FRIB physics (lecture 1)

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overview

- what is FRIB
- FRIB big science questions
- connection to QCD
- the hardest many-body problem ever
- typical approximations
- why exotic stuff
- nuclear reactions as a tool
- production of the exotic stuff

FRIB facility for rare isotope beams

Google FRIB?

The Facility for Rare Isotope Beams (FRIB) will be a new national user facility for nuclear science that will provide intense beams of rare isotopes (that is, short-lived nuclei not normally found on Earth).

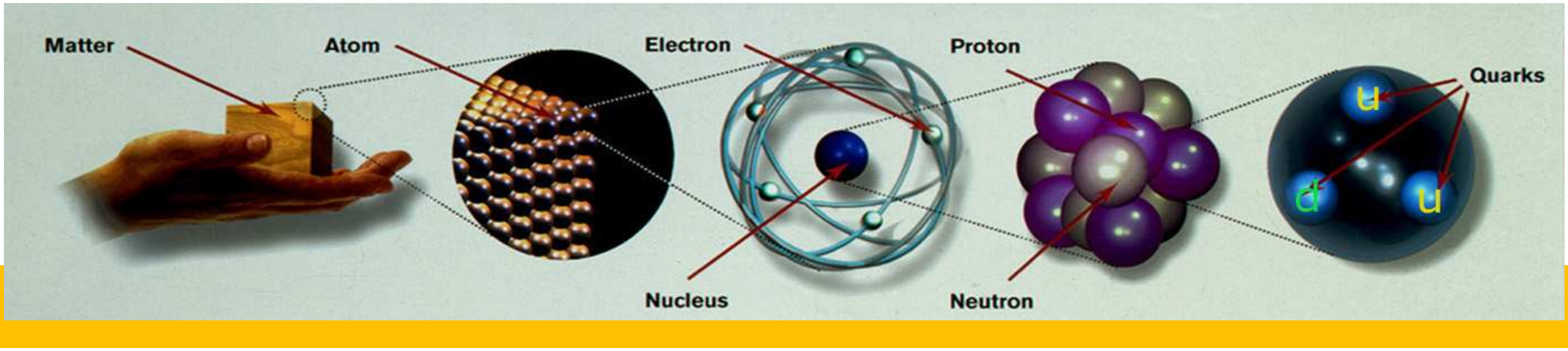
FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society.

Big science questions: why is matter stable?

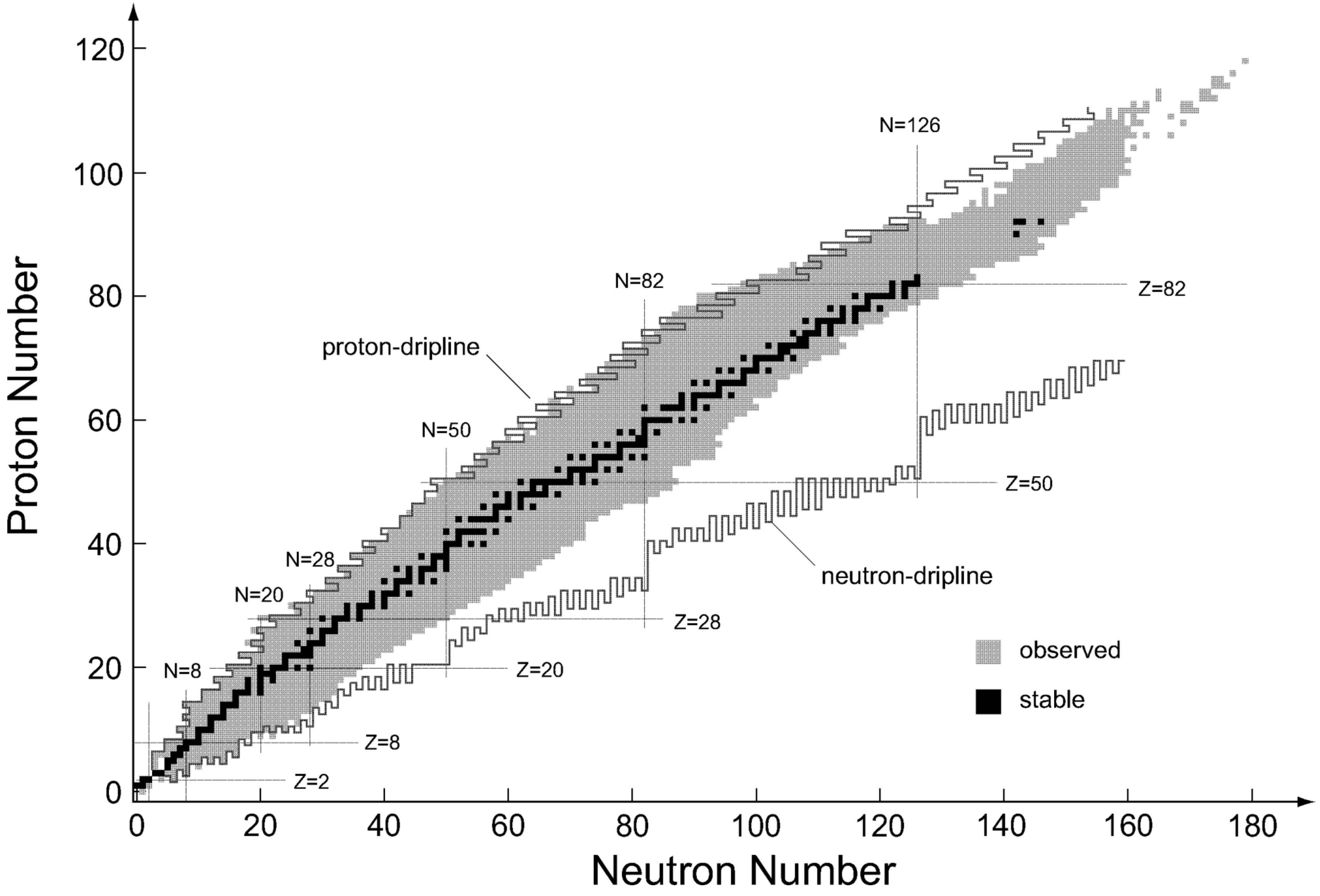
- JLAB addresses the nature and stability of nucleons, protons and neutrons, and how their properties may change inside a nucleus

- FRIB addresses the stability of finite nuclei and extended nuclear matter.
    - What makes the nuclei of atoms possible?
    - How and why do they decay?
    - What is the nature of neutron star matter?

- FRIB addresses how nuclei interact. It probes the low-energy reaction of nuclei relevant to astrophysics, energy, and other fields



properties of nuclei: chart of nuclei



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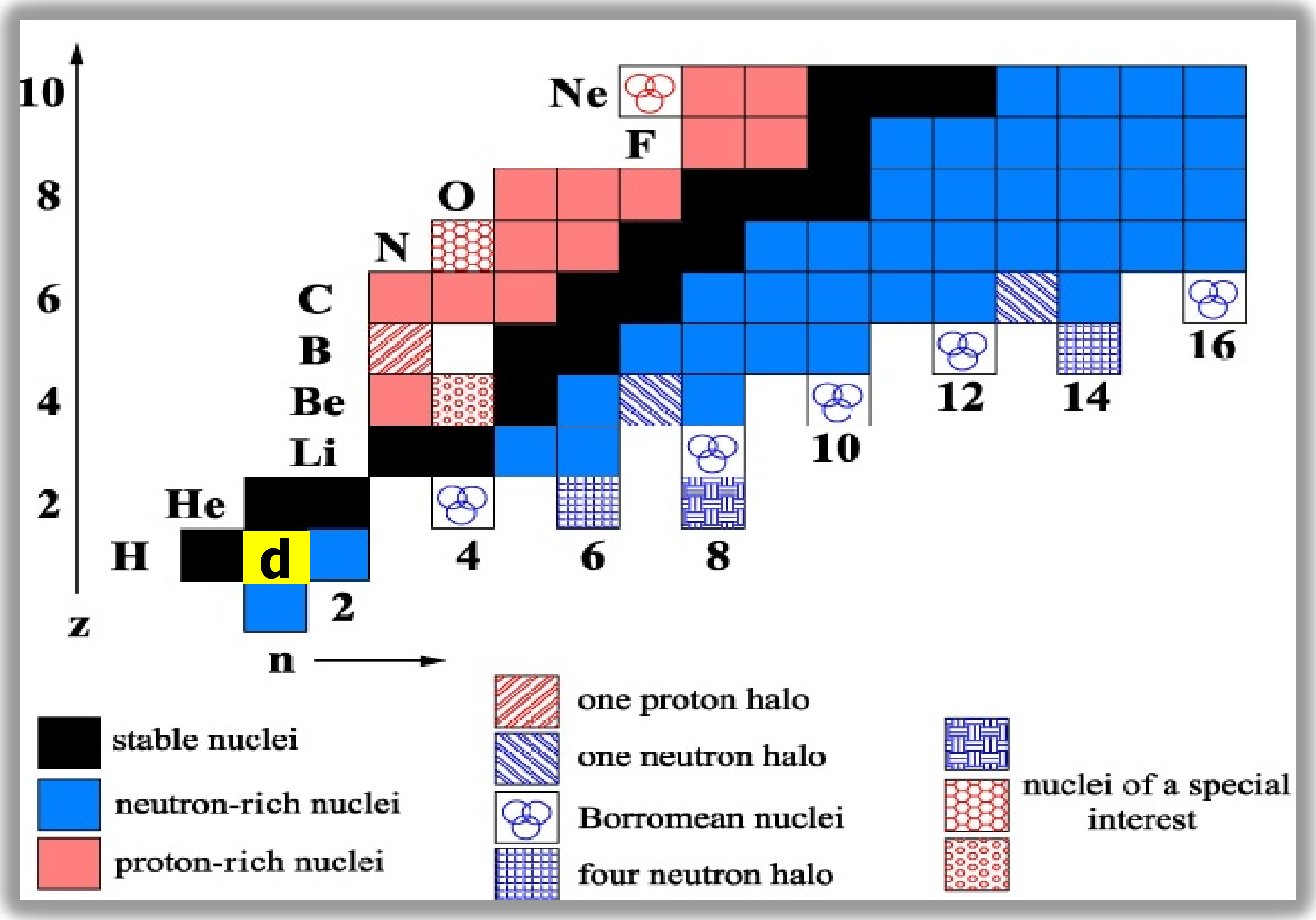
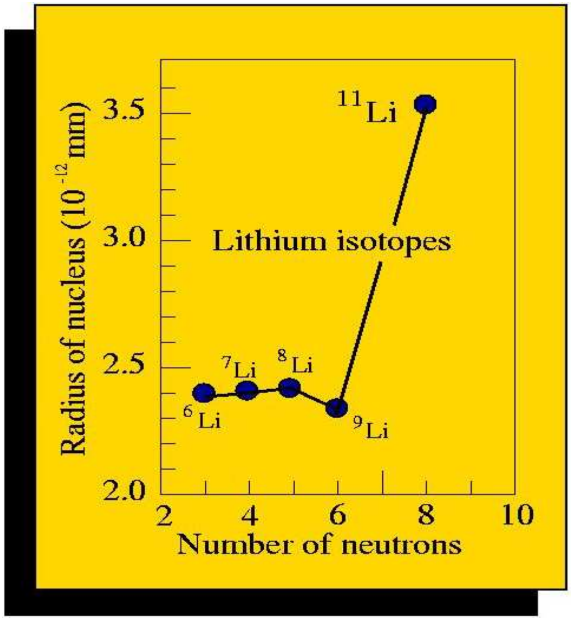
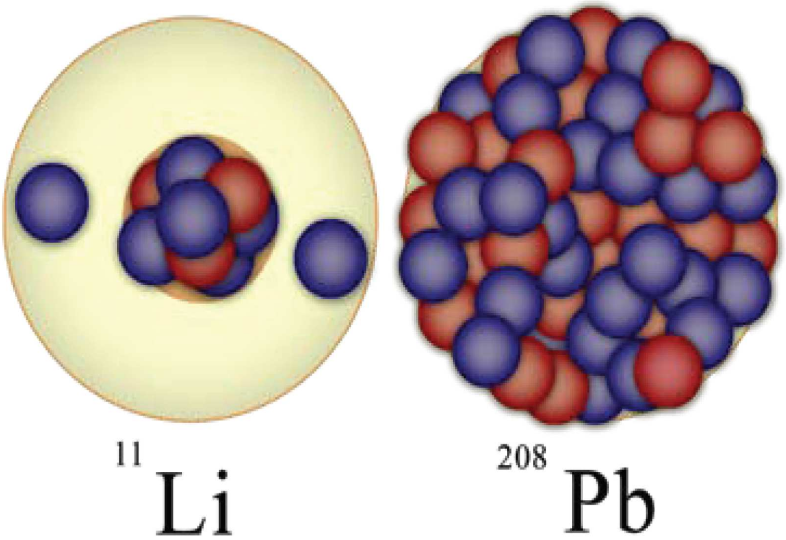


weakly bound systems: halo nuclei





Very large spatial extension:
correct asymptotic behaviour needed
finite range effects crucial

the heaviest halo so far

^{22}C

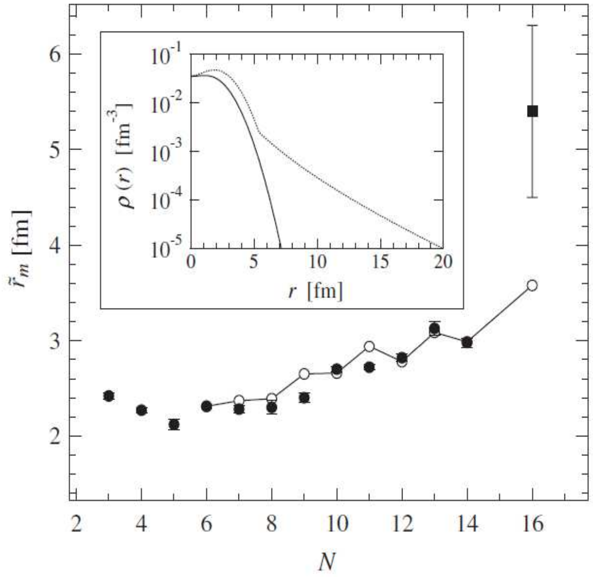


FIG. 2. The $\tilde{r}_m$ as a function of the neutron number of C isotopes. The filled square and circles show the present result and those determined at GSI [14], respectively, while open symbols are the result of the calculation [22]. The lines connect the open circles. The inset shows $\rho_p(r)$ (solid line) and $\rho_n(r)$ (dotted line) of ^{22}C for the determined parameter. See text.

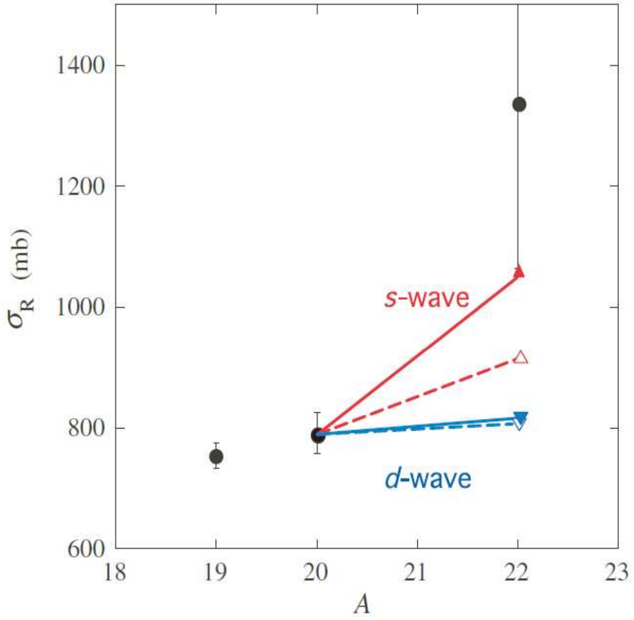
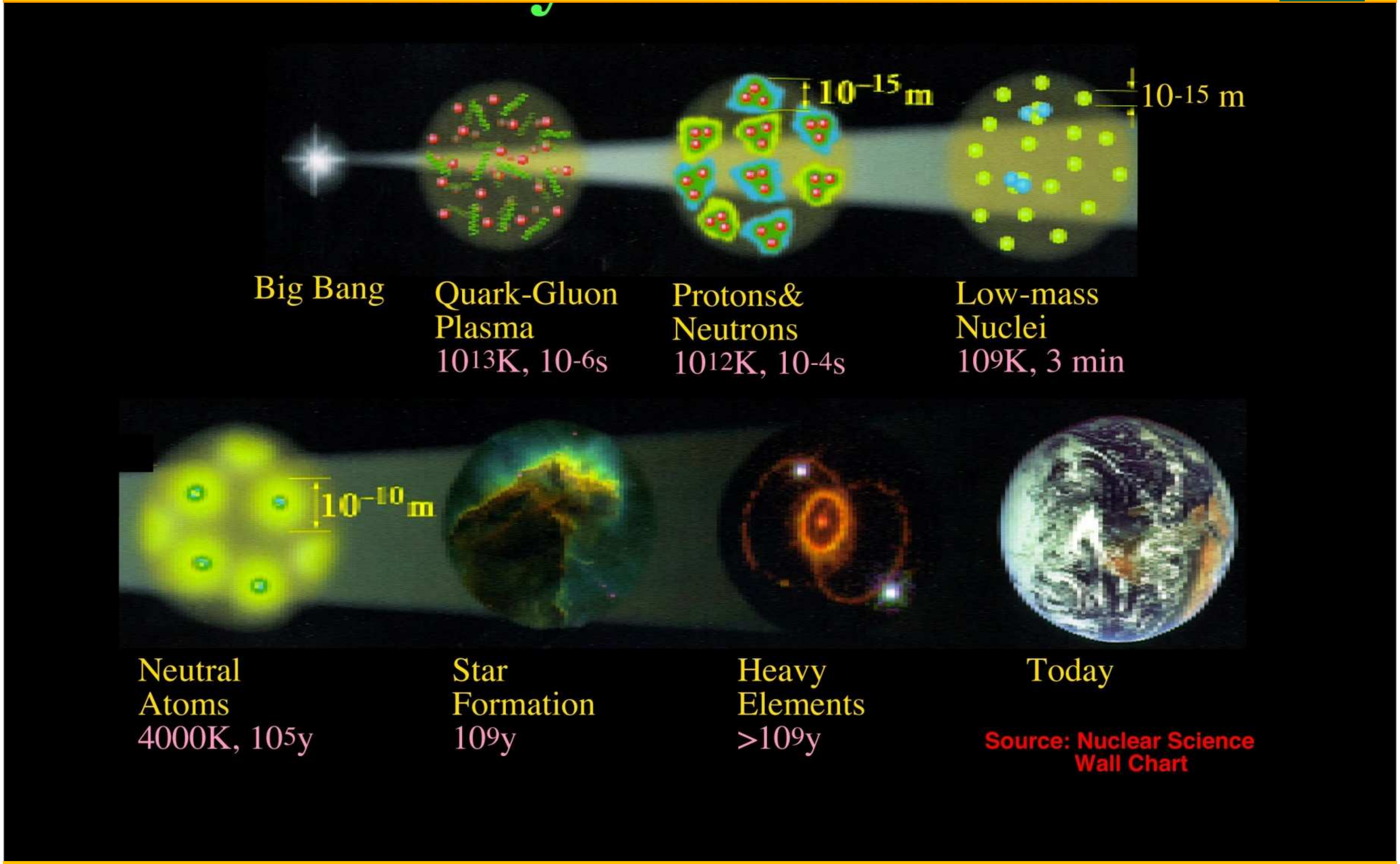


FIG. 3 (color). The σ_R for $f = 1.0$ (red triangles) and that for $f = 0.0$ (blue triangles), with $S_{2n} = 420$ keV (open symbols) and $S_{2n} = 10$ keV (closed symbols), respectively. The lines are to guide the eye. The experimental data (solid circles) as a function of the mass number of C isotopes are also plotted.

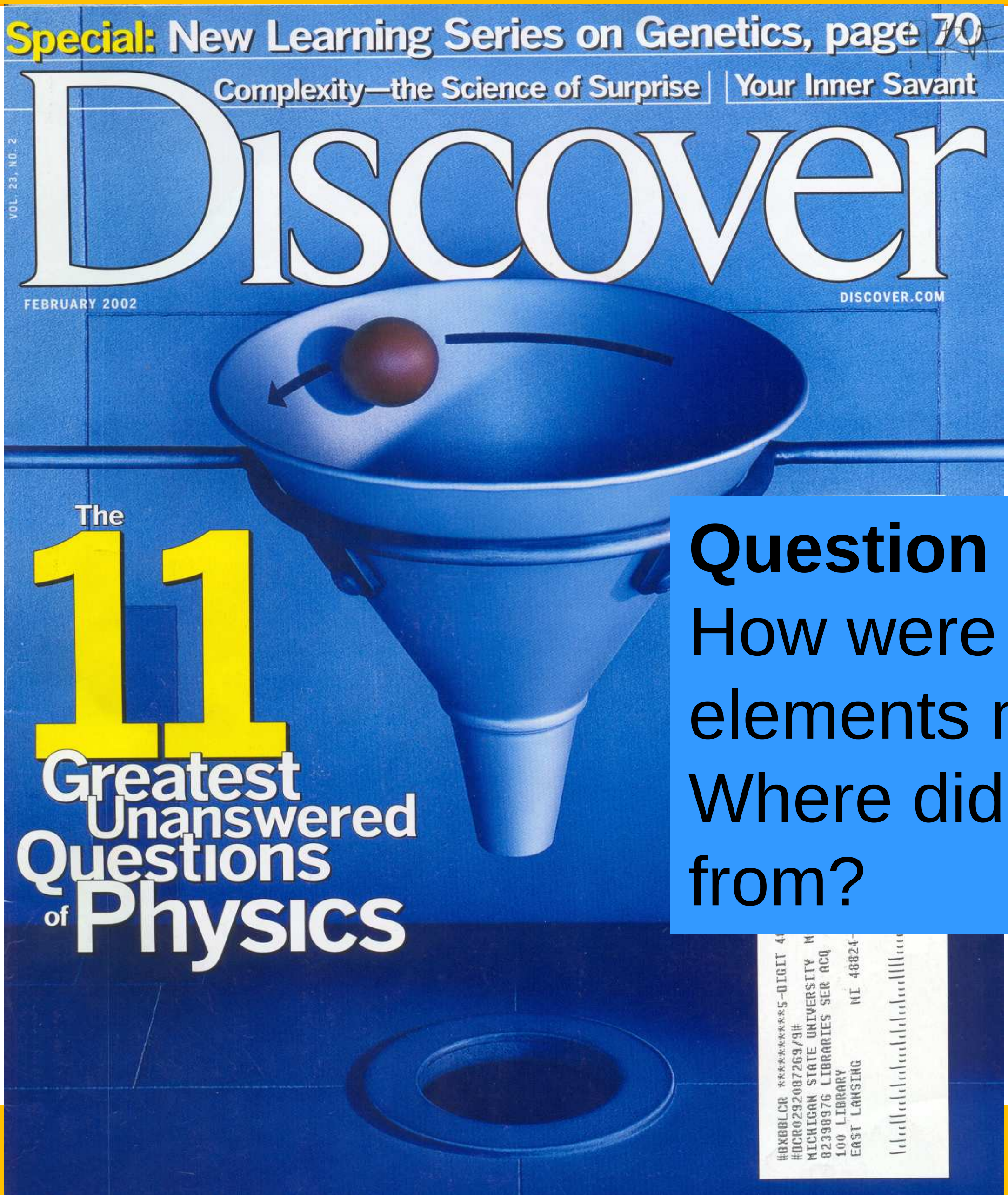
PRL **104**, 062701 (2010)

Big science questions: our history



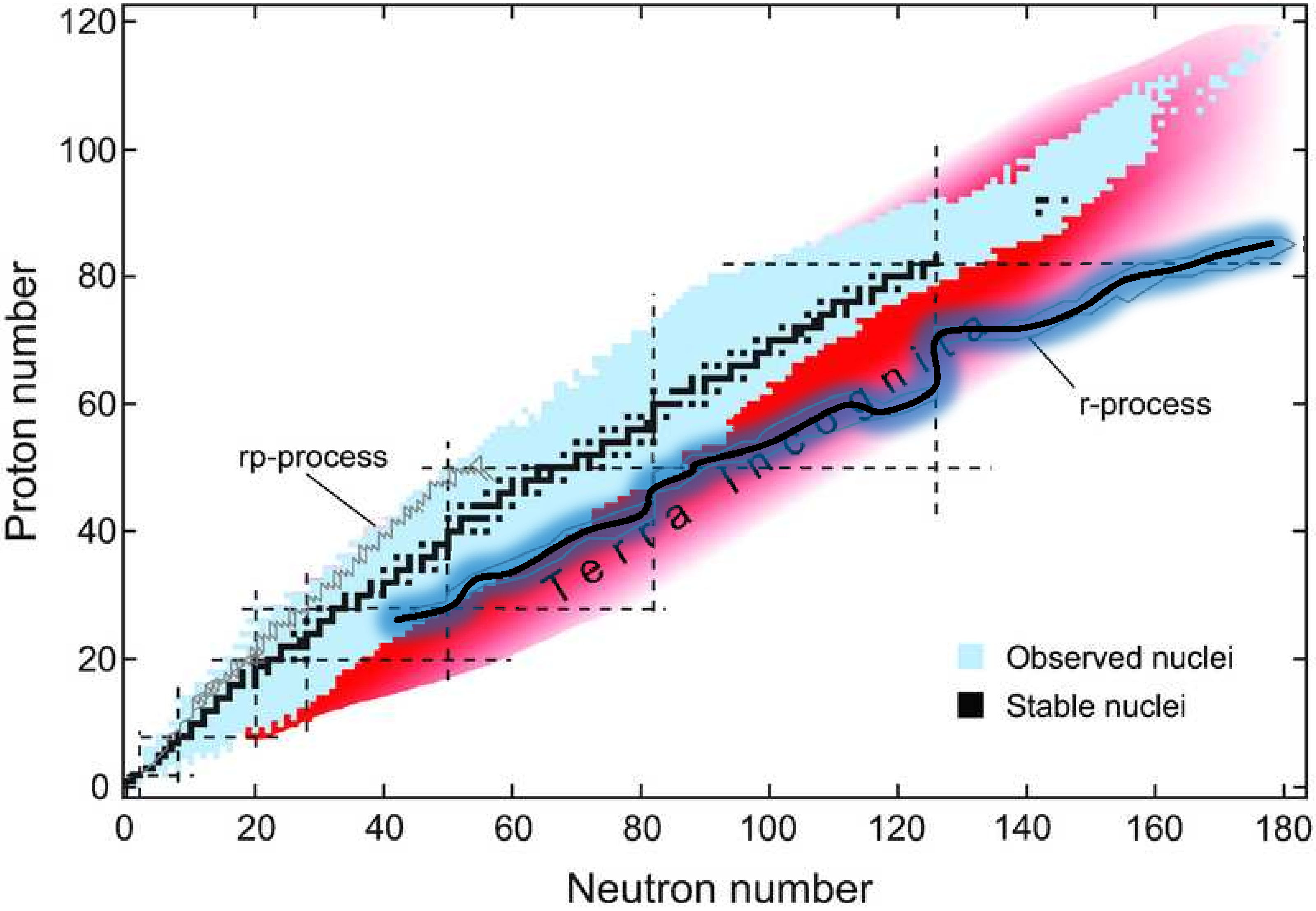
Source: Nuclear Science Wall Chart

Big science questions: origin of the elements



Question 3
How were the heavy elements made? Where did it come from?

heavy elements: r-process in the chart

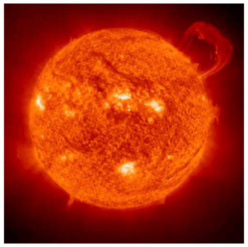


Big science questions: origin of the elements

- The stability of matter is closely related to its origin.
- FRIB explores the likely series of nuclear reactions and decays that have led to the synthesis of the elements and their isotopes.

- Experimentally the study of the origin of matter has two parts
  - Nuclear astrophysics with intense stable beams studies the reactions of stable isotopes in stars – role for stable beam facilities and an underground accelerator
  - FRIB addresses the key role unstable isotopes play in astrophysical processes

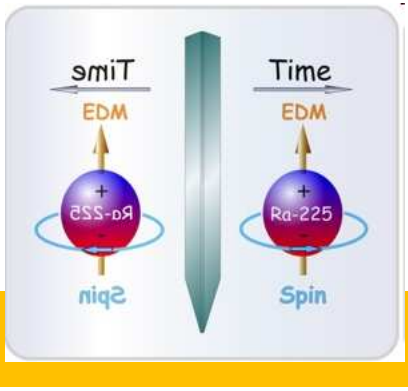
- With data from FRIB and improved astrophysical modeling it will be possible to use abundance data from stars to infer the local history – "stellar archeology"



Big science questions: fundamental symmetries

o FRIB will use of the decay of unstable nuclei to explore fundamental symmetries in physics.

