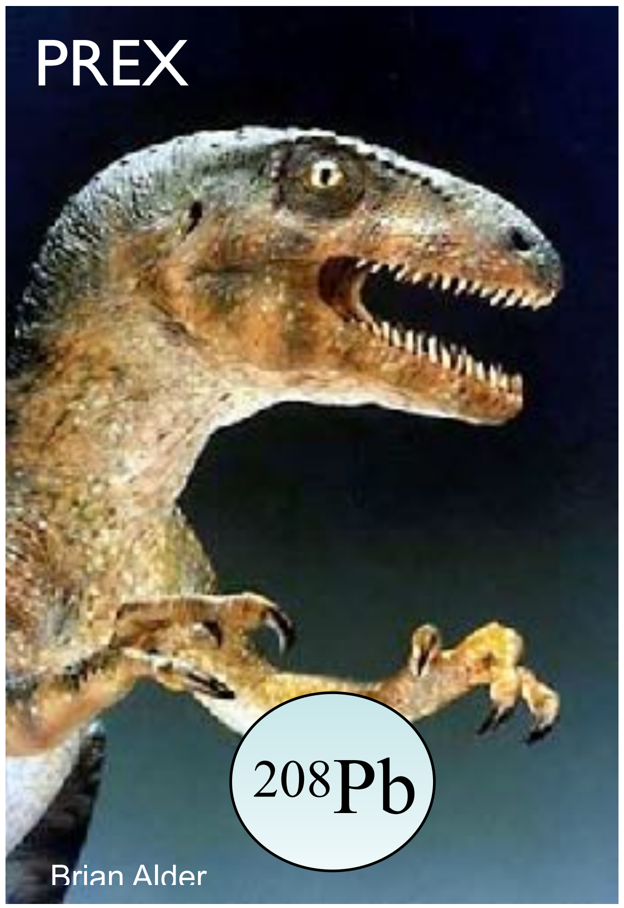
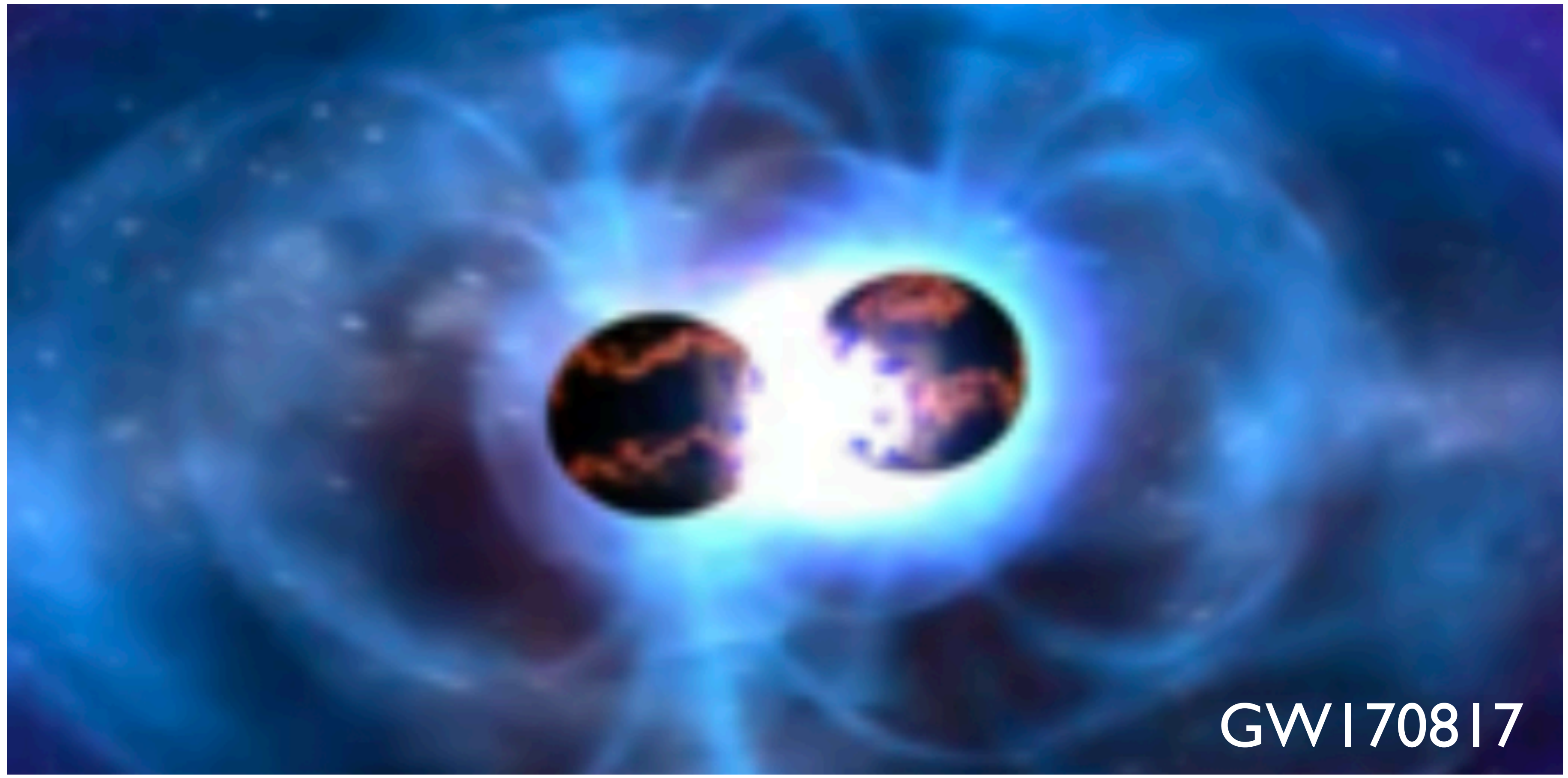
Neutron skins, neutron rich matter, and neutron stars





Chuck Horowitz, Indiana U., MITP, April 2018

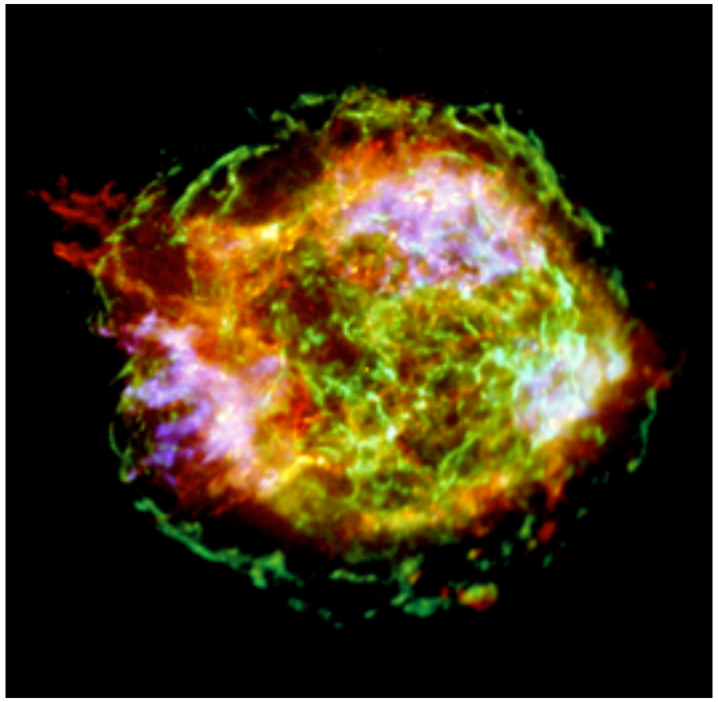
U.S. DEPARTMENT OF ENERGY | Office of Science

NUCLEI Nuclear Computational Low-Energy Initiative

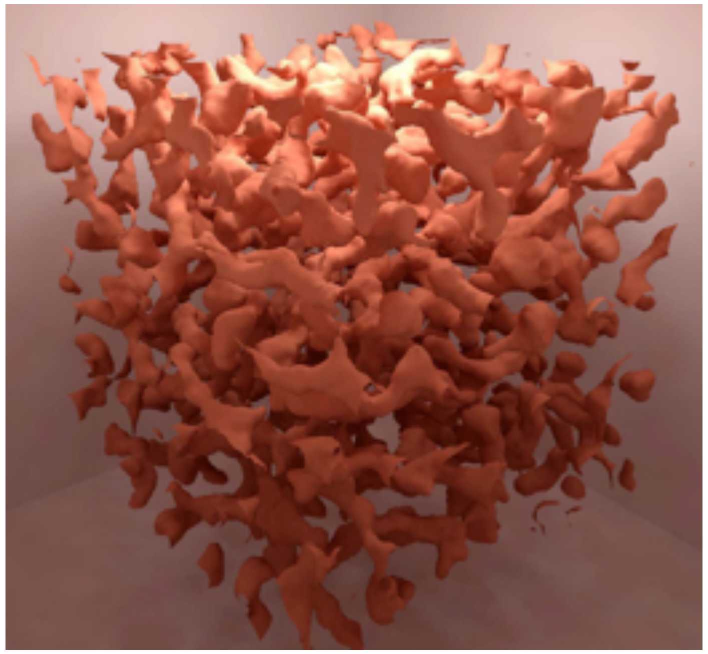
OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

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

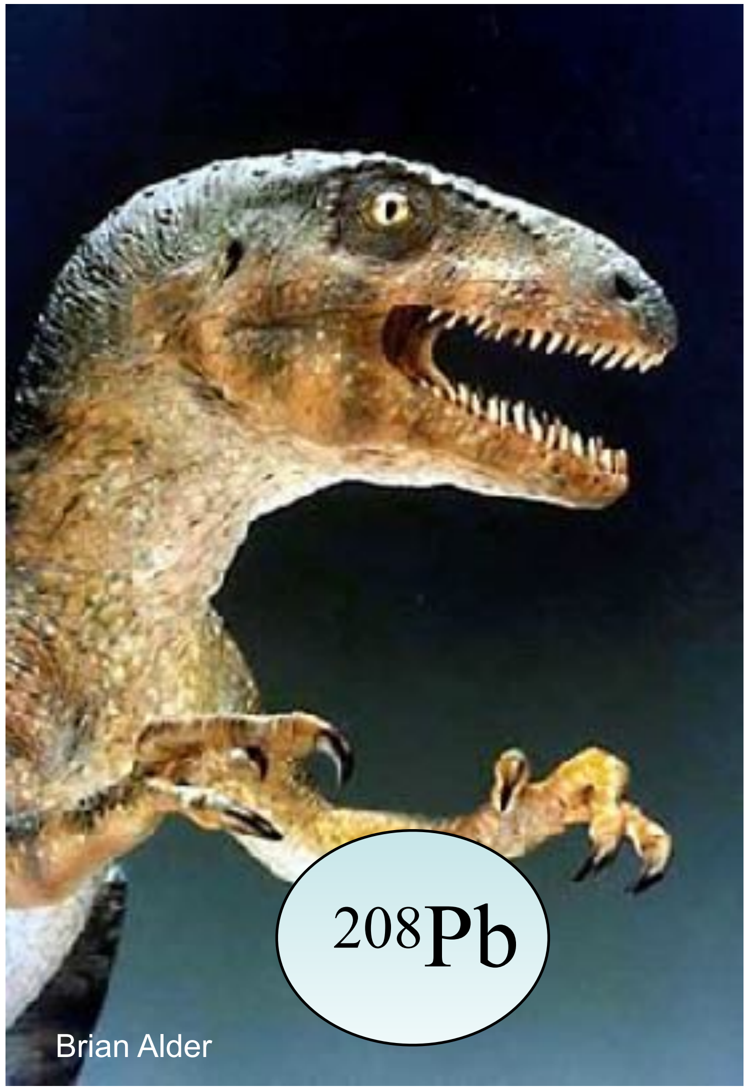


MD simulation of Nuclear Pasta with 100,000 nucleons

Neutron rich matter

- ^{208}Pb: PREX, PREX II
- ^{48}Ca: CREX
- Neutron stars: LIGO (gravitational waves), NICER (X-rays)
- ^{208}Pb: MREX

Laboratory probes of neutron rich matter



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.

