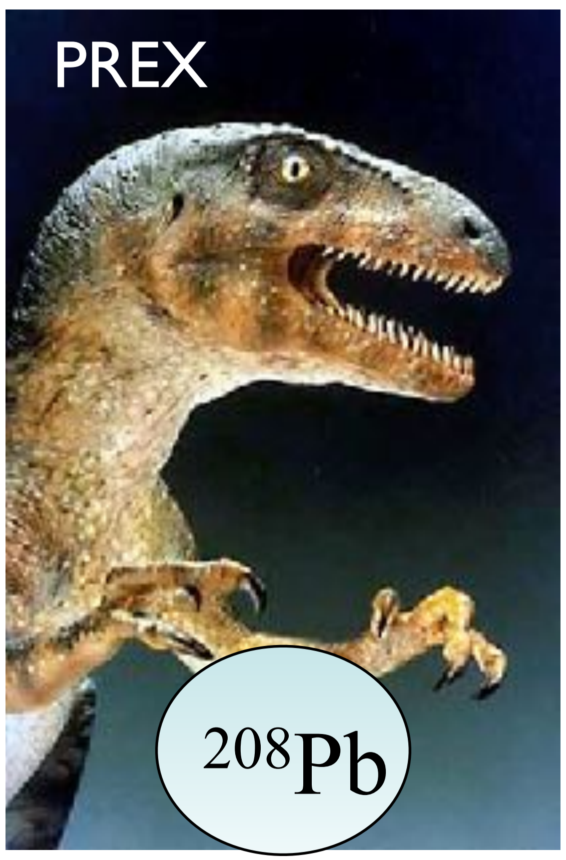
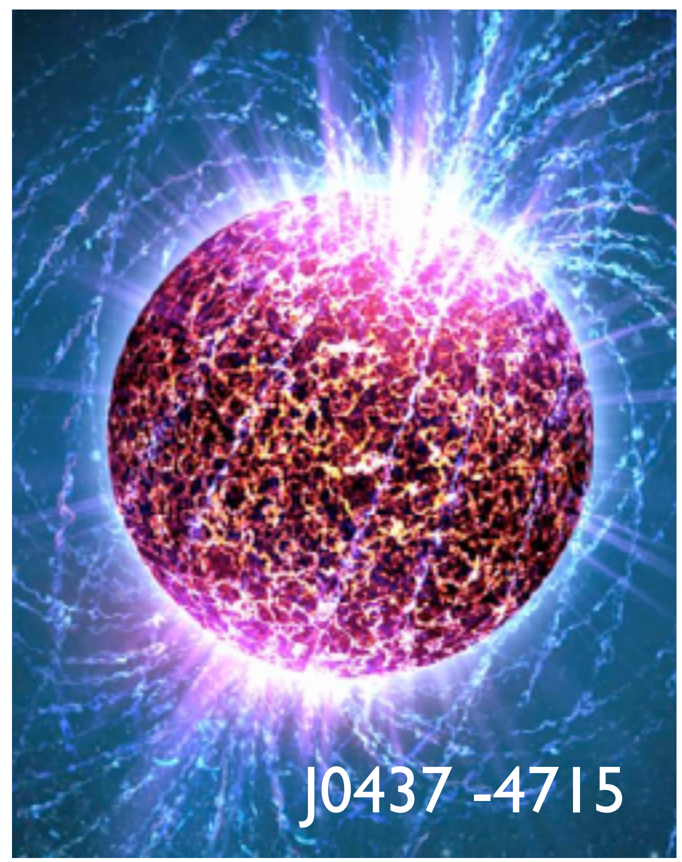
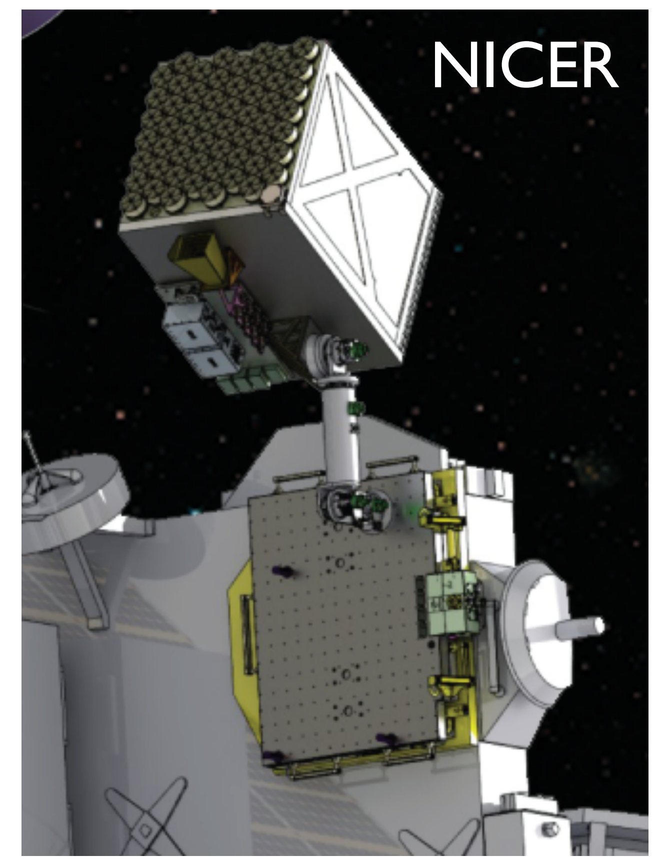
# Electroweak scattering from (heavy) nuclei




Chuck Horowitz, Indiana U., JLAB Users Meeting, June 2017

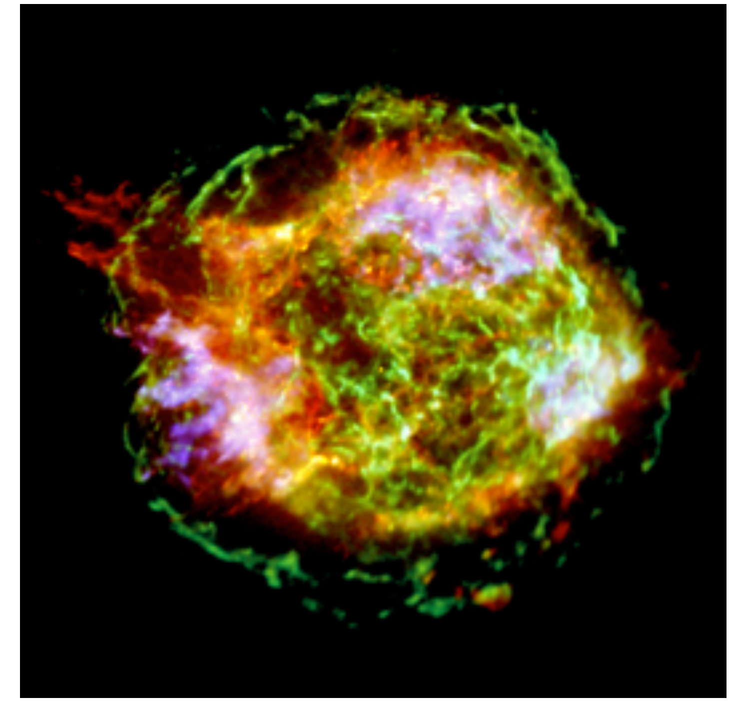
U.S. DEPARTMENT OF ENERGY | Office of Science

NUCLEI
Nuclear Computational Low-Energy Initiative

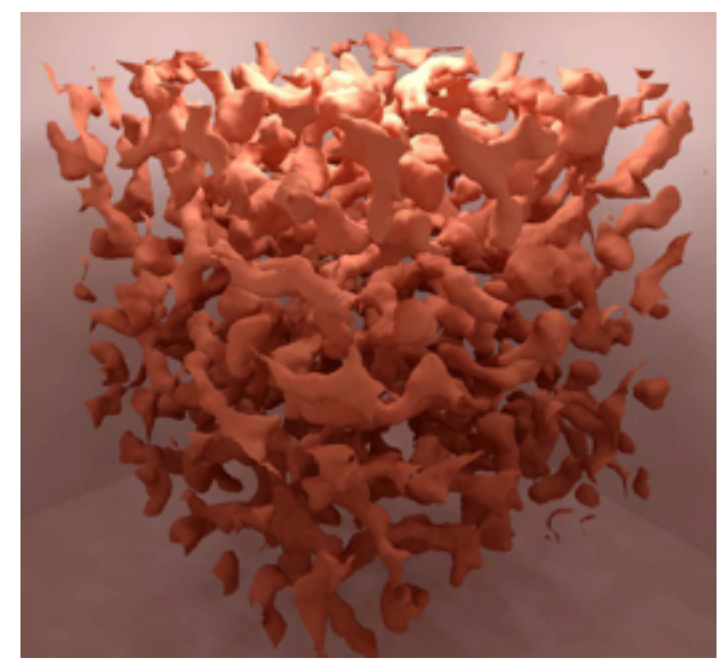
OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

# 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 ***liquid, gas, solid***, *plasma, liquid crystal (nuclear pasta), superconductor ($T_c=10^{10}$ K!), superfluid, color superconductor...*

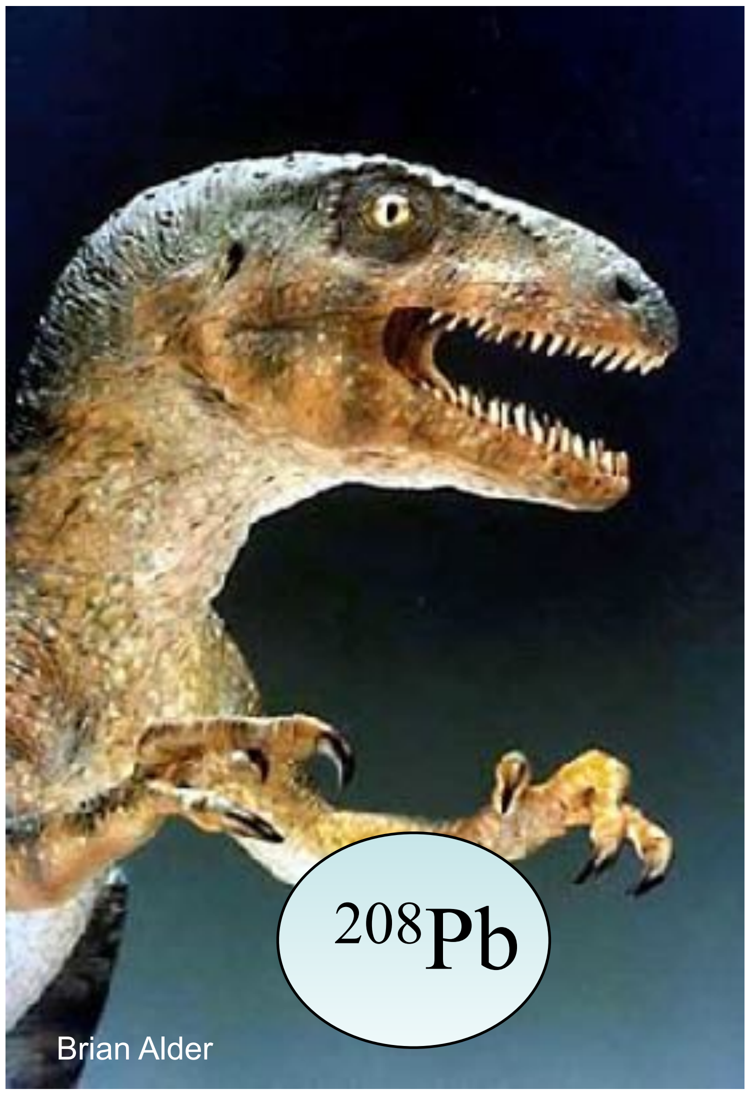


Supernova remanent Cassiopea A in X-rays



MD simulation of Nuclear Pasta with 100,000 nucleons

# 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

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

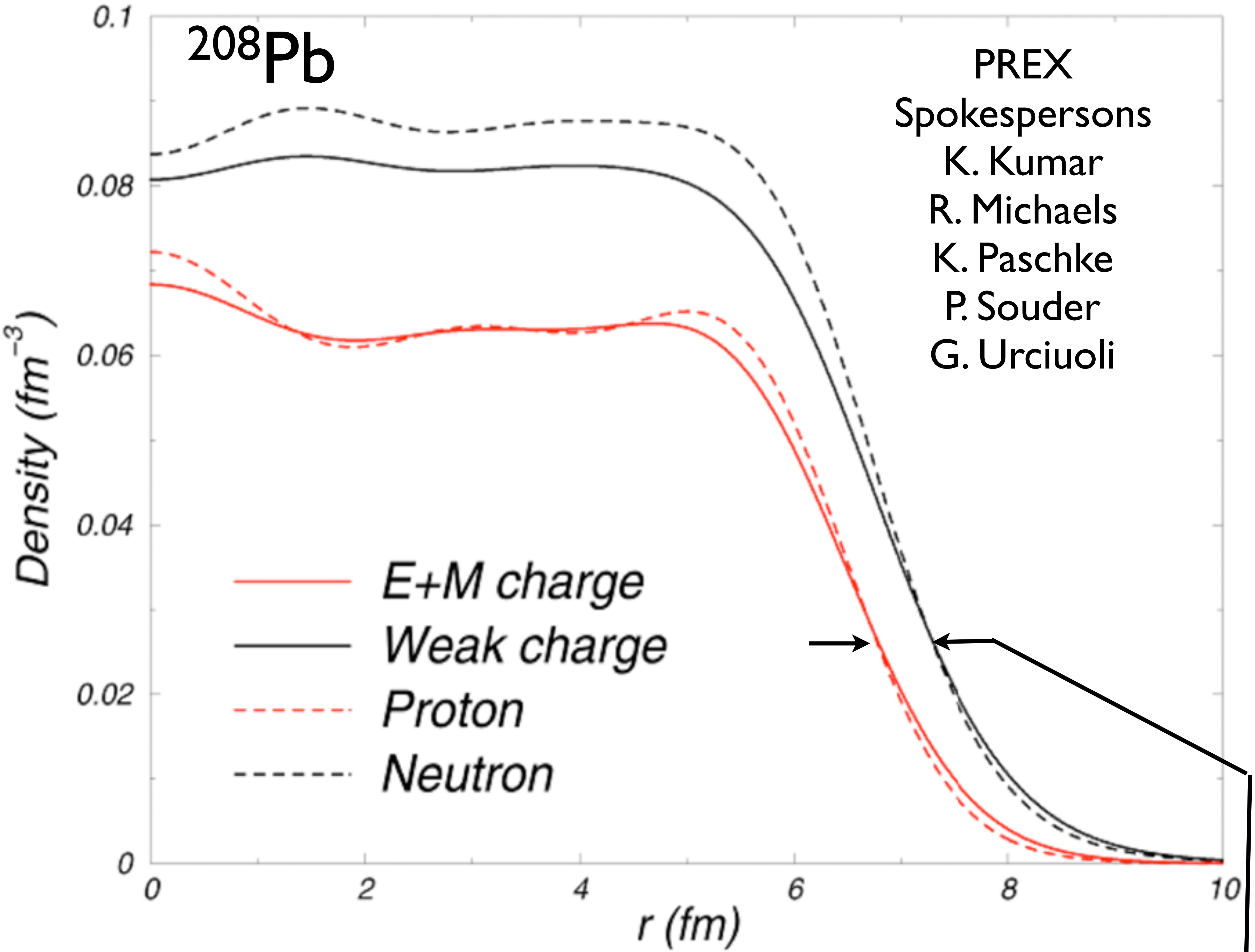
- $A_{pv}$ from interference of photon and $Z^0$ exchange. In Born approximation