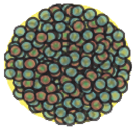
o Angular correlations in β-decay and search for scalar and tensor weak currents (mass scale for new particle comparable with LHC, possibly with ^{6}He and ^{18}Ne at 10^{12}/s)
o Testing time reversal with Electric Dipole Moments: ^{225}Ac, ^{223}Rn, ^{225}Ra, ^{229}Pa (~10,000x more sensitive than ^{199}Hg; ^{229}Pa > 10^{10}/s)
o Parity non-conservation in atomic transitions: long chain of francium isotopes at >10^{9}/s)
o Unitarity of CKM matrix: V_{ud} by super-allowed Fermi decay, and probe the validity of nuclear corrections
o Neutrinoless double-beta decay in nuclei and the majorana neutrinos



Big science questions: how can rare isotopes by used for societal benefit

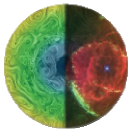
- Many sciences use isotopes as diagnostics for physical and biological process (FRIB will provide access to the widest range of isotopes ever available and will be able to provide them for exploratory studies with a very short development time).
- What quantities of key isotopes can be used for targeted cancer therapy?
- Study relevant nuclear reactions needed for the US Forensics and Stewardship missions
- Separated samples of all actinides and allow their properties and fission products to be measured, in connection to energy generation.
- FRIB will provide isotopes for study of climate change, biological catalyst pathways, production of advanced materials, etc.

FRIB Scientific Program



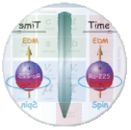
Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.
- The limits of stability of elements and isotopes



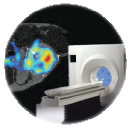
Astrophysical processes

- Stellar archeology
- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts …
- Properties of neutron stars



Tests of fundamental symmetries

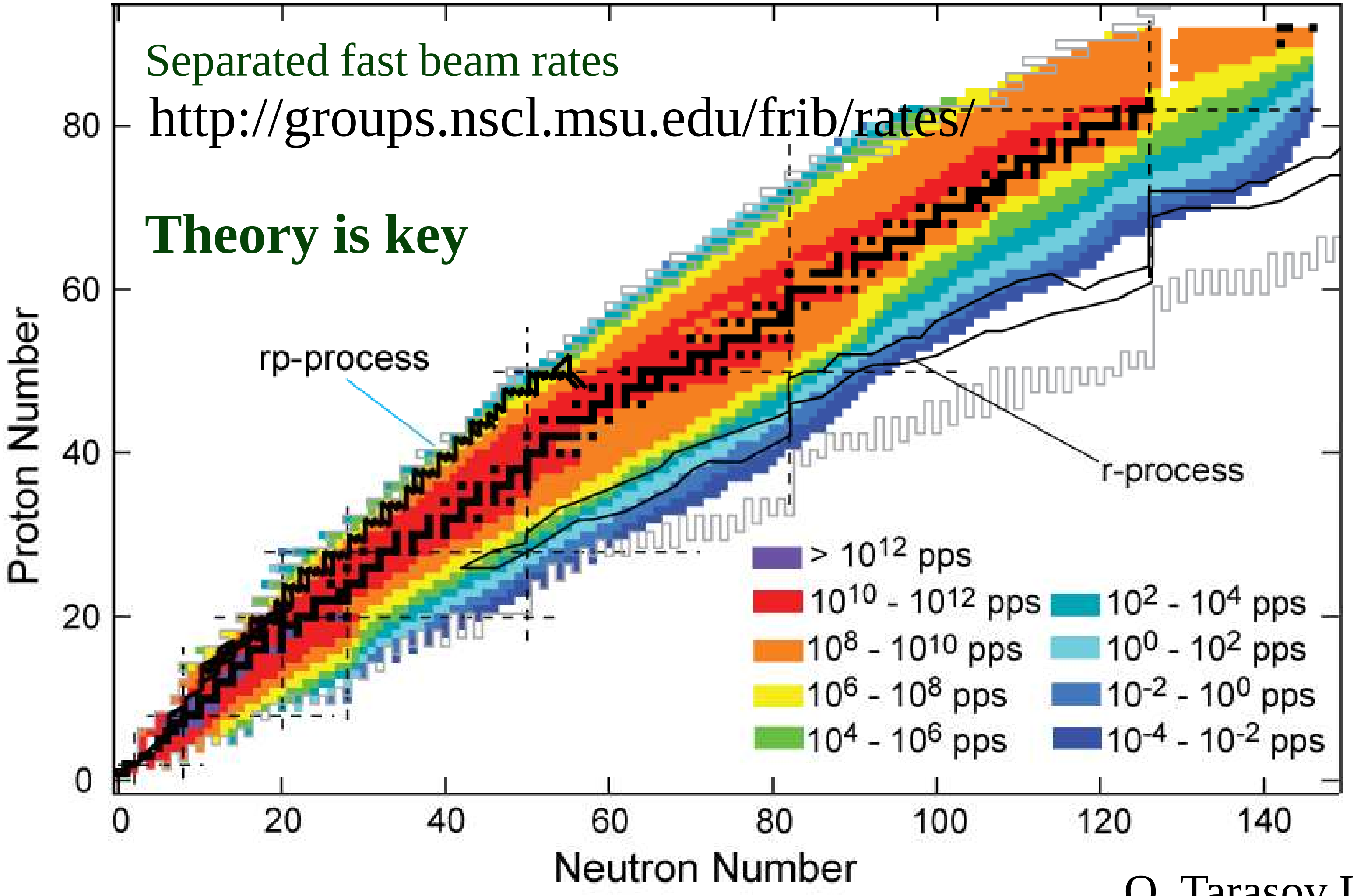
- Effects of symmetry violations are amplified in certain nuclei



Societal applications and benefits

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

The Reach of FRIB – Designer Isotopes



Separated fast beam rates

http://groups.nscl.msu.edu/frib/rates/

Theory is key

O. Tarasov LISE++

Questions?

overview

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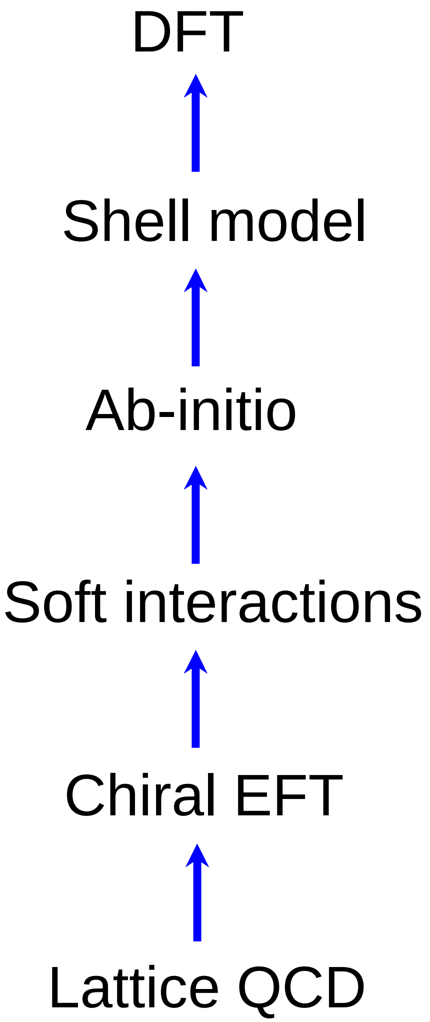
theory rooted on the fundamental interactions



DFT

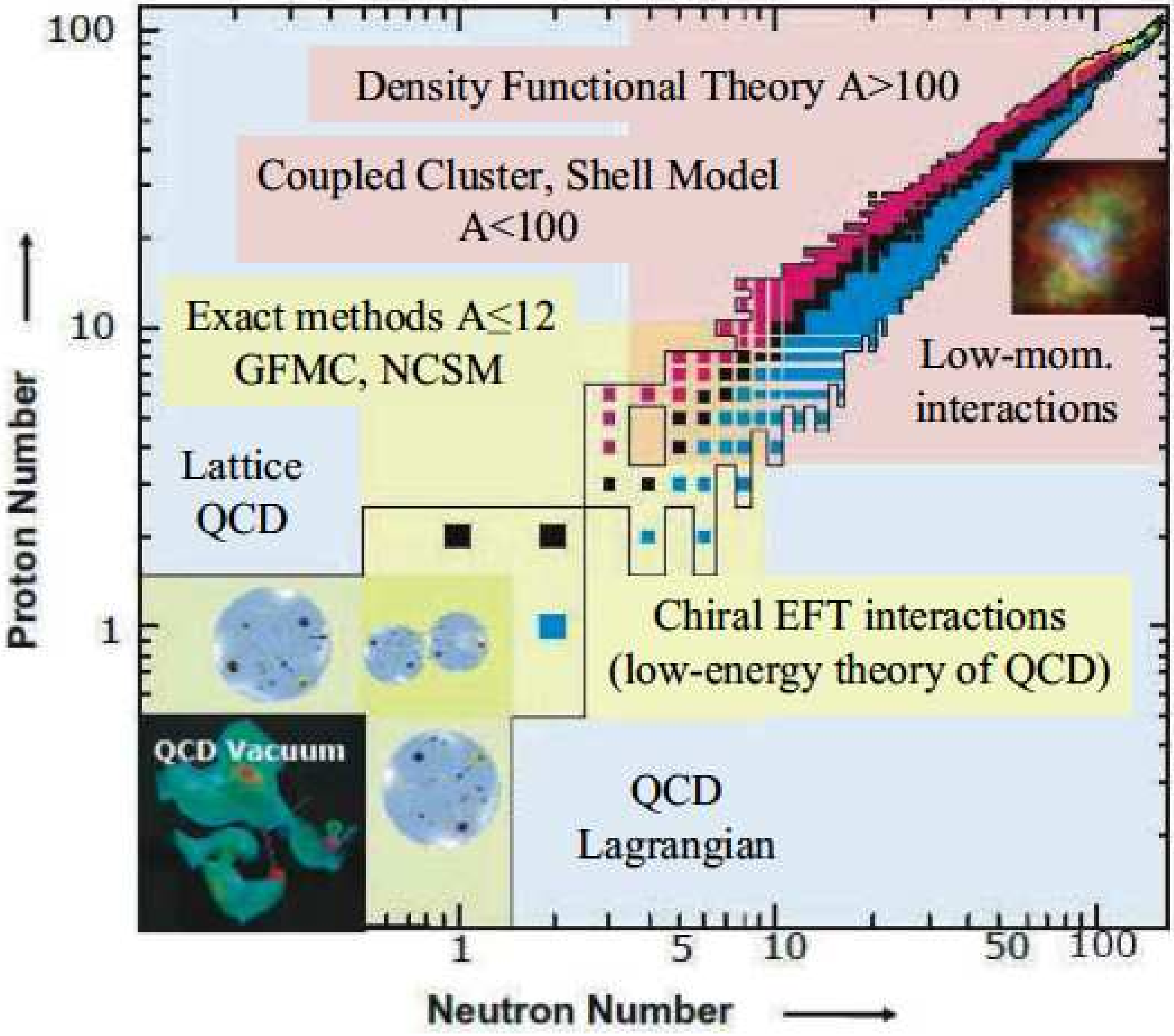
Shell model

Ab-initio

Soft interactions

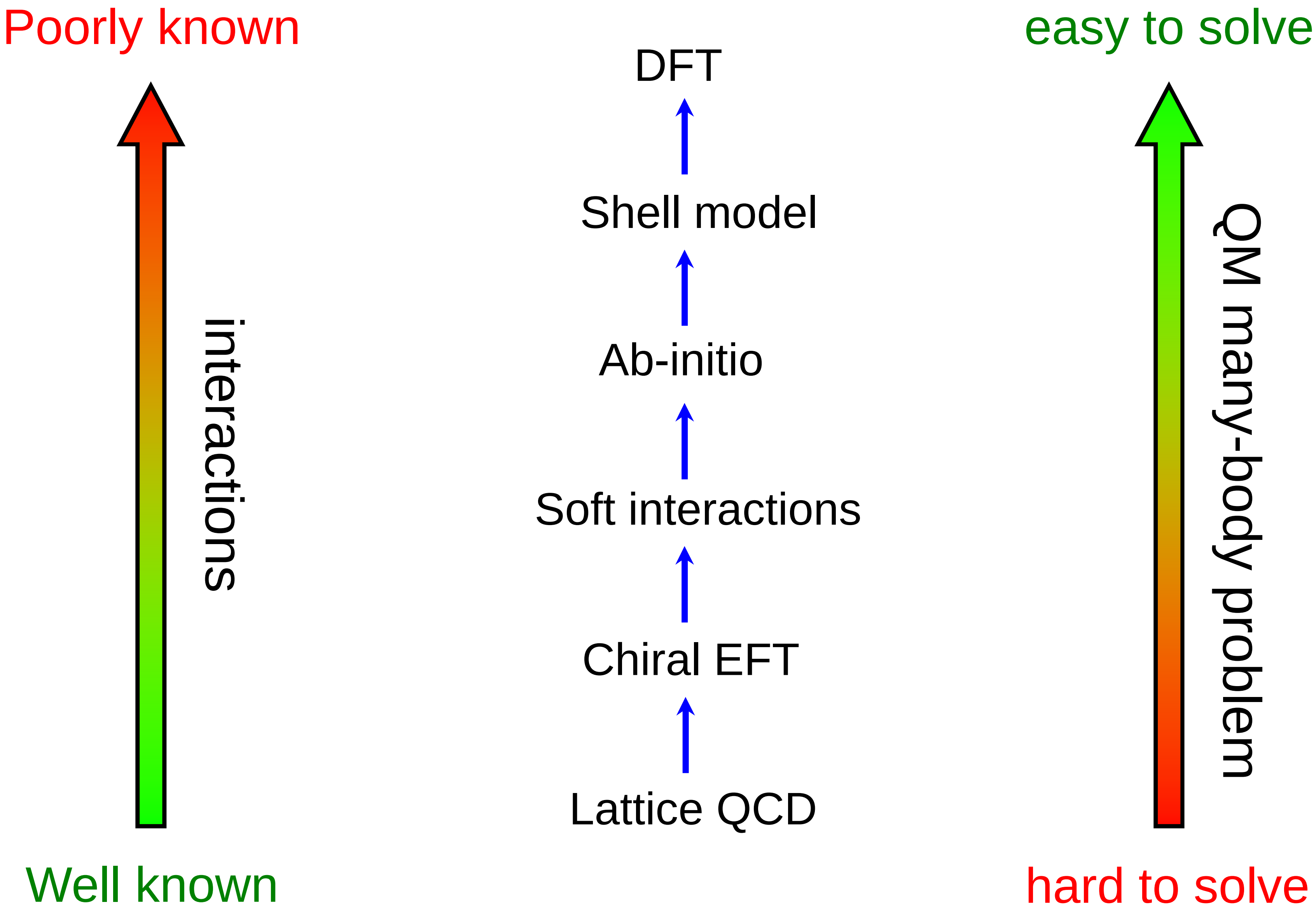
Chiral EFT

Lattice QCD



[Scott Bogner, Colloquium MSU 2012]

No-free-lunch theorem



Poorly known

interactions

Well known

DFT

↑

Shell model

↑

Ab-initio

↑

Soft interactions

↑

Chiral EFT

↑

Lattice QCD

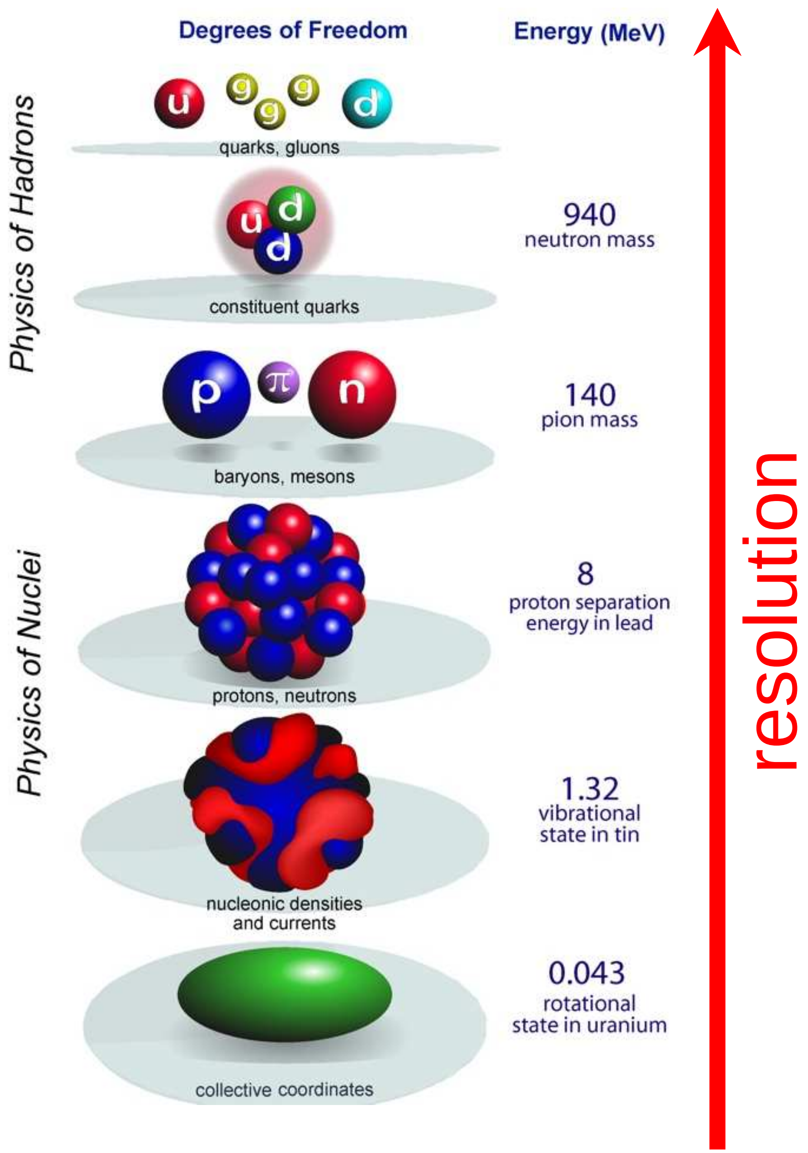
easy to solve

QM many-body problem

hard to solve

[Scott Bogner, Colloquium MSU 2012]

Multiple Scales in Nuclear Physics



Old View

- Multiple scales complicate life
- No easy way to connect them

Modern View

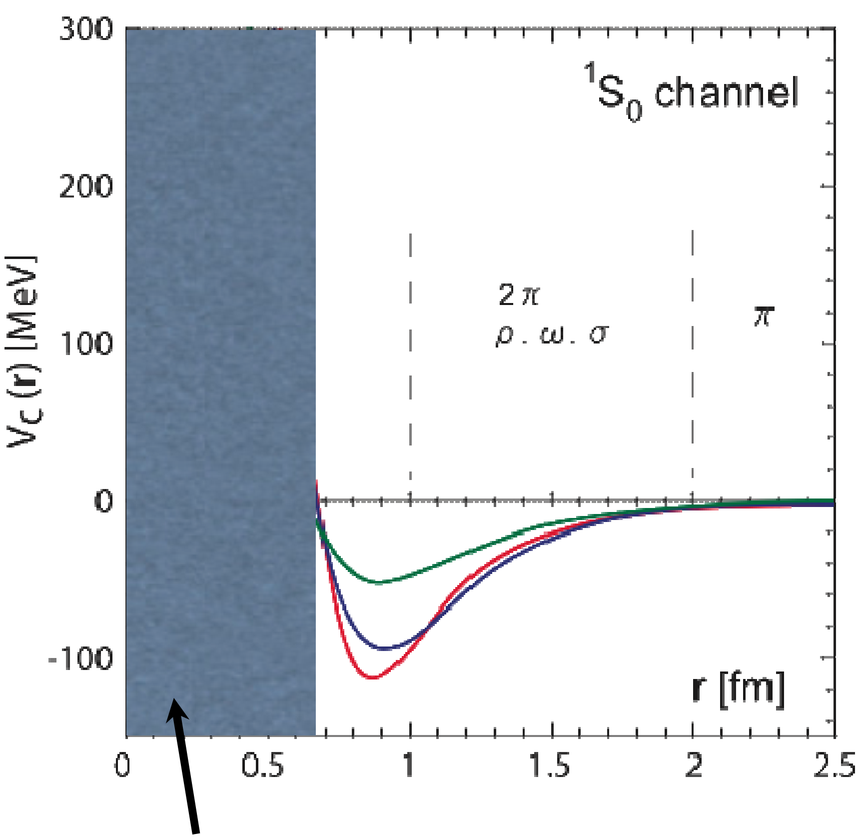
- Ratio of scales => small parameters!
- Effective theories at each scale connected by renormalization group

$$V(\Lambda) = V_{2N}(\Lambda) + V_{3N}(\Lambda) + \cdots$$

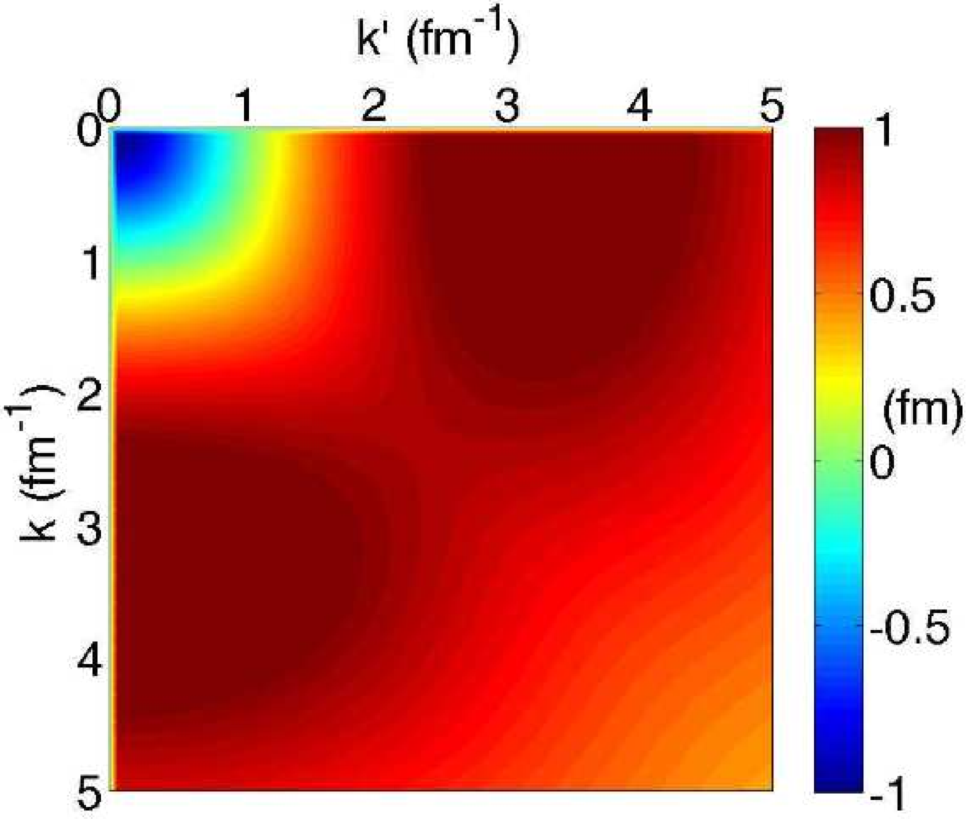
Use RG to pick a convenient Λ "resolution scale"

[Scott Bogner, Colloquium MSU 2012]

Why are nuclear many-body problems hard?



"hard-core" of V(r) => strong offdiagonal V(k,k')

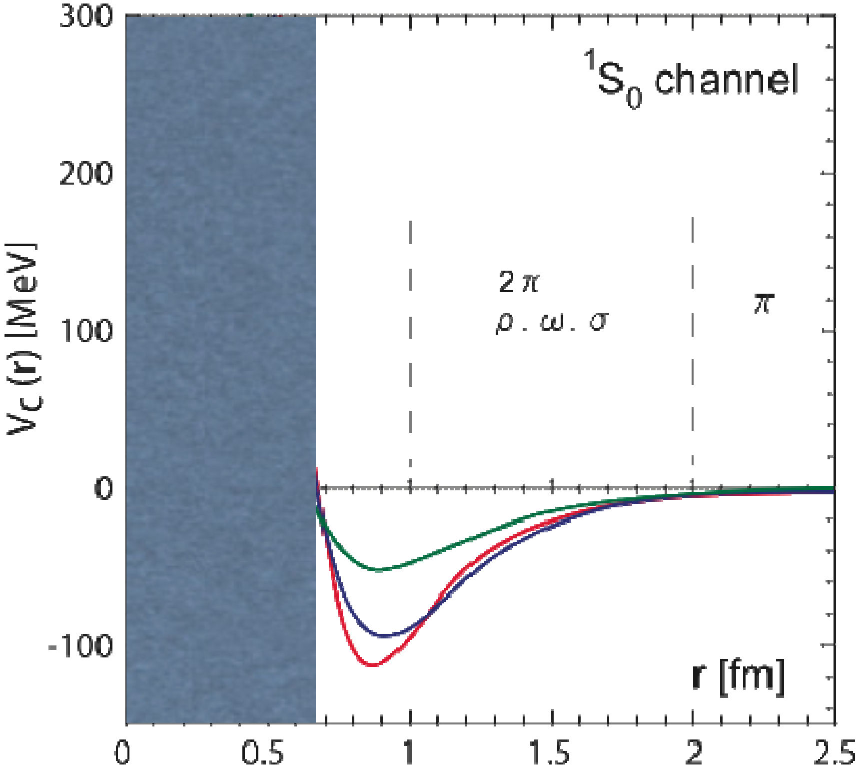


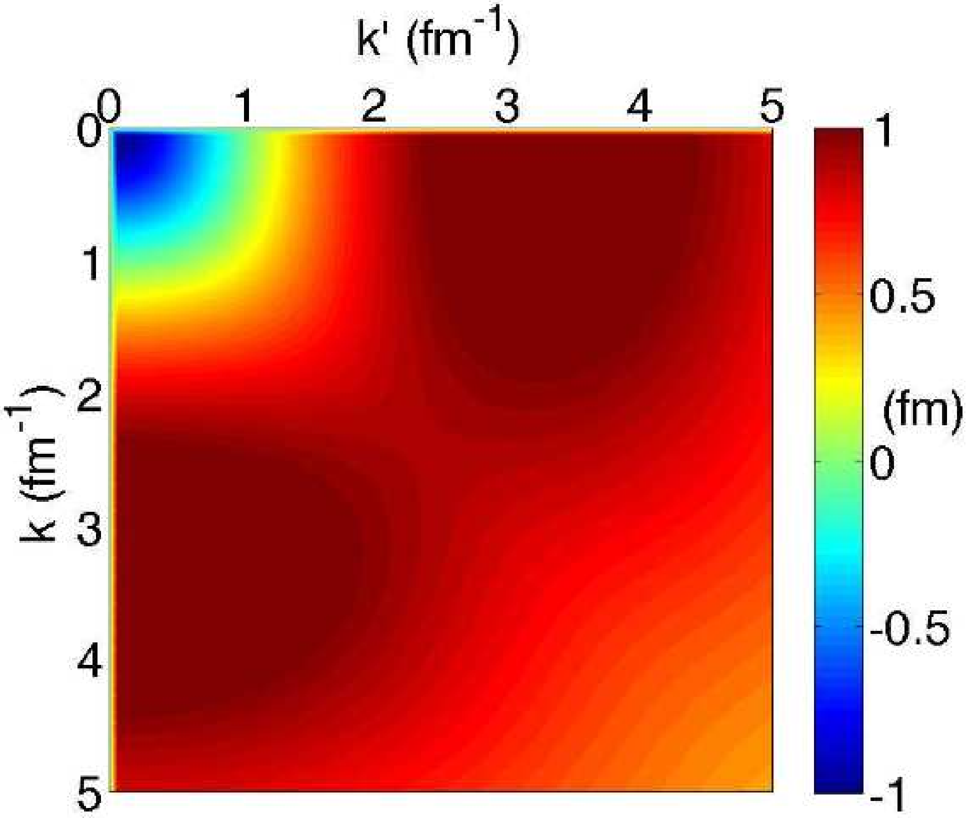
$$V_{l=0}(k,k') = \int d^3r\, j_0(kr)\, V(r)\, j_0(k'r')$$

Characteristic $k_F \sim 1\ \mathrm{fm}^{-1}$

[Scott Bogner, Colloquium MSU 2012]

Why are nuclear many-body problems hard?



