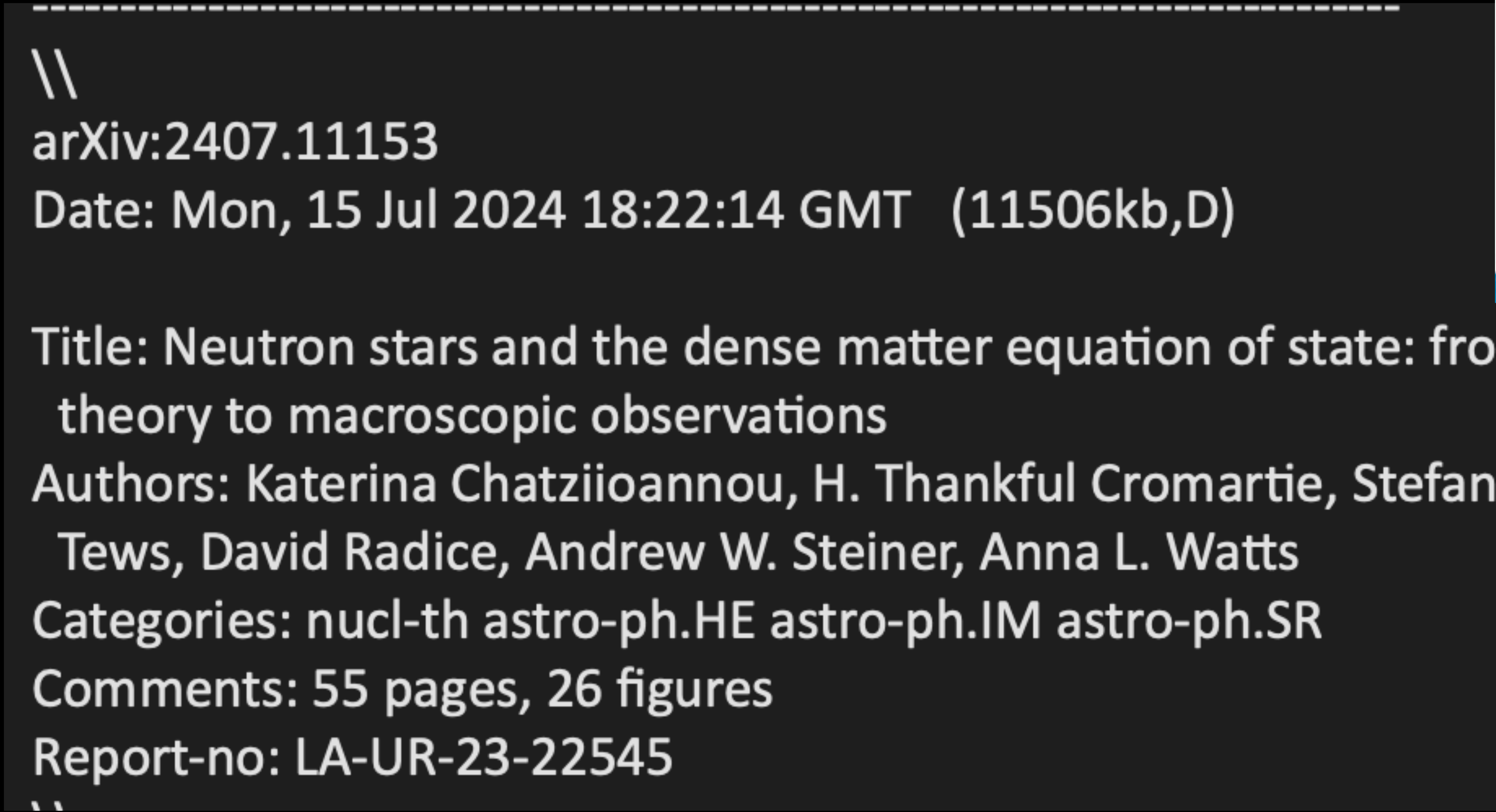
We are all one big happy family!



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arXiv:2407.11153
Date: Mon, 15 Jul 2024 18:22:14 GMT   (11506kb,D)

Title: Neutron stars and the dense matter equation of state: from microscopic
  theory to macroscopic observations
Authors: Katerina Chatziioannou, H. Thankful Cromartie, Stefano Gandolfi, Ingo
  Tews, David Radice, Andrew W. Steiner, Anna L. Watts
Categories: nucl-th astro-ph.HE astro-ph.IM astro-ph.SR
Comments: 55 pages, 26 figures
Report-no: LA-UR-23-22545
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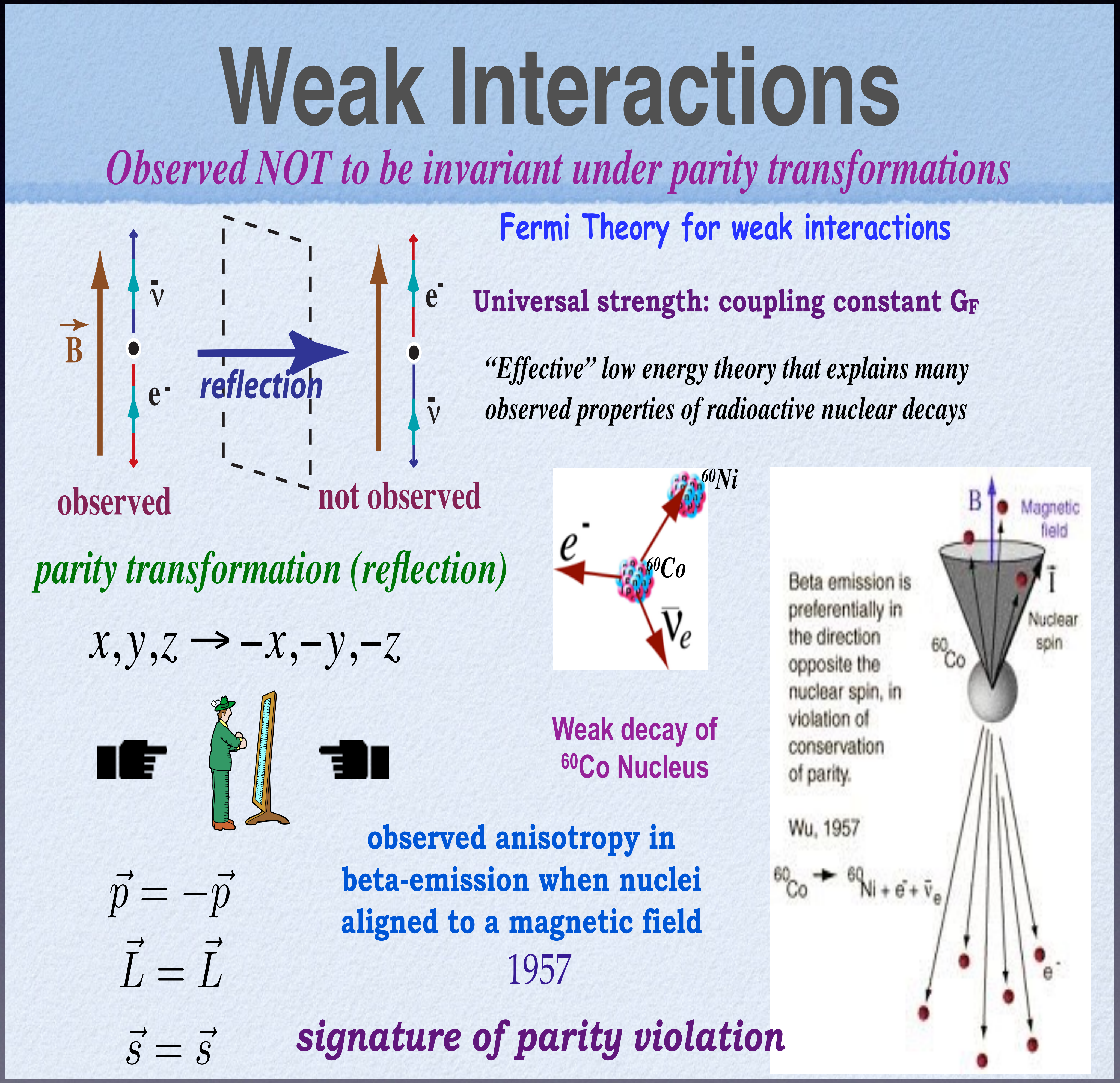
Fermi Theory of the Weak Interactions
The very "first" effective field theory



Weak Interactions

Observed NOT to be invariant under parity transformations

Fermi Theory for weak interactions

Universal strength: coupling constant G_F

"Effective" low energy theory that explains many observed properties of radioactive nuclear decays

parity transformation (reflection)

$x,y,z \rightarrow -x,-y,-z$

$\vec{p} = -\vec{p}$

$\vec{L} = \vec{L}$

$\vec{s} = \vec{s}$

Weak decay of ^{60}Co Nucleus

observed anisotropy in beta-emission when nuclei aligned to a magnetic field

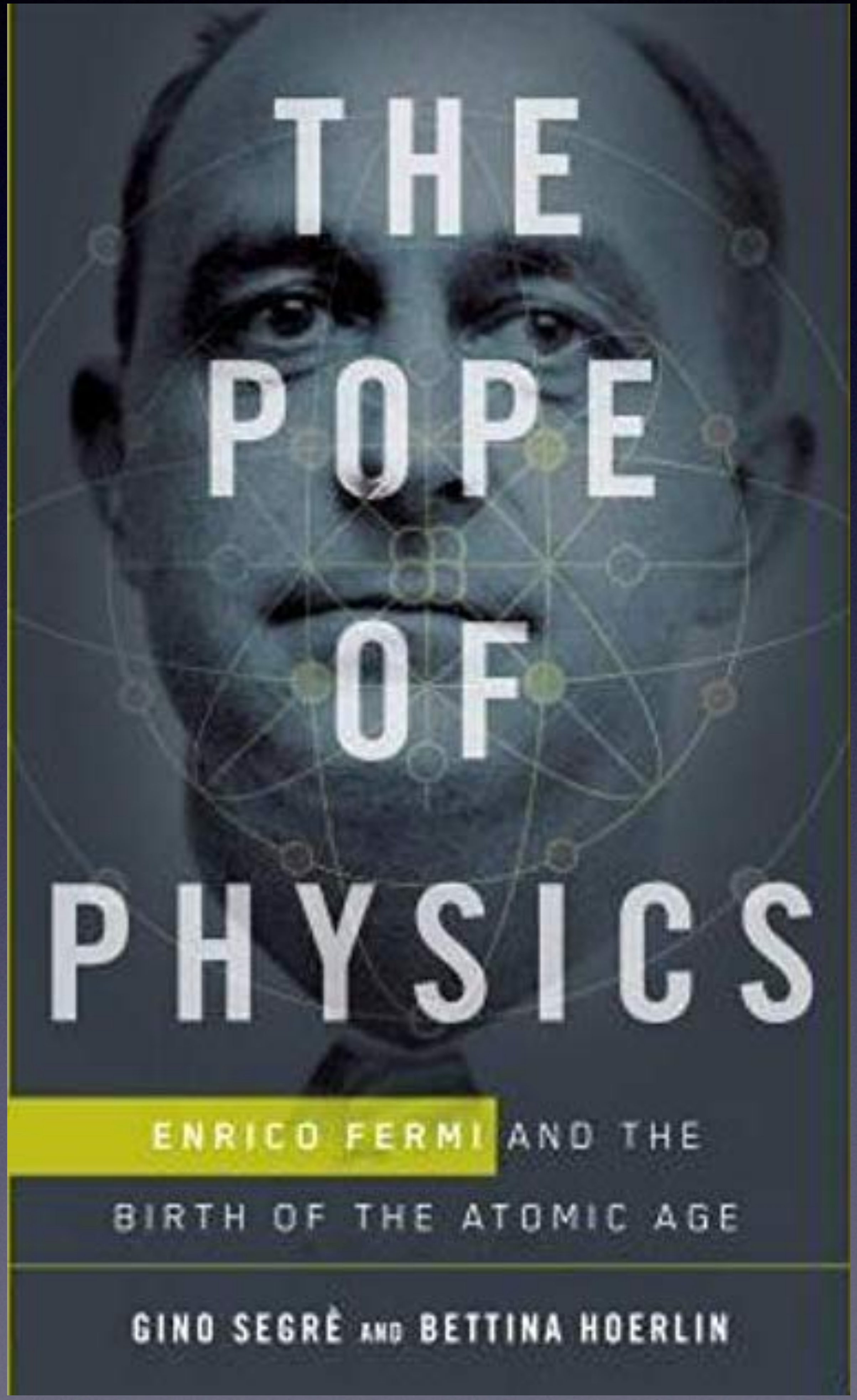
1957

signature of parity violation

Beta emission is preferentially in the direction opposite the nuclear spin, in violation of conservation of parity.

Wu, 1957

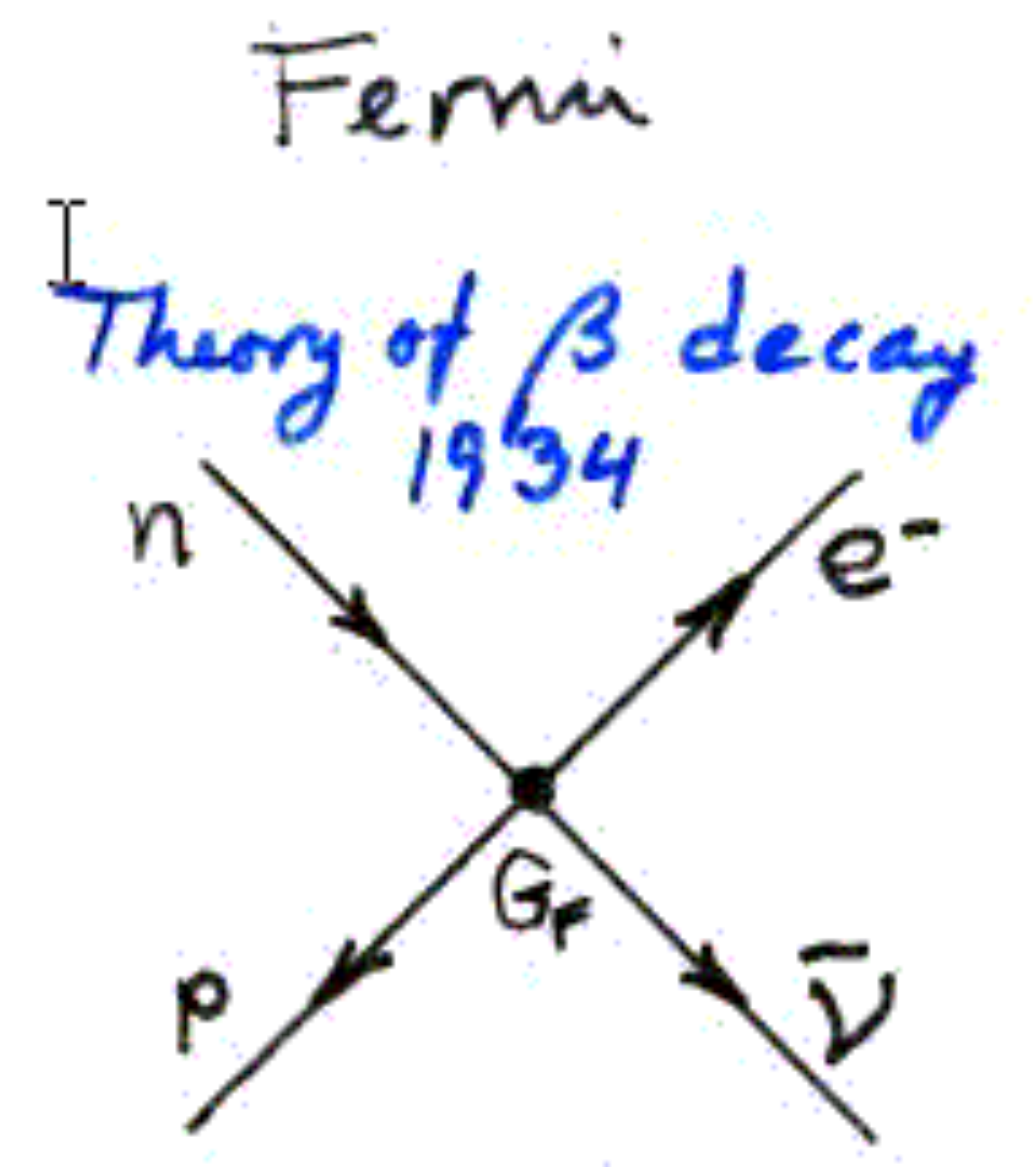
$^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e$



THE POPE OF PHYSICS

ENRICO FERMI AND THE BIRTH OF THE ATOMIC AGE

GINO SEGRÈ AND BETTINA HOERLIN



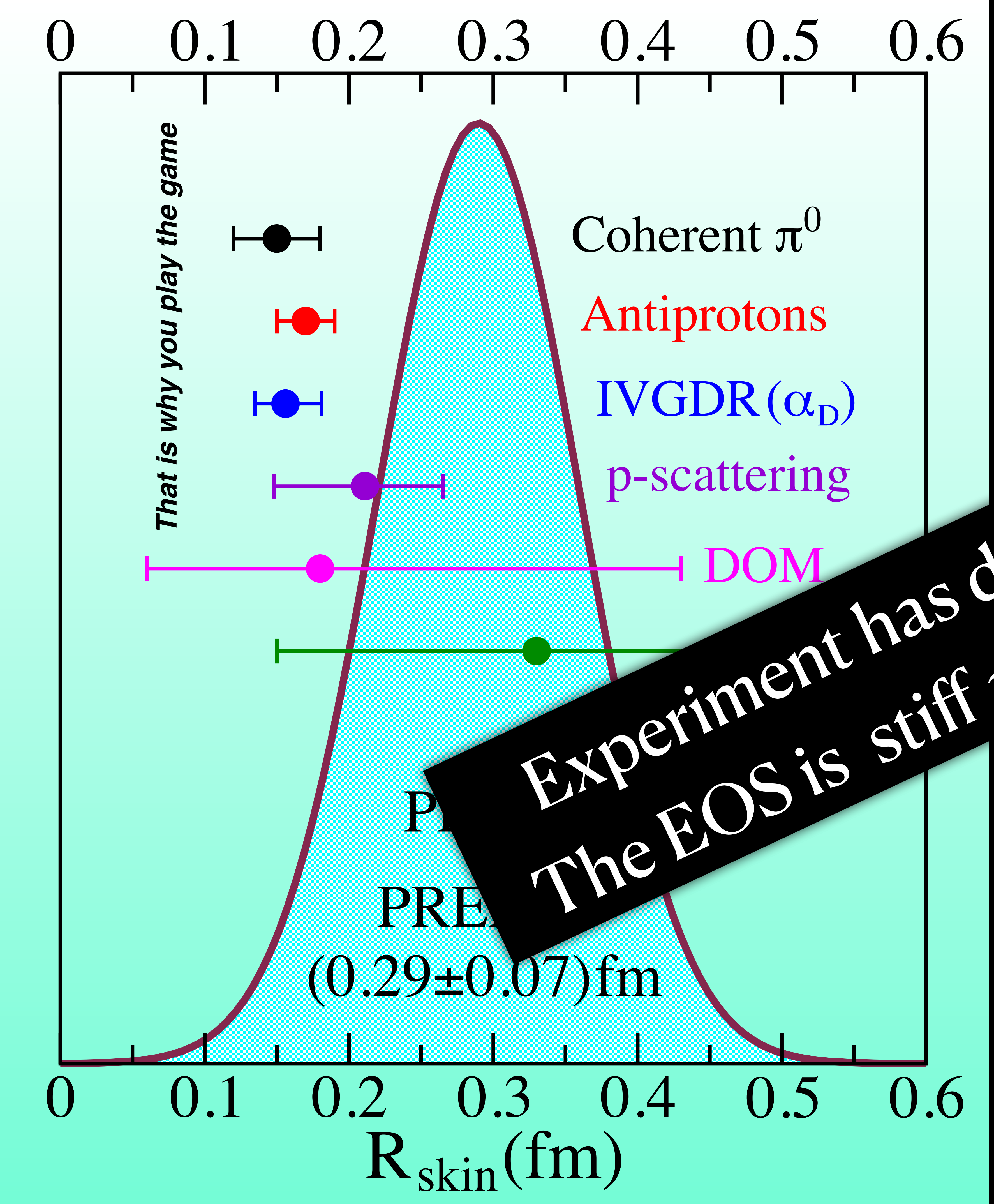
Fermi four-fermion theory of beta decay

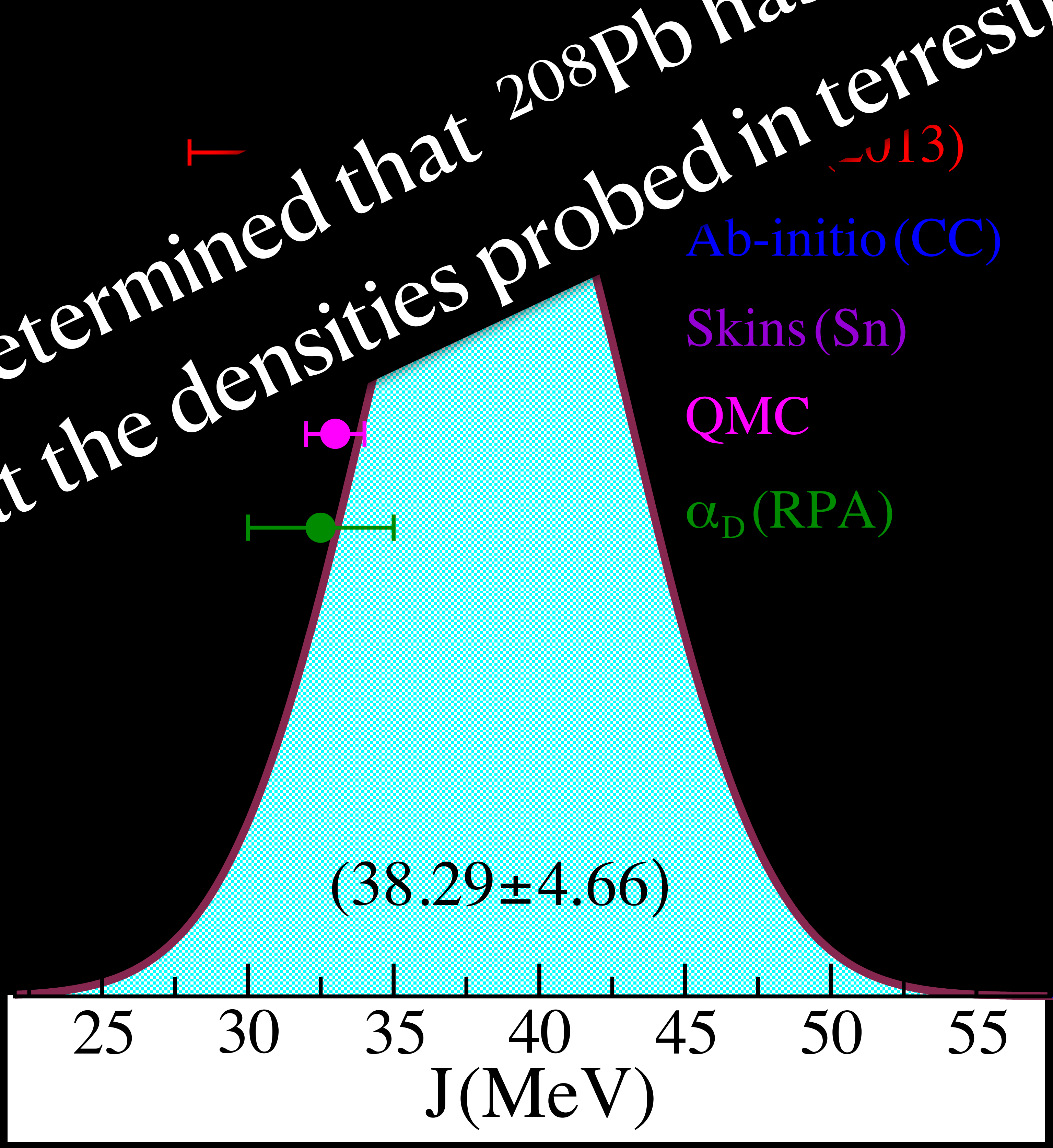
PREX-2 (Oct 29, 2020)
Ciprian Gal - DNP Meeting
Adhikari et al., PRL 126, 172502 (2021)

