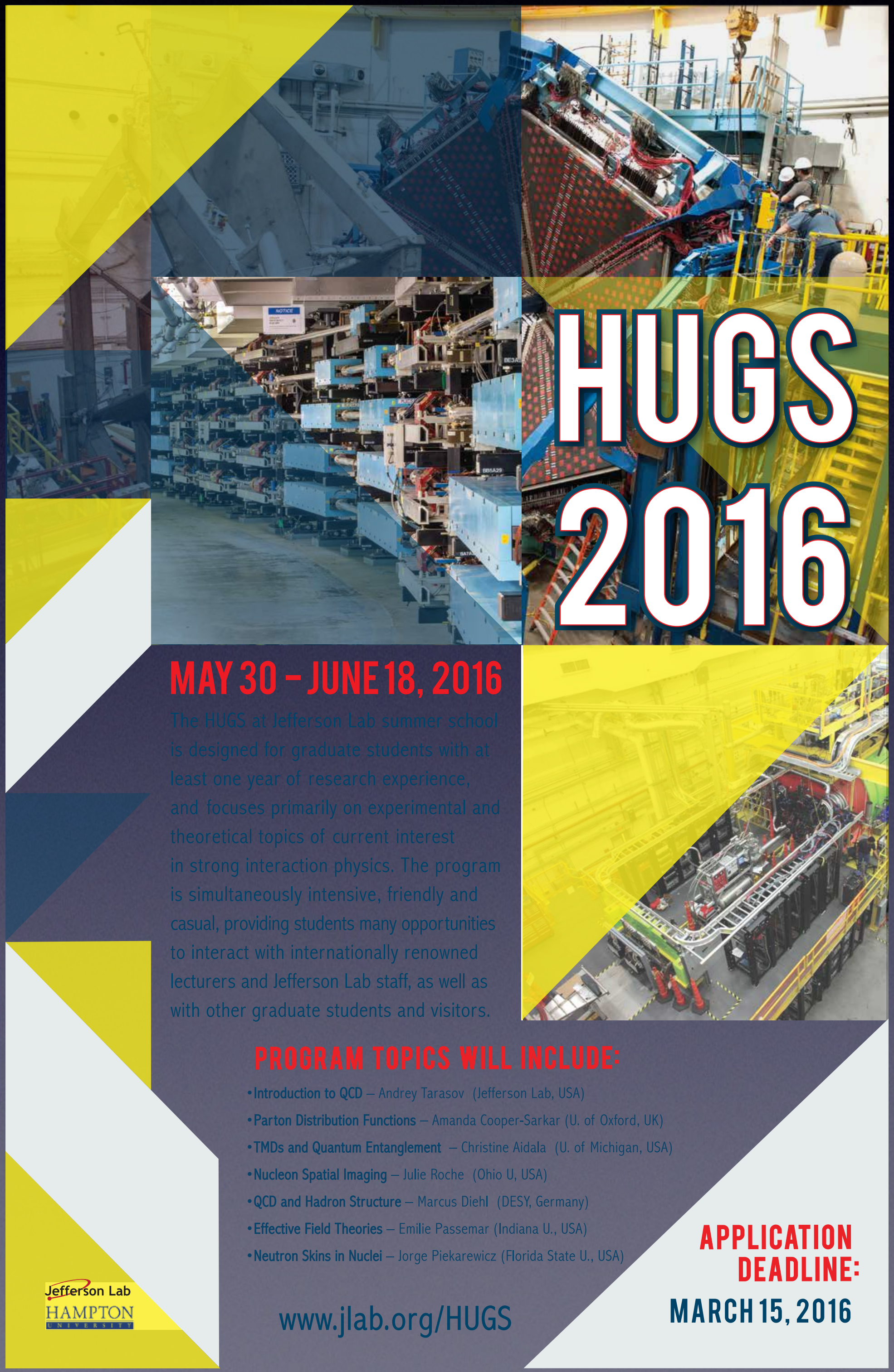
Neutron Skins in Nuclei

31st Annual HUGS Program

(Jorge Piekarewicz - FSU)



My Collaborators

My FSU Collaborators

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

My Outside Collaborators

- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (MSU)
- 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)

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U.S. DEPARTMENT OF ENERGY | Office of Science

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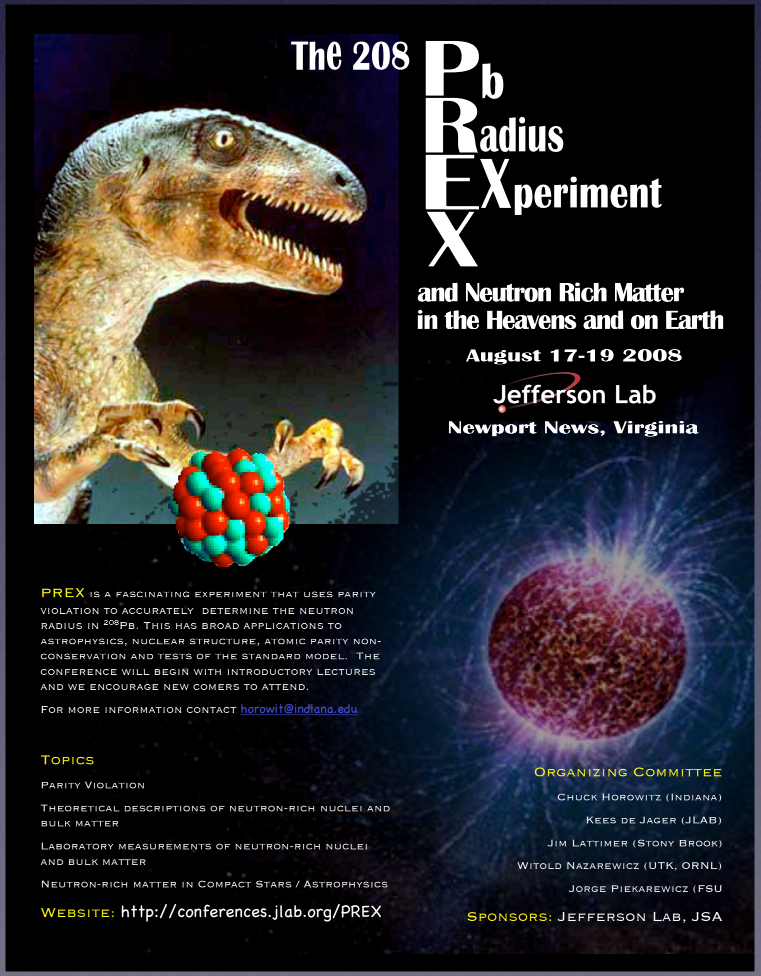
Heaven on Earth
PREX informing Astrophysics

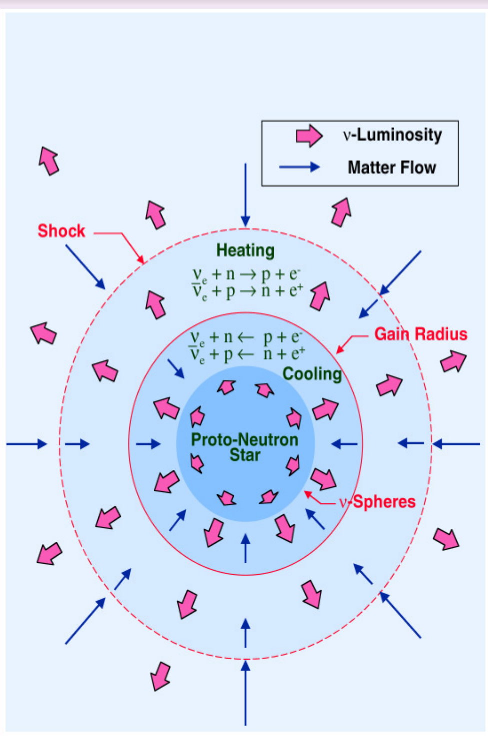
Outline

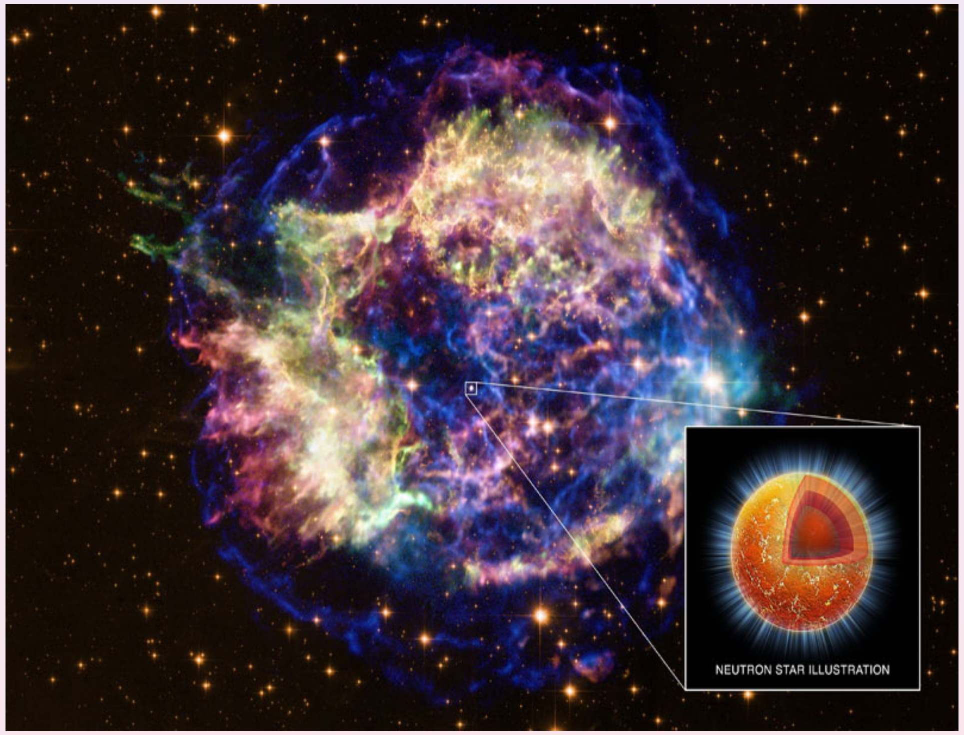
The impact of the neutron skin of ^{208}Pb on the physics of neutron stars



Death of a Star Birth of a Pulsar

- 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



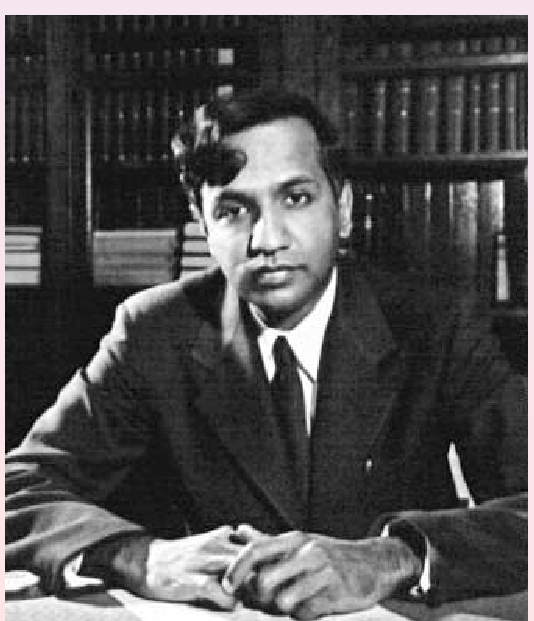


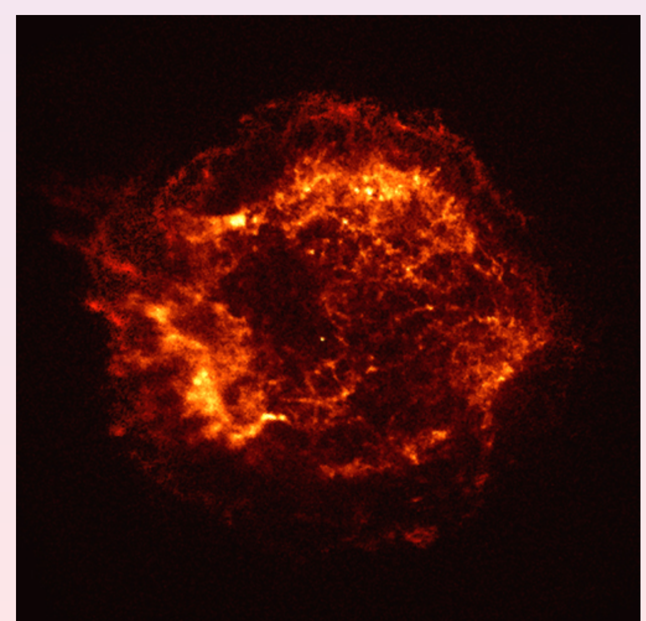
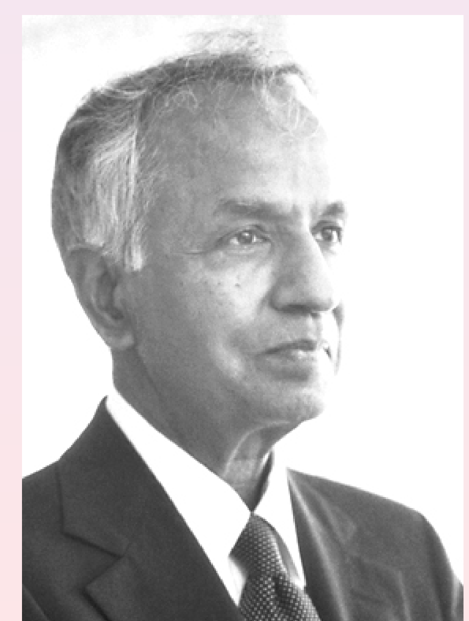
Neutron stars are solar mass objects with 10 km radii

Core collapse mechanism and r-process site remain uncertain!

