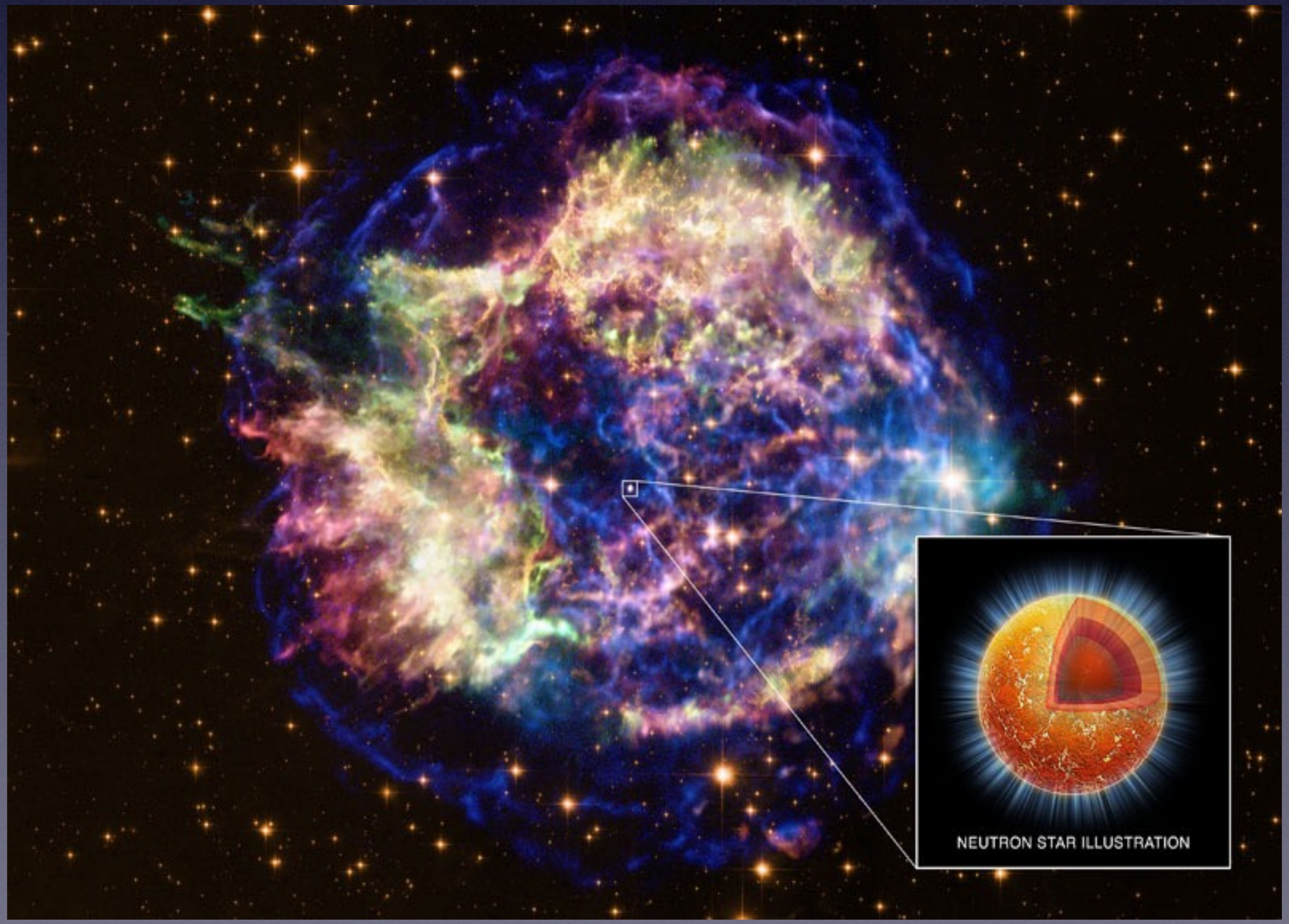
U.S. DEPARTMENT OF ENERGY | Office of Science

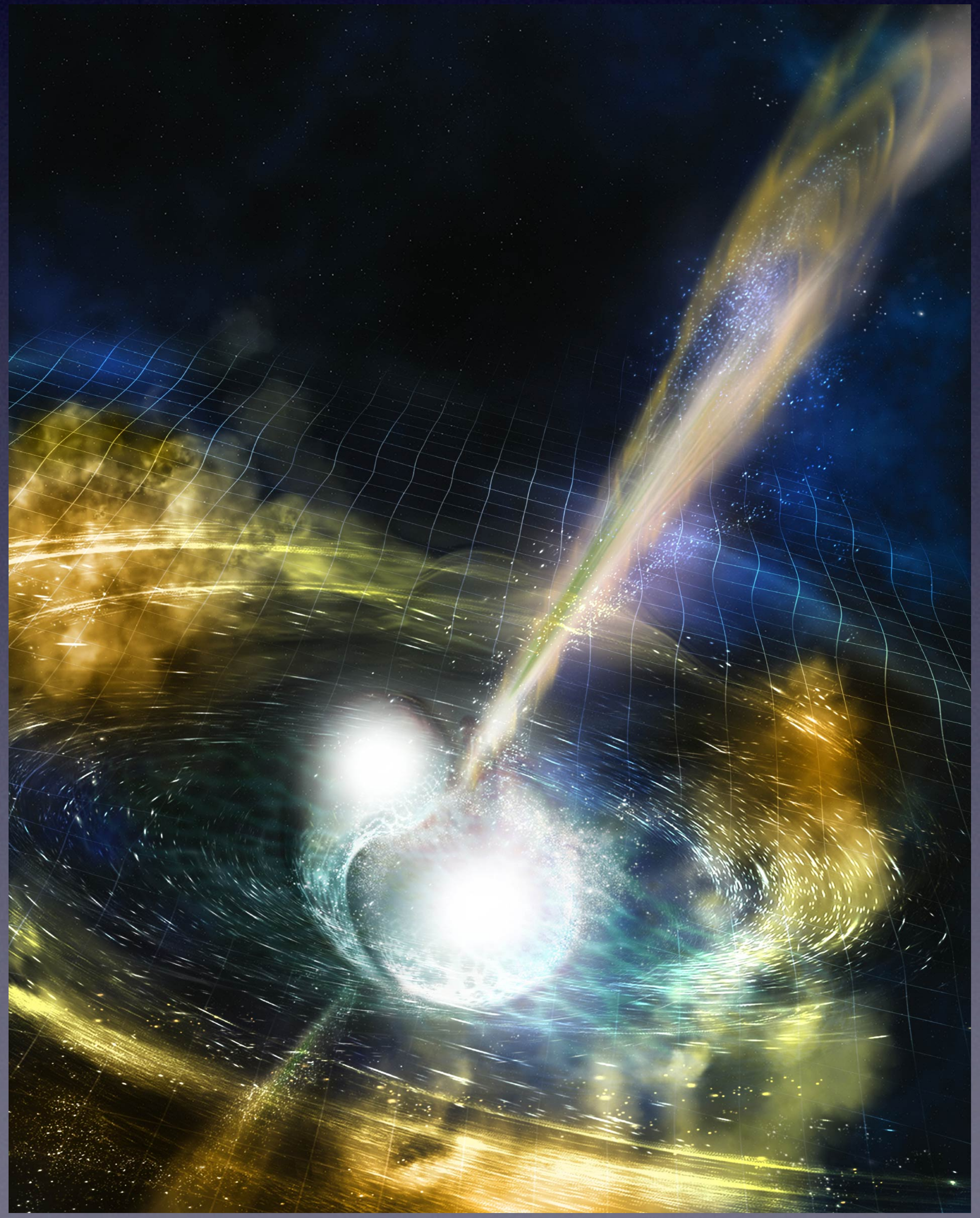
# The Impact of PREX and CREX on the Neutron Star EOS

FLORIDA STATE UNIVERSITY 1851

J. Piekarewicz


JLUO Annual Meeting
June 10 -12, 2024





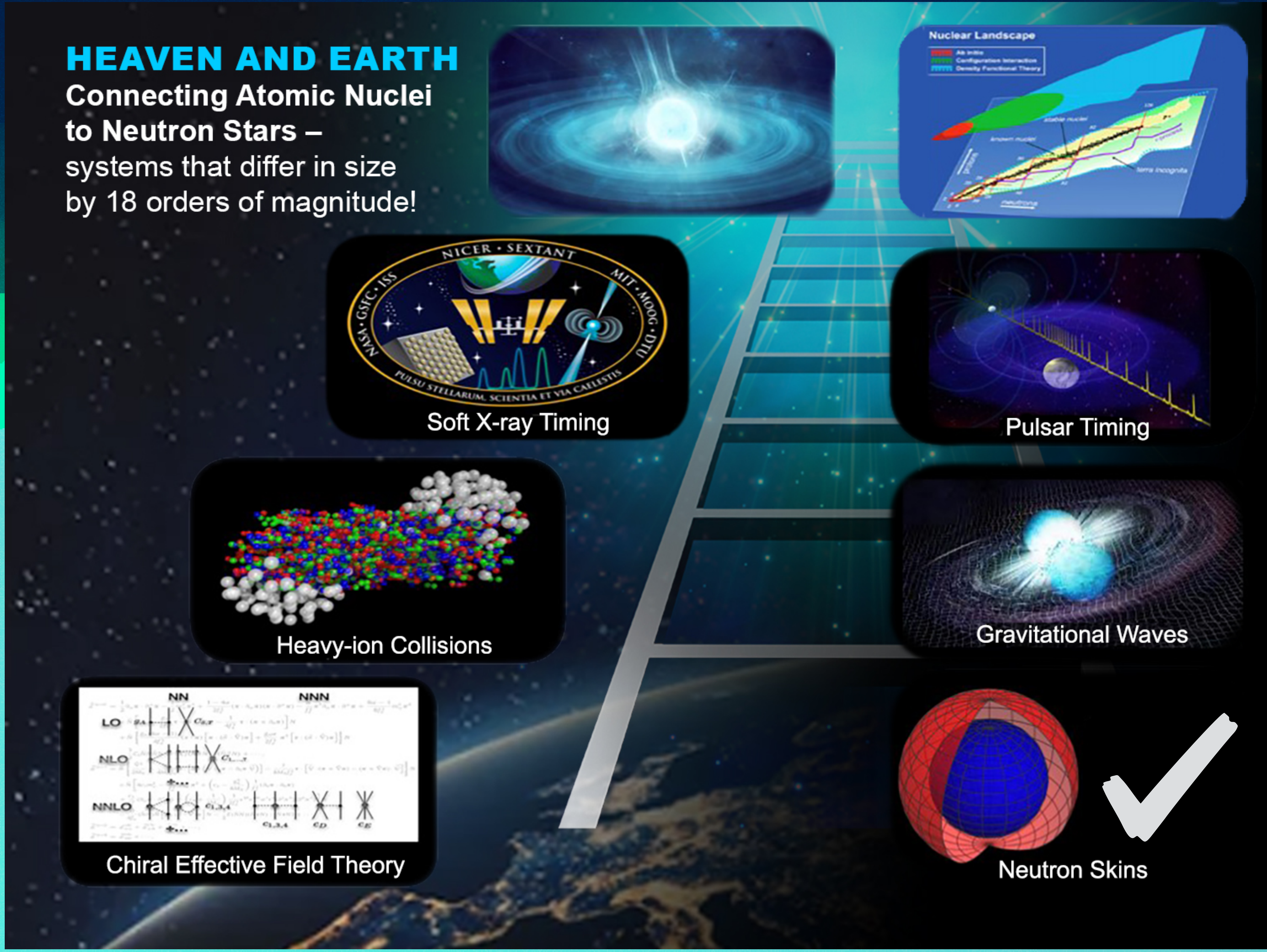
# Heaven and Earth: Nuclear EOS Density Ladder

No single method can constrain the EOS over the entire density domain. Instead, each rung on the ladder provides information that can be used to determine the **EOS** at neighboring rungs

A NEW ERA OF DISCOVERY

THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

2023 | VERSION 1.1



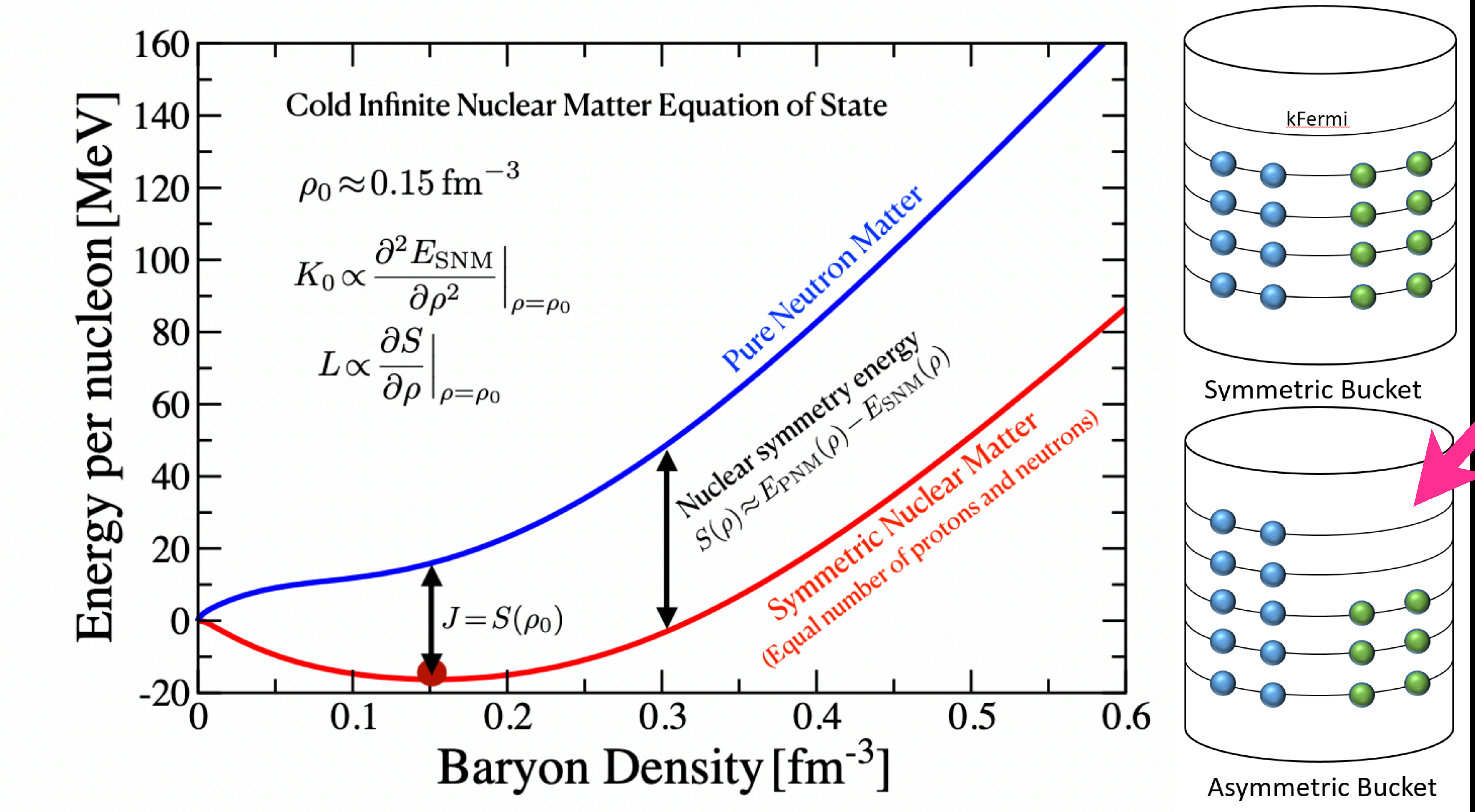
**HEAVEN AND EARTH**

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

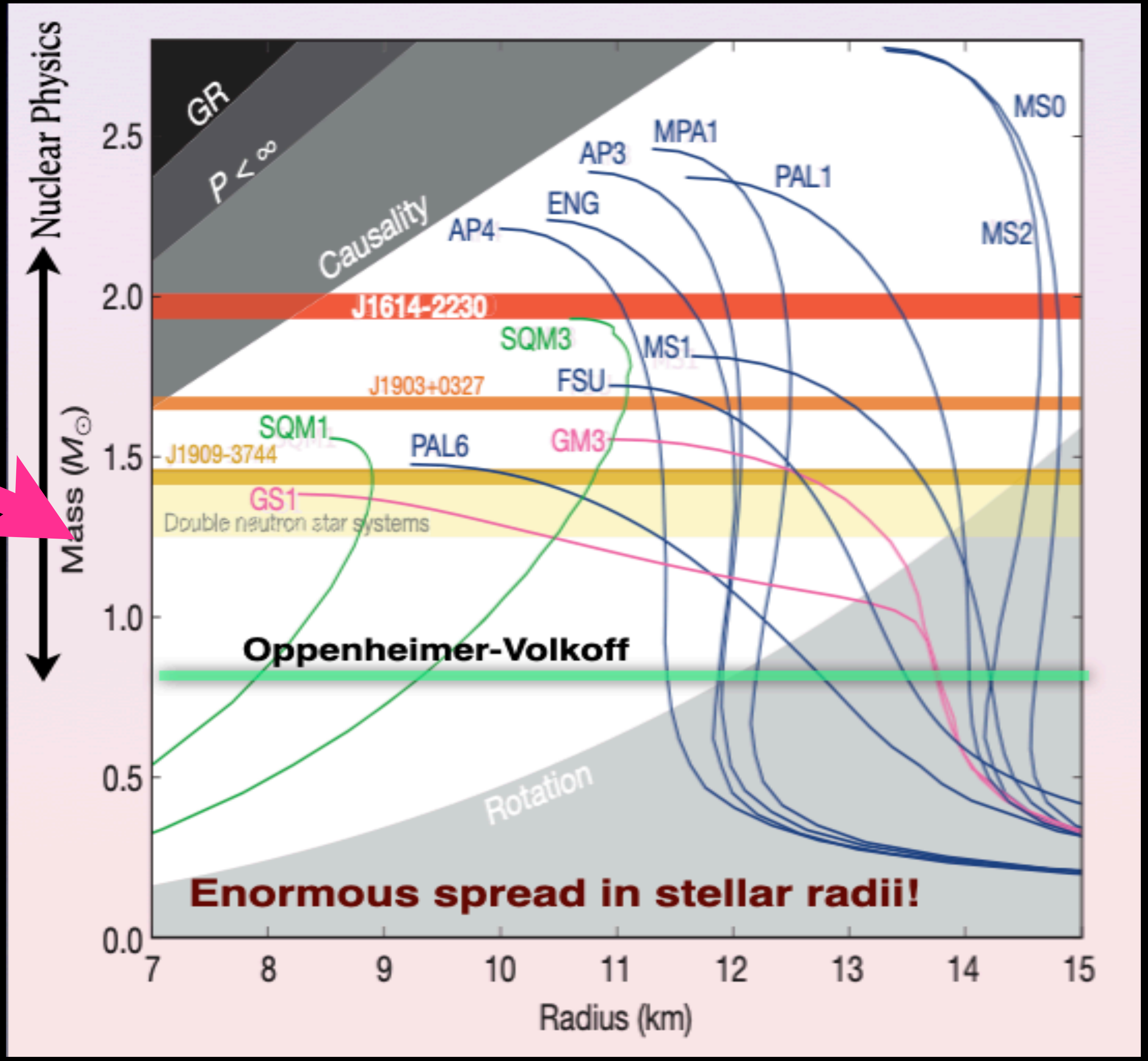
Electroweak Probes of Nuclear densities

PREX+CREX

# Neutron Stars and The Equation of State of Neutron-Rich Matter



Micro-Macro Connection



*Only Physics that the TOV equation is sensitive to is the Equation of State*

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

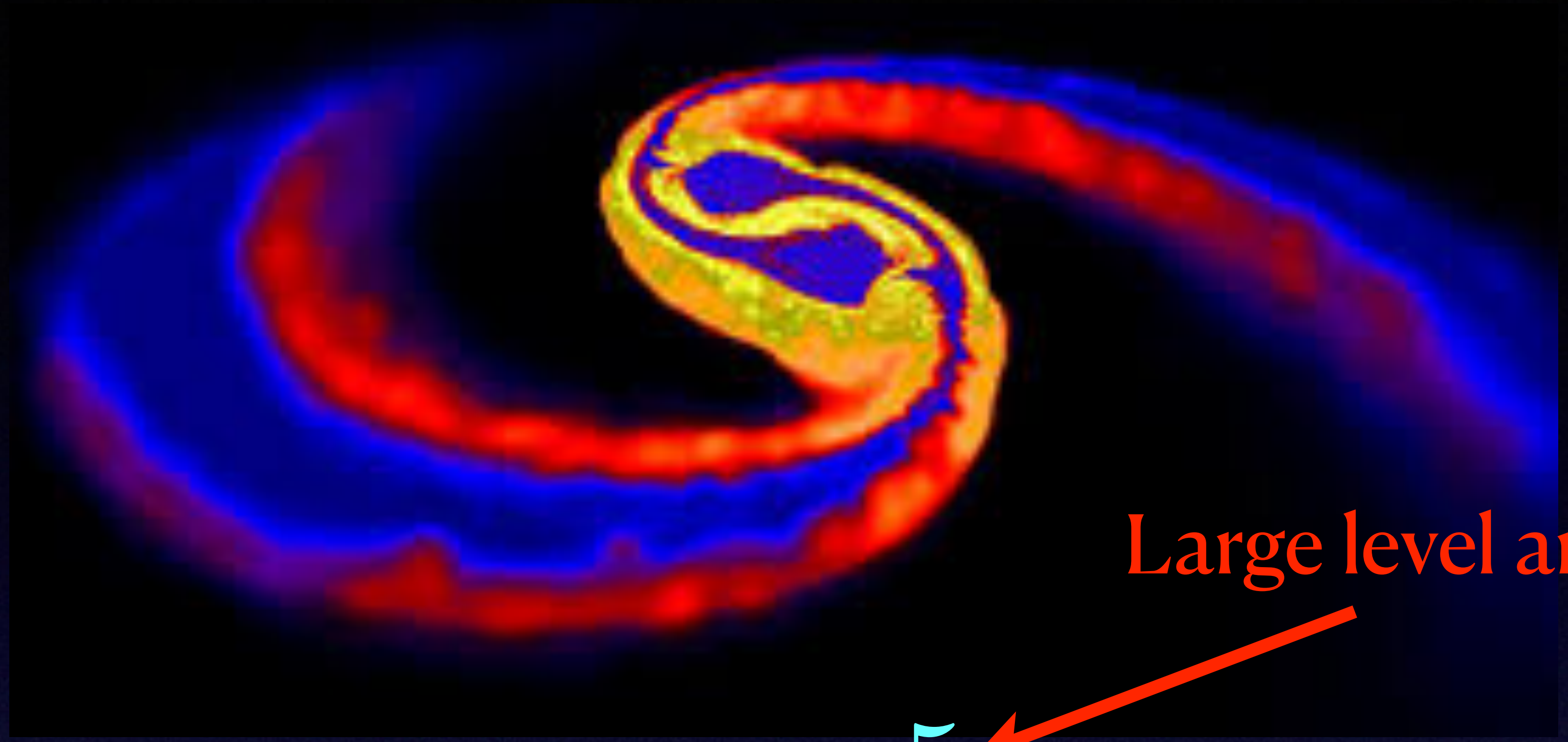
$$P_{\rm PNM} \approx \frac{1}{3} L \rho_0 \ (\text{Pressure of PNM})$$

“Stiff” ⟶ L large
“Soft” ⟶ L small

*PREX constrains L!*

# Tidal Polarizability and Neutron-Star Radii (2017)

## Tidal Polarizability(Deformability):

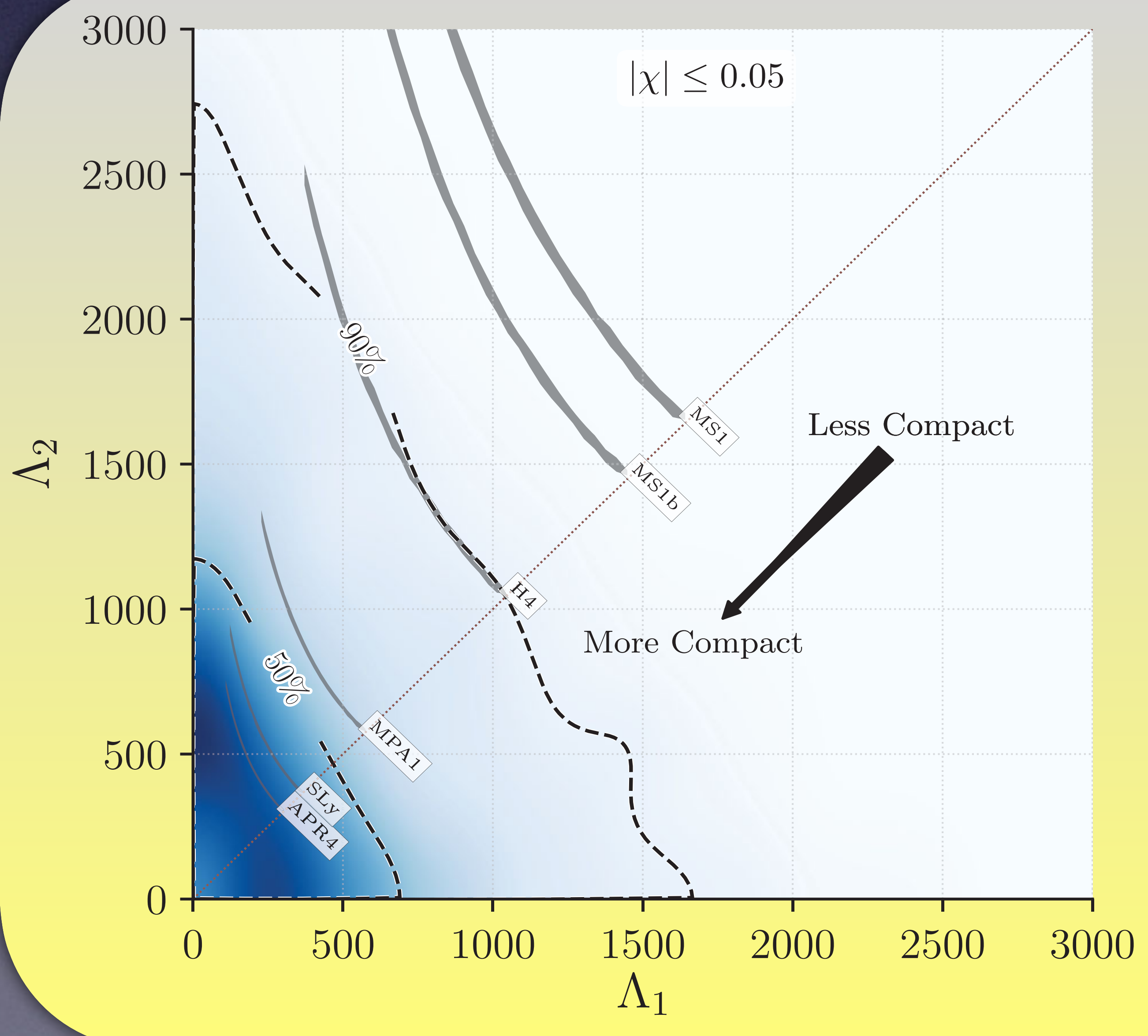


- Tidal field induces a mass polarization
- A time dependent mass quadrupole emits gravitational waves

Large level arm!

