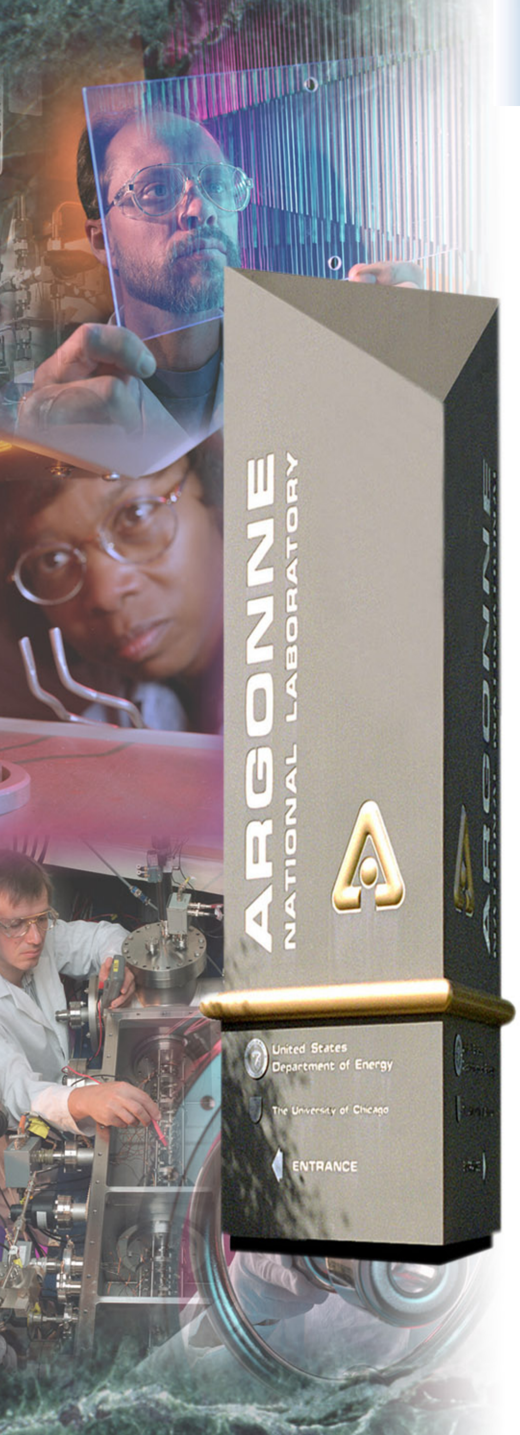


ARGONNE NATIONAL LABORATORY

What Do I Think I Know and What Do I Want to Know in Nuclear Science?

Donald Geesaman

Physics Division

Argonne National Laboratory

THE UNIVERSITY OF CHICAGO

Office of Science U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is managed by The University of Chicago for the U.S. Department of Energy

“The Mission of Nuclear Physics is to understand the origin, evolution and structure of baryonic matter in the universe – the matter that makes up stars, planets and human life itself.”

NSAC Subcommittee on Guidance for Implementing the 2002 Long Range Plan – June 2005

This talk is a personal view, but I liberally stole information from the beautiful material prepared for this subcommittee.

What does this mean to me?

Given a lump of nuclear material – real or hypothetical

- What are its properties?
- Where does it come from?
- What fundamental forces are at work?
- What forces were needed to create it, but have disappeared?
- What is it good for?
  - advancing our understanding of what the universe looks like and how we come to be here
  - advancing technology

Zen and the Art of Nuclear Physics

- “And what is good, Phaedrus
  And what is not good –
  Need we ask anyone to tell us these things”

- No, but we do have to convince other people why what we are doing has “Quality”

The Final Stage

The Ox-herding Pictures

- 12th Century Zen Master

Kuo-an Shih-yuan (Kakuan)

Enlightenment is not enough. Such experience is to be radiated, not jealously guarded.

Publish (says a Division Director)

Call the New York Times (says a Lab Director)

He leads innkeepers and fishmongers in the Way of the Buddha.

withered trees he swiftly brings to bloom.

10 / ENTERING THE MARKETPLACE WITH HELPING HANDS / The gate of his cottage is closed and even the wisest cannot find him. His mental panorama has finally disappeared. He goes his own way, making no attempt to follow the steps of earlier sages. Carrying a gourd, he strolls into the market; leaning on his staff, he returns home. He leads innkeepers and fishmongers in the Way of the Buddha.

Barechested, barefooted, he comes into the marketplace.
Muddied and dust-covered, how broadly he grins!
Without recourse to mystic powers,
withered trees he swiftly brings to bloom.

What is it good for? The role of phenomena

We often see unexpected phenomena – are they important?

- Identify the most important collective (emergent) degrees of freedom.
- Illustrate unusual features of quantum mechanics, QCD and many body physics
  - Bose-Einstein condensation – superconductivity, nuclear superfluidity
  - Rydberg atoms - Halo nuclei
  - Algebraic solutions and supersymmetry
  - QCD states with exotic quantum numbers
- Often dominate response to external probes
  - plasma oscillations – giant resonances
  - fission
- Can explore new regions of phase space
  - high energy density matter
- Can be critical for quantitative understanding
  - deformation in heavy nuclei and atomic clusters
  - Effective field theories can provide systematic procedures for very accurate calculations by interrelating phenomenology.

One of the keys of a field are its decisions on when is a phenomena important.

Scope of the problem

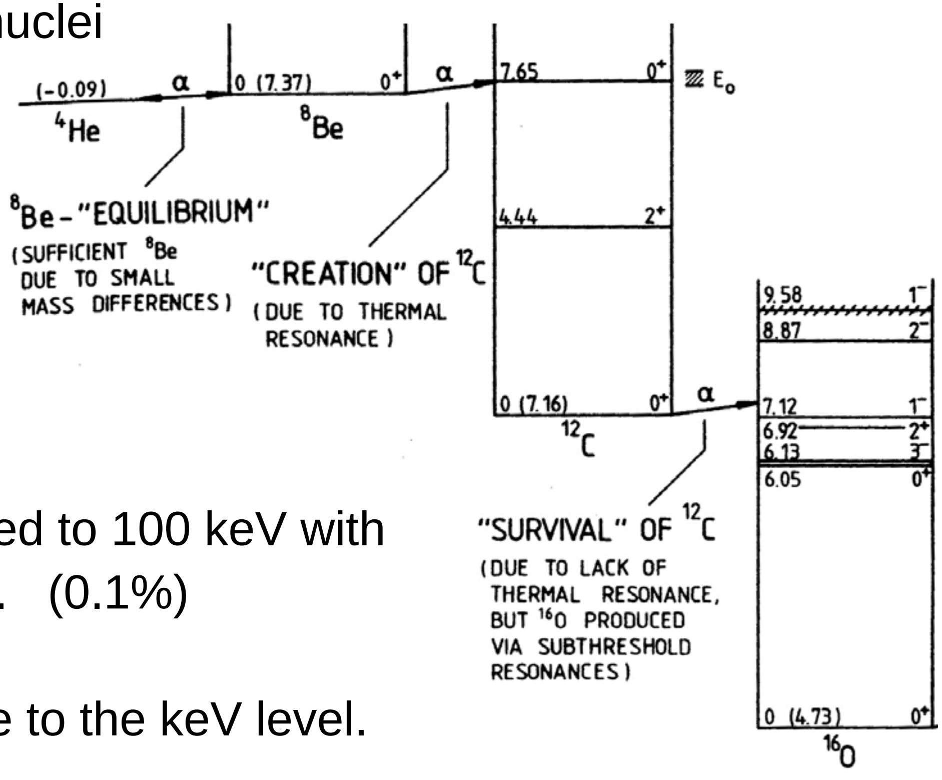
The origin of nuclei provides extreme examples

- Binding of the deuteron

Deuteron Binding Energy, 2.2 MeV ~ M_p-M_n ~ m_u ~ m_d

N-N Interaction Range $$M_\pi^2 = -\frac{<\bar{q}q>}{f_\pi^2}(m_u + m_d)$$

- Role of lack of mass 5 and 8 stable nuclei
  - ^{8}Be unbound by 92 keV
  - Big Bang nucleosynthesis and stellar evolution



Binding Energy of ^{12}C ~ 100 MeV

- triple alpha reaction to Carbon

The resonance energy could be predicted to 100 keV with the hazy information of 50 years ago. (0.1%)

- Tests of the standard model sensitive to the keV level.

