# Frontiers of Nuclear Physics

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Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

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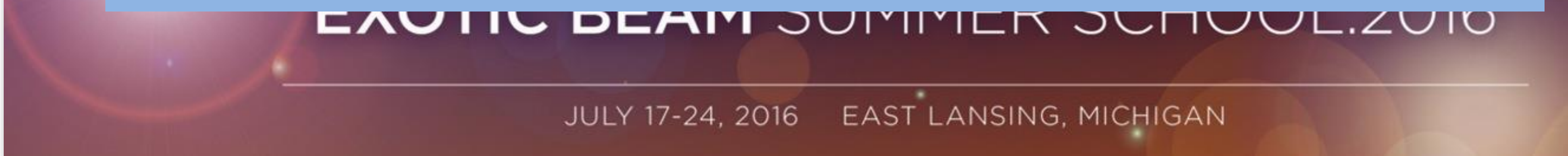
With Many Thanks to:
R.M.Clark, H.L.Crawford, A.Gade, and D.Bazin



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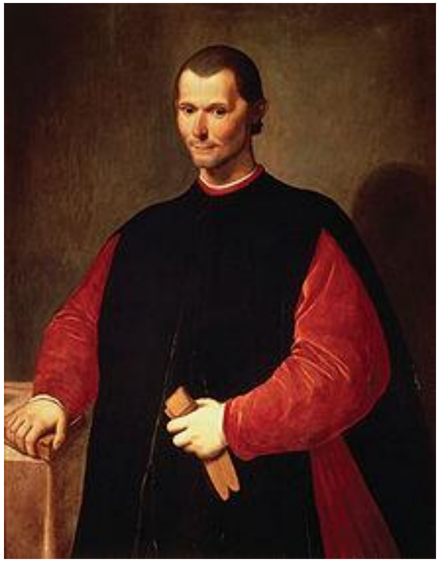
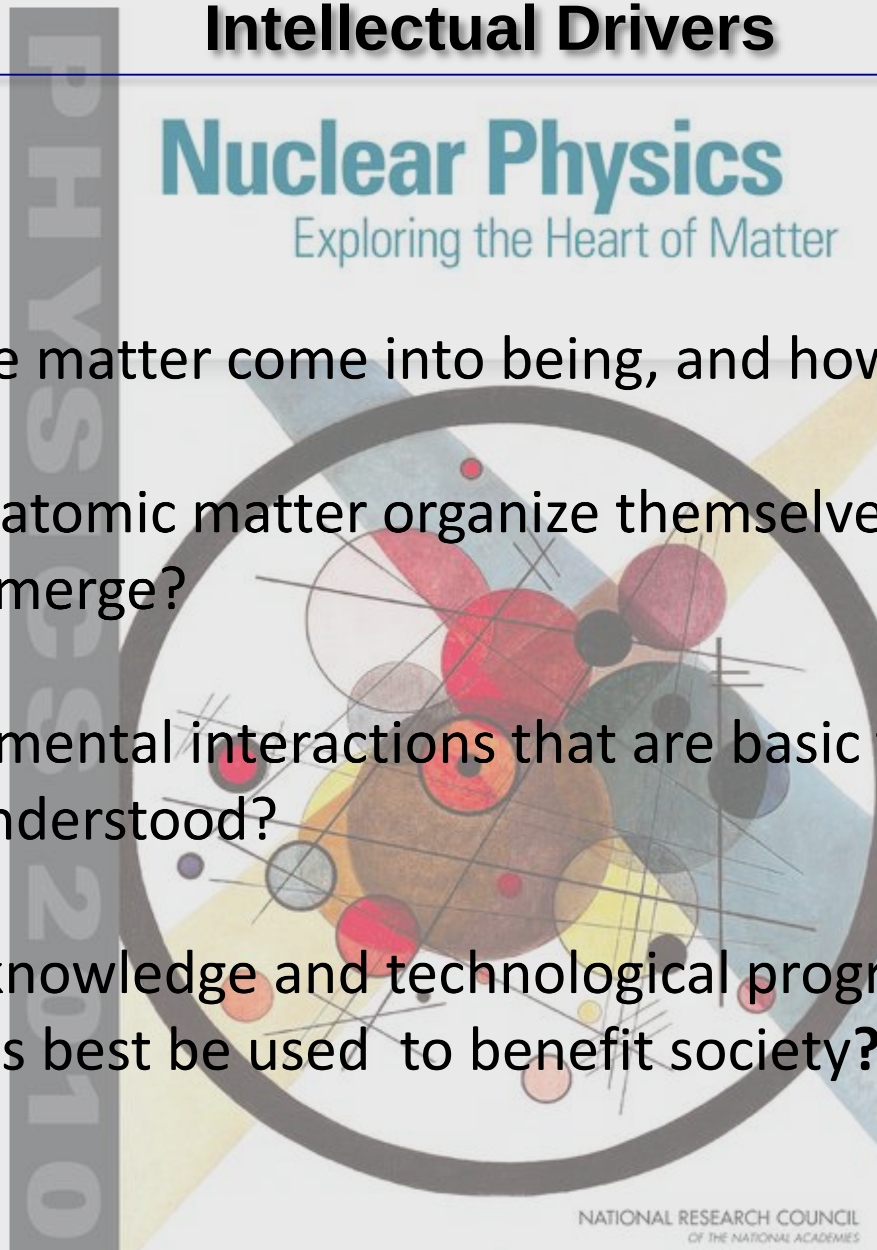
… and apologies from



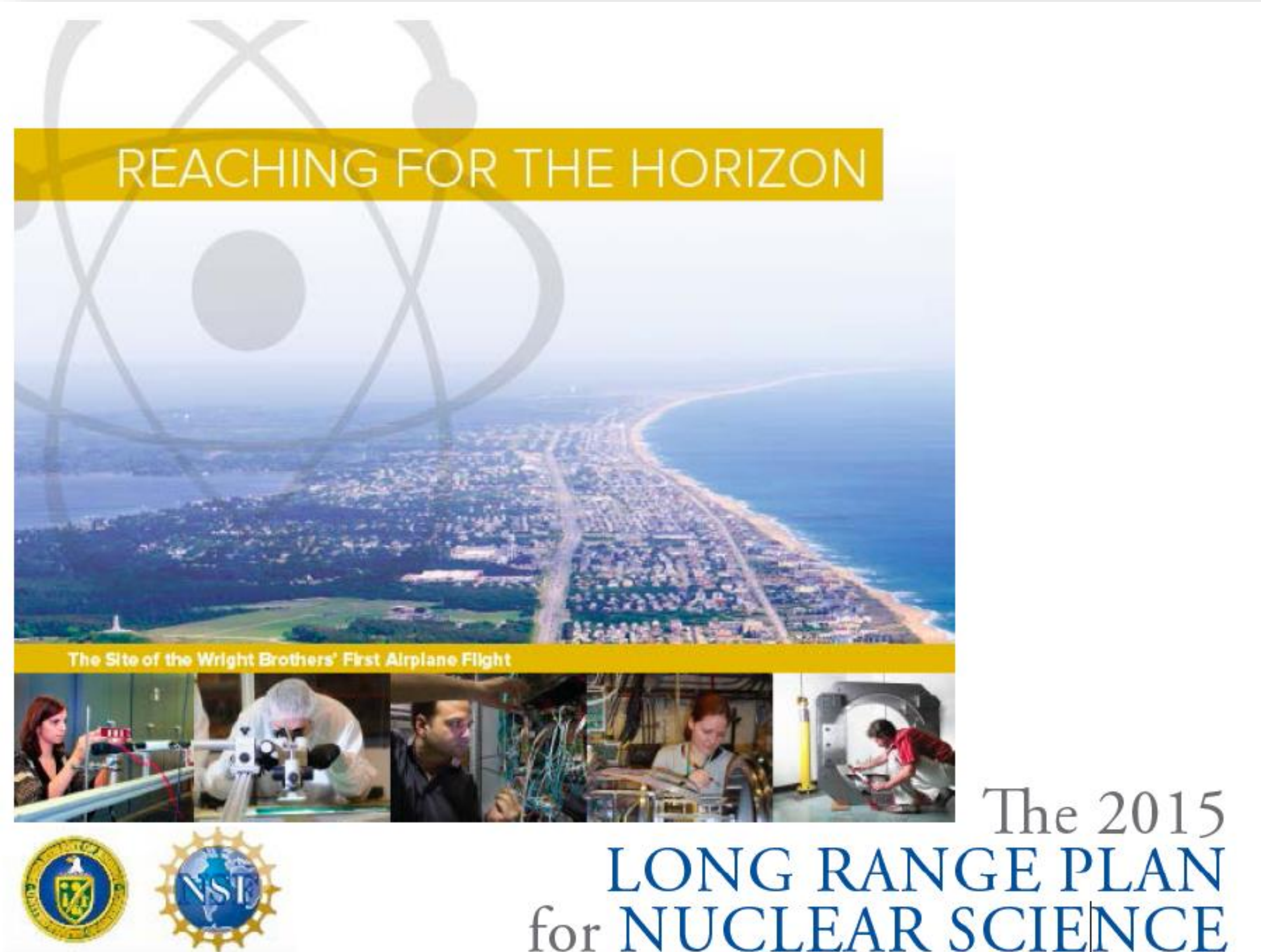

MACHIAVELLI
RISERVA
PRODUCT OF ITALY
CHIANTI CLASSICO
2006

# Intellectual Drivers



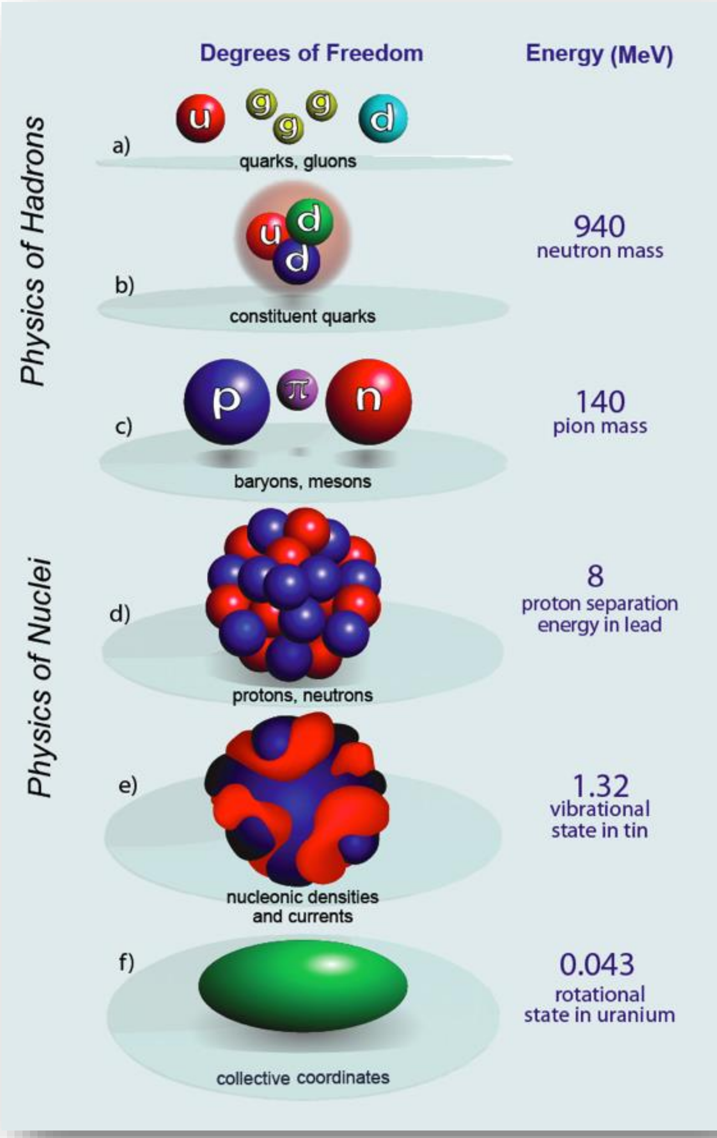

- How did visible matter come into being, and how does it evolve?
- How does subatomic matter organize themselves, and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

