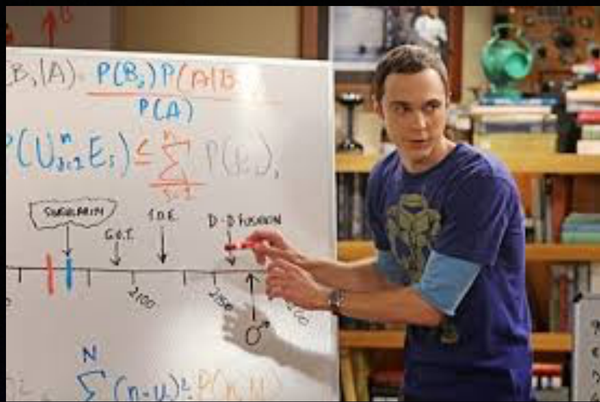
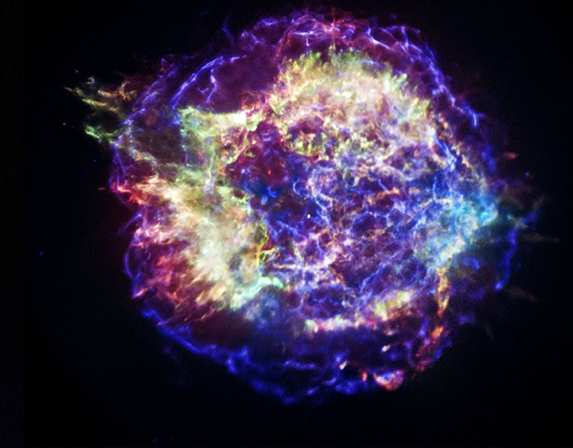
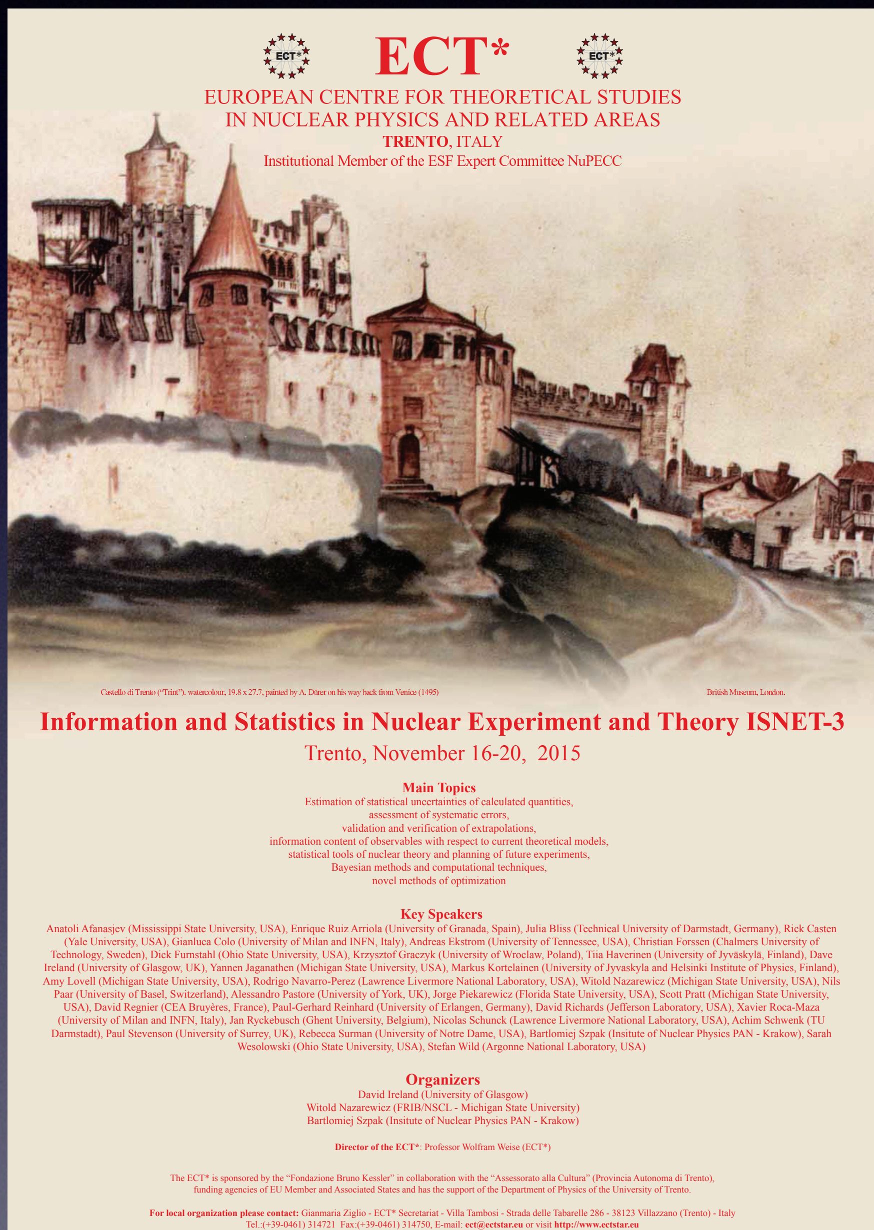


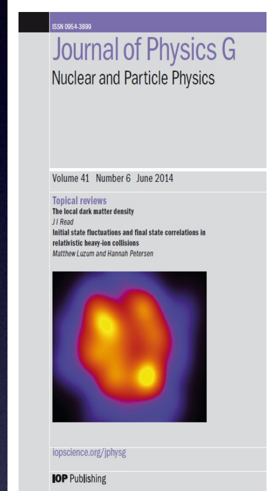
Density Functional Theory meets Bayesian Neural Networks: A New Paradigm in the Study of Neutron Stars

Jorge Piekarewicz - Florida State University



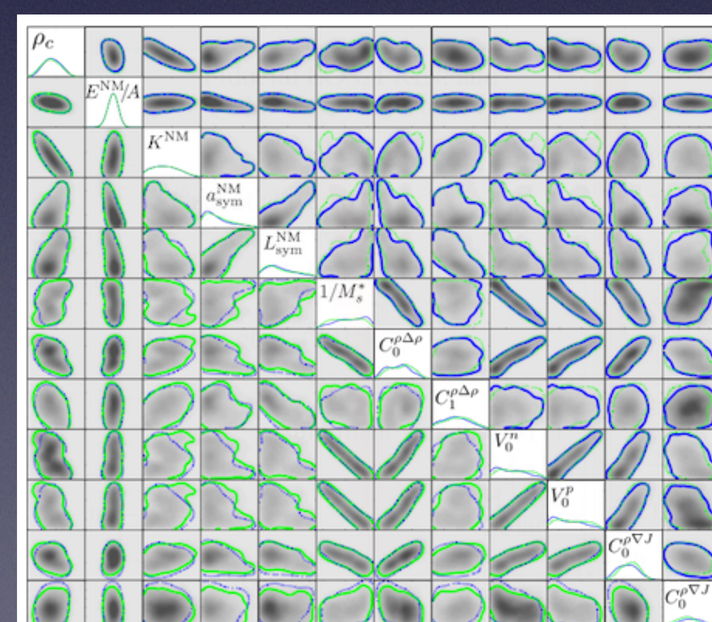


Highlights of 2015



Welcome to JPhysG's 2015 highlights! Before you get to the articles, here are a few of my personal choices.

First, the way the community reacted and engaged with our focus issue, Enhancing the interaction between nuclear experiment and theory through information and statistics was outstanding. Linking theory with experiment is vital for any field and I look forward to seeing more research on the topic in both nuclear and particle physics.



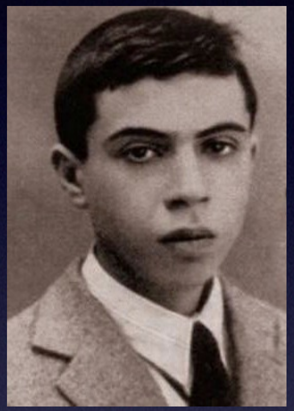
Bayesian Methods in Nuclear Physics INT Program 2016

2017 ICNT Program: *Extracting Bulk Properties of Neutron-Rich Matter with Transport Models in Bayesian Perspective.*
March 22 — April 12, 2017 at FRIB/MSU

Neutron Stars: Very Few 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)

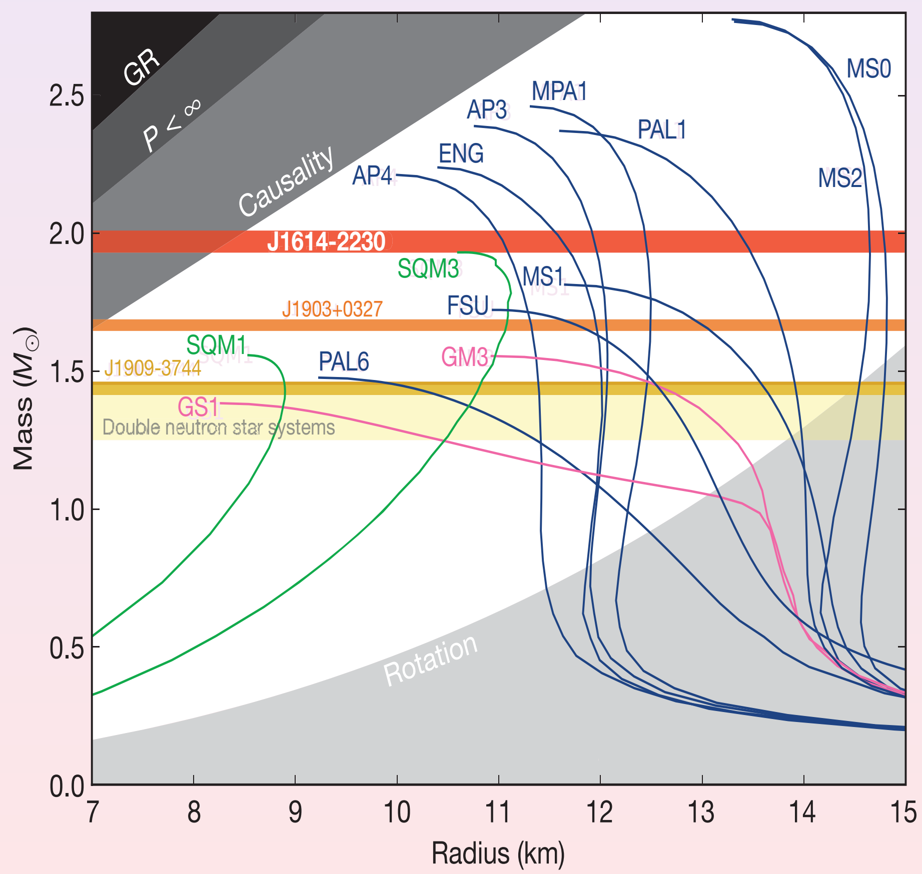
- Jocelyn Bell discovers neutron stars (1967)

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 M_{sun} transfers ownership to Nuclear Physics!*
- Predictions on stellar radii differ by several kilometers!