Subrahmanyan Chandrasekhar … and Chandra's X-ray Telescope

- White dwarfs resist gravitational collapse through electron degeneracy pressure rather than thermal pressure (Dirac and R.H. Fowler 1926)
- 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!)
- For masses in excess of $M = 1.4\,M_\odot$ electrons becomes relativistic and the degeneracy pressure is insufficient to balance the star's gravitational attraction ($P \sim n^{5/3} \to n^{4/3}$)
- *"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)
- Arthur Eddington (1919 bending of light) publicly ridiculed Chandra's on his discovery
- Awarded the Nobel Prize in Physics (in 1983 with W.A. Fowler)
- In 1999, NASA lunches "Chandra" the premier USA X-ray observatory



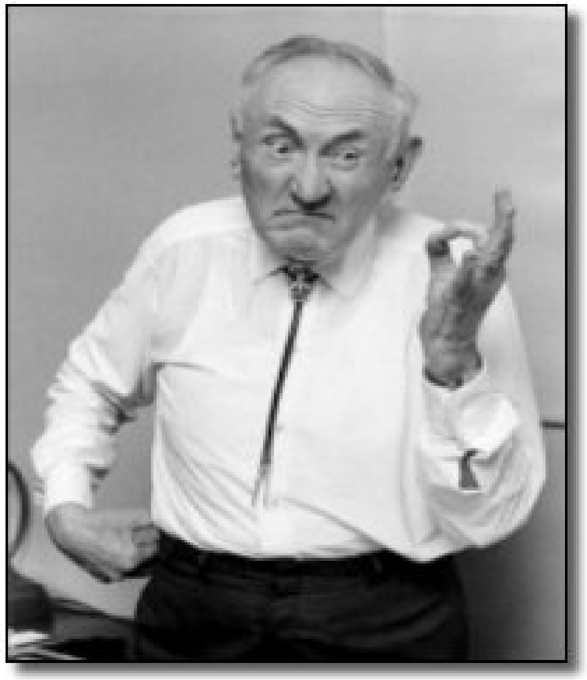



The Main Actors

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)
- Gold and Pacini propose basic lighthouse model (1968)
  Pulsars are rapidly rotating Neutron Stars!






The Main Actors: Some Historical Facts

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- Chadwick discovers the neutron (1932)
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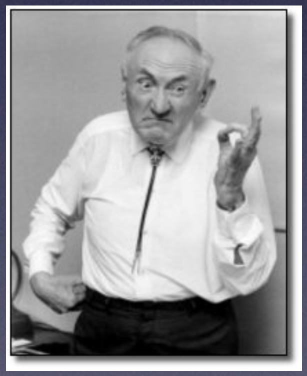
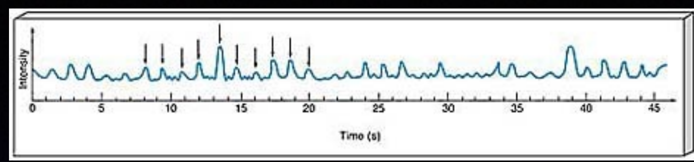


- Baade-Zwicky introduce the concept of a neutron star (1933)
  (… Landau mentions dense stars that look like giant nuclei)

- Oppenheimer-Volkoff use GR to compute the structure of neutron stars (1939)
  (… predict 0.7 solar masses as maximum neutron star mass)

Neutron Stars: Dame Jocelyn Bell Burnell

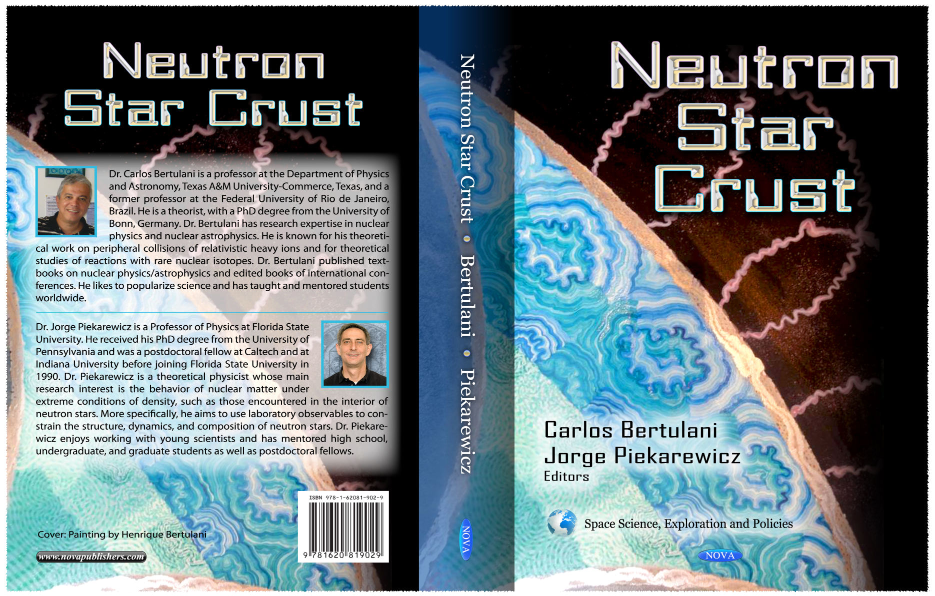


- Detected a bit of “scruff” (1967)
- Discovers amazing regularity in the signal
  (P=1.33730119 seconds)
- May the signal be from an alien civilization?
  (Little Green Man 1)
- Paper announcing first pulsar published
  [*Observation of a Rapidly Pulsating Radio Source*
  A Hewish, SJ Bell, et al., Nature 217, 709 (1968)]
- Nobel awarded to Hewish and Ryle (1974)
- “No-Bell” roundly condemned (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”

Neutron Star Crust

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

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The Crab Pulsar

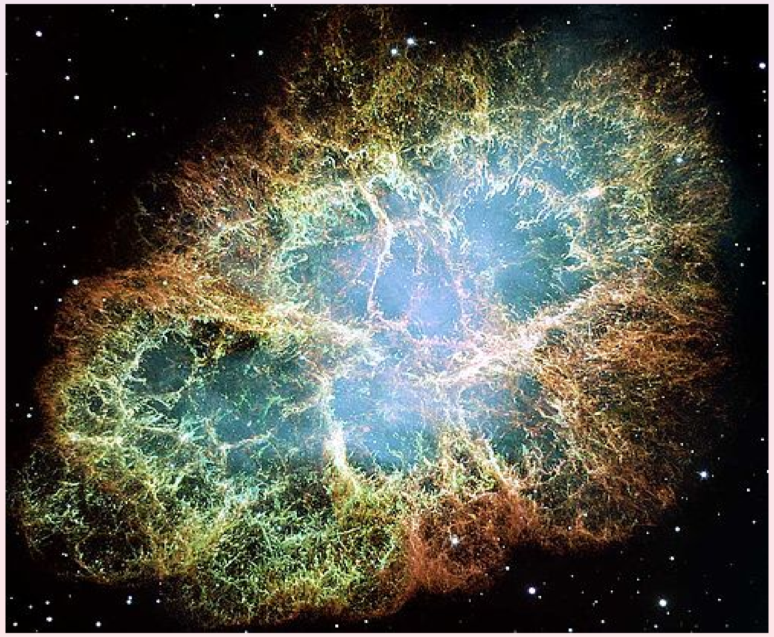
https://www.youtube.com/watch?v=Qyc4bgK7AXE

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

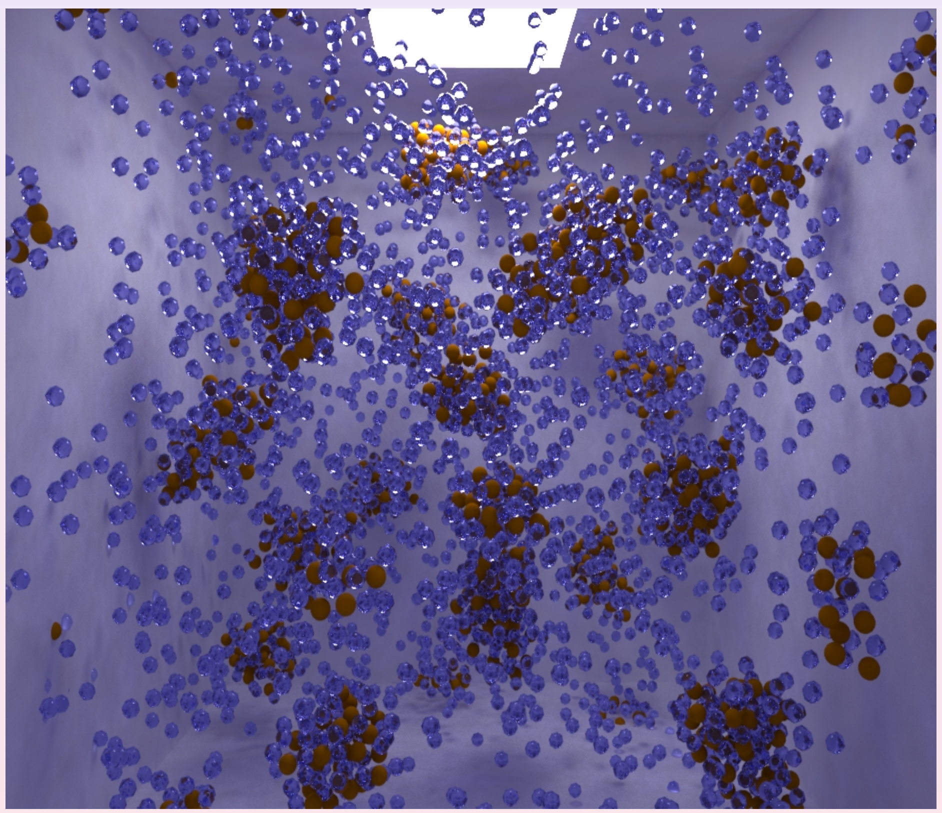
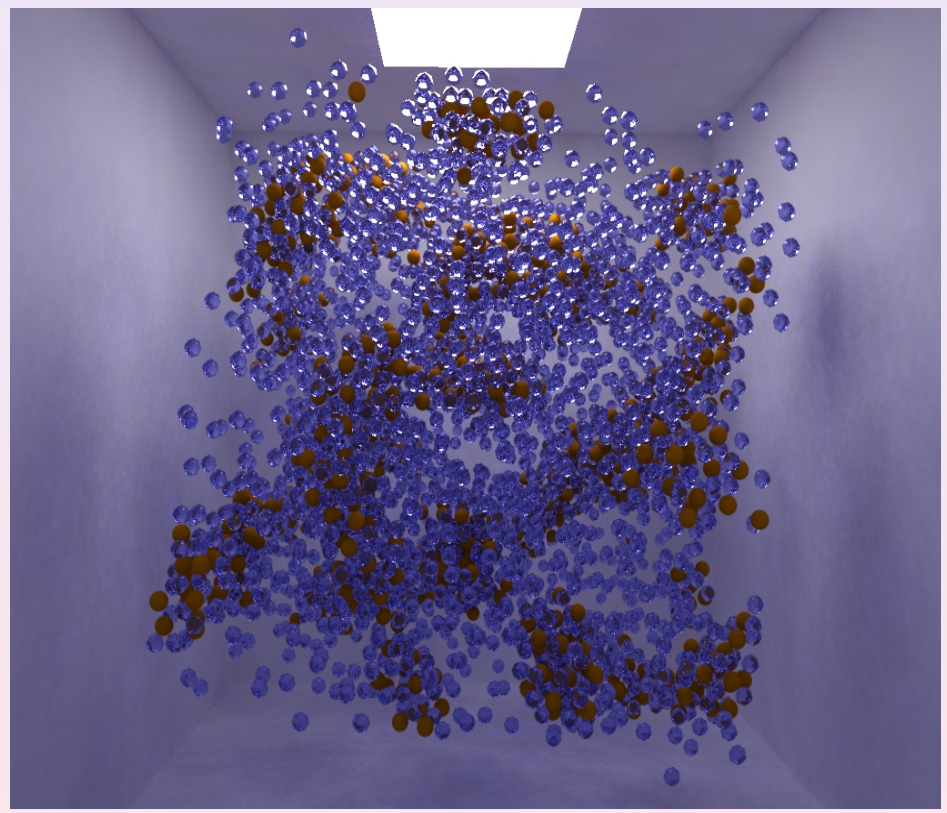
Distance: 6,500 ly
Temperature: 10^6 K
Density: 10^{14}g/cm^3
Pressure: 10^{29} atm
Magnetic Field: 10^{12} G



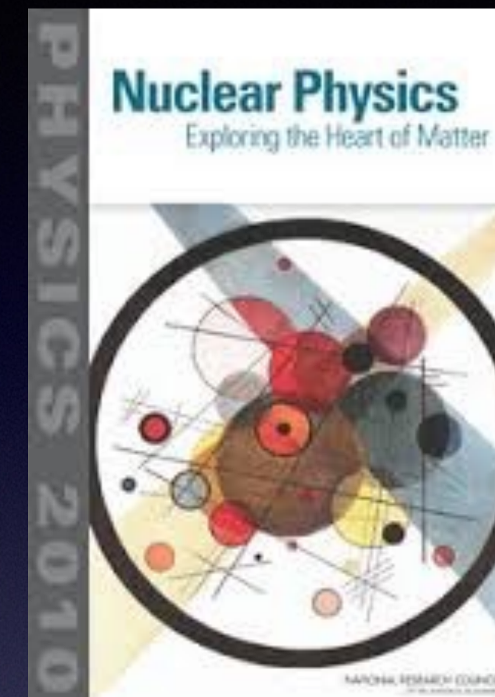
A Grand Challenge: How does subatomic matter organize itself?

