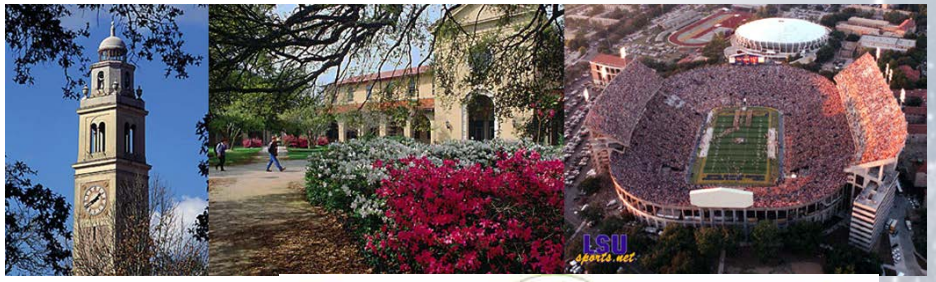
Low Energy Nuclear Theory

KD Launey
Louisiana State University



LSU
CENTER FOR COMPUTATION & TECHNOLOGY

LONI
Louisiana Optical Network Initiative

LIGO

CAMD LA Light Source

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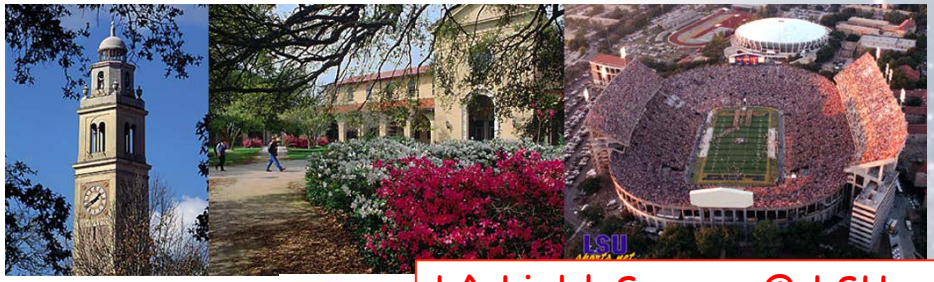
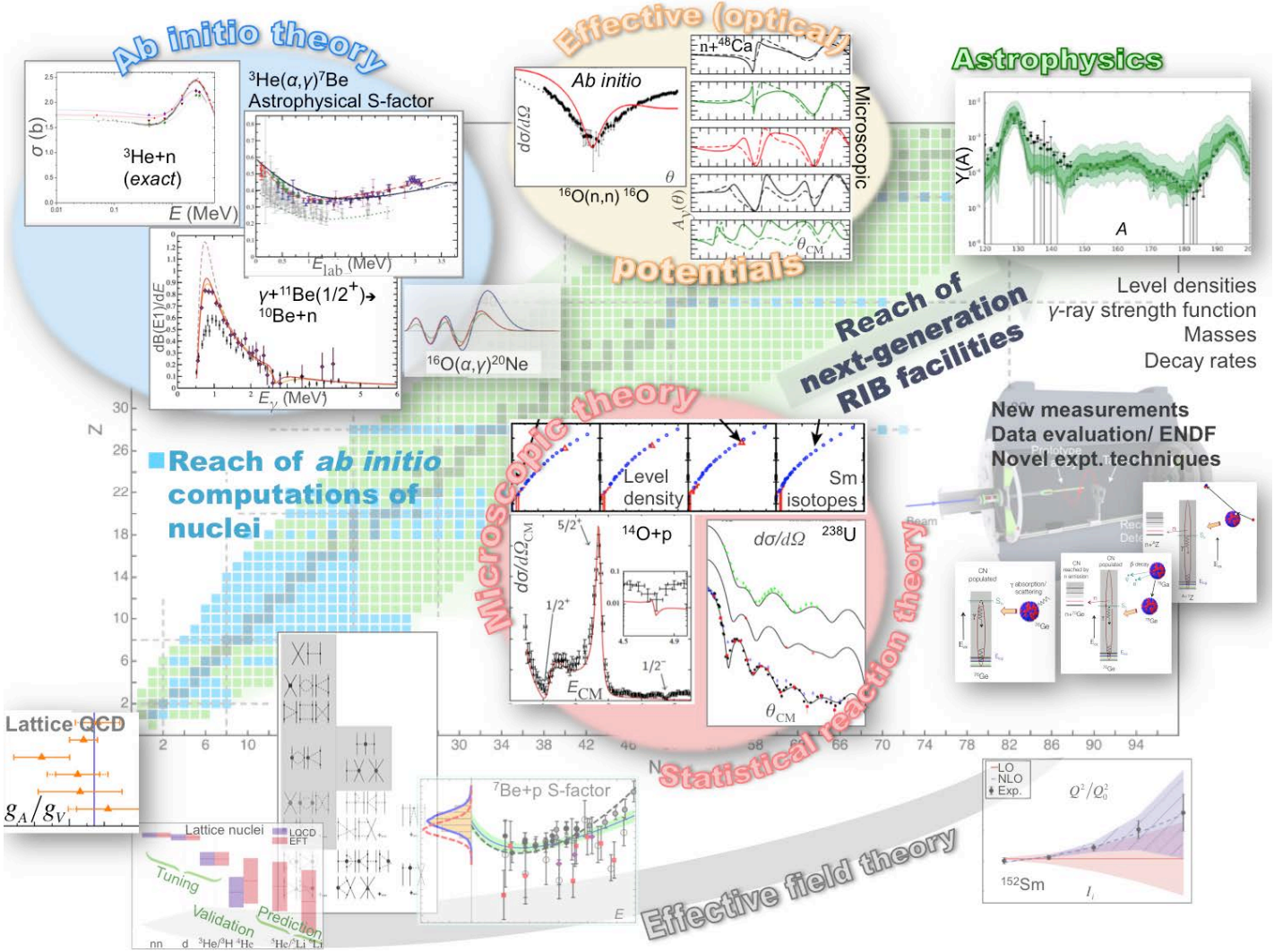


LA Light Source @ LSU

Modeling nuclei: structure …and reactions

Numerous successful approaches…

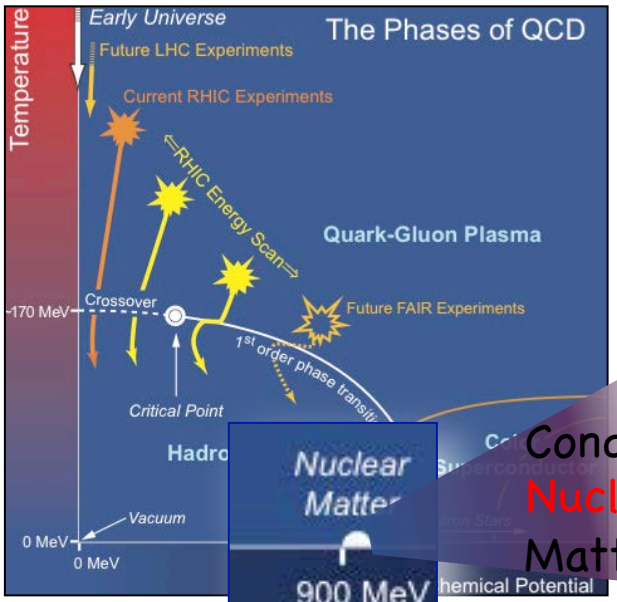
I will focus on how to build on first principles (rooted in QCD)



From INT-17-1a program "Toward Predictive Theories of Nuclear Reactions Across the Isotopic Chart"

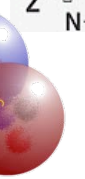
From Nucleons to Stars

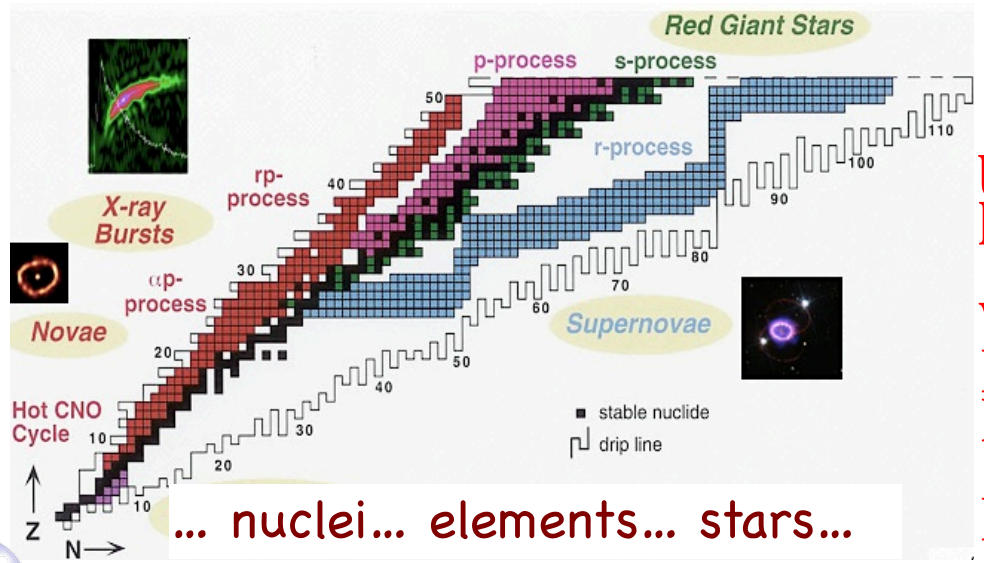
quarks & gluons



protons neutrons

Condensed Nuclear Matter





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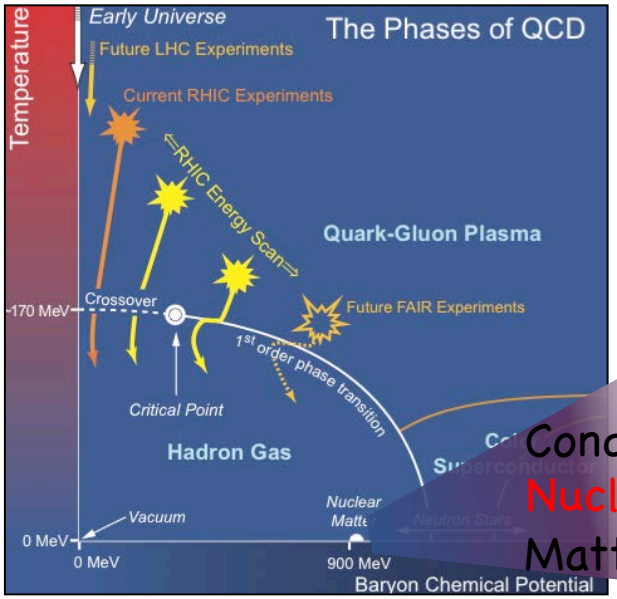
The Big Science Questions

