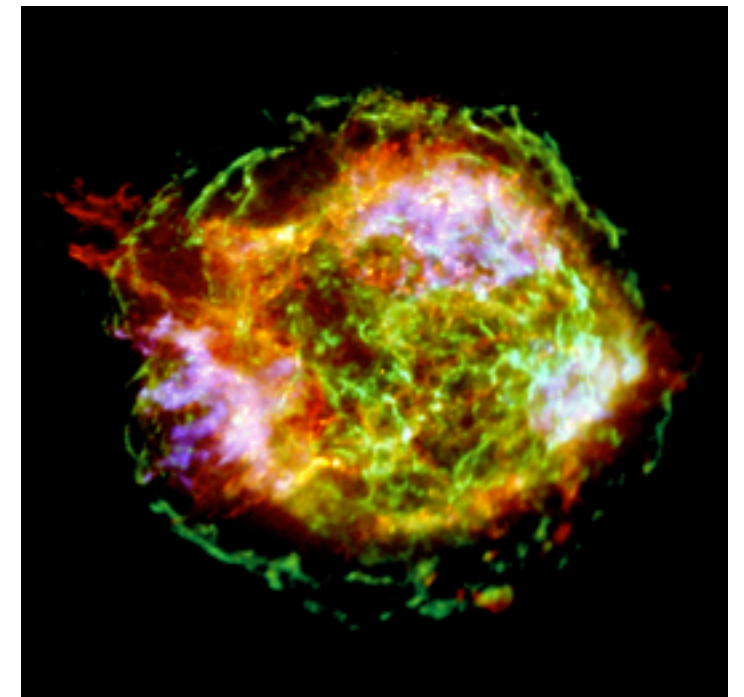


Neutron stars and the equation of state of dense matter

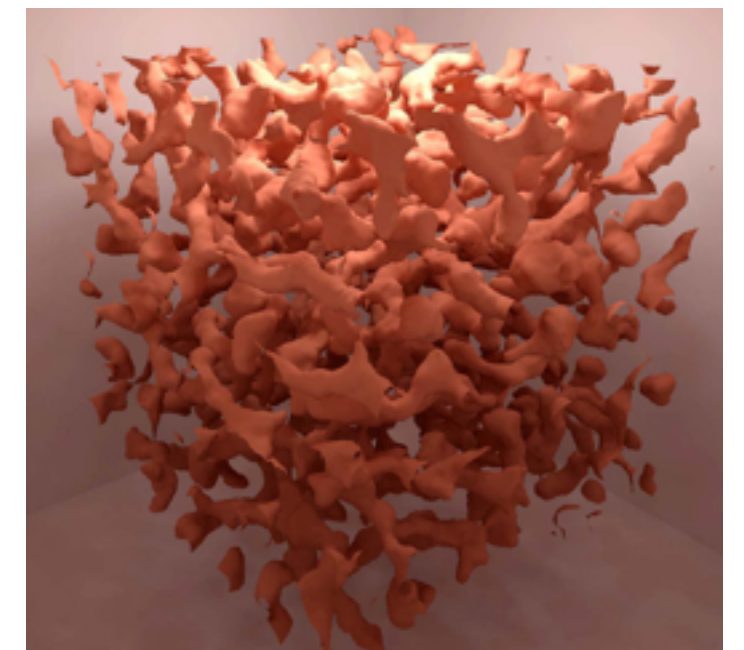
Chuck Horowitz, Indiana U., Bormio, Italy, Jan. 2019

Neutron Rich Matter

- Compress almost anything to $10^{11}+$ g/cm³ 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

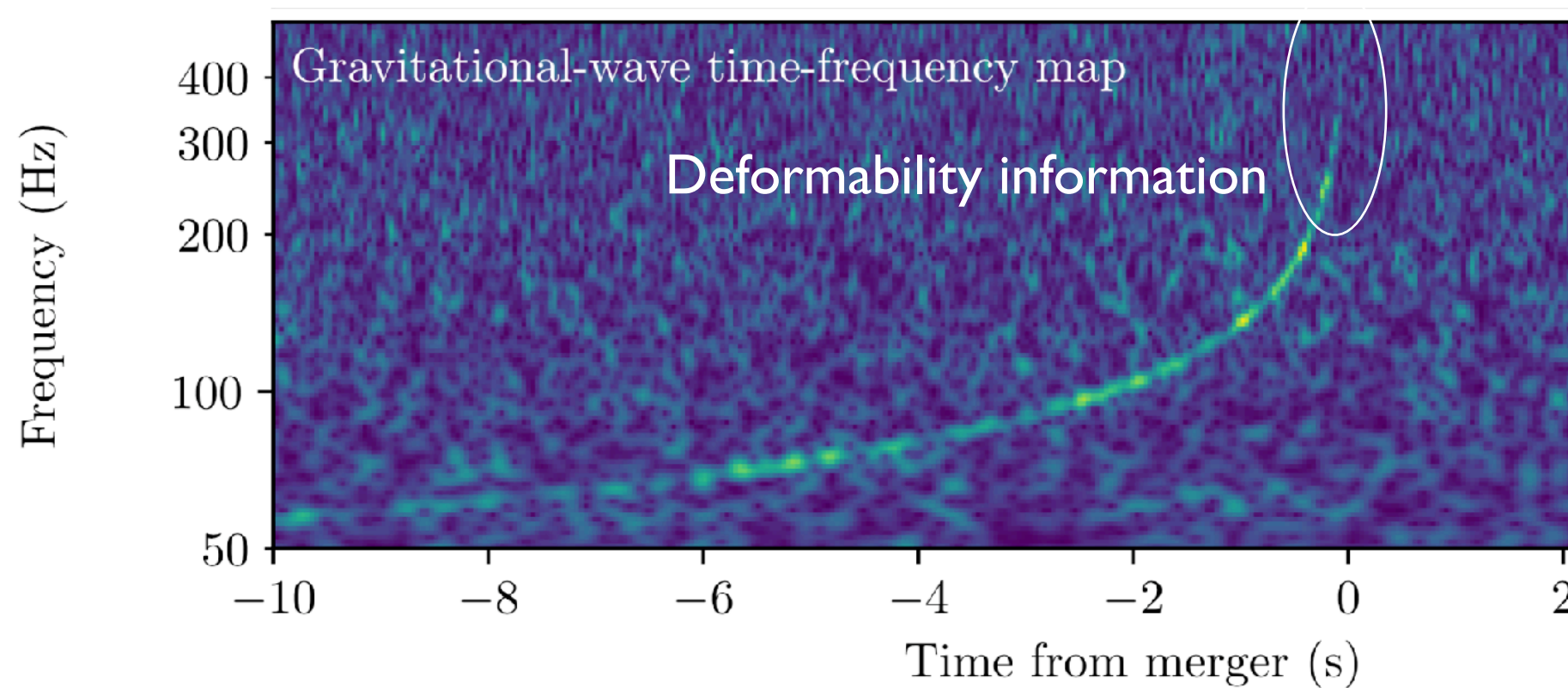
1. What does neutron rich matter look like to LIGO and VIRGO?
2. What does neutron rich matter look like in the laboratory?
3. How does neutron rich matter hold up a two solar mass neutron star?
4. What are neutron stars made of?
What are the effective degrees of freedom (quark, hadron...) of dense neutron rich 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 detected this event at X-ray, ultra-violet, visible, infrared, and radio wavelengths.



Merger GW170817: deformability of NS

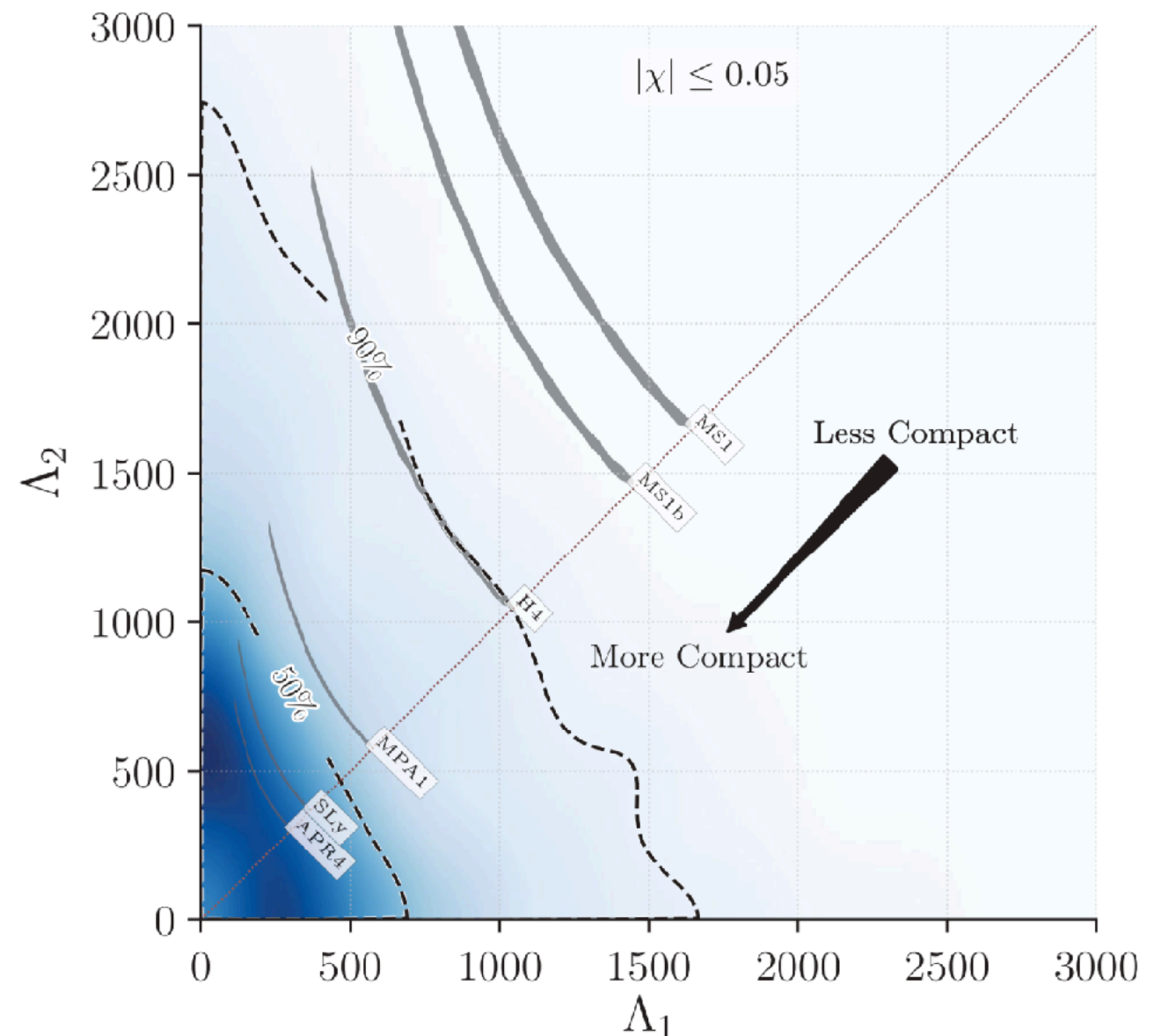
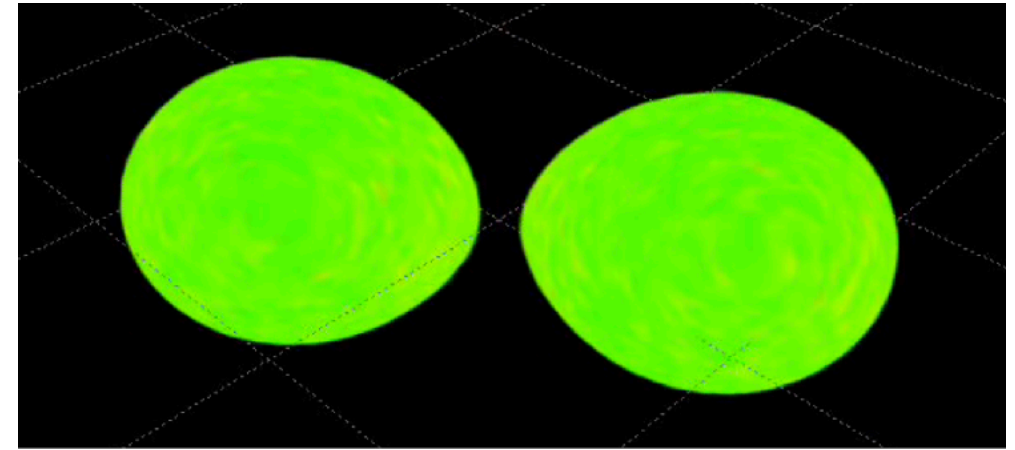
- Gravitational tidal field distorts shapes of neutron stars just before merger.
- Dipole polarizability of an atom $\sim R^3$.

