

# Department of Energy, Office of Nuclear Physics Neutron Star Research

Office of Nuclear Physics (NP)

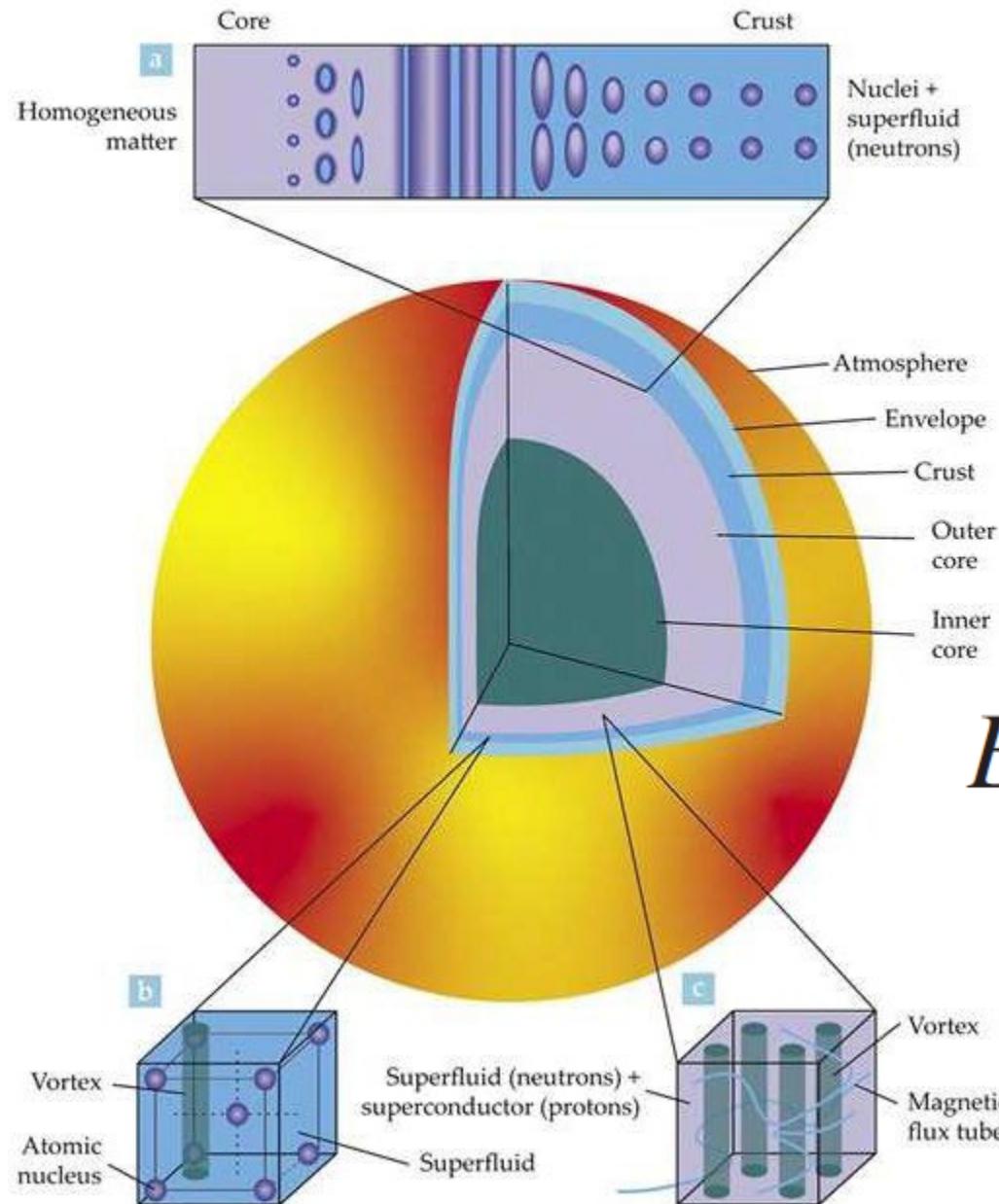
May 7, 2024

Sharon Stephenson



U.S. DEPARTMENT OF  
**ENERGY** | Office of  
Science

[Energy.gov/science](https://Energy.gov/science)



- What is the nuclear-matter equation of state?

$$[E/A](\rho)$$

- Symmetry pressure  $L$  particularly important.

