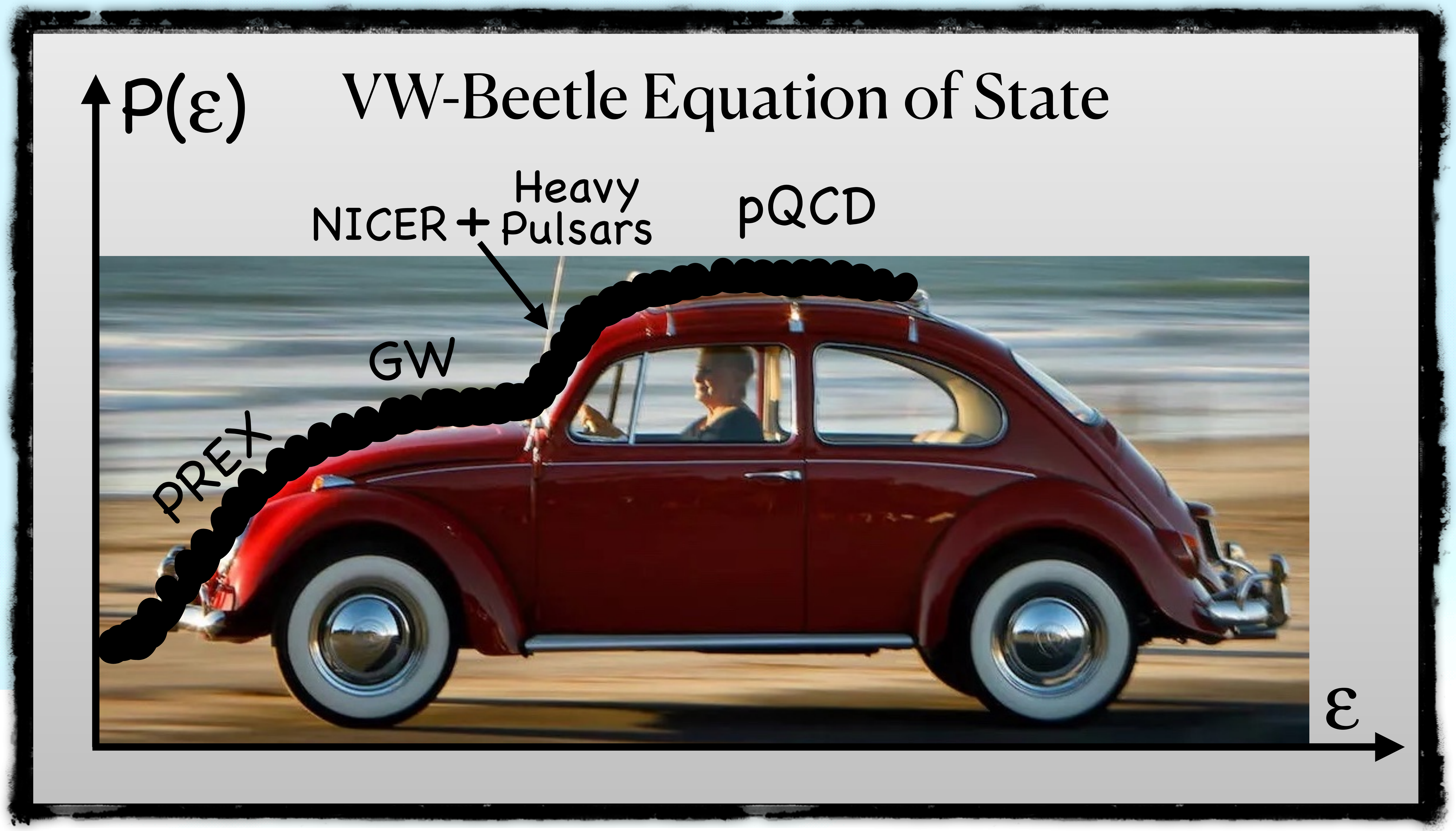
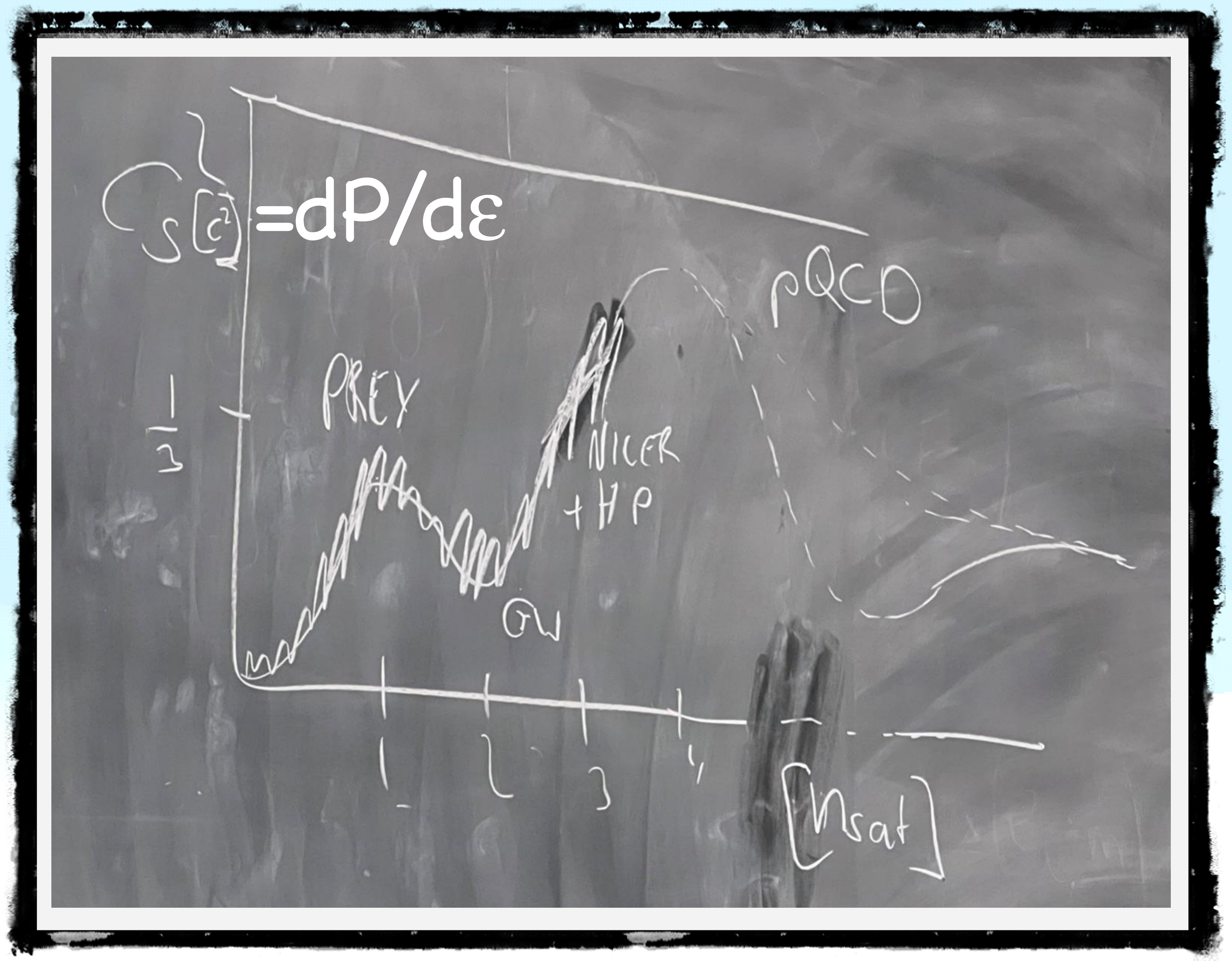
