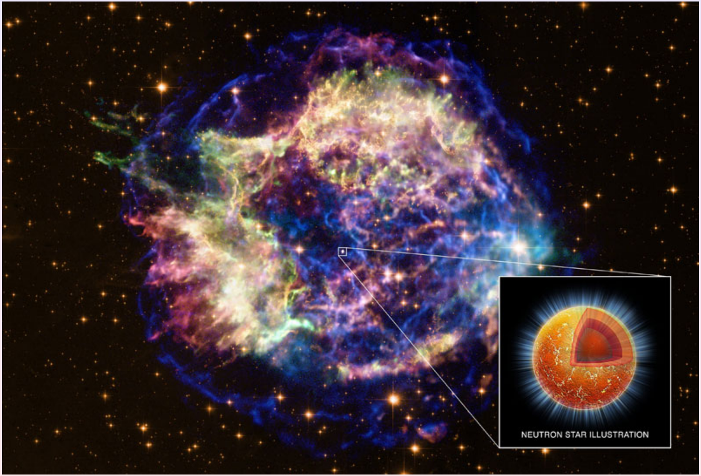
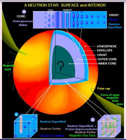
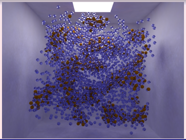
Neutron Stars as Physics Gold Mines

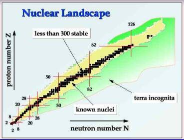


Cassiopeia A: Chandra's First Light

1. **Postdocs**
   - Genaro Toledo-Sanchez (UNAM, México)
   - Karim Hasnaoui
2. **Graduate Students**
   - Bonnie Todd-Rutel (Raising a family)
   - Brad Futch (Lightbox Interactive; game programmer)
   - Jutri Taruna (Concordia College, MN)
   - Farrukh Fattoyev (Texas A&M, Commerce)
   - Wei-Chia Chen
   - Raditya Utama
3. **Undergraduate Students (UROP)**
   - Kaelyn Badura
   - Aaron Magilligan
   - Jennifer Ranta
   - Cornelius van Wyk





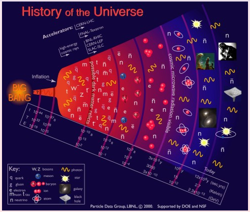


A Star is Born

- The Universe was created about 13.7 billion years ago (Big Bang!)
- H, He, and traces of light elements formed 3 minutes after the Big Bang (BBN)
- Stars and galaxies form from H and He clouds about 1 billion years after BB
- In stellar nurseries molecular clouds convert gravitational energy into thermal energy
- At about 10 million K protons overcome their Coulomb repulsion and fuse (pp chain)

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

- **ALL** (gravity, strong, electroweak) interactions critical to achieve stardom
- Thermonuclear fusion halts the gravitational collapse
- Stellar evolution continues through several thermonuclear stages



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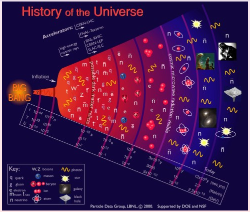

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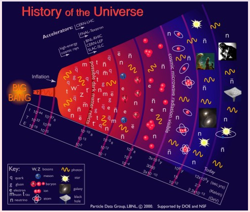

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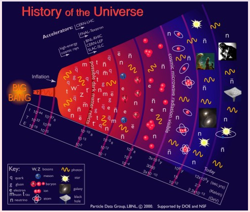

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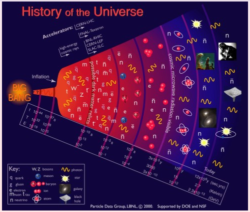

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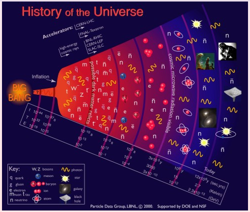
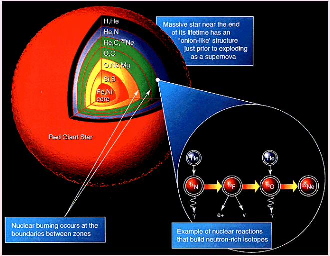
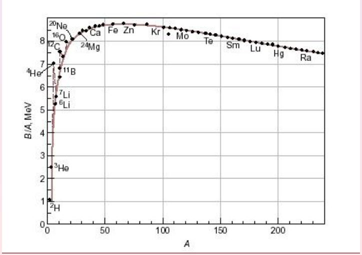


Stellar Nucleosynthesis

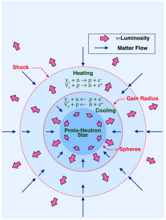
- Stars are incredibly efficient thermonuclear furnaces
  After H-burning terminates the stellar core contracts
  Gravitational energy is transformed into thermal energy
  The heavier He-ashes (with a larger Z) can now fuse
- Thermonuclear fusion continues until the formation of an Iron core
  Thermonuclear fusion terminates abruptly: Supernova!
  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*

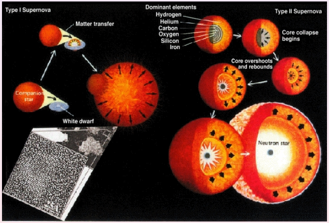




Death of a Star — Birth of a Pulsar: Core-Collapse Supernova

- Massive stars create all chemical elements: from ^{6}Li to ^{56}Fe
- Once ^{56}Fe is produced the stellar core collapses
- Core overshoots and rebounds: Core-Collapse Supernova!
- 99% of the gravitational energy radiated in neutrinos
- An incredibly dense object is left behind: A neutron star or a black hole





Neutron stars are solar mass objects with 10 km radii

Core collapse mechanism and r-process site remain uncertain!

