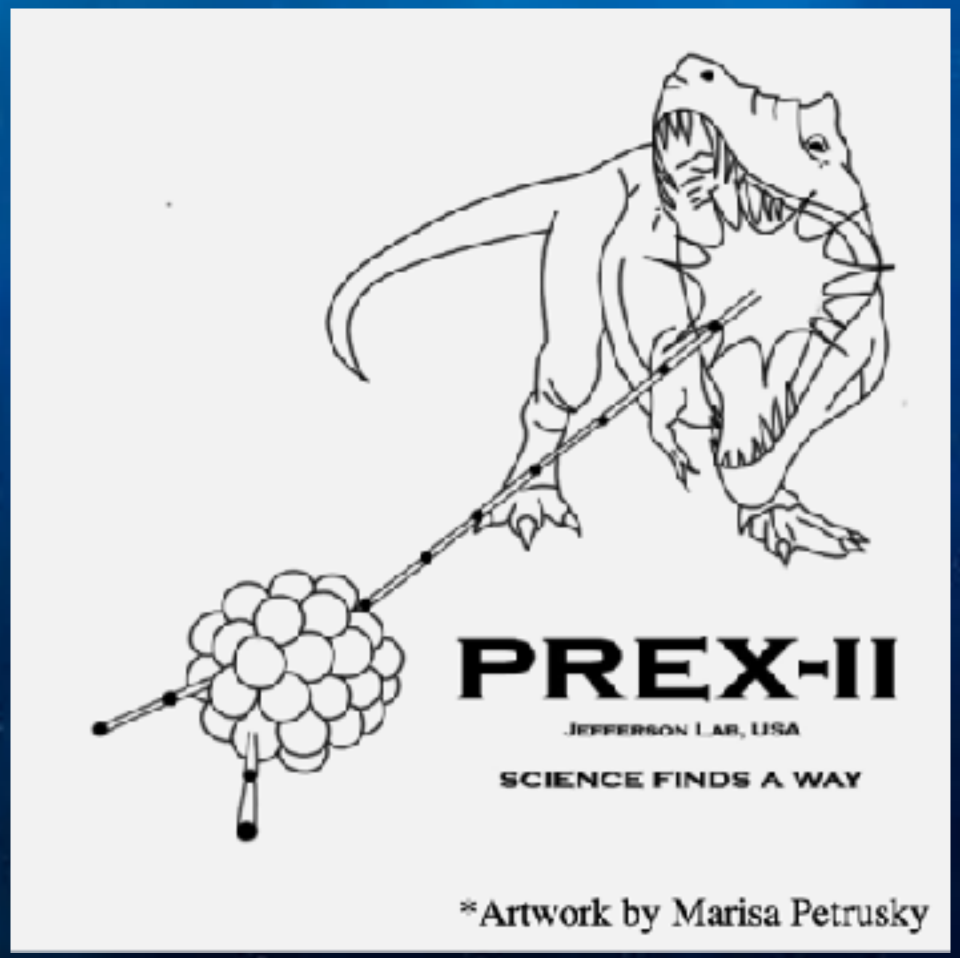
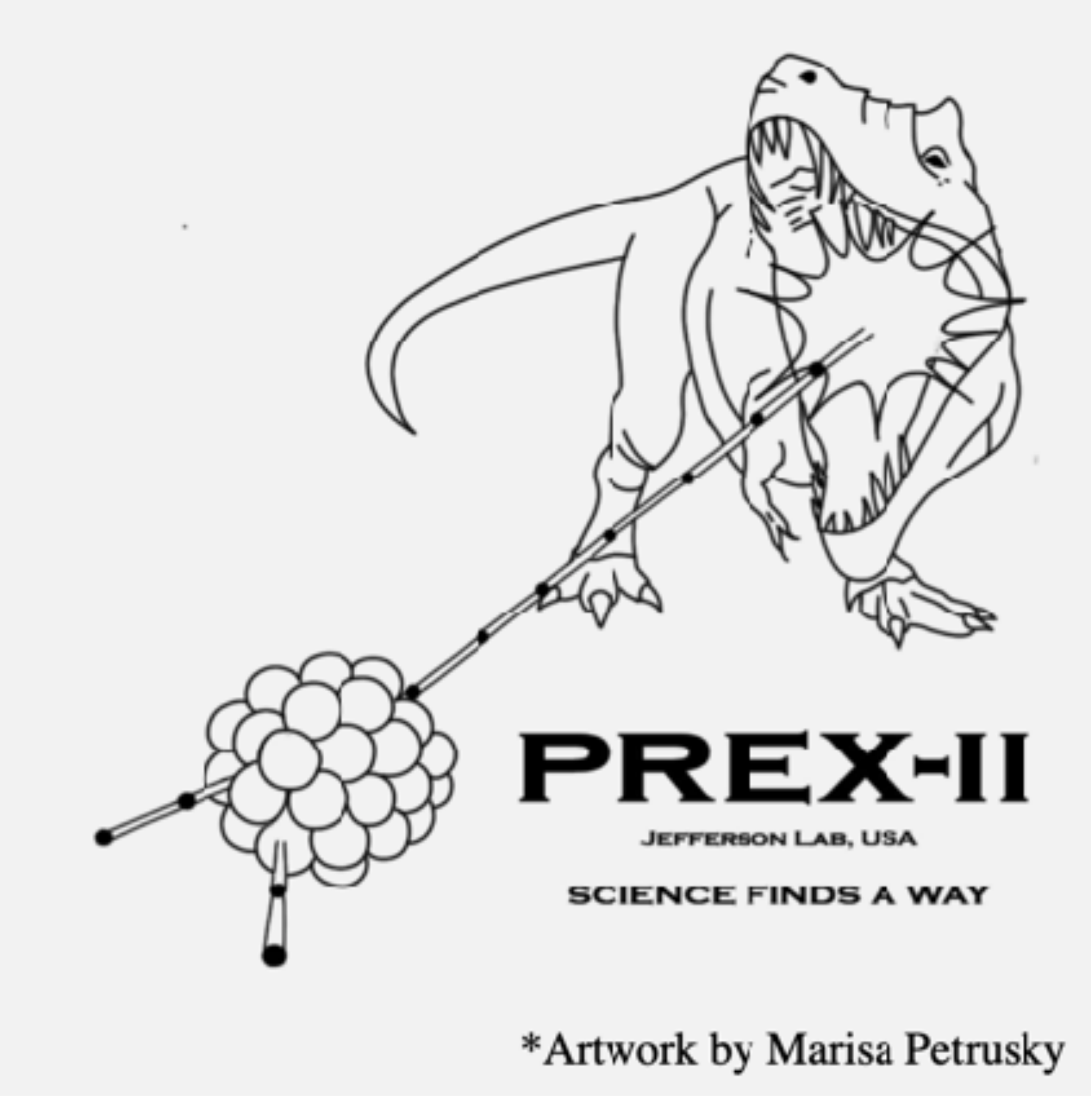
Future of neutron rich matter: neutron skins to neutron stars

Chuck Horowitz, Indiana U.   Amherst, Oct. 2022



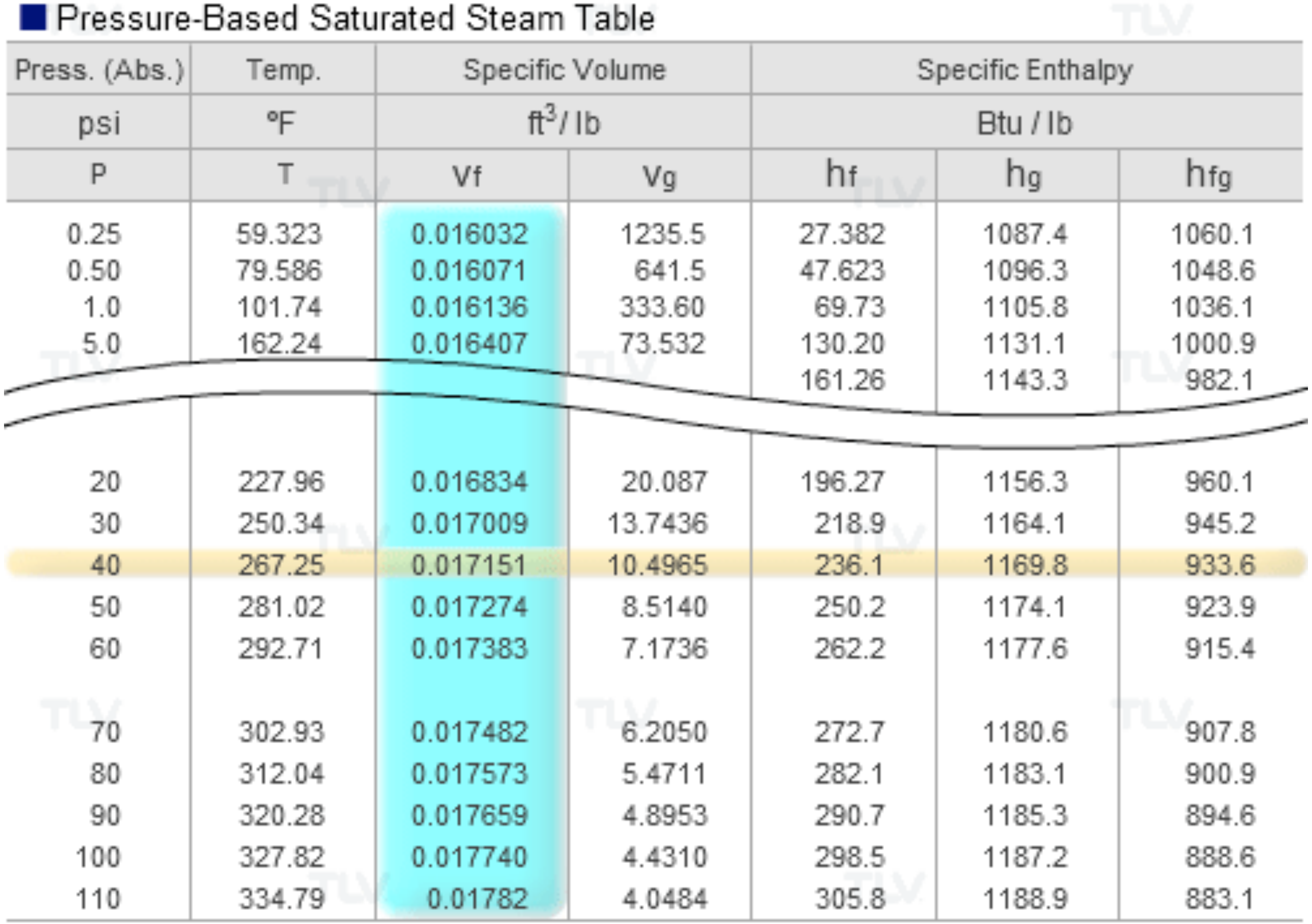
Future of neutron rich matter: neutron skins to neutron stars