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

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

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

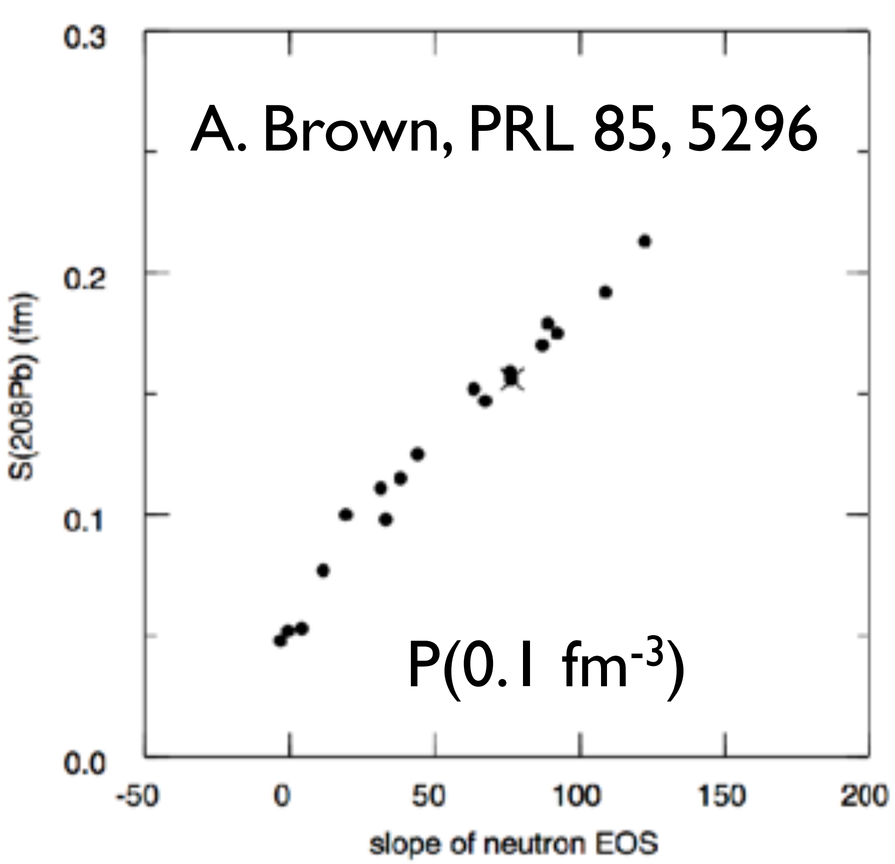
— Donnelly, Dubach, Sick first suggested PV to measure neutrons.

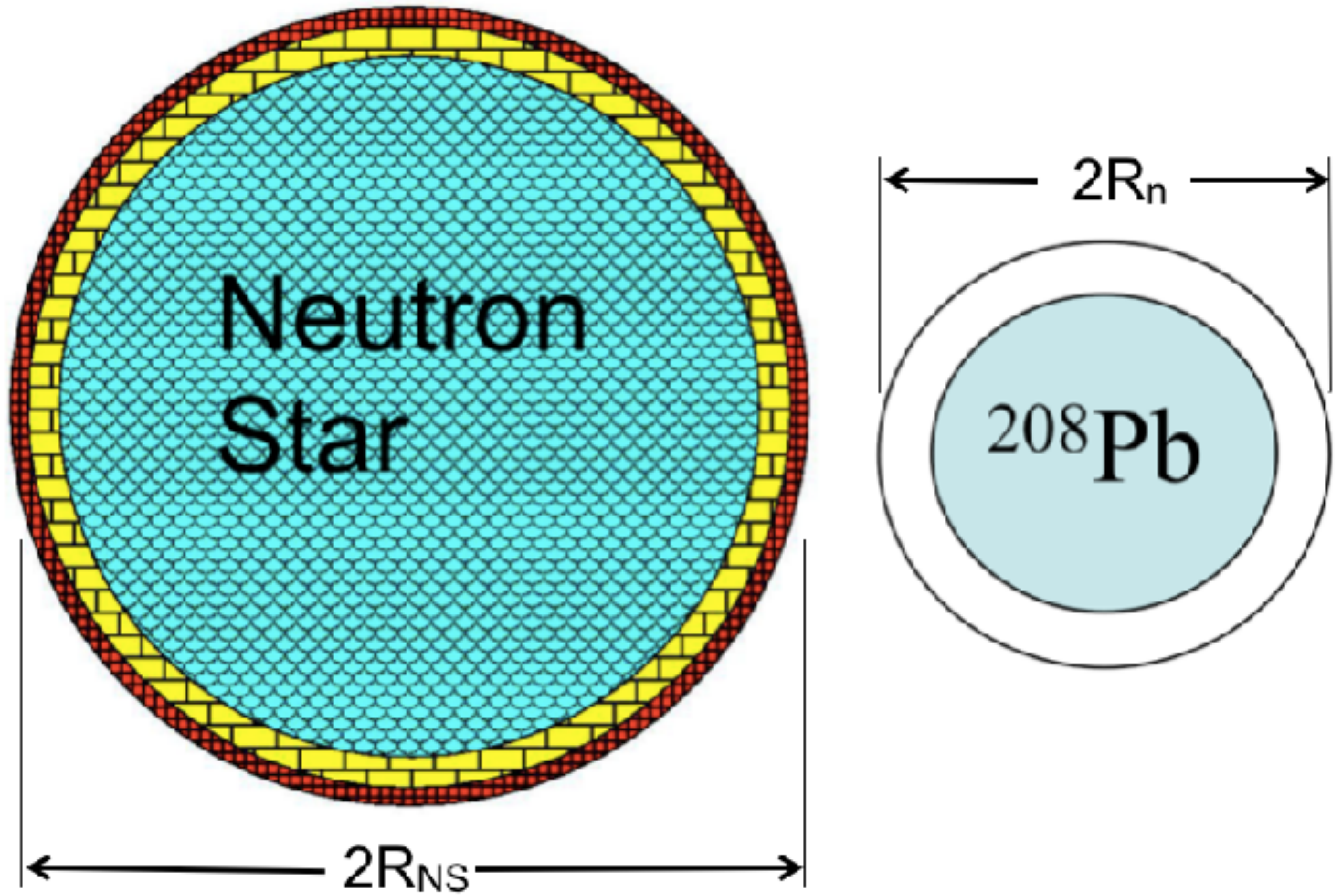



- PREX measures how much neutrons stick out past protons (neutron skin).

# 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.
- Measurement of $R_n$ ($^{208}$Pb) in lab has important implications for the EOS and structure of NS.

