Questions: 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?

What binds protons and neutrons into stable nuclei and rare isotopes?

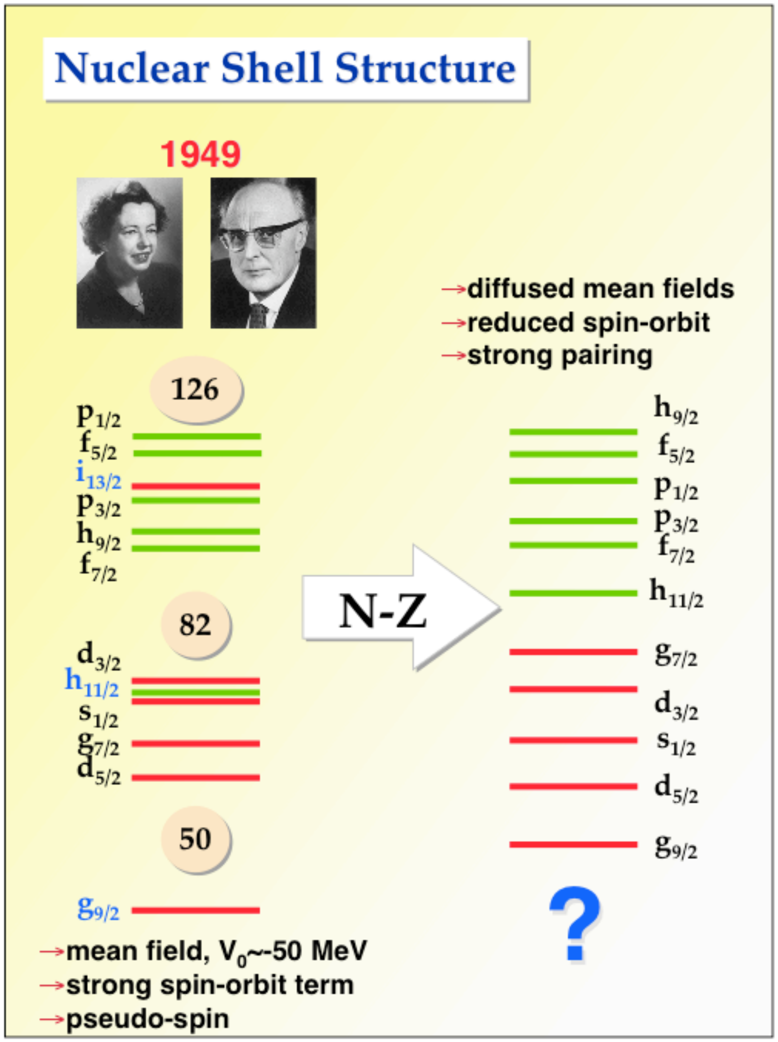
Using our knowledge of the basic nucleon-nucleon interaction, nuclear physicists are now able to calculate the features of lighter nuclei with astonishing precision.

As with other complex systems such as proteins, however, the properties of heavy nuclei cannot be easily described in terms of elementary interactions among their isolated constituents. Today, developing a comprehensive, predictive theory of these heavy, complex nuclei lies at the forefront of nuclear physics. **Indeed, recent observations made possible by the emerging technology of radioactive beams demonstrate strikingly anomalous behavior in rare isotopes, indicating that our knowledge of the inner workings of the nucleus is far from complete.** The study of nuclei having high neutron or proton imbalances will provide the missing links in our present understanding.

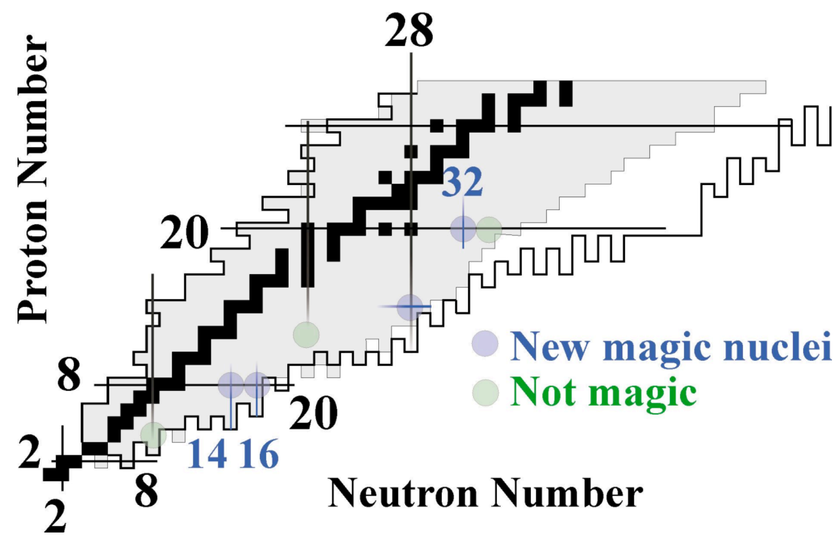
- How are nuclei assembled from their fundamental building blocks and interactions?
- How many elements and nuclei are yet to be discovered?
- How can nuclei best be exploited for the benefit of mankind?

Old paradigms, universal ideas, are not correct

Near the drip lines nuclear structure may be dramatically different.