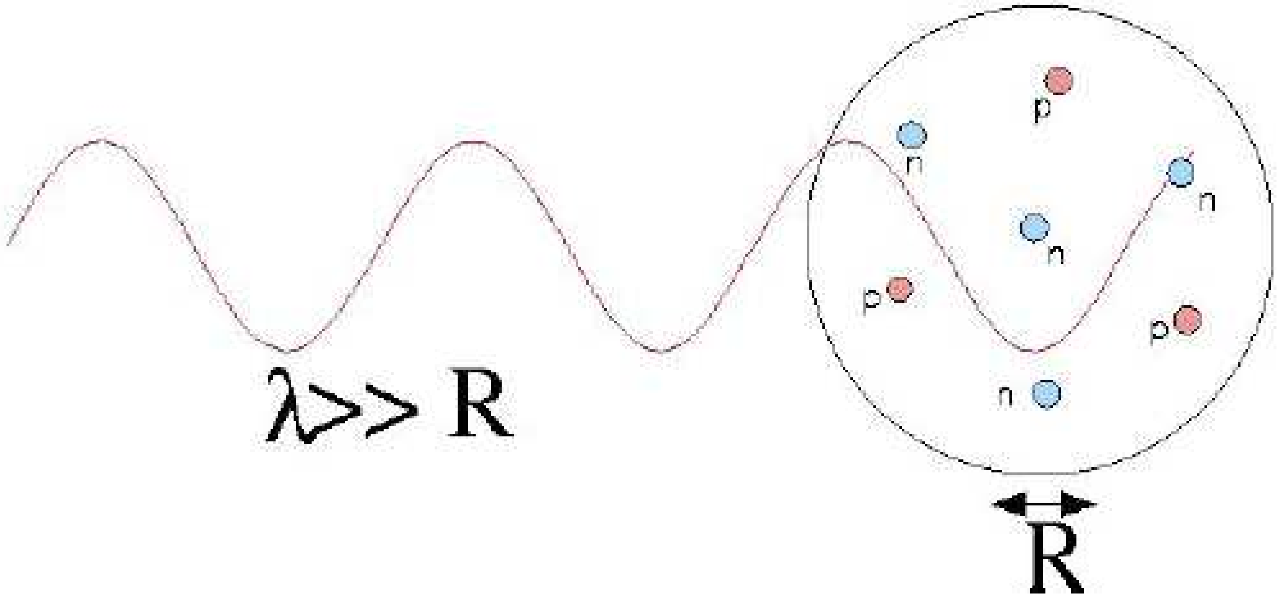


Complications: strong correlations, non-perturbative, poorly convergent basis expansions, ...

Characteristic $k_F \sim 1$ fm^{-1}

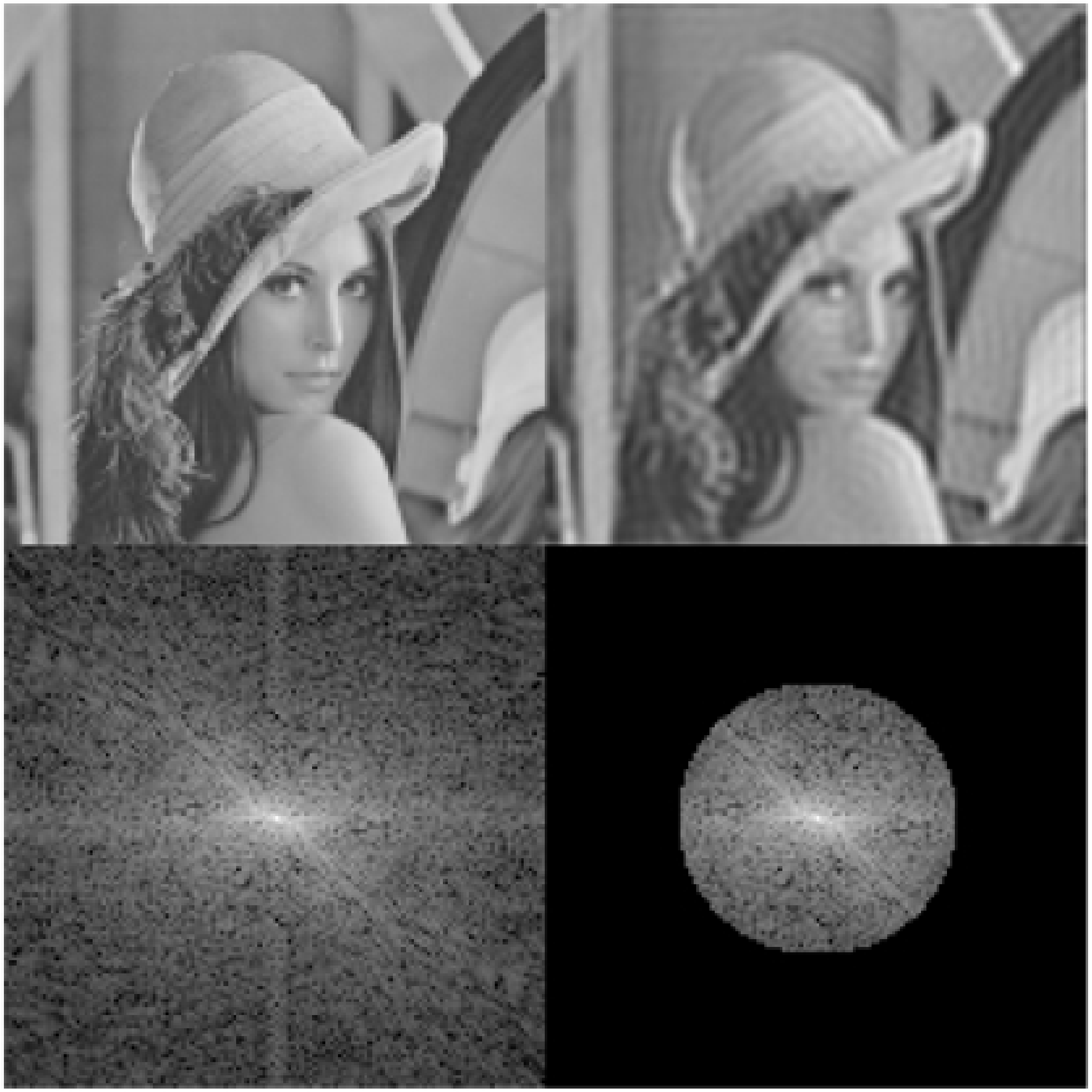
[Scott Bogner, Colloquium MSU 2012]

Principle of Low-Energy Effective Theories



- If a system is probed at low energies, fine details not resolved
- Use convenient dof to describe low-energy processes
- Complicated short-distance structure replaced by something simpler without distorting low-E observables

Ex: Low-pass filter on fourier transform of a 2d-image



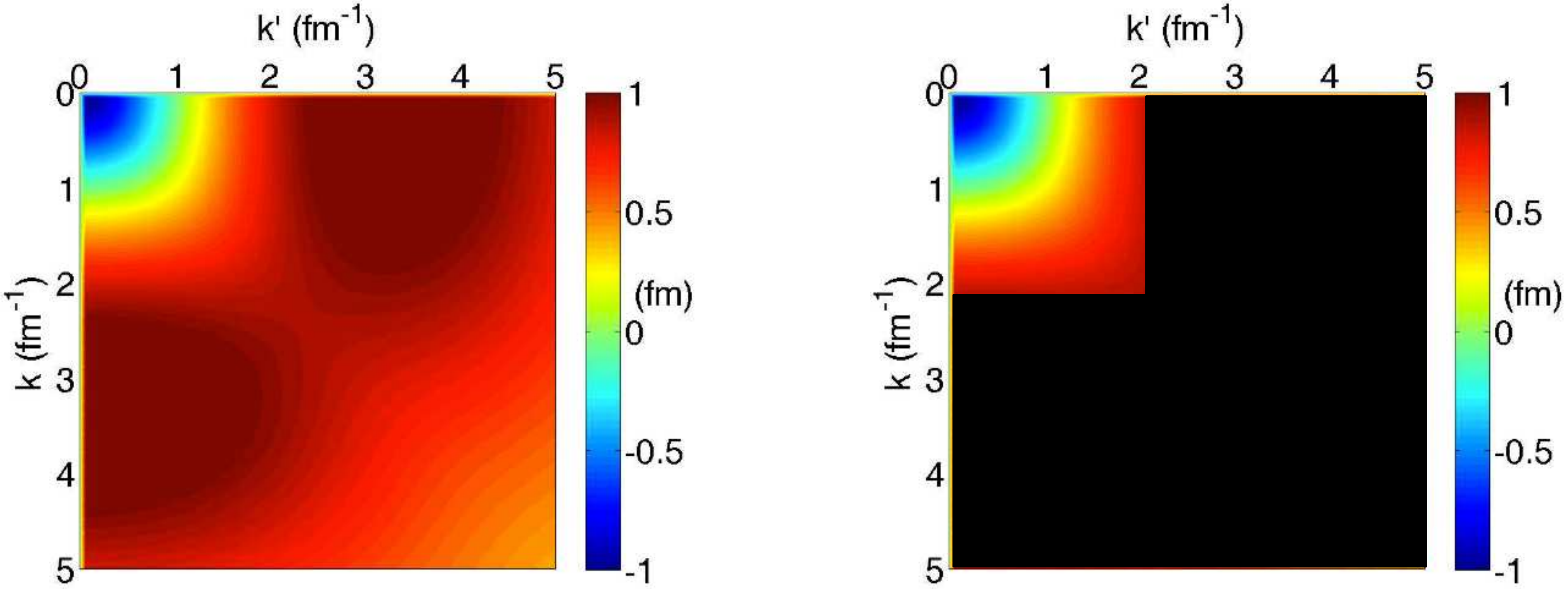
filtered image contains
much less information

BUT

Long-wavelength info
preserved

[Scott Bogner, Colloquium MSU 2012]

Try a naive "low-pass" filter on V:



$$V_{filter}(k', k) \equiv 0 \quad k, k' > 2.2 \text{ fm}^{-1}$$

Now calculate low E observables (e.g., NN scattering) and see what happens...

[Scott Bogner, Colloquium MSU 2012]

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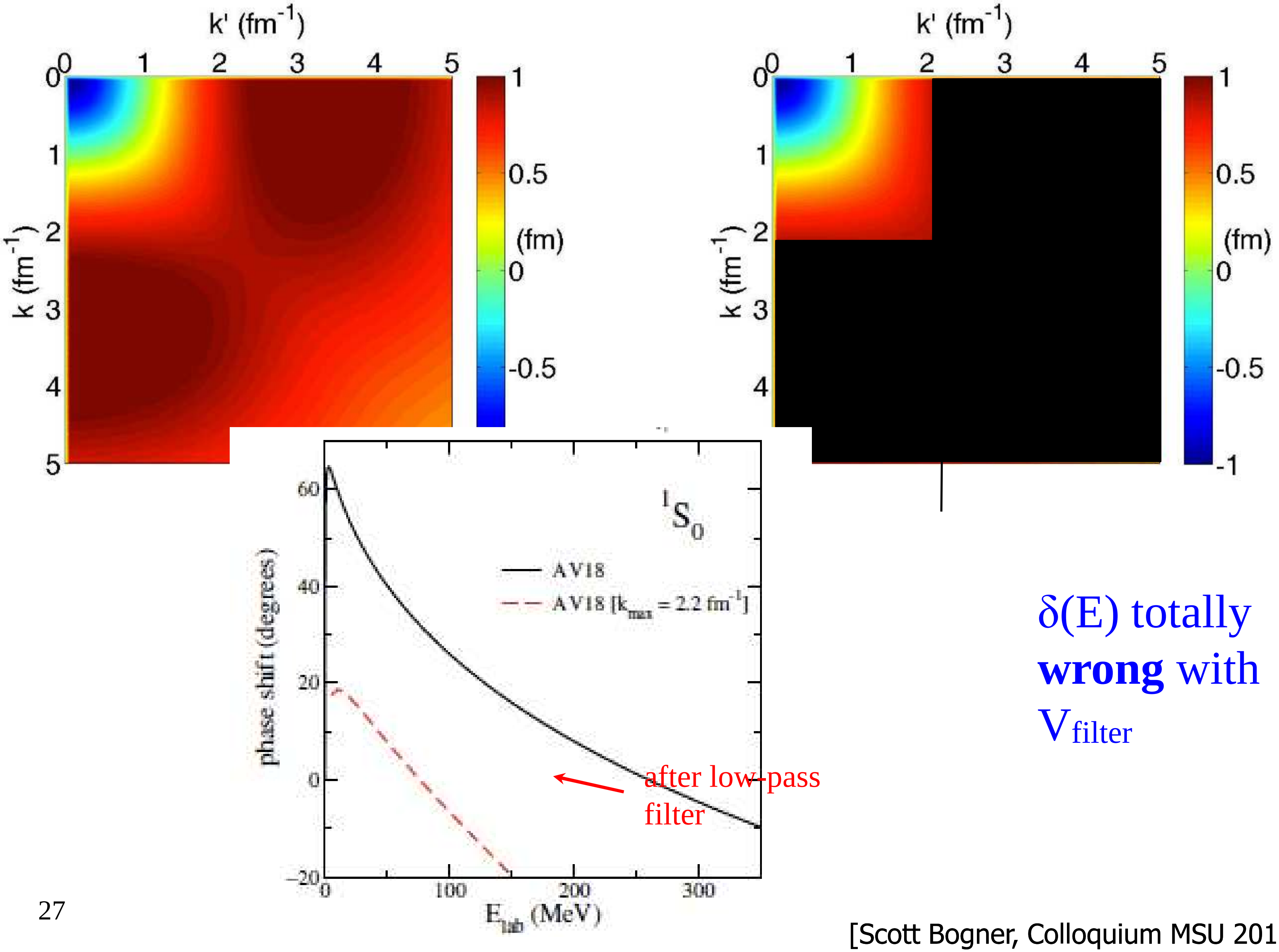
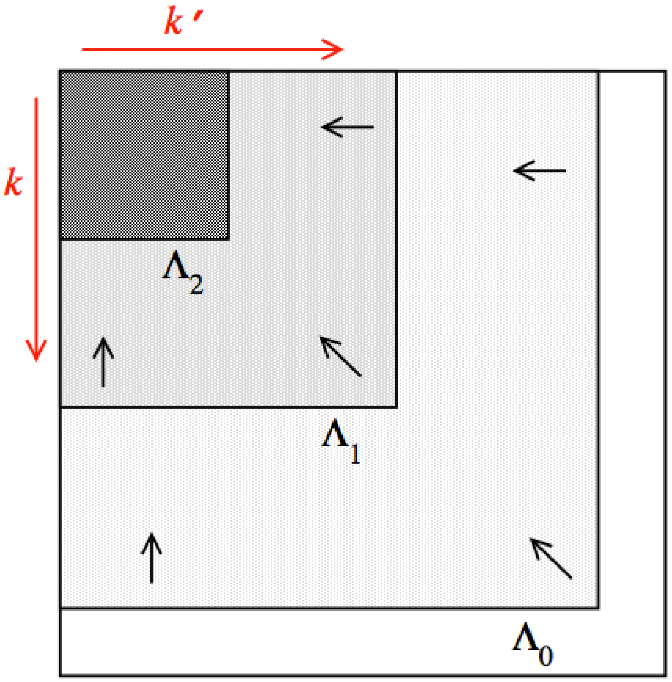


after low-pass filter

δ(E) totally **wrong** with V_{filter}

[Scott Bogner, Colloquium MSU 2012]

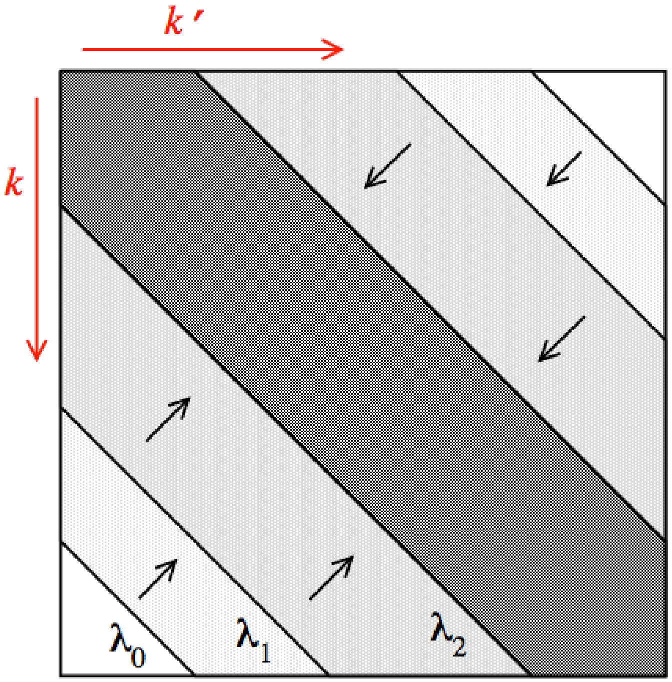
2 Types of Renormalization Group Transformations



“$V_{\text{low k}}$”

integrate-out high k states

preserves observables for k < Λ



“Similarity RG”

eliminate far off-diagonal coupling

preserves “all” observables

Identical simplifications despite differences in appearance!

Bogner, Furnstahl, Schwenk, Prog. Part. Nucl. Phys. **65** (2010)

Low energy effective theories

Generic form of the effective theory

$$V_{eff} = V_L + \delta V_{c.t.}(\Lambda)$$

$$\delta V_{ct} = C_0(\Lambda)\delta^3(\mathbf{r}) + C_2(\Lambda)\nabla^2\delta^3(\mathbf{r}) + \cdots$$

encodes the
effects of integrated
dof on low-E physics

universal form; depends
only on symmetries

The complicated short-distance structure of the “true” theory is encoded in a few numbers that can be calculated from the the underlying theory

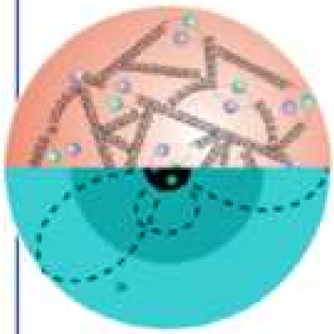
OR

in cases where the short-distance structure is unknown or too complicated, can be extracted from low E data

Effective Field Theory (EFT) is based on these ideas

Λ / Resolution dependence of nuclear forces

with high-energy probes:
quarks+gluons



Effective theory for NN, 3N, many-N interactions and electroweak operators: resolution scale/Λ-dependent

$$H(\Lambda) = T + V_{\mathrm{NN}}(\Lambda) + V_{\mathrm{3N}}(\Lambda) + V_{\mathrm{4N}}(\Lambda) + \ldots$$

$\Lambda_{\mathrm{chiral}}$

momenta $Q \sim \lambda^{-1} \sim m_\pi$: chiral effective field theory (EFT)

neutrons and protons interacting via pion exchanges
and shorter-range contact interactions

$\Lambda_{\mathrm{pionless}}$

$Q \ll m_\pi$: pionless effective field theory

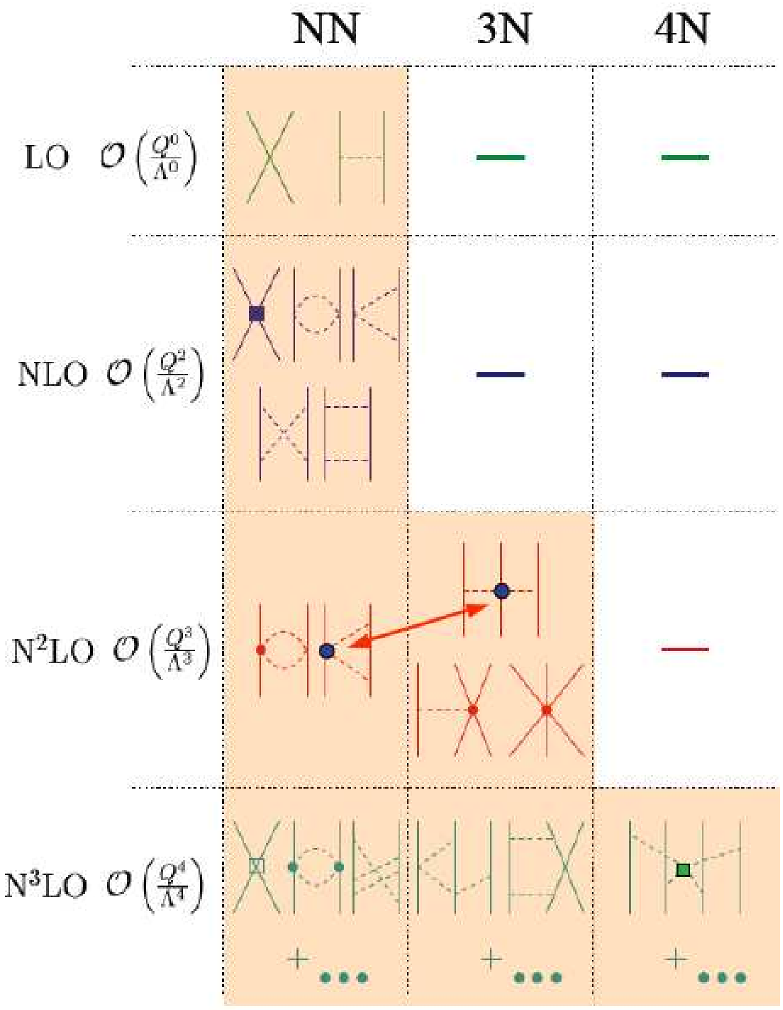
large scattering length physics and corrections

Nuclear forces from Chiral EFT

Separation of scales: low momenta Q << Λ_b breakdown scale

- Include long-range pion physics explicitly
- Short-distance **details** not resolved, Encoded in short-range couplings fit to data once
- Systematic: can work to desired accuracy

$$\Delta \mathcal{O}_\nu \sim \left(\frac{Q}{\Lambda}\right)^{\nu+1}$$

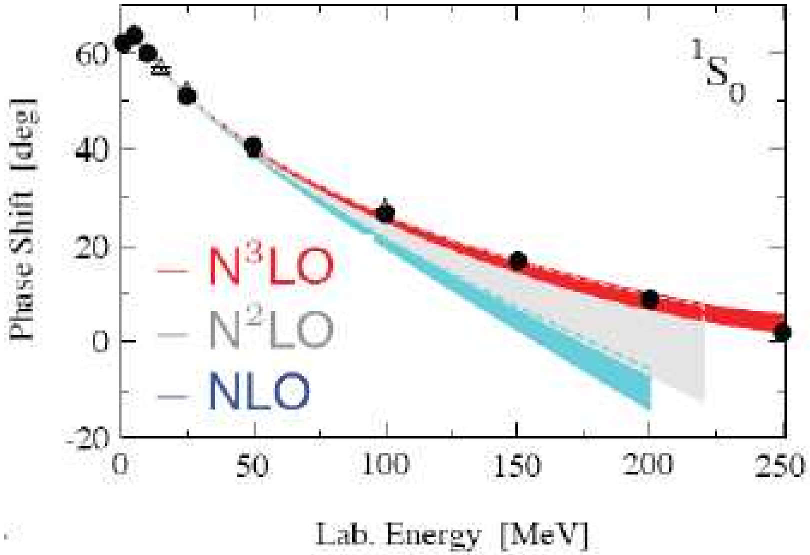


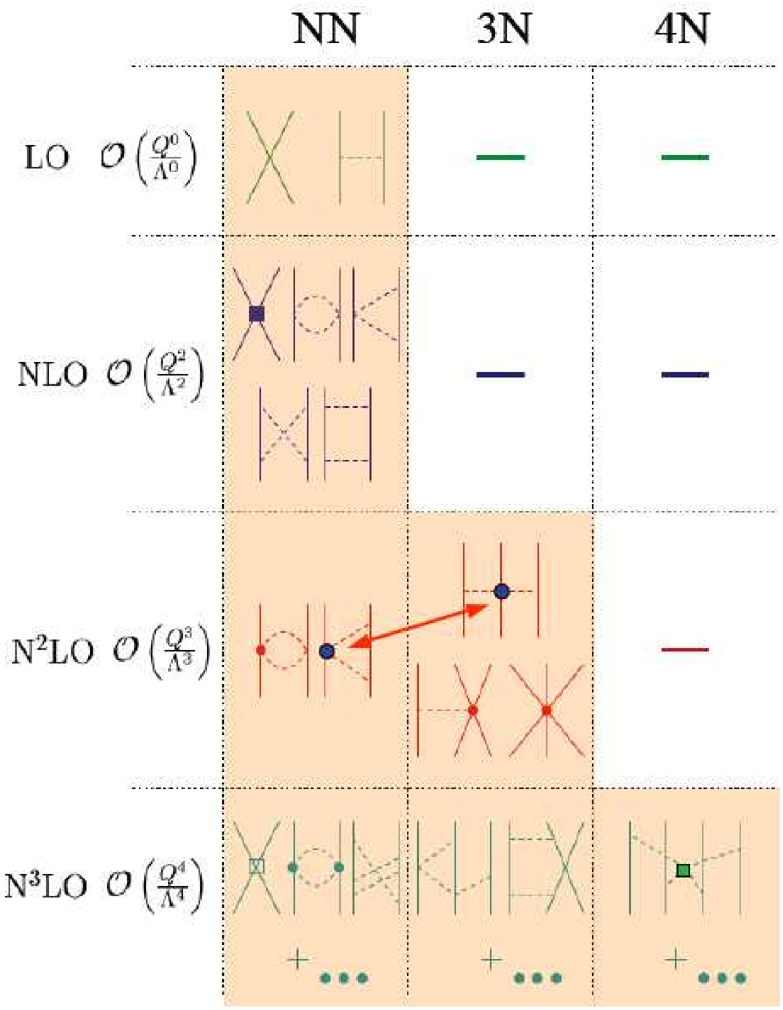
Weinberg, van Kolck, Epelbaum, Meissner, Machleidt, …

Nuclear forces from Chiral EFT

Separation of scales: low momenta Q << Λ_b breakdown scale

- Explains why 2N>3N>4N
- Error determined from Λ variation

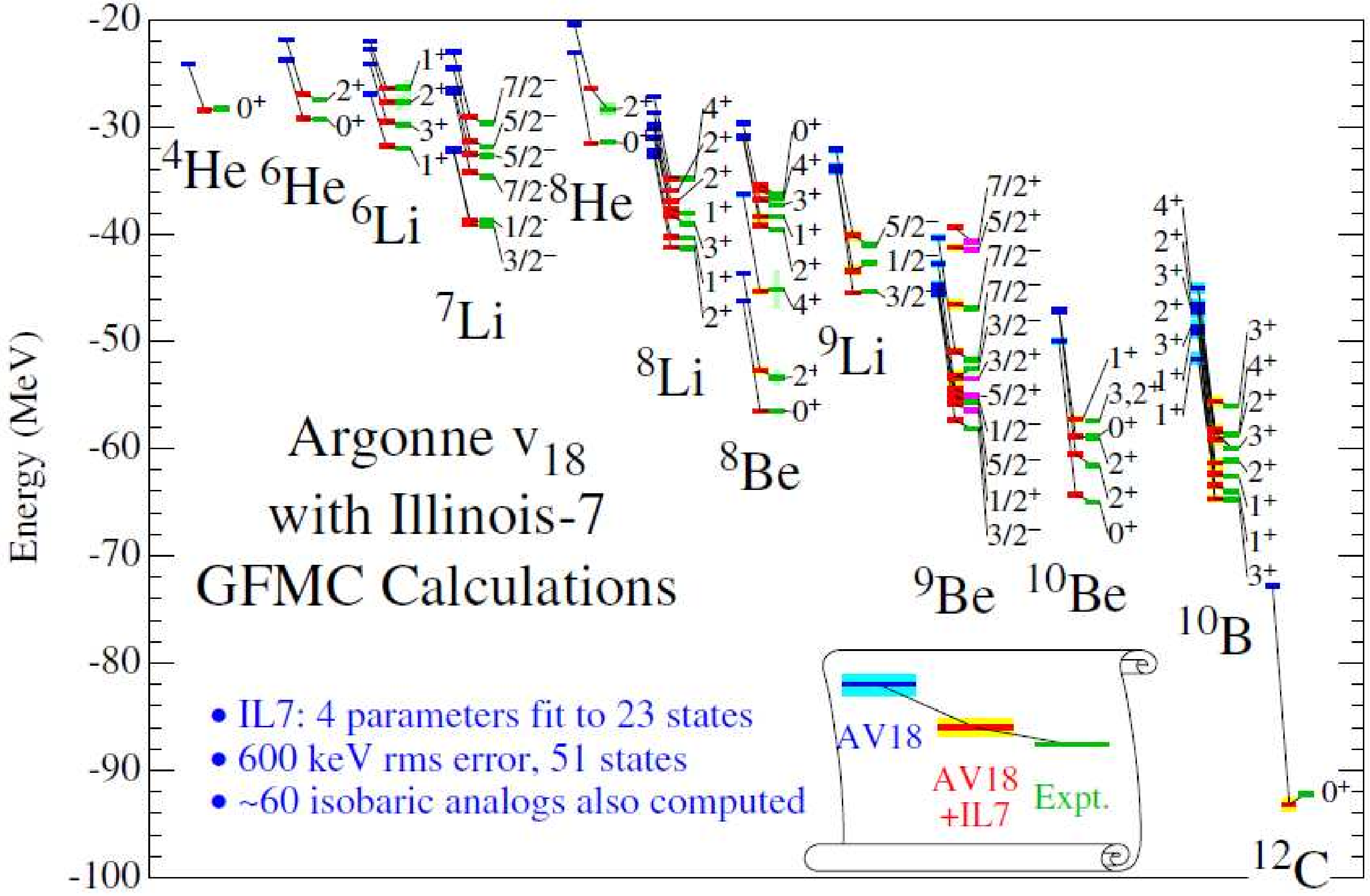




Weinberg, van Kolck, Epelbaum, Meissner, Machleidt, …

Beyond two-body forces

Nuclear properties require at least 3N forces
But 3N forces are a computational nightmare!



