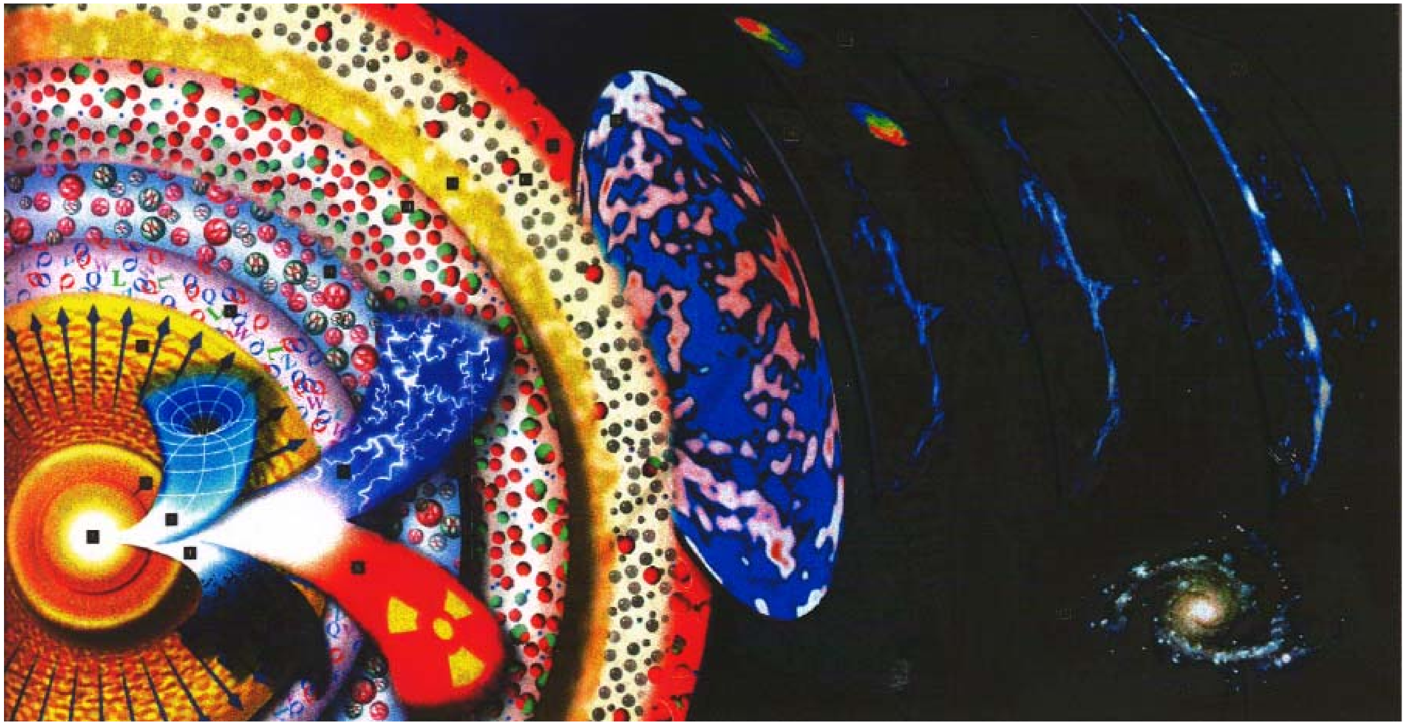
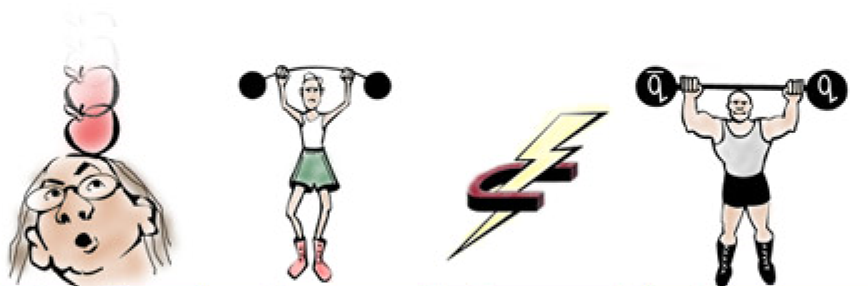
Understanding Nature's Building Blocks: What Do We Know, What Do We Not?



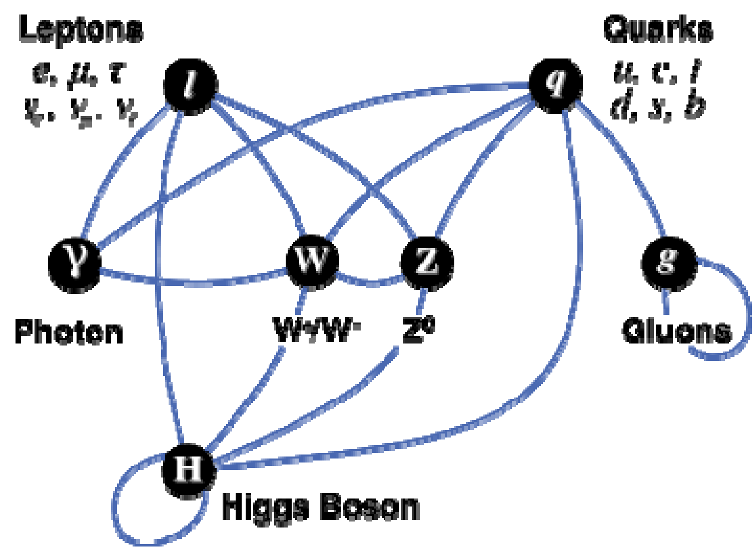
R. E. Tribble

Where do we start?

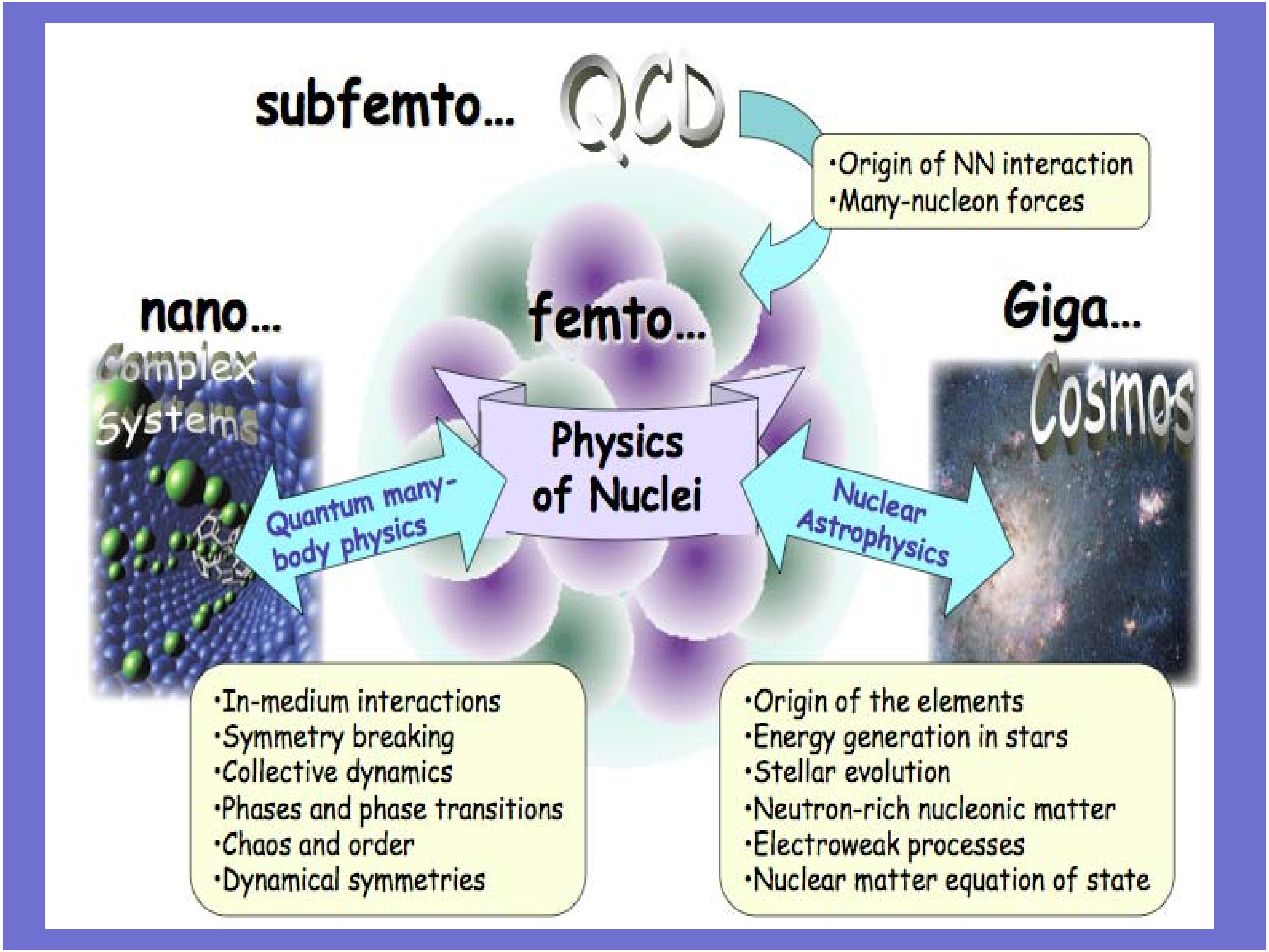
In all forms of matter, from isolated protons to neutron stars, all the interactions of the Standard Model of subatomic physics play a role



	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons



Fortunately, gravity is weak, and in nuclear applications can be ignored.


subfemto...
QCD
·Origin of NN interaction
·Many-nucleon forces
nano...
Complex Systems
femto...
Giga...
Cosmos
Physics of Nuclei
Quantum many-body physics
Nuclear Astrophysics
·In-medium interactions
·Symmetry breaking
·Collective dynamics
·Phases and phase transitions
·Chaos and order
·Dynamical symmetries
·Origin of the elements
·Energy generation in stars
·Stellar evolution
·Neutron-rich nucleonic matter
·Electroweak processes
·Nuclear matter equation of state

Recent progress in understanding matter triggered by:

- Advances in computational tools coupled with great theoretical insight
  - Lattice QCD – After a 30 year quest, ab initio calculations of proton structure guided by controlled applications of effective field theories to extrapolate to the continuum limit
  - After a 70 year quest, very successful ab-initio calculations of light nuclei from nucleon interactions allow us to do the many-body nuclear physics right at the hadron level and carefully examine many body approximations.
  - Dynamics of stellar explosions – Supernova that explode!
  - Duality techniques from string theory

- Advances in accelerators and detectors
  - Nucleon structure – **JLAB**
  - The strongly interacting Quark-Gluon liquid – **RHIC**
  - Nuclear structure and astrophysics – **RIB facilities**
  - Search for failures in the Standard Model of particles and interactions – ***large*** **underground detectors**

U.S. Nuclear Science

[Today and for the Next Decade]

General goal:
Explain the origin, evolution, and structure of the visible matter of the universe—the matter that makes up stars, planets, and human life itself.