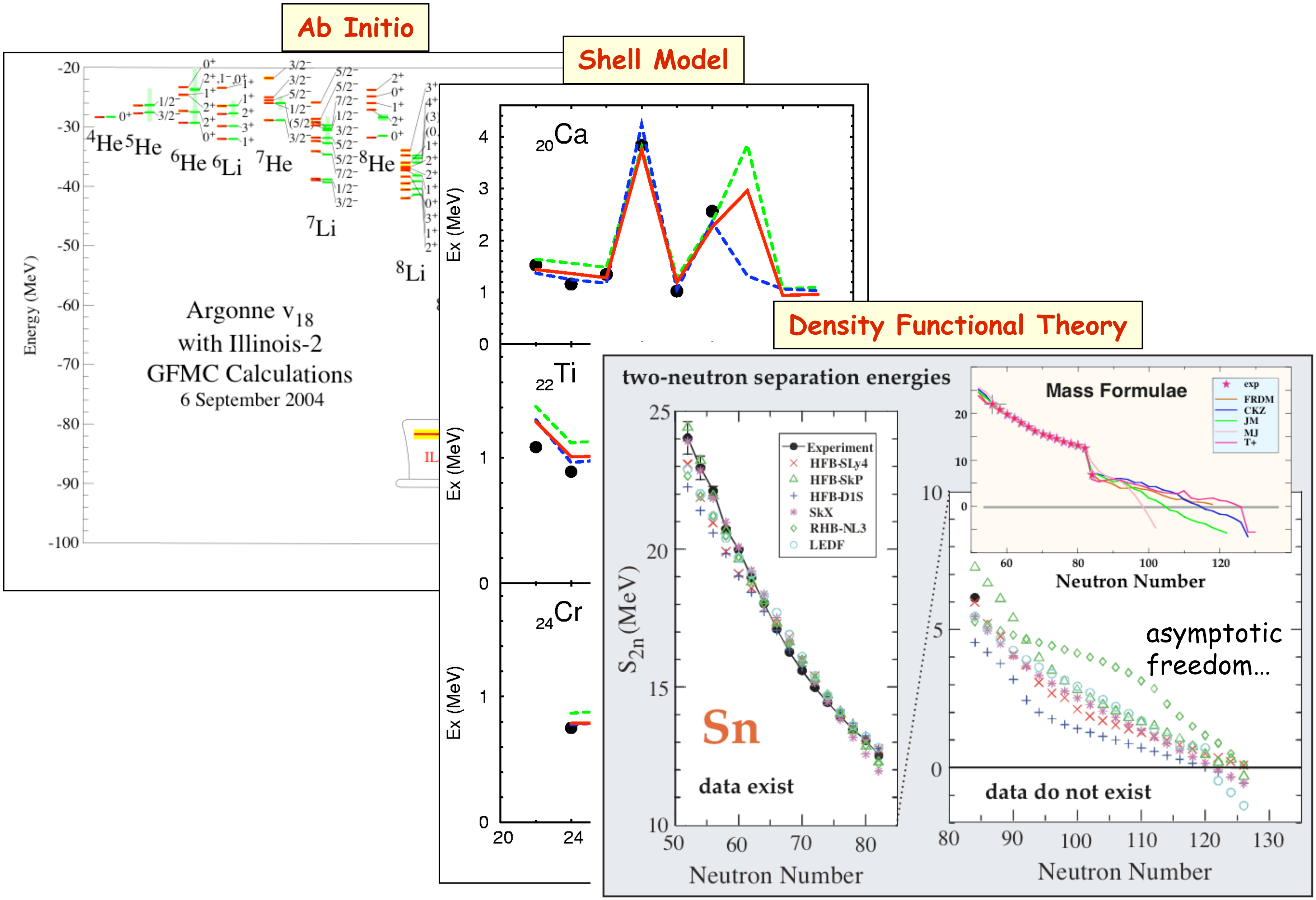


First experimental indications demonstrate significant changes



No shell closure for N=8 and 20 for drip-line nuclei; new shells at 14, 16, 32…

What are the missing pieces?

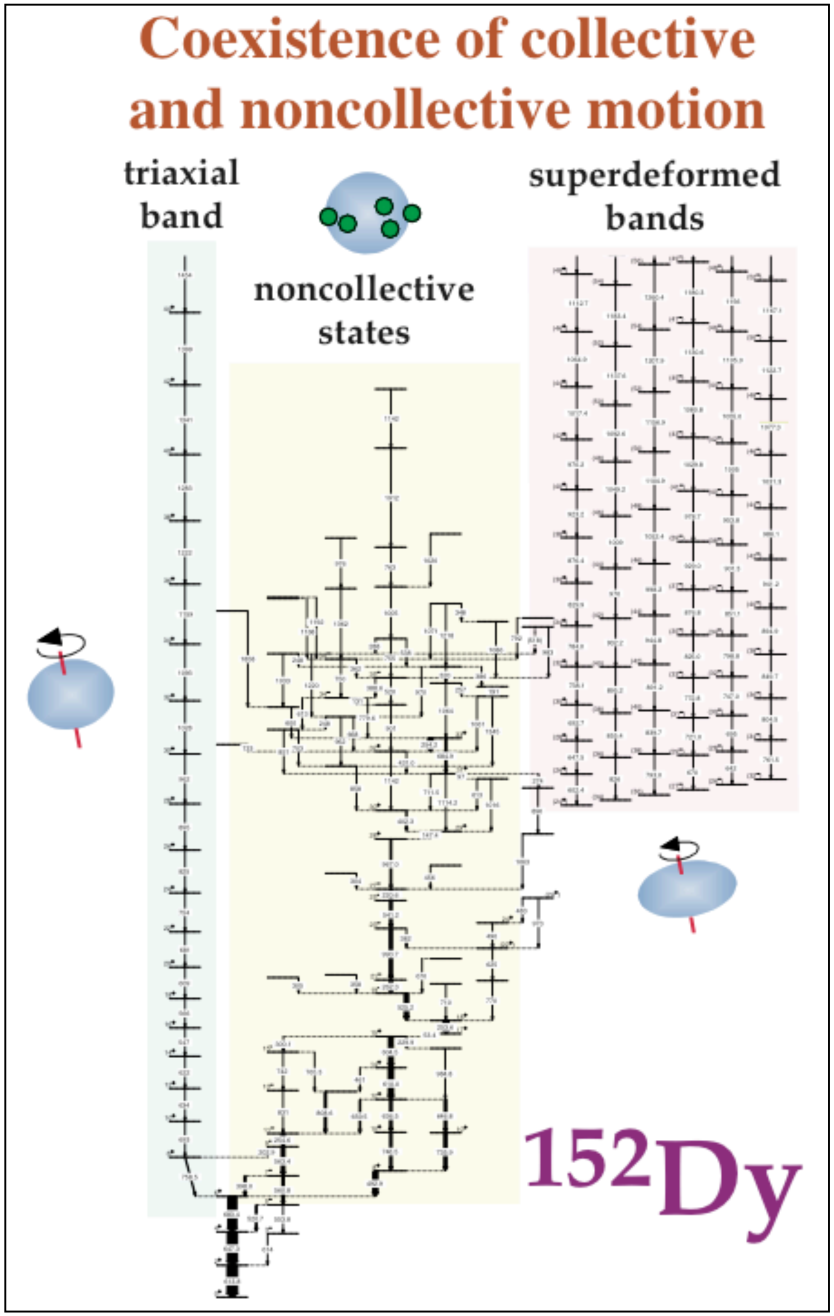


What is the origin of simple patterns in complex nuclei?

Simplicity from Complexity. Emergent Phenomena

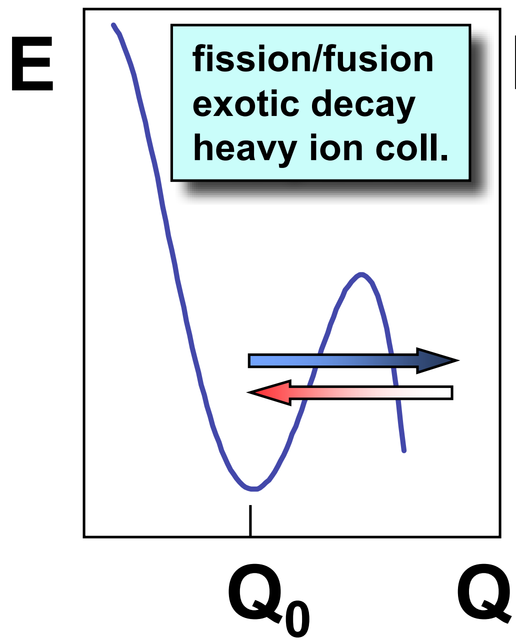
Complex systems often display amazing simplicities; nuclei are no exception.

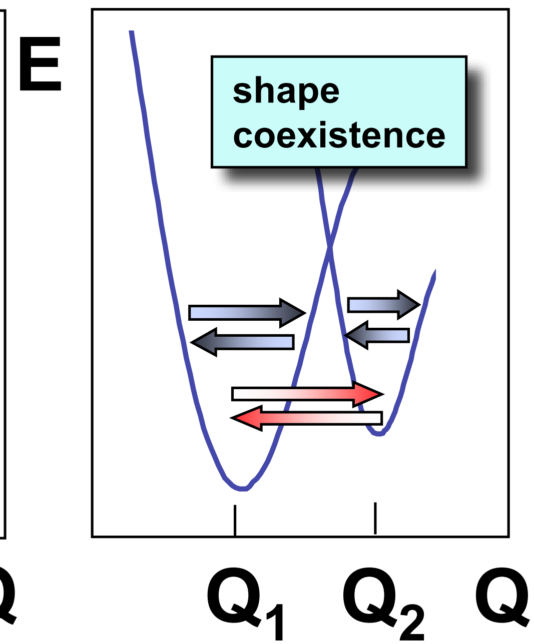
It is remarkable that a heavy nucleus consisting of hundreds of rapidly moving protons and neutrons can exhibit collective motion, where all particles slowly dance in unison. To fully understand this behavior, further insights gained from the study of new forms of rare nuclei are needed. Nuclear physicists expect to observe a broad range of new collective phenomena, which are predicted to emerge in neutron-rich systems. The very existence of these exotic nuclei hangs on the subtle balance between the individual motion of protons and neutrons and nuclear superconductivity.