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

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

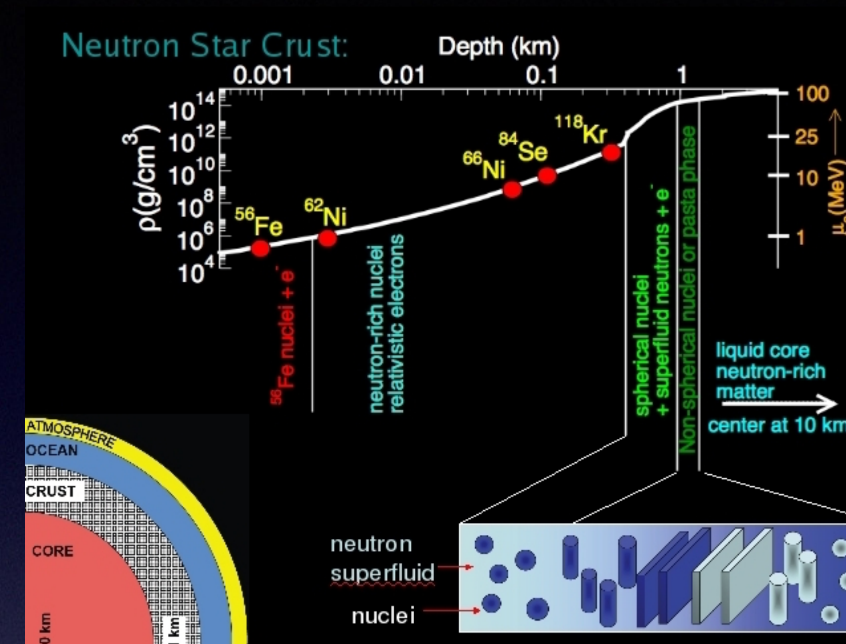
Need an EOS: $P = P(\mathcal{E})$ relation

Nuclear Physics Critical

The Composition of the Outer Crust

Enormous sensitivity to nuclear masses

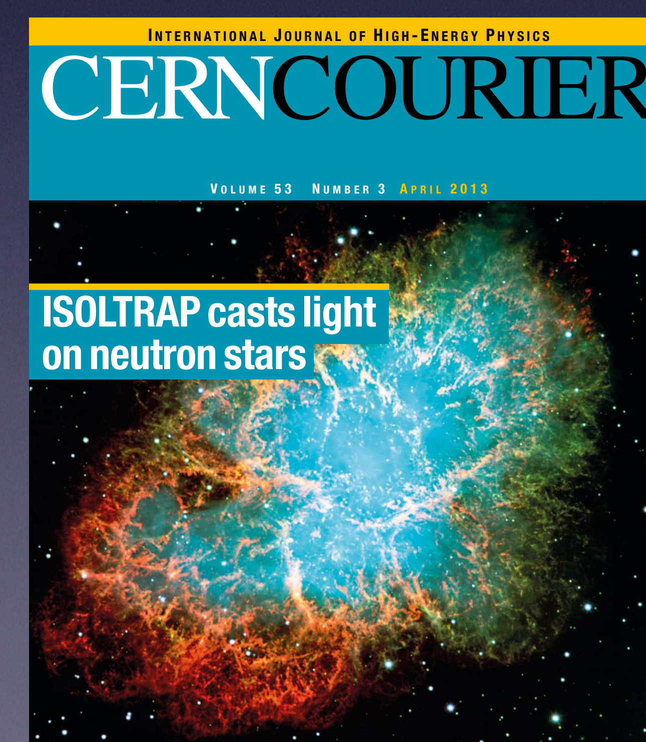
- System unstable to cluster formation
  - BCC lattice of neutron-rich nuclei imbedded in e-gas

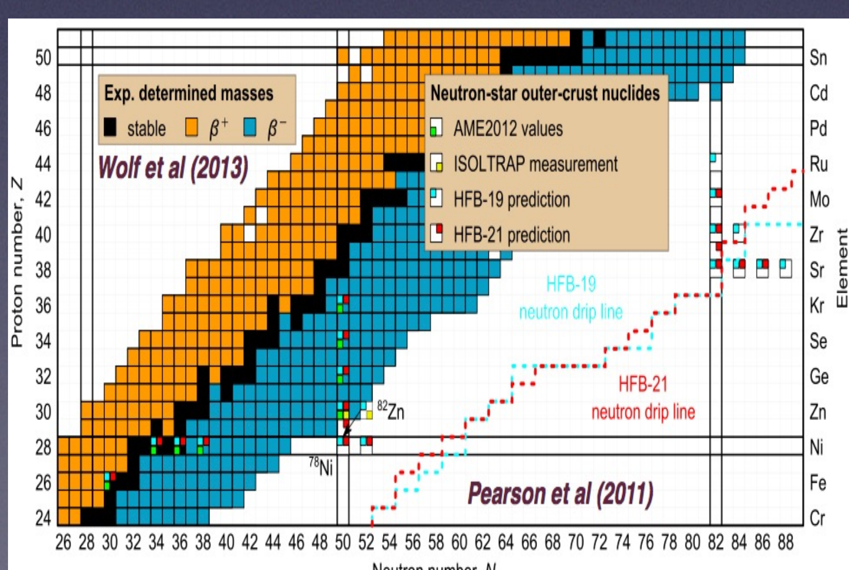


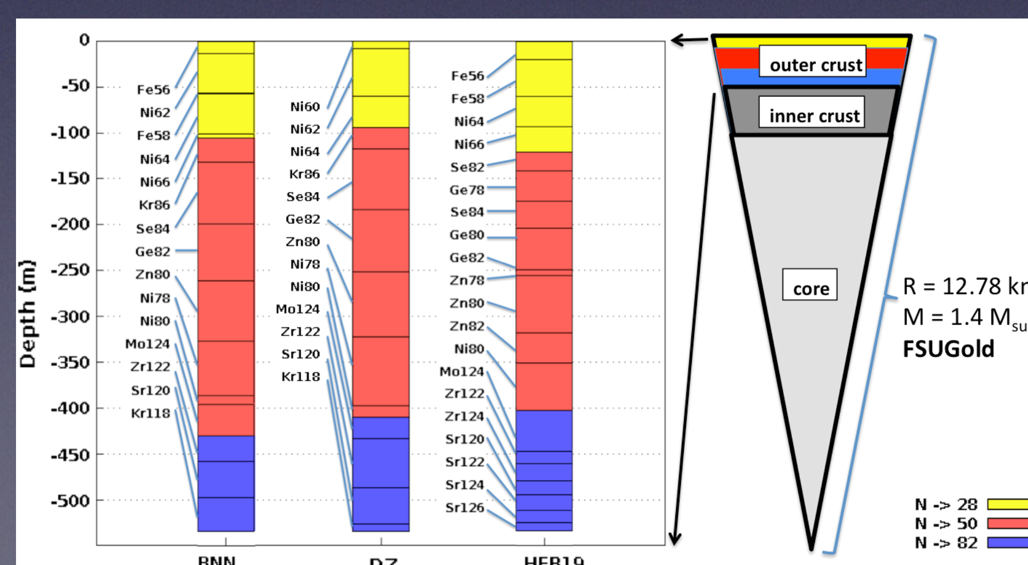
- Composition emerges from relatively simple dynamics
  - Competition between electronic and symmetry energy

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

- 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

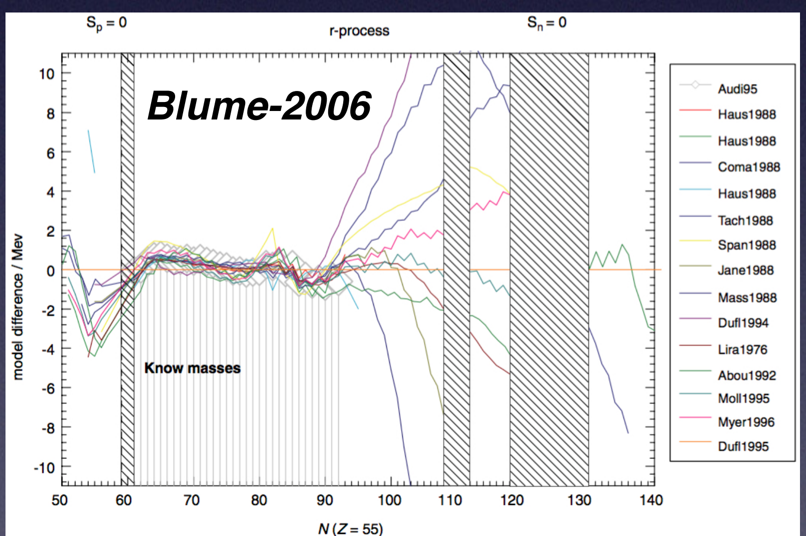
R. Utama,* J. Piekarewicz,† and H. B. Prosper‡
Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

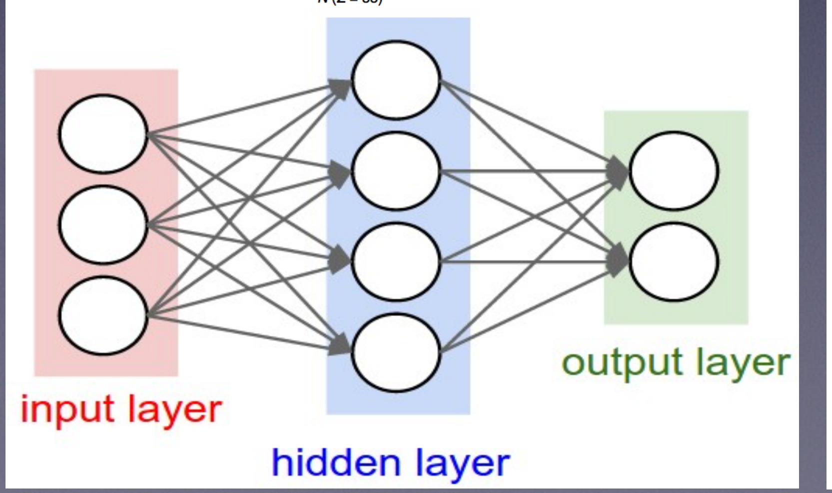
- Use DFT to predict nuclear masses
- Train BNN by focusing on residuals

