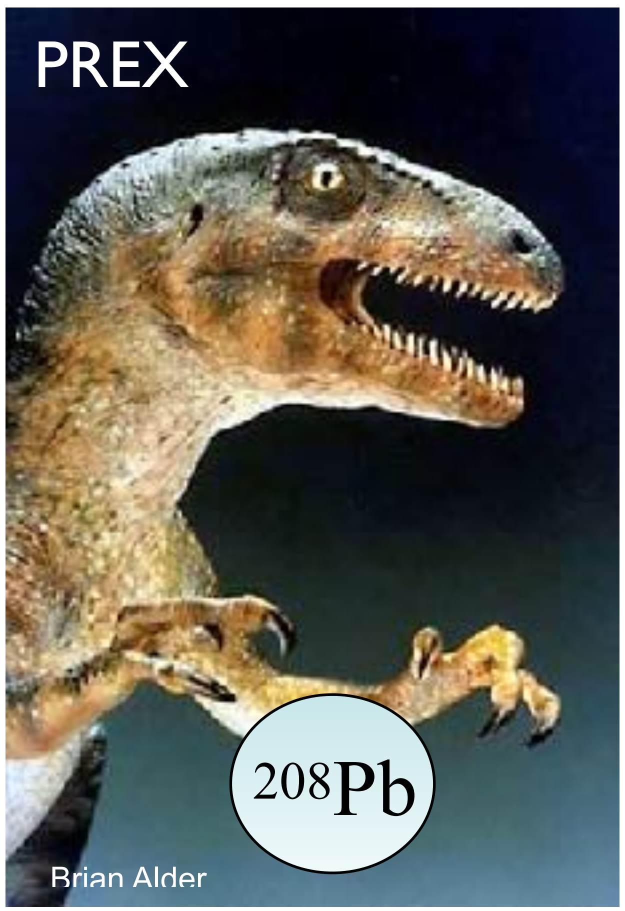
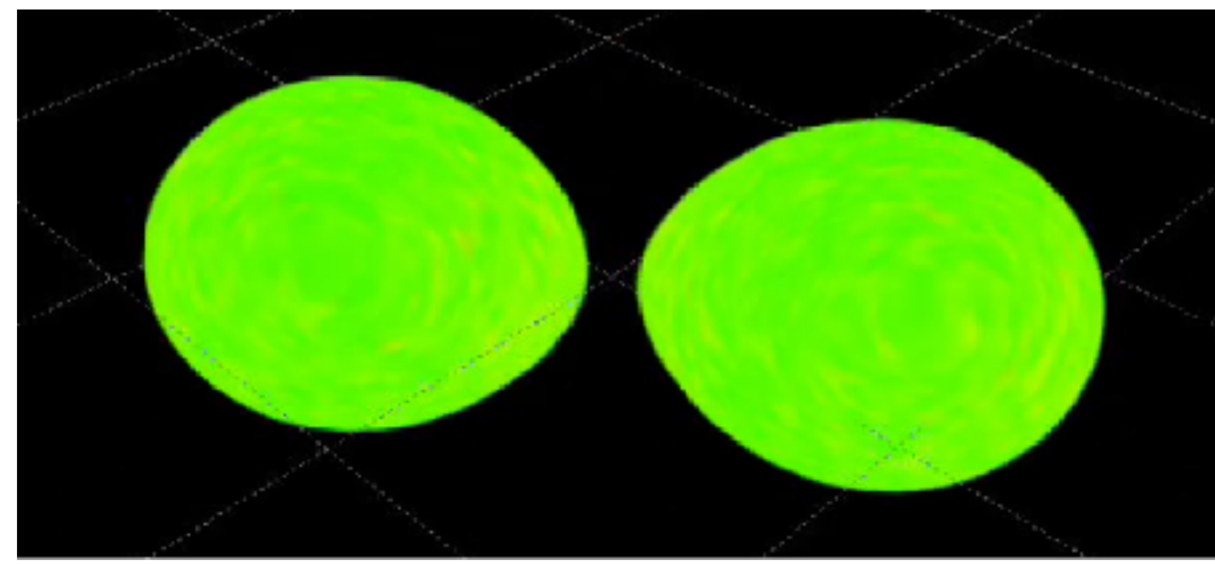
Gravitational waves and nature of dense matter





Chuck Horowitz, Indiana U., KITP, Santa Barbara, Jun. 2019

NUCLEI
Nuclear Computational Low-Energy Initiative
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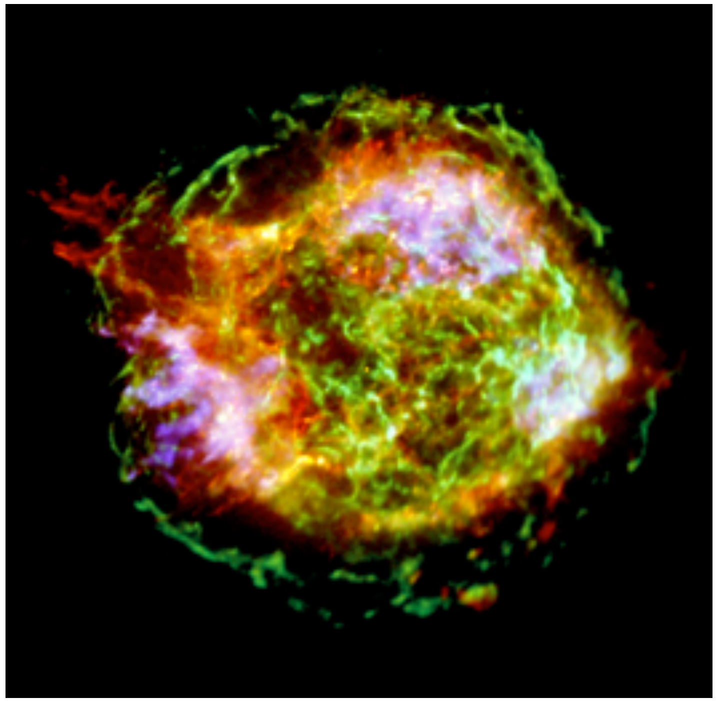
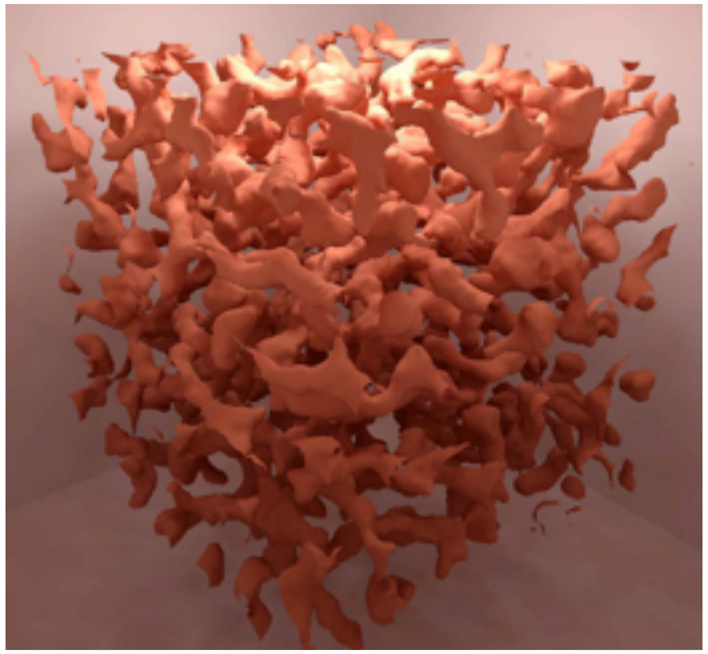
Neutron Rich Matter

- 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

Neutron rich matter

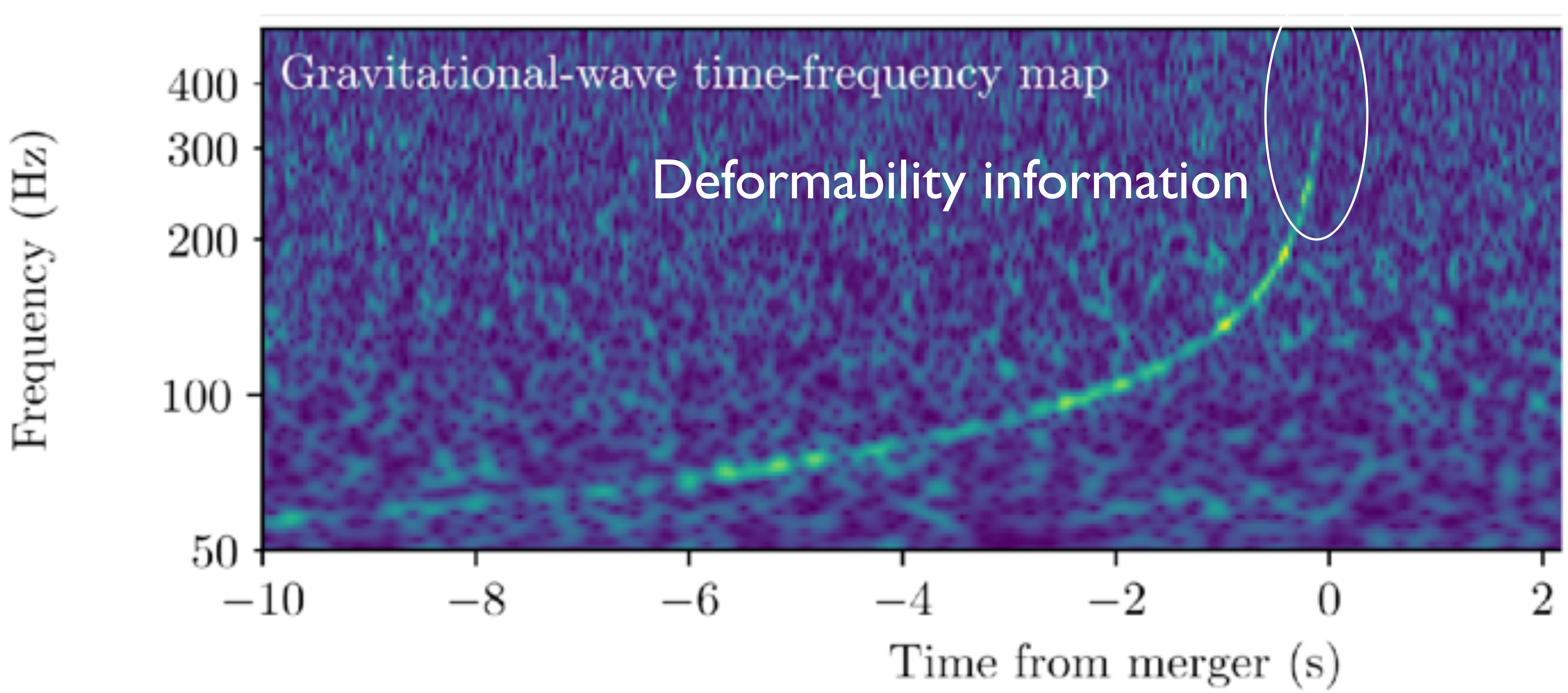
1. What does neutron rich matter look like to LIGO and VIRGO?
2. What does neutron rich matter look like in the laboratory?
3. What holds up a two solar mass neutron star?
4. What are neutron stars made of? [What is the composition: quarks, baryons…? of dense matter?]