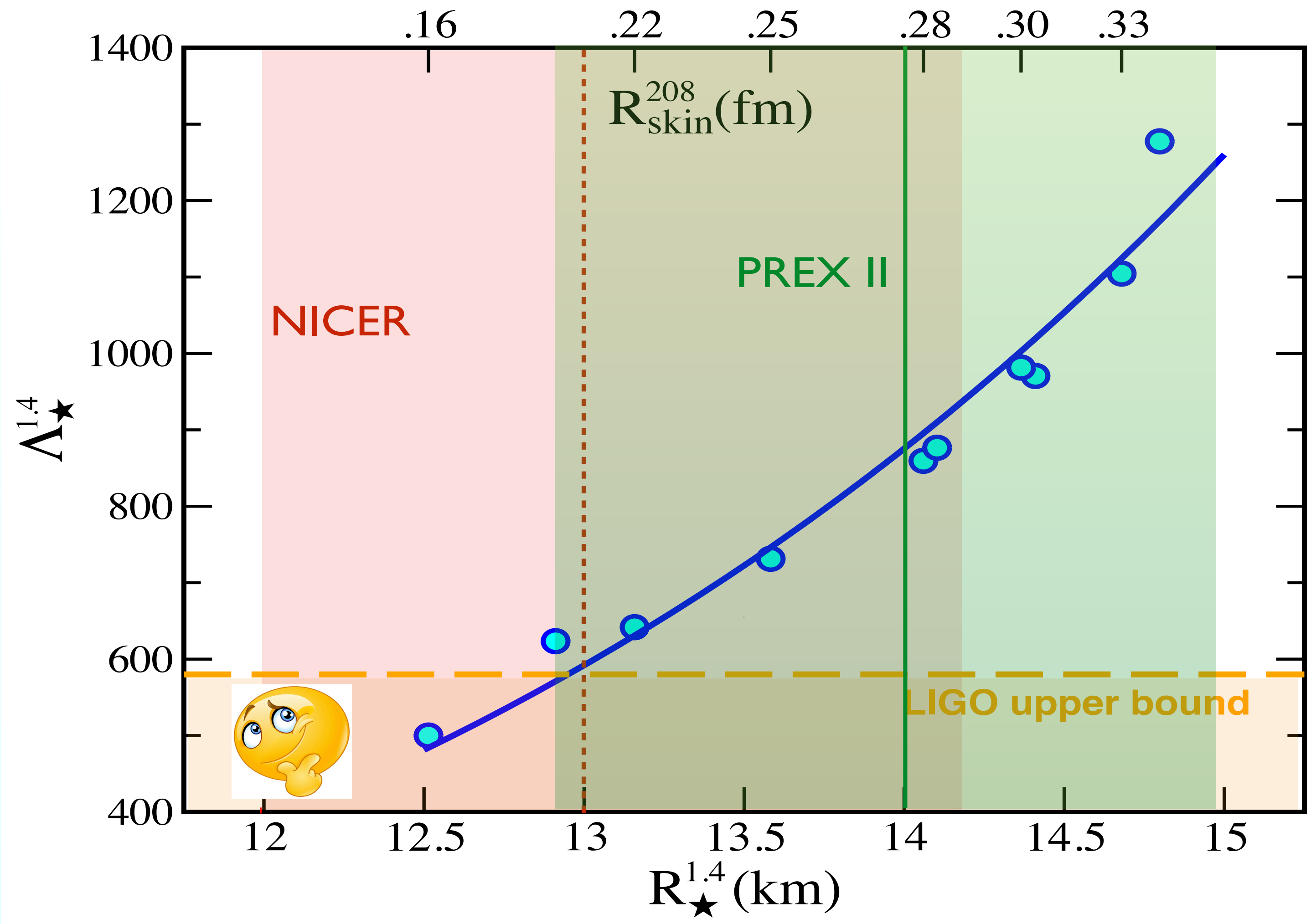
The Equation of State