S. Chandrasekhar and X-Ray Chandra

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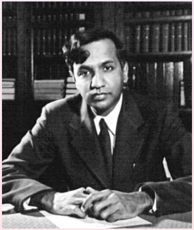

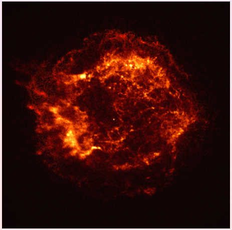
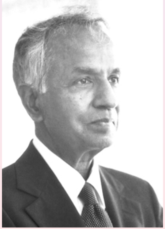

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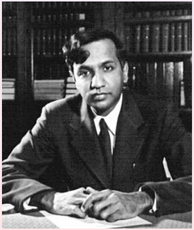

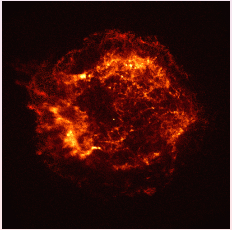
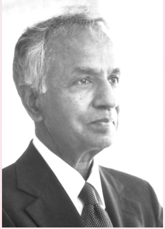

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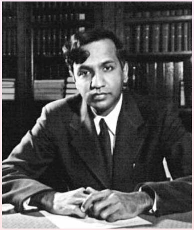

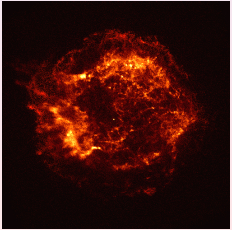
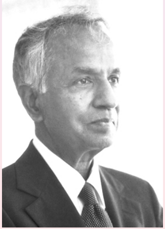

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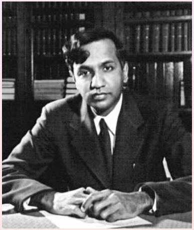

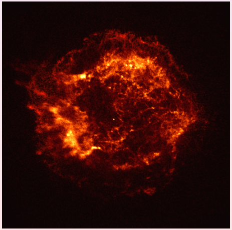
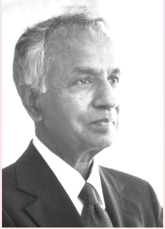

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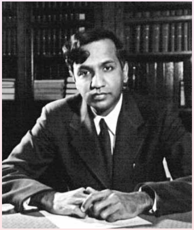

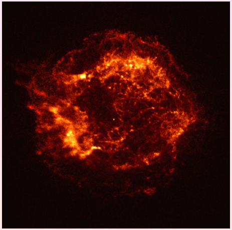
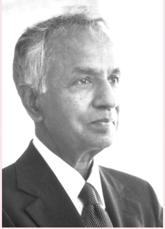

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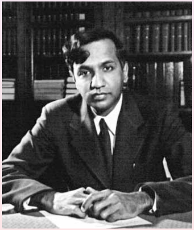

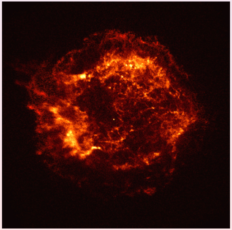
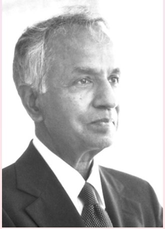

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- Chadwick discovers the neutron (1932)
  ... predicted earlier by Ettore Majorana but never published!
- Baade and Zwicky introduce the concept of neutron stars (1933)
- Oppenheimer-Volkoff compute masses of neutron stars using GR (1939)
  Predict $M_{\star} \simeq 0.7\, M_{\odot}$ as maximum NS mass or minimum black hole mass
- Jocelyn Bell discovers pulsars (1967)
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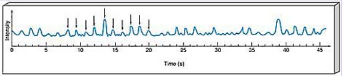
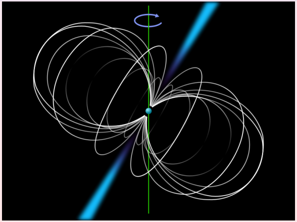
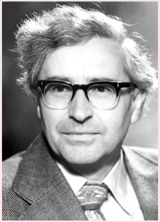
Jocelyn Bell

- Worked with Anthony Hewish on constructing a radio telescope to study quasars
- In 1967 as a graduate student (at the age of 24!) detected a bit of "scruff"



- Jocelyn Bell discovers amazing regularity in the radio signals ($P = 1.33730119\,s$)
- Speculated that the signal might be from another civilization **(LGM-1)**
- Paper announcing the first pulsar published in Nature (February 1968)
  A Hewish, S J Bell, J D H Pilkington, P F Scott, R A Collins
- Antony Hewish and Martin Ryle awarded the Nobel Prize in Physics in 1974
- The "No-Bell" roundly condemned by many astronomers (Fred Hoyle)
- *"I believe it would demean Nobel Prizes if they were awarded to research students, except in very exceptional cases, and I do not believe this is one of them"*

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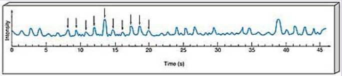