*Micro-Macro*

$$Q_{ij} = \Lambda\mathcal{E}_{ij} \qquad \Lambda = k_2\left(\frac{c^2R}{2GM}\right)^5 = k_2\left(\frac{R}{R_s}\right)^5$$



GW170817 rules out very large neutron star radii!

Neutron Stars must be compact

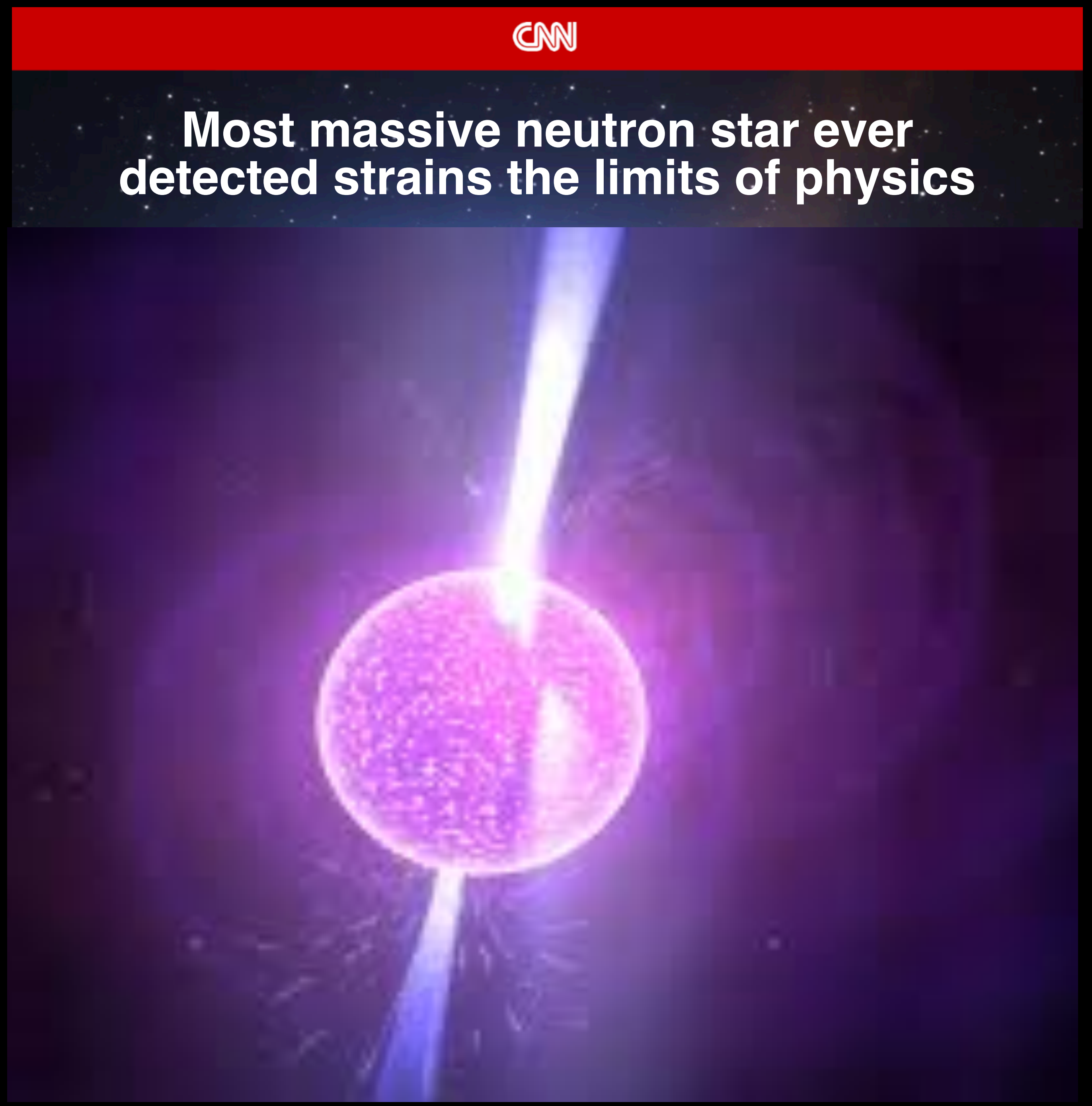
$$\Lambda_{1.4} = 390^{+190}_{-120}\ (90\%)$$

(Latest LIGO/Virgo analysis)

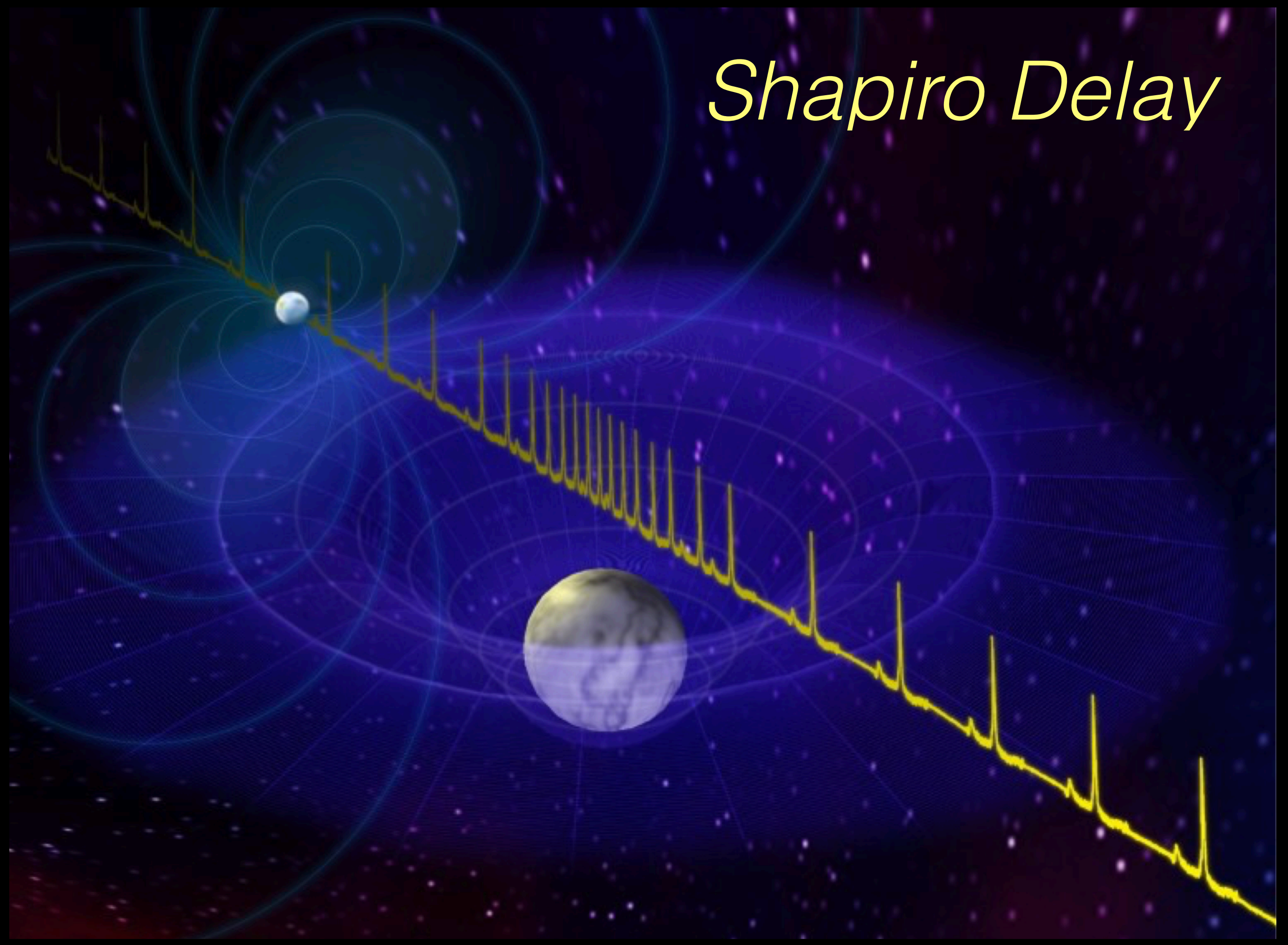
**Soft EOS!**
**Small L!**

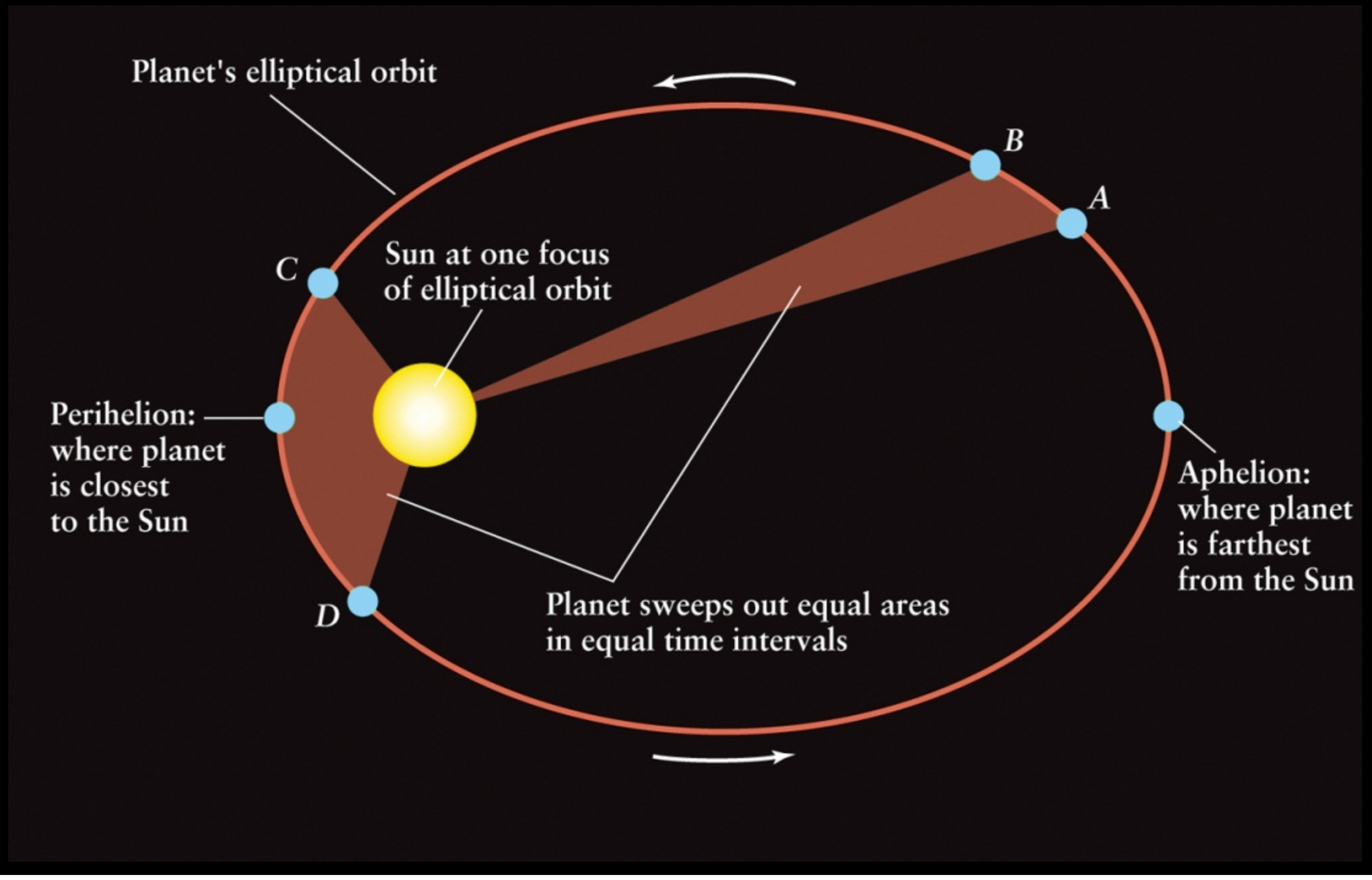
The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation. Very sensitive to stellar radius!

# Measuring Heavy Neutron Stars (2019)
## Shapiro Delay: General Relativity to the Rescue


CNN

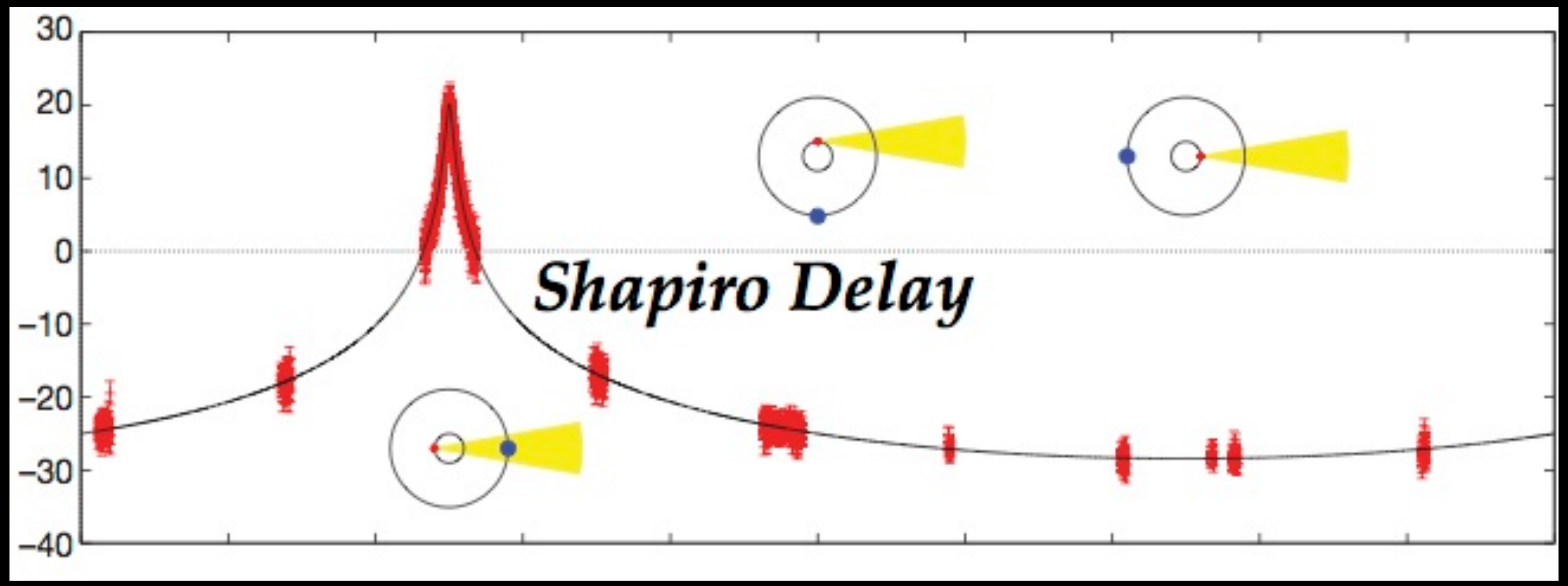
Most massive neutron star ever detected strains the limits of physics





Newtonian Gravity sensitive to the total mass of the binary
Kepler's Third Law

$$G(M_{\rm ns}+M_{\rm wd}) = 4\pi^2\frac{a^3}{P^2}$$



Shapiro delay — a purely General Relativistic effect can break the degeneracy

$$\delta t = \frac{2GM_{\rm WD}}{c^3}\ln\left(\frac{4R_\star R_\oplus}{d^2}\right) \approx 10\mu s$$

Stiff EOS!
Large L!

$$M = 2.08 \pm 0.07 M_\odot$$

Cromartie/Fonseca et al. (2020)

# *Neutron-star Interior Composition Explorer (NICER)*
# *Simultaneous Mass and Radius Measurements (2019-2021)*

NICER was launched from Kennedy's Space Center on June 3, 2017 aboard SpaceX Falcon 9 Rocket and docked at the International Space Station two days later.

NICER measures the compactness of the Neutron Star by looking at back of the star!

Pulse Profile: The stellar compactness controls the light profile from the hot spot

$$\xi = \frac{2GM}{c^2R} = \frac{R_S}{R}$$

$$M = 2.08 \pm 0.07\,\mathrm{M}_\odot$$

Shapiro delay: Cromartie *et al.* (2020)

$$R_{2.0} = 12.39^{+1.30}_{-0.98}\ \mathrm{km}$$

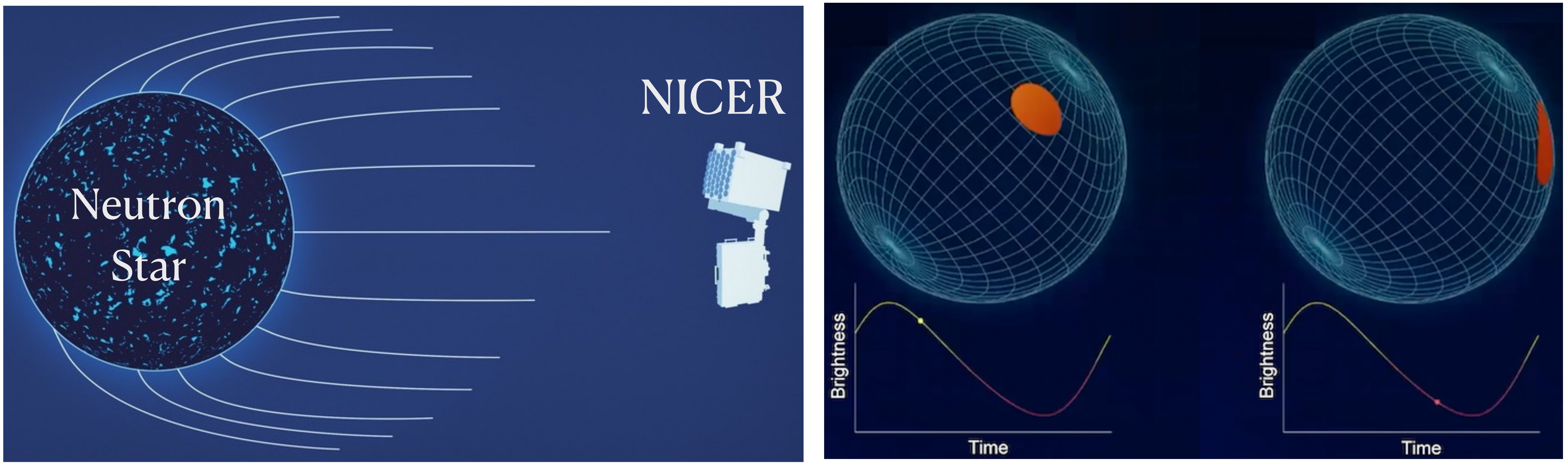
Riley *et al.* (2021)

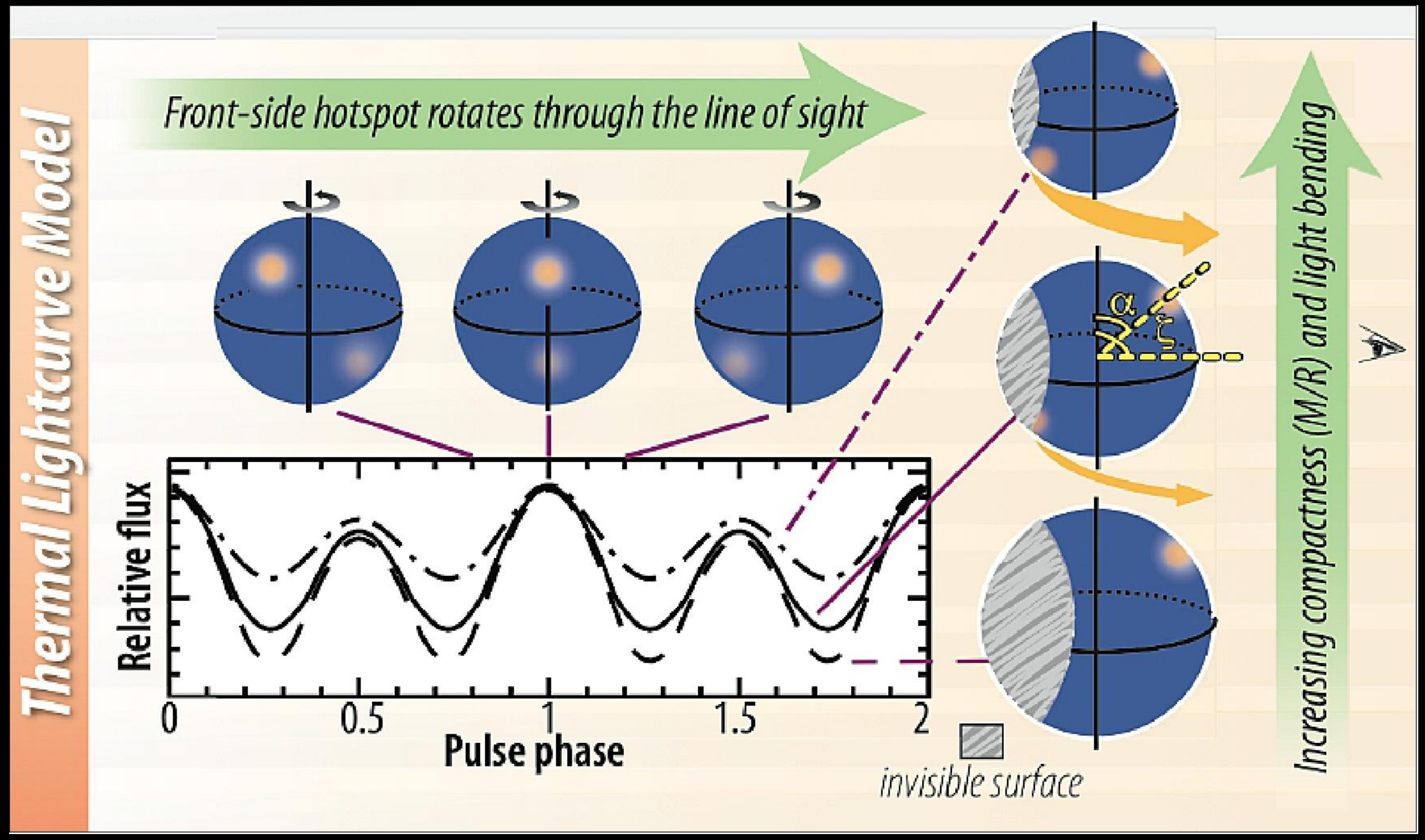
$$R_{2.0} = 13.7^{+2.6}_{-1.5}\ \mathrm{km}$$

Miller *et al.* (2021)

