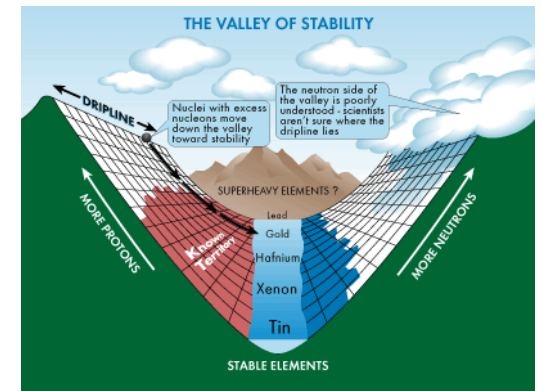
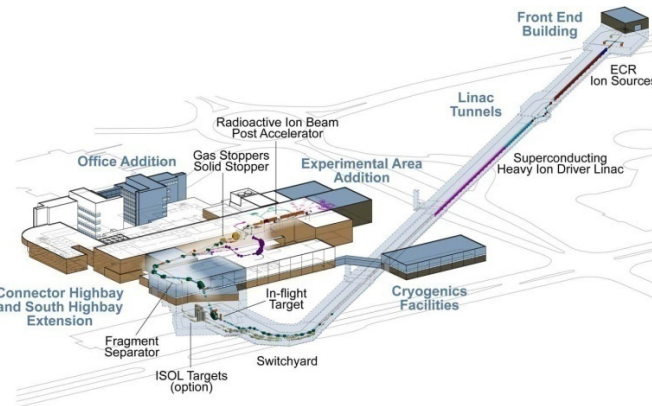
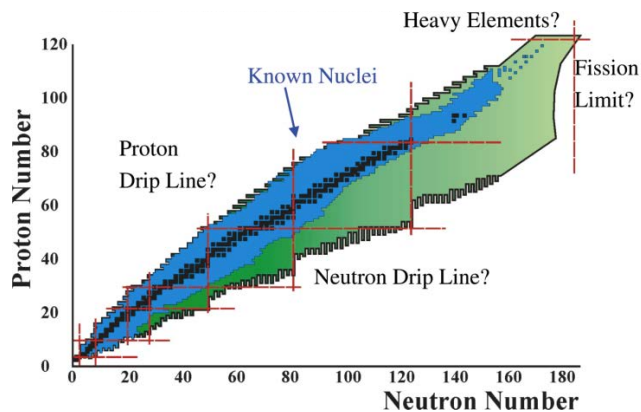
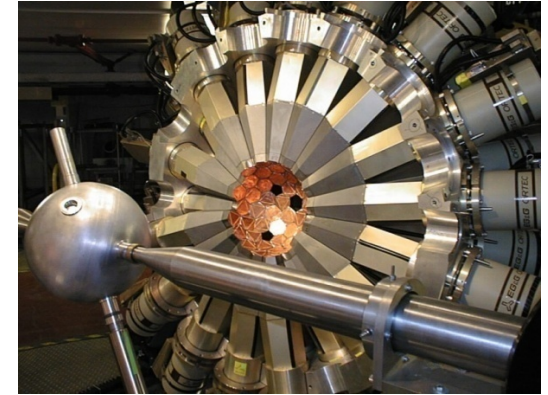
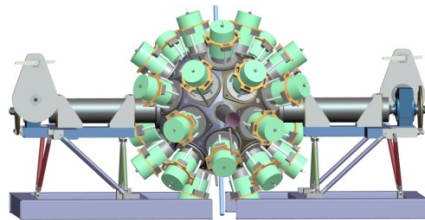


Gamma-Rays: The Key to Unlocking the Mysteries of the Atomic Nucleus



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**

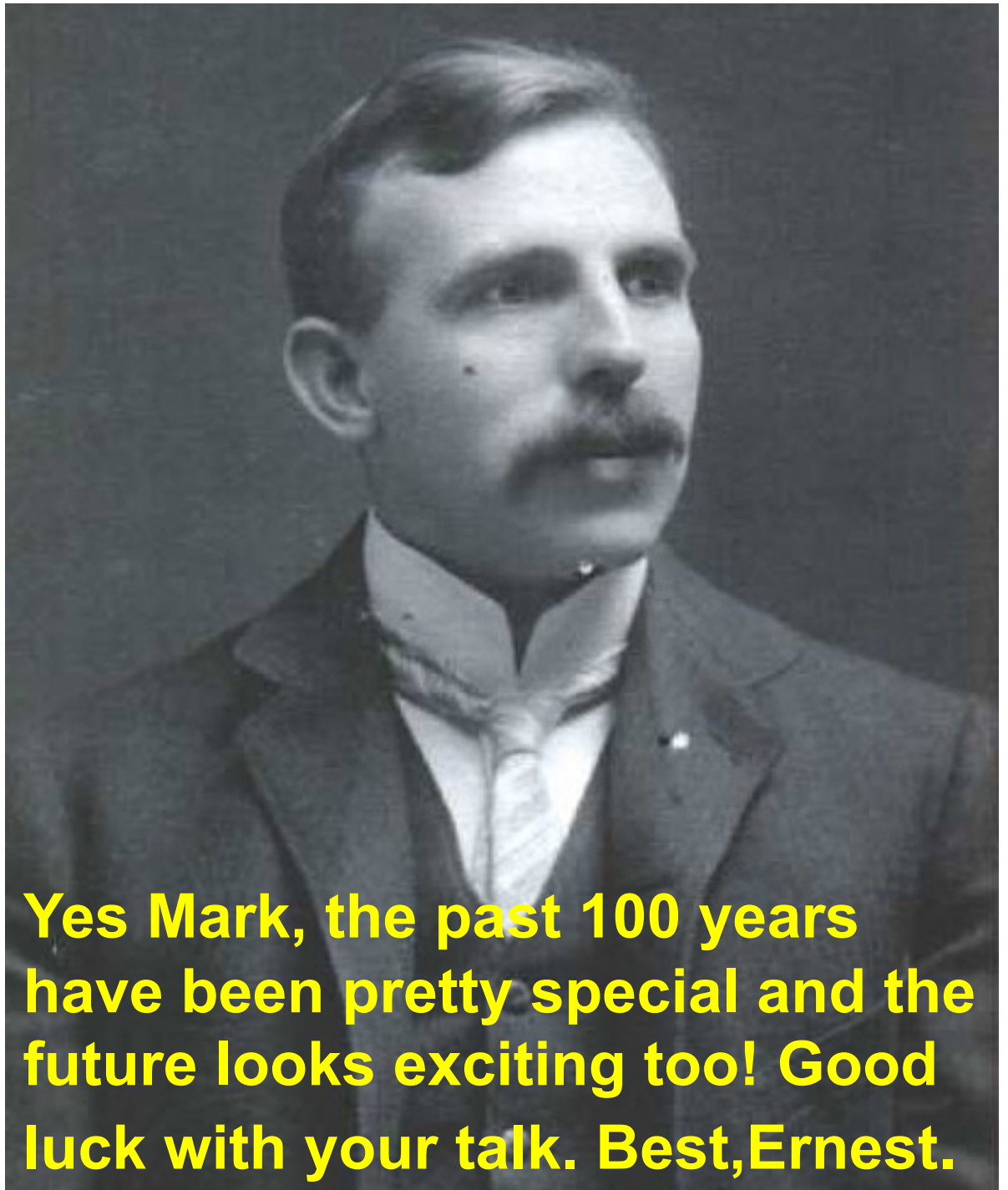
E. Rutherford, F.R.S.*

Philosophical Magazine

Series 6, vol. 21

May 1911, p. 669-688

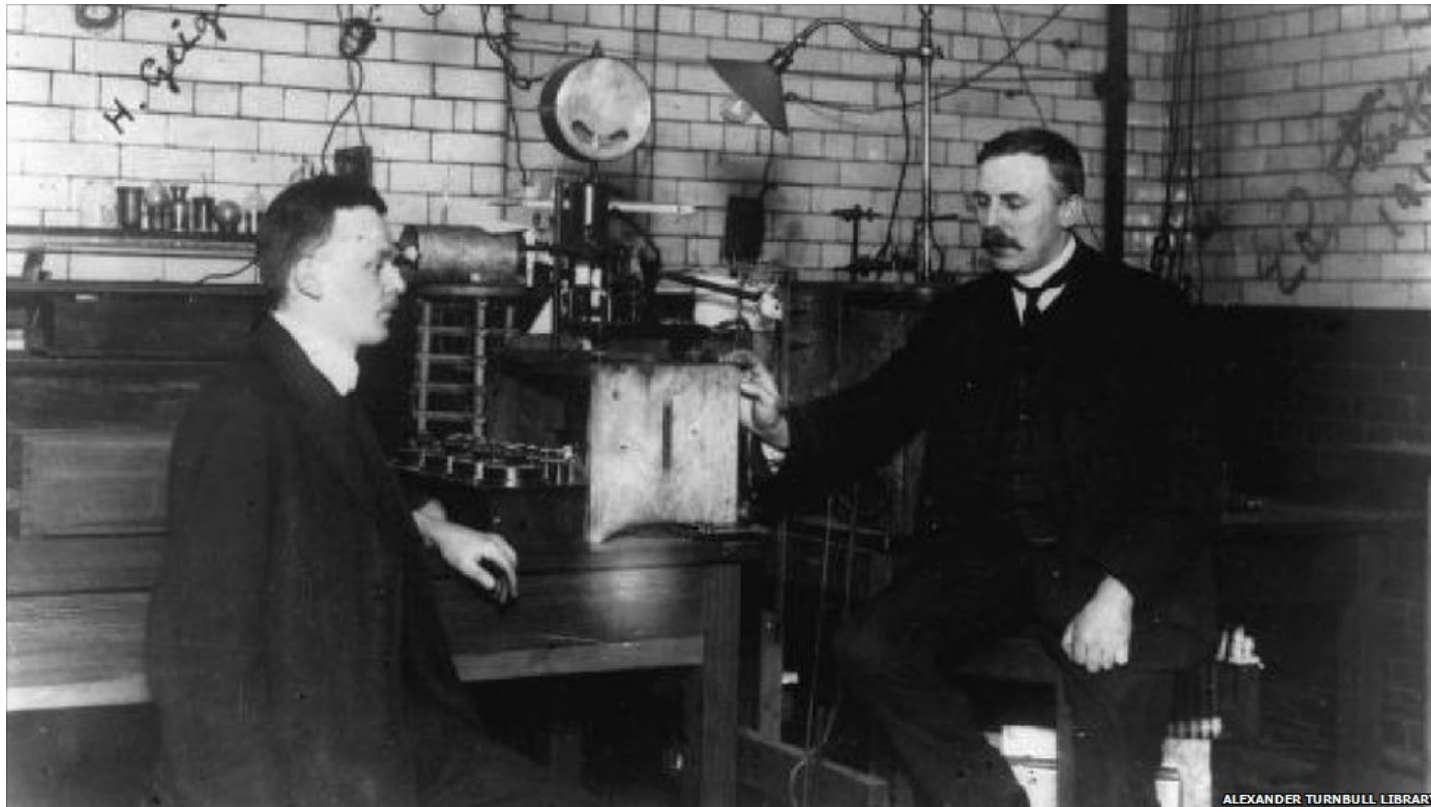
“It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter.... the atom must be a seat of an intense electric field..”



**Yes Mark, the past 100 years
have been pretty special and the
future looks exciting too! Good
luck with your talk. Best, Ernest.**



Rutherford's Lab in Manchester ~1910





Rutherford's Lab in Manchester ~1911



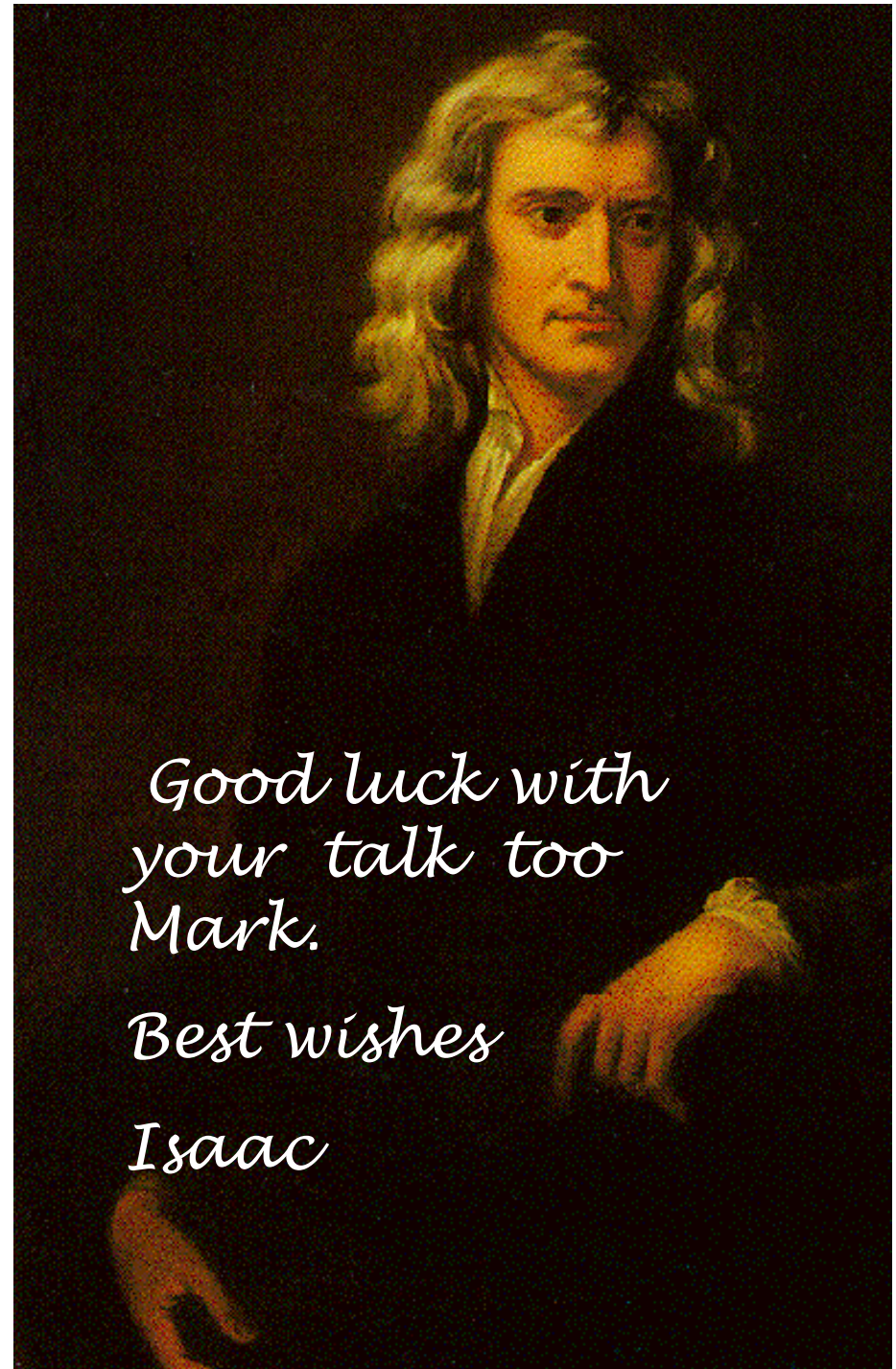
Niels Bohr at Manchester

“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)



*Good luck with
your talk too
Mark.*

Best wishes

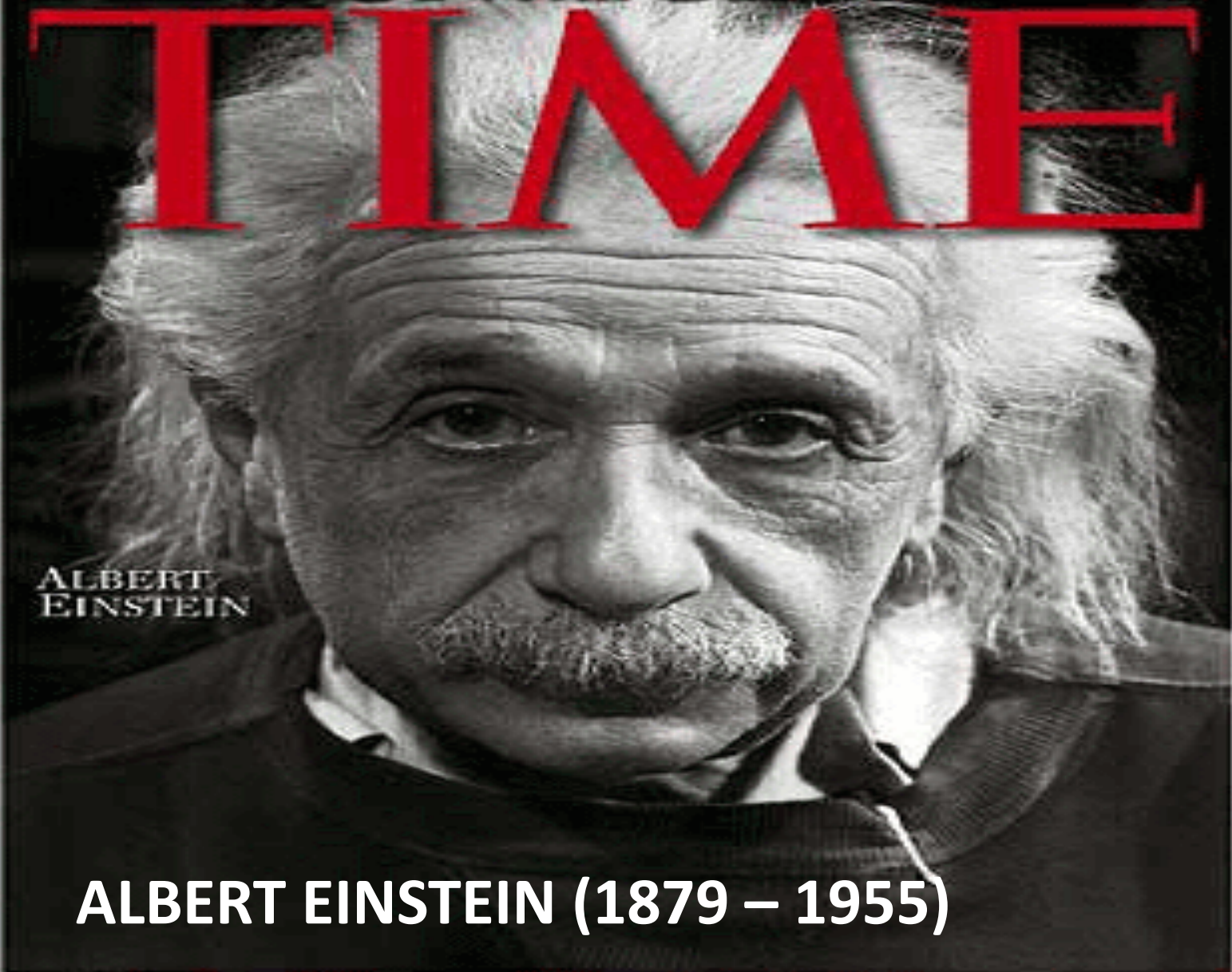
Isaac

DECEMBER 29, 1999 - \$4.50

www.time.com

PERSON OF THE CENTURY

TIME



ALBERT
EINSTEIN

ALBERT EINSTEIN (1879 – 1955)

© 1999 TIME INC.

A Recent FSU Physics Open House



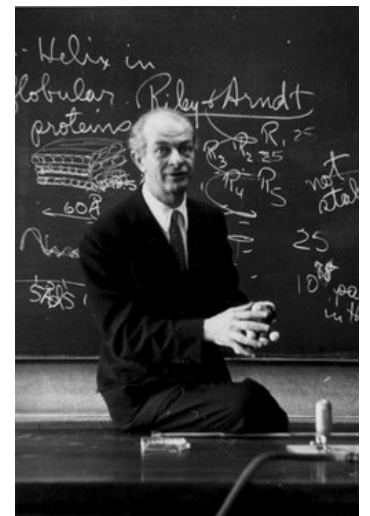


Einstein in his 20's YOUR AGE!
When he did all his best work!
And had his best haircut.