The Speed of Sound







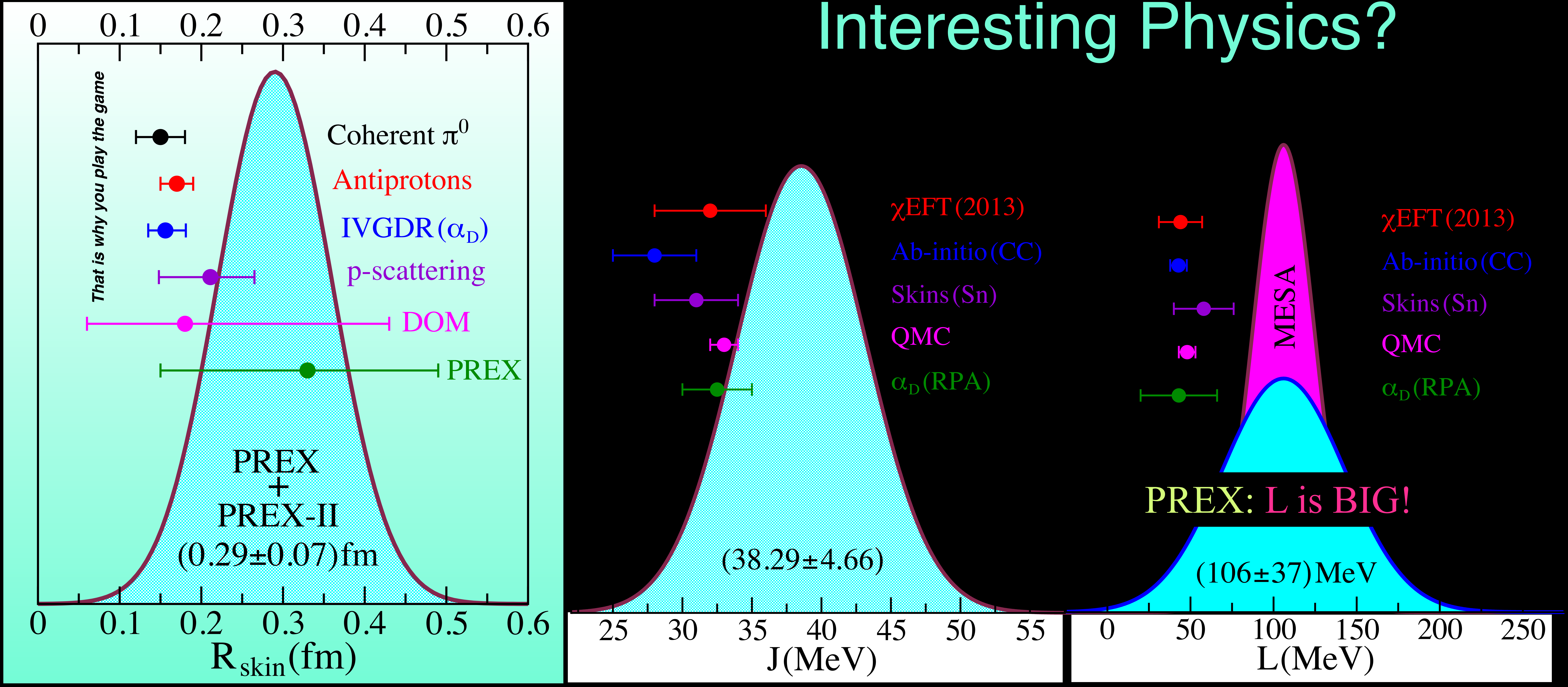
Tantalizing Possibility

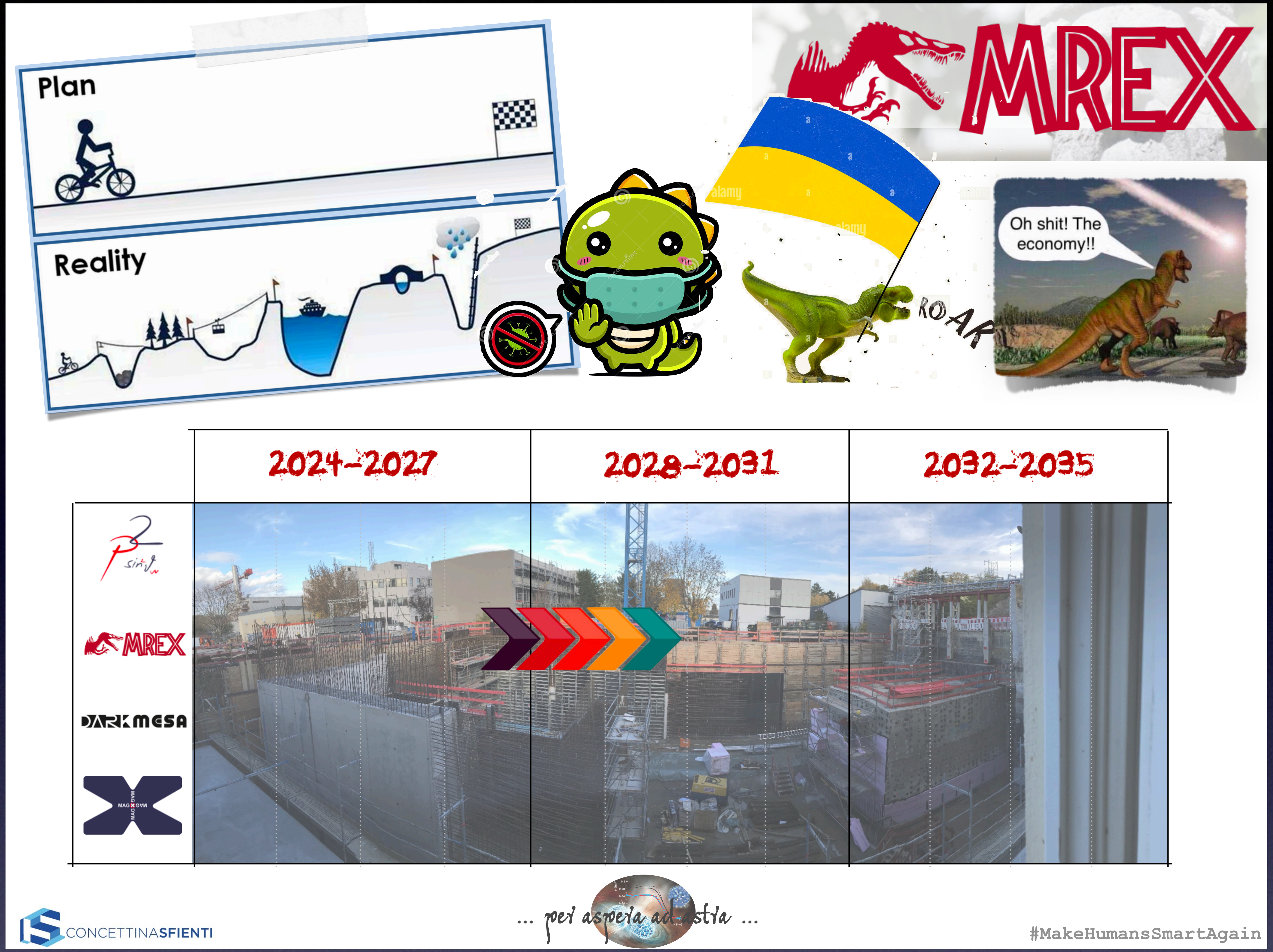
- *Laboratory Experiments suggest large neutron radii for Pb* $\lesssim 1\rho_0$
- *Gravitational Waves suggest small stellar radii* $\gtrsim 2\rho_0$
- *Electromagnetic Observations suggest large stellar masses* $\gtrsim 4\rho_0$