*Micro-Macro*

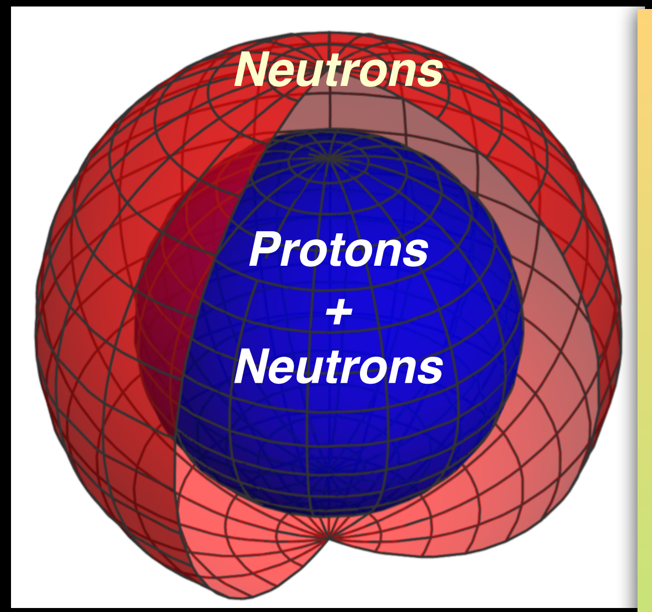
***Stiff EOS! Large L!***

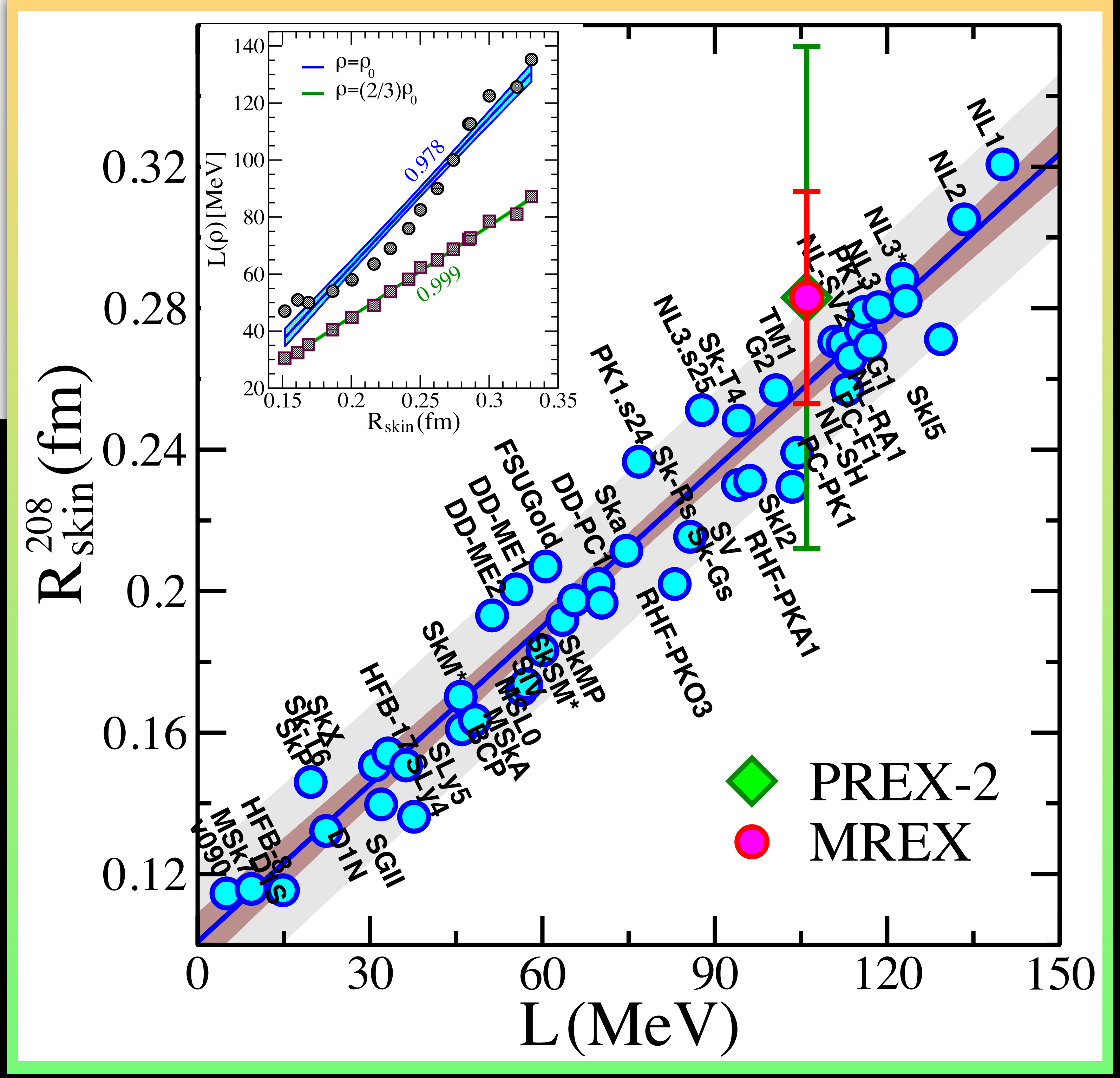




# Heaven and Earth

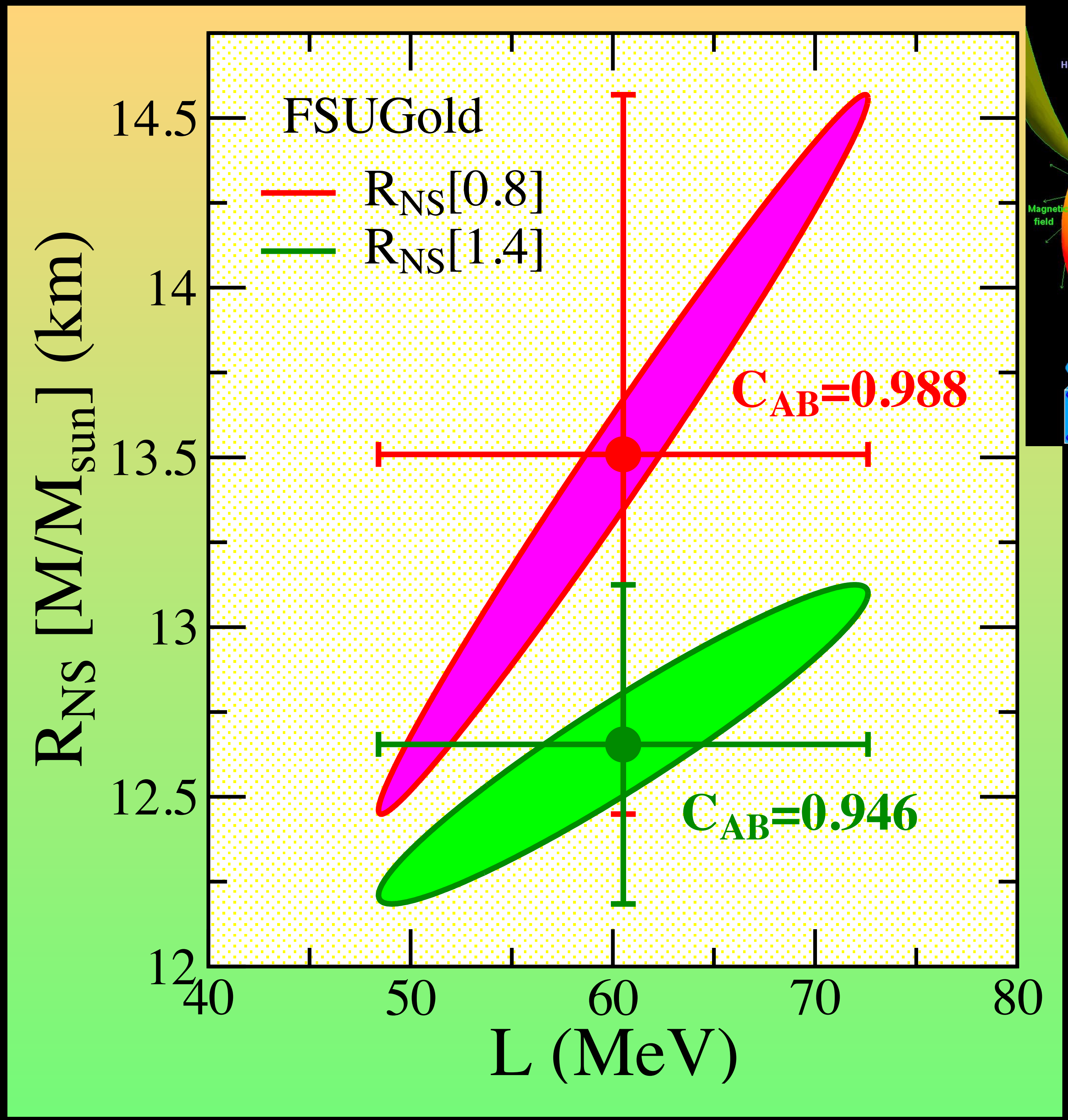
## Laboratory Constraints on the EOS

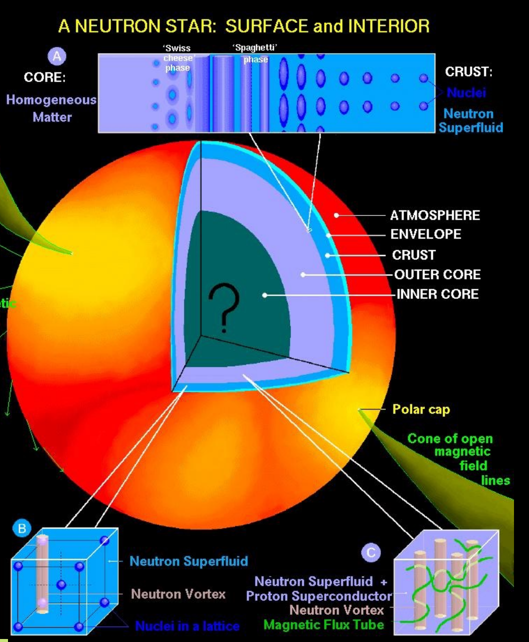




18 orders

magnitude



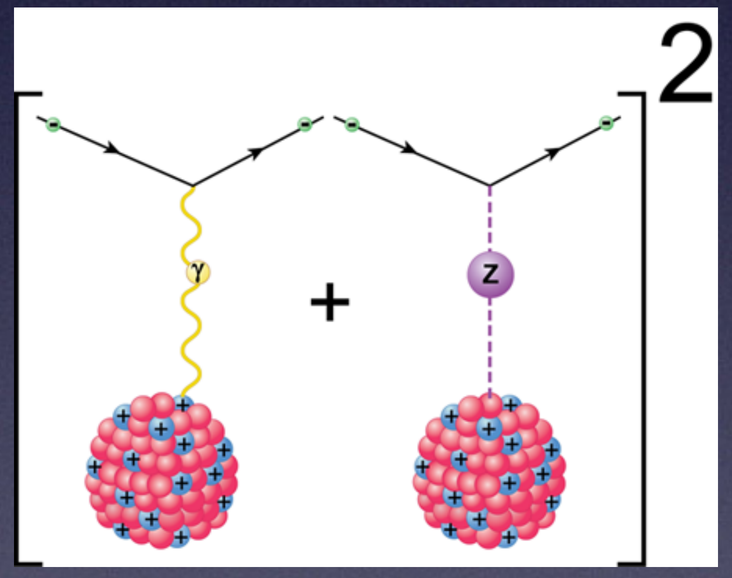


*The slope of the symmetry energy L controls both the neutron skin of heavy nuclei as well as the radius of (low mass) neutron stars — objects that differ in size by 18 orders of magnitude!*

# Parity Violating e-Nucleus Scattering

## Searching for an accurate picture of the neutron distribution

- Charge (proton) density known with enormous precision
  - Probed via parity-conserving elastic e-scattering
- Weak-charge (neutron) density known very poorly known
  - Probed via parity-violating elastic e-scattering

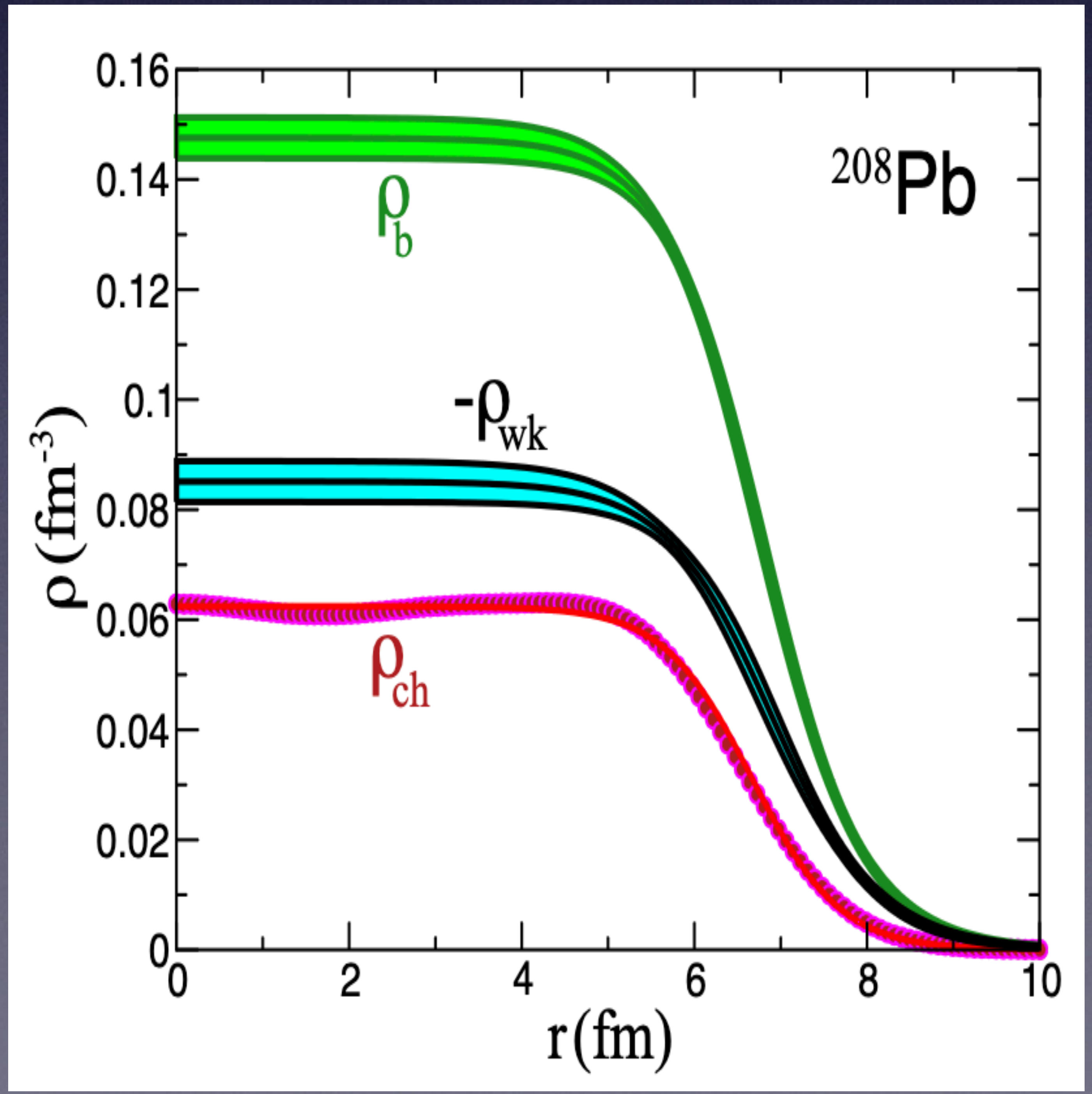


$$A_{\rm PV} \equiv \left[\frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L}\right] = \left(\frac{G_{\rm F} Q^2}{4\pi\alpha\sqrt{2}}\right)\frac{F_{wk}(Q^2)}{F_{ch}(Q^2)} \simeq 10^{-6}$$

- *Electric-charge density dominated by protons*
- *Weak-charge density dominated by neutrons*

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

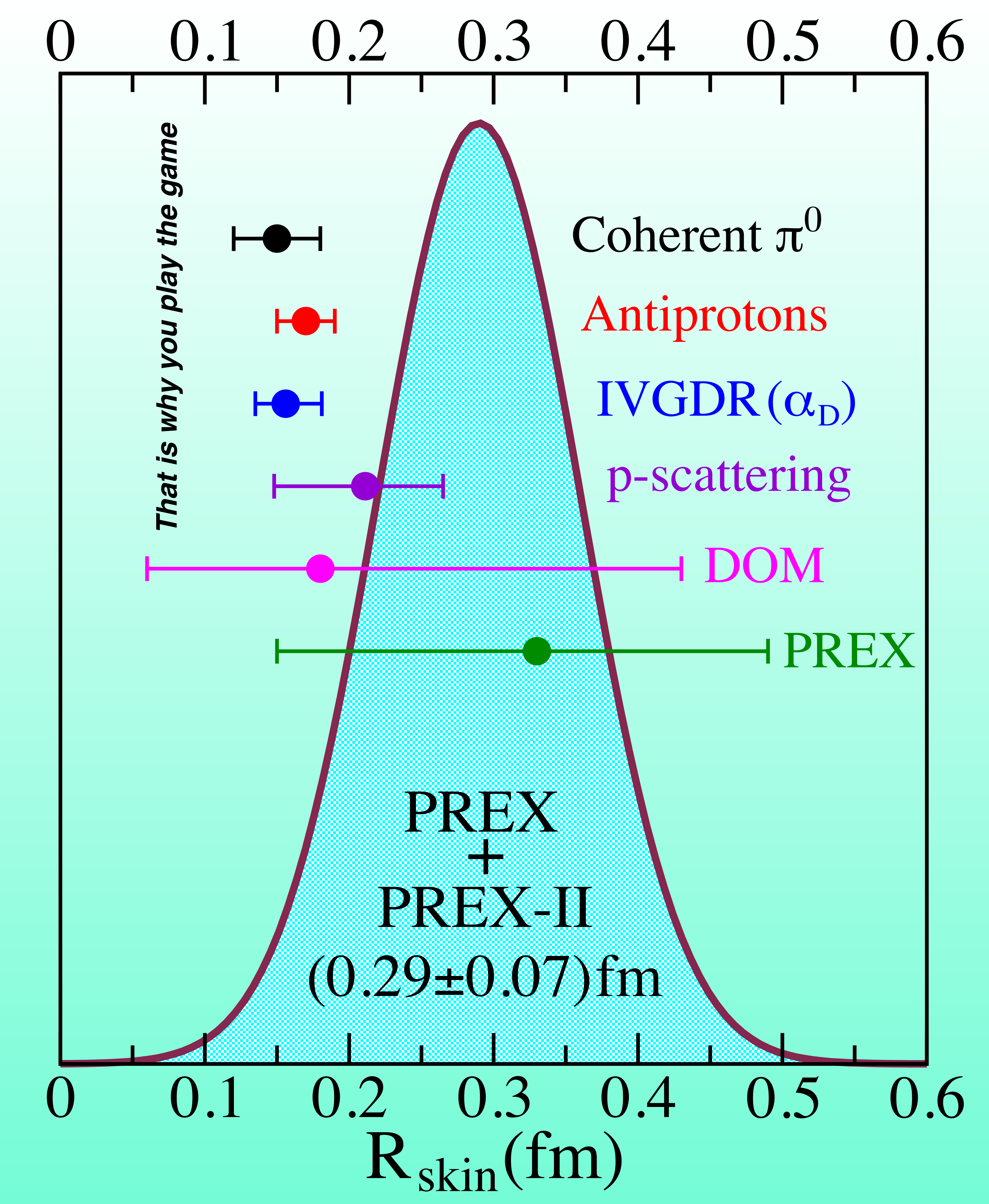
$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$



## PREX-2 (Oct 29, 2020)

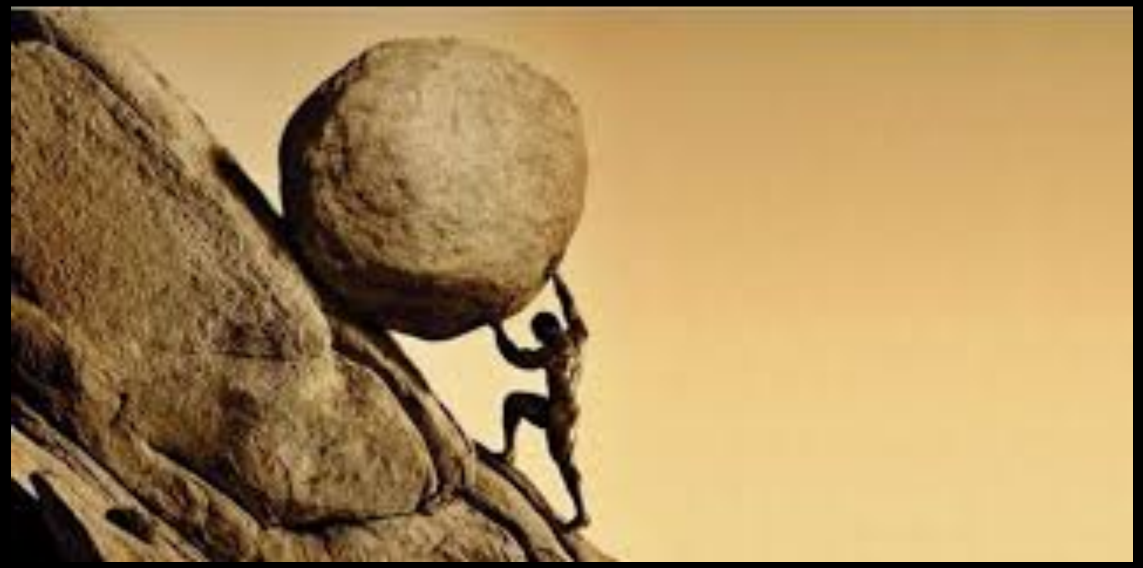
Ciprian Gal - DNP Meeting

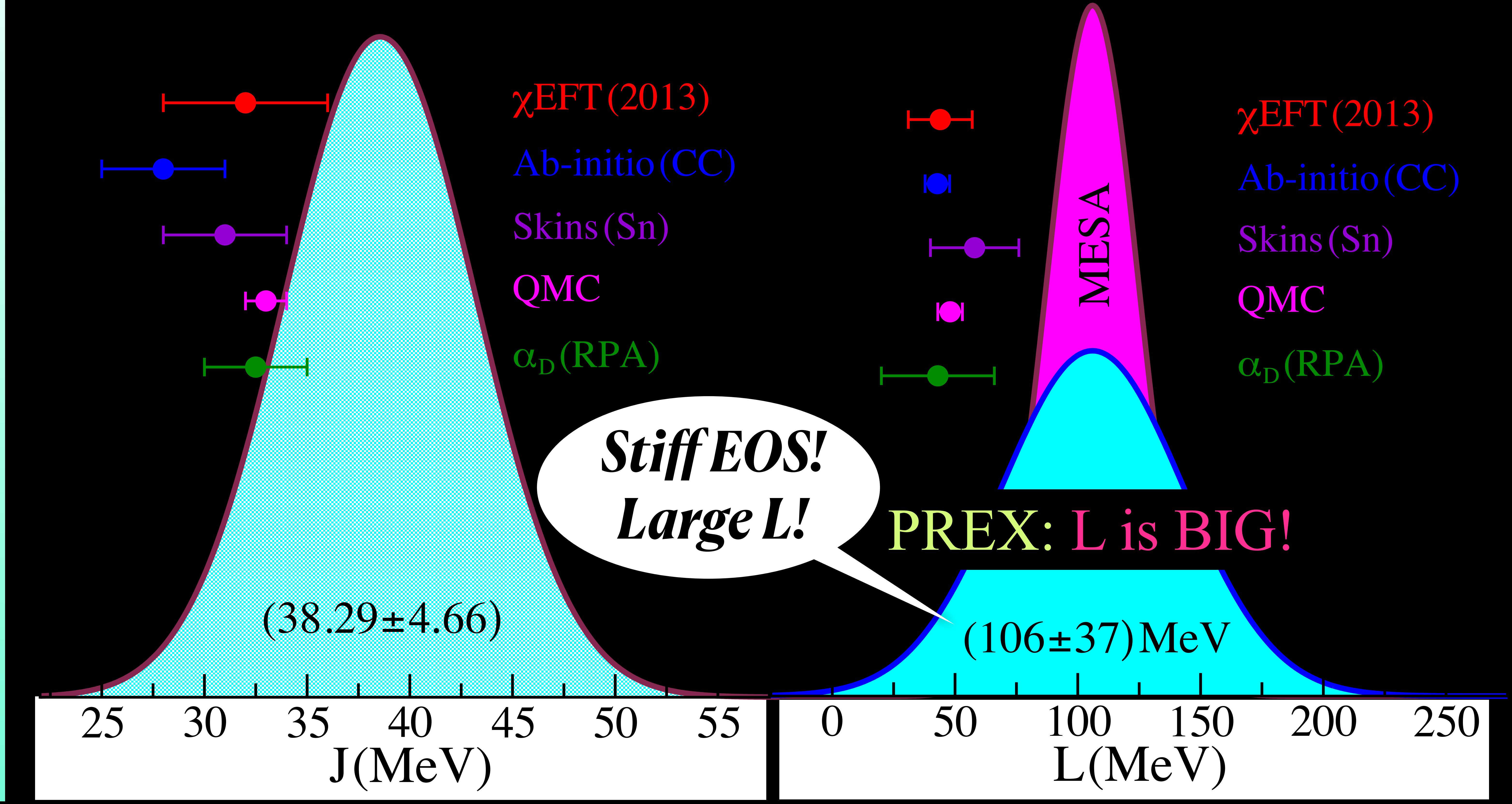
*Adhikari et al., PRL 126, 172502 (2021)*



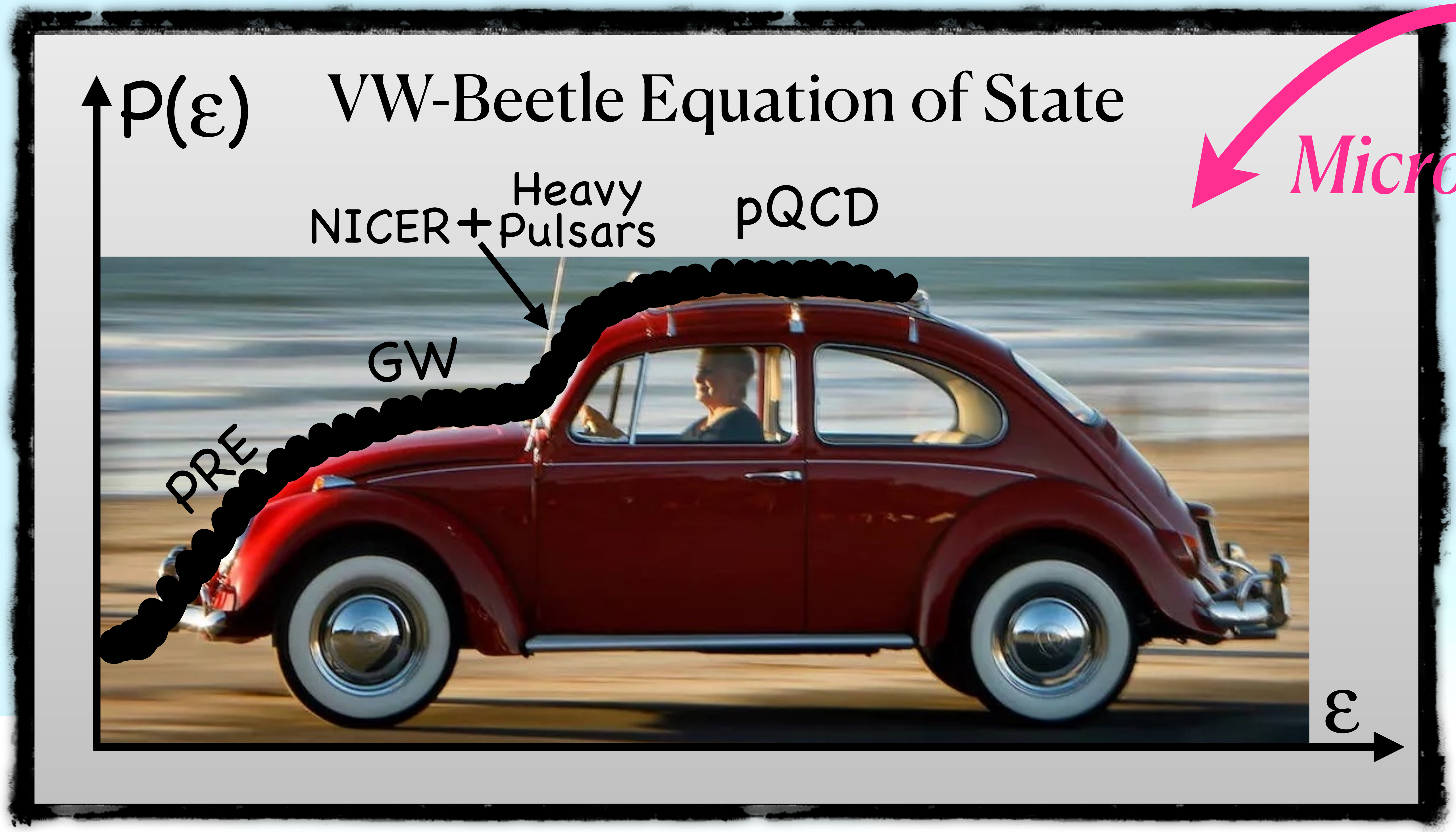
## Conservation of difficulty: PVES provides the cleanest constraint on the EOS of neutron-rich matter in the vicinity of saturation density