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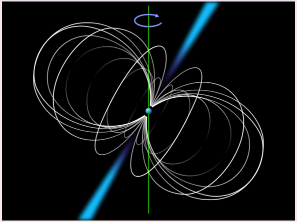
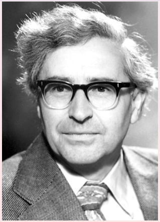

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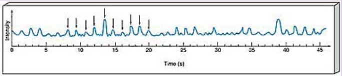

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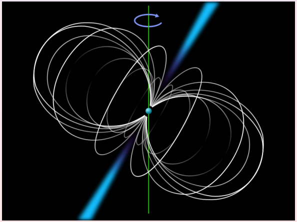

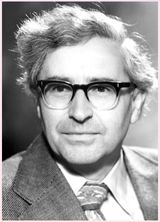

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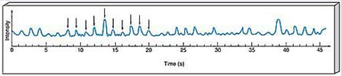

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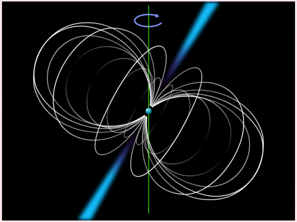

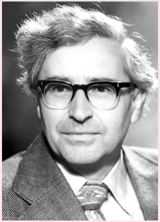

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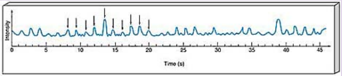

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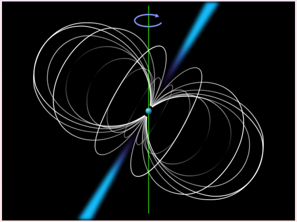
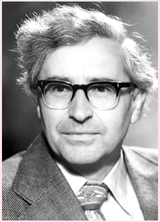

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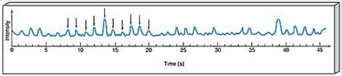

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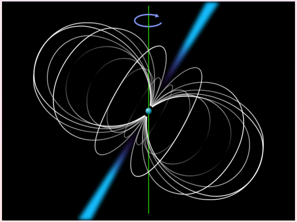
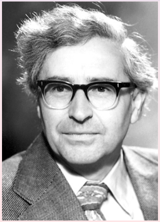

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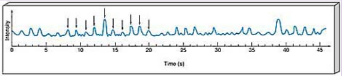

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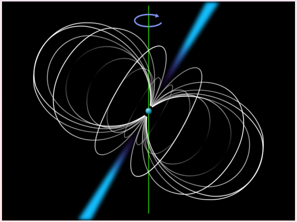
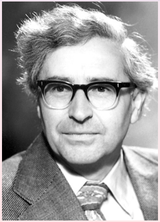
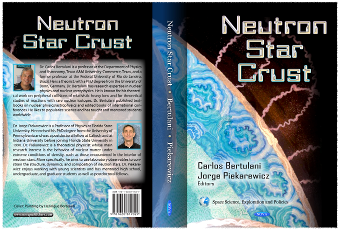



Neutron Star Crust: Preface by Jocelyn Bell



Jocelyn Bell Burnell *
University of Oxford, Denys Wilkinson Building
Keble Road, Oxford OX1 3RH, UK

I judge myself fortunate to be working in an exciting and fast moving area of science and at a time when the public has become fascinated by questions regarding the birth and evolution of stars, the nature of dark matter and dark energy, the formation of black holes and the origin and evolution of the universe.

The physics of neutron stars is one of these fascinating subjects. Neutron stars are formed in supernova explosions of massive stars or by accretion-induced collapse of smaller white dwarf stars. Their existence was confirmed through the discovery of radio pulsars during my thesis work in 1967. Since then this field has evolved enormously. Today we know of accretion-powered pulsars which are predominantly bright X-ray sources, rotation-powered pulsars observed throughout the electromagnetic spectrum, radio-quiet neutron stars, and highly magnetized neutron stars or magnetars. No wonder there has been an explosion in the research activity related to neutron stars!

It is now hard to collect in a single book what we already know about neutron stars along with some of the exciting new developments. In this volume experts have been asked to articulate what they believe are the critical, open questions in the field. In order for the book to be useful to a more general audience, the presentations also aim to be as pedagogical as possible.

This book is a collection of articles on the neutron stars themselves, written by well-known physicists. It is written with young researchers as the target audience, to help this new generation move the field forward. The invited authors summarize the current status of

*j.bellburnell@physics.ox.ac.uk

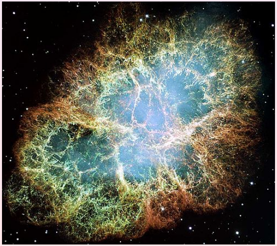
Table of Contents

Biography of a Neutron Star: The Crab Pulsar

- SN 1054 first observed as a new *"star"* in the sky on July 4, 1054
- Event recorded in multiple Chinese and Japanese documents
- Event also recorded by Anasazi residents of Chaco Canyon, NM
- Crab nebula and pulsar became the SN remnants