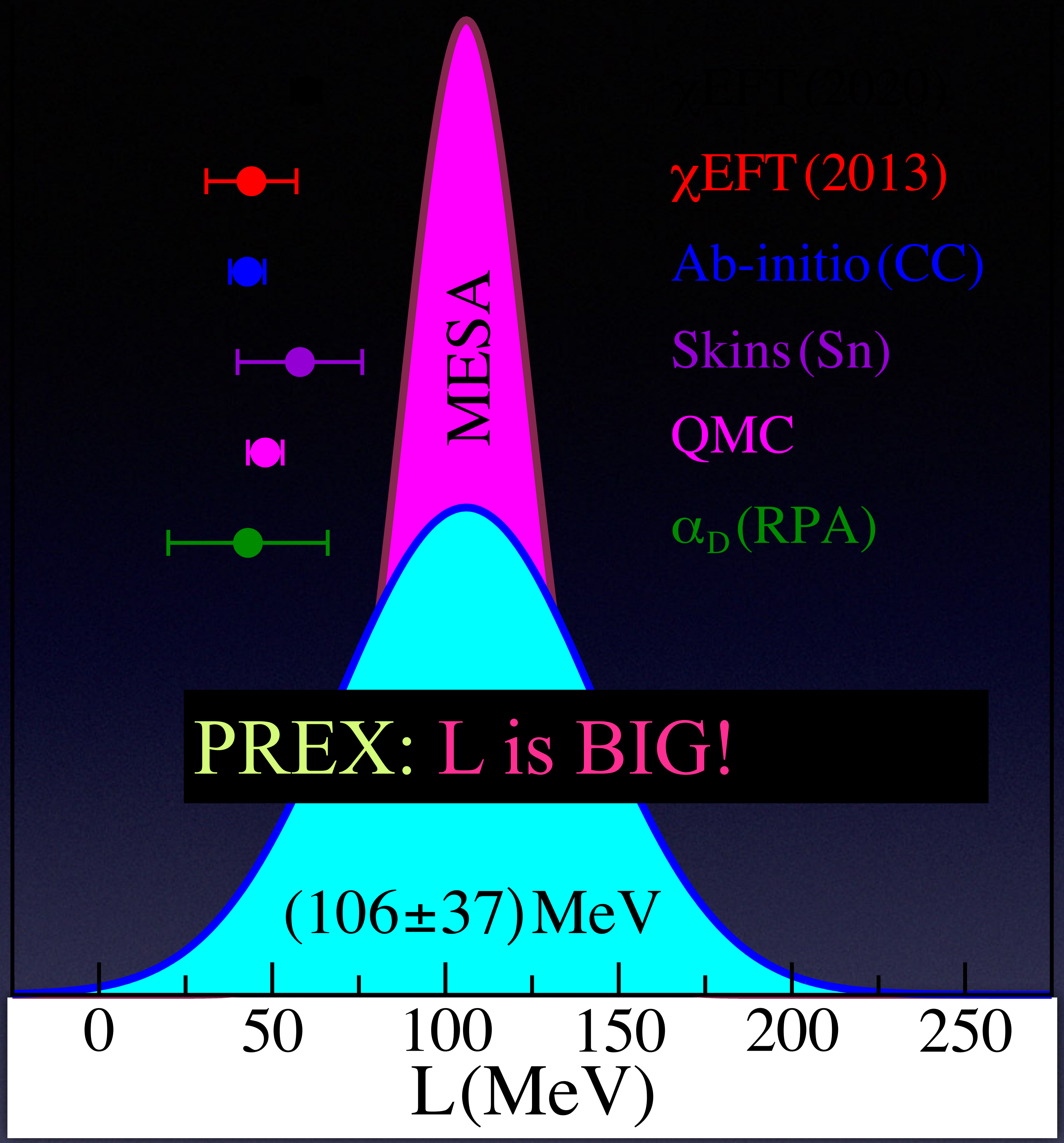
Exciting possibility: If all are confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?)

PREX, PREX-II, MREX

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

Nuclear Excitation Modes

	Laboratory measurements on nuclei	Astronomical observations of neutron stars
Radius	PREX, CREX	NICER
Polarizability	Electric dipole	Gravitational deformability