Parity Violation Isolates 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

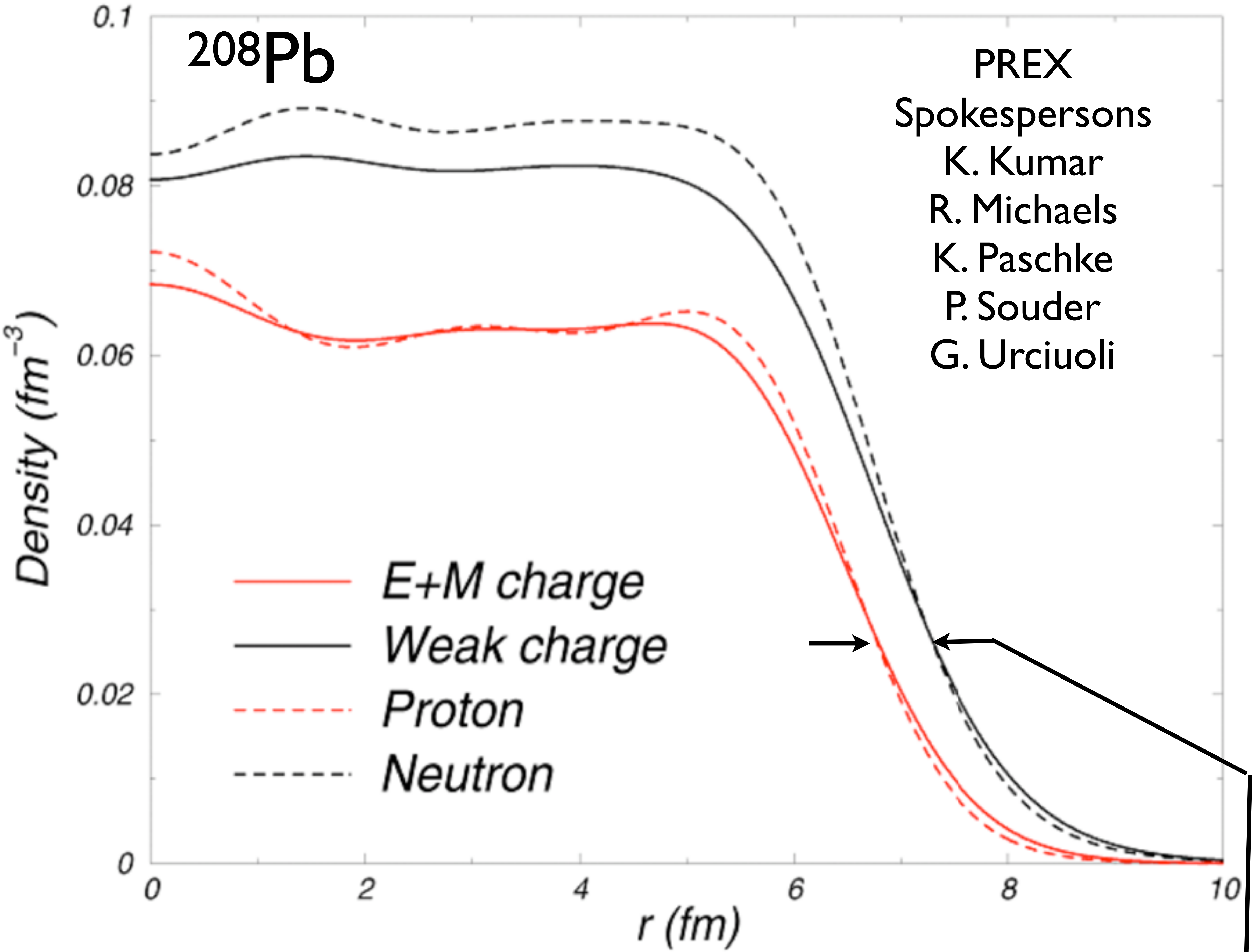
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

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

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

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

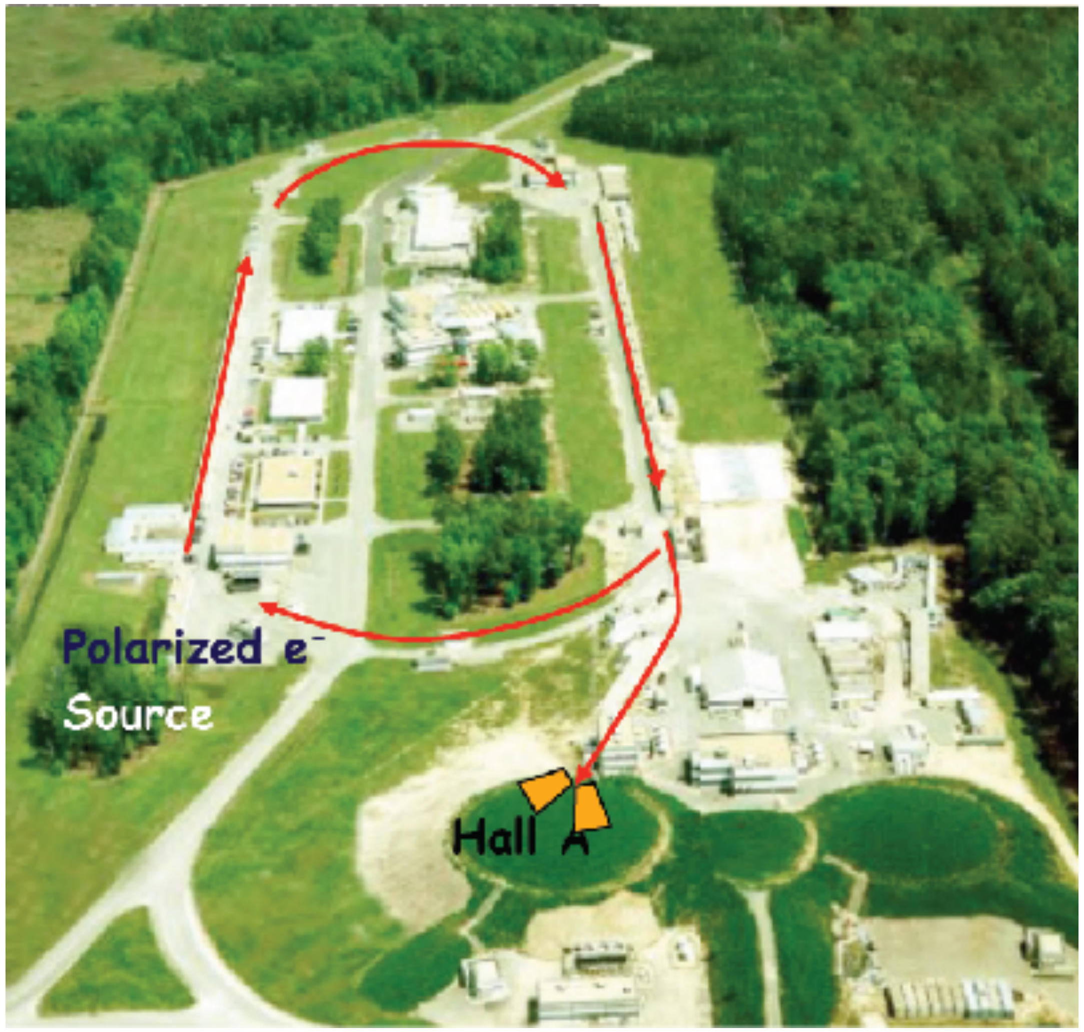
- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**



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

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

PREX in Hall A 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.

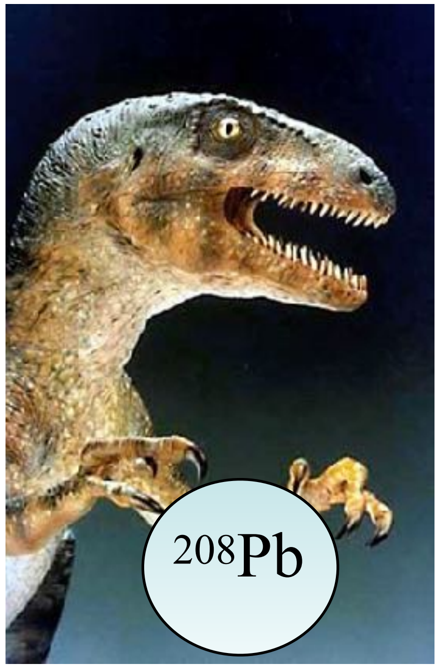
- Next run (plan is 2019)

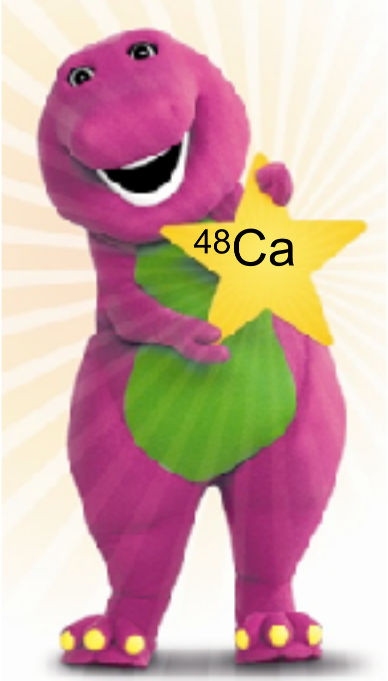
- **PREX-II**: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm.

- **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*.

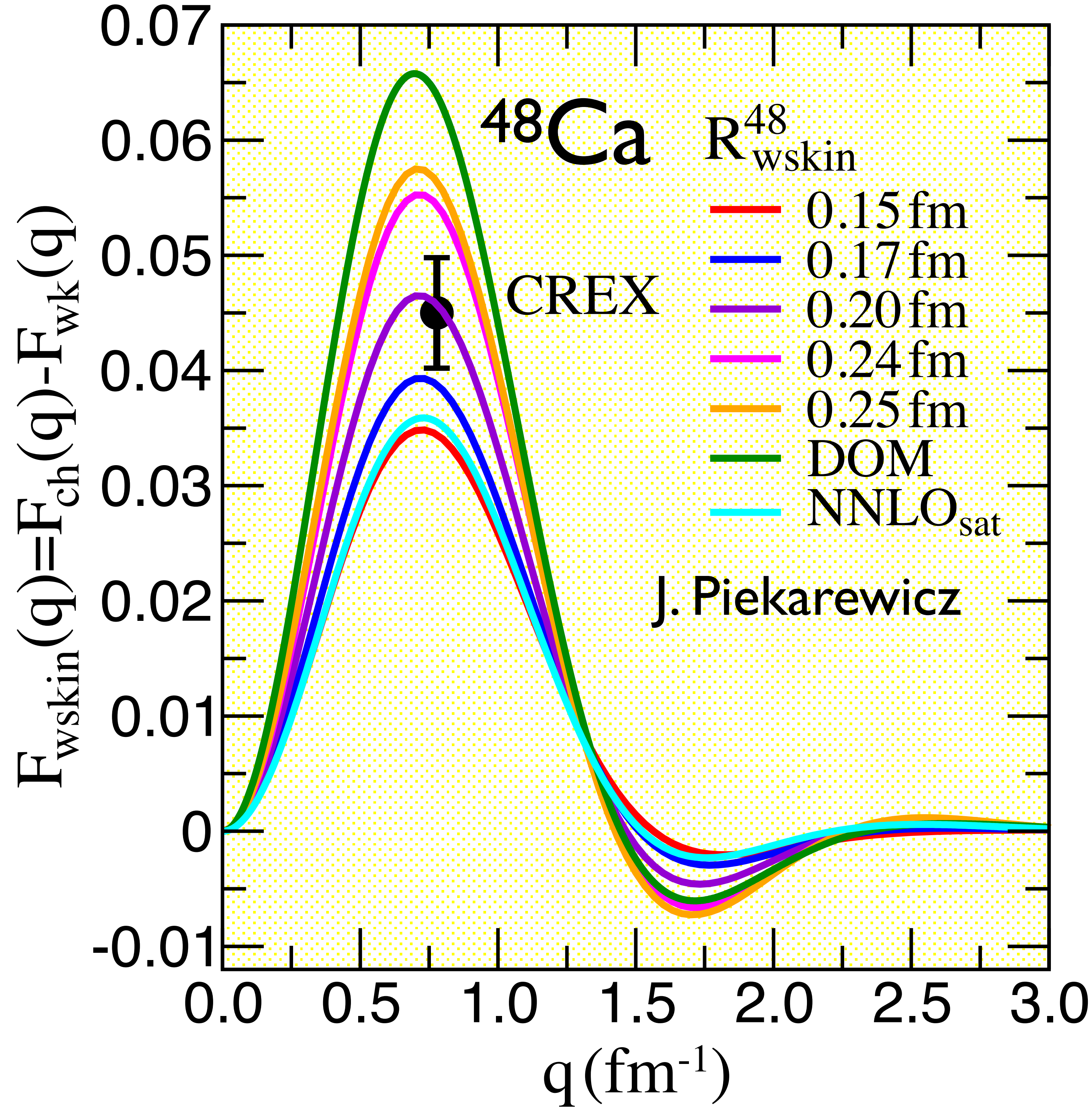
Why PREX and CREX?

- Which targets to probe?
- Require neutron rich nuclei that are stable.
- Nuclei with closed proton and neutron shells have simpler nuclear structure that allow one to more closely relate neutron skin thicknesses to properties of neutron rich matter.
- *In all of nature there are only two neutron rich, stable, closed shell nuclei: ^{208}Pb and ^{48}Ca.*
- The larger ^{208}Pb is a more direct probe of the equation of state of neutron rich matter and the density dependence of the symmetry energy. The smaller ^{48}Ca is more closely related to microscopic 2 and 3 nucleon forces.





