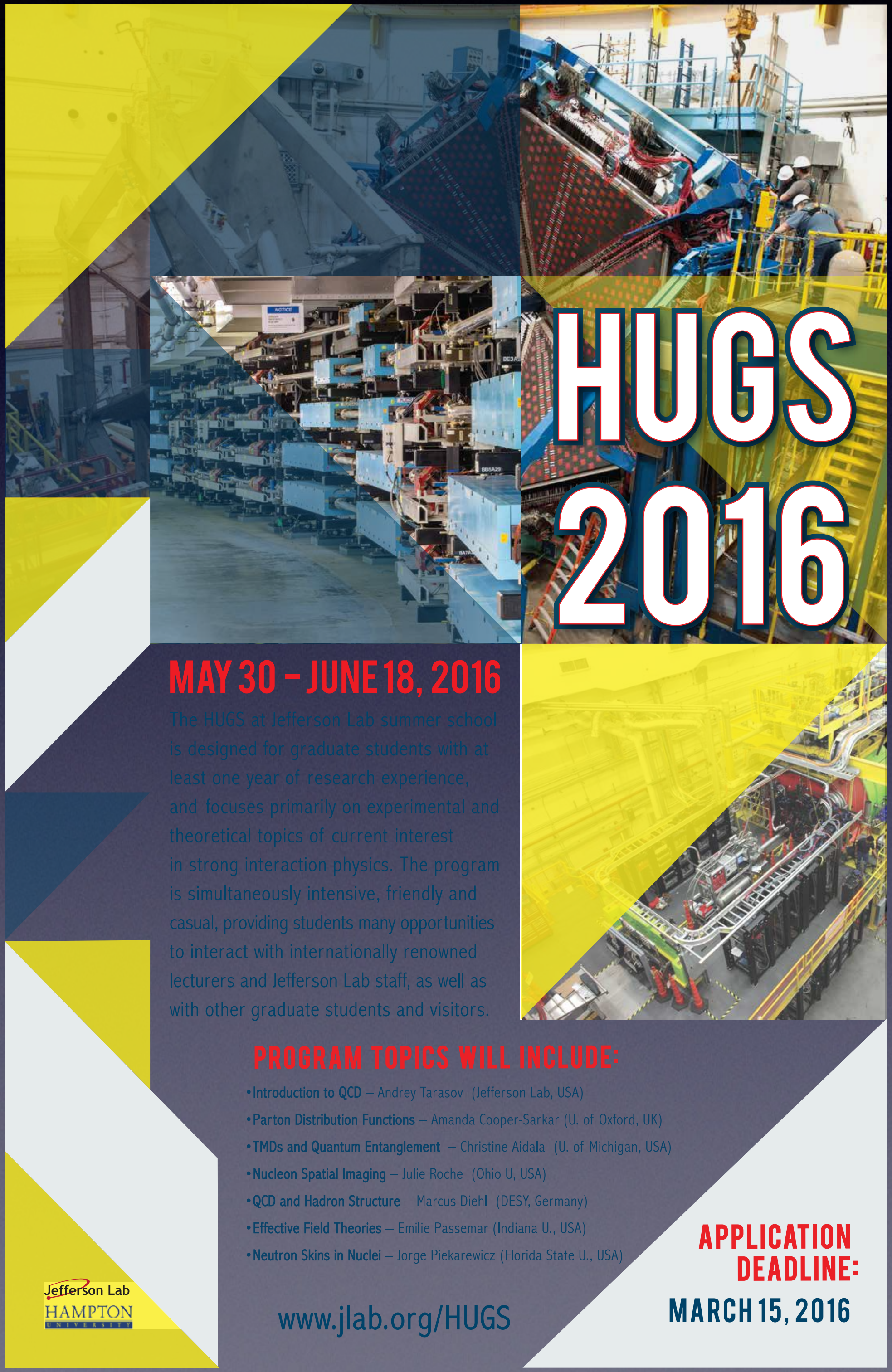
# Neutron Skins in Nuclei

## 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

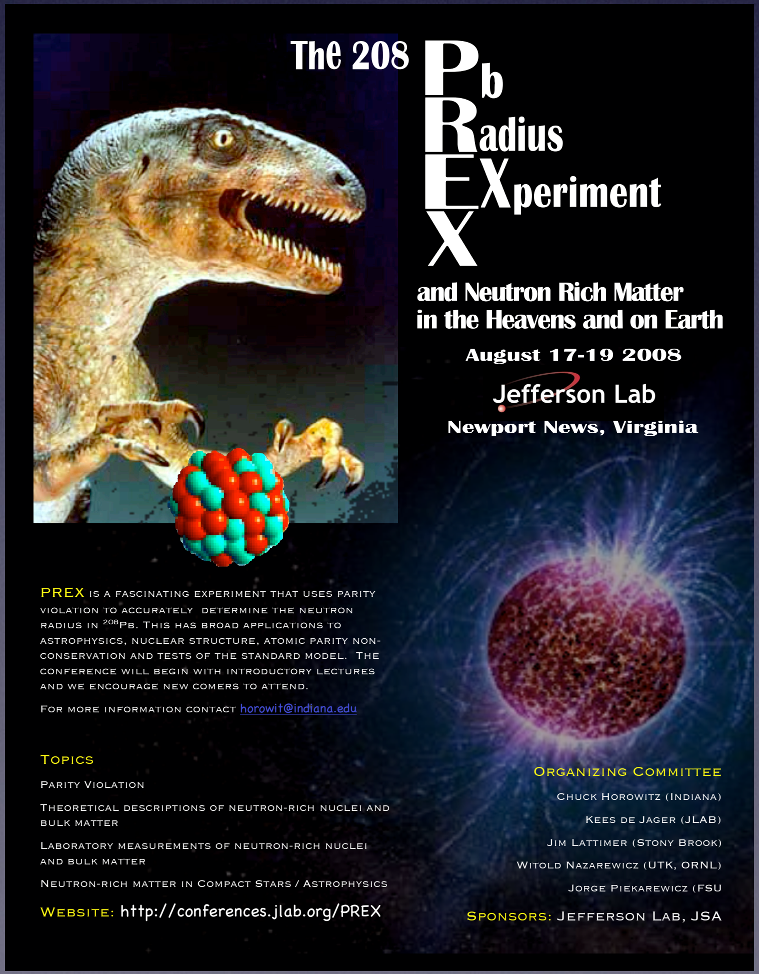
Sponsors: Jefferson Lab, JSA

# 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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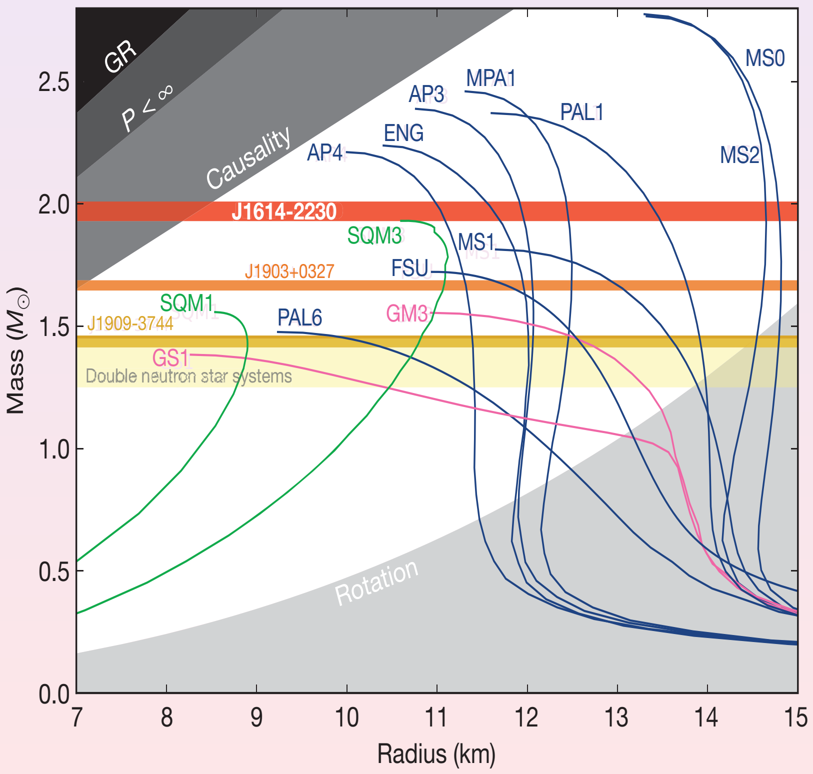
