

Nuclear Physics of Neutron Stars

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Nuclear physics and Multi-messenger Astronomy

Nuclear physics of neutron stars

Discuss the discovery of neutron stars and how NS properties depend on the nature of dense matter. Observations of NS masses and radii help determine the dense matter equation of state, or pressure versus density relation.

Nuclear physics of supernovae

Core collapse supernovae are gigantic explosions of massive stars that radiate 10^{58} (10 to the 58) neutrinos, synthesis many chemical elements, accelerate cosmic rays, and form neutron stars. Review the historic observations of **SN1987a**, discuss neutrino interactions in dense matter, and introduce some large neutrino detectors.

Nuclear physics of neutron star mergers

Neutron stars in close binary orbits radiate gravitational waves (GW) and merge. Review the extraordinary multi-messenger observations of the 2017 merger **GW170817**. Introduce the LIGO detectors and discuss merger observations with next generation GW detectors.

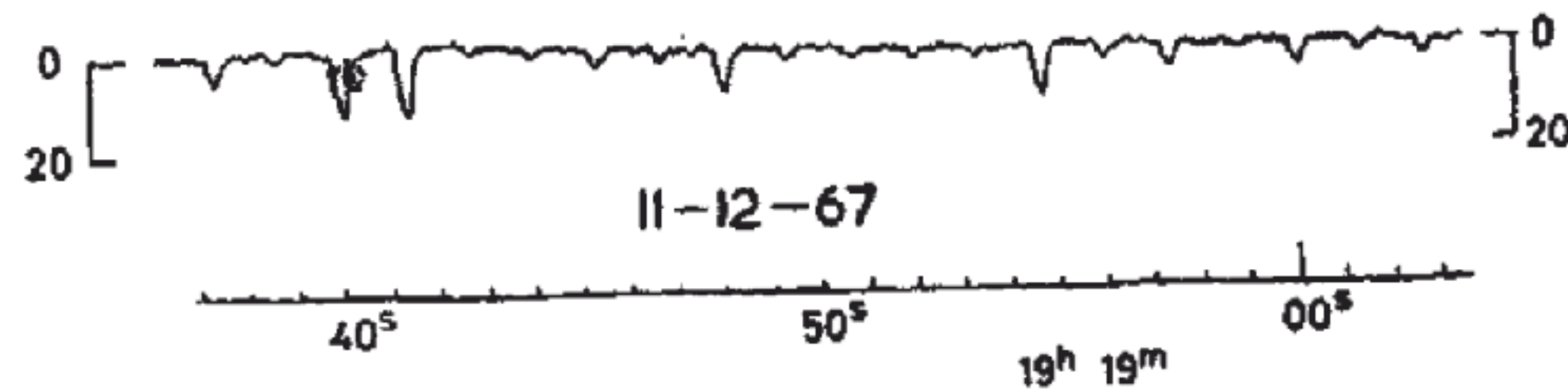
Neutron Stars



Jocelyn Bell Burnell

First pulsars

- J. Bell discovered the first four pulsars, Nature **217** (1968) 709.



$$P_0 = 1.3372795 \pm 0.0000020 \text{ s}$$

- Shortly thereafter, others, using the 300 ft Green Bank telescope in West Virginia and then the 300 m Arecibo telescope, discovered the Crab pulsar with a short 33 ms period.