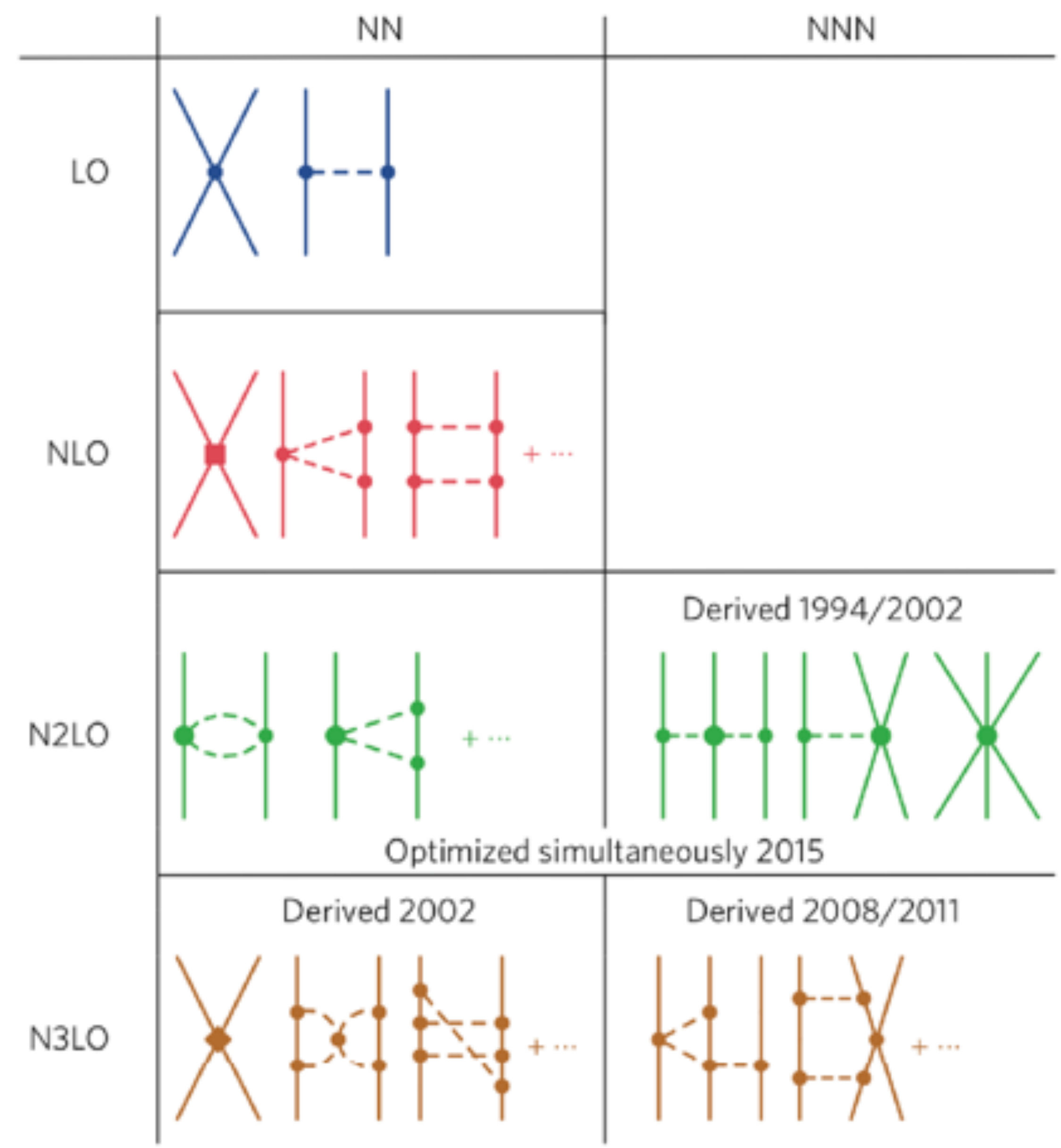
CREX



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

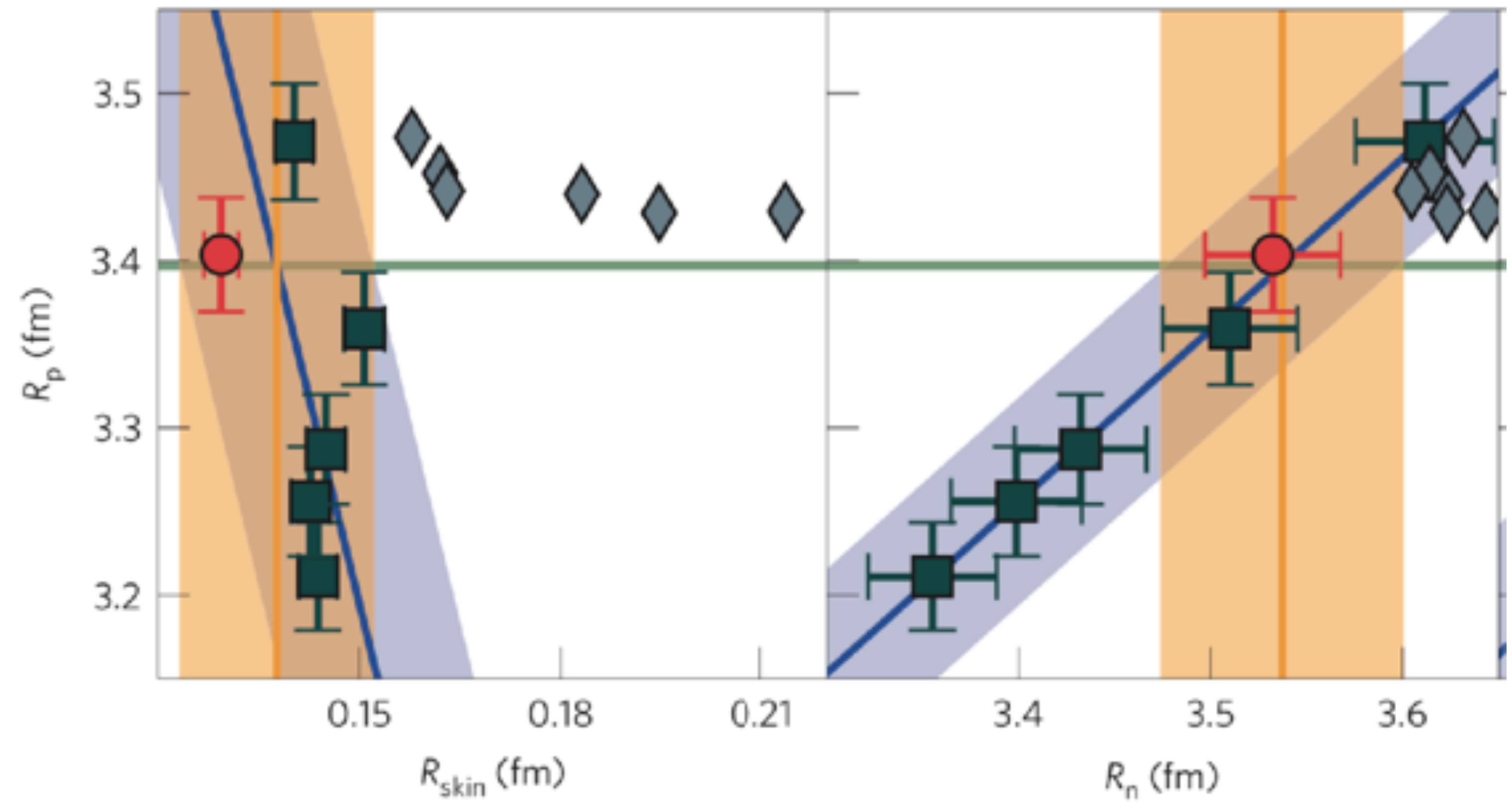
^{48}Ca Chrial EFT calculations

- G. Hagen et al, Nature Physics **12**(2016)186.
- Uses microscopic two nucleon and three nucleon interactions calculated from Chiral EFT and fitted to two nucleon scattering data plus masses and charge radii of selected nuclei up to A=25. *Note, $NNLO_{sat}$ interaction only fits phase shifts up to ~200 MeV.*
- Coupled cluster calculations include all single, double and some triple particle -hole excitations.



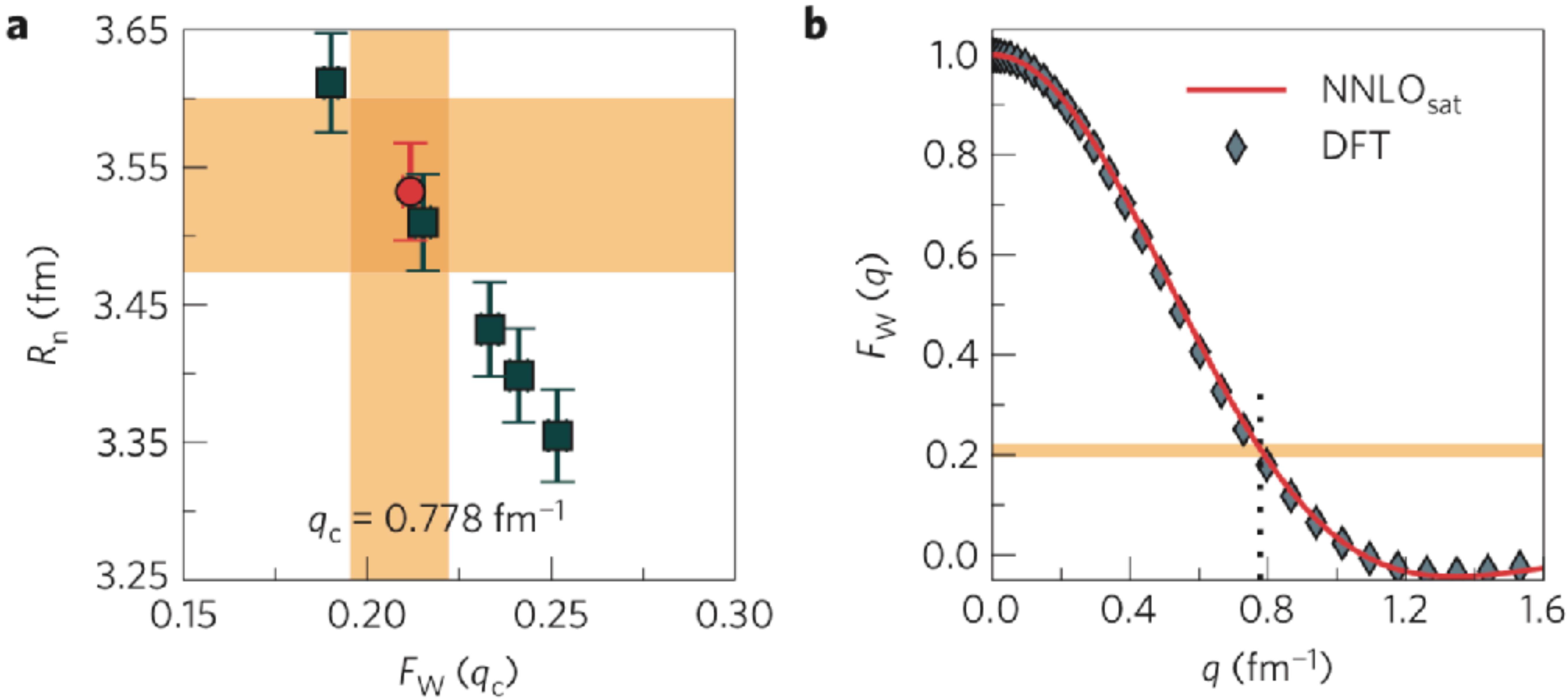
Nuclear saturation hard to predict

- Chiral EFT calculations to a given order have an uncertainty band.
- **Good news**: this band may include the empirical saturation point for nuclear matter.
- **Bad news**: the width of the band may preclude accurate ab initio predictions of the absolute size of ^{48}Ca.



- Calculate R_n or R_n-R_p vs R_p and fit to experimental R_p. —> Skin $\mathbf{R_n\text{-}R_p=0.12}$ **to 0.15 fm** determined more accurately than R_n.
- NNLO$_{sat}$ is somewhat of a hybrid between interactions fit only to scattering data and energy functionals fit only to nuclear data.

Predictions for R_n and $F_W(q)$

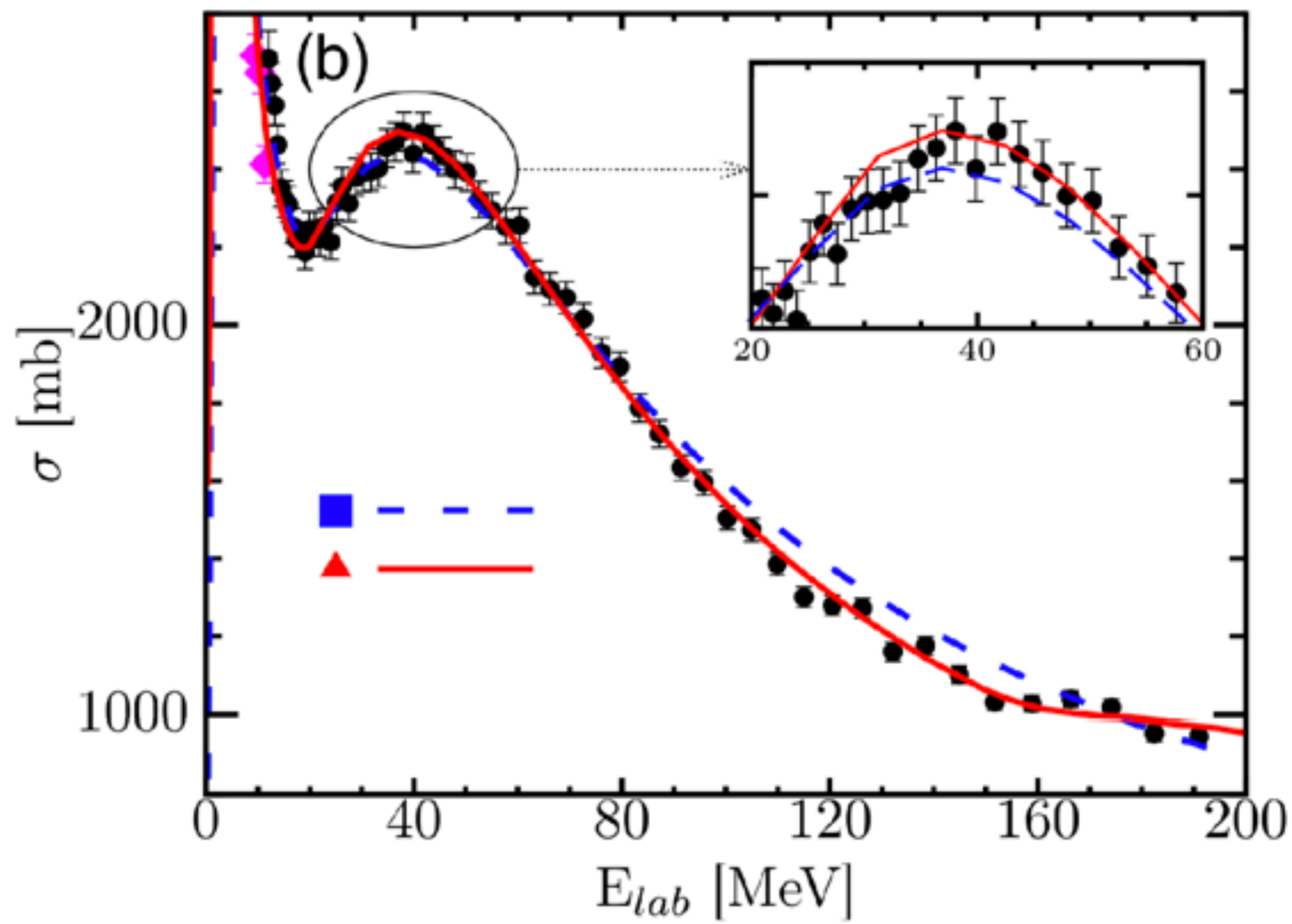


- Can make sharper prediction for $F_{ch}(q)$ - $F_W(q)$ than for $F_W(q)$ alone.

