Long Range Planning for Physics of Nuclei and Nuclear Astrophysics

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JLab Users Group Meeting
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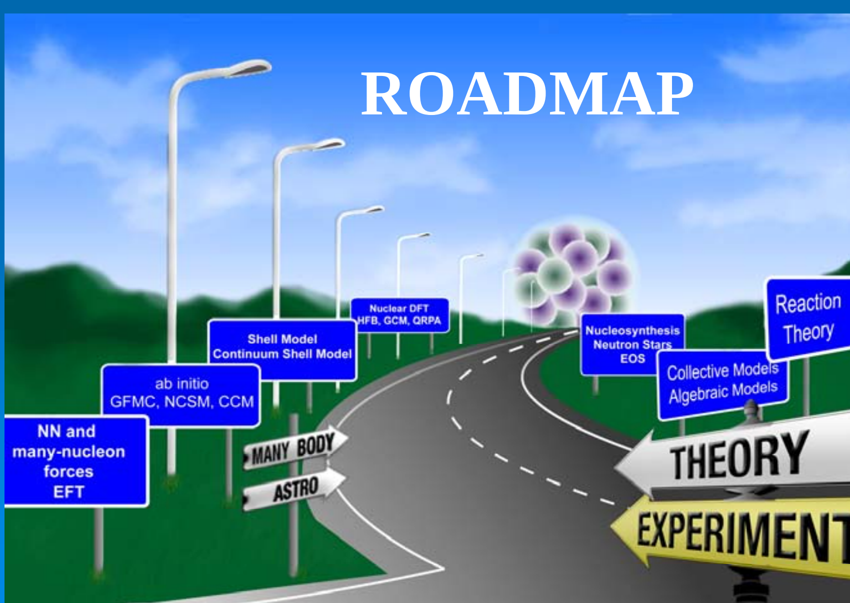
"The shell must break before the bird can fly." -- Tennyson

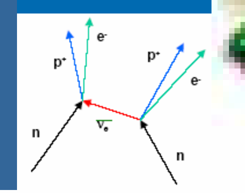
Key science drivers of rare isotopes

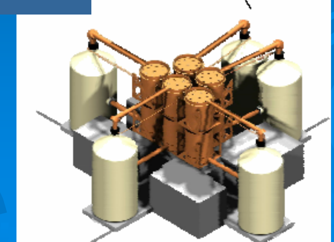
- Test the predictive power of models by extending experiments to new regions of mass and proton-to-neutron ratio
- Identify new phenomena that will challenge existing many-body theory

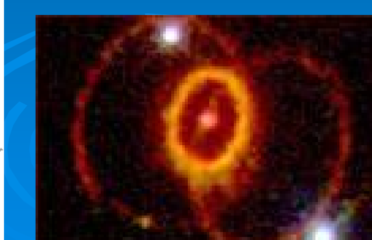
- Create and study super heavy nuclei
- Characterize neutron skins and excitation modes
- Constrain r-process site and explosive nucleosynthesis
- Constrain nuclear equation of state (neutron star crusts)
- Societal Applications: Energy, Security
- Beyond ‘Standard Model’: $\beta\beta 0\nu$ decay; Dark Matter, EDM…



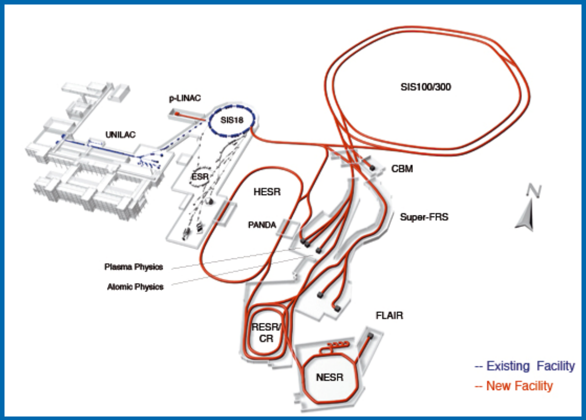
Xe XENON Dark Matter Project

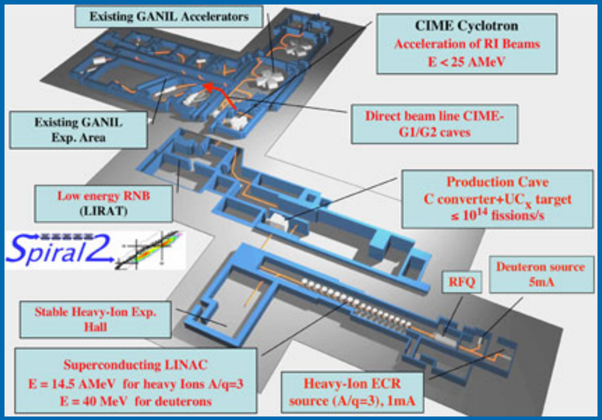




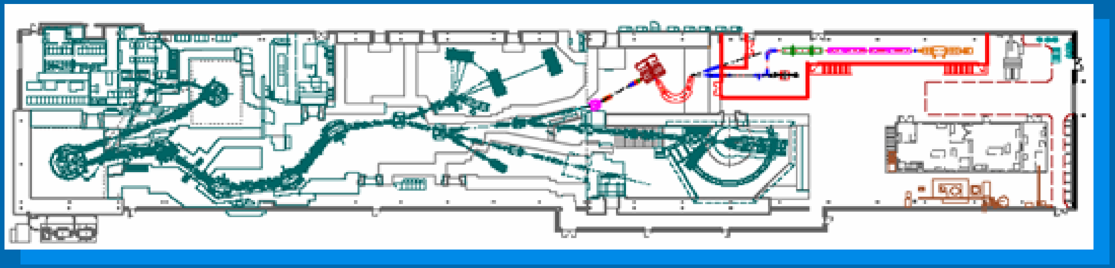


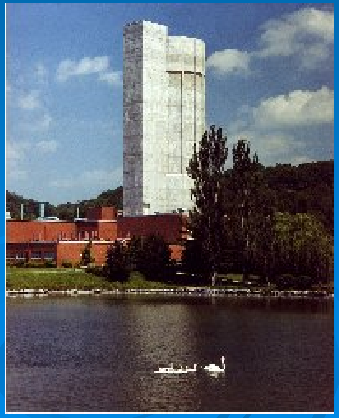
Present and next Generation Radioactive Ion Beam facilities (multi $100M investments world wide)





"[C]ountries throughout the world are aggressively pursuing rare-isotope science, often as their highest priority in nuclear science, attesting to the significance accorded internationally to this exciting area of research"
NAS RISAC Report





Future U.S. FRIB based on a heavy-ion linac driver a high priority.

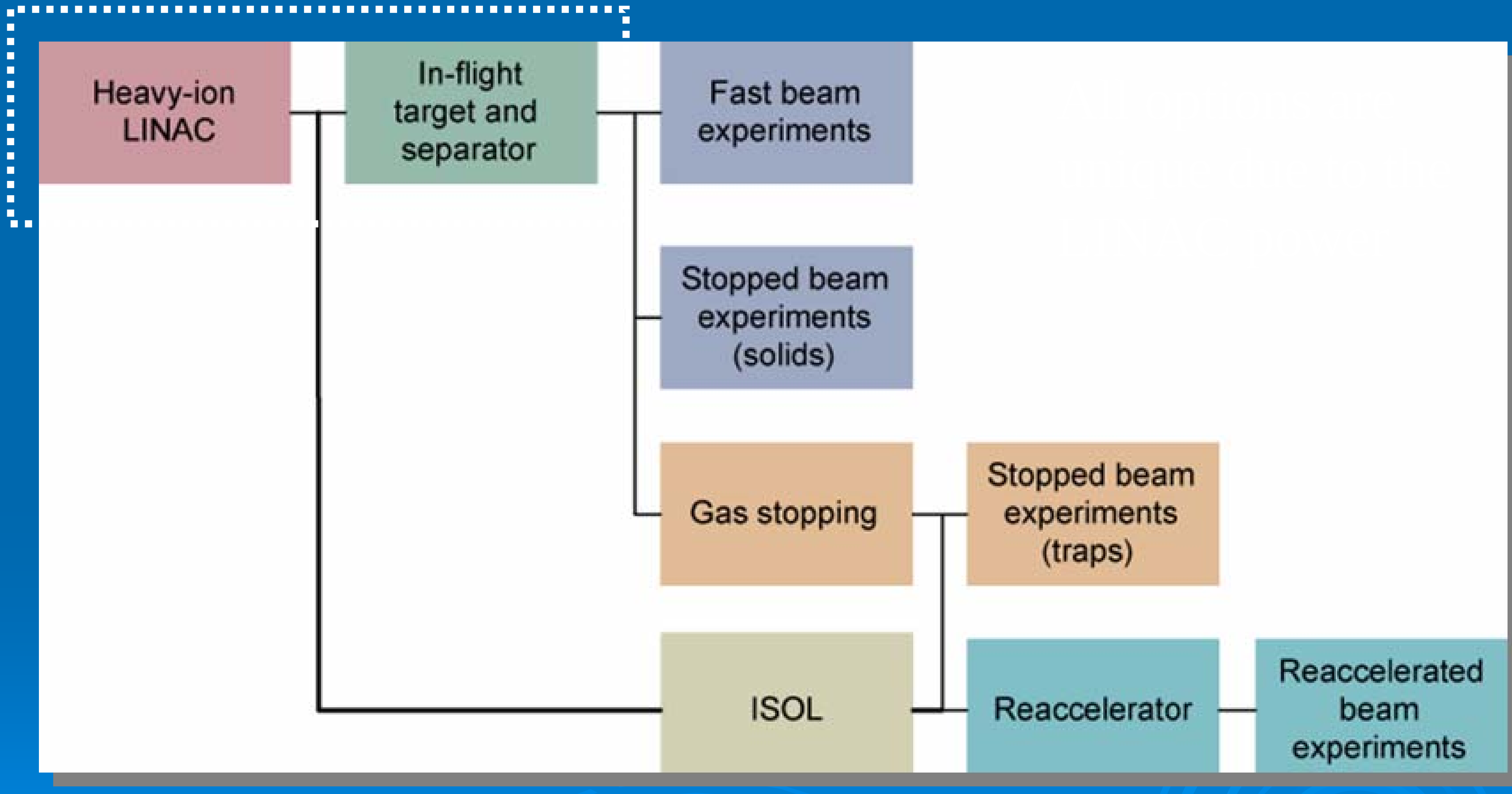
Nuclear Physics LRP07 Recommendations

- We recommend completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.
- We recommend construction of the Facility for Rare Isotope Beams, FRIB, a world-leading facility for the study of nuclear structure, reactions and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.
- We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet unseen violations of time-reversal symmetry, and other key ingredients of the new standard model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to US leadership in core aspects of this initiative.
- The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.

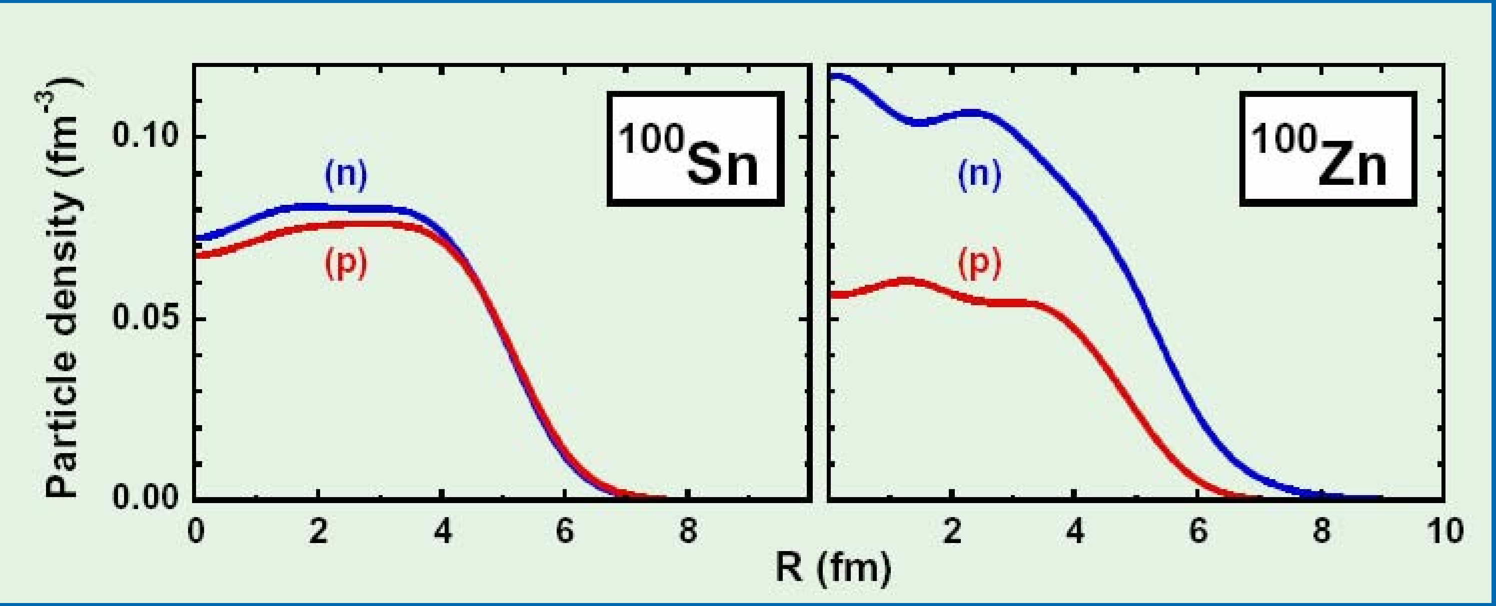
From the technical side of things

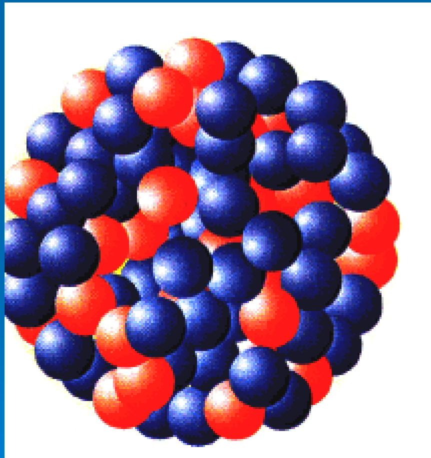
- Production of key rare isotopes
  - 10^{-5} pps (existence, perhaps lifetime, decay modes)
  - 10^{-4} to 10^{-3} pps (half live, mass, basic structural information)
  - 10^{-2} to 10^{-1} pps(some detailed structural information)
  - 10^{3} pps (full details of structure transfer, multicoulex,…)
  - 10^{5} pps and up (astrophysical reaction rates)
  - 10^{6} pps weak interaction strengths
  - 10^{8} to 10^{12} pps production of superheavy elements
- Highest power heavy ion driver possible (at present) is a superconducting LINAC. The energy should be 200 MeV/u (Symons Committee)