## Heroic effort from our experimental colleagues

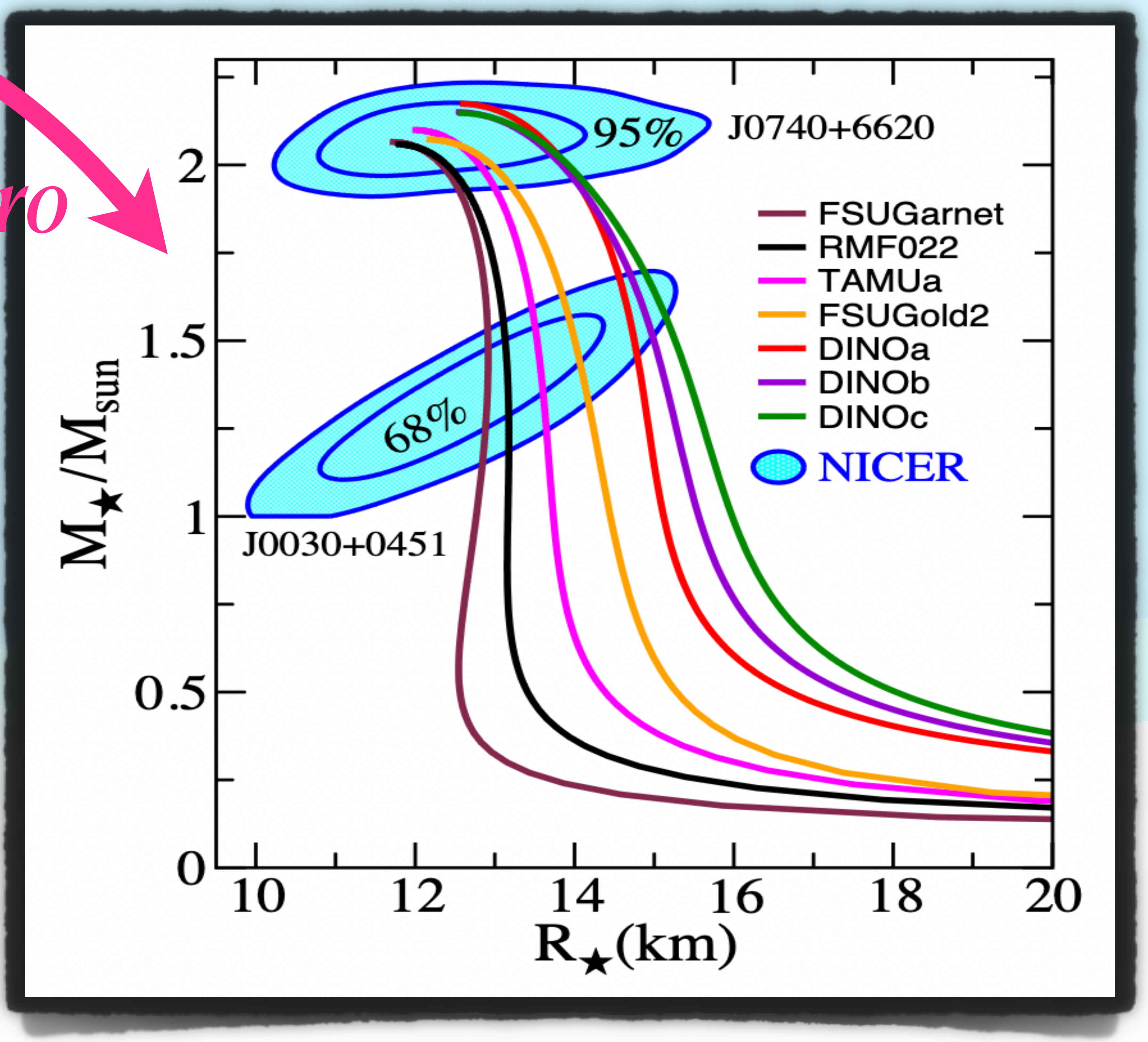


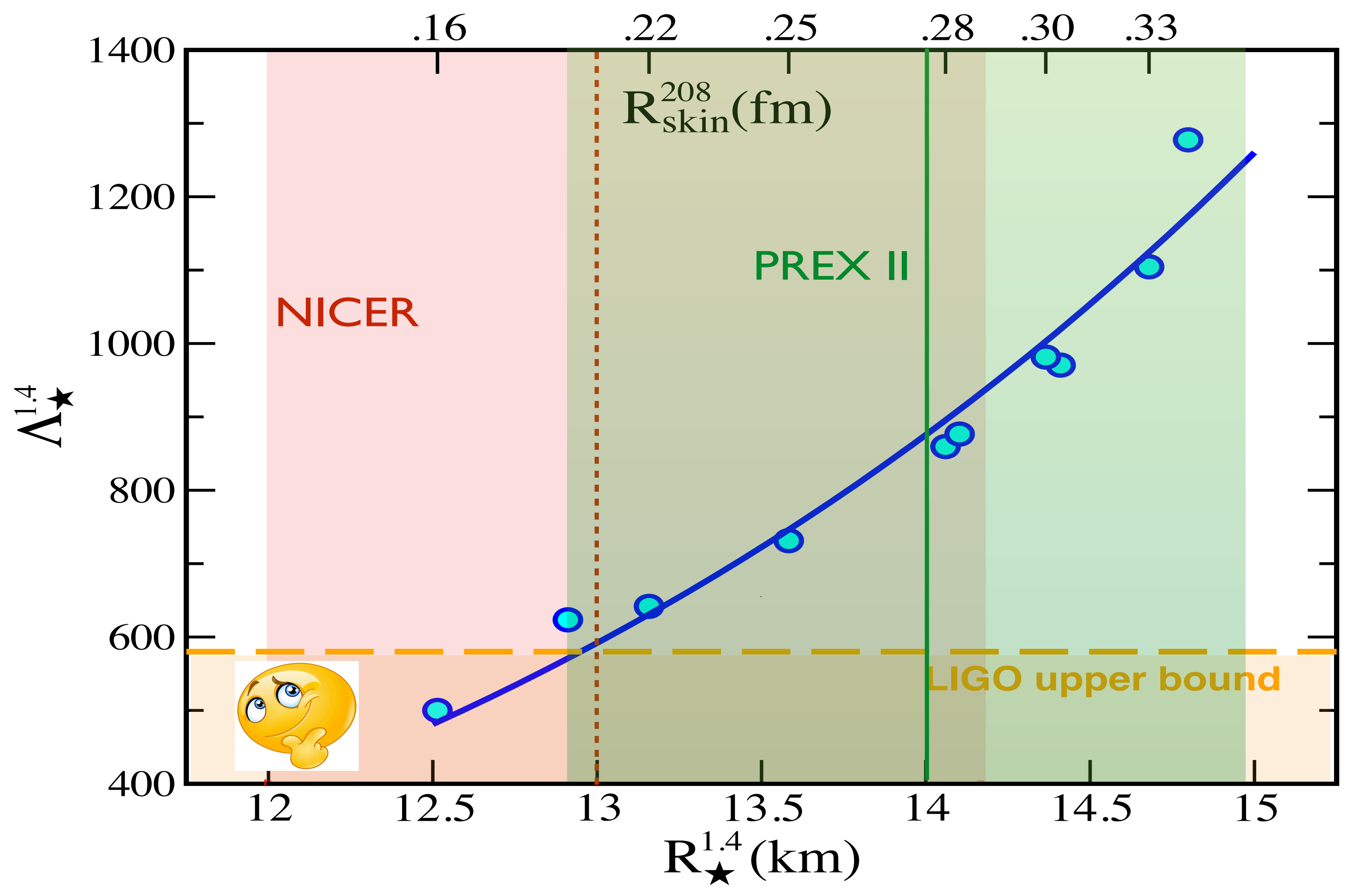


# The Dawn of a Golden Era in Neutron-Star Physics



Micro-Macro





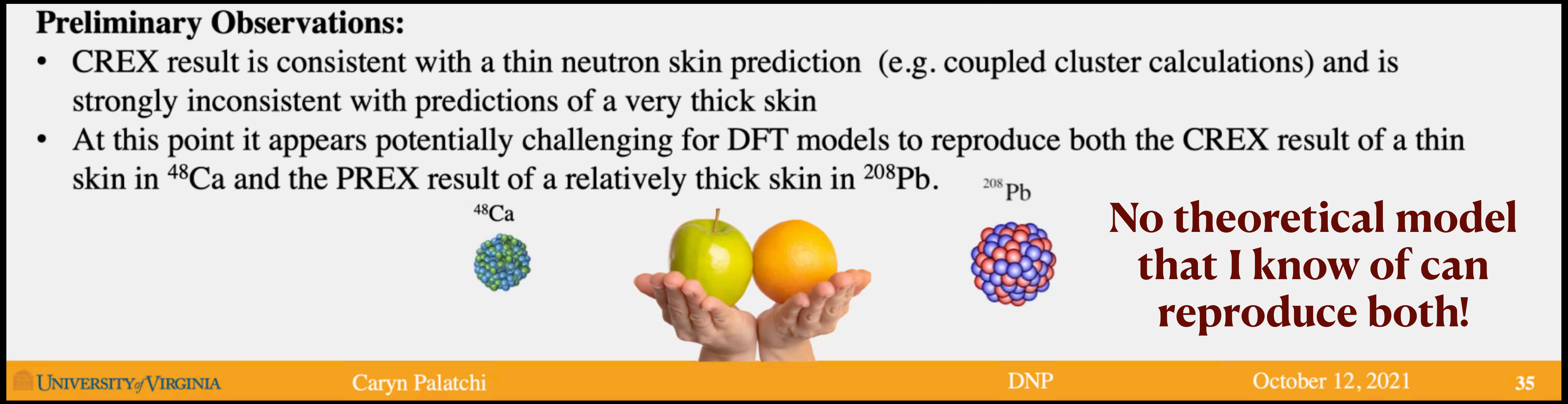
## ***Tantalizing Possibility***

- *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?)***

# Who Ordered That?

Isidor Isaac Rabi

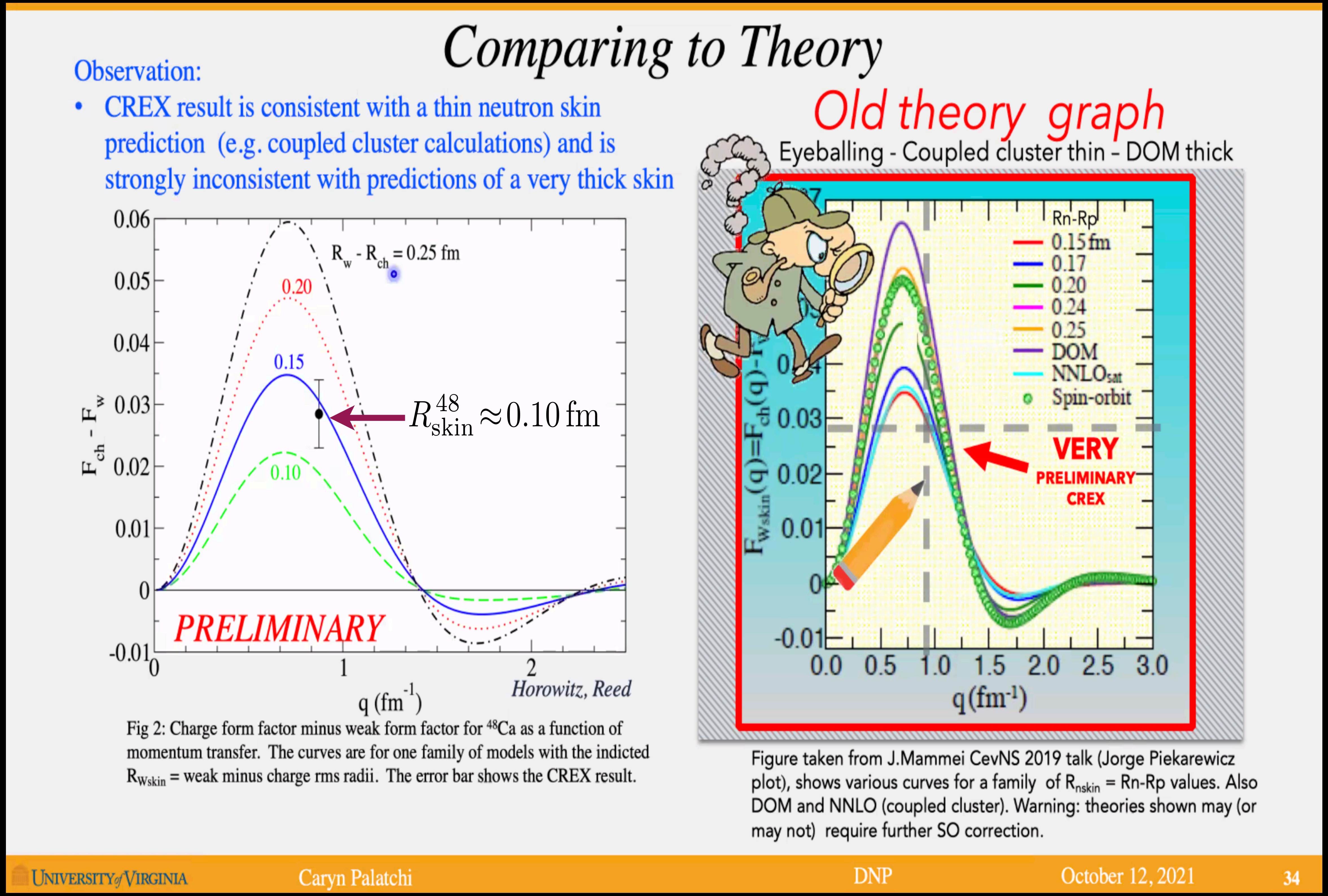


**Preliminary Observations:**

- CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin
- At this point it appears potentially challenging for DFT models to reproduce both the CREX result of a thin skin in $^{48}$Ca and the PREX result of a relatively thick skin in $^{208}$Pb.

**No theoretical model that I know of can reproduce both!**

University of Virginia Caryn Palatchi DNP October 12, 2021 35



*Comparing to Theory*

Observation:

- CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin

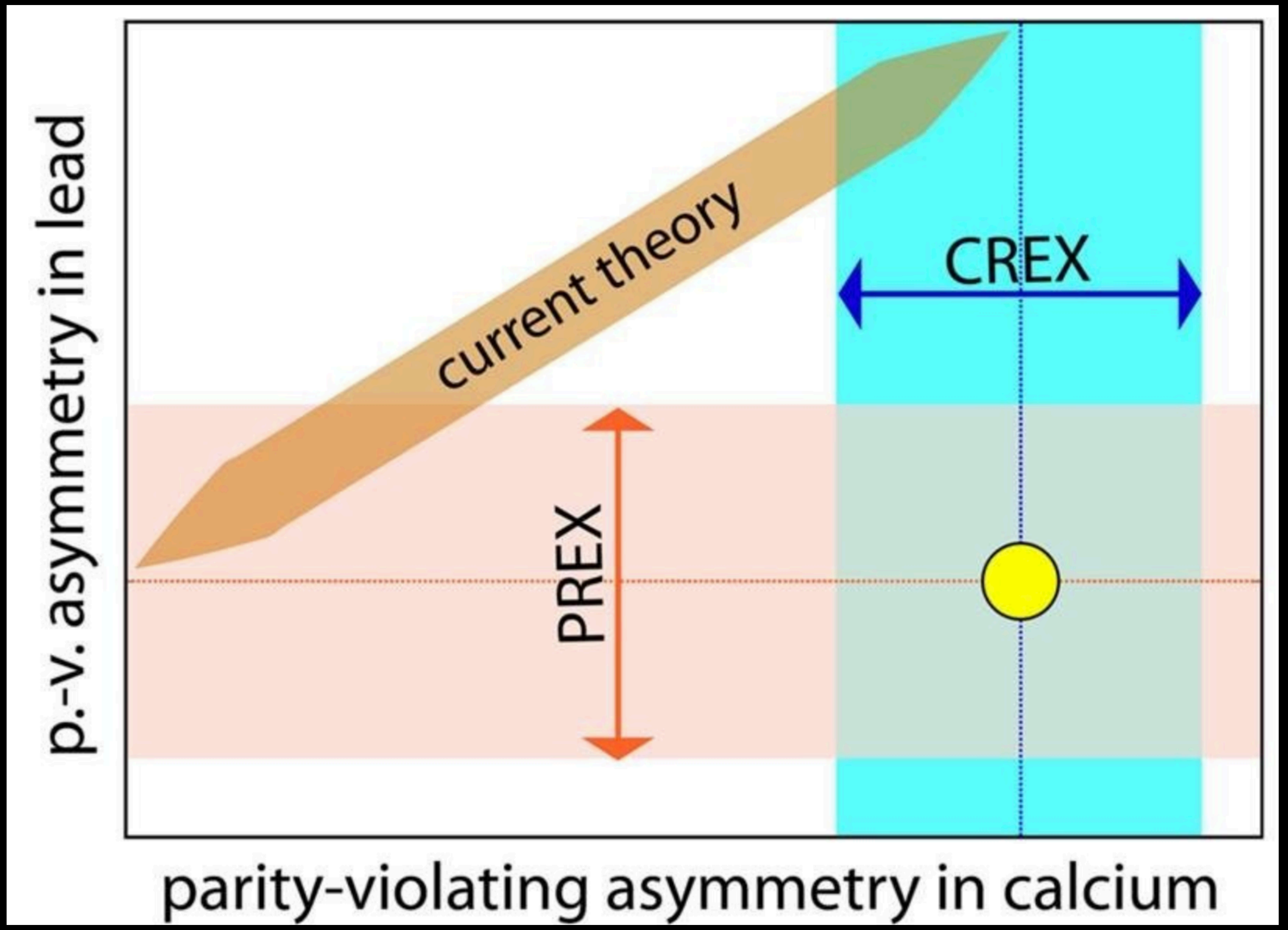
Fig 2: Charge form factor minus weak form factor for $^{48}$Ca as a function of momentum transfer. The curves are for one family of models with the indicted $R_{Wskin}$ = weak minus charge rms radii. The error bar shows the CREX result.

*Old theory graph*

Eyeballing - Coupled cluster thin - DOM thick

Figure taken from J.Mammei CevNS 2019 talk (Jorge Piekarewicz plot), shows various curves for a family of $R_{nskin}$ = Rn-Rp values. Also DOM and NNLO (coupled cluster). Warning: theories shown may (or may not) require further SO correction.

University of Virginia Caryn Palatchi DNP October 12, 2021 34



**PREX, CREX, and Nuclear Models: The Plot Thickens by W. Nazarewicz**

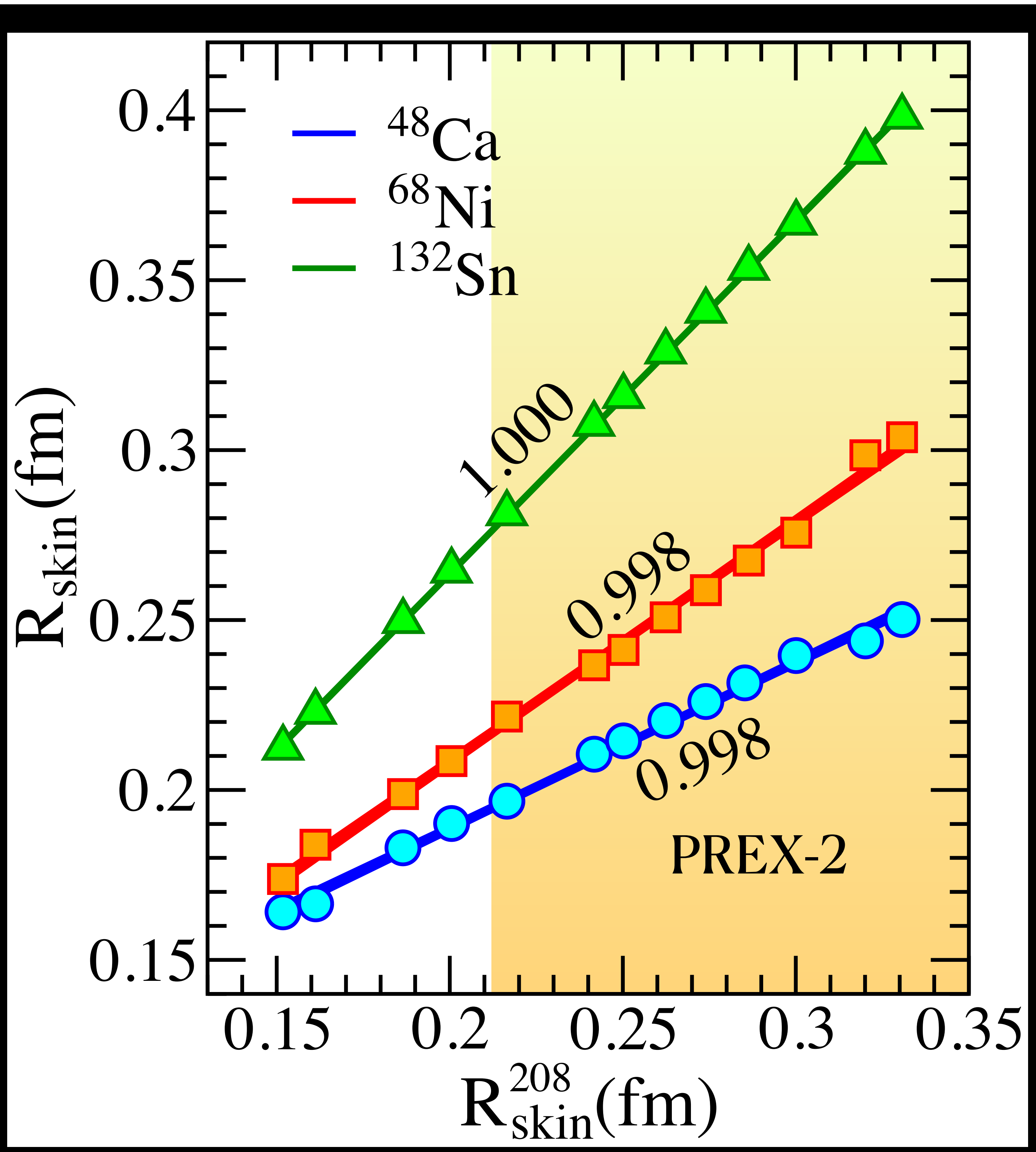
# The PREX-CREX Dilemma

## (No theoretical model can reproduce both!)

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

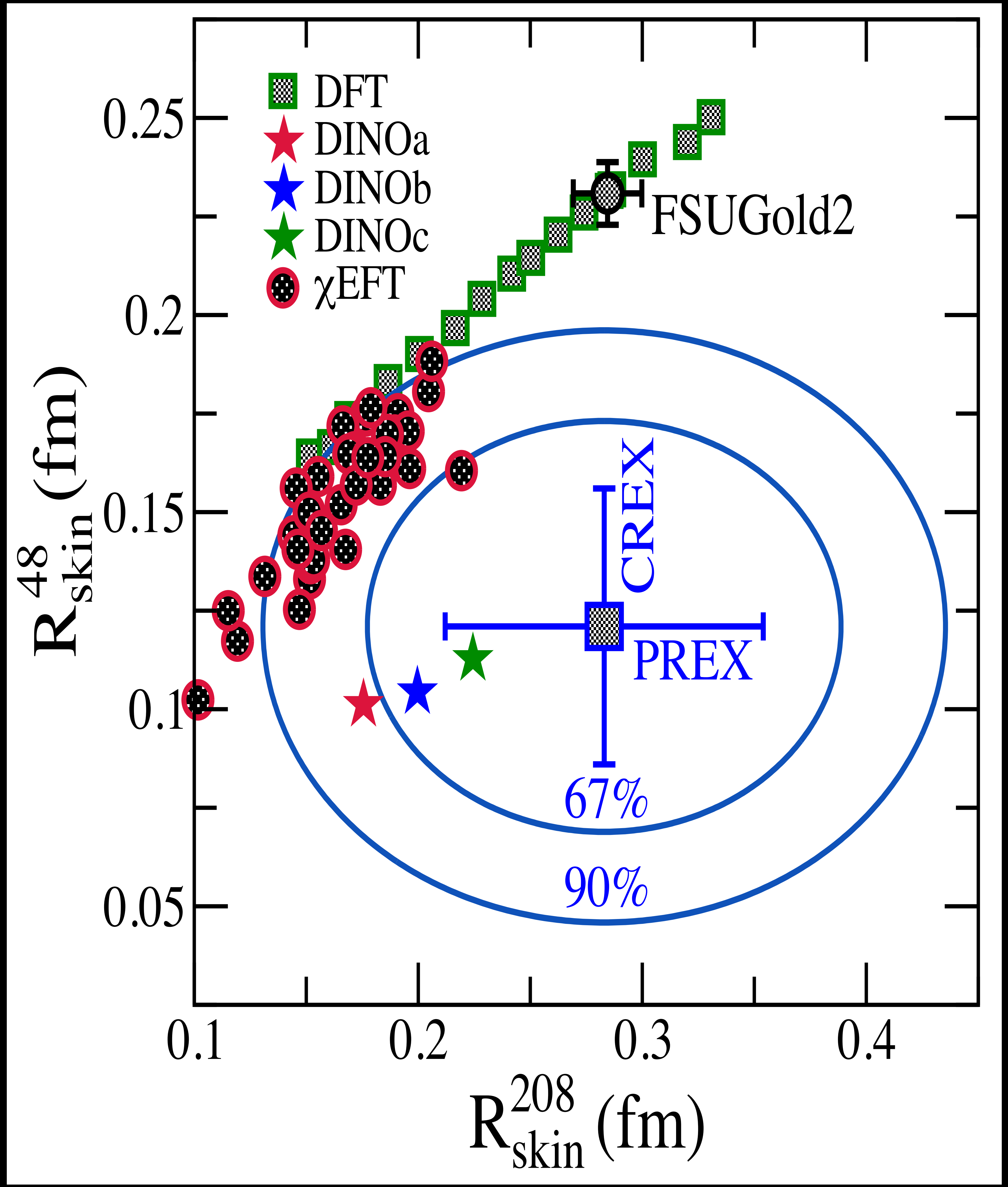
Paul-Gerhard Reinhard[1,*], Xavier Roca-Maza[2,†] and Witold Nazarewicz[3,‡]

*“We conclude that the simultaneous accurate description of the PV asymmetry in calcium and lead cannot be achieved by our models that accommodate a pool of global nuclear properties …”*



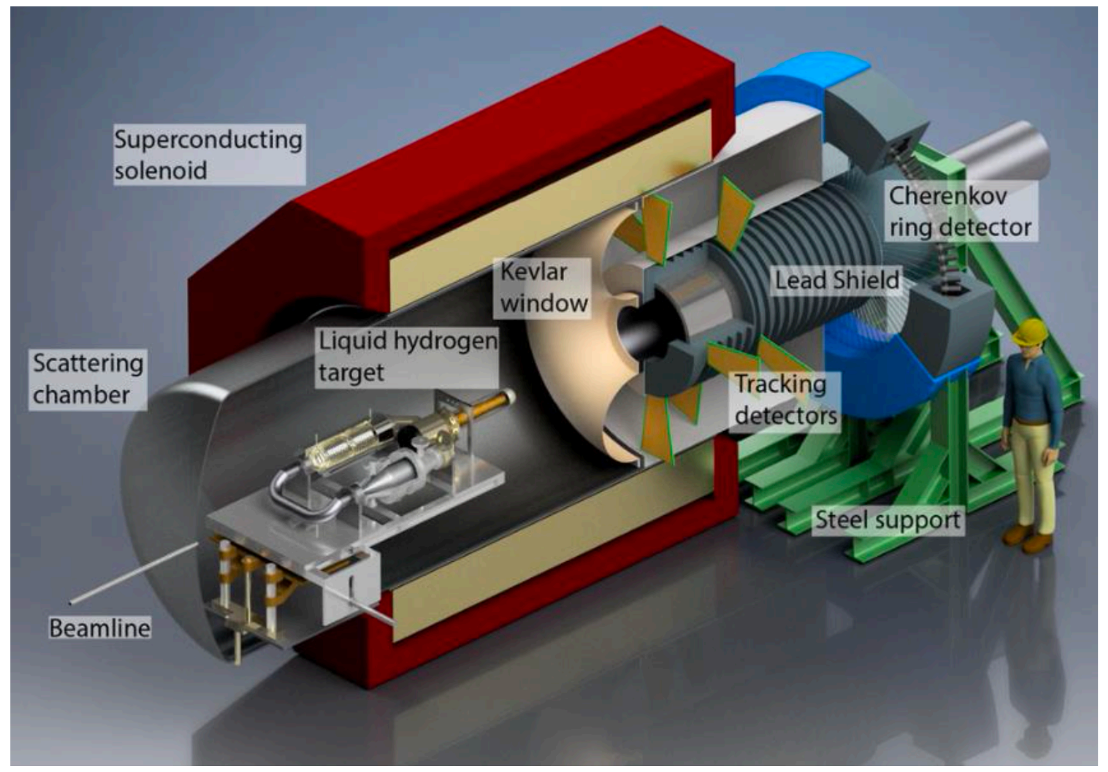
- Density Functional Theory in all its flavors predicts a strong correlation
- 34 “non-implausible” chiral interactions also display a similar correlation
- Modifications to existent DFT models can “break” the strong correlation — but at the expense of generating unphysical behavior in other observables