- Goal: determine *nature* of dense matter.
- Standard model of nuclear physics circa 1980s and how it was broken.
- Nuclear and astronomical systematic errors and our future. *The future is enabled by measurements with small systematic errors.*



*Artwork by Marisa Petrusky

Common goal is equation of state $p=p(\rho)$ and more



Pressure-Based Saturated Steam Table

Press. (Abs.)	Temp.	Specific Volume		Specific Enthalpy		
psi	°F	ft^3/ lb		Btu / lb		
P	T	V_f	V_g	h_f	h_g	h_{fg}
0.25	59.323	0.016032	1235.5	27.382	1087.4	1060.1
0.50	79.586	0.016071	641.5	47.623	1096.3	1048.6
1.0	101.74	0.016136	333.60	69.73	1105.8	1036.1
5.0	162.24	0.016407	73.532	130.20	1131.1	1000.9
				161.26	1143.3	982.1
20	227.96	0.016834	20.087	196.27	1156.3	960.1
30	250.34	0.017009	13.7436	218.9	1164.1	945.2
40	267.25	0.017151	10.4965	236.1	1169.8	933.6
50	281.02	0.017274	8.5140	250.2	1174.1	923.9
60	292.71	0.017383	7.1736	262.2	1177.6	915.4
70	302.93	0.017482	6.2050	272.7	1180.6	907.8
80	312.04	0.017573	5.4711	282.1	1183.1	900.9
90	320.28	0.017659	4.8953	290.7	1185.3	894.6
100	327.82	0.017740	4.4310	298.5	1187.2	888.6
110	334.79	0.01782	4.0484	305.8	1188.9	883.1

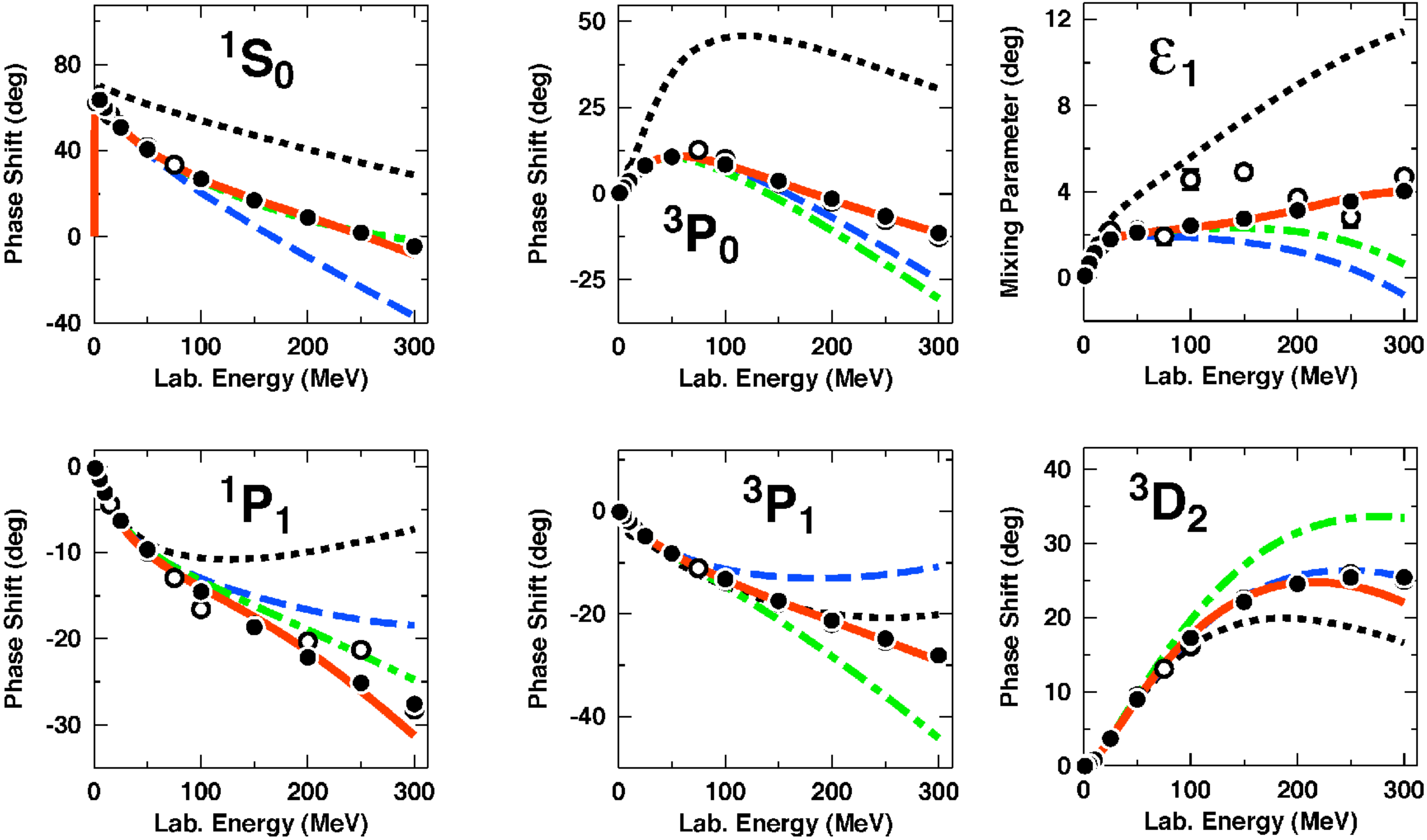
Specific Volume (ft^3/lb) of Saturated Water at 40 psi

Nature of dense matter

- What are neutron stars made of?
- How are quarks and gluons organized in NS interior?
- What are effective degrees of freedom (quark or hadron)?
- NS masses, and radii determine EOS not deg. of freedom.
- **Transport properties** such as viscosity, thermal conductivity, neutrino emmisivity may provide important additional information. ==> NS cooling
- EOS is an important beginning of the search, not the end.