http://www.nap.edu/catalog/13438/nuclear-physics-exploring-the-heart-of-matter




http://science.energy.gov/np/nsac/

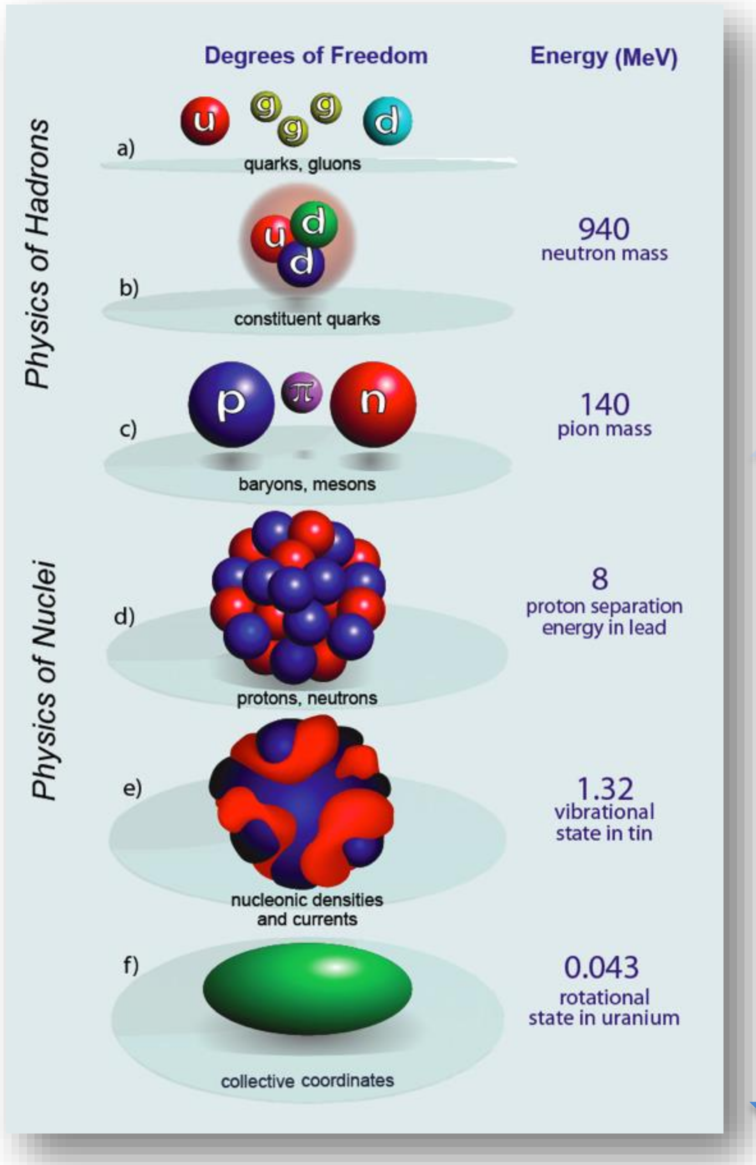
# A Hierarchy of Scales




From the 2007 NSAC Long Range Plan

# A Hierarchy of Scales

Theory and Accelerators




Heavy Ion

Medium Energy

Low Energy

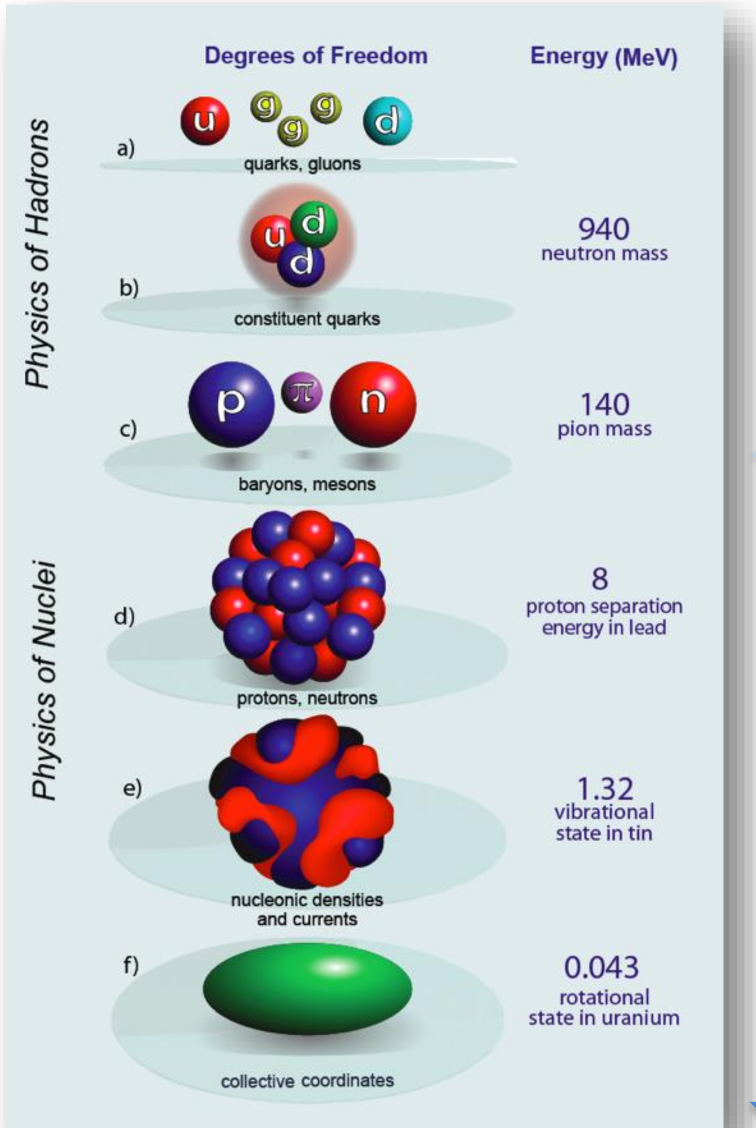
Nuclear Structure and Astrophysics

Fundamental symmetries

From the 2007 NSAC Long Range Plan

# A Hierarchy of Scales

INSTRUMENTATION



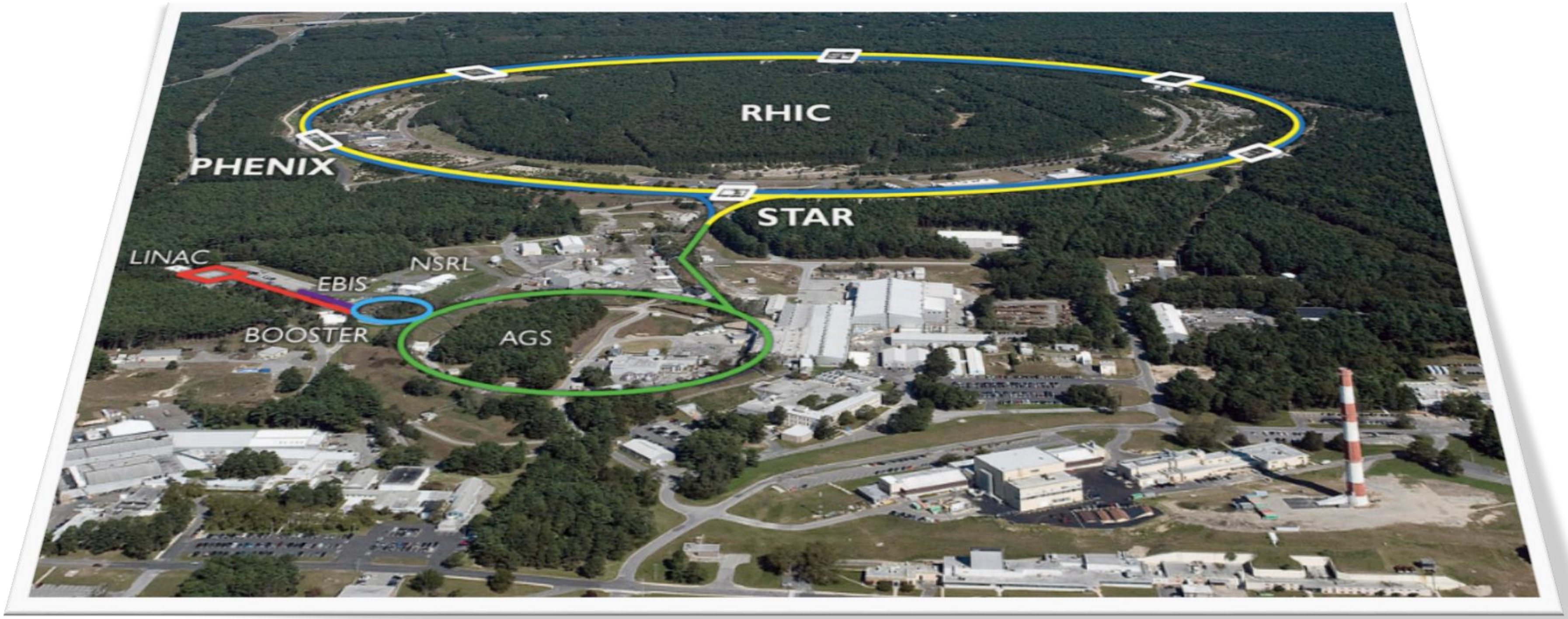

RHIC

JLAB
JPARC
FAIR

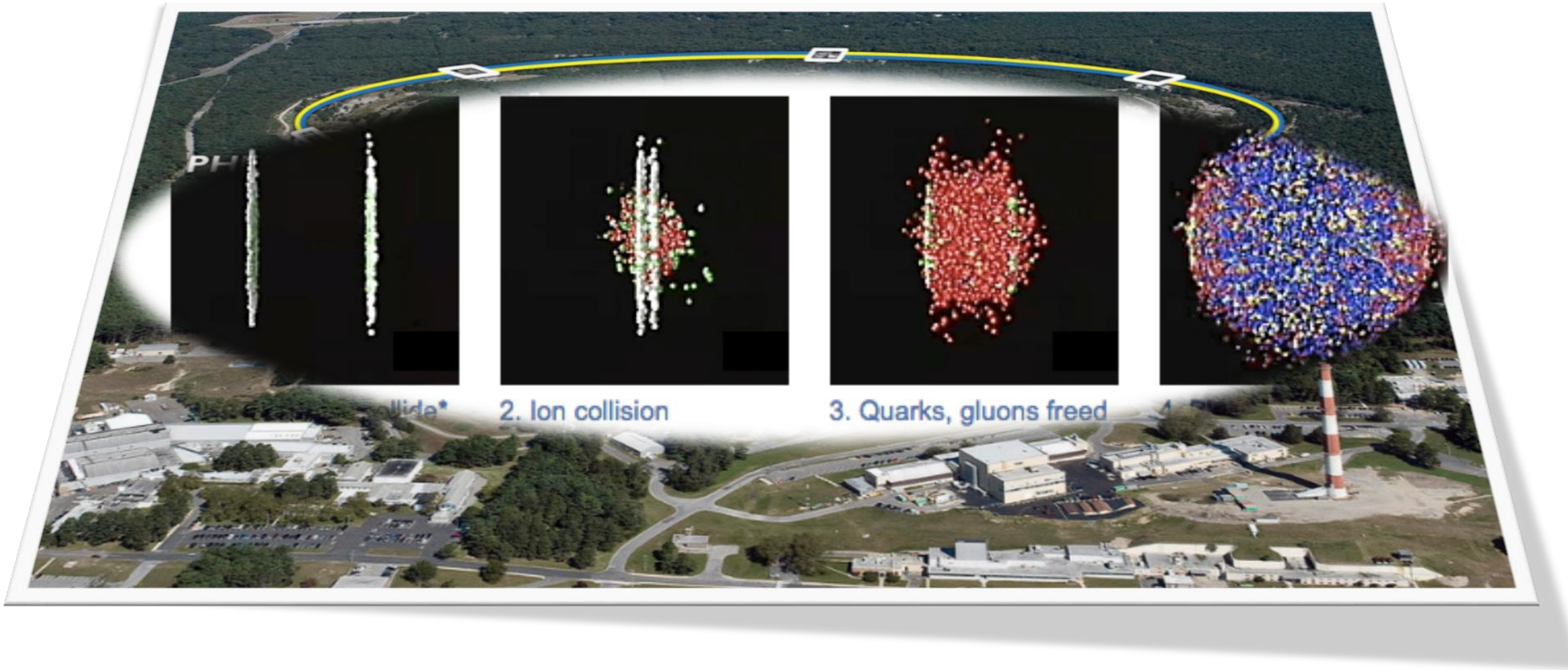
NSCL
ATLAS
RIBF
GANIL
FAIR
FRIB

From the 2007 NSAC Long Range Plan

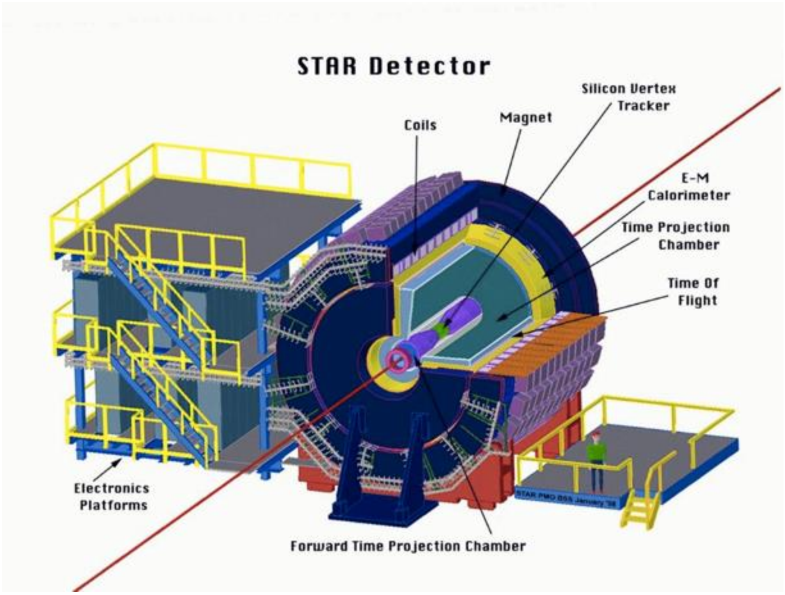
# The Relativistic Heavy Ion Collider

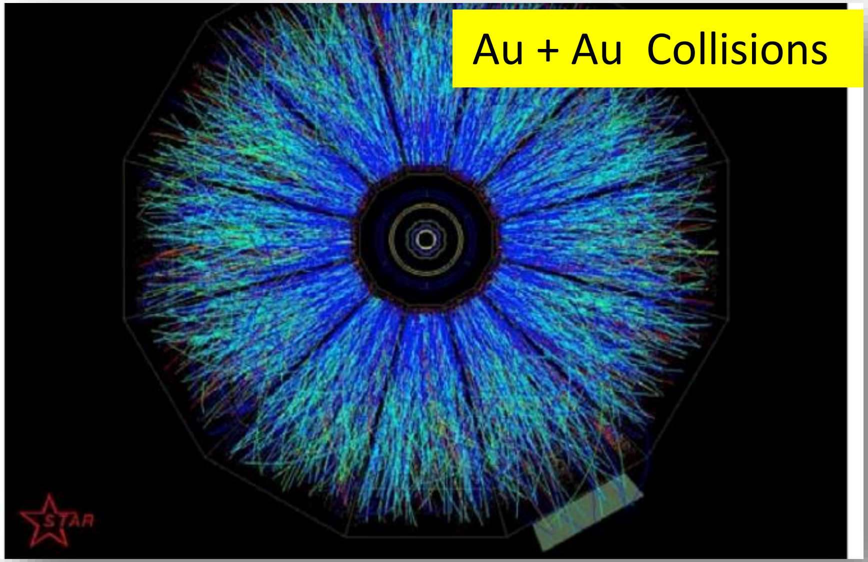


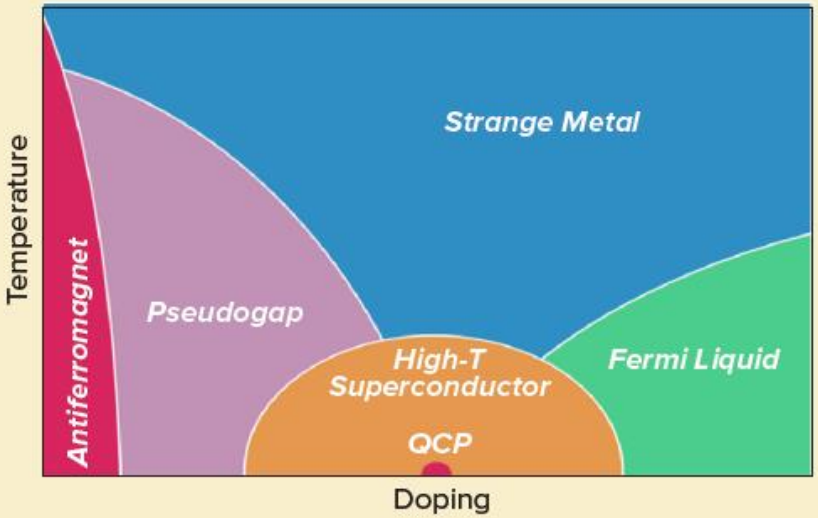
# The Relativistic Heavy Ion Collider

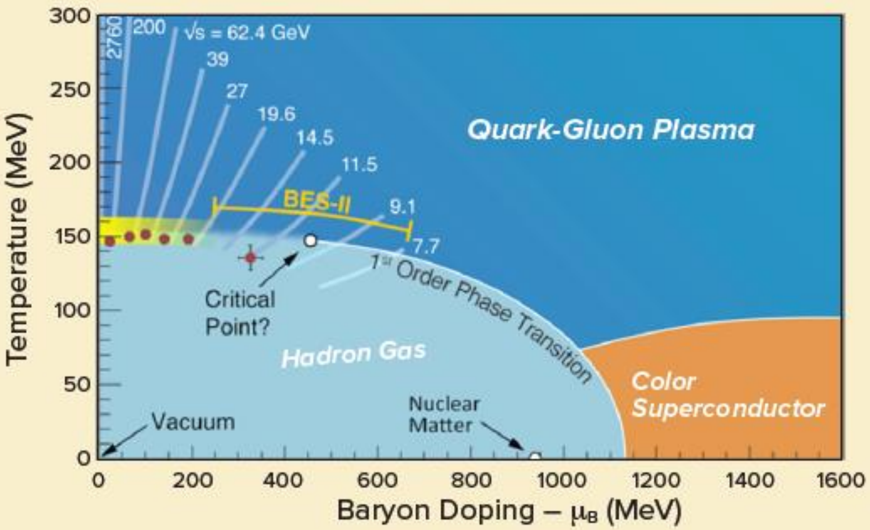


The study of states of matter governed by the strong force parallels progress in other fields in which surprising **"emergent phenomena"** have been discovered.



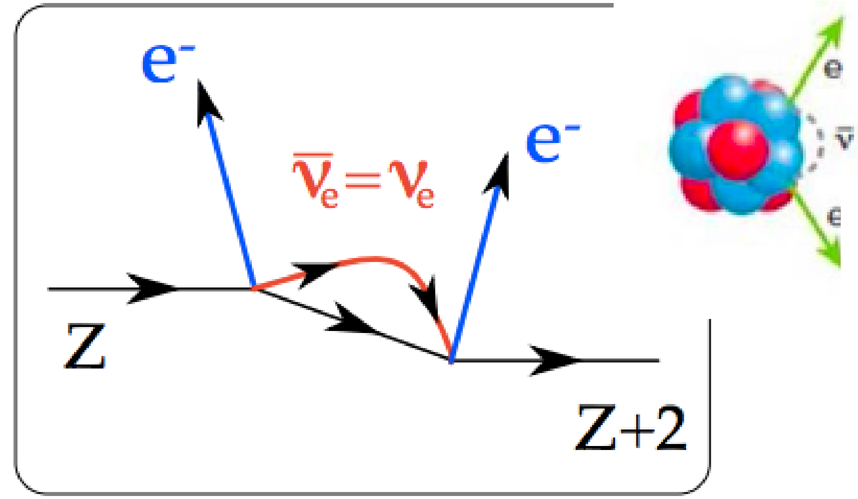



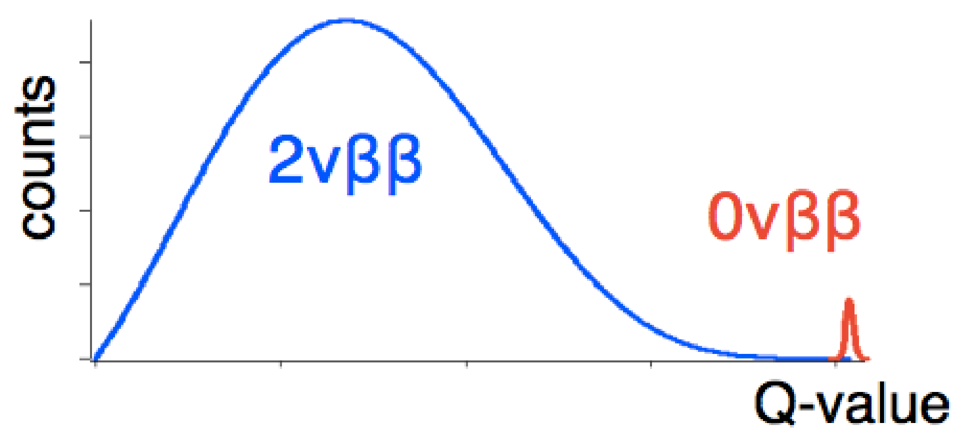



# Neutrinoless Double Beta Decay

Observation of Neutrinoless Double Beta Decay would

- Demonstrate the **lepton number is not conserved**
- Prove that a neutrino is an elementary Majorana particle, that is, **its own antiparticle**.
- Suggest that a **new mechanism for mass generation**, not the Higgs mechanism, is at work.
- Provide evidence for one of the key ingredients that could explain the preponderance of matter over antimatter in the universe, leptogenesis.

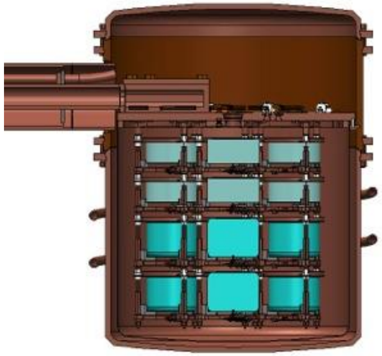


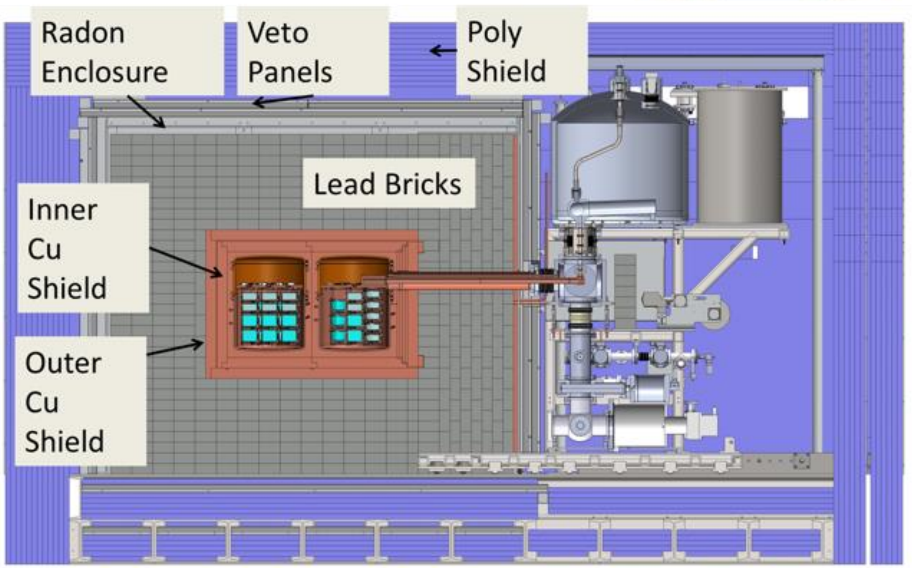
# The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics,
with additional contributions from international collaborators.

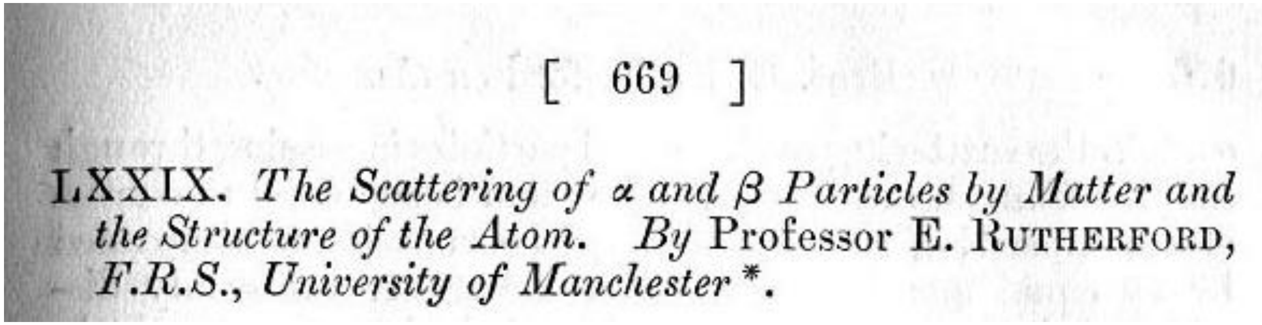
**Goals:** - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.



- **Located underground at 4850' Sanford Underground Research Facility**
- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)**
  **3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5**
  *scales to 1 count/ROI/t/y for a tonne experiment*
- **44-kg of Ge detectors**
  - **29 kg of 87% enriched $^{76}$Ge crystals**
  - **15 kg of $^{nat}$Ge**
  - **Detector Technology: P-type, point-contact.**
- **2 independent cryostats**
  - **ultra-clean, electroformed Cu**
  - **20 kg of detectors per cryostat**
  - **naturally scalable**
- **Compact Shield**
  - **low-background passive Cu and Pb shield with active muon veto**

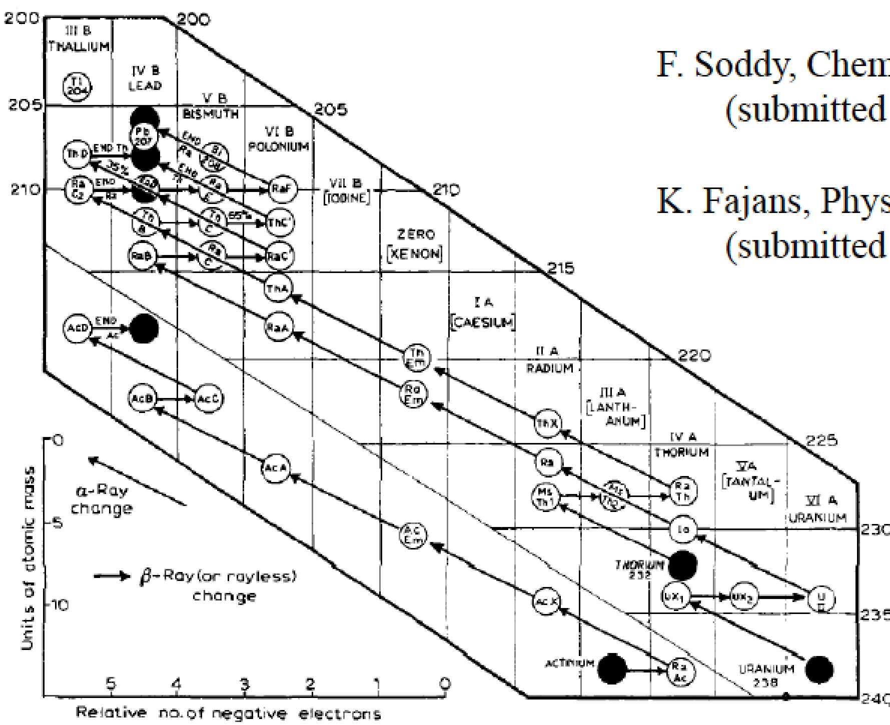


# Where it all started


[ 669 ]

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom. By* Professor E. RUTHERFORD, *F.R.S., University of Manchester*.*

Philosophical Magazine - Series 6, vol. 21 May 1911, p. 669-688




F. Soddy, Chem. News **107** (1913) 97
(submitted Feb. 18, 1913)

K. Fajans, Physik. Z. **14** (1913) 131
(submitted Dec. 31, 1912)

F. Soddy,
Nobel Lecture, 1922

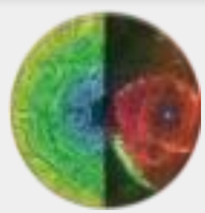
# The Physics of Nuclei: Science Drivers

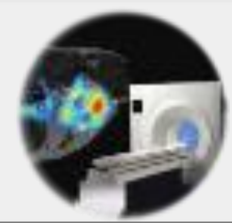
| Nuclear Structure | Nuclear Astrophysics | Tests of Fundamental Symmetries | Applications of Isotopes |
|---|---|---|---|

Overarching questions from NSAC Long Range Plan 2015

| | | | |
|---|---|---|---|
| How are nuclei made and organized?<br><br>What is the nature of dense nuclear matter? | Where do nuclei and elements come from?<br><br>What combinations of neutrons and protons can form a bound atomic nucleus?<br><br>How do neutrinos affect element synthesis? | Are neutrinos their own antiparticles?<br><br>Why is there more matter than antimatter in the present universe? | What are practical and scientific uses of nuclei? |

**Overarching questions are answered by rare isotope research**

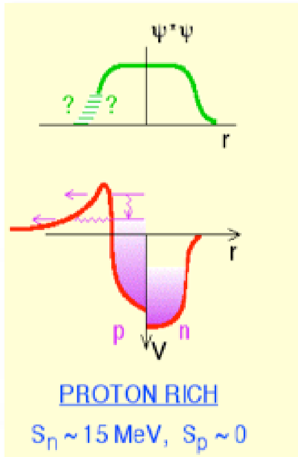


**Facility for Rare Isotope Beams (FRIB)**

***State of the art*** **instrumentation**

**Theory**

# The Nuclear Landscape

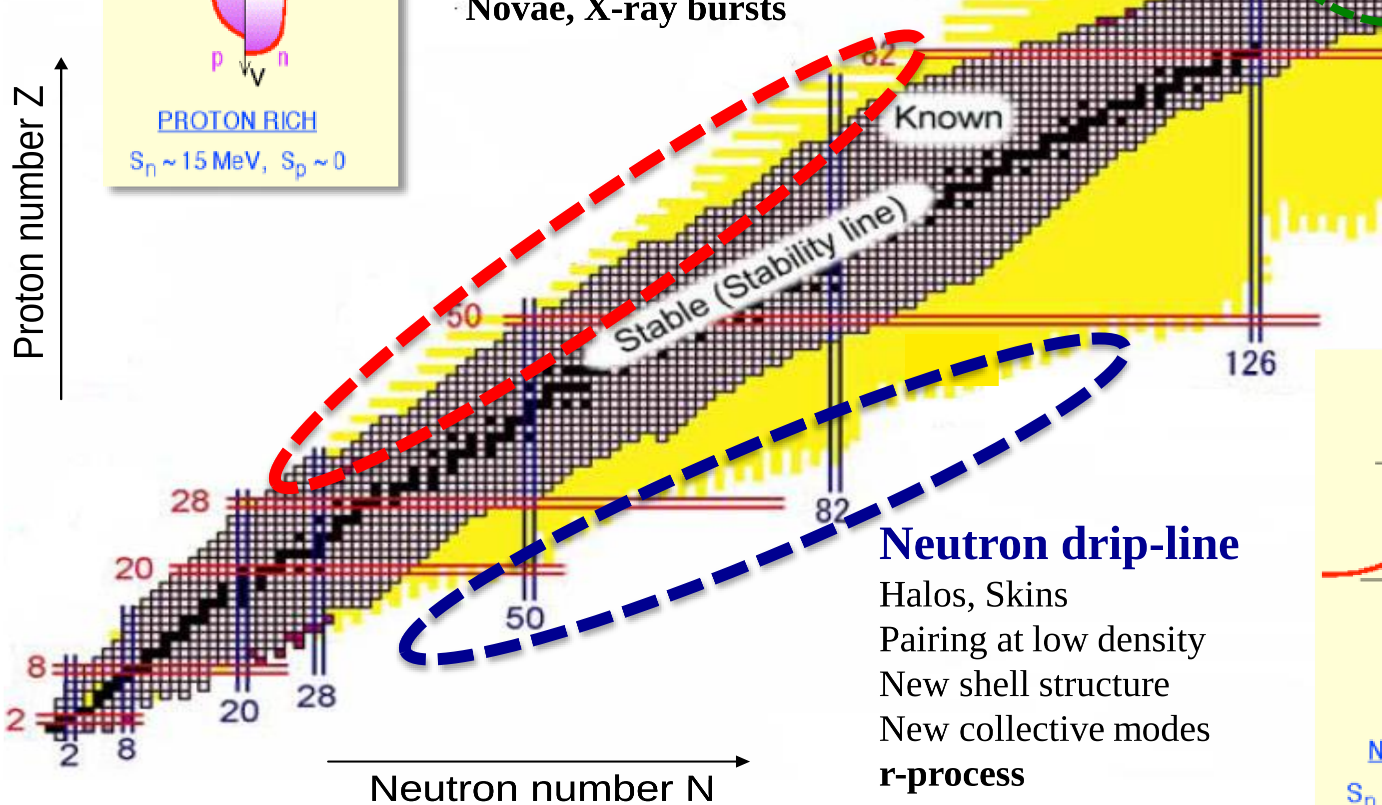



**Proton drip-line**

Mirror symmetry
p and 2p tunneling
Spin triplet superconductivity
(T=0 pairing)
**rp-process**
**Novae, X-ray bursts**

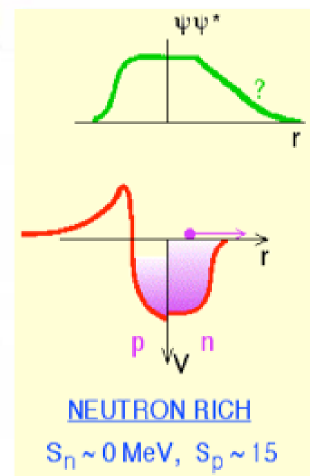
**Heavy Elements**

Shell stability
Island of SHE



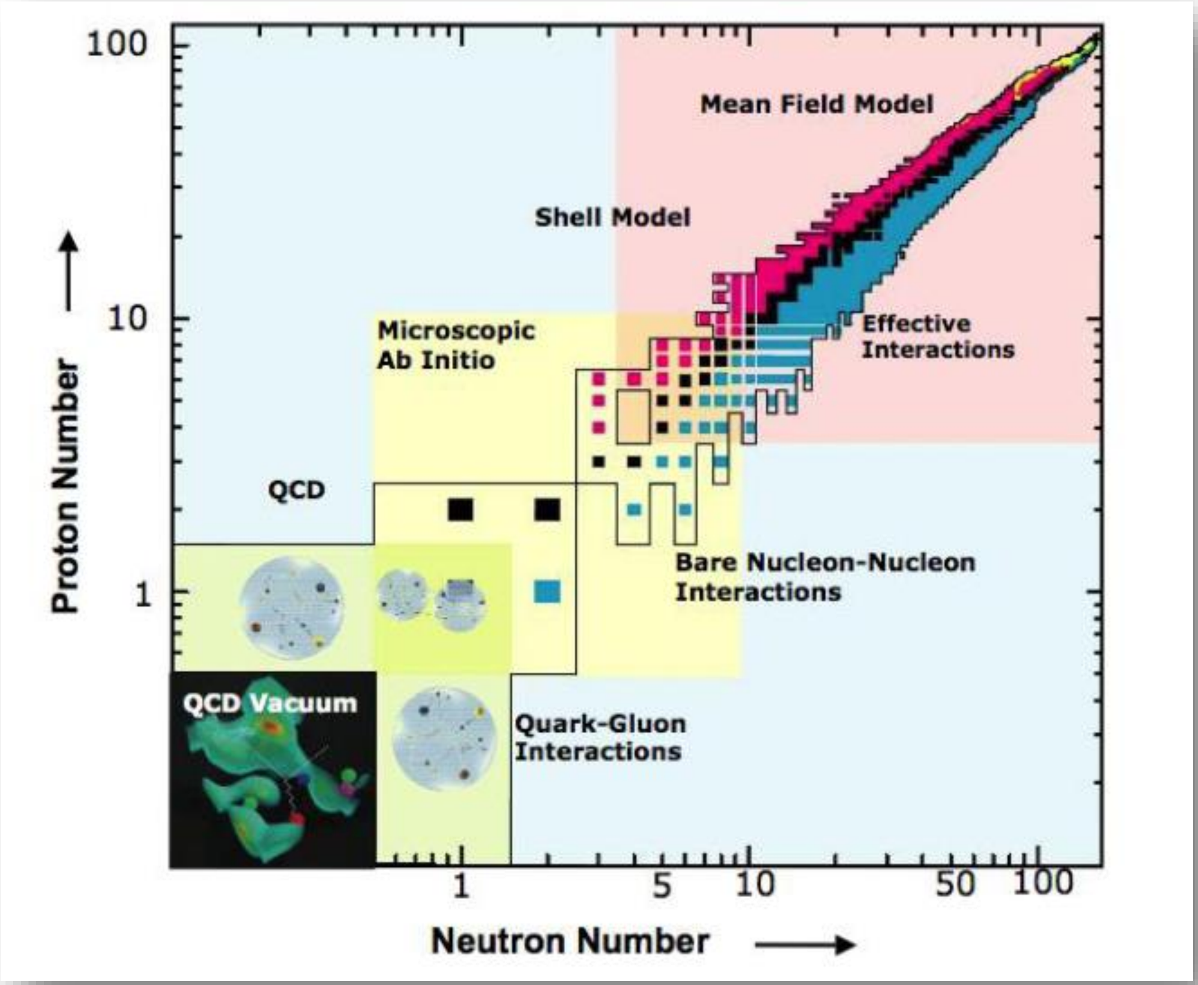

**Neutron drip-line**

Halos, Skins
Pairing at low density
New shell structure
New collective modes
**r-process**
**Stars, Supernovae**



