

Experimental Studies of Nuclei

Robert V. F. Janssens

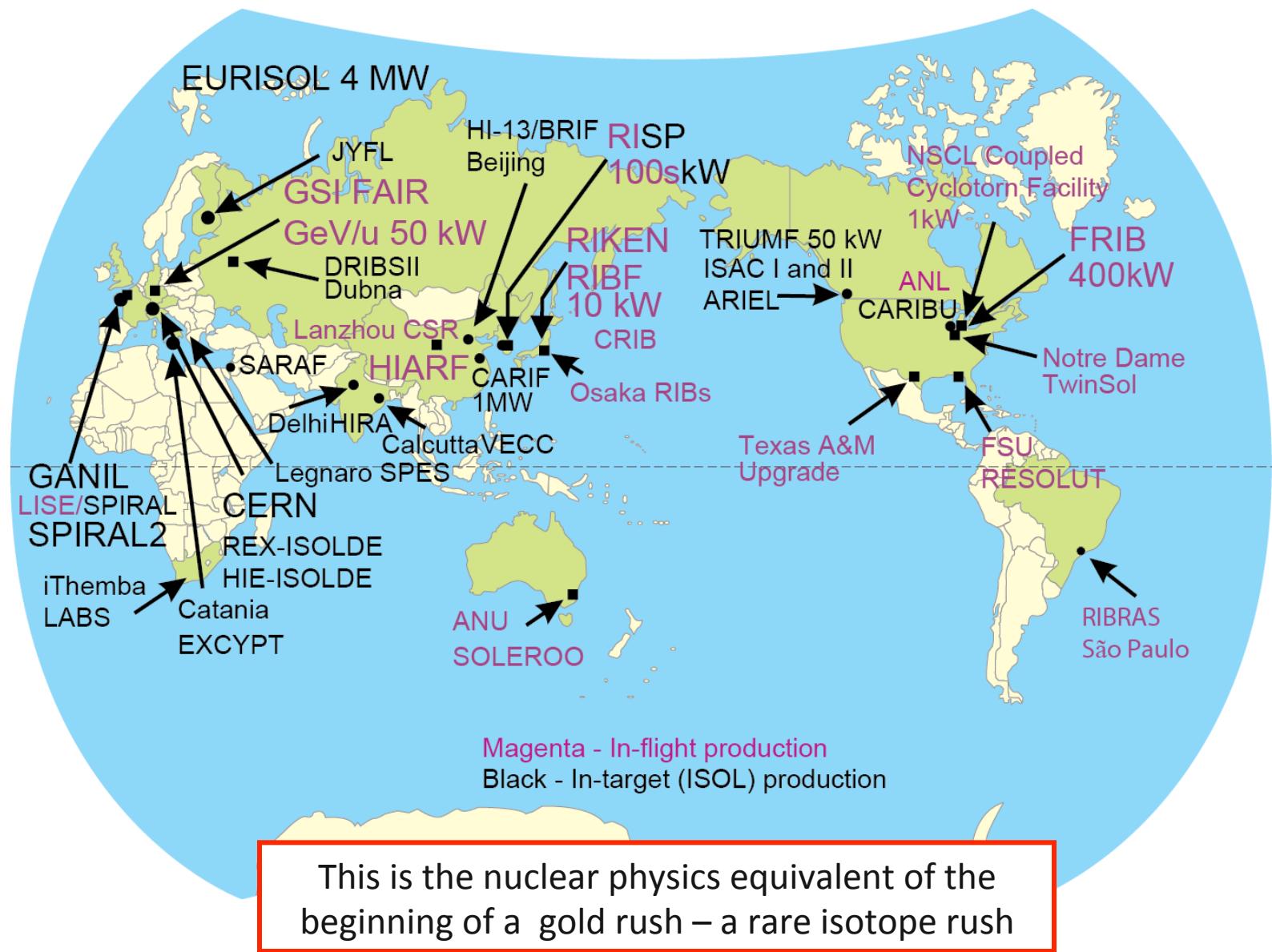
Joint DNP Town Meetings on Nuclear Structure and Nuclear Astrophysics
August 21 – 23, 2014
Texas A&M University

OUR SCIENCE CASE: The Nuclear Landscape and the Big Questions (NAS report)

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself 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?

- Fundamental aspects (reduction)
 - Nature of building blocks
 - Nature of fundamental interactions
- Self-organization of building blocks (emergence)
 - Nature of composite structures and phases
 - Origin of simple patterns in complex systems

Worldwide Efforts in Rare Isotope Science



Courtesy of B. Sherrill

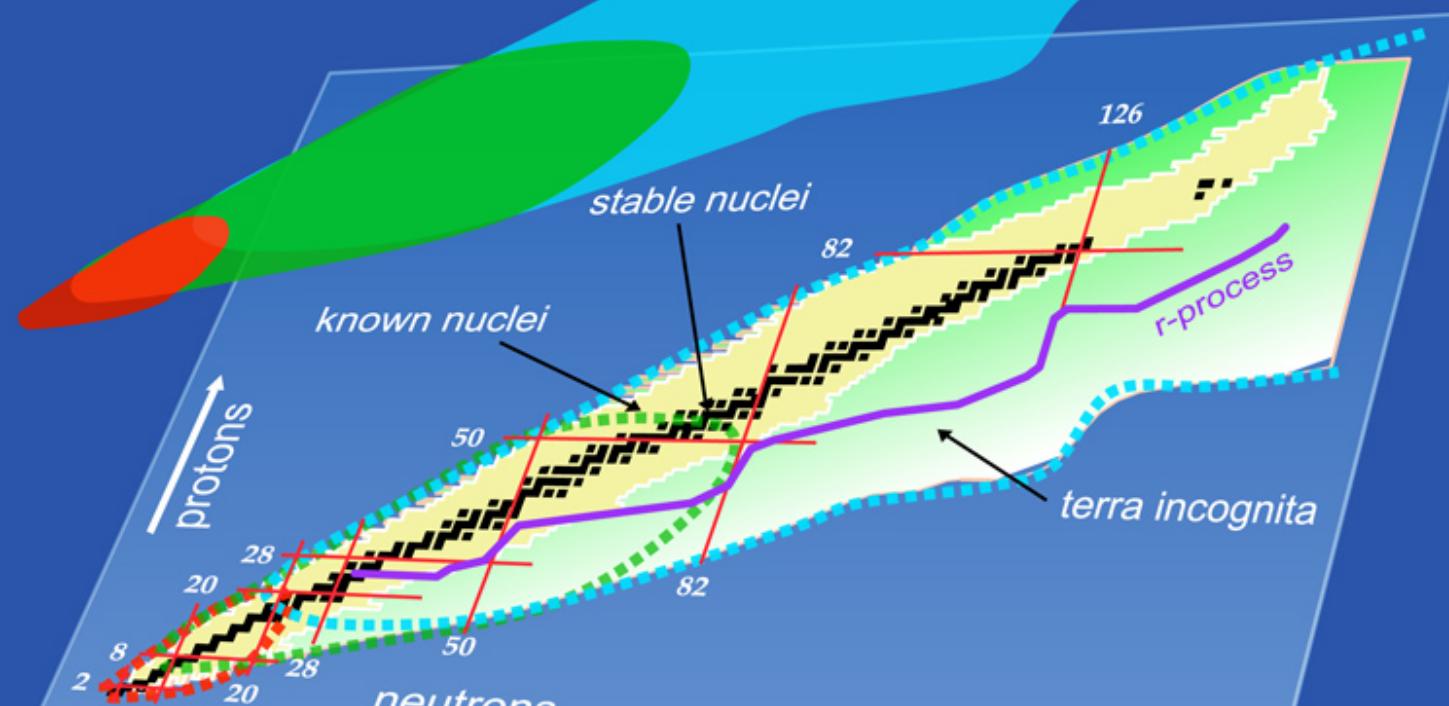
Experimental Equipment (Incomplete list)



A unified theory of the nucleus: The theory road map

Nuclear Landscape

Ab initio
Configuration Interaction
Density Functional Theory



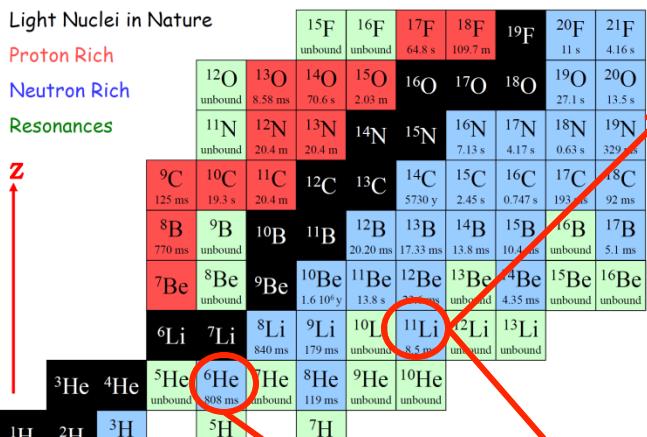
Theoretical Approaches overlap and bridges need to be built between them

Courtesy of W. Nazarewicz

Lightest nuclei: Determining the nucleon interactions from QCD & Structure and Reactions of light nuclei

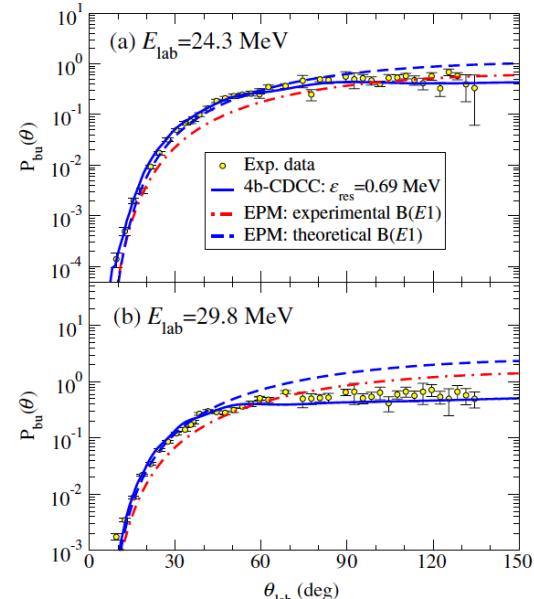
Lightest nuclei: Structure and Reactions of light nuclei

J.P. Fernandez-Garcia et al., PRL 110, 142701

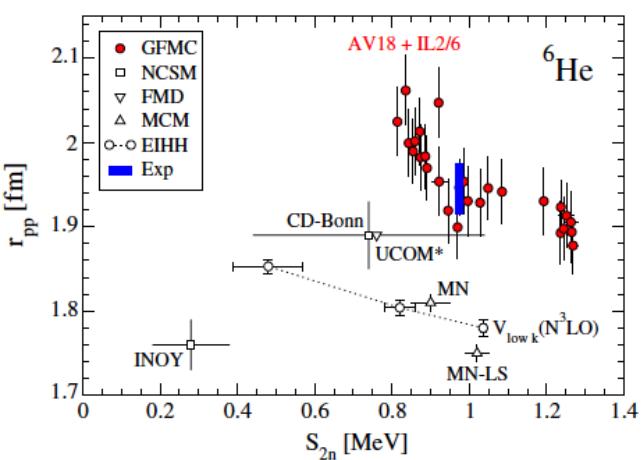


^{11}Li breakup on ^{208}Pb around Coulomb Barrier

- Sizable ^9Li yield even below barrier
- Data & cont.-discretized CC calculations support presence of low energy dipole resonance in the ^{11}Li continuum



Z.-T. Lu, M. Watanabe et al., PRL 105, 132505, 1383

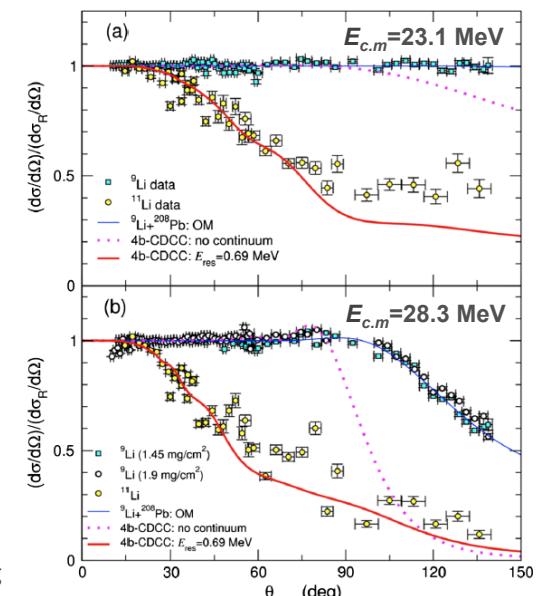


Importance of 3N forces

Does Halo nucleus follow Rutherford Scattering below the barrier?

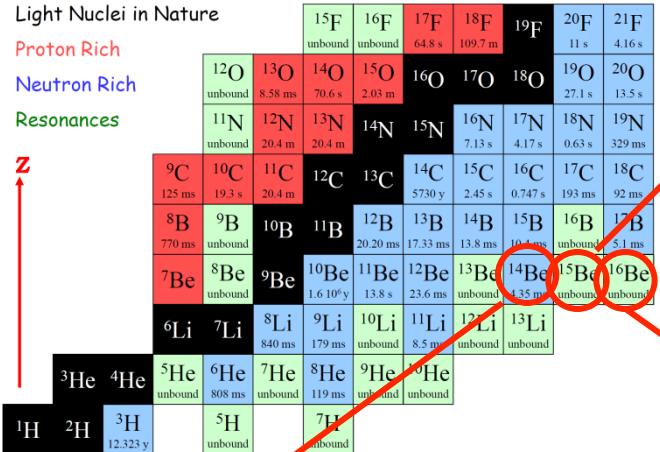
- Strong reduction (vs ^9Li) even well below barrier
- 4-body cont.-discretized CC calculations indicate reduction due to strong Coulomb coupling to dipole states in continuum ← low-lying dipole resonance close to break up threshold

M. Cubero et al., PRL 109, 262701



Courtesy J. Dilling

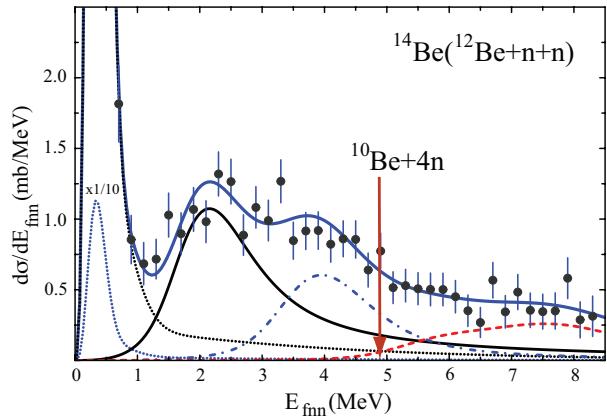
Lightest nuclei: Structure and Reactions of light nuclei



Coupling bound \leftrightarrow continuum states:
 ^{14}Be continuum & 2^+_2 state