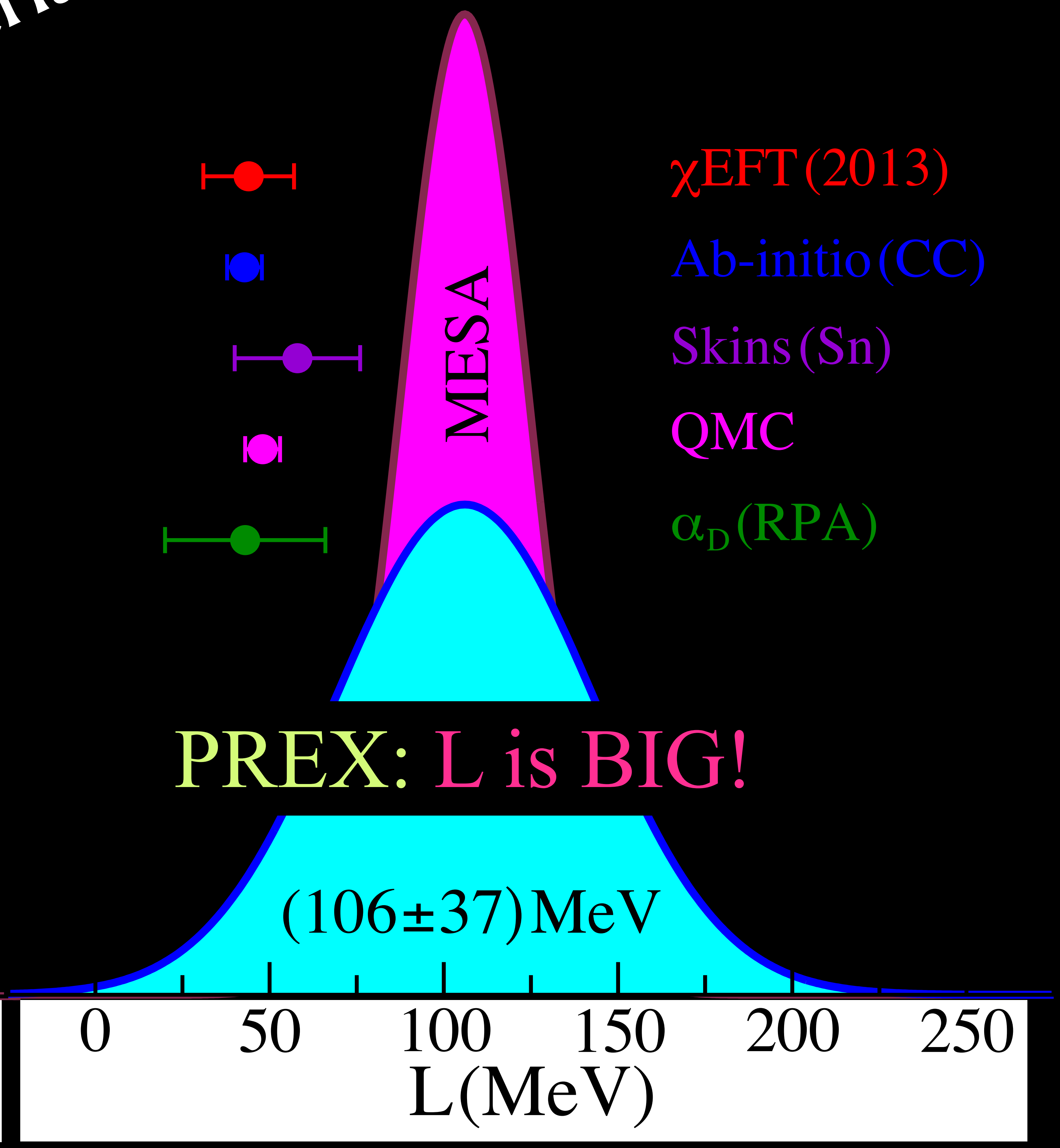
Conservation of difficulty: PVES provides the cleanest constraint on the EOS of neutron-rich matter in the vicinity of saturation density

Heroic effort from our experimental colleagues

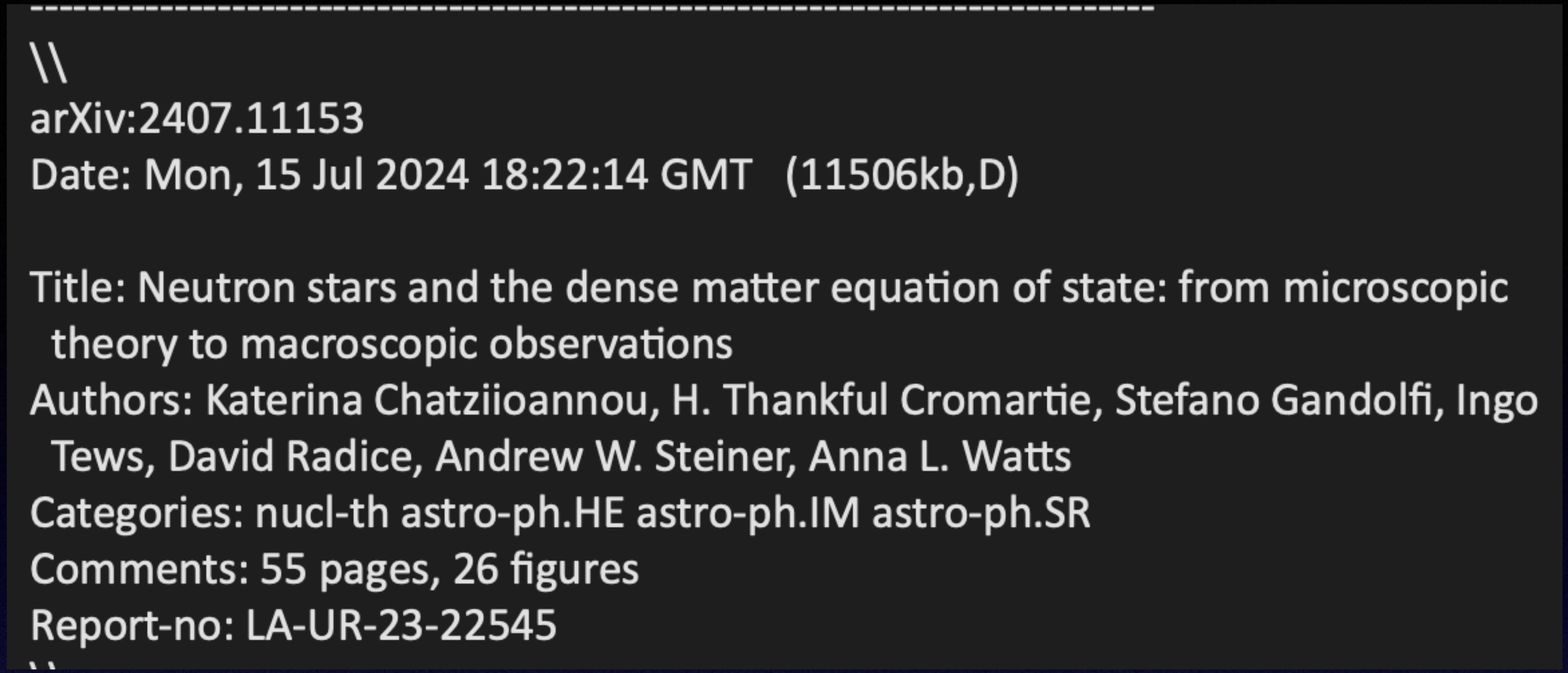
Experiment has determined that ^{208}Pb has a thick neutron skin.
The EOS is stiff at the densities probed in terrestrial experiments!







PREX: L is BIG!



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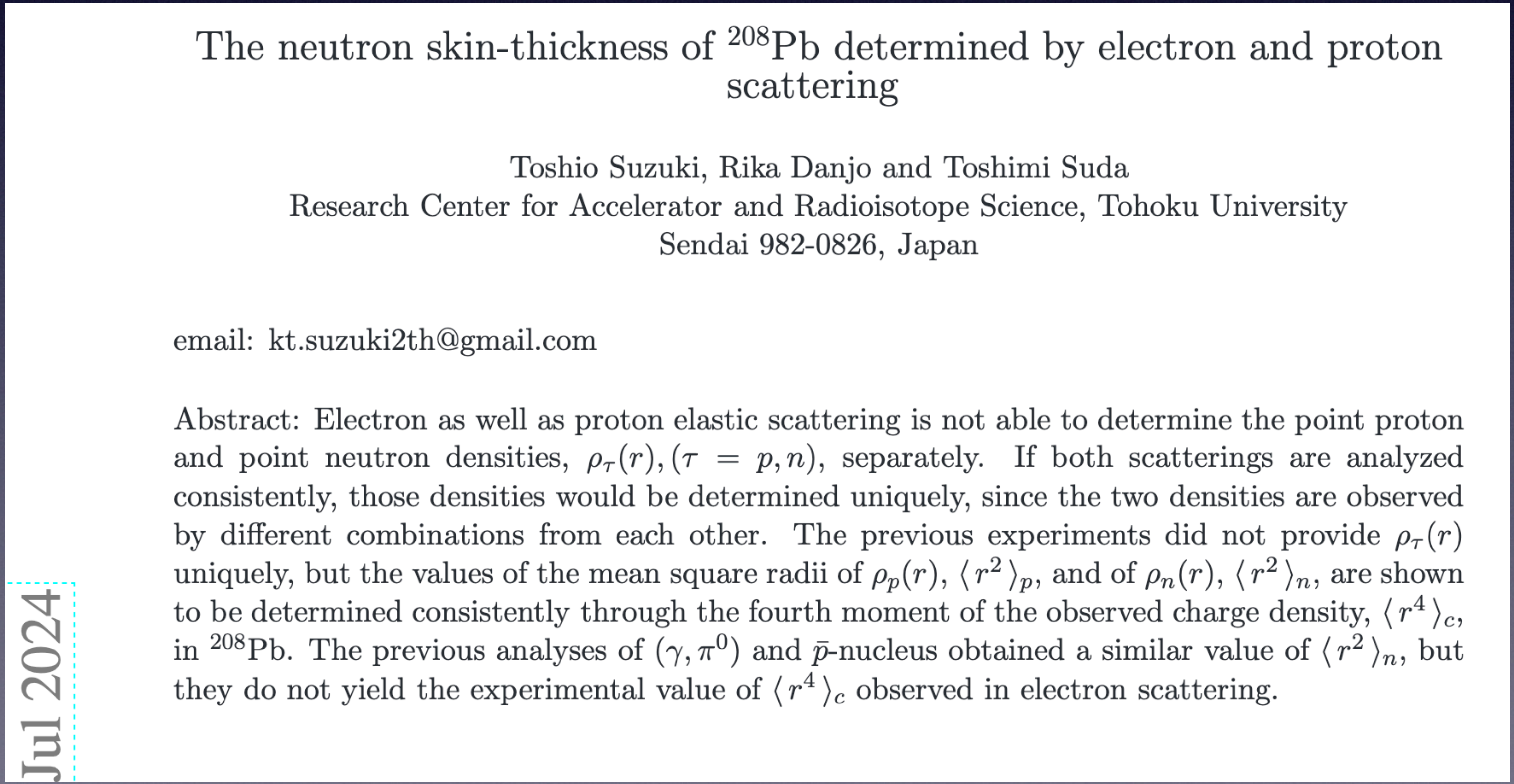


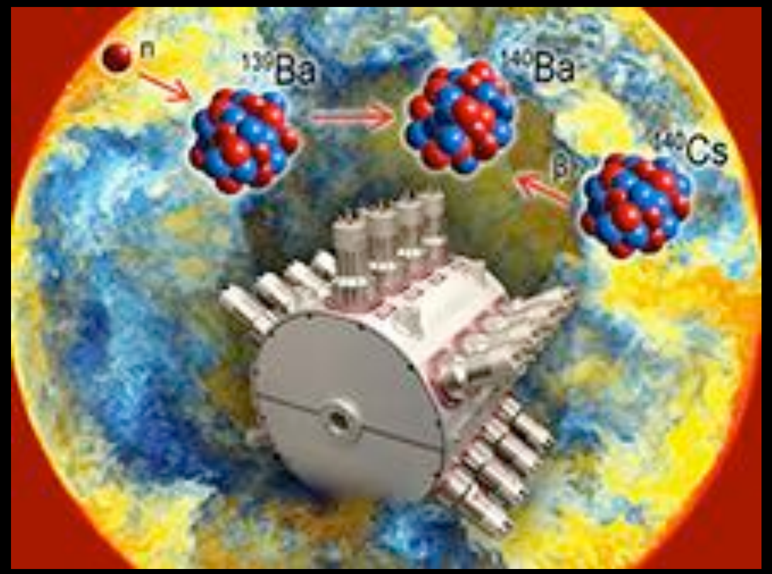
The neutron skin-thickness of ^{208}Pb determined by electron and proton scattering

Toshio Suzuki, Rika Danjo and Toshimi Suda
Research Center for Accelerator and Radioisotope Science, Tohoku University
Sendai 982-0826, Japan

email: kt.suzuki2th@gmail.com

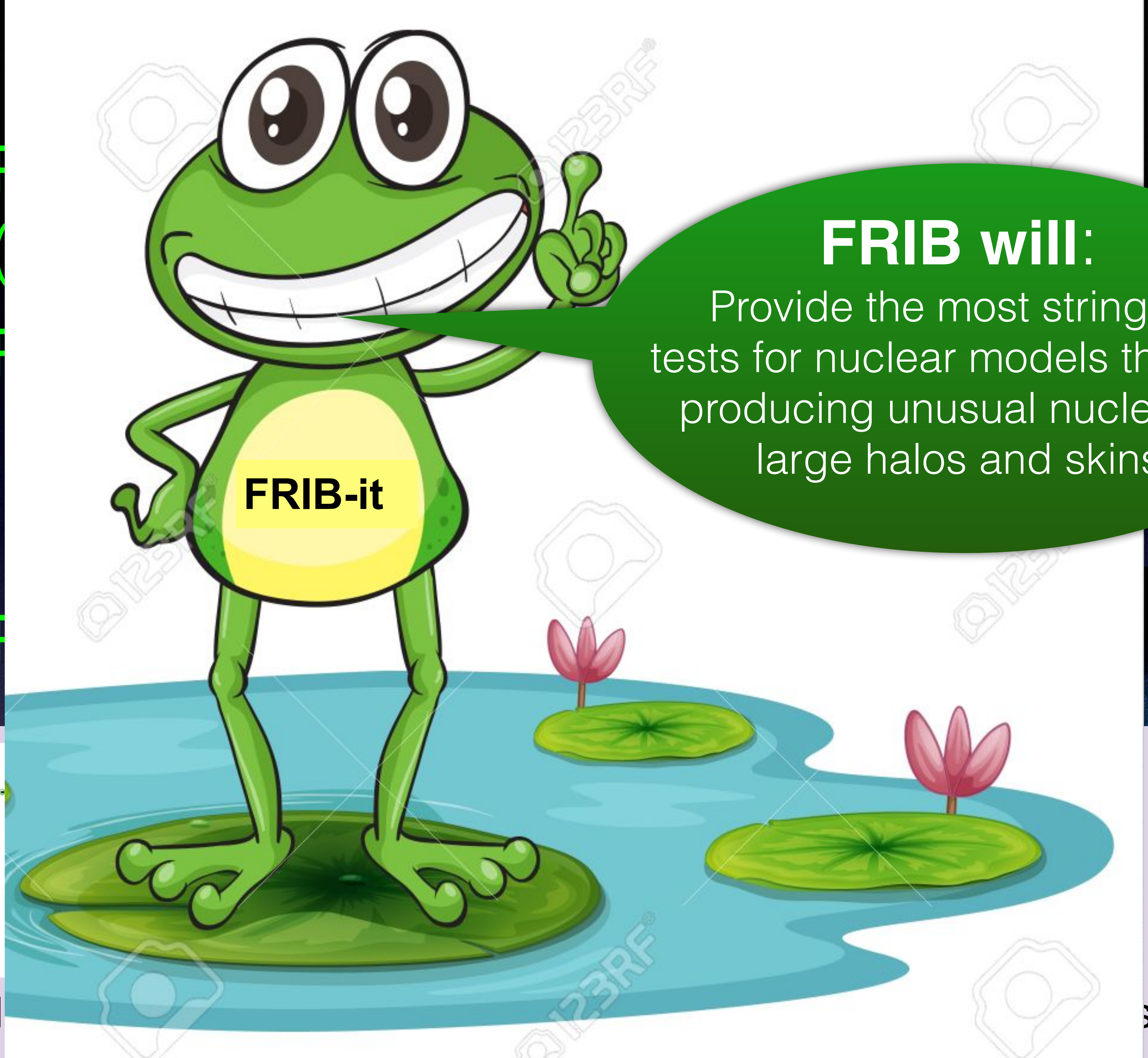
Abstract: Electron as well as proton elastic scattering is not able to determine the point proton and point neutron densities, $\rho_\tau(r), (\tau = p, n)$, separately. If both scatterings are analyzed consistently, those densities would be determined uniquely, since the two densities are observed by different combinations from each other. The previous experiments did not provide $\rho_\tau(r)$ uniquely, but the values of the mean square radii of $\rho_p(r)$, $\langle r^2 \rangle_p$, and of $\rho_n(r)$, $\langle r^2 \rangle_n$, are shown to be determined consistently through the fourth moment of the observed charge density, $\langle r^4 \rangle_c$, in ^{208}Pb. The previous analyses of (γ, π^0) and $\bar{p}$-nucleus obtained a similar value of $\langle r^2 \rangle_n$, but they do not yield the experimental value of $\langle r^4 \rangle_c$ observed in electron scattering.

