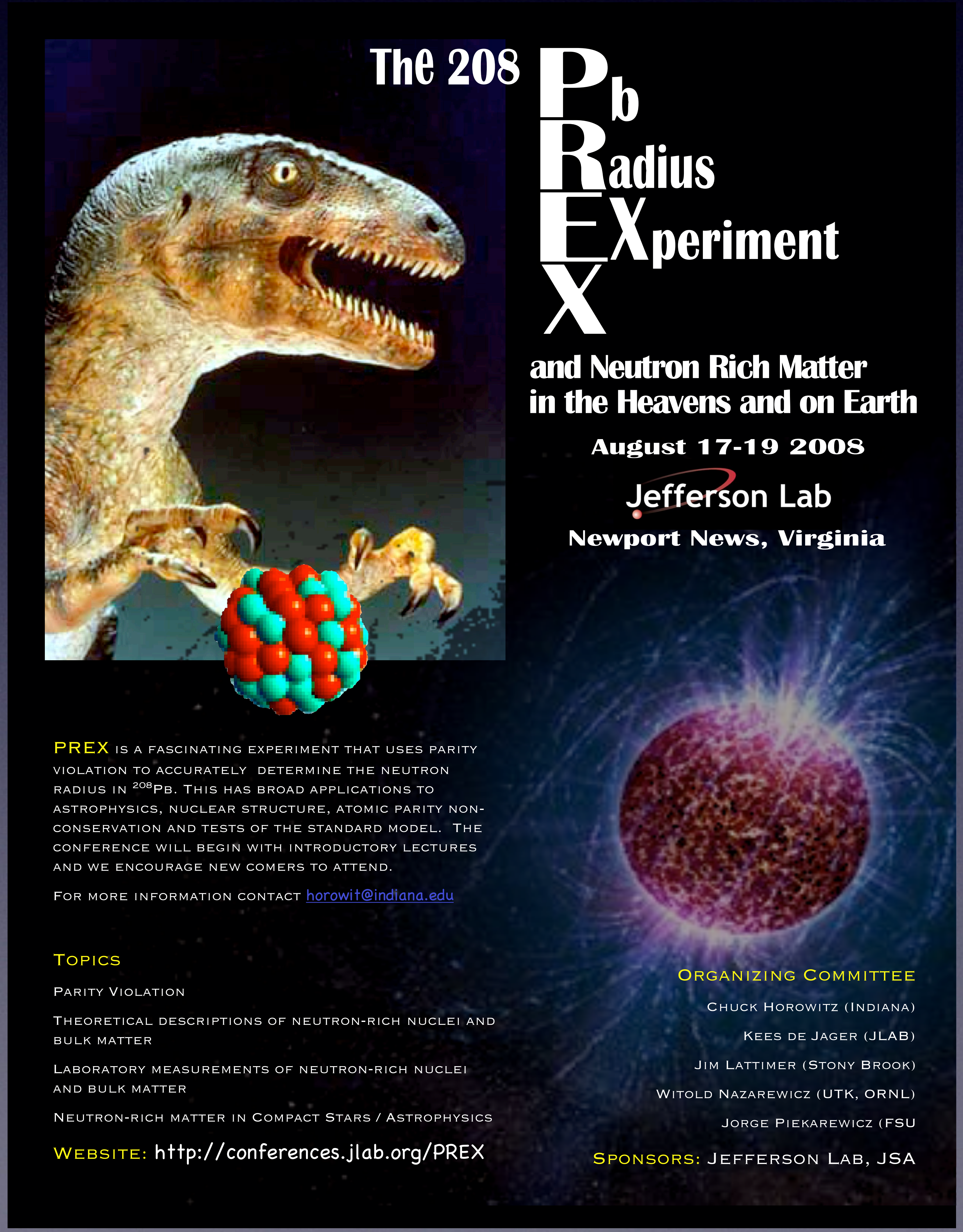
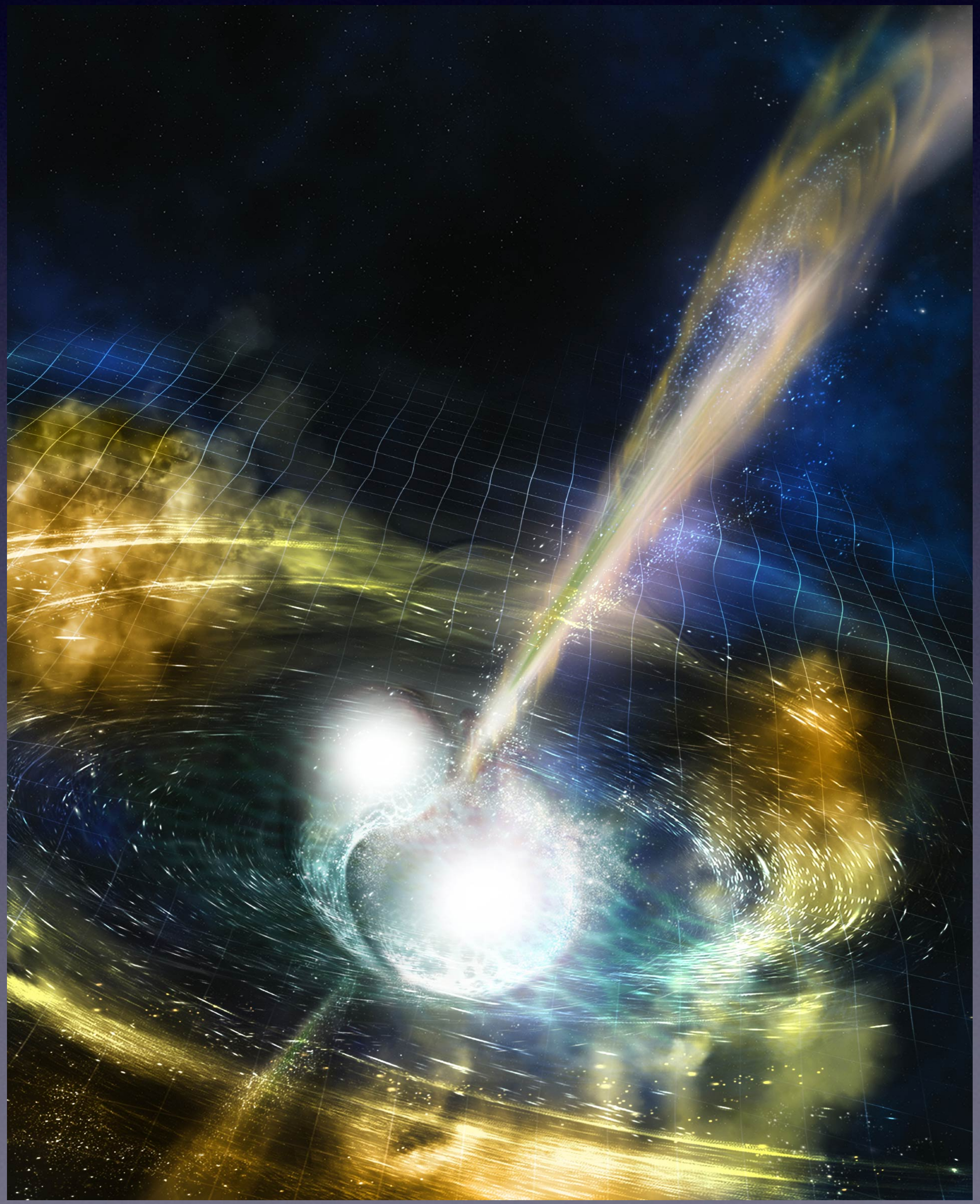
Neutron-rich matter in Heaven and Earth