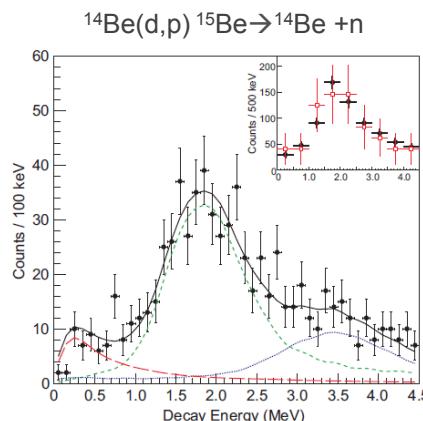
1.54(13) MeV, $2^+_1 (0d_{5/2})^2$

3.54(16) MeV, $2^+_2 (1s_{1/2}, 0d_{5/2})^2$

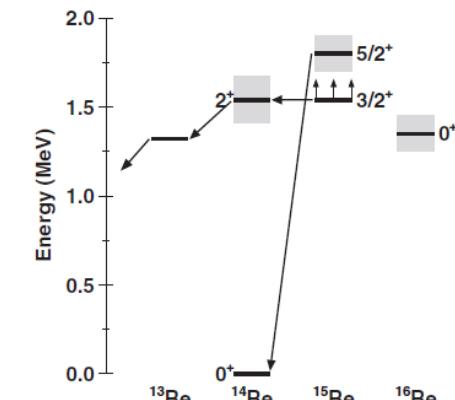


Yu. Aksyutina et al., PRL 111, 142501

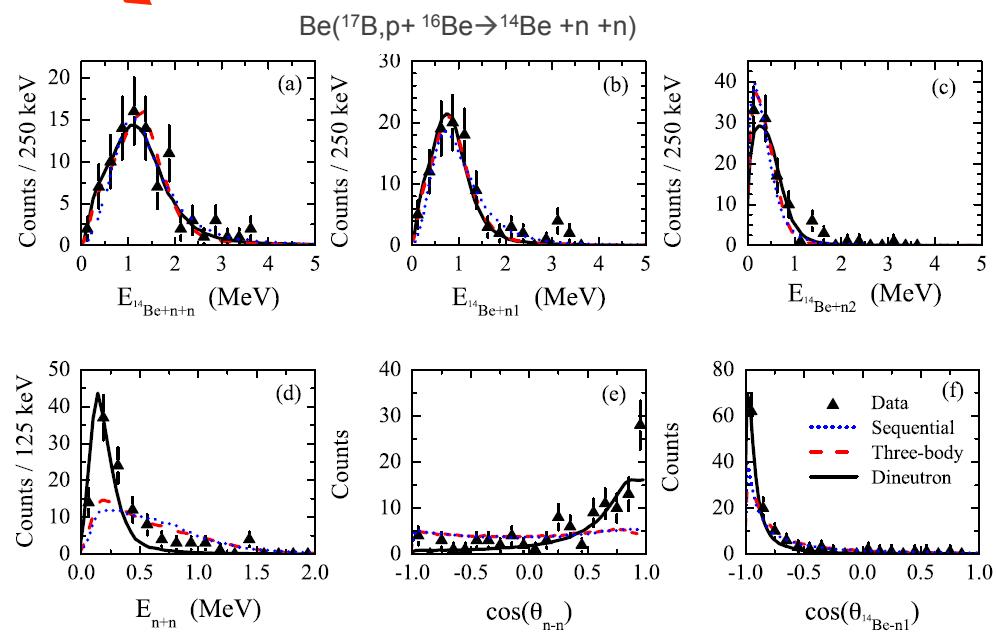
First observation of ^{15}Be



J. Snyder et al., PRC 88, 031303(R)



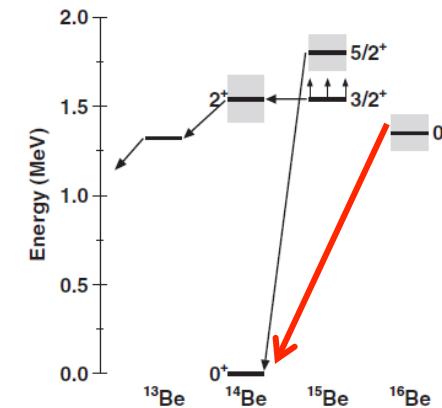
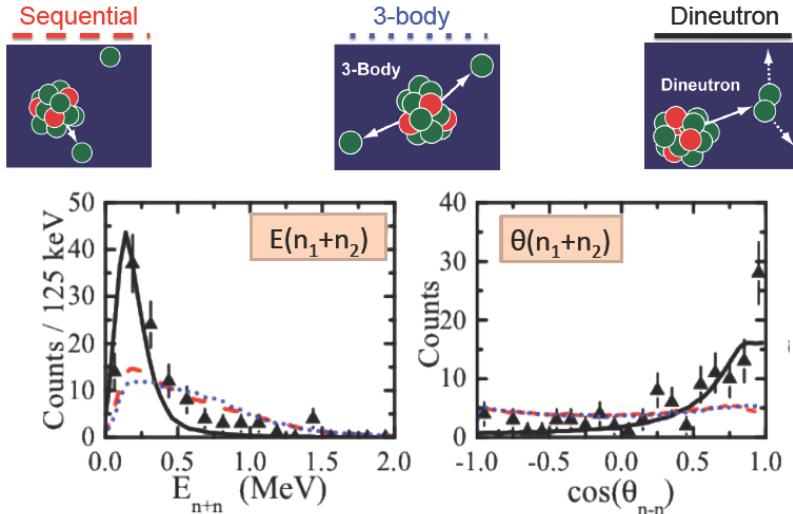
First observation of dineutron decay (?)



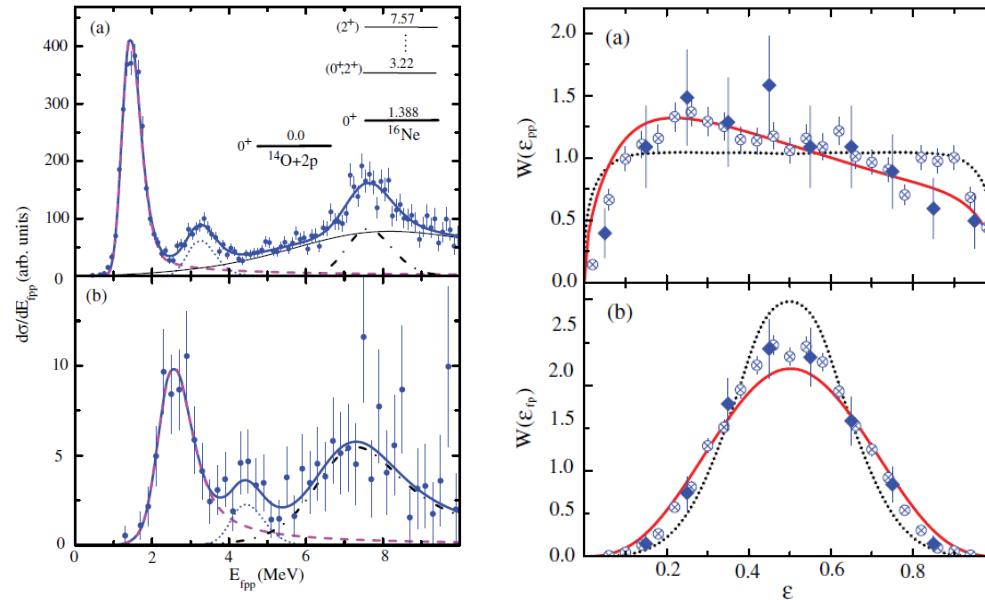
A. Spirou et al., PRL 108, 102501

Two-nucleon emission :Unbound p-rich vs unbound n-rich

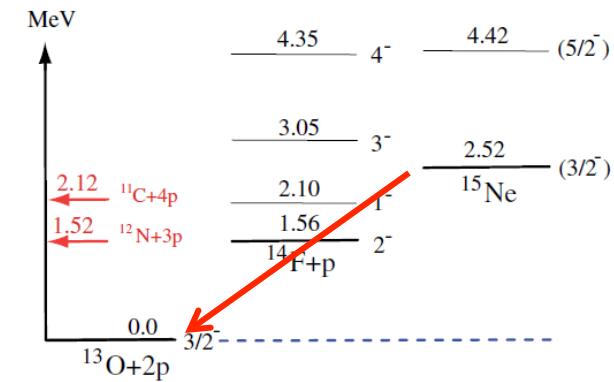
A. Spirou et al., PRL 108, 102501



F. Wamers et al., PRL 112, 132502



2-p emission:
Sequential ...
3-body decay --



^{15}Ne : → decay proceeds to ^{13}O with simultaneous 2p emission, no sequential decay though ^{14}F .

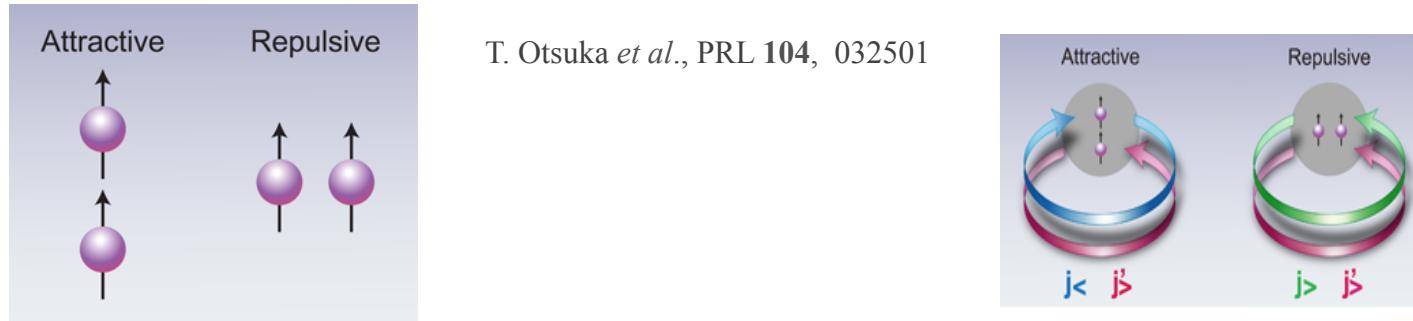
→ 2 protons around ^{13}O : 63(5)% ($1s_{1/2}$) 2

Shell Evolution, Binding and the Oxygen Isotopes

Shell evolution and nuclear forces

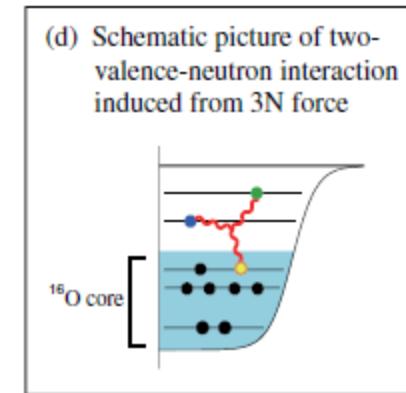
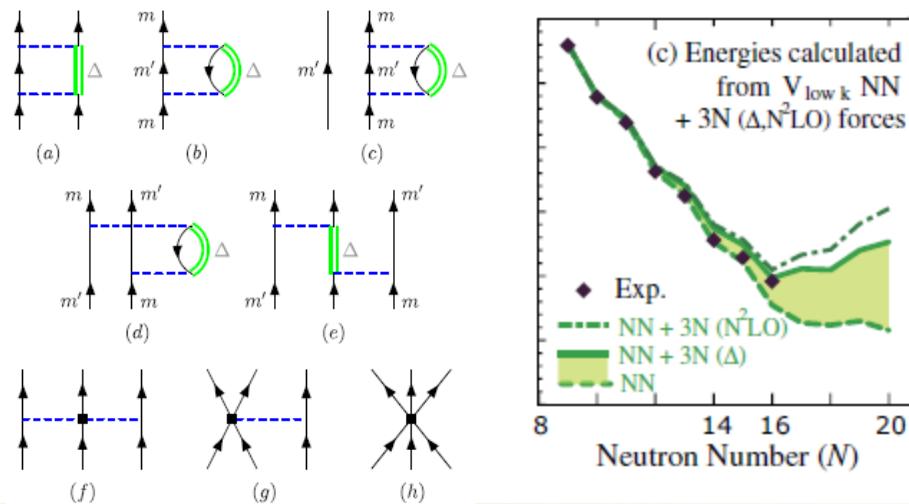
N.A. Smirnova *et al.*, PLB 686 , 109

Novel Features of Nuclear Forces and Shell Evolution in Exotic Nuclei



Three-Body Forces and the Limit of Oxygen Isotopes

T. Otsuka *et al.*, PRL 105, 032501



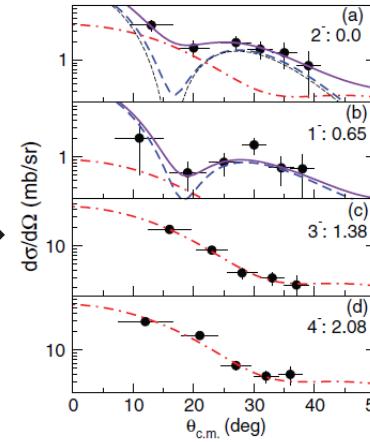
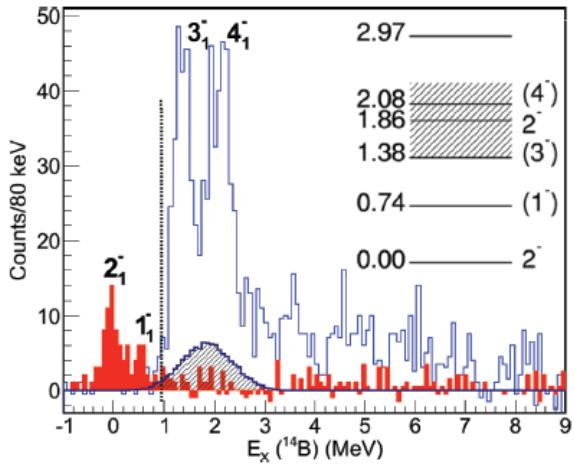
Courtesy of B. Jonson

Shell Evolution with neutron binding

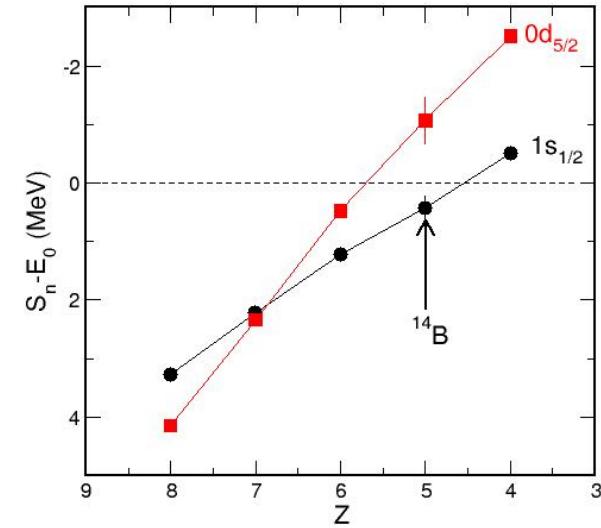
Example:

$^{13}\text{B}(\text{d},\text{p})^{14}\text{B}$ 204 MeV, 3×10^4 pps

S. Bedoor *et al.*, PRC 88, 011304(R)

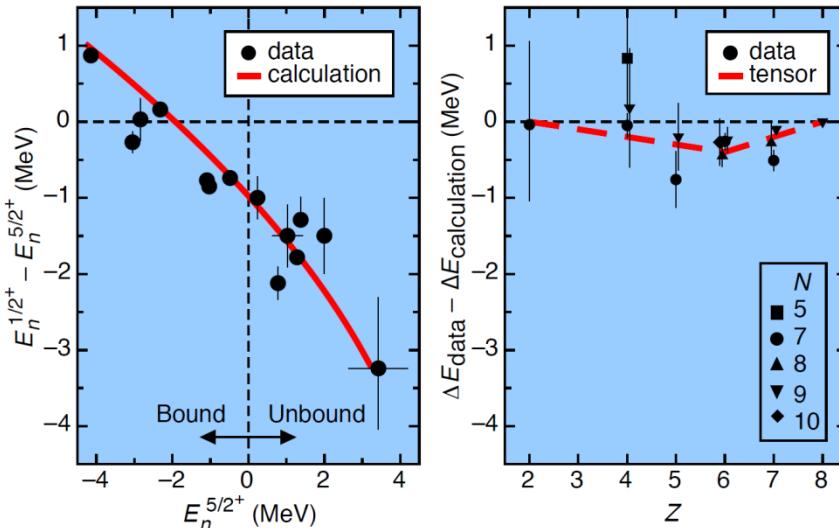


$N = 9$

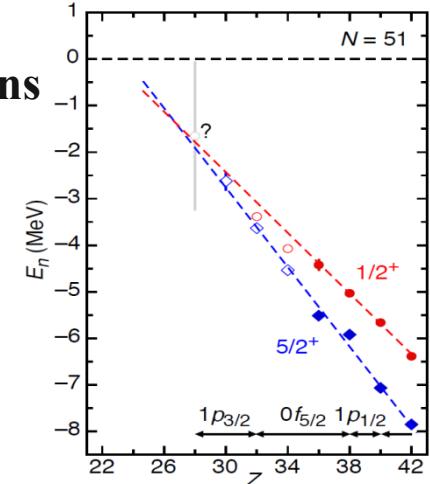
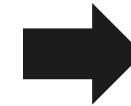


Systematics & comparison with theory:

v $s_{1/2}$ & $d_{5/2}$ for $N=5-10$, $Z=3-8$



Future: other regions
e.g. ^{78}Ni , ...



Courtesy of B.P. Kay

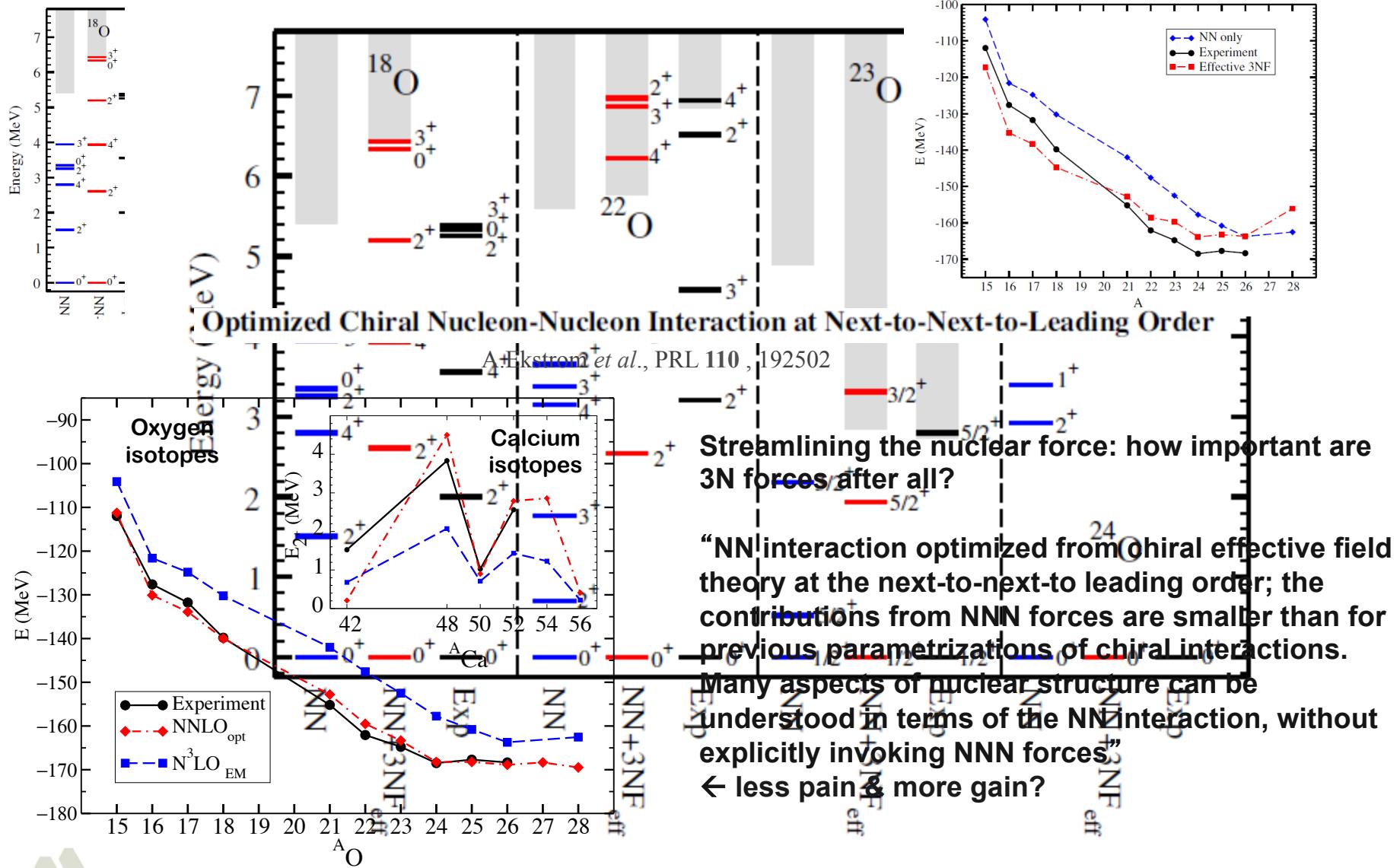


C.R. Hoffman *et al.*, PRC 89, 061305(R)

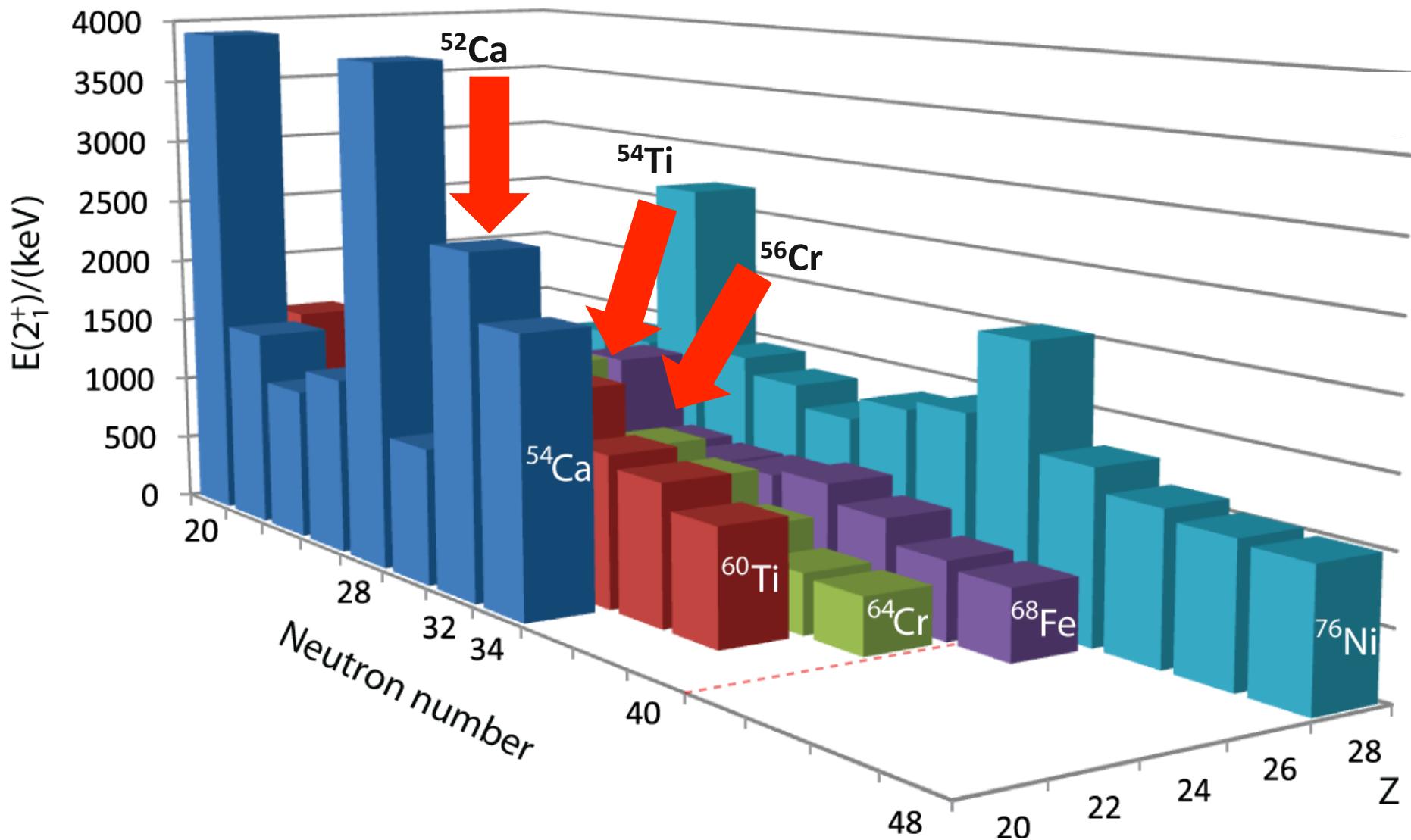
Shell Evolution, Binding and the Oxygen Isotopes

Continuum Effects and Three-Nucleon Forces in Neutron-Rich Oxygen Isotopes

G. Hagen *et al.*, PRL 108 , 242501



New Shell Closures $N = 32$ & 34 : the Ca – Ni Region

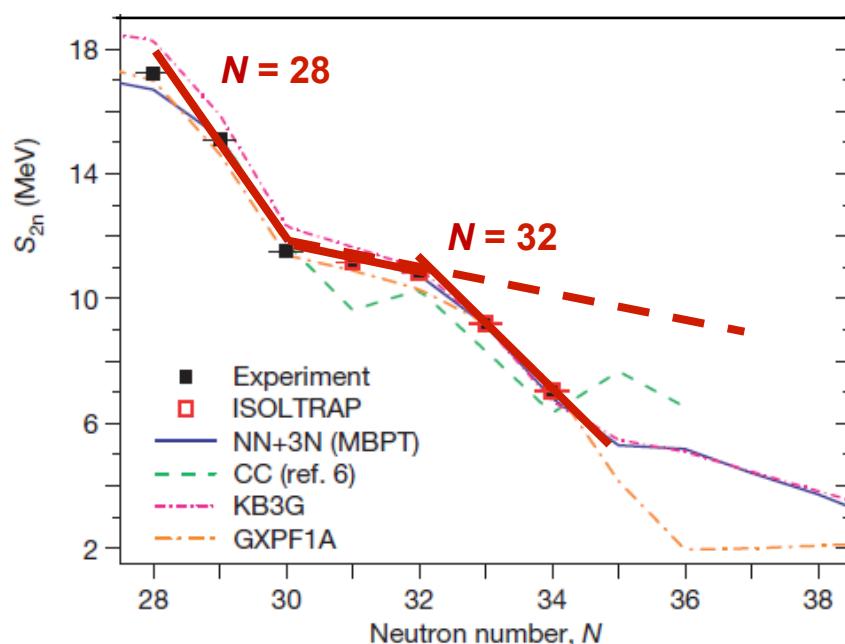
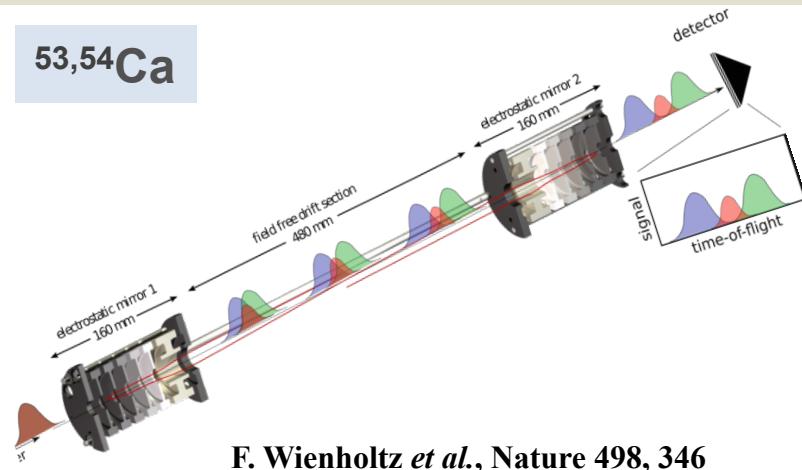
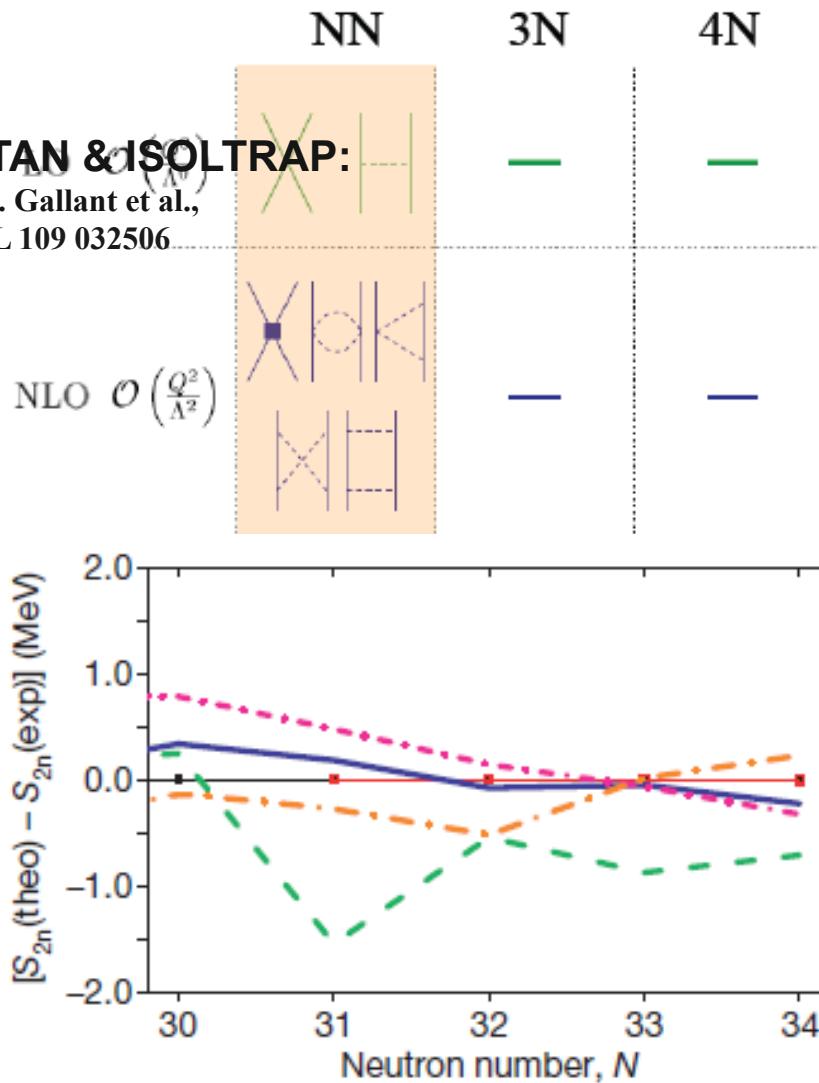