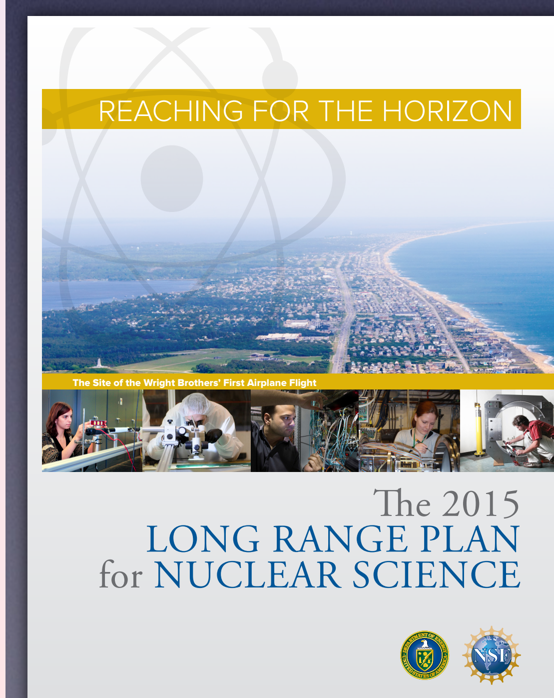
- Consider nucleons (A) and electrons (Z) in a volume V at $T \equiv 0$
- Enforce charge neutrality $protons = electrons + muons$
- Enforce conservation laws: Charge and Baryon number

  $n \rightarrow p + e^{-} + \bar{\nu}$ (beta decay) $p + e^{-} \rightarrow n + \nu$ (electron capture)

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

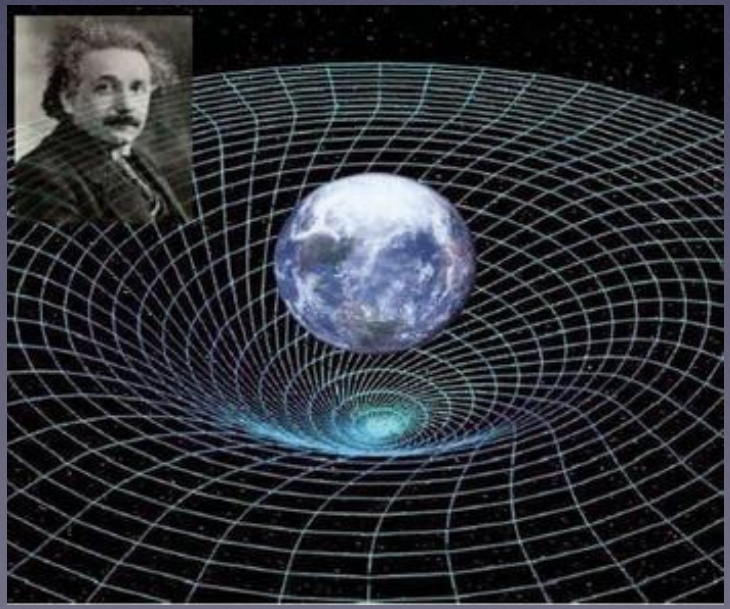


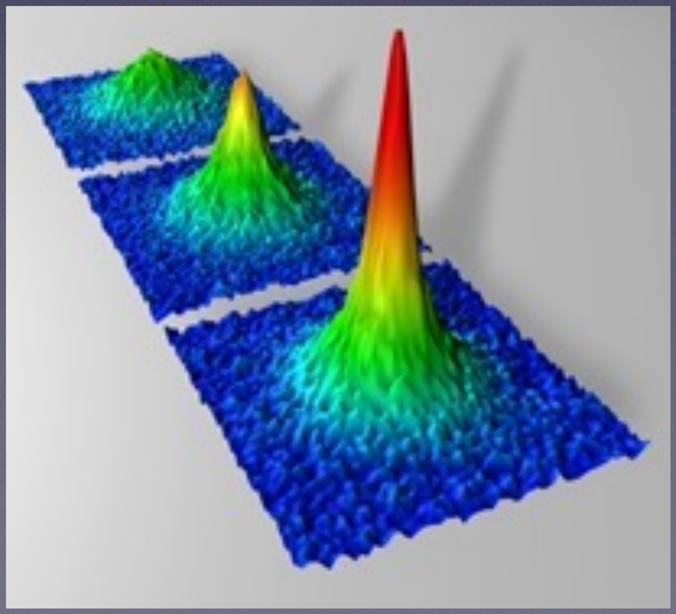


Addressing the Grand Challenge: Gravitationally Bound Neutron Stars

- Neutron stars are bound by gravity NOT by the strong force
  Binding energy per nucleon ~ 100 MeV (pure neutron matter is unbound!)
- Gravity is the catalyst for the formation of novel/exotic states of matter
  Coulomb ("Wigner") crystals of progressively more exotic neutron-rich nuclei
  Topologically complex Coulomb frustrated "Nuclear Pasta"
  Exotica(?): Strange-Quark matter, meson condensates, color superconductors
- Such exotic states can NOT be reproduced in terrestrial laboratories

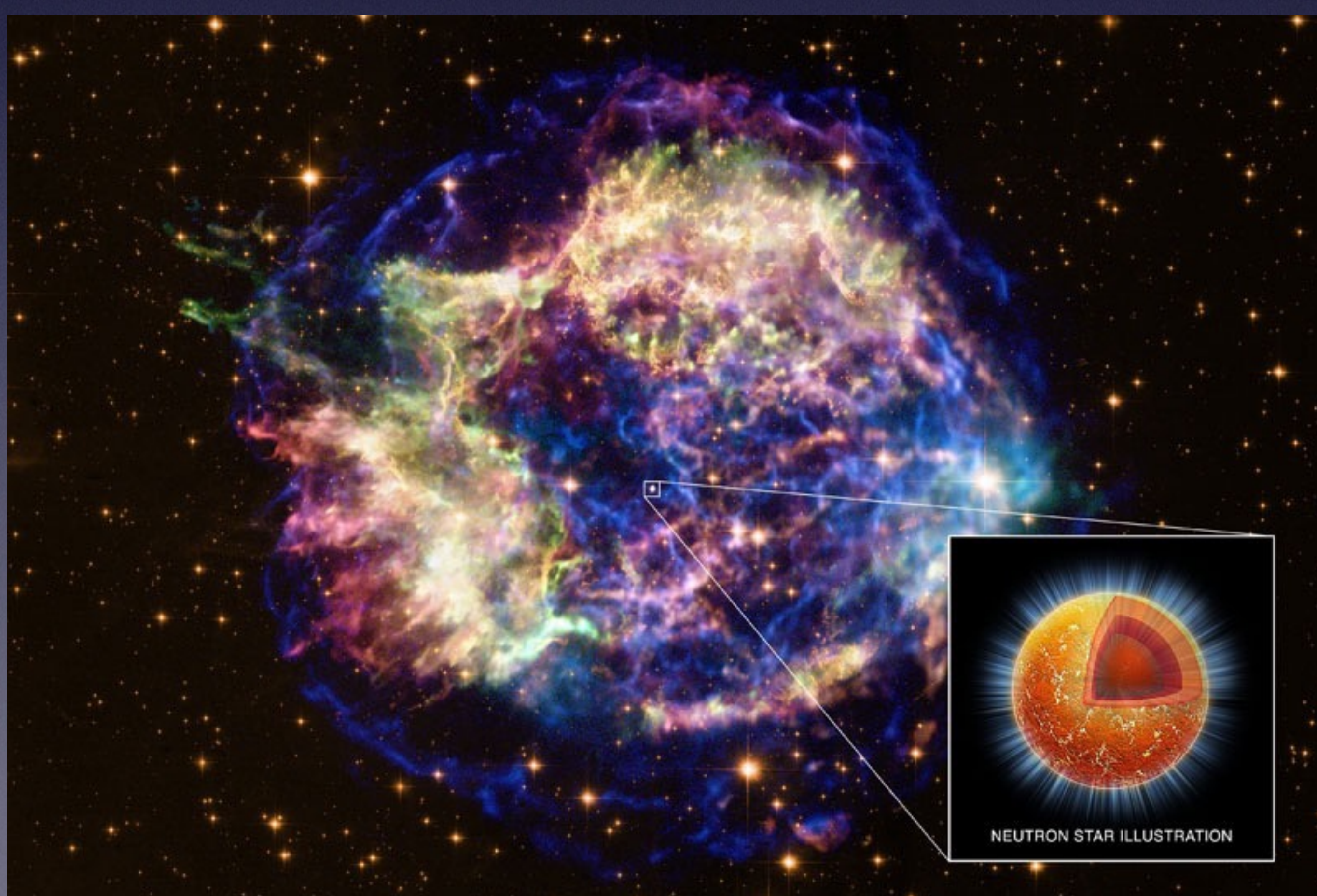
Neutron Stars are the natural meeting place of astrophysics, general relativity, nuclear, particle, and condensed matter physics

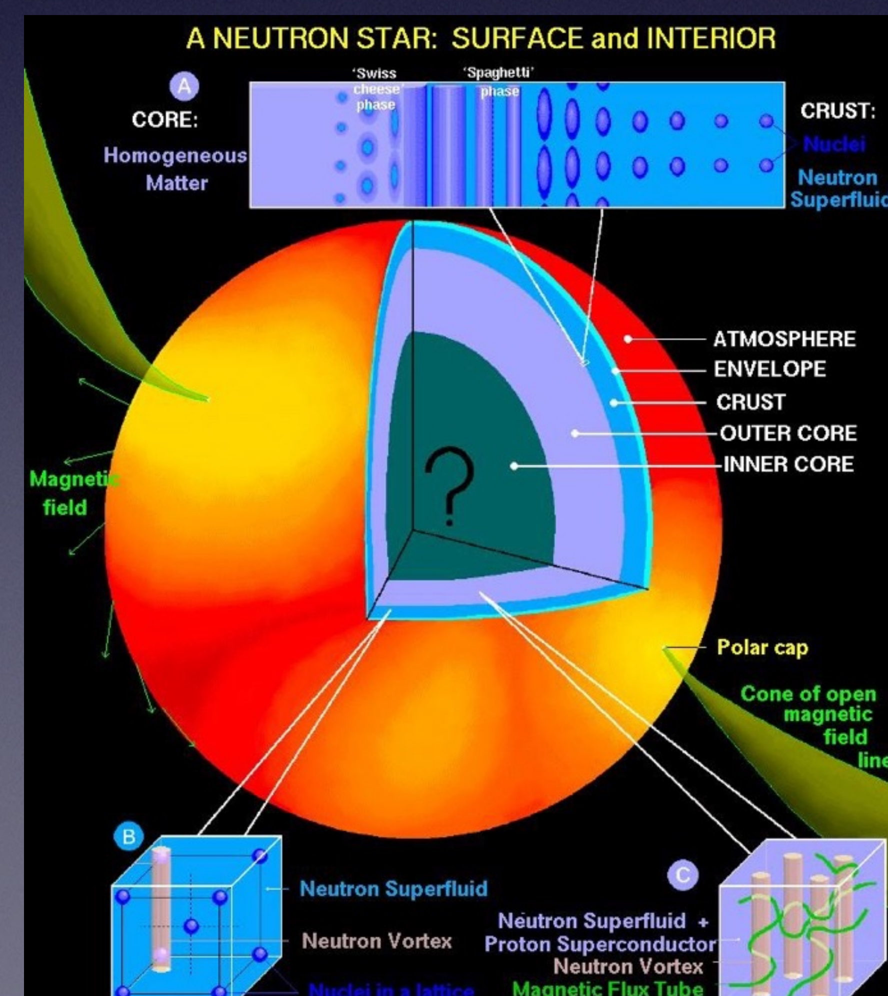




The Anatomy of a Neutron Star

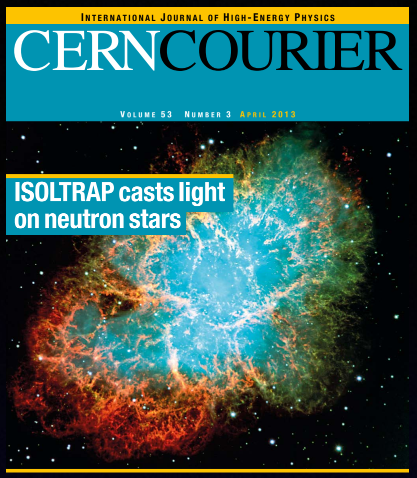
- Atmosphere (10 cm): Shapes Thermal Radiation ($L=4\pi\sigma R^2T^4$)
- Envelope (100 m): Huge Temperature Gradient (10^8K $\leftrightarrow$ 10^6K)
- Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)
- Inner Crust (1 km): Coulomb Frustration (“Nuclear Pasta”)
- Outer Core (10 km): Uniform Neutron-Rich Matter (n,p,e,μ)
- Inner Core (?): Exotic Matter (Hyperons, condensates, quark matter)





