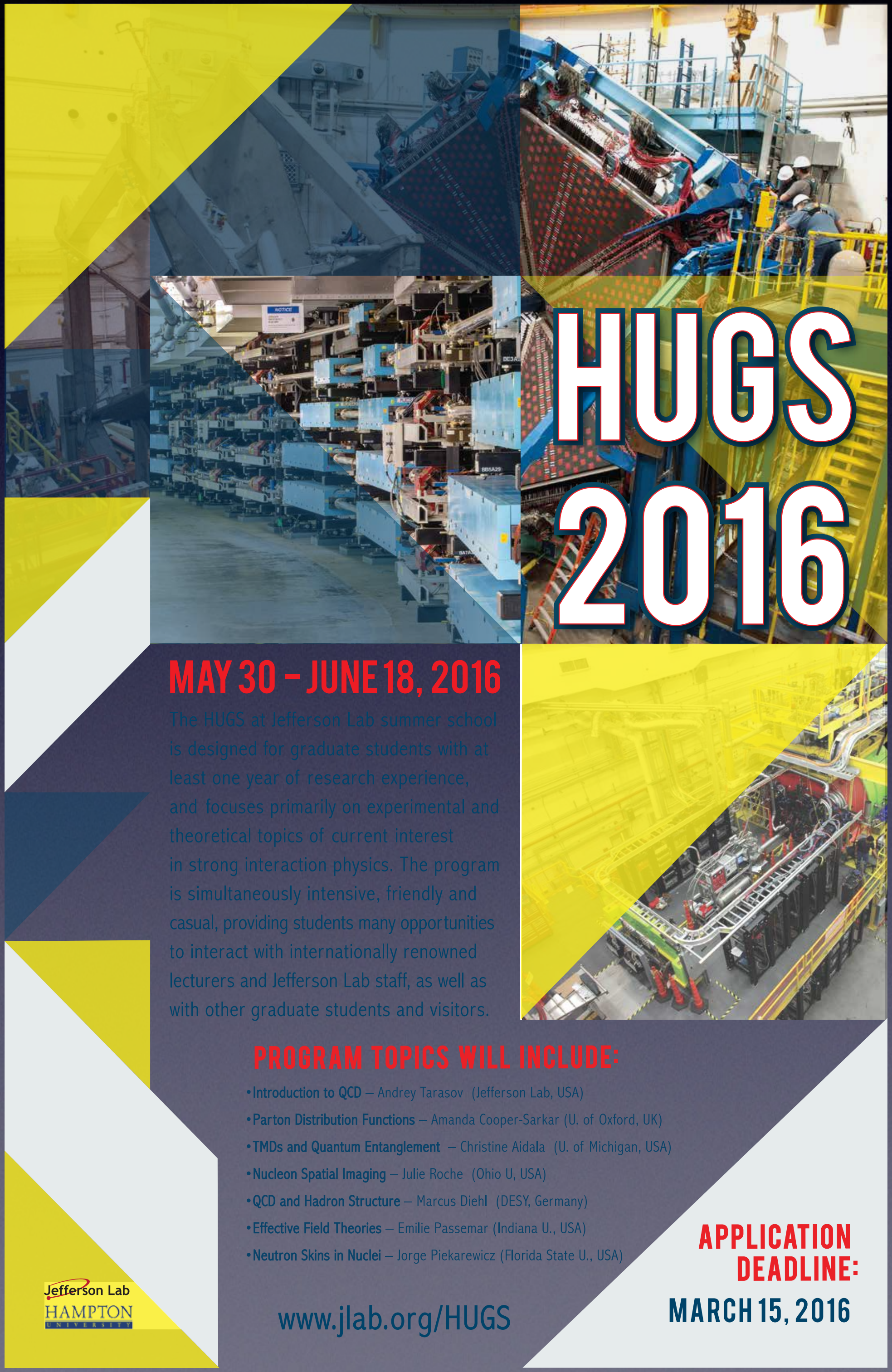
Neutron Skins in Nuclei

31st Annual HUGS Program

(Jorge Piekarewicz - FSU)



HUGS 2016

MAY 30 – JUNE 18, 2016

The HUGS at Jefferson Lab summer school is designed for graduate students with at least one year of research experience, and focuses primarily on experimental and theoretical topics of current interest in strong interaction physics. The program is simultaneously intensive, friendly and casual, providing students many opportunities to interact with internationally renowned lecturers and Jefferson Lab staff, as well as with other graduate students and visitors.

PROGRAM TOPICS WILL INCLUDE:

- **Introduction to QCD** – Andrey Tarasov (Jefferson Lab, USA)
- **Parton Distribution Functions** – Amanda Cooper-Sarkar (U. of Oxford, UK)
- **TMDs and Quantum Entanglement** – Christine Aidala (U. of Michigan, USA)
- **Nucleon Spatial Imaging** – Julie Roche (Ohio U, USA)
- **QCD and Hadron Structure** – Marcus Diehl (DESY, Germany)
- **Effective Field Theories** – Emilie Passemar (Indiana U., USA)
- **Neutron Skins in Nuclei** – Jorge Piekarewicz (Florida State U., USA)

www.jlab.org/HUGS

APPLICATION DEADLINE:
MARCH 15, 2016

Jefferson Lab
HAMPTON UNIVERSITY

The 208 Pb Radius EXperiment
PREX

and Neutron Rich Matter in the Heavens and on Earth

August 17-19 2008

Jefferson Lab

Newport News, Virginia

PREX is a fascinating experiment that uses parity violation to accurately determine the neutron radius in ^{208}Pb. This has broad applications to astrophysics, nuclear structure, atomic parity non-conservation and tests of the standard model. The conference will begin with introductory lectures and we encourage new comers to attend.

For more information contact horowit@indiana.edu

TOPICS

Parity Violation

Theoretical descriptions of neutron-rich nuclei and bulk matter

Laboratory measurements of neutron-rich nuclei and bulk matter

Neutron-rich matter in Compact Stars / Astrophysics

Website: http://conferences.jlab.org/PREX

ORGANIZING COMMITTEE

Chuck Horowitz (Indiana)
Kees de Jager (JLAB)
Jim Lattimer (Stony Brook)
Witold Nazarewicz (UTK, ORNL)
Jorge Piekarewicz (FSU

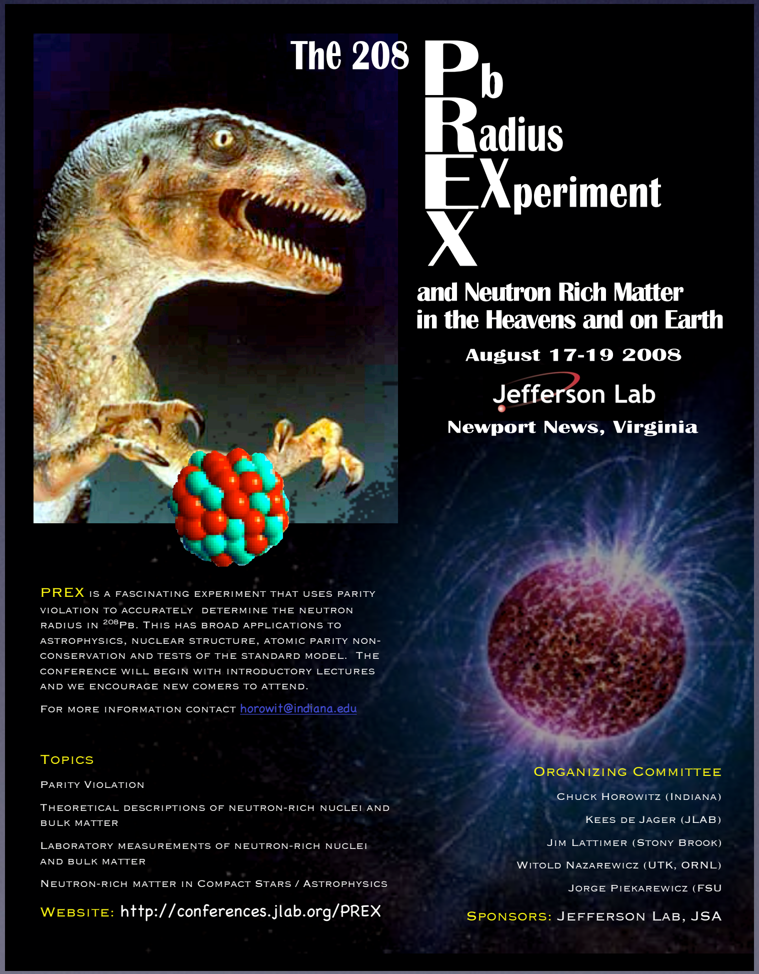
Sponsors: Jefferson Lab, JSA

Heaven on Earth
PREX informing Astrophysics

Outline

1. Historical Context
2. How does matter organize itself?
3. Gravitationally Bound Neutron Stars
4. Anatomy of a Neutron Star
5. The Nuclear Symmetry Energy
6. Laboratory Constraints on the EOS
7. Astrophysical Constraints on the EOS
8. Conclusions and Outlook

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



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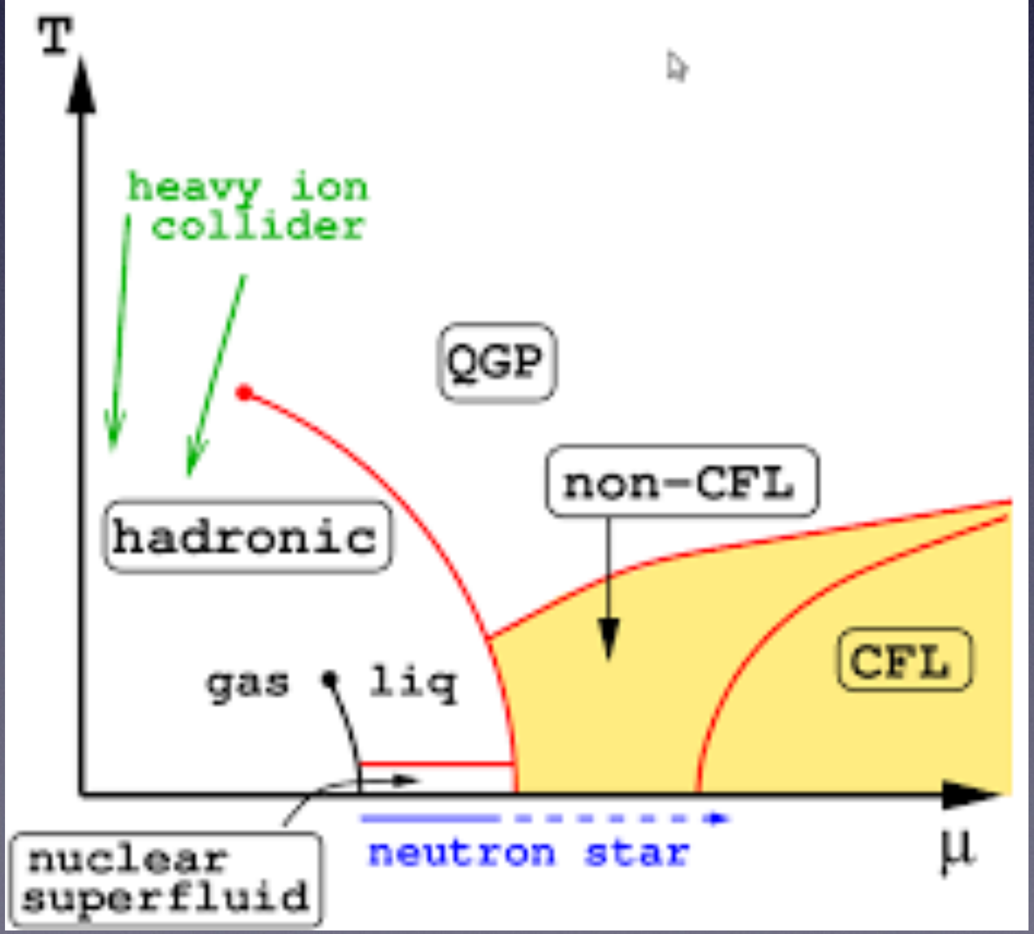
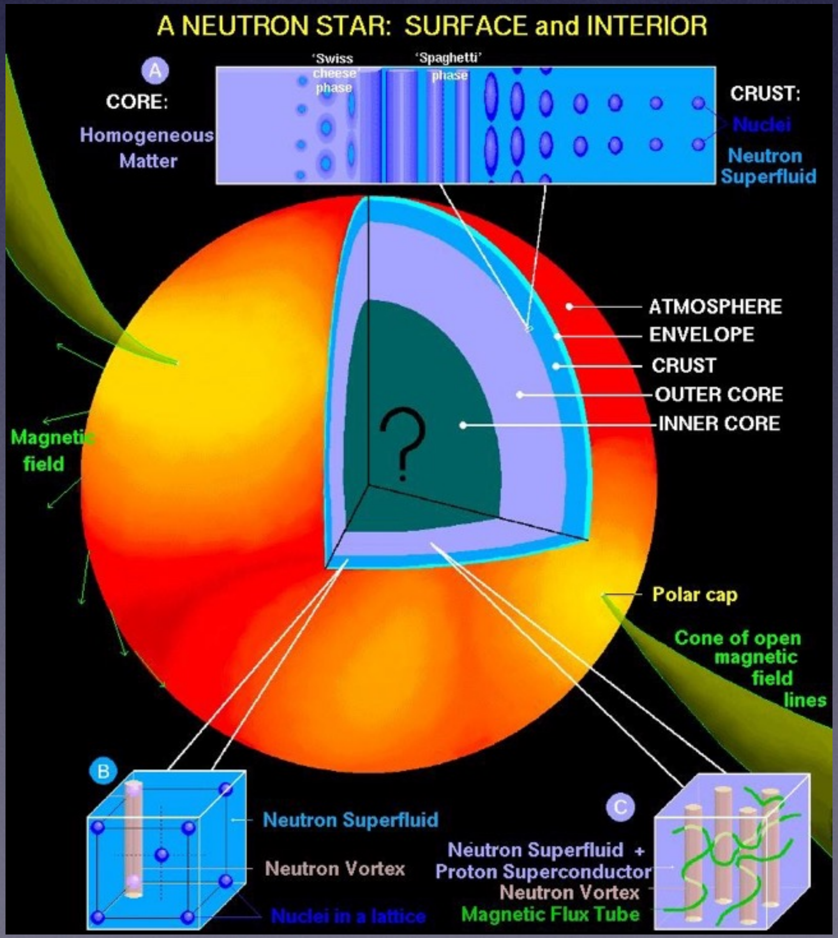
Color Superconductivity in Quark Matter

- At small distance scales QCD becomes asymptotically free
- At high densities Color-Coulomb interaction is weak and attractive
- At ultra-high densities (u,d,s) quarks are effectively massless
- Ground state: color-flavor locked (CFL) superconductor
  Pairing Instability "locks" color and flavor $\langle q_i^a q_j^b \rangle \sim \Delta \epsilon_{ijk} \epsilon^{abc} \delta_c^k$
- However, if $m_s \simeq \mu$ it is unclear the most favorable pairing pattern





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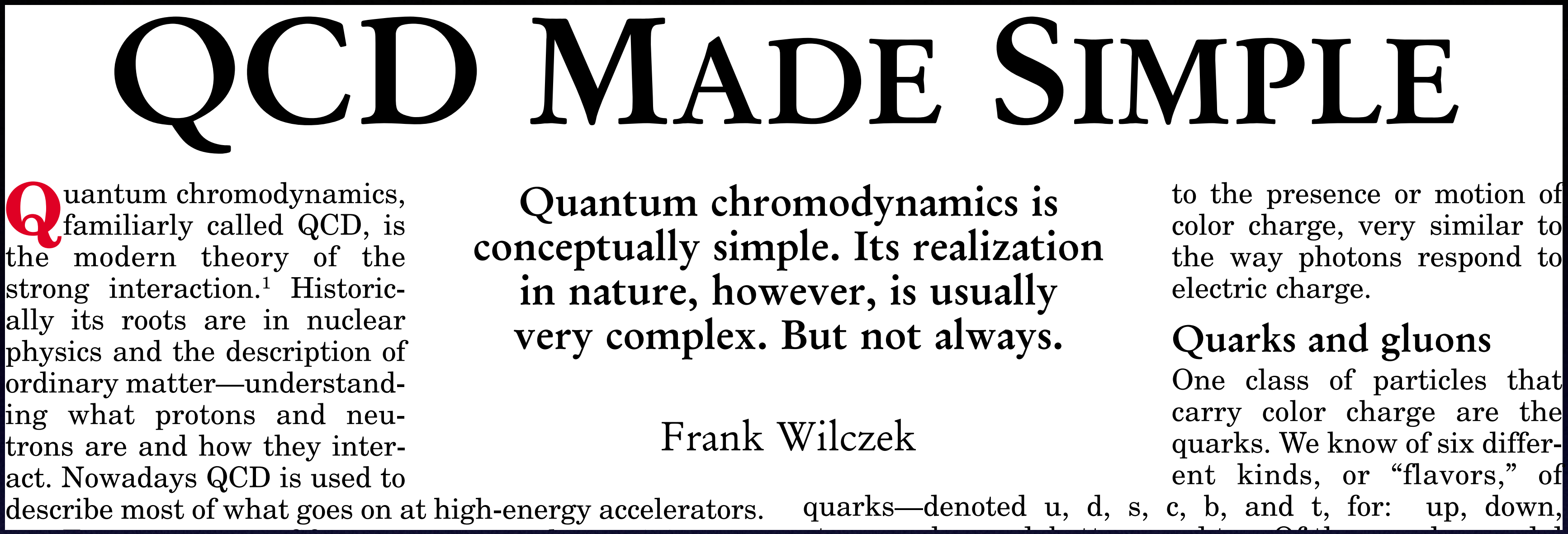