1. How did visible matter come into being and how does it evolve?
2. How does subatomic matter organize itself and what phenomena emerge?
3. Are the fundamental interactions that are basic to the structure of matter fully understood?
4. What are the origins of heavy elements?

quarks & gluons



protons neutrons

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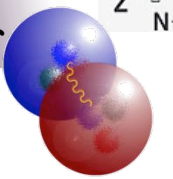

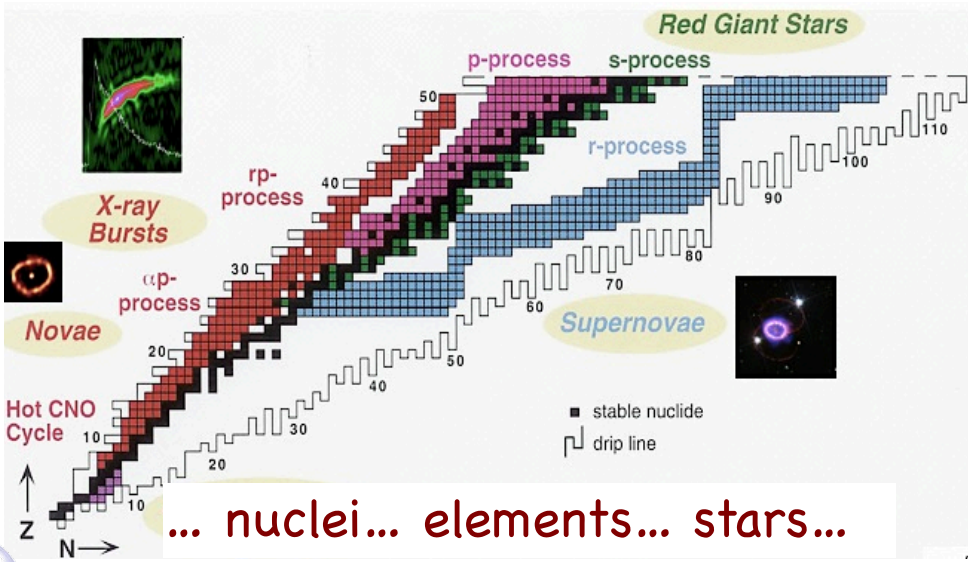

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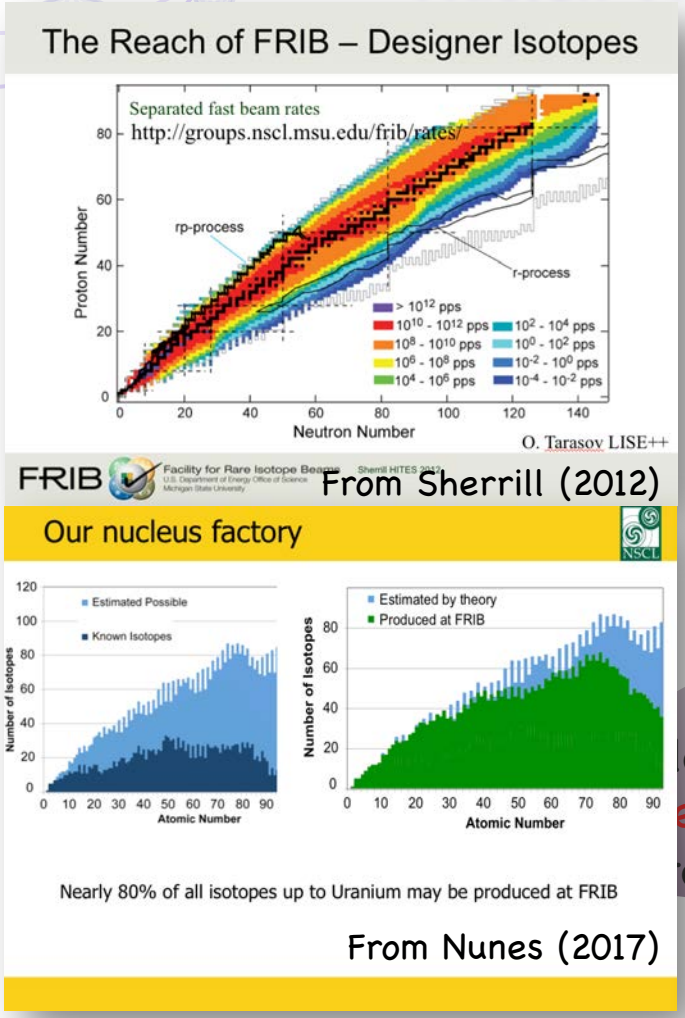
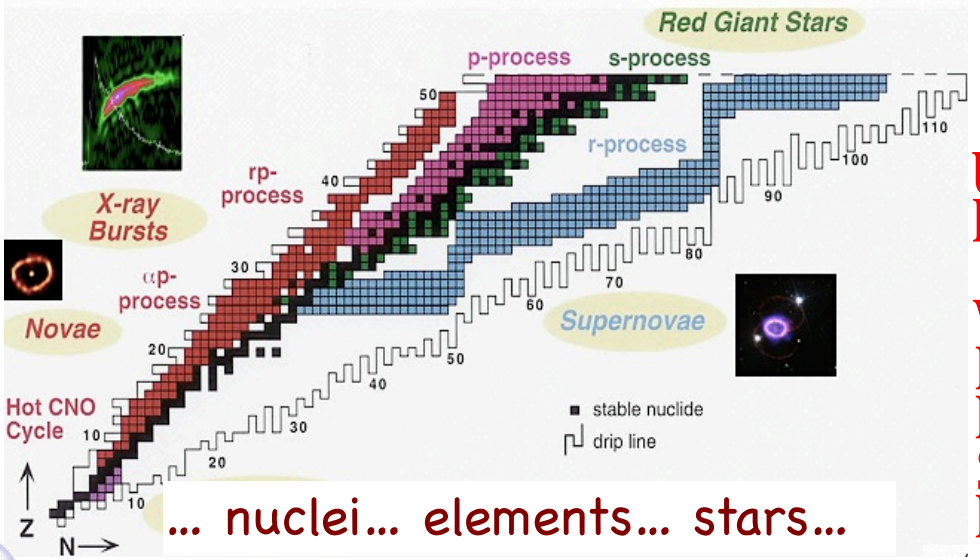
Nuclei: fuel of the Cosmos and ideal labs!



Astrophysics: the origin of the elements

FRIB (Facility for Rare Isotope Beams)

Advanced LIGO



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protons neutrons

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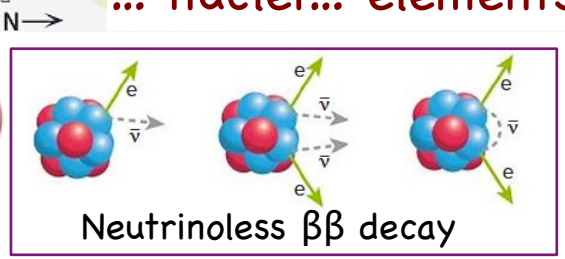
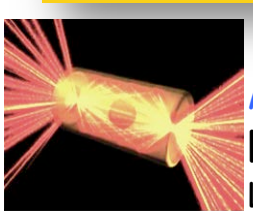


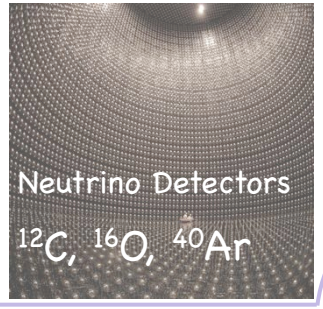


Applied energy

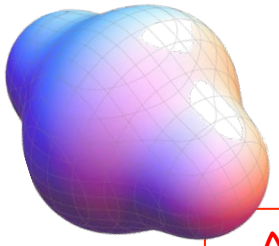
NIF (National Ignition Facility) at Lawrence Livermore National Lab

Neutrino physics; fundamental symmetries

T2K; DUNE



Nuclei: fuel of the Cosmos and ideal labs!