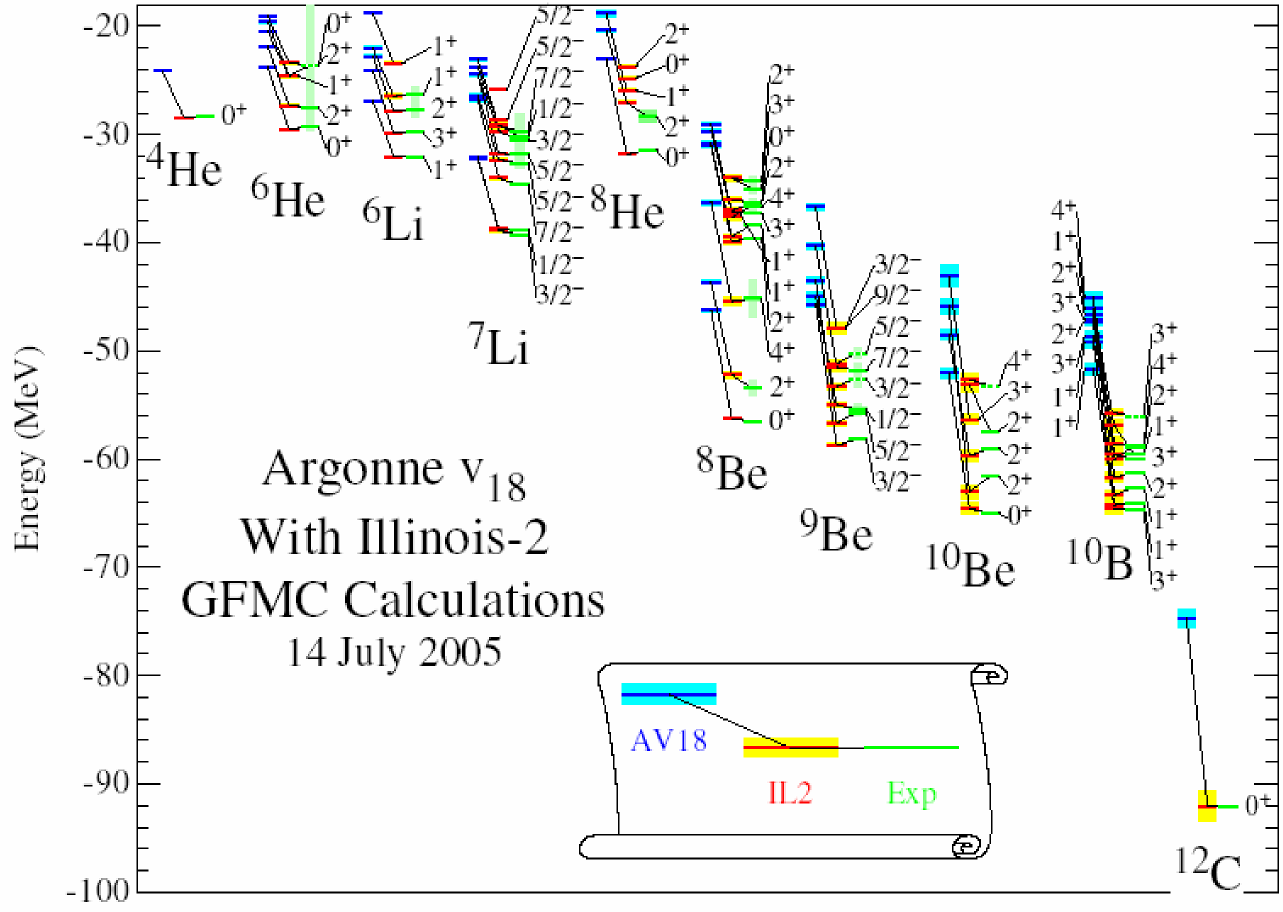
What do we know

- The nuclei for which we can **do the many-body physics accurately** are well described by interactions of nucleons with potentials

- This requires accurate N-N potentials

- 3 – body NNN interaction

- macroscopic features like the mean field spin-orbit potential are sensitive to 3-body forces

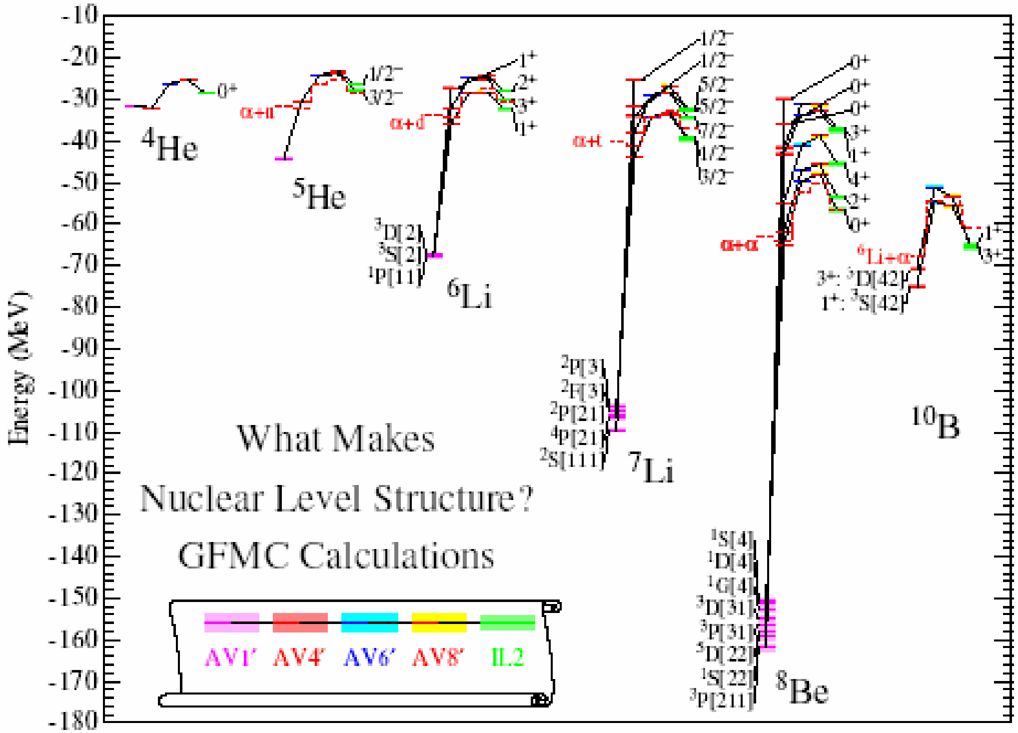


You need the full complexity of the N-N interaction to reproduce nuclear structure

We have a very complicated nuclear Hamiltonian – is it all necessary?

Systematically remove features from nuclear Hamiltonian and look at effects on nuclear level energies

- Full AV18 v_{ij} + Illinois V_{ijk} reproduces experiment
- AV8′ - basic level structure; relative stability correct
- AV6′ - Removing $L{\cdot}S$ gives no SO splittings; has A=5,8 gaps but weak A=6,7 binding
- AV4′ - Removing tensor force introduces spurious degeneracies; somewhat overbinds nuclei; A=8 bound
- AV1′ - Pure central force "upside-down" spectrum & no nuclear saturation



Effective field theory can show us much of the structure and the need for 3-body forces.

What do we need to know

- What are the Nucleon-Nucleon Interactions?
    - *We believe QCD is the right theory.*

- How do we build up the structure of hadrons, and the hadronic interactions from QCD?

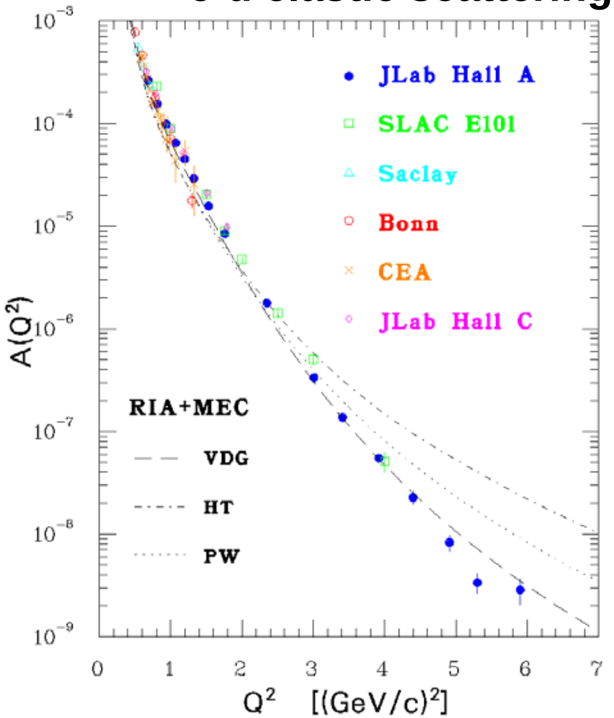
- Does hadron structure change inside the nucleus?
  – we know based on theory and experiment that it must at high densities and temperature.

This is why we built JLAB.

What do we know

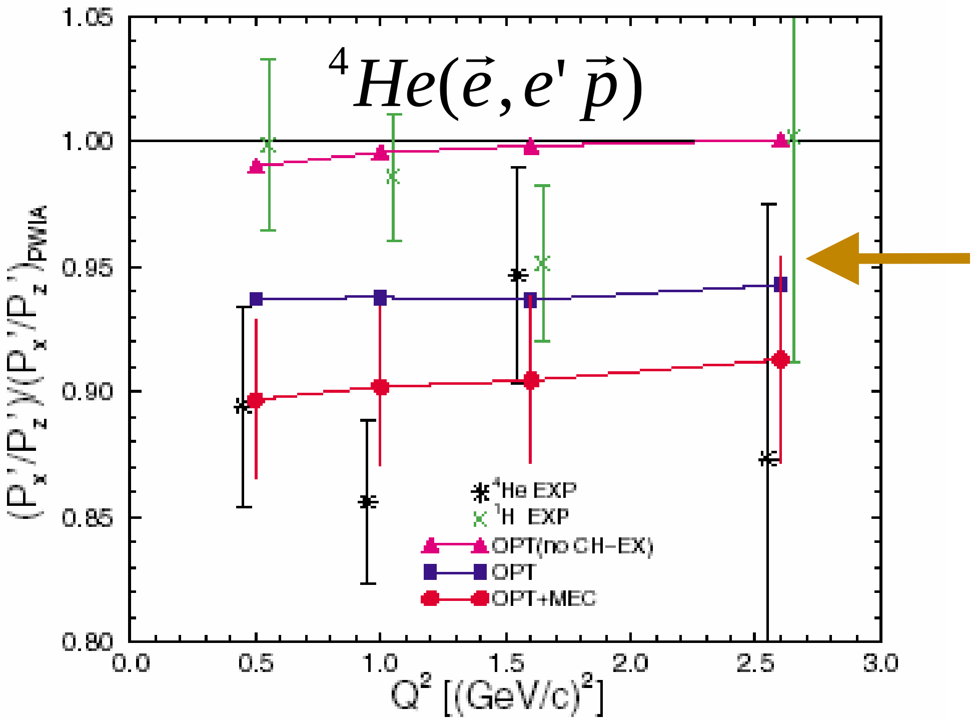
JLAB has taught us that hadron structure/interactions do not change much (to the precision we can determine today) at normal matter densities.

e-d elastic scattering



Alexa et al PRL 82, 1374 (99)

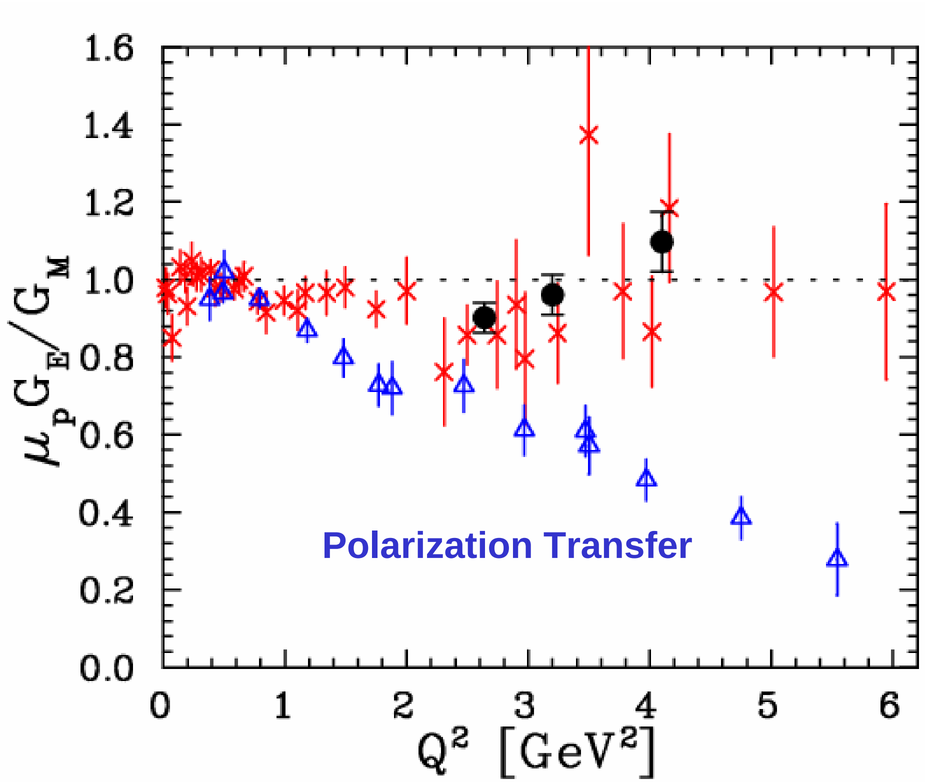
Perhaps the smoking gun?