Possibilities with a heavy-ion linac



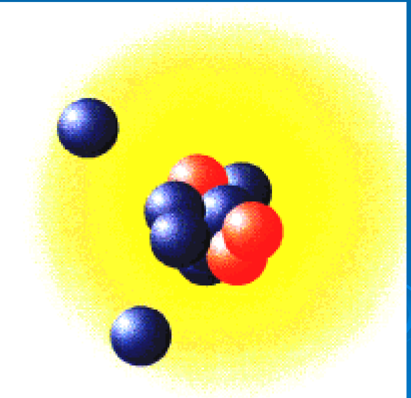
The challenge of neutron rich nuclei





^{208}Pb: Well Bound Heavy Nucleus

	‘normal’	‘rare’
Half-life	Long/stable	Short
Size	Compact	Halos
Continuum	Unimportant	Important
Shell closures	Normal magic numbers	New magic numbers
Scattering Cross section	‘Normal’	Enhanced



^{11}Li: Borromean Halo Nucleus

The challenge of theory for nuclei

"The first, the basic approach, is to study the elementary particles, their properties and mutual interaction. Thus one hopes to obtain knowledge of the nuclear forces. If the forces are known, one should, in principle, be able to calculate deductively the properties of individual nuclei. Only after this has been accomplished can one say that one completely understands nuclear structure….The other approach is that of the experimentalist and consists in obtaining by direct experimentation as many data as possible for individual nuclei. One hopes in this way to find regularities and correlations which give a clue to the structure of the nucleus….The shell model, although proposed by theoreticians, really corresponds to the experimentalist's approach."
–M. Goeppert-Mayer, Nobel Lecture

Two ways of doing business (I typically focus on the first):

- QCD → NN (and NNN) forces → calculate → predict → experiment
- Experiment → effective forces → calculate → predict
- Progress involves feedback…

Theory for all nuclei

Theoretically describe nuclei and their reactions – with quantifiable error bars.

Step 1: Use *ab initio* theory and study of exotic nuclei to determine the interactions of nucleons in light nuclei and connect these to QCD by effective field theory

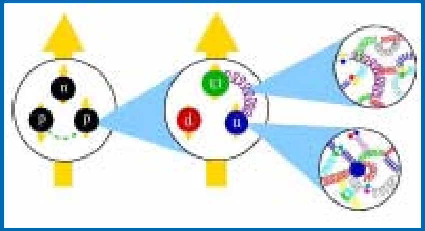
Step 2: For mid-mass nuclei use configuration space models (overlapping with ab initio).The degrees of freedom and interactions must be determined from exotic nuclei

Step 3: Use density functional theory to connect to heavy nuclei. Exotic nuclei help determine the form and parameters of the DFT.

One size does not fit all, but there are overlaps

Progress on the interaction: Effective Field Theory

Thus one hopes to obtain knowledge of the nuclear forces. If the forces are known… (MGM)



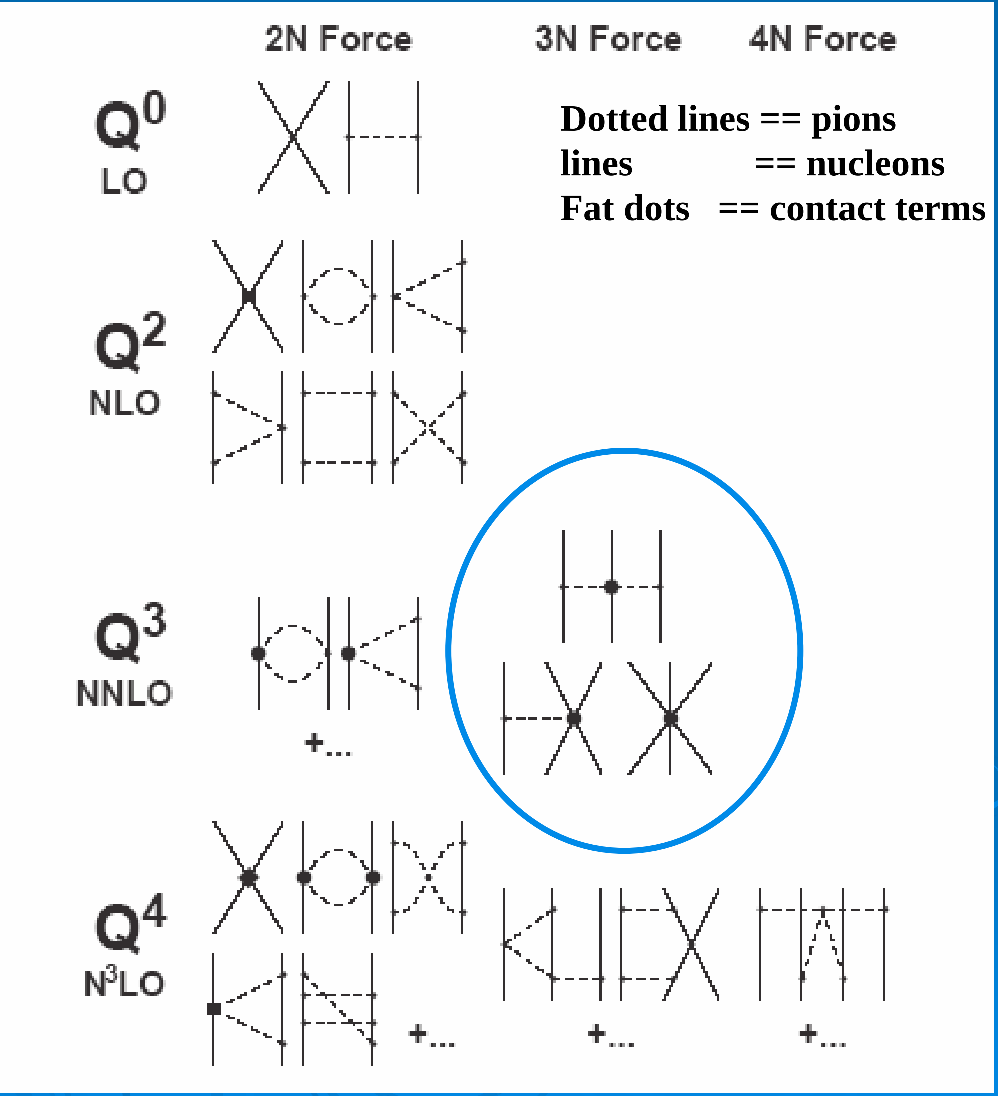
Effective Lagrangian → obeys QCD symmetries (spin, isospin, chiral symmetry breaking)

Lagrangian
→ infinite sum of Feynman diagrams.

Invoke power counting:
Expand in $O(Q/\Lambda_{QCD})$
Weinberg, Ordonez, Ray, van Kolck

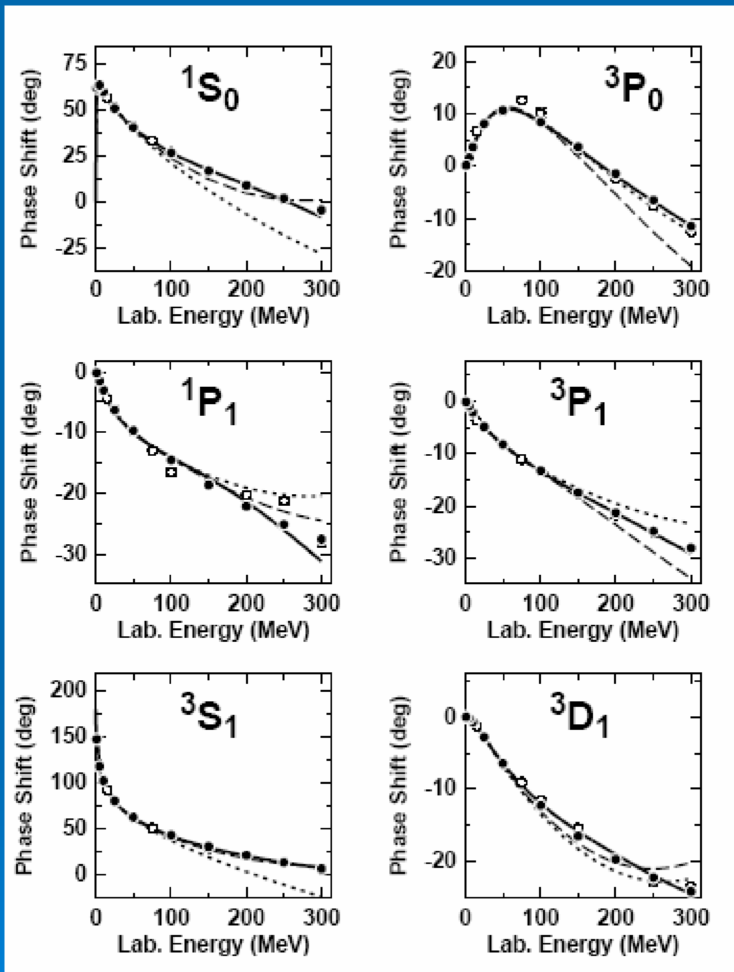
NN amplitude uniquely determined by two classes of contributions: contact terms and pion exchange diagrams.

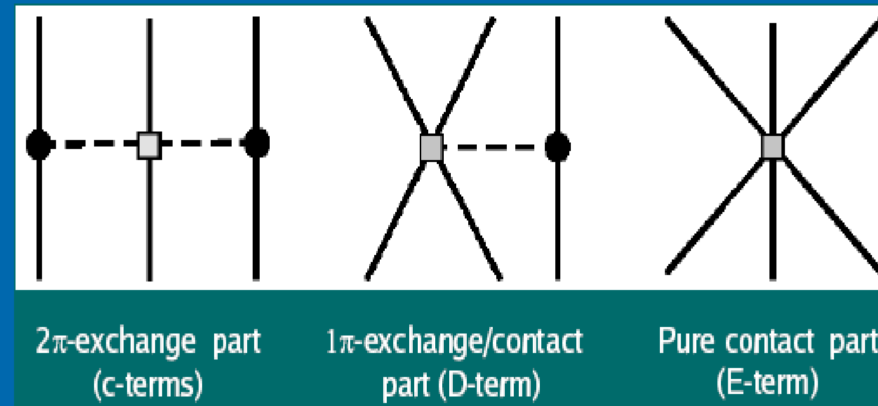
3-body (and higher) forces are inevitable.

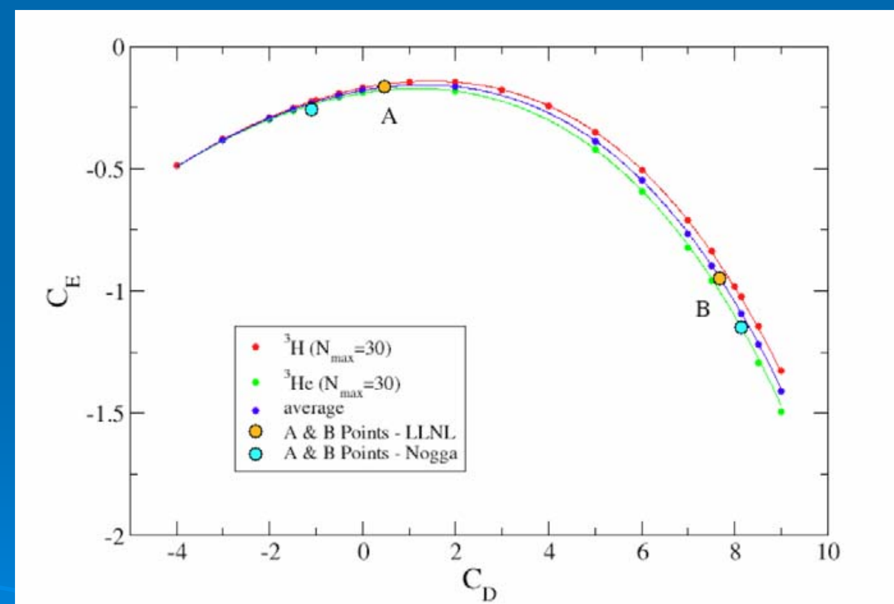


Effective field theory potentials bring a 3-body force

"…the force should be chosen on the basis of NN experiments (and possibly subsidiary experimental evidence…) (Bethe)







dashed → NLO
dot → N^2LO
solid → N^3LO

Challenge: Deliver the best NN and NNN interactions with their roots in QCD (eventually from LQCD, see Ishii, Aoki and Hatsuda, arXiv:nucl-th/0611096)

From the interaction to solving the nuclear many-body problem

Begin with a NN (+3N) Hamiltonian

$$H = -\frac{\hbar}{2}\sum_{i=1}^{A}\frac{\nabla_i^2}{m_i} + \frac{1}{2}\sum_{i<j} V_{2N}\left(\vec{r}_i, \vec{r}_j\right) + \frac{1}{6}\sum_{i<j<k} V_{3N}\left(\vec{r}_i, \vec{r}_j, \vec{r}_k\right)$$

Bare (GFMC)
(Local only, Av18 plus adjusted 3-body)

Basis expansion (explore forces)

Basis expansions:
- **Determine the appropriate basis**
- **Generate H_{eff} in that basis**
- **Use many-body technique to solve problem**