Standard model of nuclear physics circa 1980s

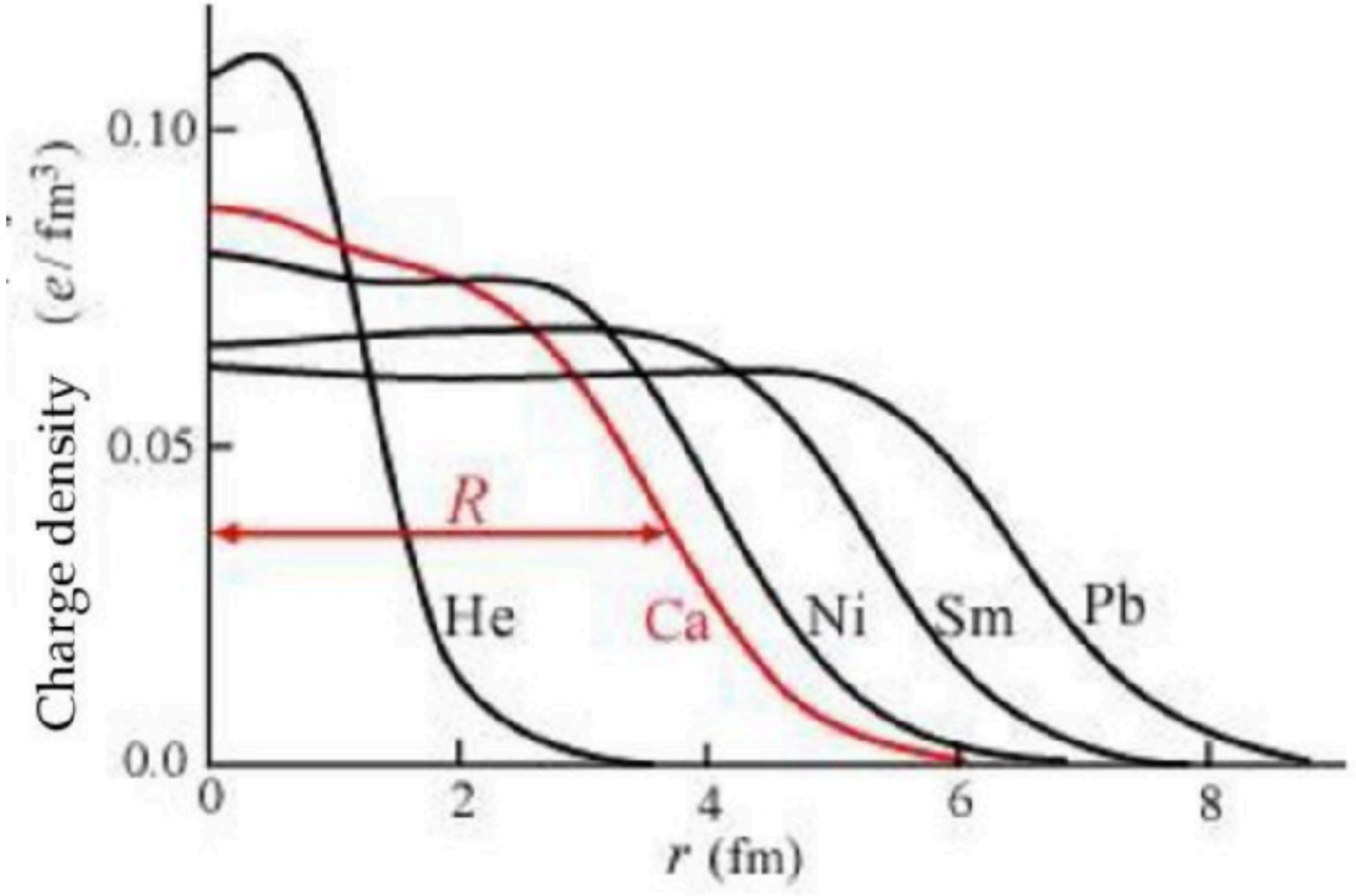
- Phenomenological NN potentials fit to scattering phase shifts (complicated strong spin and L dependence tensor force …)
- Three nucleon forces assumed to be small.
- Solve many-body HΨ=EΨ as well as you can.
- Ben Day broke standard model [PRL **47**(1981)226] Remarkable calc. showed nuclear matter with only NN forces saturates at too high a density -> need three nucleon forces.


$^1S_0$
$^3P_0$
ε_1
$^1P_1$
$^3P_1$
$^3D_2$
Phase Shift (deg)
Mixing Parameter (deg)
Lab. Energy (MeV)
80
40
0
-40
50
25
0
-25
12
8
4
0
-10
-20
-30
-40
40
30
20
10
100
200
300

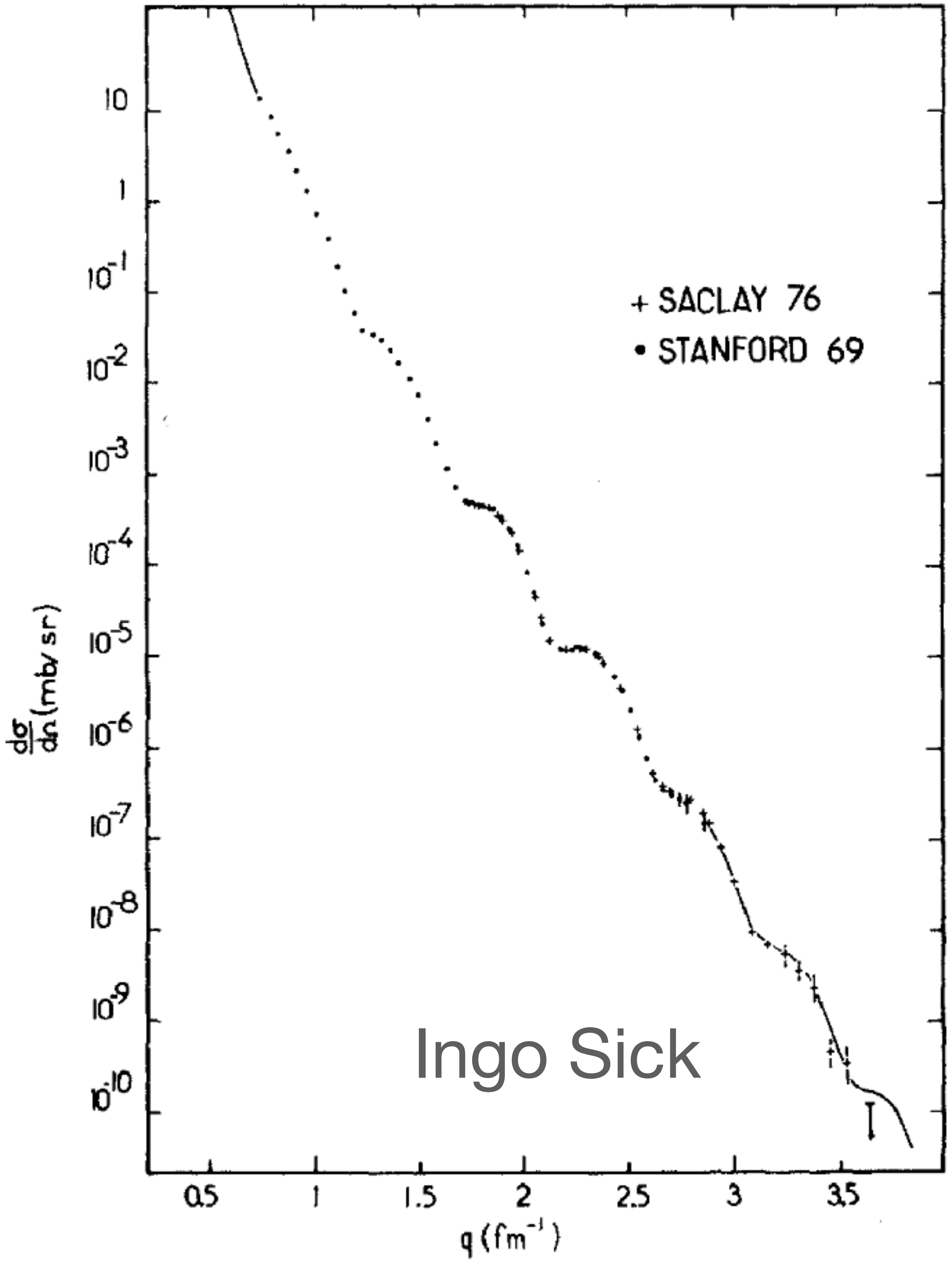
Nuclear saturation

← Nuclear density 0.16 fm-3

- Infinite nuclear matter has a minimum binding energy of 16 MeV at nuclear density thought to be 0.16 fm^{-3}.
- Interior baryon density of a heavy nucleus goes to an A (mass #) independent constant close to nuclear density.