Facility for Rare Isotope Beams
at Michigan State University

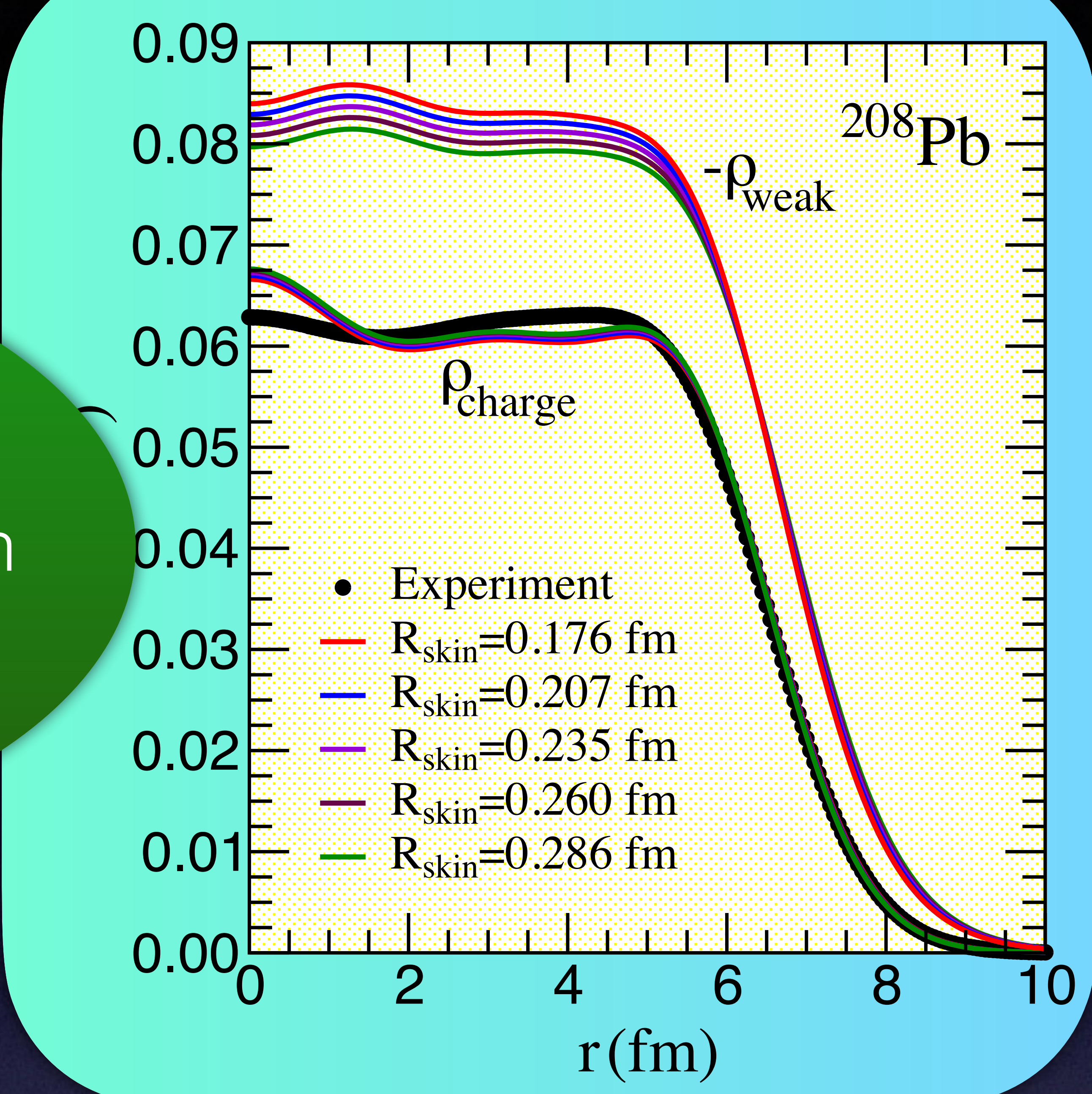



FRIB RESEARCHERS LEAD TEAM TO MERGE NUCLEAR PHYSICS **EXPERIMENTS** AND **ASTRONOMICAL OBSERVATIONS** TO ADVANCE **EQUATION-OF-STATE** RESEARCH

Use PREX/CREX/MREX to calibrate future hadronic experiments at FRIB that will aim to extract the neutron skin of very exotic neutron-rich nuclei such as 60Ca, 78Ni, 132Sn



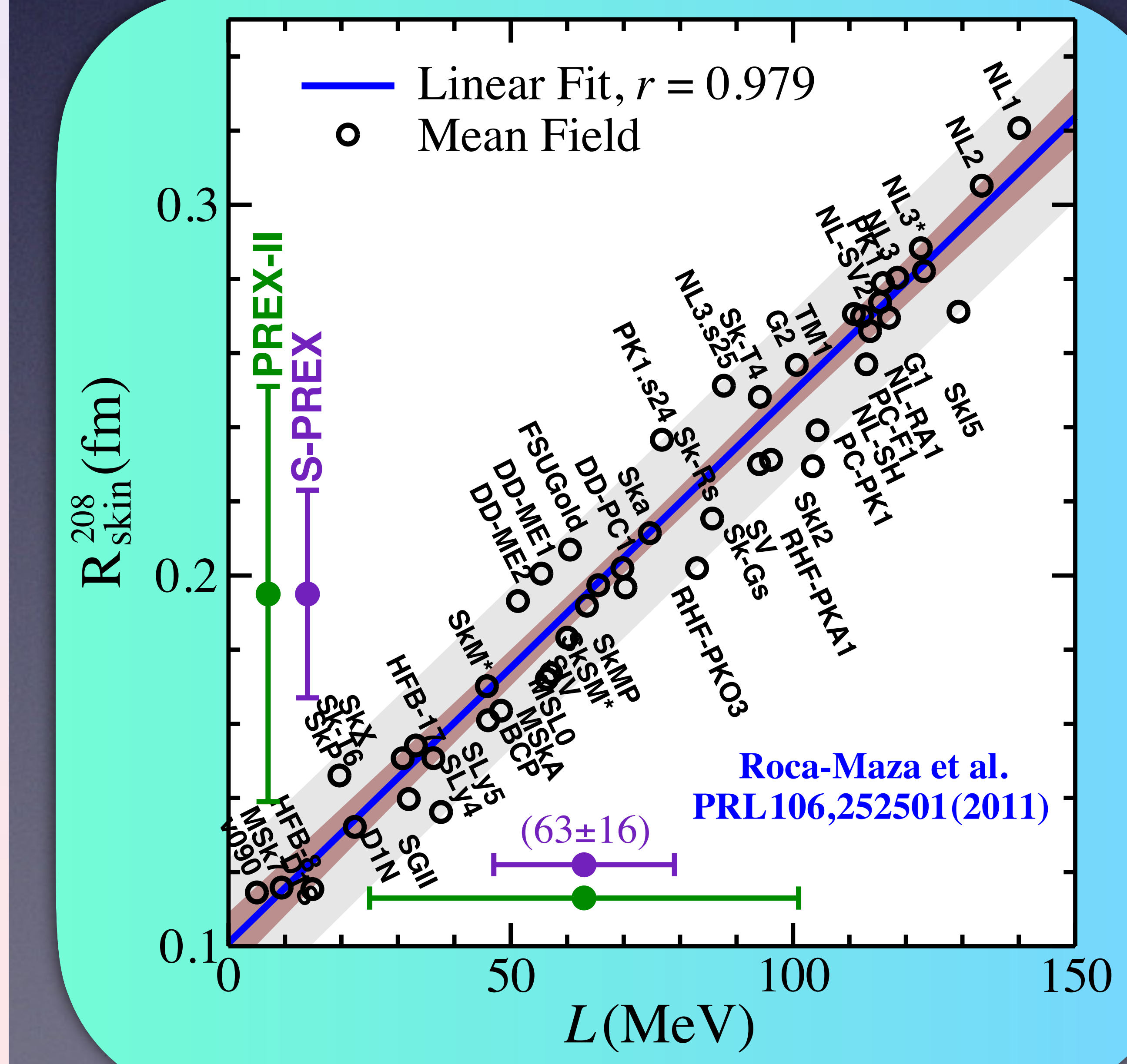
FRIB will:
Provide the most stringent tests for nuclear models through producing unusual nuclei with large halos and skins



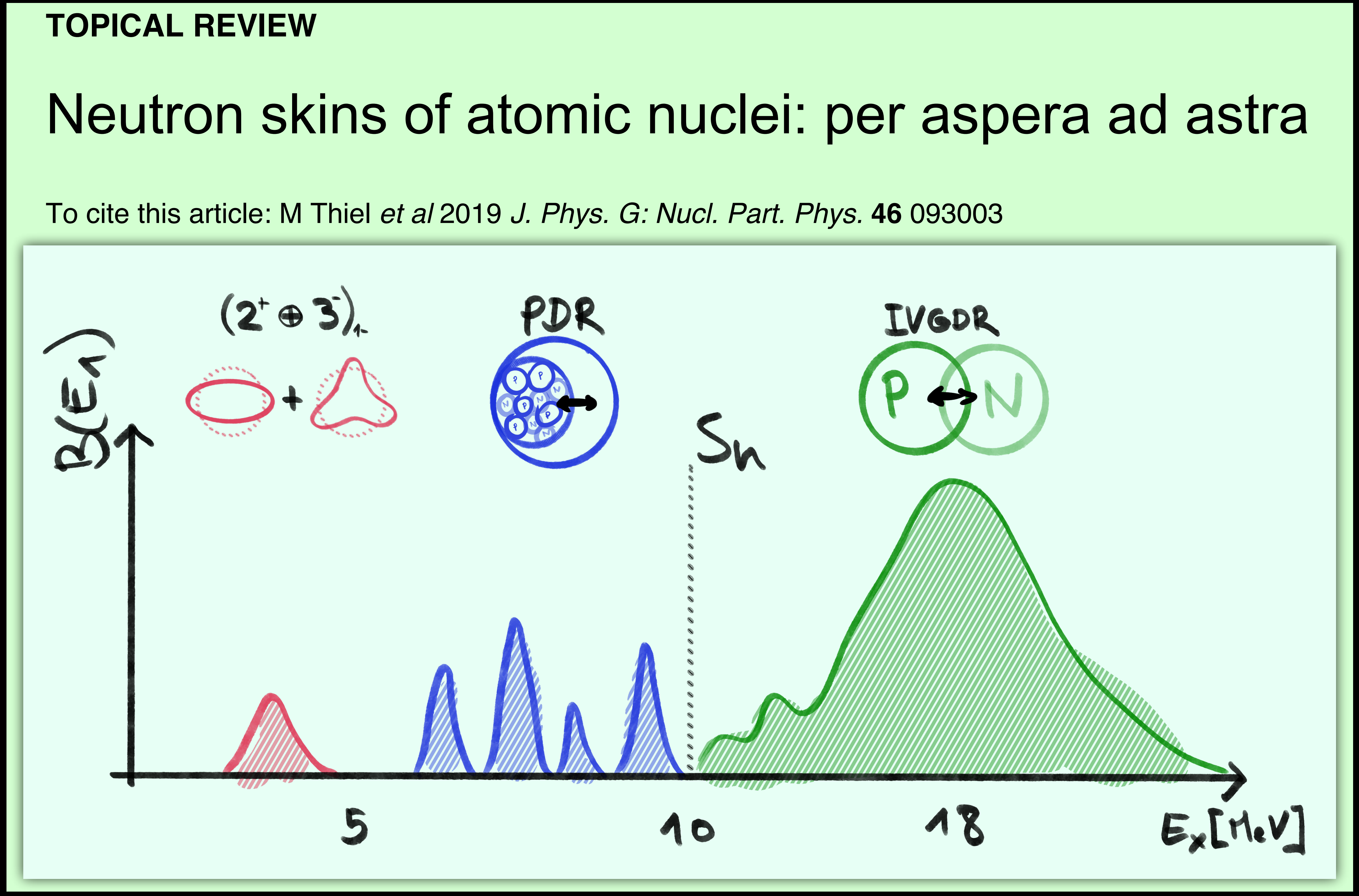
- PV provides a clean measurement of neutron densities (and R_n)

	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

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

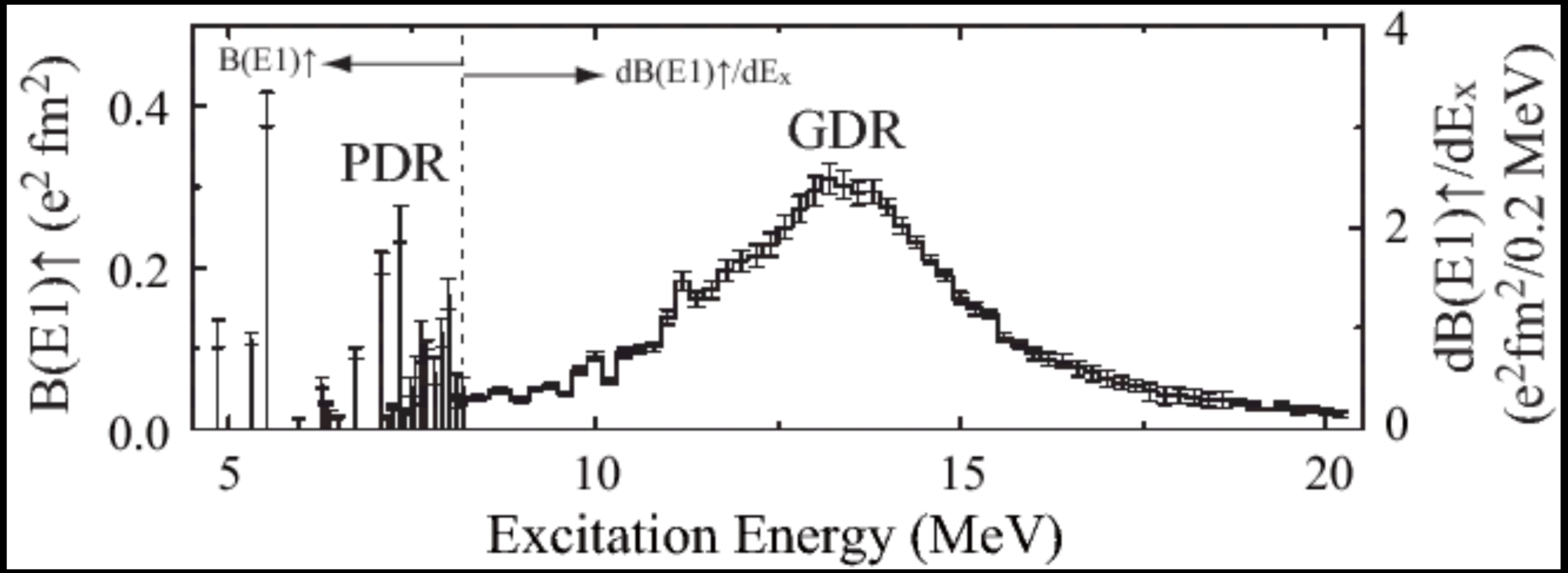


Electric Dipole Response


TOPICAL REVIEW

Neutron skins of atomic nuclei: per aspera ad astra

To cite this article: M Thiel *et al* 2019 *J. Phys. G: Nucl. Part. Phys.* **46** 093003



IVGDR: The quintessential nuclear excitation

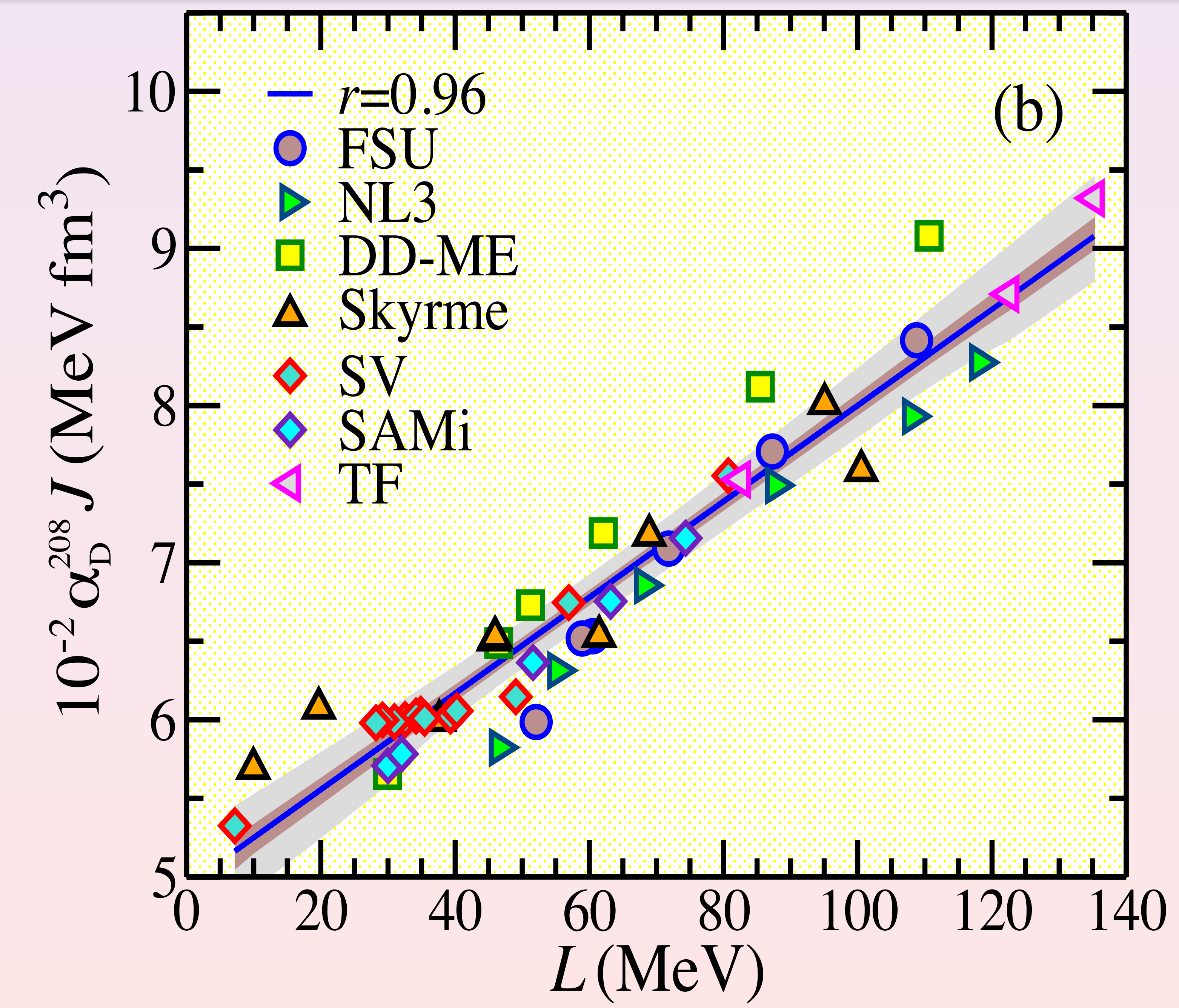
- Out-of-phase oscillation of neutrons vs protons
  Symmetry energy acts as restoring force
- Pygmy dipole resonance a soft mode with neutron rich skin oscillating against the symmetric core
- High quality data from RCNP, GSI, HIGS, …
  On a variety of nuclei such as Pb, Sn, Ni, Ca, …
  hopefully in the future along isotopic chains