Astrophysics: the origin of the elements

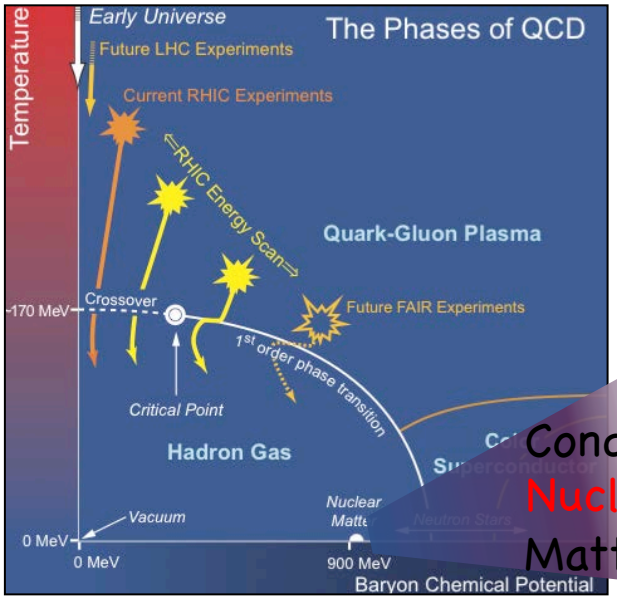
FRIB (Facility for Rare Isotope Beams)

Advanced LIGO

Ab initio Theory

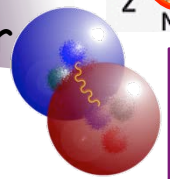
Density Functional Theory

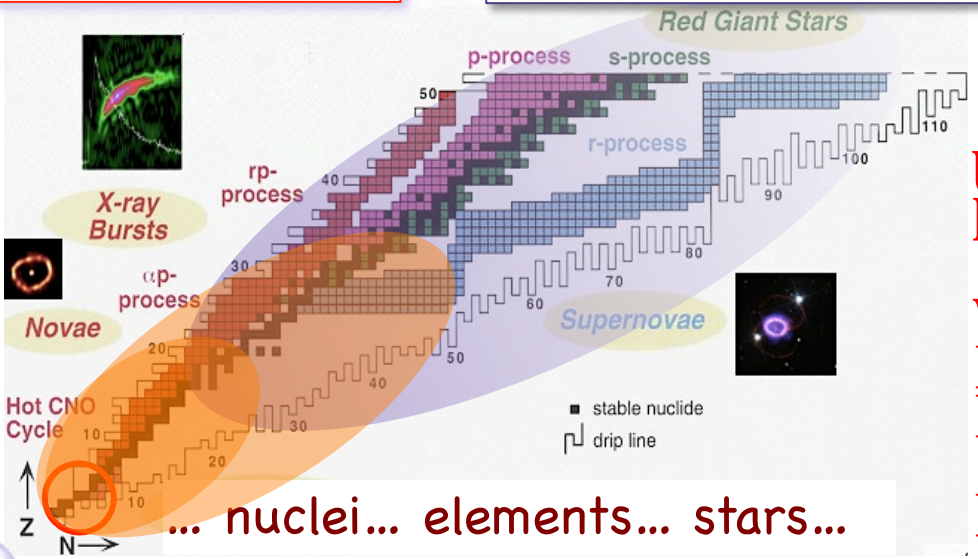
quarks & gluons



protons neutrons

Condensed Nuclear Matter





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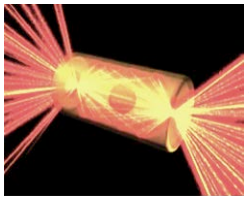

Applied energy

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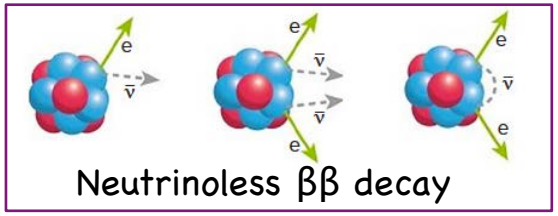
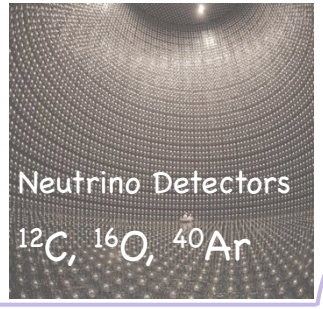


Neutrino physics; fundamental symmetries

T2K; DUNE



Why Ab initio?

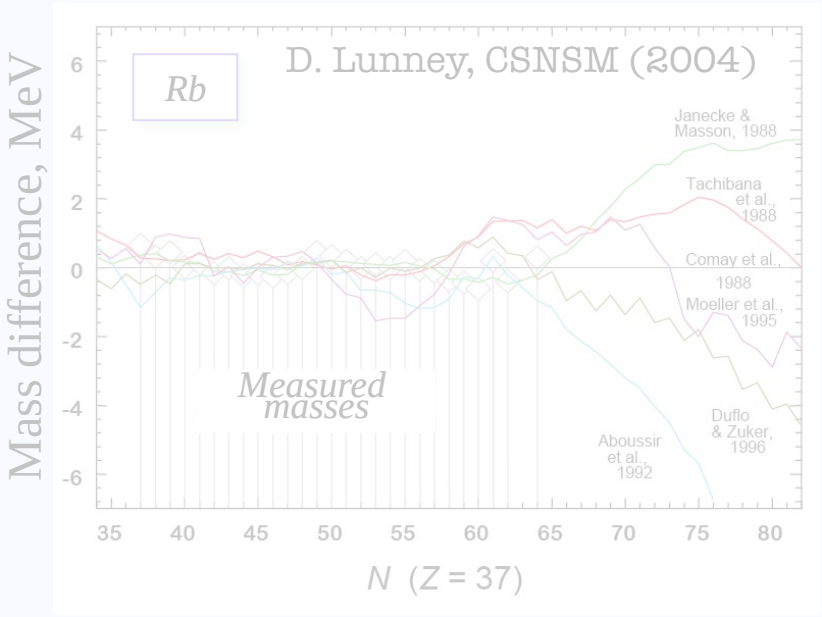
✓Explains ✓Predicts

Astrophysics: the origin of the elements

FRIB (Facility for Rare Isotope Beams)

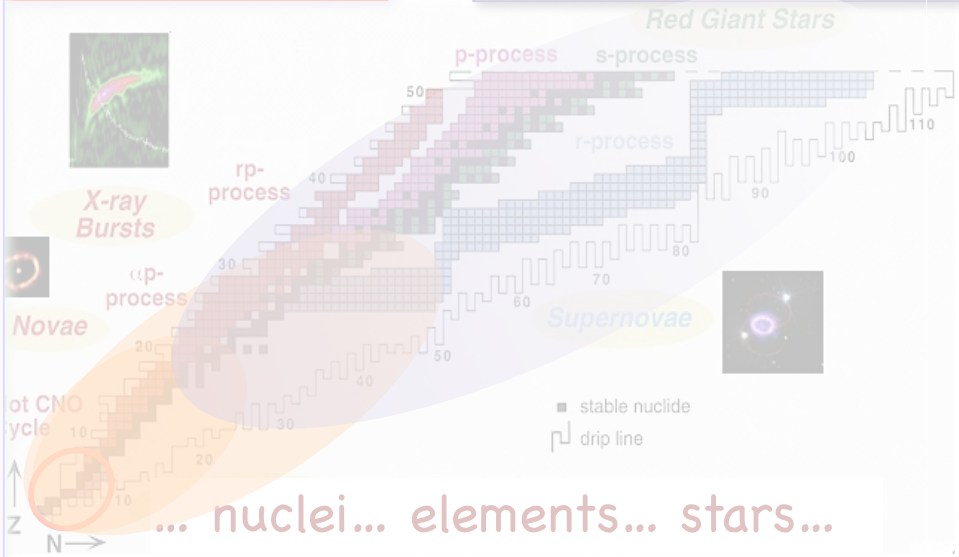
Advanced LIGO

Unstable nuclei: need reliable prediction (mass models diverge)



Ab initio Theory

Density Functional Theory



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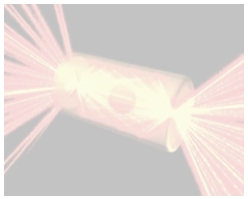
... nuclei... elements... stars...



Applied energy

NIF (National Ignition Facility) at Lawrence Livermore National Lab

Neutrino physics; fundamental symmetries

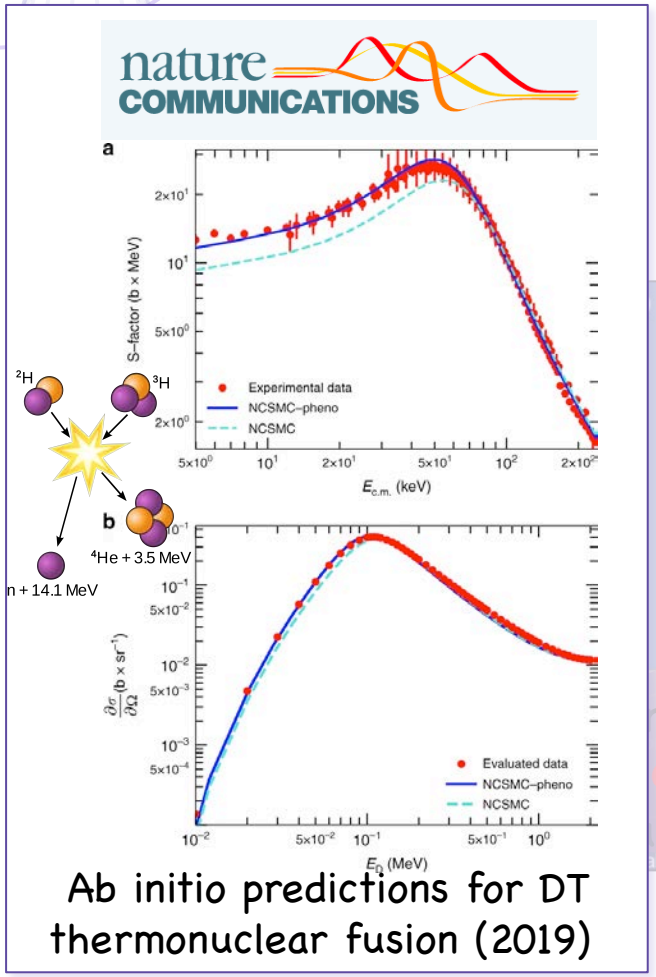
T2K; DUNE

Resolving open questions…

Astrophysics: the origin of the elements

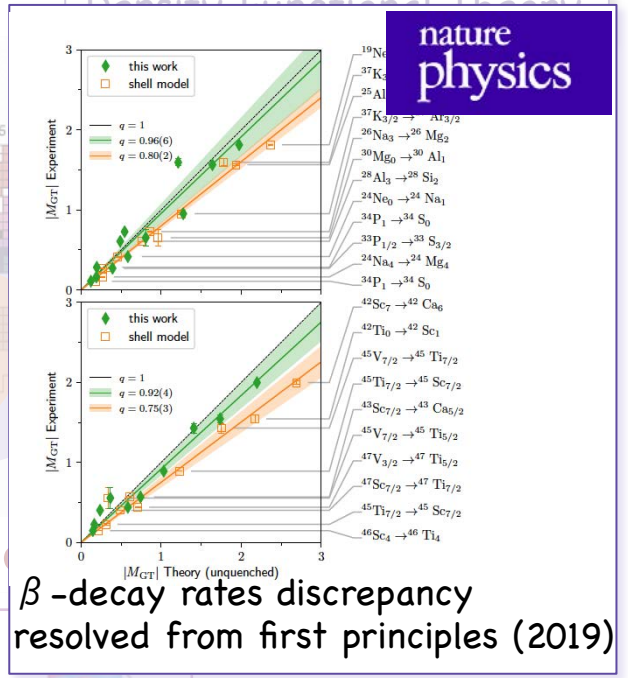
FRIB (Facility for Rare Beams)