# Neutron Stars: Unique Cosmic Laboratories

- 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

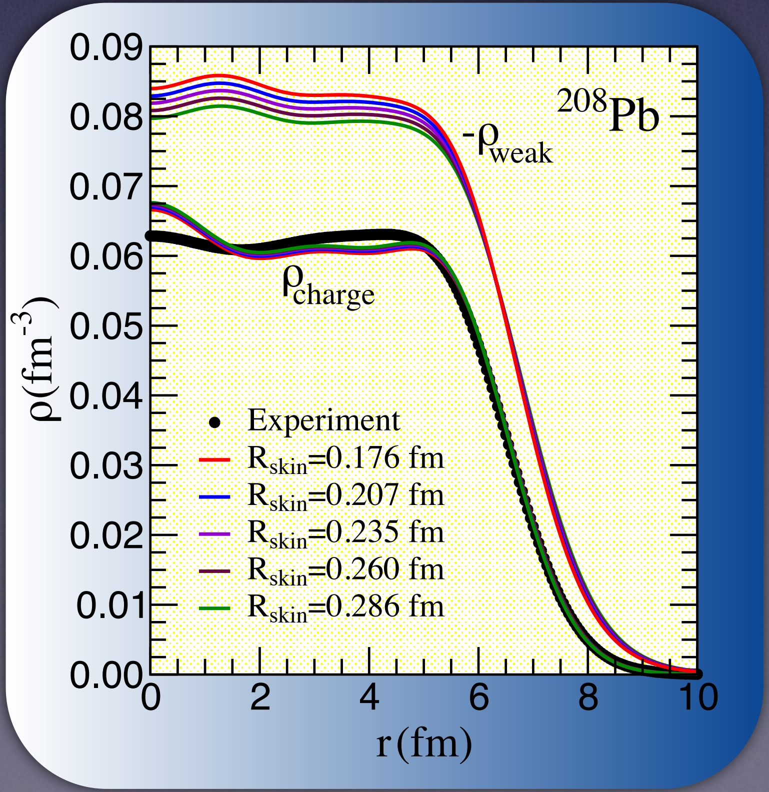
Nuclear Physics Critical

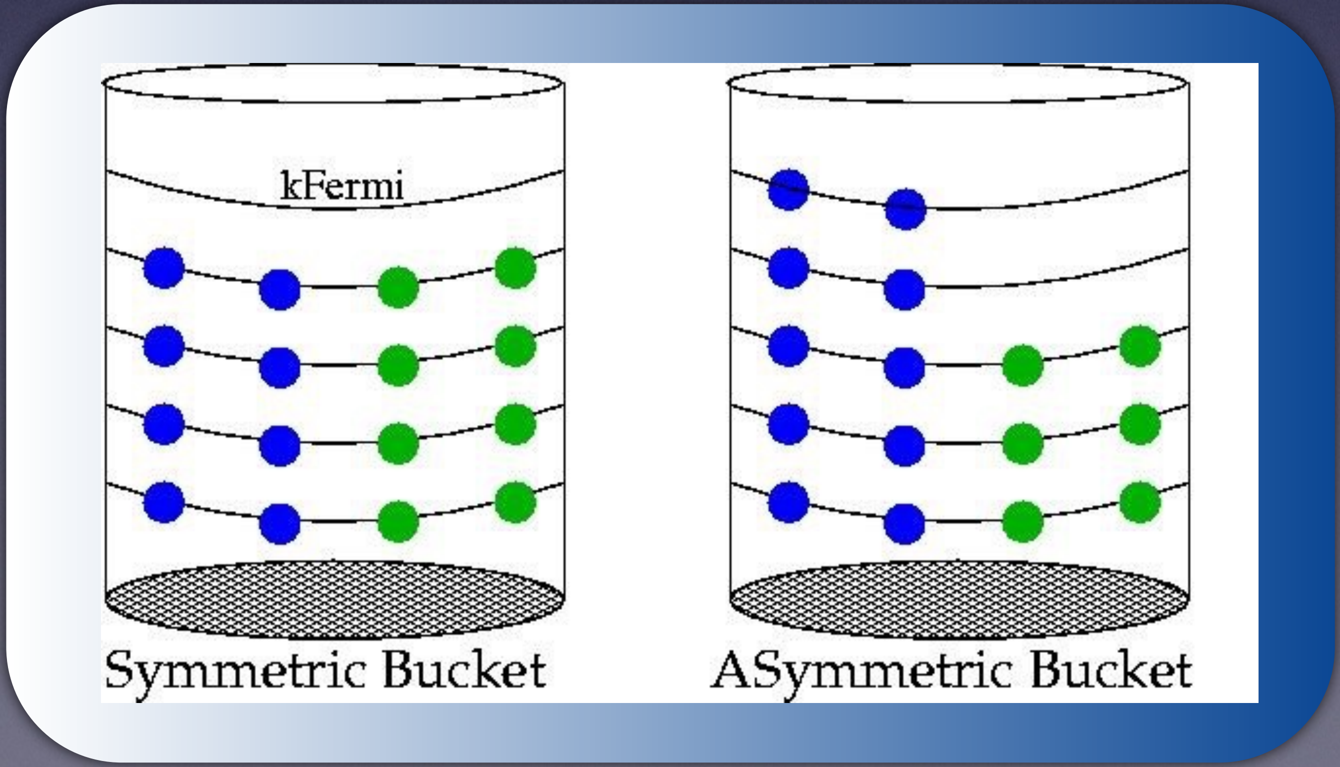
# The Equation of State of Neutron-Rich Matter