1. What does neutron rich matter look like to LIGO?

- LIGO observed black holes in 2015. The neutron star merger observed in 2017 likely had a deformability.
- A neutron star, made of neutron rich matter, has a finite extent and thus a **polarizability or deformability** compared to a point mass black hole.

Spectacular event GW170817

- On Aug. 17, 2017, the merger of two NS observed with GW by the LIGO and Virgo detectors.
- The Fermi and Integral spacecrafts independently detected a short gamma ray burst.
- Extensive follow up observed this event at X-ray, ultra-violet, visible, infrared, and radio wavelengths.



Merger GW170817: deformability of NS

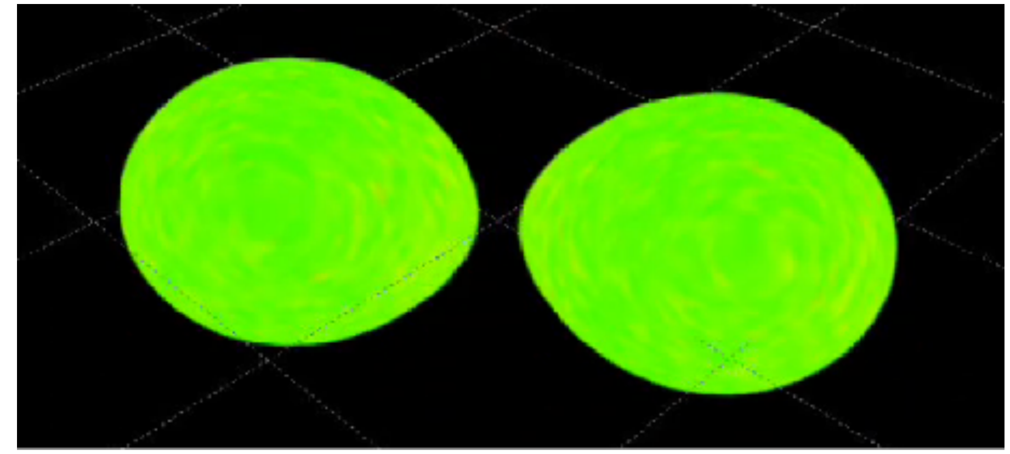
- Gravitational tidal field distorts shapes of neutron stars just before merger.
- Dipole polarizability of an atom ~ R^3.

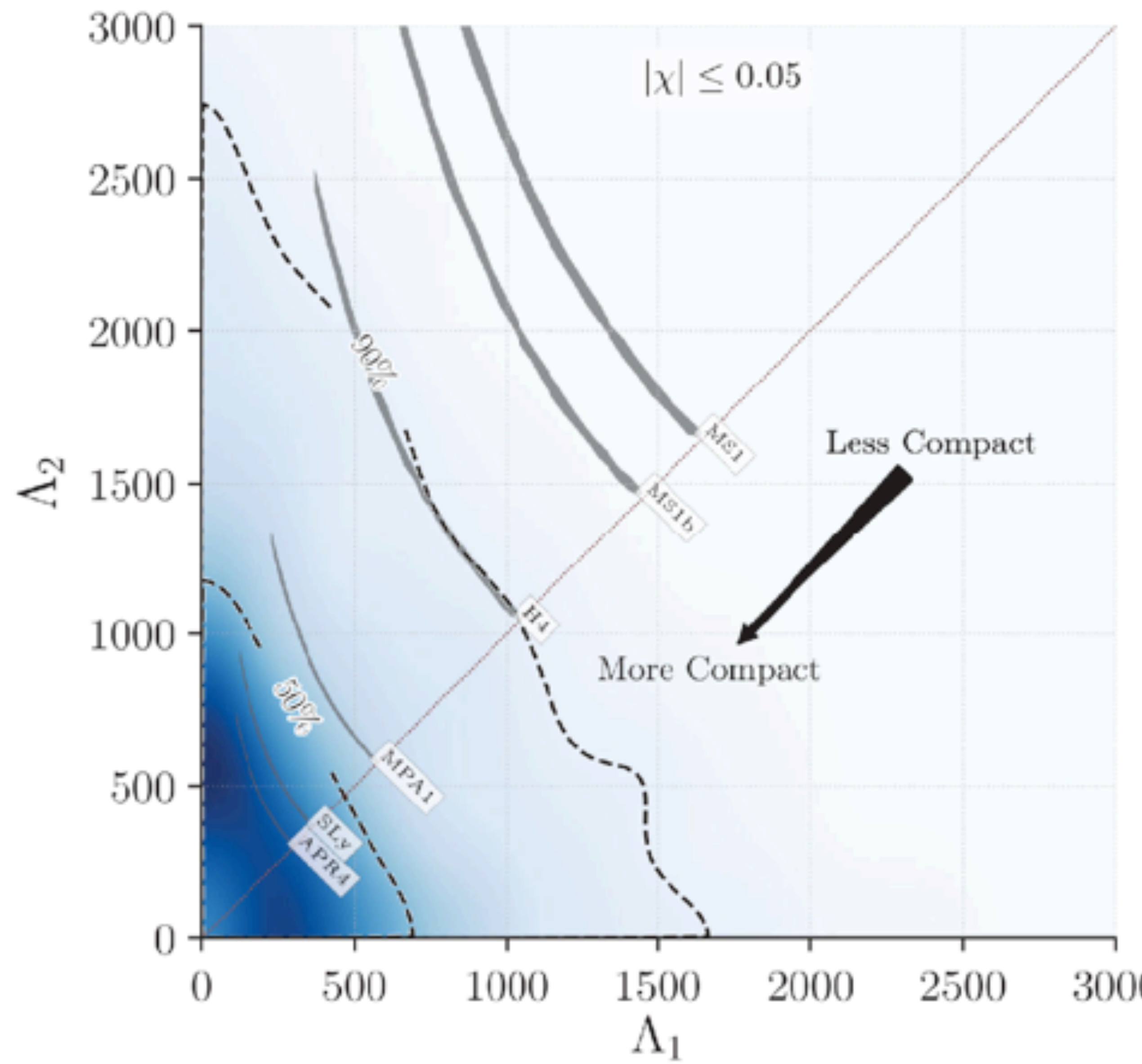
$$\kappa = \Sigma_f \frac{|\langle f|rY_{10}|i\rangle|^2}{E_f - E_i} \quad \propto R^3$$

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

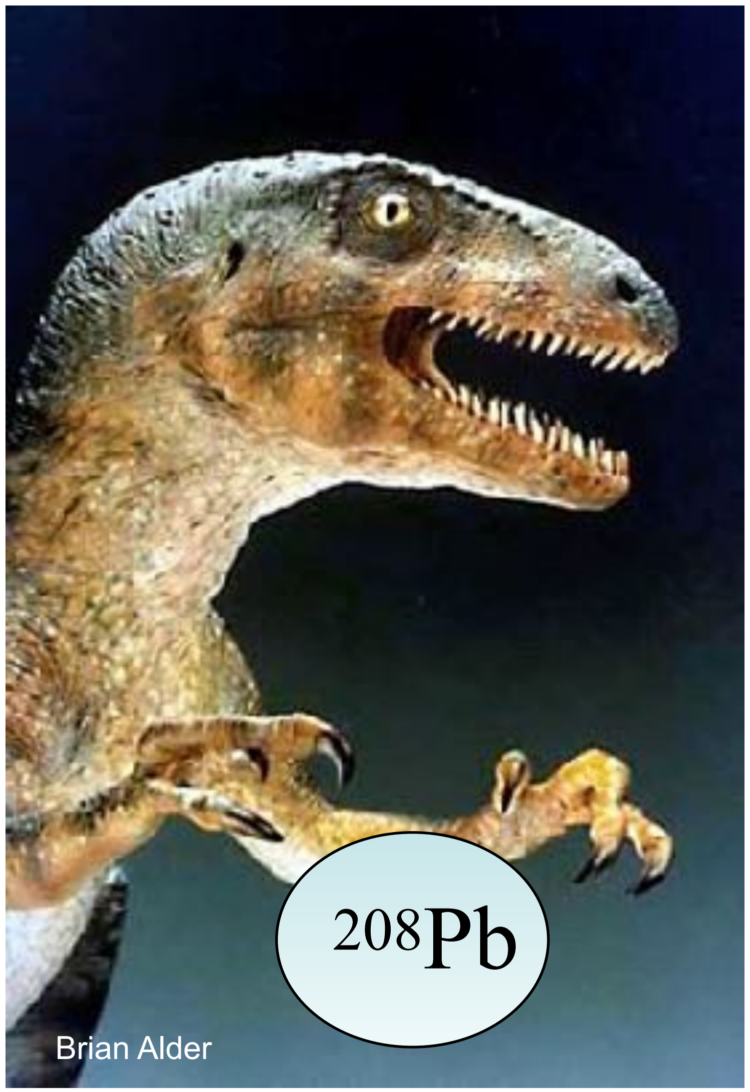
$$\Lambda \propto \Sigma_f \frac{|\langle f|r^2Y_{20}|i\rangle|^2}{E_f - E_i} \quad \propto \quad R^5$$

- GW170817 observations set upper limits on Λ_1 and Λ_2.