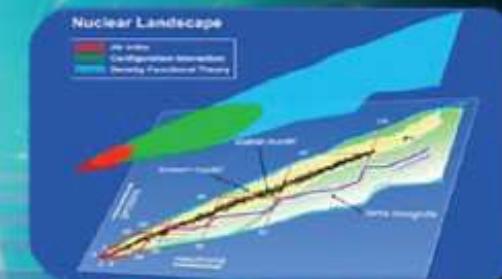
$$E_{\text{sym}}(\rho) = [E/A](\rho) - [E/N](\rho)$$

$$L = 3\rho[\partial E_{\text{sym}}(\rho)/\partial \rho]|_{\rho=\rho_0}$$

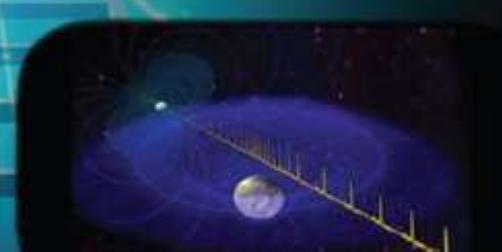
Jorge Piekarewicz, Farrukh J. Fattoyev; Neutron-rich matter in heaven and on Earth. *Physics Today* 1 July 2019; 72 (7): 30–37. <https://doi.org/10.1063/PT.3.4247>

# HEAVEN AND EARTH

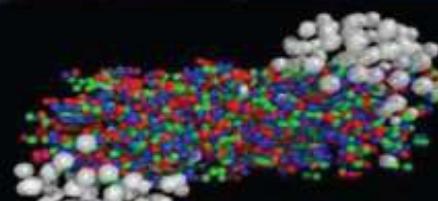
Connecting Atomic Nuclei  
to Neutron Stars –  
systems that differ in size  
by 18 orders of magnitude!



Soft X-ray Timing



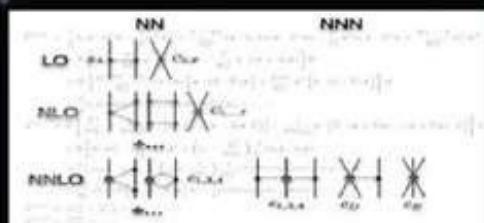
Pulsar Timing



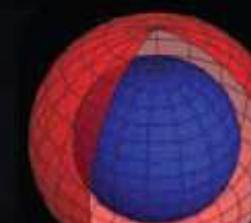
Heavy-ion Collisions



Gravitational Waves



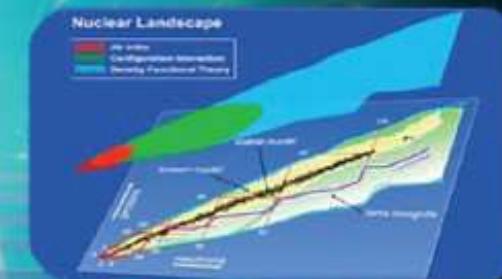
Chiral Effective Field Theory



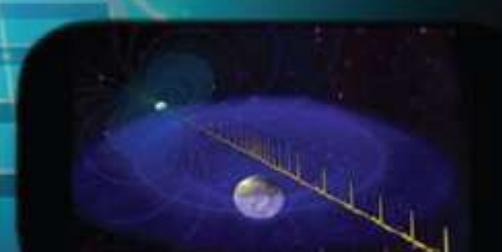
Neutron Skins

# HEAVEN AND EARTH

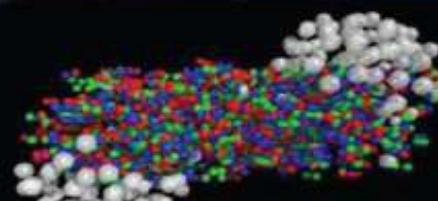
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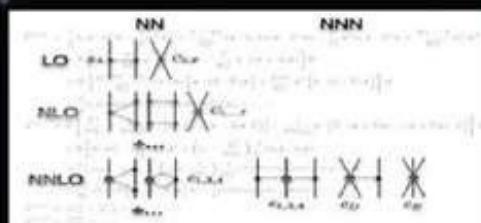
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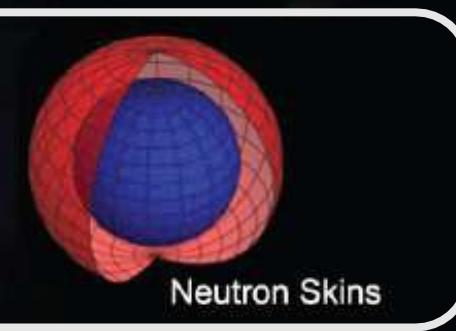
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Gravitational Waves