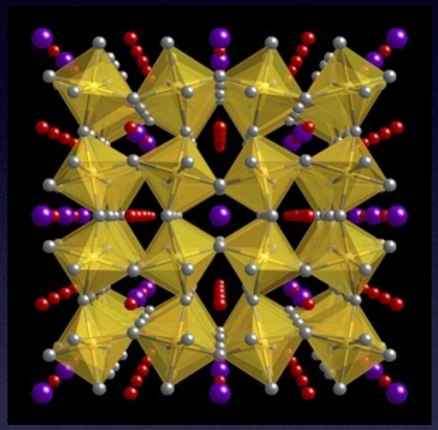
The Composition of the Outer Crust

High sensitivity to nuclear masses

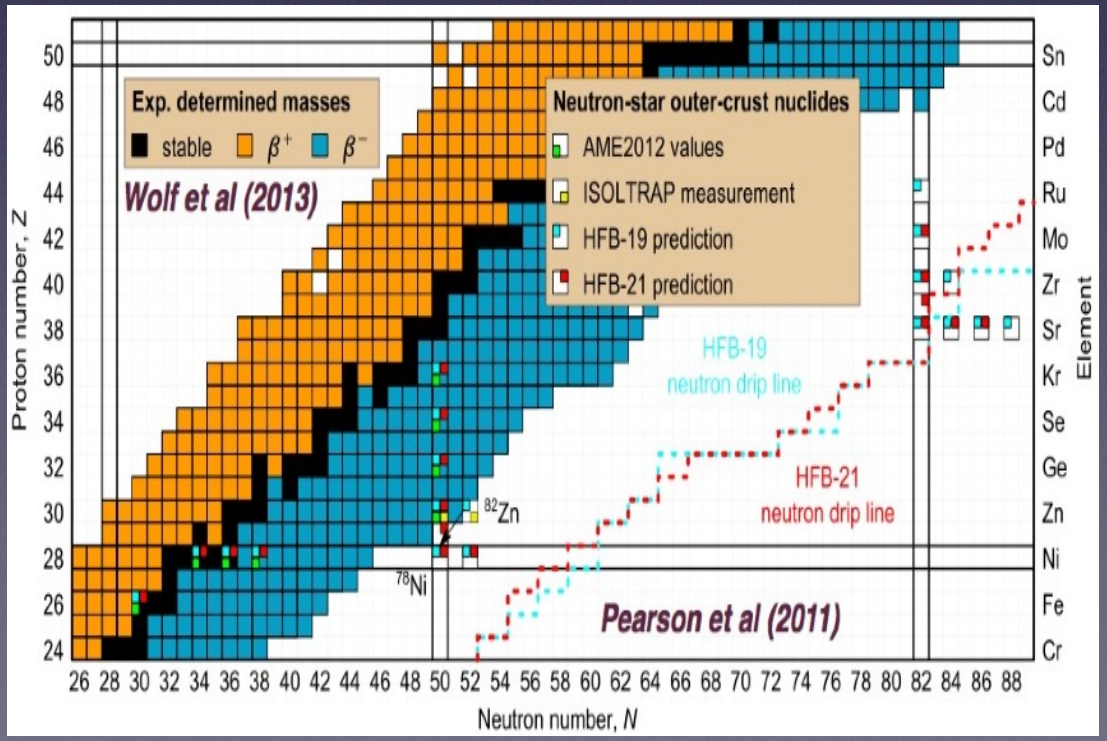


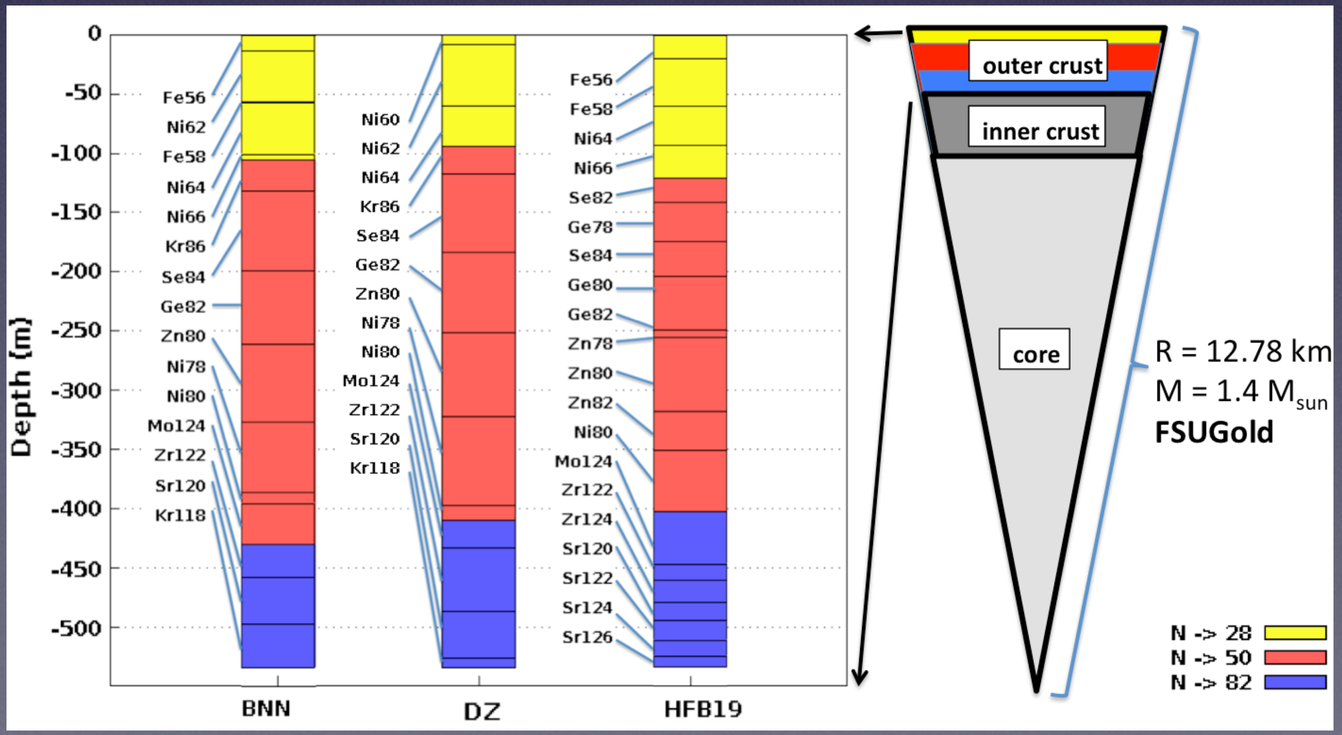
- System unstable to cluster formation
  - BCC lattice of neutron-rich nuclei imbedded in e-gas
- Composition emerges from relatively simple dynamics
  - Subtle composition between electronic and symmetry energy

$$E/A_{\rm tot} = M(N,Z)/A + \frac{3}{4}Y_e^{4/3}{\rm k_F} + {\rm lattice}$$



- Precision mass measurements of exotic nuclei is essential
  - Both for neutron-star crusts and r-process nucleosynthesis





DFT meets BNN

PHYSICAL REVIEW C 93, 014311 (2016)

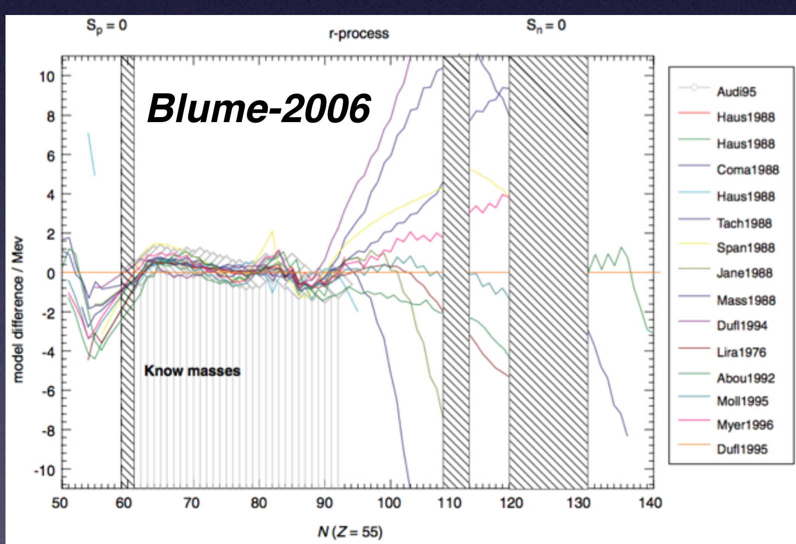
Nuclear mass predictions for the crustal composition of neutron stars: A Bayesian neural network approach

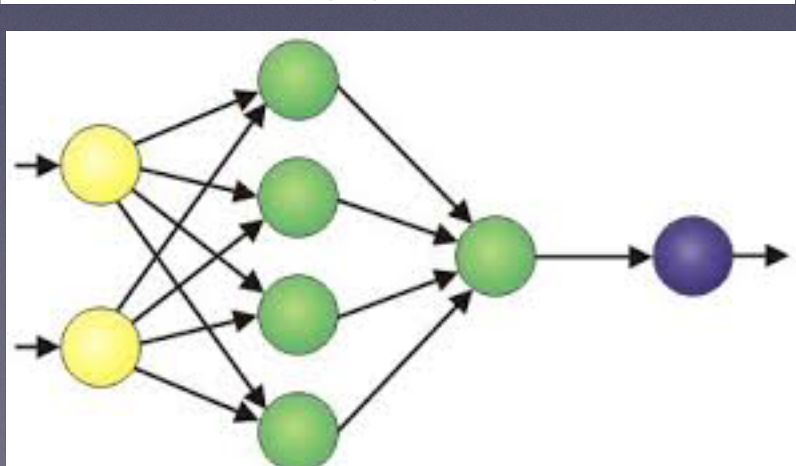
R. Utama,[*] J. Piekarewicz,[†] and H. B. Prosper[‡]
Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

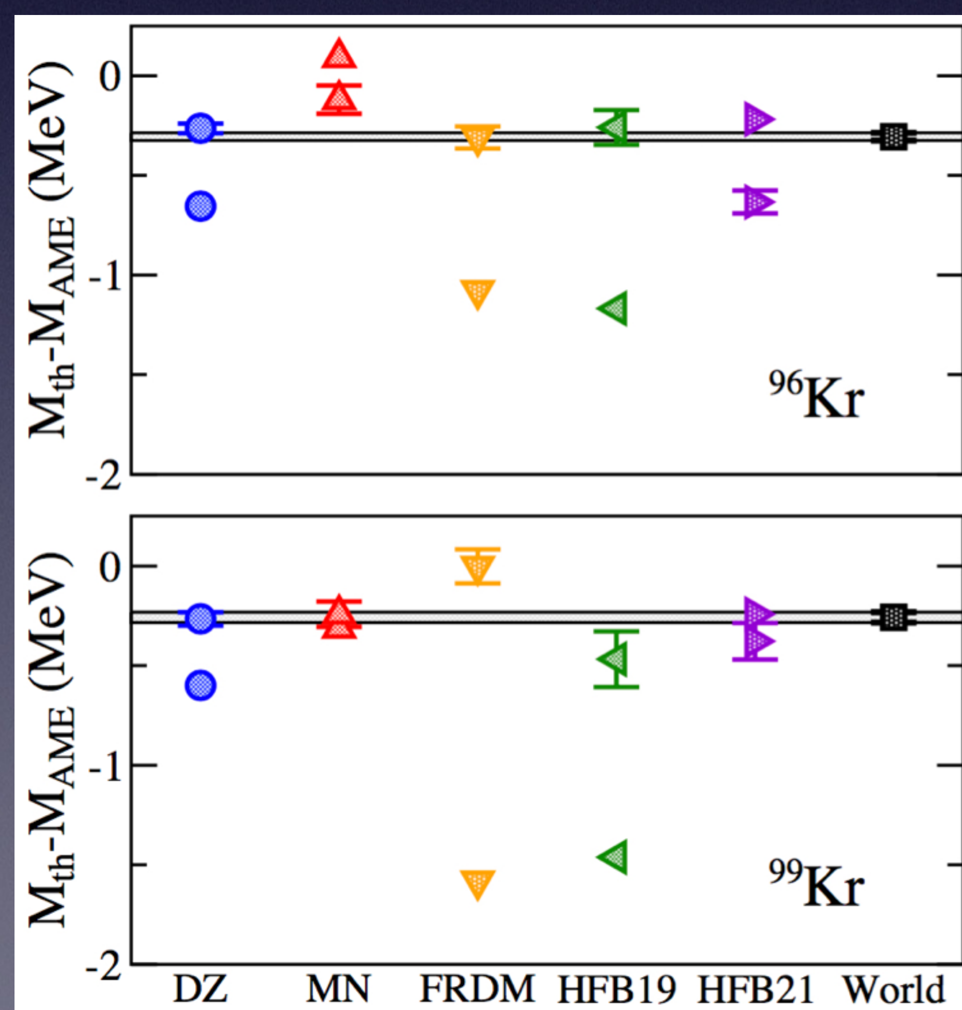
- Use DFT to predict nuclear masses
- Train BNN by focusing on residuals

$$M(N,Z) = M_{DFT}(N,Z) + \delta M_{BNN}(N,Z)$$

- Systematic scattering greatly reduced
- Predictions supplemented by theoretical errors