Nuclear collective motion

Rotational Transitions ~ 0.2-2 MeV
Vibrational Transitions ~ 0.5-12 MeV
Nucleonic Transitions ~ 7 MeV



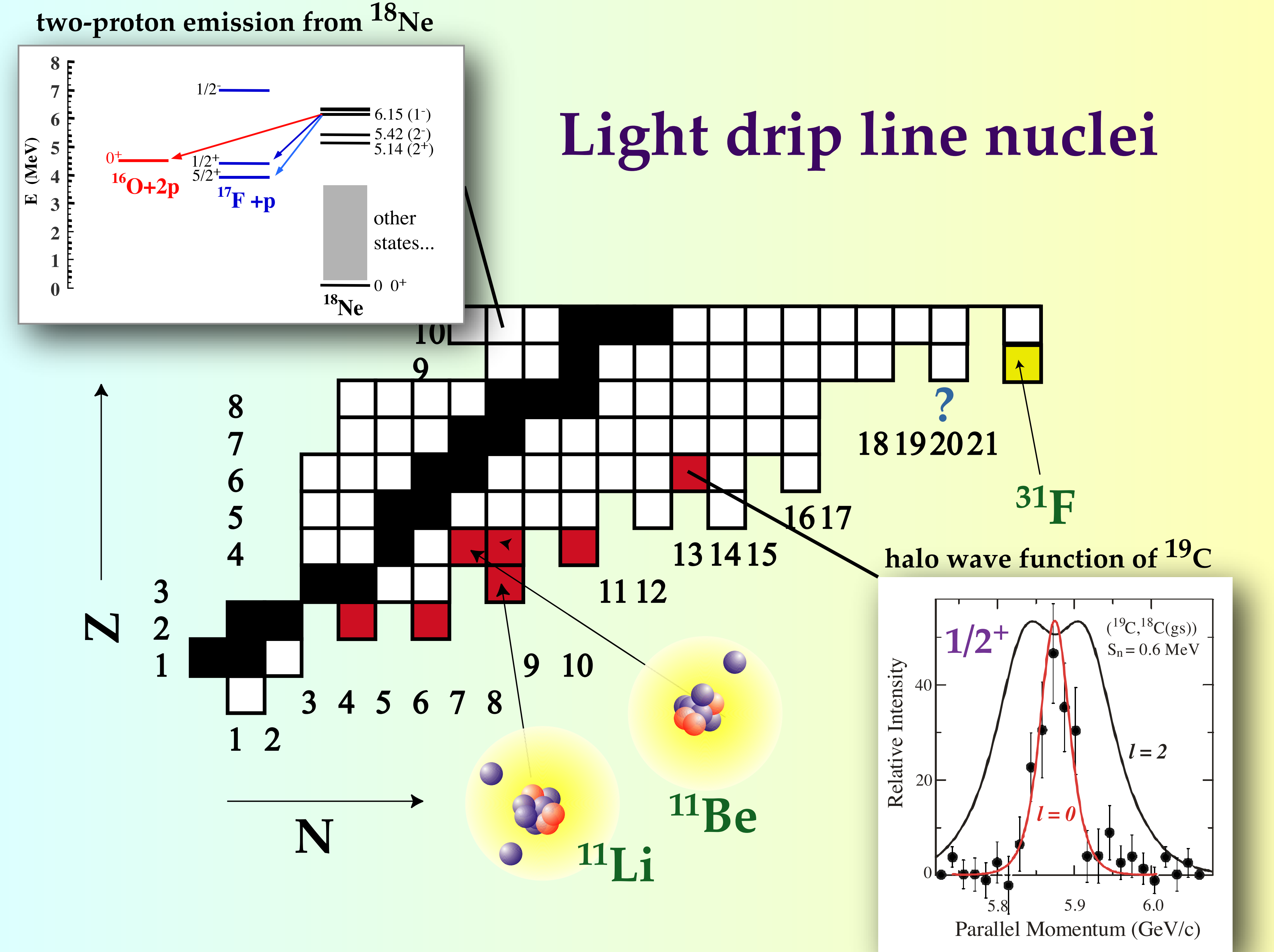


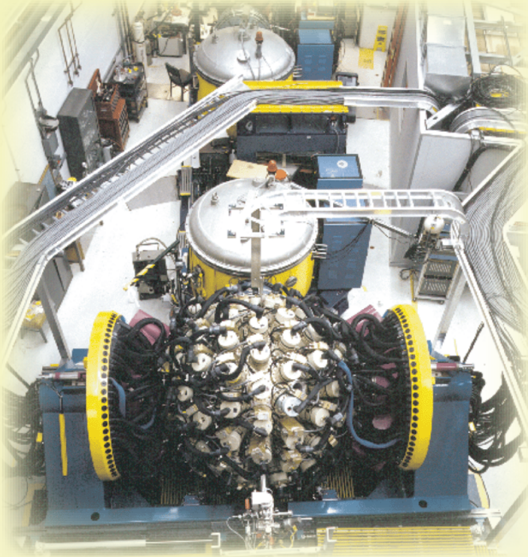
RECENT ACCOMPLISHMENTS (cont.)

Challenging traditional descriptions of the atomic nucleus—Exploration of the unknown regions of the nuclear landscape, toward the limits of nuclear existence, has begun. Studies of exotic nuclei point to drastic alterations of the nuclear shell model, a hallmark of our understanding for half a century. In very heavy nuclei, observations that they can sustain rapid rotation demonstrate unexpected stability against disruptive centrifugal forces and confirm that the path to "superheavy elements" goes through nuclei with deformed shapes. Striking evidence for phase transitional behavior in nuclei has emerged from observations of sudden changes with mass between spherical and deformed systems, and from evidence of changes between liquid and gaseous forms of nucleonic matter. Advances in theory, such as calculations with realistic forces in nuclei containing up to 10 nucleons—an achievement thought impossible just a few years ago—offer the promise of a unified description of the nucleus based on the theory of the strong interaction.

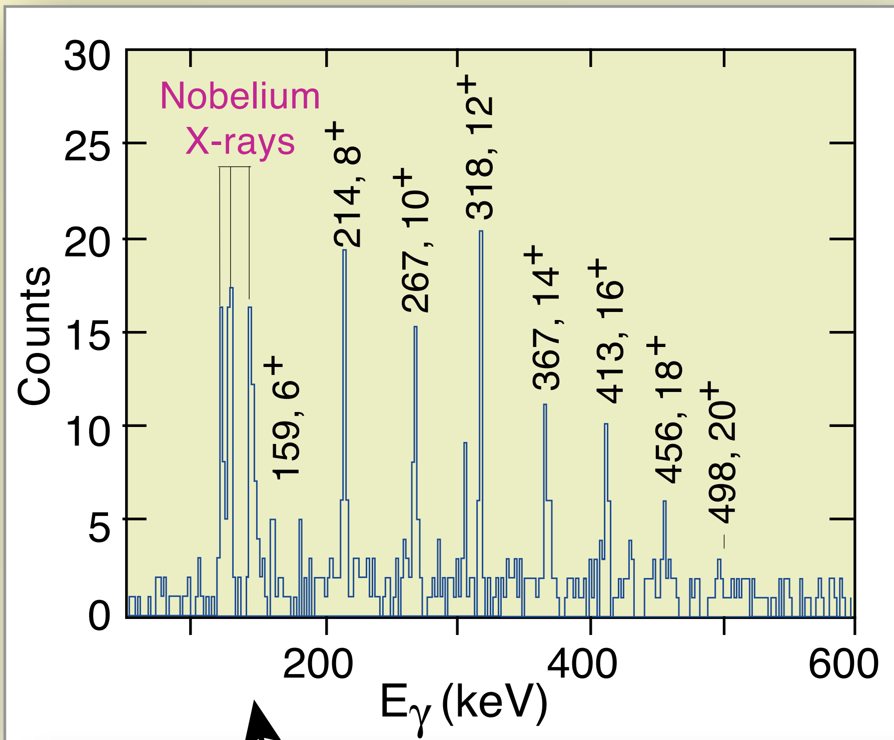
- Shell structure in exotic nuclei. Investigations of nuclear shell structure far from stability are fundamental to our understanding of nuclei and their synthesis within the cosmos. Recent landmark experiments include the observation of the doubly-magic unstable nuclei 48-Ni (Z = 28, N= 20) and 78-Ni (Z = 28, N= 50). In lighter neutron-rich nuclei, spectroscopic studies have demonstrated clear evidence for a reordering of nucleonic shells; for a weakening of the familiar shell closures around N= 8, 20, and 28. First signatures of a new form of pairing have been seen in nuclei with equal numbers of protons and neutrons, and a new decay mode, nonsequential two-proton radioactivity, has been discovered.
- Collective excitations. We gain insight into the properties of nuclei by establishing and studying their basic modes of excitation. Recent advances include the discovery of the first candidates for the new collective modes of chiral rotation and wobbling motion in triaxial nuclei.
- Synthesis, structure, and chemistry of the heaviest elements. The discovery and investigation of the heaviest nuclei test our understanding of which combinations of neutrons and protons can give rise to long-lived superheavy nuclei, and extends the periodic table, fundamental to all of chemistry. The first chemical studies of seaborgium (Z = 106), bohrium (Z = 107), and hassium (Z = 108); and the first in-beam gamma-ray spectroscopy of the trans-fermium nucleus nobelium (Z = 102).