Frontiers:

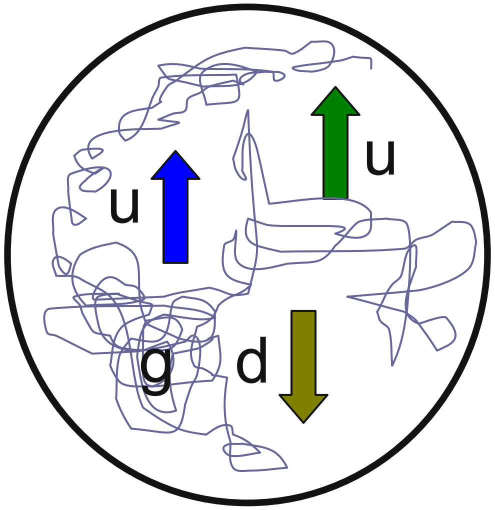
- Quantum Chromodynamics (QCD)
- Physics of Nuclei and Astrophysics
- Fundamental Symmetries and Neutrinos

The Strong Interaction: Quantum Chromodynamics

- QCD is about color interactions. The QCD Lagrangian only includes coupling to quark flavor in mass terms. It is color SU(3) which determines that there are 3 valence quarks in a baryon and mesons are $q\bar{q}$ pairs.

  $m_u \sim 4$ MeV, $m_d \sim 7$ MeV $\ll \Lambda_{QCD}$

  $m_s \sim 150$ MeV



$$\mathcal{L} = \sum_{j\ flavors} \bar{\Psi}_j \left[\gamma_\mu \left(i \frac{\partial}{\partial x_\mu} - \frac{g}{2} \Lambda^a A^a_\mu \right) + m_j \right] \Psi_j - \frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a$$

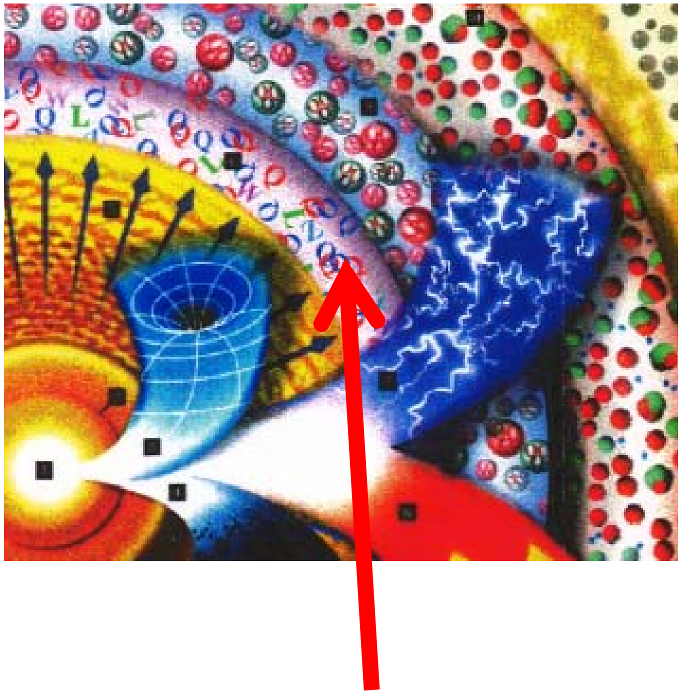
Because the gluons couple to themselves, QCD behaves very counter-intuitively

- quarks and gluons are never seen in isolation
- the interaction is very strong at long distances
- the interaction is weak at short distances and can be accurately calculated
- as coupling constant increases, mass of self-bound systems increases

The Science Questions – QCD

- What are the phases of strongly interacting matter and what roles do they play in the cosmos?
- What is the internal landscape of the nucleons?
- What governs the transition of quarks and gluons into pions and nucleons?
- What is the role of gluons in nucleons and nuclei and where do their self-interactions dominate?
- What does QCD predict for the properties of strongly interacting matter?
- What determines the key features of QCD and what is their relation to the nature of gravity and spacetime?

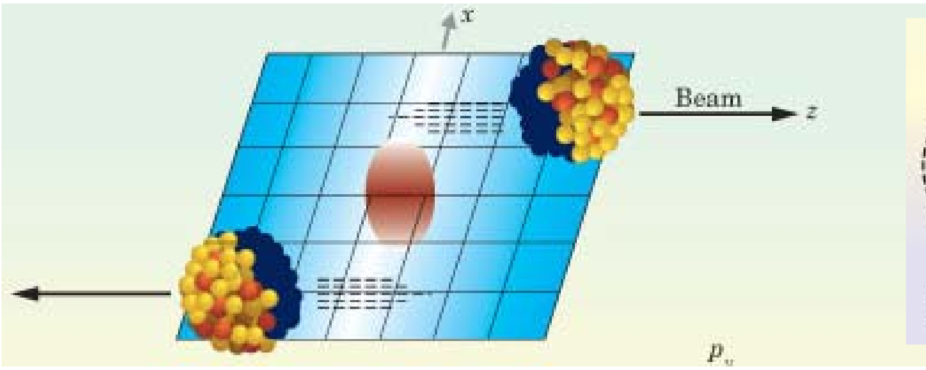
Let's start with the quark-gluon state and the QCD phases

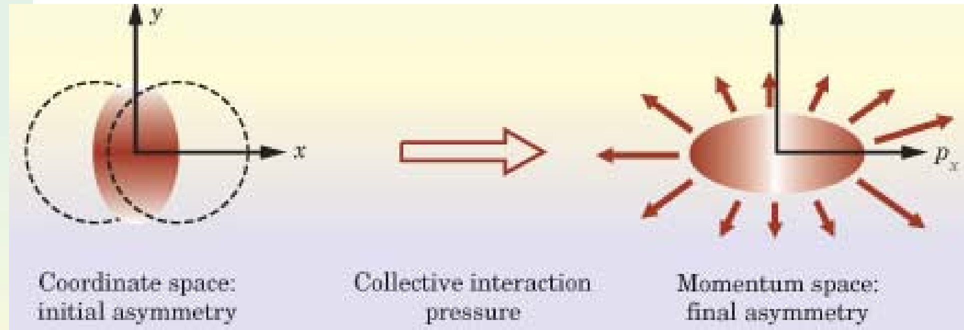


The quark-gluon plasma

By colliding Gold nuclei together at high energy, we have recreated this state of matter from the first microseconds

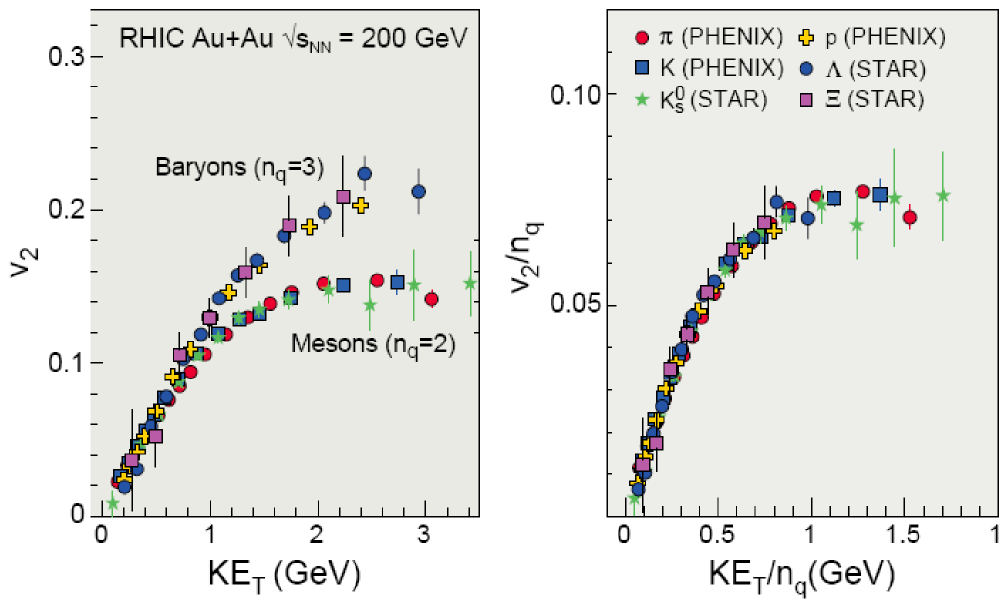
The stuff made in a high energy relativistic heavy-ion collision flows like a perfect liquid.





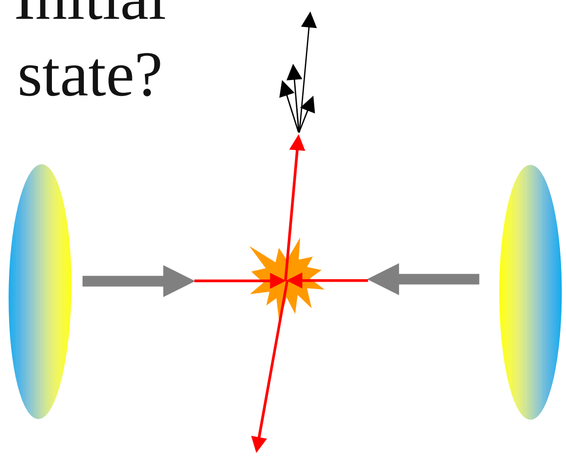
v_2 measures the cos2θ asymmetry of the particle distributions.

The flow scales like the number of quarks!

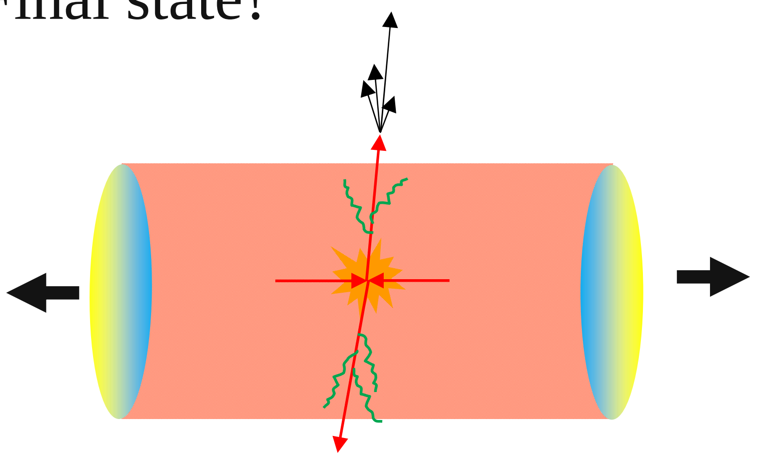


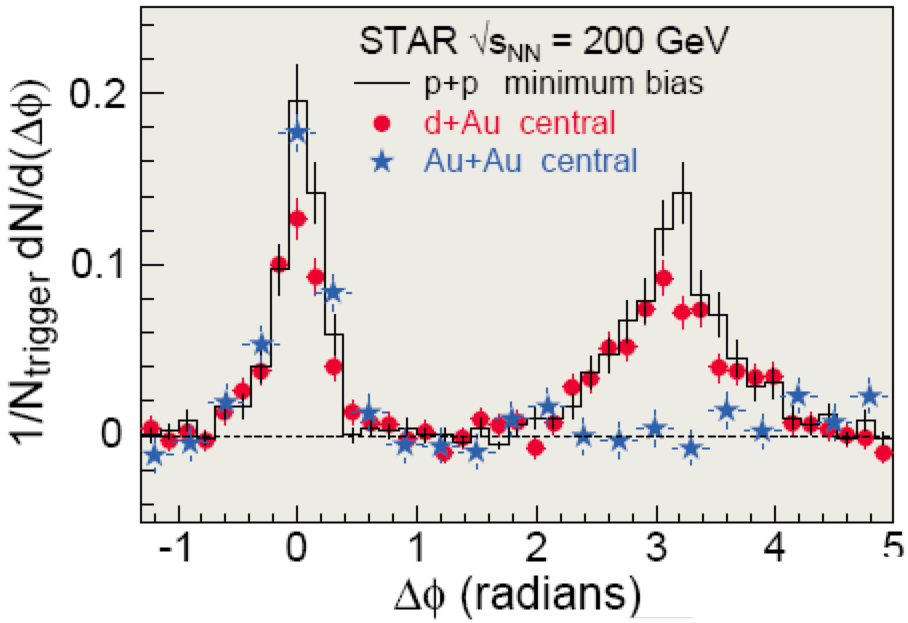
Jet Quenching - The stuff is strongly interacting

Initial state?



