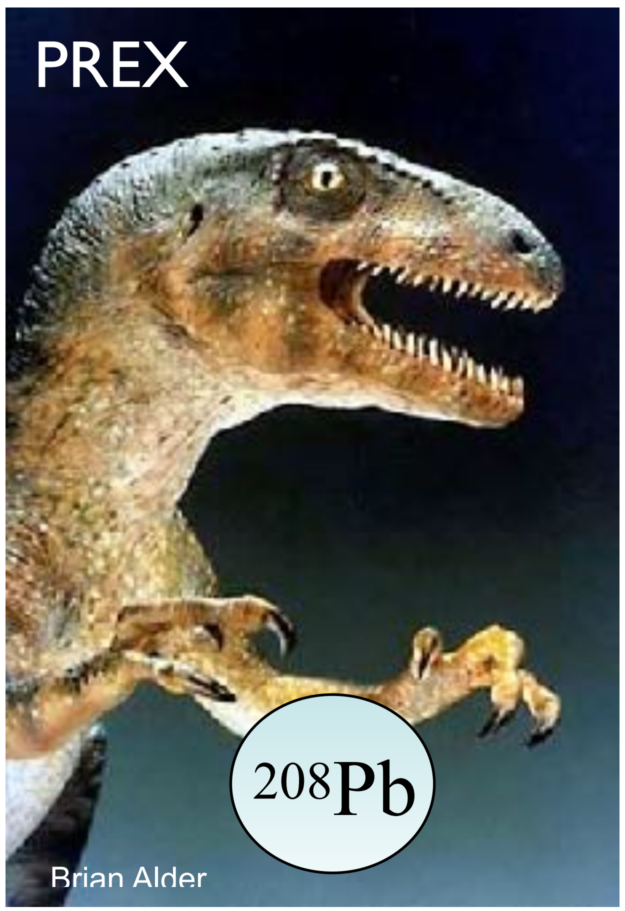
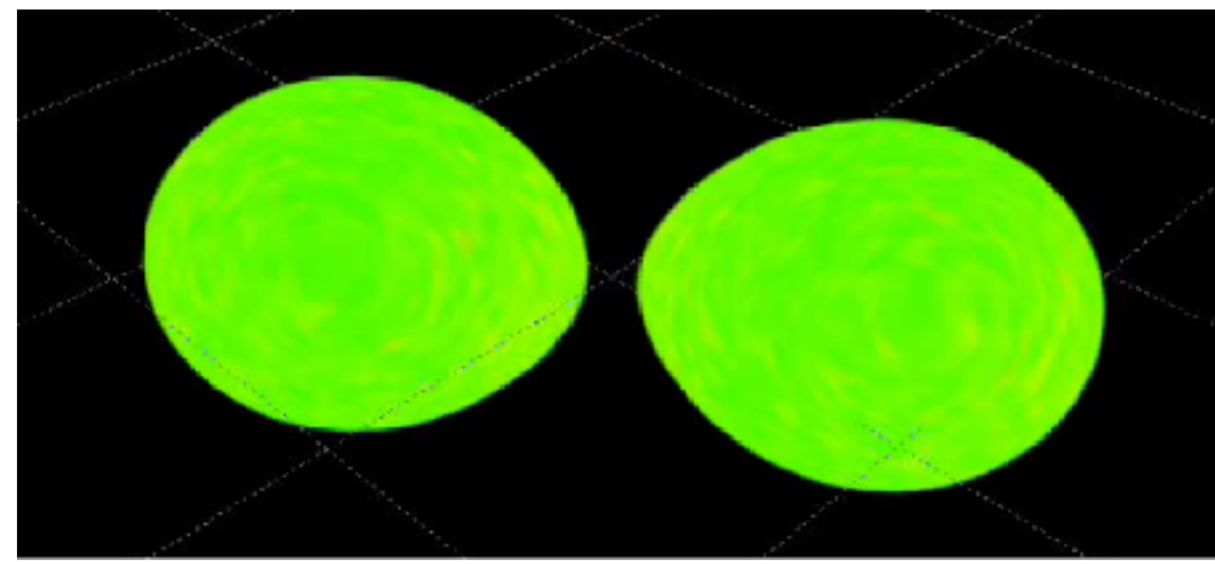
Mergers and the PREX neutron density experiment





Chuck Horowitz, Indiana U., First compact star merger, ECT*, Oct. 2019

NUCLEI Nuclear Computational Low-Energy Initiative A SciDAC-4 Project

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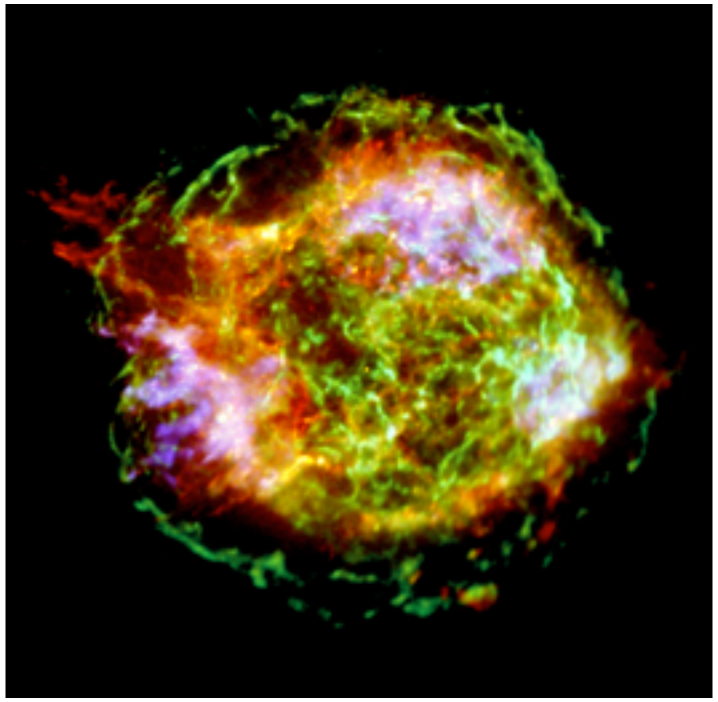
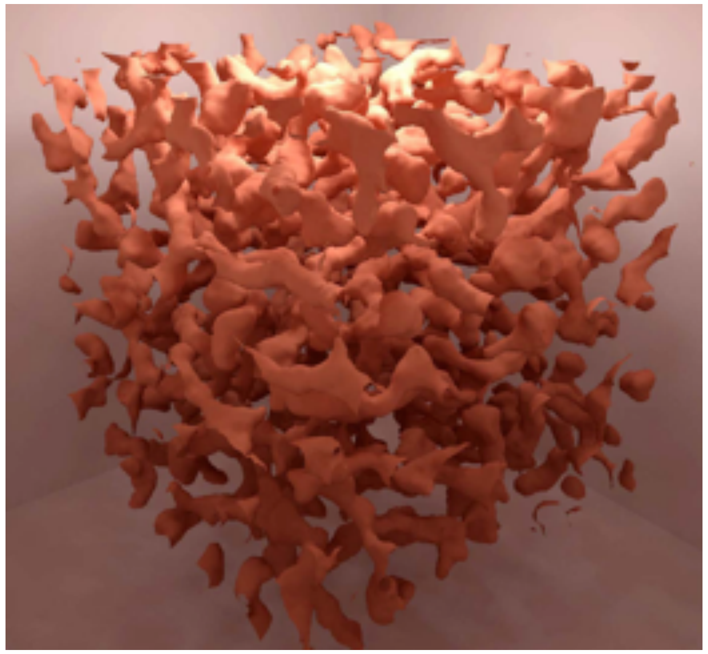
Neutron Rich Matter

- Compress almost anything to 10^{11}+ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.
  - What are the high density phases of QCD?
  - Where did chemical elements come from?
  - What is the structure of many compact and energetic objects in the heavens, and what determines their electromagnetic, neutrino, and gravitational-wave radiations?
- Interested in neutron rich matter over a tremendous range of density and temperature were it can be a *gas, liquid, solid, plasma, liquid crystal (nuclear pasta), superconductor (T_c=10^{10} K!), superfluid, color superconductor...*



