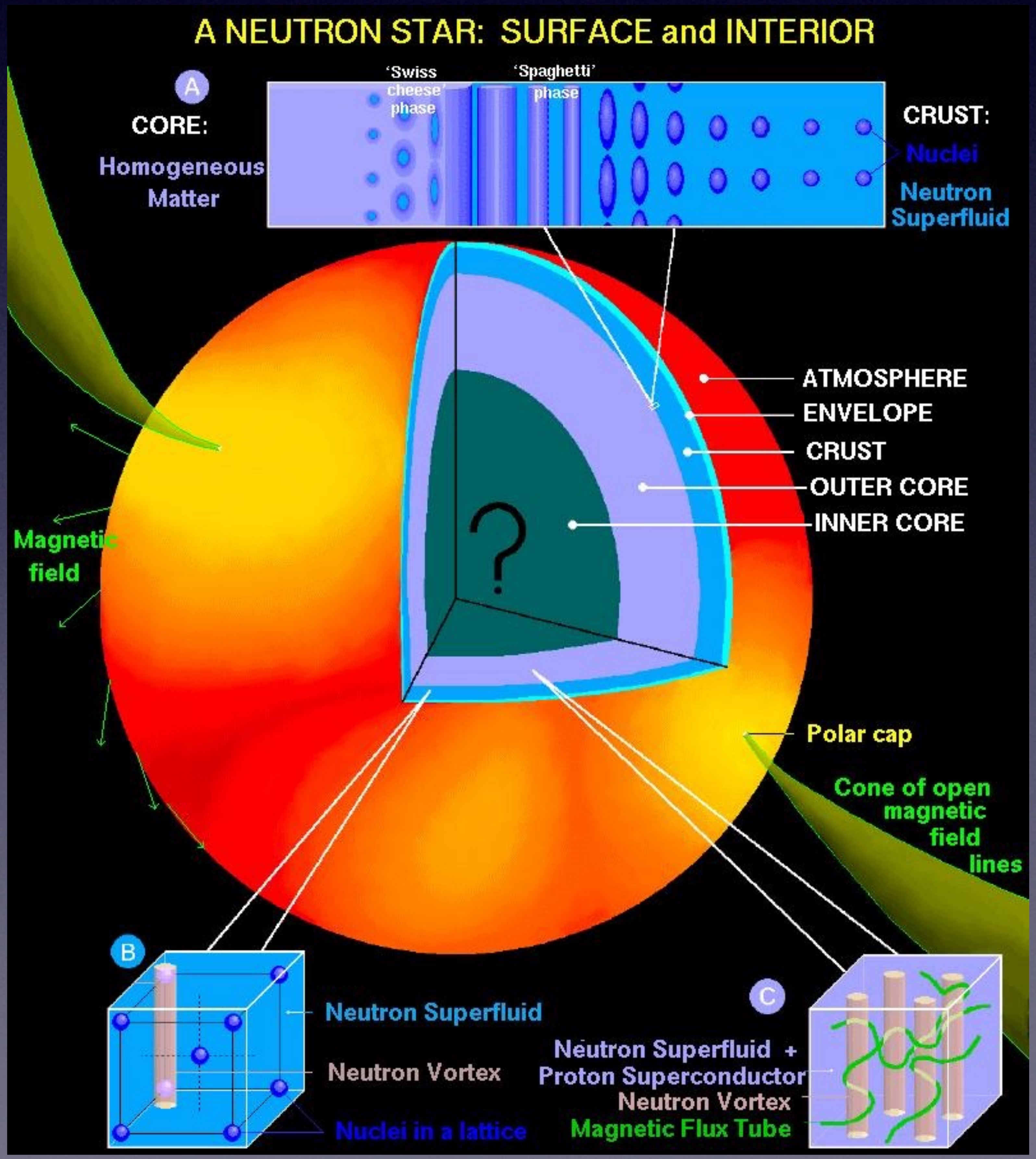
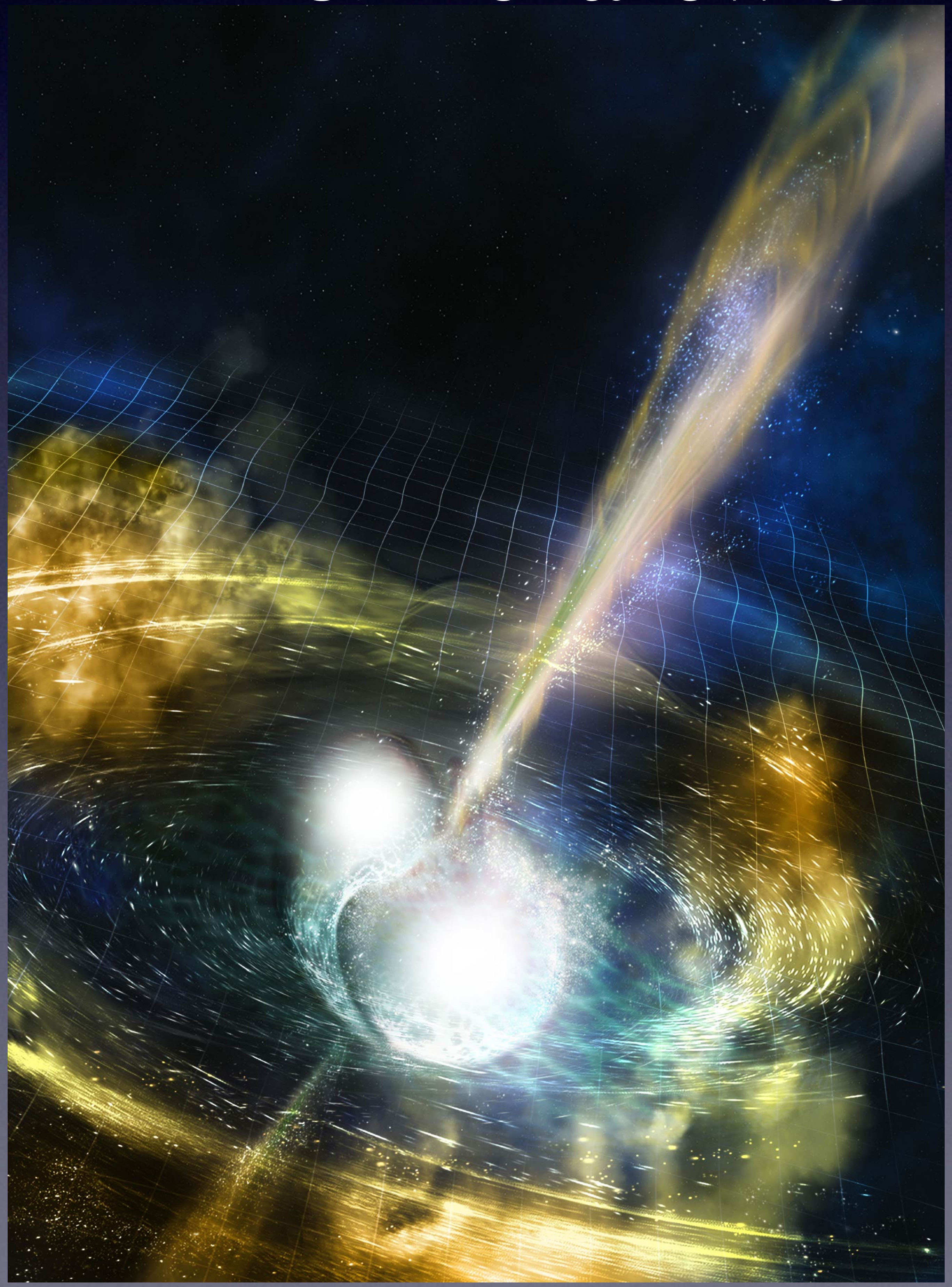
U.S. DEPARTMENT OF ENERGY | Office of Science

Heaven and Earth: Nuclear Astrophysics in the Multimessenger Era

UC RIVERSIDE | 2023 National Nuclear Physics Summer School

J. Piekarewicz



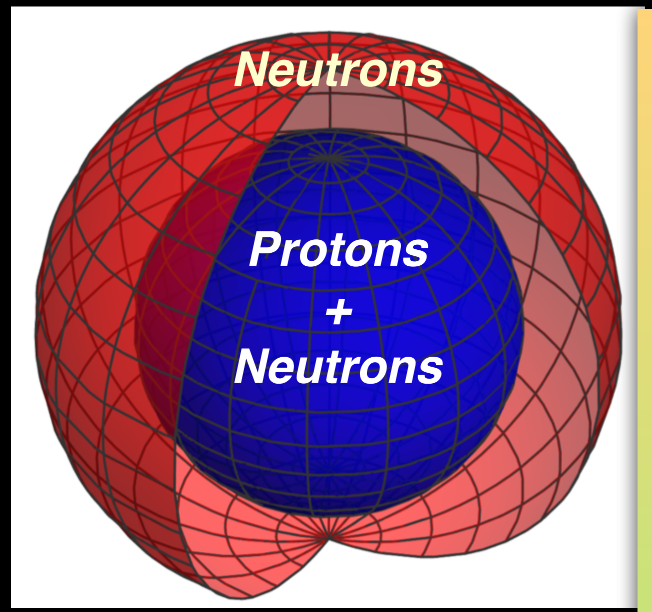


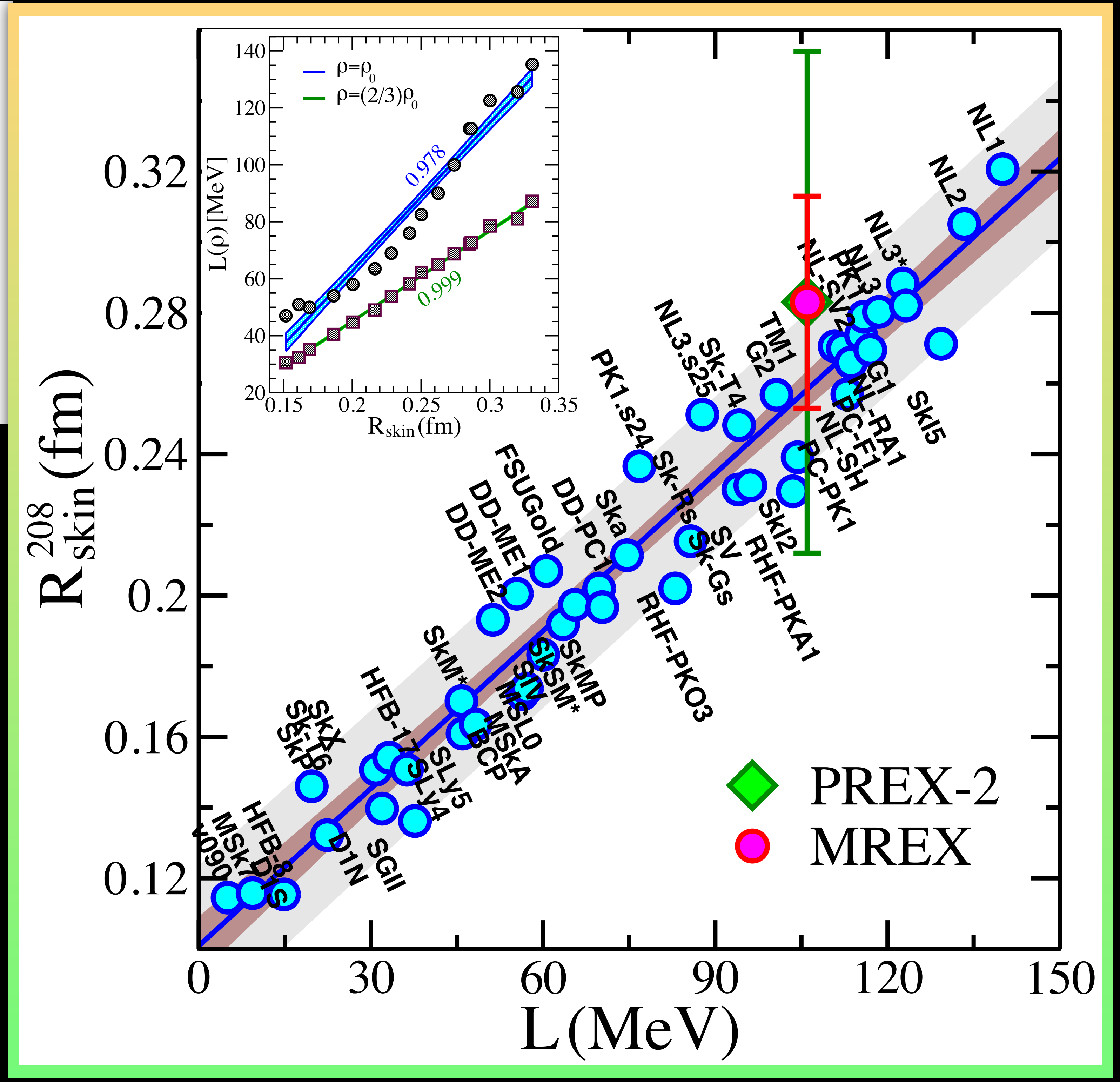
Lectures will attempt to provide an overall <u>personal</u> picture of the emergent field of multi-messenger astronomy from a nuclear physics perspective

Please ask questions!