Courtesy of A. Gade

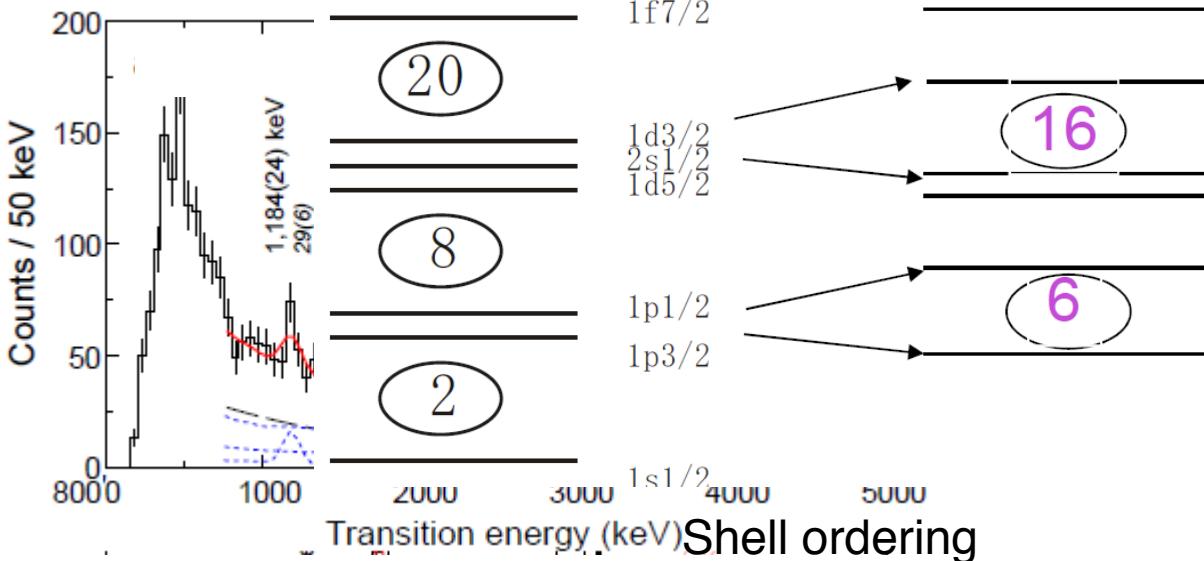
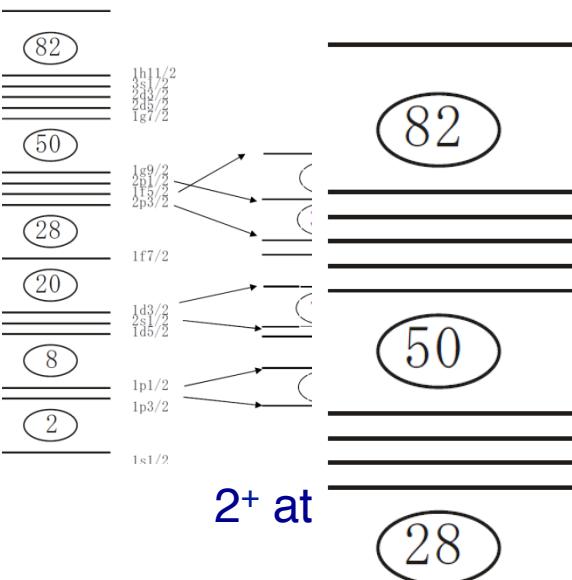
$\text{Ca} \rightarrow \text{Shell Closure at } N = 32$

Multi-reflection time-of-flight and Penning-trap mass spectrometry

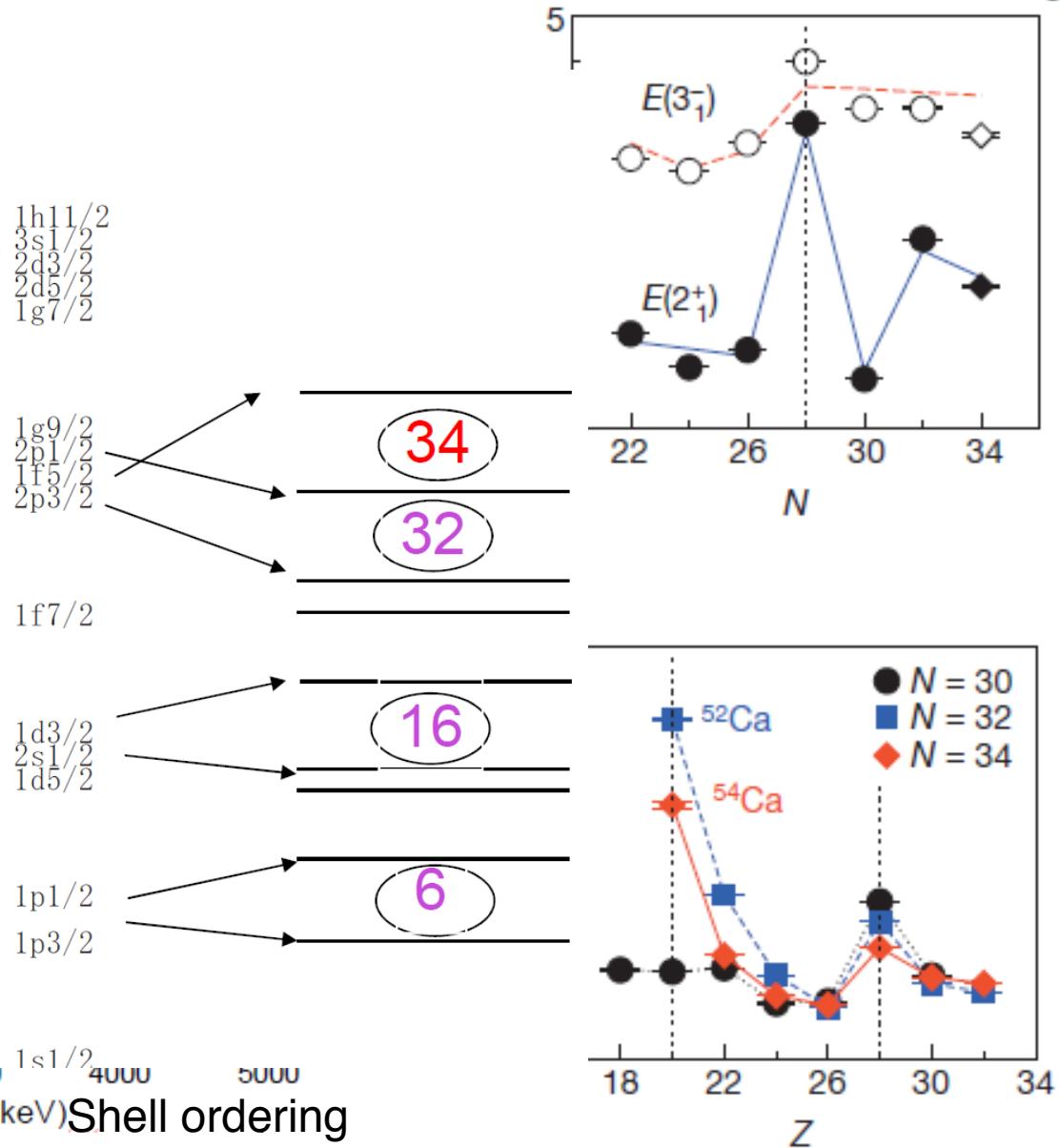
TITAN & ISOLTRAP:
A.T. Gallant et al.,
PRL 109 032506



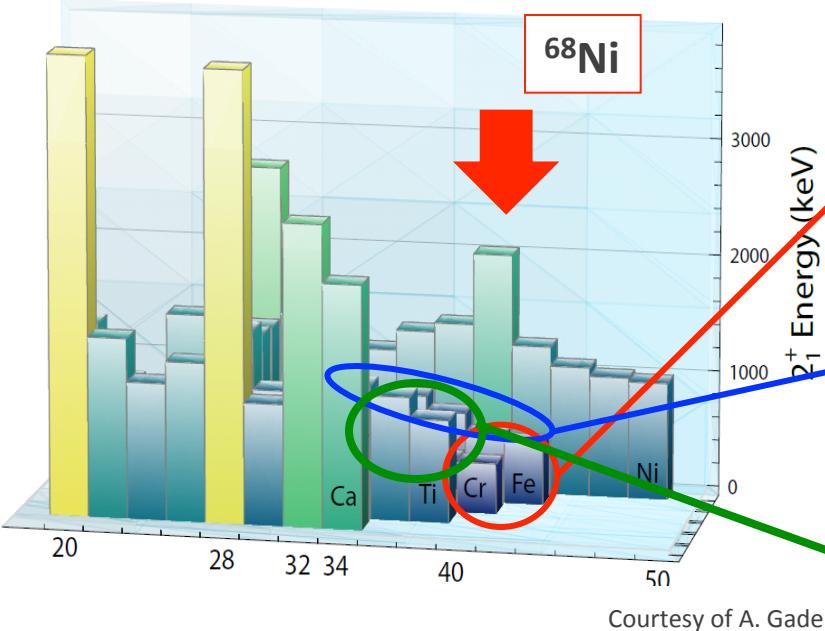
Ca → Shell Closure at $N = 34$



D. Steppenbeck *et al.*, Nature 502, 207



From Ca to Ni ← testing the effective interactions



N=40 Cr & Fe: evidence for collectivity from
(1) Lowest $E(2^+)$ in the region
(2) Large $B(E2)$ values

A. Gade *et al.*, PRC 81, 051304(R)

J. Ljungvall *et al.*, PRC 81, 061301(R)

N=34-40 Cr & Fe: Shape Coexistence from
Higher spin studies (deep inelastic
reactions)

→ Importance of both $g_{9/2}$ & $d_{5/2}$ neutrons
in driving collectivity

M.P. Carpenter *et al.*, PRC 87, 041305(R)

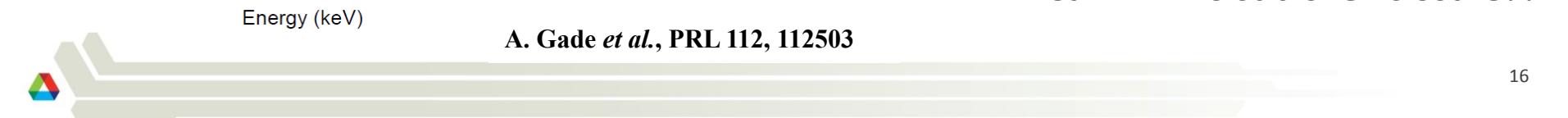
N=36,38 Ti:

→ Steep decrease in collectivity when
compared to Cr & Fe

→ Closure at N=40? ← SM calc. with
modified LNPS interaction suggests
small gap, and configuration dominated
by 2p-2h + 4p-4h

N=40 Ca: 6 more neutrons to add to ^{54}Ca

$^{60}\text{Ca} \leftarrow$ N=40 sub-shell closure??

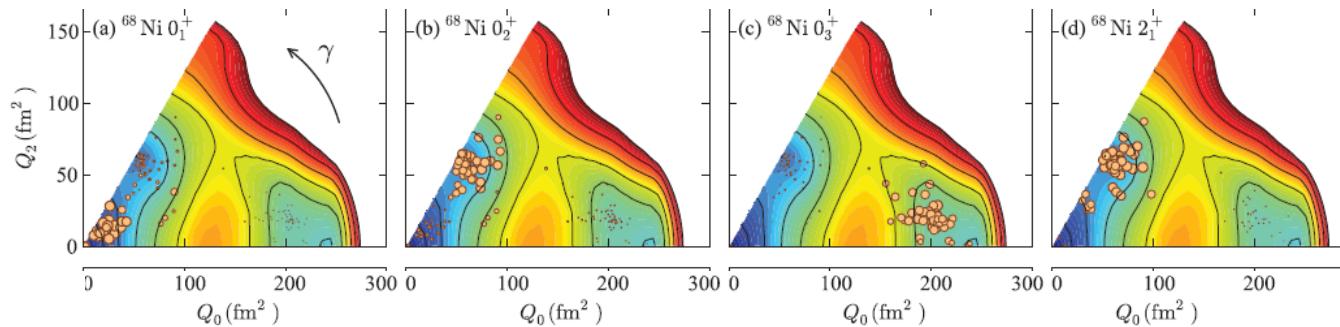


A. Gade *et al.*, PRL 112, 112503

From Ca to Ni ← testing the effective interactions

Y. Tsunoda *et al.*, PRC 89, 031310(R)

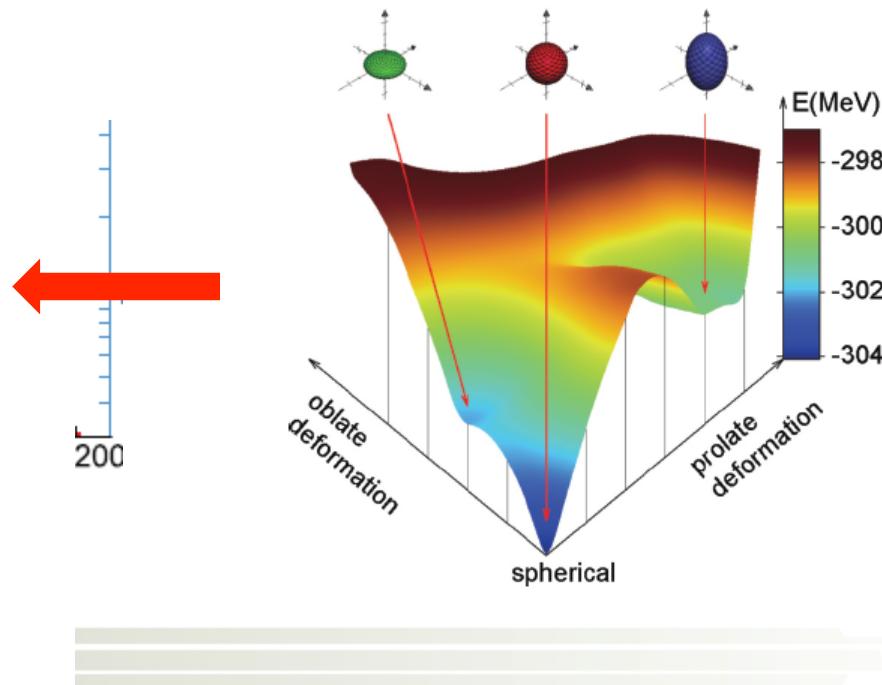
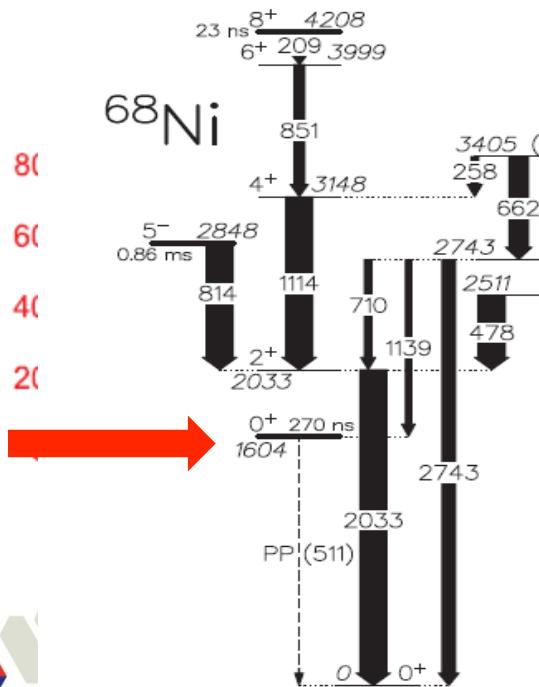
Novel shape evolution in exotic Ni isotopes and configuration-dependent shell structure



