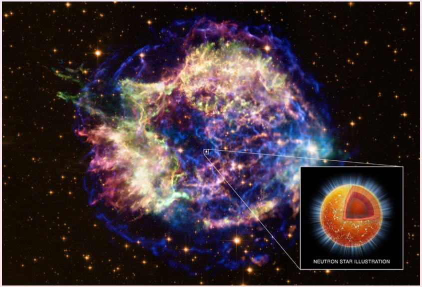
The Nuclear Physics of Neutron Stars

The VII European Summer School on
Experimental Nuclear Astrophysics
Santa Tecla, Italy
September 2013



Outline

My FSU Collaborators

- Genaro Toledo-Sanchez
- Karim Hasnaoui
- Bonnie Todd-Rutel
- Brad Futch
- Jutri Taruna
- Farrukh Fattoyev
- Wei-Chia Chen

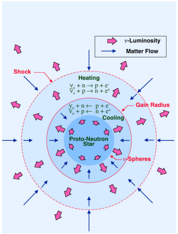
My Outside Collaborators

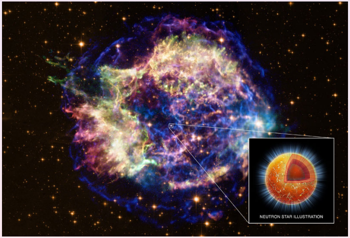
- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (U. Tennessee)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)

From Tallahassee to Santa Tecla

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

- Big Bang creates H, He, and traces of light elements
- 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!

. . . see *“Blingnova: The origin of gold” (Washington Post)*

S. Chandrasekhar and X-Ray Chandra

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- During his travel to graduate school at Cambridge under Fowler, Chandra works out the physics of the relativistic degenerate electron gas in white dwarf stars (at the age of 19!)
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- *"For a star of small mass the white-dwarf stage is an initial step towards complete extinction. A star of large mass cannot pass into the white-dwarf stage and one is left speculating on other possibilities"* (S. Chandrasekhar 1931)
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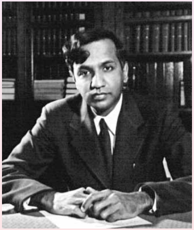

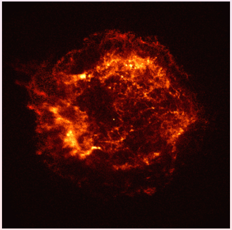
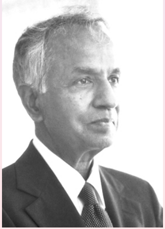

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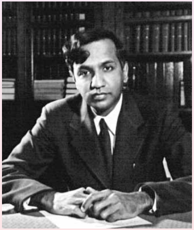

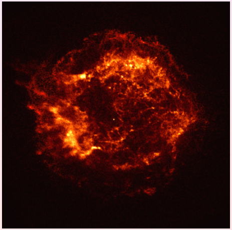
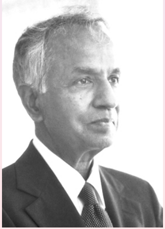

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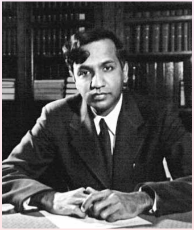

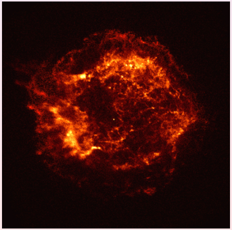
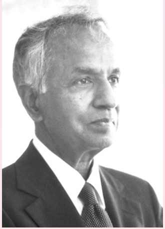

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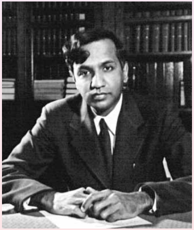

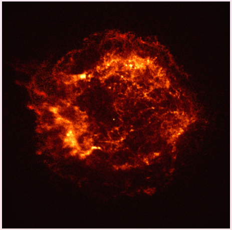
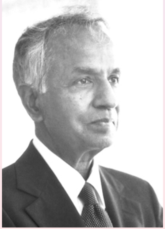

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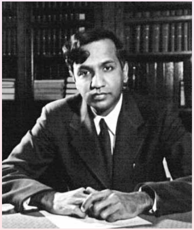

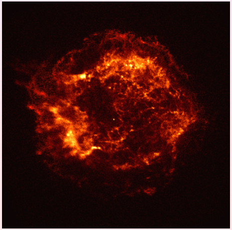
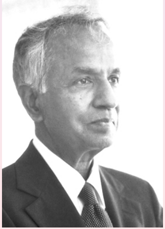

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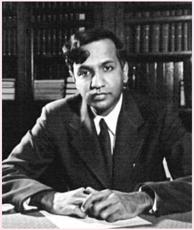