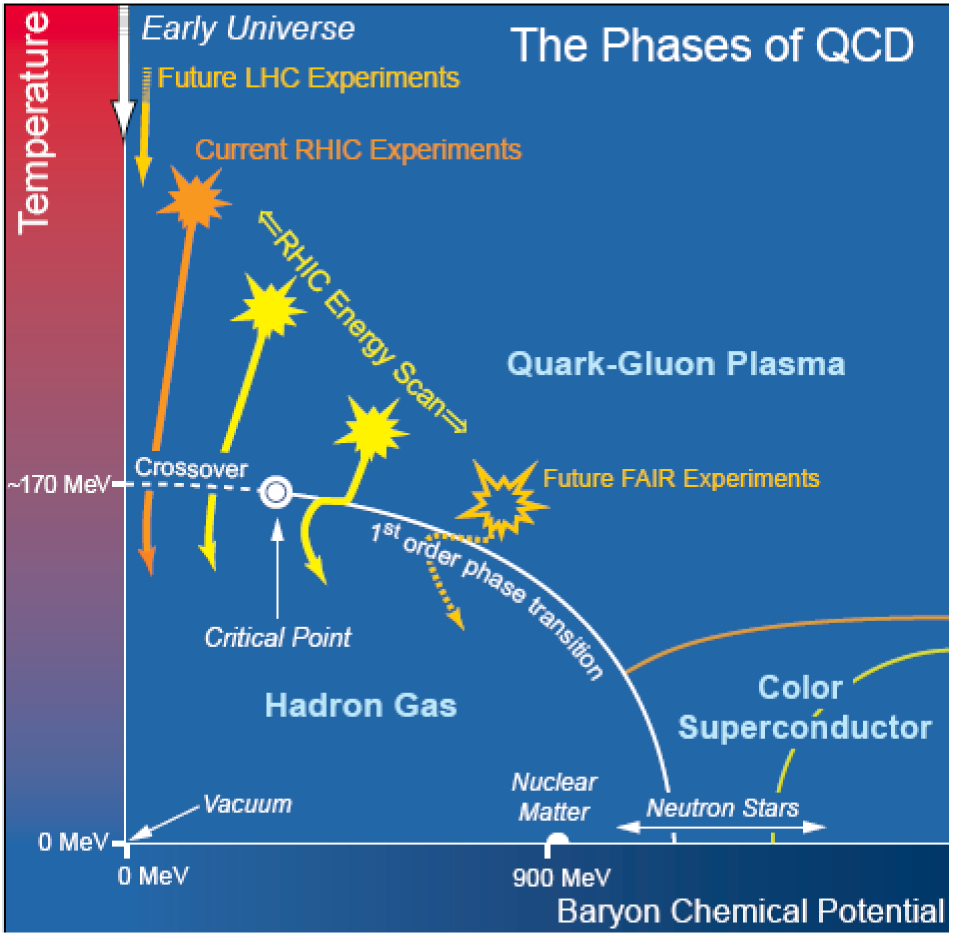
Final state?





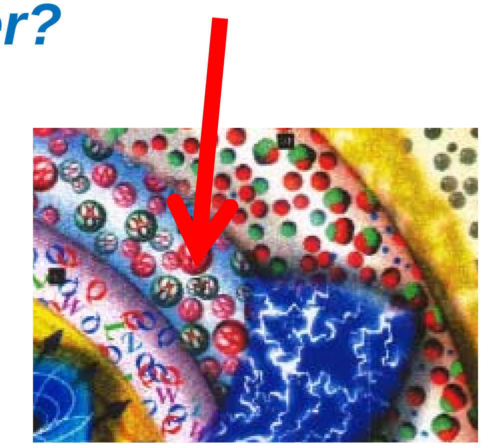
What do we need to know

- How did the properties of the Quark Gluon Plasma and the quark-gluon to hadron phase transition affect the evolution of the universe?
- Does the nature of the plasma and the quark-hadron transition give us new insight into QCD and confinement?
- Do states of de-confined quark and gluon matter exist now, i.e. at the core of neutron stars?

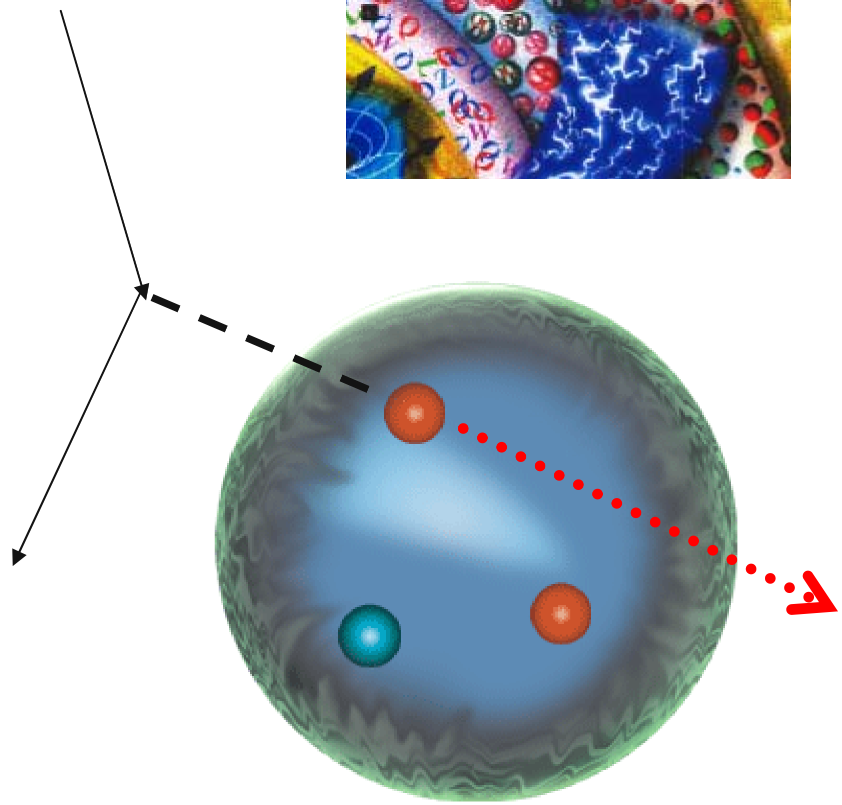


After the quark phase condenses, what are the properties of the "colorless" strongly interacting matter?

Jefferson Lab

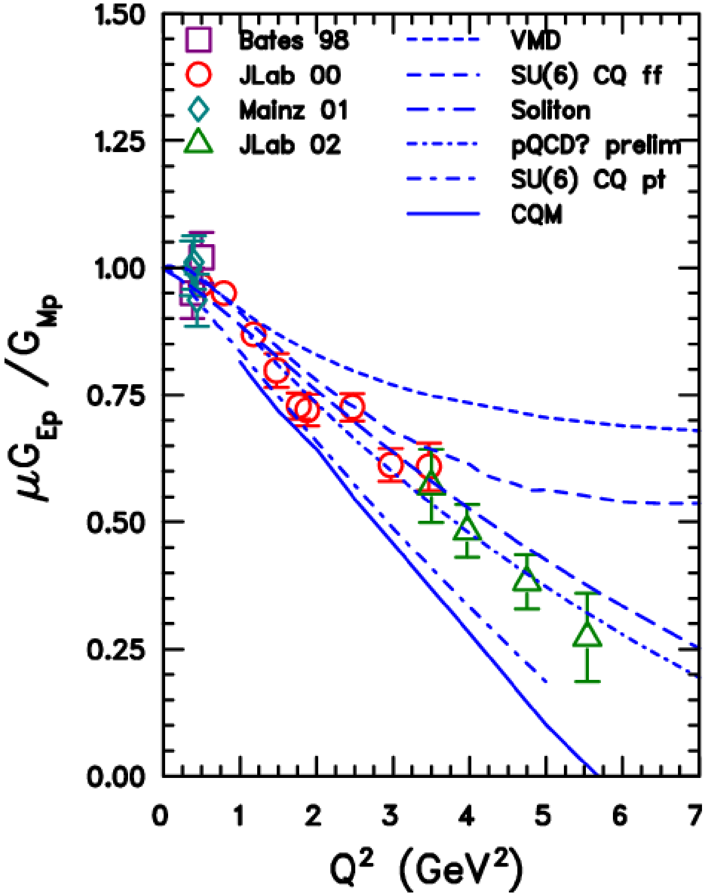


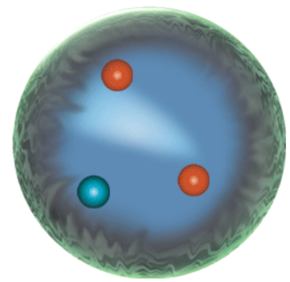
electron

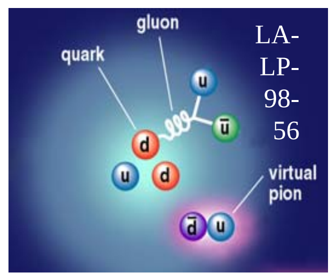


Baryon Structure

Proton Charge and Magnetization

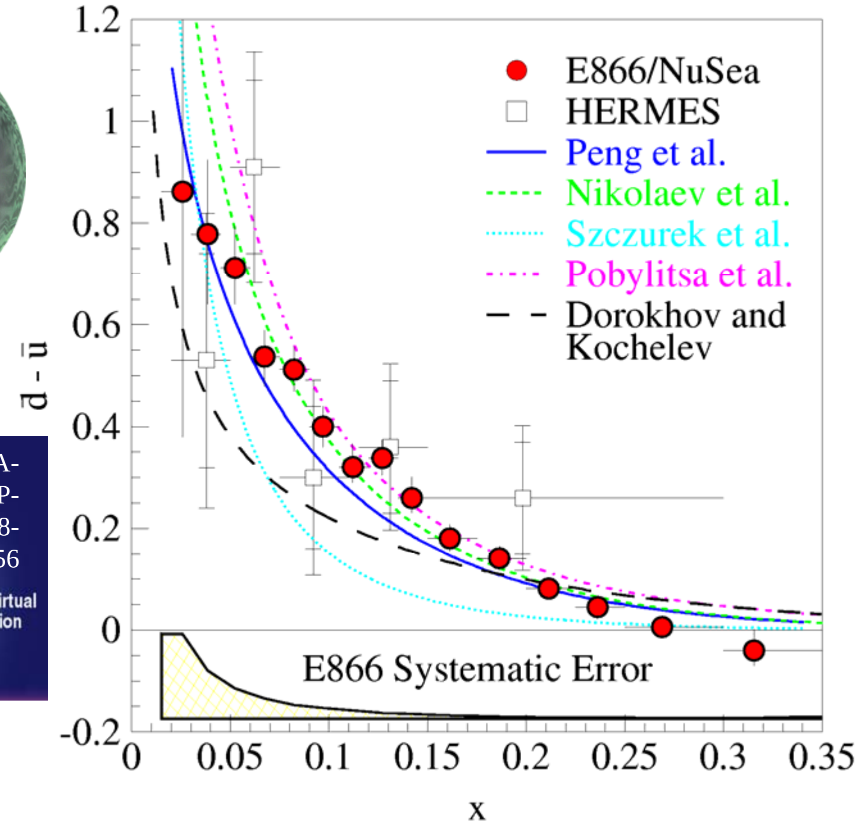






The distribution of charge and magnetization are different

The importance of the anti-quark sea

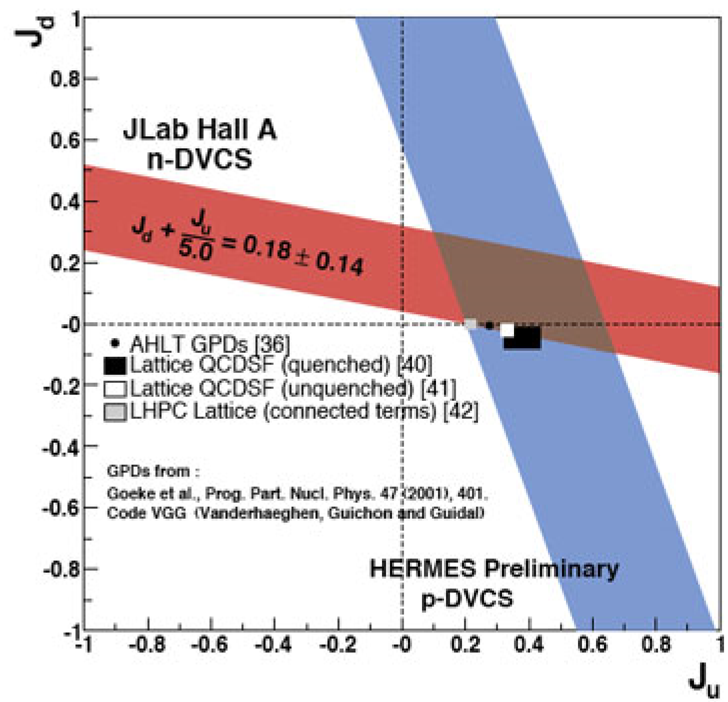


There are more down-anti-down quark pairs than up-anti-up quarks pairs in the sea of the proton.

