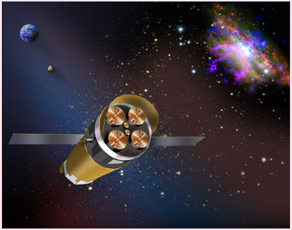
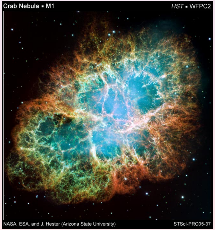
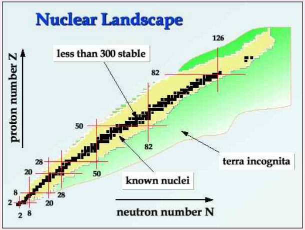
A Tour to the Stars

Some Compelling Questions

- The chemical elements essential for life:
  How did they form? Where did they form?
- Stars:
  How are they born? How do they live? How do they die?
- The stellar graveyard:
  White dwarfs, Neutron stars, Black holes



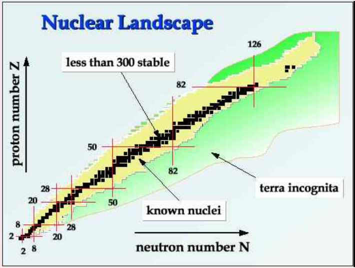


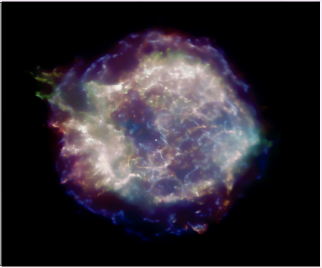


Outline

From NSAC Long Range Plan (Galveston, May 2007)

"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."

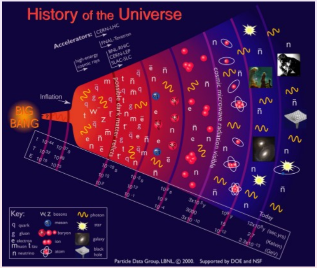


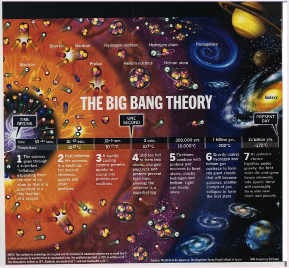


A $500-million facility to be built at MSU

The Big Bang!

- We believe that the Universe was created about 13.6 billion years ago
- We do not understand what happened at the instant of creation!
- H, He, and traces of light elements were formed 3 minutes after creation
- Stars and galaxies form from H and He clouds after about 1 billion years

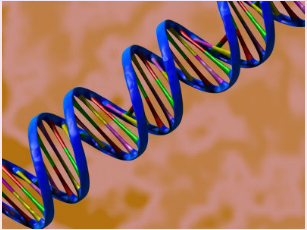


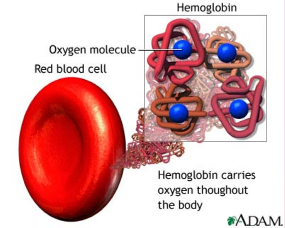


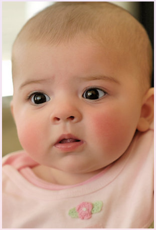
The Solar System is rich in chemical elements other than H and He; how and where did they come from?

The Human Blueprint

- Human beings are carbon-based lifeforms
- Human beings have calcium making our bones
- Human beings have iron running through our blood
- Human beings breath air which is rich in Nitrogen and Oxygen



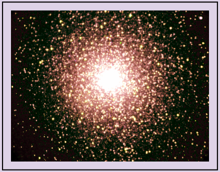




If only Hydrogen and Helium were made in the Big Bang, how and where did the rest of the chemical elements form?