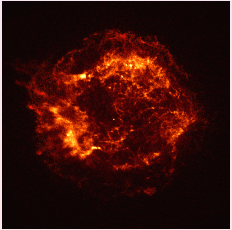
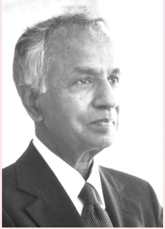

Some Historical Facts

- Chandrasekhar shows that massive stars will collapse (1931)
- 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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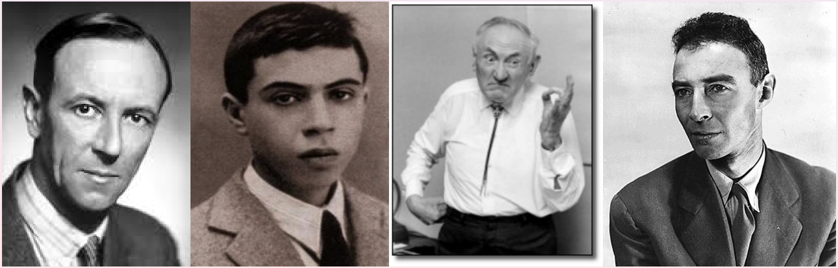

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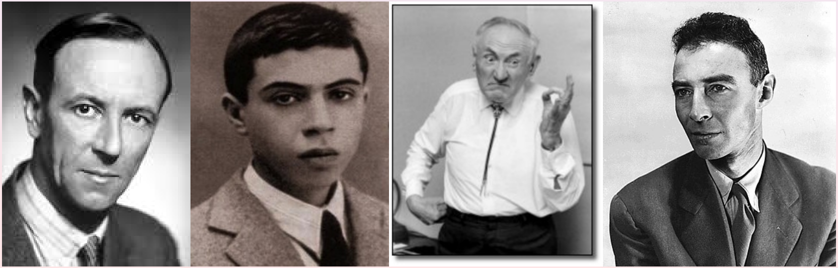

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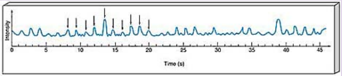

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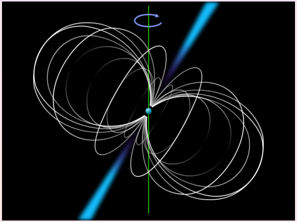

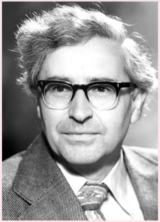

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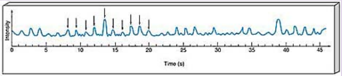

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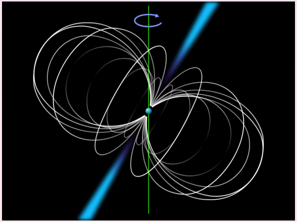

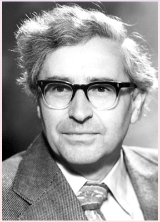

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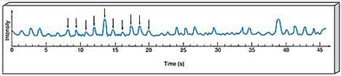

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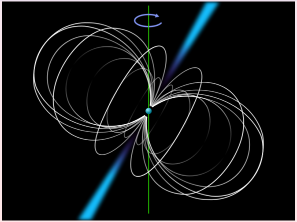

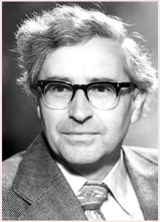

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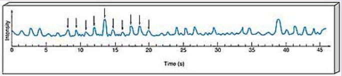

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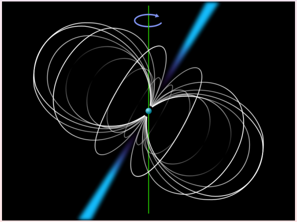
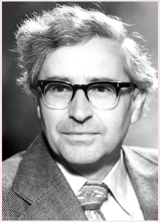

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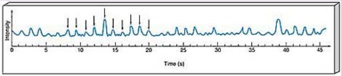

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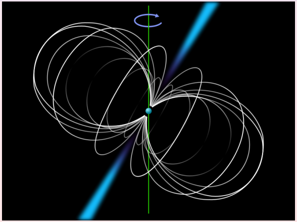
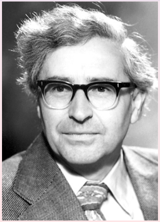

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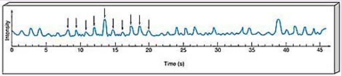

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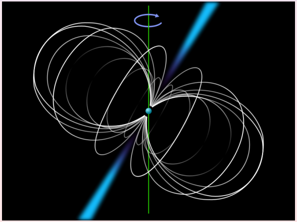
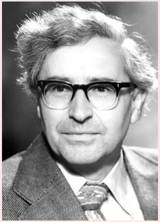
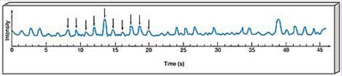
- *"I believe it would demean Nobel Prizes if they were awarded to research students, except in very exceptional cases, and I do not believe this is one of them"*