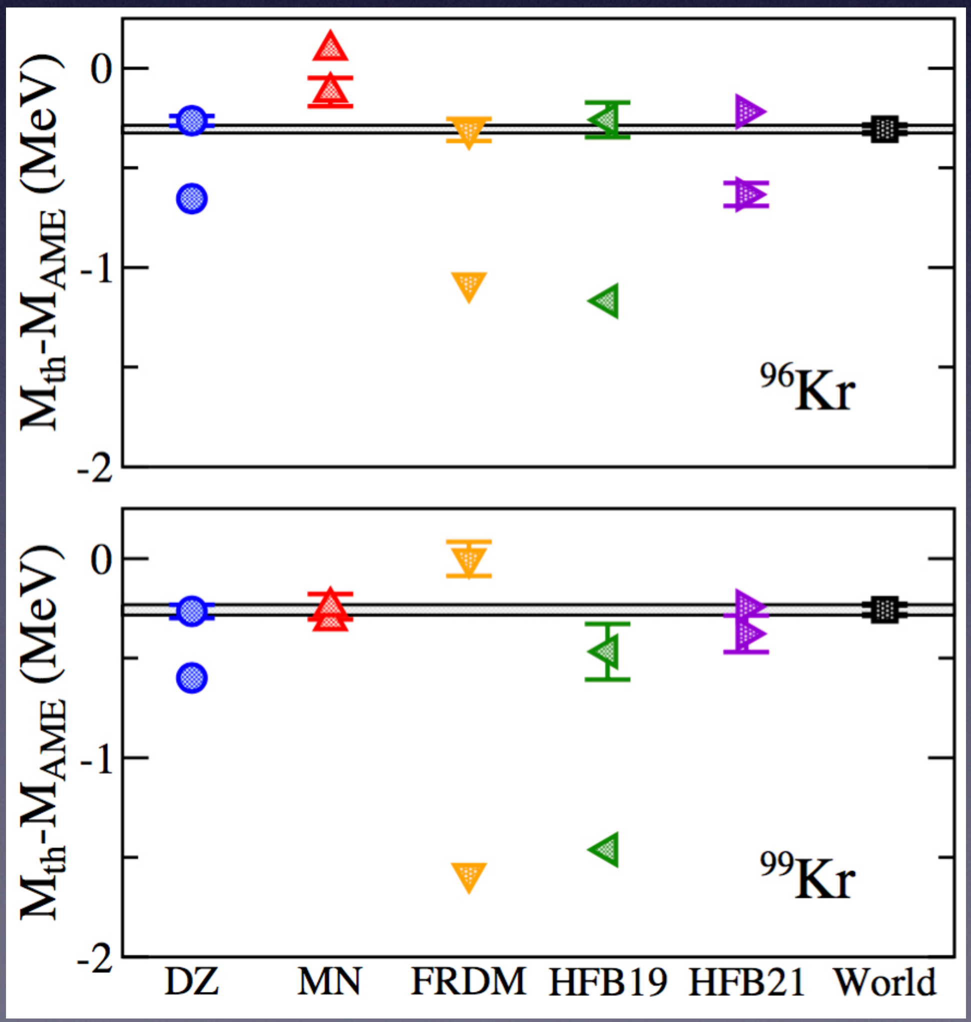
} *The paradigm*

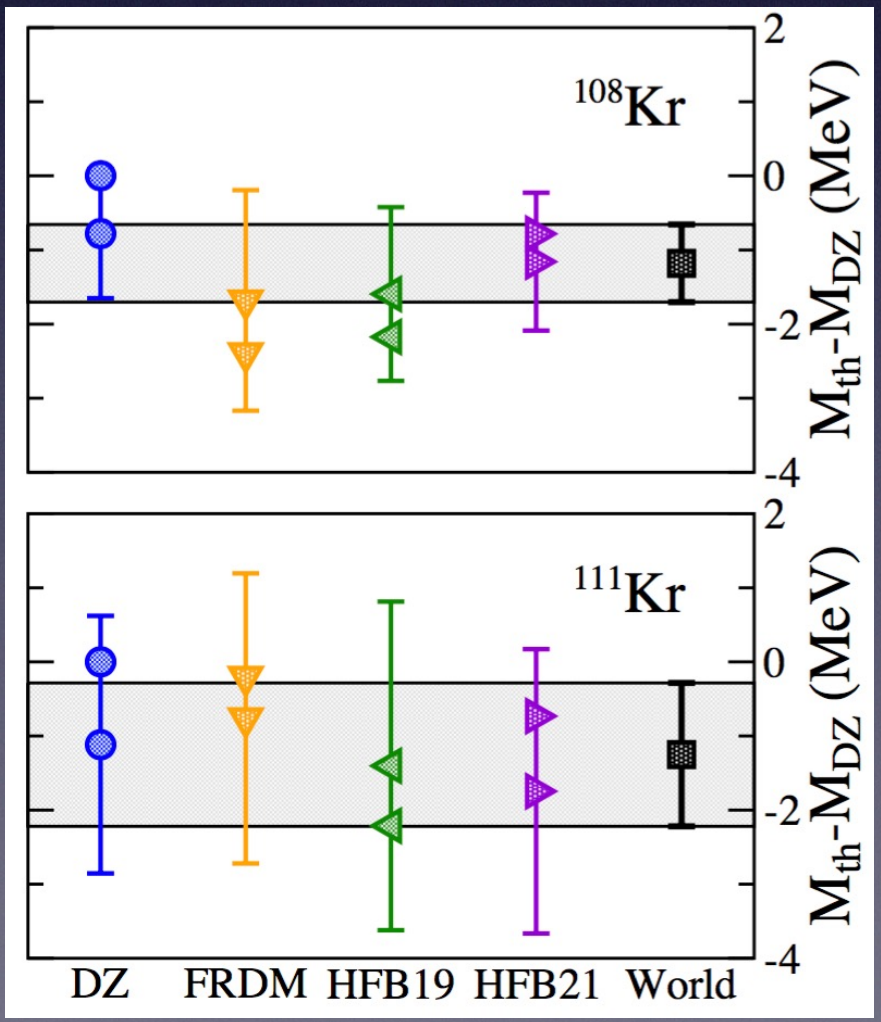
$$M(N,Z) = M_{DFT}(N,Z) + \delta M_{BNN}(N,Z)$$

- Systematic scattering greatly reduced
- Predictions supplemented by theoretical errors









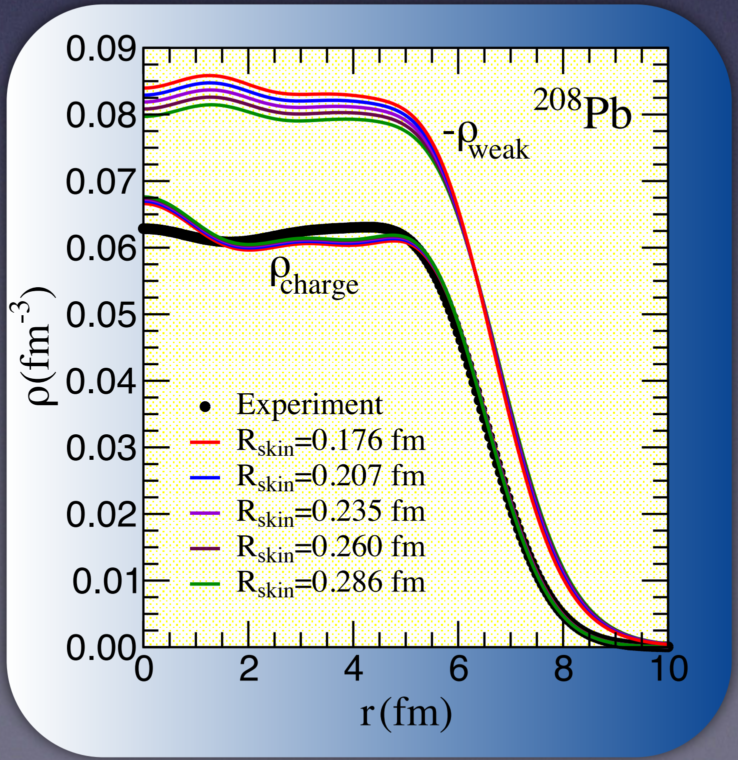
The Equation of State of Neutron-Rich Matter

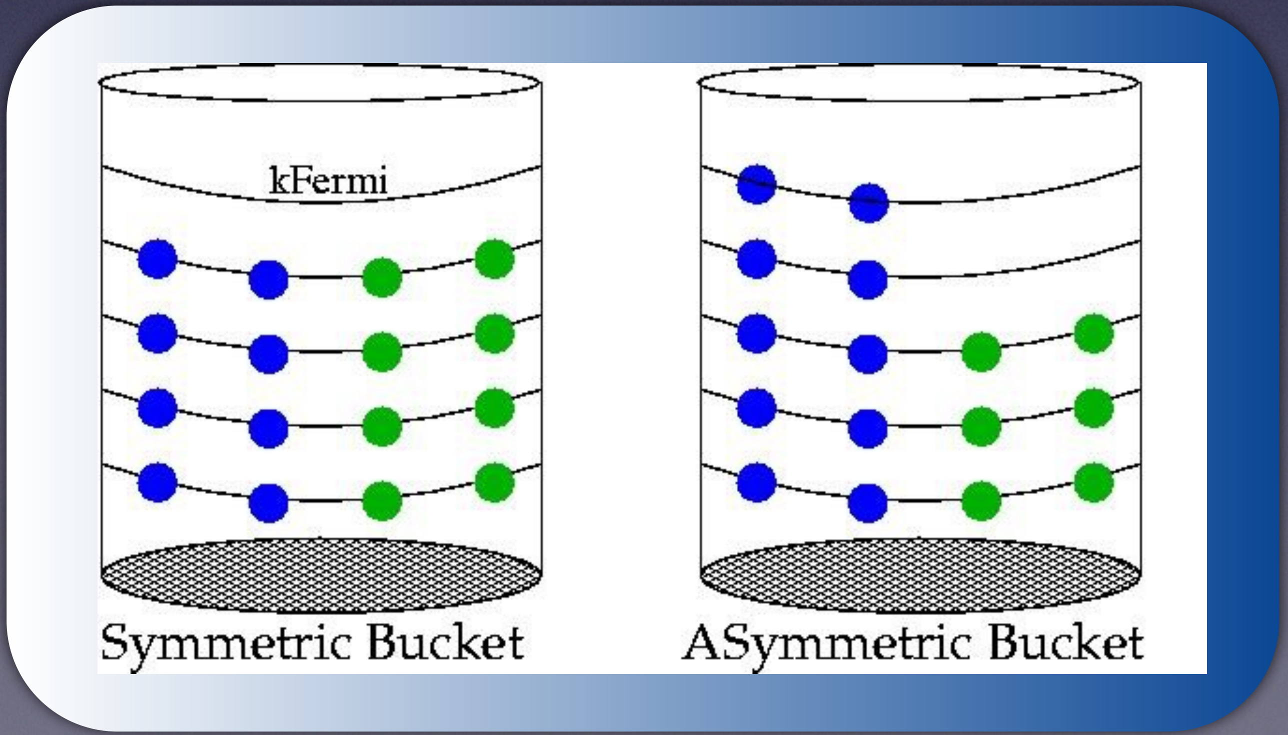
- The EOS of asymmetric matter: α=(N-Z)/A; x=(ρ−ρ_0)/3ρ_0; T=0
  - ρ_0 $\simeq$0.15 fm-3 — saturation density ↔ nuclear density

$$\mathcal{E}(\rho,\alpha) \simeq \mathcal{E}_0(\rho) + \alpha^2\mathcal{S}(\rho) \simeq \left(\epsilon_0 + \frac{1}{2}K_0x^2\right) + \left(J + Lx + \frac{1}{2}K_{\rm sym}x^2\right)\alpha^2$$

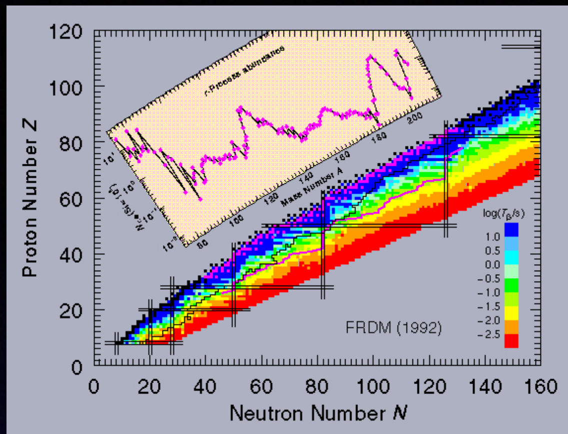
- Symmetric nuclear matter saturates:
  - ε_0 $\simeq$-16 MeV — binding energy per nucleon ↔ nuclear masses
  - $K_0$$\simeq$230 MeV — nuclear incompressibility ↔ nuclear “breathing” mode

- 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 ?