Advanced LIGO

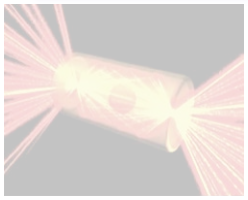


Ab initio predictions for DT thermonuclear fusion (2019)

Ab initio alpha-alpha scattering (2015)



β-decay rates discrepancy resolved from first principles (2019)



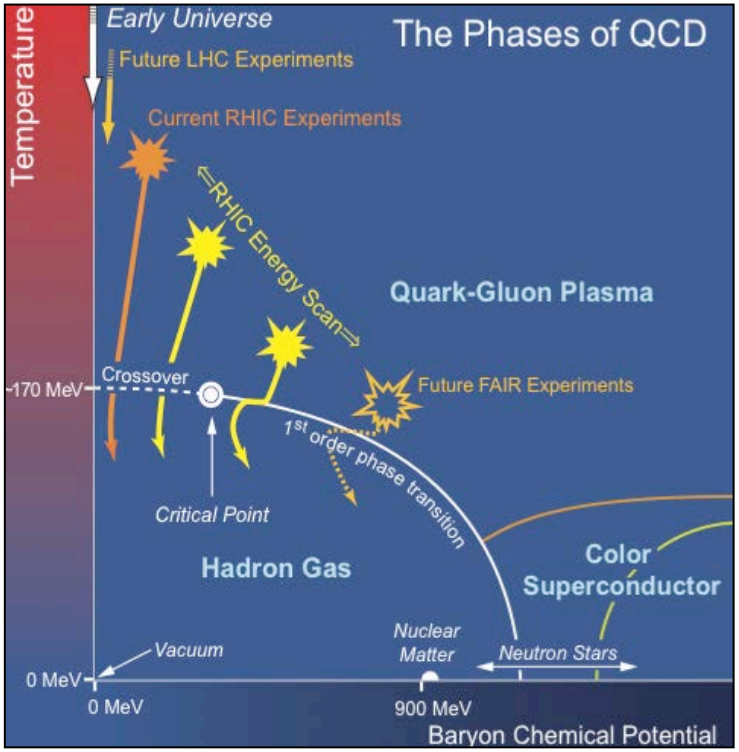
Applied energy

NIF (National Ignition Facility) at Lawrence Livermore National Lab

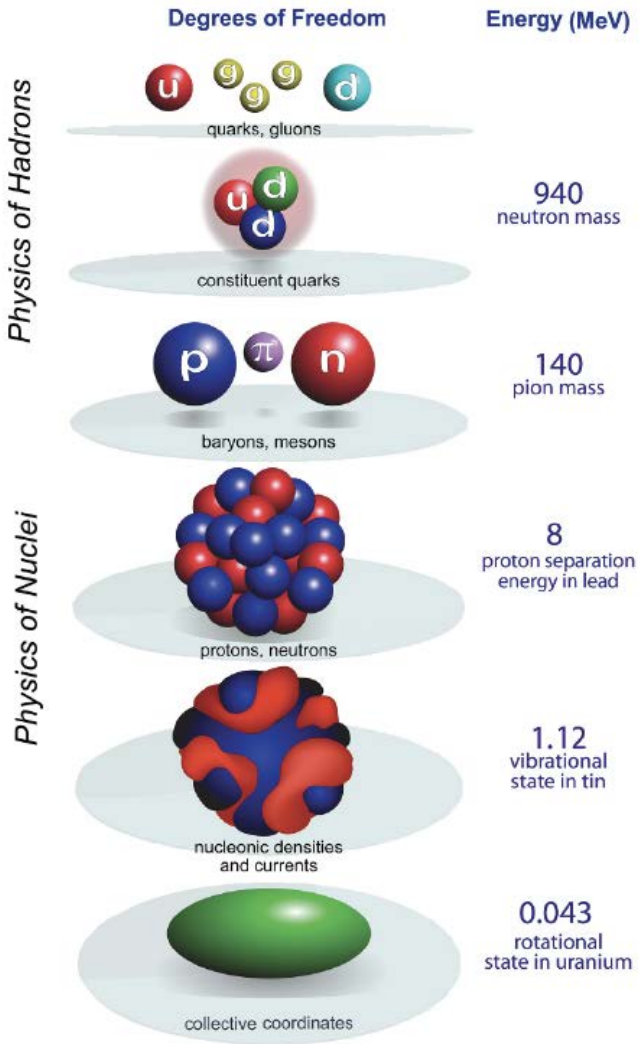
Neutrino physics; fundamental symmetries

T2K; DUNE

Nucleus – relevant scales



baryon chemical potential = measure of net baryon density

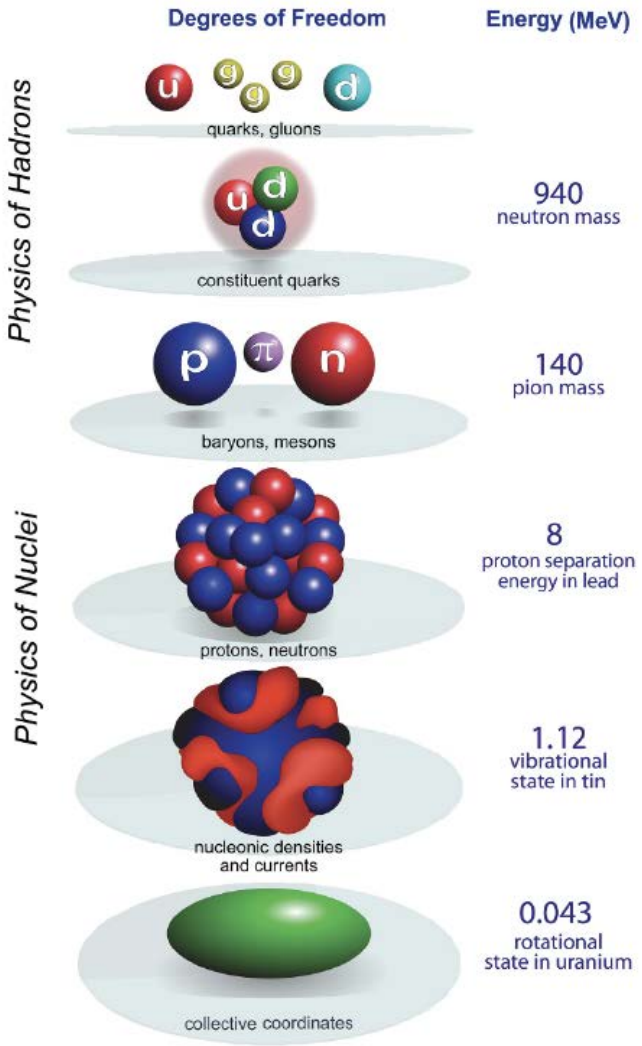


baryon = made of 3 quarks (protons, neutrons, ...)

mesons = made of quark-antiquark (pions, ...)

} hadrons

Nucleus – relevant scales



Mass of nucleon (proton or neutron)

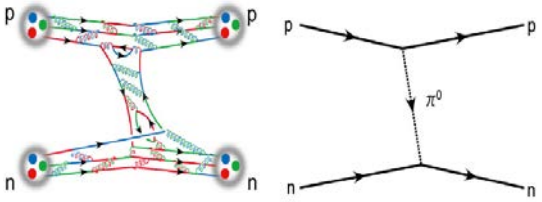
~1 GeV = 10^3MeV

Separation energy per particle

6-8 MeV

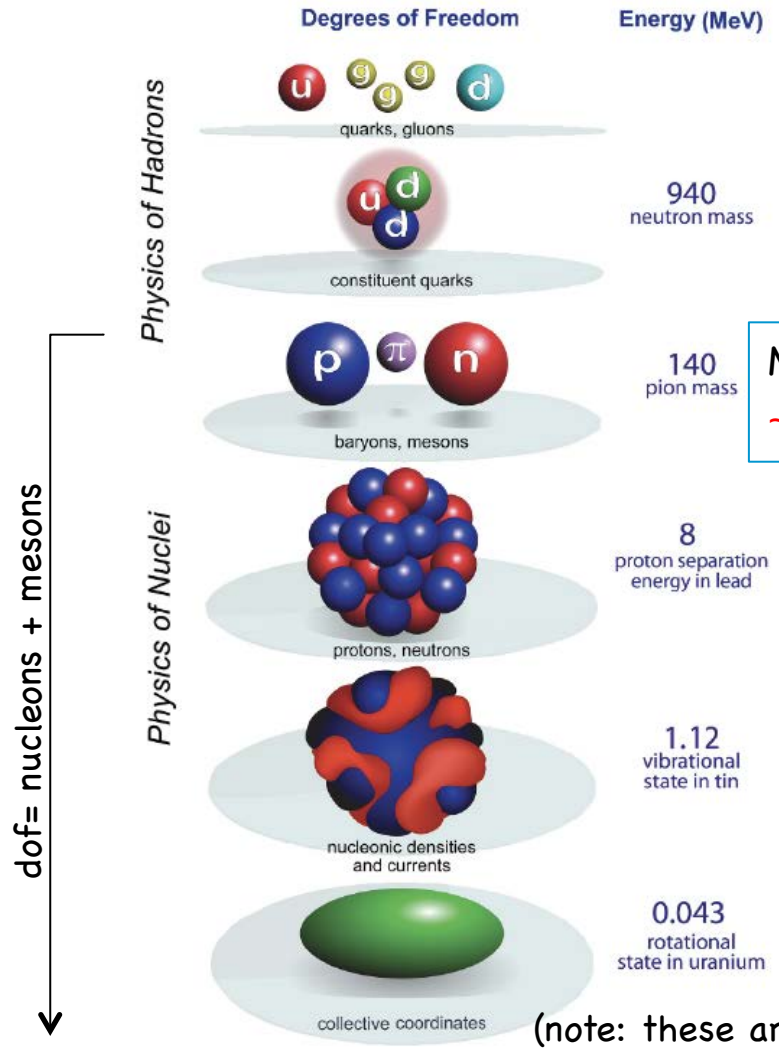
Nucleus – relevant scales

Nuclear forces are induced through exchange by mediating quanta: (virtual) *mesons*