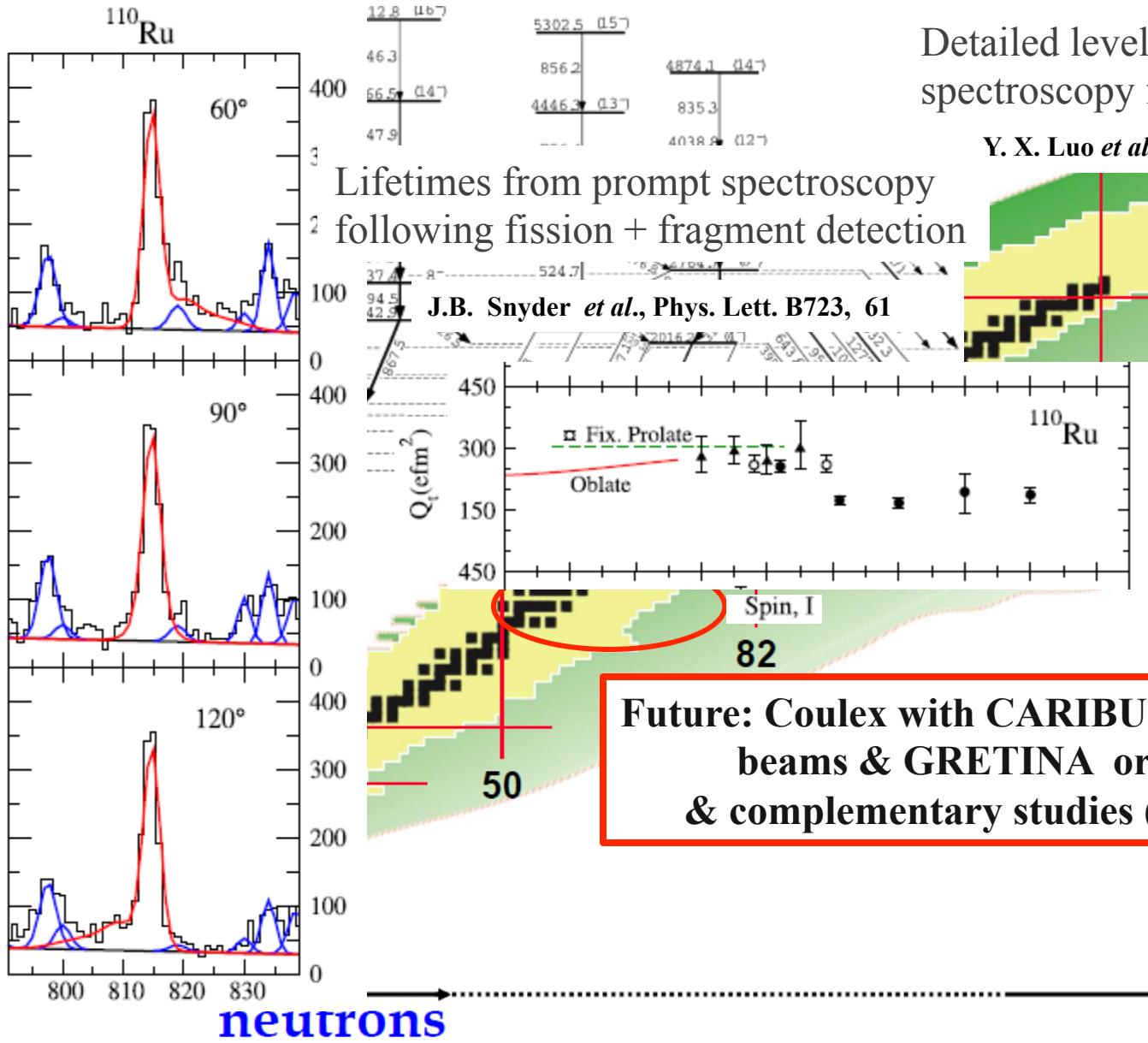
Monte Carlo SM
 $pf\text{-}g_{9/2}\text{-}d_{5/2}$

S. Suchyta *et al.*, PRC 89, 021301(R)

Shape coexistence in ^{68}Ni

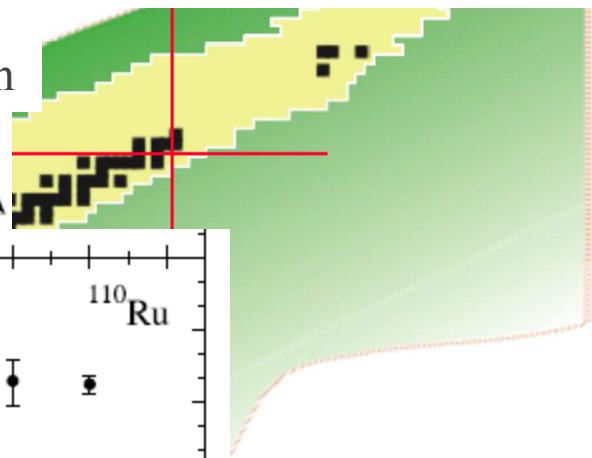


From Ni to Sn: High-spin frontier in *n*-rich nuclei



Detailed level structure from prompt spectroscopy following fission

Y. X. Luo *et al.*, Phys. Lett. B670, 307

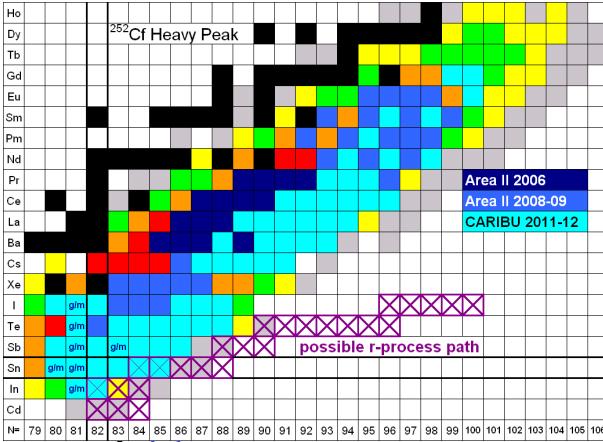


Shell Structure near Z=50, N=82

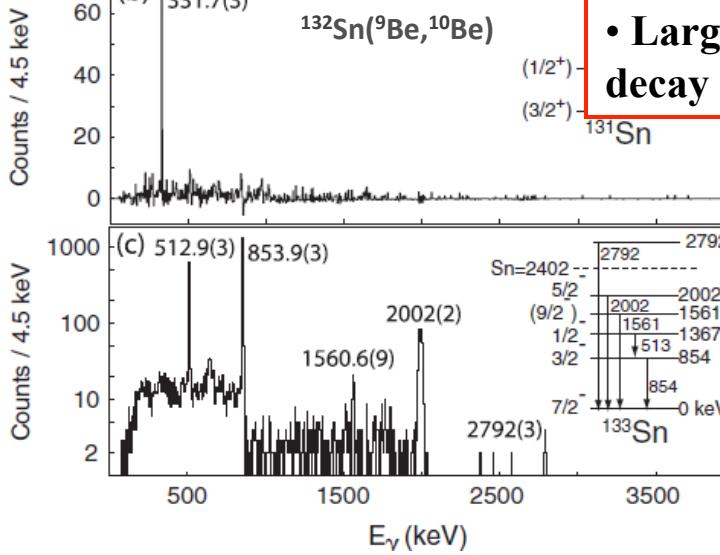
Z=50 (Sn)

Mass Measurements: informing theory

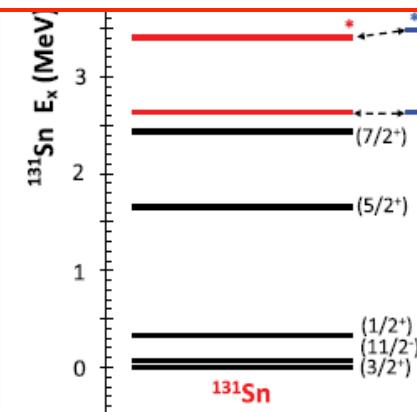
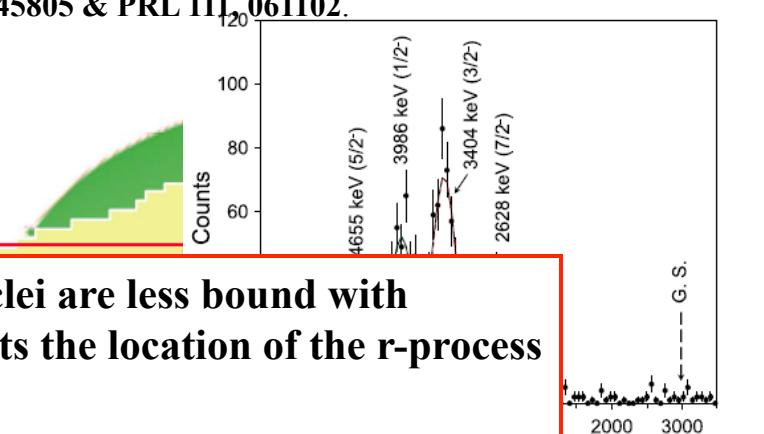
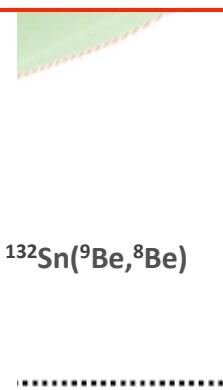
J. Van Schelt *et al.*, PRC 85, 045805 & PRL 111, 061102.



proto



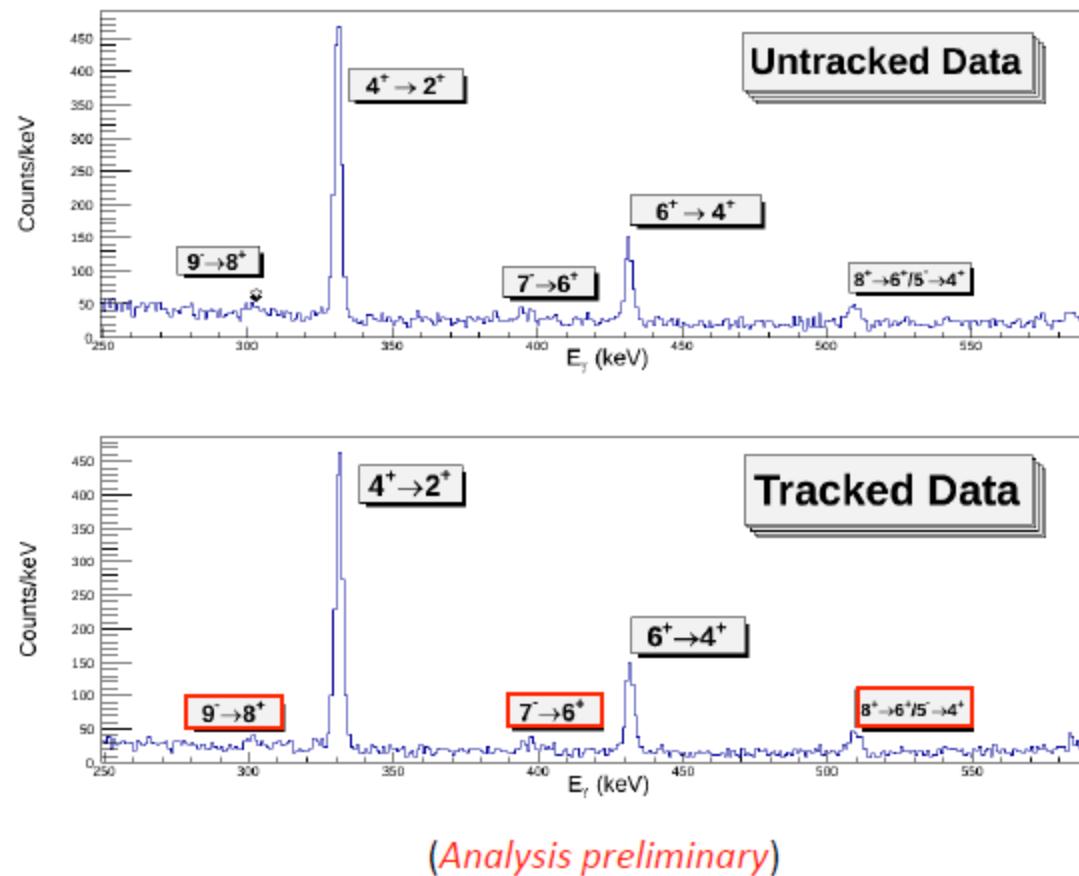
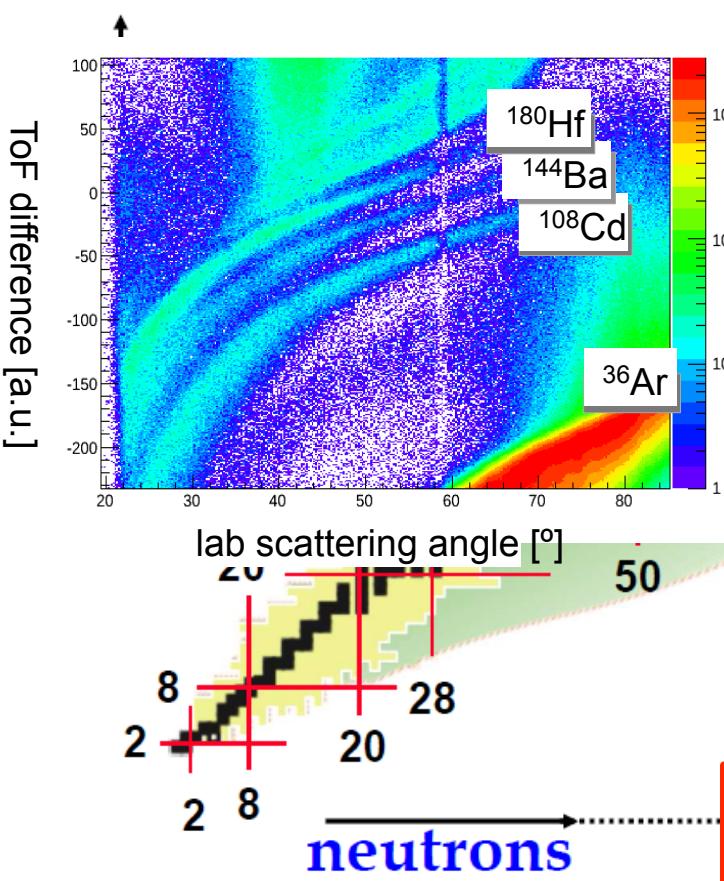
- Trends indicate nuclei are less bound with neutron excess (affects the location of the r-process path)
- Good agreement between all trap results and reaction Q value measurements
- Large disagreement with results obtained with β -decay measurements



