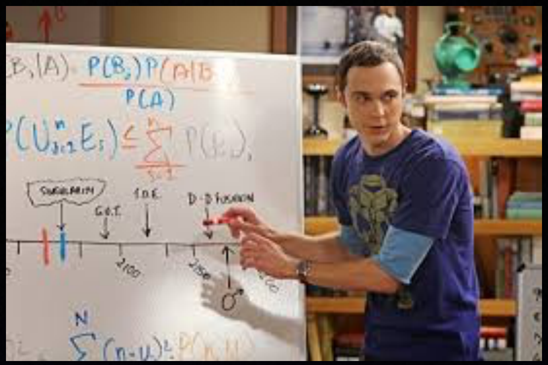
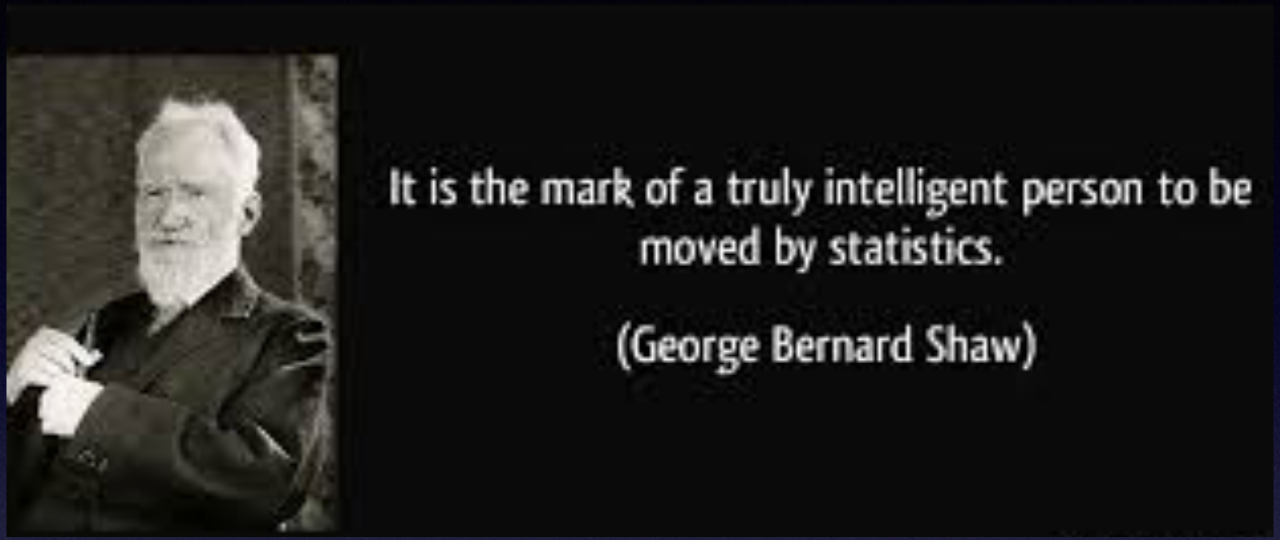
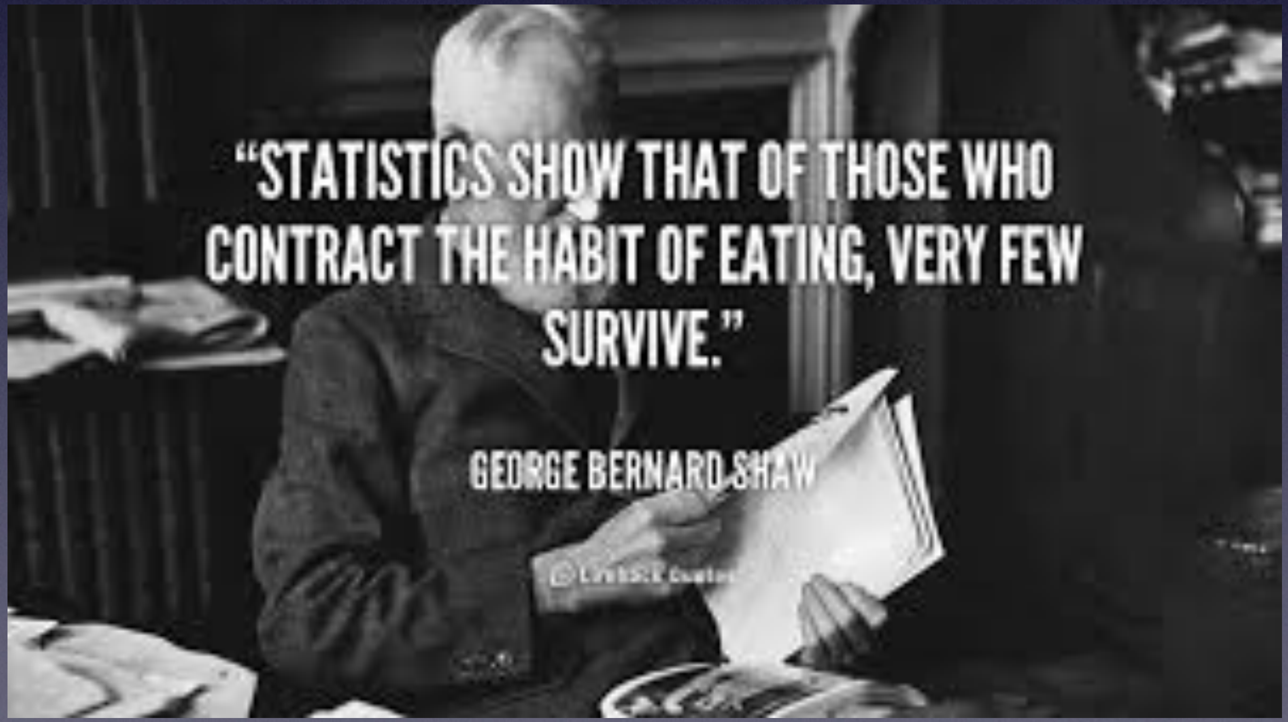
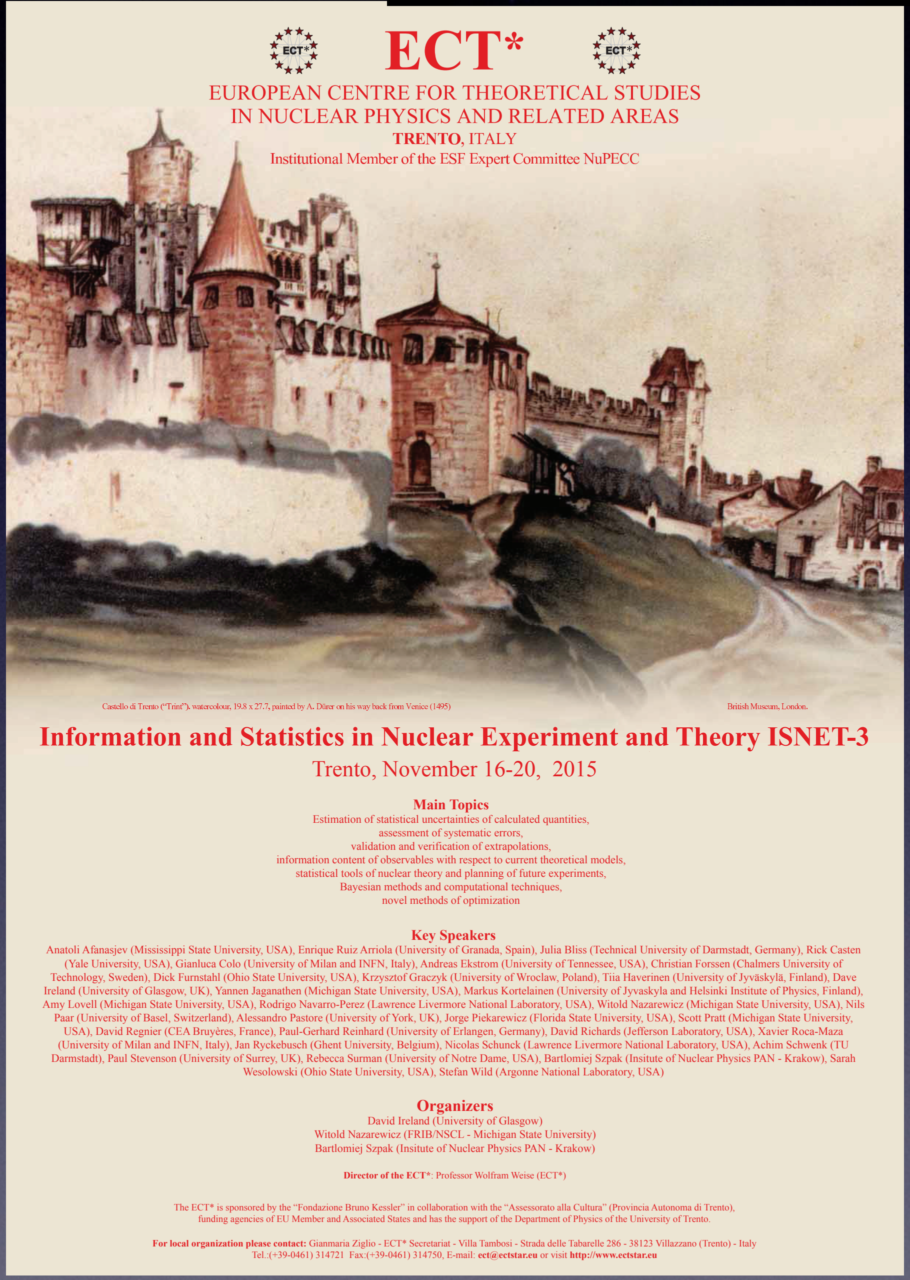