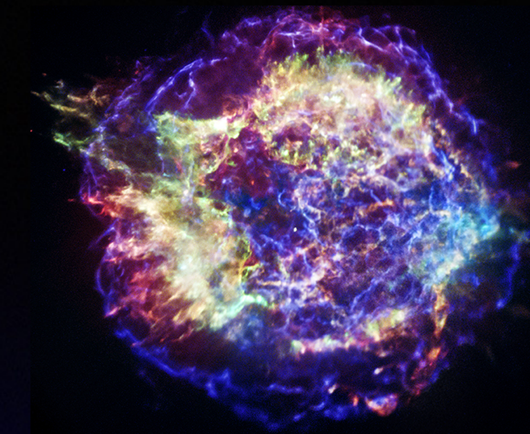
Model Building: The Protocol



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



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

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

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 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

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 $P(D|M) = \exp(-\chi^2/2)$

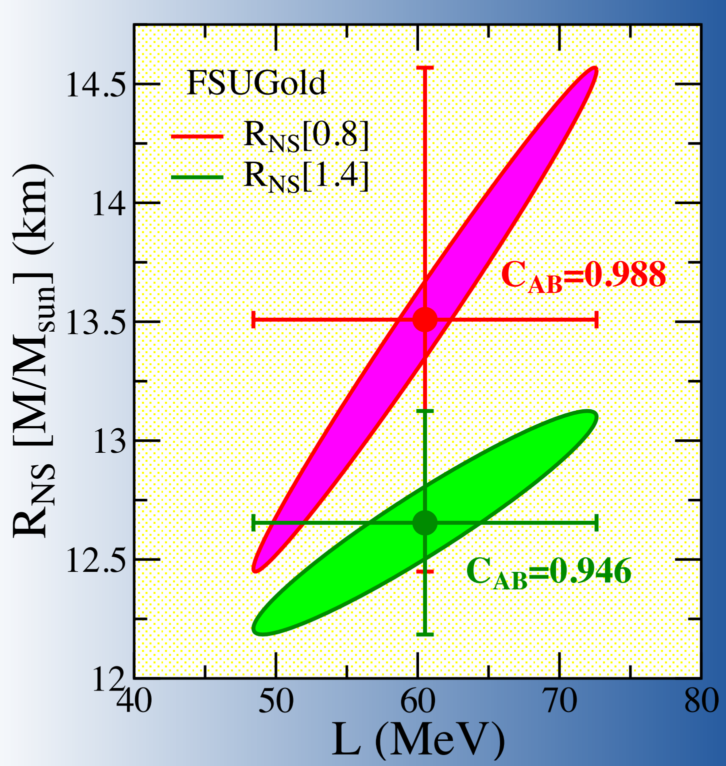
$$\chi^2(D,M) = \sum_{n=1}^{N} \frac{\left(O_n^{\rm (th)}(M) - O_n^{\rm (exp)}(D)\right)^2}{\Delta O_n^2}$$

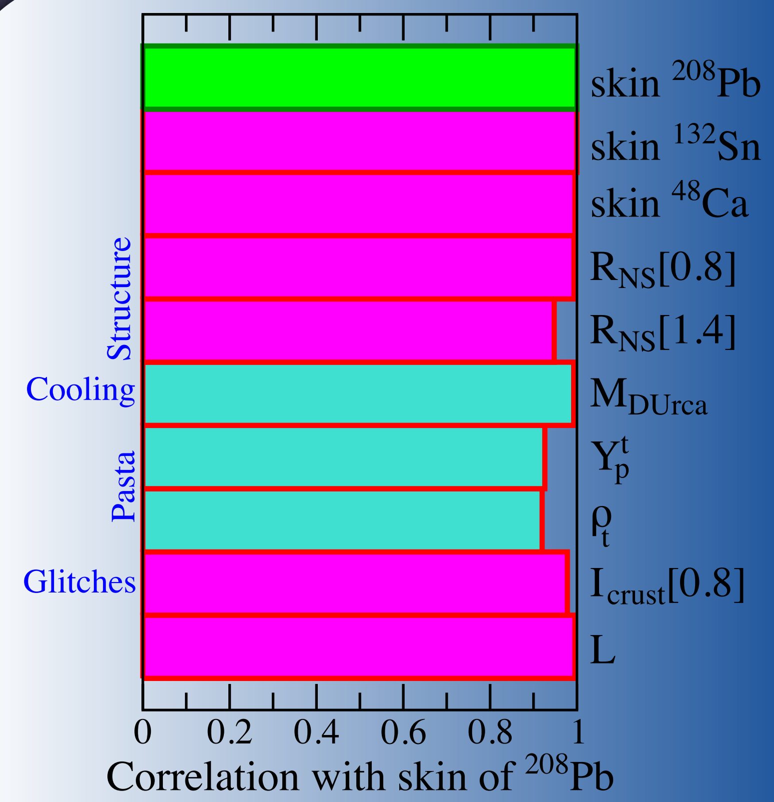
- The Marginal Likelihood; overall normalization factor

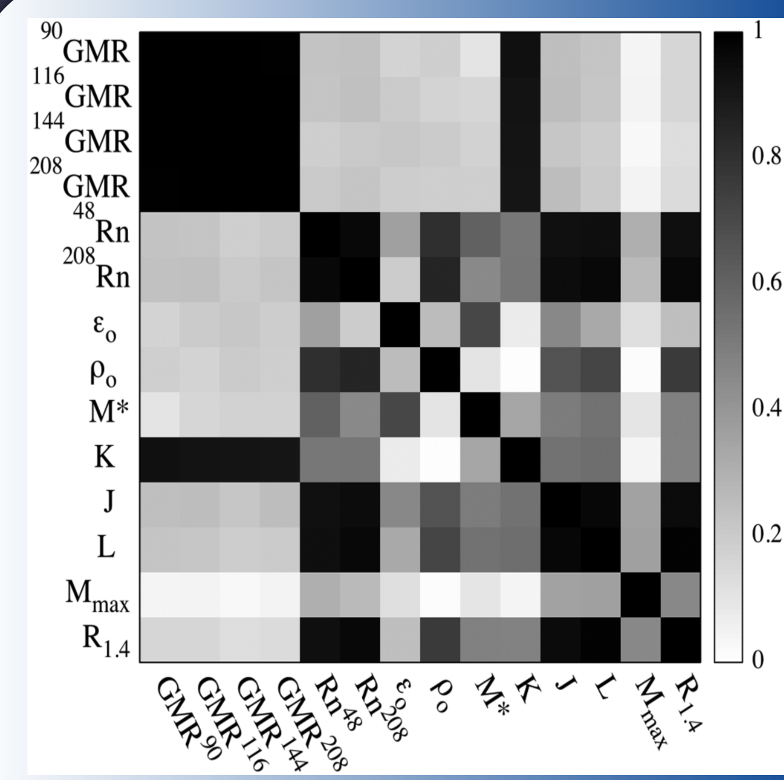
Heaven and Earth

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
- Neutron skin of heavy nuclei and NS radii driven by same physics
  - Difference in length scales of 18 orders of magnitude!!







Searching for L: The Strategy

- Establish a powerful physical argument connecting L to R_{skin}
  - Where do the extra 44 neutrons in ^{208}Pb go?

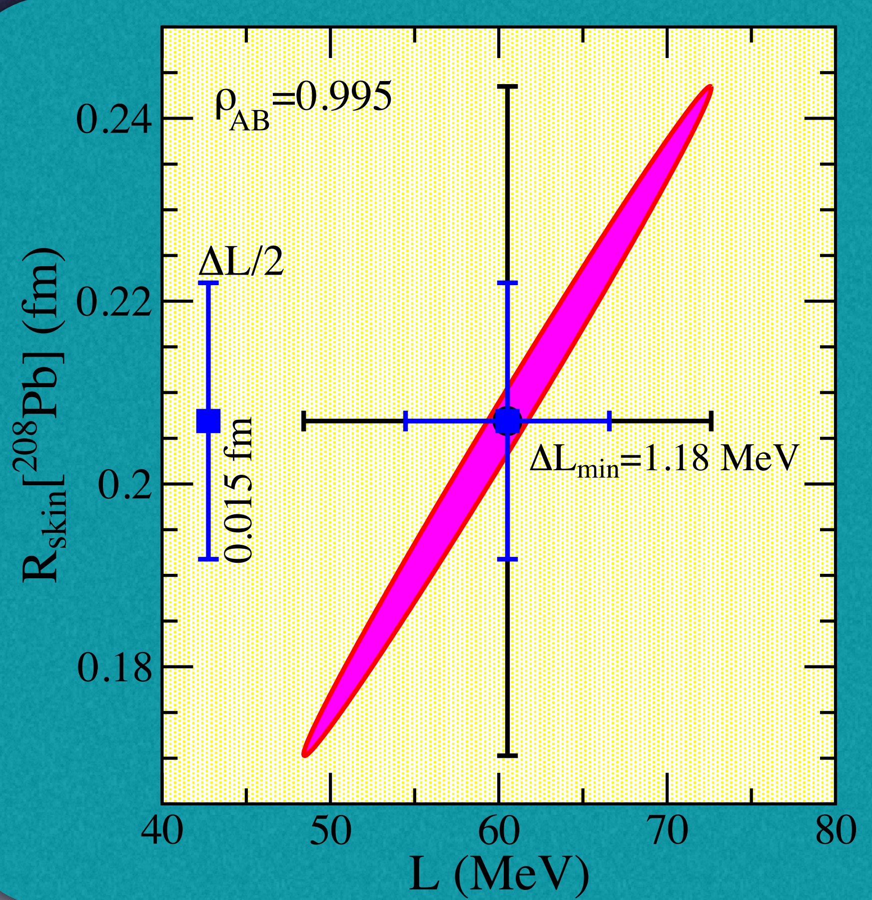
    Competition between surface tension and the ***difference*** $S(\rho_0)-S(\rho_{surf}) \simeq L$.