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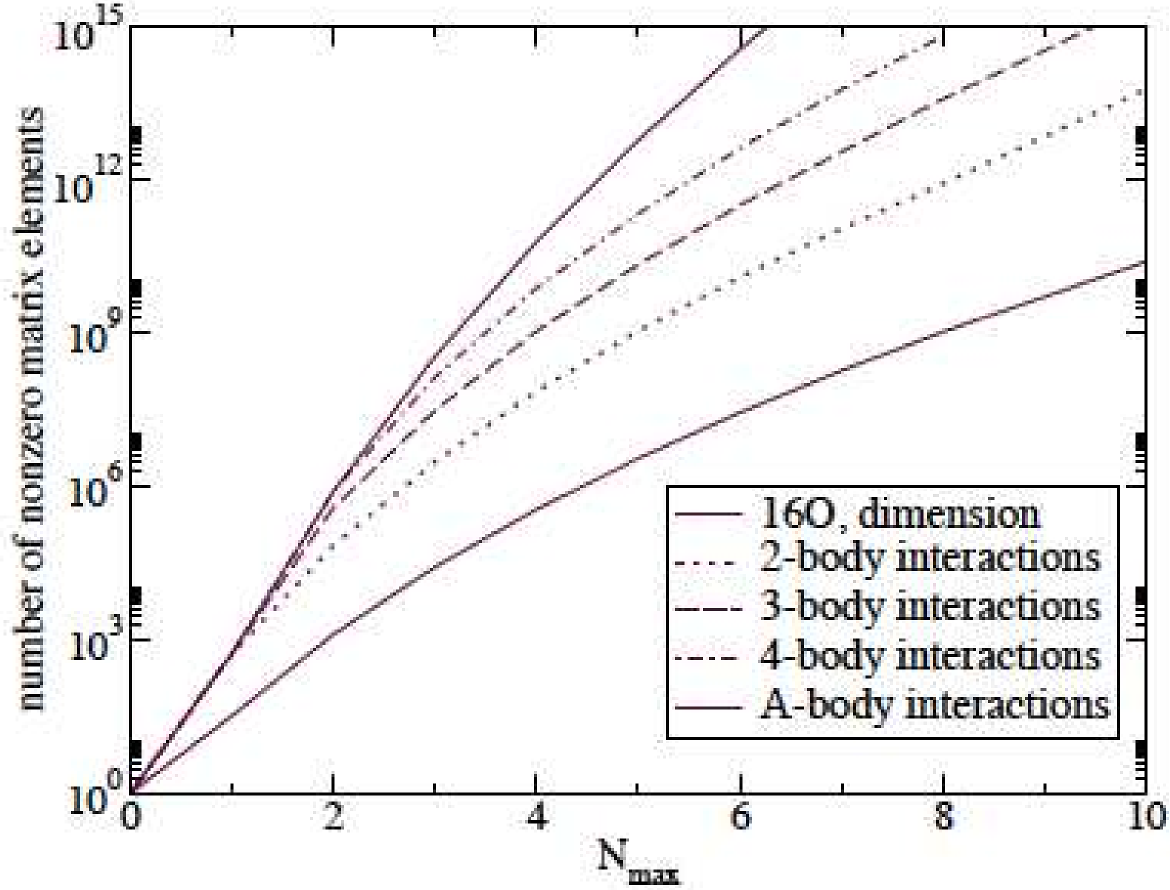


nuclei: the hardest many body problem ever

$$H_A = -\sum_{i=1}^{A} \frac{\hbar^2}{2m_i} \nabla^2_{\mathbf{r}_i} + \frac{\hbar^2}{2M} \nabla^2_{\mathbf{S}} + \sum_{i>j}^{A} V^{(2)}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i>j>k}^{A} V^{(3)}(\mathbf{r}_i - \mathbf{r}_j, \mathbf{r}_i - \mathbf{r}_k),$$

$$\boxed{H_A \Phi_{I\mu}(\boldsymbol{\rho}_1, \ldots, \boldsymbol{\rho}_{A-1}) = E_I \Phi_{I\mu}}$$

$$\lim_{\boldsymbol{\rho}_i \to \infty} \Phi_{I\mu}(\ldots, \boldsymbol{\rho}_i, \ldots) = 0$$

$$\int \mathrm{d}\boldsymbol{\rho}_1 \ldots \int \mathrm{d}\boldsymbol{\rho}_{A-1} |\Phi_{I\mu}(\boldsymbol{\rho}_1, \ldots, \boldsymbol{\rho}_{A-1})|^2 = 1$$

soft forces make it more like quantum chemistry
lead to approximations/controlled truncations

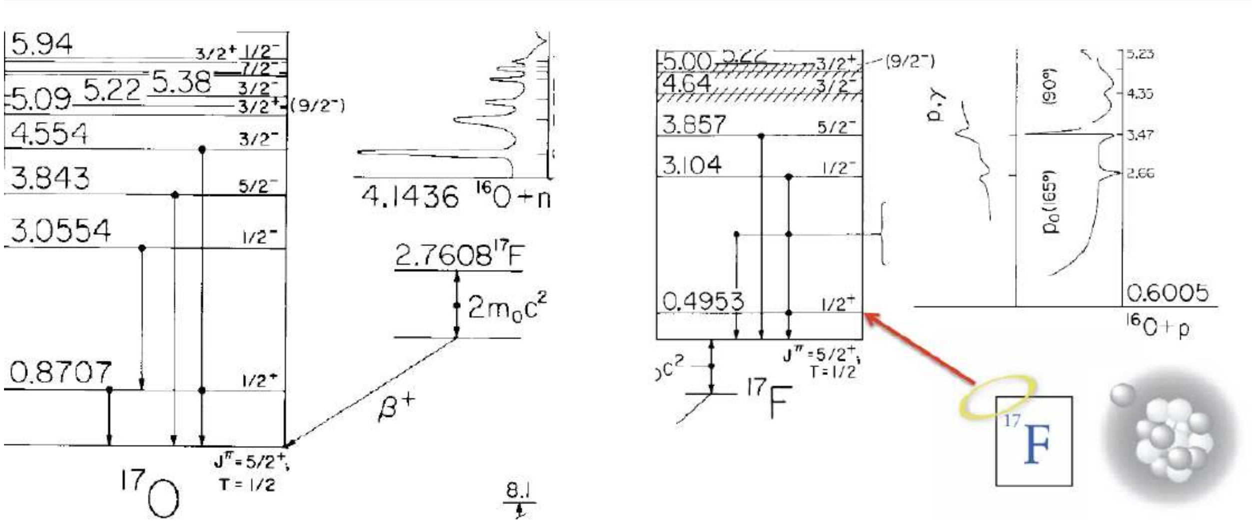
Ab-initio methods

- no core shell model (NCSM)
  - based on harmonic oscillators
  - good for energies, not so good for other observables
  - up to A=16

- green's function monte carlo (GFMC)
  - need a good starting variational wavefunction
  - implemented for specific forces
  - computationally demanding: hard limit A=12

- coupled cluster method (CC)
  - widely used in quantum chemistry
  - ansatz contains correlations in the exponential
  - scaling better than NCSM
  - implemented with the gamow basis (continuum)
  - applications up to 2 nucleons away from closed sub-shell

Ab-initio methods: coupled cluster for halos

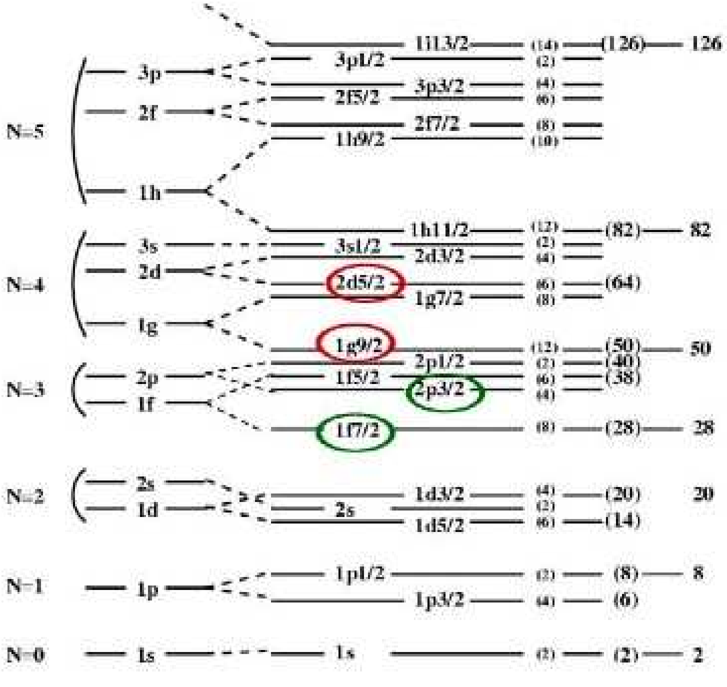


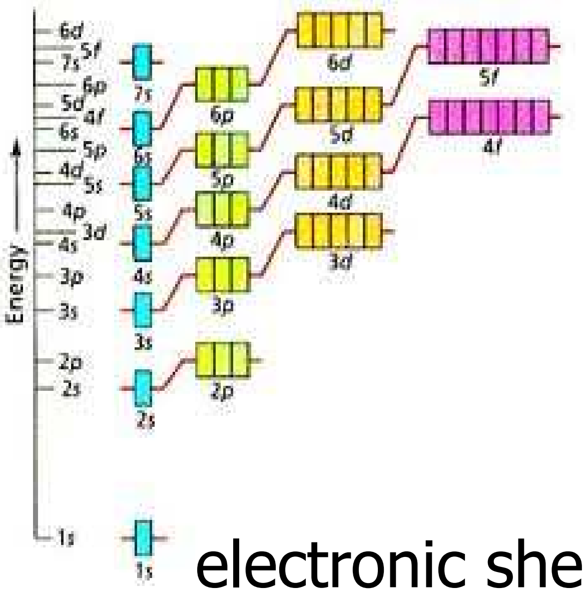
	^{17}O			^{17}F		
	$(1/2)_1^+$	$(5/2)_1^+$	$E_{\mathrm{s.o.}}$	$(1/2)_1^+$	$(5/2)_1^+$	$E_{\mathrm{s.o.}}$
OHF	-1.888	-2.955	4.891	0.976	0.393	4.453
GHF	-2.811	-3.226	4.286	-0.082	0.112	3.747
Exp.	-3.272	-4.143	5.084	-0.105	-0.600	5.000

	^{17}O $(3/2)_1^+$		^{17}F $(3/2)_1^+$	
	$\mathrm{Re}[E_{sp}]$	Γ	$\mathrm{Re}[E_{sp}]$	Γ
PA-EOMCCSD	1.059	0.014	3.859	0.971
Experiment	0.942	0.096	4.399	1.530

Traditional shell model

nuclear shell model





electronic shells

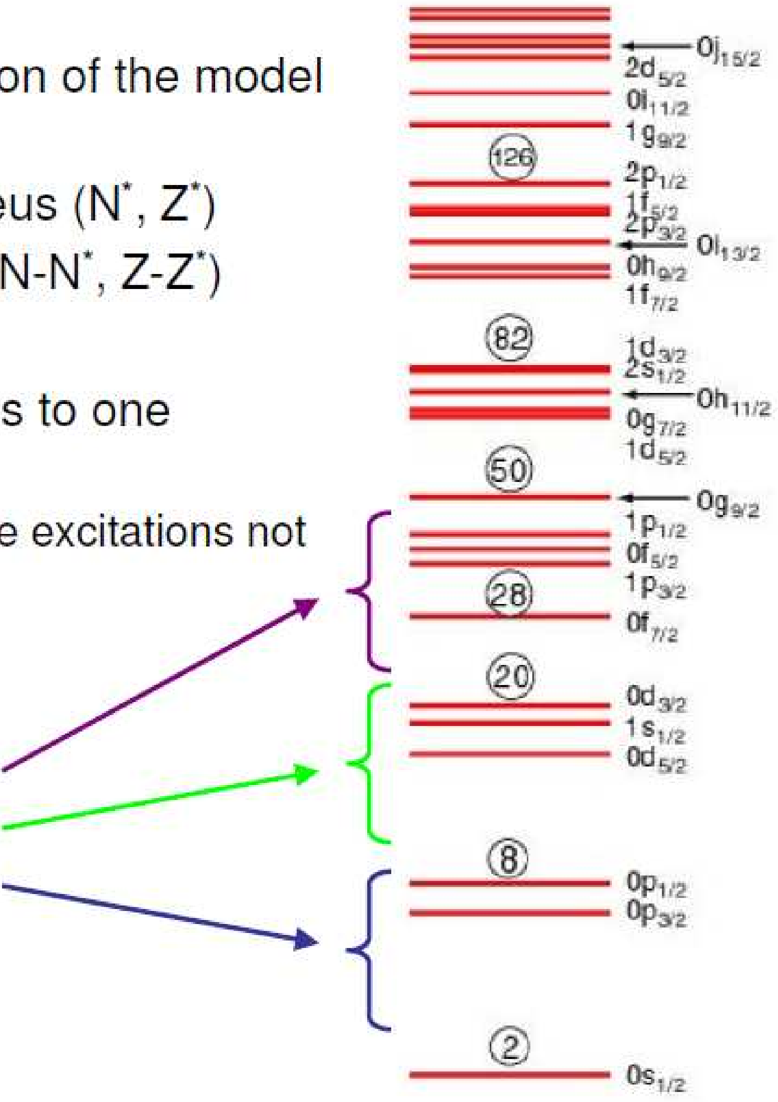
Traditional shell model

Main idea: Use shell gaps as a truncation of the model space.

- Nucleus (N,Z) = Double magic nucleus (N^*, Z^*)
  + valence nucleons ($N-N^*$, $Z-Z^*$)

- Restrict excitation of valence nuclons to one oscillator shell.
  - Problematic: Intruder states and core excitations not contained in model space.

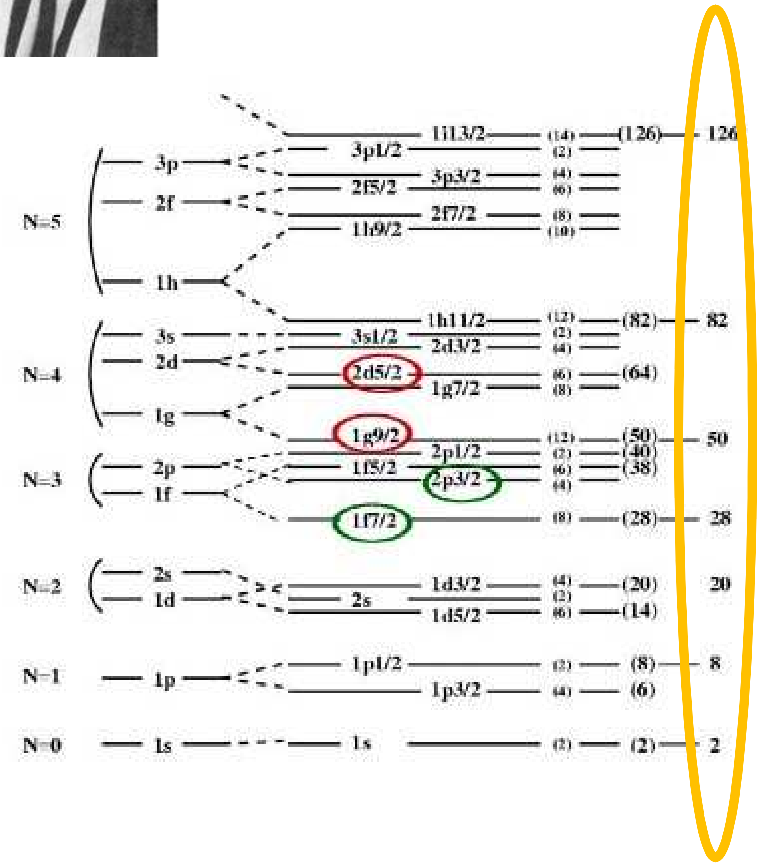
- Examples:
  - pf-shell nuclei: ^{40}Ca is doubly magic
  - sd-shell nuclei: ^{16}O is doubly magic
  - p-shell nuclei: ^{4}He is doubly magic



From Thomas Papenbrock's lecture slides

Traditional shell model

nuclear shell model



magic numbers

^{208}Pb

^{100}Sn, ^{132}Sn

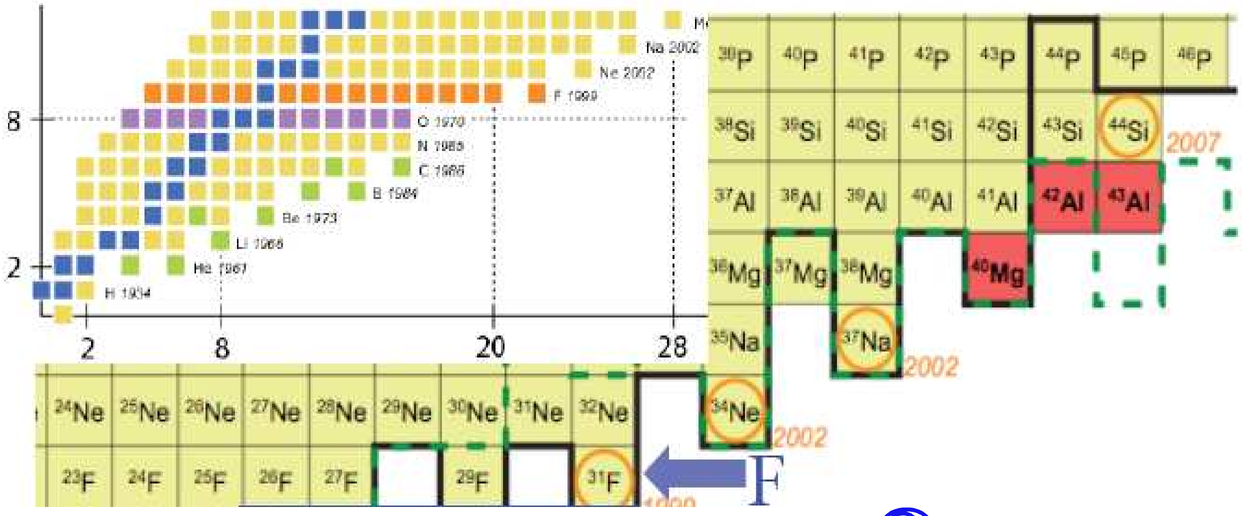
^{56}Ni, ^{78}Ni

^{40}Ca, ^{48}Ca

^{16}O

Doubly magic nuclei

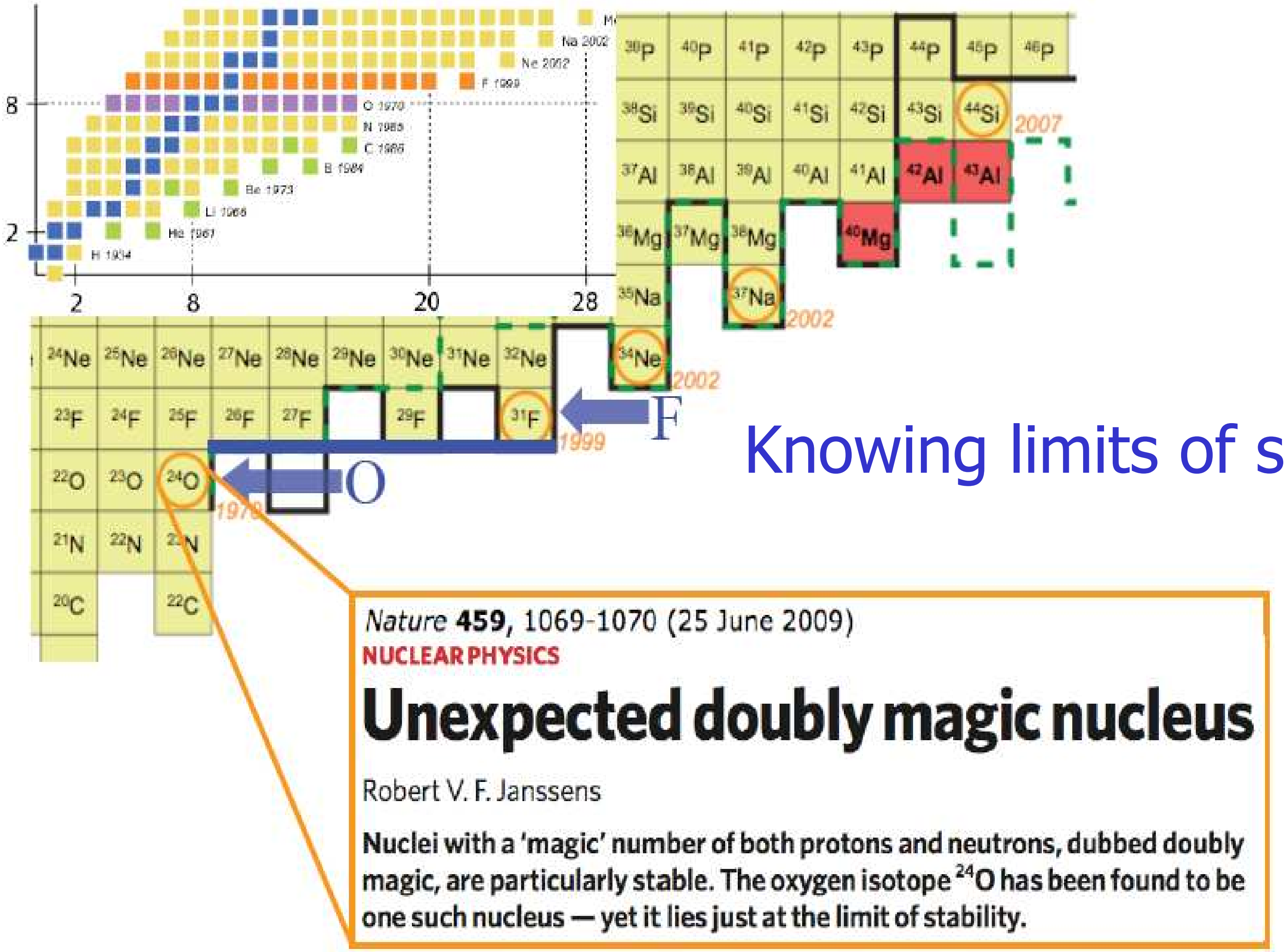
understanding nuclei



?

where is the oxygen dripline?

understanding nuclei



Knowing limits of stability

Nature **459**, 1069-1070 (25 June 2009)

NUCLEAR PHYSICS

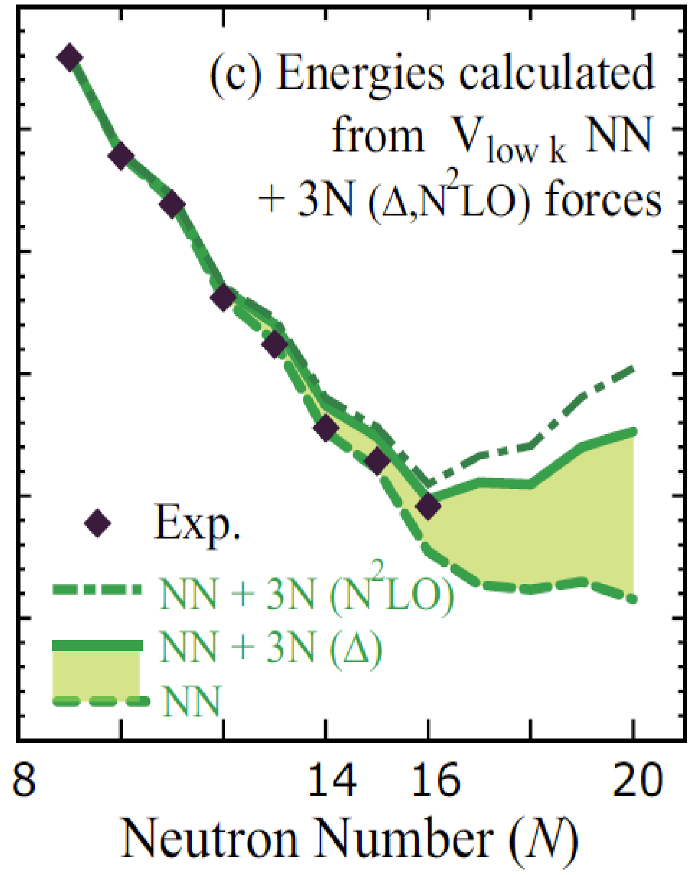
Unexpected doubly magic nucleus

Robert V. F. Janssens

Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

Slide from INT talk, A. Schwenk

three-body force for Oxygen isotopes

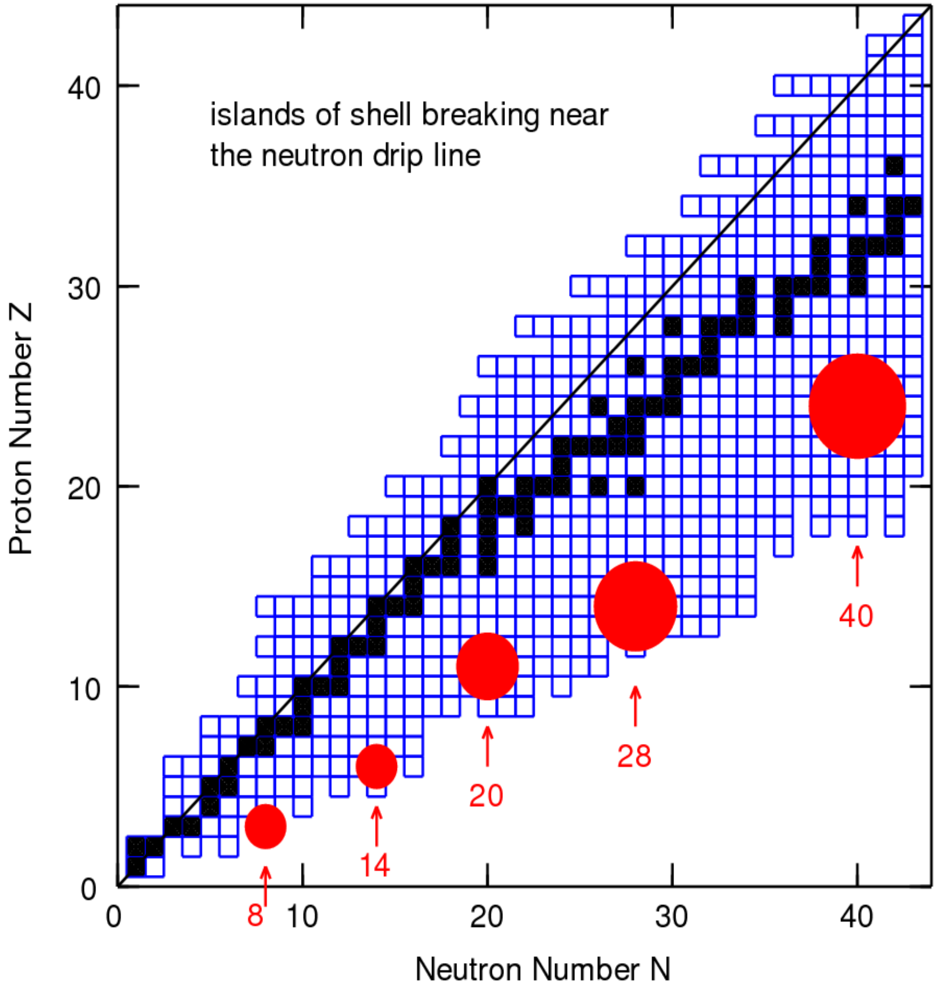


Otsuka, Suzuki, Holt, Schwenk, Akaishi, PRL (2009)

shell structure away from stability

what happened to our magic numbers?

