

**PREX** is a fascinating experiment that uses parity VIOLATION TO ACCURATELY DETERMINE THE NEUTRON RADIUS IN <sup>208</sup>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

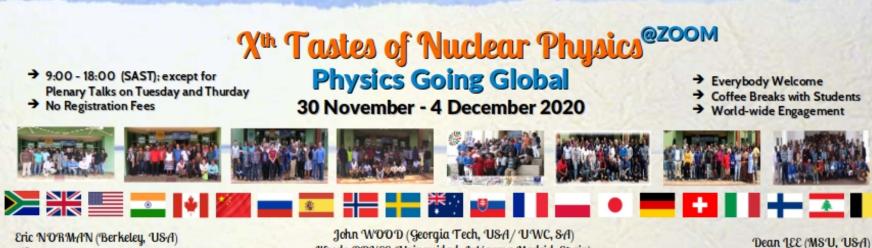
# adius **X**periment

### and Neutron Rich Matter in the Heavens and on Earth

August 17-19 2008 Jefferson Lab Newport News, Virginia

> ORGANIZING COMMITTEE CHUCK HOROWITZ (INDIANA) KEES DE JAGER (JLAB) JIM LATTIMER (STONY BROOK) WITOLD NAZAREWICZ (UTK, ORNL) JORGE PIEKAREWICZ (FSU

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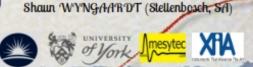
MaNuS/ MatSci Honours/MSc @ UWC/UNIZULU http://nuclear.uwc.ac.za/index.php/tnp2020

# Neutron-rich matter in Heaven and Earth



J. Piekarewicz Florida State University

> Alfredo POVES (Universidad Autónoma Madrid, Spain) ALEX BROWN (MSU, USA) Morten HJORTH-JENSEN (MSU+Oslo, USA+Norway) Paul GARRETT (Guelph, Canada/UWC, SA) Dmitry VOSKRESENSKY (MEPh1/JINR, Russia) Mark RMEY (Florida State, USA) Tomás RODRÍGUEZ (Universidad Autónoma Madrid, Spain Carles BERTULANI (TAMU, USA) Nontobeko KHUMALO (NNR, SA) Pawel NAPTORKOWSKI (Warsaw, Poland) Ronald Fernando GARCIA RUIZ (MIT, USA) Song GUO (Academy of Sciences, China) Alejandro ALGORA (IFIC, Spain) Jens DILLING (TRIUMF, Canada) Nikita BERNIER (UWC/UNIZULU, SA) Azwinndini MURONGA (Nelson Mandela, SA) Martin VENHART (Slovak Academy of Sciences, Slovakia) Luis ROBLEDO (Universidad Autónoma Madrid, Spain) Jacek DOBACZEWSKI (York, UK) Marcus SCHECK (West Scotland, UK) Janne PAKARINEN (Jyväskylä, Finland) John SHARPEY-SCHAFER (UNIZULU, SA) Adriana BANU (James Madison University, USA) David Edwin ALVAREZ CASTILLO (INP, PAS & JINR, Poland / Russia) +TALKS by the NEXT GENERATION



Björn JONSON (Chalmers, Sweden)

Gerda NEYENS (CERN, Switzerland)

Krish BHARUTH-RAM (UKZN, SA)

David JENKINS (York, UK / UWC)

Corina ANDREOTU (Simon Fraser, Canada)

Phil ADSLEY (WITS /iThemba LABS, SA)

Jorge PIEKAREWICZ (Florida State, USA)

Vivek DATAR (TIFR, India)

Nigel WARR (Cologne, Germany)

Alison BRUCE (Brighton, UK)

Robbie LINDSAY (UWC, SA)

Liam GAFFNEY (Liverpool, UK)

Ramon WYSS (KTH, Sweden)

Costel PETRACHE (Orsay, France)

Tom LEADBEATER (UCT, SA)

Xavier Roca Maza (Milan, Italy)

Jason HOLT (TRIUMF, Canada)

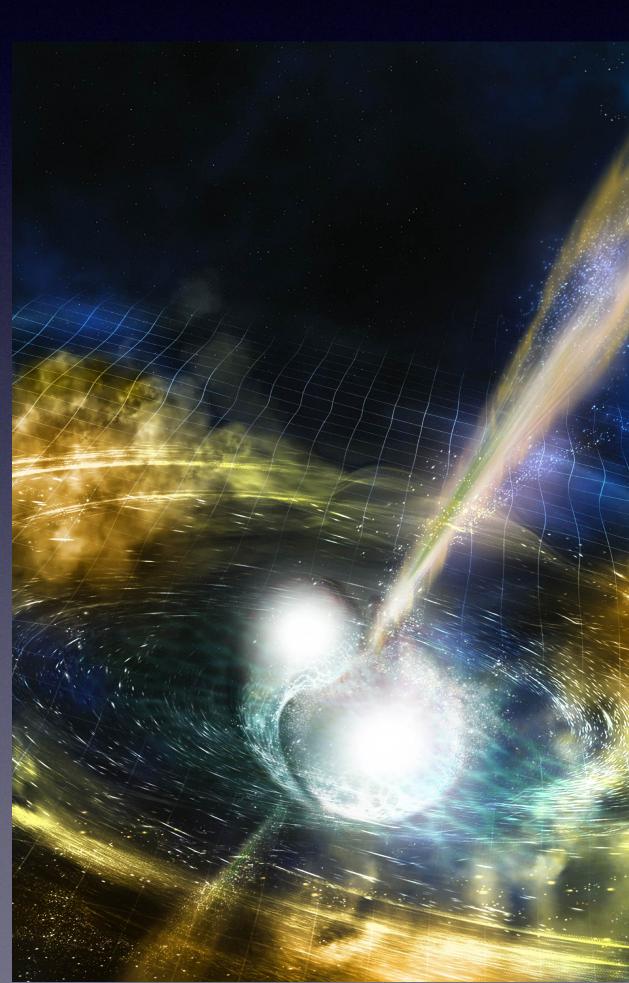
Werner RICHTER (SU, SA)

Simon CONNELL (UJ, SA)

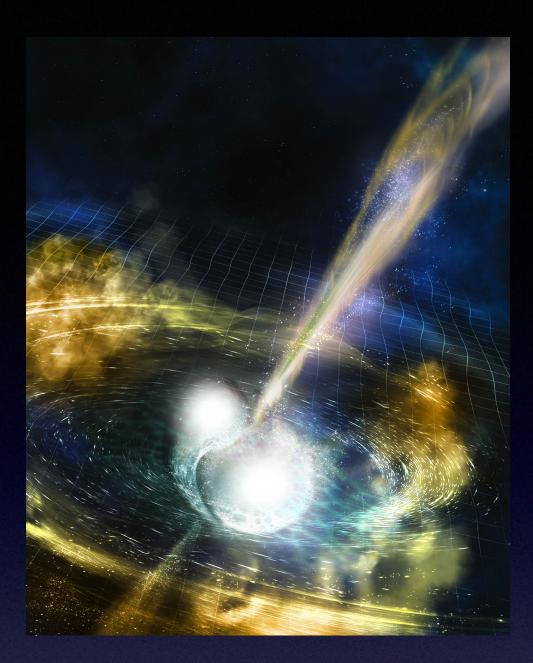
21 VAN ZYL (SU, SA)

Karl JOHNSTON (CERN, Switzerland)









# Heaven on Earth The Beautiful Game





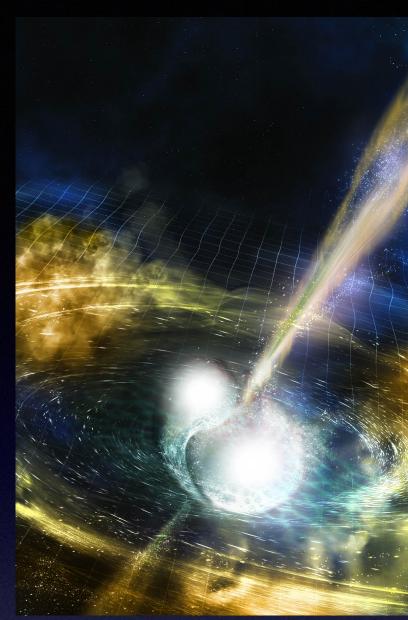
### World Cup · Group A · Matchday 1 of 3

