Ecole Internationale Joliot Curie: New Avenues with Radioactive Ion Beams Lecture 2

September, 2011

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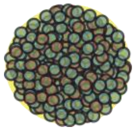
U.S. DEPARTMENT OF ENERGY

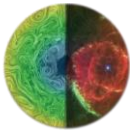
Office of Science

Broad Overview of Rare Isotope Science



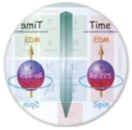
Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Understand the origins of the nuclear force in terms of QCD
- Many-body quantum science: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.



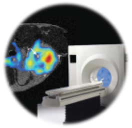
Astrophysical processes

- Chemical history of the universe; use this for stellar archaeology
- Model explosive environments
- Properties of neutron stars, EOS of asymmetric nuclear matter



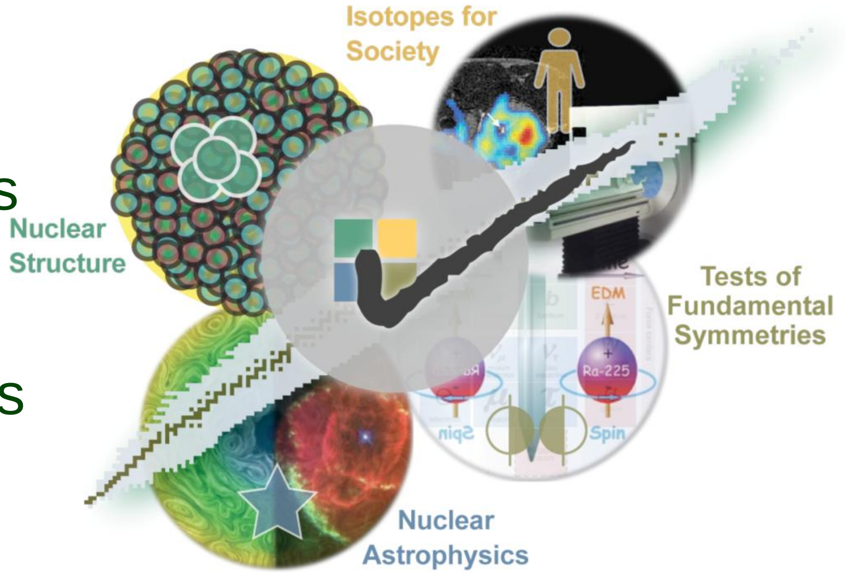
Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei

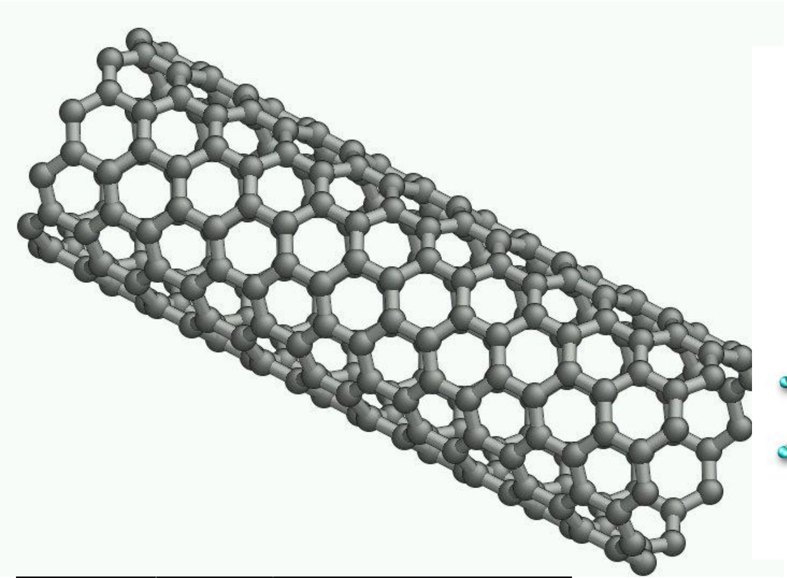


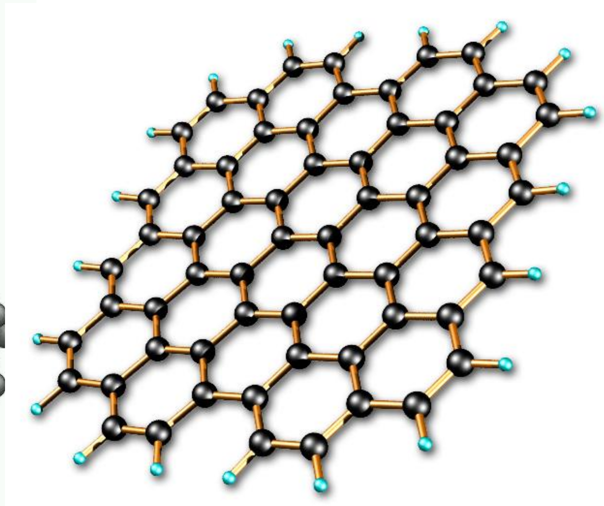
Societal applications and benefits

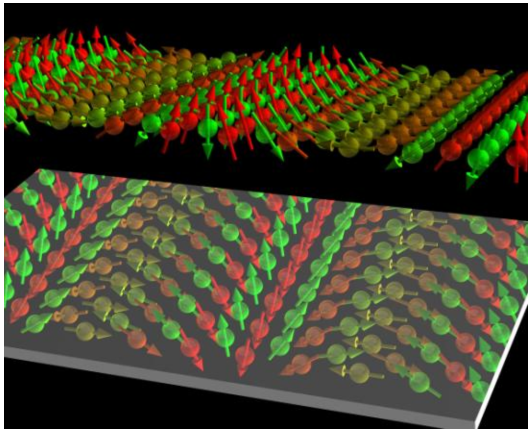
- Biology, medicine, energy, material sciences, national security

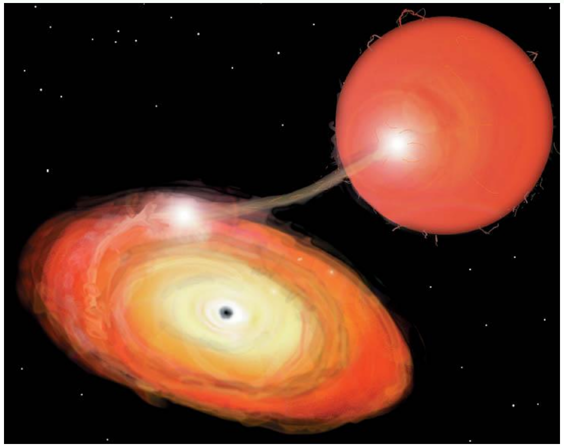


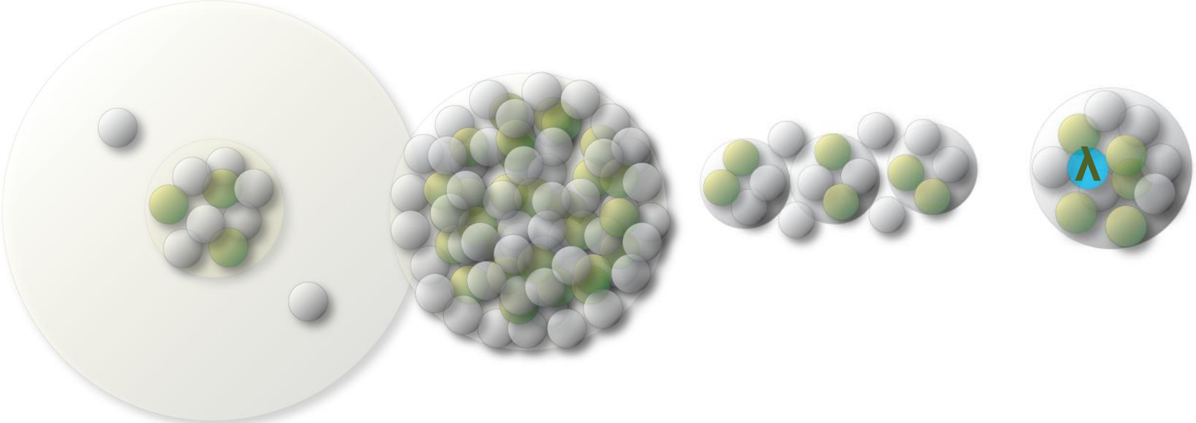
New Frontiers in Science -
Novel Quantum Structures











This Talk – novel quantum structures in atomic nuclei

FRIB specialty – Produce new exotic isotopes

- Large neutron skins
- Modified mean field

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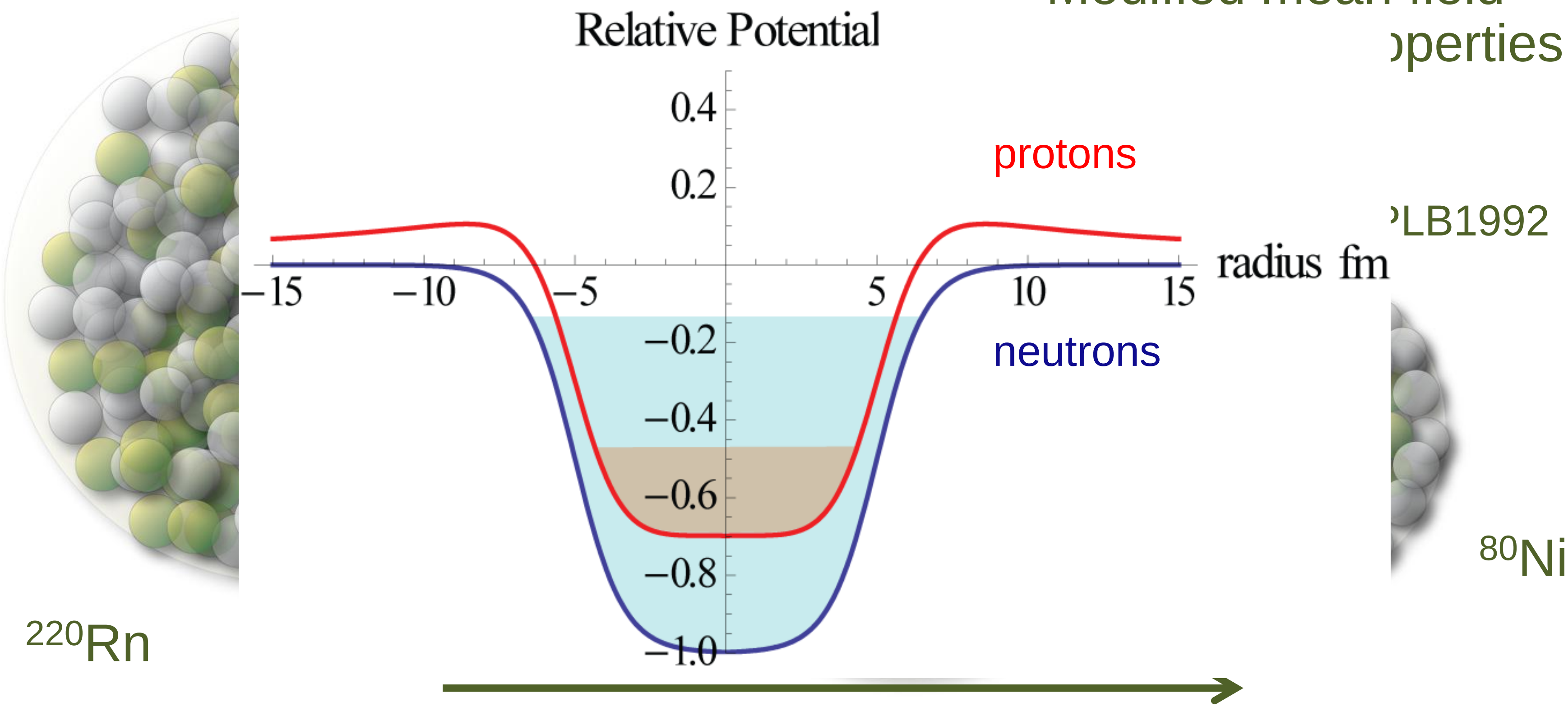
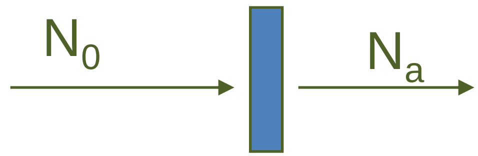
LB1992



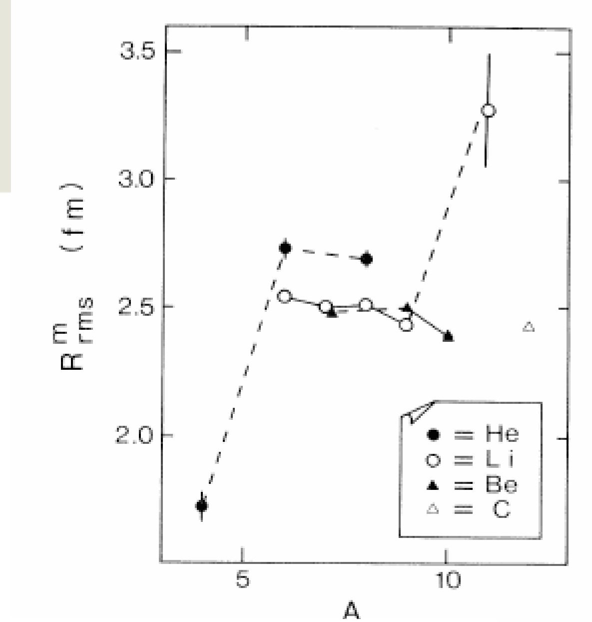
<u>Science:</u> Pairing in low-density material, new tests of nuclear models, open quantum system, interaction with continuum states - Efimov States - Reactions

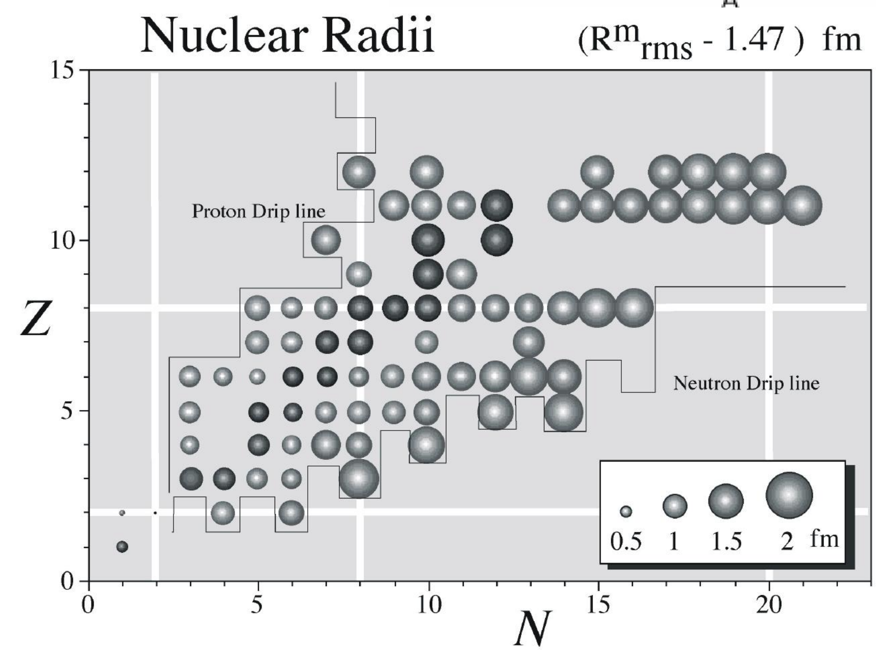
Experimental "Discovery" of Halos

- Evidence for the size of ^{11}Li was found from total interaction cross section measurements (Tanihata PRL1985)
- One of the first thing we learn about nuclei is that Nuclear radii follow the formula: $r = r_0 A^{1/3}$ (Equation 1.2 Wong *Introductory Nuclear Physics*)
- This is incorrect