Name: PSR B0531+21
POB: Taurus
Mass: 1.4 $M_\odot$
Radius: 10 km
Period: 33 ms

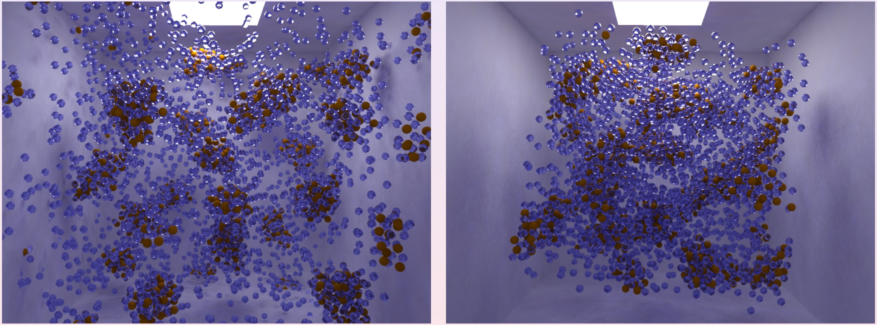
Distance: 6,500 ly
Temperature: 10^6 K
Density: 10^{14}g/cm^3
Pressure: 10^{29} atm
Magnetic Field: 10^{12} G



A Grand Challenge: How does subatomic matter organize itself?

"Nuclear Physics: Exploring the Heart of Matter" **(2010 Committee on the Assessment and Outlook for Nuclear Physics)**

- Consider nucleons (A) and electrons (Z) in a volume V at $T \equiv 0$
- Enforce charge neutrality $protons = electrons + muons$
- Enforce conservation laws: Charge and Baryon number
  $n \to p + e^- + \bar{\nu}$ (beta decay) $\quad p + e^- \to n + \nu$ (electron capture)

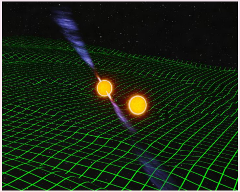


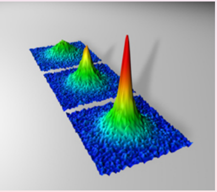
Impossible to answer such a question under normal laboratory conditions — as such a system is in general unbound!

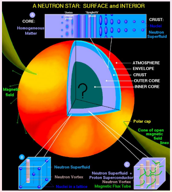
Solution: Gravitationally Bound Neutron Stars

- Neutron Stars are bound by gravity NOT by the strong force
  Binding Energy/nucleon $\sim$ 100 MeV (neutron matter is unbound!)
- Gravity is the catalyst for the formation of novel states of matter
  Coulomb (“Wigner”) crystal of neutron-rich nuclei
  Coulomb frustrated pasta structures
  Strange quark matter, meson condensates, color superconductors
- None of these exotic states can be produced in the laboratory!

Neutron stars are the natural meeting place of astrophysics, general relativity, atomic, nuclear, particle, and condensed-matter physics.

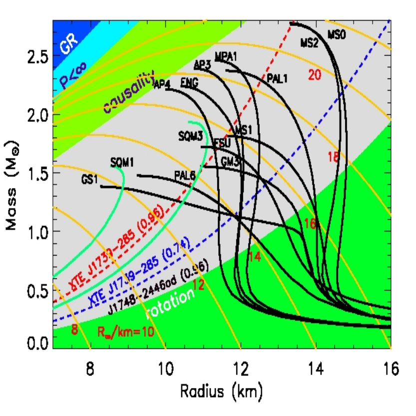






Neutron Stars as Nuclear Physics Gold Mines

- Neutron Stars satisfy the Tolman-Oppenheimer-Volkoff equation
  General-Relativistic extension of Newtonian gravity
  $\sqrt{R_{\rm s}/R_{\star}} = v_{\rm esc}/c \sim 1/2$
- Only Physics sensitive to is: **Equation of State**
- EOS must span 10-11 orders of magnitude in baryon density



$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

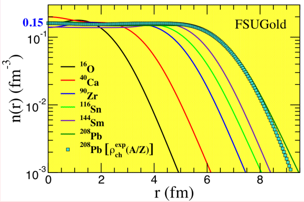
Need an $\mathcal{E}$ *vs* P relation!

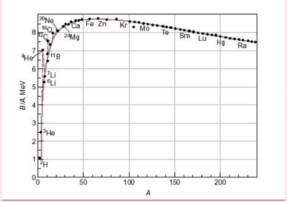
NP-101: Bethe-Weizsäcker Mass Formula (*circa* 1935-36)

- Nucleus as two (proton/neutron) quantum drops
- Nuclear forces saturate ⇒ equilibrium density
- Nuclei penalized for developing a surface
- Nuclei penalized by the Coulomb repulsion
- Nuclei penalized if $N \neq Z$
- $B(Z,N) = -a_{\rm v} A + a_{\rm s} A^{2/3} + a_{\rm c} Z^2/A^{1/3} + a_{\rm a} (N-Z)^2/A + \ldots$
  $+$ **shell corrections** $(2, 8, 20, 28, 50, 82, 126, \ldots)$

$$a_{\rm v} \simeq 16.0,\ a_{\rm s} \simeq 17.2,\ a_{\rm c} \simeq 0.7,\ a_{\rm a} \simeq 23.3 \text{ (in MeV)}$$

Neutron stars are gravitationally bound ($a_{\rm v} < a_{\rm a}$)





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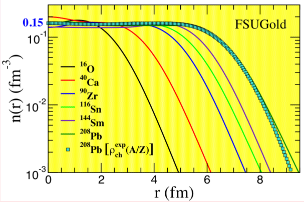