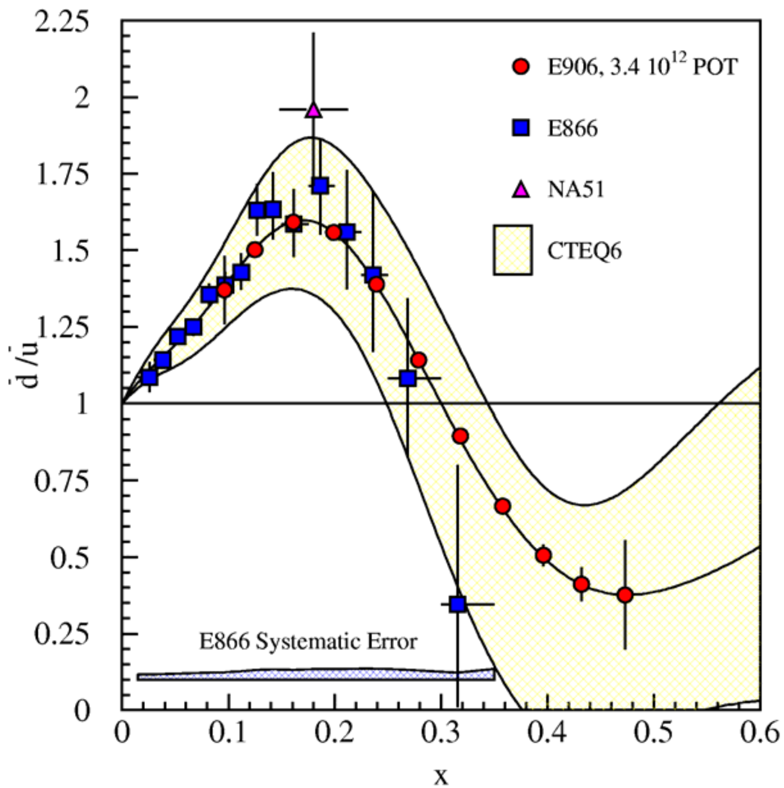
Schiavilla et al PRL 94, 072303 (05)

Baryon Structure

Proton Charge and Magnetization



Importance of antiquarks



This led us to study the nature and origin of confinement, exotics, pentaquarks, glueballs, strange quark form factors, parton structure and spin structure, generalized parton distributions....

Theory – Lattice and continuum methods, Models...

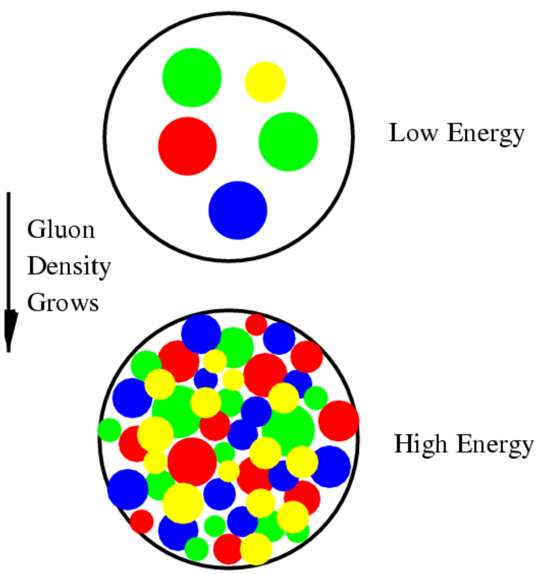
But this cannot be true at all levels

What do we know:

- **EMC effect – the parton distributions are not the same in nuclei**
- **Things have to change at high density and temperature**
- **In hadrons and nuclei, is there a component of all hadronic matter at small x where gluon fields saturate?**

Color Glass Condensate? – weakly coupled effective field theory

large number of gluons, occupation number ~ $1/\alpha_s$, k_t ~ Q_s



Gluon density grows very rapidly

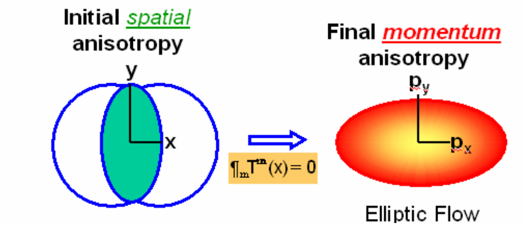
QCD coupling becomes weak, but interactions are strong because of coherence

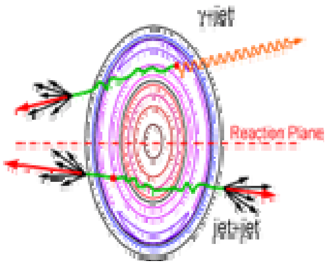
Small fractional momentum partons correspond to large longitudinal distances

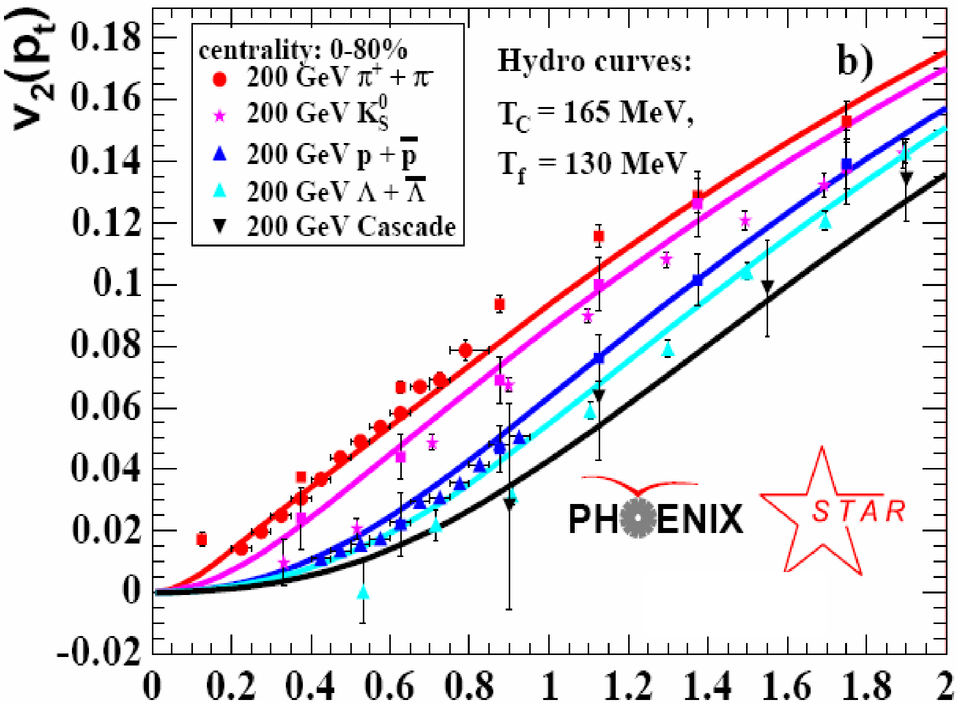
We know that nuclear parton distributions change at low x

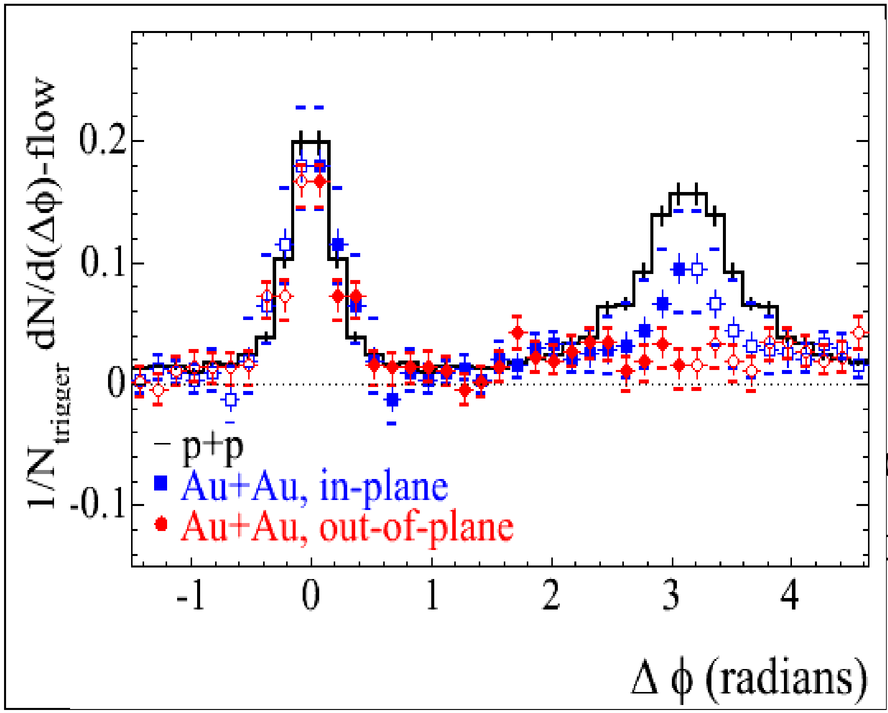
What do we know

- **At high energy density we have created a new state of matter- Strongly Interacting Quark Liquid**