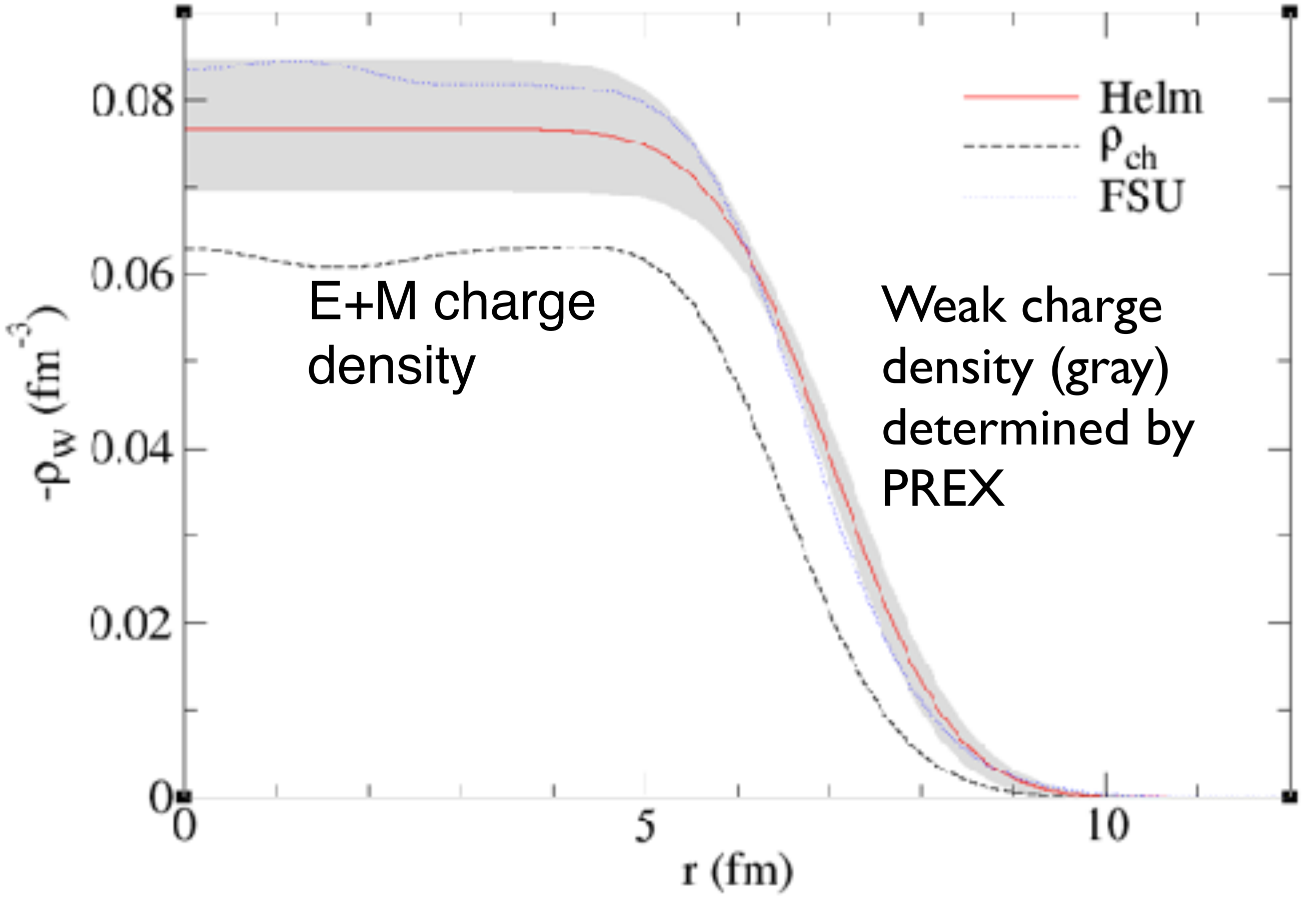


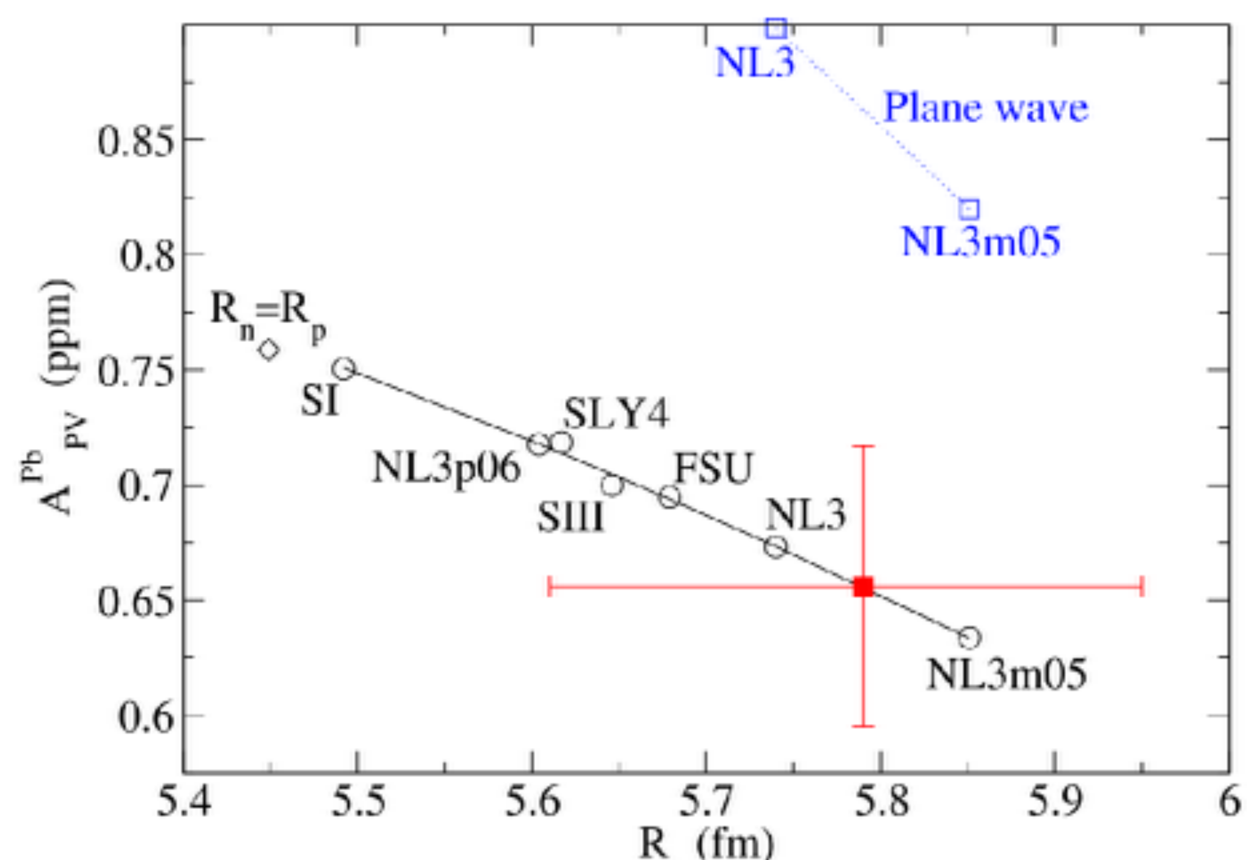




Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

# PREX results from 2010 run

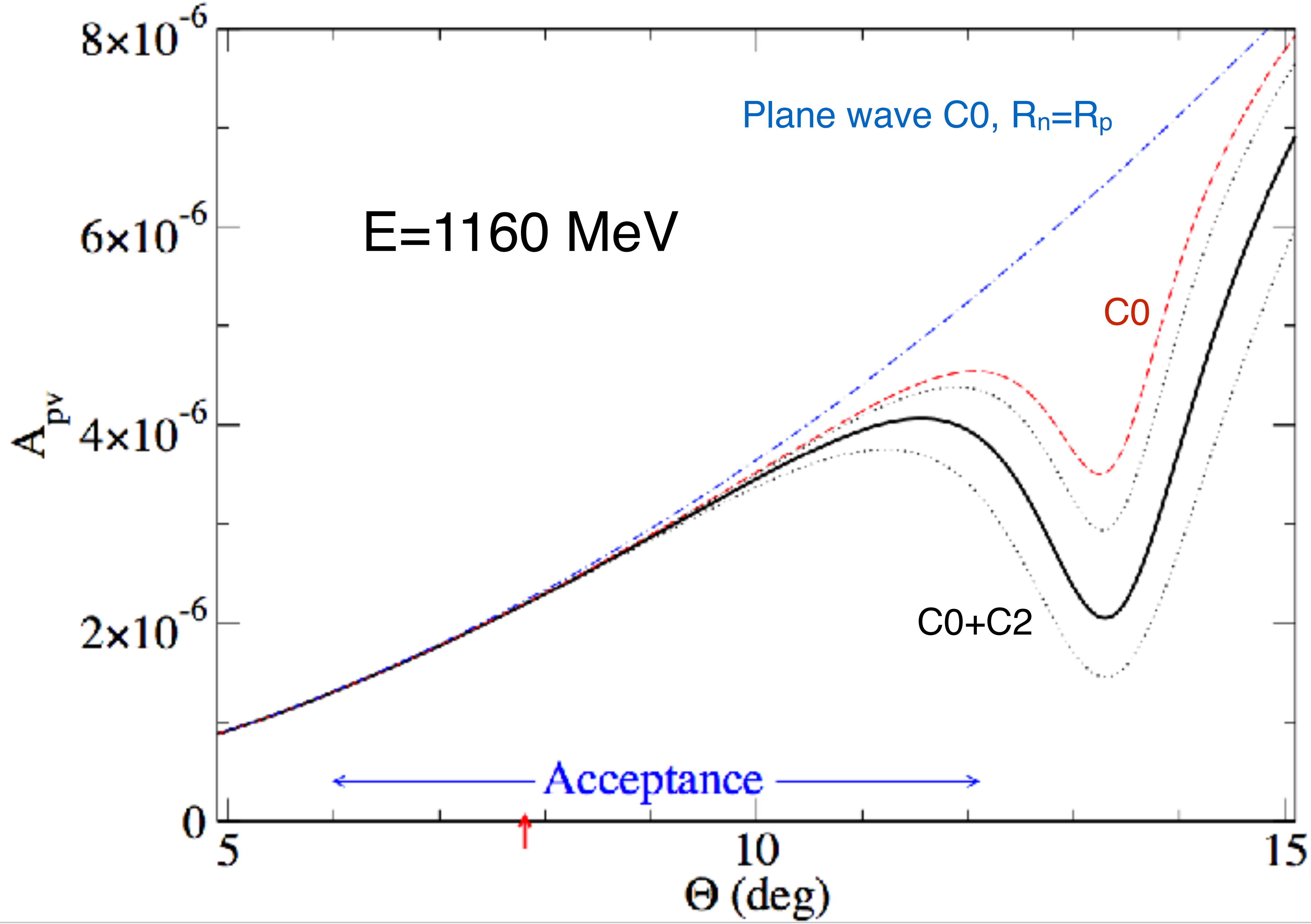
- 1.05 GeV electrons elastically scattering at ~5 deg. from $^{208}$Pb
- **$A_{PV}$ = 0.657 ± 0.060(stat) ± 0.014(sym) ppm**
- Weak form factor at q=0.475 fm$^{-1}$: $F_W(q)$ = 0.204 ± 0.028
- Radius of weak charge distr. $R_W$ = 5.83 ± 0.18 fm ± 0.03 fm
- Compare to charge radius $R_{ch}$=5.503 fm --> 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)



# QWEAK $^{27}$Al Measurement

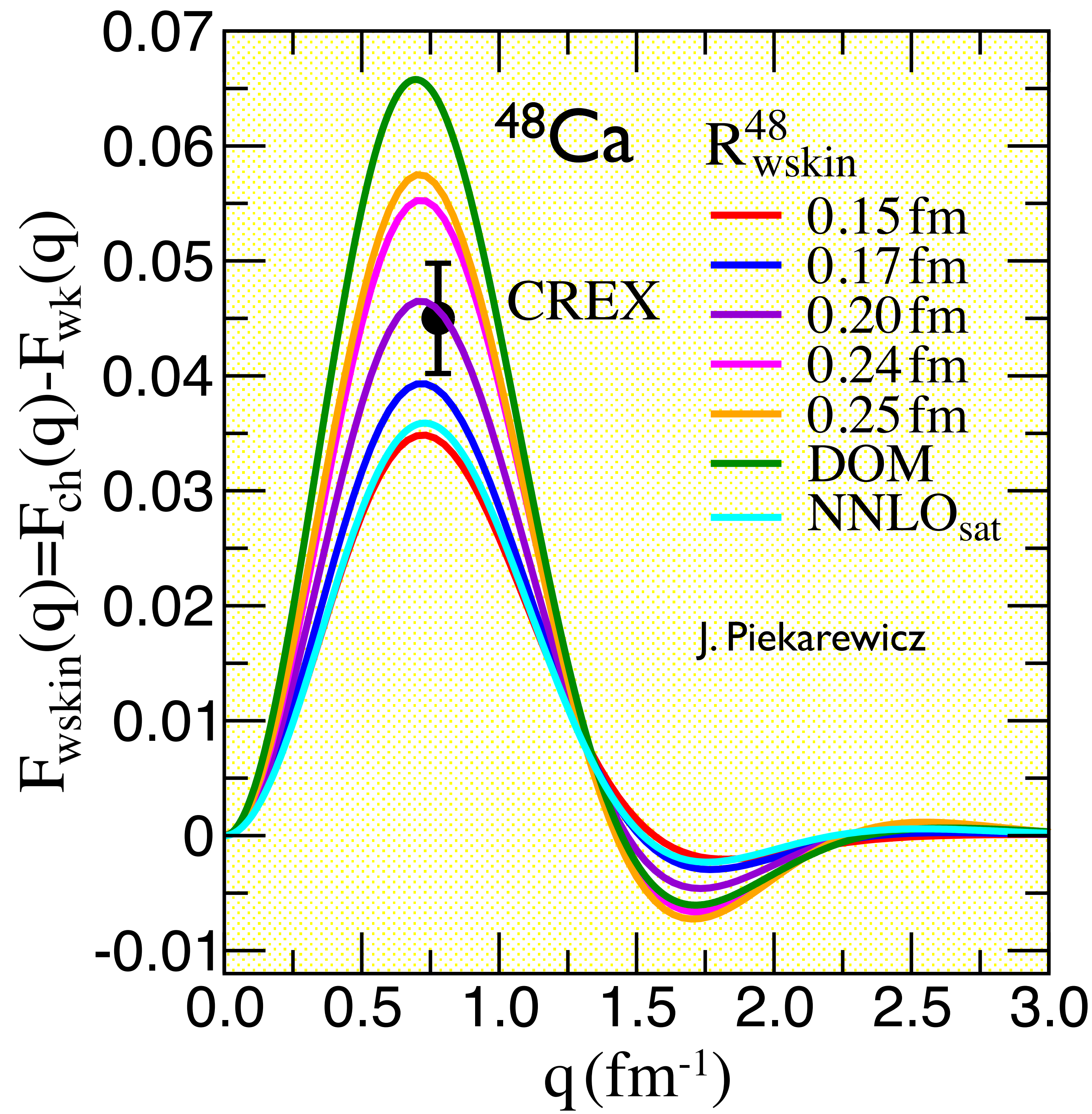
- Al windows of $Q_{weak}$ target important background because $A_{pv}$ much larger for Al than H.
- High statistics $^{27}$Al $A_{pv}$ to 4.5%!
- My prediction Full distorted wave for C0, add small C2 in Born approx.




Working on inelastic contributions, given modest energy resolution. $^{27}$Al $A_{pv}$ provides important theory + experiment check and check on inelastics for future measurements.

# Parity violating neutron radius experiments

- Next runs 2018(?)
- **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*.
- Microscopic coupled cluster calculations for $^{48}$Ca make sharp prediction $R_n$-$R_p$=0.135±0.015 fm using chiral interaction $NNLO_{sat}$ [Nature Physics **12** (2016) 186].
- Many DFT calc. have larger skins, and dispersive optical model (DOM) gives $R_n$-$R_p$=0.25±0.02 fm.