2. What does neutron rich matter look like in the laboratory?

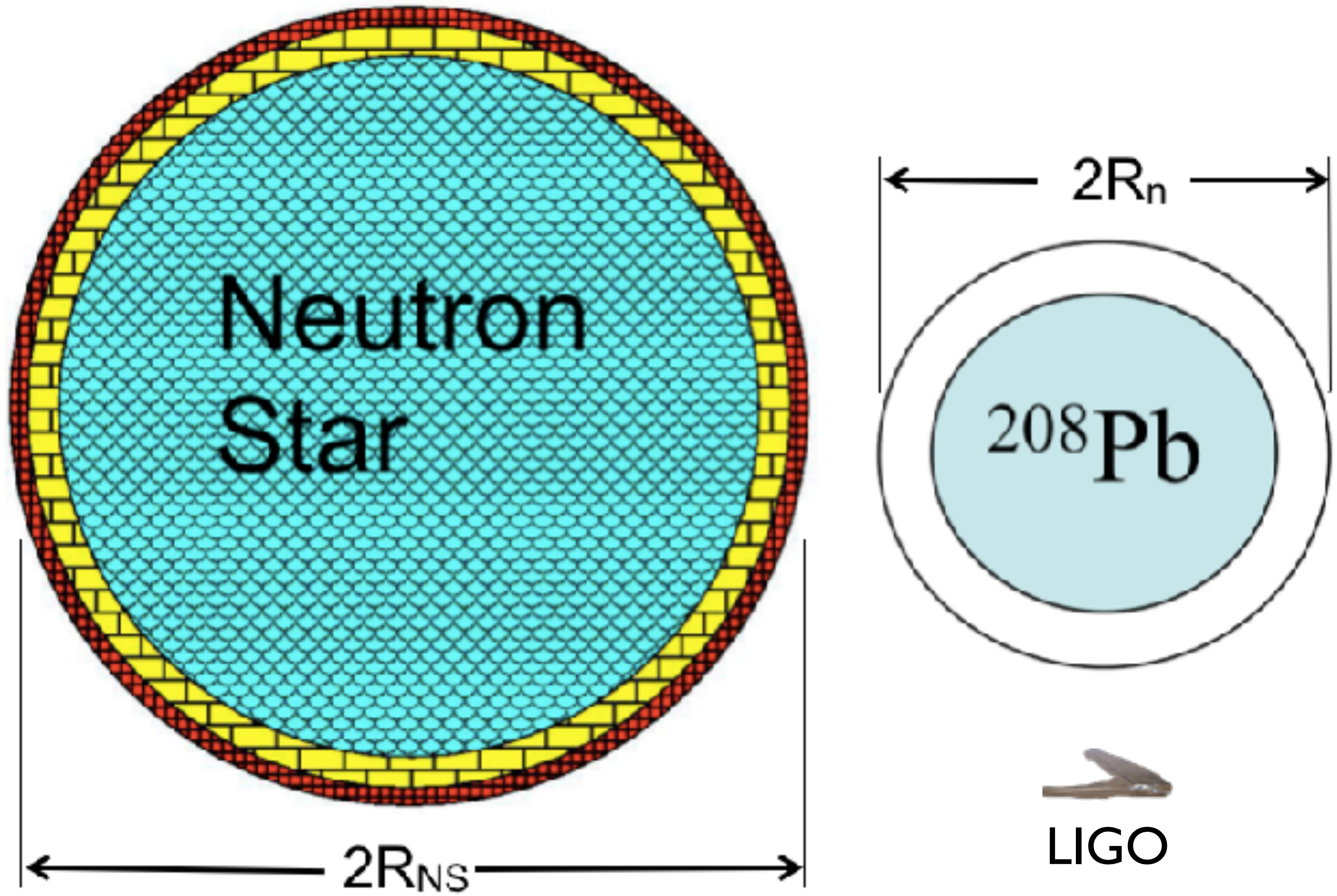


PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb.

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

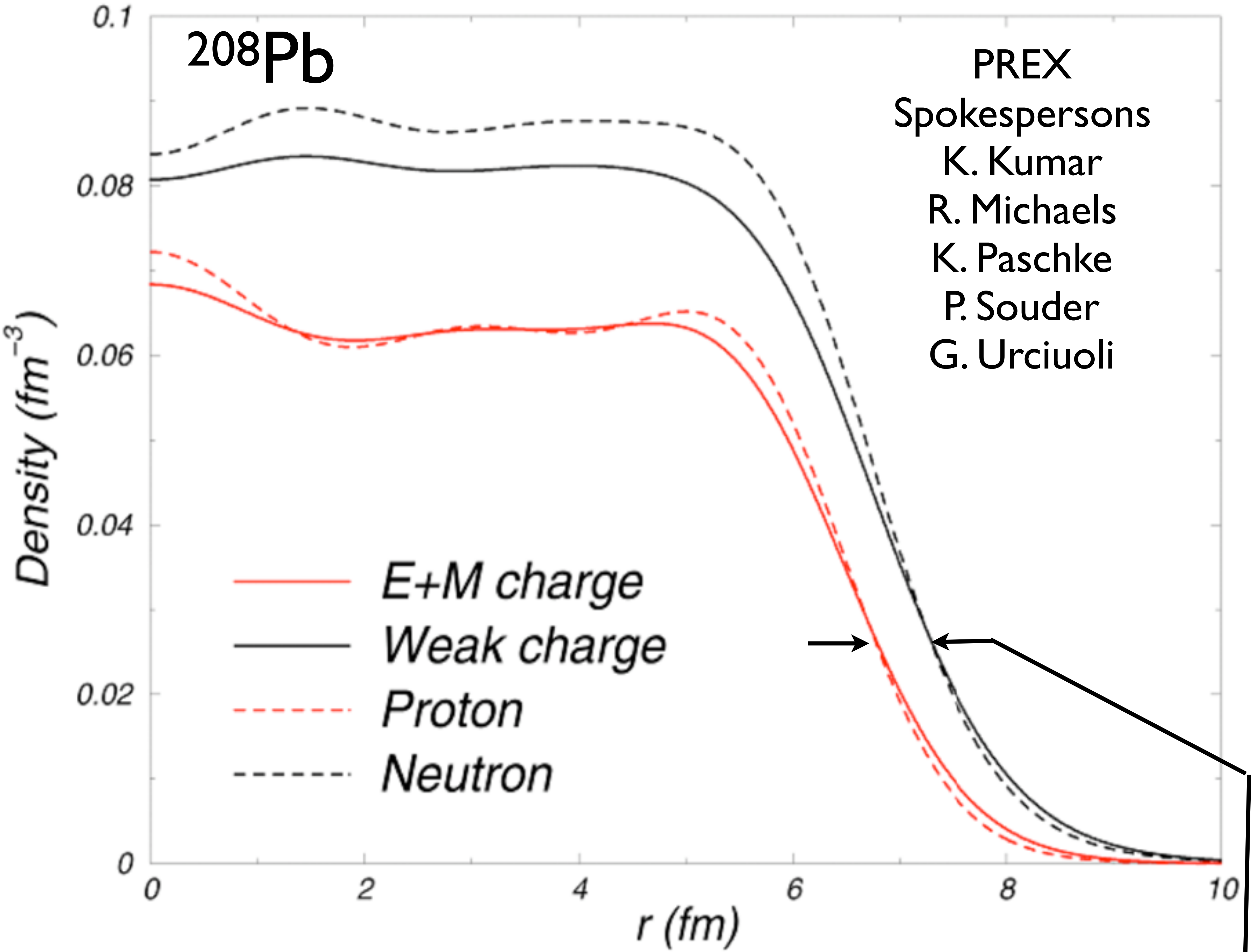
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

- 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.**

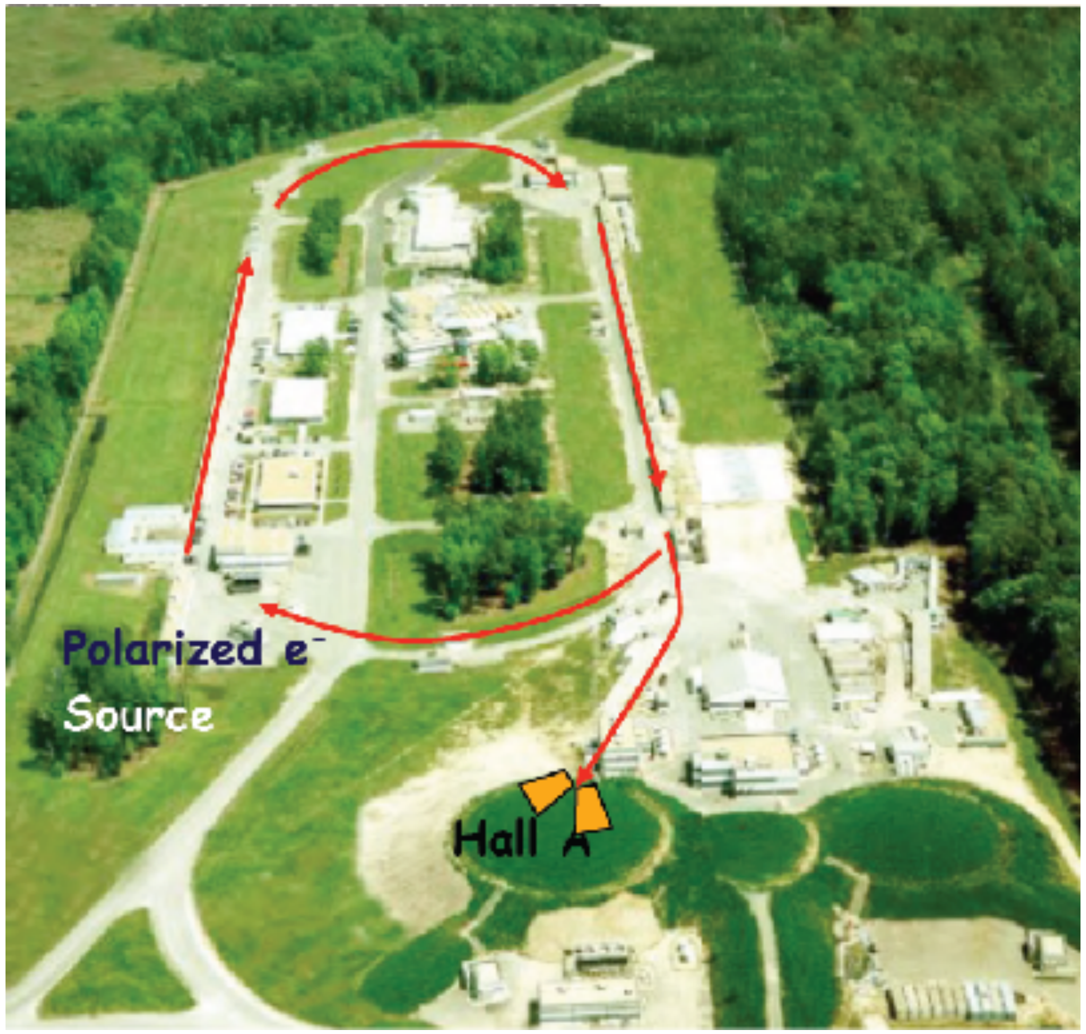


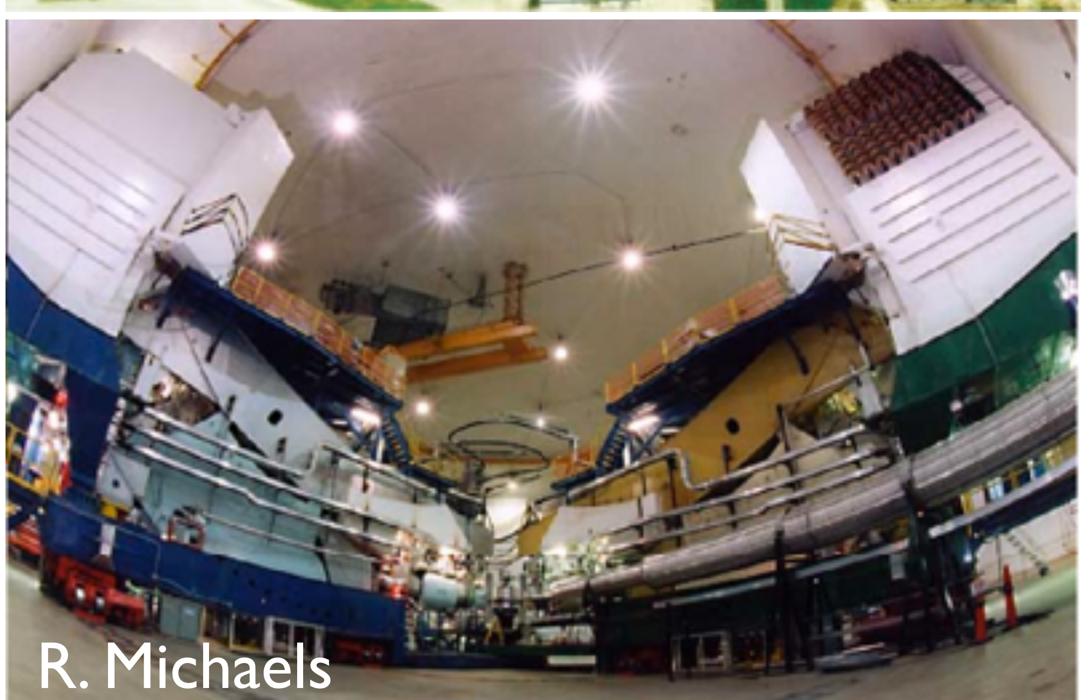
- PREX measures how much neutrons stick out past protons (neutron skin).