Information and Statistics: A New Paradigm in the Study of Neutron Stars

Jorge Piekarewicz - Florida State University







Nuclear Physics Division

CEA Saclay, France

May 13, 2016

My Collaborators

My FSU Collaborators

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

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- W. Nazarewicz (MSU)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
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- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)

U.S. DEPARTMENT OF ENERGY | Office of Science

Neutron Stars: Some Historical Facts

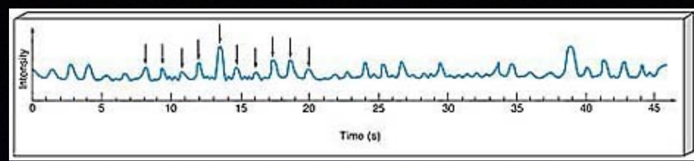
- Chandrasekhar shows that massive stars will collapse (1931)

- Chadwick discovers the neutron (1932)
  (… predicted earlier by Majorana but never published)

- 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 $M_\star \simeq 0.7\, M_\odot$ as maximum neutron star mass)

Neutron Stars: Dame Jocelyn Bell Burnell

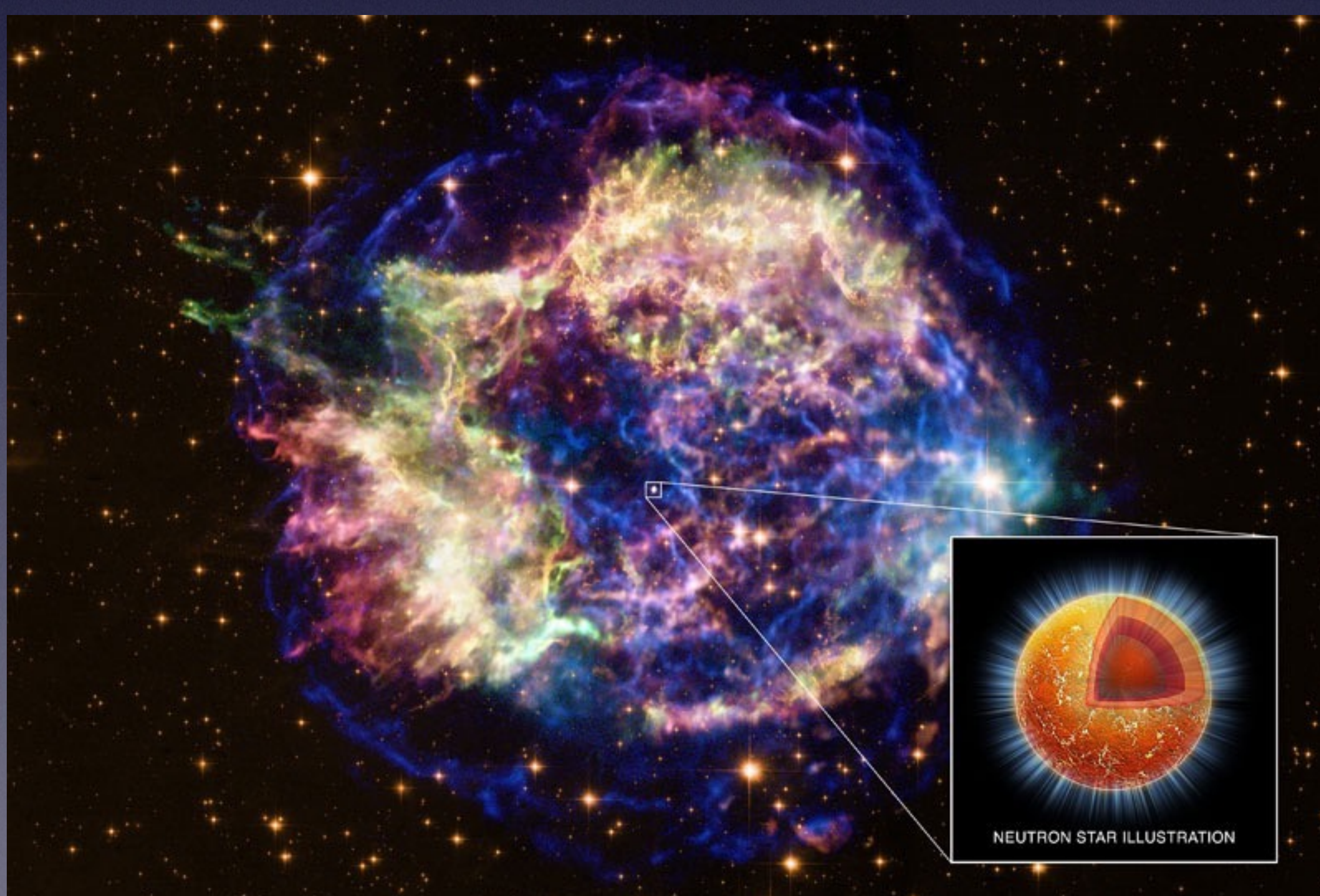


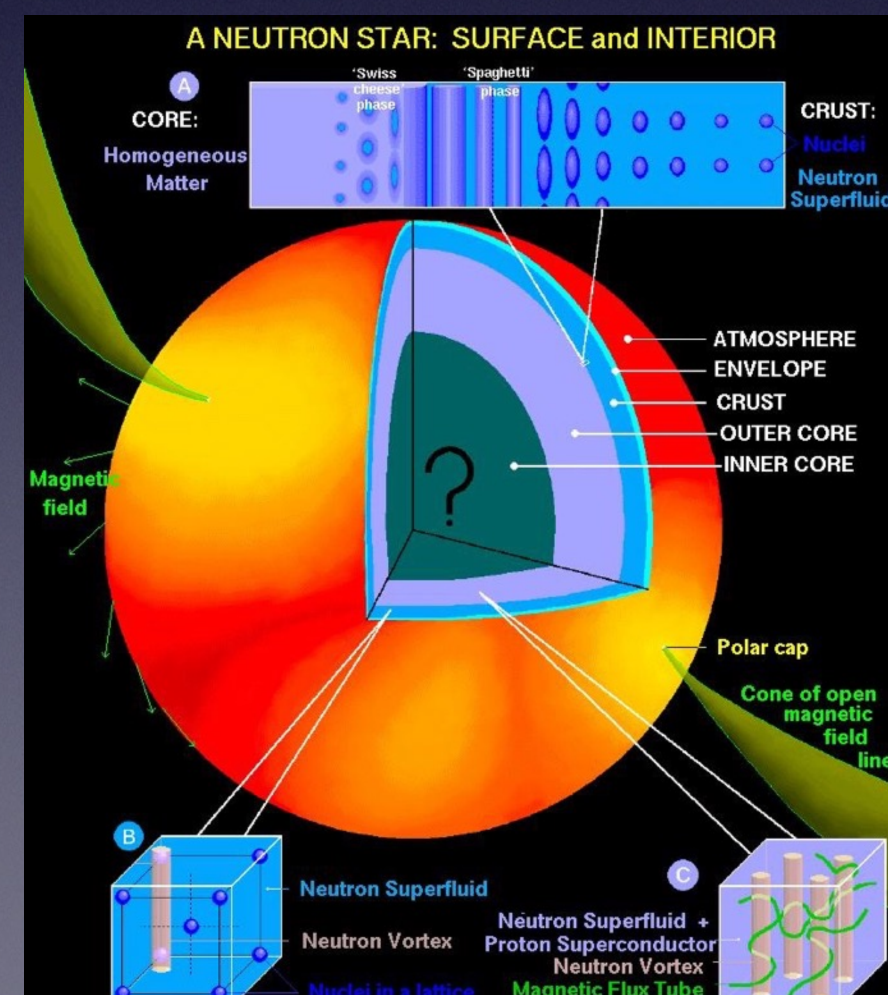
- Detected a bit of “scruff” (1967)
- Discovers amazing regularity in the signal
  (P=1.33730119 seconds)
- May the signal be from an alien civilization?
  (Little Green Man 1)
- Paper announcing first pulsar published
  [*Observation of a Rapidly Pulsating Radio Source*
  A Hewish, SJ Bell, et al., 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”