$$\sigma_{interaction} = -\mu \ln(N_a/N_0)$$

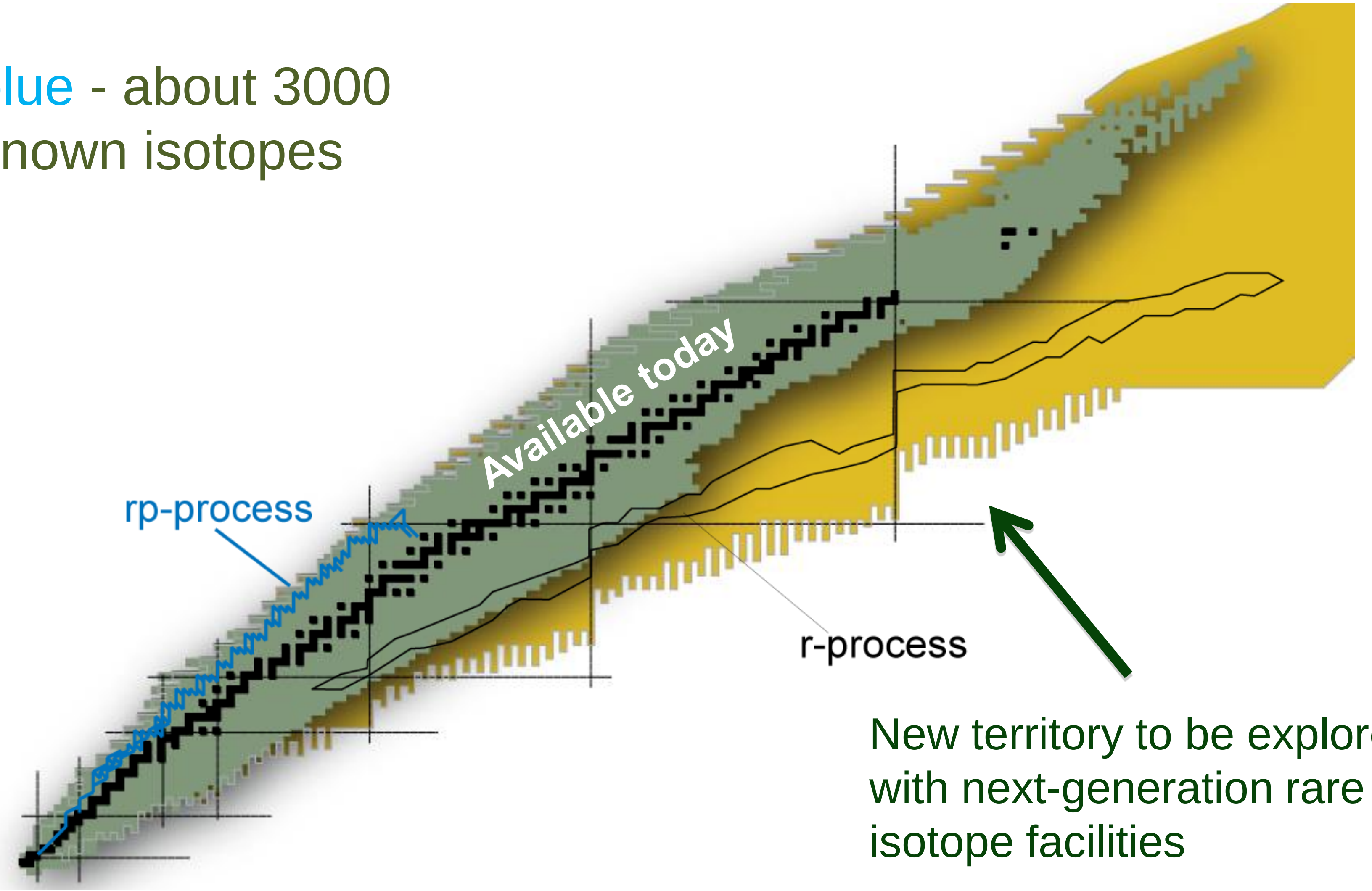




I. Tanihata, OSAKA

The Availability of Rare Isotopes

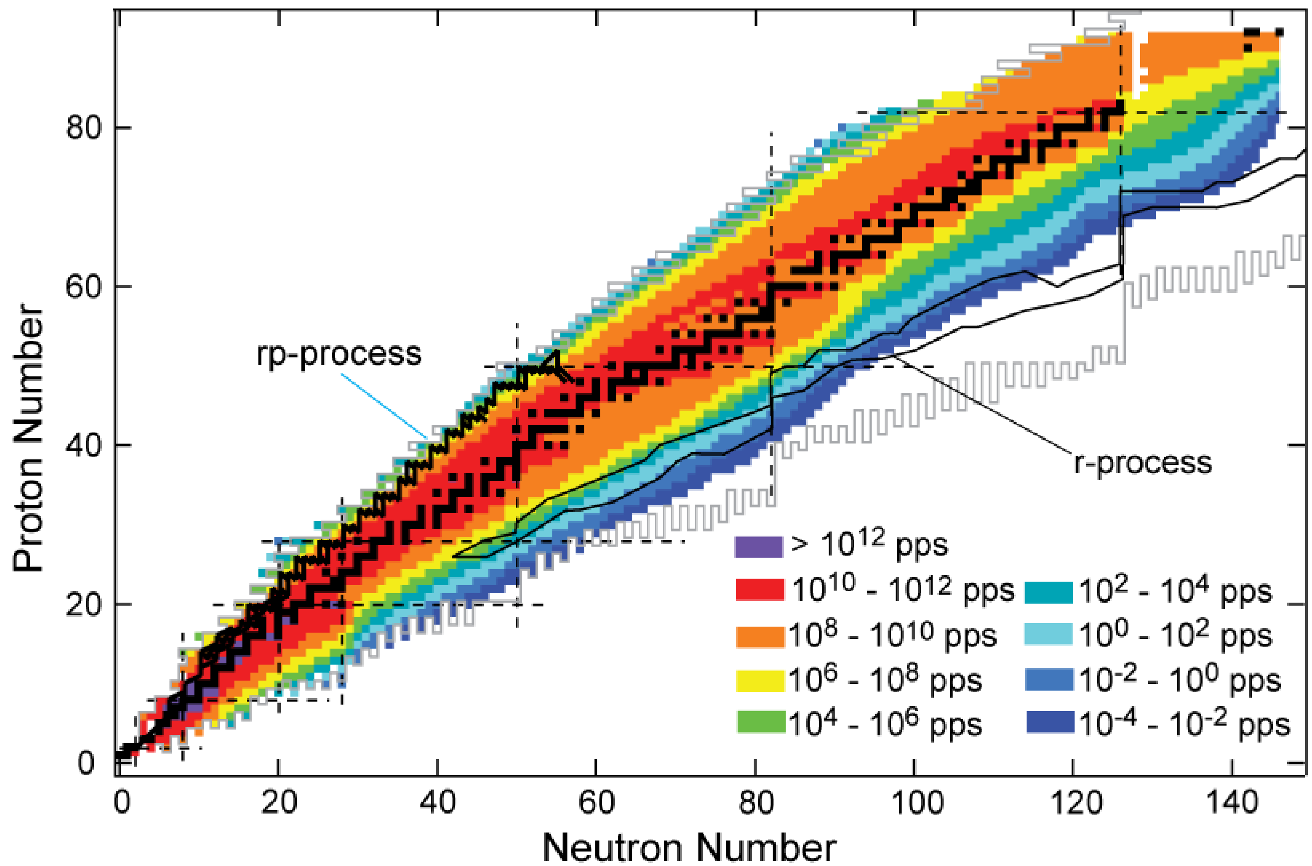
blue - about 3000 known isotopes



New territory to be explored with next-generation rare isotope facilities

The Reach of Modern Isotope Production Facilities

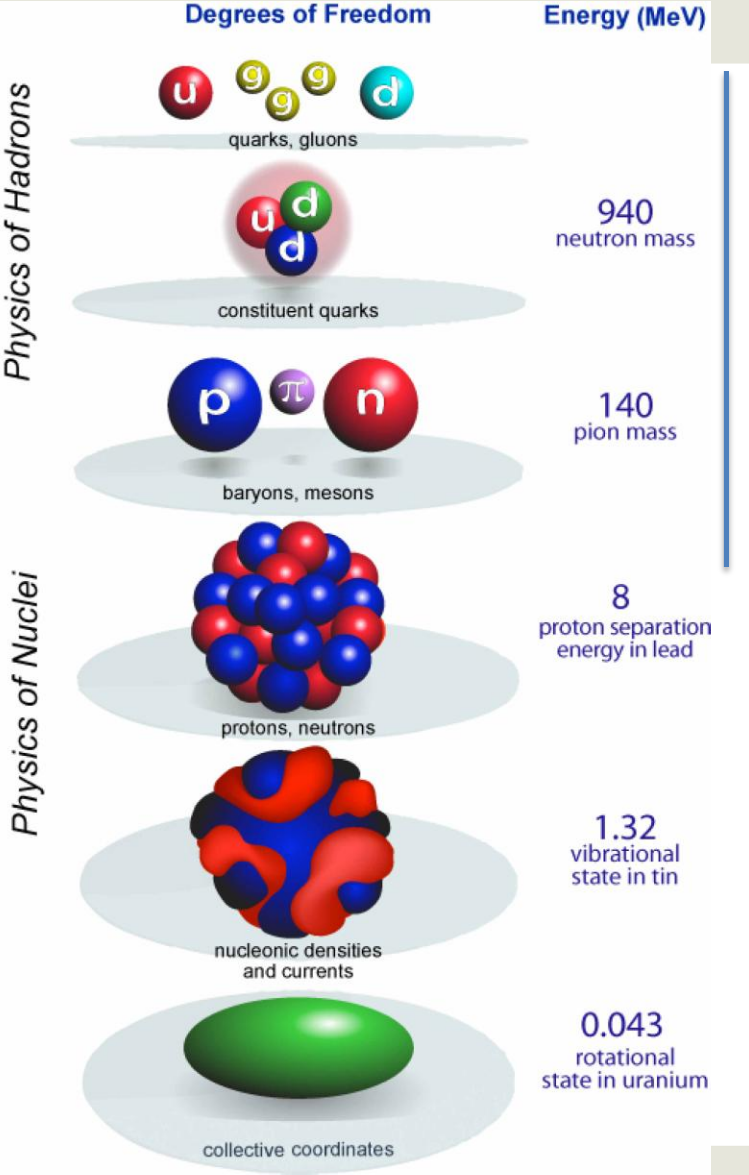
- Next generation facilities will produce more than 1000 NEW isotopes at useful rates (5000 available for study; compared to 1700 now)
- Exciting prospects for study of nuclei along the drip line to A=120(compared to A=24)
- Production of most of the key nuclei for astrophysical modeling
- Theory is key to making the right measurements and interpreting them



Rates are available at http://groups.nscl.msu.edu/frib/rates/

A Challenge for Nuclear Science

- We want to model physical phenomena that are the result of the strong force
- This includes understanding atomic nuclei, hadrons, QGP, …
- We have made remarkable progress in modeling hadrons – Nobel prize in 2004 Gross, Politzer, Wilczek ; LQCD calculation of nucleon and meson masses (Dürr, Fodor, Lippert et al., Science 322 (2008))
- There is room for significant progress in understanding atomic nuclei
- Illustration from David Dean



JPARC
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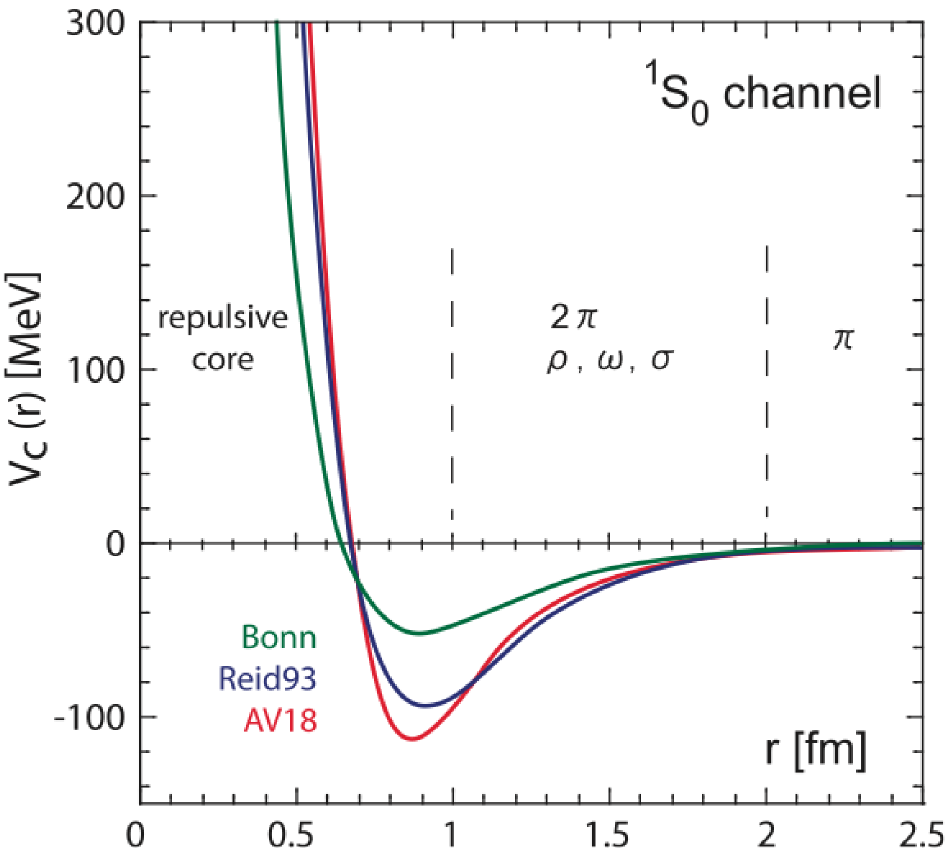
How do we model nuclei? One approach, start with NN forces

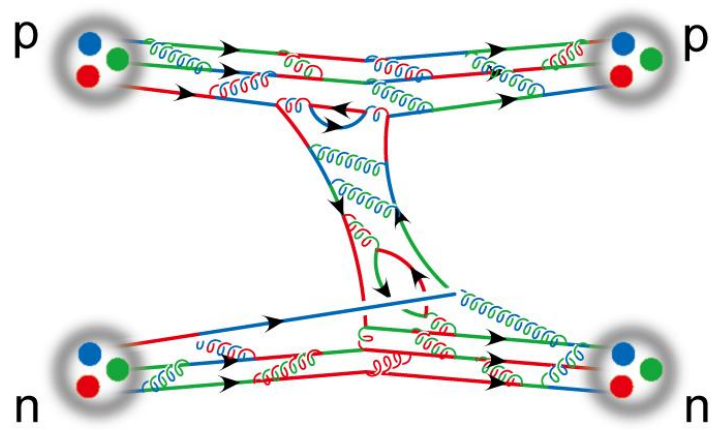
- Approach: Construct NN potentials based on neutron and proton scattering data and properties of light nuclei (Bonn, Reid, Illinois AV18, Nijmegen, etc.)
- More recent approach is to construct the potentials some more fundamental theory
  - QCD Inspired EFT
  - String Theory Inspired – Hashimoto et al
  - Lattice QCD



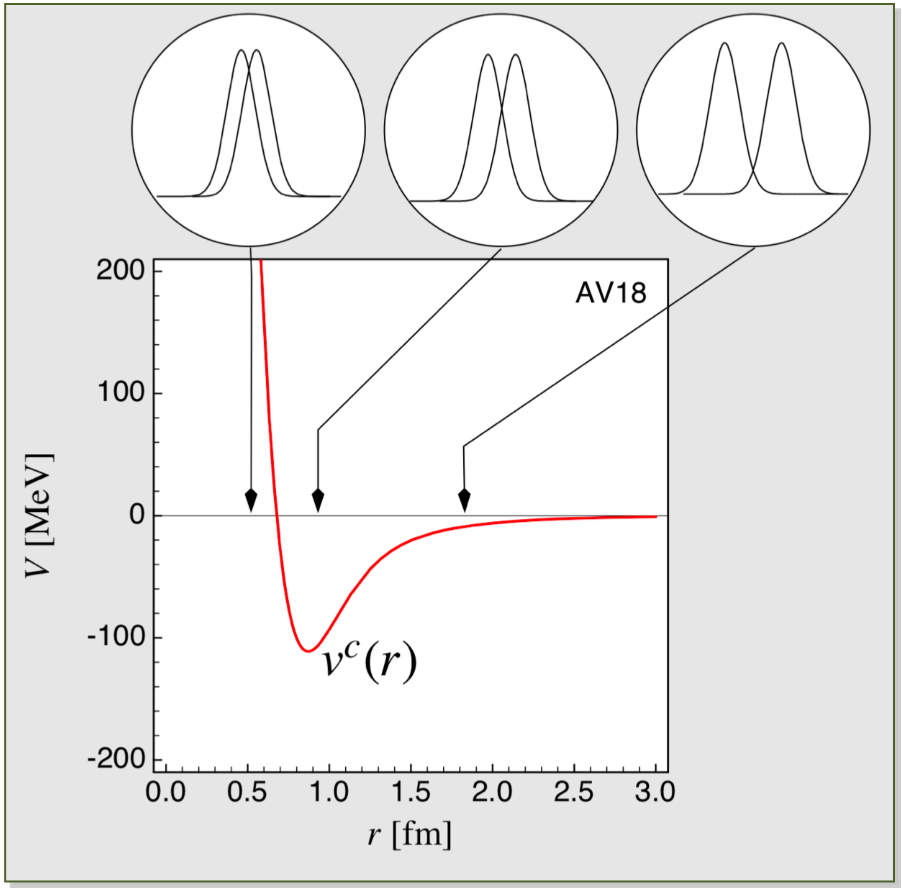
Yukawa 1935

N. Ishii, S. Aoki, and T. Hatsuda, Phys. Rev. Lett. 99, 022001 (2007)

The Nucleon-Nucleon Force



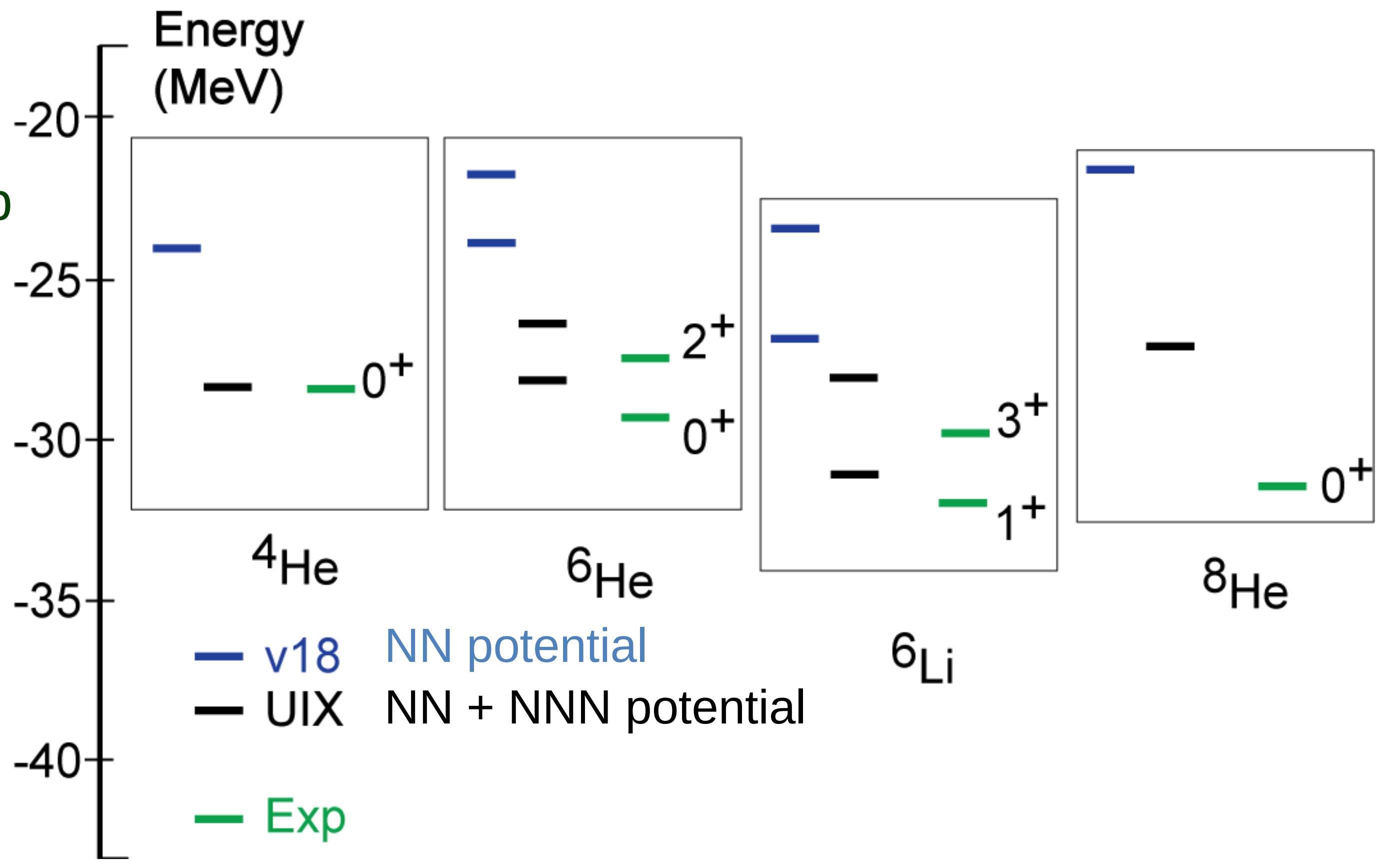
N. Ishii, S. Aoki, T. Hatsuda, Phys. Rev. Lett. **99,** 022001 (2007)



In nuclei even more complications since nucleons have structure and three-body forces are also very important (four-body, …)

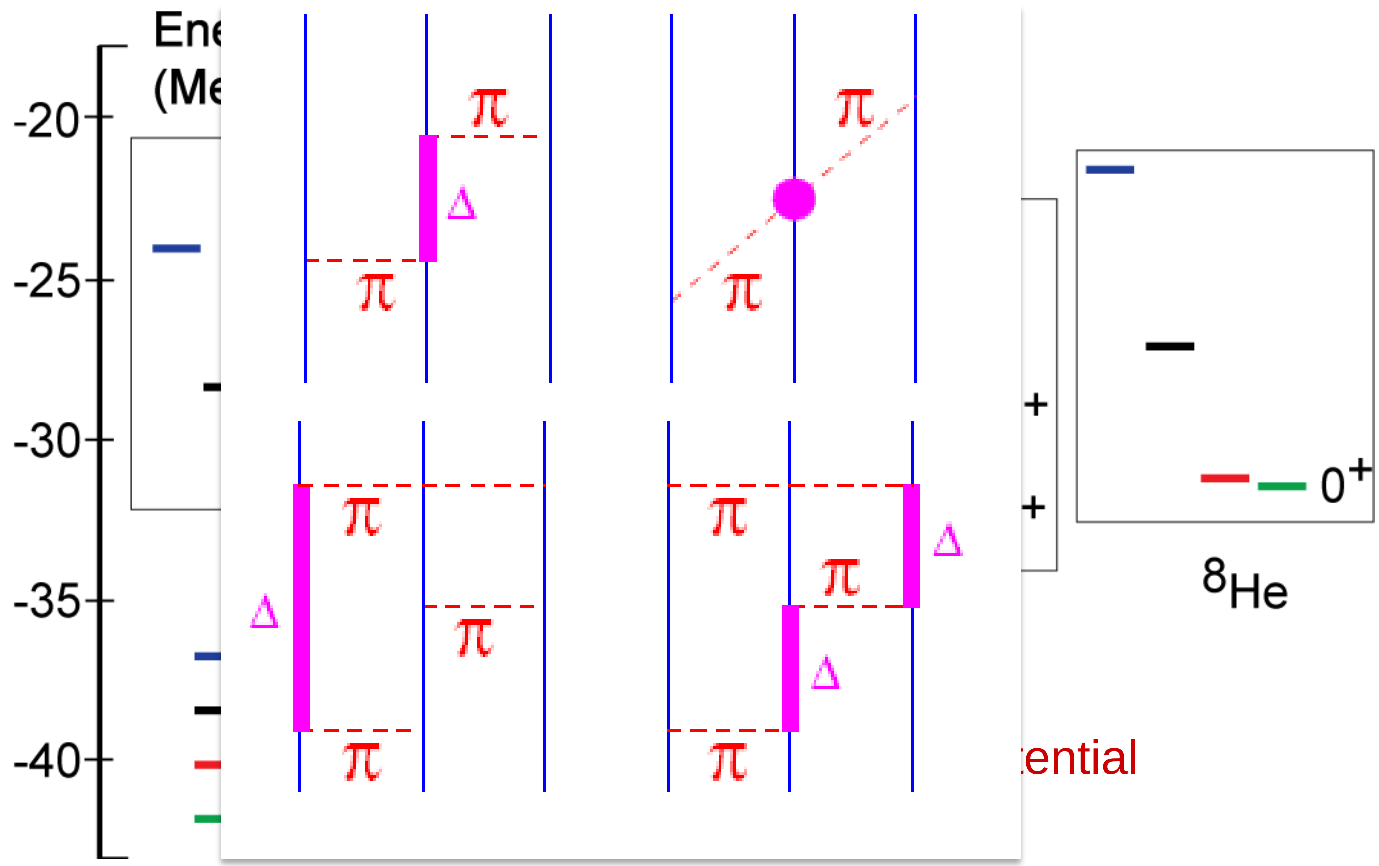
Comparison of Calculated and Measured Binding Energies with NN models

- Greens Function Monte Carlo techniques allow up to mass number 12 to be calculated
- Example blue 2-body forces V_{18}
- S. Pieper B.Wiringa, *et al.*