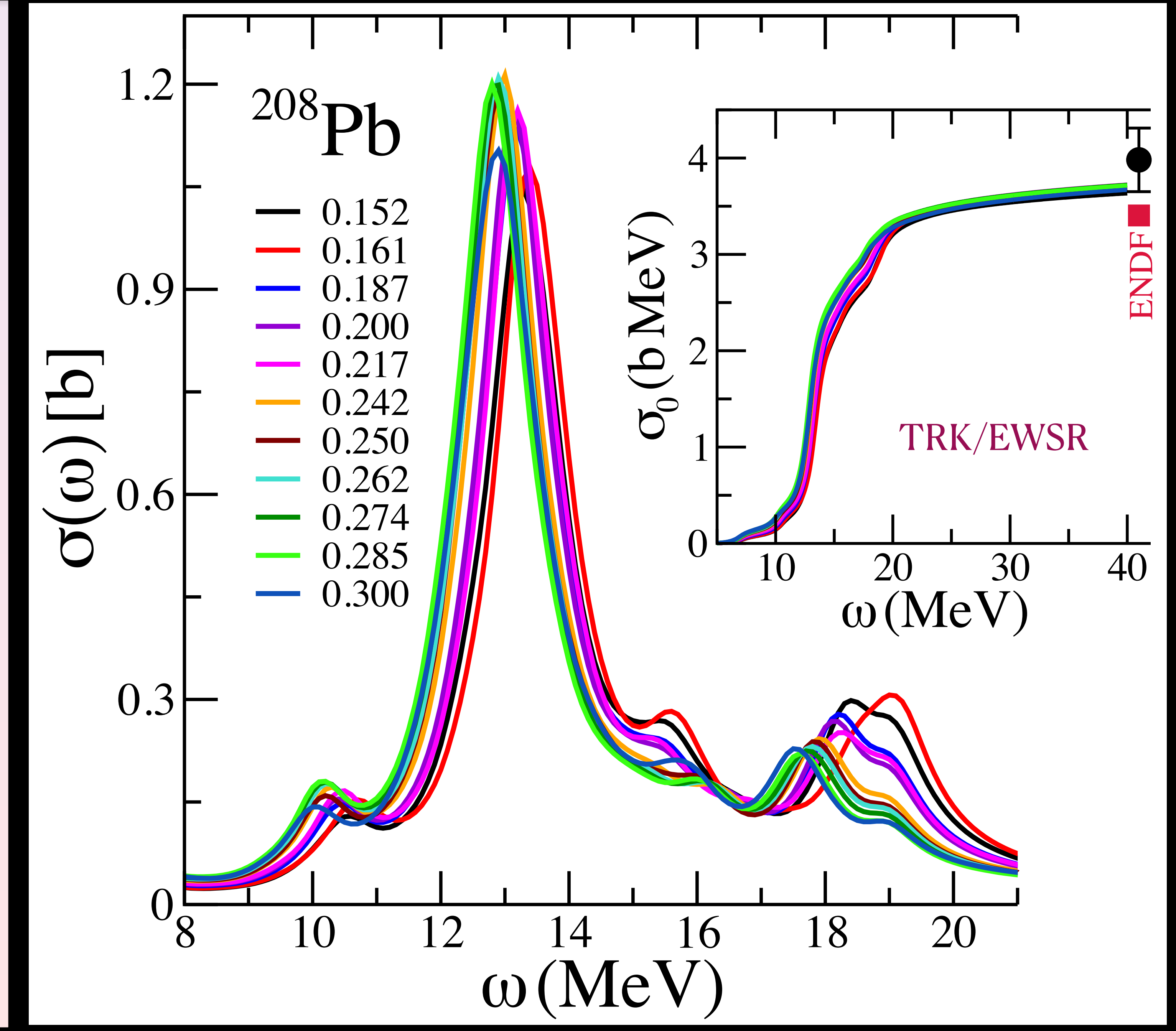
Electric Dipole Polarizability α_D

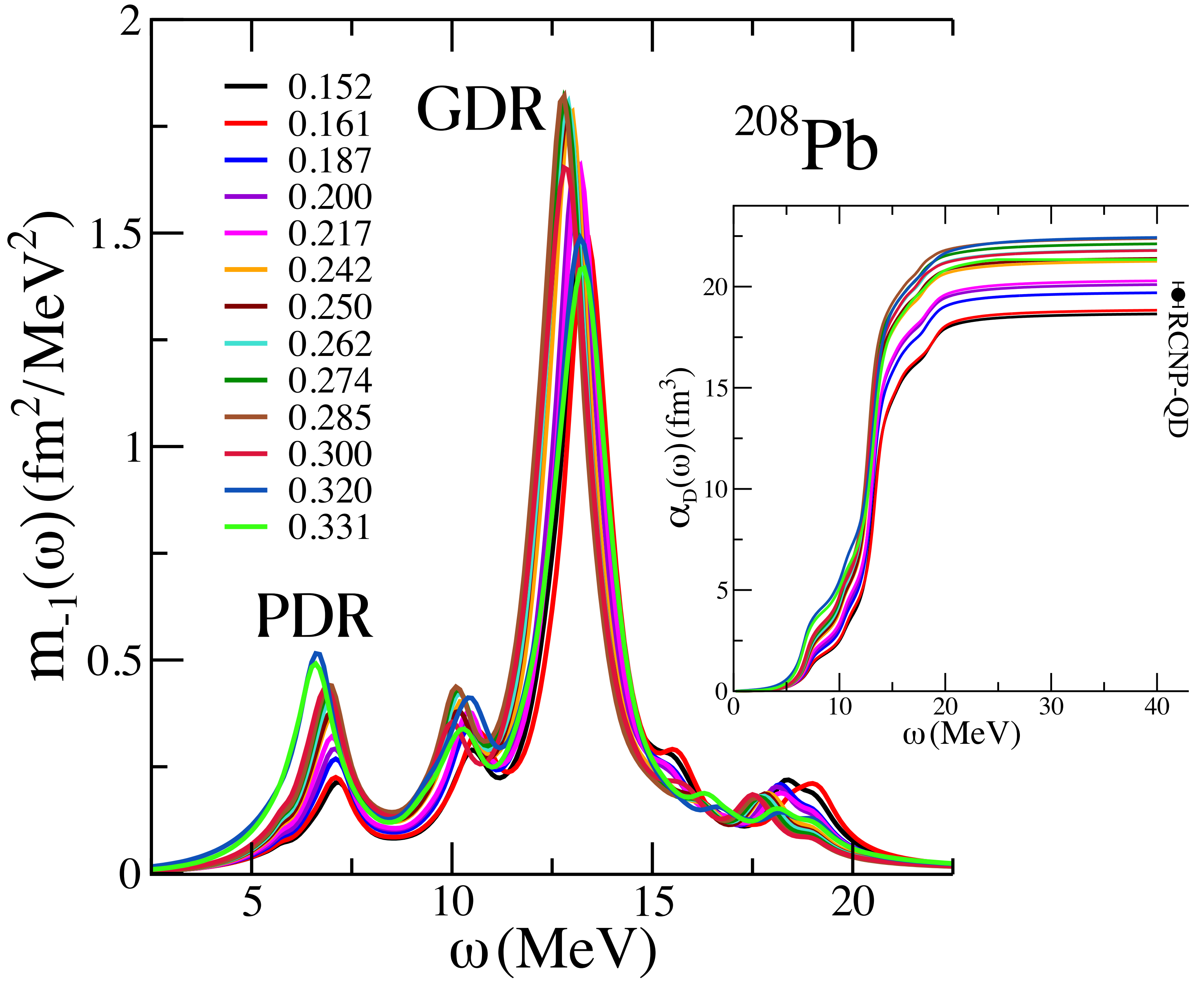
- A powerful electroweak complement to Rskin (γ-absorption experiments)
- Correlation to symmetry energy almost as strong as in the case of Rskin
- Energy weighted sum rule largely model independent
- Inverse energy weighted sum strongly correlated to L
    - Important contribution from PDR

$$\mathrm{EWSR} = \int_0^\infty \sigma(\omega)d\omega \approx 60\left(\frac{NZ}{A}\right)\,\mathrm{MeV\,mb}$$

$$\alpha_D = \left(\frac{\hbar c}{2\pi^2}\right)\int_0^\infty \frac{\sigma(\omega)}{\omega^2}d\omega = \left(\frac{8\pi e^2}{9}\right) m_{-1}$$



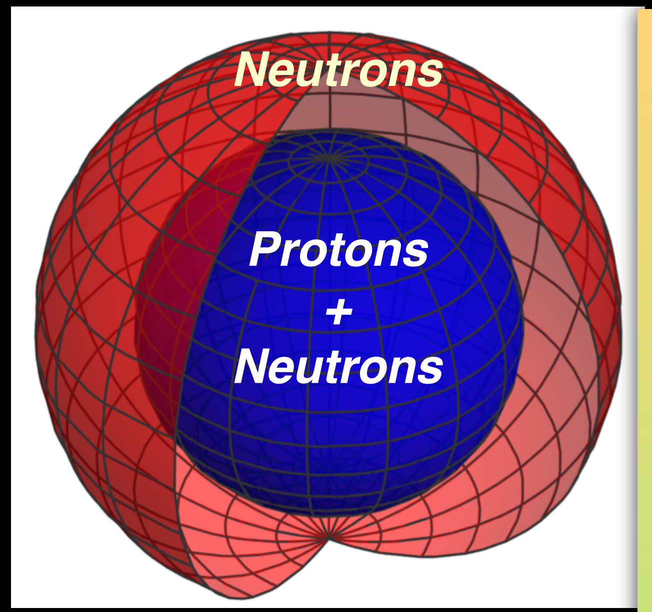


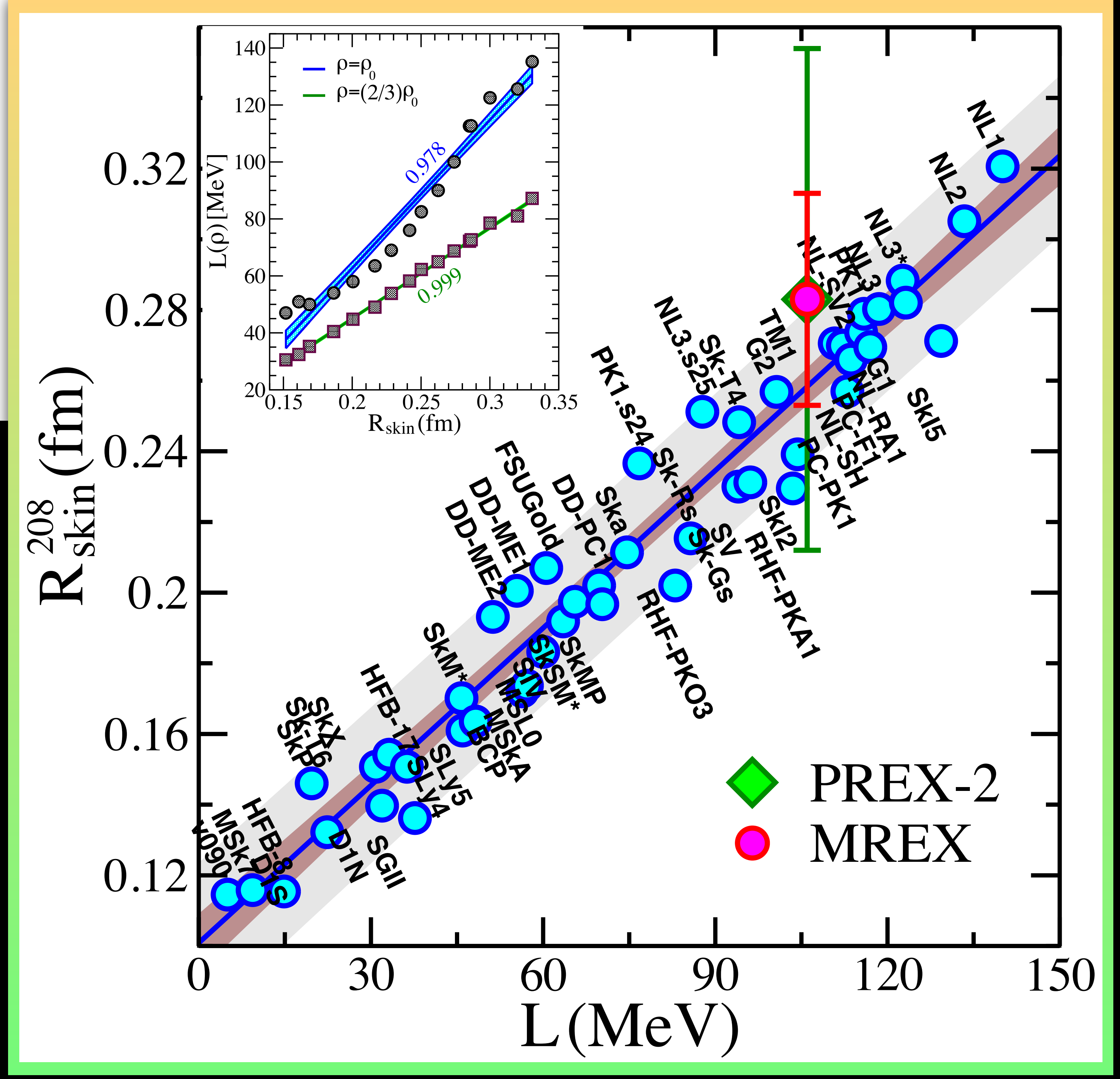


Lectures will attempt to provide an overall (personal) picture of the field

Heaven and Earth

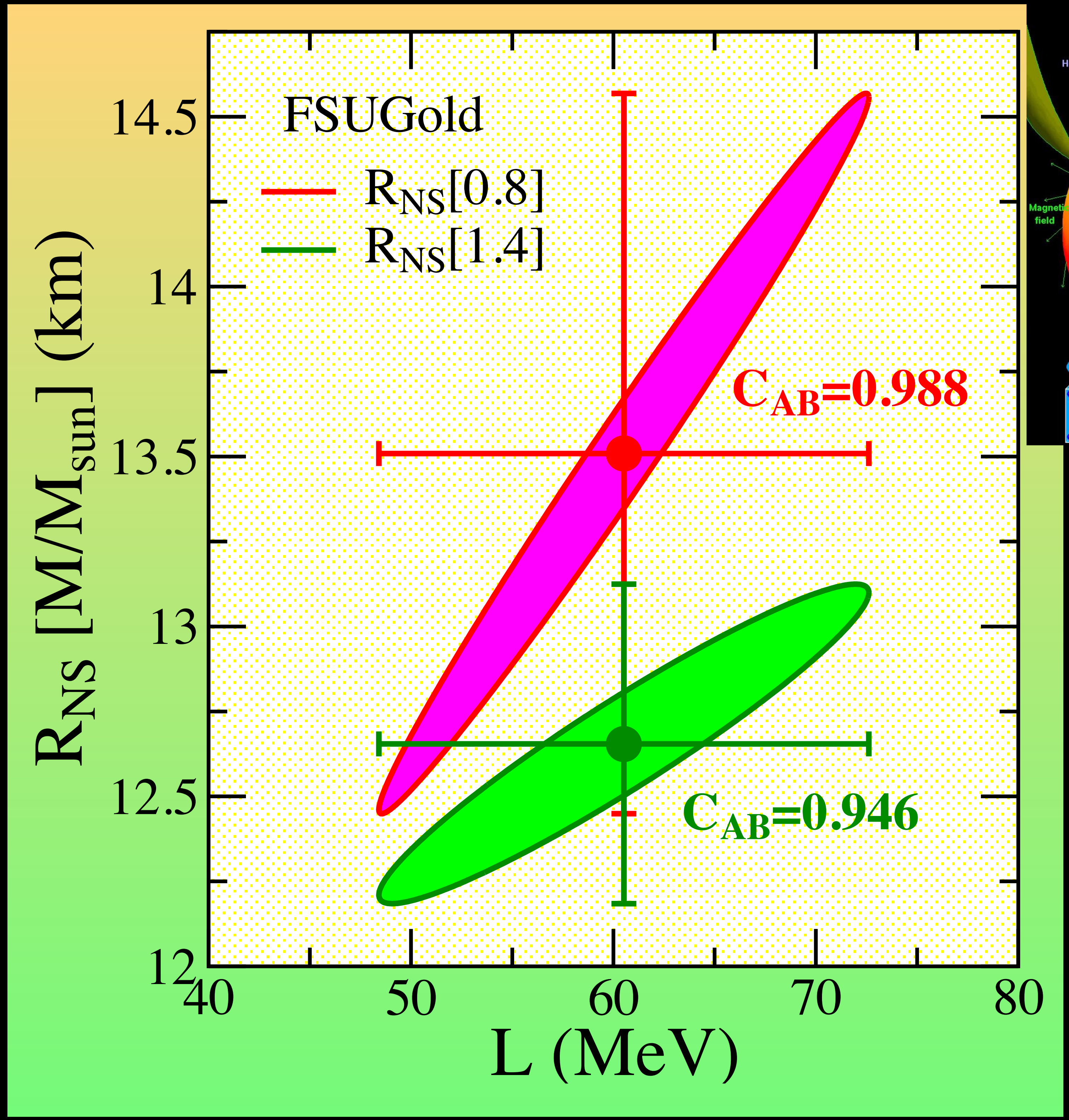
Laboratory Constraints on the EOS

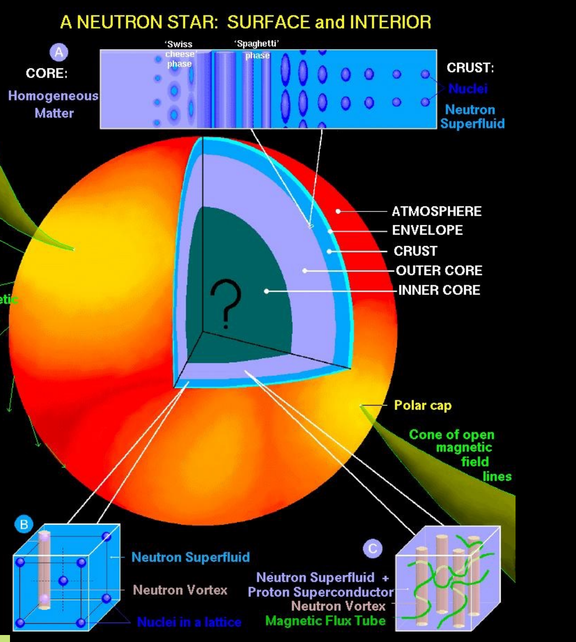




18 orders

magnitude





Nuclear interaction is responsible for describing finite nuclei and neutron stars!

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!

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

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

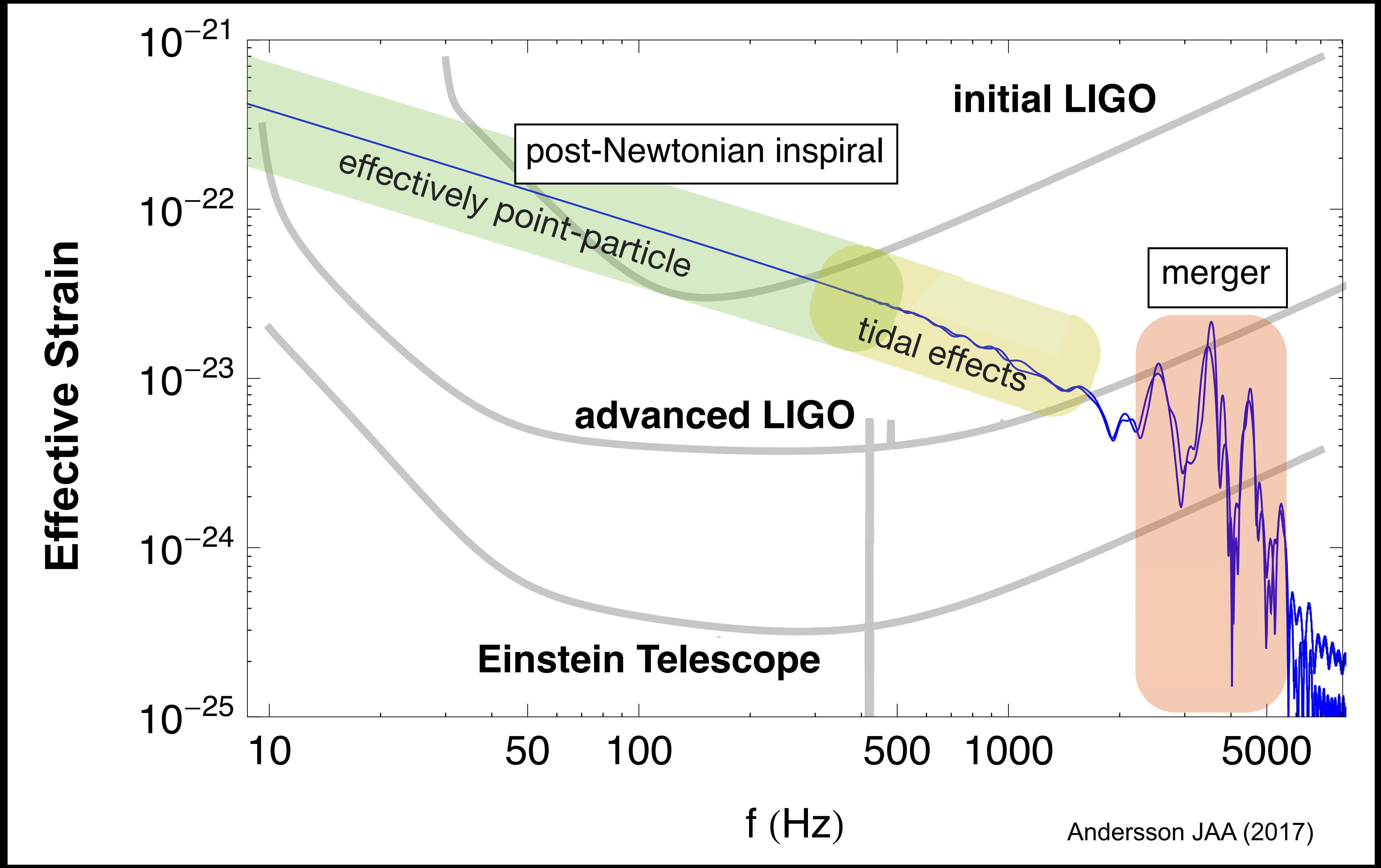
    Orbital separation:1000 km (20 minutes)

- 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

$$\text{If} \quad \ddot{I}(t) \to Ma^2\omega^2$$

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

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

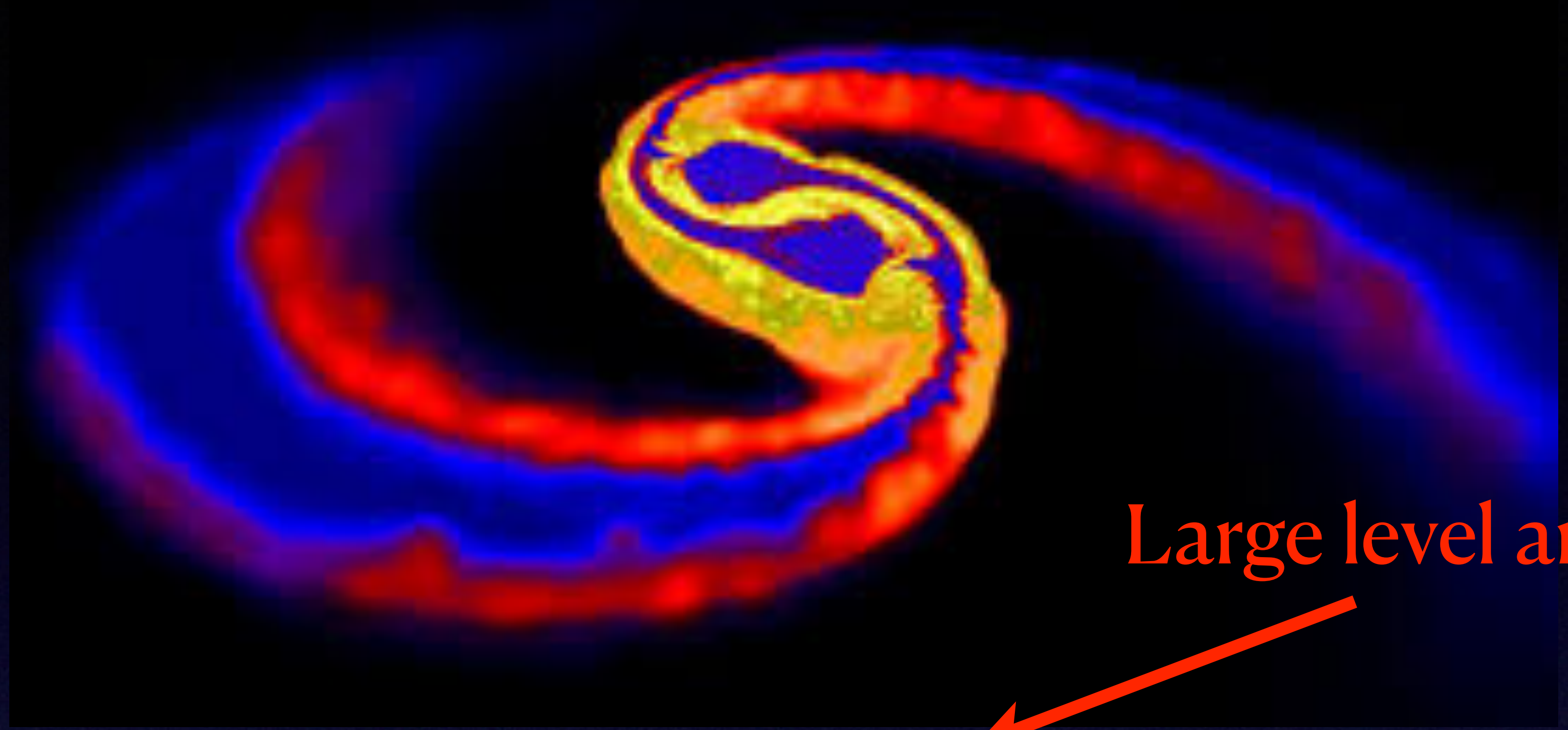
At $h=10^{-21}$ and with an arm length of 4km displacement is 1000 times smaller than proton!