(similar to electromagnetic interaction: generated by the exchange of photons)

low-energy nuclear physics



Mass of nucleon (proton or neutron)
~1 GeV = 10^3MeV

Mass of pion
~140 MeV

Separation energy per particle
6-8 MeV

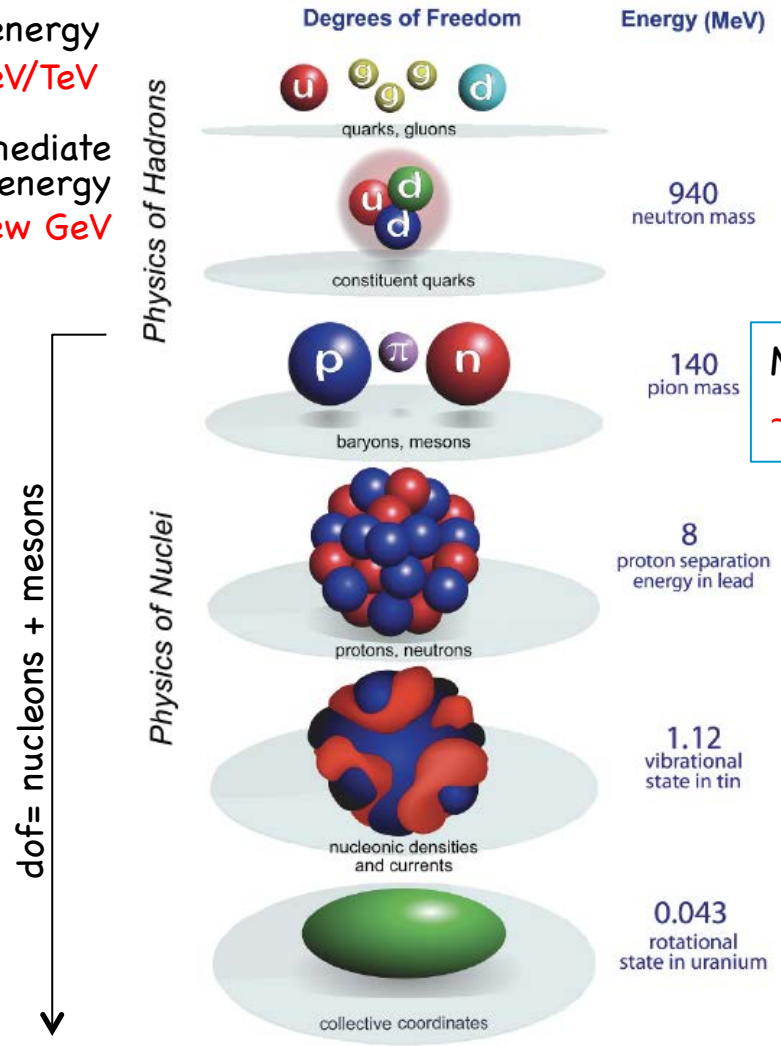
(note: these are excitation energies of nucleus, not binding energy, nor beam energy)

Nucleus – relevant scales

Size ~0.8 fm

High energy
GeV/TeV

Intermediate energy
a few GeV



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Radioactive beam facilities (FRIB)

low-energy nuclear physics

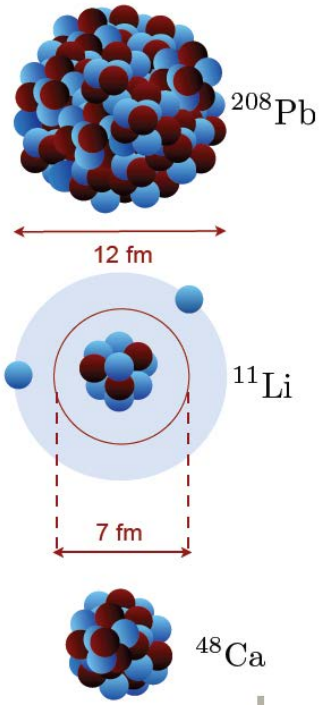
Nucleus – relevant scales

Size ~0.8 fm

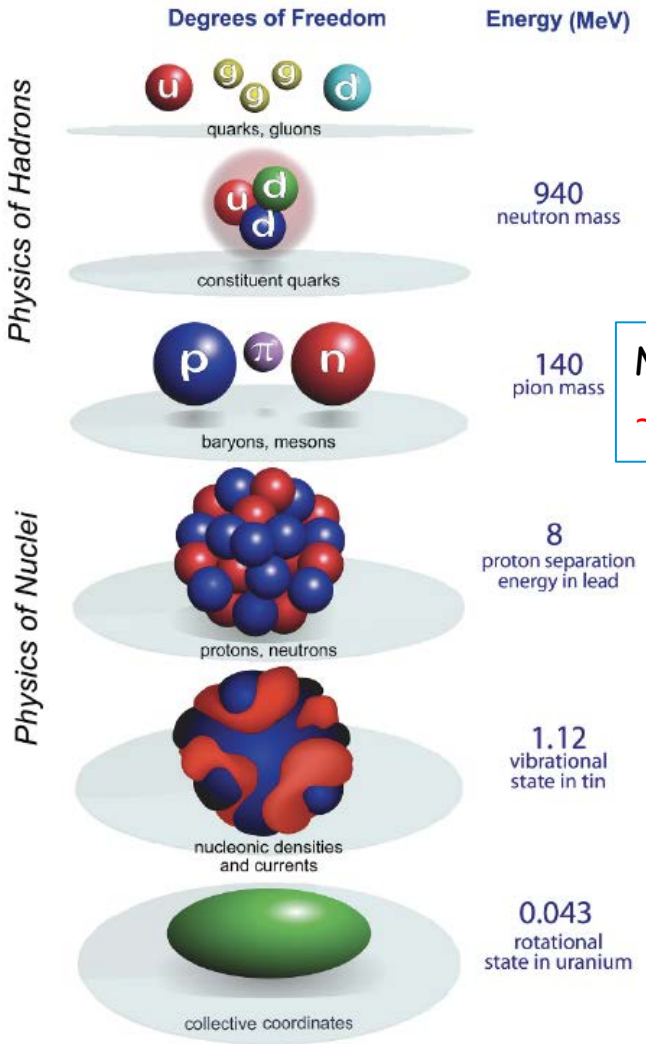
High energy
GeV/TeV

Intermediate energy
a few GeV

Many surprises: nuclear sizes!



dof= nucleons + mesons



Mass of nucleon (proton or neutron)
~1 GeV = 10^3MeV

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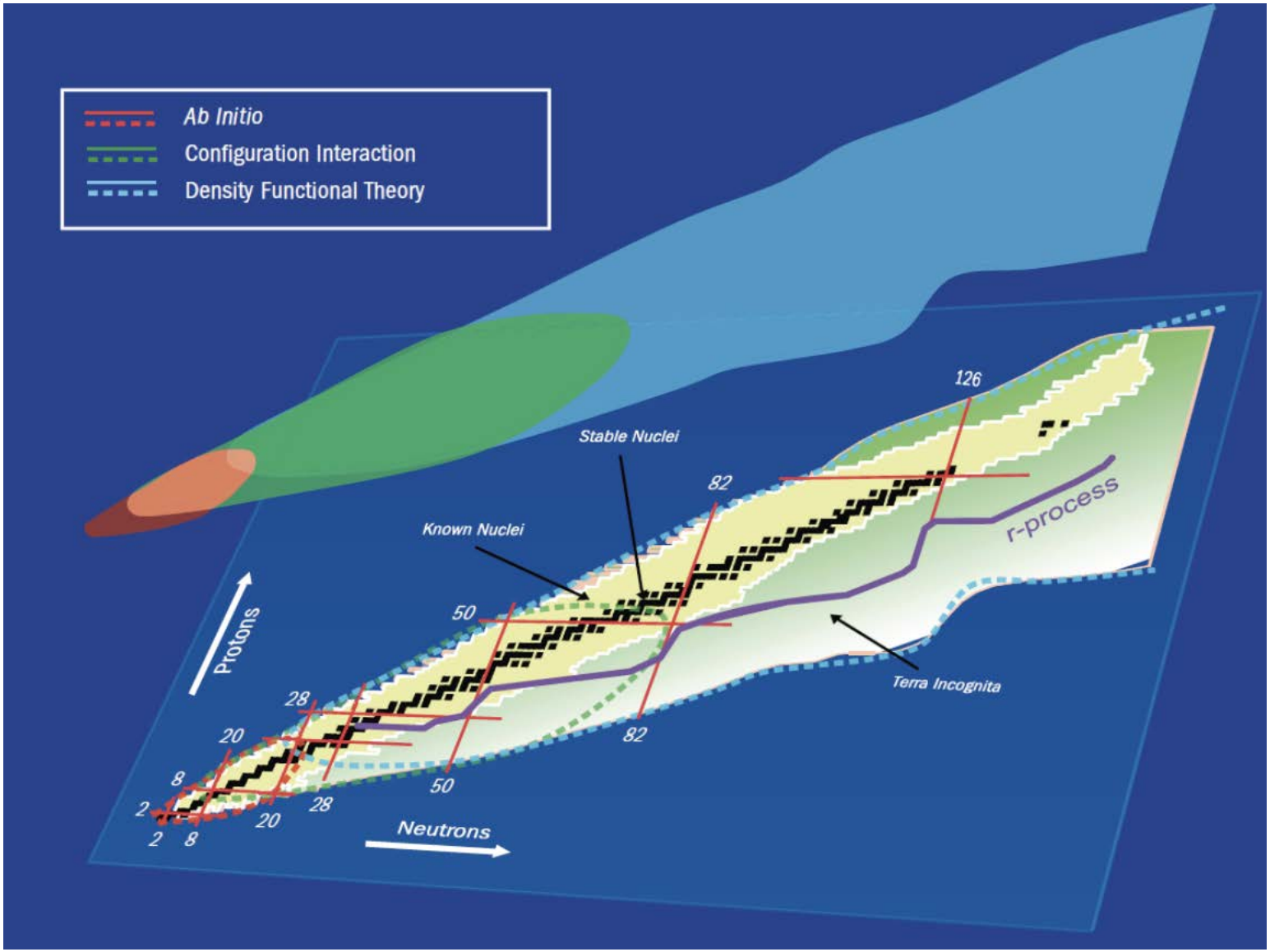
~140 MeV