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)
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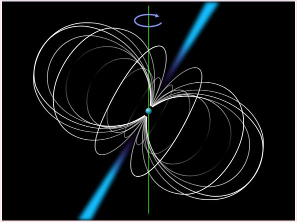
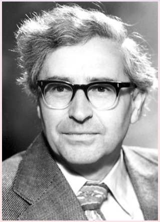
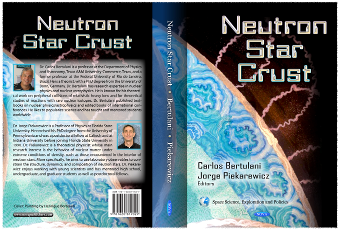




Neutron Star Crust: Preface by Jocelyn Bell



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

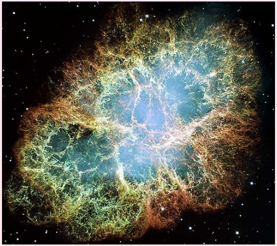
Table of Contents

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

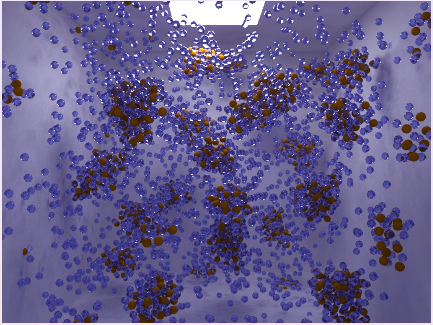


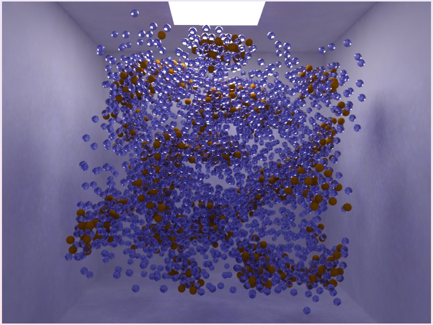
A Grand Challenge: How does subatomic matter organize itself?

"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)



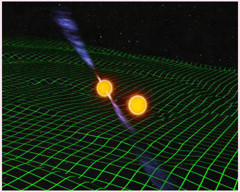
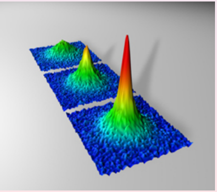
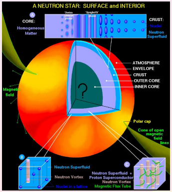


Impossible to answer such a question under normal laboratory conditions — as such a system is in general unbound!

Solution: Gravitationally Bound Neutron Stars

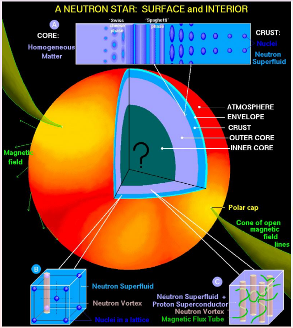
- Neutron Stars are bound by gravity NOT by the strong force
  Binding Energy/nucleon $\sim$ 100 MeV (neutron matter is unbound!)
- Gravity is the catalyst for the formation of novel states of matter
  Coulomb (“Wigner”) crystal of neutron-rich nuclei
  Coulomb frustrated pasta structures
  Strange quark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

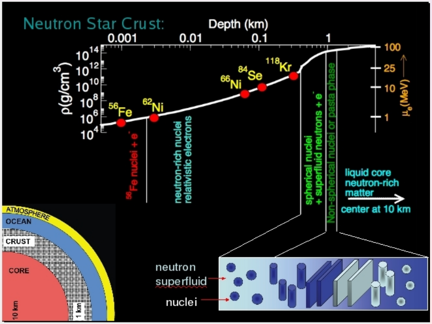
Neutron stars are the natural meeting place of astrophysics, general relativity, atomic, nuclear, particle, and condensed-matter physics.

From Crust to Core (Figures courtesy of Dany Page and Sanjay Reddy)

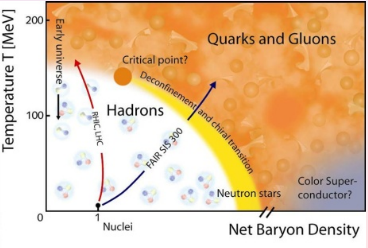
- Outer Crust: $10^{-10}\rho_0 \lesssim \rho \lesssim 10^{-3}\rho_0$
  "Coulomb Crystal" of progressively more neutron-rich nuclei
- Inner Crust: $10^{-3}\rho_0 \lesssim \rho \lesssim 10^{-1}\rho_0$
  "Nuclear Pasta" Exotic shapes immersed in a neutron vapor
- Outer/Inner Core: $10^{-1}\rho_0 \lesssim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