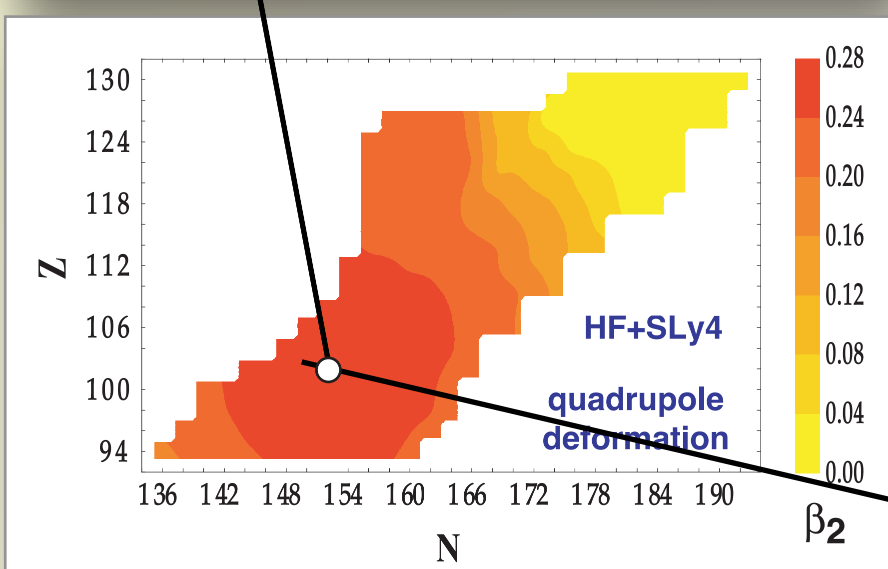
Light drip line nuclei

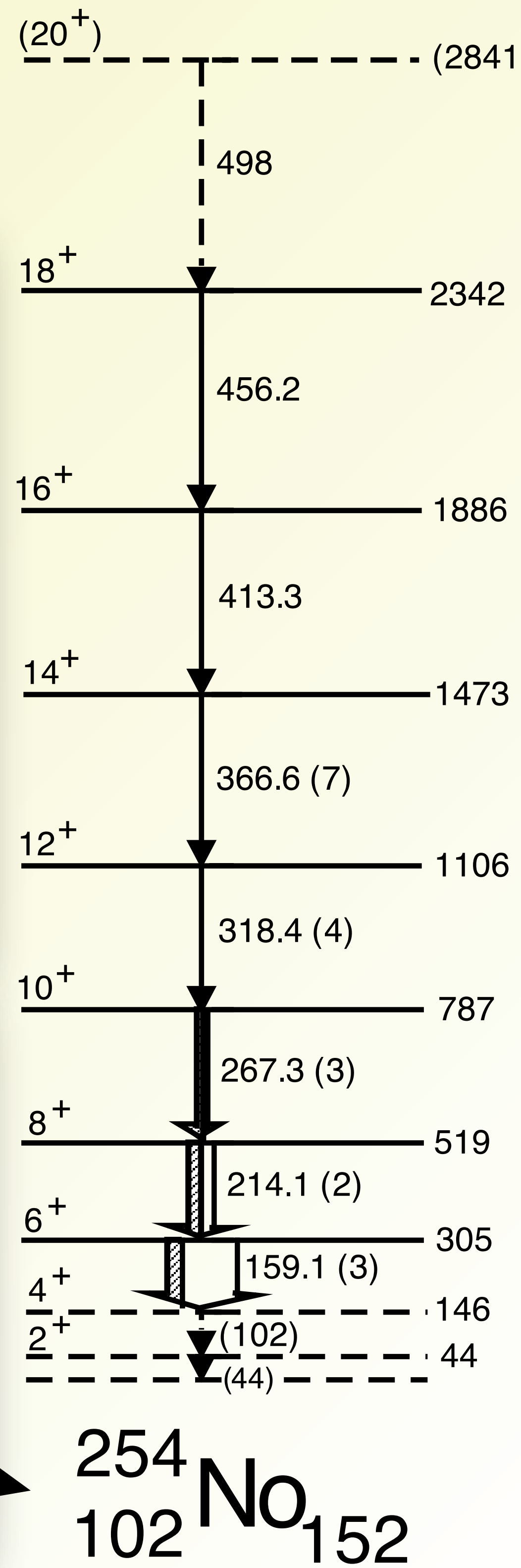




Spinning the heaviest elements at Gammasphere....