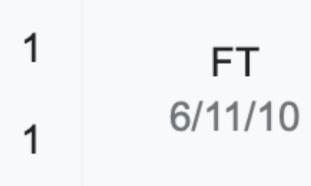


South Africa



Mexico



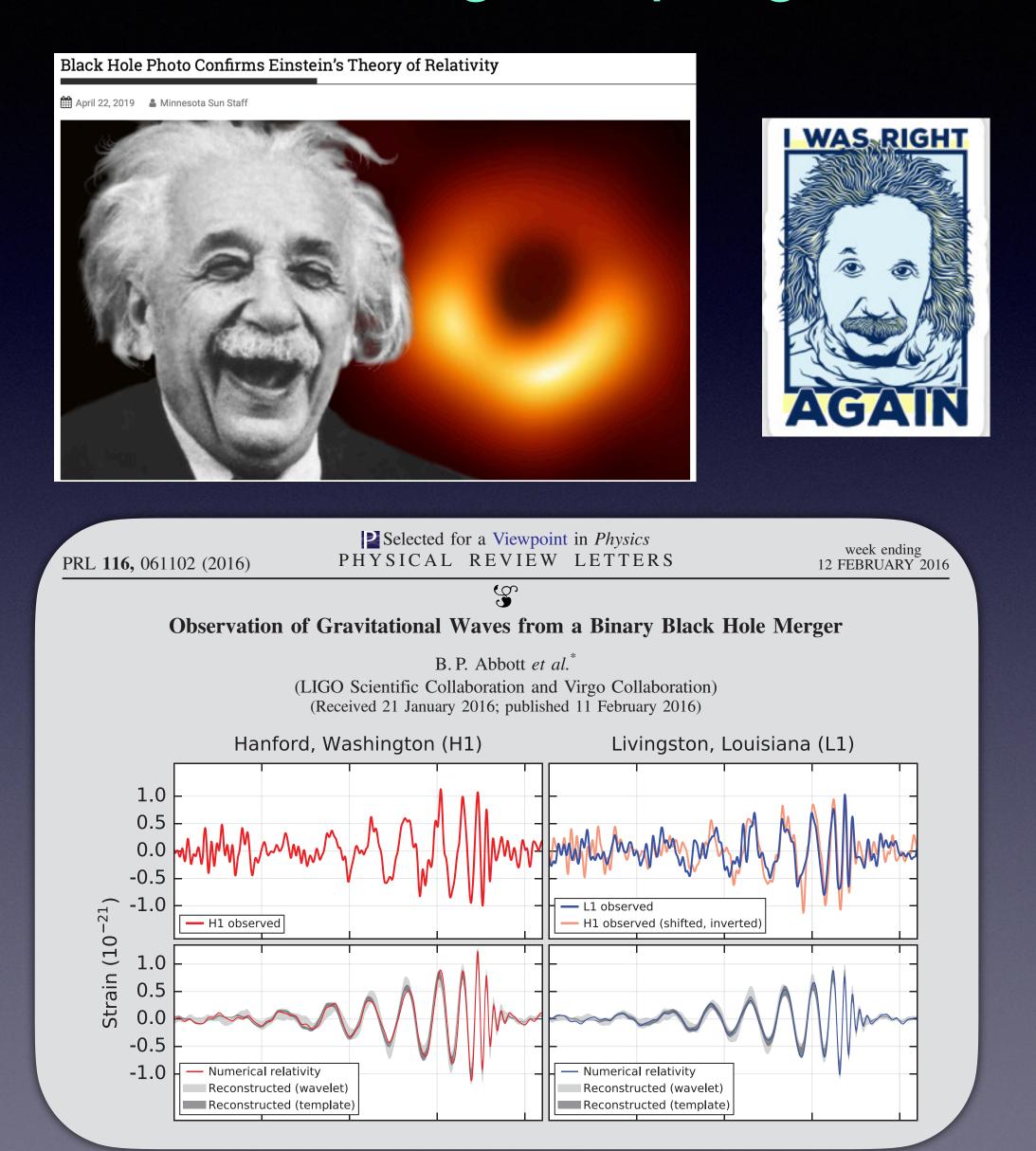






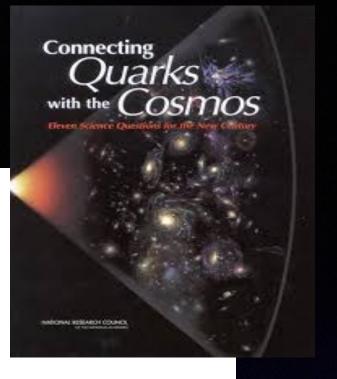


### Testing General Relativity in the Strong Coupling Limit



### ElevenScience Questions for the Next Century

- 1. What is Dark Matter?
- 2. What is the Nature of Dark Energy?
- 3. How did the Universe Begin?
- 4. Did Einstein Have the Last Word on Gravity?
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## "We have detected gravitational waves; we did it" David Reitze, February 11, 2016

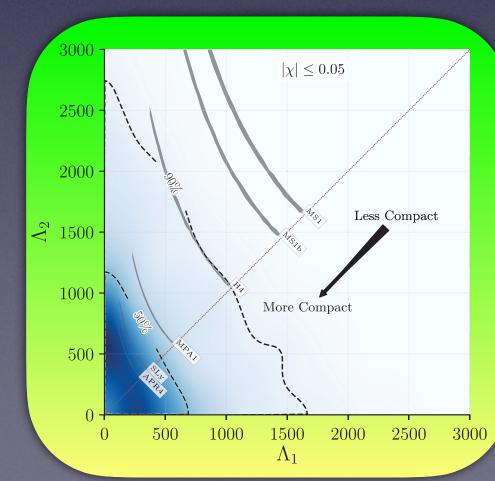


The dawn of a new era: GW Astronomy Initial black hole masses are 36 and 29 solar masses Final black hole mass is 62 solar masses; 3 solar masses radiated in Gravitational Waves!









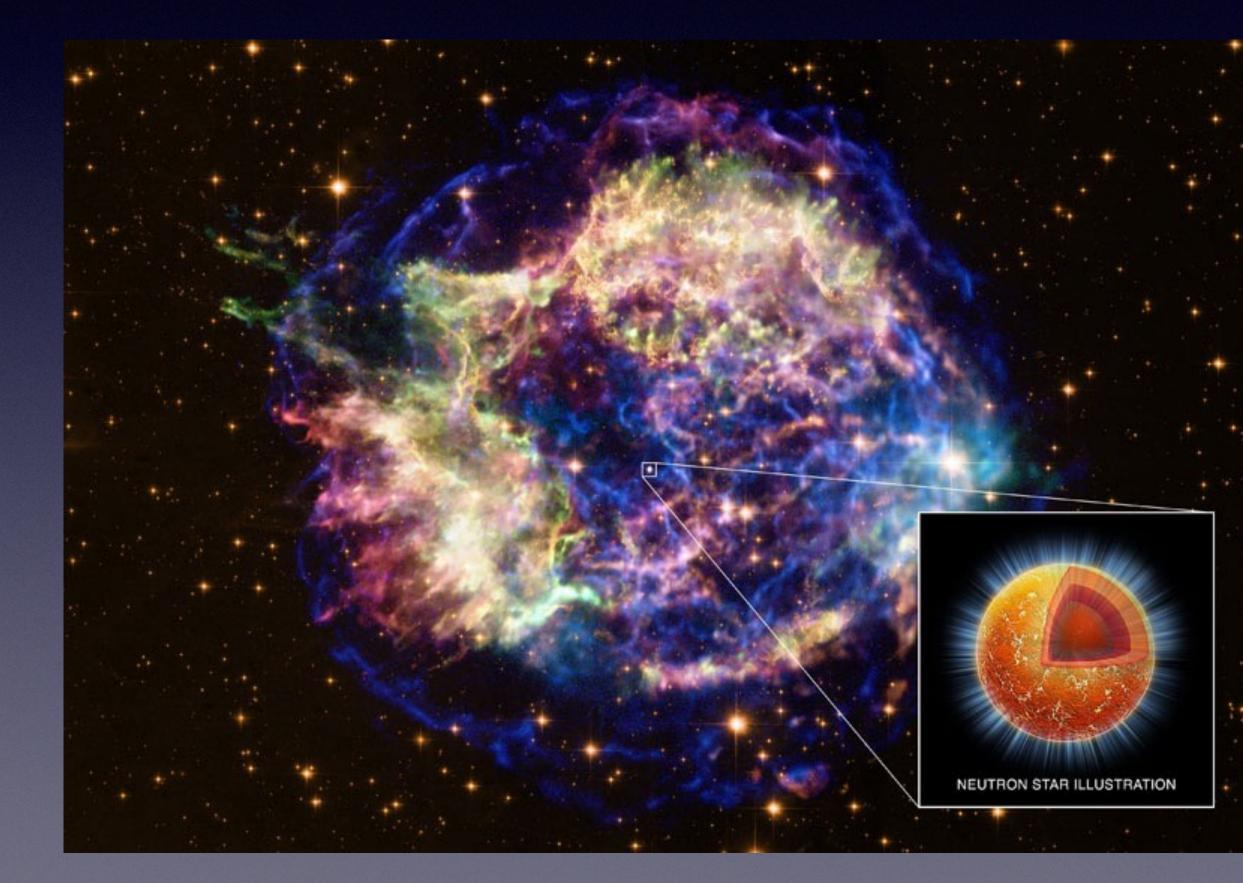
Equations of state (EOS) that predict very large neutron star radii are ruled out!