Nucleus	4 shells	7 shells
4He	4E4	9E6
8B	4E8	5E13
12C	6E11	4E19
16O	3E14	9E24

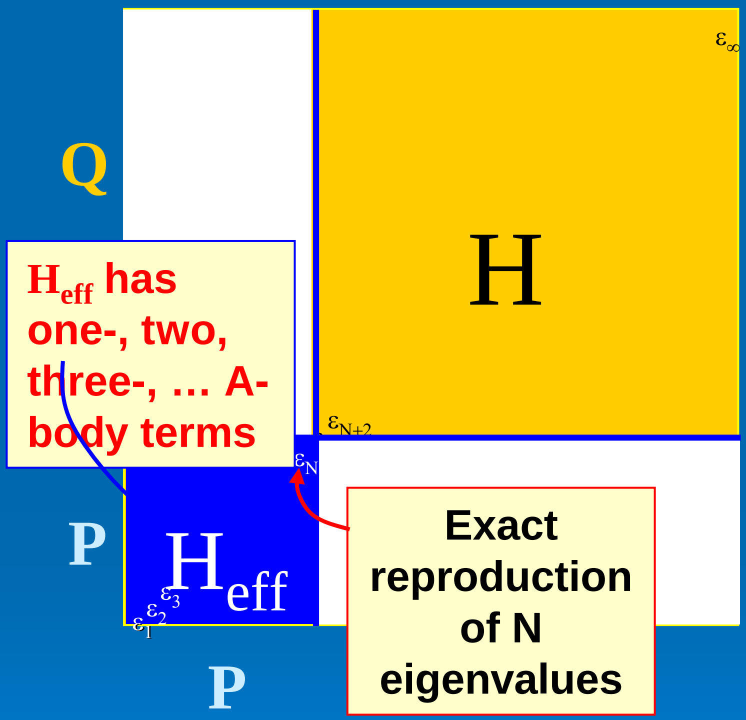
Oscillator single-particle basis states

Many-body basis states

Substantial progress in many-body developments
- **GFMC; AFDMC**
- **No Core shell model (not a model)**
- **Coupled-cluster theory**
- **UCOM,…**
- **AFMC**

Progress: Embracing renormalization

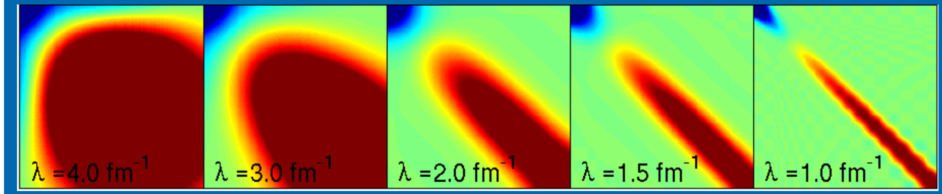
Project H into large basis;
Perform Lee-Suzuki (NCSM)
Use Heff as 2-(+3) body interaction



Recovers Bare A-body in large space
Requires addition of 3-body force
for experimental binding (adjust to He-4)
Challenge: slow convergence

$$\frac{d}{d\Lambda} V_{\mathrm{low}\,k}^{\Lambda}(k',k) = \frac{2}{\pi} \frac{V_{\mathrm{low}\,k}^{\Lambda}(k',\Lambda)\, T^{\Lambda}(\Lambda,k;\Lambda^2)}{1-(k/\Lambda)^2}$$

- Renormalize at a momentum cutoff Λ
- Project onto oscillator basis
- Preserves phase shifts to the cutoff
- “reasonable” convergence



Challenges:
- Does not recover bare result
- Requires 3-body force for experimental binding …adjust to He-4
- Λ-independence

Schwenk, Bogner, Furnstahl,…

Progress (example): Coupled Cluster Calculations in ^{16}O

$$|\Psi\rangle = \exp(T)|\Phi\rangle$$

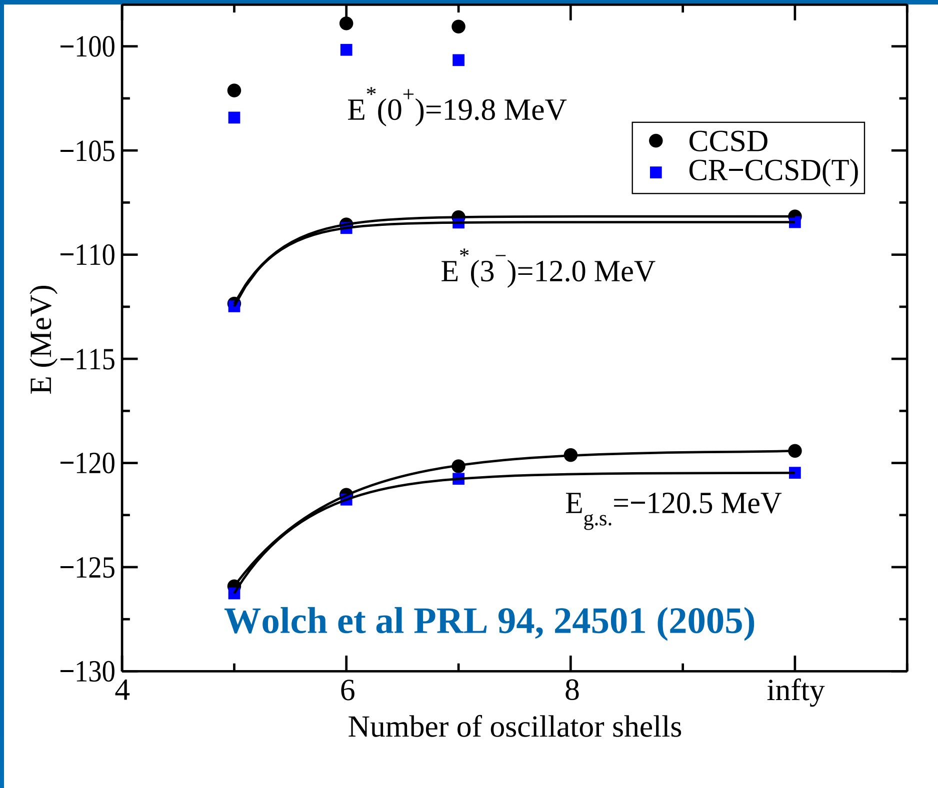
$$T = T_1 + T_2 + T_3 + \cdots$$

$$E = \langle\Phi|\overline{H}|\Phi\rangle = \langle\Phi|e^{-T}He^{T}|\Phi\rangle$$

$$\langle\Phi_{ij\cdots}^{ab\cdots}|\overline{H}|\Phi\rangle = 0$$

$$R\overline{H}|\Phi\rangle = E^{*}R|\Phi\rangle$$

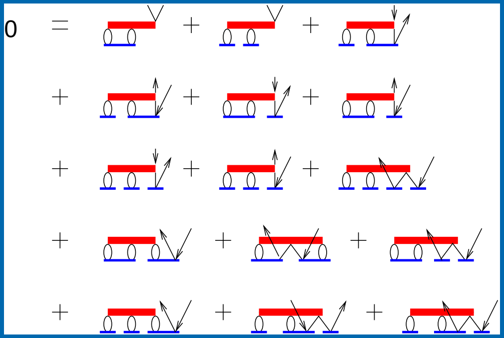
$R =$ excitation operator



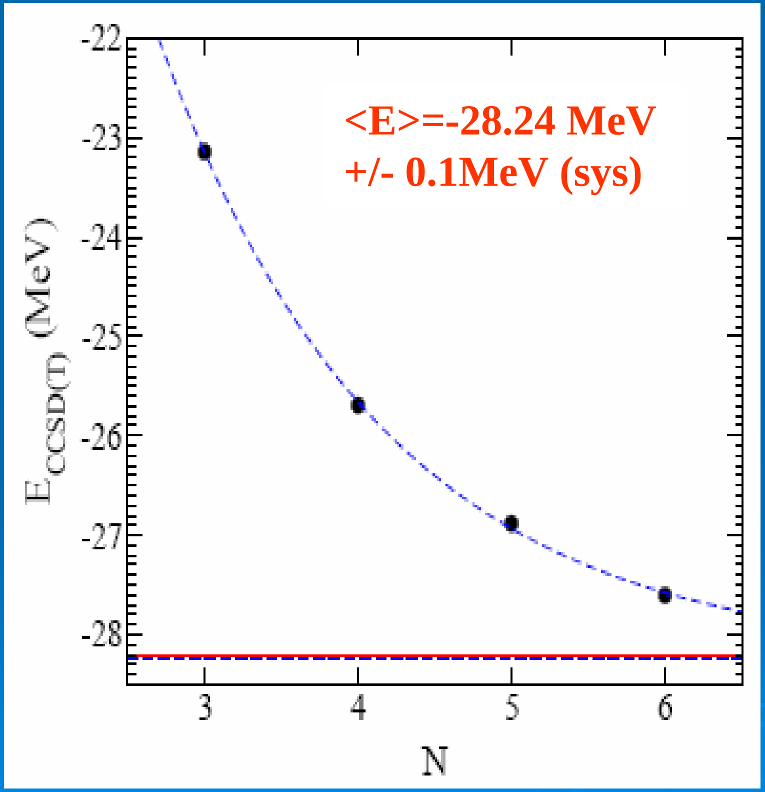
Note, converged spectrum but 3^- is 6 MeV high.

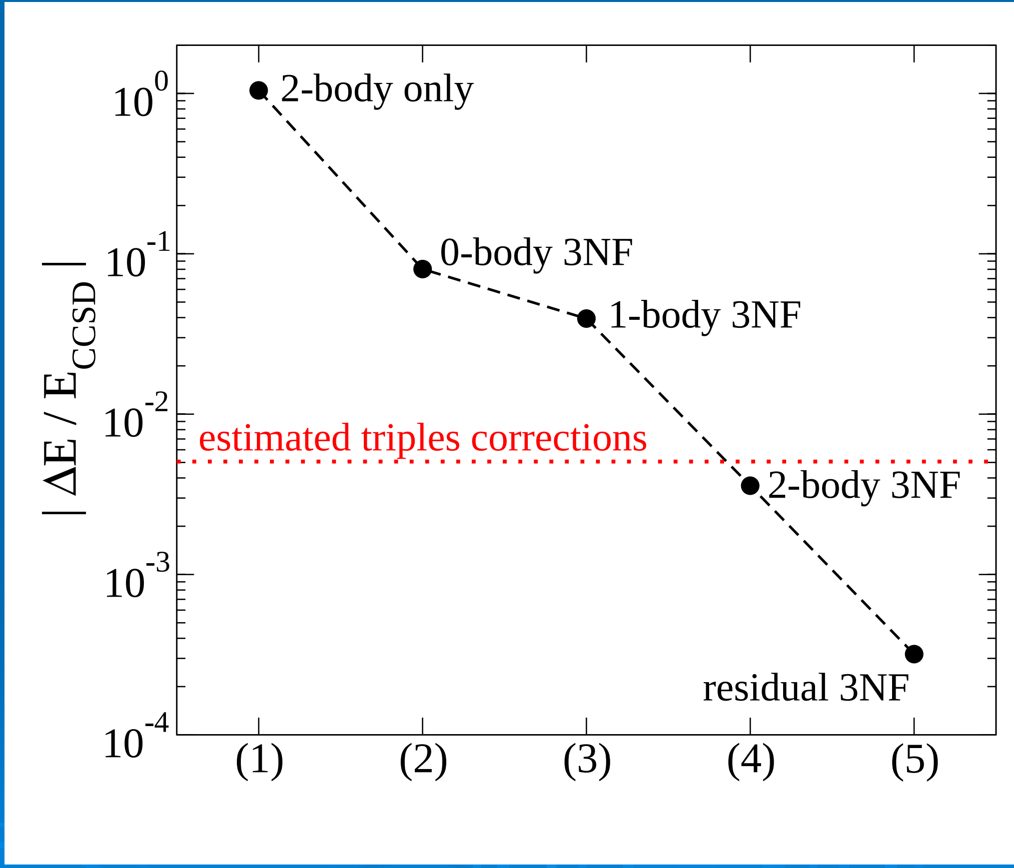
Challenge: how does the 3-body force affect these states?

Progress: inclusion of full TNF in CCSD: F-Y comparisons in ^{4}He



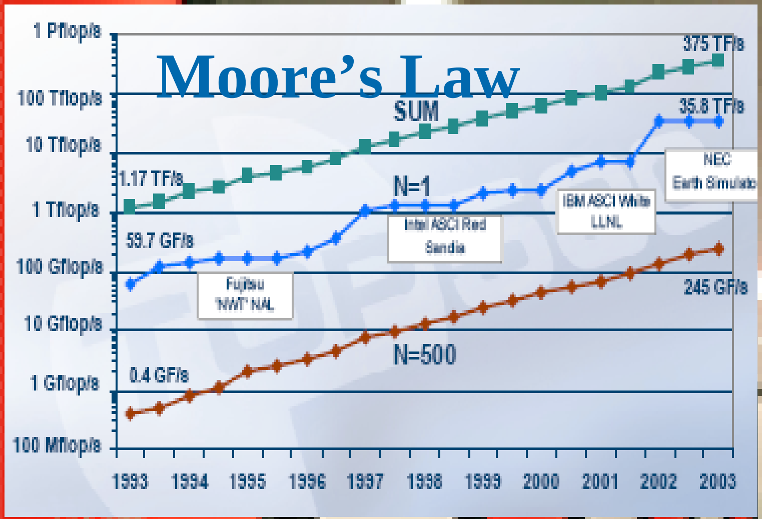
Solution at CCSD and CCSD(T) levels involve roughly 67 more diagrams…..

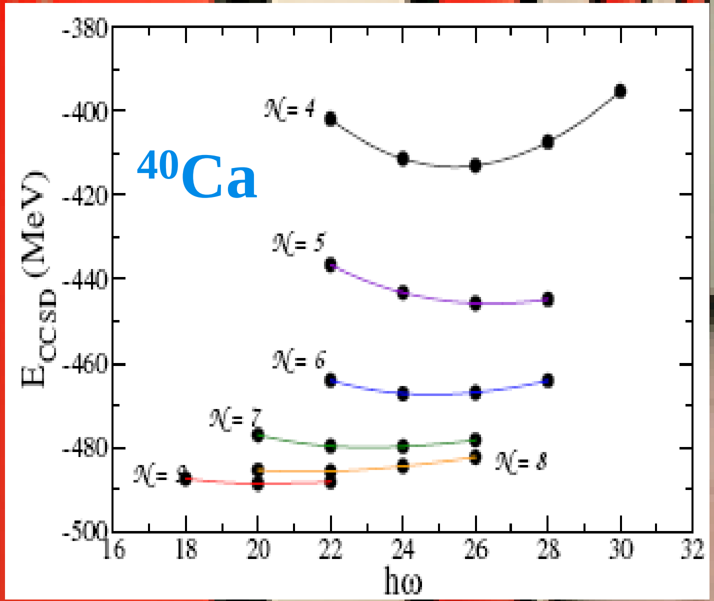




3-body force, or just its density dependent terms?