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.



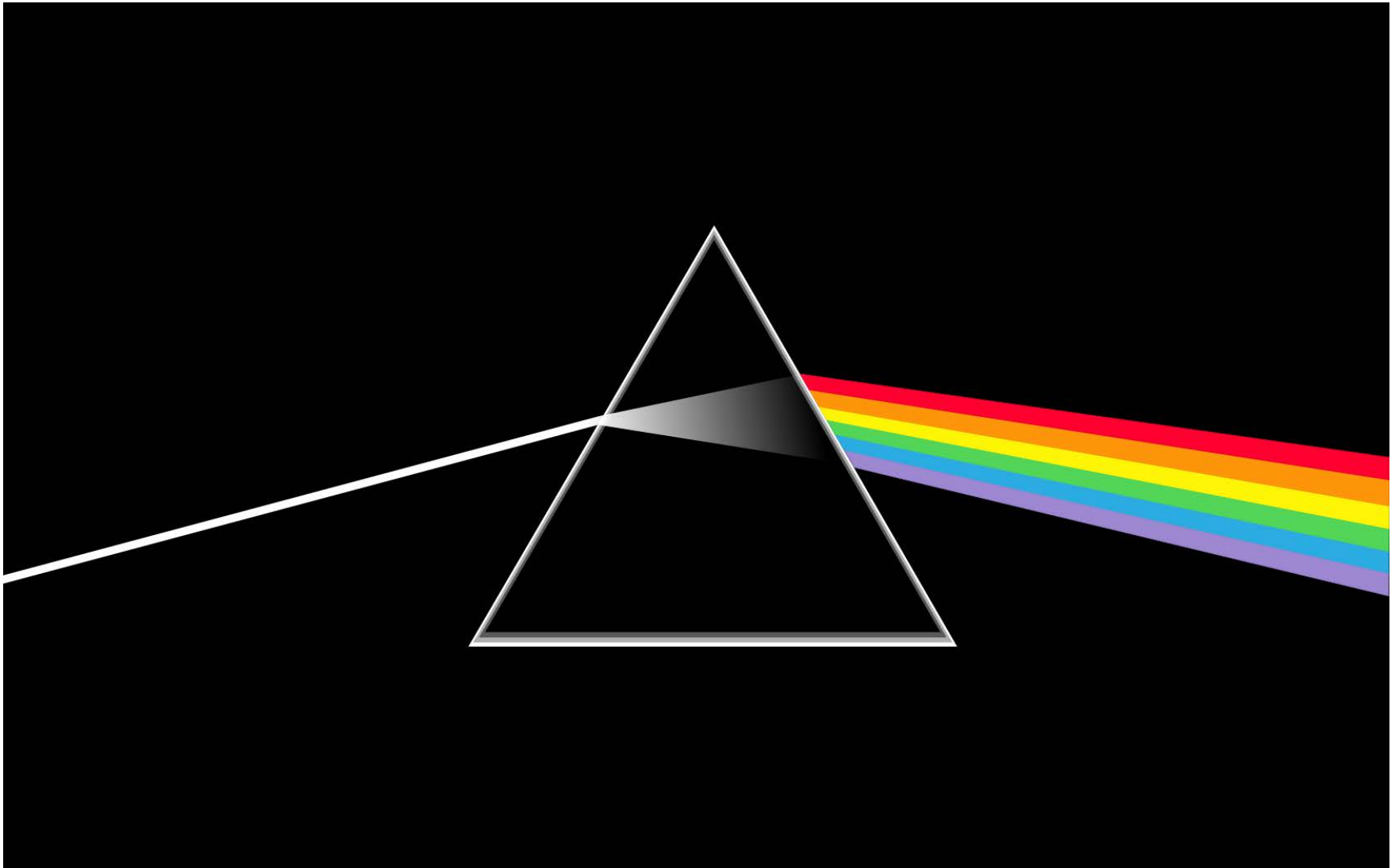
**And now for something
completely different**

My third hero at college

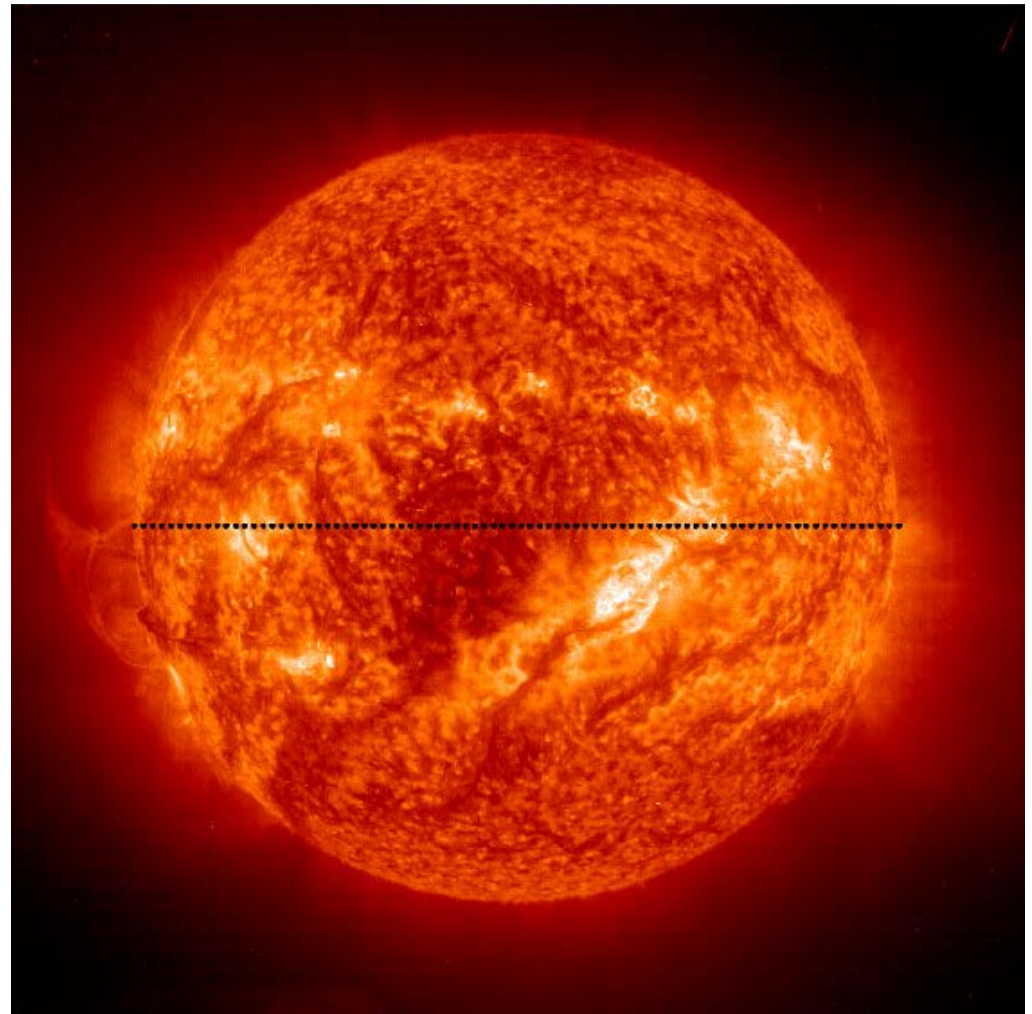
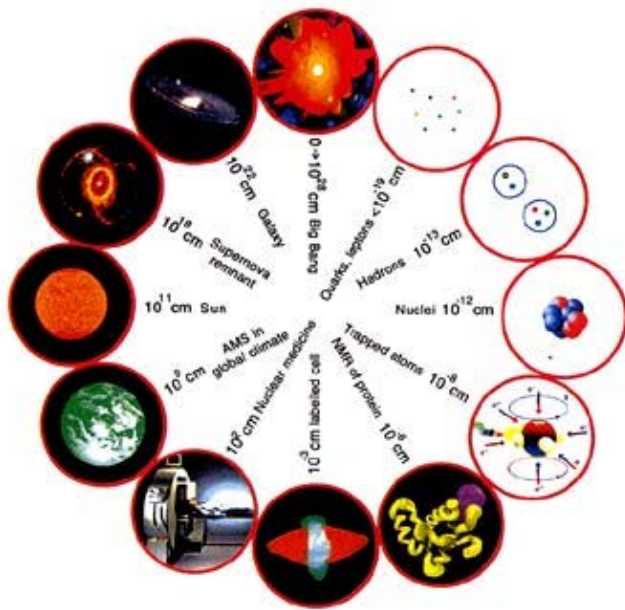
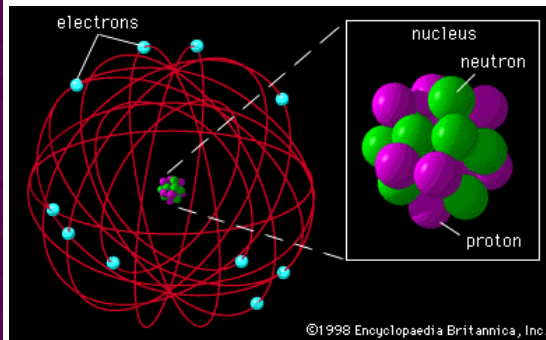
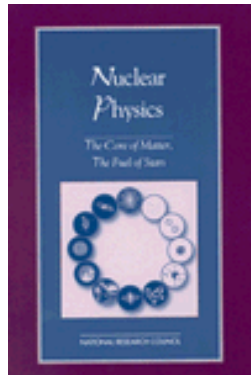
Monty Python!



Music heroes too!



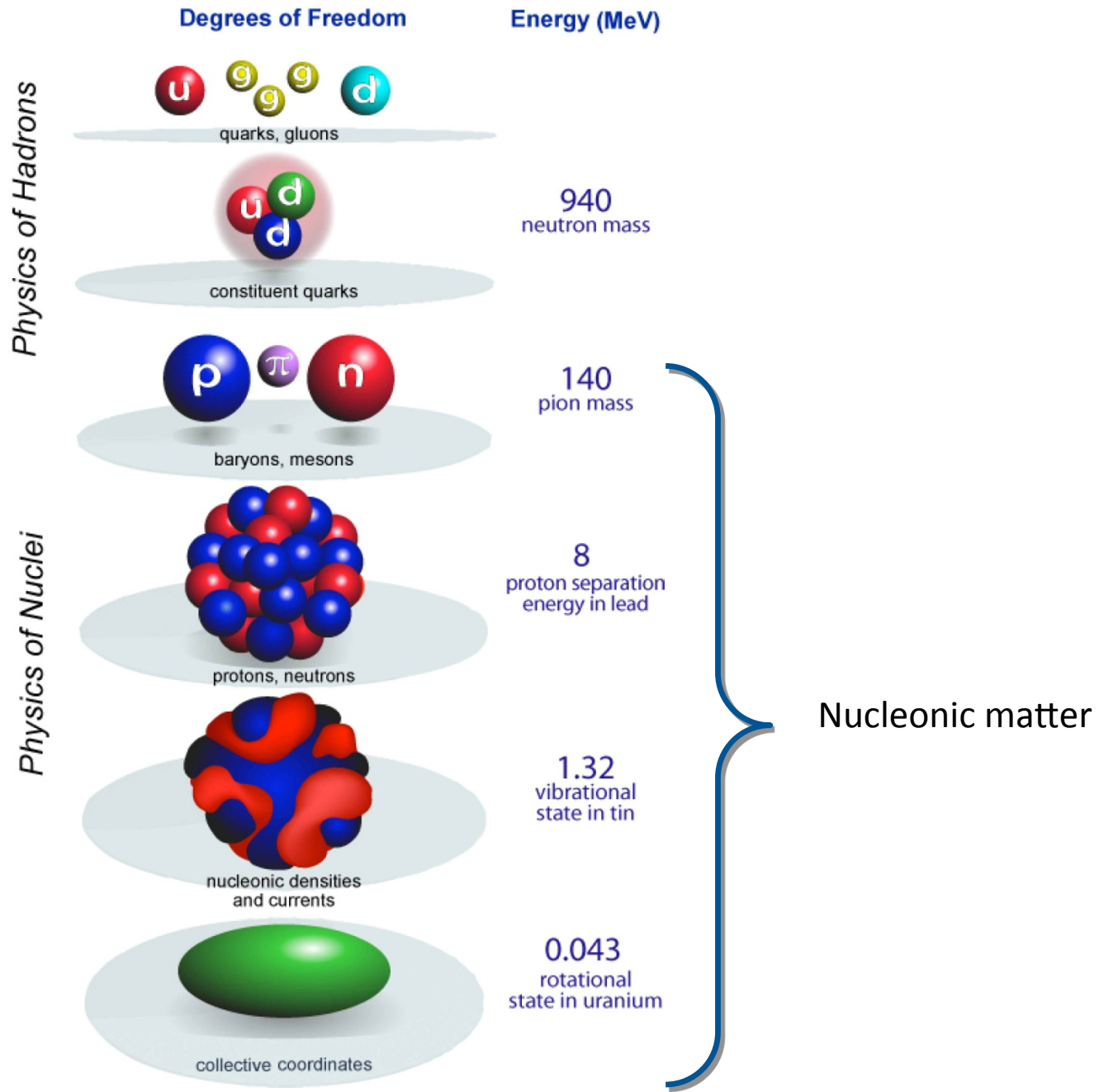
Nuclear Physics: The Core of Matter, The Fuel of Stars. (NRC “Schiffer” Report)



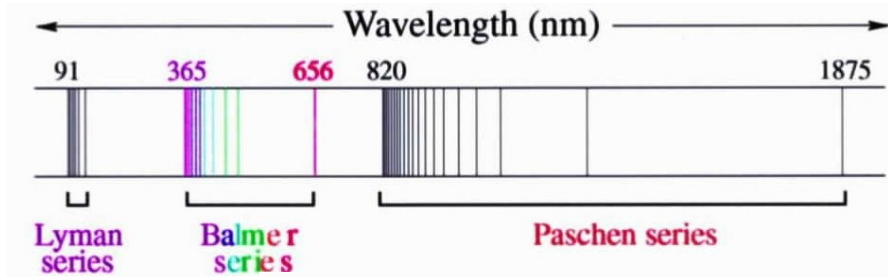
Nuclear Physics: Exploring the Heart of Matter June 2012

- 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 through 2020 and beyond.**

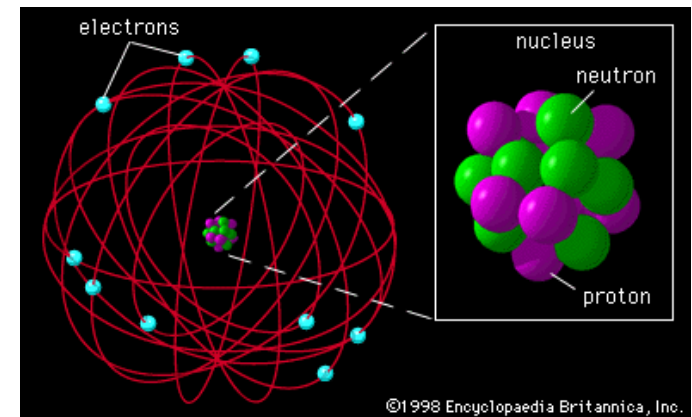
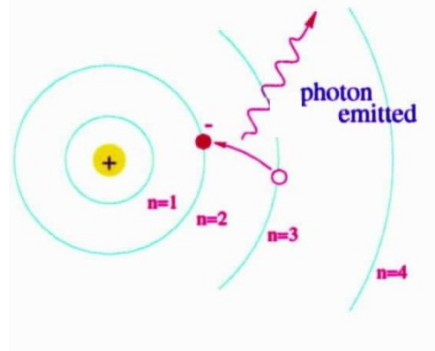
http://www.nap.edu/catalog.php?record_id=13438



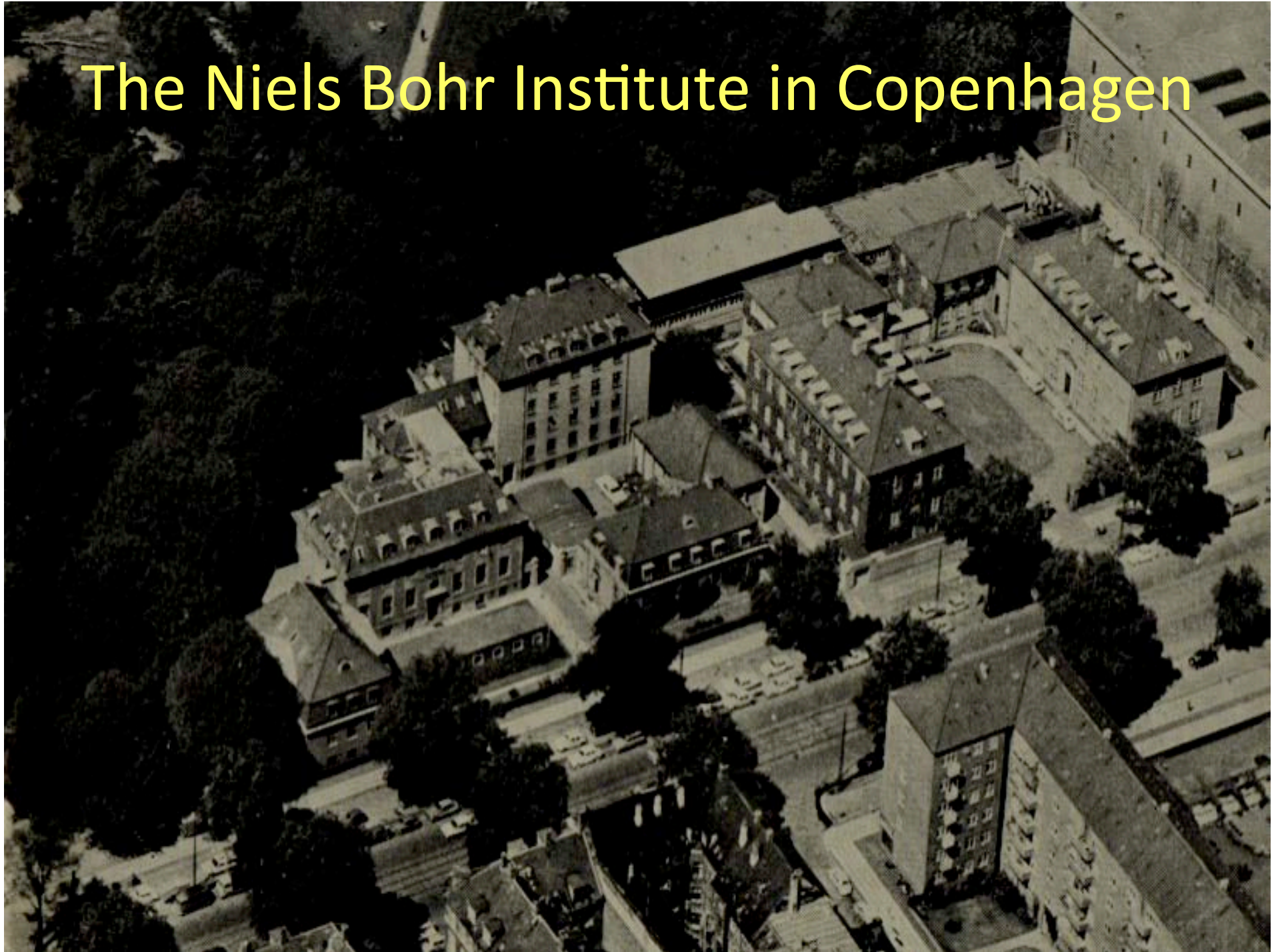
- In 1937 Bohr and Kalckar proposed that we could learn about the structure of nuclei by detecting their gamma-ray emissions.
- The picture of the atomic nucleus that has emerged since this pioneering suggestion is extremely rich, displaying a wealth of static and dynamical facets. It continues to amaze and fascinate!
- The number of nucleons is sufficient in this strongly interacting multi-fermion system (<300) to allow correlations but yet finite.