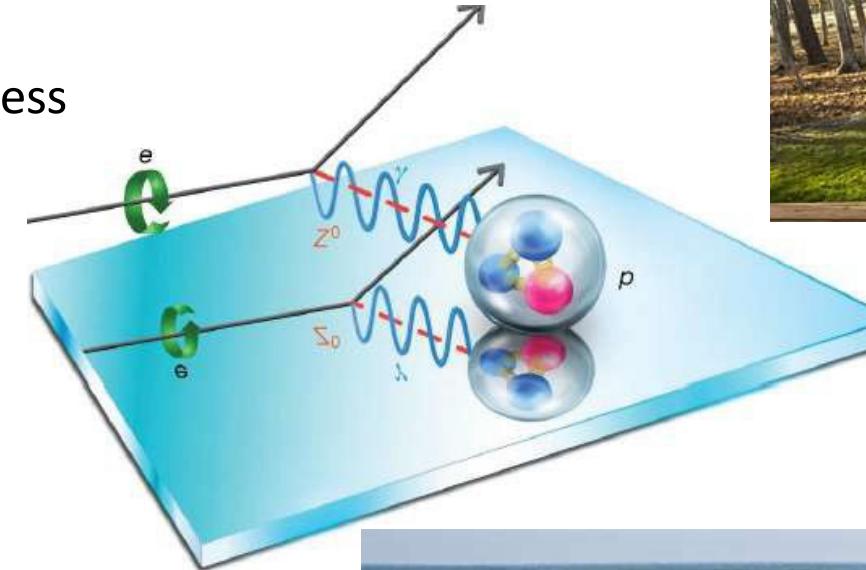
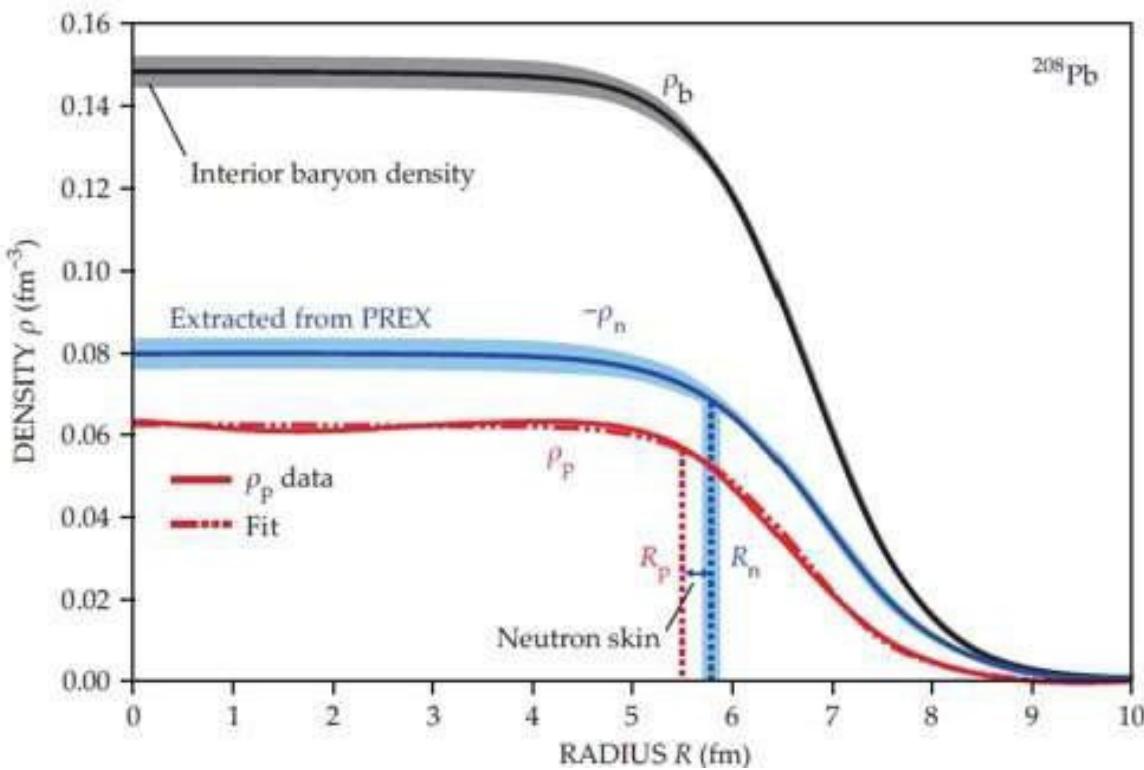
Chiral Effective Field Theory



Neutron Skins

# Neutron skins, Pb Radius Experiment PREX

- Parity-violation: flip electron spin, measure scattering rates at CEBAF
- Symmetry pressure  $L$  correlated to neutron skin thickness



Kent Paschke



Jefferson Lab

Includes researchers from **Croatia, China, Italy, Germany, Armenia, India, Canada, and VA, LA, CT, MA, NY, PA, MS, CA, TX, ID, IN, IL, OH** in the U.S.

# Neutron skins, PREX and beyond

## PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About

Combined Theoretical Analysis of the Parity-Violating Asymmetry for  $^{48}\text{Ca}$  and  $^{208}\text{Pb}$

Paul-Gerhard Reinhard, Xavier Roca-Maza, and Witold Nazarewicz  
Phys. Rev. Lett. **129**, 232501 – Published 2 December 2022

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NEWS PHYSICS

## Neutron stars may be bigger than expected, measurement of lead nucleus suggests

Thick skin of neutrons on nucleus suggests nuclear matter is relatively stiff

27 APR 2021 • BY ADRIAN CHO

# Science



Physics Letters B  
Volume 843, 10 August 2023, 138013



Can the PREX-2 and CREX results be understood by relativistic mean-field models with the astrophysical constraints?