Separation energy per particle
6-8 MeV

Various dof
- Collective
- Clusters
- Halo

Modeling Nuclei and Nuclear Reactions



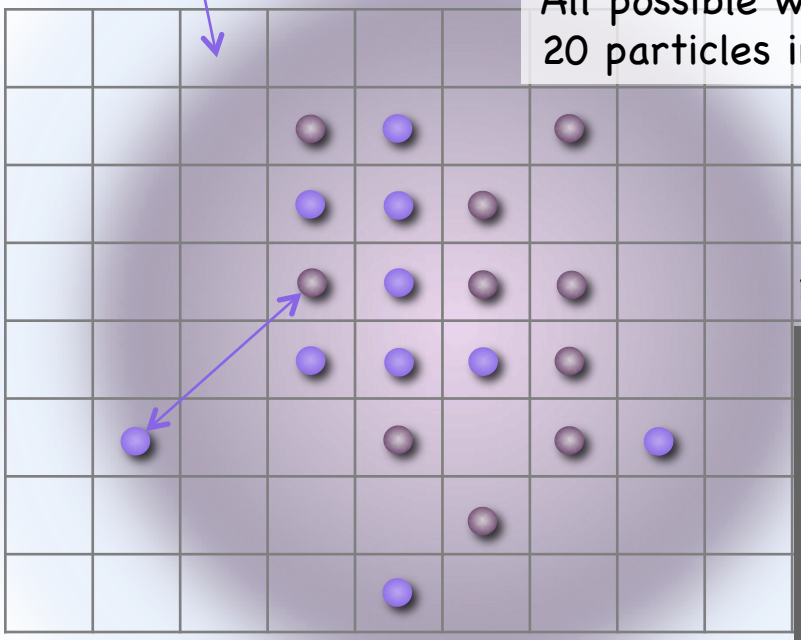
Modeling the nucleus … The challenges

States

Model space available to nucleus

HUGE!

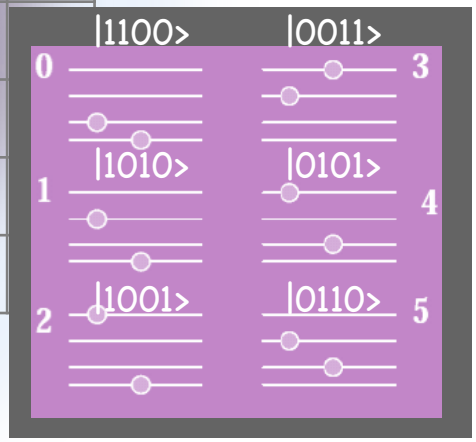
All possible ways:
20 particles in 80 states



Interaction between particles

NN, 3N, …

E.g., 2 particles in 4 states



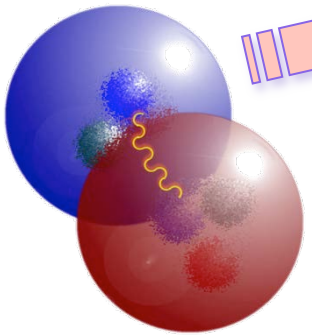
E.g., 6 particles in 200 states:
8×10^{10} ways !!!

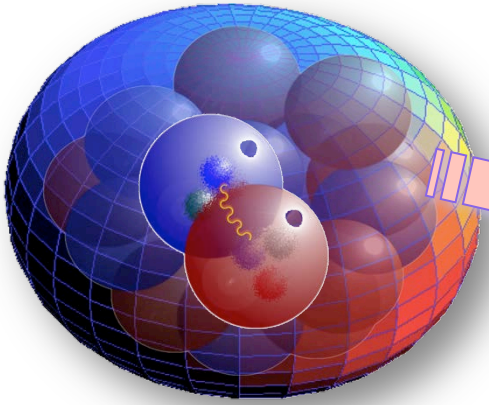
Modeling the nucleus … The ingredients

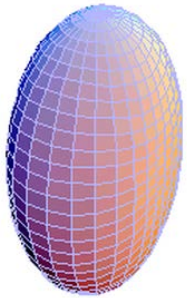
Nuclear force

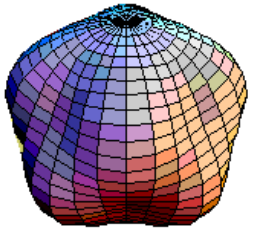
Many-body Approach

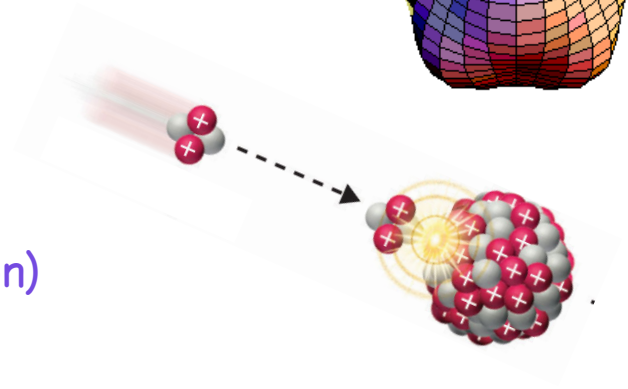
Nuclear properties: structure & reactions











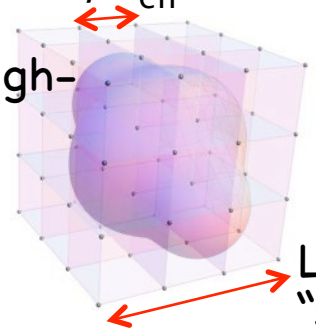
Reproduces NN scattering (these are free nucleons, not in nuclear medium; I will refer to this force as "bare")

In addition, there might be 3N, 4N, …

Specified by basis, model space (size & resolution)

"resolution" $1/\Lambda_{eff}$

Resolving high-momentum physics

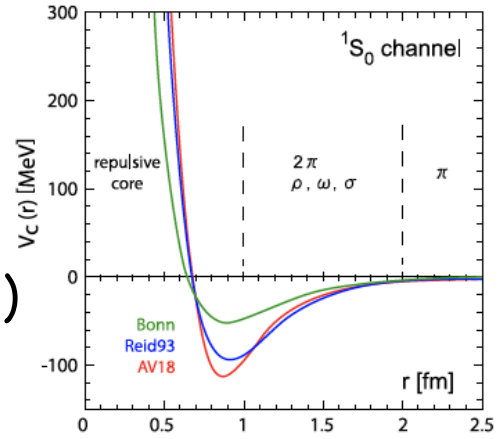


Important for wave function tail, large shapes/clusters, asymptotics, etc.

Interaction

The nuclear force

Two-body problem



- A=2: pp (^{2}He), pn (^{2}H), nn (?)
- Non-relativistic quantum mechanics: $H = T_{rel} + V(\mathbf{r},\mathbf{r}')$

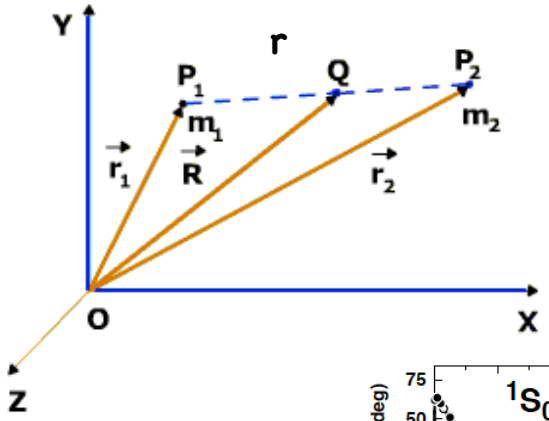
Position: $\mathbf{R} = \frac{1}{2}(\mathbf{r}_1 + \mathbf{r}_2), \quad \mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$

Center of mass (CM) — Relative (intrinsic)

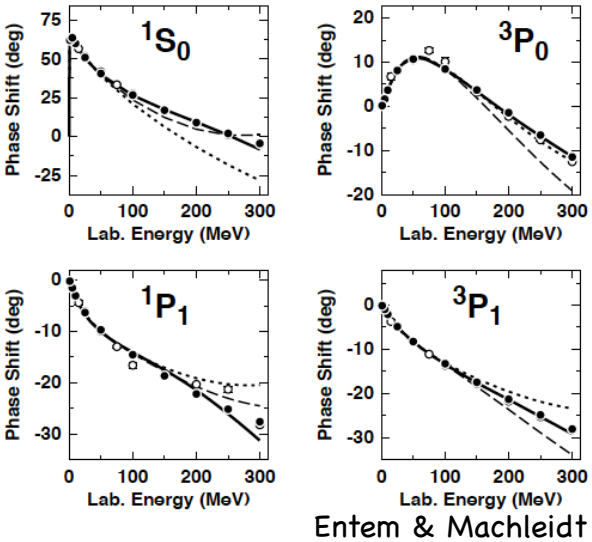
Momentum: $\mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2, \quad \mathbf{p} = \frac{1}{2}(\mathbf{p}_1 - \mathbf{p}_2)$

$$T = \frac{\mathbf{p}_1^2}{2M} + \frac{\mathbf{p}_2^2}{2M} = \frac{\mathbf{P}^2}{4M} + \frac{\mathbf{p}^2}{M}$$