Hagen, Papenbrock, Dean, Schwenk, Nogga, Wloch, Piecuch arXiv:0704.3439





"…be able to calculate deductively the properties of individual nuclei"

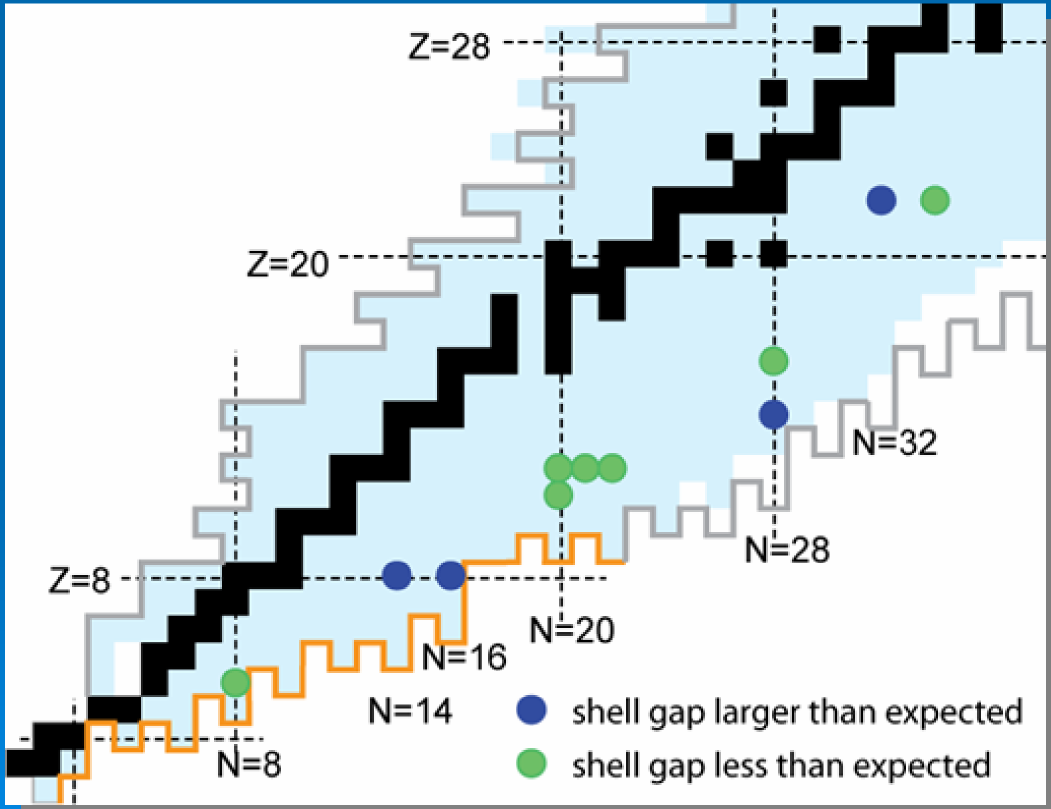
- Computation absolutely essential
- "Moore's law" power law in raw computing power: 2 year doubling time.
- Petascale: 3 years
- Exascale: 10 years

- Challenge: develop algorithms that will effectively utilize both core speed and memory to attack nuclear problems.

- Measure of success: predictive nuclear theory in medium-mass nuclei (to mass 100).

Evolution of shell structure

Step 2: Develop an understanding of the nature of effective interactions and operators used in nuclear structure models

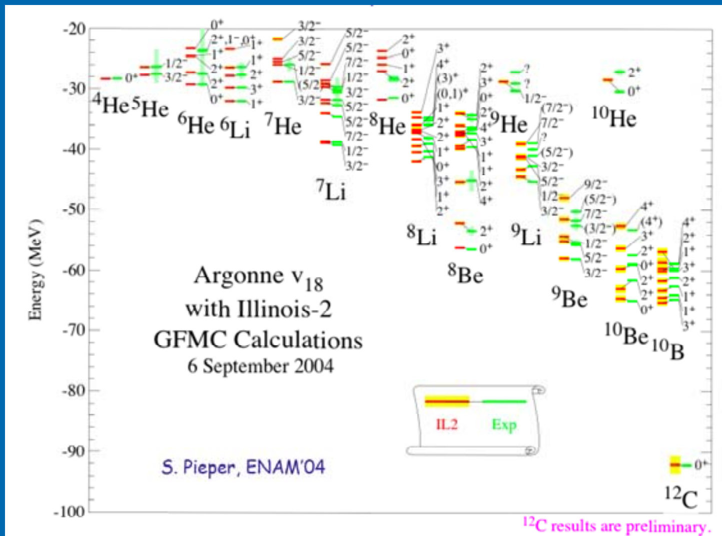


Insight into tensor and 3-body forces in nuclei (e.g. *Otsuka et al*.)

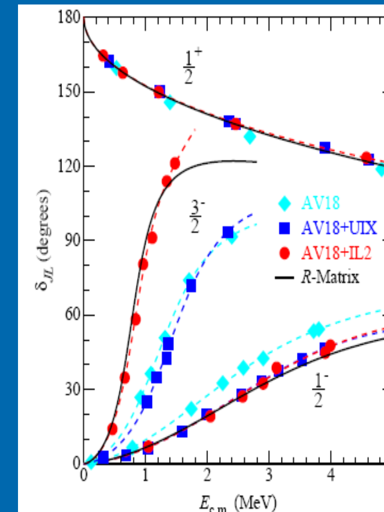
If the concept of shells is still valid, then use the 'shell model'.

Challenge: rigorous derivation of useful effective interactions

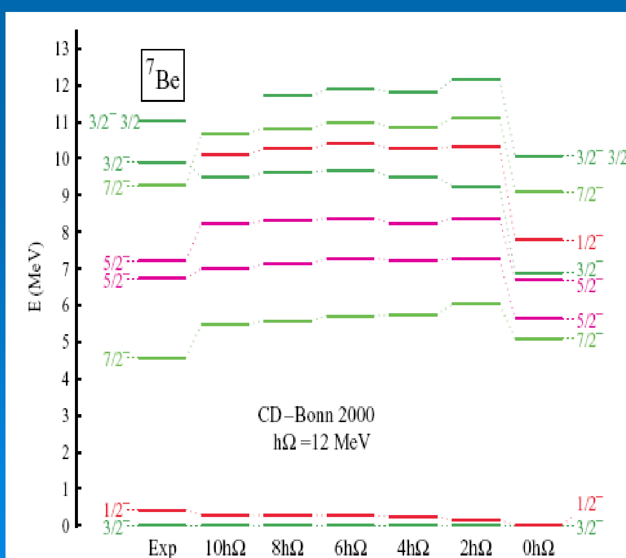
Progress: from structure to reactions in the same framework



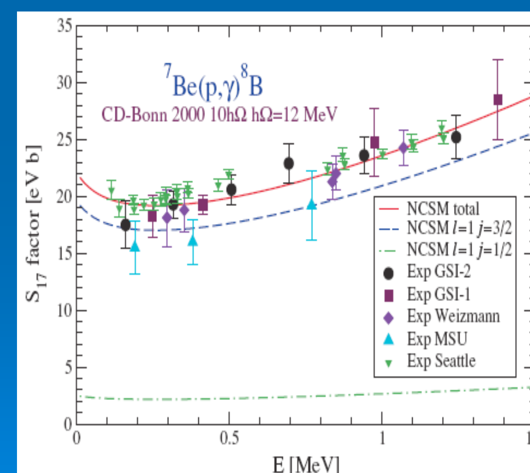
n-α scattering



Nollett et al, nucl-th/0612035



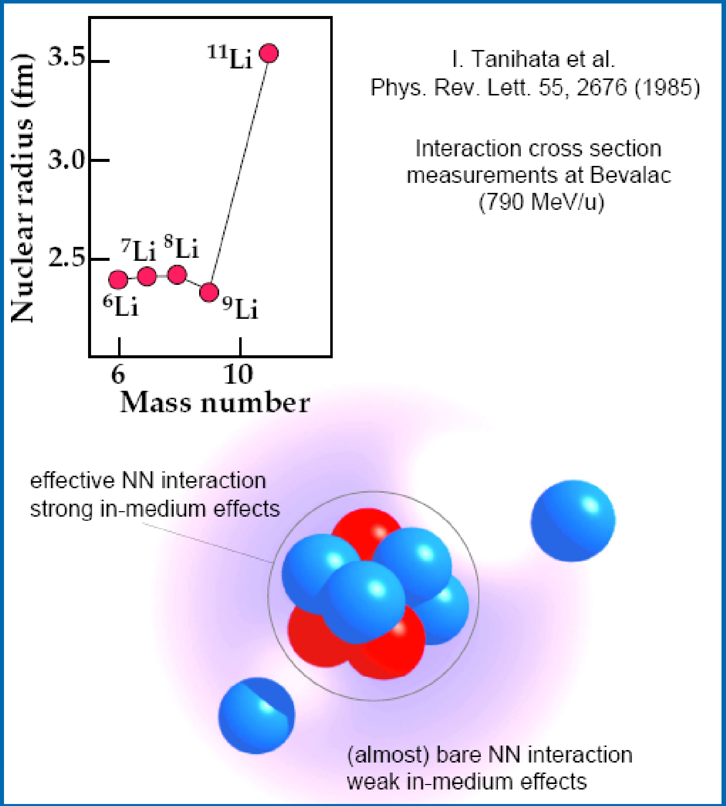
NCSM clusters



Navratil et al., PRC73, 065801 (2006)

For a reaction theorist's view, see Tostiven's talk

Progress: understanding scale separation



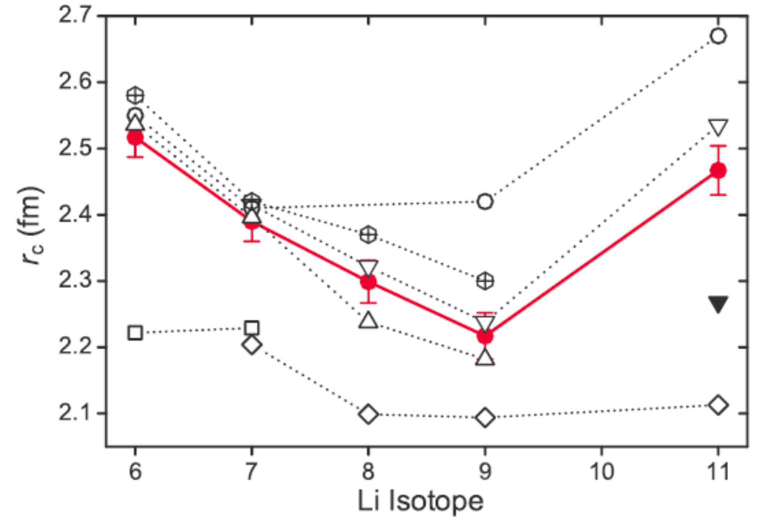
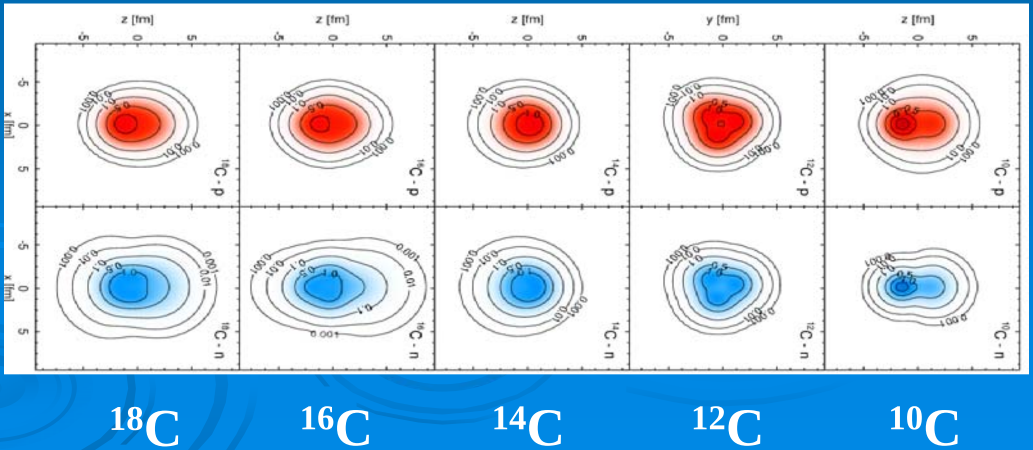


FIG. 2 (color online). Experimental charge radii of lithium isotopes (red, ●) compared with theoretical predictions: △: GFMC calculations [4,22], ▽: SVMC model [27,28] (▼: assuming a frozen ^{9}Li core), ⊕: FMD [26], ○: DCM [19], □ and ◇: *ab initio* NCSM [23,24].

