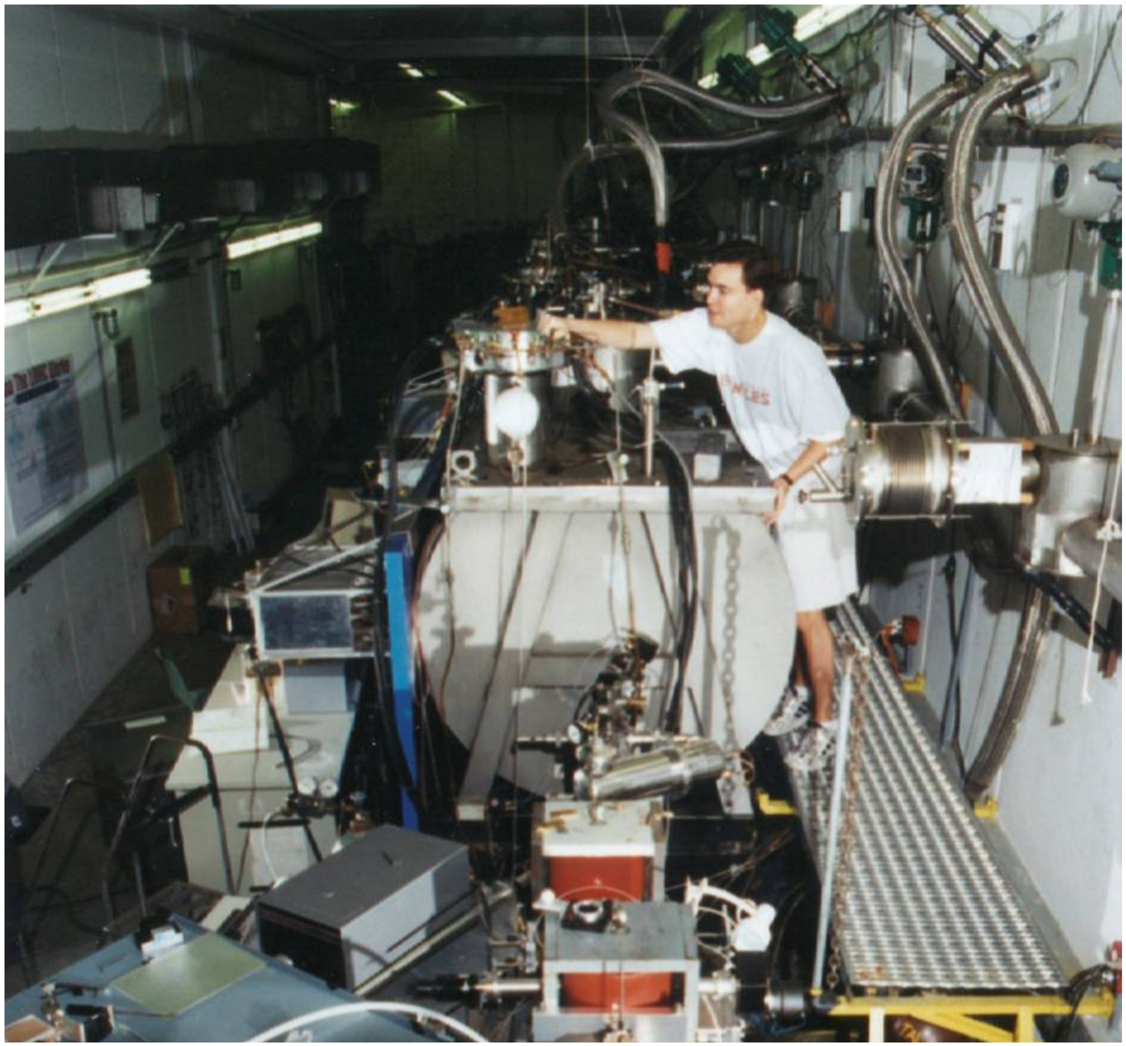
γ ray Array

Tandem

- SNICS and Polarized Li Sources
- 9 MV Tandem Van De Graff
- 12 resonator LINAC
- RESOLUT Radioactive Beam Upgrade!
- 20 Element HPGe γ Ray Detector Array



# Rob Laird at the start



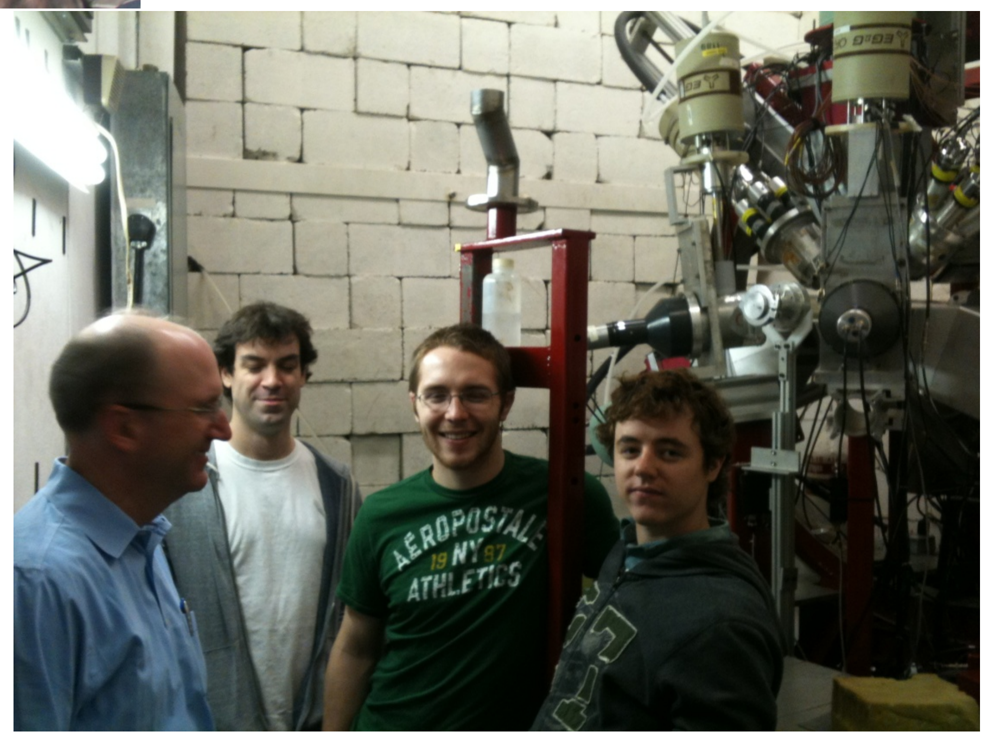
# Rob upon graduation!

# Skills learnt at FSU in high demand.

# Many go into careers at Nat. Labs

Daniel Archer, R&D 100 Winner in 2005, seen here with the Secretary of Homeland Security, Tom Ridge, and the National Press describing the ARAM radiation detector system which he developed and is now in production and in use at airports, seaports and border crossings.

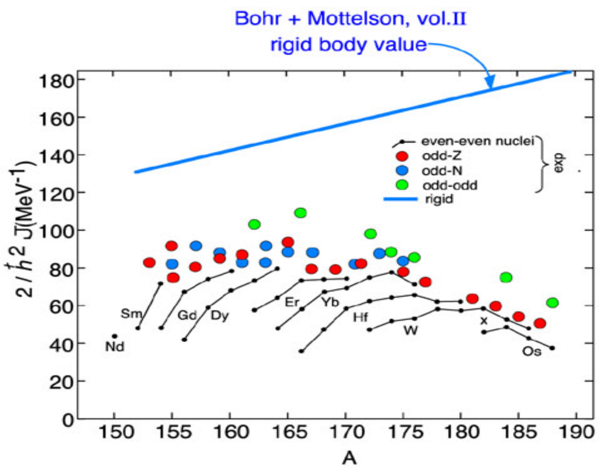
In Fall 2010 I invited Dan back to speak to the new crop of students. Here he is back in the Gamma Cave encouraging the students to work hard and finish their PhD studies because the country needs their expertise and there are jobs out there!



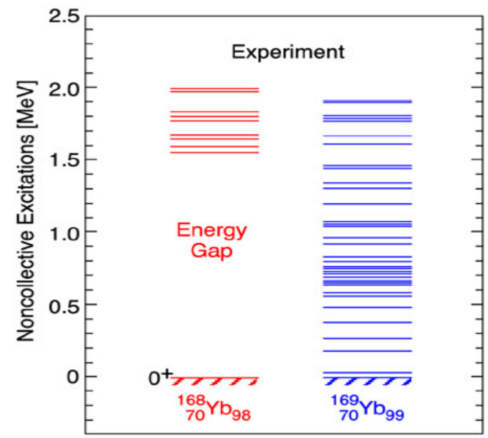
# Backbending

# Nuclear Superfluidity and Rotation

The unique laboratory of the nucleus is found to display superfluid properties.