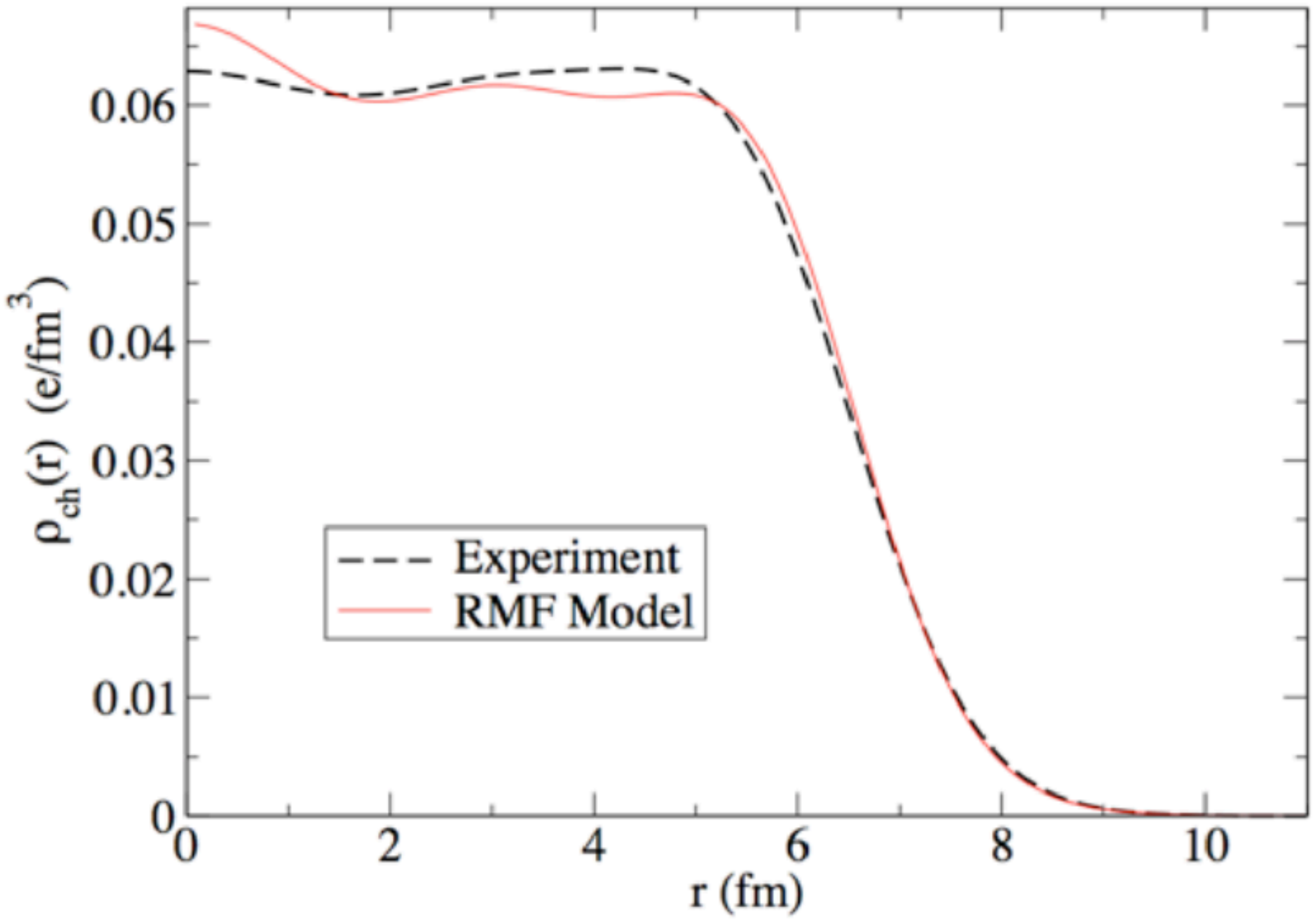


Charge Density of ^{208}Pb, accurately measured in elastic electron scattering.



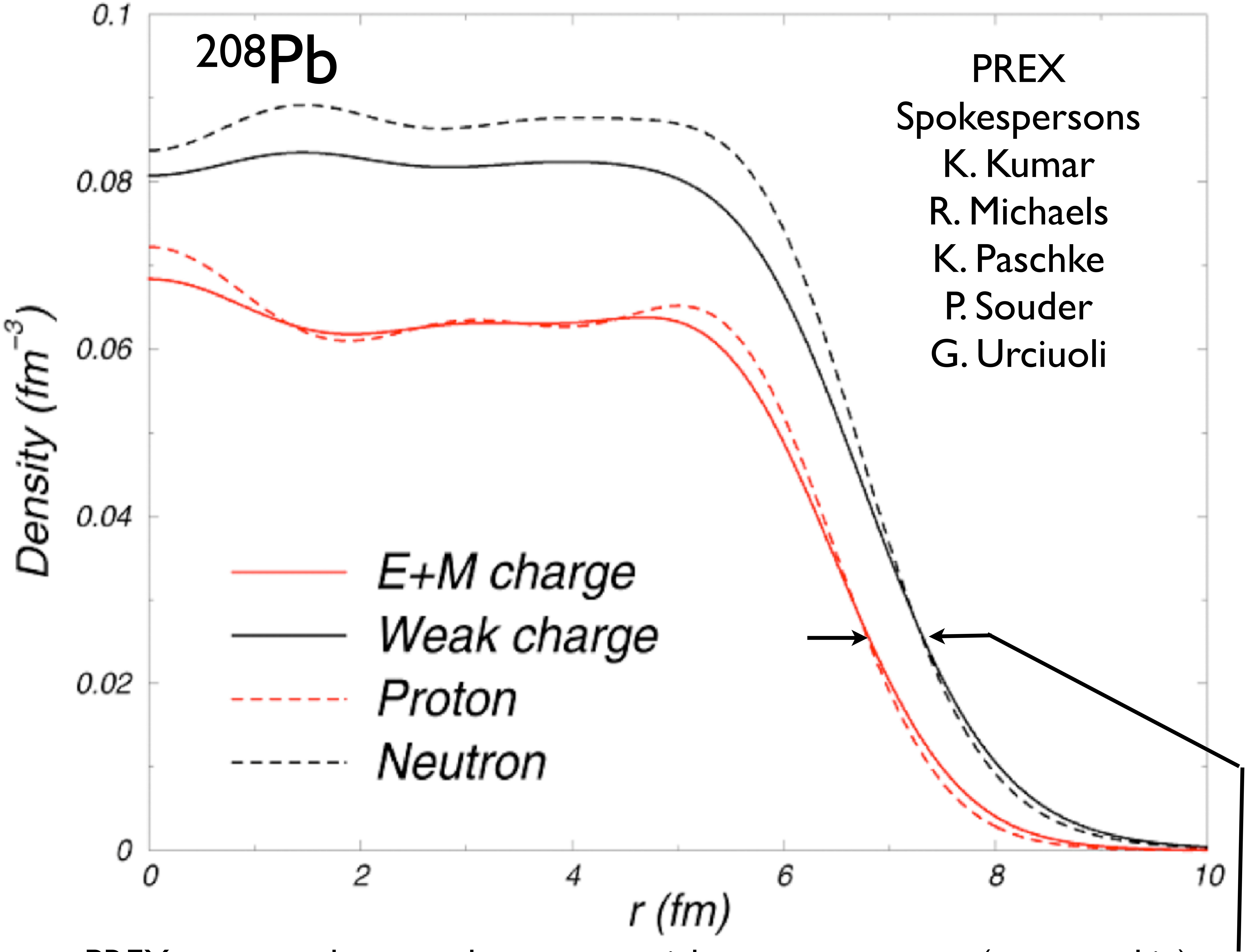
Ingo Sick

Cross section measured over 12 orders of magnitude.



These elastic charge densities ***are*** our picture of the atomic nucleus!

1961 Nobel Prize
Robert Hofsadter



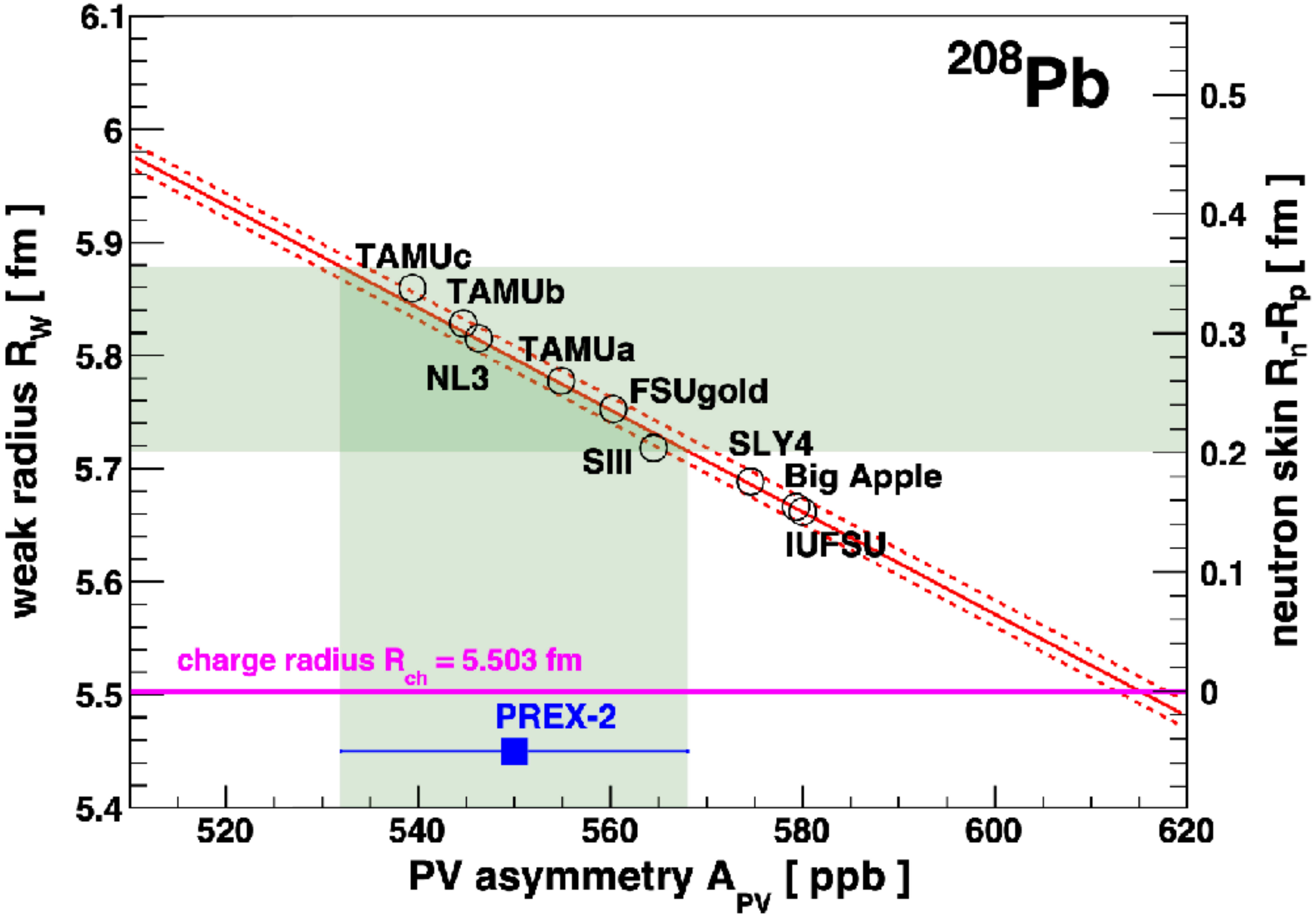
PREX
Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli

- PREX measures how much neutrons stick out past protons (neutron skin).