New information from exotic isotopes

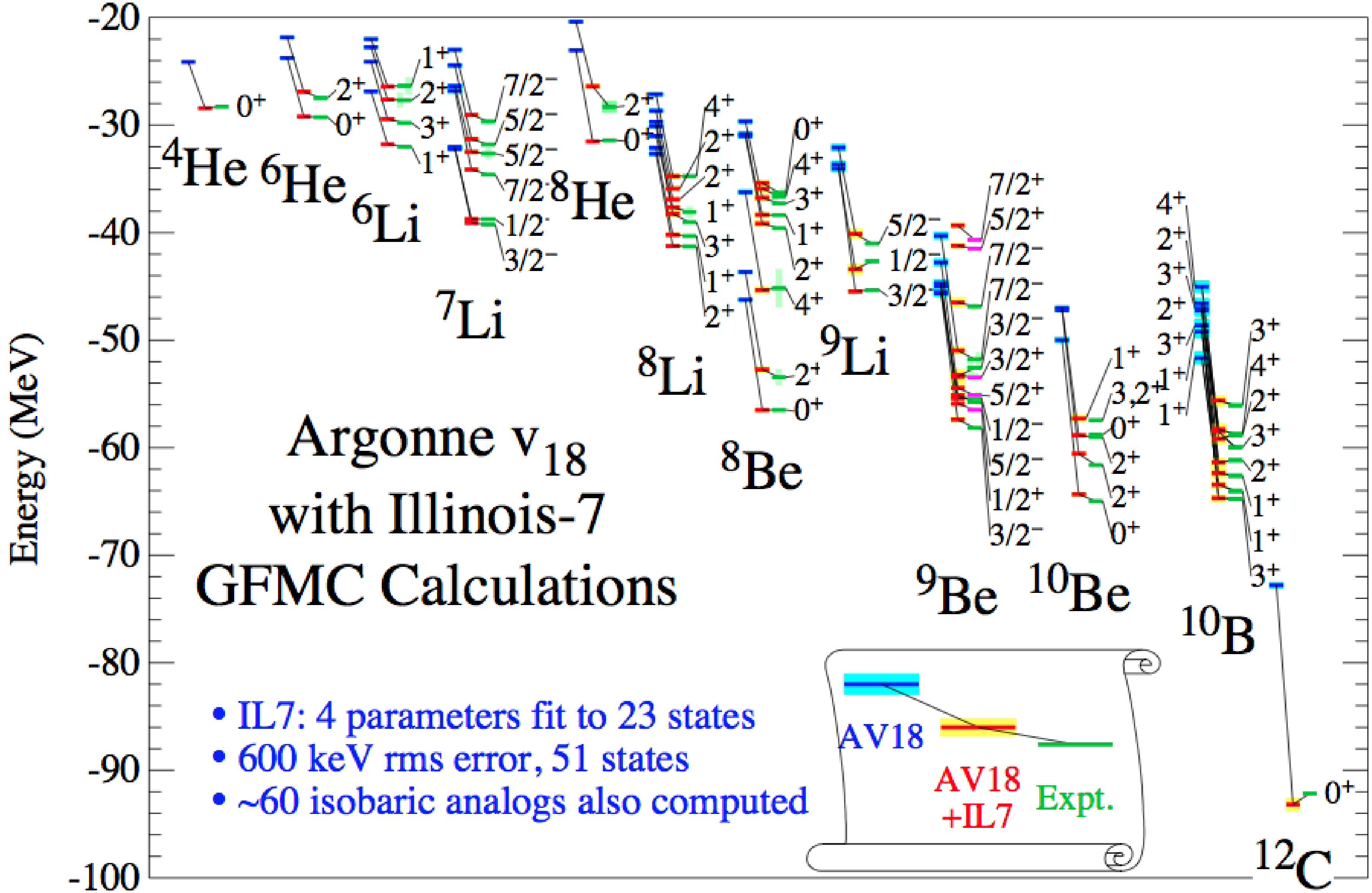
- Neutron rich nuclei were key in determining the isospin dependence of 3-body forces and the development of IL-2R from UIX
- New data on exotic nuclei continues to lead to refinements in the interactions



T. Otsuka *et al.* PRL 2010: NNN force may be the solution to understanding the Oxygen drip line

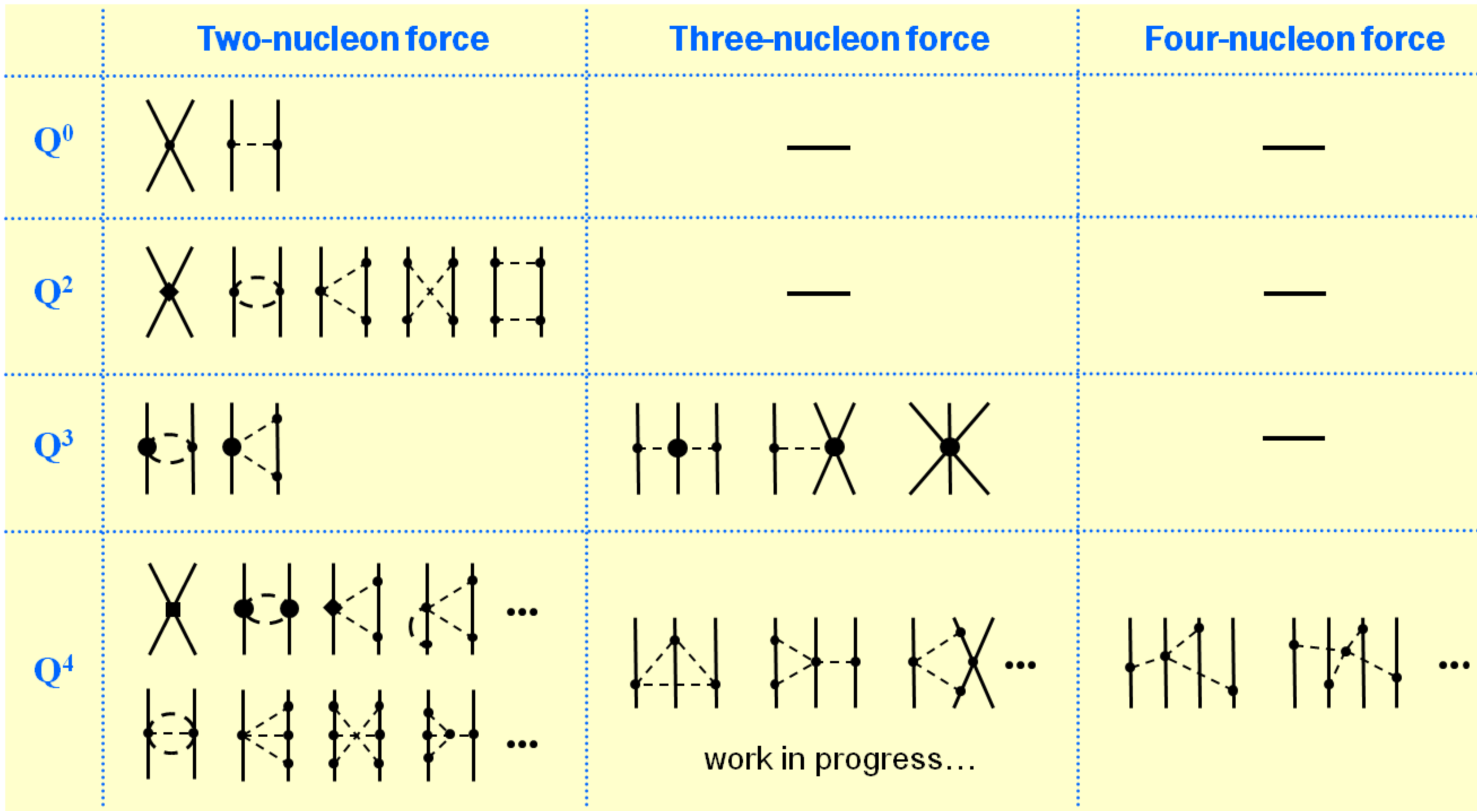
Properties of exotic isotopes are essential in determining NN and NNN potentials

Current status of the GFMC calculations



Next Steps: EFT based on QCD Symmetries – "Chiral"

- Use the features of the pion in constructing an effective theory



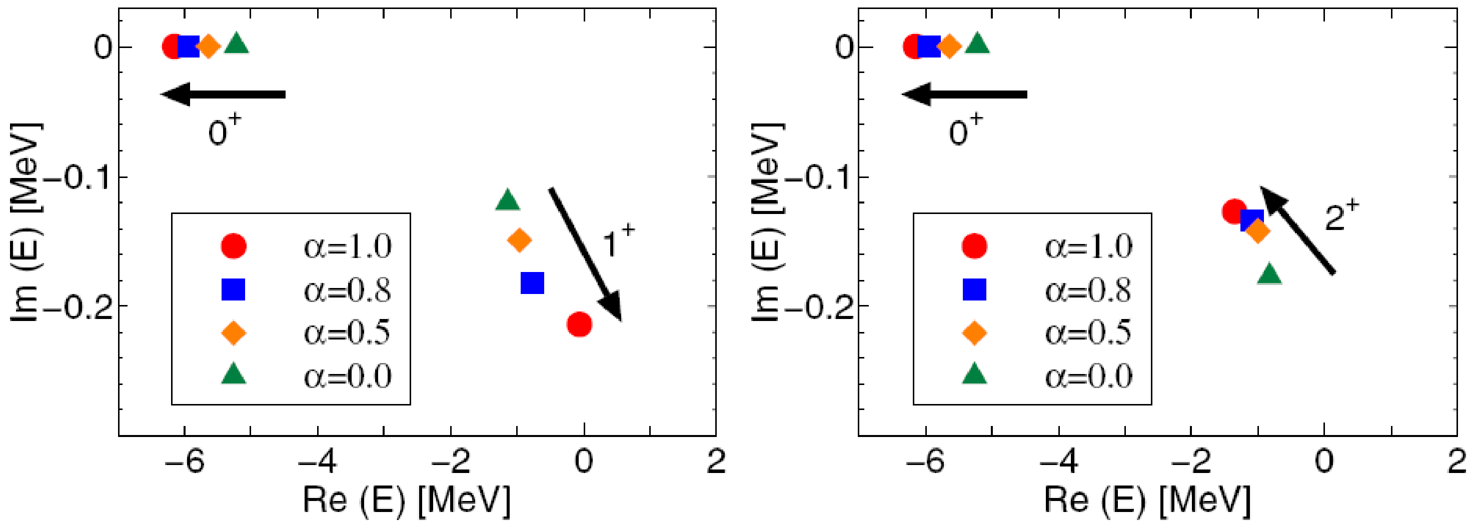
Cut-off parameter $\Lambda \cong 500$ MeV

Contact interactions have constants that are fit to experiment

Effective Field Theory, EFT, based on QCD Symmetries (Epelbaum ,Furnstahl, van Kolck, Navrátil,…)

New Isotopes - Sensitivity of Nuclear Properties to Model Parameters

- Example: Level structure of ^{24}O and the $^1S_0$ NN interaction
- Structure of these loosely bound or unbound isotopes is strongly influenced by the $^1S_0$ component of the NN interaction
- Calculation of ^{24}O in a shell model that correctly treats weakly-bound and continuum states (specifically Gamow Shell Model)



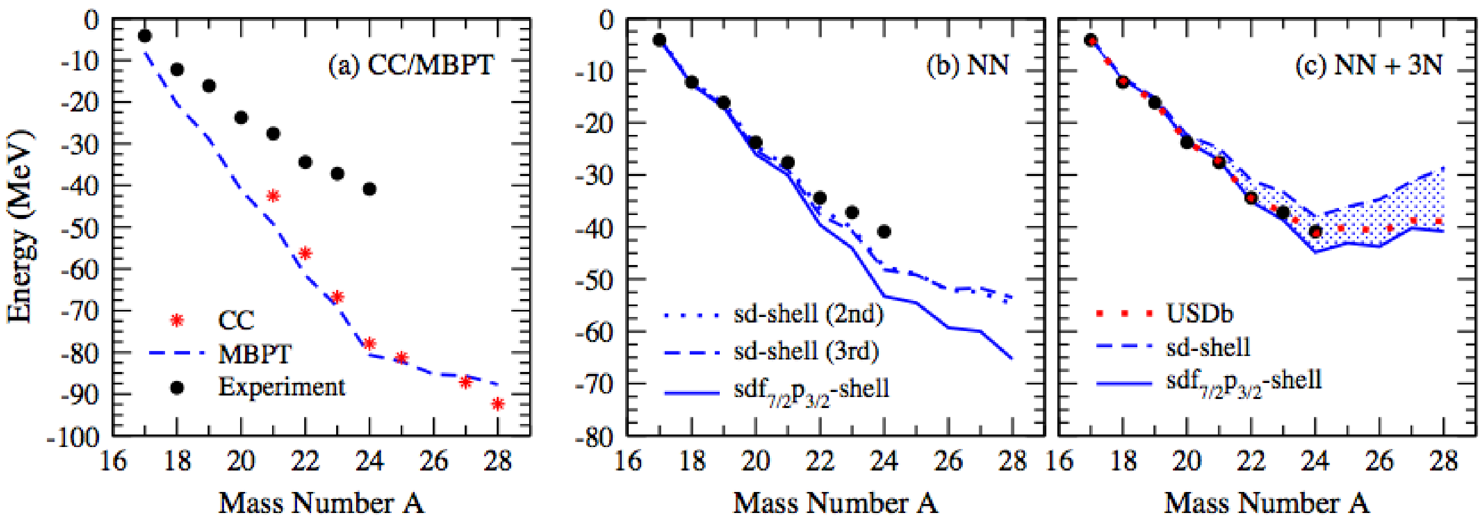
(a)The ground state and the 1^+ in ^{24}O

(b)The ground state and the 2^+ in ^{24}O

Tsukiyama, Horth-Jensen, Hagen PRC 80 051301(2009)

Three-body forces determined from exotic isotopes

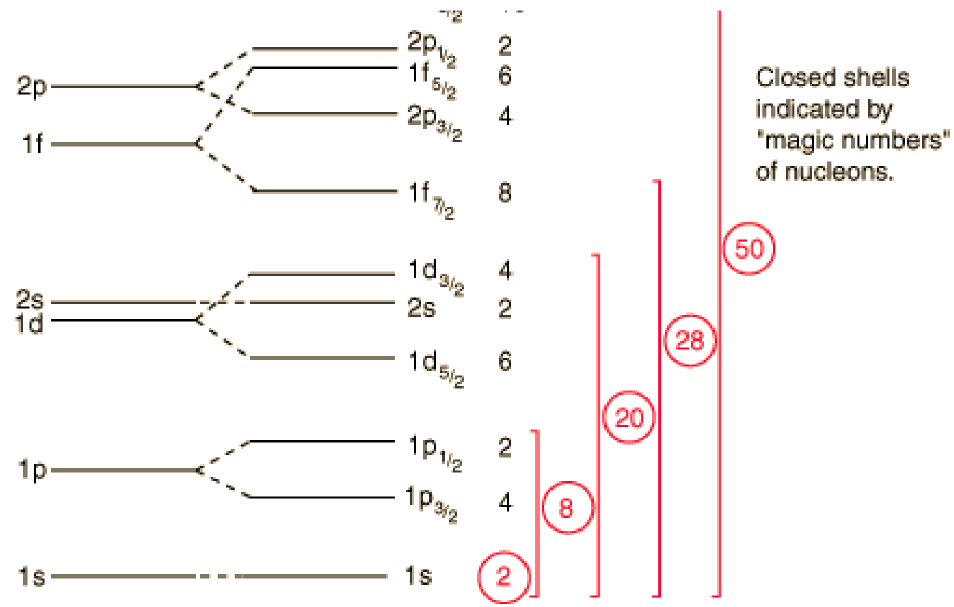
- _Holt and Schwenk arXiv:1108.2680
- Theories based on NN interaction predict ^{28}O to be particle bound (stable to the decay by the strong force)
- Three body forces tend to be repulsive and reduce the strength of the NN potentials



- Oxygen isotopes can be used to determine the strength of the 3N forces in nuclei

Configuration Space Models

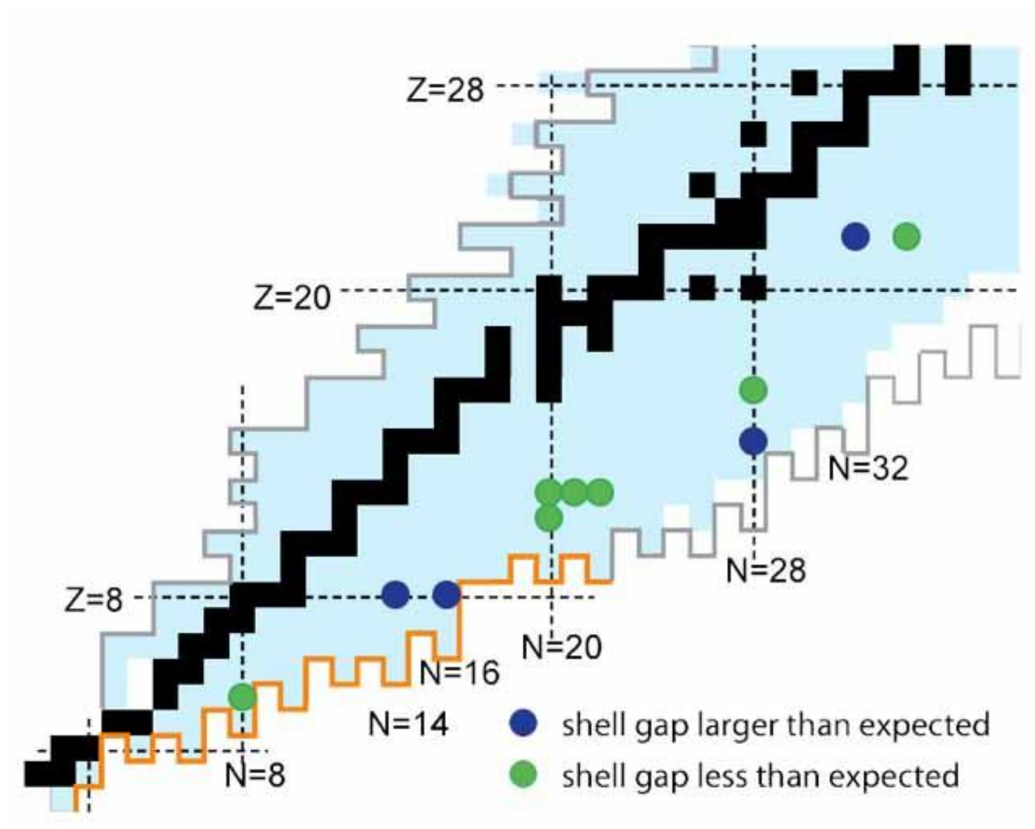
- Lectures by A. Poves
- Shell Model is the most common in nuclear science
- Solve the equation HΨ=EΨ
- Introduce a basis (usually harmonic oscillator) and solve the matrix equation
- Can assume an inert closed core (e.g. N=Z=20)
- No core shell model does not make this assumption but uses effective operators

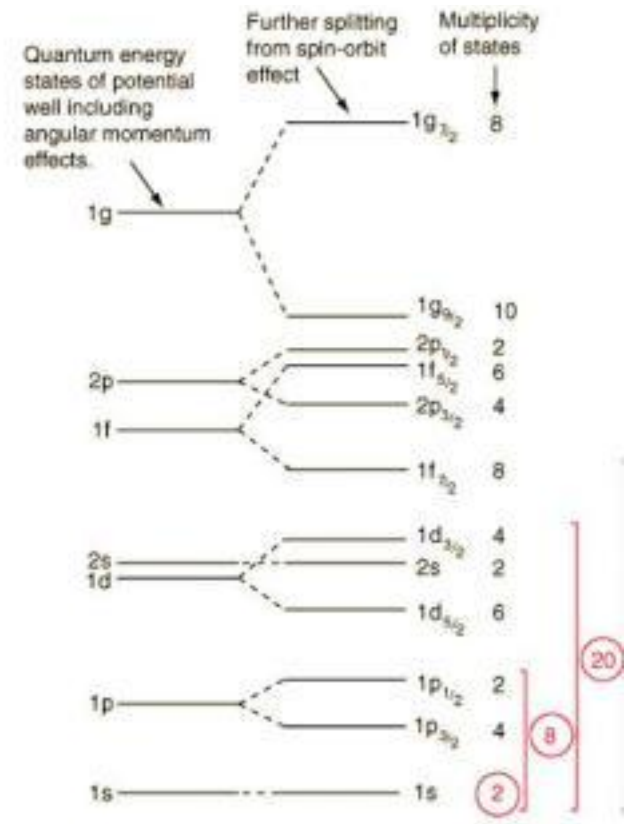


$$H_A = T_{rel} + \mathcal{V} = \frac{1}{A}\sum_{i<j=1}^{A}\frac{(\vec{p}_i - \vec{p}_j)^2}{2m} + \sum_{i<j=1}^{A} V_{NN}\left(+\sum_{i<j<k}^{A} V_{ijk}^{3b}\right)$$