- The EOS of asymmetric matter: $\alpha$=(N-Z)/A; $x=(\rho-\rho_0)/3\rho_0$; $T=0$
  - $\rho_0$ $\simeq$0.15 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(BIA) = 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(AIB) = 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

Prior

Likelihood

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

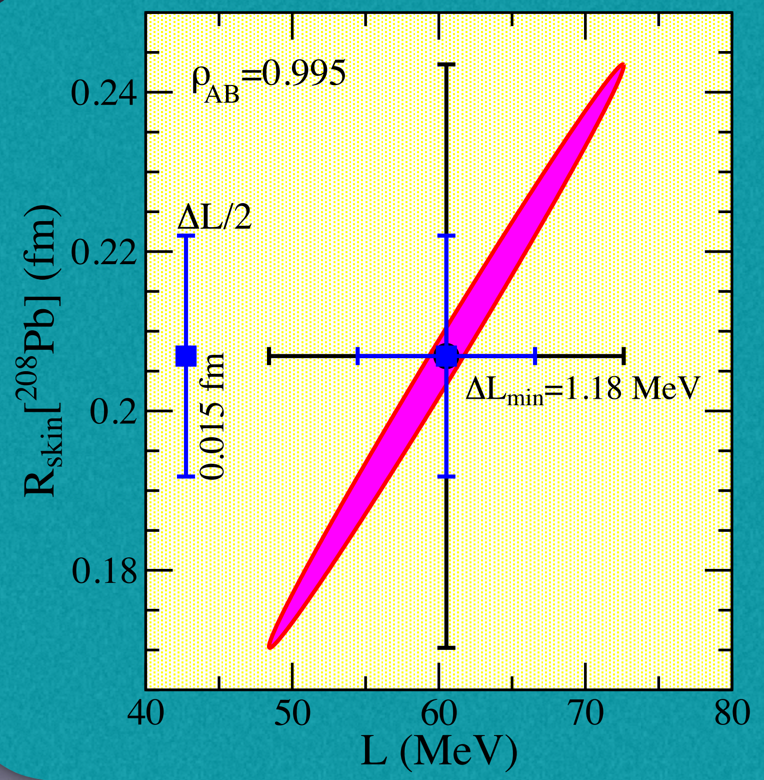
# Searching for L: The Strategy

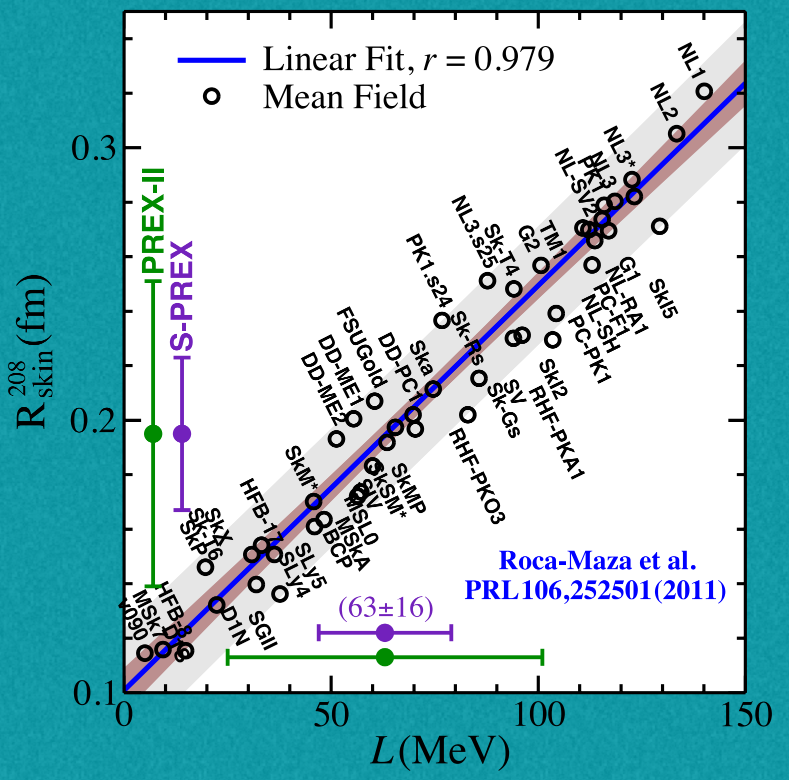
## $P_{PNM} \simeq L\rho_0/3$ is not a physical observable

- 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 Rskin in Pb (error bars too large!)

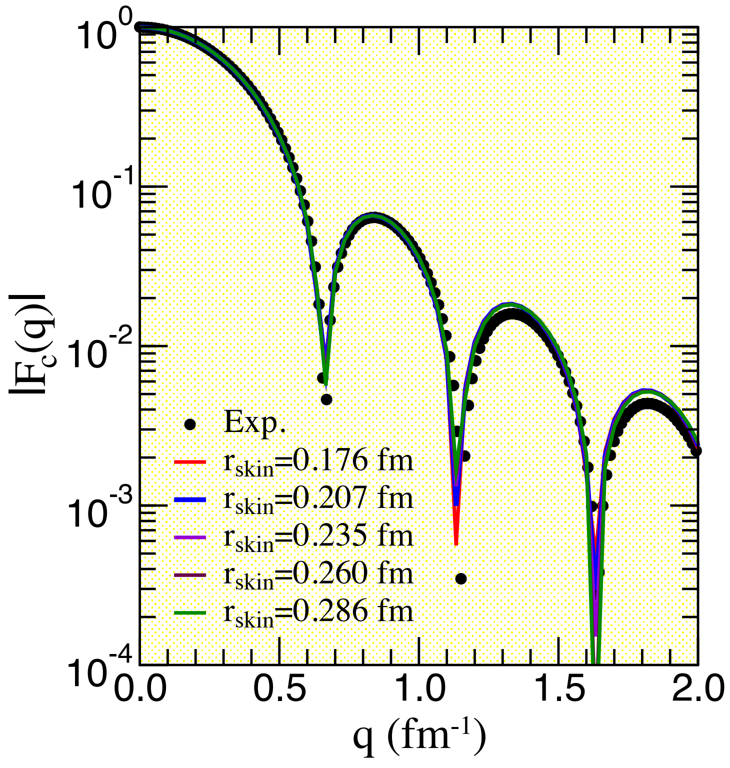
- Precision required in the determination of the neutron radius/skin?
  - As precisely as “humanly possible” - fundamental nuclear structure property (*cf.* charge density)
  - To strongly impact Astrophysics?