$$\kappa = \sum_f \frac{|\langle f | r Y_{10} | i \rangle|^2}{E_f - E_i} \propto R^3$$

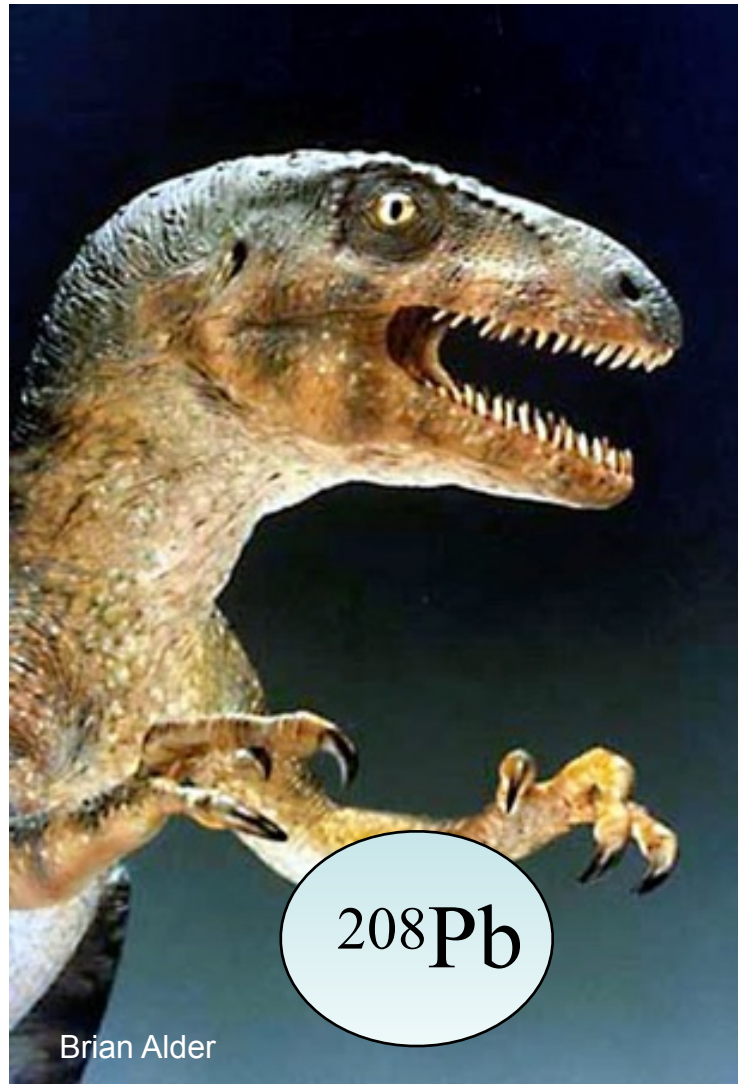
- Tidal deformability (or mass quadrupole polarizability) of a neutron star scales as R^5 .

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

- GW170817 observations set upper limits on Λ_1 and Λ_2 .



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

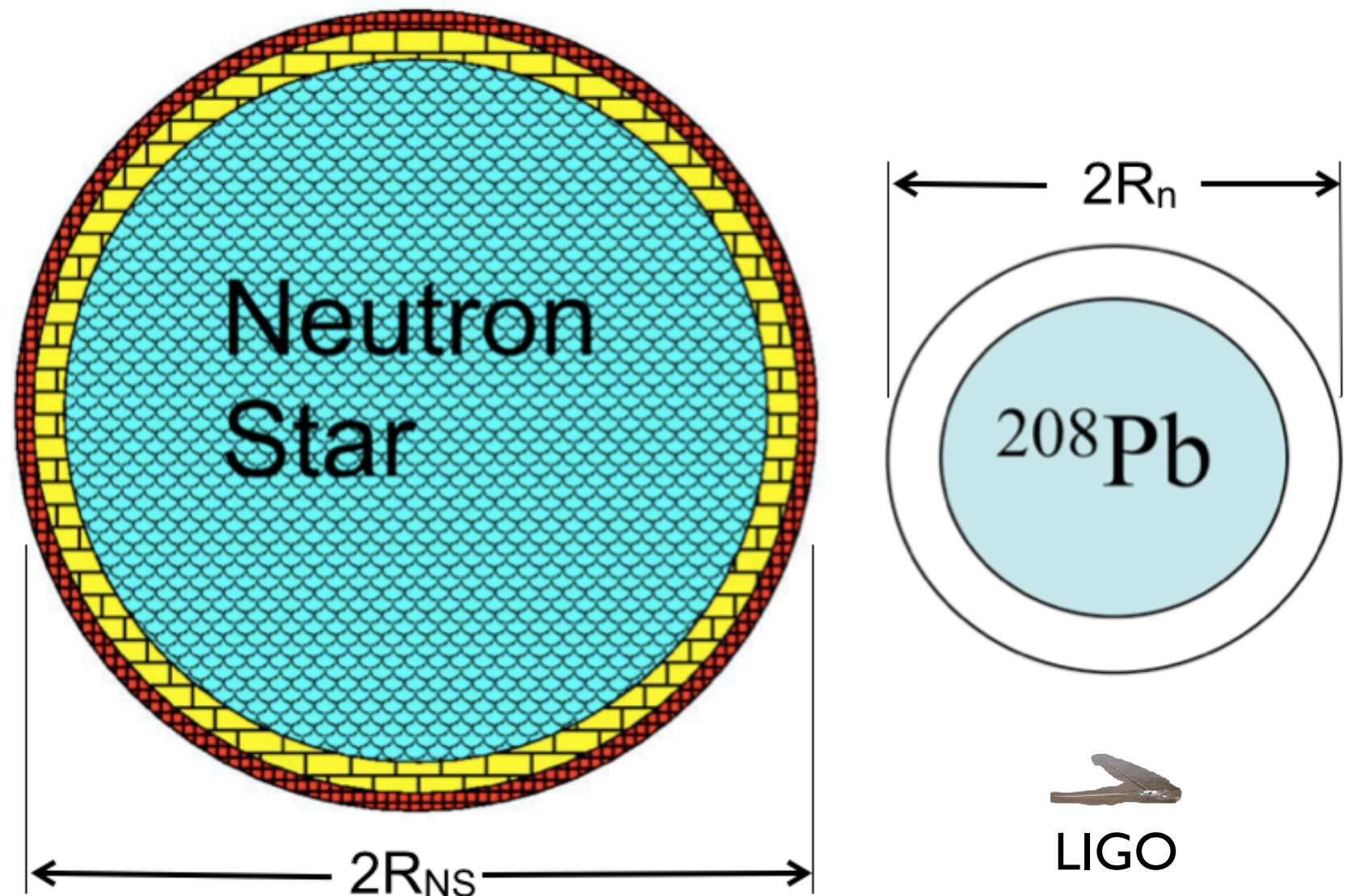


PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb .

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 $\Rightarrow R_n - R_p$ 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

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

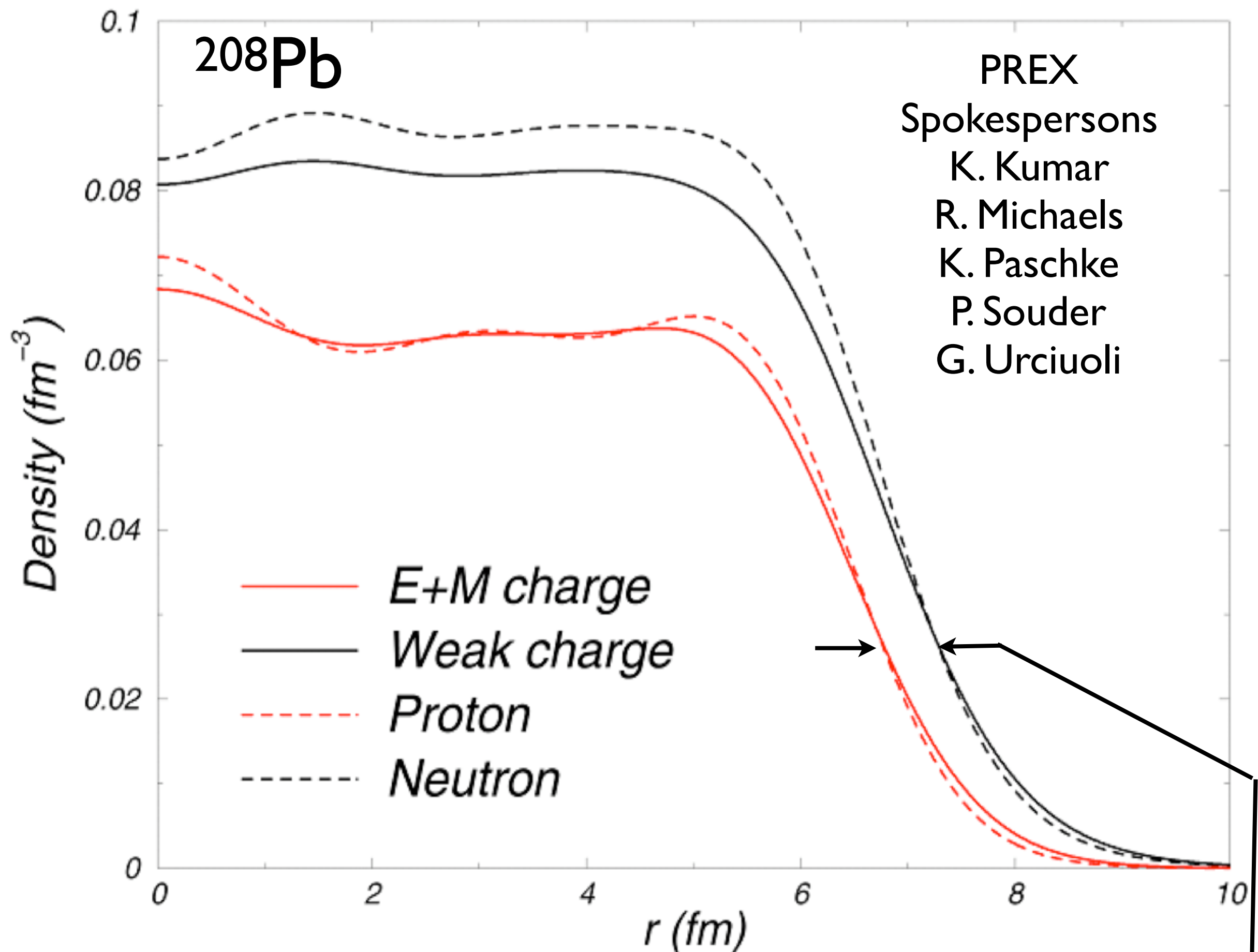
- A_{pv} from interference of photon and Z^0 exchange. In Born approximation