Heaven and Earth

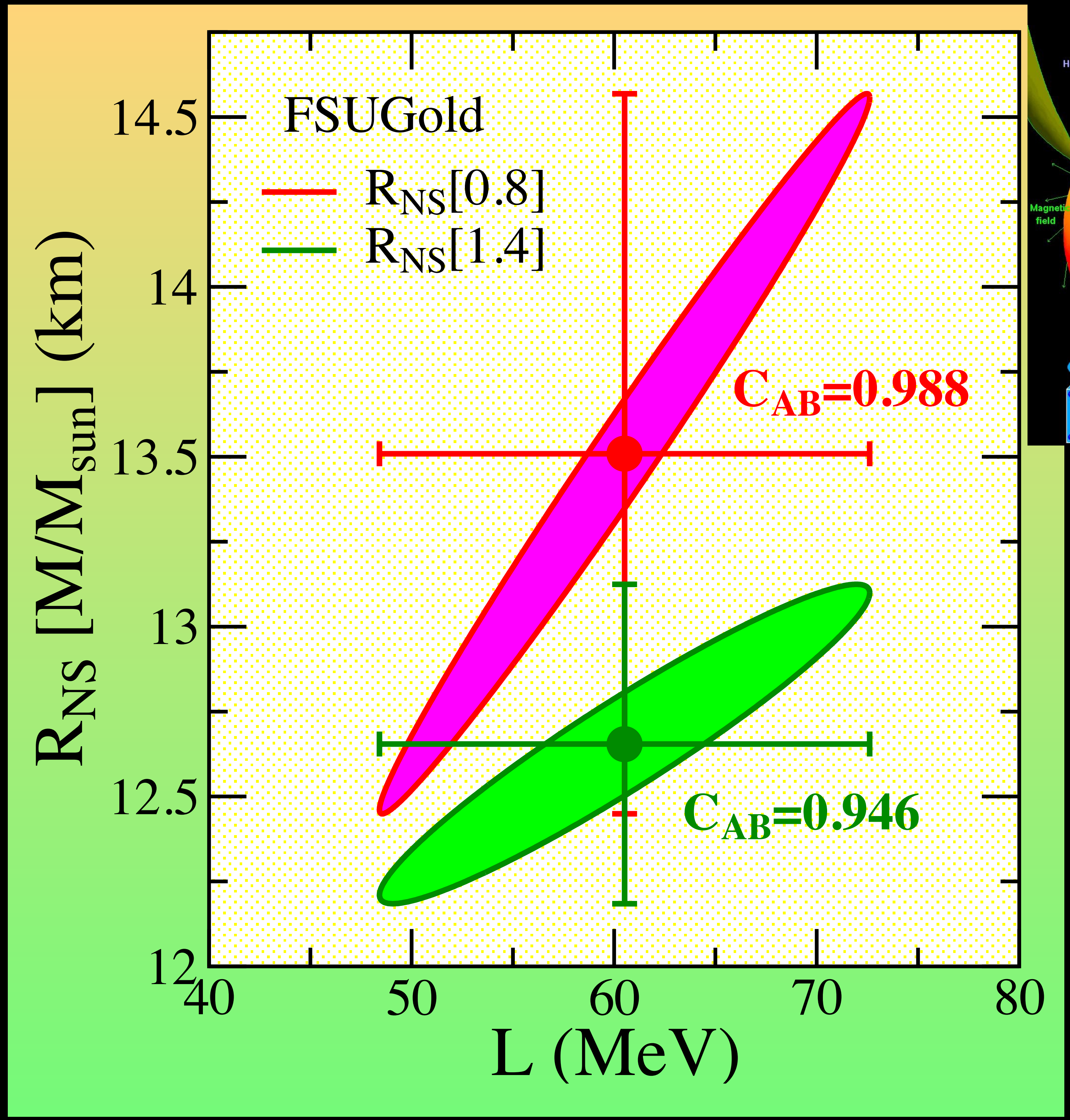
Laboratory Constraints on the EOS

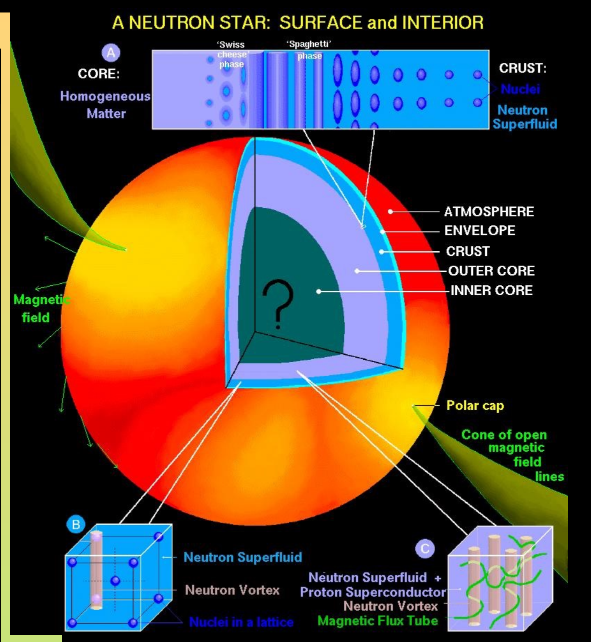




18 orders

magnitude



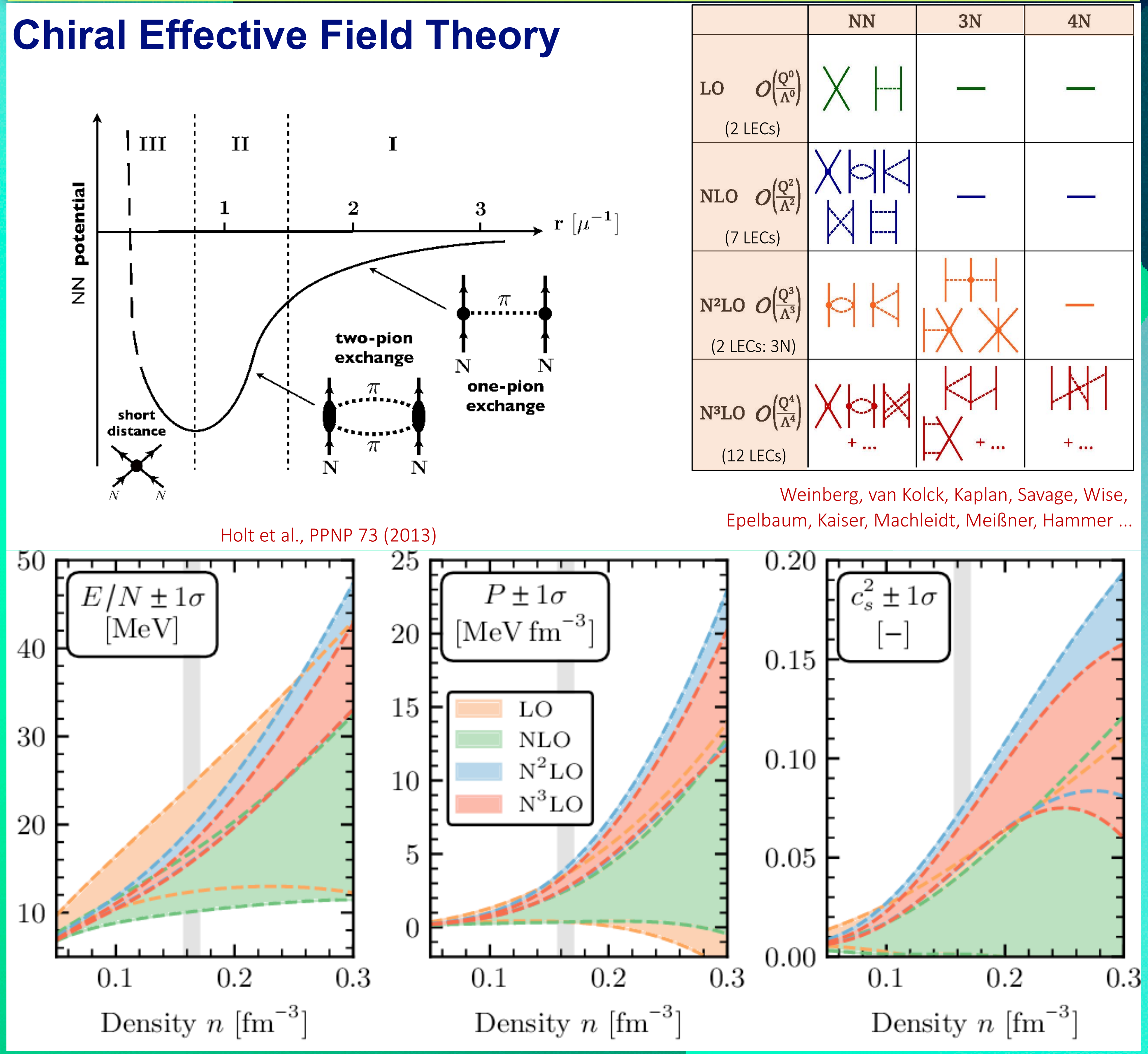


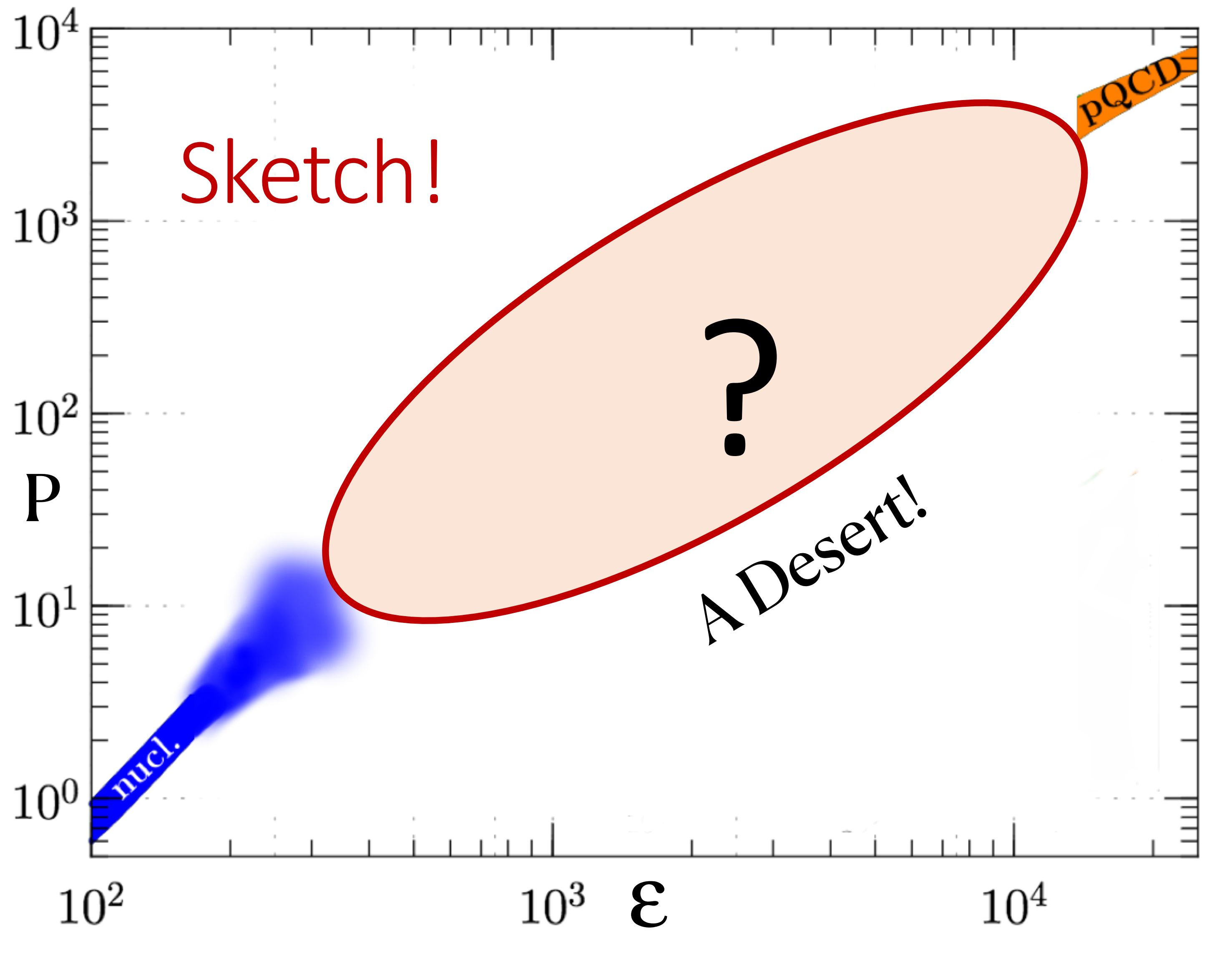
The slope of the symmetry energy L controls both the neutron skin of heavy nuclei as well as the radius of (low mass) neutron stars — objects that differ in size by 18 orders of magnitude!

The Tools of the Trade

Chiral Effective Field Theory

- A theory of nucleons, pions, and unresolved contact interactions
- Systematic, Improvable, and quantifiable
- Breaks down at ~1.5 normal nuclear density

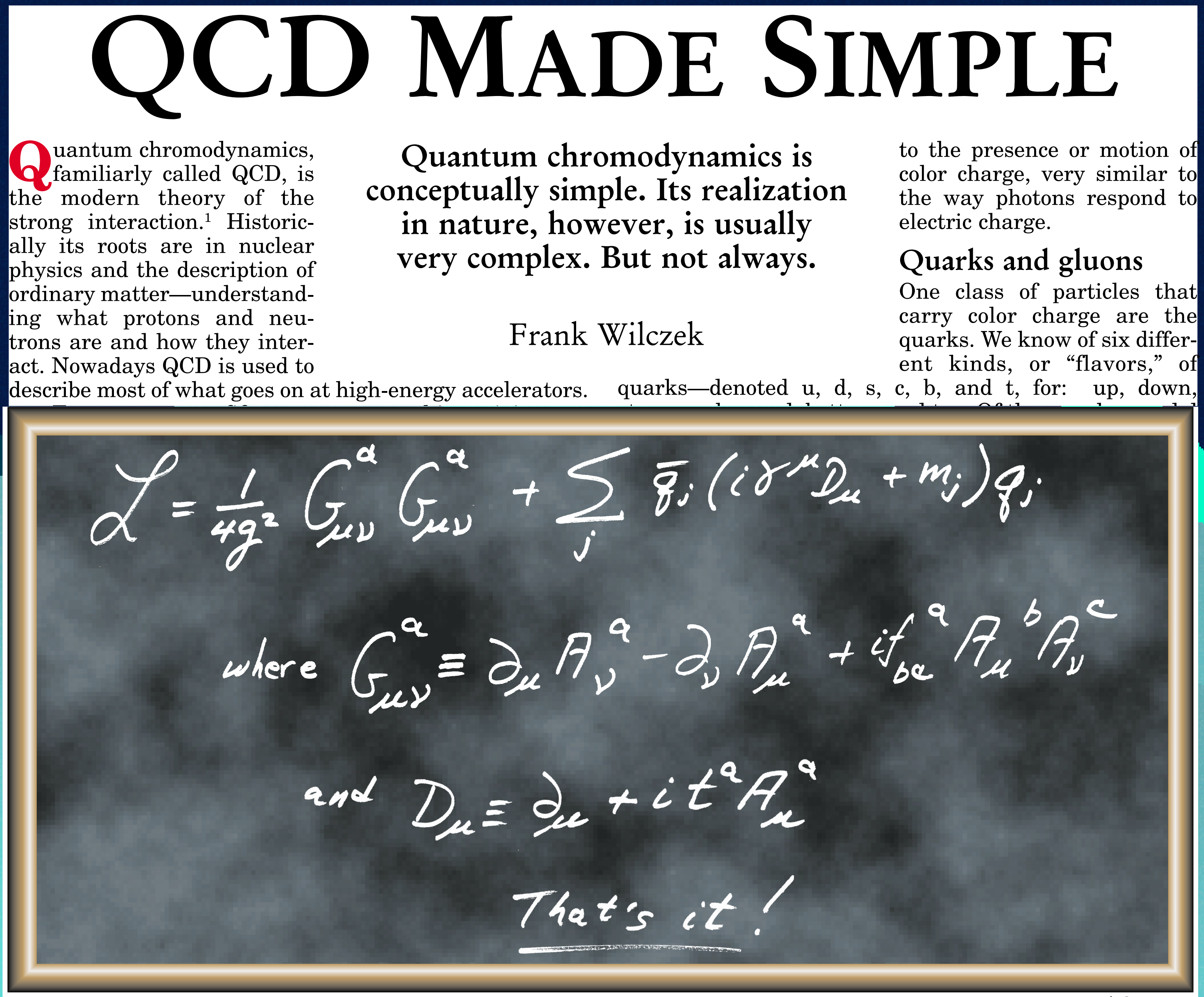




How to link χEFT to pQCD

Lattice QCD at finite density ($\mu/T \ll 1$)

Covariant Density Functional Theory
(Relativistic MFT with a slight twist)



QCD MADE SIMPLE

Quantum chromodynamics is conceptually simple. Its realization in nature, however, is usually very complex. But not always.

Frank Wilczek

Quantum chromodynamics, familiarly called QCD, is the modern theory of the strong interaction.[1] Historically its roots are in nuclear physics and the description of ordinary matter—understanding what protons and neutrons are and how they interact. Nowadays QCD is used to describe most of what goes on at high-energy accelerators.

to the presence or motion of color charge, very similar to the way photons respond to electric charge.

Quarks and gluons

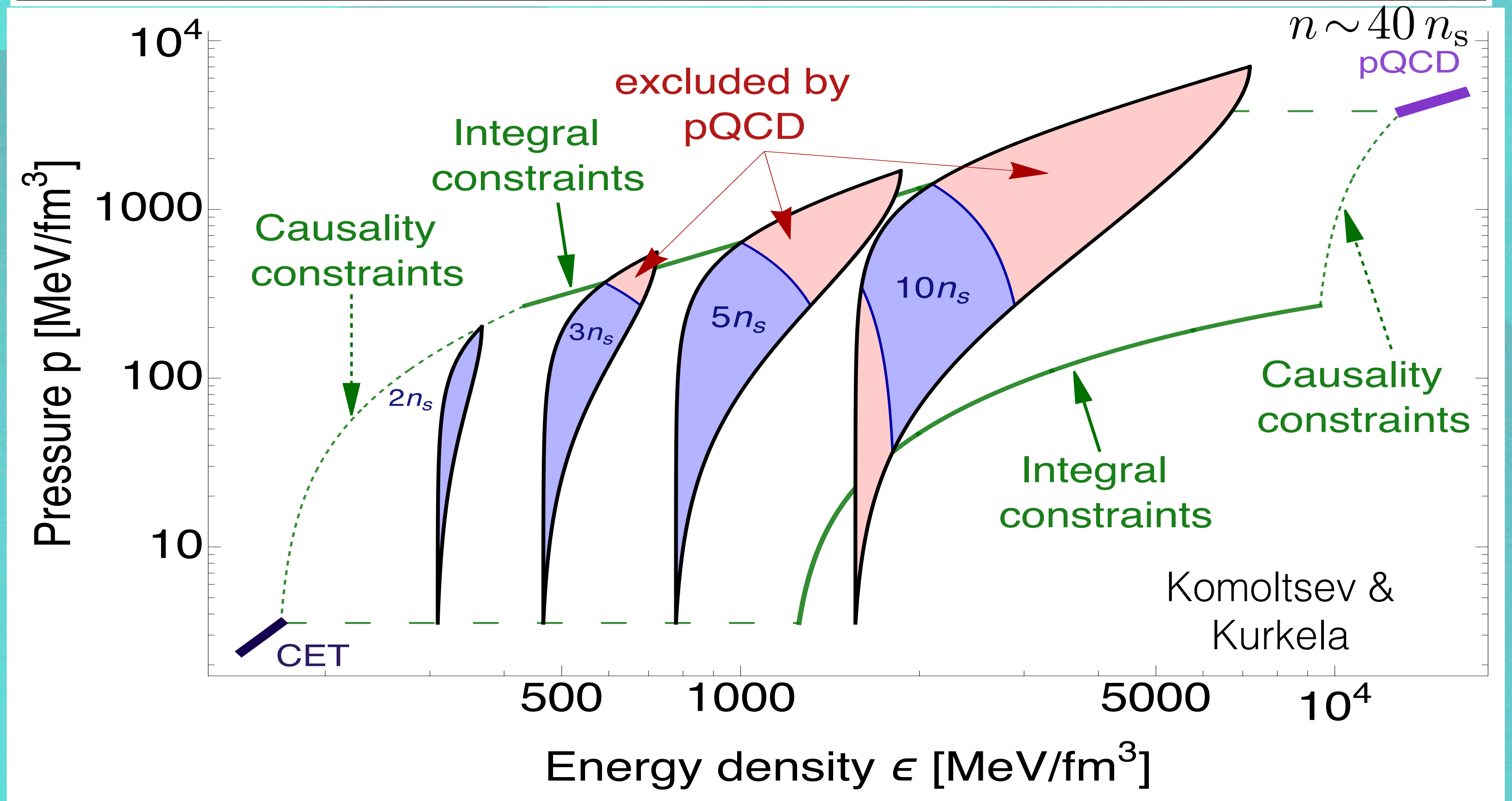
One class of particles that carry color charge are the quarks. We know of six different kinds, or "flavors," of quarks—denoted u, d, s, c, b, and t, for: up, down,

$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$

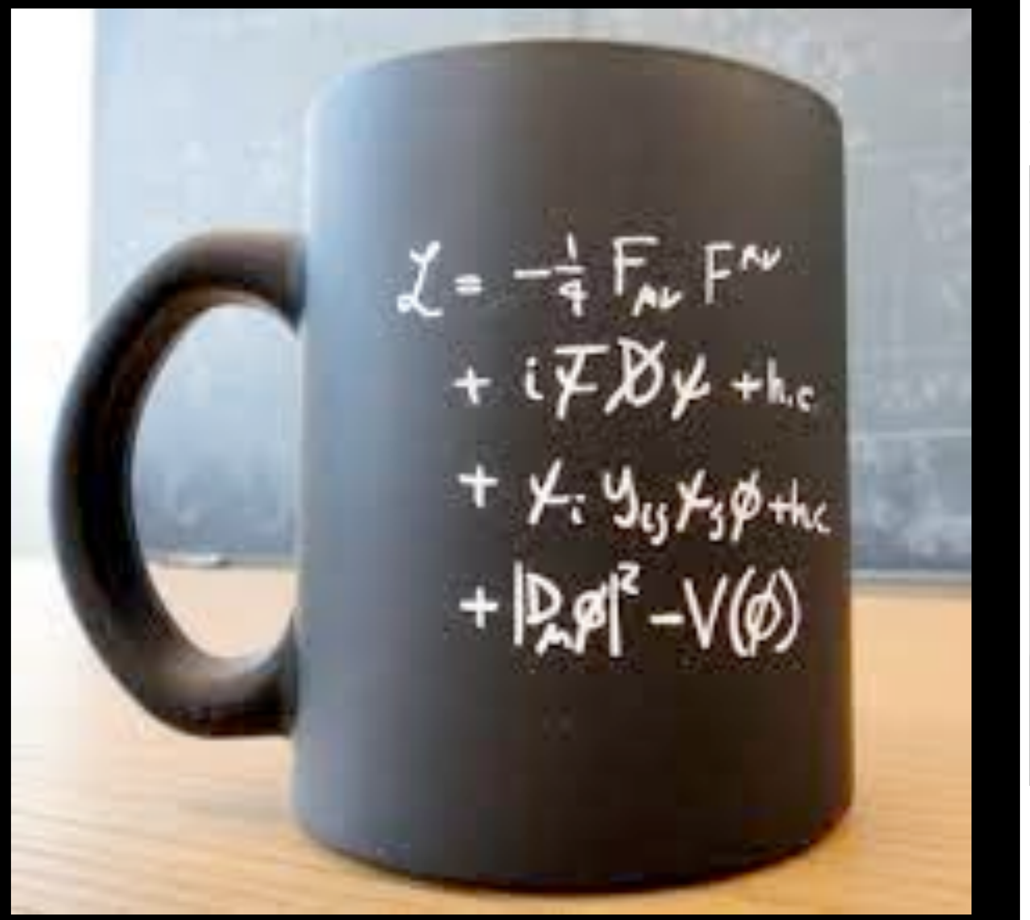
and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

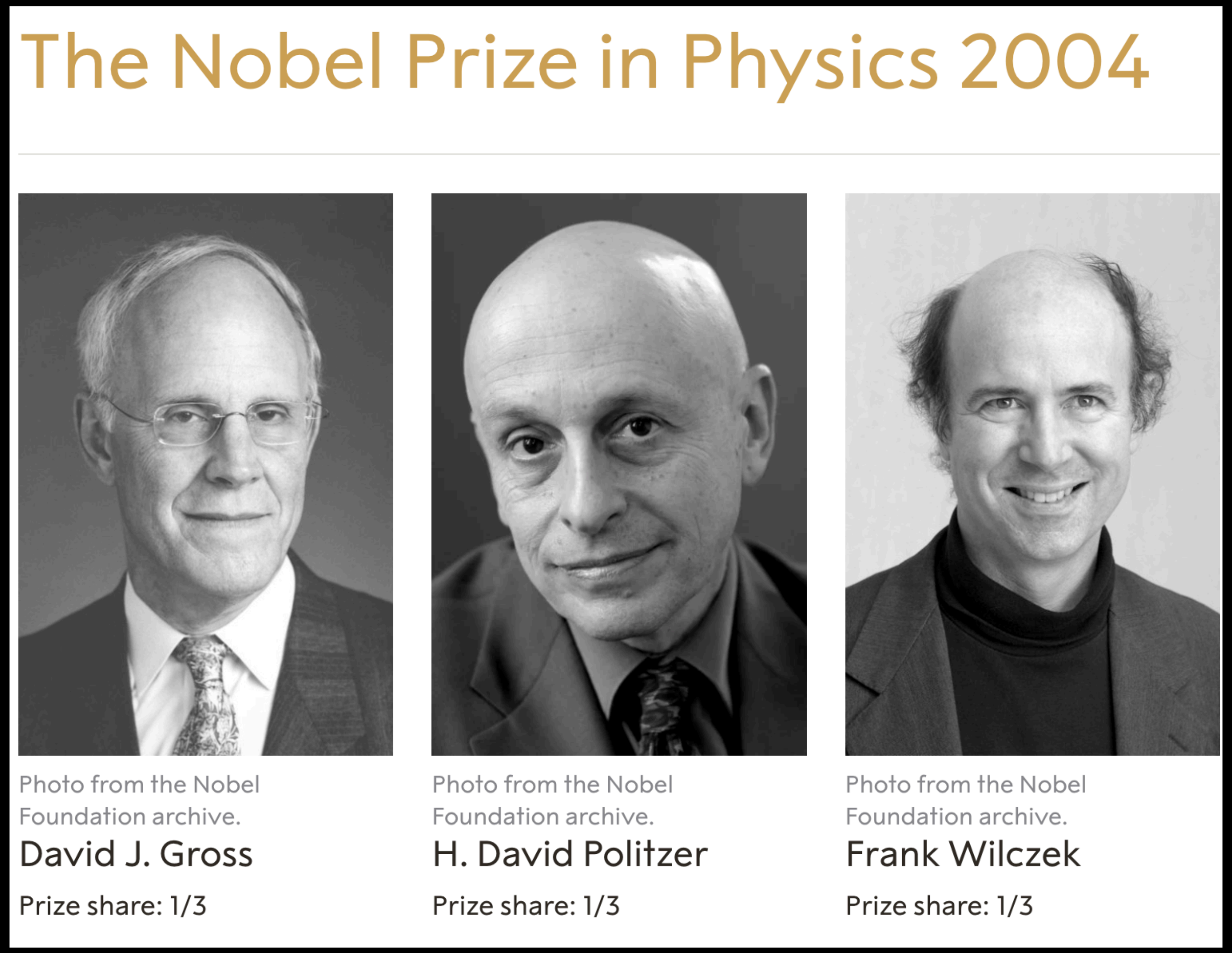
That's it!



Neutron Stars meet Bayesian Inference I

Model Building for the understanding of atomic nuclei and neutron stars





Walter Kohn
Nobel Laureate
Chemistry 1998

Quantum Chromodynamics (QCD) is the fundamental theory of the strong interactions

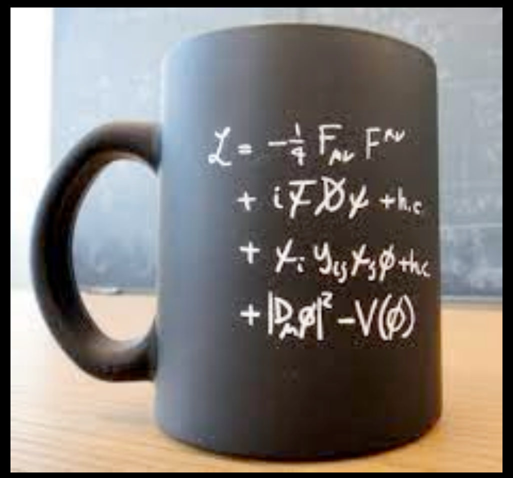
- Although the basic equations can be written in a coffee cup, their exact solution in the region of interest to atomic nuclei and neutron stars are unknown
- One must then resort to models that (hopefully!) embody the properties of QCD
- One such model is Density Functional Theory

Covariant Density Functional Theory

- Empirical parameters calibrated to physical observables
- Ground state properties emerge from functional minimization

$$\mathcal{L}_{\rm Yukawa} = \bar{\psi}\left[g_{\rm s}\phi - \left(g_{\rm v}V_\mu + \frac{g_\rho}{2}\tau\cdot\mathbf{b}_\mu + \frac{e}{2}(1+\tau_3)A_\mu\right)\gamma^\mu\right]\psi$$