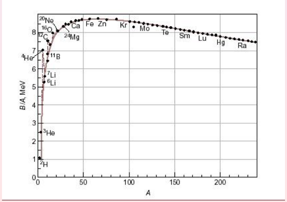

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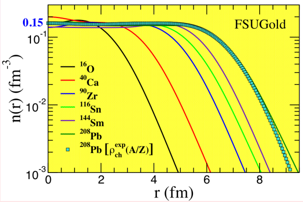

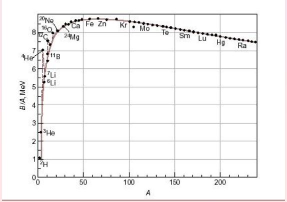

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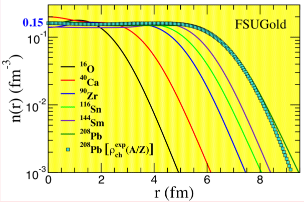

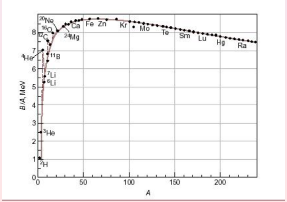

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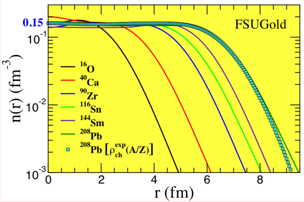

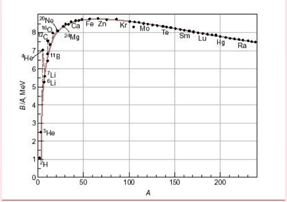

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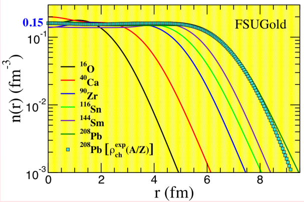
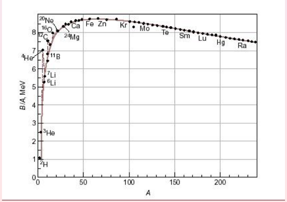
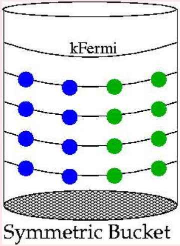
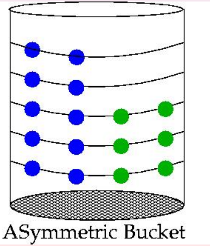


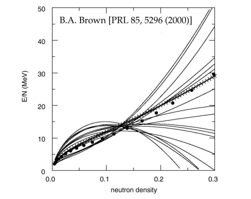


Neutron Radii and the Symmetry Energy

- Neutron densities still uncertain after more than 80 years
  Poor understanding of the symmetry energy/pure neutron matter
- Penalty for breaking $N=Z$ symmetry
  Symmetry Energy ≈ PNM - SNM $[B(Z,N) = -a_a(N-Z)^2/A + \ldots]$
  Slope (pressure) of pure neutron matter poorly constrained
- **Neutron skin** strongly correlated to the pressure of pure neutron matter
- Pressure of PNM pushes against surface tension ⇒ neutron skin
- Pressure of PNM pushes against gravity ⇒ neutron-star radius
- **The larger the neutron skin, the larger the neutron-star radius!!**







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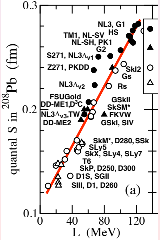

Neutron Radii and the Symmetry Energy

- Neutron densities still uncertain after more than 80 years
  Poor understanding of the symmetry energy/pure neutron matter
- Penalty for breaking $N=Z$ symmetry
  Symmetry Energy $\approx$ PNM - SNM $\quad [B(Z,N) = -a_{\rm a}(N-Z)^2/A + \ldots]$
  Slope (pressure) of pure neutron matter poorly constrained
- **Neutron skin** strongly correlated to the pressure of pure neutron matter
- Pressure of PNM pushes against surface tension $\Rightarrow$ neutron skin
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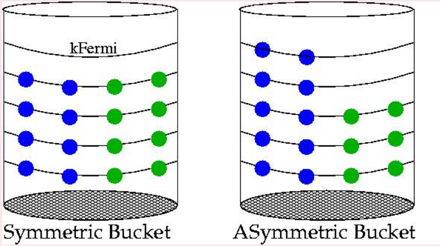
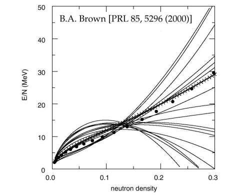
- **The larger the neutron skin, the larger the neutron-star radius!!**





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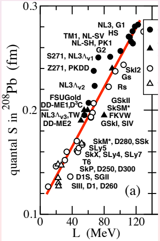

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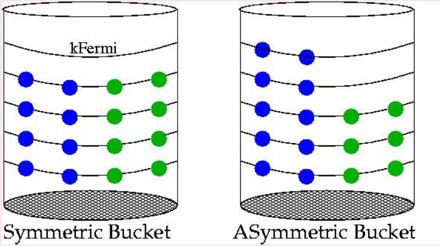

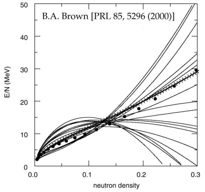

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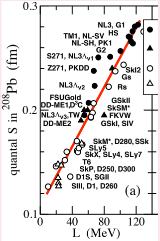

