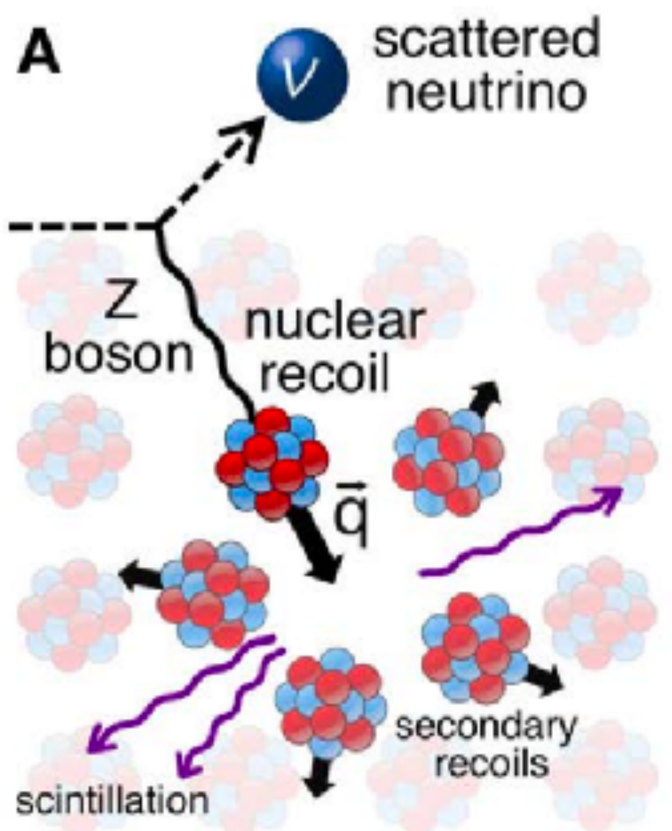
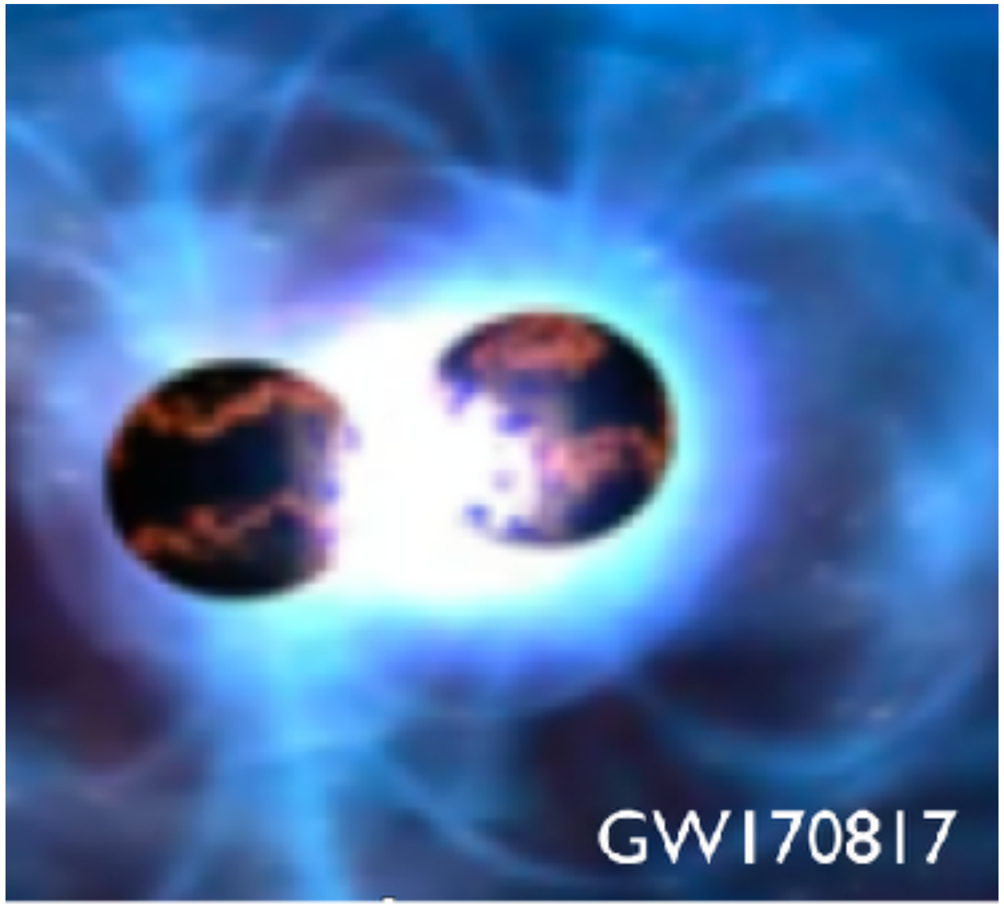
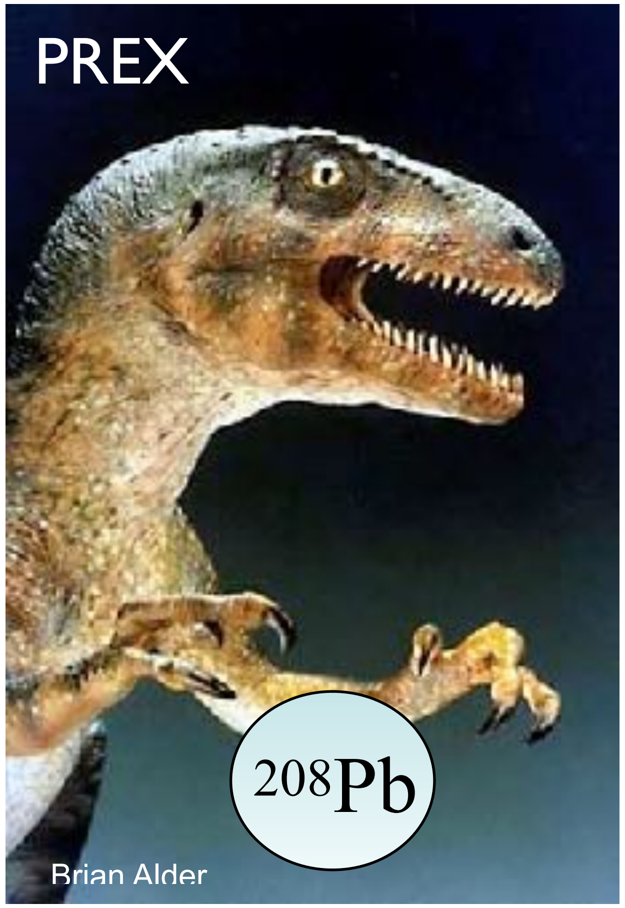
CEvNS at the SNS: nuclear physics