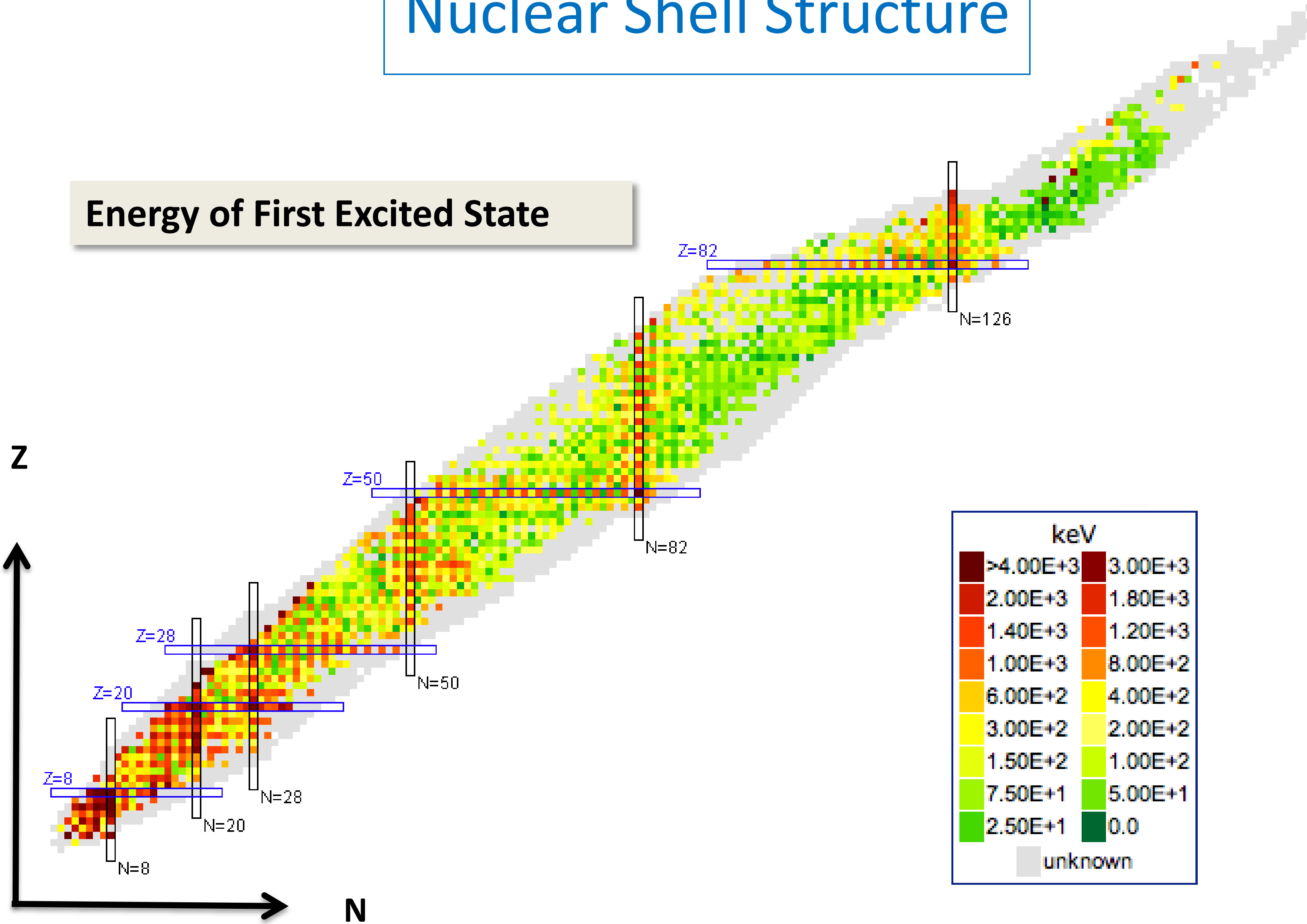
# The Ultimate Goal

- A comprehensive and quantified model of atomic nuclei does not yet exist
- In recent years, enormous progress has been made with measurements of properties of rare isotopes and developments in nuclear theory and computation
- Access to key regions of the nuclear chart constrains models and identifies missing physics
- Theory identifies key nuclei and properties to be studied



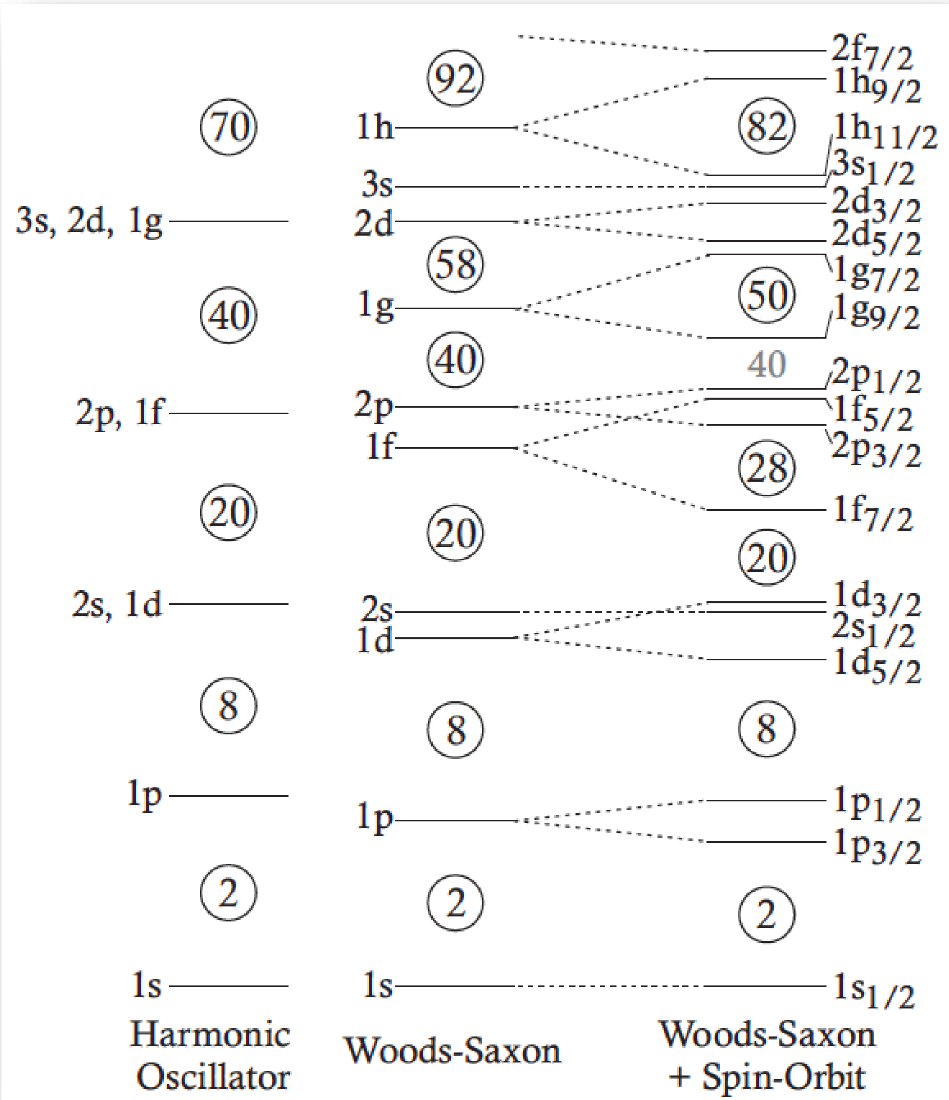
# Nuclear Shell Structure

## Energy of First Excited State




NNDC National Nuclear Data Center BROOKHAVEN NATIONAL LABORATORY

# Nuclear Shell Structure





Maria Goeppert-Mayer &
Hans D. Jensen
1963

Maria Goeppert-Mayer, Phys. Rev. **75**, 1969 (1949).
O. Haxel, Phys. Rev. **75**, 1766 (1949).

# Nuclear shell model

In principle if the form of the bare nucleon-nucleon interaction is known, then the properties and structures of a given nucleus can be calculated ***ab-initio*:**

$$H = \sum_{k=1}^{A} T_k + \sum_{k=1}^{A} \sum_{l=k+1}^{A} W(\vec{r}_k, \vec{r}_l), \quad + \text{3-body} + \ \ldots$$

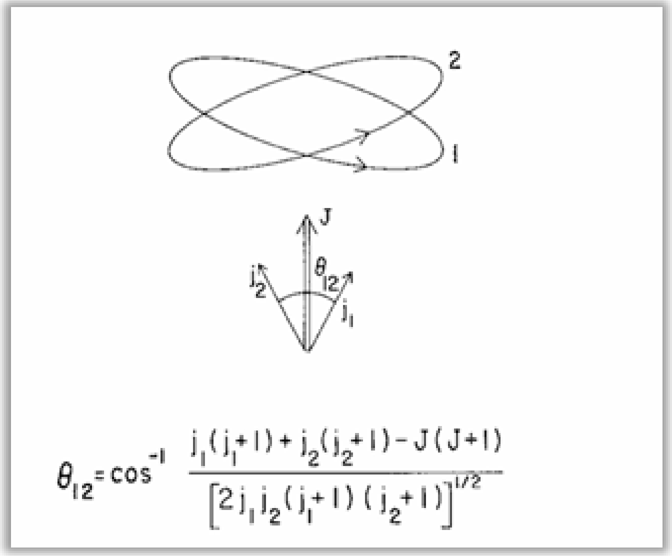
In the shell model we make the following approximation to the problem:

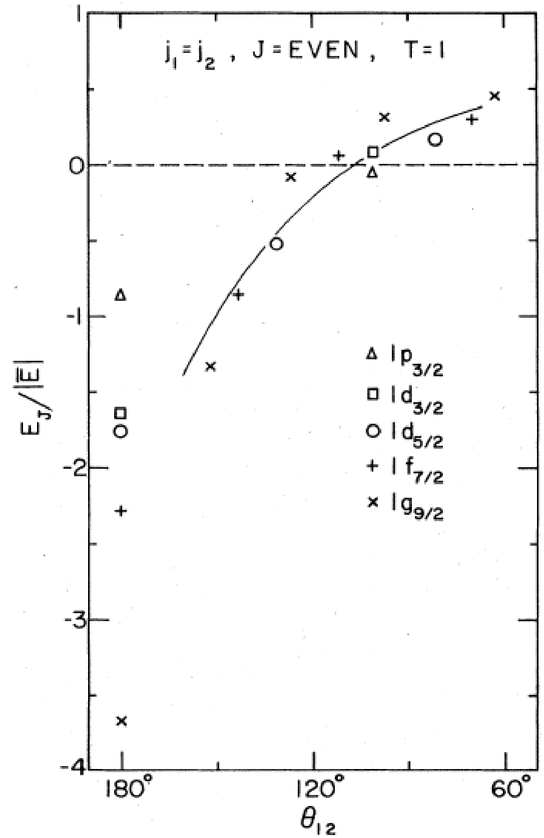
$$H = \underbrace{\sum_{k=1}^{A} [T_k + U(r_k)]}_{H^{(0)}} + \underbrace{\sum_{k=1}^{A} \sum_{l=k+1}^{A} W(\vec{r}_k, \vec{r}_l) - \sum_{k=1}^{A} U(r_k)}_{H^{(1)}},$$

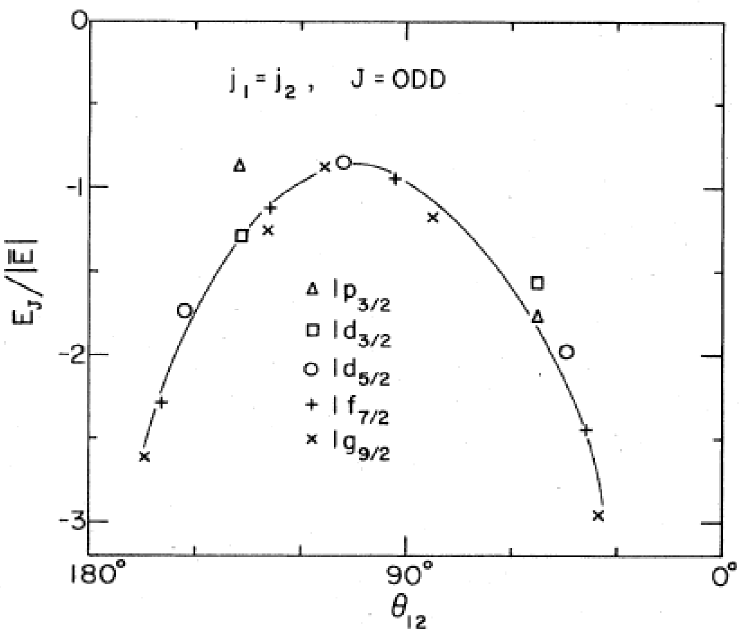
Mean Field

Residual Interaction, V(1,2)
→ Correlations

# The residual interaction: the very basics




$$V(1,2) \approx G\delta(\theta_{12}) + V_2 P_2(\theta_{12})$$

Short-range (Pairing ) + long-range (Quadrupole)

$$G \approx 20 MeV / A \qquad V_2 \approx 50 MeV / A$$

Aage Bohr, Ben Mottelson
1975

$$E_{pairing} \approx \frac{N}{2}\Delta = \frac{N}{2}G\Omega$$

$\Omega$
Levels

N valence particles

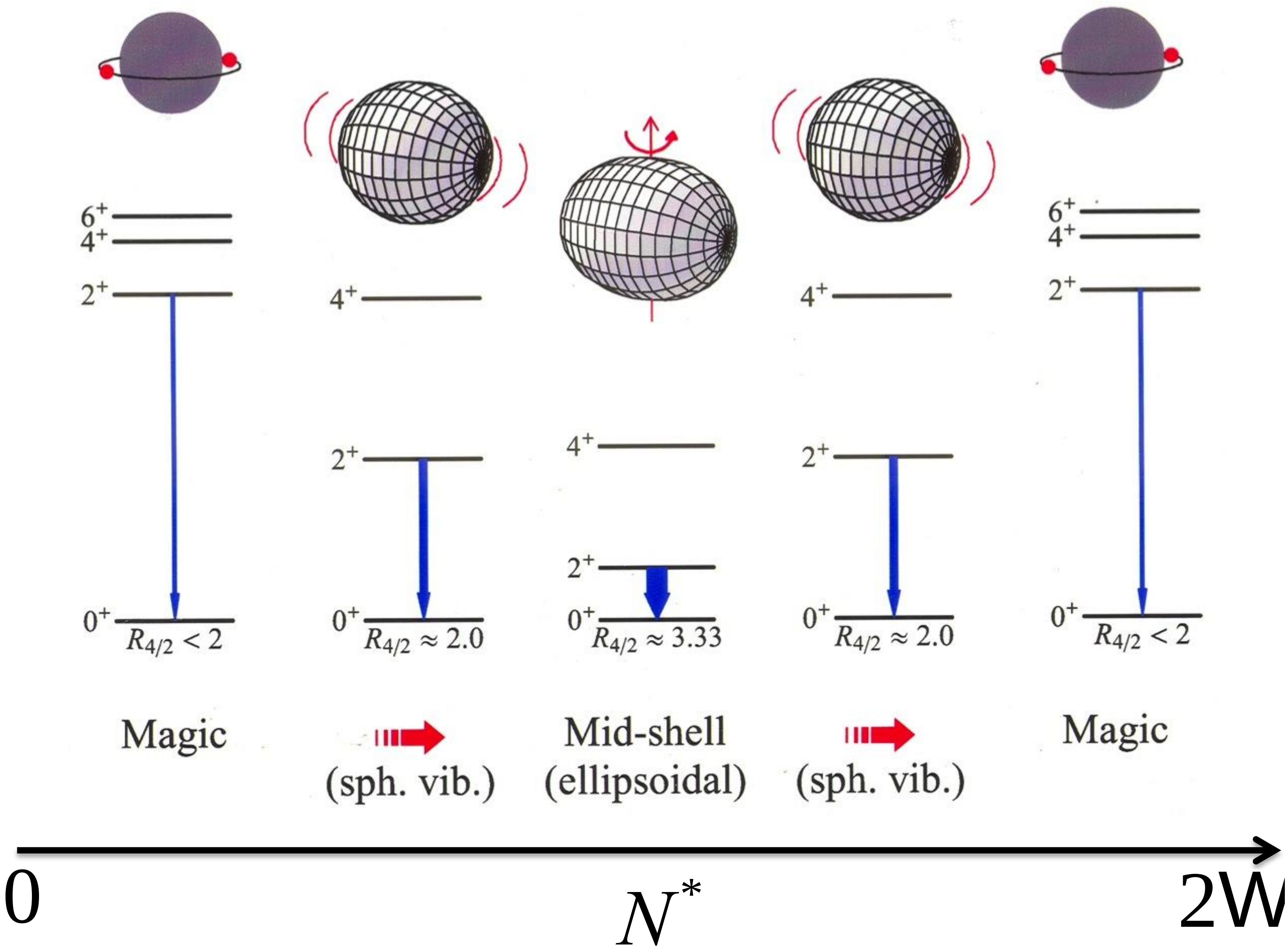
$$E_{quadrupole} \approx \frac{N^2}{2}V_2$$

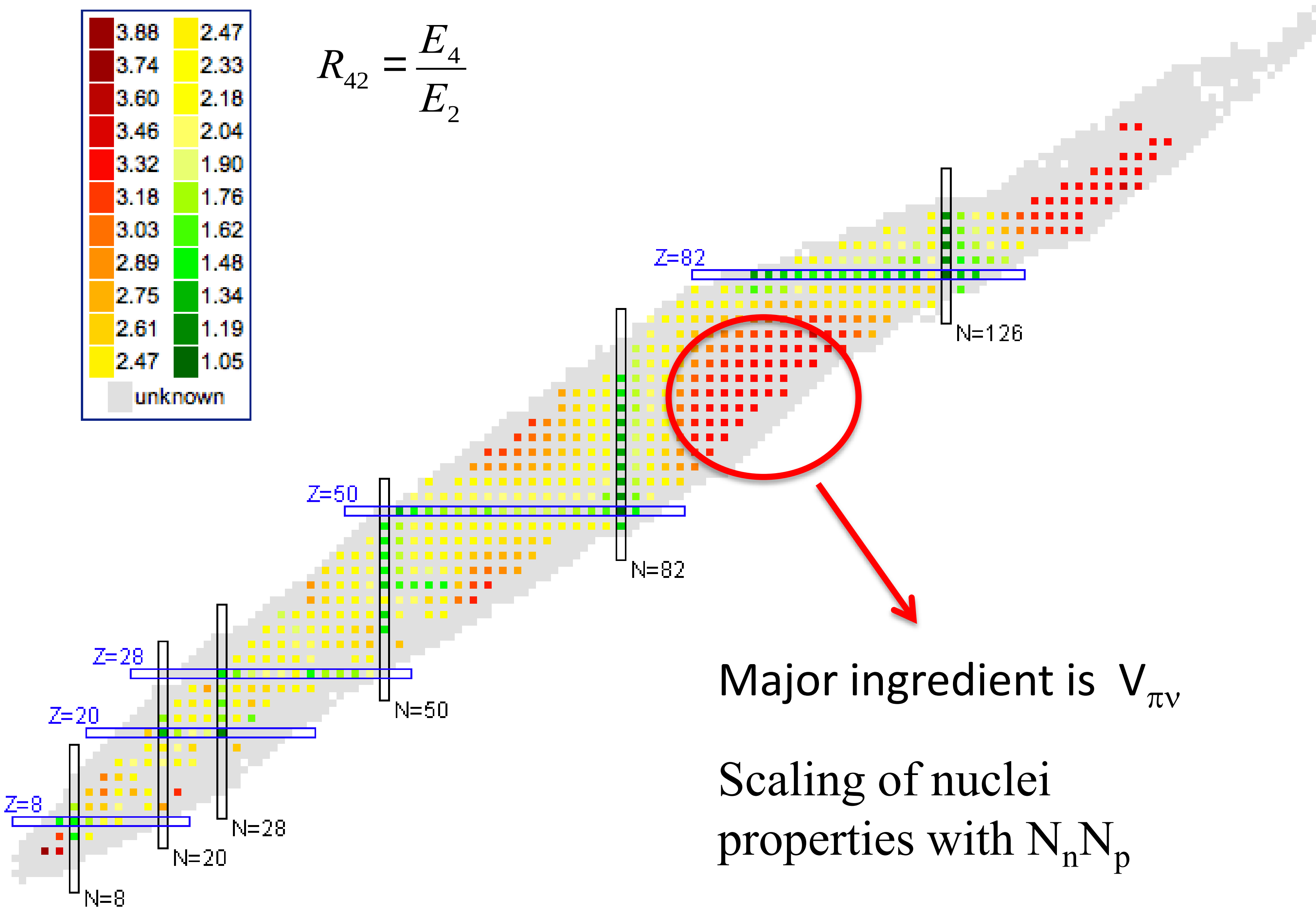
$2\Omega$
max
number of
particles

Closed shell nucleus, $A_0$

$$N^* \approx \left(\frac{G}{V_2}\right)\Omega \quad \text{and} \quad \left(\frac{G}{V_2}\right) \leq 1$$

Adapted from Rick Casten





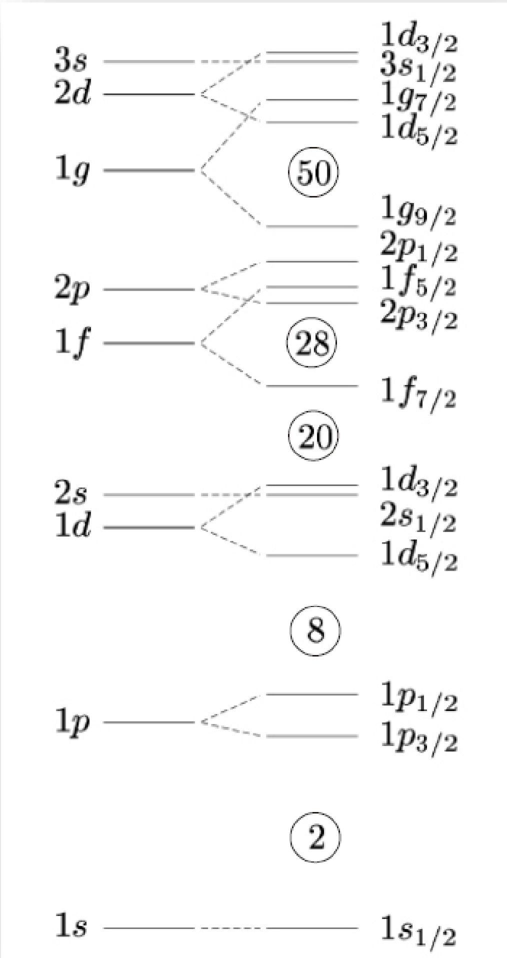

Major ingredient is $V_{\pi\nu}$

Scaling of nuclei properties with $N_n N_p$

I. Hamamoto, Nucl. Phys. 73 (1965) 225.

R. Casten, Phys. Lett. 152B (1985) 145.

# “Exotic” Shell Structure and Collectivity

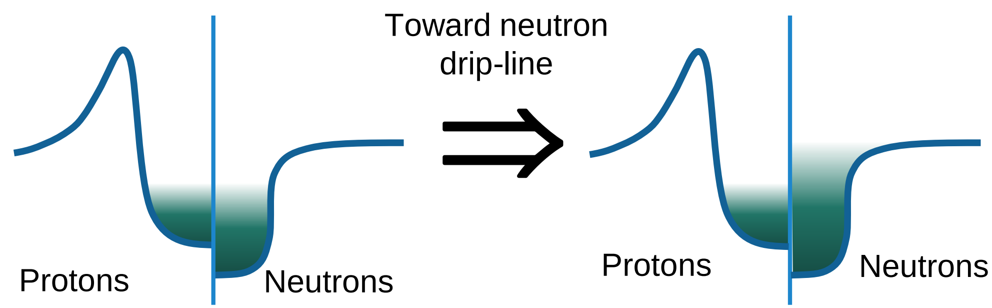



**Near the valley of β stability**

⇒ ?