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



Neutron Stars meet Bayesian Inference II

Model Building for the understanding of atomic nuclei and neutron stars

$$P(M|D) = \frac{P(D|M)\,P(M)}{P(D)}$$

Posterior

Prior

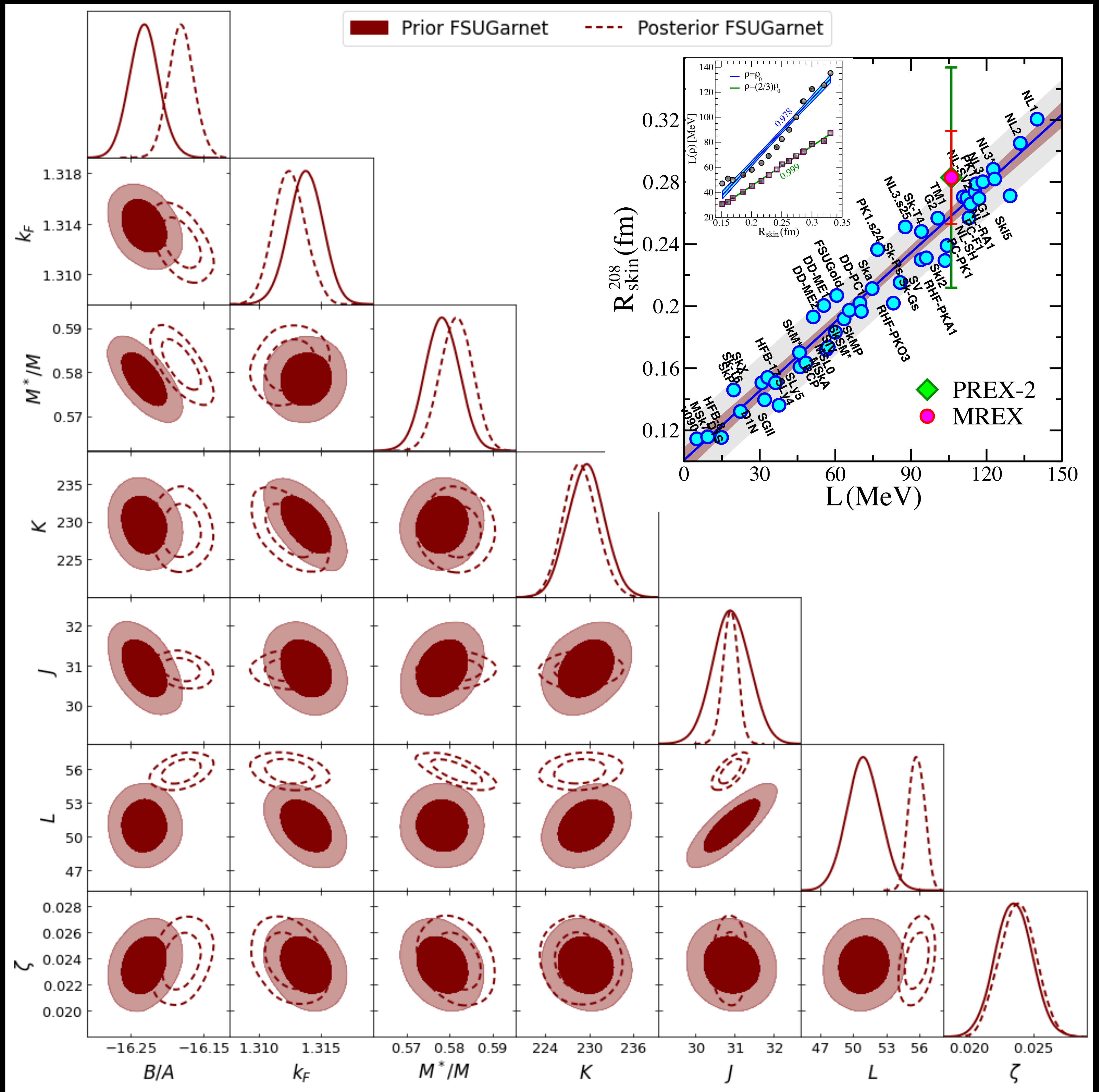
Likelihood

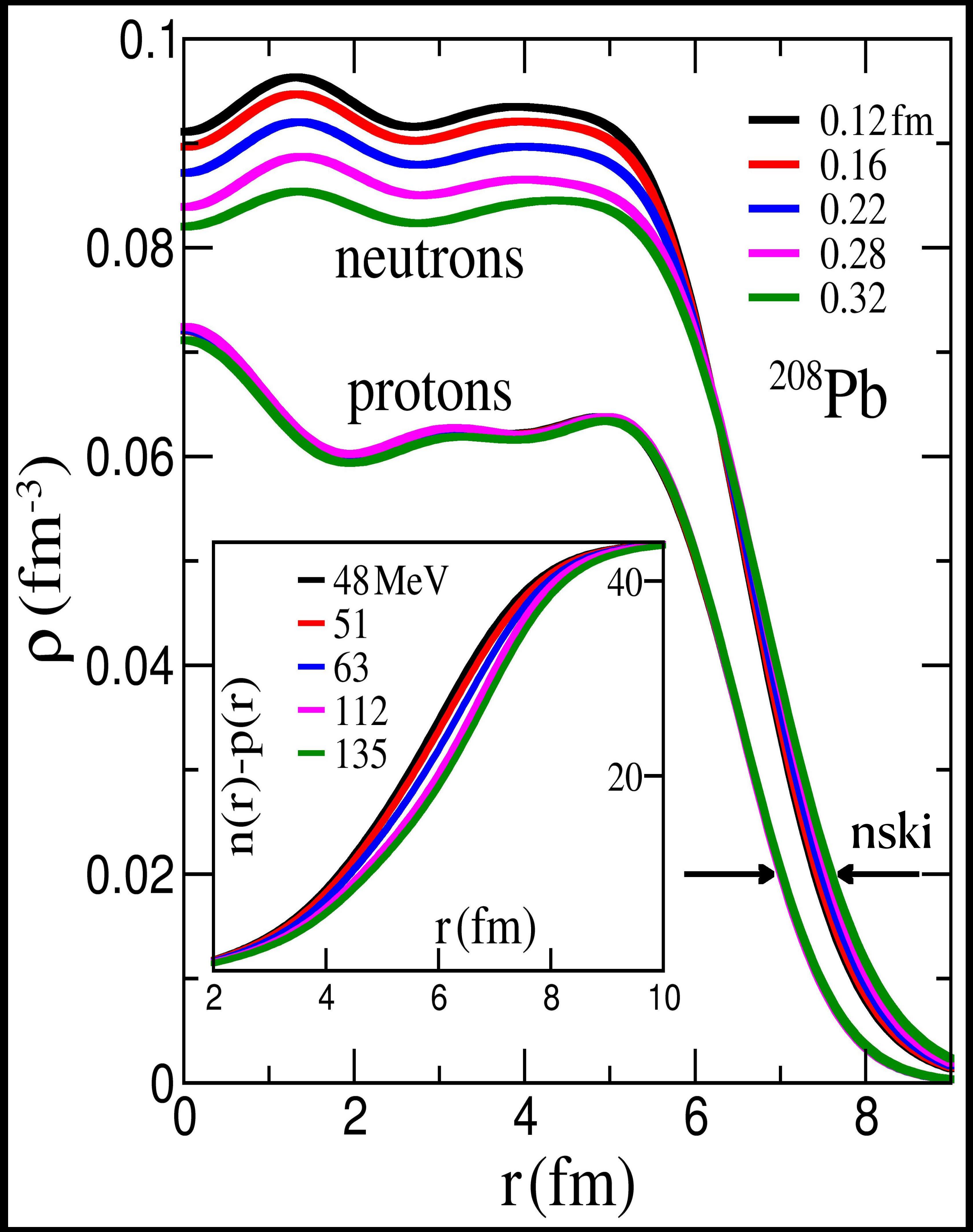
Marginal Likelihood

$$\mathcal{L}_{\rm Yukawa} = \bar{\psi}\left[g_{\rm s}\phi - \left(g_{\rm v}V_{\mu} + \frac{g_{\rho}}{2}\tau\cdot\mathbf{b}_{\mu} + \frac{e}{2}(1+\tau_3)A_{\mu}\right)\gamma^{\mu}\right]\psi$$

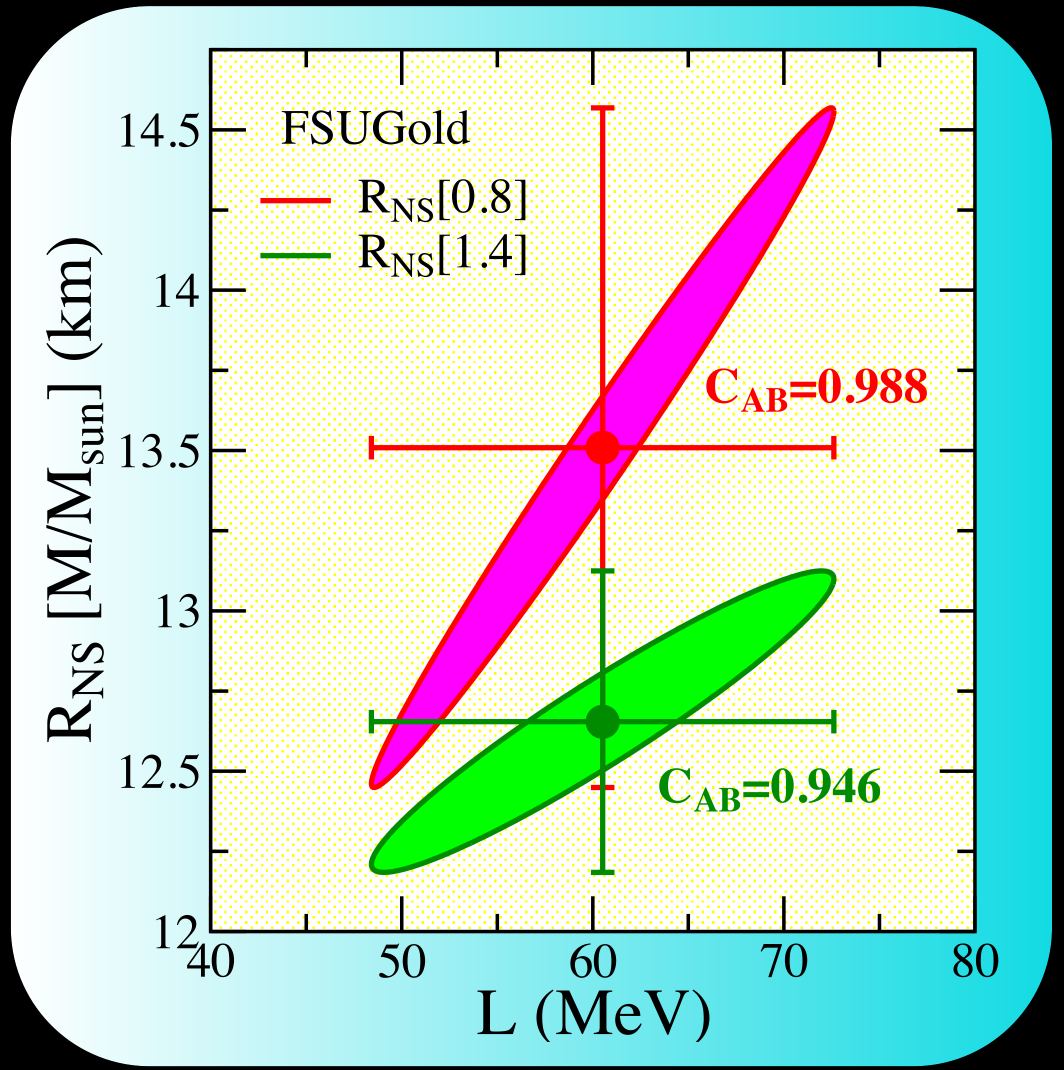
$$\mathcal{L}_{\rm self} = \frac{\kappa}{3!}(g_{\rm s}\phi)^3 - \frac{\lambda}{4!}(g_{\rm s}\phi)^4 + \frac{\zeta}{4!}g_{\rm v}^4(V_{\mu}V^{\mu})^2 + \Lambda_{\rm v}\left(g_{\rho}^2\,\mathbf{b}_{\mu}\cdot\mathbf{b}^{\mu}\right)\left(g_{\rm v}^2V_{\nu}V^{\nu}\right)$$

$$(g_{\rm s}, g_{\rm v}, g_{\rho}, \kappa, \lambda, \Lambda_{\rm v}) \Longleftrightarrow (\rho_0, \epsilon_0, M^*, K, J, L)$$

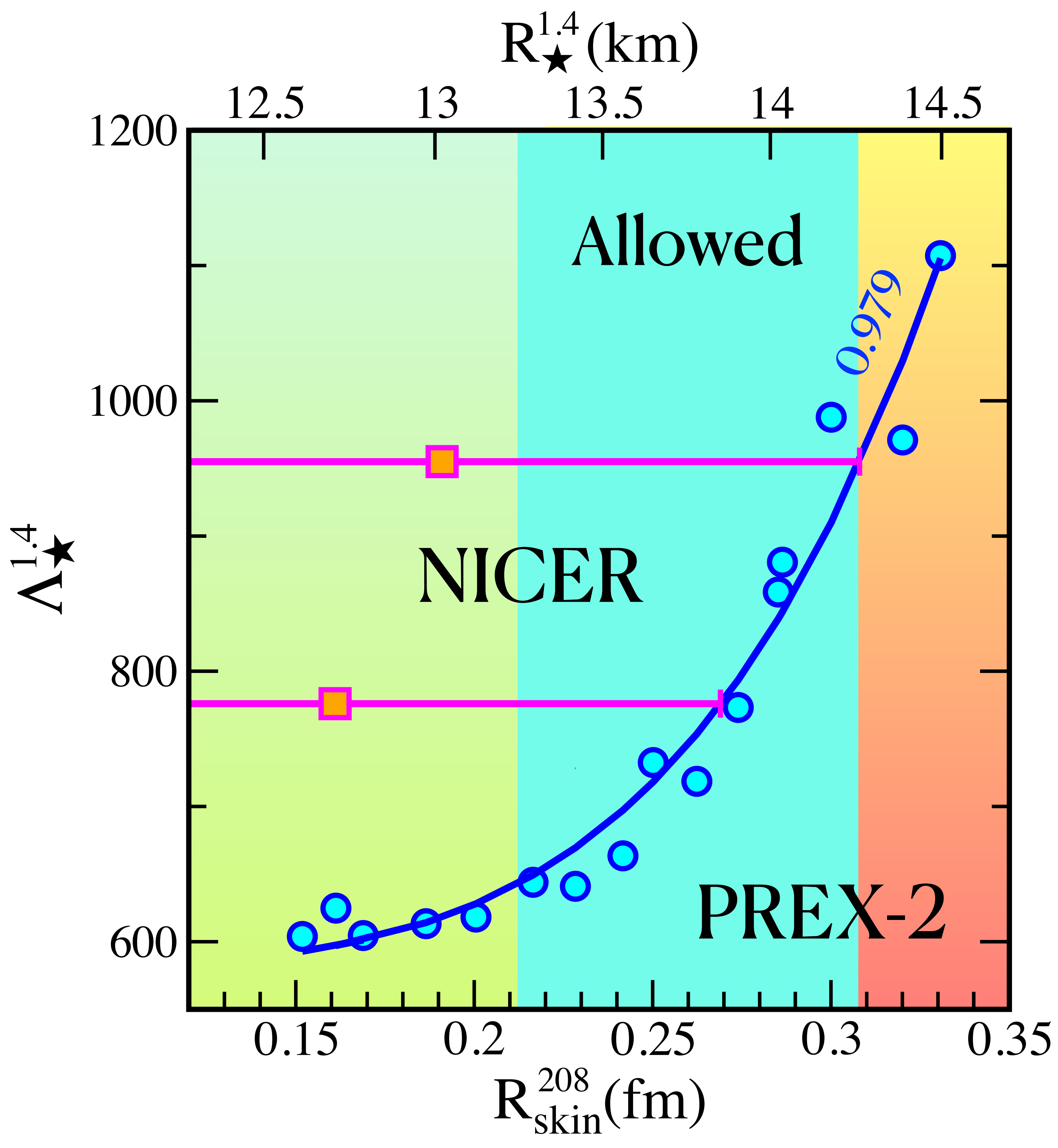


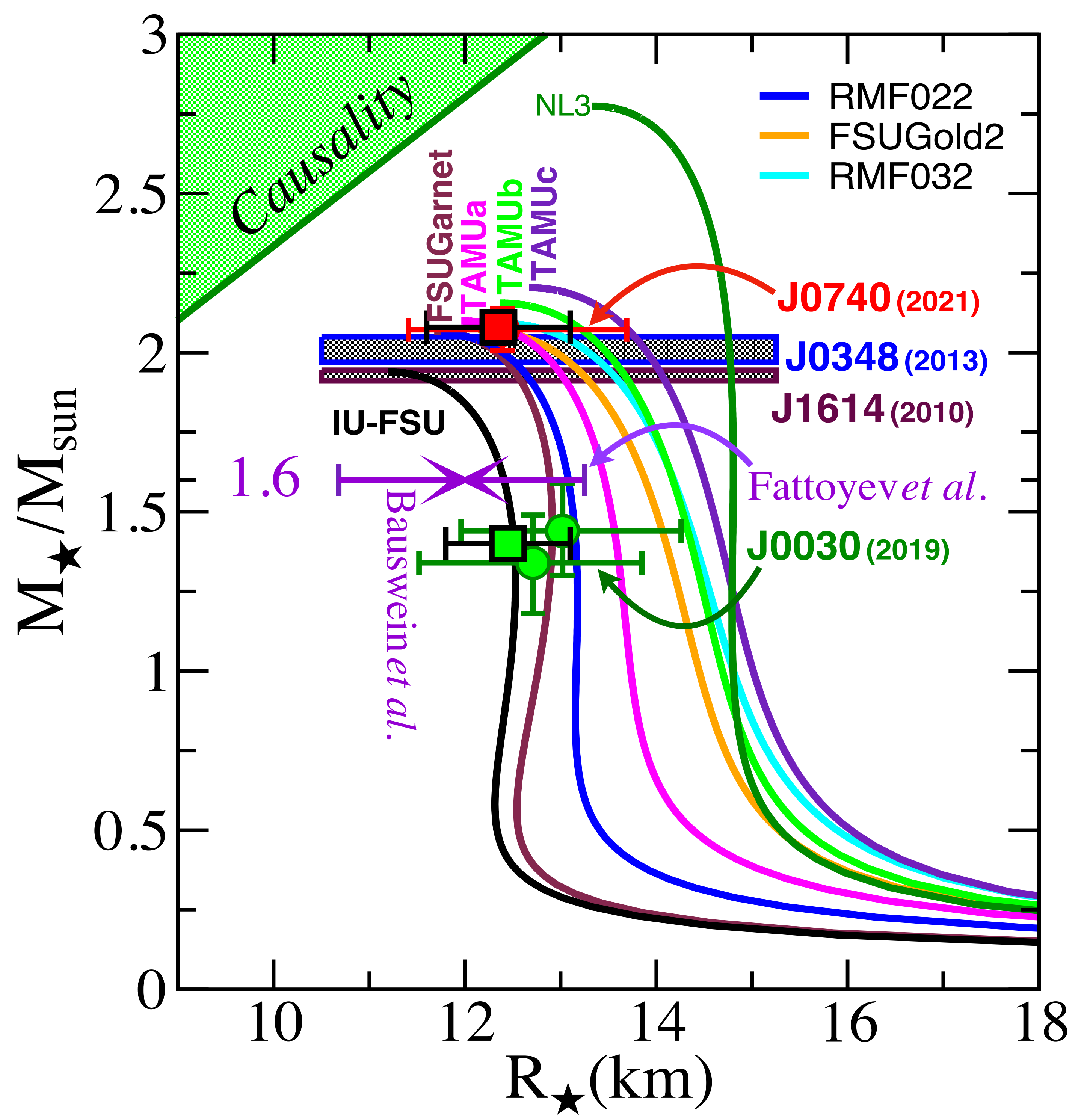


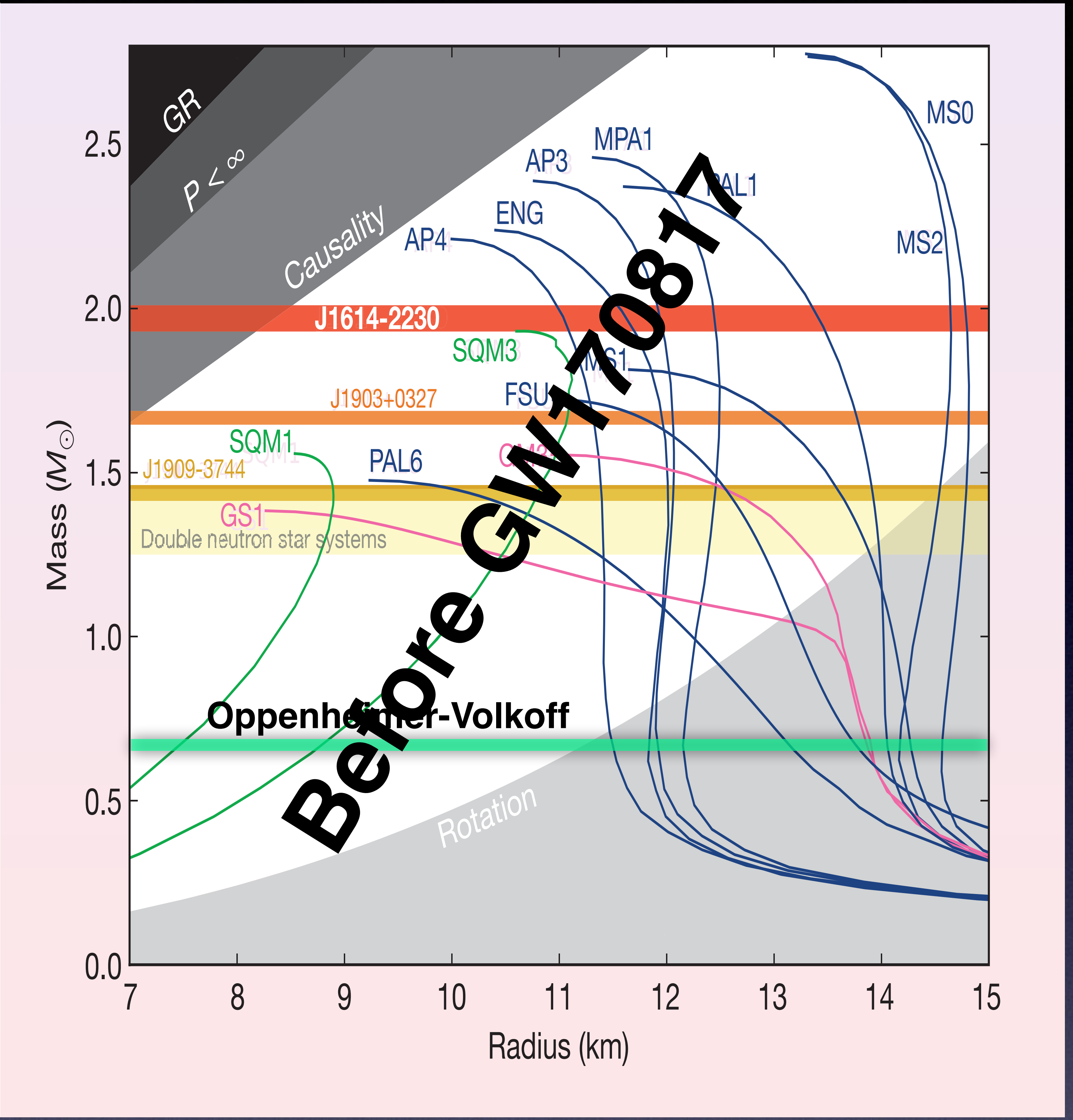
Neutron skins and stellar radii differ by 18 orders of magnitude — yet all observables calculated under the same theoretical framework!