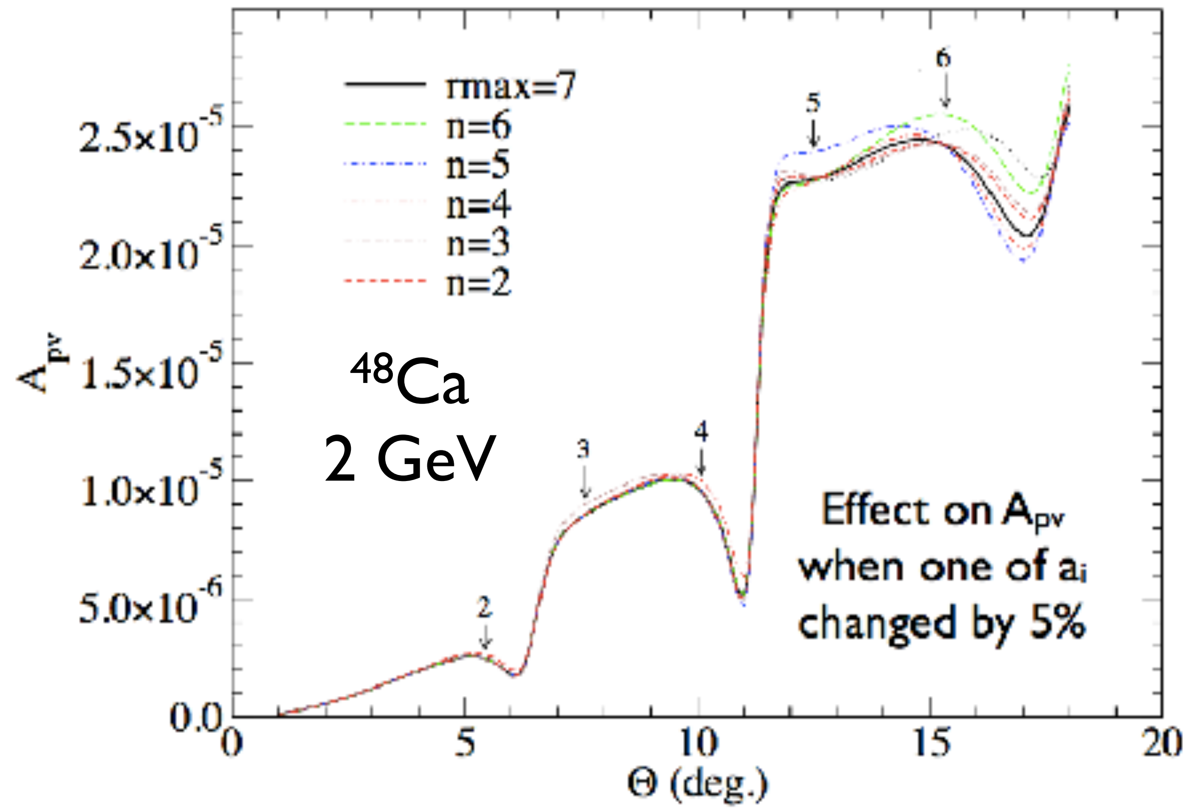


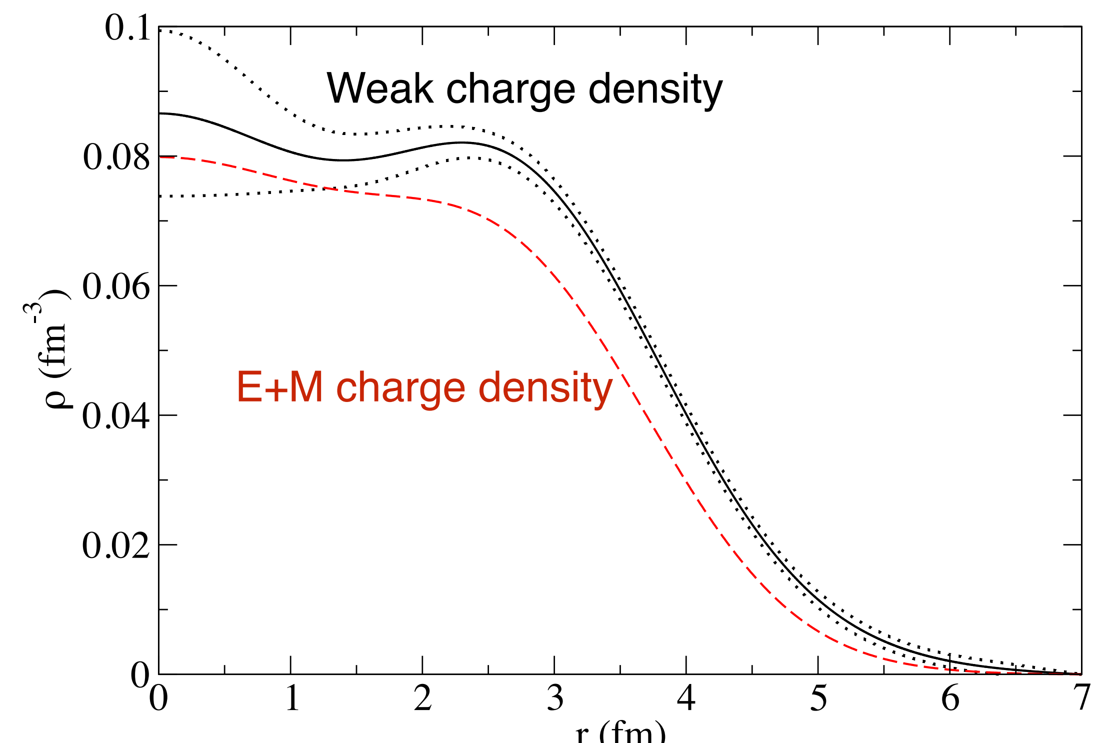
# Full $^{48}$Ca weak charge density

- 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…



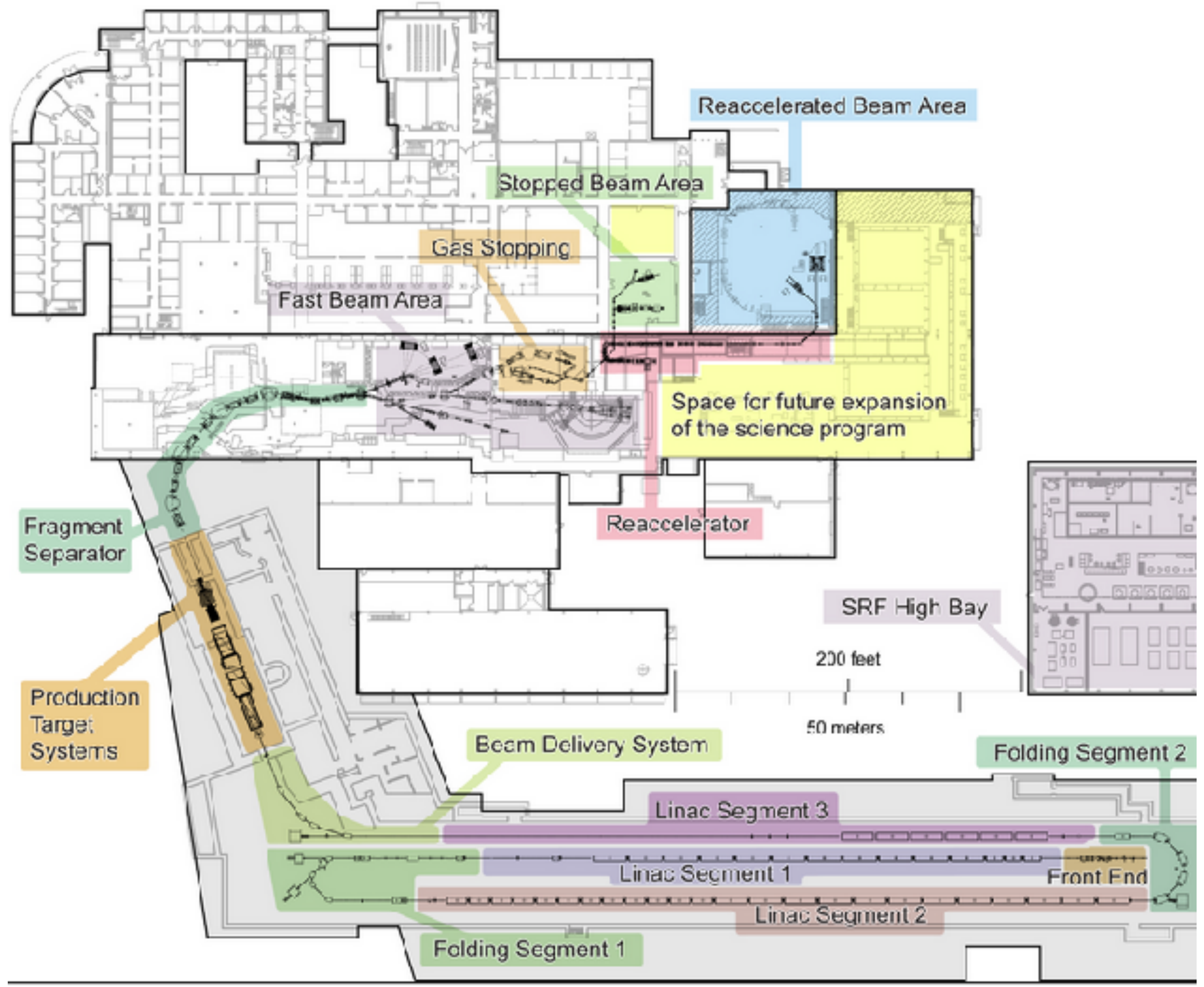




with Zidu Lin

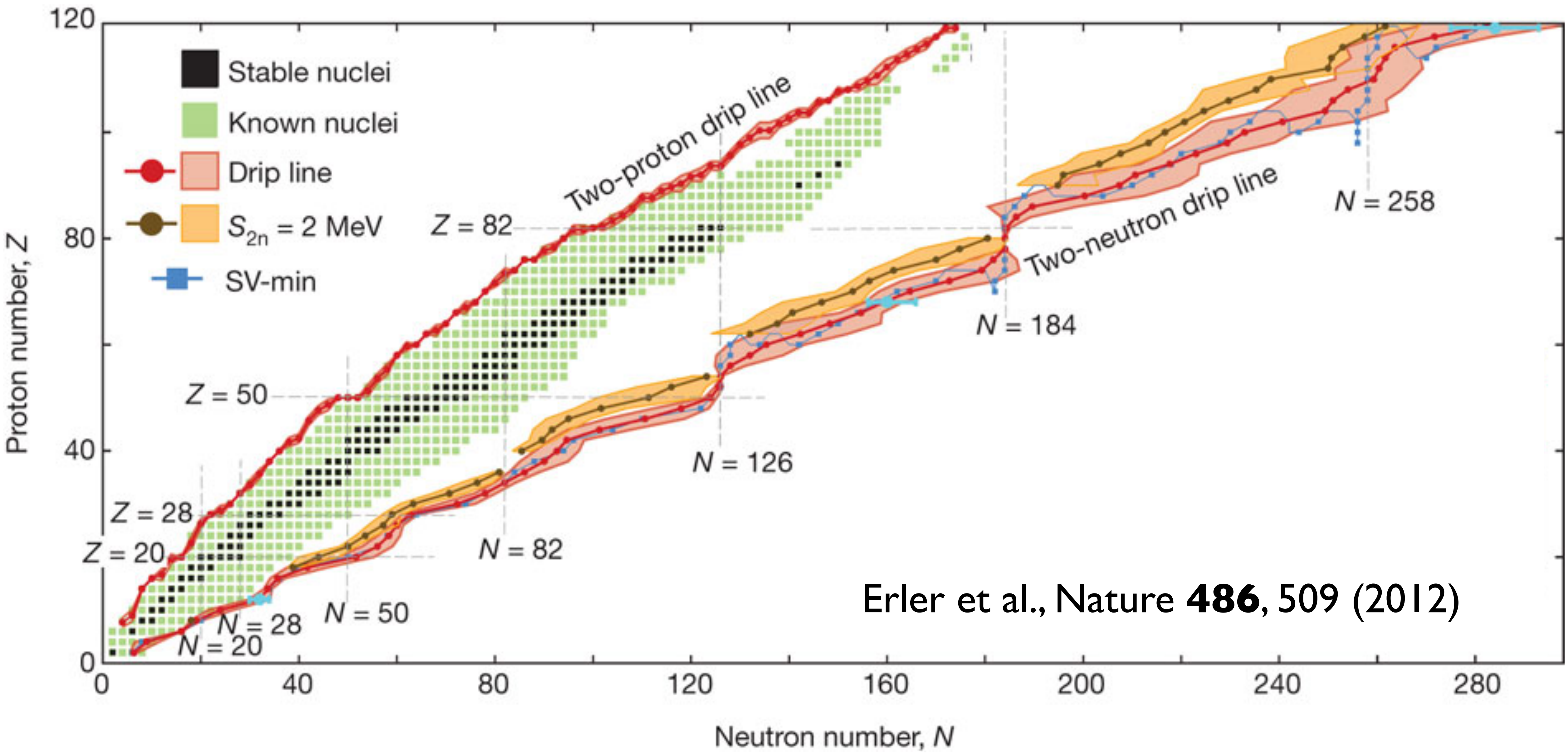
# JLAB vs Facility for Rare Isotope Beams

- FRIB is intense radioactive beam accelerator that can produce ~80% of all particle bound isotopes with Z < 90.

- 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



# Landscape of particle bound even-even nuclei: how many large hadrons exist?

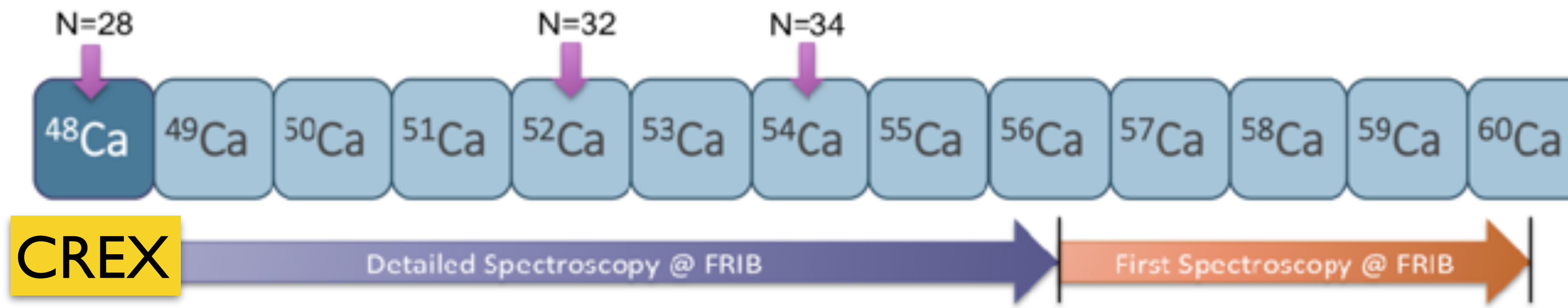


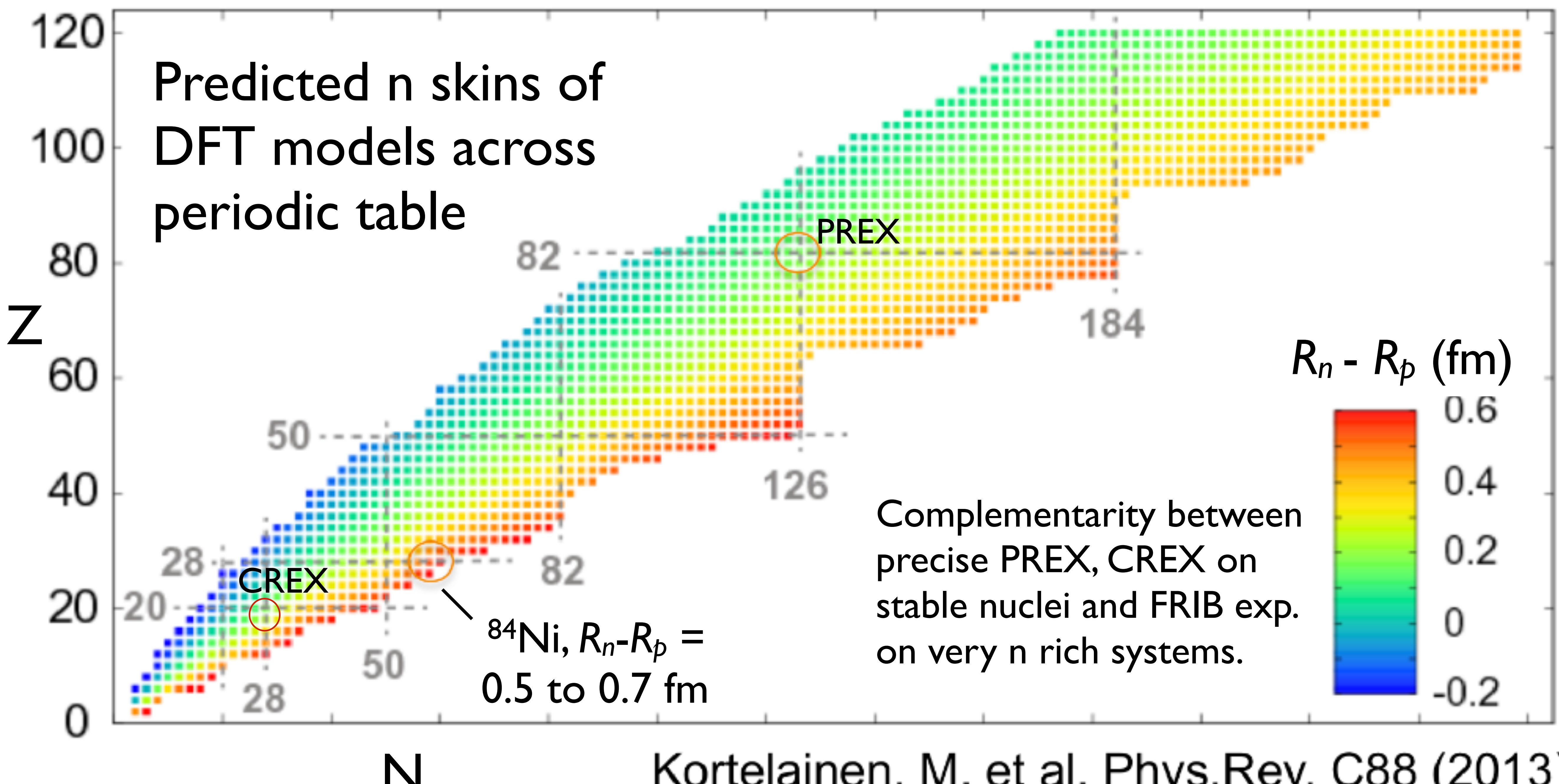

Erler et al., Nature **486**, 509 (2012)

- Erler et al. used four density functionals to predict location of neutron drip line (red region).
- FRIB can make many presently unknown neutron rich nuclei (white region) that may be important for r-process nucleosynthesis.