- Is there a need for a systematic study over “many” nuclei?
  PREX, CREX, SREX, ZREX, …

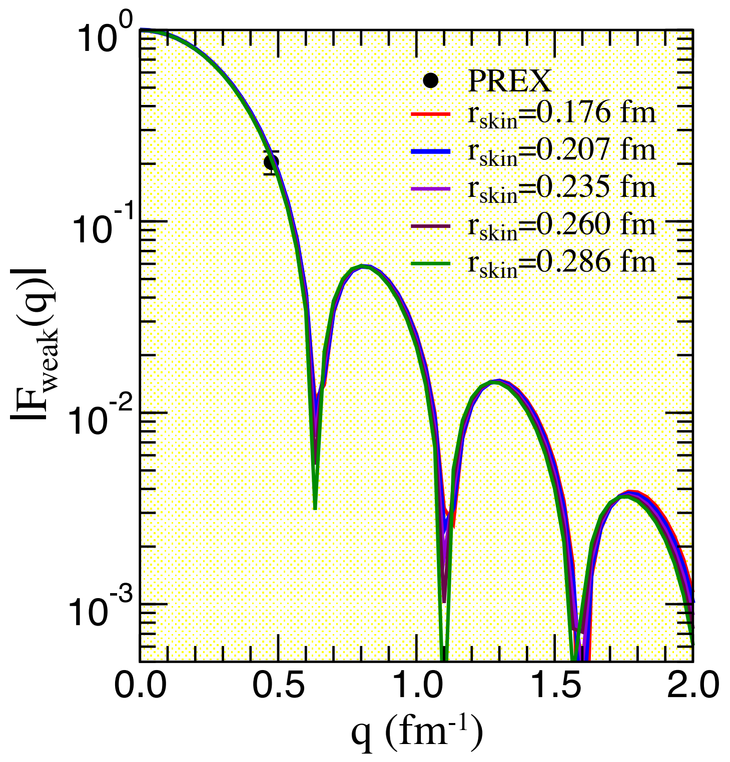
- Is there a need for more than one q-point?
  Radius and diffuseness … or the whole form factor?

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

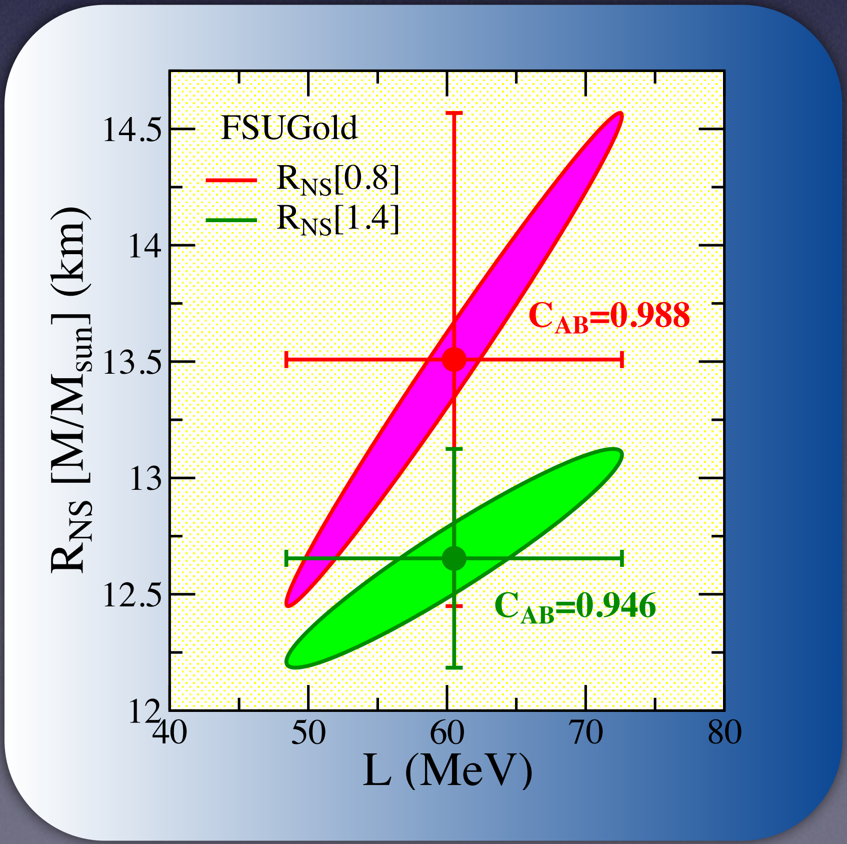
## The enormous reach of the neutron skin

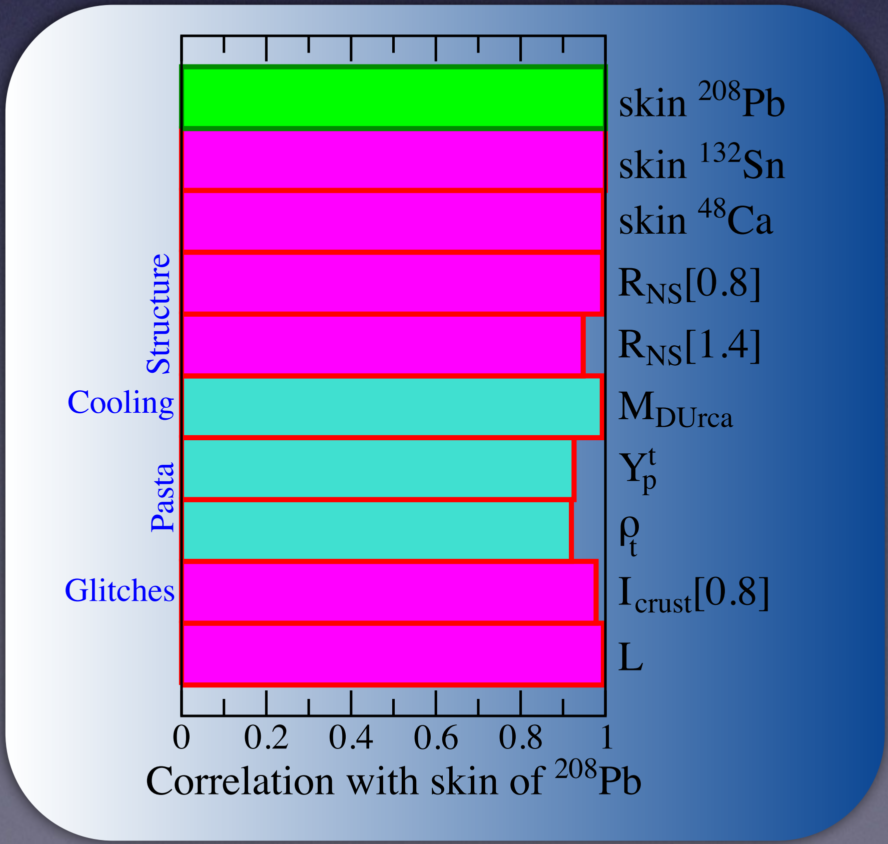
- Neutron-star radii are sensitive to the EOS near $2\rho_0$
  - Neutron star masses sensitive to EOS at much higher density