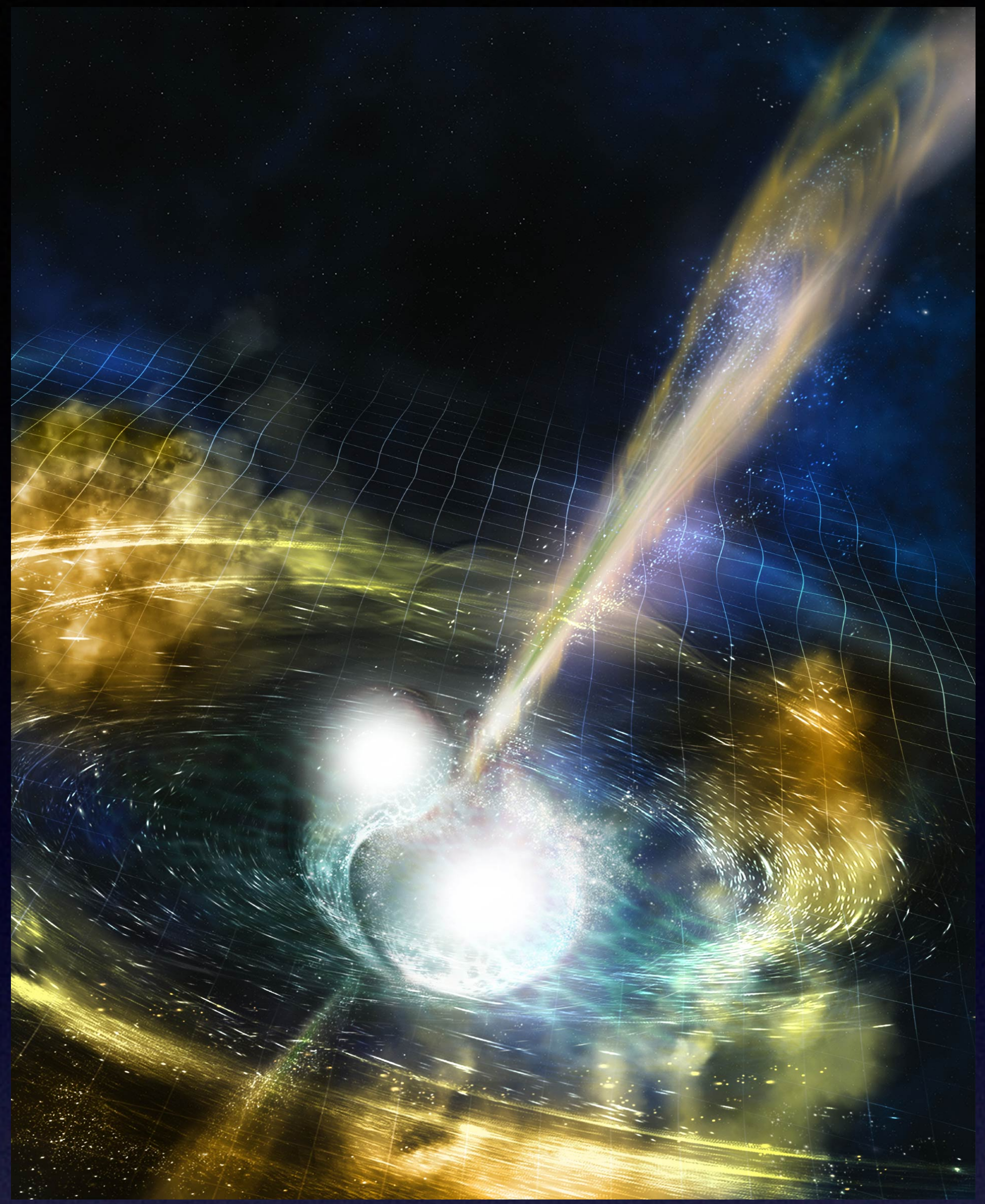
X^th^ Tastes of Nuclear Physics

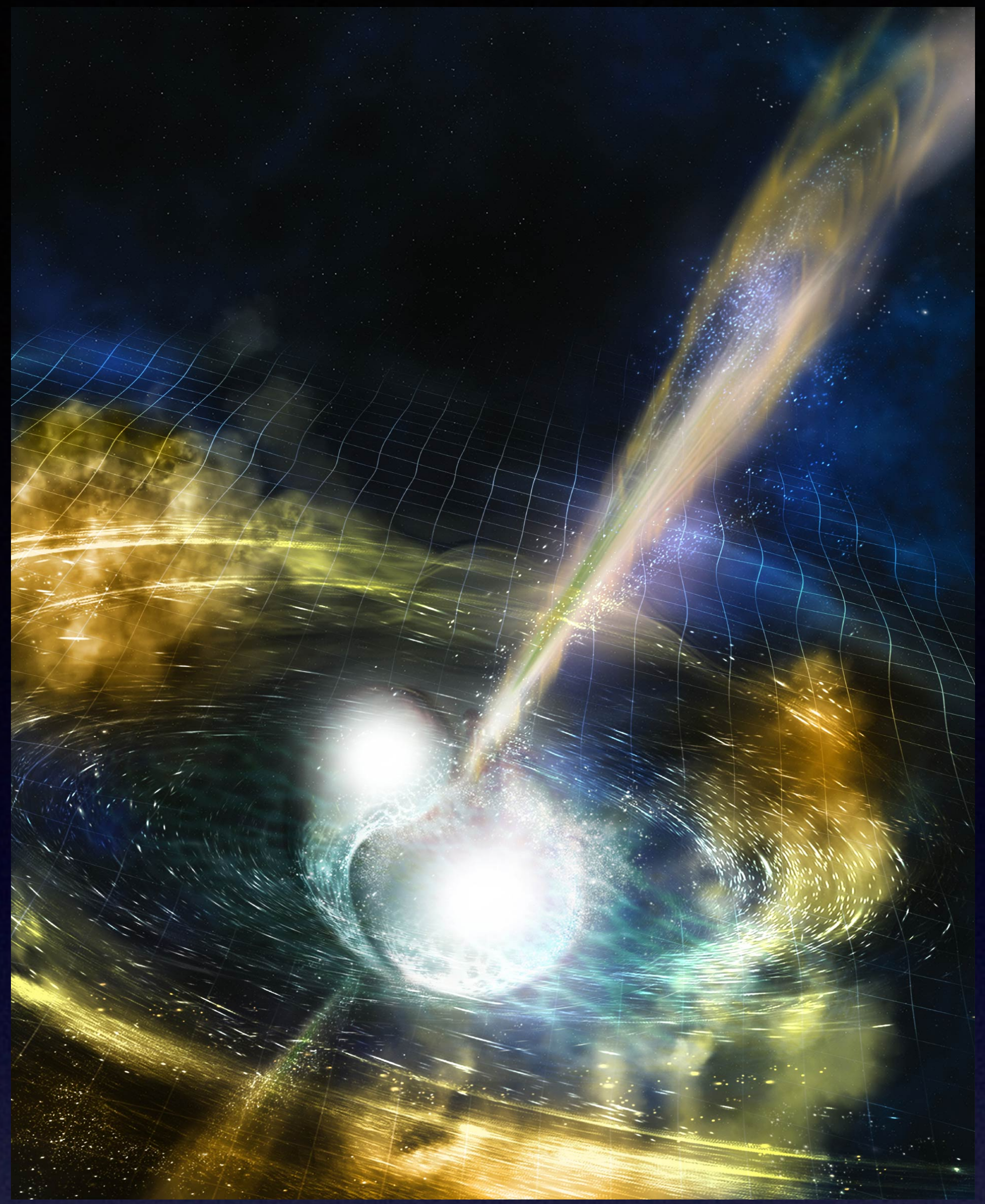
J. Piekarewicz
Florida State University





Heaven on Earth
The Beautiful Game

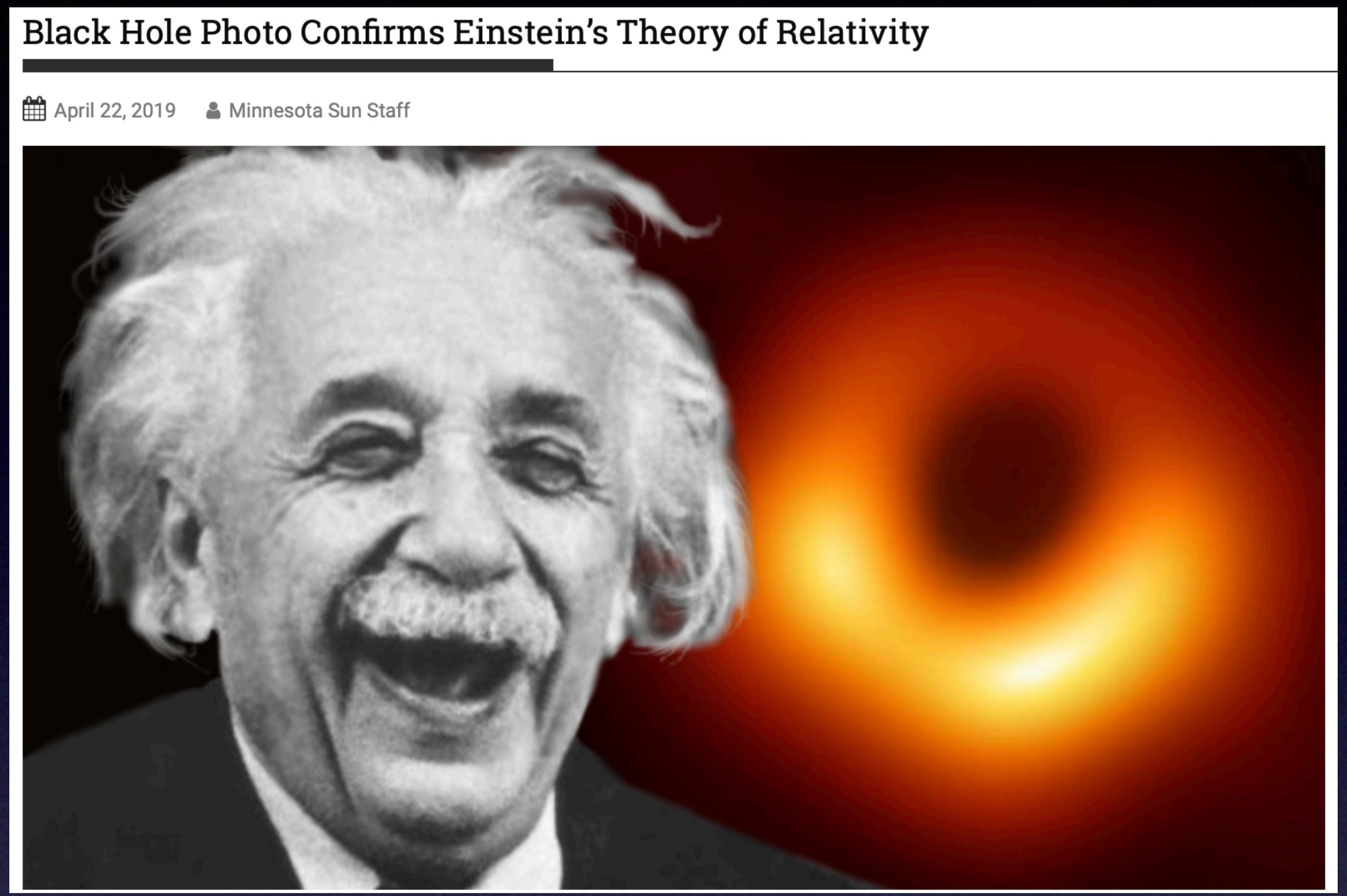




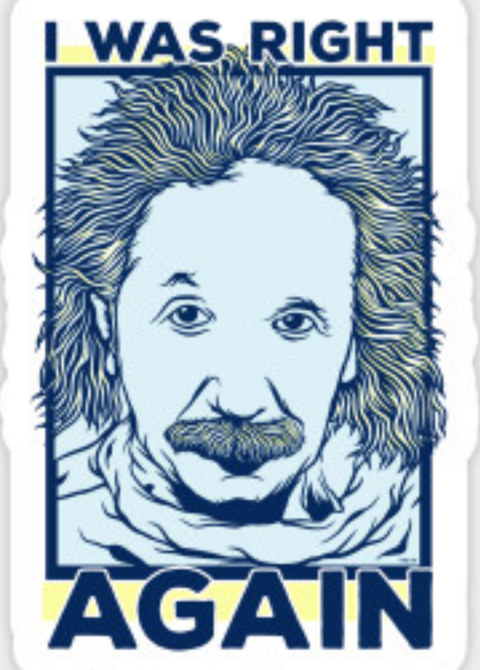
World Cup · Group A · Matchday 1 of 3

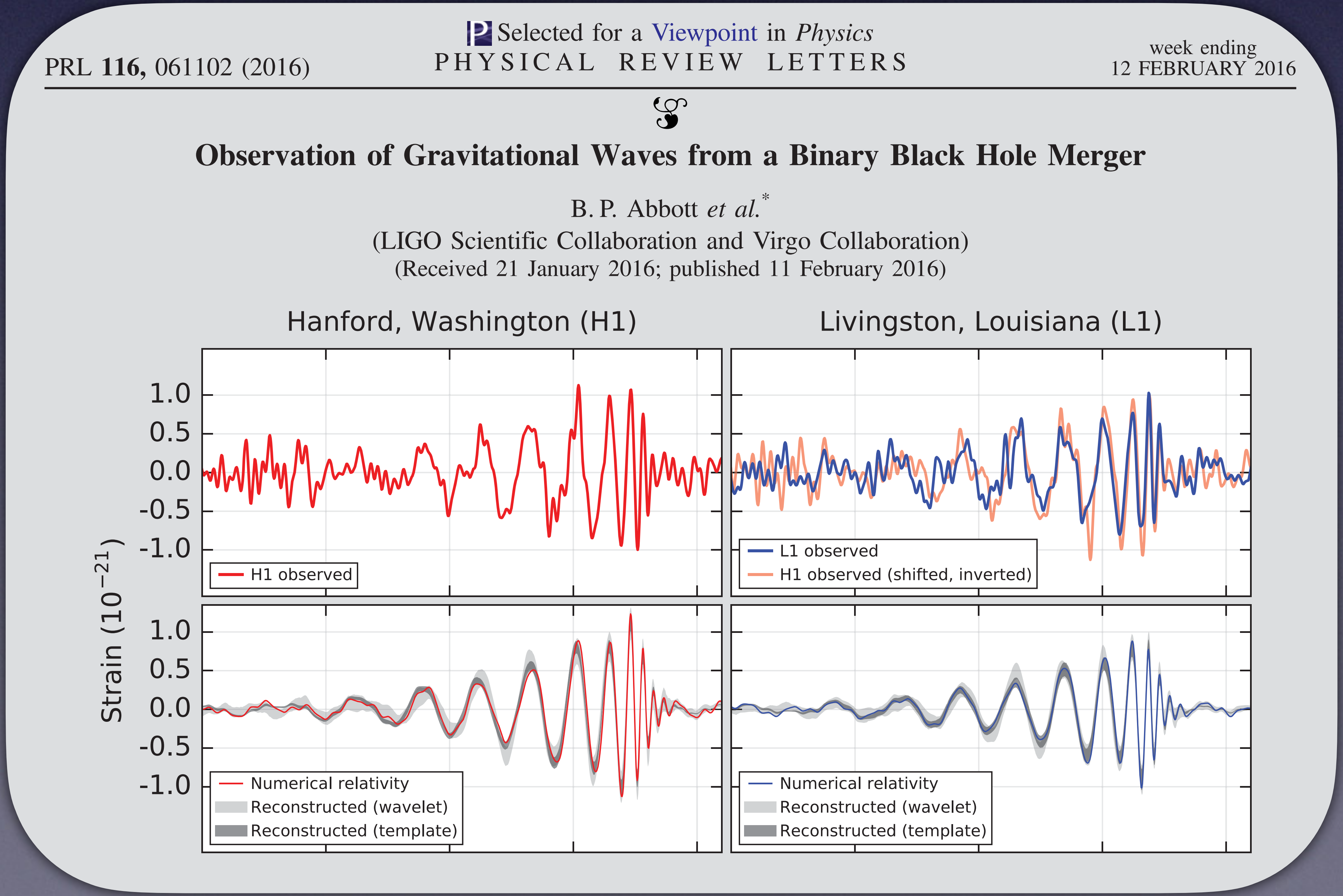
South Africa	1	FT
Mexico	1	6/11/10

Testing General Relativity in the Strong Coupling Limit


Black Hole Photo Confirms Einstein's Theory of Relativity

April 22, 2019 Minnesota Sun Staff




Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

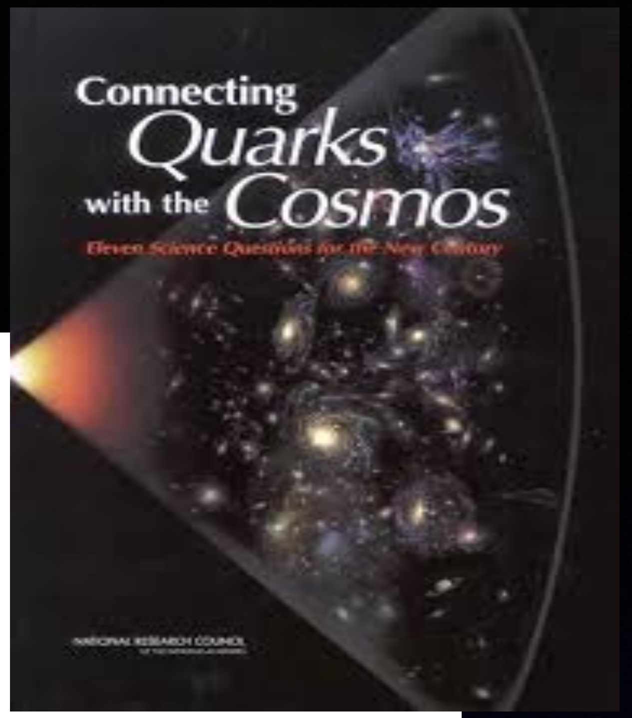
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

ElevenScience Questions for the Next Century



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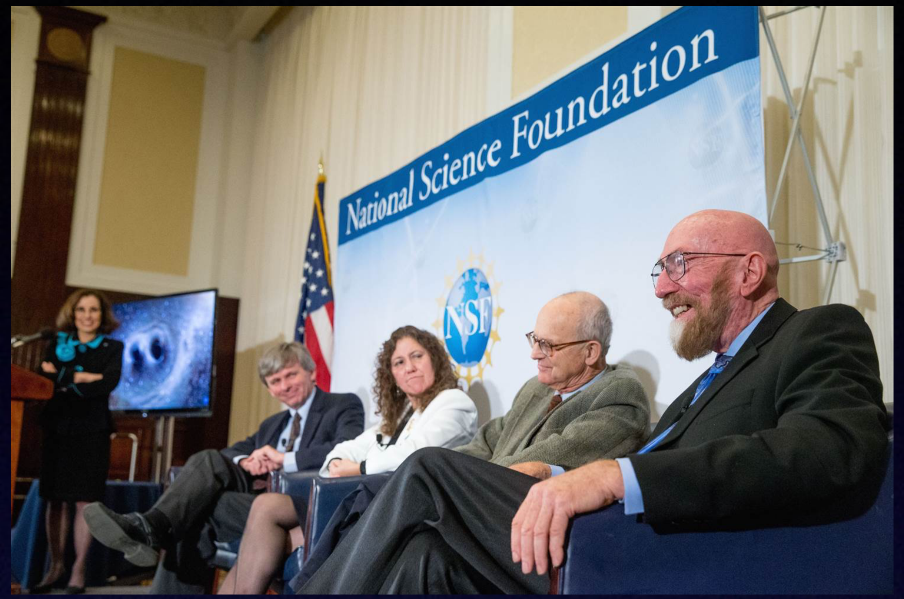
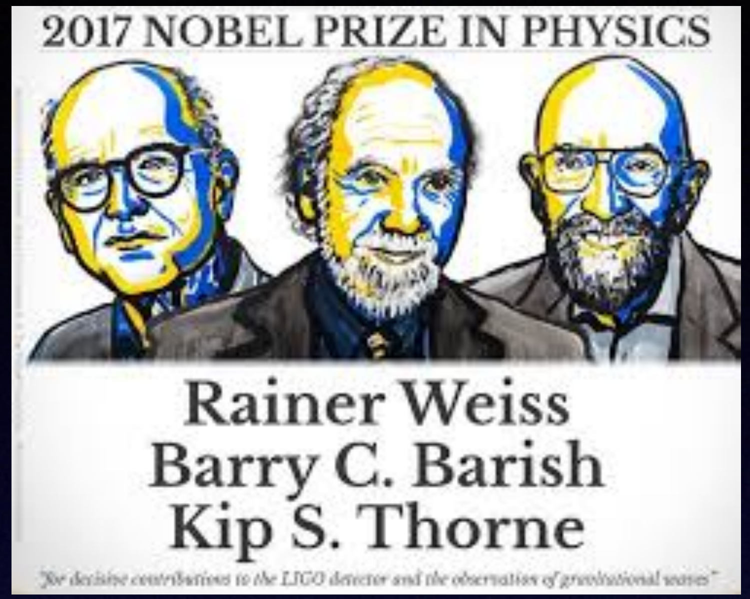
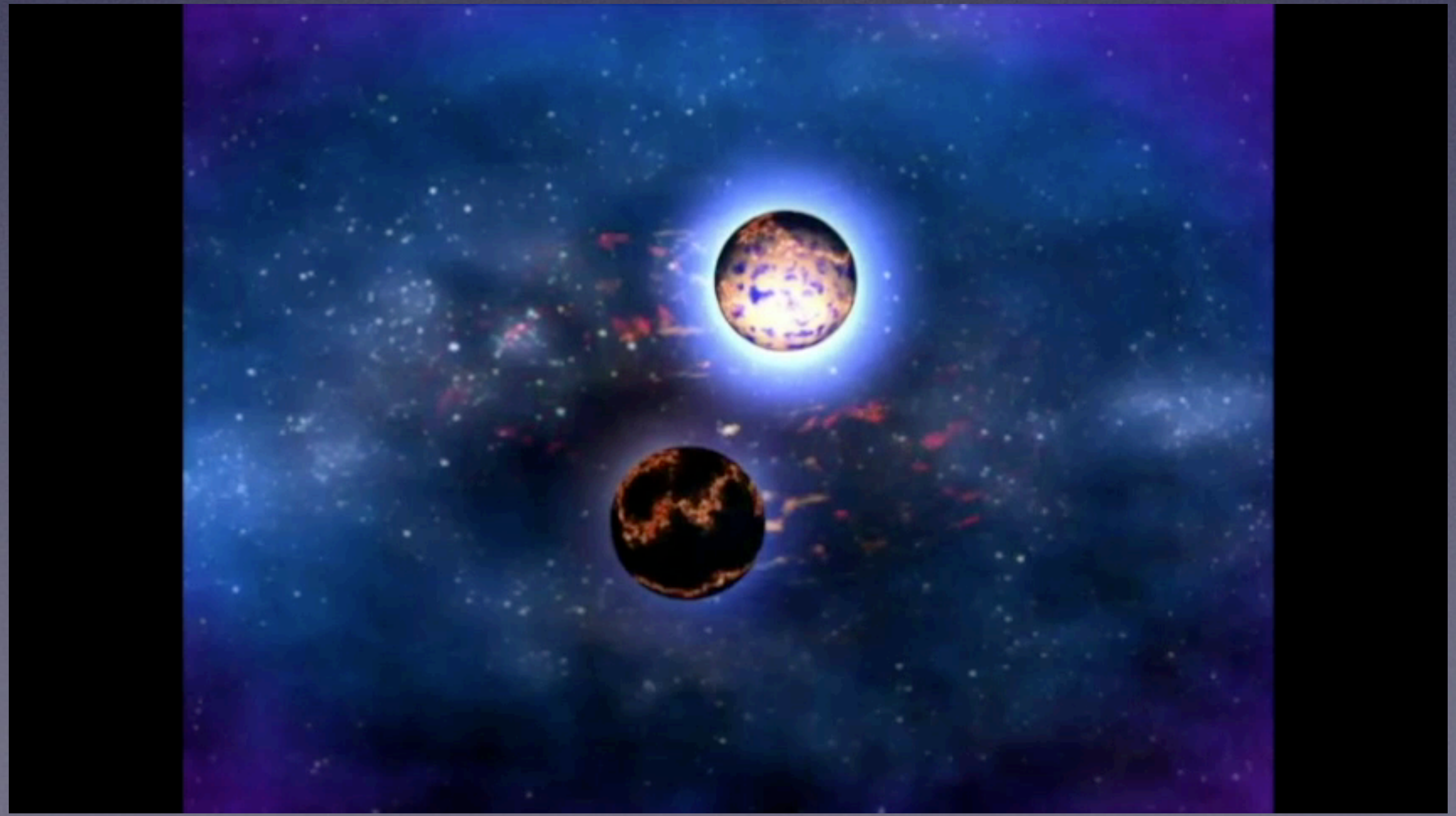
"We have detected gravitational waves; we did it"
David Reitze, February 11, 2016

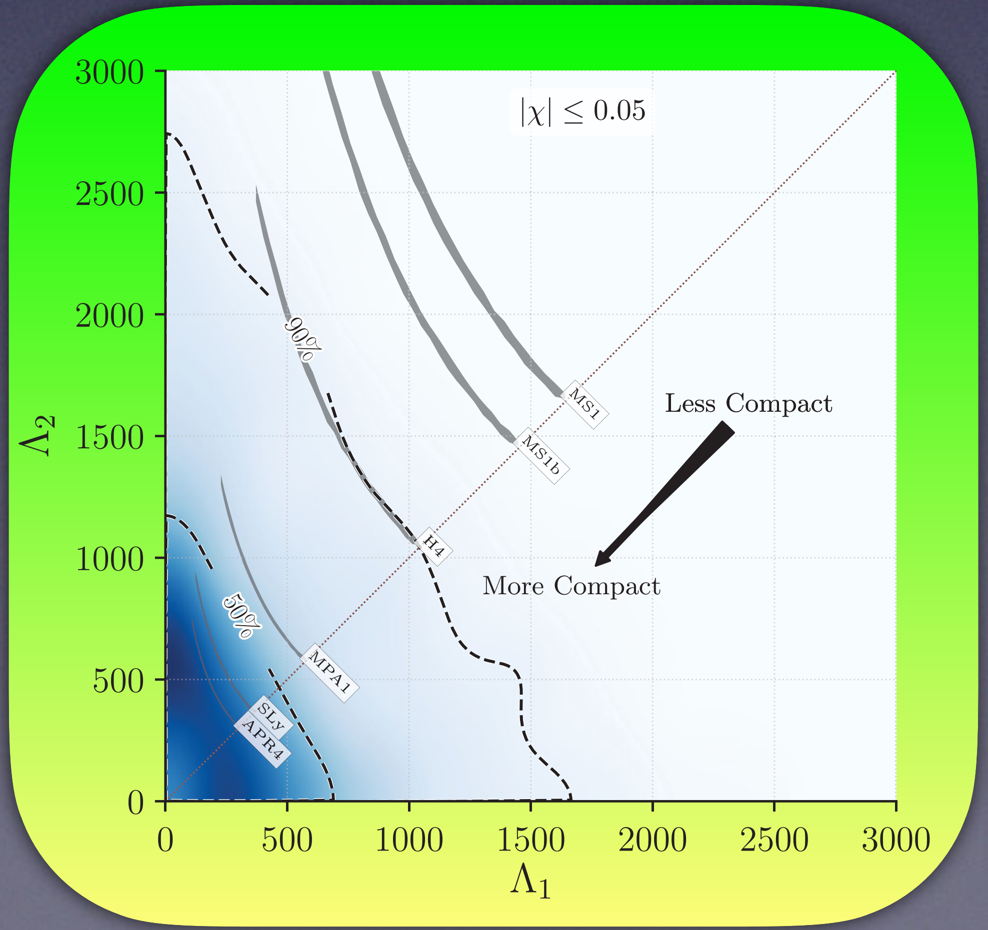
GW170817





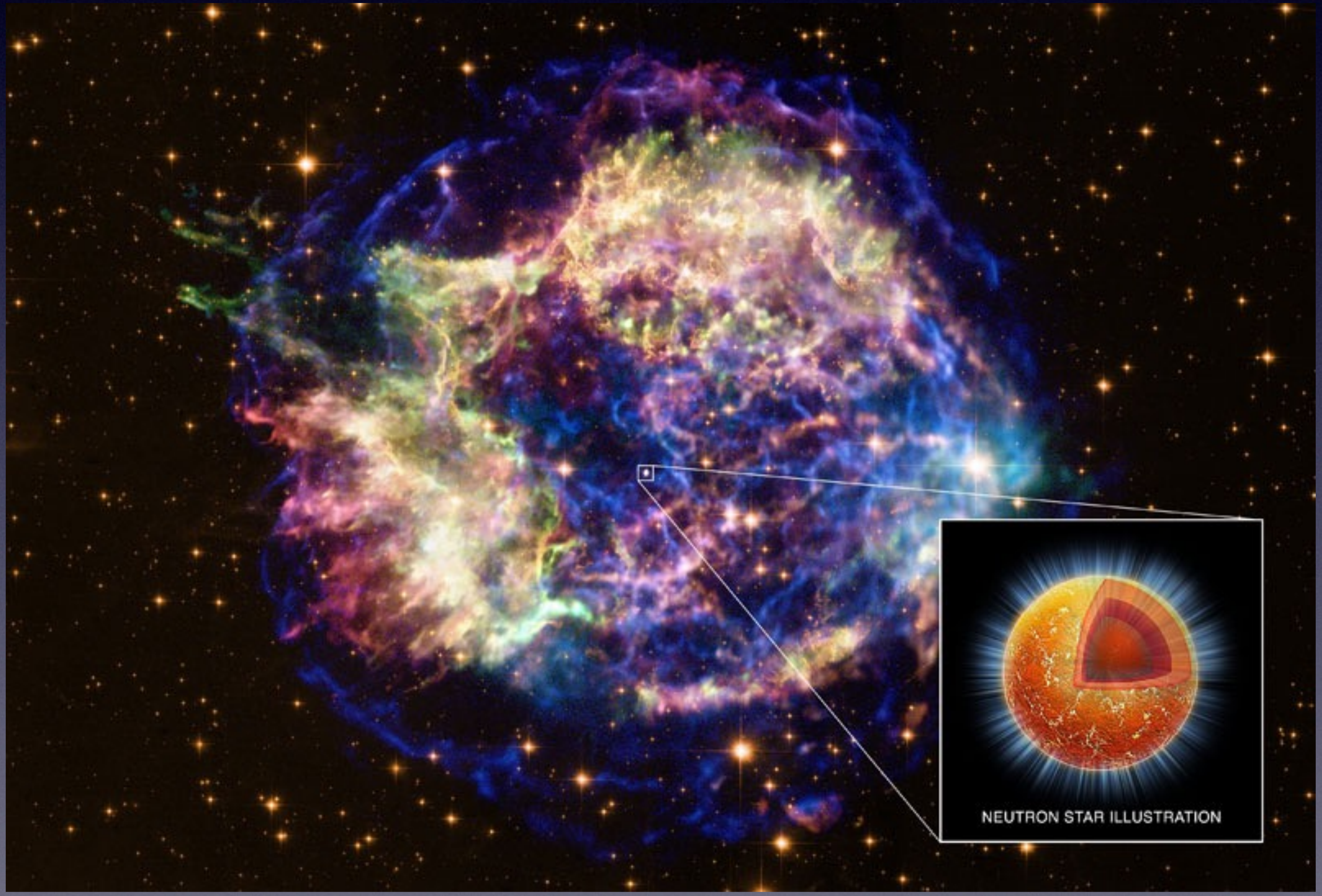
- The dawn of a new era: GW Astronomy
  - Initial black hole masses are 36 and 29 solar masses
  - Final black hole mass is 62 solar masses;
    3 solar masses radiated in Gravitational Waves!