# Study more n rich nuclei at FRIB

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




Kortelainen, M. et al. Phys.Rev. C88 (2013)

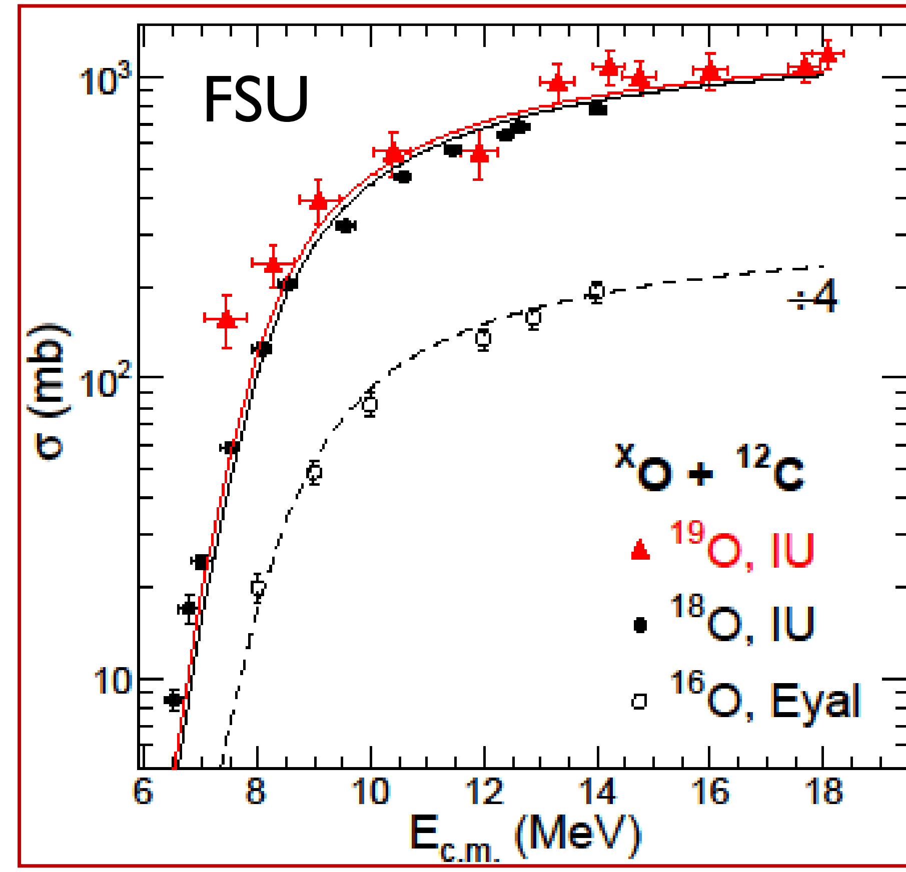
# Fusion of n-rich nuclei and n skins

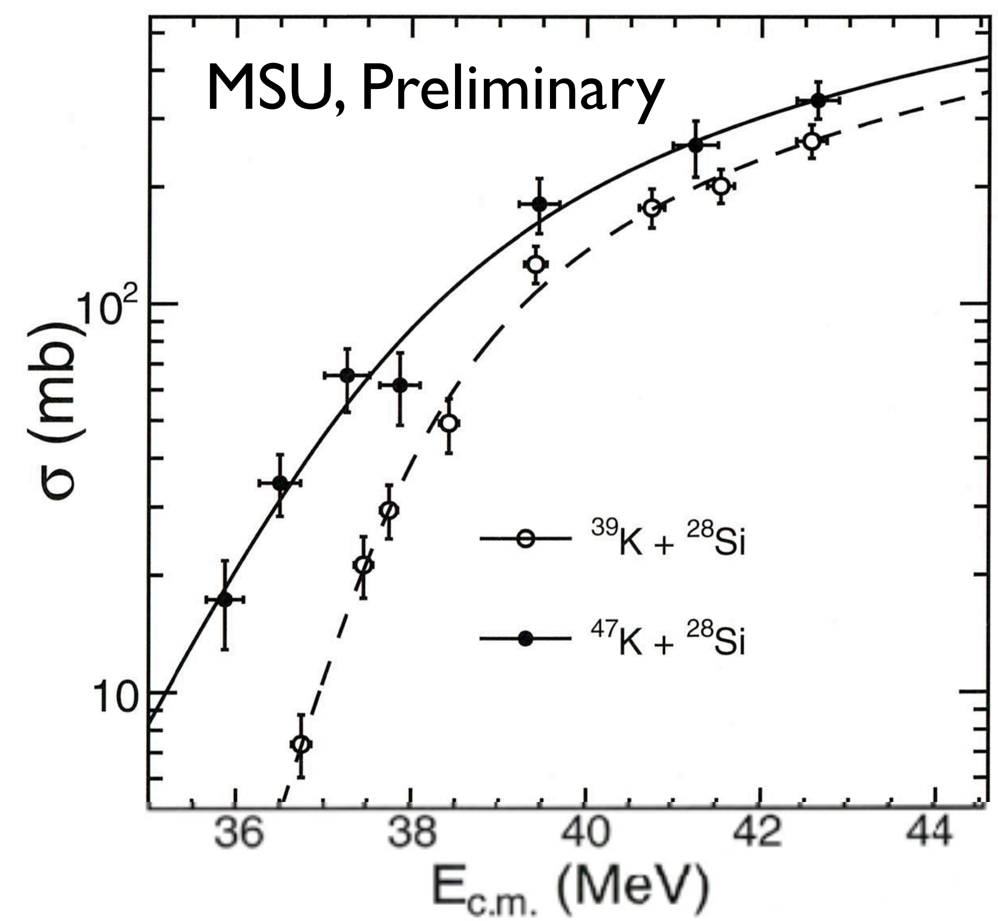
- Sub-barrier fusion of n-rich nuclei may be very sensitive to extent and dynamics of neutron skins. Tunneling depends exp on small changes in E.

- Indiana Nuclear Chemistry group (R. deSouza, S. Hudan…) has measured $^{18,19}O+^{12}C$ fusion at FSU.

- Experience at FSU led to approved experiment on $^{39,47}K$ + Si at NSCL / FRIB and very successful recent run. First physics result with ReA3 reaccelerated beam line.

- Neutron rich $^{47}K$ + $^{28}Si$ significantly larger cross section than $^{39}K+^{28}Si$.



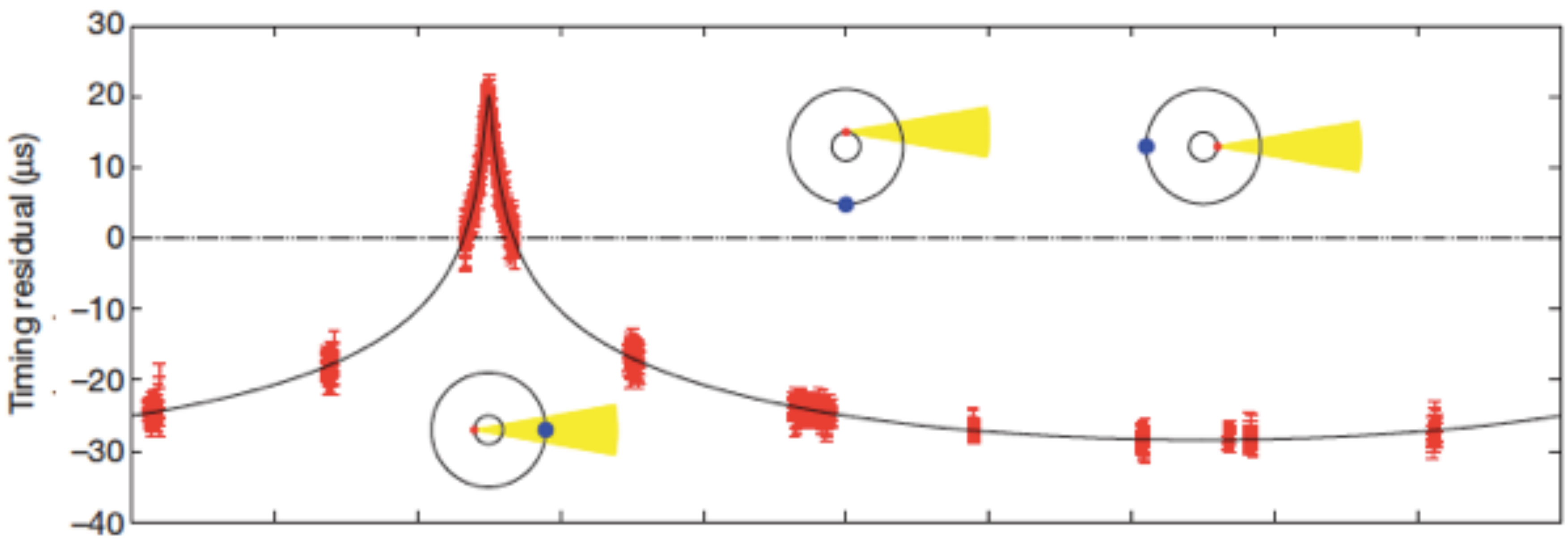
# JLAB's place in the heavens

- Compare PREX, CREX to astronomical observations of neutron stars and neutron rich matter using E+M, neutrino, or gravitational wave radiations.
- Cold dense QCD: we have no way to calculate properties of cold dense matter! This greatly increases importance of astronomical observation.
- In the last 10 years, what is the most important theory, experiment or observation for cold dense QCD?

# Discovery of $2M_{sun}$ Neutron Star

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

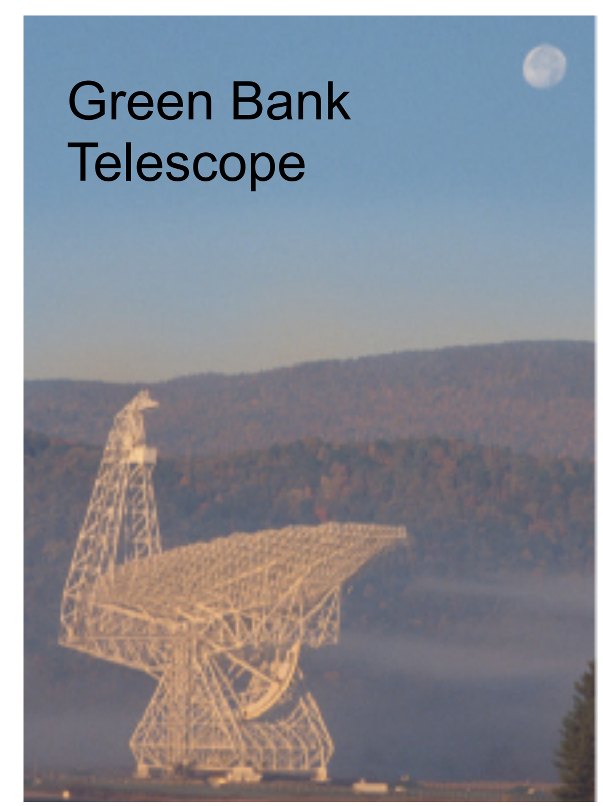
Delay in pulse arrival




NS + White Dwarf Binary

Orbital phase

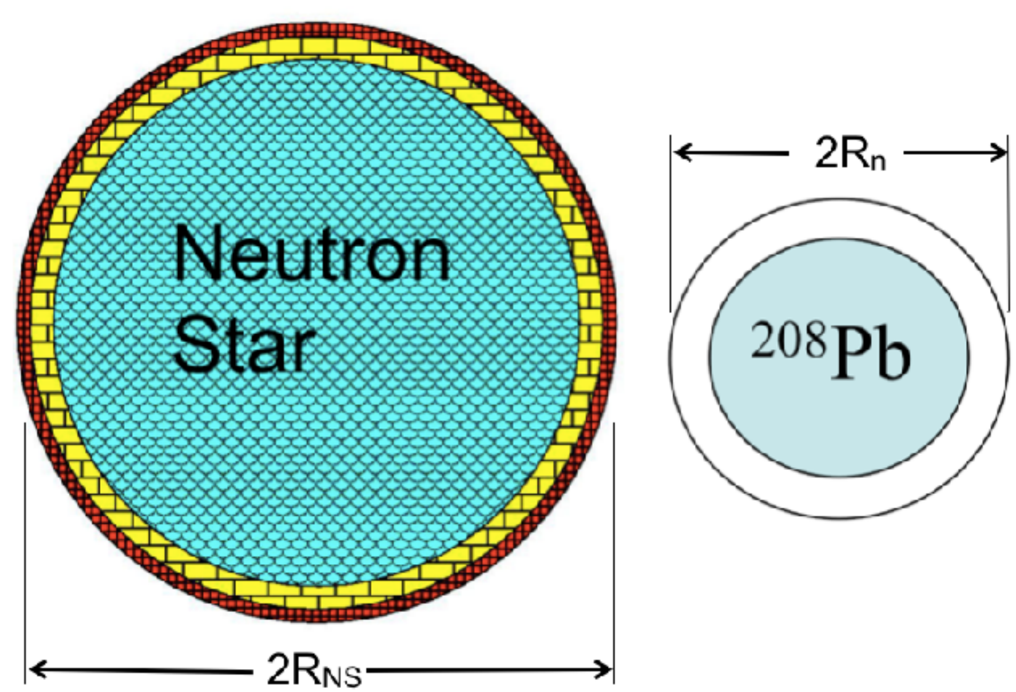
- The equation of state of neutron rich matter (pressure vs density) at high densities must be stiff enough (have a high enough p) to support this mass against collapse to a black hole. *All soft EOS are immediately ruled out!*
- *However this does not tell composition of dense matter be it neutron/ proton, quark, hyperon...*
- *NS cooling (by neutrinos) sensitive to composition.*