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

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

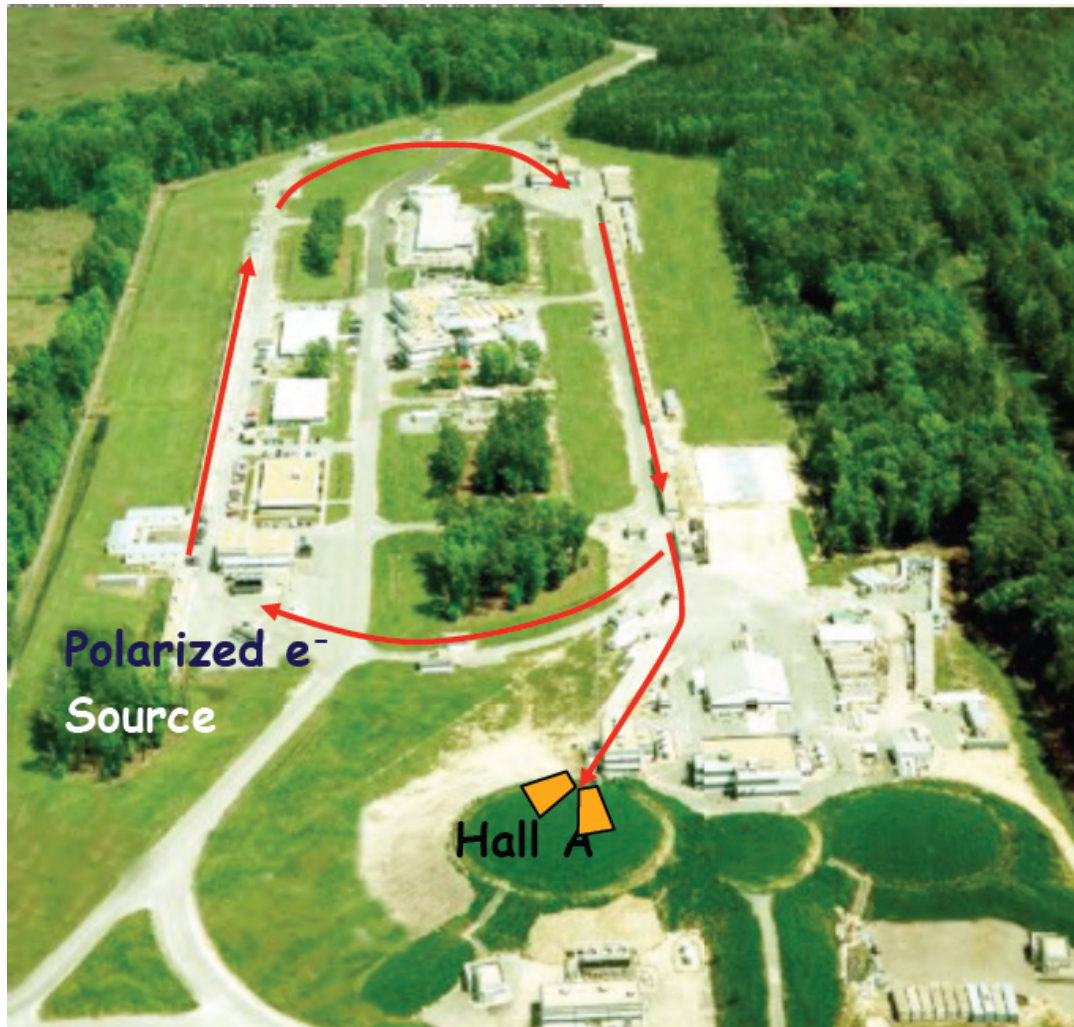
- Model independently map out distribution of weak charge in a nucleus.

- **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

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

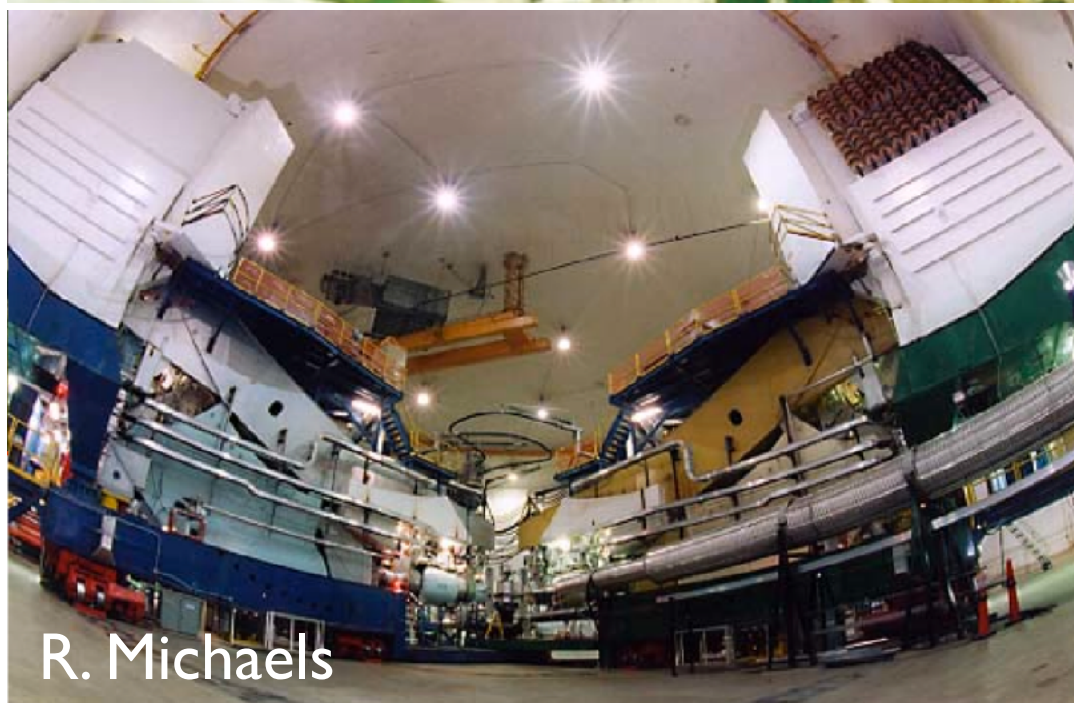
- From A_{PV} I inferred neutron skin:

$$R_n - R_p = 0.33^{+0.16}_{-0.18} \text{ fm.}$$

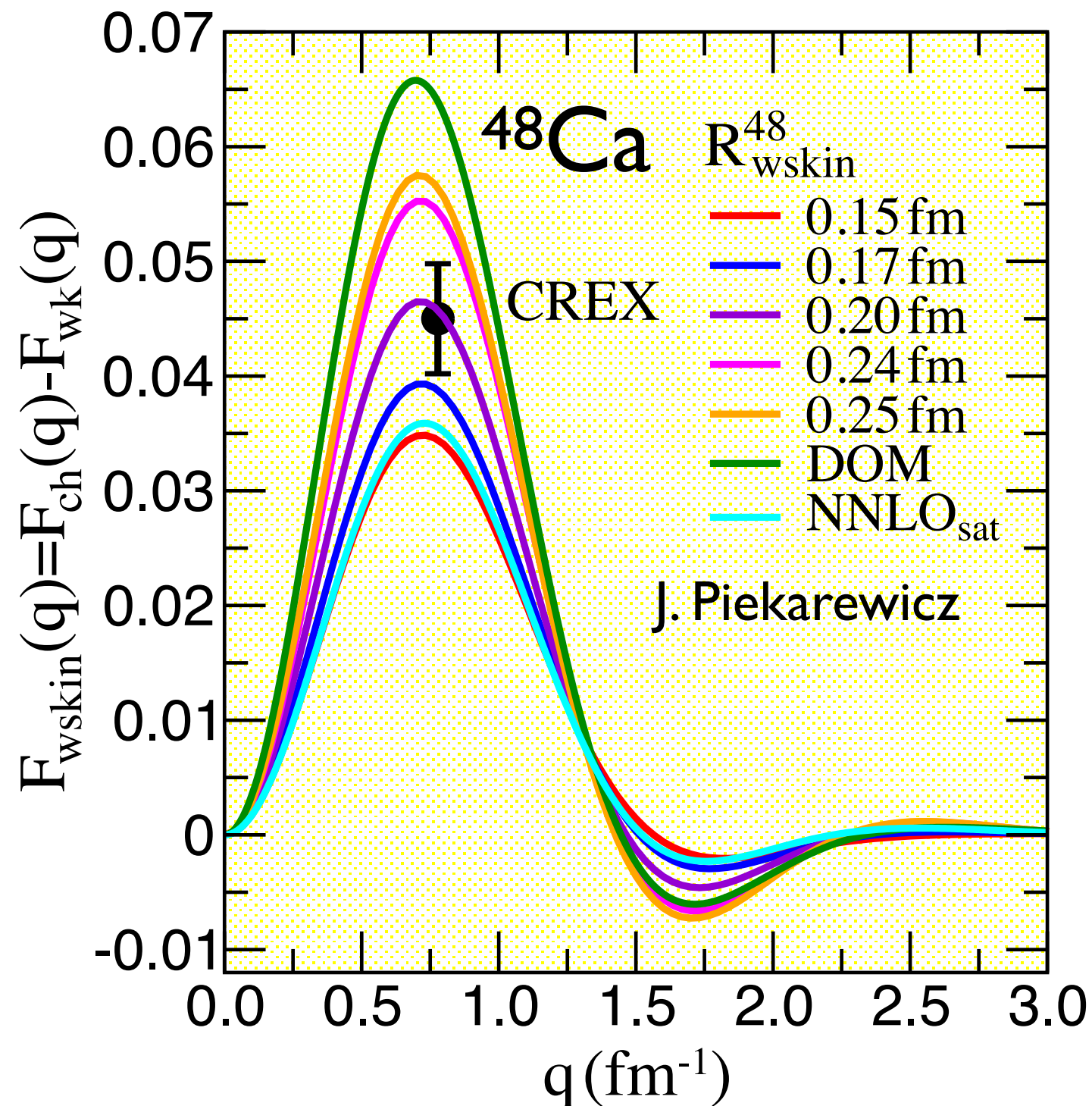
- Next runs (Scheduled for 2019)

- **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*.