Chuck Horowitz, Indiana U., FPSTS19, Oak Ridge, Jul. 2019

Coherent nu scattering depends on square of nuclear form factor F(Q)²

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

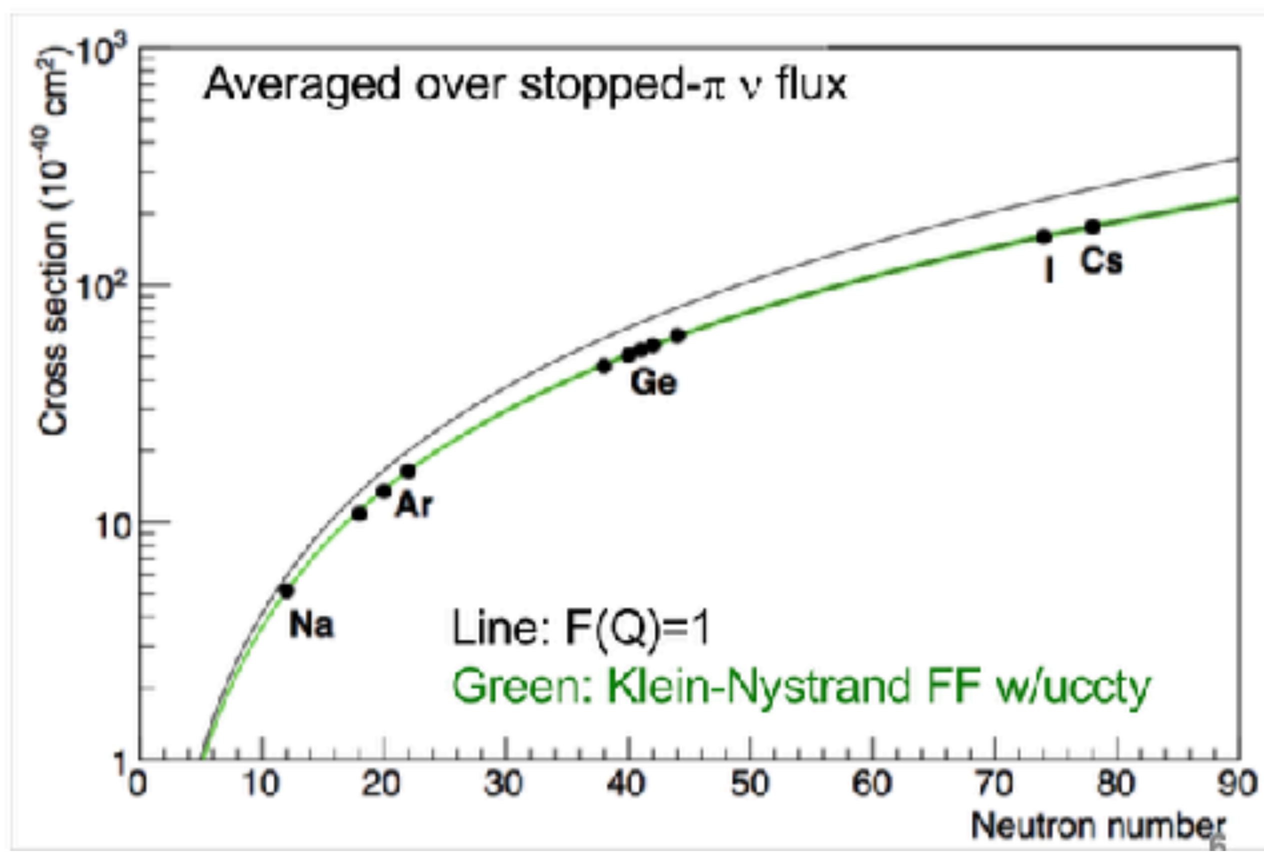
E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

Form factor: F=1 ➔ full coherence

weak nuclear charge

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

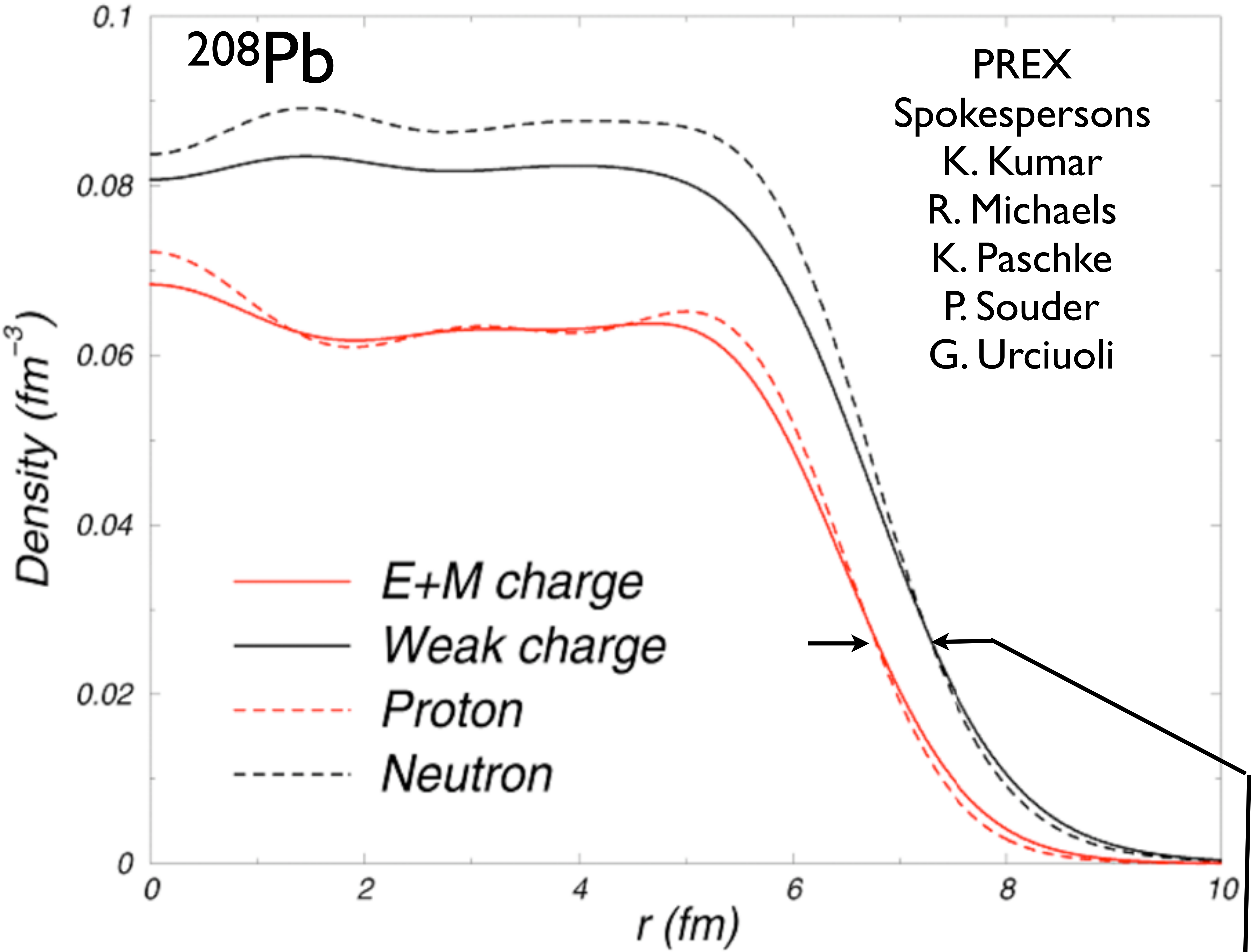
$$\Rightarrow \frac{d\sigma}{dT} \propto N^2$$



Kate Scholberg

CEvNS at the SNS: nuclear physics

- **Coherent nuclear form factor**: calculated with chiral EFT, also measured with PV electron scattering.
- **Implications of form factor** for equation of state of neutron rich matter and structure of neutron stars.
- **Inelastic neutrino scattering** example: charged current neutrino-Ar cross section: *calibrate DUNE for supernova neutrinos*.