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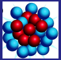

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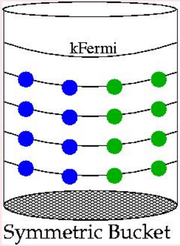

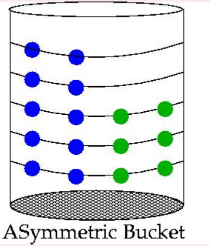

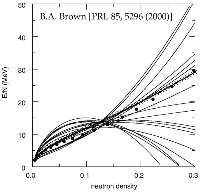

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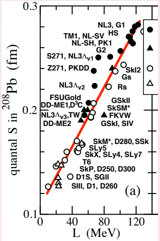

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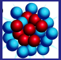

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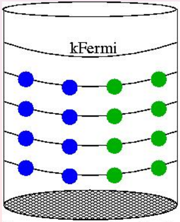
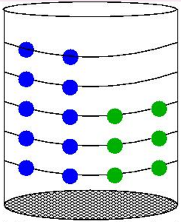
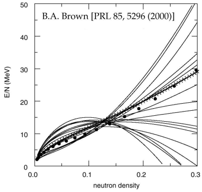


Symmetric Bucket



ASymmetric Bucket



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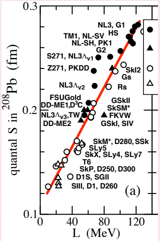

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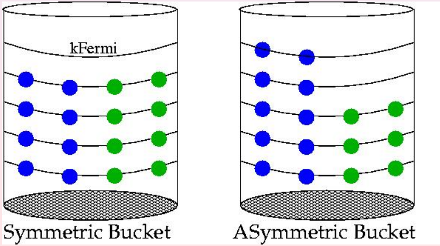

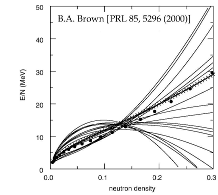

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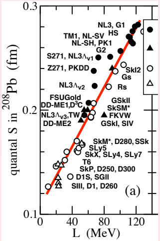
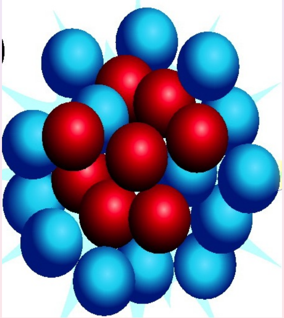
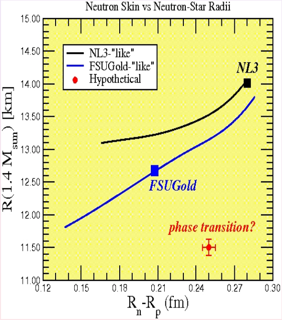
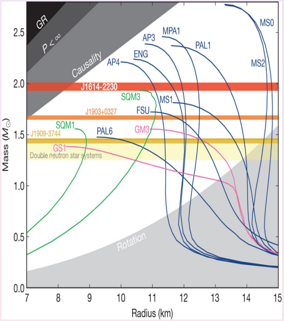


Heaven on Earth: Neutron-Star Structure

- Same dynamical origin to neutron skin and NS radius
  Same pressure creates neutron skin and NS radius
- Correlation among observables differing by 18 orders of magnitude!
- Large neutron skin and small neutron radius?
  May be evidence in favor of a phase transition (quark matter?)



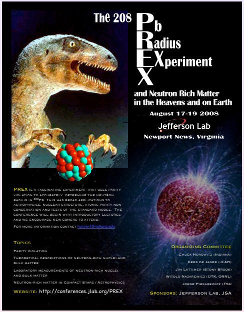


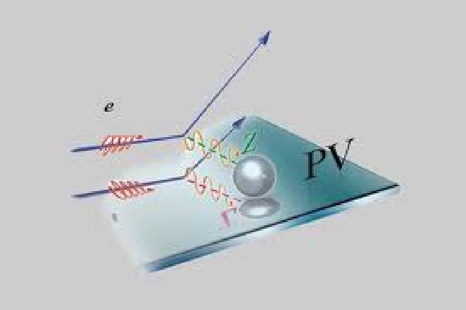


Synergy between astrophysical and laboratory observables!

PREX: Pb Radius EXperiment

- First purely electroweak (clean!) measurement of $R_n(^{208}\mathrm{Pb})$
- Promised a 1% measurement of $R_n(^{208}\mathrm{Pb})$
- Uses parity violation as Z_0 couples preferentially to neutrons





	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

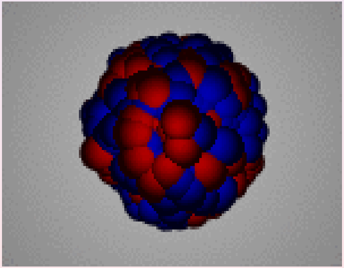
$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

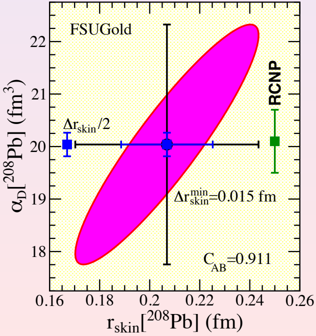
PREX: Measurement of the Neutron Radius of ^{208}Pb

through Parity Violation in Electron Scattering; PRL 108, 112502 (2012) [Ran for 2 months April-June 2010]

We report the first measurement of the parity-violating asymmetry A_{PV} in the elastic scattering of polarized electrons from ^{208}Pb. A_{PV} is sensitive to the radius of the neutron distribution (R_n). The result $A_{PV} = 0.656 \pm 0.060(\text{stat}) \pm 0.014(\text{syst})$ ppm corresponds to a difference between the radii of the neutron and proton distributions $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nucleus.