# Density Dependence of EOS

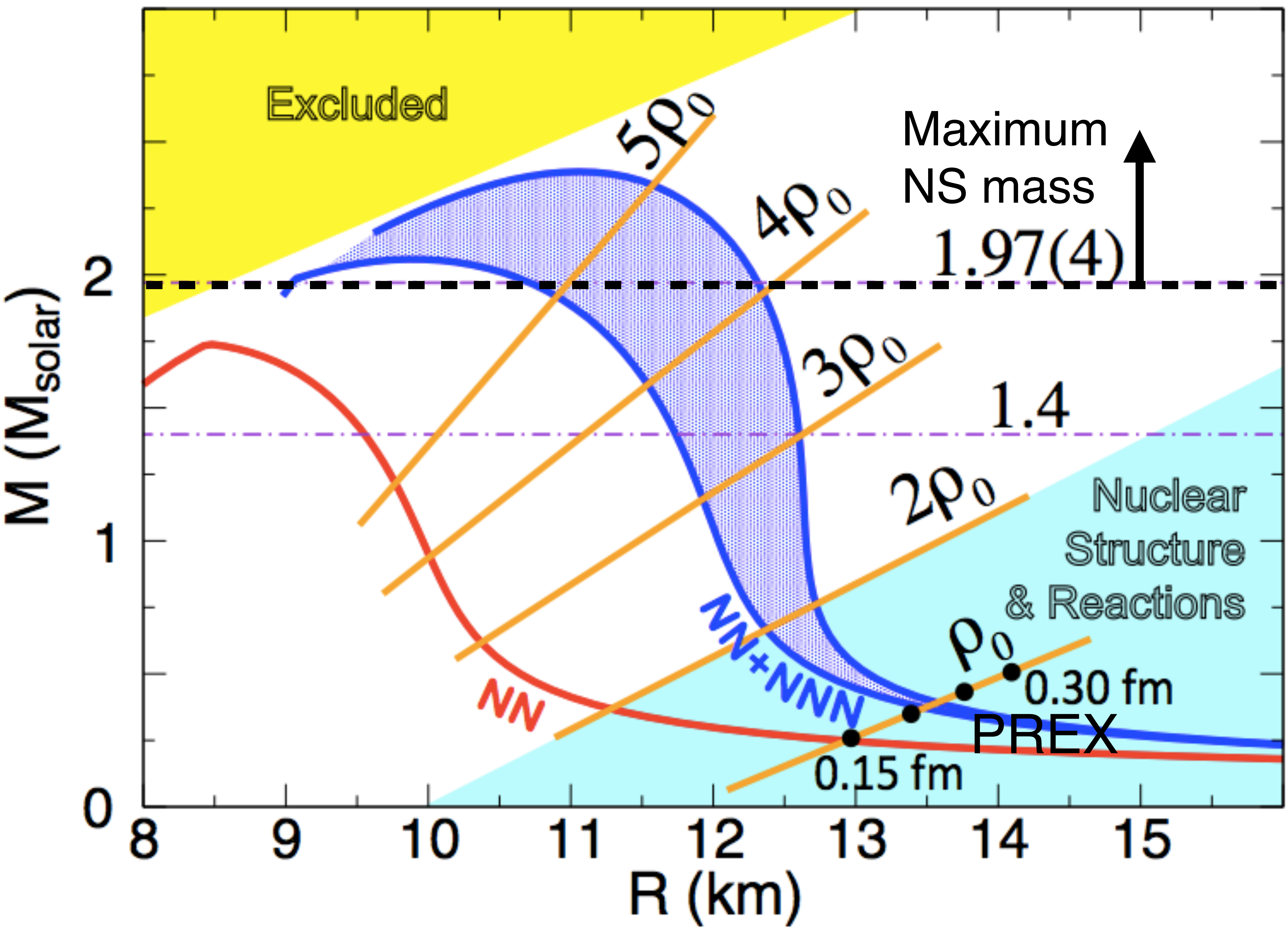
- Pressure of neutron matter pushes neutrons out against surface tension ==> $R_n$-$R_p$ of $^{208}$Pb determines P at low densities of about $2/3\rho_0$ (average of surface and interior $\rho$).
- Radius of ($\sim 1.4 M_{sun}$) NS depends on P at medium densities of $\rho_0$ and above.
- Maximum mass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

Neutron Star radius versus $^{208}$Pb Radius



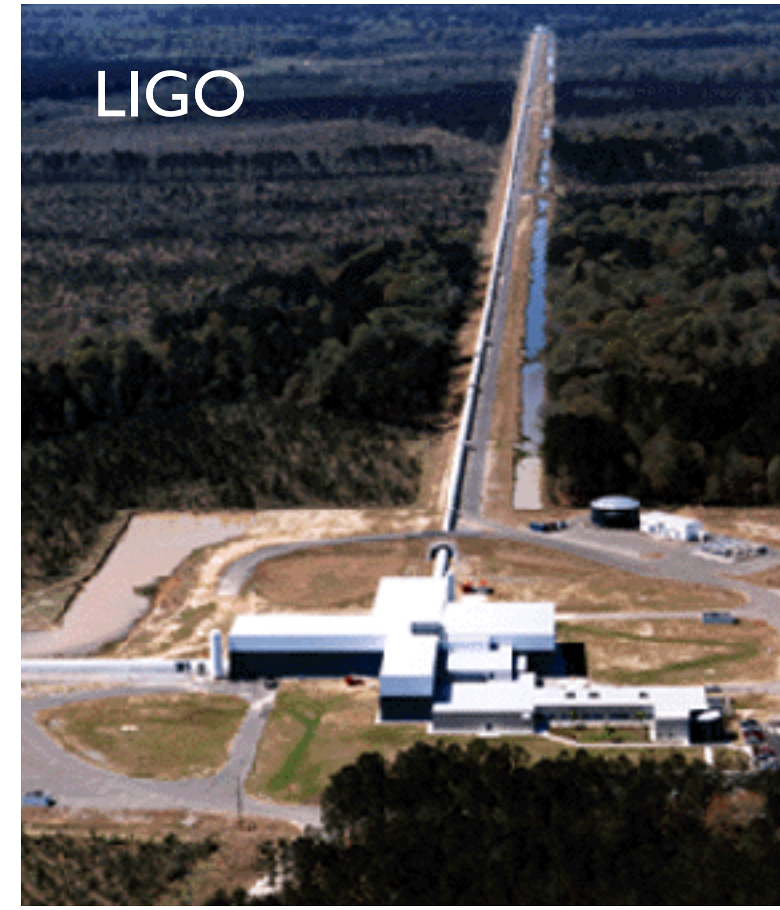

- These three measurements constrain density dependence of EOS and possible pressure changes from phase transitions.

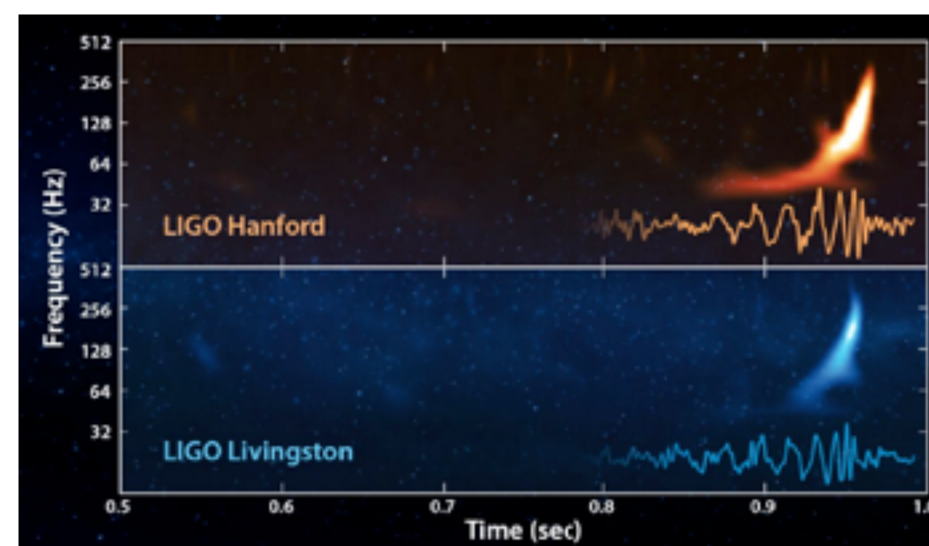
Gandolfi et al. PRC85, 032801 (2012)



# NS radii from gravitational waves

- Historic 2015 observation of gravitational waves from merger of two black holes.
- Measure chirp signal as two bodies radiate GW and spiral in to higher frequencies
- For neutron stars (NS) additional orbital energy lost to internal deformation. Orbital frequency increases at faster rate.
- JLAB —> Electric, Magnetic polarizability.
- LIGO —> Gravitational polarizability of NS ~ $R^5$ —> measure radius of NS.
- Hope to see NS-NS mergers soon as LIGO reaches full design sensitivity.



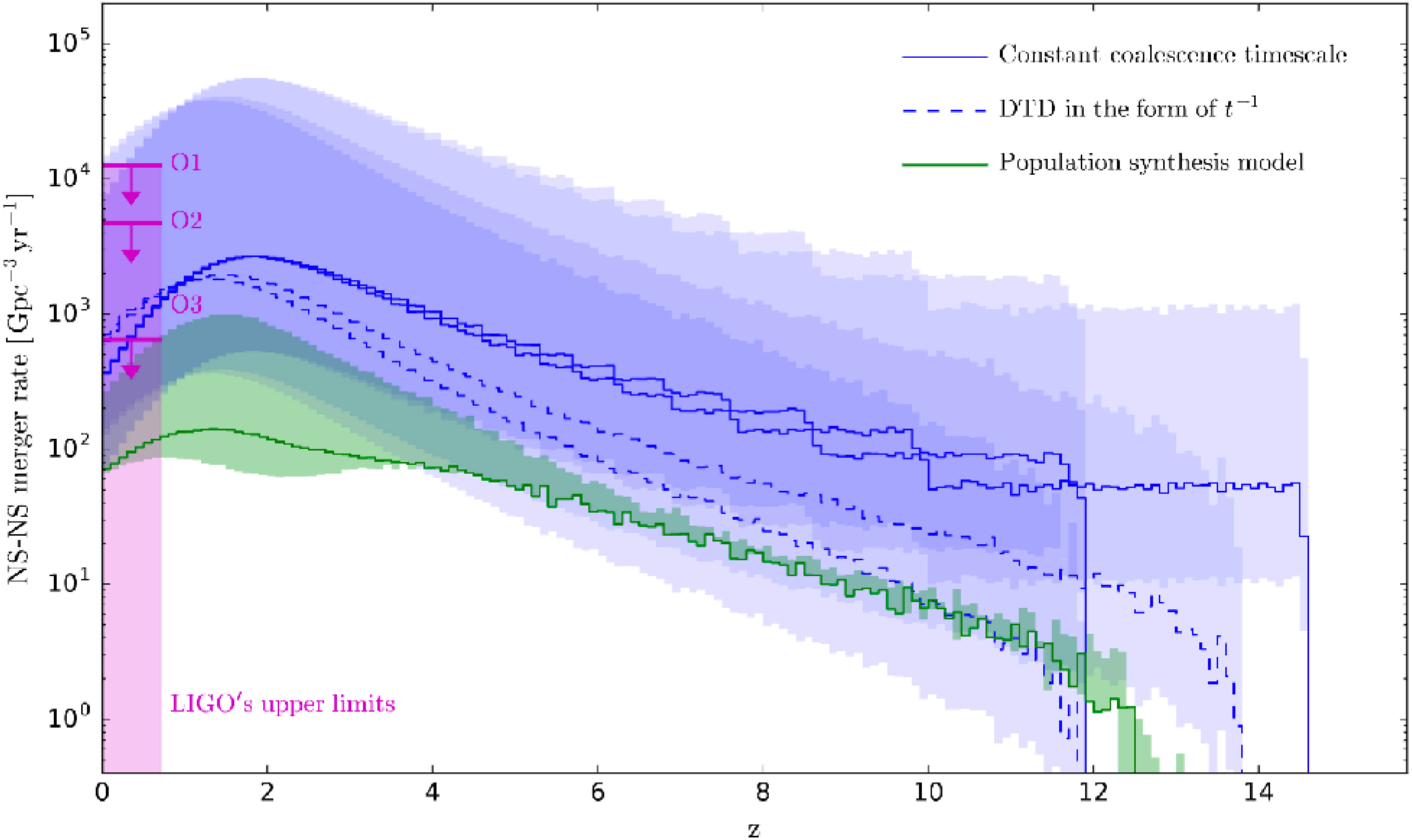



FIG. 12.— Predicted cosmic NS-NS merger rate densities as a function of redshift. The blue lines show the rate needed in galactic chemical evolution simulations, assuming different delay-time distribution functions (different line styles) and a total of $2 \times 10^{-5}$ NS-NS merger event per stellar mass formed. The blue shaded areas highlight the possible range of values generated by using different ejected masses for NS-NS mergers and different Fe yields for massive stars (see Figure 10). The green line shows the predictions associated with the standard population synthesis model, while the green shaded area shows the possible range of values defined by the two alternative models. The pink shaded area represents the upper limits established by Advanced LIGO during their first run of observations (Abbott et al. 2016b). O1 shows the current established value, while O2 and O3 are the expected values for the next observing runs. The Advanced LIGO horizon goes up to $z \sim 0.7$ for the most massive BH-BH mergers, but should be reduced for NS-NS and BH-NS mergers.