Dispersive Optical Model

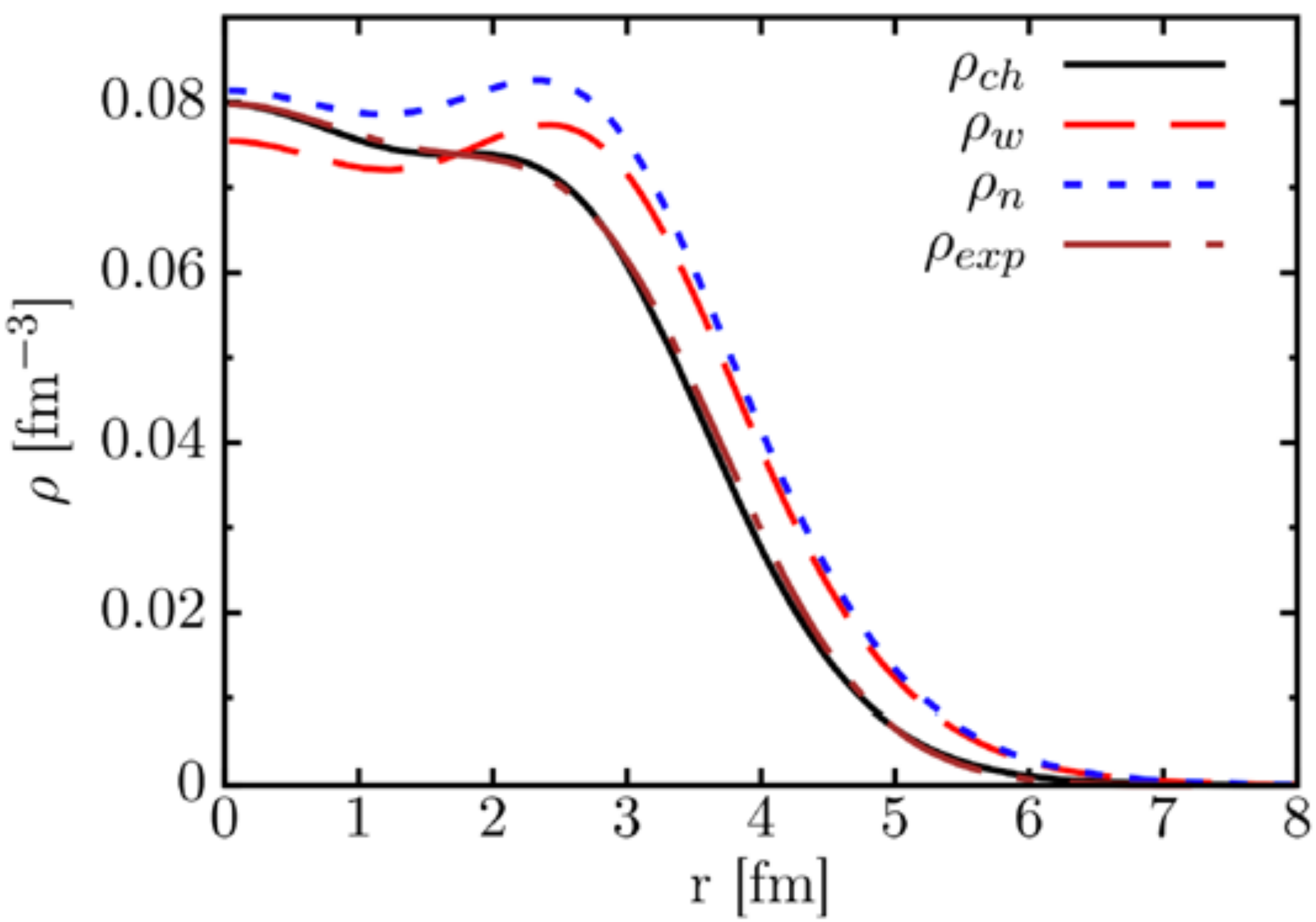
- Mahzoon et al, PRL **119** (2017) 222503 predicts R_n-R_p=0.249 +/- 0.023 fm
- Consider nucleons moving in a self-energy (or optical potential) Σ.
- Fit bound state and scattering data to determine Σ.
- From Σ determine single particle greens function, and then neutron density, from Dyson's eq.

Total cross section for n from ^{48}Ca.

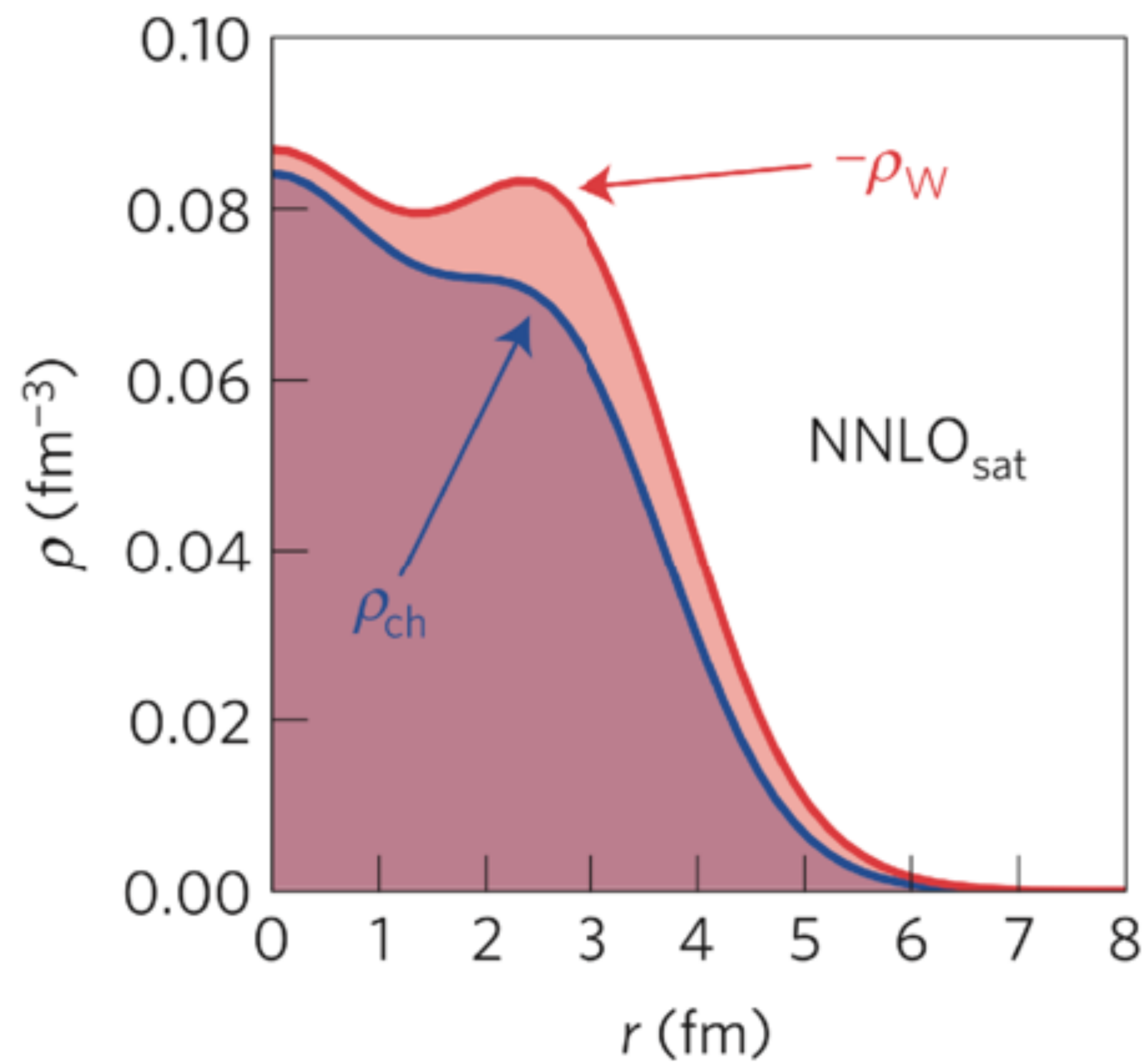


- Red curve: R_n-R_p=0.249 fm
- Blue dashed: R_n-R_p=0.132 fm

^{48}Ca weak and charge densities



Dispersive optical model



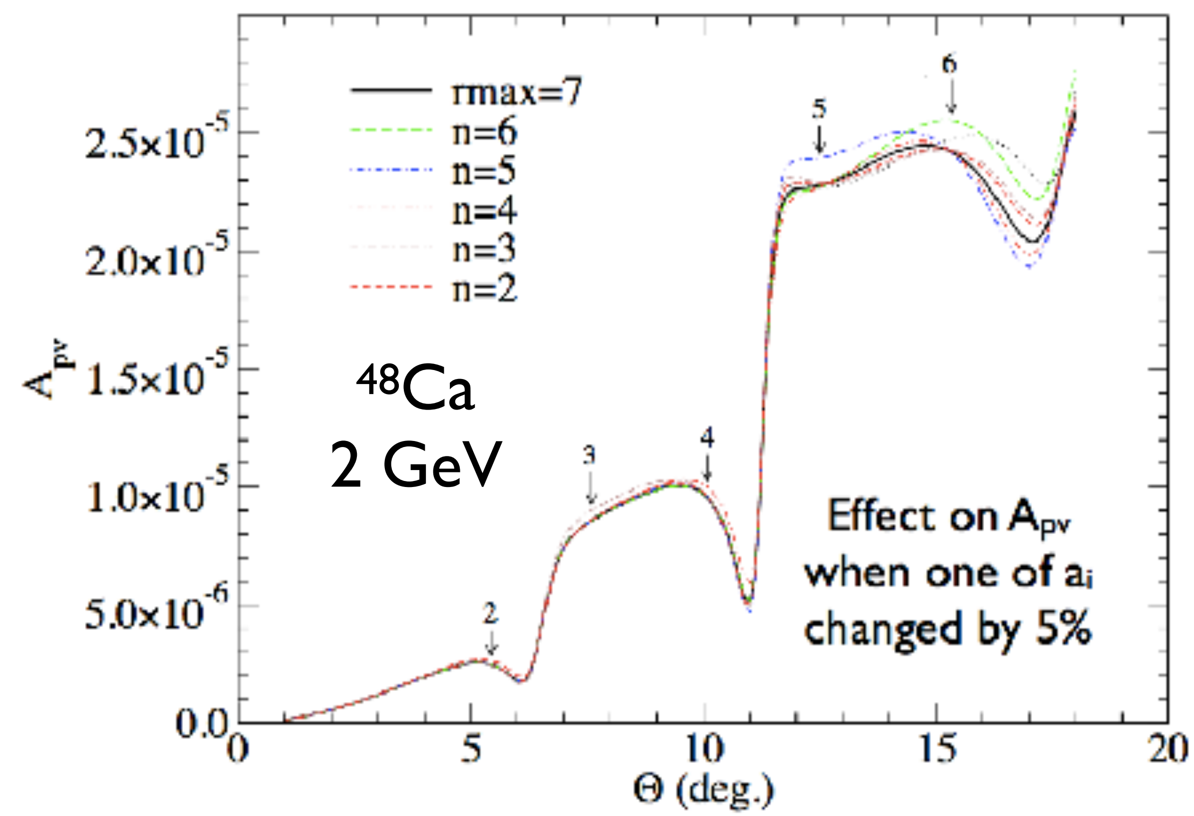
Chiral EFT calculations

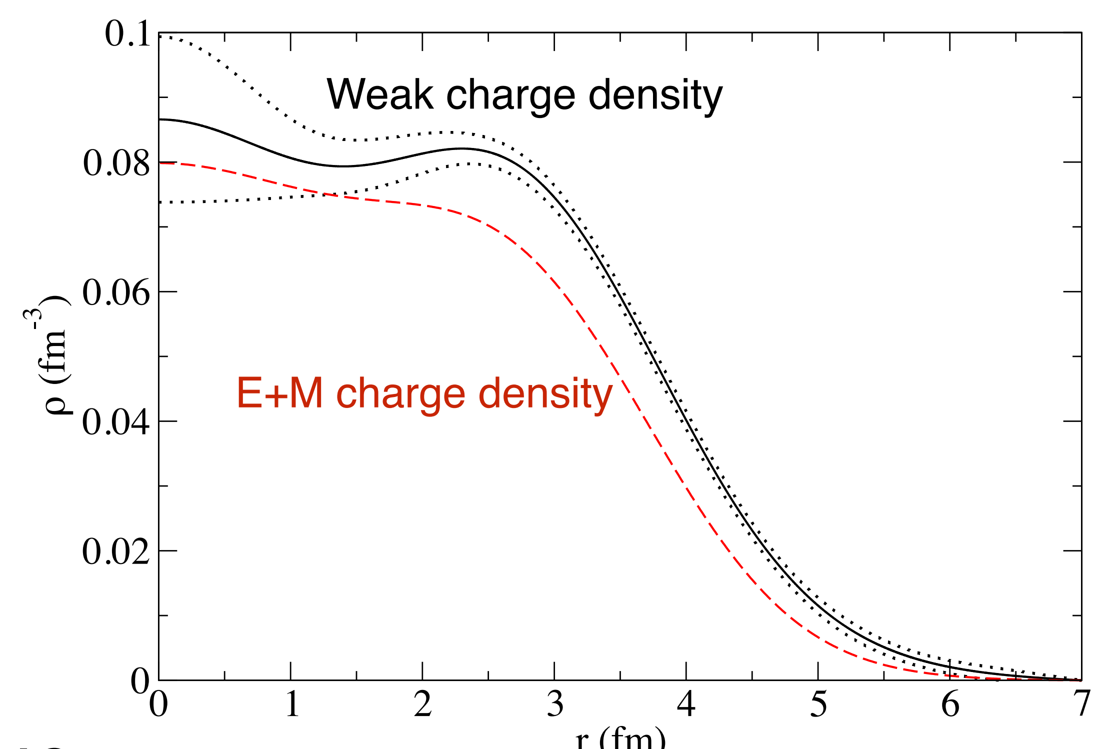
Full ^{48}Ca weak charge density

- Measure A_{pv} at multiple q^2 points to determine the full radial form of the weak density. This is feasible for ^{48}Ca, really hard for ^{208}Pb.
- Expand in Fourier Bessel series:

$$\rho_W(r) = \sum_{i=1}^{n_{max}} a_i j_0(q_i r)$$

- Stat. error shown for 60 days total for all Q^2 points, needs optimization.
- Would provide *text book picture of where neutrons and protons are located in a nucleus.*
- Learn about shell oscillations of neutrons, saturation density of nuclear matter, neutron skin thickness, surface thickness of the neutrons…