QCD Made Simple

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

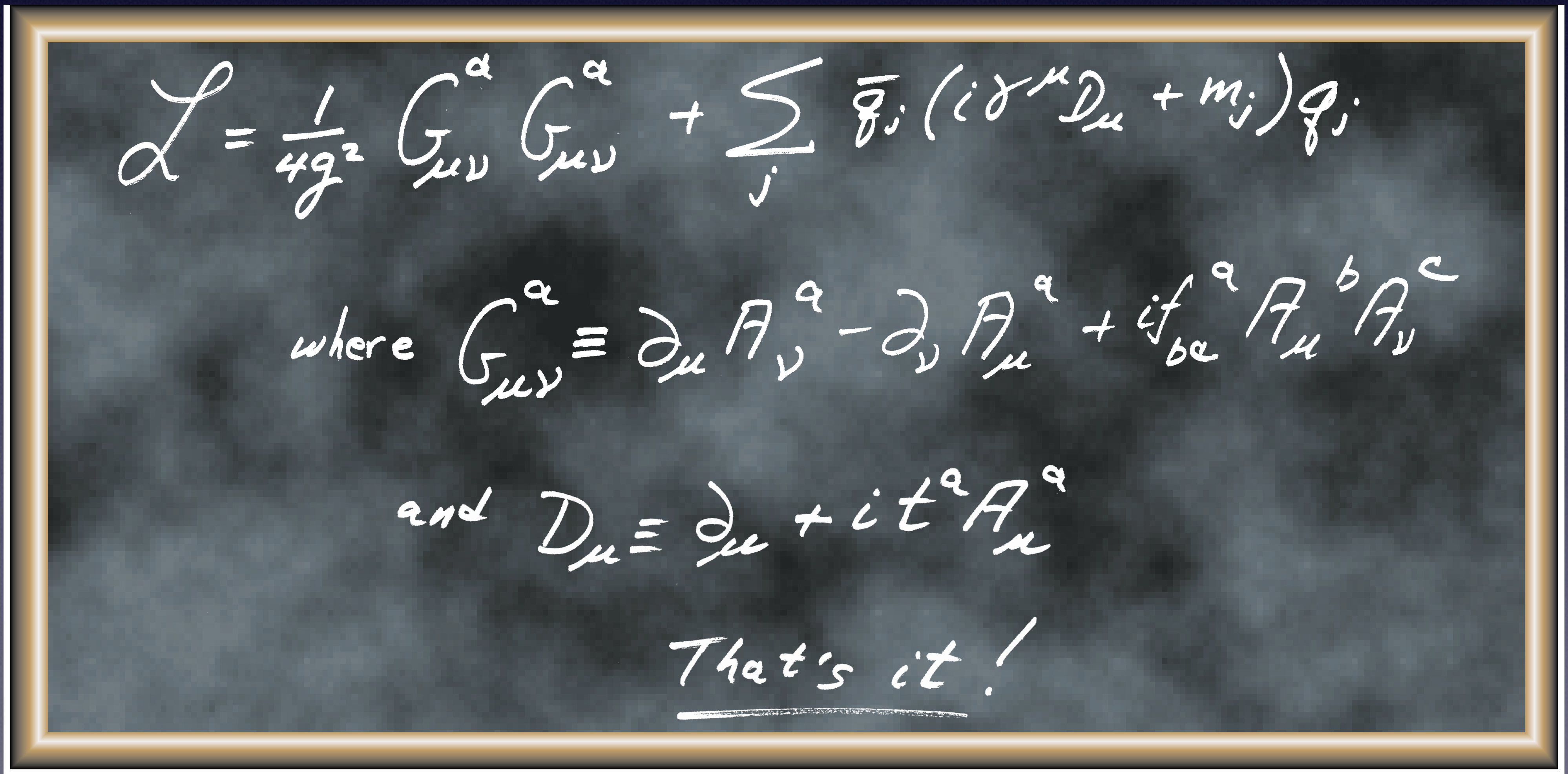
One class of particles that carry color charge are the quarks. We know of six different kinds, or "flavors," of quarks—denoted u, d, s, c, b, and t, for: up, down,

Frank Wilczek

2004 Nobel Laureate

Herman Feshbach Professor of Physics

Massachusetts Institute of Technology



$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

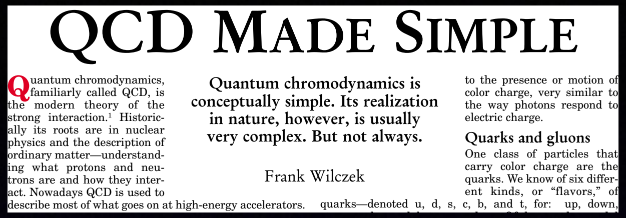
where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$

and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

That's it!

Physics Today - August, 2000

Emergent Phenomena in QCD



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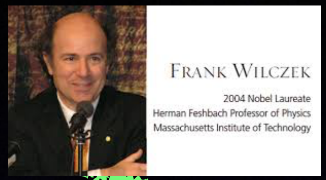

FRANK WILCZEK
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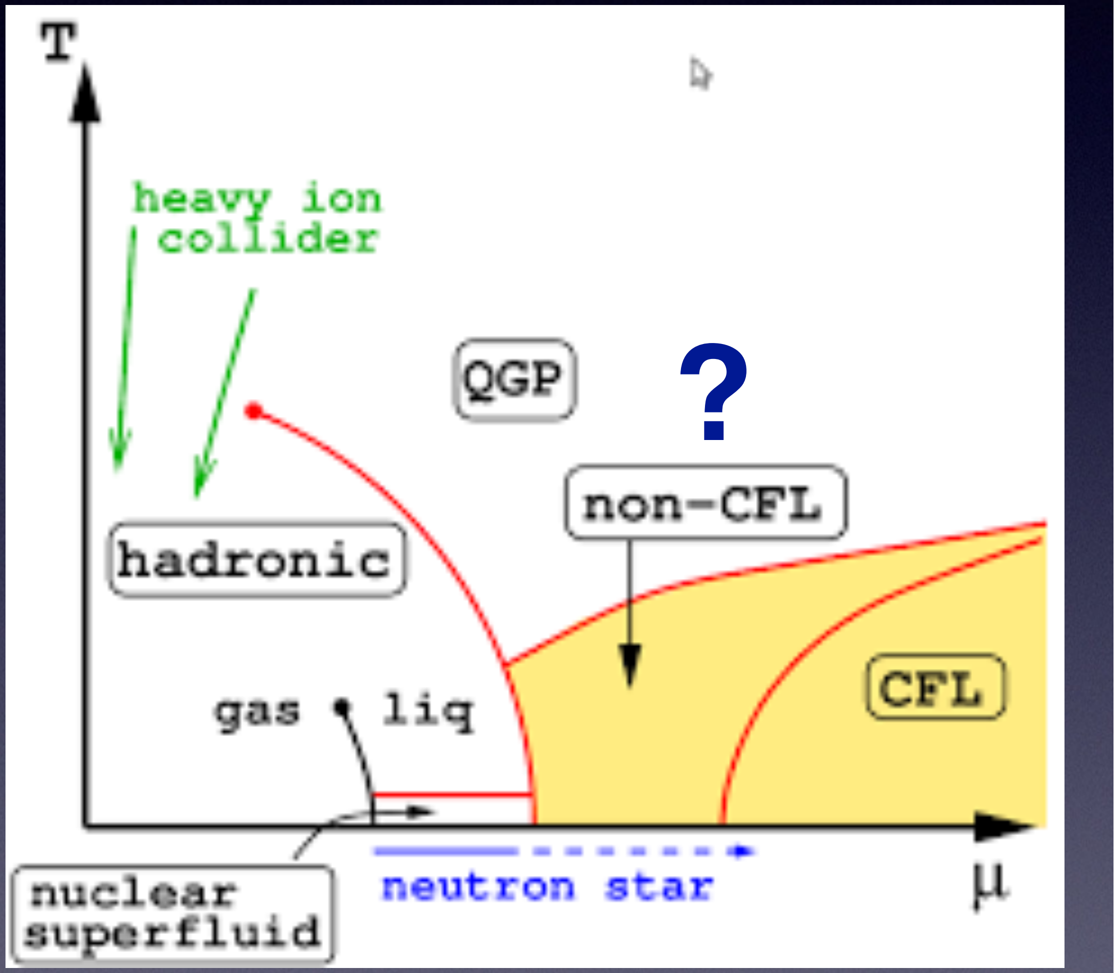