A Star is Born

- A protostar achieves stardom at 10 million K
- Gravitational energy converted into thermal (kinetic) energy
- Protons overcome their Coulomb repulsion and fuse:



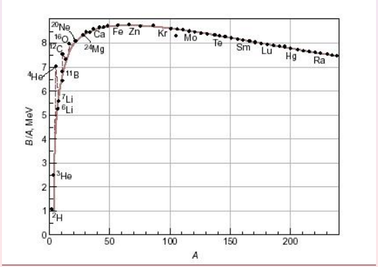
$$p + p \rightarrow d + e^{+} + \nu_e$$
$$p + d \rightarrow {}^{3}He + \gamma$$
$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$$

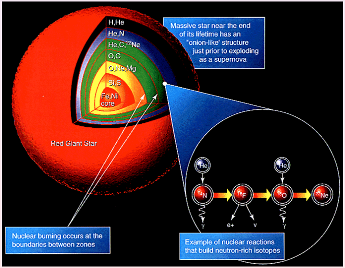
The proton-proton chain:

- **ALL** interactions in nature essential to achieve stardom
- Thermonuclear fusion halts the gravitational collapse
- Stellar evolution continues through several thermonuclear stages

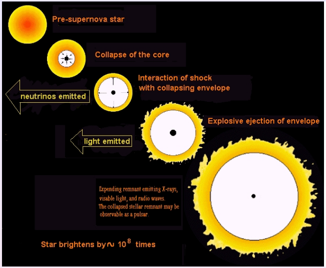
Stellar Nucleosynthesis

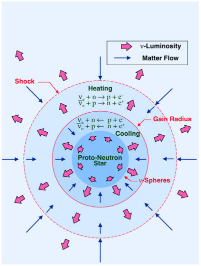
- Stars are incredibly efficient thermonuclear furnaces
  After H-burning terminates the stellar core contracts
  Gravitational energy is transformed into thermal energy
  The heavier He-ashes (with a larger *Z*) can now fuse
- Thermonuclear fusion continues until the formation of an Iron core
  Thermonuclear fusion terminates abruptly
  Every C in our cells, O in the air, and Fe in our blood was made in stars
  We all truly are "star stuff"...*Carl Sagan*





The Core-Collapse Paradigm



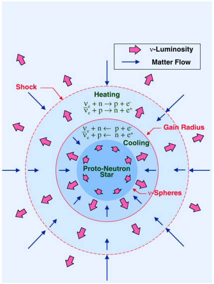


Supernova Explosion!

- Massive stars create all chemical elements: from ^{6}Li to ^{56}Fe
- Once ^{56}Fe is produced, core collapse ensues
- Core overshoots and rebounds: **Supernova!**
- 99% of the gravitational energy radiated in neutrinos

Core-Collapse Supernovae

- Massive stars create all chemical elements from Lithium to Iron
- Once Iron is produced, the very rapid collapse of the core ensues
- As nucleons (mostly neutrons) start to touch, core overshoots and rebounds: **Supernovae Explosion**
- 99% of the gravitational energy of the collapse radiated in neutrinos
- An incredible dense object is left behind: **A neutron star or a black hole**



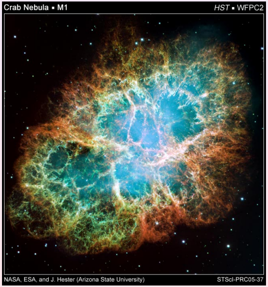
Some Historical Facts

- Chandrasekhar shows that massive stars will collapse (1931)
- Chadwick discovers the neutron (1932)
- Baade and Zwicky introduce the concept of neutron stars (1933)
- Oppenheimer-Volkoff compute masses of neutron stars using GR (1939)
  Predict $M_{\star} = 0.72\ M_{\odot}$ as the maximum mass of a NStar; **WRONG!**
- Jocelyn Bell discovers pulsars (1967)
  PSR 1919+21; $P = 1.33730119\,s$
- Gold and F. Pacini propose basic lighthouse model (1968)

Biography of a Neutron Star: The Crab Pulsar

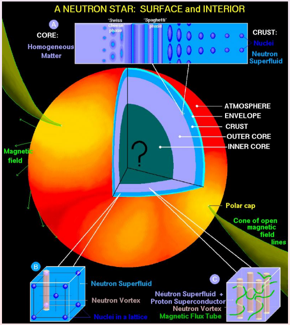
Name: PSR J0534+2200
DOB: 1054 AD
Mass: 1.4 $M_\odot$
Radius: 10 km
Period: 33 ms