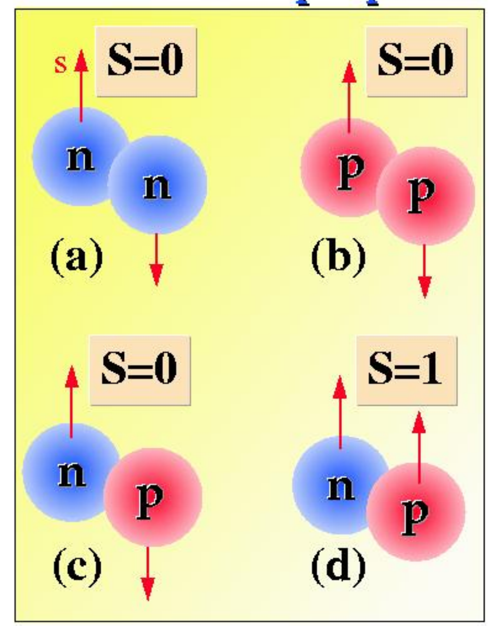



For deformed nuclei
$\mathcal{J} \approx 30\%\ \mathcal{J}_{rigid}$



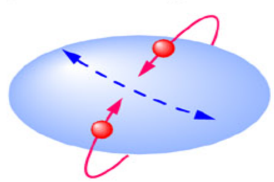

For even-even nuclei $I^{\pi}_{g.s.}=0^{+}$ and show a large energy gap as compared to odd-nuclei.

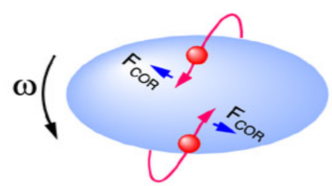
## nucleonic Cooper pairs

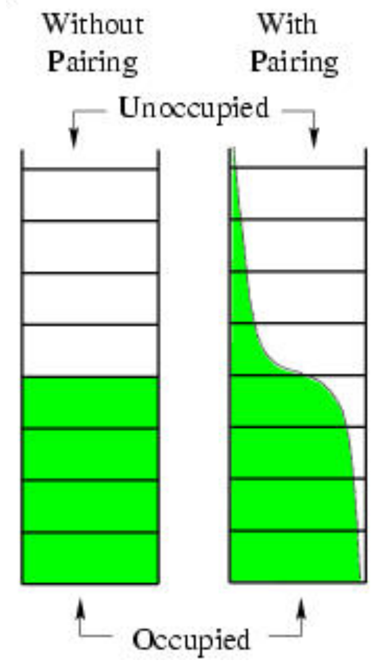


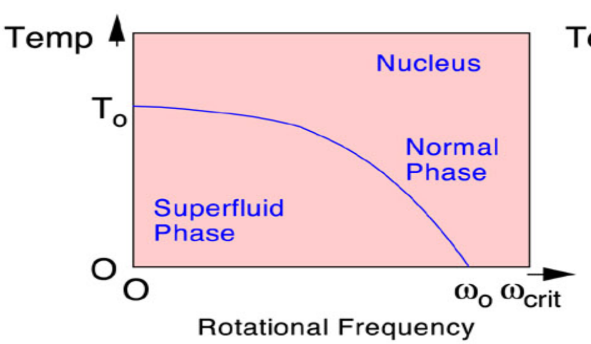

The superfluid condensate arises from nucleons teaming up in time-reversed "Cooper" pairs and scattering coherently.

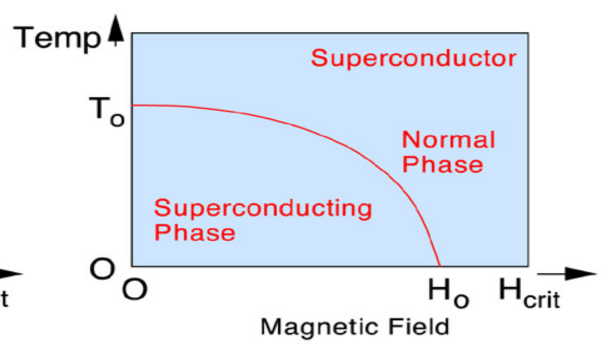
But collective rotation of the nucleus tries to break these correlated fermions apart (The Mottelson-Valatin Effect).