BREAKTHROUGH

of the YEAR



## Neutron Stars as Unique Cosmic Laboratories for the Study of Dense Matter

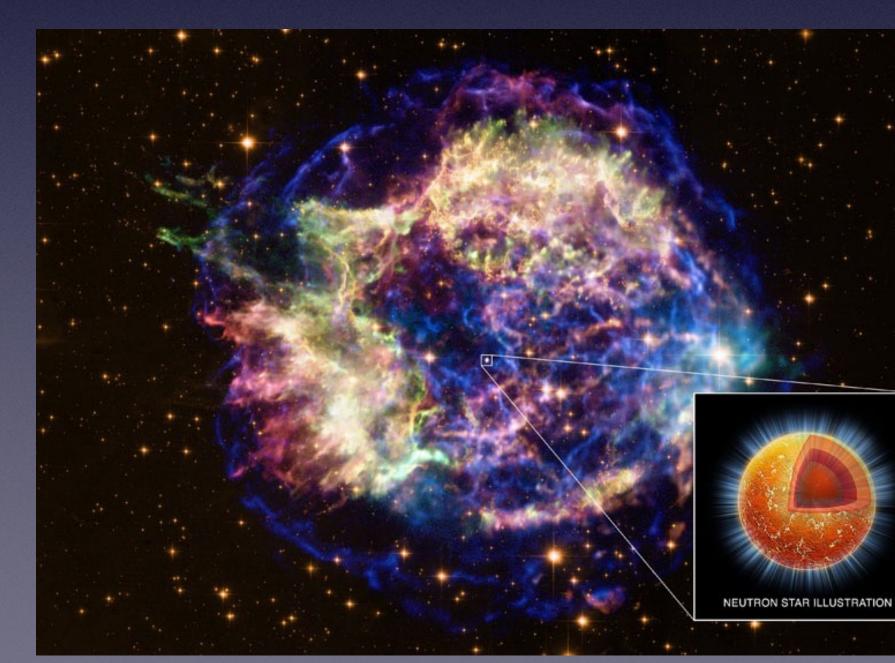


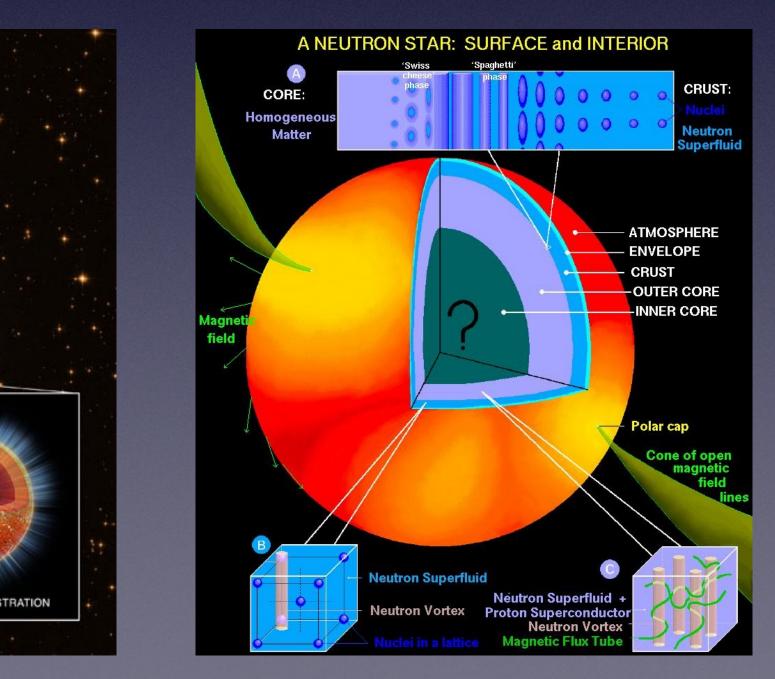
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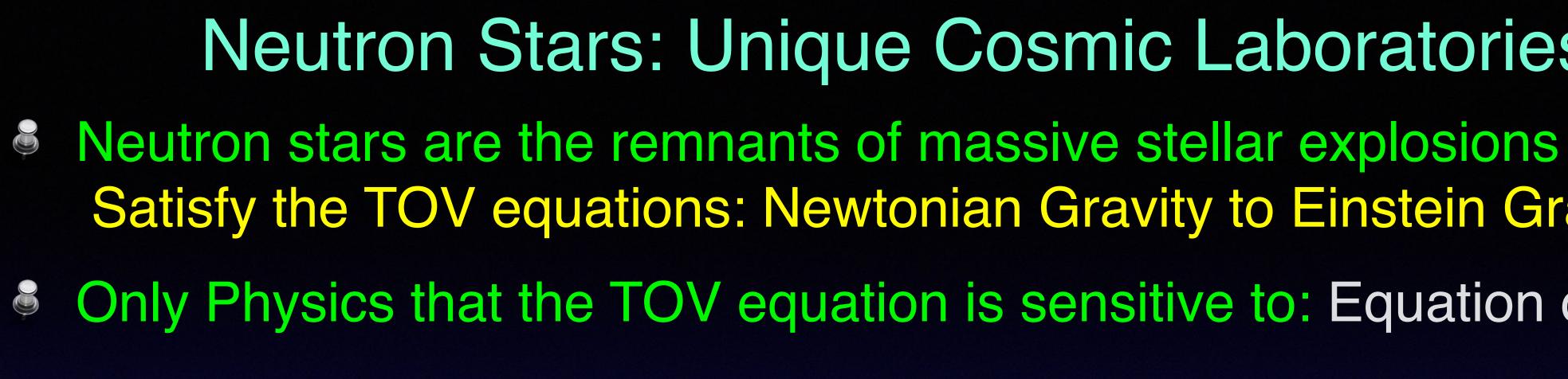
- The Anatomy of a Neutron Star
- <sup>&</sup> Atmosphere (10 cm): Shapes Thermal Radiation (L=4 $\pi\sigma$ R<sup>2</sup>T<sup>4</sup>) Similar Envelope (100 m): Huge Temperature Gradient (10<sup>8</sup>K  $\leftrightarrow$  10<sup>6</sup>K) Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei) Inner Crust (1 km): Coulomb Frustration ("Nuclear Pasta")

- <sup>®</sup> Outer Core (10 km): Uniform Neutron-Rich Matter (n,p,e,µ)
- Inner Core (?): Exotic Matter (Hyperons, condensates, quark matter)

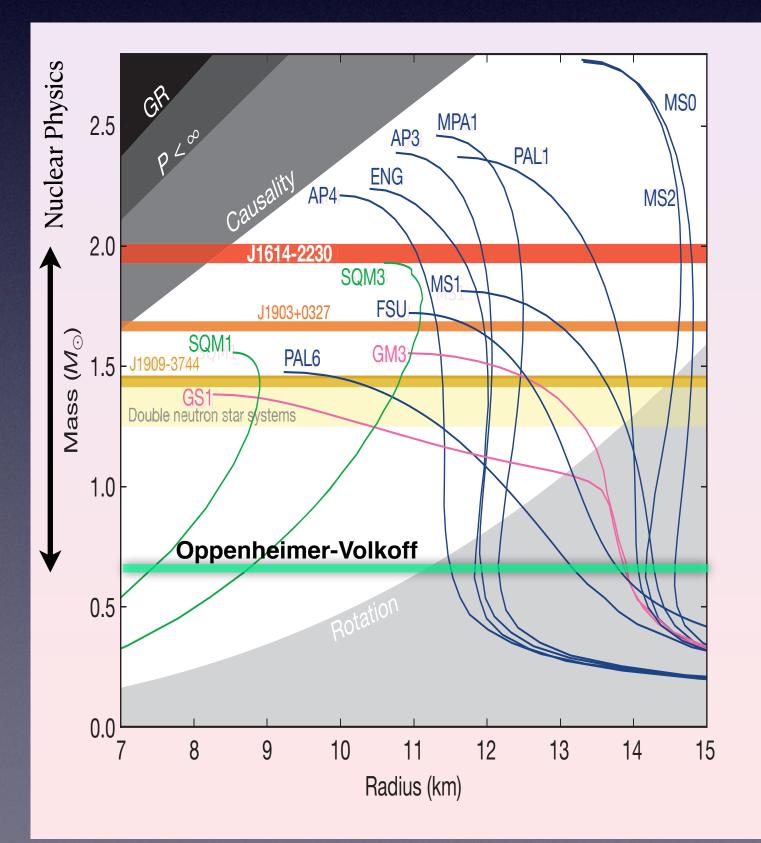


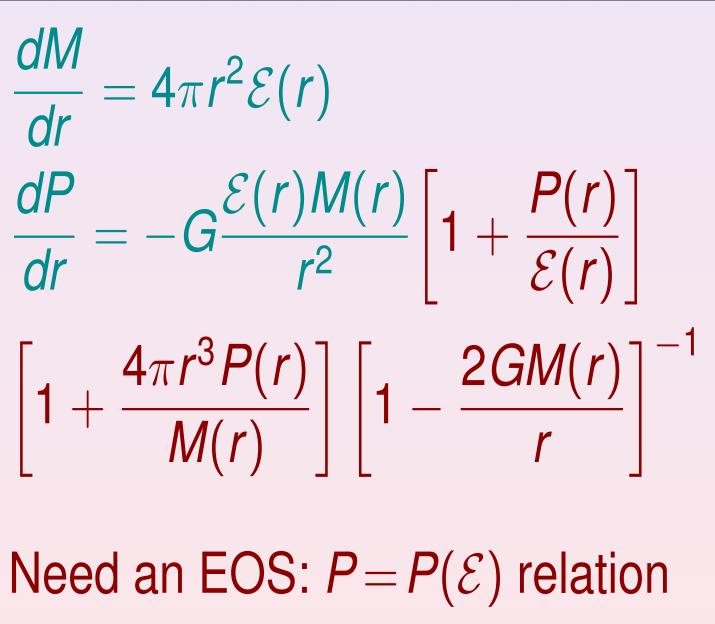






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**Nuclear Physics Critical** 

Neutron Stars: Unique Cosmic Laboratories Satisfy the TOV equations: Newtonian Gravity to Einstein Gravity Only Physics that the TOV equation is sensitive to: Equation of State Increase from  $0.7 \rightarrow 2$  Msun transfers ownership to Nuclear Physics!