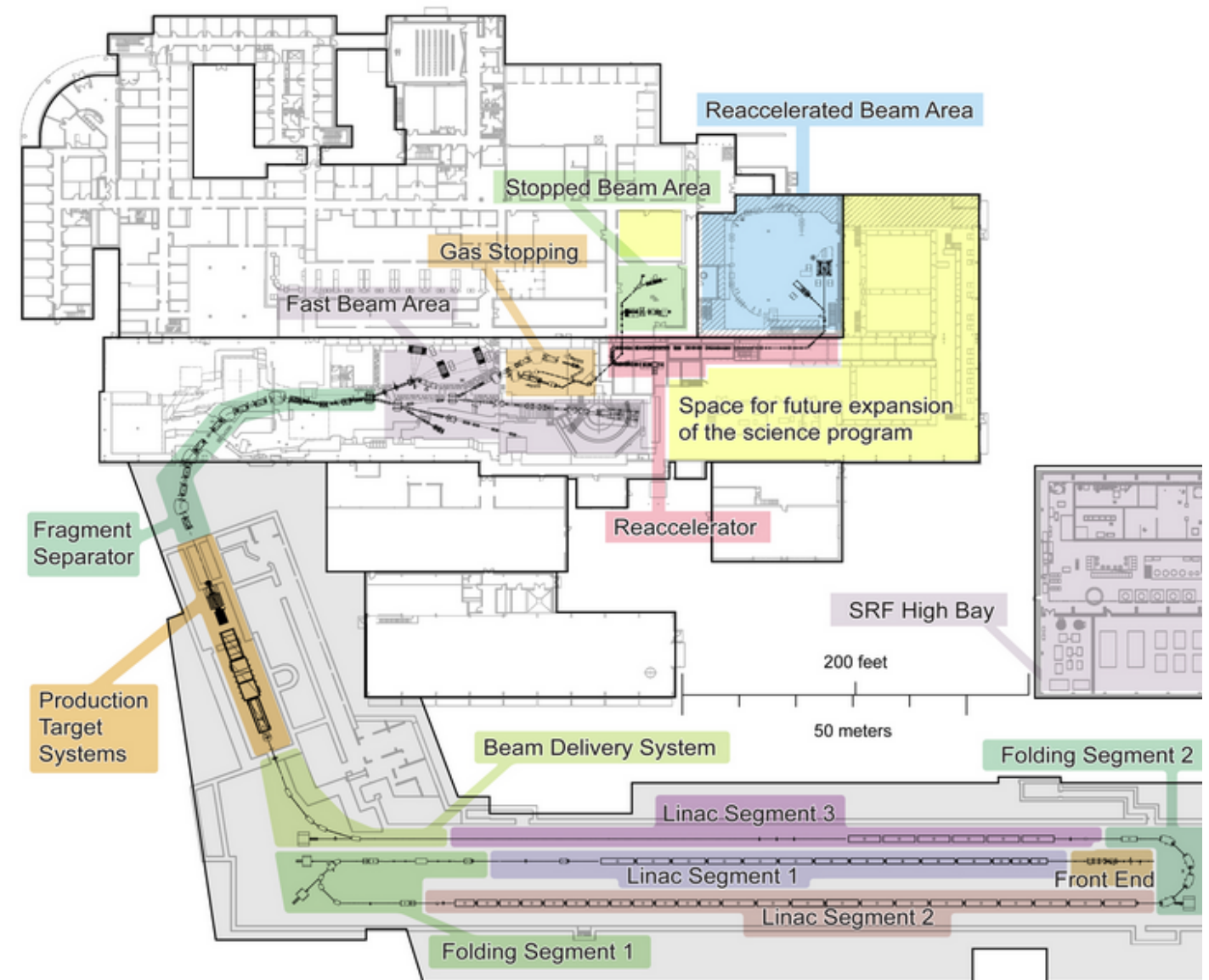
CREX



- Microscopic coupled cluster calculations $\rightarrow R_n - R_p = 0.135 \pm 0.015 \text{ fm}$ using chiral interaction NNLO_{sat} [Nature Physics **12** (2016) 186].
- Dispersive optical model (DOM) $\rightarrow R_n - R_p = 0.25 \pm 0.02 \text{ fm}$. [W. Dickhoff et al]
- Many density functional theory (DFT) calculations in between.

Facility for Rare Isotope Beams

- Intense radioactive beam accelerator that can produce ~80% of all particle bound isotopes with $Z < 90$. First beam ~2021.
- FRIB will have unique capabilities to answer fundamental questions about the inner workings of the atomic nucleus, *the formation of the elements in our universe, and the evolution of the cosmos.* — 2012 National Academies report
- FRIB funded, in part, to study r-process. LIGO funded, in part, to observe neutron star mergers. Now appears they are studying the same events in very different ways.

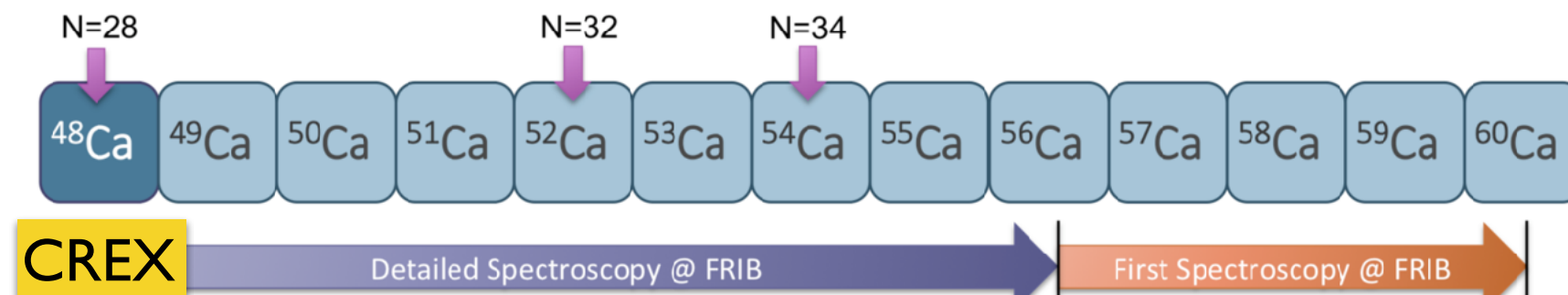


FRIB

- Important scientific opportunity for both facilities LIGO and FRIB!

Study more n rich nuclei at FRIB

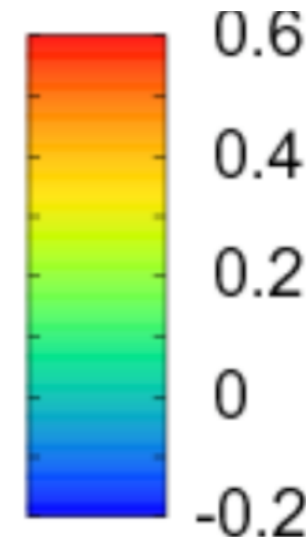
- ^{40}Ca ($Z=N=20$) is stable. FRIB can make ^{60}Ca ($N=40$)



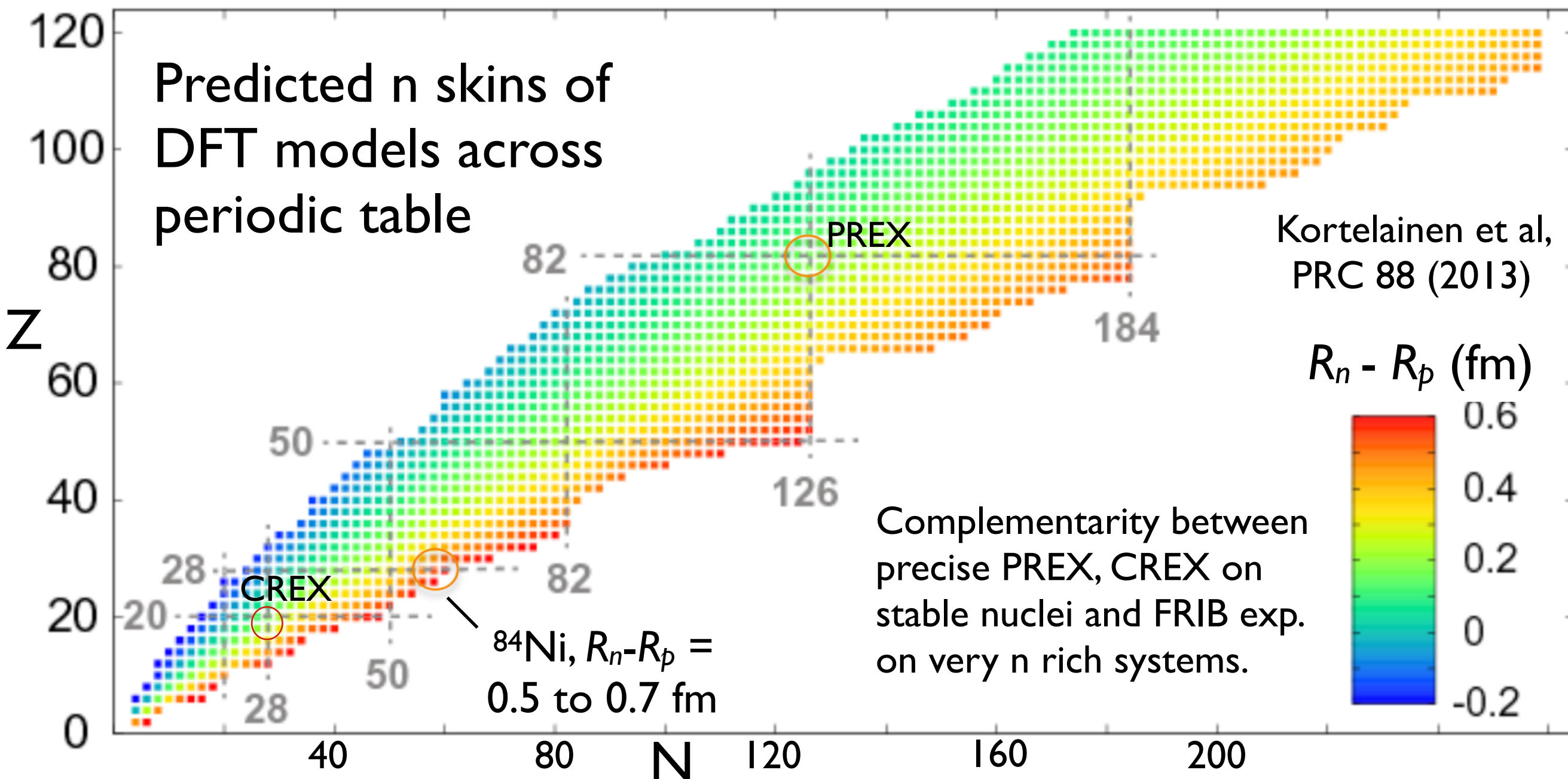
Predicted n skins of DFT models across periodic table