- Dipole polarizability as a proxy for the neutron skin in ^{208}Pb
- Strong correlation between dipole polarizability and neutron skin

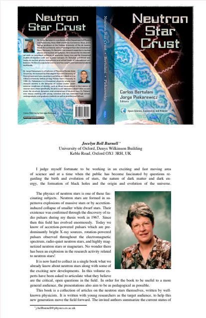


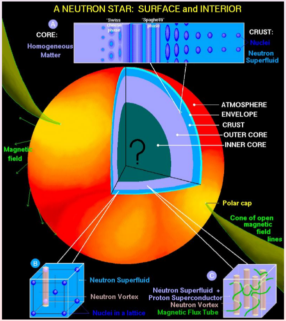


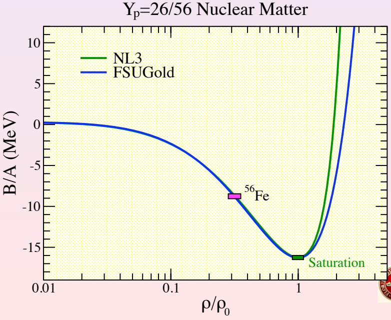
The Stellar Crust: Non-Uniform Nuclear Matter

FACILITY FOR RARE ISOTOPE BEAMS

- Neutron stars contain a non-uniform crust above the liquid core
- Neutron star crust extends for about 1 km out of about 10-12 km
- Uniform neutron-rich matter is unstable against cluster formation even at the expense of creating a surface
- Exotic states speculated to exist in the stellar crust:
  Coulomb crystal of neutron-rich nuclei (outer crust)
  Coulomb frustrated pasta structures (inner crust)

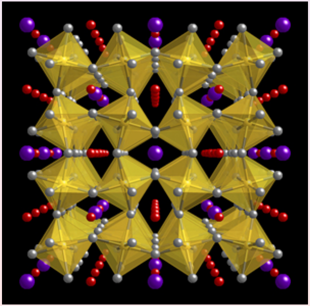


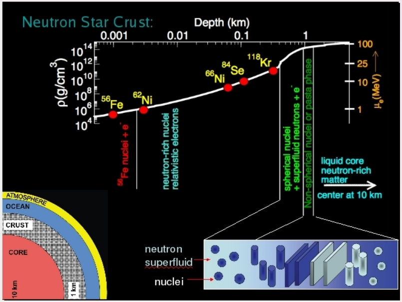




Coulomb Crystal of Neutron-Rich Nuclei

- Neutrons, protons, and a uniform electron Fermi gas
- Composition emerges from relatively simple dynamics:
  $E/A_{\rm tot} = M(N,Z)/A + 3/4\, Y_e^{4/3} k_{\rm Fermi} + {\rm lattice}$
- bcc Crystal of neutron-rich nuclei immersed in a uniform e^- gas
- As density increases in the outer crust, ^{56}Fe, ^{62}Ni, ..., $^{118}_{36}{\rm Kr}_{82}$(?)
- Neutron-drip line defines the outer-inner crust interface

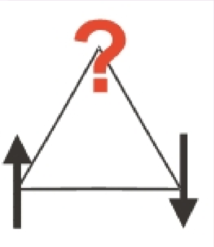


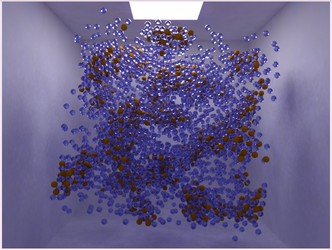


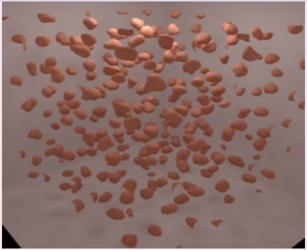
The Inner Crust: $10^{-3}\rho_0 \lesssim \rho \lesssim 10^{-1}\rho_0$

"Frustration and Nuclear Pasta"

- Frustration emerges from a dynamical (or geometrical) competition
- Impossibility to simultaneously minimize all elementary interactions
- Emergence of a multitude of competing (quasi) ground states
- Universal in complex systems (nuclei, e^- systems, magnets, proteins,...)
- Emergence of complex topological shapes *"Nuclear Pasta" or "Micro-emulsions"*
  "In 2D-electron systems with Coulomb interactions, a direct transition—whether first or second order—from a liquid to a crystalline state is forbidden" (Spivak-Kivelson)







Coherent neutrino scattering from "warm" nuclear pasta may play an important role in the energetics of core-collapse supernovae

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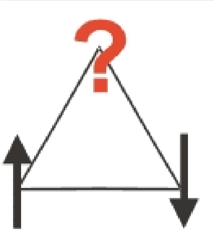