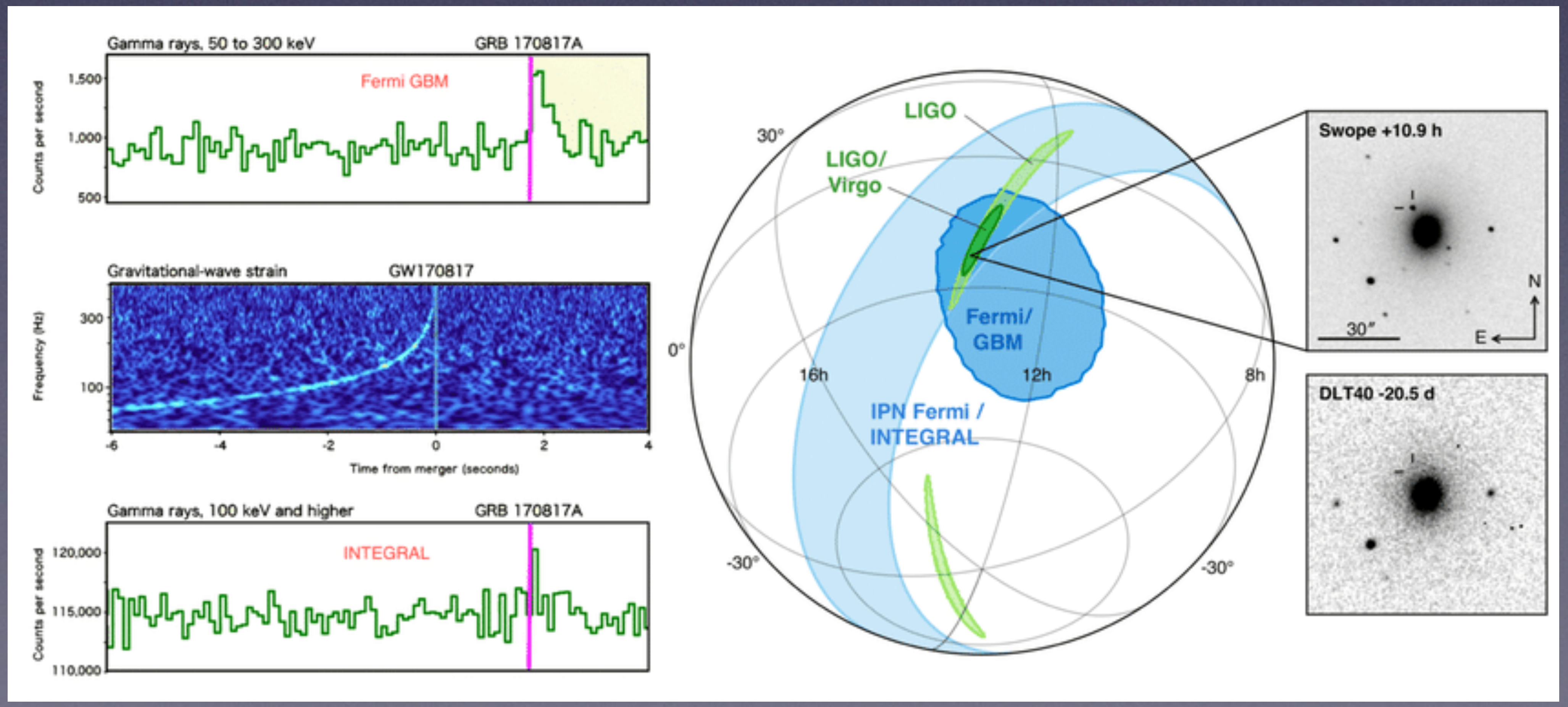


The Dawn of a Golden Era in Neutron-Star Physics





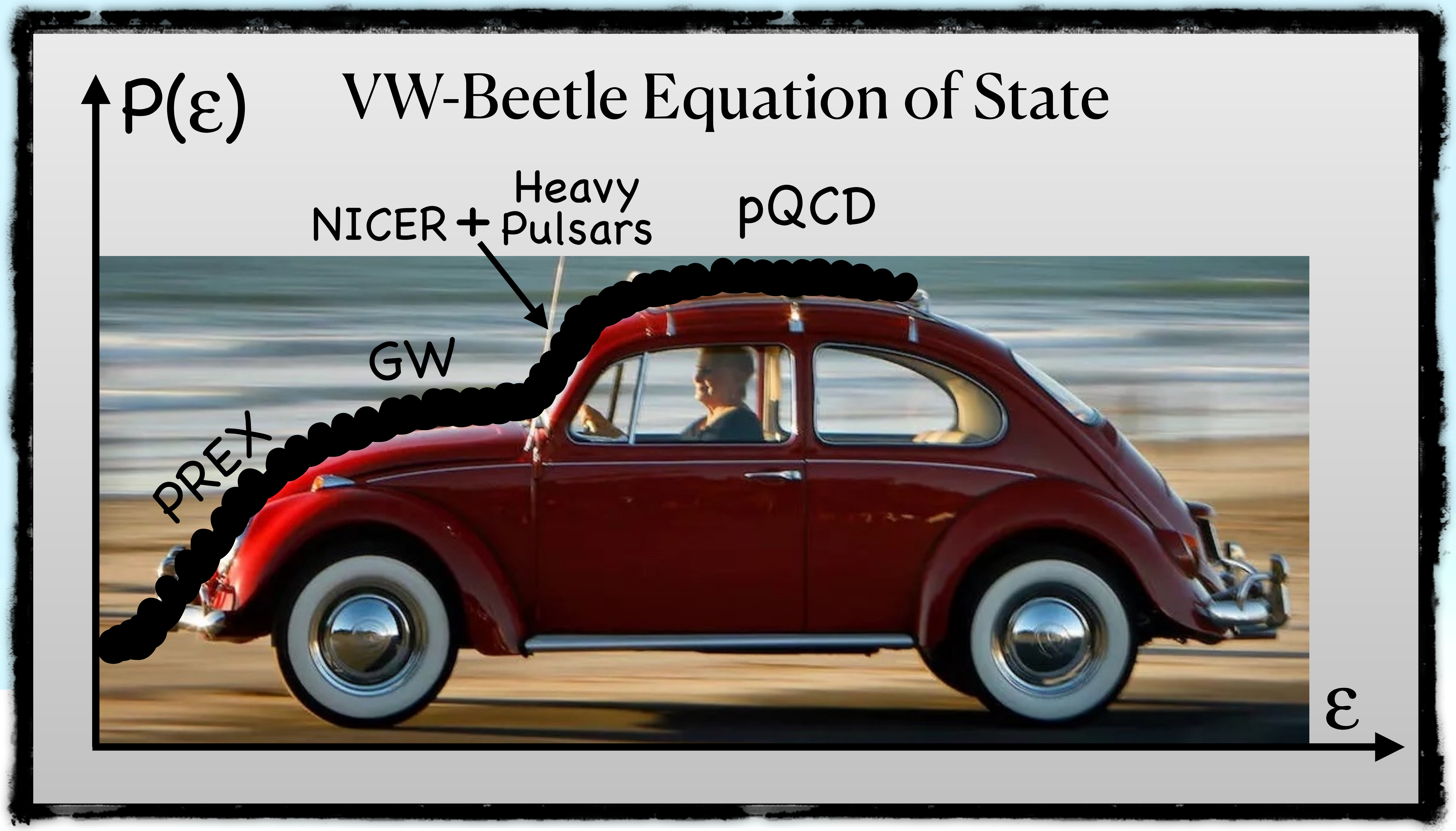




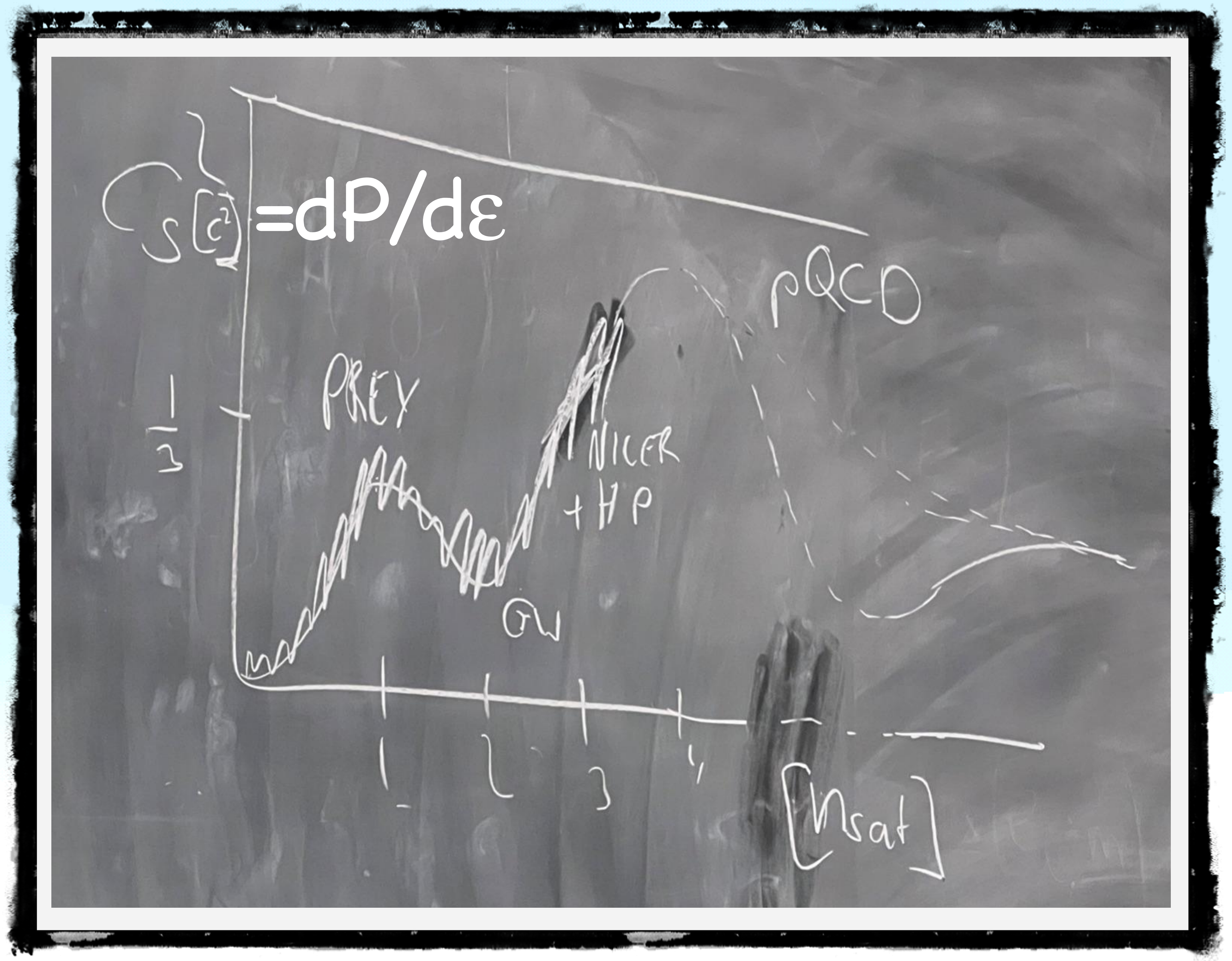
What have we learned since GW170817

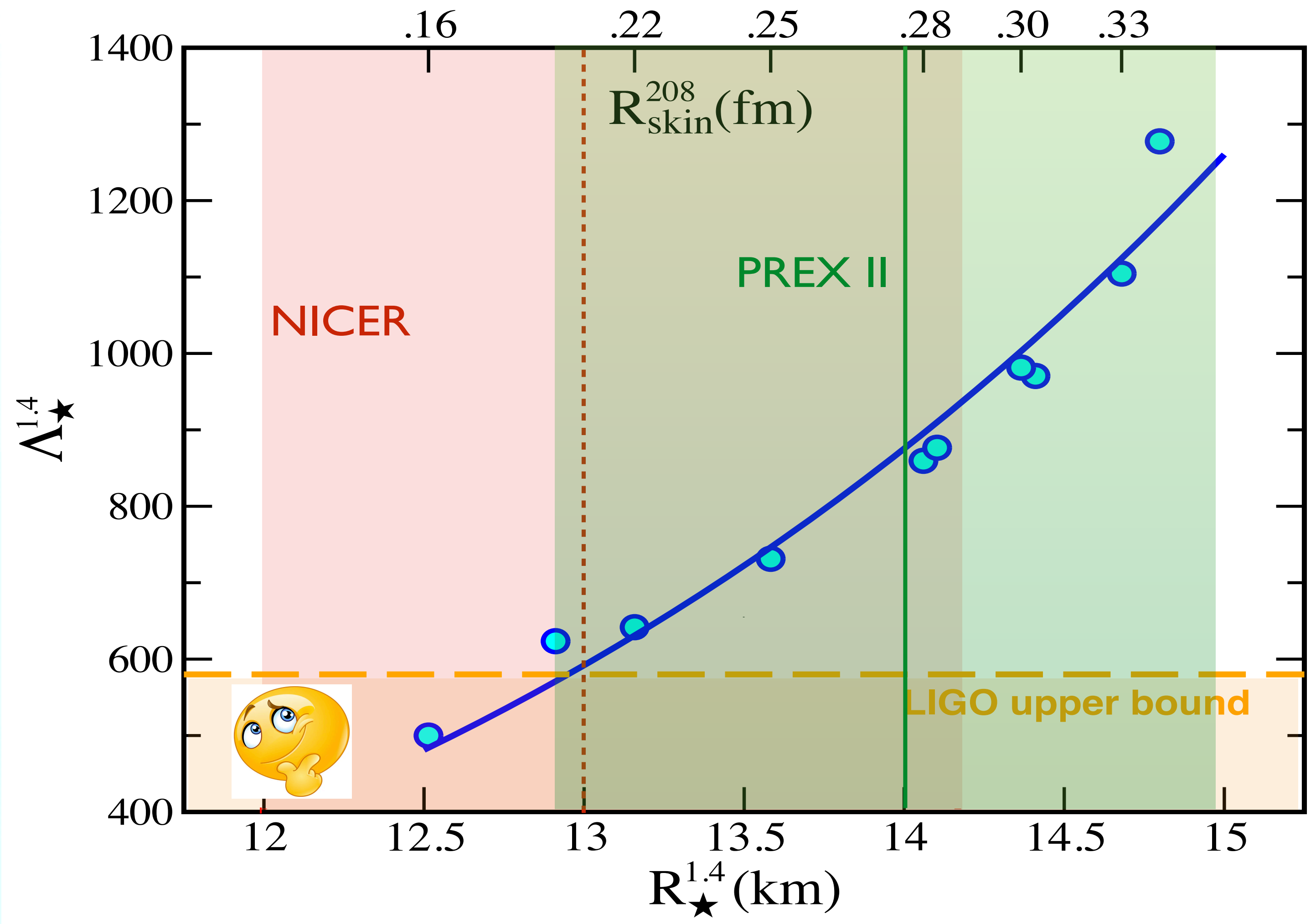
- PREX suggest a **stiff** EOS around saturation density although CREX has muddled the waters!
- LIGO-Virgo favor a **soft** EOS at around $2n_0$ although see Gamba et al., PRD 103, 124015 (2021)
- NICER/Pulsar Timing suggest a **stiff** EOS at $\sim 4n_0$

The Equation of State



The Speed of Sound





Tantalizing Possibility

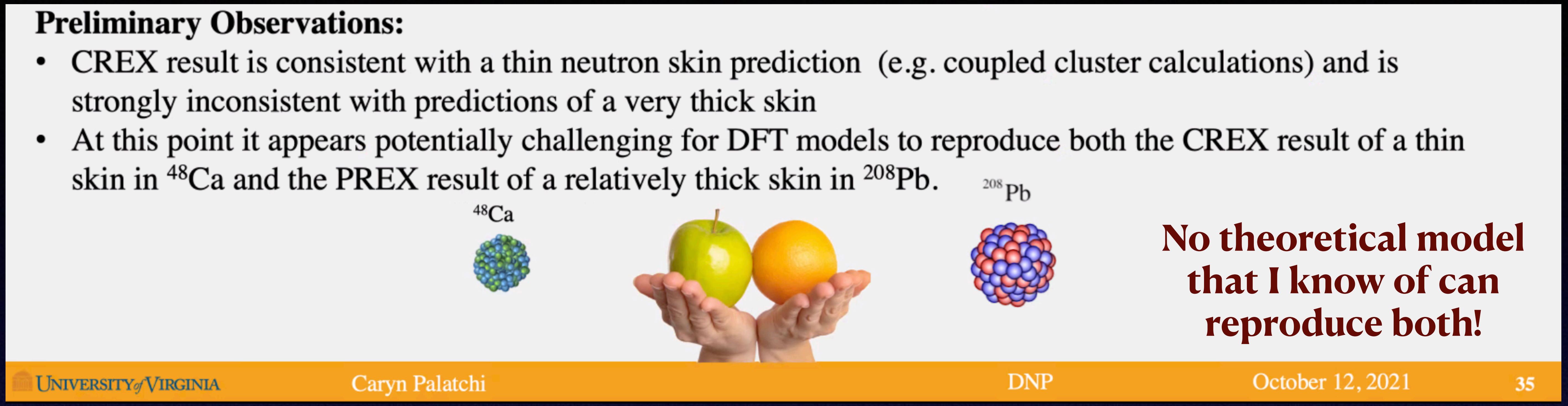
- *Laboratory Experiments suggest large neutron radii for Pb* $\lesssim 1\rho_0$
- *Gravitational Waves suggest small stellar radii* $\gtrsim 2\rho_0$
- *Electromagnetic Observations suggest large stellar masses* $\gtrsim 4\rho_0$

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

Questions, Challenges, and Opportunities

Who Ordered That?

Isidor Isaac Rabi



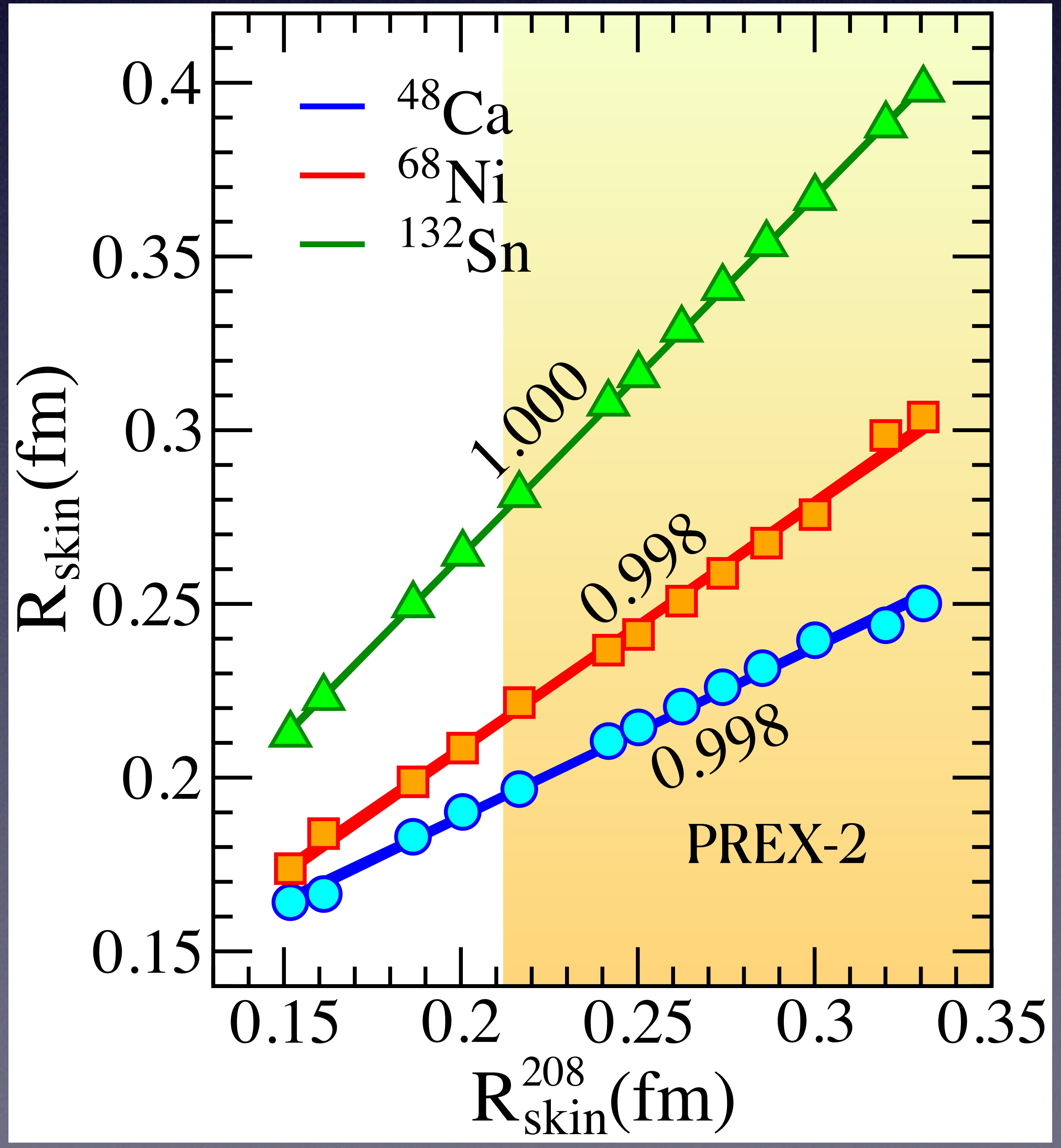
Preliminary Observations:

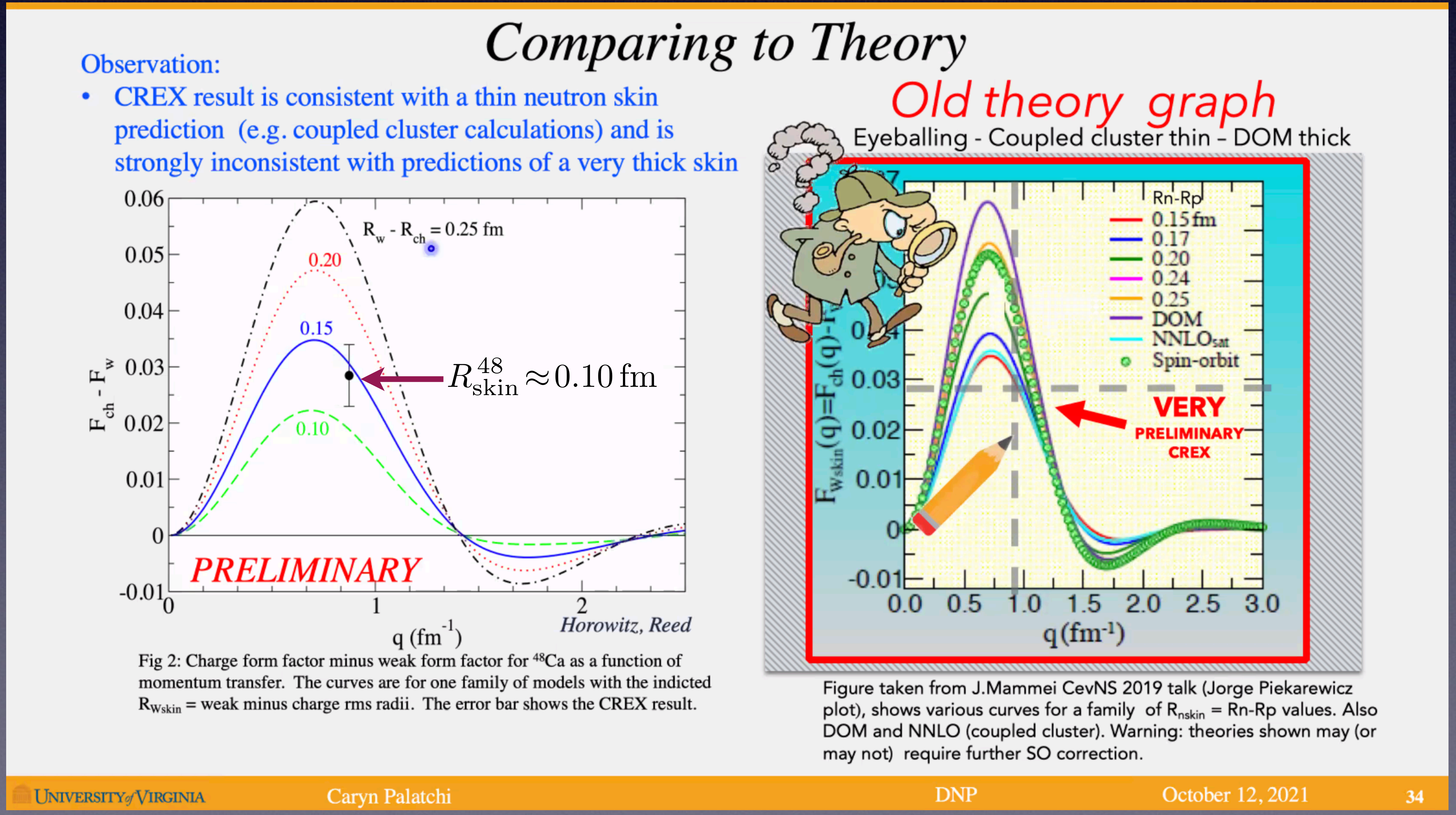
- CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin
- At this point it appears potentially challenging for DFT models to reproduce both the CREX result of a thin skin in ^{48}Ca and the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

^{48}Ca ^{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.