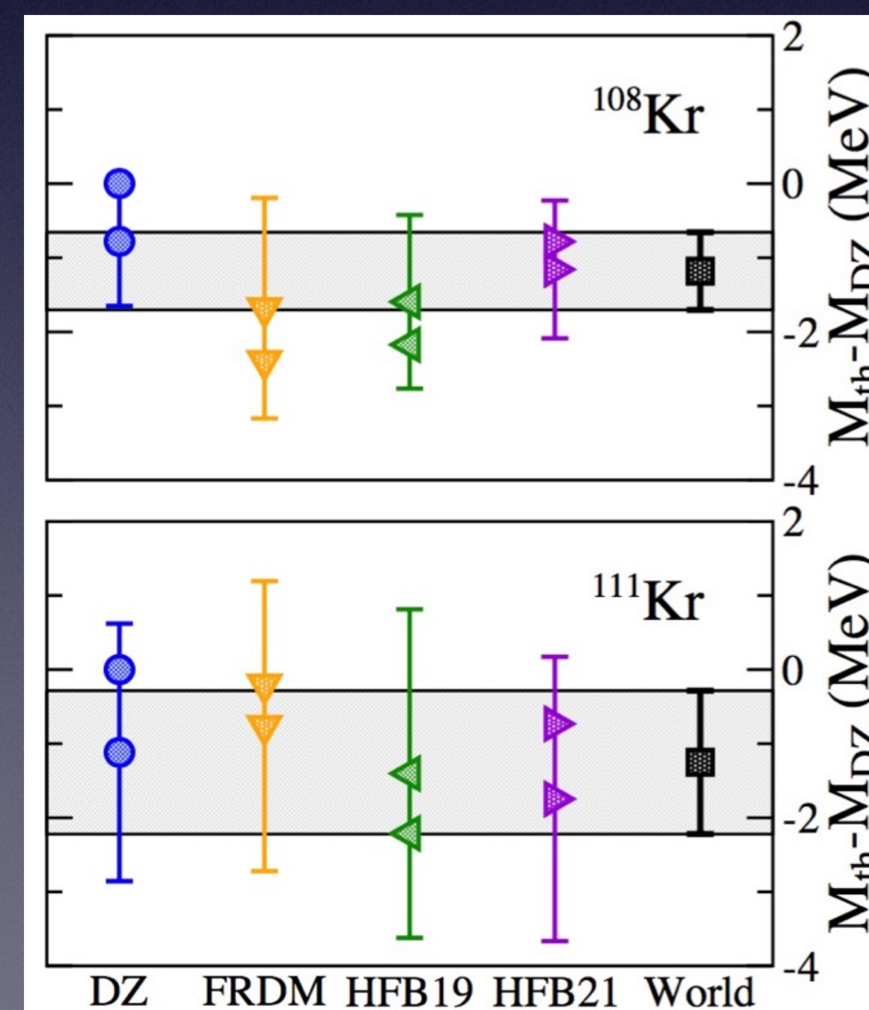


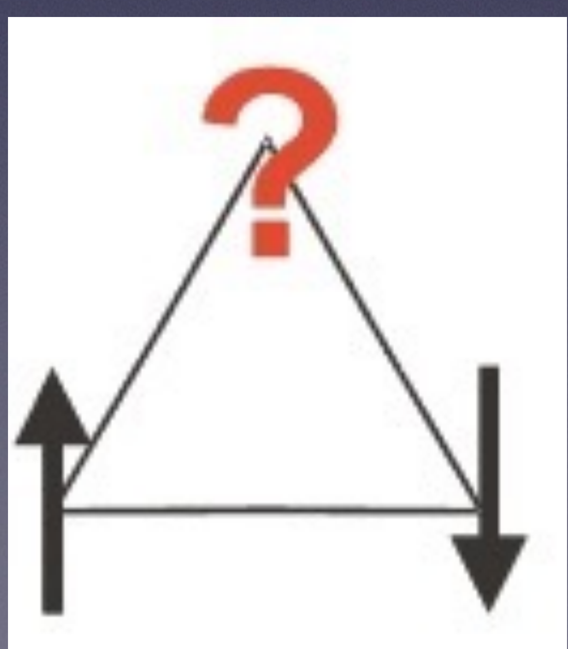
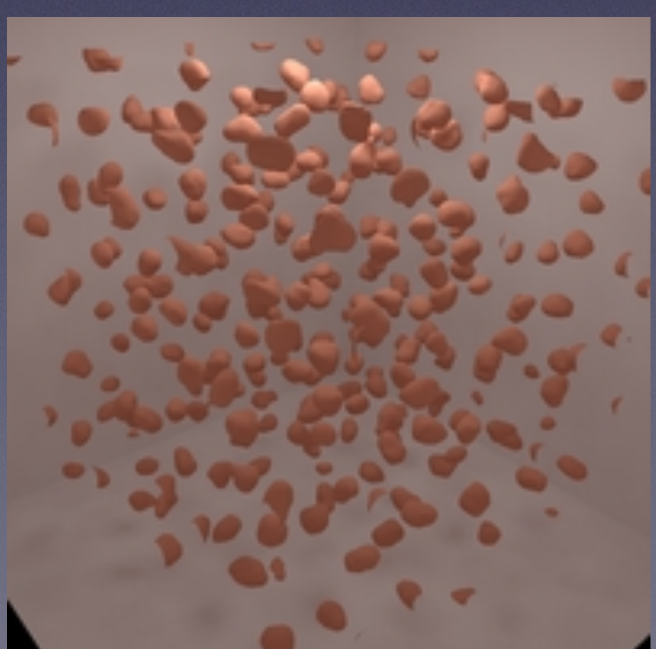
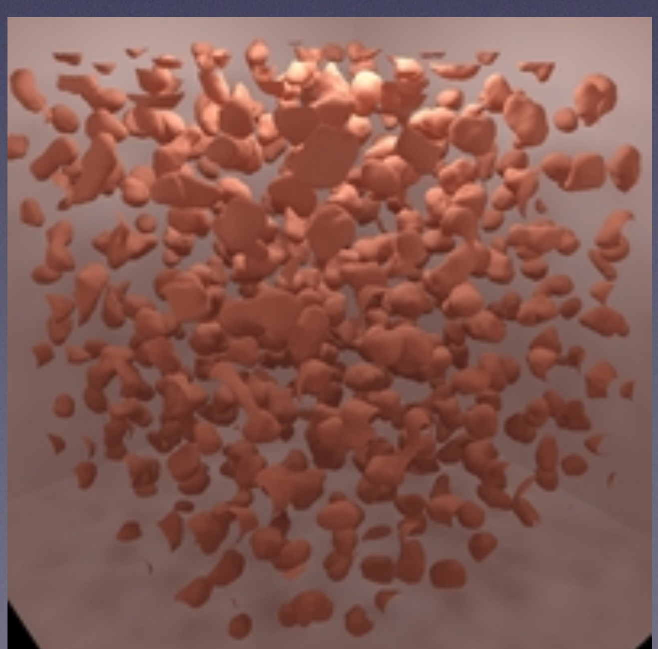
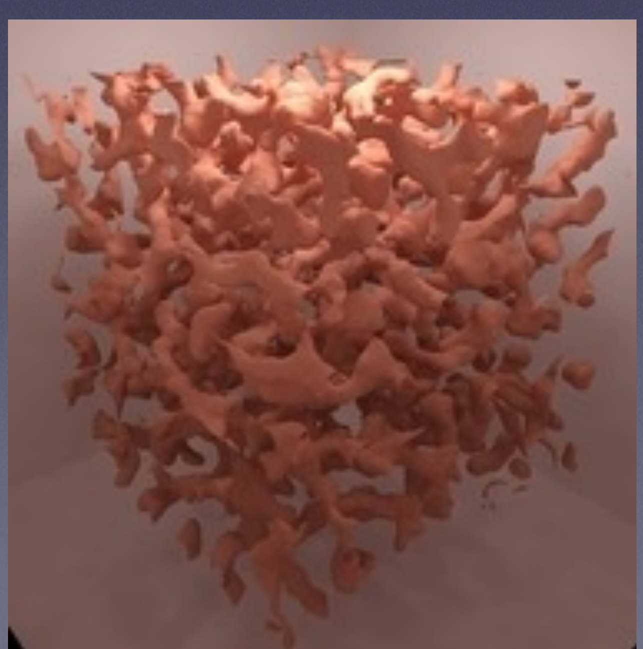
Image Reconstructions meets BNN

- Nature provides precise image of the world
- Models (DFT) aim to reproduce such image
- Image reconstruction (BNN) provides fine tuning

The Composition of the Inner Crust

Universal Phenomenon: Coulomb Frustration

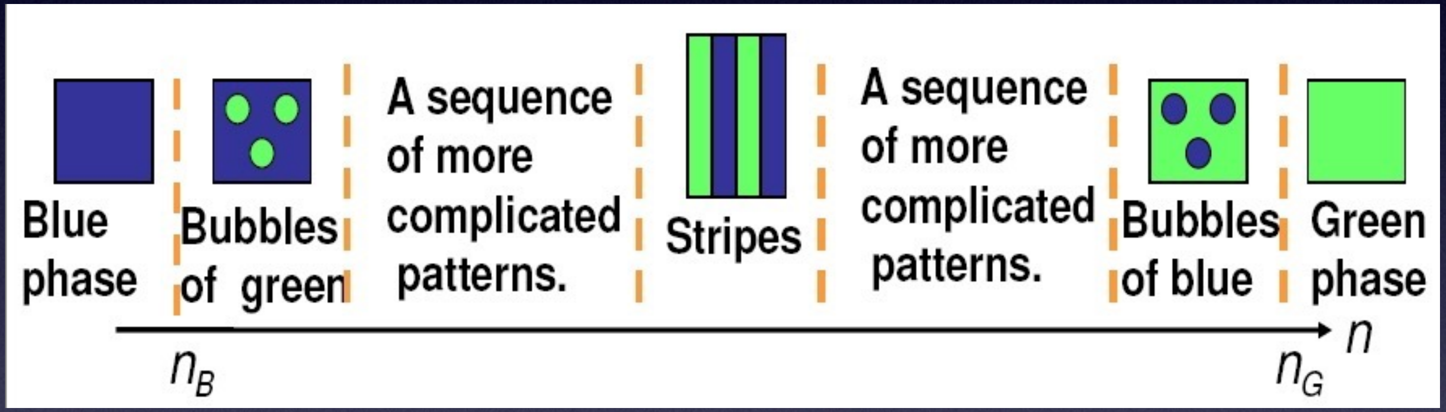
- Emerges from a dynamical competition:
  Between short-range nuclear attraction and long range Coulomb repulsion
- Impossibility to minimize all elementary interactions
  Simple to understand in the case of "geometric" frustration
- Emergence of multitude of competing "quasi" ground states
- Universal in complex systems
  Atomic nuclei, spin glasses, protein folding …
- Results in the emergence of complex topological nuclear shapes
  "Nuclear Pasta"

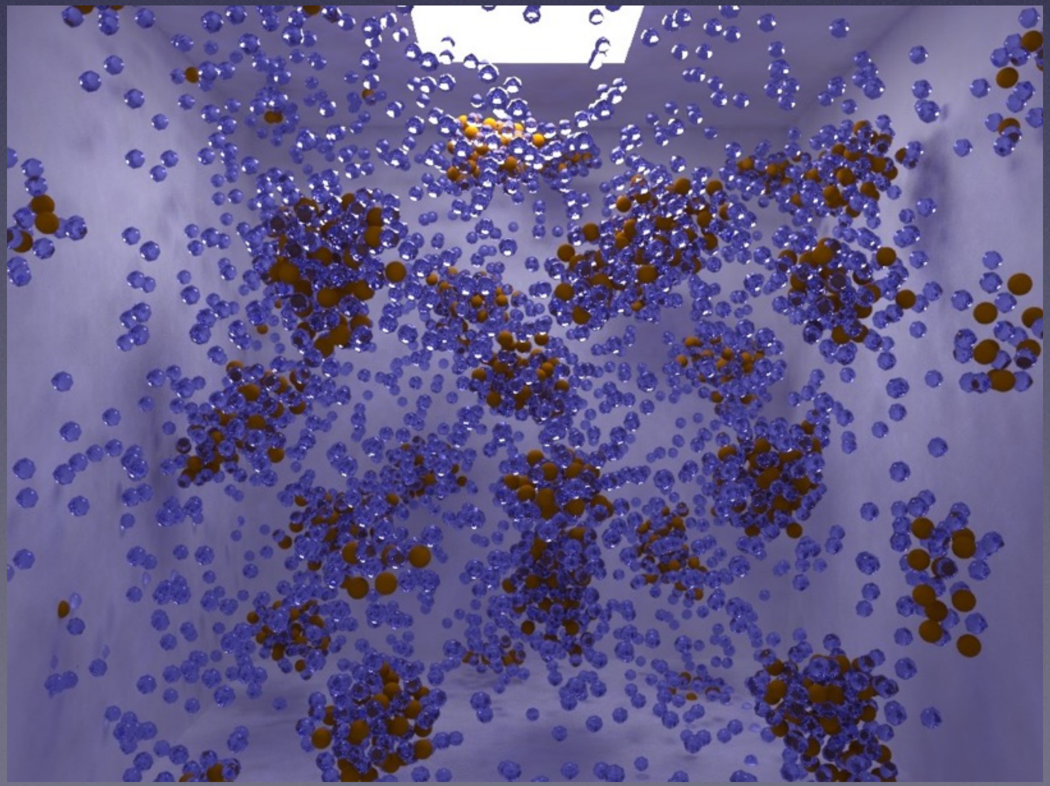





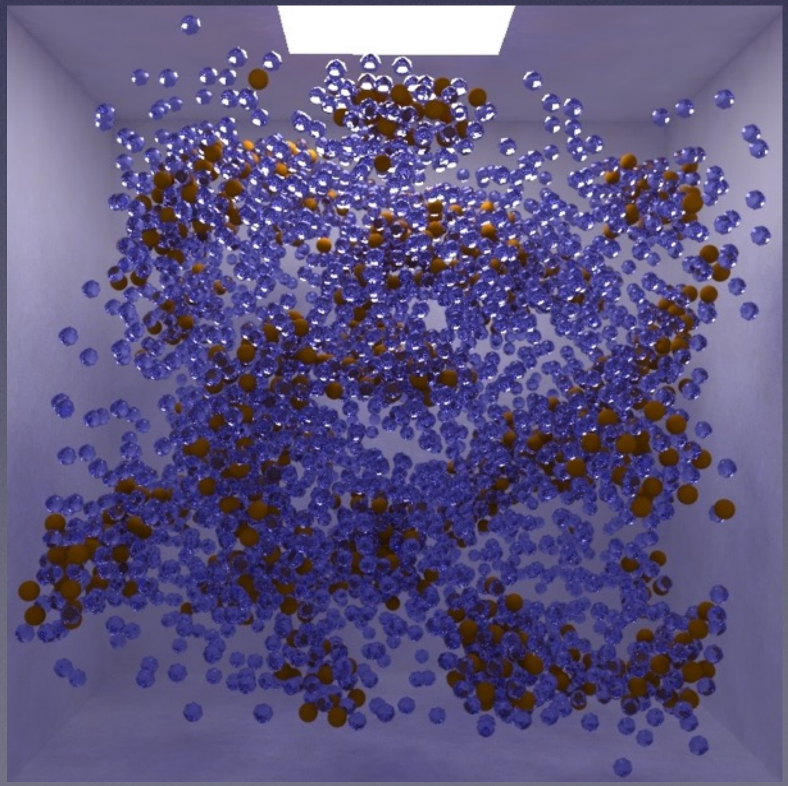
Universality of Coulomb Frustration: The two-dimensional electron gas