Symmetry Energy

- Symmetry energy S(rho) describes how energy of nuclear matter rises as one goes away from equal numbers of neutrons and protons.
- Allows extrapolation from laboratory systems with small n excess to very n rich astrophysical systems.
- Putting 44 extra n in 208Pb in center costs S at high density, putting them in surface costs S at low density.
- Thickness of n skin measures *density dependence of Symmetry energy dS/drho.*

PREX in Hall A at Jefferson Lab





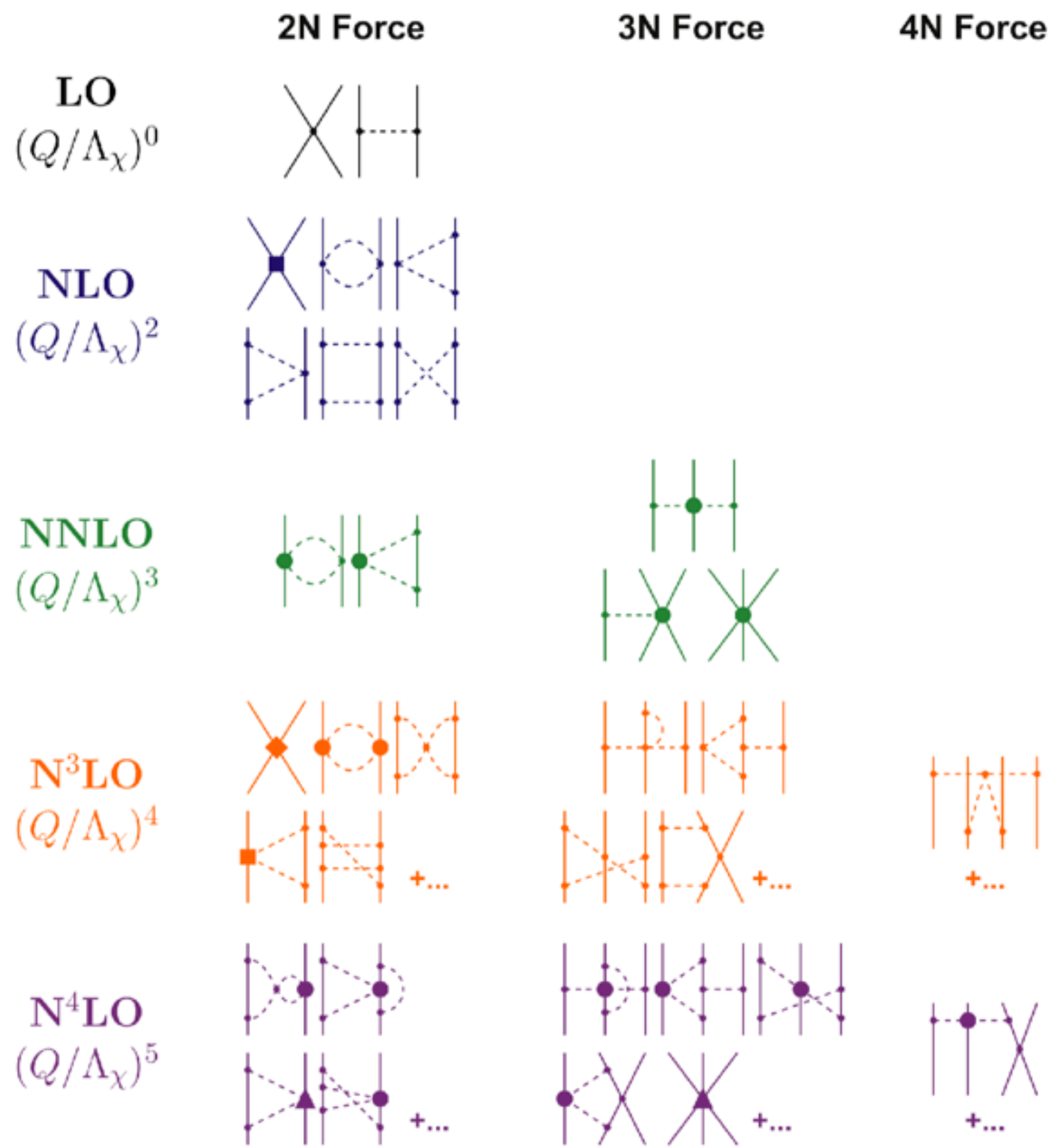
- **PREX**: ran in 2010. 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb

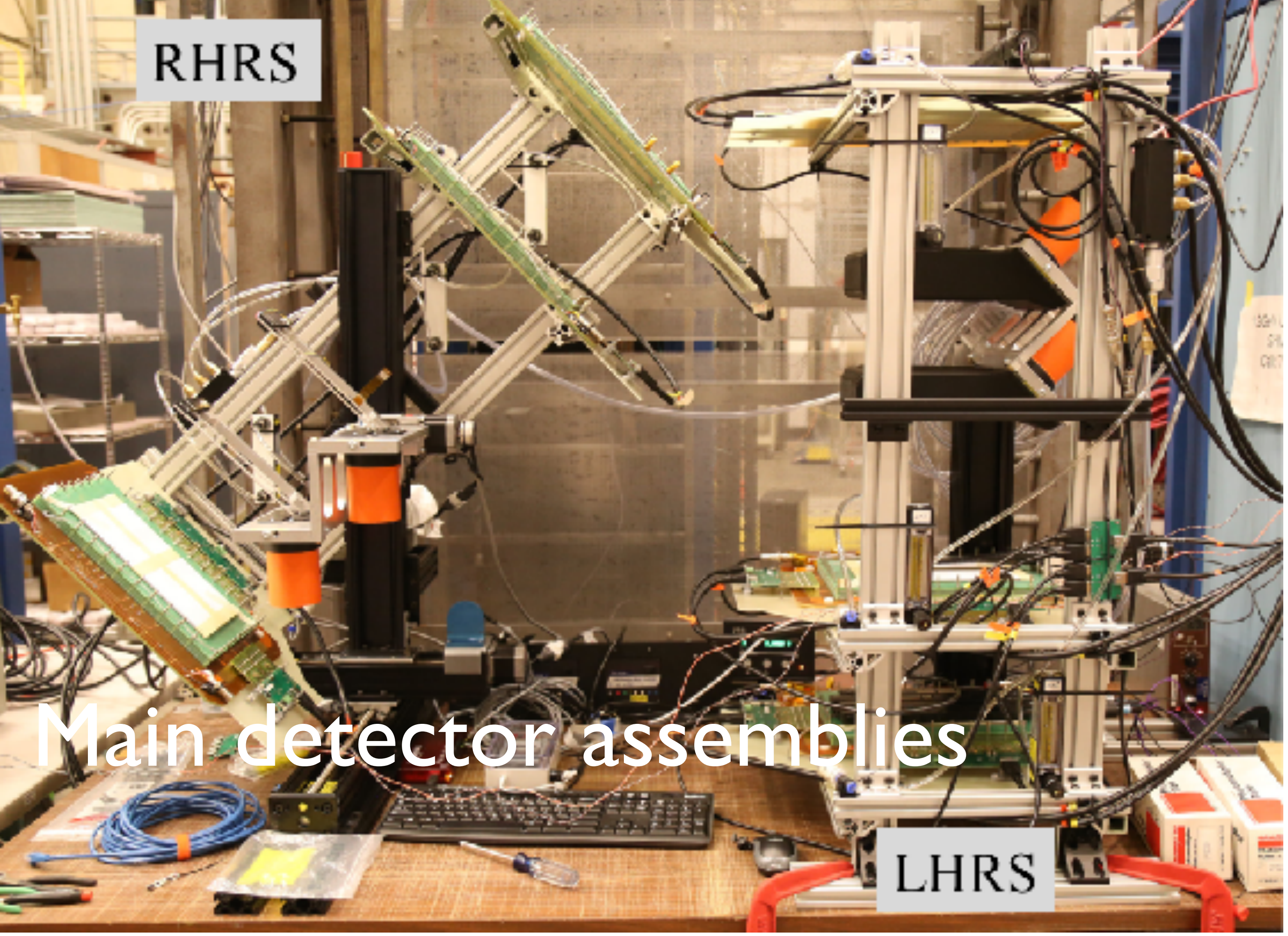
  A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sym) ppm

- 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.
- **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*.
- Install this Spring, run in Summer (PREX II), Fall to Spring (CREX)