The Anatomy of a Neutron Star

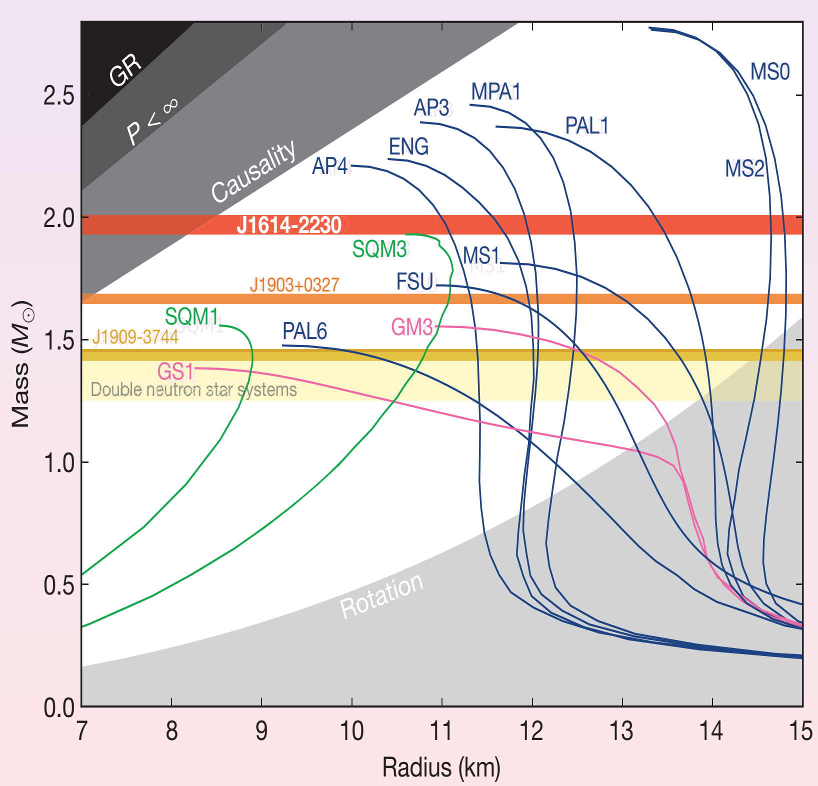
- Atmosphere (10 cm): Shapes Thermal Radiation ($L=4\pi\sigma R^2 T^4$)
- Envelope (100 m): Huge Temperature Gradient (10^8K $\leftrightarrow$ 10^6K)
- Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)
- Inner Crust (1 km): Coulomb Frustration (“Nuclear Pasta”)
- Outer Core (10 km): Uniform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





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

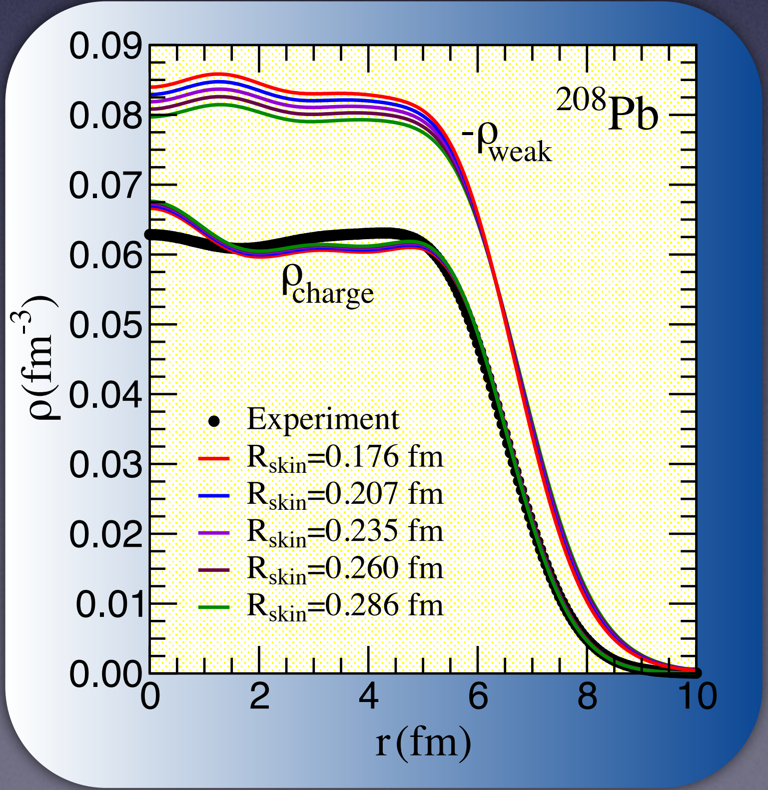
The Equation of State of Neutron-Rich Matter

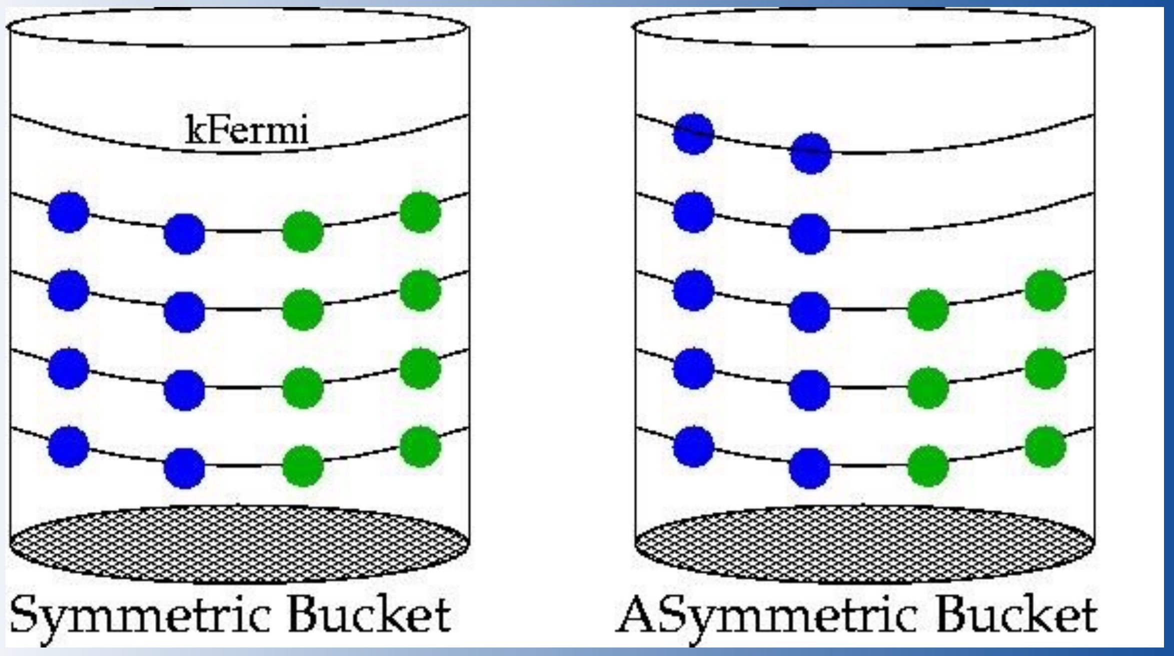
- The EOS of asymmetric matter: α=(N-Z)/A; $x=(\rho-\rho_0)/3\rho_0$; $T=0$
  - $\rho_0 \simeq 0.15$ fm-3 — saturation density ↔ nuclear density