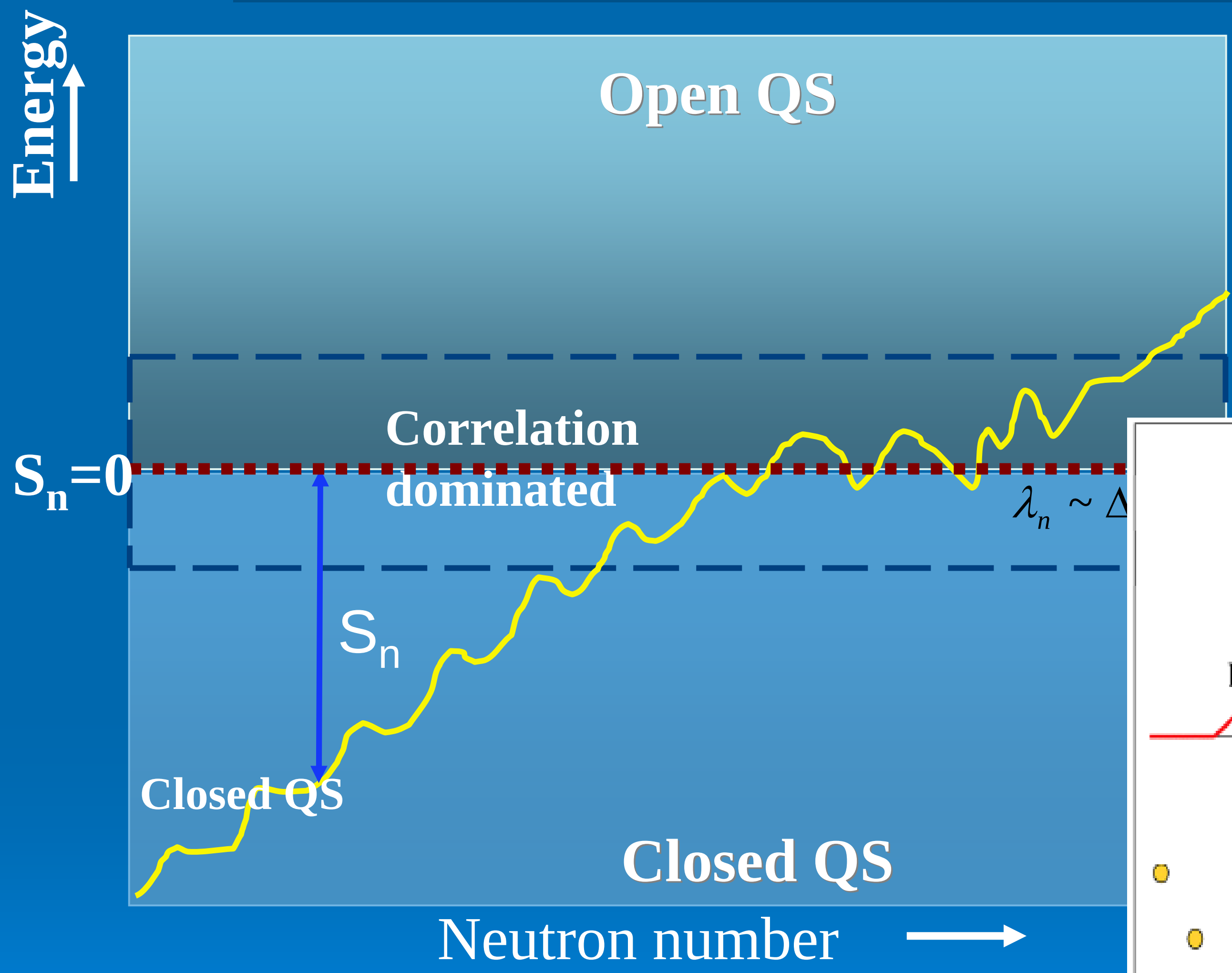
R. Sanchez et al, PRL. 96 (2006) 33002.

Decoupling of proton and neutron deformation in FMD calculations (Feldmeier et al)

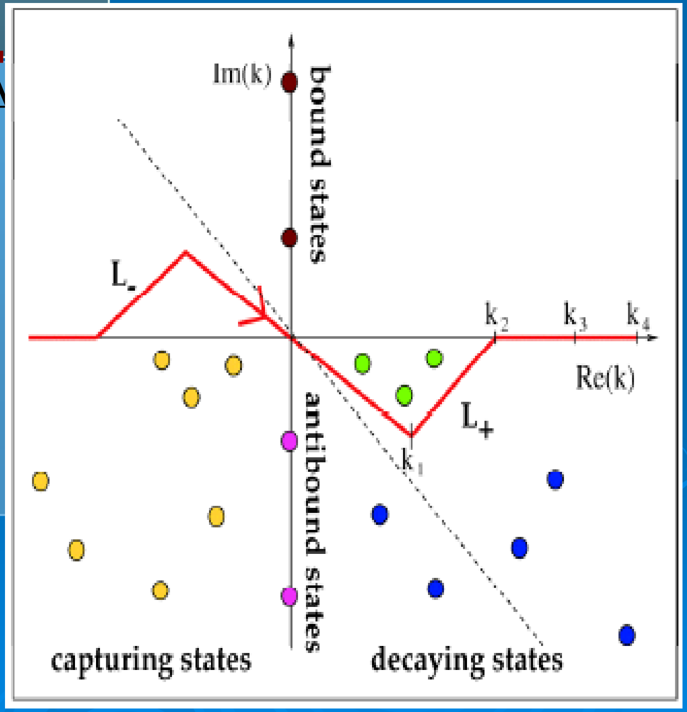


Challenge: the continuum

Progress: Coupling of nuclear structure and reaction theory (microscopic treatment of open channels)

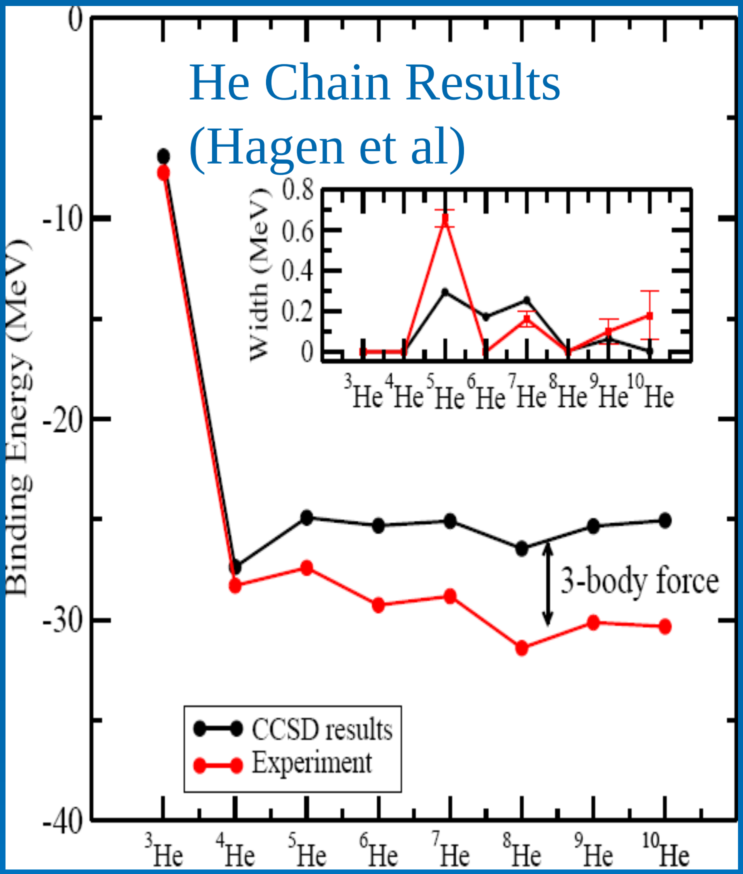


Important interdisciplinary aspects…(see recent ECT* workshop on subject)



Introduction of
Continuum basis states (Gamow, Berggren)
→Continuum shell models
(many including: Michel, Rotureau, Volya, Ploszajczak, Liotta, Nazarewicz,…)

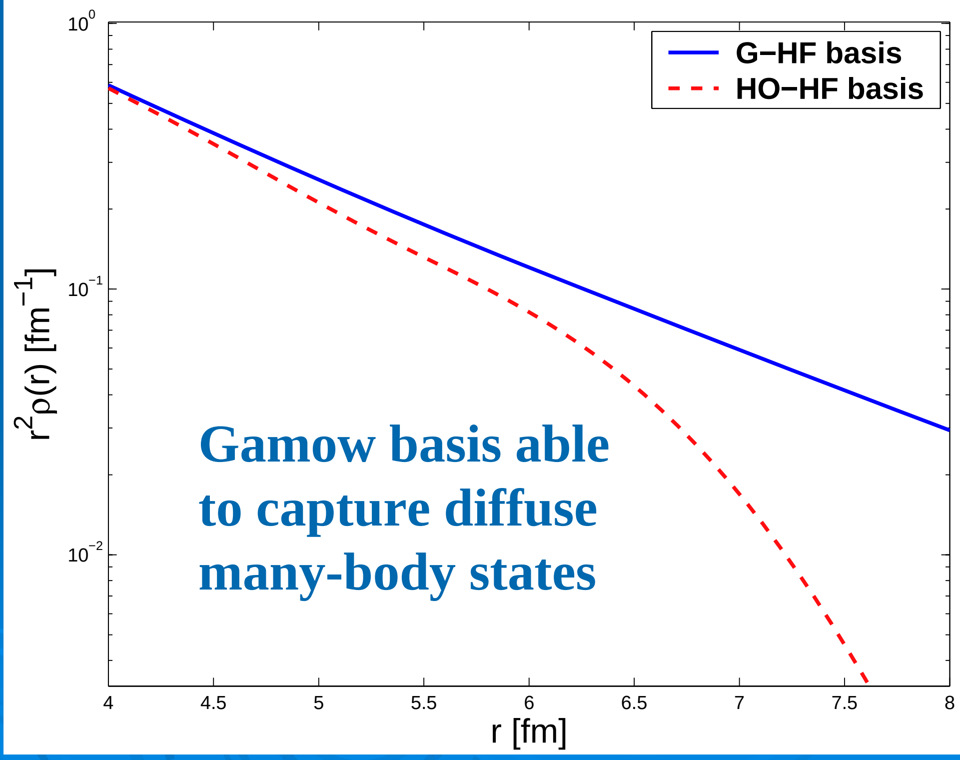
Progress: ab initio weakly bound and unbound nuclei



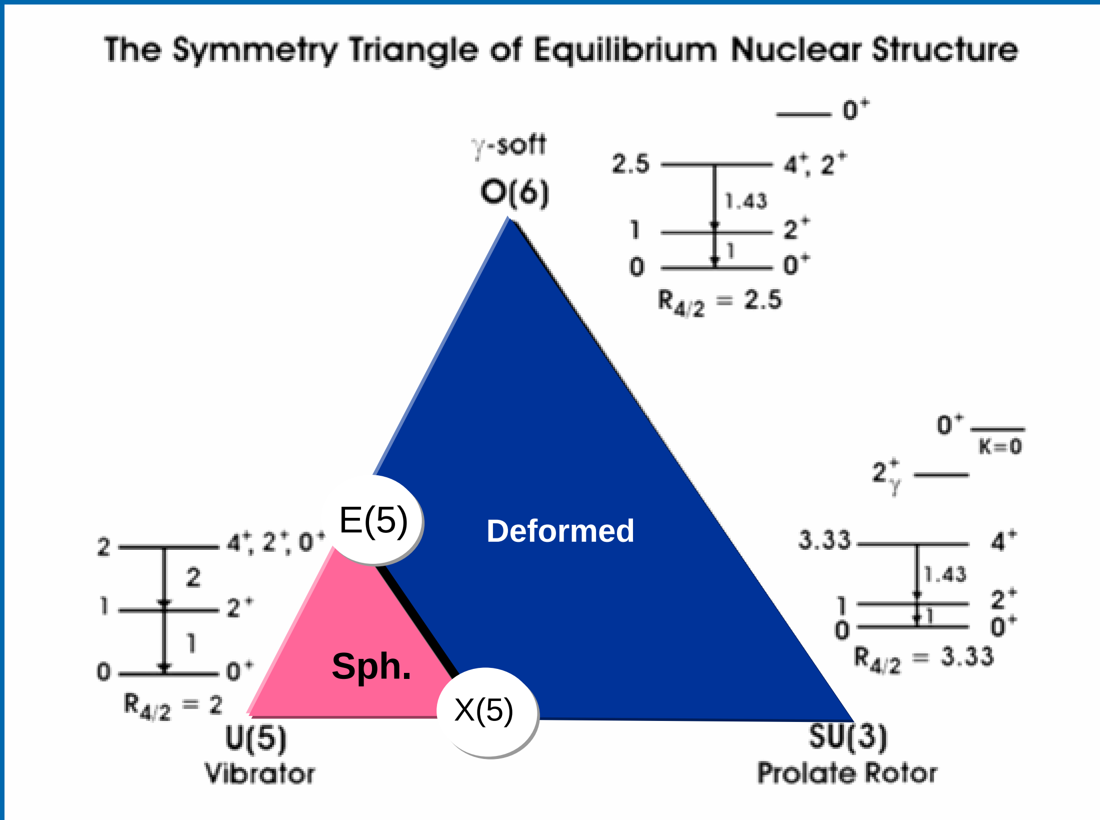
N^{3}LO V$_{lowk}$ (λ=1.9 fm^{-1})

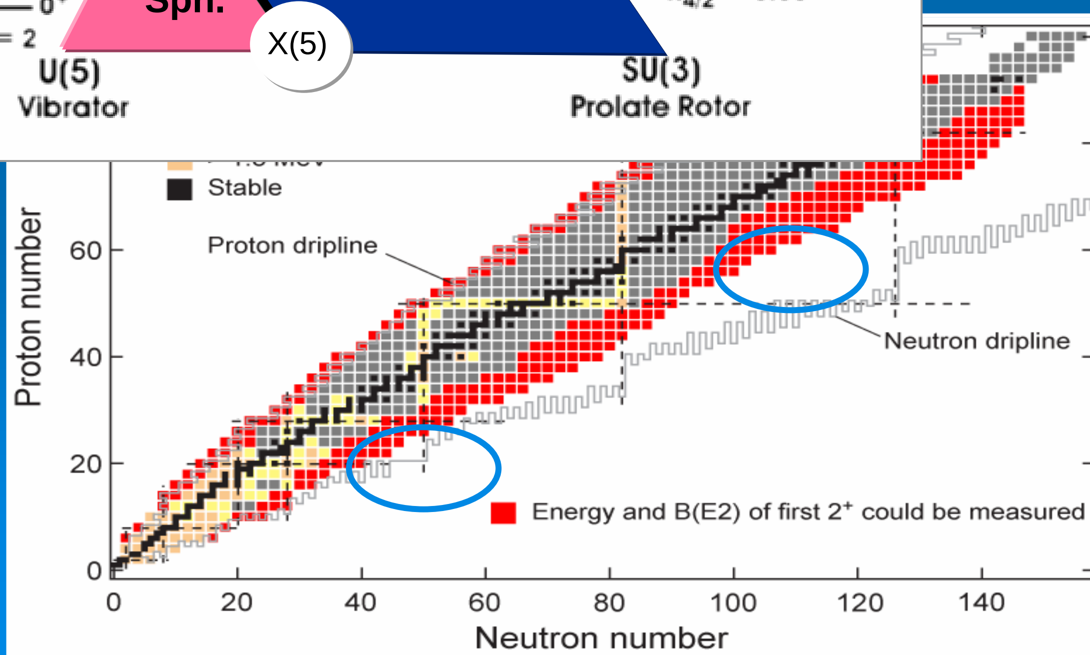
Challenge: include 3-body force

Single-particle basis includes bound, resonant, non-resonant continuum, and scattering states
ENORMOUS SPACES….almost 1k orbitals.
10^{22} many-body basis states in ^{10}He