Supernova remanent Cassiopea A in X-rays

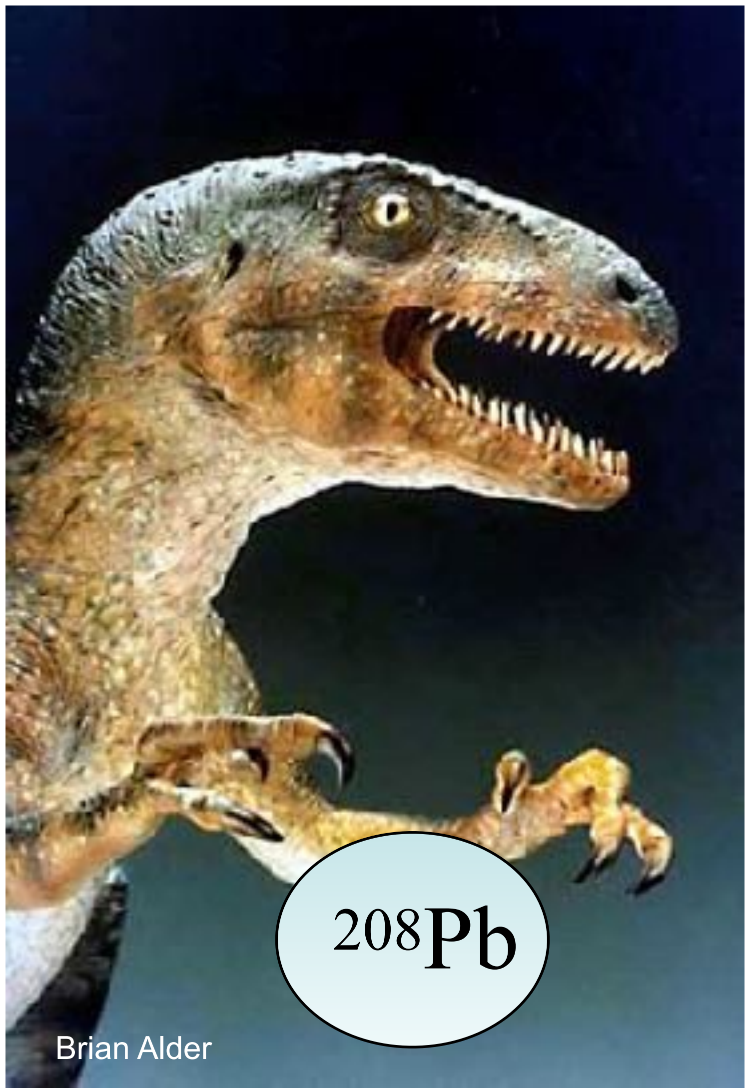


MD simulation of Nuclear Pasta with 100,000 nucleons

Equation of state and three numbers

- EOS gives pressure P as a function of density ρ for neutron rich matter: $P=P(\rho)$.
- **Low density:** nuclear structure observables including ***neutron skin*** thickness probe EOS near nuclear density n_0. [^{208}Pb: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm]
- **Medium density:** NS radius or ***deformability*** probe EOS at about $2n_0$. [$\Lambda_{1.4} = 190^{+390}_{-120}$]
- **High density:** maximum NS mass or ***fate*** of merger remnant probes EOS at high densities. [PSR J0740+6620 has mass $2.14^{+0.10}_{-0.09}$ M_{sun}]

What does neutron rich matter look like in the laboratory?

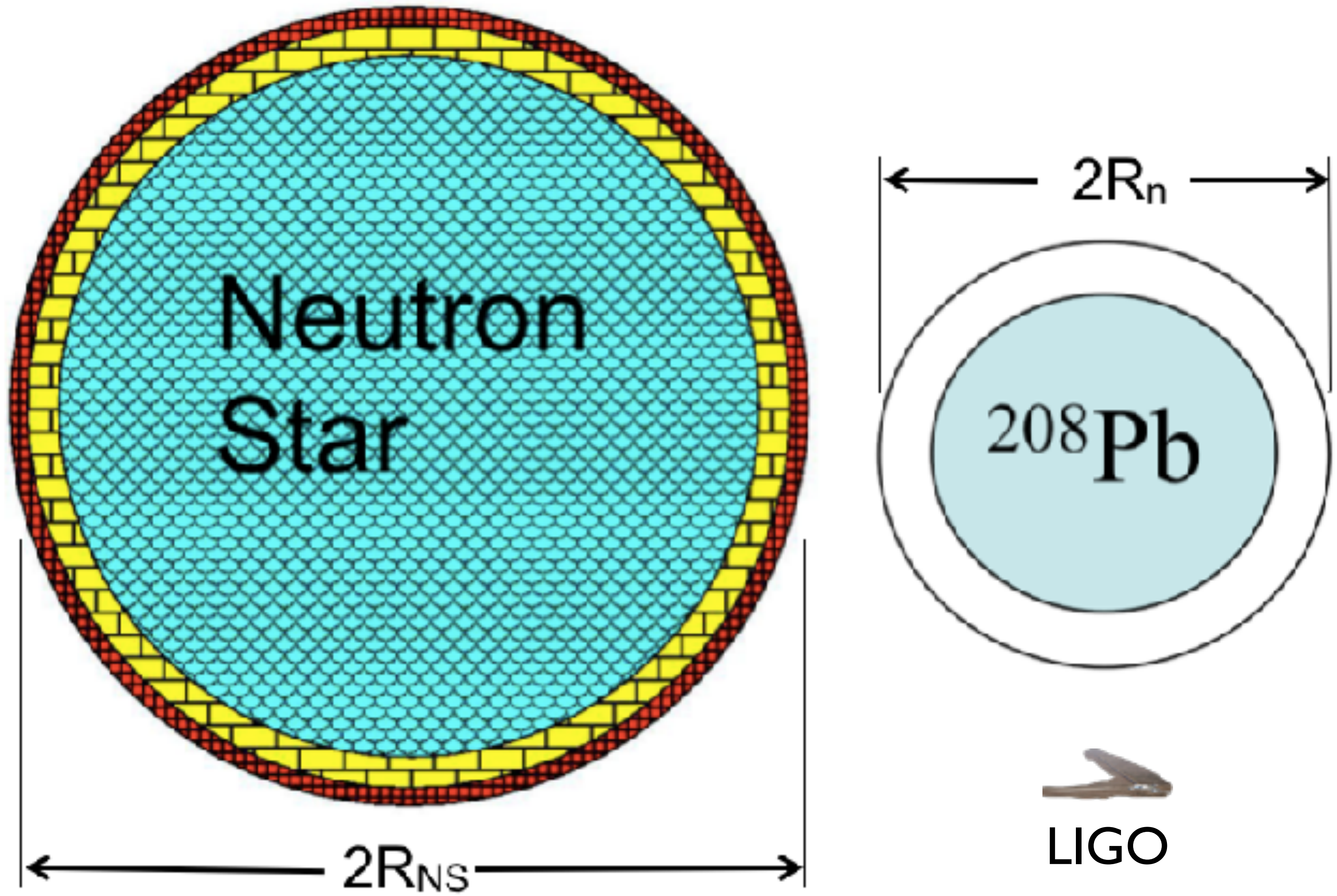


PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb.

This has important implications for neutron rich matter and astrophysics.