### Status before GW170817

Many nuclear models that account for the properties of finite nuclei yield enormous variations in the prediction of neutron-star radii and maximum mass

Only observational constraint in the form of two neutron stars with a mass in the vicinity of  $2M_{sun}$ 



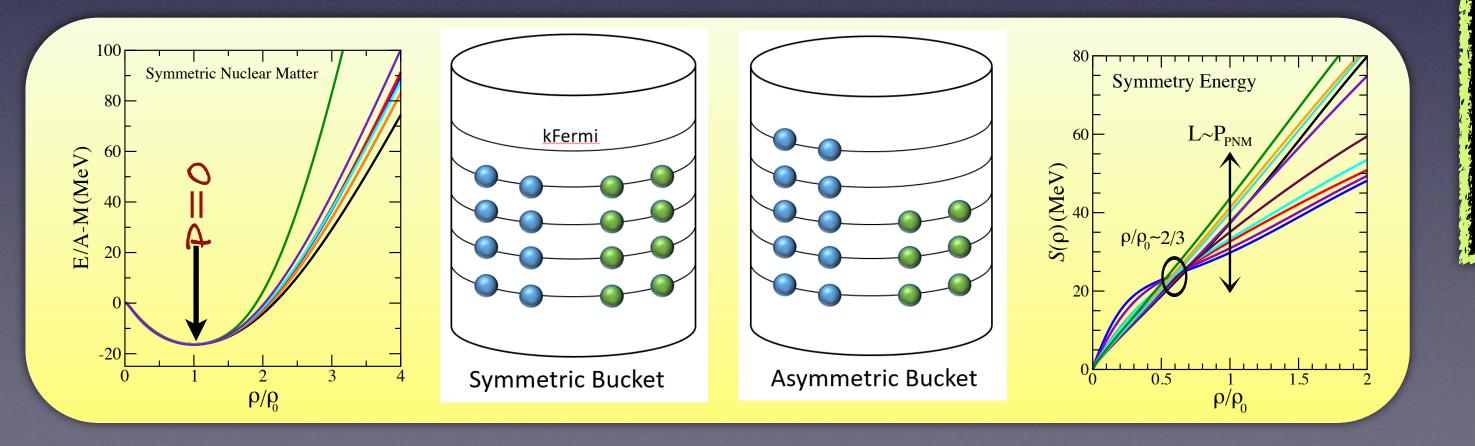
## The Equation of State of Neutron-Rich Matter

Equation of state: textbook examples

Non-interacting classical gas high temperature, low density limit

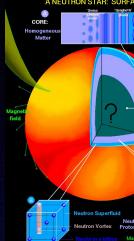
$$P(n,T) = nk_{\rm B}T \leftrightarrow P(\mathcal{E}) = \frac{2}{3}\mathcal{E}$$

Solution Non-interacting (UR) quantum gas high density, low temperature limit  $P(n, T=0) \approx n^{4/3} \leftrightarrow P(\mathcal{E}) = \frac{1}{3}\mathcal{E}$ 



Equation of state of neutron-rich matter: NON-textbook example

Strongly-interacting quantum fluid high density, low temperature limit

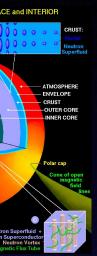


- Solution Two "quantum liquids" in  $\mu$ -equilibrium
- Charge-neutral system (neutralizing leptons)
- Density dependence and isospin asymmetry of the EOS poorly constrained

 $S(\rho_0) \approx \left( E_{\rm PNM} - E_{\rm SNM} \right) (\rho_0) = J$  $P_{\rm PNM} \approx \frac{1}{2} L \rho_0 \ ({\rm Pressure of PNM})$ 

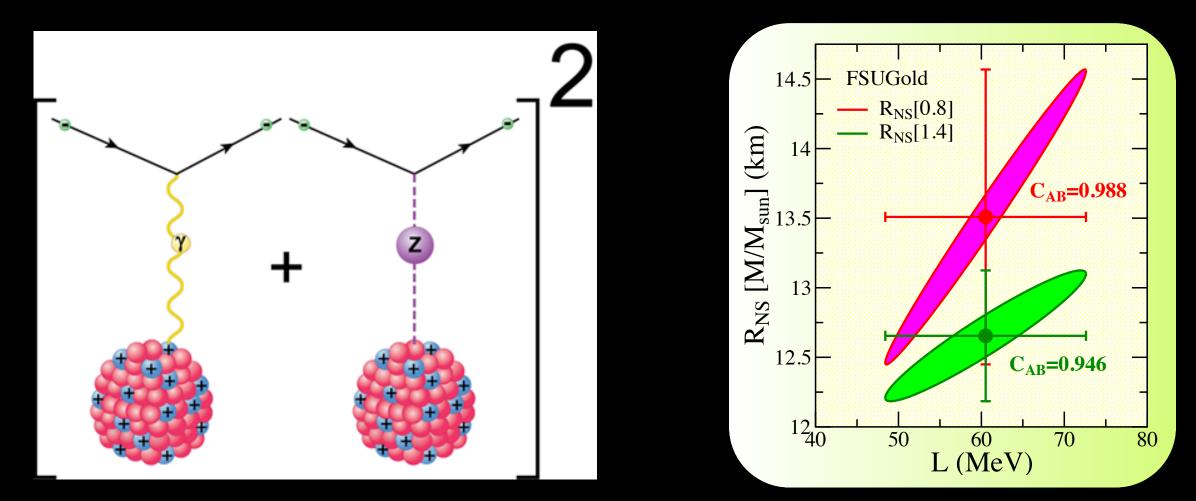
"Stiff" → L large

"Soft"  $\longrightarrow$  L small

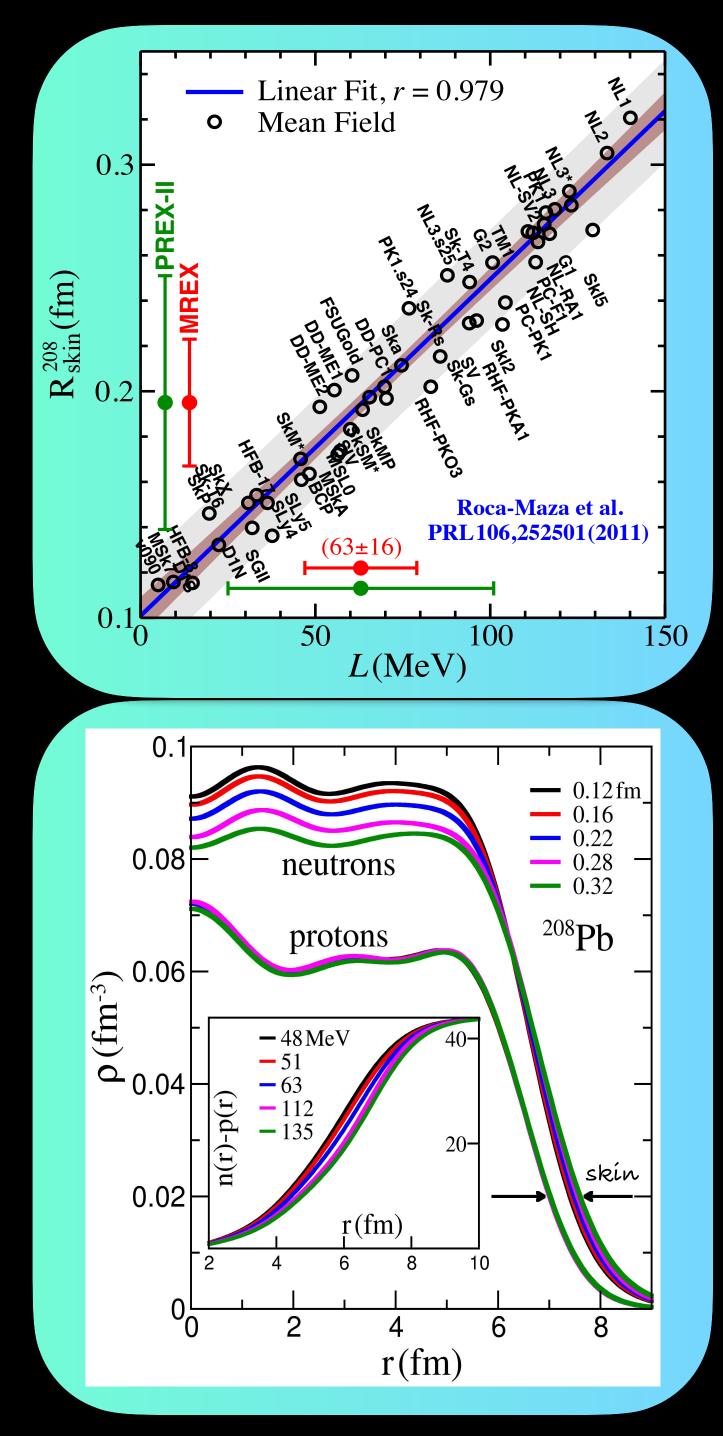




## Heaven and Earth Laboratory Constraints on the EOS

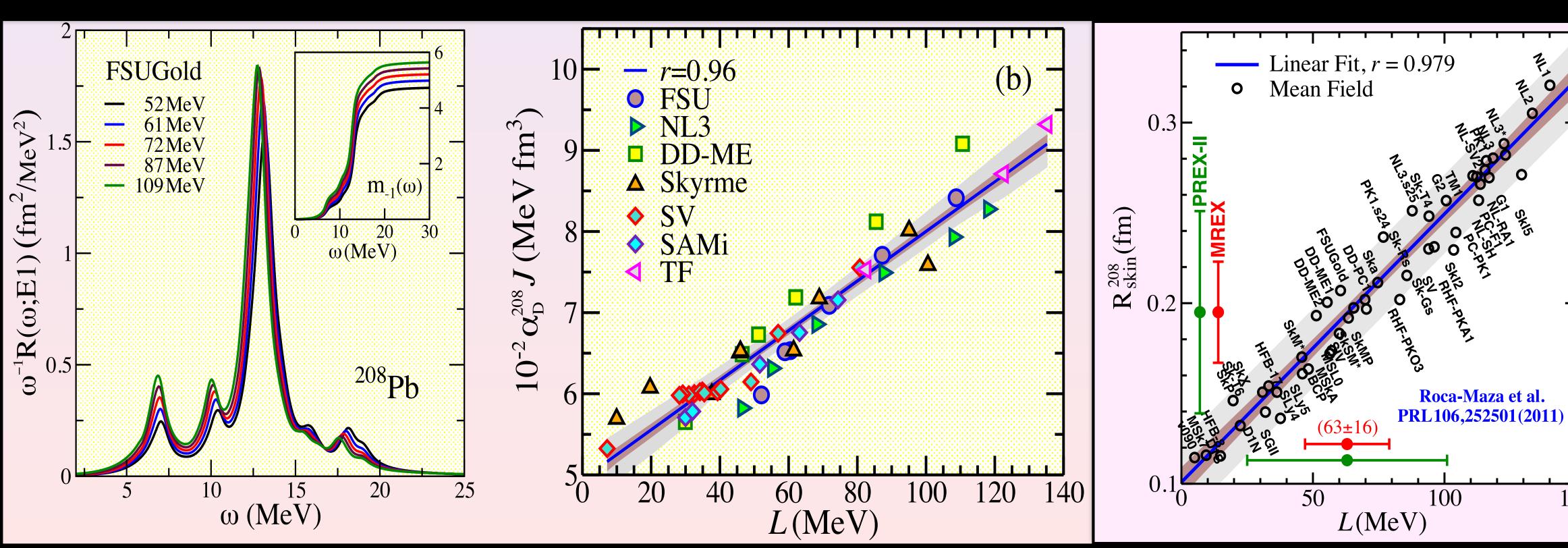


- Laboratory experiments constrain the EOS of pure neutron matter around saturation density: P<sub>PNM</sub>=L
- Although a fundamental parameter of the EOS, L is not a physical observable — yet is strongly correlated to one: the neutron-rich skin of a heavy nucleus such as <sup>208</sup>Pb
  - Parity-violating elastic electron scattering is the cleanest experimental tool to measure the neutron radius of lead (PREX, PREX-II, and MREX)



# Electric Dipole Polarizability $\alpha_{D}$

 Electric dipole polarizability a powerful electroweak complement to Rskin Important contribution from Pygmy resonance (inverse energy weighted sum)
Low-energy strength of relevance to (n,γ) reactions in stellar environments

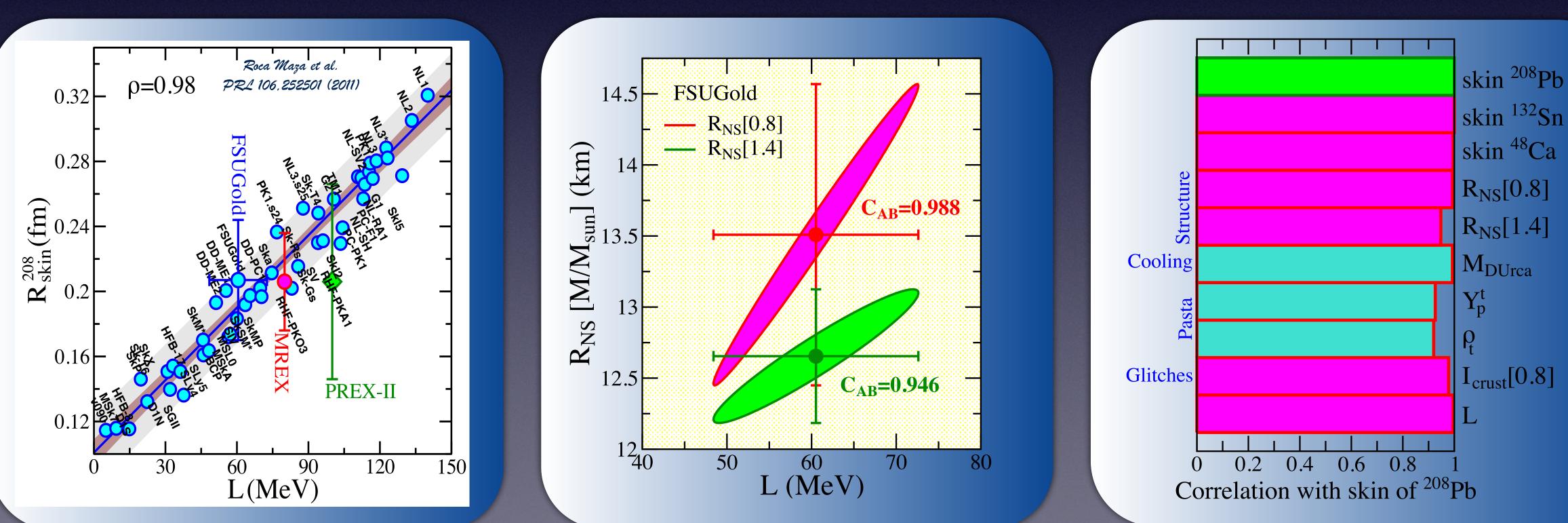




# Heaven and Earth

Strong correlation emerges between the neutron skin thickness of <sup>208</sup>Pb and L
L controls both the neutron skin of <sup>208</sup>Pb and the radius of a neutron star

18 orders of magnitude!!

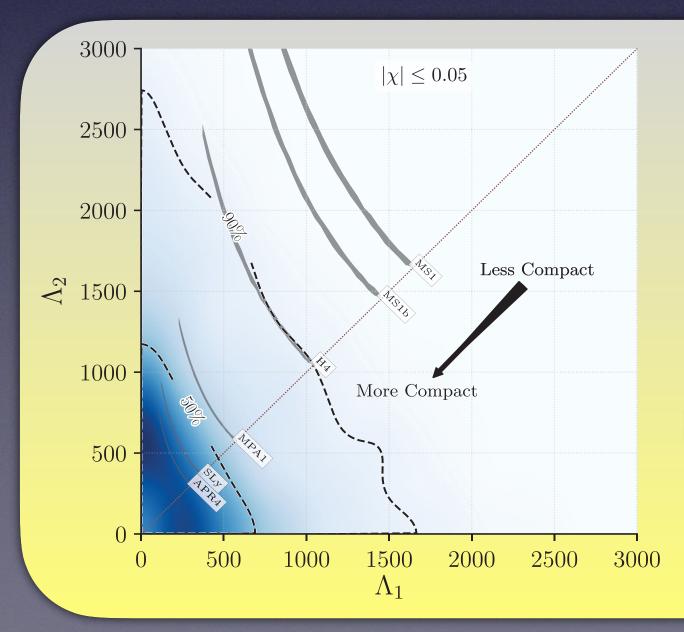


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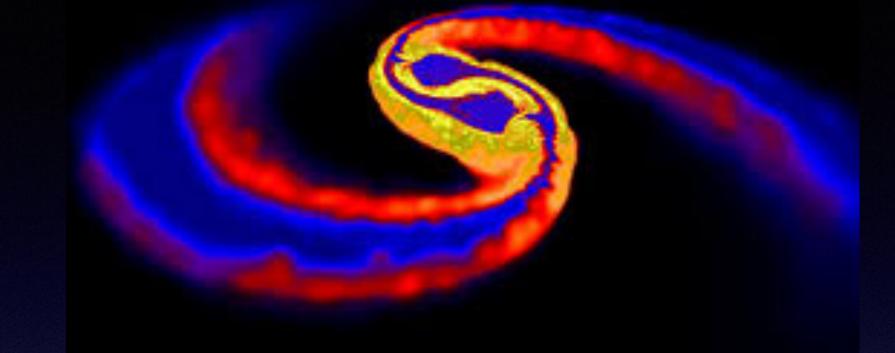
## Tidal Polarizability and Neutron-Star Radii

- Electric Polarizability:
- Electric field induced a polarization of charge
- A time dependent electric dipole emits electromagnetic waves:  $P_i = \chi E_i$
- Tidal Polarizability:
- Tidal field induces a polarization of mass
- A time dependent mass quadrupole emits gravitational waves:  $Q_{ij} = \Lambda \mathcal{E}_{ij}$