300 ft Green Bank Telescope





300m Arecibo telescope





Five Chariots

Moon

Net

SN 1054A

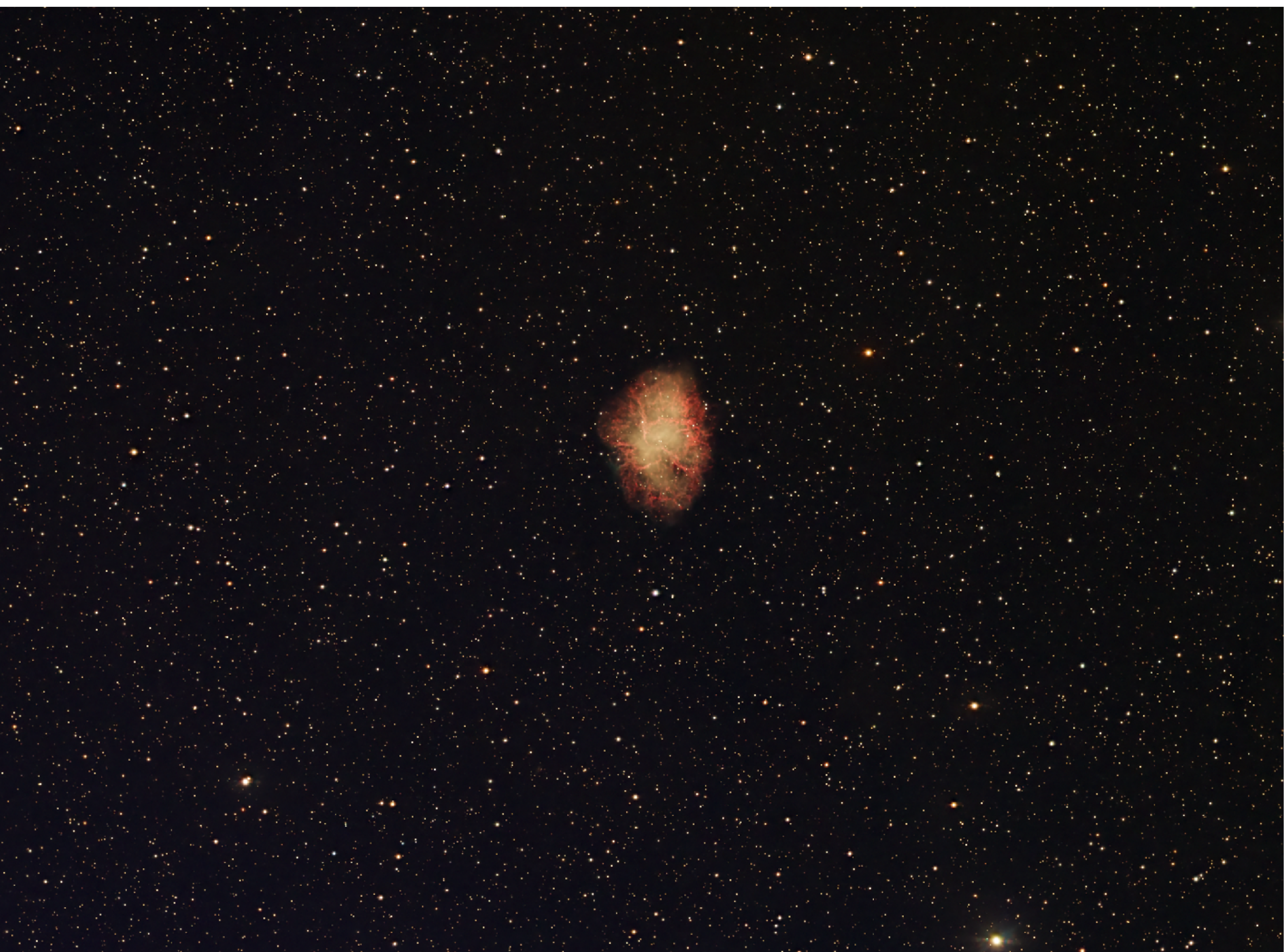
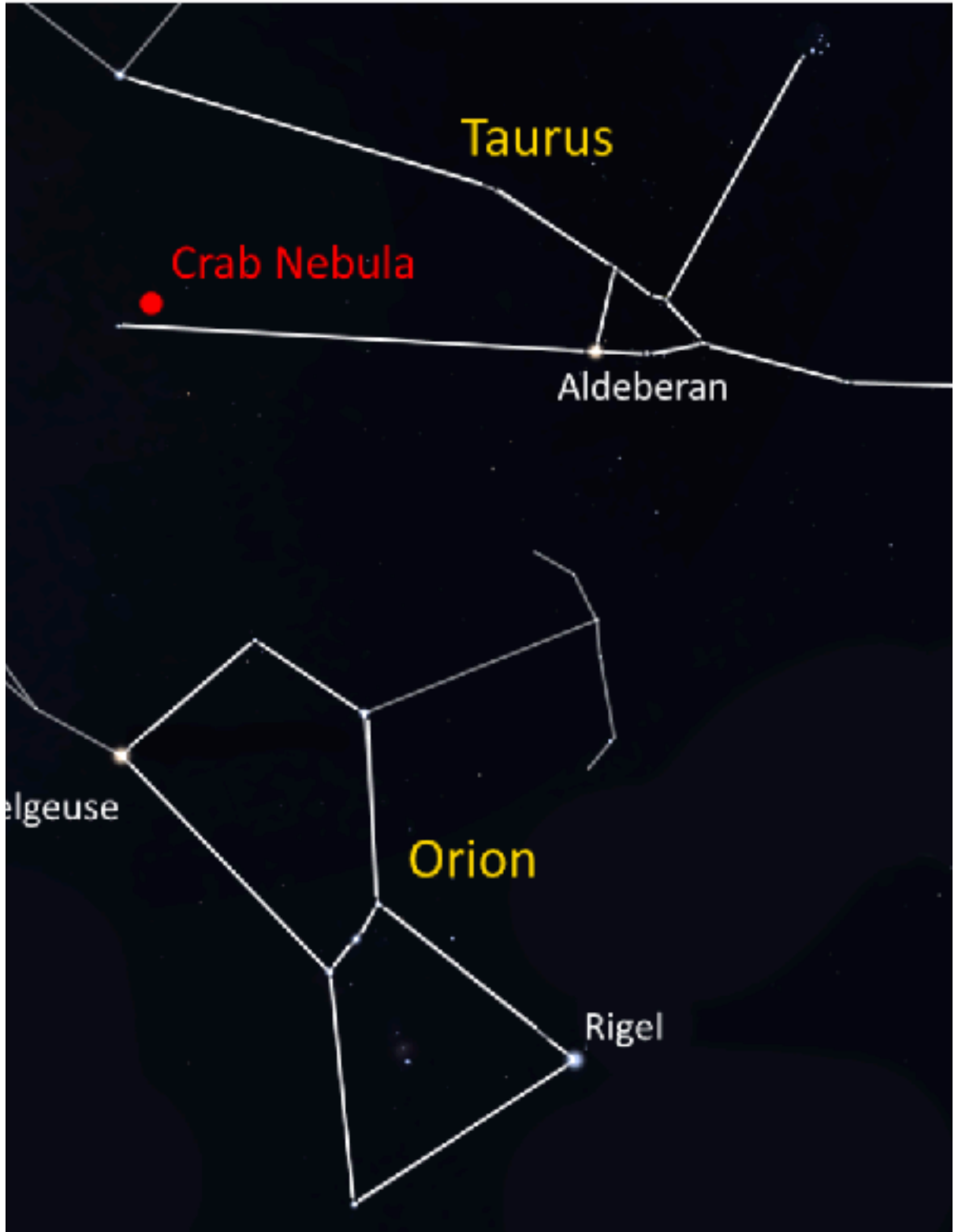
Five Feudal Kings
North River