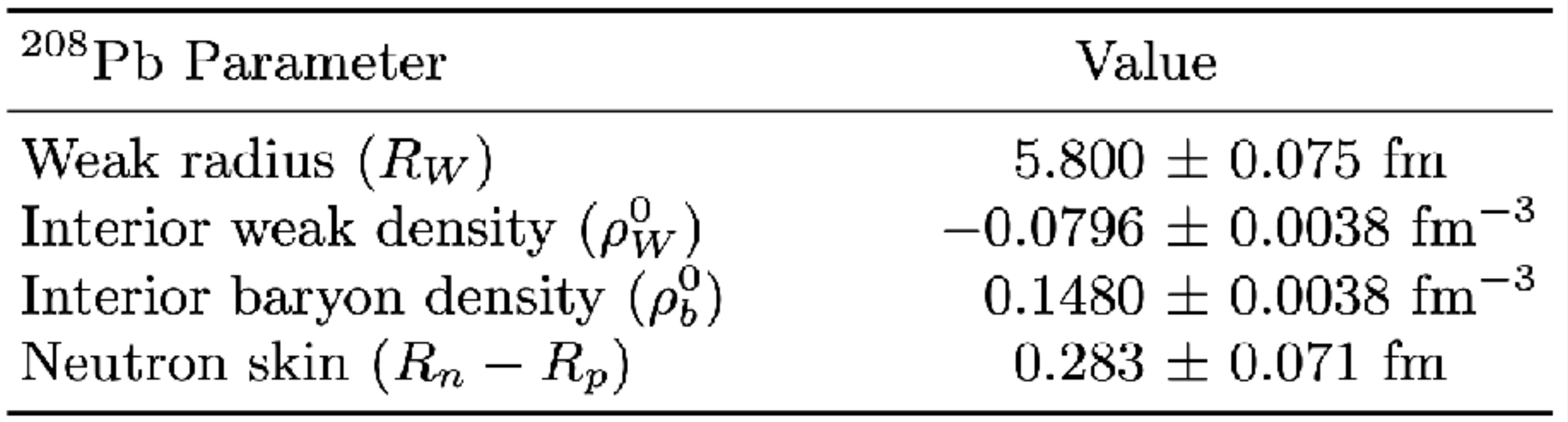
PREX-II

$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

$$\approx \frac{G_F Q^2 |Q_W|}{4\pi\alpha\sqrt{2}Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$