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

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

- 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

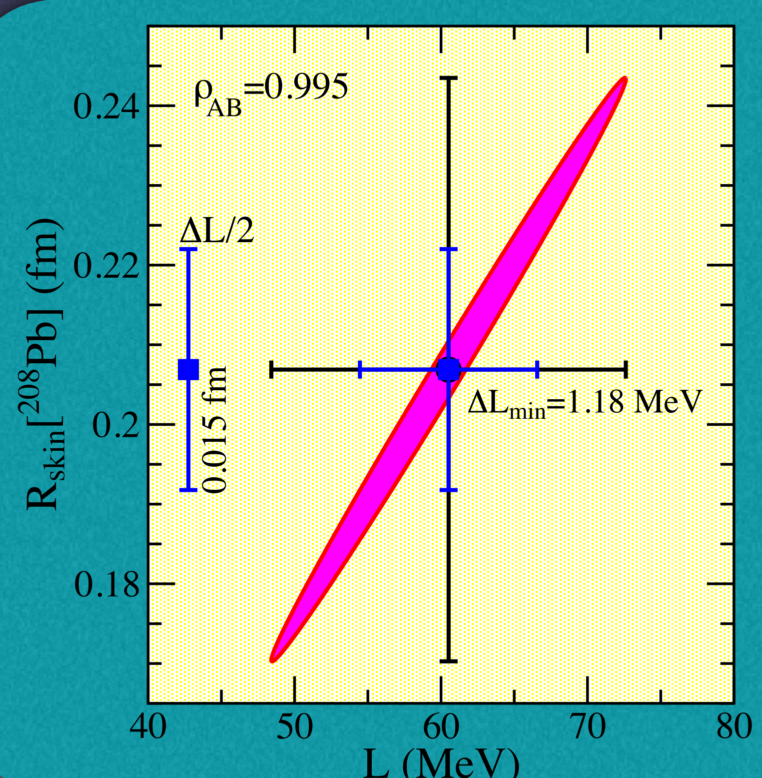
Searching for L: The Strategy

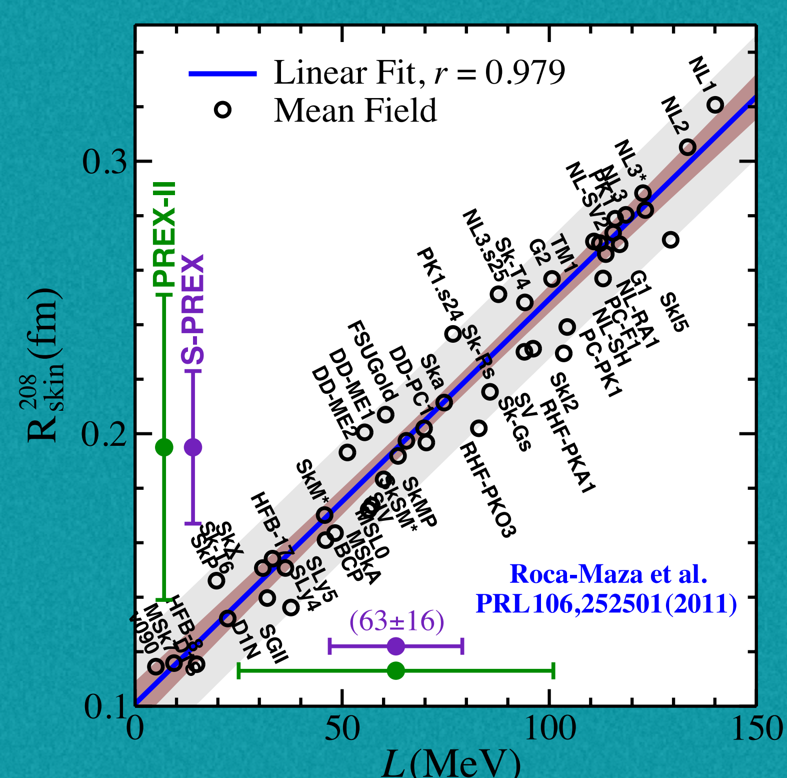
$P_{PNM} \simeq L\rho_0/3$ is not a physical observable

- 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")





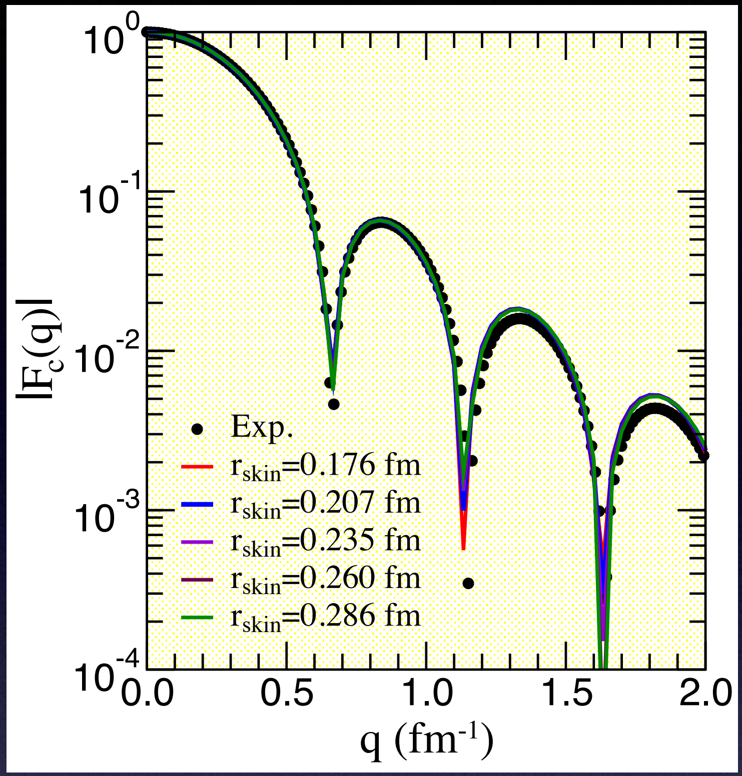
New era in Nuclear Theory where predictability will be typical and uncertainty quantification will be demanded …

Theory Informing Experiment

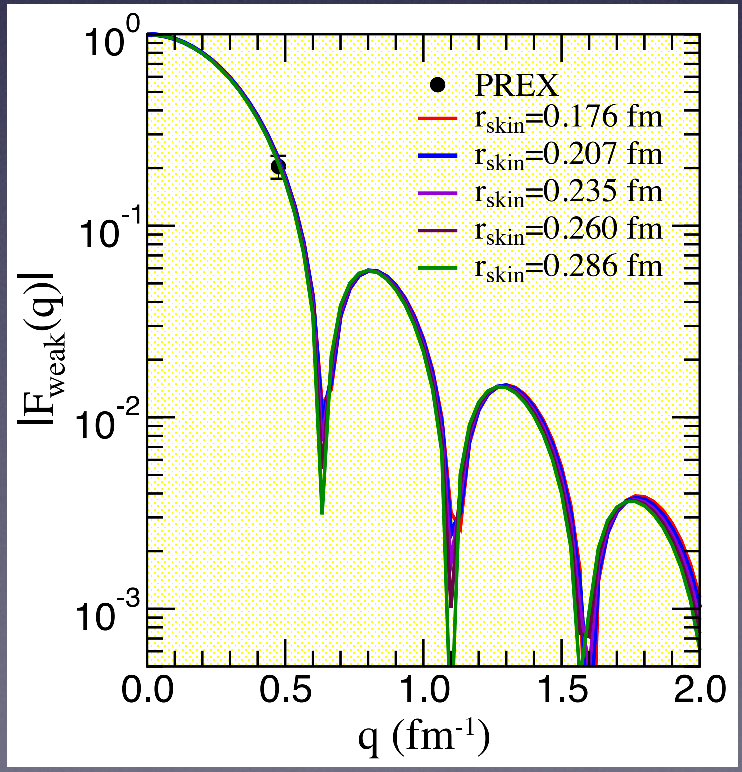
- PREX@JLAB: First electroweak evidence in favor of R_{skin} in Pb (error bars too large!)
- Precision required in the determination of the neutron radius/skin?
  - As precisely as "humanly possible" - fundamental nuclear structure property (*cf.* charge density)
  - To strongly impact Astrophysics?
- 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 will be 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

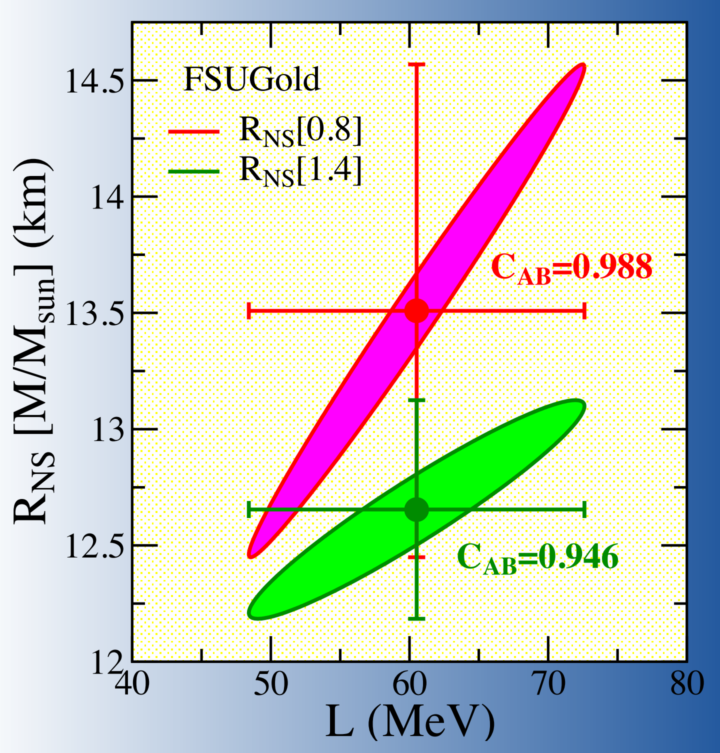


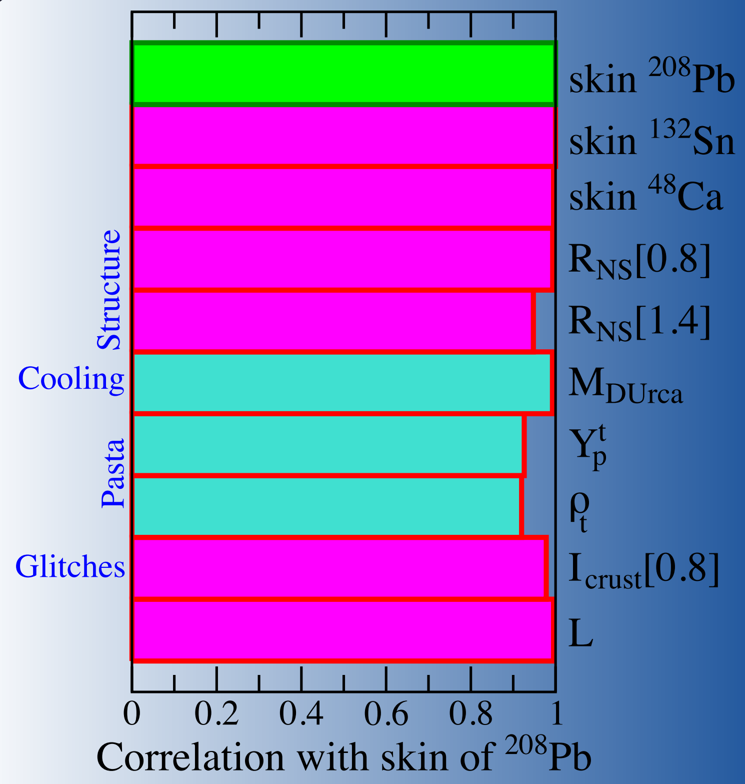
Heaven and Earth

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!