Symmetries in the many-body system



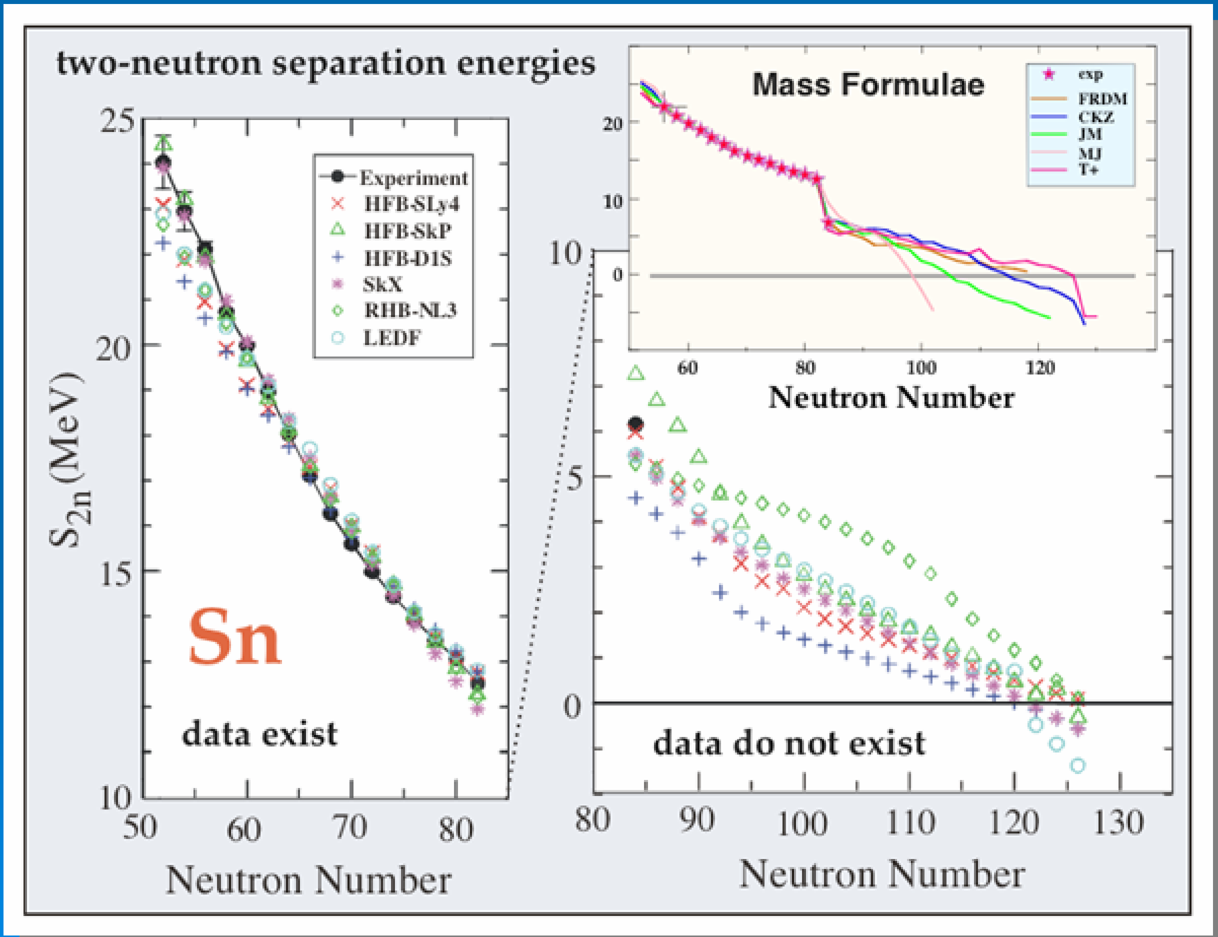


Key 'new' benchmark quantities are in reach with FRIB

Many other programs are needed. Scattering experiments will allow the fission barrier mass surface to be studied.

To the extremes

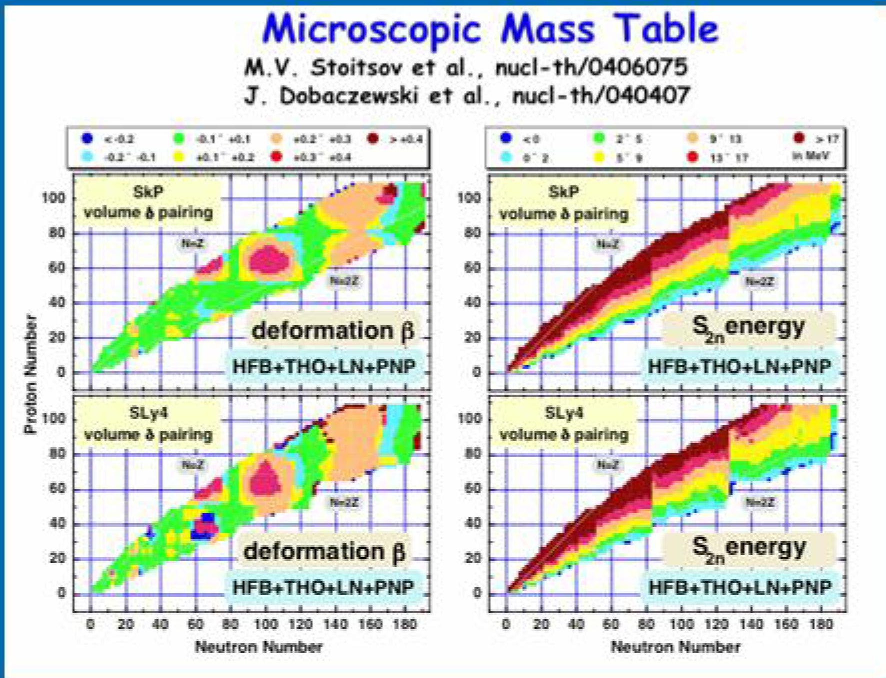
Step 3: Develop predictive density-functional theory for nuclei and nuclear matter. (FRIB will have the furthest reach)

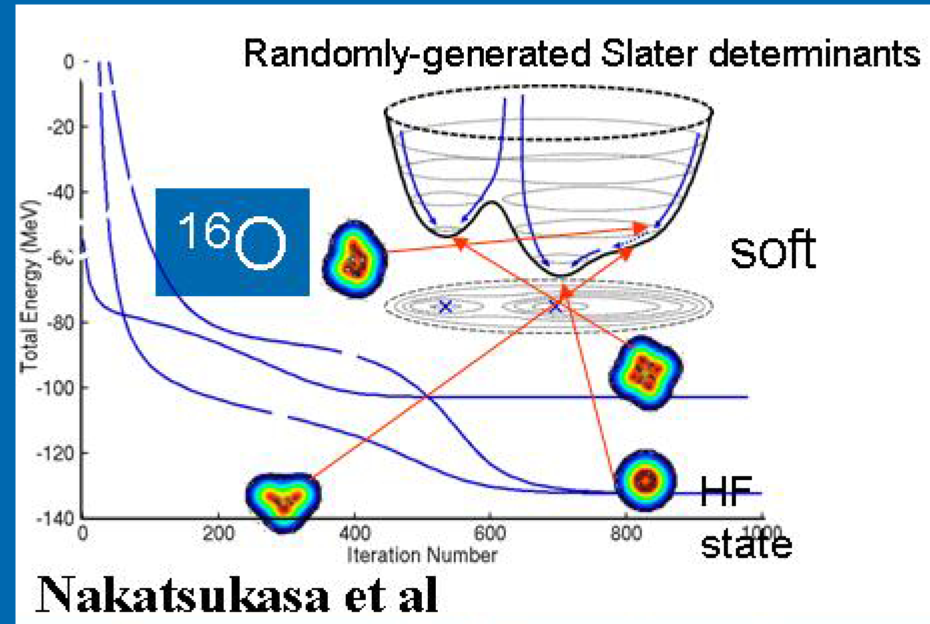


Data on masses and other properties (radii, deformation, etc.) of rare isotopes are critical for:

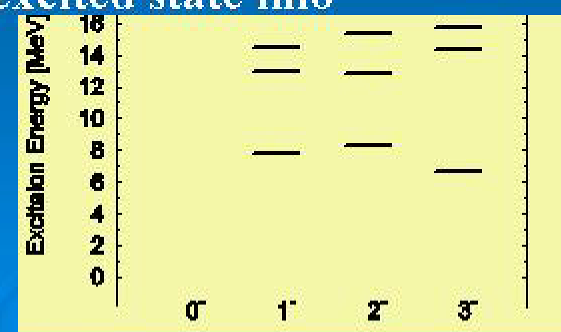
- testing models
- fixing parameters
- defining terms in nuclear energy density functional.

DFT: toward a universal energy density functional and beyond





- Generate multiple Slater determinants
- Project
- Diagonalize norm matrix
- obtain excited state info



Compares nicely with expt.

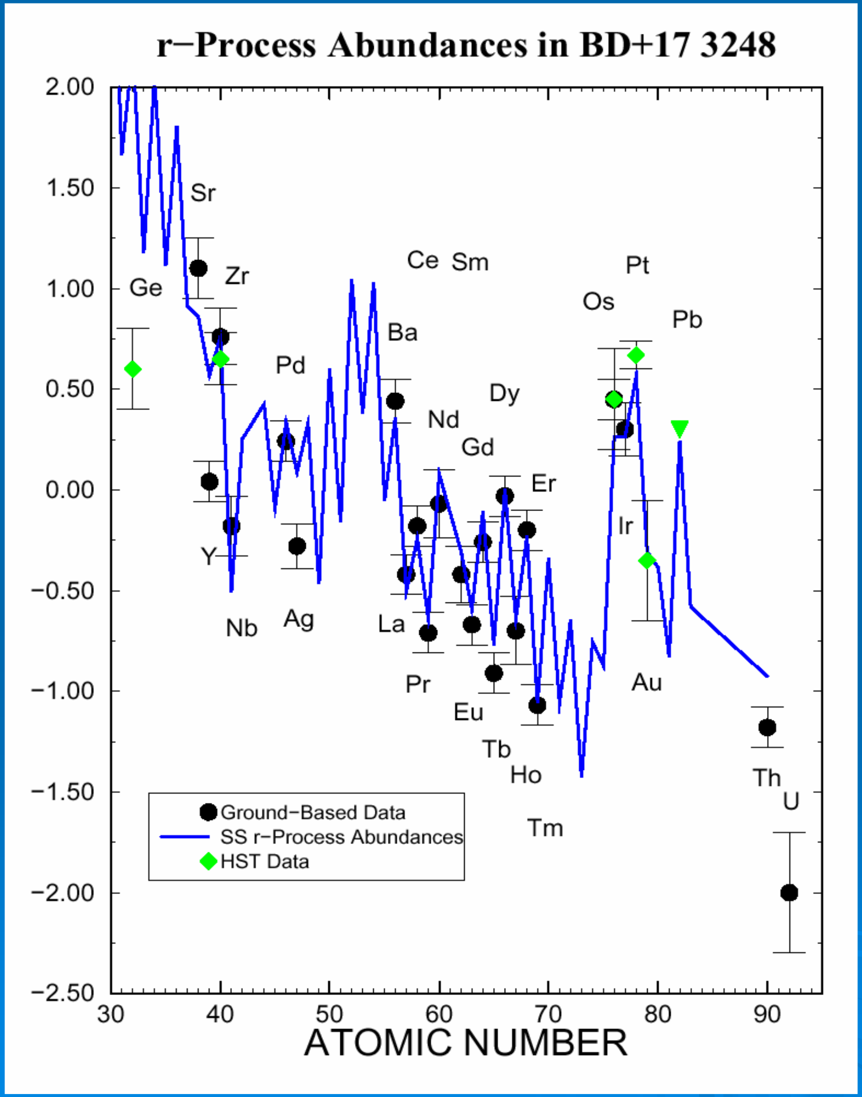
Deformed Mass Table

- HFB mass formula: $\Delta m \sim 700$keV
- Good agreement for mass differences

Challenges:

- Connection to QCD via EFT?
- 300 keV accuracy with one density functional?
- Justify excited state DFT

Study of the oldest stars – pure r-process abundances?



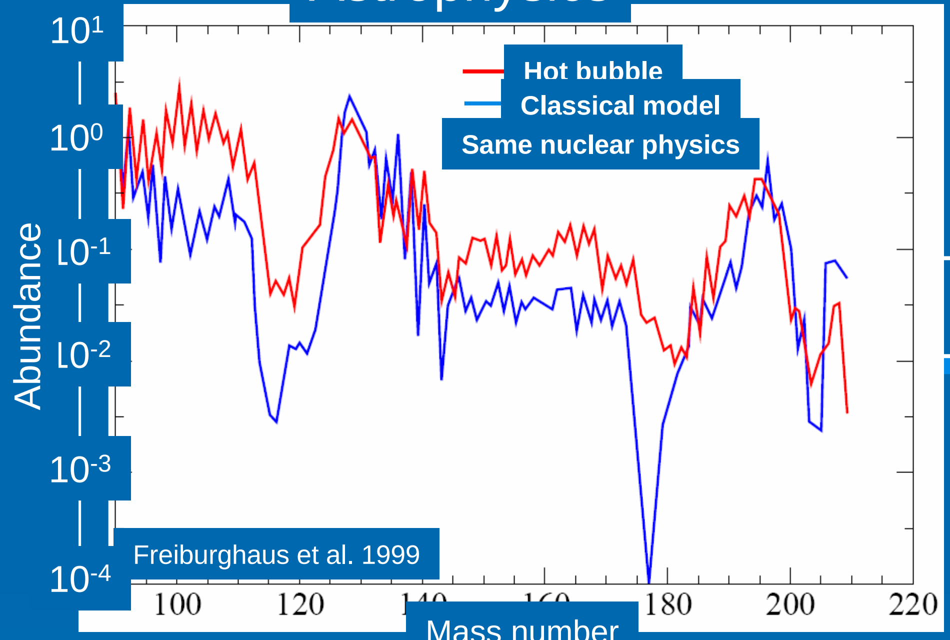
[Fe/H] < -3 dex (0.1% metal abundance of the Sun)
J. Cowen *et al.*

Stars born in early universe (measured by Subaru, HST and KECK telescopes) match Solar r-process element distributions for heavier elements.