# Electroweak Radius Experiments

| Experiment | Nucleus | Accuracy |
|---|---|---|
| **PRAD** | p | <1% |
| **CREX** | $^{48}Ca$ | 0.6% |
| **PREX II** | $^{208}Pb$ | 1% |
| **NICER** | PSR J0437 | 5% |

# PSR J0437

- Is closest and brightest millisecond pulsar
- Rotation period 5.75 ms
- Distance to earth 156.3 parsec (509.8 light years)
- Mass 1.8 $M_{sun}$ (in orbit with white dwarf)

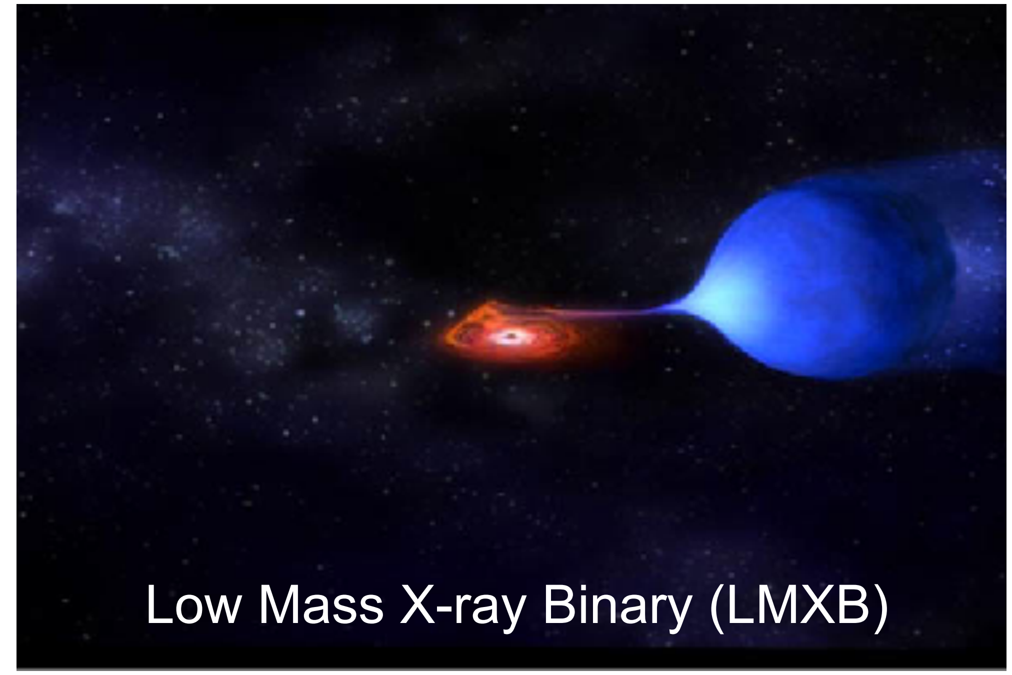
NICER
Neutron star Interior Composition ExploreR
Keith Gendreau, NASA GSFC
Principal Investigator
NASA
GSFC
MIT KAVLI
INSTITUTE

# X-ray observations of NS radii

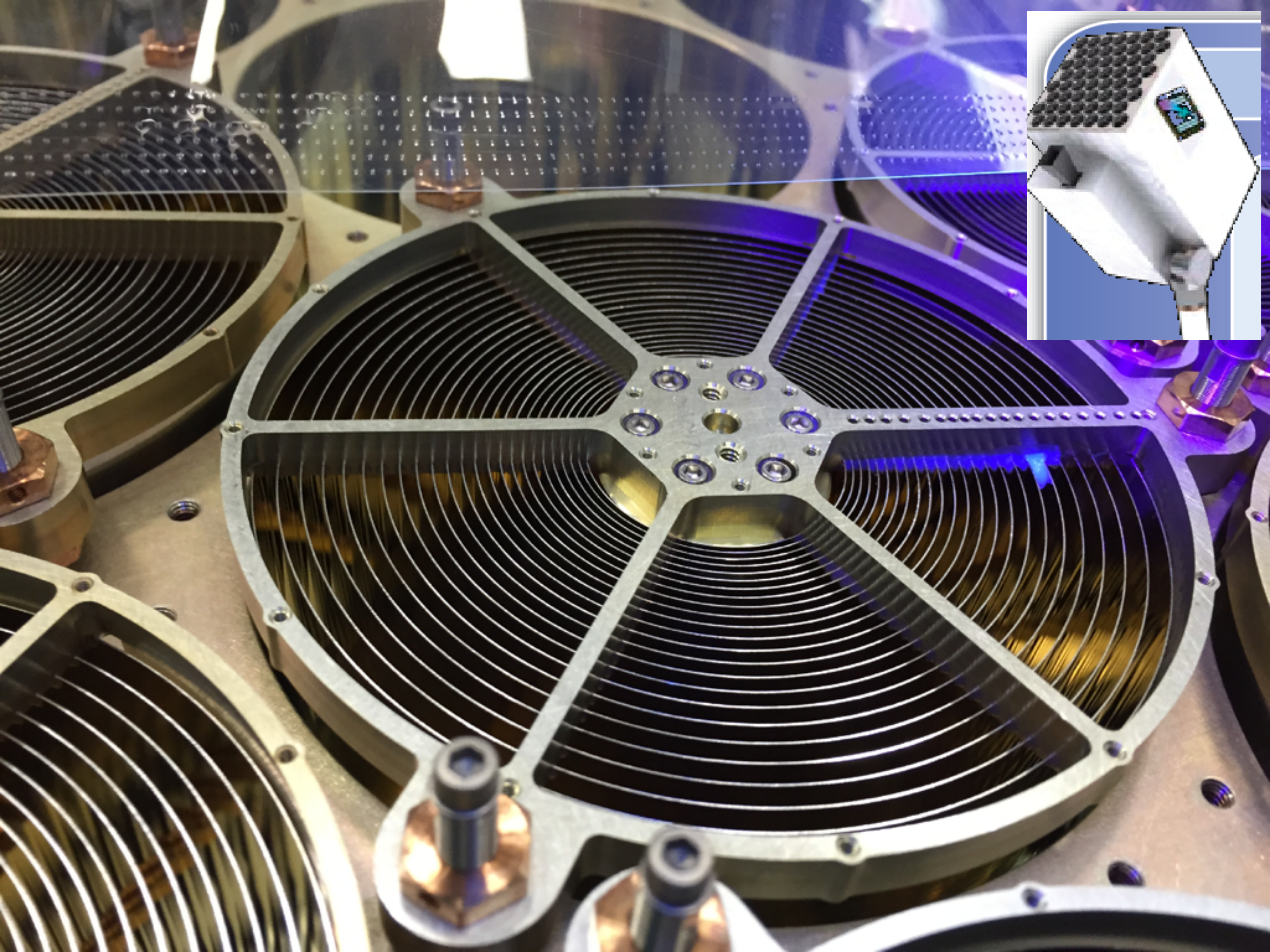
- Deduce surface area from luminosity, temperature from X-ray spectrum.

$$L_\gamma = 4\pi R^2 \sigma_{SB} T^4$$

- Complications:
  - Need distance (parallax for nearby isolated NS...)
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Curvature of space: measure combination of radius and mass.
  - Hot spots and nonuniform temperatures.
- NS in globular clusters: expect simple nonmagnetic hydrogen atmospheres and know distance.



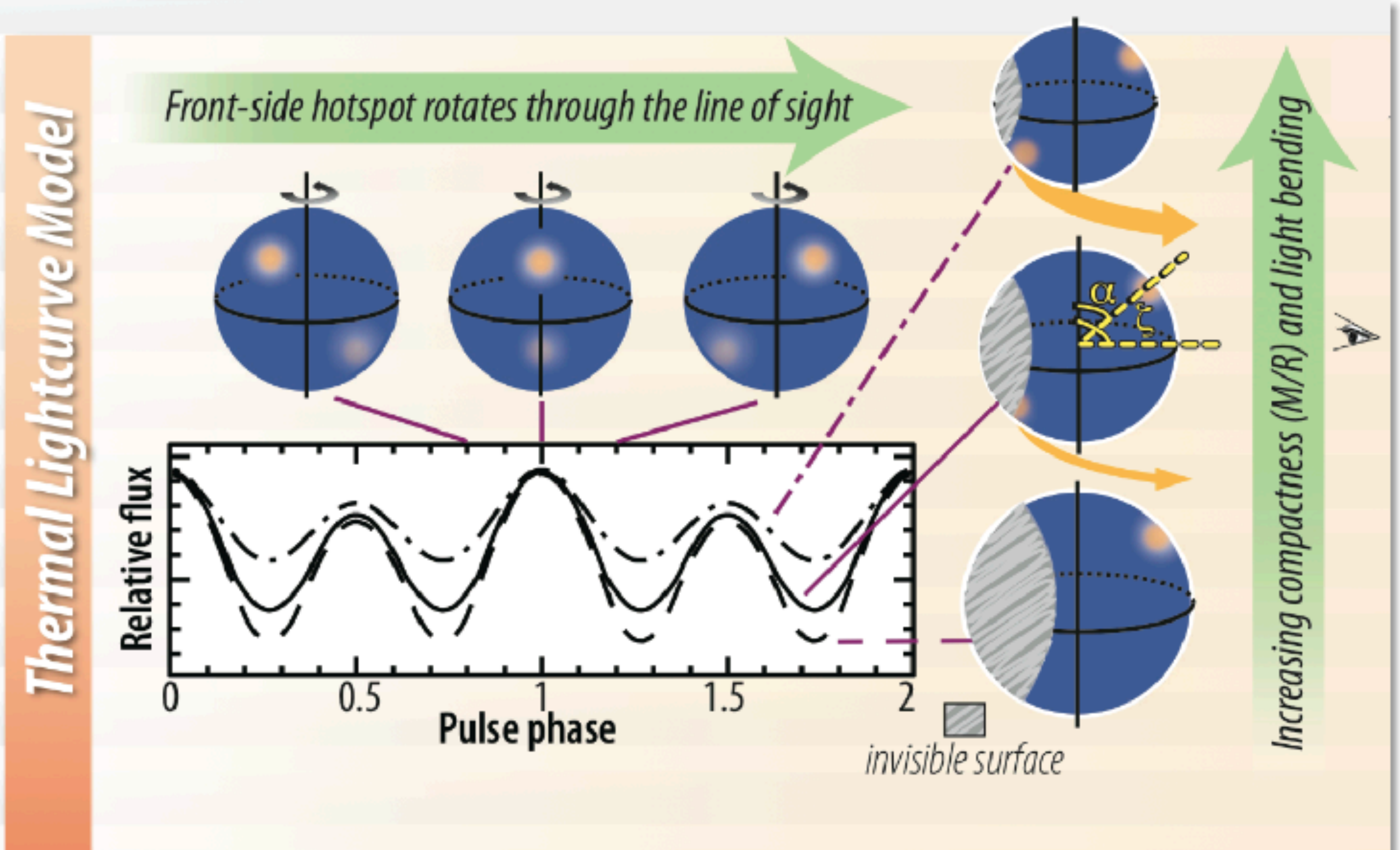

- X-ray bursts: NS accretes material from companion that ignites a runaway thermonuclear burst.
- Eddington luminosity: when radiation pressure balances gravity --> gives both M and R!
- However important uncertainties may remain in extracted radii. Suleimanov and Poutanen use more sophisticated atmosphere models and find larger radii.



# Science Measurements

NICER

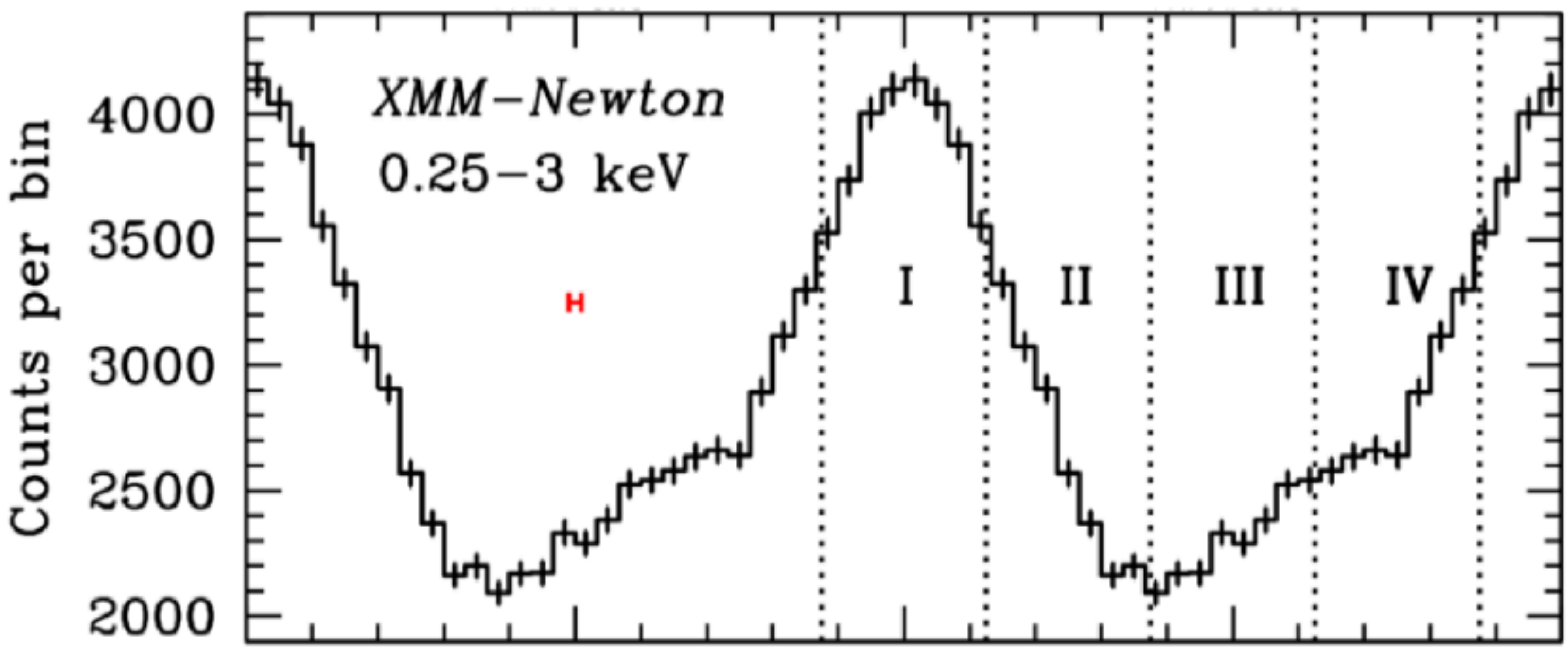
*Reveal stellar structure through lightcurve modeling, long-term timing, and pulsation searches*




***Lightcurve modeling*** constrains the compactness (*M/R*) and viewing geometry of a non-accreting millisecond pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots, thanks to gravitational light-bending…