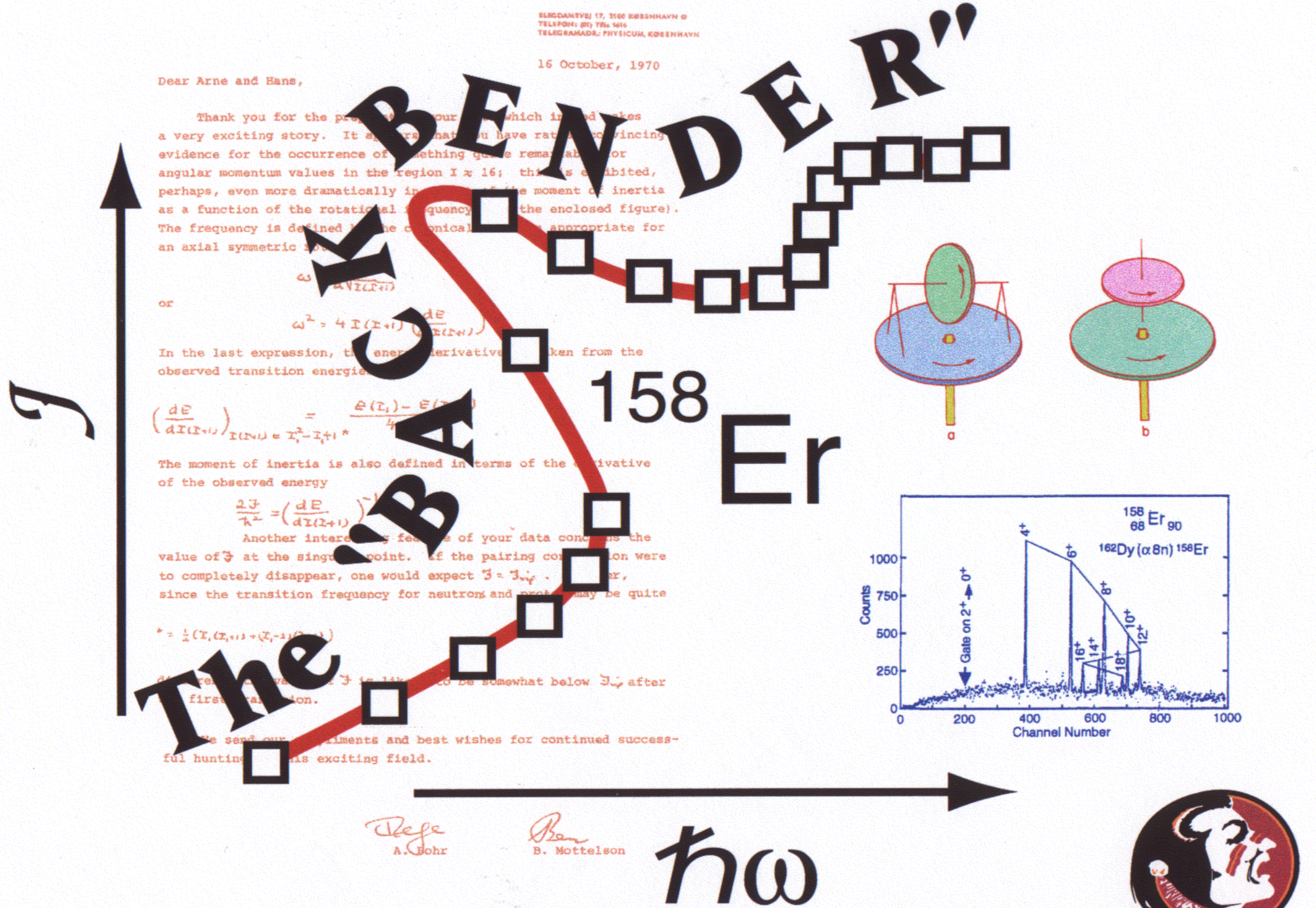




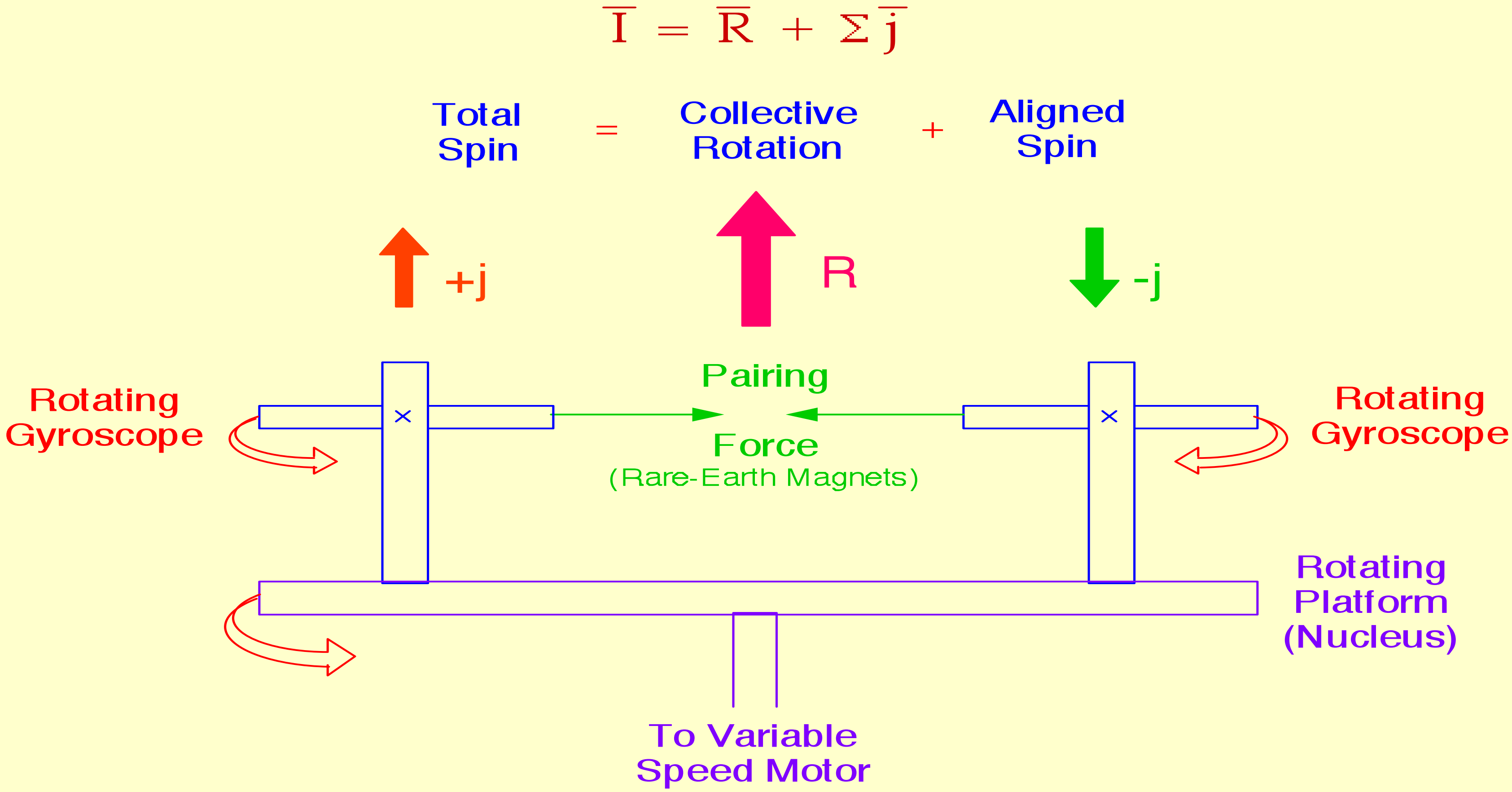






Built by Ray Willis
Nuclear Research Workshop, FSU, 1997




"Backbending" Demonstration Schematic

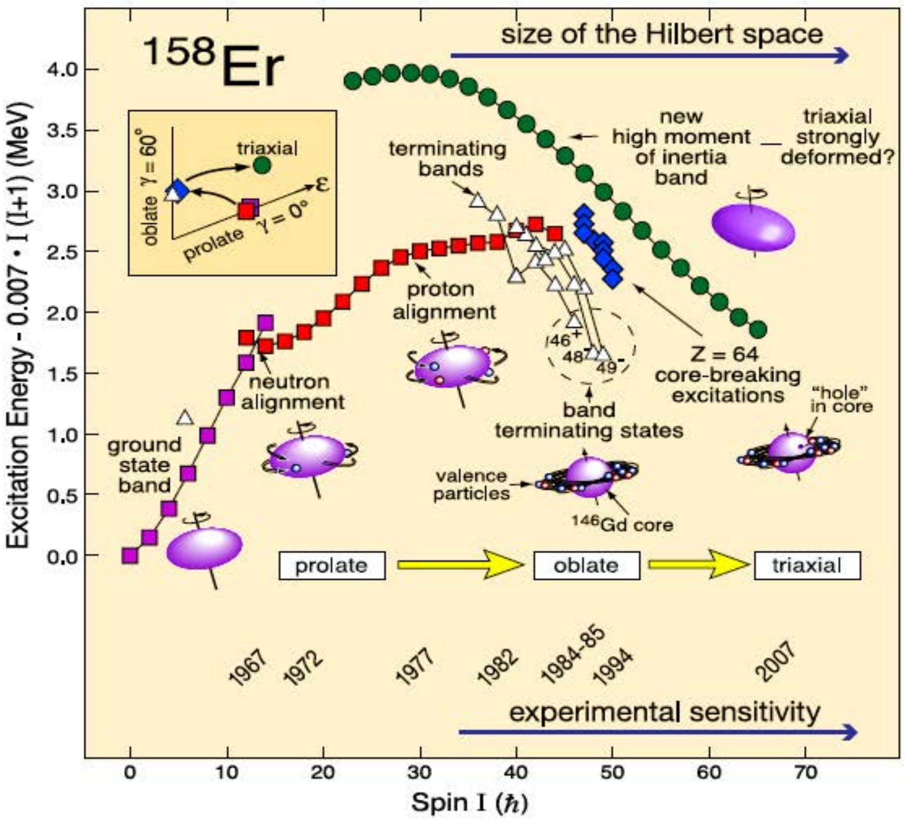
Riley 15 25GM

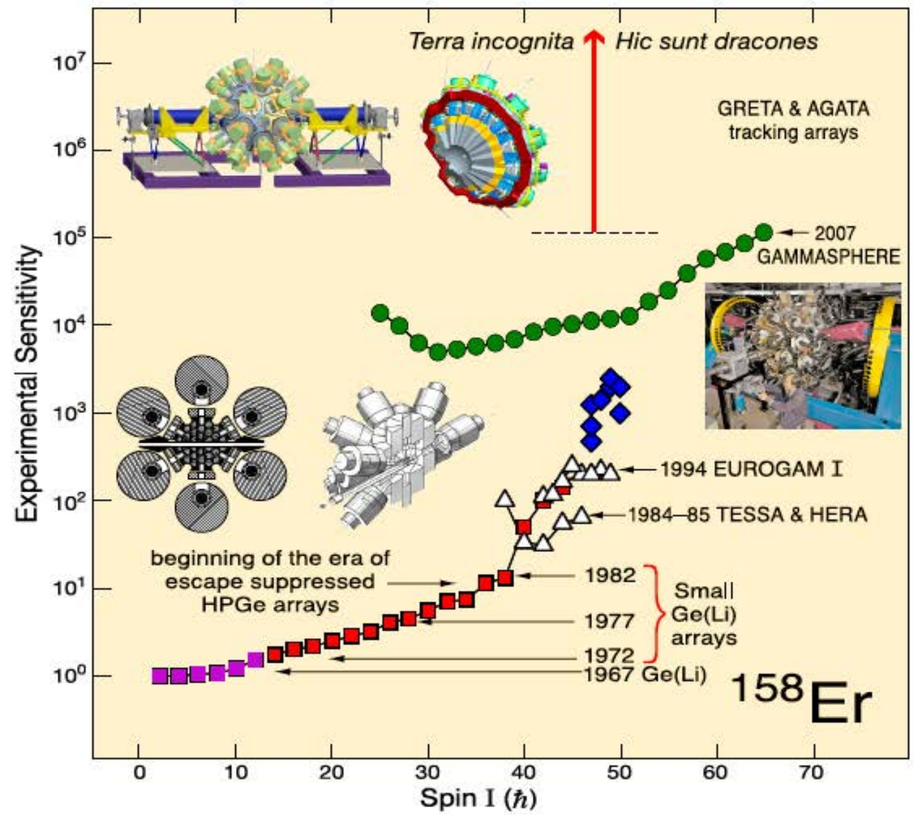
Show video

# Evolution of Gamma-Ray Spectroscopy and $^{158}$Er

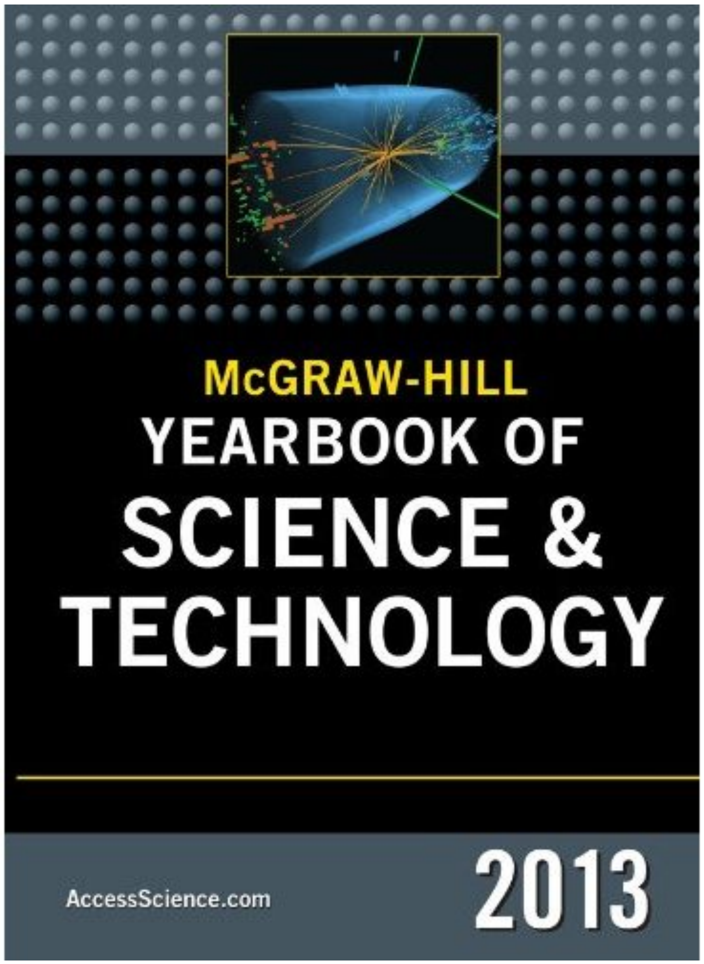

(Nat. Acad. Sci. Decadal Report June 2012, p 49