Radii of ^{208}Pb and Neutron Stars

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

PREX uses Parity V. to Isolate Neutrons

- In Standard Model Z^0 boson couples to the weak charge.
- Proton weak charge is small:

$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

- Neutron weak charge is big:

$$Q_W^n = -1$$

- Weak interactions, at low Q^2, probe neutrons.
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons

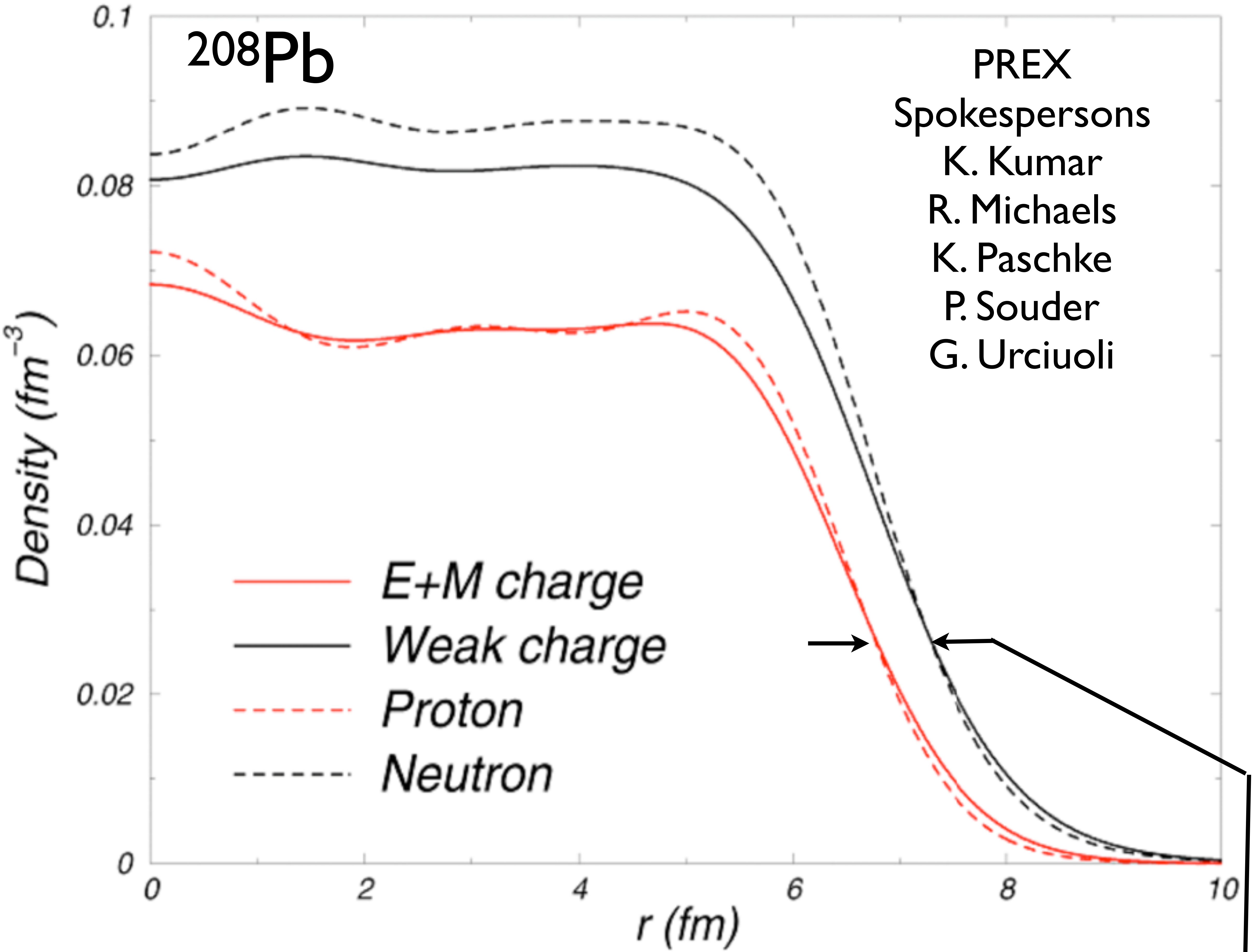
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

- A_{pv} from interference of photon and Z^0 exchange. In Born approximation

$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\rm ch}(Q^2)}$$

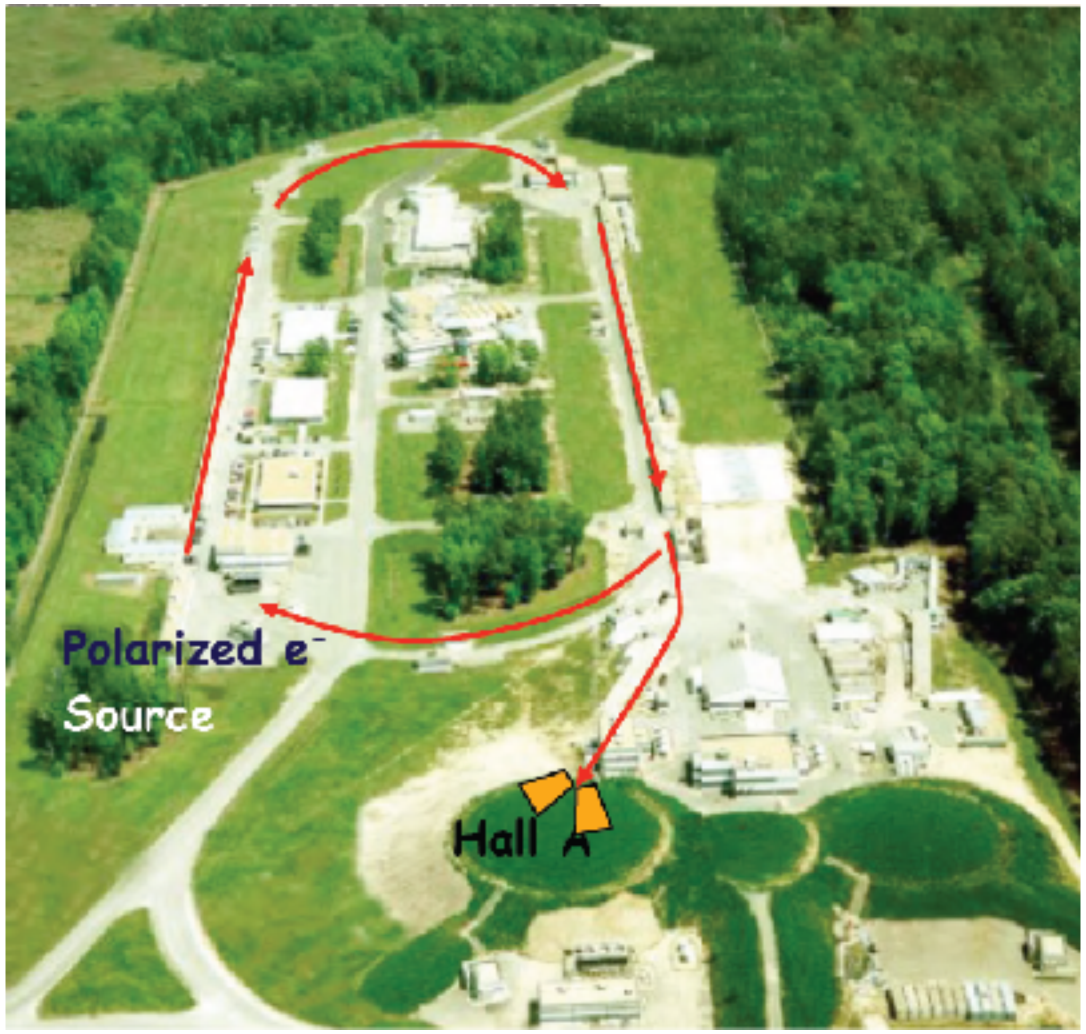
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

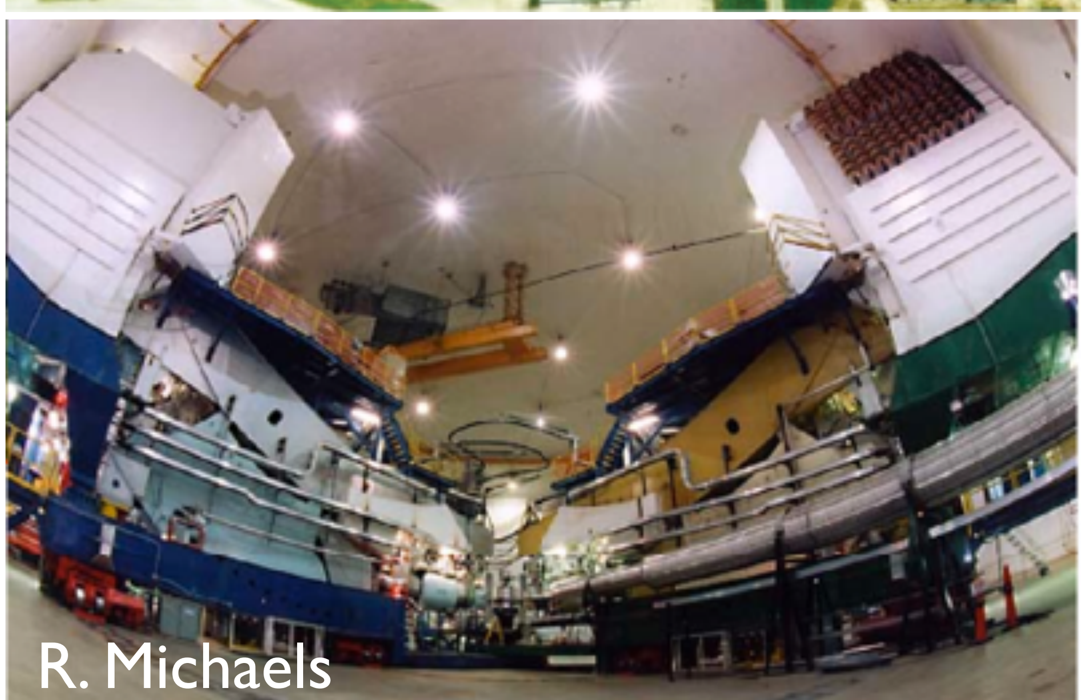
- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**



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

PREX in Hall A at Jefferson Lab





- **PREX**: ran in 2010. 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb

  $A_{PV} = 0.657 \pm 0.060(stat) \pm 0.014(sym)$ ppm

- From A_{pv} I inferred neutron skin: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm.

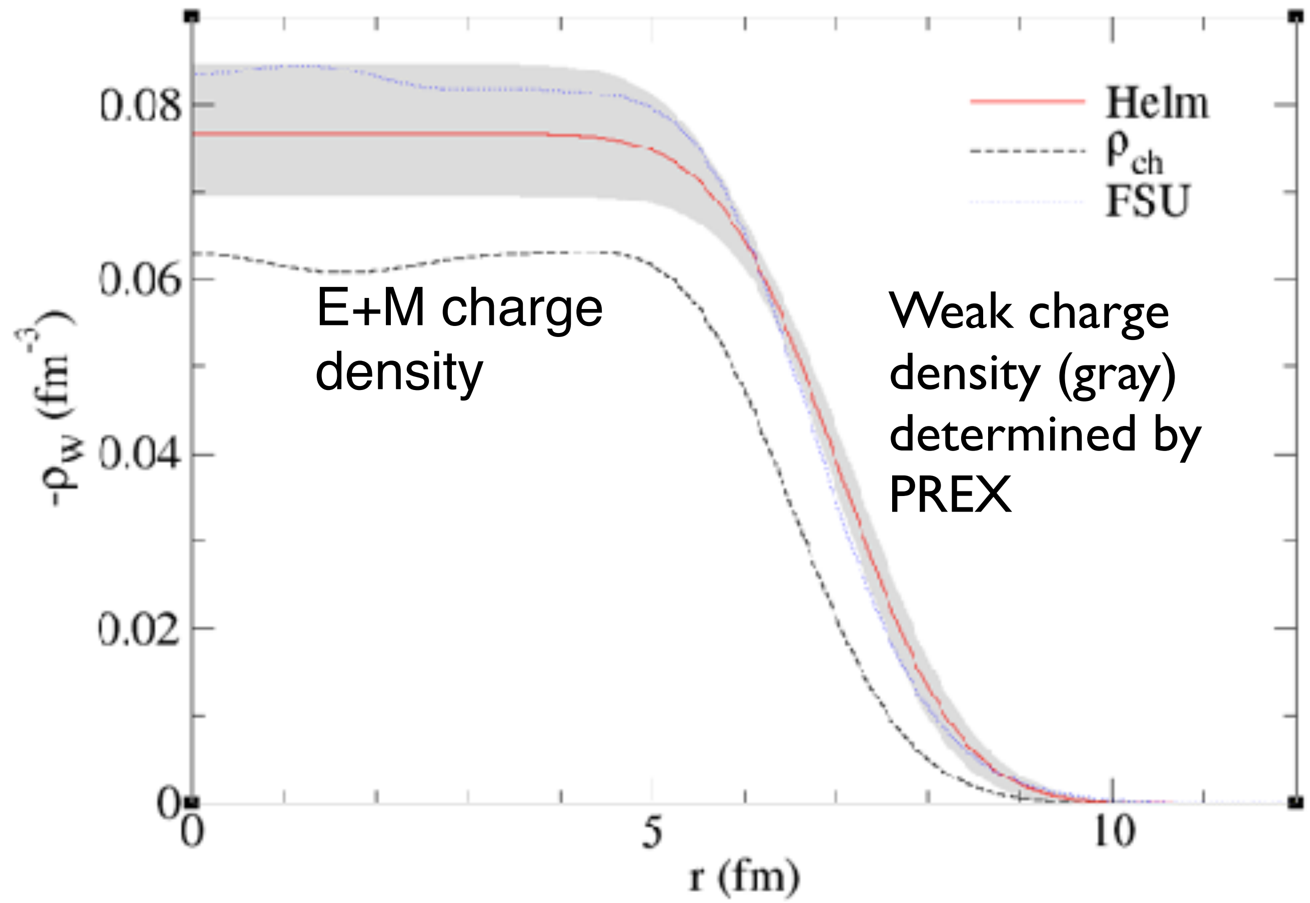
- Next measurements:

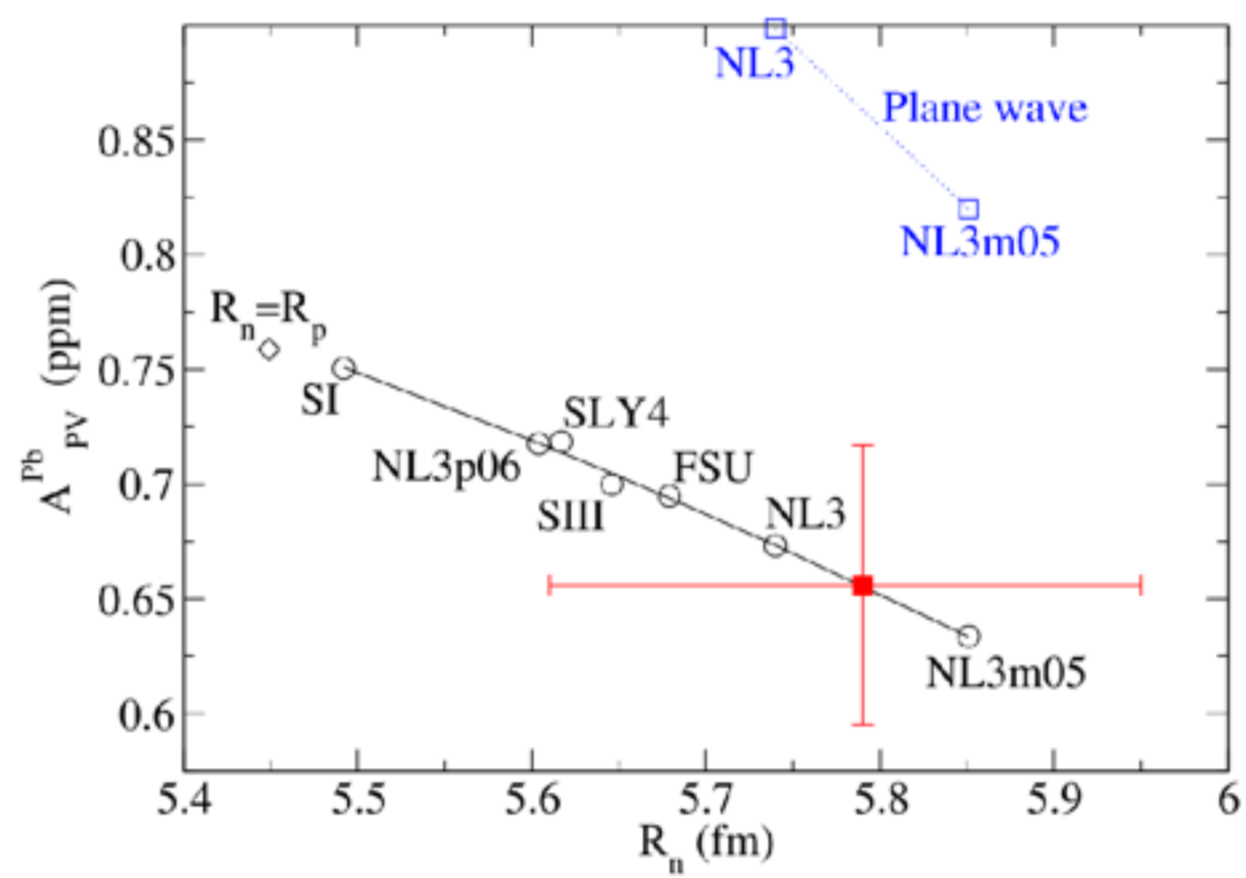
- **PREX-II**: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm. Ran this summer! Ended 8am Monday, Sep. 9, 2019.