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

Parity violating elastic electron scattering measures form factor F(Q)

- 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

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

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

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

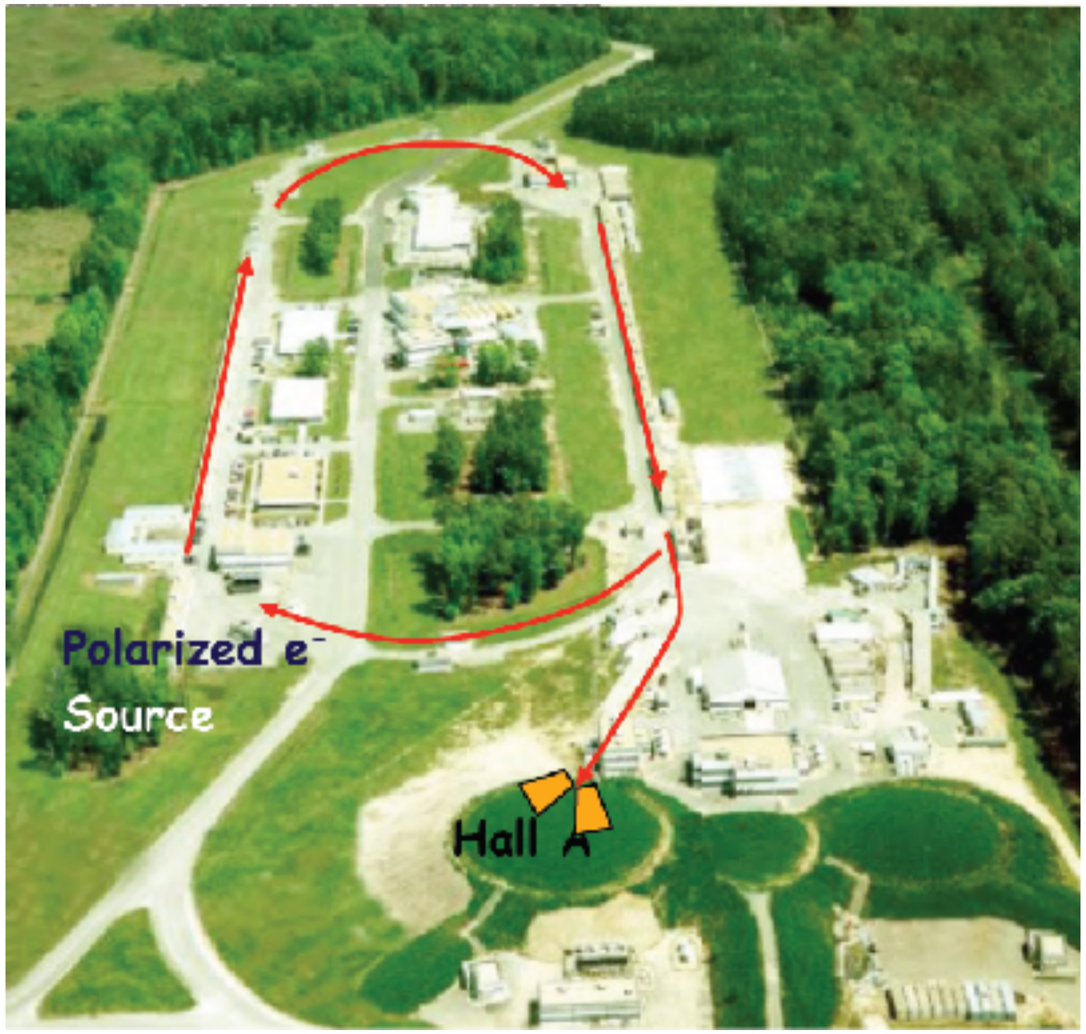
$$Q^p_W = 1 - 4\sin^2\Theta_W \approx 0.05$$

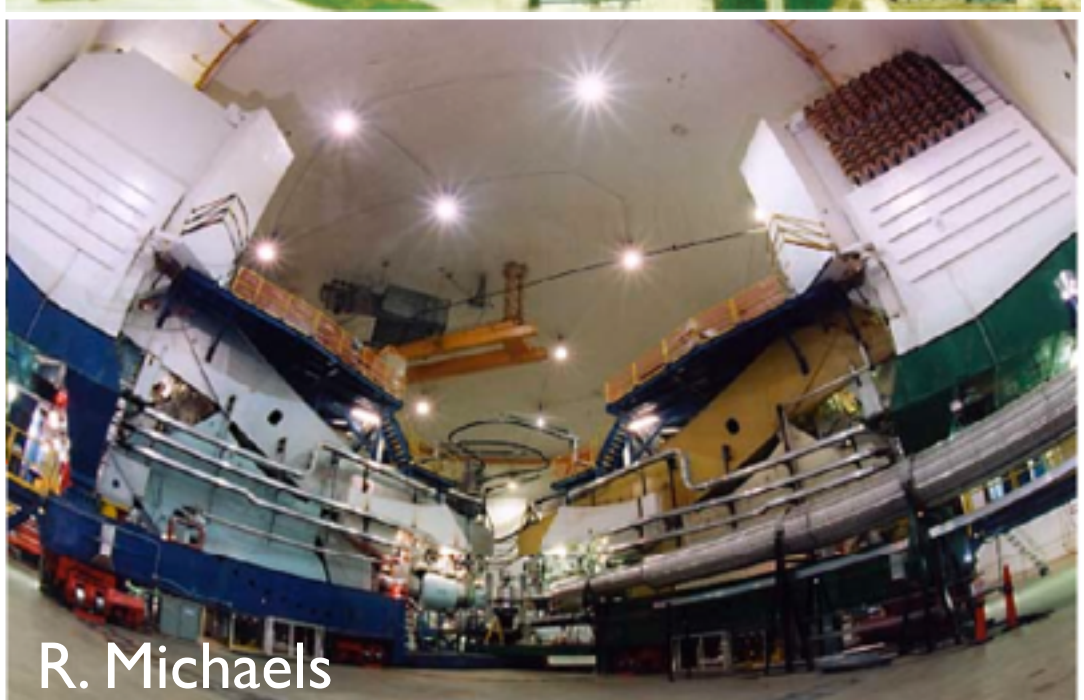
- Neutron weak charge is big:

$$Q^n_W = -1$$

- Weak interactions, at low Q^2, probe neutrons
- Form factor is Fourier transform of neutron density.