- 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 …*

# Have We Discovered Quark Stars?

**NASA** National Aeronautics and Space Administration

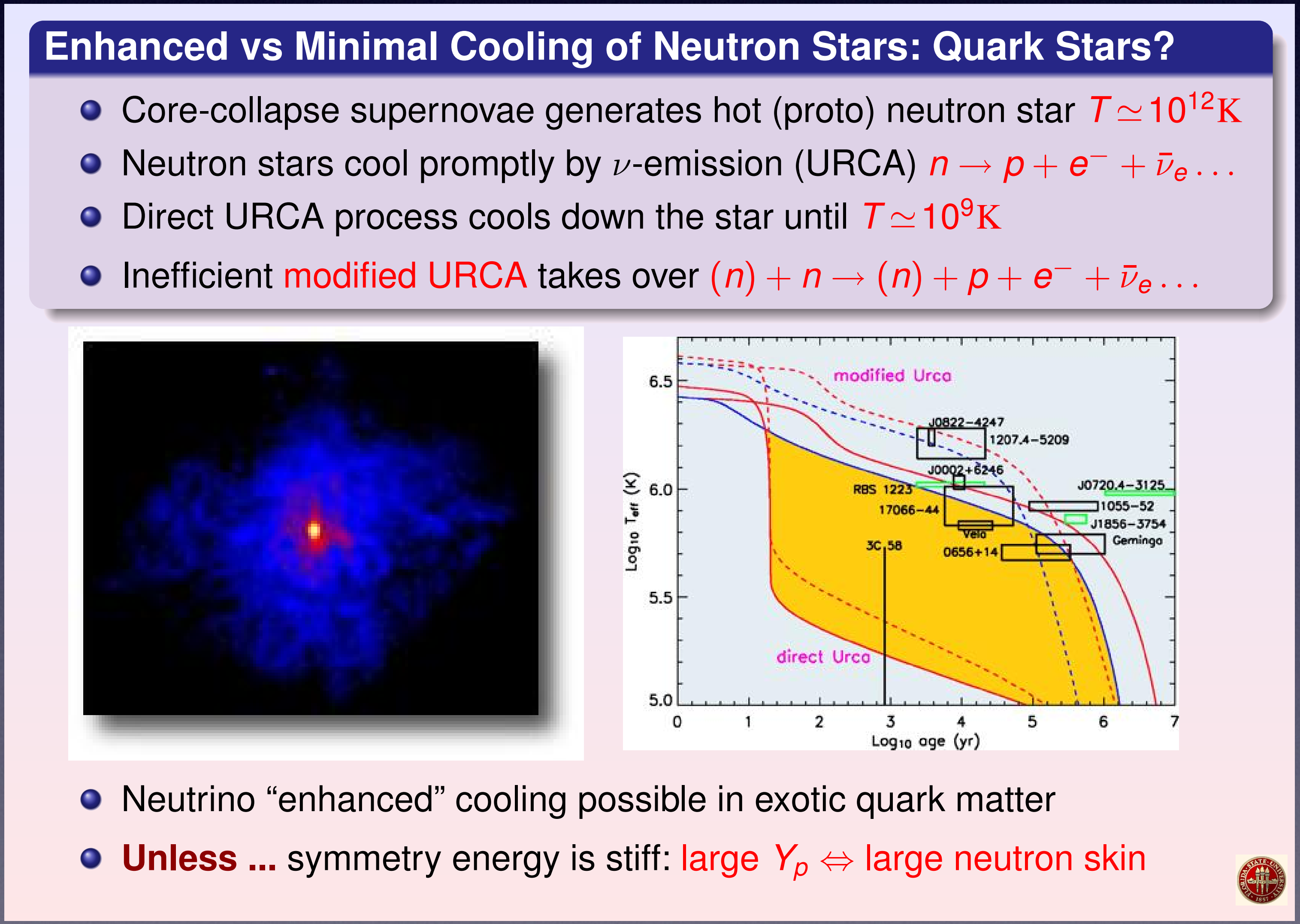
**News Release**

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

**For Release:** April 10, 2002

**Release:** 02-082

**Cosmic X-rays reveal evidence for new form of matter**



**Enhanced vs Minimal Cooling of Neutron Stars: Quark Stars?**

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

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

- Assume $R_n - R_p \lesssim 0.18$ fm and $M(3C58) \lesssim 1.3 M_\odot$
- Then the pulsar in 3C58 may indeed be a quark star