**THE PLOT THICKENS**

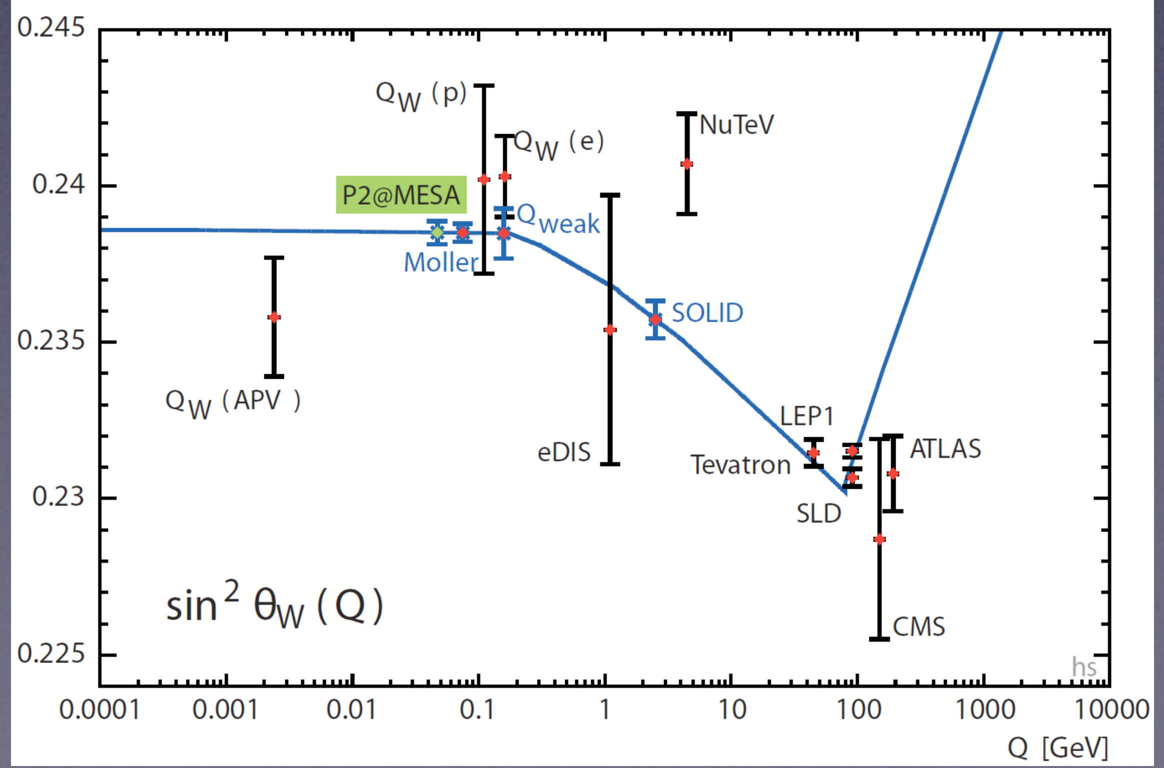


# Was PREX a Statistical Fluke?

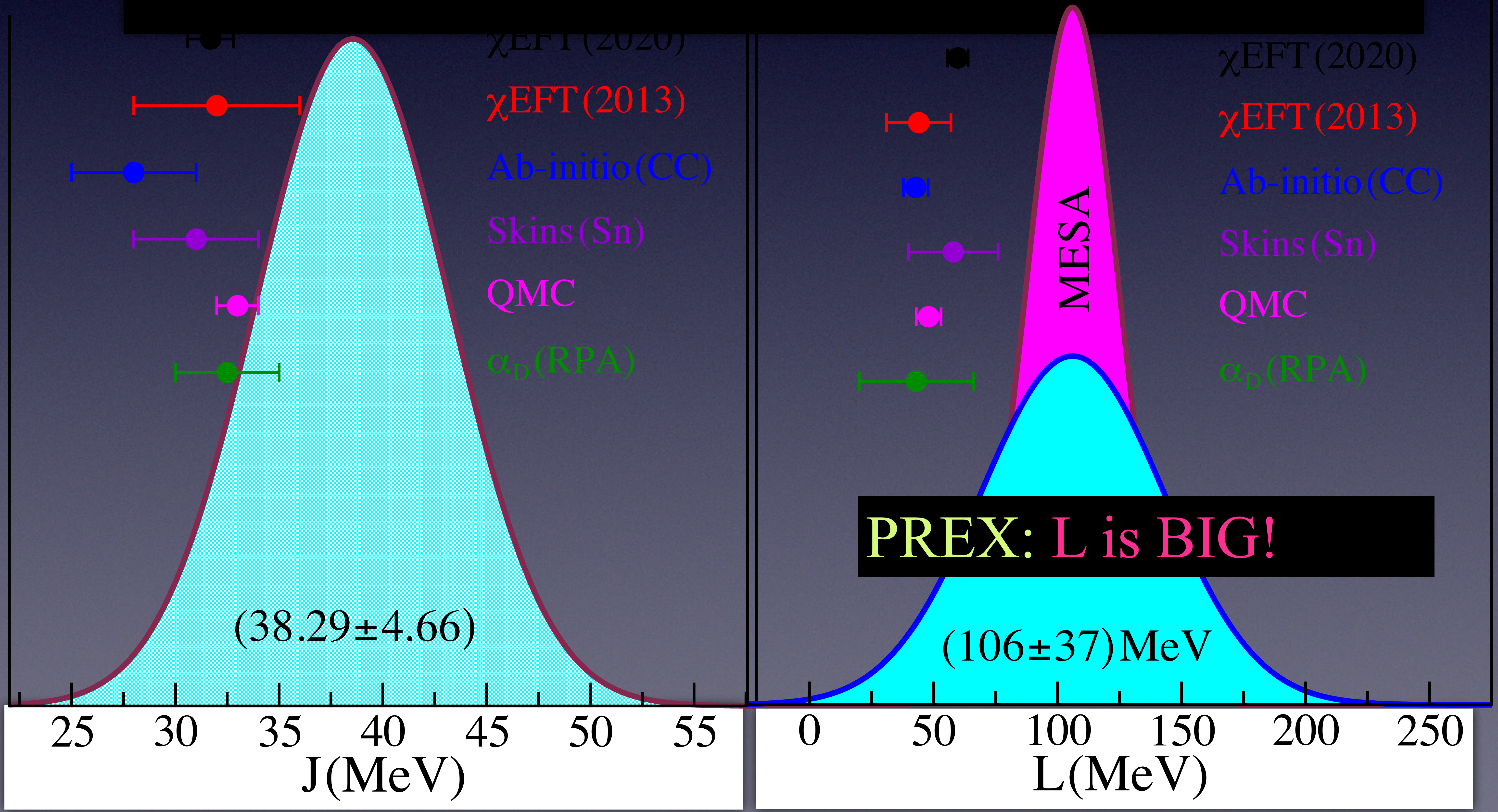
## The P2 experiment



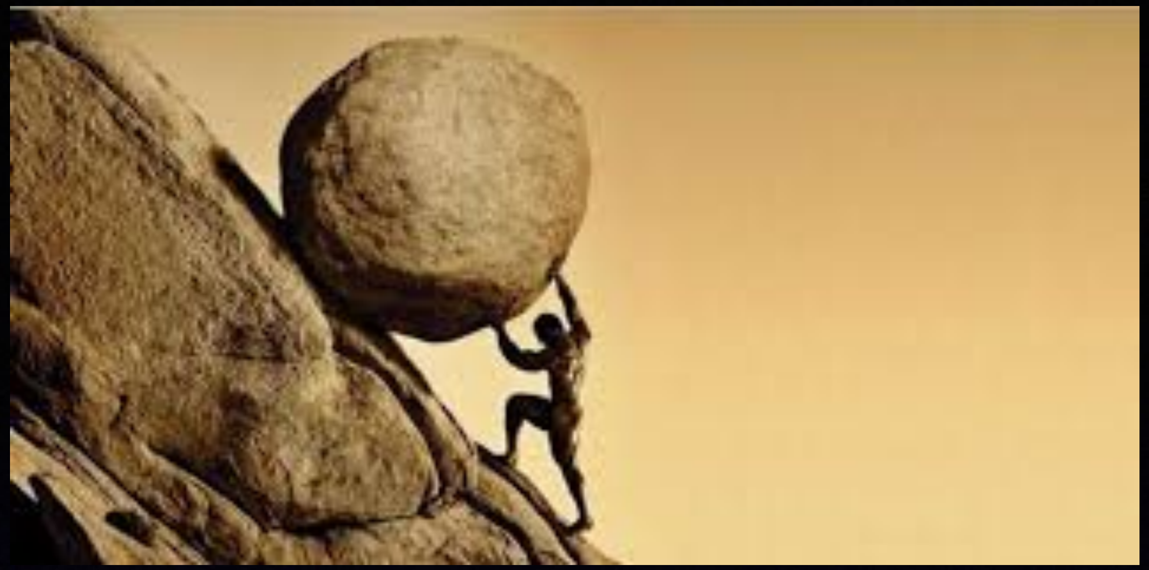
- Aimed to measure weak mixing angle $\sin^2\theta_W$ through parity-violating elastic electron scattering on hydrogen
- Uses solenoid spectrometer with tracking detectors and Cherenkov detector
- The same setup but with $^{208}$Pb target can be used for neutron skin measurement to confirm/confront PREX results



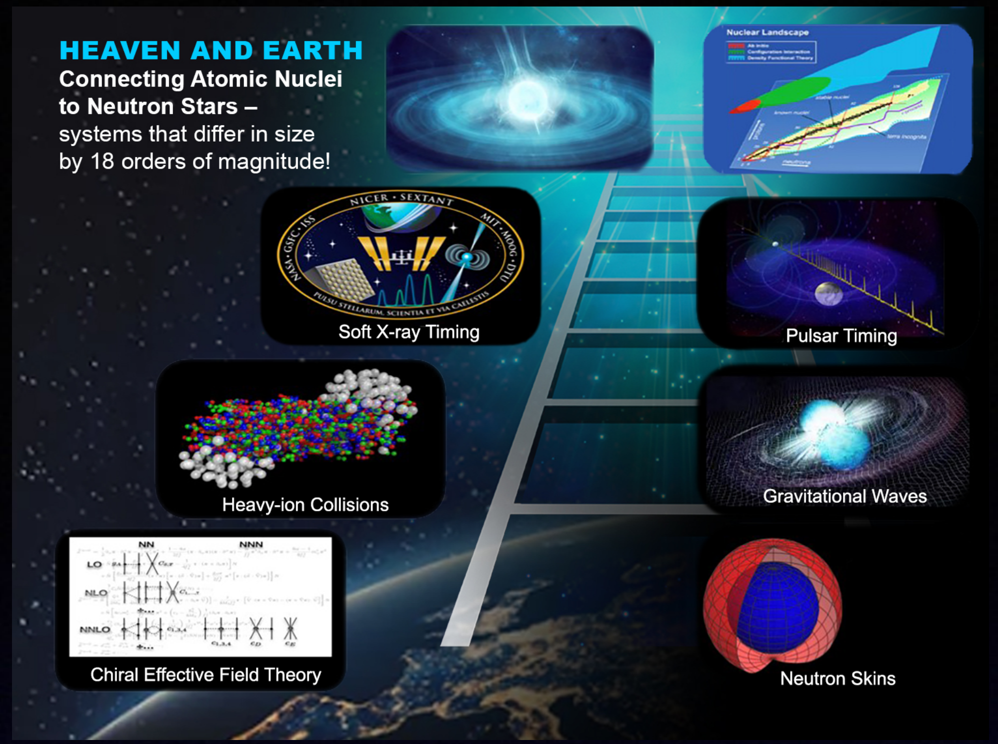
The MESA Facility in Mainz will provide the most precise electroweak measurement of the neutron skin thickness of 208Pb (+/- 0.03 fm)

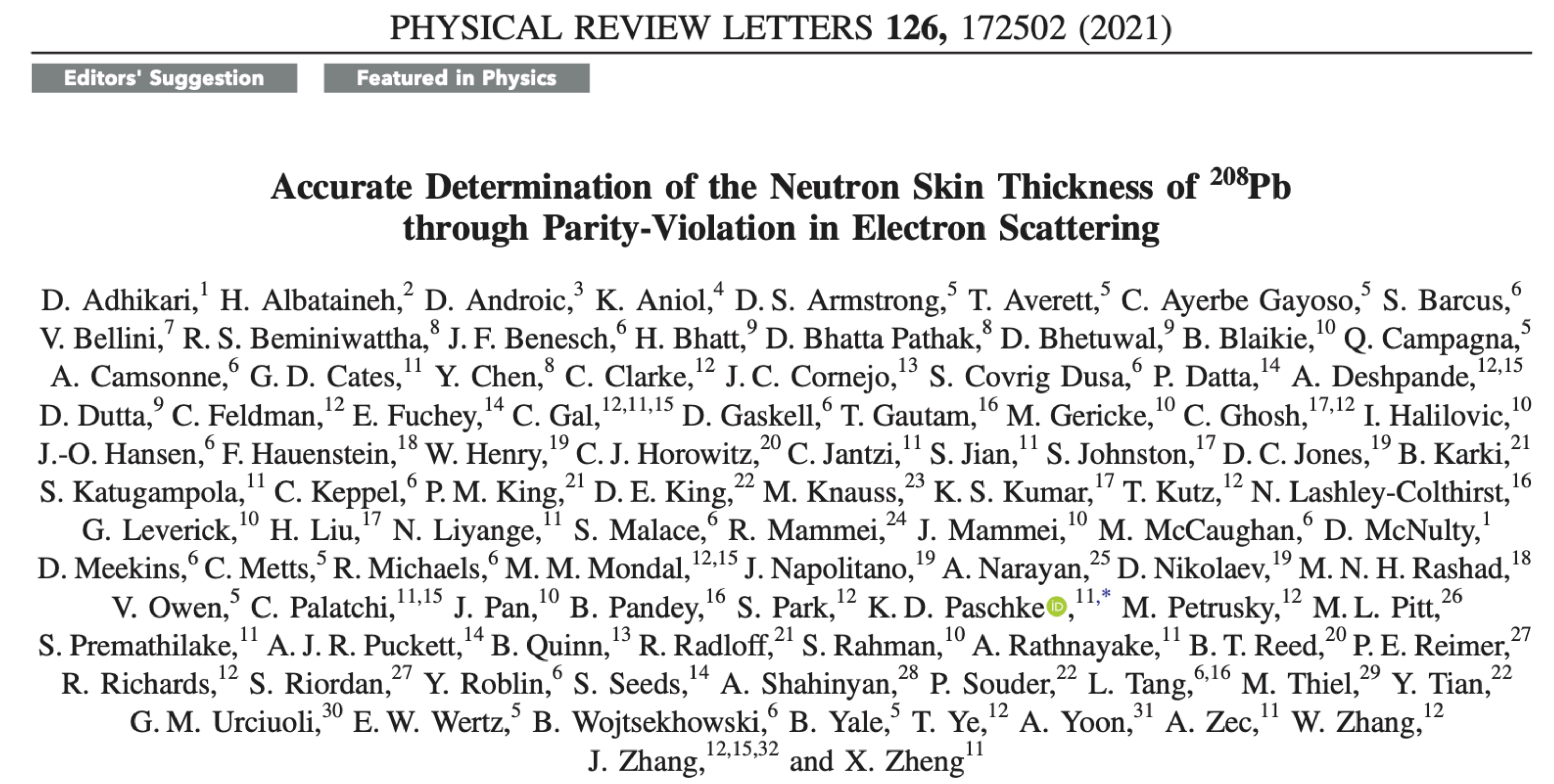


PREX: L is BIG!



# The community owes a great debt of gratitude to Jefferson Lab — and especially to our experimental colleagues for their heroic effort



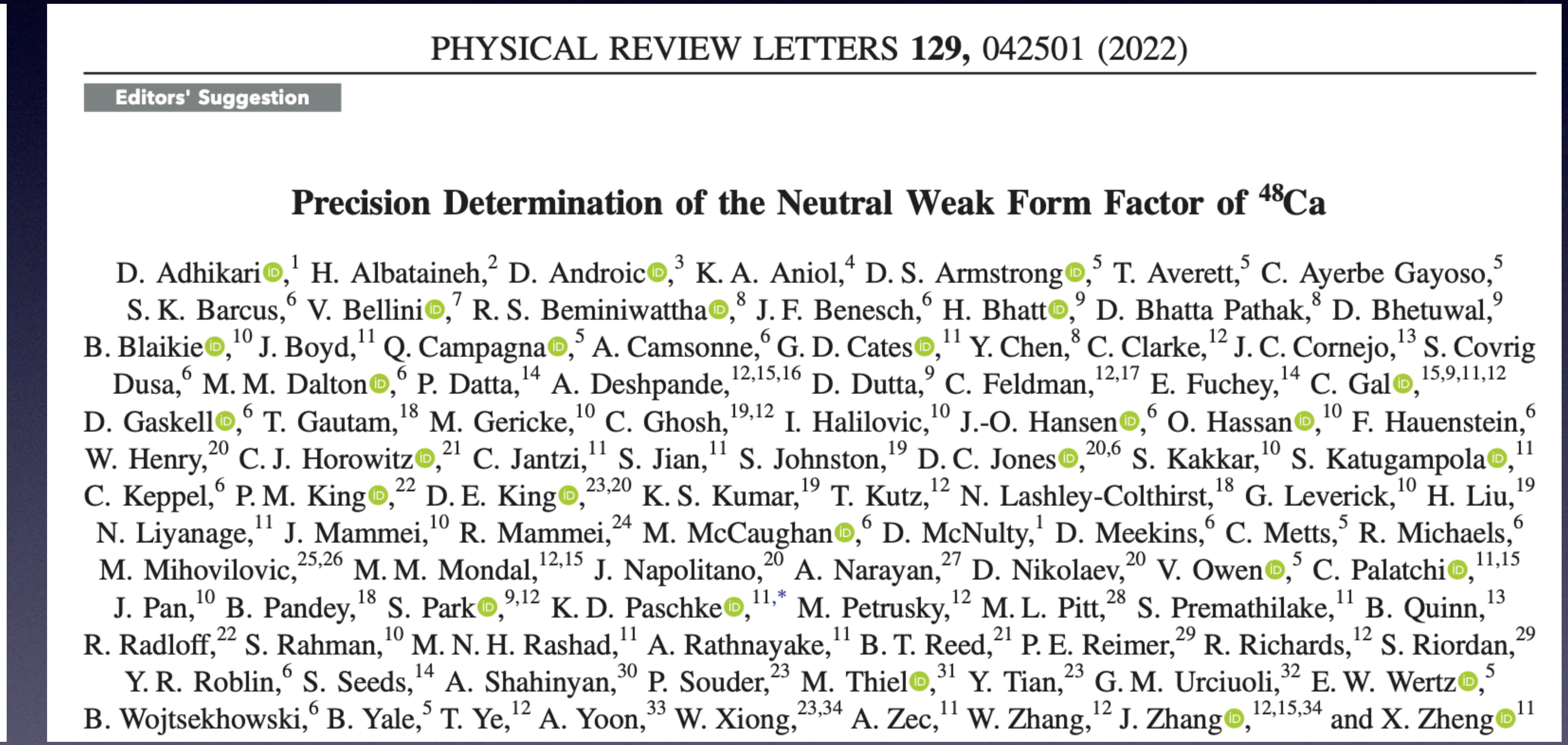


PHYSICAL REVIEW LETTERS **126,** 172502 (2021)

**Editors' Suggestion** **Featured in Physics**

**Accurate Determination of the Neutron Skin Thickness of $^{208}$Pb through Parity-Violation in Electron Scattering**

D. Adhikari,[1] H. Albataineh,[2] D. Androic,[3] K. Aniol,[4] D. S. Armstrong,[5] T. Averett,[5] C. Ayerbe Gayoso,[5] S. Barcus,[6] V. Bellini,[7] R. S. Beminiwattha,[8] J. F. Benesch,[6] H. Bhatt,[9] D. Bhatta Pathak,[8] D. Bhetuwal,[9] B. Blaikie,[10] Q. Campagna,[5] A. Camsonne,[6] G. D. Cates,[11] Y. Chen,[8] C. Clarke,[12] J. C. Cornejo,[13] S. Covrig Dusa,[6] P. Datta,[14] A. Deshpande,[12,15] D. Dutta,[9] C. Feldman,[12] E. Fuchey,[14] C. Gal,[12,11,15] D. Gaskell,[6] T. Gautam,[16] M. Gericke,[10] C. Ghosh,[17,12] I. Halilovic,[10] J.-O. Hansen,[6] F. Hauenstein,[18] W. Henry,[19] C. J. Horowitz,[20] C. Jantzi,[11] S. Jian,[11] S. Johnston,[17] D. C. Jones,[19] B. Karki,[21] S. Katugampola,[11] C. Keppel,[6] P. M. King,[21] D. E. King,[22] M. Knauss,[23] K. S. Kumar,[17] T. Kutz,[12] N. Lashley-Colthirst,[16] G. Leverick,[10] H. Liu,[17] N. Liyange,[11] S. Malace,[6] R. Mammei,[24] J. Mammei,[10] M. McCaughan,[6] D. McNulty,[1] D. Meekins,[6] C. Metts,[5] R. Michaels,[6] M. M. Mondal,[12,15] J. Napolitano,[19] A. Narayan,[25] D. Nikolaev,[19] M. N. H. Rashad,[18] V. Owen,[5] C. Palatchi,[11,15] J. Pan,[10] B. Pandey,[16] S. Park,[12] K. D. Paschke,[11,*] M. Petrusky,[12] M. L. Pitt,[26] S. Premathilake,[11] A. J. R. Puckett,[14] B. Quinn,[13] R. Radloff,[21] S. Rahman,[10] A. Rathnayake,[11] B. T. Reed,[20] P. E. Reimer,[27] R. Richards,[12] S. Riordan,[27] Y. Roblin,[6] S. Seeds,[14] A. Shahinyan,[28] P. Souder,[22] L. Tang,[6,16] M. Thiel,[29] Y. Tian,[22] G. M. Urciuoli,[30] E. W. Wertz,[5] B. Wojtsekhowski,[6] B. Yale,[5] T. Ye,[12] A. Yoon,[31] A. Zec,[11] W. Zhang,[12] J. Zhang,[12,15,32] and X. Zheng[11]



PHYSICAL REVIEW LETTERS **129,** 042501 (2022)

**Editors' Suggestion**

**Precision Determination of the Neutral Weak Form Factor of $^{48}$Ca**

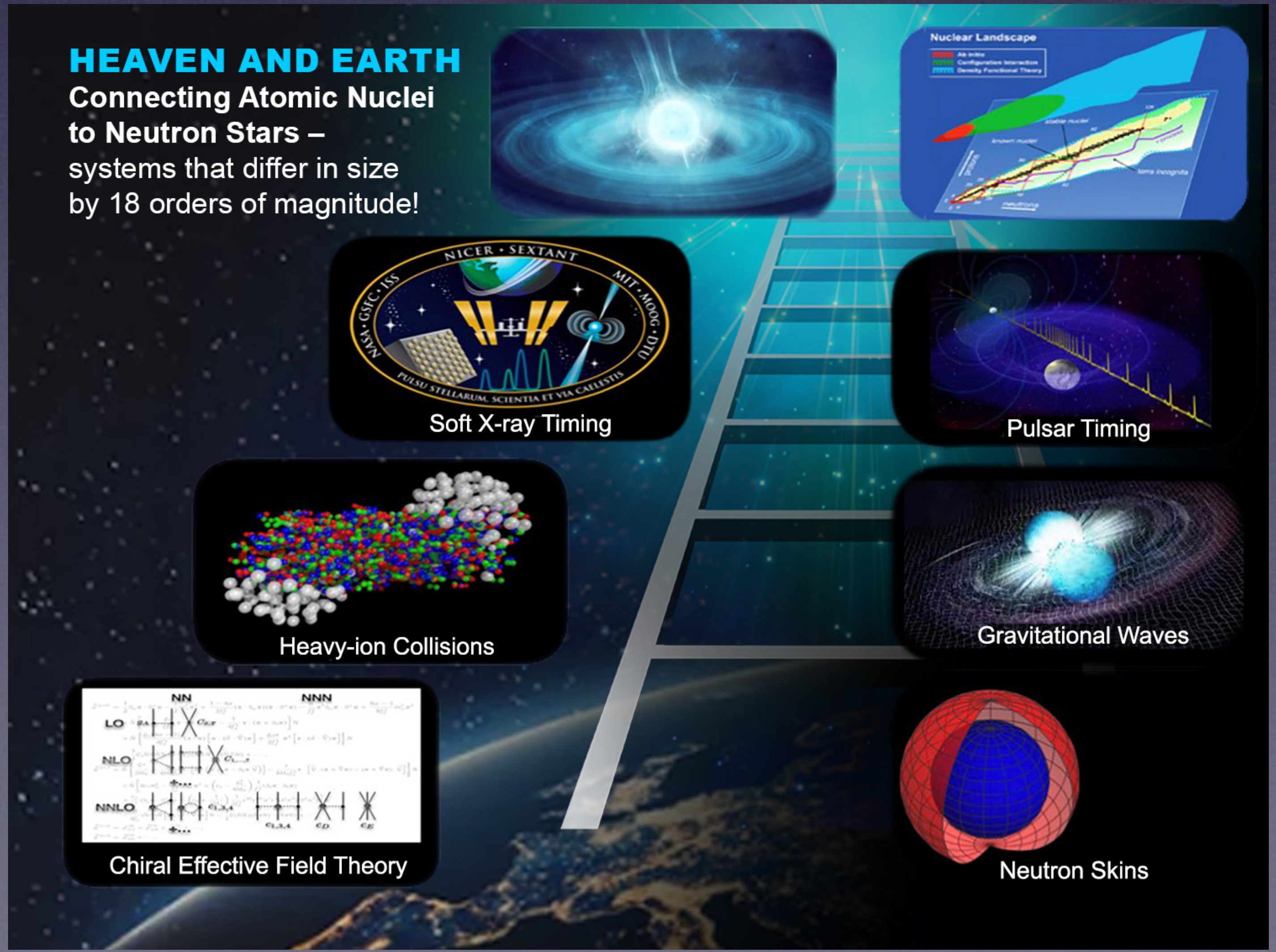
D. Adhikari,[1] H. Albataineh,[2] D. Androic,[3] K. A. Aniol,[4] D. S. Armstrong,[5] T. Averett,[5] C. Ayerbe Gayoso,[5] S. K. Barcus,[6] V. Bellini,[7] R. S. Beminiwattha,[8] J. F. Benesch,[6] H. Bhatt,[9] D. Bhatta Pathak,[8] D. Bhetuwal,[9] B. Blaikie,[10] J. Boyd,[11] Q. Campagna,[5] A. Camsonne,[6] G. D. Cates,[11] Y. Chen,[8] C. Clarke,[12] J. C. Cornejo,[13] S. Covrig Dusa,[6] M. M. Dalton,[6] P. Datta,[14] A. Deshpande,[12,15,16] D. Dutta,[9] C. Feldman,[12,17] E. Fuchey,[14] C. Gal,[15,9,11,12] D. Gaskell,[6] T. Gautam,[18] M. Gericke,[10] C. Ghosh,[19,12] I. Halilovic,[10] J.-O. Hansen,[6] O. Hassan,[10] F. Hauenstein,[6] W. Henry,[20] C. J. Horowitz,[21] C. Jantzi,[11] S. Jian,[11] S. Johnston,[19] D. C. Jones,[20,6] S. Kakkar,[10] S. Katugampola,[11] C. Keppel,[6] P. M. King,[22] D. E. King,[23,20] K. S. Kumar,[19] T. Kutz,[12] N. Lashley-Colthirst,[18] G. Leverick,[10] H. Liu,[19] N. Liyanage,[11] J. Mammei,[10] R. Mammei,[24] M. McCaughan,[6] D. McNulty,[1] D. Meekins,[6] C. Metts,[5] R. Michaels,[6] M. Mihovilovic,[25,26] M. M. Mondal,[12,15] J. Napolitano,[20] A. Narayan,[27] D. Nikolaev,[20] V. Owen,[5] C. Palatchi,[11,15] J. Pan,[10] B. Pandey,[18] S. Park,[9,12] K. D. Paschke,[11,*] M. Petrusky,[12] M. L. Pitt,[28] S. Premathilake,[11] B. Quinn,[13] R. Radloff,[22] S. Rahman,[10] M. N. H. Rashad,[11] A. Rathnayake,[11] B. T. Reed,[21] P. E. Reimer,[29] R. Richards,[12] S. Riordan,[29] Y. R. Roblin,[6] S. Seeds,[14] A. Shahinyan,[30] P. Souder,[23] M. Thiel,[31] Y. Tian,[23] G. M. Urciuoli,[32] E. W. Wertz,[5] B. Wojtsekhowski,[6] B. Yale,[5] T. Ye,[12] A. Yoon,[33] W. Xiong,[23,34] A. Zec,[11] W. Zhang,[12] J. Zhang,[12,15,34] and X. Zheng[11]