TOPICAL REVIEW

Neutron skins of atomic nuclei: per aspera ad astra

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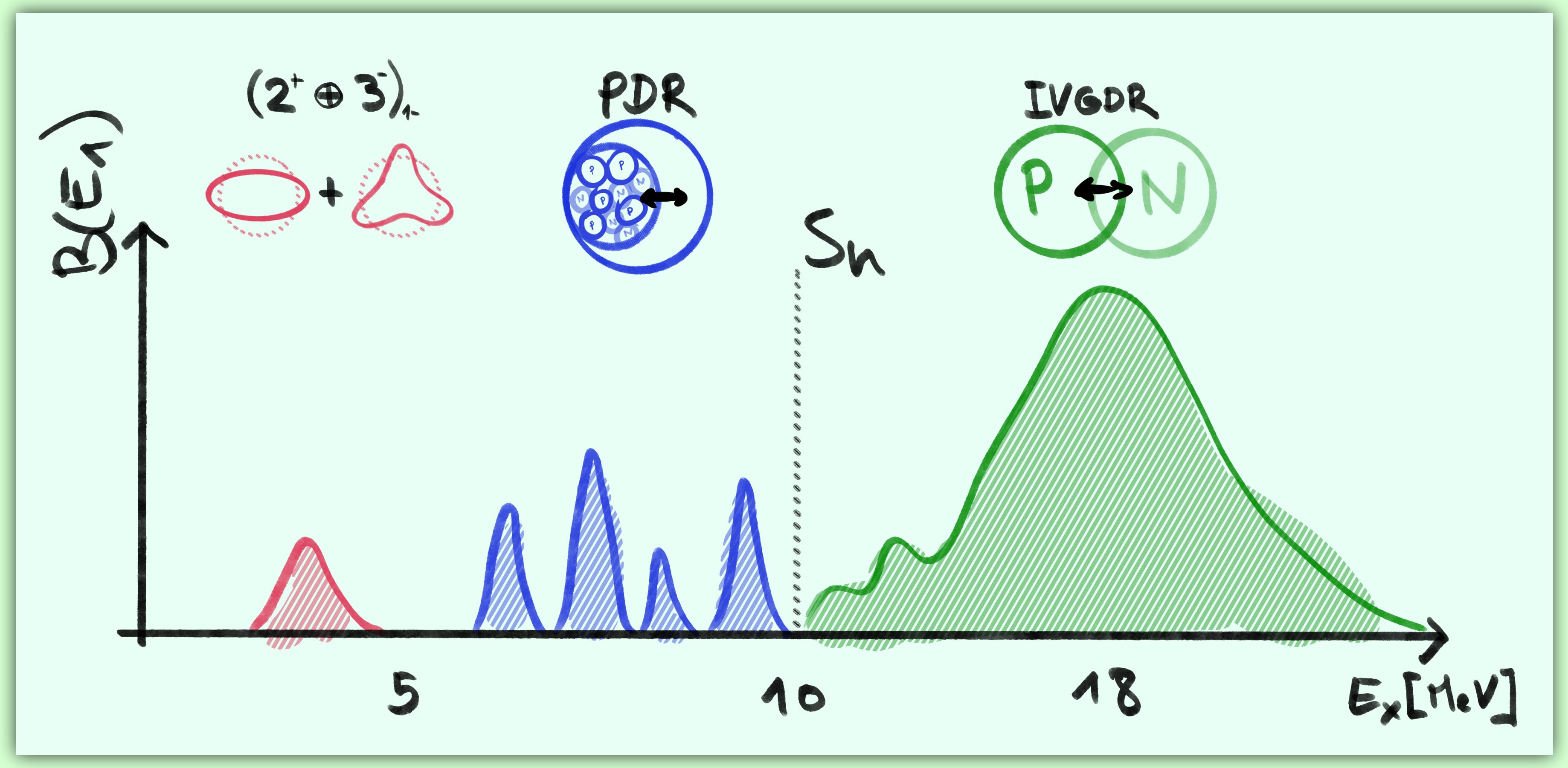