Changes in Shell Structure – The Traditional Nuclear Shell Model is Incomplete

Traditional Shell Picture





Possible origins - Weak binding, tensor force, three-body force, …

Density Functional Theory

- Lectures by T. Papenbrock
- The idea was introduced in atomic physics and is widely used in Chemistry (calculation of molecular properties as good as experiment)
- Relies on the variation concept where observables are treated as variational parameters, e.g. local density ρ(r)
- Minimize the variational equation $\delta(E(\rho) - \int V(r)\rho(r)\,dr) = 0$, $E=\langle \hat{H} \rangle$
- Two step procedure
  - Equation ensures that the total energy is minimized at a fixed ρ(r)
  - Minimization of E(ρ(r)) with ρ(r) gives the exact ground state energy and the exact value of ρ(r) for the ground-state wave function
- Example: Skyrme functional

$$\mathcal{E}[\rho,\tau,\mathbf{J}] = \frac{1}{2M}\tau + \frac{3}{8}t_0\rho^2 + \frac{1}{16}t_3\rho^{2+\alpha} + \frac{1}{16}(3t_1+5t_2)\rho\tau + \frac{1}{64}(9t_1-5t_2)(\nabla\rho)^2 - \frac{3}{4}W_0\rho\nabla\cdot\mathbf{J} + \frac{1}{32}(t_1-t_2)\mathbf{J}^2$$

- where $\rho(x) = \sum_i |\phi_i(x)|^2$ and $\tau(x) = \sum_i |\nabla\phi_i(x)|^2$ (and $\mathbf{J}$)

S Bogner

Science: The Big Picture

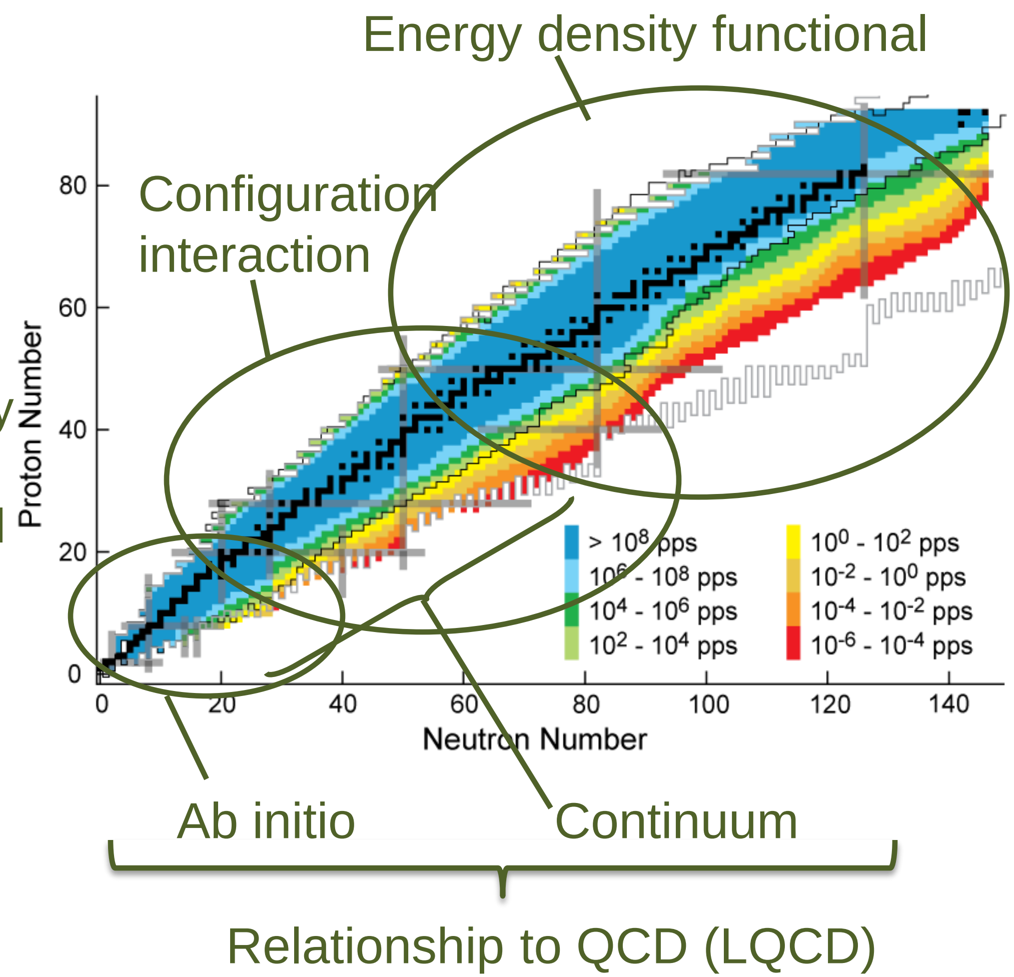
Model and accurately describe nuclei and their reactions. The ability to calculate reactions like $^{7}Be(p,\gamma)$ (responsible for source of neutrinos from the core of the Sun) from first principles would be transformational.

Theory Roadmap – RIA Theory Blue Book 2005

- 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. 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.

Theory Road Map: Comprehensive Model of Nuclear Structure and Reactions

- Theory Road Map – comprehensive description of the atomic nucleus
  - Ab initio models – study of neutron-rich, light nuclei helps determine the force to use in models (measurement of sensitive properties for N=14, 16 nuclei)
  - Configuration-interaction theory; study of shell and effective interactions (study of key nuclei such as ^{54}Ca, ^{60}Ca, ^{122}Zr)
  - The universal energy density functional (DFT) – determine parameters (broad view of mass surface, BE(2)s, BE(4)s, fission barrier surface, etc.)
  - The role of the continuum and reactions and decays of nuclei (halo studies up to A ~100)

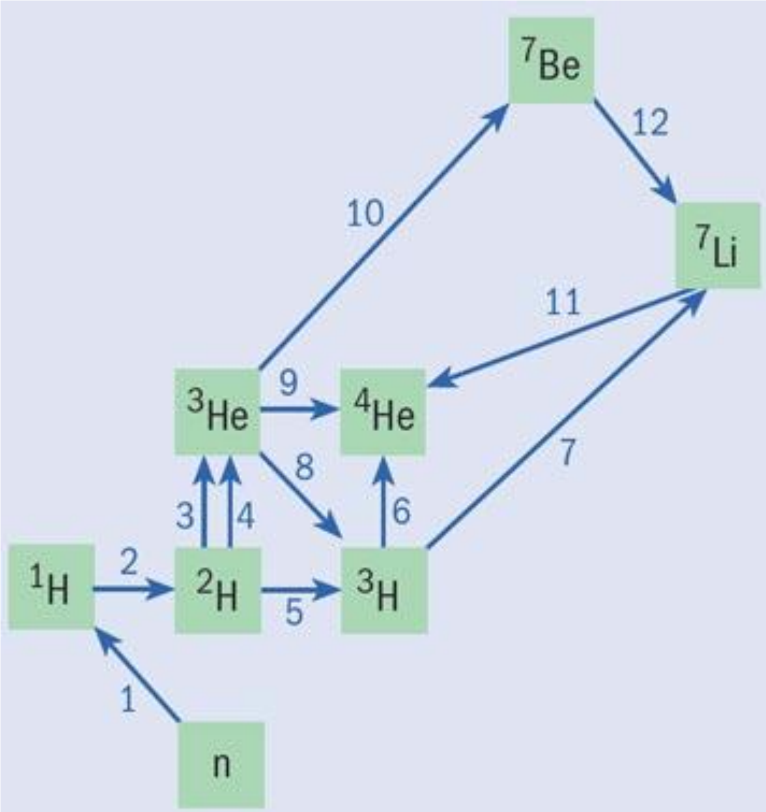


Goals of Nuclear Astrophysics

- Understand the origin and history of atoms in the Universe
  - Model the chemical history of the Milky Way
  - Trace the chemical history of the Universe back to the first stars
  - Learn about the early Universe from what atoms were produced in the Big Bang
- Use the chemical nature of a star, cluster or galaxy to infer something about its origin and history
- Allow accurate modeling of astrophysical objects and allow observations to be used to infer conditions at the site
  - For example, using the light as a function of time (called a light curve) of an X-ray burst to determine the size of emitting region.
  - Use observations to tell us about extreme environments in the universe; neutron stars, supernovae, novae, black holes, the Big Bang, etc.

Example: The lightest elements were made in the Big Bang

- BBN – Big Bang Nucleosynthesis
- H, He, Li were made in the Big Bang (BBN is one of the three main pieces of evidence for the Big Bang; expansion, cosmic microwave radiation, big Bang nucleosynthesis)
- The reaction network and the conditions during the Big Bang allow the elemental abundances to be calculated

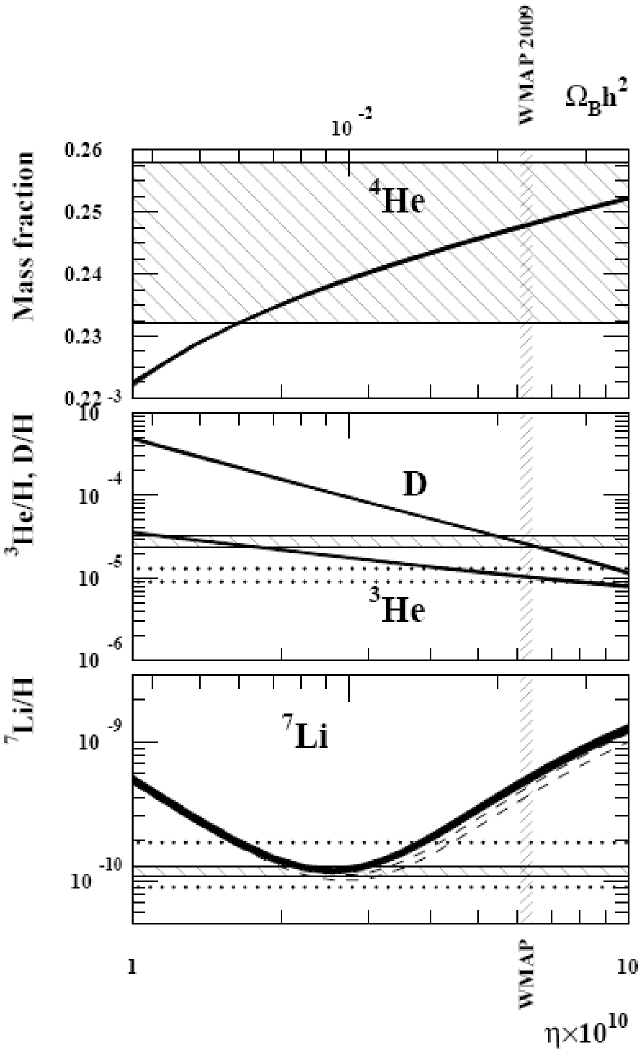


1 $n \rightarrow {}^1H + e^- + \bar{\nu}$
2 ${}^1H + n \rightarrow {}^2H + \gamma$
3 ${}^2H + {}^1H \rightarrow {}^3He + \gamma$
4 ${}^2H + {}^2H \rightarrow {}^3He + n$
5 ${}^2H + {}^2H \rightarrow {}^3H + {}^1H$
6 ${}^2H + {}^3H \rightarrow {}^4He + n$
7 ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8 ${}^3He + n \rightarrow {}^3H + {}^1H$
9 ${}^3He + {}^2H \rightarrow {}^4He + {}^1H$
10 ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11 ${}^7Li + {}^1H \rightarrow {}^4He + {}^4He$
12 ${}^7Be + n \rightarrow {}^7Li + {}^1H$

Sample of a Reaction Network Physics World

Example: Predicted versus Observed BBN

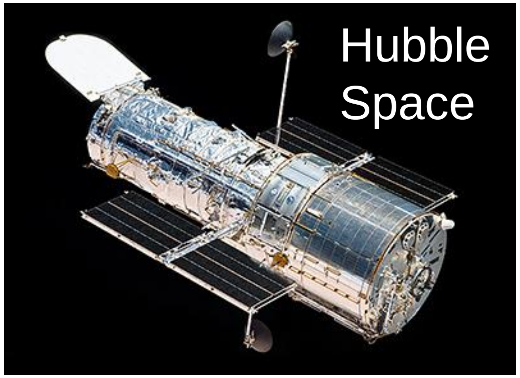
- The abundances following the Big Bang can be calculated from measured nuclear reaction rates (NACRE website: http://pntpm.ulb.ac.be/Nacre/nacre_d.htm)
- The abundance of ^{7}Li relative to H does not agree with the models
- Does this tell us something about the structure of the Universe, or the nature of fundamental particles in the Universe?
- Most people agree it is not due to inaccurate or missing nuclear astrophysics data.
- Summary of BBN(Fields and Sarkar) at http://pdg.lbl.gov/2011/reviews/rpp2011-rev-bbang-nucleosynthesis.pdf

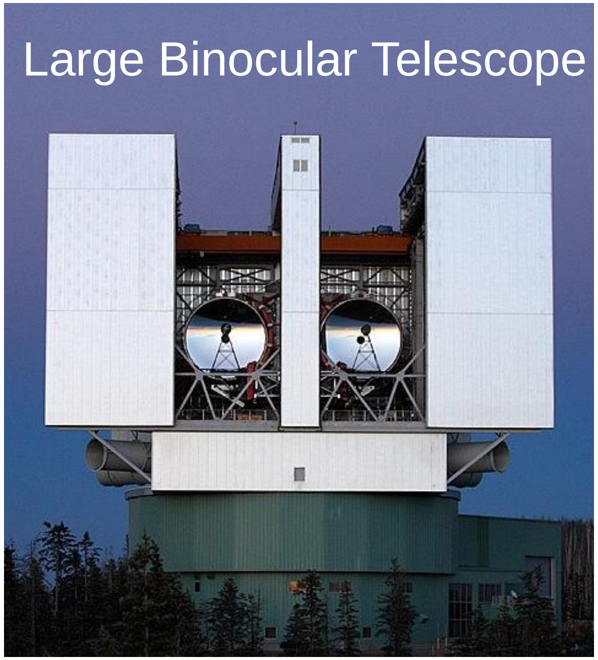


A. Coc and E. Vangioni, 2010 J. Phy. Conf. Ser. 202 012001; IOP Publishing

Forefront of Observational Astronomy: High Resolution Telescopes

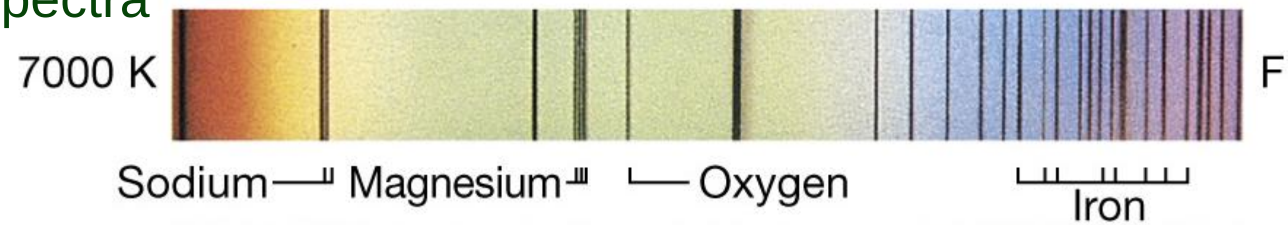
- The measurement of elemental abundances is at the forefront of astronomy using large telescopes
- Large mirrors enable high resolution spectroscopic studies in a short time (Subaru, Hubble, LBT, Keck, …)
- Surveys provide large data sets (SDSS, SEGUE, RAVE, LAMOST, SkyMapper, …)
- Future missions: JWST - "is specifically designed for discovering and understanding the formation of the first stars and galaxies, measuring the geometry of the Universe and the distribution of dark matter, **investigating the evolution of galaxies and the production of elements by stars,** and the process of star and planet formation."



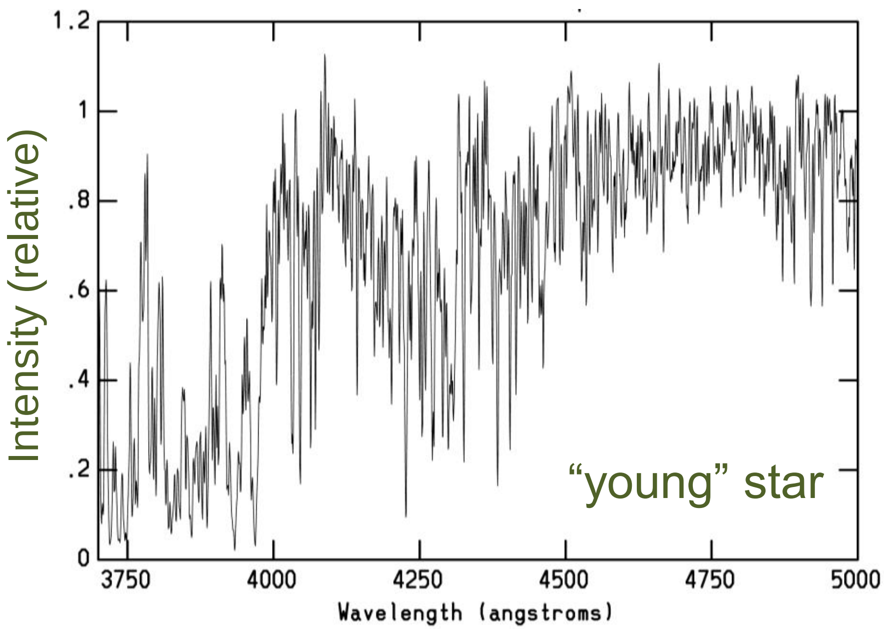


Abundances are inferred from stellar absorption spectra

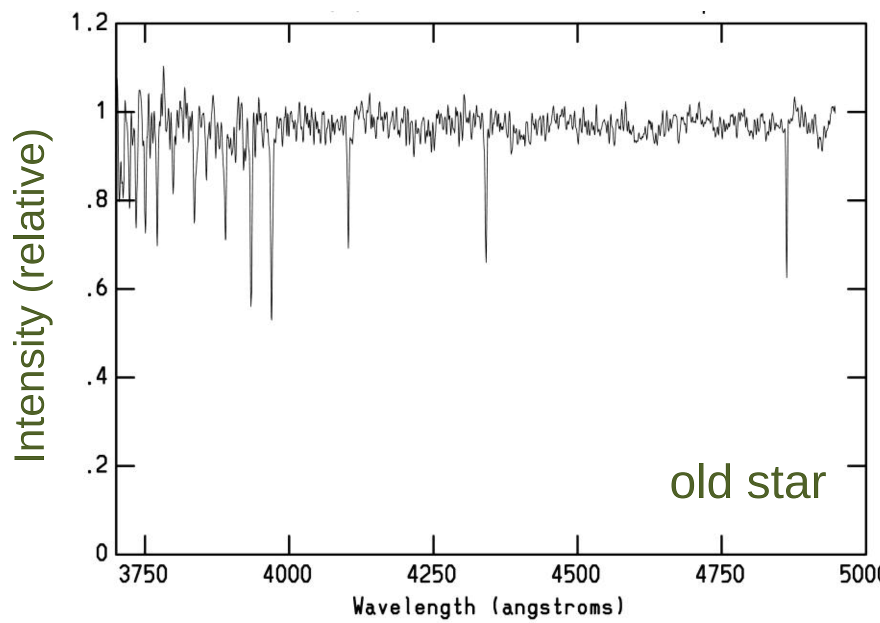
- Stellar absorption spectra



- Not all stellar absorption spectra of the same surface temperature are identical



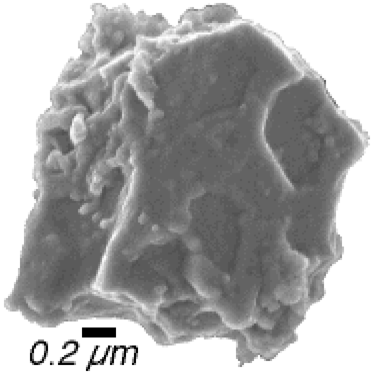
T=4800 K; elements like our sun

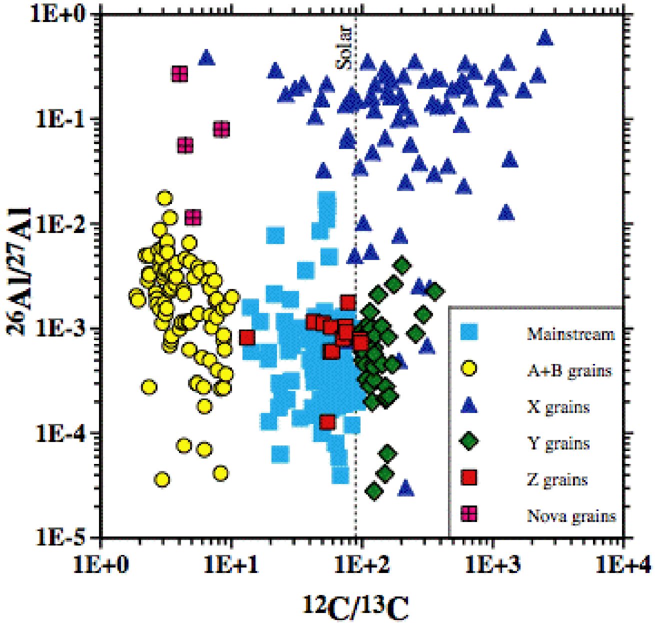


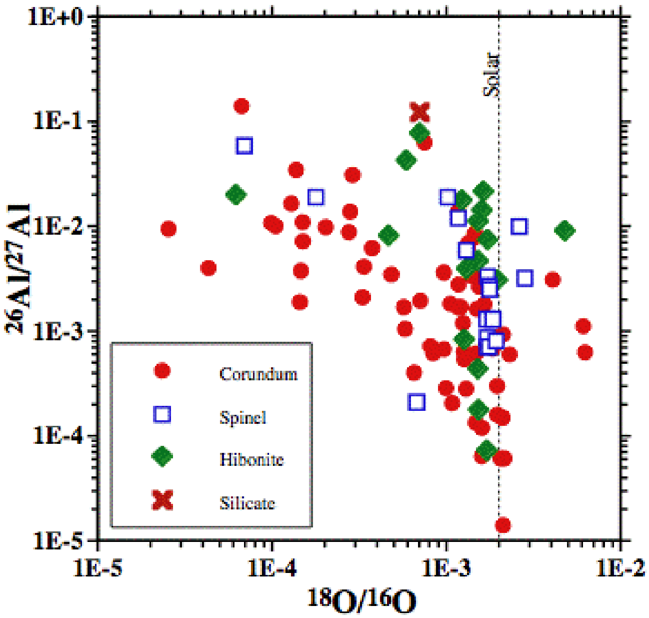
T=4700 K; only 1/10,000 heavy elements

Abundances can also com from Presolar Grains Meteorite Grains

- Another wealth of new data come from the isotopic measurements of individual meteorite grains (pictures from Washington Univ website)
- Other data will come from isotopic analysis cosmic rays
- Measured by Secondary Ion Mass Spectroscopy