A challenging Homework Problem!!

flavors. But in the imagined color–flavor locked state they become correlated. Both color symmetry and flavor symmetry, as separate entities, are spontaneously broken, and only a certain mixture of them survives unscathed.

Color–flavor locking in high-density QCD drastically affects the properties of quarks and gluons. As we have already seen, the gluons become massive. Due to the commingling of color and flavor, the electric charges of particles, which originally depended only on their flavor, are modified. Specifically, some of the gluons become electrically charged, and the quark charges are shifted. The electric charges of these particles all become integral multiples of the electron's charge!

Thus the most striking features of confinement—the absence of long-range color forces, and integer electric charge for all physical excitations—emerge as simple, rigorous consequences of color superconductivity. Also, because both left- and right-handed flavor symmetries are locked to color, they are also effectively locked to each other. Thus chiral symmetry, which required independent transformations among the left- and the right-handed components of the quarks, is spontaneously broken.

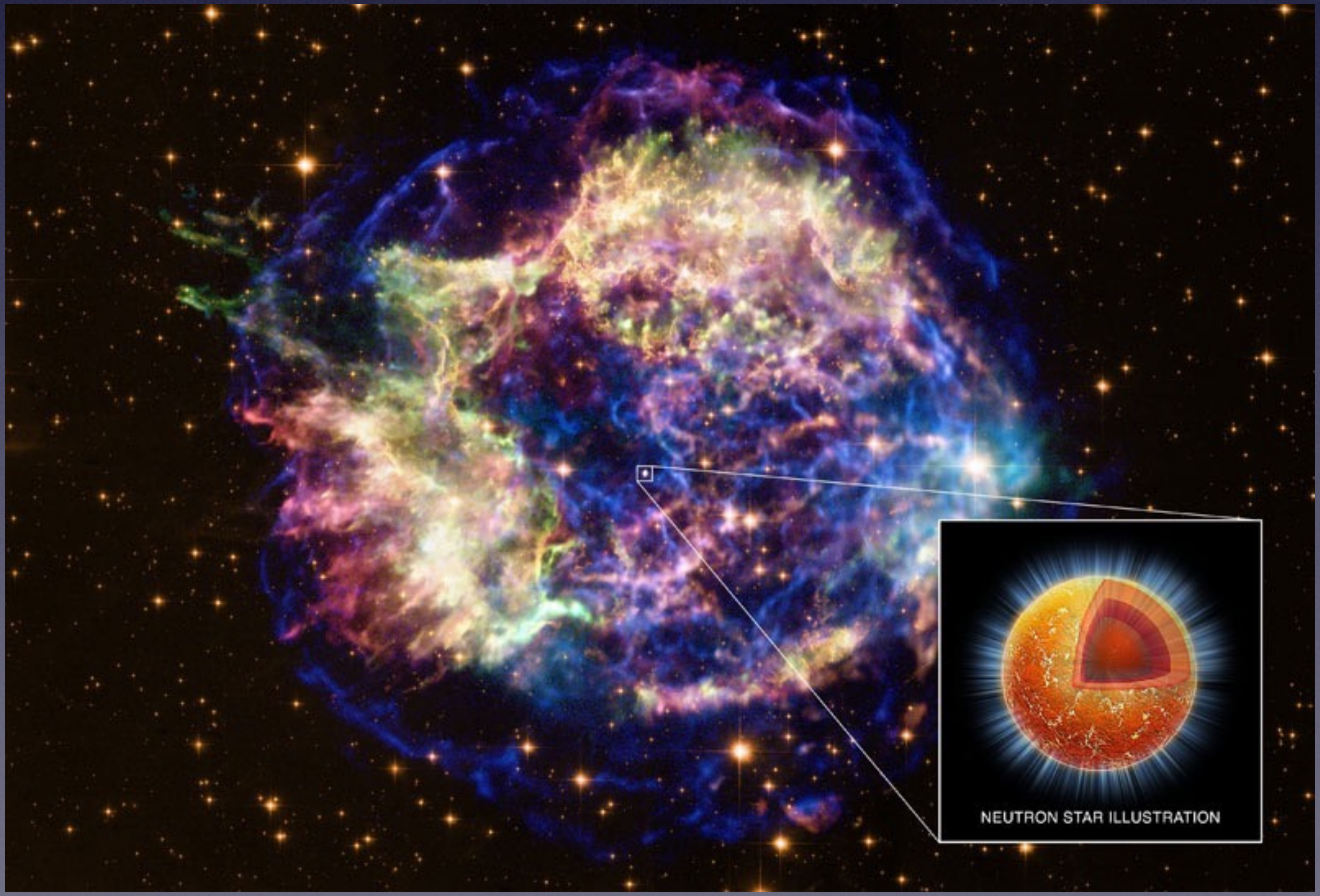
Altogether, there is a striking resemblance between the *calculated* properties of the low-energy excitations in the high-density limit of QCD and the *expected* properties—based on phenomenological experience and models—of hadronic matter at moderate density. This suggests the conjecture that there is no phase transition separating them.

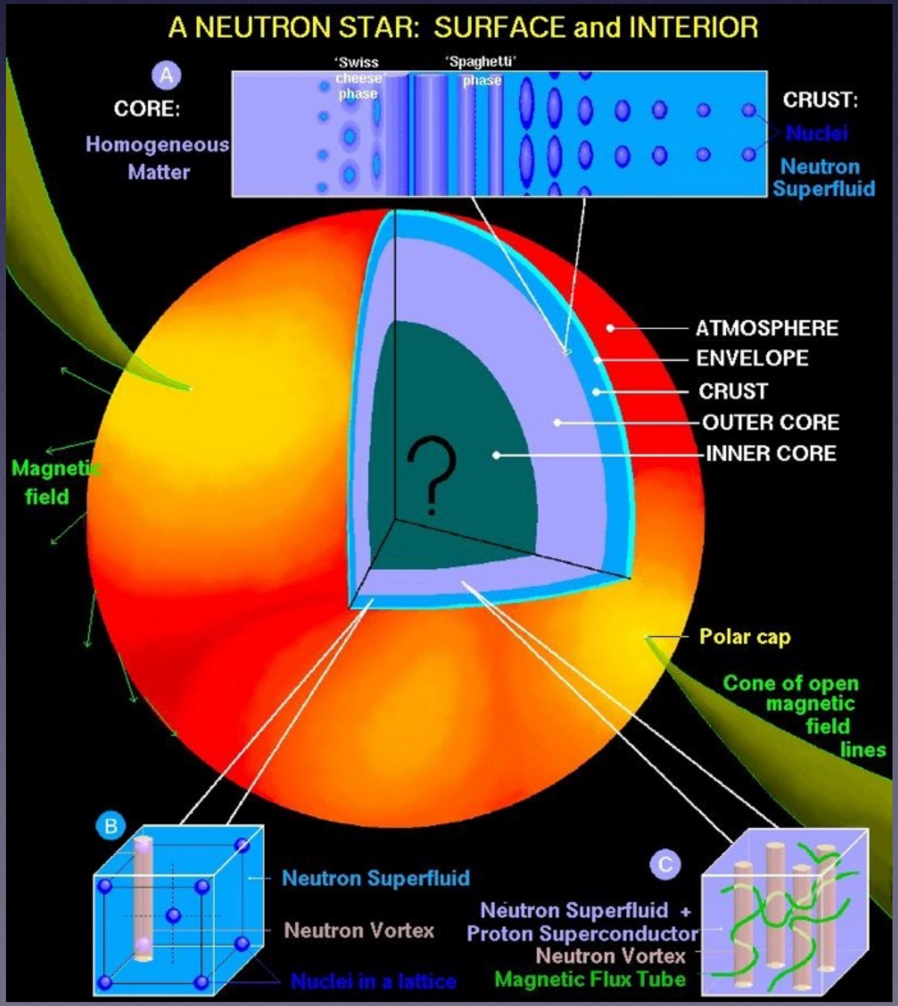
Unfortunately both numerical and direct experimental tests of this conjecture seem out of reach at the moment. So it is not certain that the mechanisms of confinement and chiral-symmetry breaking we find in the calculable, high-density limit are the same as those that operate at moderate or low density. Still, I think it astonishing that these properties, which have long been regarded as mysterious and intractable, have been simply—yet rigorously—demonstrated to occur in a physically interesting limit of QCD.