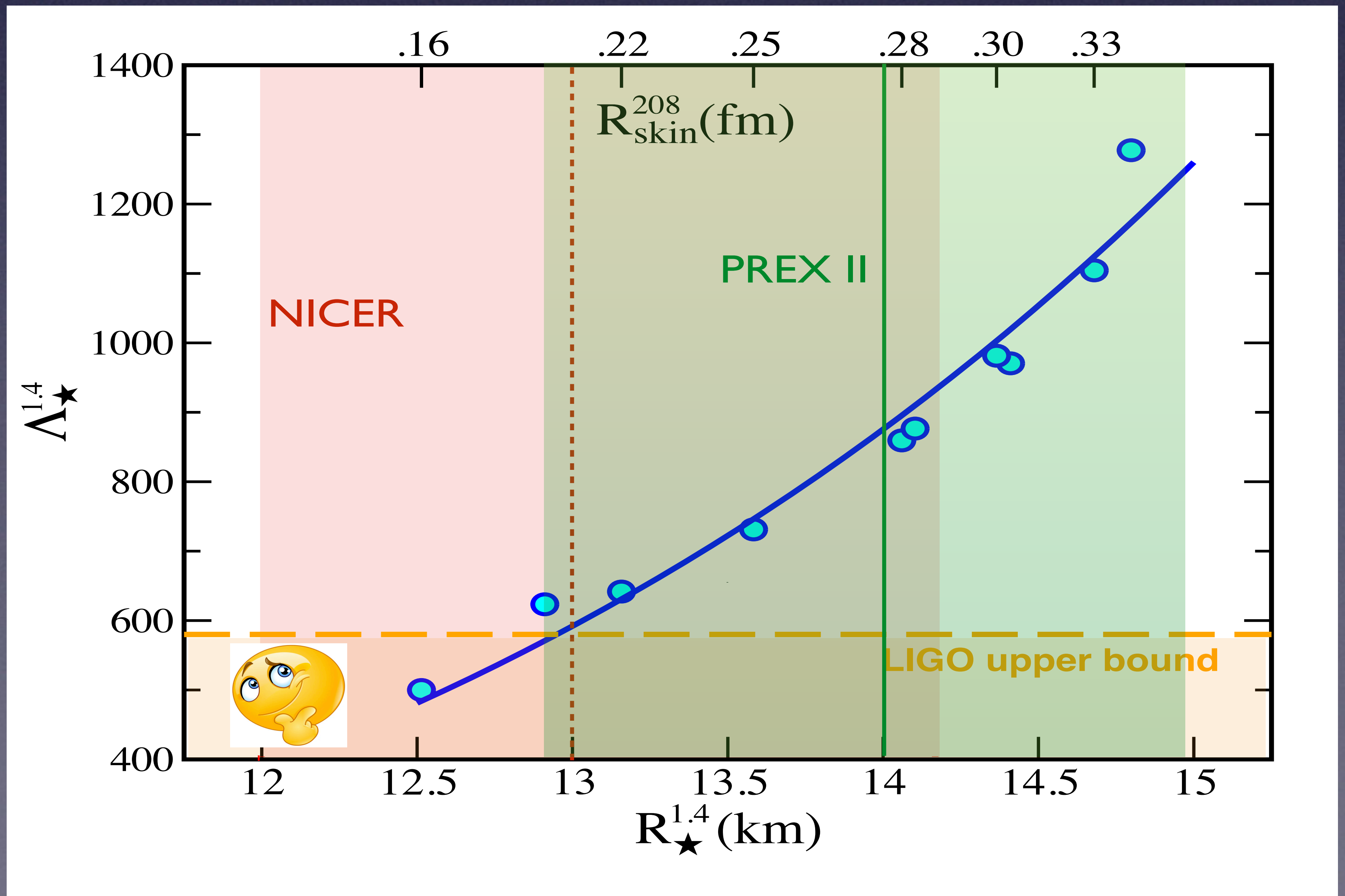
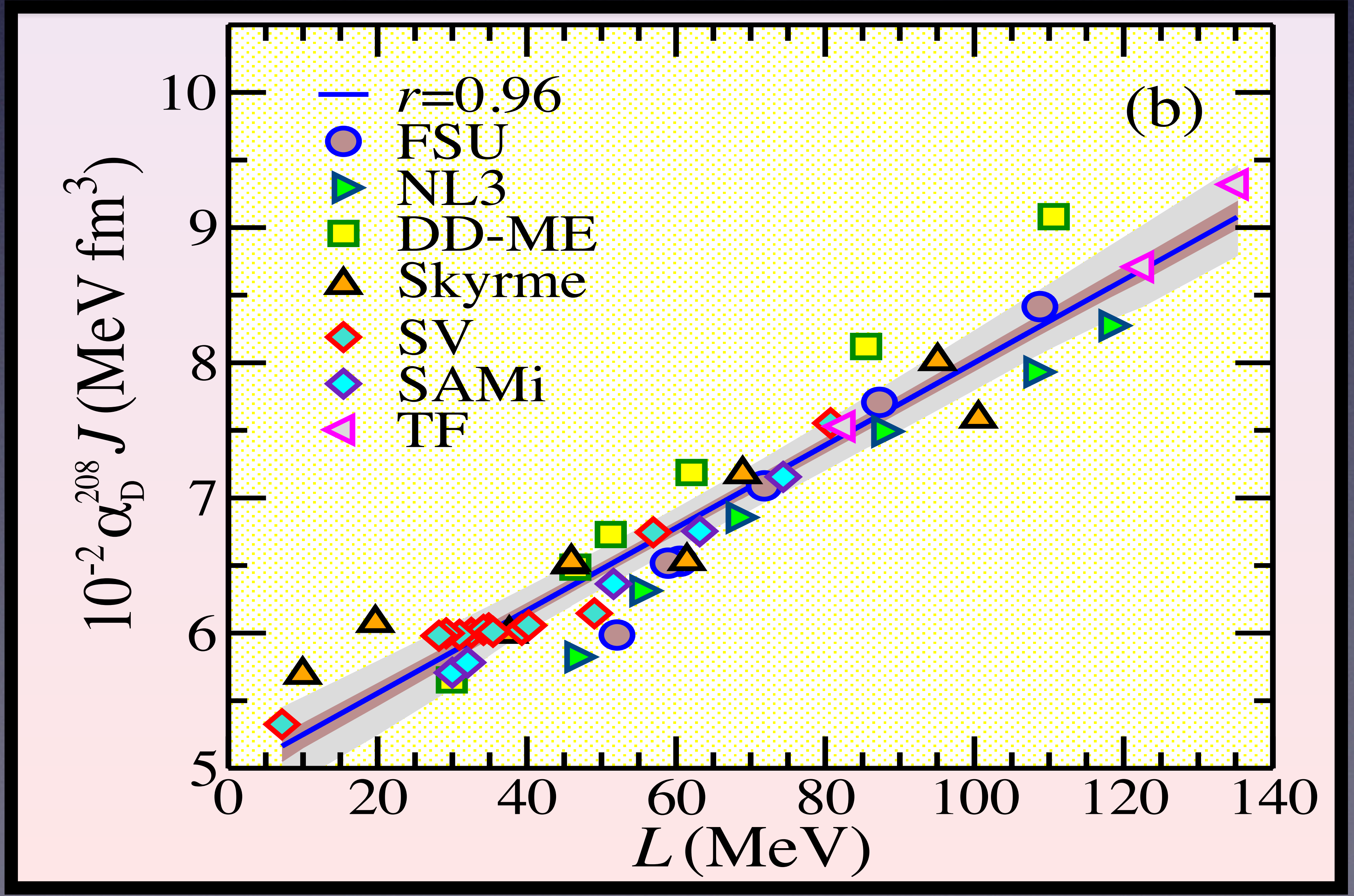
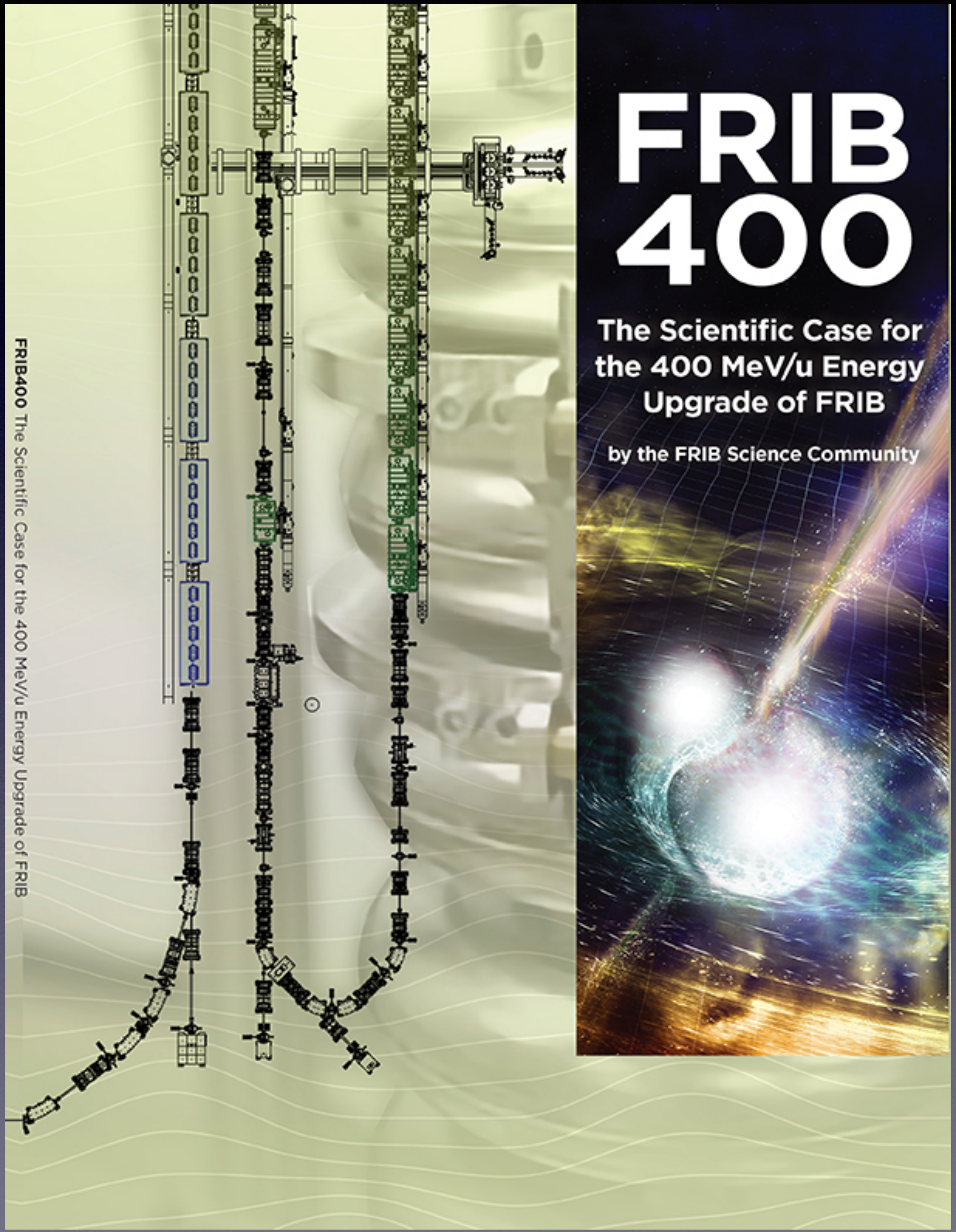