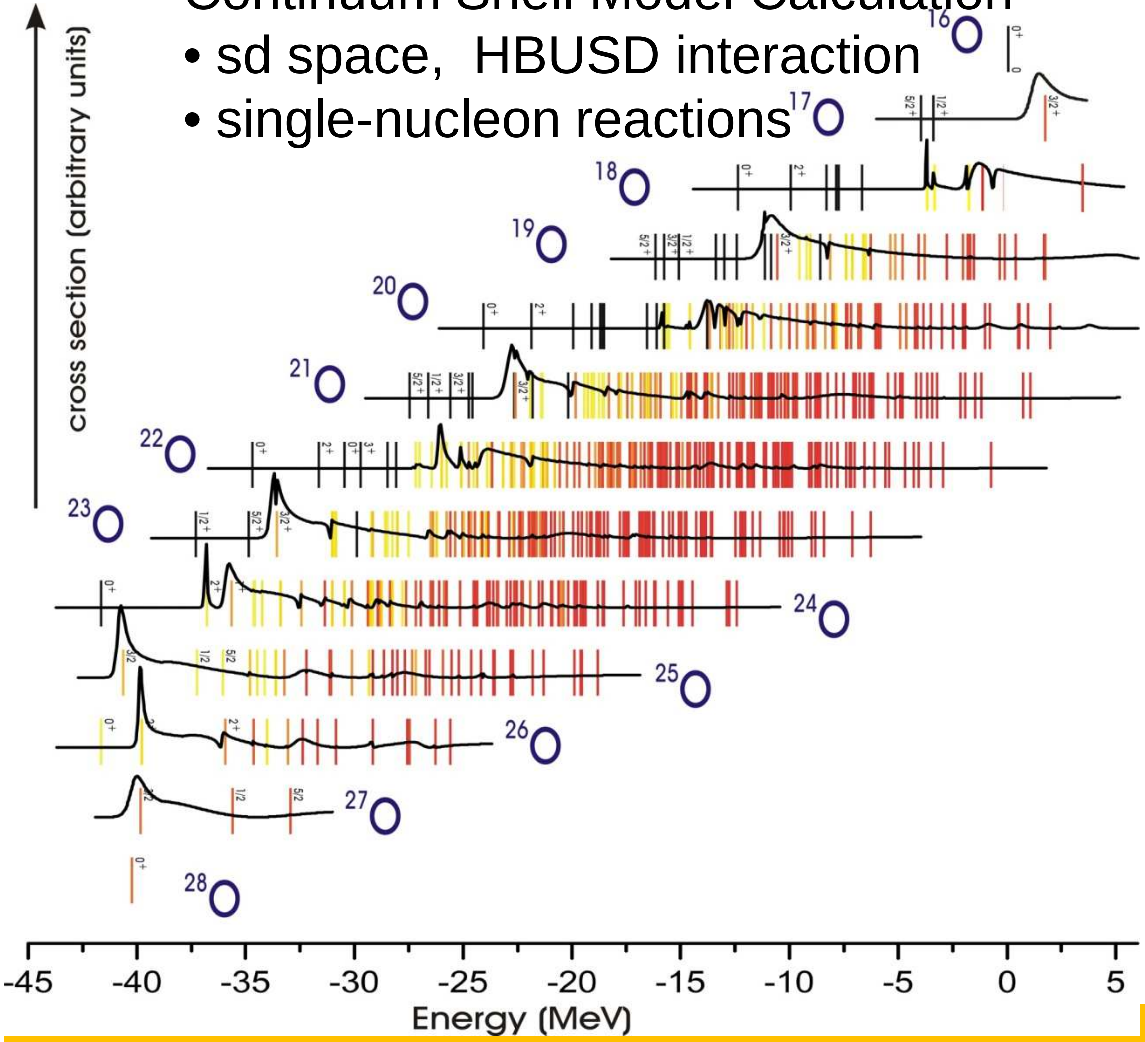
Brown, Viewpoint 2010



Continuum shell model

Oxygen Isotopes
Continuum Shell Model Calculation

- sd space, HBUSD interaction
- single-nucleon reactions



Volya, Zelevinsky

Density functional approach

- Hohenberg-Kohn: there exists a universal energy functional
- approximate the energy functional
- introduce orbitals and minimize energy functional
- self-consistent

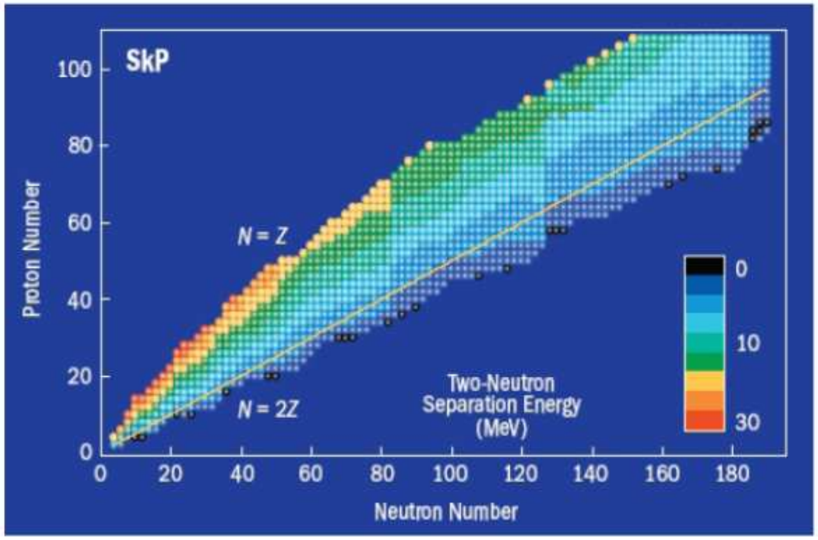
Phenomenological Skyrme Functionals

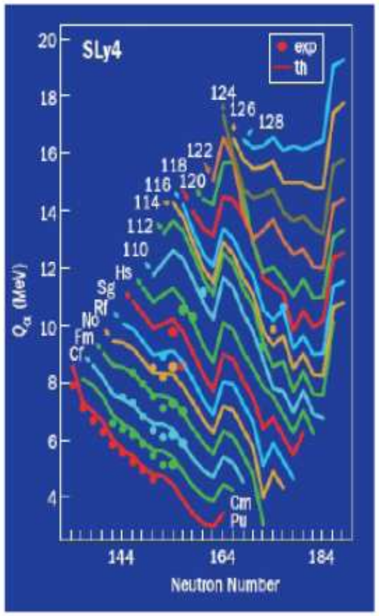
- Minimize $E = \int d\mathbf{x}\, \mathcal{E}[\rho(x), \tau(x), \mathbf{J}(\mathbf{x}), \ldots]$ (for $N = Z$):

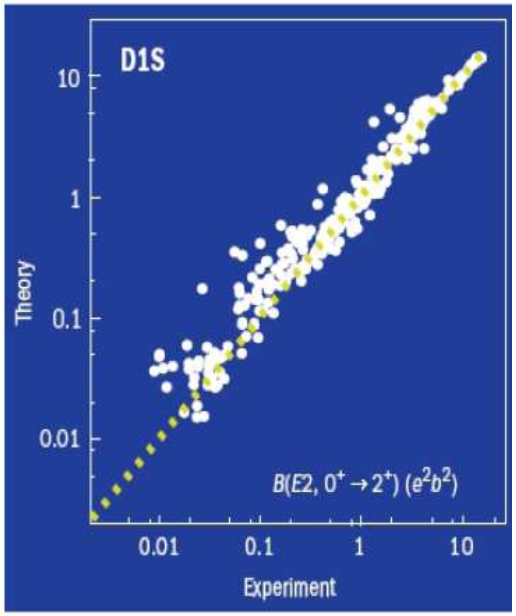
$$\begin{aligned}\mathcal{E}[\rho,\tau,\mathbf{J}] \;=\; & \frac{1}{2M}\tau + \frac{3}{8}t_0\rho^2 + \frac{1}{16}t_3\rho^{2+\alpha} + \frac{1}{16}(3t_1+5t_2)\rho\tau \\ & + \frac{1}{64}(9t_1-5t_2)(\nabla\rho)^2 - \frac{3}{4}W_0\rho\nabla\cdot\mathbf{J} + \frac{1}{32}(t_1-t_2)\mathbf{J}^2\end{aligned}$$

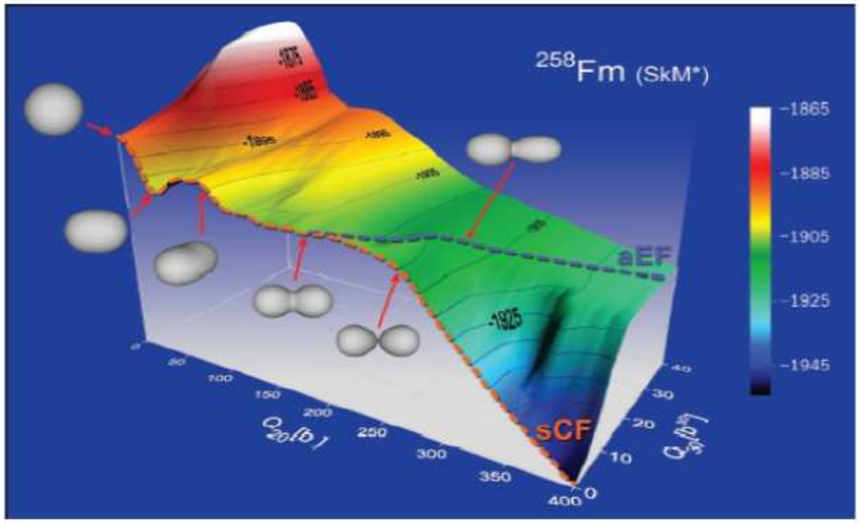
- where $\rho(x) = \sum_i |\phi_i(x)|^2$ and $\tau(x) = \sum_i |\nabla\phi_i(x)|^2$ (and $\mathbf{J}$)

Density functional approach





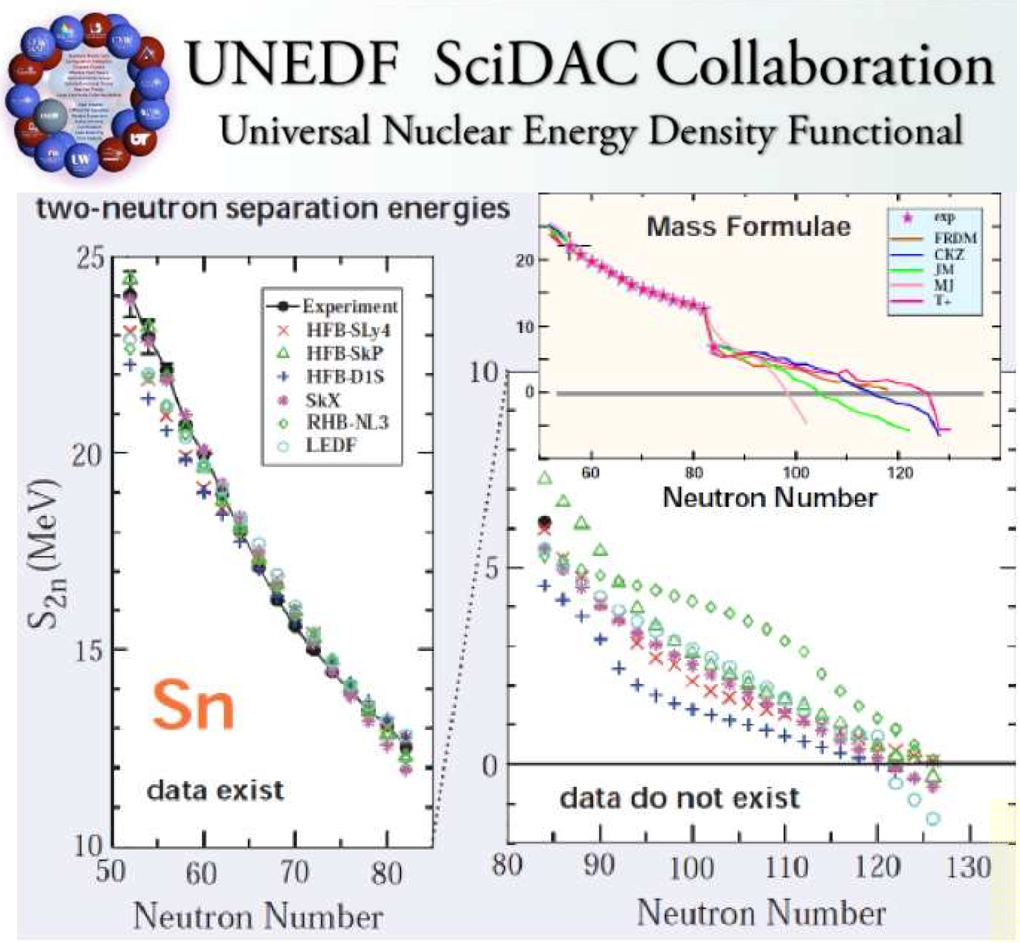




2N separation energies, Quadrupole an
BE2 values, Fission energy surfaces,
mass tables in a day, plus many other
impressive feats

BUT...

Density functional approach



What is missing from Skyrme?

- Simplistic density dependence
- No connection to pion-exchange (NN+NNN)
- Does not capture different spin-orbit NN and NNN mechanisms (short versus long range)

Turn to underlying NN+NNN forces + microscopic many-body theories for guidance

Why exotic stuff?

Nuclear forces constrained in the valley of stability

predict diverging properties away from stability
need exotic nuclei for reliability
feeds back into our understanding of stable matter

Moving along an isotopic line: provides sensitivity to isospin
Moving to low binding energies: sensitivity to 3N
Moving toward nuclear dripline: probes density dependence

Wider variety of nuclear phenomena away from stability

Questions?

FRIB physics (lecture 2)

Filomena Nunes

NSCL+PA, Michigan State University

overview

- what is FRIB
- FRIB big science questions
- connection to QCD
- the hardest many-body problem ever
- typical approximations
- why exotic stuff
- nuclear reactions as a tool
- production of the exotic stuff

why do reactions? elastic

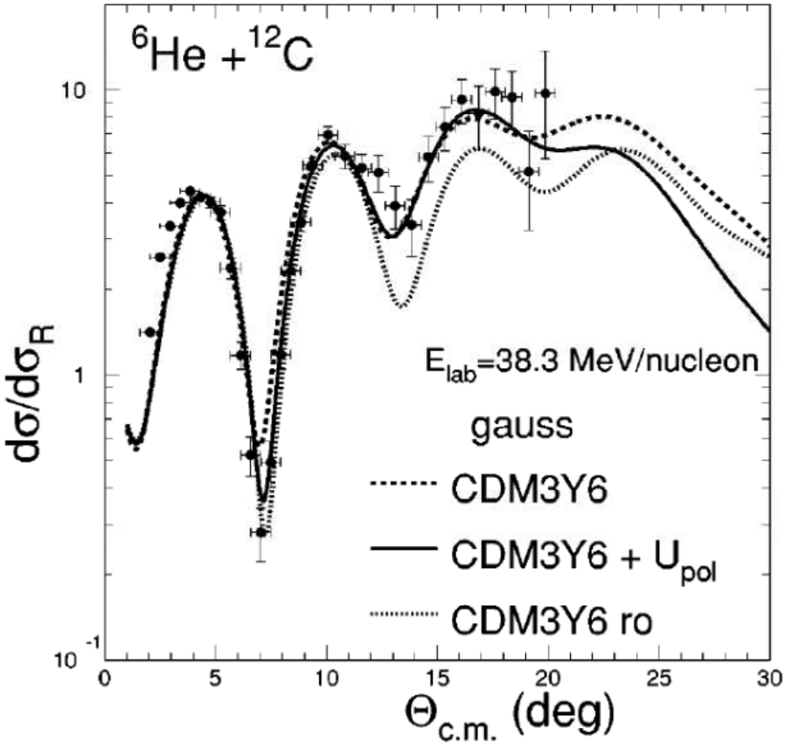
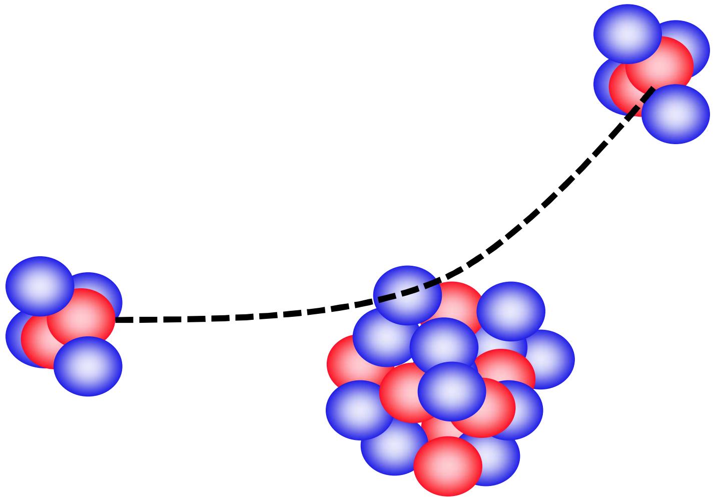


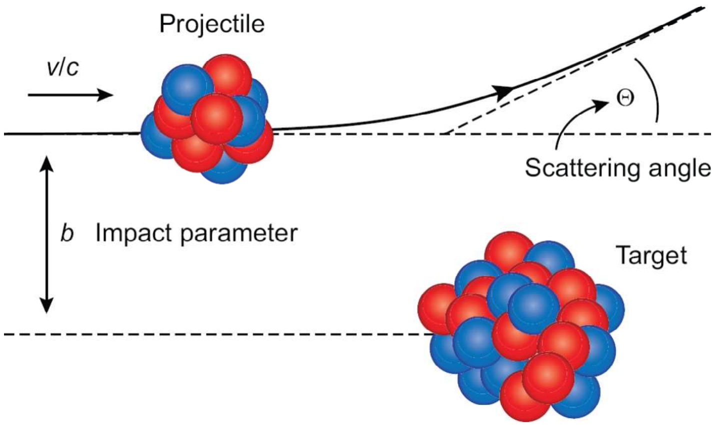
FIG. 10. Elastic scattering for ^{6}He+^{12}C at 38.3 MeV/nucleon in comparison with the OM results given by the real folded potential (obtained with the CDM3Y6 interaction and the Gaussian *ga* density for ^{6}He). The dashed curve is obtained with the unrenormalized folded potential only. The solid curve is obtained by adding a complex surface polarization potential to the real folded potential. Its parameters, and those of the imaginary part, are explained in the text. The dotted line is obtained by folding the CDM3Y6 interaction with the compact Gaussian density *ro*.

[Lapoux et al, PRC 66 (02) 034608]



traditionally used to extract optical potentials, rms radii, density distributions.

why do reactions? inelastic



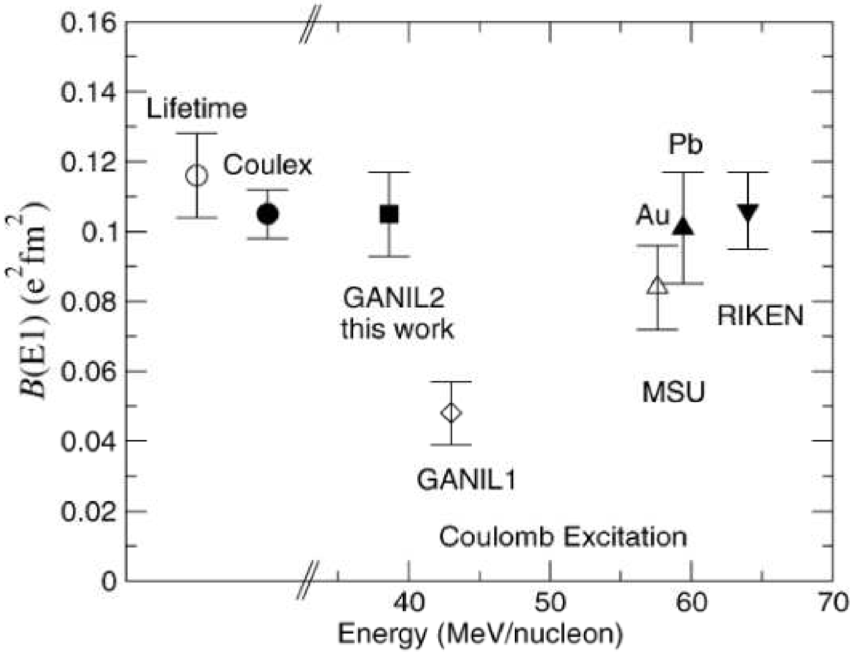


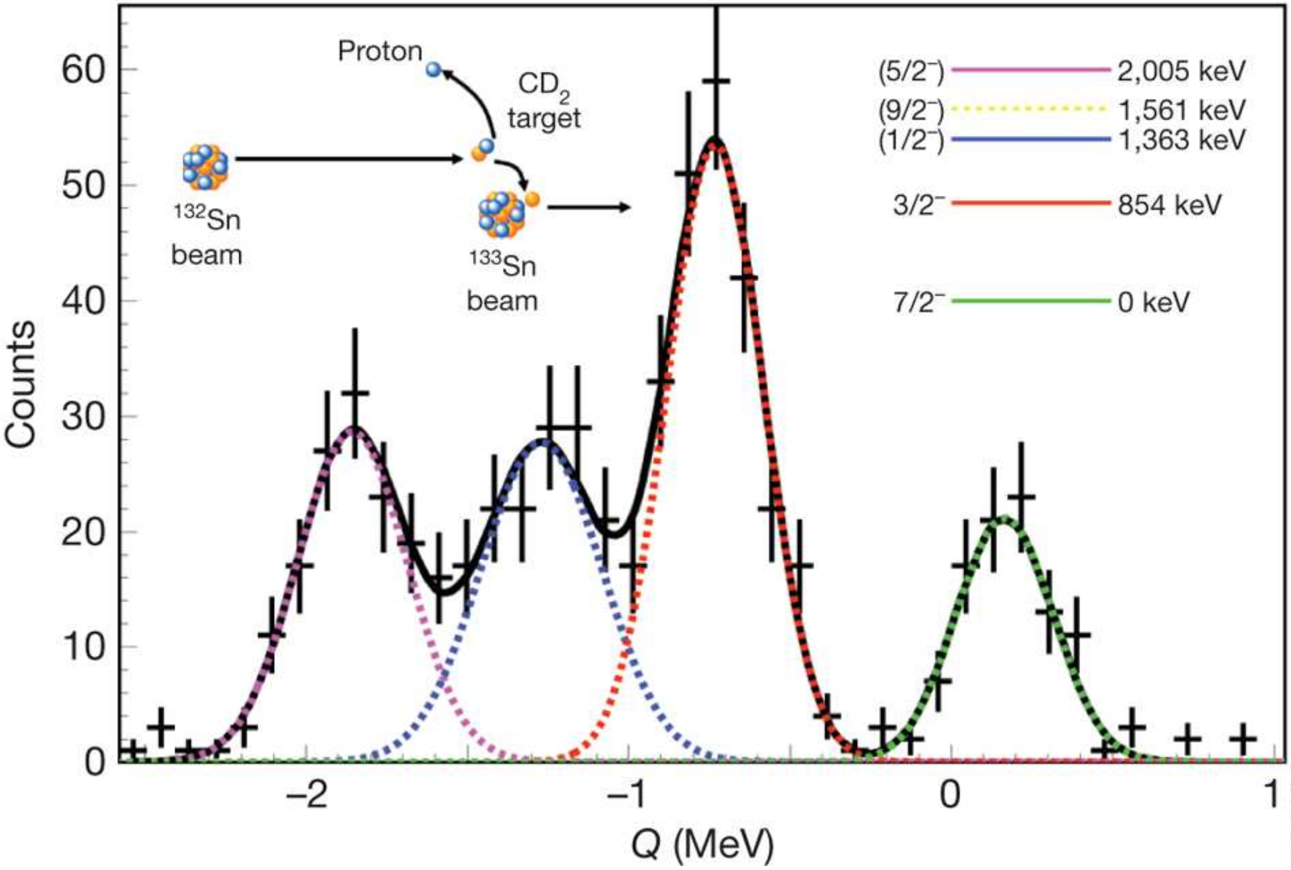
Fig. 2. Comparison of B(E1) values obtained from lifetime and Coulomb excitation measurements. The weighted average of lifetime measurements [3] (open circle) is plotted on the left along with the weighted average (solid circle) of three Coulomb excitation measurements (solid symbols). The individual Coulomb excitation measurements, GANIL (this work, square), MSU (up triangle) [6], RIKEN (down triangle) [7], and a previous GANIL experiment (diamond) [4], are plotted versus the beam energy.

traditionally used to extract electromagnetic transitions or nuclear deformations

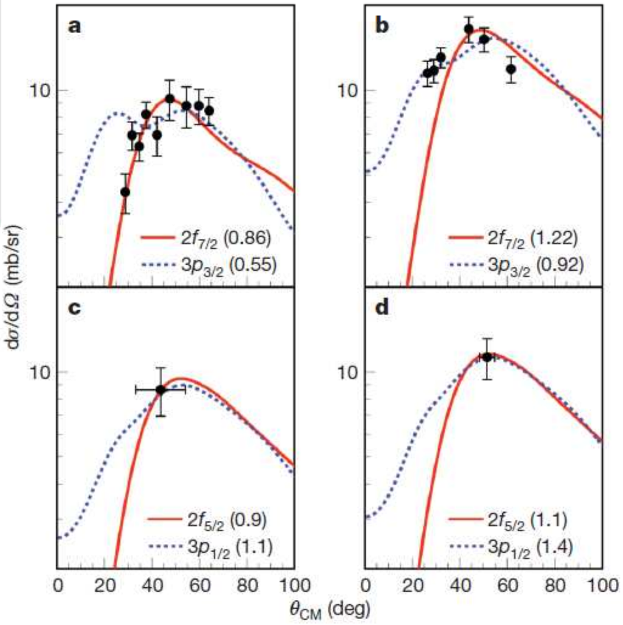
[Summers et al, PLB 650 (2007) 124]

why do reactions? transfer

d(^{132}Sn,^{133}Sn)p@5 MeV/u



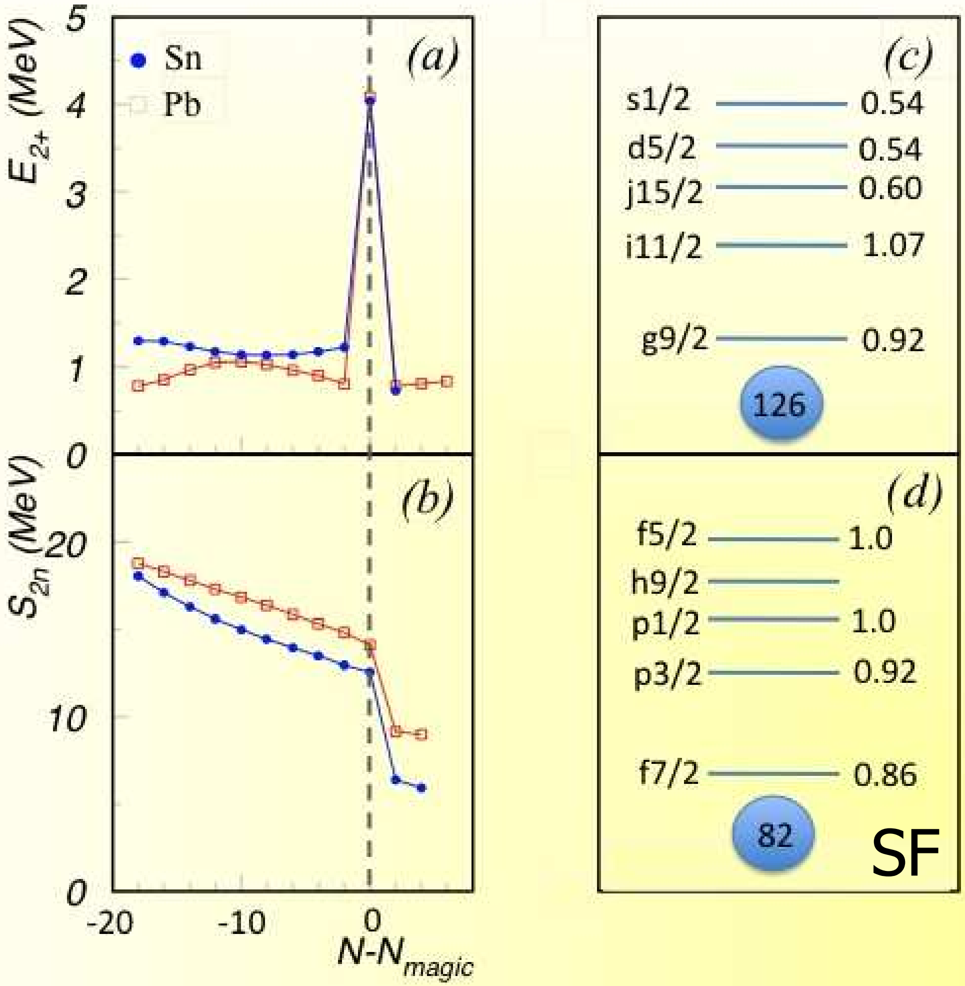
traditionally used to extract spin,parity and probabilities