How do the internal parts of the nucleon add up to give the spin of the proton and neutron?

Mazouz et. al. PRL 99 242501 (08)

$\frac{1}{2} = S_{quarks} + S_{glue} + L_{quarks} + L_{glue}$



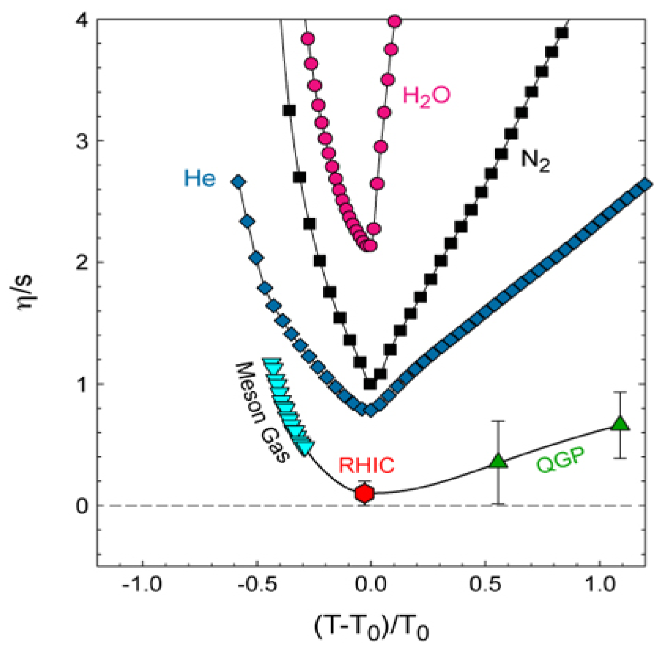
- Contribution of quark spins is only about 30%
- First results indicate the contribution of the glue is small.
- Orbital angular momentum must be important.

New insights from "far away" – Anti-deSitter /Conformal Field Theory

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

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

This allows strong interaction problems to be solved in a dual theory where the interaction is tractable.



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.

Now how do we put this altogether to build up nuclei?

- We want to be able to describe
  - The structure of nuclei far from stability for the formation of the chemical elements and stellar explosions

- We want to use this to
  - Measure neutrino masses from neutrino-less double beta decay rates
  - Constrain extensions to the standard model in electric dipole moment experiments
  - Understand the structure of dense matter in neutron stars and exotic matter in neutron star crusts
  - Help explore new reactor concepts for the Global Nuclear Energy Partnership

The Science Questions – Physics of Nuclei and Nuclear Astrophysics

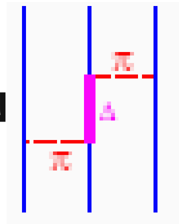
- **What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?**
- **What is the origin of simple patterns in complex nuclei?**
- **What is the nature of neutron stars and dense nuclear matter?**
- **What is the origin of the elements in the cosmos?**
- **What are the nuclear reactions that drive stars and stellar explosions?**

Ab initio Calculations: a major step forward in the many-body physics

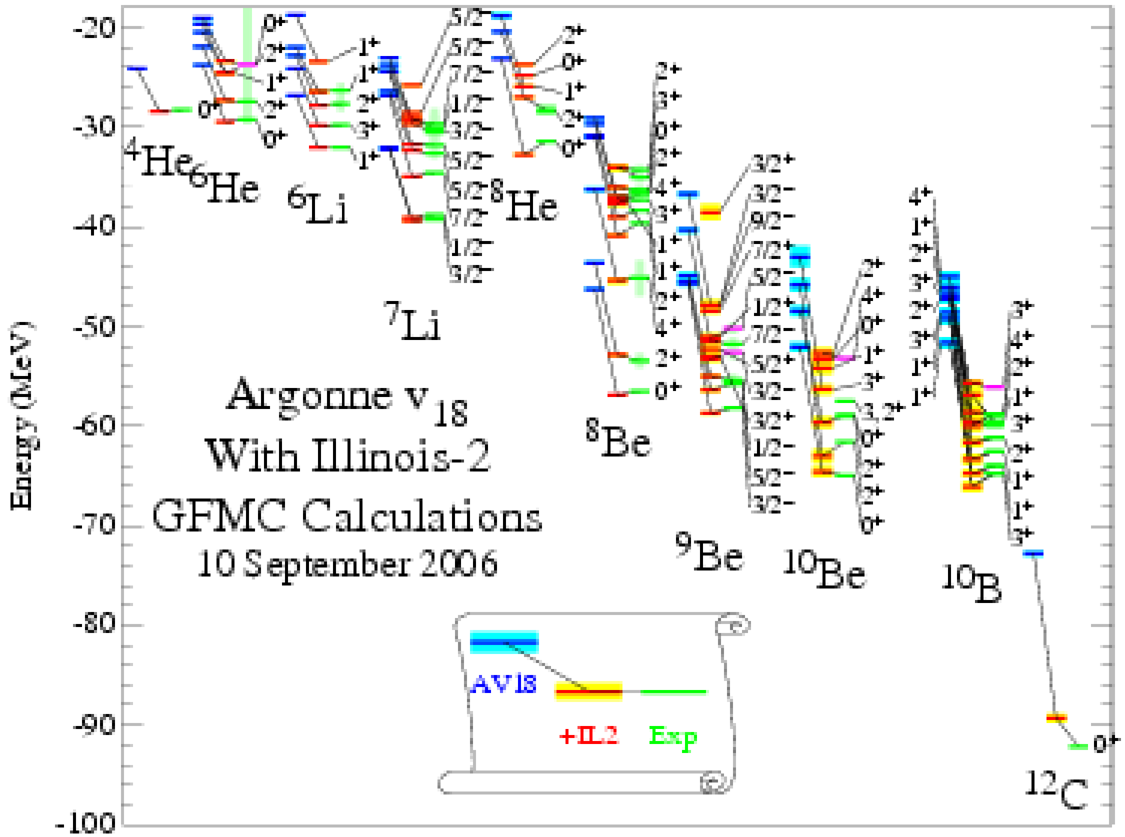
- The nuclei for which we can **do the many-body physics accurately** are well described by interactions of nucleons with potentials : Green's function Monte Carlo, no-core shell model, coupled cluster.

- This requires accurate N-N potentials

- **3 – body NNN interaction**

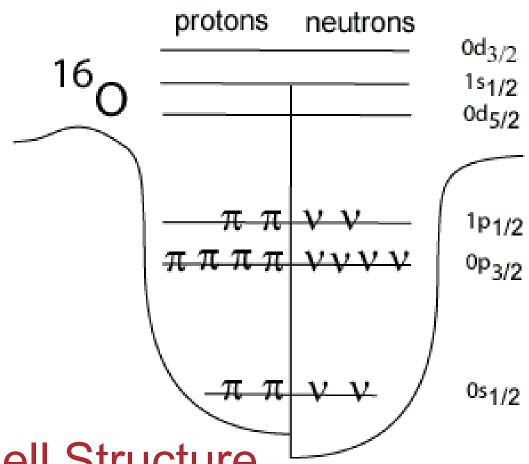


- Macroscopic features like the mean field spin-orbit potential are sensitive to 3-body forces



You need the full complexity of the interaction to get it right. The major uncertainty is in the isospin dependence of the 3-body interaction. No 3 identical nucleon scattering data

Remarkable many-body phenomena emerge - links to atomic and condensed matter physics