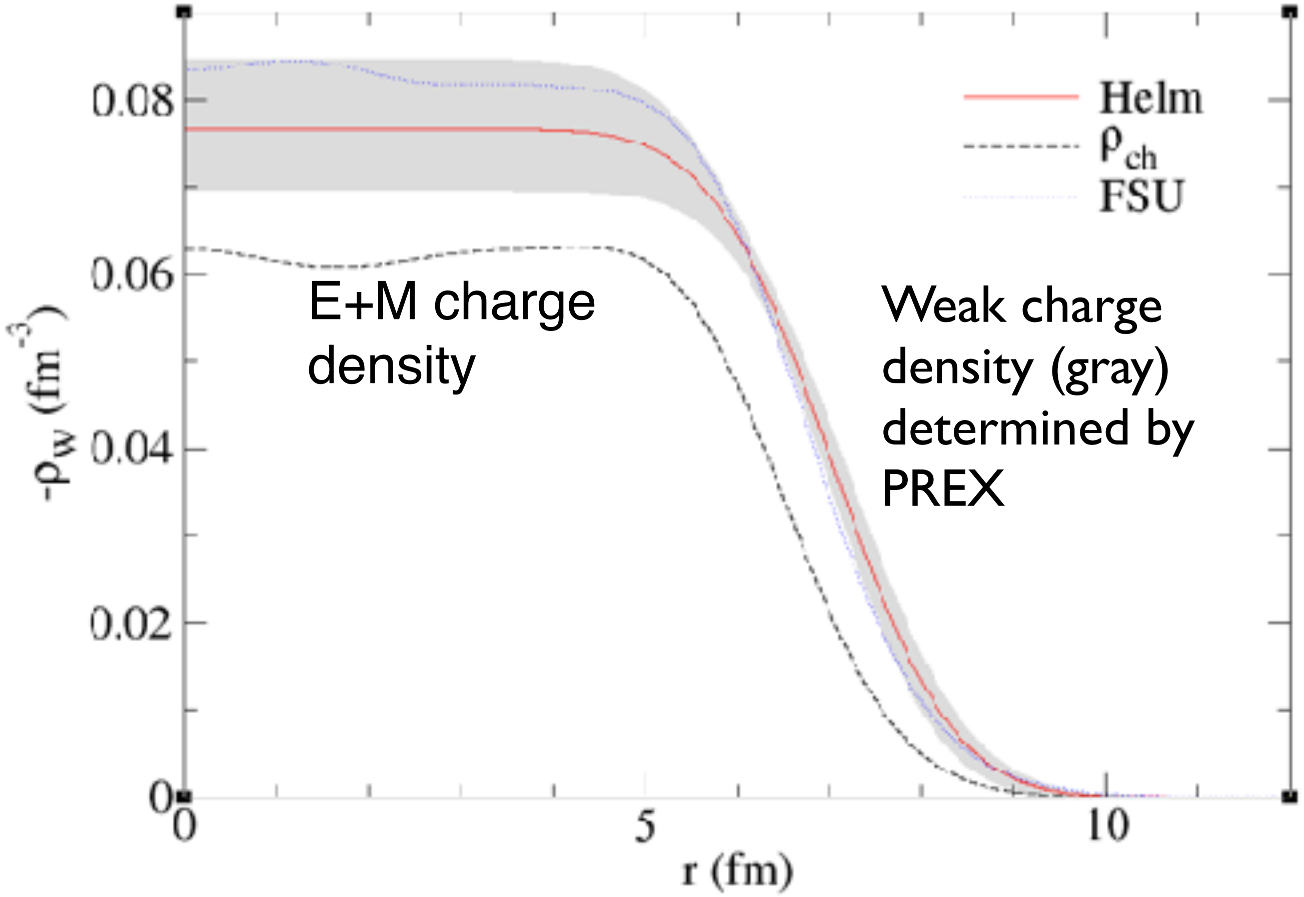


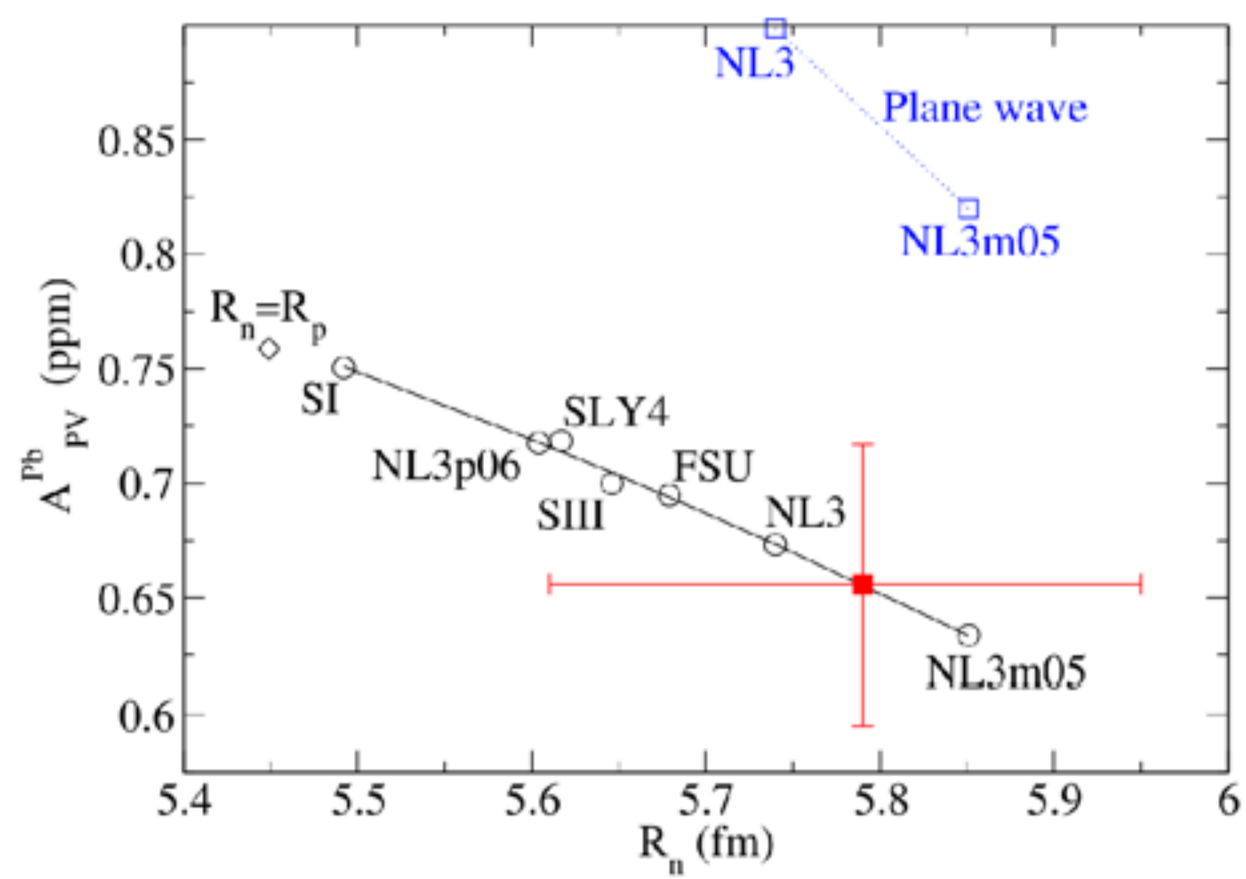
PRC **92**(2015)014313

with Zidu Lin

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 $q=0.475\ fm^{-1}$: $F_W(q) = 0.204 \pm 0.028$
- Radius of weak charge distr. $R_W = 5.83 \pm 0.18$ fm ± 0.03 fm
- Compare to charge radius R_{ch}=5.503 fm --> weak skin: $R_W - R_{ch} = 0.32 \pm 0.18 \pm 0.03$ 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)

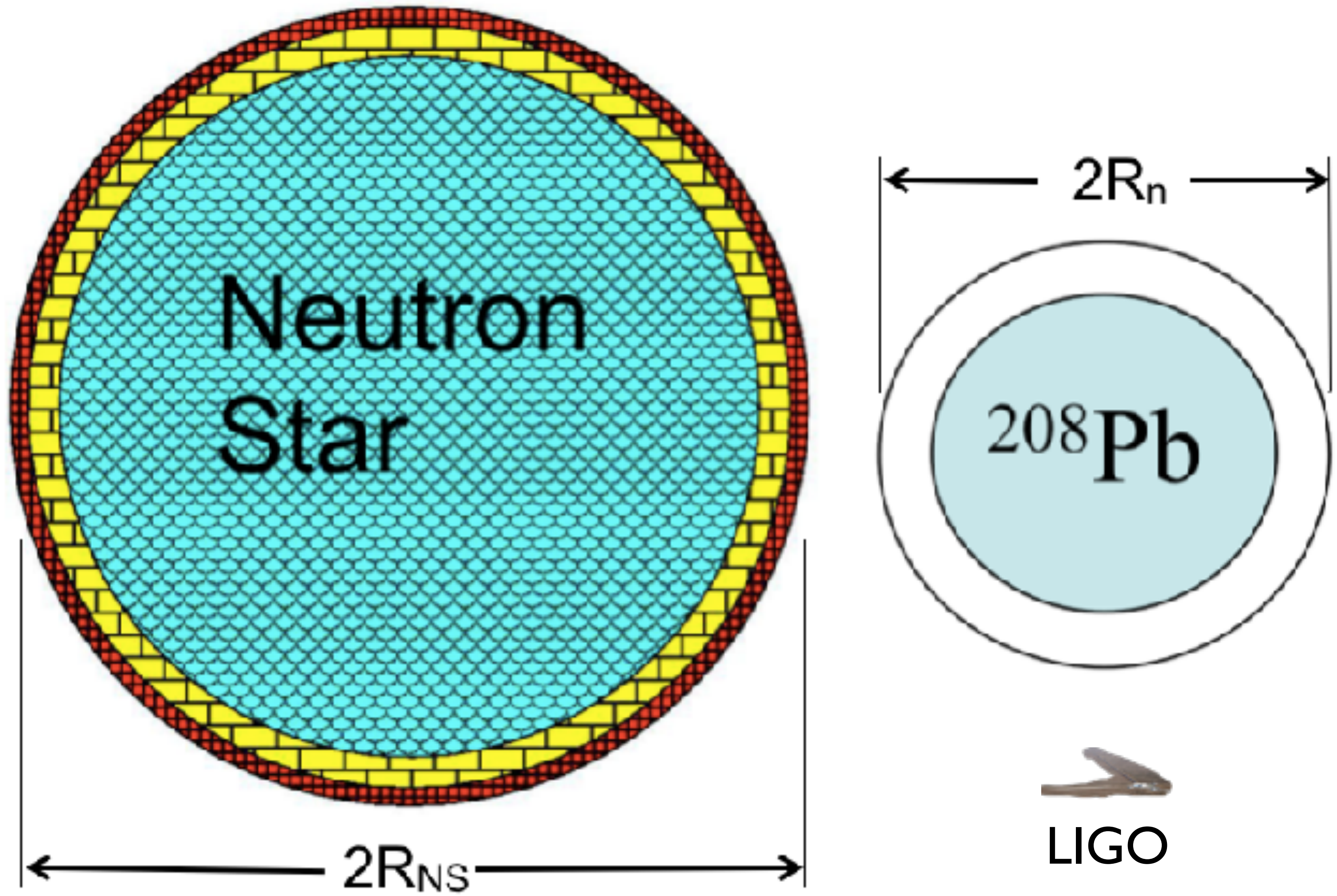




Neutron rich matter in astrophysics

Radii of ^{208}Pb and Neutron Stars

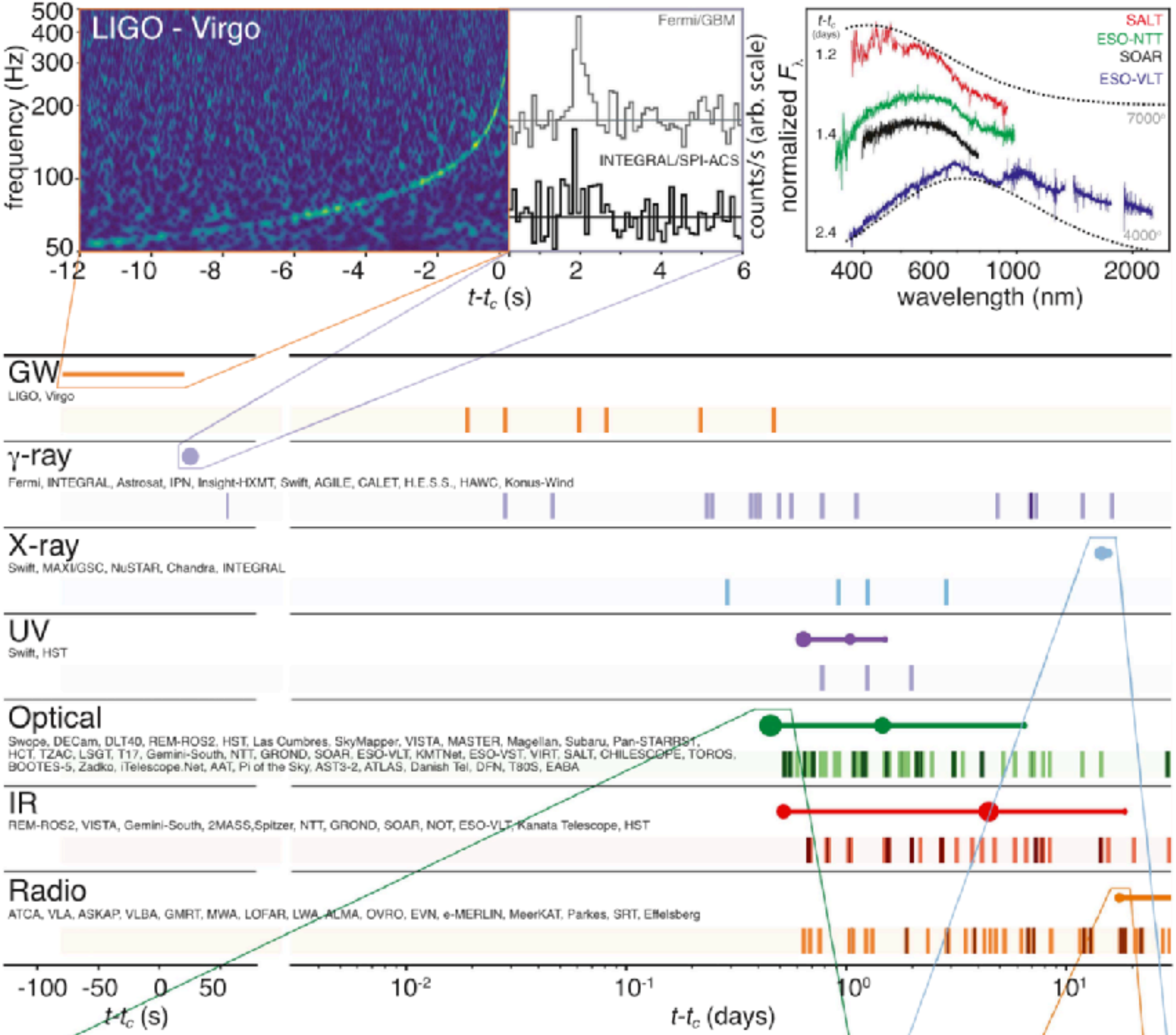
- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