- **CREX**: Measure R_n of ^{48}Ca to ±0.02 fm. Microscopic calculations feasible for light n rich ^{48}Ca to relate R_n to *three neutron forces.* Runs Nov. '19 through Spring '20

Physics Data Analysis for PREX, CREX

- 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb
- **A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sym) ppm**
- Weak form factor at q=0.475 fm^{-1}: $F_W(q)$ = 0.204 ± 0.028
- Radius of weak charge distr. R_W = 5.83 ± 0.18 fm ± 0.03 fm
- Compare to charge radius R_{ch}=5.503 fm --> weak skin: $R_W - R_{ch}$ = 0.32 ± 0.18 ± 0.03 fm
- First observation that weak charge density more extended than (E+M) charge density --> weak skin.
- Unfold nucleon ff--> neutron skin: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm
- Phys Rev Let. **108**, 112502 (2012), Phys. Rev. C **85**, 032501(R) (2012)





PREX II, CREX

- PREX II took data this summer ending Sep. 9, 2019 (^{208}Pb goal R_n to +/- 0.06 fm)
- CREX (^{48}Ca goal R_n to +/- 0.02 fm) will run Dec 2019 through March 2020
- Now PREX II analysis (~1 year): statistics, false asymmetries from helicity correlated beam properties, backgrounds, nonlinearities, beam polarization, acceptance and effective Q^2 —> Physics Asymmetry. -> Weak formfactor, weak radius, neutron radius.

Merger GW170817: deformability of NS

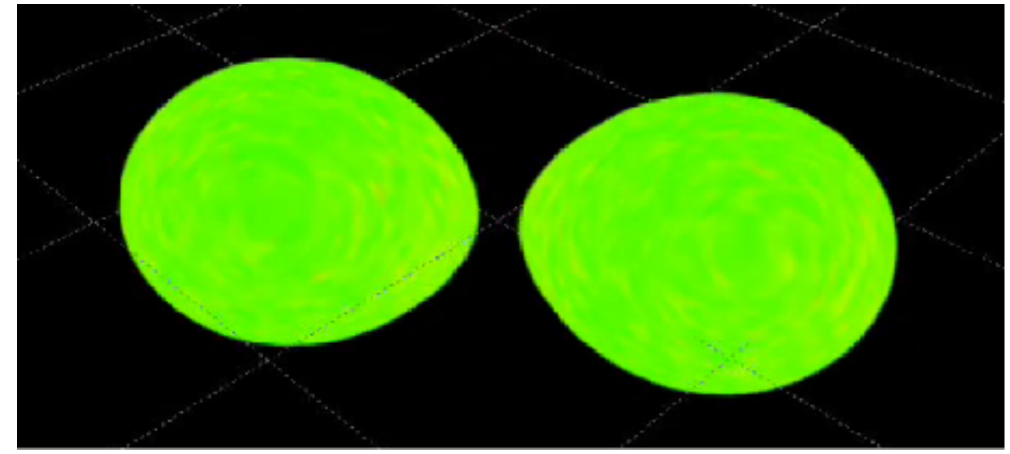
- Gravitational tidal field distorts shapes of neutron stars just before merger.
- Dipole polarizability of an atom ~ R^3.

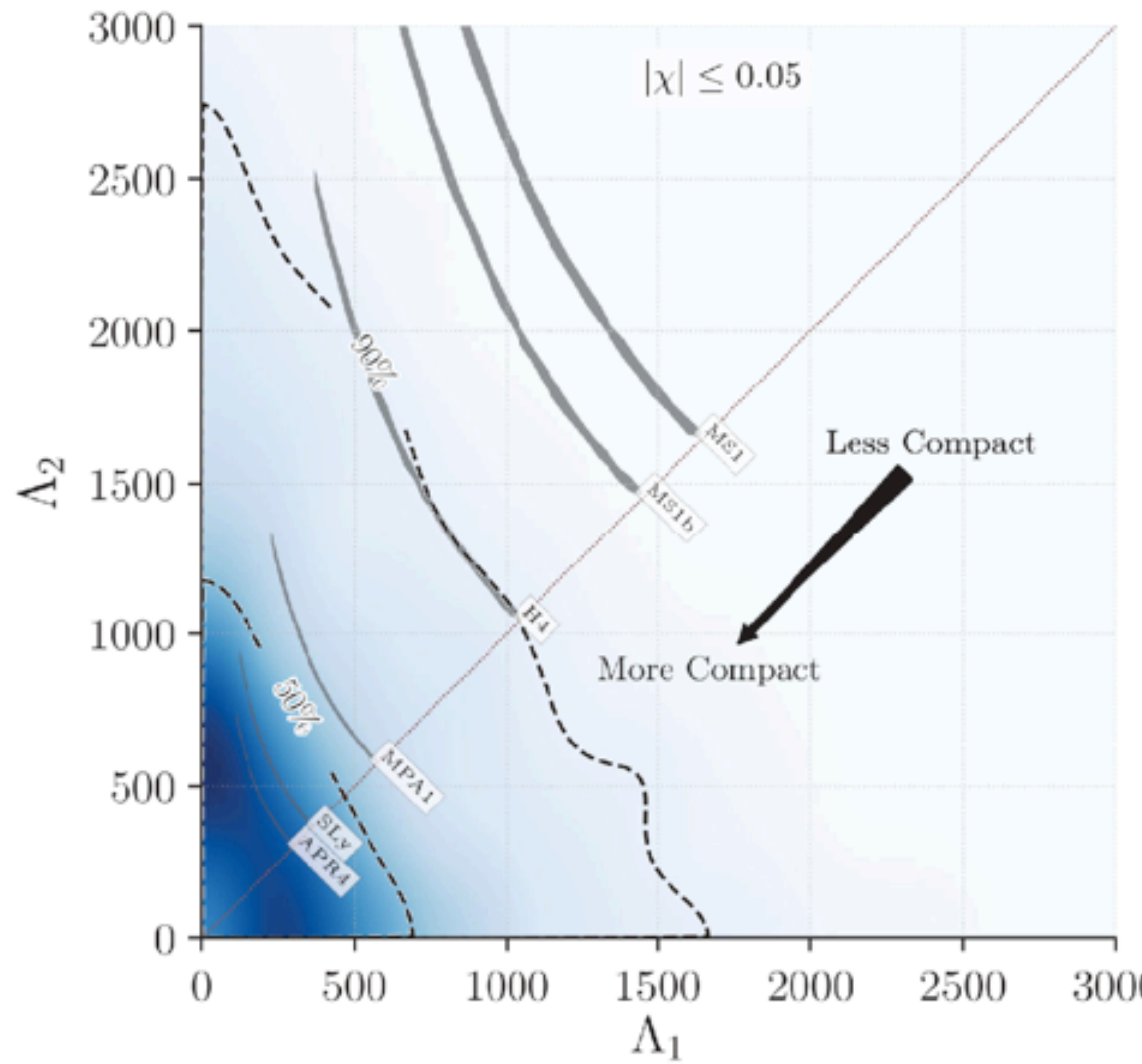
$$\kappa = \Sigma_f \frac{|\langle f|rY_{10}|i\rangle|^2}{E_f - E_i} \quad \propto R^3$$

- Tidal deformability (or mass 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 limits on Λ_1 and Λ_2.