Bohr Atom



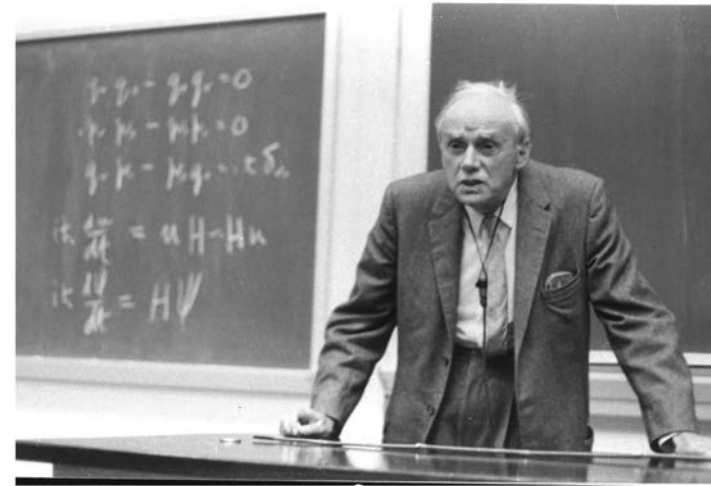
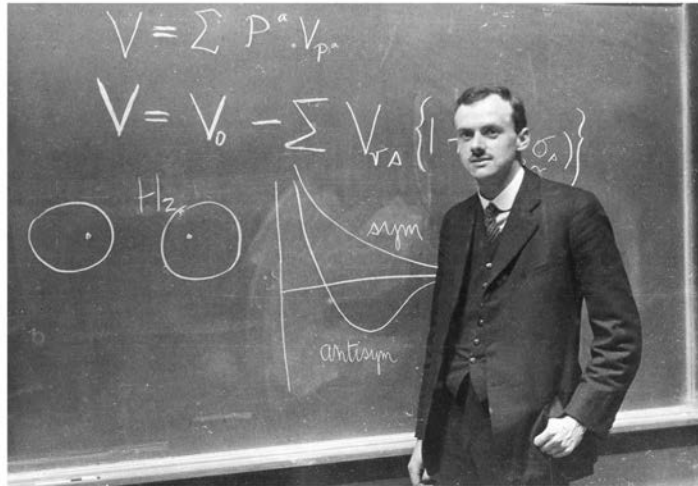
The Niels Bohr Institute in Copenhagen



The Niels Bohr Institute in Copenhagen



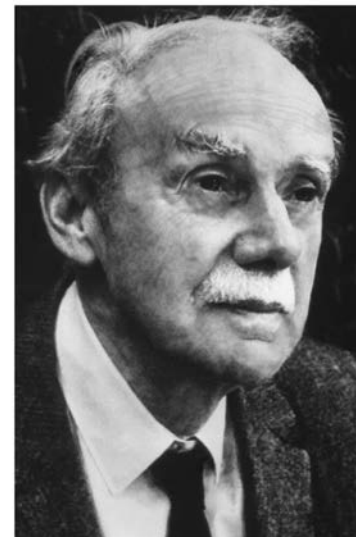
Paul Dirac at Cambridge and FSU



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)

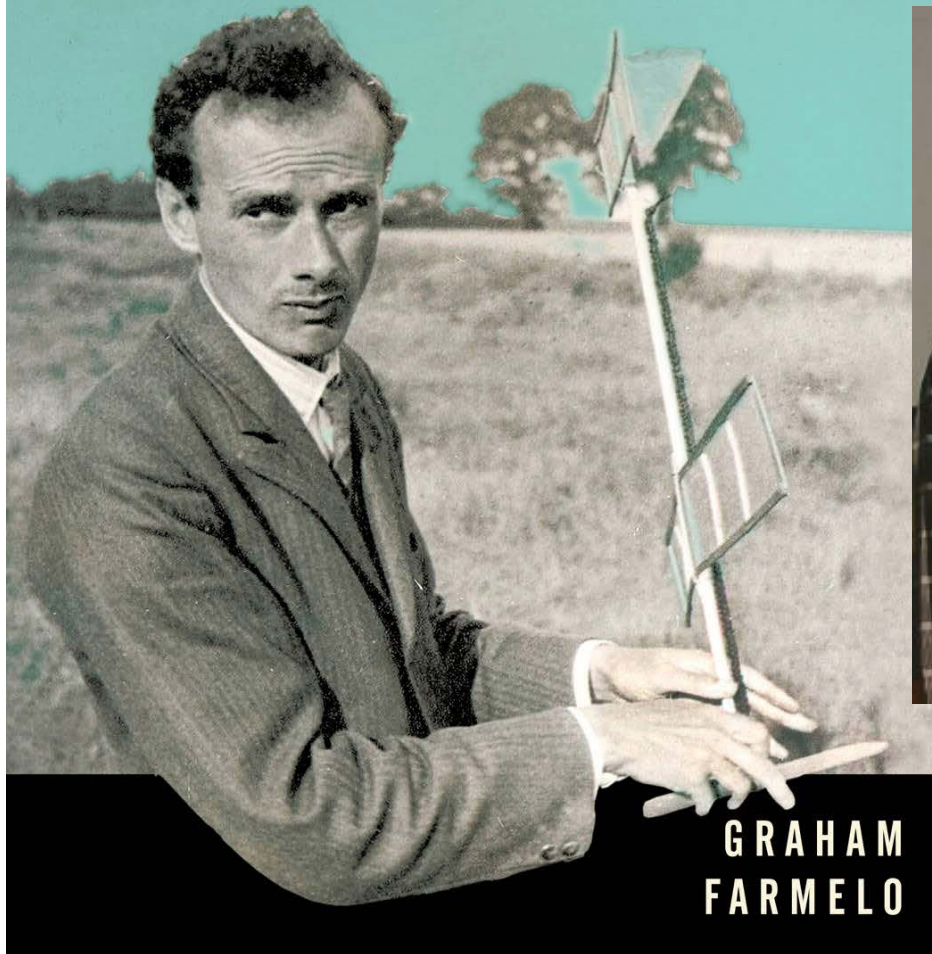
Among other discoveries, he formulated the Dirac equation, which describes the behavior of fermions and which led to the prediction of the existence of antimatter.

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

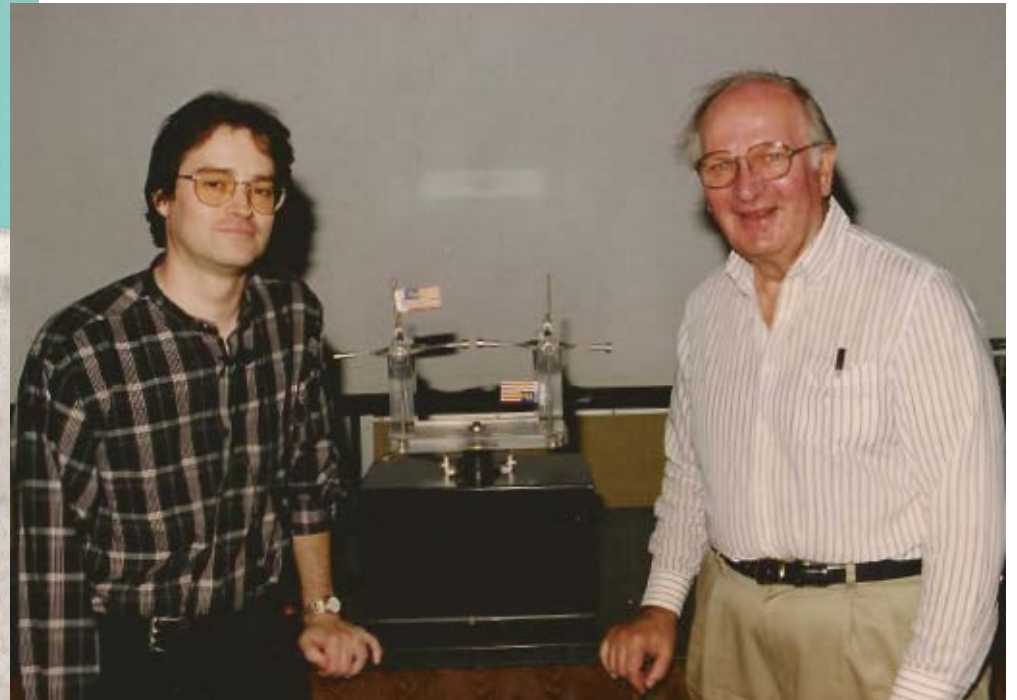
Paul Dirac spent the last fourteen years of his life at Florida State University.

The Strangest Man

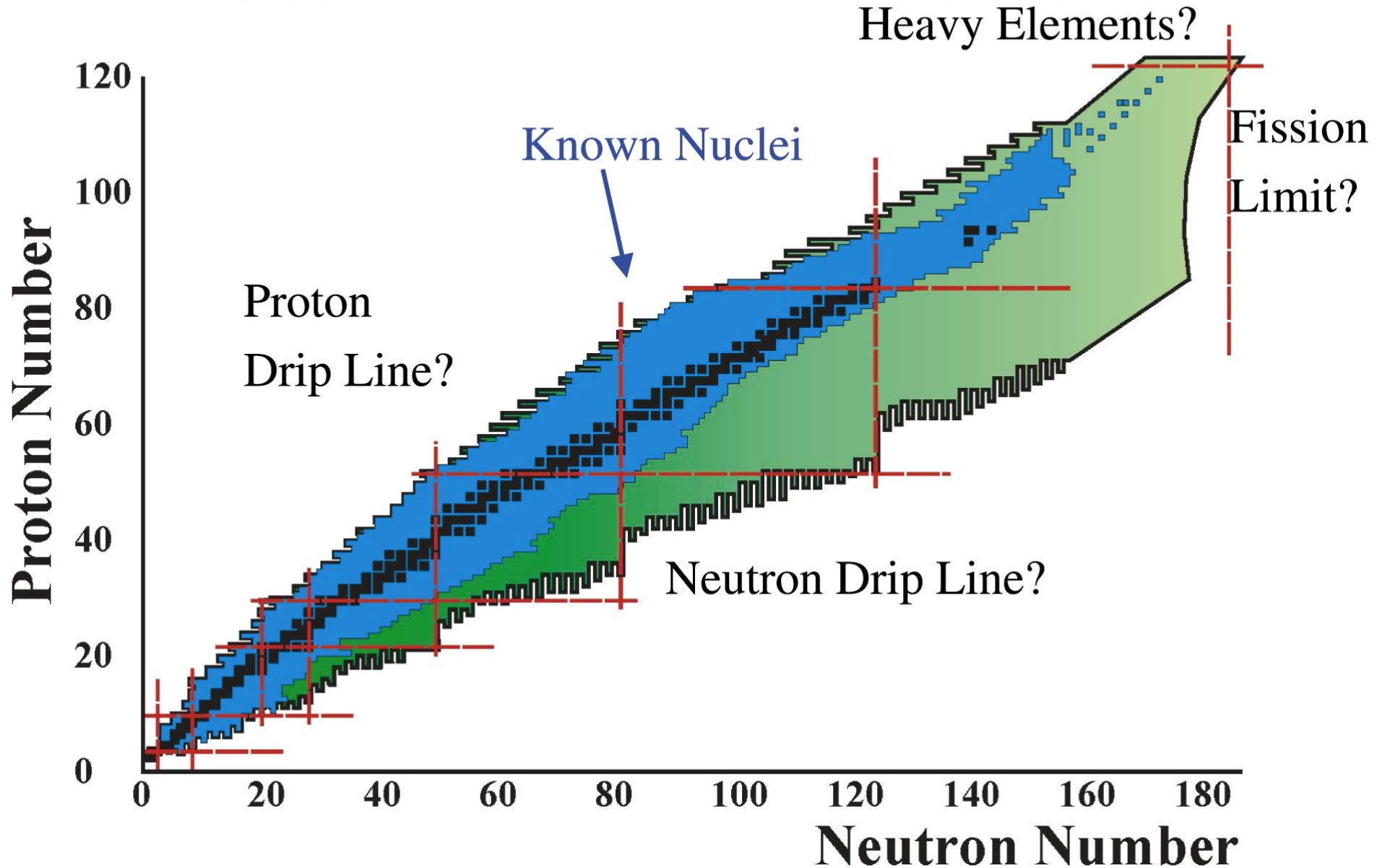
THE HIDDEN LIFE OF PAUL DIRAC,
MYSTIC *of the* ATOM



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

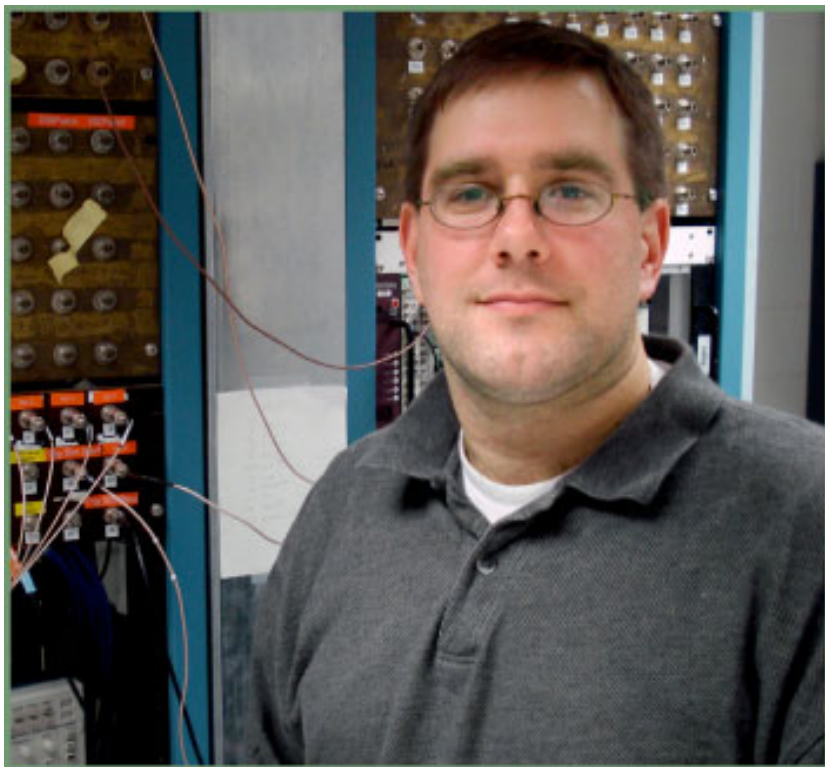


The Chart of the Nuclides



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 10.811	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 65.38	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 (282)	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)		

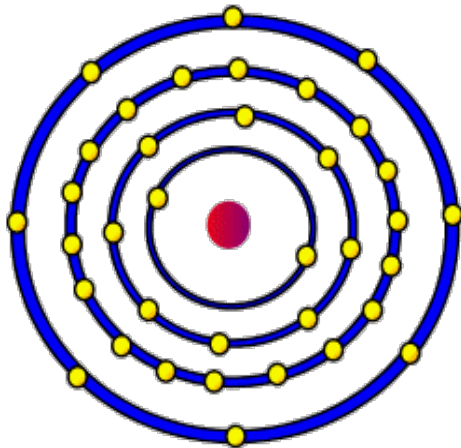
1 H 1.0079																	2 He 4.0026
3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
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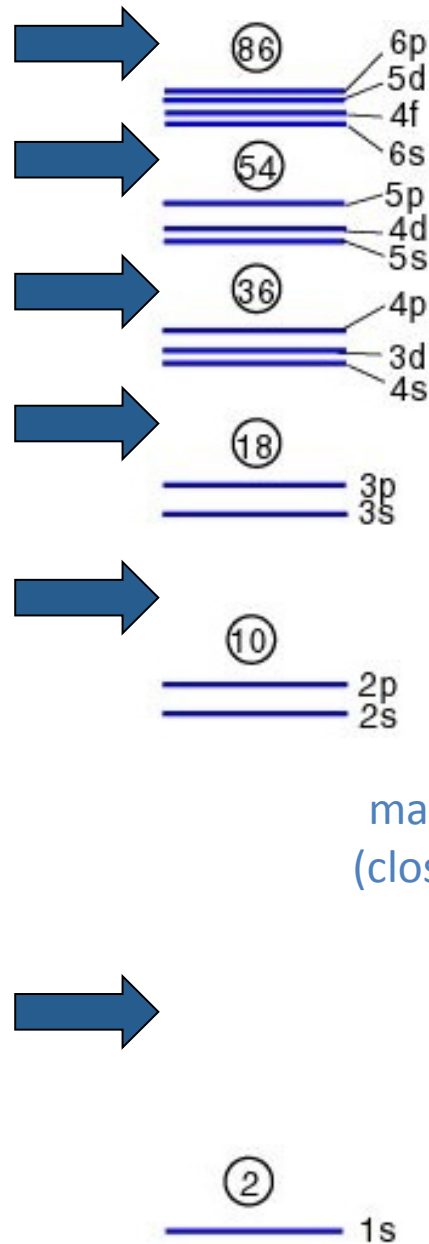
89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)
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Atom:
electron shells

noble gases
(closed shells)



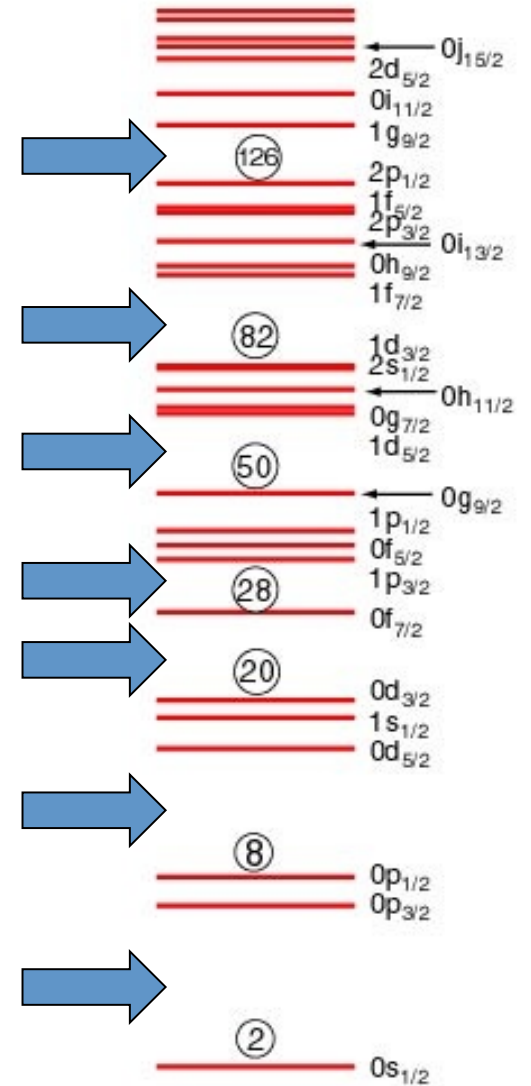
Krypton Atom



magic nuclei
(closed shells)