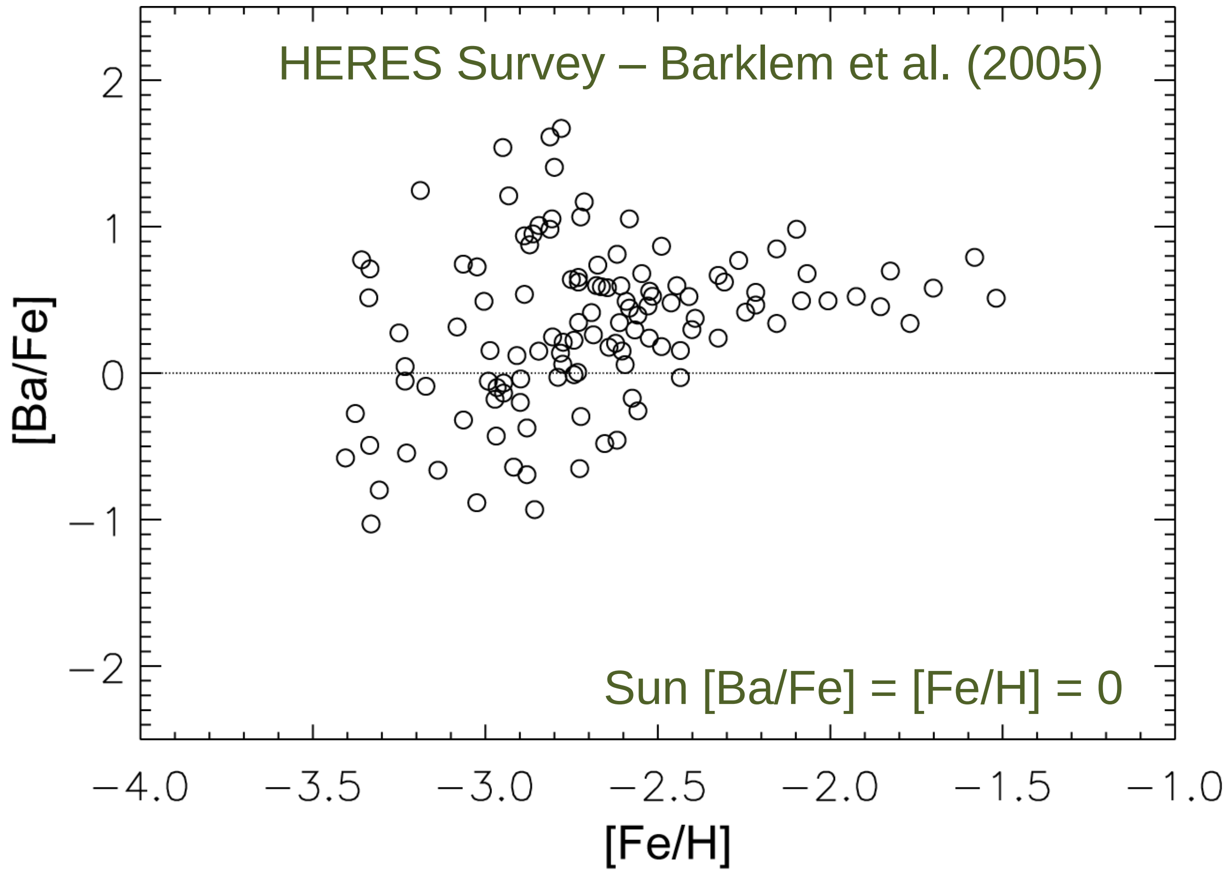






Chemical History of the Universe – the Fossil Evidence of the First Stars

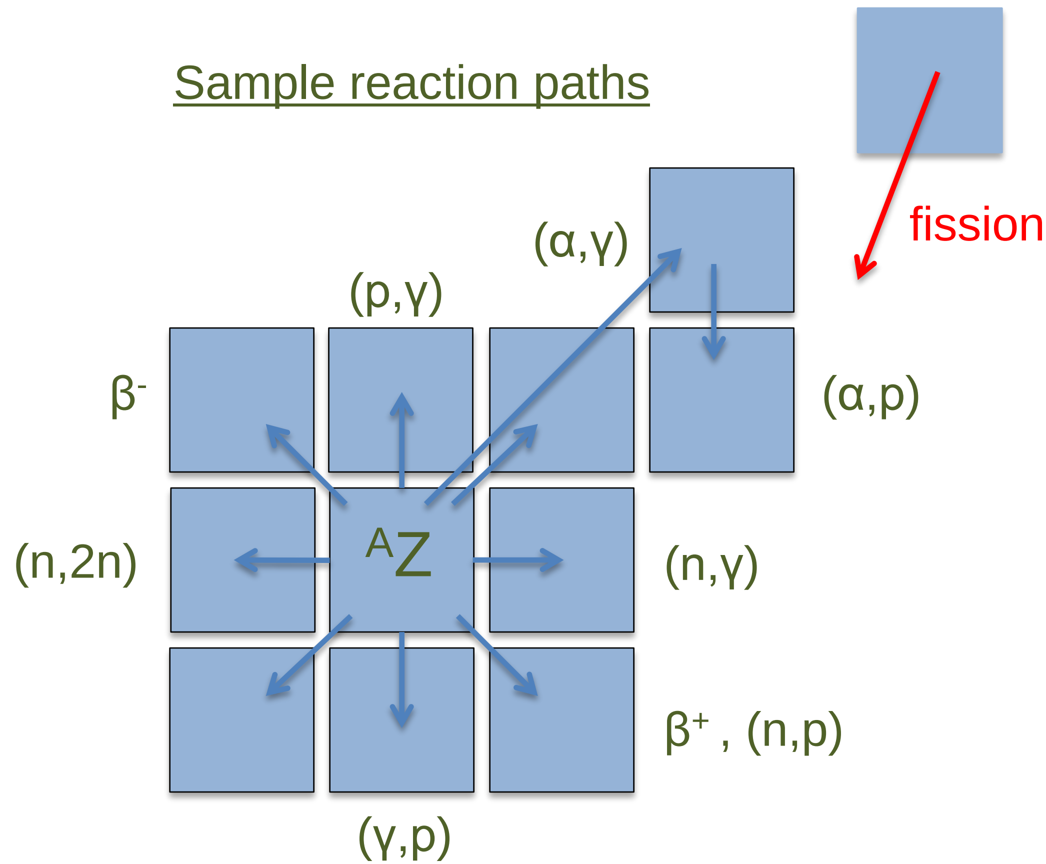
- Not all stars are the same
- By measuring the differences we learn about the history of the star
- The process that makes Barium (Ba) in early stars must be different from the main process that makes Iron (Fe)
- There are many mysteries, only one example is that the [Ba/Fe] is not understood in early stars



$$[\mathrm{Fe/H}] = LOG\left(\frac{(Fe_{abundance}/H_{abundance})_{Star}}{(Fe_{abundance}/H_{abundance})_{Sun}}\right)$$

There are a number of nucleosynthesis processes that must be modeled

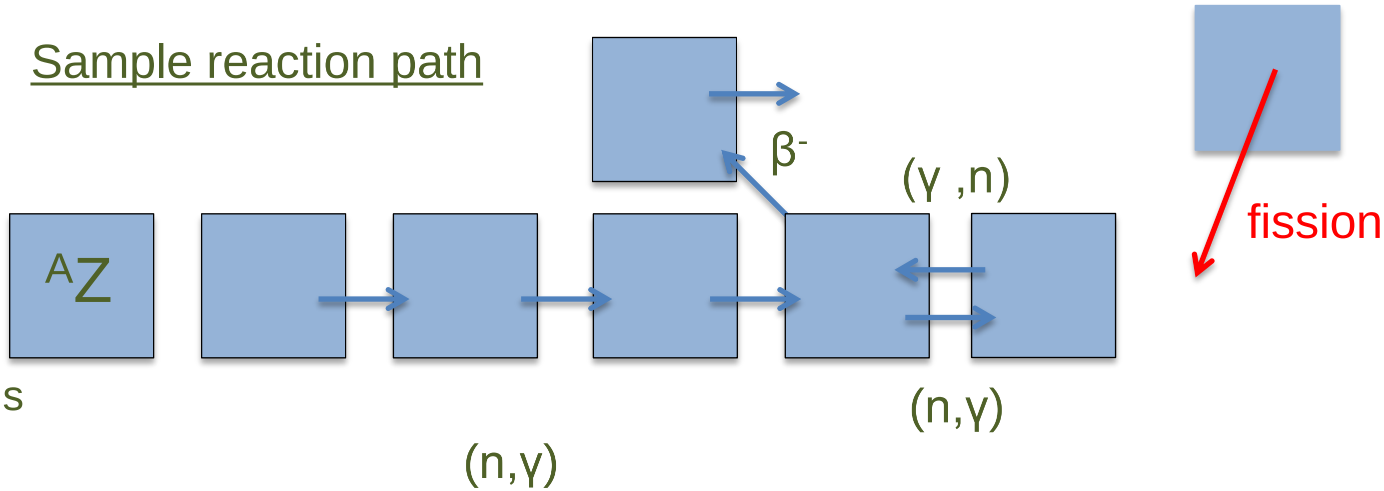
- Big Bang Nucleosynthesis
- pp-chain
- CNO cycle
- Helium, C, O, Ne, Si burning
- s-process
- r-process
- rp-process
- νp – process
- p – process
- α - process
- fission recycling
- Cosmic ray spallation
- pyconuclear fusion
- + others

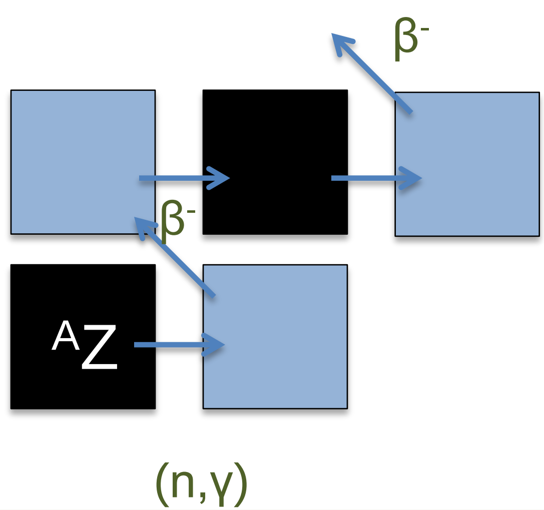


Neutron-capture processes leading to elements heavier than iron

- r-process
  - Fast, few s
  - $10^{20\text{-}26}$ n/cm^3
  - Runs out to where (n,γ) and (γ,n) are similar in rate
  - Adds 30-40 neutrons
  - Site unknown
- s-process
  - Occurs over a time of hundreds of thousands of years
  - Technetium observed in red giant stars
  - Occurs in AGB Stars (C,O core; He and H fusion shells)

Sample reaction path

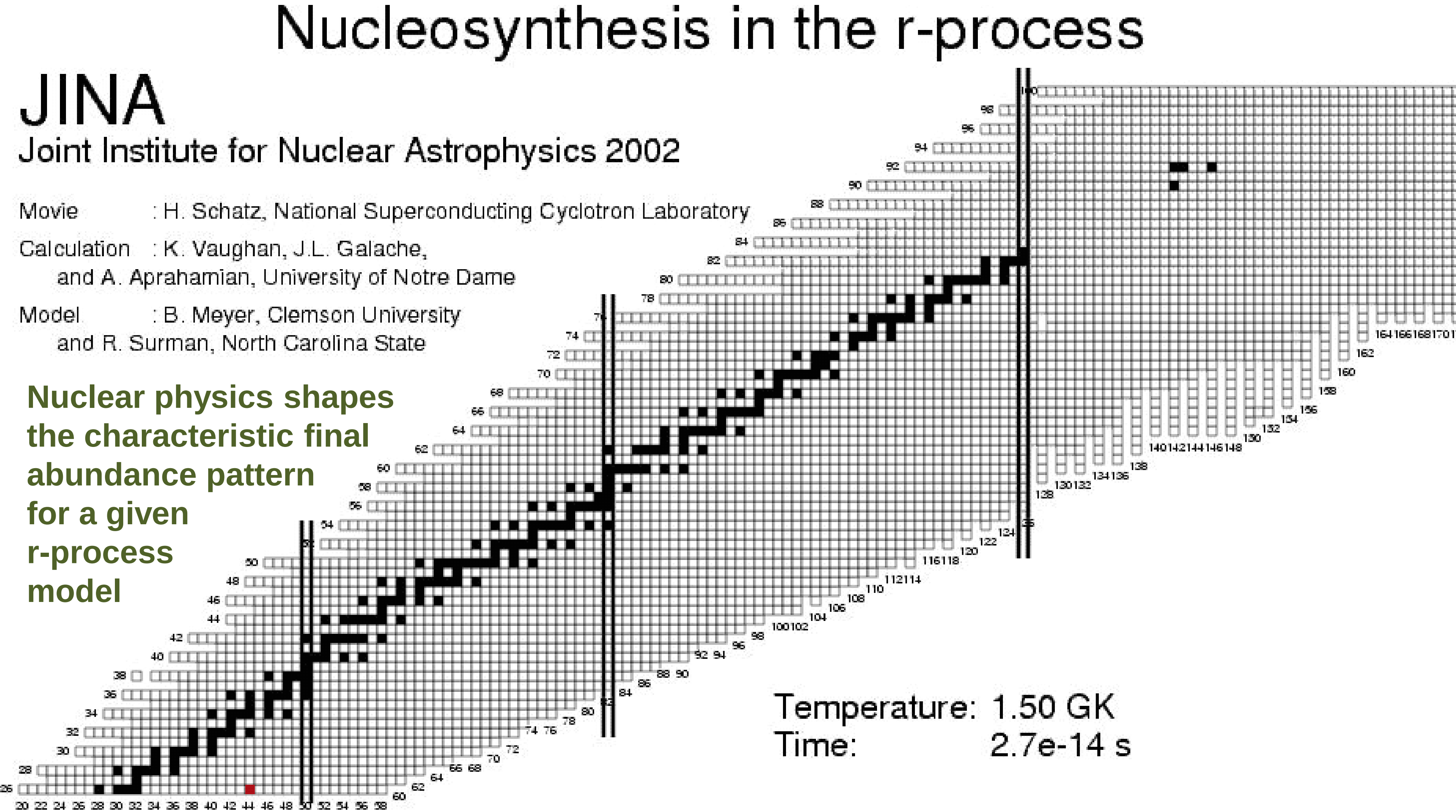




Can we measure and model the relevant nuclear reactions?

- No, not now, but we are getting close. We have a path to fill in this part of the puzzle.
- Produce the rare isotopes that are important for modeling and measure their properties and reactions
- Develop a comprehensive model of nuclear properties and reactions

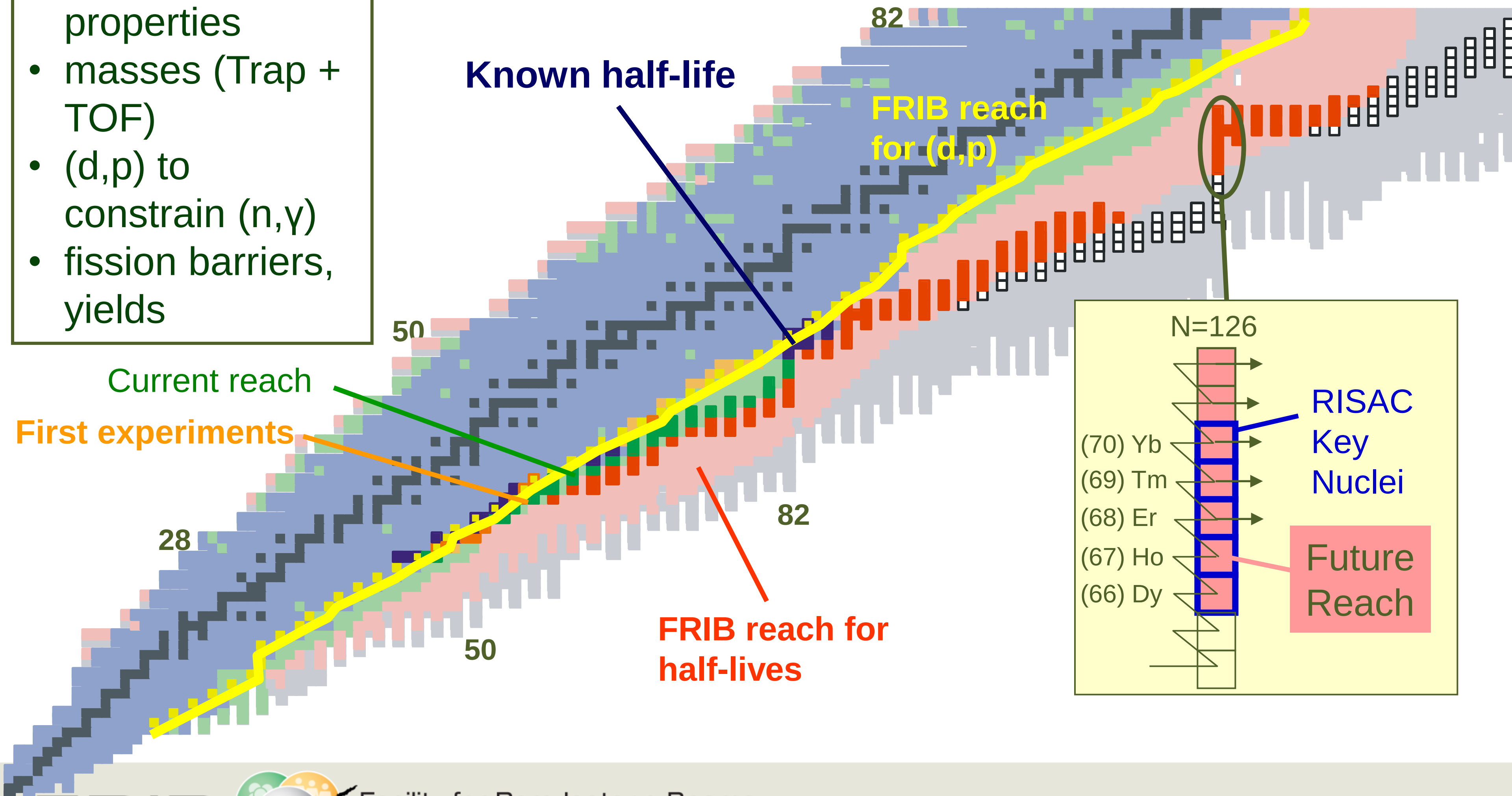
About Half of Heavier Elements must be made in an r-Process



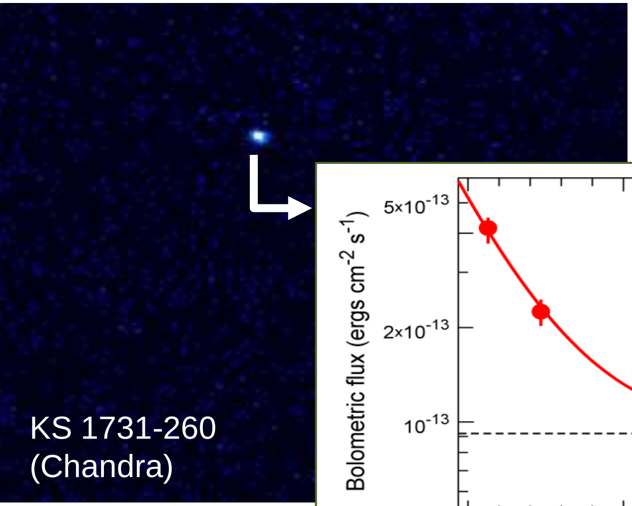
Nuclear physics shapes the characteristic final abundance pattern for a given r-process model