A driving question in nuclear science:

Is the shell-model description static across the entire chart of nuclides?




Approaching the drip-lines

NUCLEAR PHYSICS

# Elusive magic numbers

Robert V. F. Janssens

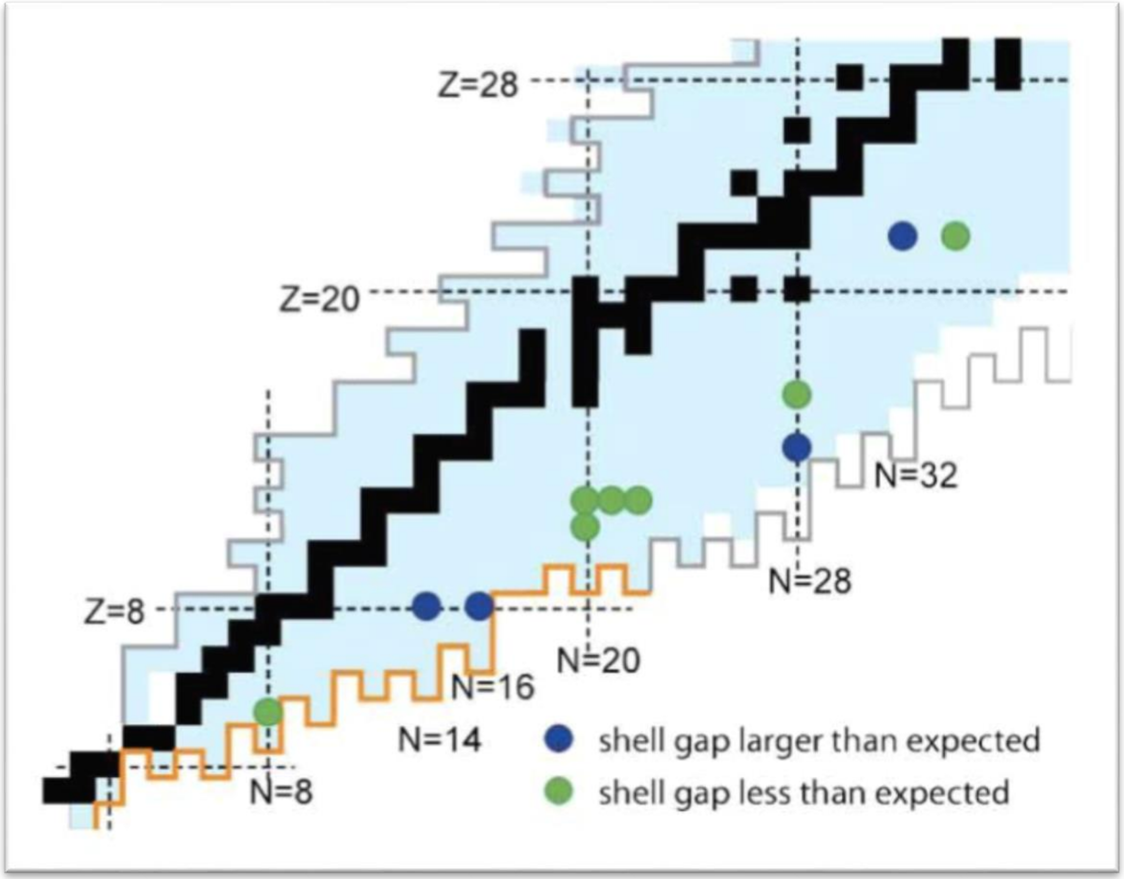
NATURE|Vol 435|16 June 2005

Standard magic numbers are generally correct only for stable and near stable isotopes

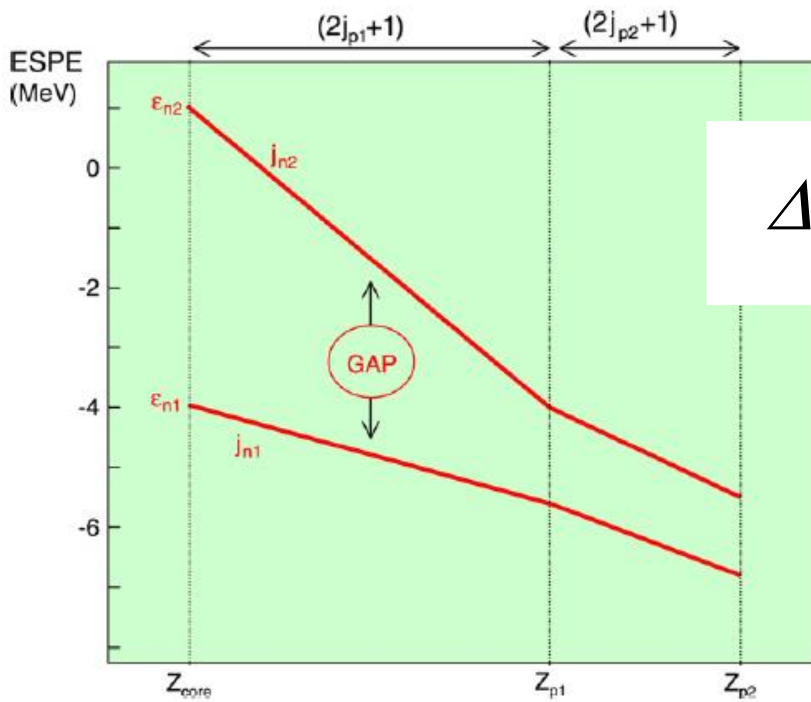
Experimental studies of new isotopes has given insight into the role of tensor and 3-body forces in nuclei

N/Z (Isospin) dependence

Role of the continuum



O. Sorlin, M.-G. Porquet / Progress in Particle and Nuclear Physics 61 (2008) 602–673




$$\Delta en(j) = \frac{1}{2}\{V^{T=0}_{j,j'} + V^{T=1}_{j,j'}\}\, n_p(j')$$

$$V^{T}_{j,j'} = \frac{\sum_J (2J+1)\langle jj'|V|jj'\rangle_{JT}}{\sum_J (2J+1)}$$

Monopole
Average

$$V(r) = V_{Central} + V_{Tensor} + V_{SpinOrbit}$$

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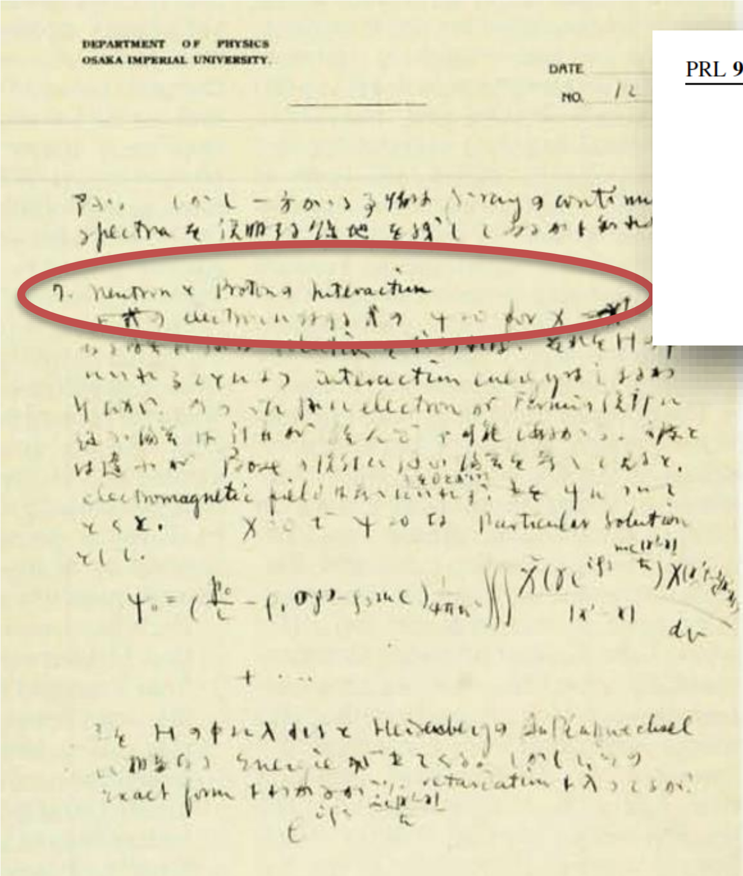
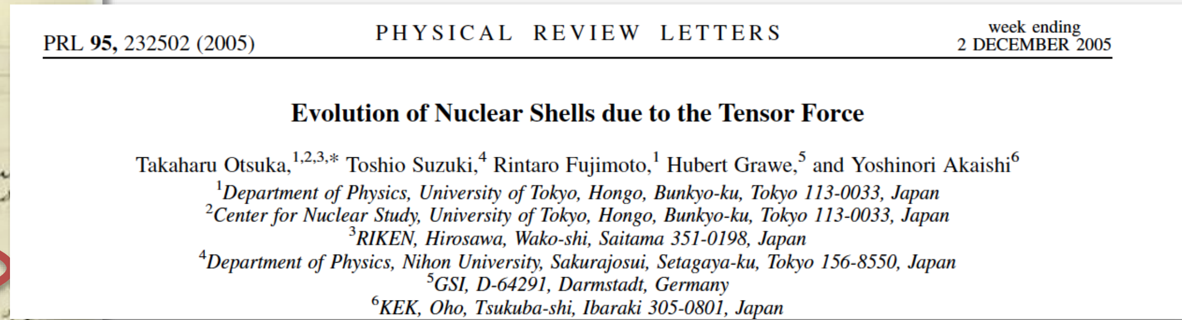



PHYSICS TODAY / DECEMBER 1986 57

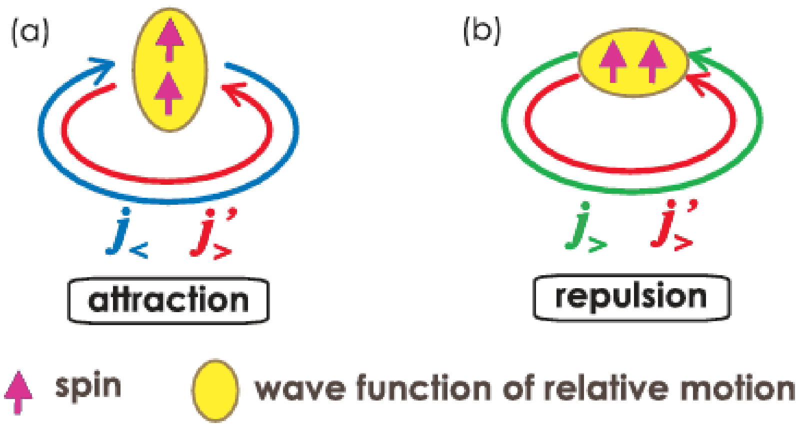


PRL 95, 232502 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

**Evolution of Nuclear Shells due to the Tensor Force**

Takaharu Otsuka,[1,2,3,*] Toshio Suzuki,[4] Rintaro Fujimoto,[1] Hubert Grawe,[5] and Yoshinori Akaishi[6]

[1]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3]*RIKEN, Hirosawa, Wako-shi, Saitama 351-0198, Japan*
[4]*Department of Physics, Nihon University, Sakurajosui, Setagaya-ku, Tokyo 156-8550, Japan*
[5]*GSI, D-64291, Darmstadt, Germany*
[6]*KEK, Oho, Tsukuba-shi, Ibaraki 305-0801, Japan*



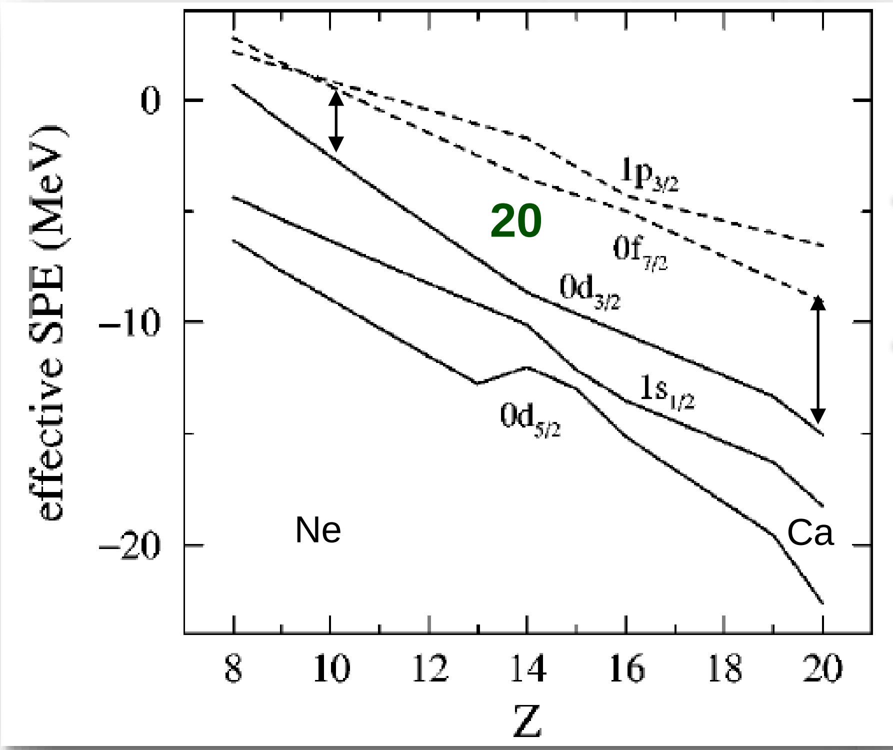

$$V_T = (\vec{\tau}_1 \cdot \vec{\tau}_2)\, S_{12}\, V(r)$$

$$S_{12} = 3\,(\vec{s}_1 \cdot \vec{r}/r)\,(\vec{s}_2 \cdot \vec{r}/r) - (\vec{s}_1 \cdot \vec{s}_2)$$

$$= 3\,(\,[\vec{s}_1 \times \vec{s}_2]^{(2)} \cdot [\vec{r} \times \vec{r}]^{(2)} / r^2)$$

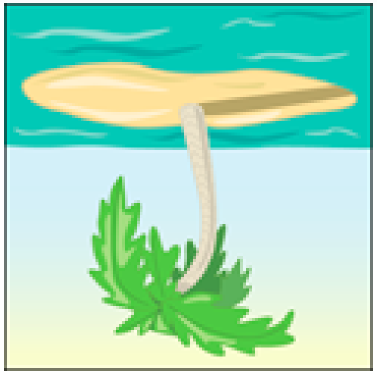
# N=20 shell gap

Y.Utsuno et al PRC 60 (1999) 011301(R)

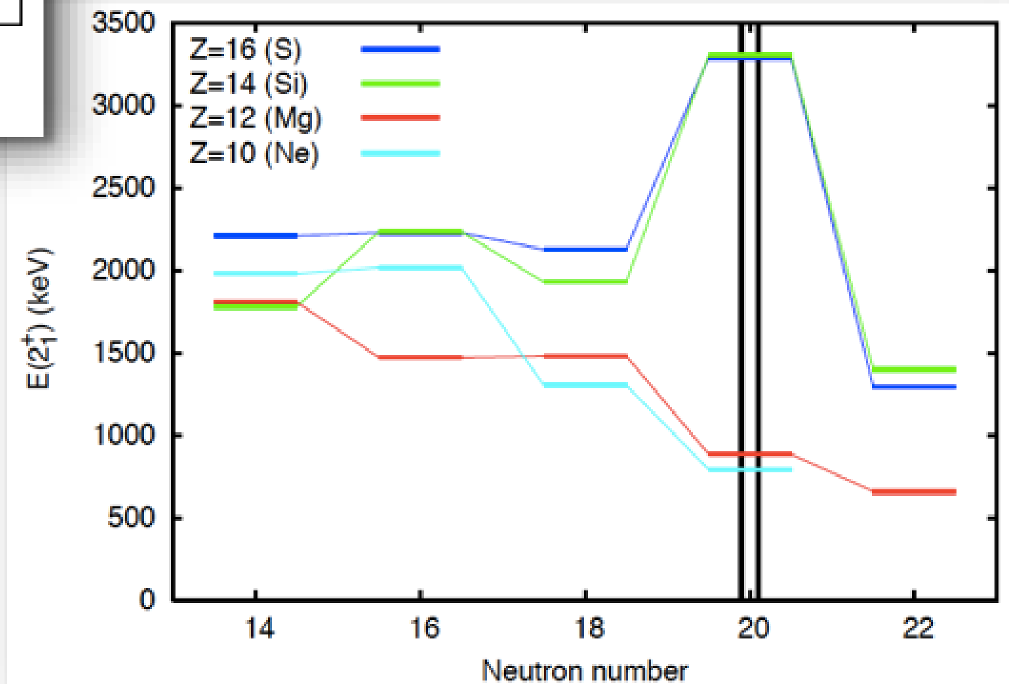


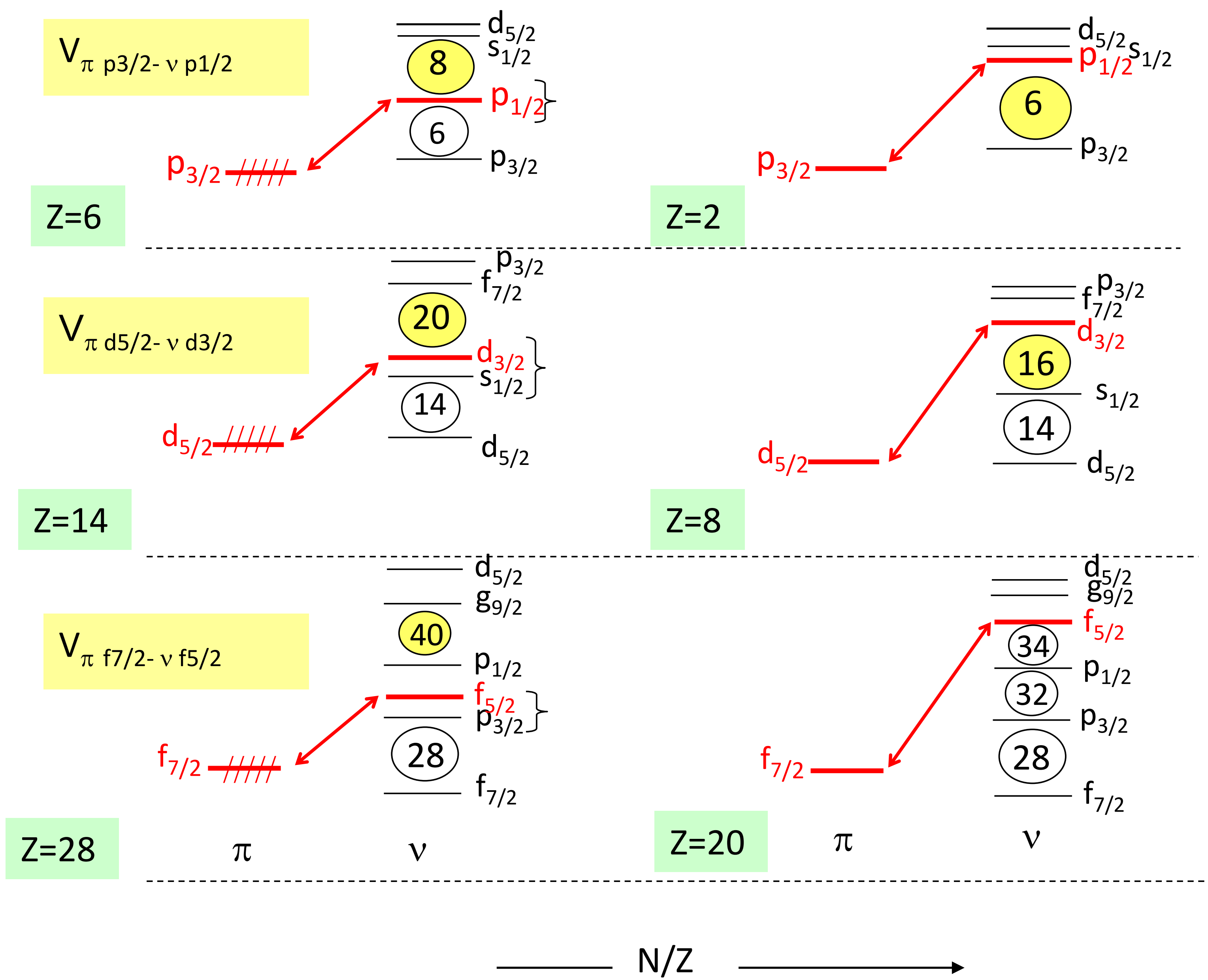

Role of the $\pi\, d_{5/2}$- $\nu\, d_{3/2}$ interaction

$\Delta l = \Delta j = 2$
→ Quadrupole Correlations



From APS/Physics Synopsis
*"Far from the stable nuclei"*
November 2010

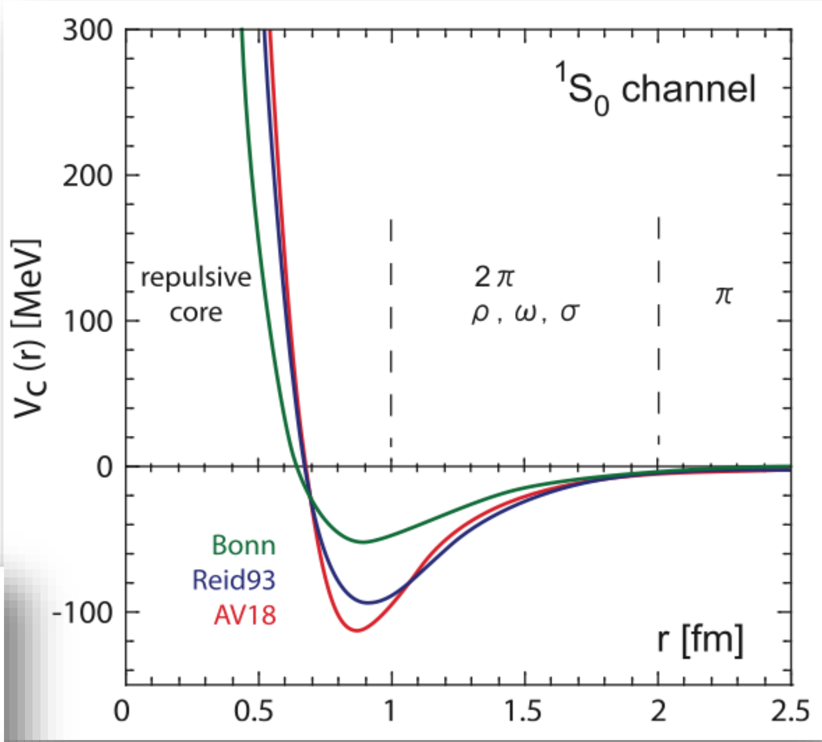


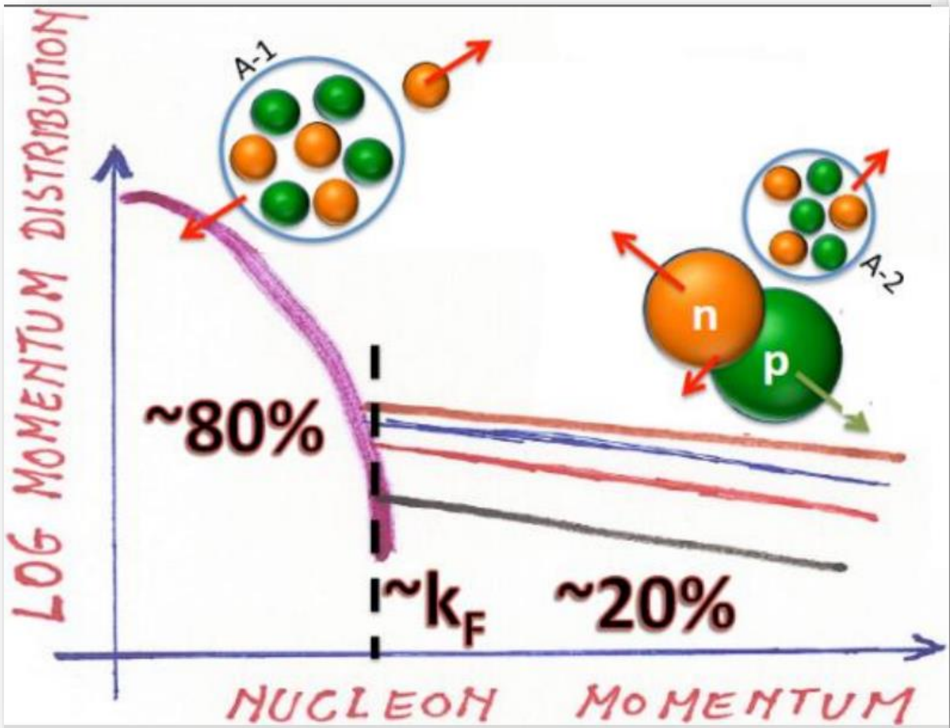


V π p3/2- ν p1/2
Z=6
p3/2
8
6
d5/2
s1/2
p1/2
p3/2
Z=2
p3/2
6
d5/2
p1/2
s1/2
p3/2
V π d5/2- ν d3/2
Z=14
d5/2
20
14
p3/2
f7/2
d3/2
s1/2
d5/2
Z=8
d5/2
16
14
p3/2
f7/2
d3/2
s1/2
d5/2
V π f7/2- ν f5/2
Z=28
f7/2
40
28
d5/2
g9/2
p1/2
f5/2
p3/2
f7/2
Z=20
f7/2
34
32
28
d5/2
g9/2
f5/2
p1/2
p3/2
f7/2
π
ν
π
ν
N/Z