Nuclear Physics: The Heart of Matter)

- New Detector Systems = New Physics



# “The Fascinating Nuclear Structure World of Erbium-158”
# Wang, Riley, Simpson and Paul

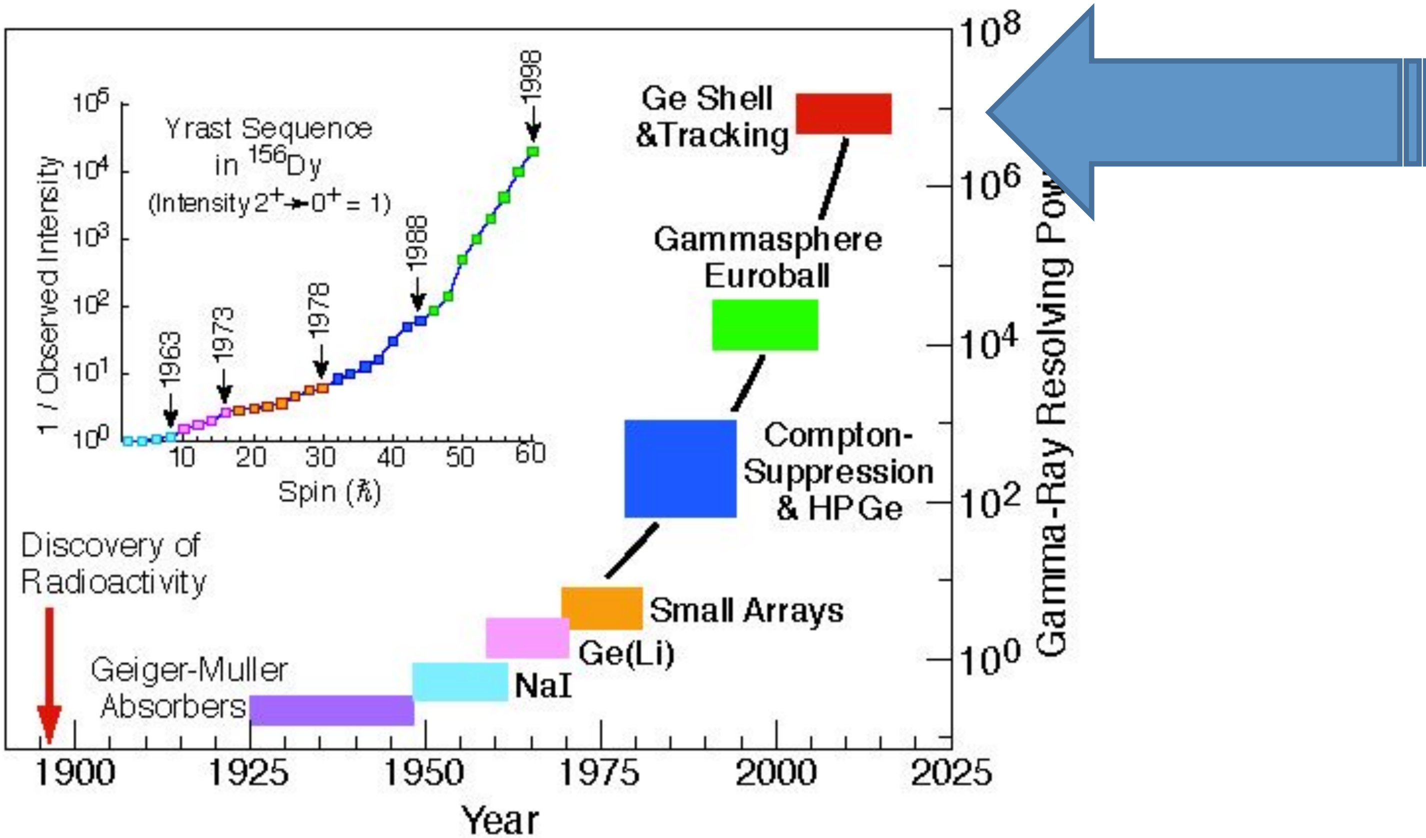



”If the theoretical spin assignments turn out to be correct, the experimental band 1 in 158Er would be the highest spin structure ever observed.”
Afanasjev, Shi, Nazarewicz, PRC 86, 031304® (2012)