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.

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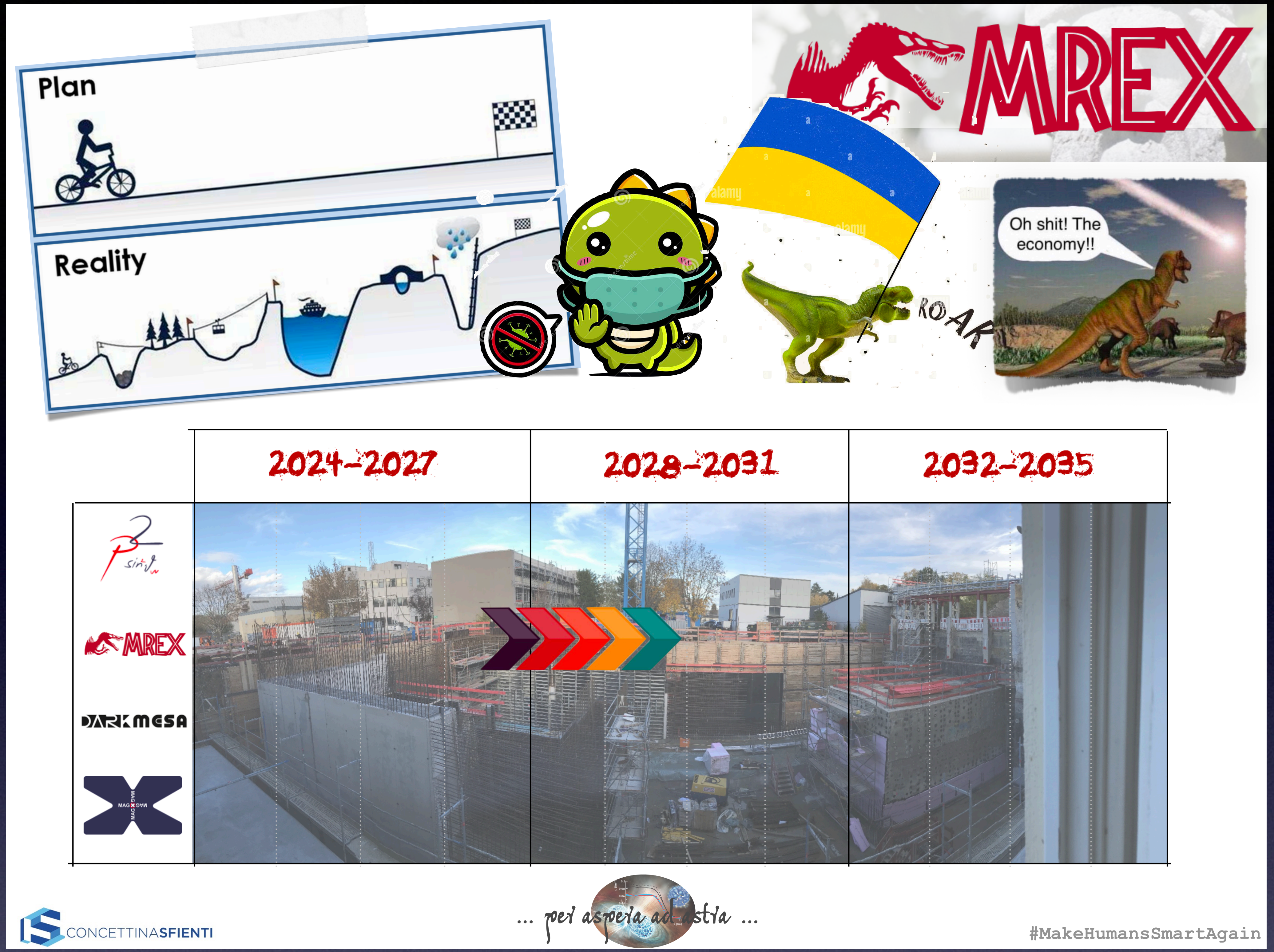
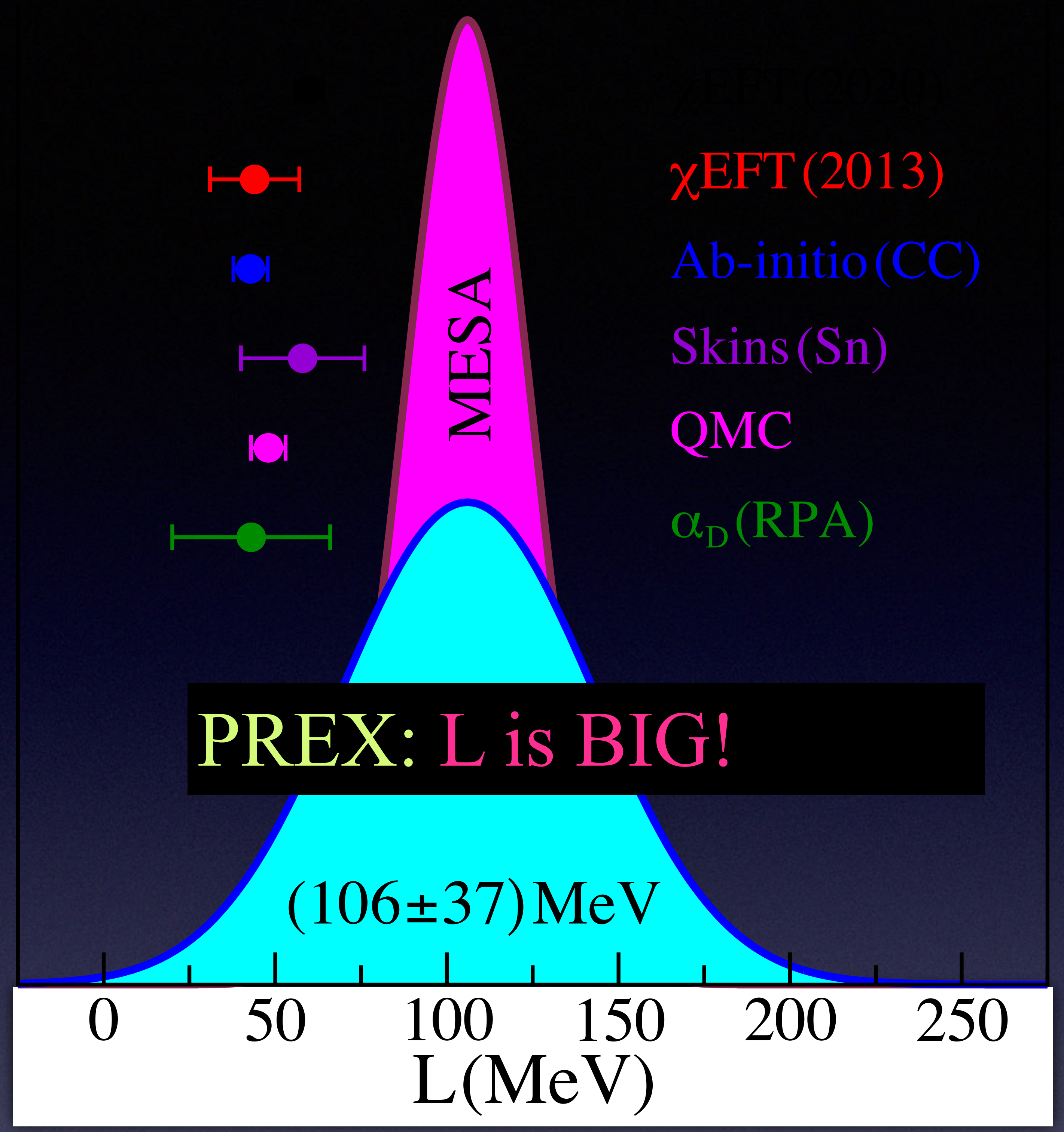
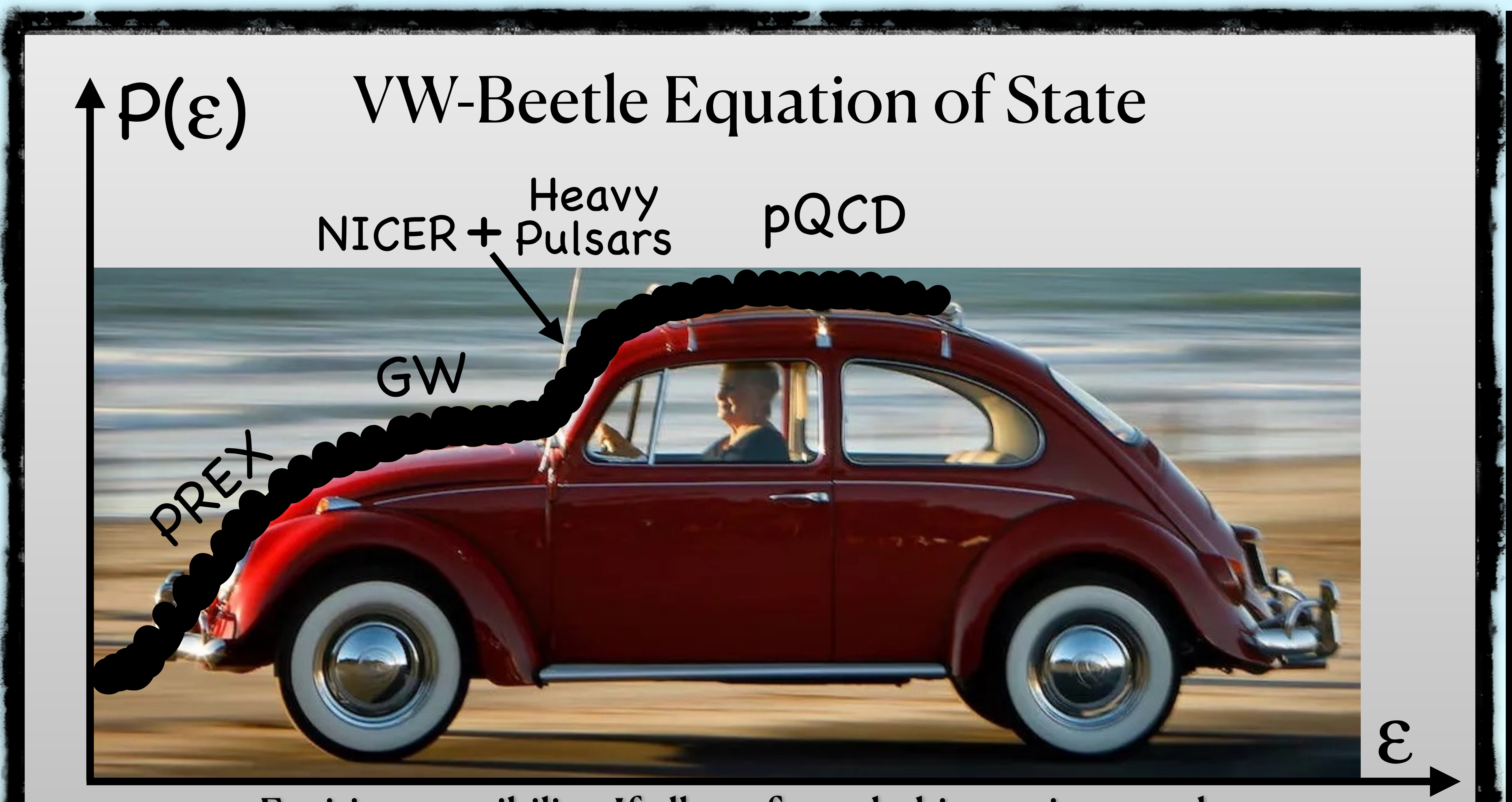
A statistical fluke or interesting Physics?

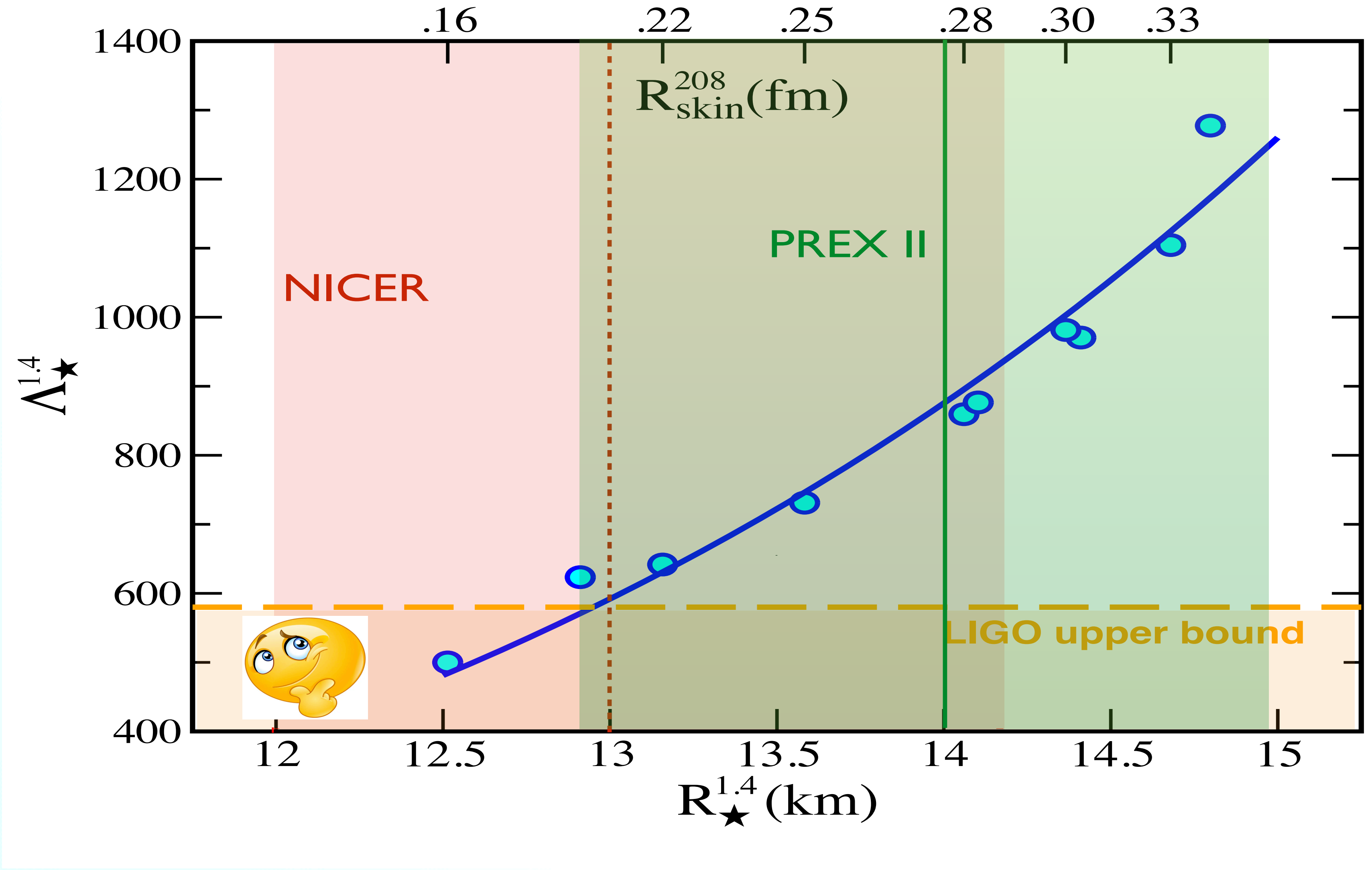




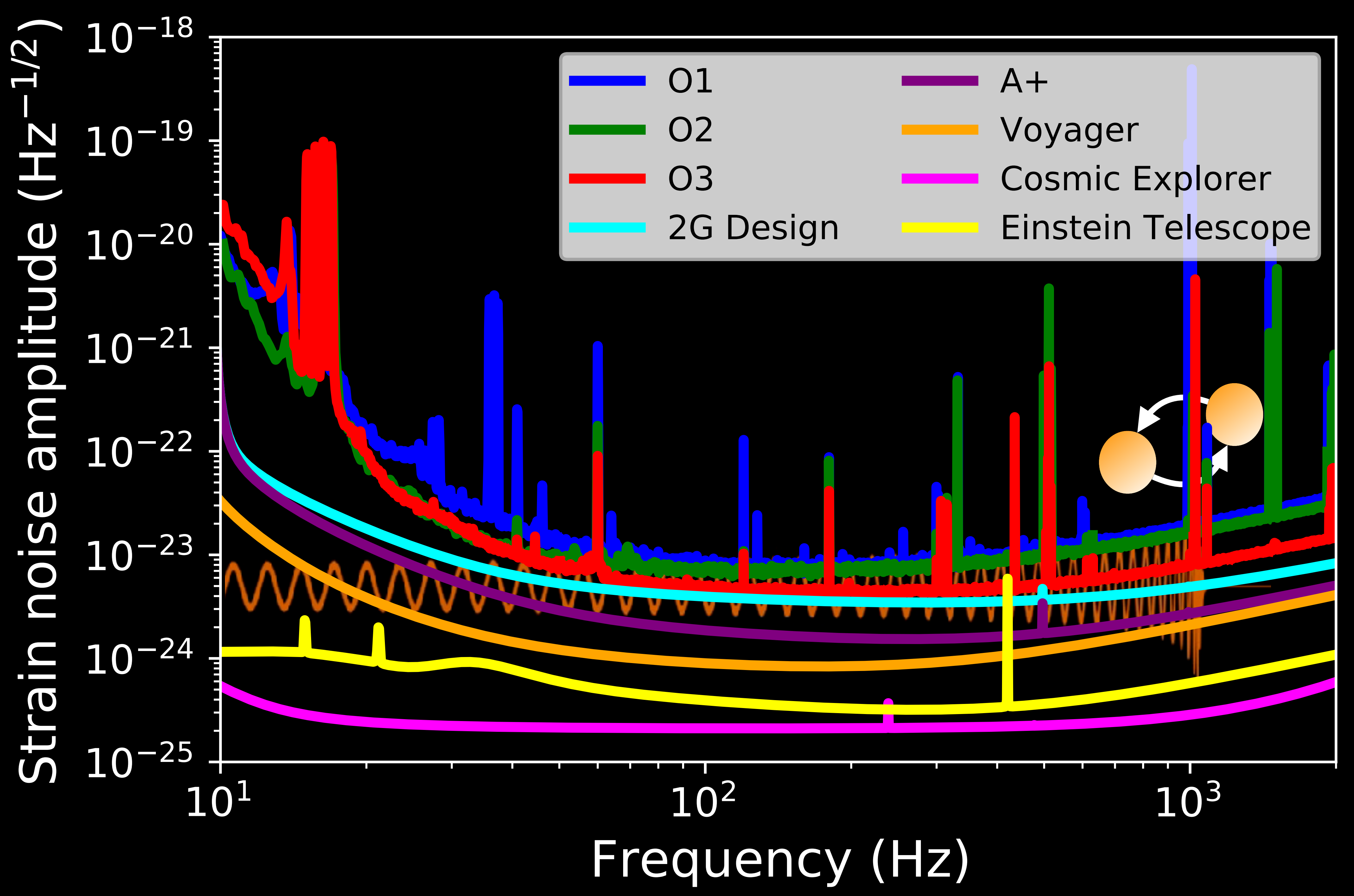
- Stable beam conditions by July 2026
- First run to reach PREX sensitivity (ΔRskin~0.07 fm) 250 hours beam time
- Result announced around mid 2027 (likely to combine PREX-MREX data)
- Final MREX result (ΔRskin~0.03 fm) likely by the end of 2028



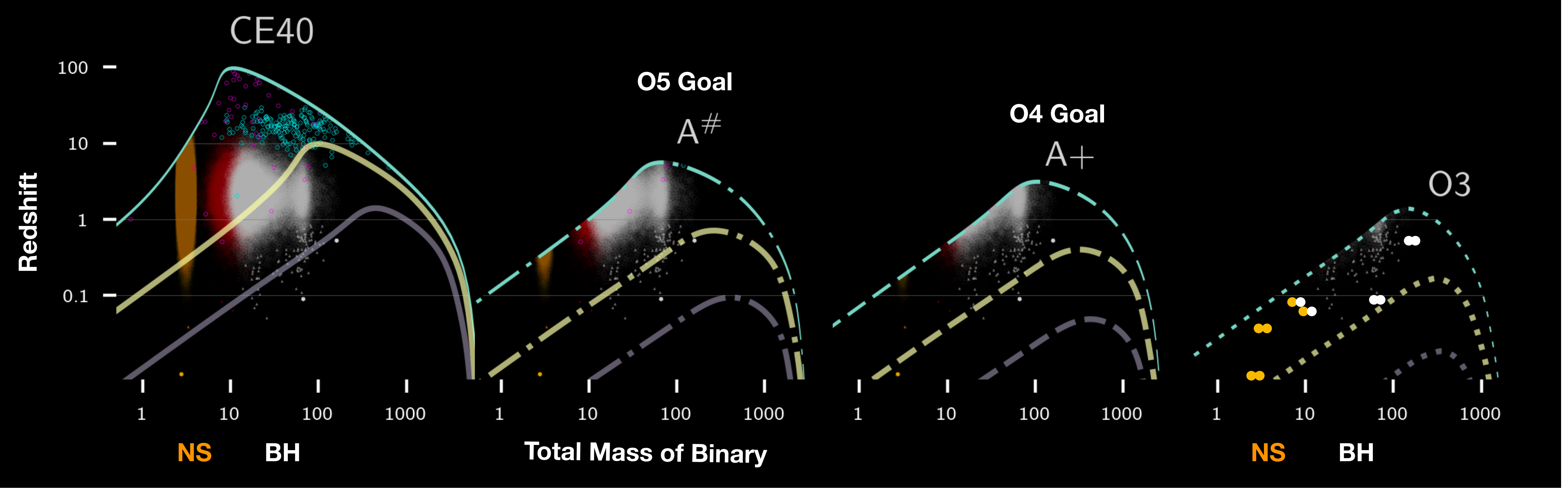
Exciting possibility: If all confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?)