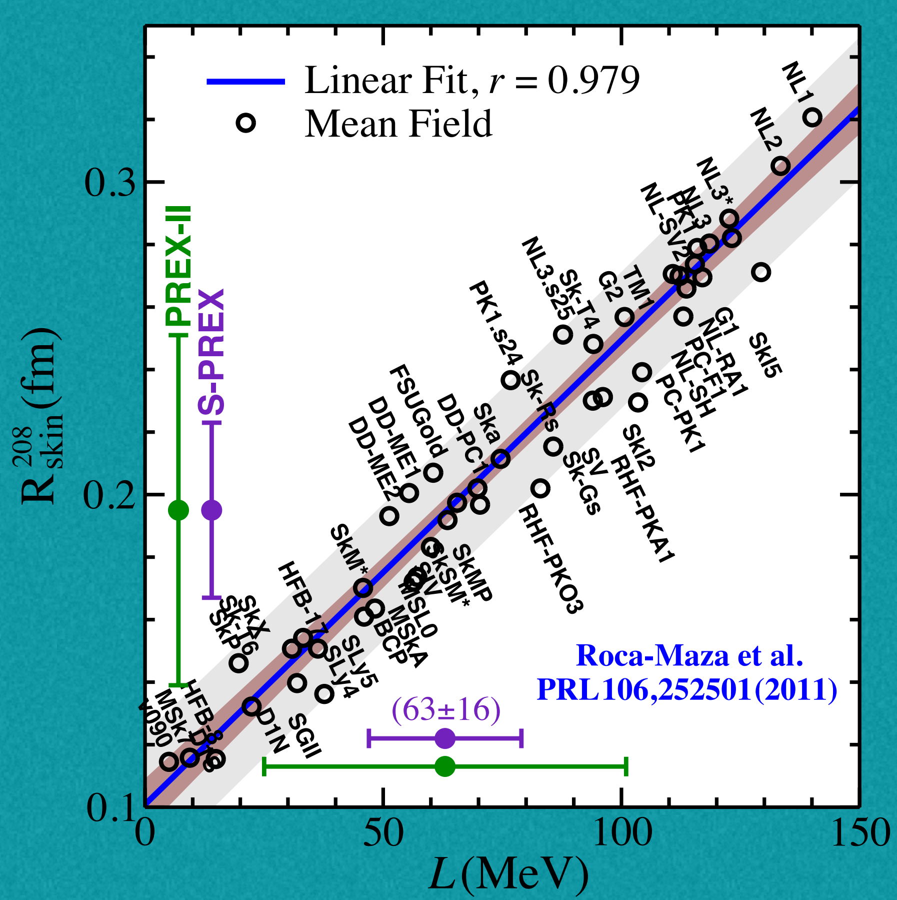
    The larger the value of L, the thicker the neutron skin of ^{208}Pb

- Ensure that "your" DFT supports the correlation

- Ensure that "all" accurately-calibrated DFT support the correlation

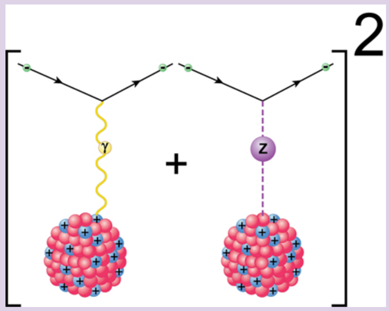
  (… "all models are equal but some models are more equal than others")





Electroweak Measurement of Neutron Densities

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



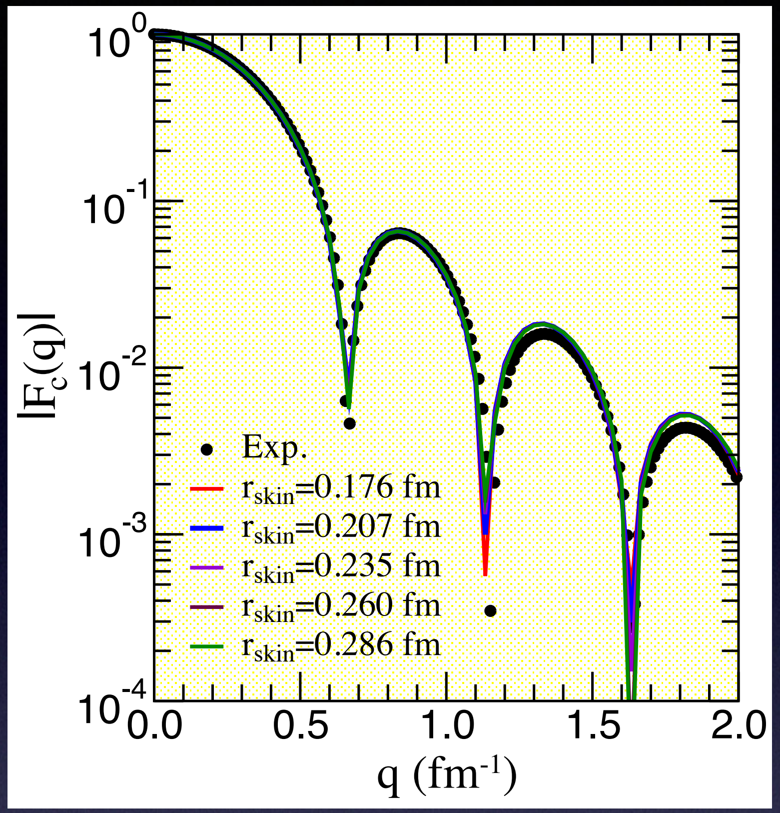
$$A_{\rm PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

- Neutral weak-vector boson Z_0 couples preferentially to neutrons
- PV provides a clean measurement of neutron densities (and R_n)

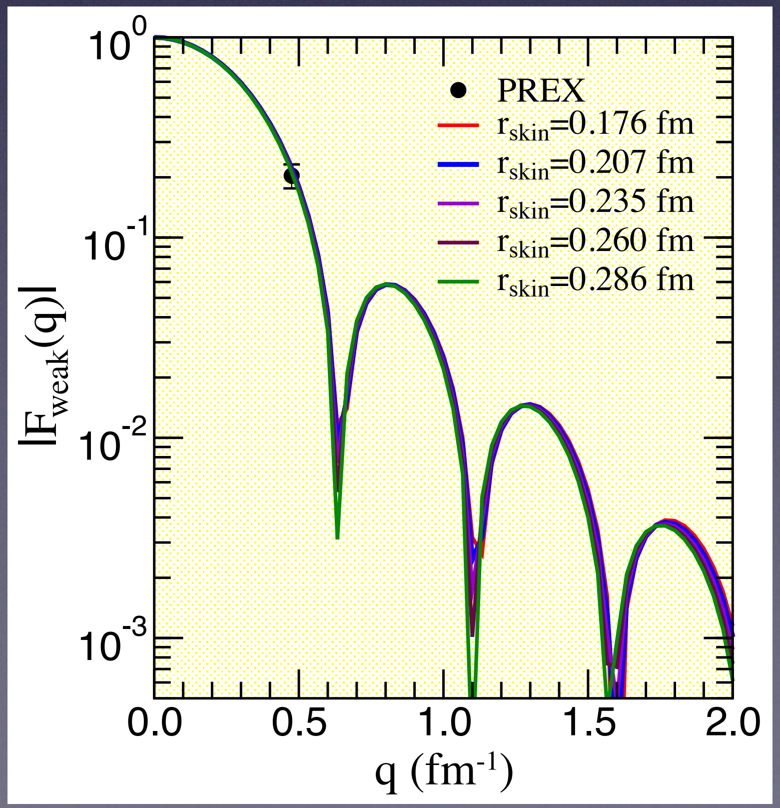
	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

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

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



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



The incompressibility of neutron rich matter: Why is tin so fluffy?

J I N A

Workshop on Nuclear Incompressibility

University of Notre Dame
July 14-15, 2005

The Joint Institute for Nuclear Astrophysics (JINA) will organize a 2-day Workshop focused on **Nuclear Incompressibility and the Nuclear Equation of State**, to be held at the University of Notre Dame during July 14-15, 2005.

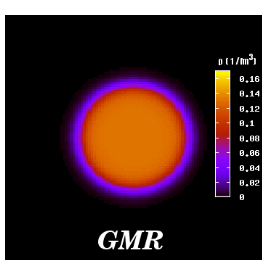
This meeting follows a similar Workshop held at Notre Dame in January 2001, and the **Symposium on Nuclear Equation of State used in Astrophysics Models**, held at the ACS meeting in Philadelphia last Summer.

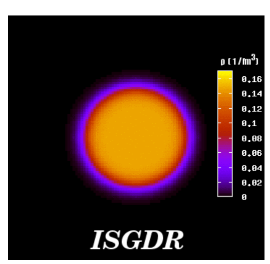
The primary aim of the Workshop is to bring together interested physicists from the areas of Astrophysics, Giant Resonances, and Heavy-Ion Reactions, to discuss current status of experiments and theoretical models related to nuclear incompressibility and the equation of state, and to explore what experiments might be needed to clarify some of the outstanding issues.

Most of the Workshop will be devoted to talks, with a lot of time allowed for discussions and interactions. In that spirit, we will follow a somewhat flexible schedule for the talks.

There is no registration fee but participants are requested to register via the **webpage** (www.jinaweb.org), so that we can make appropriate arrangements.

For further information, please contact:
Kathy Burgess (kburgess@nd.edu)
or
Umesh Garg (garg@nd.edu)





The Joint Institute for Nuclear Astrophysics
May 18, 2005

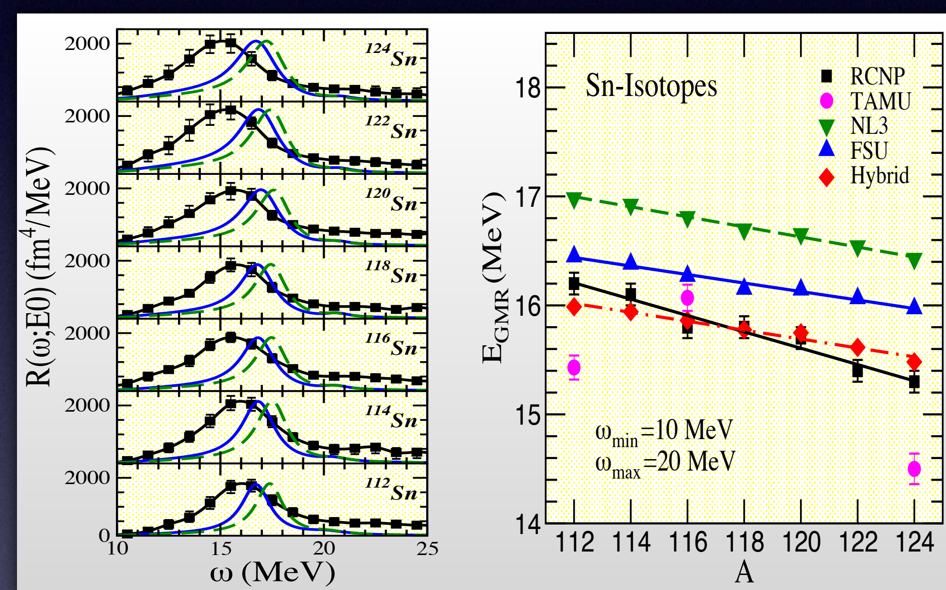
Outcome: A window into L through systematic measurements of the GMR across a long isotopic chain

ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
NUCLEAR PHYSICS A
Nuclear Physics A 788 (2007) 36c–43c

The Giant Monopole Resonance in the Sn Isotopes: Why is Tin so "Fluffy"?

U. Garg,[a] T. Li,[a] S. Okumura,[b] H. Akimune[c] M. Fujiwara,[b] M.N. Harakeh,[d] H. Hashimoto,[b] M. Itoh,[e] Y. Iwao,[f] T. Kawabata,[g] K. Kawase,[b] Y. Liu,[a] R. Marks,[a] T. Murakami,[f] K. Nakanishi,[b] B.K. Nayak,[a] P.V. Madhusudhana Rao,[a] H. Sakaguchi,[f] Y. Terashima,[f] M. Uchida,[h] Y. Yasuda,[f] M. Yosoi,[b] and J. Zenihiro[f]

$$K_0(\alpha) = K_0 + K_\tau \alpha^2;$$
$$K_\tau = K_{\rm sym} - 6L + \ldots$$



PHYSICAL REVIEW C 76, 031301(R) (2007)

Why is the equation of state for tin so soft?