Beyond mean field

Short Range correlations



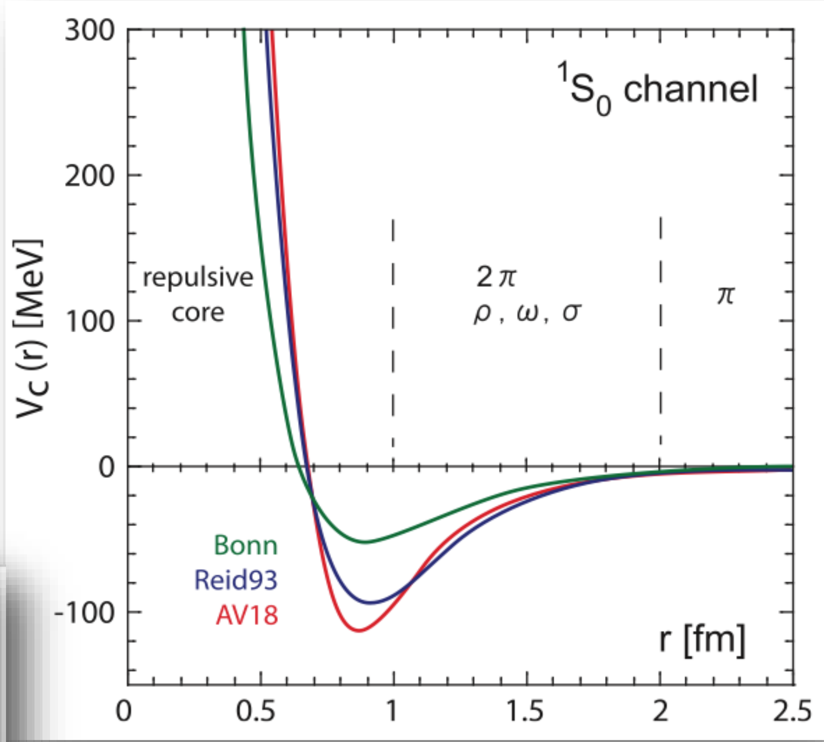



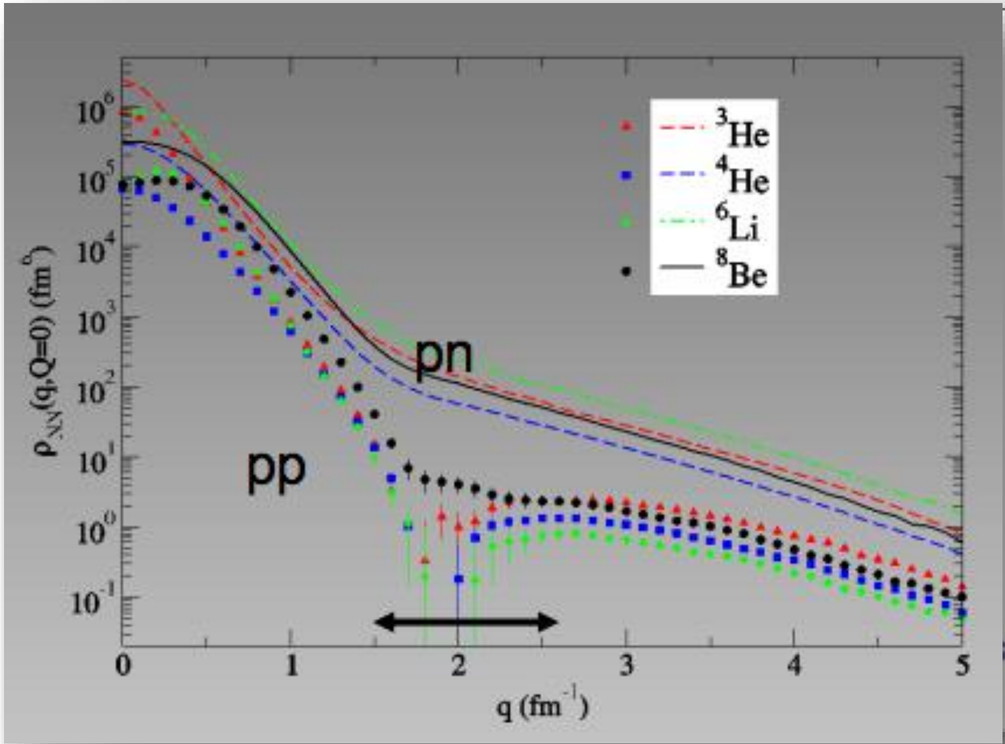

"Dressed" quasi-nucleons

Tensor force

Beyond mean field

Short Range correlations



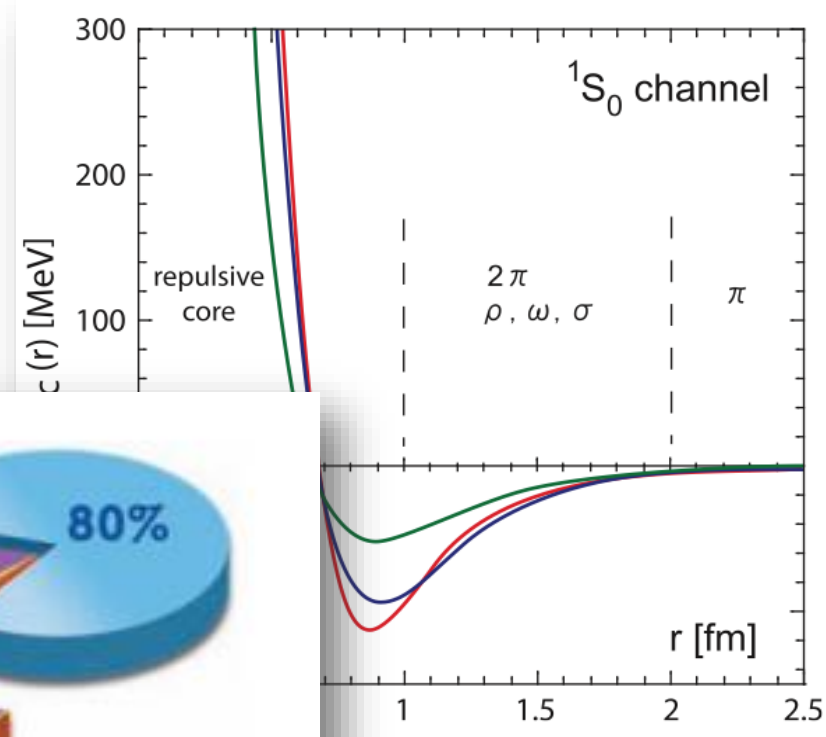

Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007)

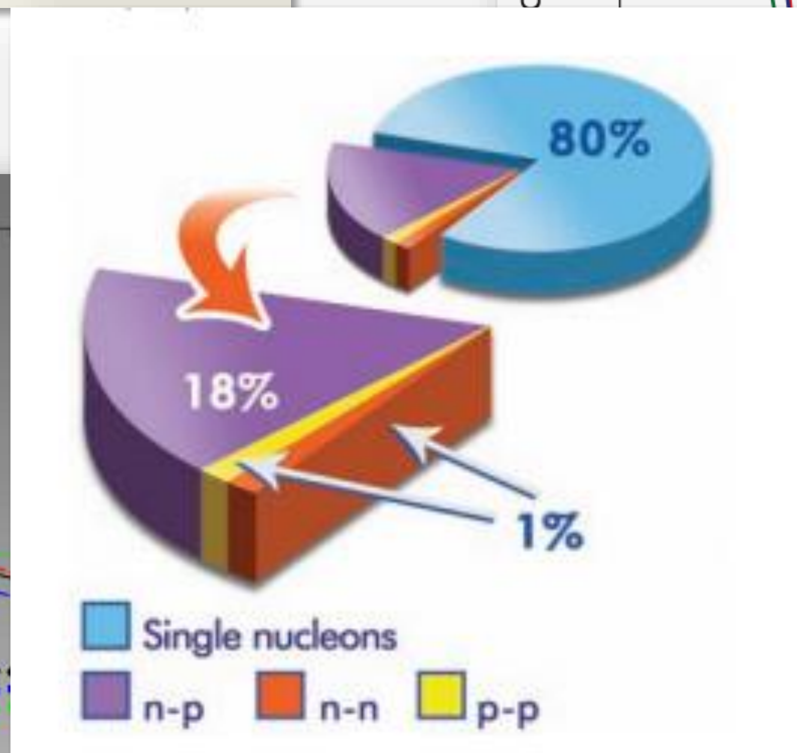
"Dressed" quasi-nucleons

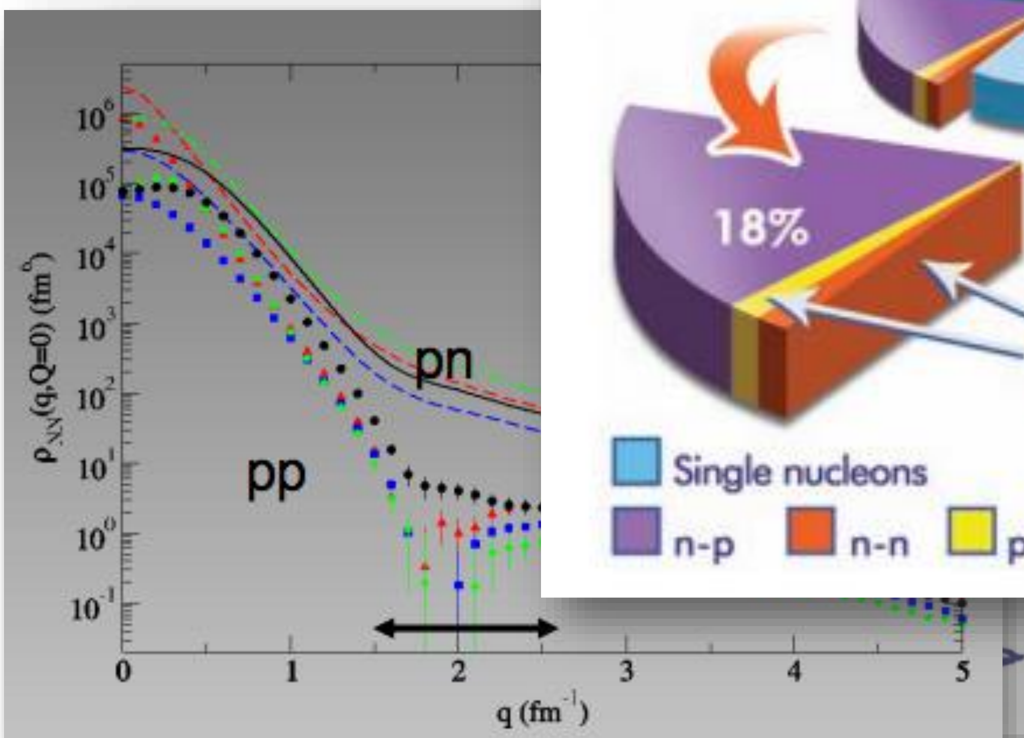
Tensor force

Beyond mean field

Short Range correlations



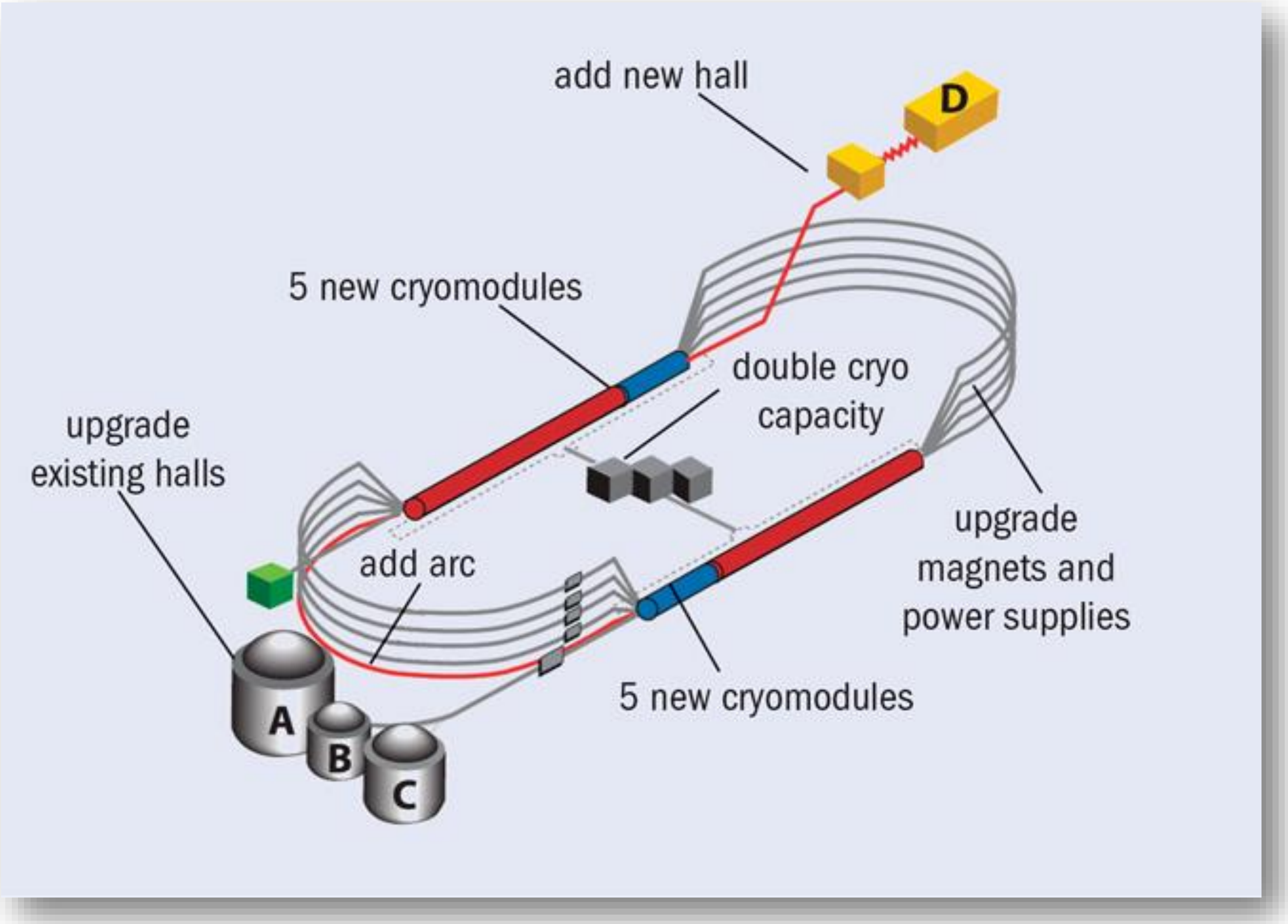




…ed” quasi-nucleons

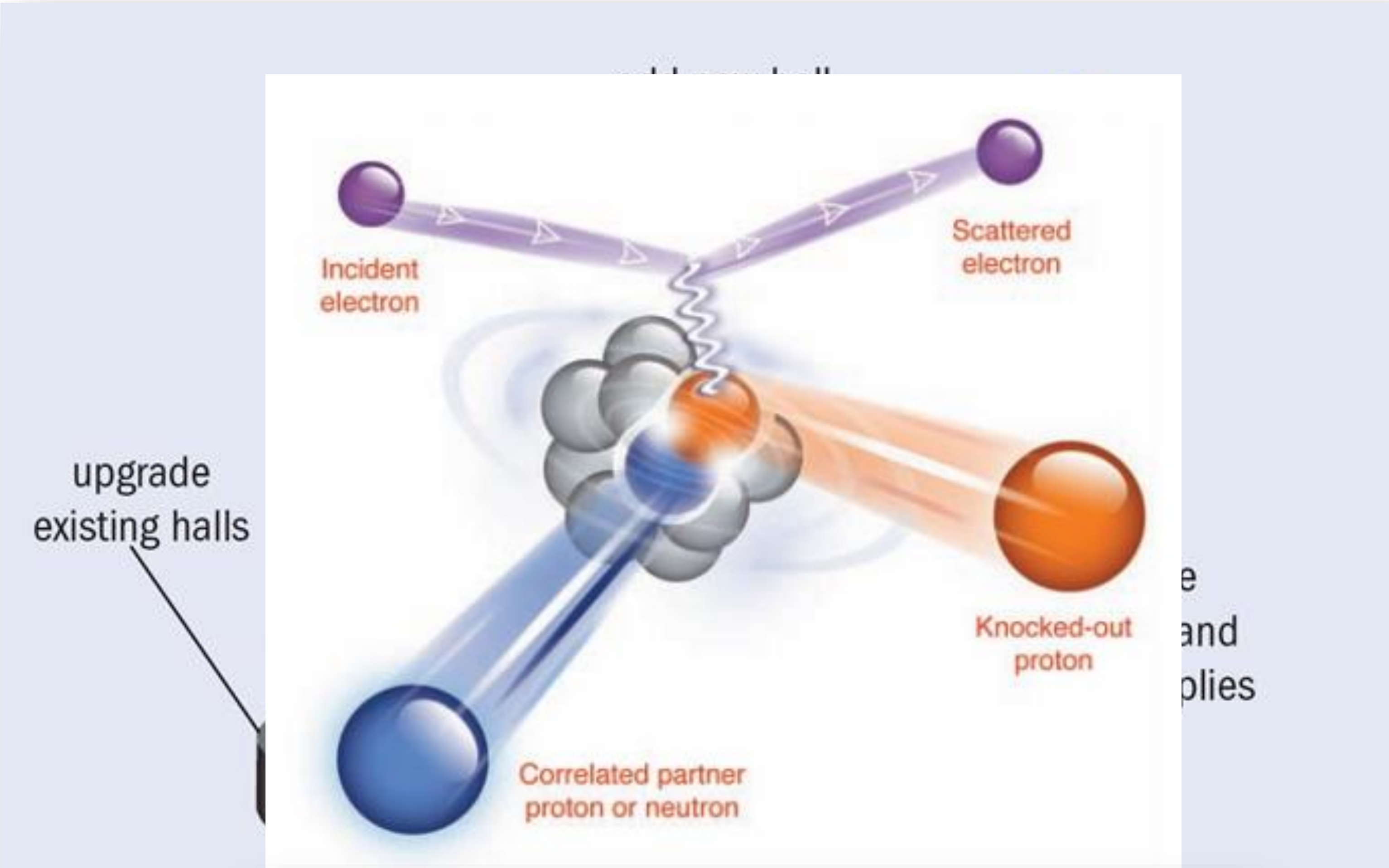
Tensor force

Schiavilla, Wiringa, Pieper, Carson, PRL 98,132501 (2007)

# Jefferson Laboratory



# Jefferson Laboratory




R. Subedi *et al.*, Science **320** (2008) 1476.

# Weakly bound systems

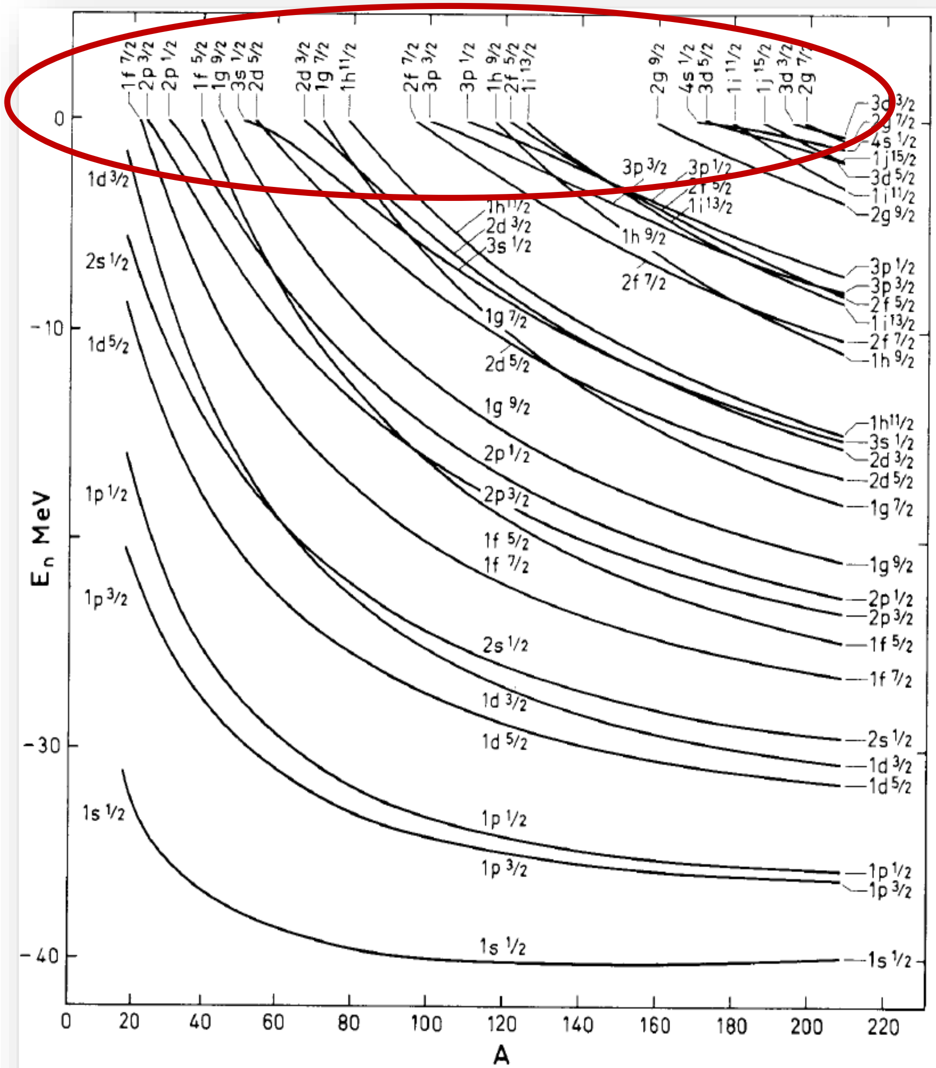



Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

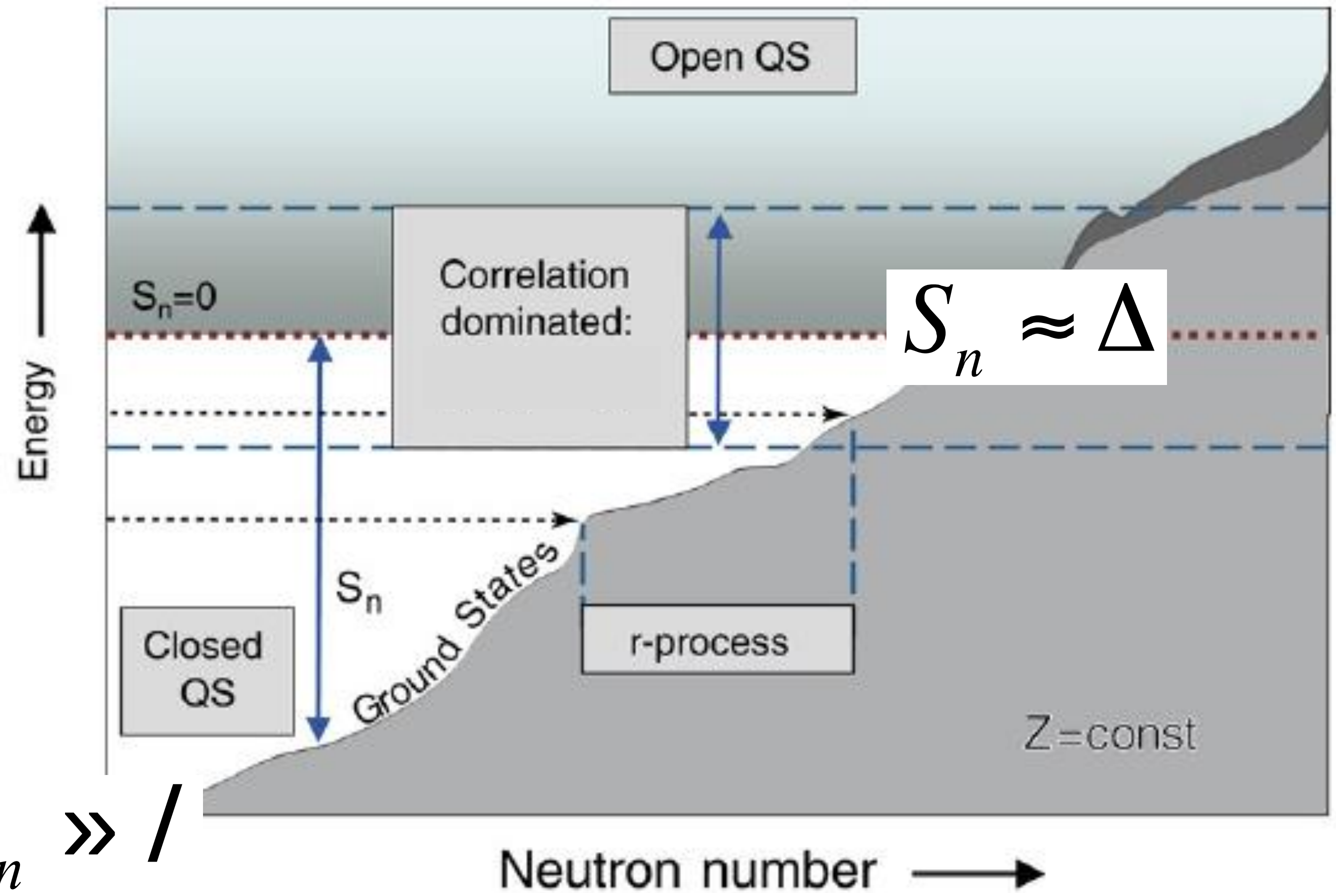
A.Bohr and B.R. Mottelson, Nuclear Structure Vol. 1