IMAGINE
06-14
158 ERB
PORSCHE

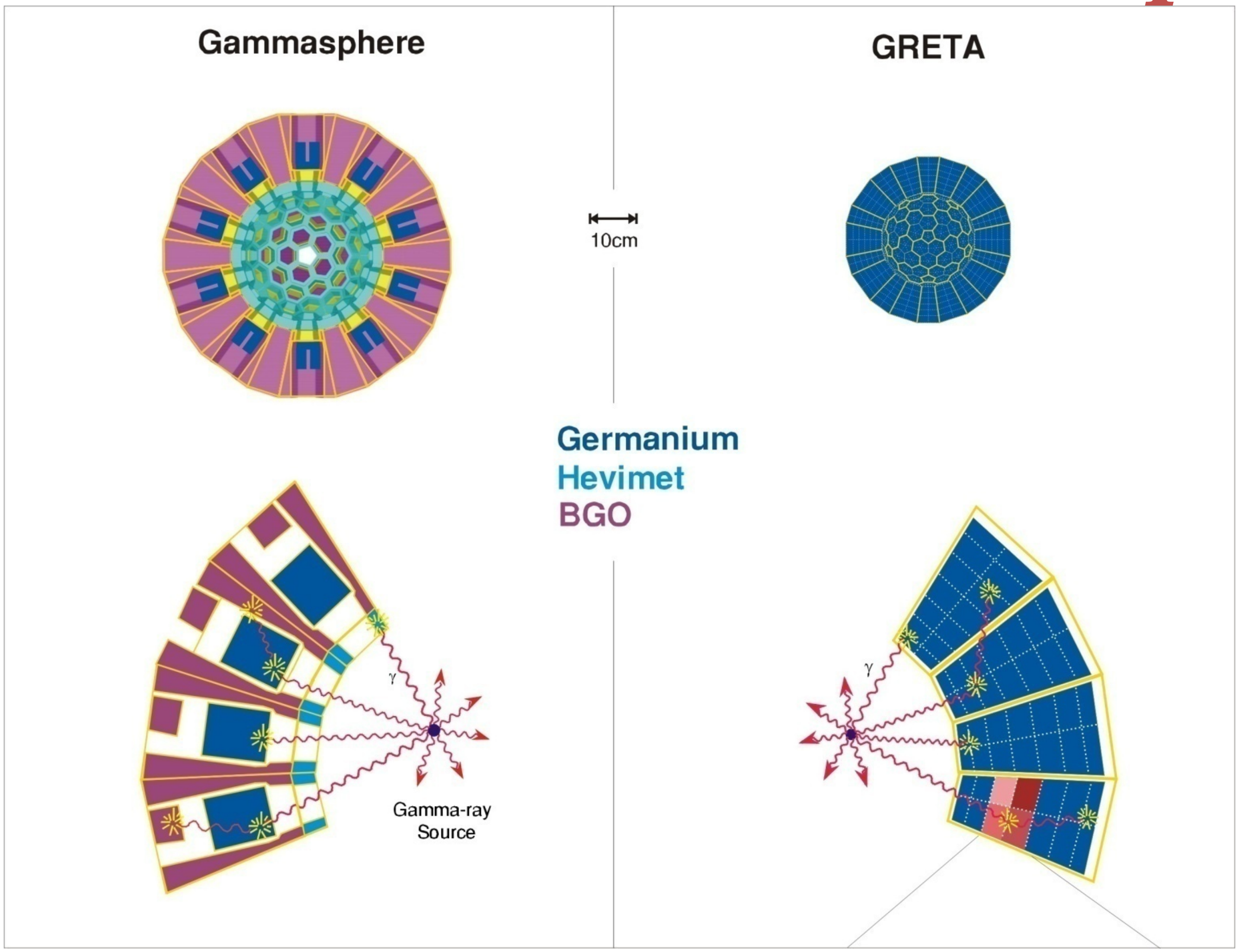
# The Future

# *Evolution of γ-ray detector technology*




**The calculated resolving power is a measure of the ability to observe faint emissions from rare and exotic nuclear states.**

# Compare GRETA with Gammasphere



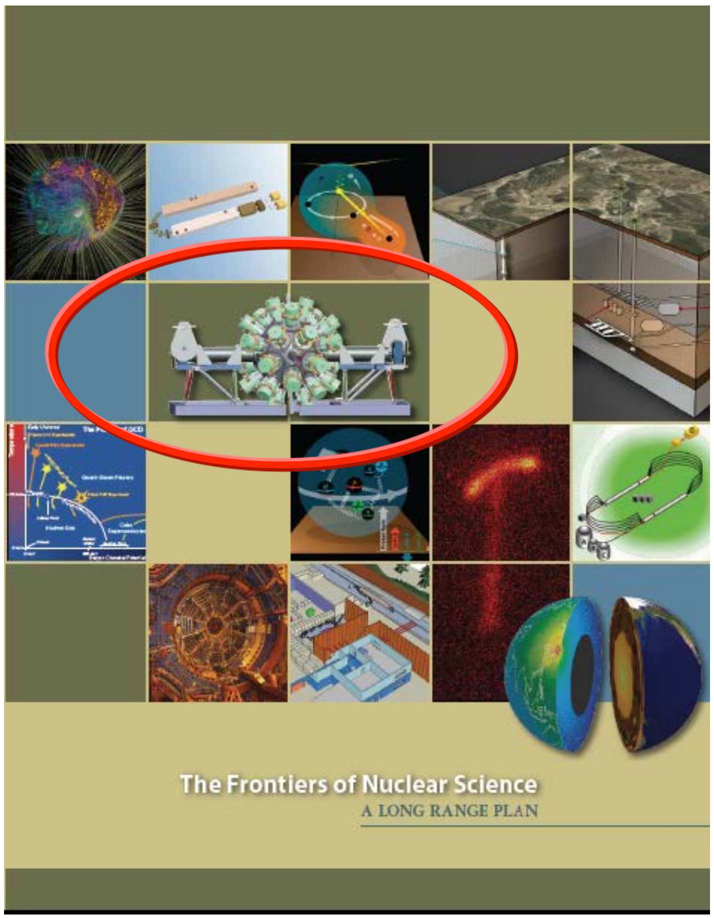

| | | |
|---|---|---|
| Efficiency (1 MeV) | 8% | 55% |
| Efficiency (15 MeV) | 0.5% | 12% |
| Peak/Total (1 MeV) | 55% | 85% |
| Position resolution | 20mm | 1 mm |


Grigory Ragochev   Alfredo Galindo-Uribarri   Krzysztof Starosta   Witek Nazarewicz   Dirk Weisshaar   Sam Tabor   Karin Lagergren   Thomas Glasmacher   David Radford

Anatoli Afanasjev   Alexander Volya   Robert Janssens   Walter Reviol

Warren Cluff   I-Yang Lee   Doug Cline   Kim Lister   Rod Clark   Paul Fallon   Mark Riley   Demetrios Sarantites