George Gamow and URCA cooling

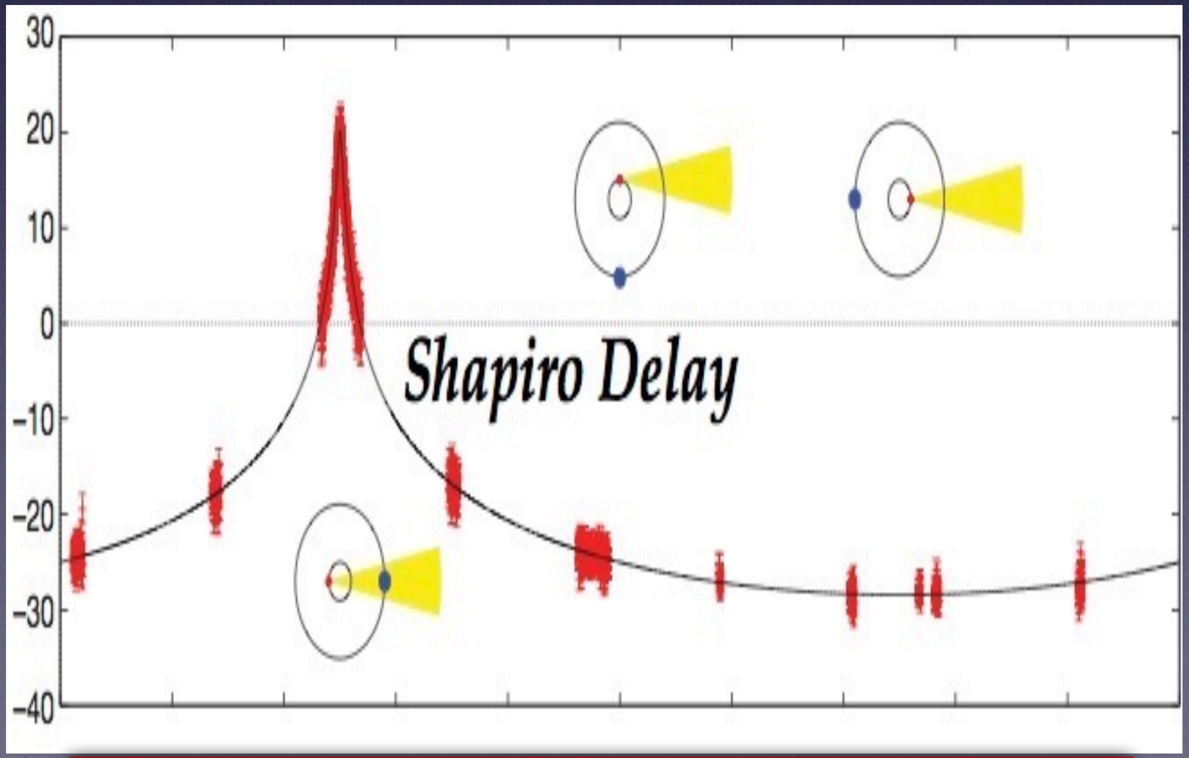
# George Gamow and URCA Cooling?

- URCA is not an acronym but rather, the name of a Casino in Rio de Janeiro where George Gamow commented to the Brazilian astrophysicist Mario Schonberg: *“The energy disappears in the nucleus of the supernova as quickly as the money disappears at the roulette table”*
- In Gamow’s Russian dialect, “urca” also means a *pickpocket*, someone that can steel your money in a matter of seconds!