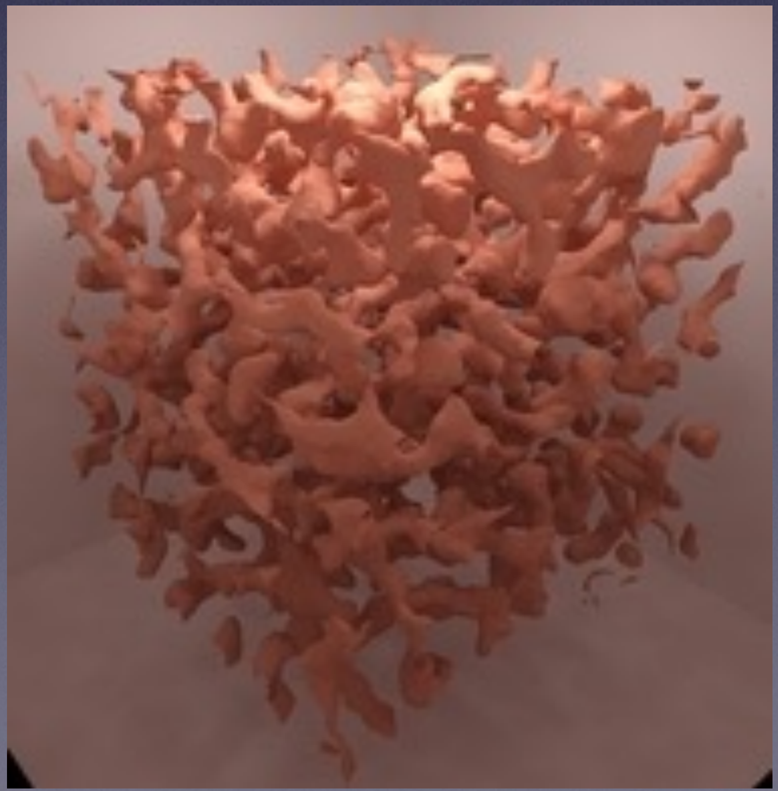
Theorem: In the presence of long range Interactions $V(r) \sim r^{-\alpha}$ no phase transition is possible for $d-1 \leq \alpha \leq d$

Rather, in place of the putative first-order phase transition there are intermediate micro emulsion phases.









How to Smell the Nuclear Pasta?

- Coulomb Crystal to Fermi Liquid transition mediated by nuclear pasta
- Experimental and observational signatures have proved elusive
- On Earth: Low-energy HI-collisions produce dilute neutron-rich matter
  However, produced matter is “warm” require model extrapolations
- On Heaven: Lack of isolated X-ray pulsars with long periods observed
  Magnetic fields with $B \gtrsim 10^{13}$ G suggest longer periods ($P \gtrsim 12$ seconds)
  Higher Resistive Layer (“Nuclear Pasta”) decreases electrical conductivity
  Decrease in electrical conductivity quenches the magnetic field
  Magnetic-field quenching hinders dipole emission limiting spin period

nature physics

ARTICLES

PUBLISHED ONLINE: 9 JUNE 2013 | DOI: 10.1038/NPHYS2640

A highly resistive layer within the crust of X-ray pulsars limits their spin periods *Nuclear Pasta?*

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.

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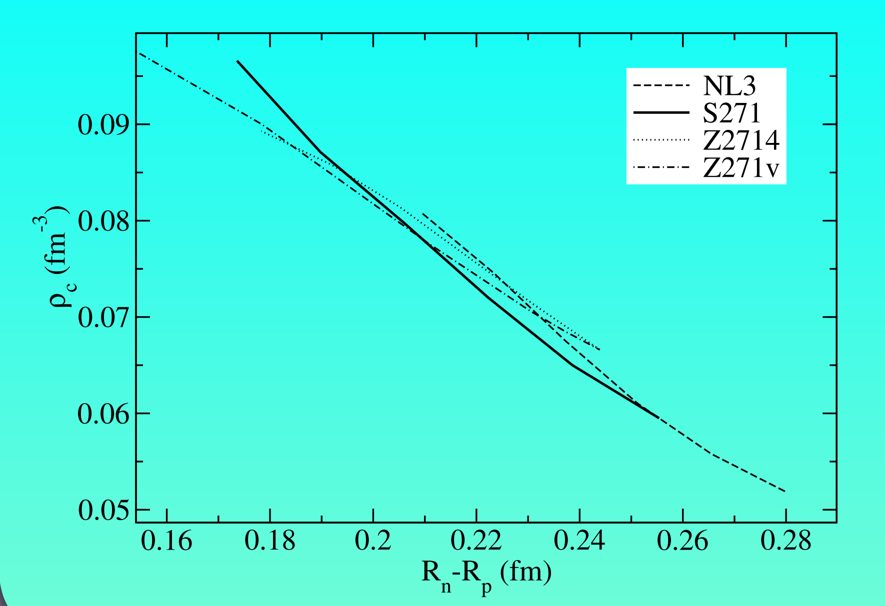


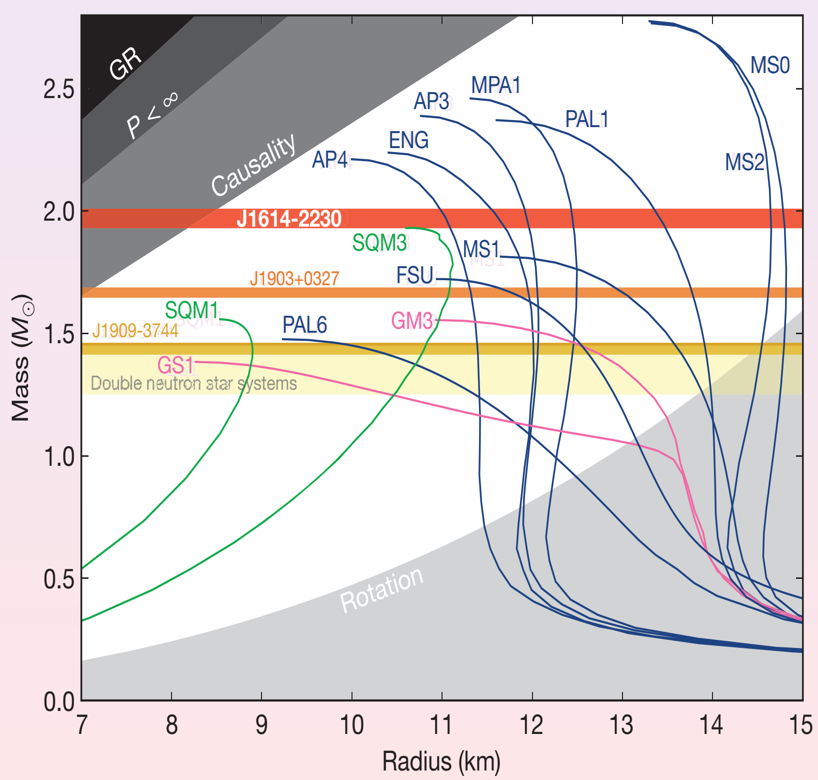
However, if skin is too thin, transition density is very high!

Neutron Stars: Unique Cosmic Laboratories

- Neutron stars are the remnants of massive stellar explosions (CCSN)
  - Bound by gravity — NOT by the strong force
  - Catalyst for the formation of exotic state of matter
  - Satisfy the Tolman-Oppenheimer-Volkoff equation ($v_{esc}/c \sim 1/2$)

- Only Physics that the TOV equation is sensitive to: Equation of State
  - EOS must span about 11 orders of magnitude in baryon density

- Increase from 0.7 → 2 Msun transfers ownership to Nuclear Physics!
- Predictions on stellar radii differ by several kilometers!



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

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

Need an EOS: $P = P(\mathcal{E})$ relation

Nuclear Physics Critical

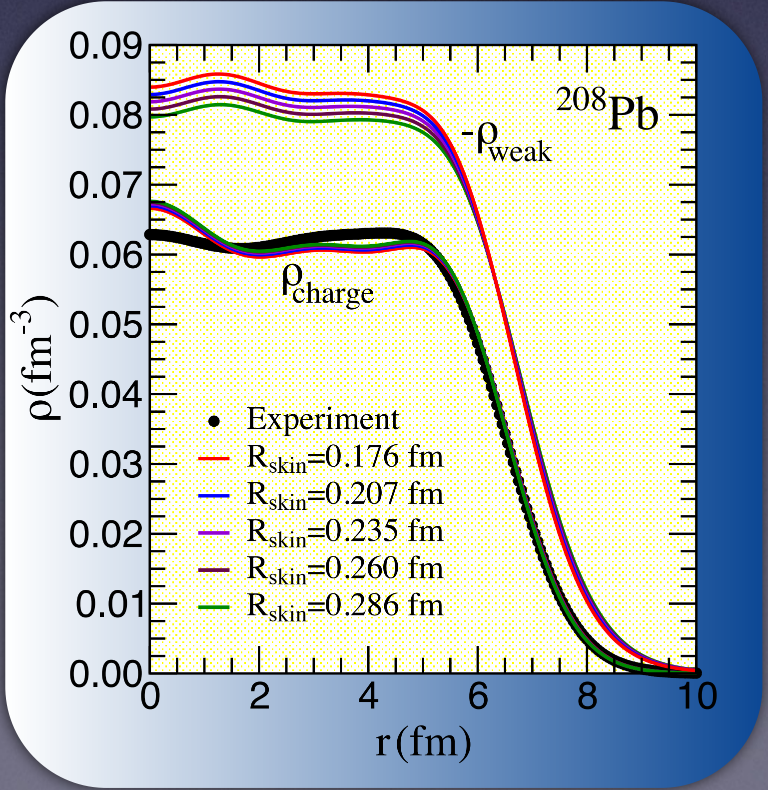
The Equation of State of Neutron-Rich Matter

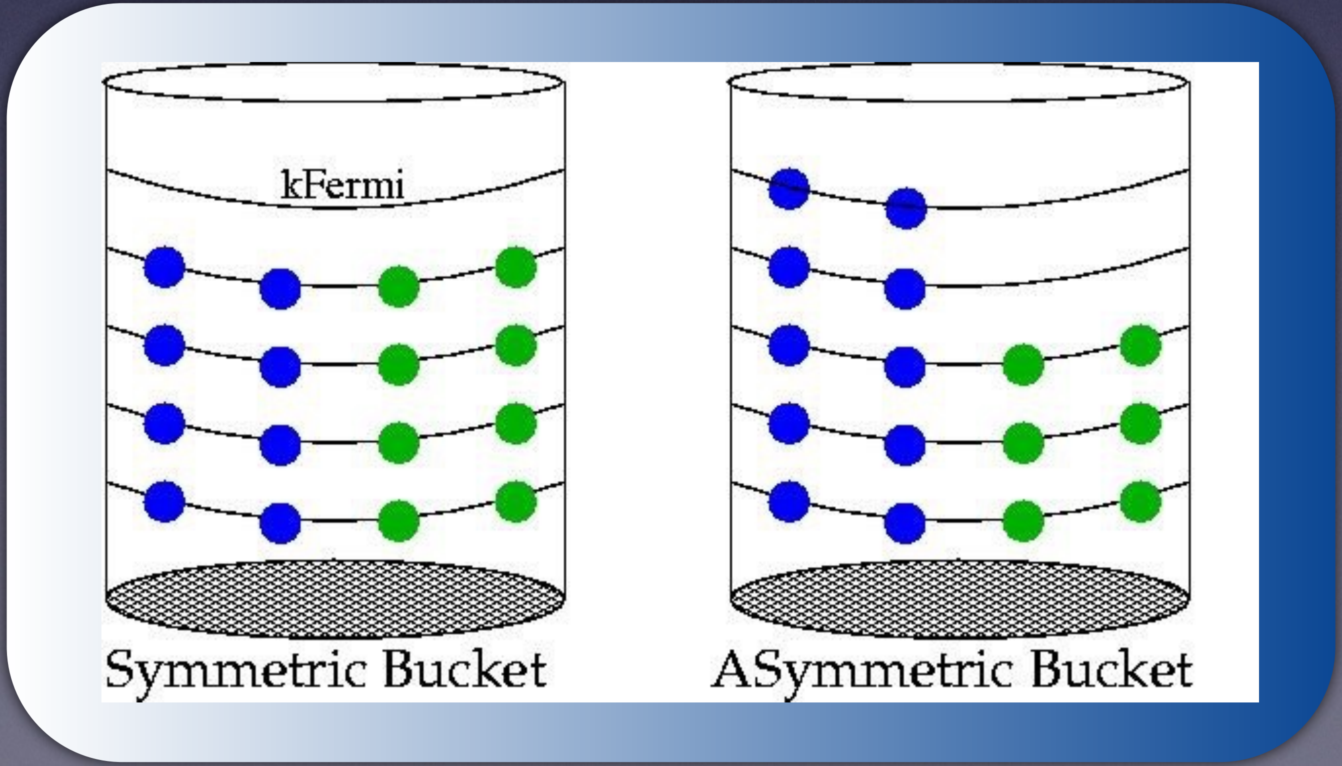
- The EOS of asymmetric matter: $\alpha=(N-Z)/A$; $x=(\rho-\rho_0)/3\rho_0$; $T=0$
  - $\rho_0 \simeq 0.15\ \mathrm{fm}^{-3}$ — saturation density ↔ nuclear density

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

- Symmetric nuclear matter saturates:
  - $\varepsilon_0 \simeq -16$ MeV — binding energy per nucleon ↔ nuclear masses
  - $K_0 \simeq 230$ MeV — nuclear incompressibility ↔ nuclear "breathing" mode

- Density dependence of symmetry poorly constrained:
  - $J \simeq 30$ MeV — symmetry energy ↔ masses of neutron-rich nuclei
  - $L \simeq$? — symmetry slope ↔ neutron skin (R_n-R_p) of heavy nuclei ?