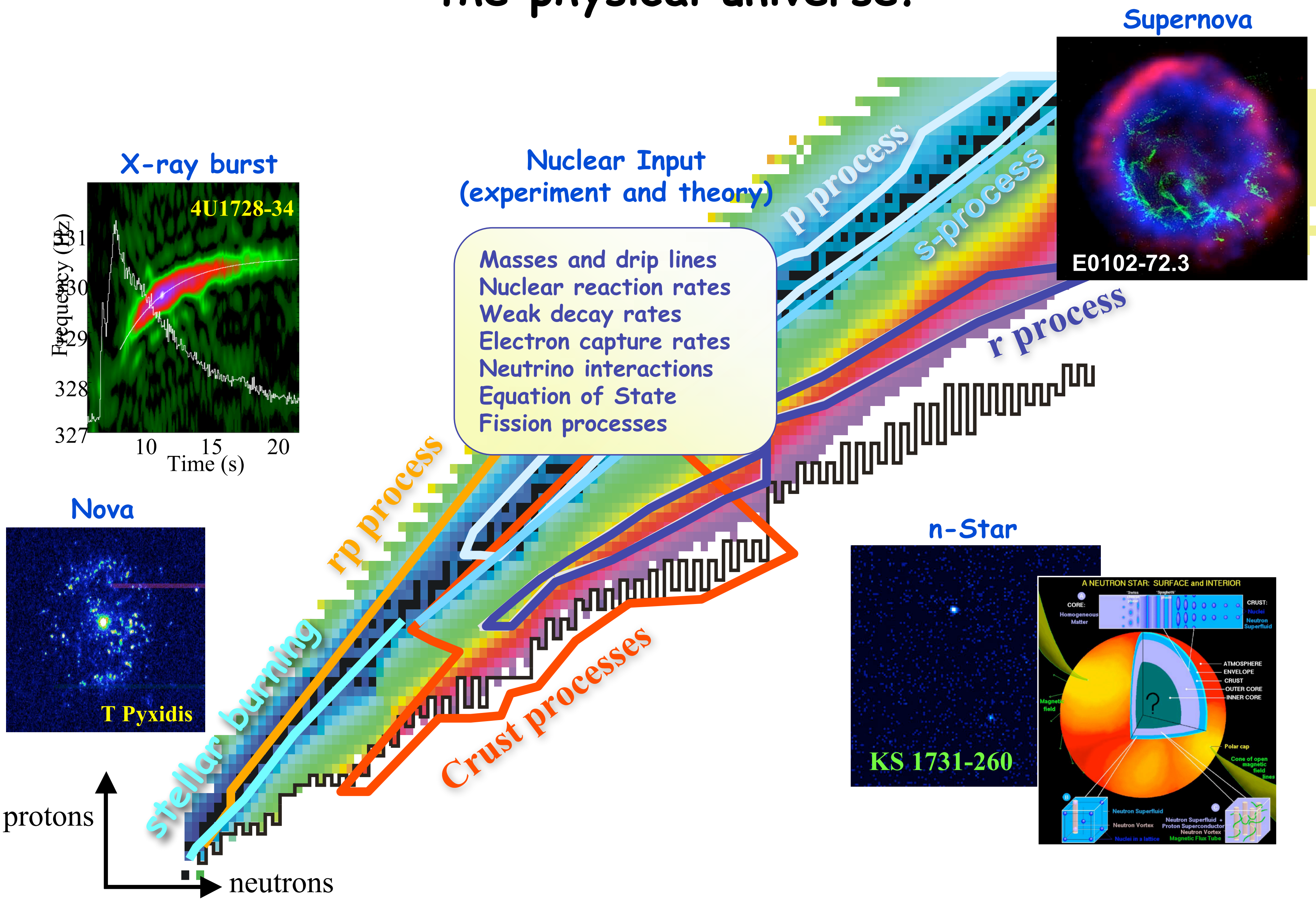


Where and how did the elements from iron to uranium originate?

While we have identified the astrophysical origin of many of the elements, the production site of about half of the elements between iron and uranium remains a perplexing mystery.

Current models suggest a series of rapid neutron captures on rare nuclei having excess neutrons may have occurred in a cataclysmic stellar environment, such as a supernova explosion. However, determining if the synthesis occurs in supernovae or other exotic cosmic locations will require a sophisticated interaction of theory, experiment, and observation. Progress requires significant theoretical advances as well as the production and analysis of rare isotopes well-beyond the reach of current laboratory experiments.

How does the physics of nuclei impact the physical universe?



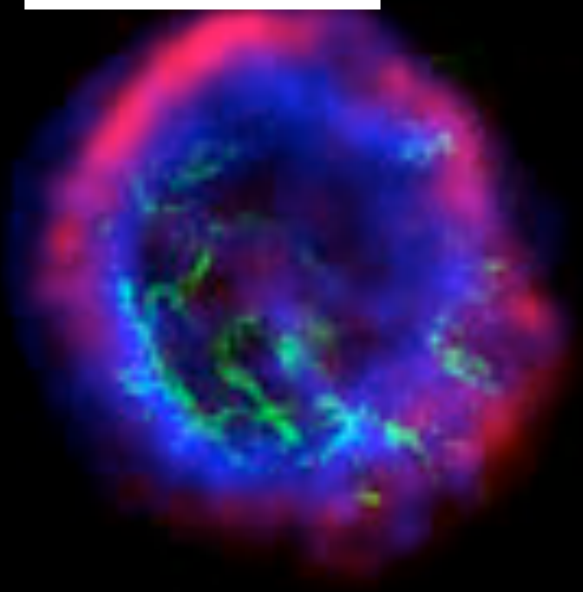
What causes stars to explode?

Thanks to the seminal work of Hans Bethe, we have known for decades that nuclear reactions fuel the evolution of stars.

However, understanding how stars explode and what exotic properties their neutron star remnants retain is still a mystery. New experimental and theoretical tools and techniques are needed to determine the relevant critical nuclear reactions and structure properties. During the past decade, we have also discovered that neutrinos play a major role in defining the fate of stars. Investigating these questions will require a new generation of experiments capable of unraveling the interactions of neutrinos with matter.

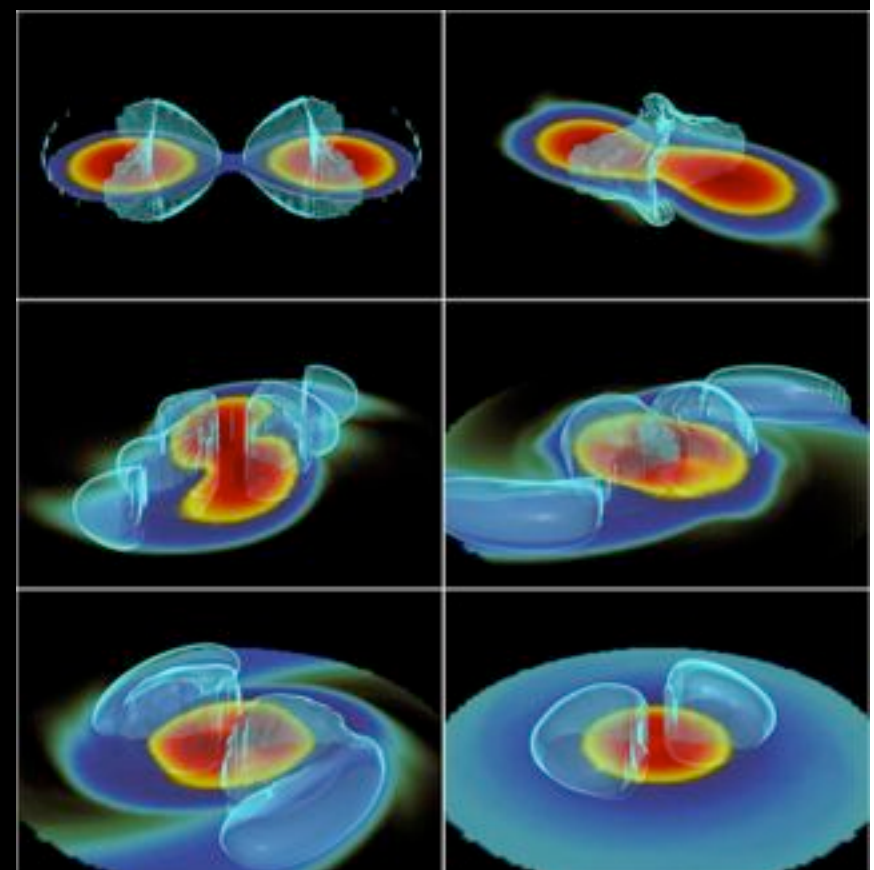
r (apid neutron capture) process

Supernovae ?



The origin of about half of elements > Fe (including Gold, Platinum, Silver, Uranium)

Neutron star mergers ?