Very clean electromagnetic experiment

Theory is lagging slightly behalf



More generally, the nature of neutron stars, their crust, and layers, involve nuclear matter significantly more neutron-rich than normal matter and its properties are relevant for interpreting a wealth of astronomical data [Sch13, Oer17]. All of these observations point to the importance of the most neutron-rich isotopes and the need for FRIB400.

The following sections show that with the extended reach of 400 MeV/u beam production, FRIB400 will be poised to answer many of the key questions, such as: What do gravitational waves tell us about the neutron-matter EOS? What do neutrino signals reveal about supernova evolution? What do neutron-star cooling rates and astronomical X-ray data tell us about the structure of neutron stars? What are the sites of the *r* process and how does it proceed to produce the heavy elements?

1.1 The nature of neutron stars and the nuclear equation of state

The EOS of nuclear matter relates temperature, pressure, and density of a nuclear system. It governs not only properties of nuclei and neutron stars but also the dynamics of nucleus-nucleus collisions and neutron-star mergers. The EOS also determines the amount of ejected matter from a neutron-star merger, which subsequently undergoes nucleosynthesis to form heavy elements up to uranium and beyond [Ros99, Bov17, Kas17, Fuj18, Hor19]. The ultimate fate of a neutron-star merger is also impacted by the EOS, determining whether the colliding neutron stars collapse promptly into a black hole, remain a single neutron star, or form a transient neutron star that collapses later into a black hole [Bau17]. The recent observation of GW170817 demonstrated that the gravitational-wave signal from neutron-star merger events encodes the properties of nuclear matter and its EOS through the tidal deformabilities of the neutron stars during in-spiral [Abb17a, Zha18, Pie19, Car19].

FRIB400 will allow laboratory study of asymmetric nuclear matter at twice normal nuclear density. Understanding dense, neutron-rich matter is important for interpretation of multi-messenger data from neutron-star mergers.

Given this sensitivity, the interpretation of multi-messenger observations from neutron-star mergers and their nucleosynthesis therefore requires a better understanding of the nuclear EOS. This makes experiments with FRIB400, which can probe the important higher density regime, particularly timely. In addition, given that gravitational-wave signals from neutron-star mergers offer unique new opportunities to directly constrain the nuclear EOS for very neutron-rich matter, laboratory constrains from measurements with neutron-rich nuclei at FRIB400 will provide additional constraints that will yield opportunities for significant new insight and discovery.

While the temperature dependence of the EOS is important for the description of mergers after the neutron stars make contact [Rad16, Han17], it builds on the understanding of cold nuclear matter. The EOS of homogeneous, cold nuclear matter can be expressed in terms of the density-dependent energy of the system. In leading order, the energy per nucleon

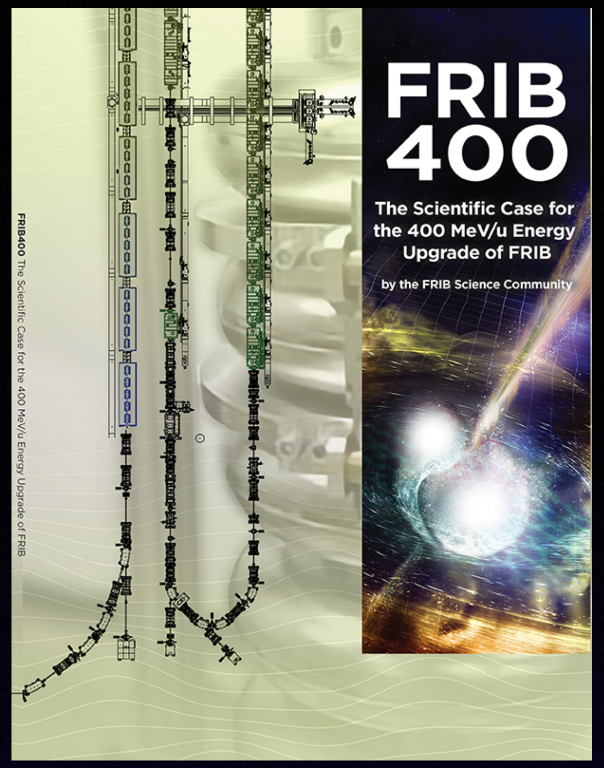
U.S. Department of Energy Office of Science Office of Nuclear Physics mission is accomplished by supporting scientists who answer overarching questions in major scientific thrusts of basic nuclear physics research