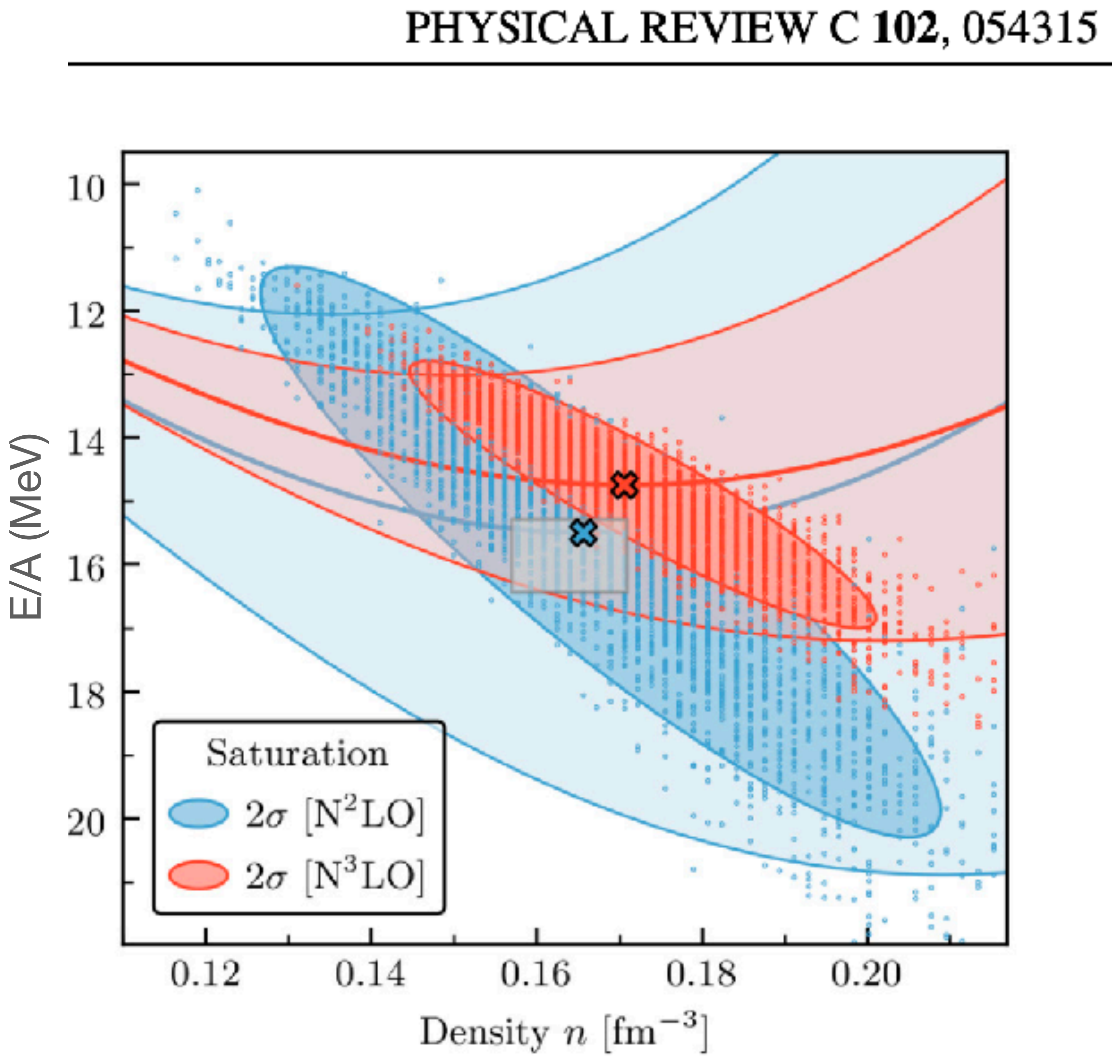
PREX-I+II Results

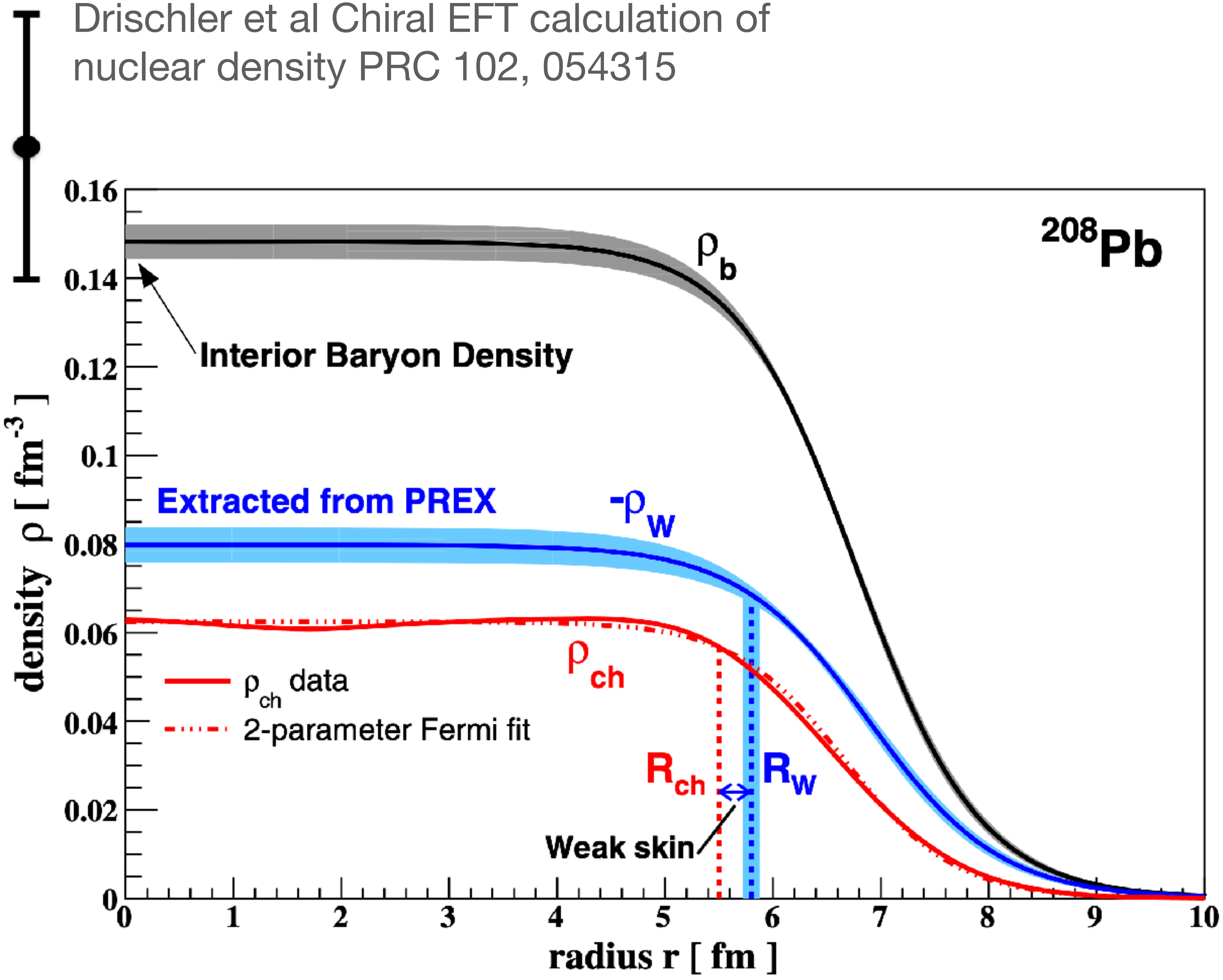


^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ^0_W)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ^0_b)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

PREX-2 weak form factor:
$F_W(q=0.398\text{fm}^{-1})=0.3676+/-.0125$

Drischler et al Chiral EFT calculation of nuclear density PRC 102, 054315


PHYSICAL REVIEW C **102**, 054315



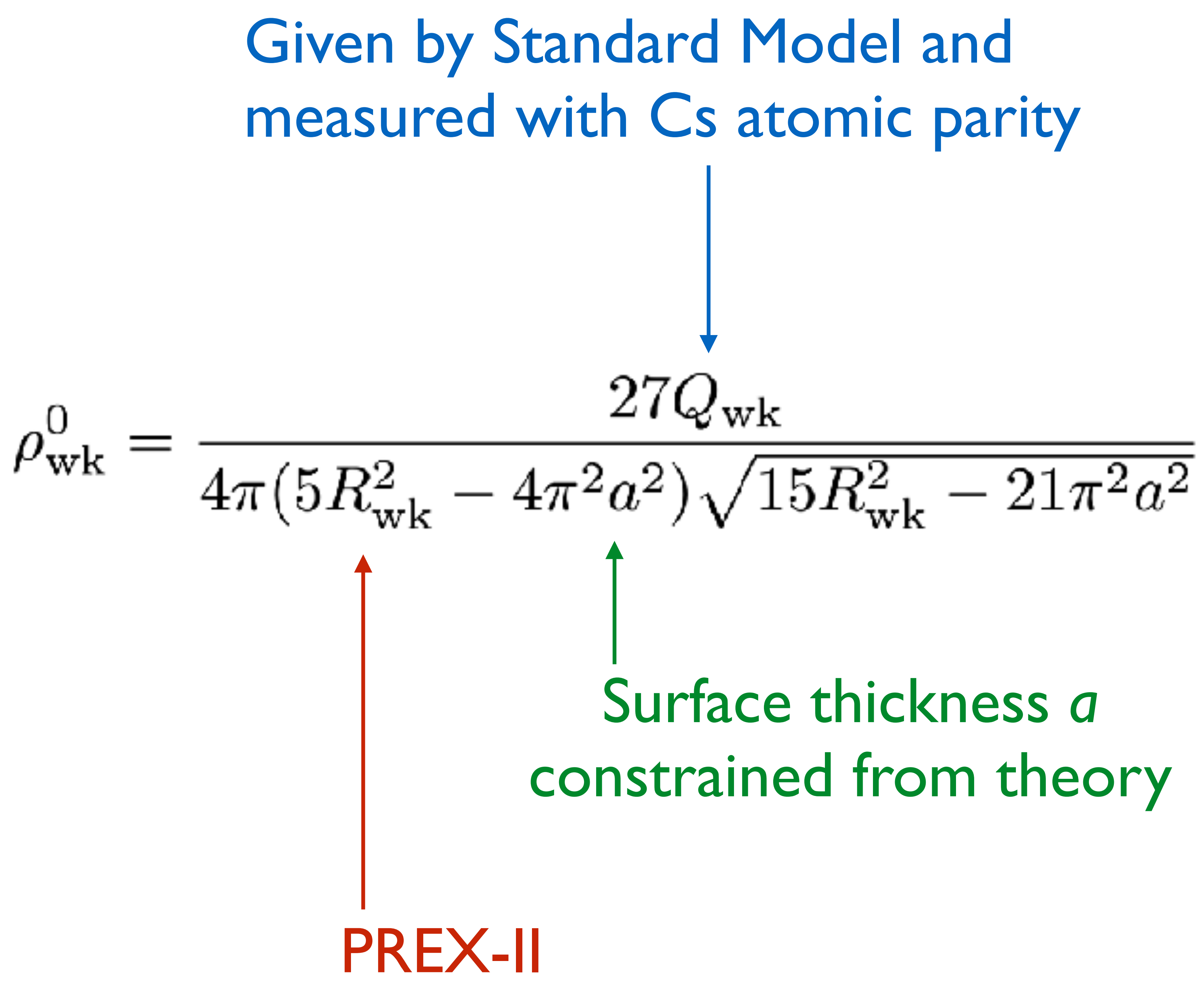
Interior weak density of ^{208}Pb

- Two parameter (sym.) Fermi function [see PRC **102**(2020) 044321]

$$\rho_{\rm wk}(r,c,a) = \rho^0_{\rm wk}\frac{\sinh(c/a)}{\cosh(r/a)+\cosh(c/a)}$$

$$R^2_{\rm wk} = \frac{1}{Q_{\rm wk}}\int r^2\rho_{\rm wk}(r)d^3r = \frac{3}{5}c^2 + \frac{7}{5}(\pi a)^2$$

- Surface thickness parameter *a*: can be measured with 2nd PV exp at higher Q^2 , feasible at Mainz [PRC **102**, 064308], or taken from theory. Many nonrel. and rel. density functionals have *a*=0.605 +/- 0.025 fm



Given by Standard Model and measured with Cs atomic parity

$$\rho^0_{\rm wk} = \frac{27Q_{\rm wk}}{4\pi(5R^2_{\rm wk} - 4\pi^2a^2)\sqrt{15R^2_{\rm wk} - 21\pi^2a^2}}$$

Surface thickness *a* constrained from theory

PREX-II

- ρ_b^0 = 0.1480+/-0.0038 fm^{-3}
- *Fundamental nuclear structure measurement, very closely related to nuclear density ρ_0 ~ 0.16 fm^{-3}.*
- *Error is small only* 2.6%

What causes nuclear saturation?

- Size of water molecules explains one g/cm^3.
- Size of nucleon "cores" from repulsive NN potential too small to explain saturation.
- Complicated interplay of tensor NN and repulsive NNN forces appears to be necessary.
- Perhaps there is a higher density where cores touch and nuclear matter turns very repulsive?

Chiral EFT

- Need important NNN interactions for nuclear saturation, hard to determine from few nucleon scattering.
- Chiral EFT organization is now crucial! Expand NN, NNN, 4N… interactions in powers of momentum over chiral scale.
- WHEN (at what density) does Chiral EFT break down?
- Much better to ask HOW does Chiral EFT break down (with density)? This may provide insight into nature of somewhat denser matter.

Experiment, theory, observation

- In last 20 years what observational, experimental, or theoretical development has taught us the most about cold dense matter?
- **Theory**: Development of Chiral EFT with many nuclear structure and nuclear matter successes.
- **Observation**: Opening of GW astronomy with GW170817 and great promise for future.
- **Experiment**: Discovery of nearly perfect fluid at RHIC

Relativistic Heavy Ion Collider at up to 200 GeV/nucleon

Hot QCD Matter at Low Baryon Density

- At low temp. only a few hadronic degrees of freedom: pi+, pi-, pi0
- At very high temperatures have many more quark and gluon, color, flavor, spin … degrees of freedom.
- RHIC finds crossover to strongly interacting quark gluon plasma.
- Interactions are so strong that quarks and gluons have short mean free path and very low shear viscosity—>nearly perfect fluid. Far away from asymptotic freedom and nearly free quarks/gluons.
- Cold dense matter in NS very likely also strongly interacting.