Perfect Liquid Behavior **Jet Quenching**

What I have heard

- Maldacena Adv. Theor. Math. Phys. **2**, 231 (1998)

Duality between super-gravity string theory in 10 dimensions and conformal super-symmetric extensions of QCD

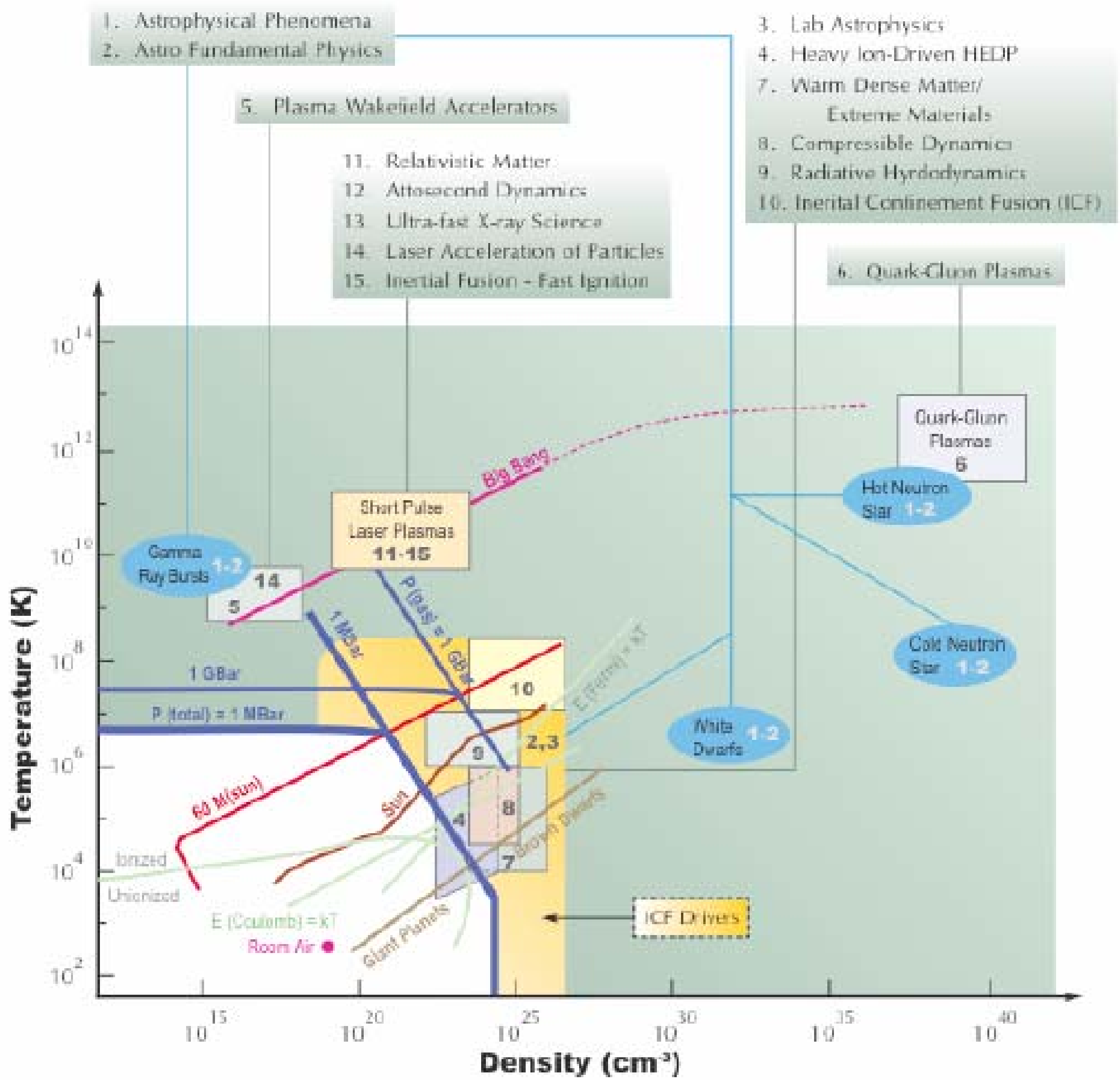
Consequences

- Power law fall off of hard exclusive hadron amplitudes can be derived without perturbation theory - quark counting rules

- Universal lower bound on viscosity for all strongly coupled systems. Perfect liquid behavior observed at RHIC seems consistent with this lower bound.

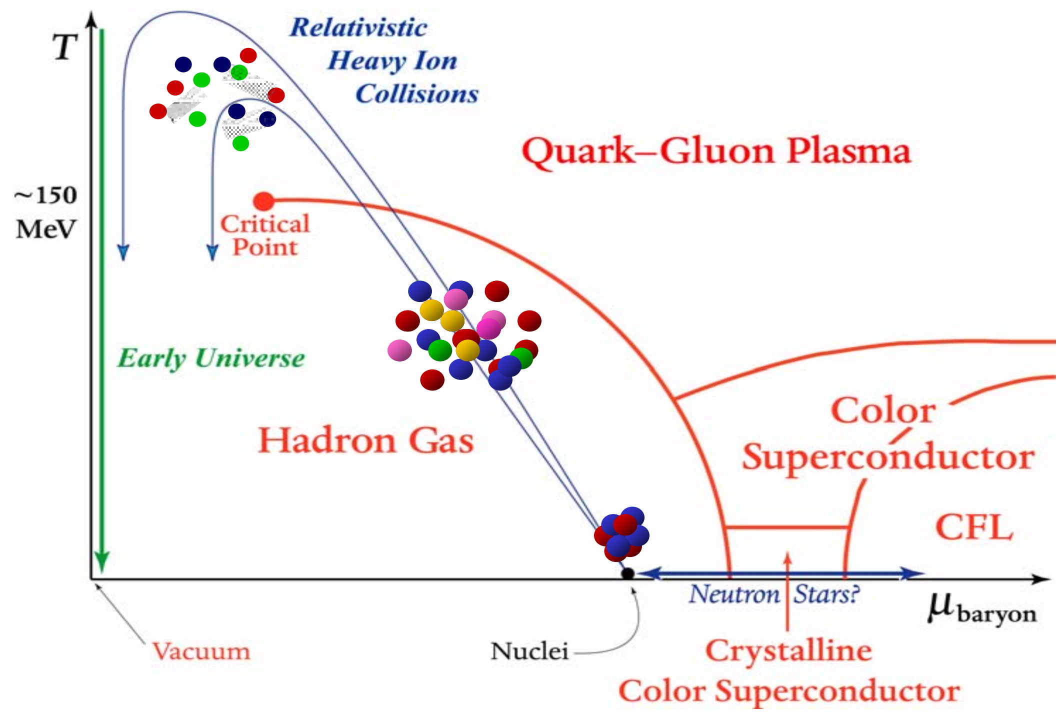
Map of the High Energy Density Universe

Frontiers of Discovery in High Energy Density Physics NSTC Interagency Working Group



What do we need to know

- What does the quark-hadron transition tell us about QCD and confinement?
- Did the properties of the Quark Gluon Plasma and the quark-gluon to hadron phase transition affect the evolution of the universe?
- Do states of deconfined quark and gluon matter exist now, i.e. at the core of neutron stars?
  - ✓ Requires that we understand the properties of neutron matter
  - ✓ Is neutron matter superfluid?
  - ✓ What about hyperon matter?



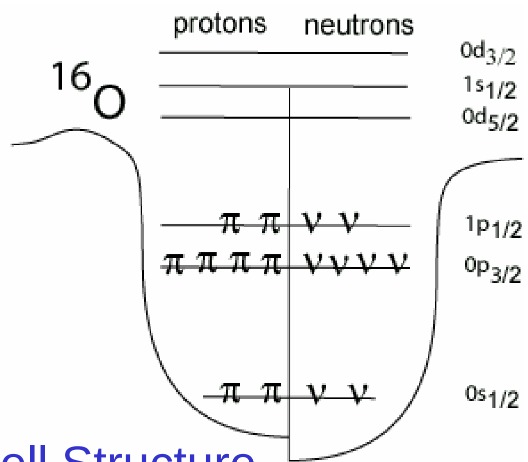
• Recent observation of a 2.1 ± 0.1 $M_{\odot}$ Pulsar Nice et al. astro-ph/0508050

• Impact of gCFL phase on cooling of neutron stars

What do we know

Ab initio calculations alone are not yet enough.