I have tried to convince you of two things: first, that the fundamentals of QCD are simple and elegant, and second, that these fundamentals come into their own, and directly describe the physical behavior of matter, under various extreme conditions.

The Anatomy of a Neutron Star

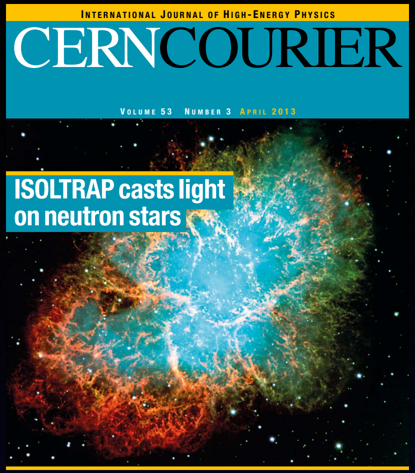
- Atmosphere (10 cm): Shapes Thermal Radiation ($L=4\pi\sigma R^2T^4$)
- Envelope (100 m): Huge Temperature Gradient (10^8K ↔ 10^6K)
- Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)
- Inner Crust (1 km): Coulomb Frustration (“Nuclear Pasta”)
- Outer Core (10 km): Uniform Neutron-Rich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





The Composition of the Outer Crust

High sensitivity to nuclear masses

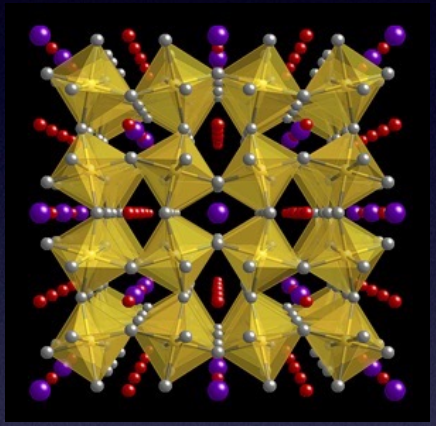

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERNCOURIER

VOLUME 53 NUMBER 3 APRIL 2013

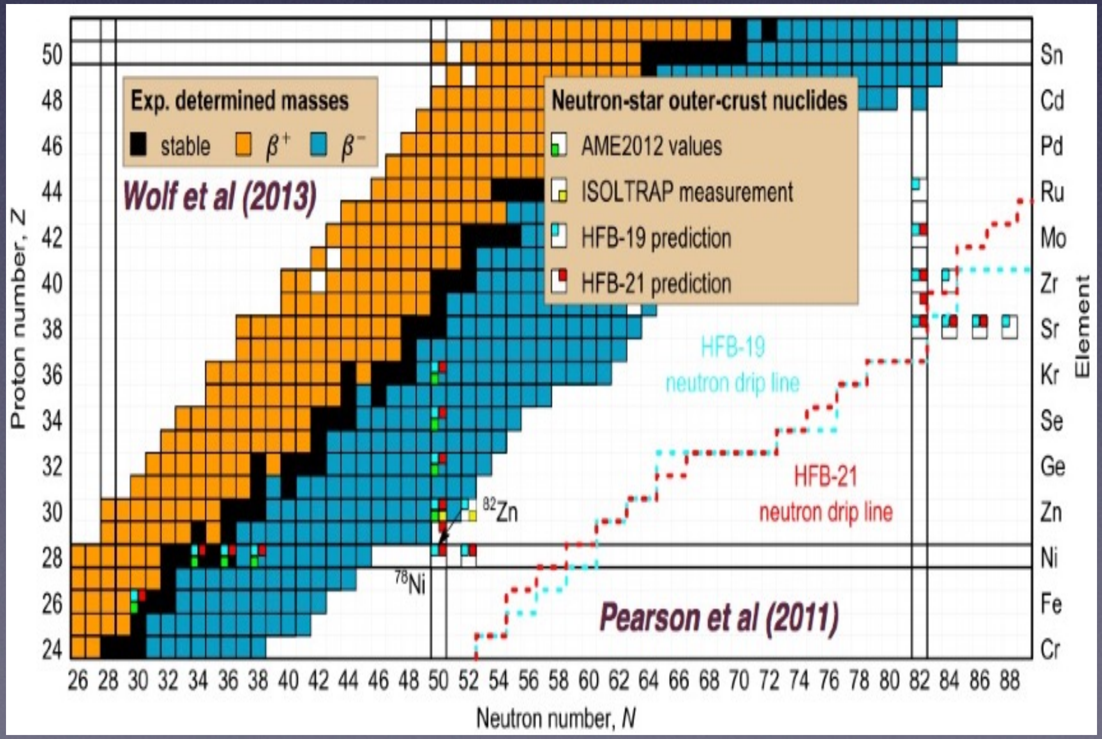
ISOLTRAP casts light on neutron stars

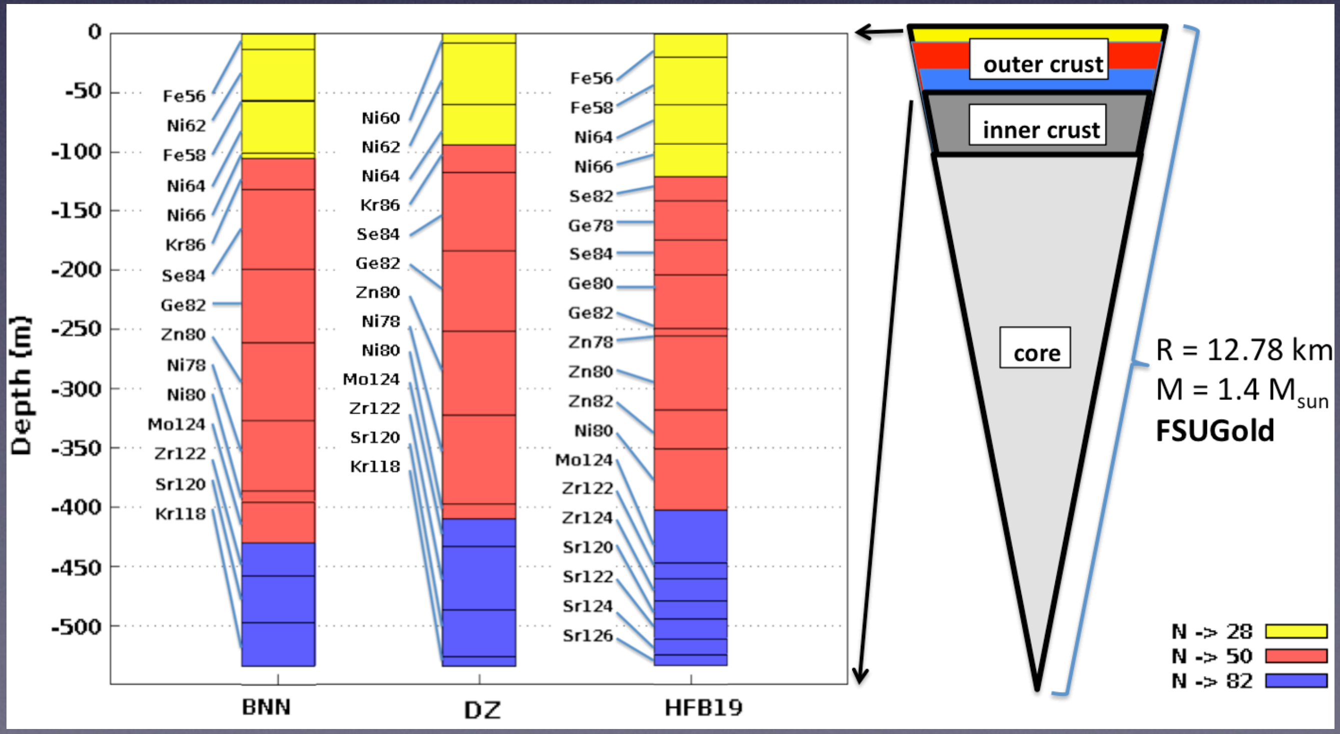
- System unstable to cluster formation
  - BCC lattice of neutron-rich nuclei imbedded in e-gas
- Composition emerges from relatively simple dynamics
  - Subtle composition between electronic and symmetry energy