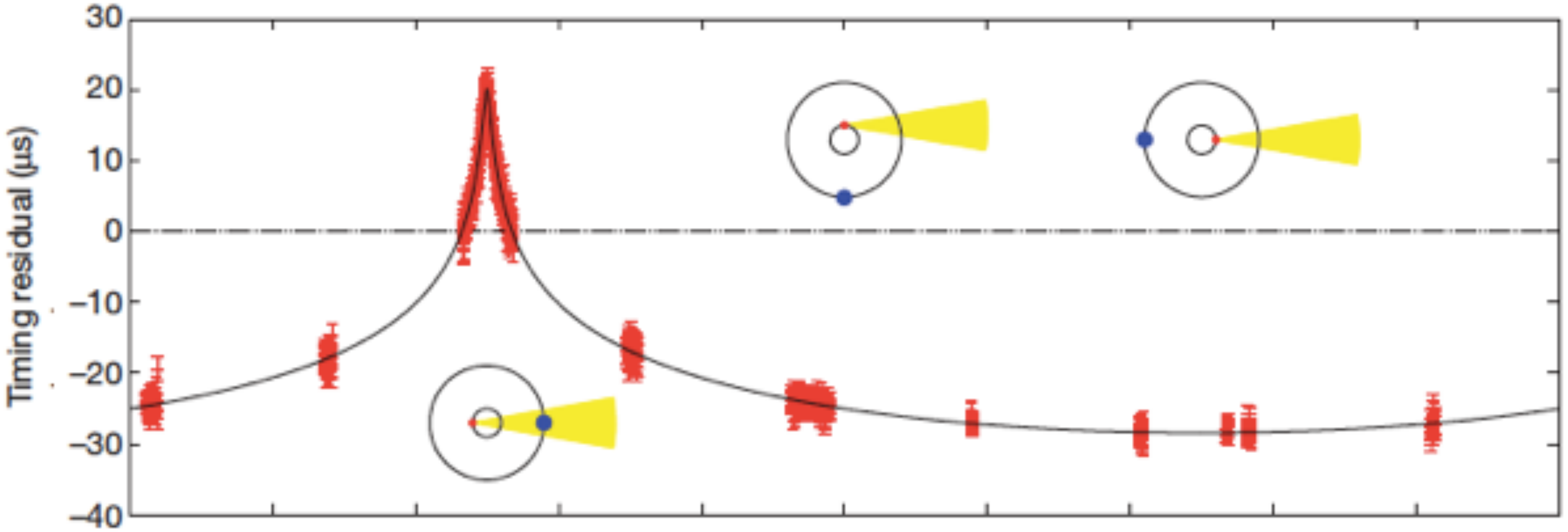
What development in theory, experiment or observation, in last 20 years, has told us the most about dense matter?

- And the winner is…

Discovery of $2M_{sun}$ Neutron Stars

Demorest et al: PSR J1614-2230 has 1.97+/- 0.04 M_{sun}.

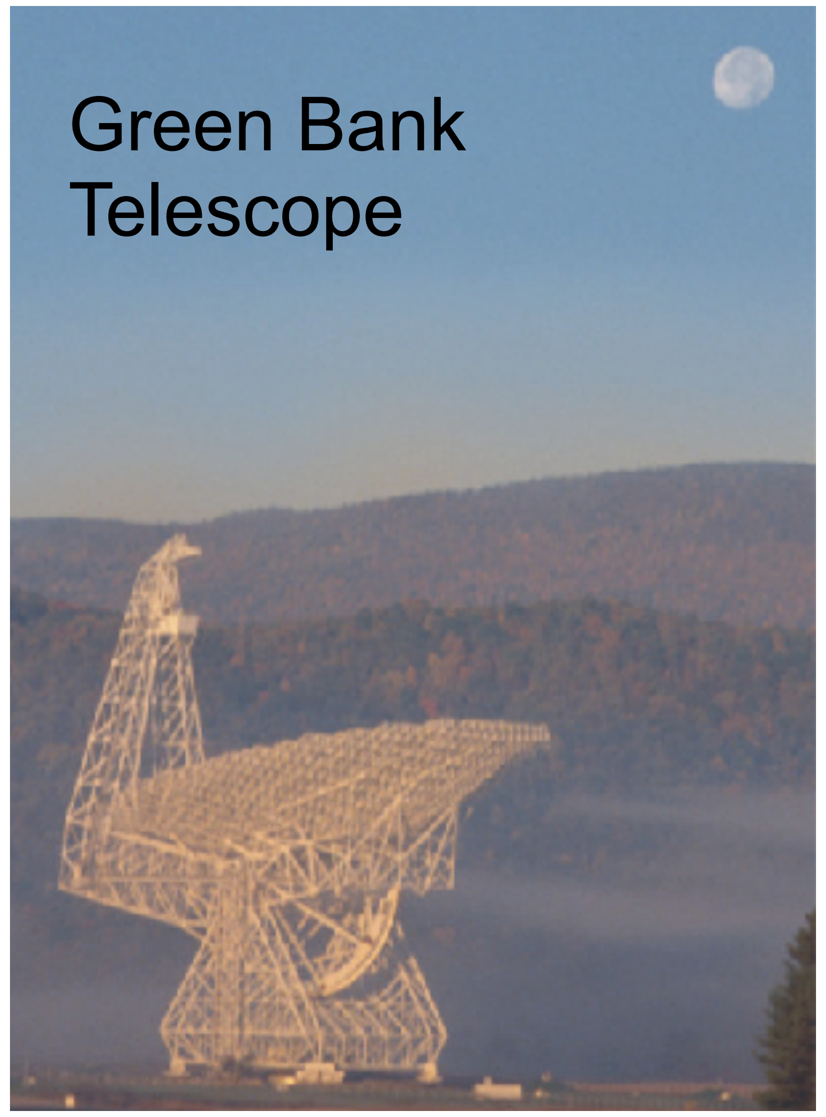
Delay in pulse arrival



NS + White Dwarf Binary

Orbital phase

- The equation of state of neutron rich matter (pressure vs density) at high densities must be stiff enough (have a high enough p) to support this mass against collapse to a black hole. *All soft EOS are immediately ruled out!*
- *However this does not tell composition of dense matter be it neutron/ proton, quark, hyperon...*
- *NS cooling (by neutrinos) sensitive to composition.*



Green Bank Telescope

What holds up 2M_{sun} NS?

- Interaction of nucleon “hard cores”
- Omega mesons: Massive spin one vector meson exchange between like baryon charges is strongly repulsive. “Heavy photon” exchange between like charges.
- Strong repulsive vector interaction between quarks in NJL models…

High speed of sound

- Large maximum NS mass—>P is high at high densities.
- GW170817 set upper limit on deformability of NS —>P is not too large near $2\rho_0$.
- P rises rapidly with density. Speed of sound $C_s^2=dP/d\rho$ is large > $(1/3)c^2$.
- Expect $C_s^2=1/3$ as ρ—>infinity in QCD. Not there yet.

Why is sound speed high?

- Massless fermions or bosons $C_s^2=1/3$
- Massive vector exchange C_s^2—>1
- Perturbative QCD —>1/3 from below as ρ —>infinity
- Dense matter in NS is strongly interacting system probably beyond Chiral EFT and not yet asym free quarks and gluons.
- Is it strongly interacting quakes or strongly interacting hadrons?

Role of Lattice QCD

- Numerically very intensive procedure for accurately solving strongly interacting QCD.
- Works at finite temperature and low baryon density and has accurately calculated low baryon density, high temperature EOS.
- Fails at high baryon density because of fermion sign problem.
- May calculate intermediate quantities for phenomenological models of cold dense matter.

Density Functionals

- E[ρ]: Parameterize E of system as a functional of densities $\rho_p(r)$, $\rho_n(r)$ and currents j_p, j_n…
- Solve for low lying states by minimizing wrt ρ(r)
- Very eff way to calculate in nuclear physics, condensed matter, chemistry
- Exact ground state from exact functional (don't know). Parameterize E[ρ] with about dozen parameters.
- Nonrel. Skyrme and Relativist (mean field theory) forms of E[ρ]

Nuclear measurement vs Astronomical Observation

To probe equation of state

PREX, CREX measure neutron radius of ^{208}Pb and ^{48}Ca. Clean electroweak rxn.

NICER measures NS radius from X-ray light curve. Some systematic errors.

Electric **dipole polarizability** from coulomb excitation. Potential systematic error from sum over excited states. Encourage ab initio calculations.

LIGO measured **gravitational deformability** (quadrupole polarizability) of NS from tidal excitation. Statistics limited but systematic errors controllable.