Emergent phenomena – Links to Condensed Matter physics



Shell Structure

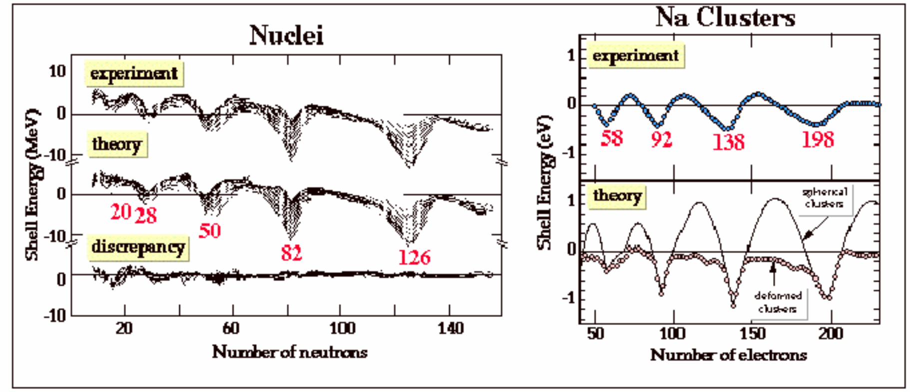
J=0
nn, np, pp

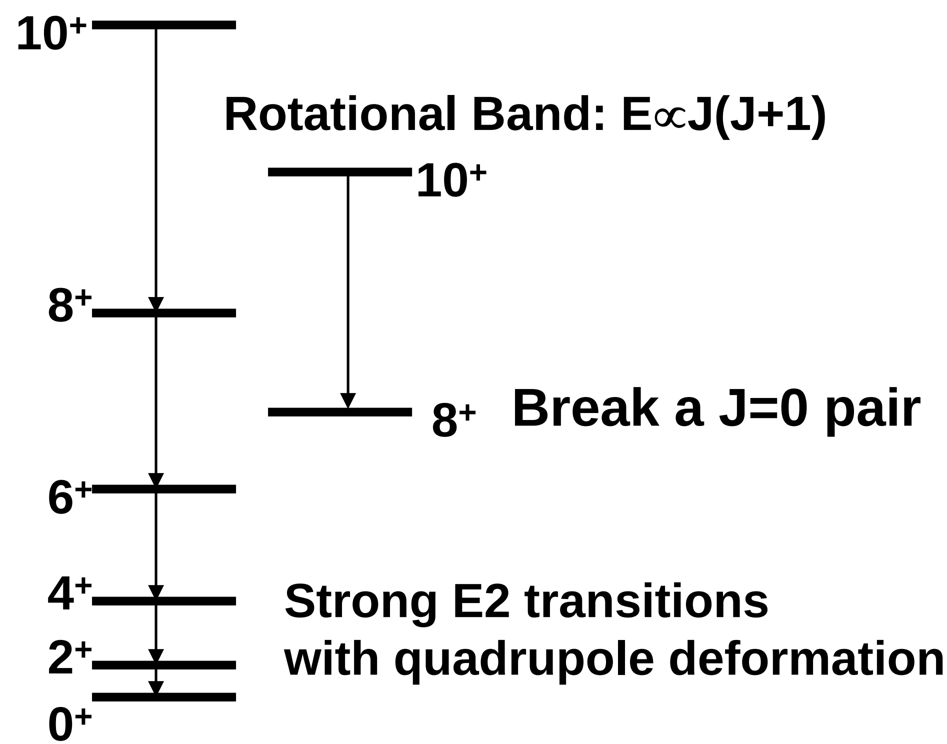
J= max
np only

Pairing

Halos, skins, clusters ...

Volume and Surface Vibrations





Macroscopic Deformation and Spontaneous Symmetry breaking

Mean Field, Deformation and Correlations in Nuclei

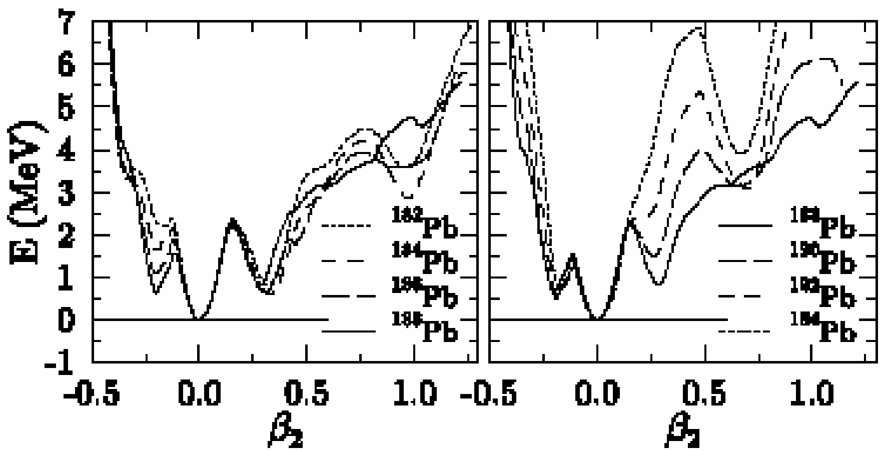


Fig. 3. Mean-field deformation energy curves for Pb isotopes.

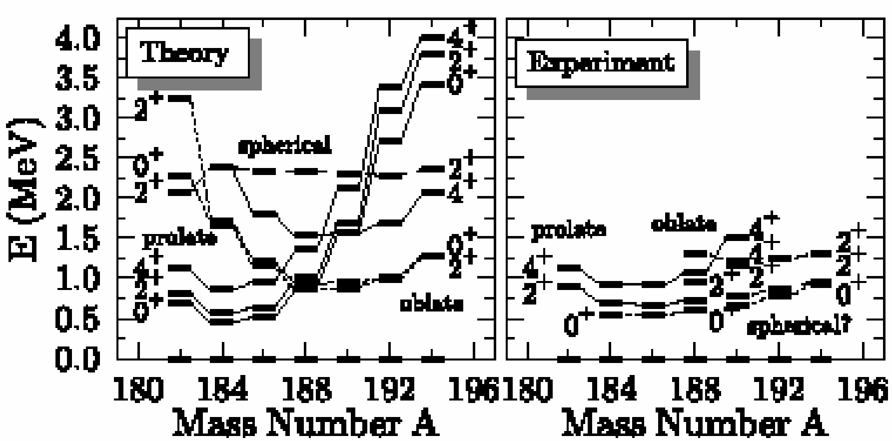
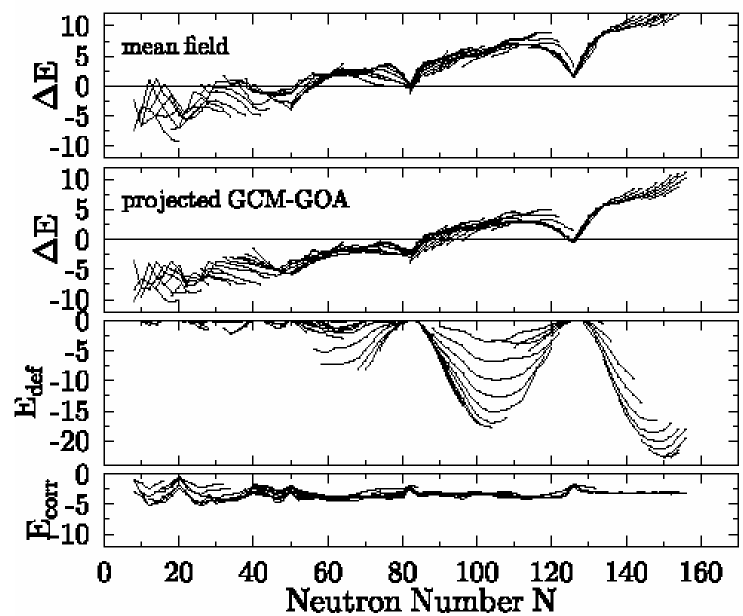


Fig. 4. Lowest collective states in the Pb isotopes.

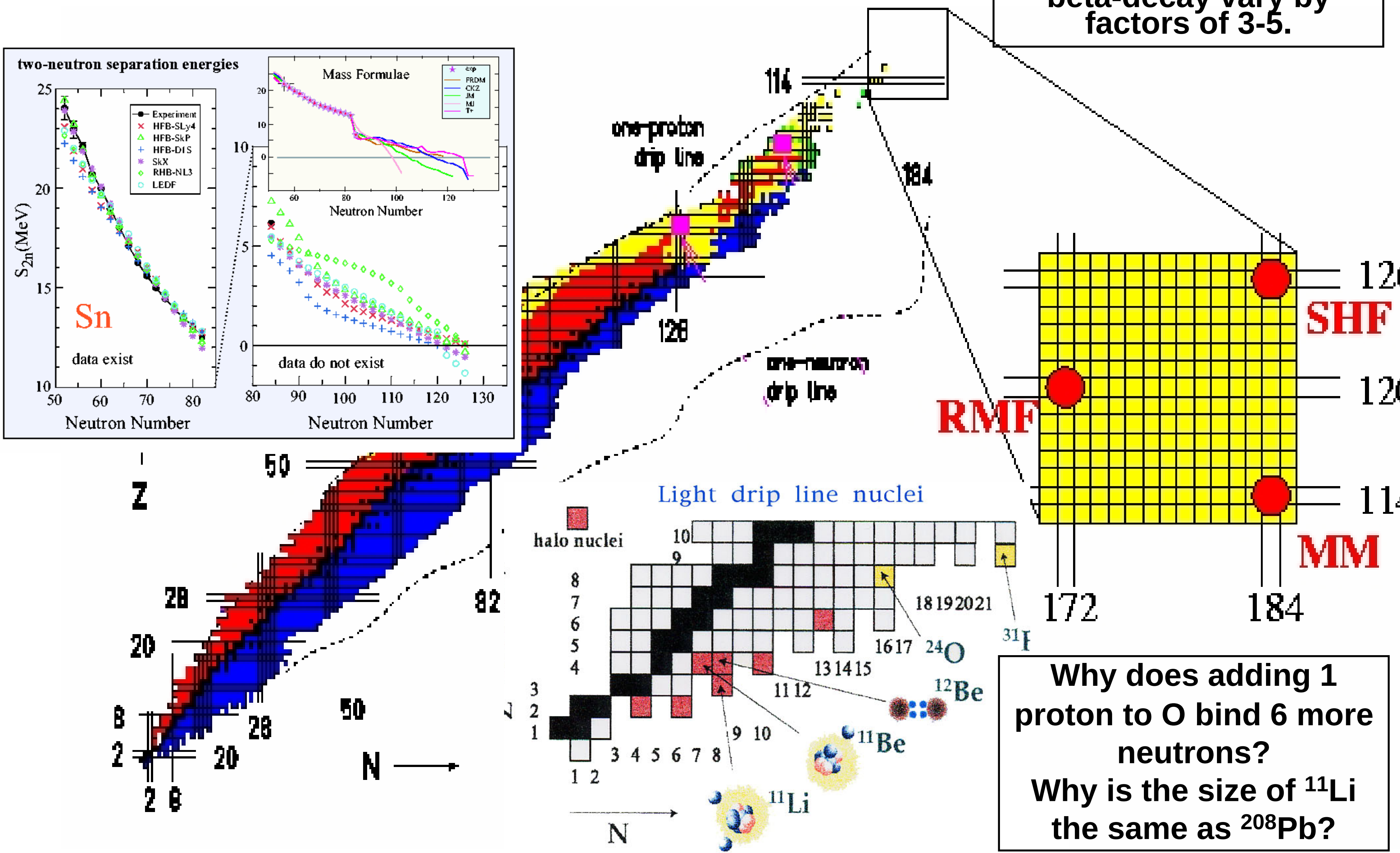


'ig. 5. Upper two panels: difference between calculated and xperimental masses. Lower two panels: mean-field deforma-ion energy E_{def} and beyond-mean-field quadrupole correlation nergy E_{corr}. All panels share the same energy scale in MeV.

Mass calculations of 605 even-even isotopes

Why can't we extrapolate to new regions and phenomena?

Calculations of nuclear matrix elements for neutrino-less double beta-decay vary by factors of 3-5.