R.L. Kozub *et al.*, PRL 109, 172501 &
J.M. Almond *et al.*, PRL 112, 172701

Shell Structure for Z>50, N>82

Re-accelerated beams at CARIBU: Coulex of ^{144}Ba @ GRETINA & CHICO-2



S. Zhu (analysis) (2014) [ANL, LLNL, etc]

Future: Coulex with CARIBU & FRIB reaccelerated beams & GRETINA or Gammasphere & CHICO2

Neutron skin: ^{208}Pb

Neutron skin: $r_{\text{skin}} = r_n - r_p$

Antiprotonic atoms:

$$r_{\text{skin}} = 0.16 \pm (0.02)_{\text{stat}} \pm (0.04)_{\text{syst}} \text{ fm}$$

Friedman and Gal, Phys. Rep. 452, 89

PREx: $F_W(q) \quad 0.34^{+0.15}_{-0.17} \text{ fm}$

S. Abrahamyan et al. (PREx Collaboration), PRL 108, 112502

Strong correlation between the dipole polarizability α_D and neutron skin predicted by DFT: P.-G. Reinhard and W. Nazarewicz, PRC 81, 051303(R)

RCNP: $\alpha_D \leftarrow \text{via } (p,p') \text{ scattering}$

A. Tamii et al., Phys. Rev. Lett. 107, 062502

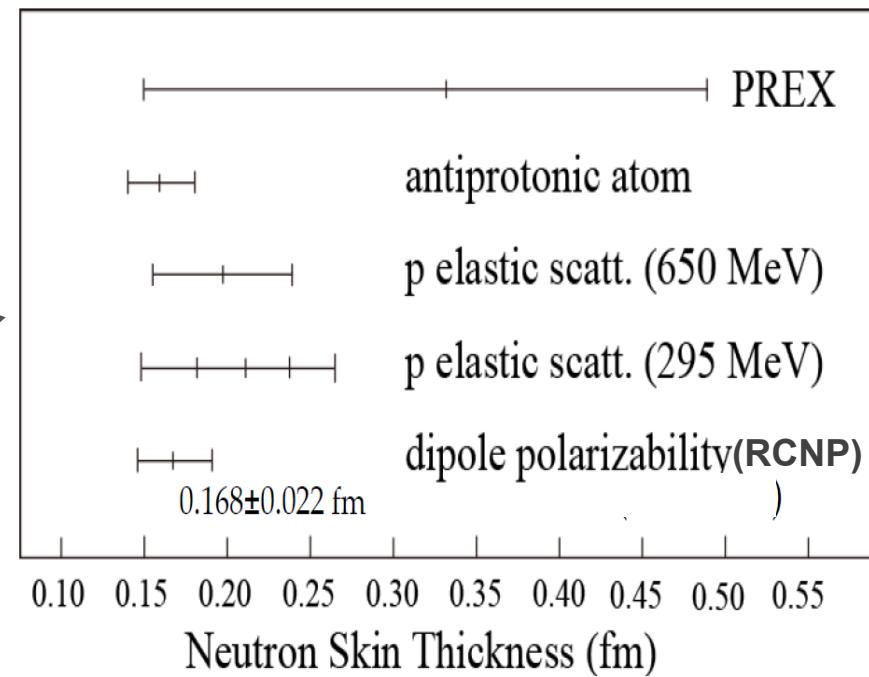


$$0.168 \pm 0.022 \text{ fm}$$

Proton elastic scattering:

$$r_{\text{skin}} = 0.211^{+0.054}_{-0.063} \text{ fm}$$

J. Zenihiro et al., PRC82, 044611



Next:

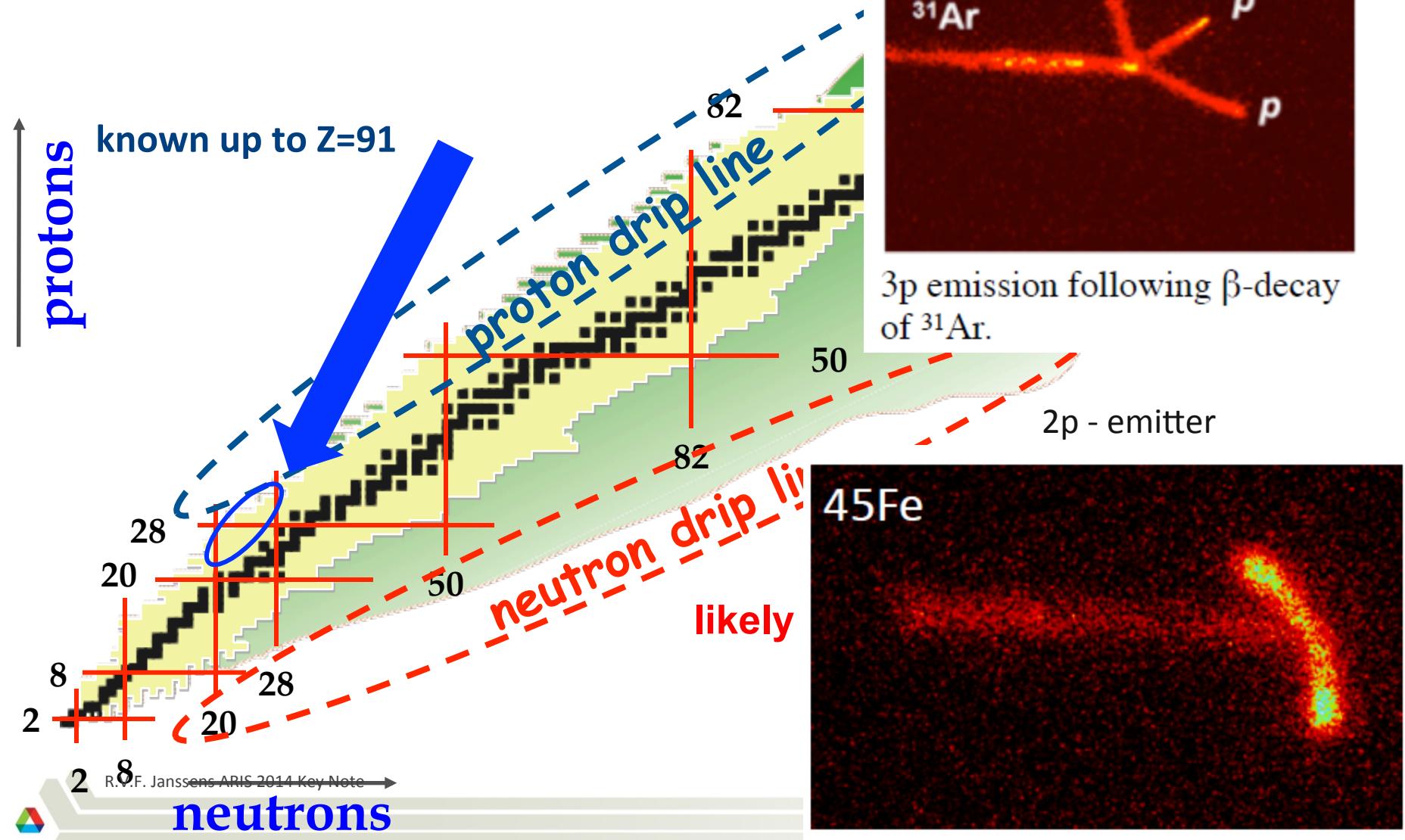
- PREx(II)
- New PREx measurement for ^{48}Ca ...
- RCNP data on α_D in ^{48}Ca ...

Courtesy of W. Nazarewicz



News from the proton drip line

New Modes: multi-p emission



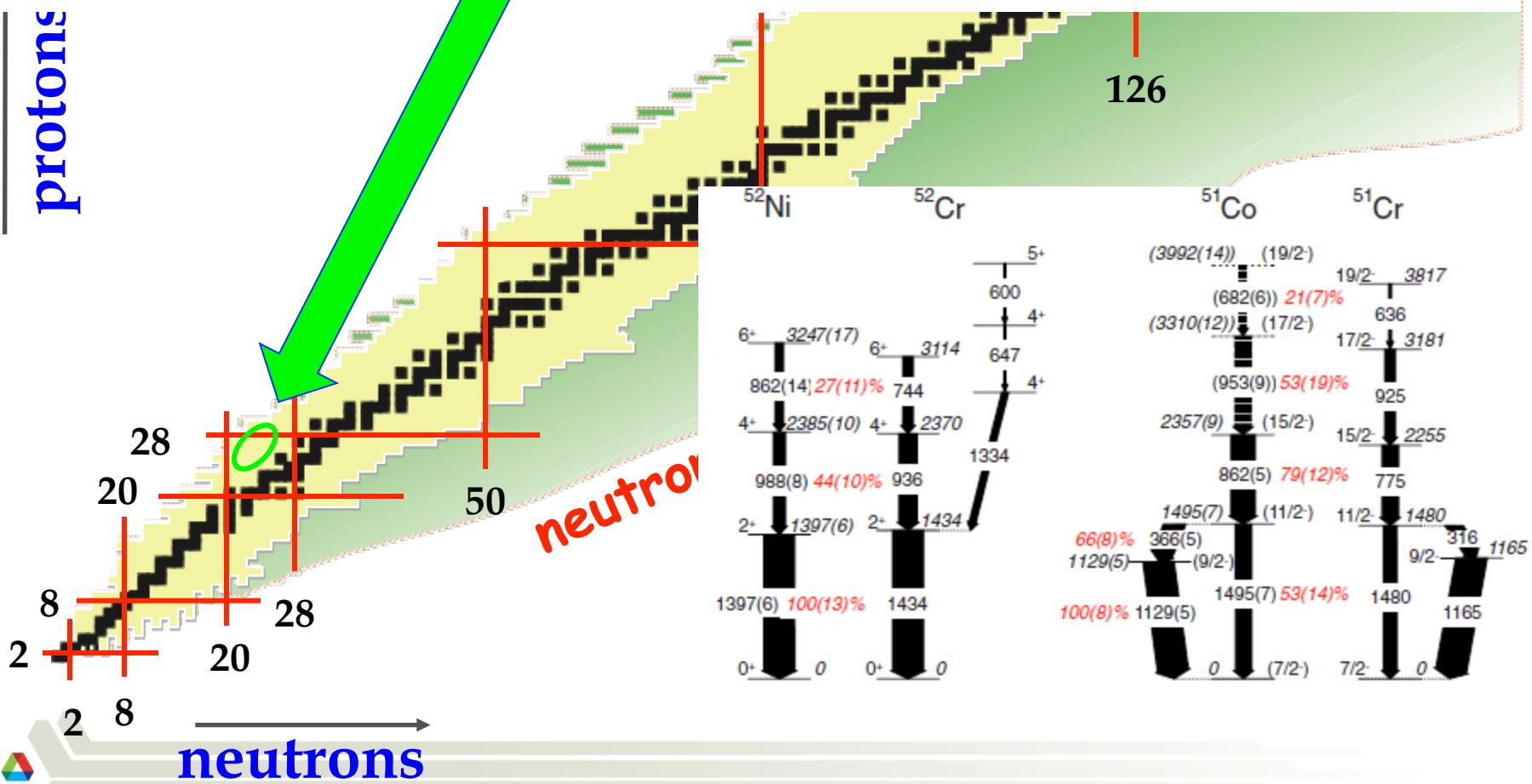
News from the proton drip line

P.J. Davies *et al.*, PRL 111, 072501

Mirror Energy Differences at Large Isospin Studied through Direct Two-Nucleon Knockout



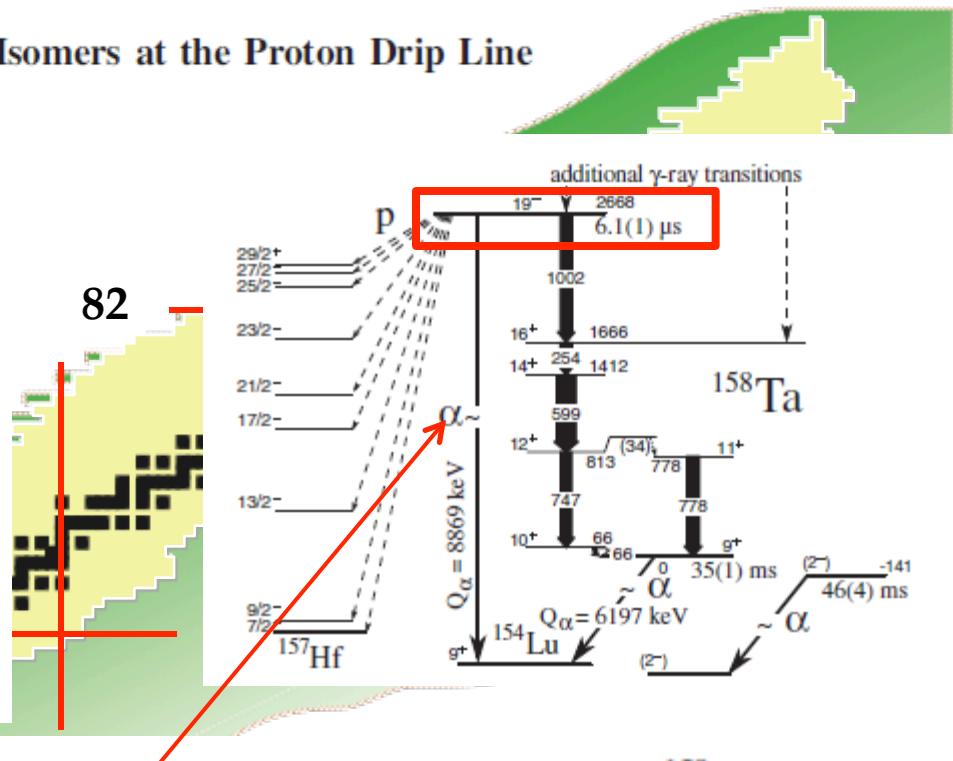
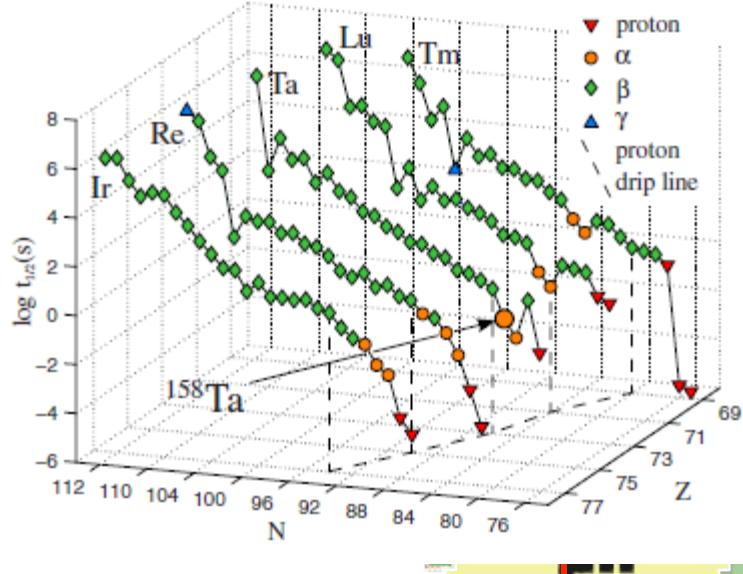
- First spectroscopy of ^{52}Ni and ^{51}Co combined with available data on ^{52}Cr and ^{51}Cr
- “Comparisons between SM calculations and data provide evidence compelling evidence that both electromagnetic and additional isospin nonconserving interactions for $J=2$ couplings are required”