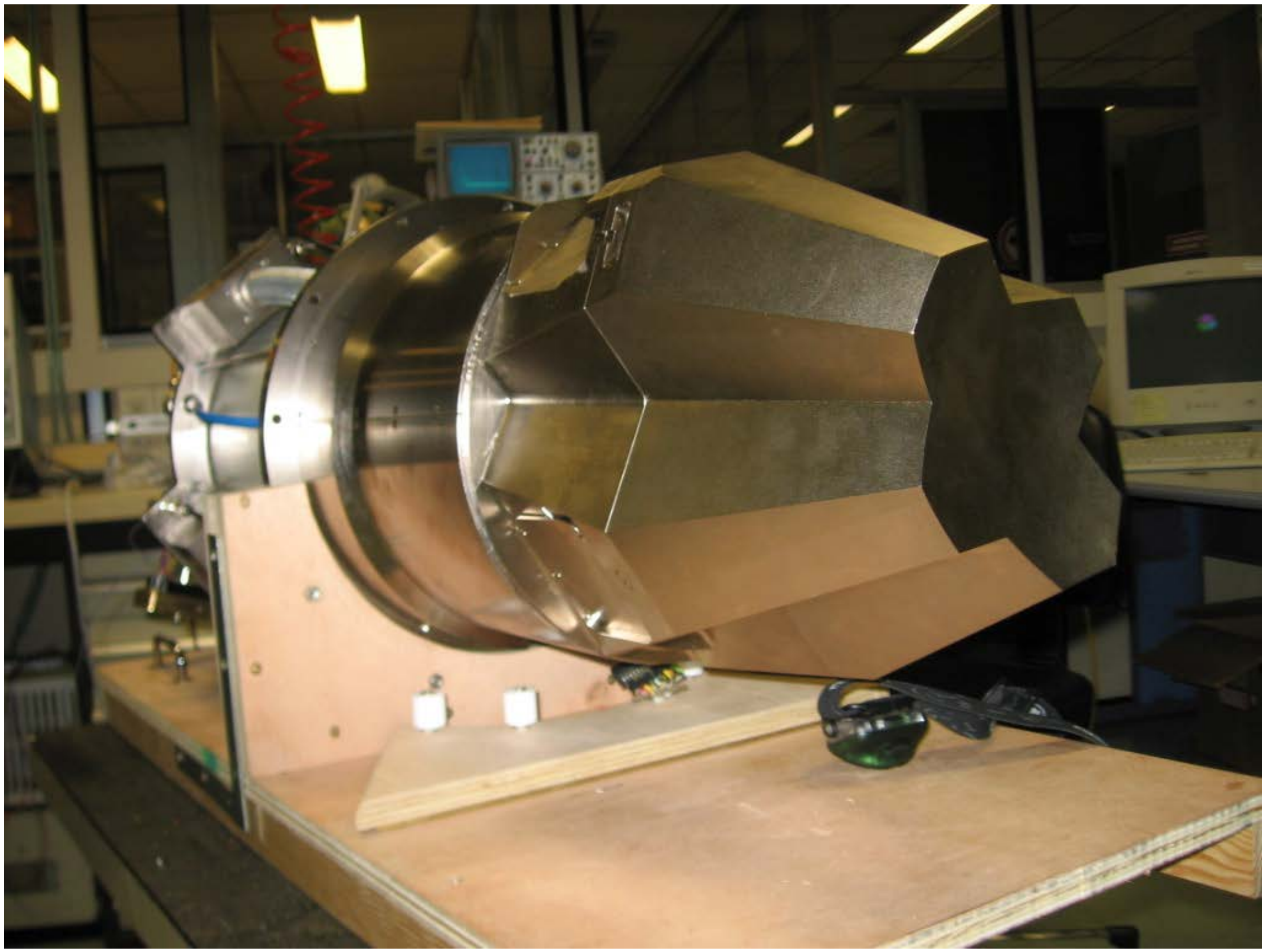
# *2007 Long Range plan*



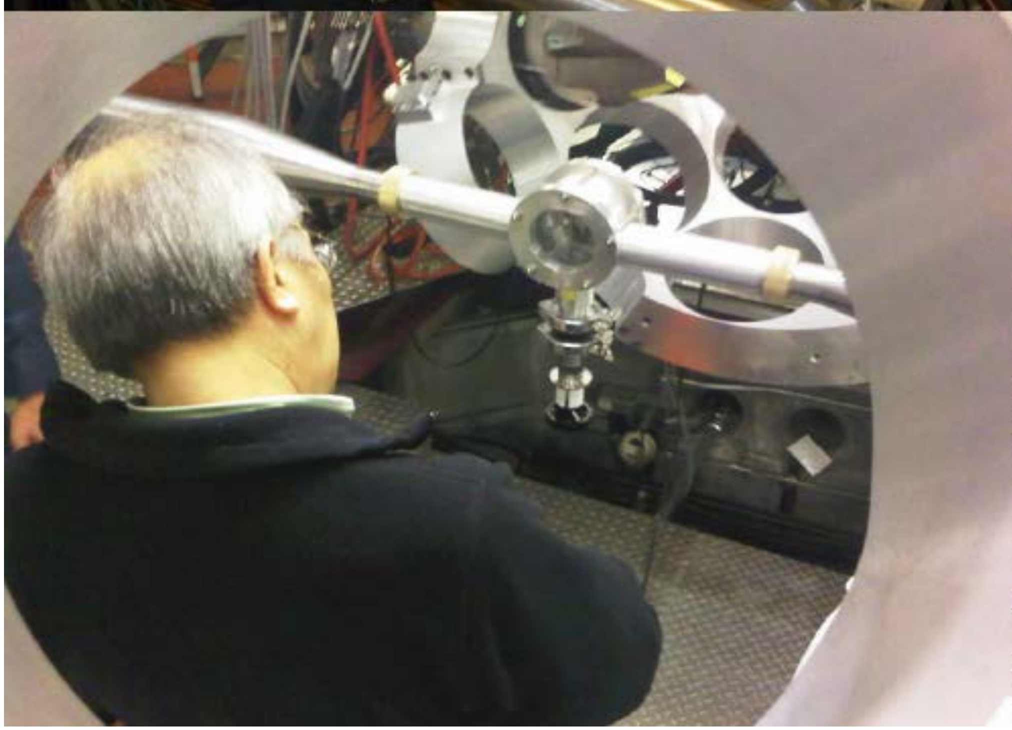

**Gamma-Ray Tracking**

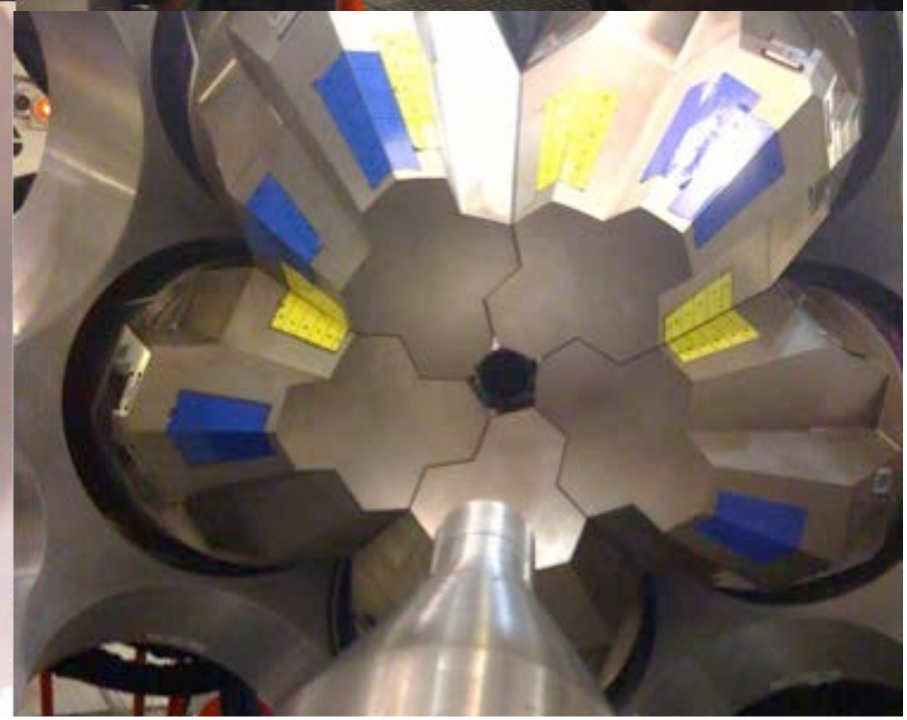
**…….the construction of GRETA should begin upon successful completion of GRETINA. This gamma-ray energy tracking array will enable full exploitation of compelling science opportunities in nuclear structure, nuclear astrophysics, and weak interactions.**