GW170817: Tidal Polarizability (2017)

Electric Polarizability: $P_i = \chi E_i$

Tidal Polarizability(Deformability):

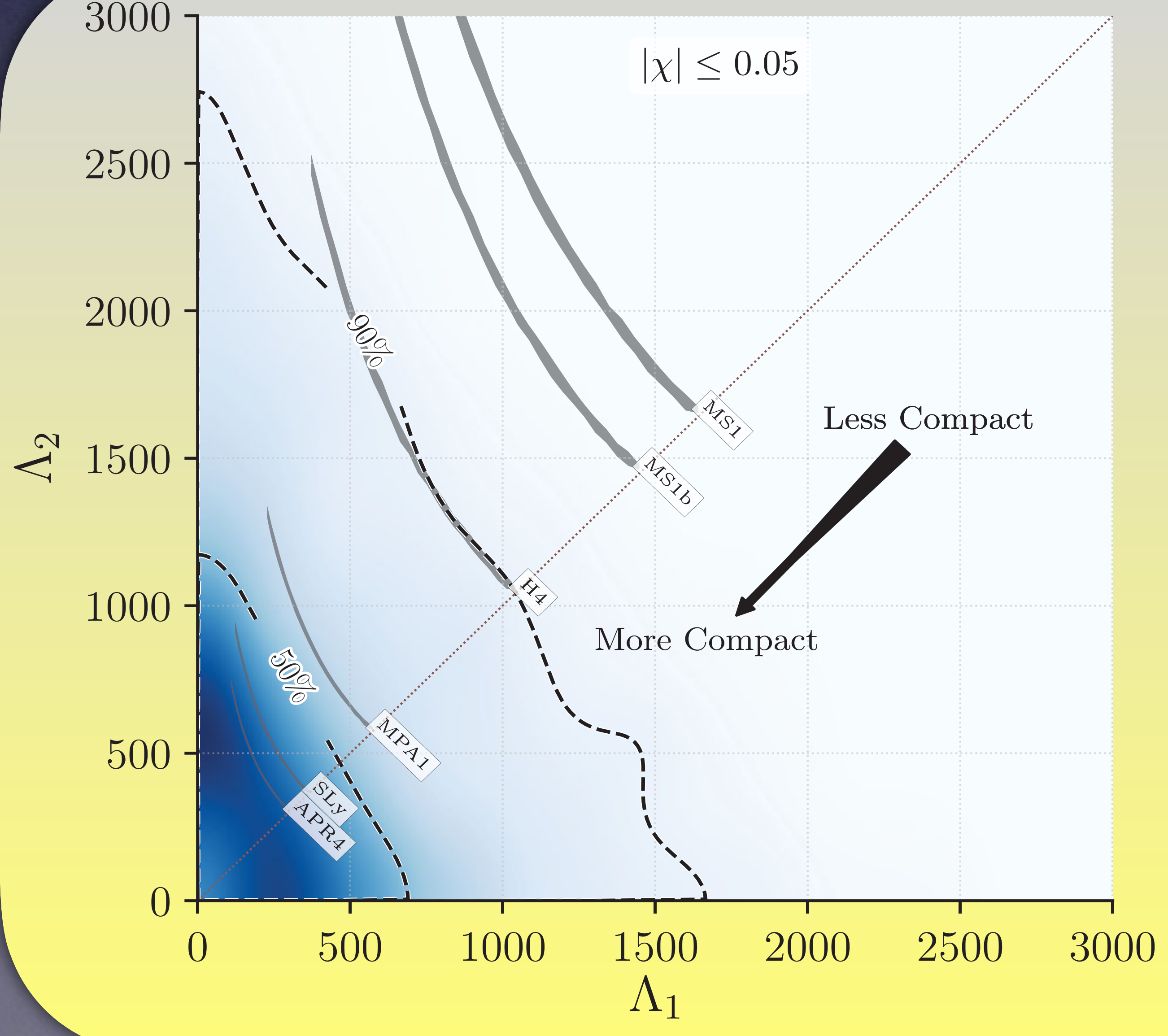
- Tidal field induces a mass polarization
- A time dependent mass quadrupole emits gravitational waves



Large level arm!

Micro-Macro

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



GW170817 rules out very large neutron star radii!

Neutron Sta
must be compa

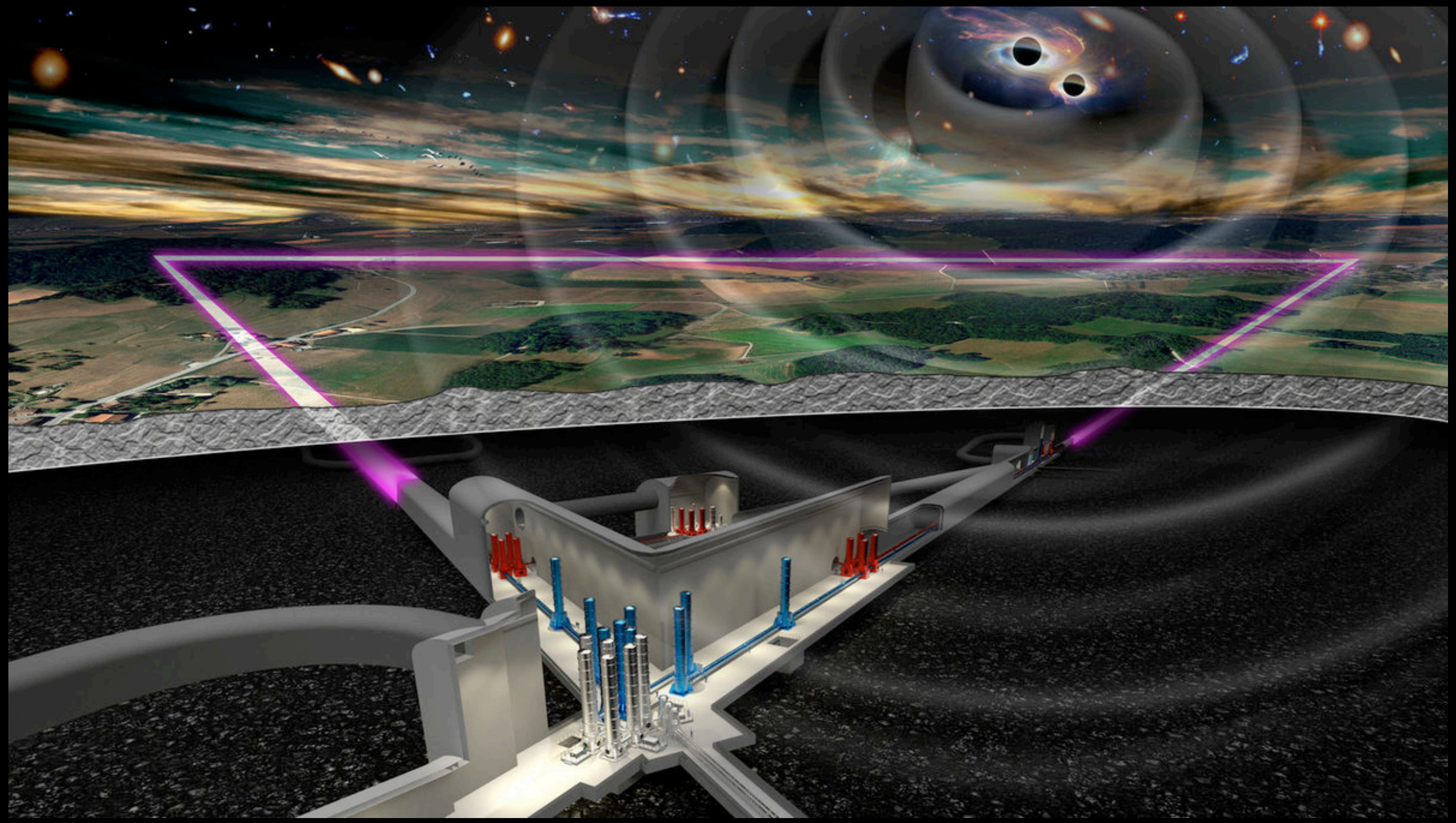
Soft EOS!
Small L!

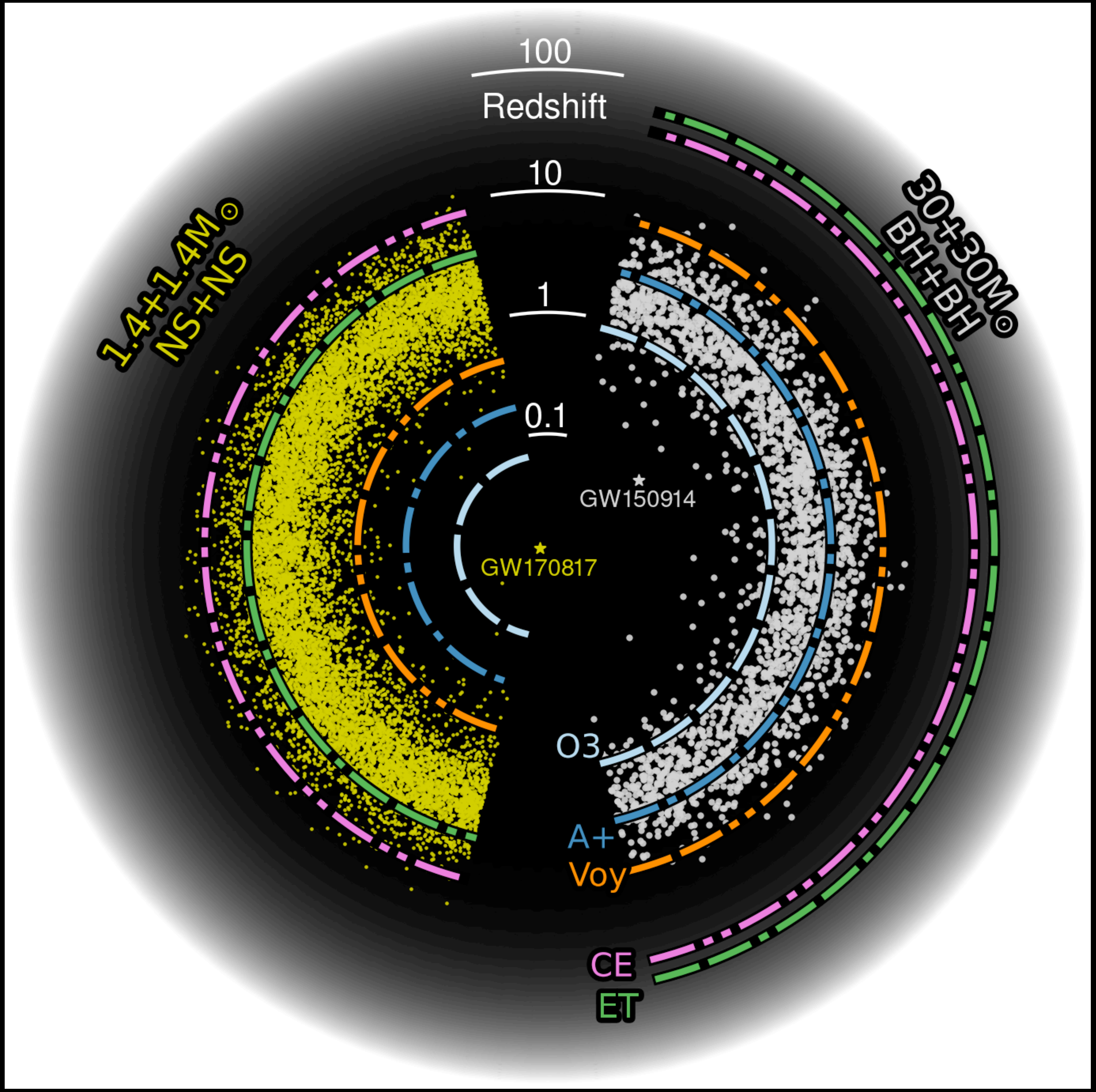
$$\Lambda_{1.4} = 390^{+190}_{-120} \ (90\%)$$

(Latest LIGO/Virgo analysis)

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

Gravitational Waves: Past, Present and Future

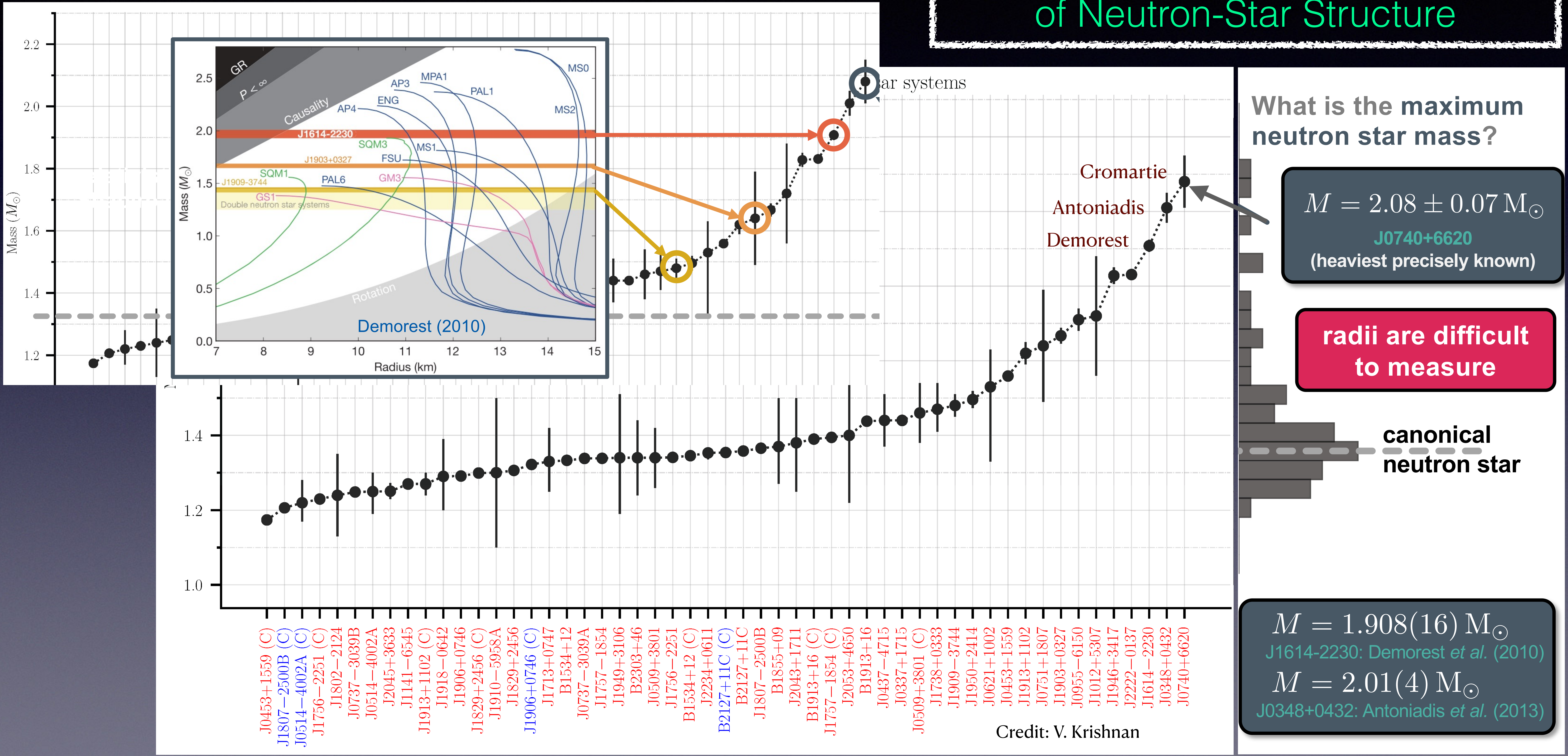




Thursday Afternoon Session: Anna Puecher

Progress in the determination of massive neutron stars — constraining the EOS at the highest densities

Mass-vs-Radius profile
is the Holy Grail
of Neutron-Star Structure



Credit: V. Krishnan

What is the maximum neutron star mass?

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

J0740+6620

(heaviest precisely known)

radii are difficult to measure

canonical neutron star

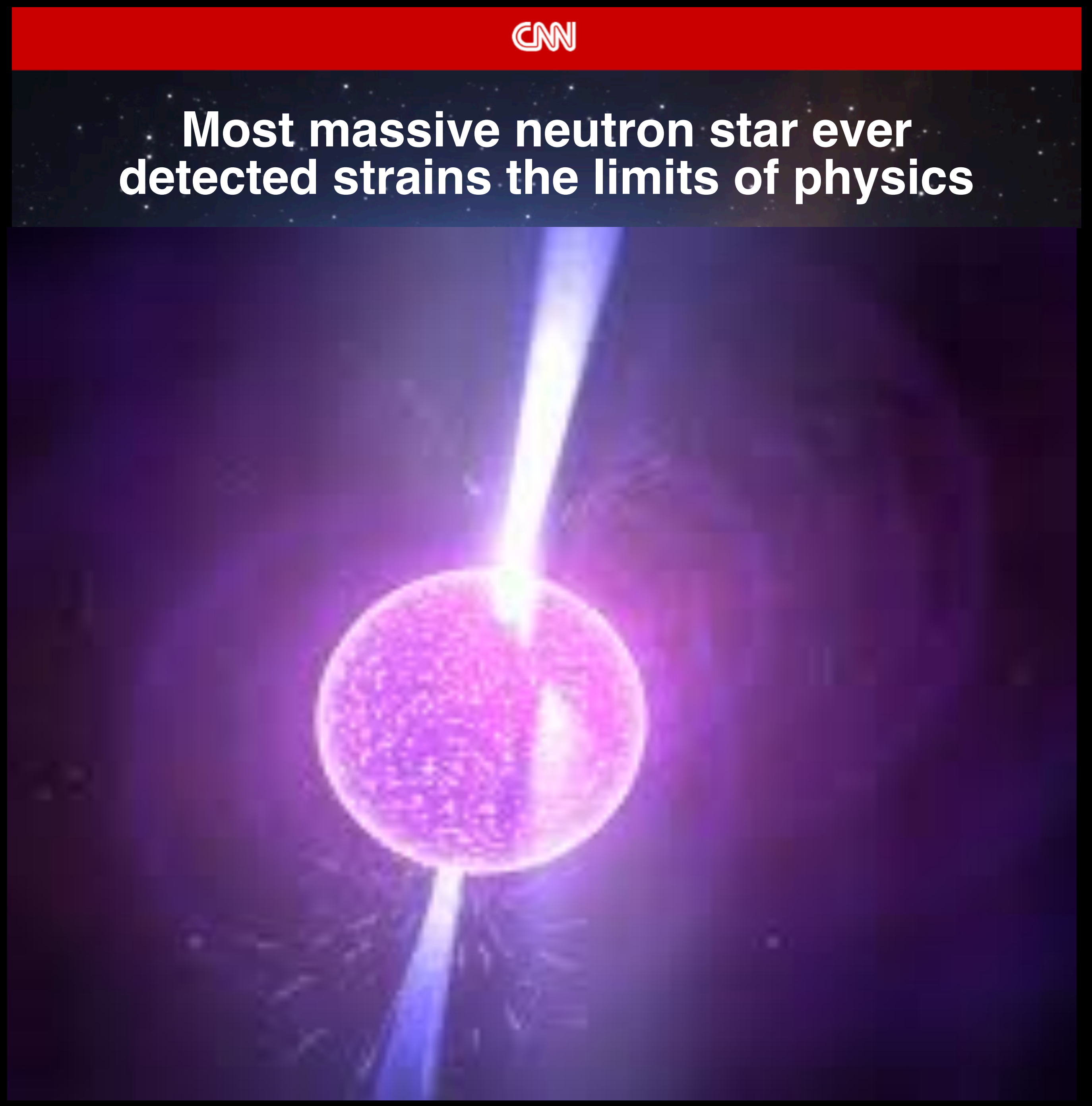
$M = 1.908(16)\,\mathrm{M}_\odot$

J1614-2230: Demorest *et al.* (2010)