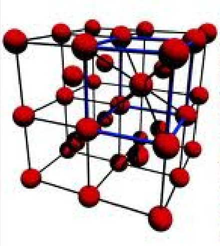


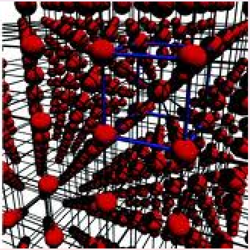


Non-Uniform Nuclear Matter

- At $\rho \lesssim \rho_0/2$, $B/A(\mathrm{uniform}) \simeq B/A(^{56}\mathrm{Fe})$
- Broken symmetry (non-uniform) state energetically favorable
- Nuclear Crystal immersed in a uniform Fermi sea of electrons
- $E/A_{\mathrm{tot}} = M(N,Z)/A + 3/4\, Y_e^{4/3} k_{\mathrm{Fermi}} + \mathrm{lattice}$
- As density increases in the outer crust, ^{56}Fe, ^{62}Ni, . . ., $^{118}_{36}\mathrm{Kr}_{82}$(?)

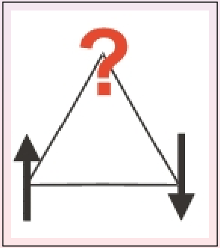


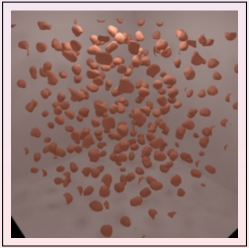


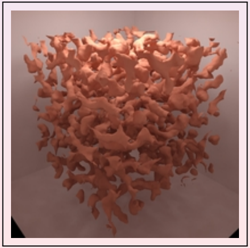


"Dynamical Frustration and Nuclear Pasta"

- Emerges from a dynamical competition
- Impossibility to minimize all elementary interactions
- Emergence of a multitude of competing (quasi)ground states
- Universal in complex systems (nuclei, spin glasses, proteins,...)
- Short-range attraction and long-range (Coulomb) repulsion
- Emergence of complex topological shapes *"Nuclear Pasta"*







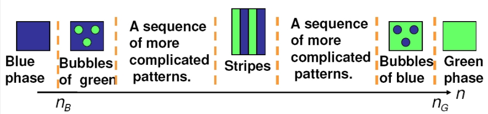
Theory of Electronic Micro-Emulsions (2D Electron Gas)

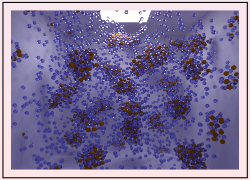
Steve Kivelson, Reza Jamei, and Boris Spivak

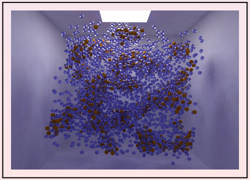
"Phases Intermediate Between the Two Dimensional Fermi Liquid and the Wigner Crystal"

A Universal Theorem:

"In the presence of long range interactions $V(r) \sim r^{-x}$, no first order phase transition is possible for $d-1 \leq x \leq d$. Rather, in place of the putative first order phase transition there are intermediate microemulsion phase(s)"



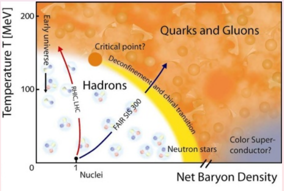




The Outer/Inner Core: $10^{-1}\rho_0 \lesssim \rho \lesssim 10\rho_0$

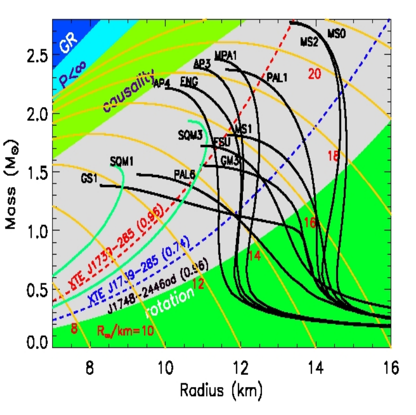
Neutron Stars are made of Neutrons!

- Uniform neutron-rich matter in chemical equilibrium
  neutrons, protons, electrons, muons, ???
- Structurally the most important component of the star
  $\sim$ 90% of the radius and all the mass reside in the core
- What is the maximum mass of a neutron star?
- What is the radius of a *"canonical"* neutron star?
- What are the phases of baryonic matter at such high densities?



Neutron Stars as 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!