Why does adding 1 proton to O bind 6 more neutrons?
Why is the size of ^{11}Li the same as ^{208}Pb?

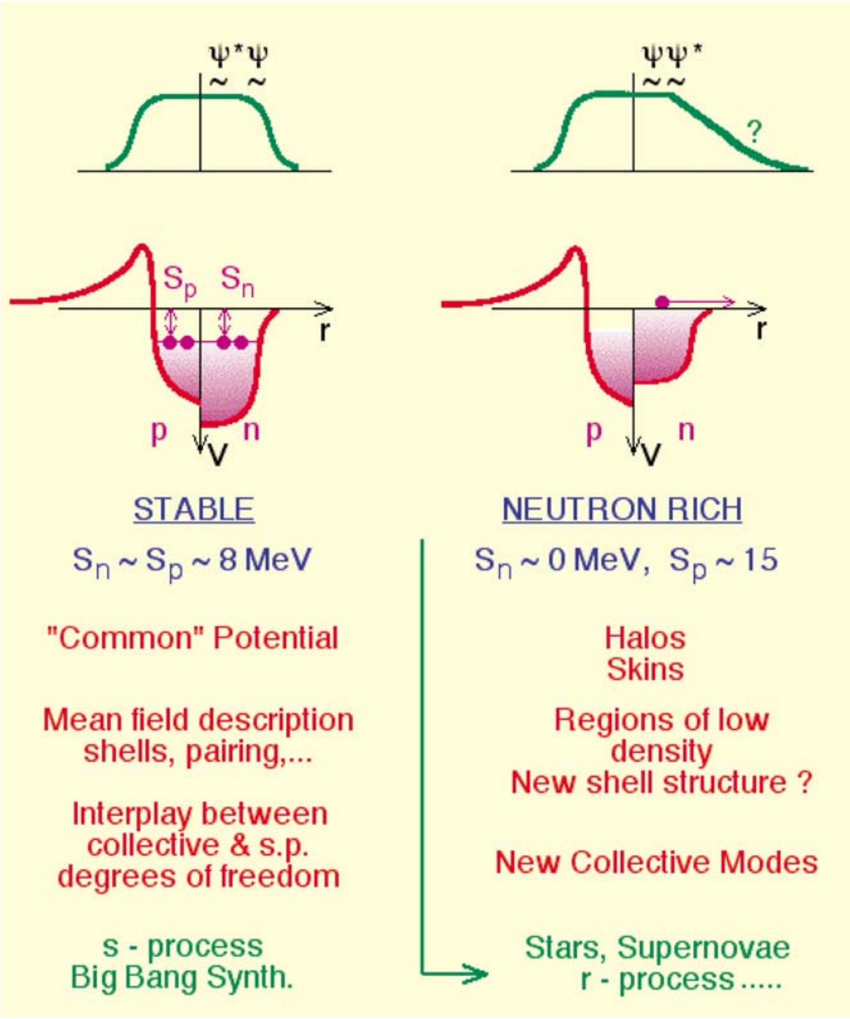
Basic "facts" of nuclear physics that are may be wrong in neutron-rich nuclei

- The charge-independence of the strong interaction makes isospin a good quantum number
- The radius and diffuseness of the neutron and proton distributions are similar

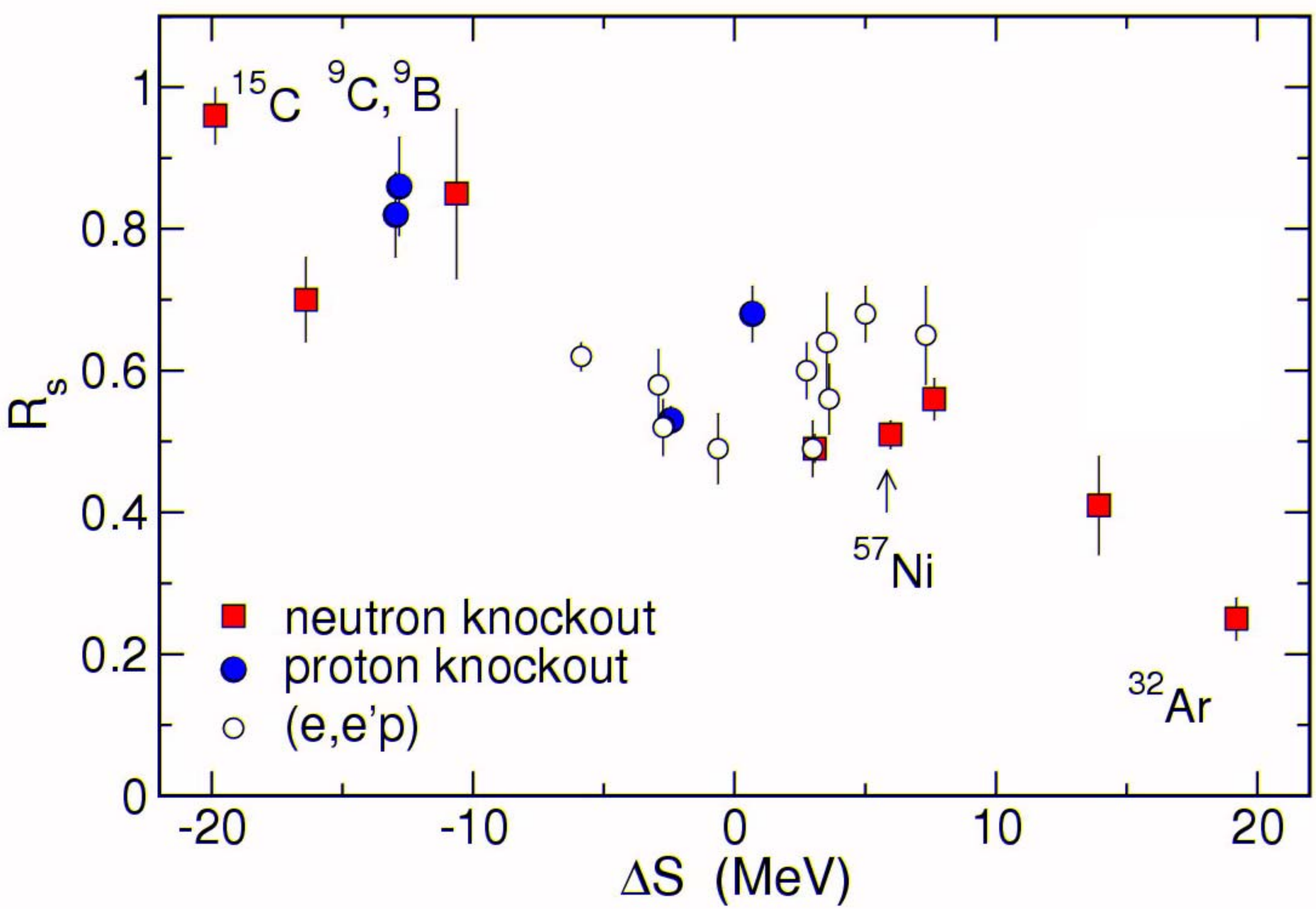
$$\rho(r) = \frac{1}{1 + \exp[(r - R)/a]}$$

R=1.2 $A^{1/3}$, a~ 0.55 fm

- The magic numbers of the shell model are fixed.
- The deformations of the neutrons and protons are similar
- The valence quasi-particles are renormalized by about 0.6 by short-range correlations.



Does the impact of short-range correlations change dramatically?