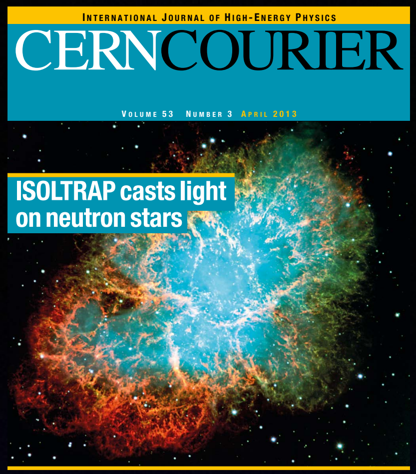


PHYSICAL REVIEW A 83, 040001 (2011)
Editorial: Uncertainty Estimates

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

The Composition of the Outer Crust

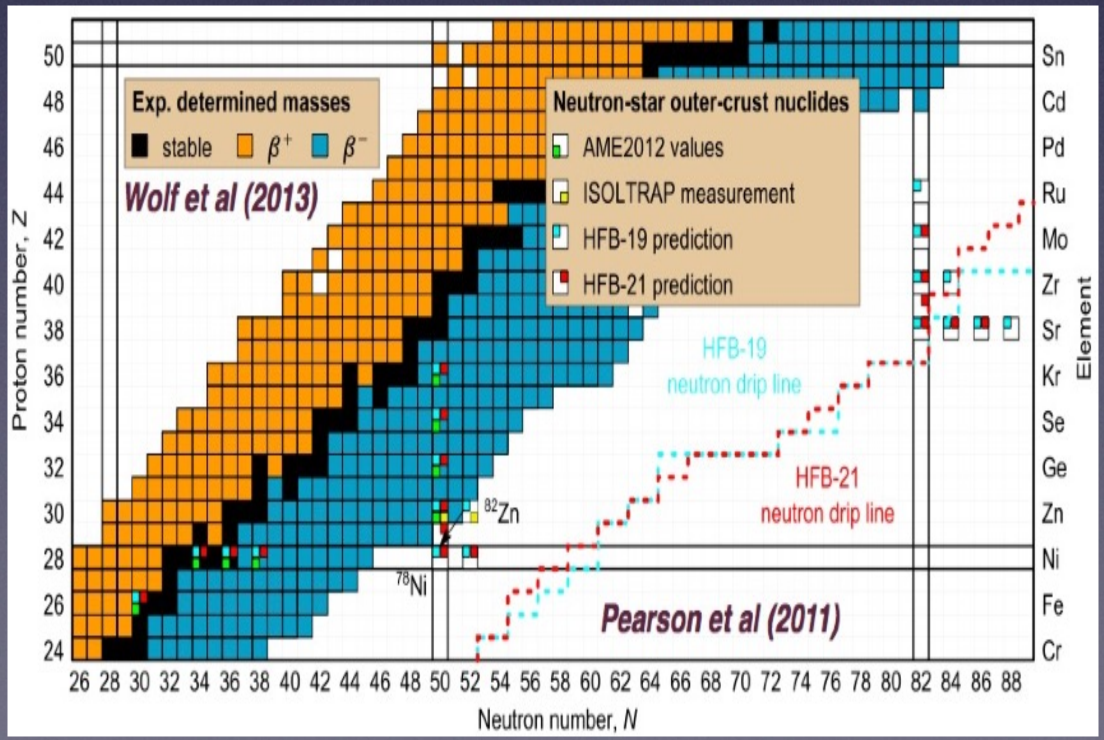
High sensitivity to nuclear masses

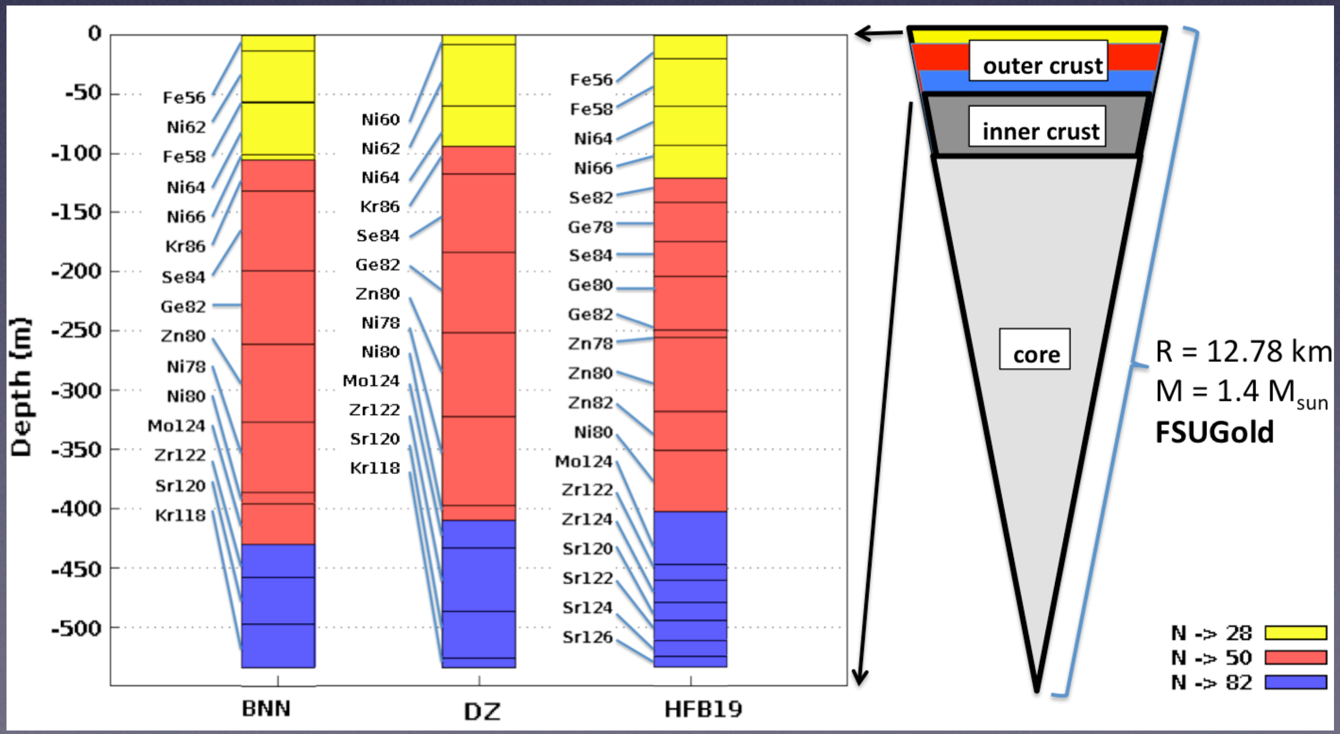


- System unstable to cluster formation
  - BCC lattice of neutron-rich nuclei imbedded in e-gas
- Composition emerges from relatively simple dynamics
  - Subtle composition between electronic and symmetry energy

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

- 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)

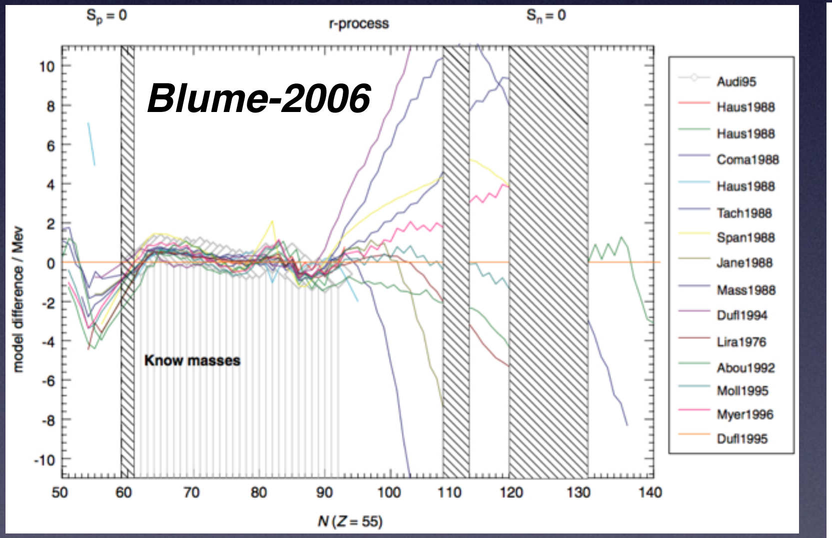
Nuclear mass predictions for the crustal composition of neutron stars: A Bayesian neural network approach

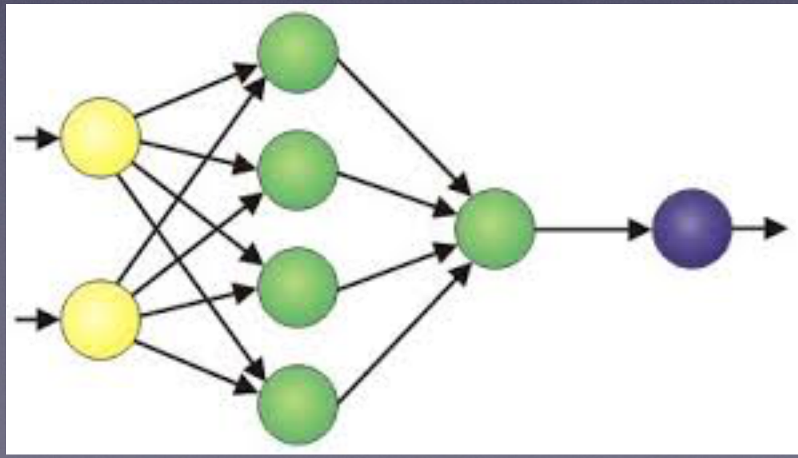
R. Utama,* J. Piekarewicz,† and H. B. Prosper‡
Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

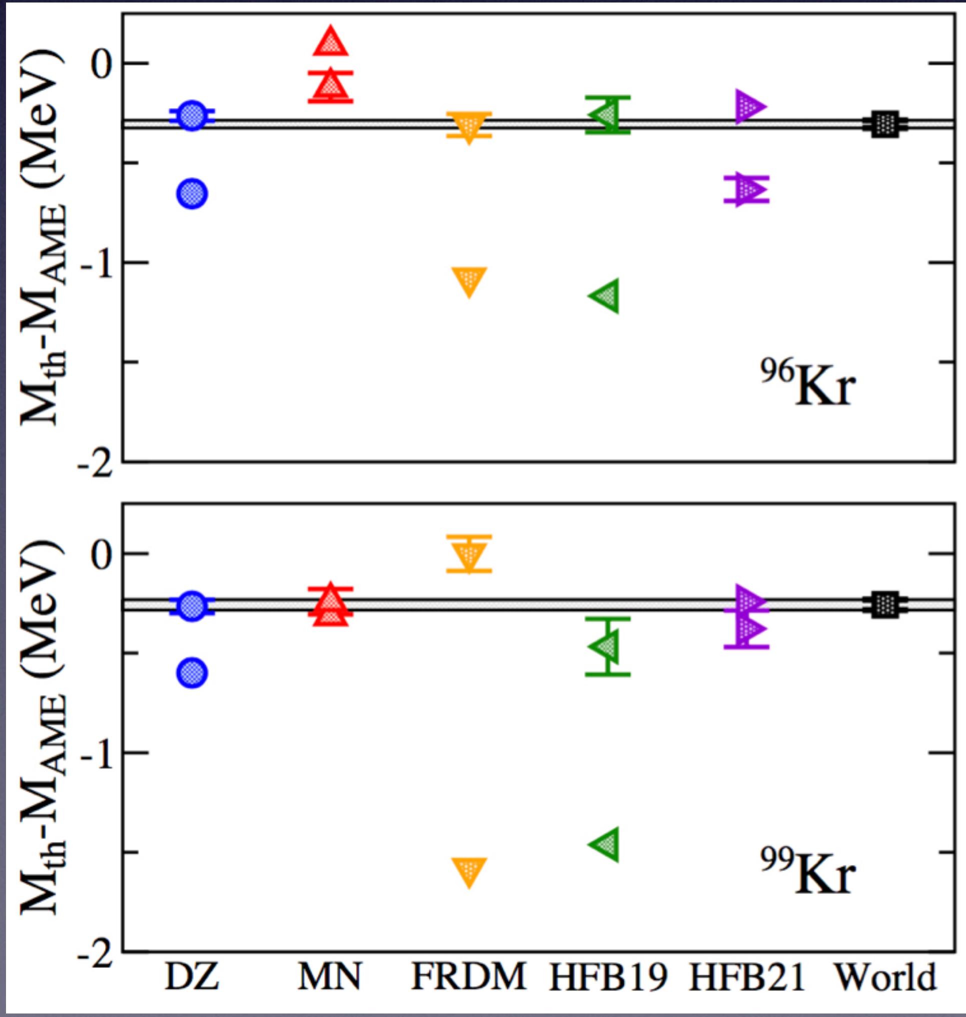
- Use DFT to predict nuclear masses
- Train BNN by focusing on residuals

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

- Systematic scattering greatly reduced
- Predictions supplemented by theoretical errors







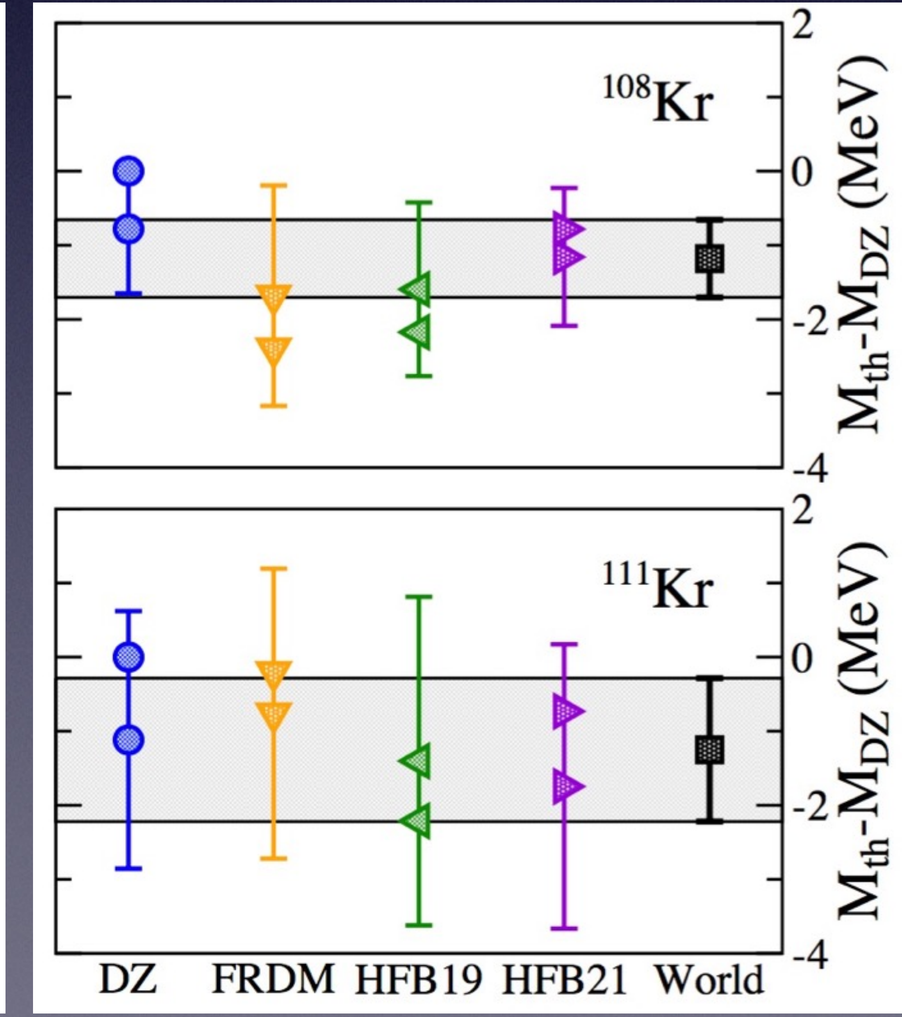
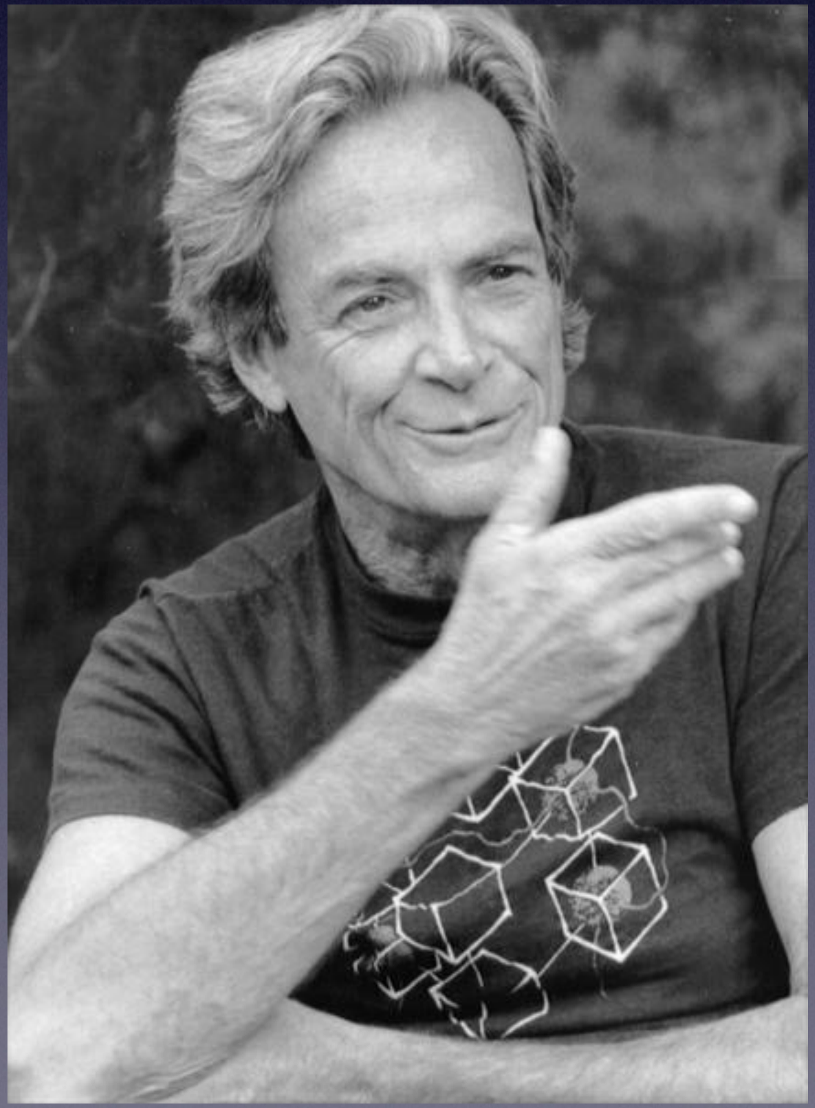
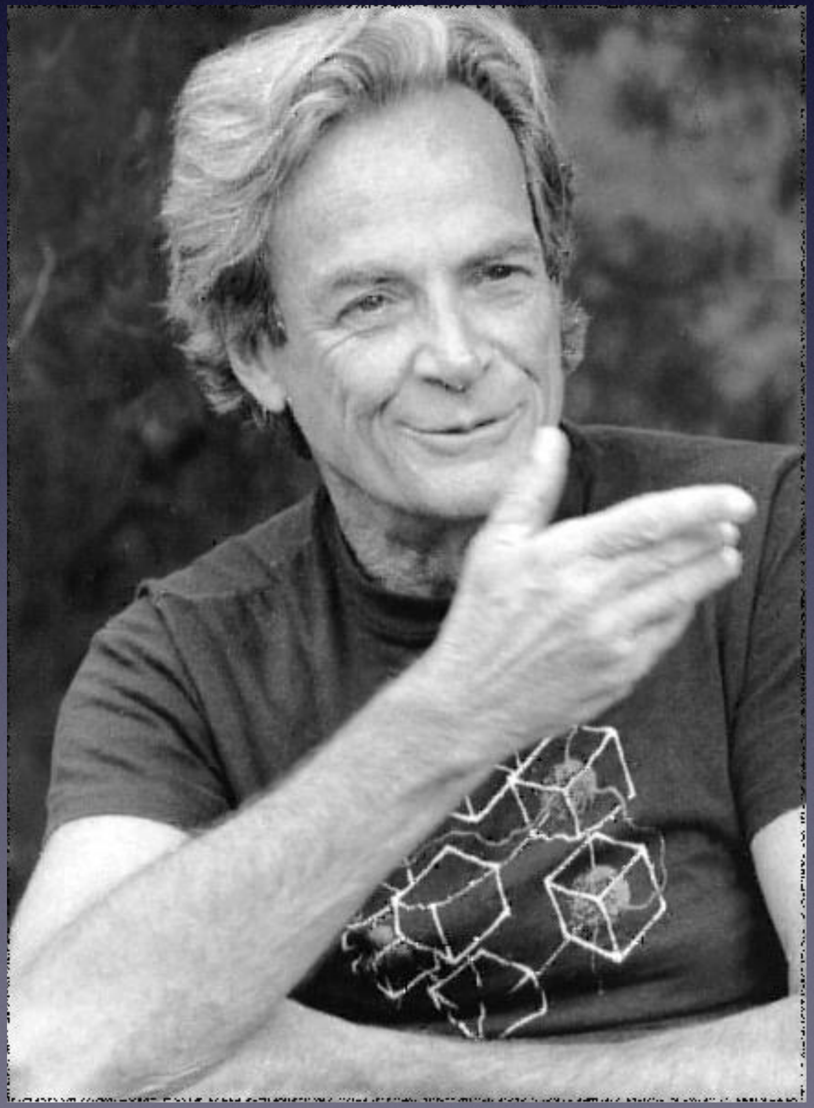


Image Reconstructions meets BNN

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

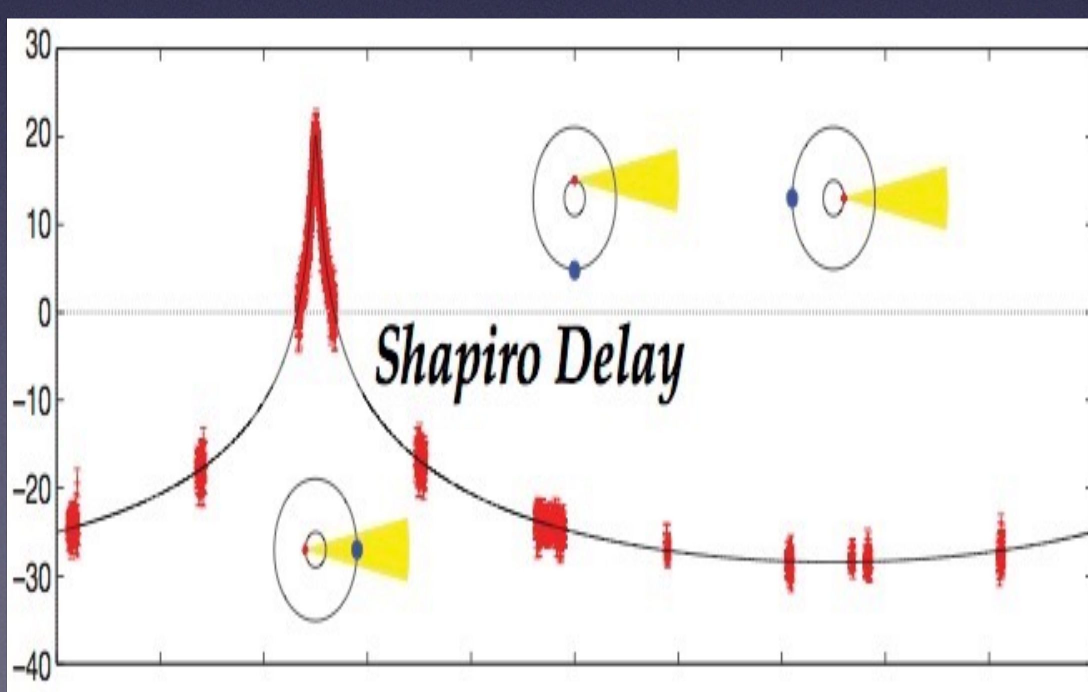
Image reconstructed using Garvey-Kelson "Mass Relations"