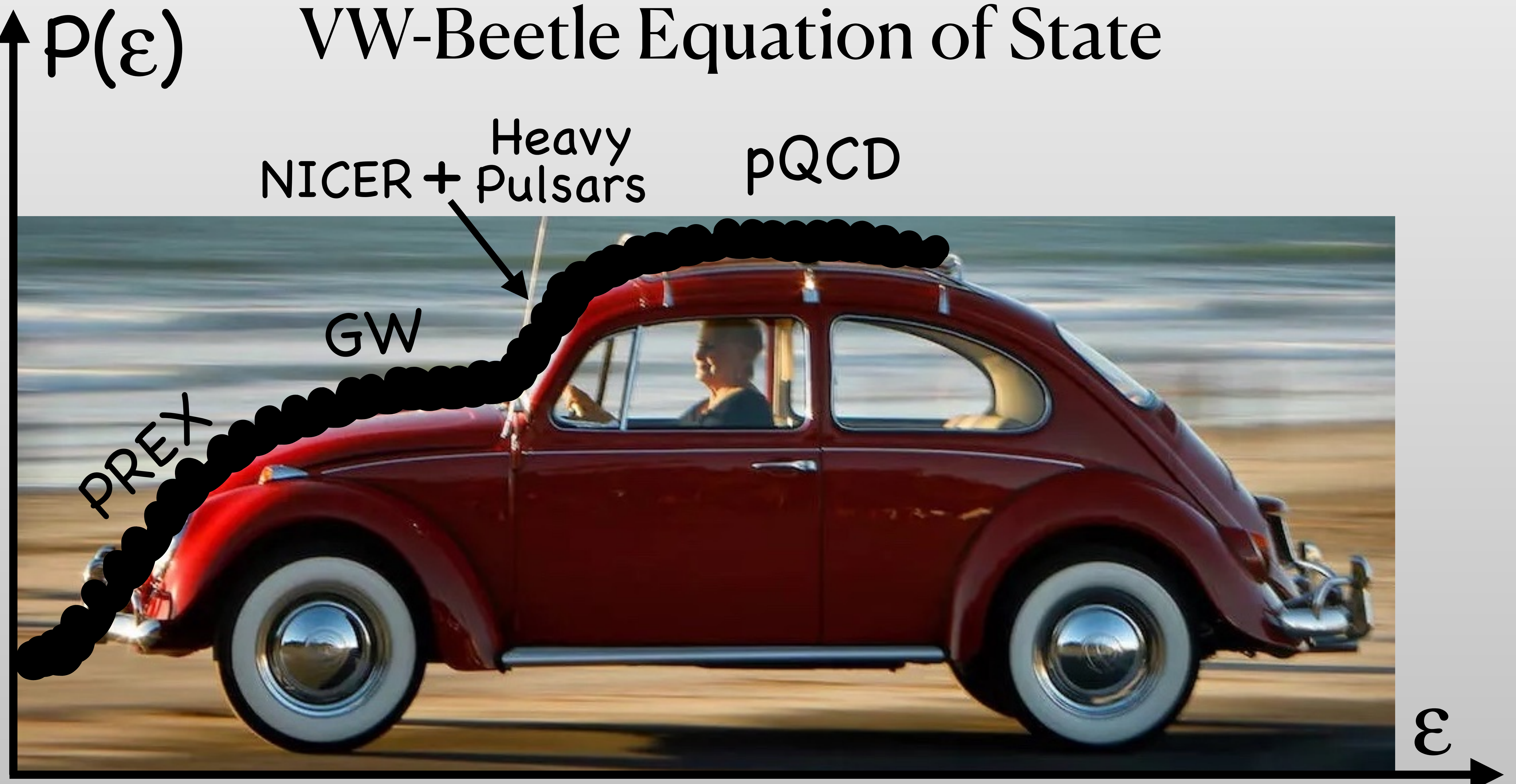


Gravitational-wave detector sensitivities

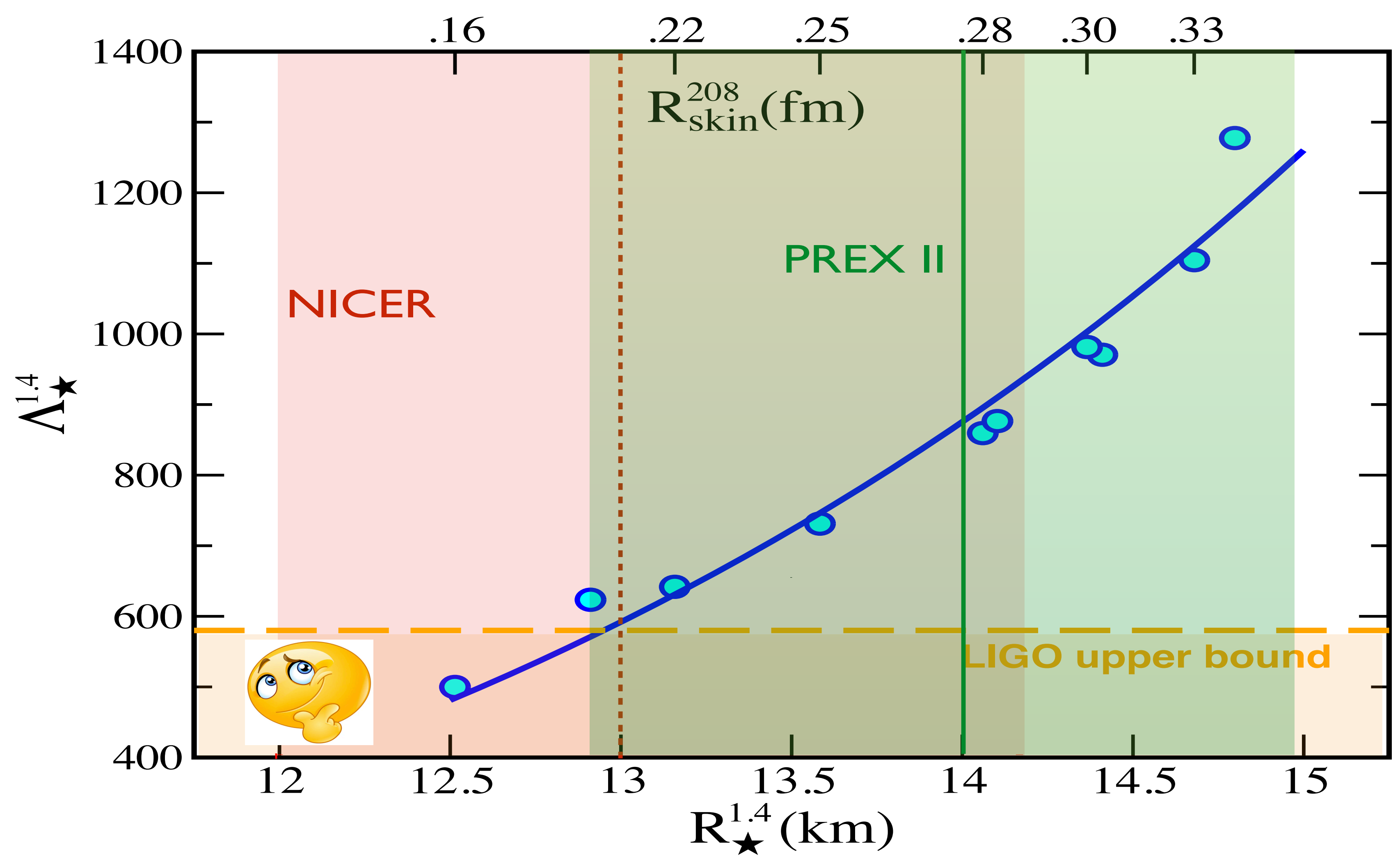


Unveiling the GW Universe



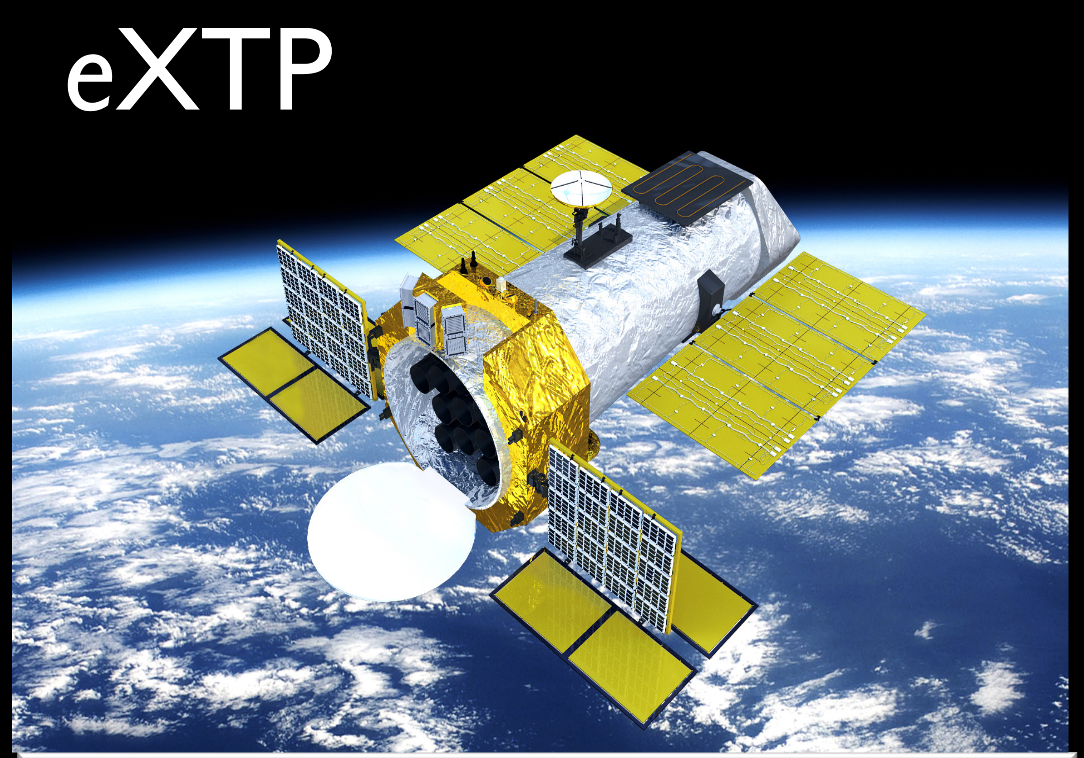


Exciting possibility: If all confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?)