# The First Detector for GRETINA ($1M!)

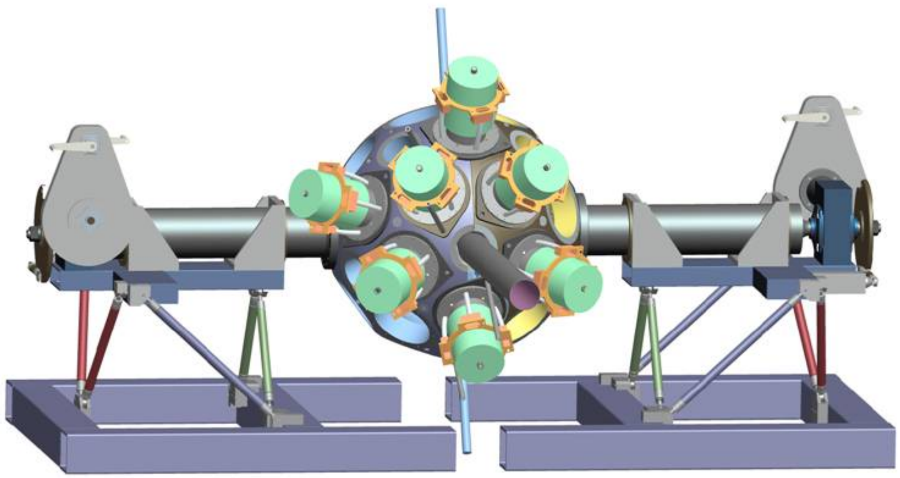


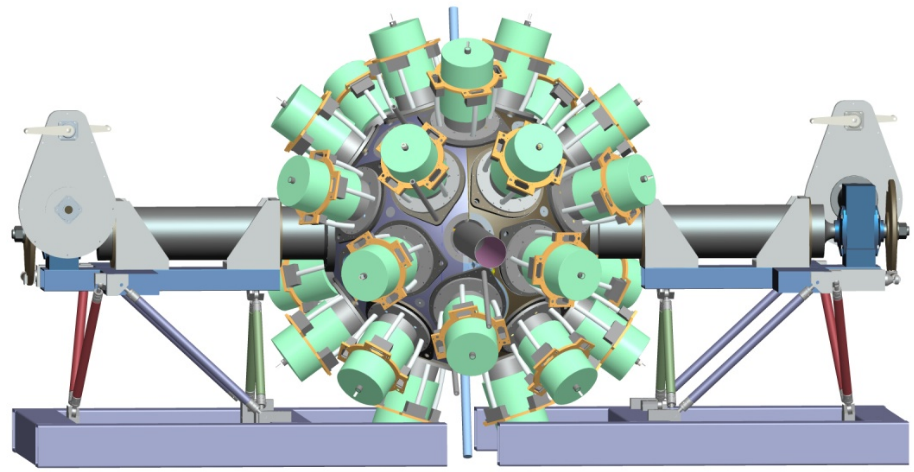
# LAWRENCE BERKELEY NATIONAL LAB - 2011

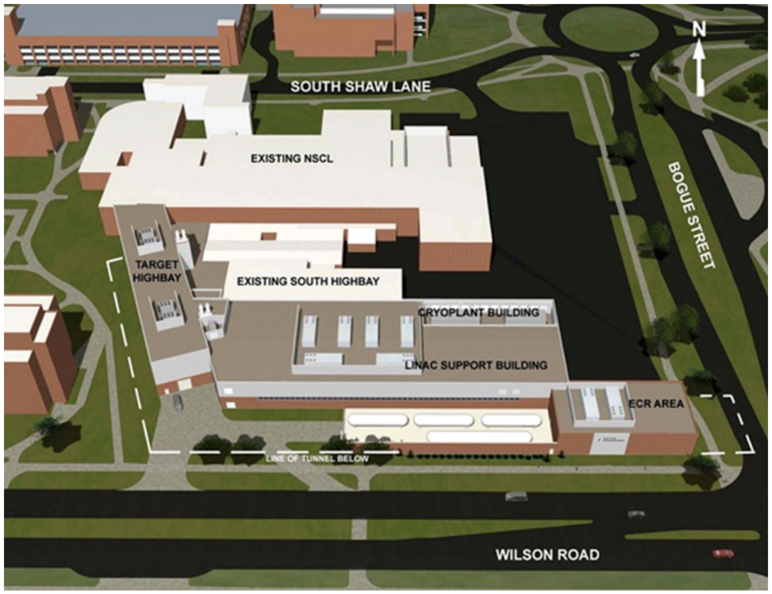




# *GRETINA to GRETA for FRIB*

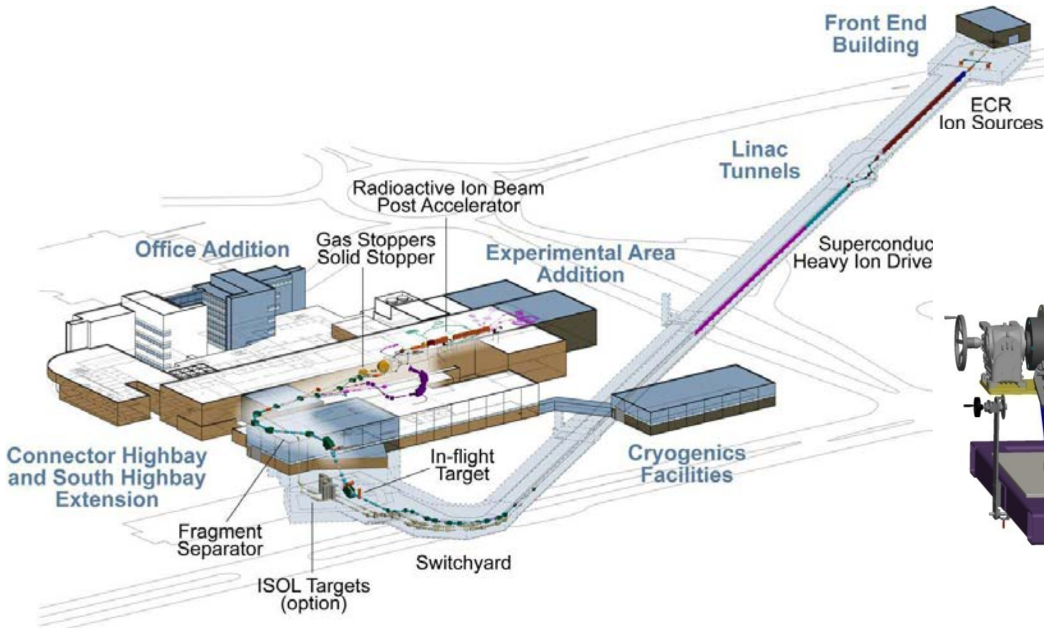


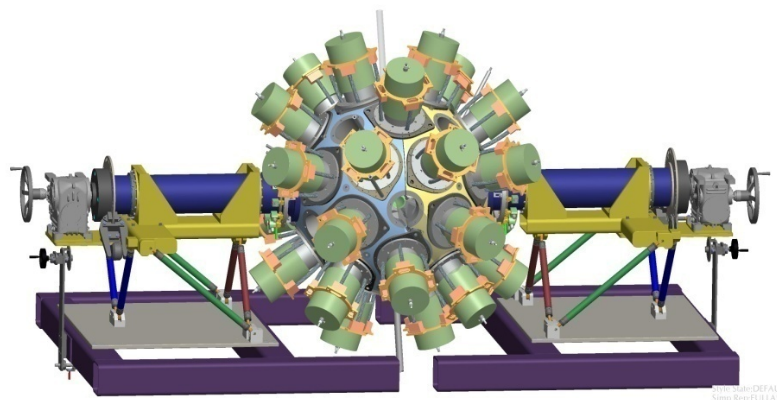





**It has been called**
**"A jewel in the crown of FRIB"**
**Tim Hallman, Aug 2011:**
**"The importance of GRETA in the out years is understood and is part of DOE planning."**