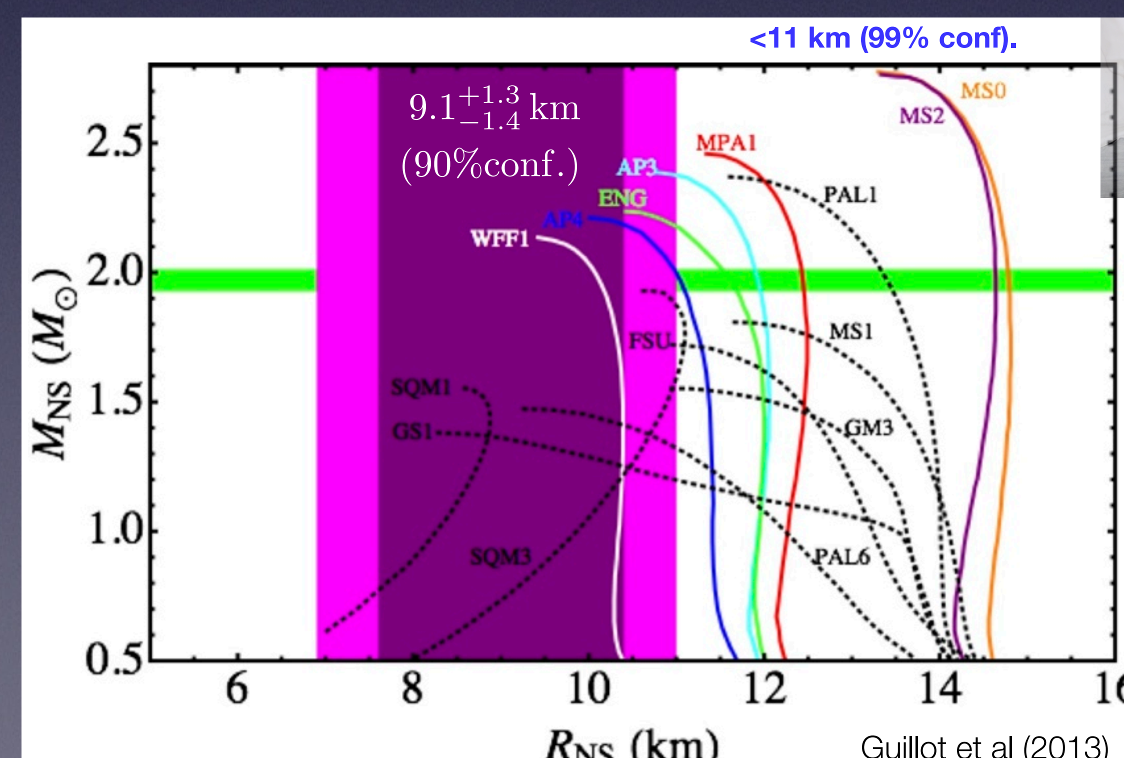


Addressing Future Challenges

- 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!

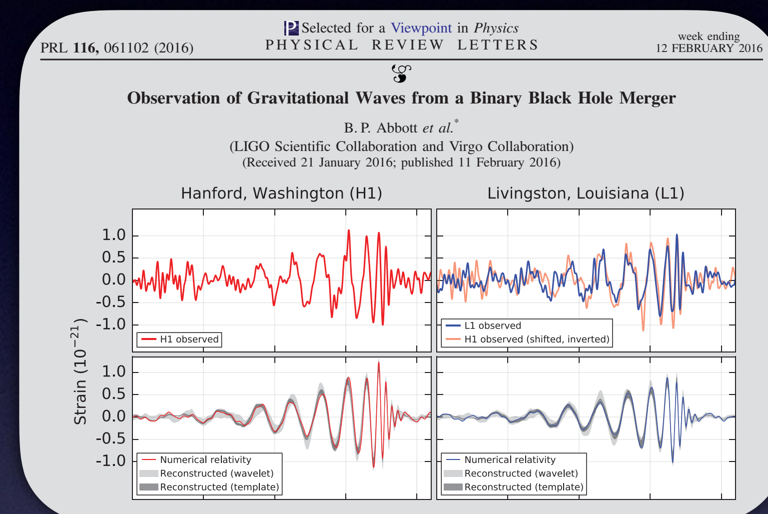


WFF1 violates causality!

"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

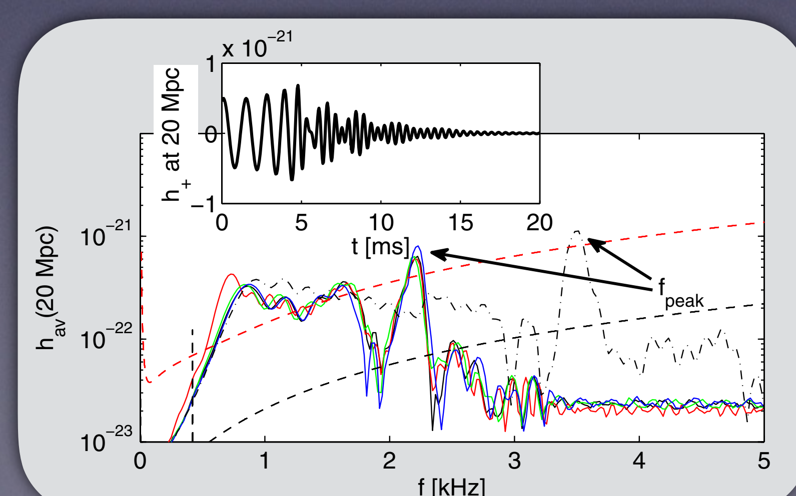

Selected for a Viewpoint in Physics
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

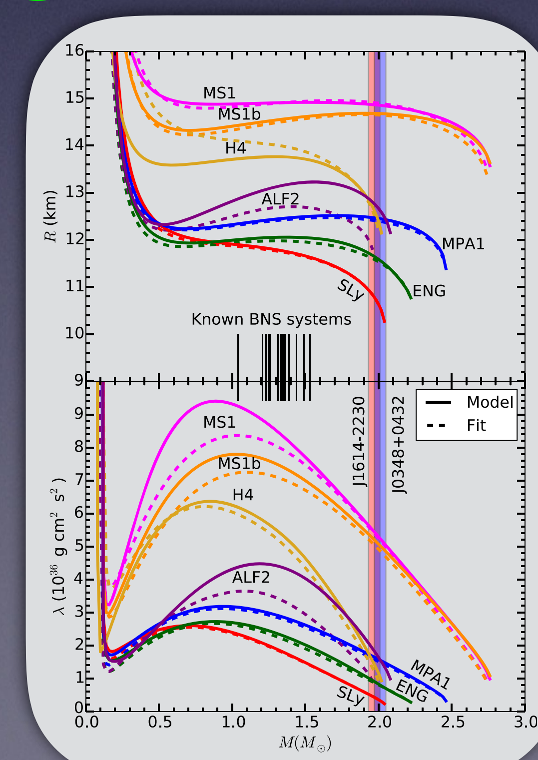
Observation of Gravitational Waves from a Binary Black Hole Merger

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!



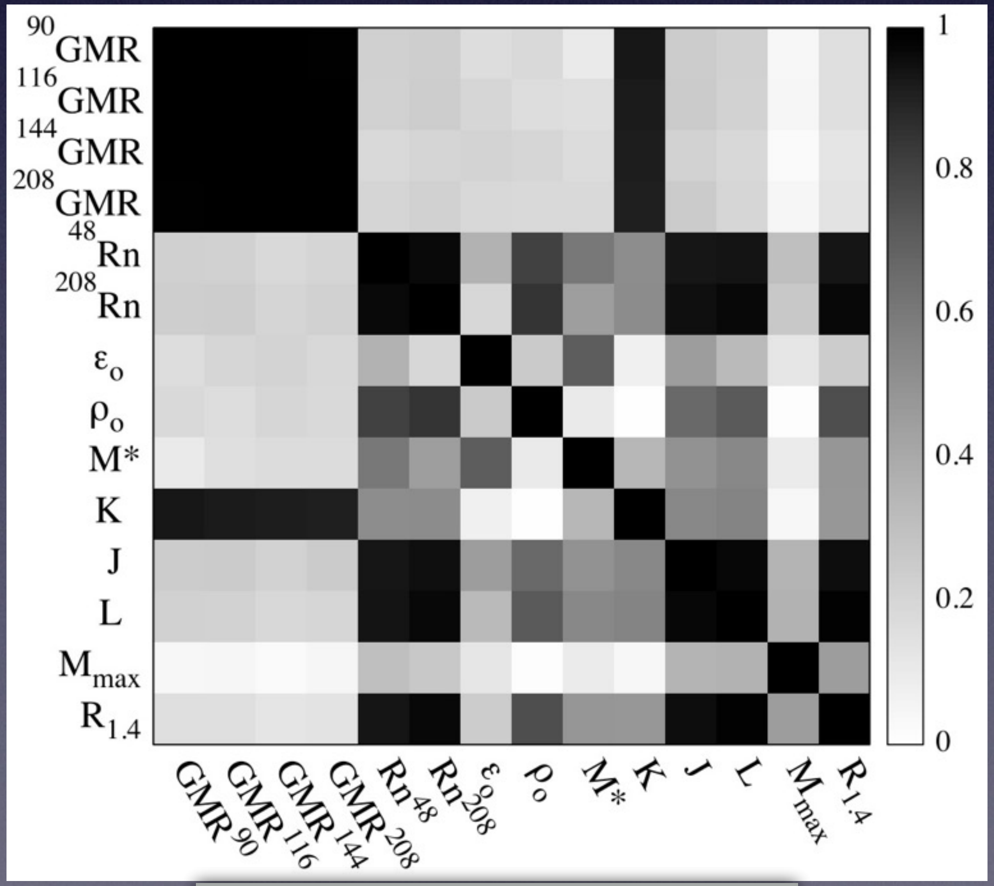


Conclusions

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 …

The train has left the station.
The need for uncertainty estimates of theoretical models has been recognized in the nuclear physics community. So the question is not whether to do it or not, but how to do it best.
(from a dedicated volume to uncertainty quantification in nuclear physics on JPG; 11/10/2015)



Wei-Chia Chen and JP
PRC 90, 044305 (2014)