Mercury
Well

Three Stars

Ja

E



Crab pulsar

Plate solve:

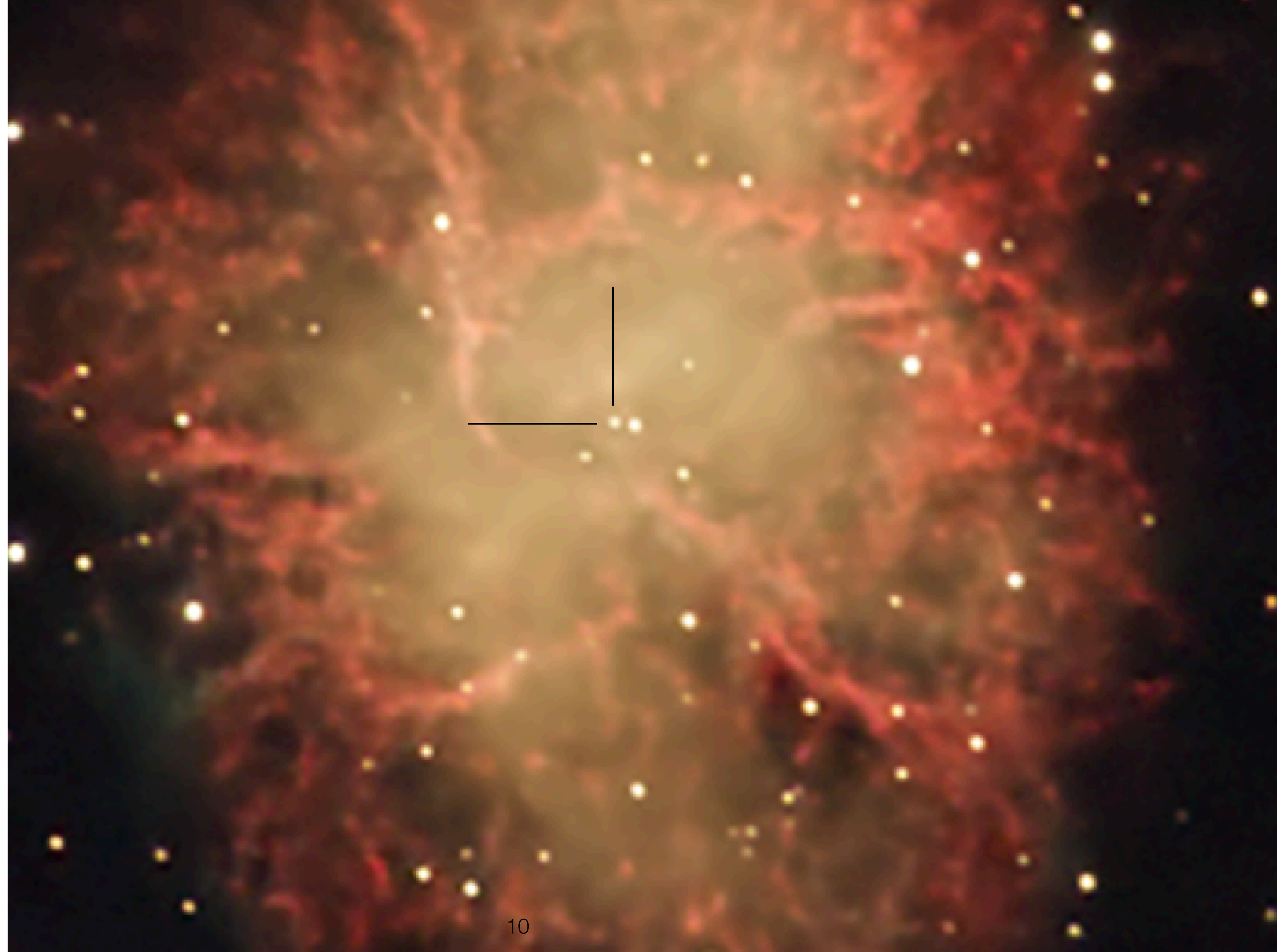
$$\alpha = 5\text{h } 34' 31.9''$$

$$\delta = 22 00' 52.1''$$

Known position:

$$\alpha = 5\text{h } 34' 31.95''$$

$$\delta = 22 00' 52.2''$$



Optical pulsations of Crab

R. LYNDS, S. P. MARAN,
AND D. E. TRUMBO

Observed Crab with a
photomultiplier and
analyzed the data using
the recently observed
radio period of 33 msec.

Crab pulsar was smoking
gun that NS are born in
SN. Crab SN observed by
Chinese in 1054.

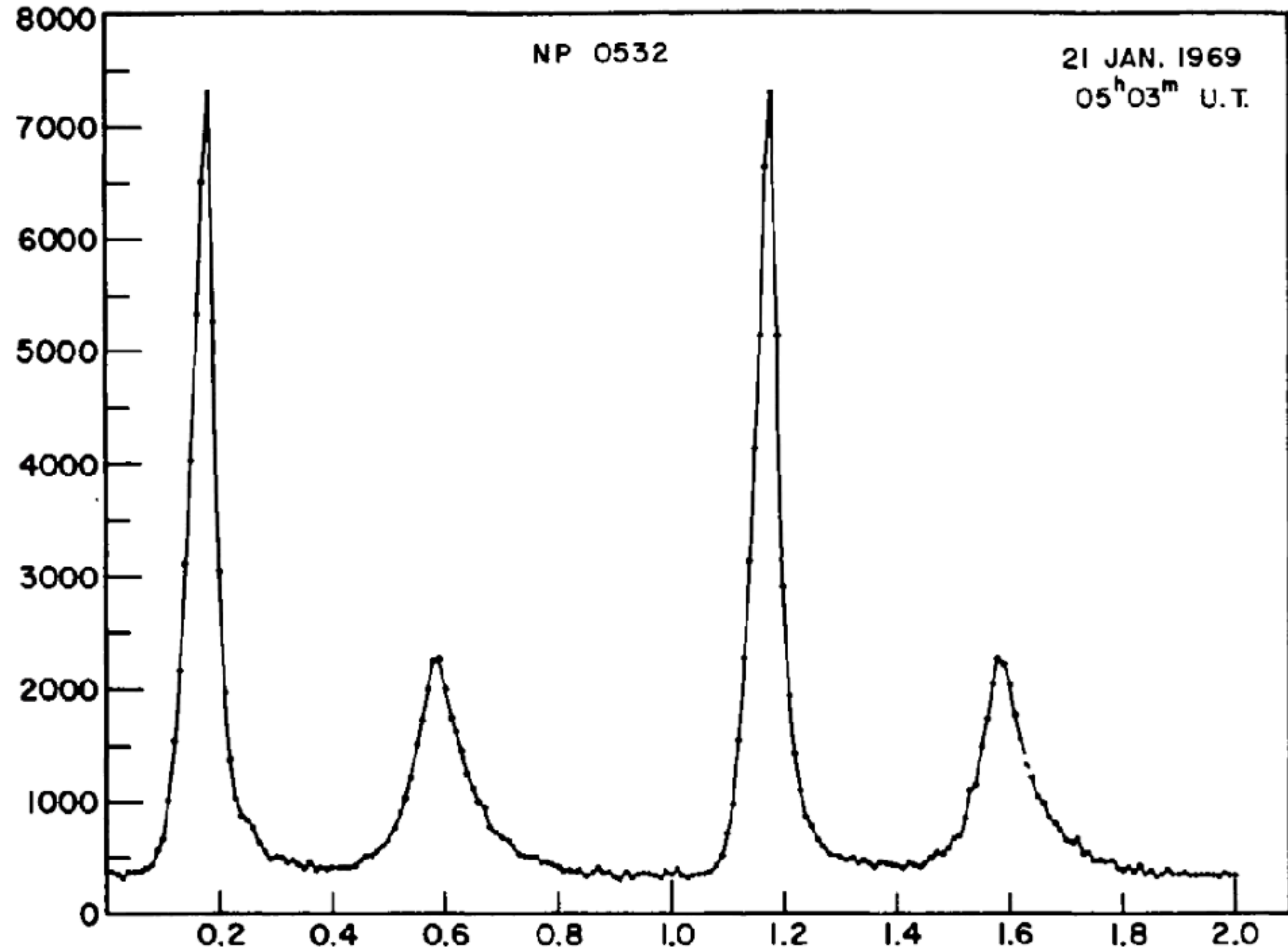


FIG. 1.—A 10-min observation of the light variation of NP 0532. Ordinate is number of photon counts per plotted point; abscissa is phase in cycles. Observations were made in white light with a 1P21 photomultiplier. The period of the variation is approximately 33 msec; two independent cycles of the variation are shown.

Rapid rotation => High Density

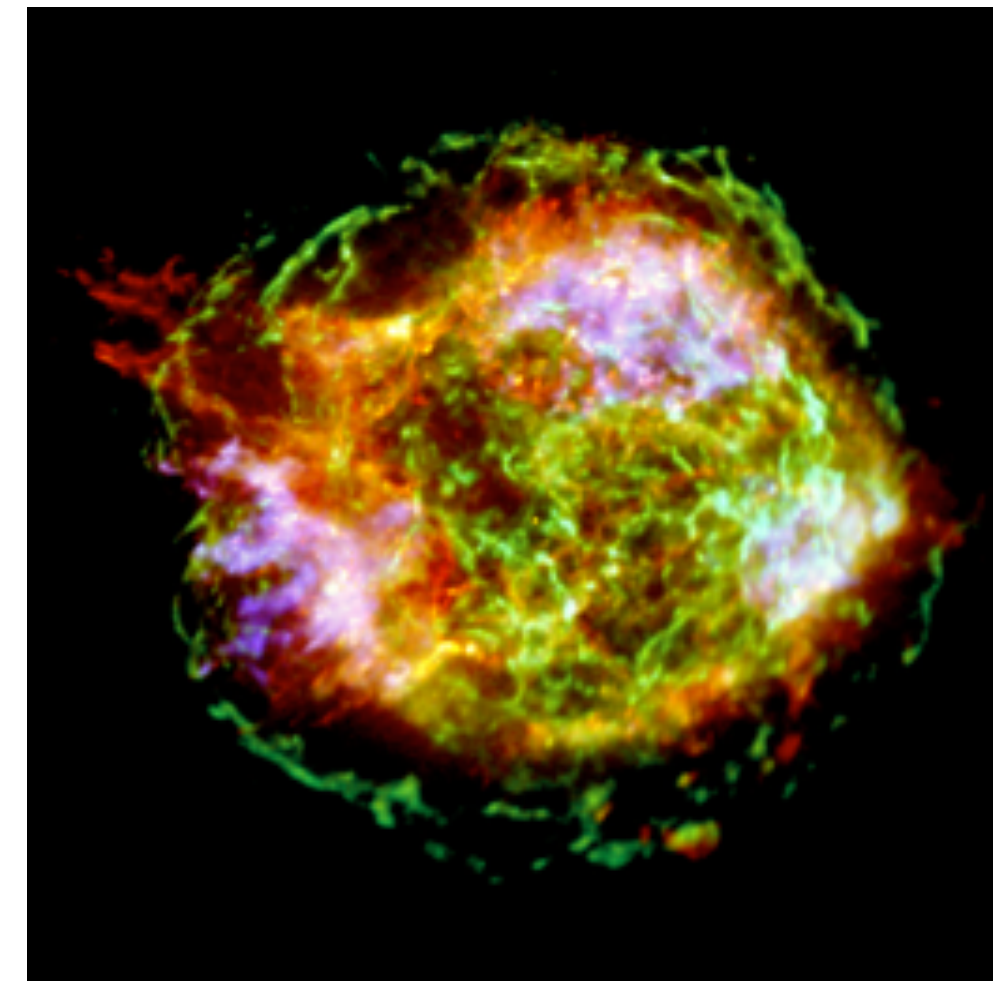
- *Gravitationally bound* system rotating with angular frequency ω must have $\omega^2 R < GM/R^2$ or $\omega^2/G < M/R^3 = (4\pi/3) M/V = (4\pi/3) \rho$
- System must have a high average density $\rho > (3/4\pi) \omega^2/G$
- For Crab ($\omega=2\pi/T_{\text{rot}}$) with $T_{\text{rot}}=33$ ms implies $\rho > 1.2 \times 10^{11} \text{g/cm}^3$.
- White dwarf average density $\sim 10^6 \text{g/cm}^3$. Central density of maximum mass WD could be 10^9g/cm^3 . Crab is denser than WD, must be neutron star. Nuclear density $3 \times 10^{14} \text{g/cm}^3$.