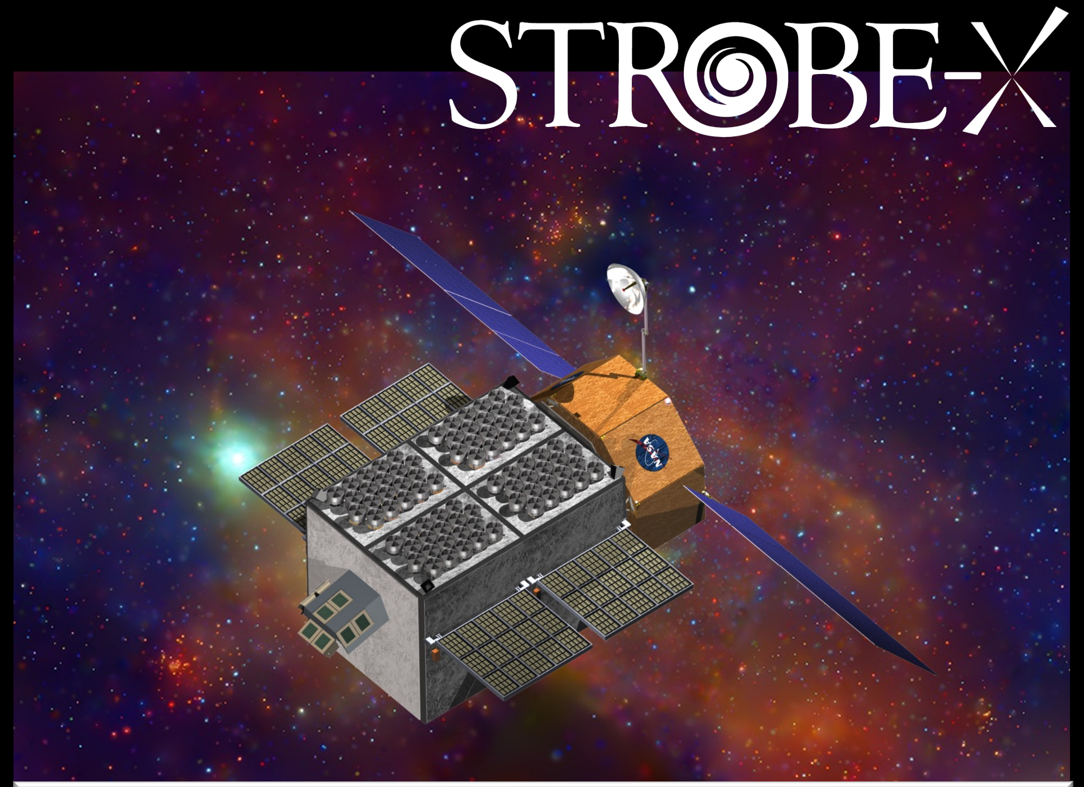


LARGE AREA X-RAY SPECTRAL-TIMING

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

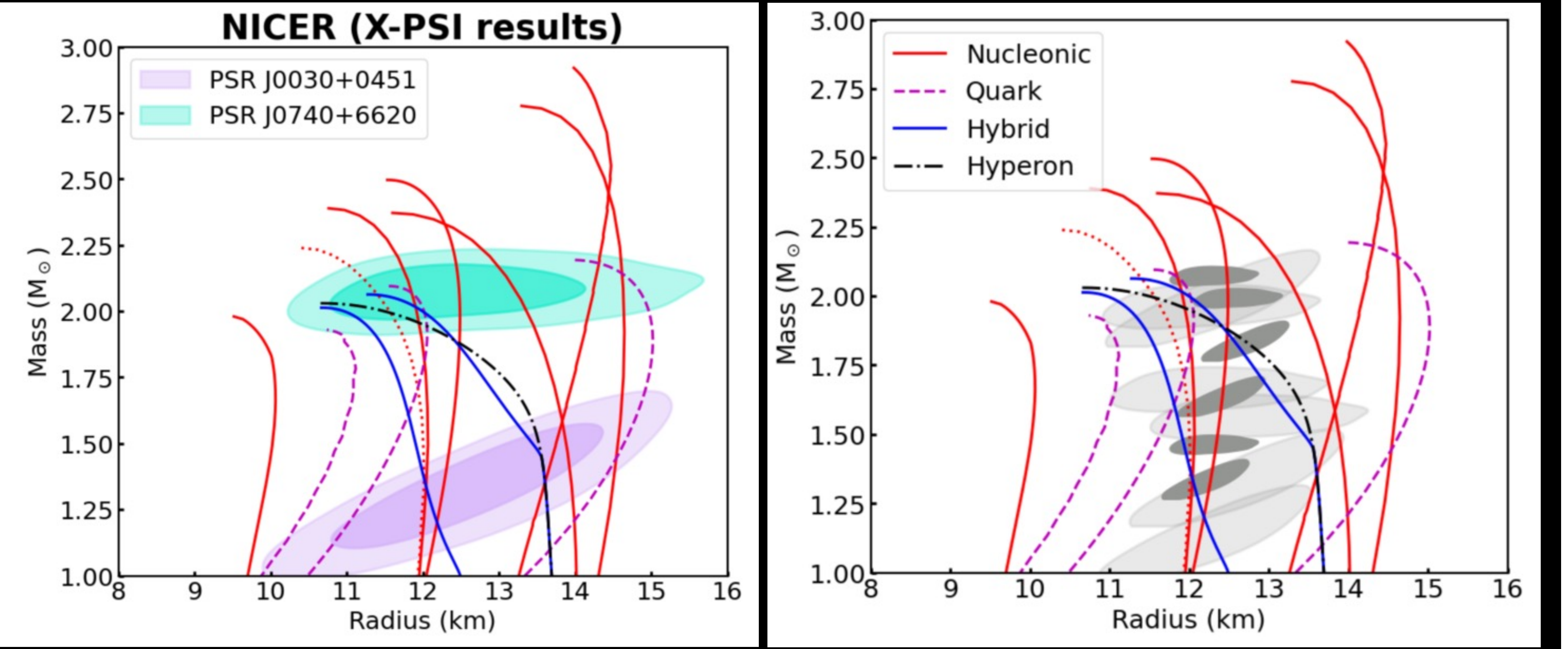


Chinese-European project
Zhang et al. 2019



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

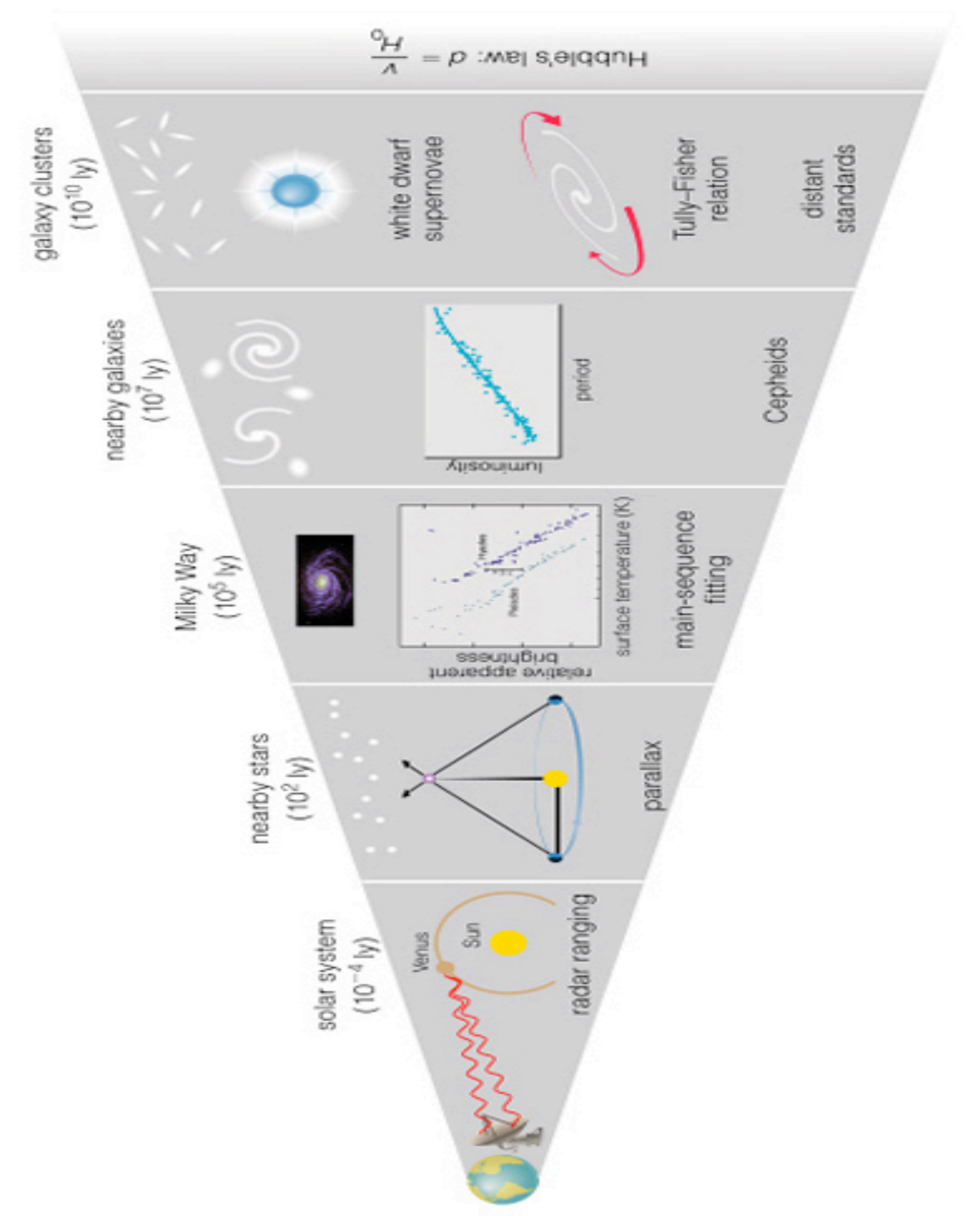
STROBE-X/EXTP PROSPECTS



95% credible regions shown

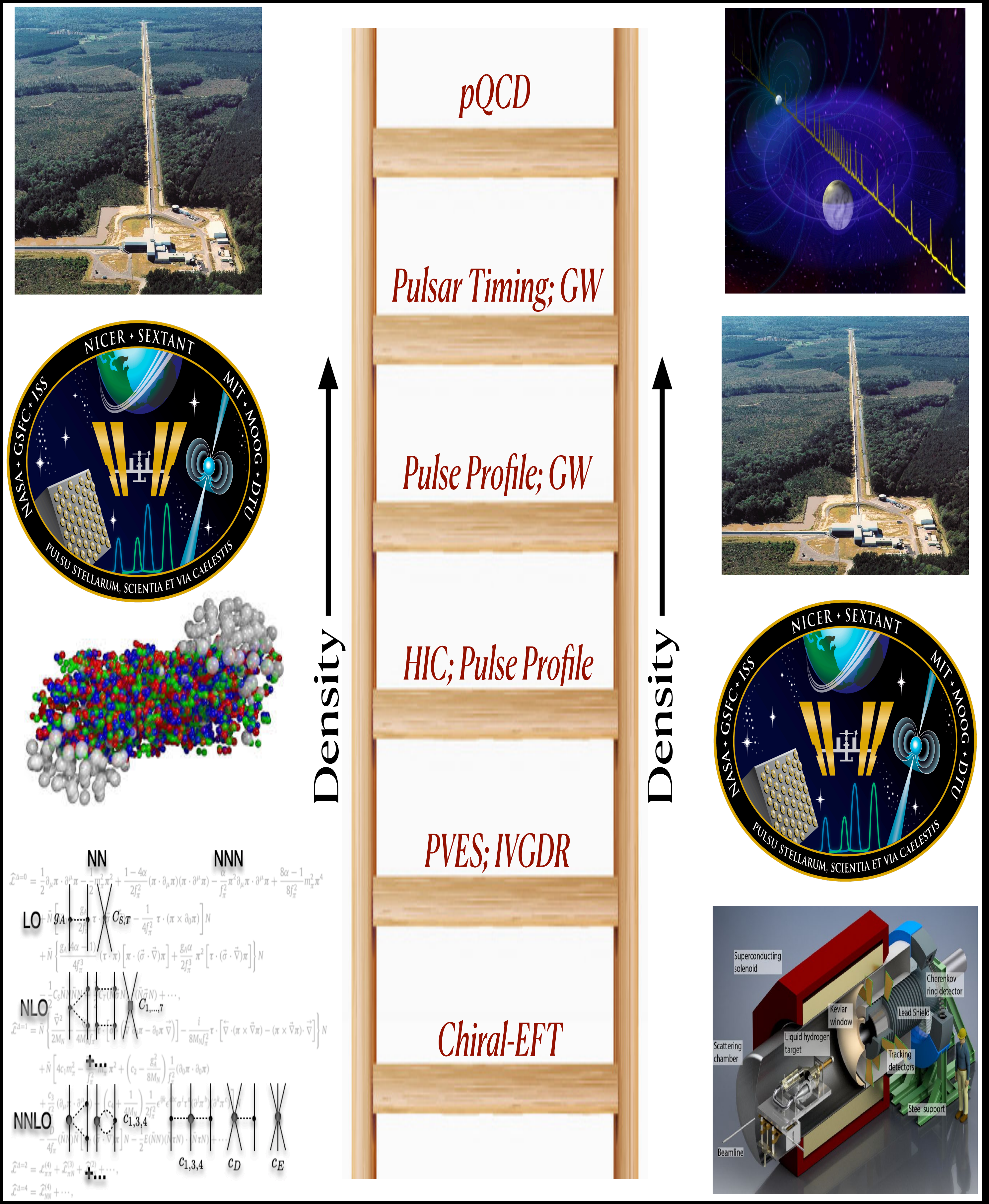
The Cosmic Distance Ladder

Succession of methods to determine the distances to celestial objects. Each rung of the ladder provides information that can be used to determine the distances at the next higher rung.



The EOS Density Ladder

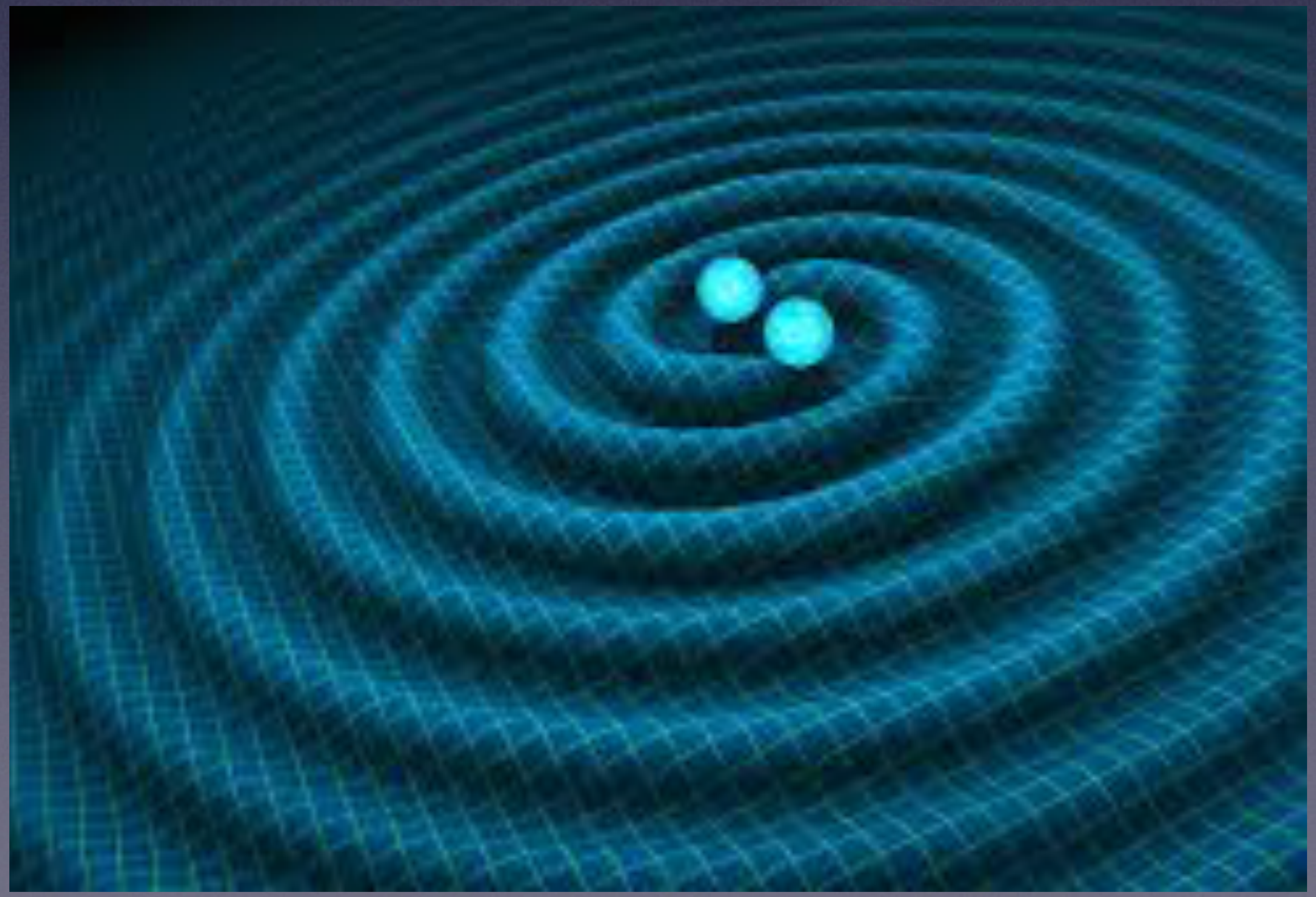
Each rung on the ladder relies on other methods for measuring the **EOS** that are often piggybacking on a neighboring one.

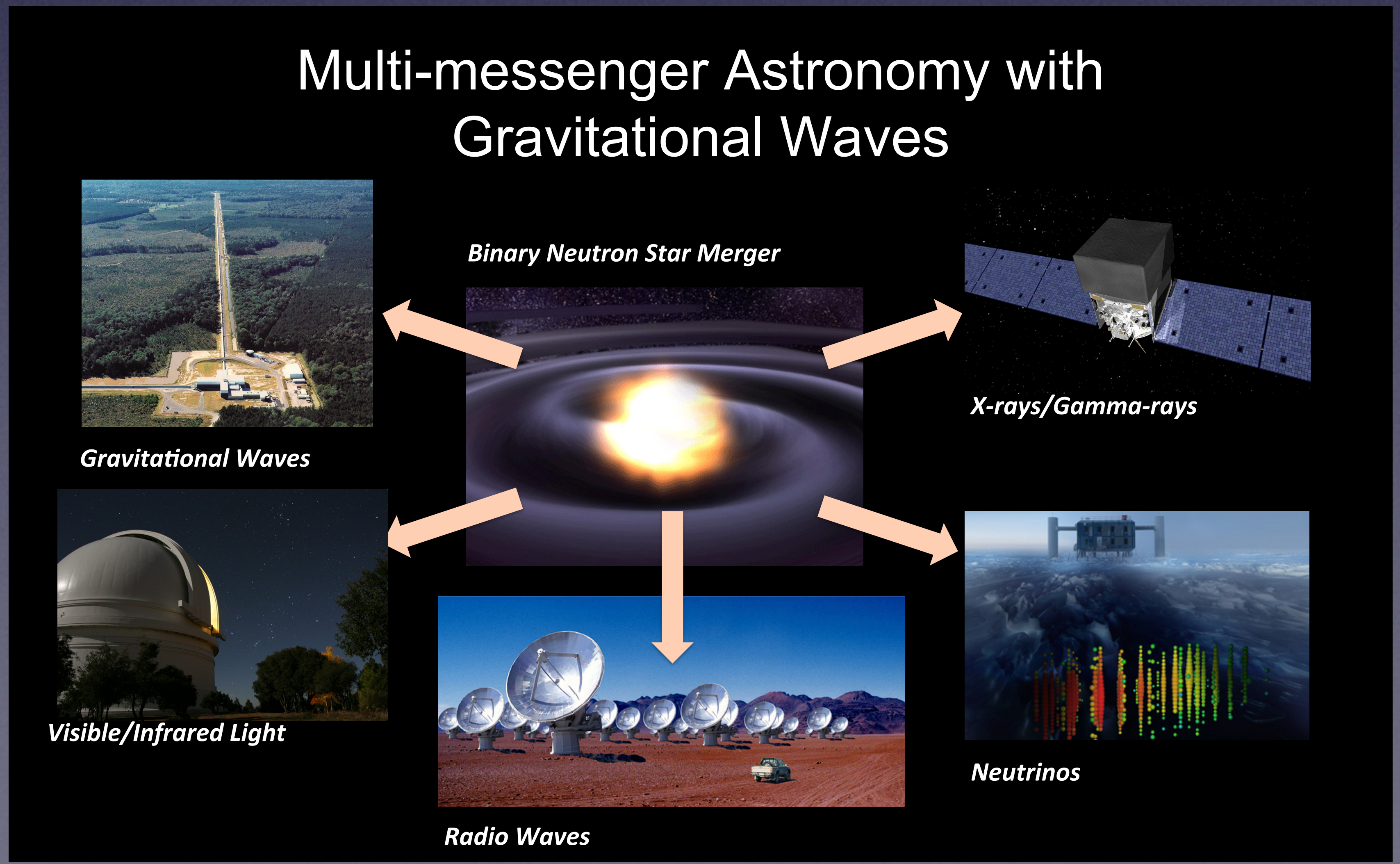


Conclusions: We have entered the golden era of neutron-star physics

- 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 fascinating physics!





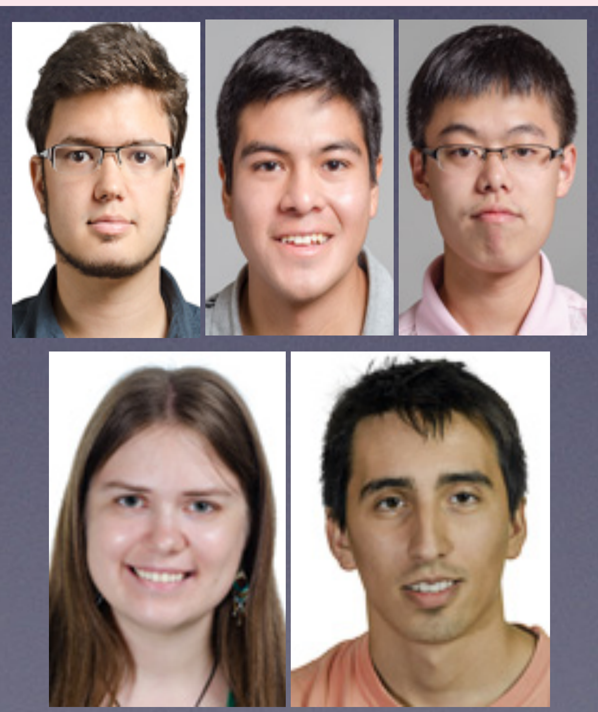
My FSU Collaborators

- 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

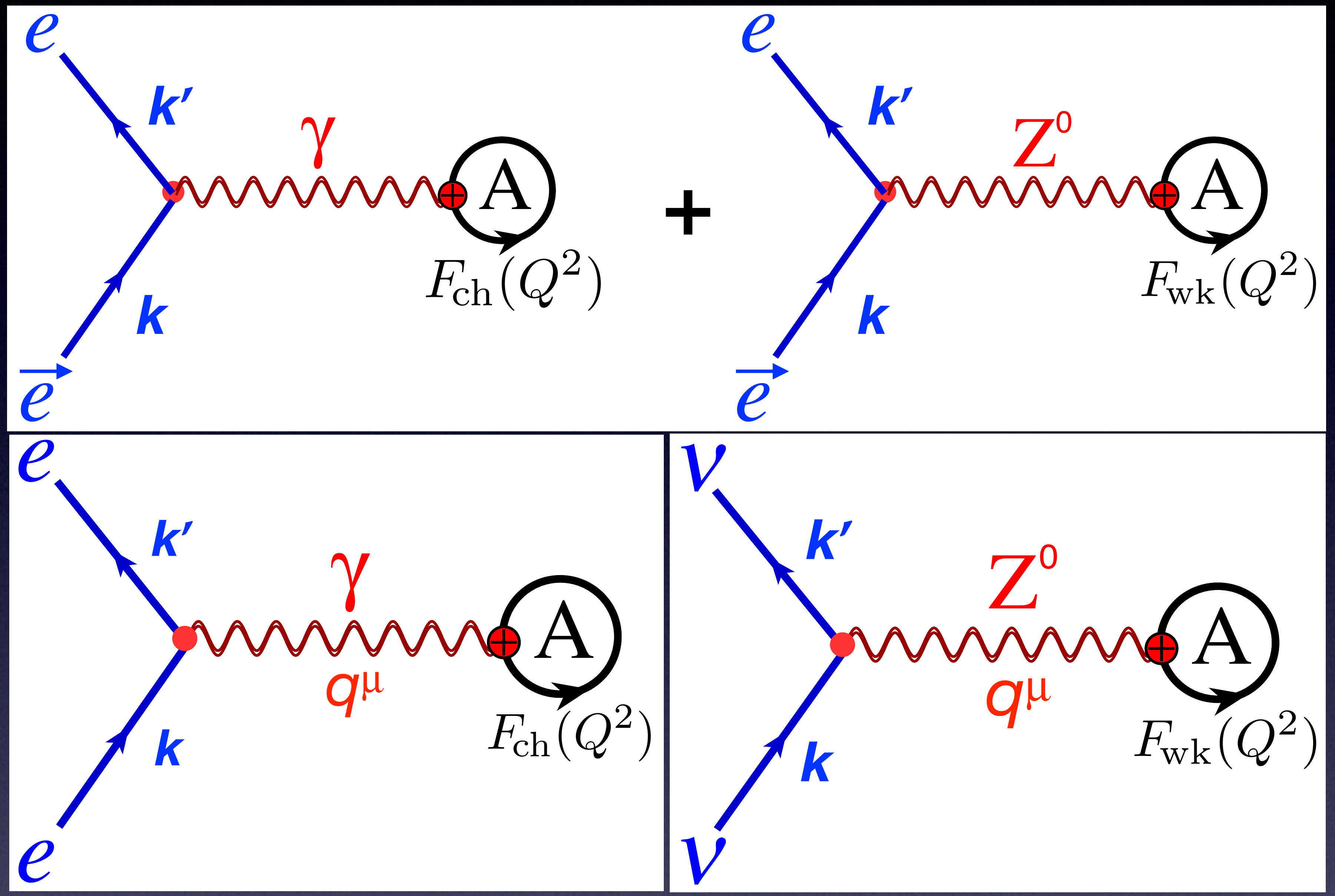
- **Pablo Giuliani**
- **Daniel Silva**
- **Junjie Yang**

The New Generation

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

Backup Slides

Electroweak Probes of Nuclear Densities

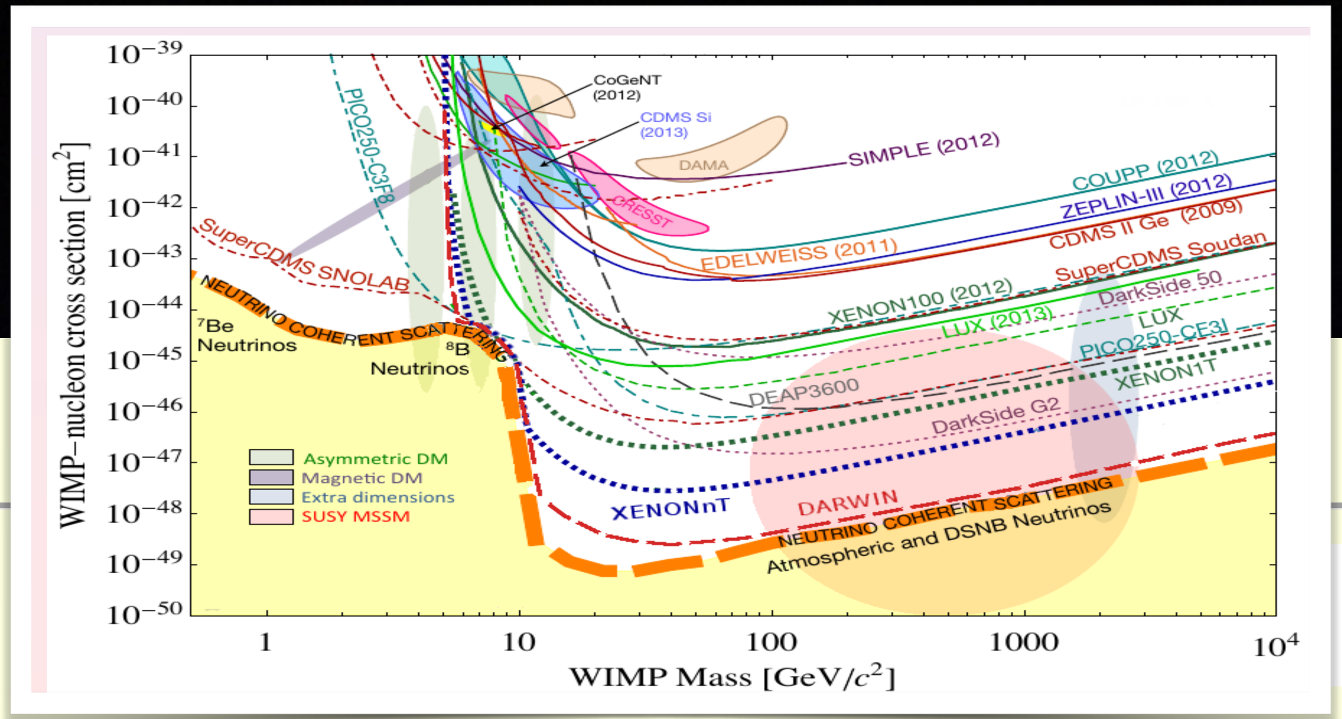


$$A_{PV}(Q^2) = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_{\rm wk} F_{\rm wk}(Q^2)}{Z F_{ch}(Q^2)}$$

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

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

CEvNS



Science REPORTS

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Observation of coherent elastic neutrino-nucleus scattering