Kortelainen et al, PRC 88 (2013)

$R_n - R_p$ (fm)

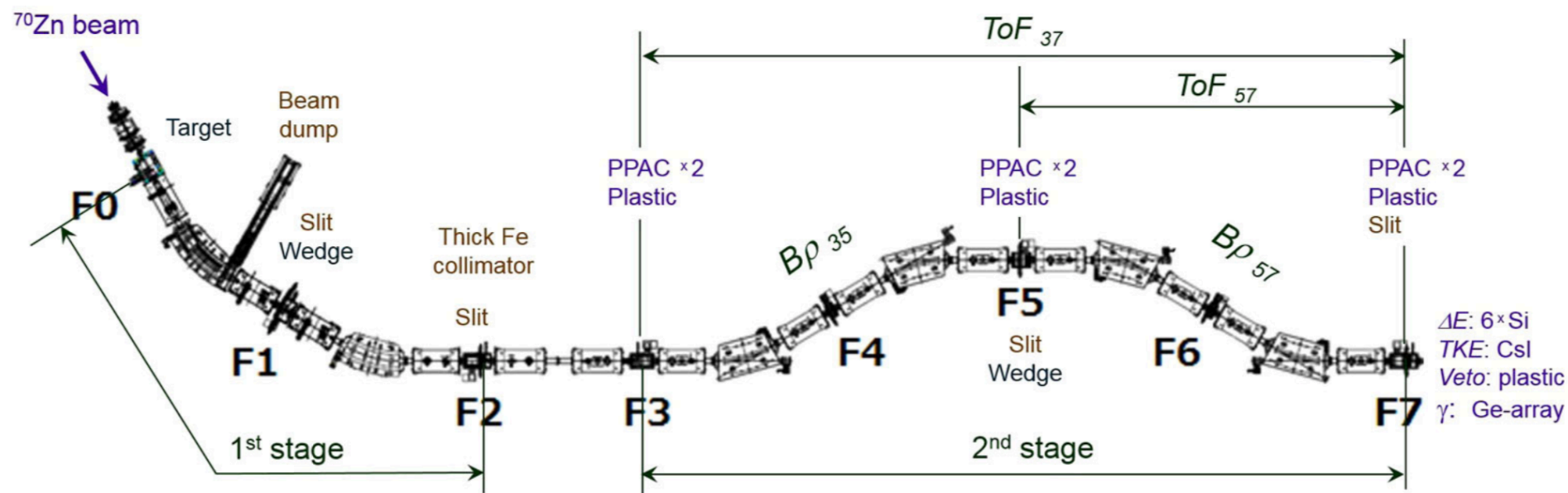
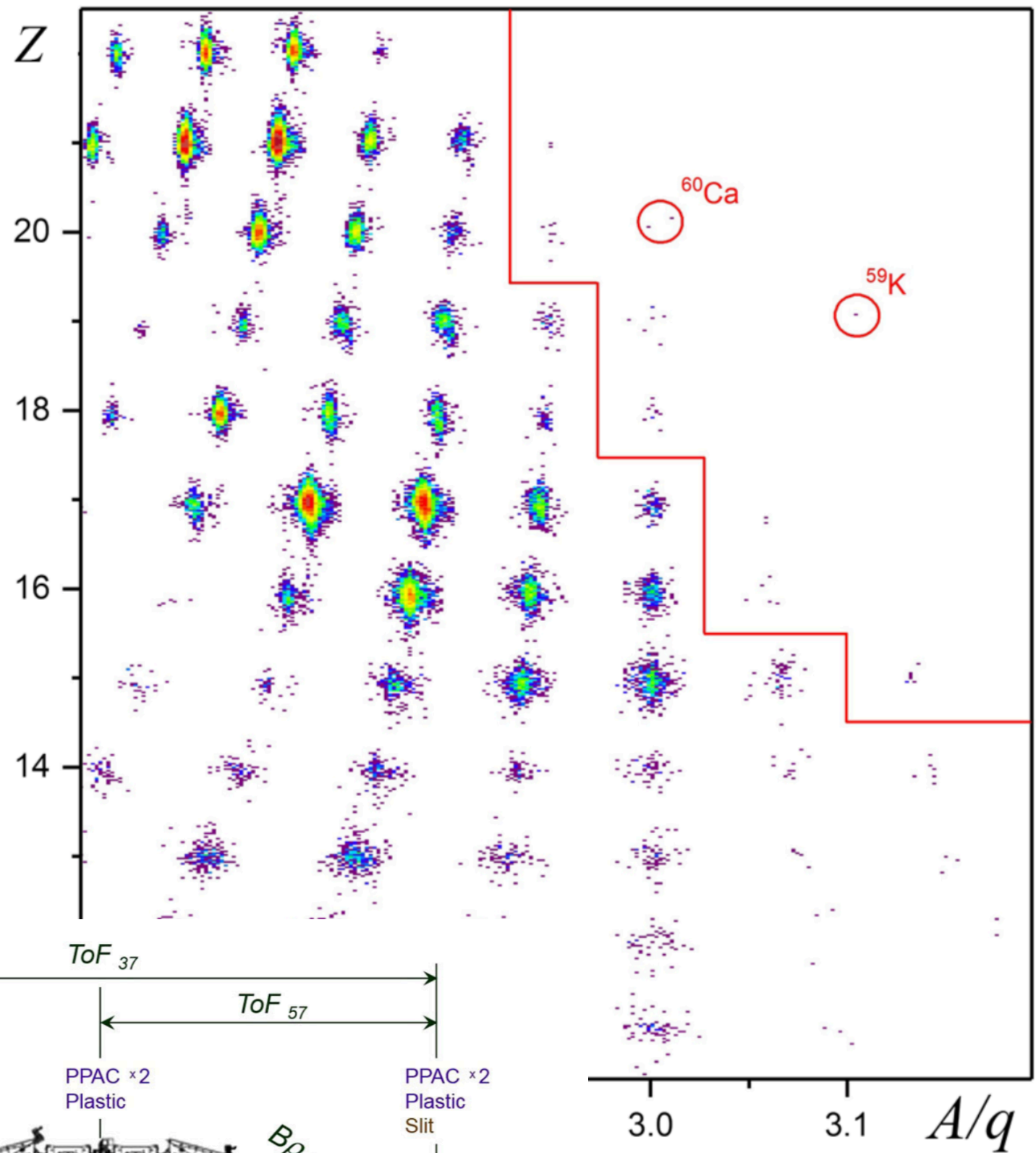


Complementarity between precise PREX, CREX on stable nuclei and FRIB exp. on very n rich systems.



- Discovery of ^{60}Ca and Implications For the Stability of ^{70}Ca

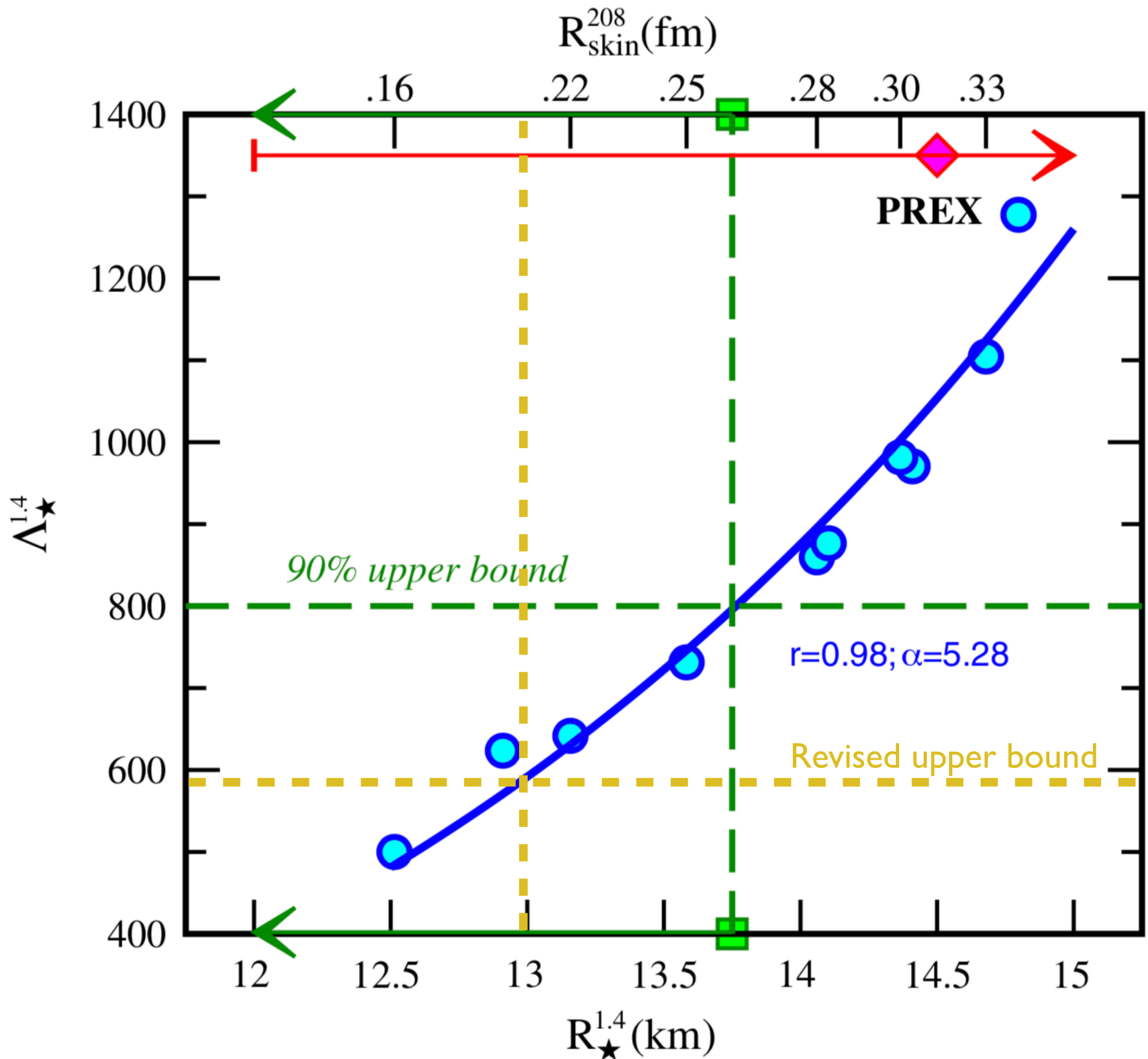
First observation of ^{60}Ca produced from fragmentation of a ^{70}Zn beam at RIKEN.
PRL **121** (2018) 022501