PREX in Hall A Jefferson Lab





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

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

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

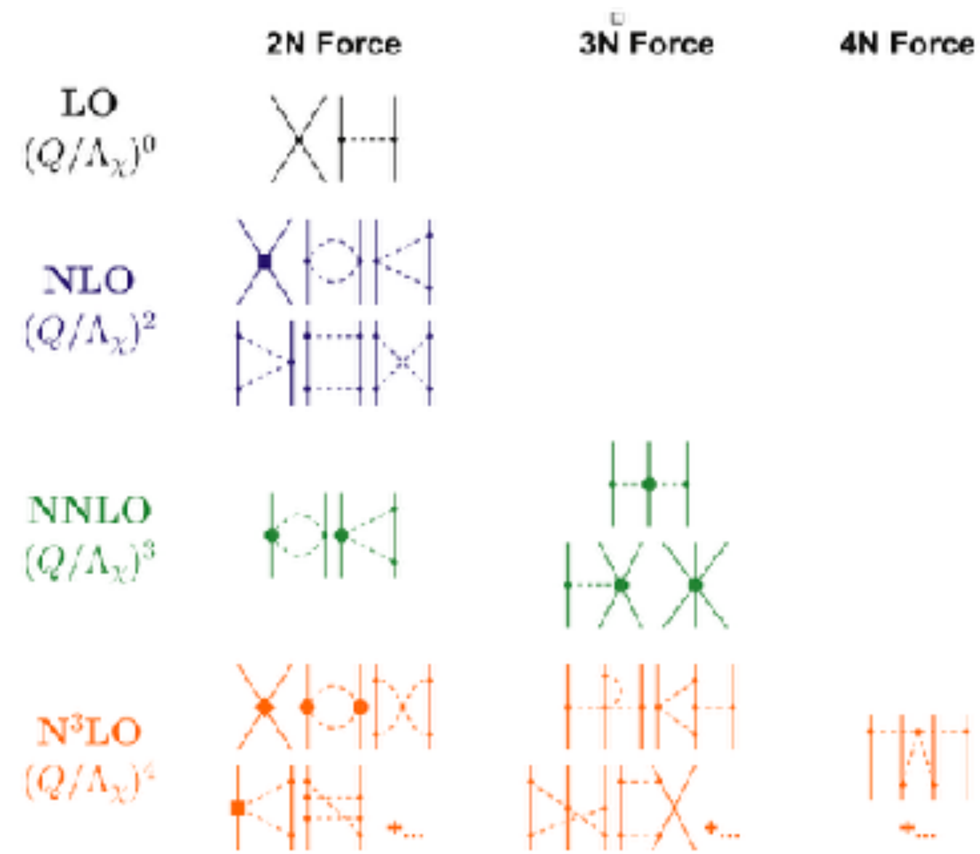
- Next runs

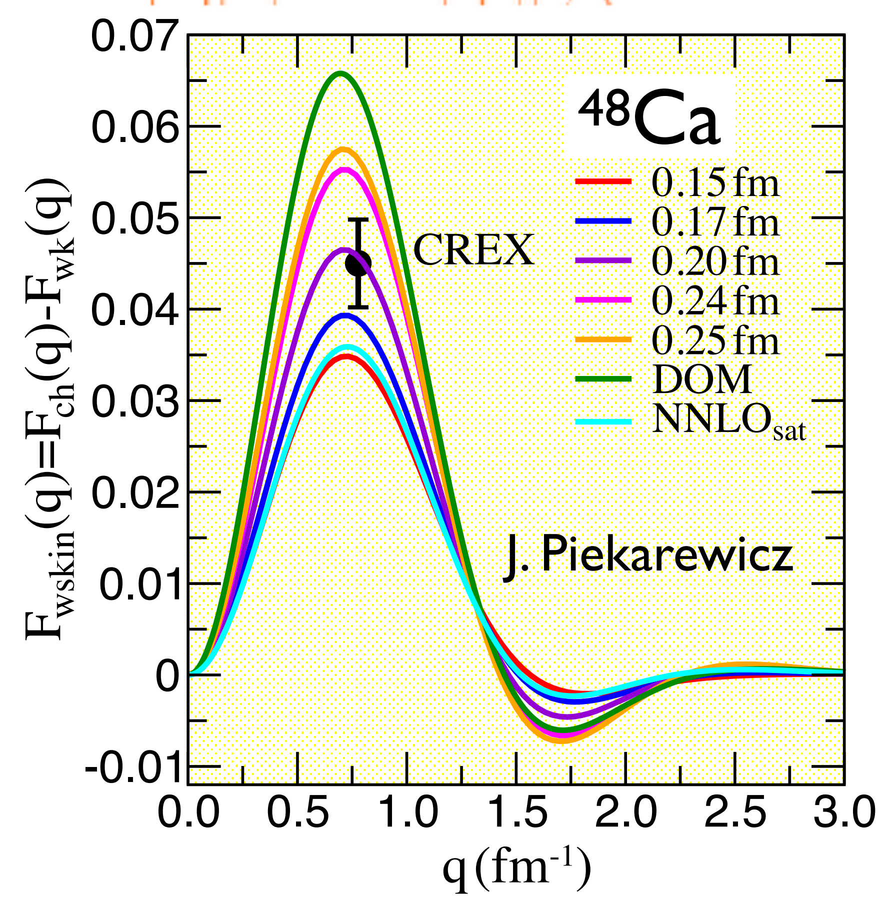
- **PREX-II**: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm. <<< NOW >>>

- **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 in Fall 2019 — Spring 2020

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.
- Microscopic coupled cluster calculations -> R_n-R_p=0.135±0.015 fm using $NNLO_{sat}$ [Nature Physics **12** (2016) 186].