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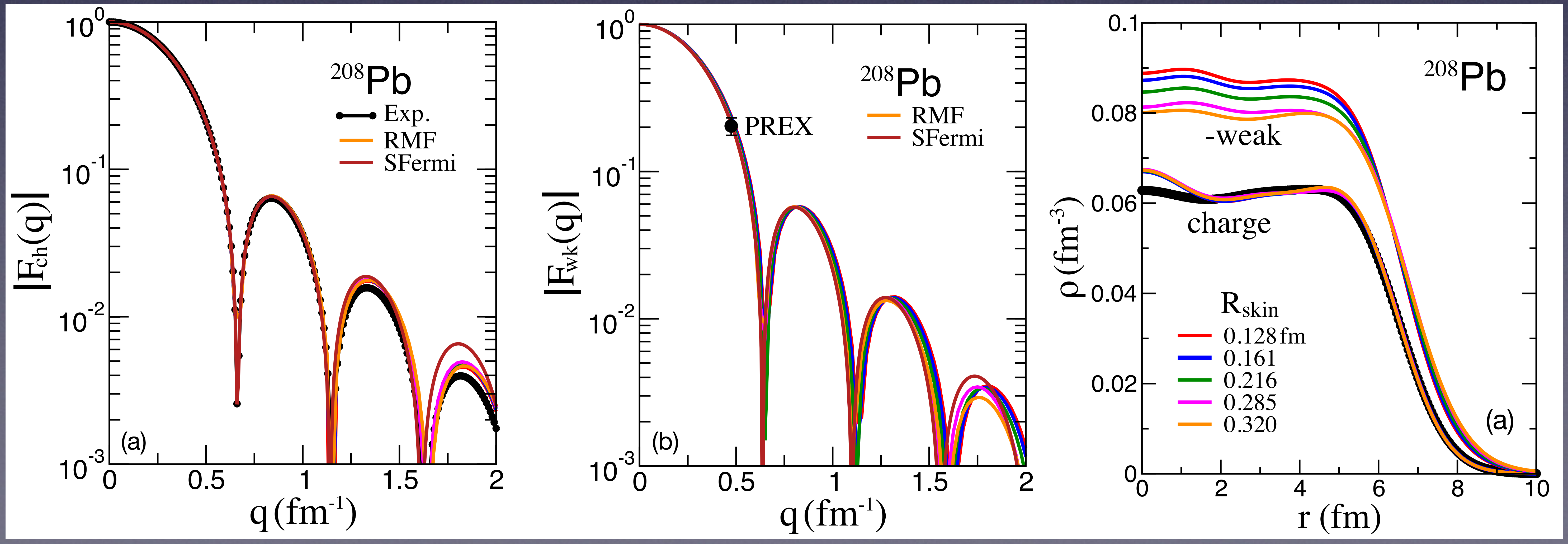
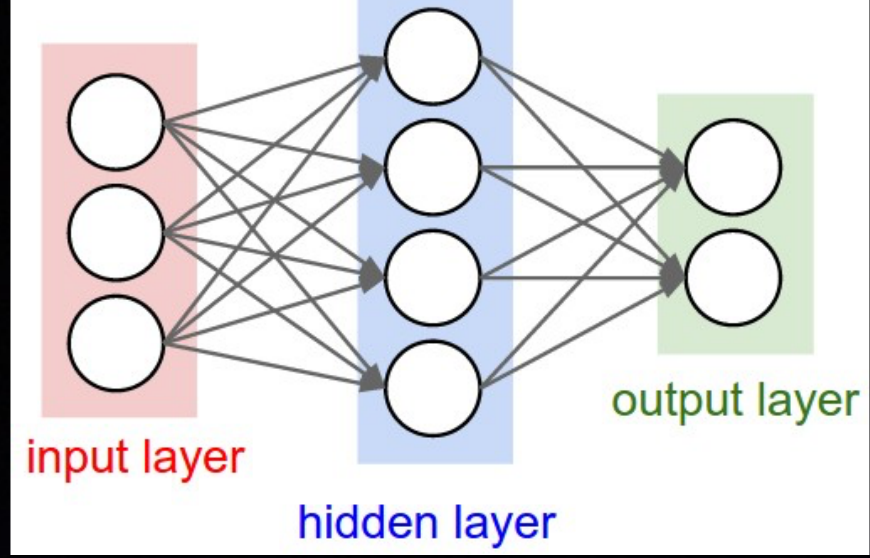
FRIB



Nuclear Theory meets Machine Learning



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

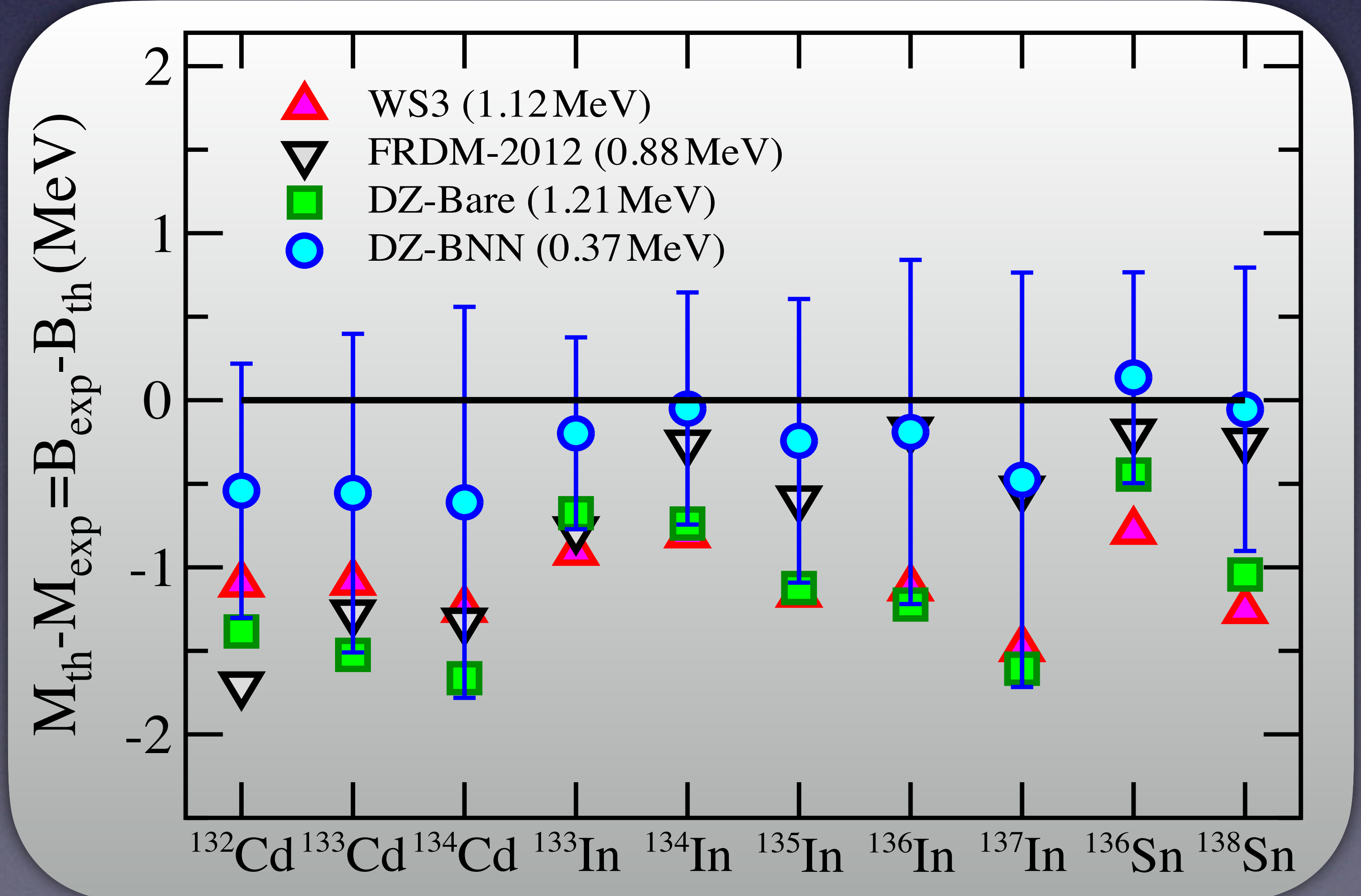
The paradigm

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

- Systematic scattering greatly reduced
- Predictions supplemented by theoretical errors

Train with AME2012
then predict AME2016

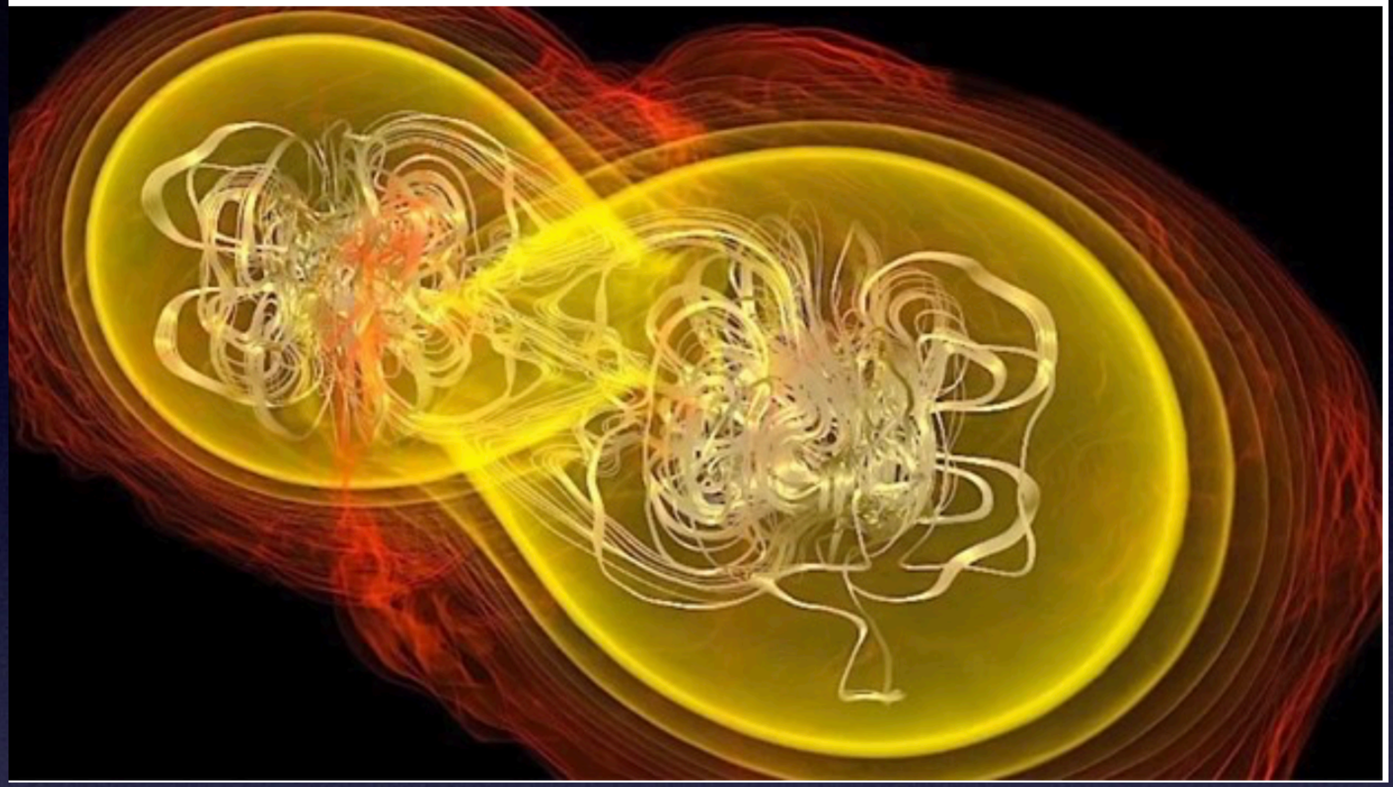
Re-generating Richard Feynman



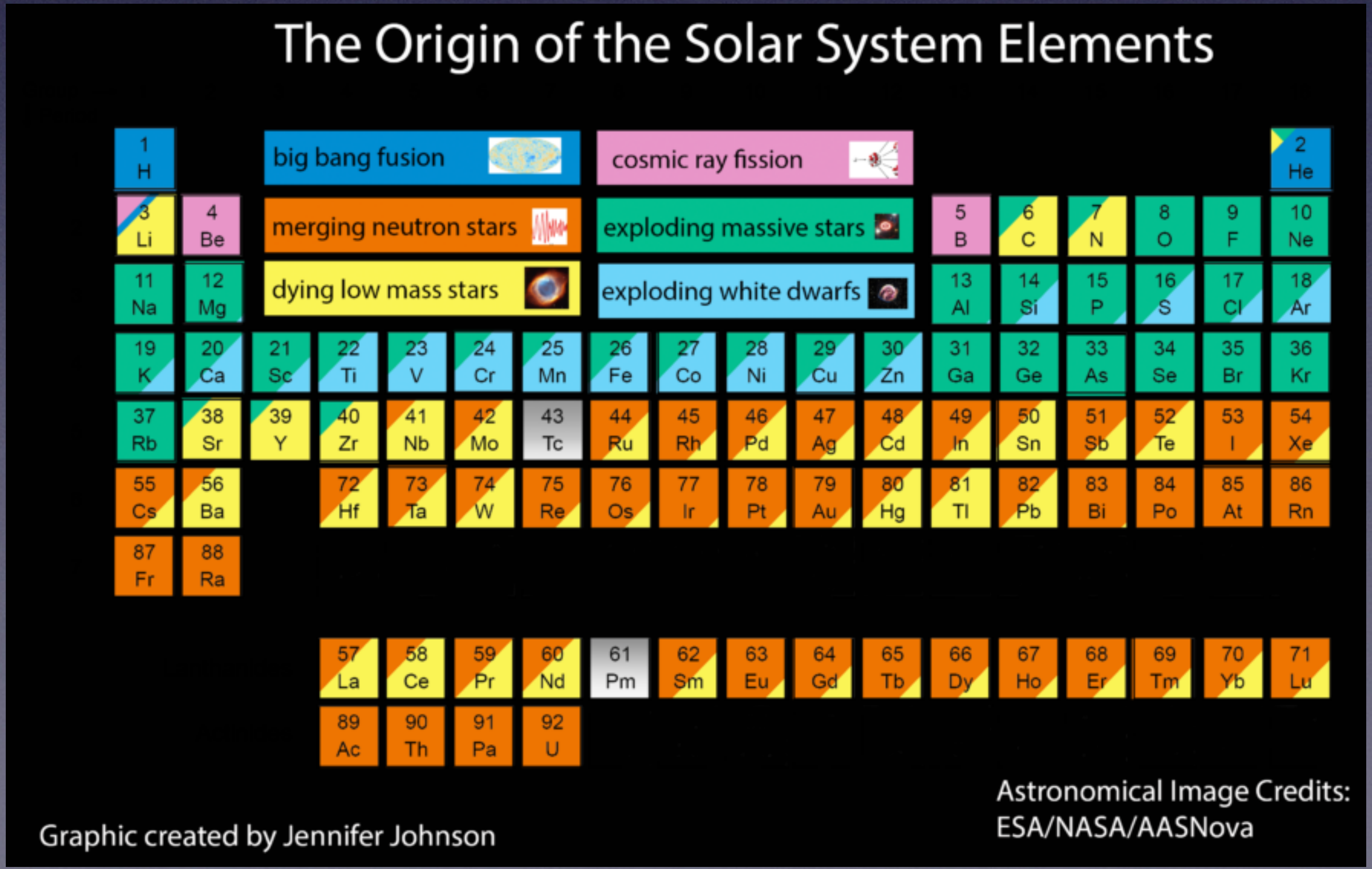
Duflo-Zuker + BNN

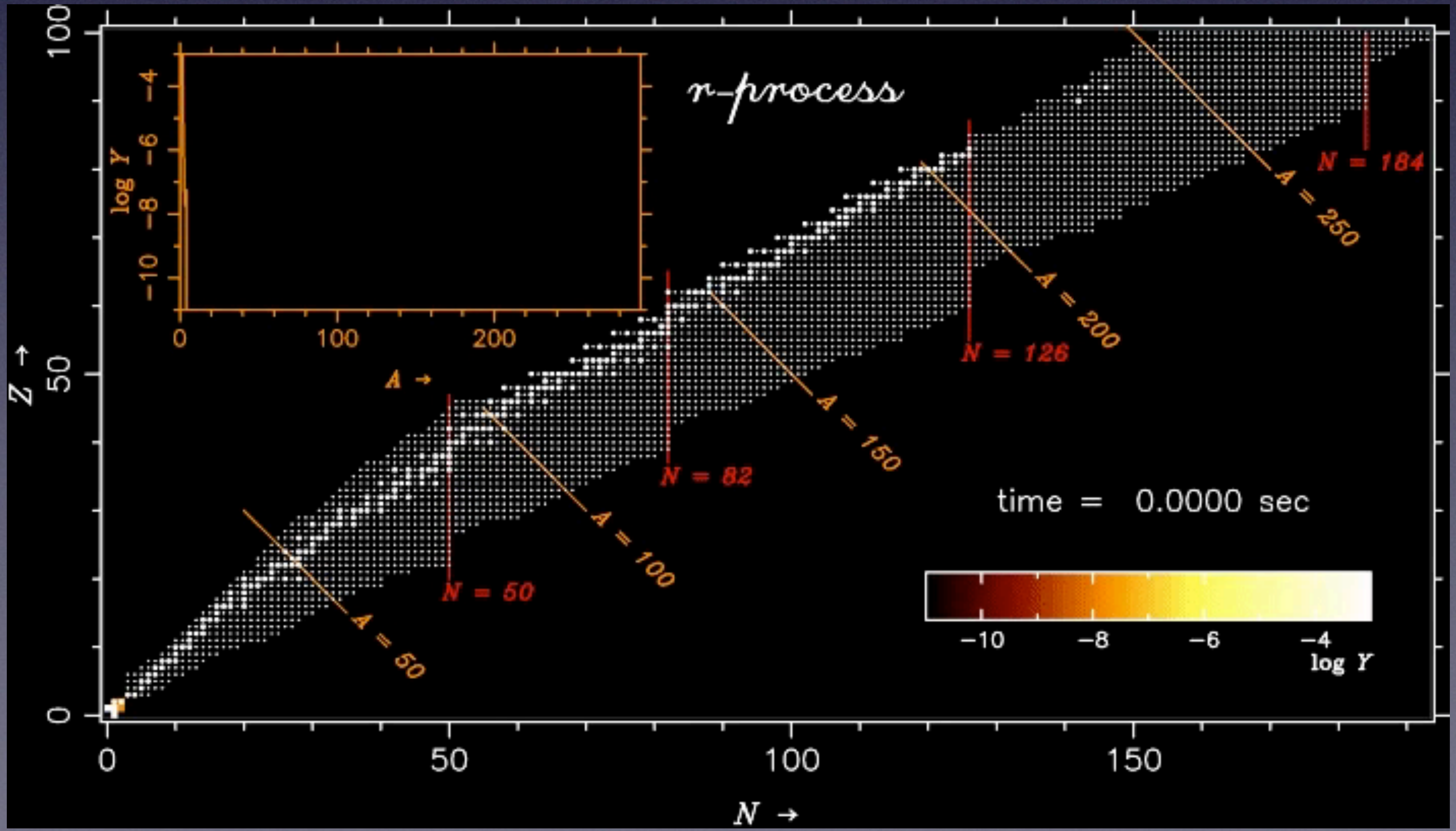
The New Periodic Table of the Elements

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





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

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

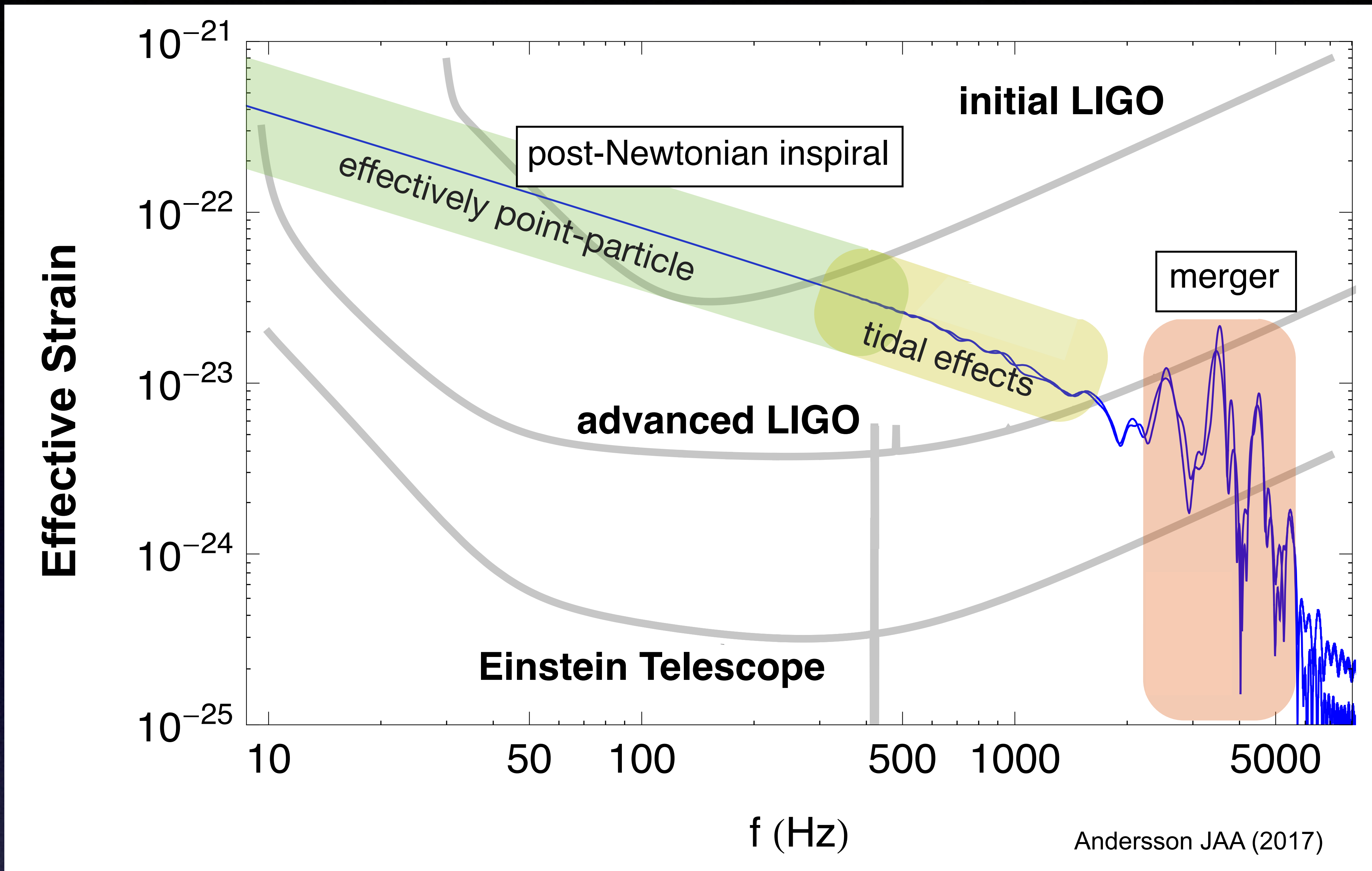
    Orbital separation:1000 km (20 minutes)

- 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)



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

I = mass quadrupole moment of the source

R = source distance

$$\text{If} \quad \ddot{I}(t) \rightarrow M a^2 \omega^2$$

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

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

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