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

LIGO and deformability of NS

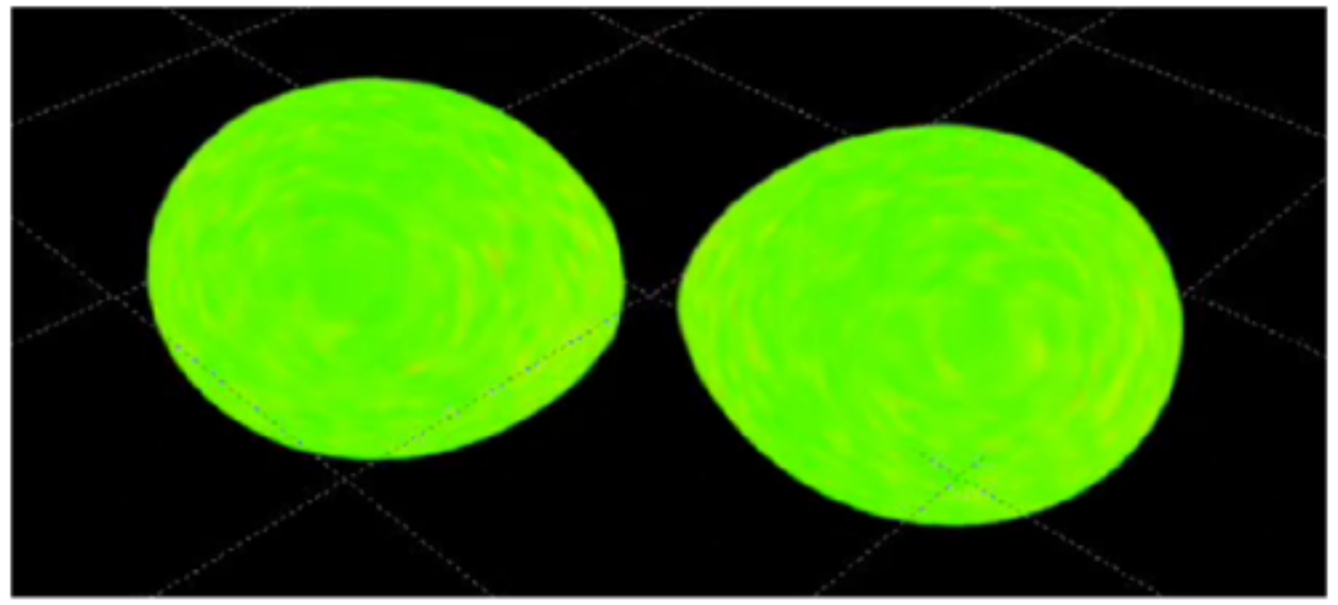
- Gravitational tidal field distorts shapes of neutron stars just before they merge.
- Dipole polarizability of an atom ~ R^3.

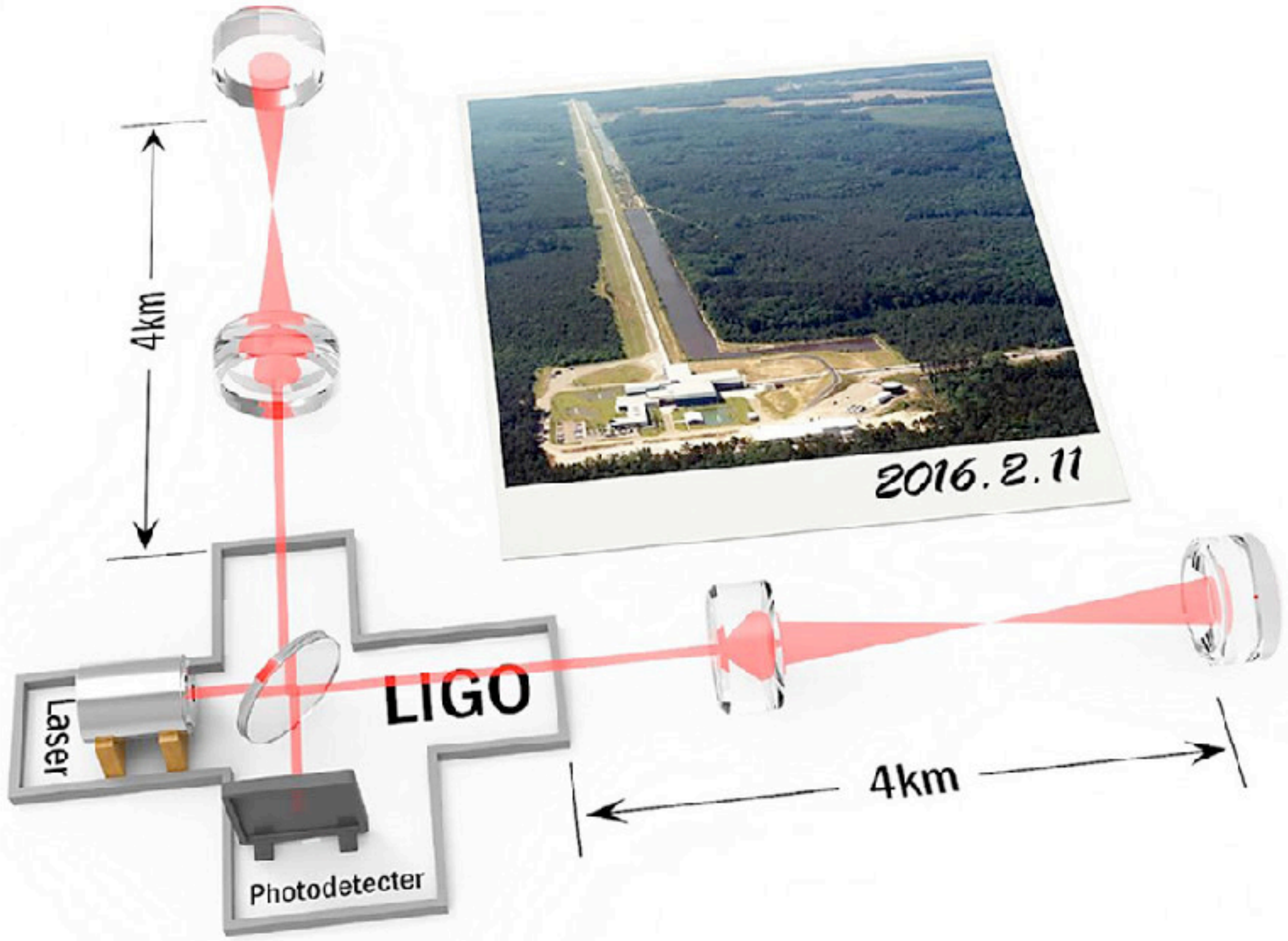
$$\kappa = \Sigma_f \frac{|\langle f|rY_{10}|i\rangle|^2}{E_f - E_i} \quad \propto R^3$$

- Tidal deformability (or quadrupole polarizability) of a neutron star scales as R^5.

$$\Lambda \propto \Sigma_f \frac{|\langle f|r^2Y_{20}|i\rangle|^2}{E_f - E_i} \quad \propto \quad R^5$$

- GW170817 observations set upper limit on Λ.





Static and dynamical polarizabilities

- Nuclear response to static electric field described by static dipole polarizability. Response to time dependent field —> dynamical polarizability.
- NS response to static tidal field —> described by gravitational deformability. Also can calculate dynamical tides.
- Important excitation modes: low energy pygme resonance for neutron rich nuclei. For NS quadrupole f-mode important for deformability. Frequency of mode somewhat greater than merger frequency limits dynamical tides.

Systematic errors

- Experiments or observations with controlled small systematic errors enable our exciting future.
- **Dipole polarizability**: Experiments need to identify and measure dipole strength over large range of excitation energy. Theory needs to calculate complex excited states over a large range of energies, may need to go beyond mean field or density functionals. Density functionals describe energy of exact ground state or low lying excited states with model functional $E=E[\rho]$.

NICER and NS radii

- Improves on previous X-ray observations of NS radii by using additional information from rotational phase resolved spectra.
- Needs to model emission of X-rays depending for example on geometry of hot spots. Two independent groups to check.
- Room for improvement with more statistics. For example observe fainter stars.

Gravitational Deformability

- Theory: depends only on GR and EOS.
- Observation: systematic errors from model wave forms, machine calibration … can be controlled.
- Next generation detectors Cosmic Explorer, Einstein Telescope with 10 times sensitivity can accurately measure deformabilities. Very exciting.

Pairty V. electron scattering

- Electroweak rxn free from most strong interaction uncertainties.
- Theory: Coulomb distortions (ok), radiative corrections probably provide limit of about 1% for A_{pv}. CREX, PREX 4-5% in Apv ok, room for 2+% MREX but not much more.
- Experiment: Helicity correlated beam properties -> Paul Souder!
- Model error (for 48Ca CREX): avoidable by theory comparing to weak form factor instead of weak radius or neutron radius.

Questions

- Why does nuclear matter saturate at ρ_0?
- How does Chiral EFT break down at high ρ?
- Why is sound speed high?
- What holds up a $2M_{sun}$ NS?
- What is nature of dense matter? Is it organized in terms of quarks or hadrons?