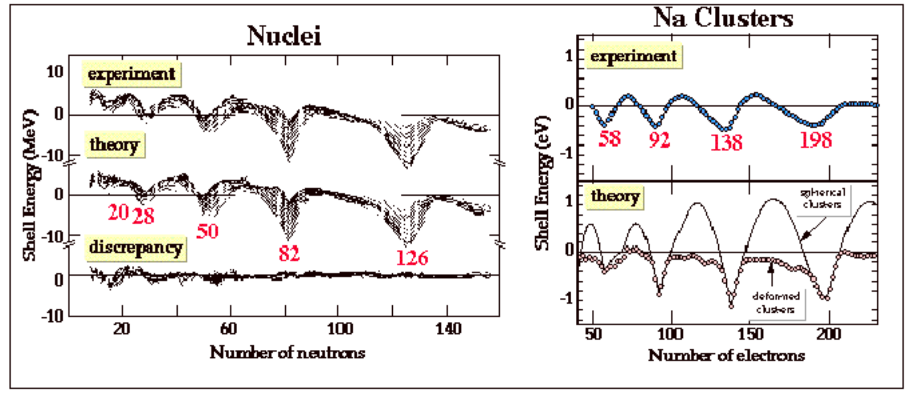


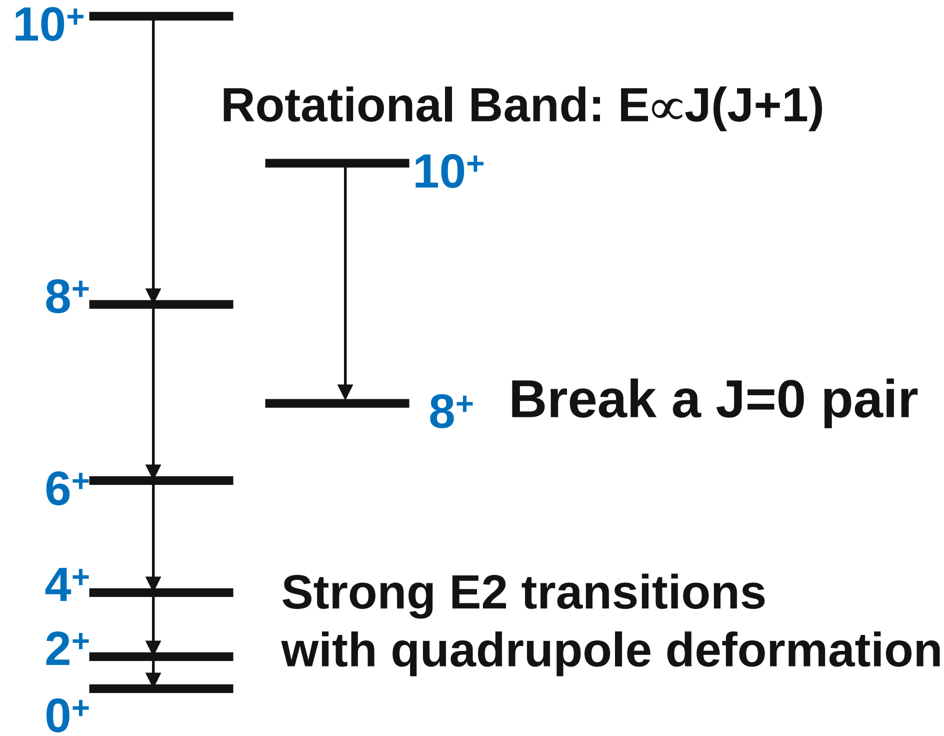
Shell Structure

J=0
nn, np, pp

J= max
np only

Pairing
Halos, skins, clusters ...
Volume and Surface Vibrations

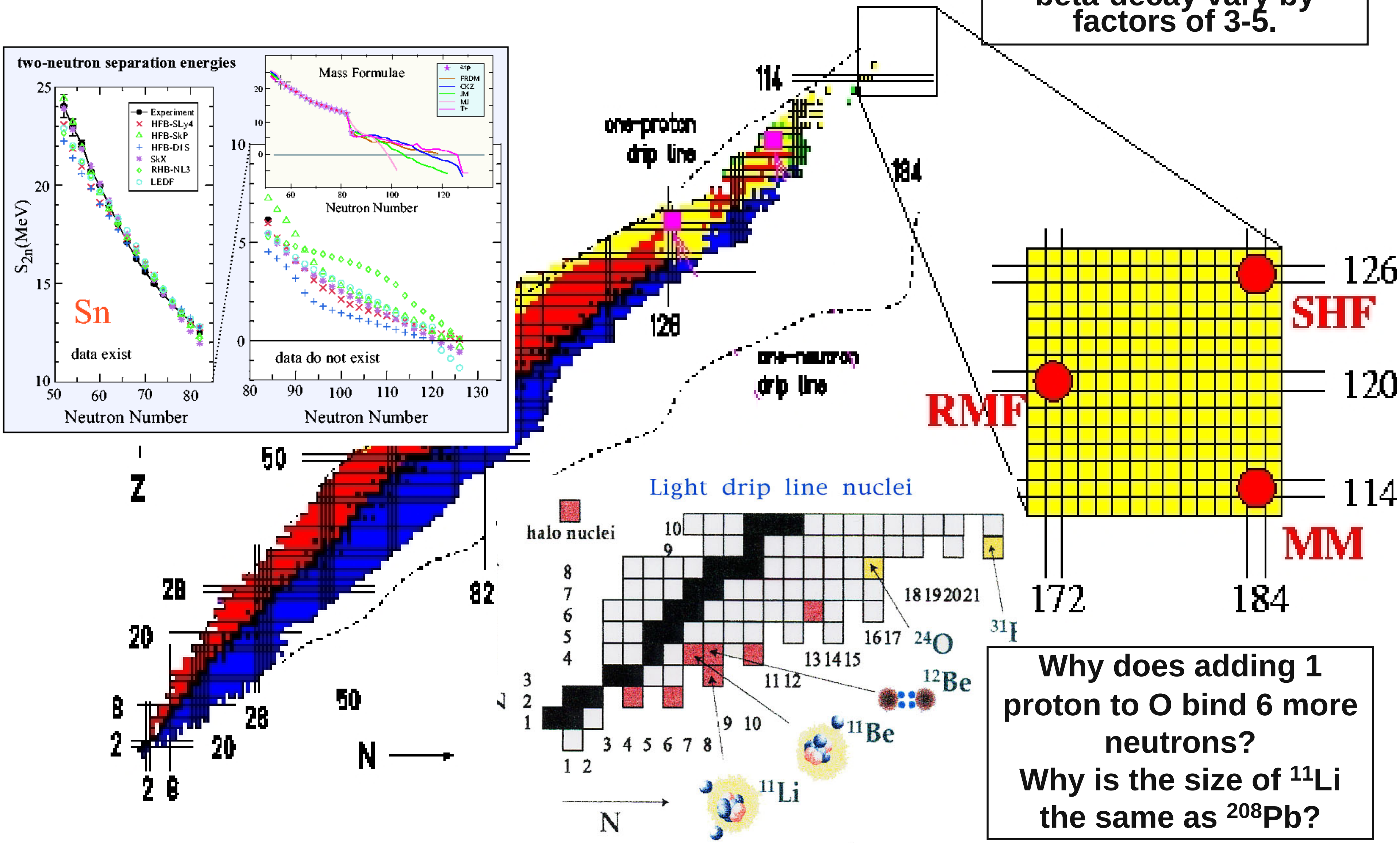




Macroscopic Deformation and
Spontaneous Symmetry breaking

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

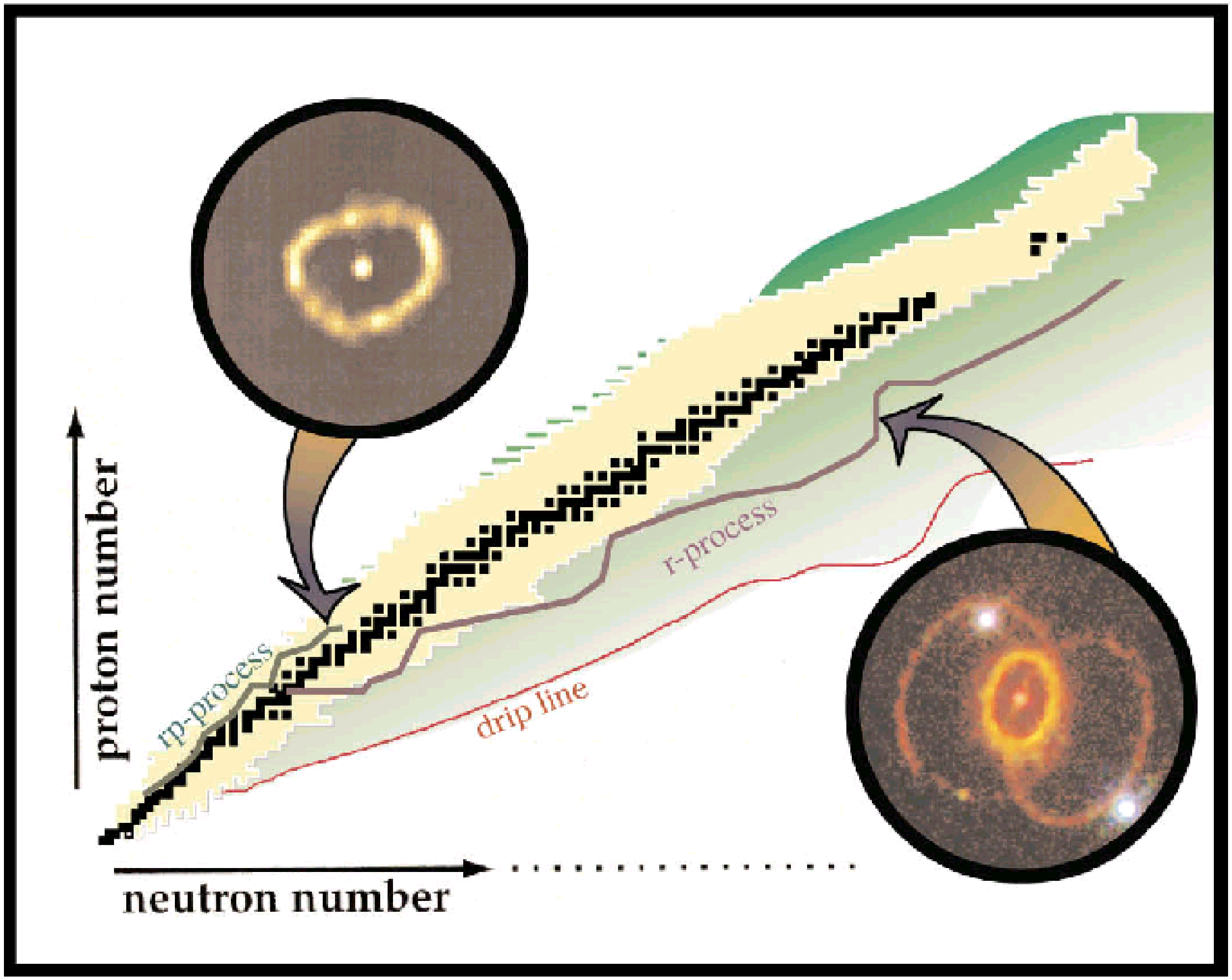
Calculations of nuclear matrix elements for neutrino-less double beta-decay vary by factors of 3-5.



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

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".**

The Science Questions – Fundamental Symmetries and Neutrinos

- **What is the nature of the neutrinos, what are their masses, and how have they shaped the evolution of the universe?**
- **Why is there now more matter than antimatter in the universe?**
- **What are the unseen forces that were present at the dawn of the universe but disappeared from view as it evolved?**

Does the sun still burn and what does that tell us about the universe?

The sun burns at its center primarily by primarily :

$4p \rightarrow {}^{4}He + 2e + 2\nu$ + energy

The neutrinos come out from the center of the sun at the speed of light, but it takes about 50,000 years for the heat to appear on the surface.

Ray Davis tried to measure these neutrinos but never found as many as were expected.

We now know that the solar neutrino puzzle was due to a property of neutrinos beyond the standard model. They have mass.

- Because they have mass, and the states of fixed mass are not states of unique flavor, neutrinos can change their flavor as they travel through the sun, from electron neutrinos to a mixture of electron, muon and tau neutrino.

Starts out $|\nu_e\rangle = \alpha\,|\nu_1\rangle + \beta\,|\nu_2\rangle + \gamma\,|\nu_3\rangle$

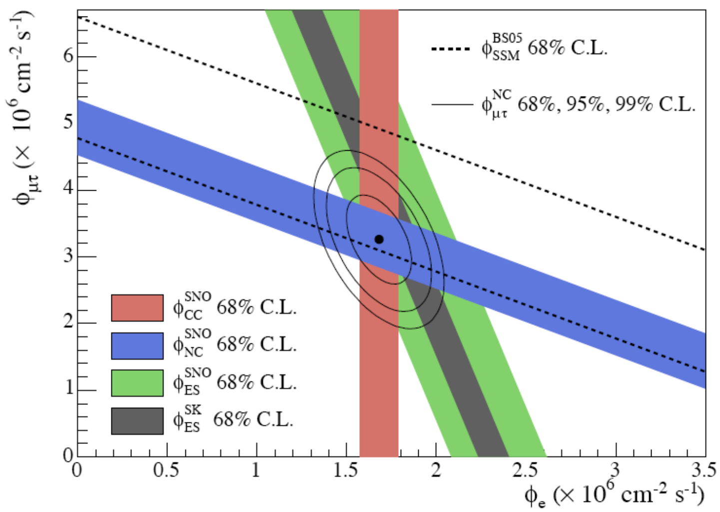
Each evolves in time $|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p}_i \cdot \vec{x})}|\nu_i(0)\rangle$

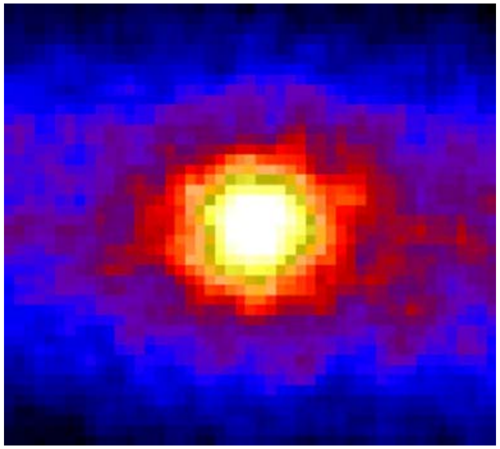
- The SNO experiment was able to measure the interactions of these neutrinos even after they changed flavor

- Our model of how the sun burns was fully validated.