Bayes' Theorem
Thomas Bayes (1701-1761)

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

- A simple example: "False Positives"
  - A: Individual is infected with the HIV virus
  - B: Individual tests positive to HIV test
- The priors and the likelihood
  - P(A) = 1/200 ("prior" knowledge; 0.5% of population is infected)
  - P(B|A) = 98/100 (likelihood of the evidence; accuracy of test)
  - P(B) = (1/200)*(98/100)+(199/200)*(2/100) = 496/(100*200)
- The odds: the posterior probability
  - P(A|B) = 49/248 $\simeq$ 20% (odds have increased from 0.5% but still very far away from 98%)

Bayes' Theorem: Application to Model Building

PHYSICAL REVIEW C **90**, 044305 (2014)

Building relativistic mean field models for finite nuclei and neutron stars

Wei-Chia Chen[*] and J. Piekarewicz[†]
Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

$$P(M|D) = \frac{P(D|M)\,P(M)}{P(D)}$$

Posterior ← $P(M|D)$; Likelihood ← $P(D|M)$; $P(M)$ → Prior; $P(D)$ → Marginal Likelihood

- QCD is the fundamental theory of the strong interactions!
  - M: A theoretical MODEL with parameters and biases
  - D: A collection of experimental and observational DATA
- The Prior *P(M)*: An insightful transformation in DFT

$$(g_{\rm s}, g_{\rm v}, g_{\rho}, \kappa, \lambda, \Lambda_{\rm v}) \Longleftrightarrow (\rho_0, \epsilon_0, M^*, K, J, L)$$

- The Likelihood $P(D|M) \simeq exp(-\chi^2/2)$

$$\chi^2(D,M) = \sum_{n=1}^{N} \frac{\left(O_n^{\rm (th)}(M) - O_n^{\rm (exp)}(D)\right)^2}{\Delta O_n^2}$$

- The Marginal Likelihood; overall normalization factor

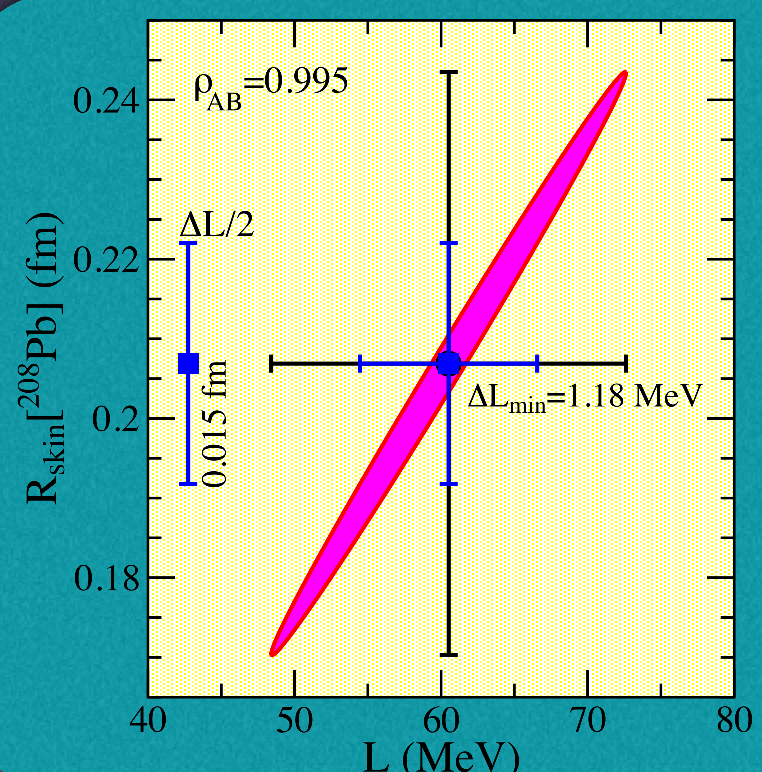
Searching for L: The Strategy

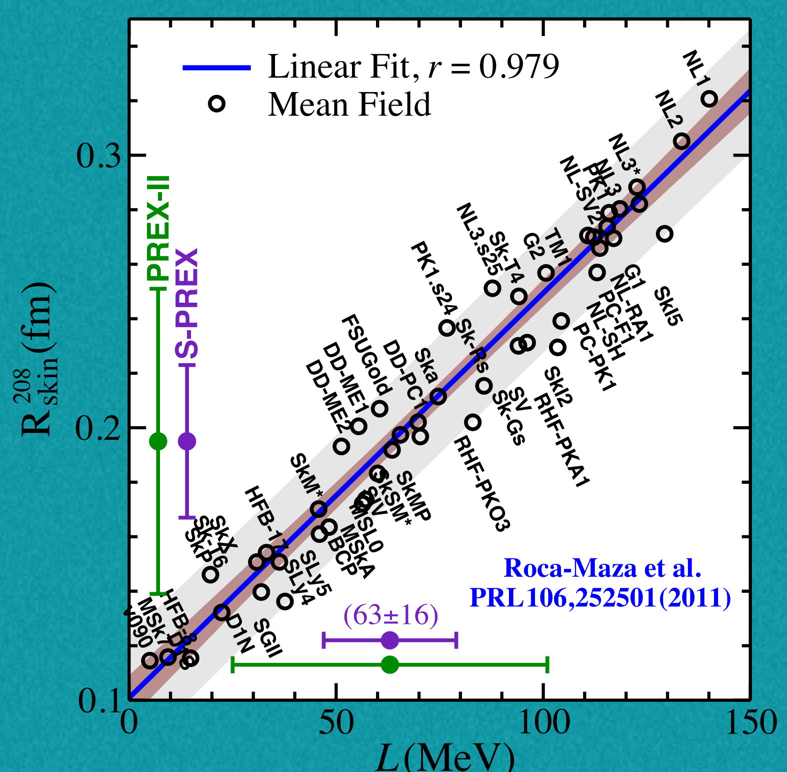
$P_{PNM} \simeq L\rho_0/3$ is not a physical observable

- Establish a powerful physical argument connecting L to R_{skin}
  - Where do the extra 44 neutrons in ^{208}Pb go? Competition between surface tension and the *difference* $S(\rho_0)$-$S(\rho_{surf}) \simeq L$.
    The larger the value of L, the thicker the neutron skin of ^{208}Pb

- Ensure that "your" accurately-calibrated DFT supports the correlation
  - Statistical Uncertainty: Theoretical error bars and correlation coefficients
  - What precision in R_{skin} is required to constrain L to the desire accuracy?

- Ensure that "all" accurately-calibrated DFT support the correlation
  - Systematic Uncertainty: As with all systematic errors, much harder to quantify
    (… "all models are equal but some models are more equal than others")





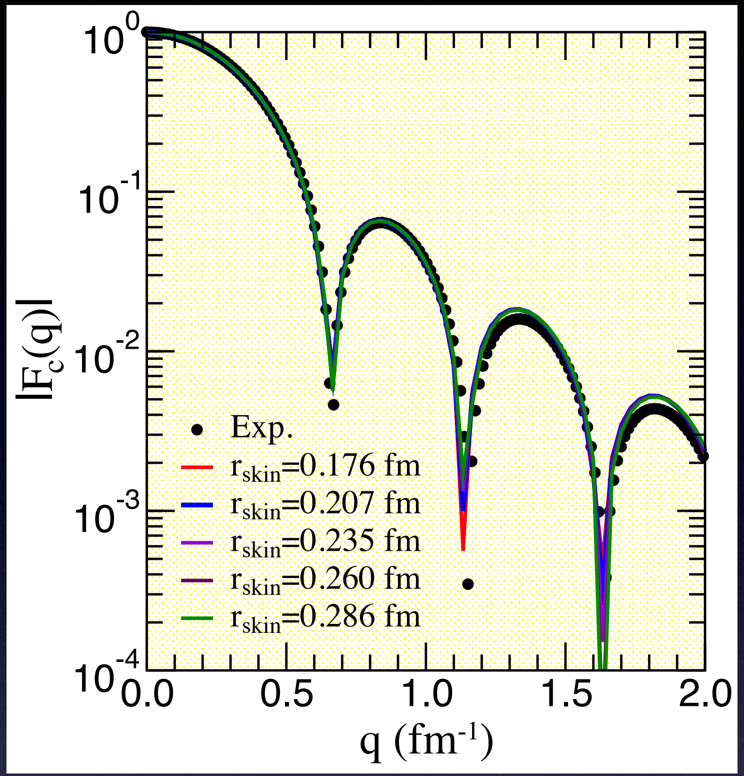
New era in Nuclear Theory where predictability will be typical and uncertainty quantification will be demanded …

Theory Informing Experiment

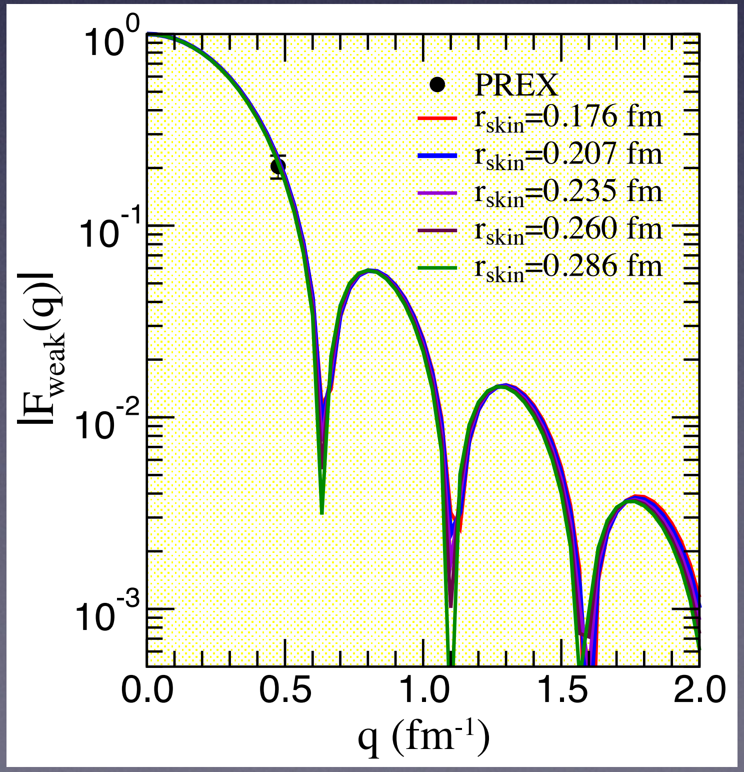
- PREX@JLAB: First electroweak evidence in favor of R_{skin} in Pb (error bars too large!)
- Precision required in the determination of the neutron radius/skin?
  - As precisely as "humanly possible" - fundamental nuclear structure property (*cf.* charge density)
  - To strongly impact Astrophysics?
- Is there a need for a systematic study over "many" nuclei?
  PREX, CREX, SREX, ZREX, …
- Is there a need for more than one q-point?
  Radius and diffuseness … or the whole form factor?

These questions were just addressed at the MITP Program "Neutron Skins of Nuclei"
Mainz, May 17-27, 2016

$R_{ch} = 5.5012(13)$ fm



$R_{wk} = 5.826(181)$ fm



Heaven and Earth

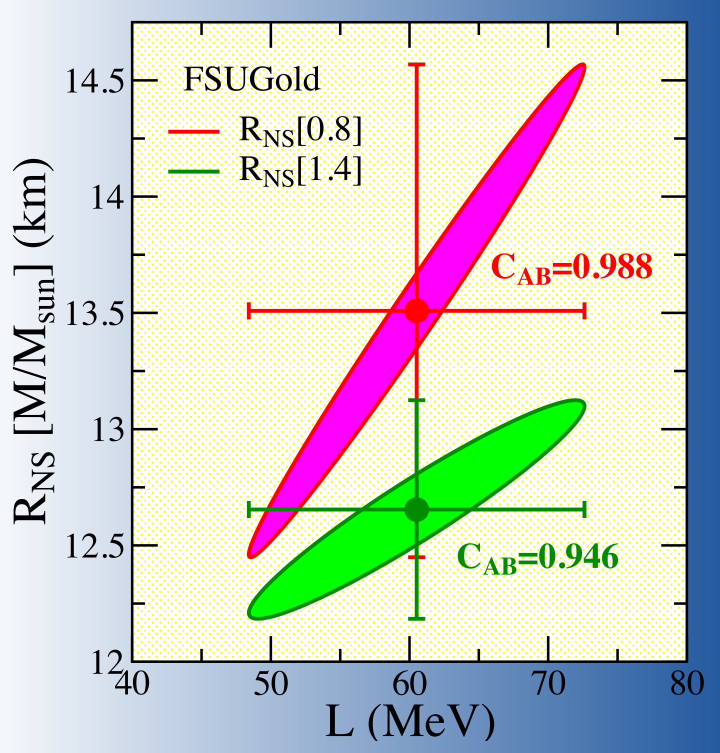
The enormous reach of the neutron skin

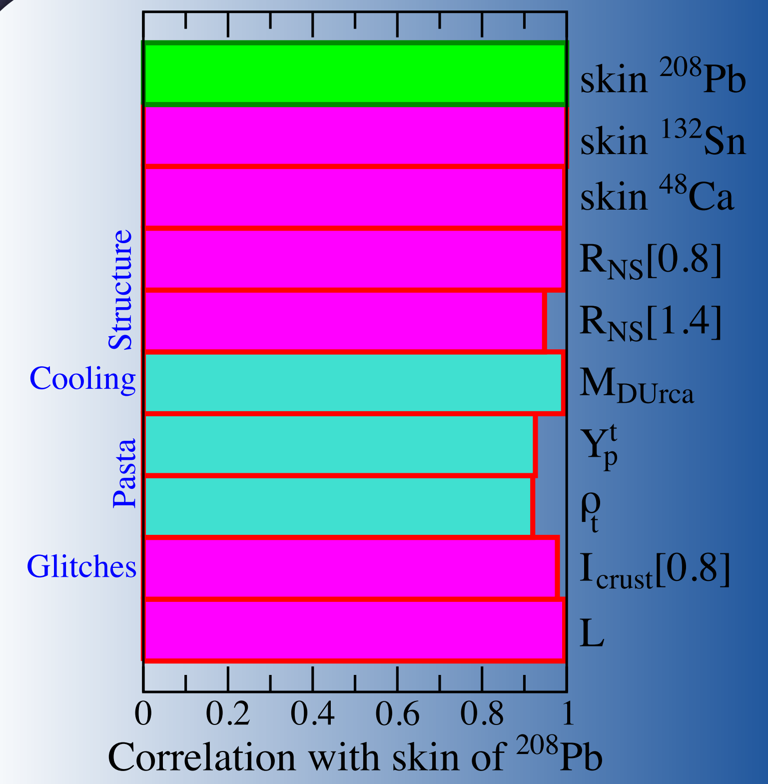
- Neutron-star radii are sensitive to the EOS near $2\rho_0$
  - Neutron star masses sensitive to EOS at much higher density

- Neutron skin correlated to a host of neutron-star properties
  - Stellar radii, proton fraction, enhanced cooling, moment of inertia

- We are at a dawn of a new era … *the train has left the station*

  Predictability typical and uncertainty quantification demanded!