A second distinct effect is due to weakly bound levels

- low *l* levels (*s*, *p*) → extended wavefunctions ("halos")
- Valence nucleons can become decoupled from the core
- Coupling to continuum states

# Weakly bound systems

*J. Dobaczewski et al. / Progress in Particle and Nuclear Physics 59 (2007) 432–445*




$$S_n \approx \Delta$$

$$S_n » /$$

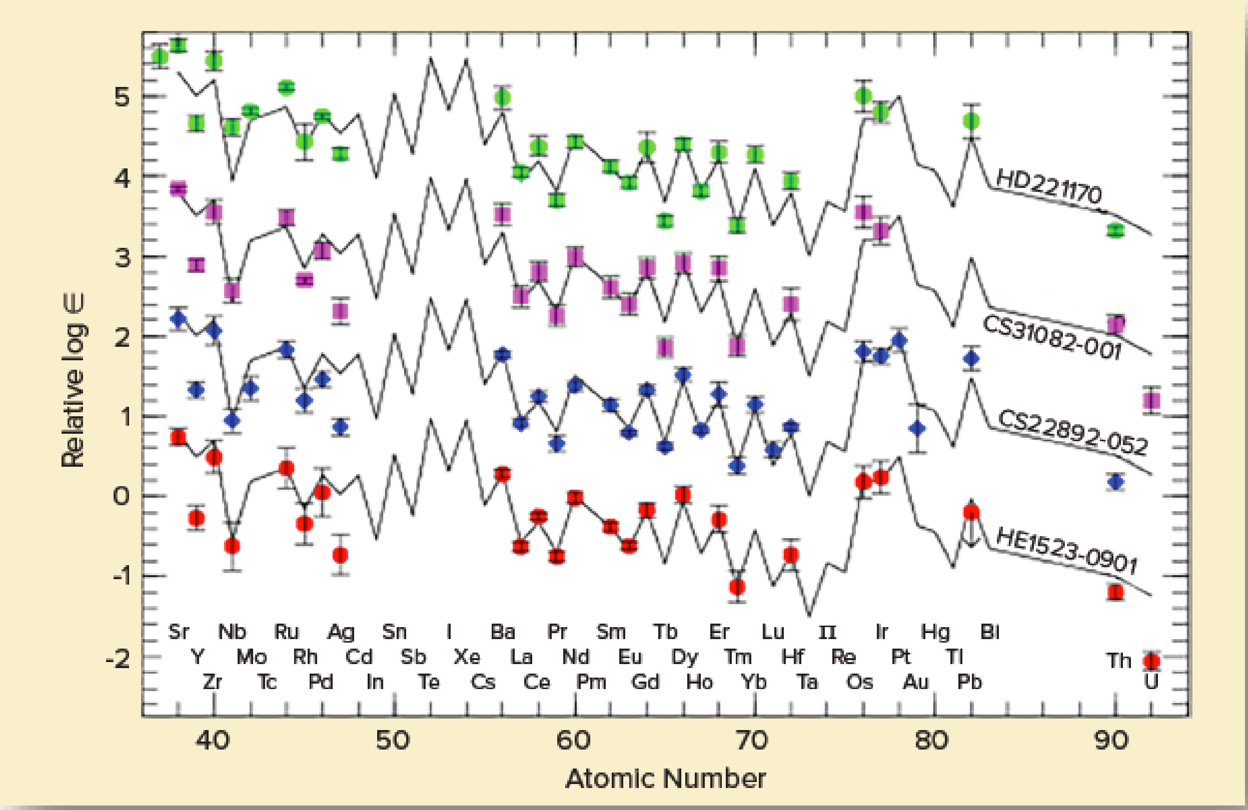
$$S_n \approx \Delta + \lambda$$

# The Origin of Heavy Elements

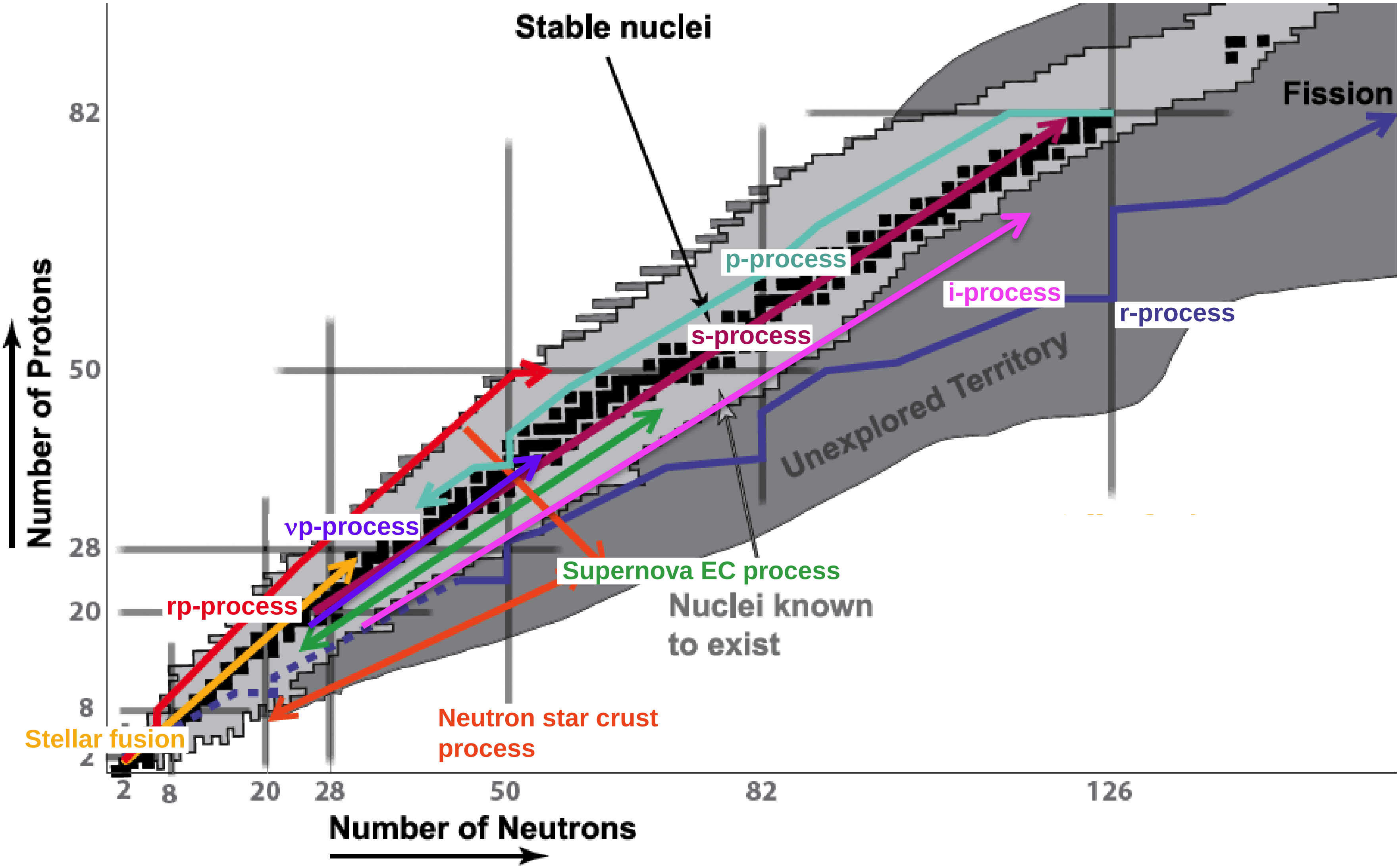
A fundamental question for nuclear astrophysics is the origin of the neutron-rich elements heavier than iron. These heavy elements are mostly produced either by a slow neutron capture process (the s-process) or by a rapid neutron capture process (the r-process) that requires a much higher temperature and density environment. The latter can only be associated with violent events generating high neutron excess..

The masses and the lifetimes of nuclei along the r-process path are the most important microscopic parameters for theoretical simulations.

These inputs are currently taken from extrapolations based on theoretical models.

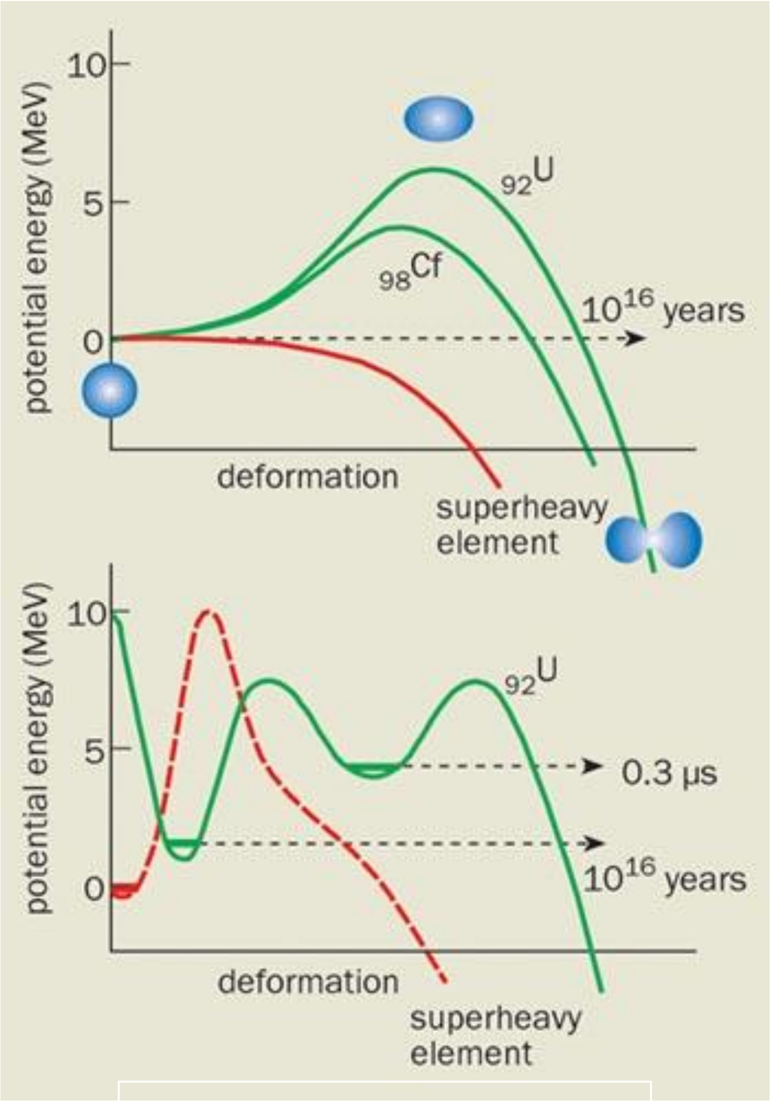


Improved nuclear physics data from FRIB are crucial to make detailed predictions and to determine potential features for identifying the actual site.




From Brad Sherrill EBSS15

# Why Do Heavy Nuclei Exist?



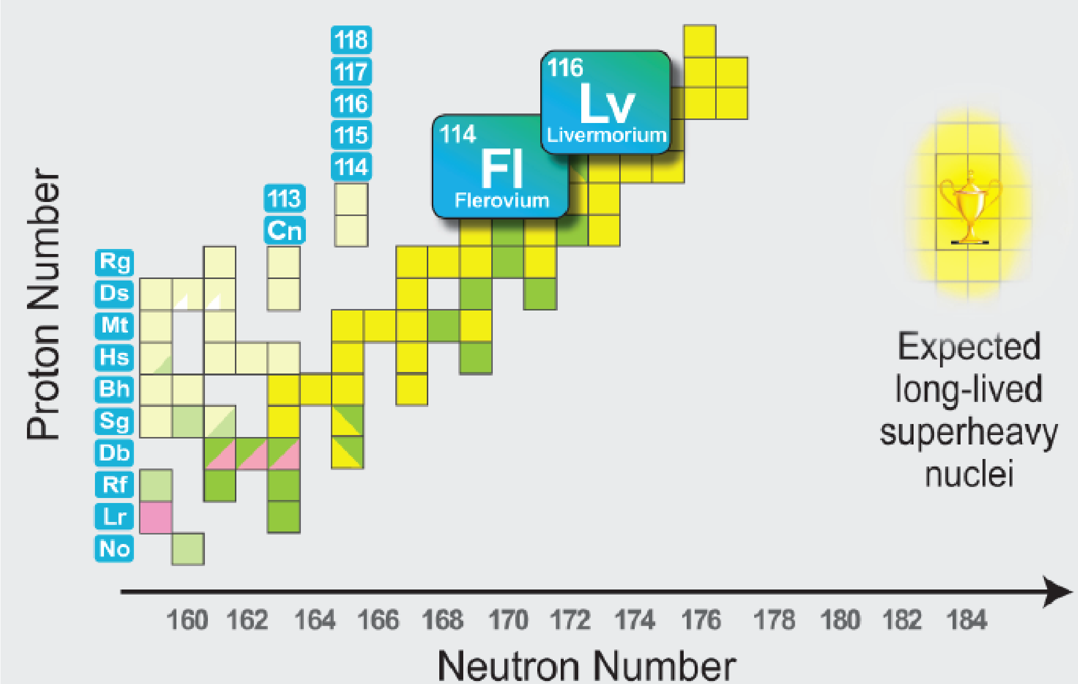

Physics World, July 2004

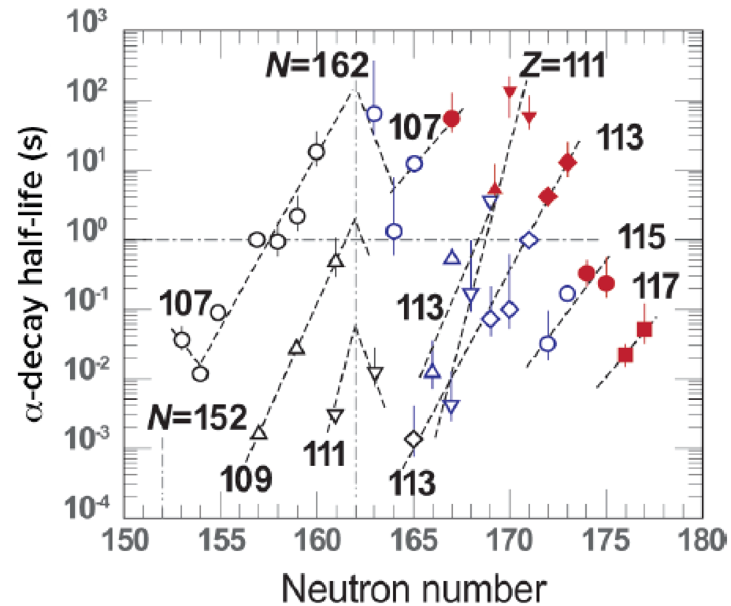
From a macroscopic viewpoint (as developed initially by Bohr and Wheeler) of the nucleus as a liquid drop, the stability of nuclei is governed by interplay of Coulomb repulsion and surface tension. Nuclei with Z>100 should immediately fall apart since there is no "barrier" to their decay (the red line).

There is also a microscopic contribution to the stability arising from the quantum structure. Regions of very low level density, quantum shell gaps, enhance the stability and heavy nuclei can develop a large "barrier" to decay (the red line).

# Super Heavy Nuclei

Nihonium and symbol Nh, for the element 113,
Moscovium and symbol Mc, for the element 115,
Tennessine and symbol Ts, for the element 117, and
Oganesson and symbol Og, for the element 118.




Recent experimental progress in this field has come from the realization that new elements can be synthesized by using neutron-rich beams, such as $^{48}Ca$, to bombard targets of very heavy elements such as berkelium.

There is a gradual onset of increasing stability for isotopes with $Z \geq 111$ when moving towards $N$=184, the anticipated center of stability in superheavy nuclei.

# Super Heavy Nuclei

Nihonium and symbol Nh, for the element 113,
Moscovium and symbol Mc, for the element 115,
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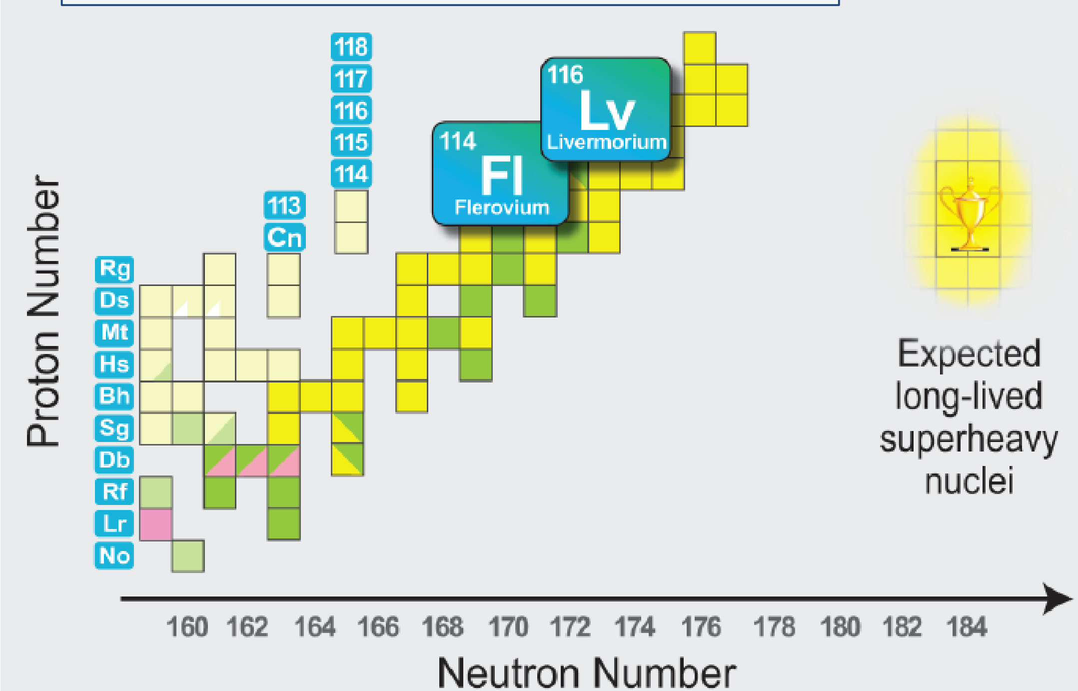
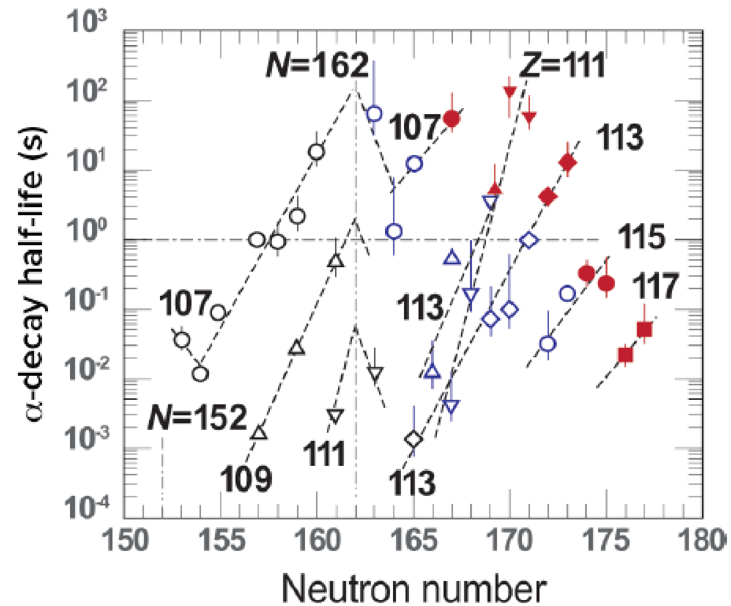


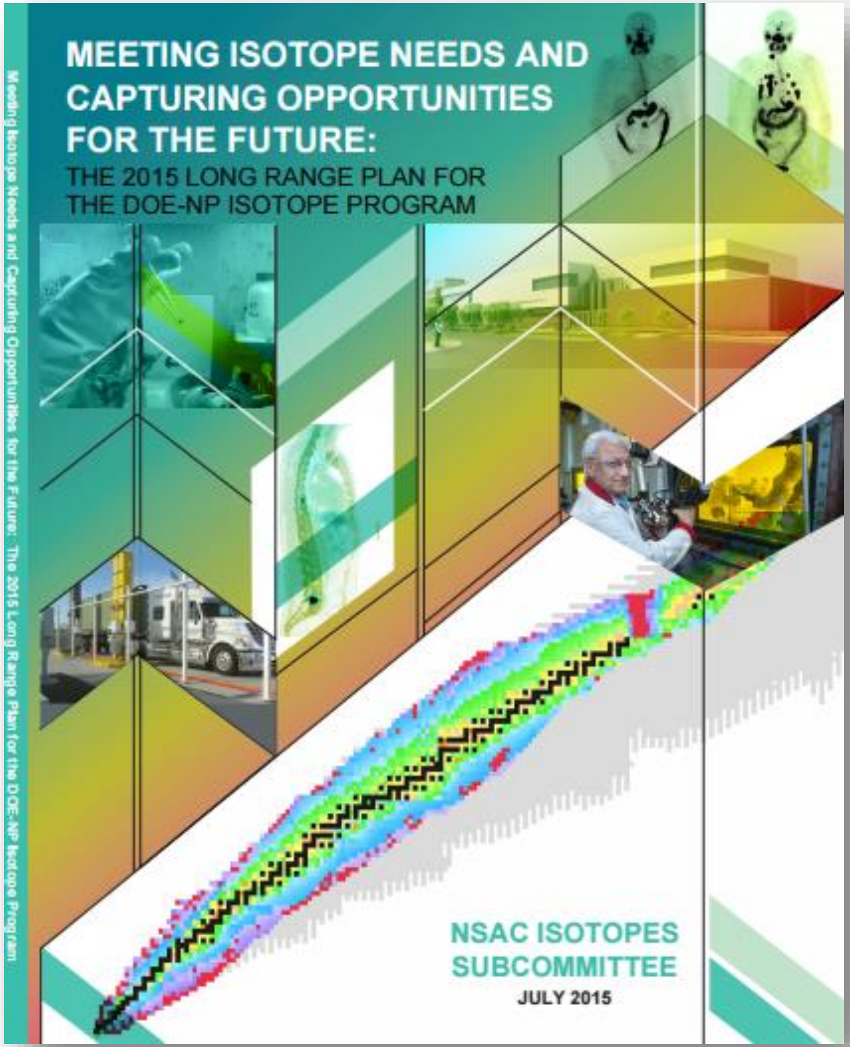

Ongoing improvements in experimental capabilities, such as K X-ray detection and a gas catcher coupled with a mass-separator, will enable the first direct *Z* and *A* identification of superheavy elements with Z ≥ 114.