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

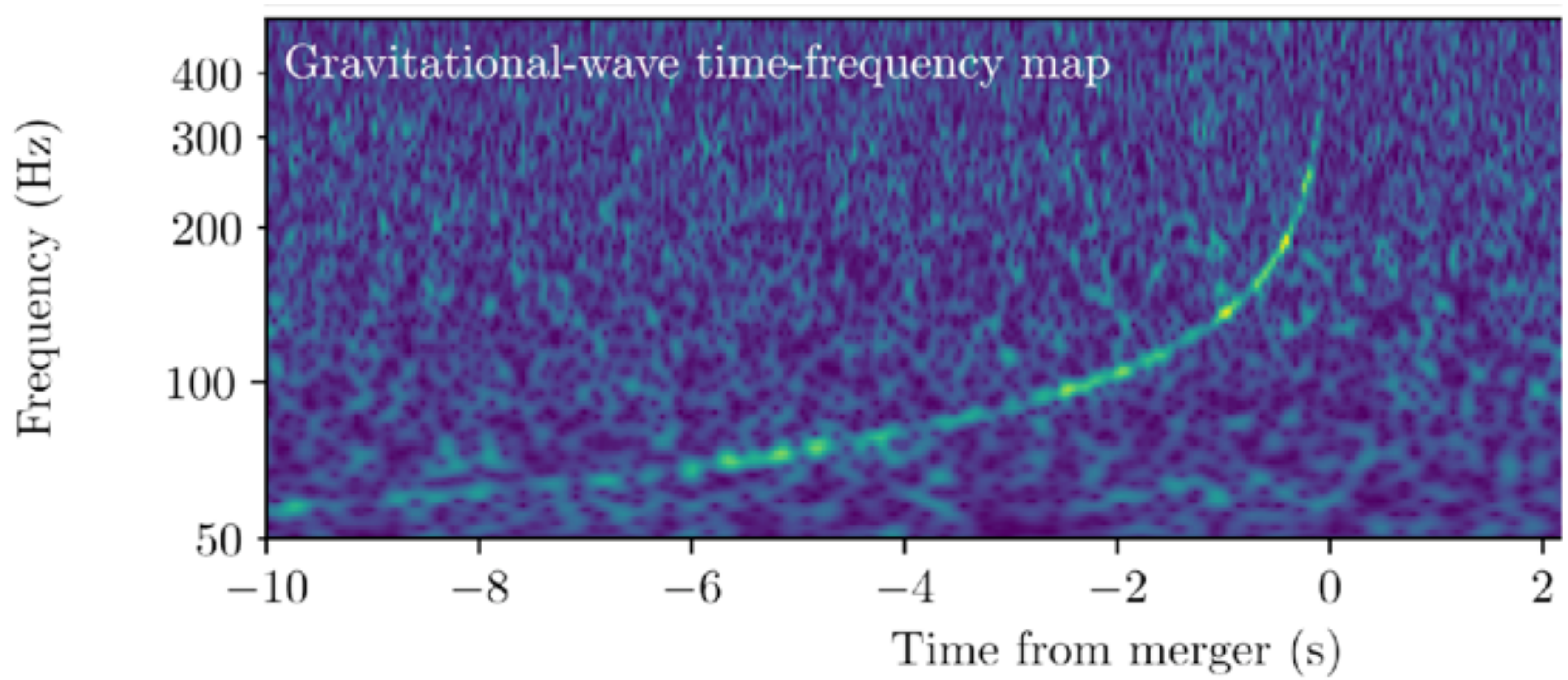
Spectacular event GW170817

- On August 17, 2017, the merger of two neutron stars was observed with gravitational waves (GW) by the LIGO and Virgo detectors.
- The Fermi and Integral spacecrafts independently detected a short gamma ray burst.
- Extensive follow up observations detected this event at X-ray, ultra-violet, visible, infrared, and radio wavelengths.
- Focus here on implications for equation of state of neutron rich matter and r-process.



LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (s)
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (s)
t-t_c (days)

Chirp signal from GW170817



- "Chirp mass" depends on orbital frequency f from Kepler's laws and df/dt from GW radiation:
  $M_{chirp} = (M_1M_2)^{3/5} / (M_1 + M_2)^{1/5} = 1.188^{+0.004}_{-0.002}\ M_{sun}$.
- Chirp mass too low for a binary black hole system.
- Total mass determined less accurately: ~ 2.75 M_{sun}.

Polarizability of giant nuclei

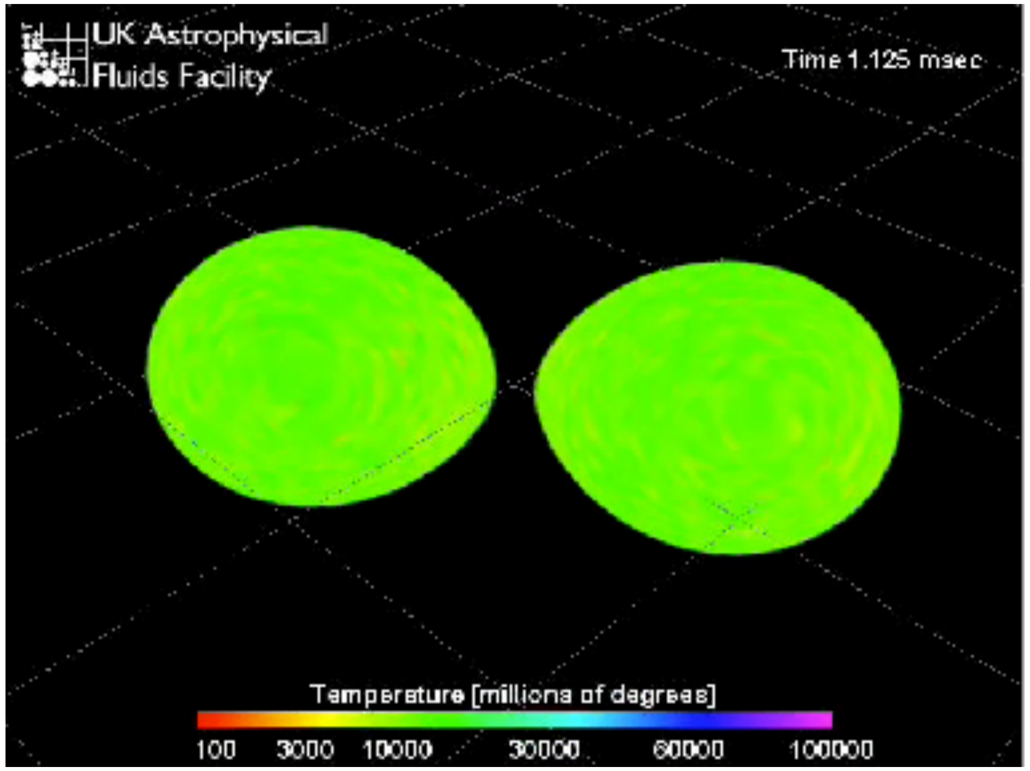
- Electric dipole polarizability of an atom scales as R^3.

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

- Mass quadrupole polarizability of a neutron star scales as R^5.

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

- LIGO is sensitive to increase in orbital frequency as system loses energy to both gravitational waves and internal excitation of neutron stars. GW170817 data place limits on polarizability (deformability) of NS and hence limits on NS radius.



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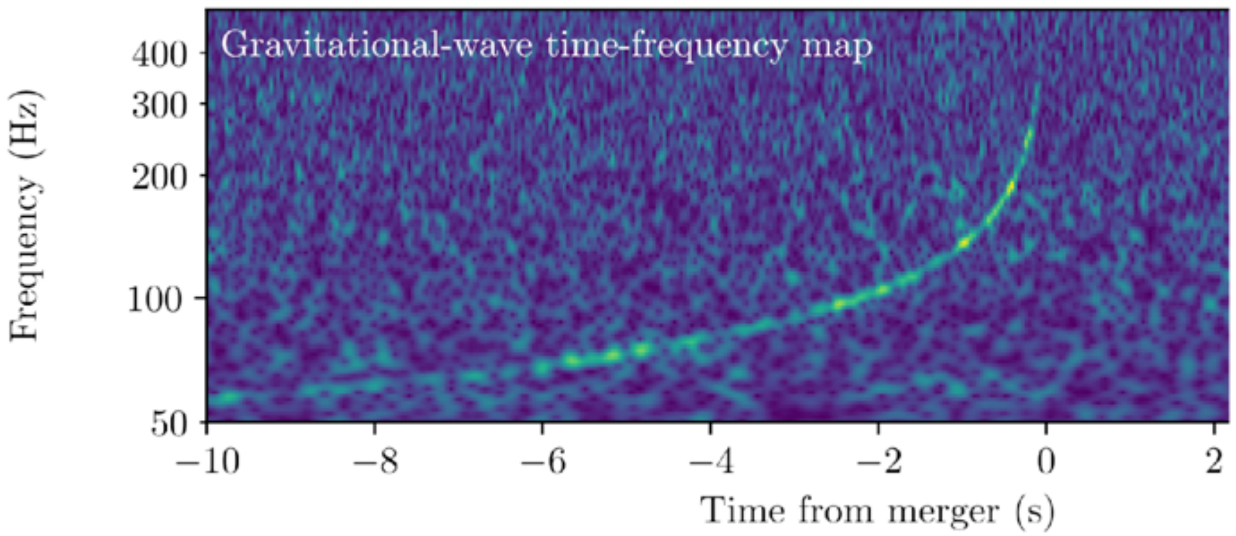
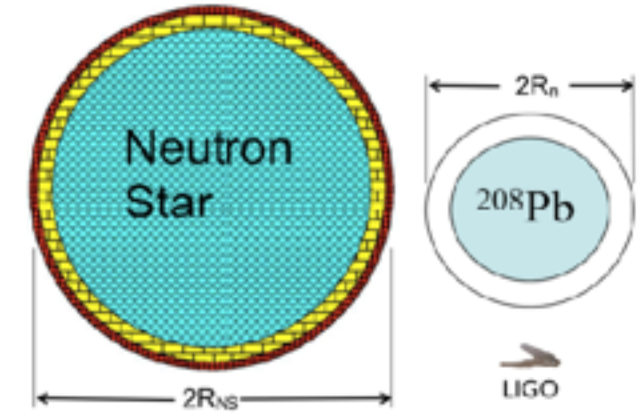
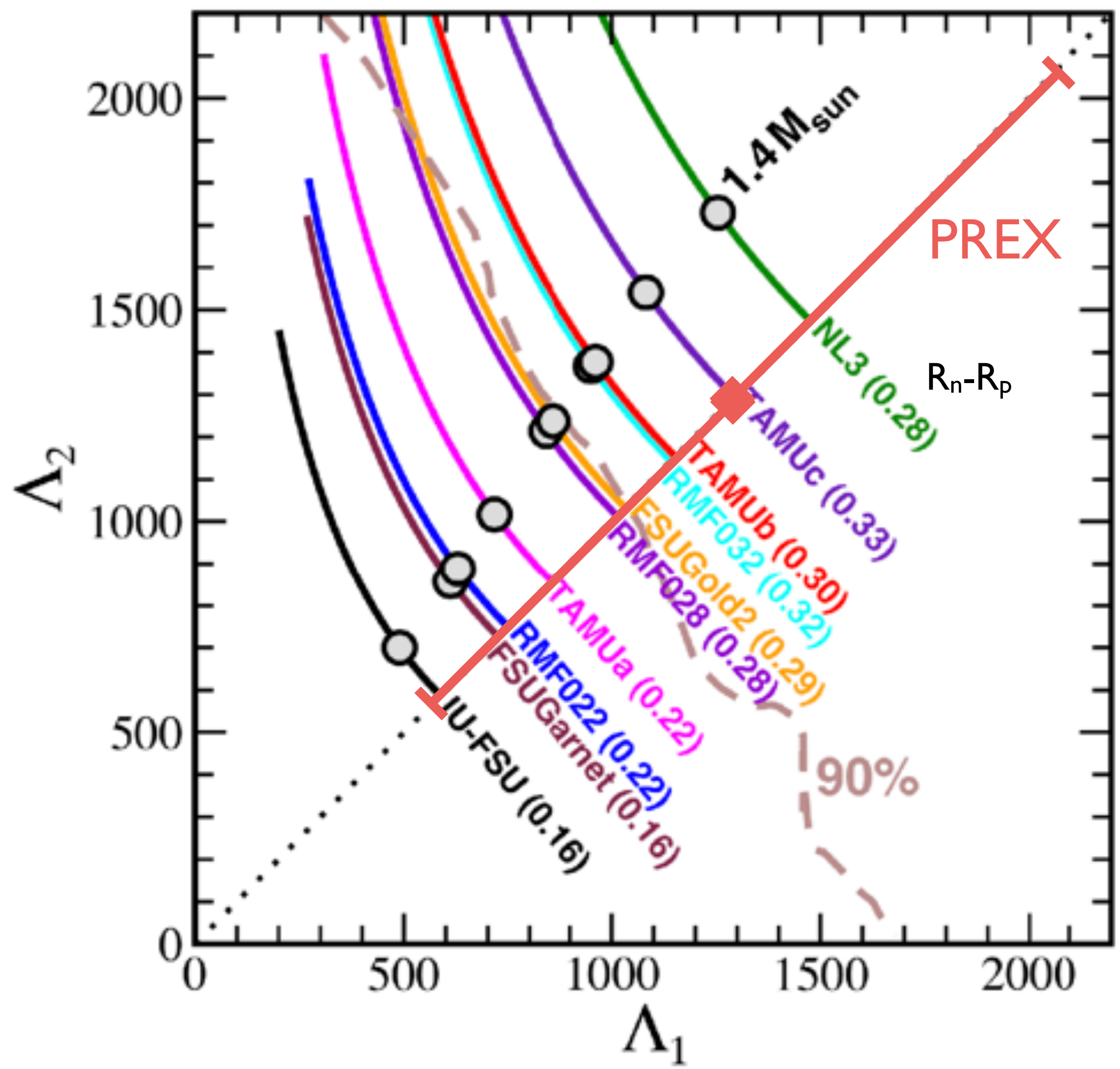