Shell Model of Atoms

Nucleus:
proton/neutron shells

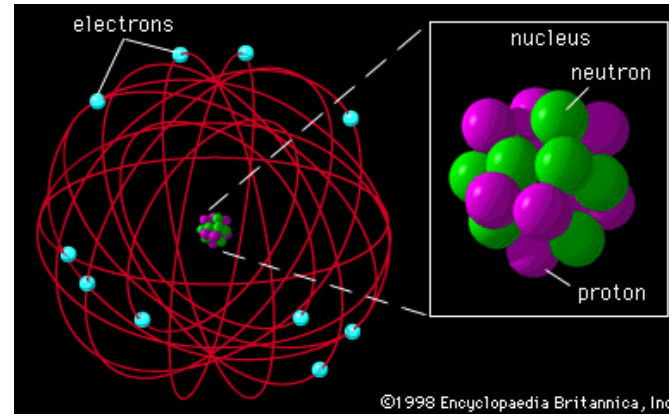


Shell Model of Nuclei

Shell Structure

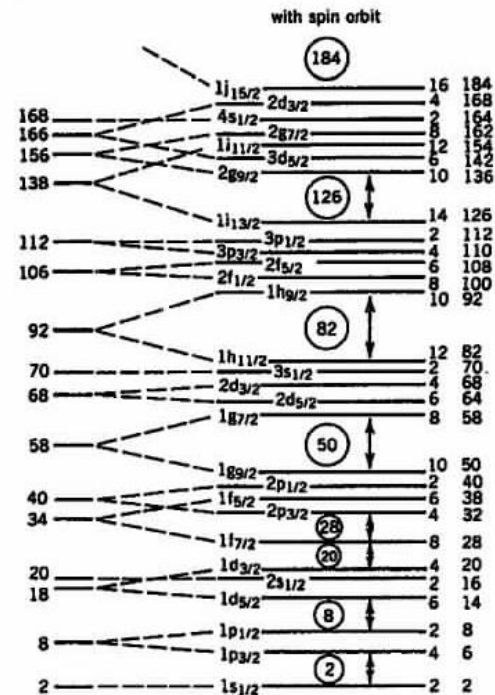
Atomic

Nuclear



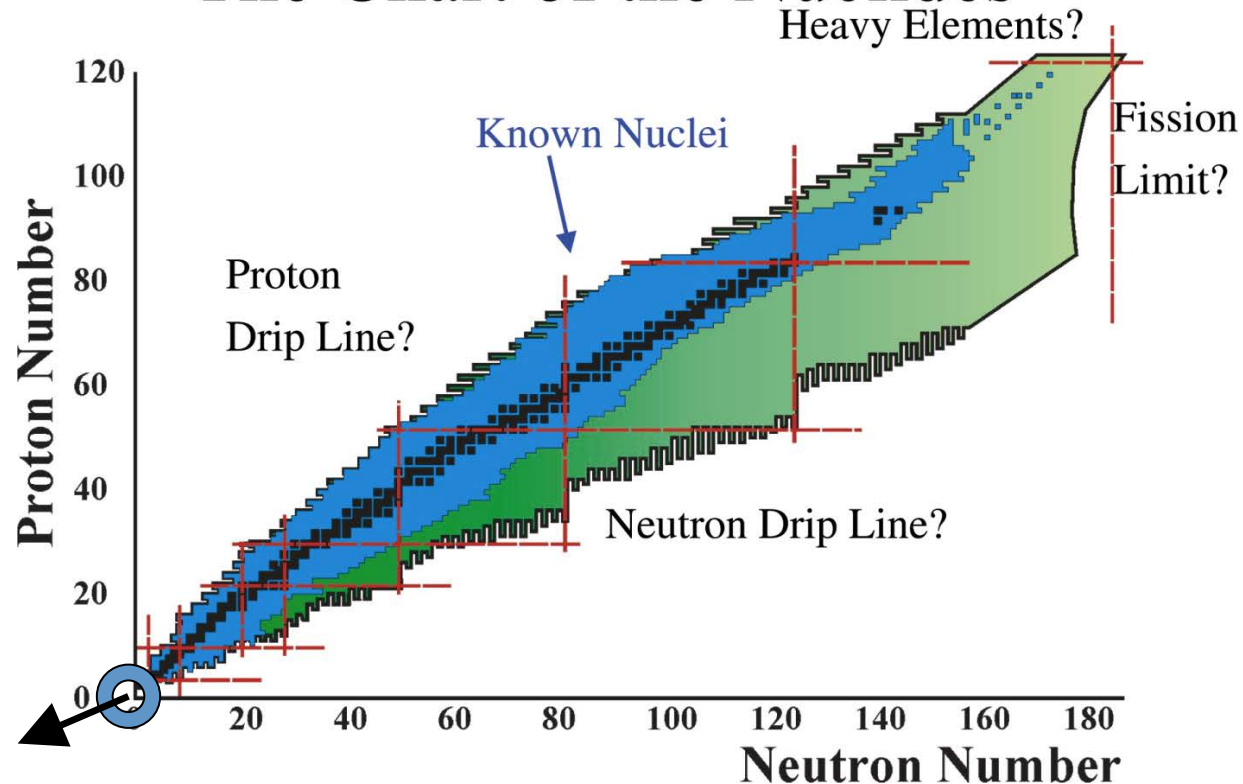
Nucleons

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?

The Chart of the Nuclides



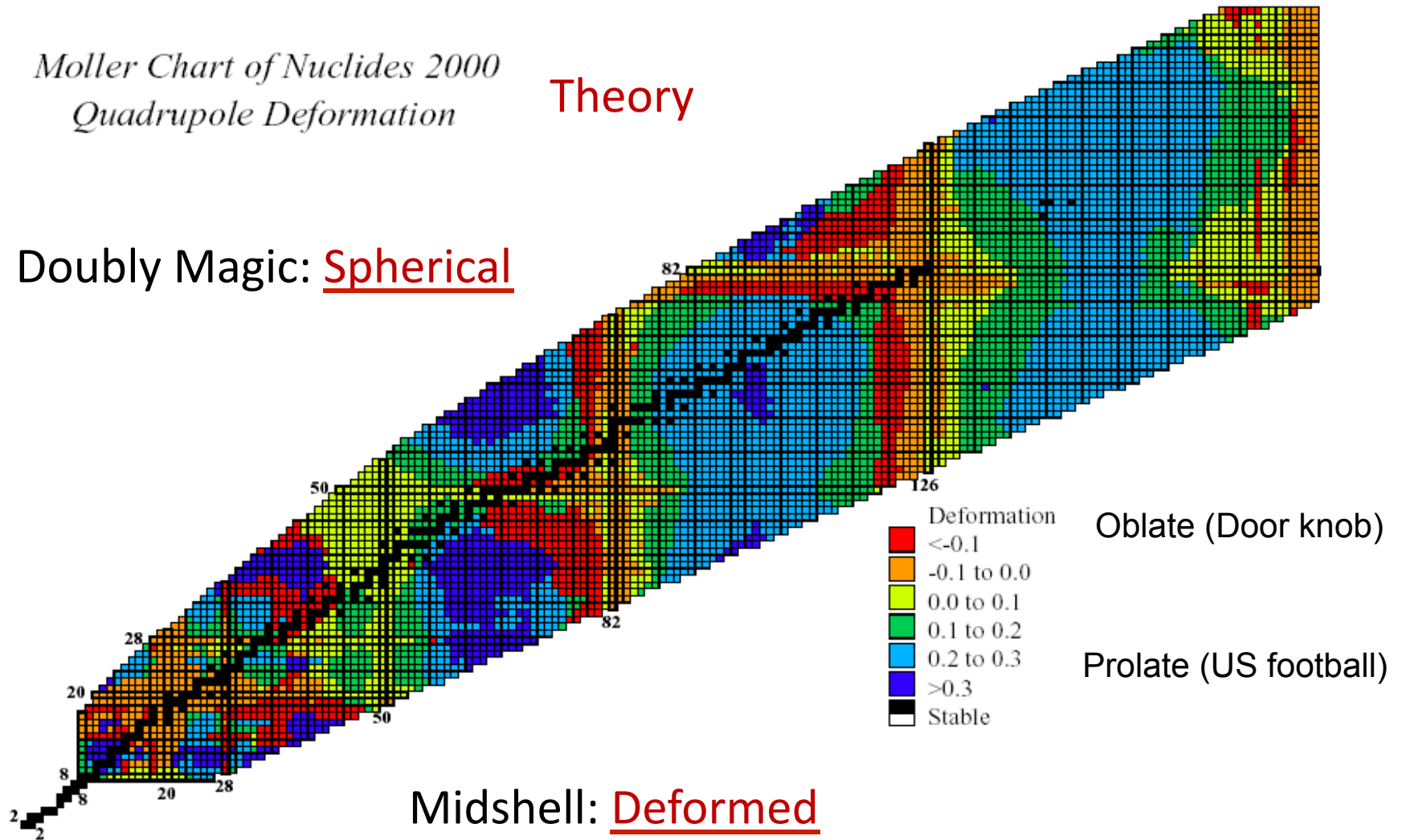
Increasing Angular Momentum and Excitation Energy: An excellent way to investigate nuclear structure, especially to see what the intruder orbitals are doing.

Deformation Systematics

Moller Chart of Nuclides 2000
Quadrupole Deformation

Theory

Doubly Magic: Spherical



Rotation can reveal information about the internal structure!

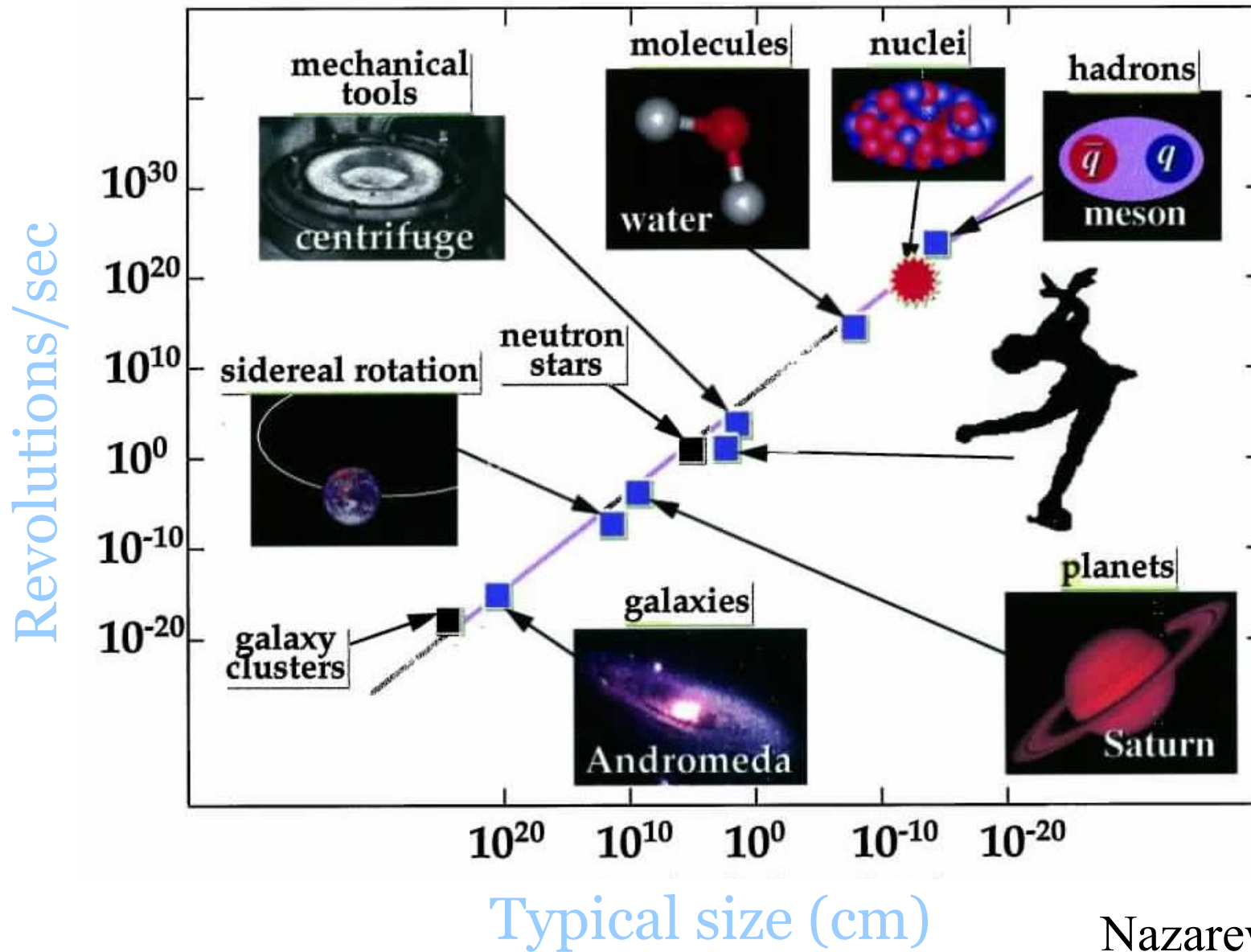
- Hard boiled and soft boiled egg experiment.



Spinning things is fun!

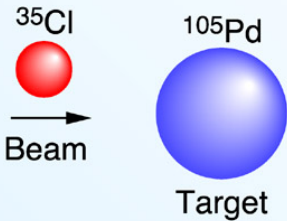
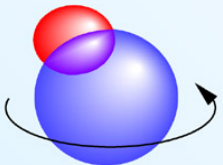
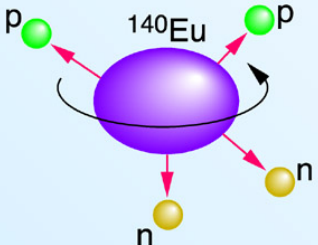
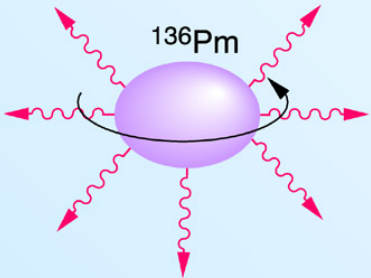



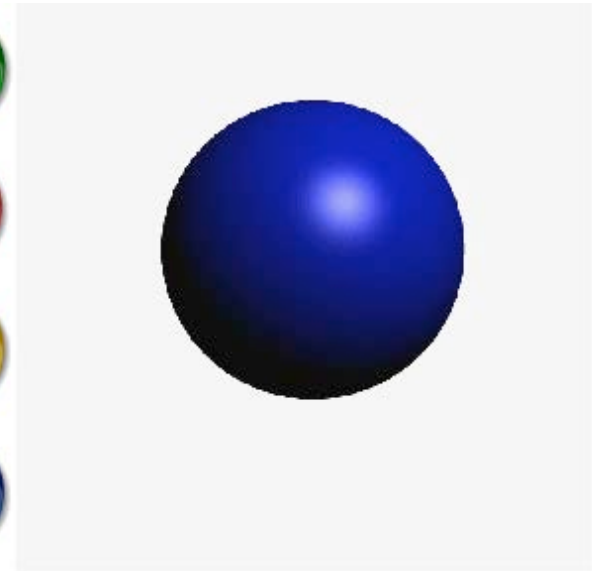
Rotations in the Universe



Nazarewicz

How to Make High Spin Nuclei

		Time Scale	Number of Rotations
1. Preformation		< 0s	0
2. Fusion		10^{-22} s	<1
3. Particle Emission		10^{-19} s	10-100
4. γ -ray Emission		10^{-17} - 10^{-10} s	10^5 - 10^{10}
5. Ground State		10^{-9} s	10^{11}



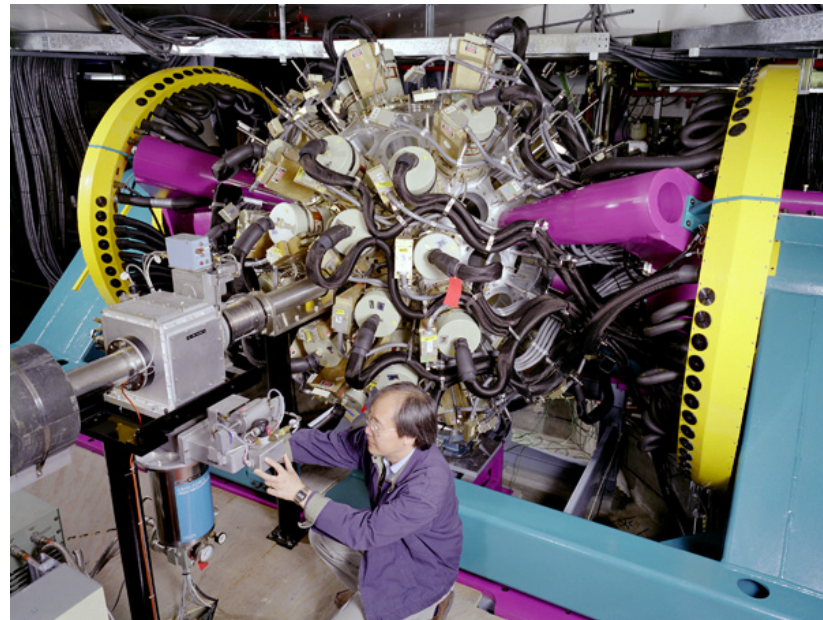
- Need to catch as many of the γ rays in each cascade as possible.