LIGO VS PREX

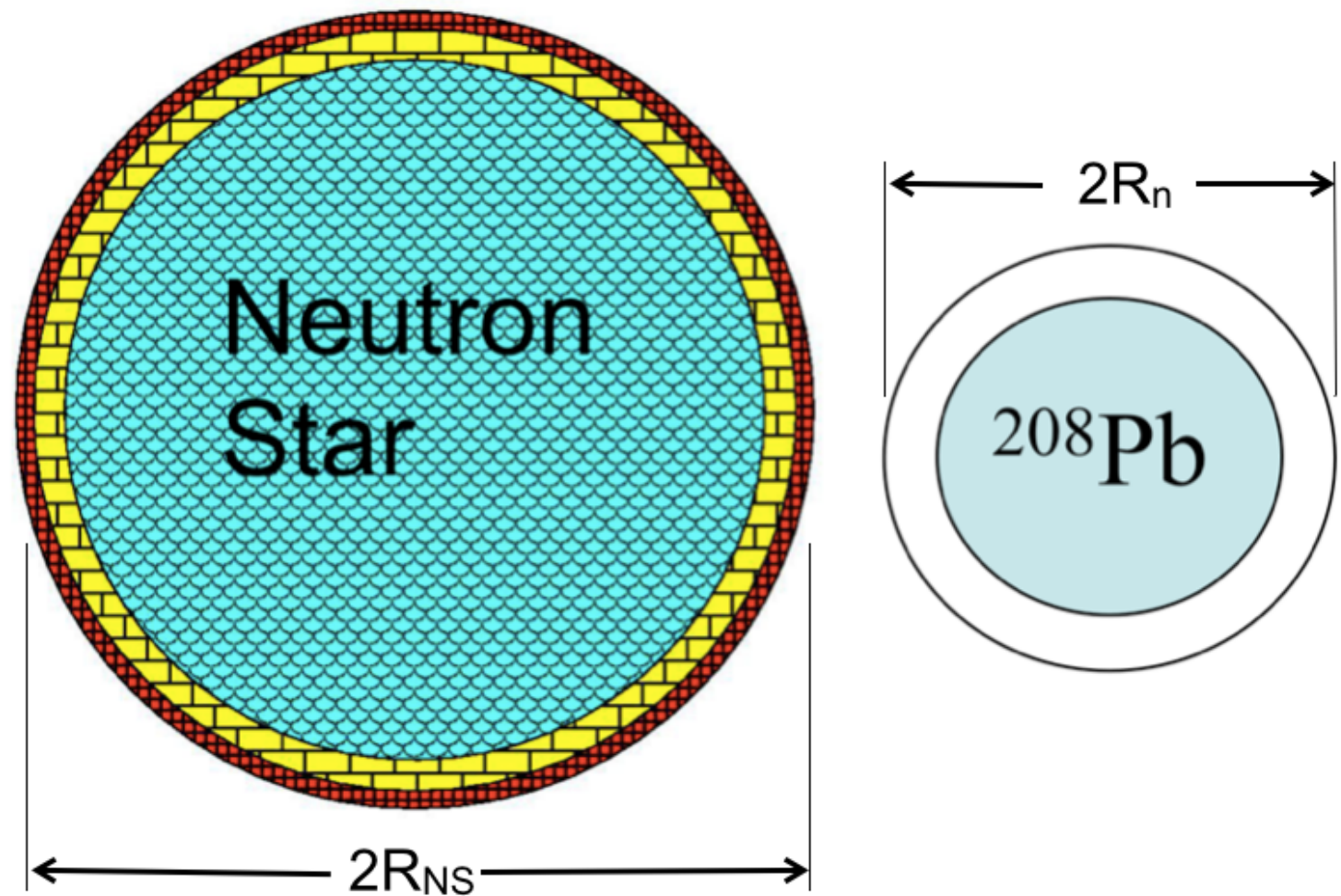
Deformability Λ
of $1.4M_{\text{sun}}$ NS
now less than
590 (Yellow
dashed). ArXiv:
1805.11581

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



Density Dependence of EOS

- Pressure of neutron matter pushes neutrons out against surface tension $\Rightarrow R_n - R_p$ of ^{208}Pb determines P at **low densities** $\sim 0.7\rho_0$
- Radius or deformability Λ of ($\sim 1.4M_{\text{sun}}$) NS depends on P at **medium densities** $\sim 2\rho_0$.
- Maximum mass of NS depends on P at **high densities** (fate of merger remnant).
- Three measurements constrain density dependence of EOS.



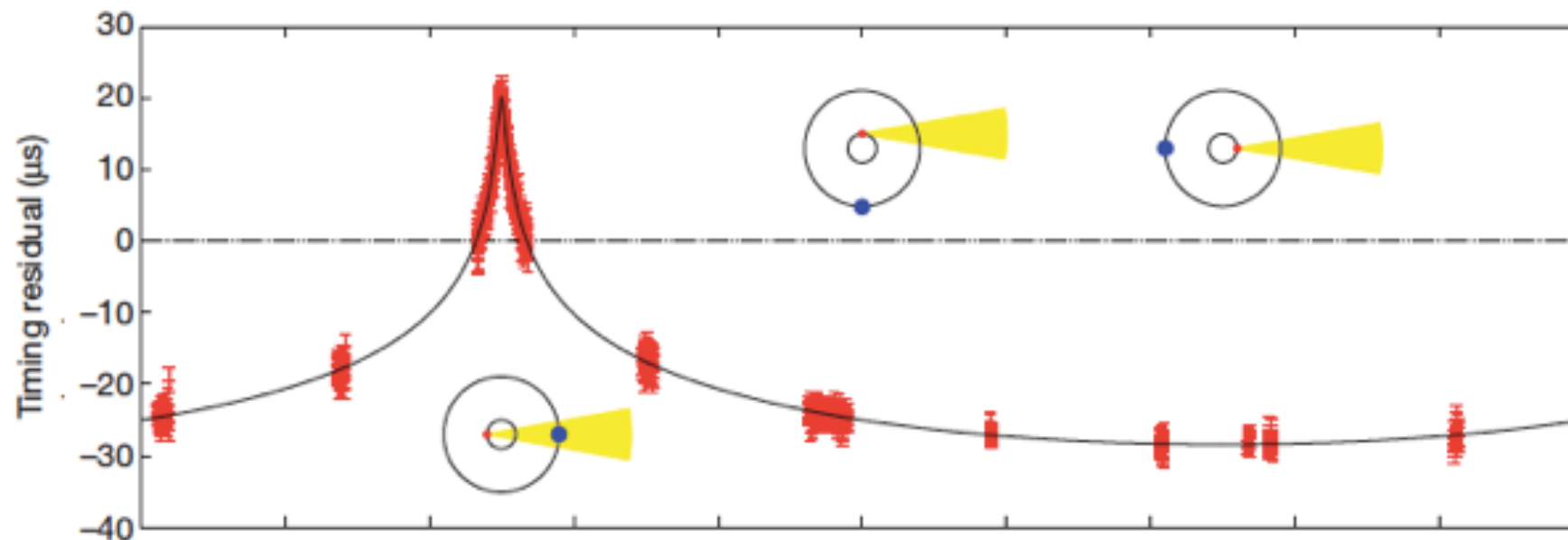
If PREX II finds a thick ^{208}Pb skin and high pressure, while NS radius or deformability appears small: this could suggest a softening of the EOS (lowering of P with increasing density) from a phase transition — perhaps from hadronic to quark matter.

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

Discovery of $2M_{\text{sun}}$ Neutron Star

Demorest et al: PSR J1614-2230 has $1.97 \pm 0.04 M_{\text{sun}}$.