2M — M/2 Reduced mass



Global motion of a free nucleus is described by a plane wave with momentum **P**
(irrelevant to the intrinsic nuclear dynamics)



Entem & Machleidt

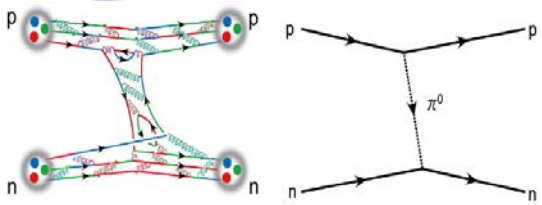
- Realistic interactions:

NN reproduce phase shifts to high precision

Chiral Potentials

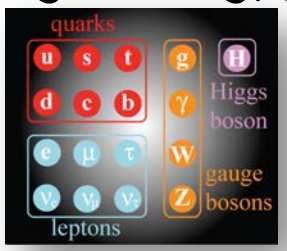
Degrees of freedom

Symmetry



High energy

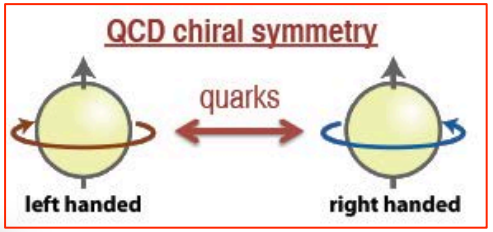
Quark/gluon dynamics (Quantum chromodynamics, QCD)



$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}_L i\gamma_\mu D^\mu q_L + \bar{q}_R i\gamma_\mu D^\mu q_R - \bar{q}\mathcal{M}q$$

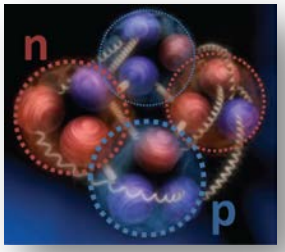
What is most important for a theory? The symmetries and not the degrees of freedom

The usual (Lorentz covariance, parity, etc.)+ Chiral symmetry

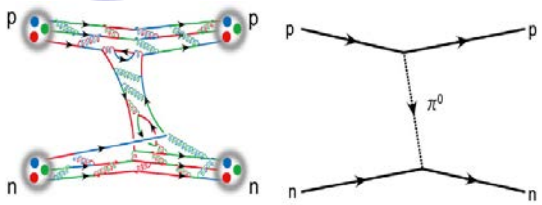


Low energy

Nucleon/pion dynamics (Effective field theory)



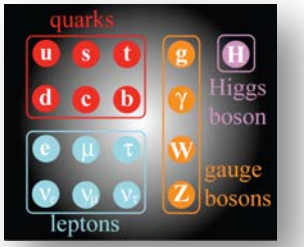
Chiral Potentials



Degrees of freedom

High energy

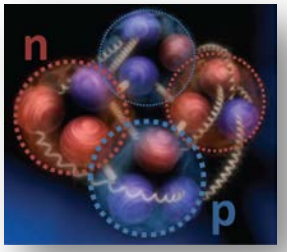
Quark/gluon dynamics (Quantum chromodynamics, QCD)



$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}_L i\gamma_\mu D^\mu q_L + \bar{q}_R i\gamma_\mu D^\mu q_R - \bar{q}\mathcal{M}q$$

Low energy

Nucleon/pion dynamics (Effective field theory)

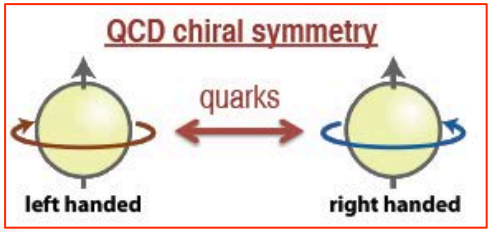


$$\mathcal{L}_{eff} = \mathcal{L}^{(2)}_{\pi\pi} + \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(2)}_{\pi N} + \mathcal{L}^{(0)}_{NN} + \mathcal{L}^{(2)}_{NN} + \ldots$$

Symmetry

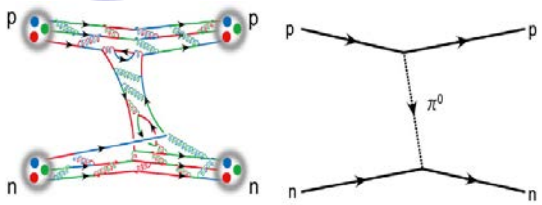
Approximate chiral symmetry

left- and right-handed quarks transform independently



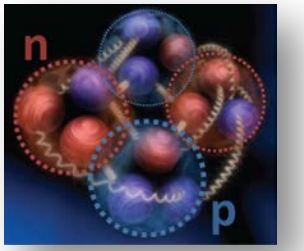
Consistent with explicit and spontaneous chiral symmetry breaking

Chiral Potentials



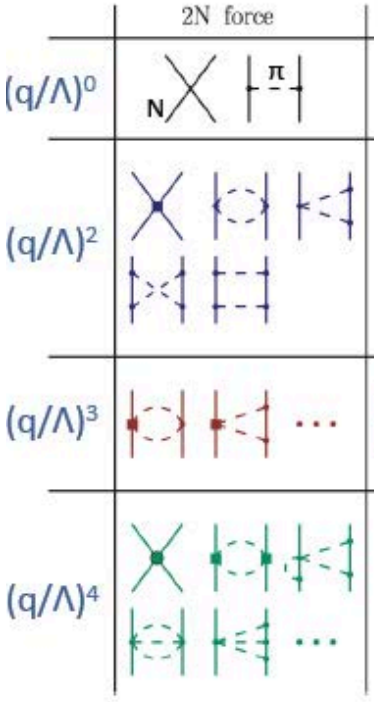
Chiral effective field theory
Low-energy theory
of nucleon/pion

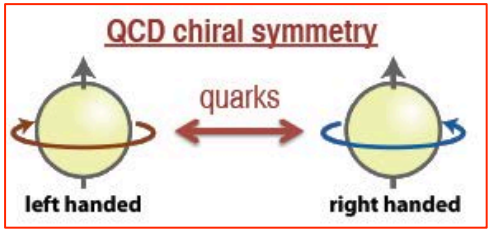
Low energy

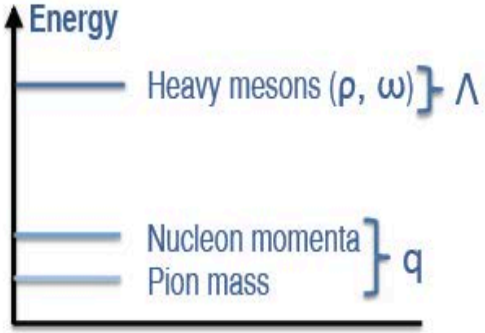


Symmetry
+
Separation
of scale

Systematic expansion







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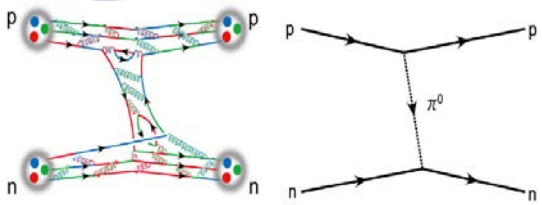
Chiral Potentials



Chiral effective field theory
Low-energy theory
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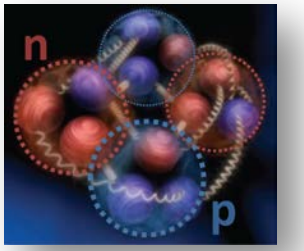
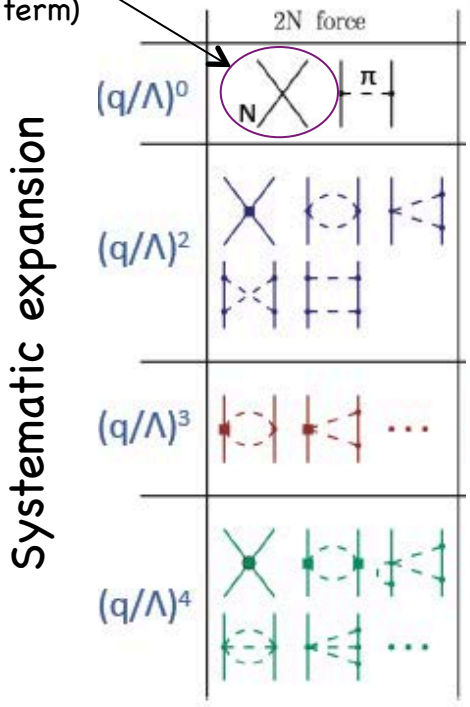
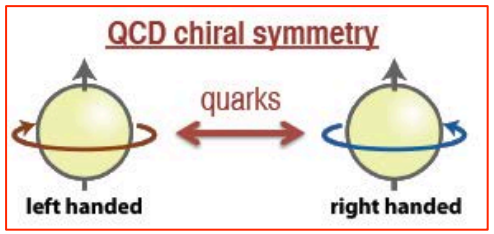
Low energy

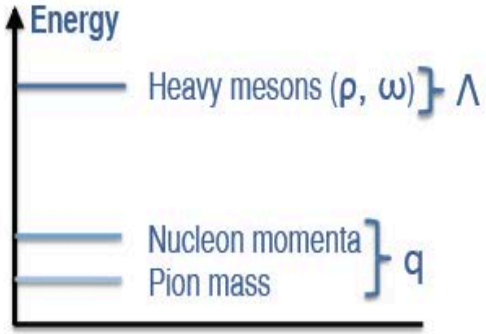


Symmetry
+
Separation
of scale

Short-range
(contact term)