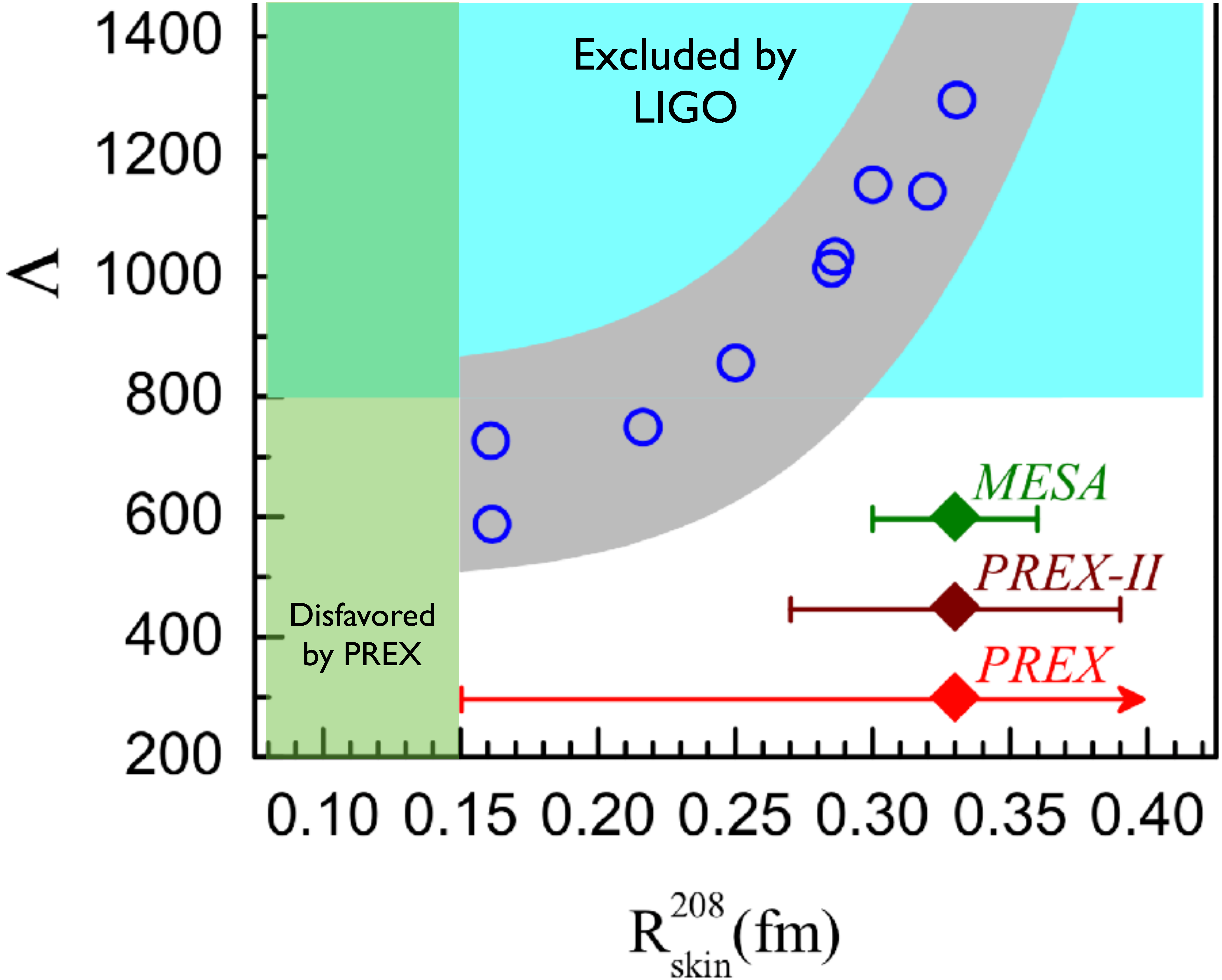
NS deformability and neutron skin of ^{208}Pb



- EOS with high pressure give thick n skin for ^{208}Pb and large deformability for a NS.
- Several relativistic mean field EOS curves with R_n-R_p (^{208}Pb) listed in fm.
- GW170817 rules out stiff EOS with neutron skins greater than about 0.29 fm.
- PREX R_n-R_p= $0.33^{+0.16}_{-0.18}$ fm. Central value ruled out. *PREX lower limit R_n-R_p=0.15 fm gives lower limit for Λ>500.*



GW170817 allowed region to lower left of 90% line. F. Fattoyev et al. ArXiv: 1711.06615

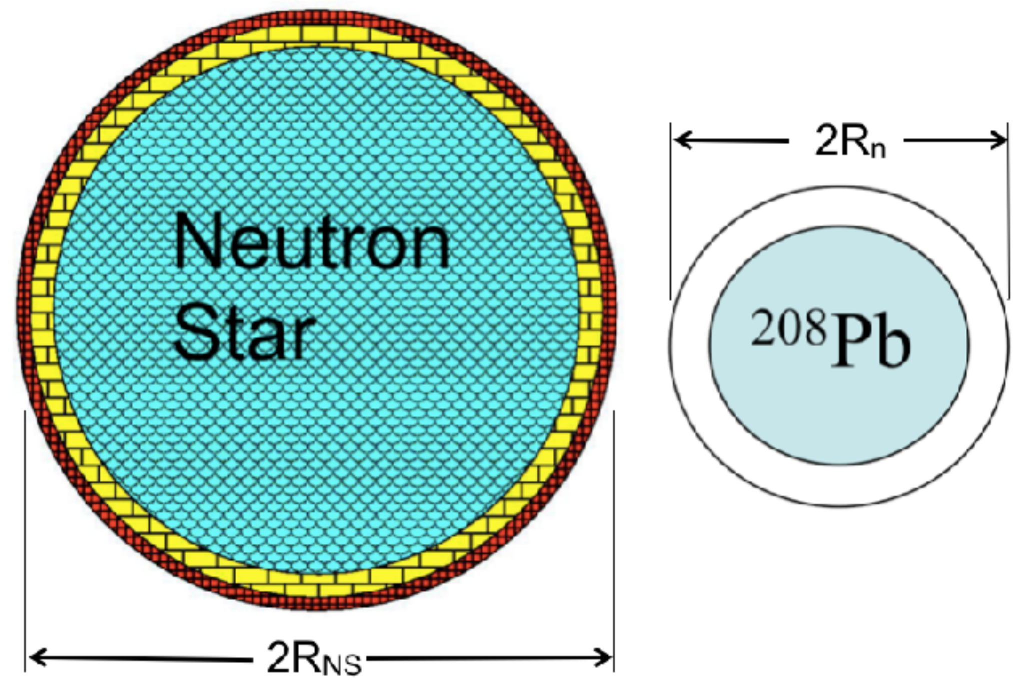


F. Fattoyev et al. ArXiv:1711.06615

Density Dependence of EOS

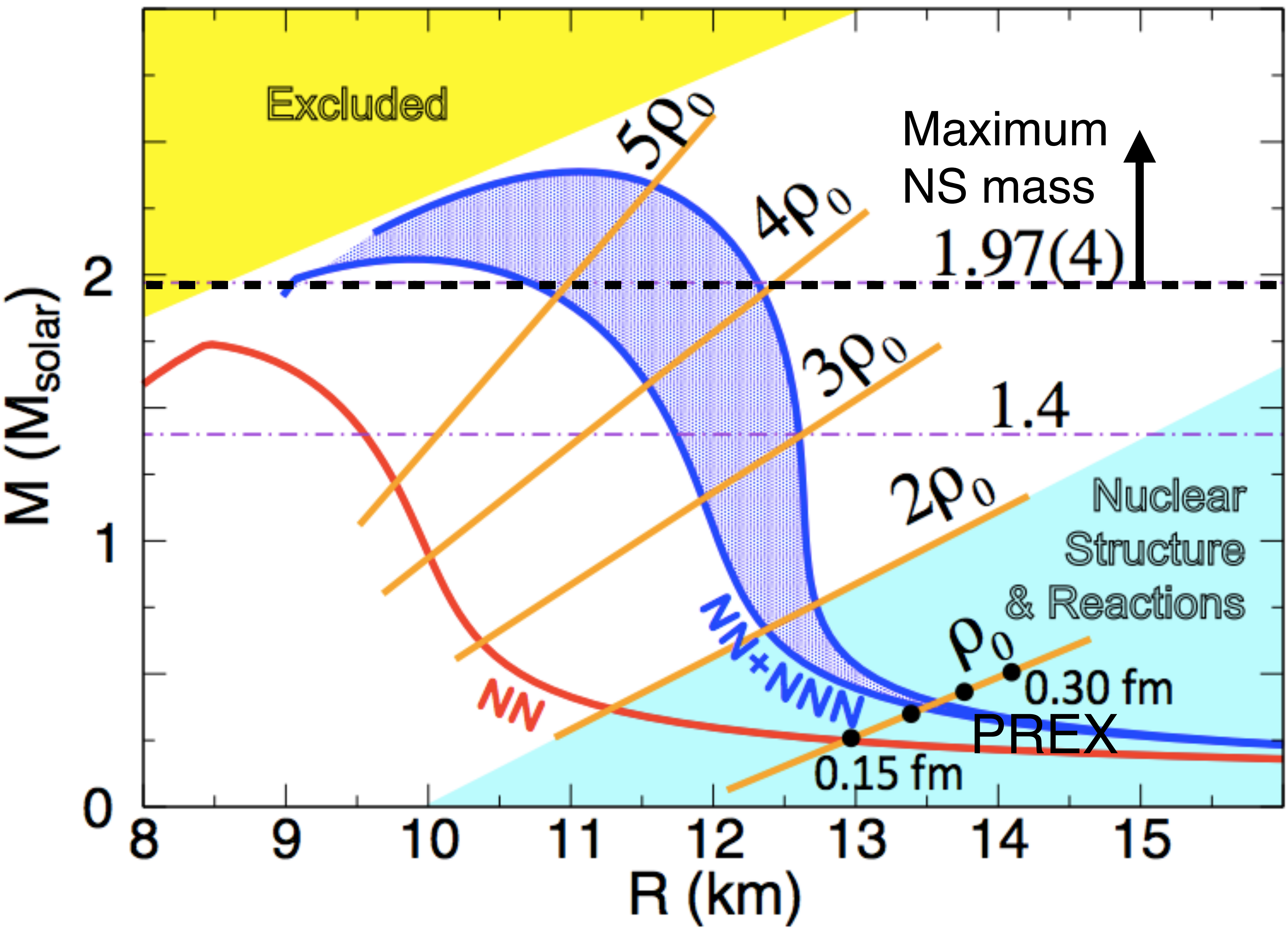
- Pressure of neutron matter pushes n out against surface tension ==> R_n-R_p of ^{208}Pb determines P at low densities ~$2/3\rho_0$ (average of surface and interior ρ).
- Radius of (~$1.4M_{sun}$) NS depends on P at medium densities ~$2\rho_0$.
- Maximum mass of NS depends on P at high densities.

Neutron Star radius versus ^{208}Pb Radius



- These three measurements constrain density dependence of EOS and possible pressure changes from phase transitions.