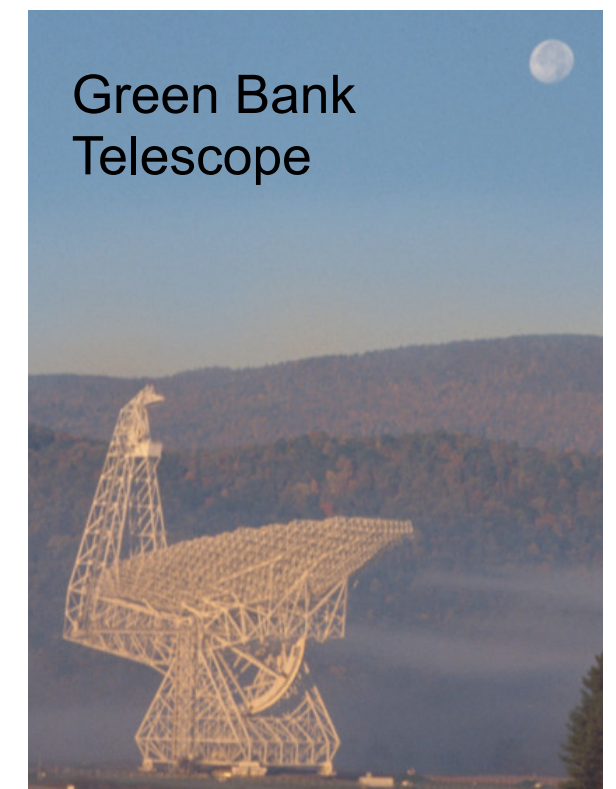
Delay
in
pulse
arrival

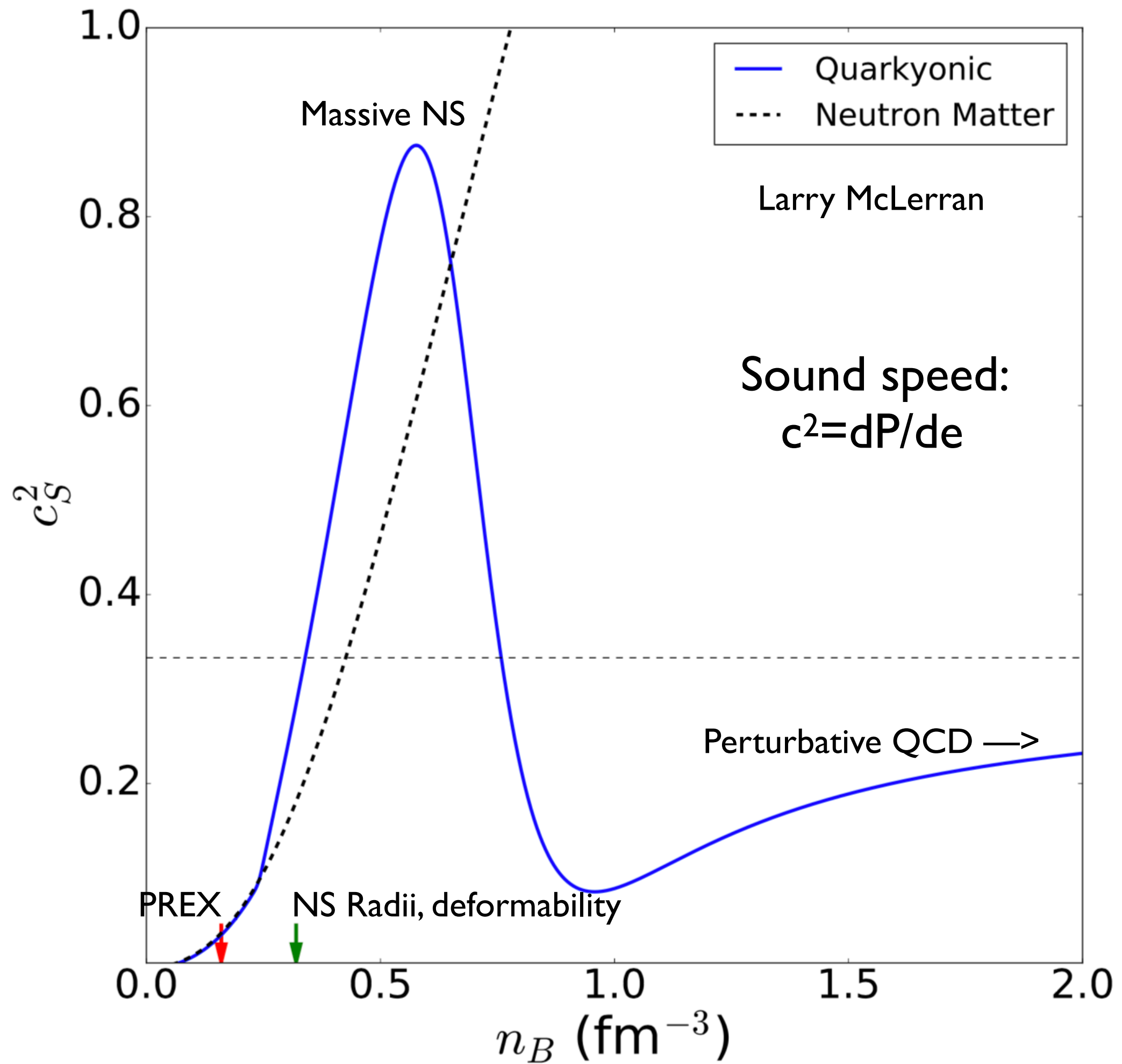


NS +
White
Dwarf
Binary

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.*



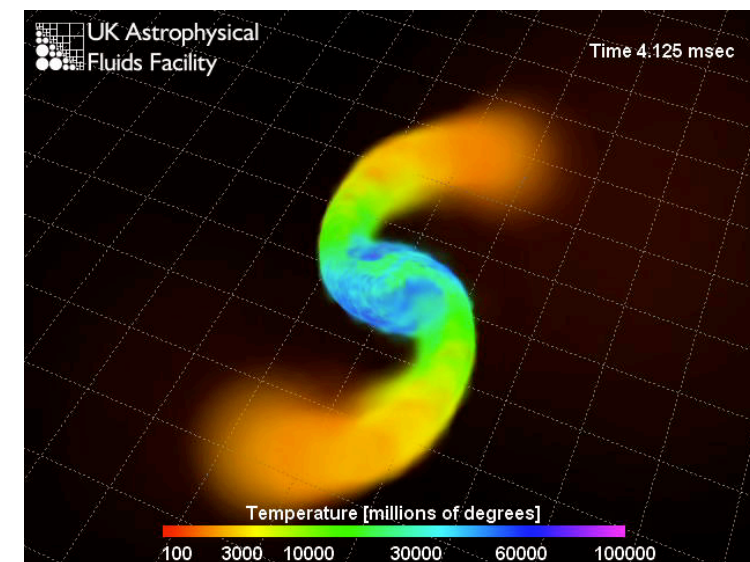


Energy increases very rapidly at a few times nuclear density

- 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.

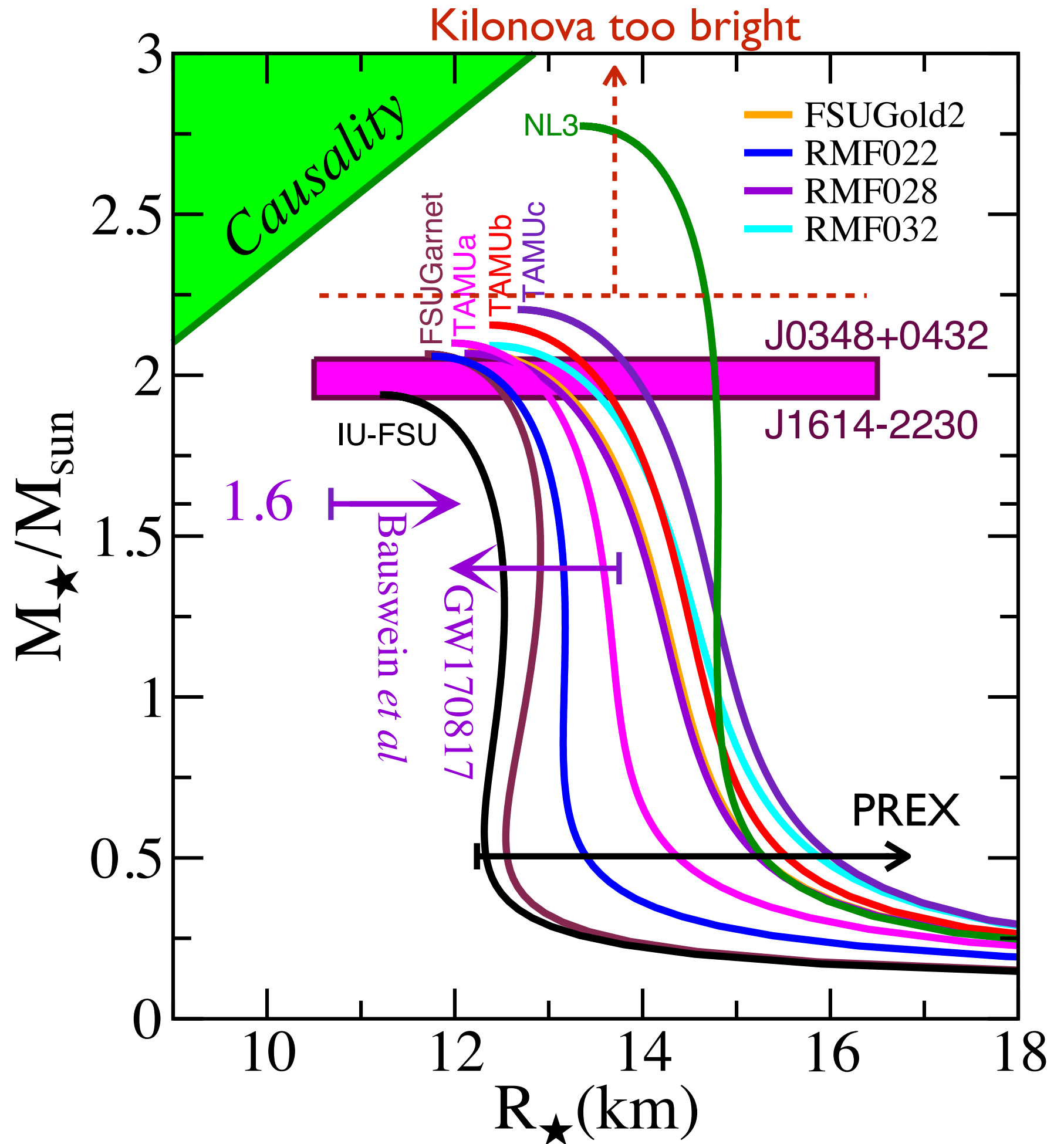
Fate of Remnant and EOS

- **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 $\Lambda > 250$
- **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

- 1) If maximum mass above 2.2 Msun remnant lives too long and transfers too much rotational E to kilonova.
- 2) If $R_{\text{NS}} < 10.5$ km collapses too fast to black hole with too little ejected mass.
- 3) If $R_{\text{NS}} > 13.7$ km deformability too large.
- 4) If $R(0.5M_{\text{sun}}) < 12.2$ km, 208Pb neutron skin too small for PREX

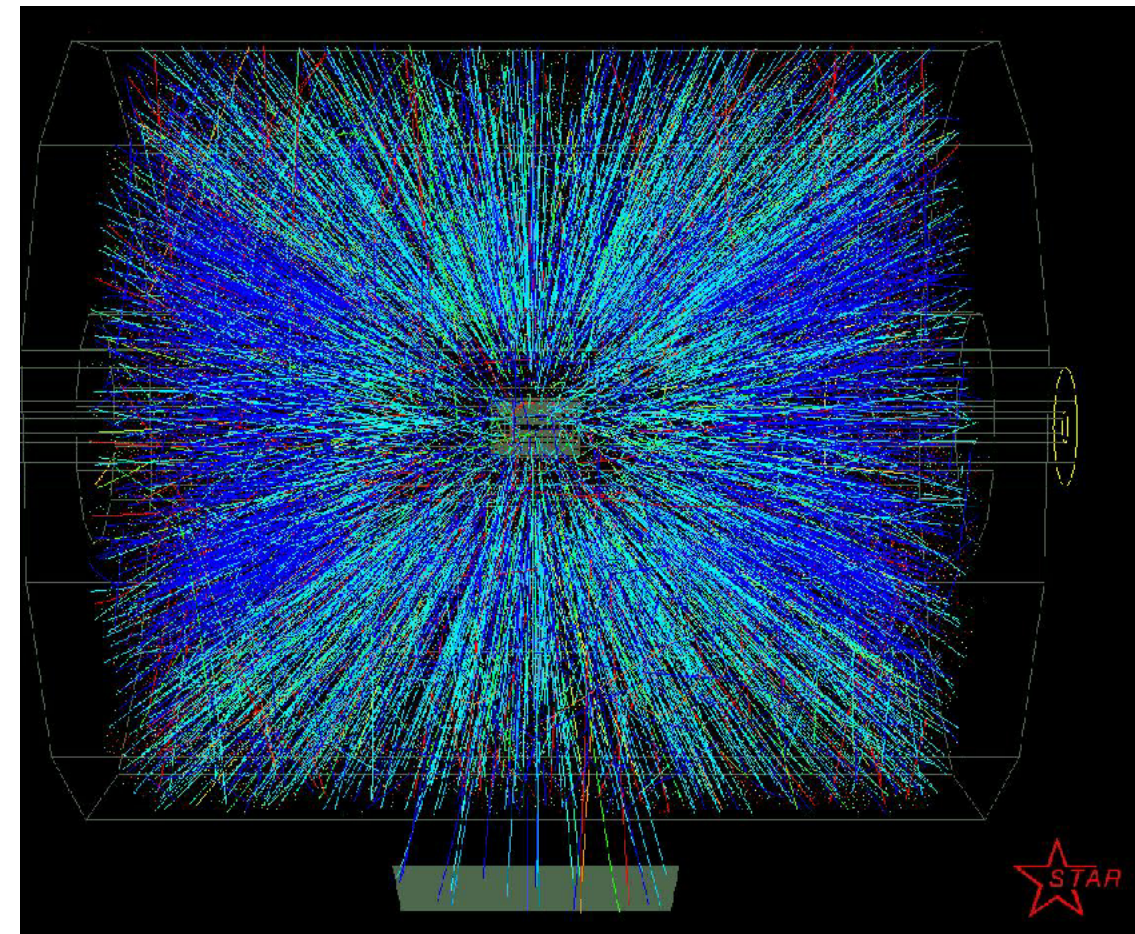


NS merger zoo

- **Multi-messenger astronomy may have started with a bang, but it is just getting going!**
- Expect observation of many more NS mergers when LIGO reaches full design sensitivity.
- Other mergers may be different from GW170817 ($\sim 2.75 M_{\text{sun}}$)
- Merger of massive NS (say $1.6 + 1.6 M_{\text{sun}}$?) could lead to a prompt collapse and little ejected mass. Perhaps a “dud” with out much nucleosynthesis or E+M fireworks.
- Merger of low mass NS (say $1.2 + 1.2 M_{\text{sun}}$?) could produce longer lived SMNS and very bright E+M fireworks??
- Merger observed at different viewing angles may have stronger or no short gamma ray burst and different ratios of red and blue optical components...

4 What are NS made of?

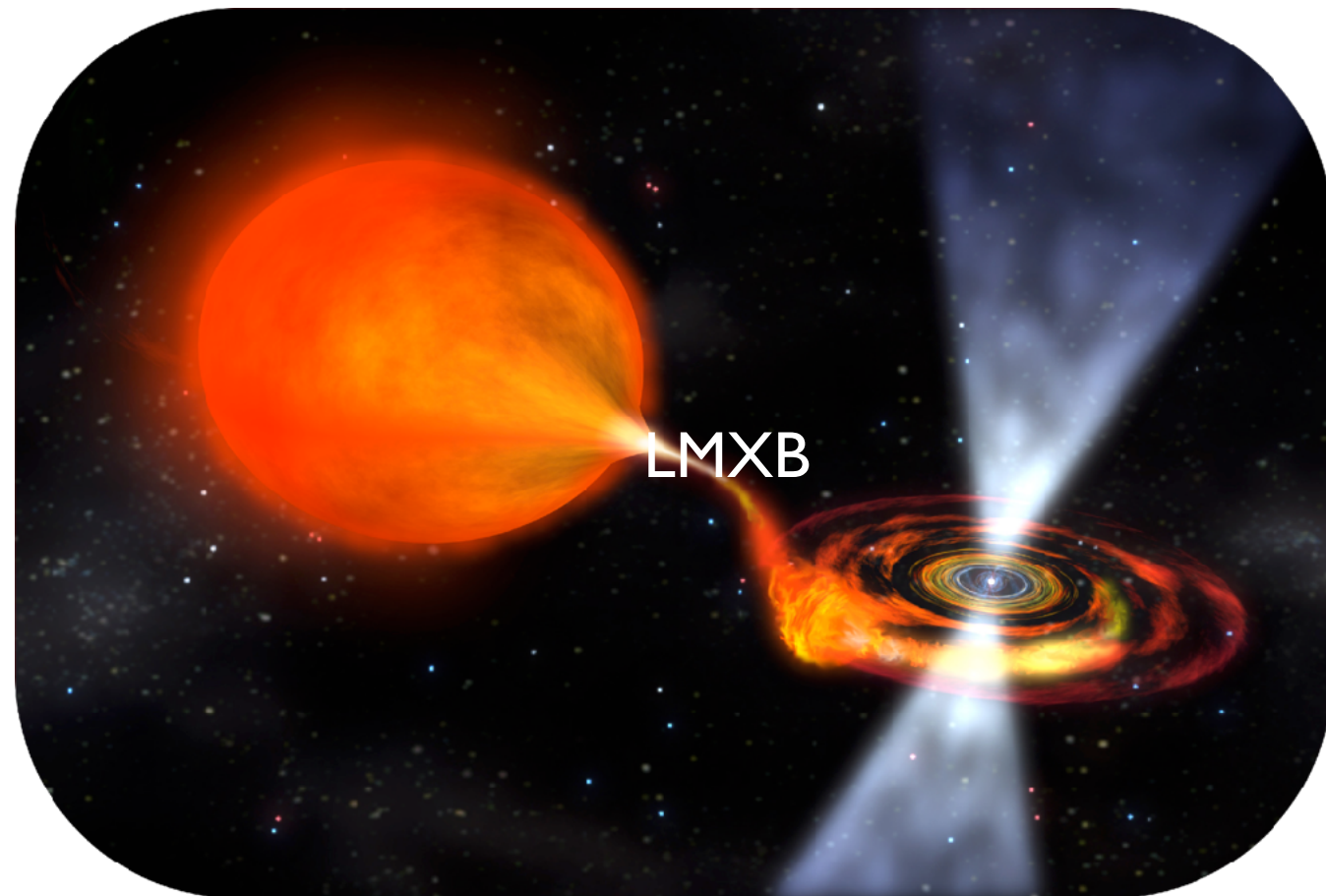
- Measurements of mass, radius, and deformability of NS constrain equation of state (P vs density).
- This doesn't determine composition.
- Observation of $2M_{\text{sun}}$ NS says interactions are strong at high densities. Could be strongly interacting neutrons or quarks.
- RHIC finds a strongly interacting 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

Heat Capacity and Deep Crustal Heating

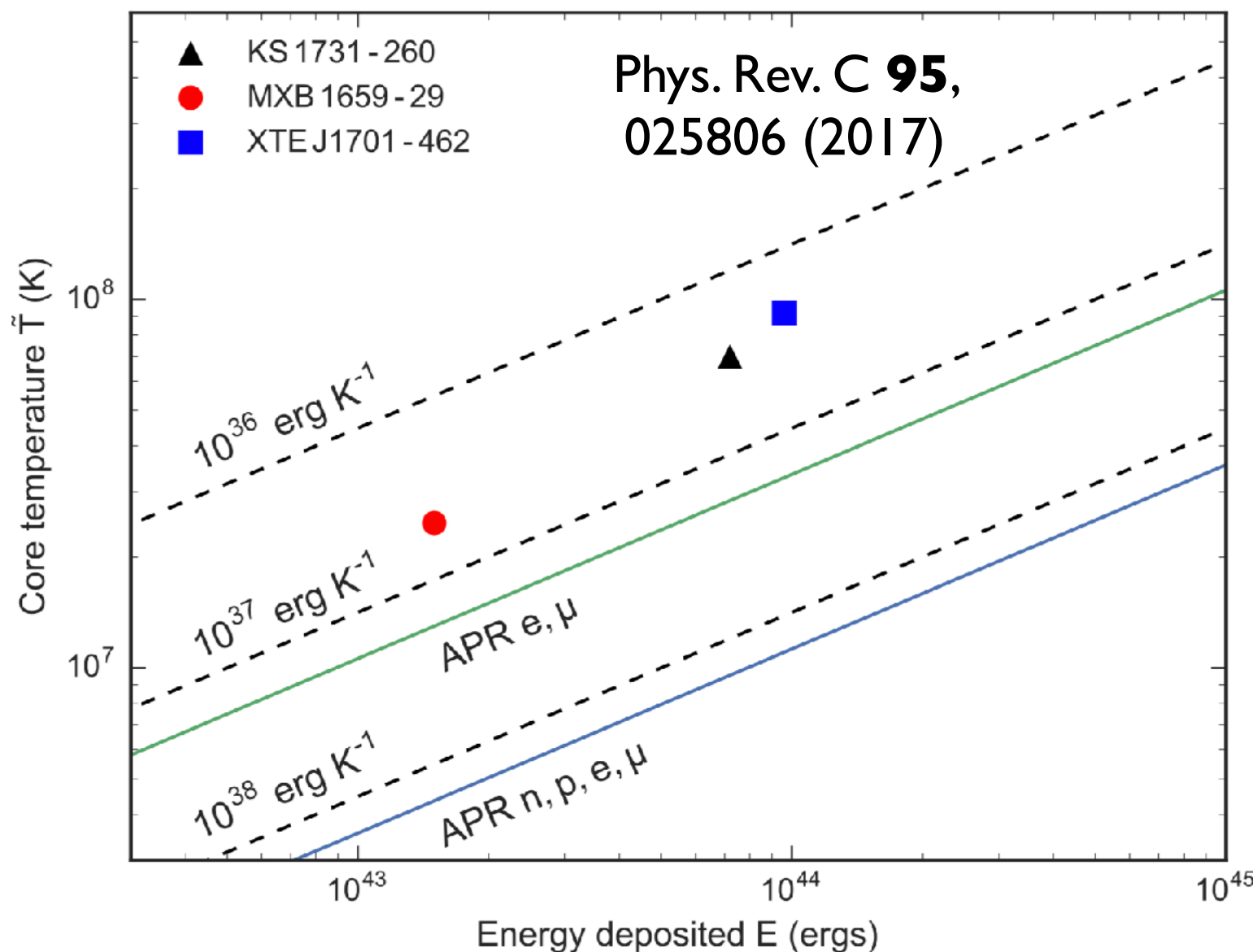
- In a low mass X-ray binary (LMXB) material accretes onto a neutron star and gets buried to increasing densities.
- Rising electron fermi energy drives e capture making nuclei increasingly n rich.
- Pycnonuclear fusion reactions of these n rich nuclei heat the crust.
- This deep crustal heating can 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” $1.4M_{\text{sun}}$ 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 stars and the equation of state of dense matter

- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke, G. Urciuoli
- NS deformability vs ^{208}Pb skin:
Farrukh Fattoyev,
Jorge Piekarewicz.
- Heat capacity, NS cooling: Ed Brown, Dany Page, Sanjay Reddy, Andrew Cumming...
- Graduate students: Zidu Lin (2018), Jianchun Yin, Matt Caplan (2017)