# Example: X-ray pulse waveform of J0437–4715

Produced by thermal emission from its heated polar caps




Pulse waveform observed using the XMM-Newton EPIC pn detector

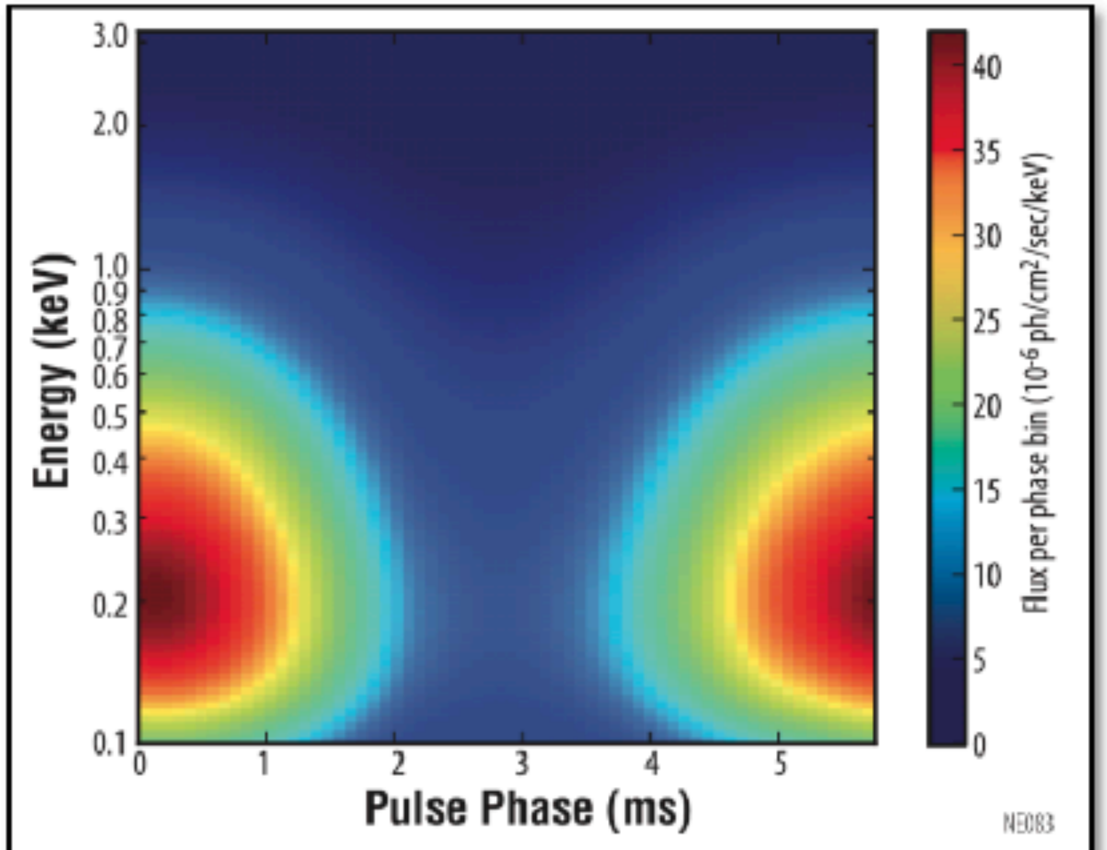
The red horizontal error bar shows the 70 $\mu s$ absolute timing uncertainty

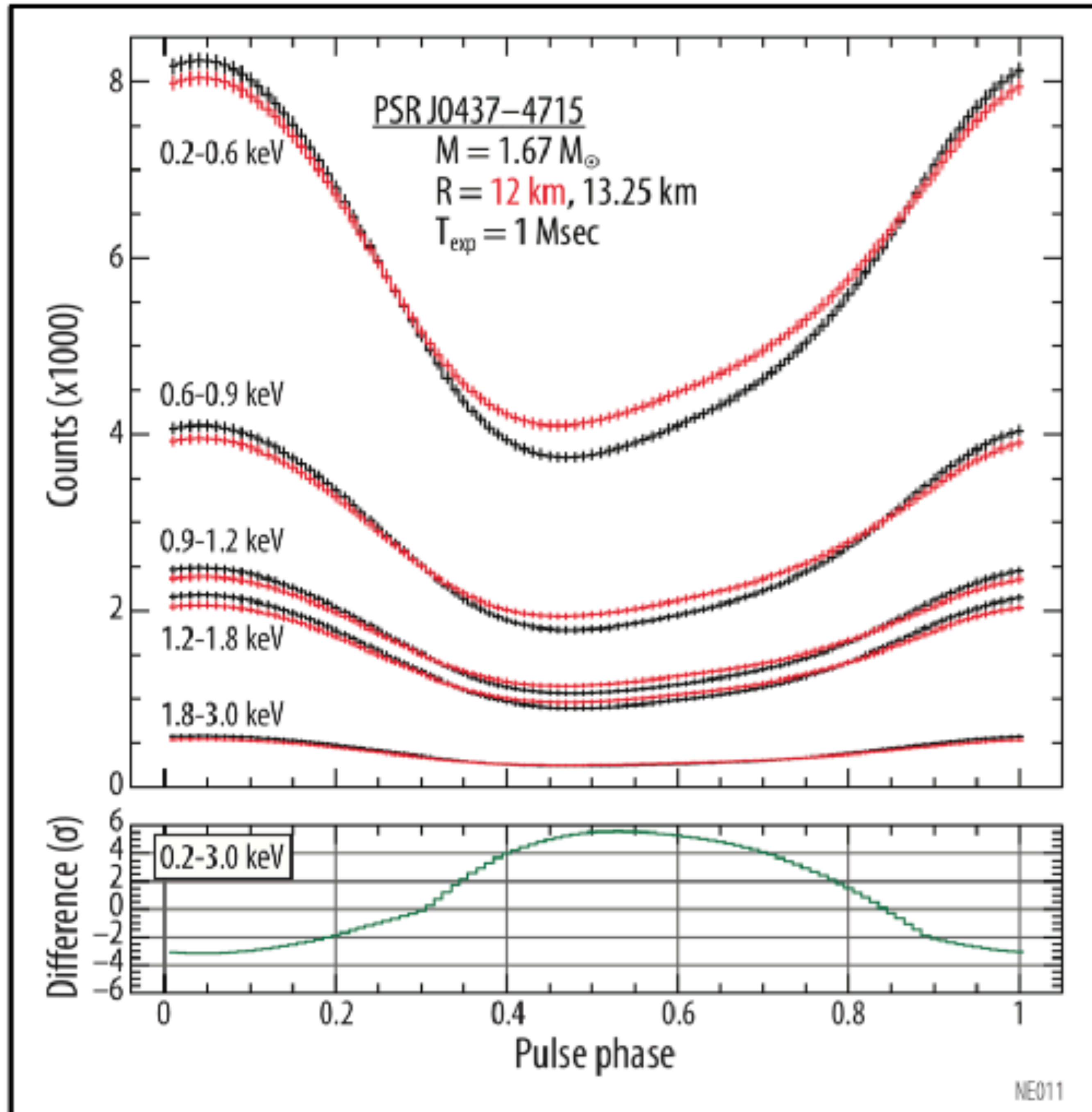
The vertical dotted lines show phase intervals used for spectroscopy

Original slide from Fred Lamb

# Science Measurements (cont.)

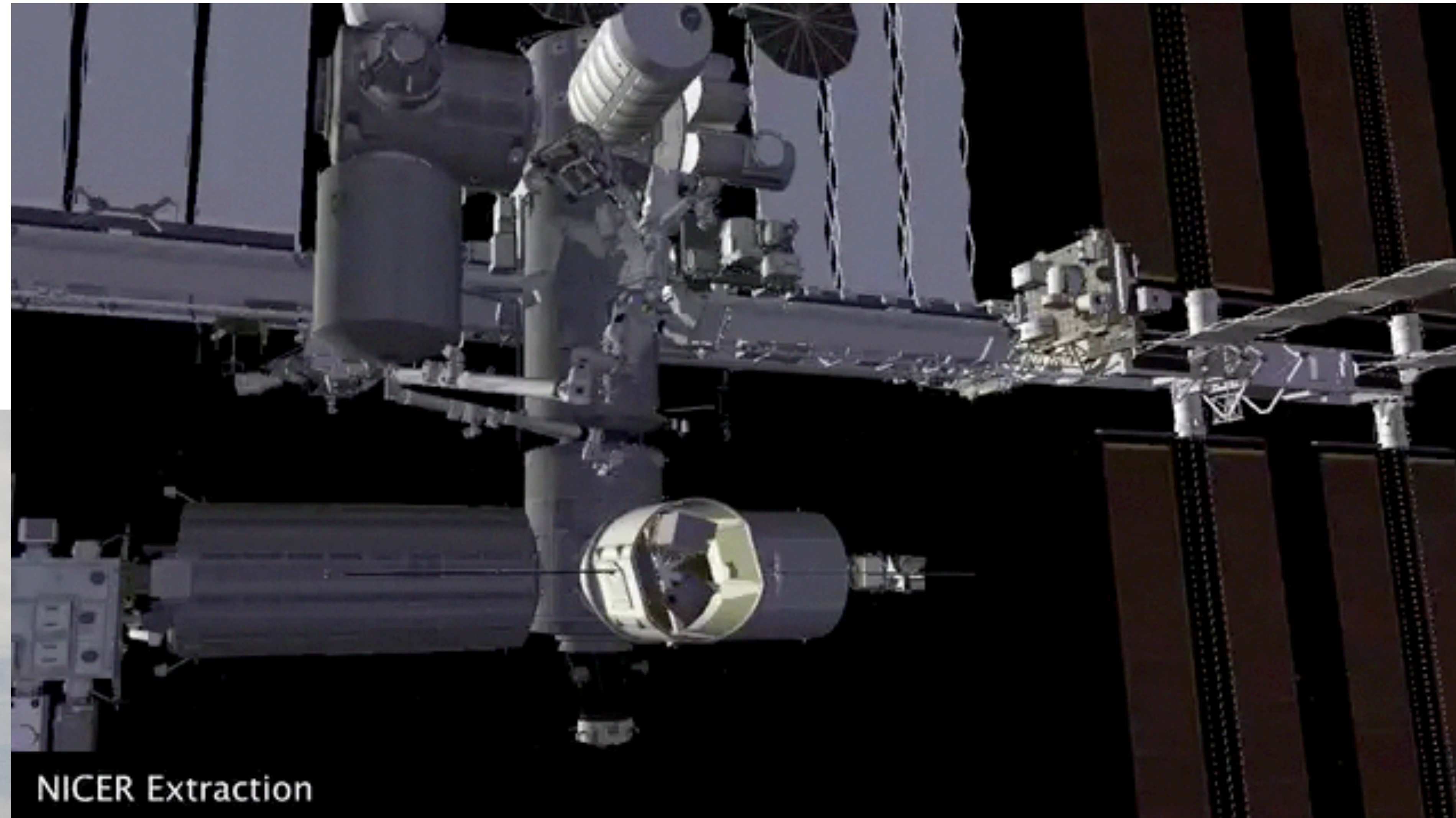
NICER

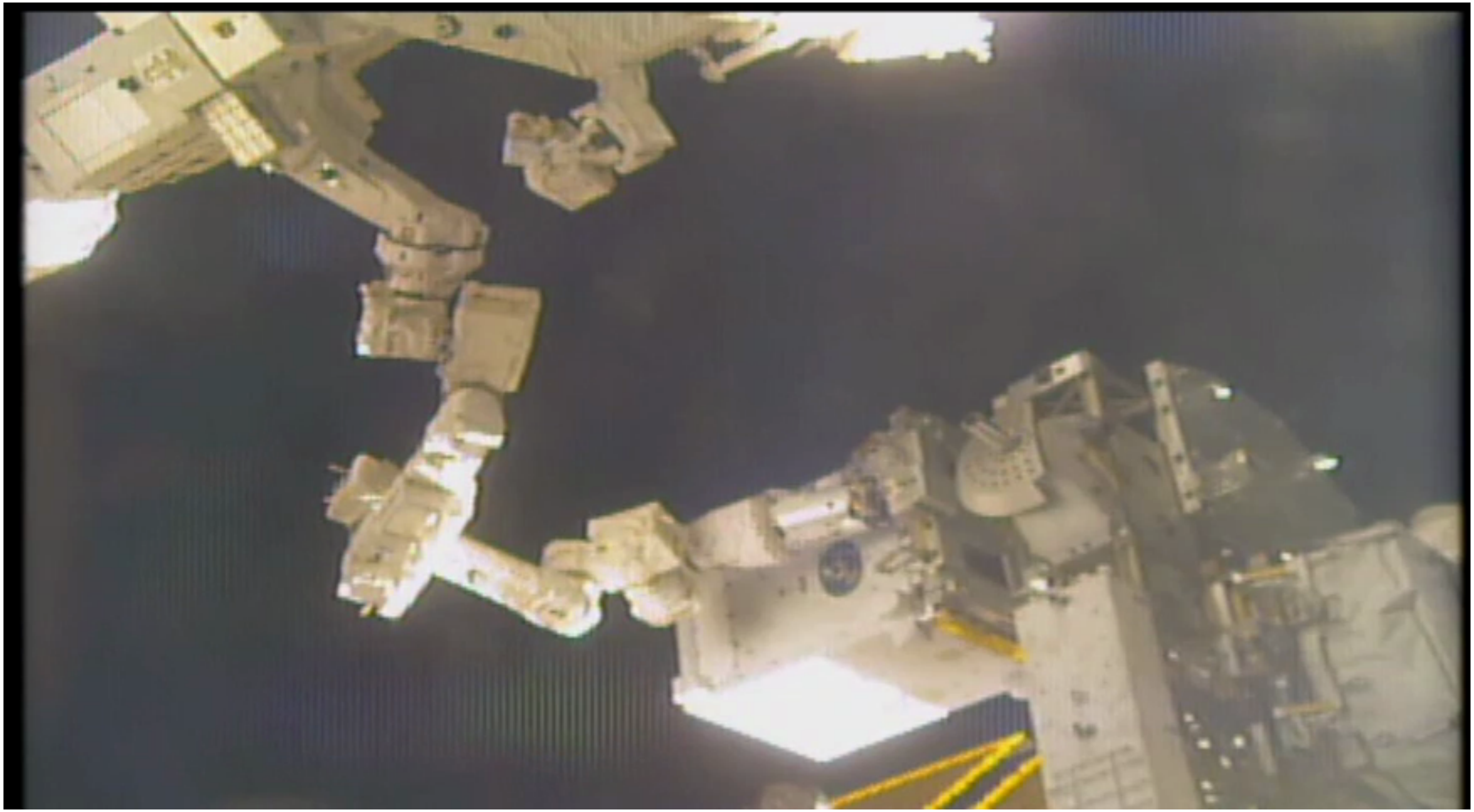



… while phase-resolved spectroscopy promises a direct constraint of radius *R*.

NICER launched June 3 and was installed June 13-14, 2017



- First NICER results in ~ one year.  It would be great to have PREX II, CREX results shortly thereafter!

# Electroweak scattering from (heavy) nuclei

- Parity violating elastic electron scattering cleanly determines thickness of neutron skin in a heavy nucleus. This constrains pressure of neutron rich matter and structure of neutron stars.
- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke…
- Full 48Ca weak density: ***Zidu Lin***, …

U.S. DEPARTMENT OF ENERGY | Office of Science

NUCLEI
Nuclear Computational Low-Energy Initiative

OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY