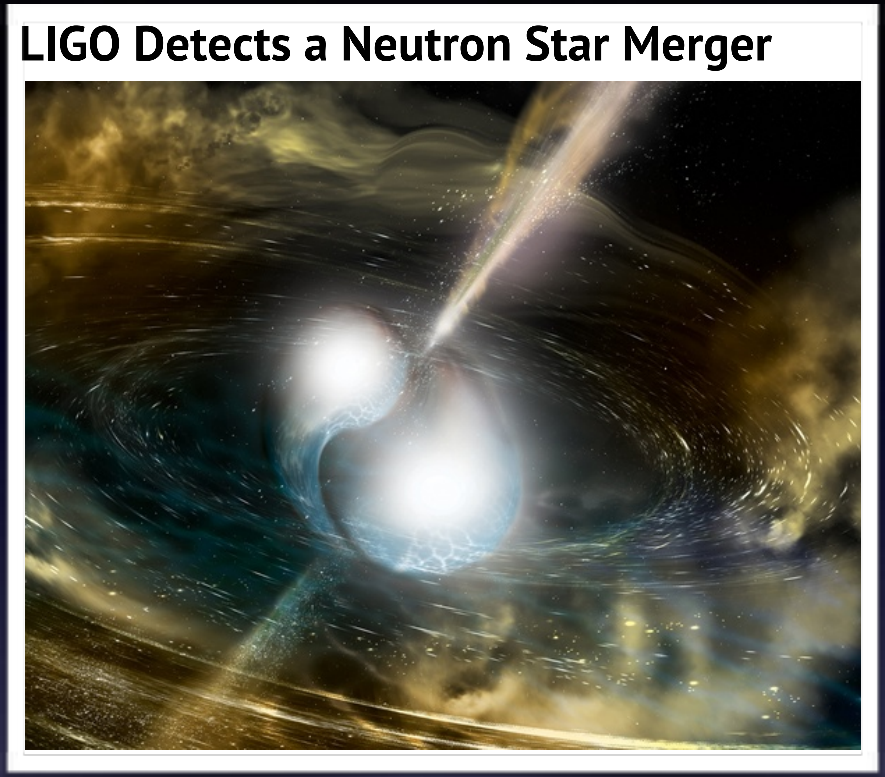
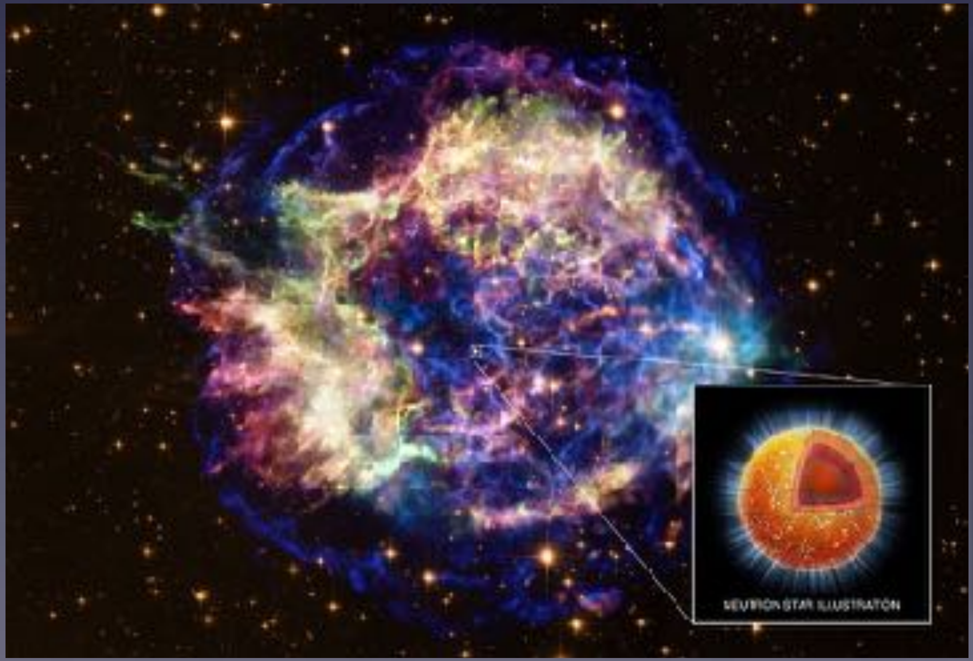
Nuclear Astrophysics in the new era of multi-messenger Astronomy


LIGO Detects a Neutron Star Merger

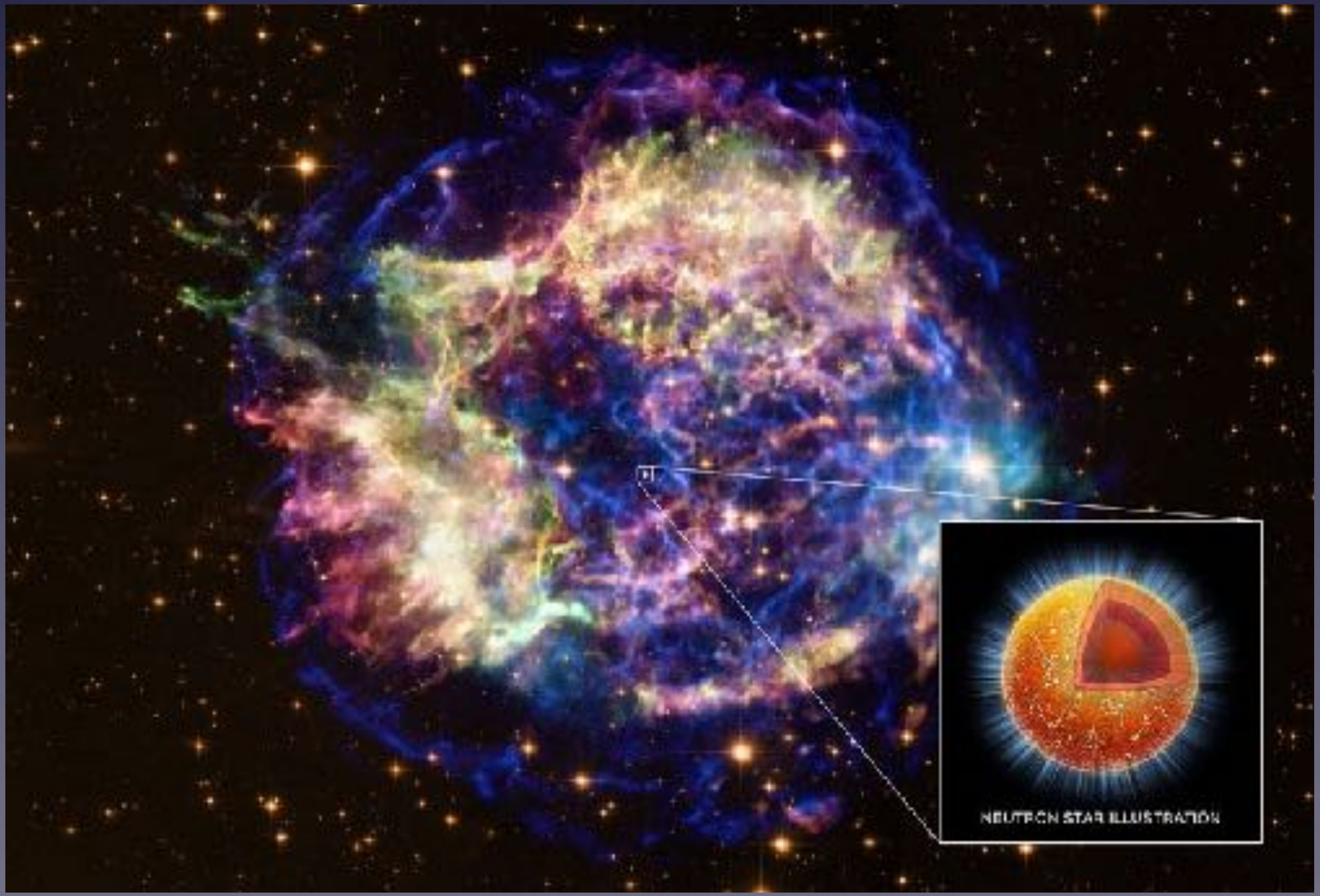


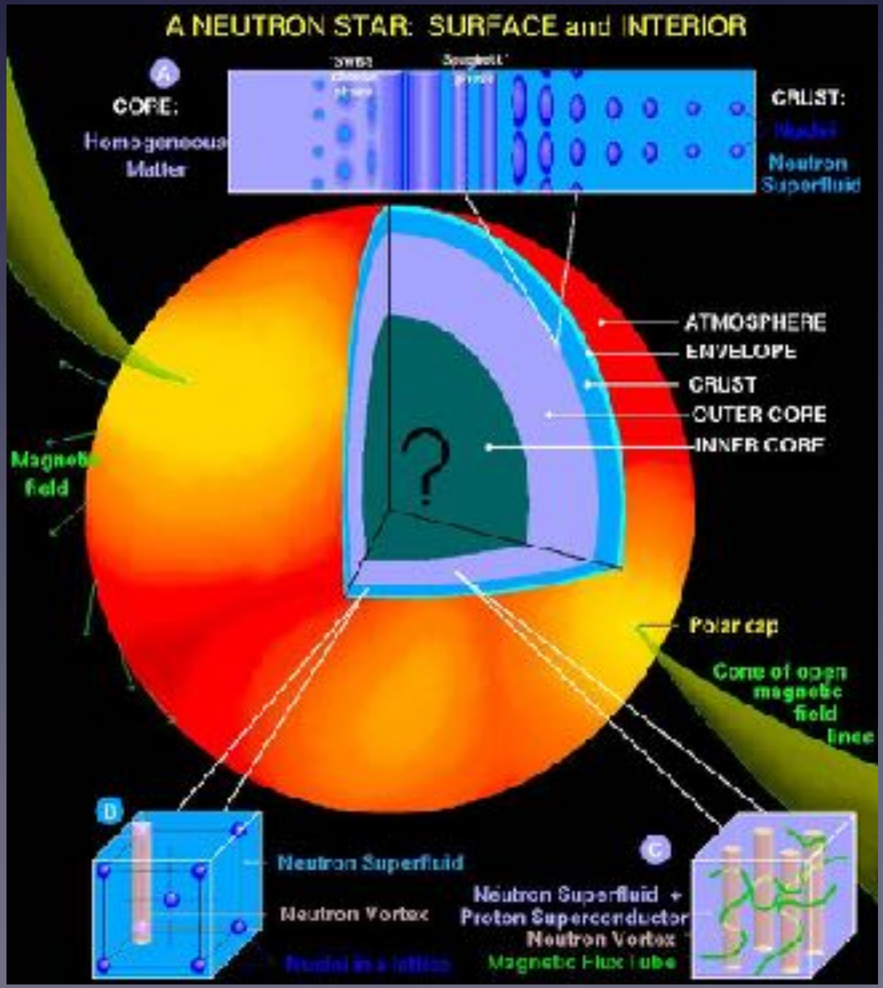
Two Stars:
Pele'
and
Cassiopeia A

Jorge Piekarewicz
Florida State University

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)



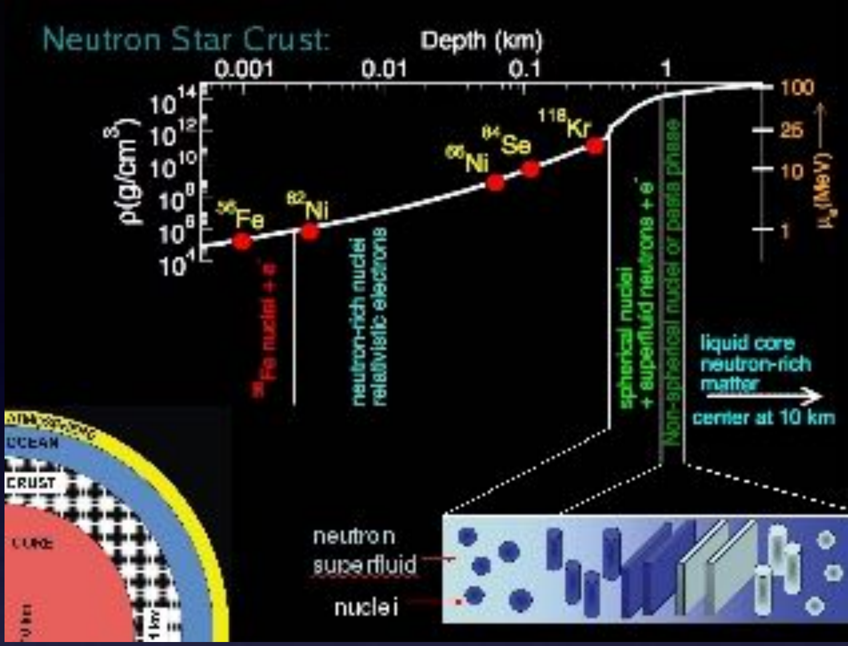


The Composition of the Outer Crust

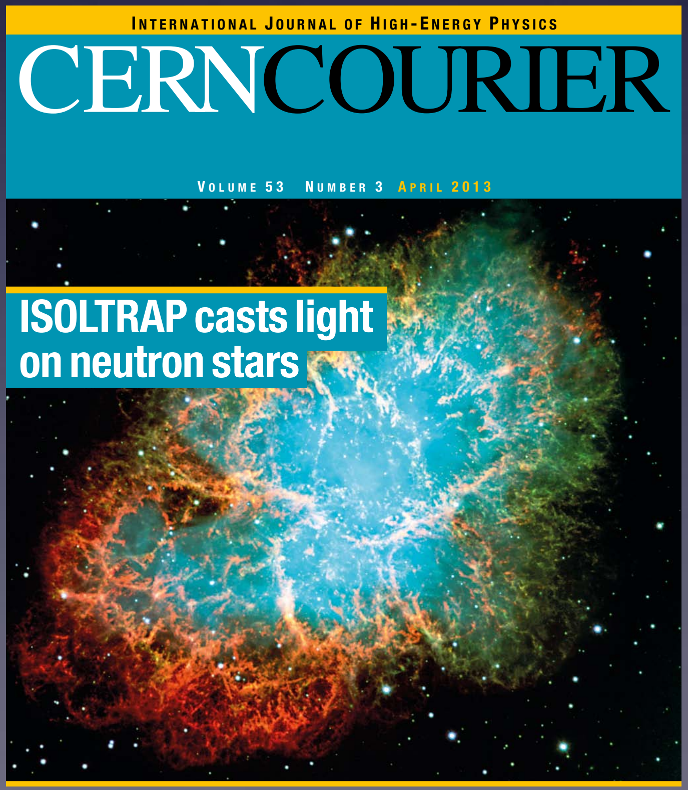
Enormous sensitivity to nuclear masses

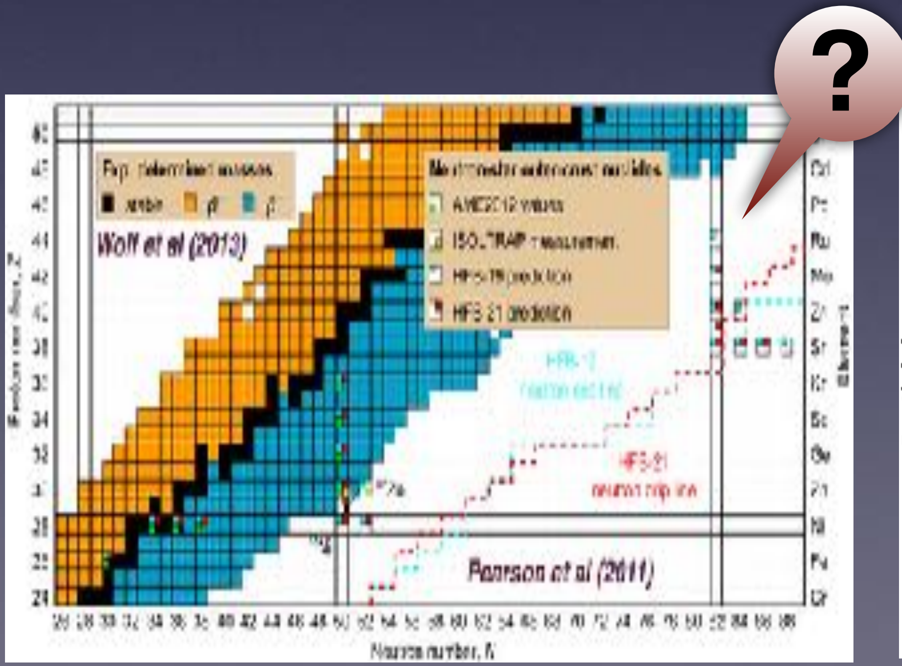
- System unstable to cluster formation
  - BCC lattice of neutron-rich nuclei imbedded in e-gas
- Composition emerges from relatively simple dynamics
  - Competition between electronic and symmetry energy

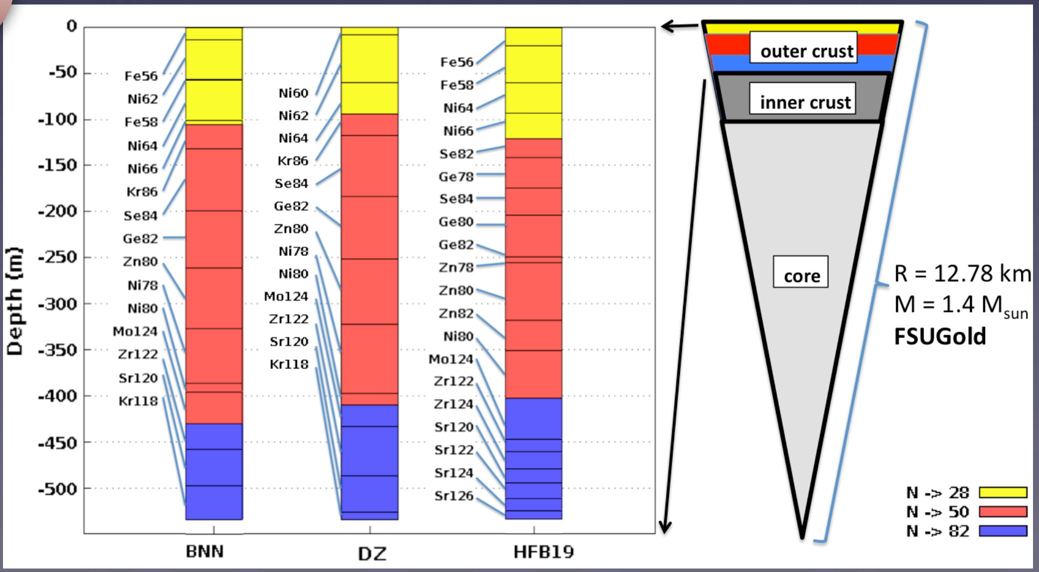
$$E/A_{\rm tot} = M(N,Z)/A + \frac{3}{4} Y_e^{4/3} k_{\rm F} + \text{lattice}$$



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



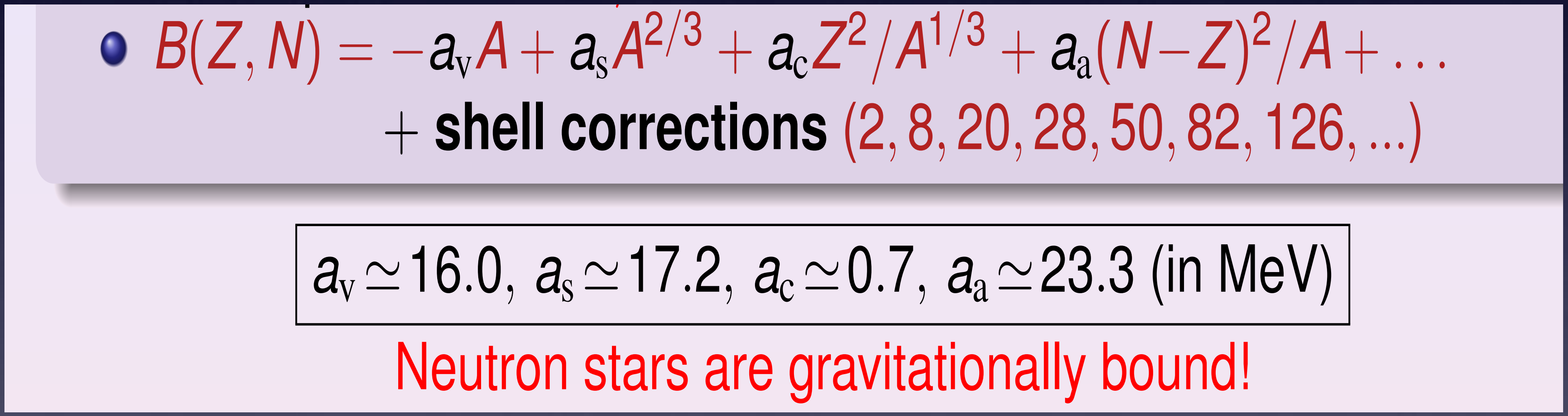




The Liquid Drop Model

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

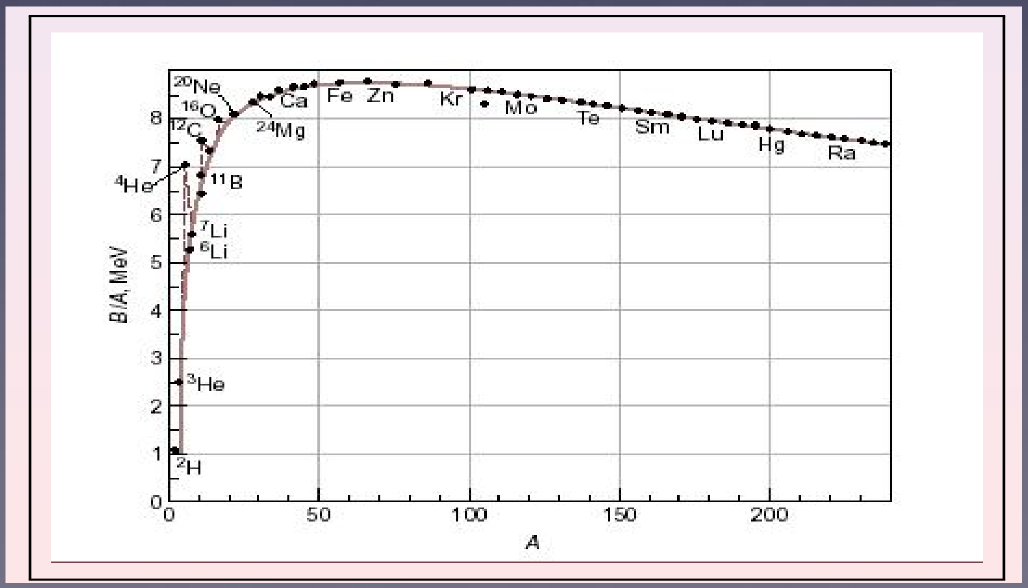
- Nuclear forces saturate $\xrightarrow{R = r_0 A^{1/3}}$ equilibrium density
- Nuclei penalized for developing a surface
- Nuclei penalized by Coulomb repulsion
- Nuclei penalized for isospin imbalance (N≠Z)

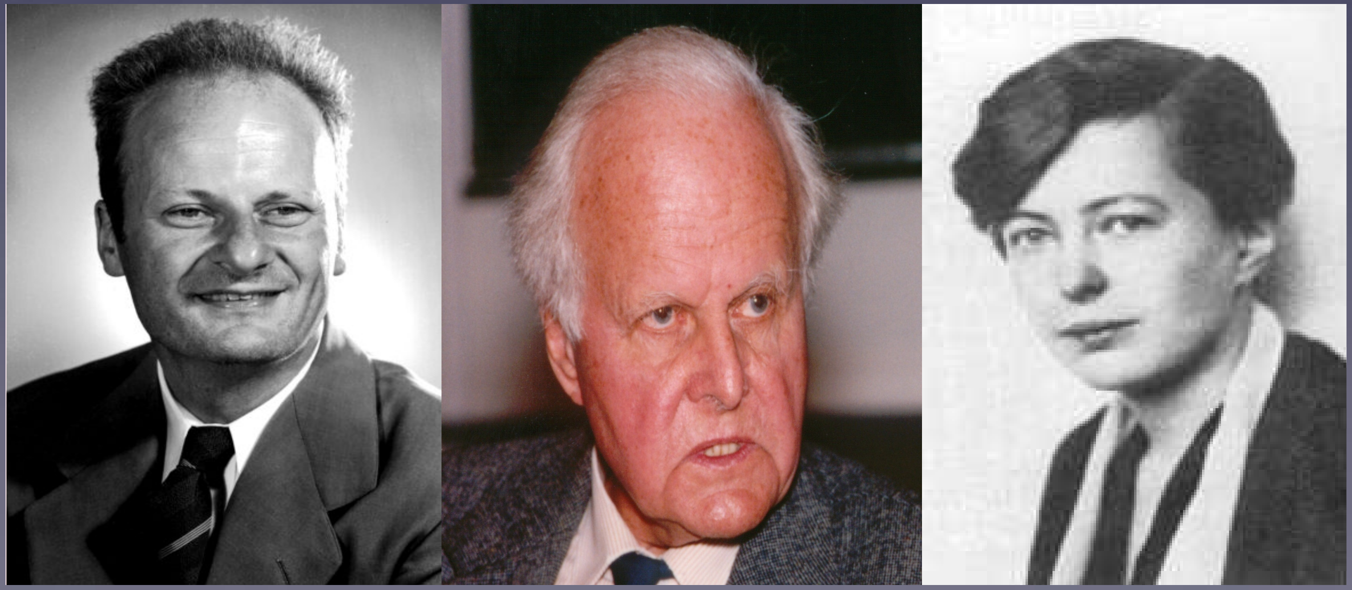


- $B(Z,N) = -a_v A + a_s A^{2/3} + a_c Z^2/A^{1/3} + a_a (N-Z)^2/A + \ldots$
  $+$ **shell corrections** (2, 8, 20, 28, 50, 82, 126, ...)

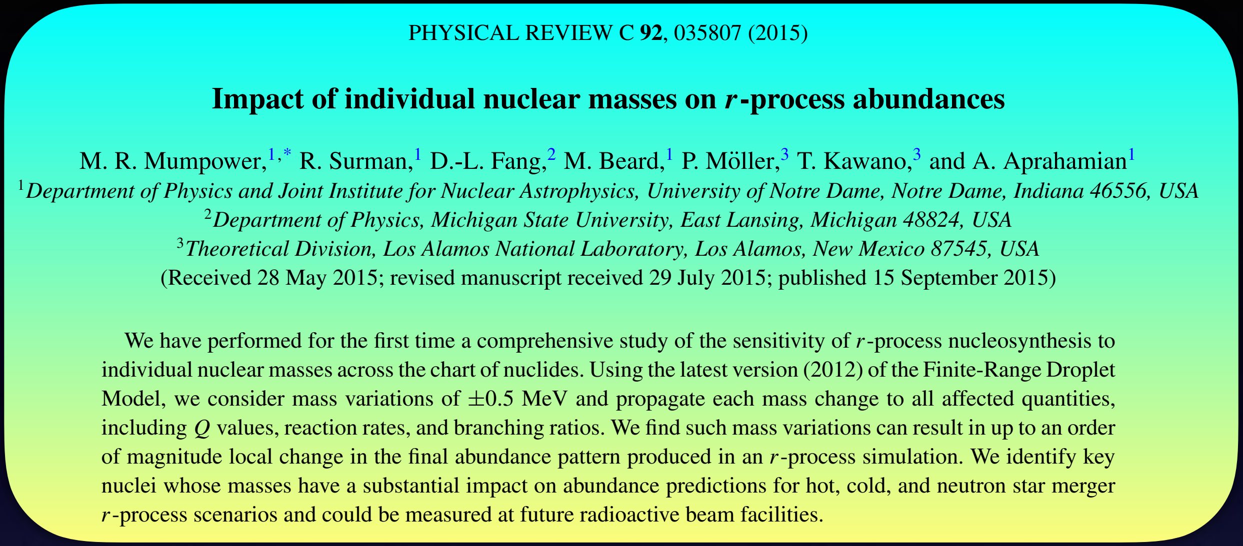
$$\boxed{a_v \simeq 16.0,\ a_s \simeq 17.2,\ a_c \simeq 0.7,\ a_a \simeq 23.3 \text{ (in MeV)}}$$

Neutron stars are gravitationally bound!





Masses of relevance to the r-process
Inevitable Theoretical Extrapolations



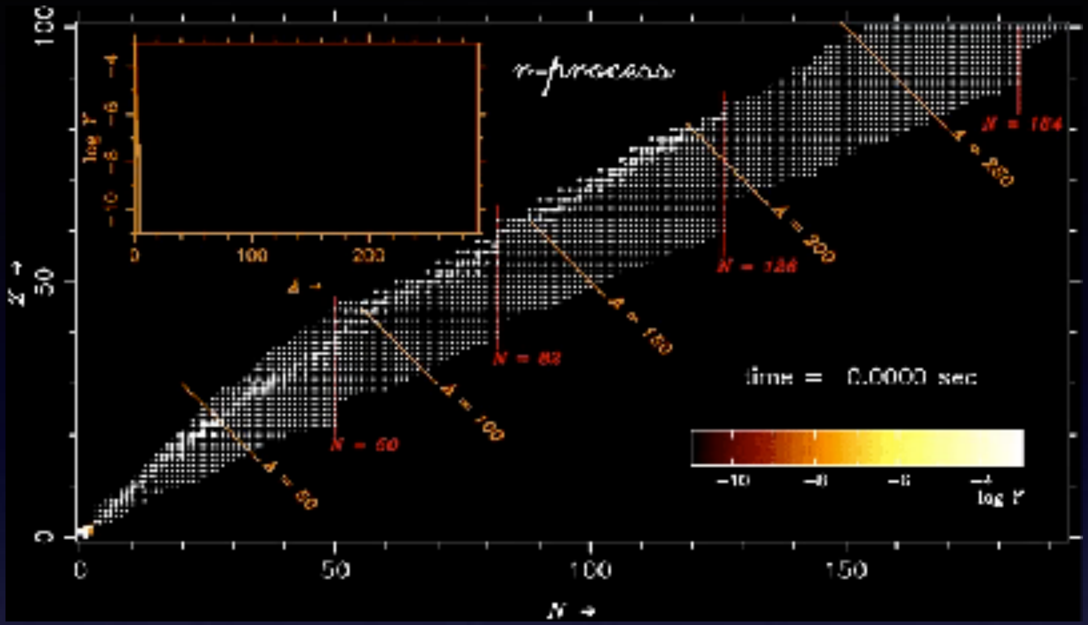
PHYSICAL REVIEW C **92**, 035807 (2015)

Impact of individual nuclear masses on *r*-process abundances

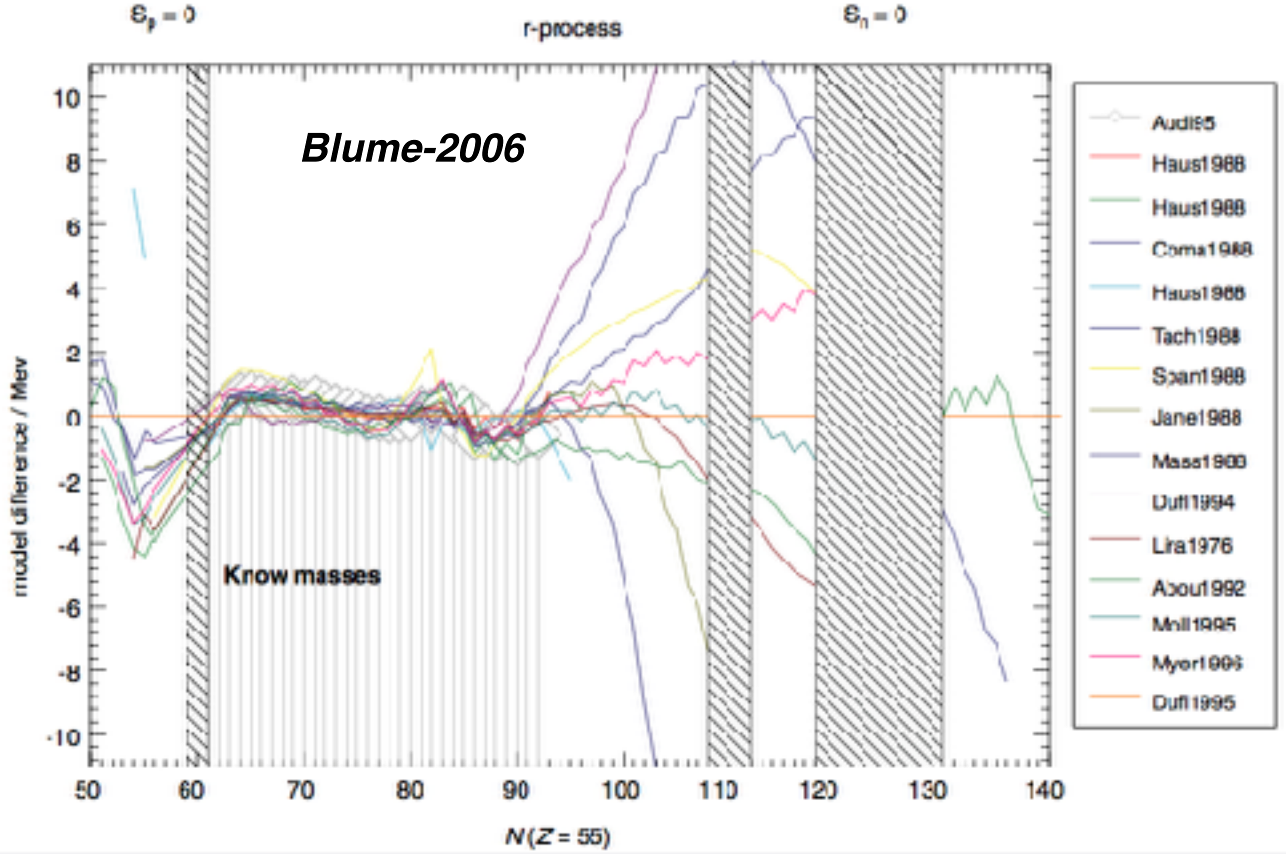
M. R. Mumpower,[1,*] R. Surman,[1] D.-L. Fang,[2] M. Beard,[1] P. Möller,[3] T. Kawano,[3] and A. Aprahamian[1]
[1] *Department of Physics and Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2] *Department of Physics, Michigan State University, East Lansing, Michigan 48824, USA*
[3] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

(Received 28 May 2015; revised manuscript received 29 July 2015; published 15 September 2015)

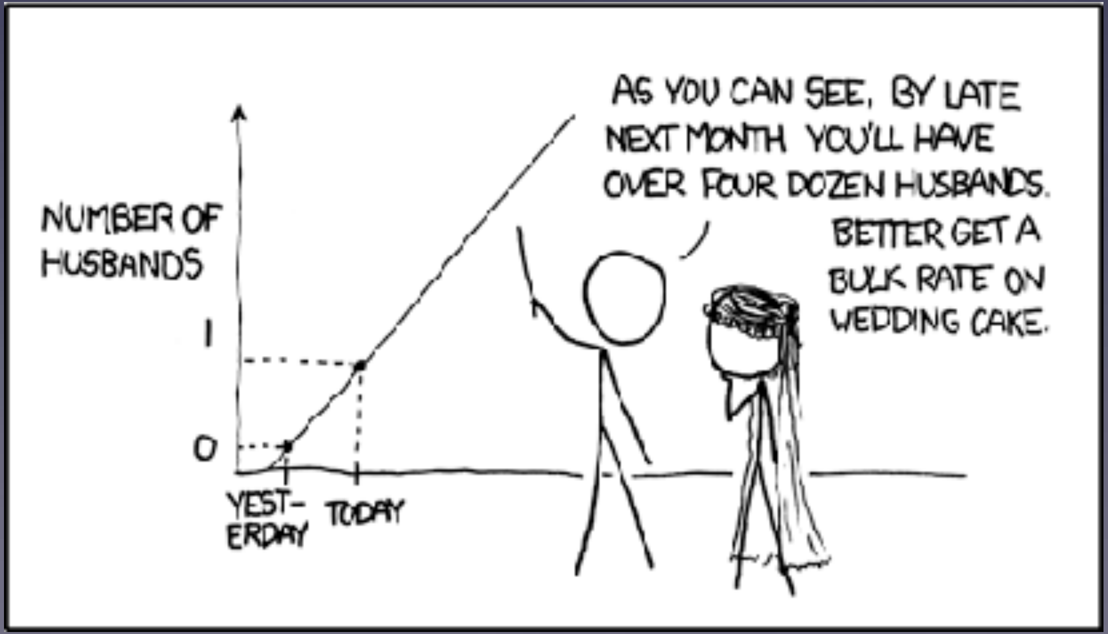
We have performed for the first time a comprehensive study of the sensitivity of *r*-process nucleosynthesis to individual nuclear masses across the chart of nuclides. Using the latest version (2012) of the Finite-Range Droplet Model, we consider mass variations of ±0.5 MeV and propagate each mass change to all affected quantities, including Q values, reaction rates, and branching ratios. We find such mass variations can result in up to an order of magnitude local change in the final abundance pattern produced in an *r*-process simulation. We identify key nuclei whose masses have a substantial impact on abundance predictions for hot, cold, and neutron star merger *r*-process scenarios and could be measured at future radioactive beam facilities.



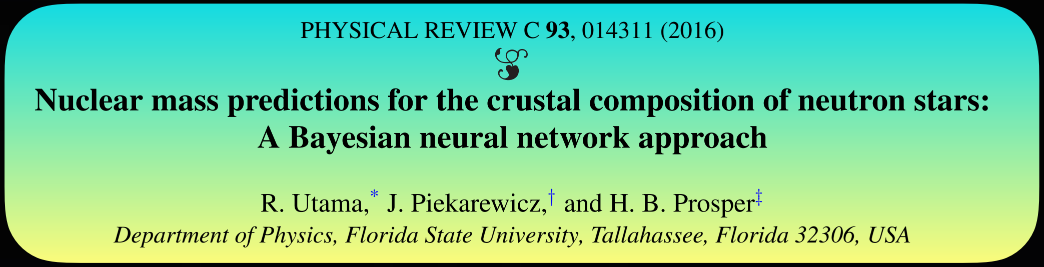
- *Theory agrees with experiment in regions where data is available*
- *Theory disagrees widely outside those regions*
- *Extrapolations are dangerous - yet inevitable!*



Machine Learning as a last resort to the extrapolation dilemma!



Nuclear Theory meets Machine Learning



PHYSICAL REVIEW C **93**, 014311 (2016)

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

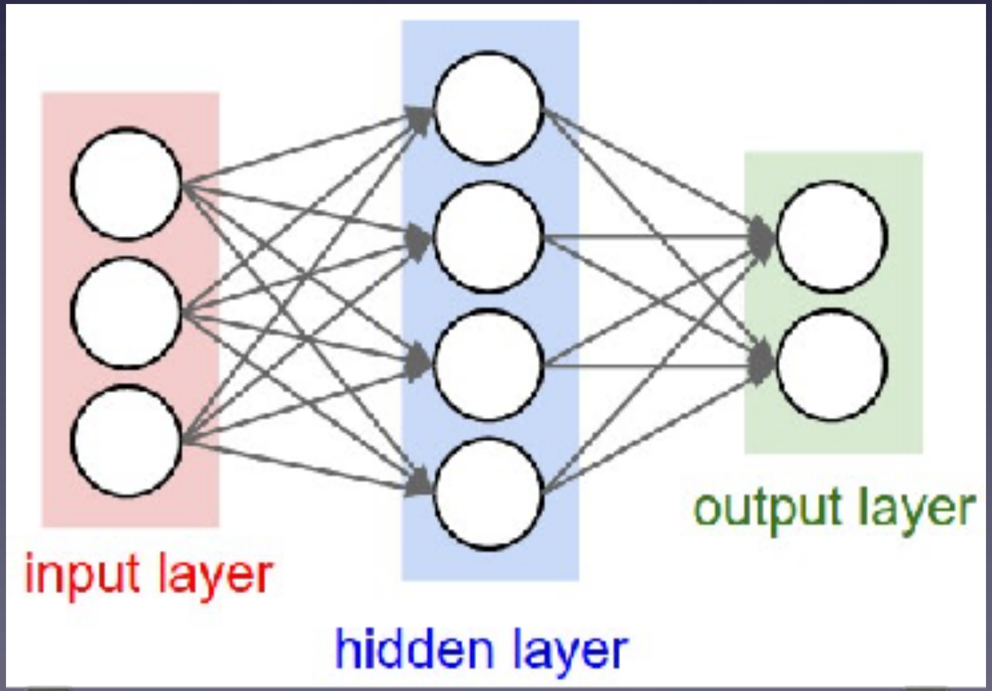
R. Utama,* J. Piekarewicz,† and H. B. Prosper‡
Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

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

} *The paradigm*

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

- Systematic scattering greatly reduced
- Predictions supplemented by theoretical errors

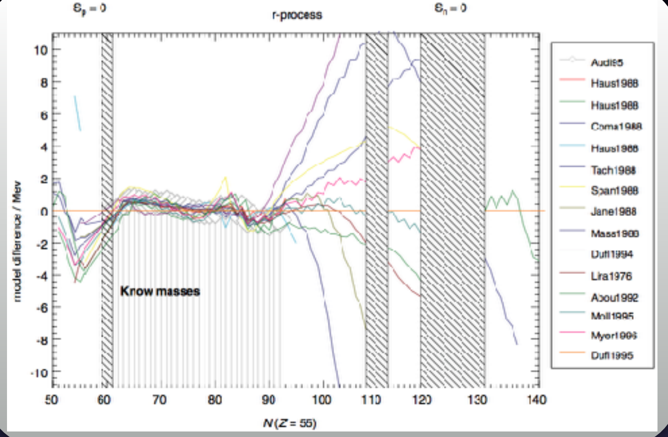


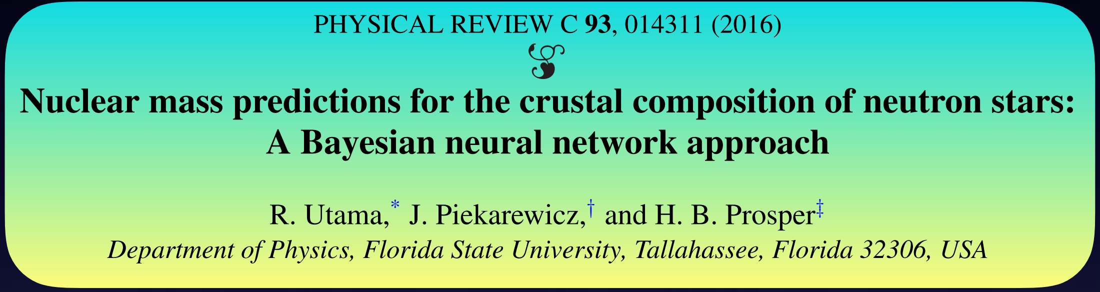
Artificial Neural Network

Re-generating Richard Feynman

Verify, Validate, and Predict

- Verify: http://www.cs.toronto.edu/~radford/ (Radford M. Neil)
- Validate: divide data into training and validation sets
- Predict: Use the model outside its comfort zone

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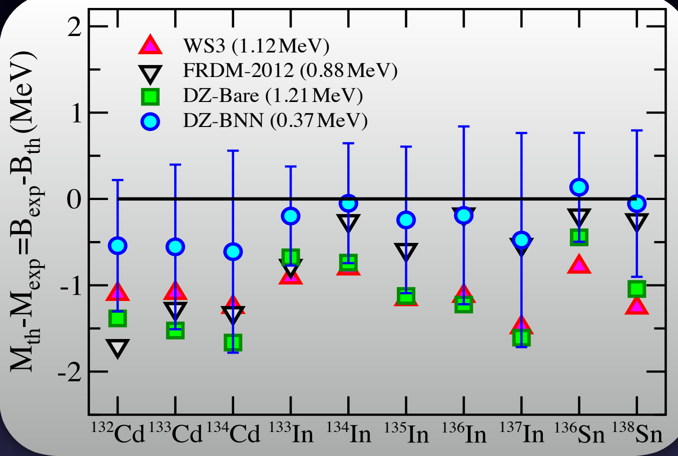
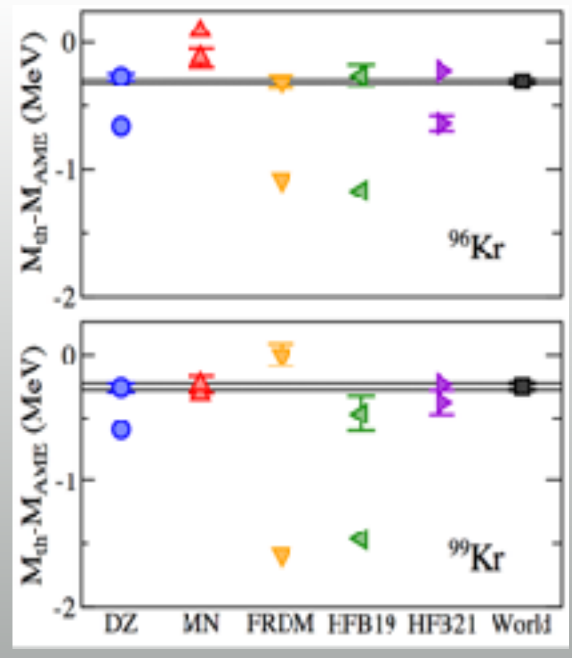
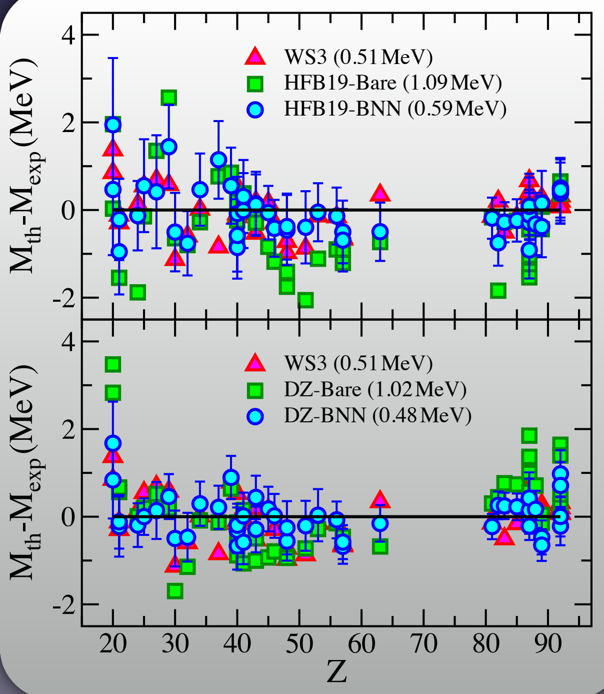


- Systematic scattering greatly reduced
  Models that over-predict tend to go down
  Models that under-predict tend to go up
- Predictions with theoretical errors
  Extrapolations are unreliable - yet errors help mitigate the problem …
- Accurate predictions for ~60 new nuclei
  New AME2016 compilation …
- Helps in our understanding of both the composition of the stellar crust and r-process nucleosynthesis

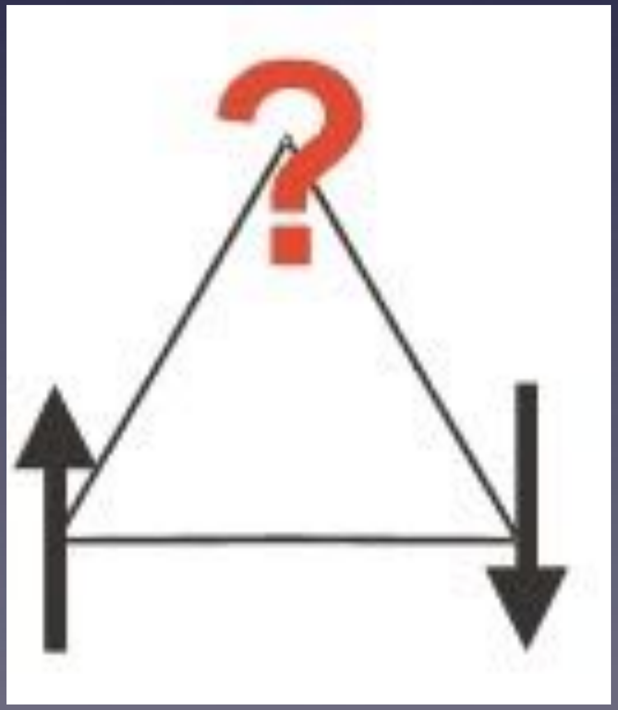


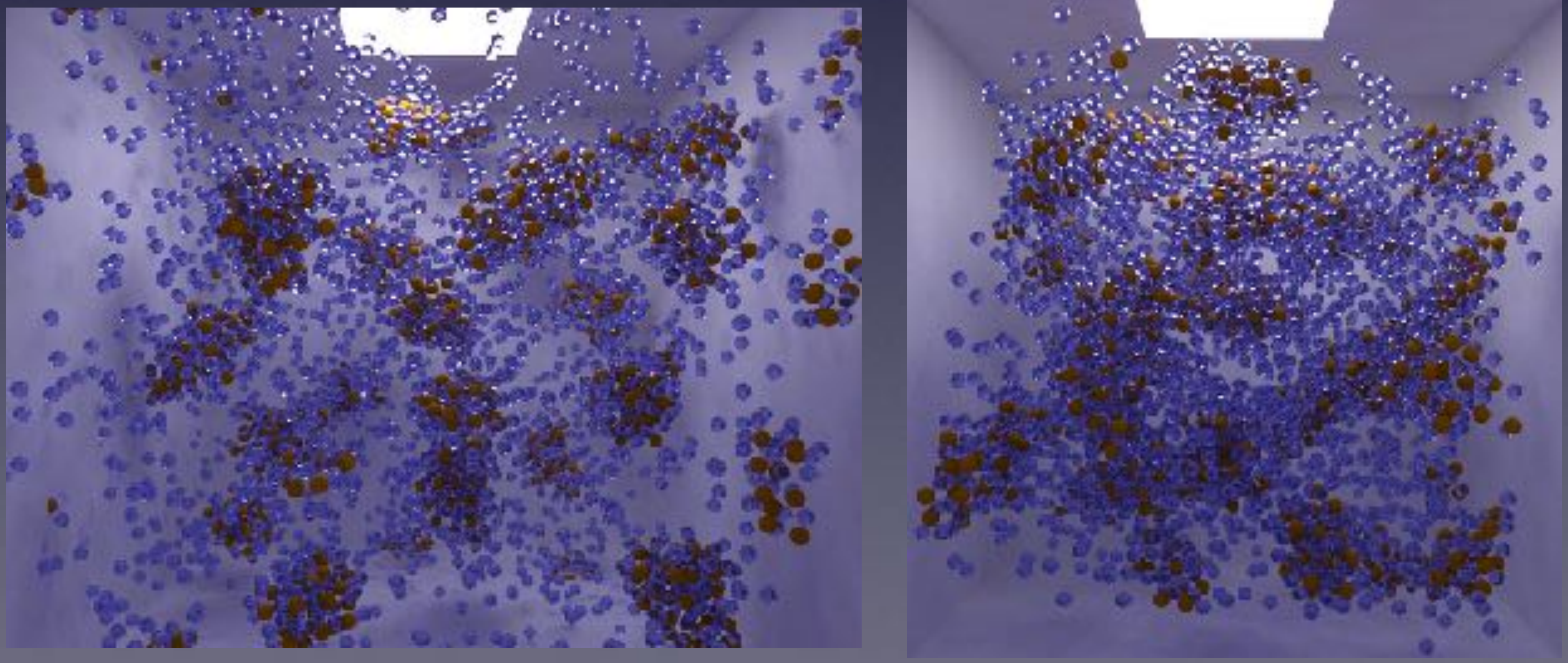


The Intriguing Inner Crust

- Top Layers: Coulomb Crystal of n-rich nuclei immersed in e- gas
  - … and a superfluid neutron vapor critical for glitches
- Bottom Layers: Coulomb frustration → *"Nuclear Pasta"*

- Emergent from a dynamical (or geometrical) competition
  - Impossible to simultaneously minimize all elementary interactions
  - Emergence of a multitude of topologically distinct (quasi) ground states
  - Universal in complex systems (low-D magnets, correlated e-, …)



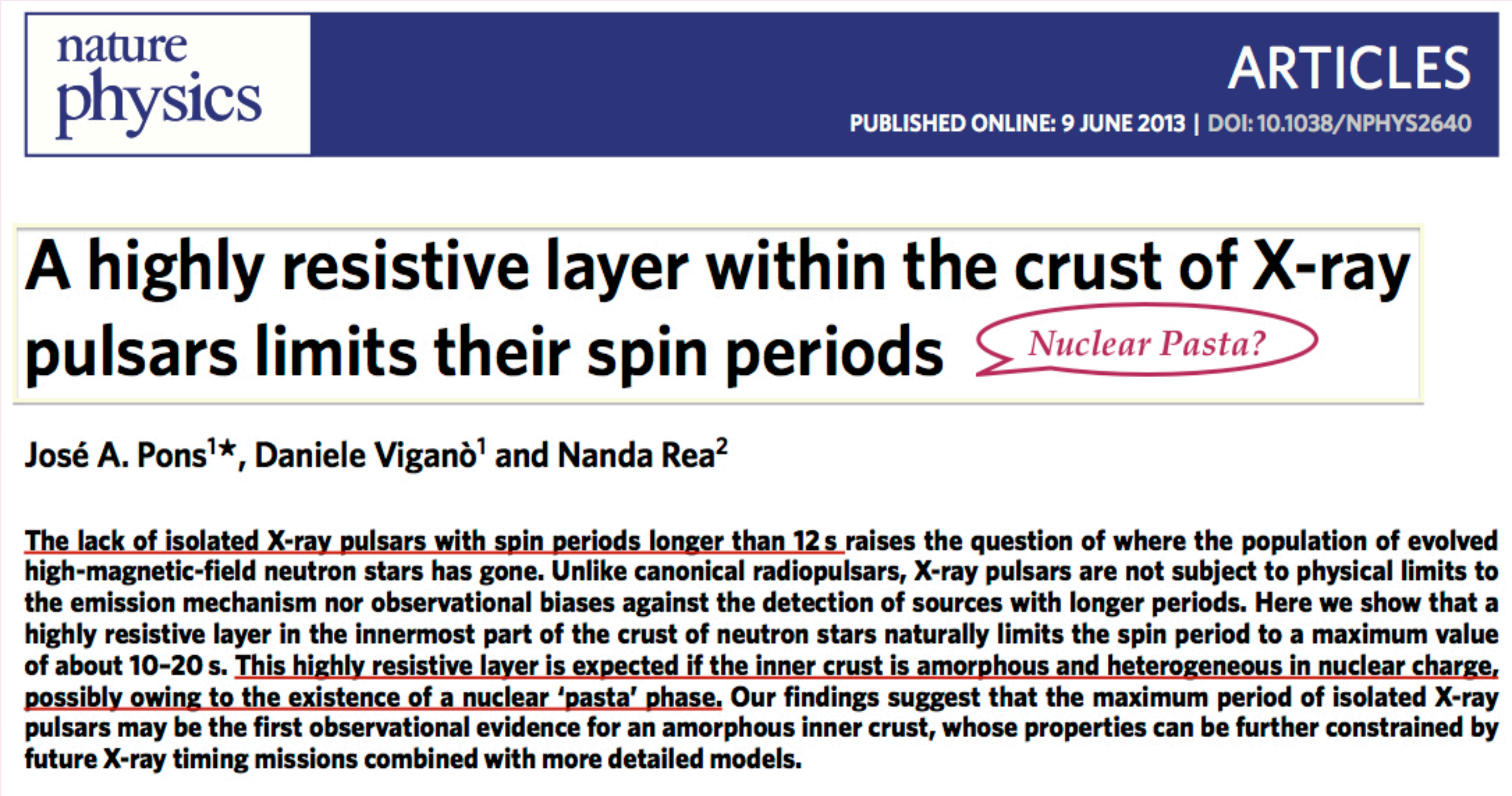


Tidal Polarizability extremely sensitive to the crustal dynamics!

The Inner Crust: *"How to smell the pasta?"*

Pons *et al.*, **Nature Physics (2013)**

- 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, matter is "warm" and models are required to extrapolate
- On Heaven: Lack of isolated X-ray pulsars with long periods $(P \gtrsim 12\,\mathrm{s})$
  Magnetic fields large enough 10^{13} G to suggest longer periods
  Highly resistive layer decreases electrical conductivity; quenches magnetic field
  Limits the pulsar spin period to at most 20s



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.

Must calculate the electrical conductivity in the nuclear pasta!

The Richness of the Neutron Star Crust

- Pulsar Glitches: Sudden spin-up of the rotational frequency
  - Constrains the fraction of the crustal moment of inertia and the EOS

- Magnetar Giant Flares: Enormous release of magnetic energy
  - Crustal pinning and eventual “snapping” of magnetic field lines

- Starquakes: Much like earthquakes but in the neutron star
  - Just as helioseismology, starquakes probe the composition of the crust

- Mass Quadrupoles: Braking strain of the stellar crust
  - “Mountains” on rapidly-rotating neutron stars are efficient sources of Gravitational Wave radiation.

- Tidal polarizability extracted from BNS mergers
  - Highly sensitive to crustal EOS

$$h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$$

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”)
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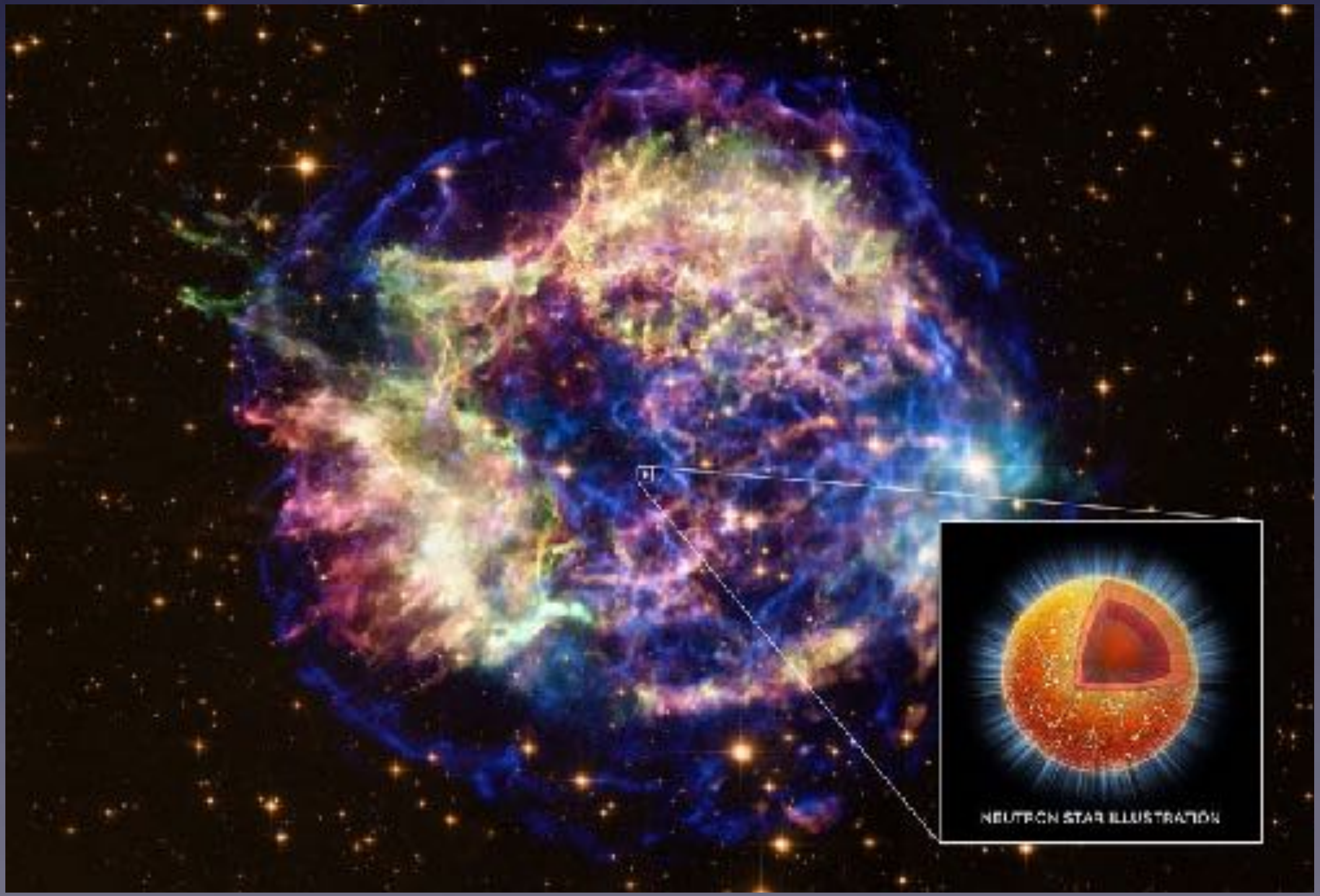
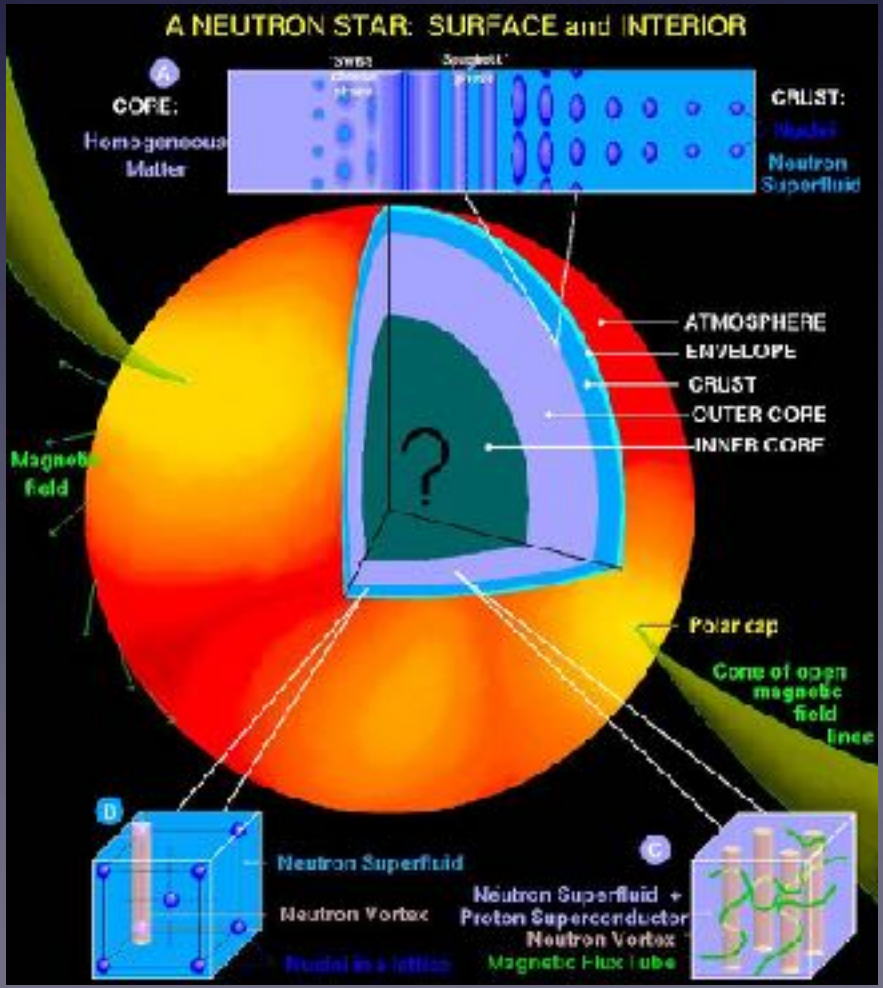
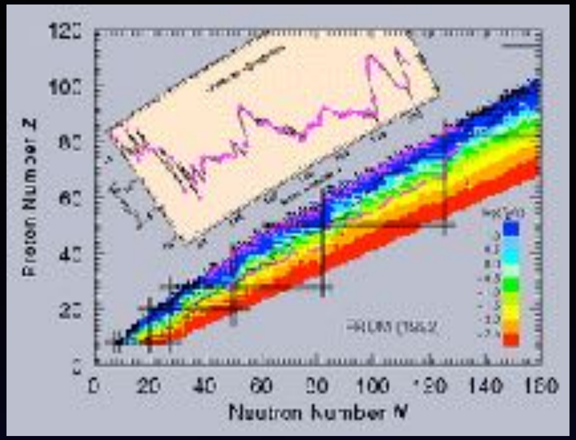




Model Building: From Finite Nuclei to Neutron Stars



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

$$\mathcal{L}_{\rm Yukawa} = \bar{\psi}\left[g_{\rm s}\phi - \left(g_{\rm v}V_{\mu} + \frac{g_{\rho}}{2}\tau\cdot\mathbf{b}_{\mu} + \frac{e}{2}(1+\tau_3)A_{\mu}\right)\gamma^{\mu}\right]\psi$$

$$\mathcal{L}_{\rm self} = \frac{\kappa}{3!}(g_{\rm s}\phi)^3 - \frac{\lambda}{4!}(g_{\rm s}\phi)^4 + \frac{\zeta}{4!}g_{\rm v}^4(V_{\mu}V^{\mu})^2 + \Lambda_{\rm v}\left(g_{\rho}^2\,\mathbf{b}_{\mu}\cdot\mathbf{b}^{\mu}\right)\left(g_{\rm v}^2V_{\nu}V^{\nu}\right)$$

Nuclear Density Functional Theory (DFT)

- ***Ab-initio calculations of heavy nuclei remains daunting task***
- ***Search for energy functional valid over a large physics domain***

  "From finite nuclei all the way to neutron stars"
- ***Incorporate physics insights into the construction of the functional***
- ***Accurately calibrated to various properties of finite nuclei***

  masses, charge radii, and giant monopole resonances
- ***Empirical constants encode physics beyond mean field***
- ***Empirical constants obtained from the optimization of a quality measure***

Nucleus	Observable	Experiment	NL3	FSU	FSU2
^{16}O	B/A	7.98	8.06	7.98	8.00
	$R_{\rm ch}$	2.70	2.75	2.71	2.73
^{40}Ca	B/A	8.55	8.56	8.54	8.54
	$R_{\rm ch}$	3.48	3.49	3.45	3.47
^{48}Ca	B/A	8.67	8.66	8.58	8.63
	$R_{\rm ch}$	3.48	3.49	3.48	3.47
^{68}Ni	B/A	8.68	8.71	8.66	8.69
	$R_{\rm ch}$	—	3.88	3.88	3.86
^{90}Zr	B/A	8.71	8.70	8.68	8.69
	$R_{\rm ch}$	4.27	4.28	4.27	4.26
^{100}Sn	B/A	8.25	8.30	8.24	8.28
	$R_{\rm ch}$	—	4.48	4.48	4.47
^{116}Sn	B/A	8.52	8.50	8.50	8.49
	$R_{\rm ch}$	4.63	4.63	4.63	4.61
^{132}Sn	B/A	8.36	8.38	8.34	8.36
	$R_{\rm ch}$	4.71	4.72	4.74	4.71
^{144}Sm	B/A	8.30	8.32	8.32	8.31
	$R_{\rm ch}$	4.95	4.96	4.96	4.94
^{208}Pb	B/A	7.87	7.90	7.89	7.88
	$R_{\rm ch}$	5.50	5.53	5.54	5.51

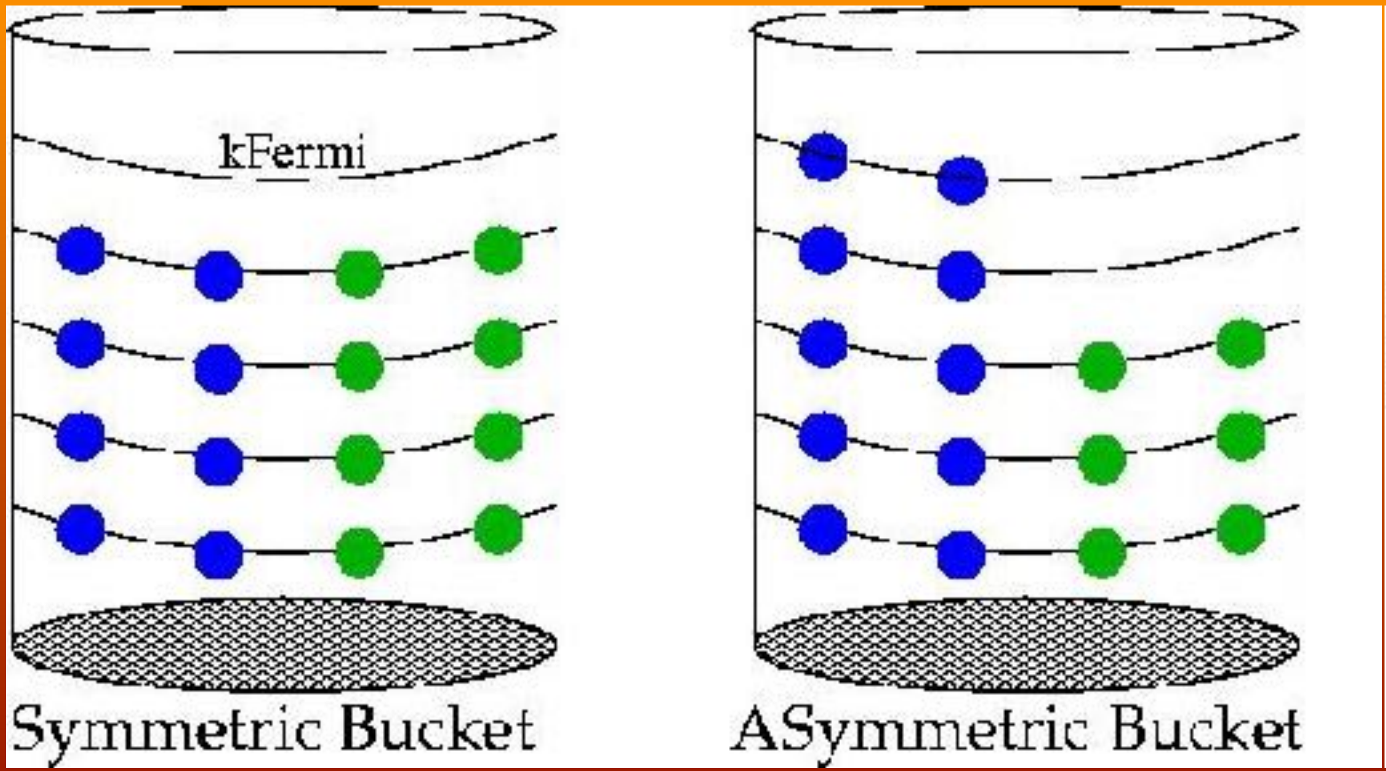
Nucleus	TAMU	RCNP	NL3	FSU	FSU2
^{90}Zr	17.81 ± 0.35	—	18.76	17.86	17.93 ± 0.09
^{116}Sn	15.90 ± 0.07	15.70 ± 0.10	17.19	16.39	16.47 ± 0.08
^{144}Sm	15.25 ± 0.11	15.77 ± 0.17	16.29	15.55	15.59 ± 0.09
^{208}Pb	14.18 ± 0.11	13.50 ± 0.10	14.32	13.72	13.76 ± 0.08

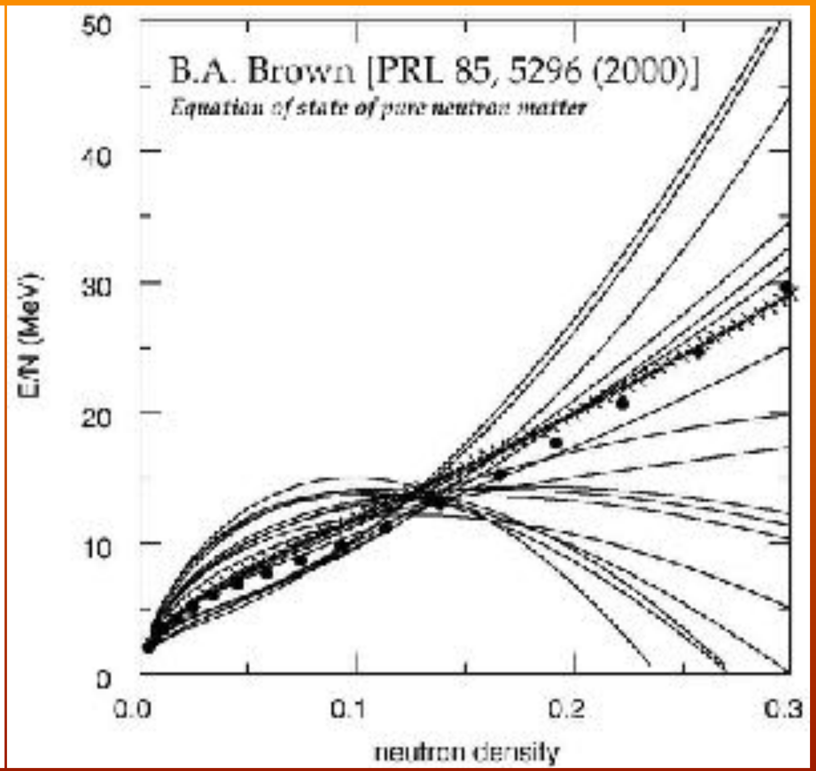
The Equation of State of Neutron-Rich Matter

- Two conserved charges: proton and neutron densities (no weak interactions)
- Equivalently; total nucleon density and asymmetry: ρ and $\alpha=(N-Z)/A$
- Expand around nuclear equilibrium density: $x=(\rho-\rho_0)/3\rho_0$; $\rho_0 \simeq 0.15\ \text{fm}^{-3}$

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

- Density dependence of symmetry energy poorly constrained!!
  "L" symmetry slope ~ pressure of pure neutron matter at saturation





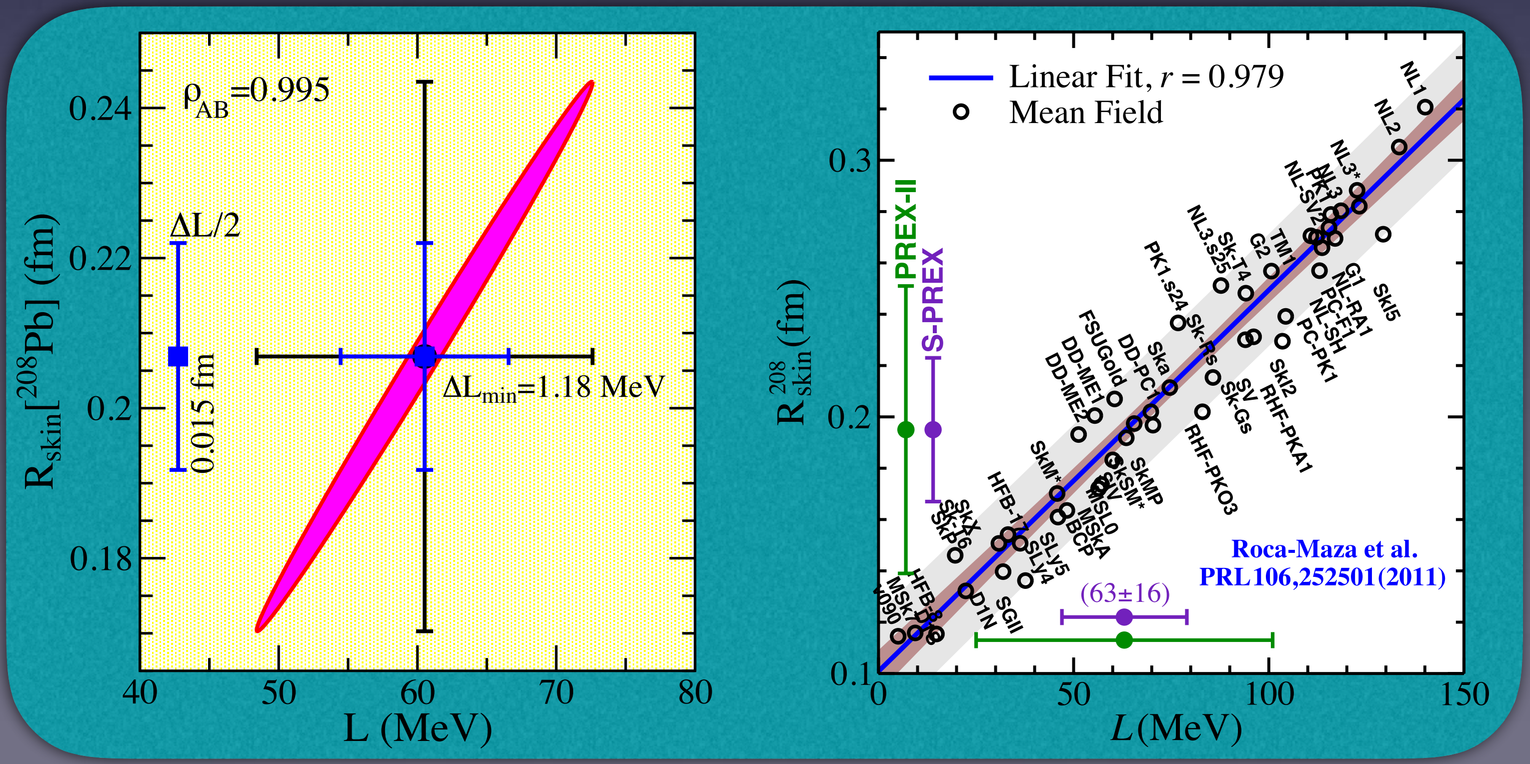
Searching for L: The Strategy

$P_{PNM} \simeq L\rho_0/3$ 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 $S(\rho_0)$-$S(\rho_{surf}) \simeq$ 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

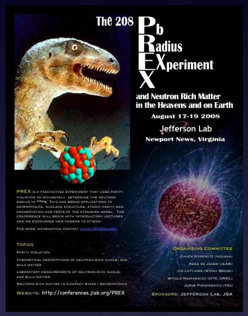
- Ensure that "all" accurately-calibrated DFT support the correlation
  - Systematic Uncertainty: Systematic errors, much harder to quantify



"All models are
equal
but some models
are more equal
than others"

The Quest for L at JLAB: R_{skin} as a proxy for L

- PREX@JLAB: First electroweak (clean!) evidence in favor of Rskin in Pb
- Precision hindered by radiation issues
  - Statistical uncertainties 3 times larger than promised: Rskin=0.33(16)fm
- PREX-II and CREX to run in 2018
  - Original goal of 1% in neutron radius



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

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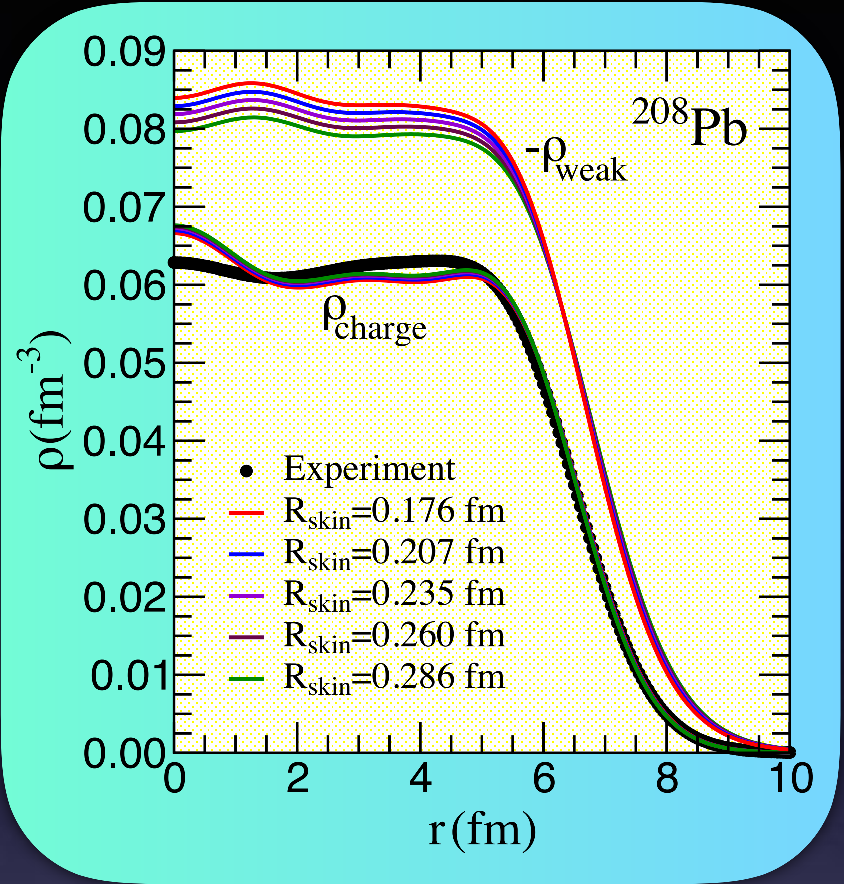
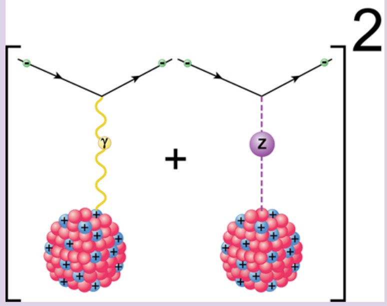


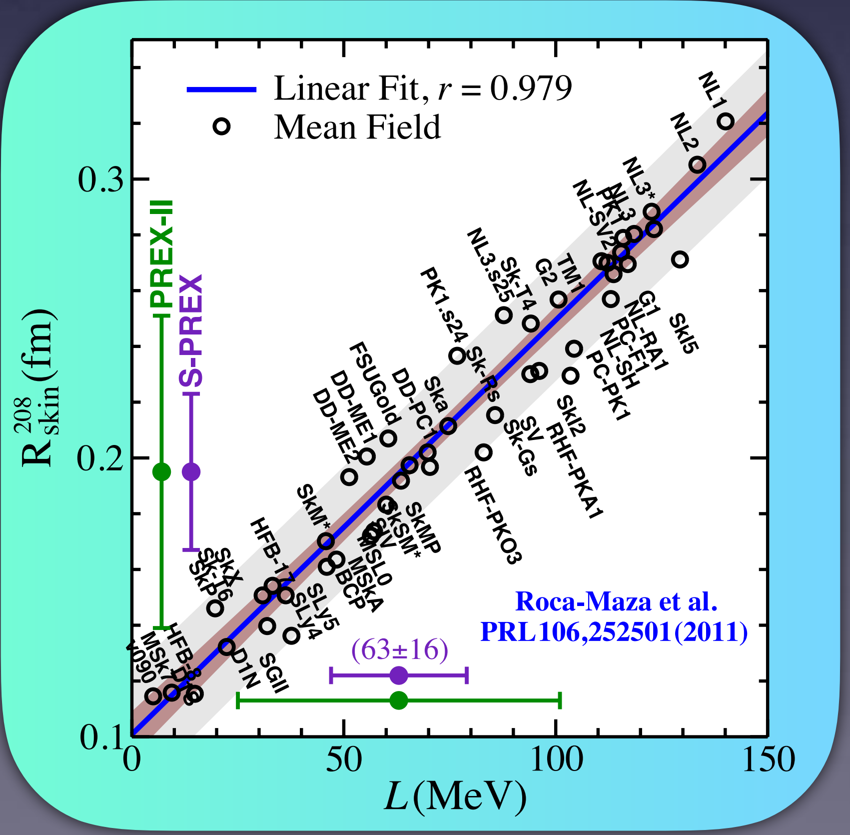


$$A_{\rm PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[\underbrace{1-4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

- Neutral weak-vector boson 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

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

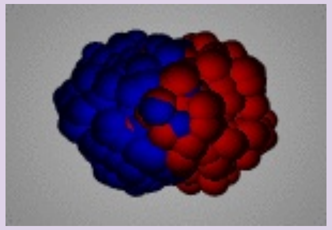


The Isovector Giant Dipole Resonance in ^{208}Pb

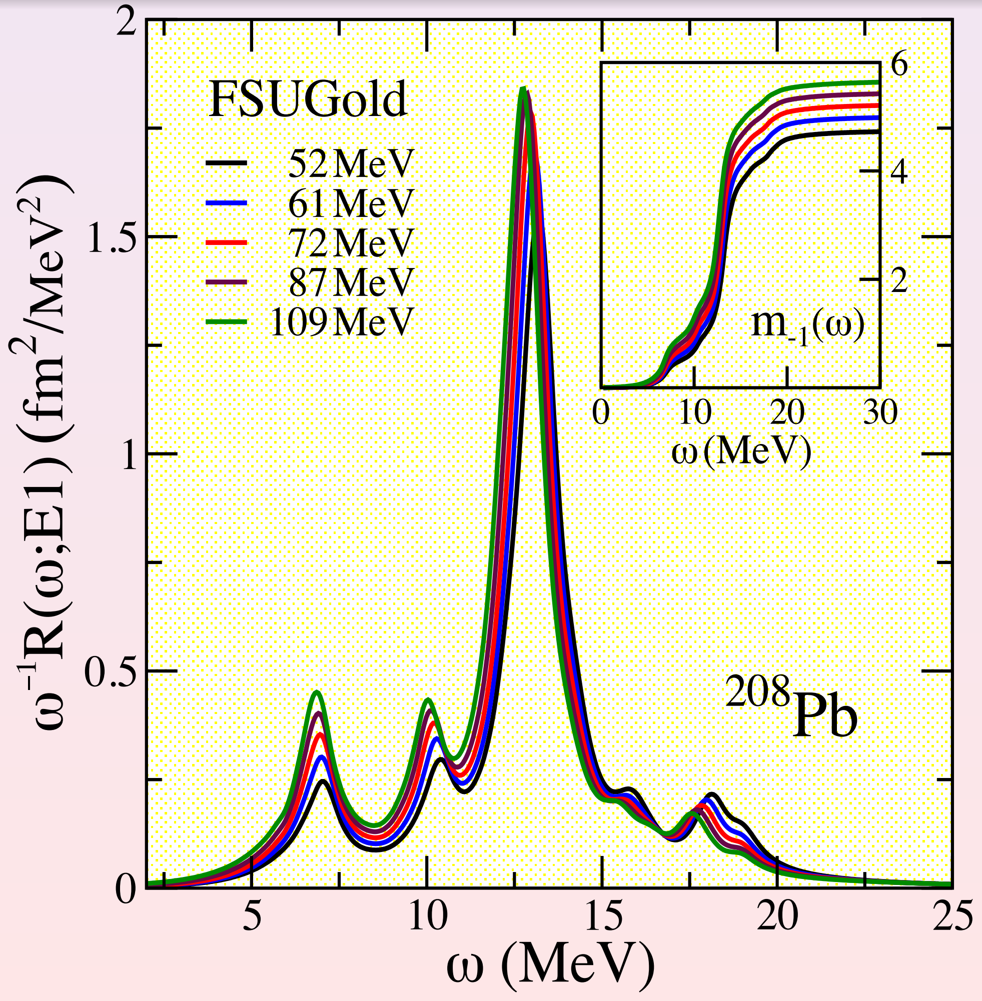
JP *et al.*, PRC85, 041302 (2012); Roca-Maza *et al.*, PRC88, 024316 (2013)

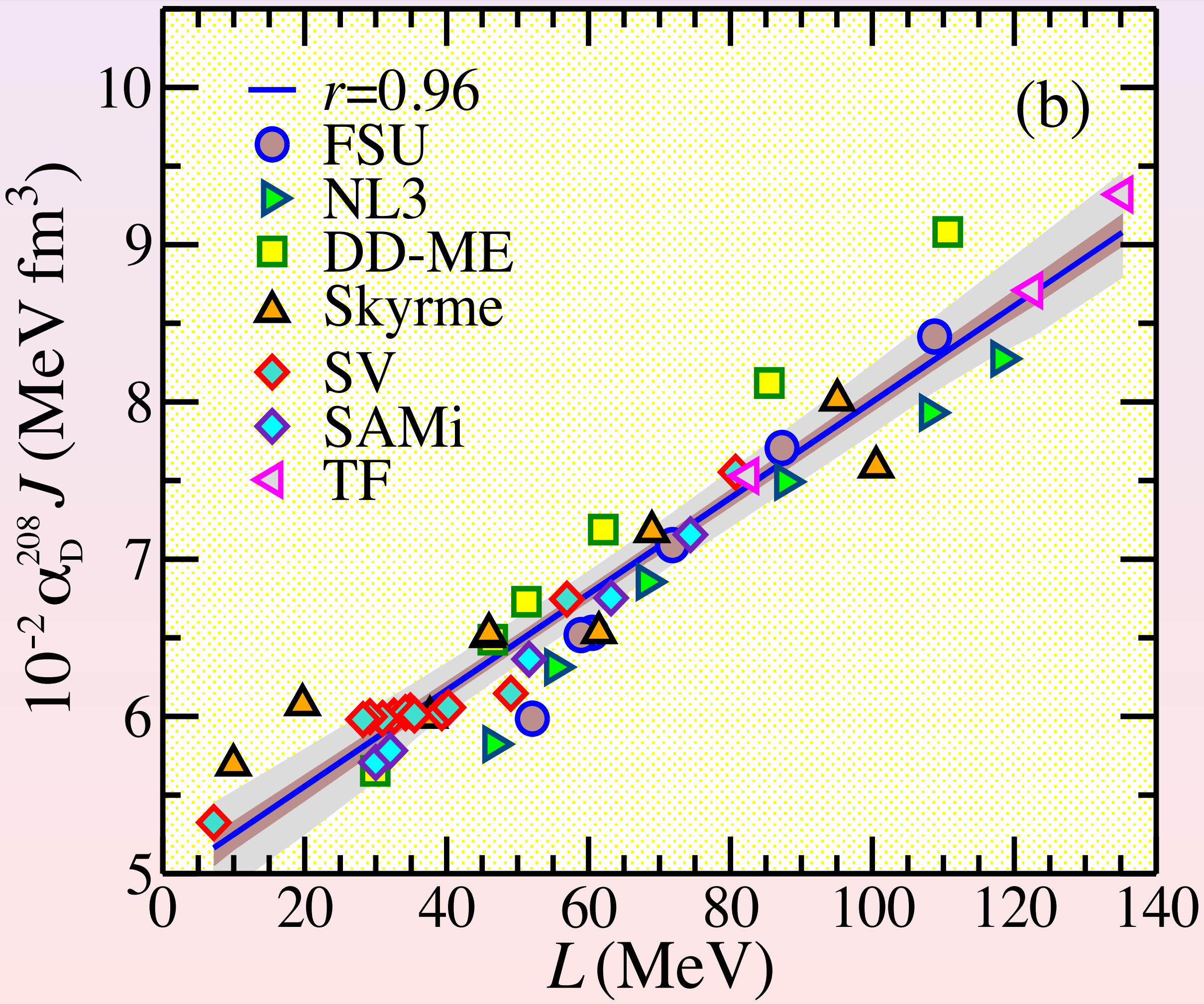
- IVGDR: *Coherent oscillations of protons against neutrons*

  Nuclear symmetry energy acts as restoring force for this mode



- Energy weighted sum rule largely model independent $\sim NZ/A$
- Electric dipole polarizability (IEWSR) sensitive to L: $\alpha_D J \sim a + bL$
- Electric dipole polarizability a powerful complement to neutron skin



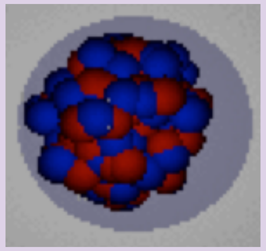


Pygmy Dipole Resonance in unstable ^{68}Ni

[O. Wieland *et al.*, PRL 102, 092502 (2009); D.M. Rossi *et al.*, PRL 111, 242503 (2013)]

- Emergence of significant low-energy *“Pygmy”* strength

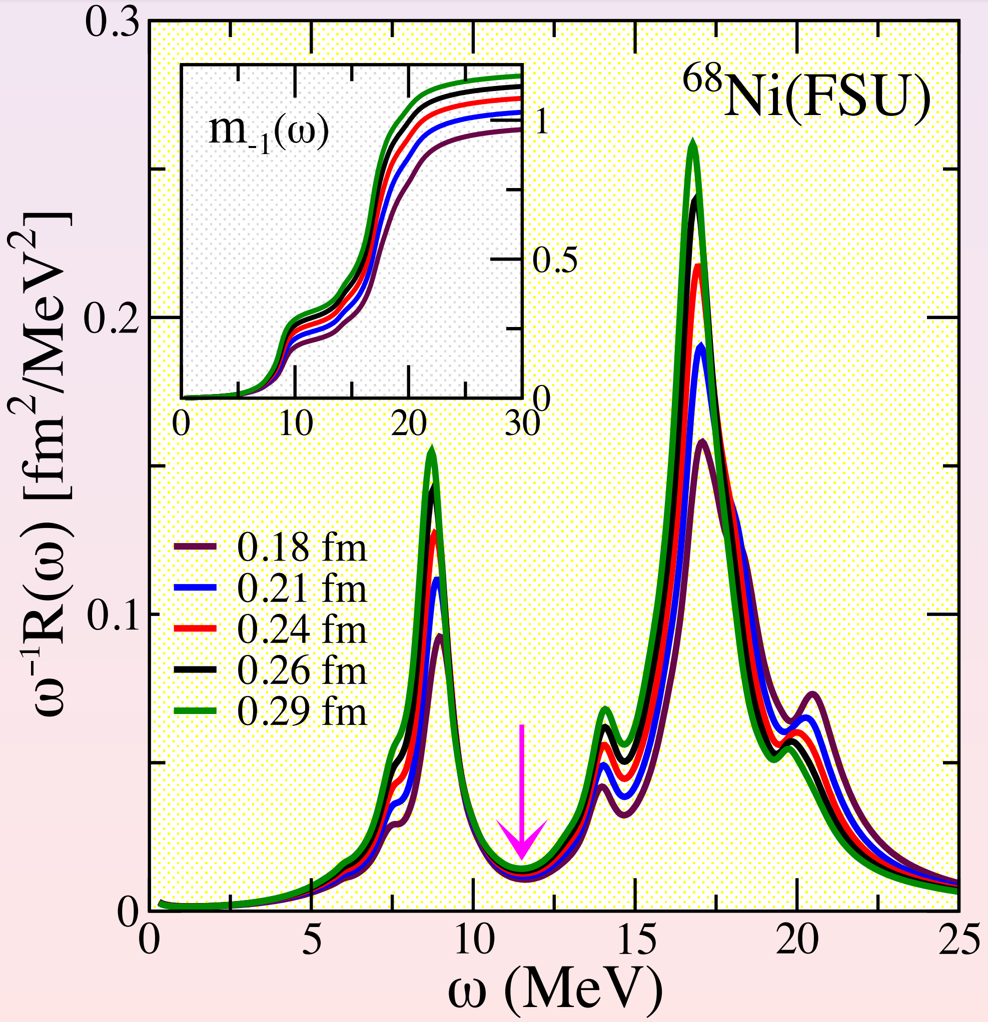
  Pygmy perceived as an oscillation of neutron-rich skin against isospin symmetric core

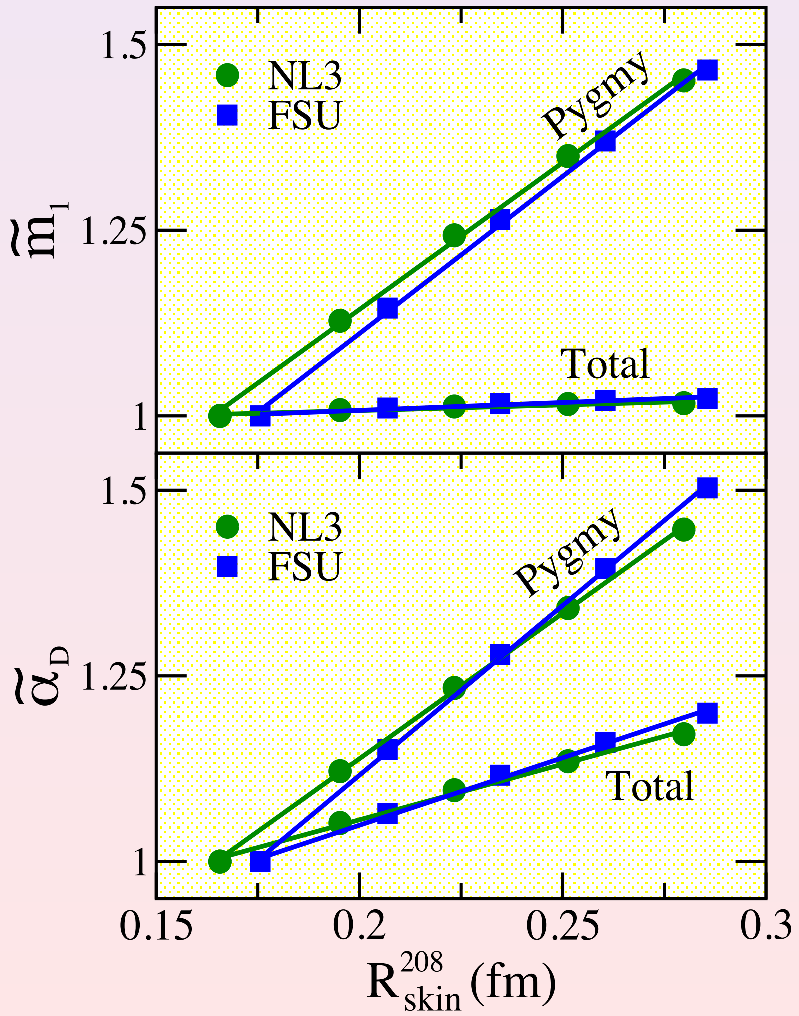


- Pygmy strength of relevance to (γ,n) reactions in stellar environments
- Pygmy strength as a possible constrain on the neutron skin?

  What is the exact nature of the low-energy Pygmy resonance?

  Is it possible to isolate the Pygmy from the Giant in a model-independent way?

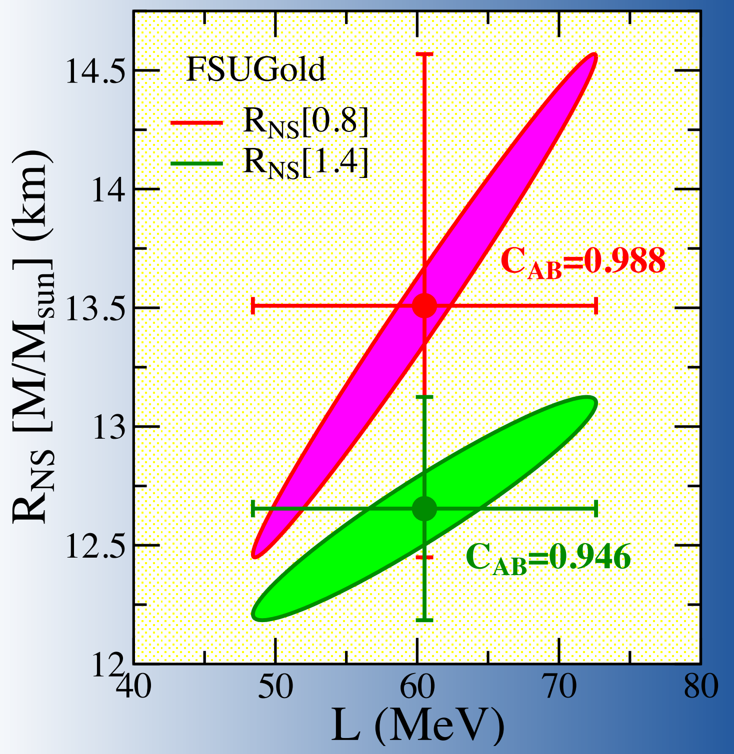


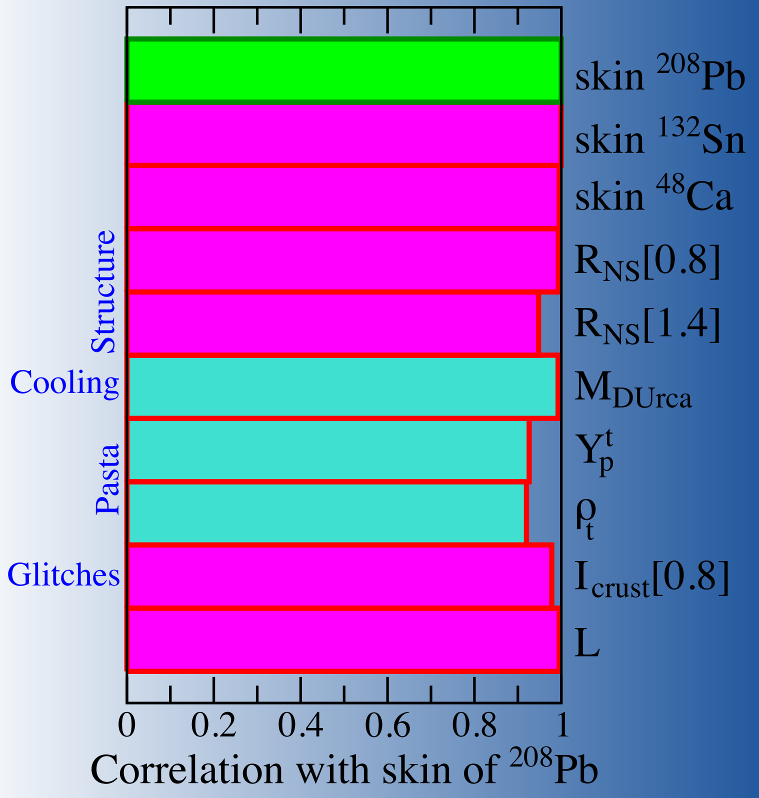


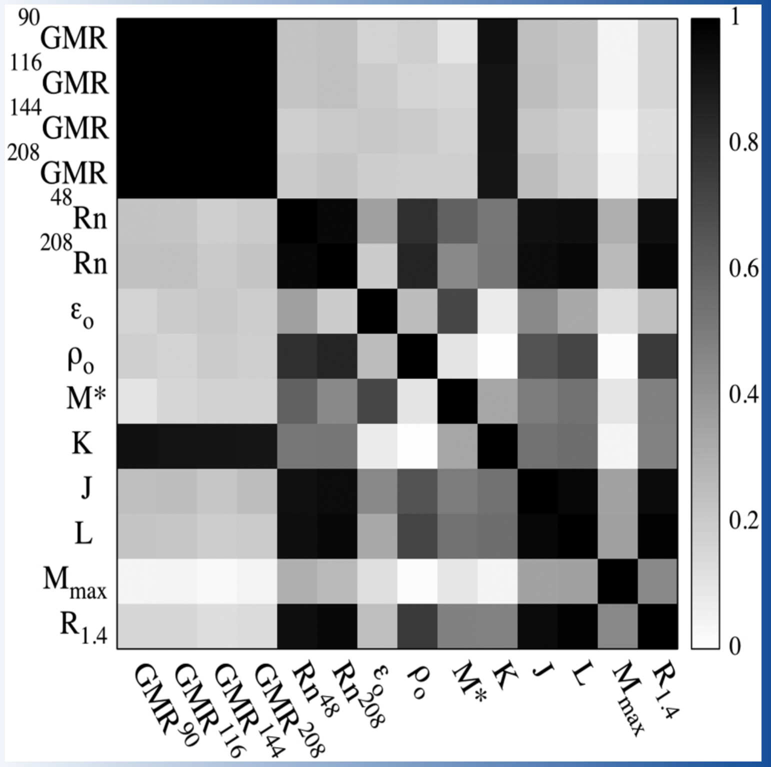
Heaven and Earth … and “L”

The enormous reach of the neutron skin

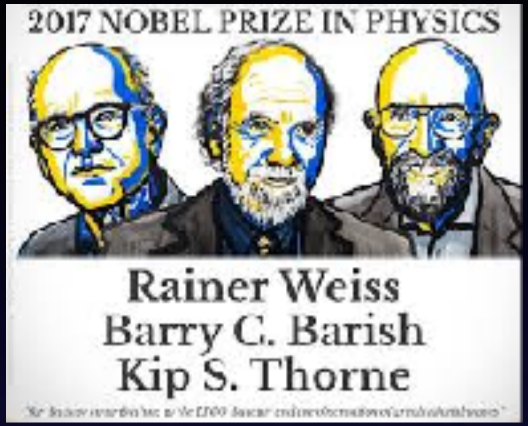
- Neutron-star radii are sensitive to the EOS near $2\rho_0$
  - Neutron star masses sensitive to EOS at much higher density
- Neutron skin correlated to a host of neutron-star properties
  - Stellar radii, proton fraction, enhanced cooling, moment of inertia
- Neutron skin of heavy nuclei and NS radii driven by same physics
  - Difference in length scales of 18 orders of magnitude!!



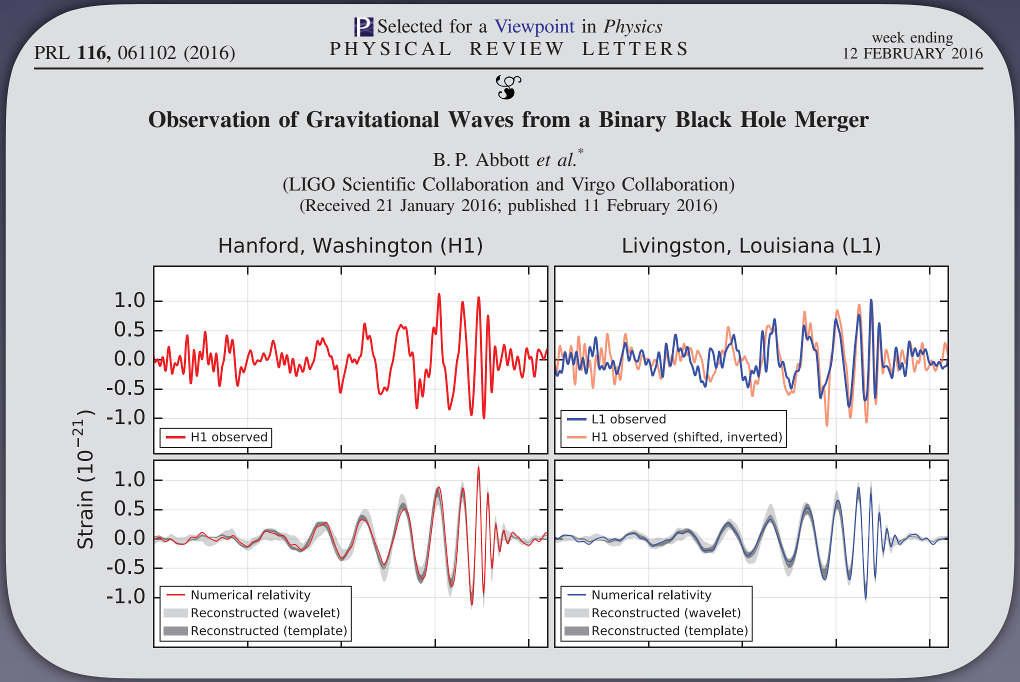




"We have detected gravitational waves; we did it"
David Reitze, February 11, 2016



- The dawn of a new era: GW Astronomy
  - Initial black hole masses are 36 and 29 solar masses
  - Final black hole mass is 62 solar masses;
    3 solar masses radiated in Gravitational Waves!



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Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

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