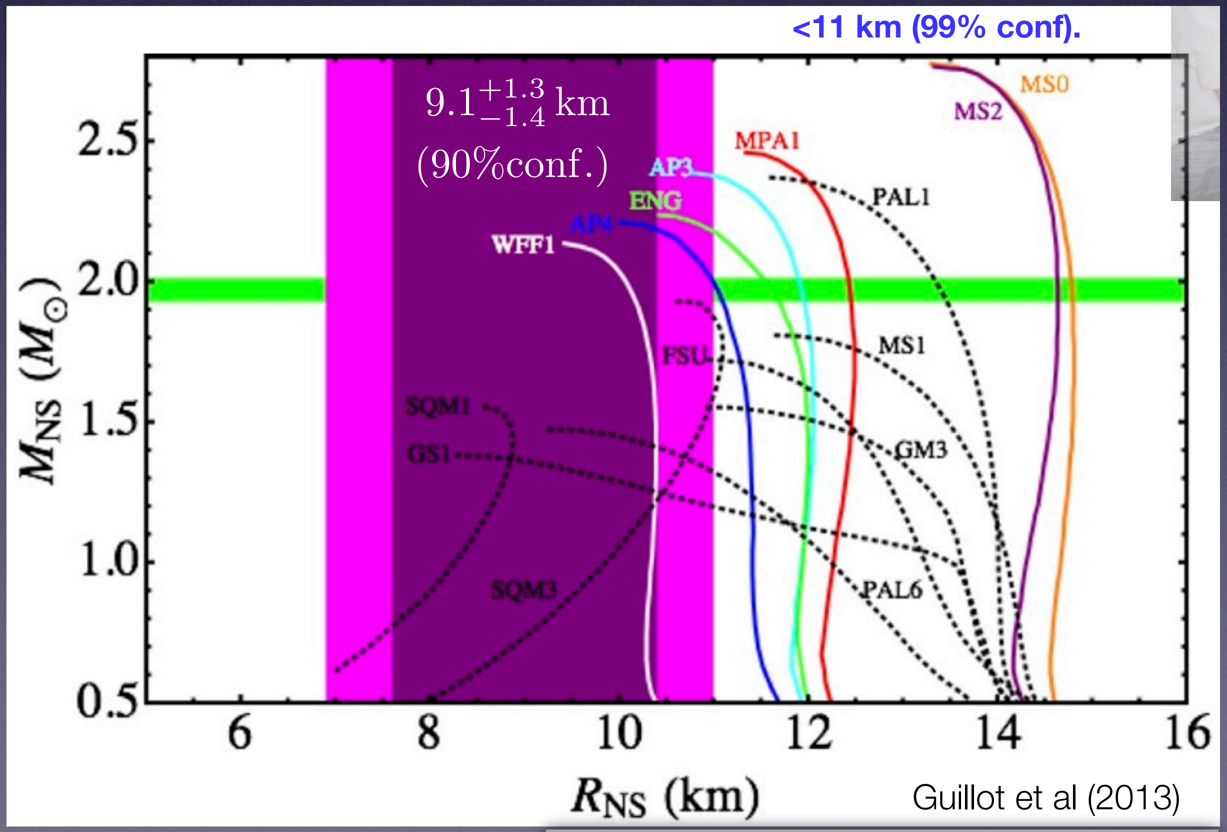
URCA Casino, Rio de Janeiro

# 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!



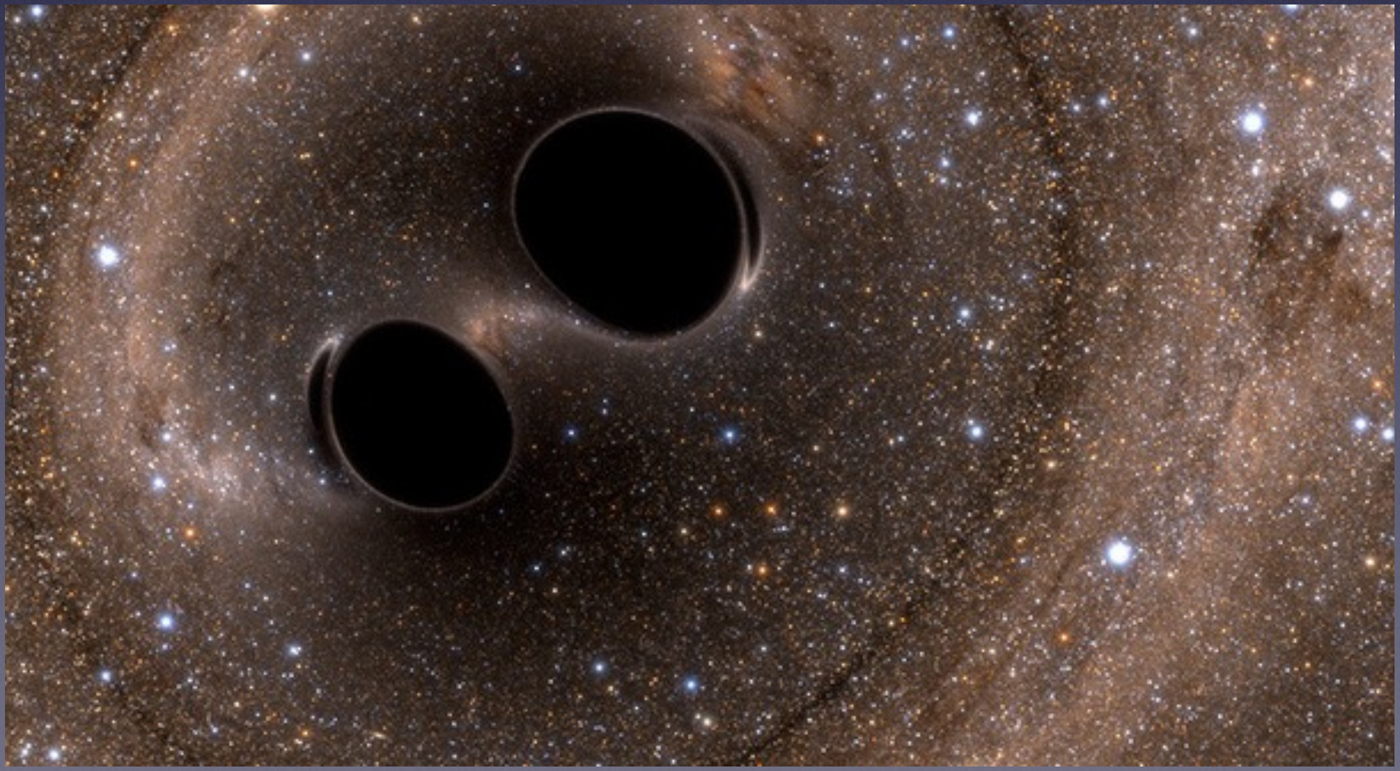
<11 km (99% conf).

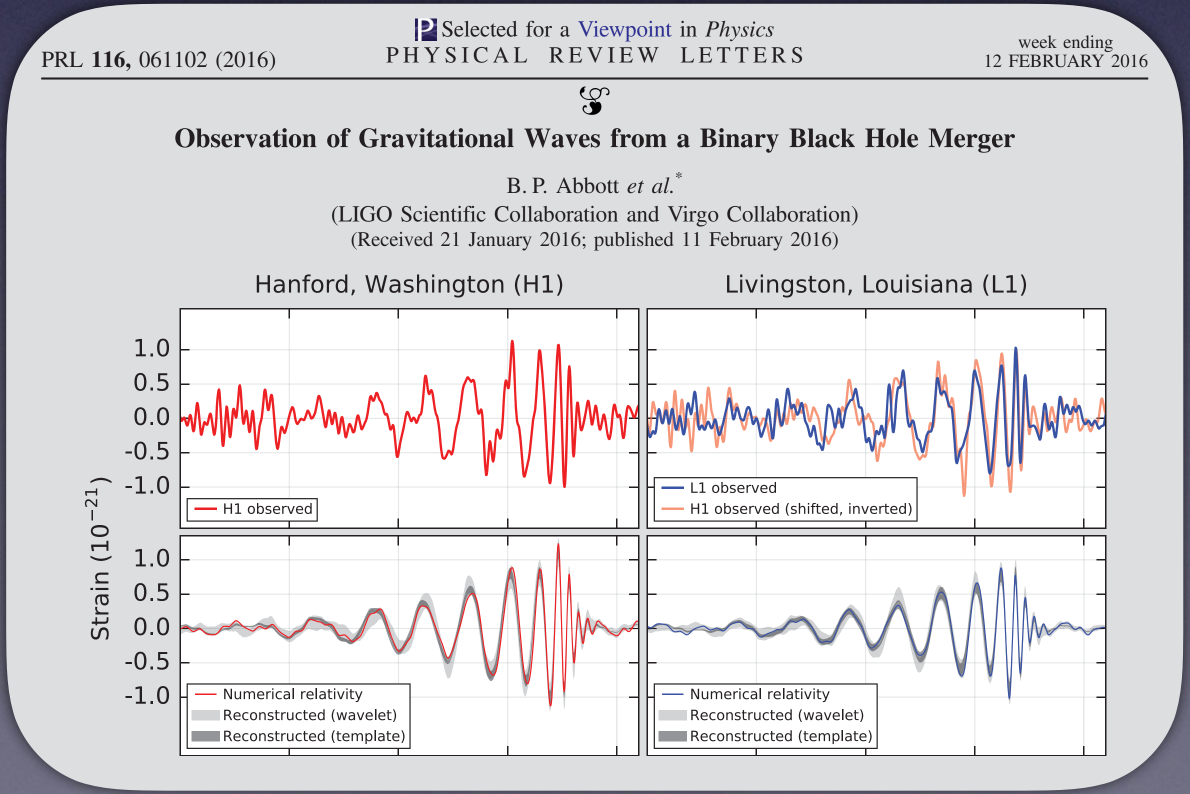
Guillot et al (2013)

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

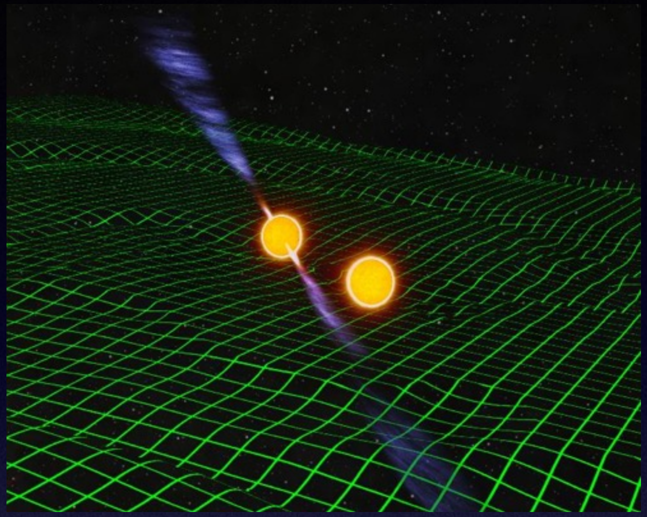
**Observation of Gravitational Waves from a Binary Black Hole Merger**