- **Need efficient detector systems!**

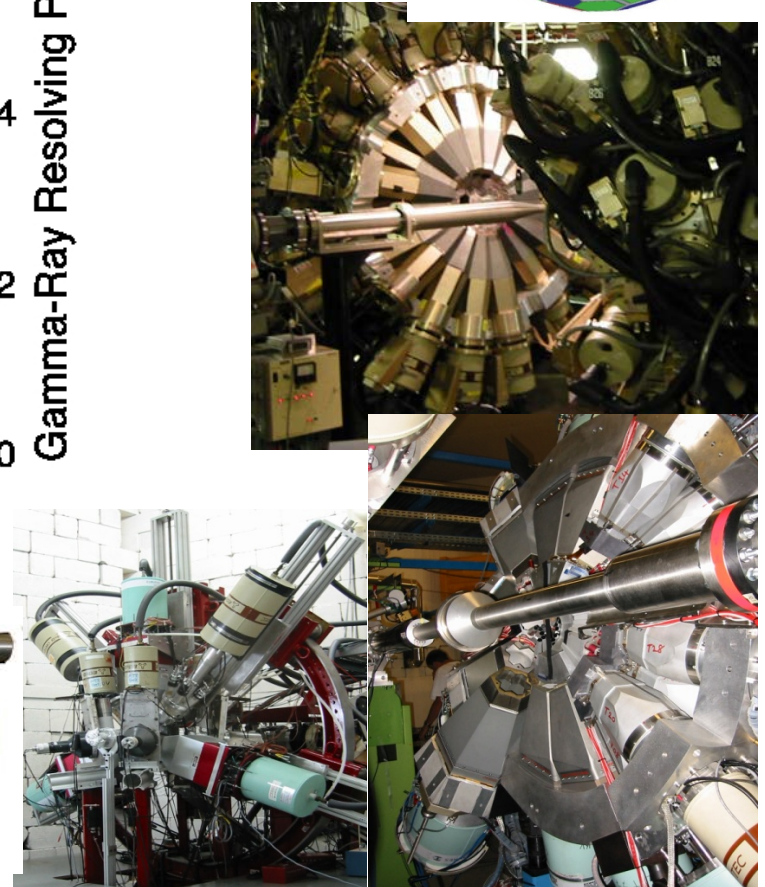
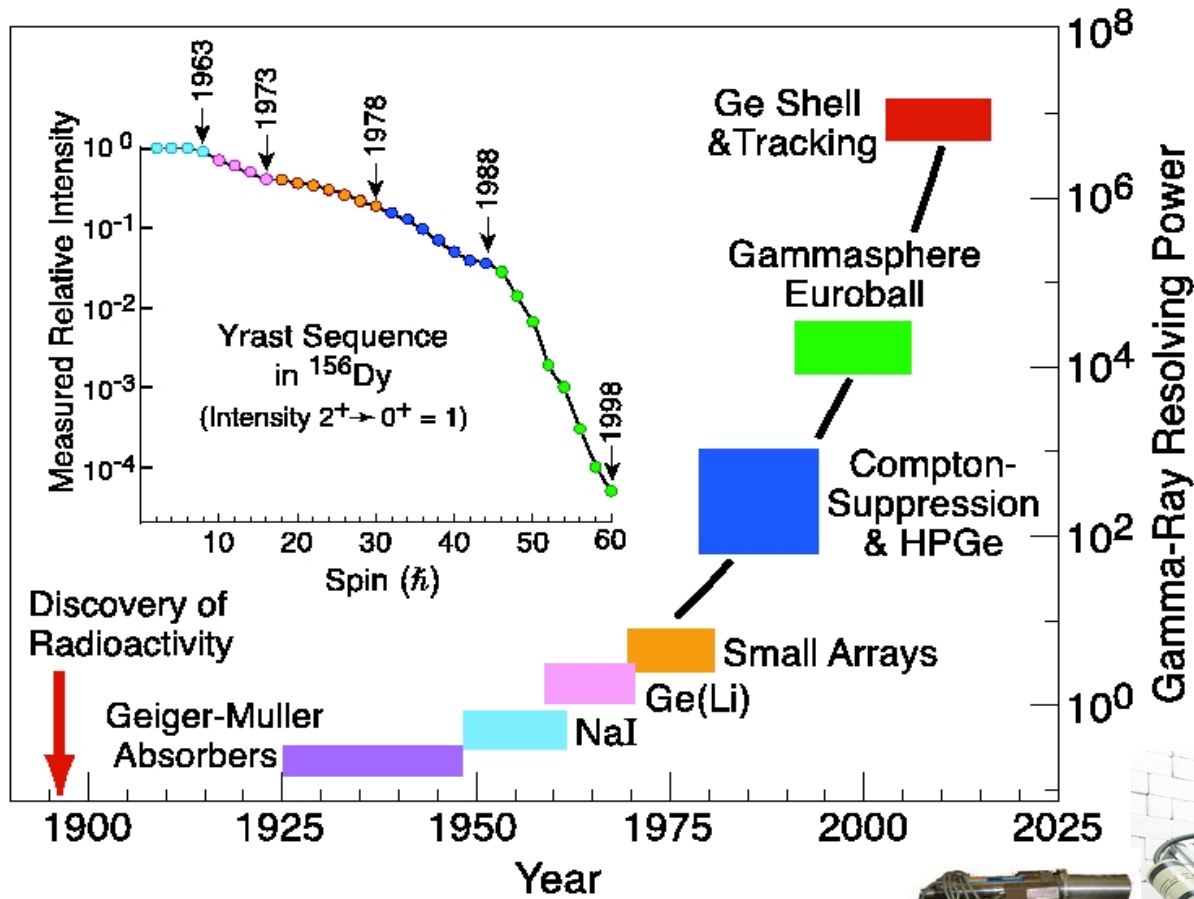
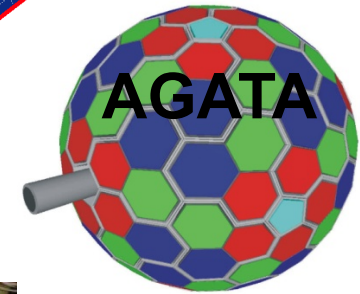


- In nuclear reactions, eg, fusion evaporation, when we create our hot, excited, rapidly rotating nuclei we need to catch as many of the γ rays emitted in each cascade or flash as possible.

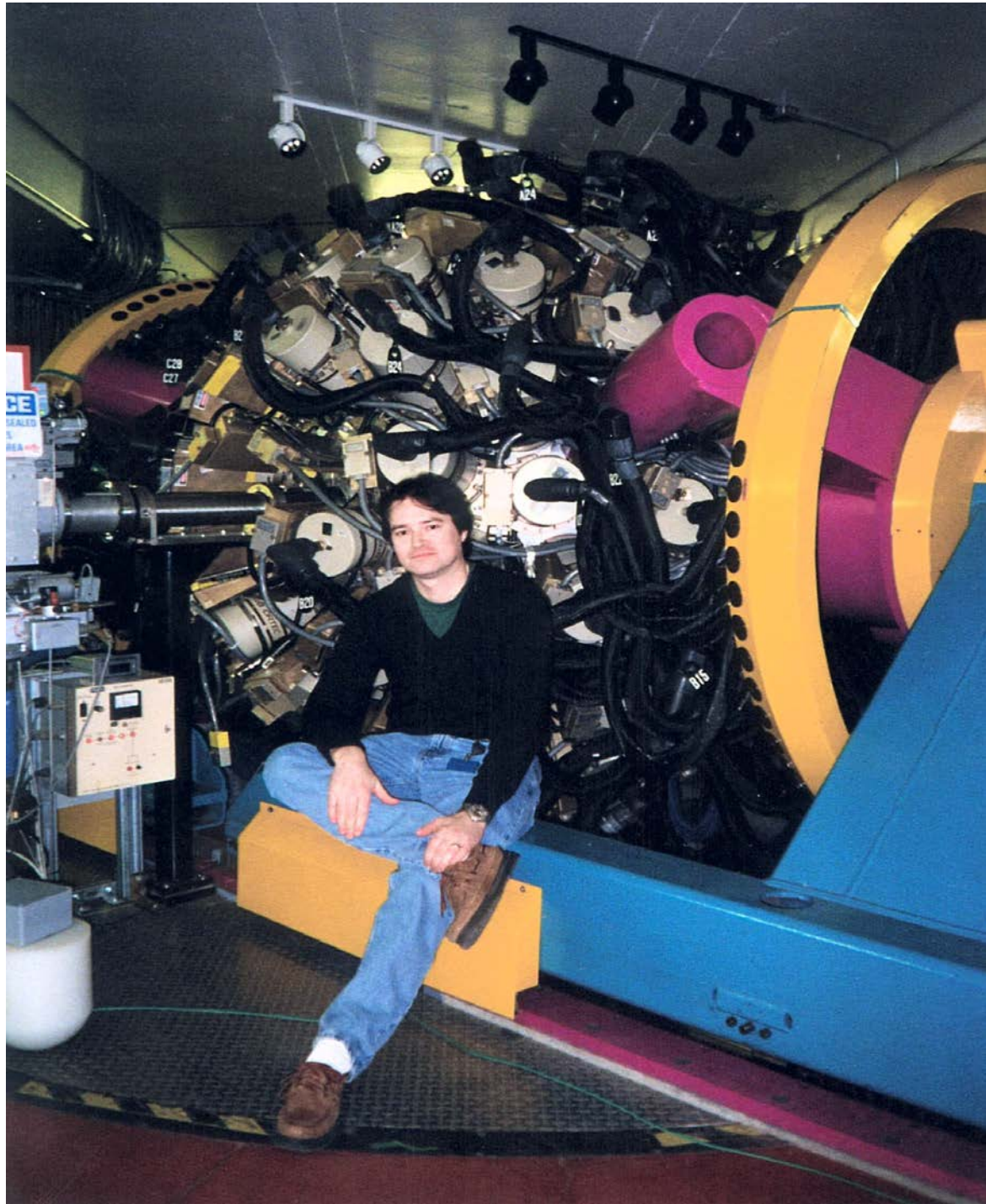
- Need efficient detector systems!

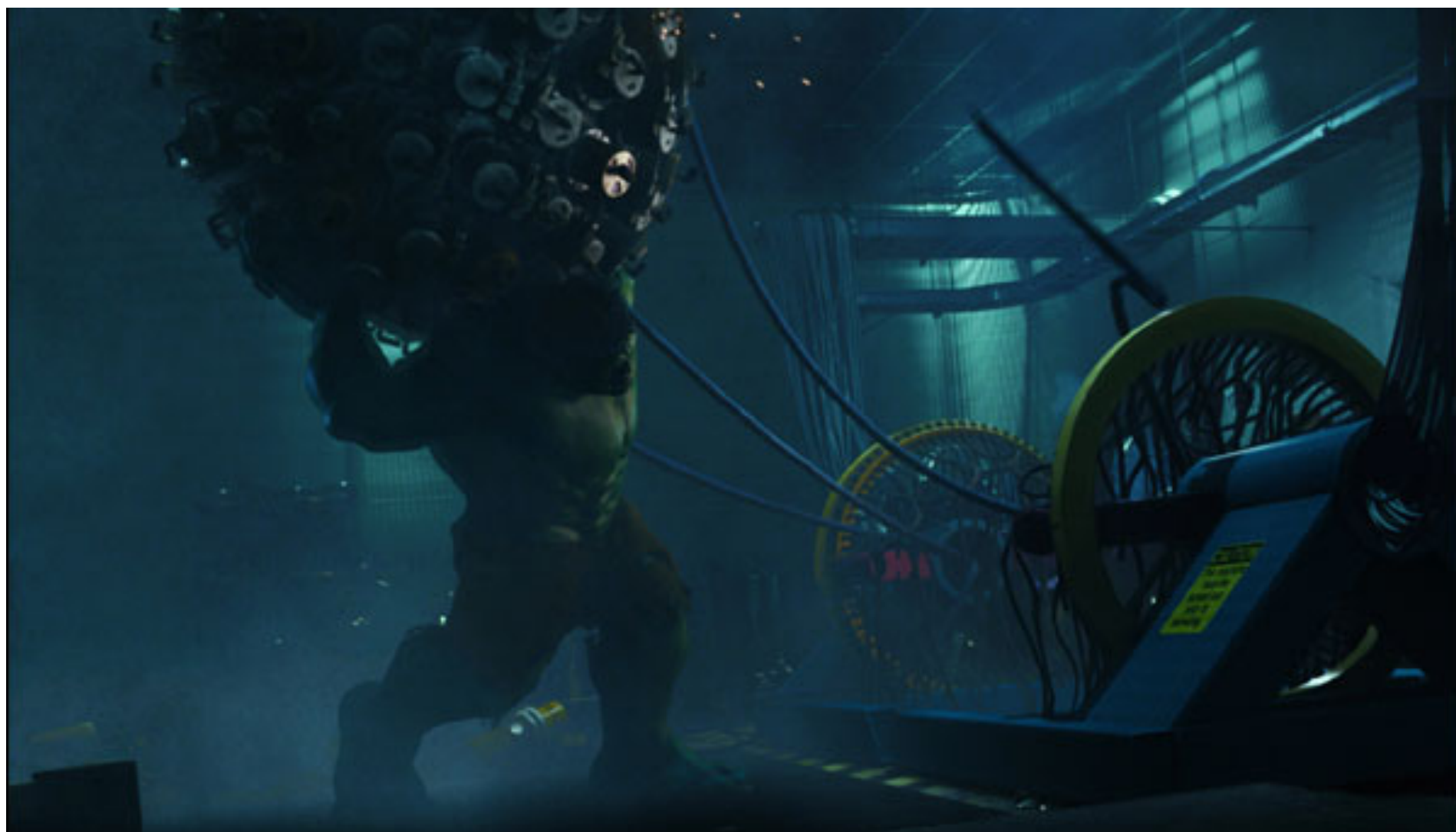


Gamma-Ray Detection Evolution



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





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

Credit: ILM/Universal

The GAMMASPHERE Collaboration

The following table lists the participating institutions and their respective countries, as shown in the graphic:

Country	Institution(s)
USA	Argonne Nat. Lab., Univ. of Arizona, Brookhaven National Lab., Univ. of California-Davis, Univ. of California-Berkeley, Carnegie-Mellon Univ., Univ. of Connecticut, Duke Univ., Florida State Univ., Georgia Tech, Idaho Nat. Eng. Lab., Iowa State Univ., Univ. of Kansas, Univ. of Kentucky, Lawrence Berkeley Nat. Lab., Lawrence Livermore Nat. Lab., Los Alamos National Lab., Univ. of Maryland, Univ. of Mass. at Lowell, Univ. of Michigan, Michigan State Univ., Mississippi State Univ., North Carolina State Univ., Univ. of Notre Dame, Oak Ridge Nat. Lab., Oregon State Univ., Univ. of Pennsylvania, Univ. of Pittsburgh, Purdue Univ., Univ. of Rochester, Rutgers Univ., SUNY-Stony Brook, Tennessee Tech Univ., Univ. of Tennessee, Texas A & M Univ., Tulane Univ., UNIRIB, Vanderbilt Univ., Washington Univ., Univ. of Washington, Wayne State Univ., Yale Univ.
Sweden	KTH-Stockholm, Univ. of Lund, MSI-Stockholm, RIT-Stockholm, TSI-Uppsala, CTH-Gothenburg
Canada	AECL-Chalk River, McMaster Univ., Univ. of Ottawa, Univ. of Toronto
UK	Univ. of Brighton, CLRC-Daresbury, Univ. of Edinburgh, Univ. of Liverpool, Univ. of Manchester, Univ. of Surrey, Univ. of York
France	Univ. of Claude Bernard, ISN-Grenoble, CRN-Strasbourg, CSNSM-Orsay, IPN-Orsay, ILL-Grenoble
Germany	Univ. of Bonn, Univ. of Cologne, GSI-Darmstadt, HMI-Berlin, Max-Planck Inst. Rossendorf, Univ. of Munich
Poland	IBJ-Krakow, IPJ-Warsaw
Italy	LNL-Legnaro, Univ. of Padova
Japan	AERI Japan, IDAC Tohoku Univ.
Israel	The Weizman Inst.
Brazil	Univ. Fed. Rio de Janeiro, Univ. de Sao Paulo
Finland	Univ. of Jyvaskyla
South Korea	Chung-Ang Univ., Hallym Univ.
Russia	JINR-Dubna
South Africa	NAC - Faure
China	Tsinghua Univ.
India	INR-Debreccen
Romania	IPNE-Bucharest
Hungary	KVI-Groningen
Argentina	CNEA
Greece	Inst. of Nuc. Research, INP-Athens
Denmark	NBI-Copenhagen
Australia	ANU-Canberra

~100 institutions, ~25 nations

Experimental Nuclear Facilities

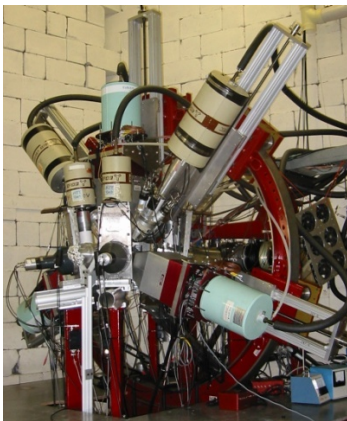
John D Fox Superconducting Accelerator Laboratory