ATLAS with upgraded intensity and FRIB with neutron-rich beams will inform us how to reach the expected region of long-lived superheavy nuclei.

# Application of Isotopes

- Next generation rare isotope facilities can provide isotopes for applied science while serving forefront nuclear research

- FRIB is designed to provide fast access to a broad range of new isotopes for research



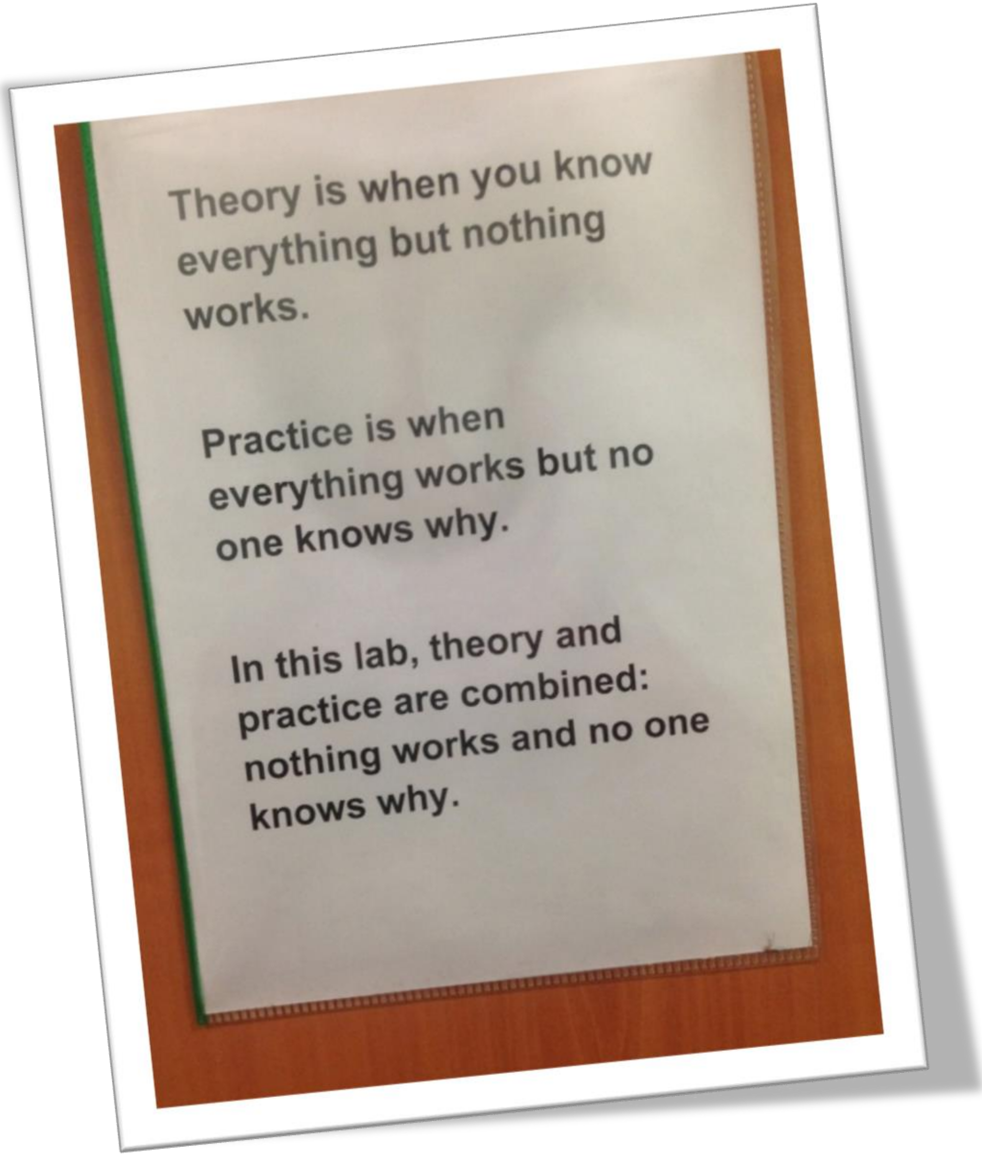

http://science.energy.gov/~/media/np/nsac/pdf/docs/2015/2015_NSACI_Report_to_NSAC_Final.pdf

# How to make and study exotic nuclei ?

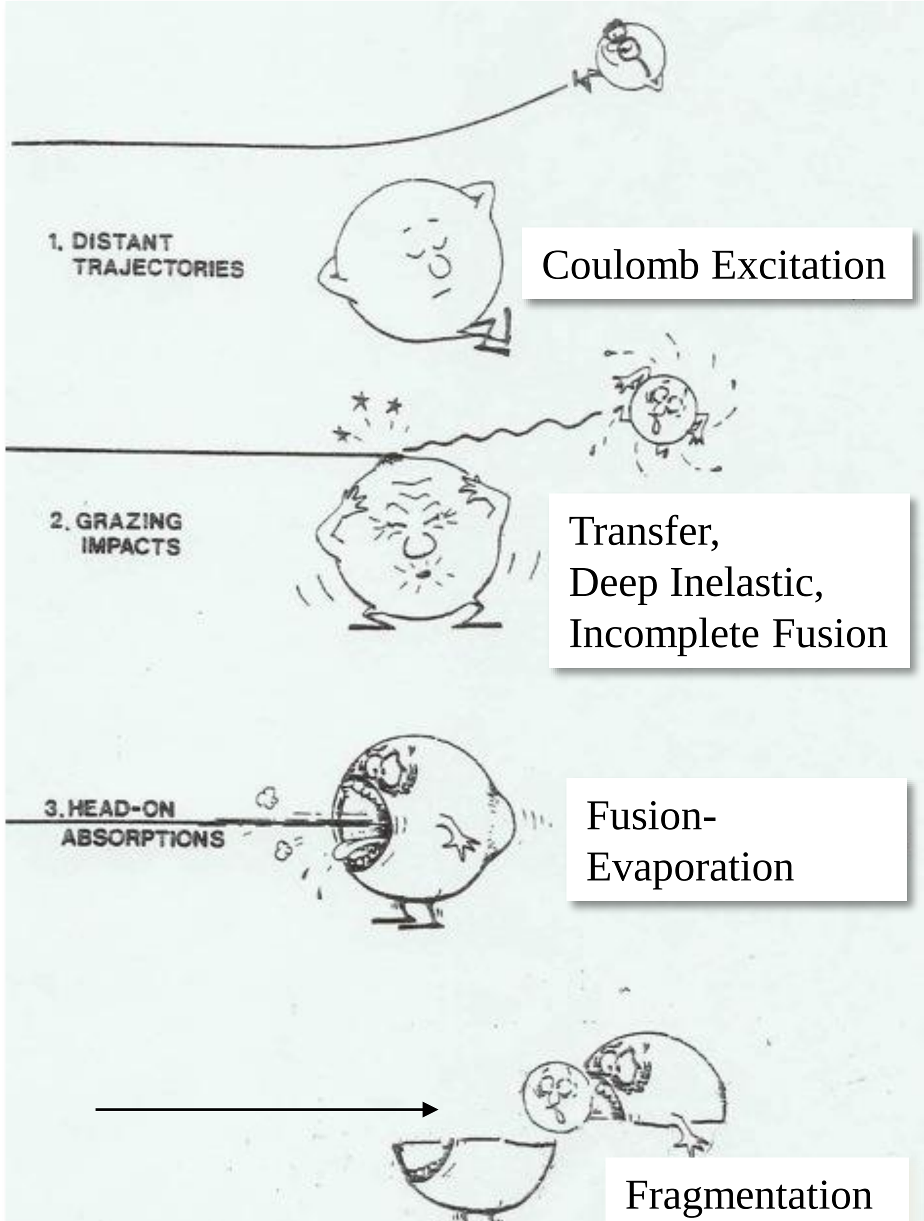
# Ingredients

- An accelerator facility to provide a beam of ions
  - Beam may be composed of unstable (radioactive) ions
  - Beam energy can be low (~100 keV) or high (~ 3 to 100 MeV per nucleon)
- A target (for higher-energy beams)
  - A small fraction of the beam ions react with target nuclei to make something of interest
- Detectors and associated electronics to study that "something"
  - Gamma-rays, light charged particle, fragments, heavy residuals, …
    - HPGe detectors
    - Double-sided strip detectors (Si or Ge)
    - Scintillators, with either PMTs or photodiodes
    - Magnetic spectrometers
    - Gas counters
    - Ion traps
    - Many more
- Theory to guide the experiments and interpret the data

# THE SYNERGY between THEORY and EXPERIMENT



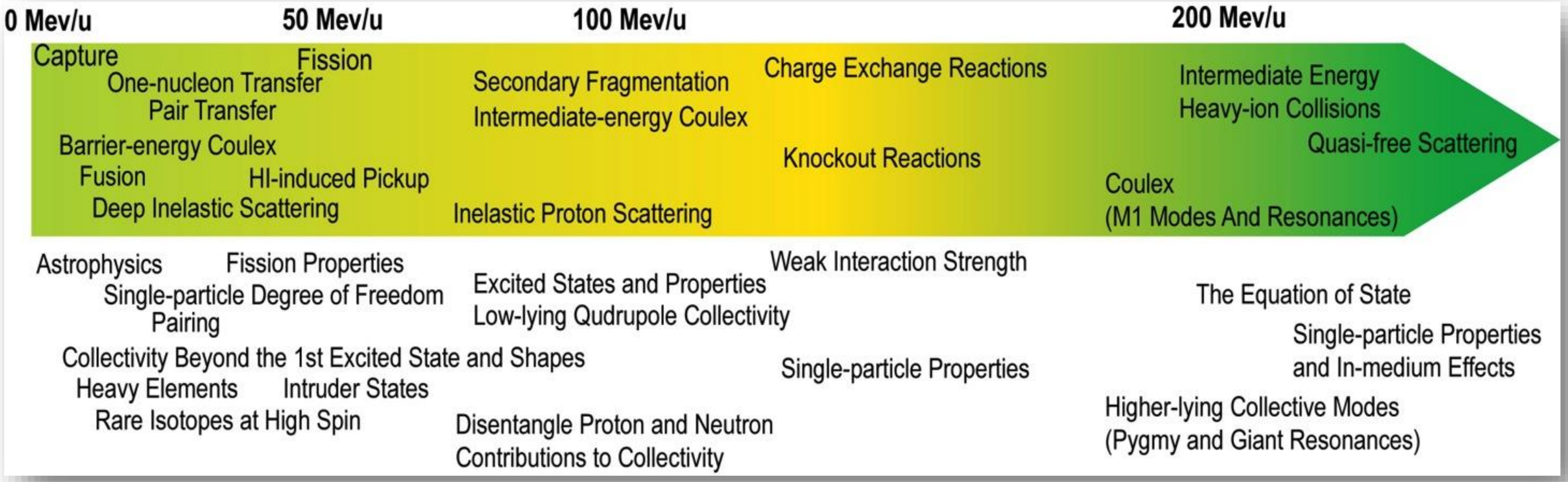
# The Physics Probes (An artist's view)




Adapted by Marcela Macchiavelli from H. A. Enge, Heavy Ions Summer Study- Oak Ridge 1972

# The Physics Probes (An expert's view)

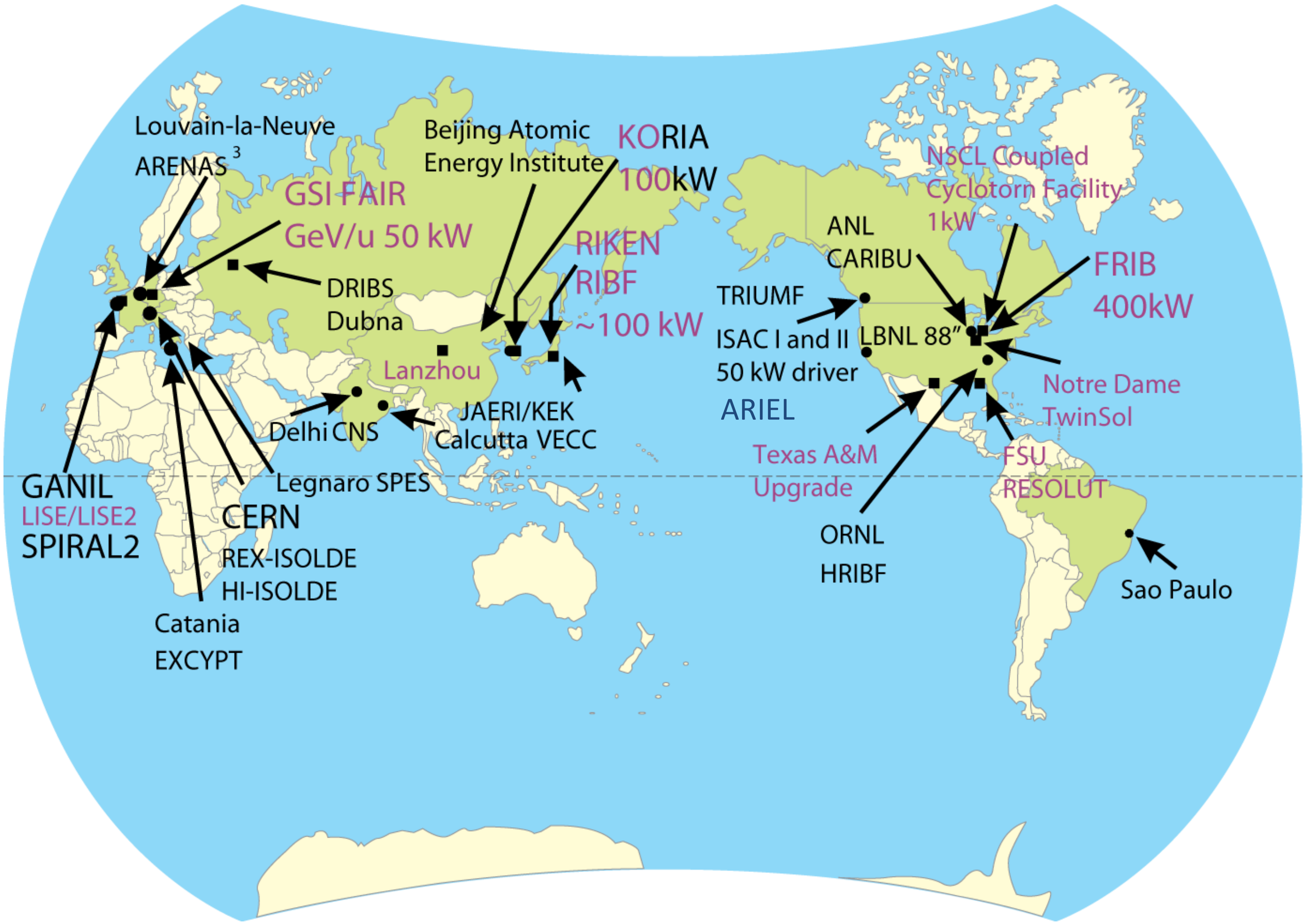
Nuclear reactions are an essential tool for the extraction of crucial information for nuclear structure physics and nuclear astrophysics
The required beam energy range spans from keV/u (astrophysics) to above 200 MeV/u for heavy-ion reactions that will constrain the nuclear equation of state




- FRIB will provide the full range of beam energies required to exploit nuclear reactions for nuclear structure and astrophysics

# FACILITIES

# World view of rare isotope facilities

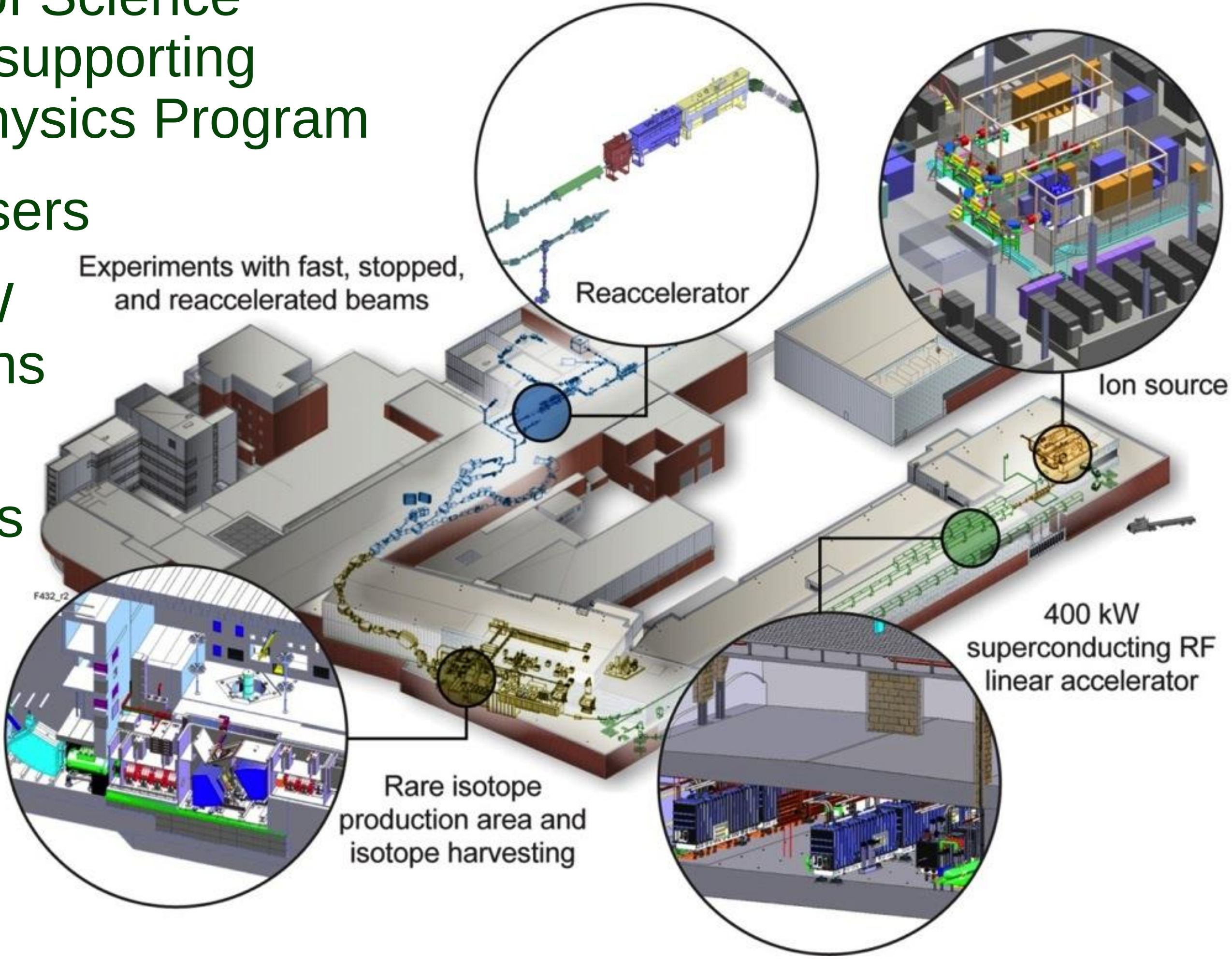



From Brad Sherrill - MSU

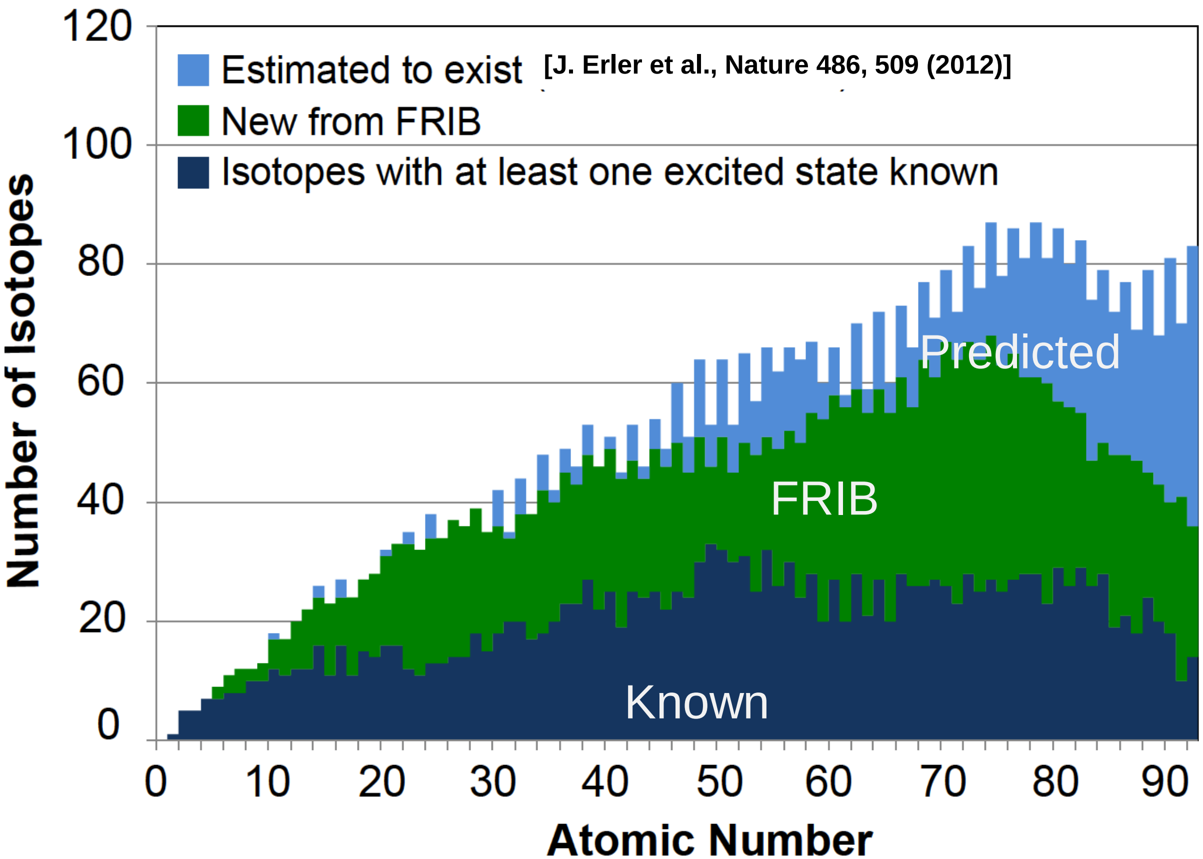
Black – production in target
Magenta – in-flight production

# FRIB

- A future DOE Office of Science scientific user facility supporting mission of Nuclear Physics Program
- Serving over 1,400 users
- Key feature is 400 kW beam power for all ions (e.g. $5\times10^{13}$ $^{238}$U/s)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - All elements and short half-lives
  - Fast, stopped, and reaccelerated beams



# Charting new areas of the Landscape




- Cross section corresponding to the production of 1 atom/week at FRIB:

  ~ 30 $\times 10^{-21}$ b (zepto) , 5 orders of magnitude lower than at present facilities

# INSTRUMENTATION

A variety of instrumentation is required to make use of science opportunities with rare isotope beams.

Improvements in instrumentation greatly extend the physics reach of the facilities.