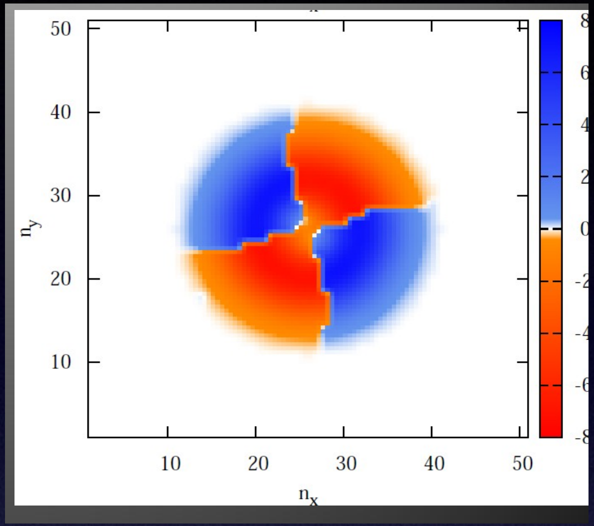
B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

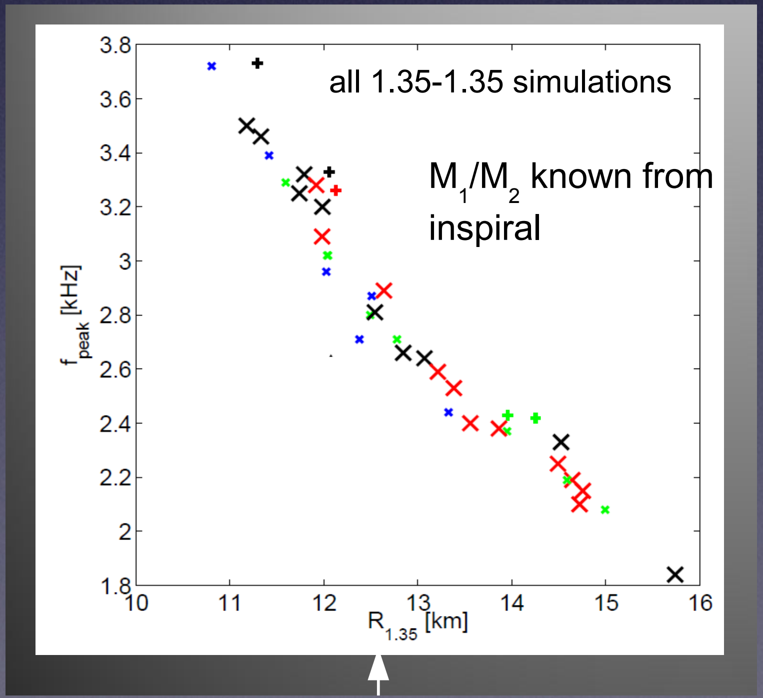
(Received 21 January 2016; published 11 February 2016)

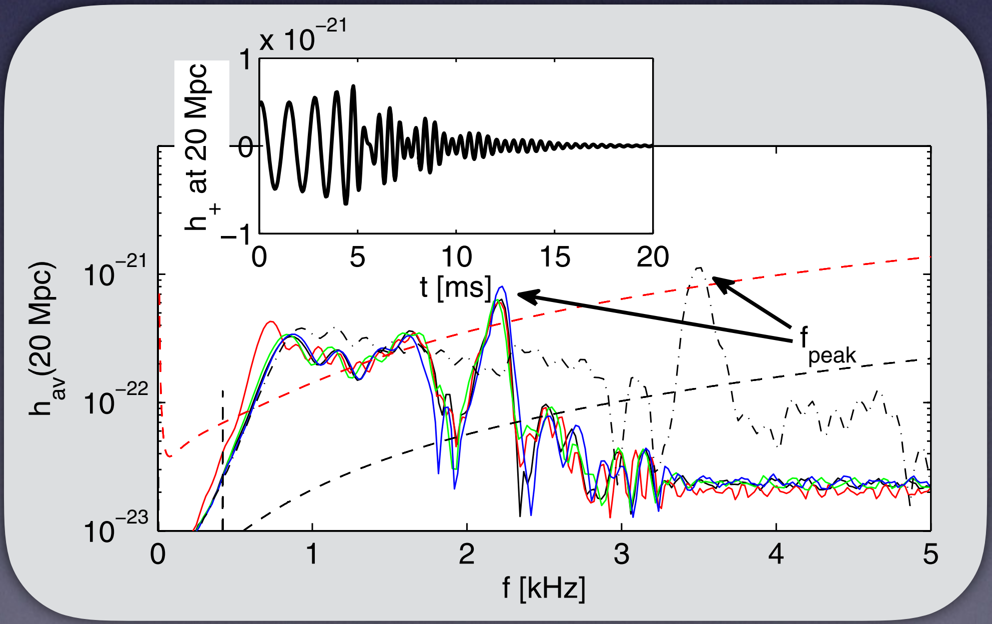
# What Will We Learn from Neutron-Star Mergers

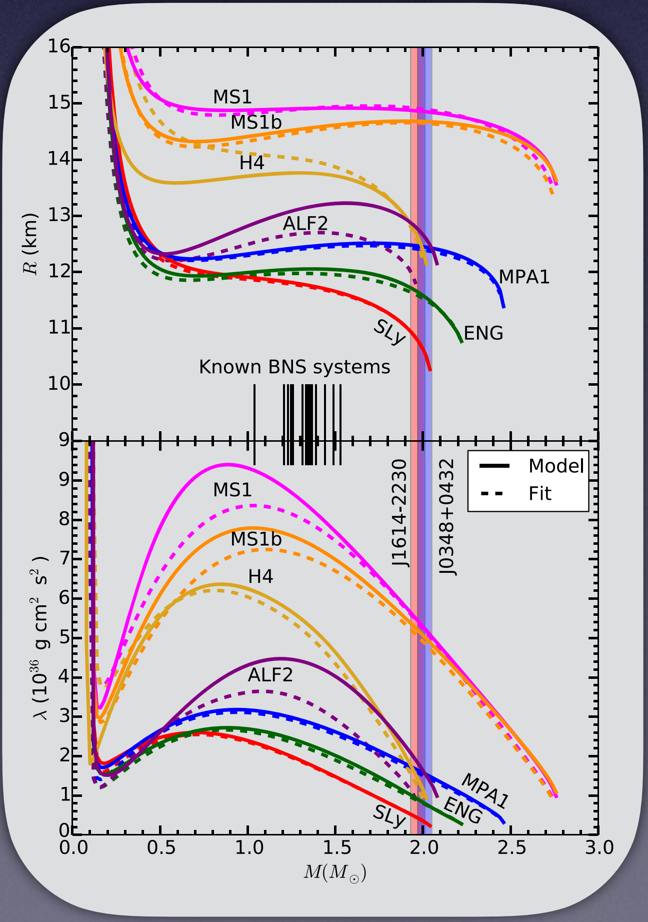




Tidal polarizability scales as R⁵ …







*NS radius 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!***