- The neutrinos do change

SNO





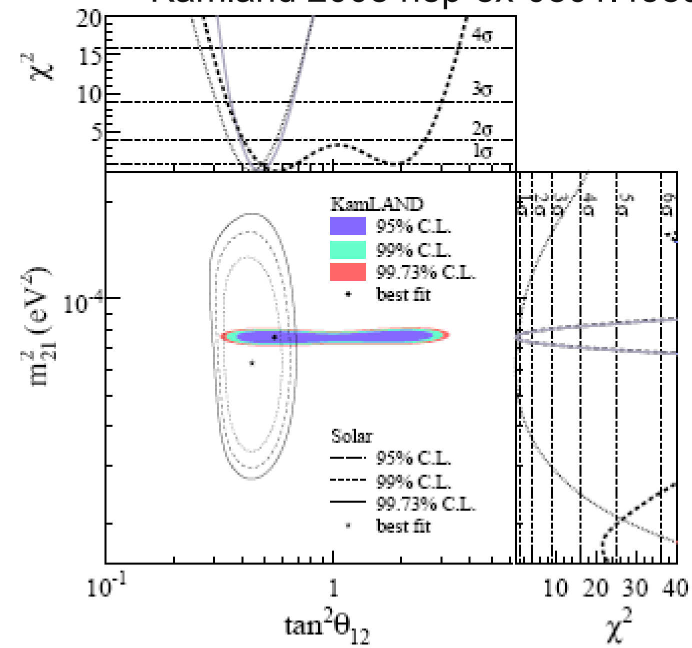
SuperK neutrino image of the sun

What Are the Properties of Neutrinos

What do we know: First crack in the standard model

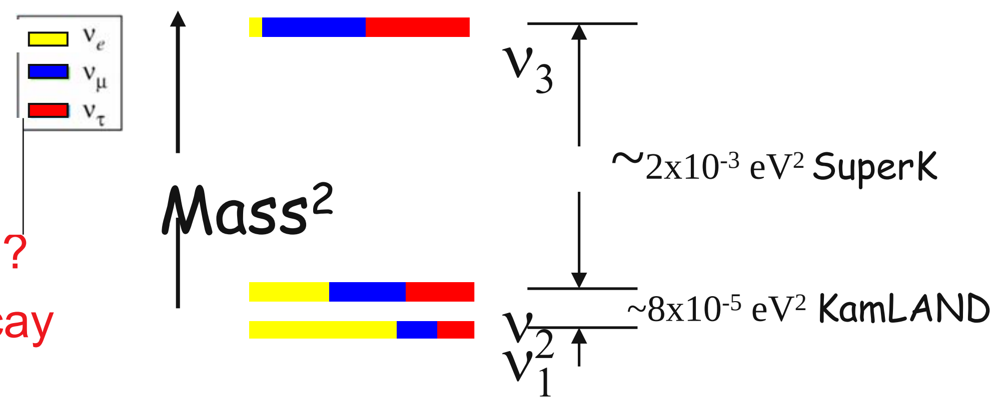
- Neutrinos mix – at least three mass eigenstates
  - We know two mass differences- Δm_{12}^2, Δm_{23}^2
  - Two mixing angles- θ_{12}, θ_{23}

Kamland 2008 hep-ex-0801.4589



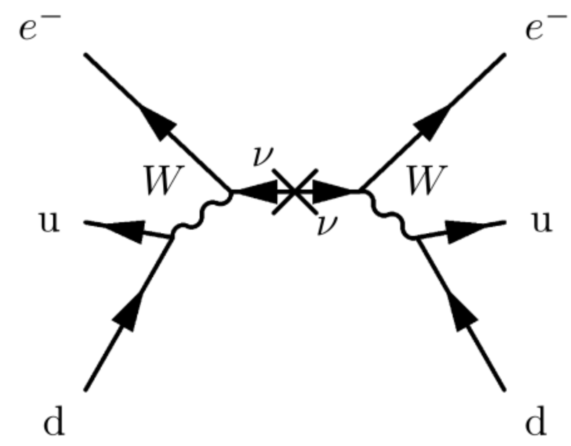
What do we need to know?

- 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 do we need to know – Neutrino-less double beta decay?



If a neutrino is its own antiparticle, then a nucleus can change into one with charge two units greater by emitting two electrons.

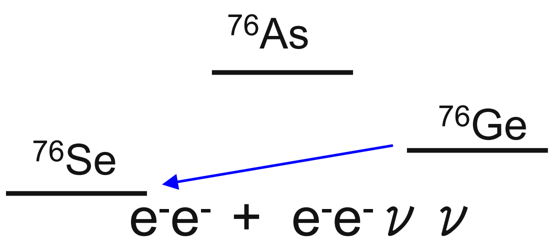
Such a process is predicted to be very rare, perhaps 1 in 10^{27} years.

1 ton of material would give 2 events every 3 years.

An observation of neutrino-less double beta decay may provide the only way to measure the mass of the neutrino, if it is very small.

$$\frac{1}{T_{1/2}} = G(E_o, Z)\left[M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu}\right]^2 \langle m_\nu \rangle^2$$

$$\langle m_\nu \rangle = \left| \sum_j m_j U_{ej}^2 \right|$$



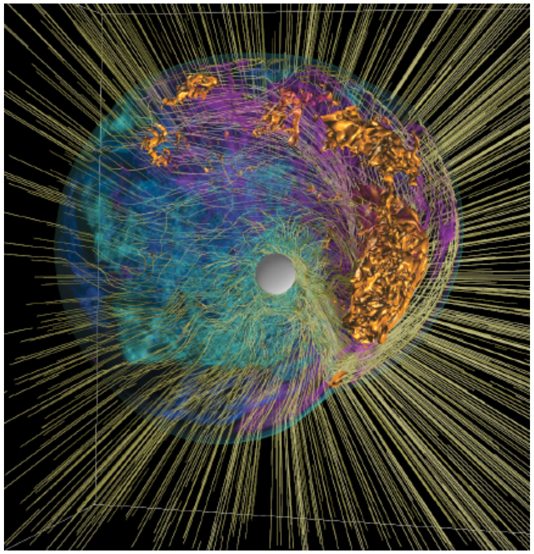
We will also have to improve our understanding of nuclear structure to do this accurately.

Supernova

What do we know

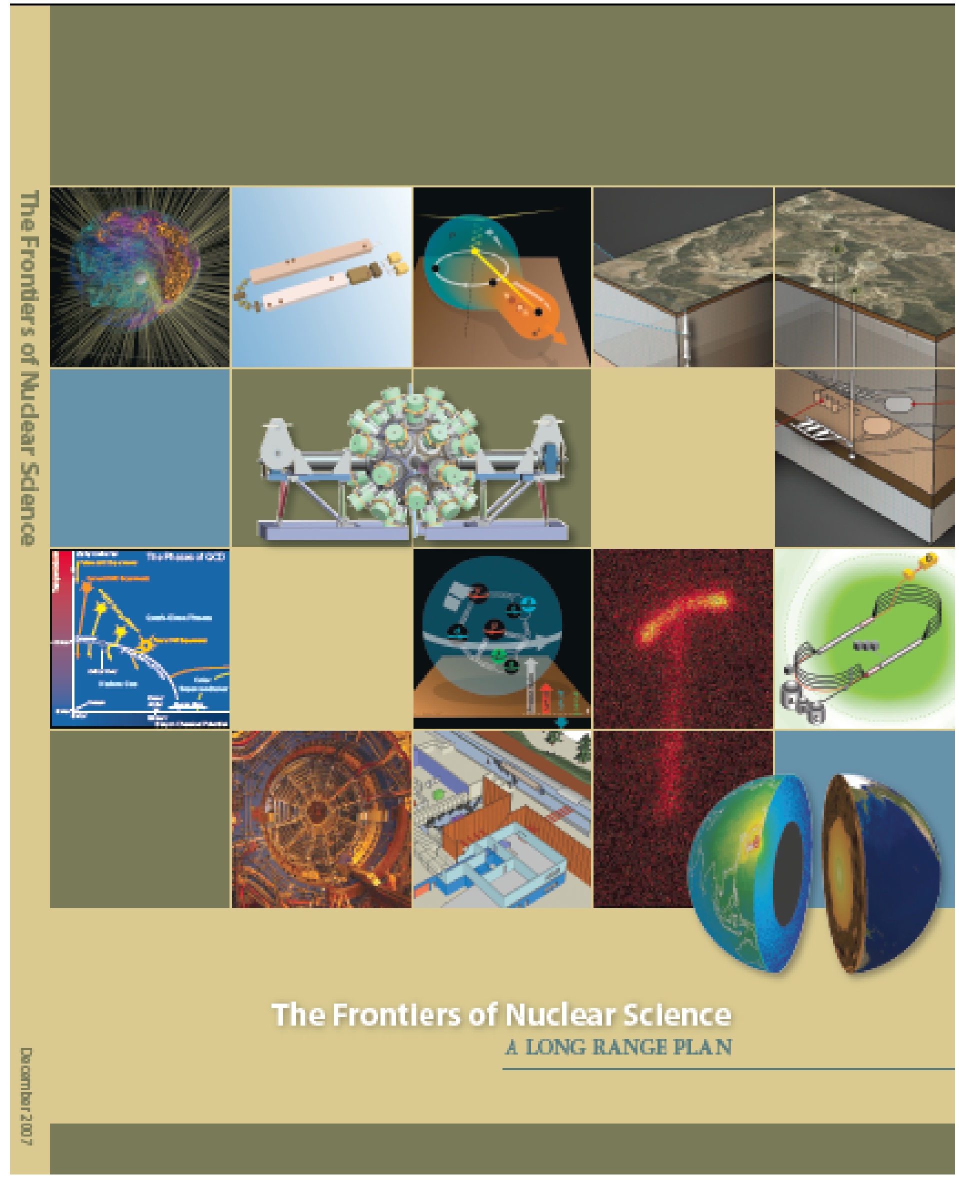
- Most of the energy of the collapse goes into neutrinos
- remnants lead to neutron stars and black holes

- 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 and what does this tell us about neutron stars?