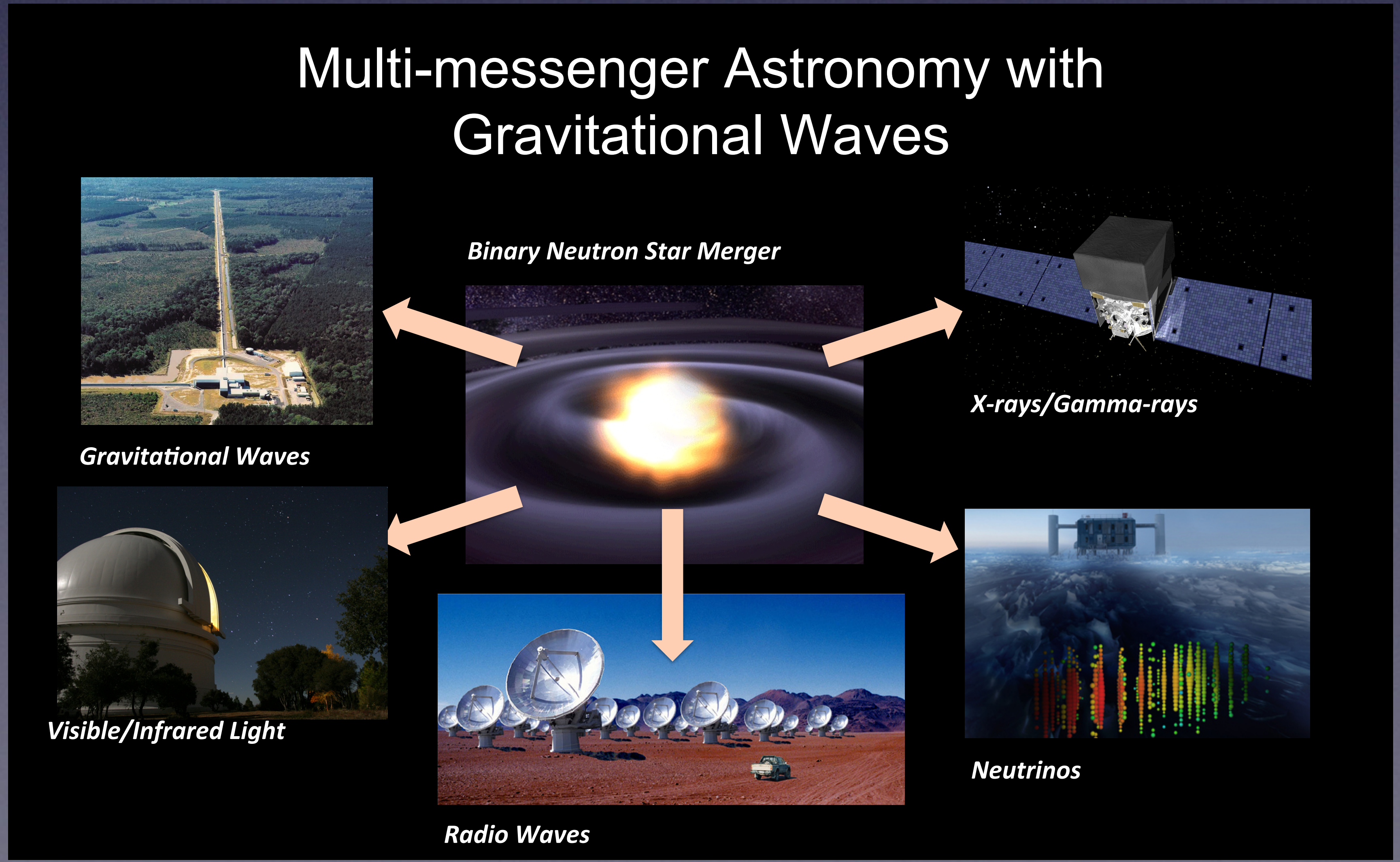
THE PLOT THICKENS

# Conclusions: We have entered the golden era of neutron-star physics

- Astrophysics: What is the minimum mass of a black hole?
- C.Matter Physics: Existence of Coulomb-Frustrated Nuclear Pasta?
- General Relativity: Can BNS mergers constrain stellar radii?
- Nuclear Physics: What is the EOS of neutron-rich matter?
- Particle Physics: What exotic phases inhabit the dense core?
- Machine Learning: Extrapolation to where no man has gone before?

***Neutron Stars are the natural meeting place for interdisciplinary, fundamental, and exciting science!***





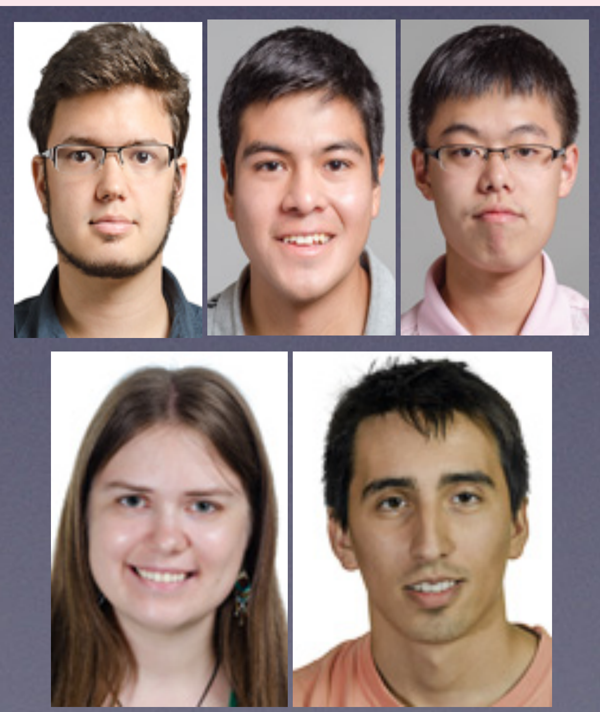
**My FSU Collaborators**

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

**Brendan Reed**

**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 "Old" Generation**

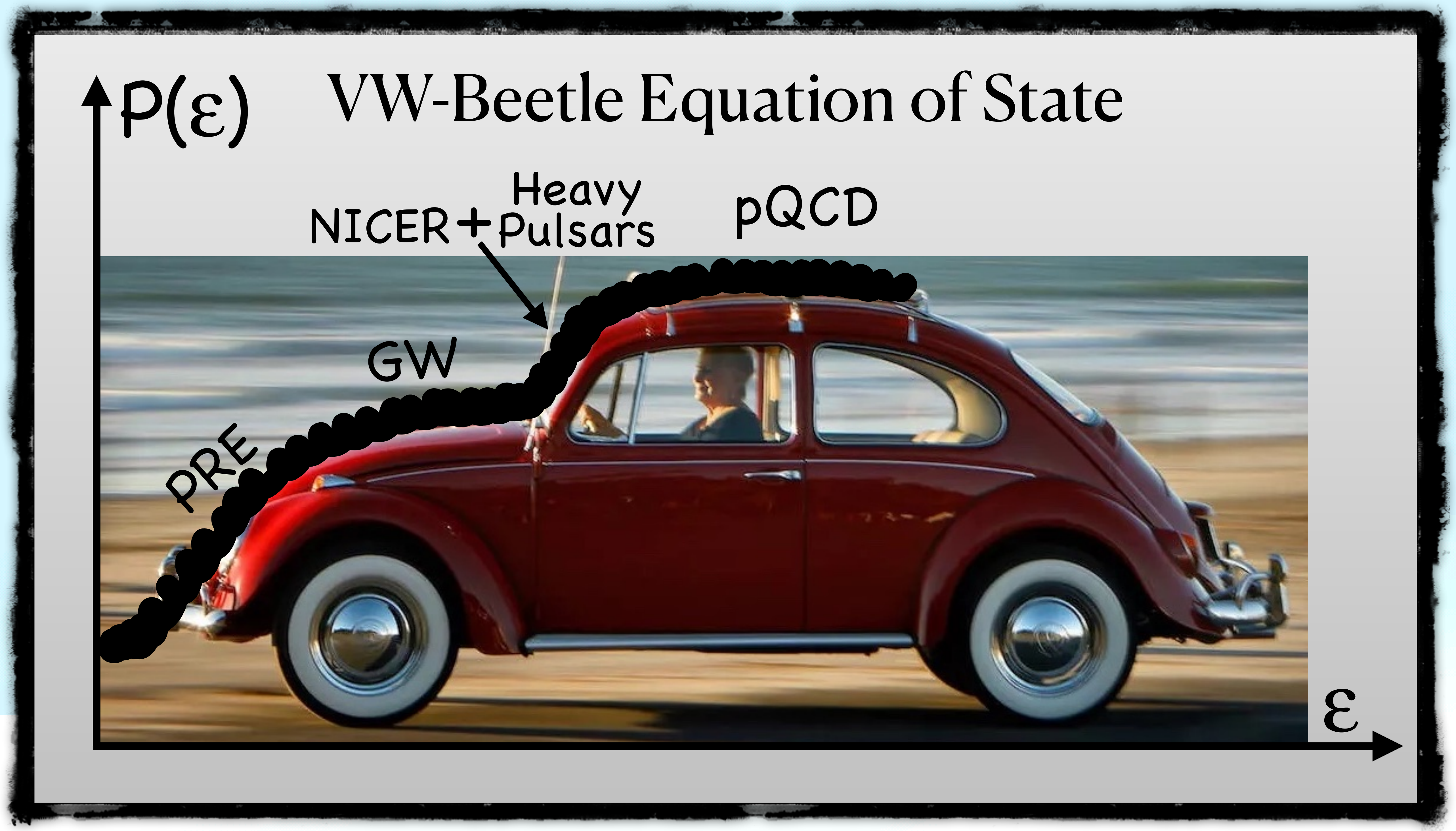
- **Pablo Giuliani**
- **Daniel Silva**
- **Junjie Yang**

**The New Generation**

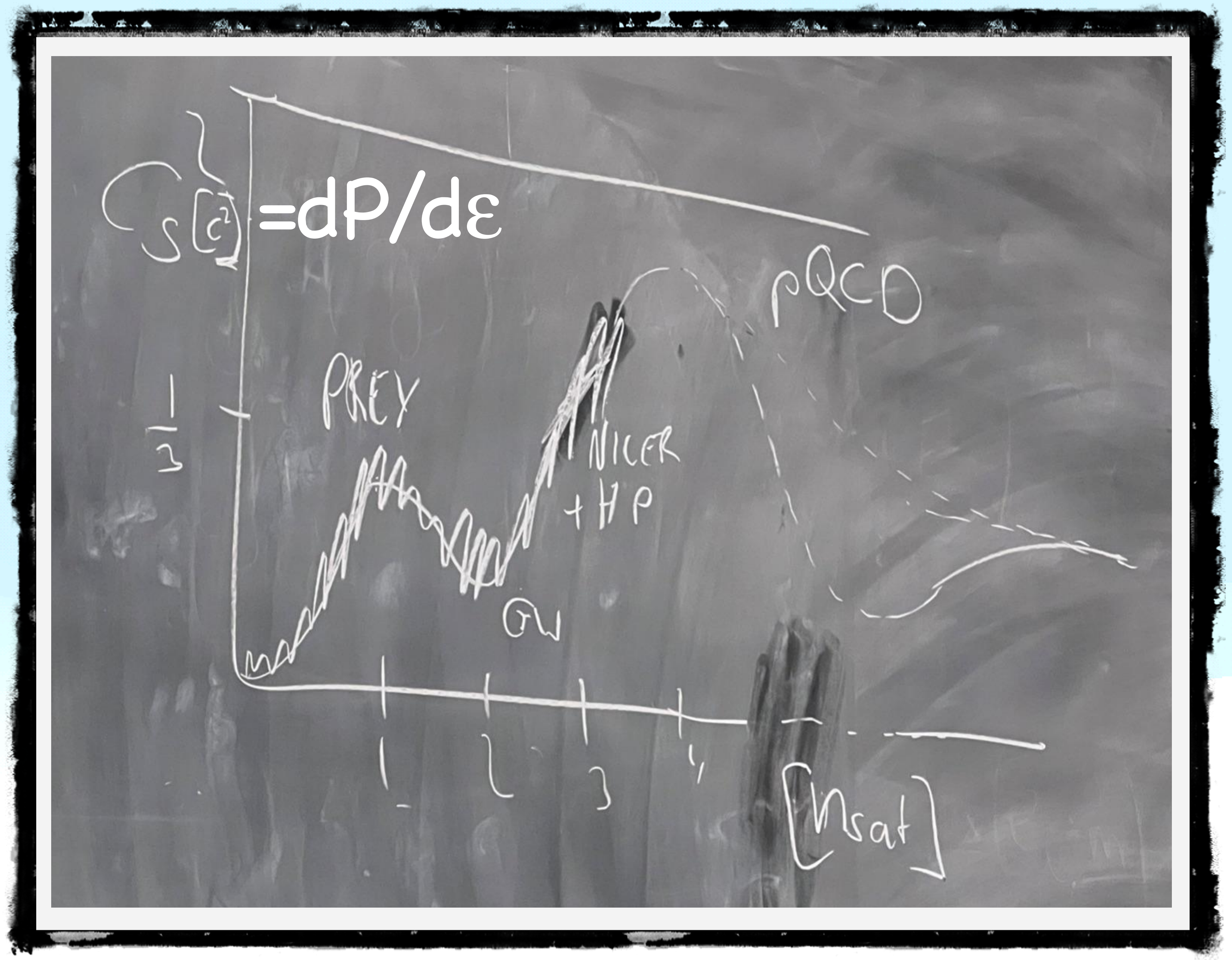
- **Amy Anderson**
- **Marc Salinas**

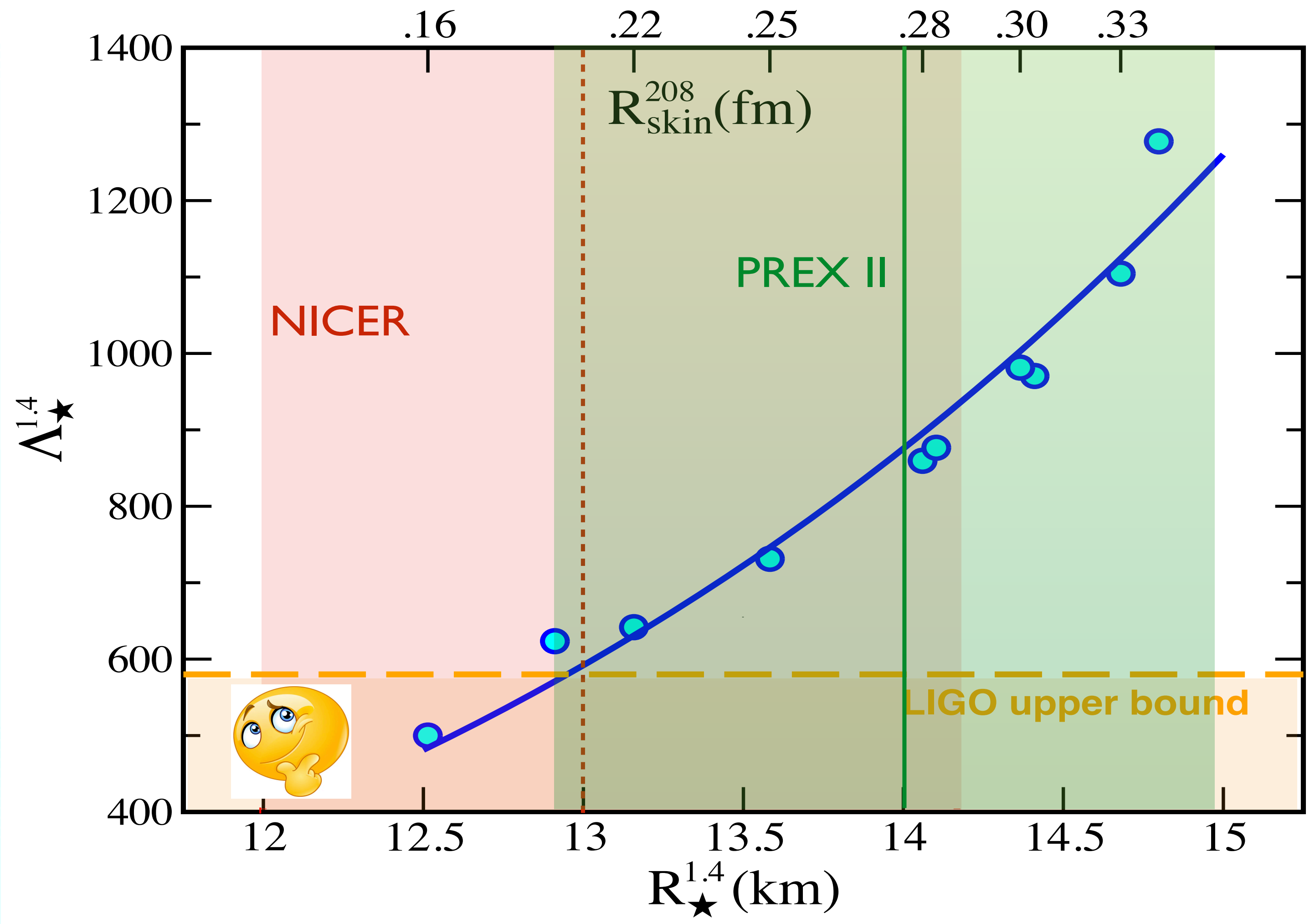
# Backup Slides

# The Equation of State



# The Speed of Sound





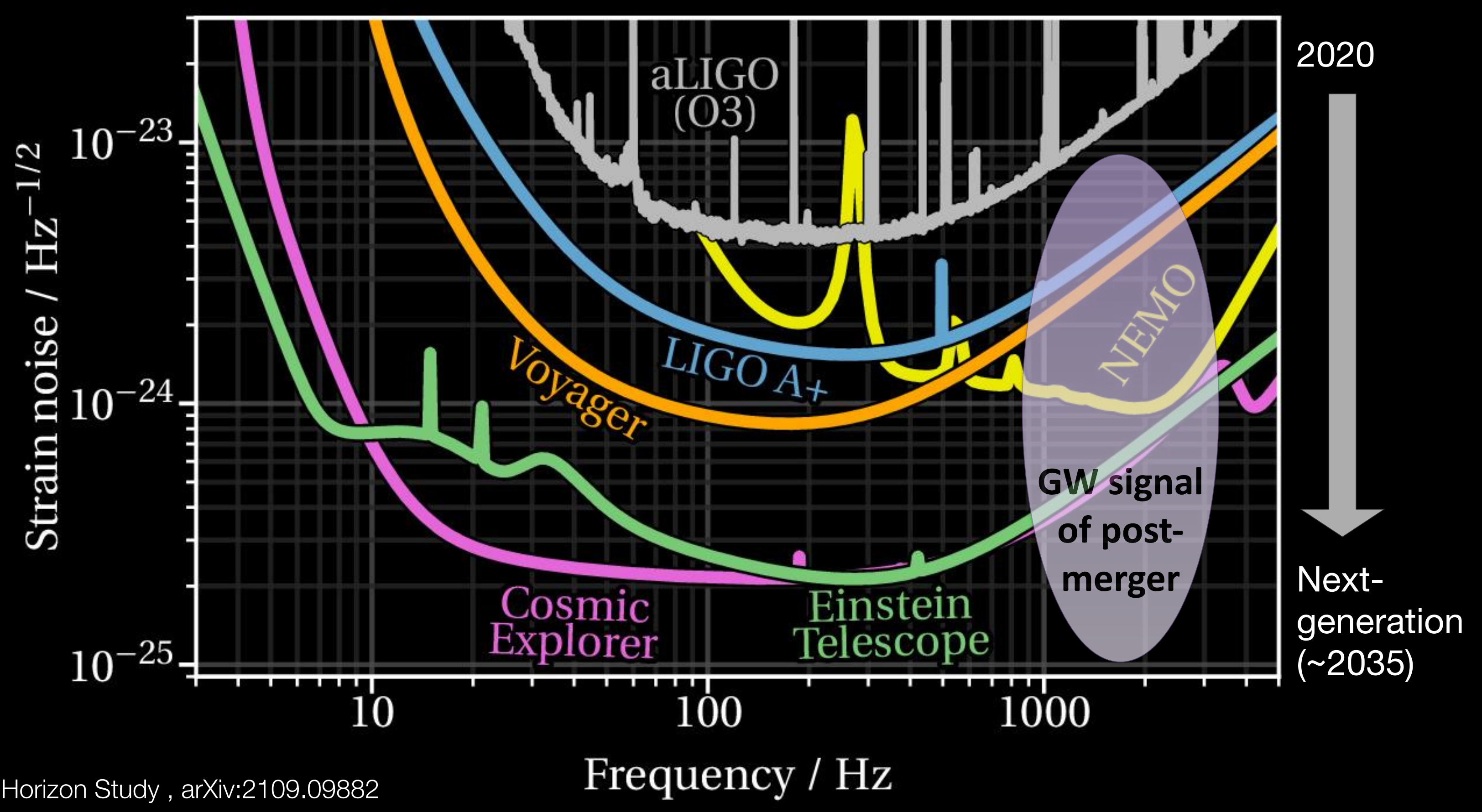
## ***Tantalizing Possibility***

- *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?)***

# Neutron-Rich Matter in Heaven

## GW Landscape



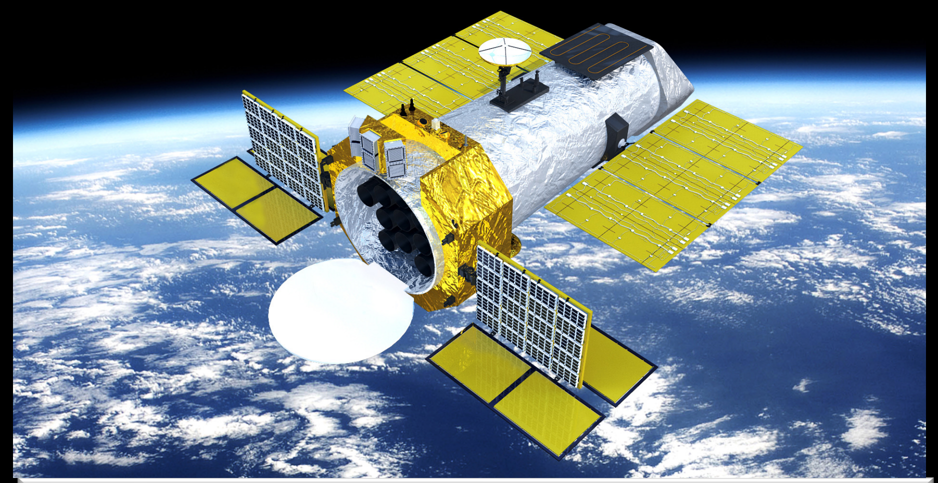
CE Horizon Study , arXiv:2109.09882

Third-generation GW observatories with unprecedented sensitivity will detect gravitational-wave sources across the entire universe. with up to millions of detections per year!