J. Piekarewicz
Department of Physics, Florida State University, Tallahassee, Florida 32306, USA
(Received 10 May 2007; published 4 September 2007)

PHYSICAL REVIEW C 78, 064304 (2008)

Microscopic linear response calculations based on the Skyrme functional plus the pairing contribution

Jun Li (李俊),[1,2,*] Gianluca Colò,[1,3] and Jie Meng (孟杰)[2,3,4,5,†]

PHYSICAL REVIEW C 79, 034309 (2009)

Description of the giant monopole resonance in the even-A $^{112-124}$Sn isotopes within a microscopic model including quasiparticle-phonon coupling

V. Tselyaev,[1,2] J. Speth,[1] S. Krewald,[1] E. Litvinova,[3,4,5] S. Kamerdzhiev,[1,5] N. Lyutorovich,[1,2] A. Avdeenkov,[1,6] and F. Grümmer[1]

PRL 99, 162503 (2007) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2007

Isotopic Dependence of the Giant Monopole Resonance in the Even-A $^{112-124}$Sn Isotopes and the Asymmetry Term in Nuclear Incompressibility

T. Li,[1] U. Garg,[1] Y. Liu,[1] R. Marks,[1] B. K. Nayak,[1] P. V. Madhusudhana Rao,[1] M. Fujiwara,[2] H. Hashimoto,[2] K. Kawase,[2] K. Nakanishi,[2] S. Okumura,[2] M. Yosoi,[2] M. Itoh,[3] M. Ichikawa,[3] R. Matsuo,[3] T. Terazono,[3] M. Uchida,[4] T. Kawabata,[5] H. Akimune,[6] Y. Iwao,[7] T. Murakami,[7] H. Sakaguchi,[7] S. Terashima,[7] Y. Yasuda,[7] J. Zenihiro,[7] and M. N. Harakeh[8]

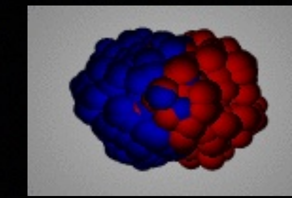
PHYSICAL REVIEW C 86, 024303 (2012)

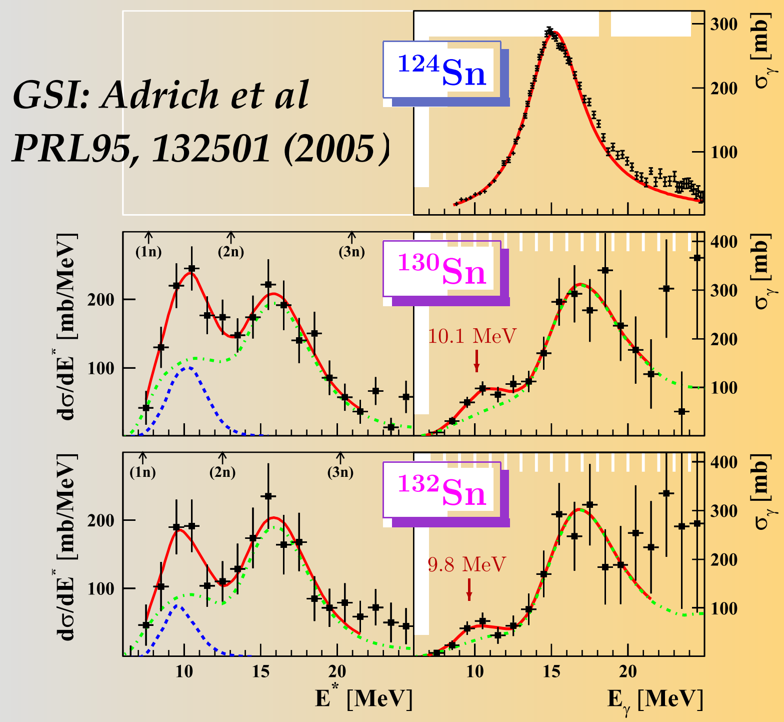
Giant monopole resonances and nuclear incompressibilities studied for the zero-range and separable pairing interactions

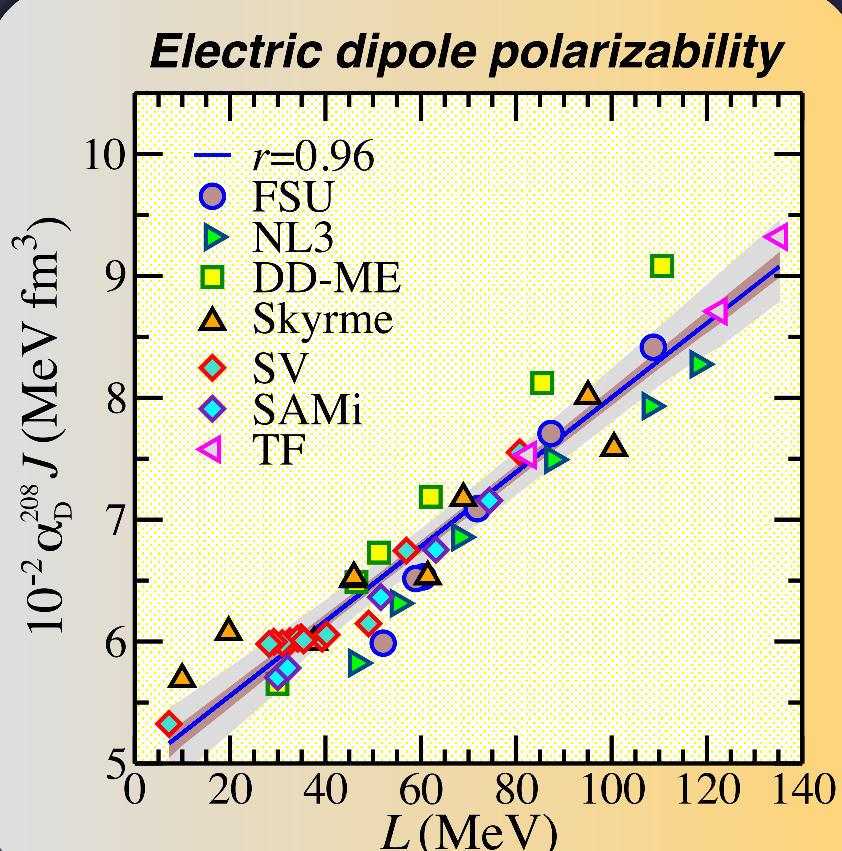
P. Veselý,[1,*] J. Toivanen,[1] B. G. Carlsson,[2] J. Dobaczewski,[1,3] N. Michel,[1] and A. Pastore[4]

Onwards and upwards to GMRs in unstable nuclei!

Electric Dipole Polarizability

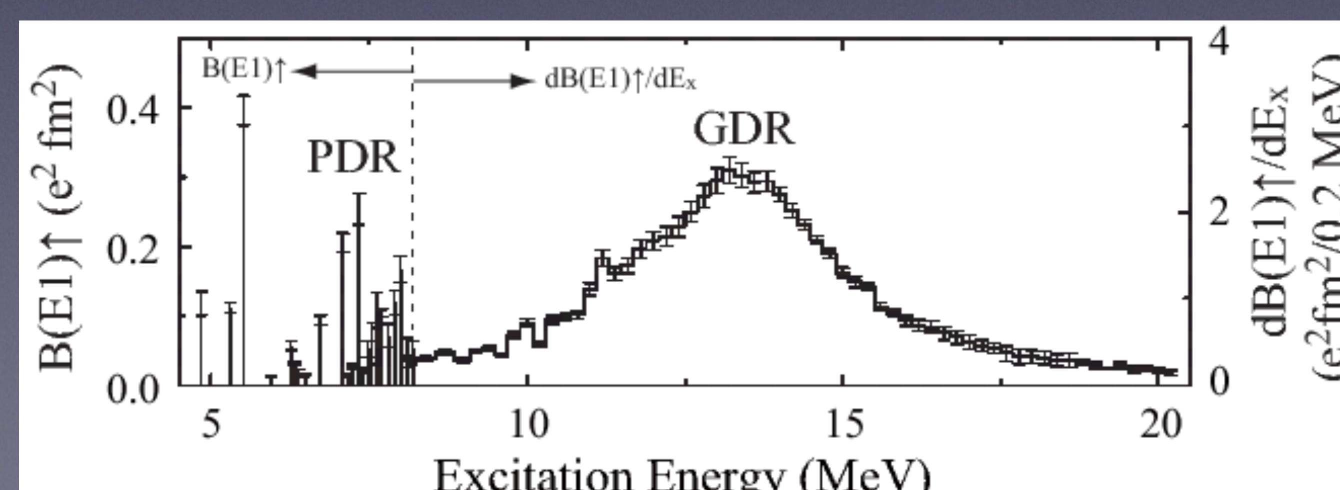






IVGDR: The quintessential nuclear excitation

- Out-of-phase oscillation of neutrons vs protons
  - Symmetry energy acts as restoring force
- Energy weighted ***sum rule*** largely model independent
- ***Inverse*** energy weighted sum strongly correlated to L
  - Actually … $J\alpha_D$ strongly correlated to L
  - Important contribution from Pygmy resonance
- High quality data emerging from RCNP, GSI, HIGS
  - On a variety of nuclei such as Pb, Sn, Ni, Ca, …
  - and hopefully in the future along isotopic chains