Tsuyoshi Miyatsu <sup>0</sup> , Myung-Ki Cheoun <sup>0</sup> , Kungsik Kim <sup>0</sup> , Koichi Saito <sup>0</sup>



Article

## Constraints on Nuclear Symmetry Energy Parameters

James M. Lattimer

Particles 2023, 6, 30–56. <https://doi.org/10.3390/particles6010003>

<https://www.mdpi.com/journal/particles>

## PHYSICAL REVIEW LETTERS

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Editors' Suggestion

Implications of PREX-2 on the Equation of State of Neutron-Rich Matter

Brendan T. Reed, F. J. Fattoyev, C. J. Horowitz, and J. Piekarewicz  
Phys. Rev. Lett. **126**, 172503 – Published 27 April 2021

PHYSICS

## Neutron stars may be bigger than expected, measurement of lead nucleus suggests

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# Science

PHYSICAL REVIEW C  
covering nuclear physics

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Compiled properties of nucleonic matter and nuclear and neutron star models from nonrelativistic and relativistic interactions

Boyang Sun, Saketh Bhattacharyya, and James M. Lattimer  
Phys. Rev. C **109**, 055801 – Published 3 May 2024

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## PHYSICAL REVIEW C

covering nuclear physics

Highlights Recent Accepted Collections Authors Referees Search Press About

Bayesian inference of the symmetry energy and the neutron skin of  $^{48}\text{Ca}$  and  $^{208}\text{Pb}$  from CREX and PREX-2

Zhen Zhang and Lie-Wen Chen  
Phys. Rev. C **108**, 024317 – Published 21 August 2023

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Phys. Rev. Lett. **126**, 172503 – Published 27 April 2021

PRL 119, 122502 (2017)

PHYSICAL REVIEW LETTERS

week ending  
22 SEPTEMBER 2017

## Mirror Charge Radii and the Neutron Equation of State

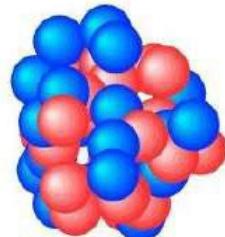
B. Alex Brown

Star Models from Nonrelativistic and Relativistic Interactions

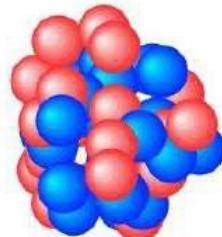
Boyang Sun, Saketh Bhattiprolu, and James M. Lattimer  
Phys. Rev. C **109**, 055801 – Published 3 May 2024

# Neutron Skins, Mirror

$^{32}\text{Ar}$   
18 14



$^{32}\text{Si}$   
14 18



PHYSICAL REVIEW LETTERS

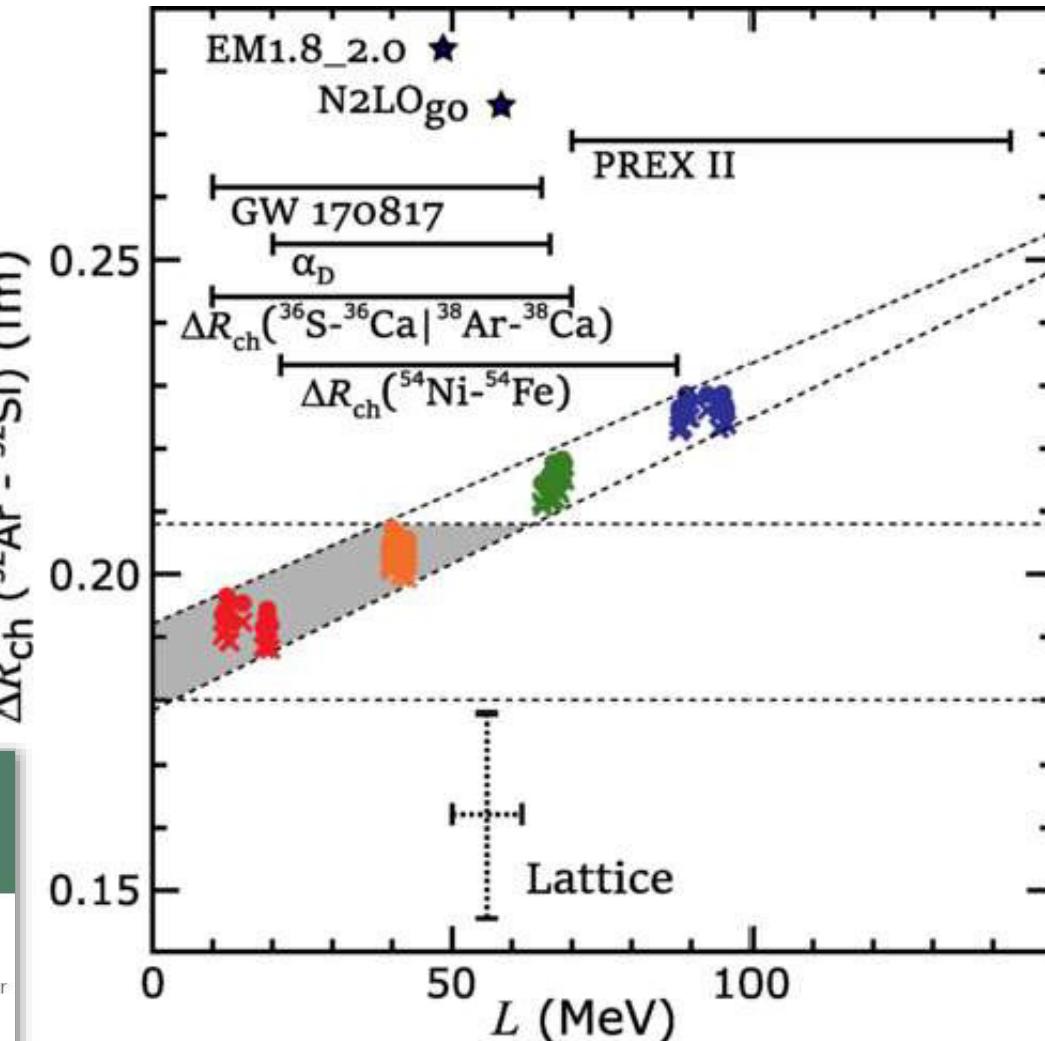
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Nuclear Charge Radii of Silicon Isotopes