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

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



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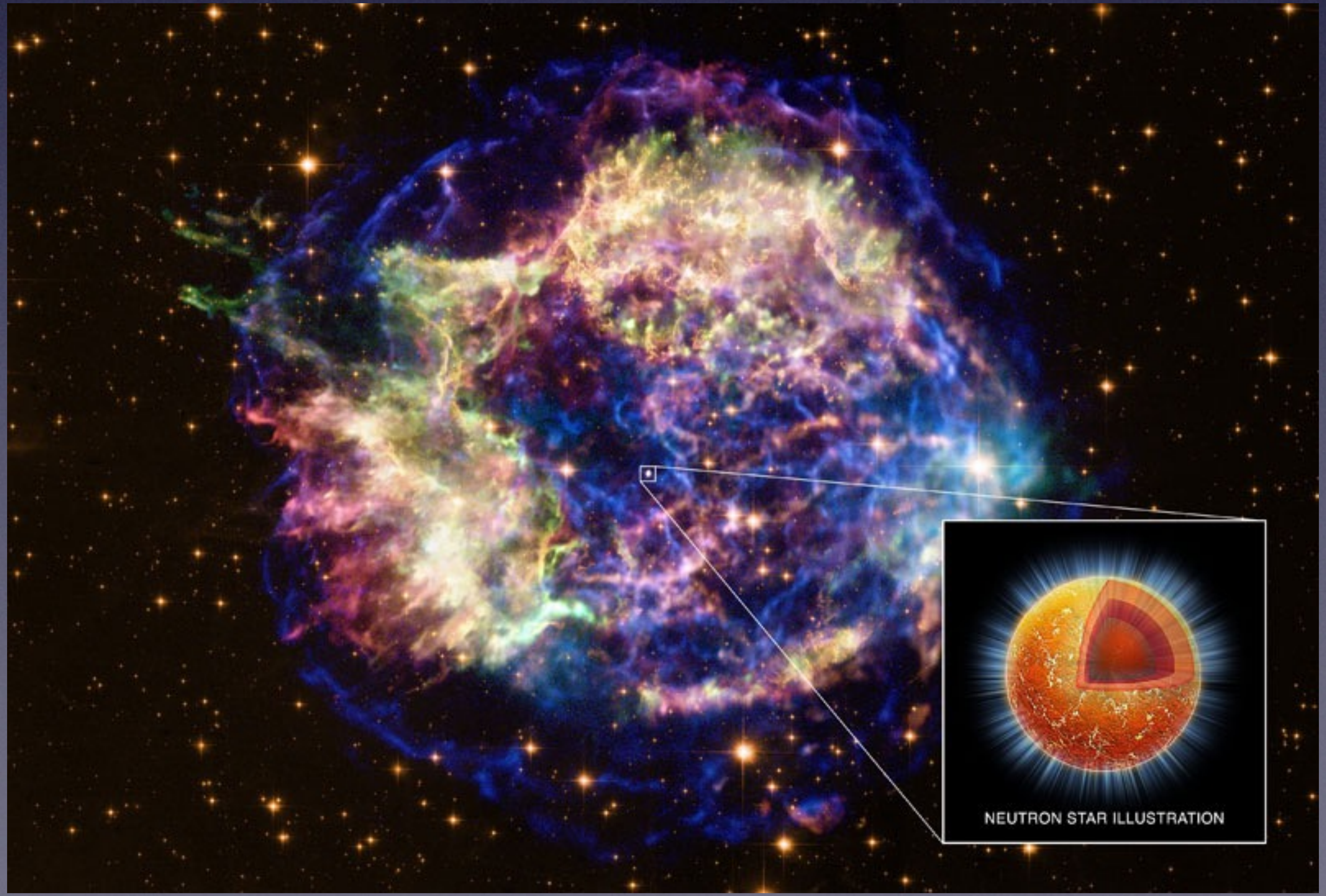
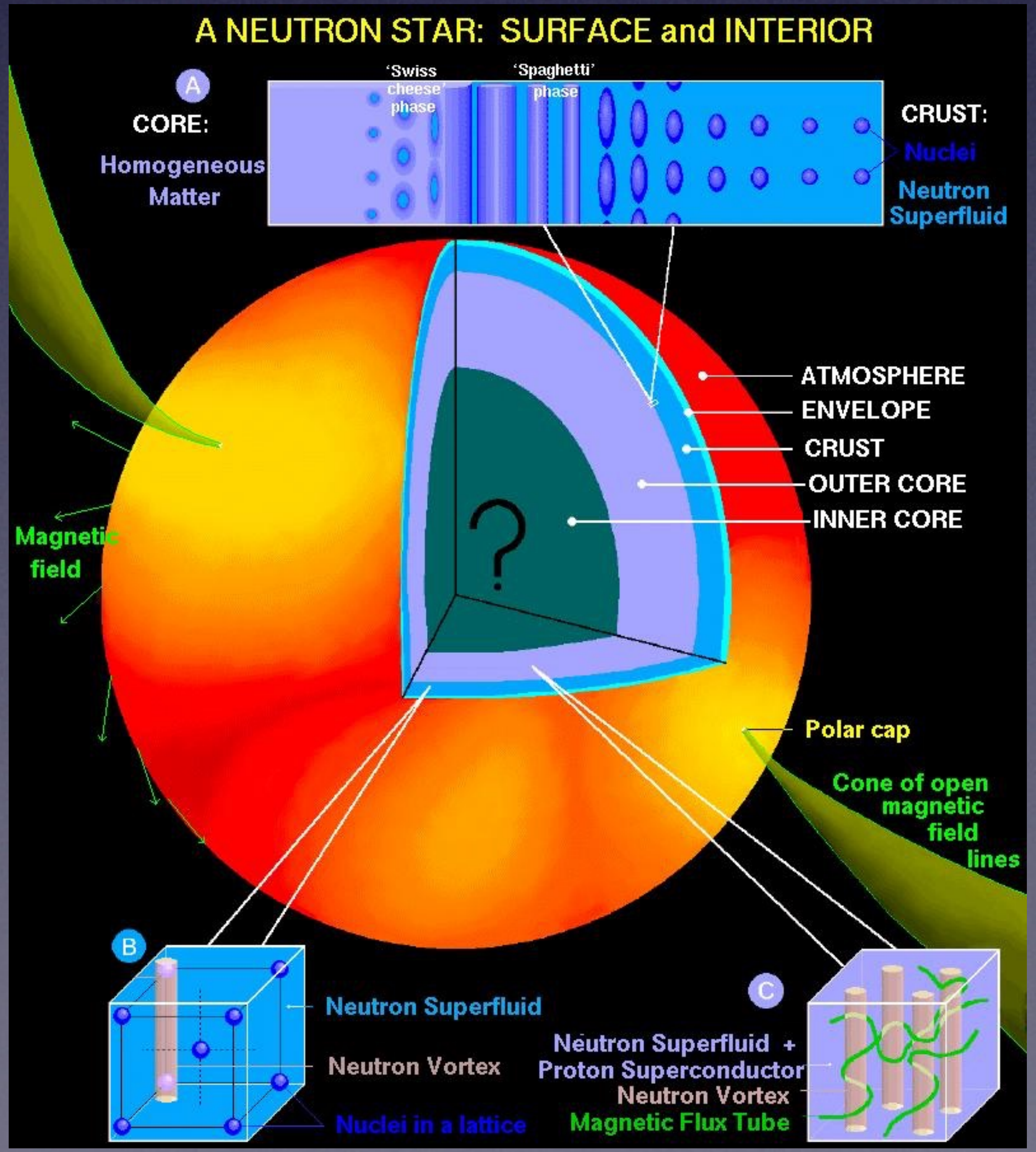
The Anatomy of a Neutron Star

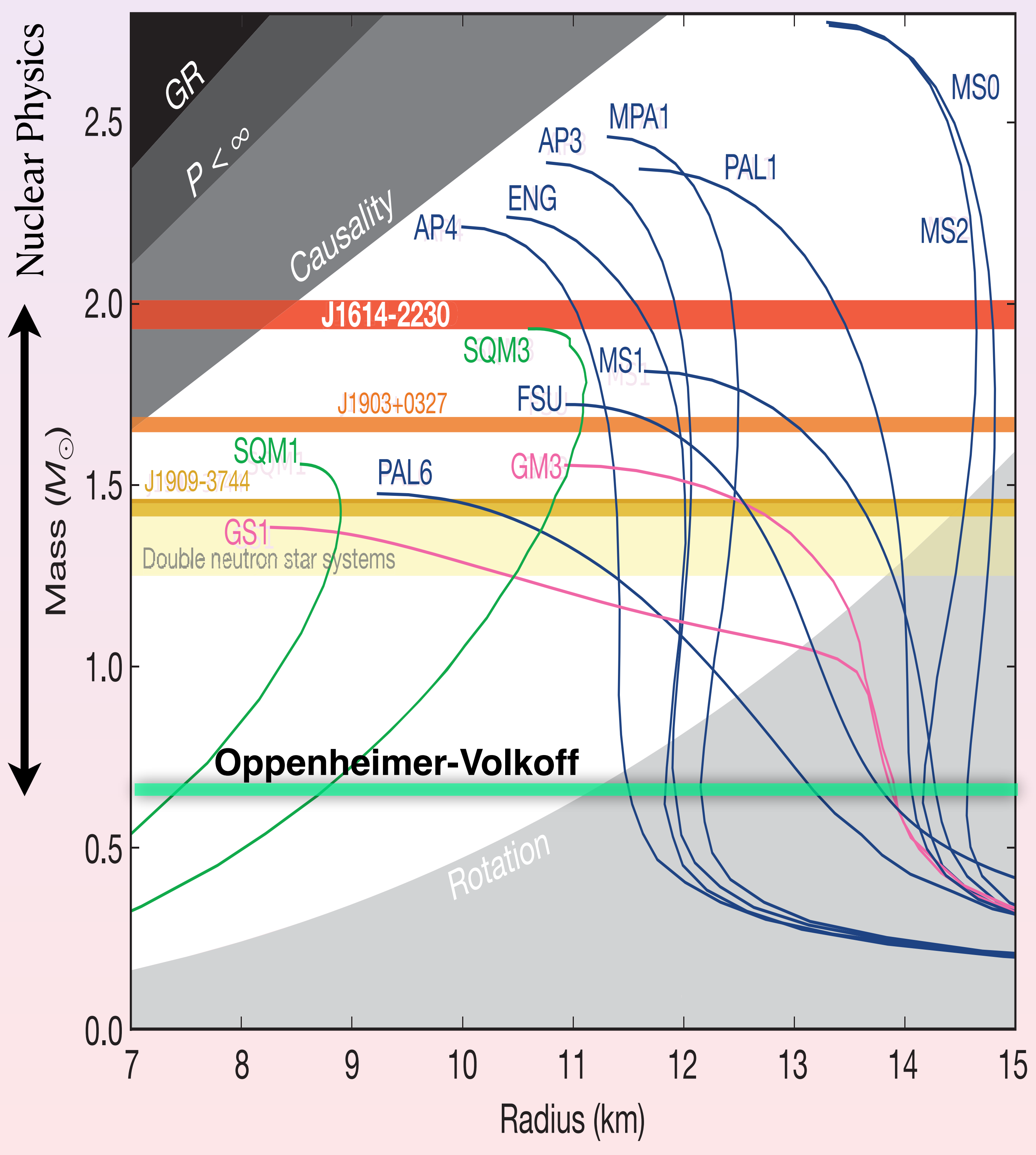
- Atmosphere (10 cm): Shapes Thermal Radiation ($L=4\pi\sigma R^2T^4$)
- Envelope (100 m): Huge Temperature Gradient (10^8K $\leftrightarrow$ 10^6K)
- Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)
- Inner Crust (1 km): Coulomb Frustration ("Nuclear Pasta")
- Outer Core (10 km): Uniform 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
  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 → 2 Msun transfers ownership to Nuclear Physics!



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

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

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

Nuclear Physics Critical

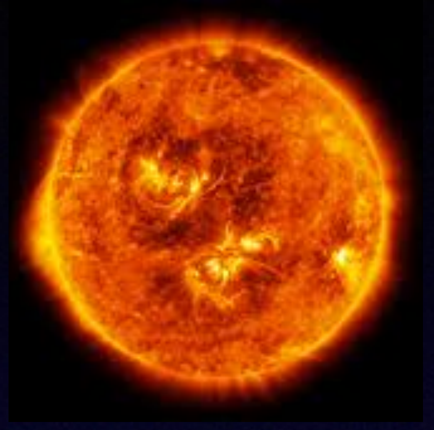
Status before GW170817

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 $2M_{sun}$

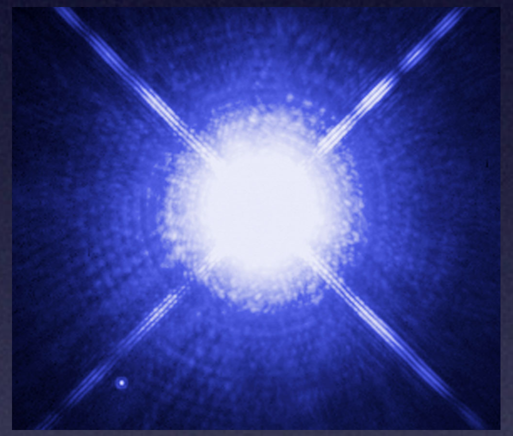
The Equation of State of Neutron-Rich Matter

Equation of state: textbook examples



- Non-interacting classical gas
  high temperature, low density limit

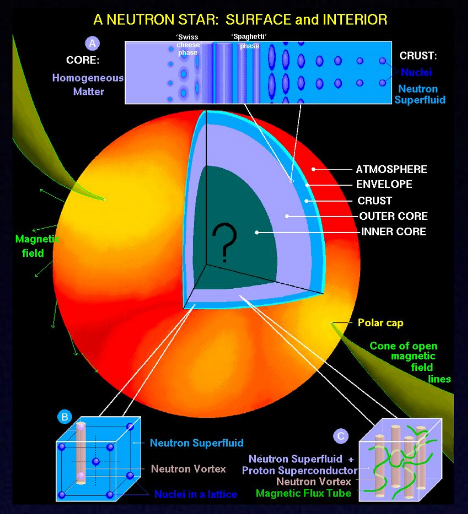
$$P(n,T) = nk_{\rm B}T \leftrightarrow P(\mathcal{E}) = \frac{2}{3}\mathcal{E}$$



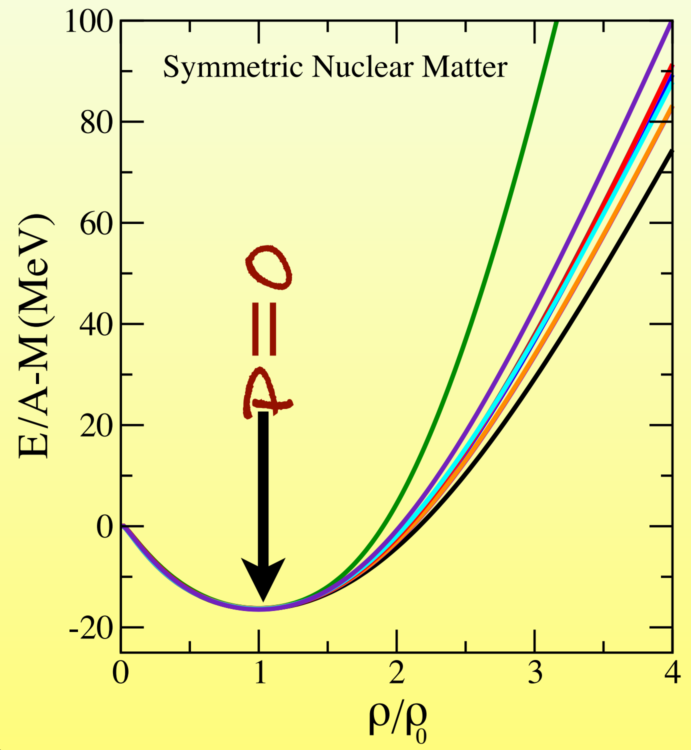
- Non-interacting (UR) quantum gas
  high density, low temperature limit

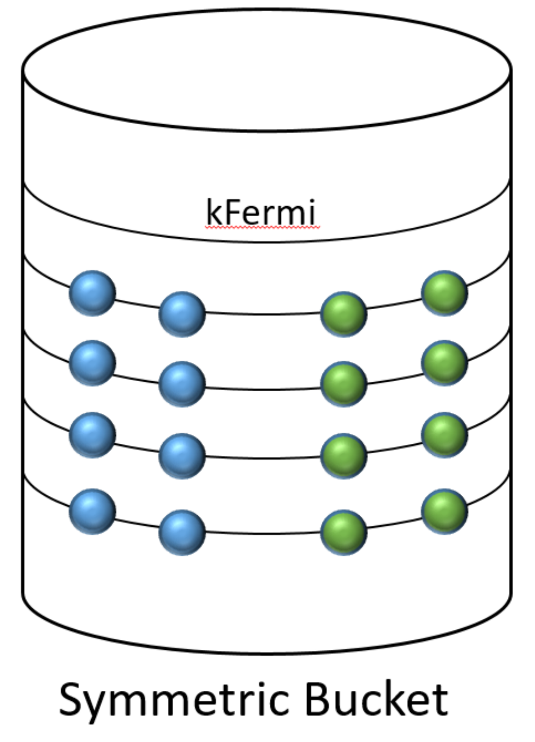
$$P(n,T\!=\!0) \approx n^{4/3} \leftrightarrow P(\mathcal{E}) = \frac{1}{3}\mathcal{E}$$

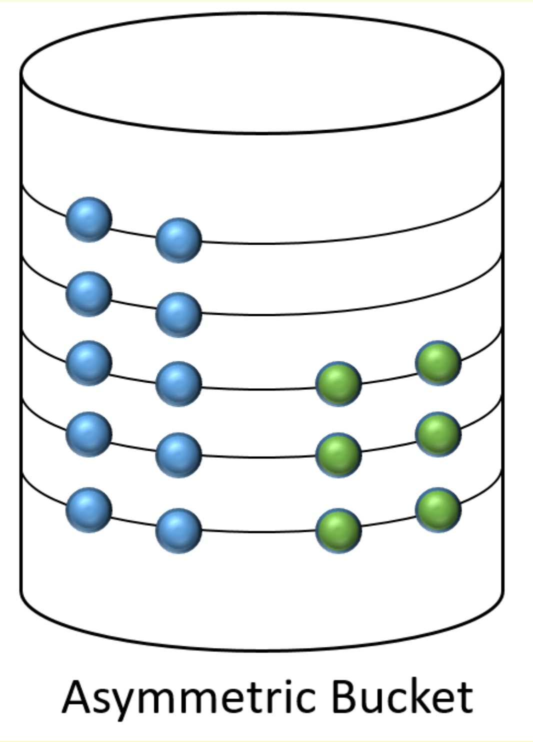
Equation of state of neutron-rich matter: NON-textbook example

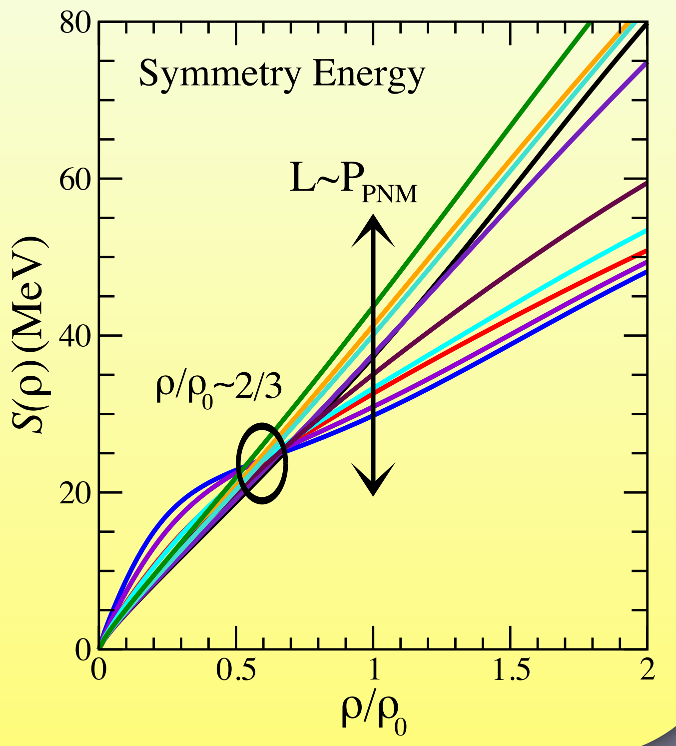


- Strongly-interacting quantum fluid
  high density, low temperature limit
- Two "quantum liquids" in μ-equilibrium
- Charge-neutral system (neutralizing leptons)
- Density dependence and isospin asymmetry of the EOS poorly constrained









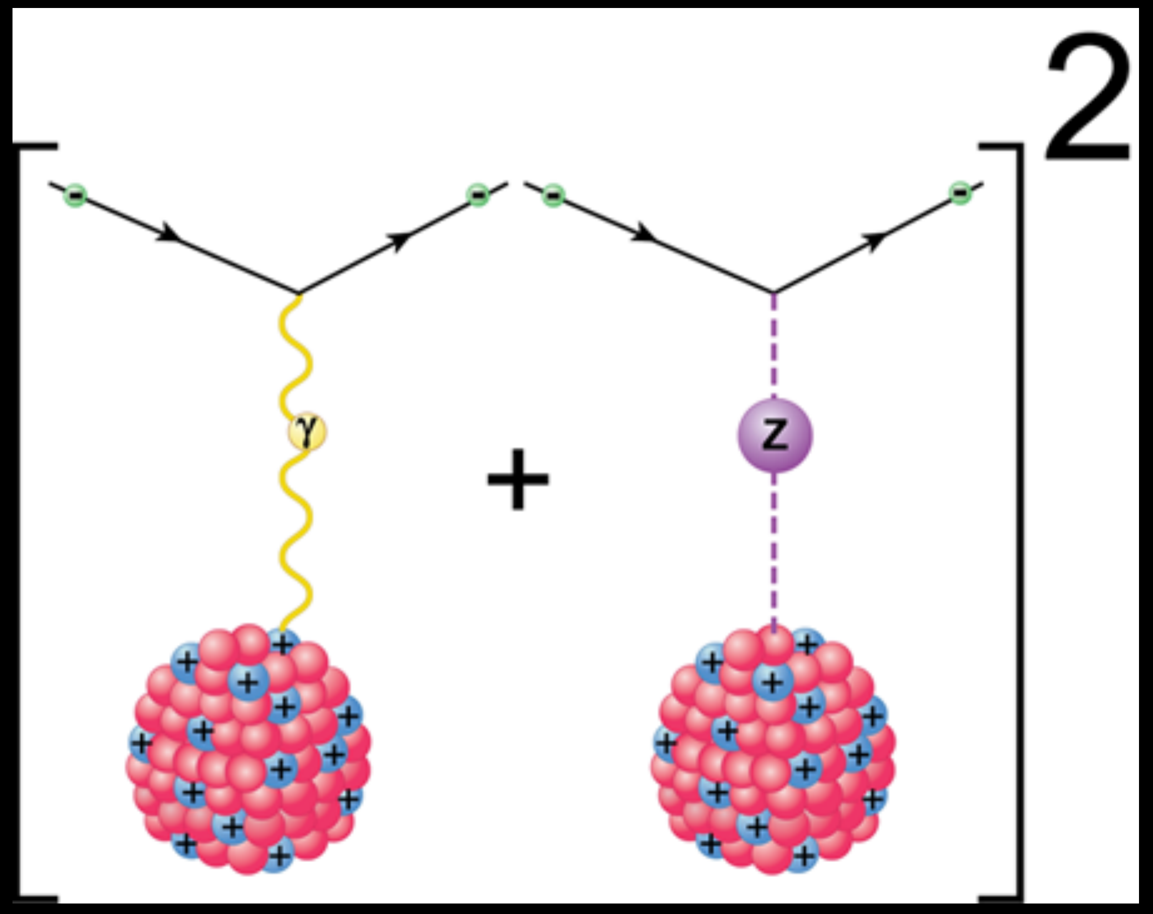
$$S(\rho_0) \approx \Big(E_{\rm PNM} - E_{\rm SNM}\Big)(\rho_0) = J$$

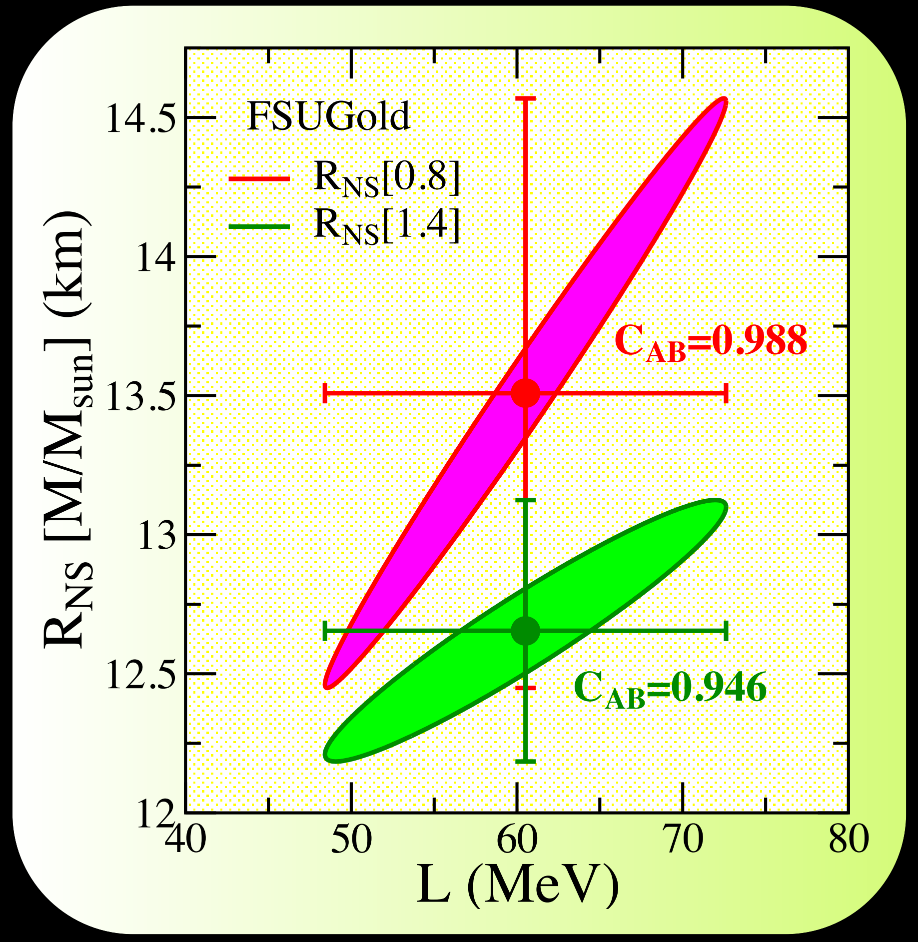
$$P_{\rm PNM} \approx \frac{1}{3}L\rho_0 \;\text{(Pressure of PNM)}$$

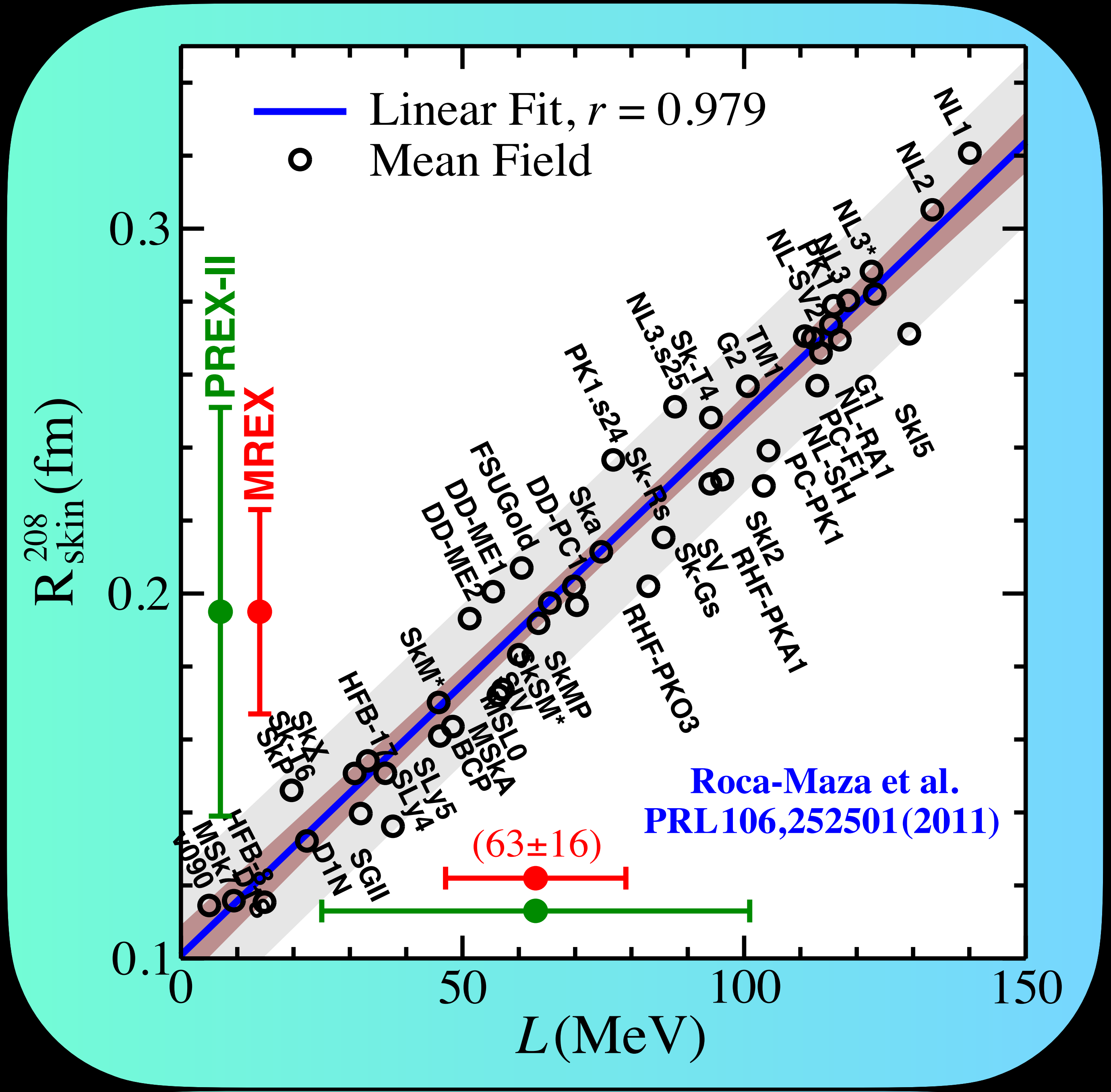
"Stiff" ⟶ L large
"Soft" ⟶ L small

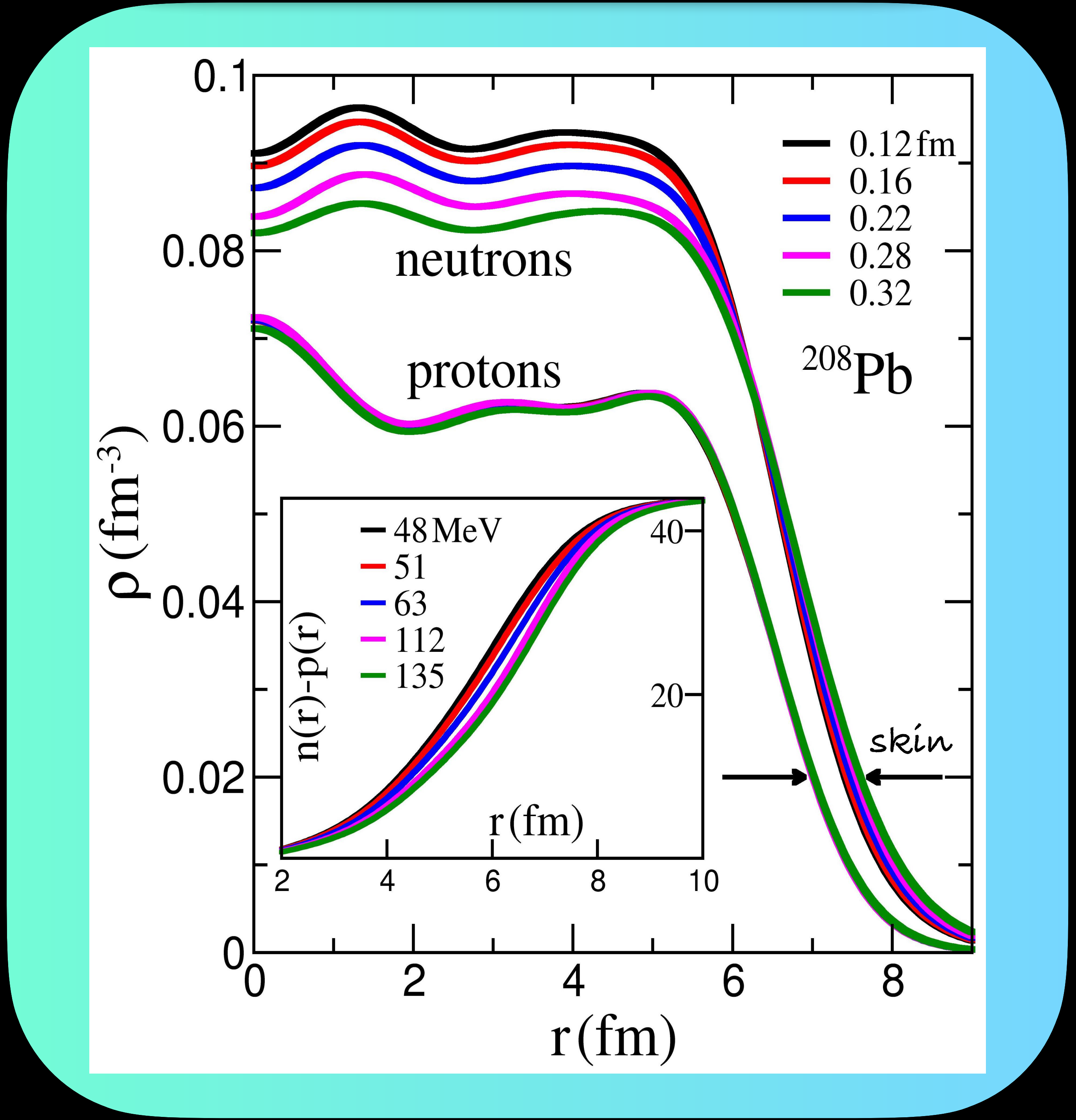
Heaven and Earth

Laboratory Constraints on the EOS





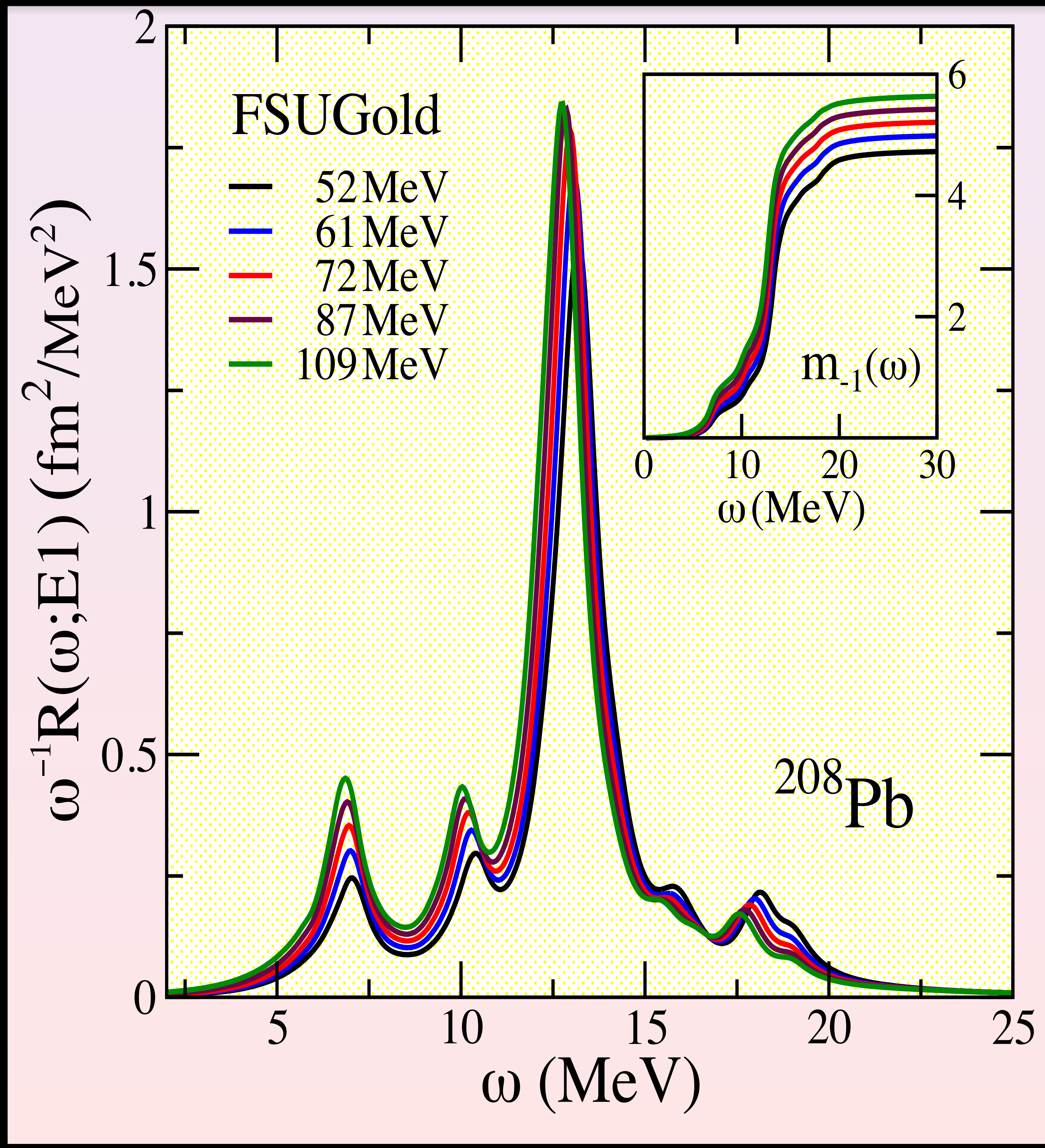


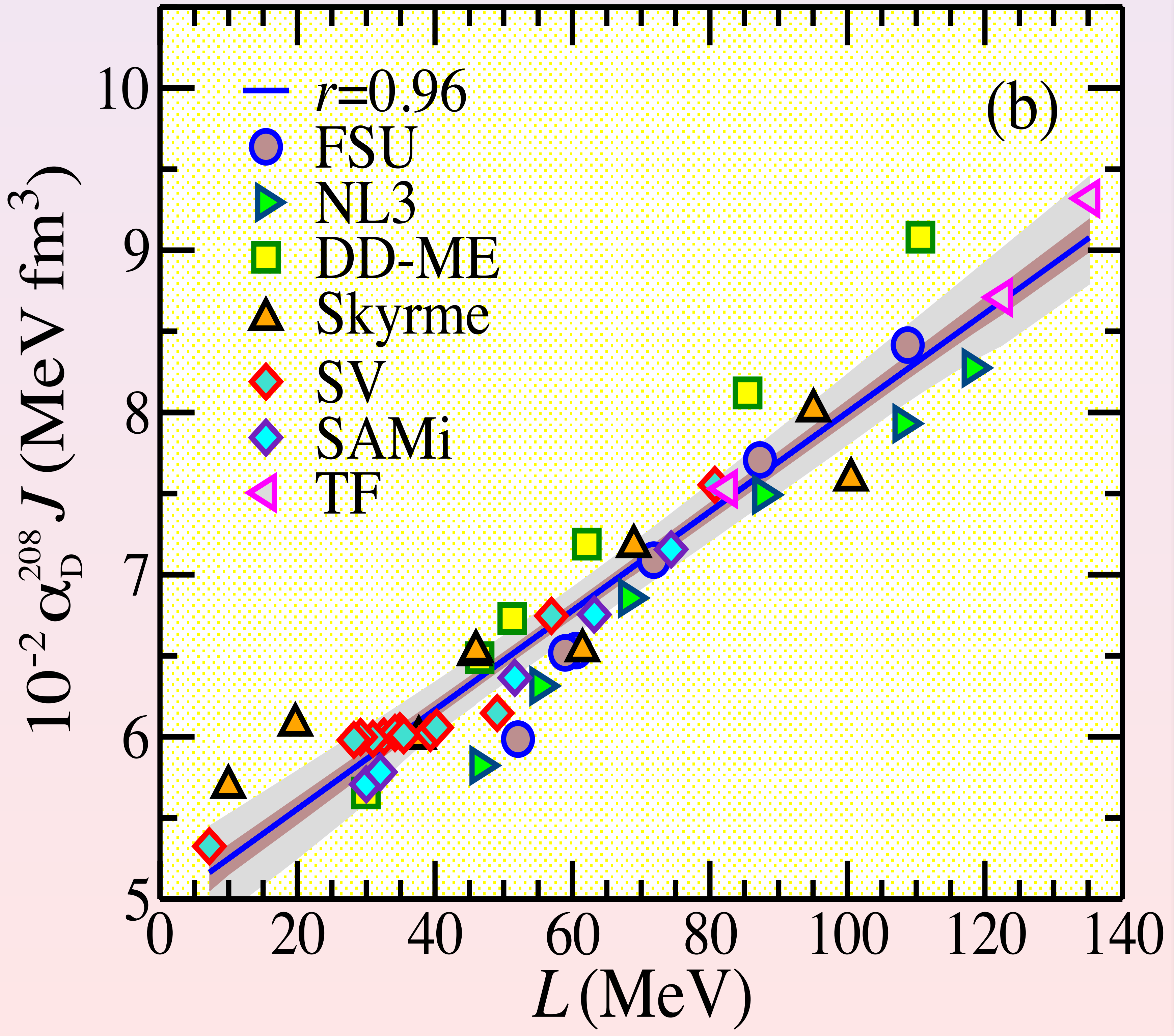


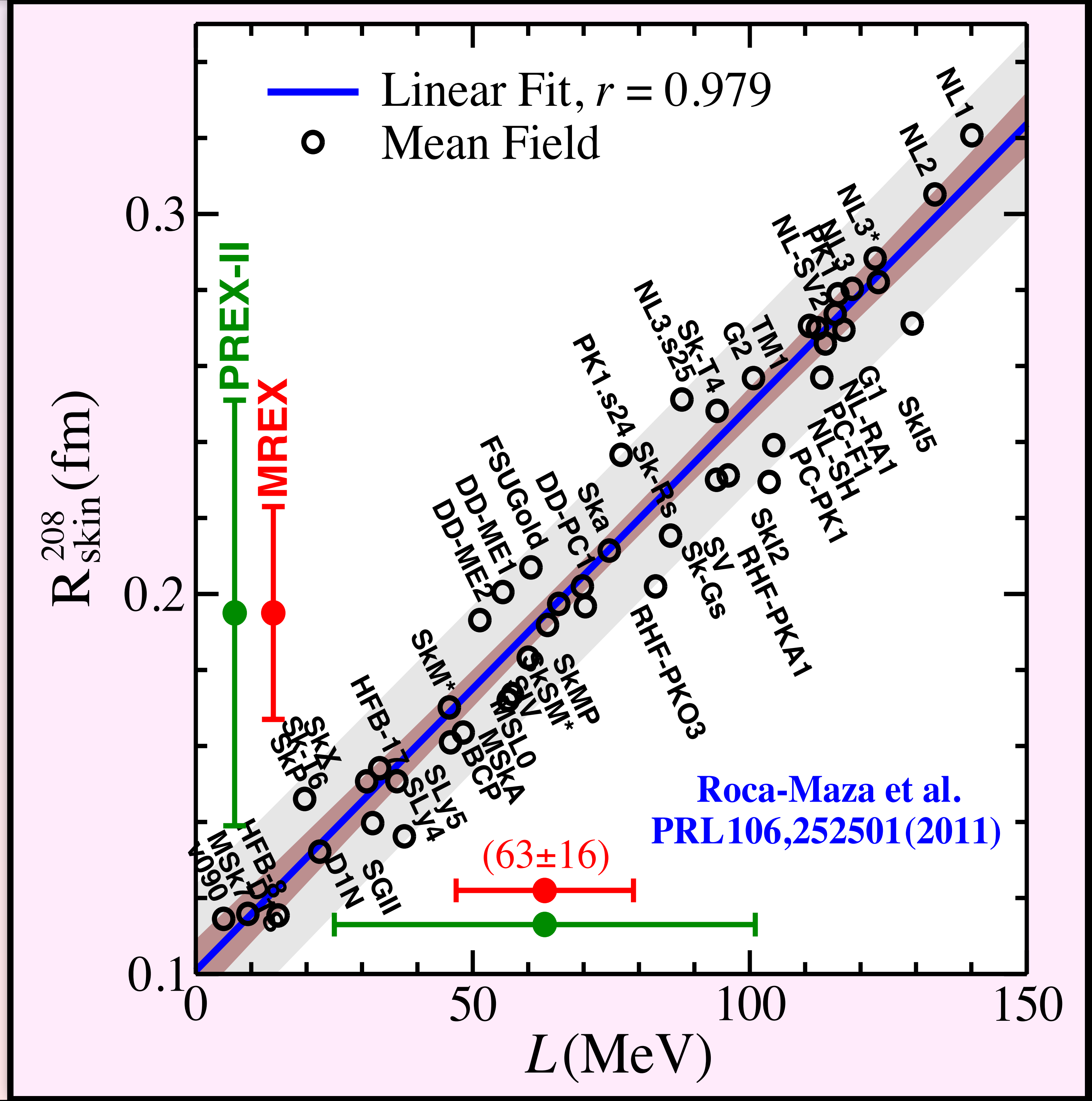
- Laboratory experiments constrain the EOS of pure neutron matter around saturation density: P_{PNM}=L
- Although a fundamental parameter of the EOS, L is not a physical observable — yet is strongly correlated to one: the neutron-rich skin of a heavy nucleus such as ^{208}Pb
- Parity-violating elastic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

Electric Dipole Polarizability α_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



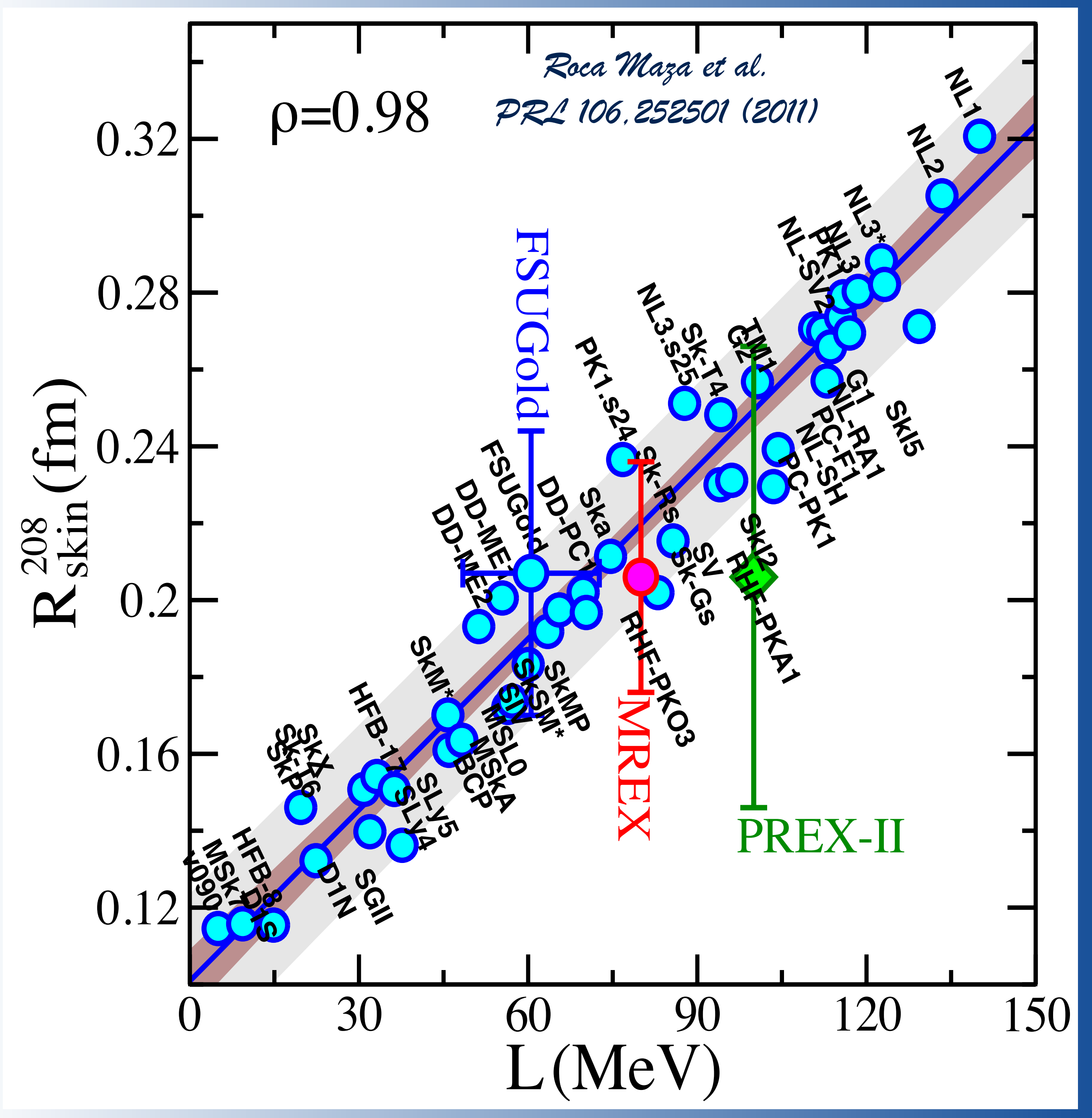


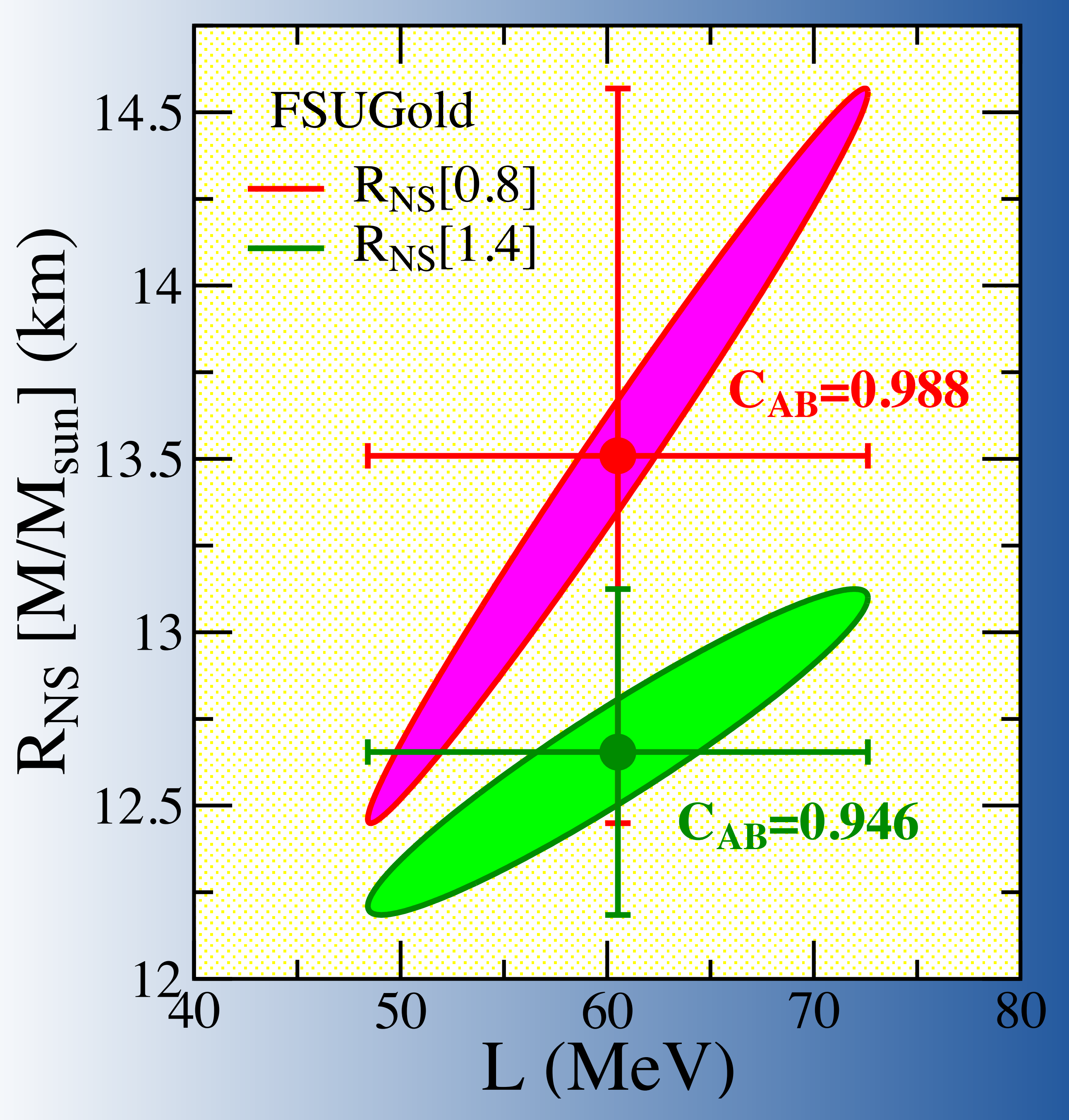


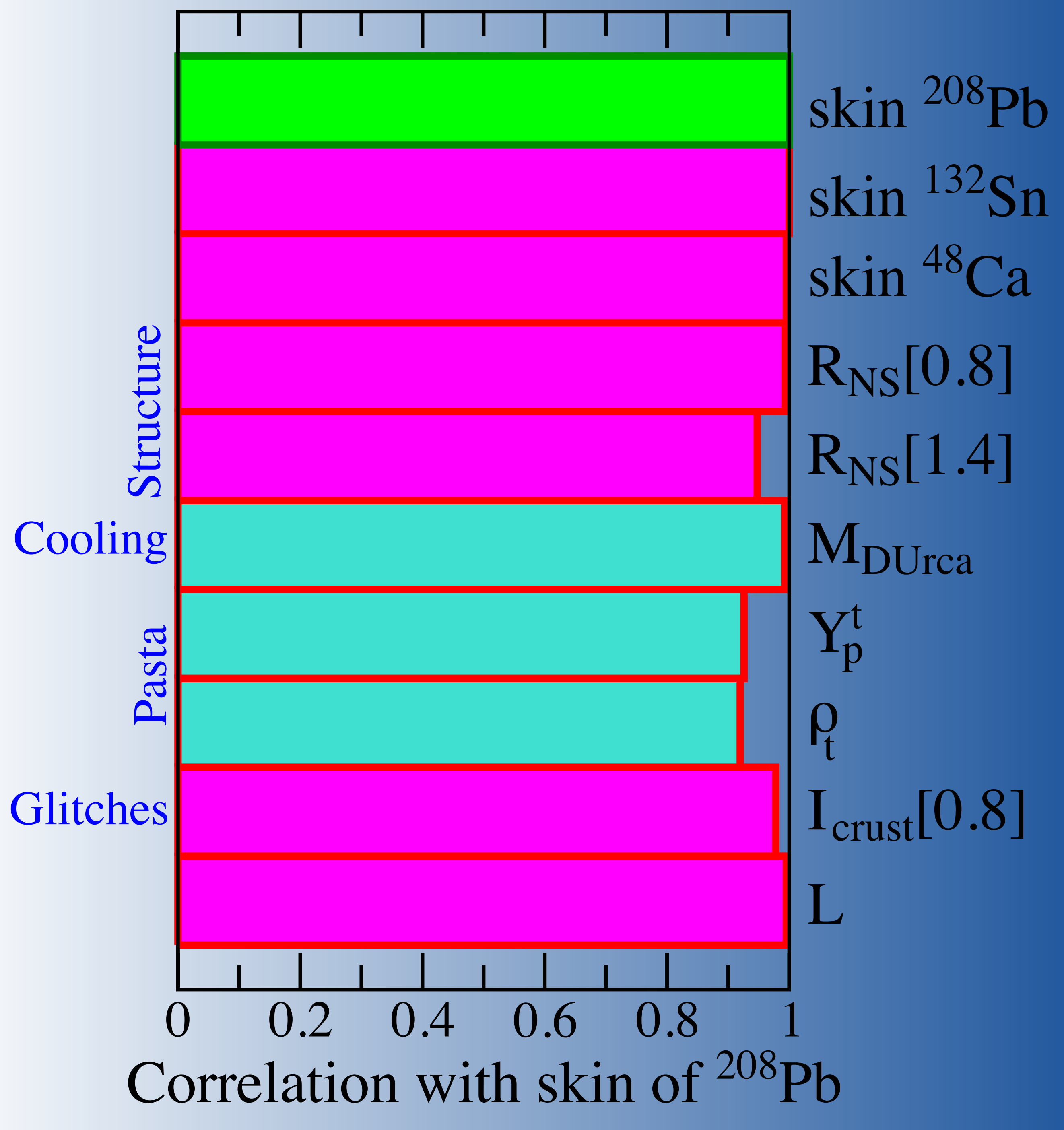
Heaven and Earth

- Strong correlation emerges between the neutron skin thickness of ^{208}Pb and L
- L controls both the neutron skin of ^{208}Pb and the radius of a neutron star

18 orders of magnitude!!

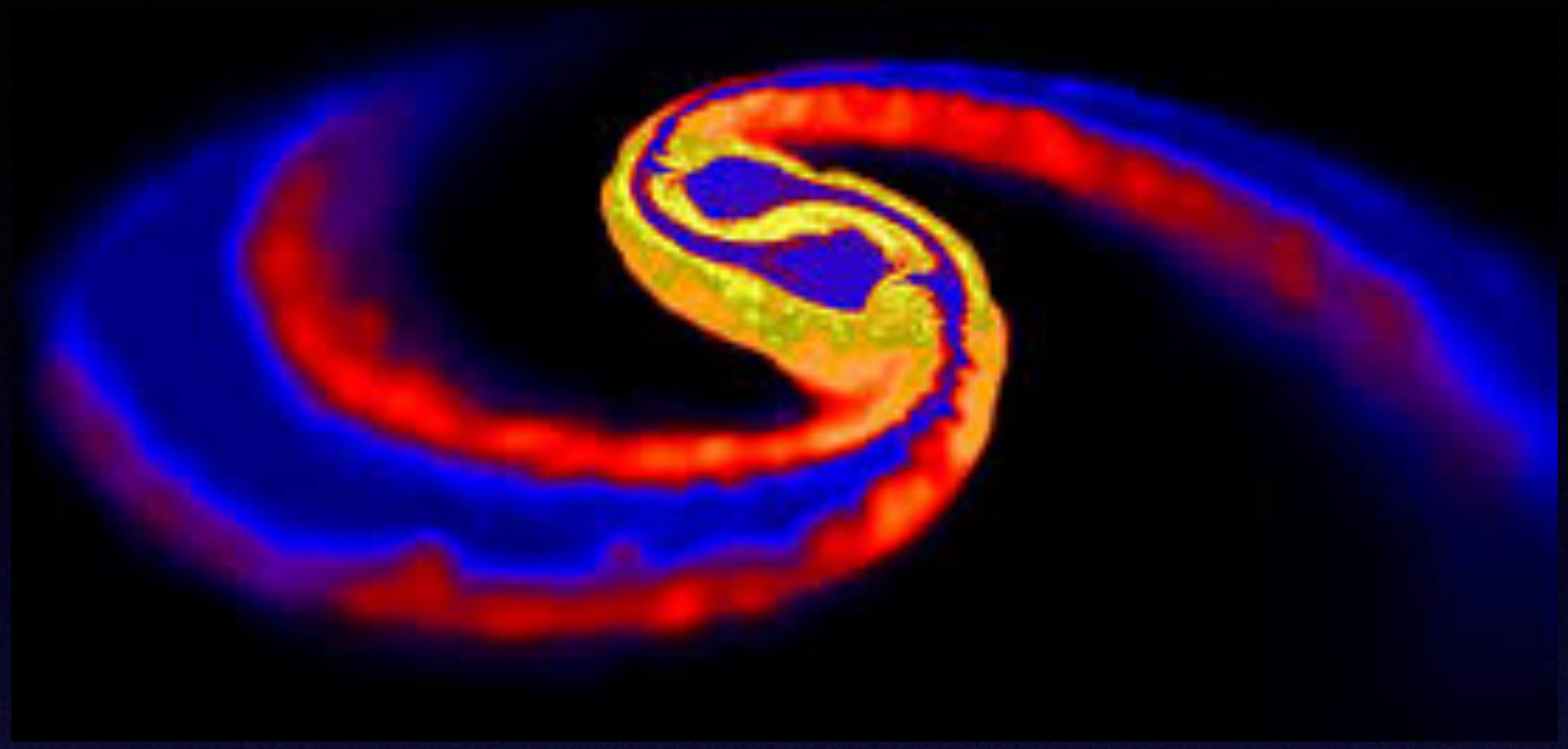




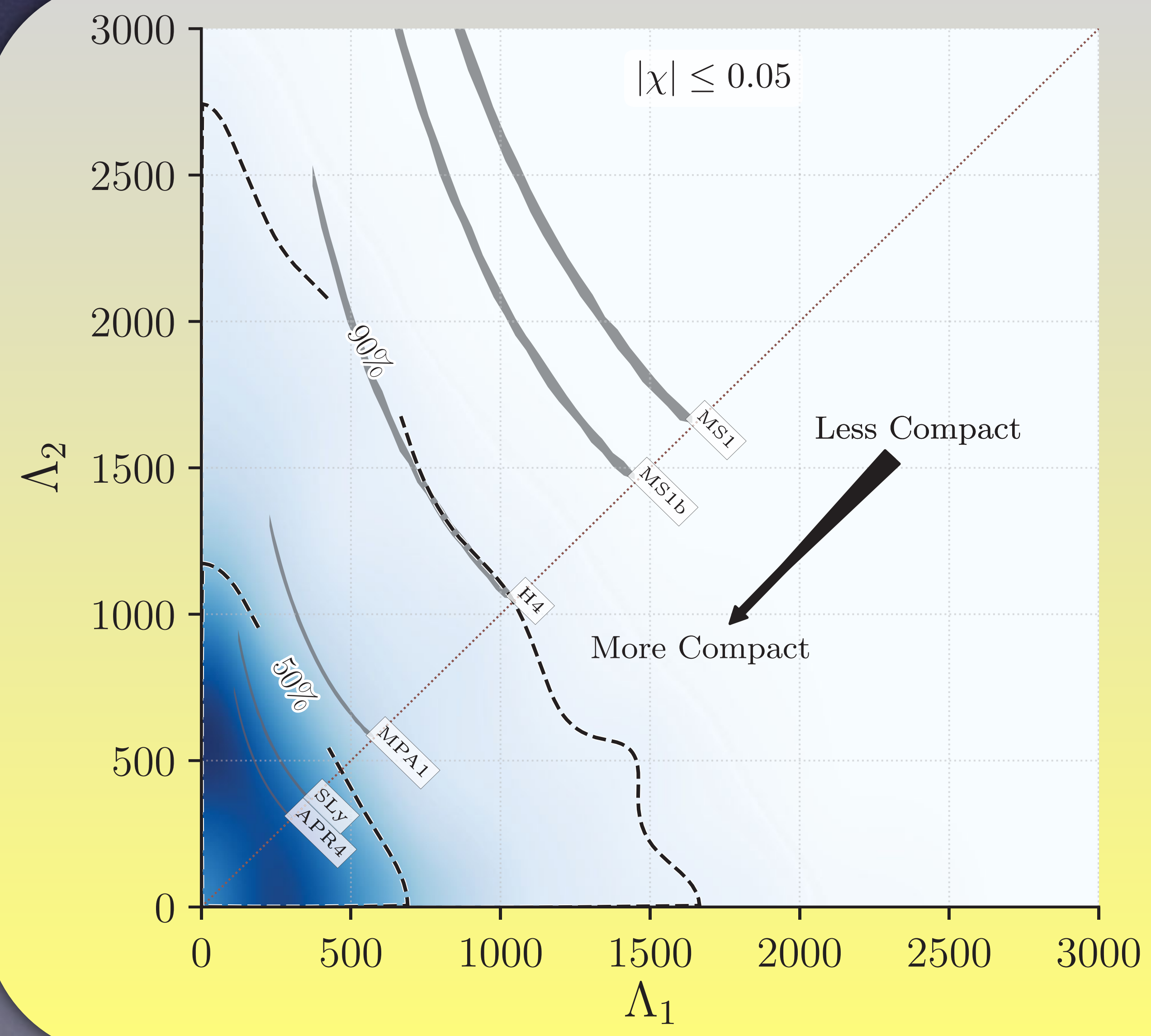


Tidal Polarizability and Neutron-Star Radii

- **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: $Q_{ij} = \Lambda \mathcal{E}_{ij}$



$$\Lambda = k_2 \left(\frac{c^2 R}{2GM}\right)^5 = k_2 \left(\frac{R}{R_s}\right)^5$$

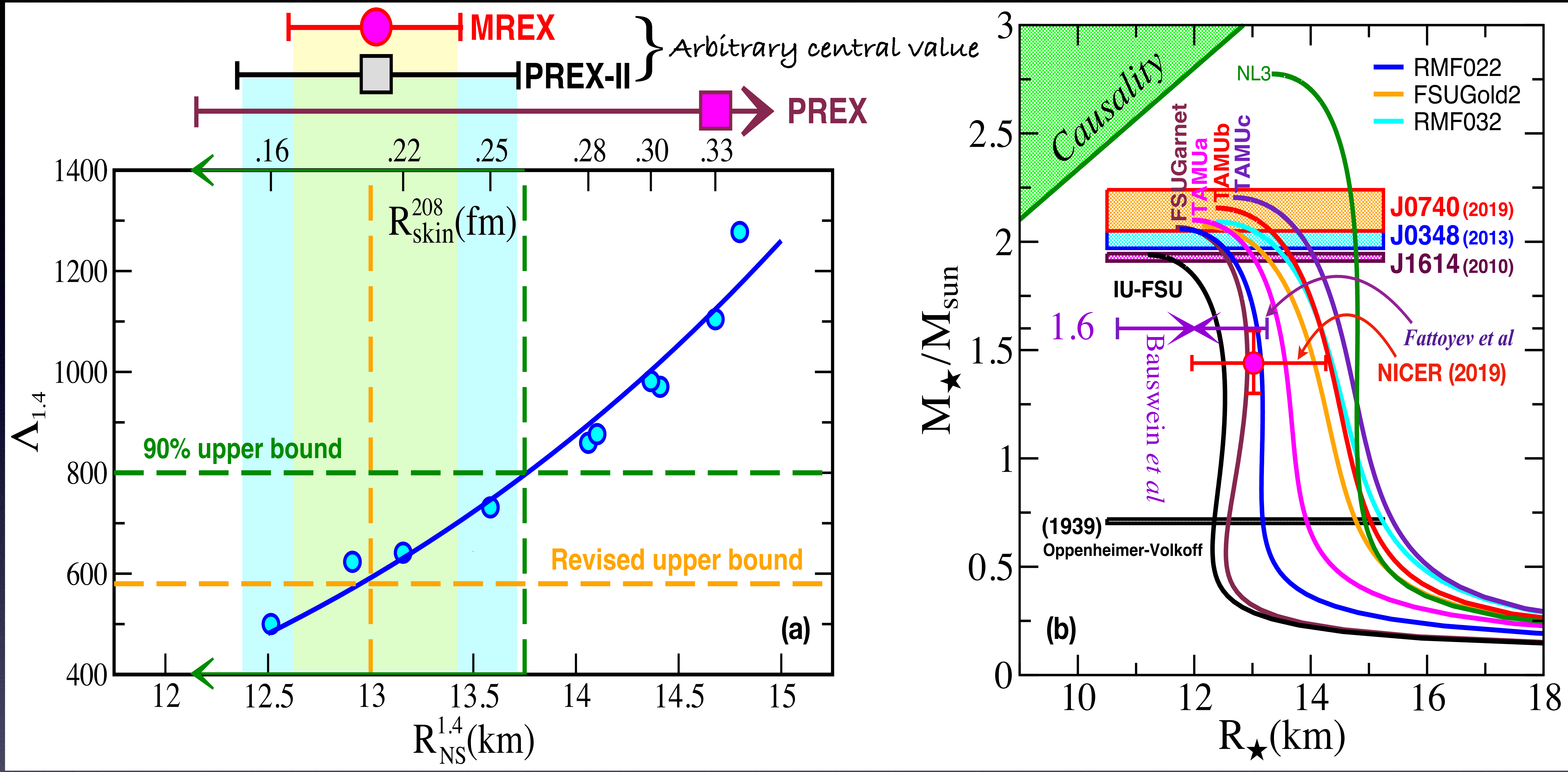


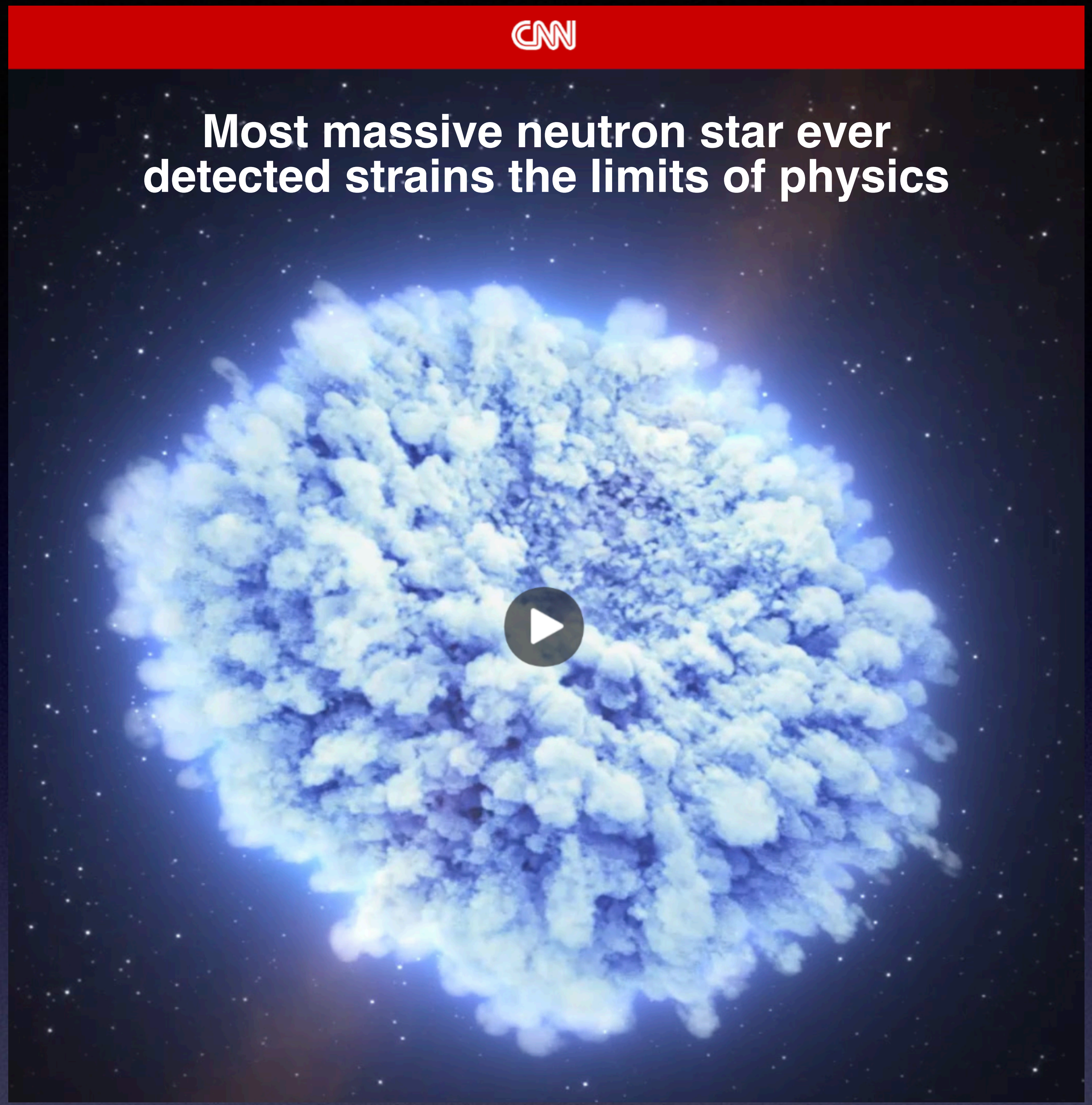
GW170817 rules out very large neutron star radii!

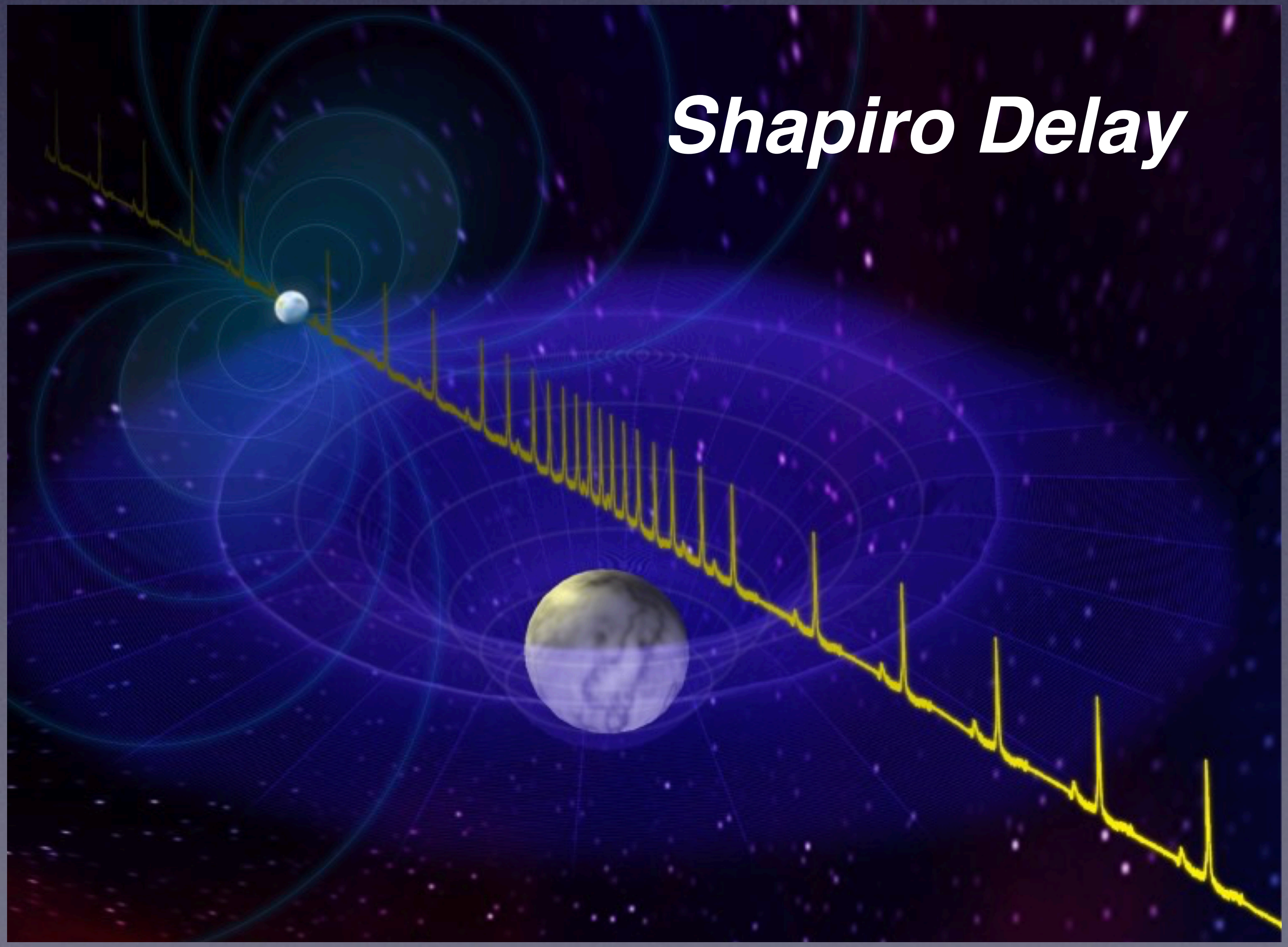
Neutron Stars must be compact

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

Progress on the EOS since GW170817





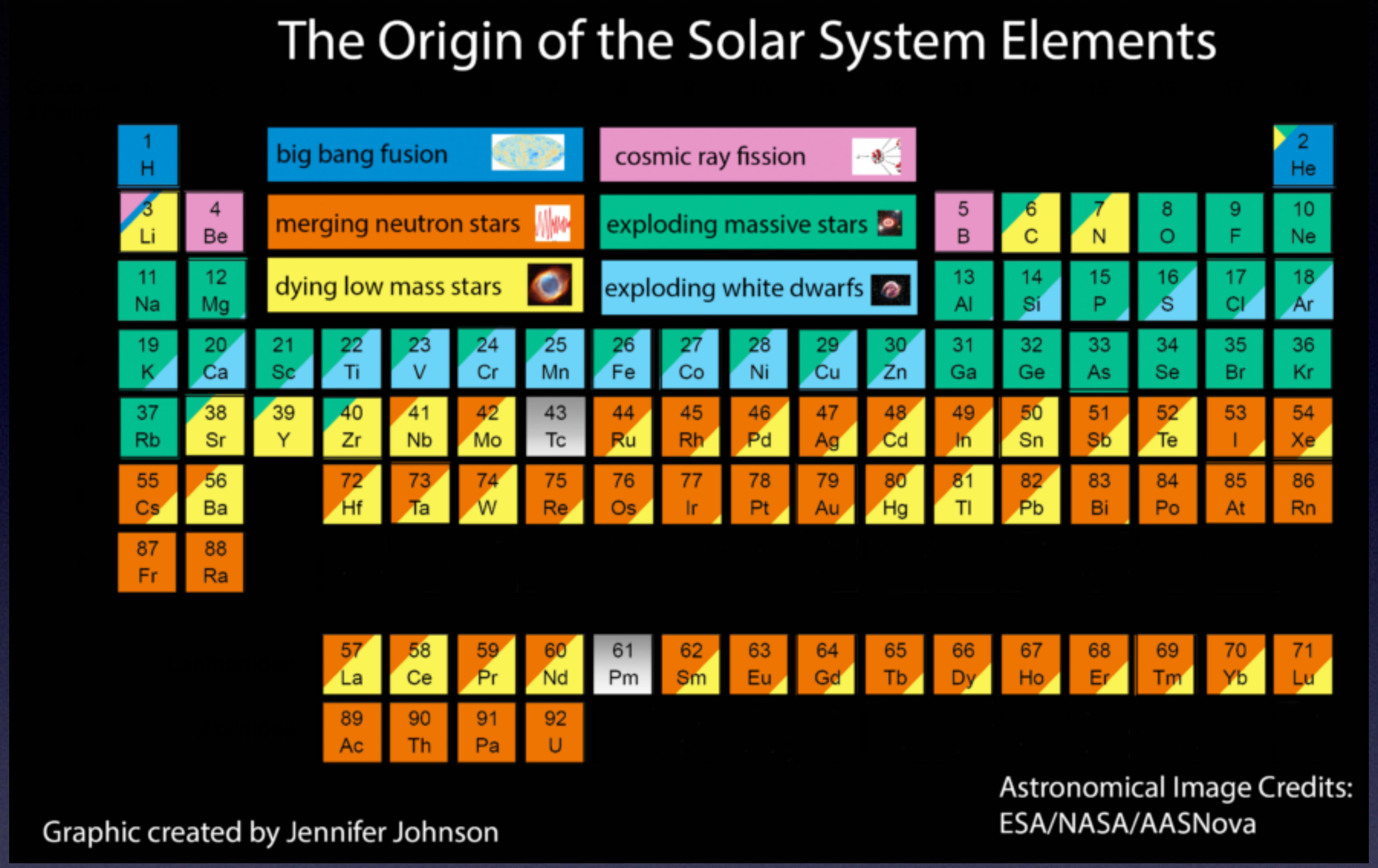


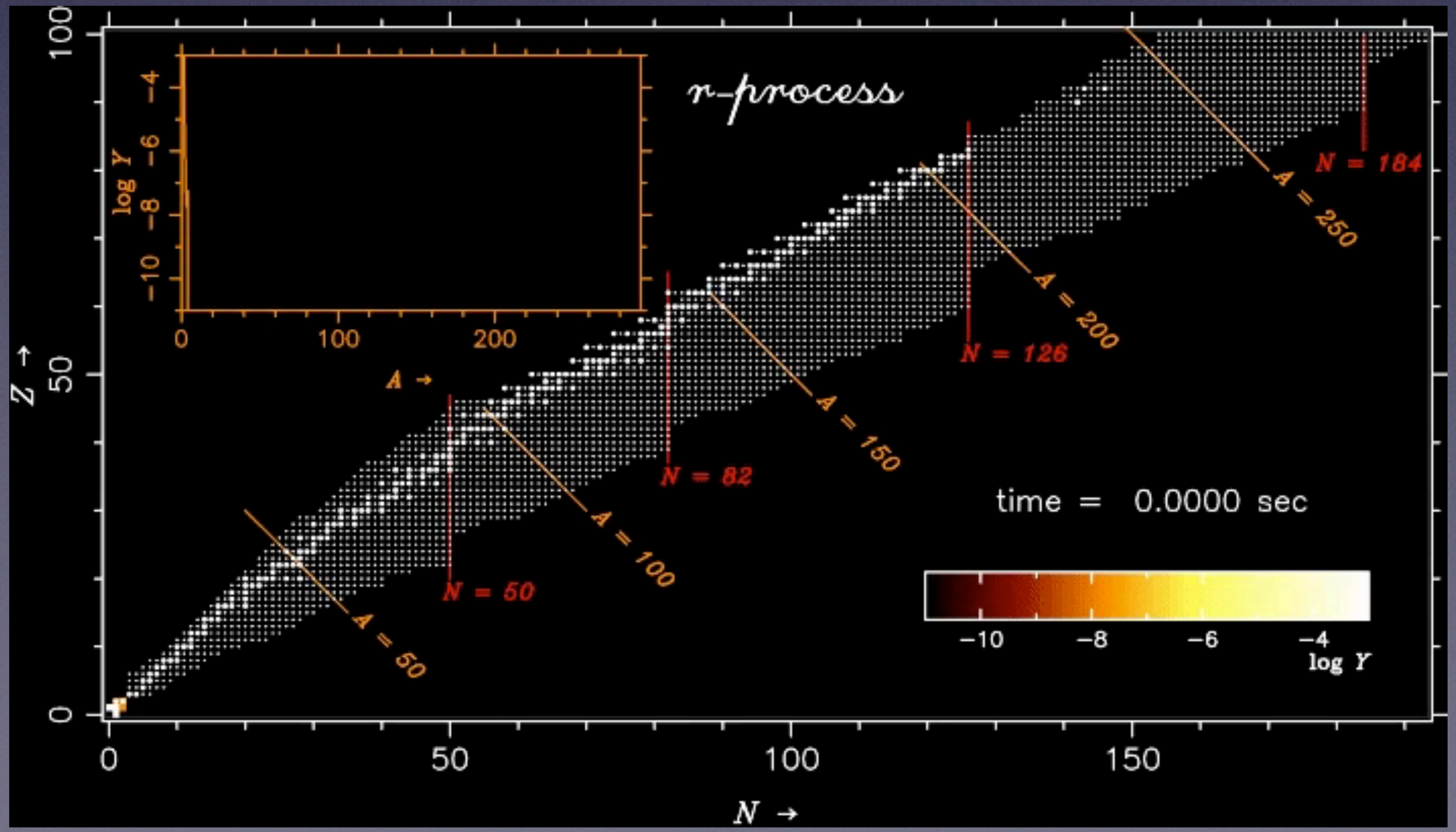
Tantalizing Possibility

- *Laboratory Experiments suggest large neutron radii for Pb* $\lesssim 1\rho_0$
- *Gravitational Waves suggest small stellar radii* $\gtrsim 2\rho_0$
- *Electromagnetic Observations suggest large stellar masses* $\gtrsim 4\rho_0$

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

How were the Elements from Iron to Uranium Made?