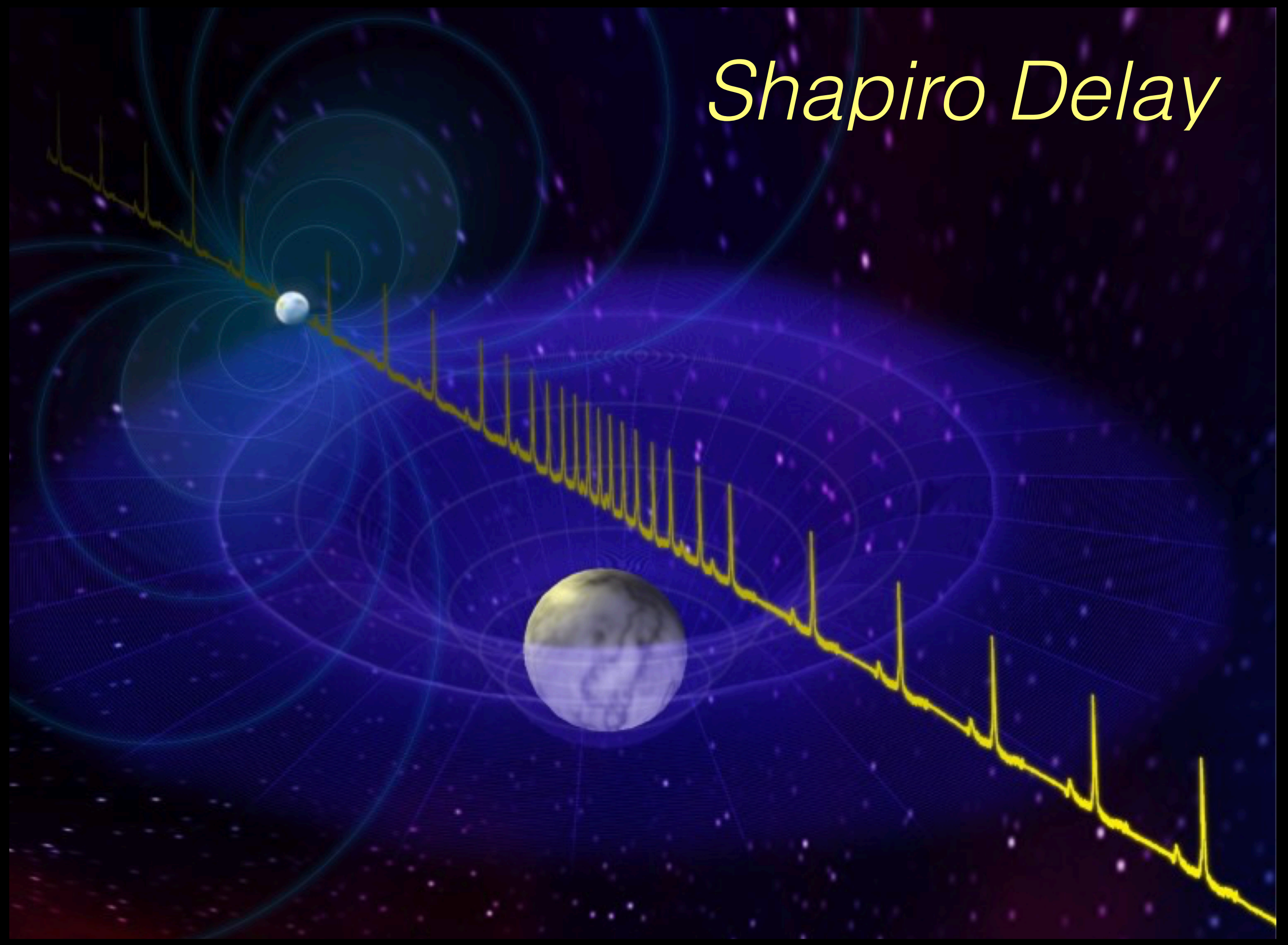
$M = 2.01(4)\,\mathrm{M}_\odot$

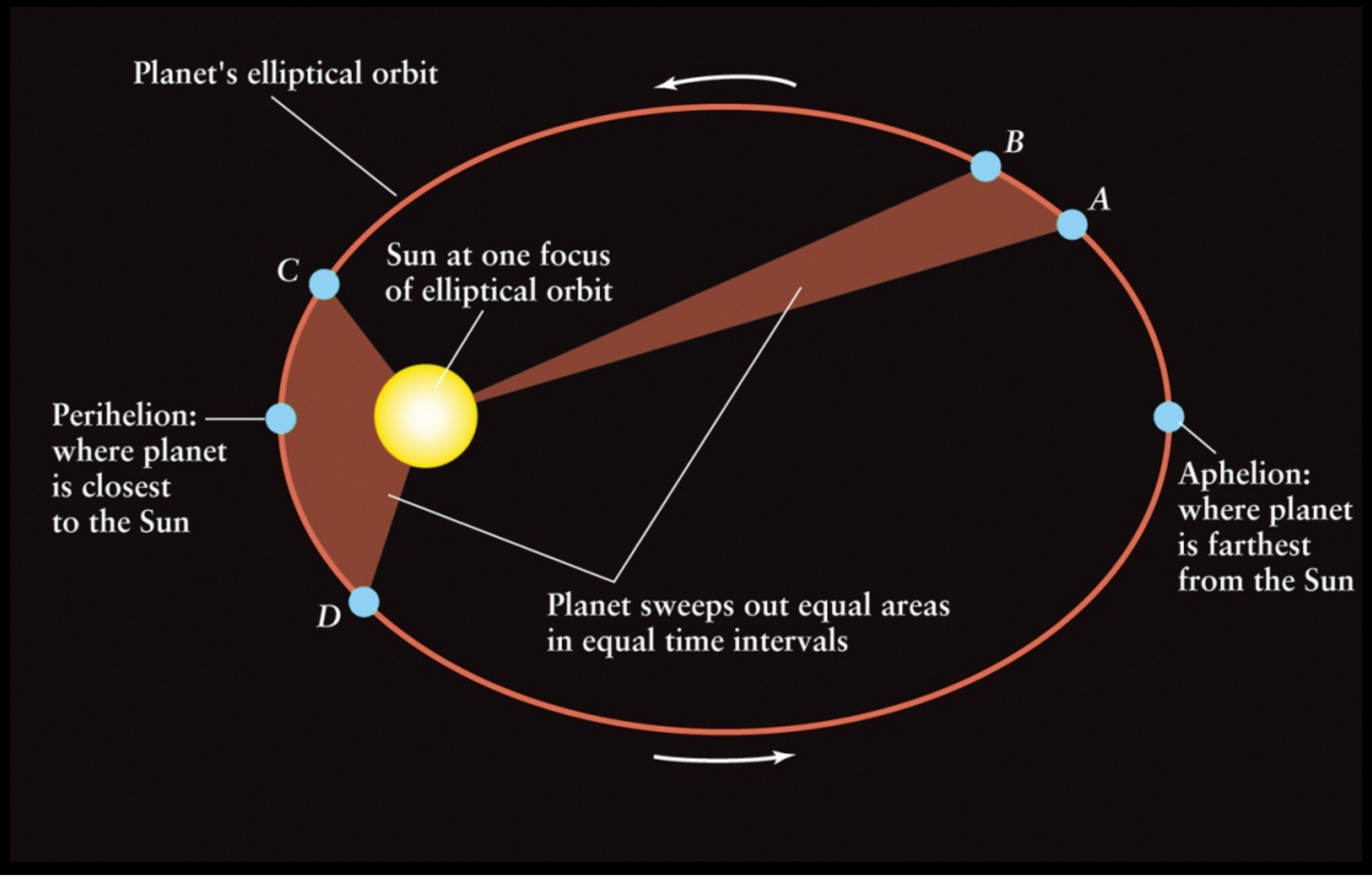
J0348+0432: Antoniadis *et al.* (2013)

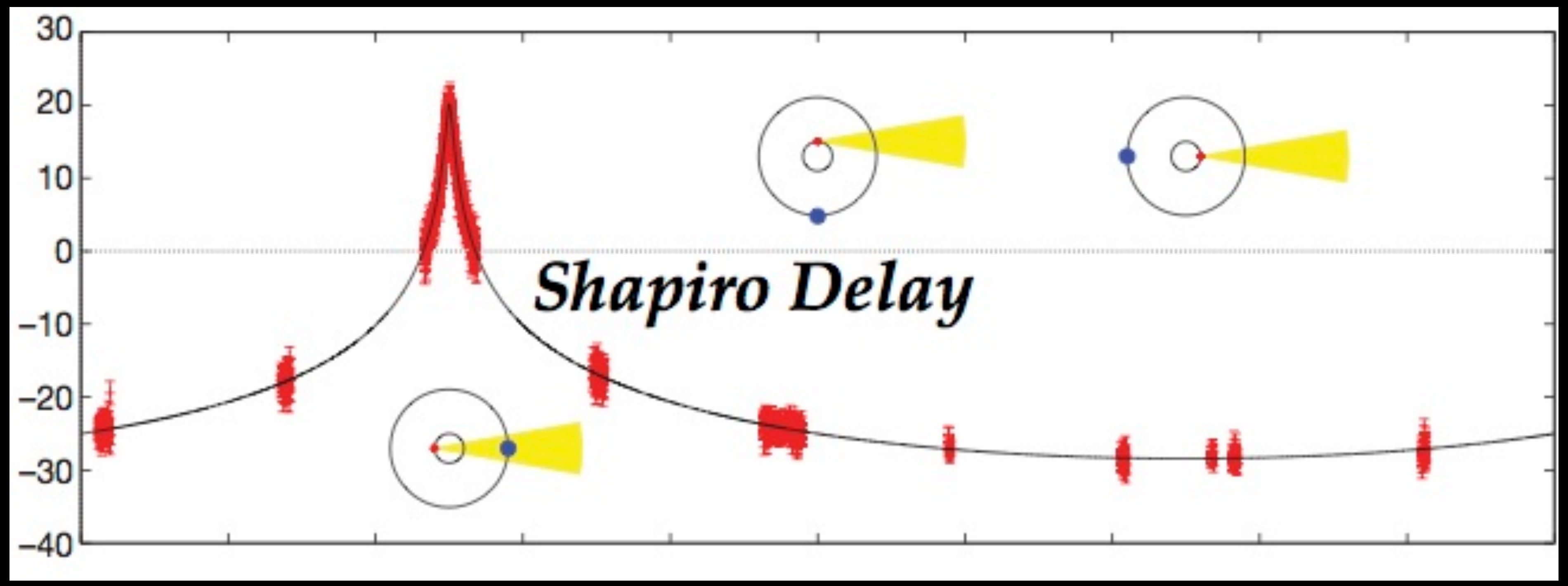
Measuring Heavy Neutron Stars (2019)
Shapiro Delay: General Relativity to the Rescue


CNN

Most massive neutron star ever detected strains the limits of physics







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

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

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

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

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

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

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

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

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

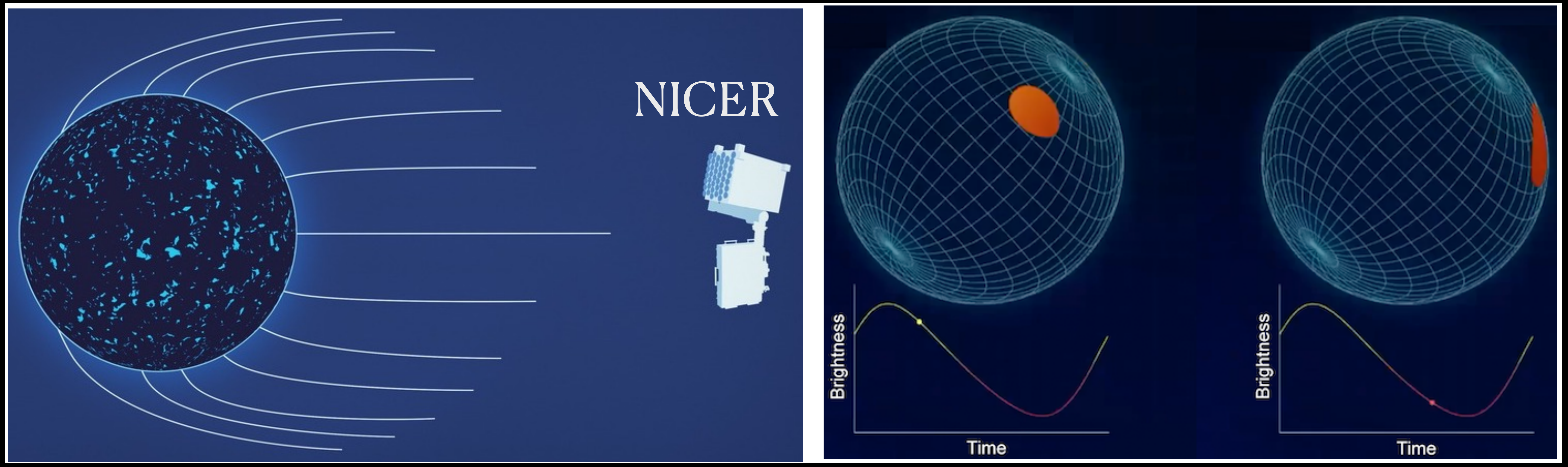
Riley *et al.* (2021)

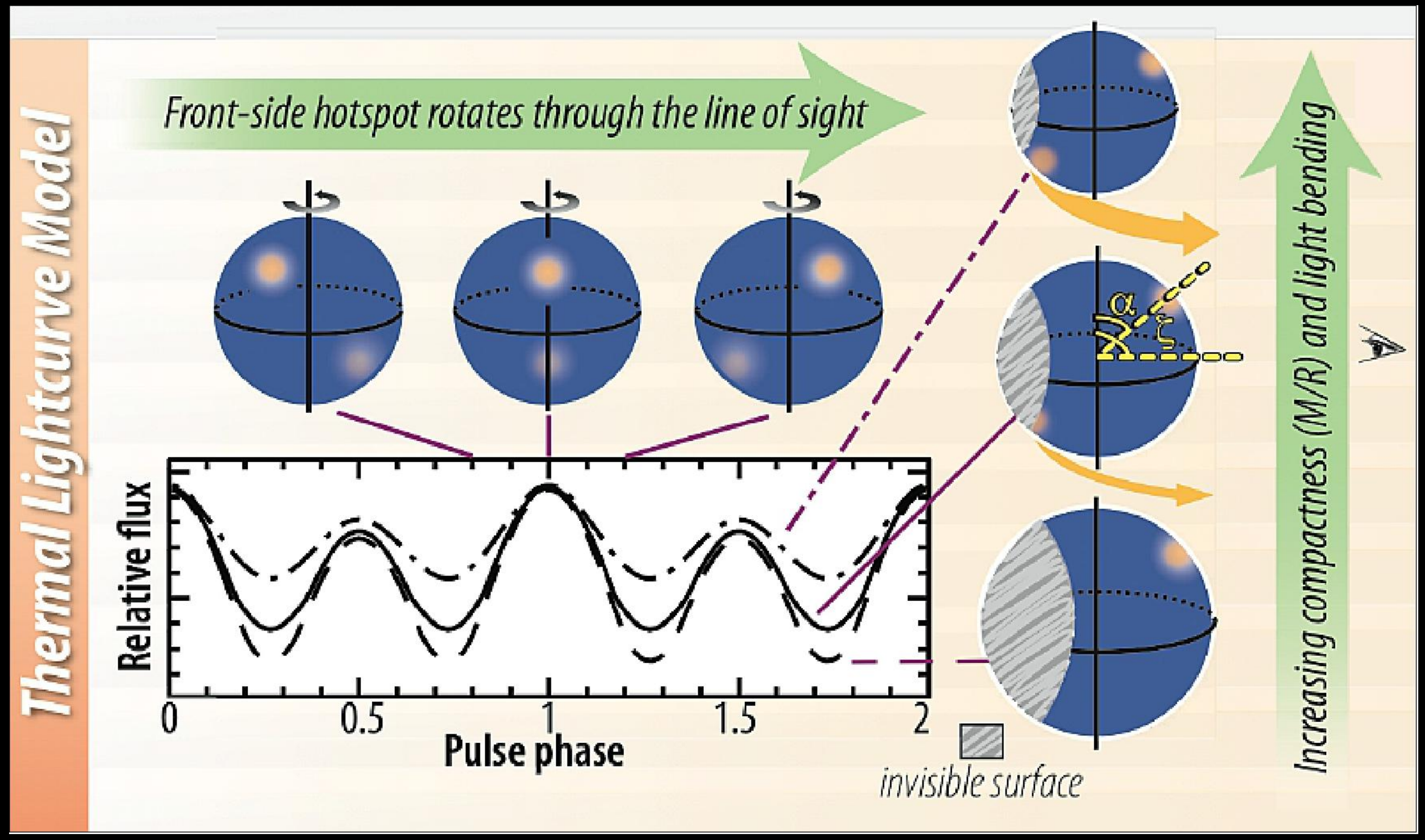
$$R_{2.0} = 13.7^{+2.6}_{-1.5}\,\mathrm{km}$$

Miller *et al.* (2021)

Micro-Macro

Stiff EOS! Large L!