Kristian König, Julian C. Berengut, Anastasia Borschovsky, Alex Brinson, B. Alex Brown, Adam Dockery, Serdar Elhatisari, Ephraim Eliav, Ronald F. Garcia Ruiz, Jason D. Holt, Bai-Shan Hu, Jonas Karthein, Dean Lee, Yuan-Zhuo Ma, Ulf-G. Meißner, Kei Minamisono, Alexander V. Oleynichenko, Skyy V. Pineda, Sergey D. Prosnjak, Marten L. Reitsma, Leonid V. Skripnikov, Adam Vernon, and Andréi Zaitsevskii

Phys. Rev. Lett. **132**, 162502 – Published 16 April 2024

Includes researchers from **Germany, Australia, Netherlands, Turkey, Israel, Canada, Russia, and MIT, FRIB/MSU, ORNL, in the U.S.**



$$L = 3\rho[\partial E_{\text{sym}}(\rho)/\partial \rho]|_{\rho=\rho_0}$$



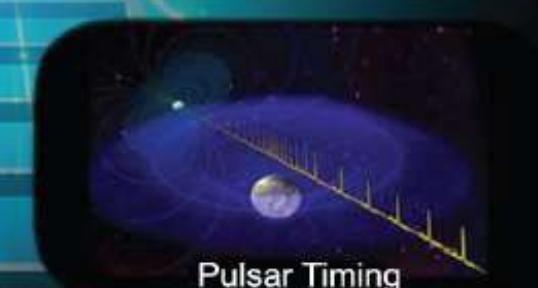
Kristian König

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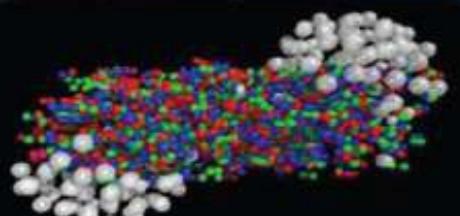
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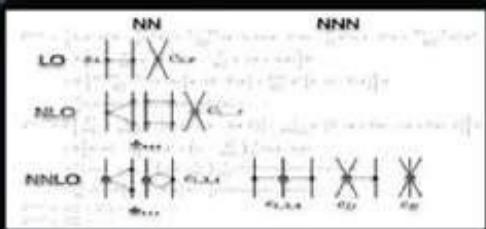
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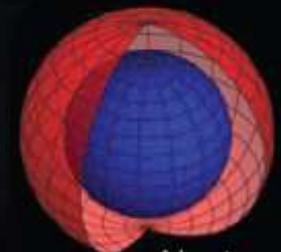
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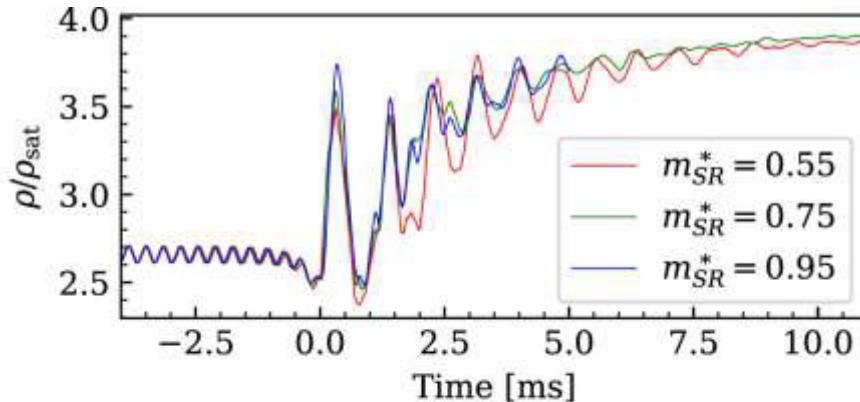


Gravitational Waves



Neutron Skins

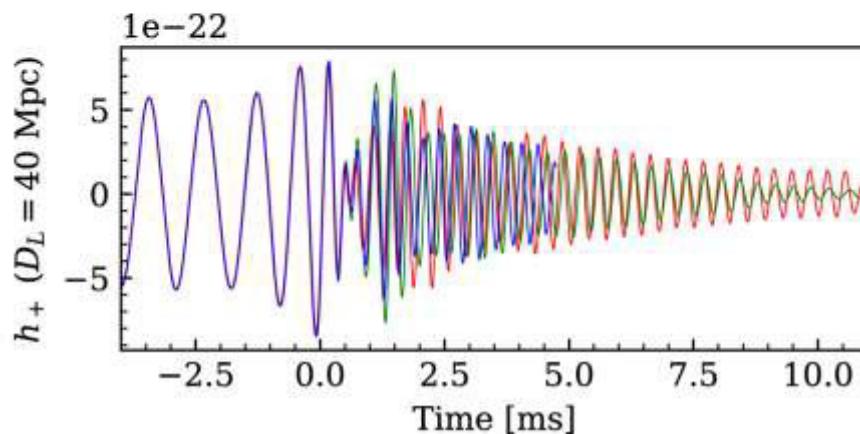
# Gravitational Waves (GW)



- Vary effective nucleon mass  $\rightarrow$  specific heat
- Maximum rest mass density (top), GW strain predictions (bottom) for  $l=2, m=2$  mode
- Measurable effects in postmerger GW with next generation observatories



David Radice



THE ASTROPHYSICAL JOURNAL LETTERS, 952:L36 (7pp), 2023 August 1

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OPEN ACCESS

<https://doi.org/10.3847/2041-8213/ace5b2>



## Thermal Effects in Binary Neutron Star Mergers

Jacob Fields<sup>1,2</sup> , Aviral Prakash<sup>1,2</sup> , Matteo Breschi<sup>3,4,5</sup> , David Radice<sup>1,2,6,8</sup> , Sebastiano Bernuzzi<sup>3</sup> , and André da Silva Schneider<sup>7</sup> 

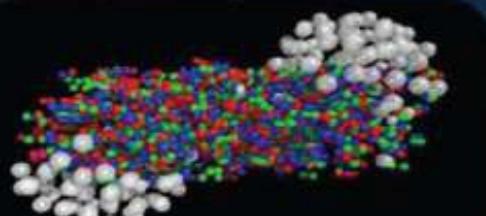
Includes researchers from **Germany, Brazil, Italy** and Penn State (PA) in the **U.S.**,  
**ENAF SCIDAC (Scientific Discovery through Advanced Computing), DOE-ASCR**

# HEAVEN AND EARTH

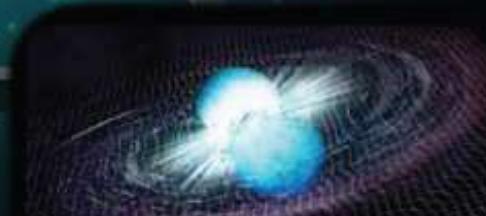
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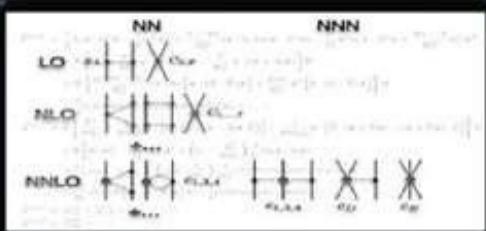
Pulsar Timing



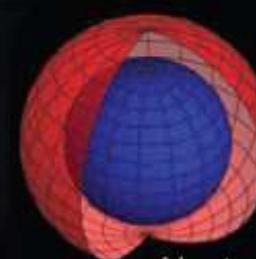
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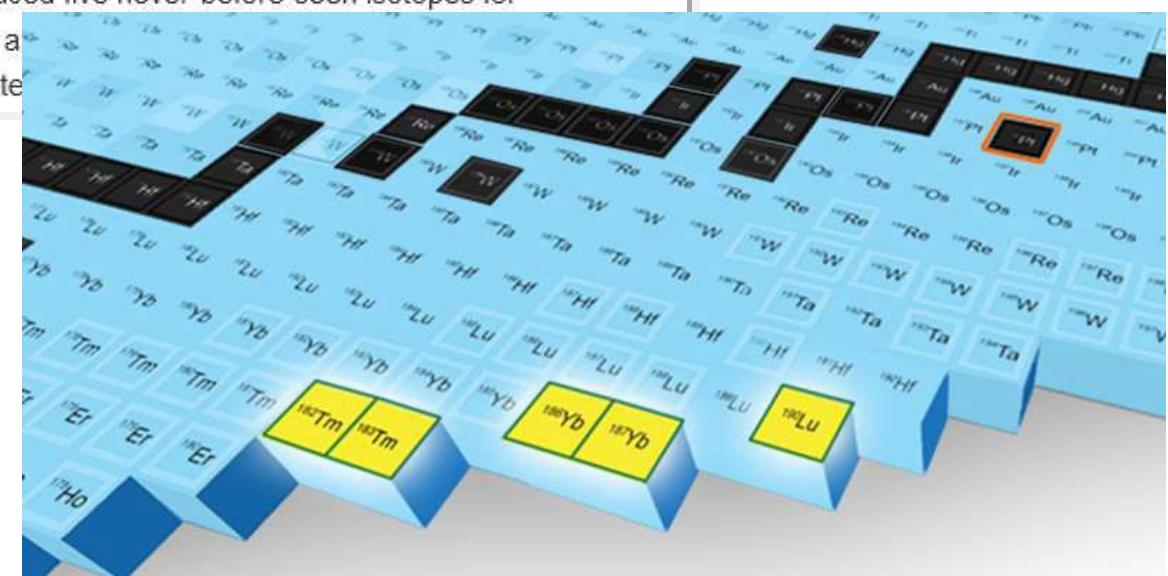
Neutron Skins