NSAC 2007 Long Range Plan

- Starting in the fall of 2006, the nuclear science community, led by the Nuclear Science Advisory Committee (NSAC) created a new Long Range Plan for the field.
- Released January 2008



http://www.sc.doe.gov/henp/np/nsac/nsac.html

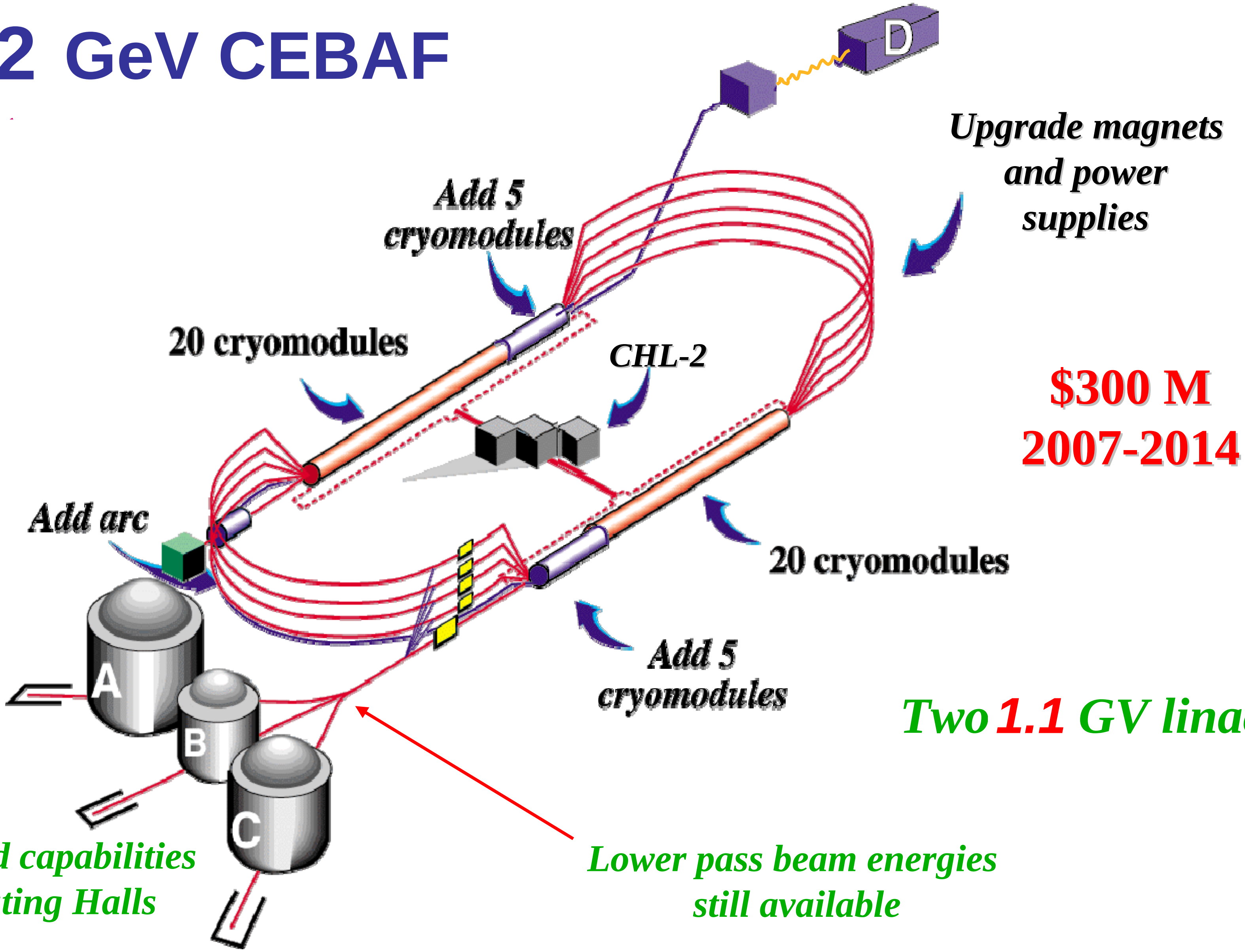
Recommendation I

- **We recommend completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.**

The Science

- Spatial structure of protons and neutrons – generalized parton distribution functions
- Gluon states in the hadron spectrum – GLUEX (quark confinement)
- Nuclei and QCD – short range correlations, role of quarks in nuclei

12 GeV CEBAF



$300 M
2007-2014

*Two **1.1** GV linacs*

Enhanced capabilities in existing Halls

Lower pass beam energies still available

Recommendation II

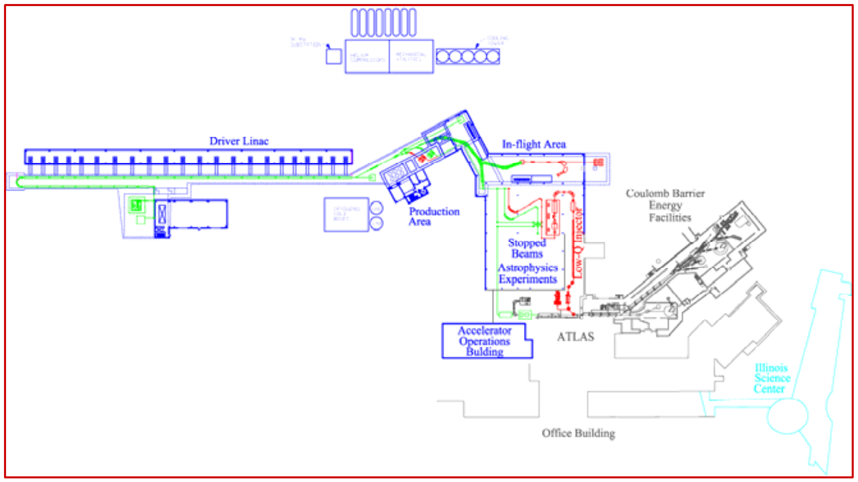
- **We recommend construction of the Facility for Rare Isotope Beams, FRIB, a world-leading facility for the study of nuclear structure, reactions and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.**

The Science

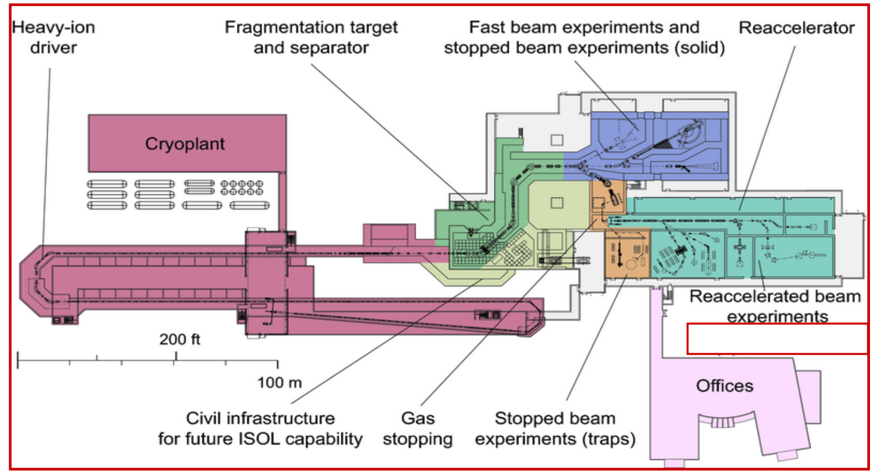
- Nuclear structure with rare isotope beams – shell closures, halos, …
- Nuclear astrophysics – rp-process, r-process, reactions on unstable nuclei, . . .

FRIB Options

Two options based on superconducting HI linac



AEBL – ANL



ISF – MSU

Both designs have:

- **Multiple charge state acceleration and transport**
- **Stripper(s) to boost to high charge states**

Cost **estimates** are comparable for two projects!

DOE has issued a call for proposals for developing FRIB!

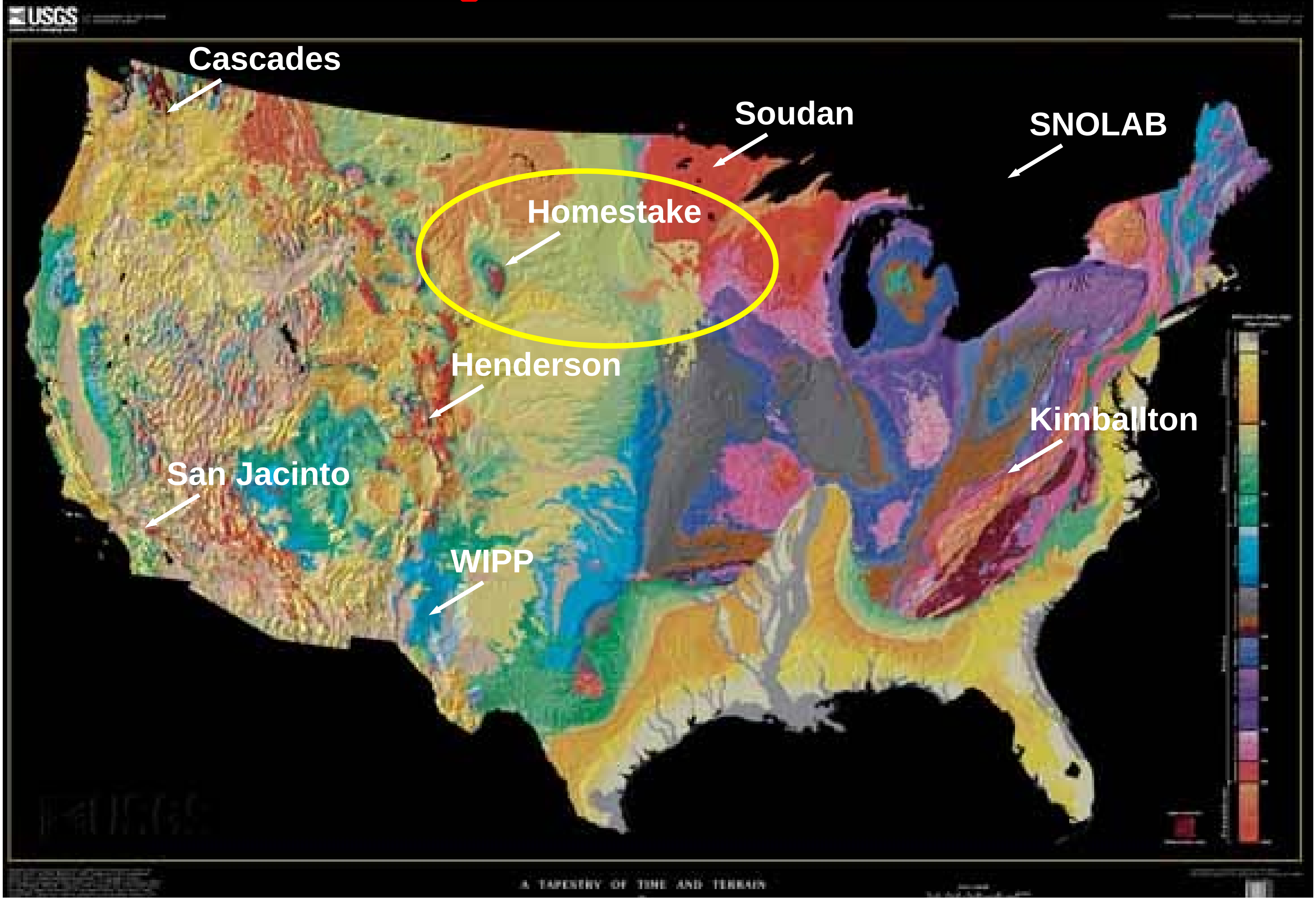
Recommendation III

- **We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet unseen violations of time-reversal symmetry, and other key ingredients of the new standard model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to US leadership in core aspects of this initiative.**

The Science

- Neutrino properties – masses, mixing angles, CP violation, ...
- Standard Model tests – EDM's, precision measurements of β decay and neutron decay, …
- The nuclear weak interaction – parity violation in nuclear systems

Following NSF Site Selection



Recommendation IV

- **The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.**

The Science

- Rare processes – hard probes
- Jet quenching through Compton processes
- Quarkonium suppression
- …

Other recommendations

Further into the Future

- We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.

Initiatives

- We recommend the funding of finite-duration, multi-institutional. topical collaborations initiated through a competitive peer-review process.
- Targeted support of proposal-driven accelerator Research and development
- The construction of the Gamma-ray Energy Tracking Array should begin upon the successful completion of GRETINA

Education

- The enhancement of programs the address the goals of increasing the visibility of nuclear science in undergraduate education and the involvement of undergraduates in research
- the development and dissemination of materials and hands-on activities that demonstrate core nuclear science principles to a broad array of audiences

Applications to Society

- Nuclear Energy
- Nuclear medicine
- Homeland security
- . . .