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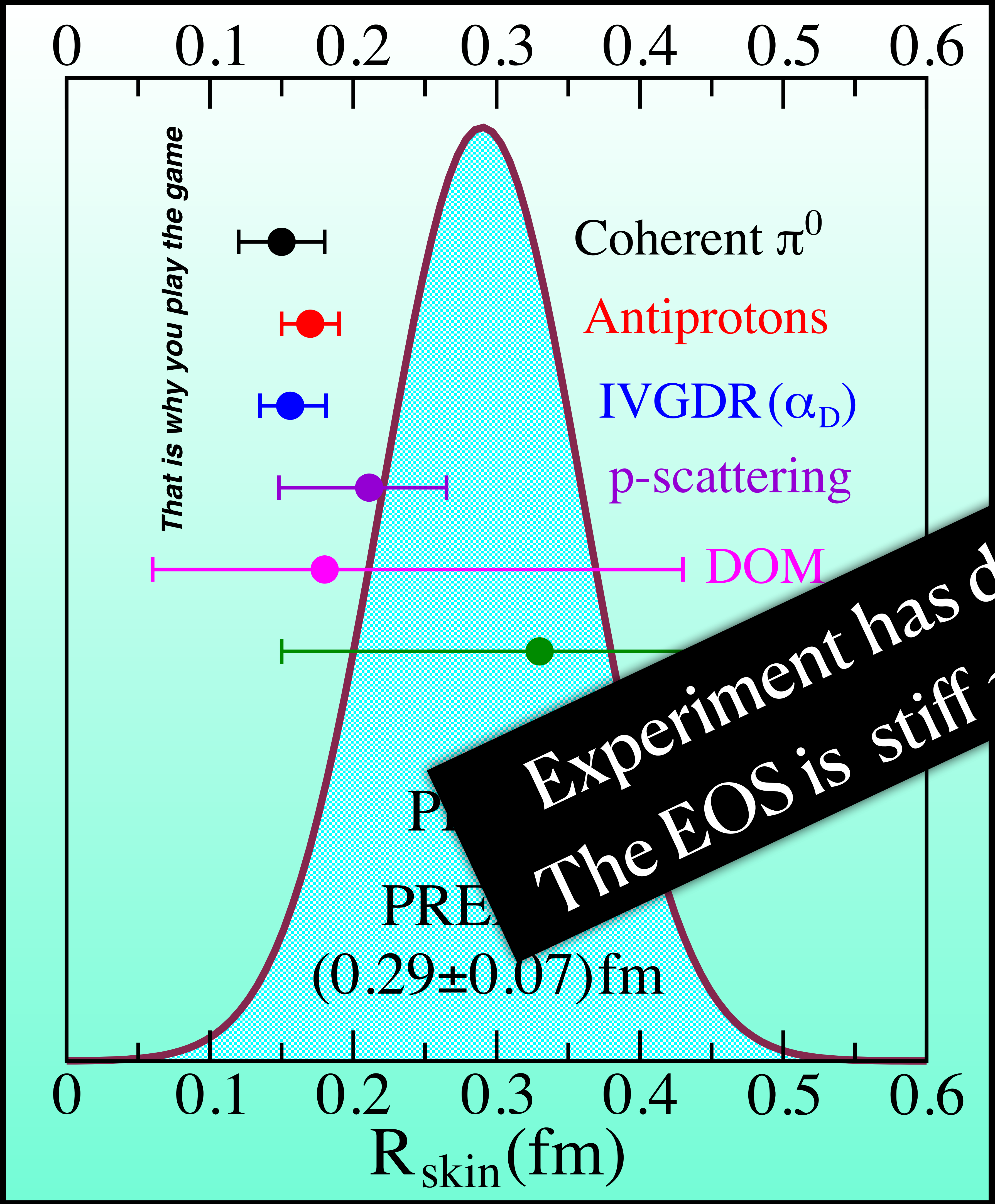
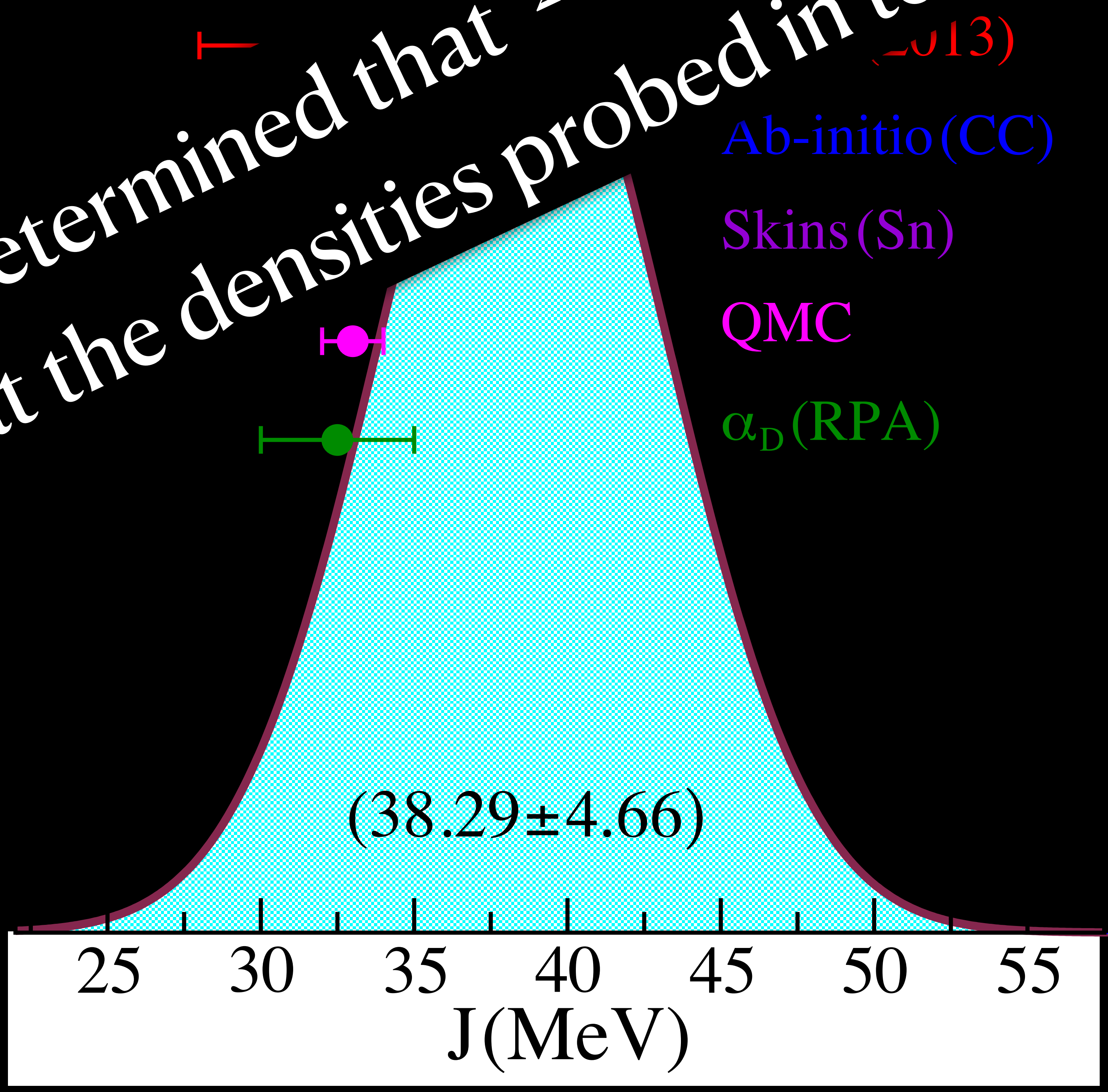
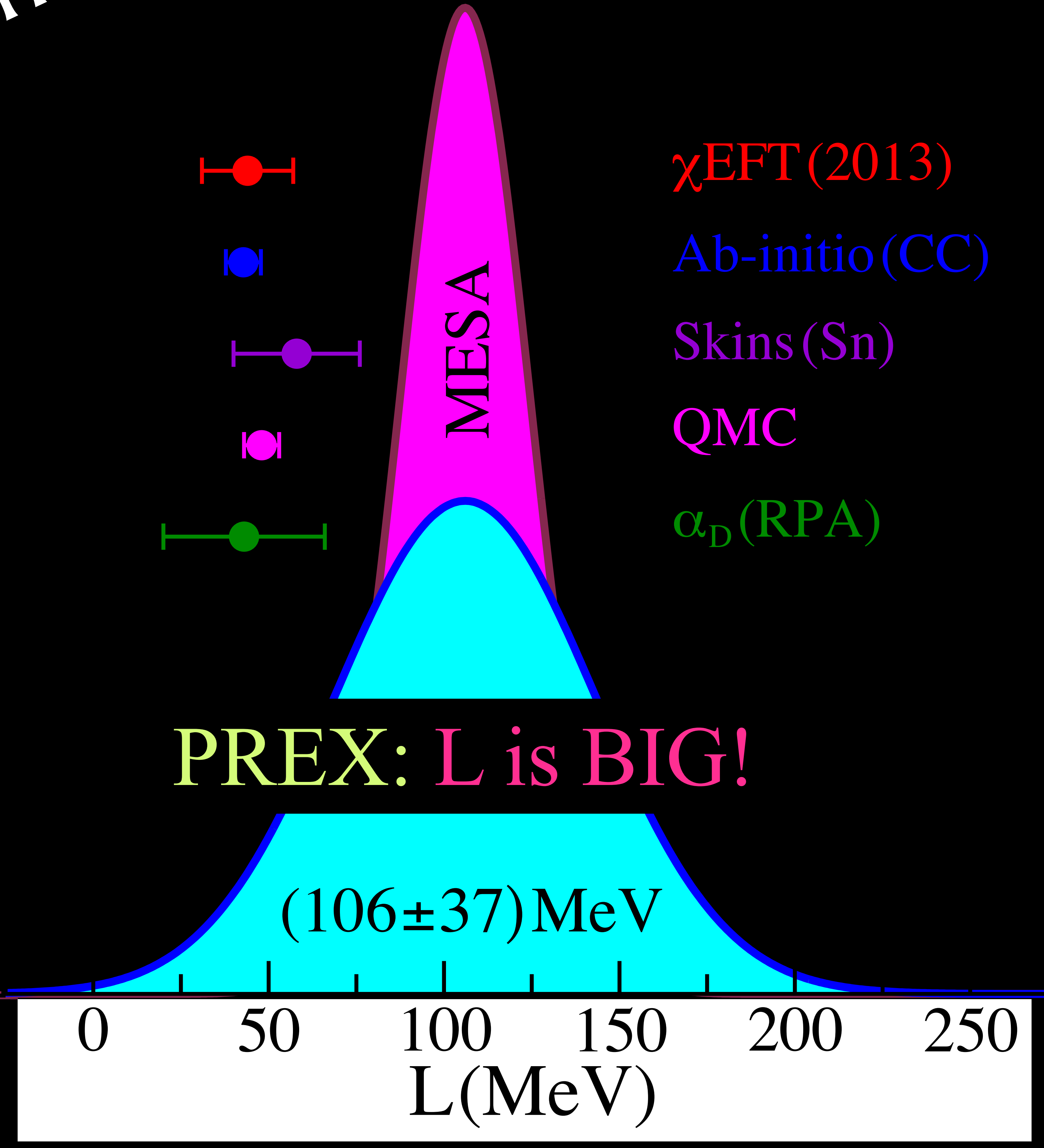


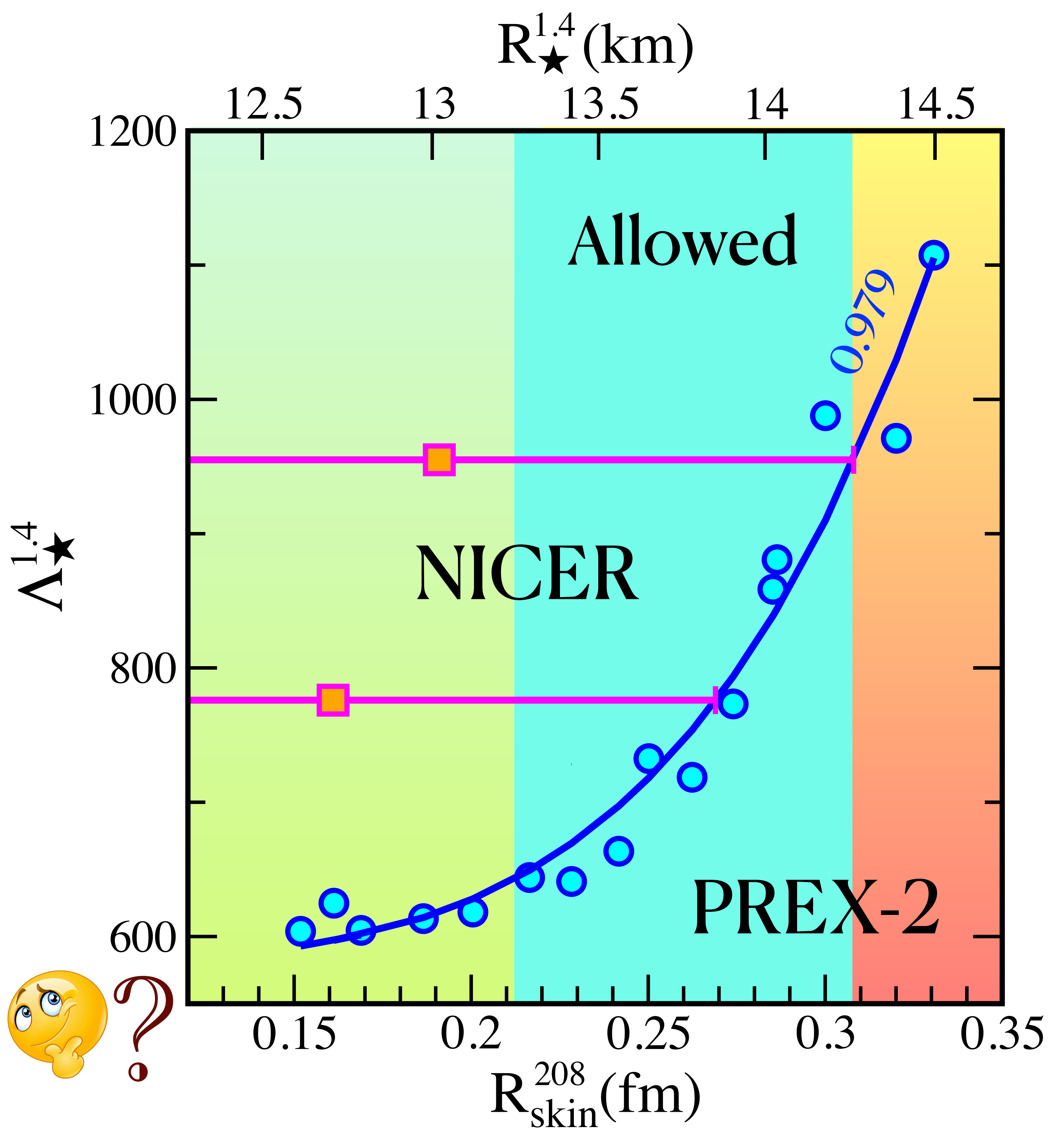


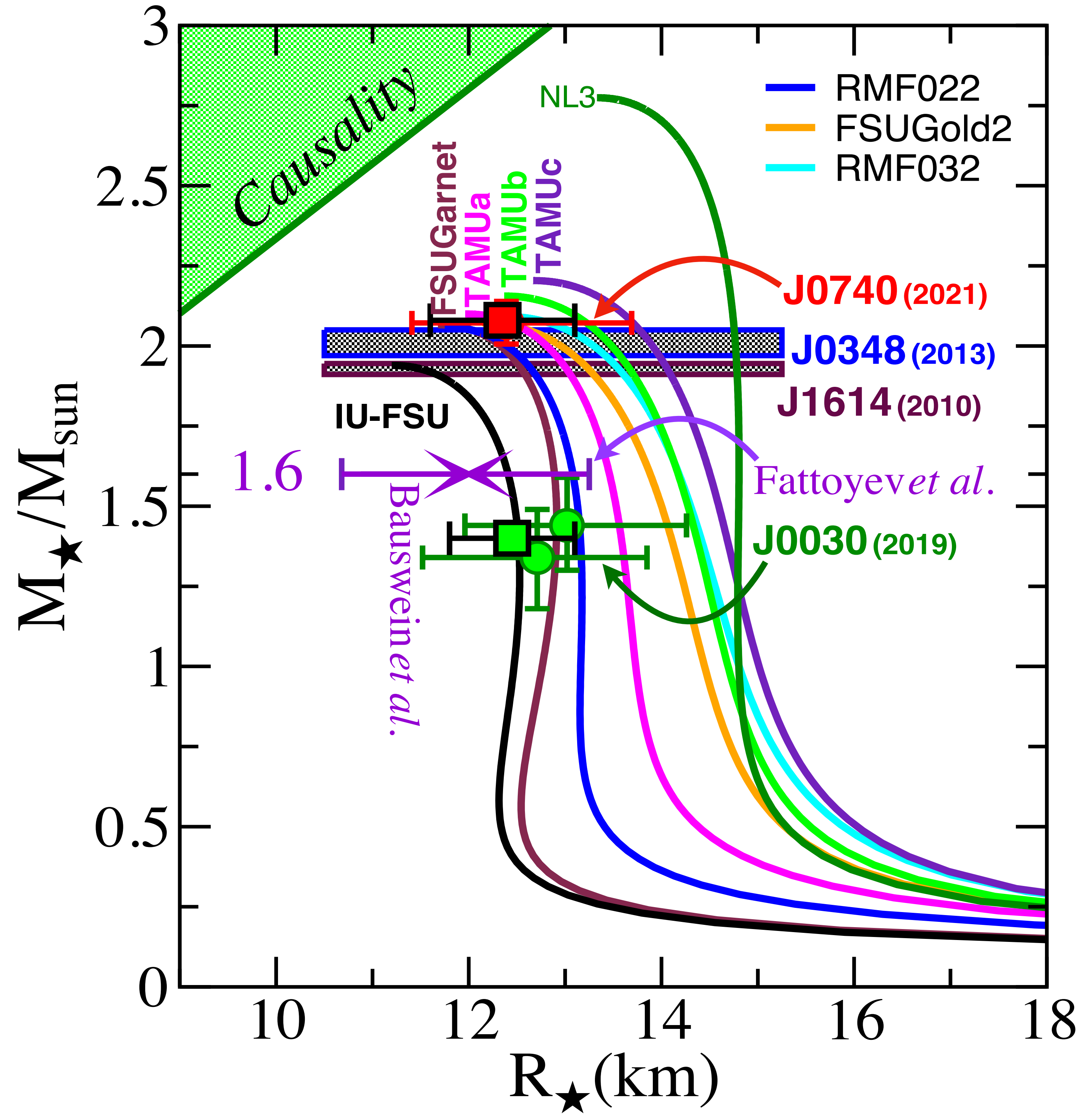


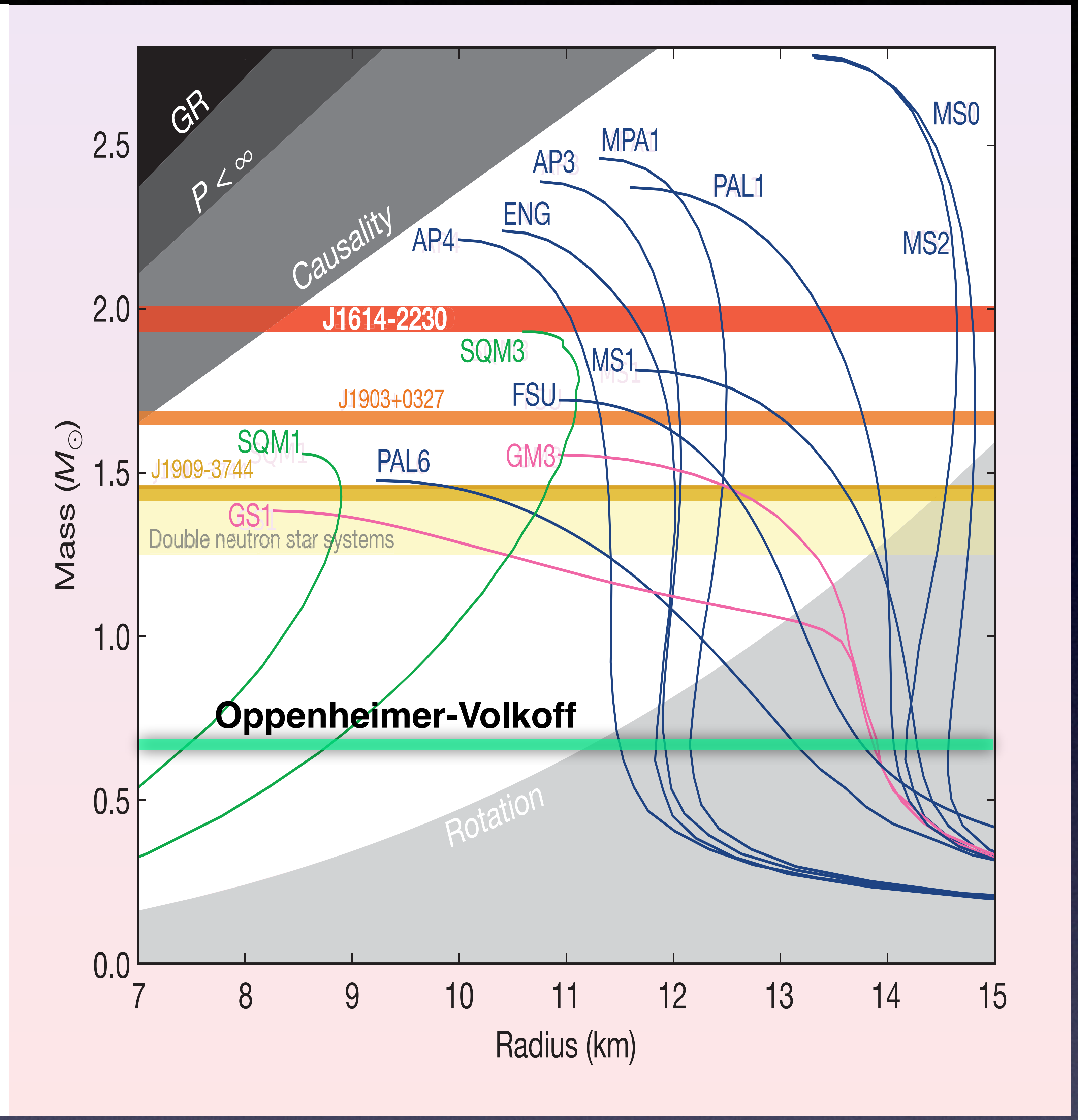
PREX: L is BIG!

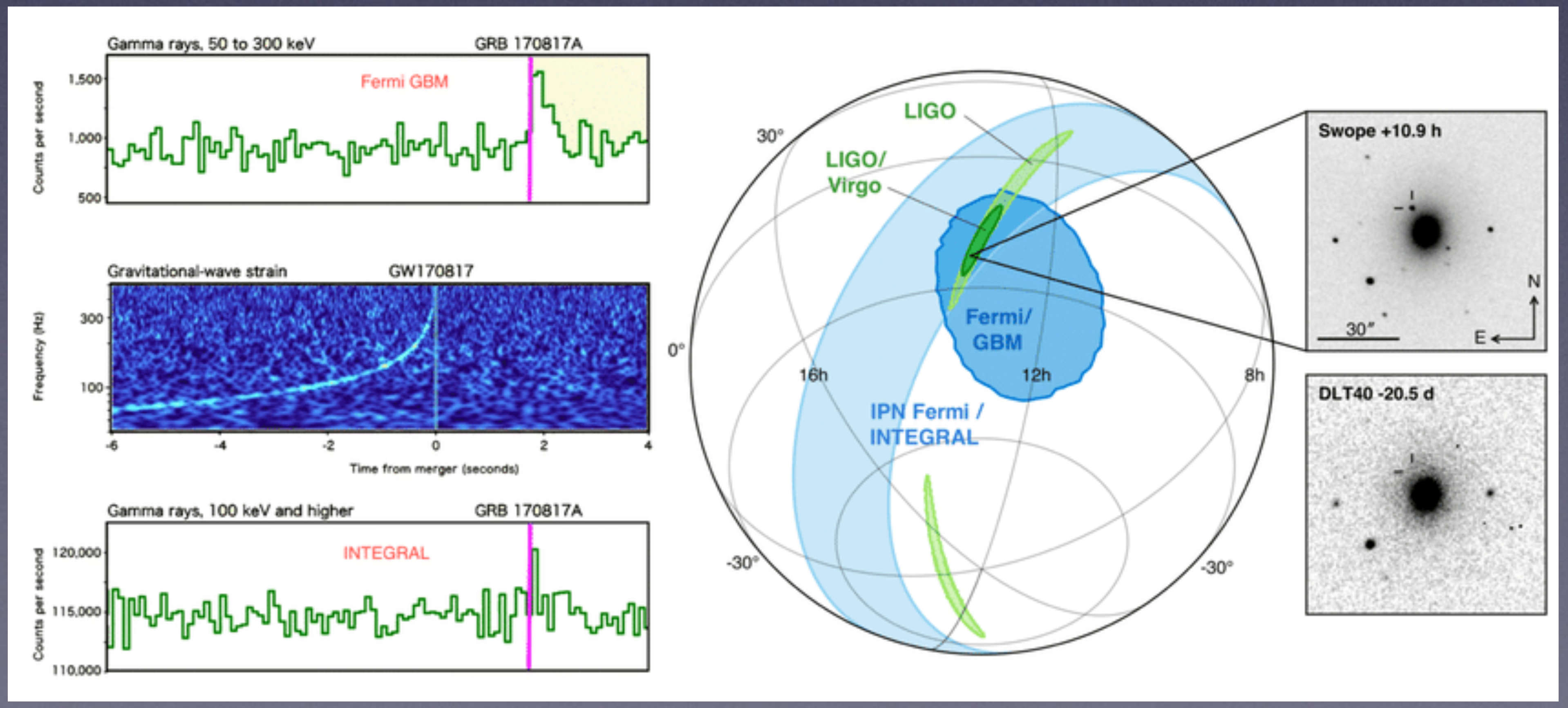
Lectures will attempt to provide an overall (personal) picture of the field