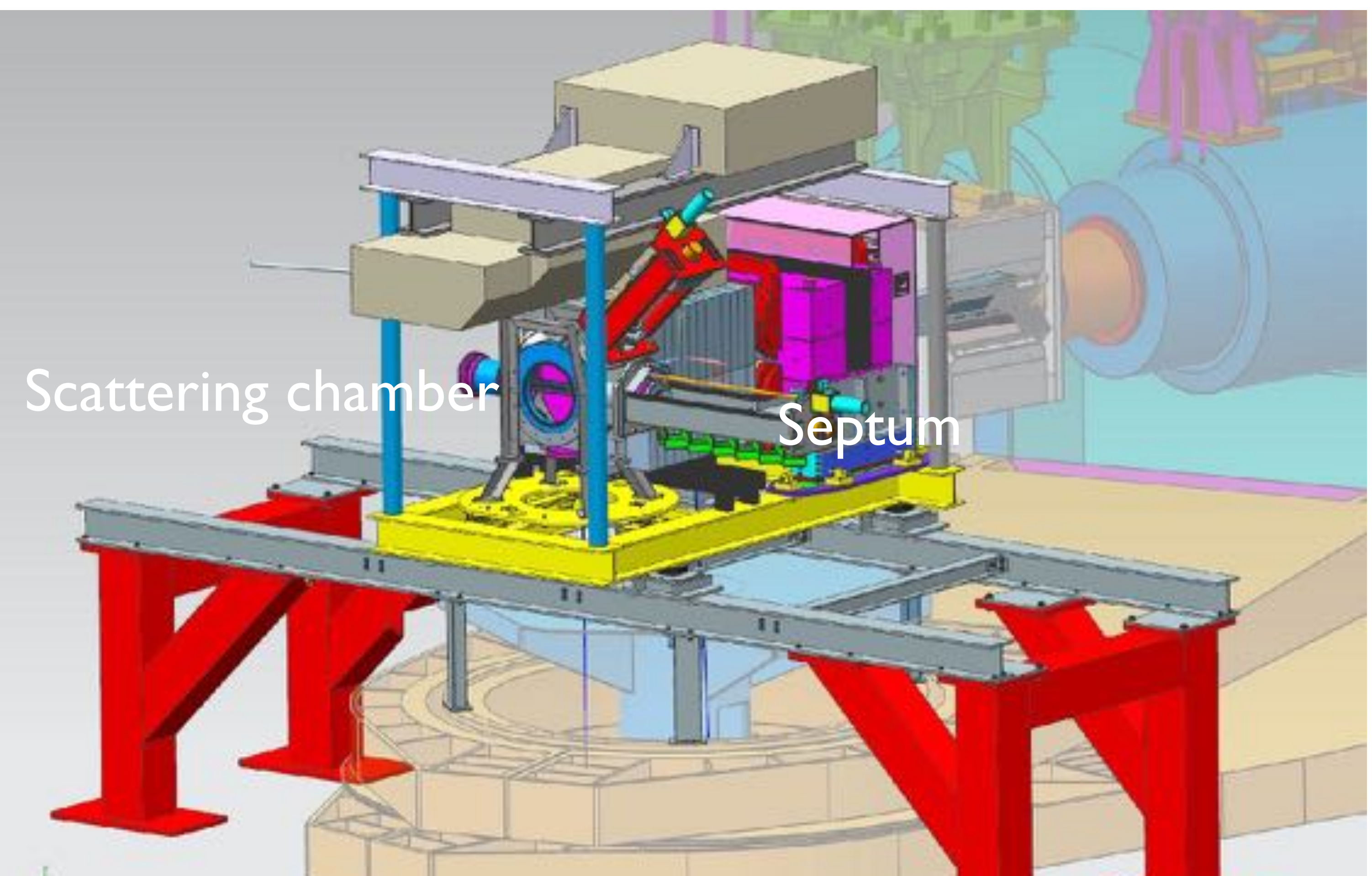
Chiral Effective Field Theory

- Interactions expanded in powers of momentum over Chiral scale.
- High momentum interactions described by contact terms with parameters fit to NN phase shifts.
- Expansion converges at low densities for finite nuclei but not at high densities in center of neutron star.
- Important three nucleon and four or more nucleon many body forces.





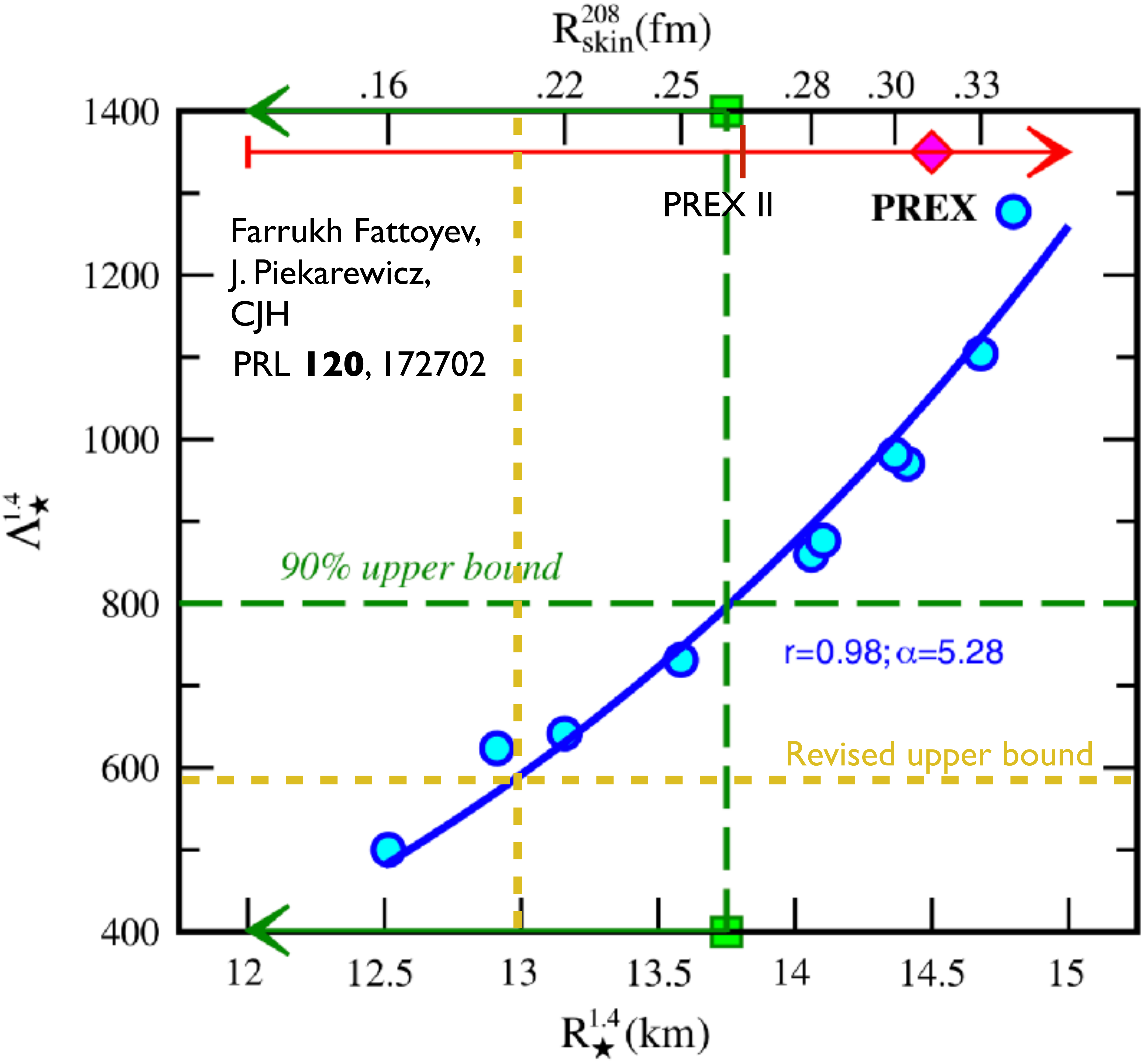
Installation going on now.
PREX II runs in summer,
CREX in fall to spring



LIGO vs PREX

Deformability Λ of 1.4M$_{sun}$ NS now less than 590 (Yellow dashed). ArXiv:1805.11581

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



Equation of state of neutron rich matter

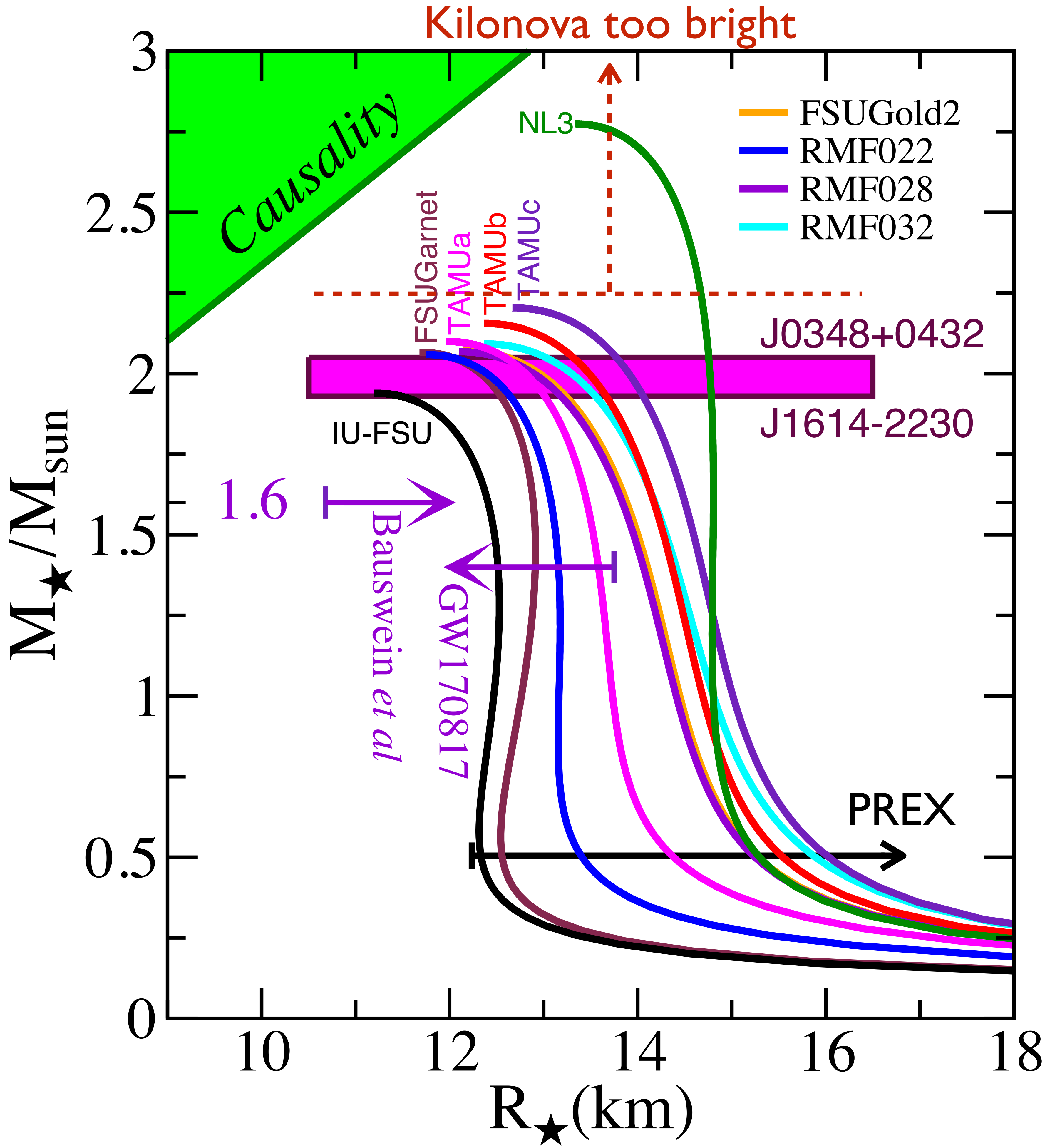
- EOS gives pressure P as a function of density ρ for neutron rich matter: $P=P(\rho)$. This depends on the strength of interactions in dense matter.
- **Low density:** nuclear structure observables including ***neutron skin*** thickness probe EOS near nuclear density. [Nuclear density ~ 3×10^{14} g/cm^3]
- **Medium density:** NS radius or ***deformability*** probe EOS at about twice nuclear density.
- **High density:** maximum NS mass or ***fate*** of merger remnant probes EOS at high densities.

- 1) If maximum mass above 2.2 Msun remnant lives too long and transfers too much rotational E to kilonova.

- 2) If R_{NS}< 10.5 km collapses too fast to black hole with too little ejected mass.

- 3) If R_{NS}>13.7 km deformability too large.