The Outer Crust: Extreme sensitivity to nuclear masses

Wolf *et al.*, PRL 110, 041101 (2013)

- Mass per nucleon: $M(N,Z)/A - m_0 = m_1(N-Z)/A - B(N,Z)/A$

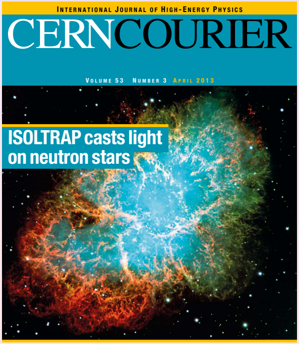
  ^{56}Fe: $B/A = 8.790\,\mathrm{MeV} \rightarrow 8.744\,\mathrm{MeV}$

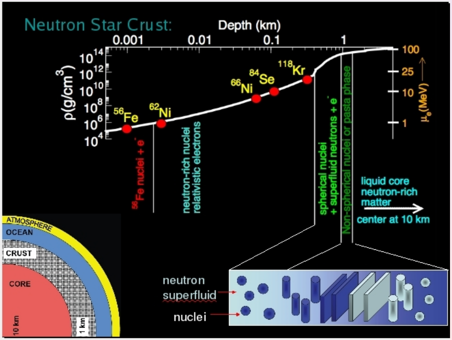
  ^{62}Ni: $B/A = 8.794\,\mathrm{MeV} \rightarrow 8.732\,\mathrm{MeV}$

- ISOLTRAP@CERN: The case of $^{82}_{30}\mathrm{Zn}_{52}$

  $ME_{\mathrm{CERN(AME2003)}} = -42.314(-42.460)\,\mathrm{MeV}$

- $^{82}_{30}\mathrm{Zn}_{52}$ is still far away from $^{118}_{36}\mathrm{Kr}_{82}$ $[(N-Z)/A = 0.27 \rightarrow 0.39]$

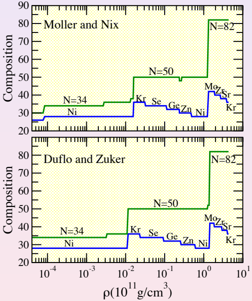


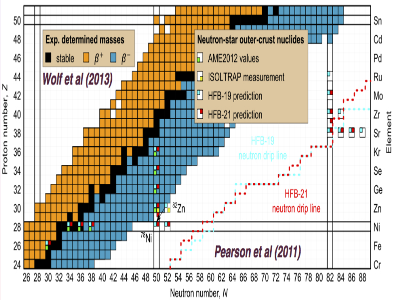


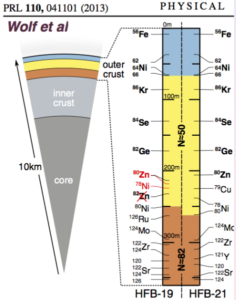
The Composition of the Outer Crust

Roca-Maza and JP, PRC 78, 025807 (2008) ; Pearson *et al.*, PRC 83, 065810 (2011) ; Wolf *et al.*, PRL 110, 041101 (2013)

- Composition emerges from relatively simple dynamics:
  All that is needed is a mass table in the $26 < Z < 50$ range
- Subtle competition between electronic and symmetry energy
- High-precision mass measurements of exotic nuclei are essential!



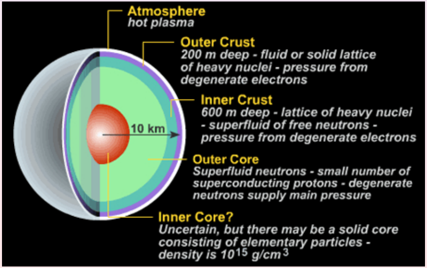


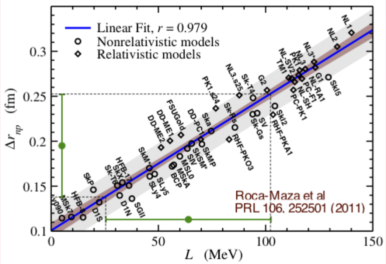


Starquakes—much like earthquakes—may be used to probe the composition of the stellar crust (Steiner, Strohmayer, Watts, . . .)

The Critical Role of the Symmetry Energy

- Most of the size and all of the mass is contained in the stellar core
- Stellar (maximum) mass strongly sensitive to the high-density EOS
- Stellar radius sensitive to density dependence of the symmetry energy
  radii controlled by the EOS in the immediate vicinity of ρ_0
  radii strongly correlated to the symmetry pressure at ρ_0 (L)
- Neutron skin also strongly correlated to the symmetry pressure L
- Neutron skin as proxy for neutron-star radii . . . and more!



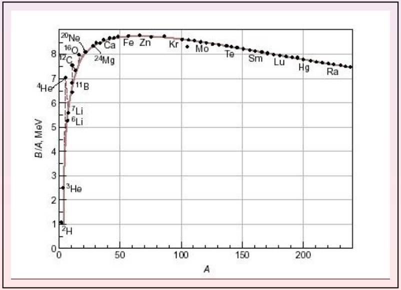


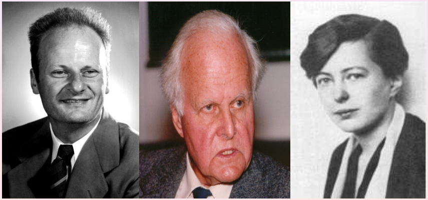
Bethe-Weizsäcker Mass Formula (*circa* 1935-36)

- Nuclear forces saturate ⇒ equilibrium density
- Nuclei penalized for developing a surface
- Nuclei penalized by 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** $(2, 8, 20, 28, 50, 82, 126, \ldots)$

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

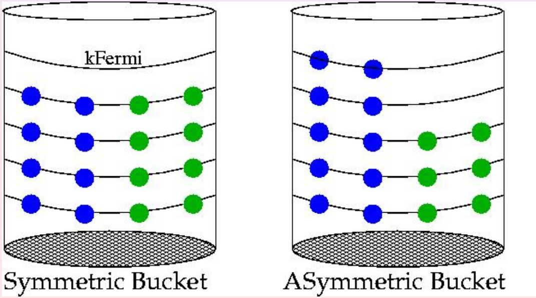
Neutron stars are gravitationally bound!





Neutron Skins and Density Dependence of the Symmetry Energy

- Proton (charge) densities known with enormous precision
  Started with Hofstadter in the late 1950's and continues to this day
- Neutron densities are as fundamental as proton densities
  Yet still elusive after more than 80 years of nuclear physics
- Hinders our understanding of density dependence symmetry energy
  Penalty for breaking $N\!=\!Z$ symmetry $[B(Z,N) = -a_{\rm a}(N\!-\!Z)^2/A + \ldots]$
- Neutron skin strongly correlated to the symmetry pressure $L \propto P_{\rm PNM}$
  Slope (pressure) of pure neutron matter poorly constrained



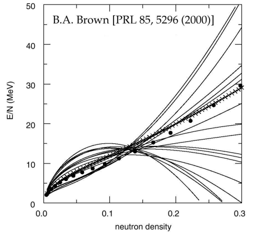


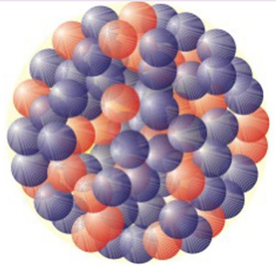
FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

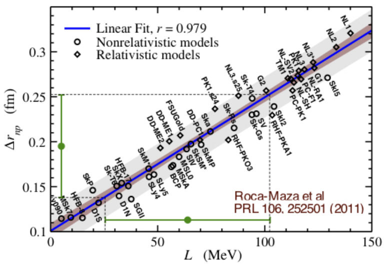
Where do the extra neutrons go?

- The EOS of asymmetric matter $\left[\alpha \equiv (N-Z)/A,\ x \equiv (\rho-\rho_0)/3\rho_0\right]$

$$\mathcal{E}(\rho,\alpha) \approx \mathcal{E}_0(\rho) + \alpha^2 \mathcal{S}(\rho) \approx \left(\epsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + \boxed{L}\, x + \frac{1}{2}K_{\rm sym} x^2\right)\alpha^2$$

- In ^{208}Pb, 82 protons/neutrons form an isospin symmetric spherical core
  Where do the extra 44 neutrons go?
- Competition between surface tension and **density dependence** of $\mathcal{S}(\rho)$
  Surface tension favors placing them in the core where $\mathcal{S}(\rho_0)$ is large
  Symm. energy favors pushing them to the surface where $\mathcal{S}(\rho_{\rm surf})$ is small
- If difference $\mathcal{S}(\rho_0)-\mathcal{S}(\rho_{\rm surf}) \propto L$ is large, then neutrons move to the surface
  The larger the value of L the thicker the neutron skin of ^{208}Pb

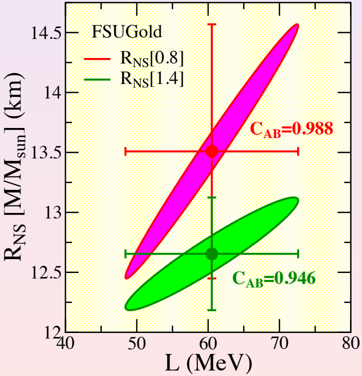


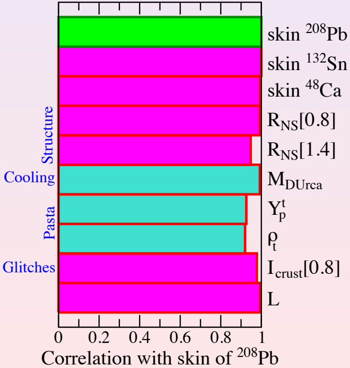


The Enormous Reach of the Neutron Skin

Reinhard-Nazarewicz, PRC 81 (2010) 051303; Fattoyev-Piekarewicz, PRC 86 (2012) 015802; PRC 84 (2011) 064302

- Neutron skin as proxy for neutron-star radii ... and more!
- Calibration of nuclear functional from optimization of a quality measure
- Predictions accompanied by meaningful theoretical errors
- Covariance analysis least biased approach to uncover correlations
- Neutron skin strongly correlated to a myriad of neutron star properties:
  Radii, Enhanced Cooling, Moment of Inertia, ...