News from the proton drip line

R.J. Carroll *et al.*, PRL 112, 092501

Blurring the Boundaries: Decays of Multiparticle Isomers at the Proton Drip Line

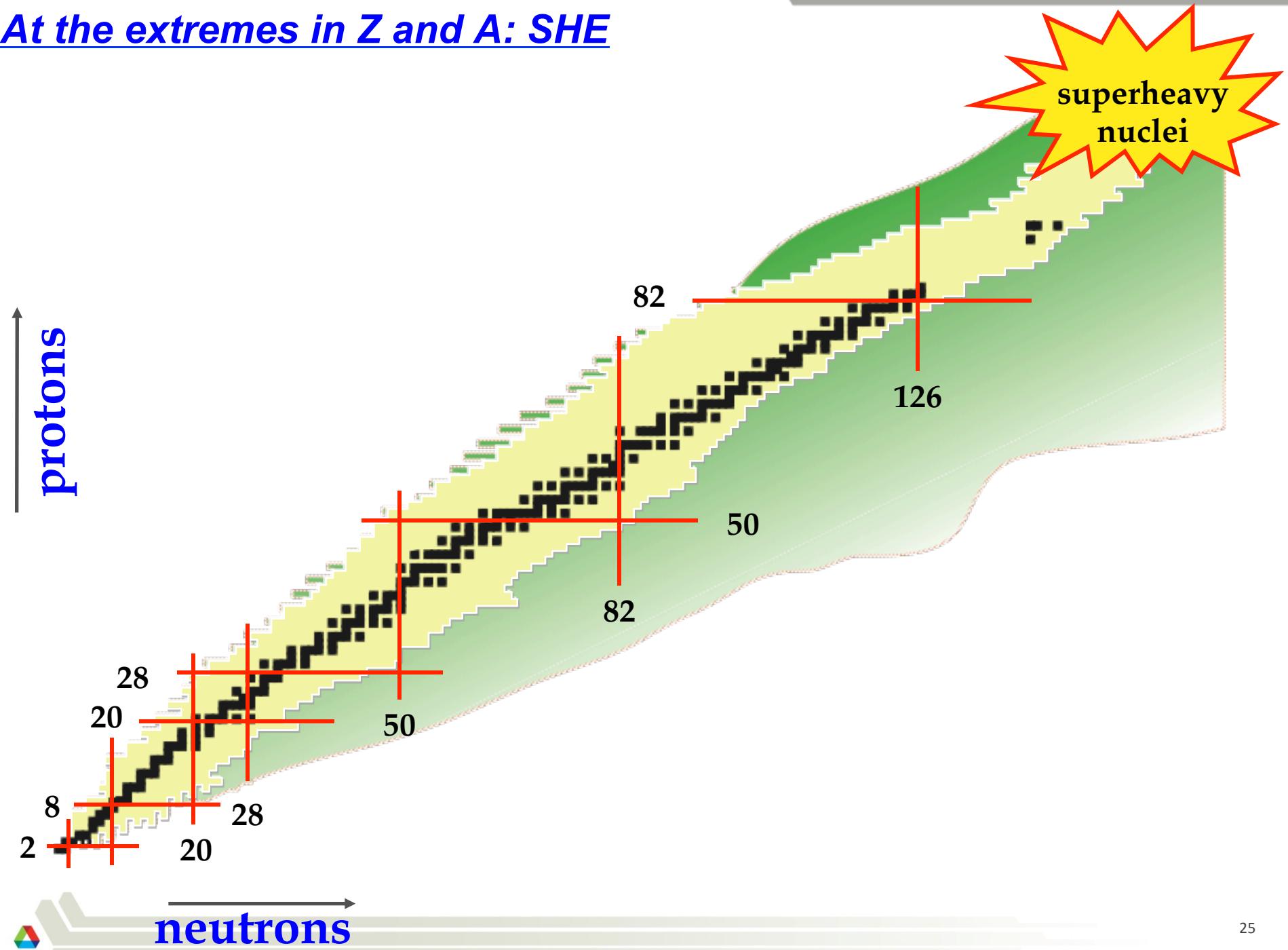


A multiparticle sp mainly decays by β^- . The isomer lies 2668 keV above the 19^- isomer. No proton-decay branch emission by 3261(1) predictions, and the implications for the extent of observable nuclides are considered.

→ Example of high-spin multiparticle isomers beyond the proton drip line, possibly with longer lifetimes than their lower-lying, low-spin states. Such isomers could blur the boundaries of the nuclear landscape by providing the last observable states beyond the proton drip line.

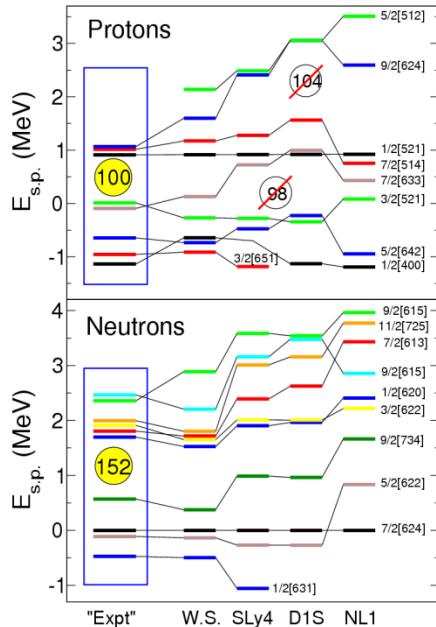
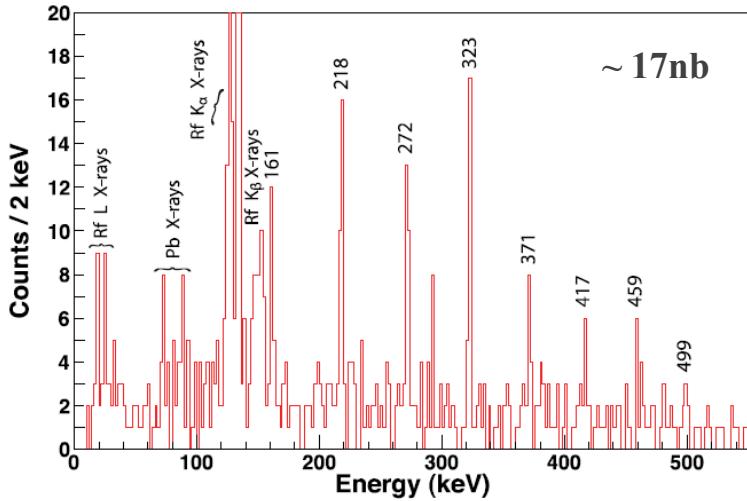
185 . The isomer data shows that it has negative parity. This state in ^{154}Lu was found to proton decay with theoretical

At the extremes in Z and A: SHE



In-beam gamma-ray spectroscopy of SHE: ^{256}Rf

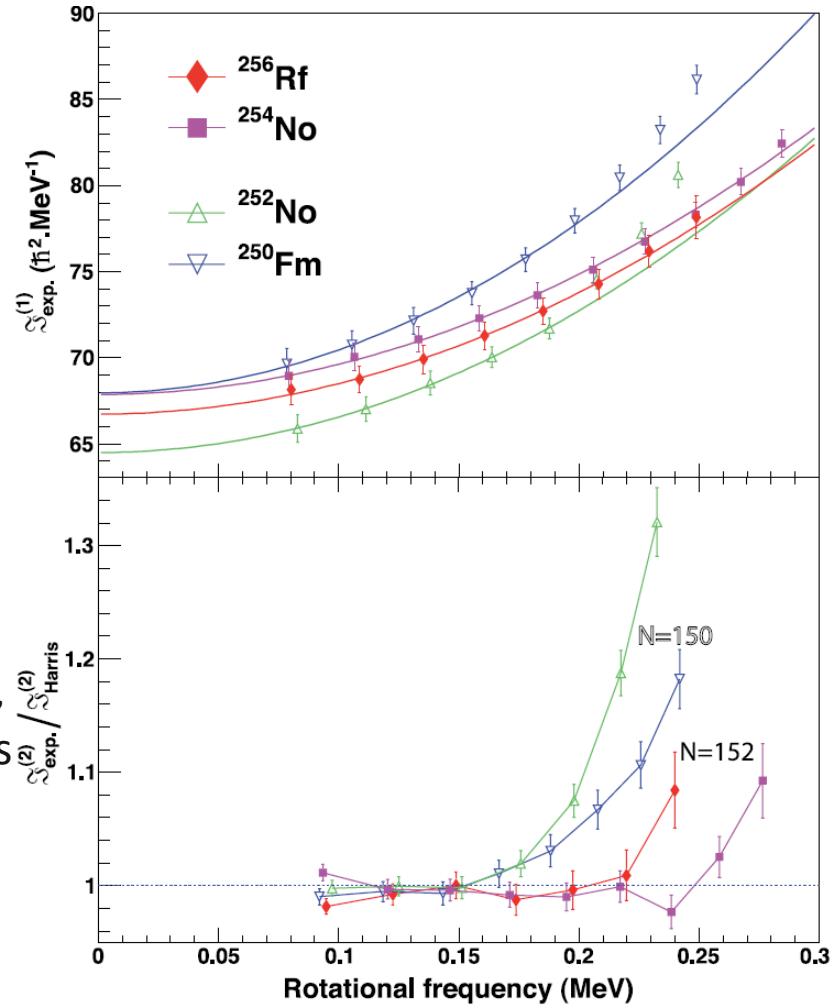
P.T.Greenlees *et al.*, PRL 109, 012501



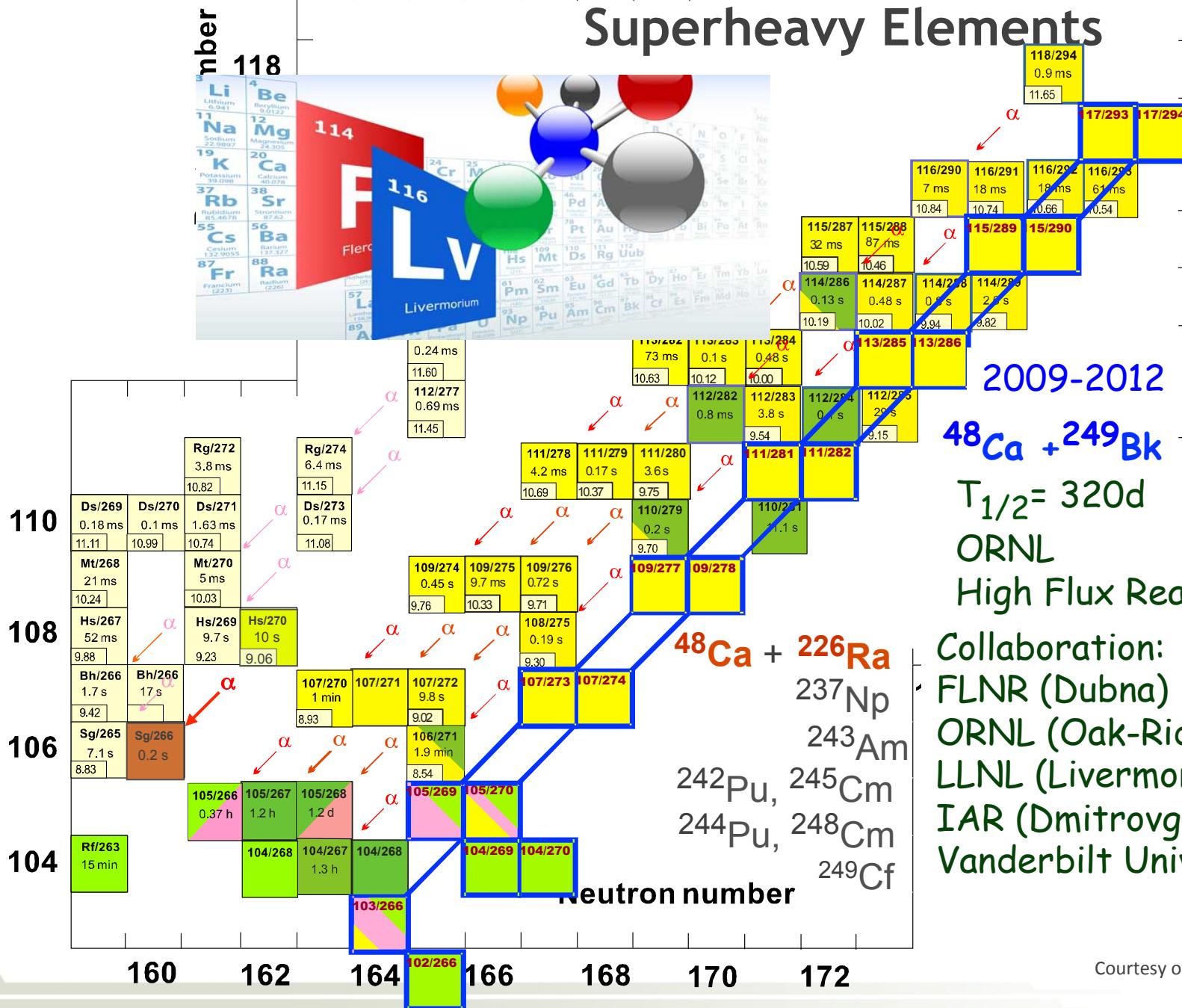
$$\mathcal{J}^{(1)}(^{250}\text{Fm}) > \mathcal{J}^{(1)}(^{254}\text{No}) > \mathcal{J}^{(1)}(^{256}\text{Rf}) > \mathcal{J}^{(1)}(^{250}\text{No})$$

At a shell gap, pairing correlations are weakened, resulting in larger moments of inertia
 → Gaps at $Z=100$ (Fm) and $N=102$ (^{254}No)
 → No gap at $Z=104$

- Moments of inertia are related to (deformed) shell gaps & pairing correlations



Superheavy Elements

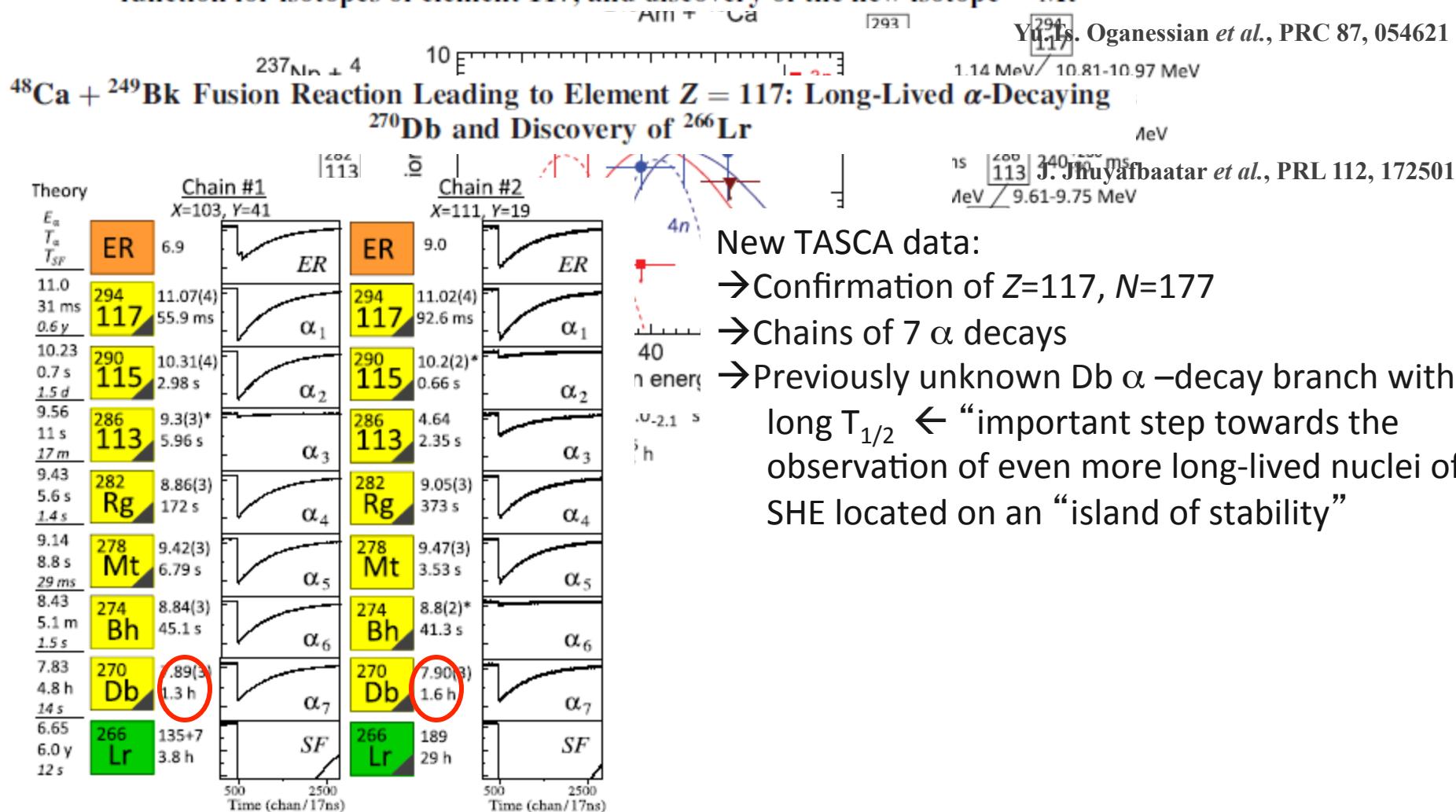


Characterizing the newest SHE & their production

Investigation of the $^{243}\text{Am} + ^{48}\text{Ca}$ reaction products previously observed
in the experiments on elements 113, 115, and 117

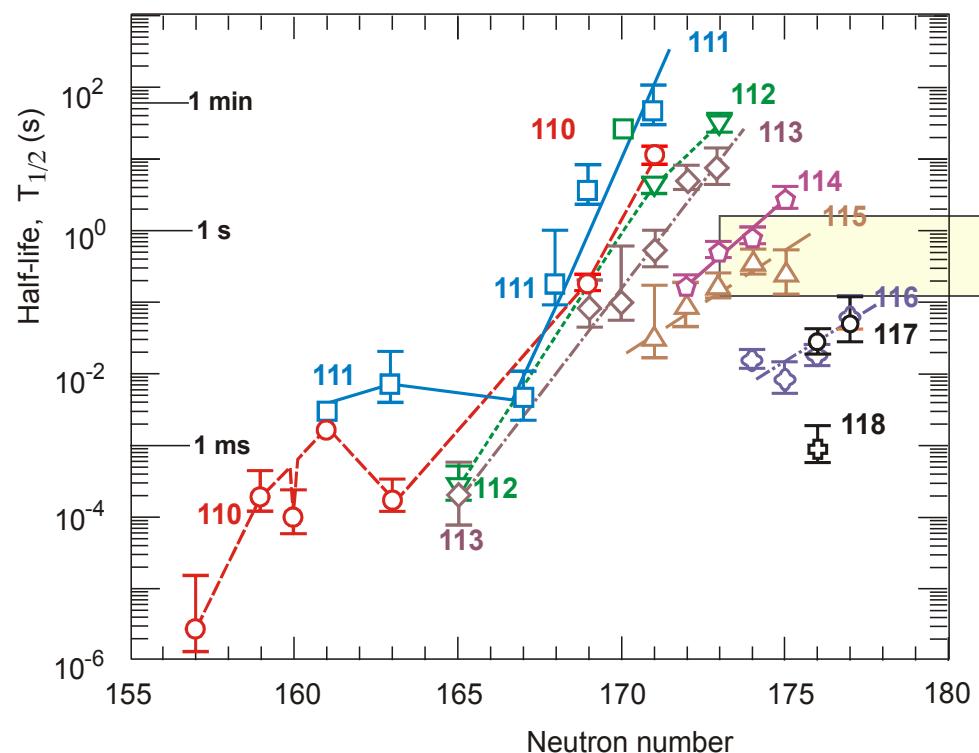
Yu.Ts. Oganessian *et al.*, PRC 87, 014302

Experimental studies of the $^{249}\text{Bk} + ^{48}\text{Ca}$ reaction including decay properties and excitation
function for isotopes of element 117, and discovery of the new isotope ^{277}Mt

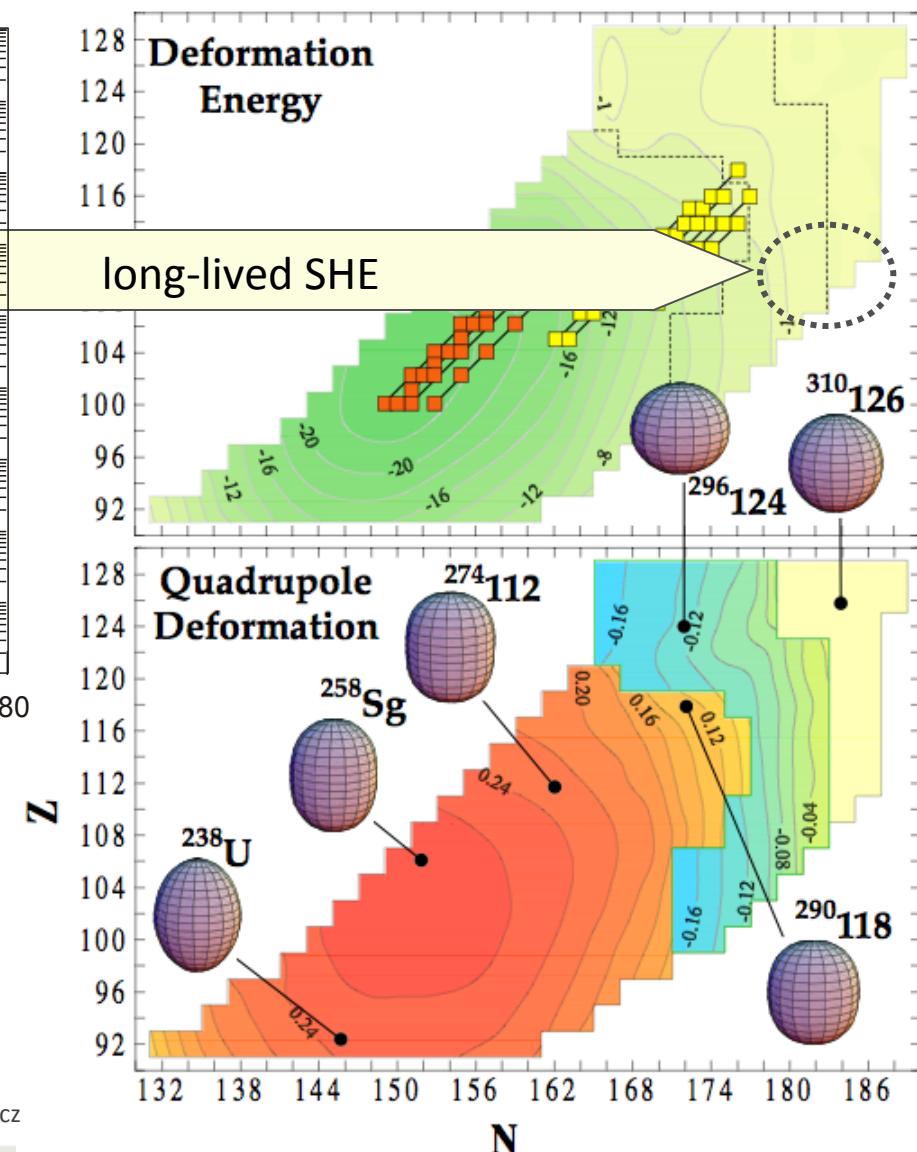


Towards long-lived SHE nuclei

S. Cwiok, P.H. Heenen, W. Nazarewicz
Nature, 433, 705 (2005)



Courtesy of W. Nazarewicz



Nuclear landscape: Challenges ahead

The previous examples are by no means a complete overview:

- much more remarkable experimental work has been done,
- in many more areas (high-spin studies, new collective modes, correlations between nucleons, decay studies,...) ← My apologies for not being more complete

The field is as exciting and challenging as ever!

Much more remains to be explored

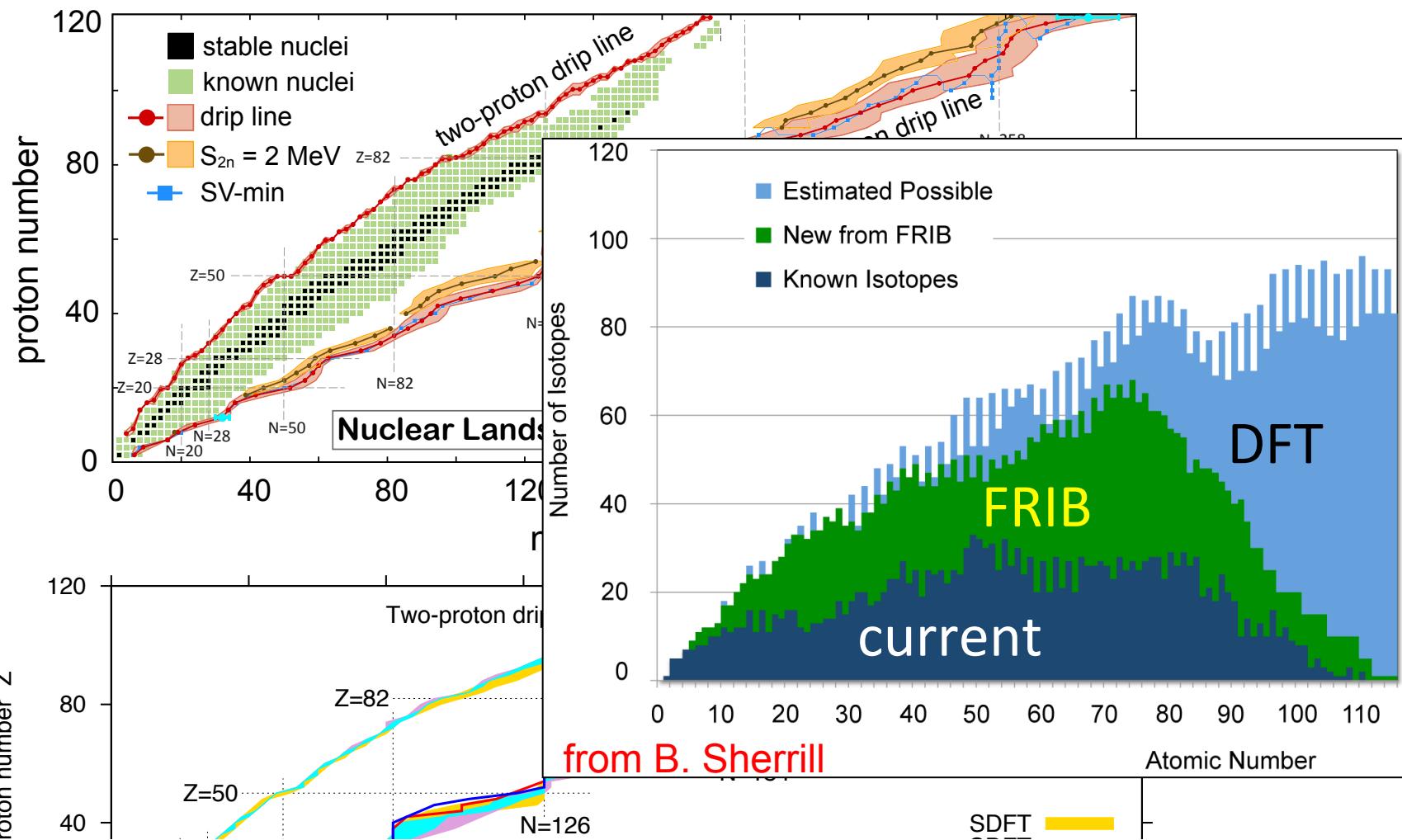
- ← Which new phenomena are awaiting discovery?
- ← Which new aspect(s) of the nuclear interaction(s) has/have escaped observation thus far; e.g., can we fulfill the ambition of the “theory road map” and get to a satisfactory description of *all* nuclei?
- ← How do we optimize the experiment – theory loop?

There is much discovery potential for the future **BUT**:

- while US scientists were involved in most of the data shown, some of the experiments used foreign facilities;
- **to remain competitive and keep scientific leadership, we need**
 - (a) FRIB construction to proceed on time & the means to initiate of its full science program from the start;
 - (b) adequate support for our existing facilities (NSCL & ATLAS & Univ.-based)
 - (c) adequate support for research (Theory & Experiment)
 - (d) targeted investments in instrumentation & accelerators.

Nuclear landscape: Challenges ahead

Erler et al. Nature 486, 509



In a nutshell:
the challenges ahead are in this vast landscape that remains to be discovered



Thank you

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AND
Thank YOU for your valuable
contributions to our field
and for your attention