- 4) If $R(0.5M_{sun})$<12.2 km, 208Pb neutron skin too small for PREX

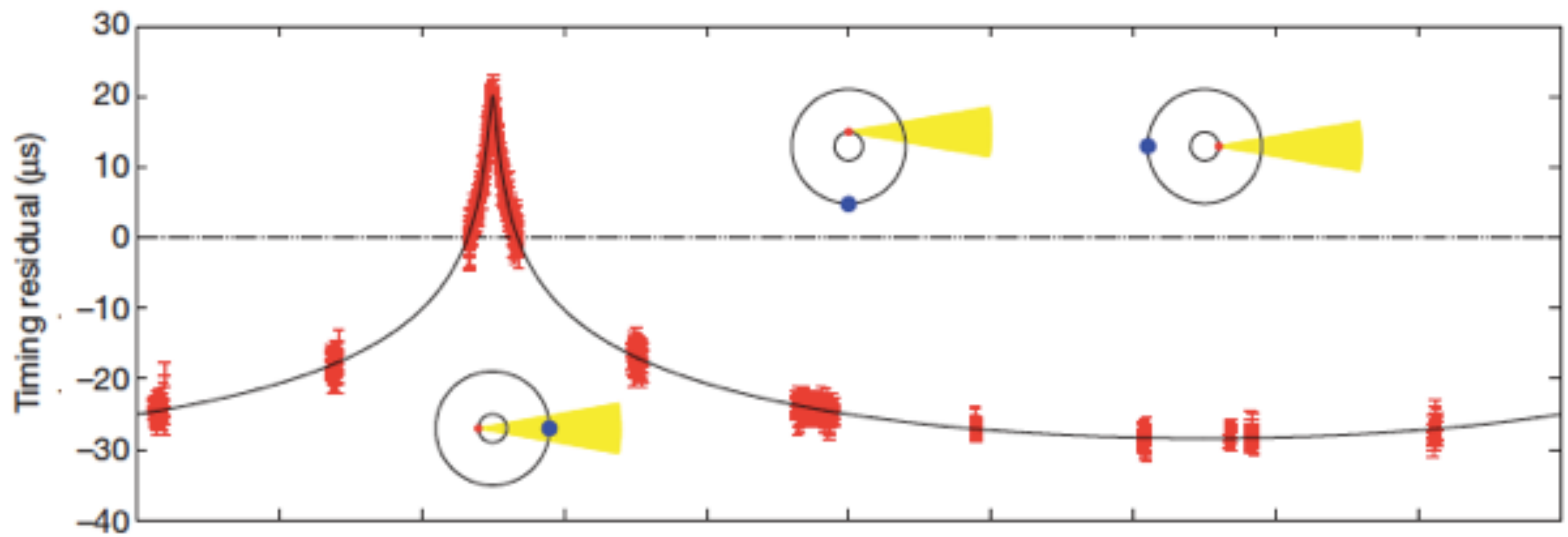


3. What holds up a two solar mass neutron star?

Discovery of $2M_{sun}$ Neutron Star

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

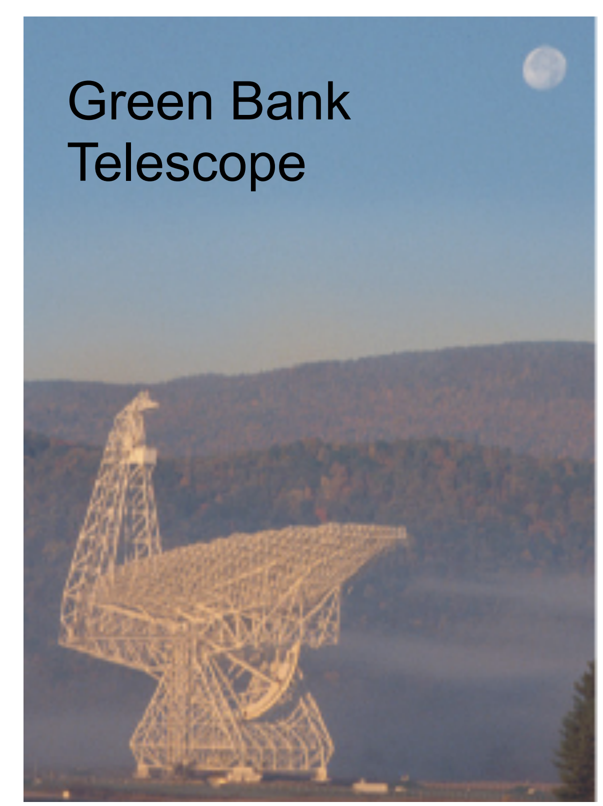
Delay in pulse arrival

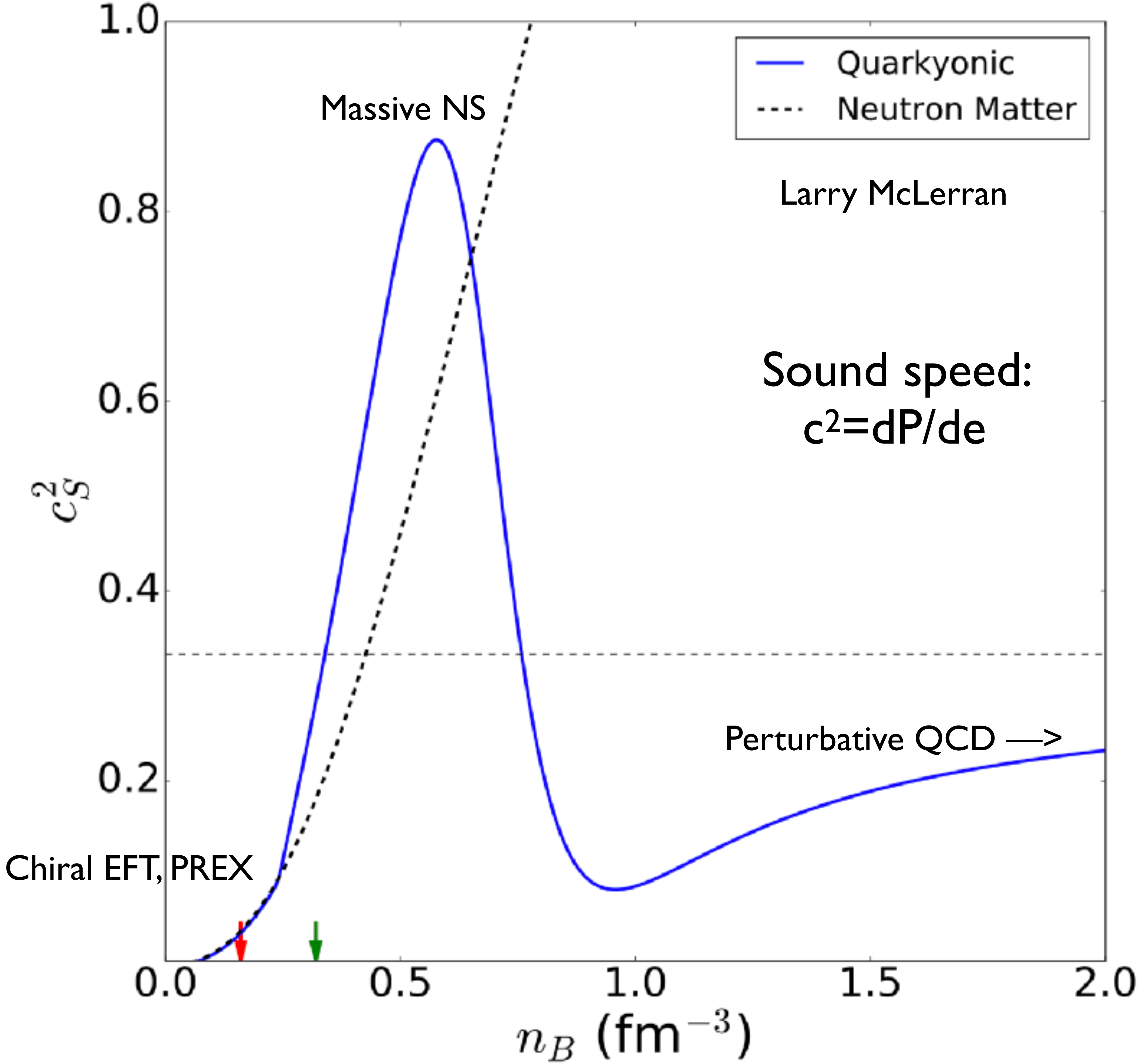


NS + White Dwarf Binary

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.*




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

Energy increases very rapidly at a few times nuclear density

- 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.

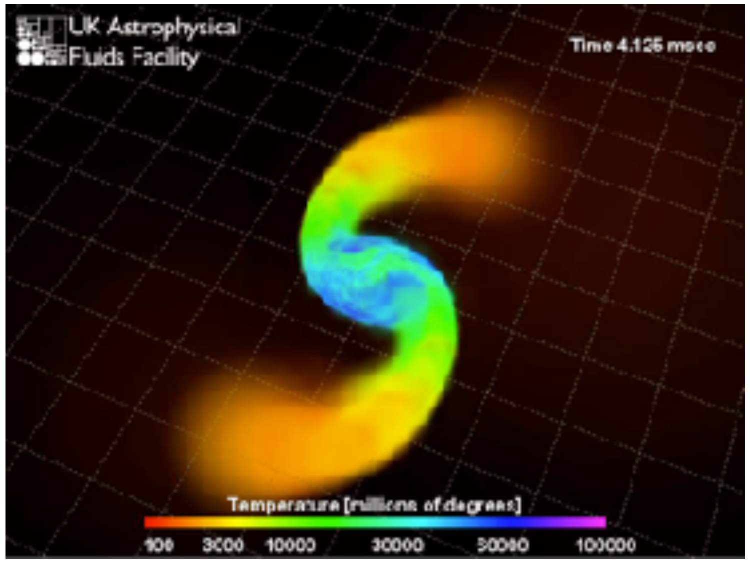
Fate of Remnant and EOS

- **Prompt collapse** to black hole (BH): Ruled out because too little mass would be ejected to provide E+M fireworks. —> A. Bauswein et al. say Λ> 250

- **Hypermassive NS** (HMNS): supported by differential rotation against collapse to BH. System collapses after 10s of ms as viscosity removes differential rotation. Likely the case for GW170817.

- **Supermassive NS** (SMNS): supported by rigid body rotation and lasts longer time before angular momentum radiated away. Margalit and Metzger argue that SMNS will transfer too much of its 10^{53} ergs of rotational energy to ejecta which were observed to have only 10^{51} ergs.