GW170817 rules out very large neutron star radíi! Neutron Stars

must be compact

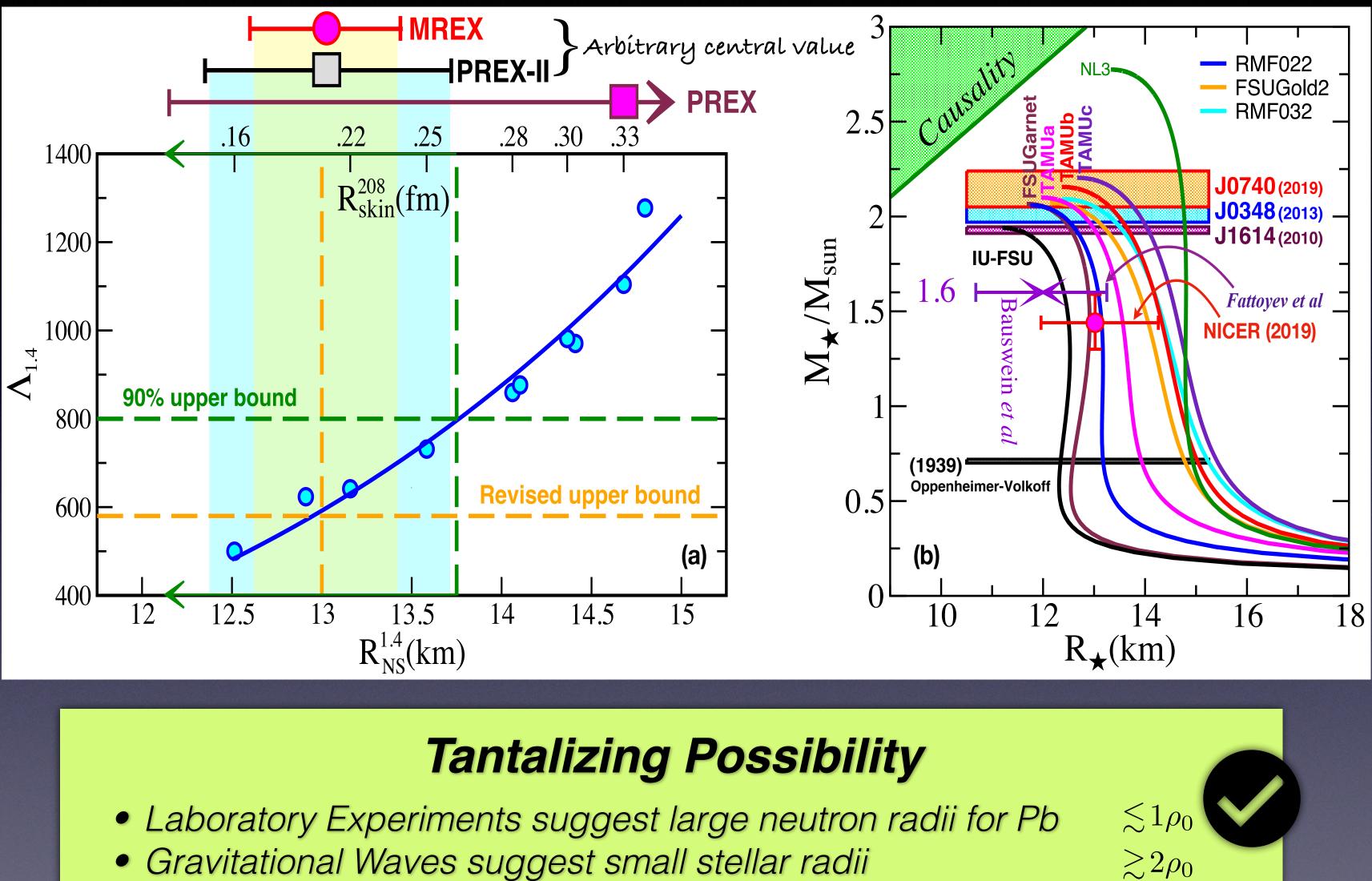


 $\Lambda = k_2 \left(\frac{c^2 R}{2GM}\right)^3 = k_2 \left(\frac{R}{R}\right)^3$ 

The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation



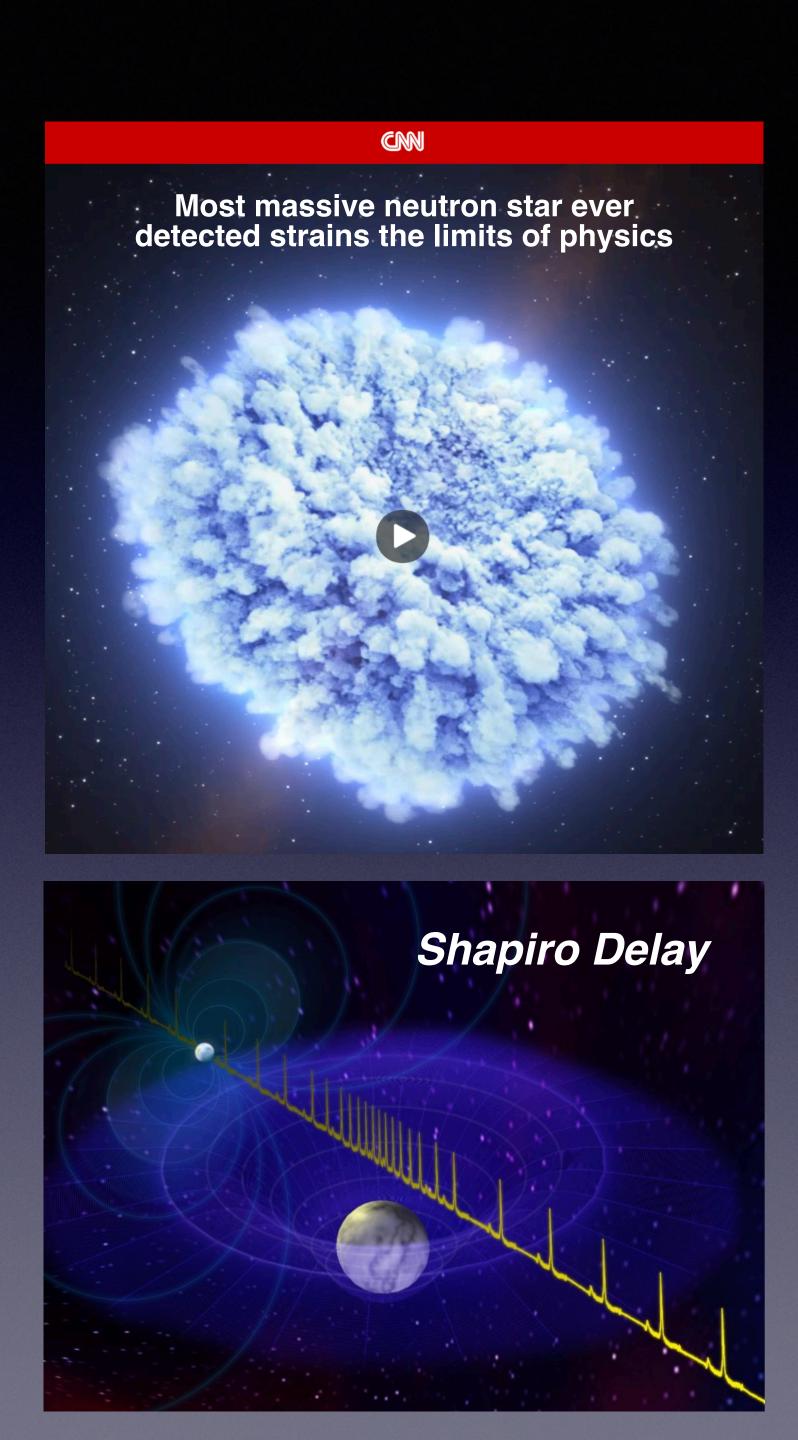
## Progress on the EOS since GW170817



- Gravitational Waves suggest small stellar radii
- Electromagnetic Observations suggest large stellar masses

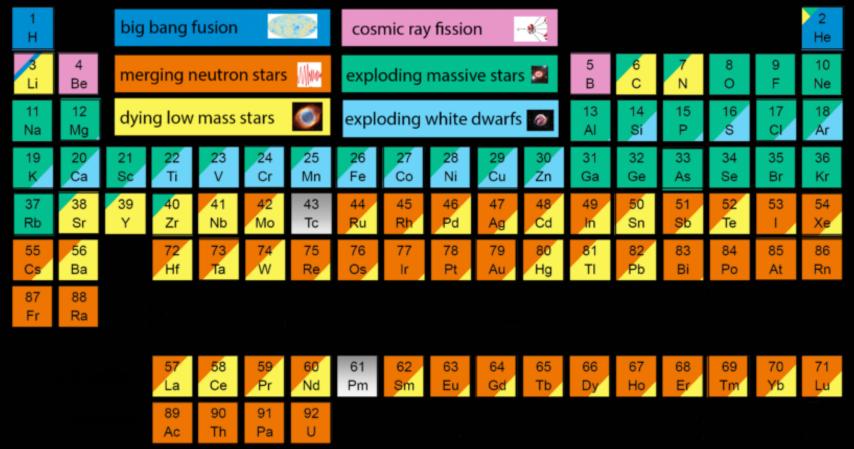
### Exciting possibility: If all are confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?)

 $\gtrsim 4\rho_0$ 



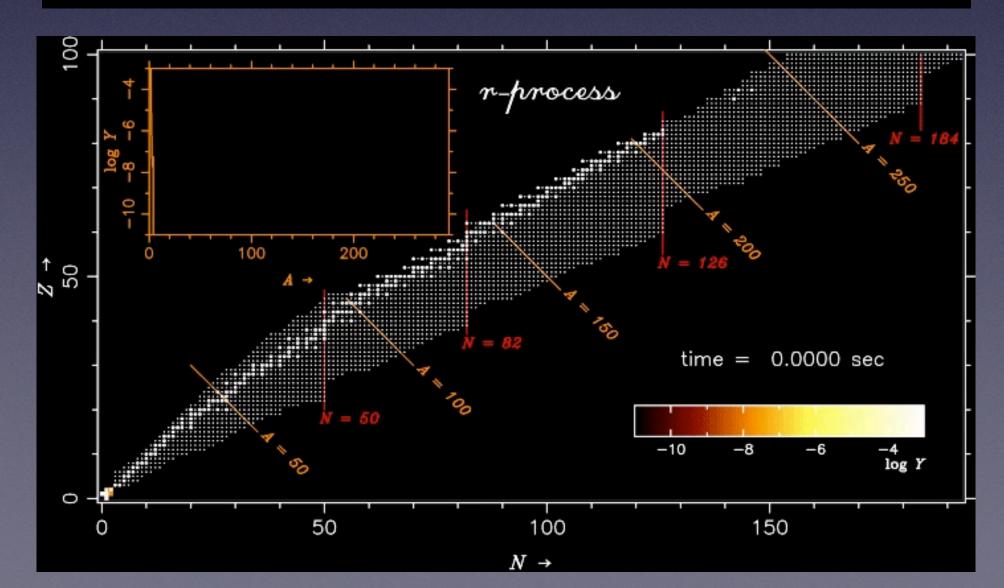
## How were the Elements from Iron to Uranium Made?