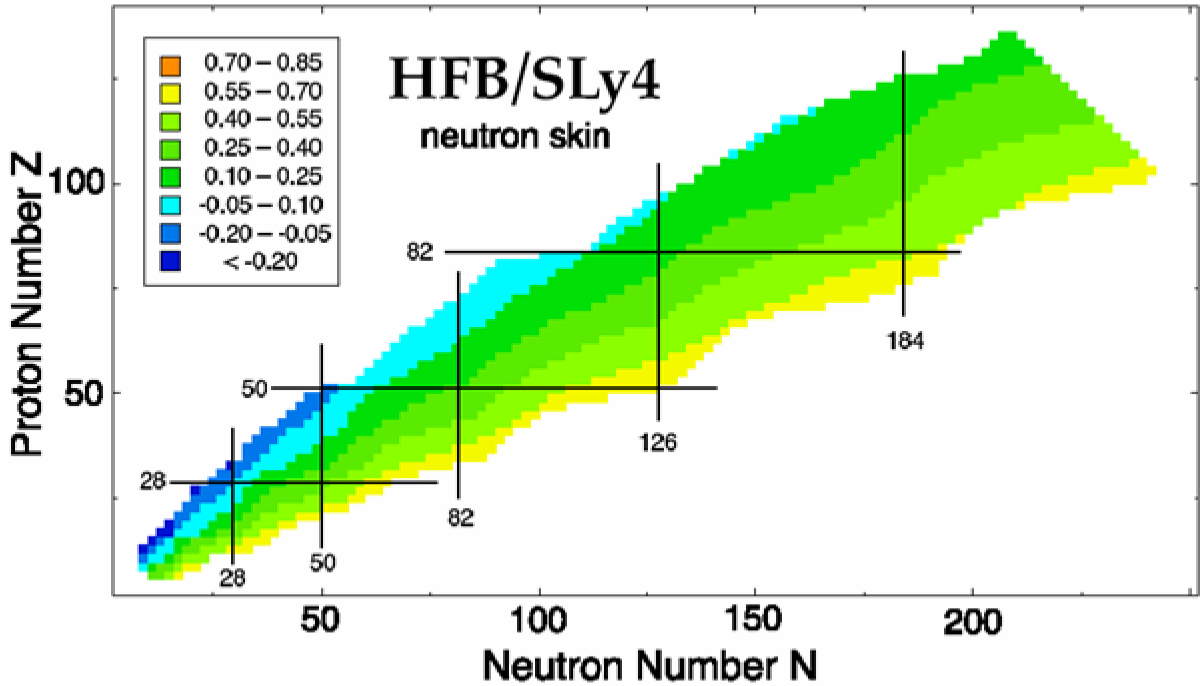


$\Delta S = S_n - S_p$ for neutron knockout and

$S_p - S_n$ for proton knockout

Neutron Skins

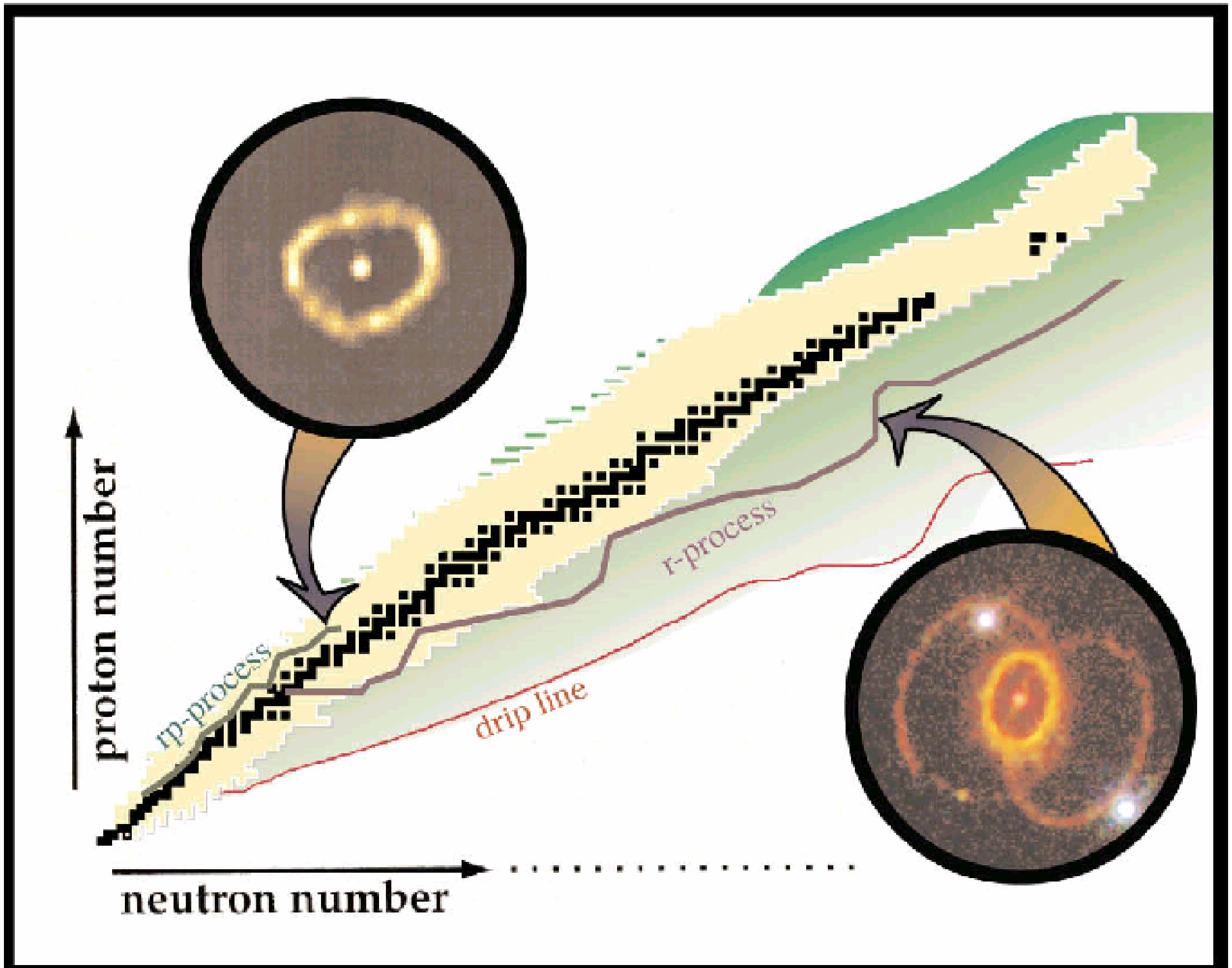
- Predicted large effects away from stability
- Critical for expectations of nuclei and neutron stars
  - Equation of State
  - Cooling
- Difficult to measure – need to calibrate hadronic probes
- Eagerly await JLab measurement in PV electron scattering on ^{208}Pb - PReX



Is clustering the physics that is left out?

What do we need to know

Half of the nuclear landscape is unexplored!

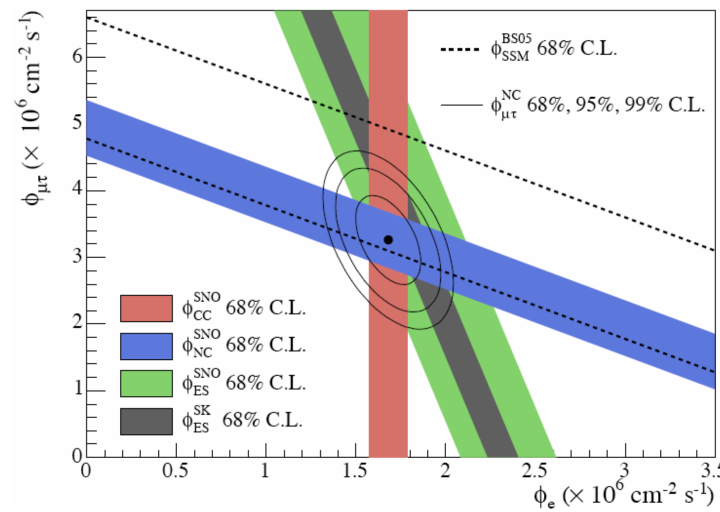


By measurement in these unexplored regions

- **We can experimentally determine the properties of the important cases to the required precision.**
- **We provide critical tests to guide the development of a unified model of nuclei.**
- **We can determine our “periodic table”.**
- **We can much better extrapolate to “neutron matter”.**

Where did nuclei come from and how do their properties affect the evolution of the universe?

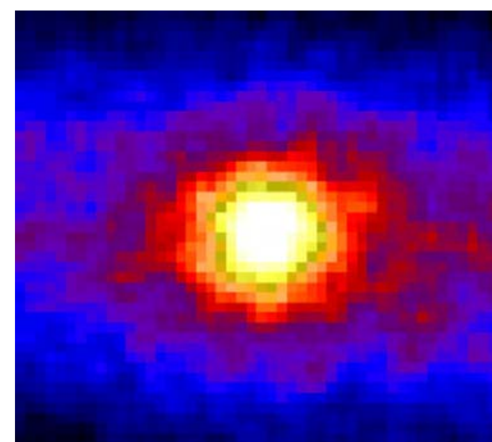
SNO



What do we know

- Stellar evolution Bethe, Fowler, Davis
  - SNO neutrino rate – Standard Solar Model Bahcall got it right.
- s-process production of heavy nuclei
- Big Bang Nucleosynthesis
  - limits on number of neutrinos
  - formation of the light elements
  - baryon density of the universe
  - time dependence of fundamental constants

- Cosmic Explosions Koshiba
- What are the effects of the Quark Gluon Plasma?



SuperK neutrino image of the sun

Supernova

What do we know

- Most of the energy of the collapse goes into neutrinos

- What do we need to know?
  - Effects of the neutrino properties
  - How is the energy transferred from the neutrinos?
  - What are the dynamics of the explosion?
  - Is this the site of the r-process?
  - How are the elements heavier than Fe formed?

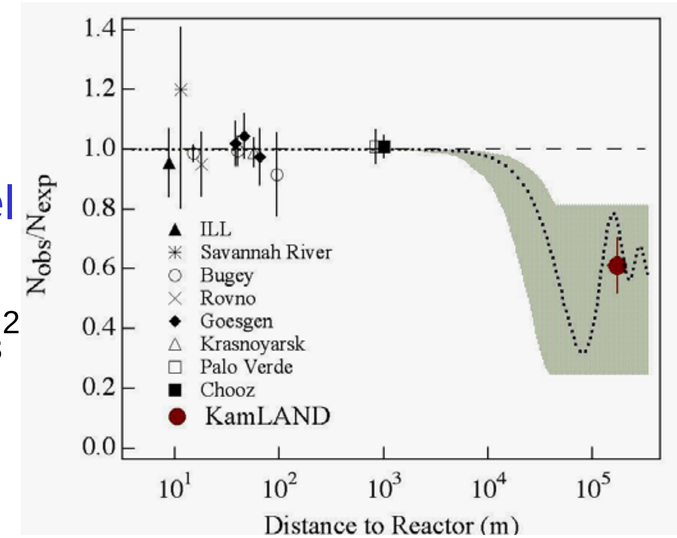
✓ Neutrino properties

✓ How do neutrinos interact with matter?

  - energy transfer, neutrino processing including fission

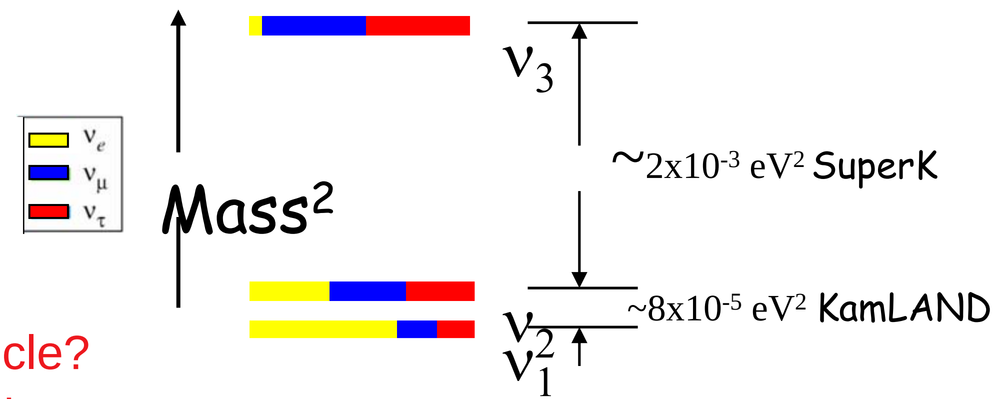
✓ What are the properties of the very neutron-rich nuclei?

What Are the Properties of Neutrinos



What do we know: First crack in the standard model

- Neutrinos mix – at least three mass eigenstates
  - We know two mass differences- Δm_{12}^2, Δm_{23}^2
  - Two mixing angles- θ_{12} , θ_{23}
- Neutrinos account for as much mass as all the stars.



What do we need to know?

- What is the mass scale?
- Is the neutrino its own antiparticle?
  - neutrino-less double beta decay
  - nuclear structure
- What is the full mixing matrix -- θ_{13}, δ
- CP violation
  - What does this tell us about the baryon asymmetry in the universe?

Normal hierarchy or inverted?