## LARGE AREA X-RAY SPECTRAL-TIMING

New telescopes will be needed – larger area, wider X–ray band than NICER

**eXTP**



Chinese-European project
Zhang et al. 2019

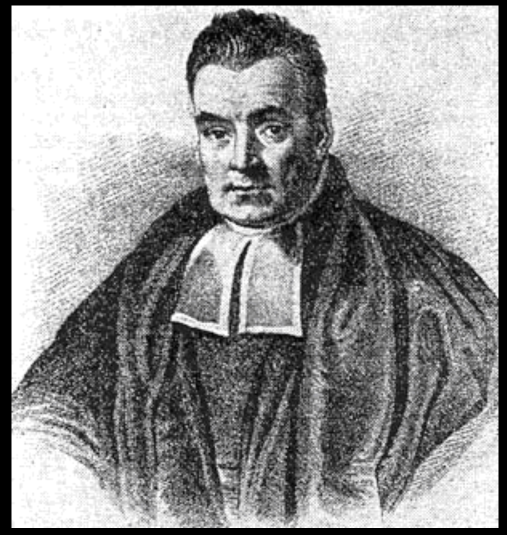
NASA probe-class proposal
Ray et al. 2019, @strobexastro

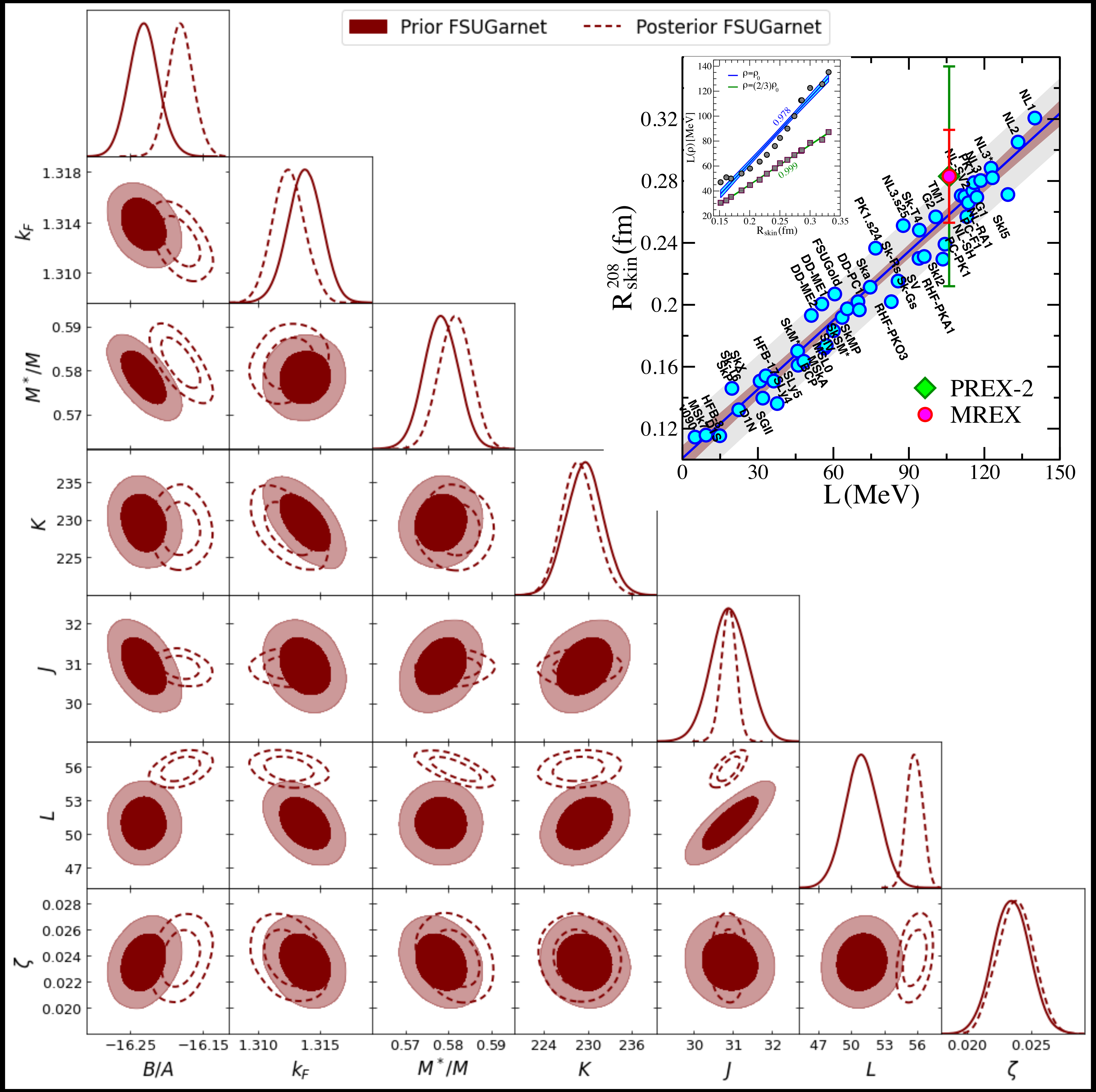
Analysis pipelines being developed and tested using simulated and real (RXTE/NICER) data

New x-ray observatories with exceptional capabilities optimized for the study of the ultra dense matter EOS will measure the mass-radius relation for more than 20 pulsars over an extended mass range!

# Neutron Stars meet Bayesian Inference

## Model Building for the understanding of atomic nuclei and neutron stars

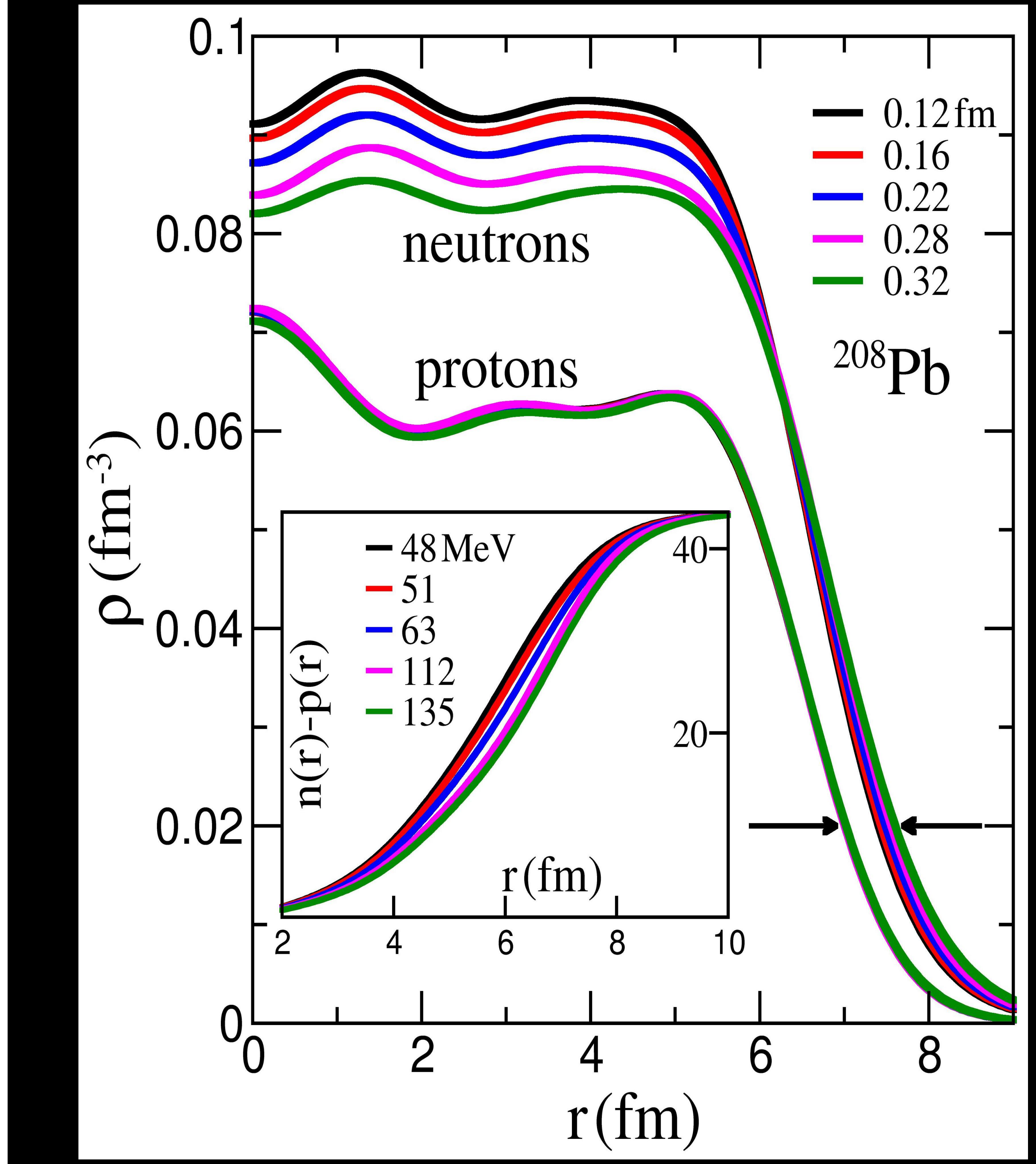




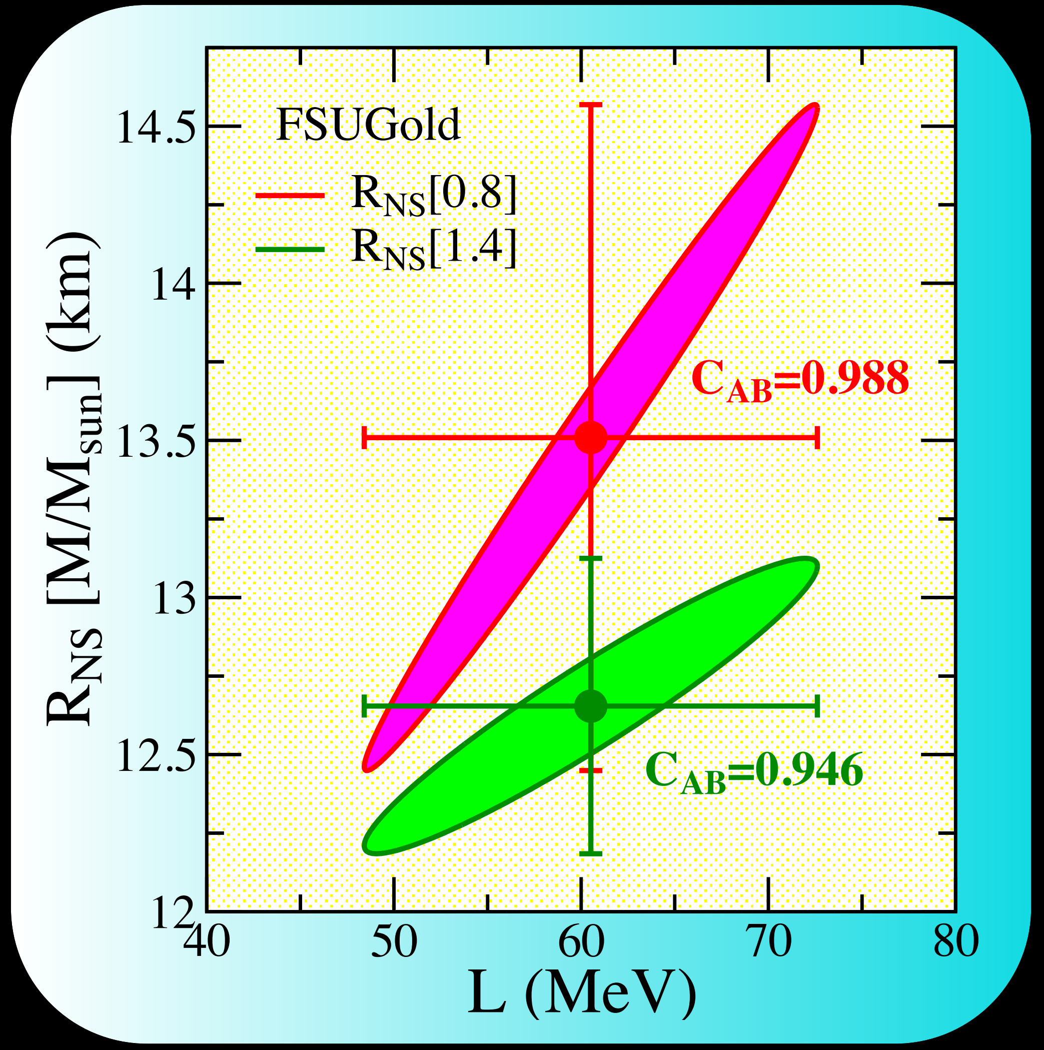
$$\mathcal{L}_{\rm Yukawa} = \bar{\psi}\left[g_{\rm s}\phi - \left(g_{\rm v}V_{\mu} + \frac{g_{\rho}}{2}\tau\cdot\mathbf{b}_{\mu} + \frac{e}{2}(1+\tau_{3})A_{\mu}\right)\gamma^{\mu}\right]\psi$$

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

$$(g_{\rm s}, g_{\rm v}, g_{\rho}, \kappa, \lambda, \Lambda_{\rm v}) \Longleftrightarrow (\rho_{0}, \epsilon_{0}, M^{*}, K, J, L)$$

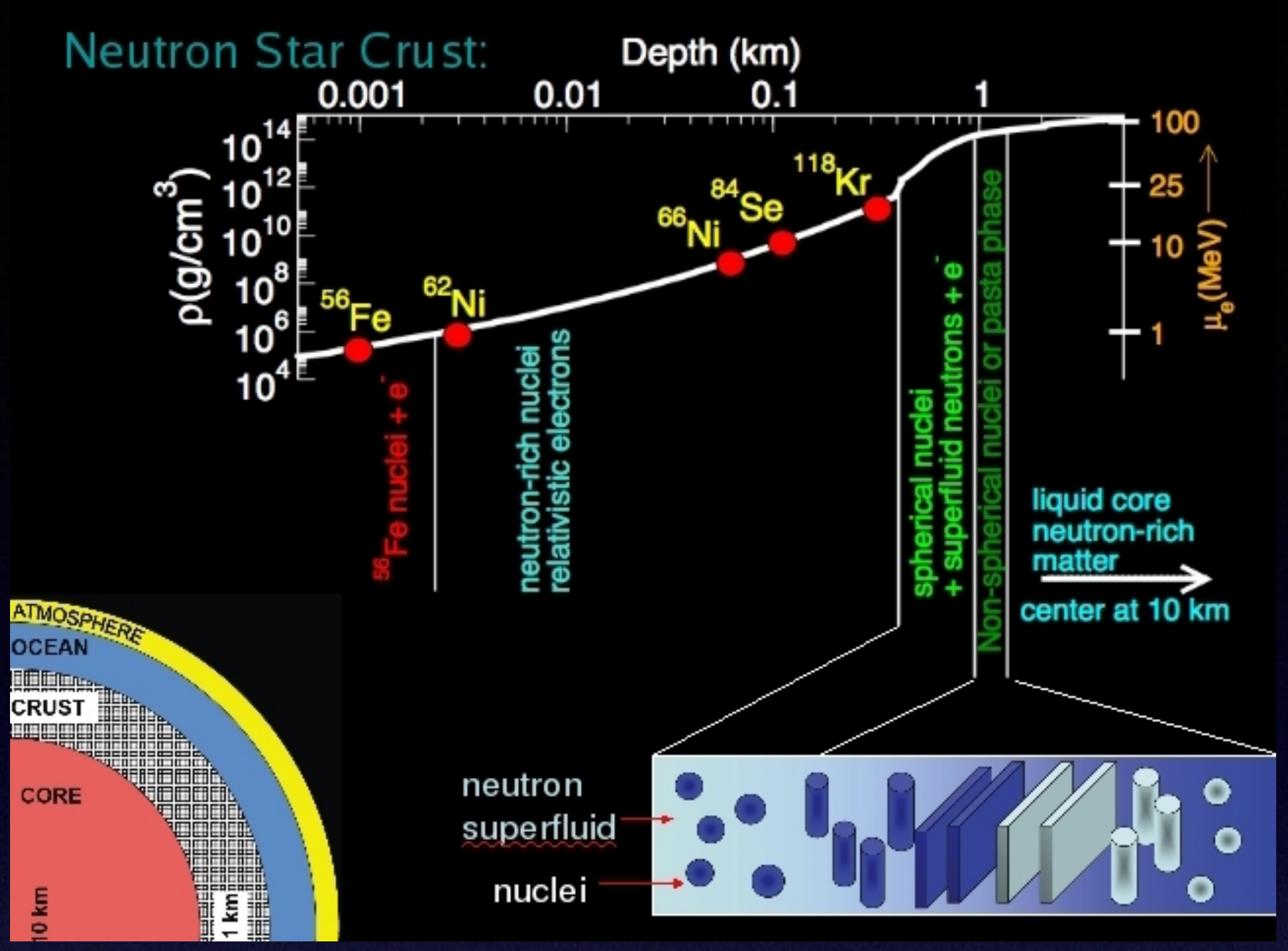


Neutron skins and stellar radii (quantities that differ by 18 orders of magnitude) are both sensitive to L!



# The Composition of the Outer Crust

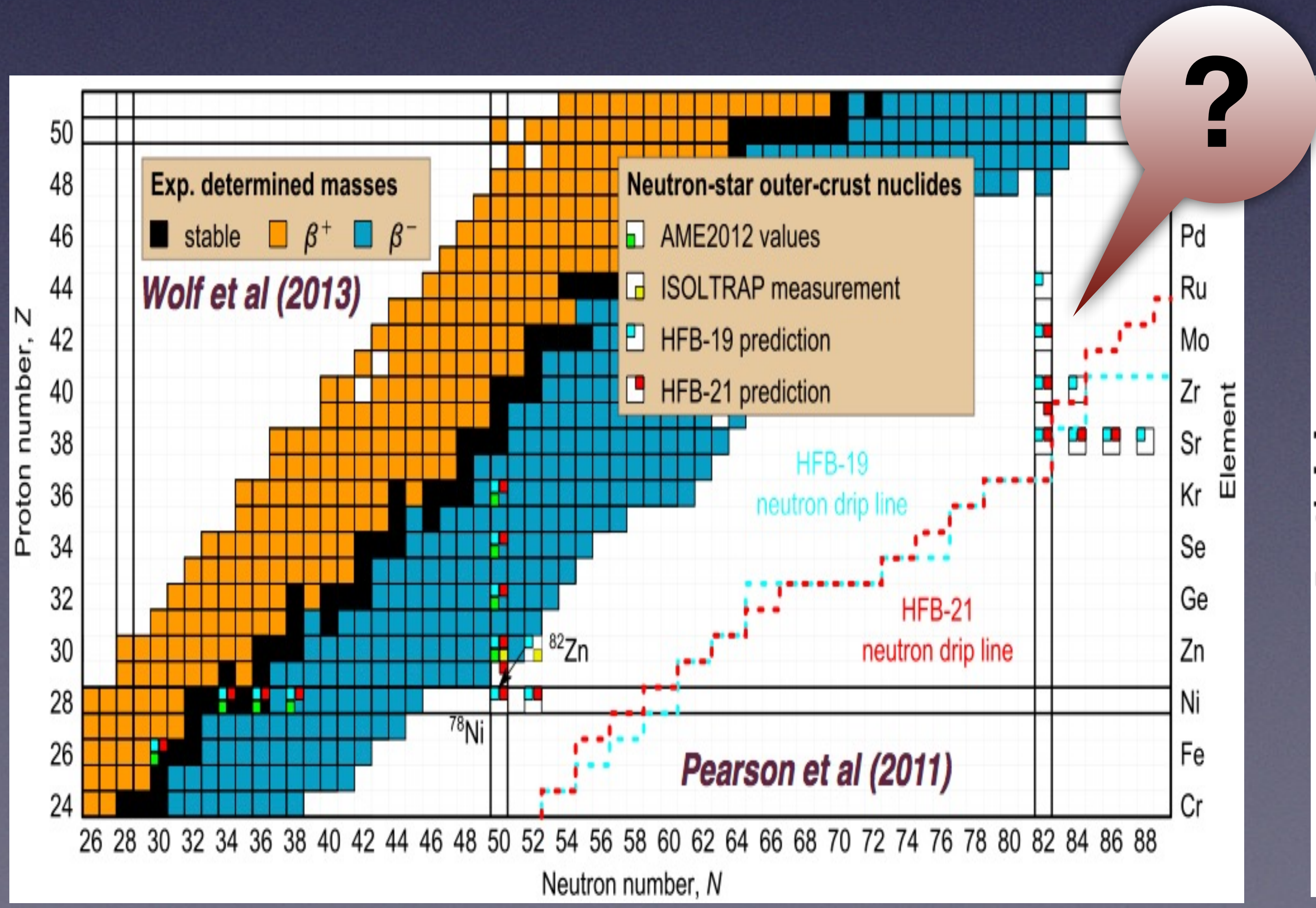
## Enormous sensitivity to nuclear masses

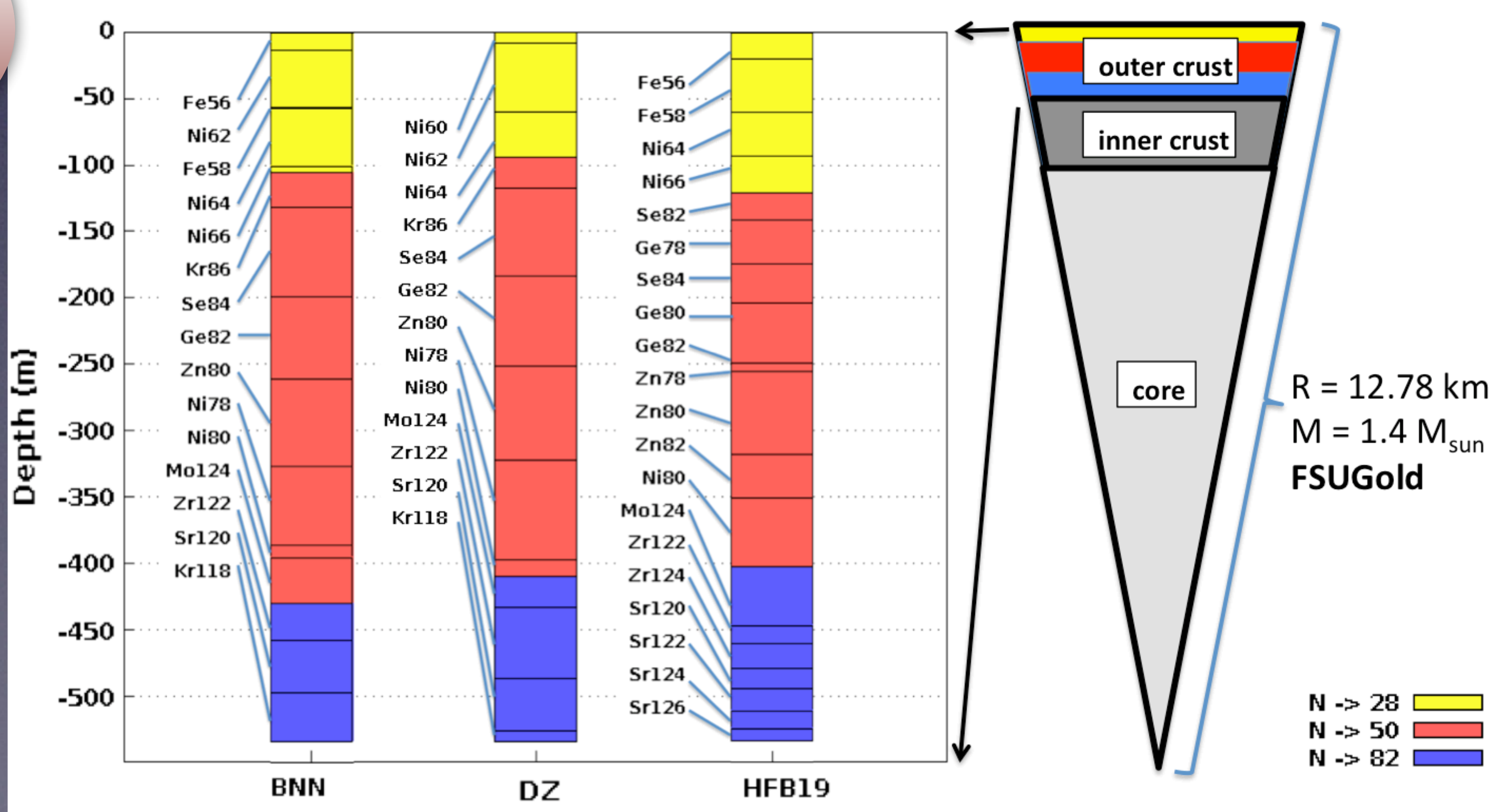


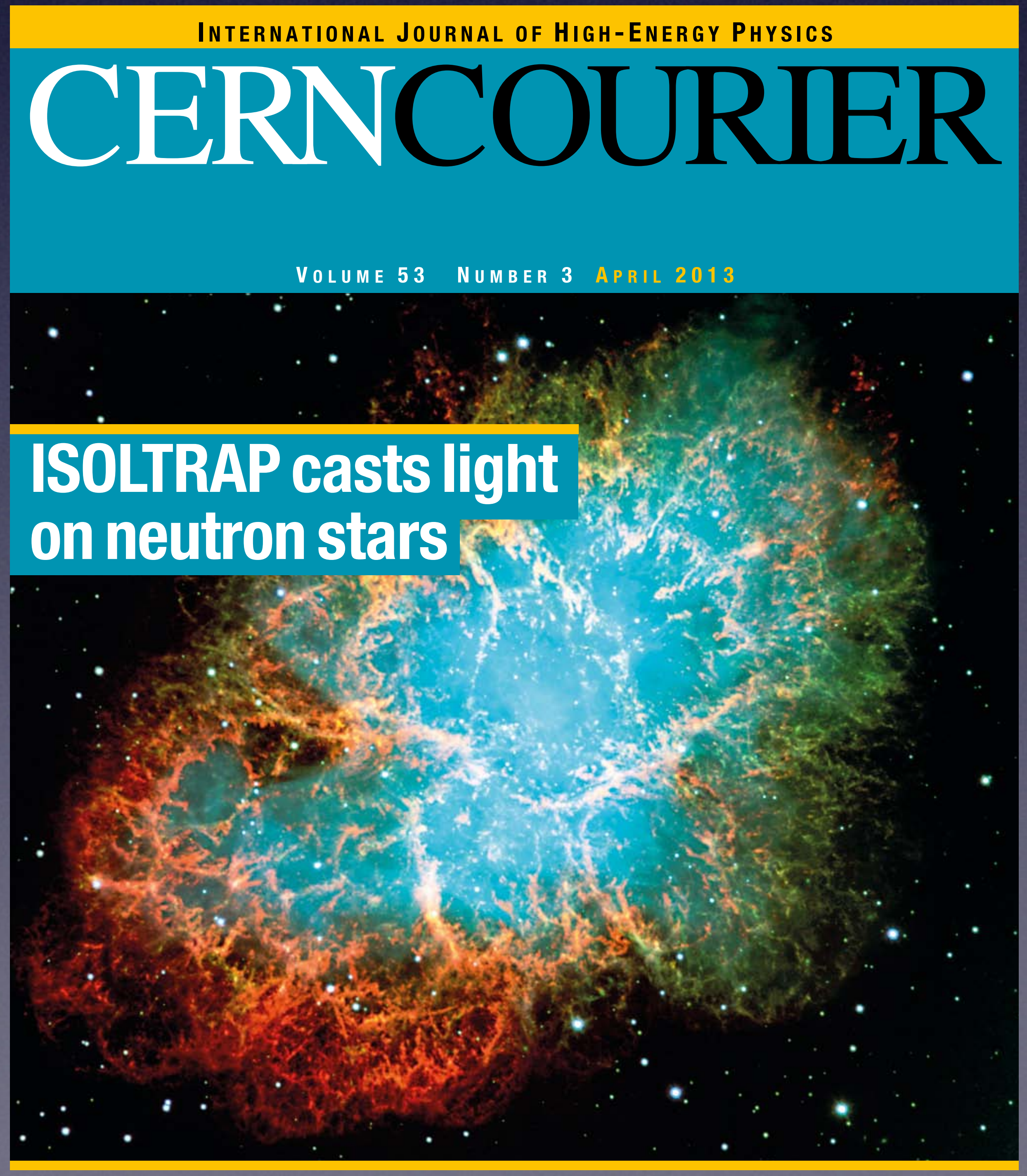
- Composition emerges from relatively simple dynamics
  - Competition between electronic and symmetry energy