Neutron-Star Radii


PRL 115, 161101 (2015) PHYSICAL REVIEW LETTERS week ending 16 OCTOBER 2015

Compactness of Neutron Stars

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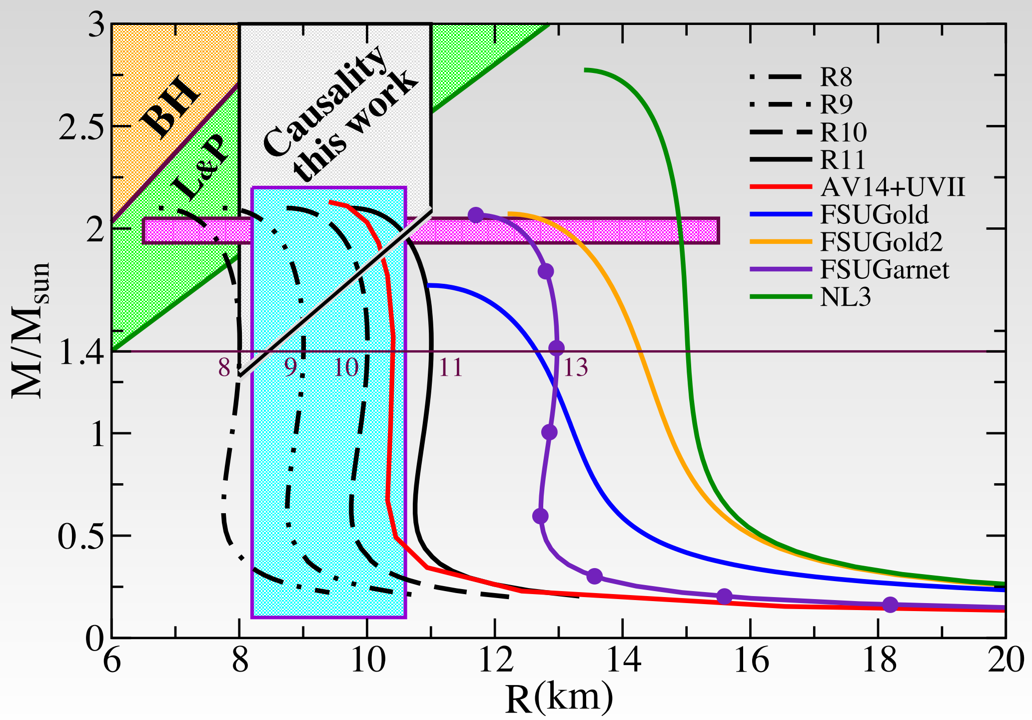
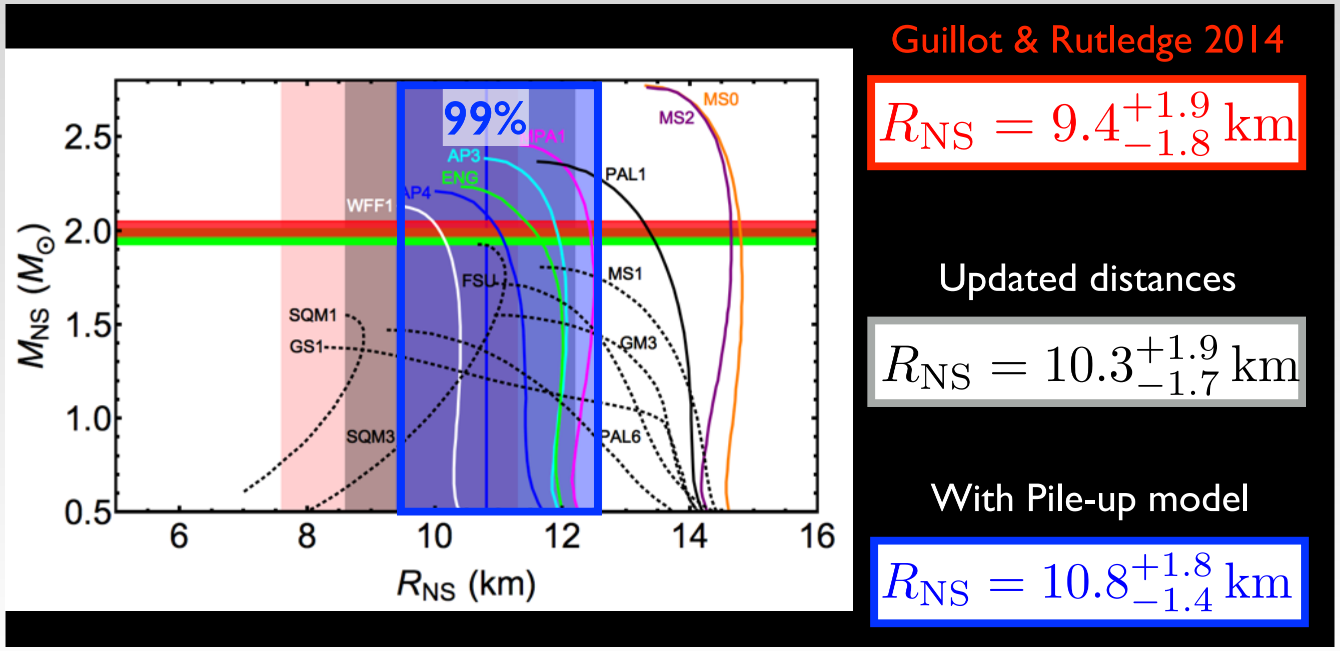
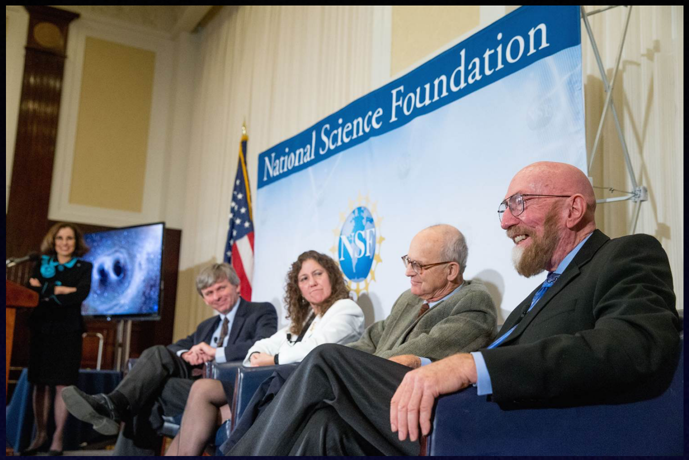
(Received 27 May 2015; published 16 October 2015)

- Guillot et al., assume all neutron stars share a common radius
  Assumption in MR observable rather than on the EOS
- One-to-one correspondence between EOS and MR
  TOV equation + EOS ⟶ Unique MR relation
- Lindblom's inversion algorithm shows the inverse also true! [APJ 398, 569 (1992)]
  TOV equation + MR ⟶ Unique Equation of State
- For a given "common" radius MR profile examine whether:
  Resulting EOS is causal or superluminal for stellar masses below $2M_\odot$
- For a given "common" radius MR profile, to prevent causality violations
  Stellar radius of a $1.4M_\odot$ must exceed 10.7 km!

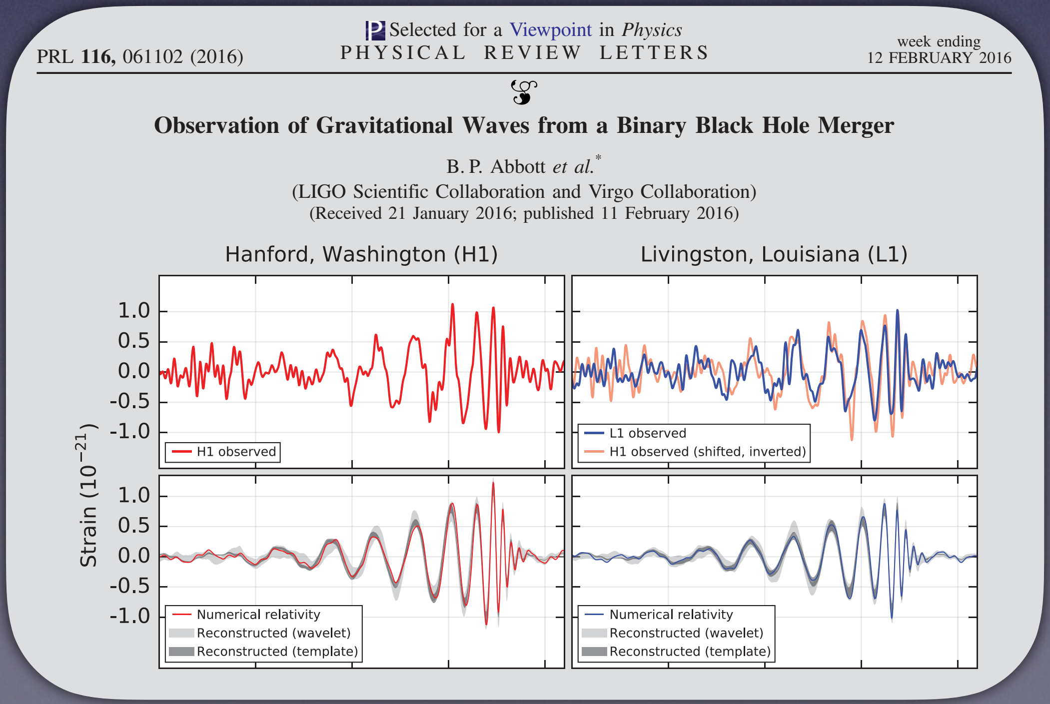




"We have detected gravitational waves; we did it"
David Reitze, February 11, 2016



- **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!



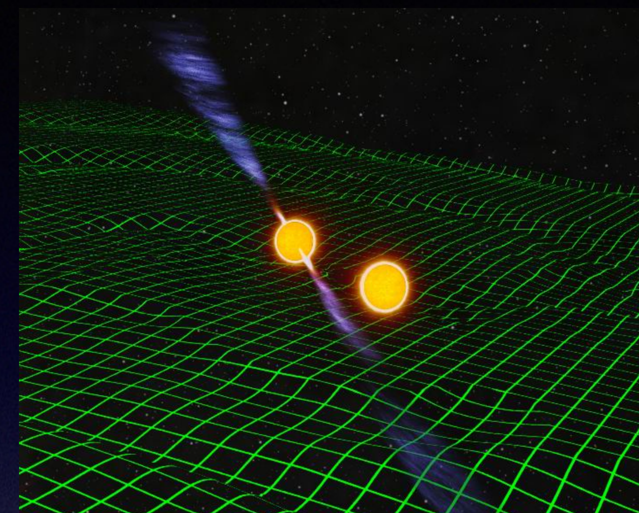
Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

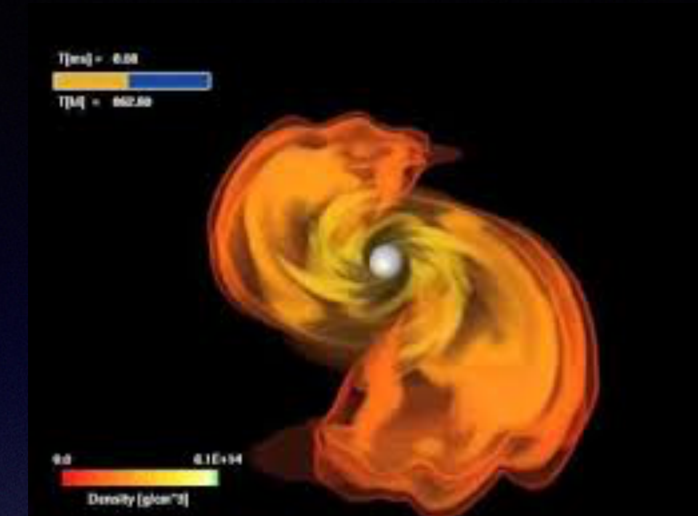
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

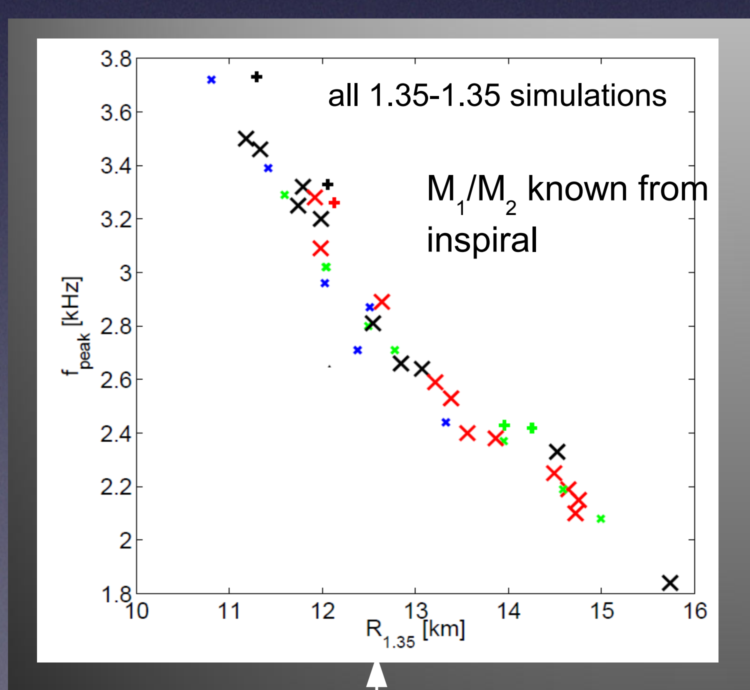
(Received 21 January 2016; published 11 February 2016)