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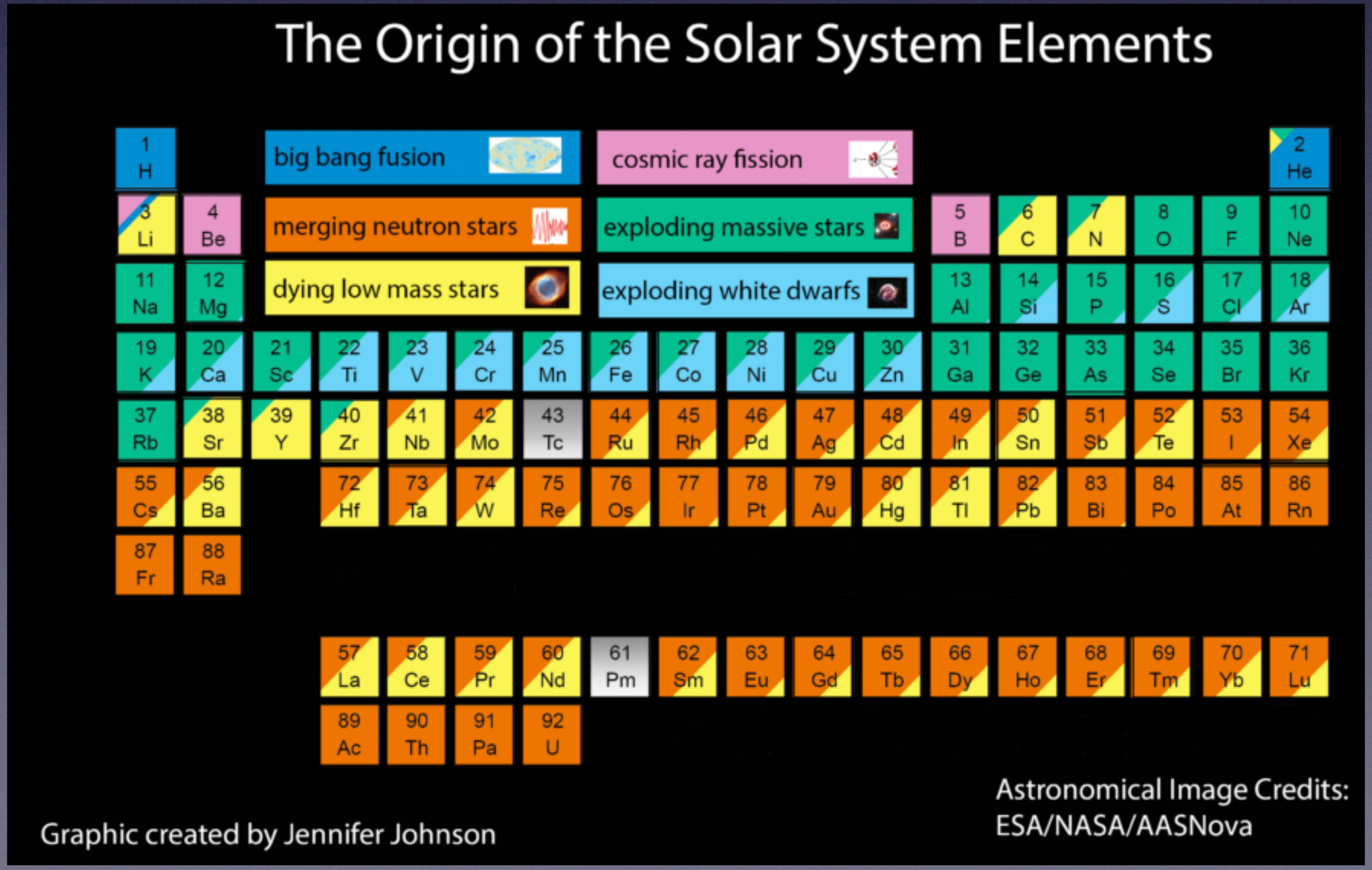
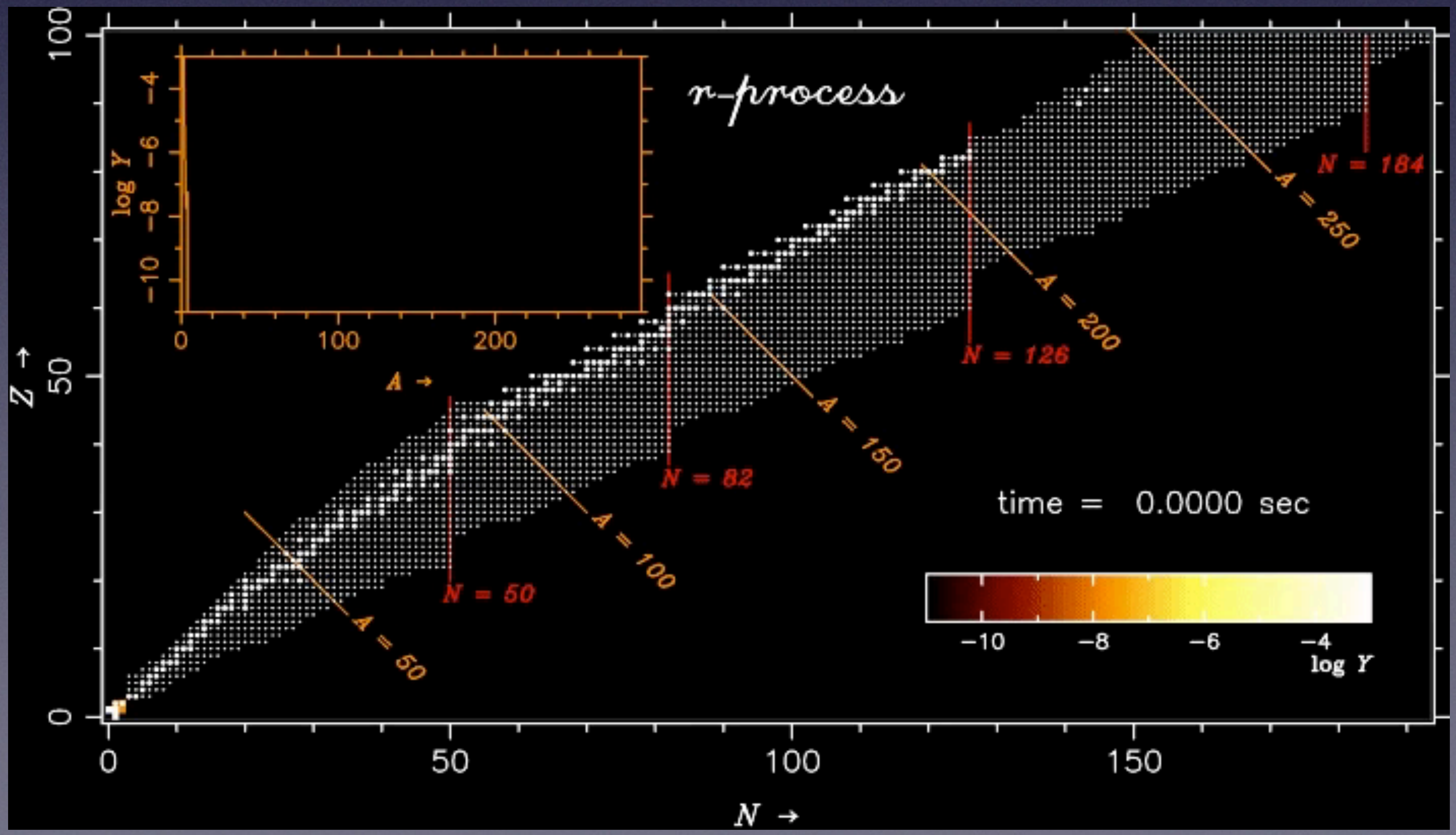
The New Periodic Table of the Elements

The optical counterpart SSS17a produced at least 5% solar masses (10^{29} kg!) of heavy elements - demonstrating that NS-mergers play a role in the r-process





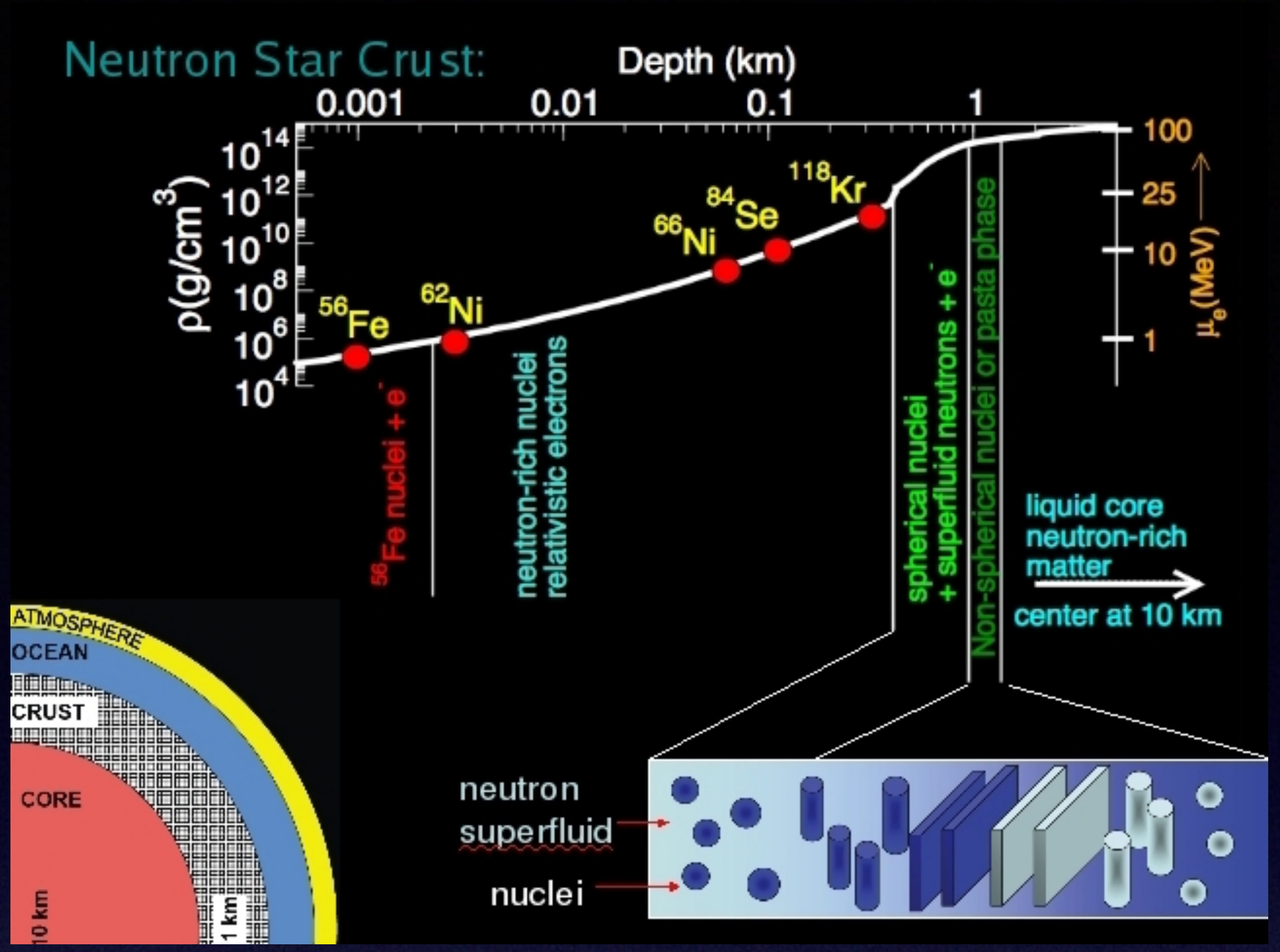
The Composition of the Outer Crust

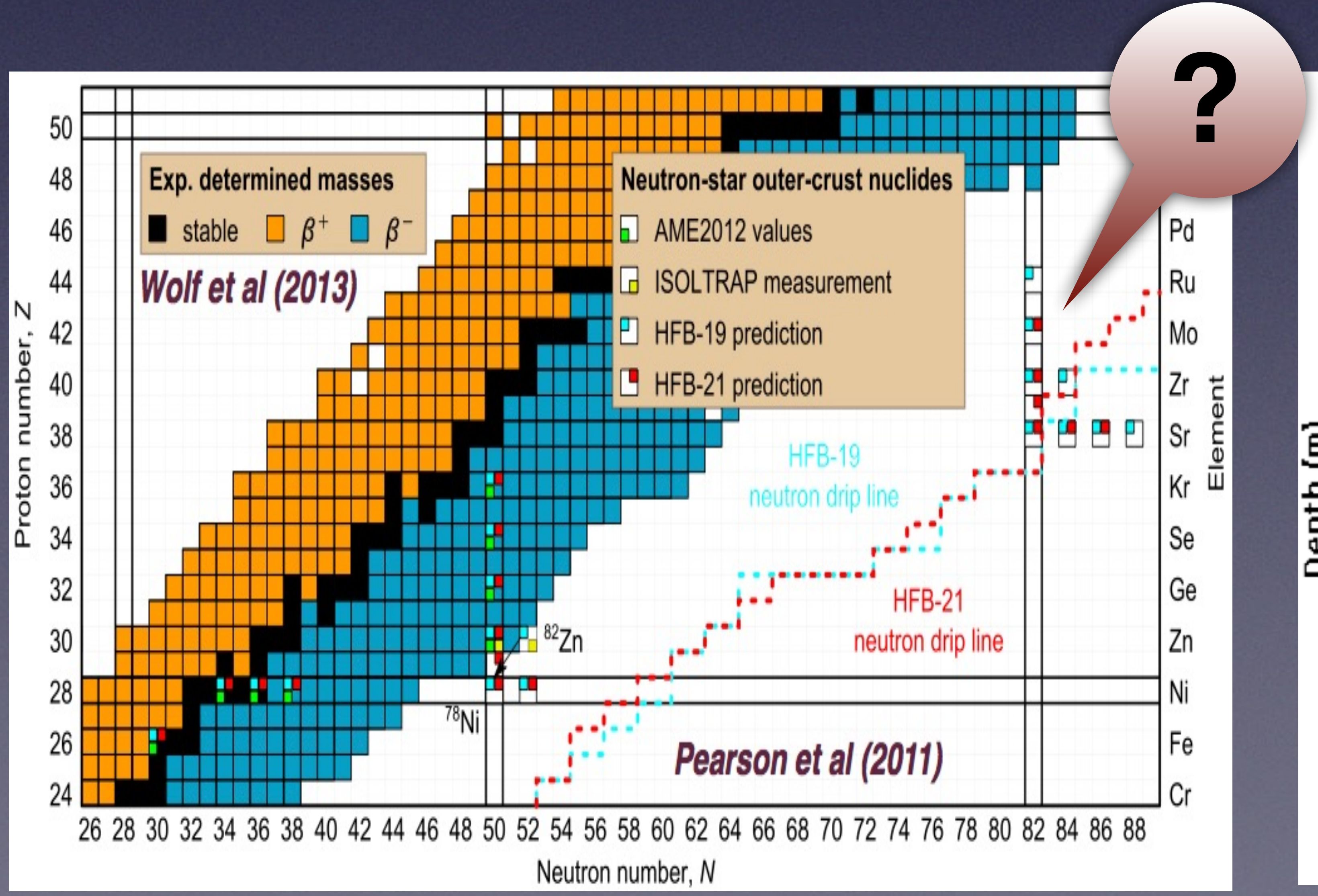
Enormous sensitivity to nuclear masses

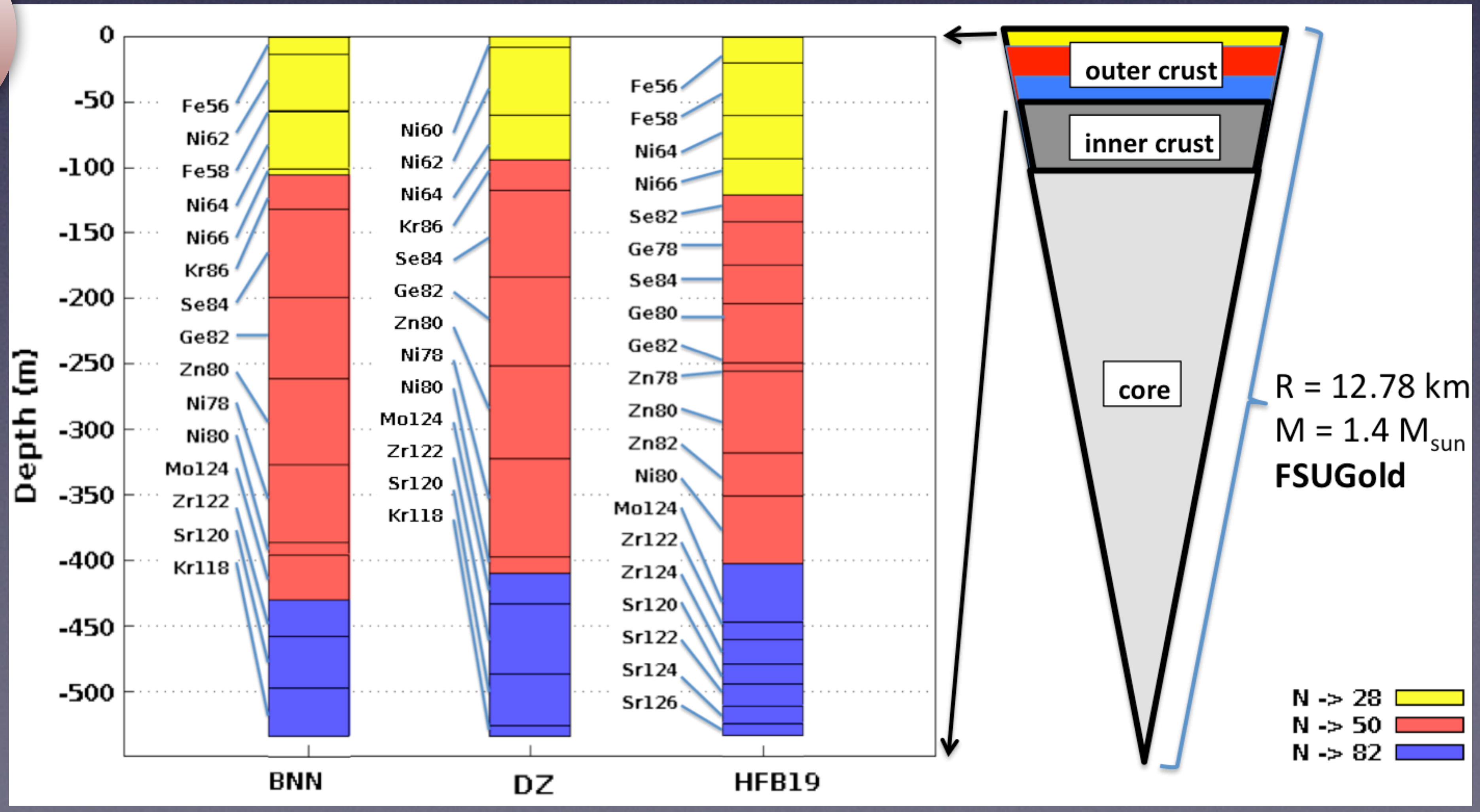
- Composition emerges from relatively simple dynamics
  - Competition between electronic and symmetry energy

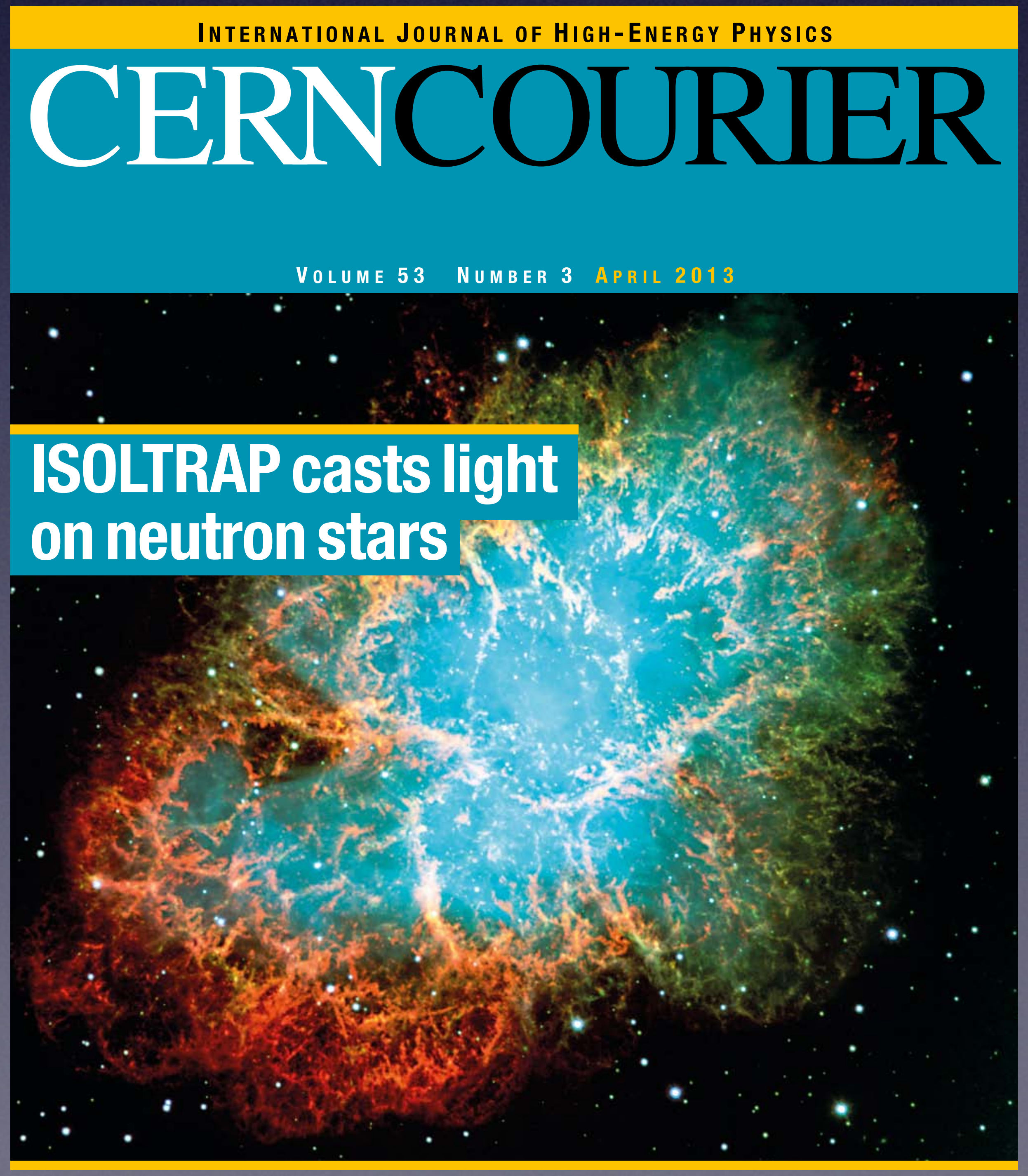
$$E/A_{\rm tot} = M(N,Z)/A + \frac{3}{4} Y_e^{4/3} k_{\rm F} + \text{lattice}$$