The Dawn of a Golden Era in Neutron-Star Physics





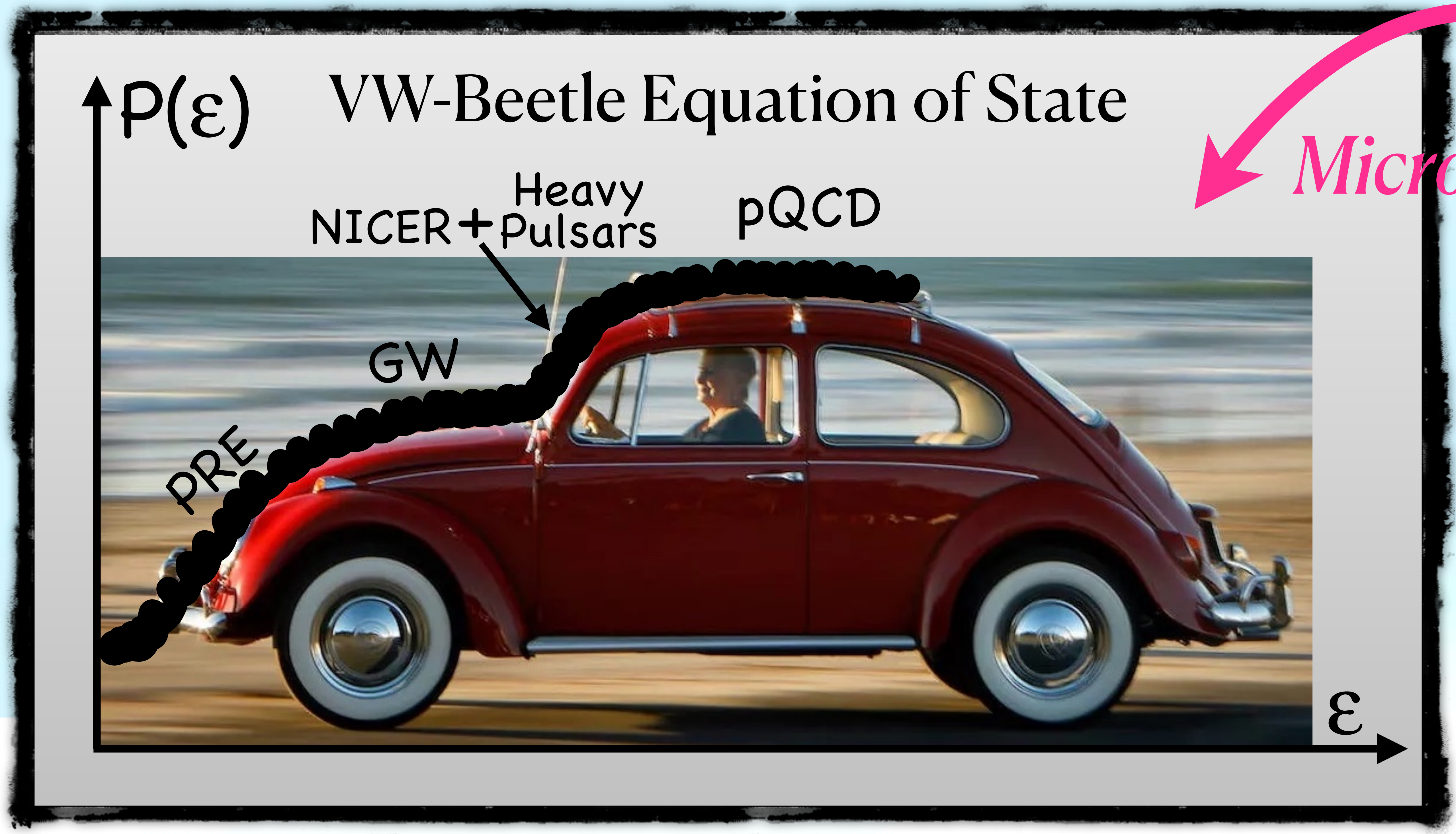




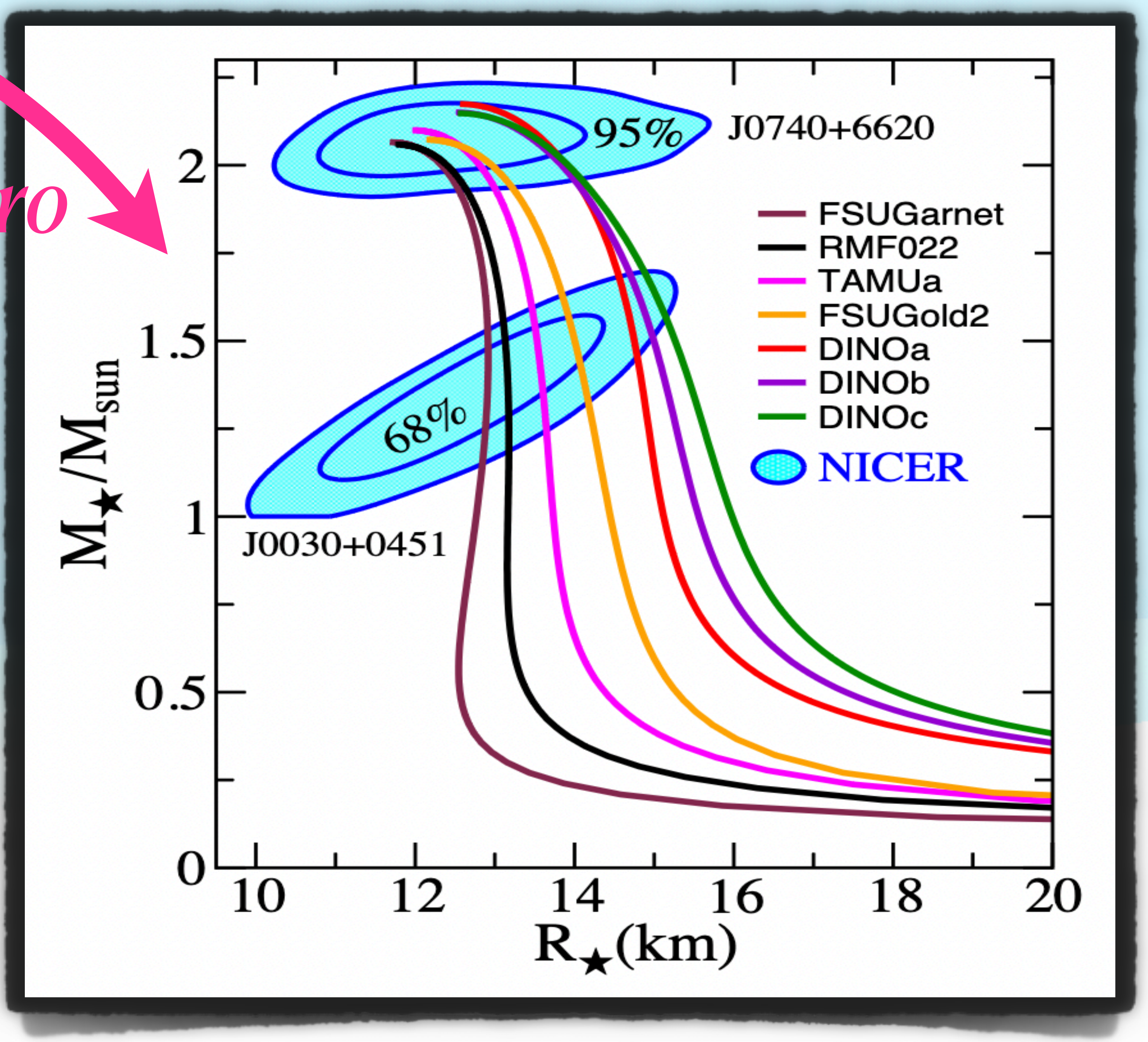
What have we learned since GW170817

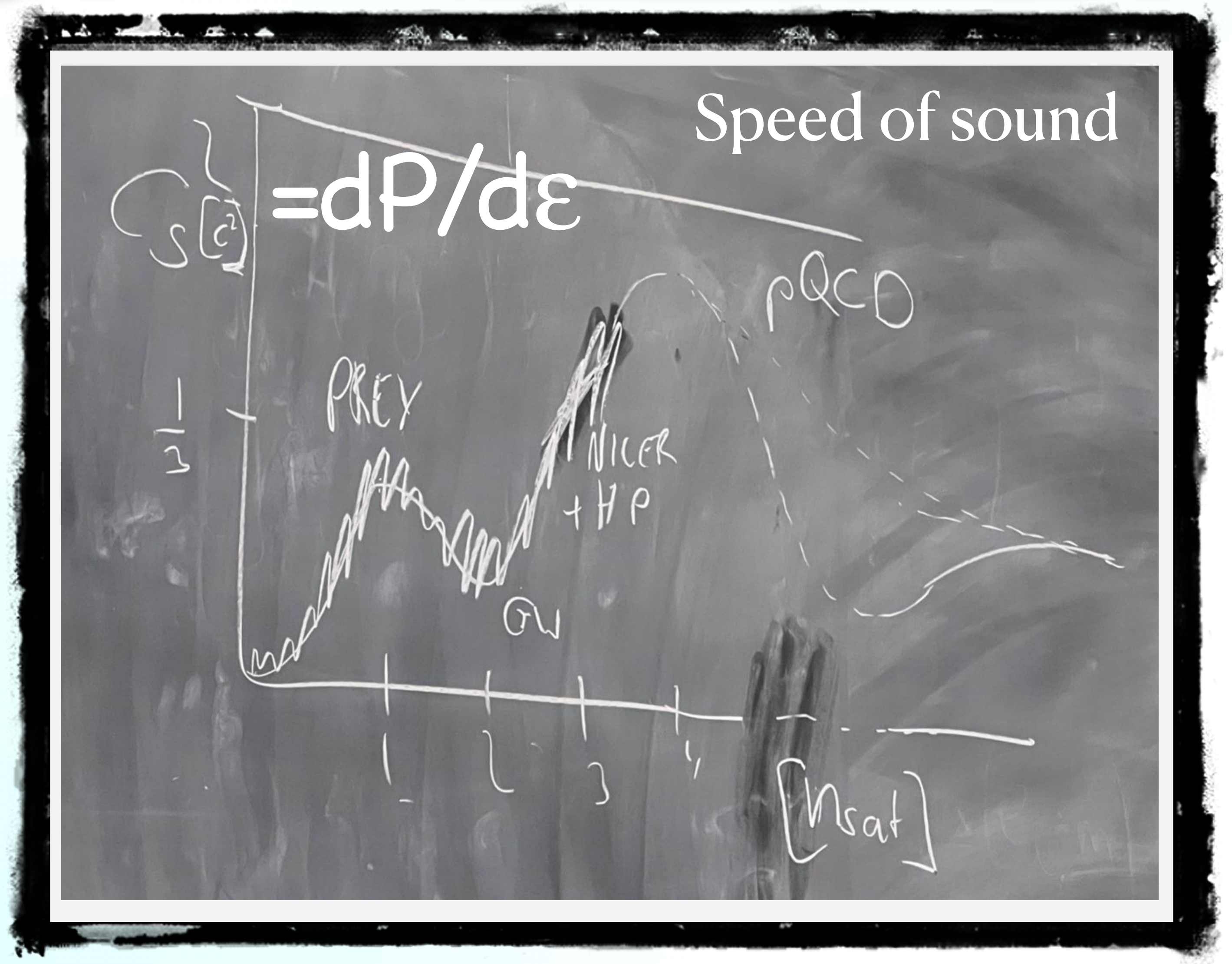
- PREX suggest a **stiff** EOS around saturation density although CREX has muddled the waters!
- LIGO-Virgo favor a **soft** EOS at around $2n_0$ although see Gamba et al., PRD 103, 124015 (2021)
- NICER/Pulsar Timing suggest a **stiff** EOS at $\sim 4n_0$

The Dawn of a Golden Era in Neutron-Star Physics



Micro-Macro





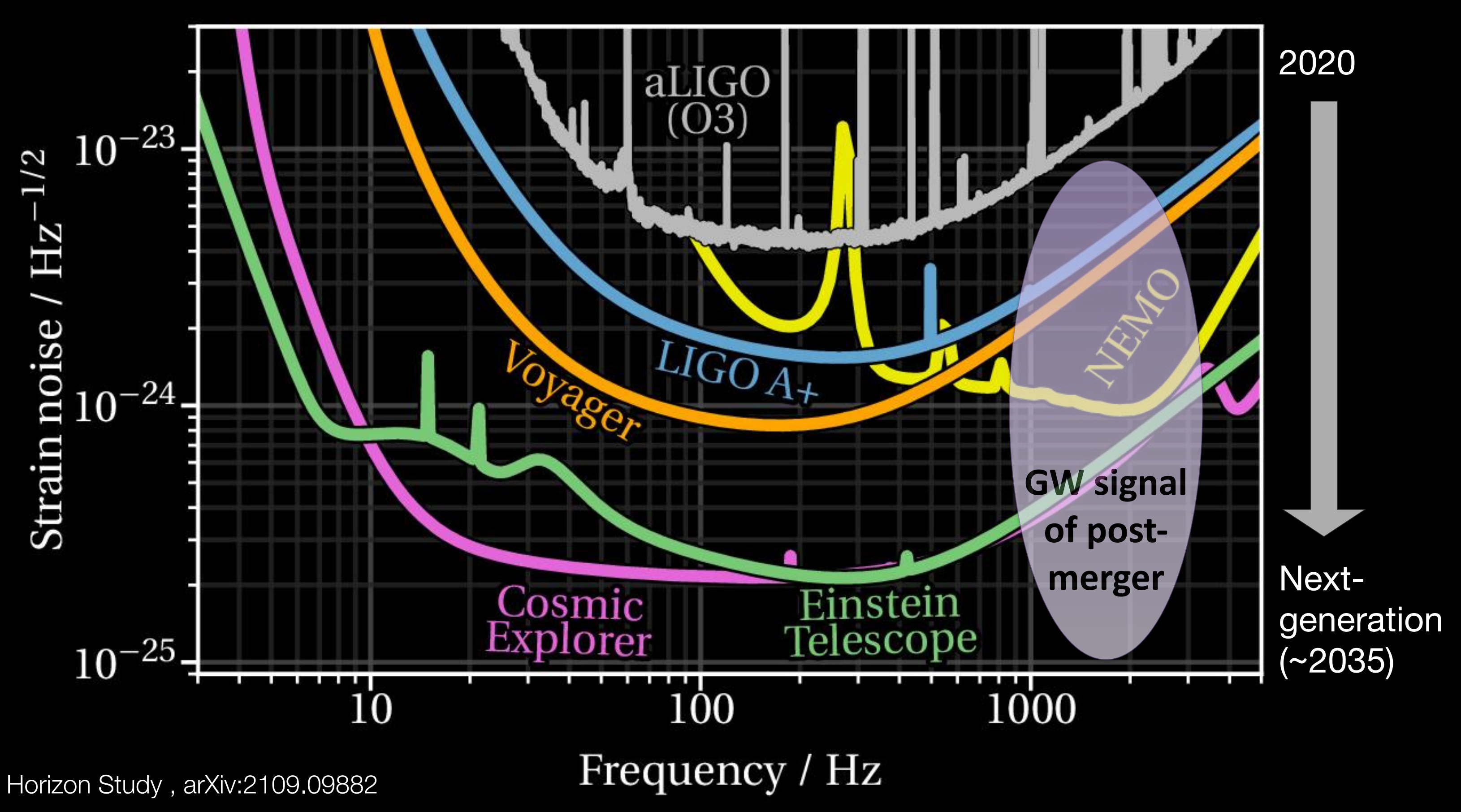
Tantalizing Possibility

- *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?)

Neutron-Rich Matter in Heaven

GW Landscape

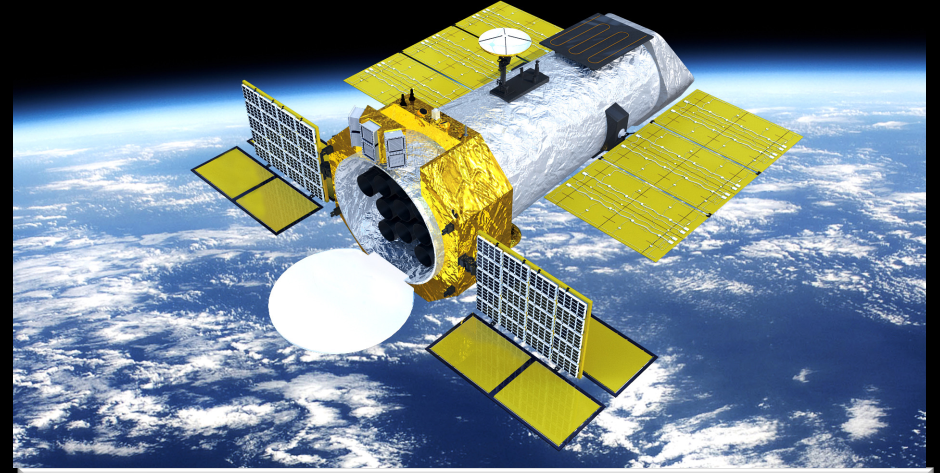


CE Horizon Study , arXiv:2109.09882

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

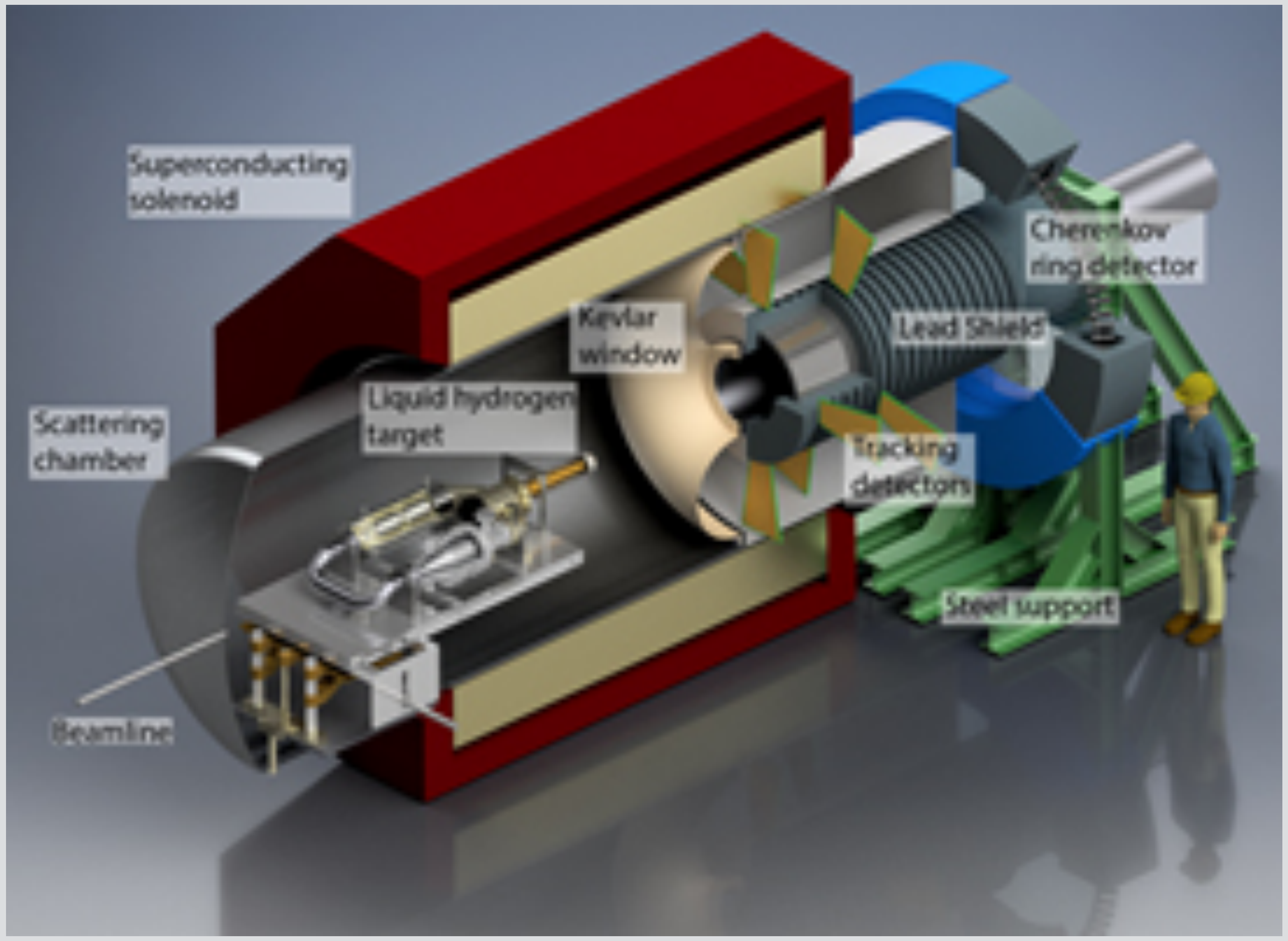
NASA probe-class proposal
Ray et al. 2019, @strobexastro

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

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

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-Rich Matter on Earth



Mainz Energy-recovery Superconducting Accelerator (MESA)

The MESA Facility
will provide the most precise
measurement of the neutron skin
thickness of 208Pb

The Facility for Rare Isotope Beams
will produce exotic nuclei at the
limits of stability that will inform
the EOS at the densities of relevance
to atomic nuclei