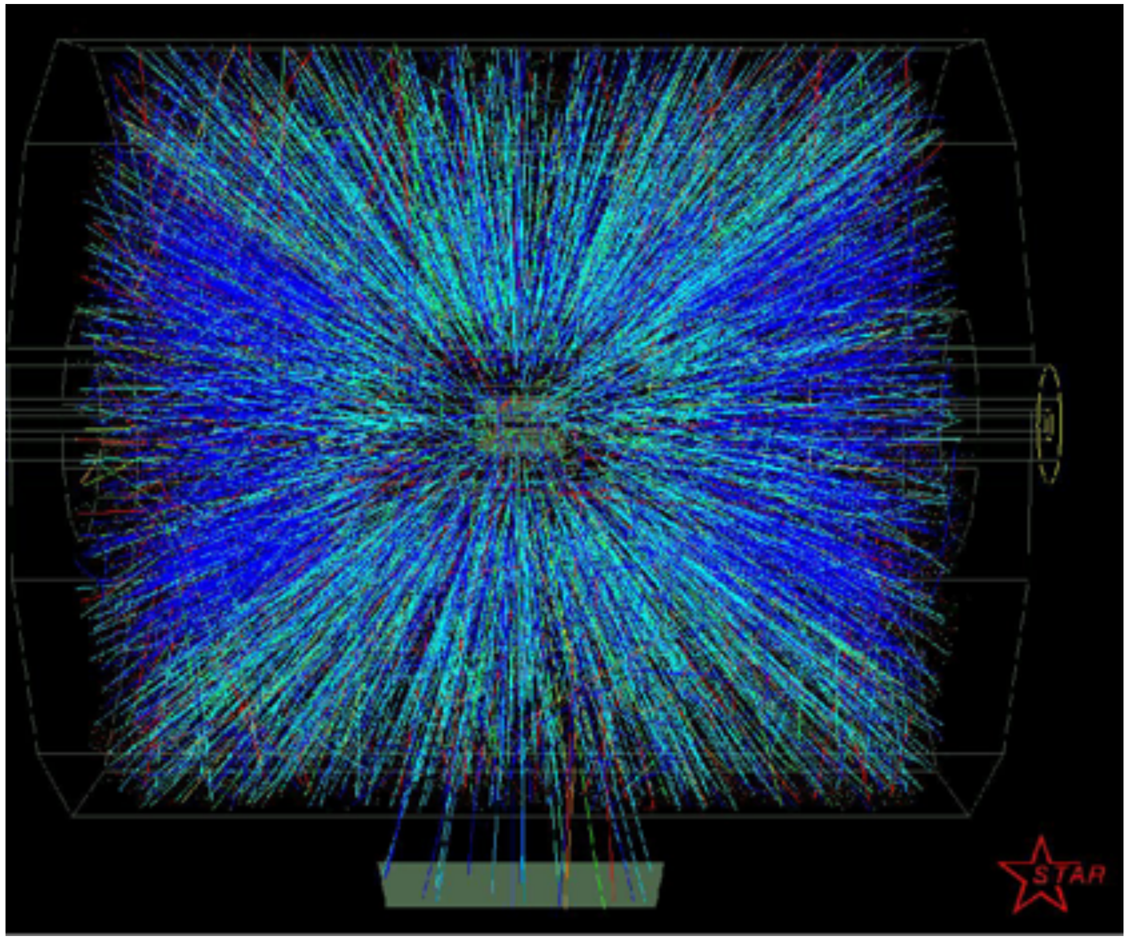
- **Stable NS**: very stiff EOS can support full mass of binary system. Merger would form ***Magnetar.*** Now ruled out by upper limit on deformability Λ.



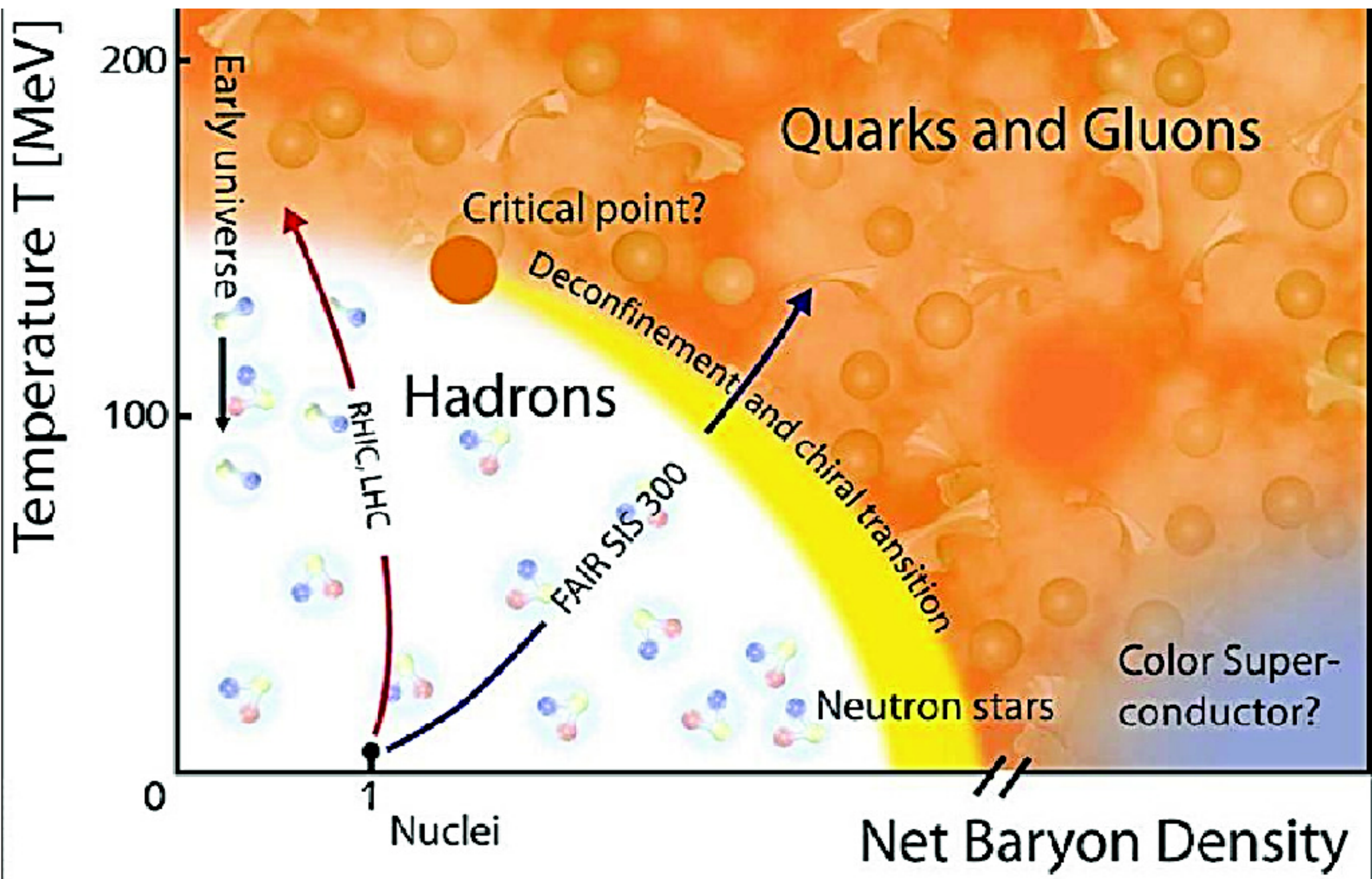
Stephan Rosswog, Richard West

4 What are NS made of?

- Measurements of mass, radius, and deformability of NS constrain equation of state (P vs density).
- This doesn't determine composition.
- Observation of $2M_{sun}$ NS says interactions are strong at high densities. Could be strongly interacting neutrons or quarks.
- RHIC finds a strongly interacting quark gluon plasma at high temperatures.
- Very likely cold dense QCD matter in a NS is also strongly interacting and is not perturbative.



Relativistic heavy ion collision

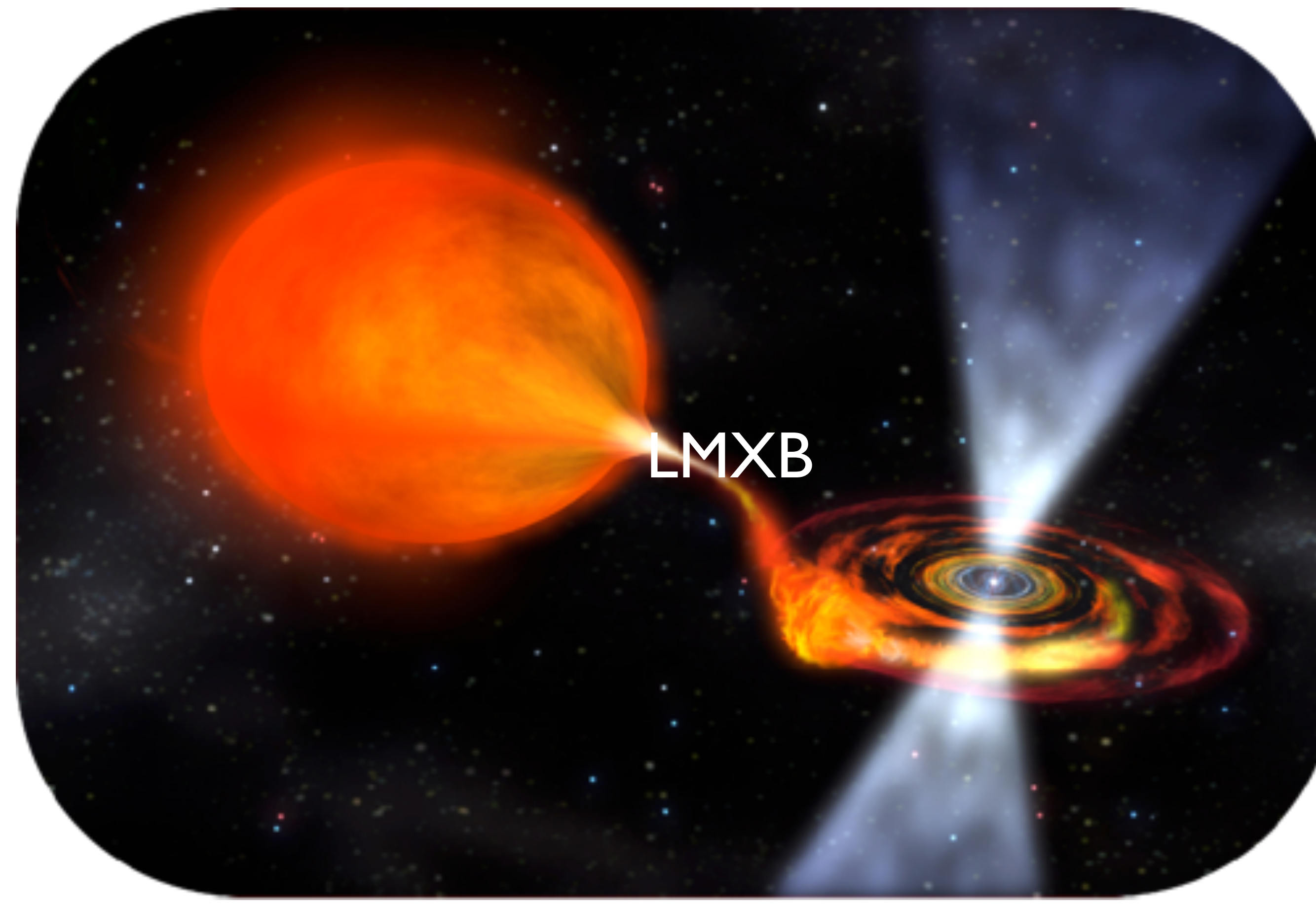

Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density
Early universe
RHIC, LHC
Quarks and Gluons
Critical point?
Hadrons
Deconfinement and chiral transition
FAIR SIS 300
Neutron stars
Color Super-
conductor?