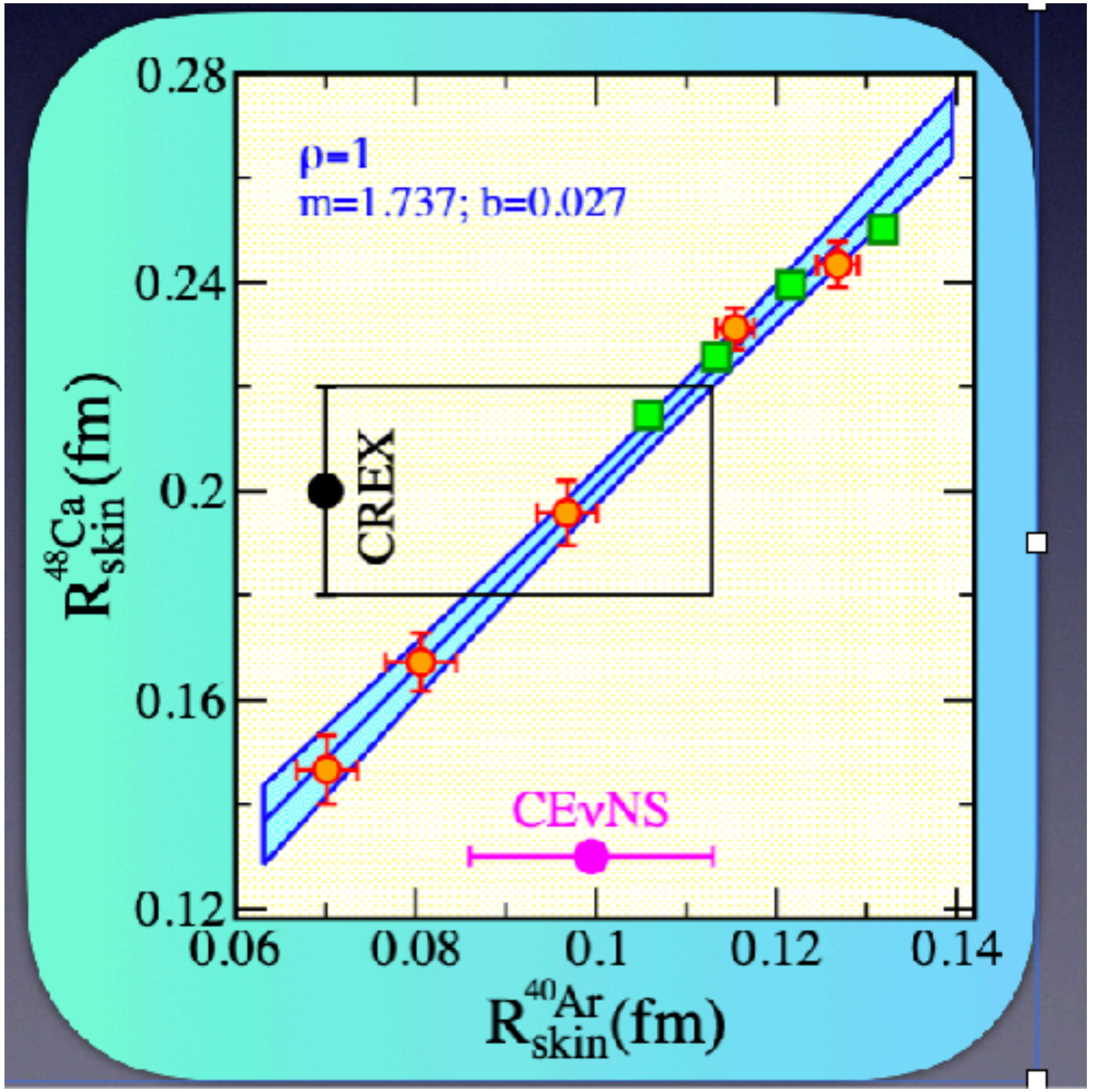




PV measurements + theory constrain coherent form factors

Experiment	Nucleus	Error in R_n
CREX	^{48}Ca	0.6%
PREX (PREX II)	^{208}Pb	**3%** (1%)
MREX	^{208}Pb	0.5%

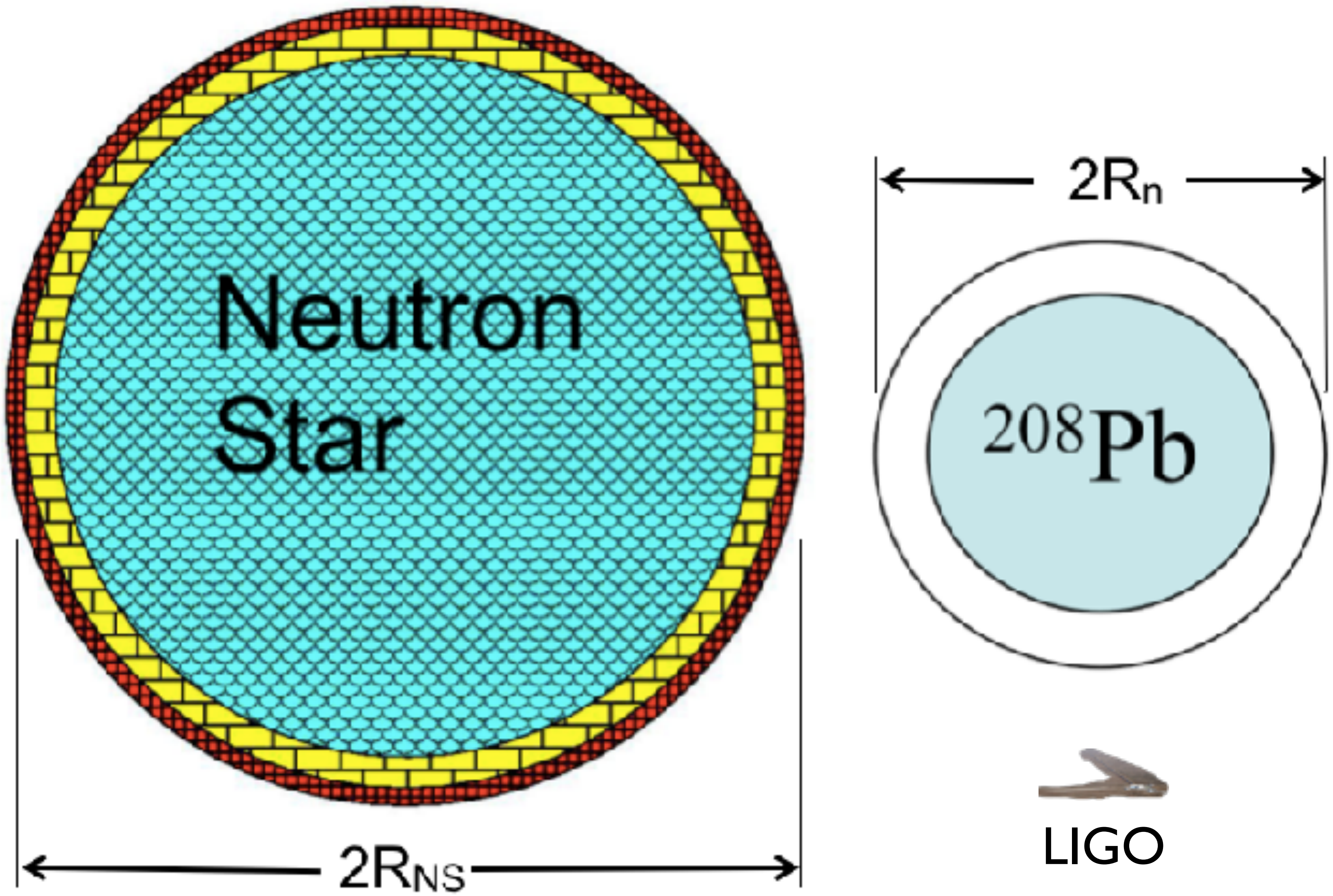
Nuclear physics measurements (PV e scattering) and theory can constrain neutron radii to a few %. Can use CEvNS to constrain new neutrino interactions …