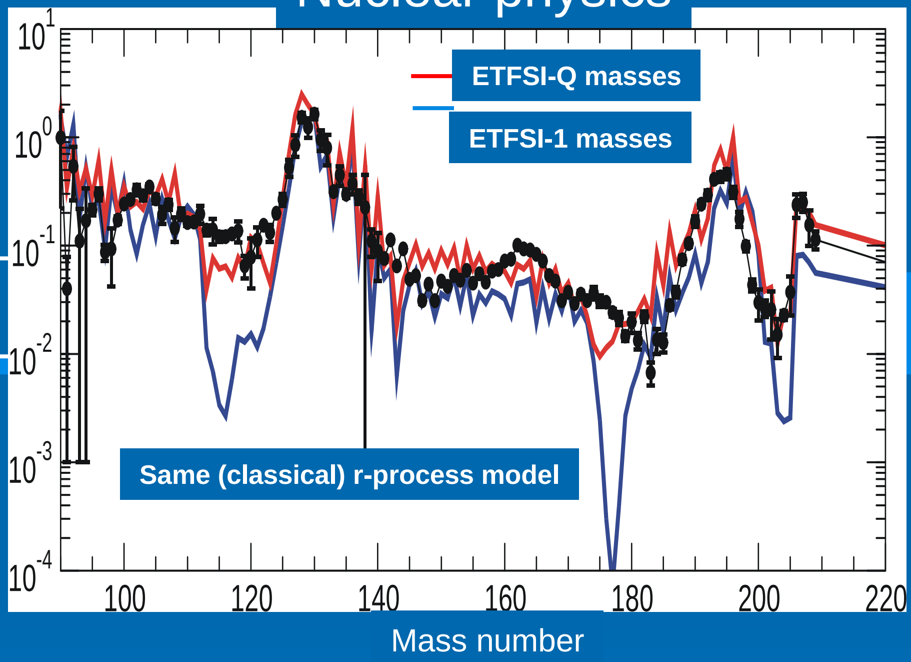
The Uranium and Thorium abundance date the age of the star.

Uncertainties between models and nuclear properties

Astrophysics



Nuclear physics



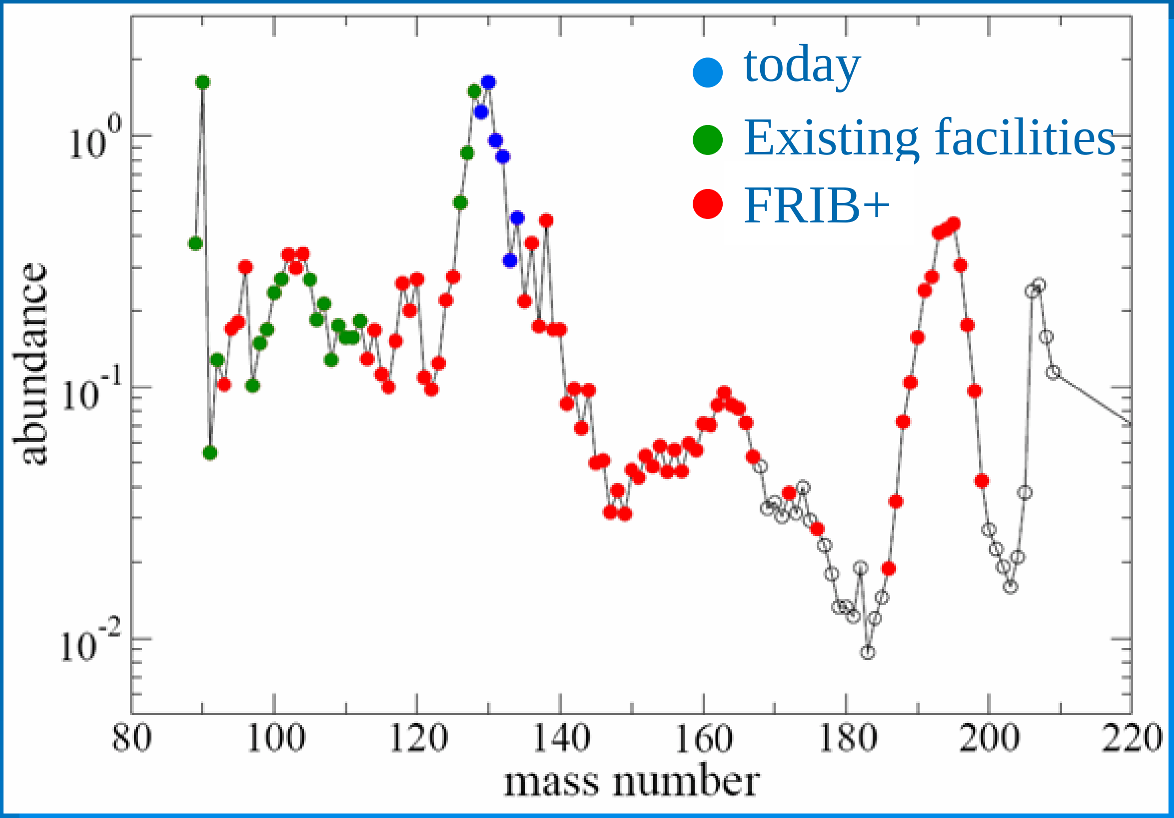
Pinning down the nuclear properties opens the door to constrain the astrophysical models, including the possible site.

Solar system r-process abundance pattern

<u>A next generation exotic beam facility will allow one to:</u>

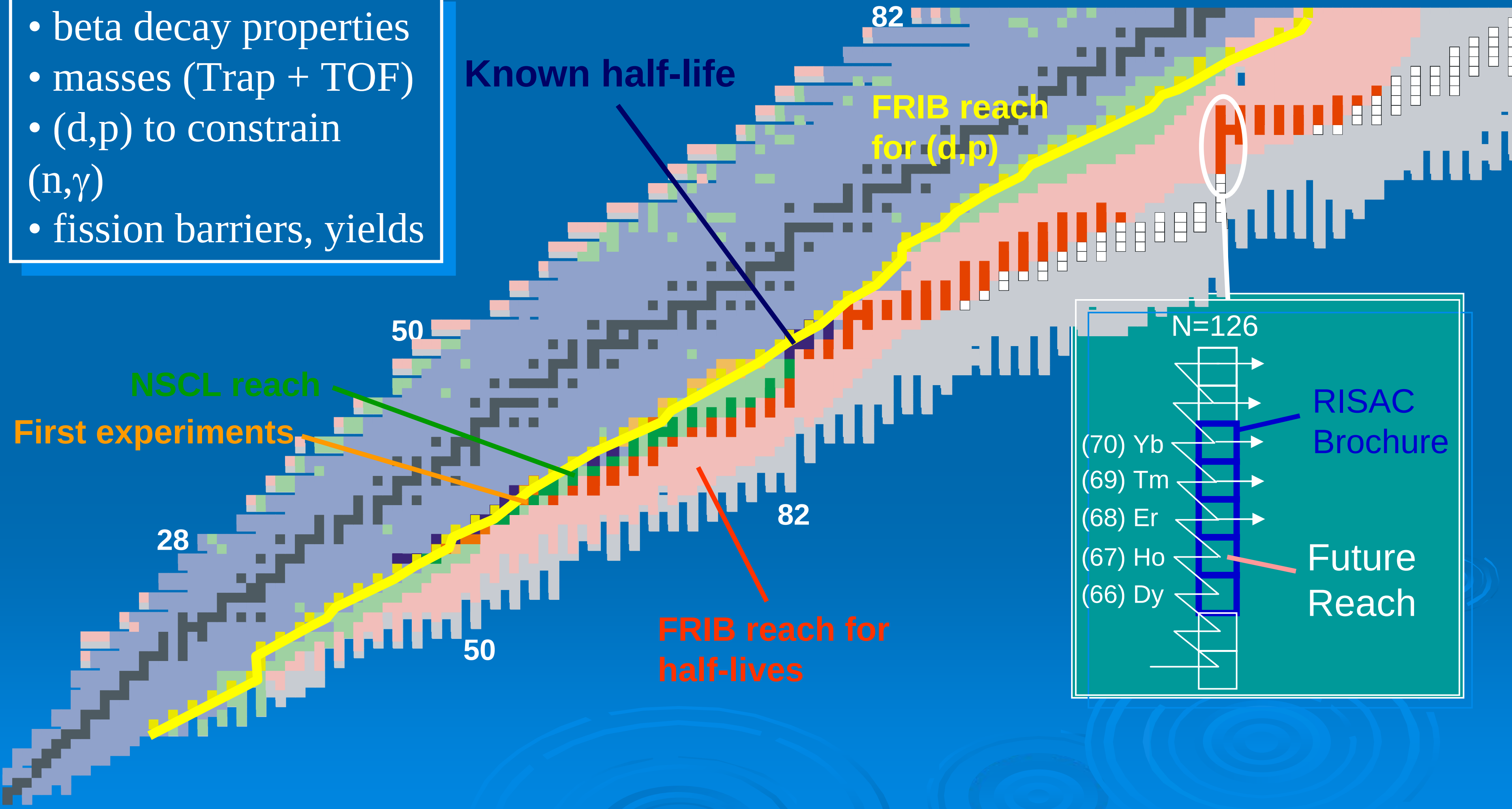
•constrain r-process theories using abundance data

• extract full information about r-process (and its environment) from observational data

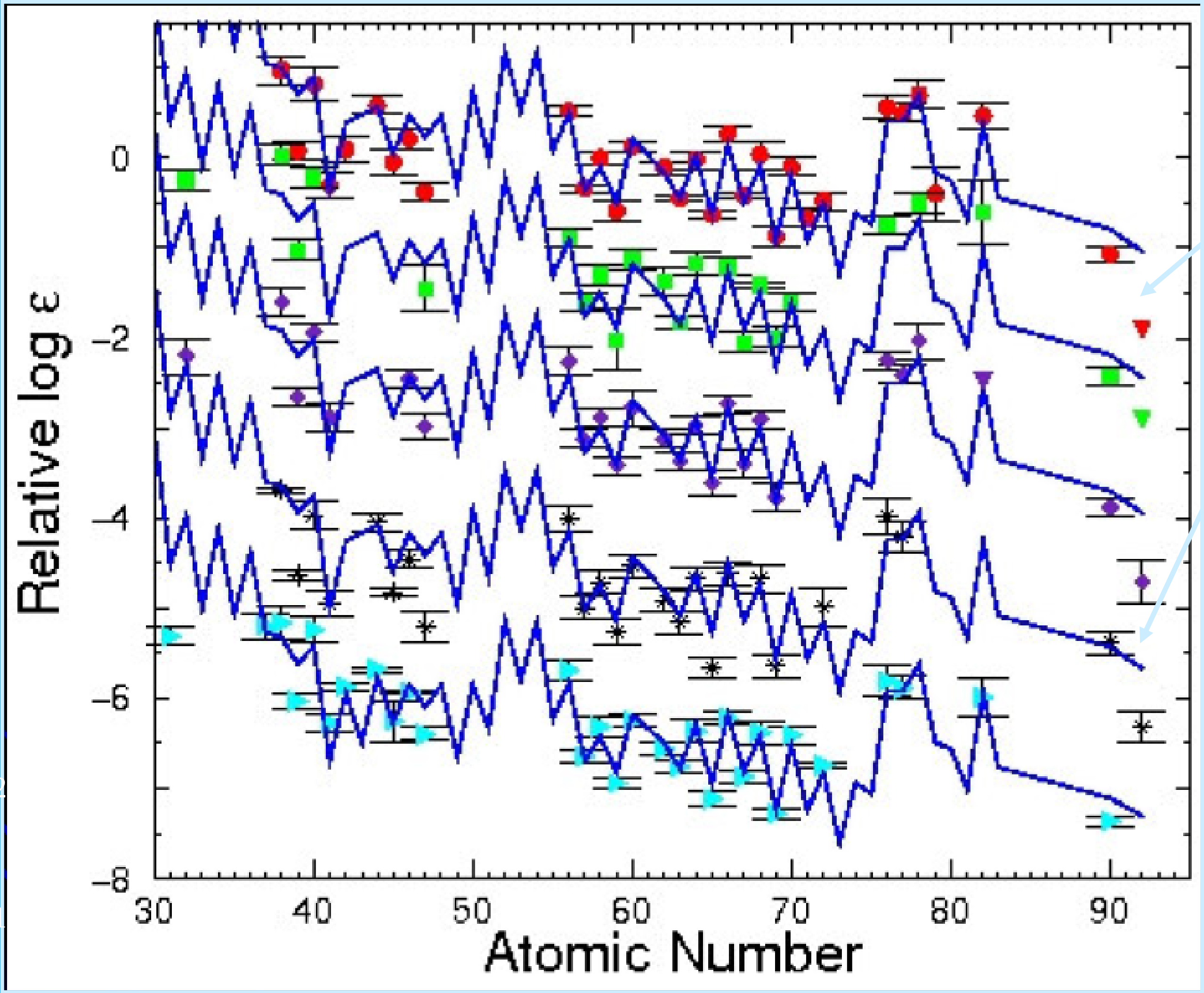


Reach of FRIB

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



Consistency of heavy-element abundances



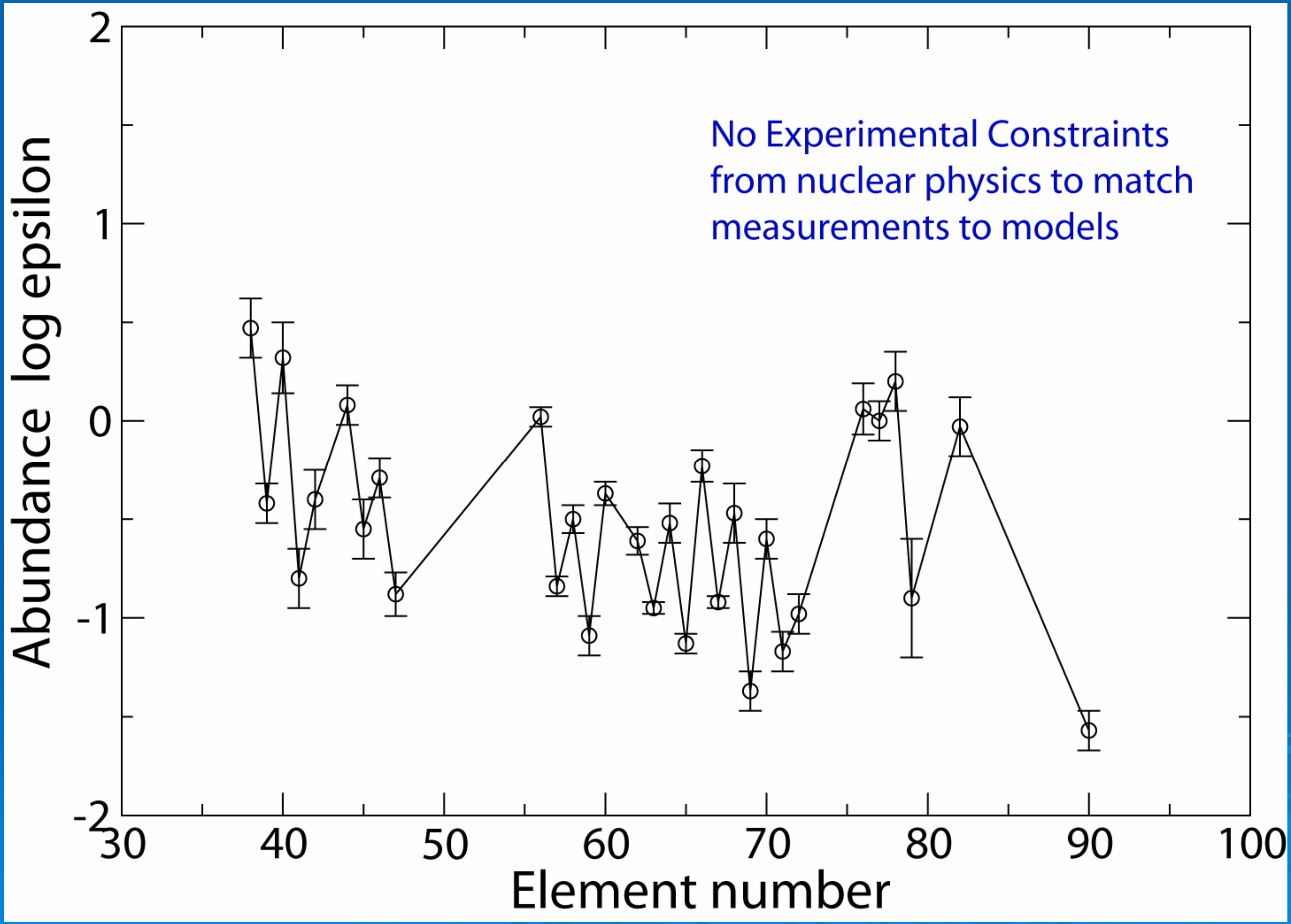
CS 22892-052
HD 115444
BD +17 3248
CS 31082-001
HD 221170

Age?