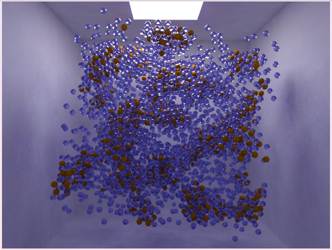

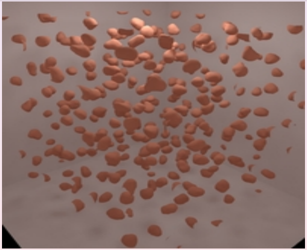

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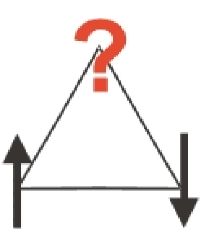

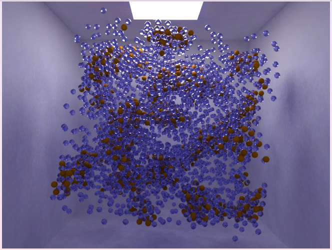

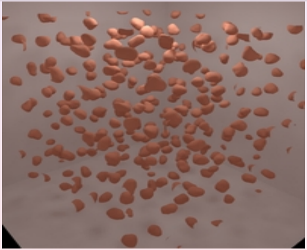

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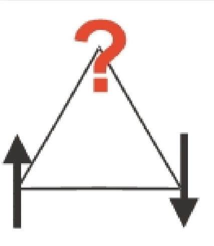

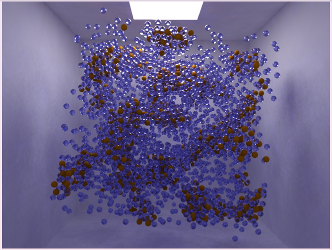

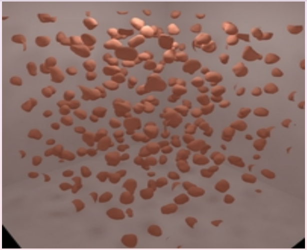

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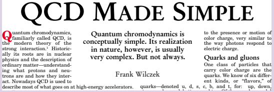
Neutron Stars as Physics Gold Mines

- Astrophysics: What is the minimum mass of a black hole?
- Atomic Physics: Pure neutron matter as a Unitary Fermi Gas
- Condensed-Matter Physics: Signatures for the liquid to crystalline state transition?
- General Relativity: Rapidly rotating neutrons stars as a source of gravitational waves?
- Nuclear Physics: What are the limits of nuclear existence and the EOS of nuclear matter?
- Particle Physics: QCD made simple — the CFL phase of dense quark matter



QCD MADE SIMPLE

Quantum chromodynamics, familiarly called QCD, is the modern theory of the strong interaction.[1] Historically its roots are in nuclear physics and the description of ordinary matter—understanding what protons and neutrons are and how they interact. Nowadays QCD is used to describe most of what goes on at high-energy accelerators.

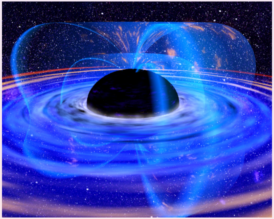
Quantum chromodynamics is conceptually simple. Its realization in nature, however, is usually very complex. But not always.

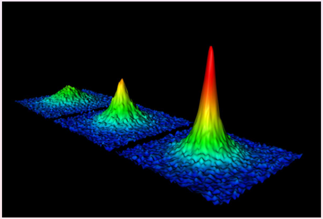
Frank Wilczek

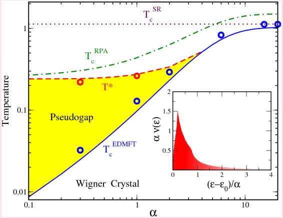
to the presence or motion of color charge, very similar to the way photons respond to electric charge.

Quarks and gluons

One class of particles that carry color charge are the quarks. We know of six different kinds, or "flavors," of quarks—denoted u, d, s, c, b, and t, for: up, down,



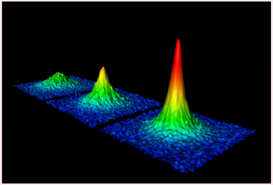


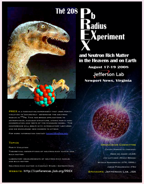


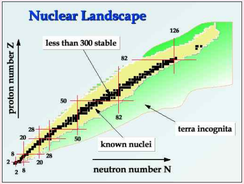
It is all connected ...

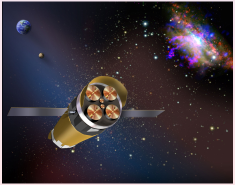
My Outside Collaborators

- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- **C.J. Horowitz** (Indiana U.)
- W. Nazarewicz (U. Tennessee)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)









Nuclear Physics at FSU

from 2007 Long Range Plan and 2010 Committee on the Assessment and Outlook for Nuclear Physics

- **Recommendation:** *We recommend completion of the 12 GeV* **CEBAF 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* (V. Crede and P. Eugenio; S. Capstick and W. Roberts)
- **Recommendation:** *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, and provide understanding of matter in the crust of neutron stars* (P. Cottle, K. Kemper, M. Riley, G. Rogachev, S. Tabor, and I. Wiedenhover; D. Robson, A. Volya)
- **Recommendation:** *The experiments at the* **Relativistic Heavy Ion Collider (RHIC)** *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* (A. Frawley)