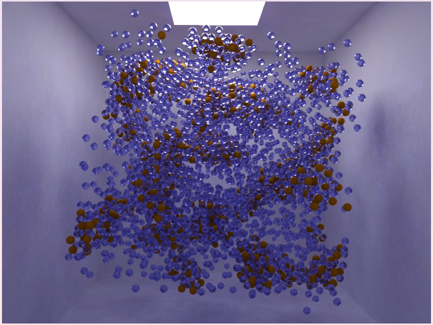
Distance: 6000 ly
POB: Taurus
Temperature: 10^6 K
Density: 10^{14}g/cm^3
Magnetic Field: 10^{12} G



From Crust to Core

- Outer Crust: $10^{-10}\rho_0 \lesssim \rho \lesssim 10^{-3}\rho_0$
  "Coulomb Crystal" of progressively more neutron-rich nuclei
- Inner Crust: $10^{-3}\rho_0 \lesssim \rho \lesssim 10^{-1}\rho_0$
  "Nuclear Pasta" Exotic nuclear shapes immersed in a neutron vapor
- Core: $10^{-1}\rho_0 \lesssim \rho \lesssim 10\rho_0$
  "Fermi Liquid" of uniform neutron-rich matter (*"Exotic Phases?"*)



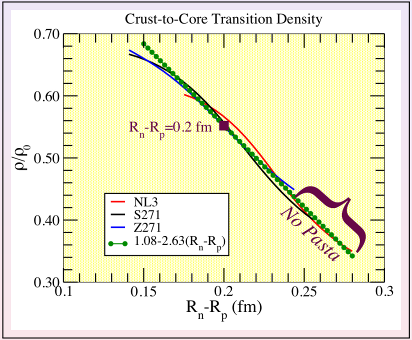


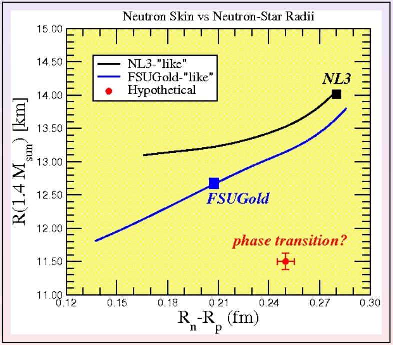
PREx: The Parity Radius Experiment

- A clean measurement of the neutron distribution in Lead
- JLAB Parity-violating elastic electron scattering: March 2010

Heaven on Earth: Three Examples

- Transition density from uniform core to non-uniform crust
- Radius of a $M_\star = 1.4\ M_\odot$ neutron star
- Enhanced cooling through the nucleon direct URCA process

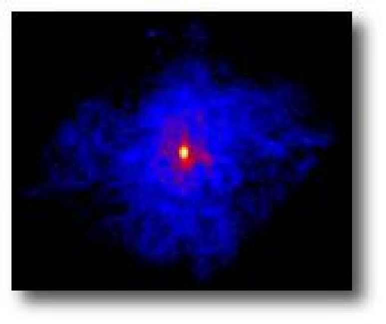




- Transition density largely model independent
- Large neutron skin and small neutron radius: phase transition?

Enhanced vs Minimal Cooling of Neutron Stars: Quark Stars?

- Core-collapse supernovae generates hot (proto) neutron star $T \simeq 10^{12}\mathrm{K}$
- Neutron stars cool promptly by ν-emission (URCA) $n \to p + e^{-} + \bar{\nu}_e \ldots$
- Direct URCA process cools down the star until $T \simeq 10^{9}\mathrm{K}$
- Inefficient modified URCA takes over $(n) + n \to (n) + p + e^{-} + \bar{\nu}_e \ldots$



- Neutrino "enhanced" cooling possible in exotic quark matter
- **Unless ...** symmetry energy is stiff: large $Y_p \Leftrightarrow$ large neutron skin

Have We Discovered Quarks Stars?