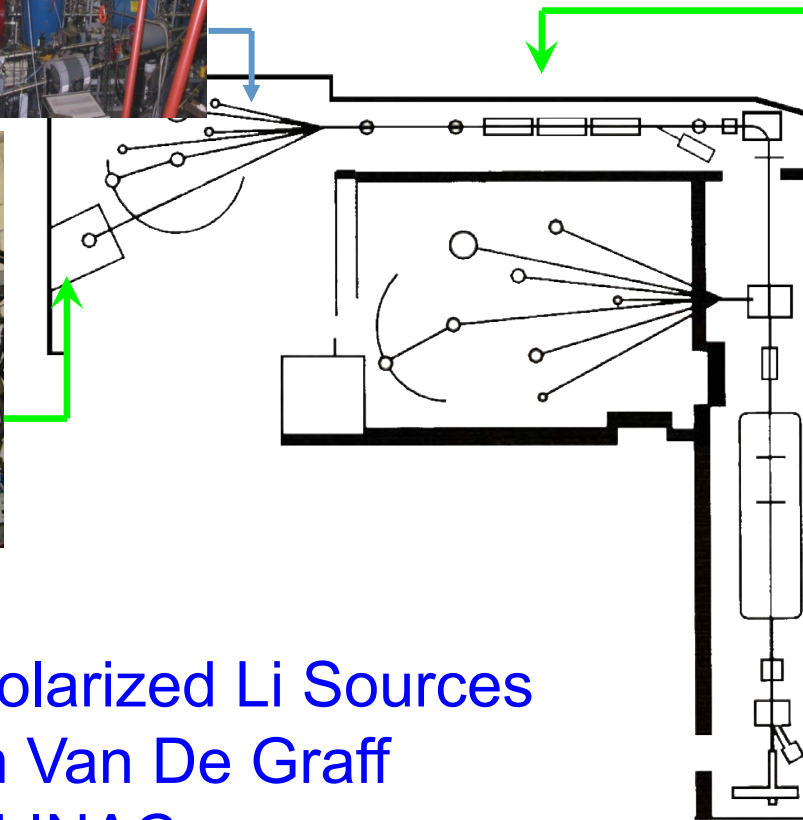
Resolut



LINAC

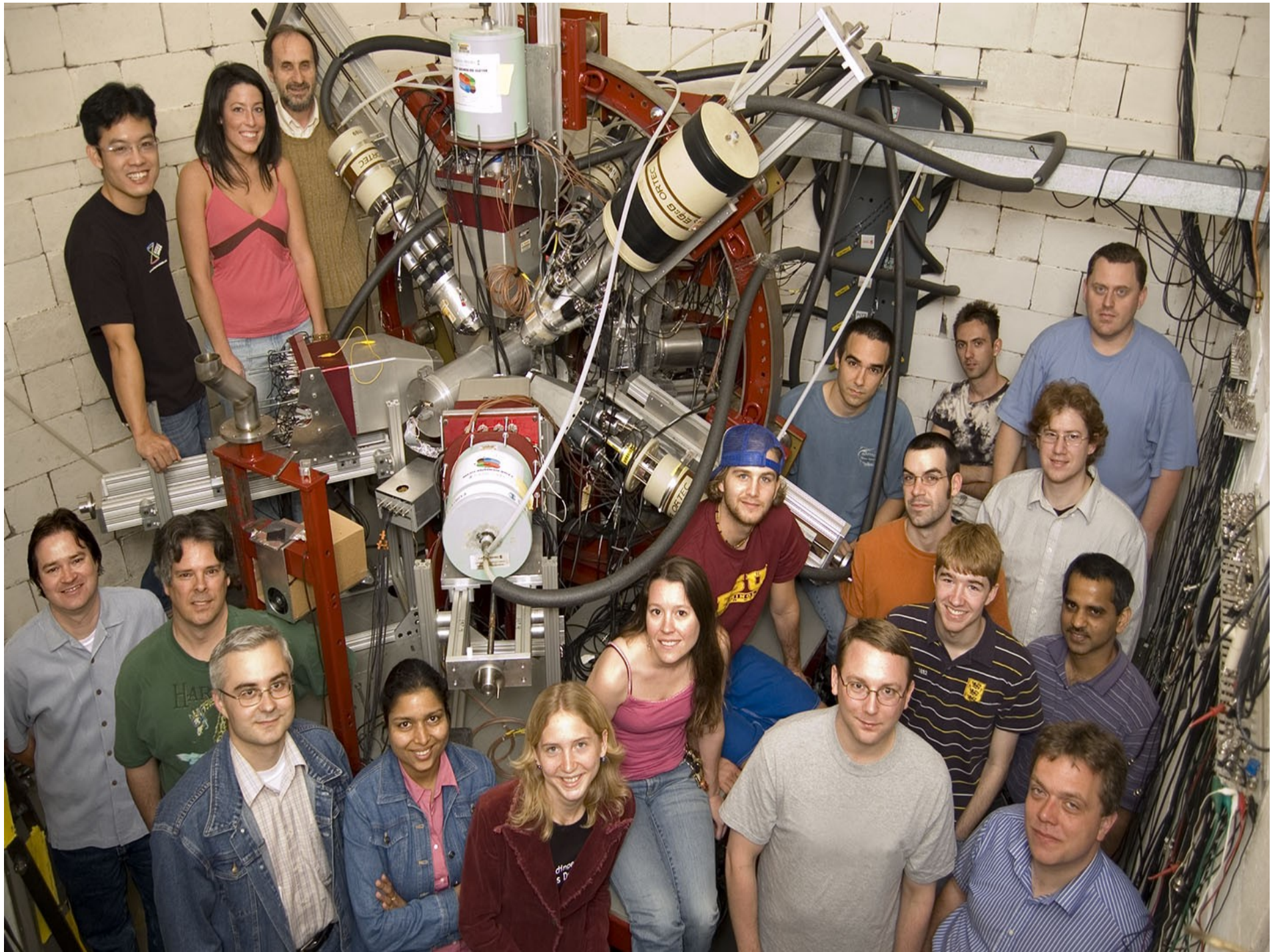


γ ray Array

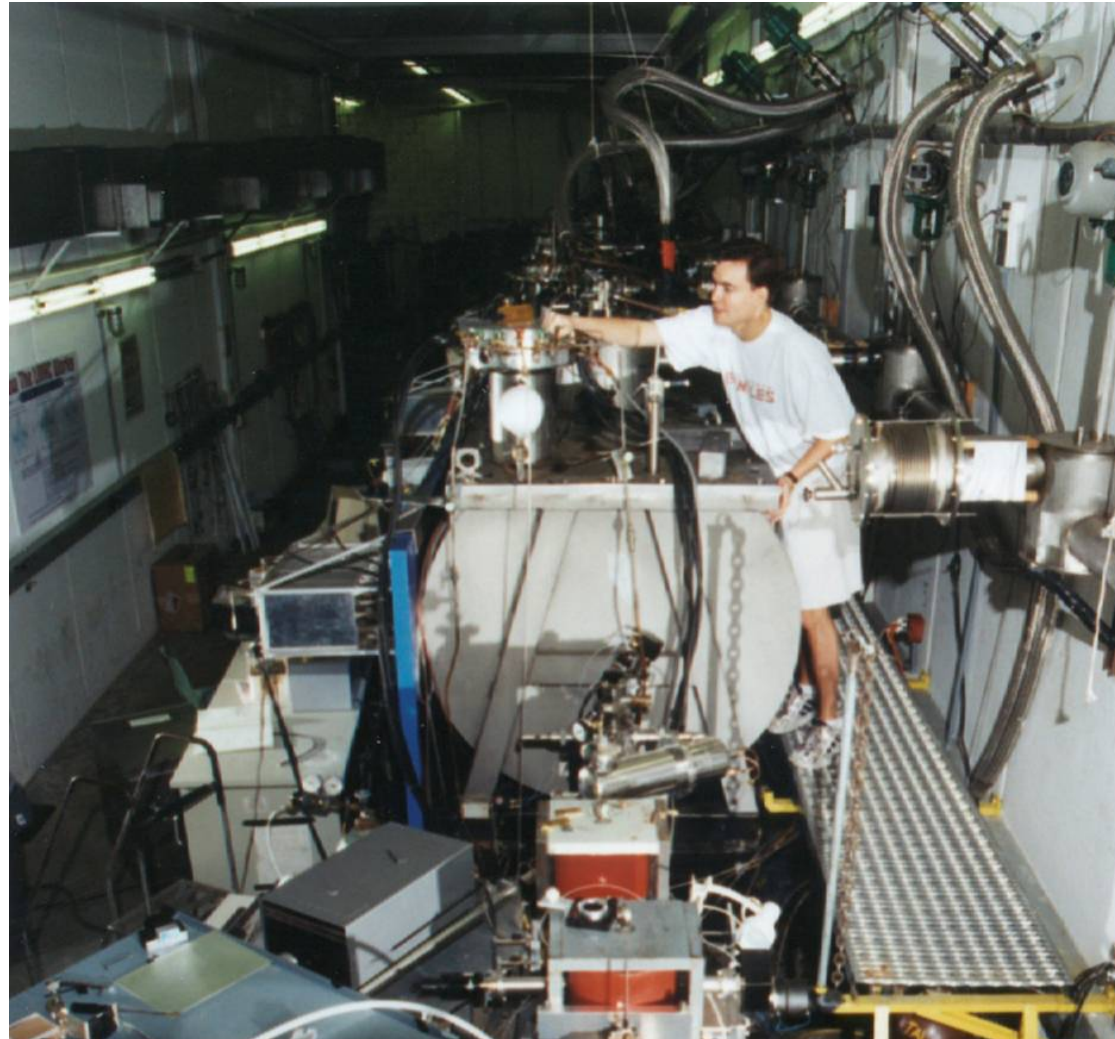


Tandem

- 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.

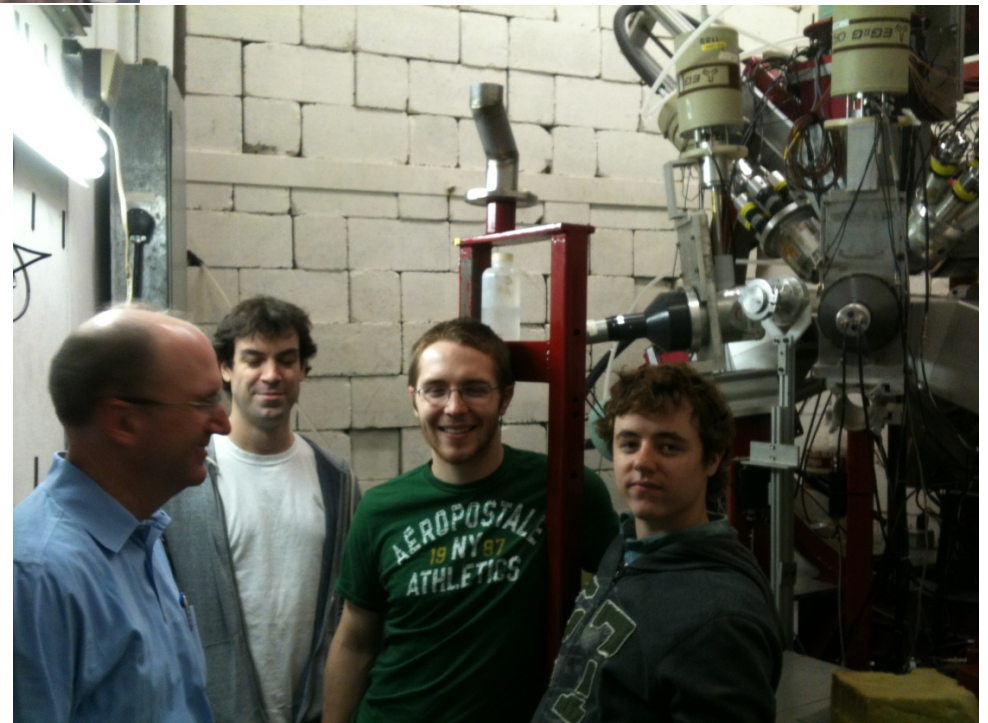
Many go into careers at Nat. Labs





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.

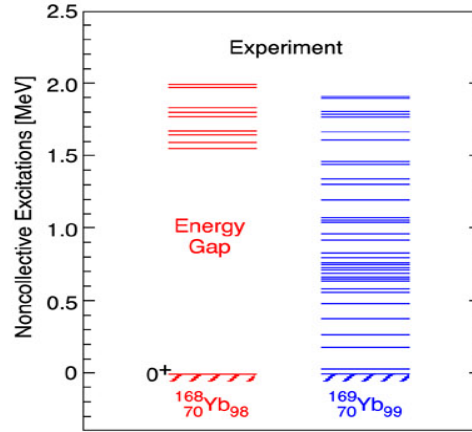
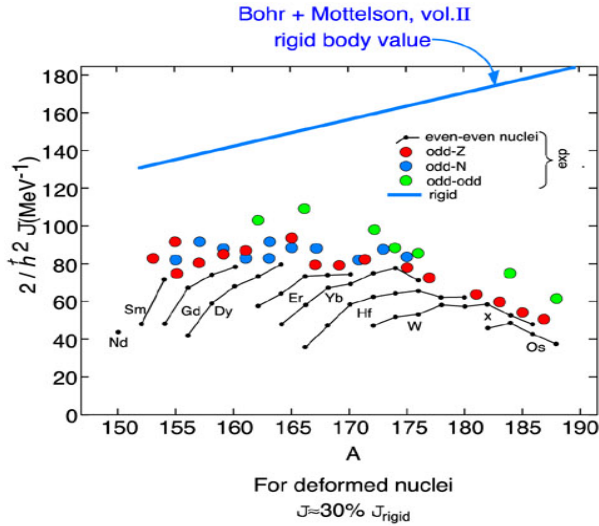
In Fall 2010 I invited Dan back to speak to the new crop of students. Here he is back in the Gamma Cave encouraging the students to work hard and finish their PhD studies because the country needs their expertise and there are jobs out there!



Backbending

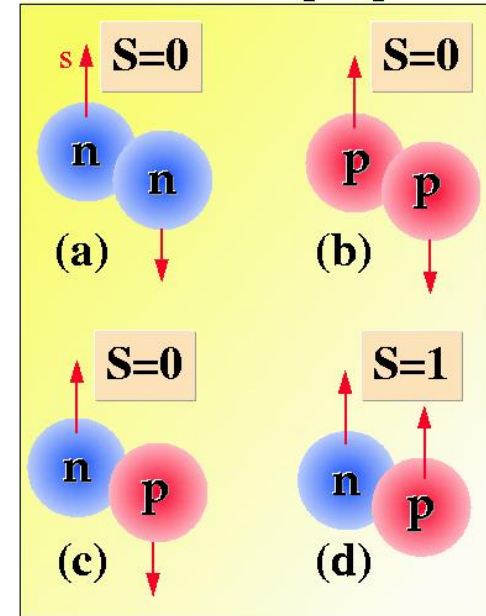
Nuclear Superfluidity and Rotation

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



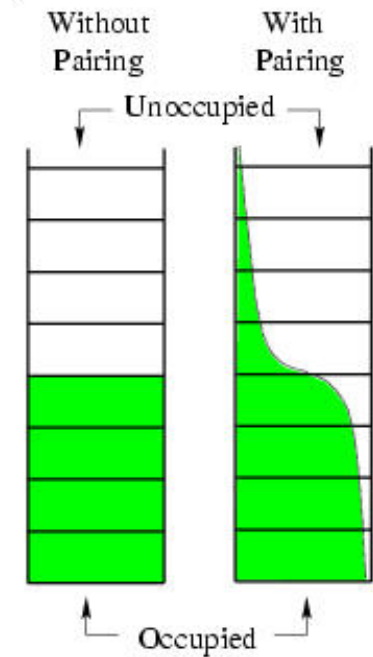
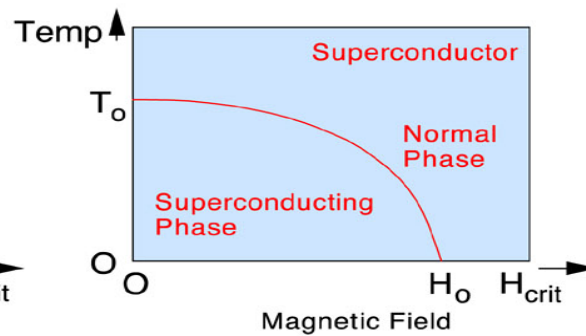
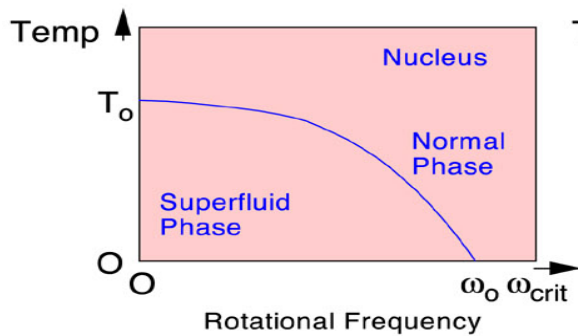
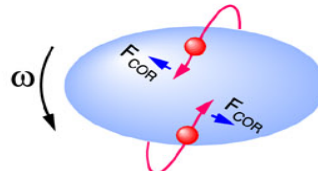
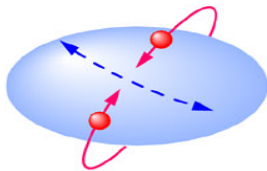
For even-even nuclei $I_{g.s.}^{\pi}=0^+$ and show a large energy gap as compared to odd-nuclei.

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).



BLISDANGVEJ 17, 1300 EDENHAVN Ø
 TELEFON: DR. 179, 161
 TELEGRAMADR. FYSICUM, EDENHAVN

16 October, 1970

Dear Arne and Hans,

Thank you for the proposal, which indeed makes a very exciting story. It appears that you have rather convincing evidence for the occurrence of something quite remarkable for angular momentum values in the region $I \approx 16$; this is admitted, perhaps, even more dramatically in the case of the moment of inertia as a function of the rotational frequency (the enclosed figure). The frequency is defined by the canonical angular momentum appropriate for an axial symmetric rotor:

$$\omega = \frac{1}{4\pi I(I+1)}$$

or

$$\omega^2 = 4 I(I+1) \left(\frac{dE}{dI(I+1)} \right)^{-1}$$

In the last expression, the energy derivative is taken from the observed transition energies:

$$\left(\frac{dE}{dI(I+1)} \right)_{I(I+1) = I_1^2 - I_1 + 1} = \frac{E(I_1) - E(I_1 - 1)}{I_1^2 - I_1 + 1}$$

The moment of inertia is also defined in terms of the derivative of the observed energy:

$$\frac{dI}{d\omega} = \left(\frac{dE}{dI(I+1)} \right)^{-1}$$

Another interesting feature of your data concerns the value of \mathcal{J} at the single point. If the pairing correlation were to completely disappear, one would expect $\mathcal{J} = \mathcal{J}_0$, since the transition frequency for neutrons and protons may be quite

$$\mathcal{J} = \frac{1}{2} (I_1(I_1+1) + (I_1-1)(I_1-2))$$

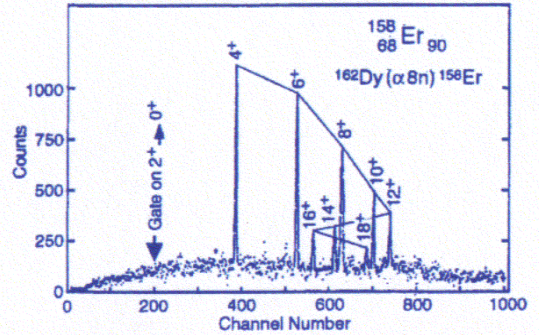
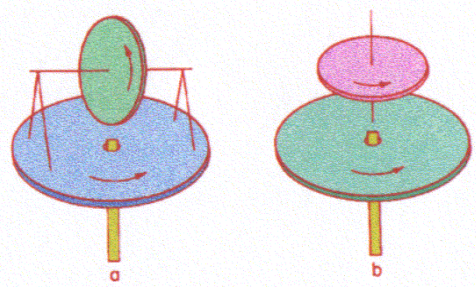
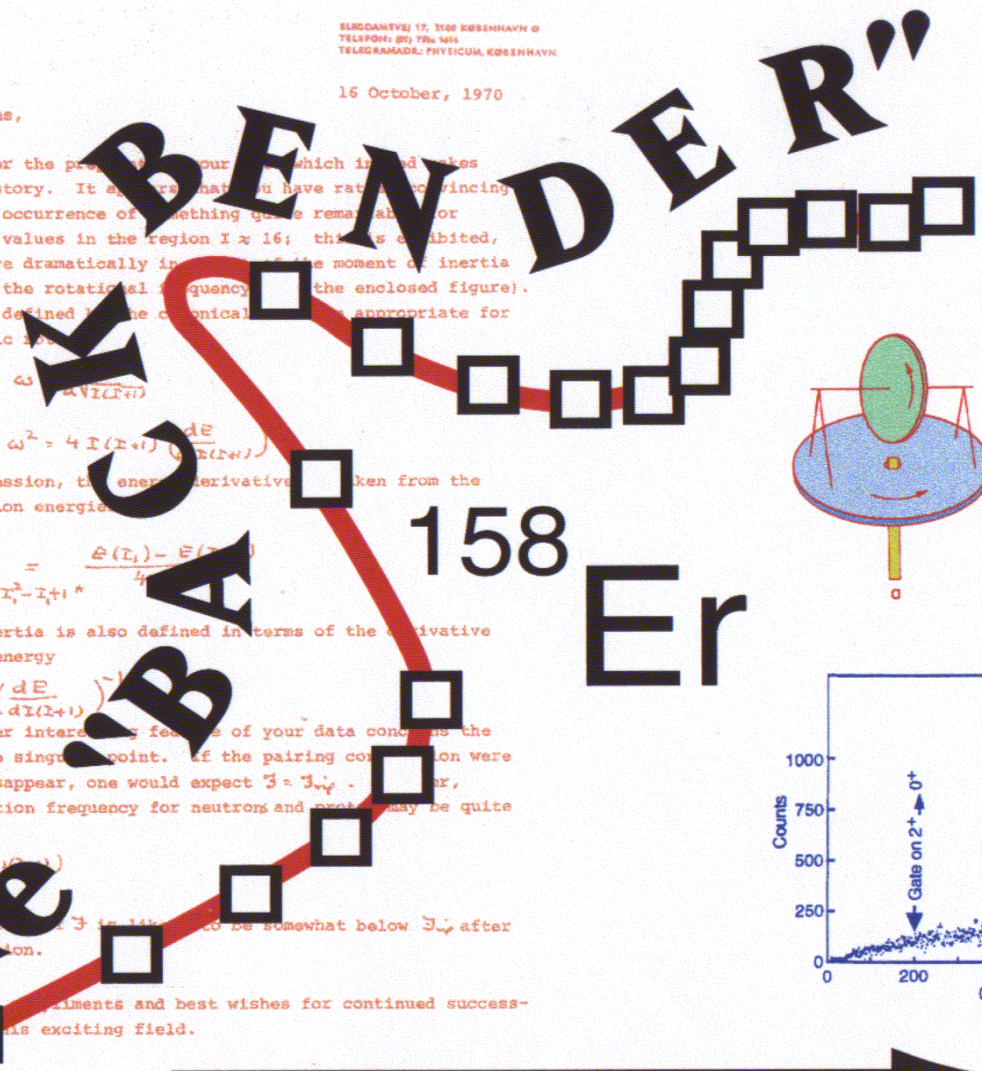
As you can see, \mathcal{J} is likely to be somewhat below \mathcal{J}_0 after the first transition.

We send our compliments and best wishes for continued successful hunting in this exciting field.