[K. Jones et al, Nature 465 (2010) 454]

reactions probe magicity

Doubly magic nuclei

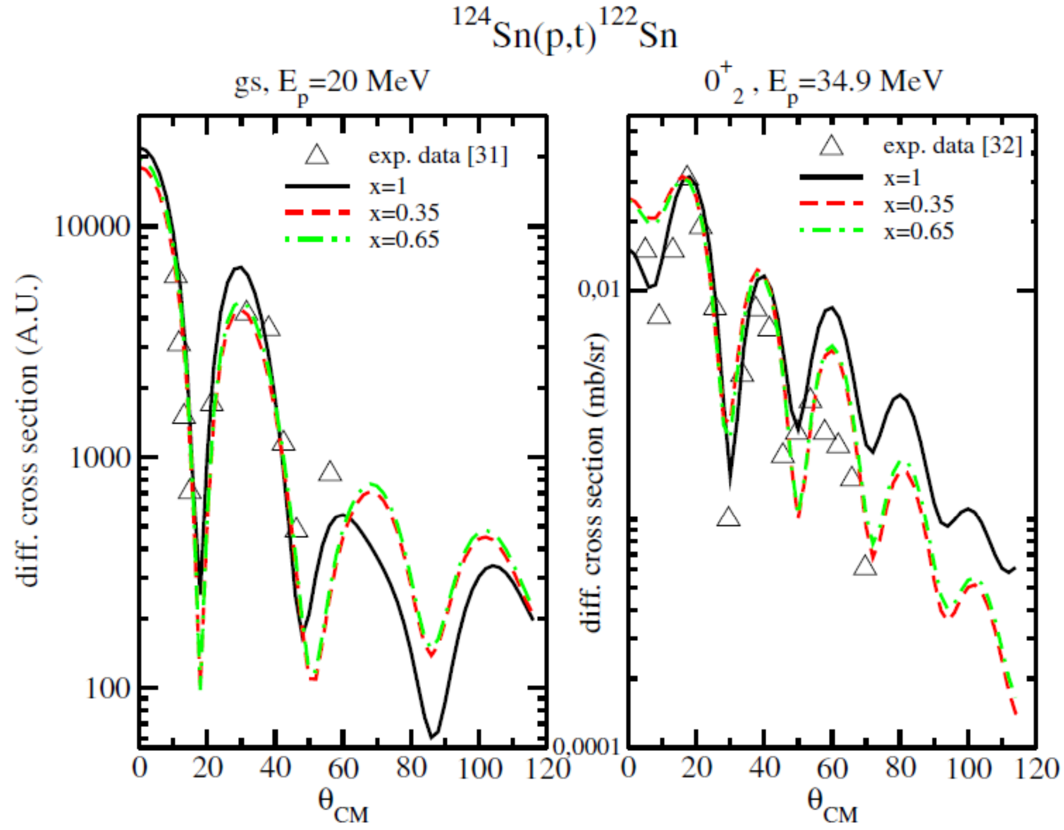


^{208}Pb(d,p)^{209}Pb

^{132}Sn(d,p)^{133}Sn

[K. Jones et al, Nature 465 (2010) 454]

why do reactions? transfer



[Pllumbi et al., Phys. Rev. C, 034613 (2011)

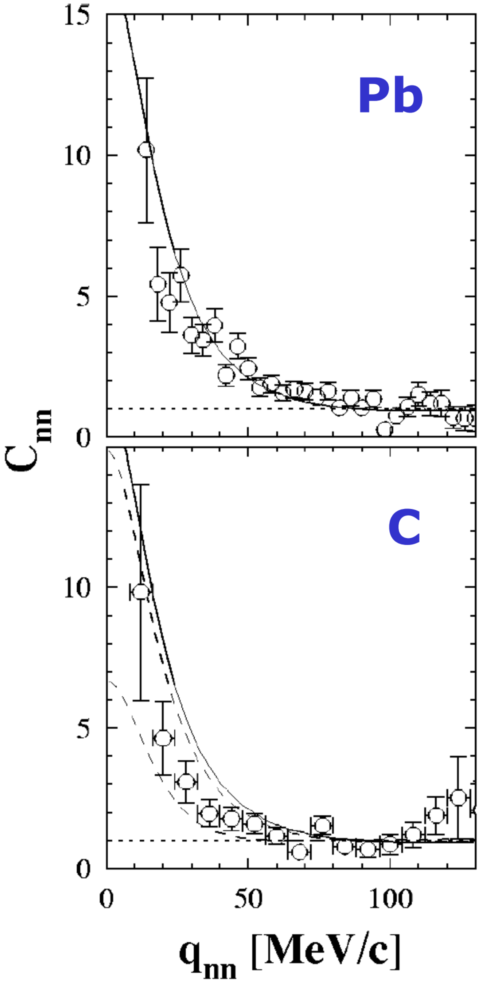
x=pairing parameter

traditionally used to study two nucleon correlations and pairing

why do reactions? breakup

two nucleon correlation function

^{14}Be → n+n+^{12}Be



[Marques et al, PRC 64 (2001) 061301]

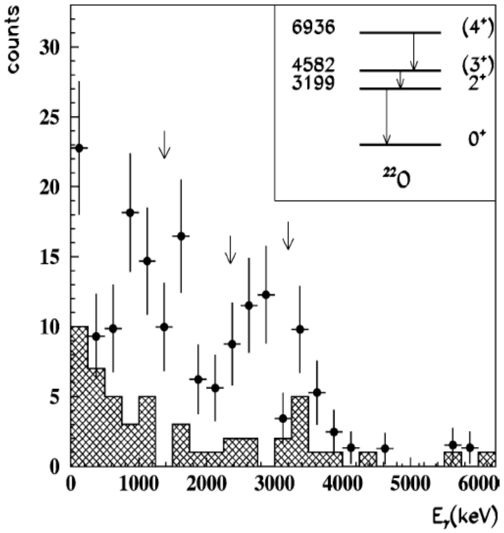
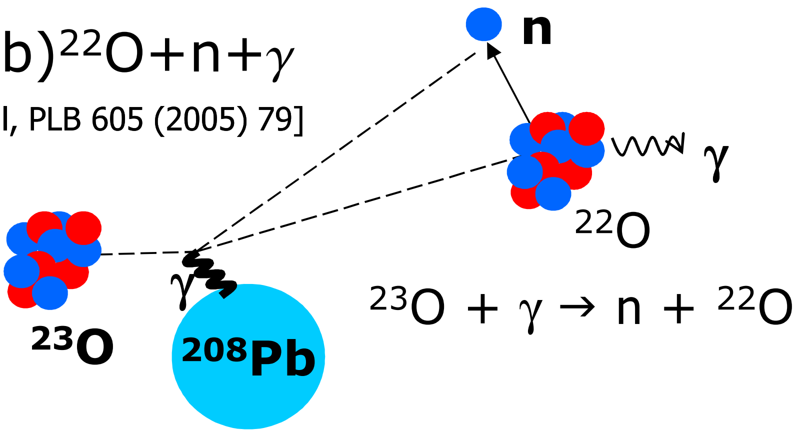


Fig. 1. Doppler corrected γ-ray spectra measured in coincidence with an ^{22}O fragment and one neutron for Pb (symbols) and C (shaded area) targets. Arrows indicate the strongest γ transitions as expected from the ^{22}O level scheme of Ref. [10] (partial level scheme shown as inset; level energies are in keV).

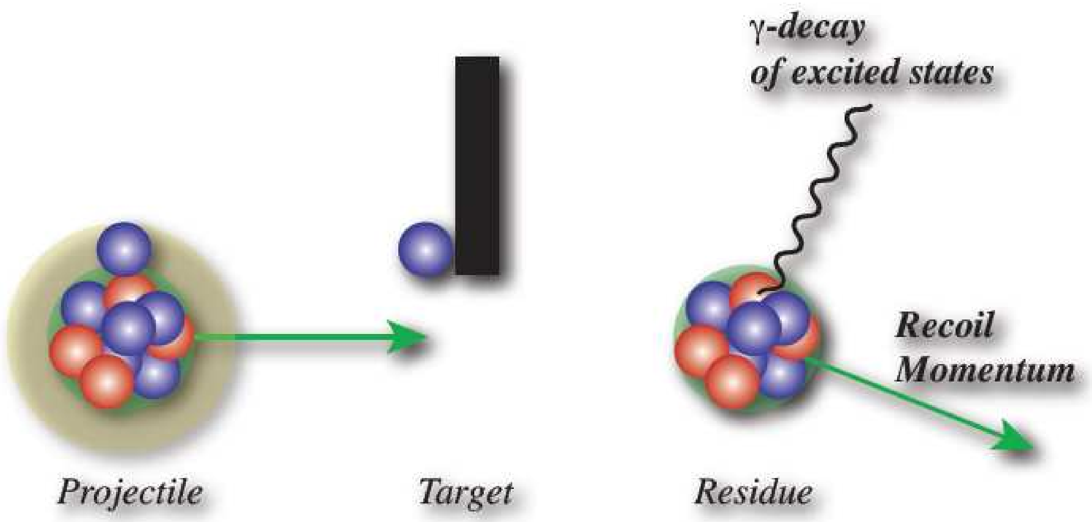
^{23}O(Pb,Pb)^{22}O+n+γ

[Nociforo et al, PLB 605 (2005) 79]



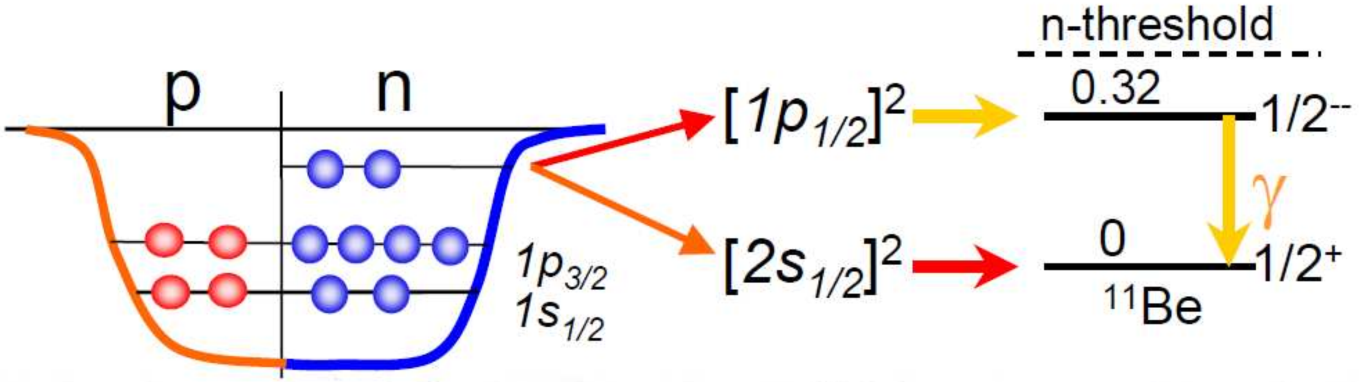
^{23}O + γ → n + ^{22}O

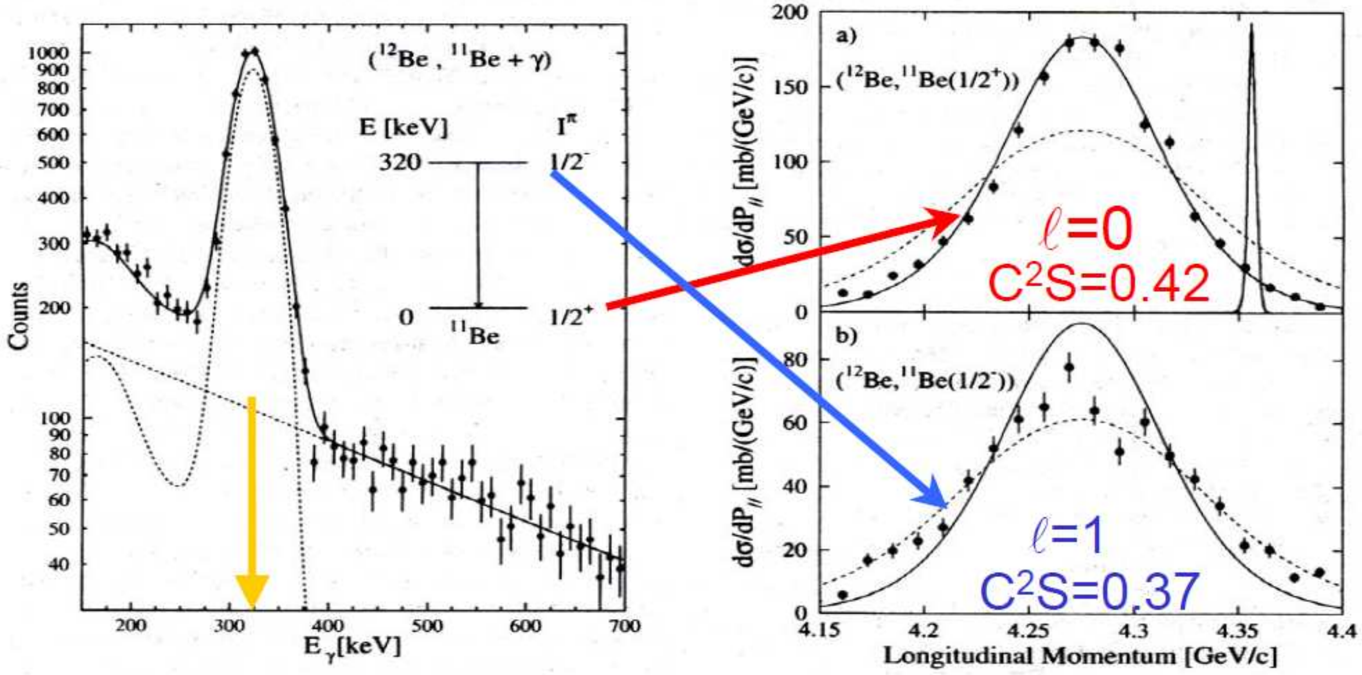
Why do reactions? knockout



- Just like (e,e’p) but with a nuclear probe
- Includes elastic and inelastic breakup as well as transfer
- Needs less beam than transfer or breakup, integrated information

Knockout typical result: ^{12}Be



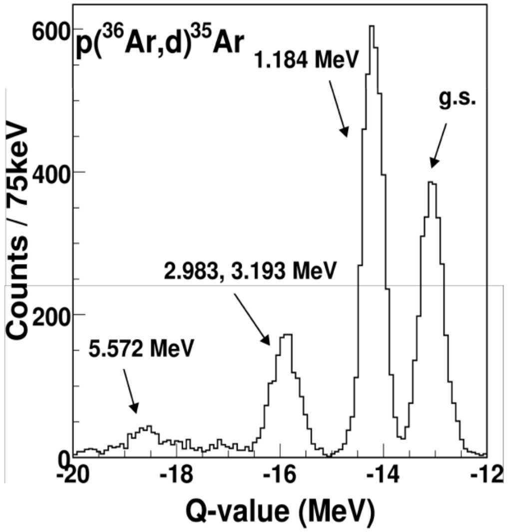


A. Navin *et al.*, Phys. Rev. Lett. **85**, 266 (2000)

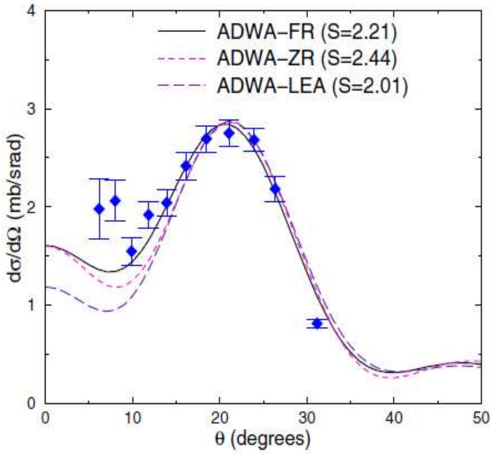
Questions?

why bother with reactions?

a) nuclei of interest are beams



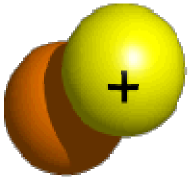
b) offers much more than energy levels



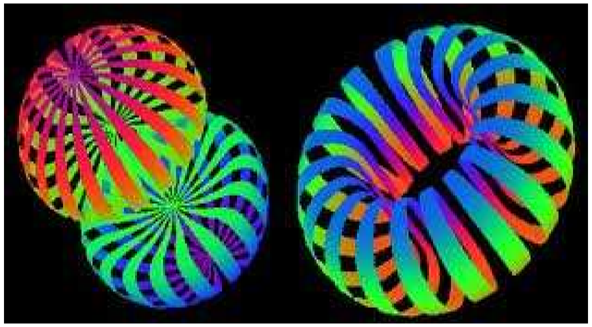
HiRA data

example of deuteron and V_{np}

any simple central interaction can give correct binding



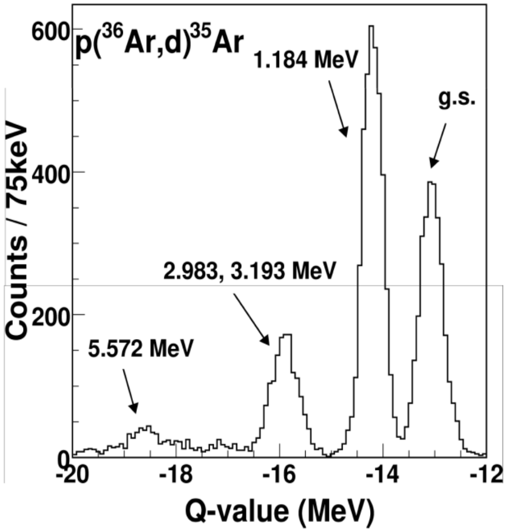
But the large body of reaction analysis could provide the detailed structure of the deuteron
and show the relevance of tensor interaction



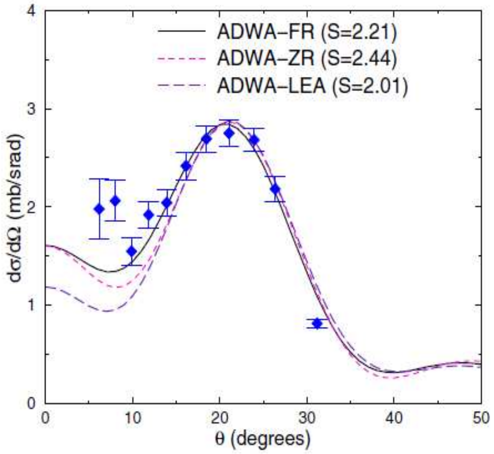
Pieper and Wiringa, ANL

why bother with reactions?

a) nuclei of interest are beams

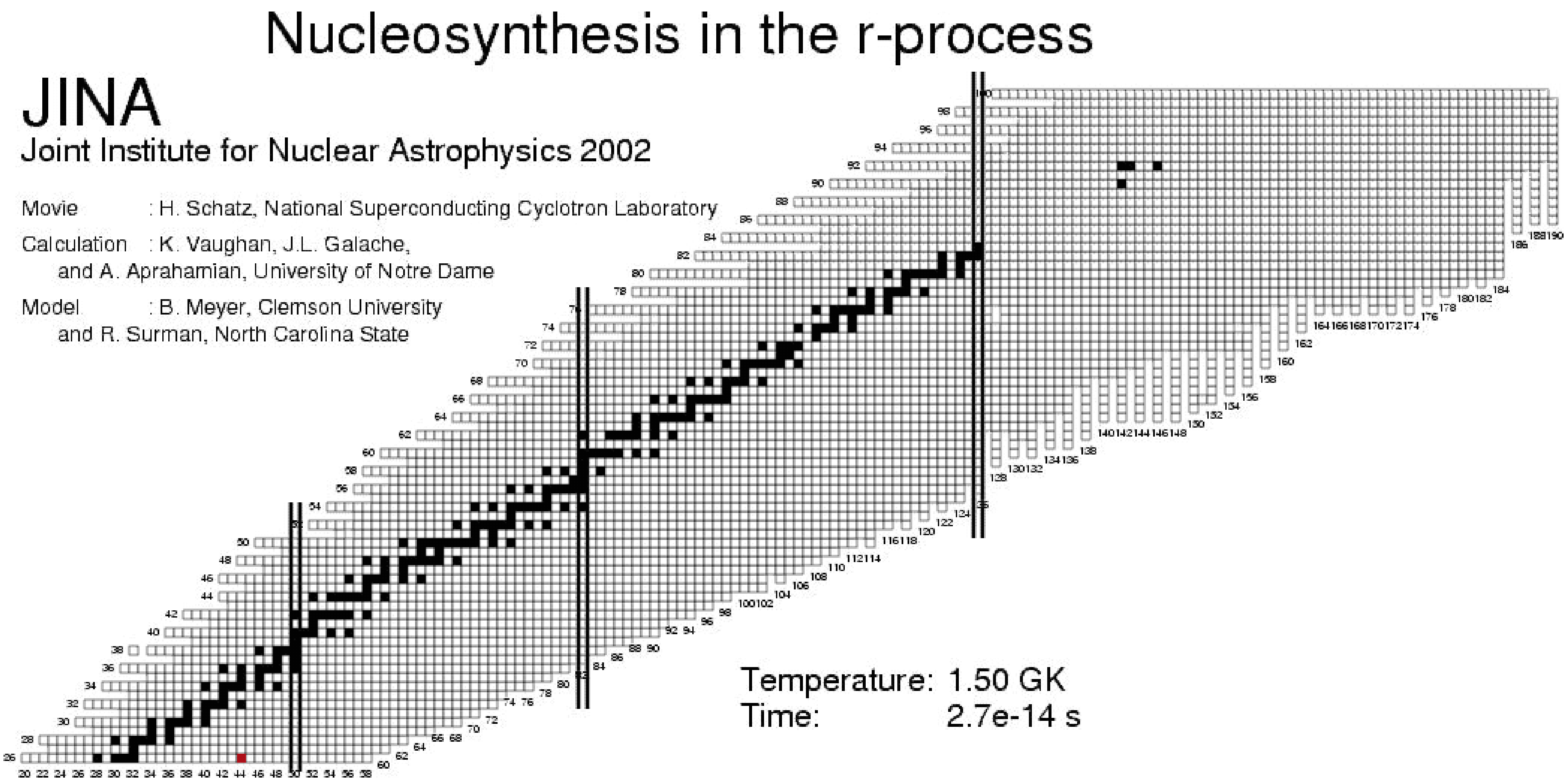


b) offers much more than energy levels



HiRA data

nucleosynthesis of the r-process



Nucleosynthesis in the r-process

JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

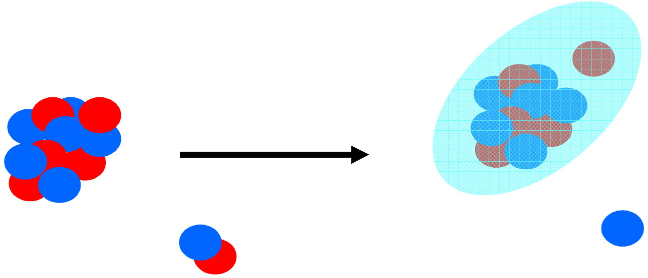
Model : B. Meyer, Clemson University
and R. Surman, North Carolina State

Temperature: 1.50 GK
Time: 2.7e-14 s

why do reactions? astrophysics

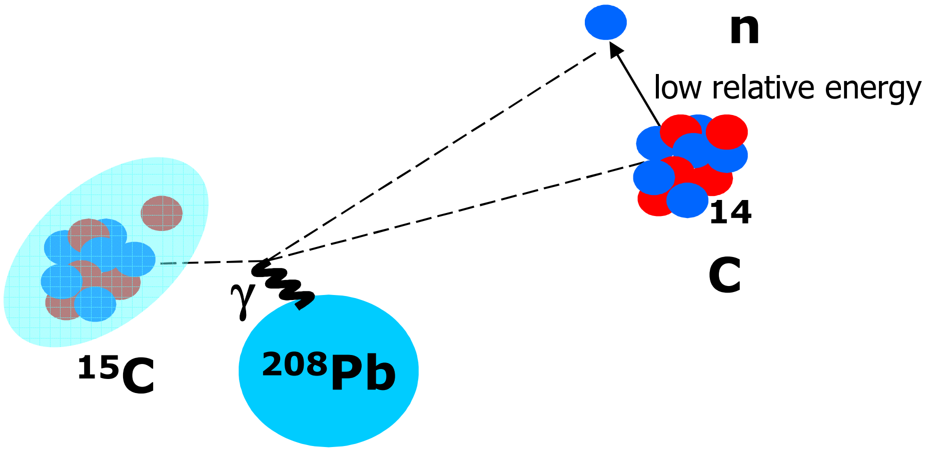
- direct measurement $^{14}C(n,\gamma)^{15}C$

- transfer reaction

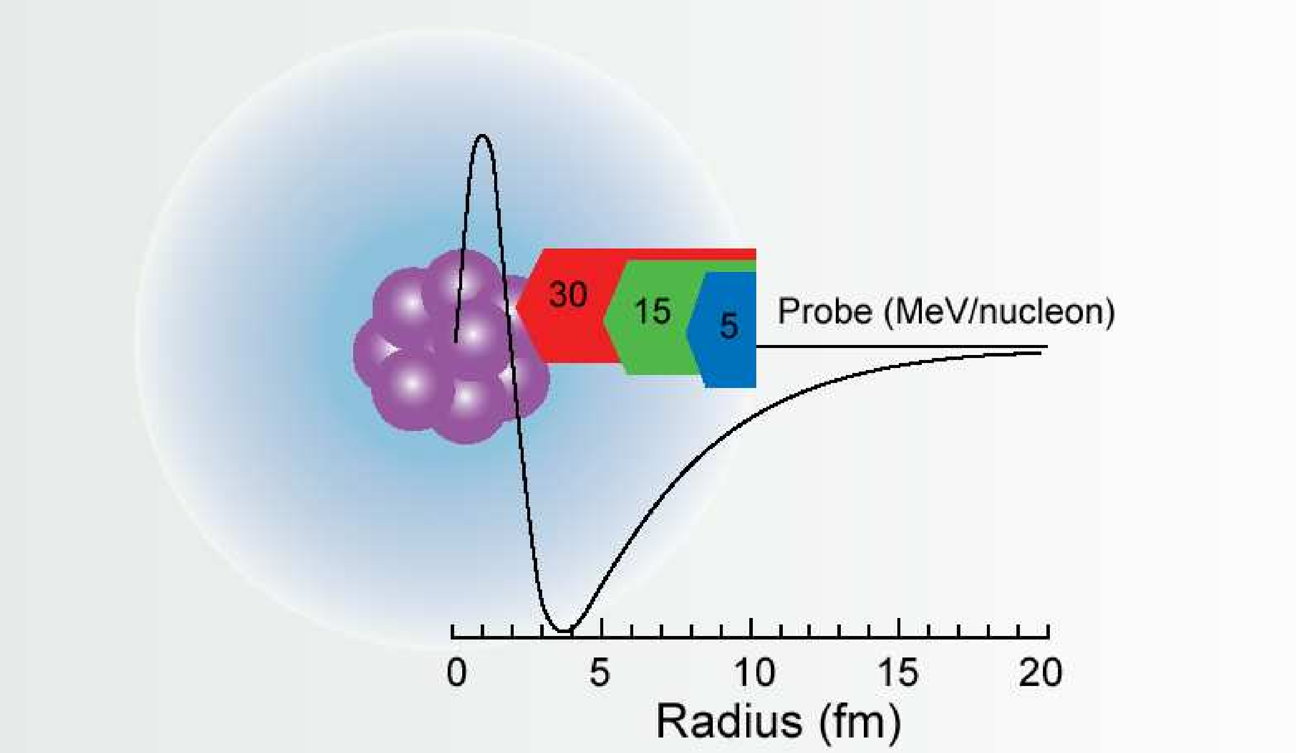


$^{14}C(d,p)^{15}C$

- Coulomb dissociation



nuclear reactions and tomography



The overlap function for $^{19}C \rightarrow n + ^{18}C$ in arbitrary units. The radial sensitivity of the $^{18}C(d,p)^{19}C$ cross section is represented by the colored bars for different beam energies.

putting reaction theory in perspective

theory = structure x reaction

Compare theory to data: structure=data/reaction

putting reaction theory in perspective

theory = restruciontaucre

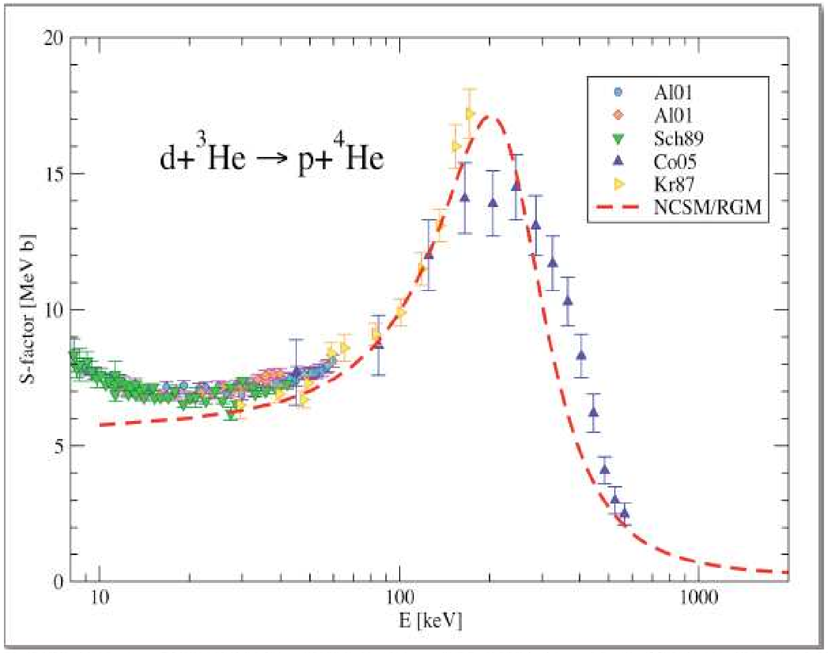
Compare theory to data:
cross section(theory)=cross section(exp) ?