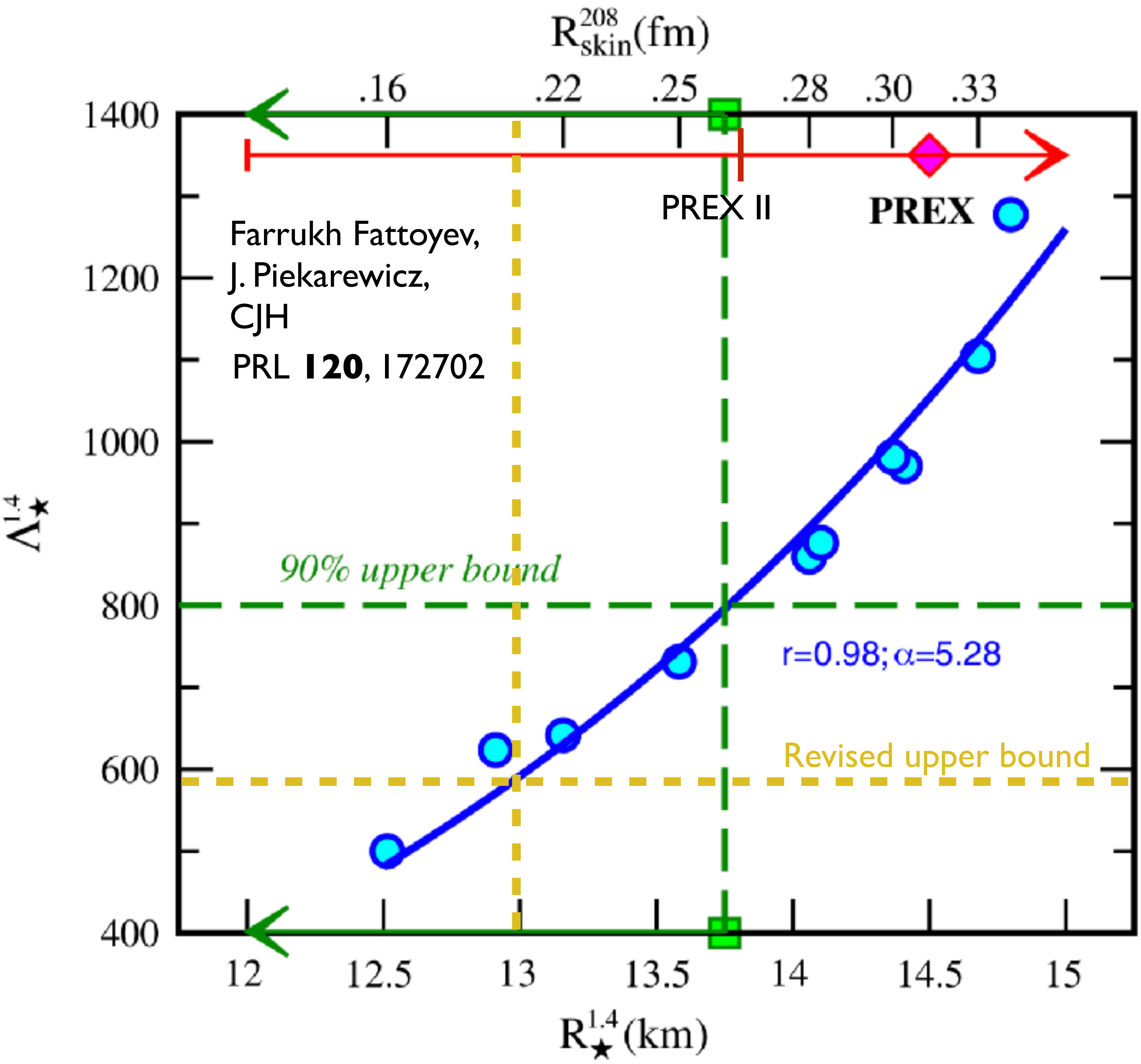




LIGO vs PREX

Deformability Λ of 1.4M_{sun} NS now less than 580 (Yellow dashed). ArXiv:1805.11581

This suggests radius of a NS is less than 13 km and $R_{skin}(^{208}Pb)$ < 0.21 fm



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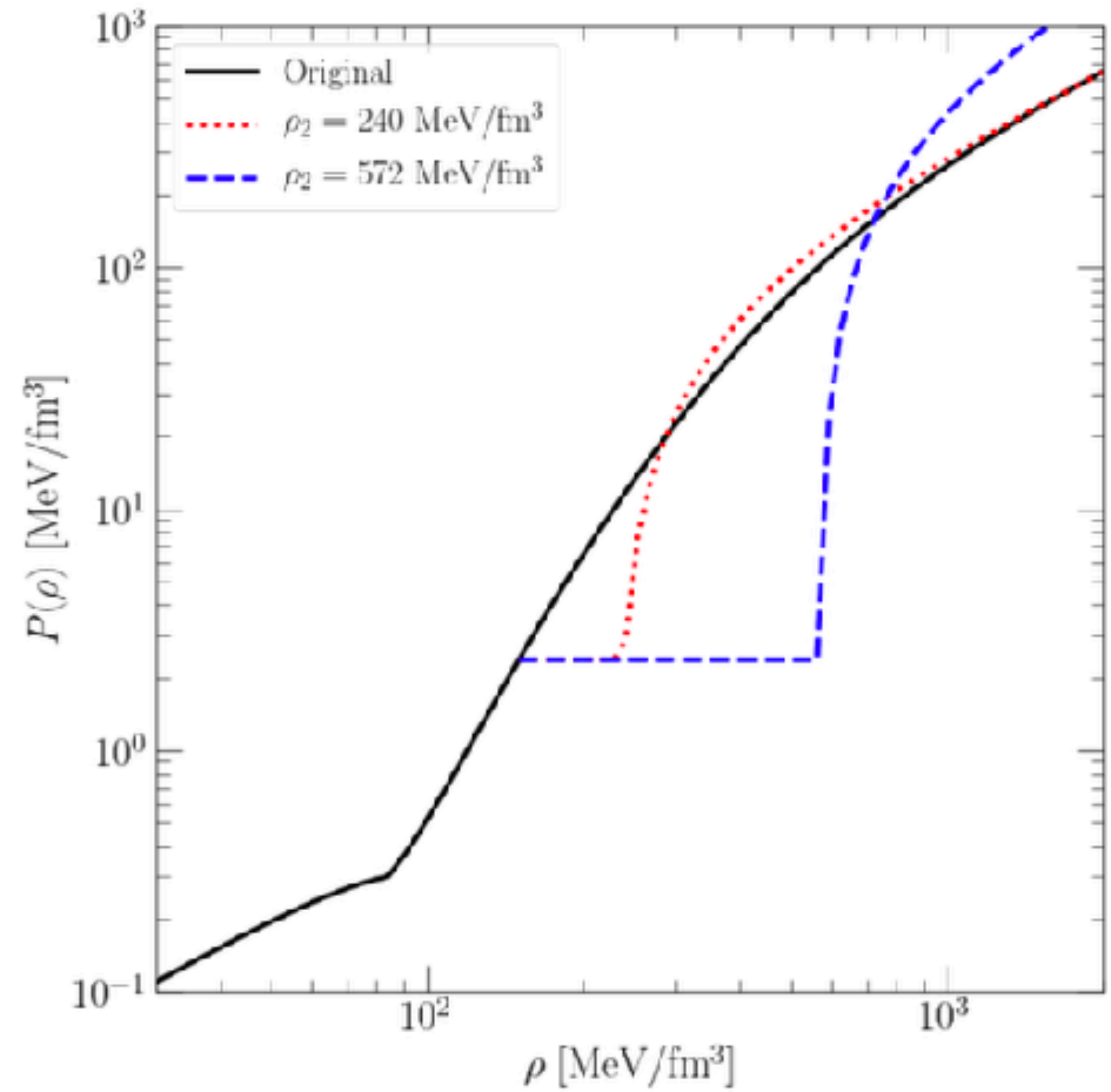
Large sound speed of dense matter and deformability of NS

- GW observations of GW170817 constrain deformability of $1.4M_{sun}$ NS to be:
  $\Lambda_{1.4} = 190^{+390}_{-120}$
- *Pressure at $2n_0$ can't be too large.*
- Radio observations of pulsar PSR J0740+6620 has mass $2.14^{+0.10}_{-0.09}\ M_{sun}$.
- *Pressure at very high density must be large* to support star against collapse.
- Pressure likely increases rapidly with density —> dense matter has a large sound speed.