### Gamma detectors

- Usually *arrays* of HPGe detectors or scintillators
- *In-beam* or *out-of-beam*

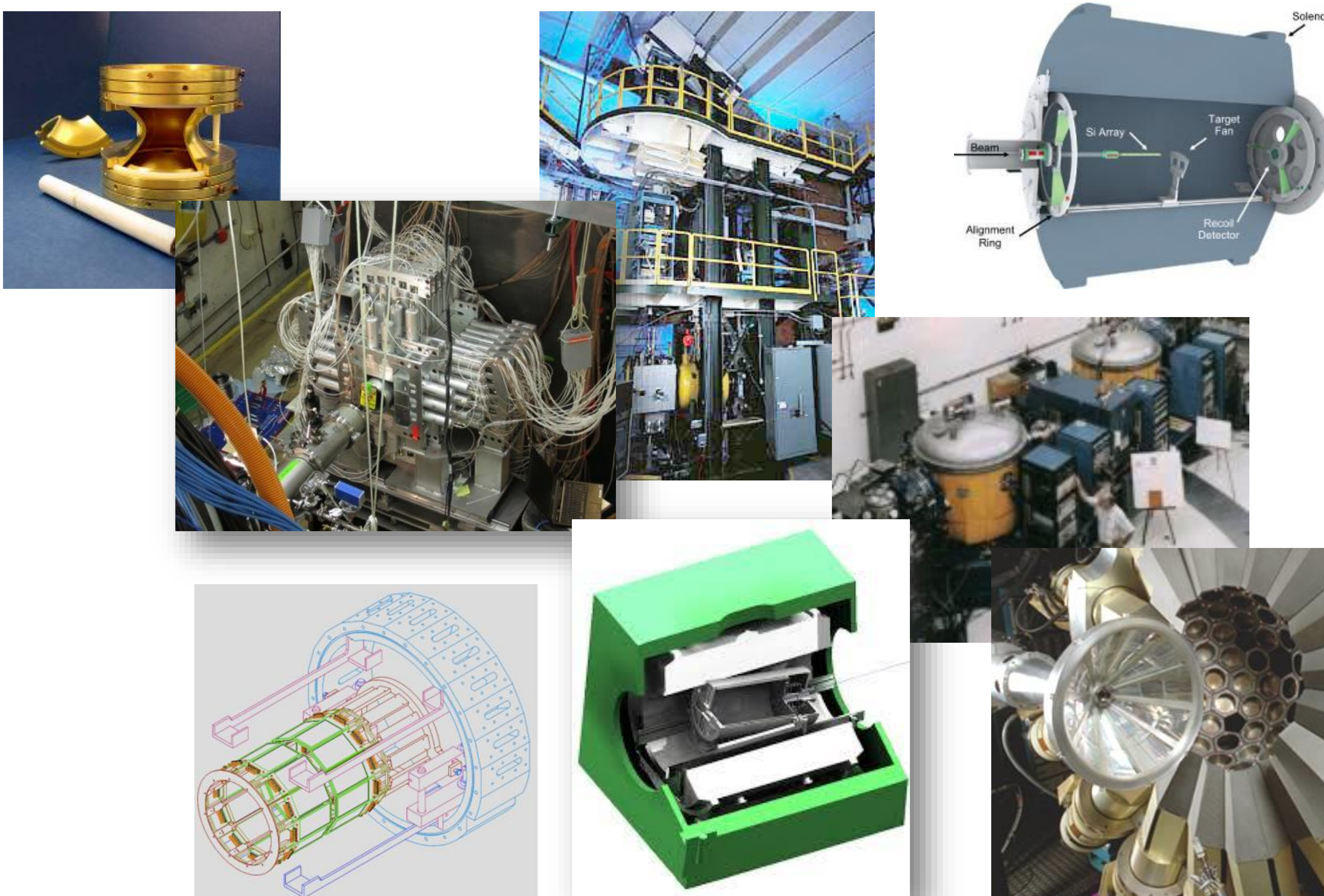
### Recoil and light-ion detectors

- Magnetic spectrometers and separators
- Gas counters
- Si detectors (usually DSSD or position-sensitive)
- Scintillators

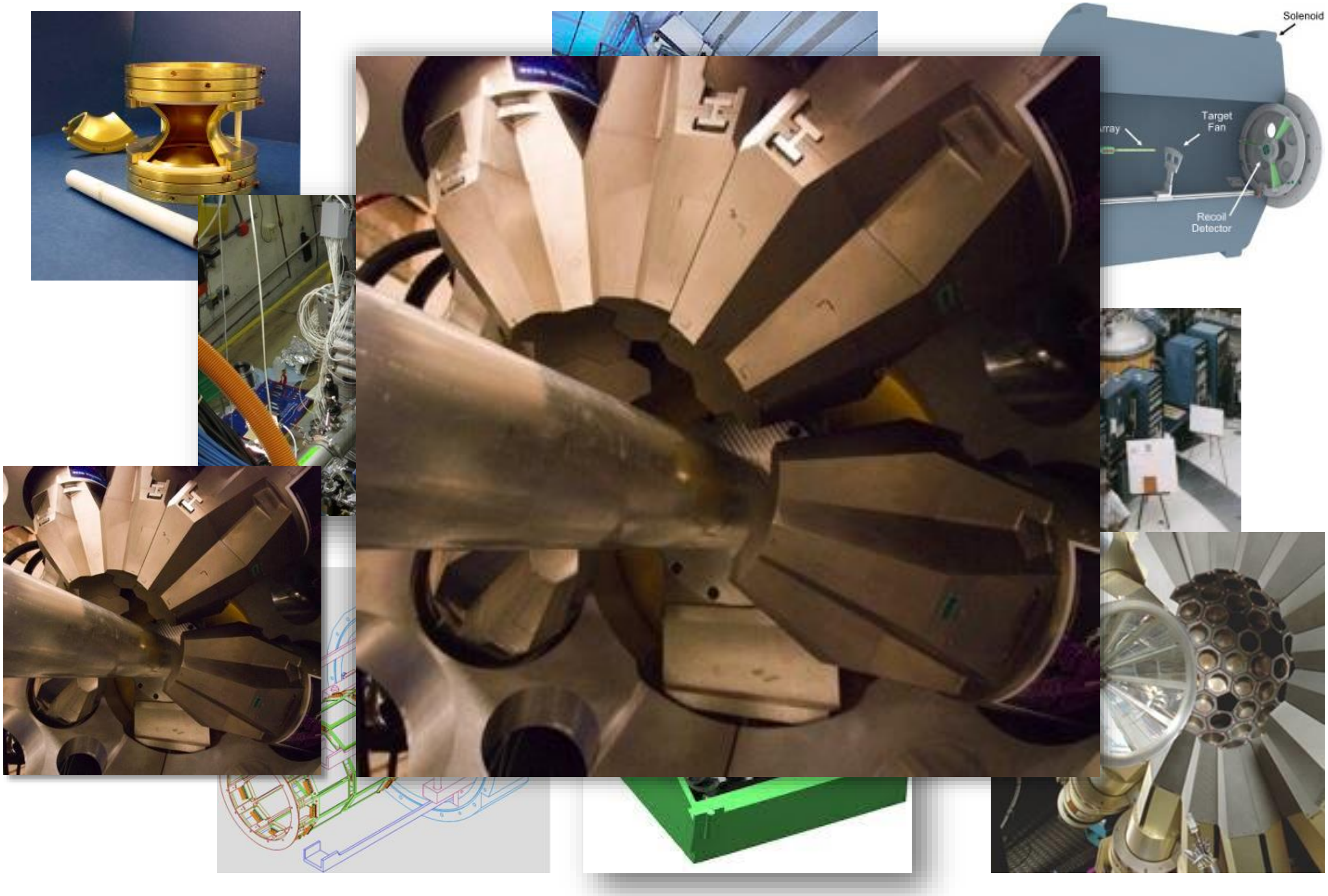
### Electronics

- Waveform digitizers, ASICs, preamps
- Digital pulse processing

# The Detectors



# The Detectors



# Gamma-ray Spectroscopy in Nuclear Physics

**Gamma-ray Spectroscopy has played a major role in our current understanding of the structure of atomic nuclei.**

**It continues to be a unique tool in the experimental studies of the nuclear structure as we push the limits of A (size), $T_z$=(N-Z)/2 (isospin), I (rotational frequency), and E* (temperature)**

**"Effective" Energy resolution**
**(Doppler broadening → Position resolution)**
**Peak-to-Total**
**Efficiency**
**Auxiliary devices**

**Resolving Power**
**(A measure of the weakest branch we can resolve in a spectrum)**

# Gamma-Ray Tracking

A ***"game changer"*** in $\gamma$-ray spectroscopy

Doppler reconstruction
(Energy resolution)

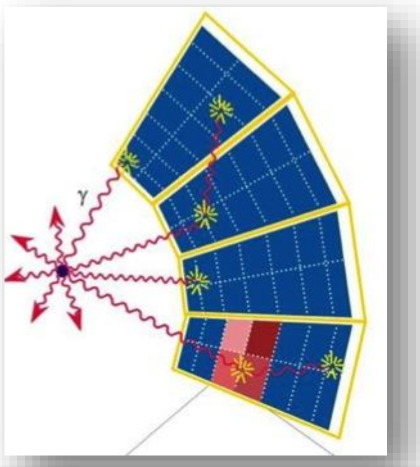
Close packing of detectors
(Efficiency,  avoiding summing)

Good P/T

# Gamma-Ray Tracking

**Pulse shape analysis in segments**

**➔ 3D position of interaction points**



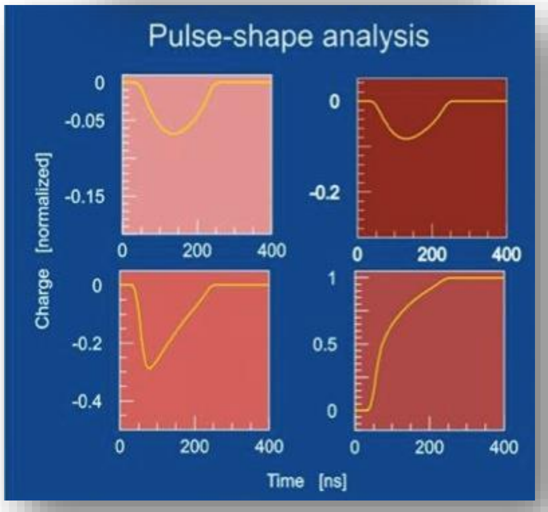

A ***"game changer"*** in γ-ray spectroscopy

Doppler reconstruction
(Energy resolution)

Close packing of detectors
(Efficiency,  avoiding summing)

Good P/T

$$t_{collection} = \frac{D}{v_{drift}} \approx 100 \frac{n\sec}{cm}$$



# Gamma-Ray Tracking

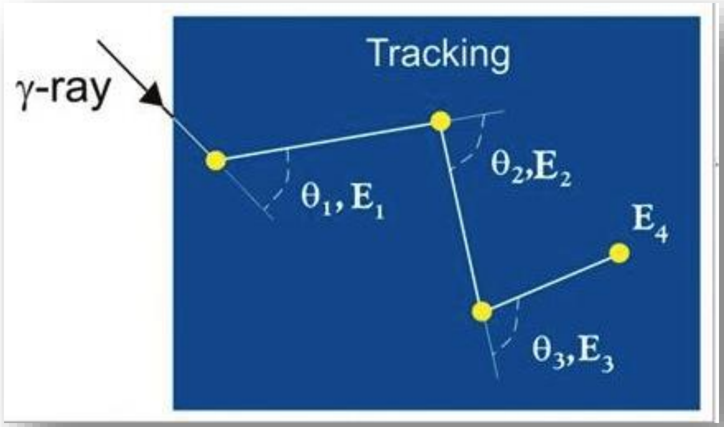
A ***"game changer"*** in γ-ray spectroscopy

Doppler reconstruction
(Energy resolution)

Close packing of detectors
(Efficiency, avoiding summing)

Good P/T

**Tracking of photon interaction points**
**➔ energy and position of γ-ray**




**Increased Resolving Power**

# Gamma-Ray Tracking


- **<u>LBNL-led $50M</u>**

Strong endorsement from the community at the LRP.

**CD0 approval October 2015**

**Key Properties**

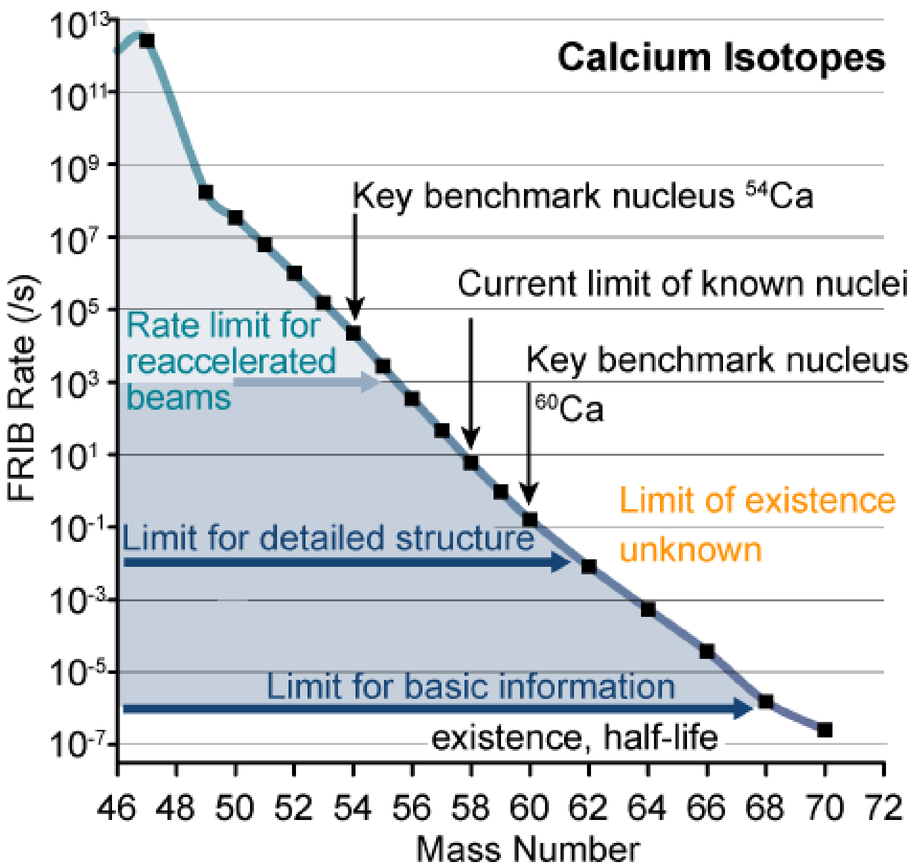
- $4\pi$ Coverage
- Position resolution ($\sigma_{x,y,z}$ = 2 mm)
- Peak-to-Total (~ 55%)
- Polarization sensitivity

GRETA marks a major advance in γ-ray detector systems and can provide order-of-magnitude gains in sensitivity.

**FRIB and ATLAS/CARIBU scientific programs will rely on GRETA**

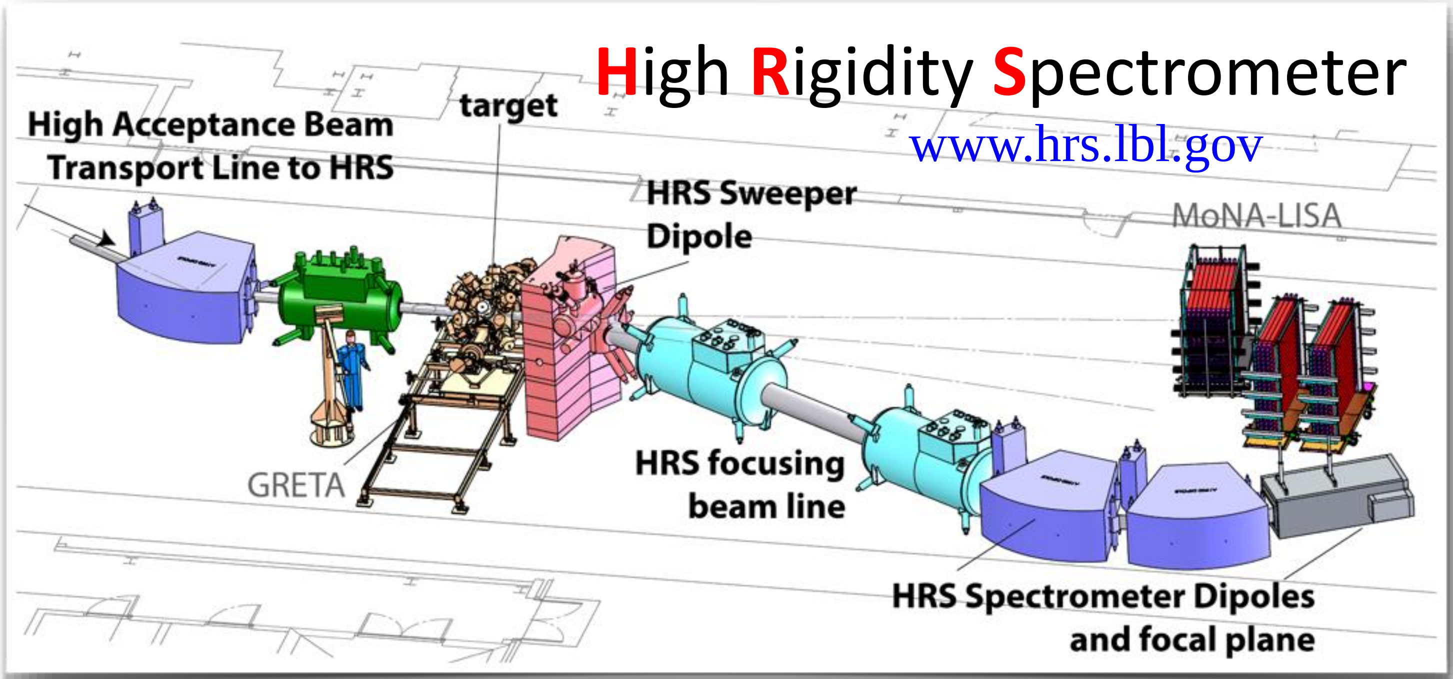
## The frontier: neutron-rich calcium isotopes
probing nuclear forces and shell structure in a neutron-rich medium

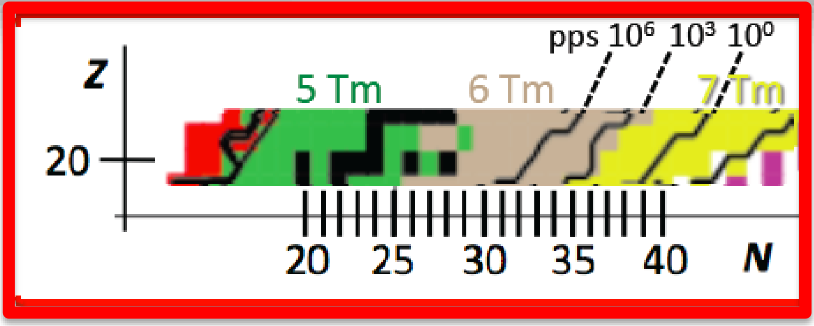
- FRIB provides access to the relevant neutron-rich Ca isotopes with intensities sufficient to measure important observables
  - Masses, half-lives, decay properties, single-particle and collective degrees of freedom
  - Structure of heavy Ca isotopes will quantify the role of the 3N forces and weak binding
- In general: Long isotopic chains are essential
  - Evolution of nuclear properties can be benchmarked as a function of isospin




# Access to Calcium isotopes at FRIB

# GRETA + HRS for fast beams physics at FRIB

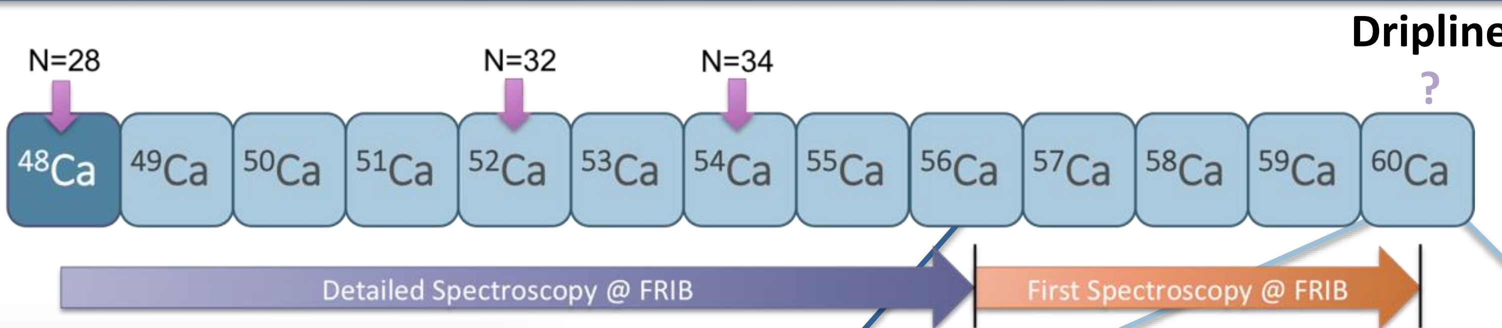


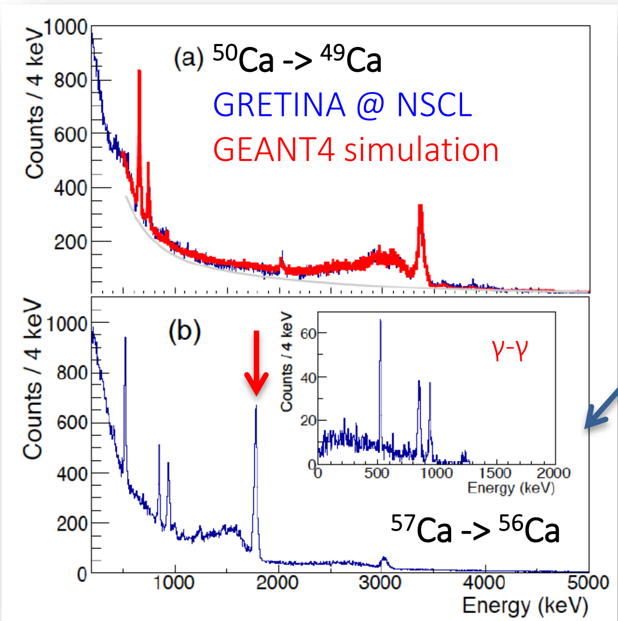




- Combination will be critical to the success of the FRIB science program

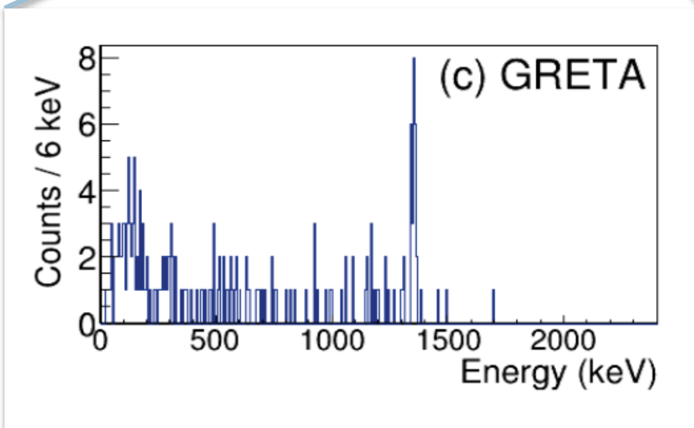
# GRETA + HRS for fast beams physics at FRIB

- The neutron-rich Ca isotopes beyond $^{48}$Ca provide dramatic examples of shell evolution
- Microscopic calculations suggest a sensitivity of the detailed structure to the inclusion of 3N forces



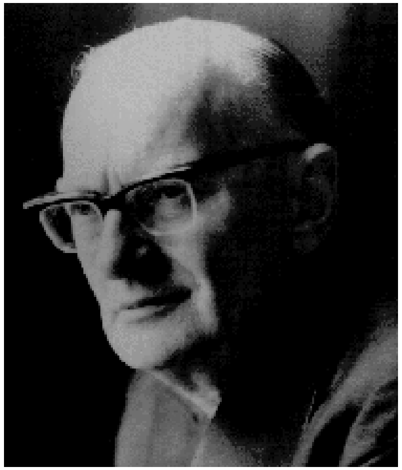

- Detailed studies of single particle structure, provide a critical test of effective interactions and 3N forces
- The structure around $^{60}$Ca informs the location of the dripline at Z = 20




$^{9}$Be($^{61}$Sc,$^{60}$Ca+γ)

***"Prediction is very difficult, especially about the future."***

Niels Bohr



***"The future isn't what it used to be."***

Arthur C. Clarke

# Augusto's Forecast

Sunny & Warm

# Thank You!

**Best wishes to you all!**