### The Origin of the Solar System Elements



### Graphic created by Jennifer Johnson

Astronomical Image Credits: ESA/NASA/AASNova

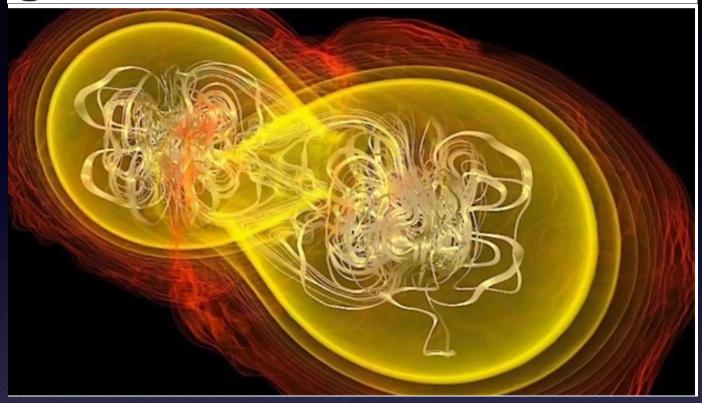


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### The New Periodic Table of the Elements

Colliding neutron stars revealed as source of all the gold in the universe



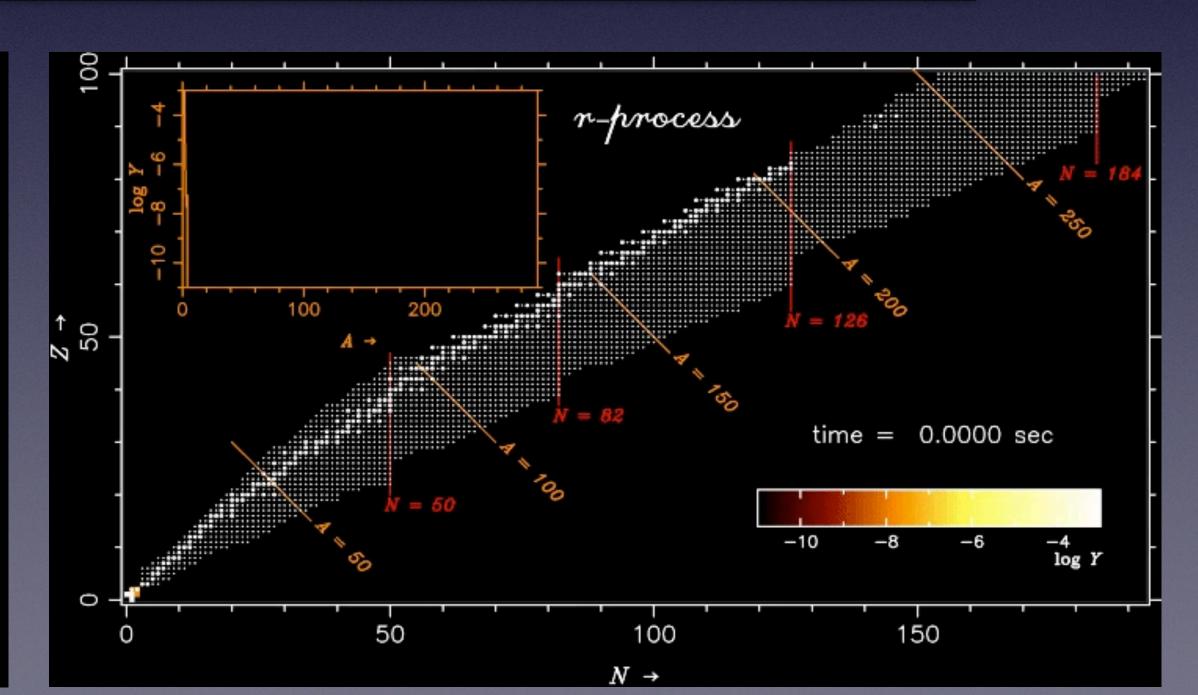
### The Origin of the Solar System Elements

1 H		big	bang	fusion			cosi	mic ray	/ fissio	n -	-						2 He
3 Li	4 Be	mer	merging neutron stars 🏨					exploding massive stars 📓					6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	dying low mass stars				exploding white dwarfs 🧑					13 Al	14 Si	15 P	16 S	17 CI	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 1	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 TI	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
			La 89	Ce 90	Pr 91	Nd 92	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Уб	Lu
	Ac Th Pa U																

Graphic created by Jennifer Johnson

Astronomical Image Credits: ESA/NASA/AASNova

The optical counterpart SSS17a produced at least 5% solar masses (1029 kg!) of heavy elements demonstrating that NS-mergers play a role in the r-process



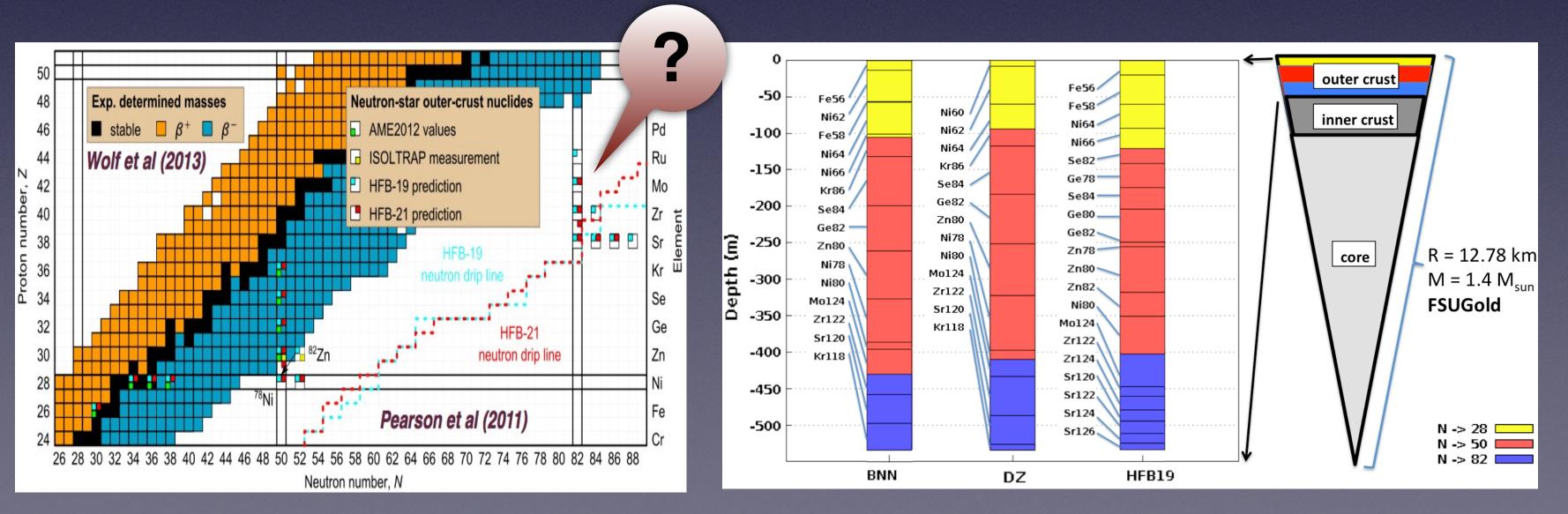


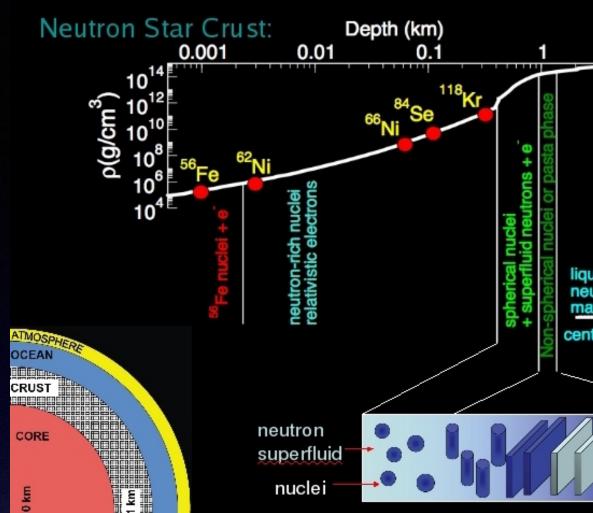
### The Composition of the Outer Crust Enormous sensitivity to nuclear masses

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

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

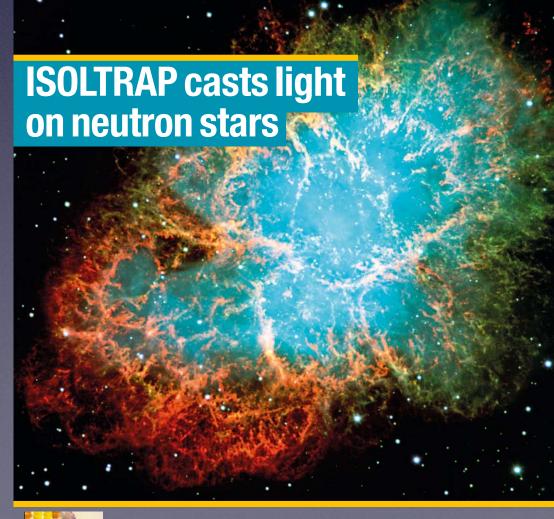
0 Mass measurements of exotic nuclei is essential For neutron-star crusts and r-process nucleosynthesis





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VOLUME 53 NUMBER 3 APRIL 201









# Nuclear Theory meets Machine Learning

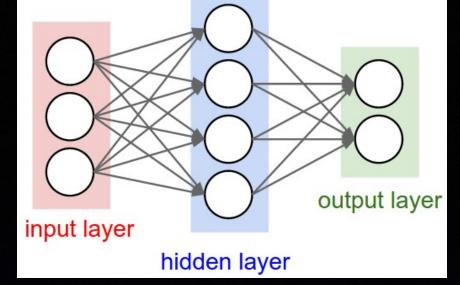
Use DFT to predict nuclear masses The paradigm Train BNN by focusing on residuals.