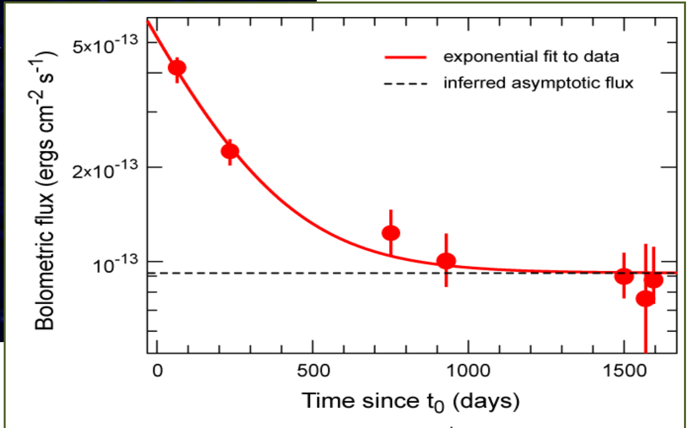
Reach of FRIB – Will Allow Modeling of the r-Process

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

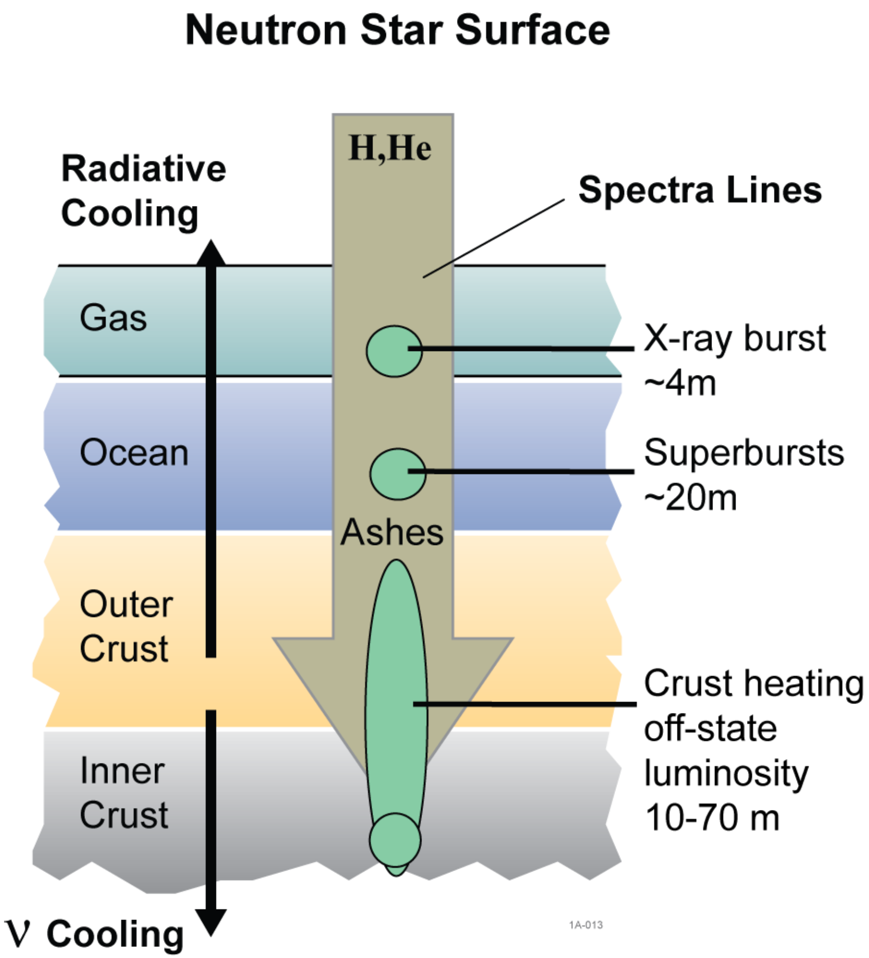


Rare Isotope Crusts of Accreting Neutron Stars





Cackett et al. 2006 (Chandra, XMM-Newton)

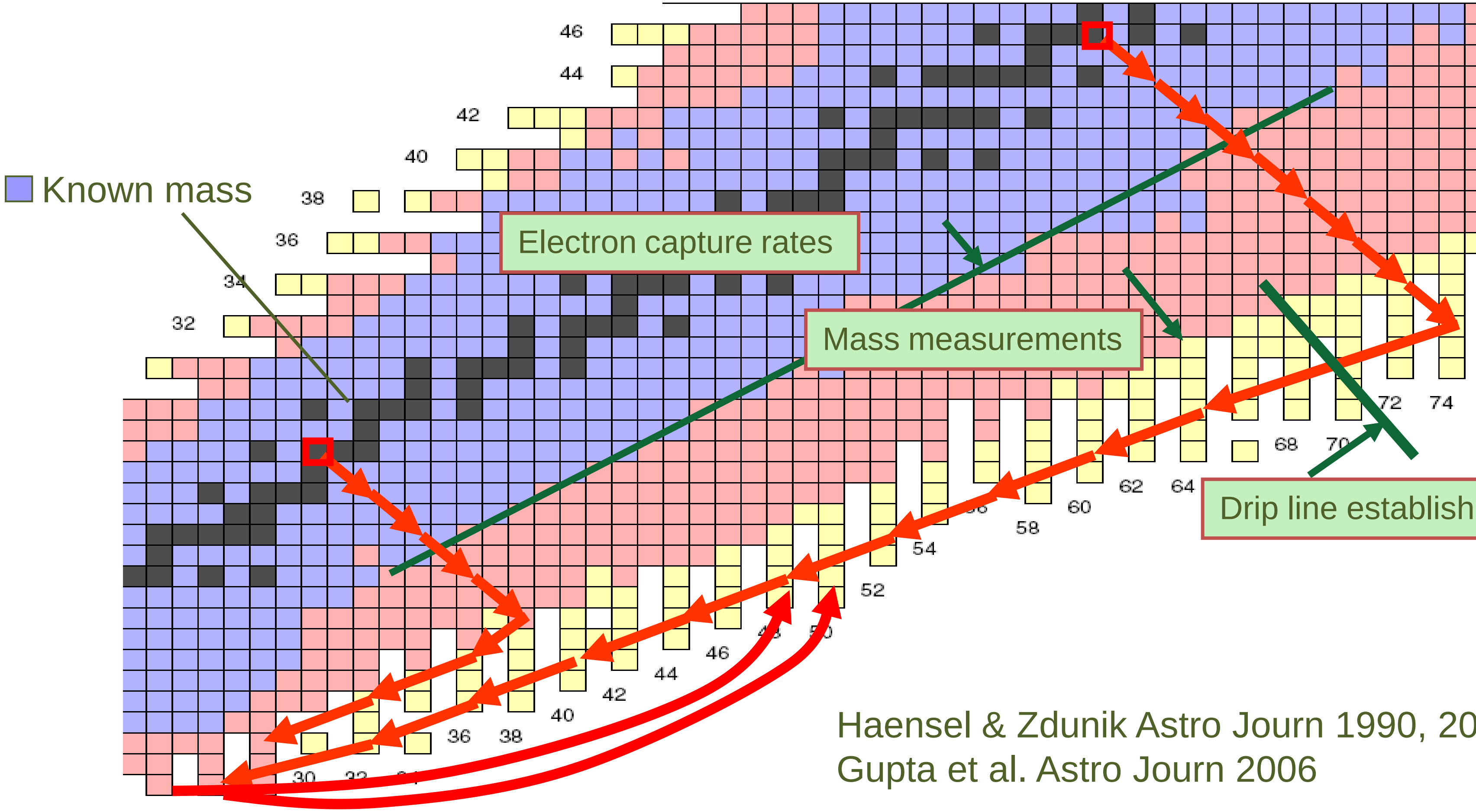


- Nuclear reactions in the crust set thermal properties
- Can be directly observed in transients
- Directly affects superburst ignition

Understanding of crust reactions offers possibility to constrain neutron star properties (core composition, neutrino emission…)

FRIB Reach For Crust Processes

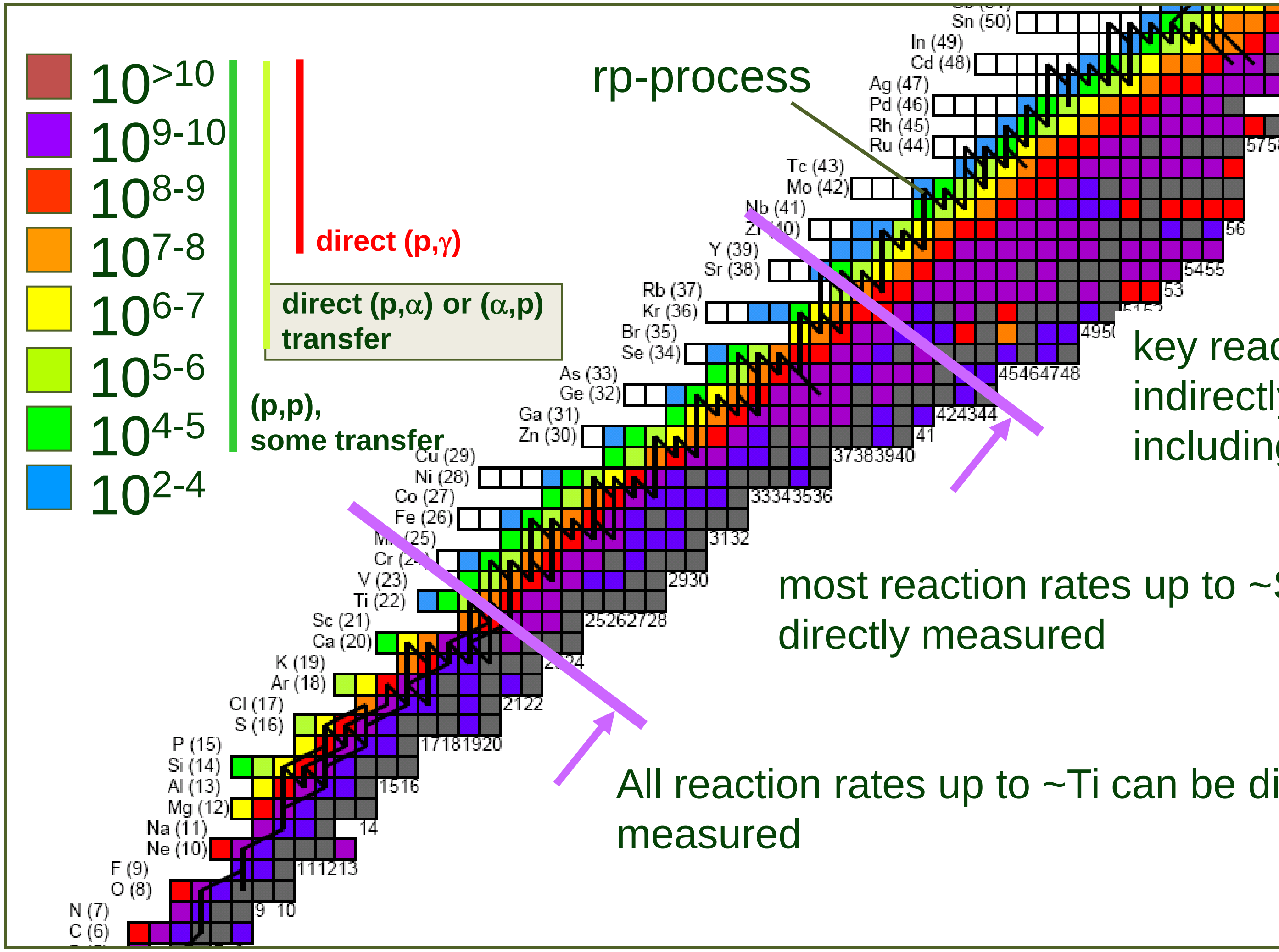
- Interesting set of reactions leading to proton-rich material converted to neutron-rich material



Haensel & Zdunik Astro Journ 1990, 2003, 2008
Gupta et al. Astro Journ 2006

H. Schatz

FRIB Reach for Novae and X-ray burst reaction rate studies



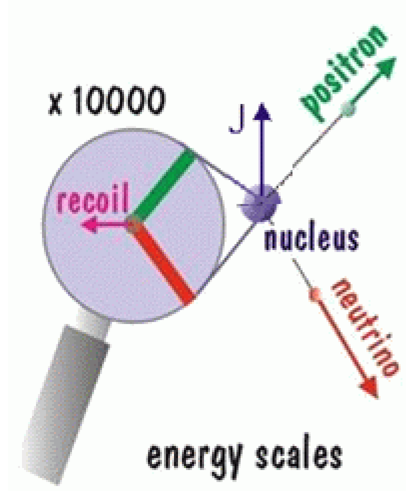
key reaction rates can be indirectly measured including ^{72}Kr waiting point

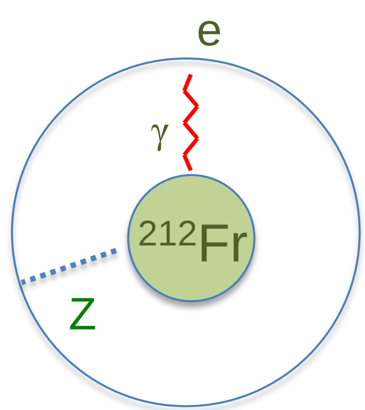
most reaction rates up to ~Sr can be directly measured

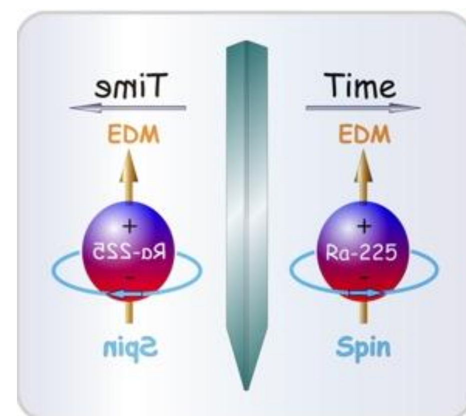
All reaction rates up to ~Ti can be directly measured

Tests of Nature's Fundamental Symmetries

- Angular correlations in β-decay and search for scalar currents
  - Mass scale for new particle comparable with LHC
  - ^{6}He and ^{18}Ne at 10^{12}/s
- Electric Dipole Moments
  - ^{225}Ac, ^{223}Rn, ^{229}Pa (30,000x more sensitive than ^{199}Hg; $^{229}Pa > 10^{10}$/s)
- Parity Non-Conservation in atoms
  - weak charge in the nucleus (francium isotopes; 10^{9}/s)
- Unitarity of CKM matrix
  - V_{ud} by super allowed Fermi decay
  - Probe the validity of nuclear corrections



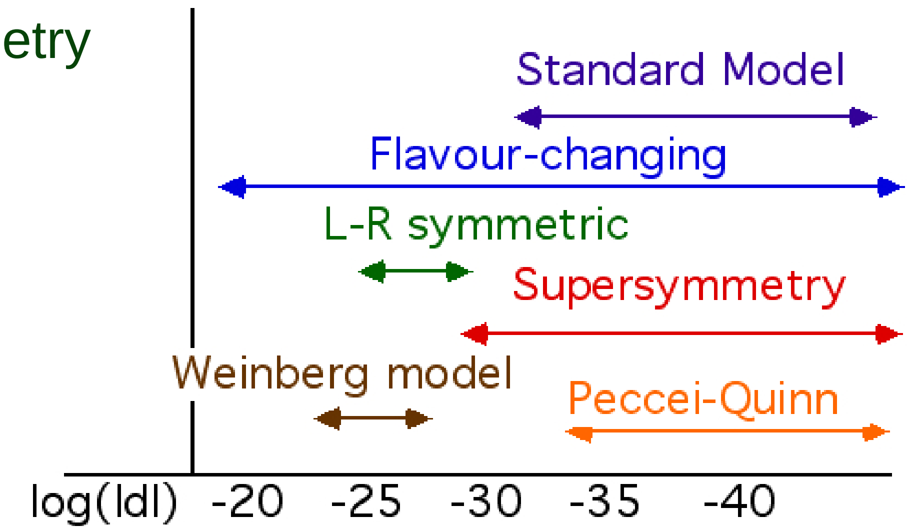




$$\begin{vmatrix} \color{red}{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix}$$

Atomic Electric Dipole Moment

- EDM violates time reversal symmetry
- Improving EDM limit is an important constraint on models
- Neutron EDM
  - Present < 3.0 x 10^{-23} e-cm
  - SNS goal 10^{-28} e-cm
- ^{199}Hg EDM
  - Present < 3.1 x 10^{-29} e-cm
- Measurements
  - Short term – identify candidate nuclei
  - Mid term – perform atomic spectroscopy measurements
  - Long term – attempt EDM measurement (may require ISOL)



^{223}Rn proposed to have 20x greater sensitivity to EDM
^{229}Pa may have 10,000x greater sensitivity

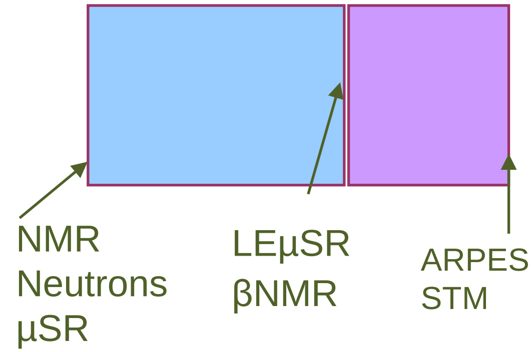
Lu, Mueller, ANL
Chupp, U of Michigan
Swenson, Guelp

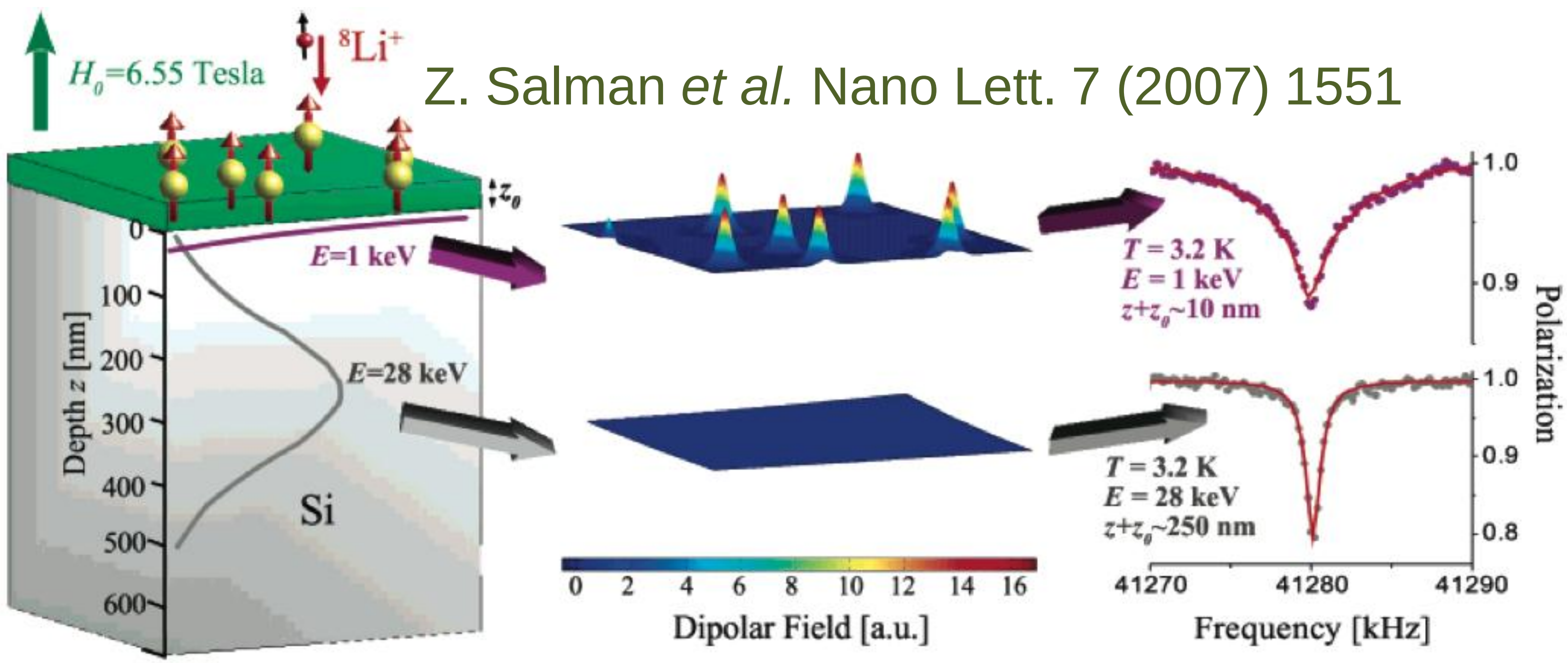
Rare Isotopes For Society

- Isotopes for medical research
  - Examples: ^{47}Sc, ^{62}Zn, ^{64}Cu, ^{67}Cu, ^{68}Ge, ^{149}Tb, ^{153}Gd, ^{168}Ho, ^{177}Lu, ^{188}Re, ^{211}At, ^{212}Bi, ^{213}Bi, ^{223}Ra (DOE Isotope Workshop)
  - α-emitters ^{149}Tb, ^{211}At: potential treatment of metastatic cancer
  - Cancer therapy of hypoxic tumors based on ^{67}Cu treatment/^{64}Cu dosimetery
- Reaction rates important for stockpile stewardship and nuclear power – related to astrophysics network calculations
  - Determination of extremely high neutron fluxes by activation analysis
  - Rare isotope samples for (n,γ), (n,n'), (n,2n), (n,f) e.g. ^{88,89}Zr
    - » Same technique important for astrophysics
  - More difficult cases studied via surrogate reactions (d,p), (^{3}He,α xn) …
  - We can produce quantities of separated fission products for tests of detection techniques
- Tracers for Marine Studies (^{32}Si), Condensed Matter (^{8}Li), industrial tracers (^{7}Be, ^{210}Pb, ^{137}Cs, etc.), …
- Novel radioactive sources for homeland security applications (for example β-delayed neutron emitters to calibrate detectors, etc.)