Jorge Piekarewicz

Radii of ^{208}Pb and Neutron Stars

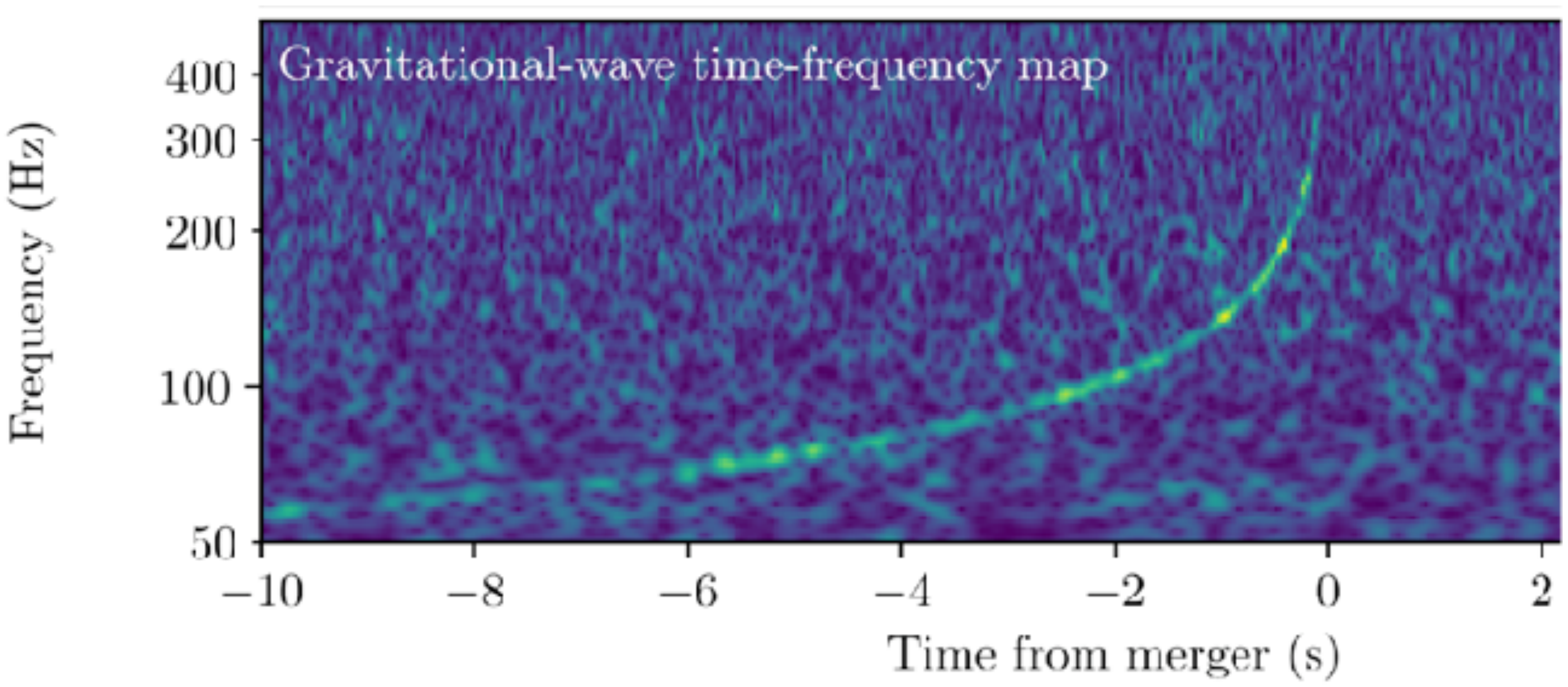
- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



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

NS radii from gravitational waves

- In 2015 observed gravitational waves (GW) from merger of *two black holes*.
- **GW170817**: On Aug. 17, 2017, the merger of *two neutron stars* observed by LIGO and Virgo.
- 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.



Chirp signal, GW frequency rises with time as NS spiral together

Merger GW170817: deformability of NS

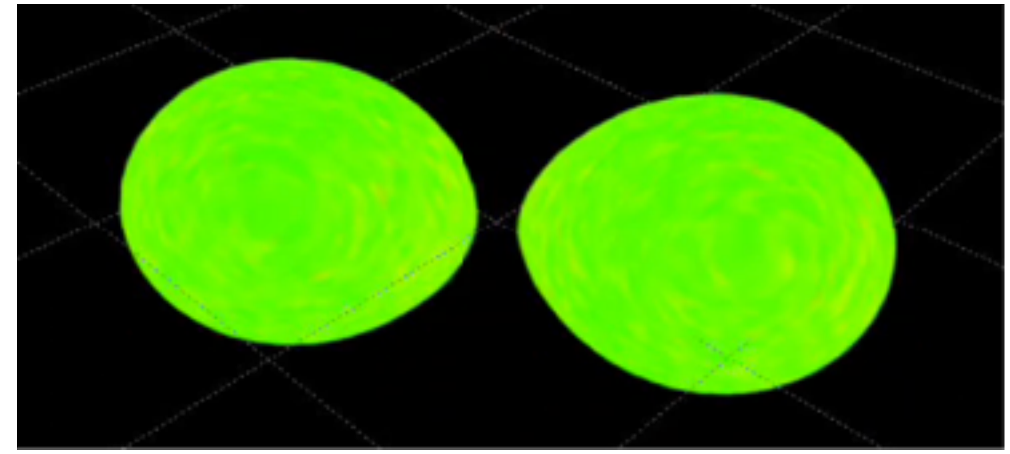
- Gravitational tidal field distorts shapes of neutron stars just before merger.
- Dipole polarizability of an atom ~ R^3.

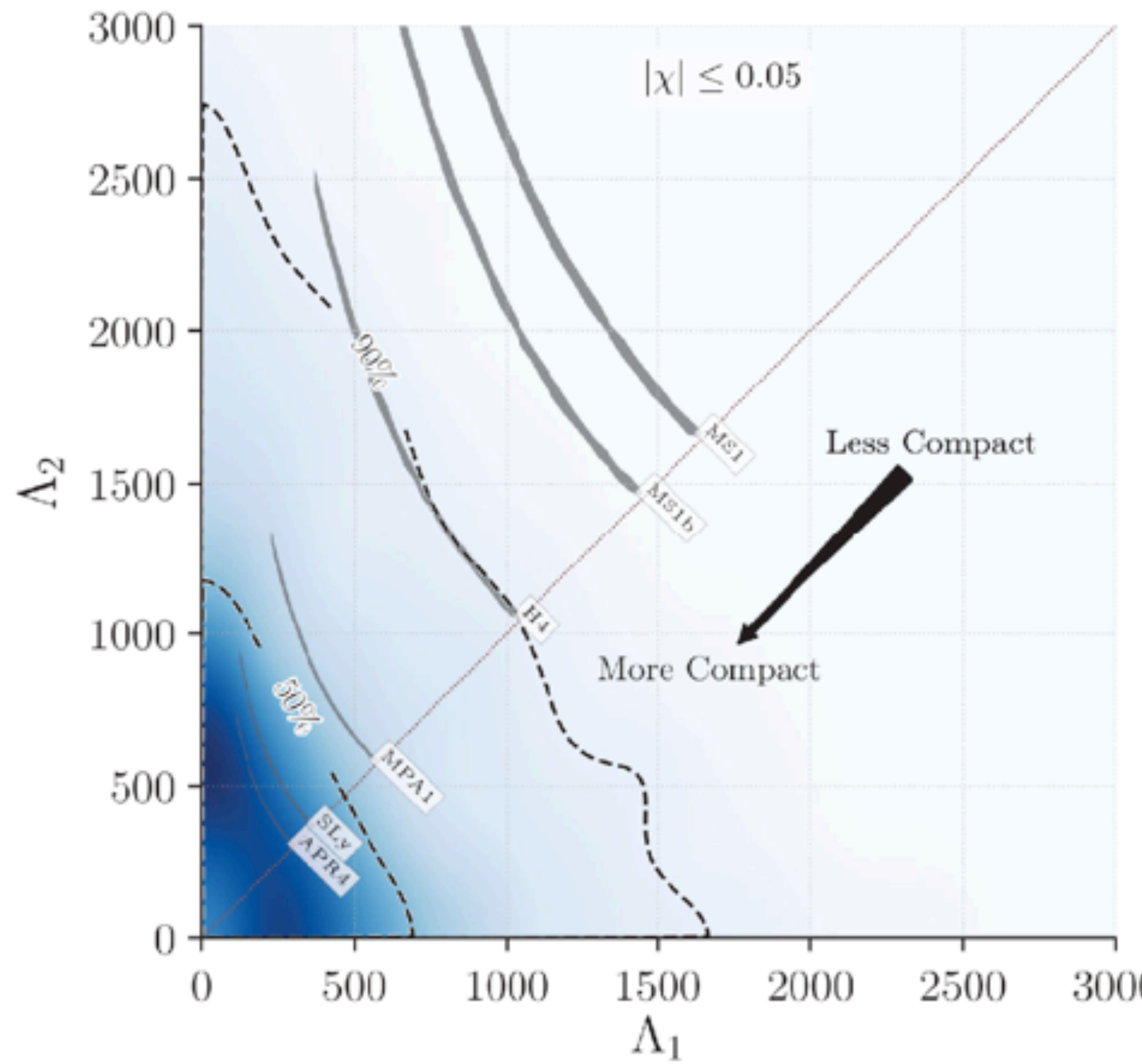
$$\kappa = \Sigma_f \frac{|\langle f|rY_{10}|i\rangle|^2}{E_f - E_i} \quad \propto R^3$$

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

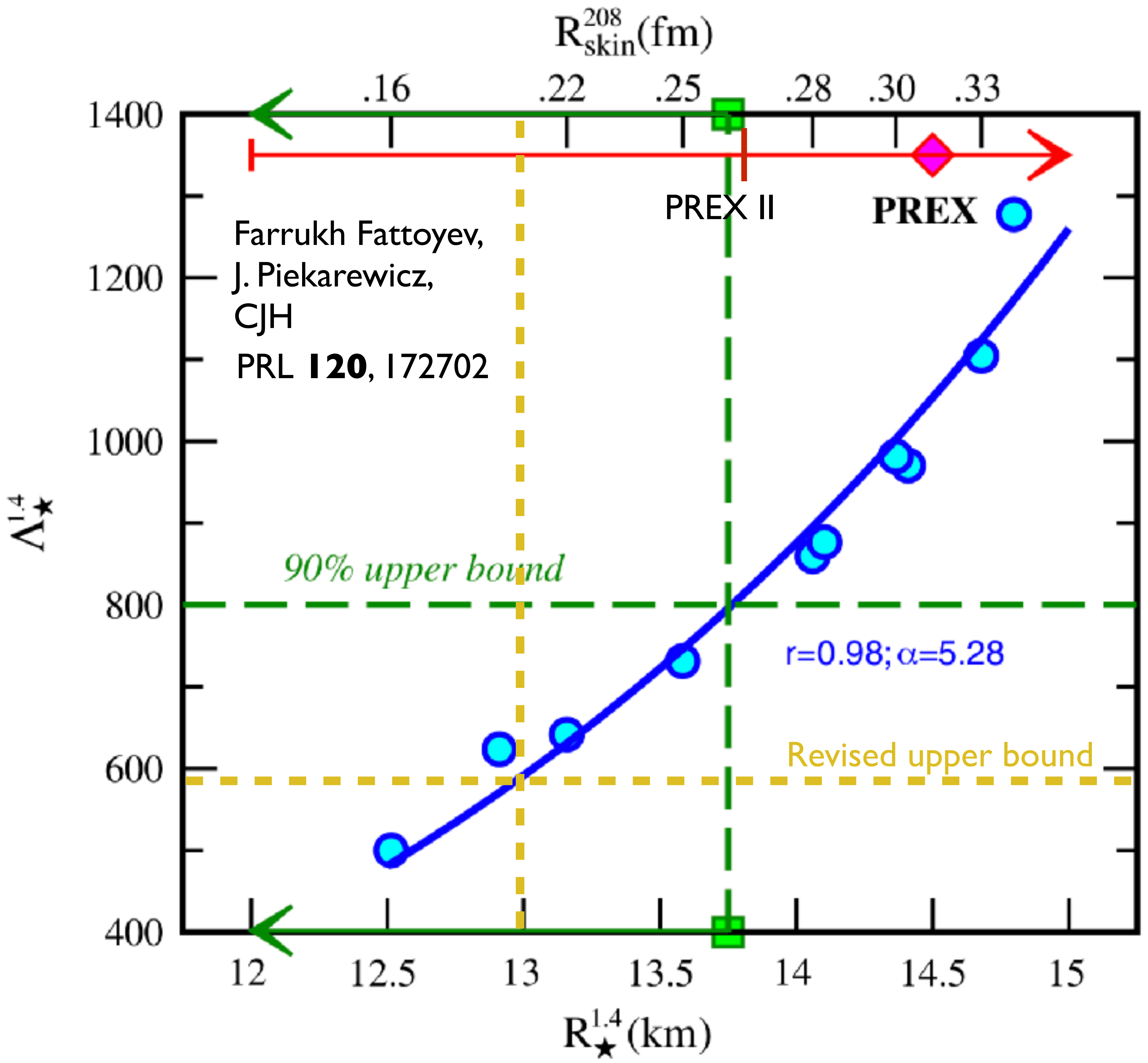
$$\Lambda \propto \Sigma_f \frac{|\langle f|r^2Y_{20}|i\rangle|^2}{E_f - E_i} \quad \propto \quad R^5$$

- GW170817 observations set upper limits on Λ_1 and Λ_2.