# FRIB + GRETA
# The Revolution in Nuclear Physics Continues!



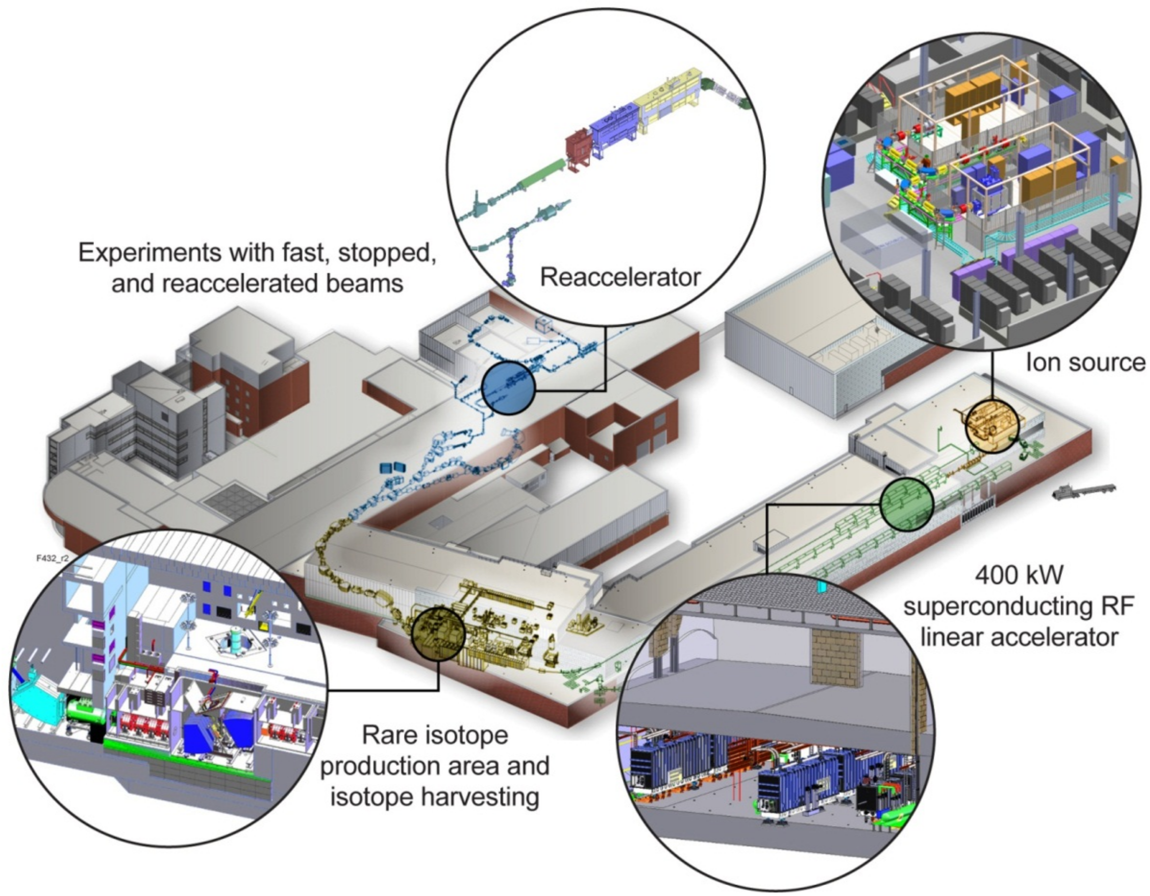



# The Future: A New Accelerator in the USA. It will be the Best in the World for Nuclear Structure Physics!

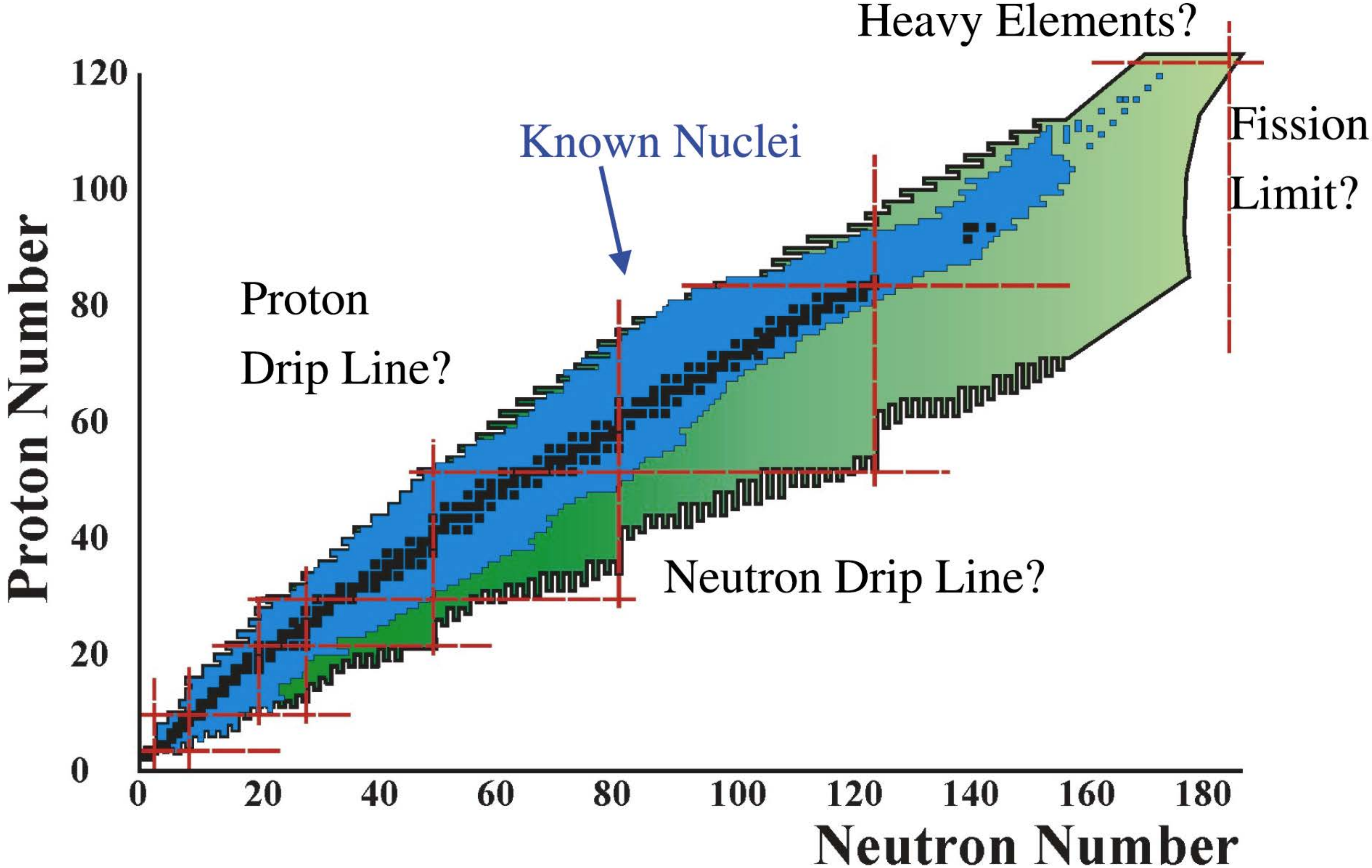
- And Detectors matter too!
- GREAT: the World’s most powerful Gamma-Ray Detector!

# Studying the Origin of the Elements: Facility for Rare Isotope Beams, FRIB

- Funded by DOE Office of Science Office of Nuclear Physics + Michigan State University, $730M.
- T. Glasmacher, Project Director, ex-FSU (Dr. Cottle).
- Completion date 2022.
- Key Feature is 400kW beam power (5 x$10^{13}$ $^{238}$U/s)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams

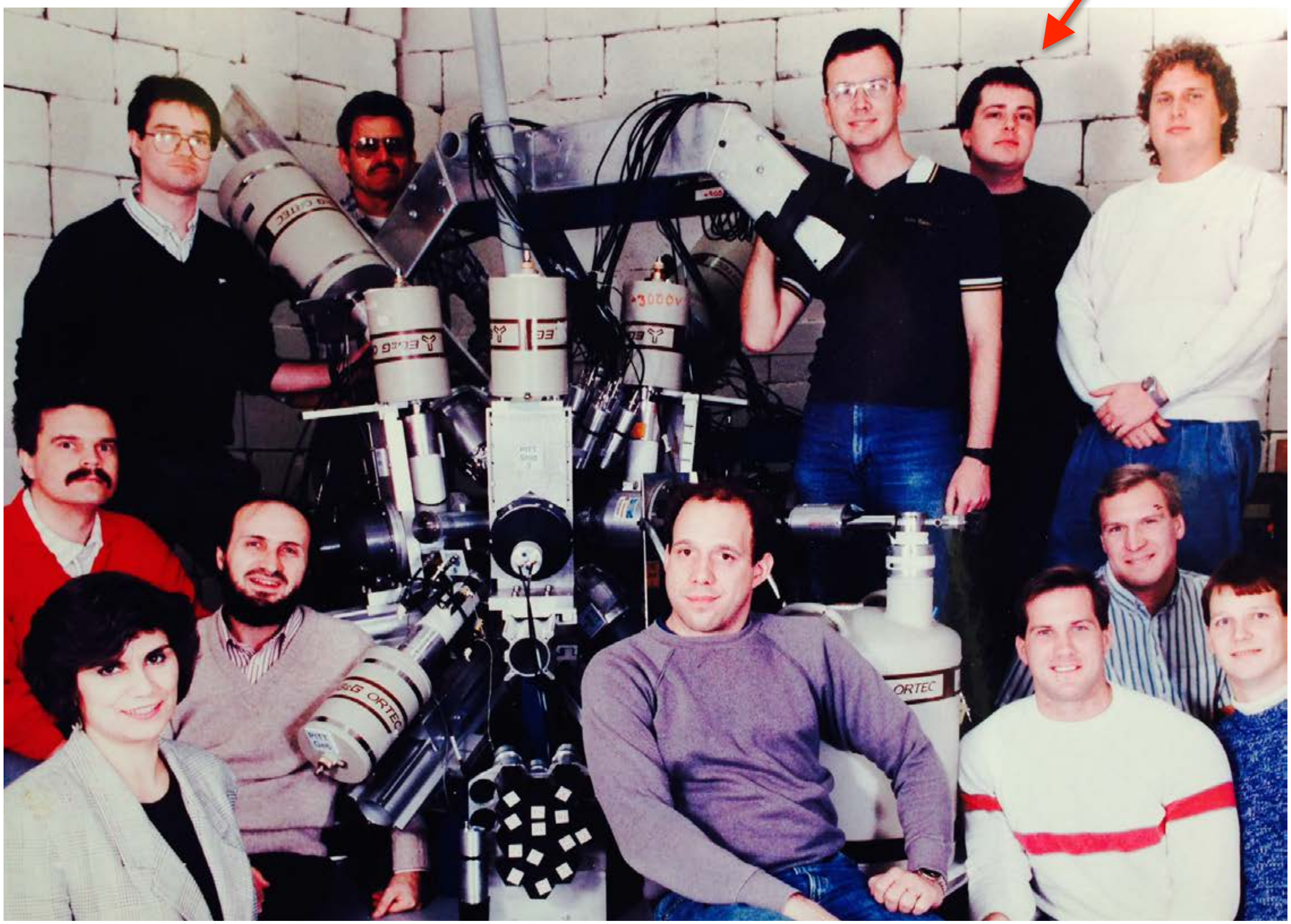


# The Chart of the Nuclides



# Facility for Rare Isotope Beams, FRIB

# Thomas at FSU 20 years ago!



# A few final quotes

Linus Pauling

“Satisfaction of one's curiosity is one of the greatest sources of happiness in life.”

Albert Einstein

“The important thing is not to stop questioning.”

# A few final quotes

Linus Pauling

“Satisfaction of one's curiosity is one of the greatest sources of happiness in life.”

Albert Einstein

“The important thing is not to stop questioning.”

Monty Python

“Always look on the bright side of life”

# Show Michael Turner video

Our best chance to understand our Universe better is you!