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

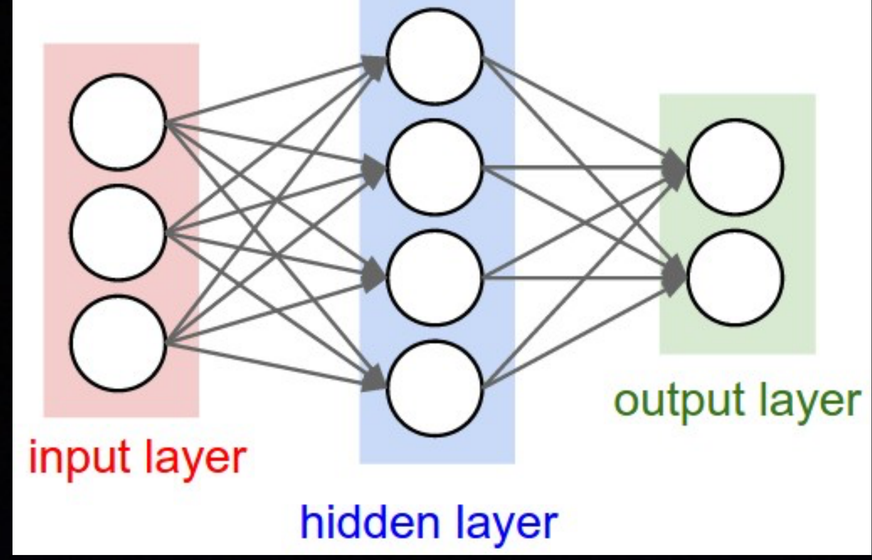








Nuclear Theory meets Machine Learning



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

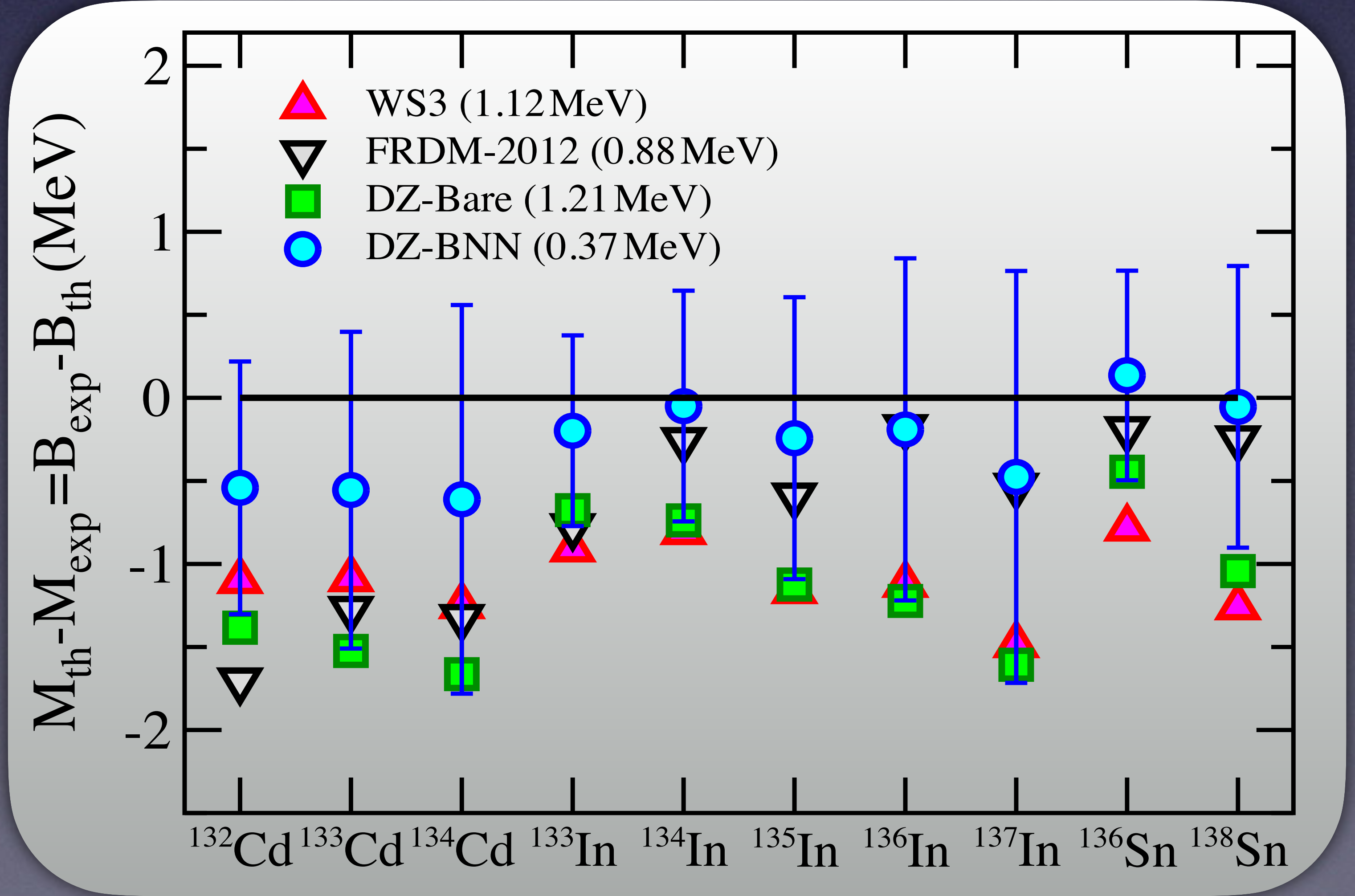
} *The paradigm*

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

- Systematic scattering greatly reduced
- Predictions supplemented by theoretical errors

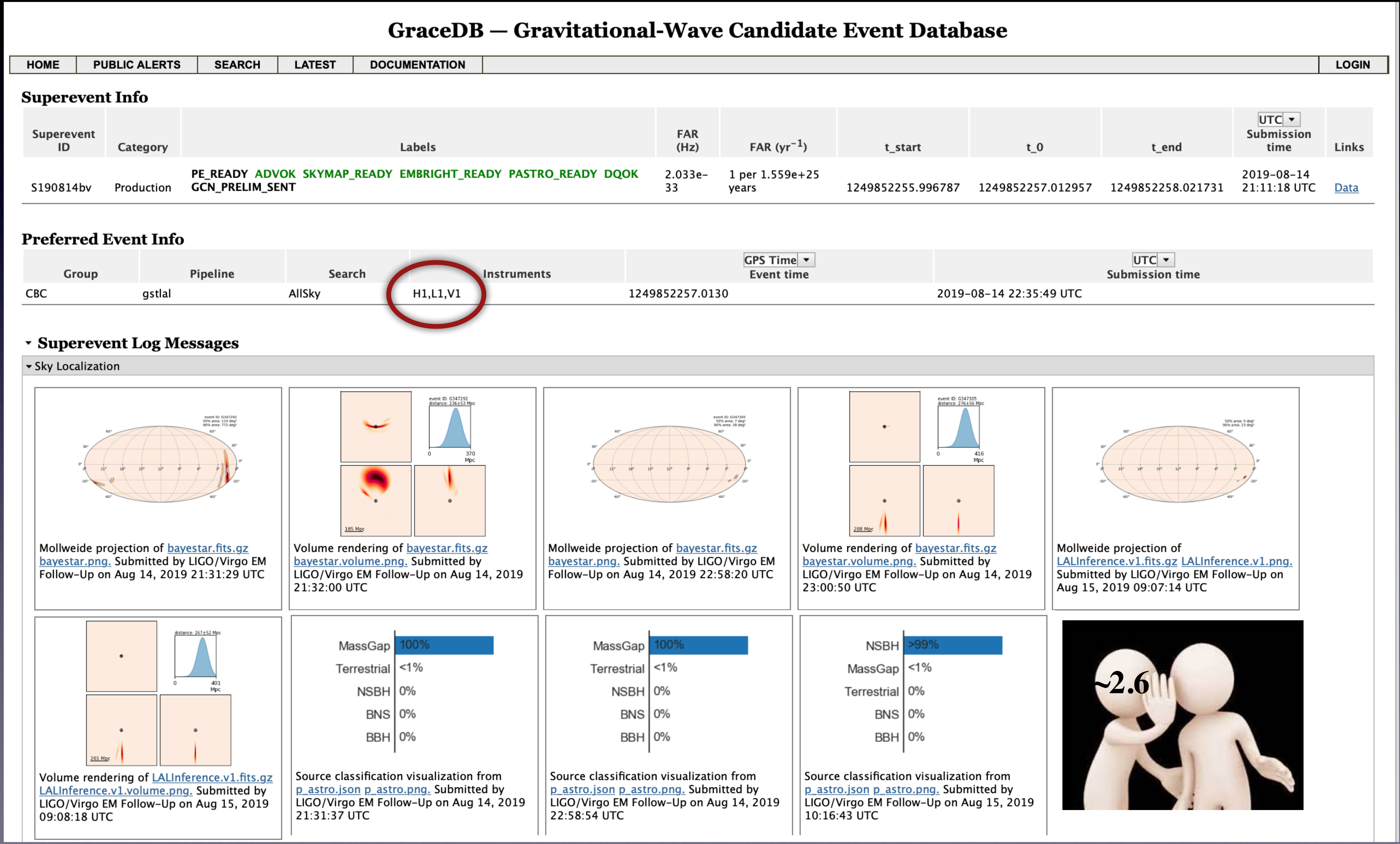
Train with AME2012
then predict AME2016

Re-generating Richard Feynman



Duflo-Zuker + BNN

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



GraceDB — Gravitational-Wave Candidate Event Database

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Superevent Info

Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S190814bv	Production	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	2.033e-33	1 per 1.559e+25 years	1249852255.996787	1249852257.012957	1249852258.021731	2019-08-14 21:11:18 UTC	Data

Preferred Event Info

Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	gstlal	AllSky	H1,L1,V1	1249852257.0130	2019-08-14 22:35:49 UTC

Superevent Log Messages

Sky Localization

Mollweide projection of bayestar.fits.gz bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 21:31:29 UTC

Volume rendering of bayestar.fits.gz bayestar.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 21:32:00 UTC

Mollweide projection of bayestar.fits.gz bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 22:58:20 UTC

Volume rendering of bayestar.fits.gz bayestar.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 23:00:50 UTC

Mollweide projection of LALInference.v1.fits.gz LALInference.v1.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 15, 2019 09:07:14 UTC

Volume rendering of LALInference.v1.fits.gz LALInference.v1.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 15, 2019 09:08:18 UTC

MassGap	100%
Terrestrial	<1%
NSBH	0%
BNS	0%
BBH	0%

Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 21:31:37 UTC

MassGap	100%
Terrestrial	<1%
NSBH	0%
BNS	0%
BBH	0%

Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 22:58:54 UTC

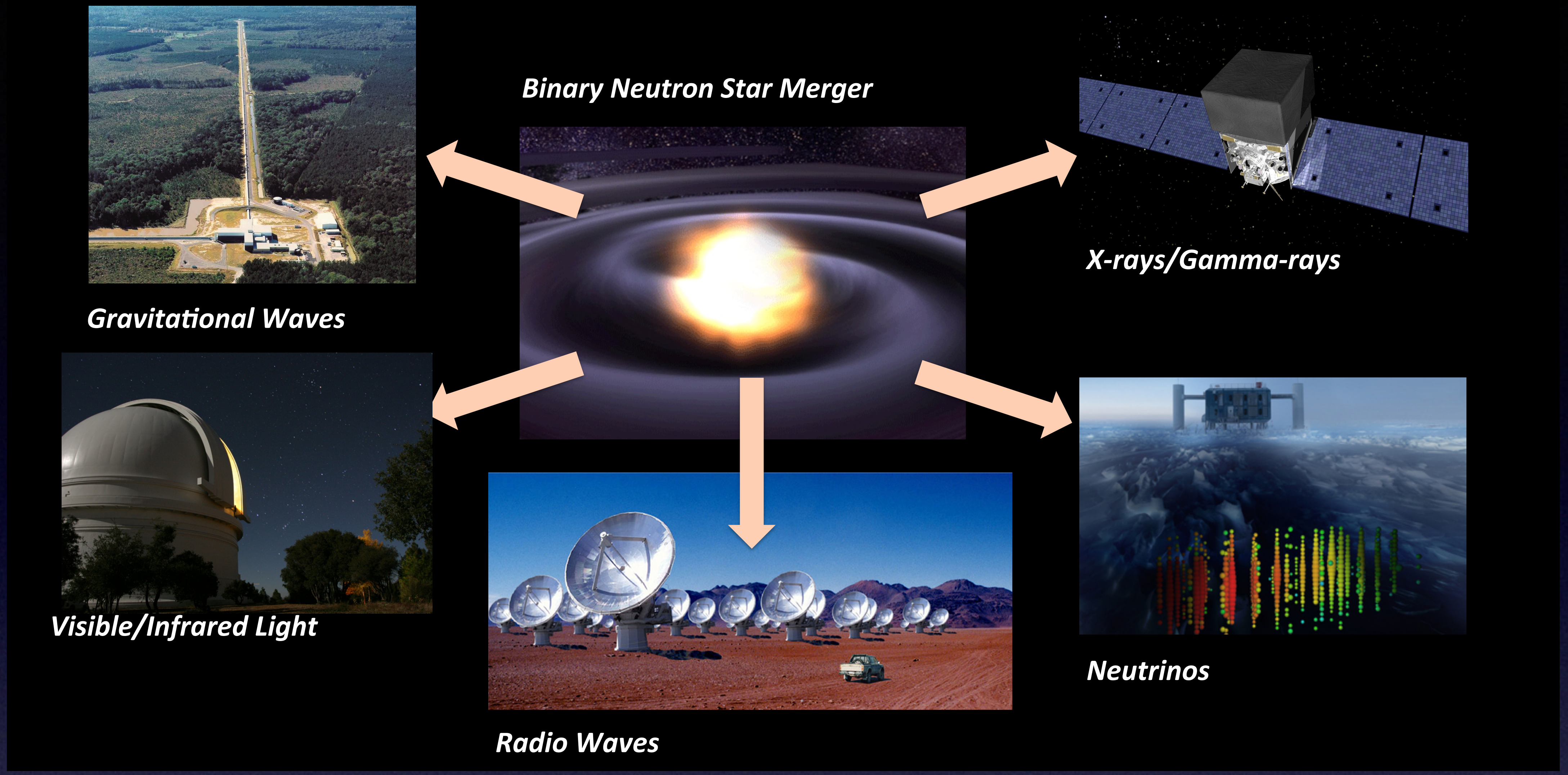
NSBH	>99%
MassGap	<1%
Terrestrial	0%
BNS	0%
BBH	0%

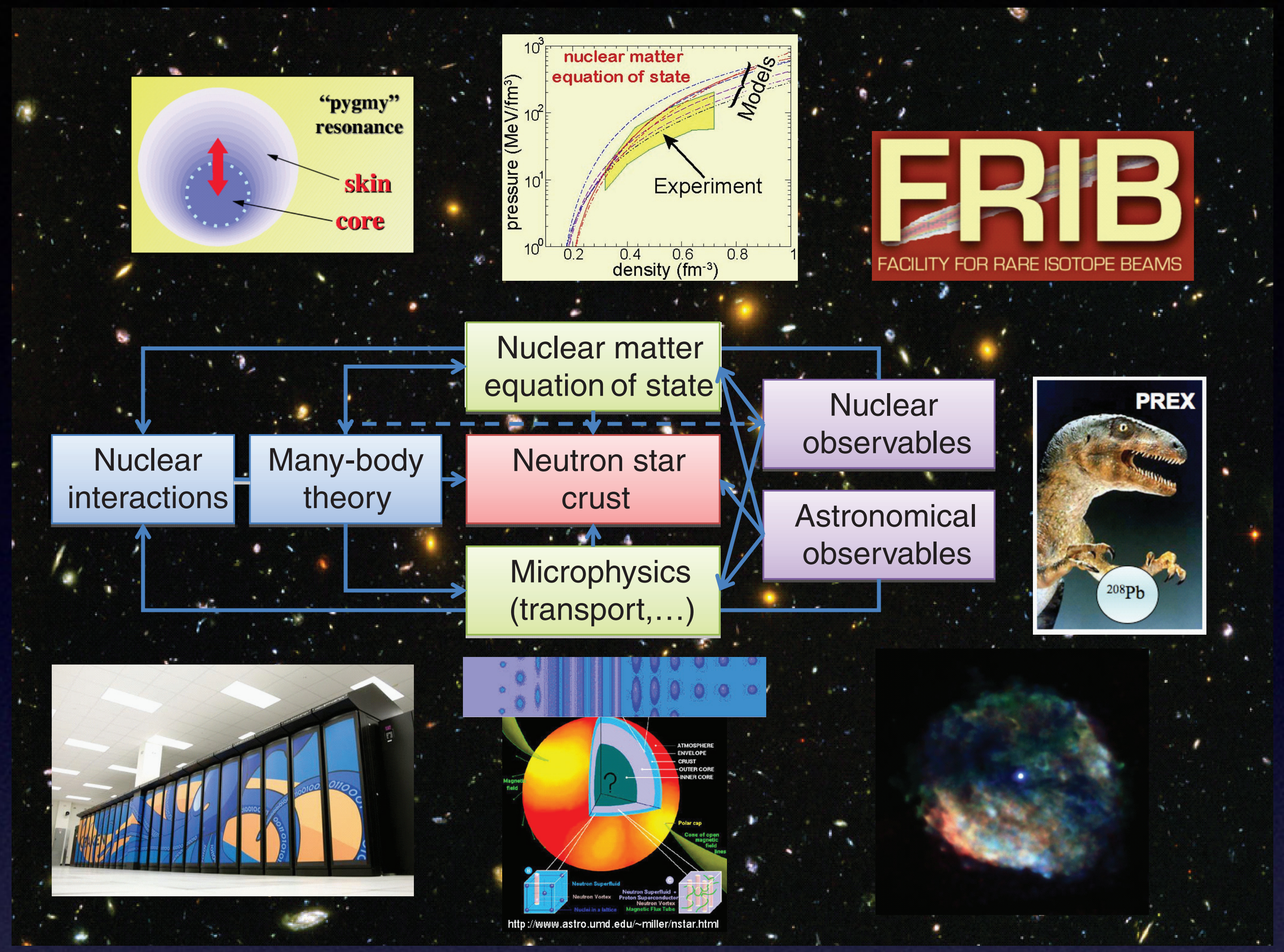
Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 15, 2019 10:16:43 UTC

~2.6

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

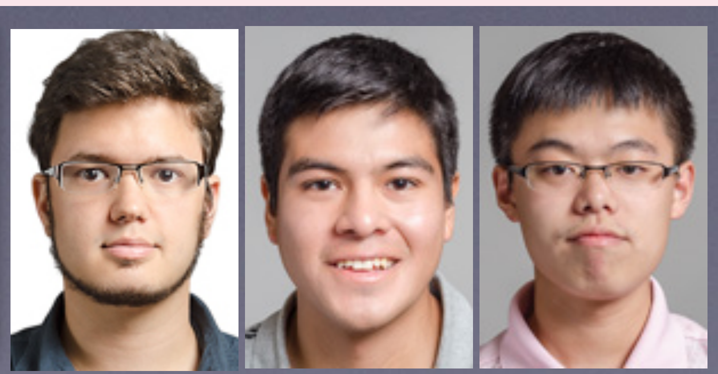
- Genaro Toledo-Sanchez
- Karim Hasnaoui
- Bonnie Todd-Rutel
- Brad Futch
- Jutri Taruna
- **Farrukh Fattoyev**
- **Wei-Chia Chen**
- **Raditya Utama**

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)

The New Generation

- **Pablo Giuliani**
- **Daniel Silva**
- **Junjie Yang**



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