Swesty, Calder, Wang

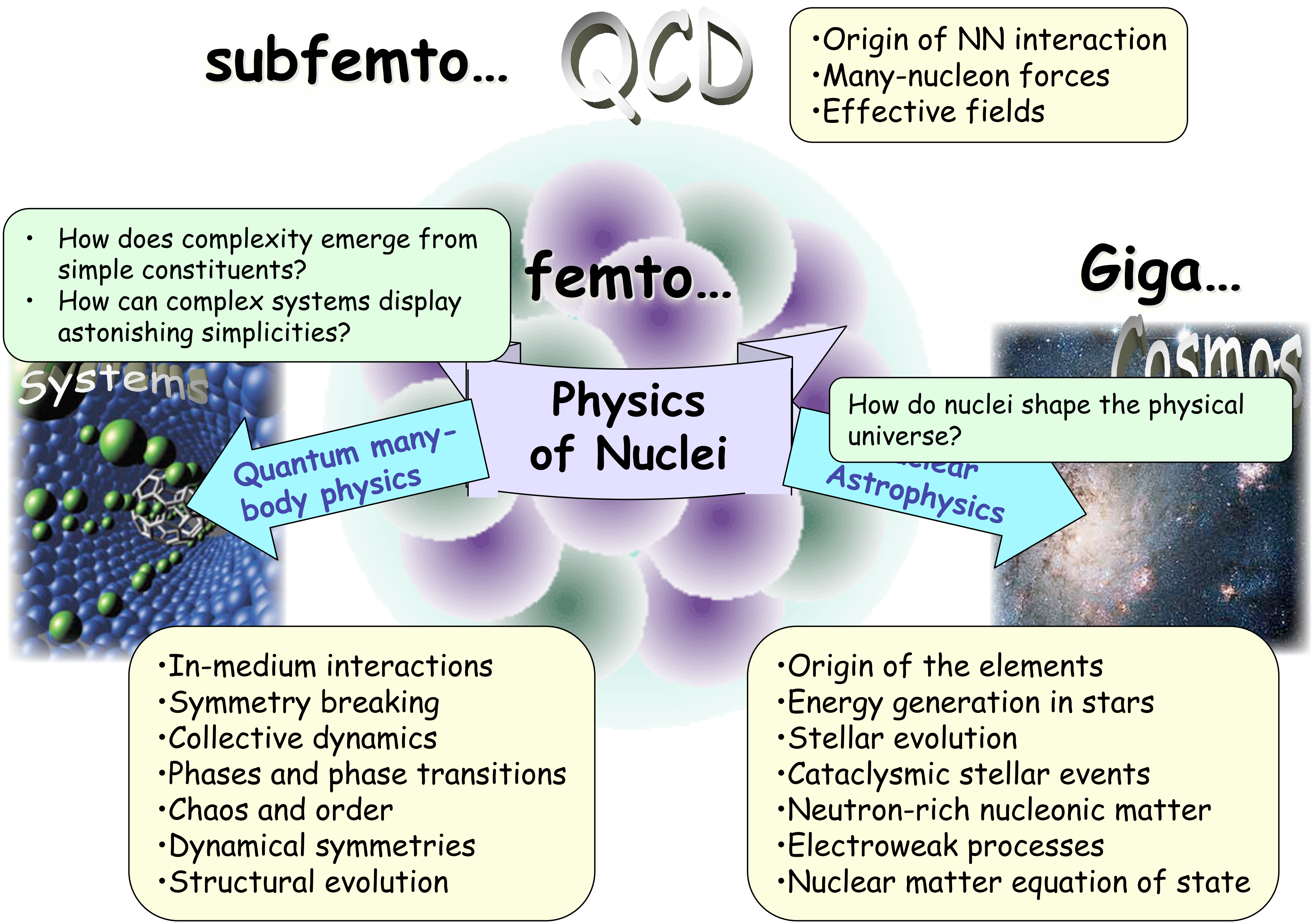
Open questions:

- Where does the r process occur ?
- New observations of single r-process events in metal poor stars
- Can the r-process tell us about physics under extreme conditions ?

RECENT ACCOMPLISHMENTS (cont.)

Probing the origin of the elements and the evolution of stars—Two long-term multidisciplinary efforts to develop standard models of Big Bang nucleosynthesis and of the sun have been validated in remarkable ways: The baryon-to-photon ratio derived from analyses of temperature fluctuations in the cosmic microwave background is in good accord with the Big Bang nucleosynthesis prediction, while the total high-energy solar neutrino flux agrees with the standard solar model prediction. Important advances have also occurred in our understanding of nuclear reactions that govern red giant evolution, novae, and supernovae. Improved measurements of ^{12}C(□,□) set the luminosity for Type Ia supernovae as cosmological candles and define the limits for the final fate of the Type II supernova core as a neutron star or black hole. Finally, nuclear measurements far from stability and a new generation of computational techniques have brought us closer to the identification of the r-process site, or sites, and to quantitative models for the production of the heavy elements.

- Beams of radioactive nuclei have been used to make the first direct measurements of key nuclear reactions driving cataclysmic explosions in binary systems.
- Elegant experiments using stable and radioactive beams have fueled real progress in understanding the capture of alpha particles on 12 C and the capture of protons on 7 Be, which are of prime importance in the evolution of massive stars and in the core of the sun, respectively.
- By use of neutron beams, the fusion rates of neutrons and heavy elements have been newly determined, yielding the first precise confirmation of the theory that tiny grains in some meteorites originate in red giant stars.
- Supernovae has been numerically exploded.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QCD
•Origin of NN interaction
•Many-nucleon forces
•Effective fields
How does complexity emerge from simple constituents?
How can complex systems display astonishing simplicities?
femto...
Giga...
Systems
Cosmos
Physics of Nuclei
Quantum many-body physics
Astrophysics
How do nuclei shape the physical universe?
•In-medium interactions
•Symmetry breaking
•Collective dynamics
•Phases and phase transitions
•Chaos and order
•Dynamical symmetries
•Structural evolution
•Origin of the elements
•Energy generation in stars
•Stellar evolution
•Cataclysmic stellar events
•Neutron-rich nucleonic matter
•Electroweak processes
•Nuclear matter equation of state

Questions: **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?

What are the masses of neutrinos and how have they shaped the evolution of the universe?

We now have clear evidence that neutrinos have mass. Neutrino oscillation experiments tell us about neutrino mass differences, but we do not know the absolute scale. To answer this question, nuclear scientists are building highly sensitive experiments on beta decay of tritium and are developing techniques to measure an extremely rare process—"neutrinoless" double beta decay. Determining the mass scale will address a number of questions in neutrino physics and will help delineate the role of neutrinos in the early evolution of the universe.

- SNO's first result publication now has over 1000 citations
- KamLAND has demonstrated reactor-anti-neutrino disappearance and made the most precise measurements of Δm^2. The results agree with solar-neutrino experiments.
- SNO has validated the theoretical determination of the solar neutrino flux
- KamLAND's determination of Δm^2 has moved us into the age of precision neutrino experiments.
- ….

RECENT ACCOMPLISHMENTS (cont.)

Tracing the missing mass of the universe—Observations of the neutrinos produced in nuclear reactions in the sun have for many years raised doubts about how the sun generates energy: Models of the sun consistently predicted the number of solar neutrinos to be much greater than observed. The solar models were recently vindicated when the SNO and SuperKamiokande experiments found that solar neutrinos change their identity on the way to the Earth, implying that they have mass. This discovery has profound implications: It provides a key to the fundamental structure of the forces of nature, and it shows that neutrinos contribute at least as much mass to the universe as do the visible stars. On the basis of these results, together with measurements of nuclear beta decay, we also now know that neutrinos do not have enough mass to stop the expansion of the universe.

- Oscillations of neutrinos from one type to another have been confirmed as the key to resolving the puzzle of the “missing” solar neutrinos.

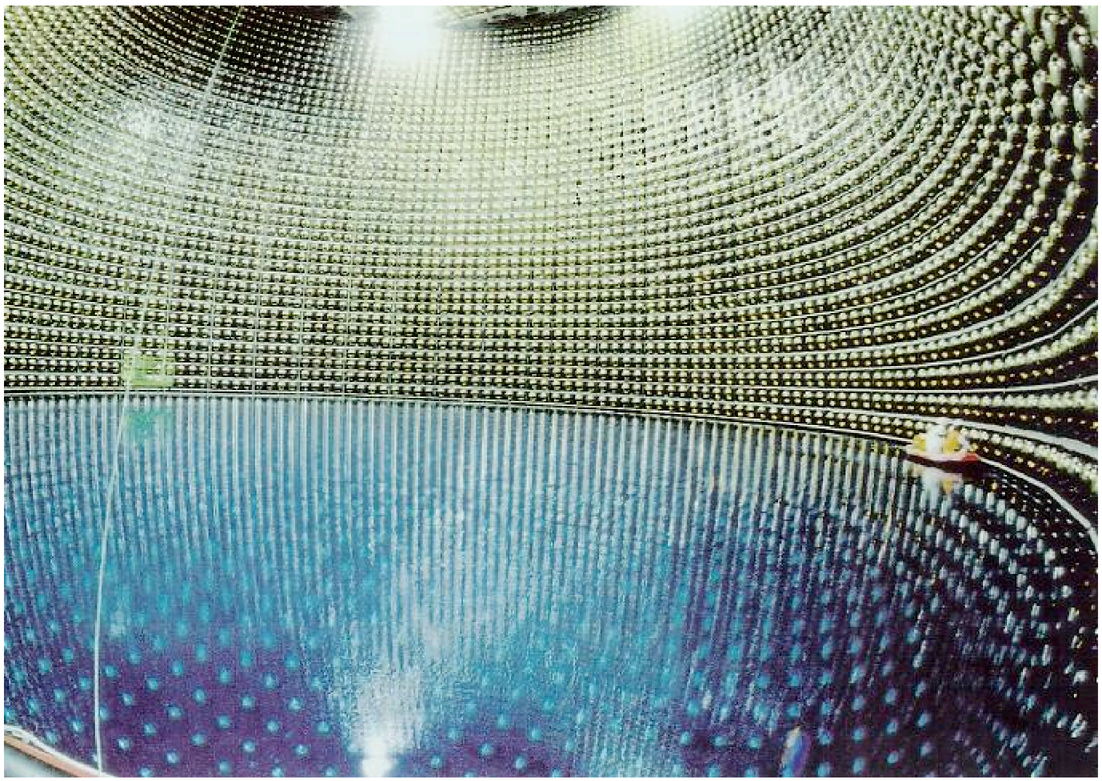
RECENT ACCOMPLISHMENTS (cont.)