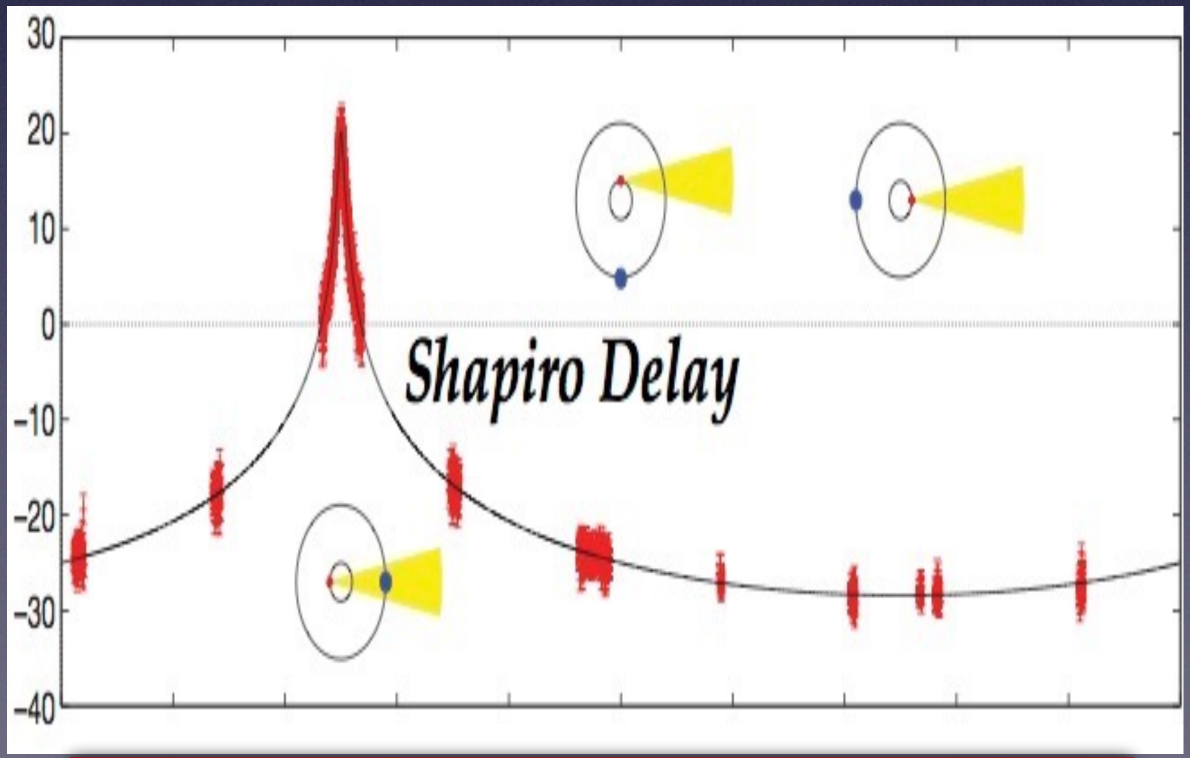


PHYSICAL REVIEW A 83, 040001 (2011)
Editorial: Uncertainty Estimates

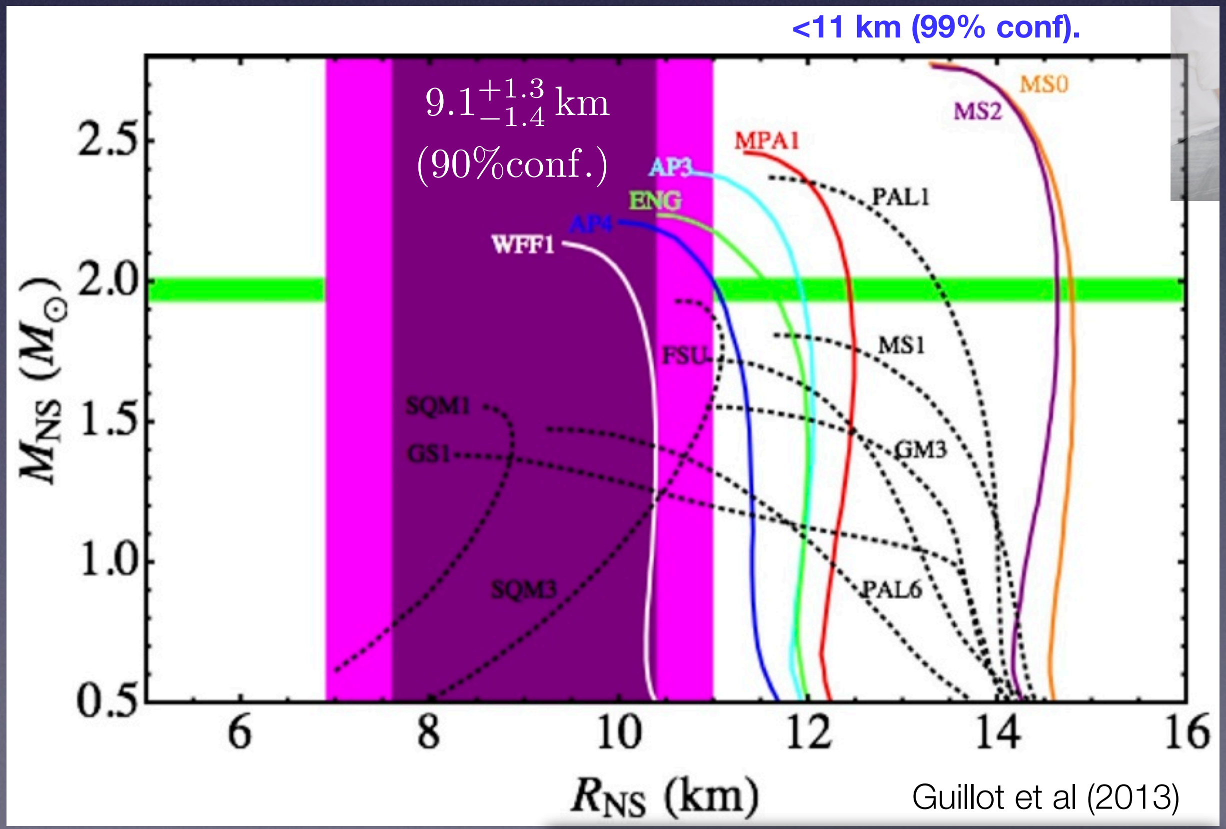
Papers presenting the results of theoretical calculations are expected to include uncertainty estimates for the calculations whenever practicable …

Addressing Future Challenges

- Same dynamical origin to neutron skin and NS radius
  - Same pressure pushes against surface tension and gravity!
  - Correlation involves quantities differing by 18 orders of magnitude!
  - NS radius may be constrained in the laboratory (PREX-II, CREX, …)
- However, a significant tension has recently emerged!
  - Stunning observations have established the existence of massive NS
  - Recent observations has suggested that NS have small radii
  - Extremely difficult to reconcile both; perhaps evidence of a phase transition?



Time delay due to NS radiation dipping into gravitational well of WD!

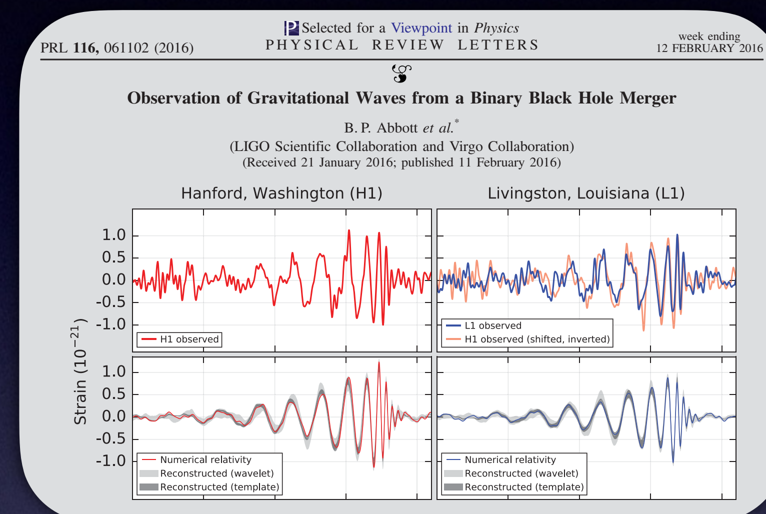


WFF1 violates causality!

"We have detected gravitational waves. We did it"
David Reitze, February 11, 2016

The dawn of gravitational wave astronomy

- Initial black hole masses are 36 and 29 solar masses
- Final black hole mass is 62 solar masses, 3 solar masses radiated in GW

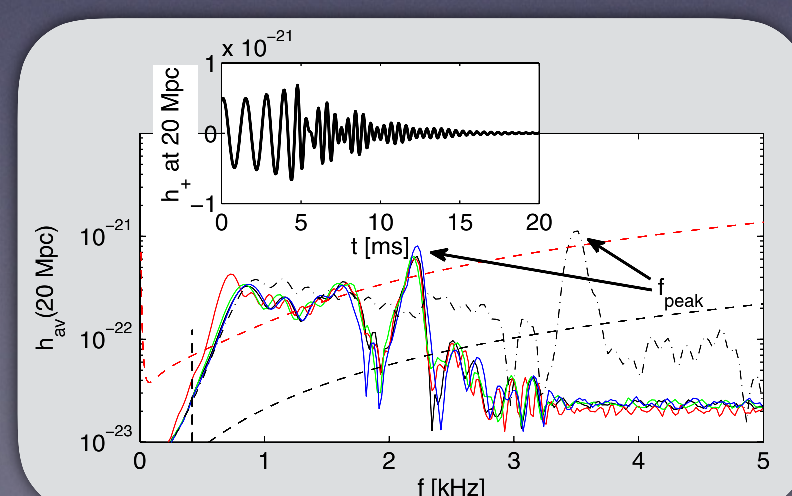

Selected for a Viewpoint in Physics
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

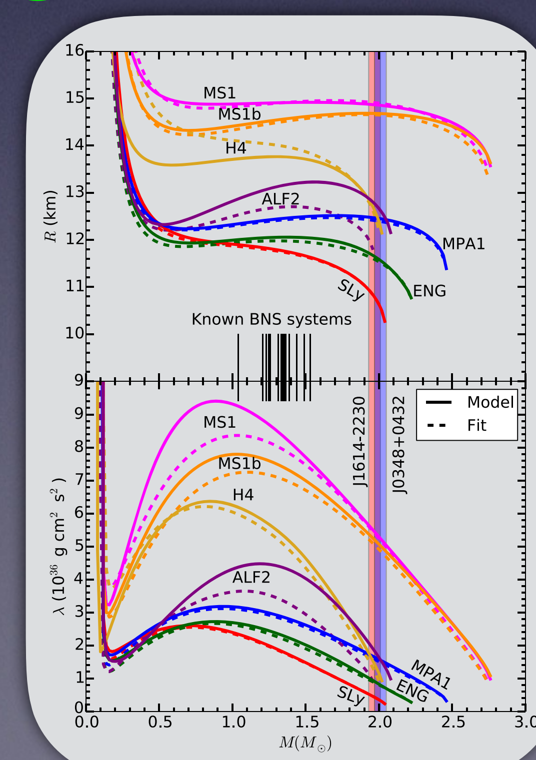
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

What will we learn from NS mergers?

- Tidal polarizability scales as R^5 …
- NS radius can be measured to better than 1km!





Conclusions: It is all Connected

- Astrophysics: What is the minimum mass of a black hole?
- Atomic Physics: Is pure neutron matter a unitary Fermi gas?
- C.Matter Physics: Is there a Coulomb crystal to Fermi liquid transition?
- General Relativity: Can NS mergers constrain stellar radii?
- Nuclear Physics: What is the EOS of neutron-rich matter?
- Particle Physics: What exotic phases inhabit the dense core?

Neutron Stars are the natural meeting place for interdisciplinary, fundamental, and fascinating physics!