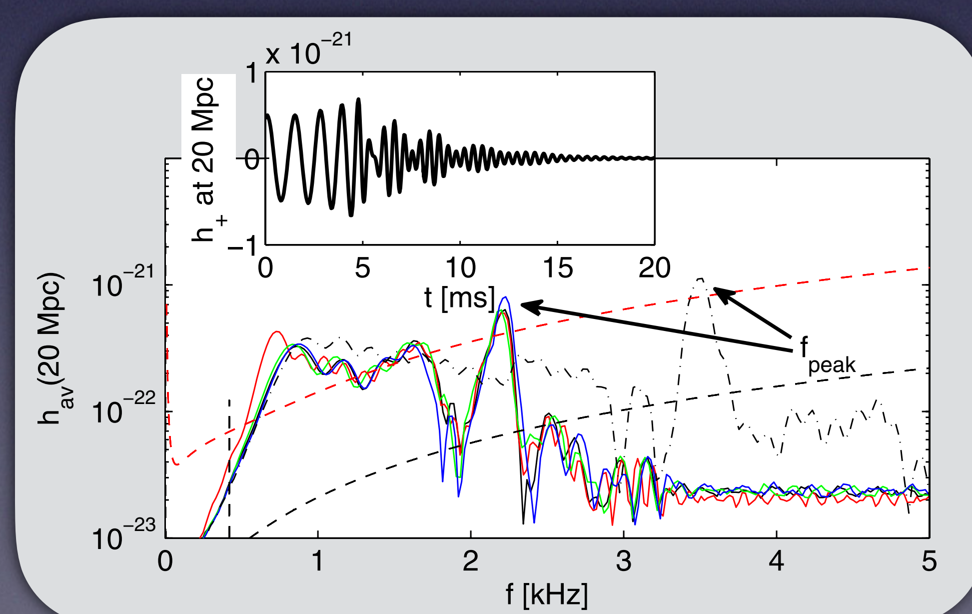
What will we learn from neutron-star mergers

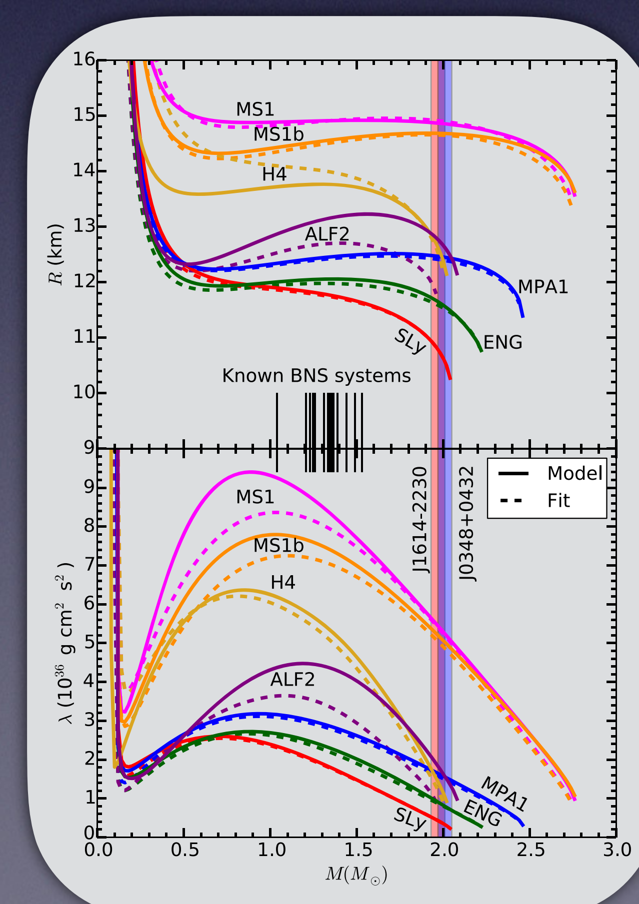




Tidal polarizability scales as R^5 !



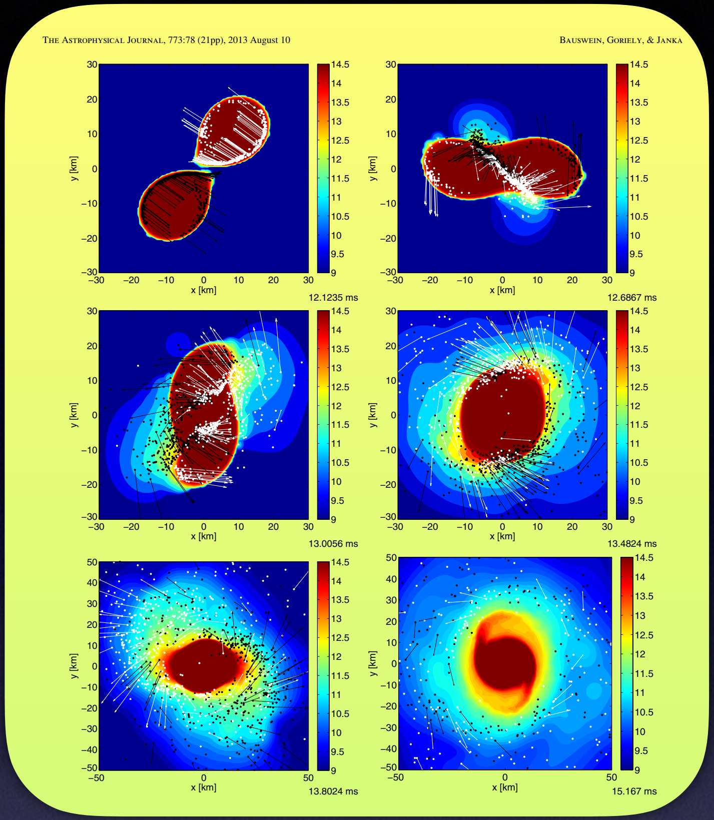




NS radius measured to better than 1km!

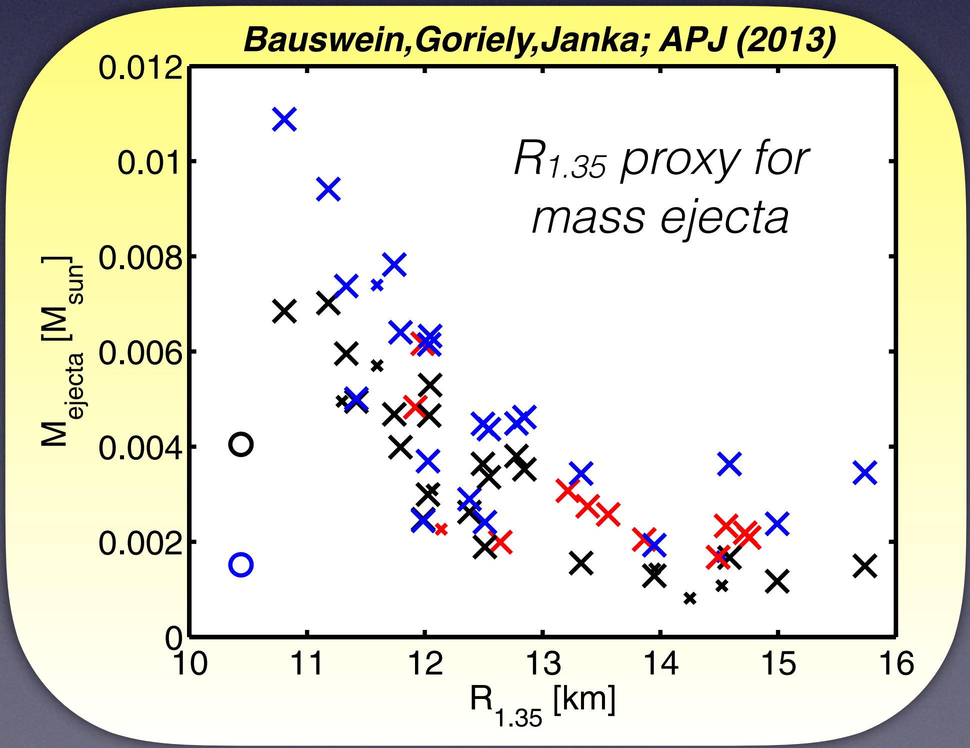
What *else* will we learn from neutron-star mergers

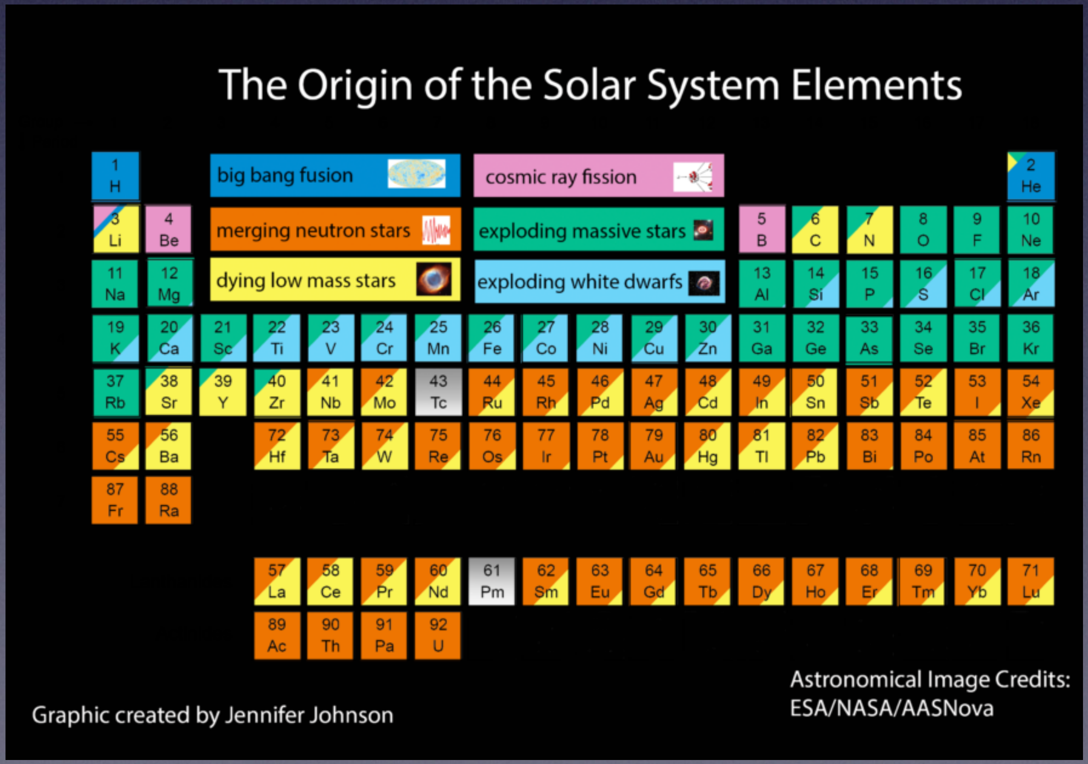
How were the heavy elements from iron to uranium made?



- LIGO will provide critical insights into the behavior of ultra dense matter
- Merger rate and ejecta mass unknown
  Galactic merger rate depends on EOS: $4x10^{-5}$ (soft) $4x10^{-4}$ (stiff) per year to account for observation

Soft: Rn-Rp is small ⟶ neutron star more compact
merger is more violent ⟶ higher abundance





My Collaborators

My FSU Collaborators

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

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- W. Nazarewicz (MSU)
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- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)