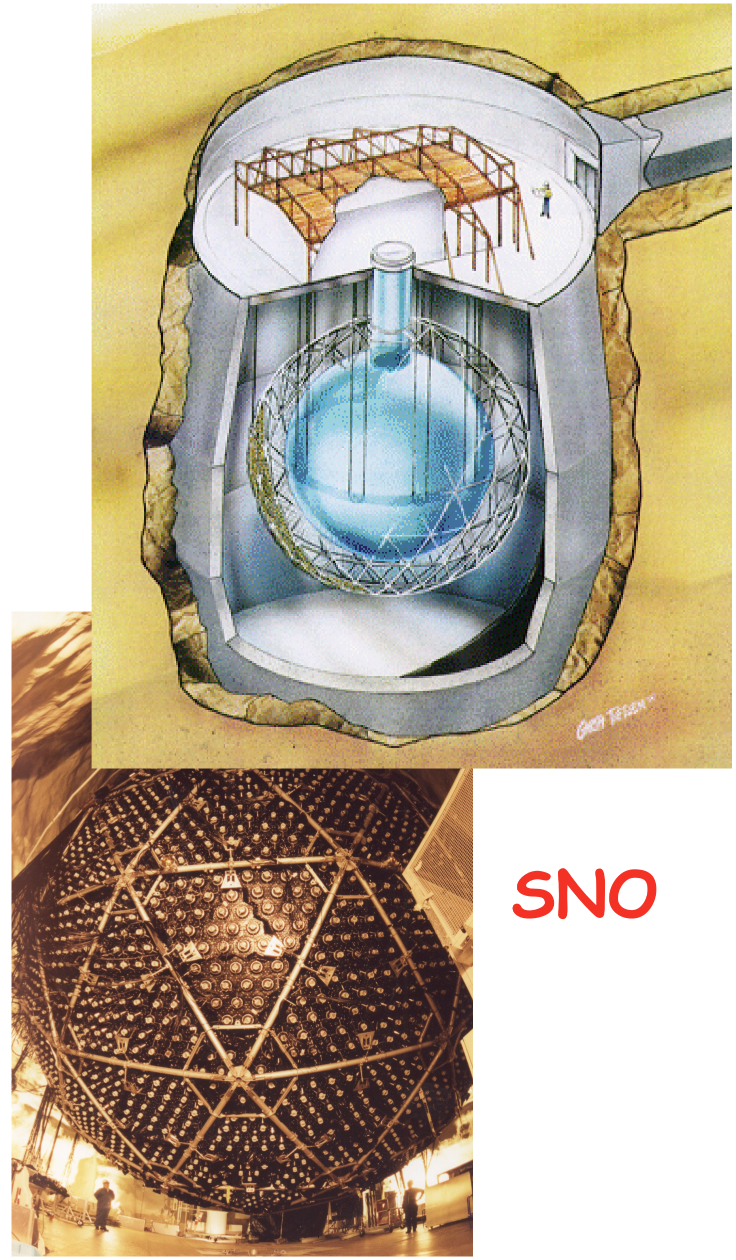
In search of the new Standard Model—The search for a single framework describing all known forces of nature has been something of a Holy Grail in physics. Accordingly, one of the triumphs of late 20th century physics has been the establishment—and experimental confirmation—of such a framework for three of the four fundamental interactions: the electromagnetic, weak, and strong forces. The Standard Model of electroweak and strong interactions has by now been tested with impressive precision (~0.1% for electroweak phenomena). Despite its successes, however, the Standard Model presents some conceptual difficulties, leading physicists to believe that it represents only a piece of a larger, more fundamental theory. For example, gravity remains to be fully incorporated into a framework including the other three forces, though the advent of string theory represents a breakthrough advance in this regard. In addition, the Standard Model itself contains 19 parameters whose origins and magnitudes are not explained by the theory but rather are taken from experiment. Indeed, the vast hierarchy of masses among the known elementary particles is not explained by the Standard Model. Similarly, the Standard Model gives no reason for the quantization of electric charge, the weak interaction's flagrant disrespect for discrete symmetries (parity, P; charge conjugation, C; and time-reversal invariance, T), or the dynamics responsible for the predominance of matter over antimatter in the universe.

- Measurements of the high-energy neutrino flux from the sun, which have demonstrated that the deficit of low-energy neutrinos on Earth is due to neutrino oscillations, implying that neutrinos have mass. This, together with the discovery of atmospheric neutrino oscillations, will require an extension to the Standard Model of fundamental interactions. This discovery also implies that neutrinos contribute at least as much mass to the universe as do the visible stars.
- A precision measurement of the magnetic moment of the muon, which has helped theorists discover an error in the Standard Model calculation and has placed important constraints on Standard Model extensions, such as supersymmetry.
- Dramatic improvements in experiments on nuclear electric dipole moments and double beta decay. These improvements place stringent bounds on violations of time-reversal symmetry and lepton number conservation.

Neutrinos do Oscillate!