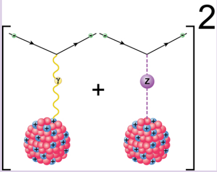




The Modern Approach: PV in Elastic Electron-Nucleus Scattering

Donnelly, Dubach, Sick, NPA 503, 589 (1989); Abrahamyan et al., PRL 108, (2012) 112502

- Charge (proton) densities known with enormous precision
  charge density probed via parity-conserving eA scattering
- Weak-charge (neutron) densities very poorly known
  weak-charge density probed via parity-violating eA scattering



$$A_{\rm PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[\underbrace{1-4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

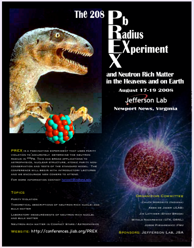
- Use parity violation as Z_0 couples preferentially to neutrons
- PV provides a clean measurement of neutron densities (and r_n)

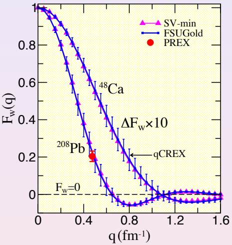
	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

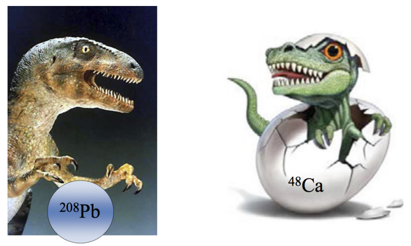
$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

PREX: The Lead Radius EXperiment Abrahamyan et al., PRL 108, (2012) 112502

- **Ran for 2 months: April-June 2010**
- First electroweak observation of the neutron-rich skin in ^{208}Pb
- Promised a 0.06 fm measurement of r_n^{208}; error 3 times as large!







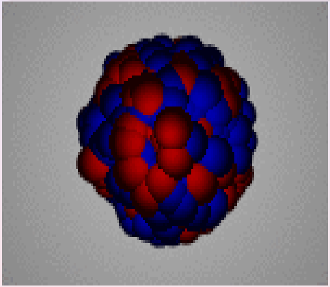
We report the first measurement of the parity-violating asymmetry A_{PV} in the elastic scattering of polarized electrons from ^{208}Pb. A_{PV} is sensitive to the radius of the neutron distribution (R_n). The result $A_{PV} = 0.656 \pm 0.060(\mathrm{stat}) \pm 0.014(\mathrm{syst})$ ppm corresponds to 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.

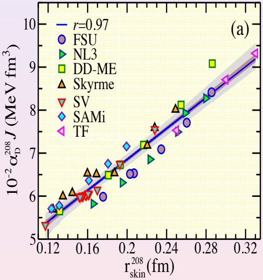
A Physics case for PREX-II and beyond!

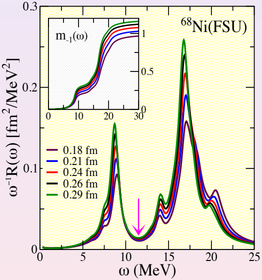
The Electric Dipole Polarizability in ^{208}Pb

RCNP: A. Tamii *et al.*, PRL 107, 062502 (2011)

- IVGDR: *Coherent oscillations of protons against neutrons*
  Nuclear symmetry energy as the restoring force
- Accurate measurement of E1 polarizability: $\alpha_{\rm D} = (20.1 \pm 0.6)\,{\rm fm}^3$
- E1 polarizability as a complement to $R^{208}_{\rm skin}$







Electric Dipole Polarizability a Fundamental Complement to Neutron Skins

Evidence for Nuclear Pasta and Strange Quark Matter?

nature physics
ARTICLES
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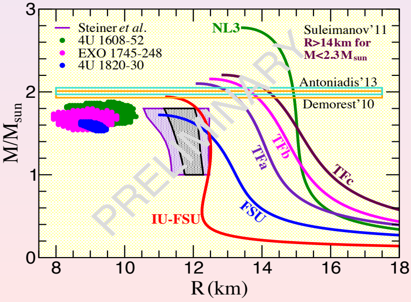
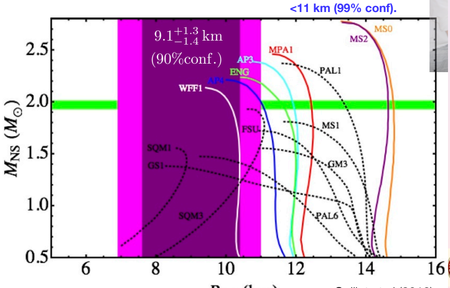
A highly resistive layer within the crust of X-ray pulsars limits their spin periods