If yes: structure assumptions correct
If no: try again!

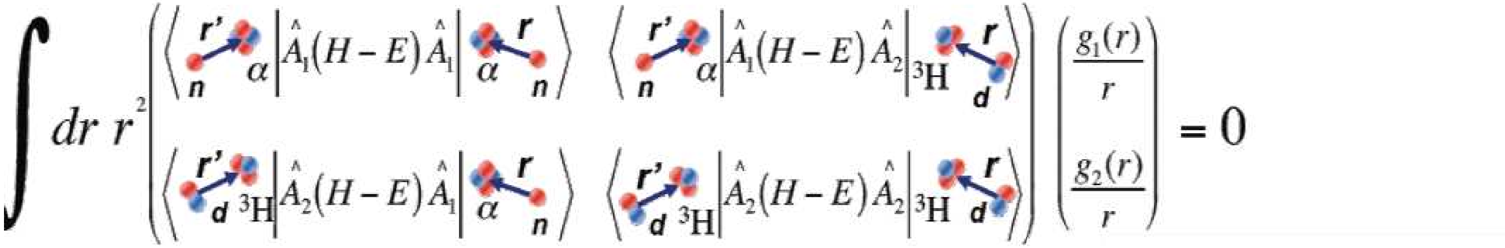
need absolute confidence in reaction model

putting reaction theory in perspective

Unified structure and reactions



[S. Quaglioni and P. Navrátil, PRL101, 092501 (2008); PRC79, 044606 (2009)]



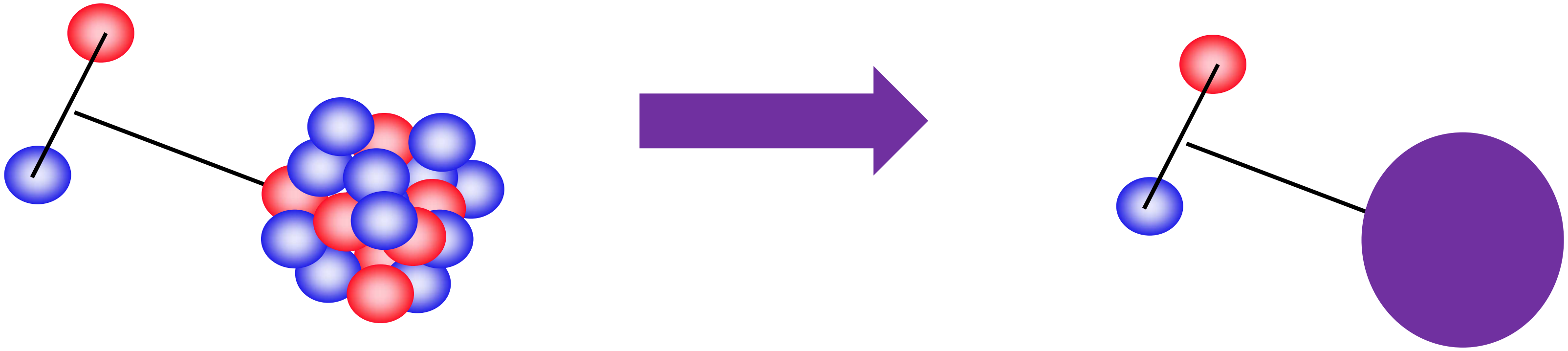
reactions at FRIB

^{3}He(d,p)^{4}He

^{140}Sn(d,p)^{141}Sn

?

reducing the many body to a few body problem



☐ isolating the important degrees of freedom in a reaction
☐ keeping track of all relevant channels
☐ connecting back to the many-body problem

☐ effective nucleon-nucleus interactions (or nucleus-nucleus)
(energy dependence/non-local)
☐ many body input

do we know how to solve the few body problem?

Benchmark of 4N bound state

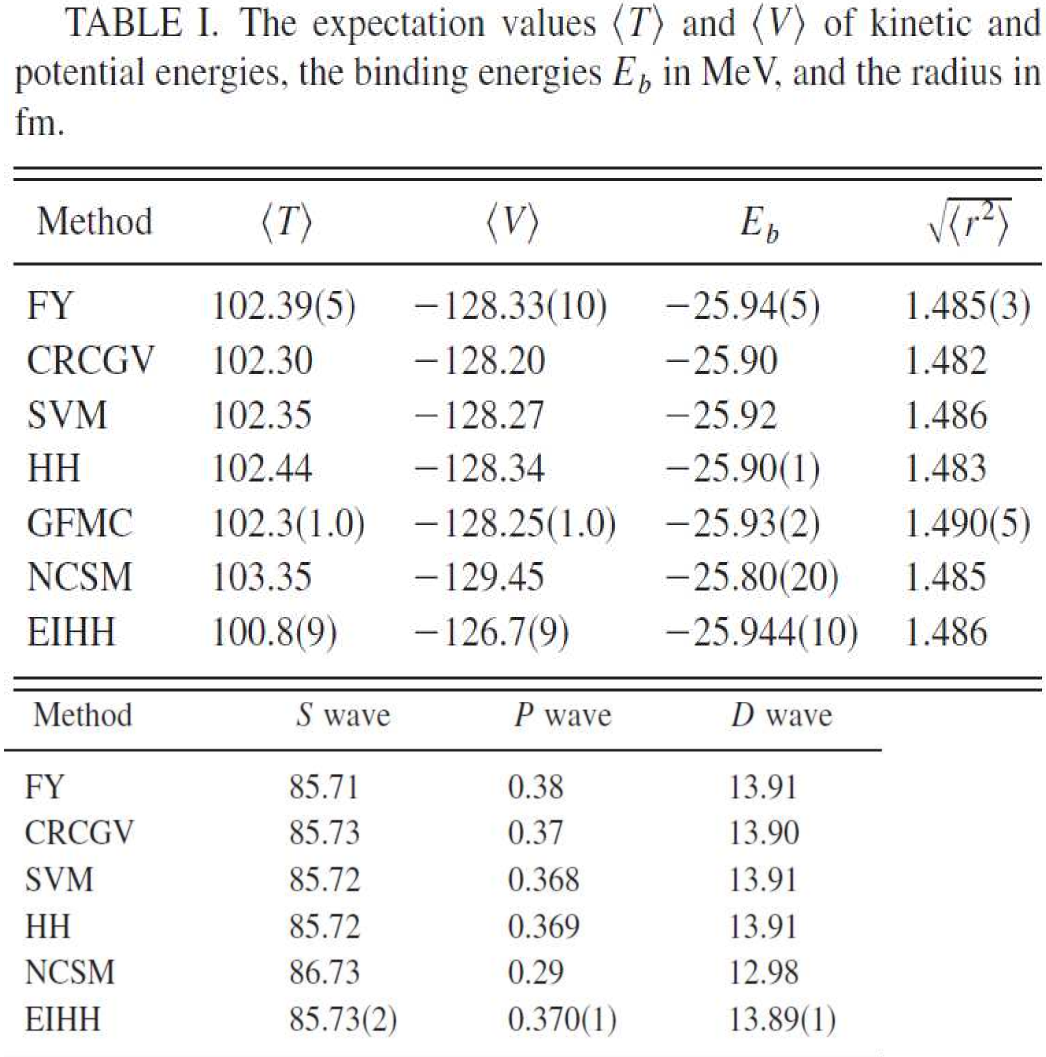


TABLE I. The expectation values $\langle T \rangle$ and $\langle V \rangle$ of kinetic and potential energies, the binding energies E_b in MeV, and the radius in fm.

Method	$\langle T \rangle$	$\langle V \rangle$	E_b	$\sqrt{\langle r^2 \rangle}$
FY	102.39(5)	−128.33(10)	−25.94(5)	1.485(3)
CRCGV	102.30	−128.20	−25.90	1.482
SVM	102.35	−128.27	−25.92	1.486
HH	102.44	−128.34	−25.90(1)	1.483
GFMC	102.3(1.0)	−128.25(1.0)	−25.93(2)	1.490(5)
NCSM	103.35	−129.45	−25.80(20)	1.485
EIHH	100.8(9)	−126.7(9)	−25.944(10)	1.486

Method	*S* wave	*P* wave	*D* wave
FY	85.71	0.38	13.91
CRCGV	85.73	0.37	13.90
SVM	85.72	0.368	13.91
HH	85.72	0.369	13.91
NCSM	86.73	0.29	12.98
EIHH	85.73(2)	0.370(1)	13.89(1)

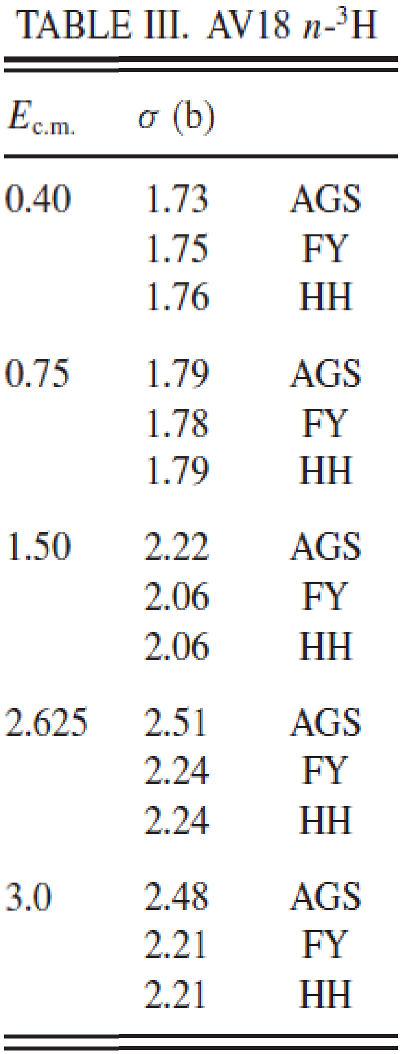


TABLE III. AV18 n-^{3}H

$E_{\text{c.m.}}$	σ (b)	
0.40	1.73	AGS
	1.75	FY
	1.76	HH
0.75	1.79	AGS
	1.78	FY
	1.79	HH
1.50	2.22	AGS
	2.06	FY
	2.06	HH
2.625	2.51	AGS
	2.24	FY
	2.24	HH
3.0	2.48	AGS
	2.21	FY
	2.21	HH

H. Kamada, et al, PRC 64, 044001 (2001)

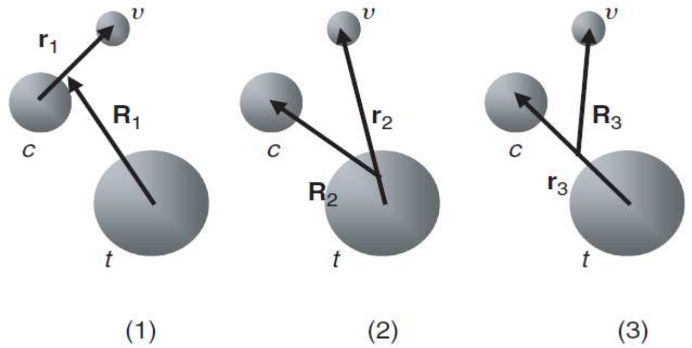
Lazauskas et al., Phys. Rev. C 71, 034004 (2005

differences between 3-body methods for d+A

Faddeev AGS:

- all three Jacobi components are included
- elastic, breakup and rearrangement channels are fully coupled
- computationally expensive

Deltuva and Fonseca, Phys. Rev. C79, 014606 (2009).



3 jacobi coordinate sets

CDCC: continuum discretized coupled channels

- only one Jacobi component
- elastic and breakup fully coupled (no rearrangement)
- computationally expensive

Austern, Kamimura, Rawistcher, Yahiro etc, Prog. Theo. Phys (1986)

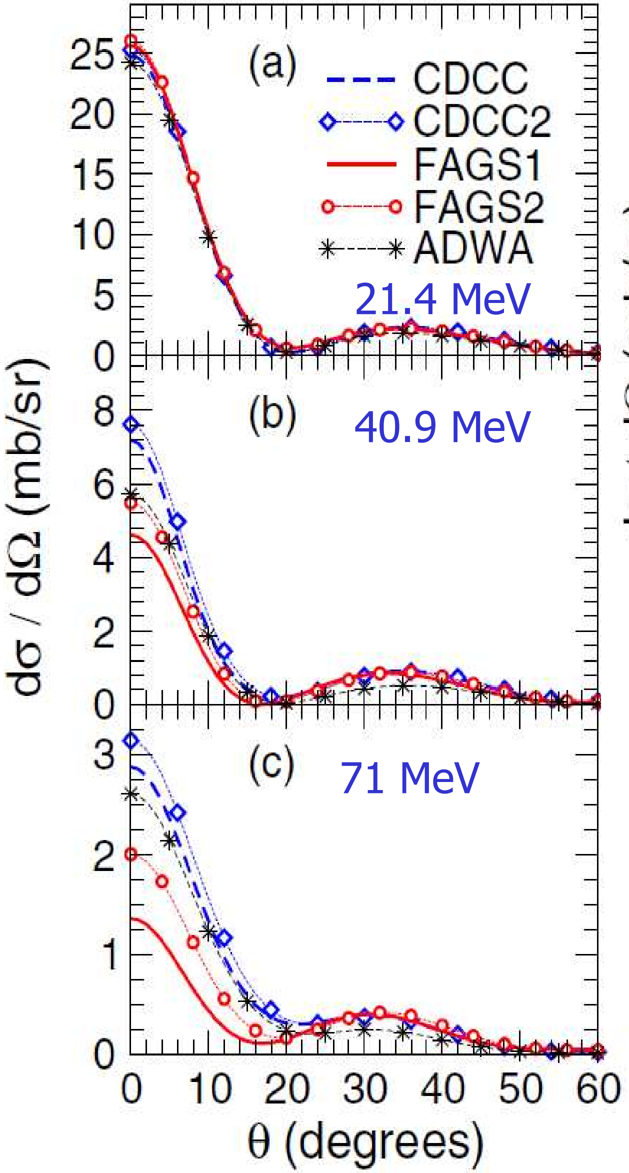
ADWA: adiabatic wave approximation

- only one Jacobi component
- elastic and breakup fully coupled (no rearrangement)
- adiabatic approximation for breakup
- only applicable to obtain transfer cross sections
- runs on desktop – practical

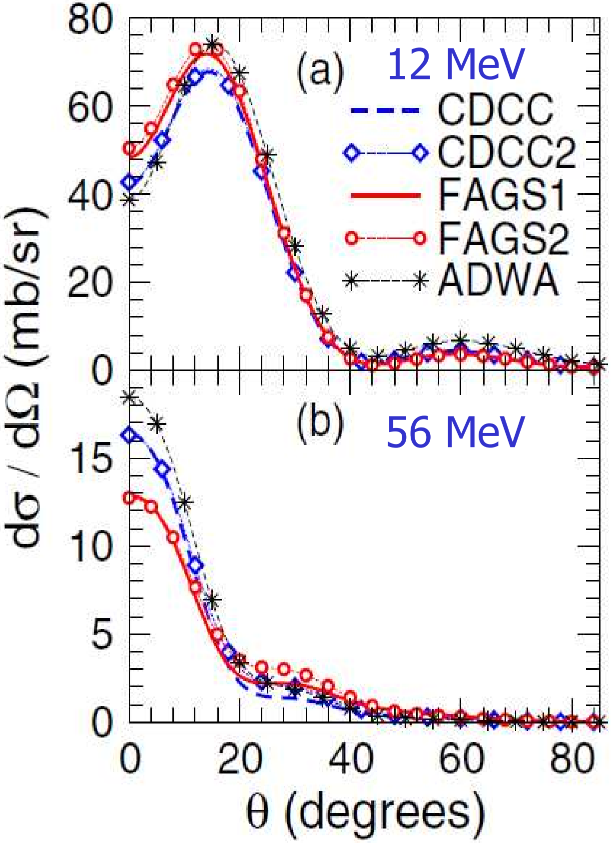
Johnson and Tandy NP (1974)

transfer (d,p): comparing ADWA, CDCC & Faddeev

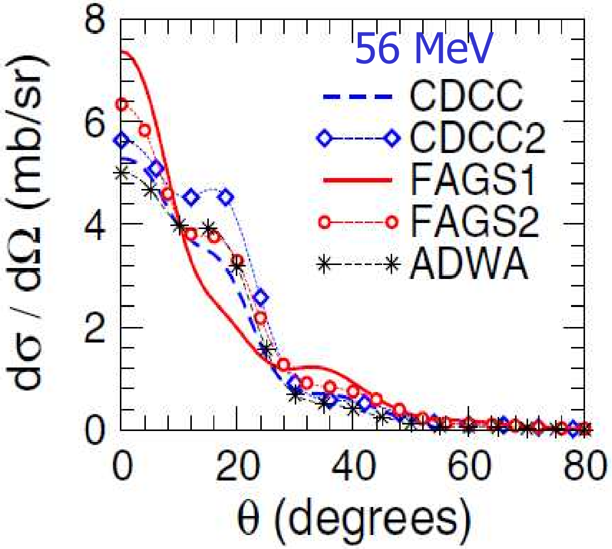
^{10}Be(d,p) ^{11}Be(g.s.)



^{12}C(d,p) ^{12}C(g.s.)

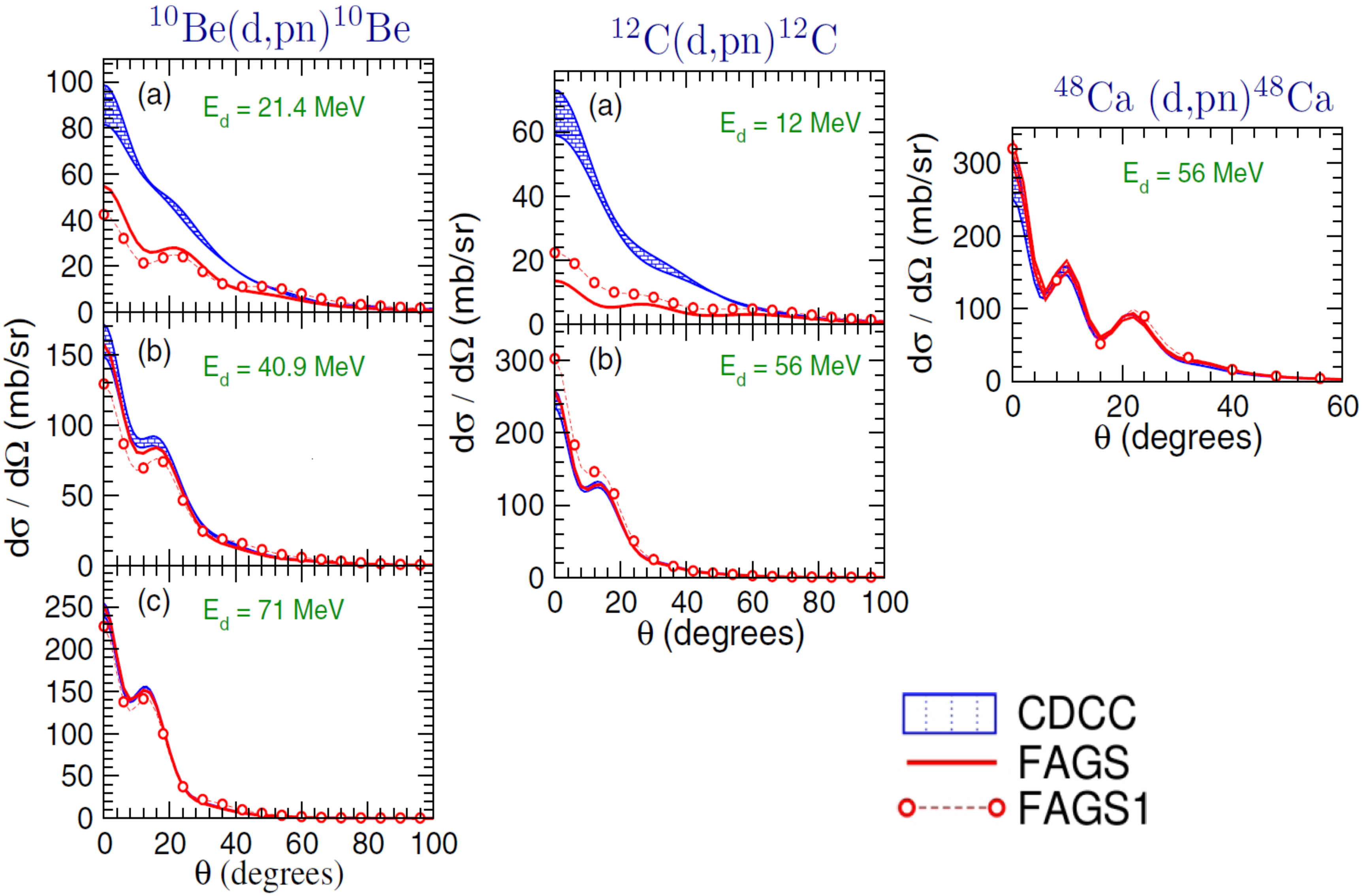


^{48}Ca(d,p) ^{48}Ca(g.s.)



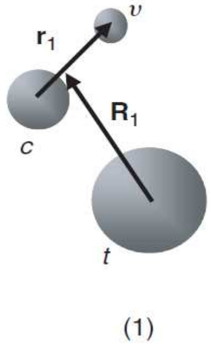
PRC 84, 034607(2011), PRC 85, 054621 (2012)

reaction methods: comparing CDCC with Faddeev



PRC 85, 054621 (2012)

Difference in method for heavy ion breakup



CDCC: (continuum discretized coupled channels)

- elastic and breakup fully coupled (no rearrangement)
- computationally expensive

TDSE: (time dep Schrodinger Eq)

- classical trajectory, lack quantum interferences
- runs on desktop

Many codes have been written to solve TDSE

[Esbensen, Bertsch and Bertulani, NPA 581, 107 (1995)]

[Typel and Wolter, Z. Naturforsch. A54, 63 (1999)]

[P.C., Baye and Melezhik, PRC 68, 014612 (2003)]

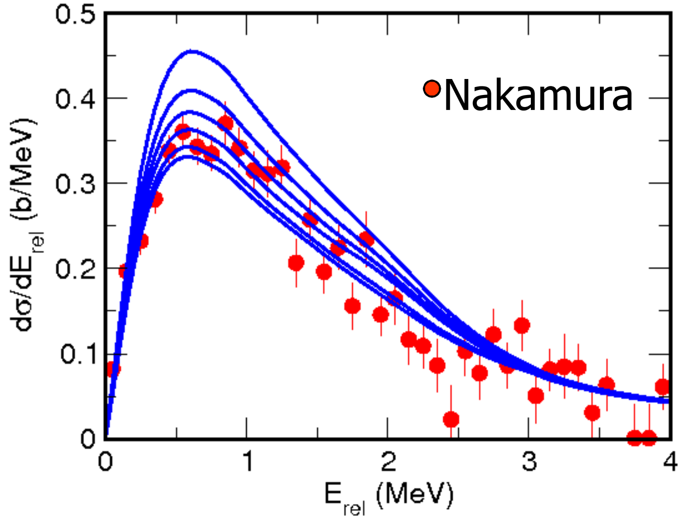
DEA: (dynamical eikonal approximation) PRL 95, 082502 (2005)

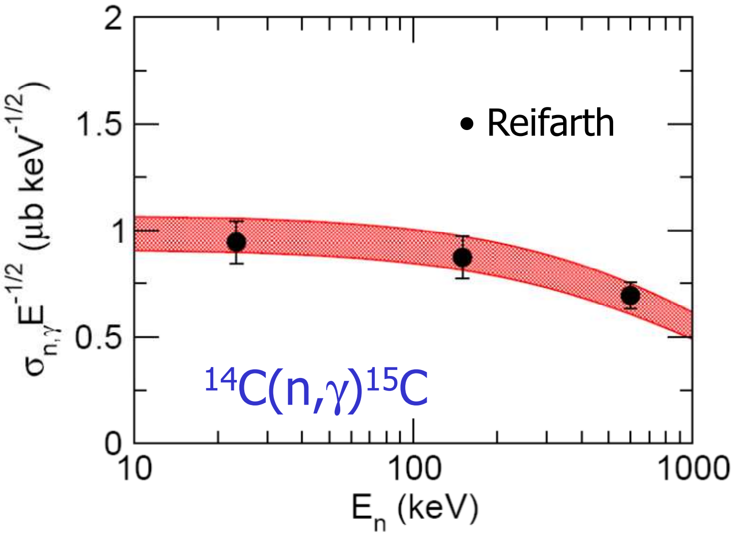
- improves TDSE by including quantal interferences
- improves eikonal by including dynamical effects
- runs on desktop – although can take days

Capel, Esbensen, Nunes, PRC(2011)

breakup reactions and (n,γ)

^{208}Pb(^{15}C,^{14}C+n)^{208}Pb@68 MeV/u





Nakamura et al, NPA722(2003)301c
Reifarth et al, PRC77,015804 (2008)

Fusion of stable versus unstable nuclei

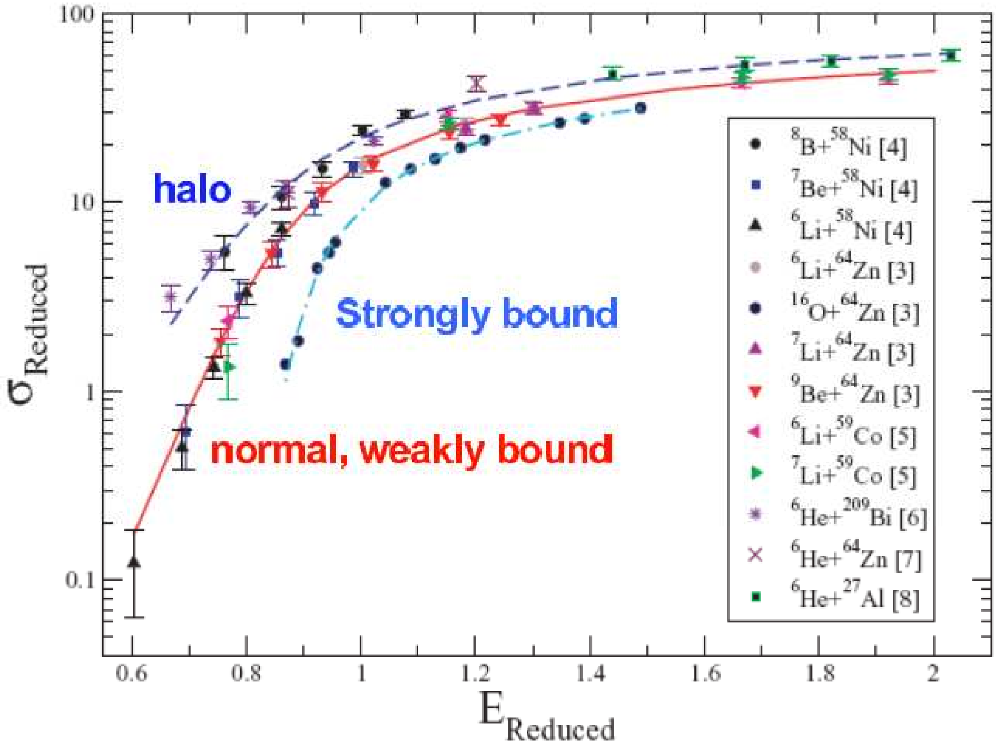


Fig. 8. Reduced cross sections for the fusion of halo, normal/weakly bound, and strongly bound nuclei. (Courtesy of Kolata).

After geometric effects are scaled out, fusion enhanced for halo nuclei!

