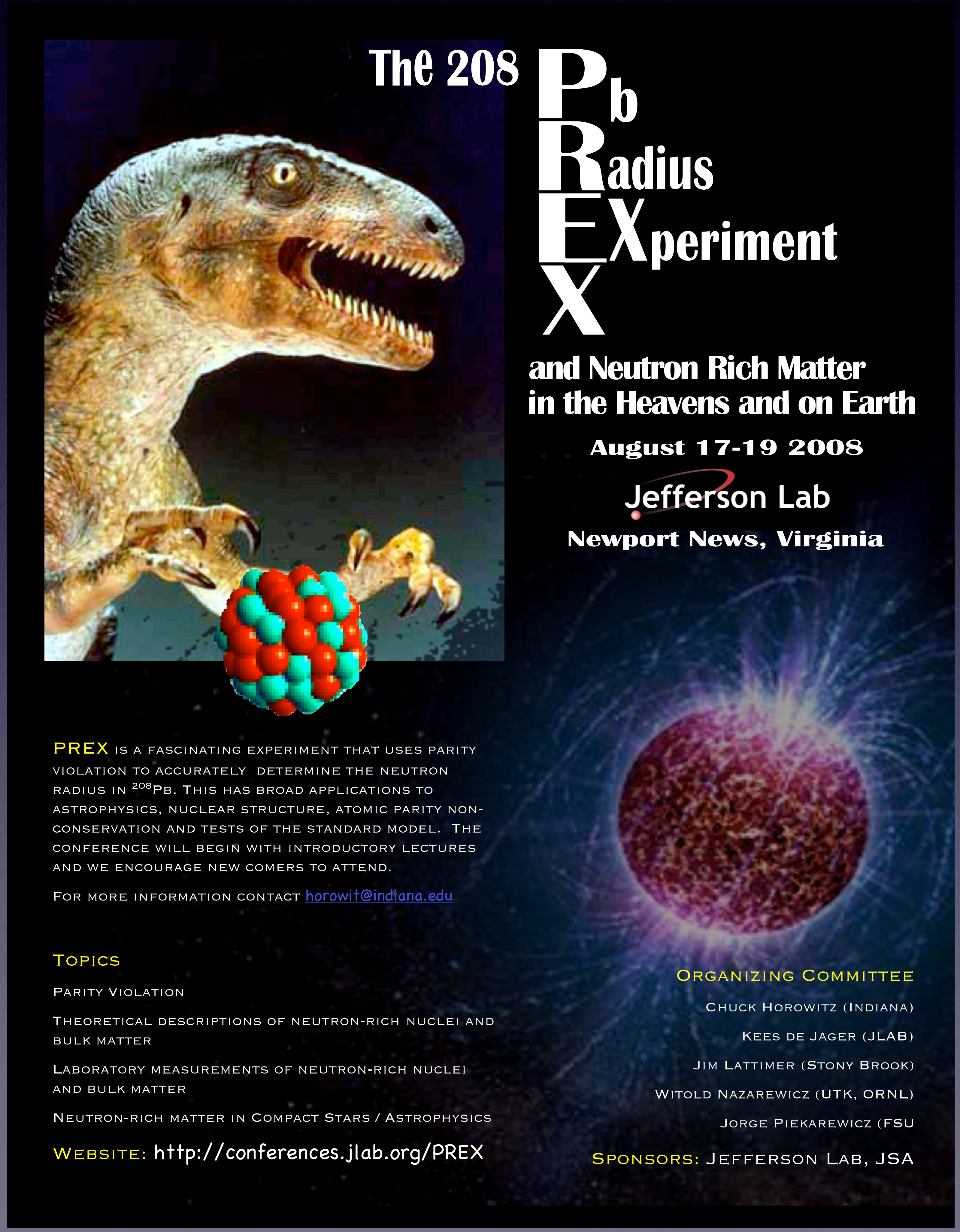
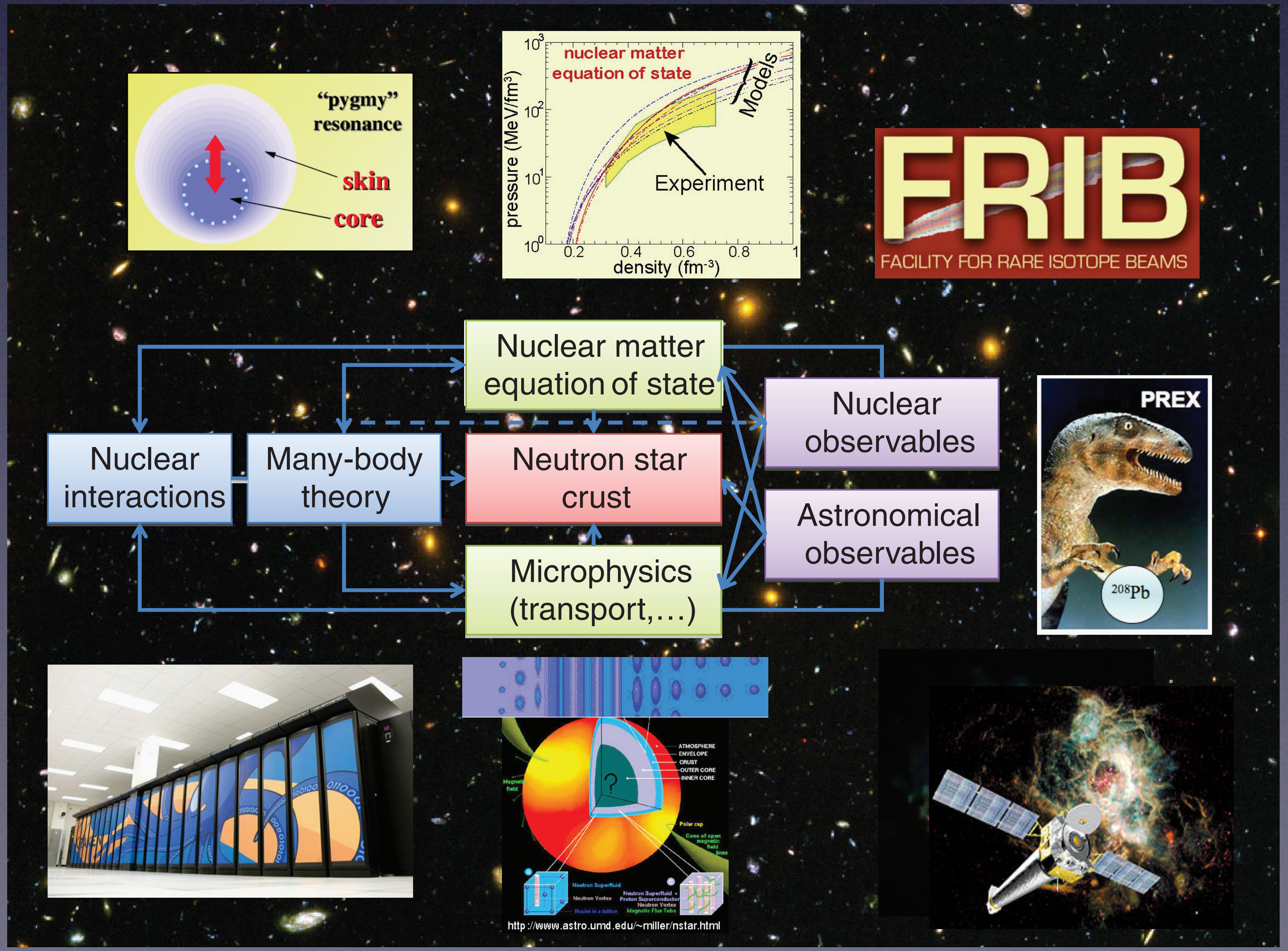
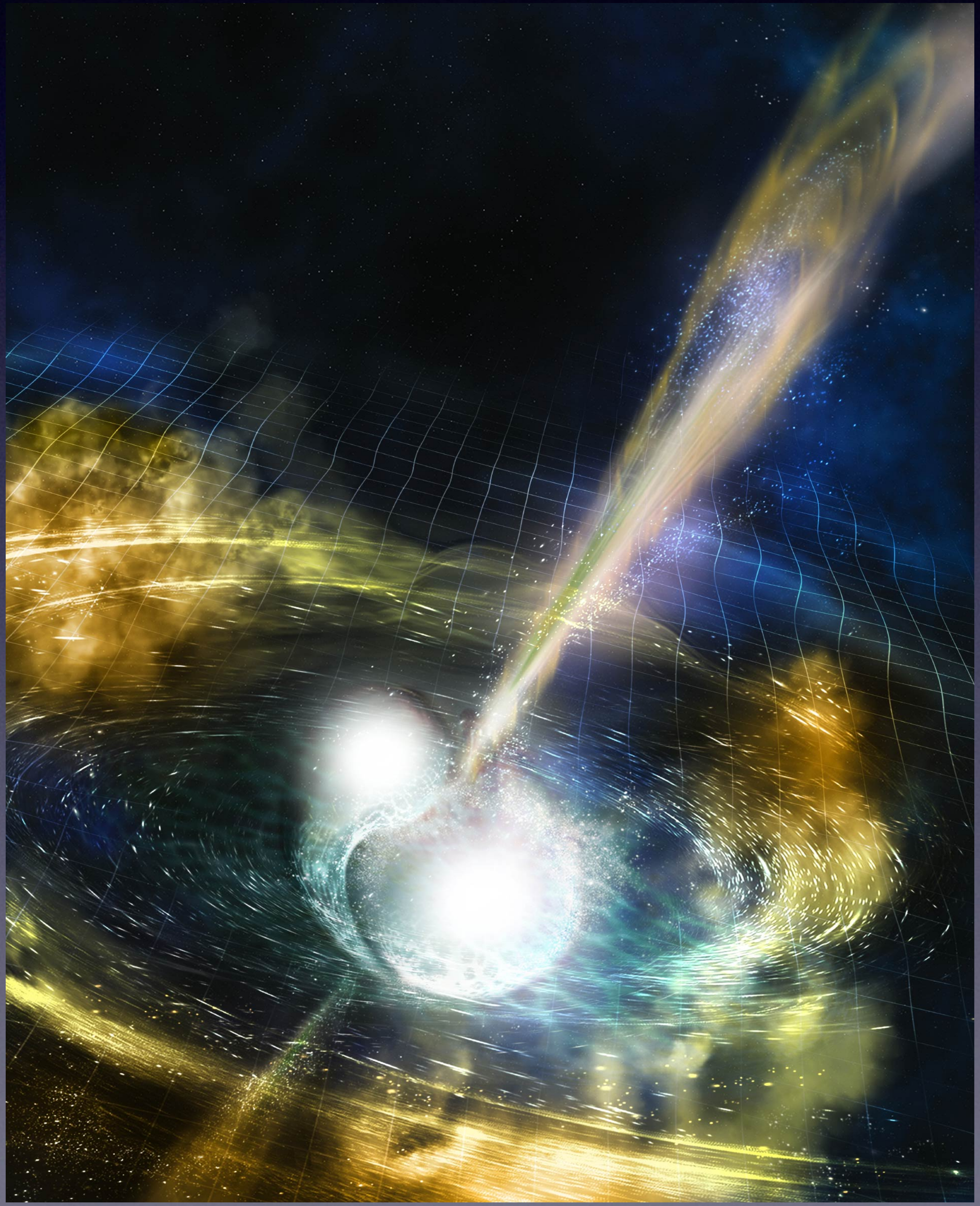
Neutron-rich matter in Heaven and on Earth

International Winter Meeting on Nuclear Physics (Bormio 2020)

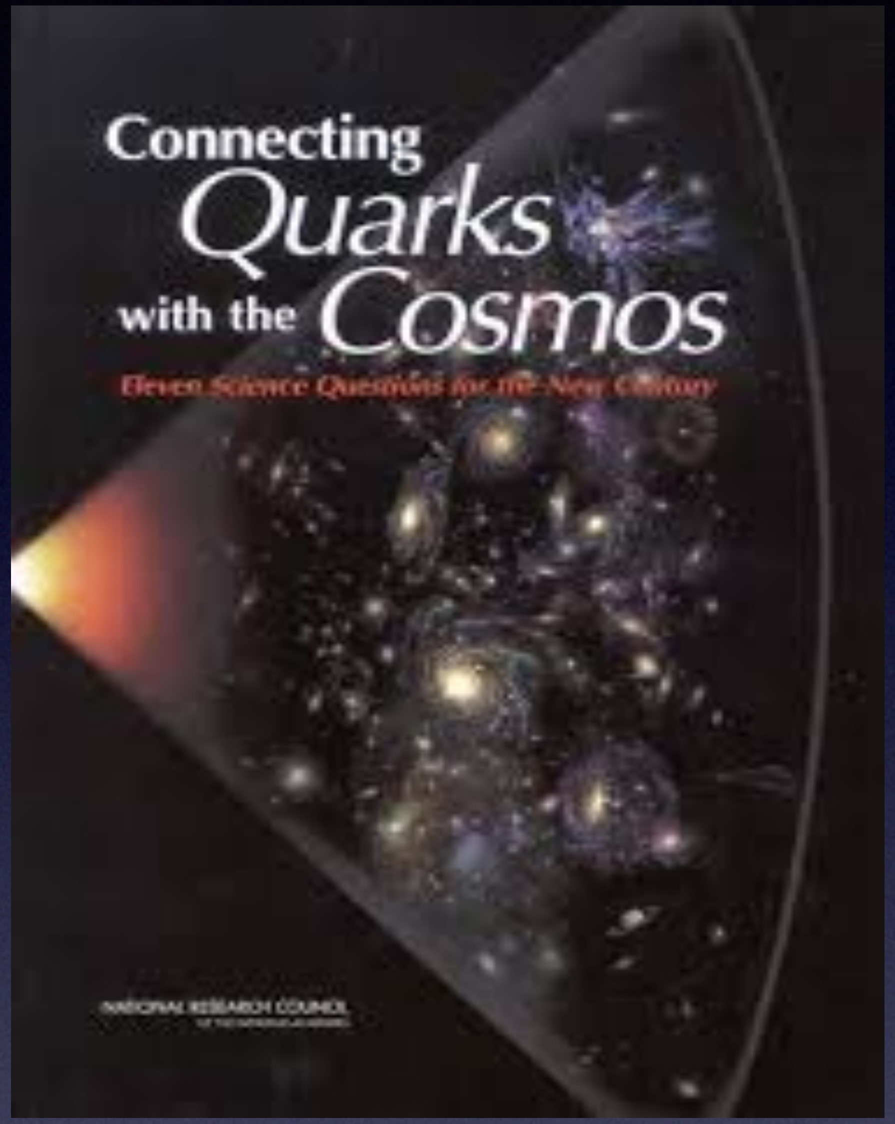
J. Piekarewicz
Florida State University

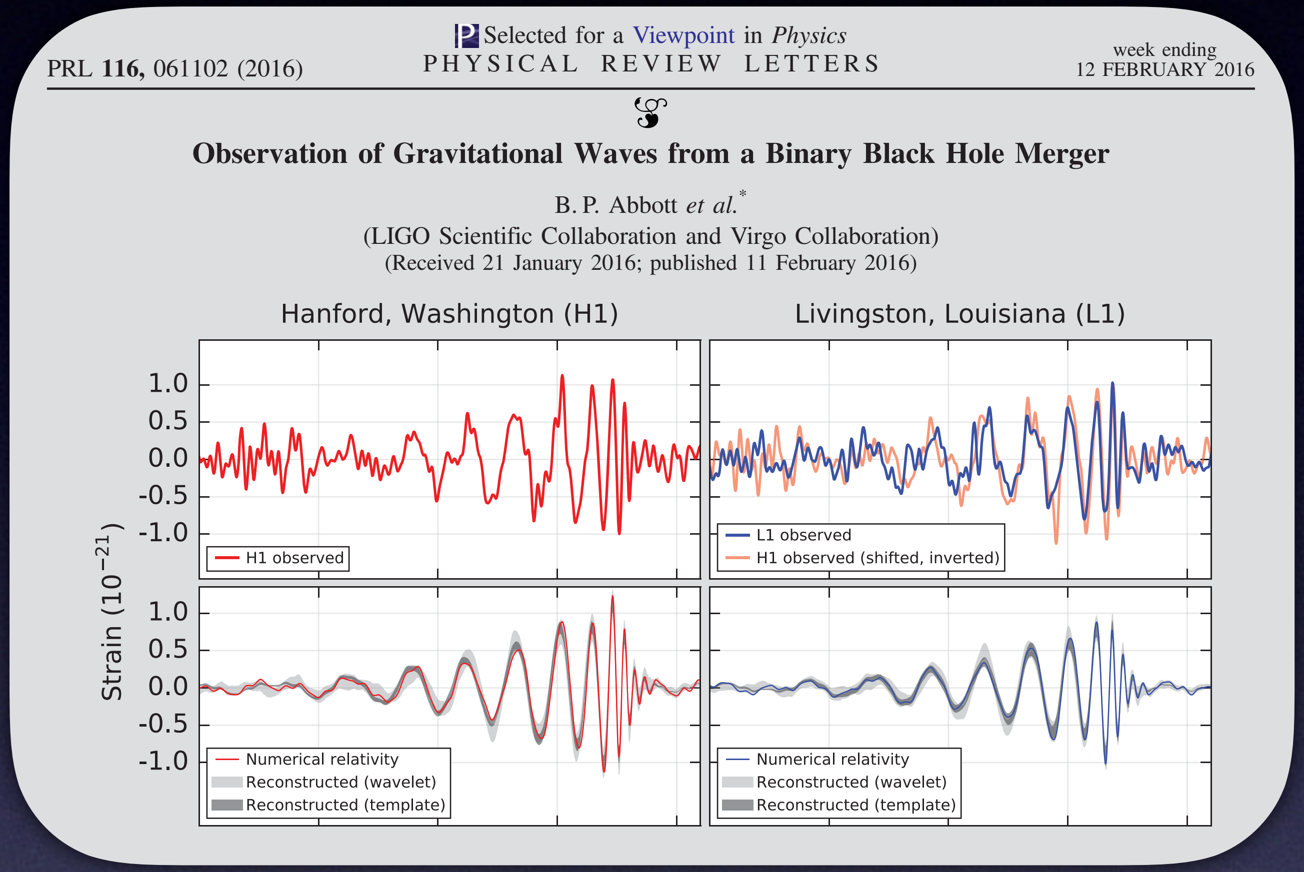






Connecting Quarks with the Cosmos
Eleven Science Questions for the Next Century



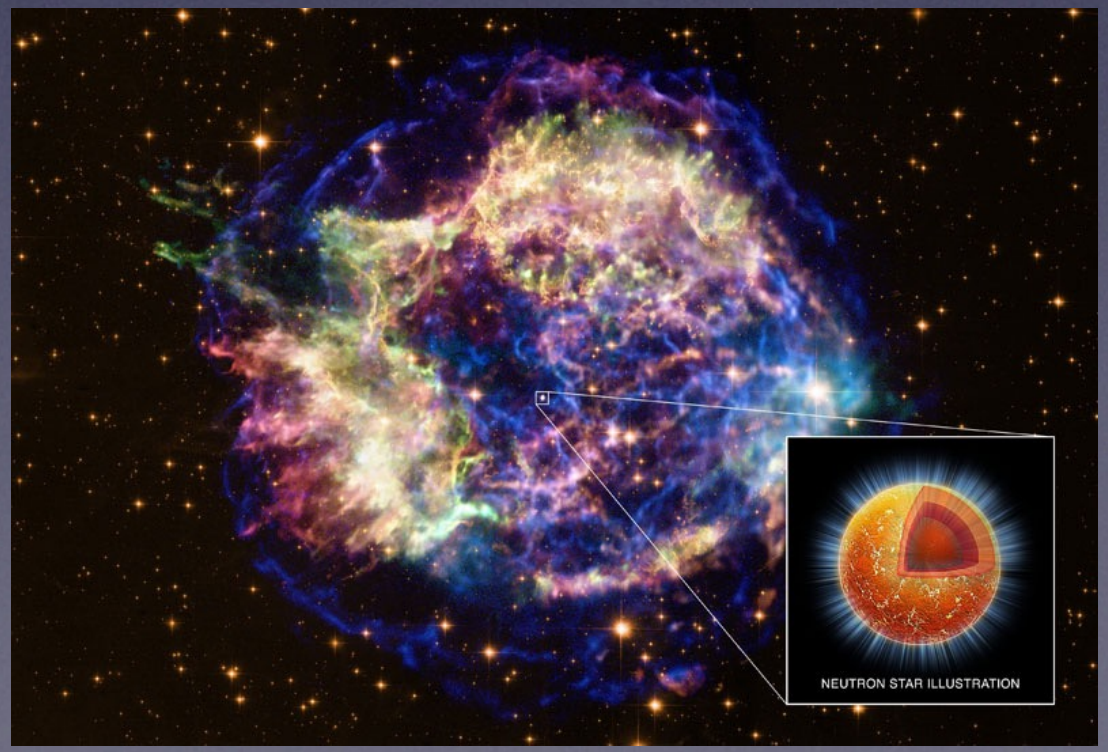


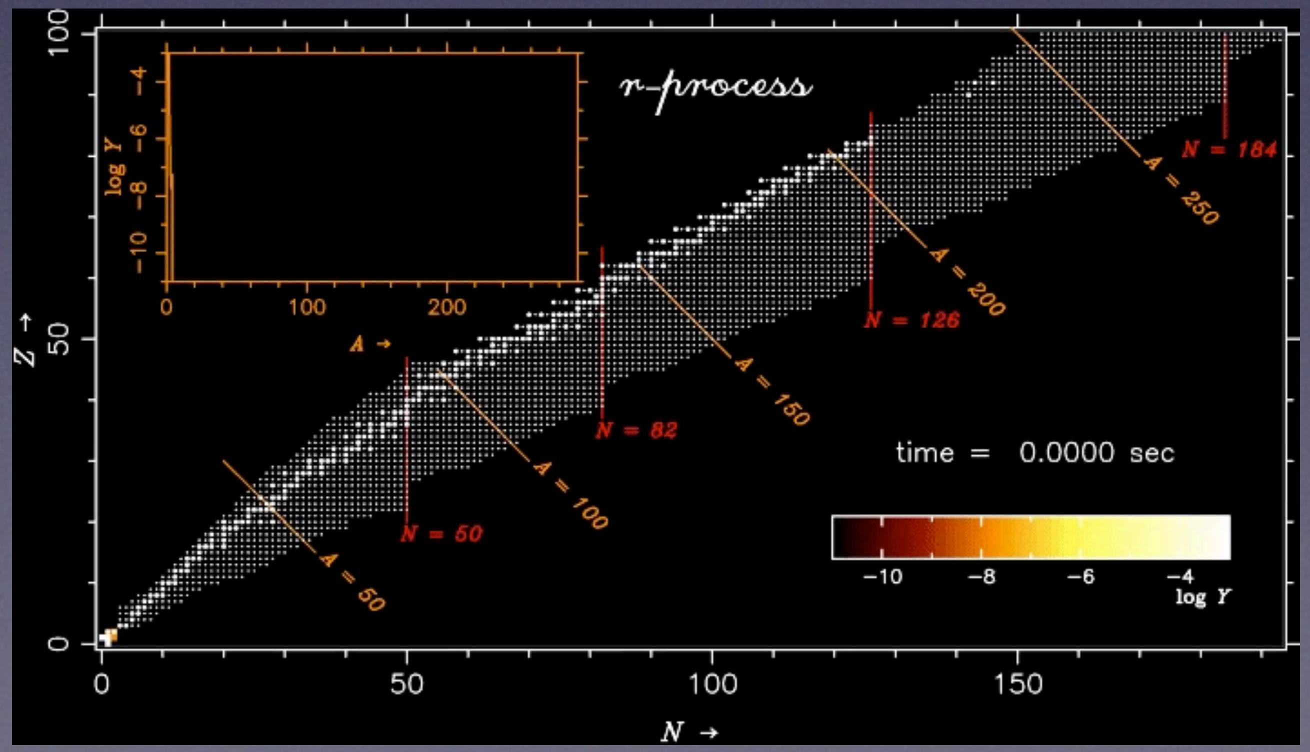
PRL 116, 061102 (2016)
Selected for a Viewpoint in Physics
PHYSICAL REVIEW LETTERS
week ending 12 FEBRUARY 2016

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)





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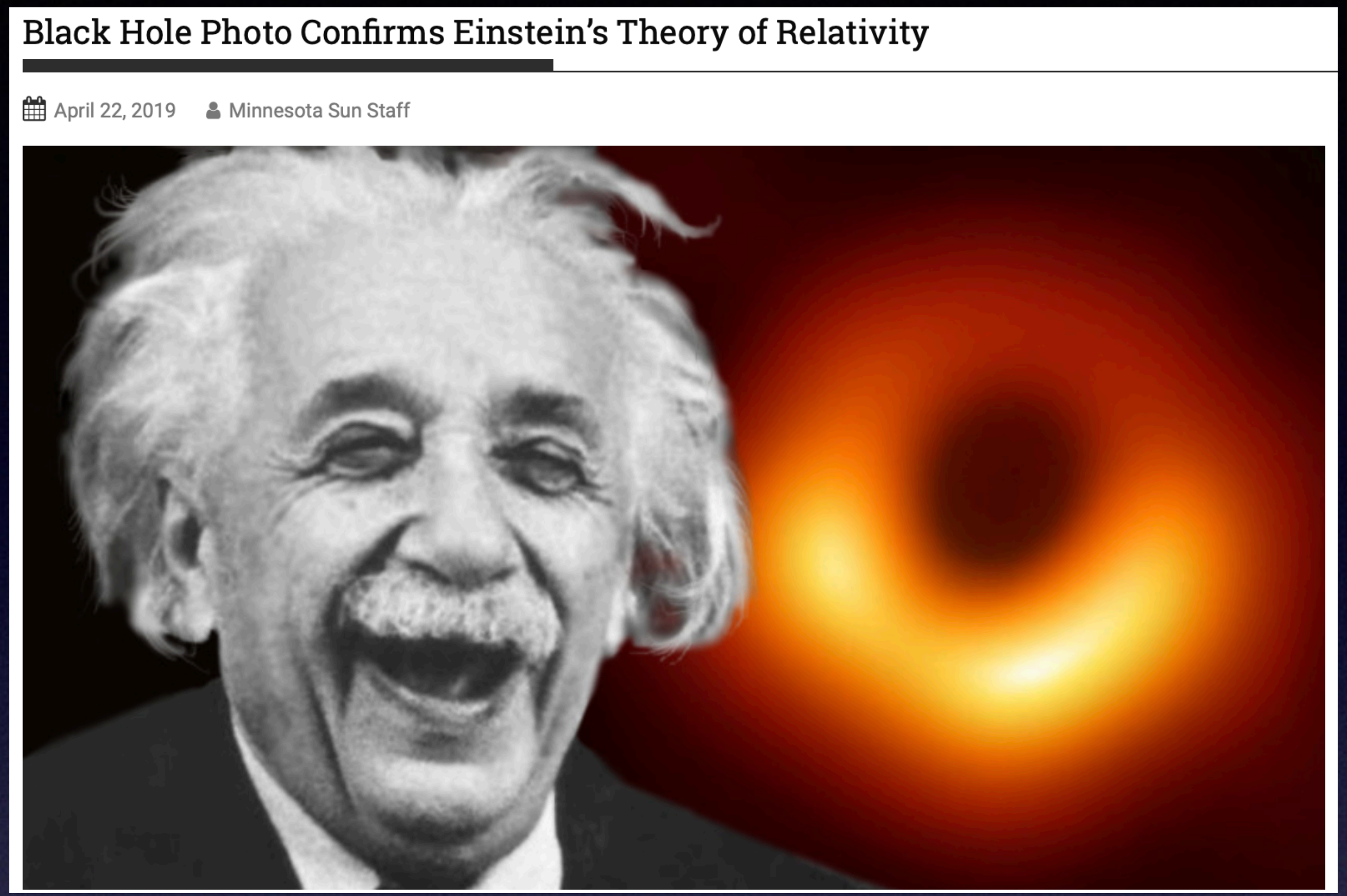
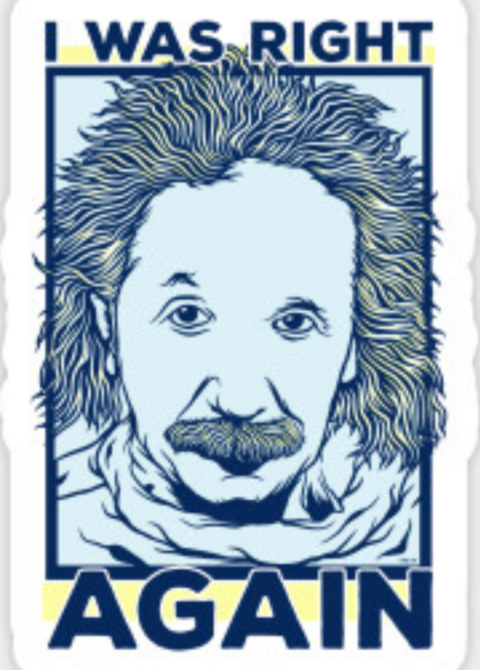
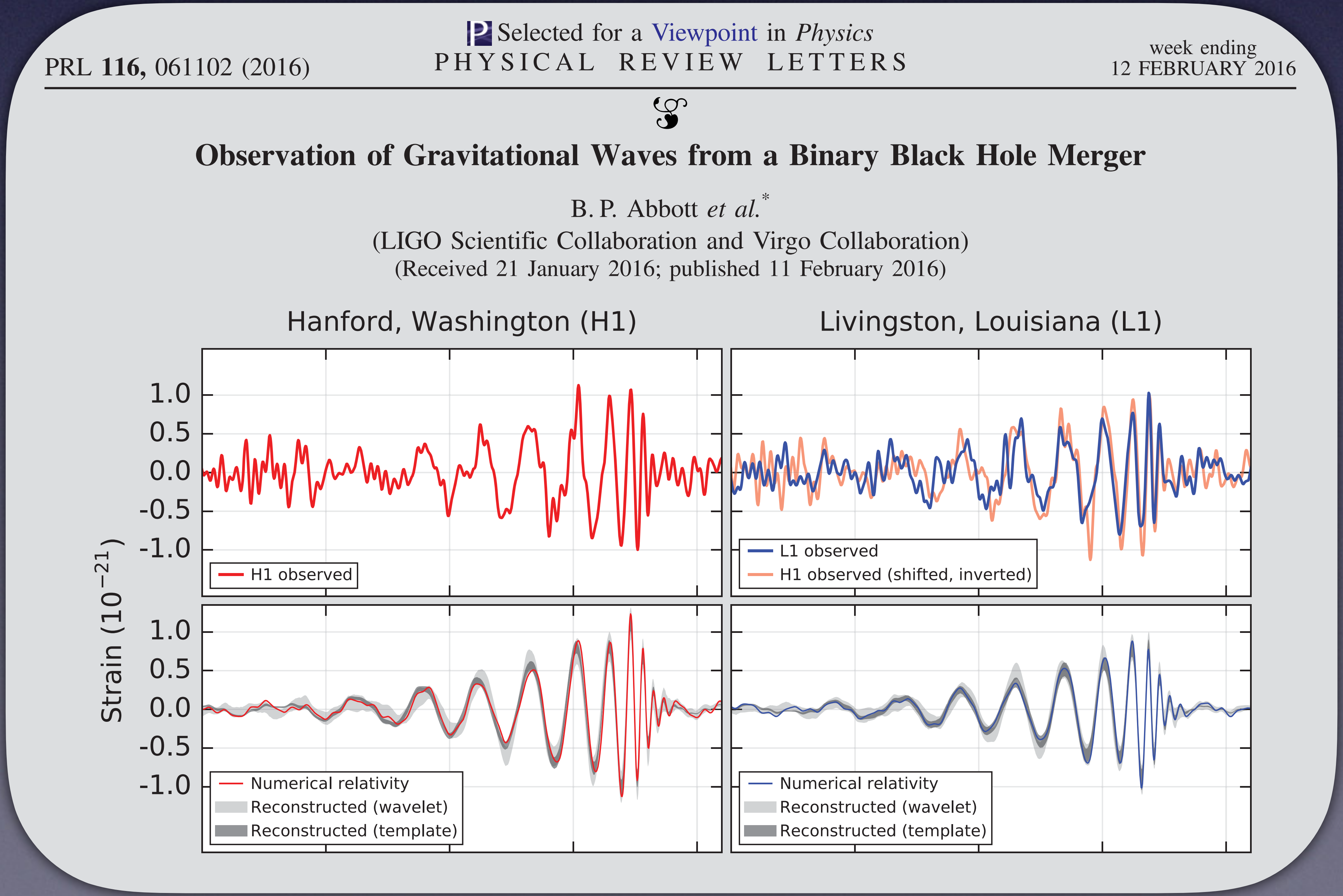
Testing General Relativity in the Strong Coupling Limit


Black Hole Photo Confirms Einstein's Theory of Relativity

April 22, 2019 Minnesota Sun Staff





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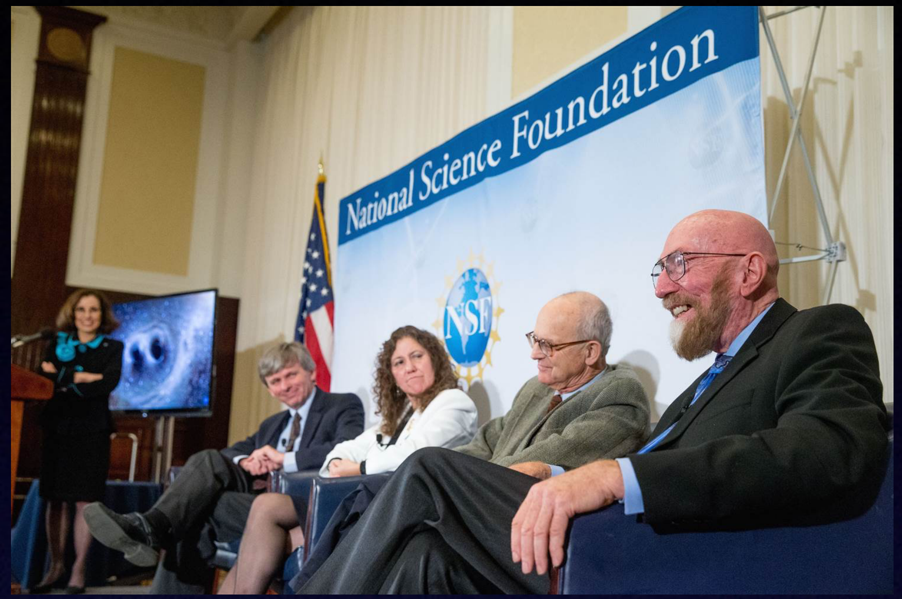
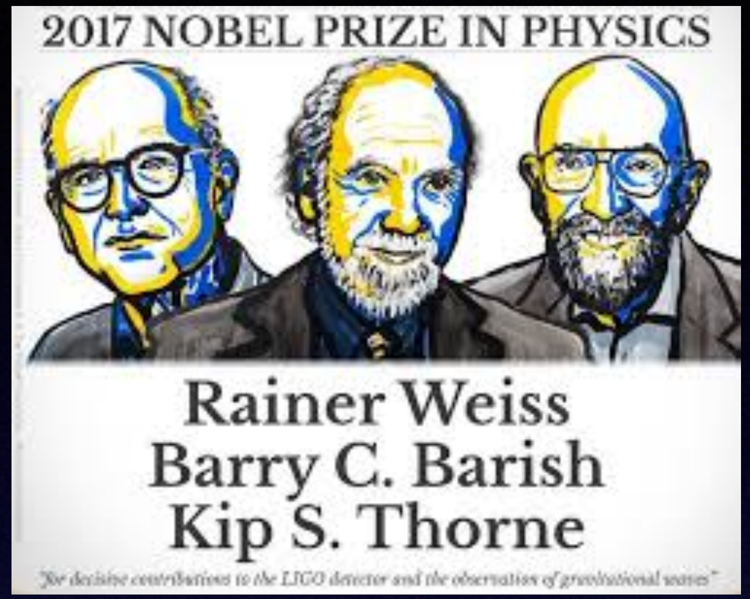
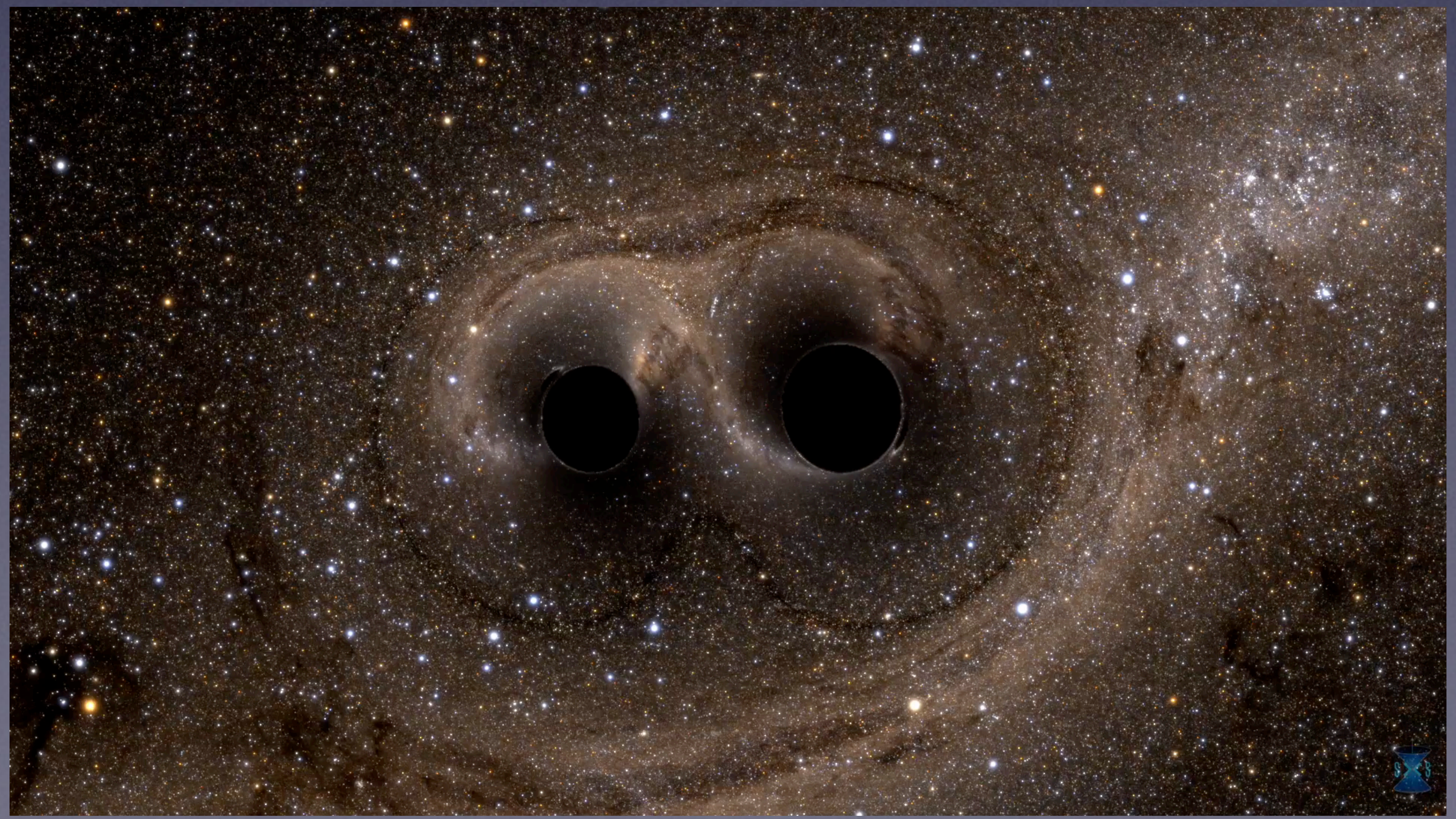
"We have detected gravitational waves; we did it"
David Reitze, February 11, 2016

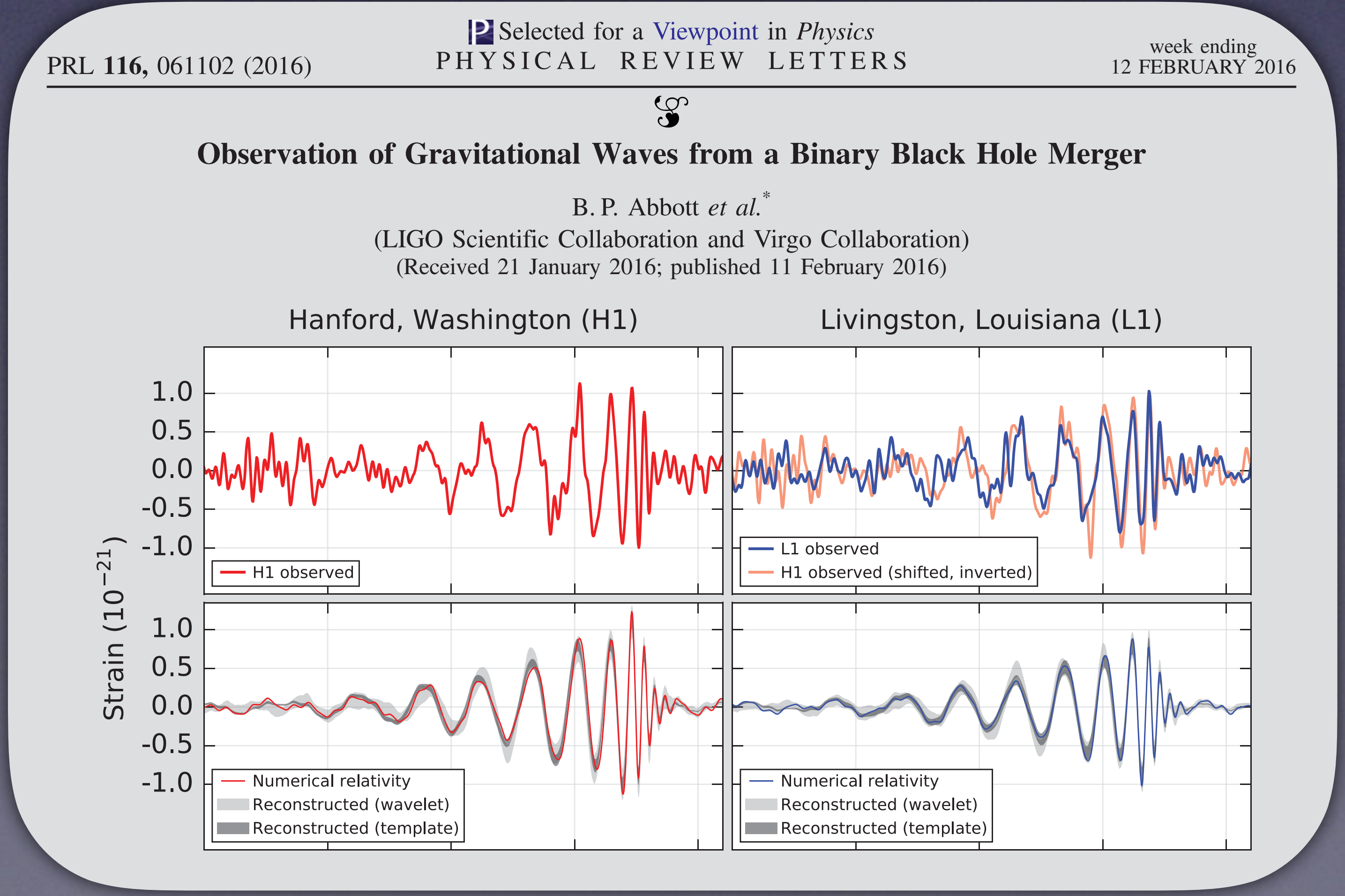
GW170817





- 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!





PRL 116, 061102 (2016) Selected for a Viewpoint in Physics 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)

Neutron Rich Matter in Heaven:

The historical first detection of gravitational waves from a binary neutron-star merger

GW170817: A play in three acts

- Act 1: LIGO detects GW from BNS merger
  - Extraction of “tidal polarizability”

    Stringent limits on the EOS of dense matter
- Act 2: Fermi/Integral detect short γ-ray burst
  - detected ~2 seconds after GW signal
  - Confirms long-held belief of the association between BNS merger and γ-ray bursts
- Act 3: ~70 telescopes tracked the “kilonova”
  - Afterglow of the explosive merger ~11 hours later
  - Powered by the radioactive decay of “r-process” elements

    BNS mergers as a critical site for the r-process!

PRL **119,** 161101 (2017)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

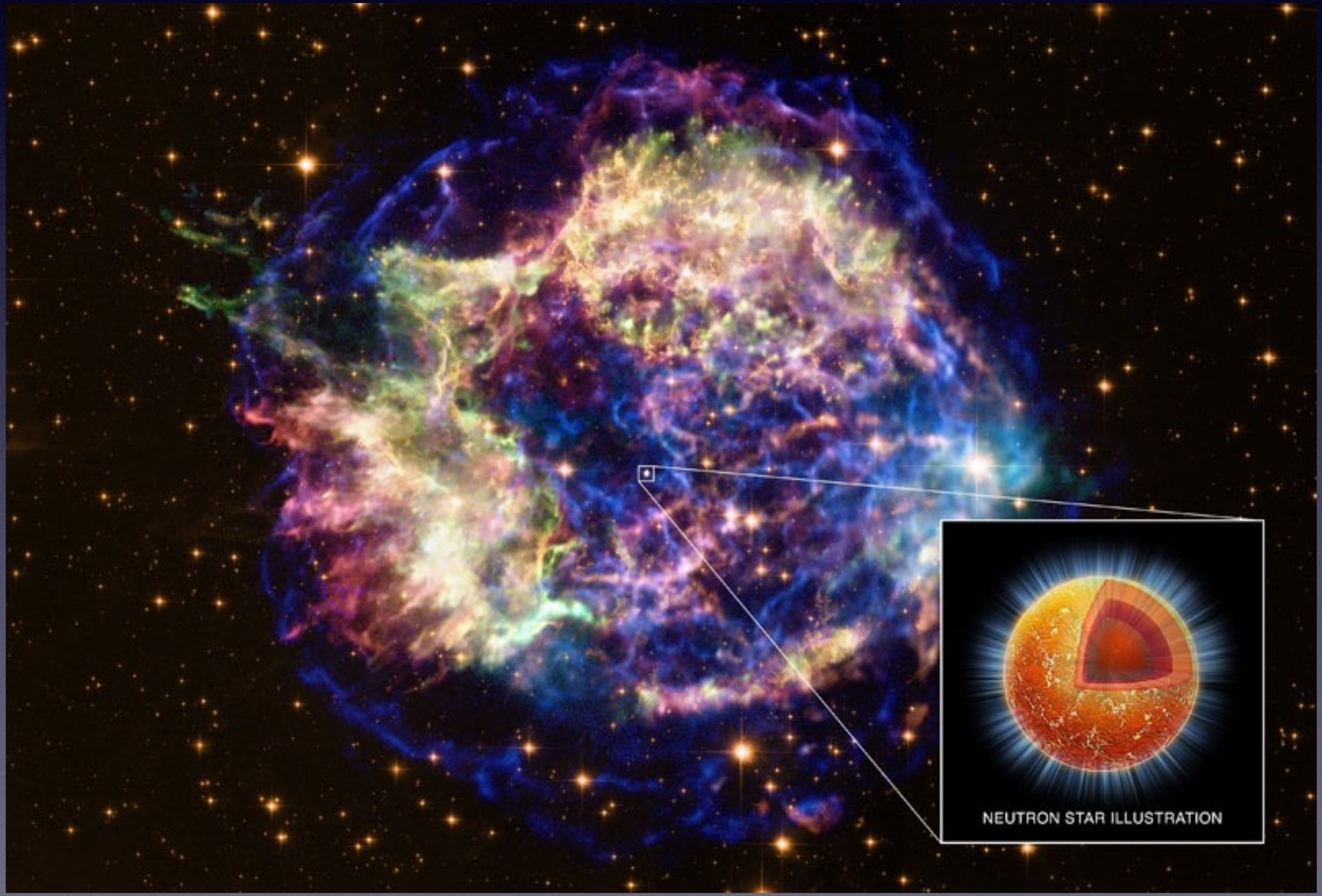
B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

Neutron-star mergers create gravitational waves, light, and gold!

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



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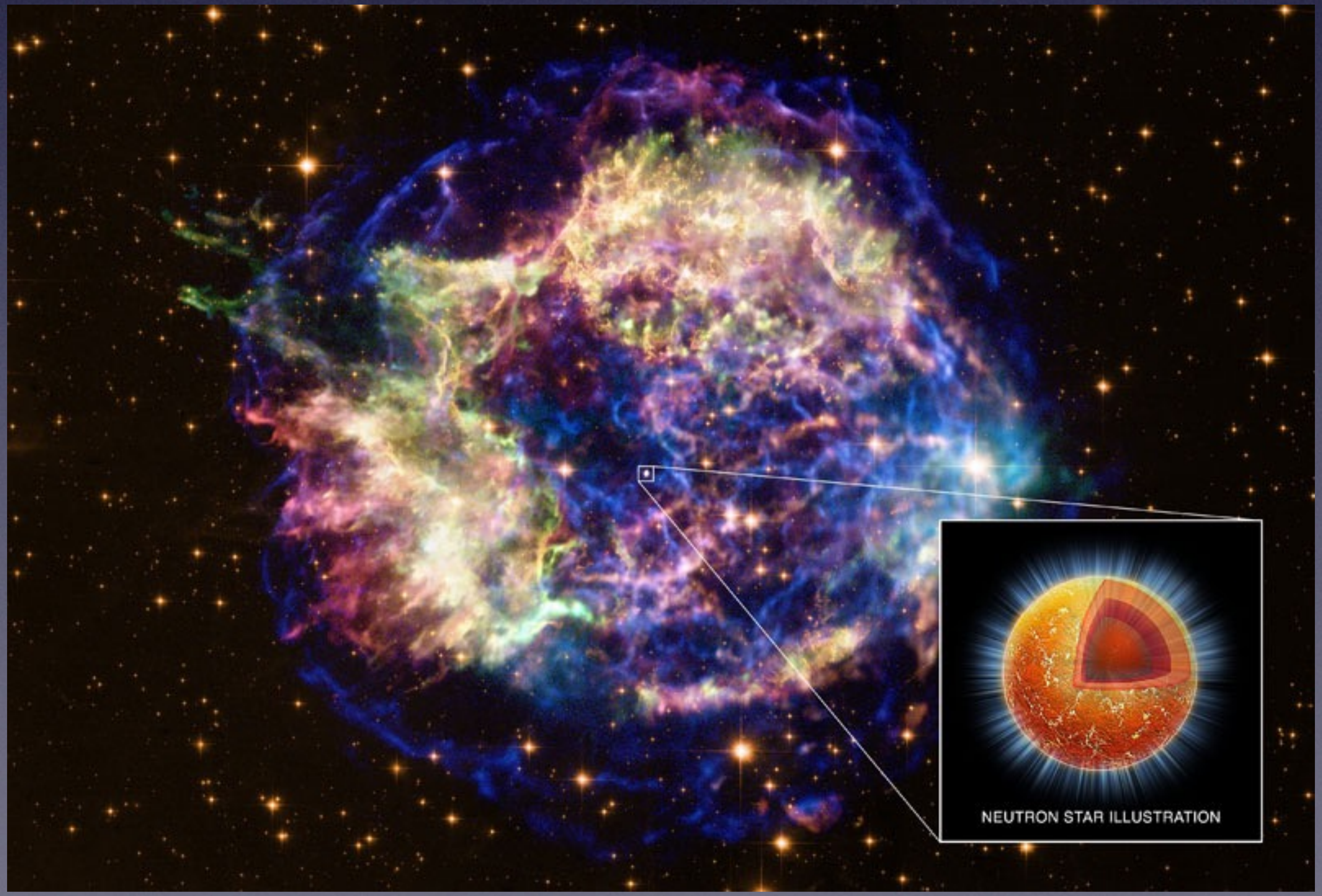
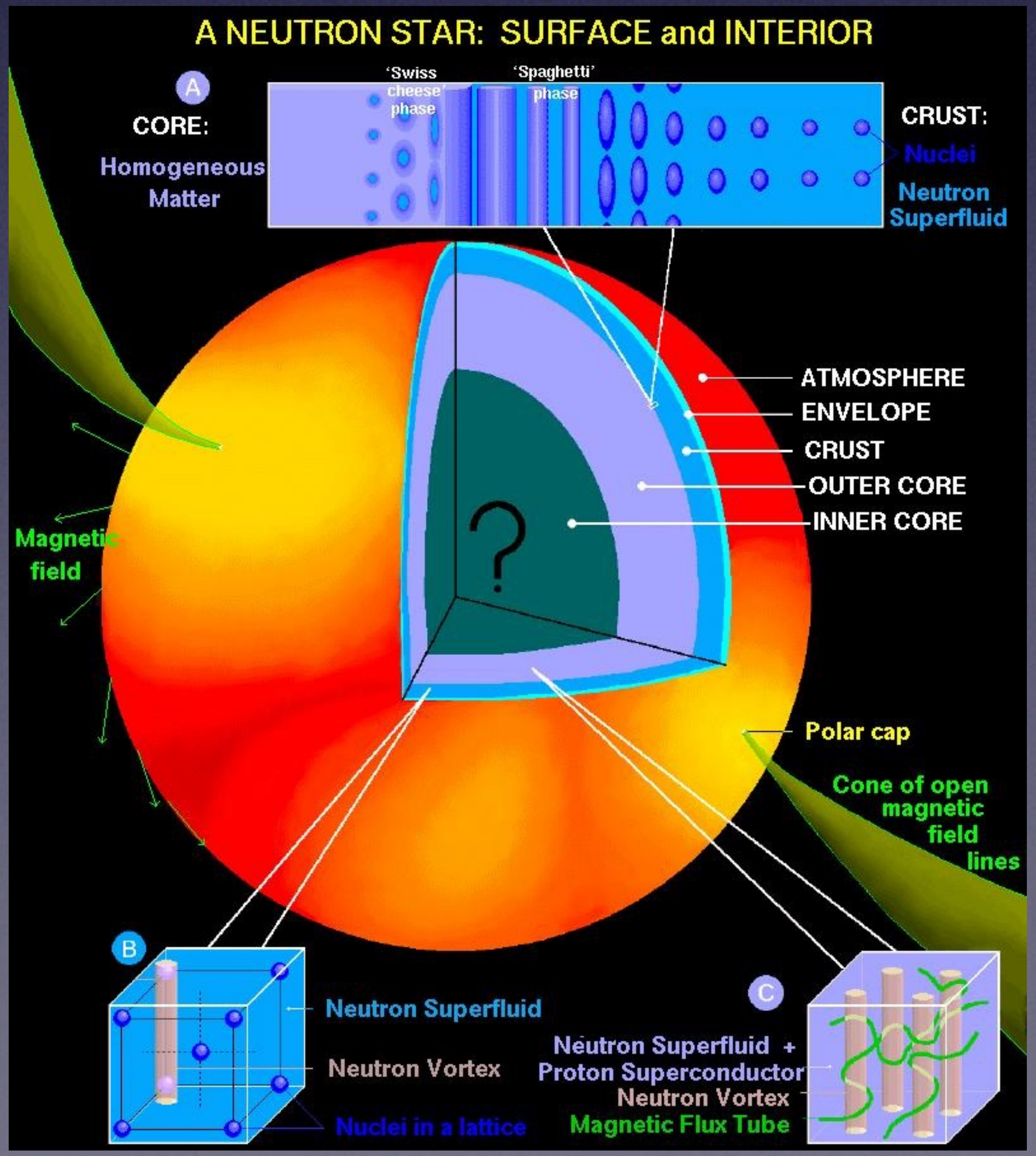
The Anatomy of a Neutron Star

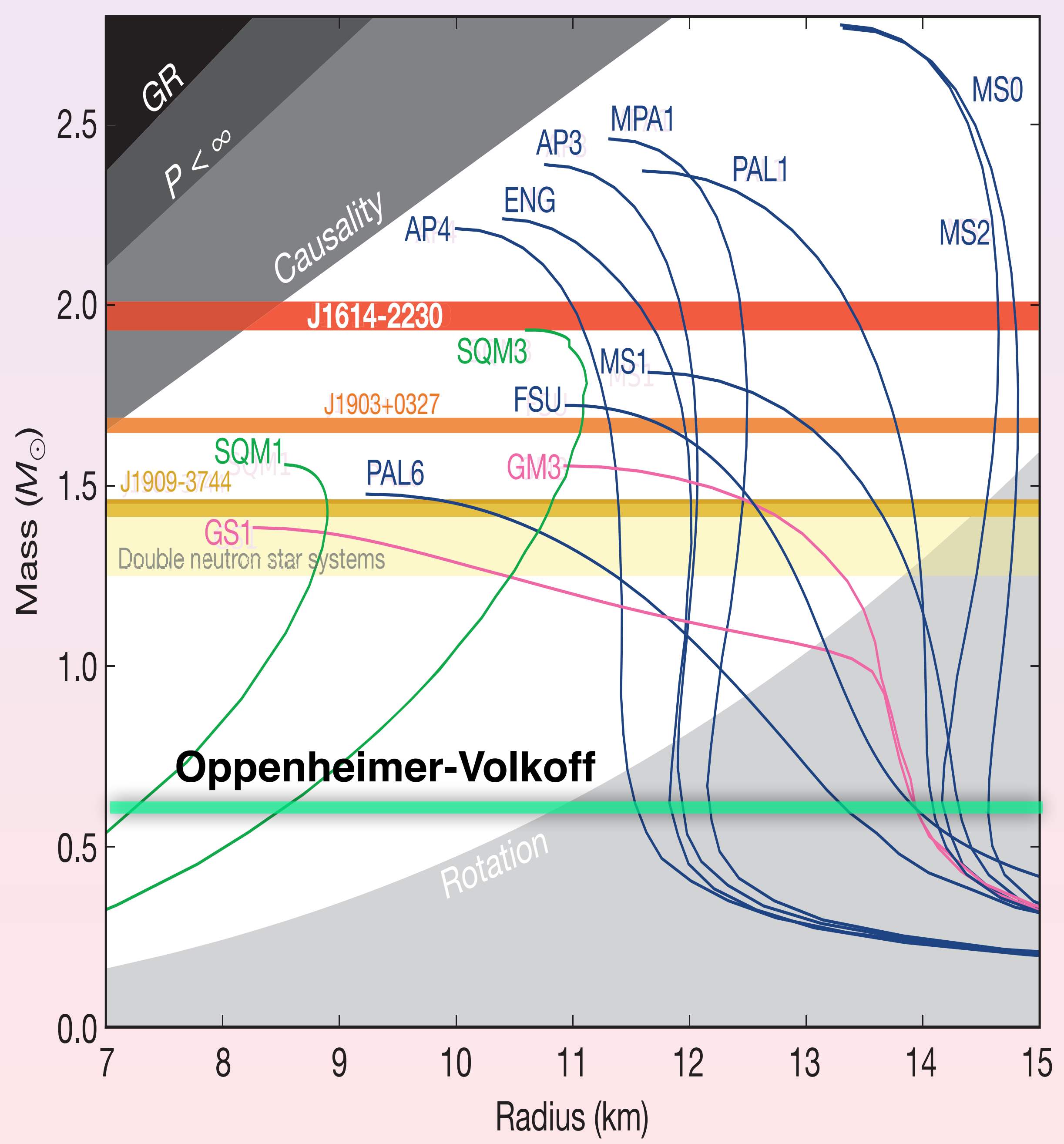
- Atmosphere (10 cm): Shapes Thermal Radiation ($L=4\pi\sigma R^2T^4$)
- Envelope (100 m): Huge Temperature Gradient (10^8K $\leftrightarrow$ 10^6K)
- Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)
- Inner Crust (1 km): Coulomb Frustration (“Nuclear Pasta”)
- Outer Core (10 km): Uniform 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
  - Bound by gravity — NOT by the strong force
  - Satisfy the TOV equations ($v_{esc}/c \sim 1/2$)
- 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

$\boxed{\text{Nuclear Physics Critical}}$

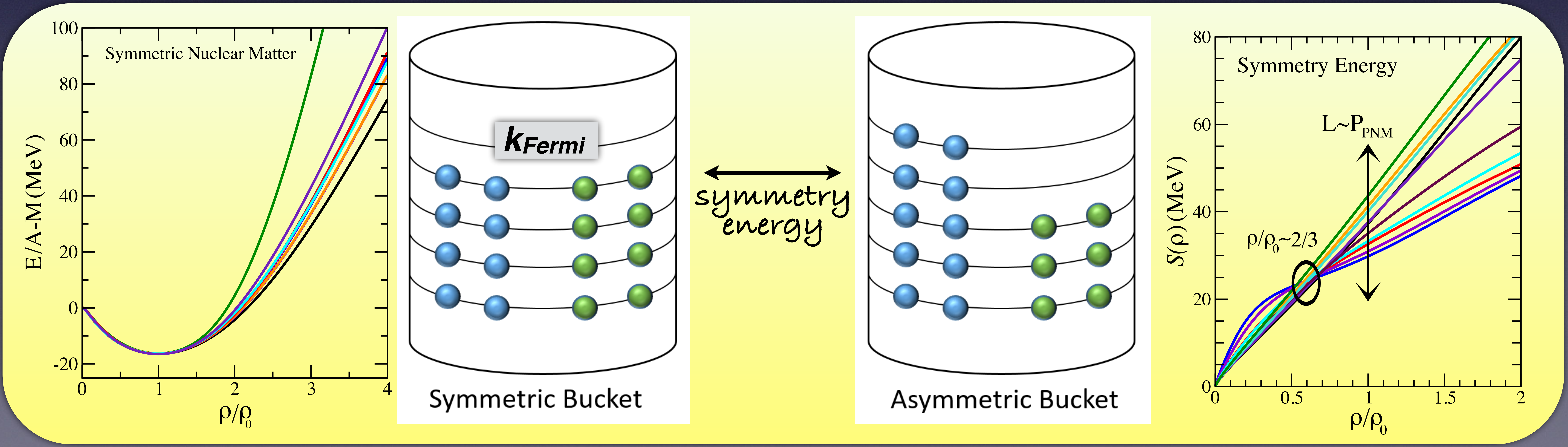
Many nuclear models that accurately predict the properties of finite nuclei yield enormous variations in the prediction of neutron-star radii and maximum mass

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: $x=(\rho-\rho_0)/3\rho_0$; $\rho_0 \simeq 0.15$ fm-3

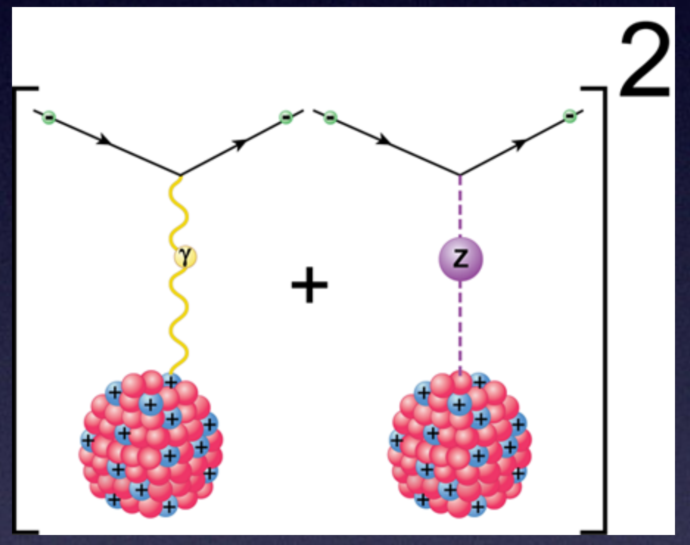
$$\mathcal{E}(\rho,\alpha) \simeq \mathcal{E}_0(\rho) + \alpha^2 \mathcal{S}(\rho) \simeq \left(\epsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + Lx + \frac{1}{2}K_{\rm sym}x^2\right)\alpha^2$$

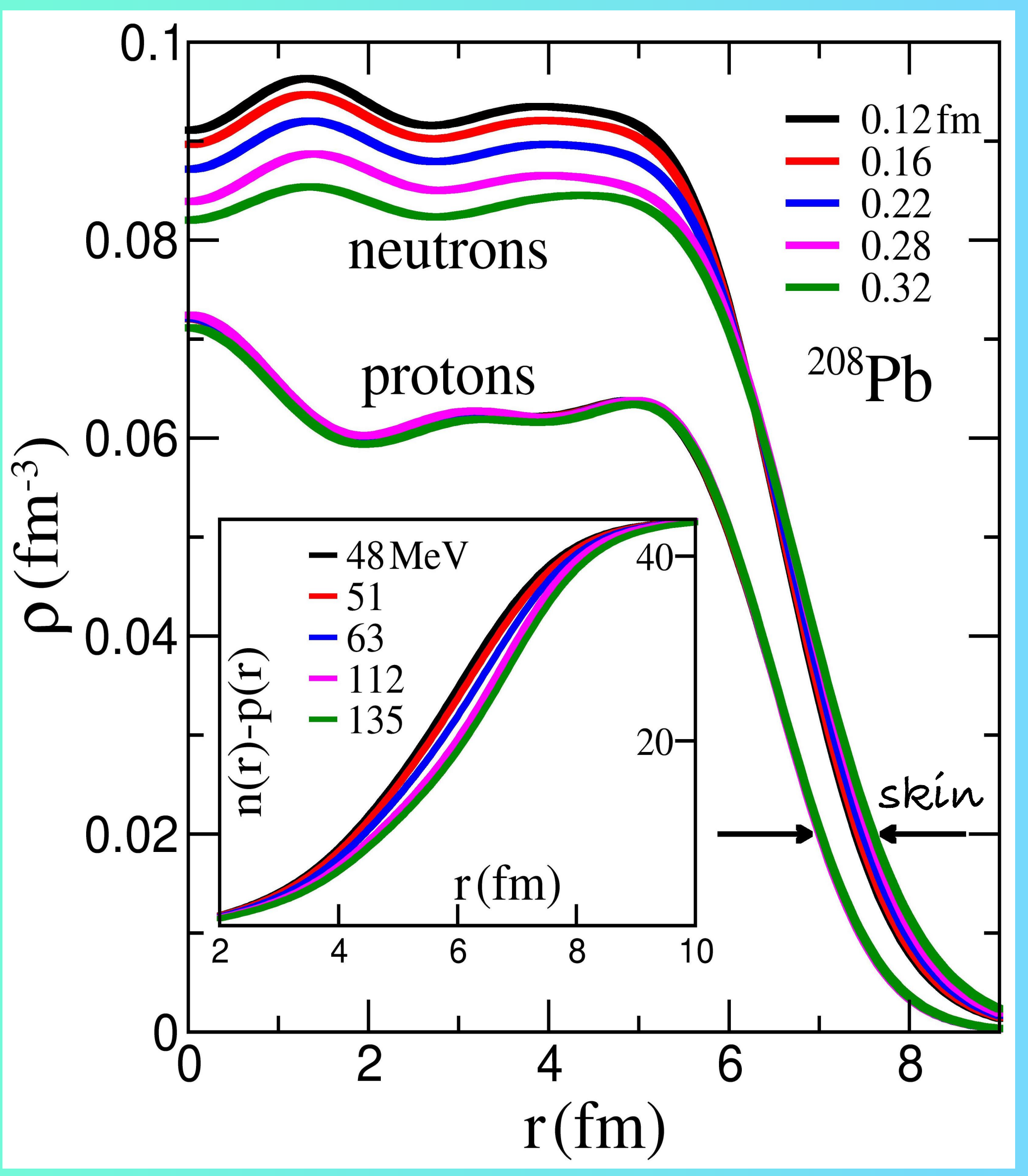
- Density dependence of symmetry energy poorly constrained!!
  "L" symmetry slope ~ pressure of pure neutron matter at saturation

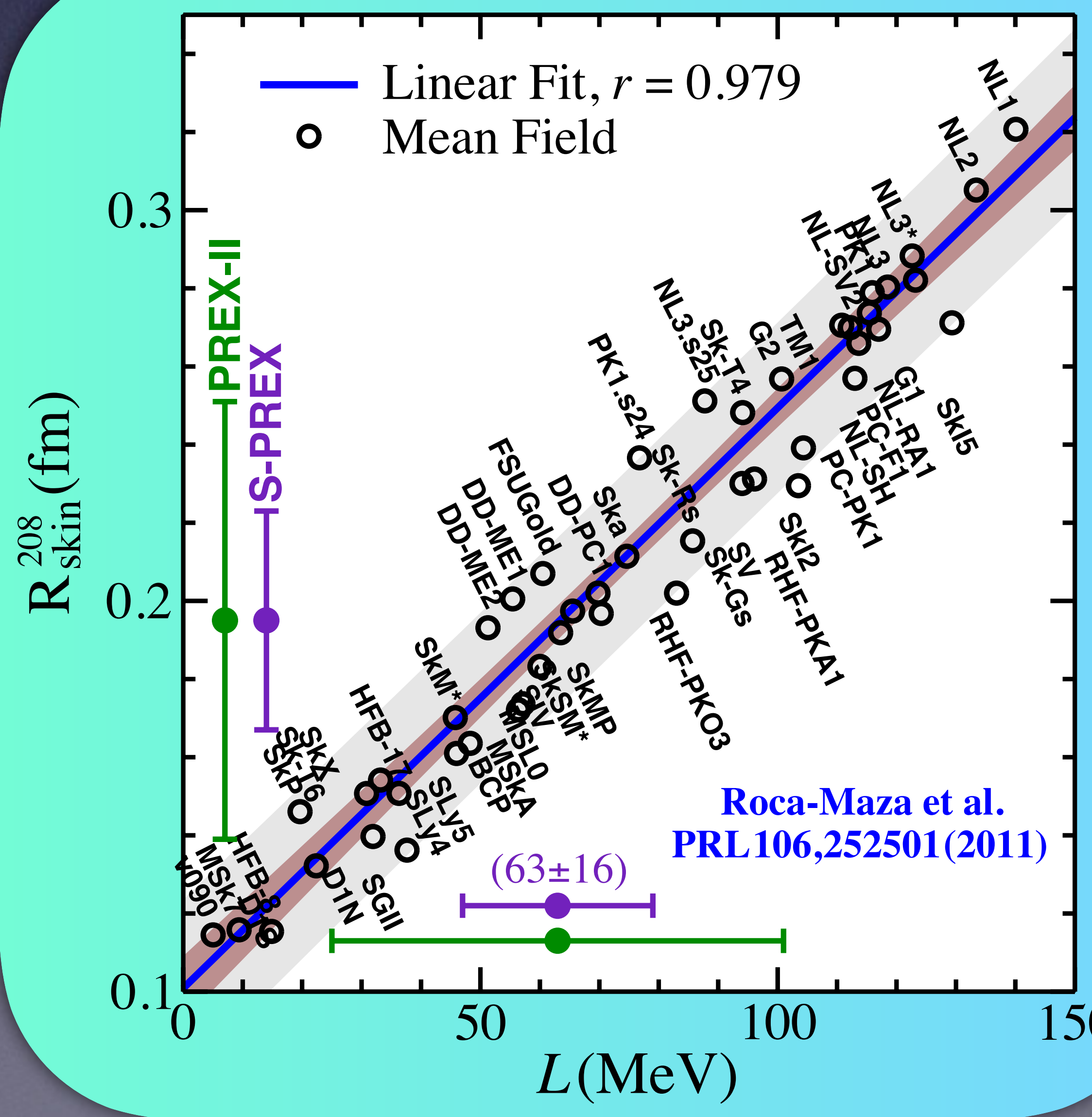


Neutron-Star Structure at JLab: R_{skin} as a proxy for L

- 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 2019
  - Original goal of 1% in neutron radius







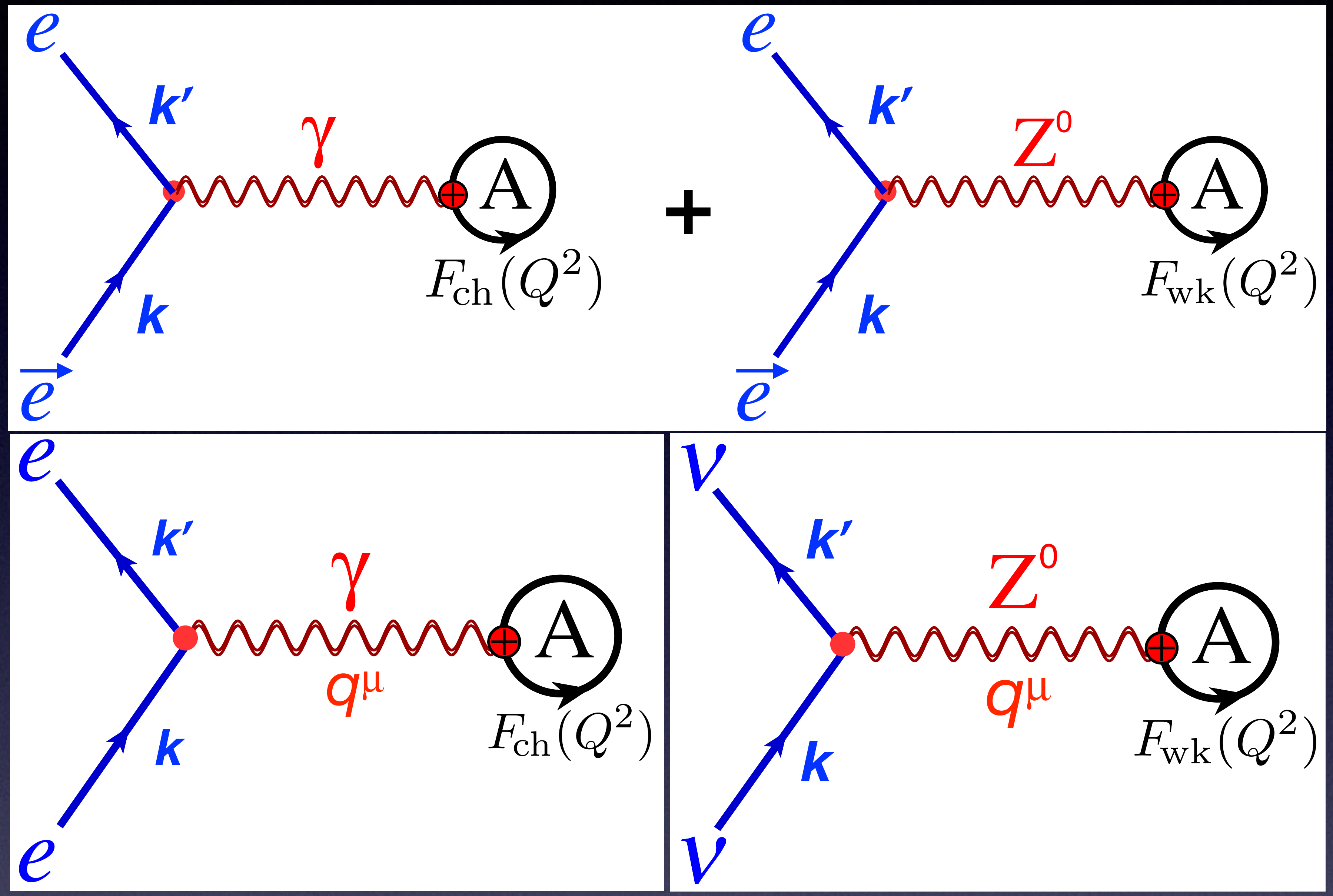
$$A_{\rm PV} \equiv \left[\frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L}\right] = \left(\frac{G_{\rm F}Q^2}{4\pi\alpha\sqrt{2}}\right)\frac{F_{wk}(Q^2)}{F_{ch}(Q^2)} \simeq 10^{-6}$$

	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

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

Electroweak Probes of Nuclear Densities

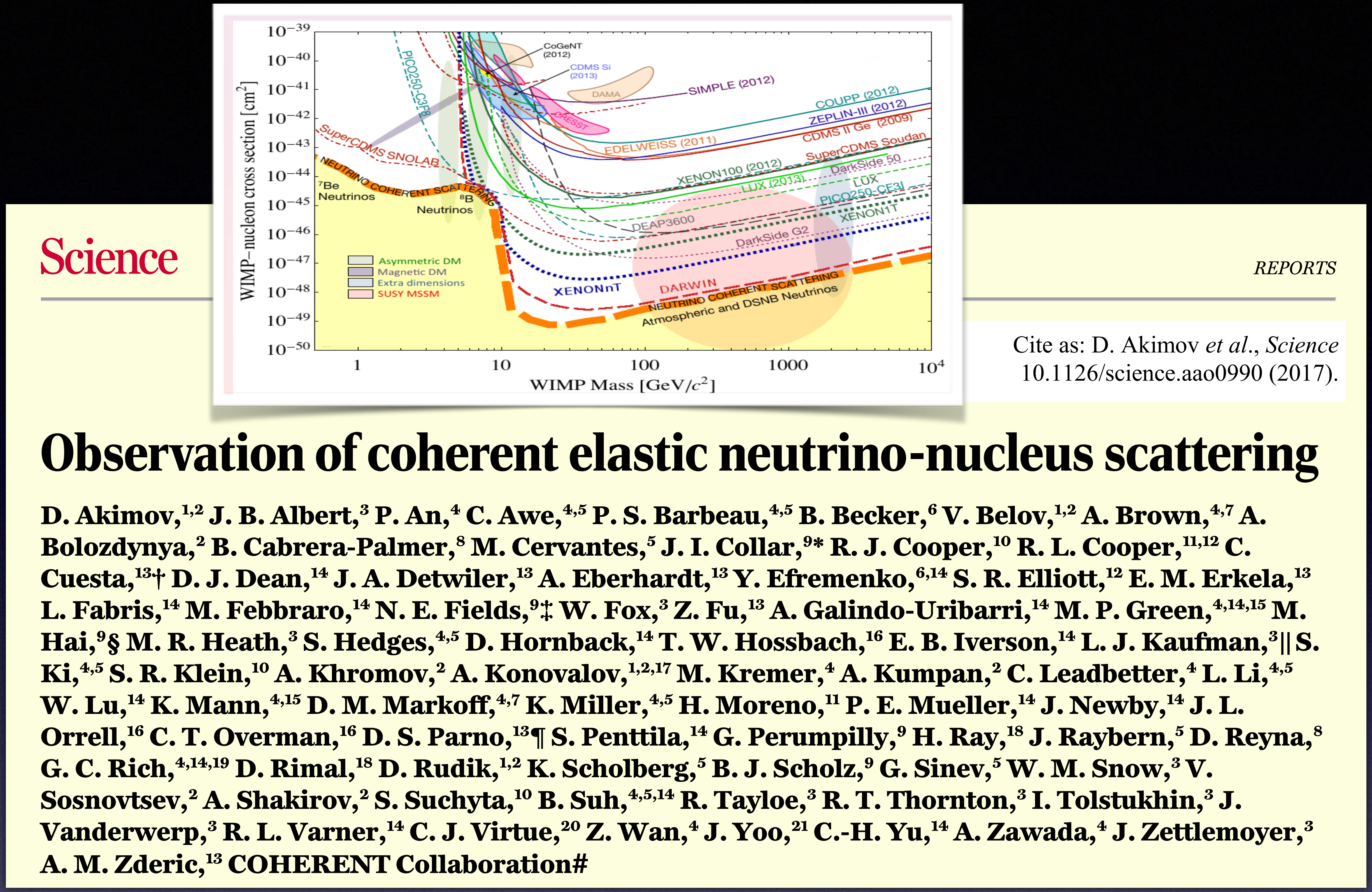
CEvNS



$$A_{PV}(Q^2) = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_{wk} F_{wk}(Q^2)}{Z F_{ch}(Q^2)}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm EM} = \left[\frac{\alpha^2 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)}\left(\frac{E'}{E}\right)\right] Z^2 F_{ch}^2(Q^2)$$

$$\left(\frac{d\sigma}{dT}\right)_{\rm NC} = \frac{G_F^2}{8\pi} M \left[2 - 2\frac{T}{E} - \frac{MT}{E^2}\right] Q_{wk}^2 F_{wk}^2(Q^2)$$



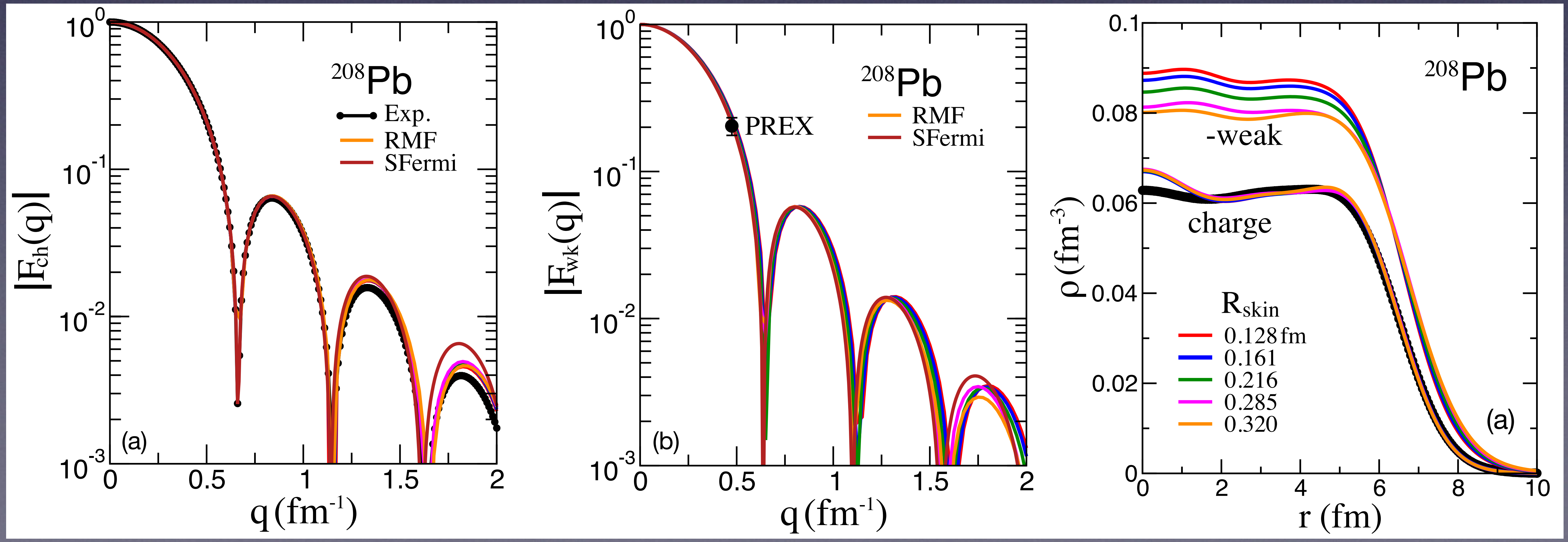
Science

REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]|| S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

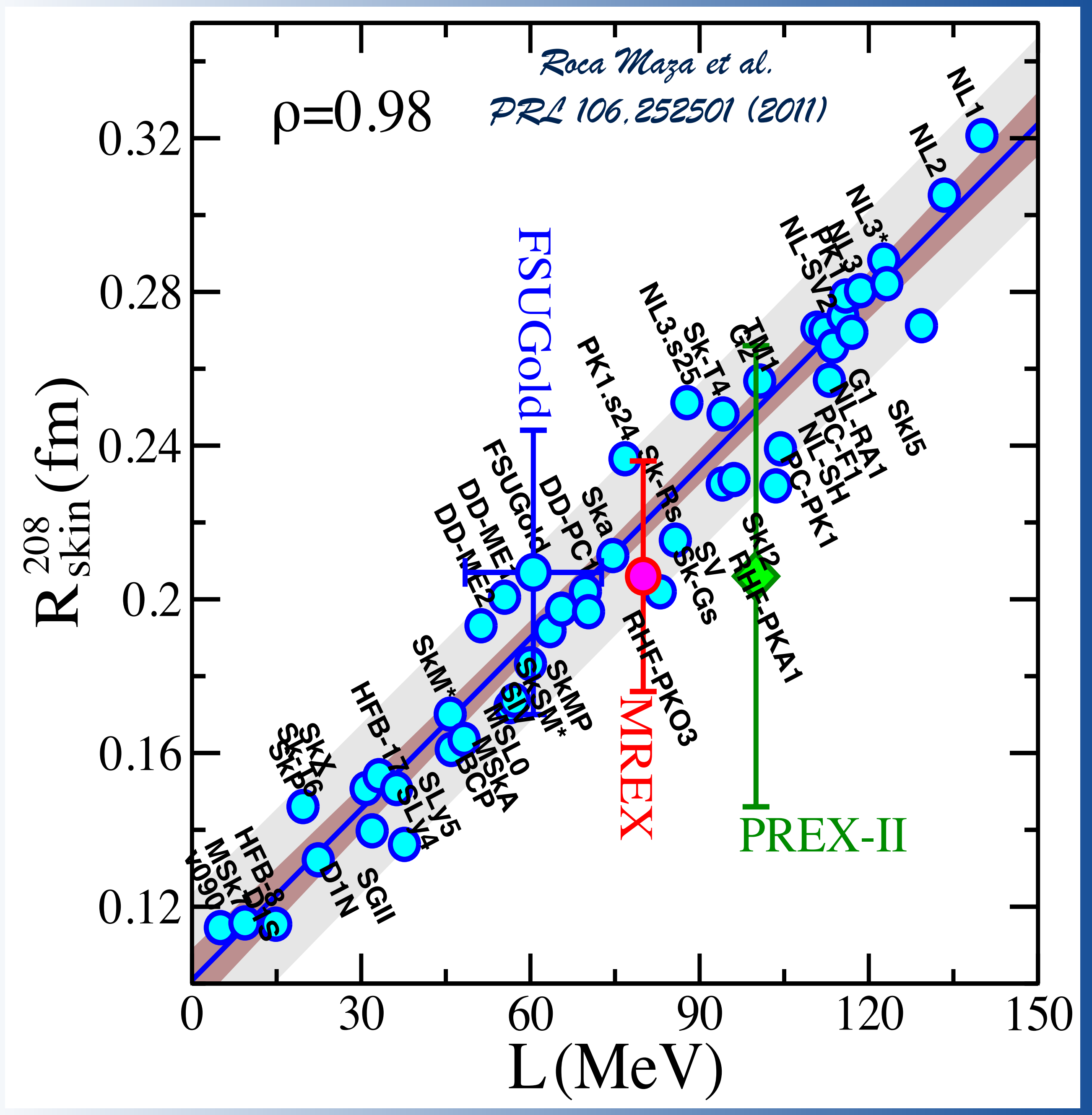


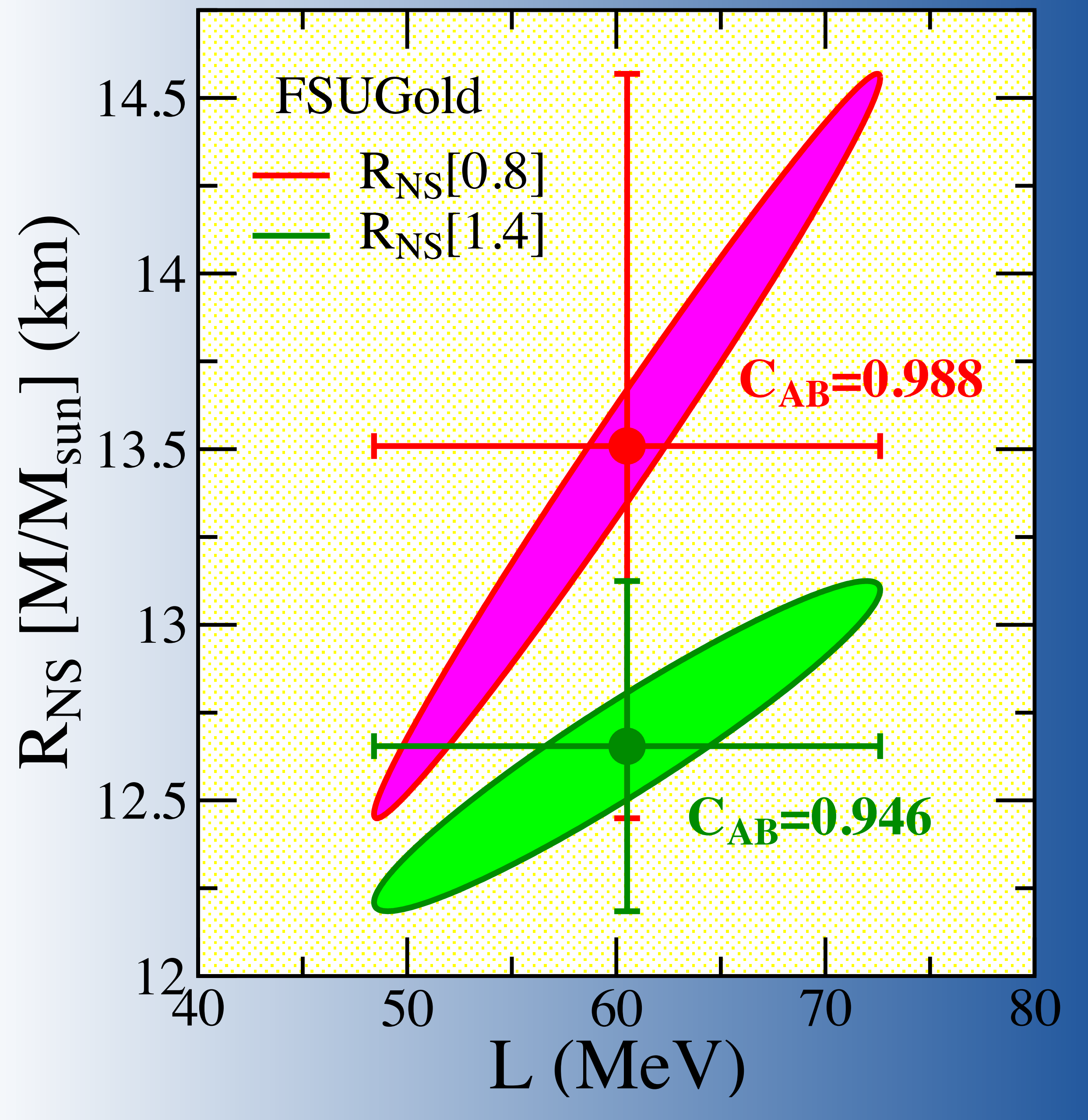
Neutron Rich Matter on Earth:

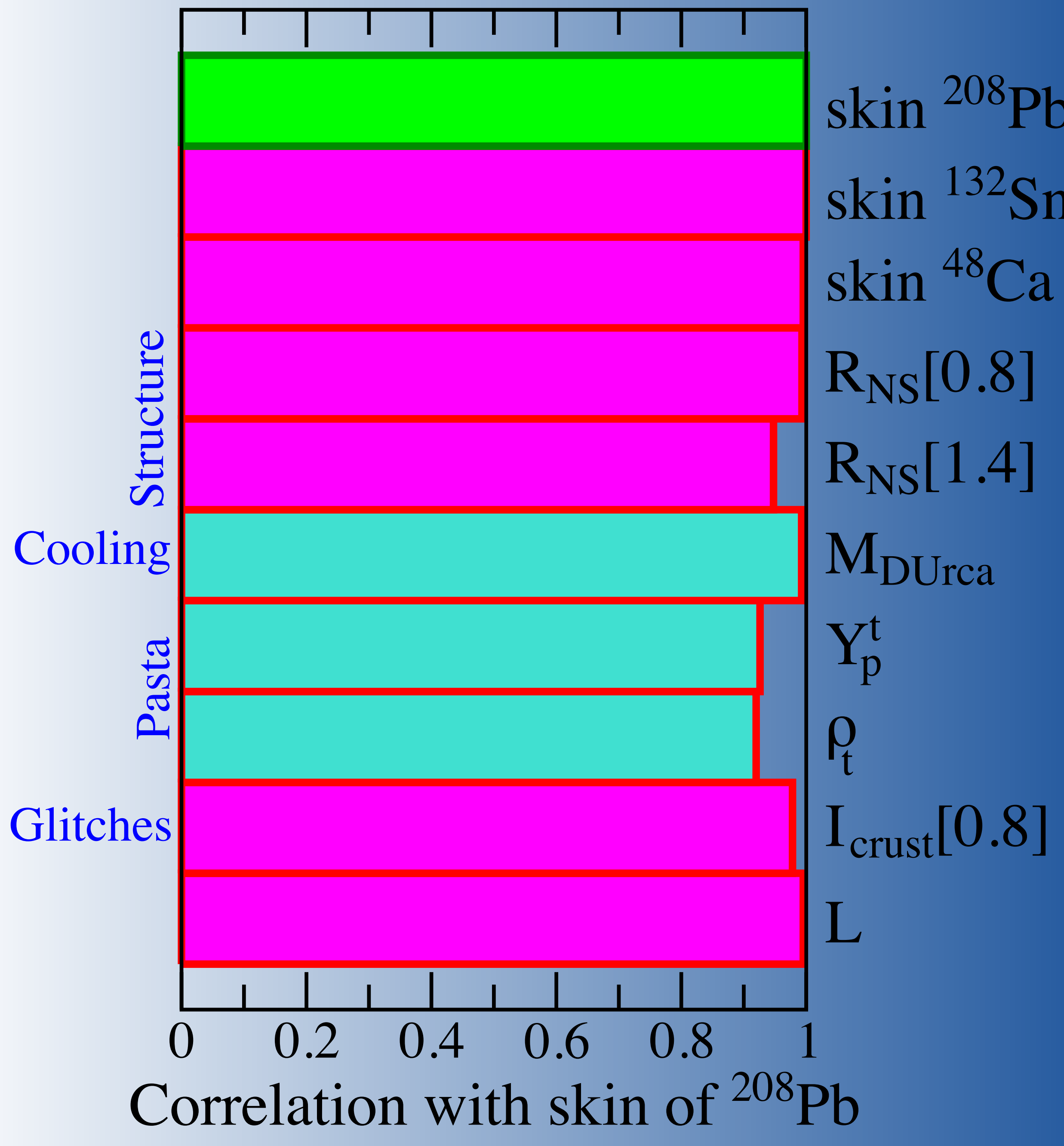
The Quest for “L” at Terrestrial Laboratories

- Although a fundamental parameter of the EOS, L is ***NOT*** a physical observable
- 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
- … As well as many other stellar properties sensitive to the symmetry energy

18 orders of magnitude!!







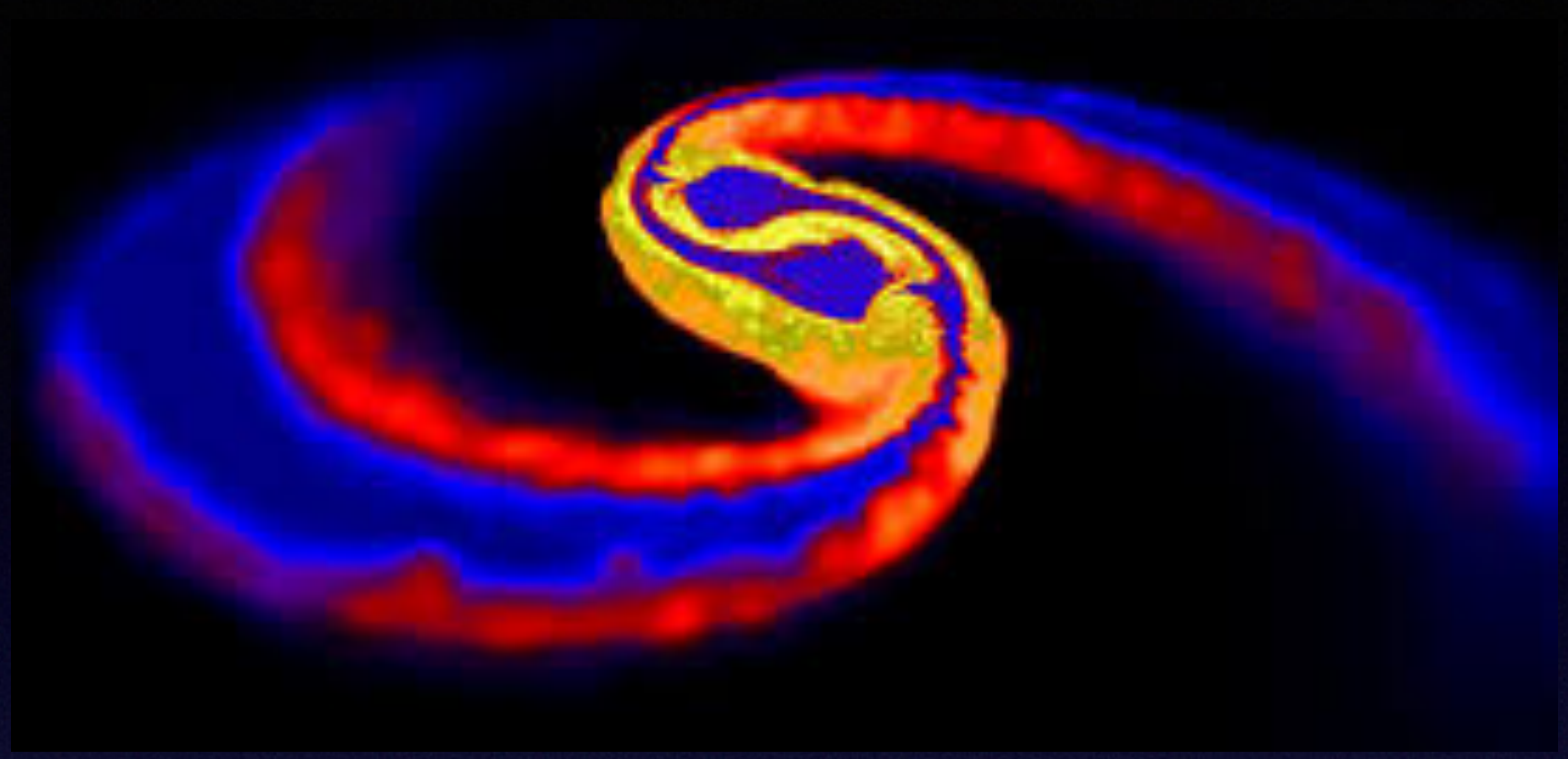
Tidal Polarizability and Neutron-Star Radii

Electric Polarizability:

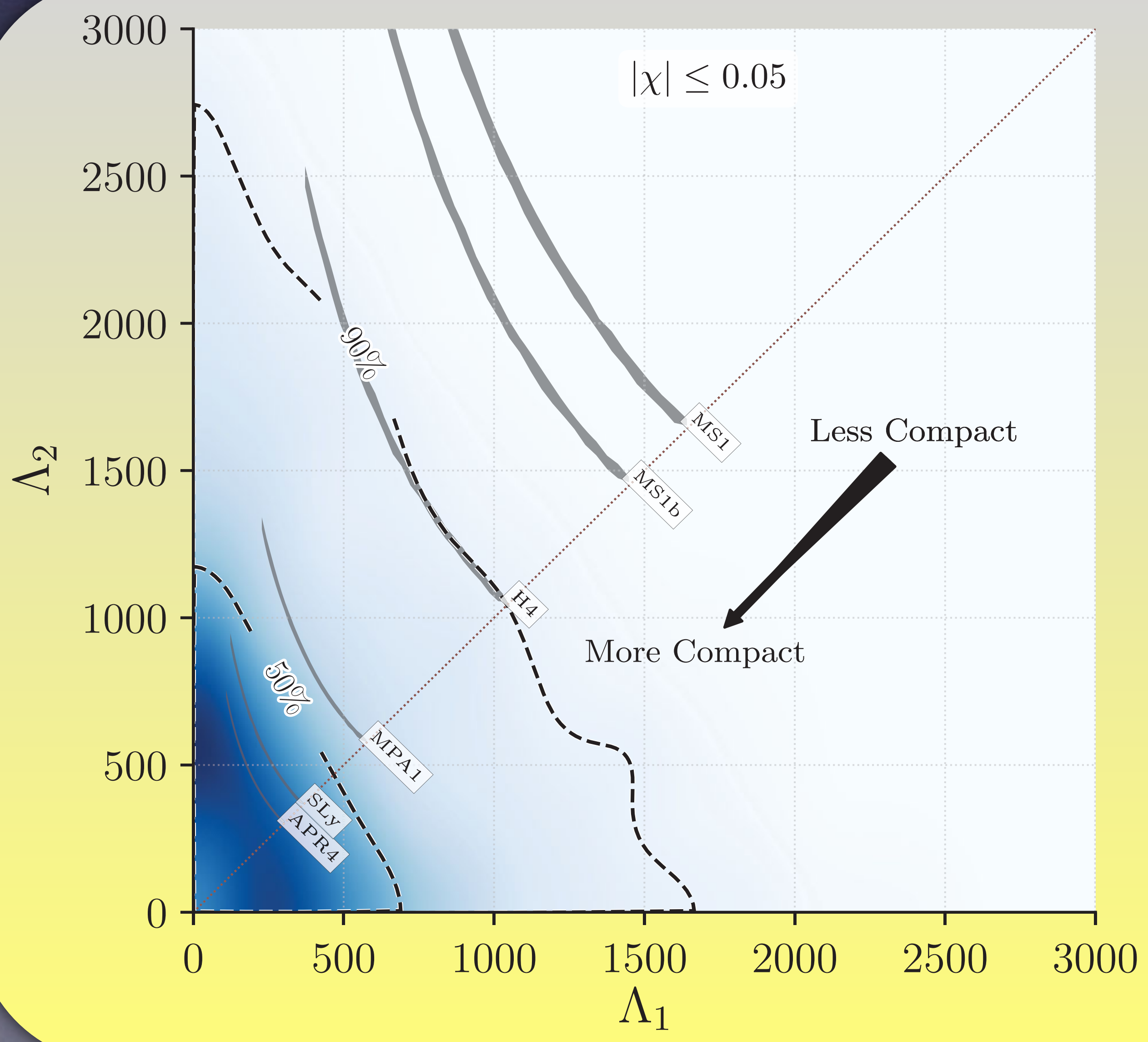
- Electric field induced a polarization of charge
- A time dependent electric dipole emits electromagnetic waves: $P_i = \chi E_i$

Tidal Polarizability:

- Tidal field induces a polarization of mass
- A time dependent mass quadrupole emits gravitational waves: $Q_{ij} = \Lambda \mathcal{E}_{ij}$



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

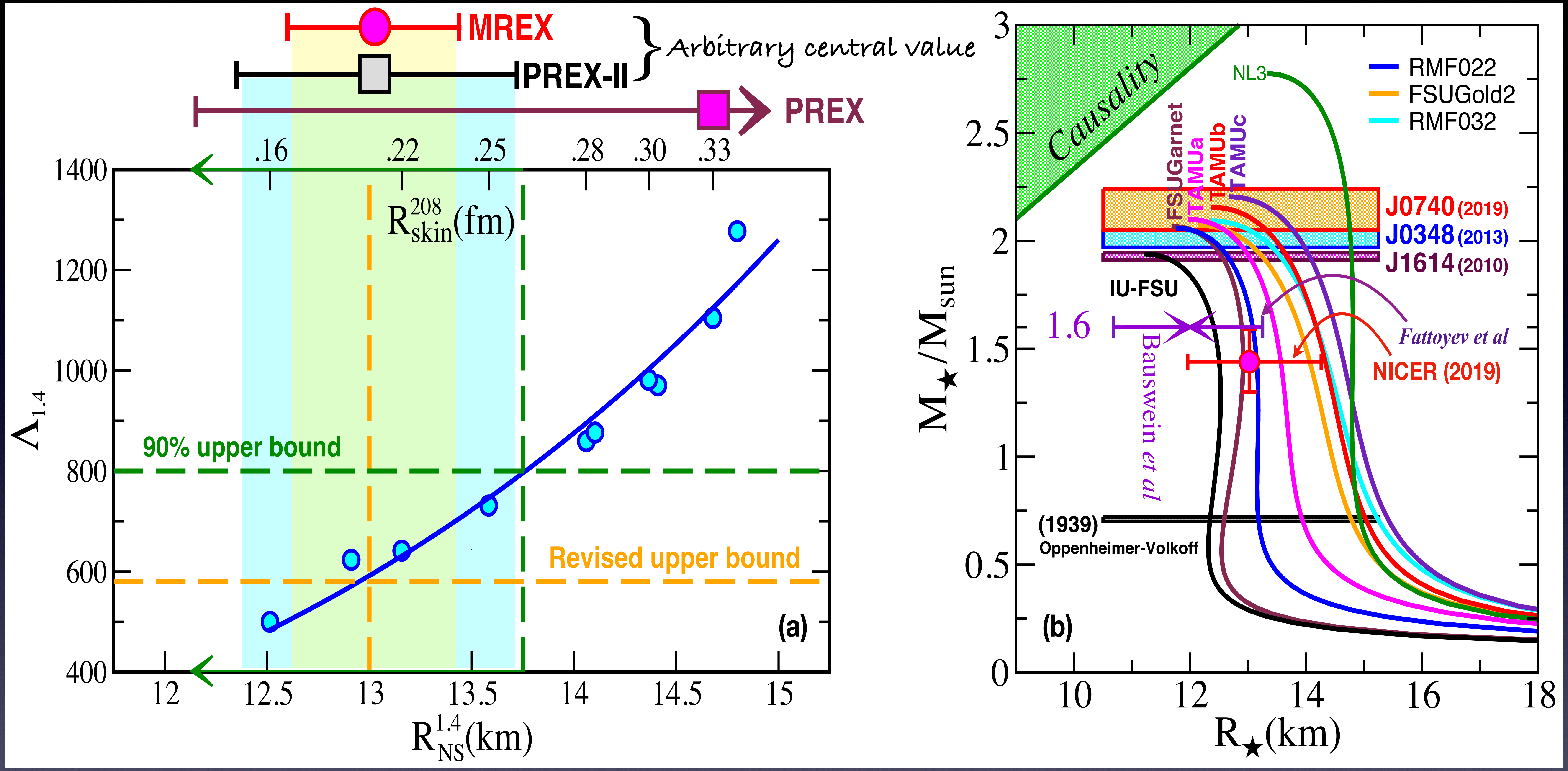


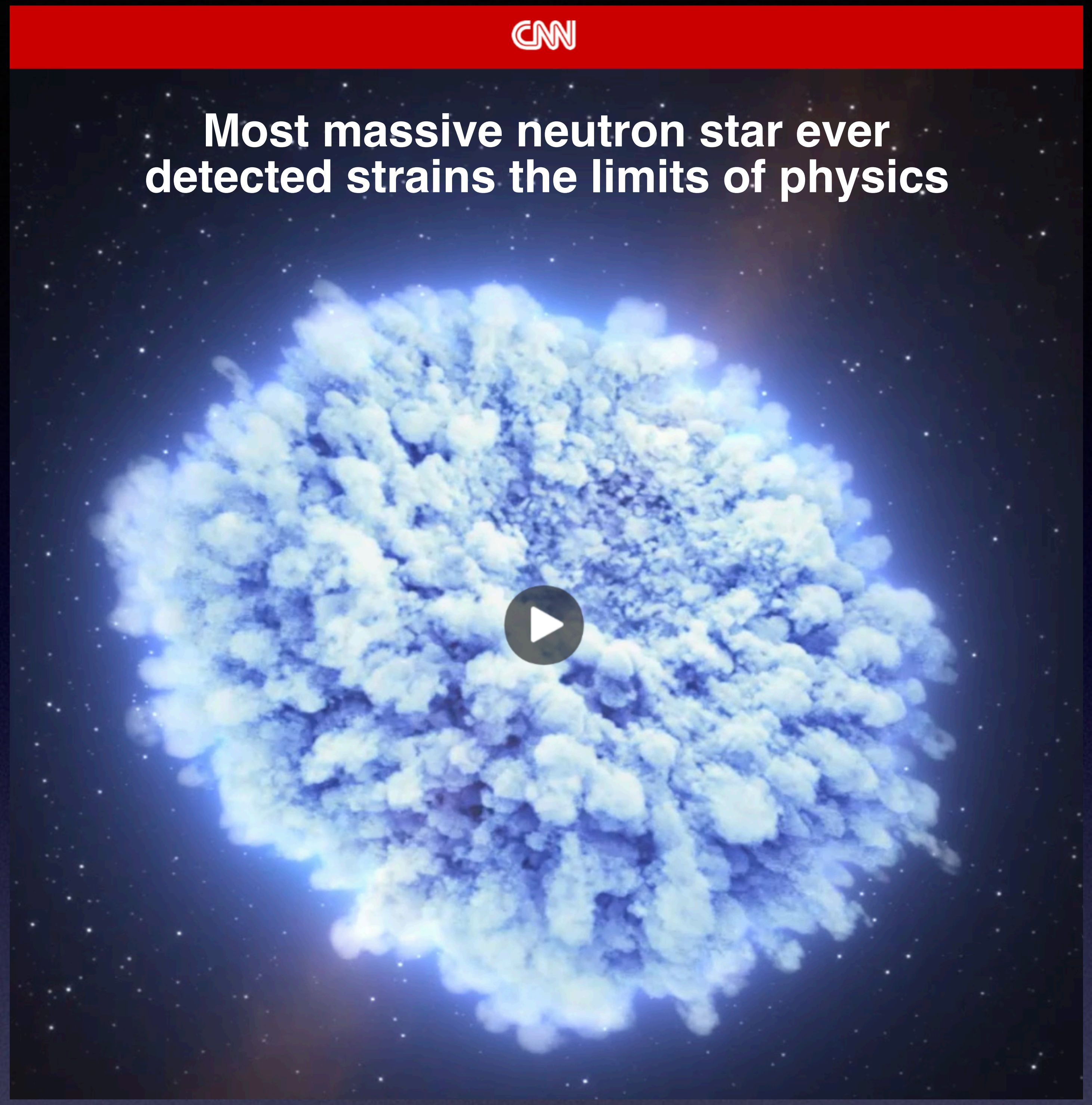
GW170817 rules out very large neutron star radii!

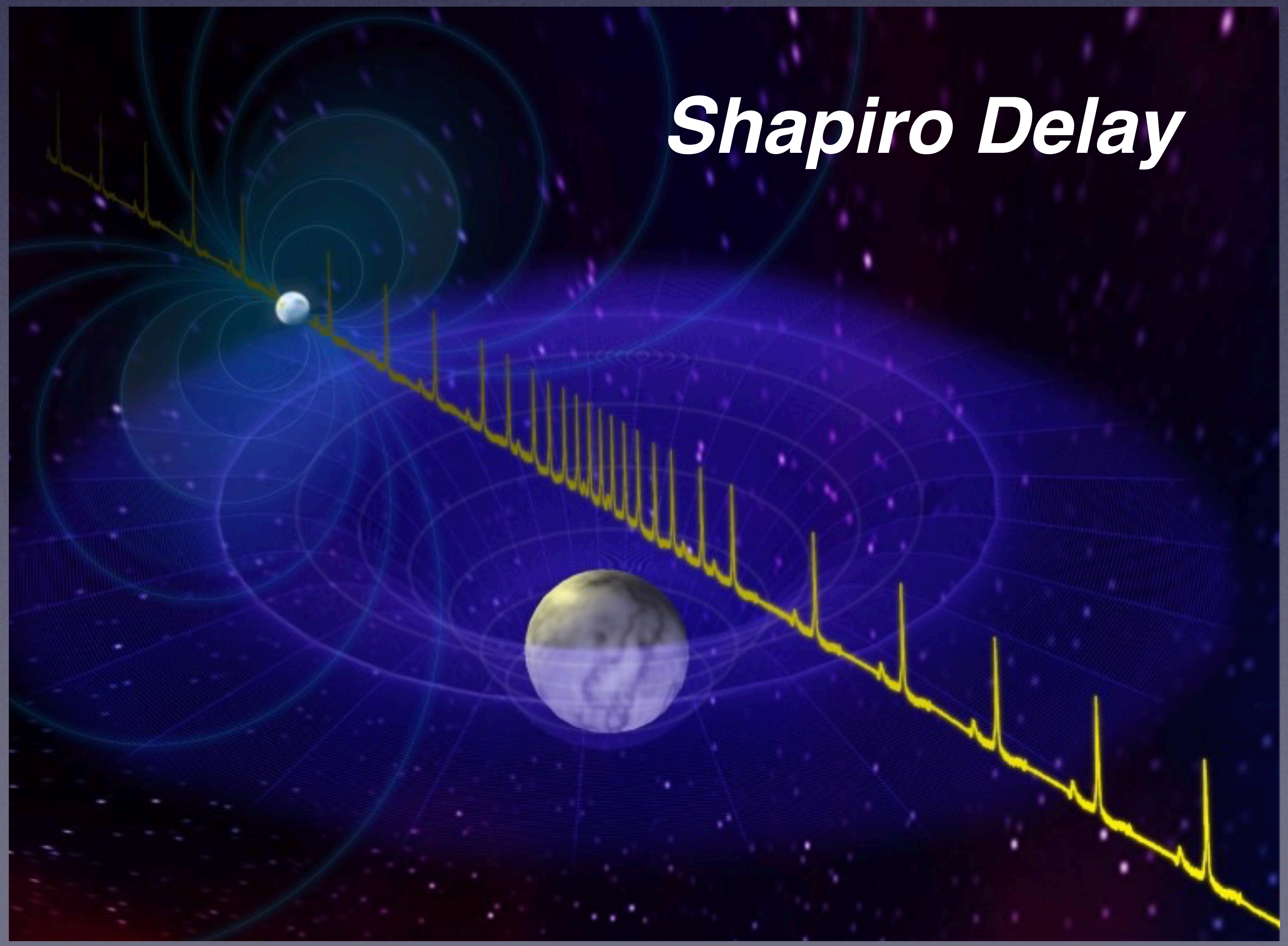
Neutron Stars must be compact

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

How can we make massive stars with small radii?





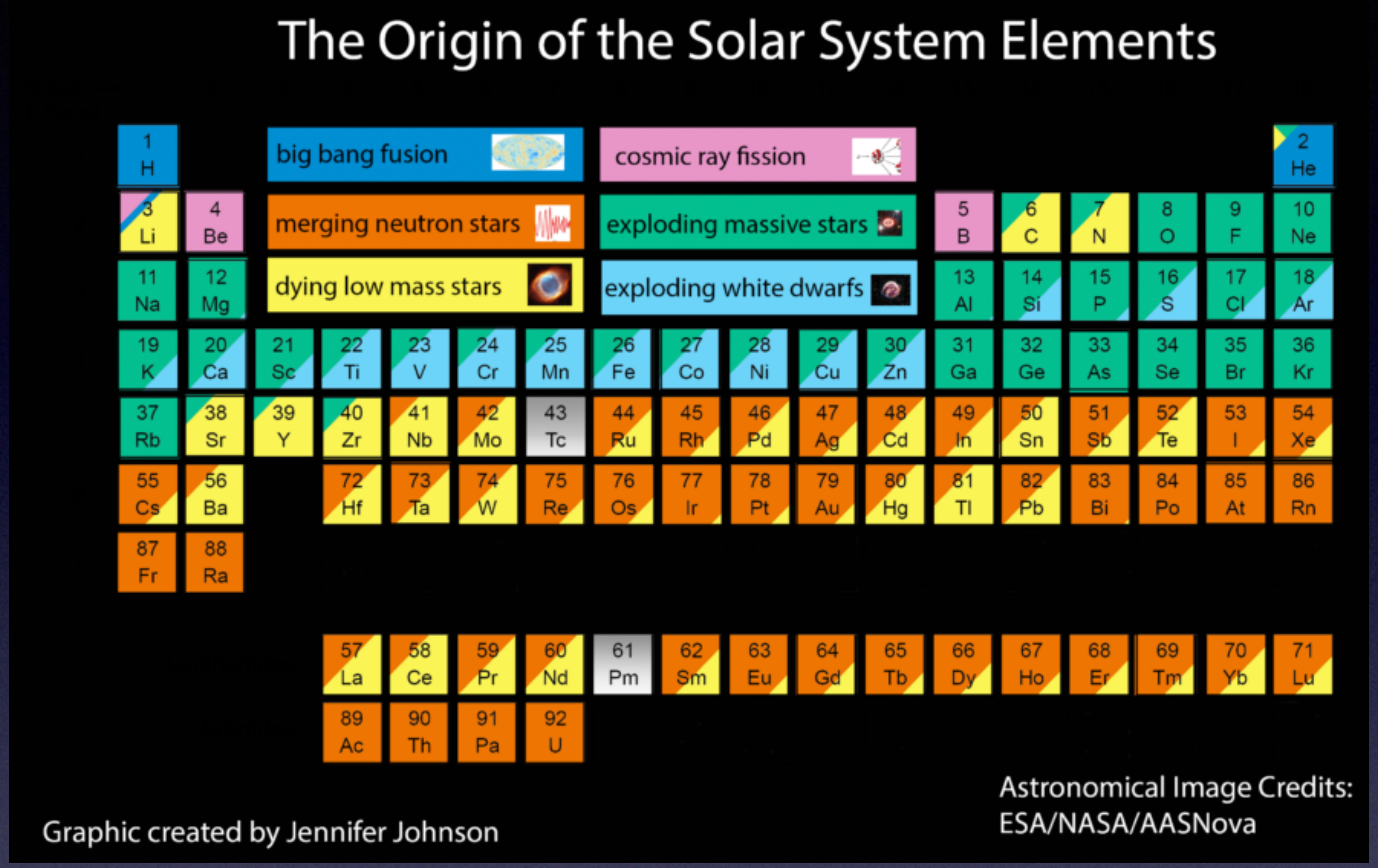


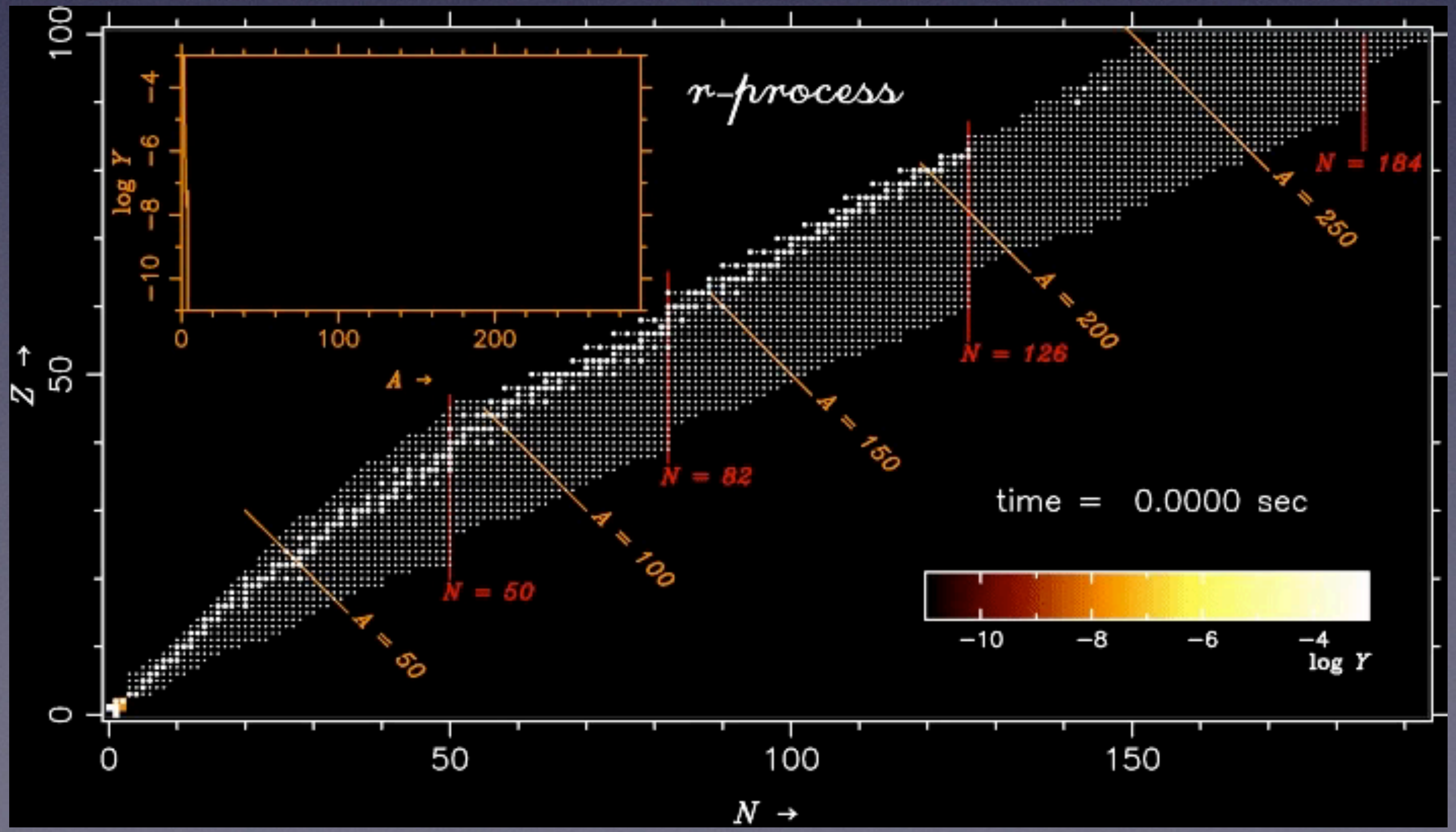
Tantalizing Possibility

- *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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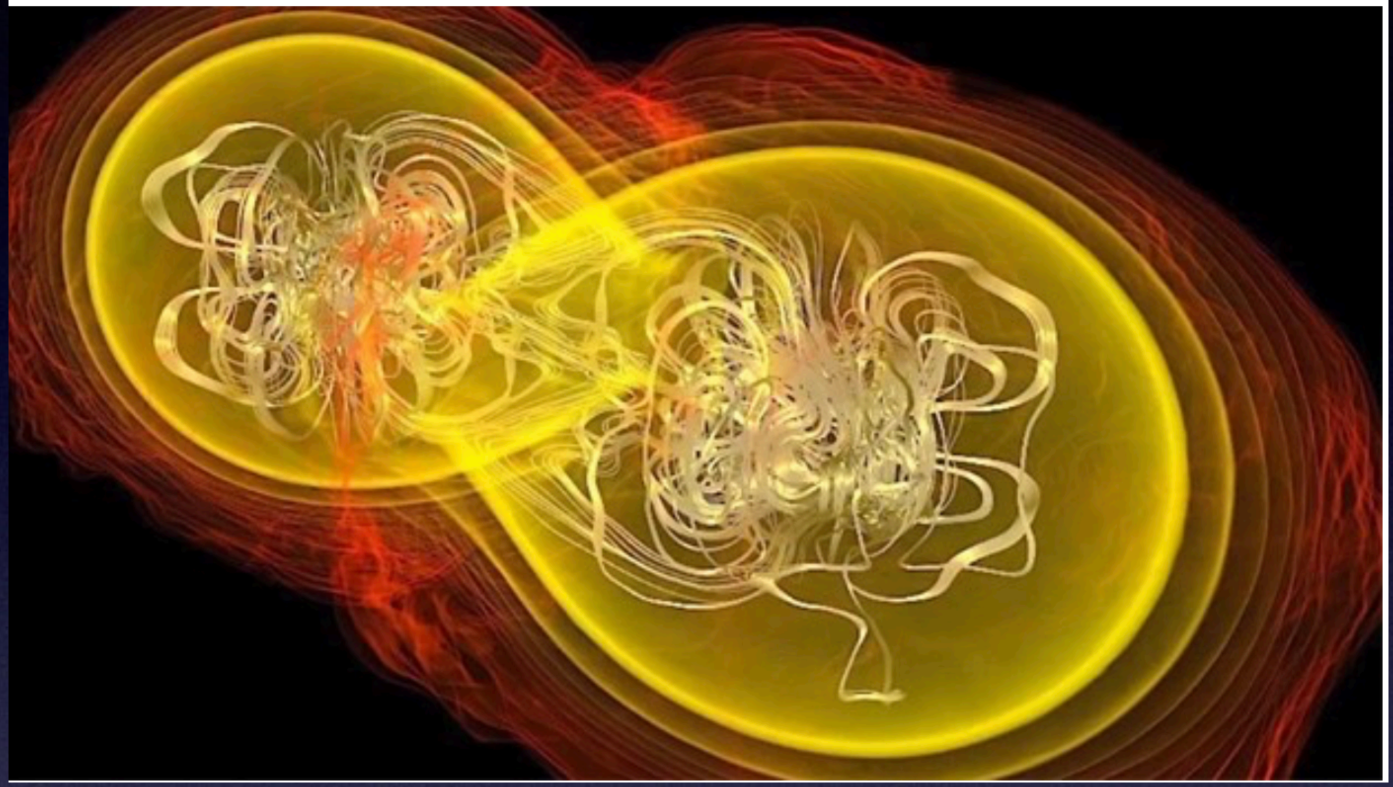
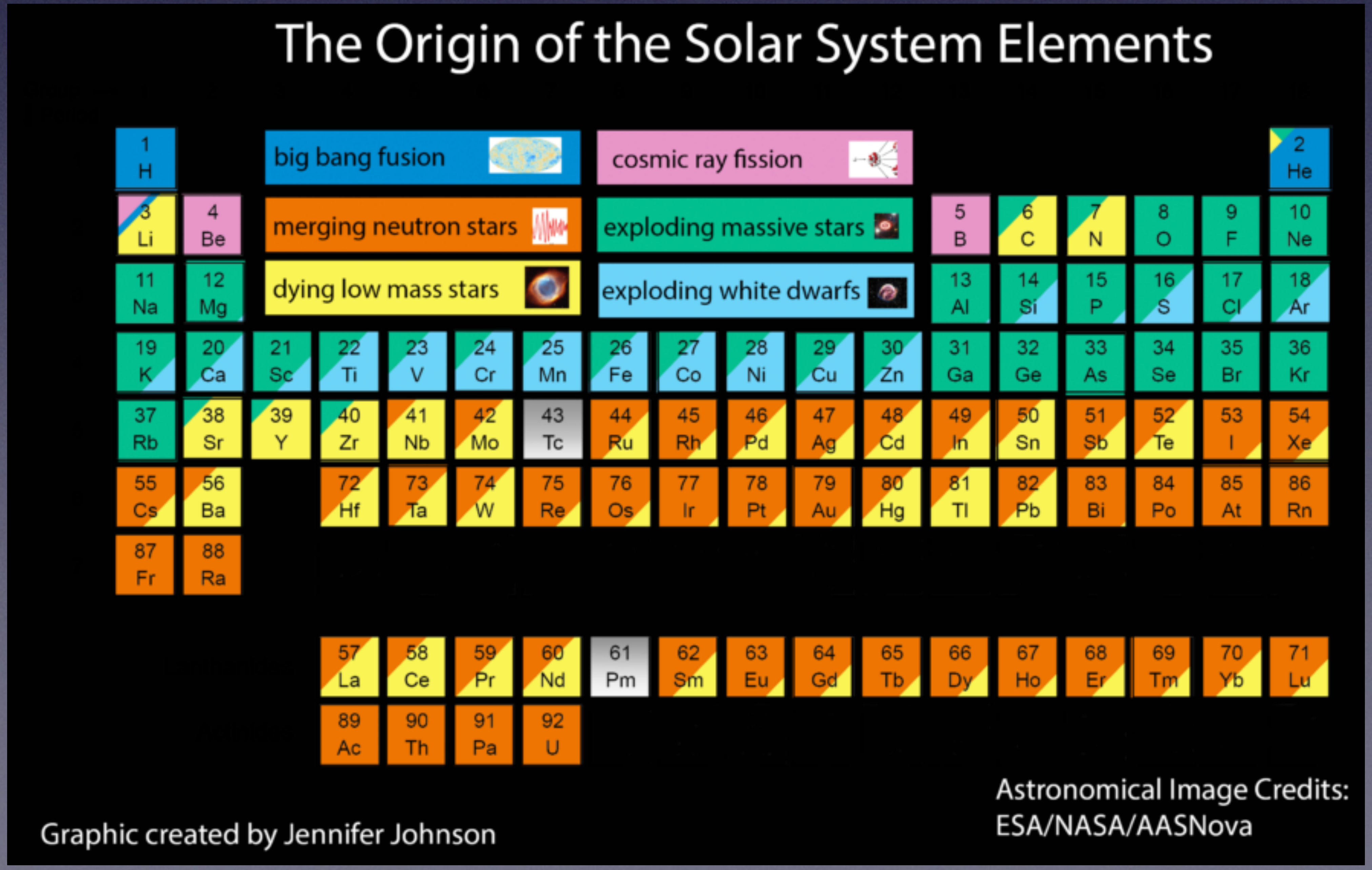
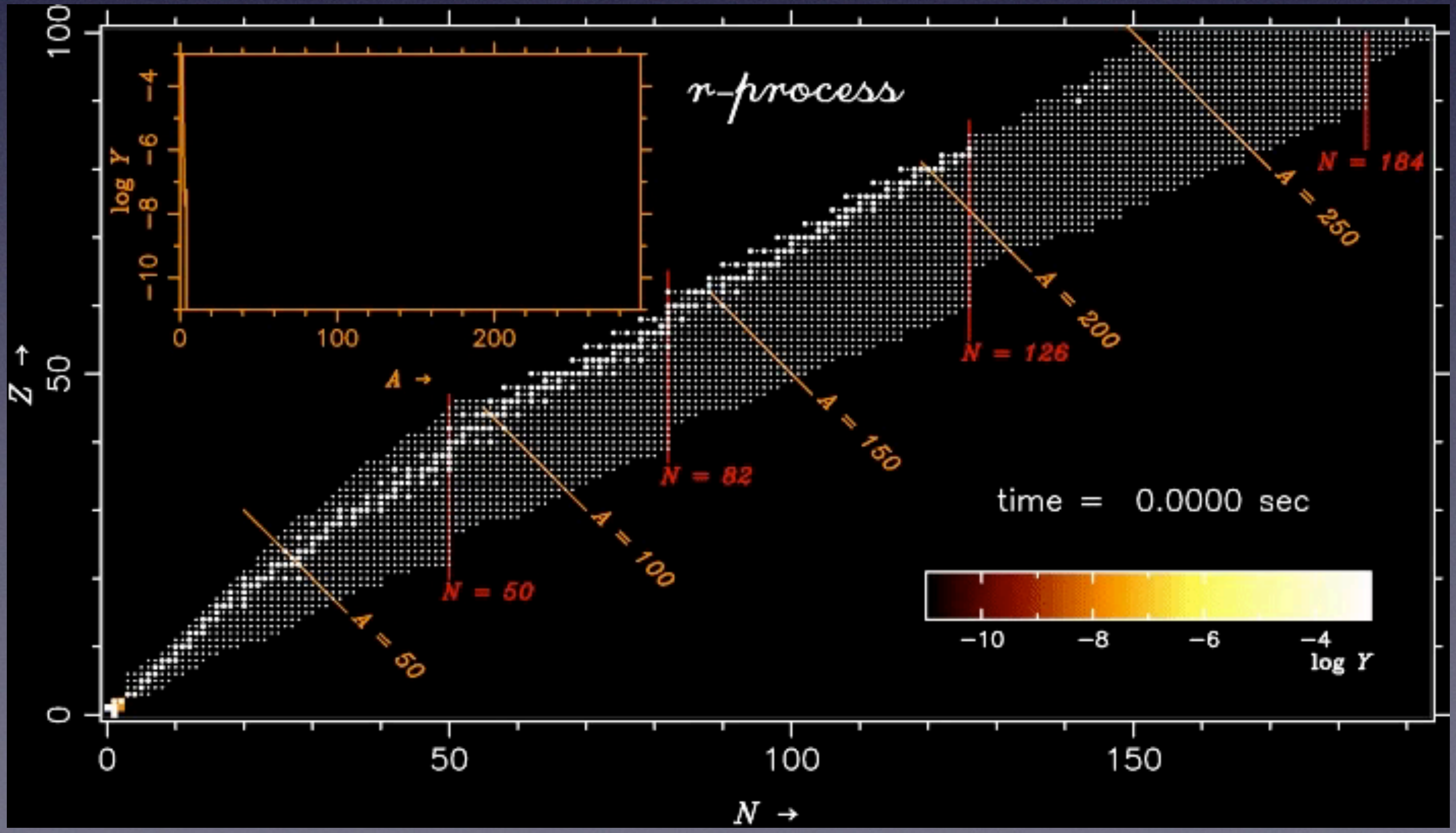
The New Periodic Table of the Elements

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



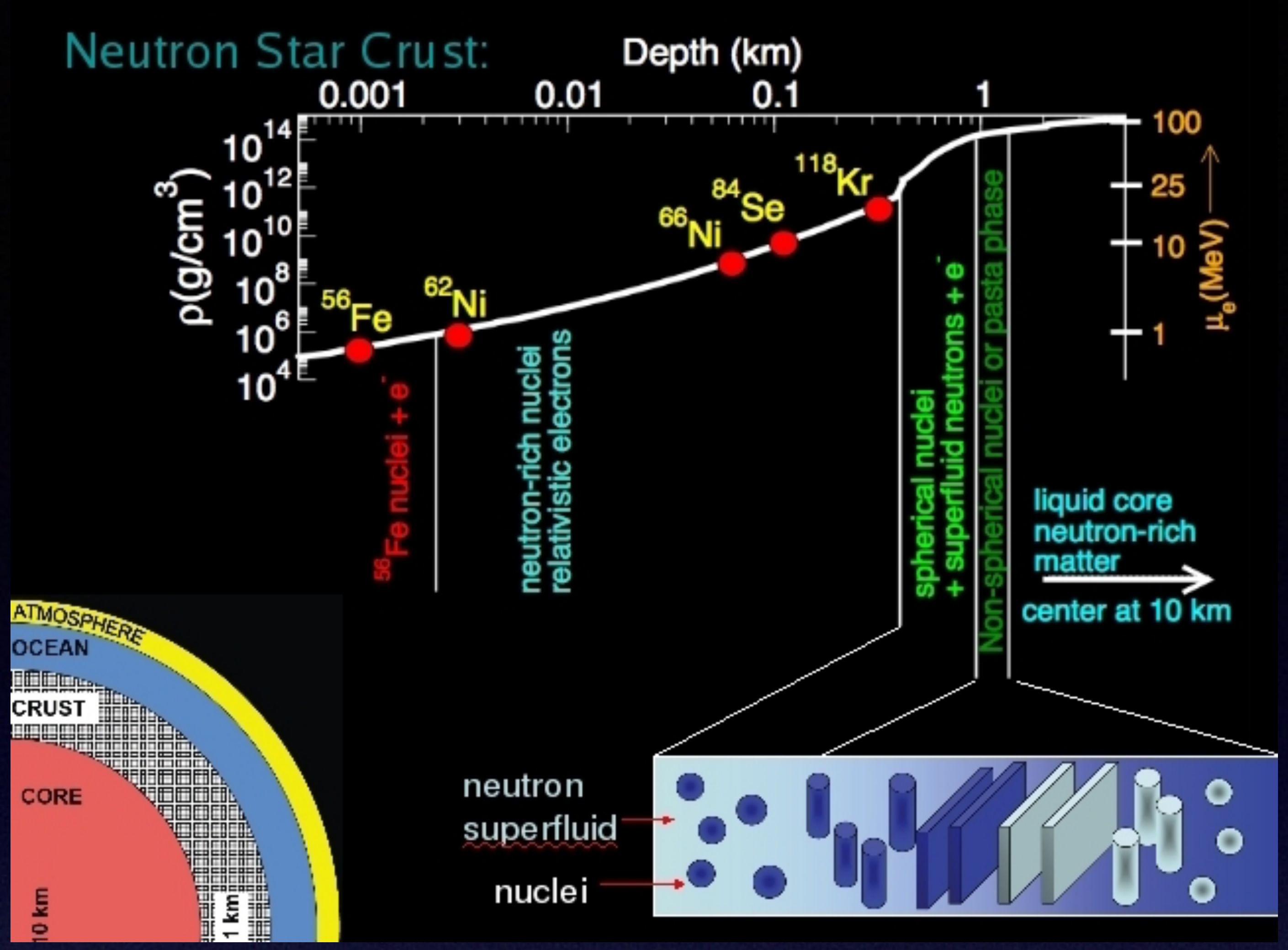
The optical counterpart SSS17a produced at least 5% solar masses (10^{29} kg!) of heavy elements - demonstrating that NS-mergers play a role in the r-process





The Composition of the Outer Crust

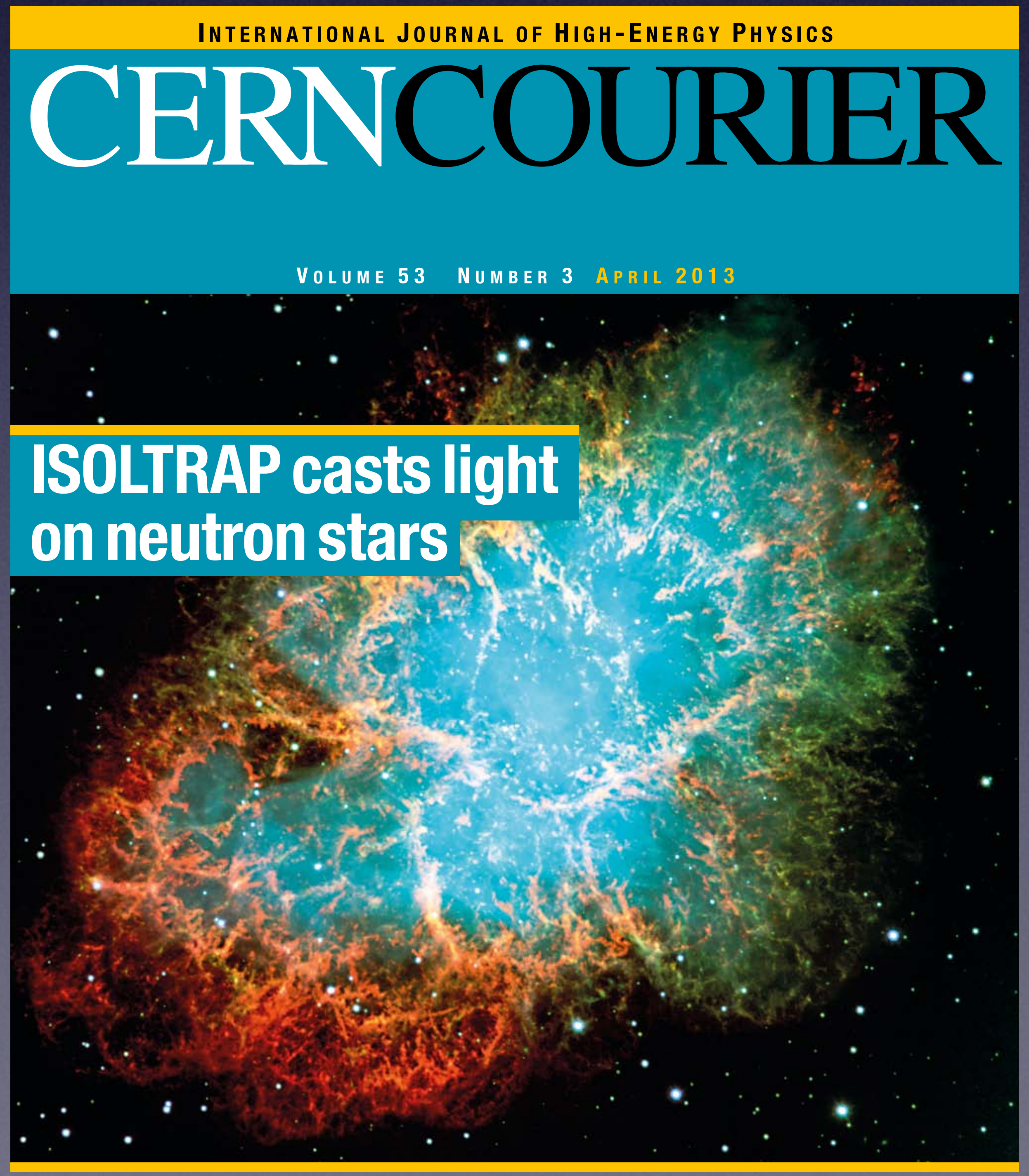
Enormous sensitivity to nuclear masses

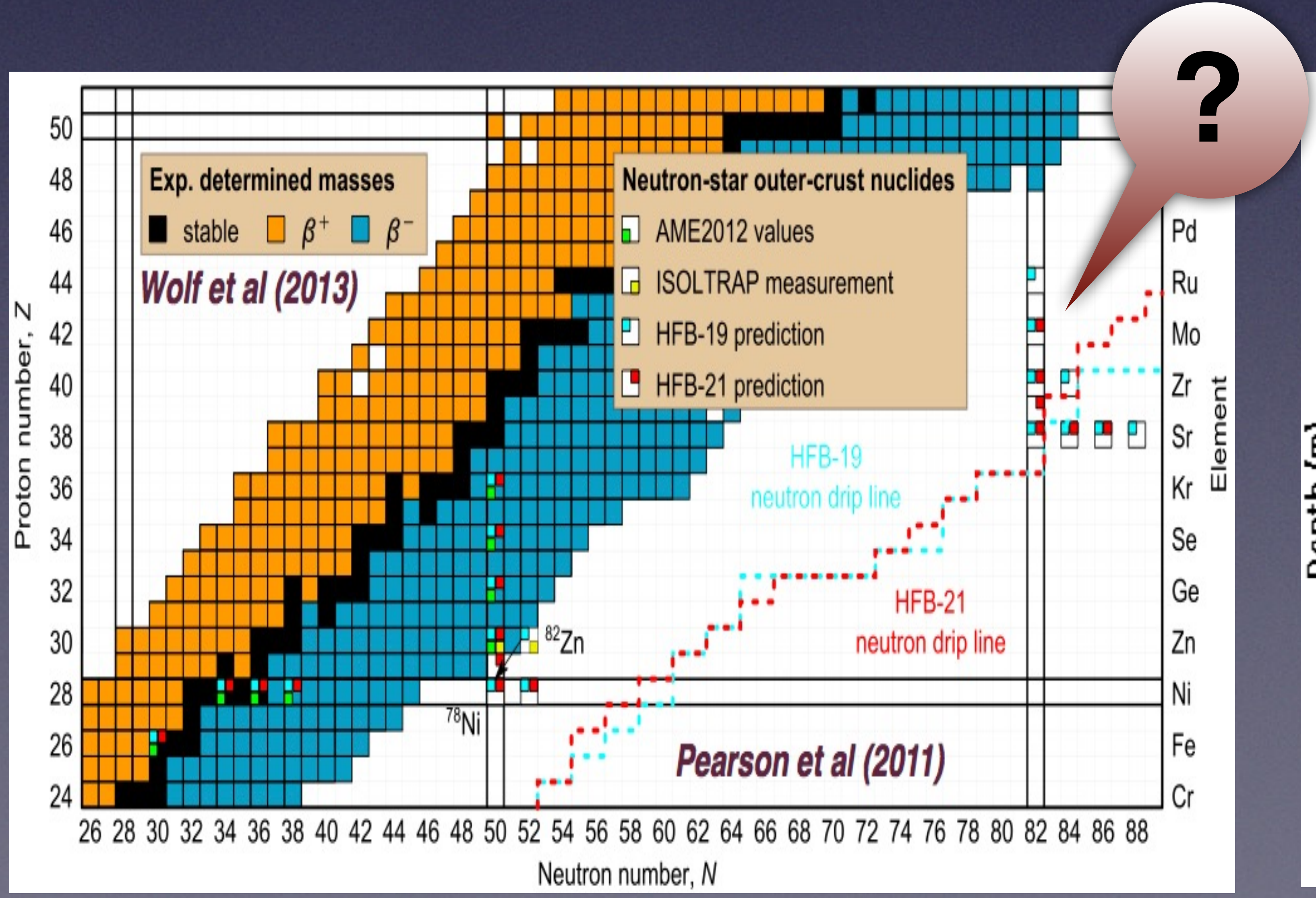


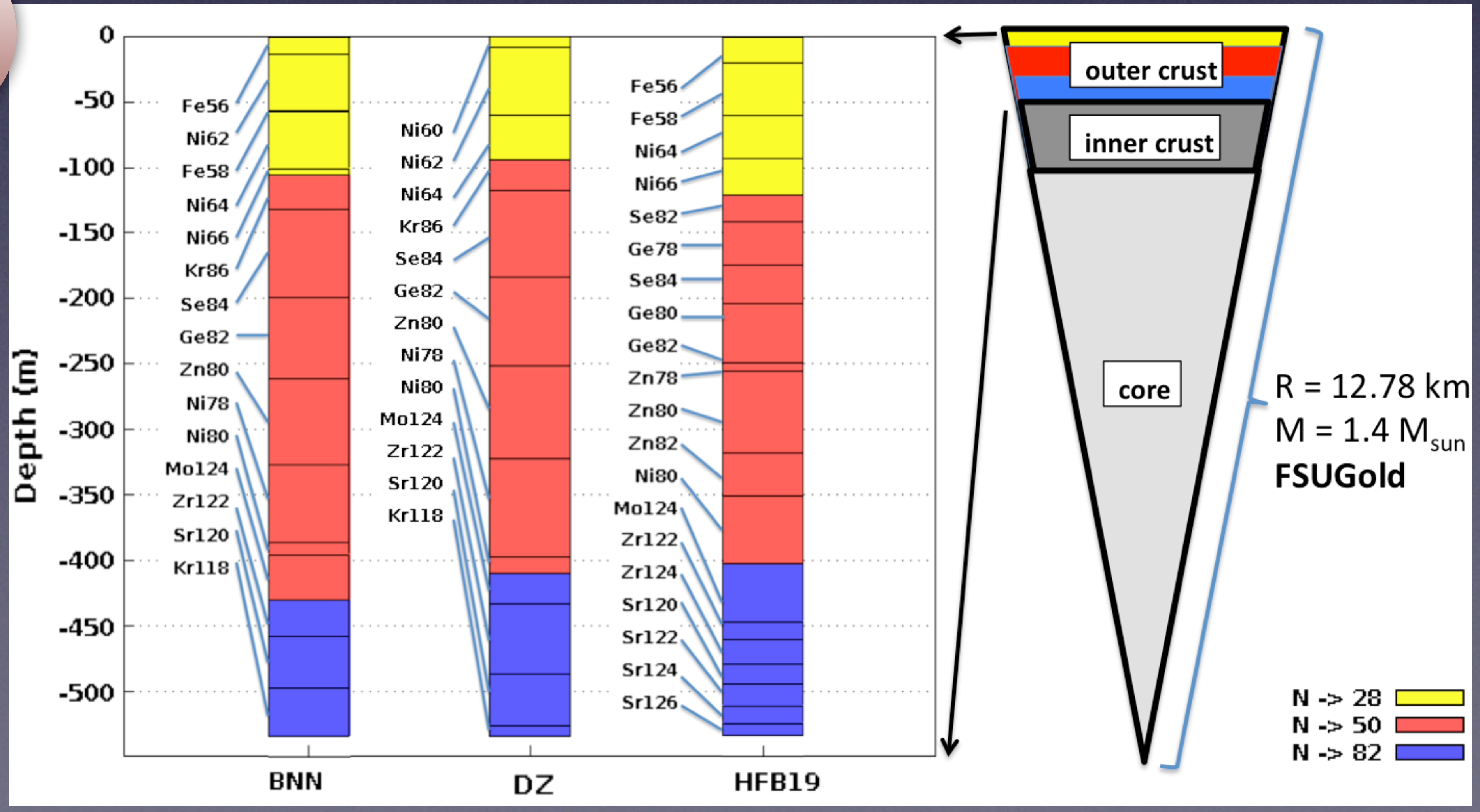
- Composition emerges from relatively simple dynamics
  - Competition between electronic and symmetry energy

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

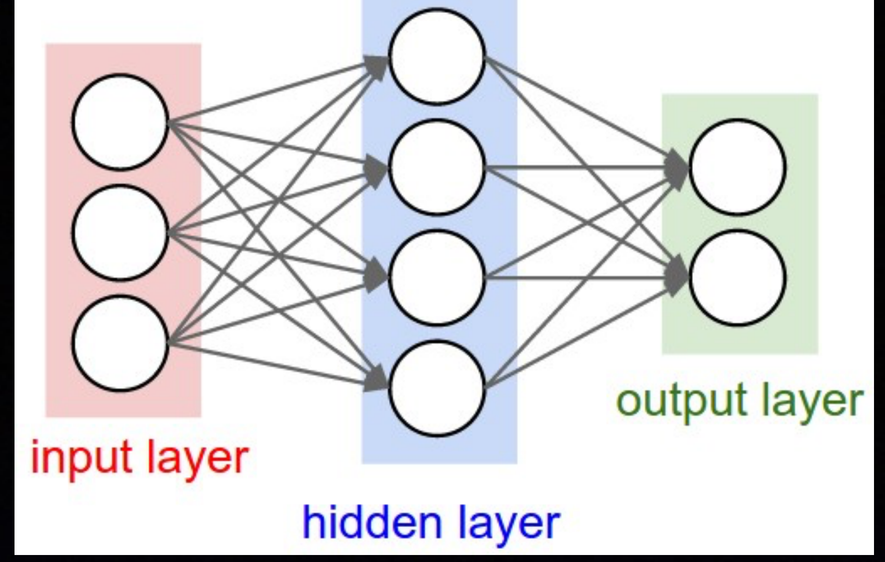
- Mass measurements of exotic nuclei is essential
  - For neutron-star crusts and r-process nucleosynthesis







Nuclear Theory meets Machine Learning



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

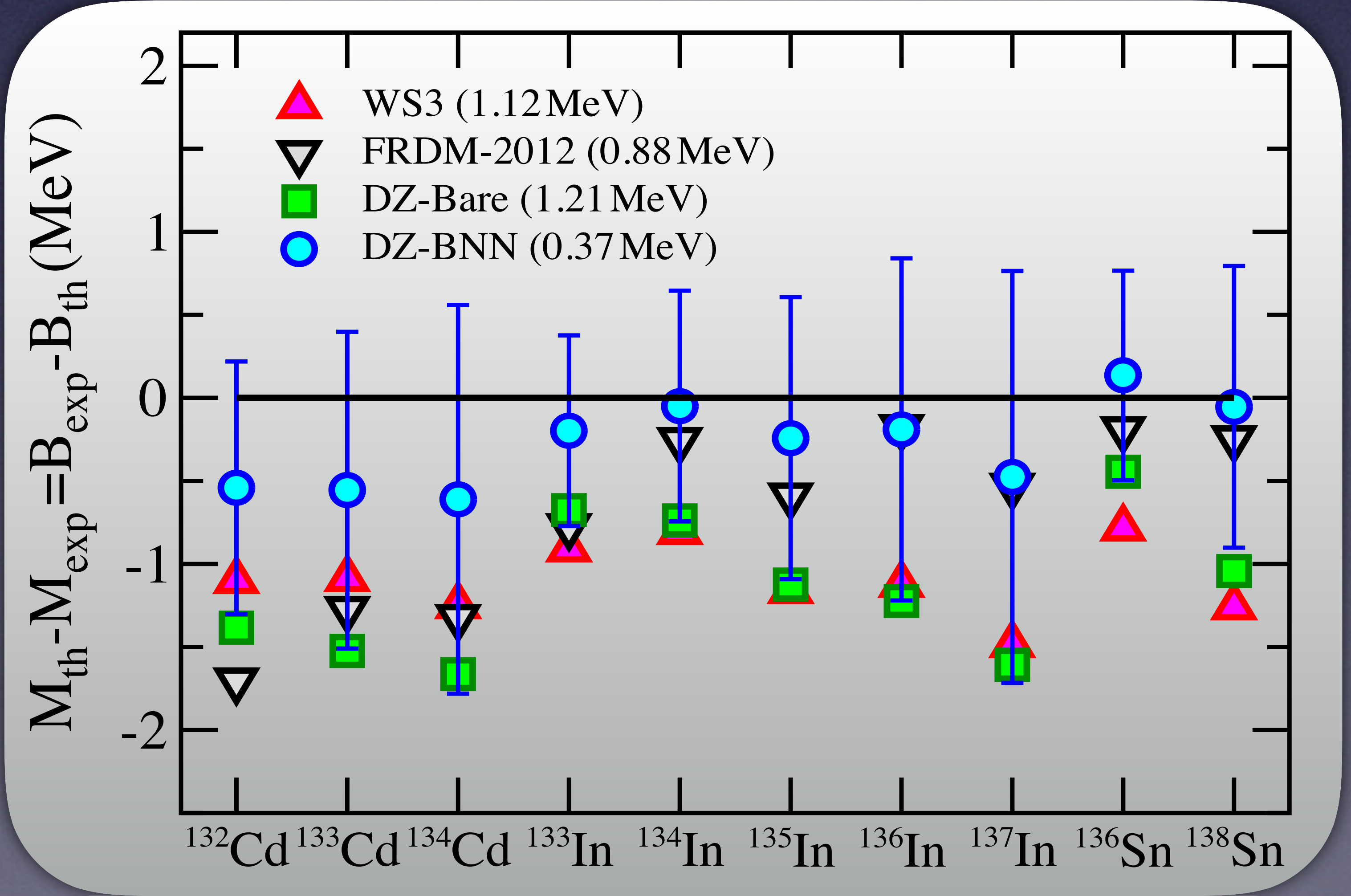
The paradigm

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

- Systematic scattering greatly reduced
- Predictions supplemented by theoretical errors

Train with AME2012 then predict AME2016

Re-generating Richard Feynman



Duflo-Zuker + BNN

GW190425: the merger of a compact binary with total mass of about 3.4 Msun

Change article language:

On April the 25th, 2019, the network of gravitational-wave (GW) detectors formed by the European Advanced Virgo, in Italy, and the two Advanced LIGO, in the US, detected a signal, named GW190425. This is the second observation of a gravitational-wave signal consistent with the merger of a binary-neutron-star system after GW170817. GW190425 was detected at 08:18:05 UTC; about 40 minutes later the LIGO Scientific Collaboration and the Virgo Collaboration sent an alert to trigger follow-up telescope observations.

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
S190425z	Production	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVOK	4.538e-13	1 per 69834 years	1240215502.011549	1240215503.011549	1240215504.018242	2019-04-25 08:18:26 UTC	Data

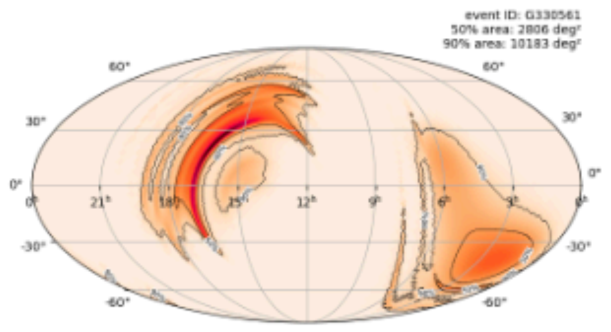
Preferred Event Info

Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	gstlal	AllSky	L1,V1	1240215503.0171	2019-04-25 08:18:25 UTC

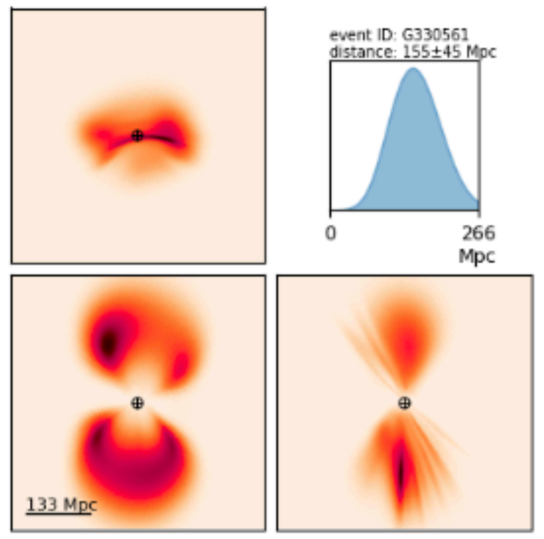
No EM counterpart

Superevent Log Messages

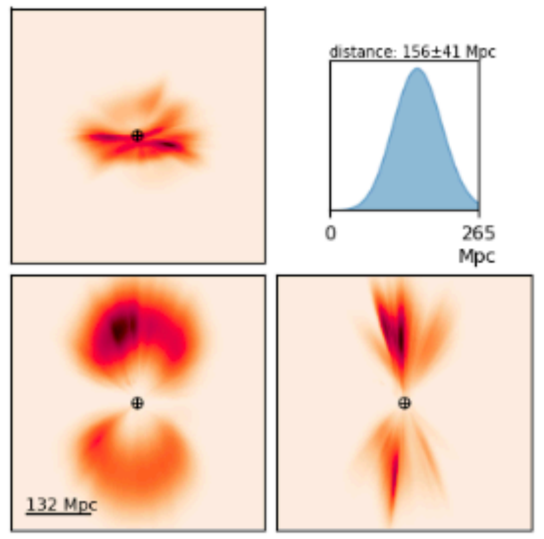
Sky Localization



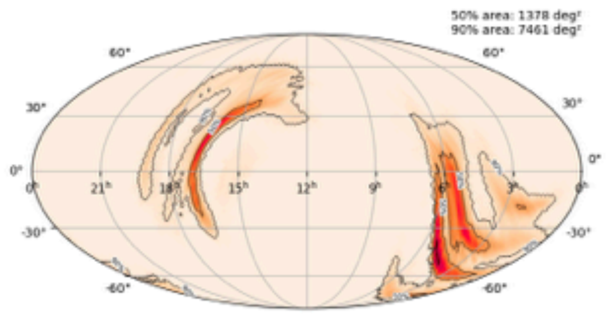
Mollweide projection of bayestar.fits bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 25, 2019 08:19:27 UTC



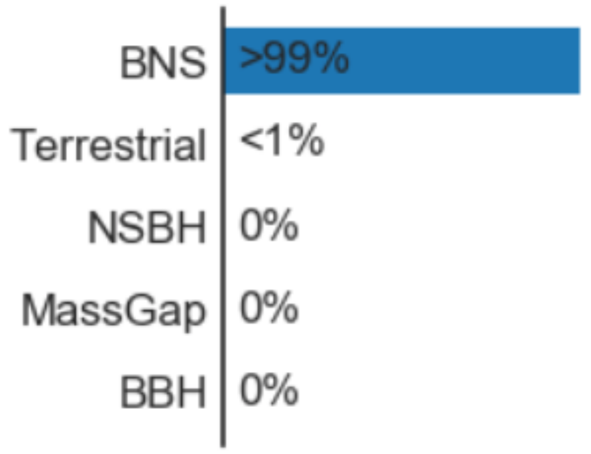
Volume rendering of bayestar.fits bayestar.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 25, 2019 08:20:11 UTC



Volume rendering of LALInference.fits LALInference.volume.png. Submitted by Gregory Ashton on Apr 26, 2019 10:17:04 UTC



Mollweide projection of LALInference.fits LALInference.png. Submitted by Gregory Ashton on Apr 26, 2019 10:48:17 UTC



Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 25, 2019 08:22:05 UTC

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

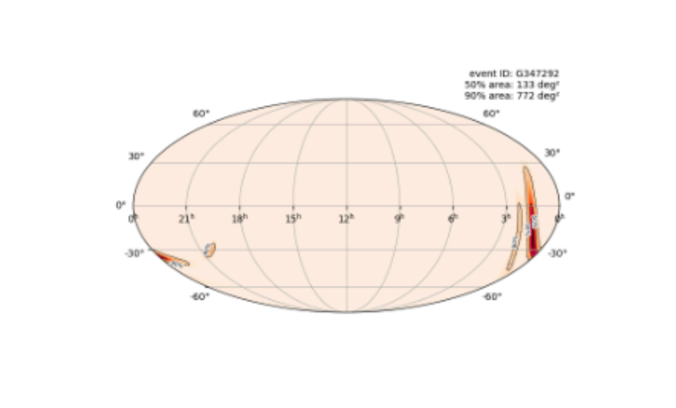
Preferred Event Info

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

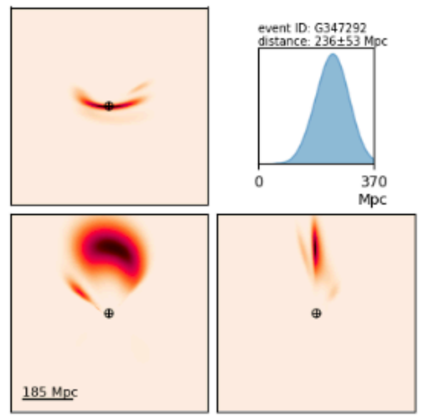
NO EM Counterpart

Superevent Log Messages

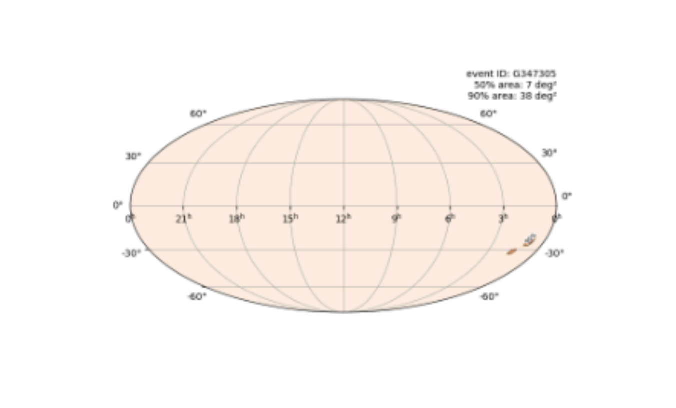
Sky Localization



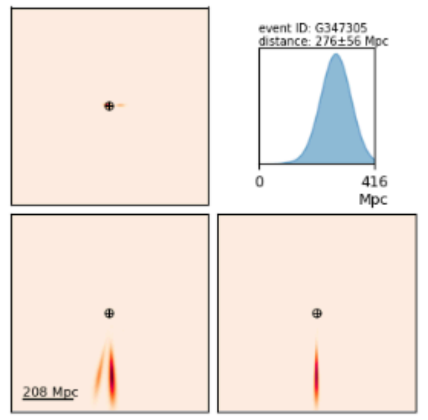
Mollweide projection of bayestar.fits.gz bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 21:31:29 UTC



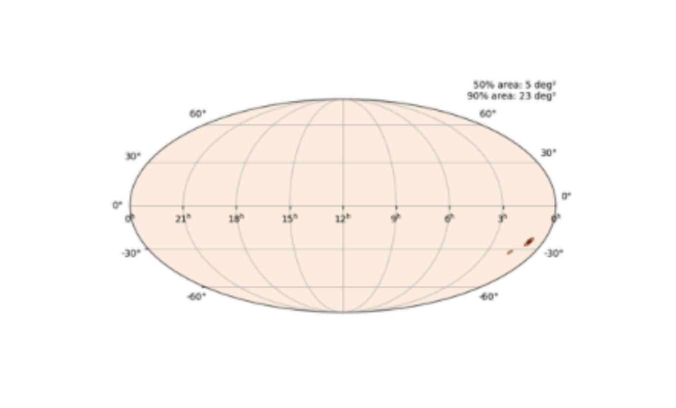
Volume rendering of bayestar.fits.gz bayestar.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 21:32:00 UTC



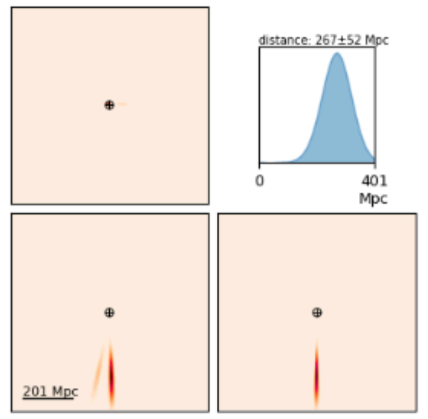
Mollweide projection of bayestar.fits.gz bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 22:58:20 UTC



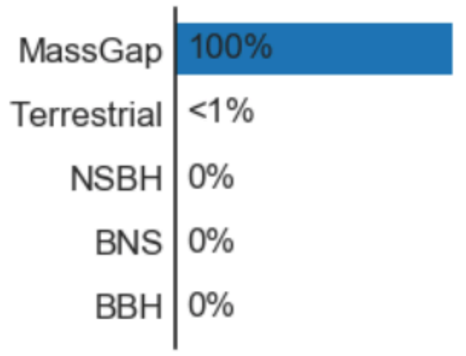
Volume rendering of bayestar.fits.gz bayestar.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 14, 2019 23:00:50 UTC



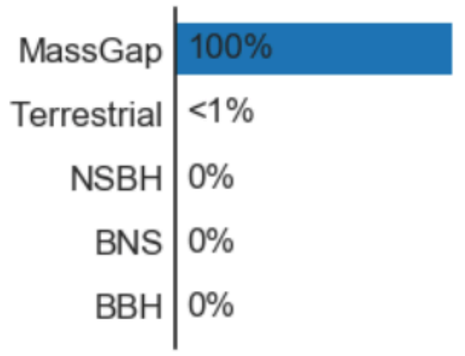
Mollweide projection of LALInference.v1.fits.gz LALInference.v1.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 15, 2019 09:07:14 UTC



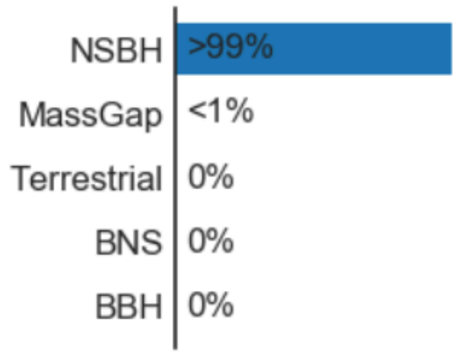
Volume rendering of LALInference.v1.fits.gz LALInference.v1.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 15, 2019 09:08:18 UTC



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



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

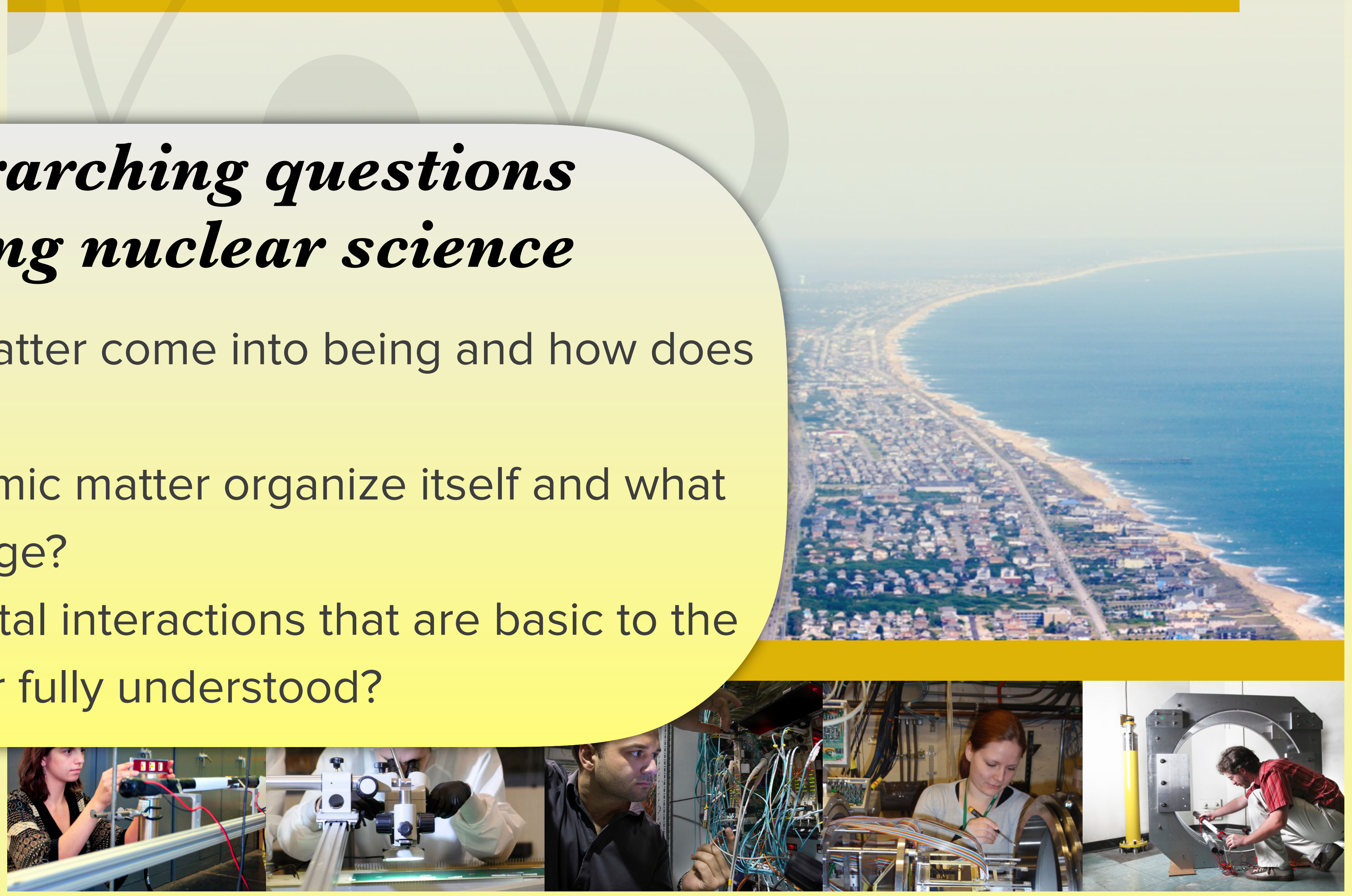


Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on Aug 15, 2019 10:16:43 UTC

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.

The Long Range Plans for Nuclear Science

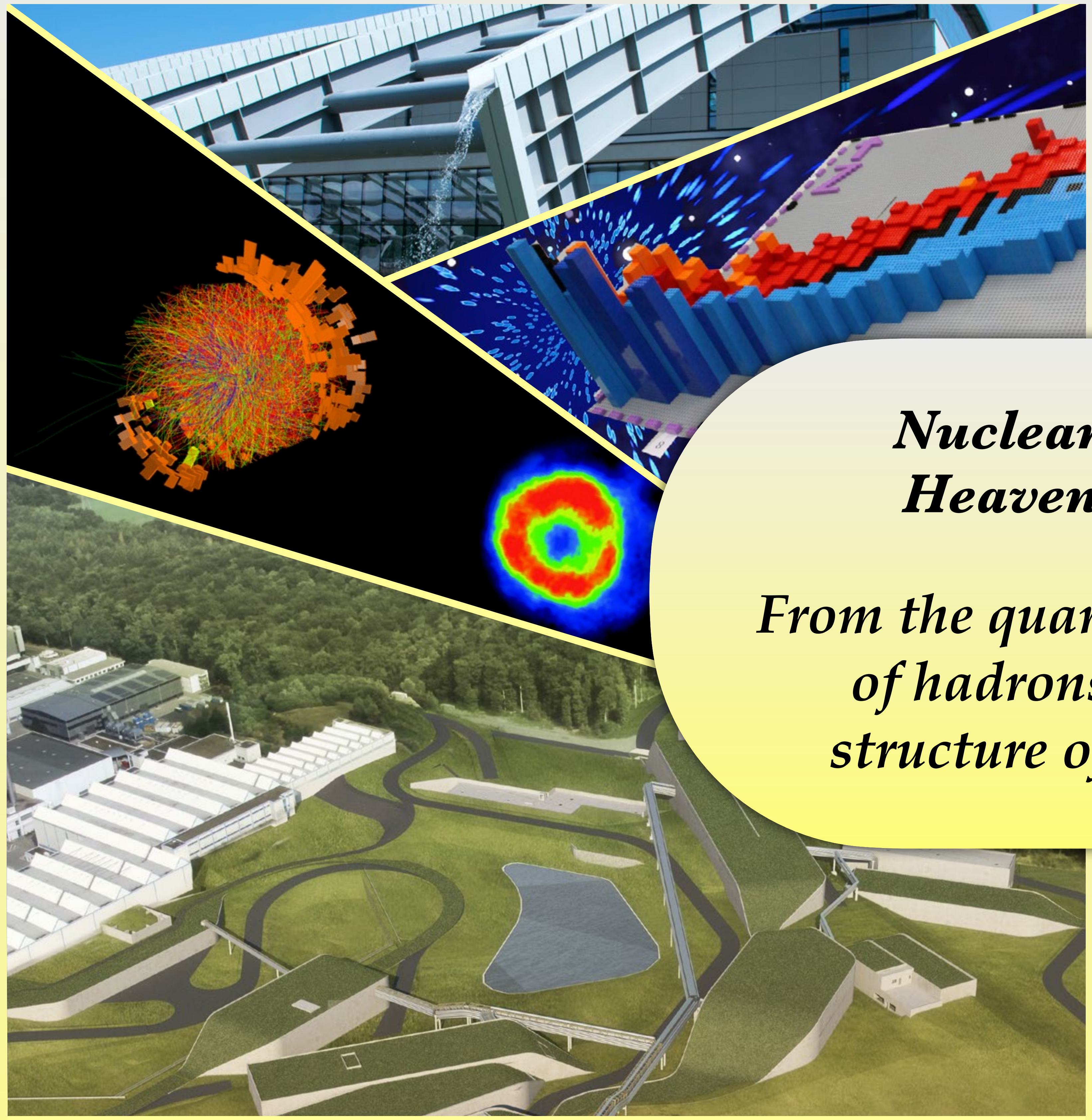
REACHING FOR THE HORIZON



The overarching questions animating nuclear science

1. How did visible matter come into being and how does it evolve?
2. How does subatomic matter organize itself and what phenomena emerge?
3. Are the fundamental interactions that are basic to the structure of matter fully understood?

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE



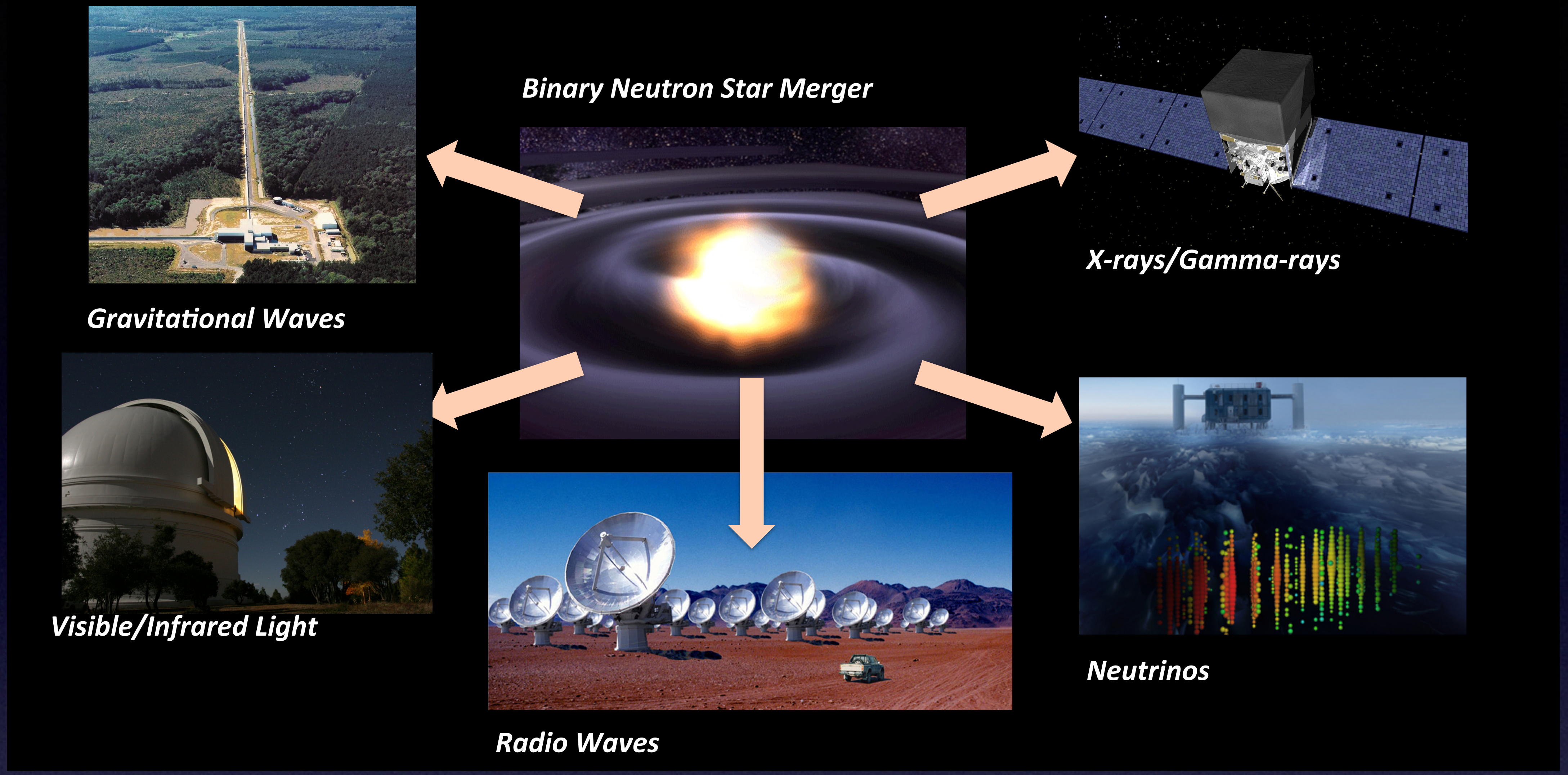
Nuclear Physics in Heaven and Earth

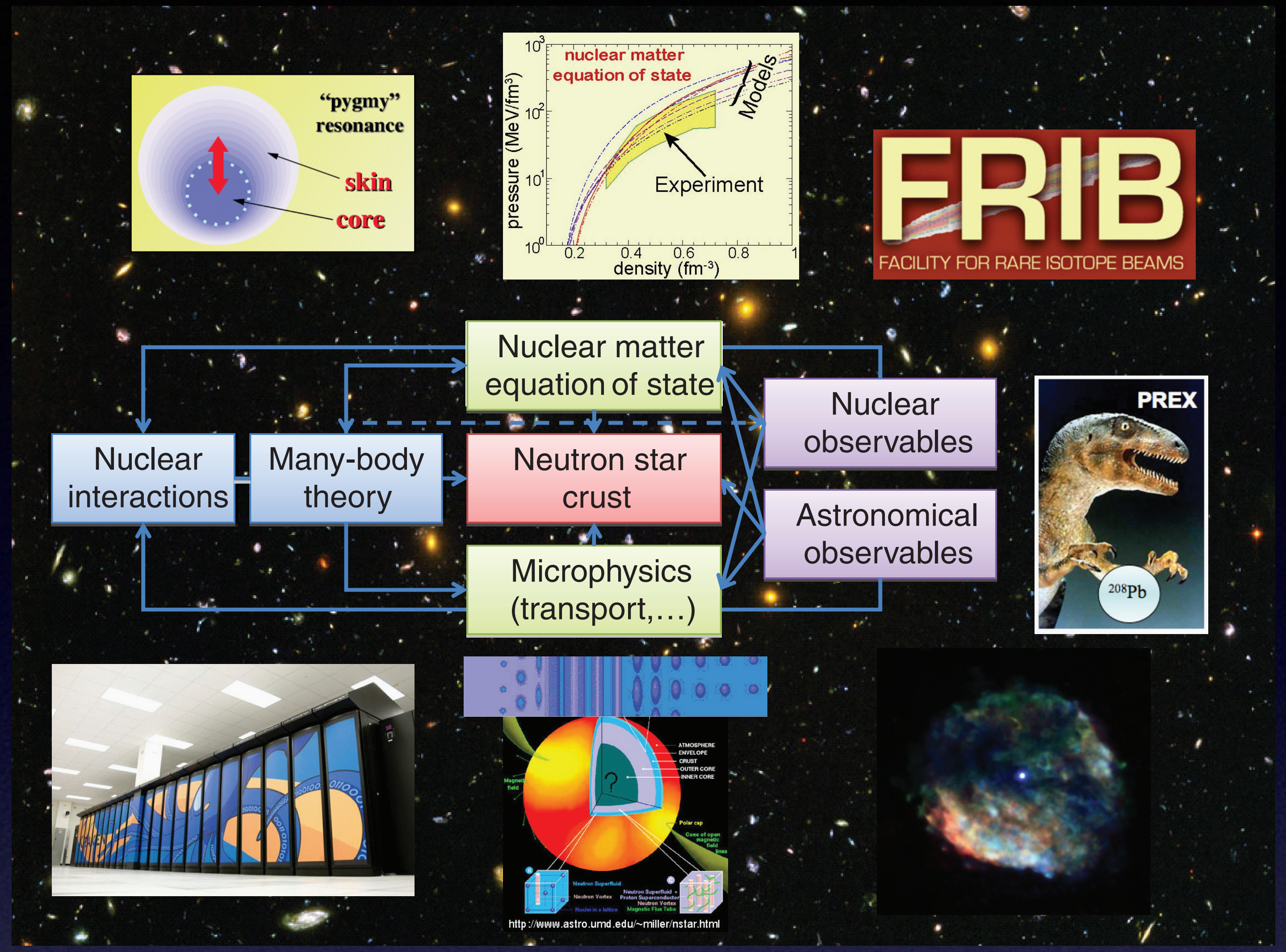
From the quark-gluon structure of hadrons to the exotic structure of neutron stars

NuPECC
Long Range Plan 2017
Perspectives
in Nuclear Physics

European Science Foundation

It is all Connected!





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

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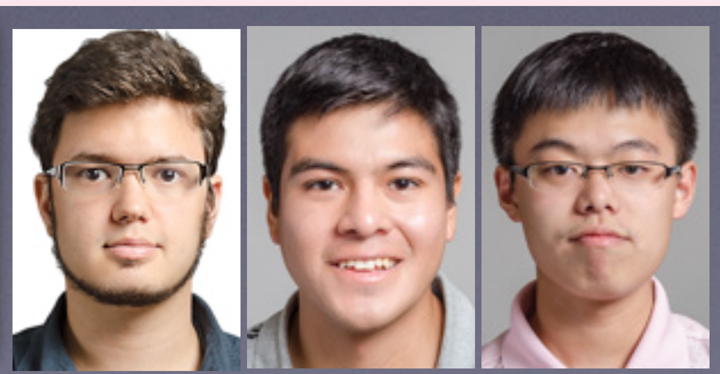
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (MSU)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)

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