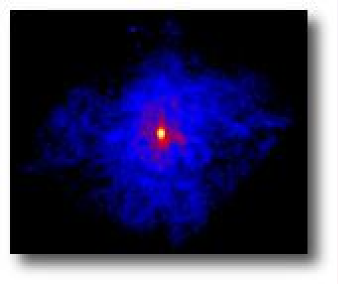
NASA National Aeronautics and Space Administration

News Release Marshall Space Flight Center - Huntsville, Ala. 35812
http://www.msfc.nasa.gov/news

For Release: April 10, 2002

Release: 02-082

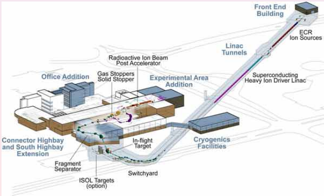
Cosmic X-rays reveal evidence for new form of matter

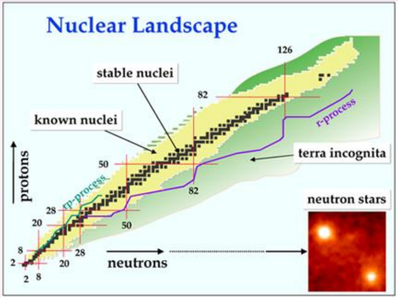


- If experiment gives $R_n - R_p \lesssim 0.18$ fm ...
- Then the pulsar in 3C58 may indeed be a quark star

Scientific Opportunities with a Rare-Isotope Facility in the US

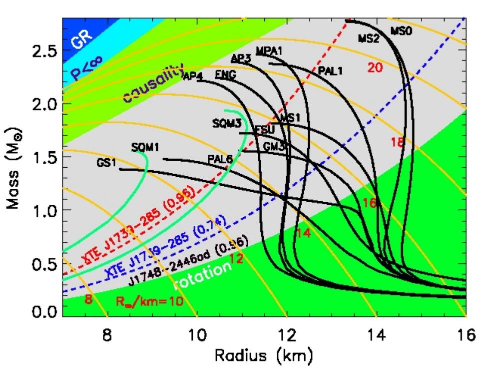
- **Nuclear astrophysics**. A FRIB would lead to a better understanding of nuclear astrophysics by creating exotic nuclei that, until now, have existed only in nature's most spectacular explosion, the supernova. A FRIB would offer new glimpses into the origin of the elements, which are produced mostly in processes very far from nuclear stability and which are barely within reach of present facilities. A FRIB would also probe properties of nuclear matter at extreme neutron richness similar to that found in neutron star crusts (www.nap.edu/catalog/11796.html).





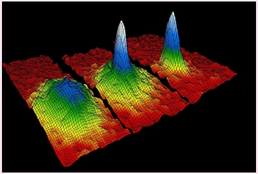
The Present: Where Are We?

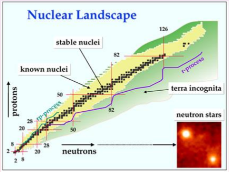
- Remarkable theoretical progress: Effective Field Theory, Density Functional Theory, Ab-initio Calculations, Path Integral Monte Carlo, ...
- Remarkable experimental progress: Nuclear Structure of Exotic Nuclei, Heavy-Ion Collisions, Cold Fermionic Atoms, ...
- Remarkable observational progress with the deployment of multi-wavelength telescopes: Hubble, Chandra, XMM-Newton, ...

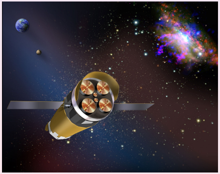


The Future: Where Do We Go?

- The Physics of neutron stars constitutes a goldmine of problems in atomic, nuclear, particle, and condensed-matter physics ...
- Fermionic superfluidity with unbalanced spin populations
- Atomic "engineering" of exotic quantum states (tuning a)
- FRIB: The future of nuclear structure (exotic nuclei)
- Constellation-X: The future of X-ray astronomy





It is all connected ...