Super-Kamiokande

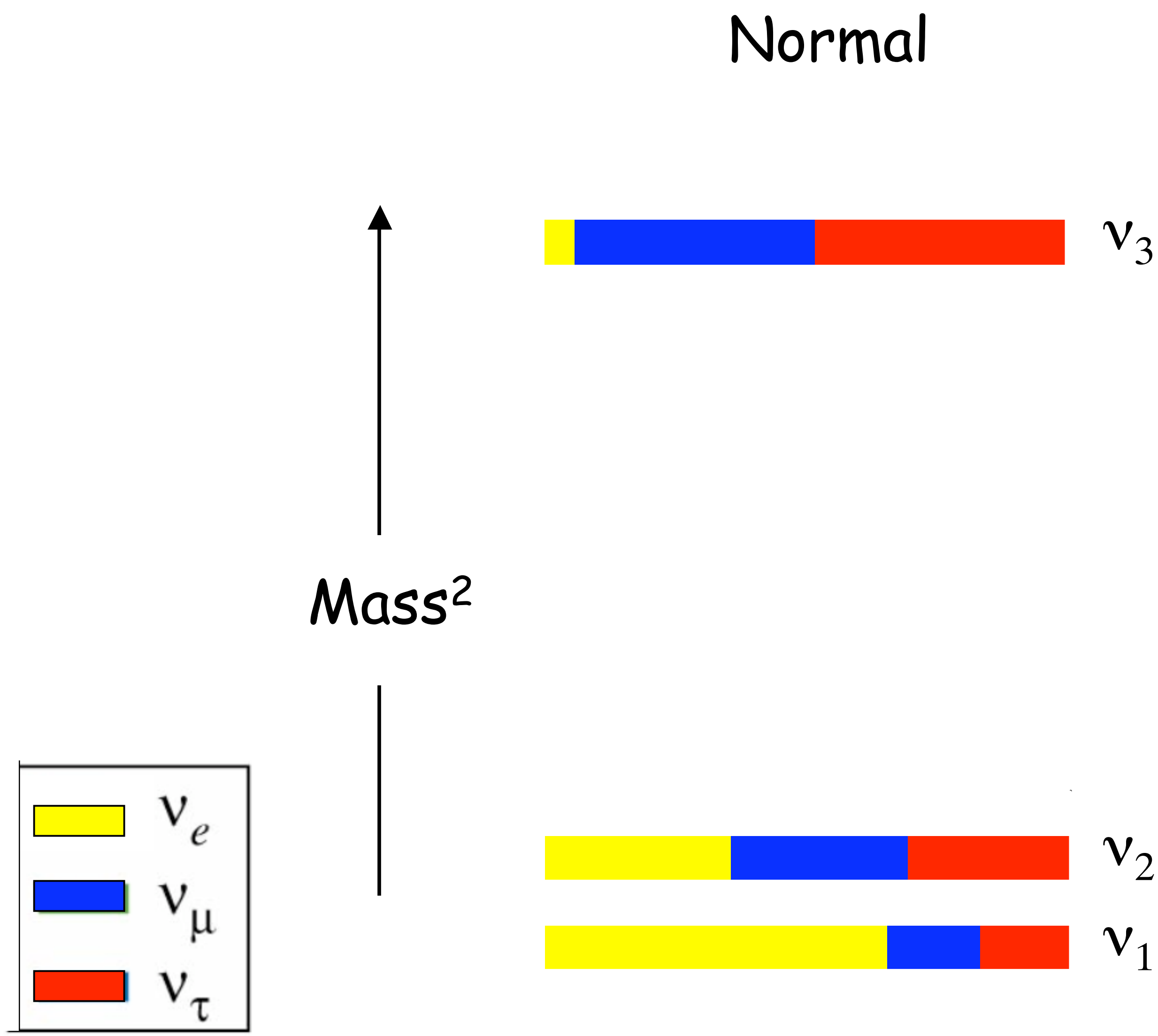




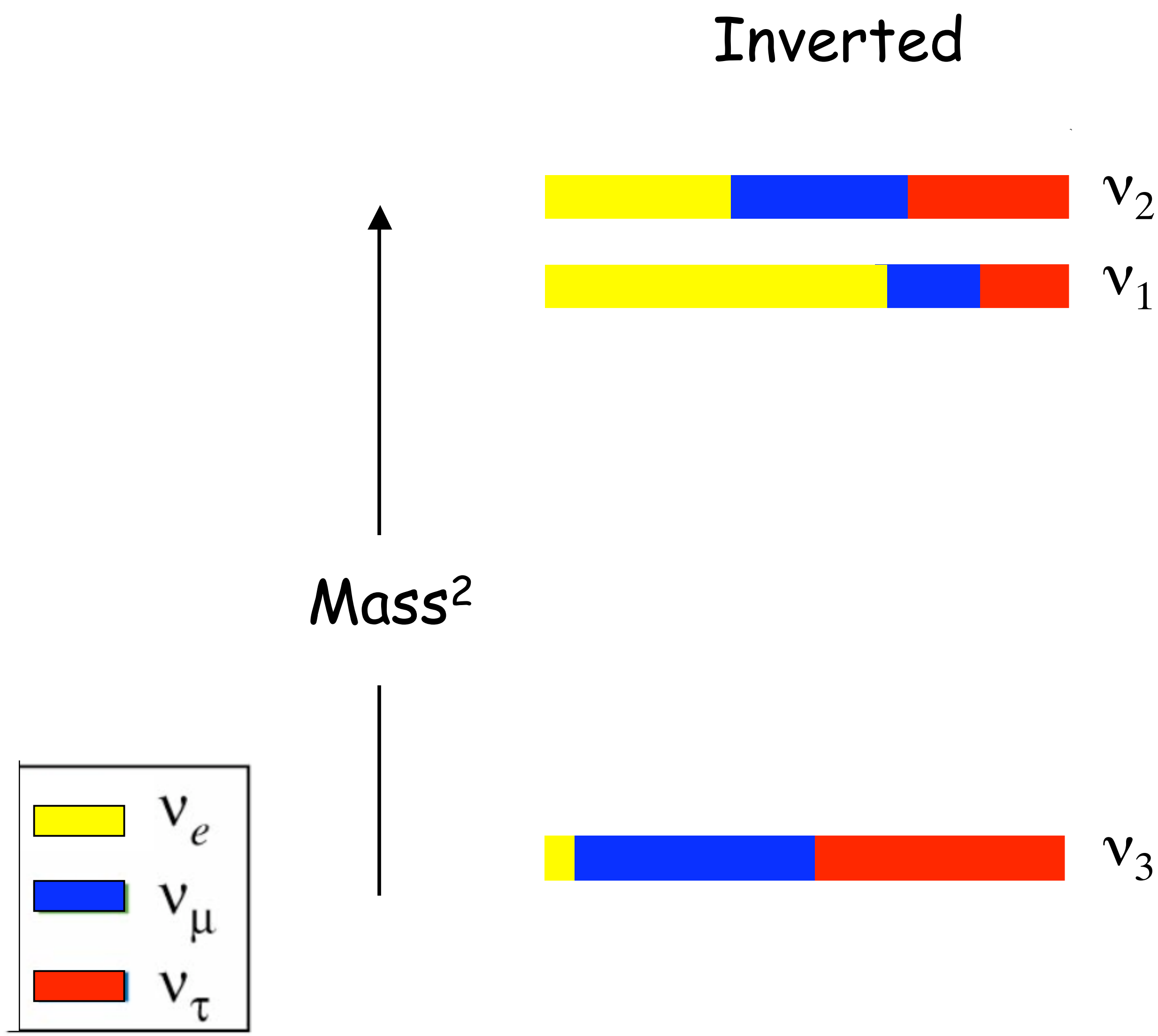
SNO

Cherenkov neutrino Detectors

Neutrino Mass



Neutrino Mass



- What are the masses of the neutrinos?
- What is the pattern of mixing among the various types of neutrinos?
- Are neutrinos their own antiparticles?

Double Beta Decay is the only way we know to discover whether the character of neutrino mass is Majorana or Dirac

Why is there more matter than antimatter?

The very existence of the visible cosmos —from the galaxies to human life itself—implies that the universe contains more matter than antimatter. But the standard model does not explain how this excess matter came to be. If the cosmos had equal amounts of matter and antimatter at its birth, what caused the imbalance as it evolved and cooled? An essential ingredient is the presence of new forces that do not look the same when the direction of time—like a video—is reversed. Nuclear scientists are seeking to discover these time-asymmetric forces with new measurements of properties of neutrons, atoms, and neutrinos.

- Electroweak baryogenesis (EWB) probed by neutron, atom, electron EDM

- Leptogenesis – is the neutrino its own anti-particle (Majorana particle) and CP violation in the neutrino sector

What are the unseen forces that disappeared from view as the universe cooled?

Most of our world is extremely well described by the standard model. But we know that this elegant model is only an incomplete version of a more comprehensive theory that describes forces of nature from the earliest moments of the universe. Both nuclear and particle physicists are searching for indications of what the more complete theory could be. The observation of neutrino oscillations has provided our first direct view of new physics. In addition to studying the properties of neutrinos, nuclear physicists are performing highly precise measurements of other particle properties to look for departures from the firm predictions of the standard model. Such departures would signal the presence of additional, undiscovered forces that played an important role when the universe was young.

- Understand the scale of electroweak symmetry breaking
- Studies of the pattern of neutrino masses and mixing provide a unique window on the symmetries that may be operative at energy scales far beyond the scale of electroweak symmetry breaking
- Perform ultra-precise measurements of electroweak interactions of baryons and leptons – such as the radioactive decay of the neutron, nuclei, and muon or parity-violating electron scattering – and studying the patterns of agreement with, or deviations from, the predictions of the SM