What forces were needed to create the universe but have “disappeared”?

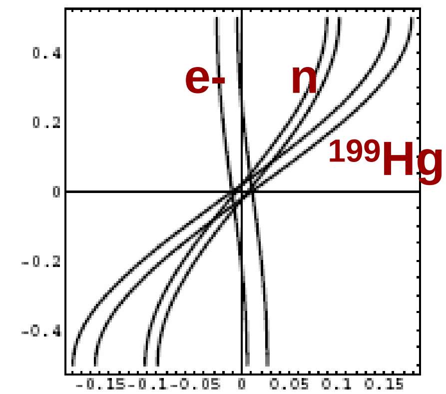
What do we know: The standard model works extremely well.

- Hints of physics beyond the standard model
- The baryon asymmetry in the universe

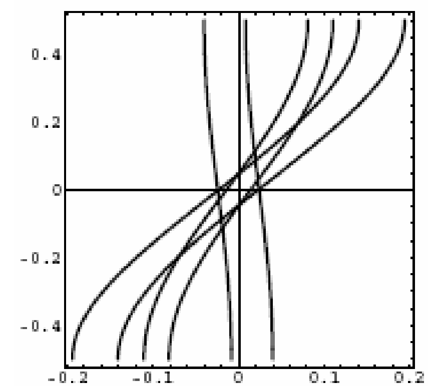
Time reversal violation
- Electric Dipole Moments
  - electron, neutron, nuclei
- Leptogenesis and neutrino properties

Are there new forces at work?
- lepton, hadron and nuclear properties and decay
  - muon g-2, muon decay, Q_{weak} ...

Are there more generations?
- Unitarity of CKM matrix
  - nuclear mass measurements



$M = 500$ GeV



$M = 750$ GeV

Limits on CP violating supersymmetric phases

Science Questions from the 2005 NSAC Subcommittee report
QCD

- **What is the nature of the quark-gluon matter of the early universe and what transitions led to our present world of protons and neutrons?**

- **Where is the glue that binds quarks into strongly interacting particles, and what are its properties?**

- **What is the internal landscape of the proton?**

- **What does QCD predict for the properties of nuclear matter?**

Science Questions from the 2005 NSAC Subcommittee report
Physics of Nuclei and Nuclear Astrophysics

- **What binds protons and neutrons into stable nuclei and rare isotopes?**
- **What is the origin of simple patterns in complex nuclei?**
- **When and how did the elements from iron to uranium originate?**
- **What causes stars to explode?**

Science Questions from the 2005 NSAC Subcommittee report
Fundamental Symmetries and Neutrinos

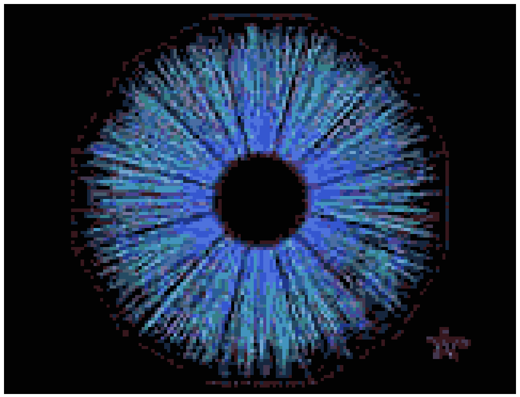
- **What are the masses of neutrinos and how have they shaped the evolution of the universe?**
- **Why is there more matter than antimatter?**
- **What are the unseen forces that disappeared from view as the universe cooled?**

Questions from the Science Magazine

125 Questions: What don't we know?

- **What is the universe made of?**
- **Can the laws of Physics be unified?**
- **Where do ultra-high energy cosmic rays come from?**
- **Why is there more matter than antimatter?**
- **Are neutrinos their own antiparticle?**
- **Is there a unified theory explaining all correlated electron systems? [hadron systems? quark systems?]**
- **Are there stable high-atomic number elements?**
- **What can replace cheap oil – and when?**

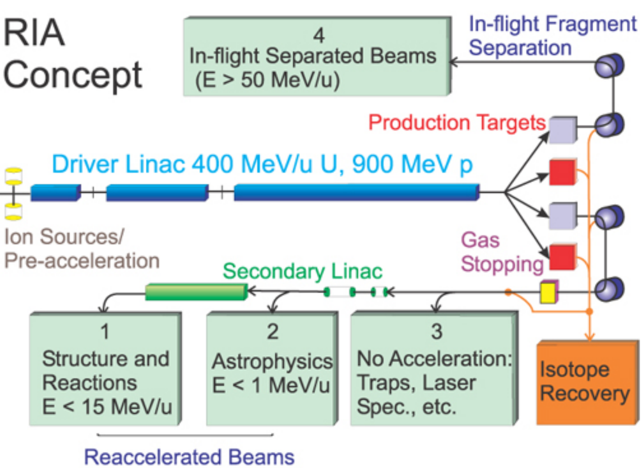
What Are the Right Tools



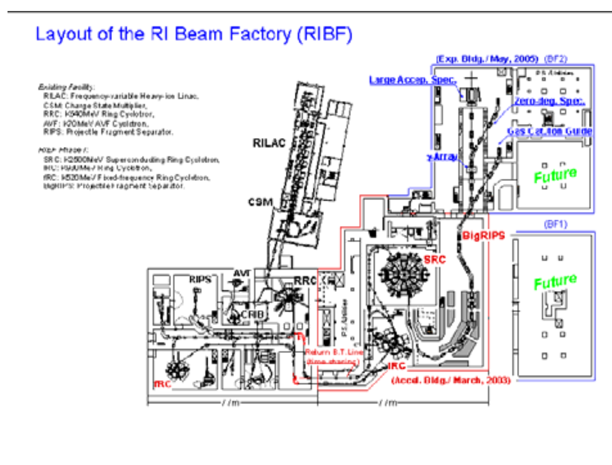
RHIC

JLAB

J-PARC



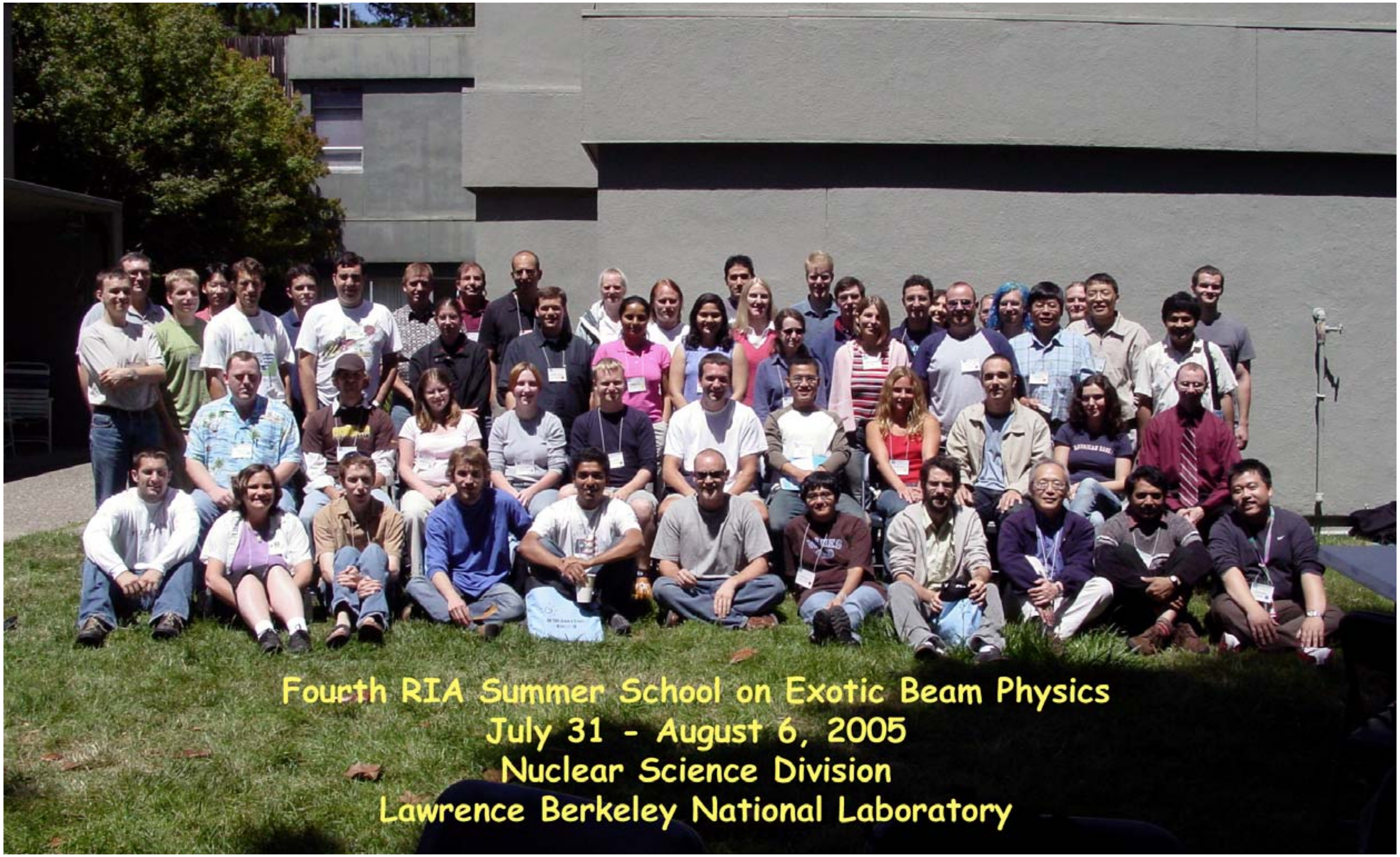
RIA



RIKEN-RIBF

DUSEL

The Next Generation of Researchers



I could have shown any of the recent summer schools, such as the very successful HUGS.

Summary

“The Mission of Nuclear Physics is to understand the origin, evolution and structure of baryonic matter in the universe – the matter that makes up stars, planets and human life itself.”

- What we know about this unique quantum system that is the nucleus is extremely impressive and growing rapidly.
- “What we don’t know” are some of the most interesting questions in modern science, with links to particle physics, astrophysics and condensed matter physics.
- The international community has charted a roadmap with the tools we need to best answer these questions.
- These discoveries are serving society: energy recovery linacs, new tools to diagnose and fight cancer, ... understanding nature, and inspiring young minds...