^{8}Li β-NMR Resonance Studies

- Discovery potential of β-NMR very high in exploring depth dependent properties, interfaces, and proximity effects from 5 to 200 nm.
- Sensitivity 10^{13} higher than NMR
- Limited by availability of ^{8}Li facilities
- Example: Study of Mn_{12} single molecule magnets on Si Surface

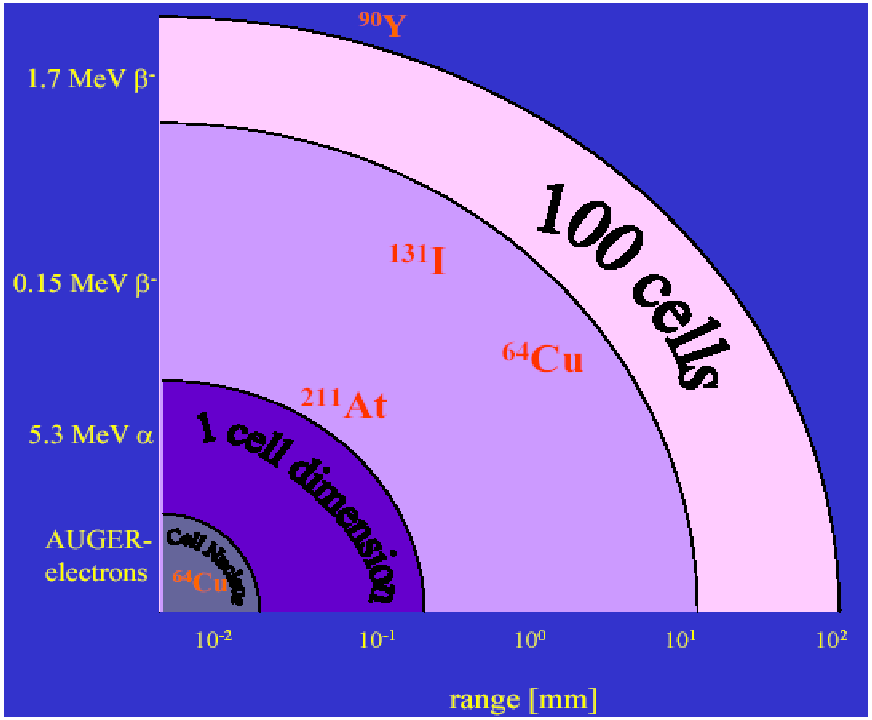




Z. Salman *et al.* Nano Lett. 7 (2007) 1551

Targeted Cancer Therapy

- Modern targeted therapies in medicine take advantage of knowledge of the biology of cancer and the specific biomolecules that are important in causing or maintaining the abnormal proliferation of cells
- These radionuclides have been relatively difficult to get in sufficient quantities[1]. The short-lived alpha emitters are particularly in demand, especially ^{225}Ac, ^{213}Bi, and ^{211}At.
- Pairs, e.g., ^{67}Cu (treatment) and ^{64}Cu (dosimetry) are particularly interesting
- DOE Isotopes program and future research facilities, e.g., FRIB and HRIBF upgrade can parasitically supply demand for many isotopes



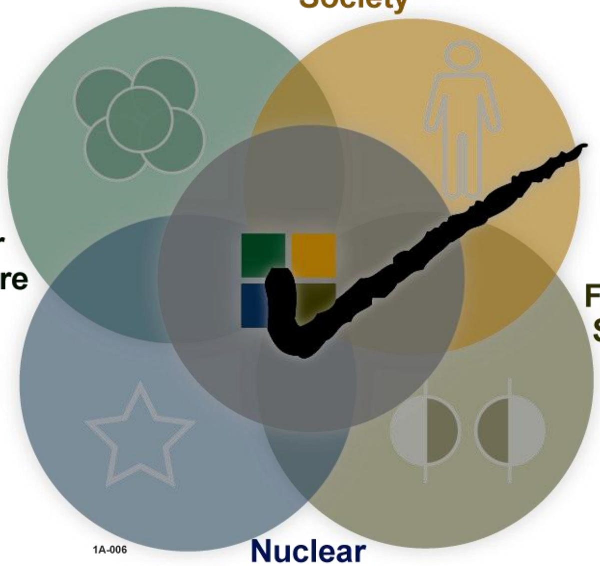
[1]Isotopes for the Nation's Future: A Long Range Plan , NSACIS 2009

Sample Interesting Isotopes from FRIB and uses

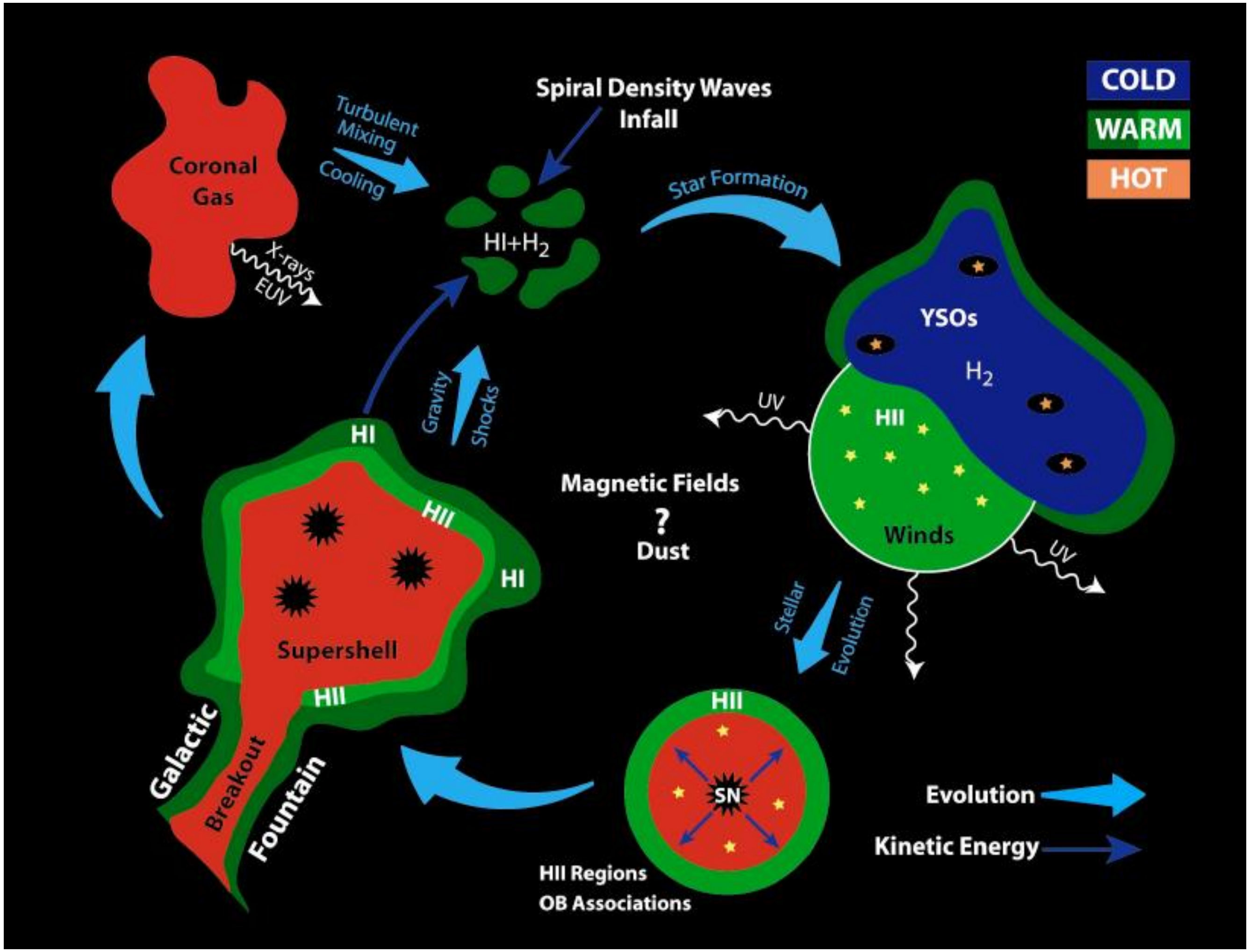
Nuclide	Half-life	Use
^{32}Si	153 y	Oceanographic studies; climate change
^{221}Rn	25 m	Targeted alpha therapy
$^{225}Ra/^{229}Po$	15 d	EDM search in atomic systems
^{85}Kr	11 y	High specific activity ^{85}Kr for nuclear reaction network studies, e.g., s-process
^{44}Ti	60 y	Target and ion-source material
^{67}Cu	62 h	Imaging and therapy for hypoxic tumors

Summary

- We have entered the age of designer atomic nuclei – new tool for science
- Current and next generation facilities will allow production of a wide range of new designer isotopes
  - Necessary for the next steps in accurate modeling of atomic nuclei
  - Necessary for progress in astronomy (chemical history, mechanisms of stellar explosions)
  - Opportunities for the tests of fundamental symmetries
  - Important source for research quantities of exotic isotopes
- Stay tuned there are likely many surprises we will find along the way



Origin of Atoms (Chemical Evolution) – Coupled Problems



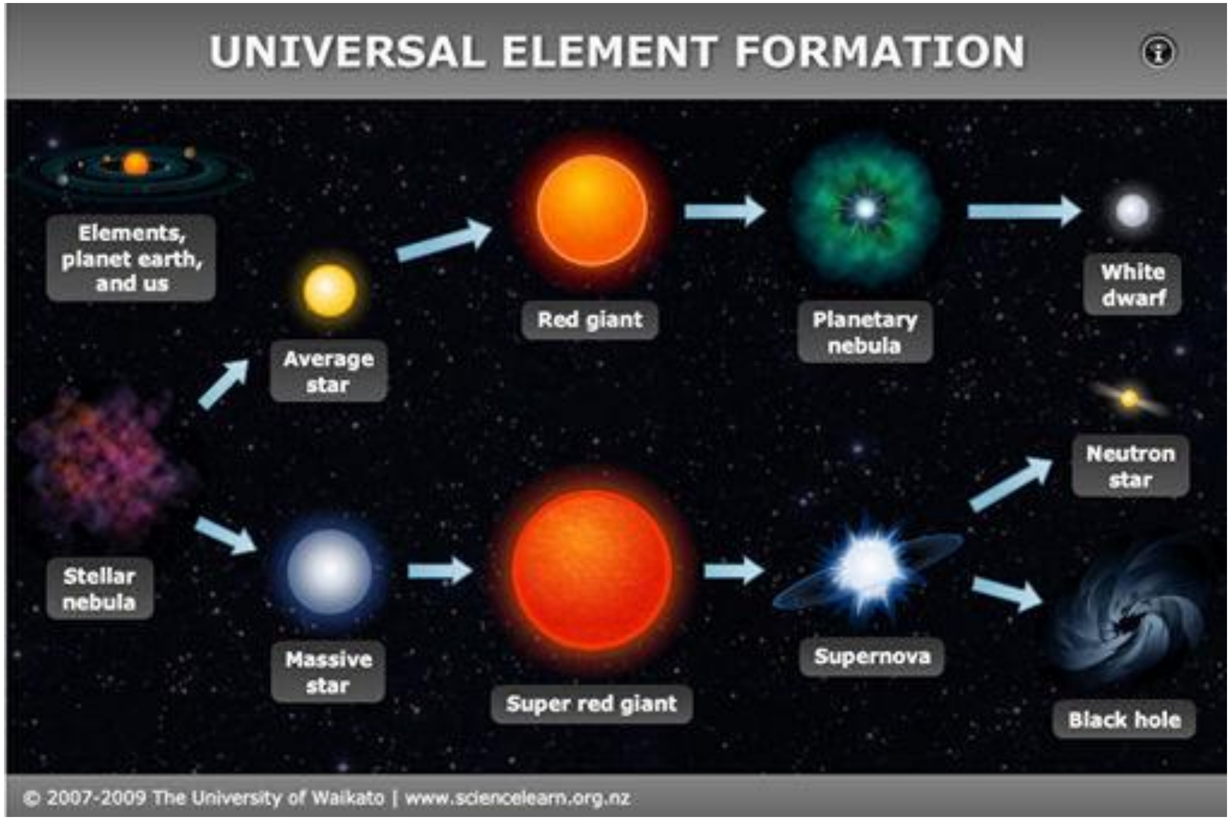
Nuclear reactions
+ Stellar evolution and explosive scenarios
+ Evolution of the Universe and Galactic collisions

Illustration of the difficulty of the problem: No one can describe why the Milky Way looks like it does.

Jason Tumlinson STSCI

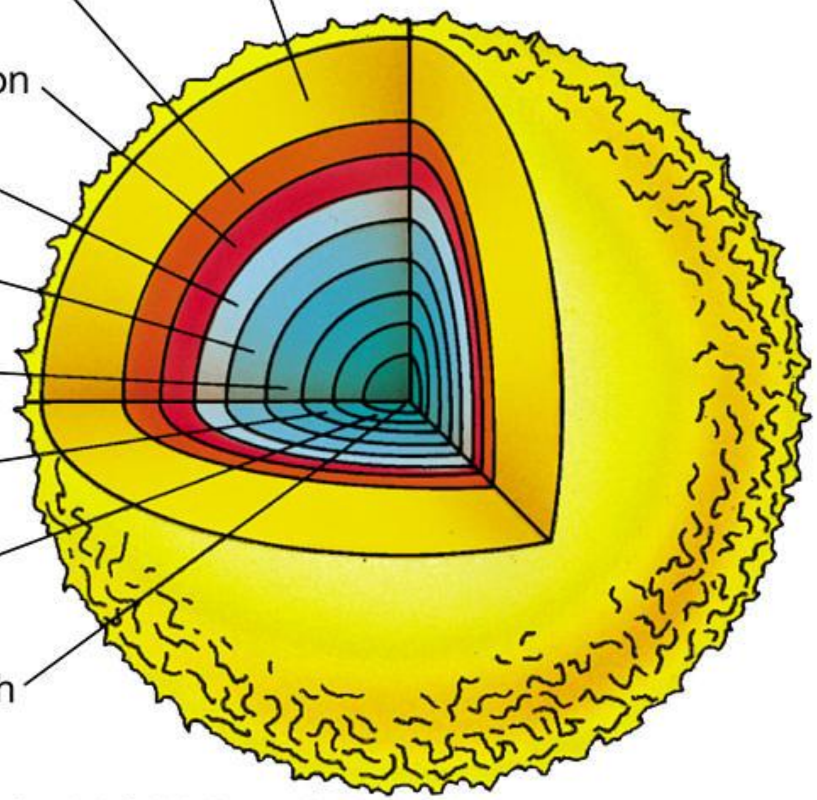
There are a number of nucleosynthetic processes

- Big Bang Nucleosynthesis
- pp-chain
- CNO cycle
- Helium, C, O, Ne, Si burning
- s-process
- r-process
- rp-process
- νp – process
- p – process
- α - process
- fission recycling
- Cosmic ray spallation
- pycnonuclear fusion
- + others



Stellar evolution of massive stars

- Stars with more than 8 times the mass of our Sun develop multiple burning layers
- Hydrogen to helium
- Helium to carbon
- Carbon to oxygen, neon, magnesium
- Oxygen to neon
- Neon to magnesium
- Magnesium to Silicon
- Silicon to Iron
- Iron is the most bound nucleus and has no exothermic nuclear reactions



Nuclei matter

- The properties of nuclei are relevant to other sciences
  - Fundamental particles and interactions, e.g., neutrinoless double-beta decay the rate is related to nuclear matrix elements, nuclei properties are important for atom EDM searches
  - Modeling astrophysical environments; e.g., nucleosynthesis in supernovae, depends on properties of exotic isotopes; neutron star properties can be inferred from properties of very neutron-rich nuclei; interpretation of X-ray bust light curves and neutron star X-ray emission to infer properties, …
- The properties of nuclei are important for a wide variety of applications
  - Nuclear power (nuclear data is needed to optimize reactor design)
  - Homeland security (forensics involves the same types of reactions, e.g. (n,2n), important for astrophysics; detection of nuclear material and other threats)
  - Stockpile stewardship (ditto)
  - Medical diagnostics (^{99}Mo ; ^{18}F; etc.)
  - Industrial and environmental tracers (^{7}Be, ^{210}Pb, ^{137}Cs, etc.)

New Isotope Search

^{238}U(345MeV/u)+ Be/Pb

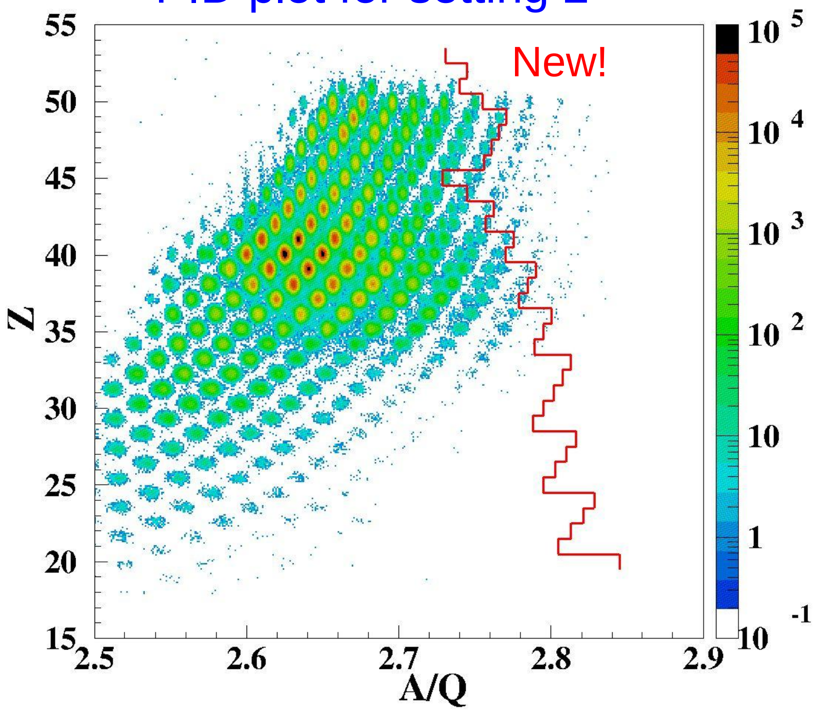
T.Ohnishi, T.Kubo et al.