A. Bohr
 A. Bohr

B. Mottelson
 B. Mottelson

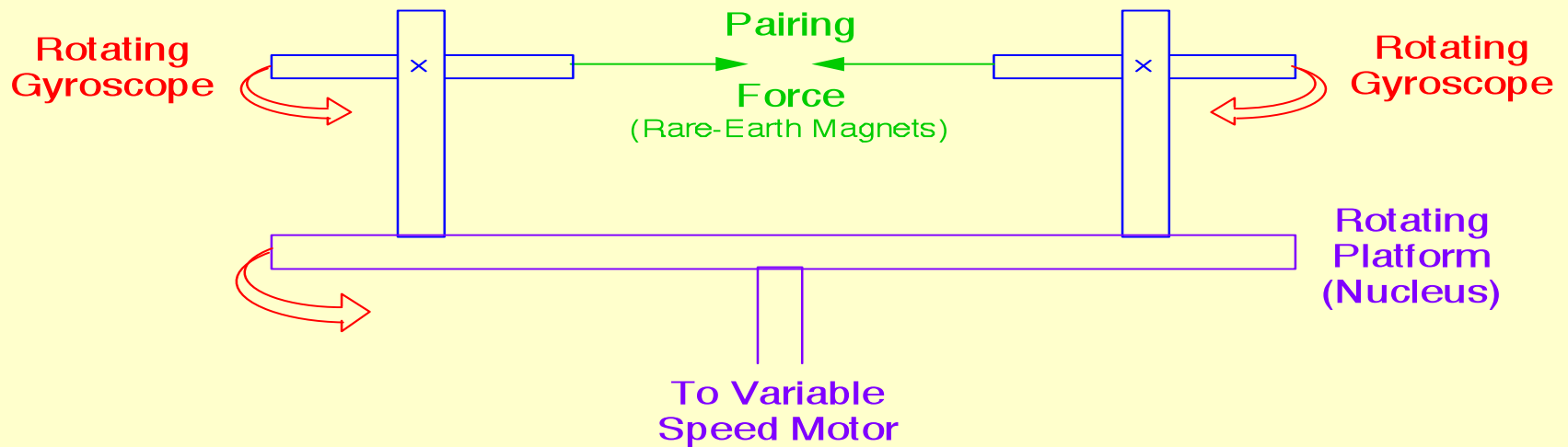
$\hbar\omega$



Built by Ray Willis
 Nuclear Research Workshop, FSU, 1997

$$\bar{I} = \bar{R} + \sum \bar{j}$$

Total Spin = Collective Rotation + Aligned Spin



"Backbending" Demonstration Schematic

Show video

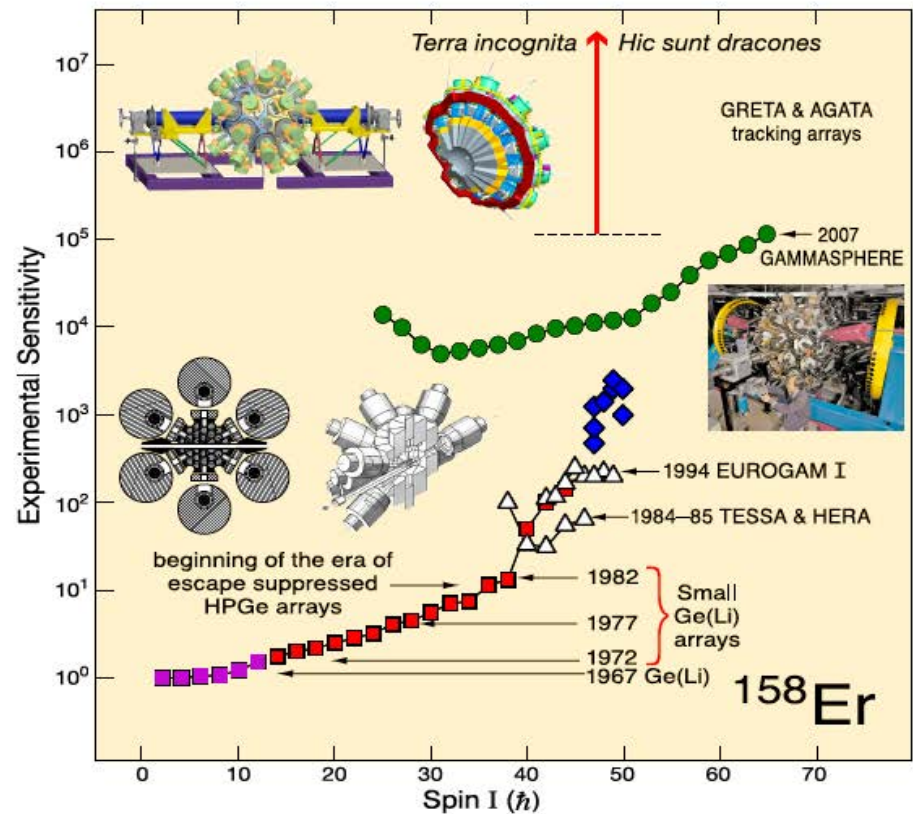
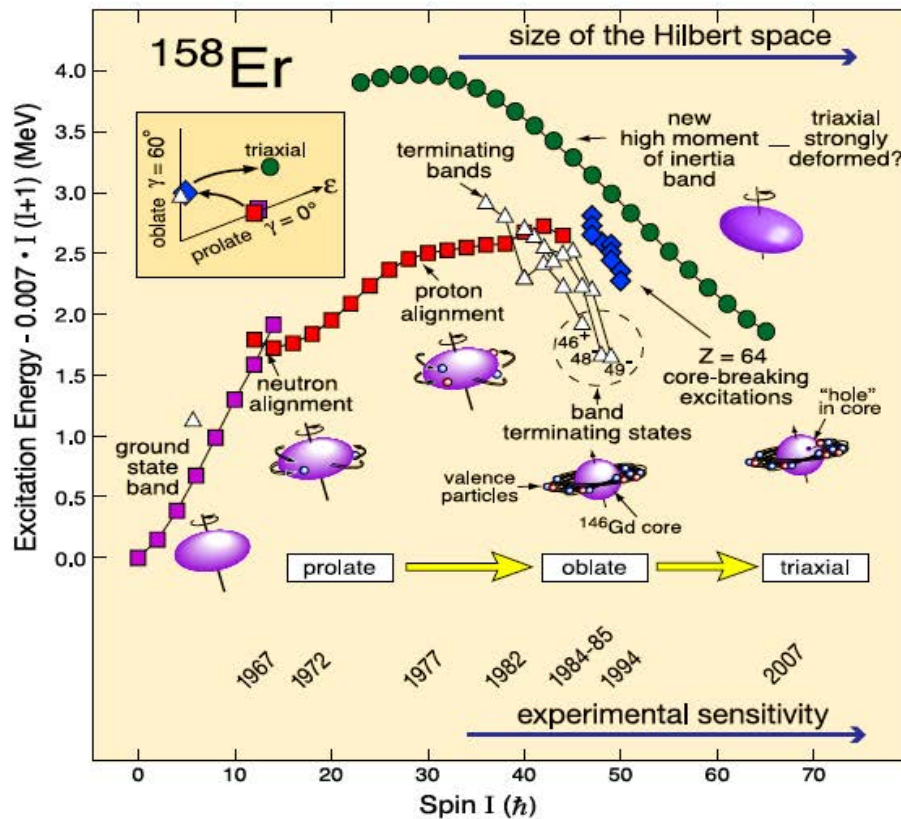
Evolution of Gamma-Ray Spectroscopy



and ^{158}Er

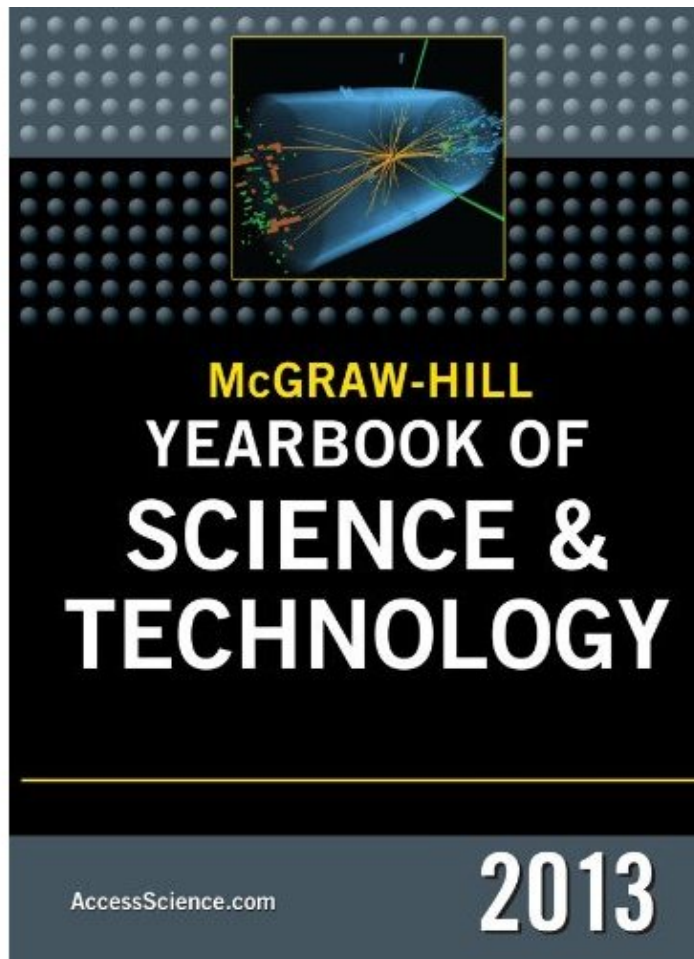
(Nat. Acad. Sci. Decadal Report June 2012, p 49
Nuclear Physics: The Heart of Matter)

- 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 ^{158}Er would be the highest spin structure ever observed.”

Afanasjev, Shi,
Nazarewicz, PRC 86,
031304[®] (2012)



IMAGINE

06-14

158

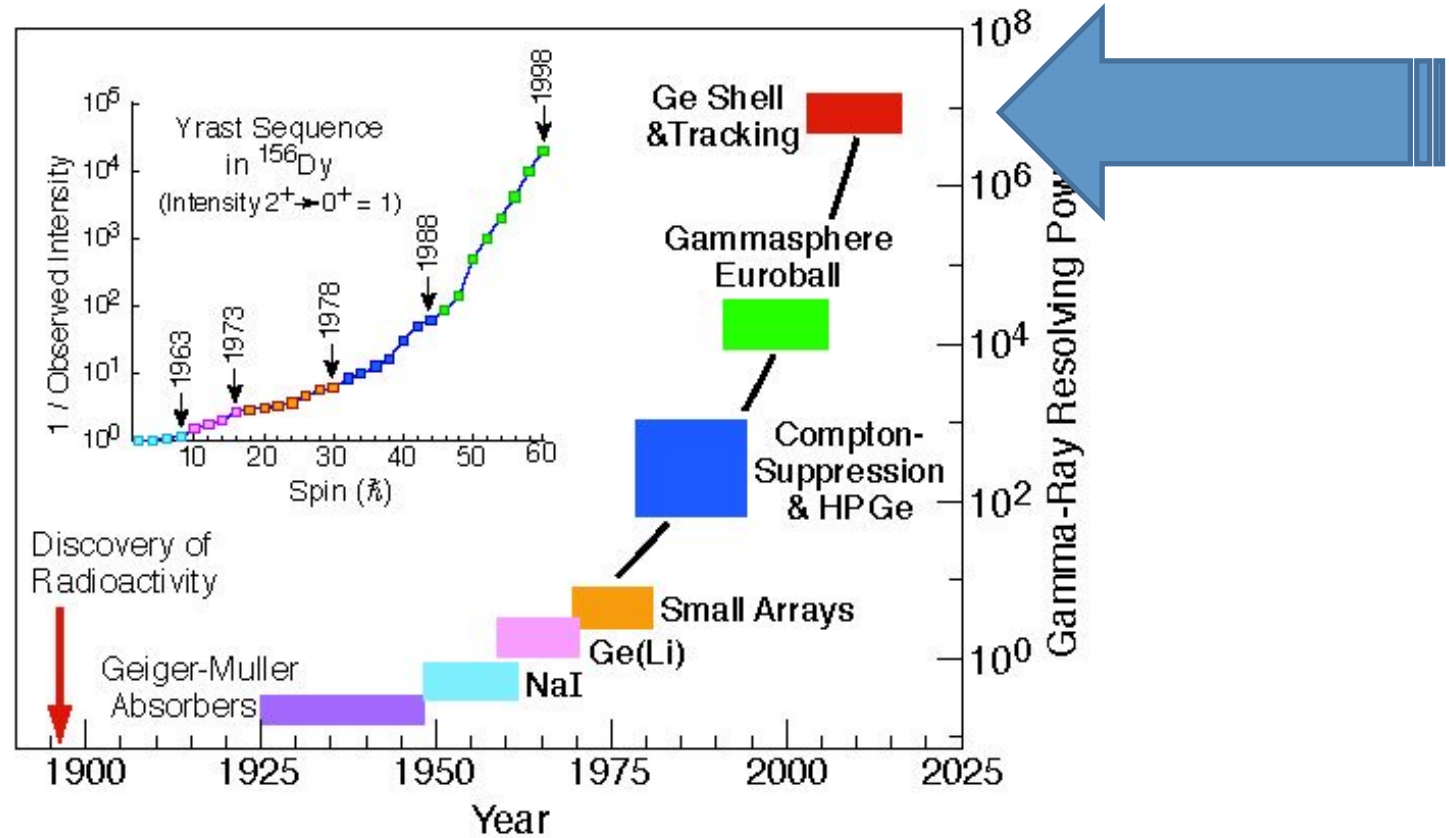


ERB

PORSCHE

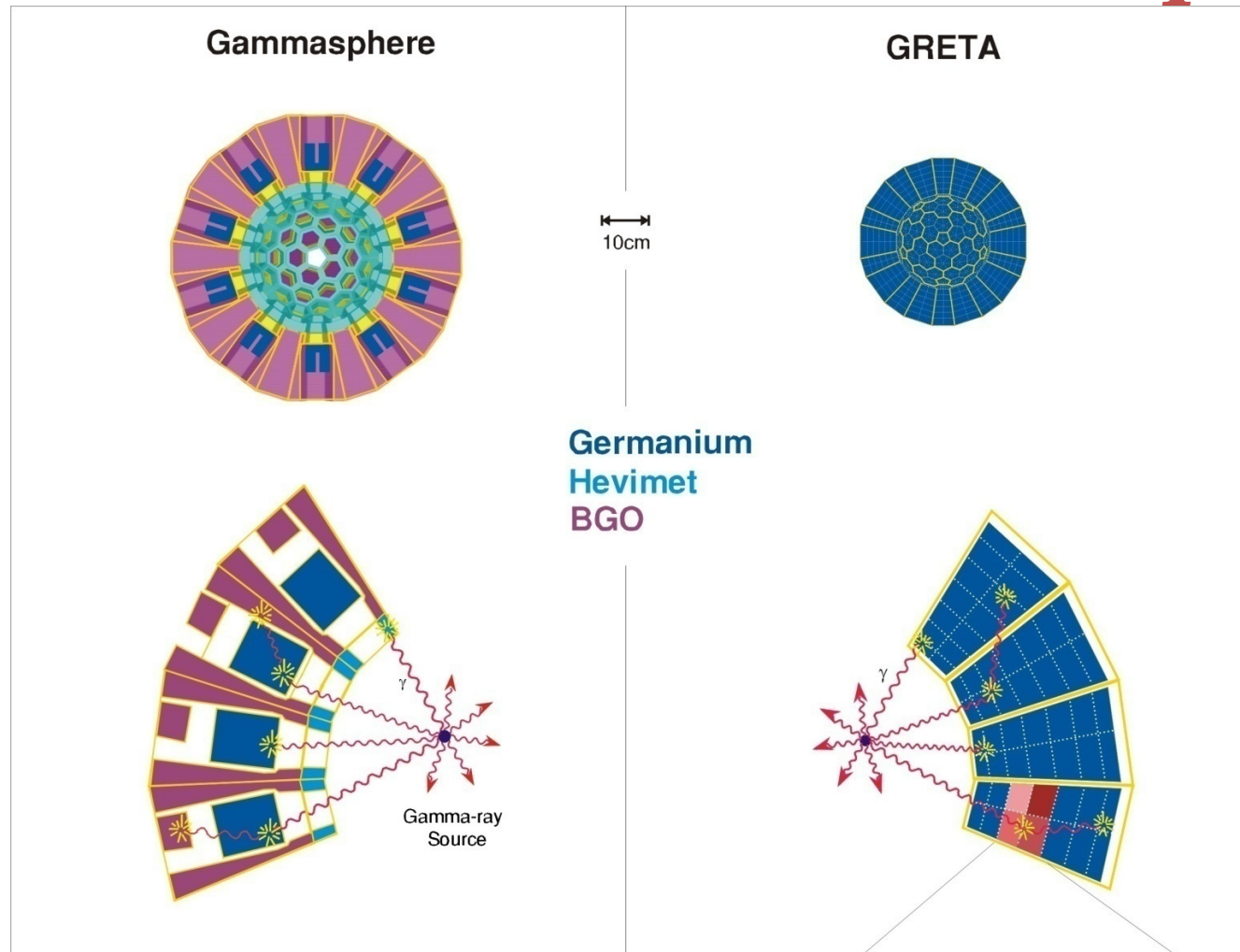
The Future

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

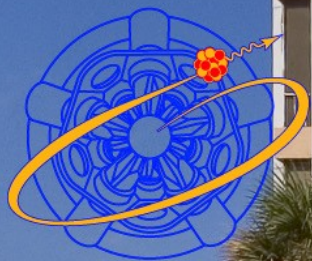


Efficiency (1 MeV)
 Efficiency (15 MeV)
 Peak/Total (1 MeV)
 Position resolution
1 mm