# Nuclear Landscape

- FRIB made 5 never-before-seen isotopes of the elements thulium, ytterbium, lutetium
- N=126 – ‘one to watch’

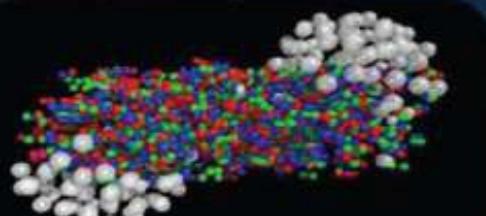


Includes researchers from RIKEN in Japan, IBS in South Korea, and MSU in the U.S.

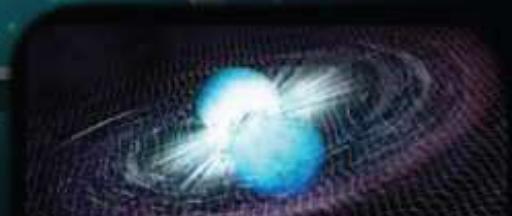


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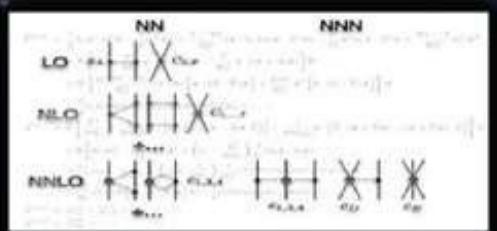
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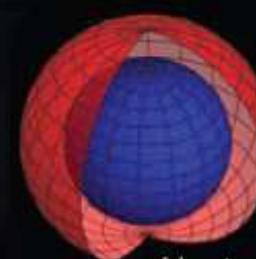
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Neutron Skins

# X-ray Binaries

## PHYSICAL REVIEW LETTERS

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First Direct Measurement Constraining the  $^{34}\text{Ar}(\alpha, \text{p})^{37}\text{K}$  Reaction Cross Section for Mixed Hydrogen and Helium Burning in Accreting Neutron Stars

J. Browne *et al.* (JENSA Collaboration)

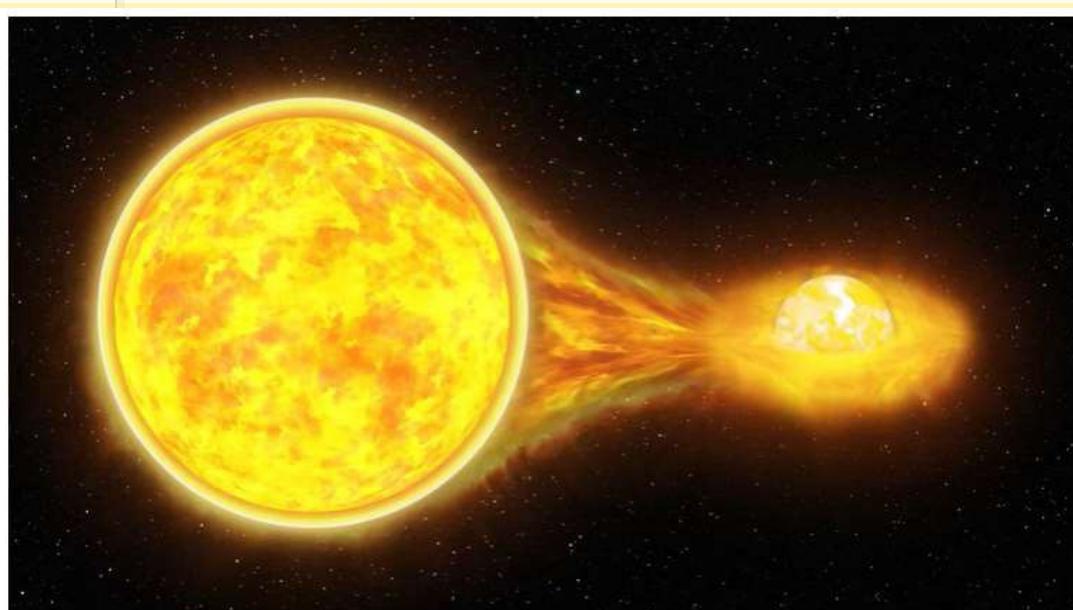
Phys. Rev. Lett. **130**, 212701 – Published 22 May 2023