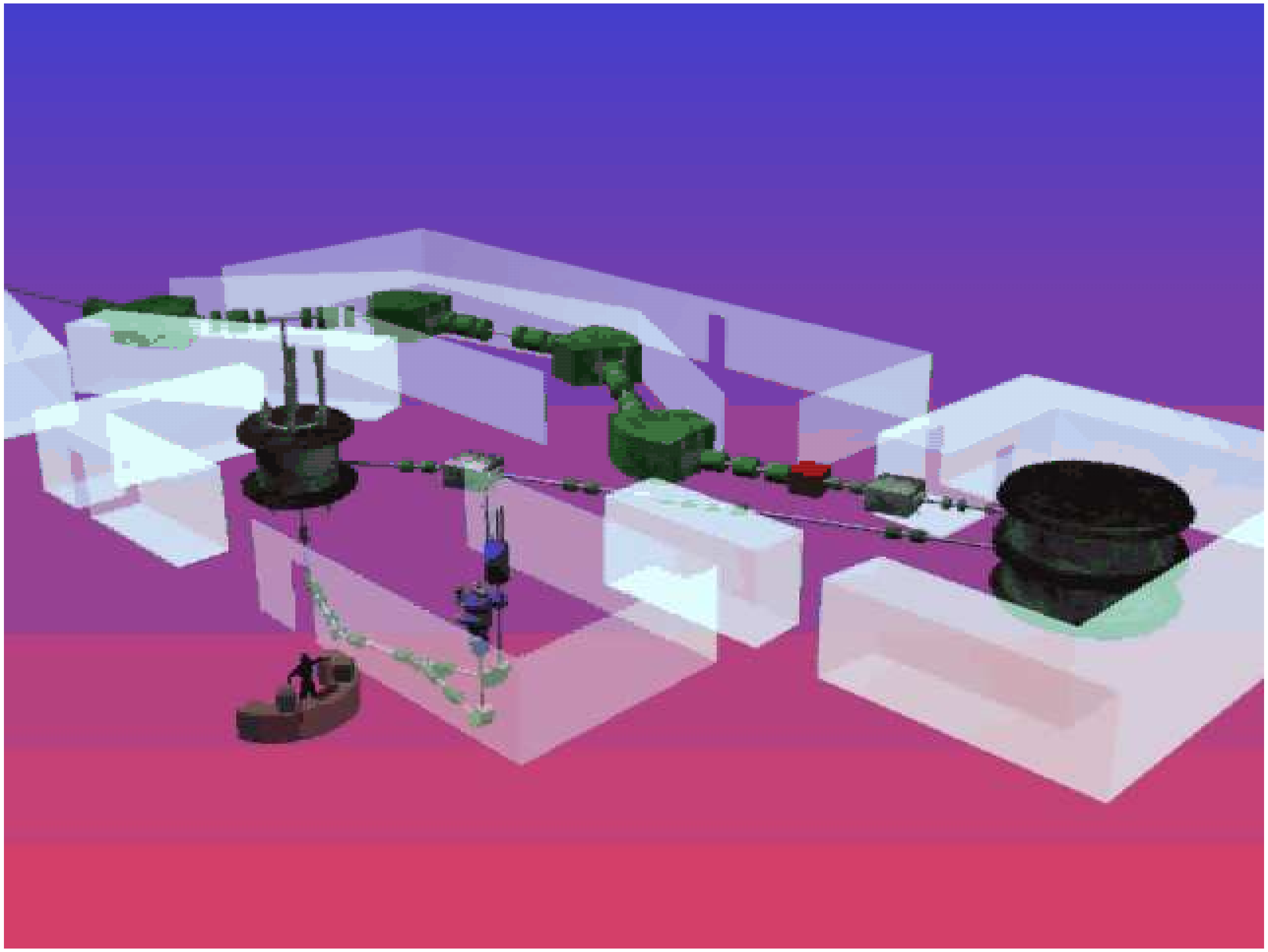
Central collision and Equation of State

Probing the equation of state of Nuclear matter:
Central collisions with unstable – probing isospin dependence
the symmetry energy
Central collisions with loosely bound – probing density dependence

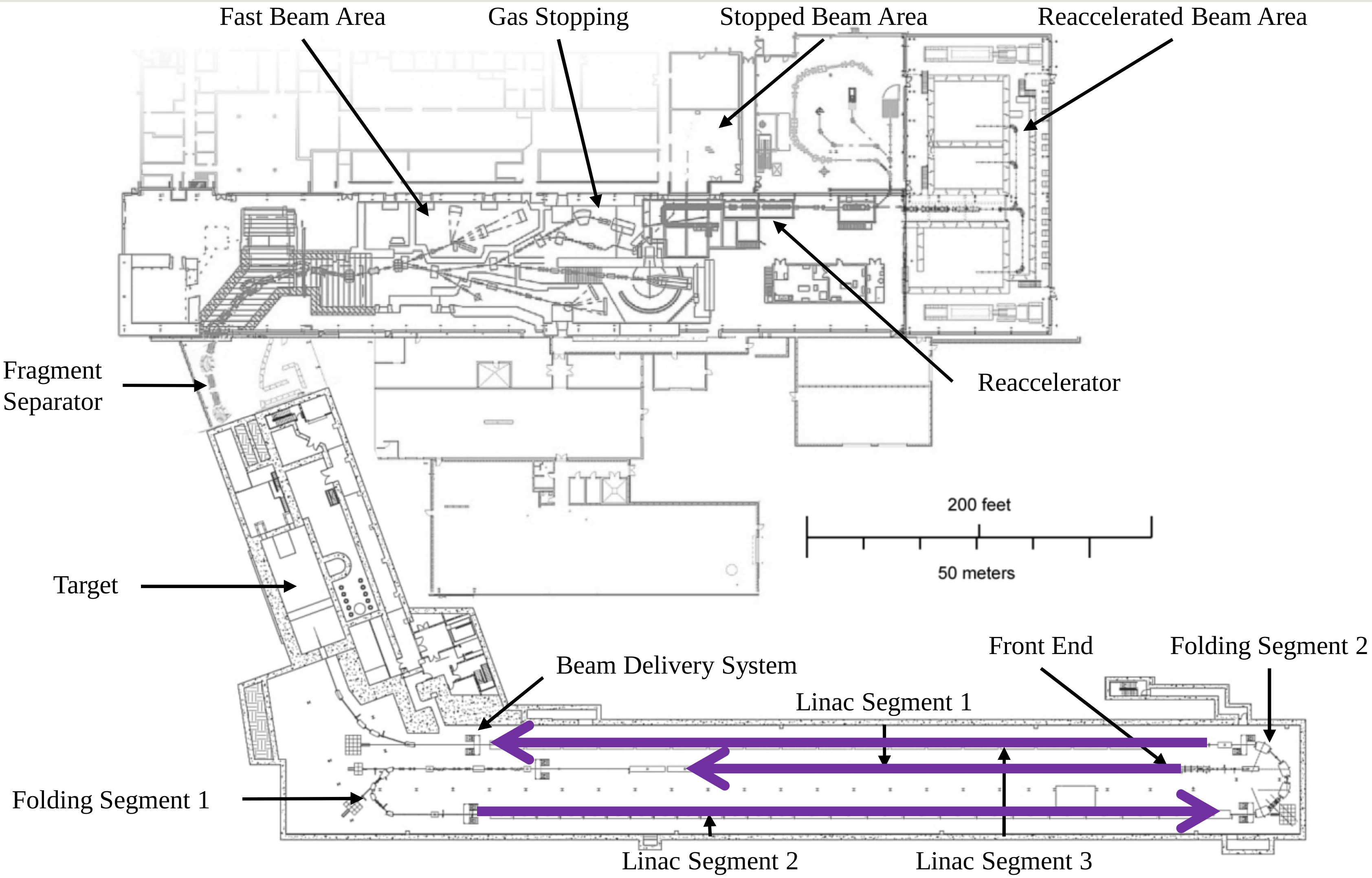
overview

- what is FRIB
- FRIB big science questions
- connection to QCD
- the hardest many-body problem ever
- typical approximations
- why exotic stuff
- nuclear reactions at a tool
- production of the exotic stuff

nscl production of rare isotopes



FRIB: Layout Frozen Since June 2011



Fast Beam Area

Gas Stopping

Stopped Beam Area

Reaccelerated Beam Area

Fragment Separator

Reaccelerator

Target

Beam Delivery System

Front End

Folding Segment 2

Linac Segment 1

Folding Segment 1

Linac Segment 2

Linac Segment 3

Key Features of FRIB

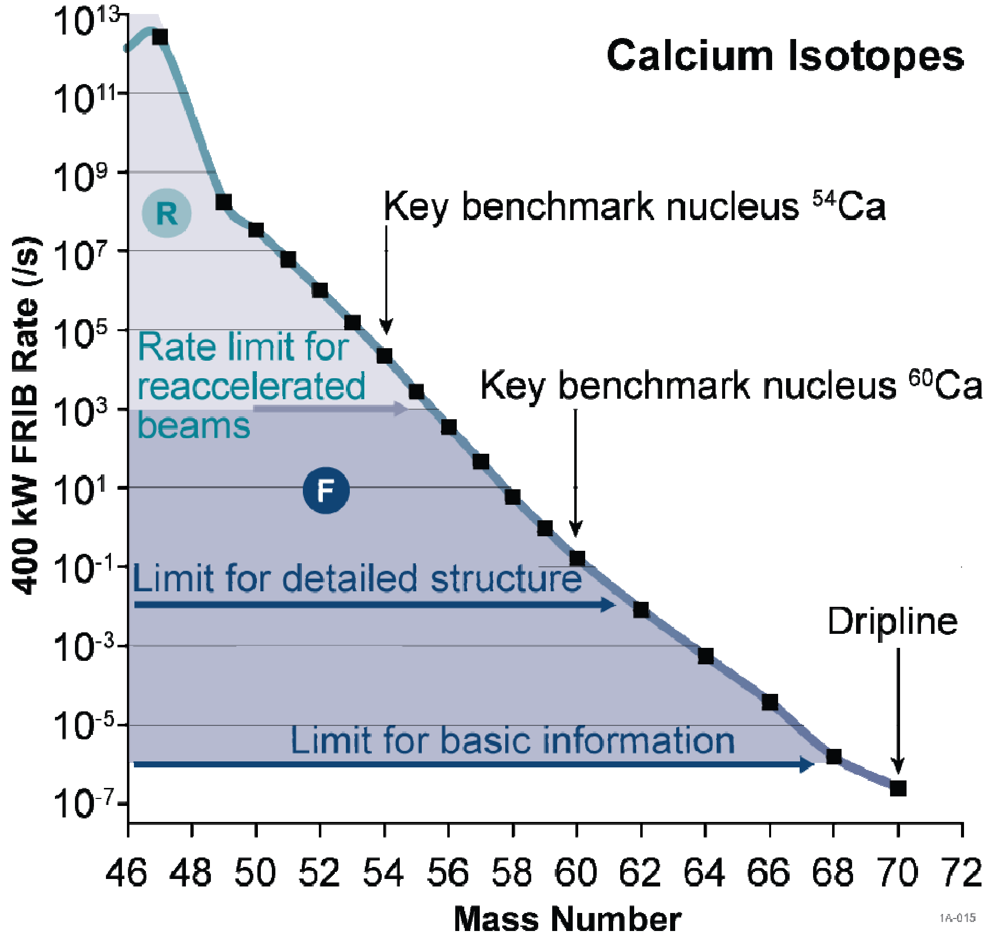
- **Heavy Ion**, superconducting **linear** accelerator with 400 kW beam power at 200 MeV/u

- FRIB will produce beams of rare isotopes at a wide range of energies
  - Options for ion trapping (from slowed ions)
  - Reaccelerated beams to 15 MeV/u (intensity of 10^{12}/s)
  - Fast beams up to 250 MeV/u (used in-flight with no slowing)

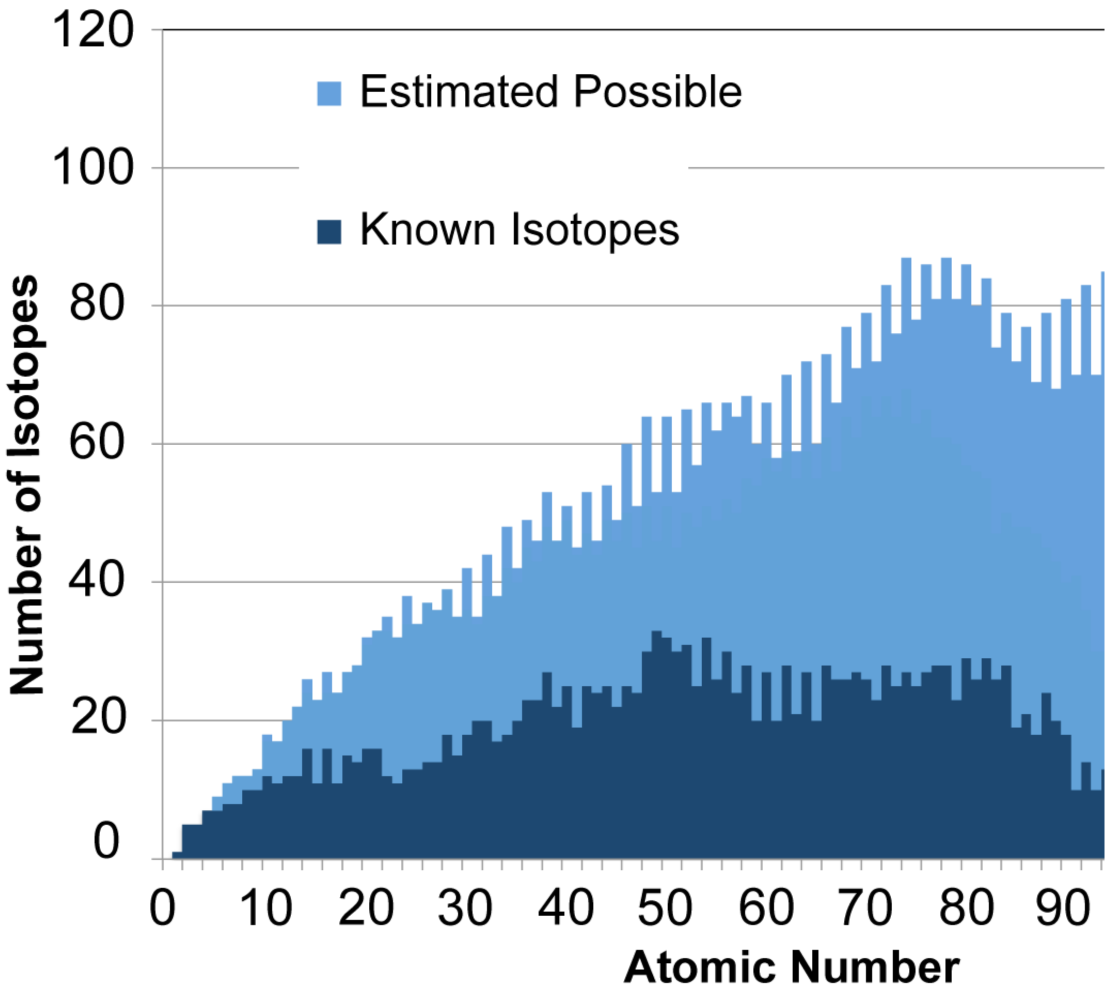
- FRIB has options for multi-user capability

FRIB Features:
Fast, Stopped, and Reaccelerated Beams

- Fast beams (>100 MeV/u)
  - Decay studies, knockout, Coulomb excitation, nuclear structure, limits of existence, EOS of asymmetric matter
- Stopped beams (0-100 keV)
  - Ion thermalization - fast, efficient
  - Precision experiments – masses, moments, atomic structure, symmetries
- Reaccelerated beams (0.2-20 MeV/u)
  - Ion thermalization and reacceleration
  - Detailed study of nucleus-nucleus collisions with exotic nuclei
  - Astrophysical reaction rates

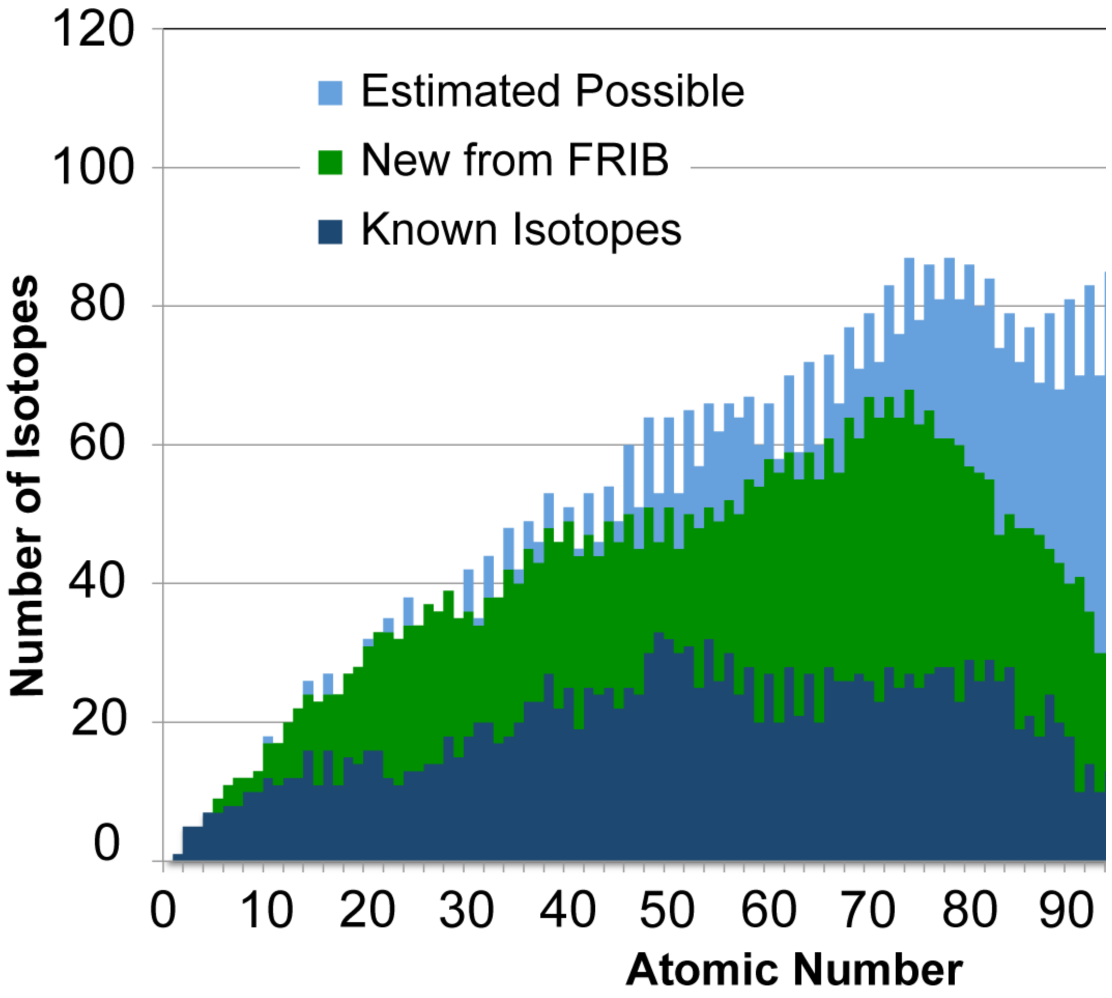


Reminder – Where we stand



- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, to be published, based on a study of EDF models
- "Known" defined as isotopes with at least one excited state known (1900 isotopes)
- The neutron drip line has only been determined to oxygen

The Number of Isotopes Available for Study at FRIB



- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, to be published, based on a study of EDF models
- "Known" defined as isotopes with at least one excited state known (1900 isotopes)
- For Z<90 FRIB is predicted to make > 80% of all possible isotopes

come and visit us!

Some additional reading

Theory road map:
http://fribusers.org/8_THEORY/3_DOCUMENTS/Blue_Book_FINAL.pdf

Research opportunities with rare isotopes
http://books.nap.edu/openbook.php?record_id=11796&page=1

Nuclear force and Effective field theories
Bogner, Furnstahl, Schwenk, Prog. Part. Nucl. Phys. **65** (2010)

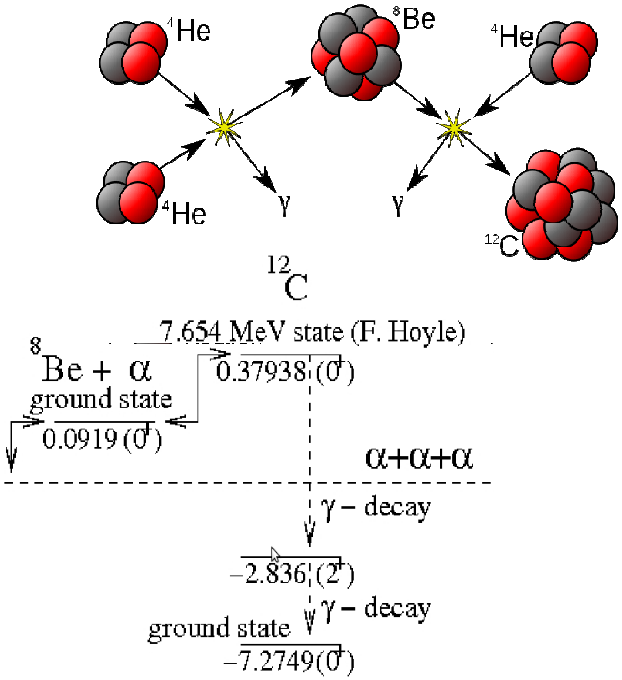
Nuclear reactions for nuclear astrophysics:
Thompson and Nunes, Cambridge University Press

Joint institute for nuclear astrophysics:
http://www.jinaweb.org

Questions?

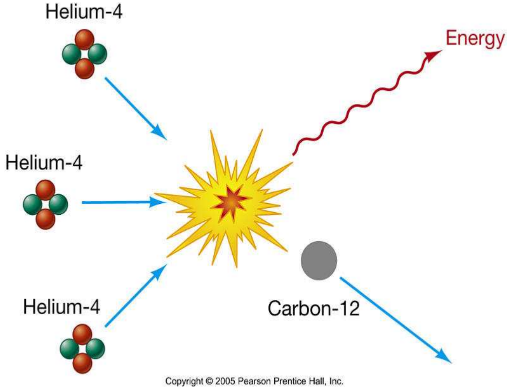
Triple alpha reaction at low temperature

Resonant process



- 2 consecutive two-body processes
- Describes the abundance of ^{12}C at high temperature (T> 10^8K) in helium burning stars.

Nonresonant process



- 3 alpha particles simultaneously fuse to create ^{12}C.
- Low temperature, cannot reach the resonance energy. Most contribution comes from non-resonant continuum states

Nguyen et al, submitted to PRL (2012)

Triple alpha reaction at low temperature

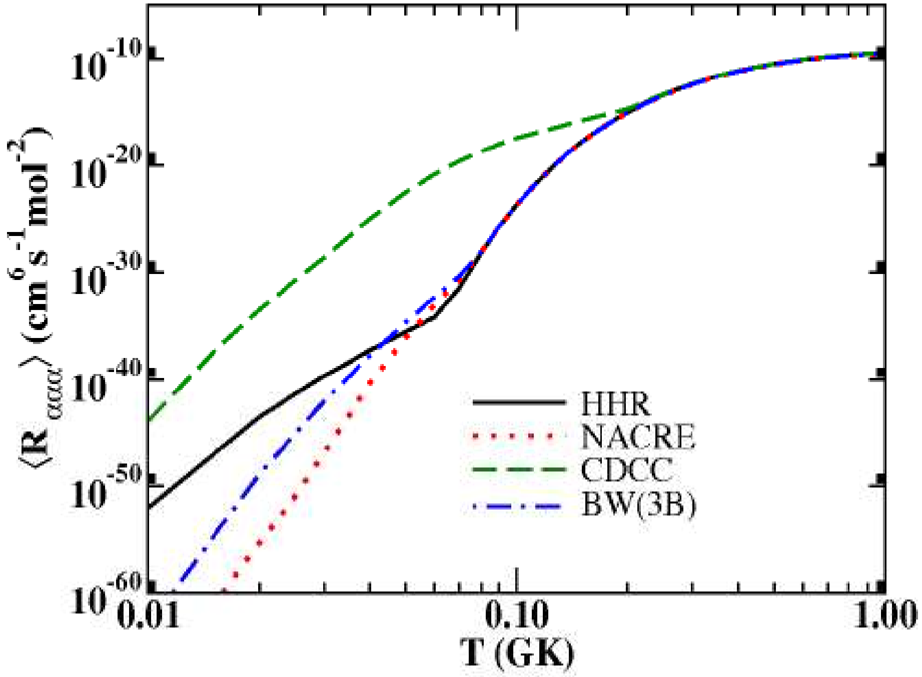


FIG. 1: (Color online) Different evaluations of the triple-alpha reaction rate: comparing the Hyperspherical Harmonic R-matrix method (solid) with NACRE (dotted), CDCC (dashed) and the three-body Breit Wigner (dot-dashed).

HHR – our work
NACRE – BW(2B) (reference)
CDCC – Ogata et al. PTP (2008)
BW(3B) – Garrido et al. EPJ (2011)

Nguyen et al, submitted to PRL (2012)

Triple alpha reaction at low temperature

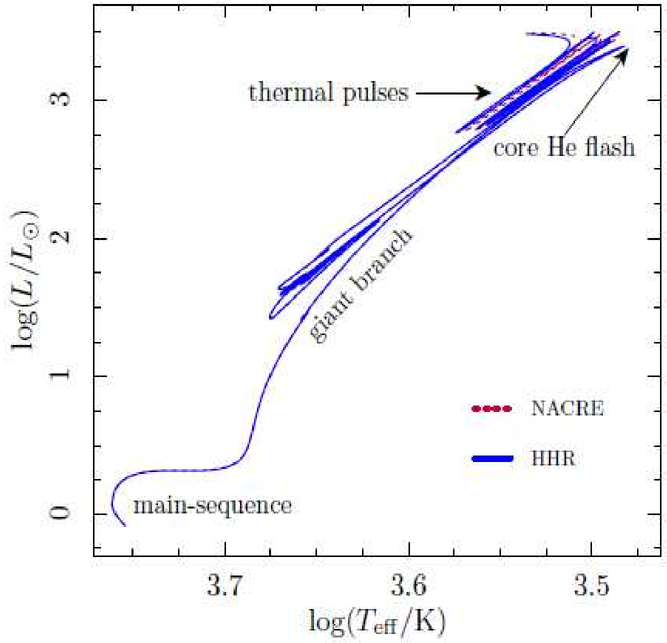


FIG. 2: (Color online) Evolutionary track (luminosity vs. surface effective temperature) of a one solar mass star with solar composition, for the HHR rate (*solid line*) and the NACRE rate (*dashed line*). The evolution is identical for both from when H fuses to He in the core ("main sequence") thorough the formation of a degenerate He core ("giant branch") and the ignition of He in the core ("core He flash"). Small differences are seen when thermally unstable H and He burning occurs in a shell about a degenerate C/O core ("thermal pulses"), but there is no difference in the final white dwarf's mass or composition.

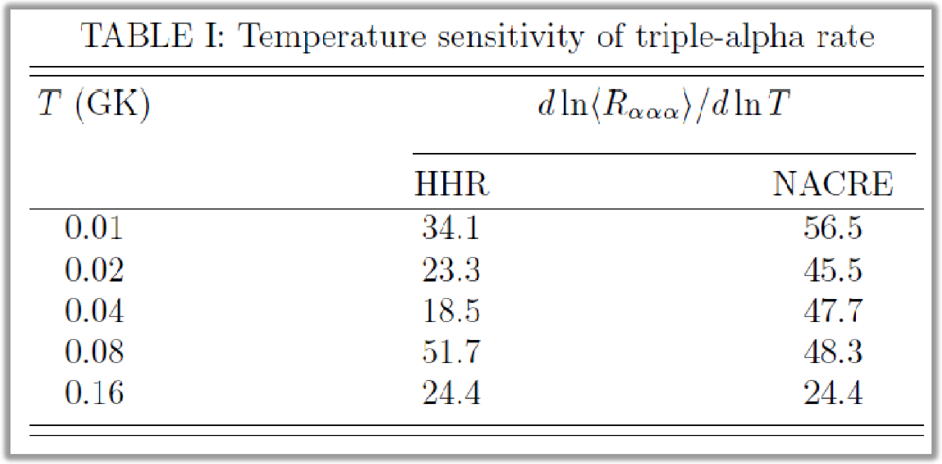


TABLE I: Temperature sensitivity of triple-alpha rate

T (GK)	$d\ln\langle R_{\alpha\alpha\alpha}\rangle/d\ln T$	
	HHR	NACRE
0.01	34.1	56.5
0.02	23.3	45.5
0.04	18.5	47.7
0.08	51.7	48.3
0.16	24.4	24.4

Nguyen et al, submitted to PRL (2012)