U-beam intensity (averaged)

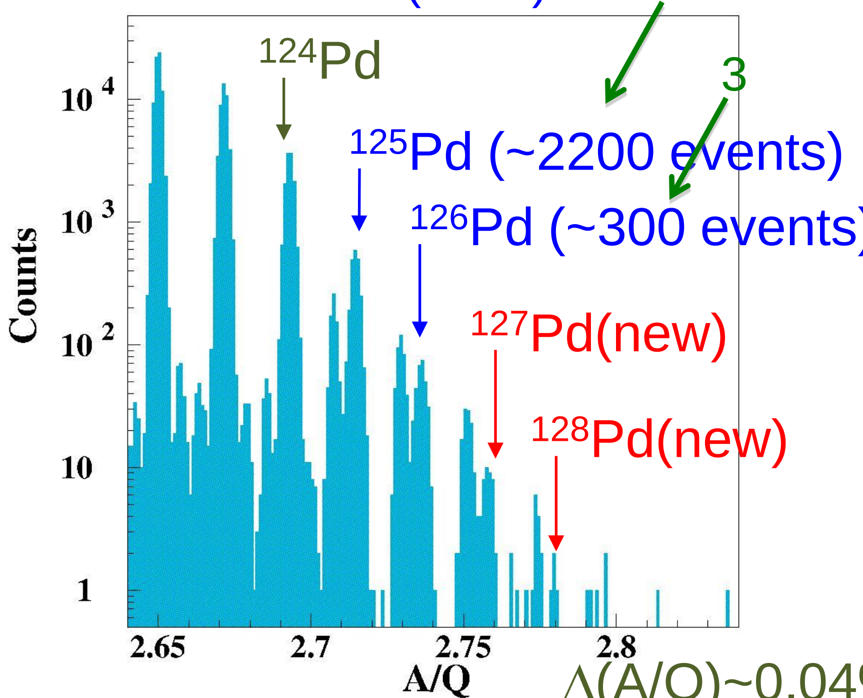
~1.8 x 10^9 pps (Nov. 2008) ← 4 x 10^7 pps (2007)

0.3pnA 0.01 pnA

PID plot for setting 2



Pd (Z=46)

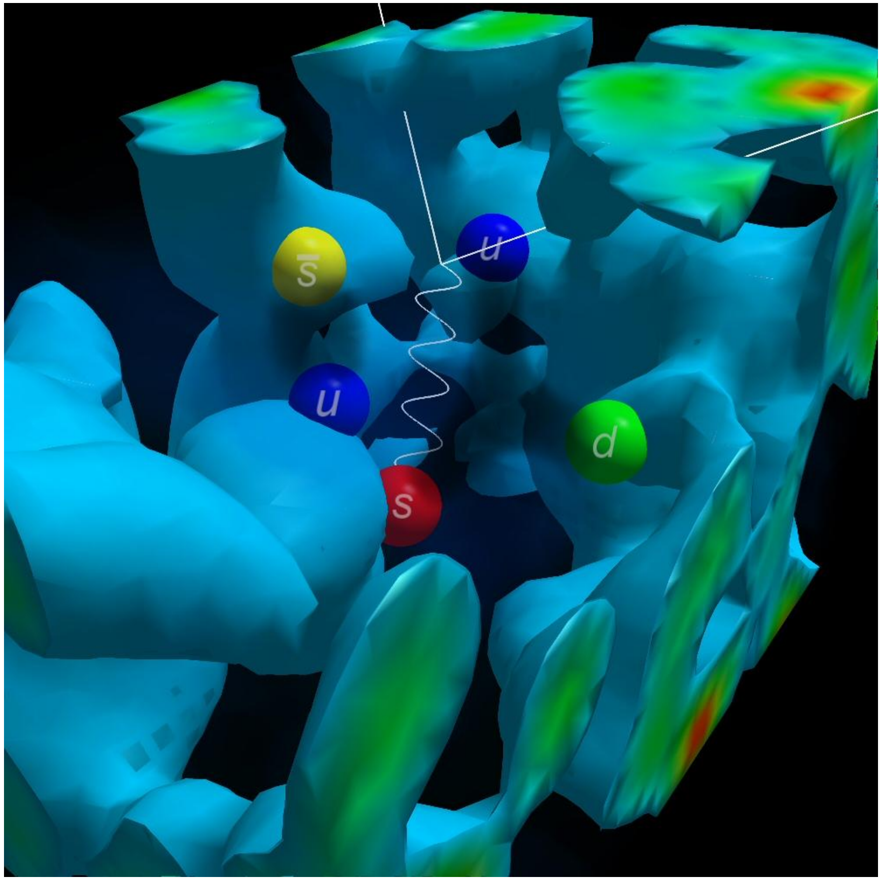


Δ(A/Q)~0.04%

Visualizations of Quantum Chromodynamics

Center for the Subatomic Structure of Matter, University of Adelaide

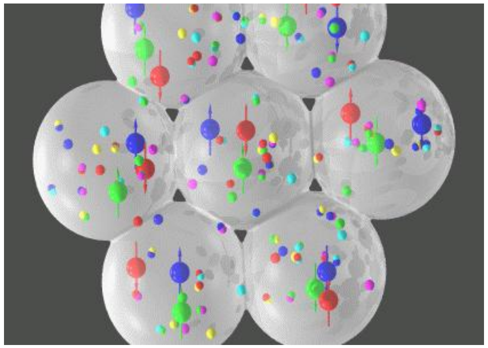
- QCD describes how Gluon fields anti-screen the strong force
- Something like 95% of the mass of a proton come from the energy associated with the Gluon fields
- Strange quarks play a role in the structure of the proton. The picture at the right illustrates the composition of a proton and how experimentalists probe its structure through electron scattering.



http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/

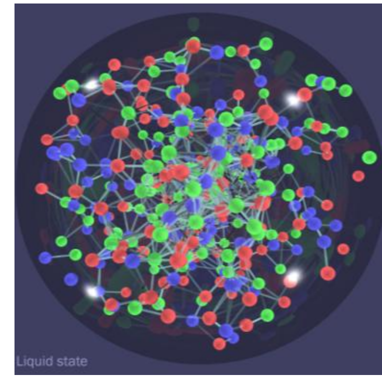
Nuclear Physics explores the structure and phases resulting from QCD

JLAB – QCD of nucleons



Picture from Stephan Scherer

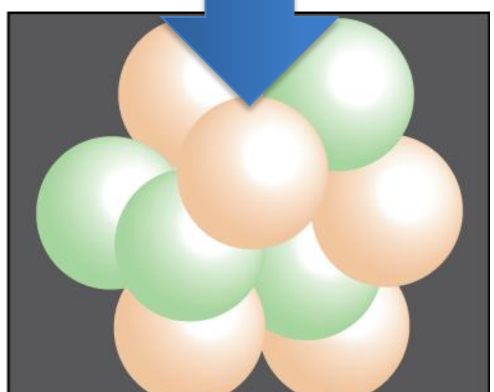
RHIC – QCD in liquid and nucleons



Pictur
e
from
BNL

$$\mathcal{L}_{\mathrm{QCD}} = \sum_n \bar{\psi}_n (i\hbar c \not{D} - m_n c^2)\psi_n - \frac{1}{4} G^{\alpha}{}_{\mu\nu} G_{\alpha}{}^{\mu\nu}$$

QCD Lagrangian



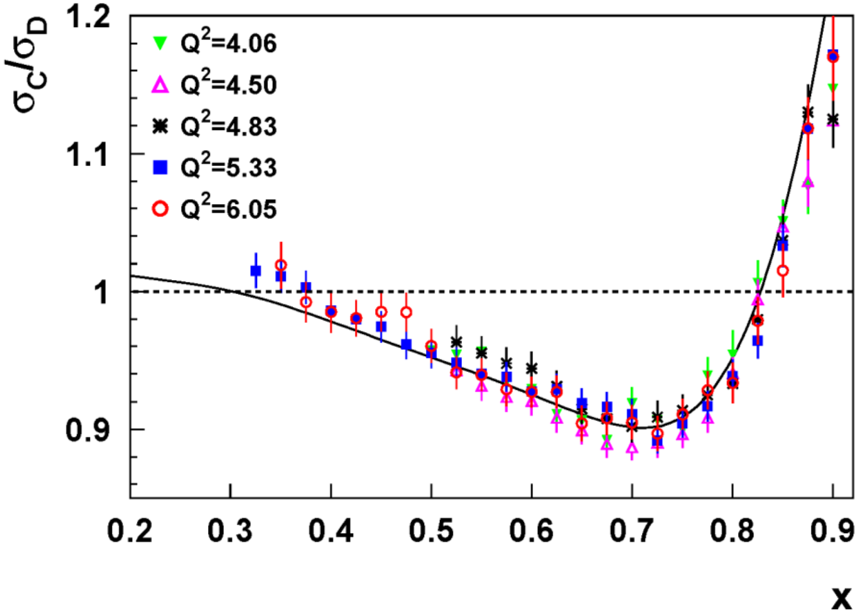
FRIB – QCD of nuclei

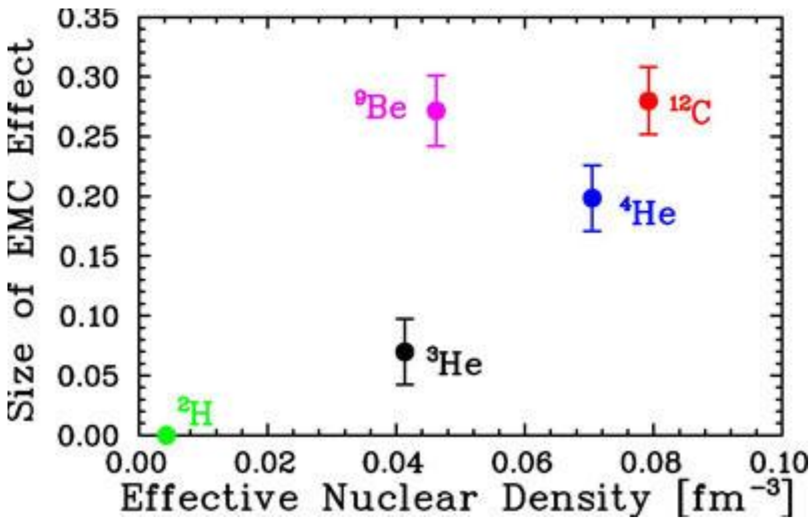
Methods:

- V_{nn} (+3body) *ab initio*
- Configuration (shell)
- Functional Theory
- Relation to QCD

However…Are Nucleons Modified in the Nuclear Medium? Maybe Yes

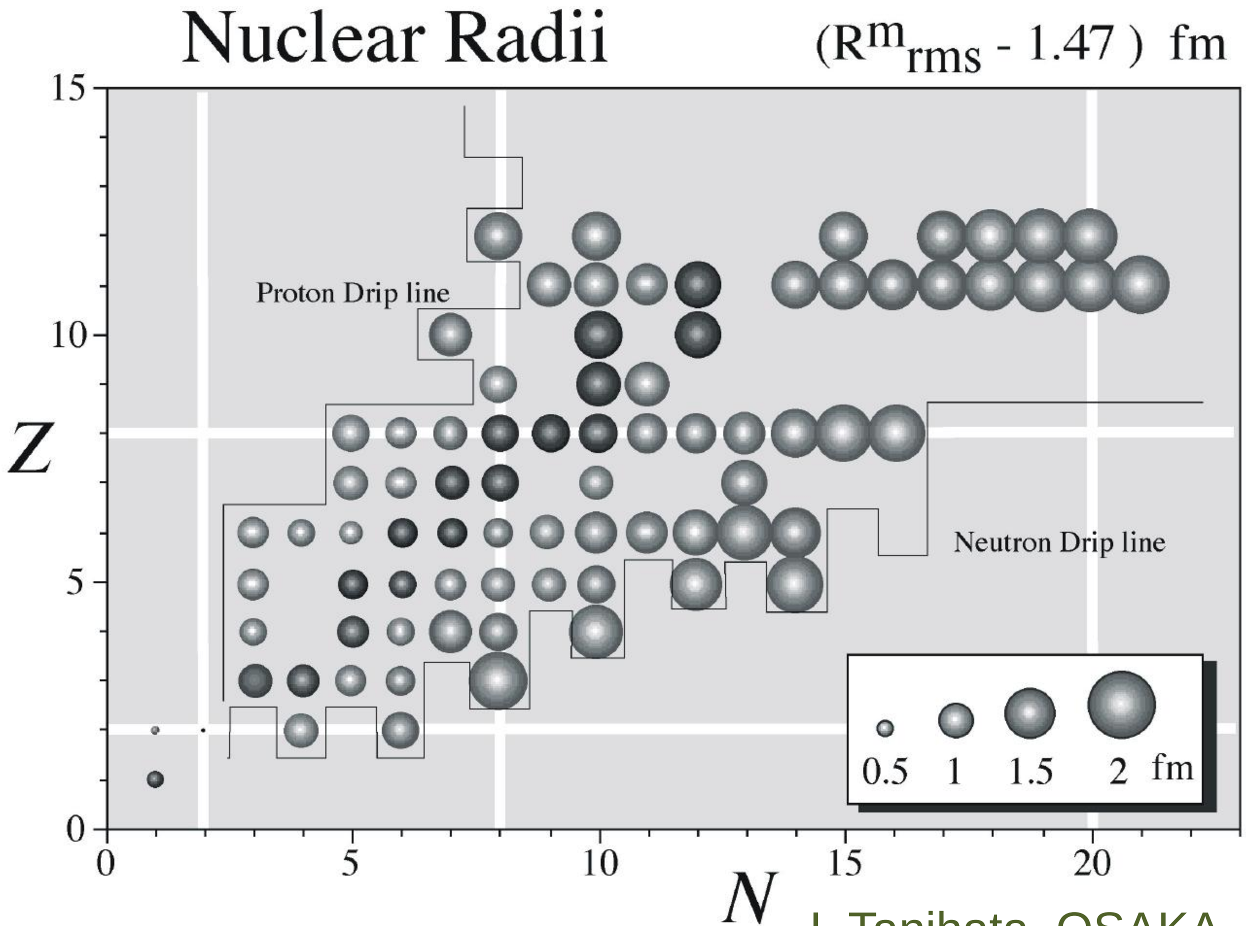
- EMC "European Muon Collaboration" Effect circa 1983, CERN
- J.Seely, A. Daniel et al, "New Measurements of the EMC Effect in Very Light Nuclei" (nucl-ex/0904.4448)





Nuclear Size Extracted from Interaction Cross Sections

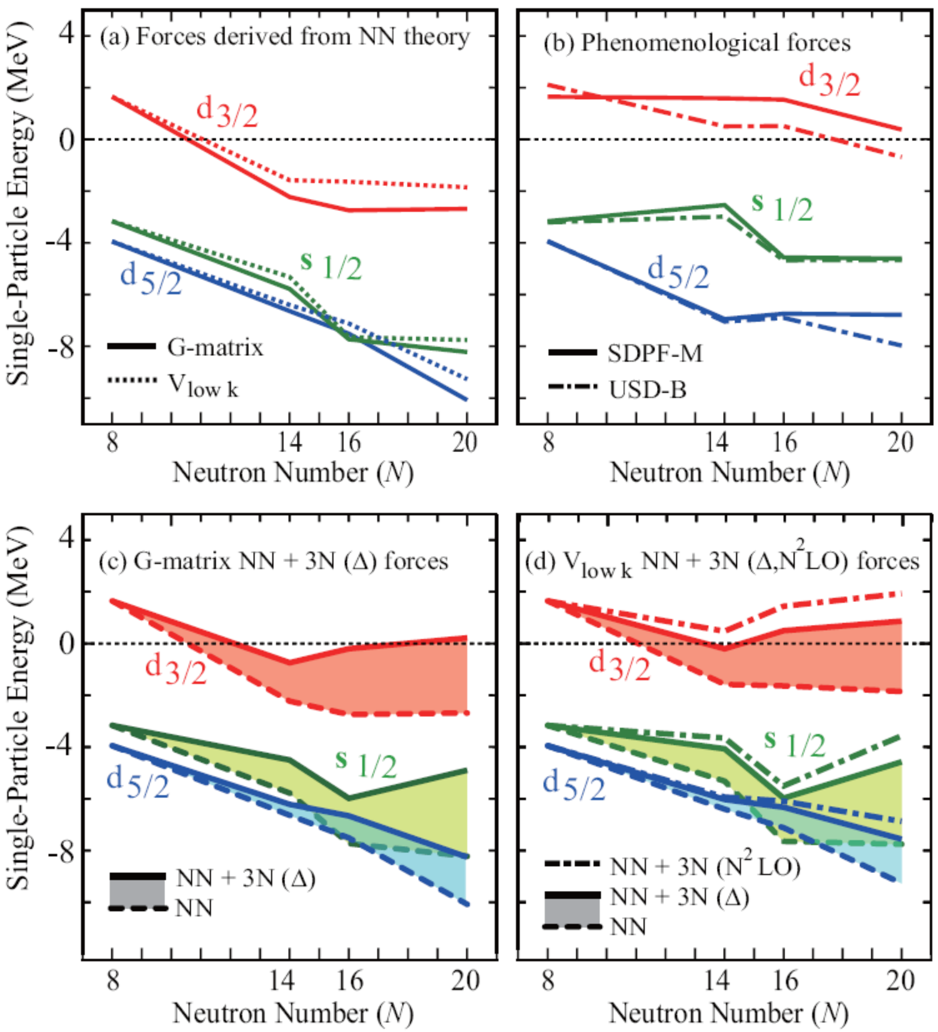
- One of the first thing we learn about nuclei is that Nuclear radii follow the formula: $r = r_0 A^{1/3}$ (Equation 1.2 Wong *Introductory Nuclear Physics*
- This is incorrect



I. Tanihata, OSAKA

Other Evidence for Three Body Forces – Evidence for QCD

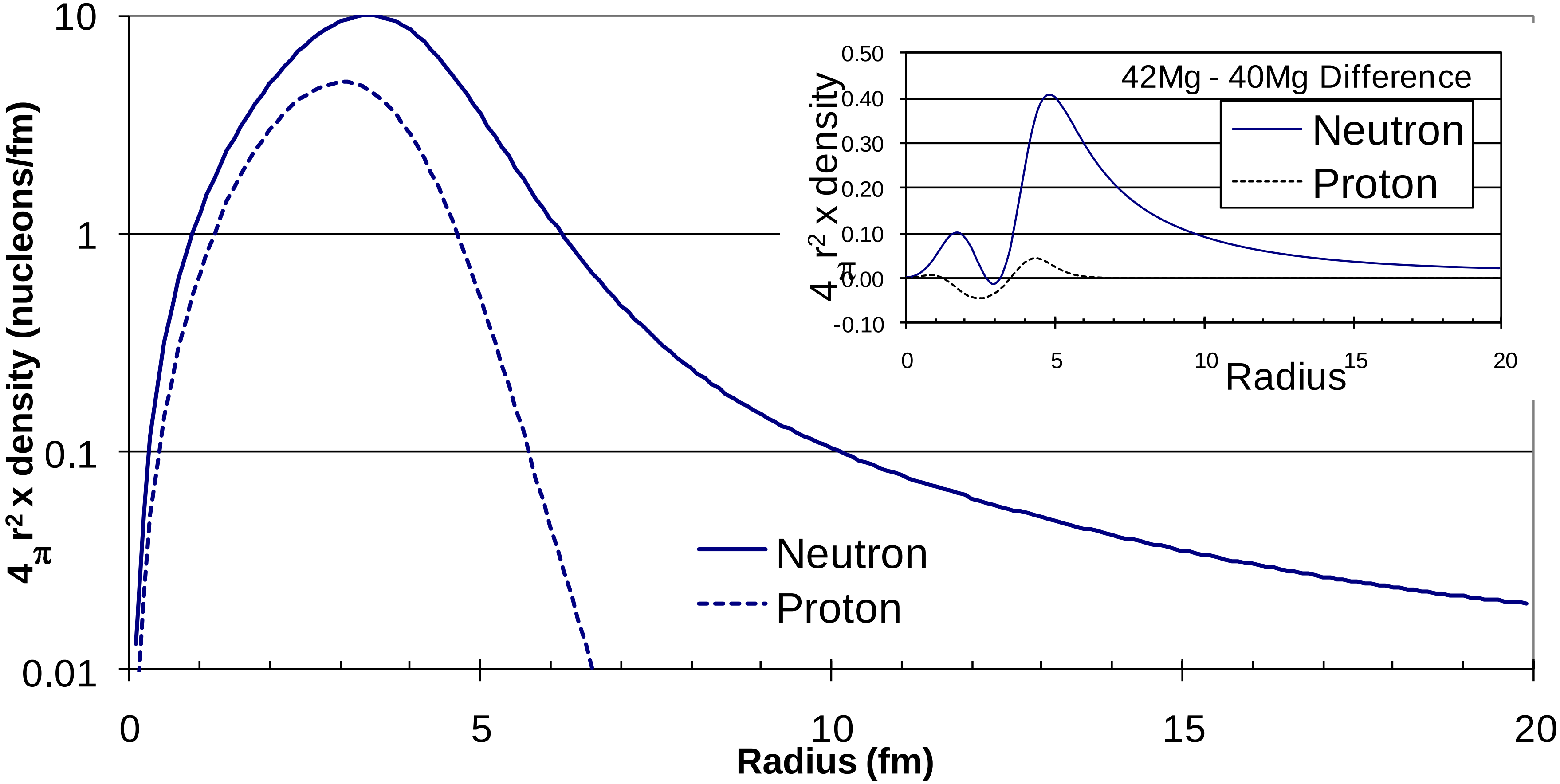
- T. Otsuka *et al.* PRL 2010: NNN force may be the solution to understanding the Oxygen drip line
- Lattice QCD may be able to provide the isospin dependence of the NNN force needed to understand nuclei
- Comparison of this dependence to rare isotope data allows a test of lattice QCD in nuclei



New insight and physics from extreme halos and skins – Example 42Mg

Estimated to be produced at 10 atoms/day

100 keV binding energy for the last two neutrons - Theory BA Brown



Tensor Force

- Otsuka *et al.* has shown the importance of a monopole part of the tensor force in nuclei (Otsuka et al. PRL 2001, 2005, 2010)
- Related to single pion exchange (Yukawa 1935)
- This modifies the standard shell picture