José A. Pons[1]*, Daniele Viganò[1] and Nanda Rea[2]

The lack of isolated X-ray pulsars with spin periods longer than 12 s raises the question of where the population of evolved high-magnetic-field neutron stars has gone. Unlike canonical radiopulsars, X-ray pulsars are not subject to physical limits to the emission mechanism nor observational biases against the detection of sources with longer periods. Here we show that a highly resistive layer in the innermost part of the crust of neutron stars naturally limits the spin period to a maximum value of about 10–20 s. This highly resistive layer is expected if the inner crust is amorphous and heterogeneous in nuclear charge, possibly owing to the existence of a nuclear 'pasta' phase. Our findings suggest that the maximum period of isolated X-ray pulsars may be the first observational evidence for an amorphous inner crust, whose properties can be further constrained by future X-ray timing missions combined with more detailed models.

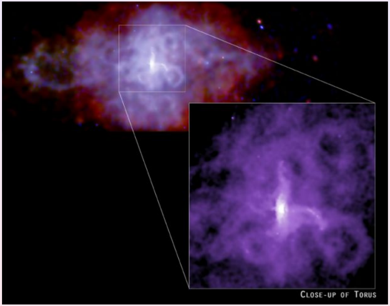


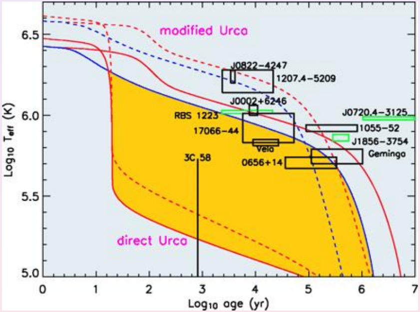


Guillot et al (2013)

Heaven on Earth: Enhanced Cooling of Neutron Stars

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





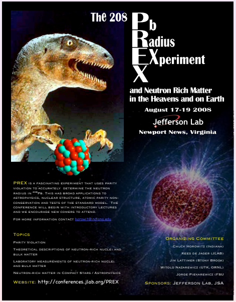
- Neutrino “enhanced” cooling possible in exotic quark matter
- The pulsar in 3C58 may indeed be a quark star
- **Unless ...** symmetry energy is stiff: large $Y_p \Leftrightarrow$ large neutron skin

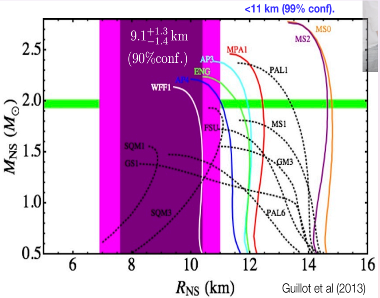
George Gamow and URCA Cooling

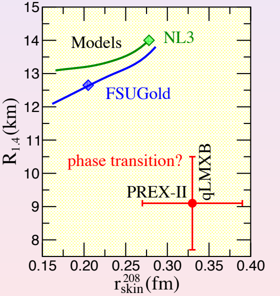
- Urca is not an acronym but the name of a casino in Rio de Janeiro at which George Gamow commented to the Brazilian astrophysicist (Mario Schönberg): *the energy disappears in the nucleus of the supernova as quickly as the money disappeared at that roulette table.*
- In Gamow's Russian dialect, urca can also mean a *pickpocket*, an individual that can steal your money in a matter of seconds!

Heaven on Earth: Radius of a $M_\star = 1.4\ M_\odot$

- 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!
- NS radius sensitive to the high-density component of the EOS
- Large neutron skin and small neutron radius?
  May be evidence in favor of a phase transition (quark matter?)



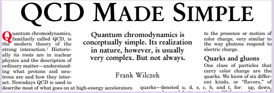




Exciting times because of the tension between theory and experiment/observation

Conclusions and Outlook: The Physics of Neutron Stars

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

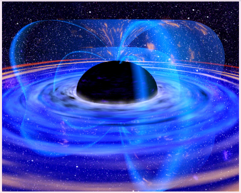
Frank Wilczek

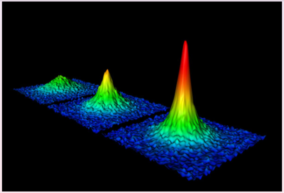
Quantum chromodynamics, familiarly called QCD, is the modern theory of the strong interaction.[1] Historically its roots are in nuclear physics and the description of ordinary matter—understanding what protons and neutrons are and how they interact. Nowadays QCD is used to describe most of what goes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

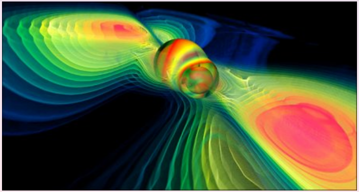
to the presence or motion of color charge, very similar to the way photons respond to electric charge.

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,







Neutron Stars are the natural meeting place for fundamental and interesting Physics