8%
 0.5%
 55%

20mm

55%
12%
85%



GRETINA-GRETA

The Future of Gamma-Ray Spectroscopy Workshop

August 17&18, 2006

Florida State University, Tallahassee, Florida



Grigory Ragochev

Alfredo Galindo-Uribarri

Krzysztof Starosta

Witek Nazarewicz

Dirk Weisshaar

Sam Tabor

Karin Glasmacher 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

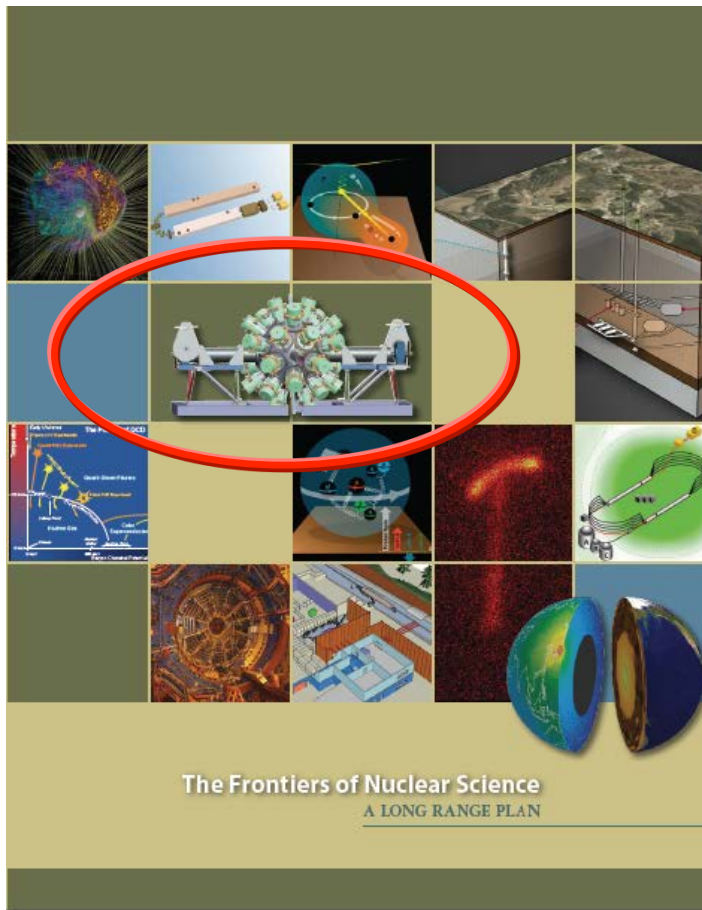
Mark Riley

Demetrios Sarantites

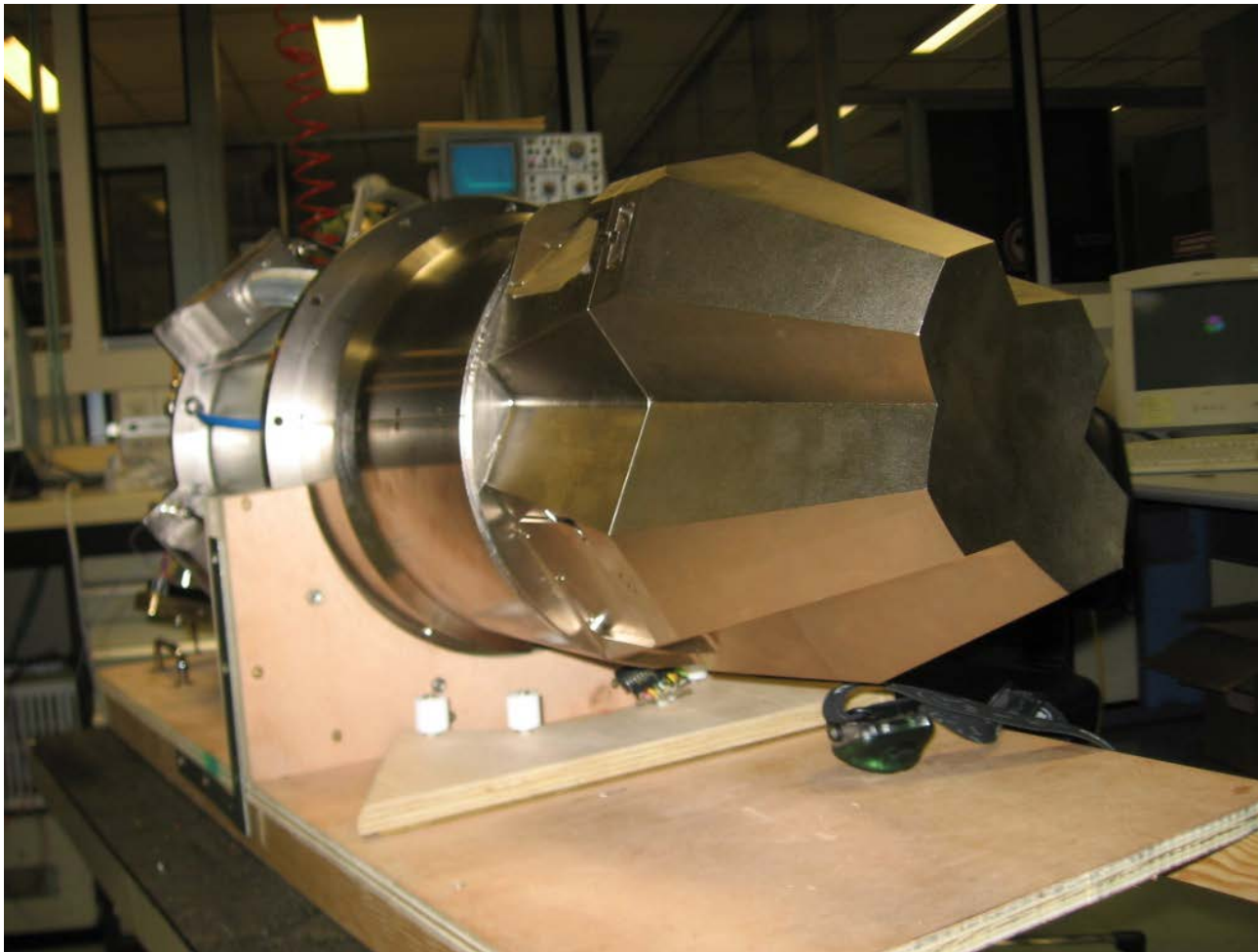
2007 Long Range plan

Gamma-Ray Tracking

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



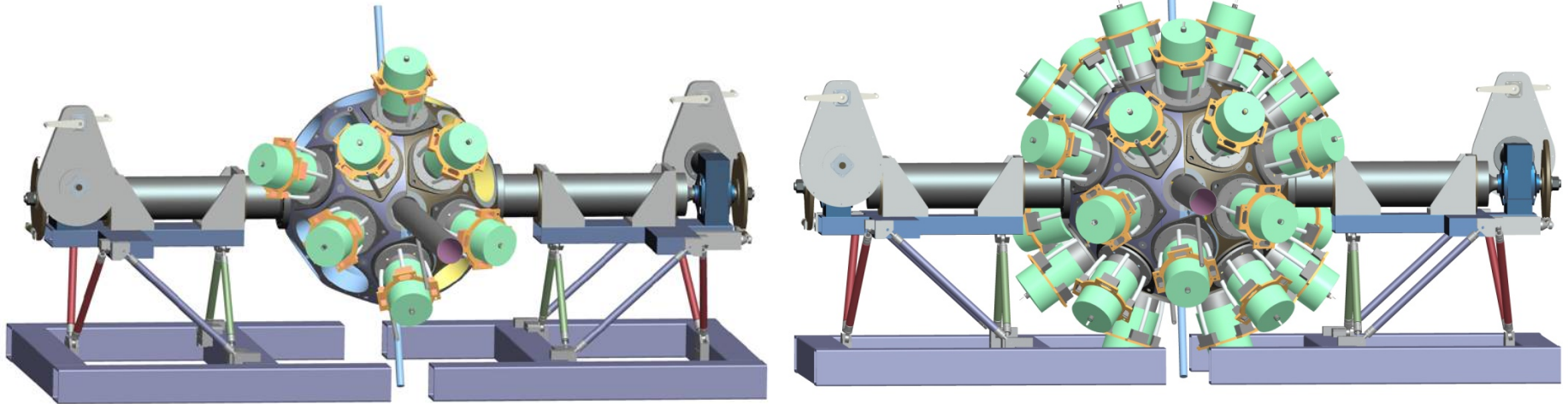
The First Detector for GRETINA (\$1M!)



LAWRENCE BERKELEY NATIONAL LAB - 2011



GRETINA to GRETA for FRIB

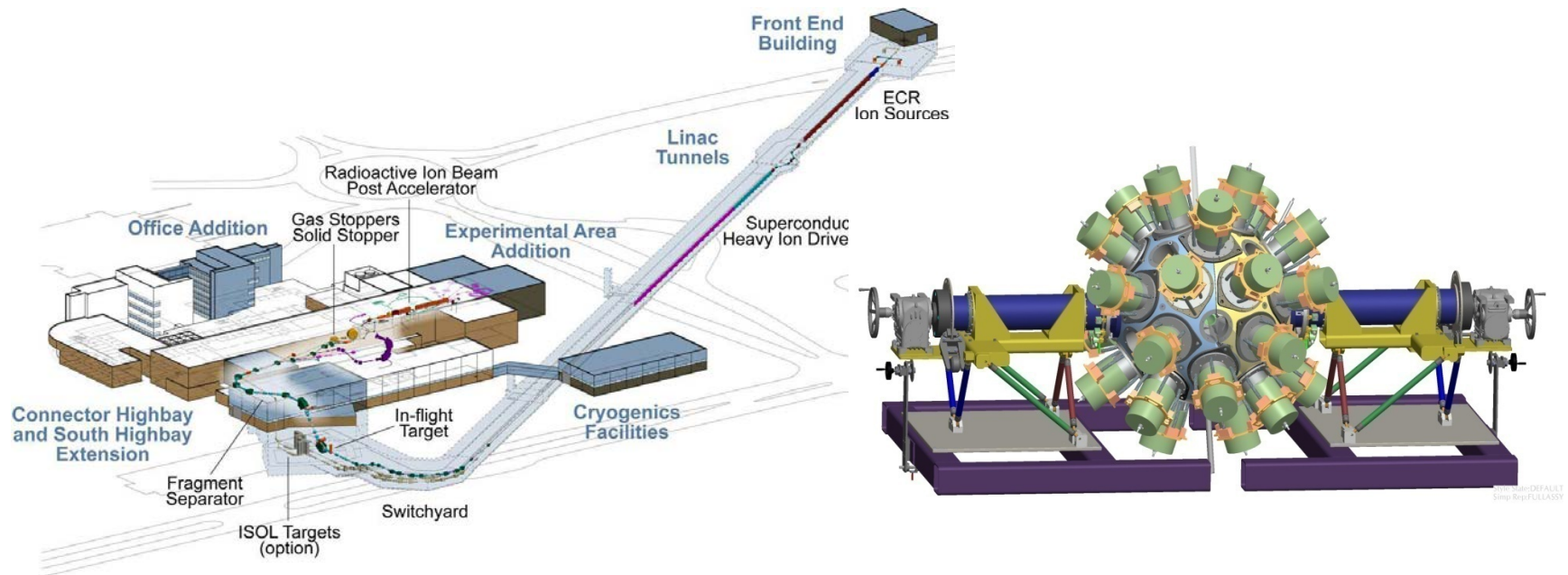


It has been called
“A jewel in the crown of
FRIB”
Tim Hallman, Aug 2011:
“The importance of GRETA
in the out years is
understood and is part of
DOE planning.”



FRIB + GRETA

The Revolution in Nuclear Physics Continues!

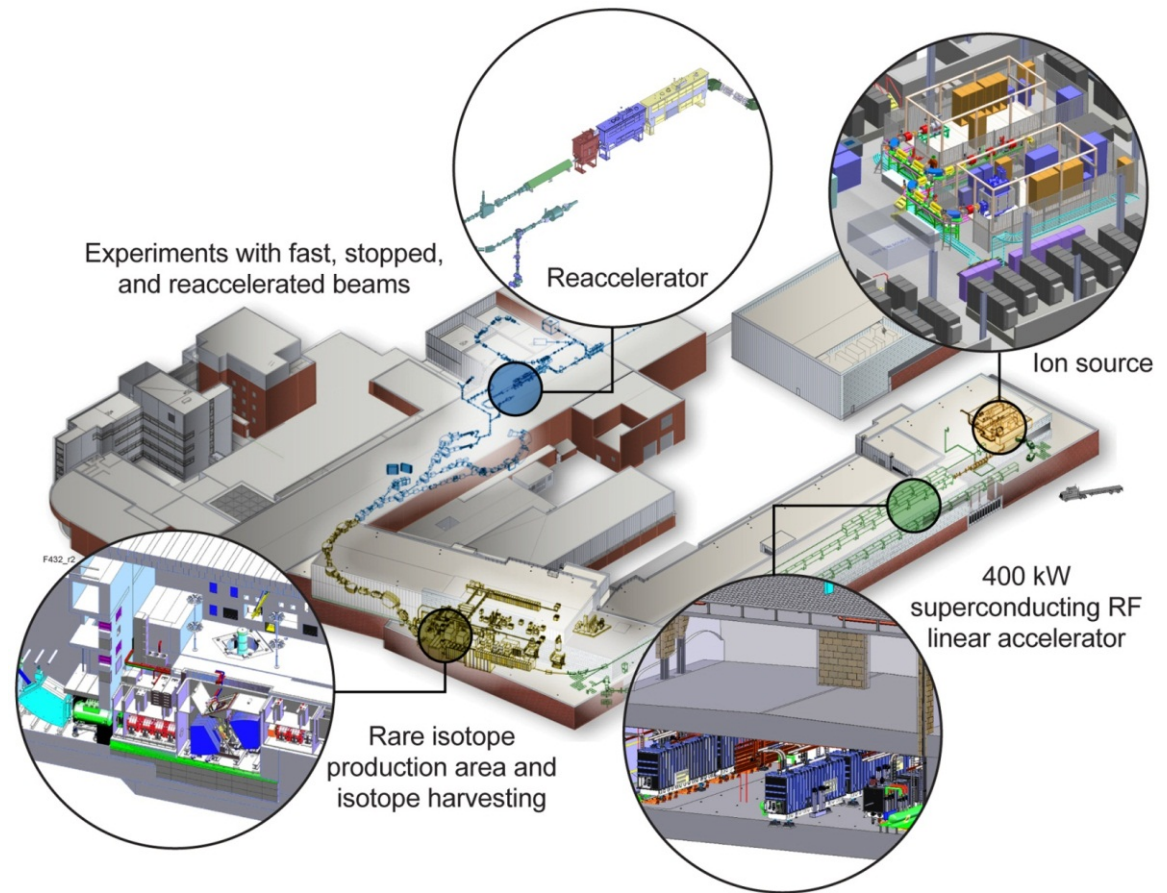


The Future: A New Accelerator in the USA. It will be the Best in the World for Nuclear Structure Physics!

- 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

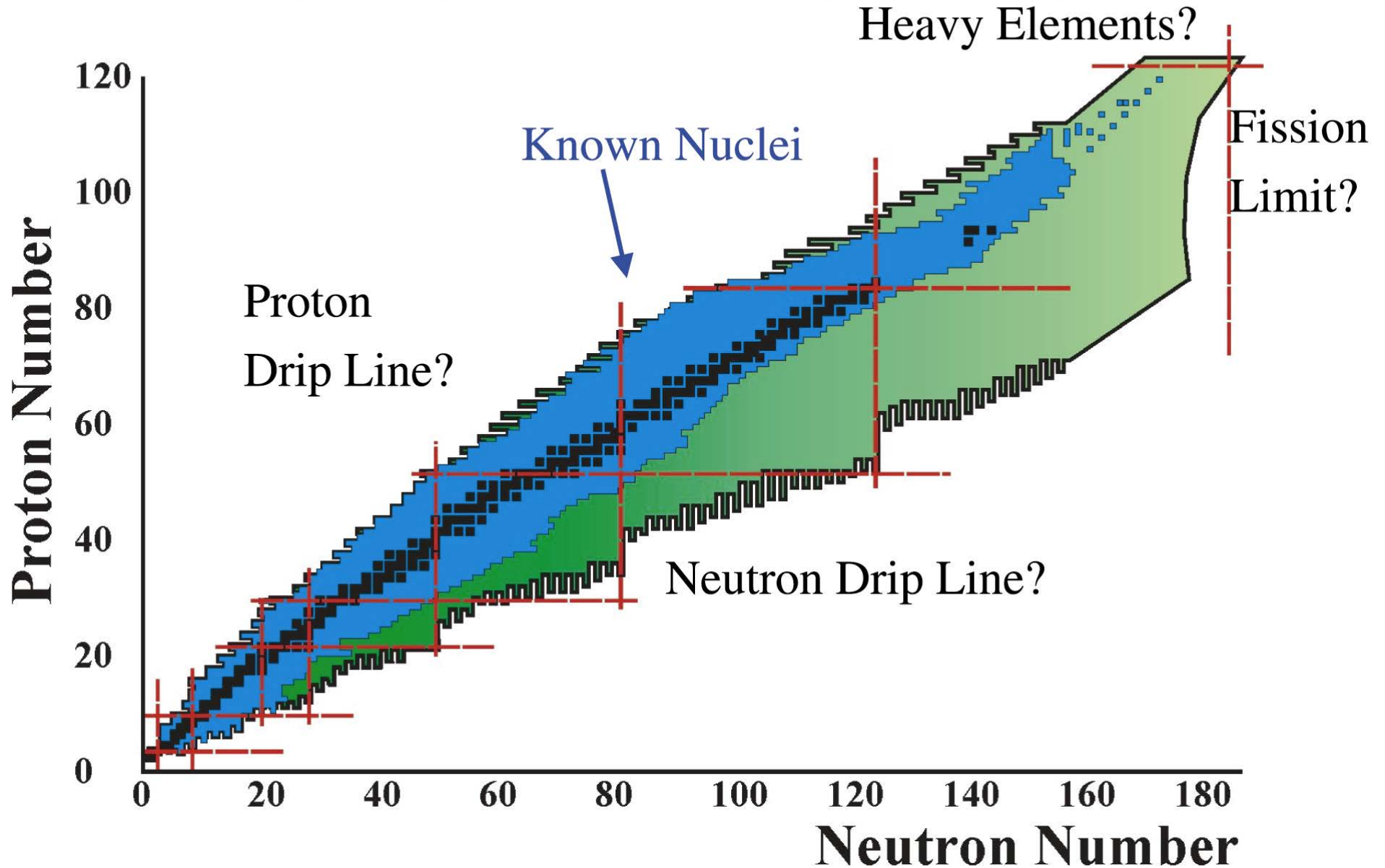
- Funded by DOE Office of Science Office of Nuclear Physics + Michigan State University, \$730M.
- T. Glasmacher, Project Director, ex-FSU (Dr. Cottle).
- Completion date 2022.
- Key Feature is 400kW beam power ($5 \times 10^{13} \text{ }^{238}\text{U/s}$)
- Separation of isotopes in-flight
 - Fast development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



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

FRIB August 2013

The Chart of the Nuclides



Facility for Rare Isotope Beams, FRIB



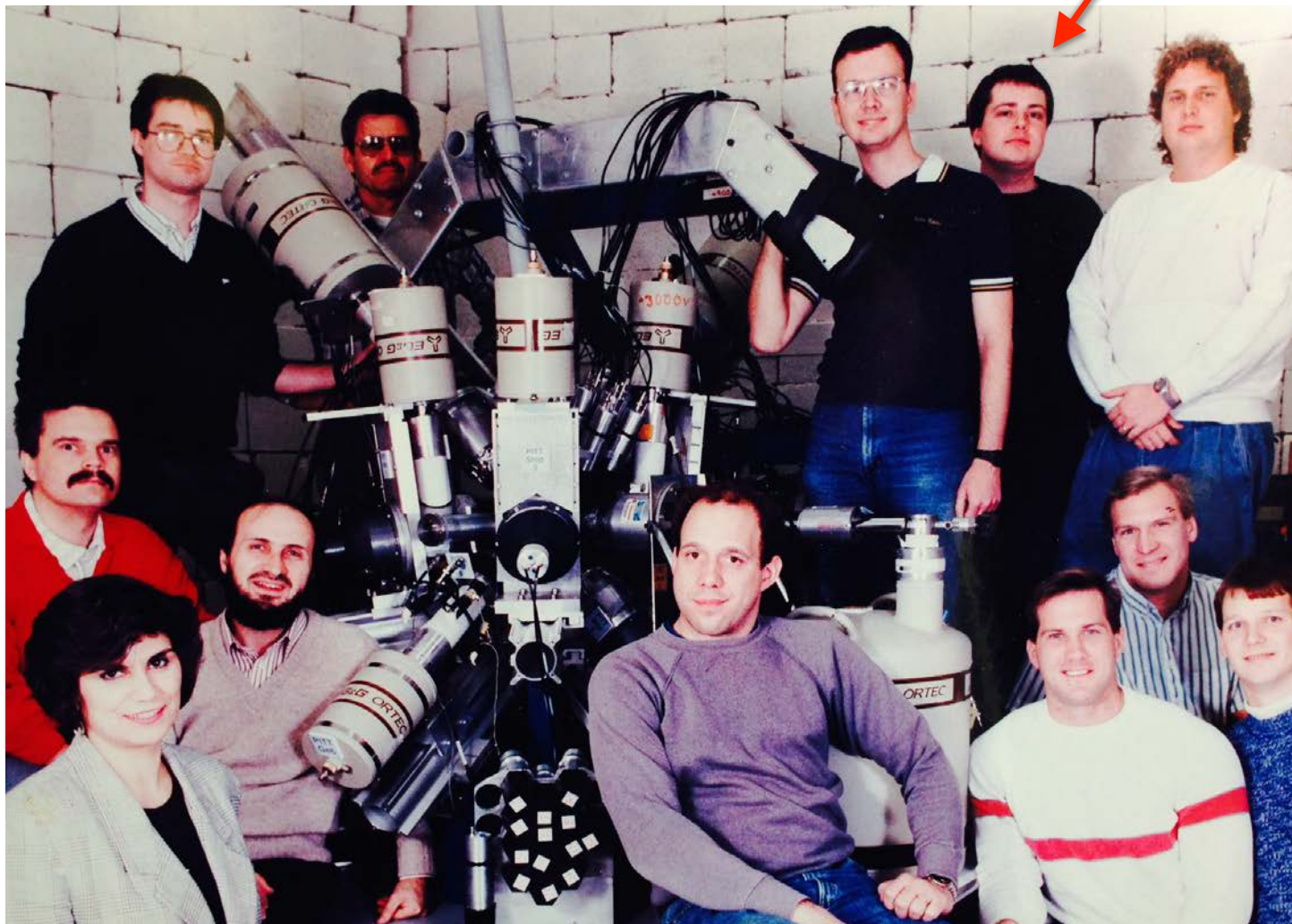
FRIB



Facility for Rare Isotope Beams

U.S. Department of Energy Office of Science
Michigan State University

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!