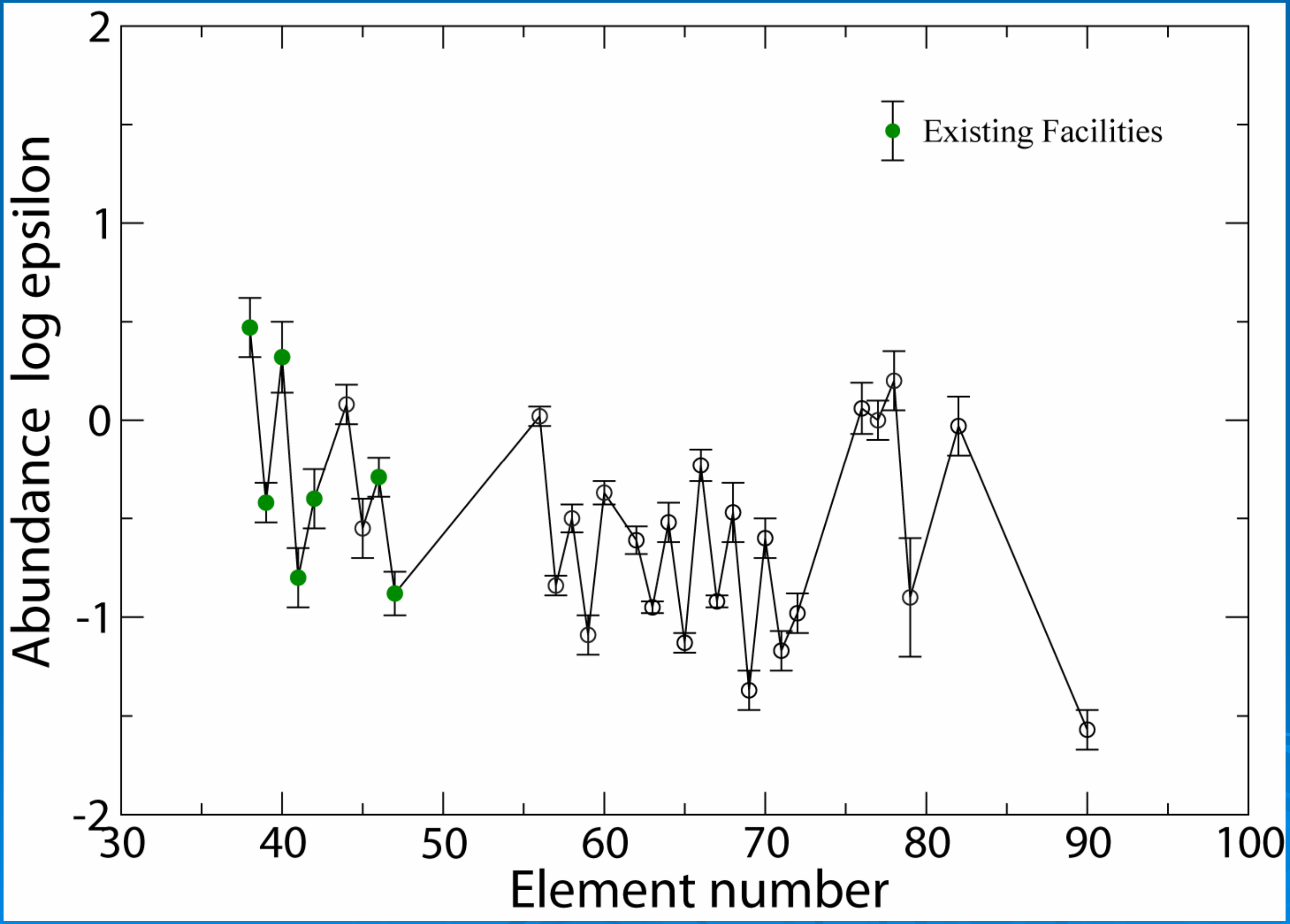
Halo Stars

Cowan and Sneden (2006)

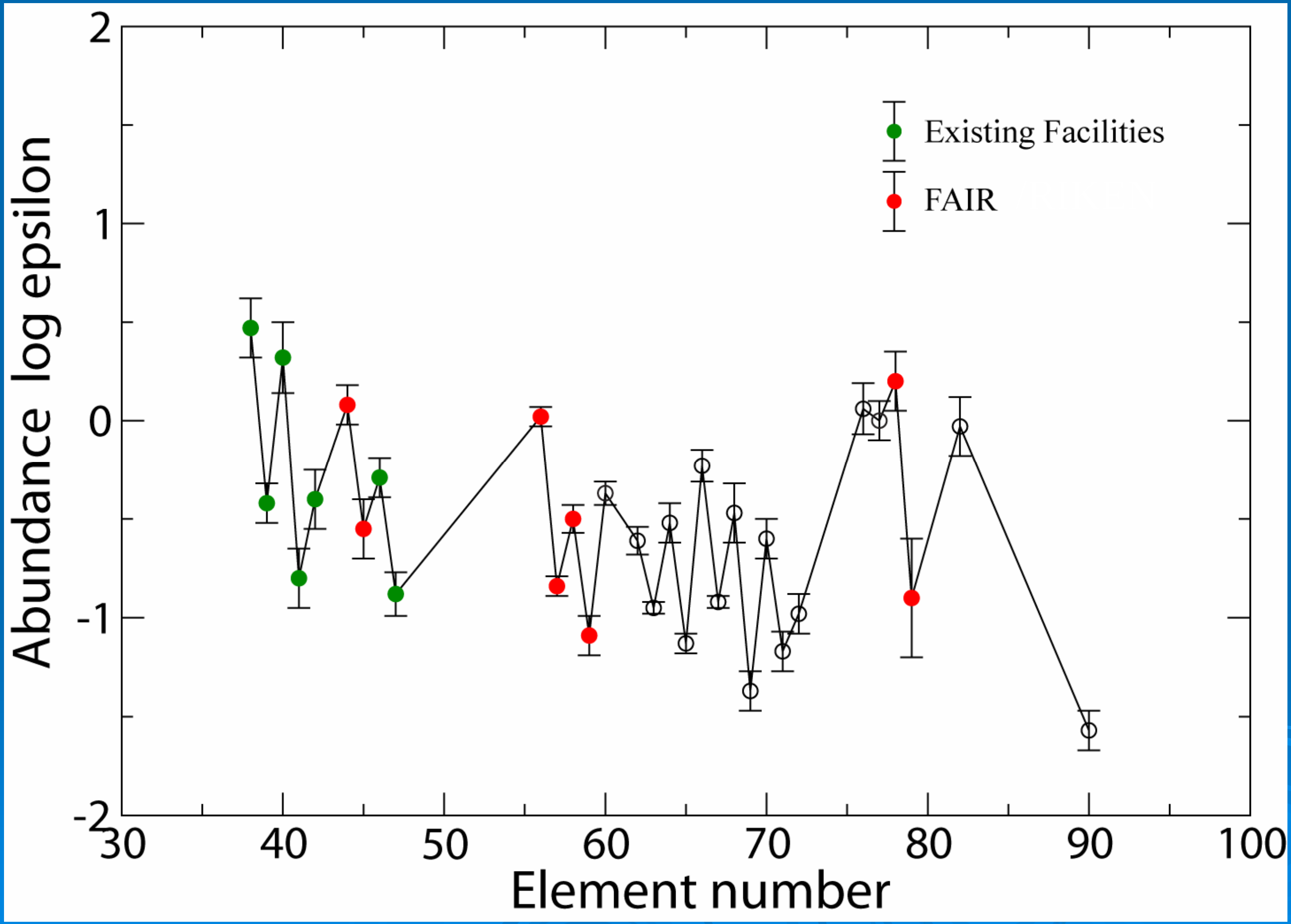
Constraints on elemental abundances: NOW



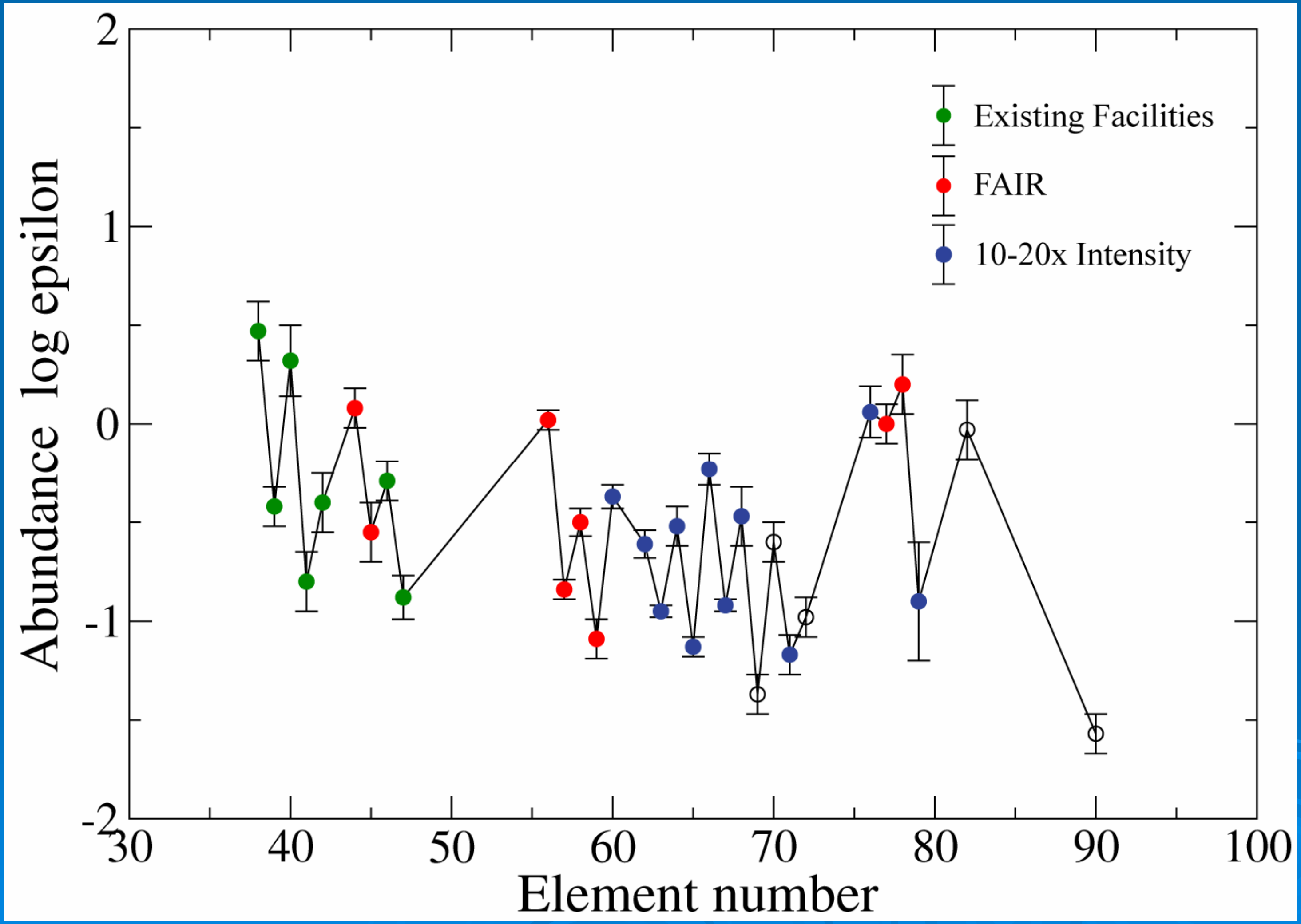
Constraints on elemental abundances



Constraints on elemental abundances



Constraints on elemental abundances



Conclusions and perspectives

- The quantum many-body problem is everywhere; its solution is one of the great intellectual challenges of our day (major international efforts)
  - The goal is a predictive theory for nuclei
- FRIB will be the most powerful machine of its kind to illucidate

  the physics of nuclei and those properties relevant to nuclear astrophysics
- Exciting physics in the neutron rich regime
  - Continuum physics (halos & skins, resonances)
  - Changes in shell structure
  - Astrophysical connections (e-capture, r-process…)
  - Simple patterns in complex nuclei
- Major benefit from computational sciences!!

- New data will help define Nuclear Energy Density Functional
- Various applications including reaction theory on heavy nuclei

- International collaborations essential