Kelly Chipps



Element creation in the lab deepens understanding of surface explosions on neutron stars



Includes researchers from **South Korea, Germany**, and ORNL, LSU, Mines, FRIB/MSU, UTK, Rutgers in the U.S.

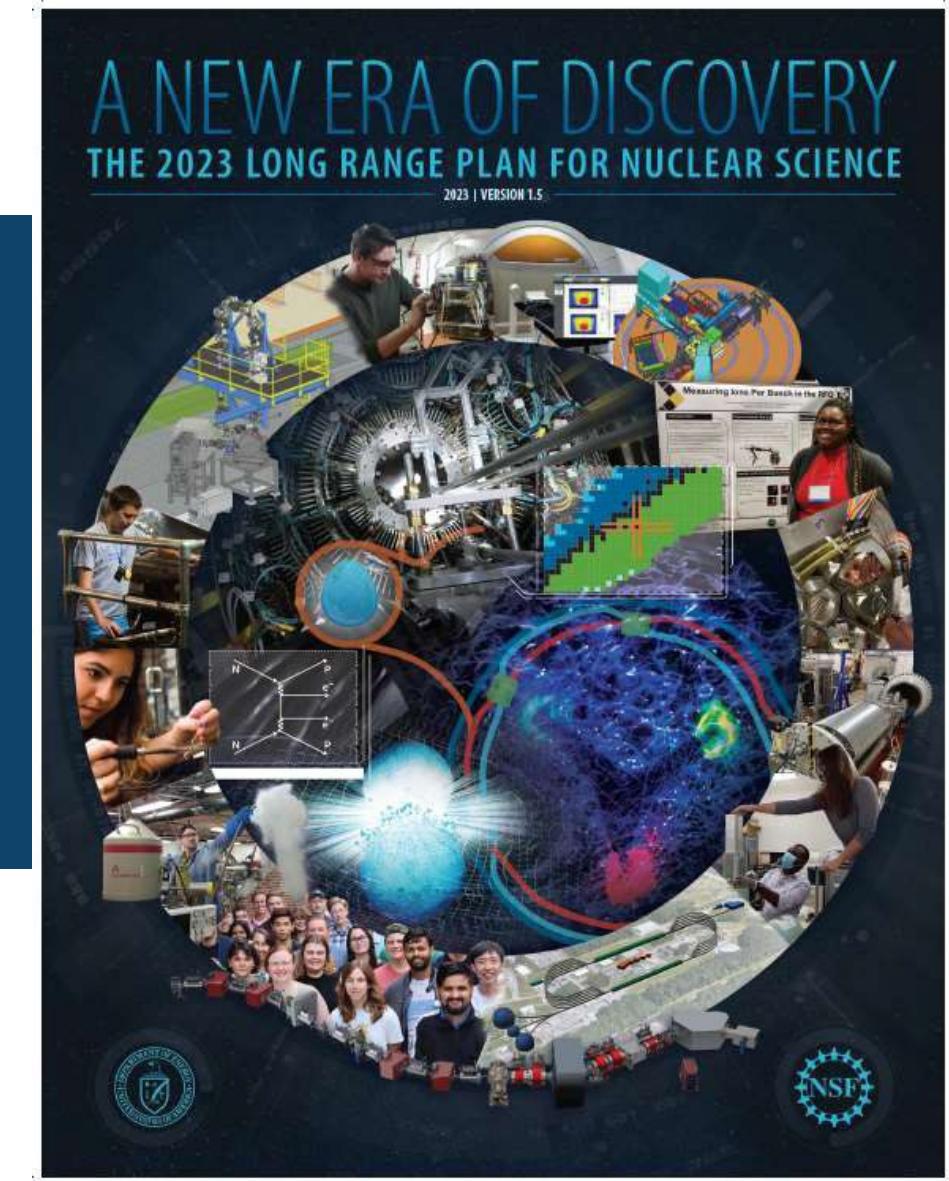


Office of  
Science

Chipps image courtesy of ORNL. Accreting NS binary by Jacquelyn DeMink, ORNL.

# Summary

- Highlighted some lab-based experiments and theoretical work relevant to neutron star properties.
- Larger picture – neutrinos, isomers, advancements in theory, kilonova, scope at ATLAS, scope at RAISOR, exascale computing, AI/ML, nuclear data.
- NSF and NASA contributions to the ‘ladder’ are greatly valued and highly leveraged.



c