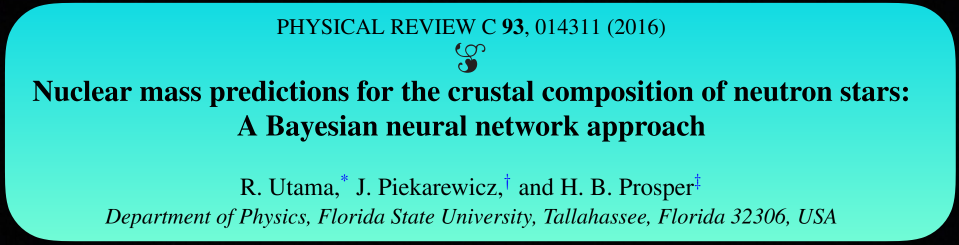
$$E/A_{\rm tot} = M(N,Z)/A + \frac{3}{4}Y_e^{4/3}{\rm k_F} + {\rm lattice}$$

- 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

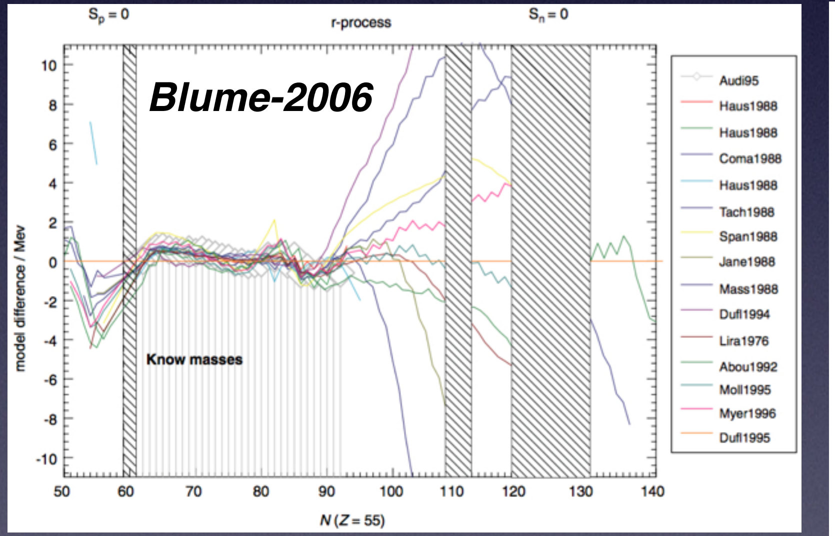
R. Utama,[*] J. Piekarewicz,[†] and H. B. Prosper[‡]

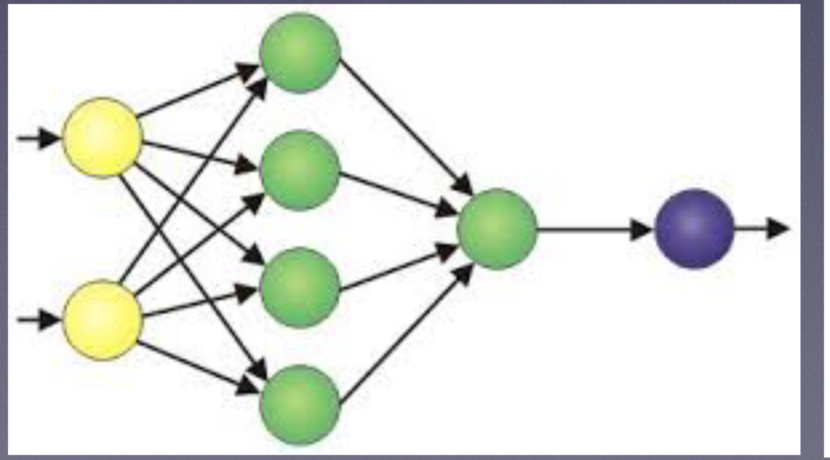
Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

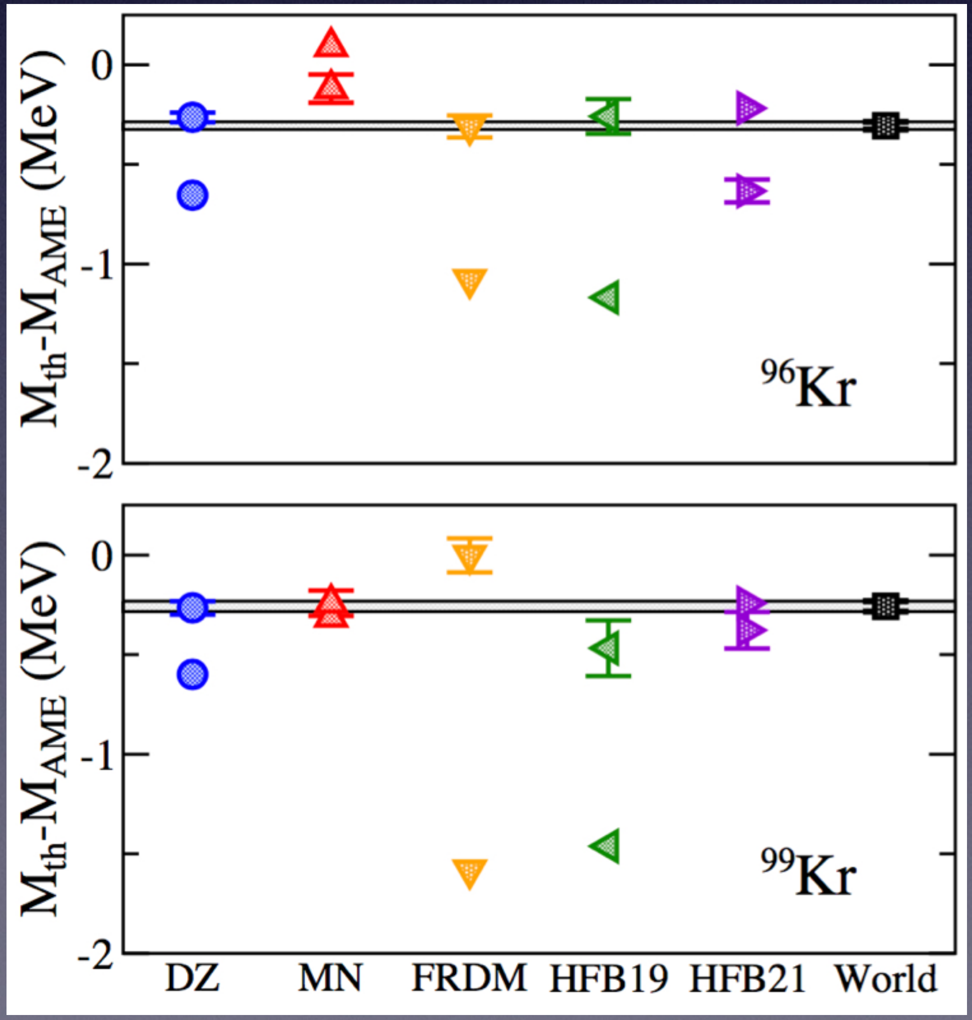
- Use DFT to predict nuclear masses
- Train BNN by focusing on residuals

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

- Systematic scattering greatly reduced
- Predictions supplemented by theoretical errors







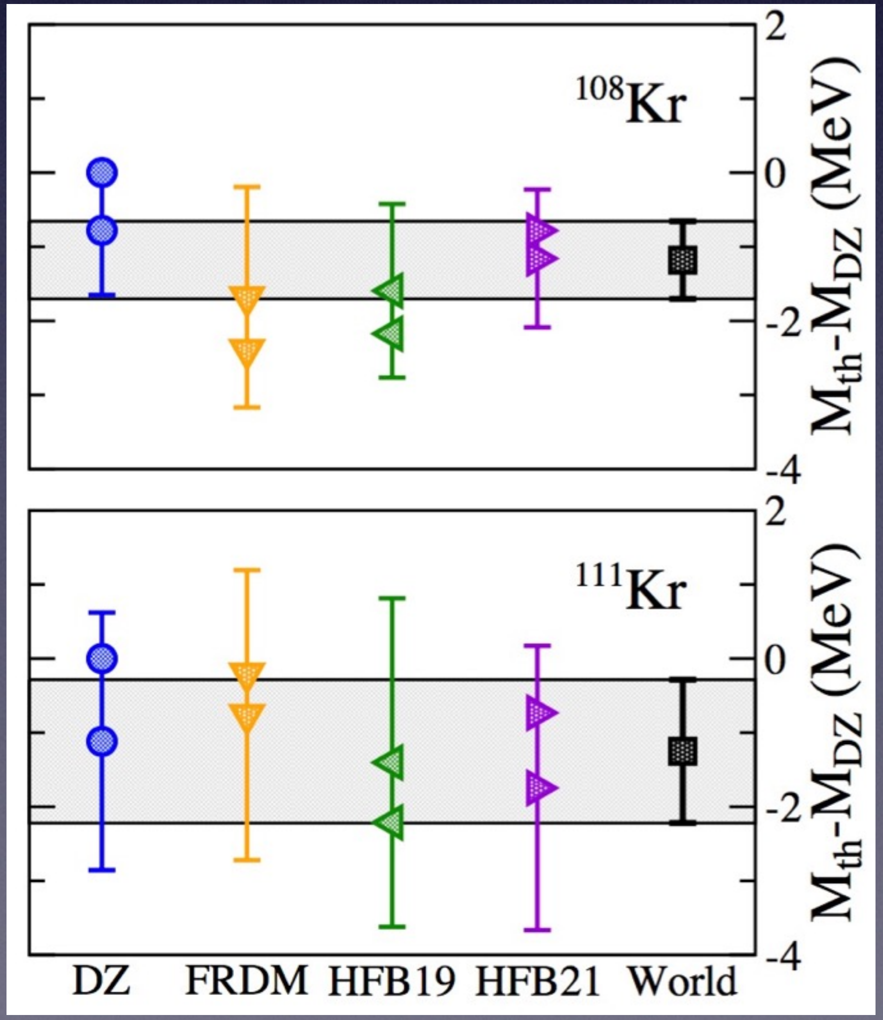


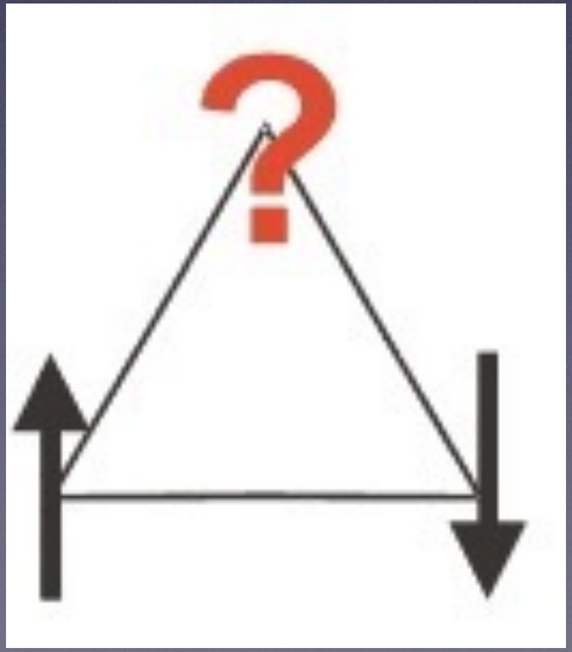
Image Reconstructions meets BNN

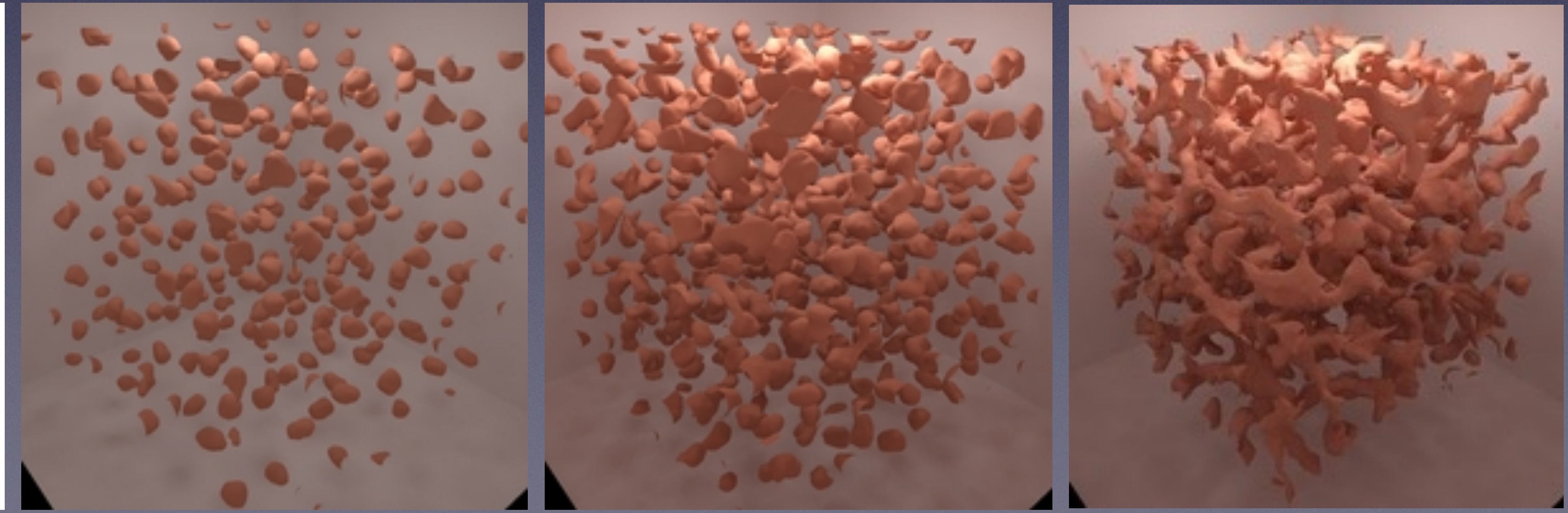
- Nature provides precise image of the world
- Models (DFT) aim to reproduce such image
- Image reconstruction (BNN) provides fine tuning

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"

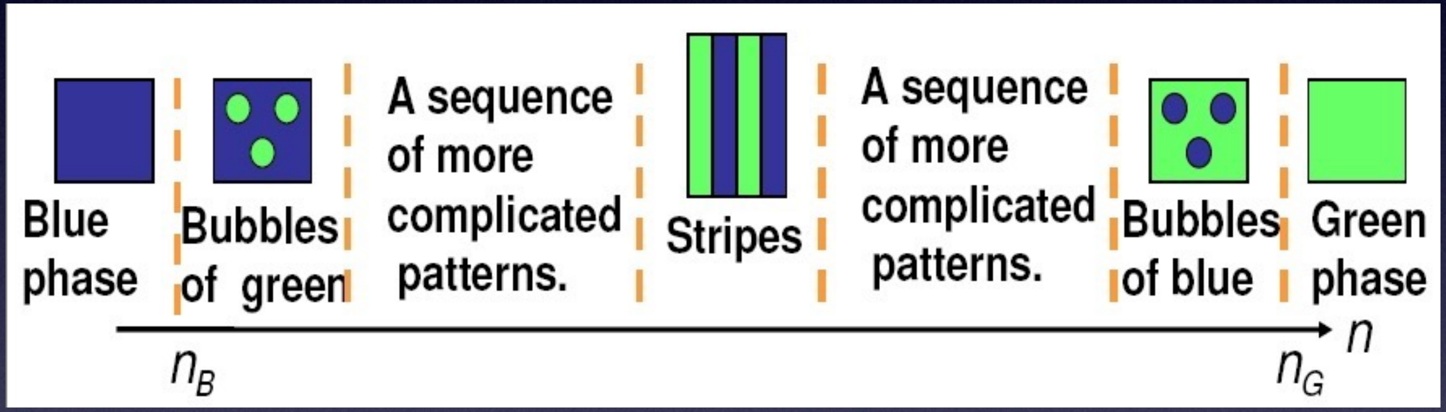


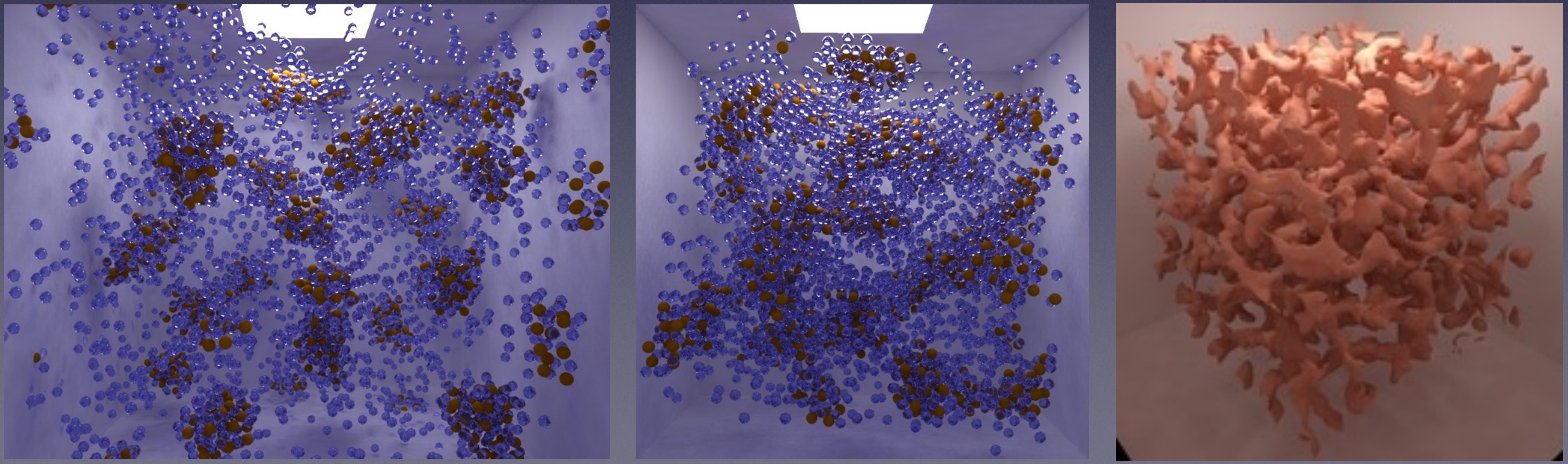


Universality of Coulomb Frustration:
The two-dimensional electron gas

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

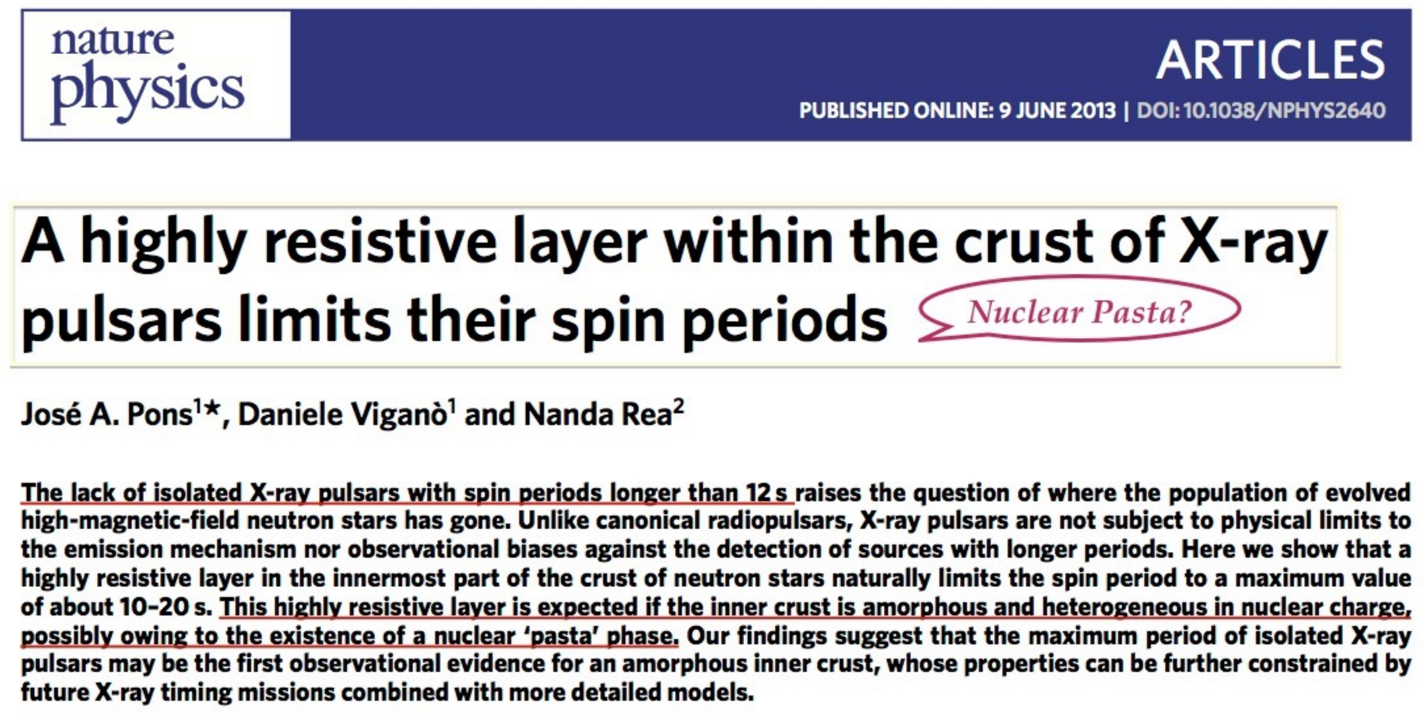
Rather, in place of the putative first-order phase transition there are intermediate micro emulsion phases.





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

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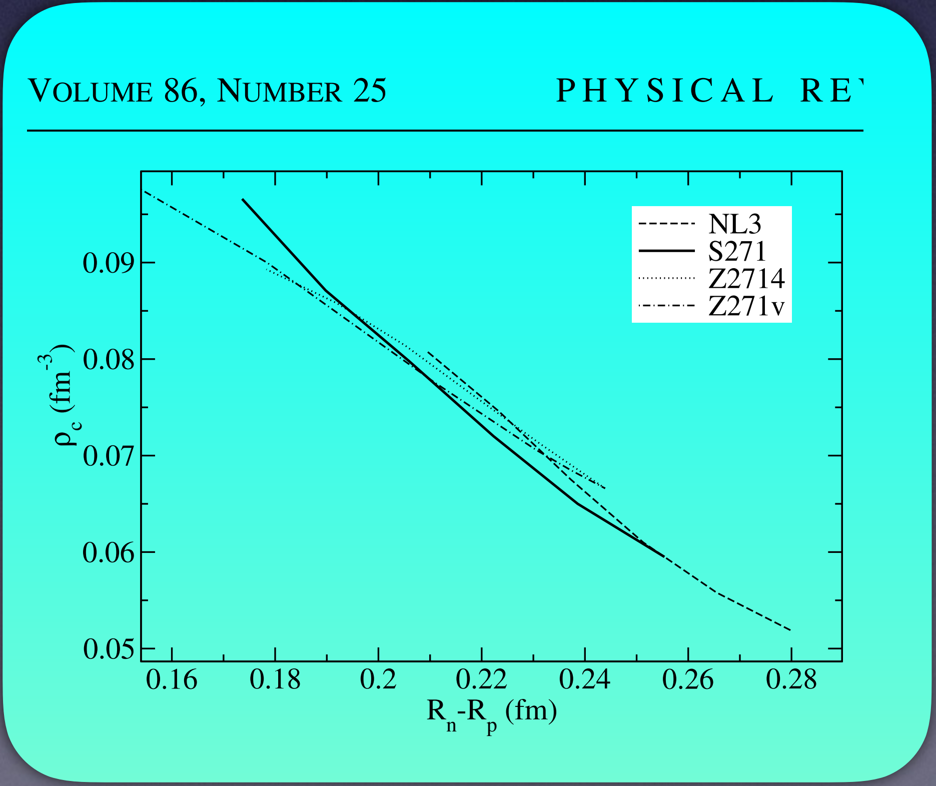
A highly resistive layer within the crust of X-ray pulsars limits their spin periods

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.



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