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Chiral Potentials

Symmetry
+
Separation
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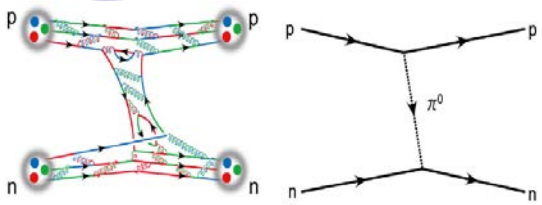
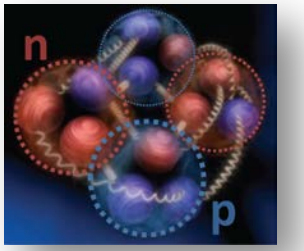


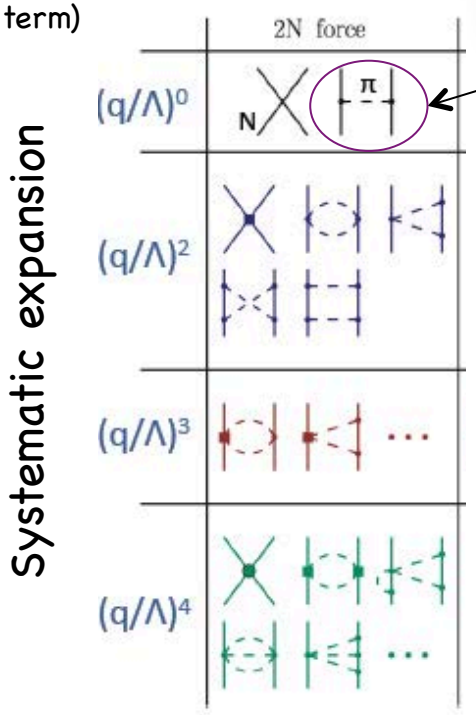
Chiral effective field theory
Low-energy theory
of nucleon/pion

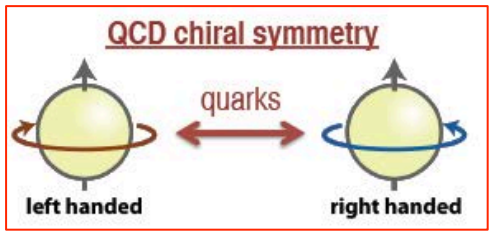
Low energy

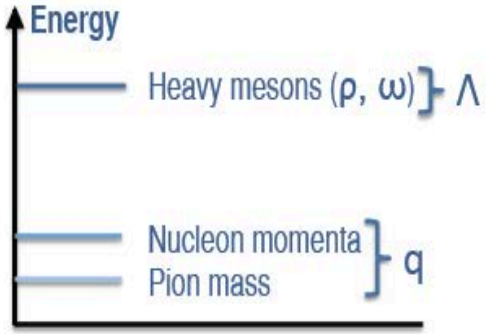


Short-range
(contact term)

Long-range
(Pion exchange)







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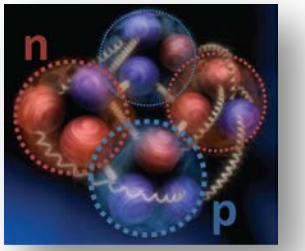
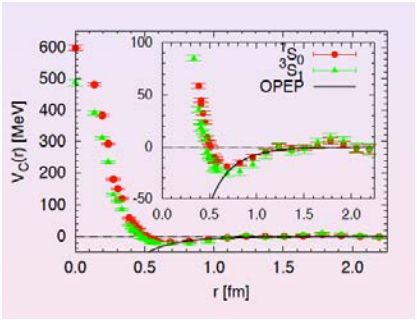
Chiral potentials … the challenges

Chiral effective field theory
Low-energy theory
of nucleon/pion



Coupling constants:

Fit to *NN* scattering
(future: lattice QCD)

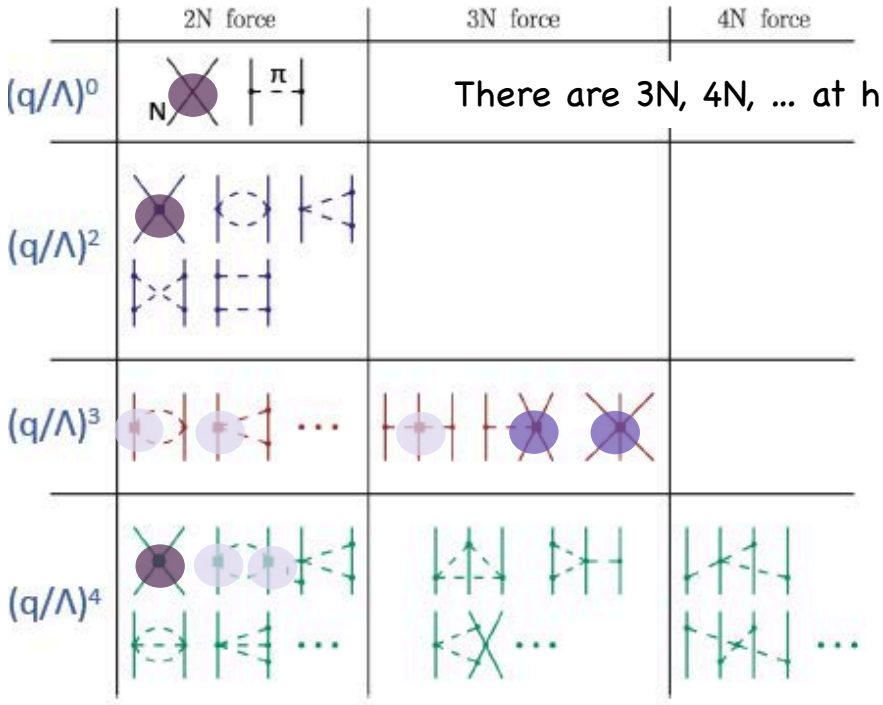


Consistent in 2N and 3N forces

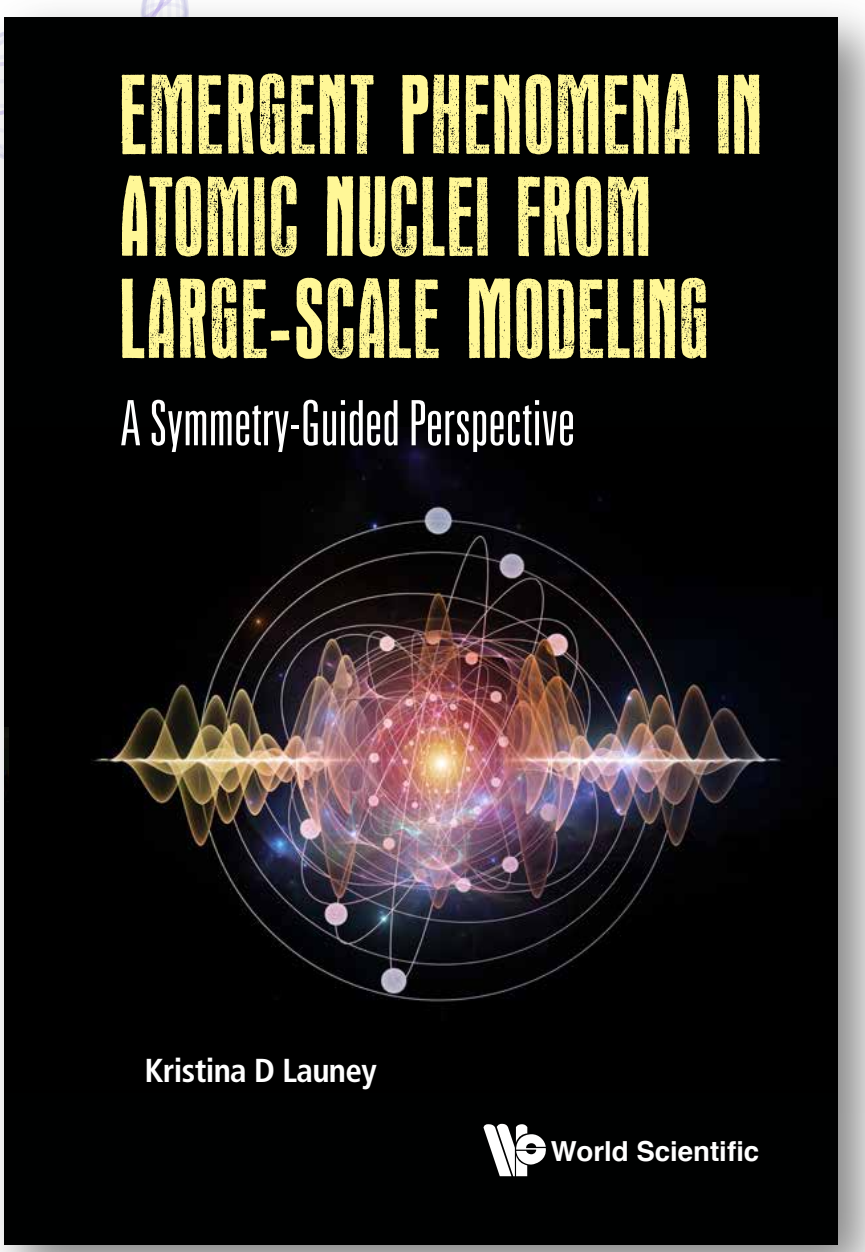
Fit to ^{3}H binding energy and lifetime

Challenges: local/non-local regulator, UV cutoff; 4N; Weinberg power counting

Systematic expansion



There are 3N, 4N, … at higher order



Nuclear Collectivity – Experimental perspective
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Configuration-interaction models
(Calvin W Johnson)

Symplectic rotor model
(David J Rowe)

Electron Scattering in the Symplectic Shell Model
(Jutta E Escher)

Lattice QCD
(Thomas Luu and Andrea Shindler)

Ab Initio Lattice Effective Field Theory
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Correlated Gaussian Approach and Clustering
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Symmetry-Adapted No-Core Shell Model
(Jerry P Draayer, Tomas Dytrych and KD Launey)

Auxiliary-Field Quantum Monte Carlo Methods
(Yoram Alhassid)

Lie Density Functional Theory
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Exactly Solvable Pairing
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