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

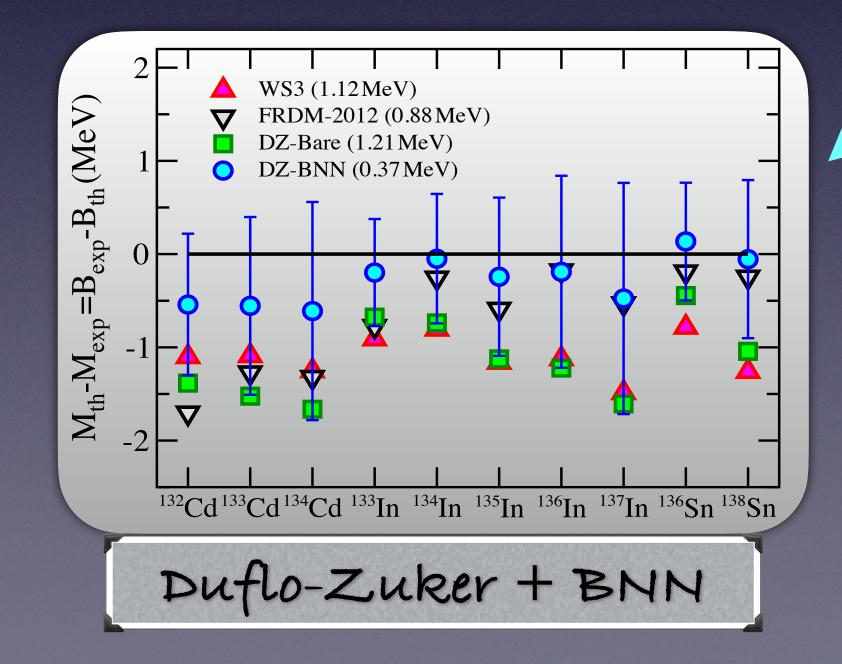
Systematic scattering greatly reduced Predictions supplemented by theoretical errors



Re-generating Richard Feynman



Train with AME2012 then predict AME2016

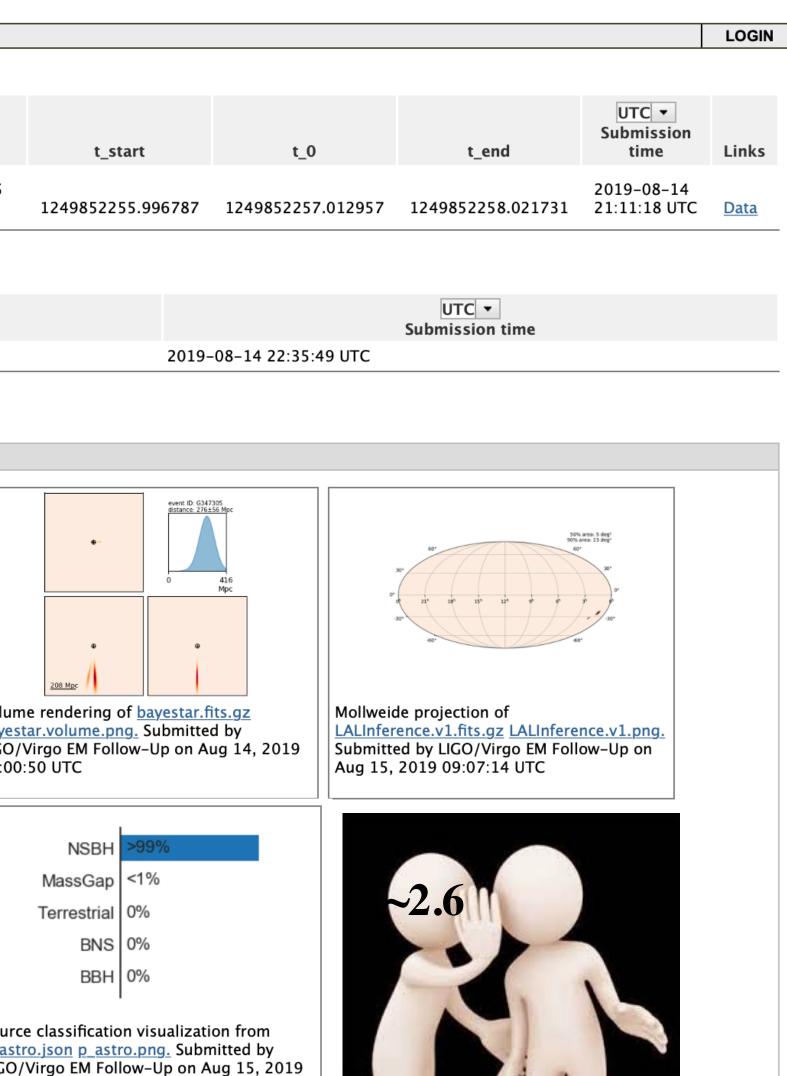




# LIGO-Virgo O3 Run Neutron Star - Black Hole (S190814)

### **GraceDB** — **Gravitational-Wave Candidate Event Database**

HOME	PUBL	IC ALERTS	SEARCH	LATEST	DOC	UMENTATION							
Supere	event I	nfo											
-										54.0			
Superevent ID Category		Category	Labels							FAR (Hz)	FAR (y	r <sup>-1</sup> )	t
PE_READY ADVO S190814bv Production GCN_PRELIM_SEM					EMBRIGHT_RE	ADY PASTI	RO_READY DQ	2.033e- 33	1 per 1.559 years	1 per 1.559e+25 /ears			
Preferi	red Ev	ent Info											
Group			Pipeline	Sear		Instrumen	ite		GPS Time				
		gstlal	ripenne	AllSky	H1,L1,V1	llistrumen	1249852257.0130						
- Supe	ereven	t Log Me	essages										
- Sky Loc	alization												
						event ID: G347292 distance: 236±53 Mpc						]	
	60'		event ID: G347292 50% area: 133 deg* 90% area: 772 deg* 60*		~			E0*		5	rent ID: G347305 50% area: 7 deg* 2% area: 38 deg* 60*		÷-
30° 0° 0° -30° -30° 0° 0° 221° 18° 15° 12° 0° 0° 0° 0° 0° 0° 0° 0° 0° 0° 0° 0° 0°					0 370 Mpc		30*			30*			
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Follow-Up on Aug 14, 2019 21:31:29 UTC				LIGO/Virgo 21:32:00 U	low-Up on Aug 1	4, 2019	Follow-Up on	Aug :	14, 2019 22:	58:20 UTC		Virgo EM F :50 UTC	
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	•	-		Ter	restrial	<1%		Terres					MassGa
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Volume	e renderi	ng of LALInf	erence.v1.fits.gz			on visualization f	-	Source classif				Sourc	e classifica
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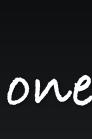




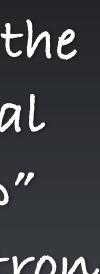
MassGap Compact binary systems with at least one compact object whose mass is in the hypothetical "mass gap" between neutron stars and black holes, defined here as 3-5 solar masses.







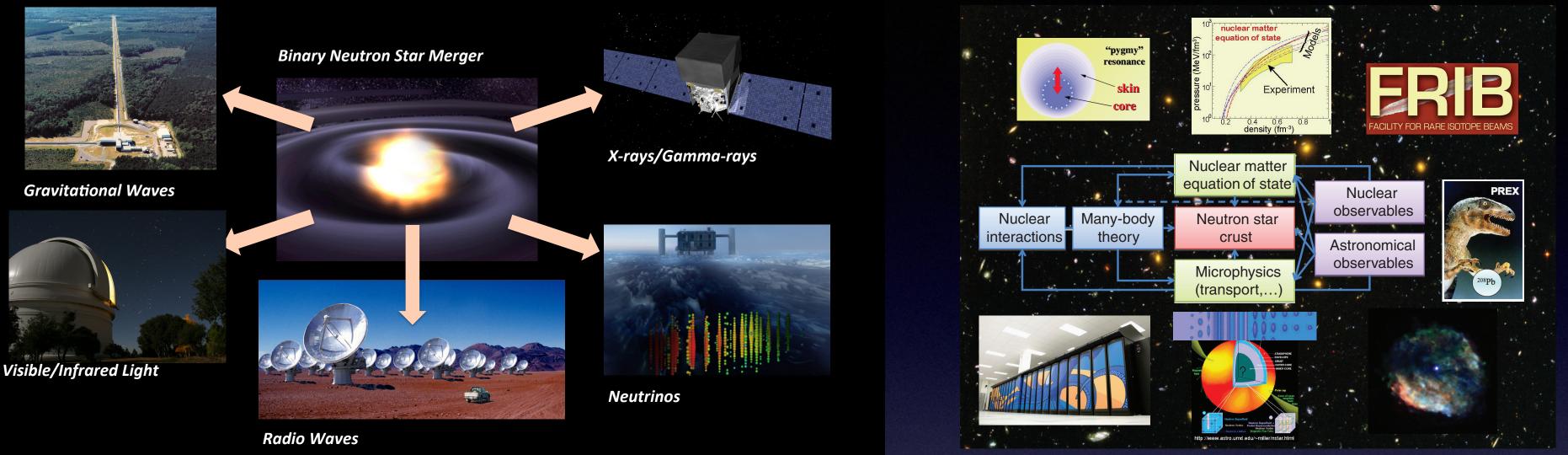








# It is all Connected!



### **My FSU Collaborators**

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



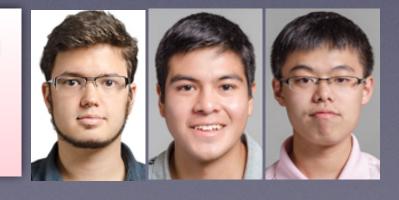
### **The New Generation**

- Pablo Giuliani
- Daniel Silva
- Junjie Yang

### **My Outside Collaborators**

- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (MSU)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)





Gravitational-wave astronomy has opened a new window into the cosmos. New capabilities in heaven and earth will unravel nature's deepest secrets