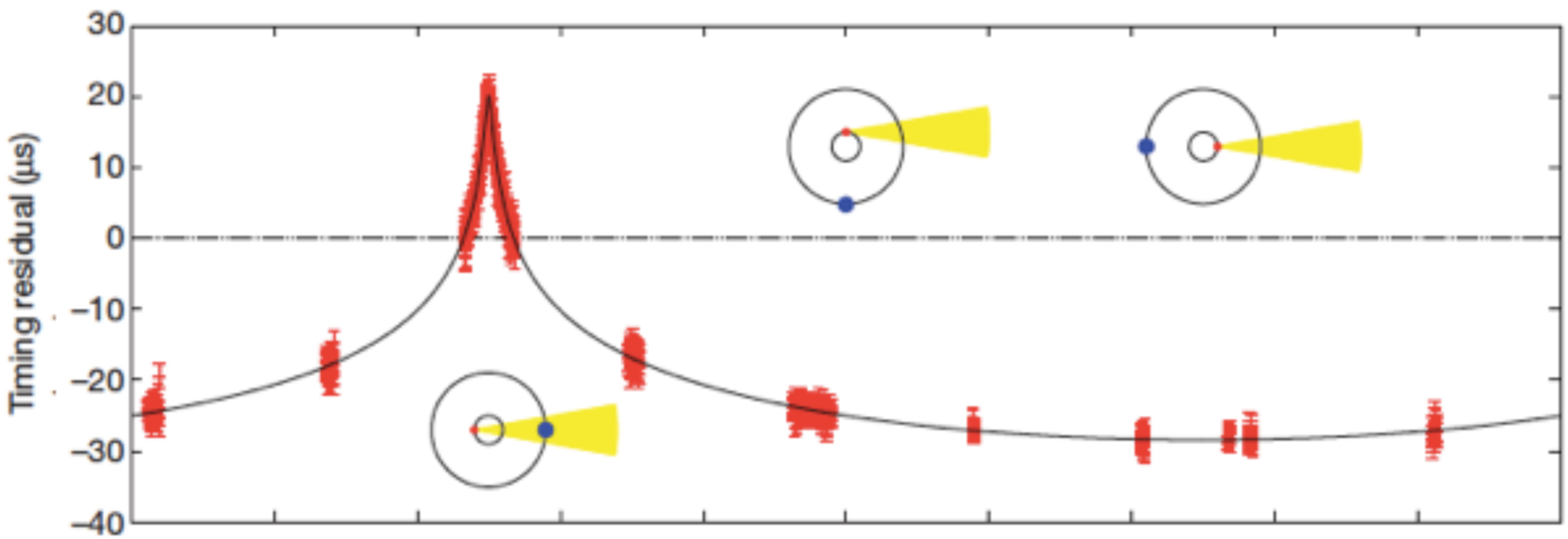
Gandolfi et al. PRC85, 032801 (2012)



Discovery of $2M_{sun}$ Neutron Star

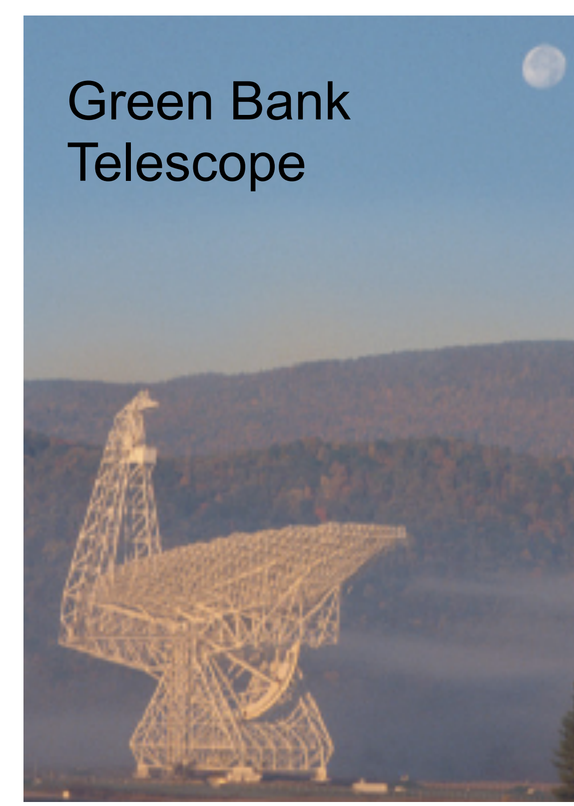
Demorest et al: PSR J1614-2230 has 1.97+/- 0.04 M_{sun}.

Delay in pulse arrival



NS + White Dwarf Binary

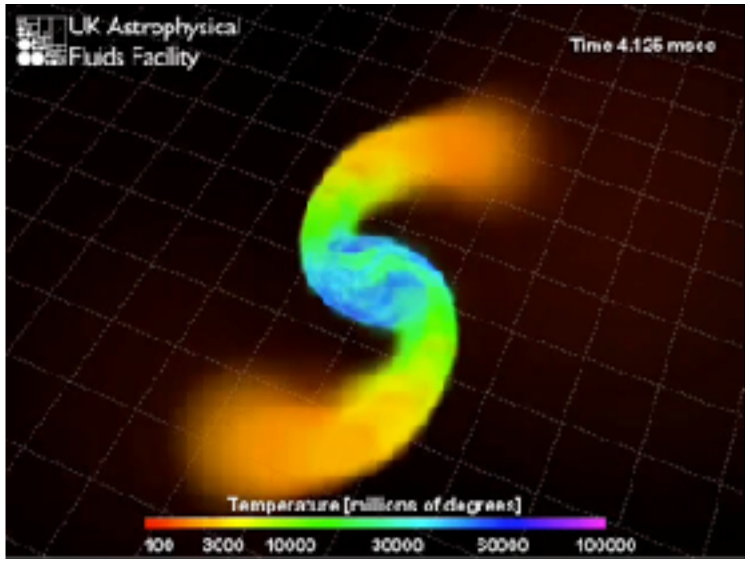
Orbital phase



- 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.*

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.



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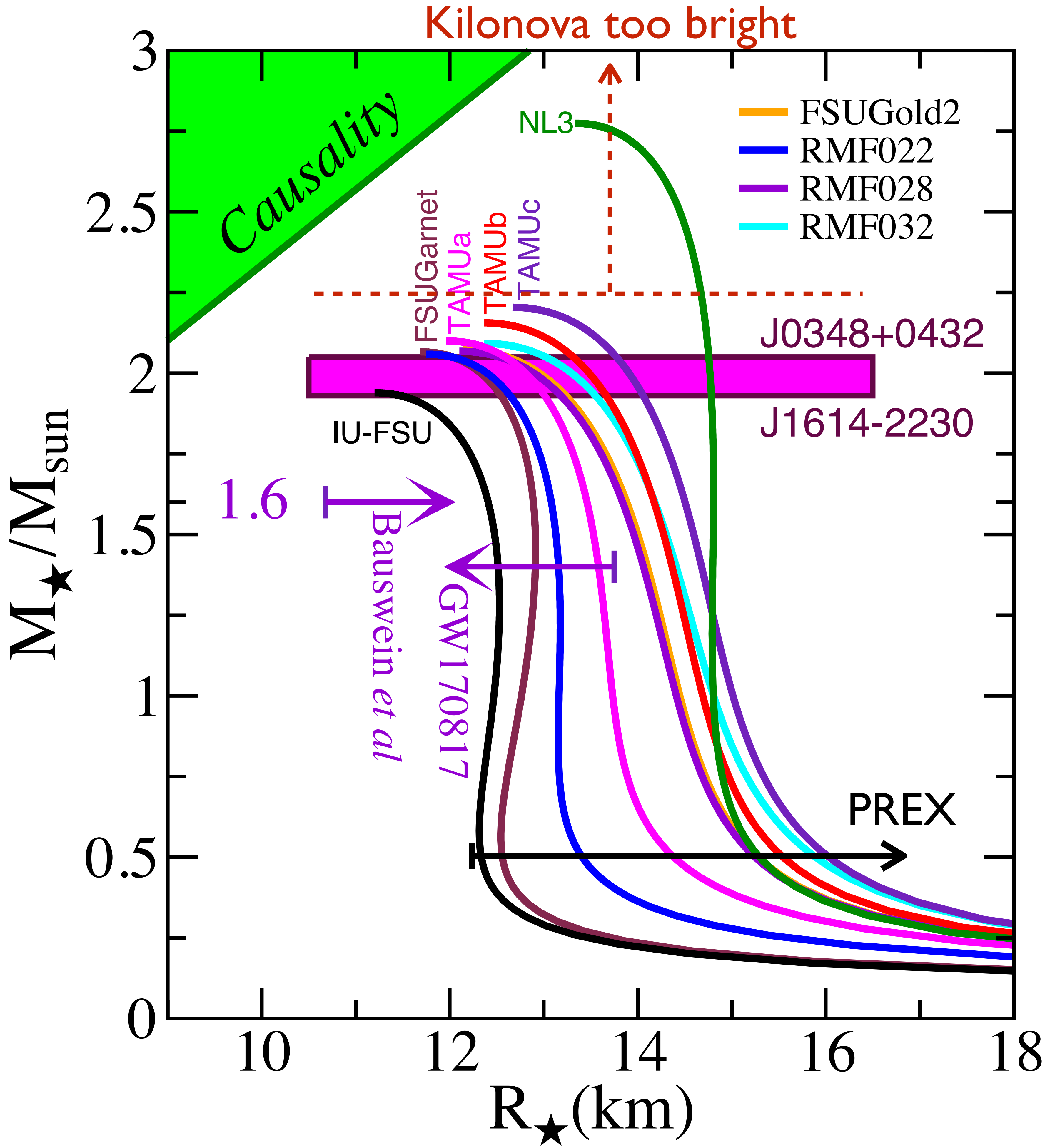
- 1) If maximum mass above 2.2 Msun remnant lives too long and transfers too much rotational E to kilonova.
- 2) If R_{NS}< 10.5 km collapses too fast to black hole with too little ejected mass.
- 3) If R_{NS}>13.7 km deformability too large.
- 4) If $R(0.5M_{sun})$<12.2 km, 208Pb neutron skin too small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

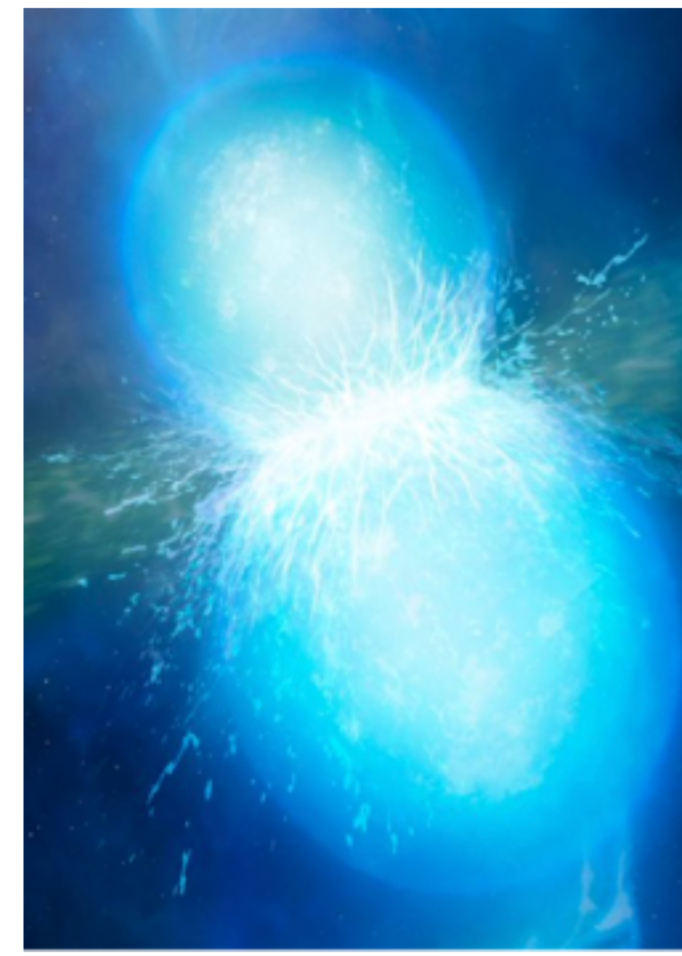


NS merger zoo

- **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 (~2.75M_{sun})
- Merger of massive NS (say 1.6+1.6 M_{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_{sun}?) could produce longer lived SMNS and very bright E+M fireworks??
- Next LIGO observing run O3 starts end of 2018.

Summer school: "Neutron star mergers for non-experts: GW170817 in the multi-messenger astronomy and FRIB eras"

- The FRIB Theory Alliance will offer a summer school May 16-18, 2018 at the Facility for Rare Isotope Beams (FRIB) in East Lansing, MI.
- The school is intended for an inclusive audience of graduate students, post docs, and more senior researchers working in nuclear physics, astrophysics, astronomy, and related areas.
- Lecturers: Brian Metzger (Columbia), C. J. Horowitz (Indiana), Katerina Chatziioanno (CITA), David Radice (Princeton), Luke Roberts (MSU), Hendrik Schatz (MSU).
- Remote participation possible: https://indico.fnal.gov/event/15789/



Ultimate n density experiments

- ^{48}Ca: CREX error goal +/- 0.02 fm well matched to Chiral EFT calc. +/- 0.015 fm. Less motivation to do better at single q^2.
- Instead could measure additional q^2 points to determine full weak charge density vs r.
- ^{208}Pb: "impossible" to determine full weak charge density vs r because cross section at needed high q^2 is way too small.

Super PREX—> MREX

- ^{208}Pb: Strong motivation to improve even PREX II error goal of +/-0.06 fm to 0.03 fm.
- To get to +/-0.03 fm for R_n need A_{pv} to 1.5% [Note PREX (9%) and PREX II (3%)].
- Coulomb distortions ($Z\alpha$) are 30% corrections to A_{pv} but accurately calculated (charge density known).
- Radiative corrections (α) could limit going much beyond 1.5% in A_{pv}.

Pressure of n matter

- Goal: From R_n determine pressure P of n matter or density dependence of symmetry energy L.
- Intrinsic width in correlation between R_n and L or P <= +/- 0.02 fm from full range of theoretical models …
- Error in extracted P (or L) scales roughly as $\Delta P/P \sim \Delta(R_n - R_p) / (R_n - R_p)$. If $R_n - R_p = 0.3$ fm than PREX II only determines P to 20%.

Chiral EFT and Neutron Stars

- To probe Chiral EFT need to constrain 3 neutron forces, cutoff dependence, and higher order contributions accurately.
- Three n forces are repulsive, hard to directly probe in the laboratory, and probably crucial for supporting $2M_{sun}$ NS. [P_{3n} may be 30% of P.]
- Density dependence of EOS (very interesting and could probe possible phase transition) from comparing NS radius or deformability information with R_n-R_p information. High premium on accuracy of both measurements.
- The accuracy of MREX +/- 0.03 fm for $R_n(^{208}Pb)$ is very well motivated and cleanly interpretable.

Neutron skins, neutron rich matter, and neutron stars

- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke…
- NS deformability vs ^{208}Pb skin: **Farrukh Fattoyev**, J. Piekarewicz.
- Graduate students: Zidu Lin (2018), Hao Lu (Astronomy), Jianchun Yin, Zack Vacanti, Matt Caplan (2017)

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