Applications to Society

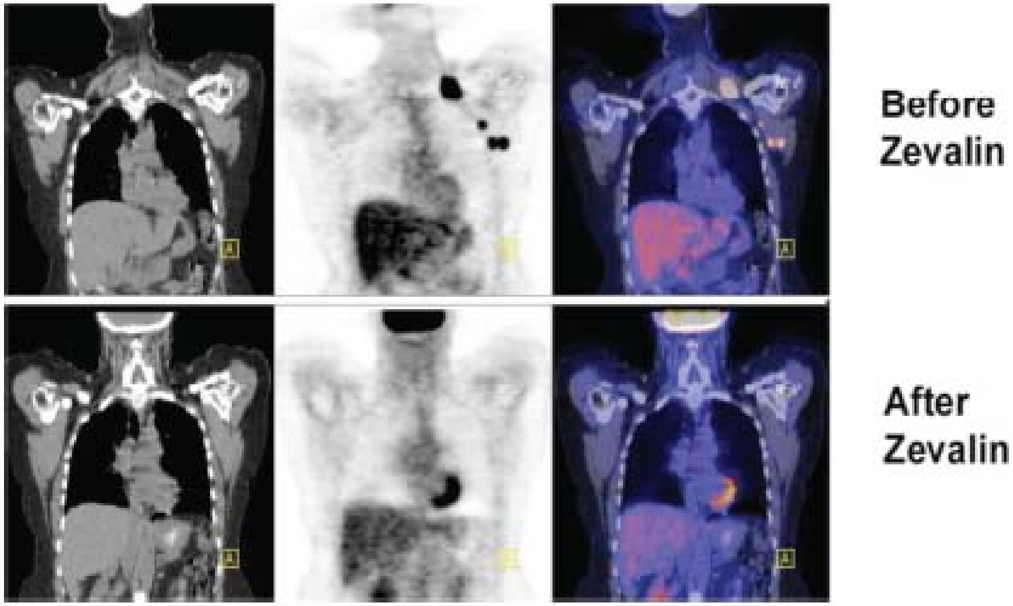


FIGURE 4.5 This set of "before and after" PET/CT images demonstrates the use of these nuclear imaging modalities to evaluate the clinical effects of radioimmunotherapy using radiopharmaceutical compounds such as yttrium-90 ibritumomab tiuxetan (Zevalin®) in the treatment of malignant lymphoma. SOURCE: Courtesy of Peter Conti, University of Southern California.

From the 2007 National Research Council Report *Advancing Nuclear Medicine Through Innovation*

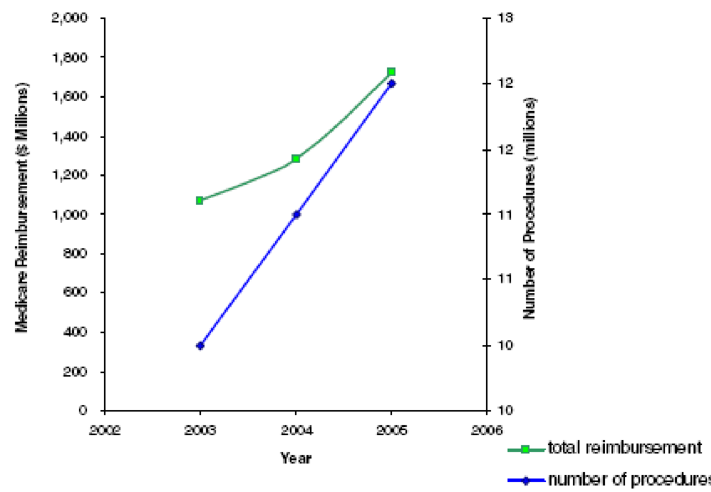
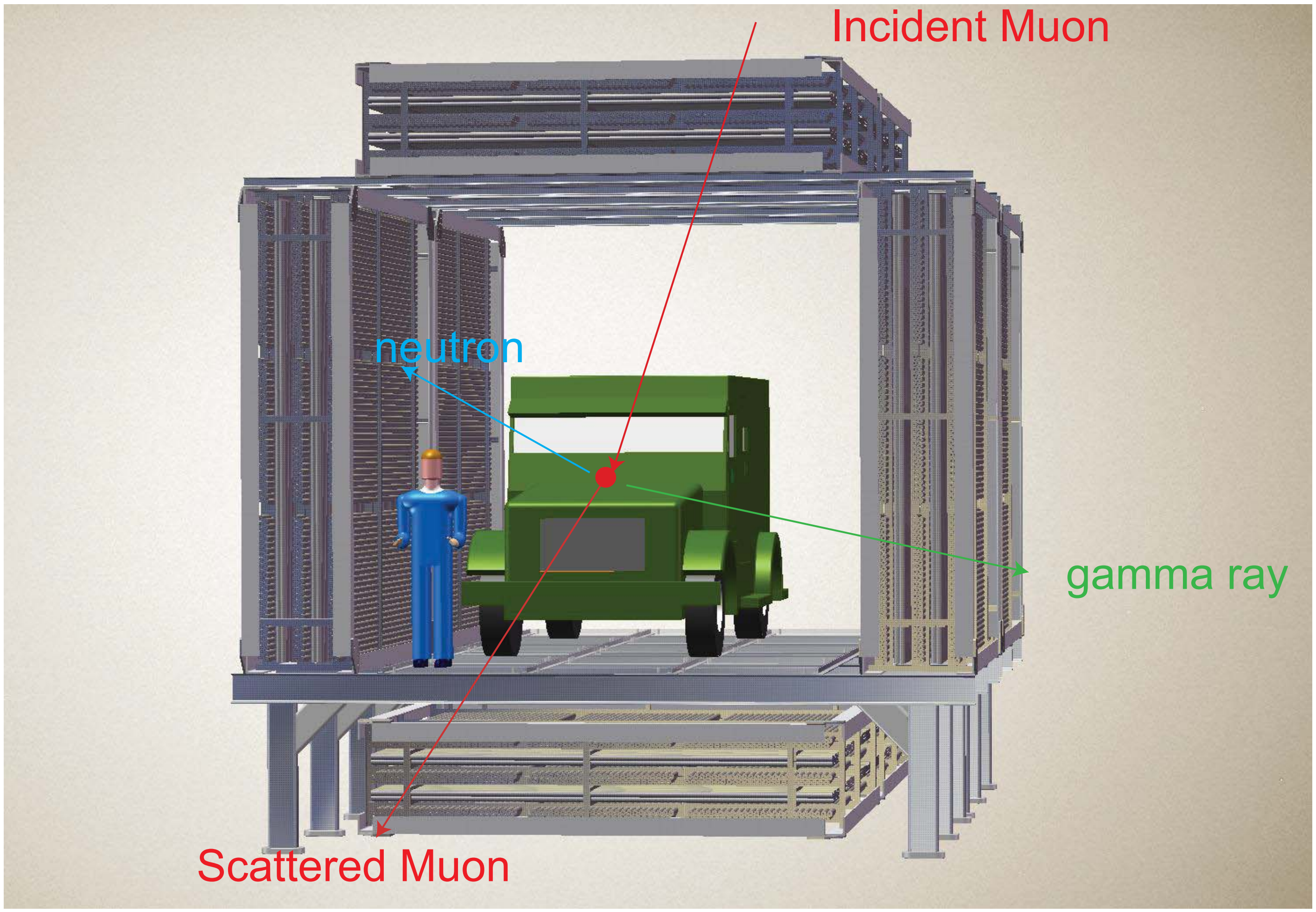


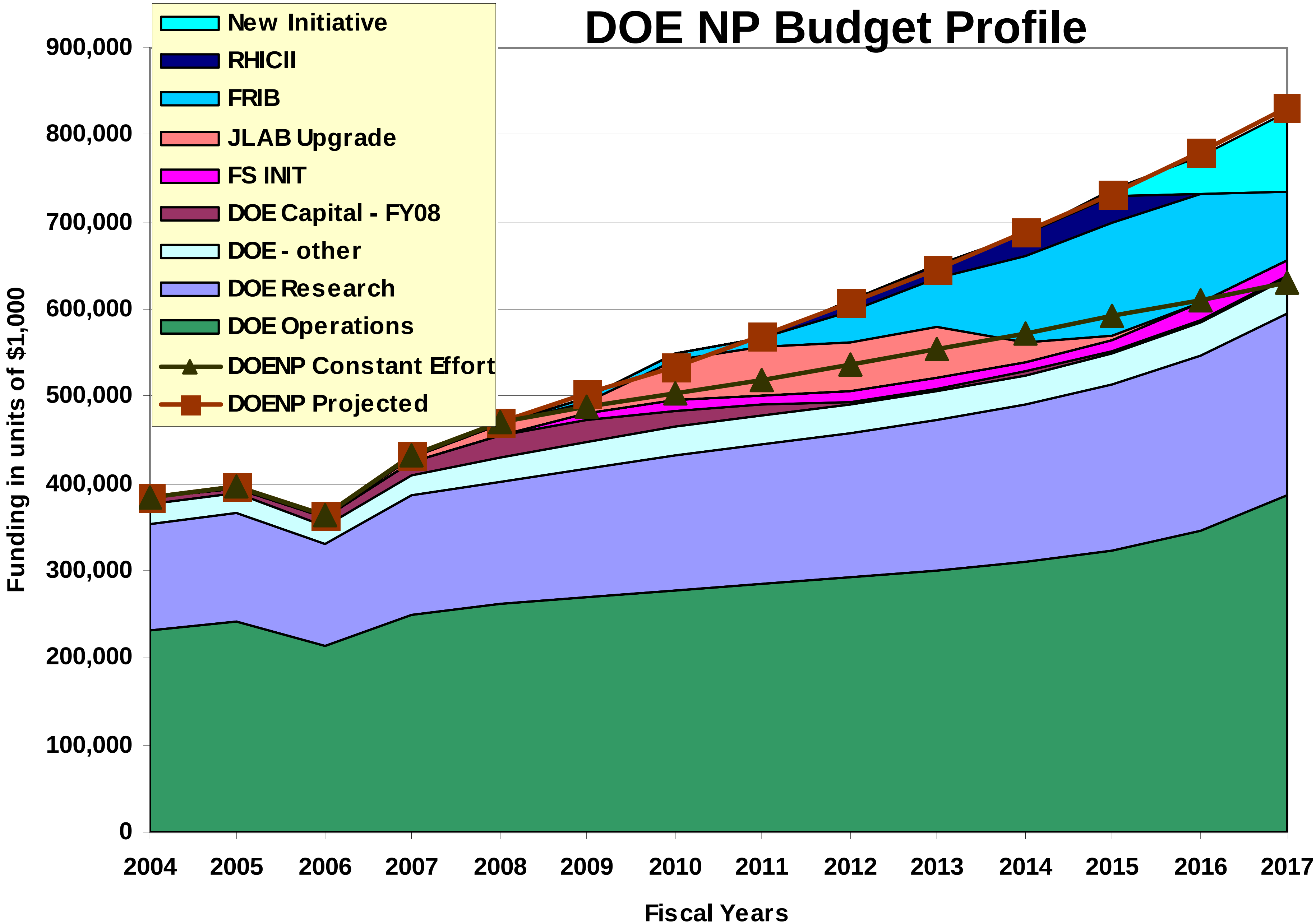
FIGURE 2.1 Number of nuclear medicine procedures that were approved for reimbursement by the Center for Medicare and Medicaid Services and total reimbursement for 2003–2005. SOURCE: Data provided by CMS.

Applications to Society

- Portal screening for nuclear material



What are the resources needed to carry out the program?


DOE NP Budget Profile
New Initiative
RHICII
FRIB
JLAB Upgrade
FS INIT
DOE Capital - FY08
DOE - other
DOE Research
DOE Operations
DOENP Constant Effort
DOENP Projected
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
Funding in units of $1,000
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Fiscal Years

This is an international endeavor

2006-2008 Organization of Economic Coordination and Development Global Science Forum Working Group on Nuclear Physics (report to be released in March 2008) is concluding:

- There is an international consensus of the key science questions that motivate future research
- The global roadmap for nuclear physics, which emerges from the proposed new and upgraded facilities reflects a high degree of coordination in optimizing the available resources.
- The proposed new and upgraded facilities in the global roadmap will produce outstanding science and discoveries.

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...