Quark-hadron duality

- For electron-nucleus scattering at "intermediate" momentum transfers can describe cross section as sum over hadron resonances or as quark/ gluon response.
- May be able to describe similar EOS in hadronic or in quark degrees of freedom.
- Efficiency of quark versus hadronic descriptions may depend on strength of "three quark correlations" in dense matter.

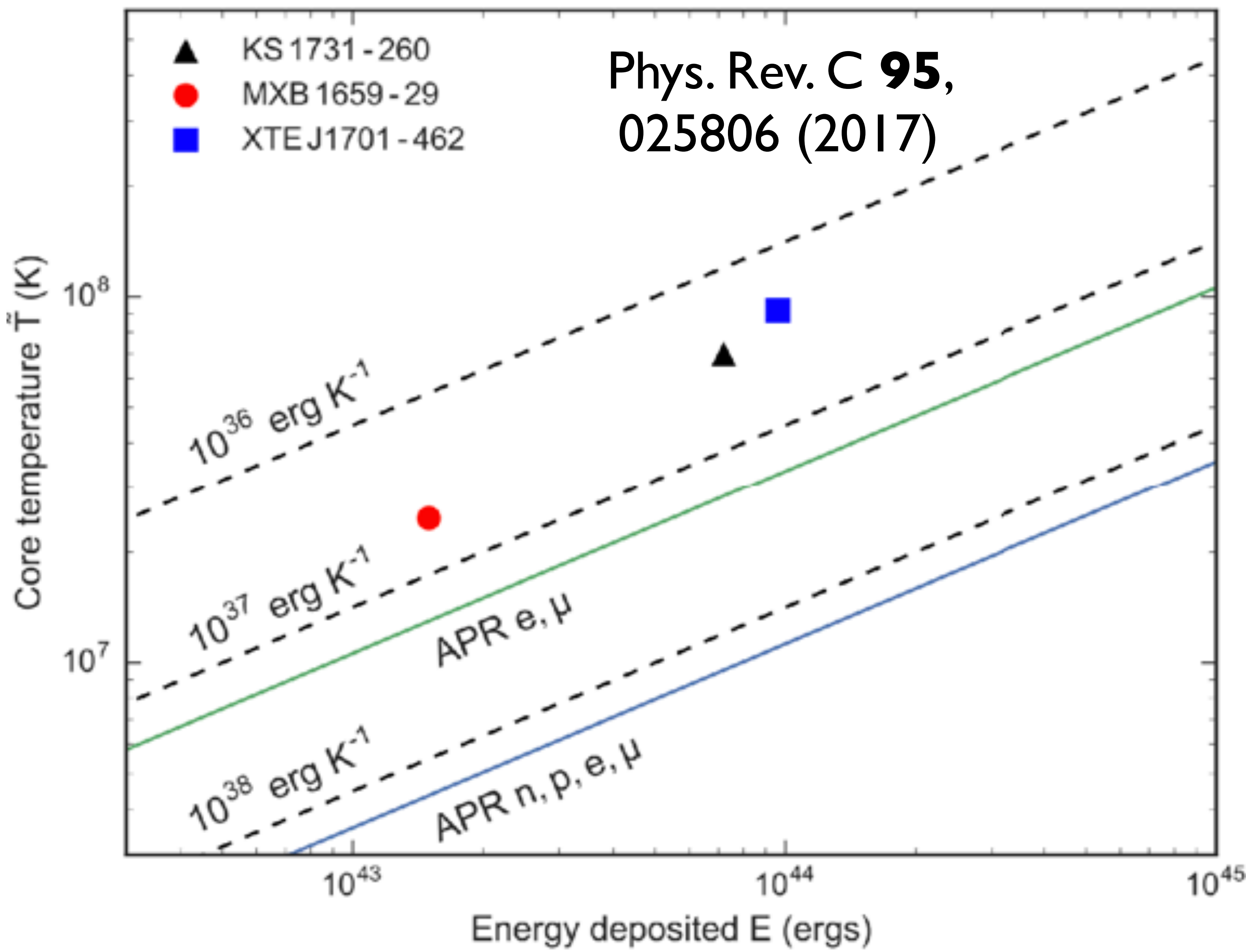
Heat Capacity and Deep Crustal Heating

- In a low mass X-ray binary (LMXB) material accretes onto a neutron star and gets buried to increasing densities.
- Rising electron fermi energy drives e capture making nuclei increasingly n rich.
- Pycnonuclear fusion reactions of these n rich nuclei heat the crust.
- This deep crustal heating can be observed at latter times as some heat diffuses to surface. Most of the heat diffuses in to the core.



Heat Capacity of NS

- NS in LMXB accretes matter during extended outburst and heats core by ΔQ (inferred from integrated X-ray luminosity).
- Observe final surface temp and infer final core temperature T_f. Heat capacity C is $C=\Delta Q/\Delta T$.
- Lower limit on heat capacity from $\Delta T=T_f - T_i < T_f$.
  $C > \Delta Q/T_f$.



Lower limits on heat capacity C are shown as colored symbols. Heat capacity of "normal" $1.4M_{sun}$ NS expected to be between green and blue lines and is consistent with observation.

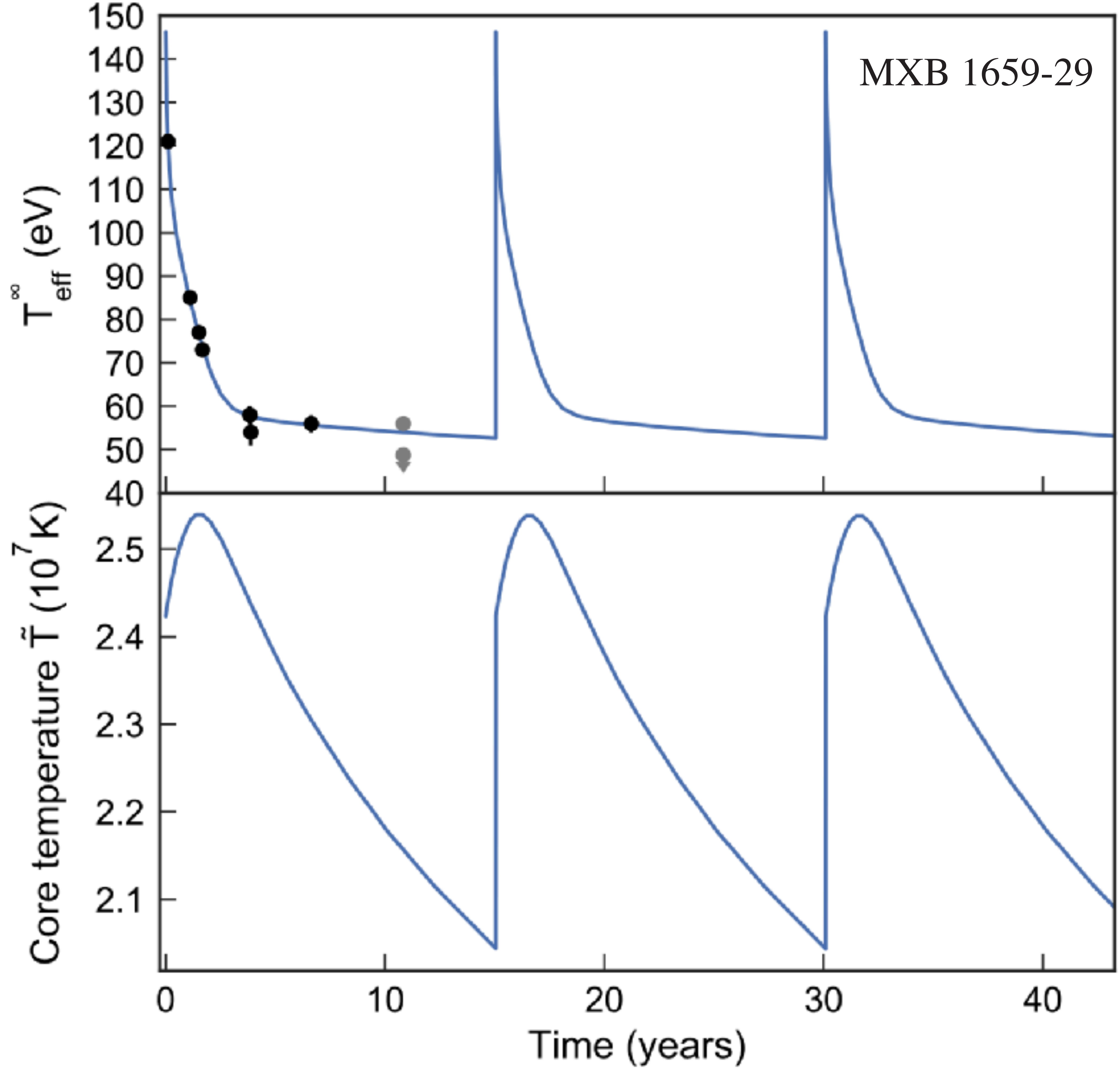
Color Superconductor

- In the color flavor locked (CFL) phase of a color superconductor, negative charges are carried by down and strange quarks with very few charged leptons. In addition all quarks are paired (to quarks of different flavors) with a large gap.
- As a result the heat capacity is predicted to be much lower than that for conventional neutron rich matter.
- The CFL phase is expected to be the ground state of QCD in the limit of very high densities.
- Our heat capacity limits rule out the most extreme (lowest transition density) CFL phase being present in MXB 1659.

A. Cumming et al, Phys. Rev. C **95**, 025806 (2017)

Neutron Star Cooling

- NS born hot in Supernovae and cool by neutrino emission from dense interior.
- **Normal cooling:** Most NS appear to cool by modified URCA process involving two correlated nucleons: n+n—>p+n+e+anti-nu, followed by e+p+n—>n+n+nu. Net result radiate anti-nu, nu pair each with ~kT energy.
- **Enhanced cooling:** If beta decay of single hadron possible cooling rate much higher: n—>p+e+anti-nu and then p+e—>n+nu. Called URCA process and needs large proton fraction.



MXB 1659-29
T^{∞}_{eff} (eV)
150
140
130
120
110
100
90
80
70
60
50
40
Core temperature $\tilde{T}$ (10^7K)
2.5
2.4
2.3
2.2
2.1
0
10
20
30
40
Time (years)

MXB 1659

- Is first star with well measured temperature that needs enhanced cooling.
- Enhanced cooling could be URCA (if large proton fraction) or beta decay of hyperons, quarks, or meson condensates.
- Large proton fraction requires large symmetry energy at high density.

Phys. Rev. Lett. 120, 182701 (2018)

Gravitational waves and nature of dense matter

- PREX II will run this summer and 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
- Heat capacity and neutrino cooling, Dany Page, A. Cumming, Ed Brown…

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