LIGO vs PREX



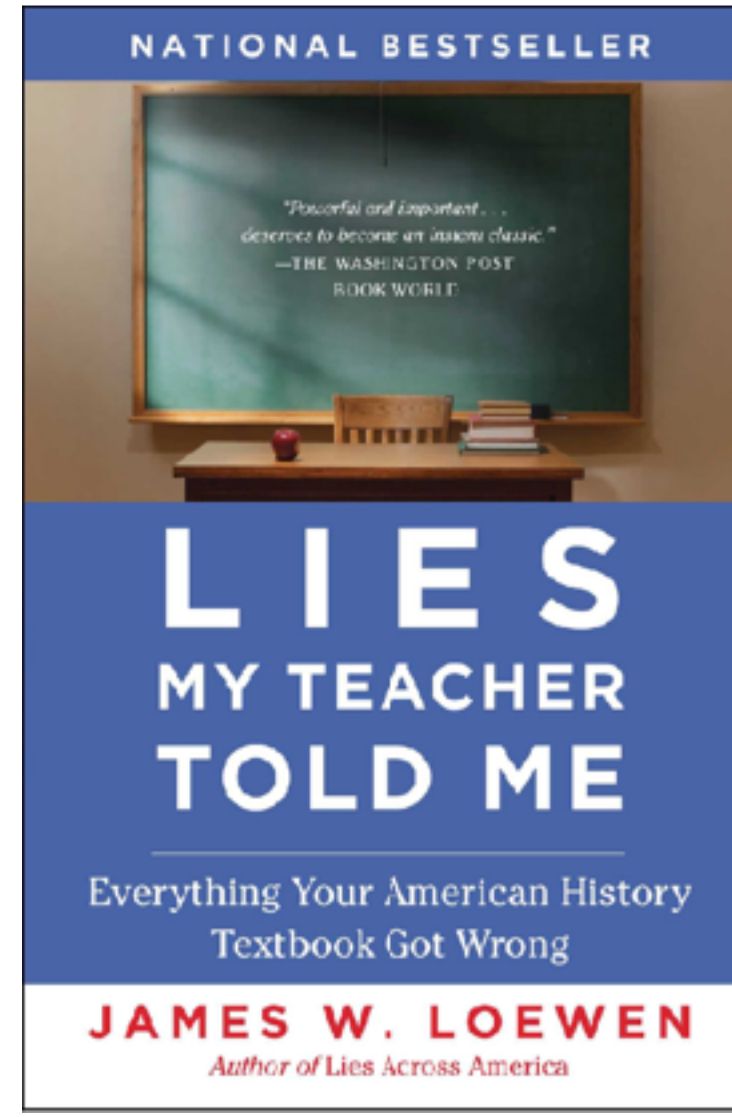
Deformability Λ of $1.4M_{sun}$ NS now less than 590 (Yellow dashed). ArXiv:1805.11581

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

Calibrate DUNE for Supernovae!

- Important to measure energy dependence of charged current neutrino-Ar cross section in order to “calibrate DUNE for SN” and to help determine the origin of gold, uranium and other heavy elements in the universe.
- Spectrum of pion decay at rest neutrinos produced at SNS similar to SN spectrum.

R-process nucleosynthesis: origin of heavy elements such as gold, uranium



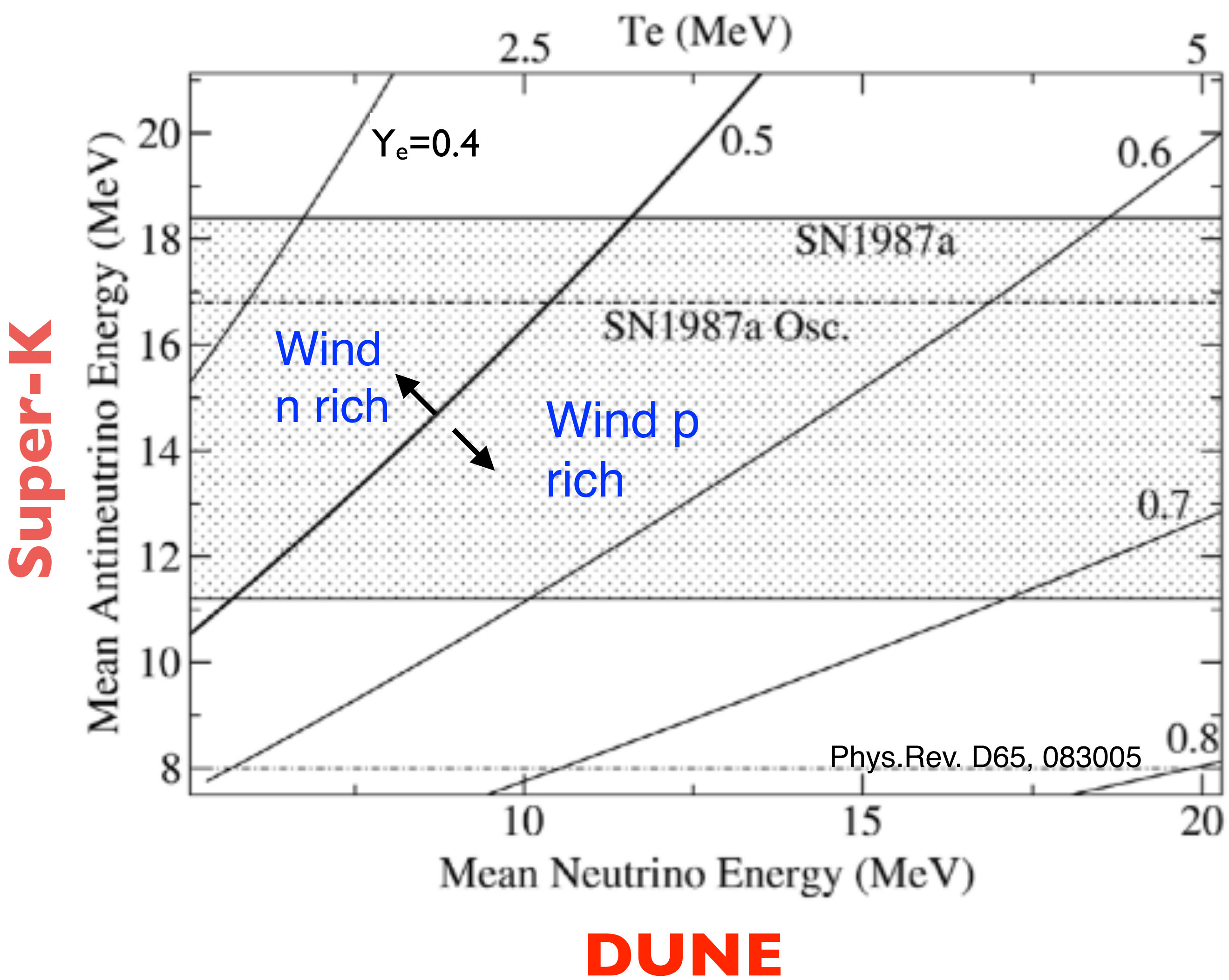
According to many textbooks, supernovae are the site of the r-process. Why are the textbooks wrong?

SN neutrinos and nucleosynthesis

- Possible site of r-process is the neutrino driven wind in a SN.
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino and anti-neutrino energies.

$$\nu_e + n \rightarrow p + e \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

- Composition of wind depends on anti-neutrino energy (Y-axis) and neutrino energy (X-axis).
- **Because of robust neutrino physics we find wind is not n rich enough for main r-process!**



- ~20 events from SN1987A
- Expect thousands of events from next galactic SN. Important to observe both anti-neutrinos (SK…) and neutrinos (DUNE)

CEvNS at the SNS: nuclear physics

- PREX II is running *now* and will 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

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