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

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





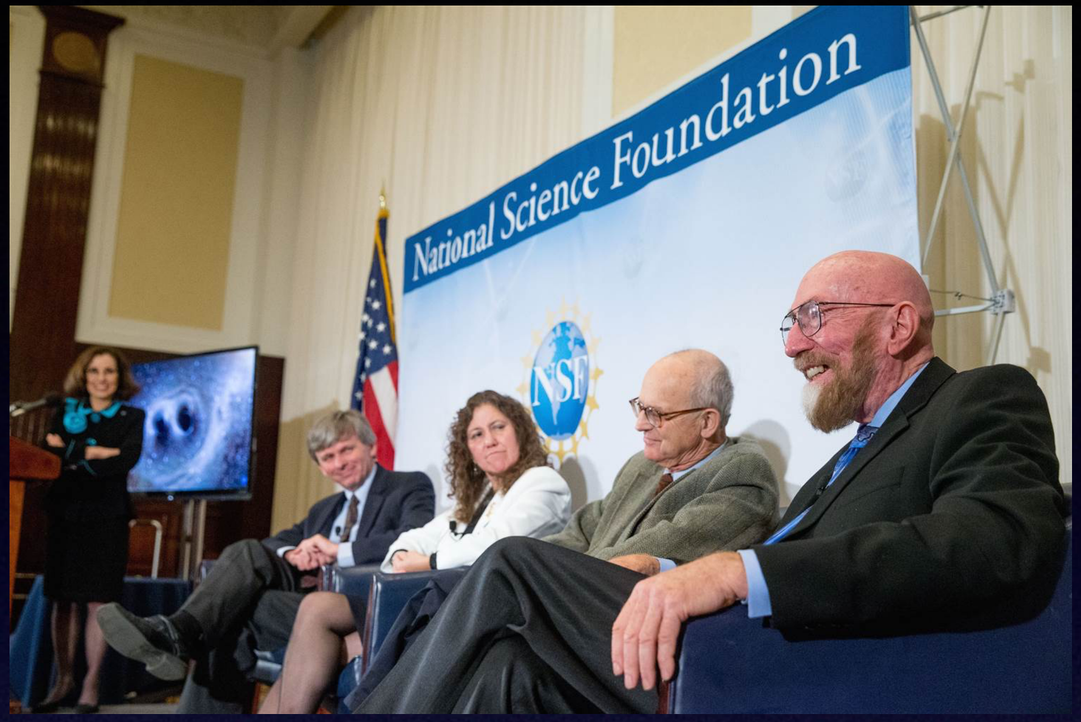

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

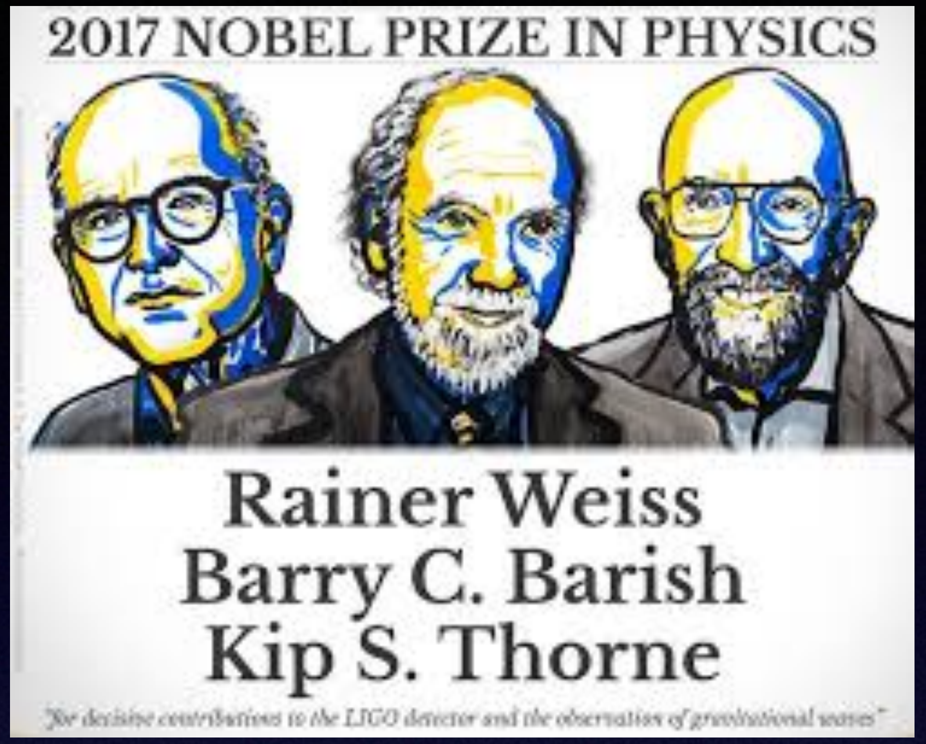
CERNCOURIER

VOLUME 53 NUMBER 3 APRIL 2013

ISOLTRAP casts light on neutron stars

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

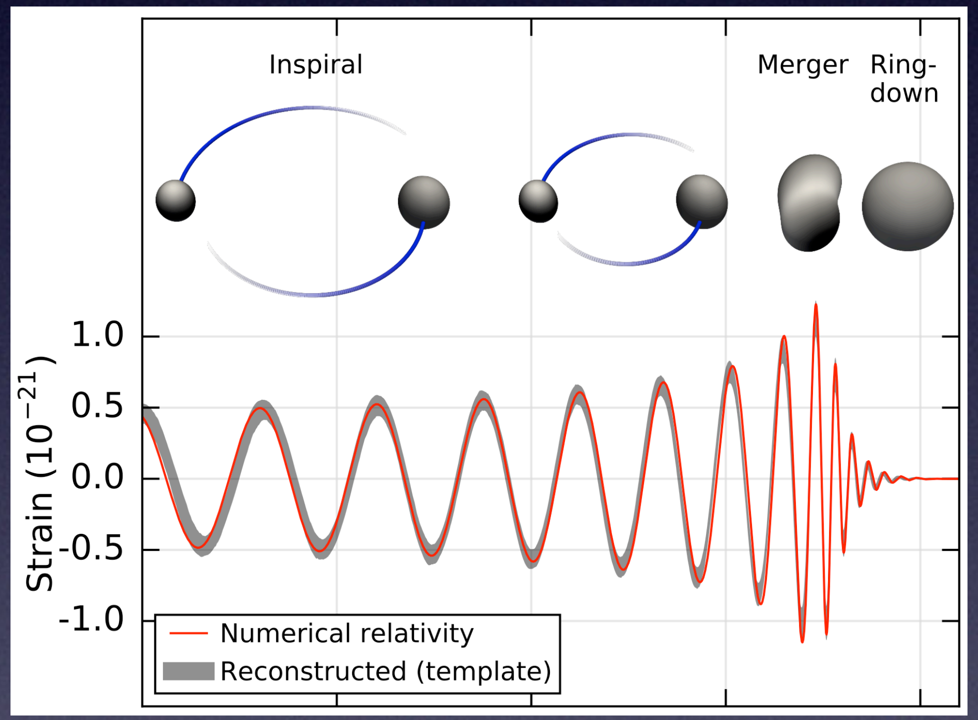


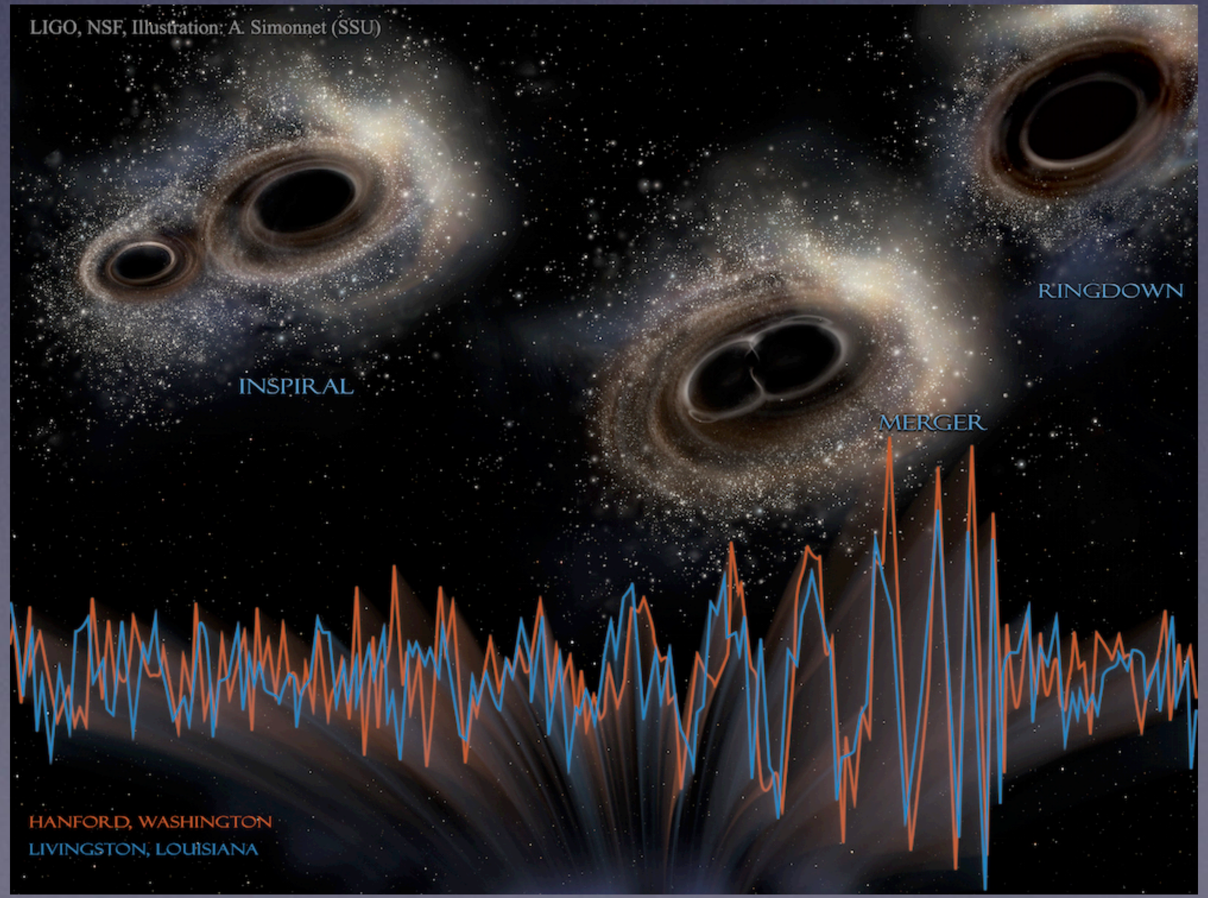

2017 NOBEL PRIZE IN PHYSICS

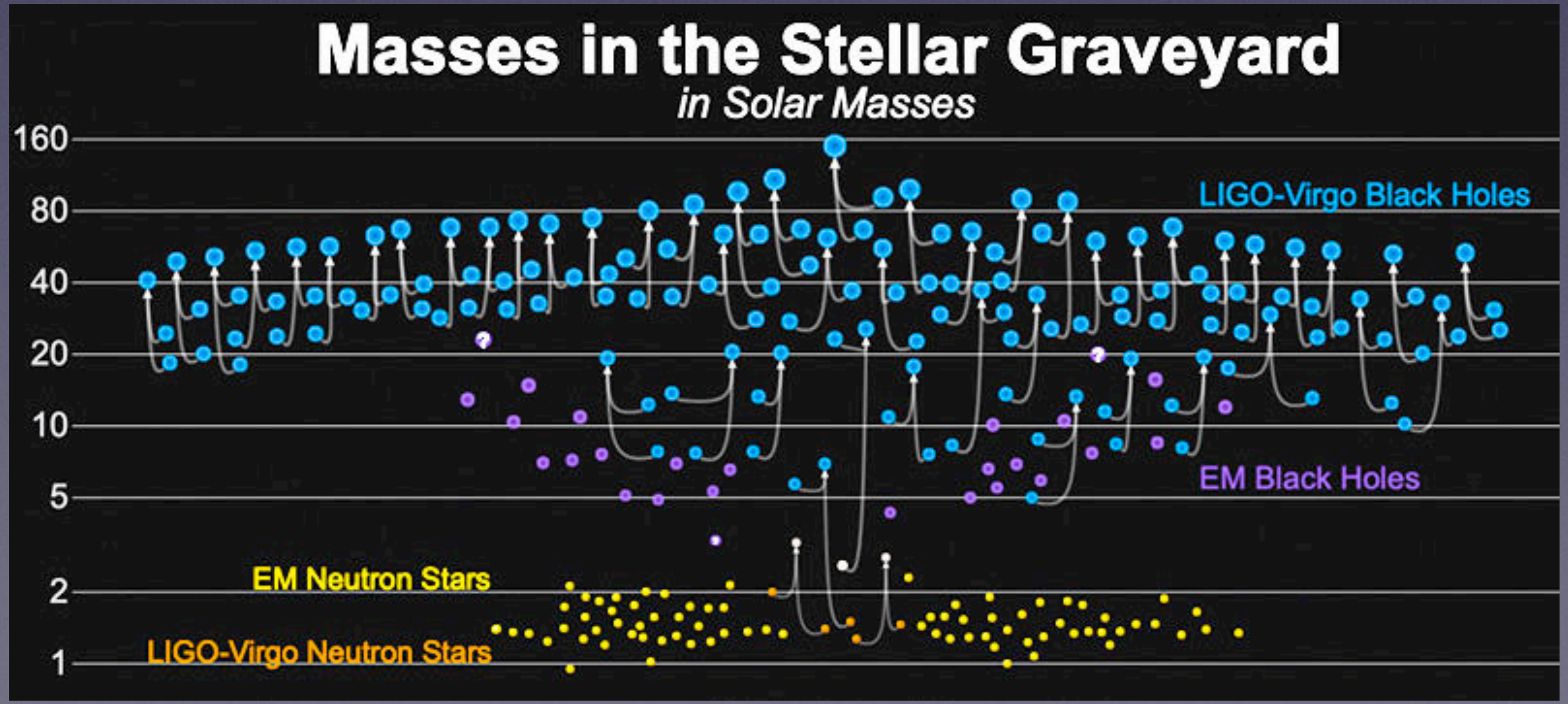
Rainer Weiss
Barry C. Barish
Kip S. Thorne

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

- 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!*







# “Listening” to the GW Signal LIGO-Virgo detection band

- Early BNS Inspiral:
  - Indistinguishable from two colliding black holes
  - Analytic “Post-Newtonian-Gravity” expansion

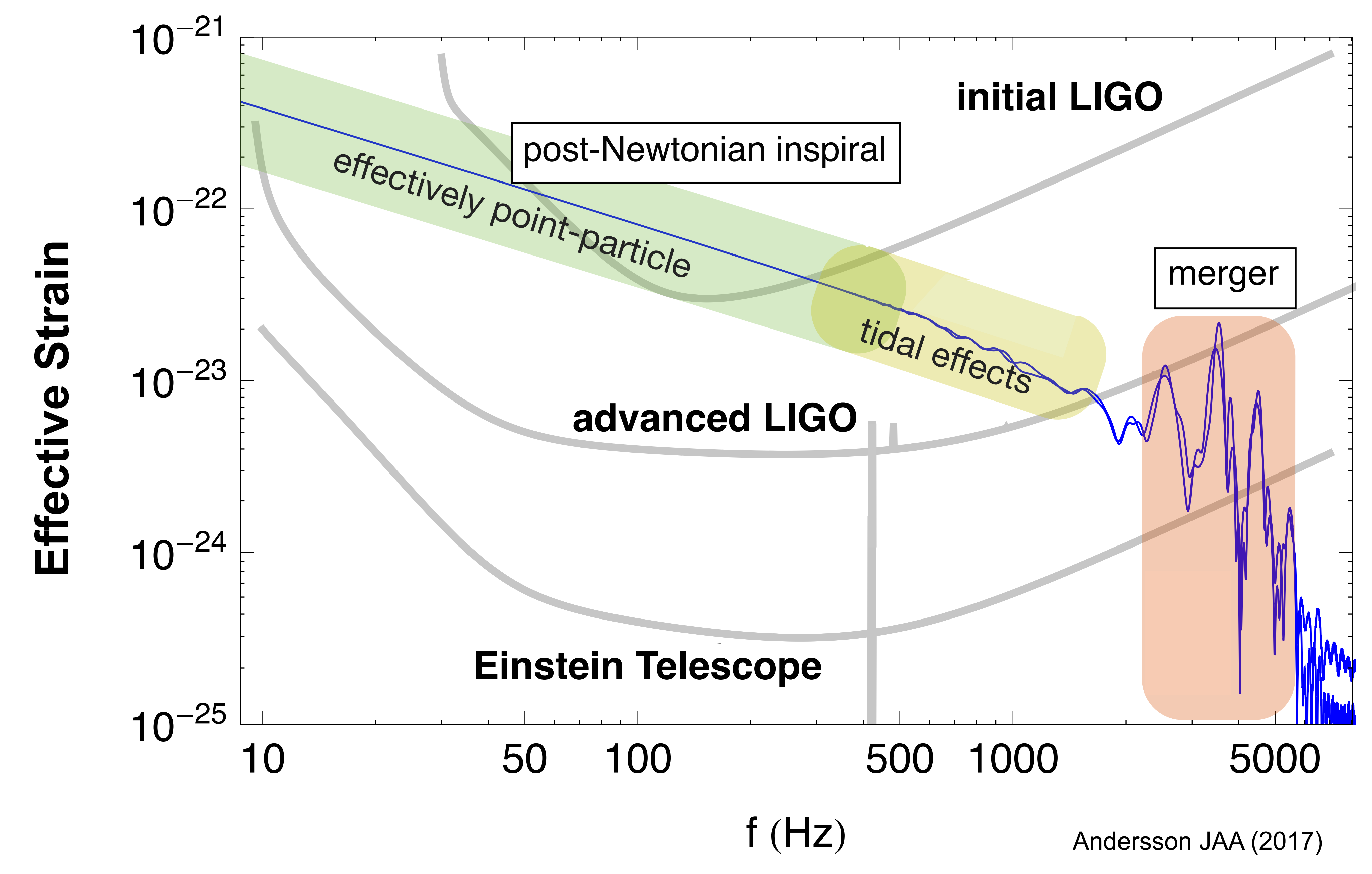
    *Orbital separation:1000 km (20 minutes)*

- Late BNS Inspiral:
  - Tidal effects become important
  - Sensitive to stellar compactness ⟶ EOS

    *Orbital separation: 200 km (2 seconds)*

- BNS Merger:
  - GRelativity in the strong-coupling regime
  - Numerical simulations with hot EOS

    *Orbital separation: 50 km (0.01 seconds)*



Andersson JAA (2017)

Dimensionless strain: $h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$

I = mass quadrupole moment of the source

R = source distance

If $\ddot{I}(t) \to M a^2 \omega^2$

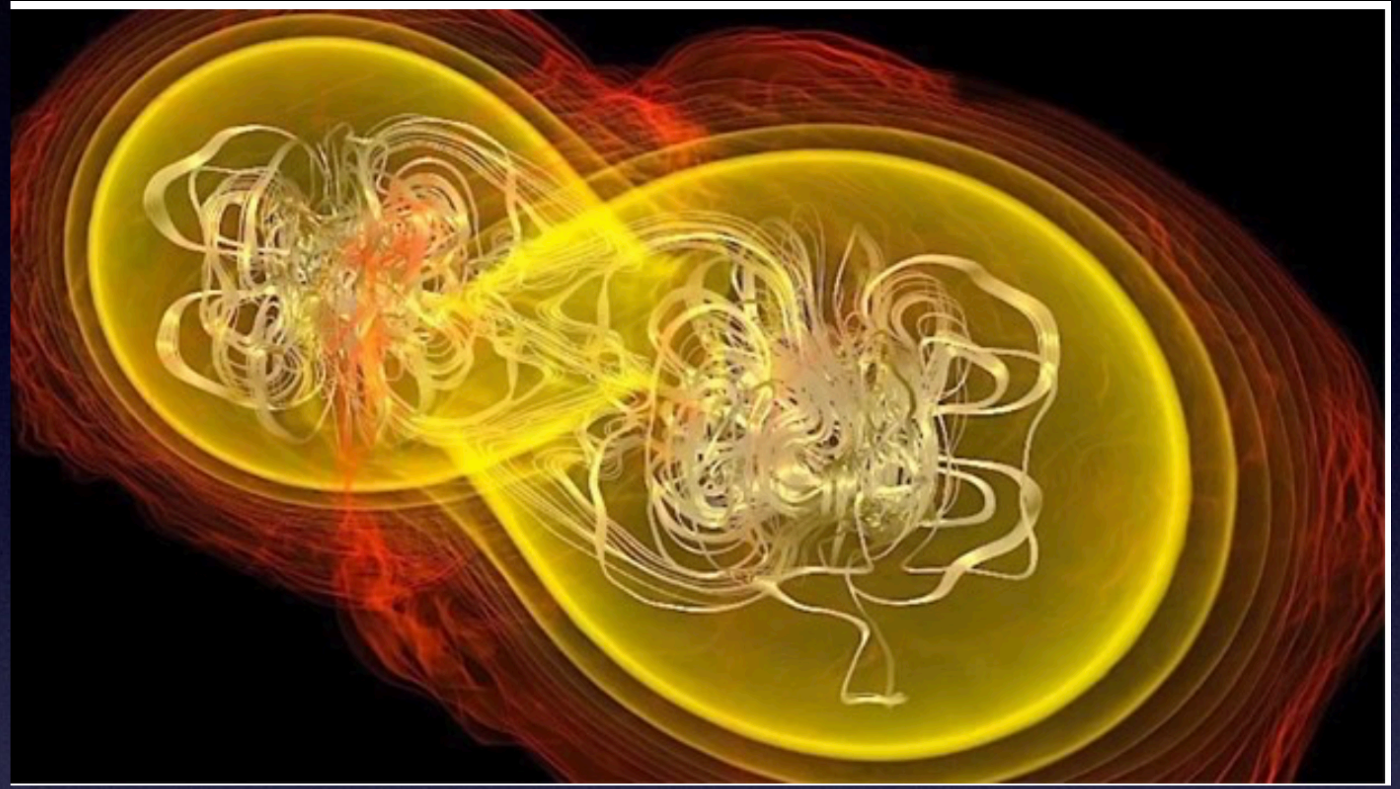
$$h(t) = \left(\frac{2GM}{c^2 R}\right)\left(\frac{a}{\lambda}\right)^2 = \left(\frac{R_s}{R}\right)\left(\frac{a}{\lambda}\right)^2$$

$$\sim 10^{-2}\left(\frac{R_s}{R}\right) \sim 10^{-23} \text{ @ } [40\,\mathrm{Mpc}]$$

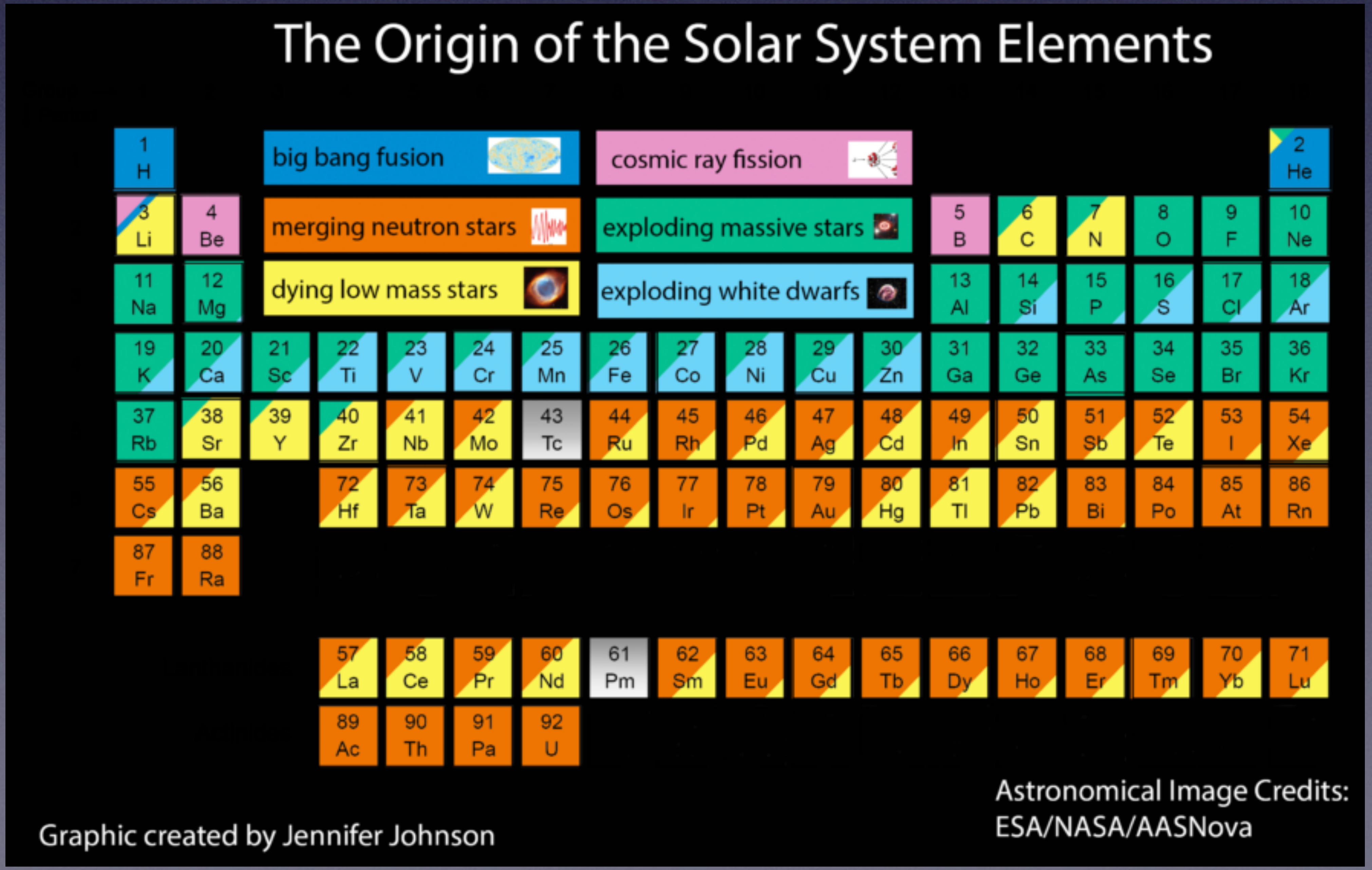
At $h=10^{-21}$ and with an arm length of 4km displacement is 1000 times smaller than proton!

# 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



Graphic created by Jennifer Johnson

Astronomical Image Credits: ESA/NASA/AASNova