ArXiv:1910.05463 B. Reed, CJH

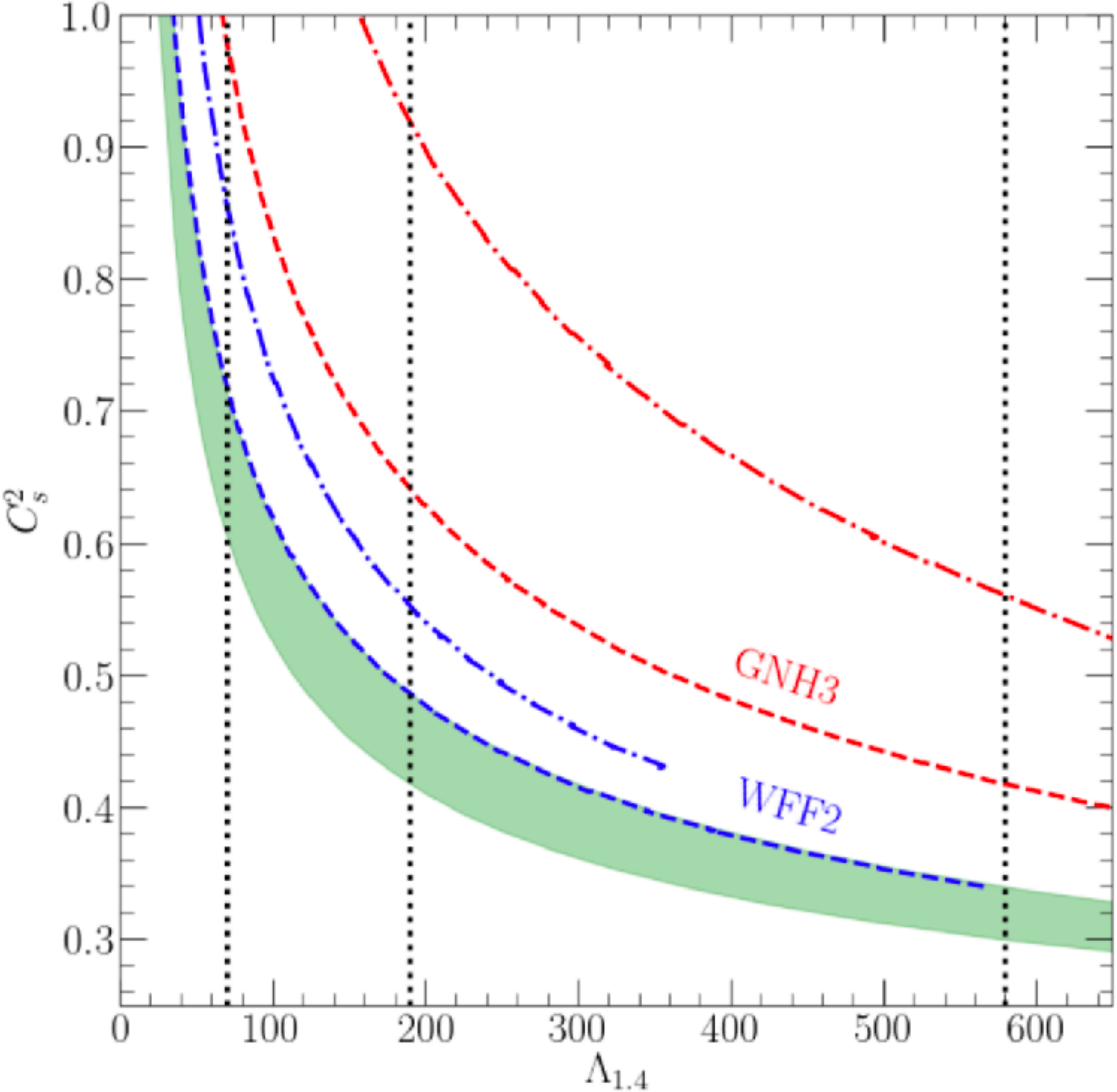
Model EOS with small deformability, large maximum mass

- Modify model EOS to reduce p near $2n_0$ and increase p at high density
- At high density constant sound speed chosen so maximum mass is $2.1M_{sun}$.

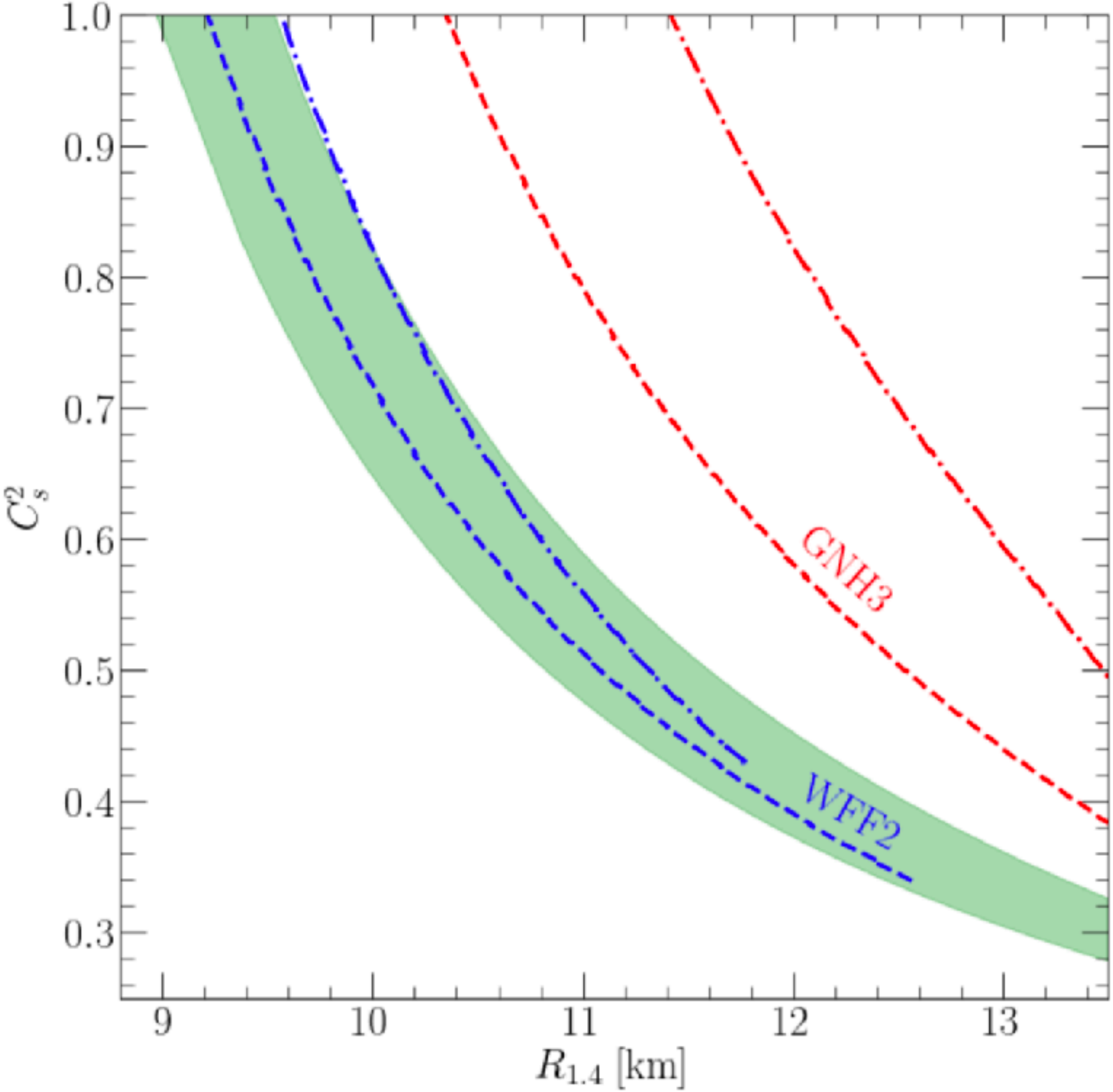


$$p(\rho < \rho_1) = p_{\text{model}}(\rho)$$

$$p(\rho > \rho_1) = p_{\text{model}}(\rho_1) + (\rho - \rho_2) C_s^2 \Theta(\rho - \rho_2)$$



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
C_s^2
0
100
200
300
400
500
600
$\Lambda_{1.4}$
GNH3
WFF2



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
C_s^2
9
10
11
12
13
$R_{1.4}$ [km]
GNH3
WFF2