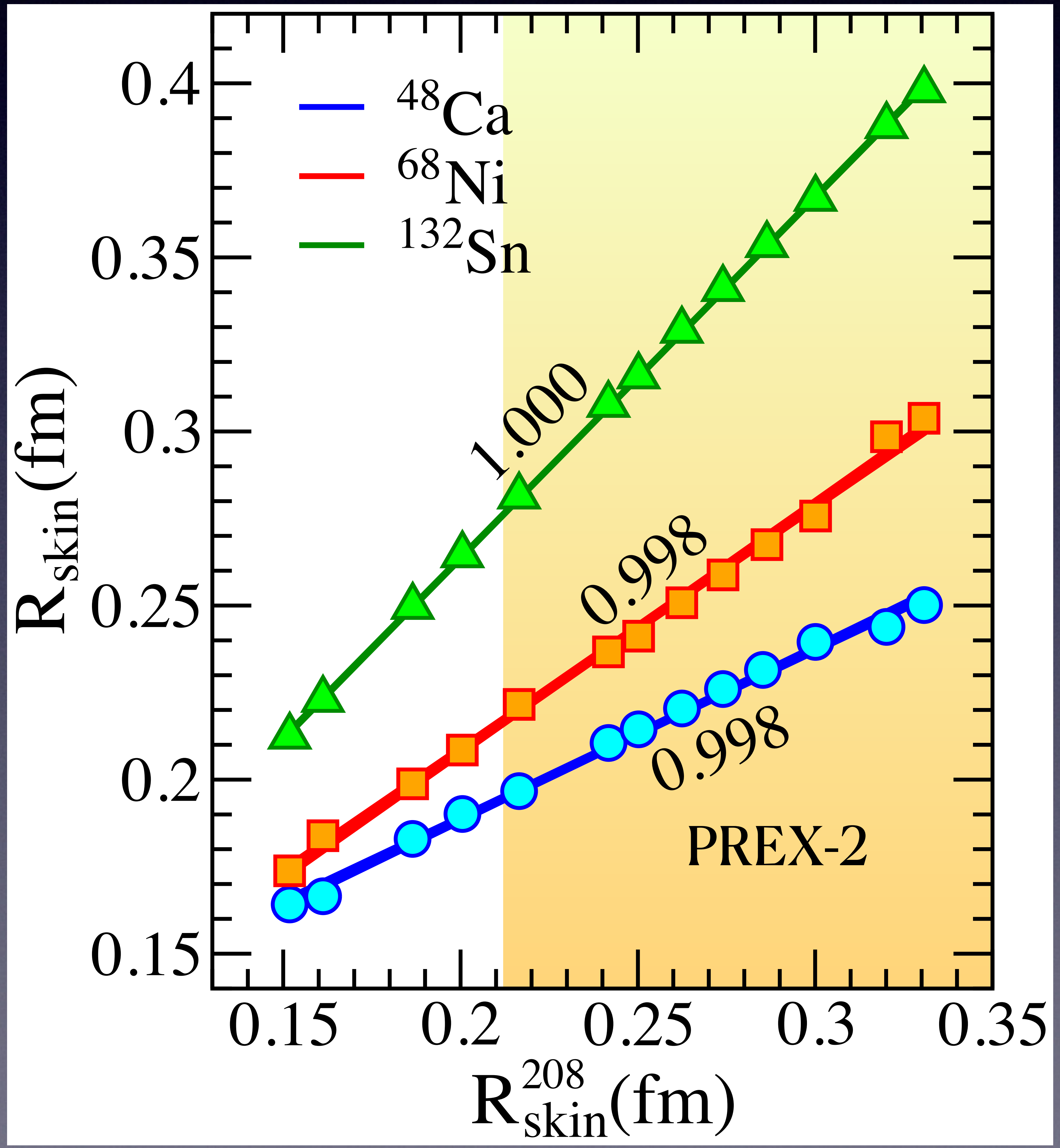
Science Drivers from the National Research Council (NRC) Rare-Isotope Science Assessment Committee (RISAC)

Nuclear Structure	**Nuclear Astrophysics**	**Tests of Fundamental Symmetries**	**Applications of Isotopes**
Intellectual challenges from 2013 NRC Decadal Study and the 2015 NSAC Long Range Plan			
How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interactions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?
Specific questions included in the challenges			
What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes? What is the origin of simple patterns in complex nuclei?	What is the nature of neutron stars and dense nuclear matter? What is the origin of the elements in the Cosmos? What are the nuclear reactions that drive stars and stellar explosions?	Why is there now more matter than antimatter in the Universe?	What are new applications of isotopes to meet the needs of society?
FRIB400 will help to answer the challenges formulated for the field			
17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research, 11 will benefit from FRIB400			
1. Shell structure 2. Superheavies **3. Skins** 4. Pairing 5. Symmetries **13. Limits of stability** **14. Weakly-bound nuclei** **15. Mass surface**	**6. Equation of state (EOS)** **7. *r* process** 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe supernovae **15. Mass surface** 16. *rp* process **17. Weak interactions**	**12. Atomic electric dipole moment**	**10. Medical** **11. Stewardship**

FRIB400 will open new opportunities across all fields of rare-isotope science

The case of ^{132}Sn





We have entered the golden era of neutron-star physics; Many communities with one overarching goal!

Nuclear EOS Density Ladder

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