EOS	C_s^2	$R_{1.4}$ [km]	ρ_2 [MeV/fm^3]	Λ_{min}
IUFSU [34]	0.429	11.8	284.97	26.9
FSUGarnet[36]	0.431	11.8	287.47	27.1
FSUGold 2 [37]	0.461	12.1	313.14	31.8
FSUGold 2H [38]	0.430	11.7	286.33	27.1
FSUGold 2R [38]	0.429	11.7	285.73	27.0
NL3 [39]	0.467	12.1	317.97	32.3
NL3$\omega\rho$ [40]	0.437	12.1	293.04	28.1
GNH3 [41]	0.486	11.7	328.82	34.8
Gapj84 [41]	0.459	12.2	311.66	30.9
GCS4 [42]	0.452	11.9	305.83	30.0
GCS8 [42]	0.447	11.9	302.00	29.5
WFF2 [43]	0.418	11.5	275.60	25.3
MPA1 [44]	0.439	11.4	291.33	27.9
SLy [45]	0.433	11.5	287.46	27.3
FPS [46]	0.421	11.5	278.27	25.7

TABLE I: Comprehensive list of the EOSs used in the text. We report here the values of the square of the sound speed in units of c, ρ_2 in MeV/fm^3, and the radius in km of a 1.4 $M_\odot$ NS at a fixed $\Lambda_{1.4} = 190$, the central value given from the LIGO observation of GW170817 [23]. We also show the minimum deformabilities of each EOS, determined from where $C_s^2 = 1$. We have chosen C_s^2 so that all EOSs have a maximum NS mass of $2.1 M_\odot$.

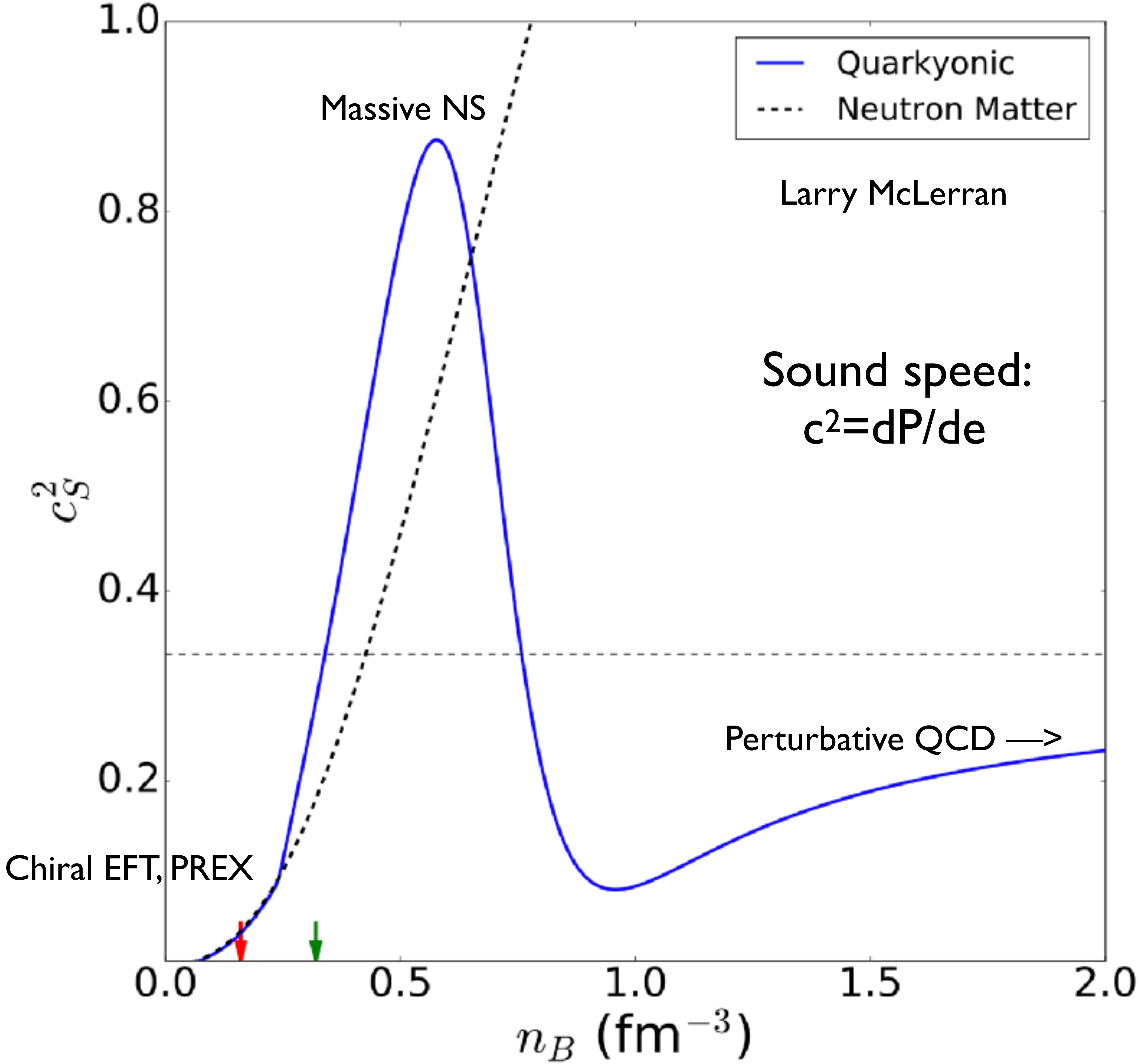
What holds up a two solar mass neutron star? [Without giving too big a deformability.]

PSR J0740+6620 has a large mass of $2.14^{+0.10}_{-0.09}\ M_{sun}$
H. T. Cromartie et al, Arxiv:1904.06759.

Speed of sound of dense matter

- Massless noninteracting quarks or gluons have $v^2=c^2/3$.
- At very high densities QCD interactions weak. Perturbative gluon exchange is attractive, so v^2 must approach $c^2/3$ from below in the limit of very high densities.
- $2M_{sun}$ NS implies QCD is not a weakly interacting quark/gluon plasma at NS densities. Must be ***strongly interacting*** plasma just as RHIC found at high T.

Yes, you can have quark matter in neutron stars but it is strongly interacting.



Massive NS
Quarkyonic
Neutron Matter
Larry McLerran
Sound speed:
c2=dP/de
Perturbative QCD —>
Chiral EFT, PREX
c_S^2
n_B (fm^{-3})
1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0

Relativistic vector exchange

- Zel'dovich showed interactions from exchange of massive vector give v->c.
- Walecka or other relativistic mean field models with omega meson mean fields have v->c at high density and often can easily hold up two solar masses.
- In one boson exchange picture, nucleon hard core from omega exchange.

What gives rise to strong repulsive interactions?

- Nuclear saturation is subtle and complicated involving three body forces.
- Nucleon "hard cores" may not fully interact at saturation density. [3 nucleon forces can halve saturation density]
- "Overlap" of hard cores at a few times nuclear density could rapidly increase energy. Hard cores could be thought of as omega meson exchange.

Chiral EFT and large sound speed

- Chiral EFT includes pion exchange and contact terms.
- Chiral EFT does not resolve omega exchange or hard cores. *Therefore it may not directly* predict large repulsion.
- Repulsion likely occurs at densities beyond where chiral EFT converges.
- Chiral EFT must break down in a way to create strong repulsion. We are observing how chiral EFT breaks down.

Are hadronic degrees of freedom still appropriate at NS densities?

- Large sound speed is consistent with hadrons.
- Asympototicly free quarks and gluons not appropriate.
- But strongly interacting quark / gluon plasma possible.
  - Why is sound speed large for quarks?

What holds up $2M_{sun}$ NS?

- Strong interactions between quarks, similar to what gives small shear viscosity at RHIC
- Vector meson (omega) exchange
- Overlap of nucleon hard cores at a few times nuclear density
- These large interactions likely “break” Chiral EFT and cause it to diverge.

Mergers and the PREX neutron density experiment

- PREX II ran this summer to measure R_n for ^{208}Pb to 1%.
- CREX will run in fall and spring and measure R_n for ^{48}Ca to 0.6%.
- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke…
- Farrukh Fattoyev, Jorge Piekarewicz, Matt Caplan, Zidu Lin, Brendan Reed

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