Electron capture at high densities

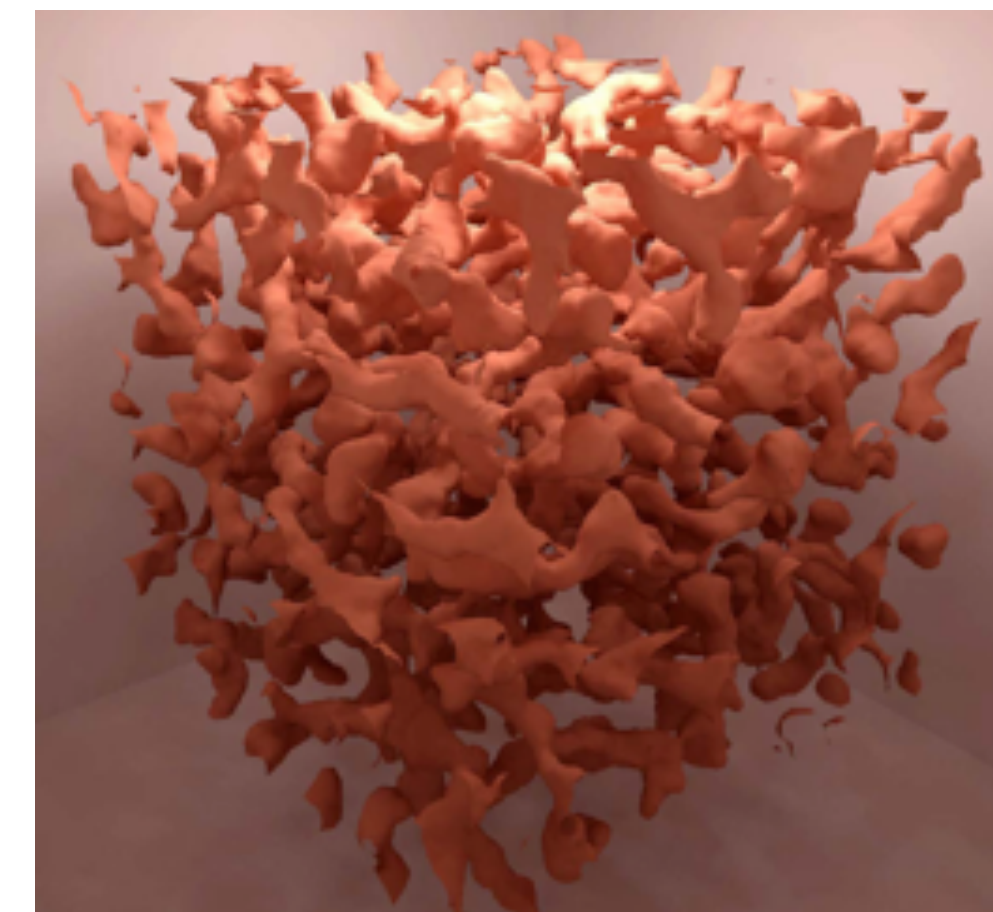
- Electron density above $10^{11} \text{g/cm}^3 < \rho = \rho_e m_n / Y_e$
- Electron fraction Y_e is electrons per baryon ~ 0.5 , nucleon mass m_n .
- Electron Fermi momentum k_F : $\rho_e = k_F^3 / 3\pi^2$. $k_F > 0.1 \text{fm}^{-1} = 20 \text{ MeV}$ (Units $\hbar c = 1 = 197.3 \text{ MeV fm}$)
- Large Fermi energy $E_F \sim k_F = 20 \text{ MeV} [(Y_e/0.5) (\rho/10^{11} \text{g/cm}^3)]^{1/3}$ drives electron capture $e + p \rightarrow n + \nu$
- Rotational period of 33 ms \rightarrow Crab is both very dense and neutron rich.

Neutron Rich Matter in Astrophysics

- Compress almost anything to $>10^{11} \text{g/cm}^3$ 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 ($T_c=10^{10} \text{K!}$), superfluid, color superconductor...*

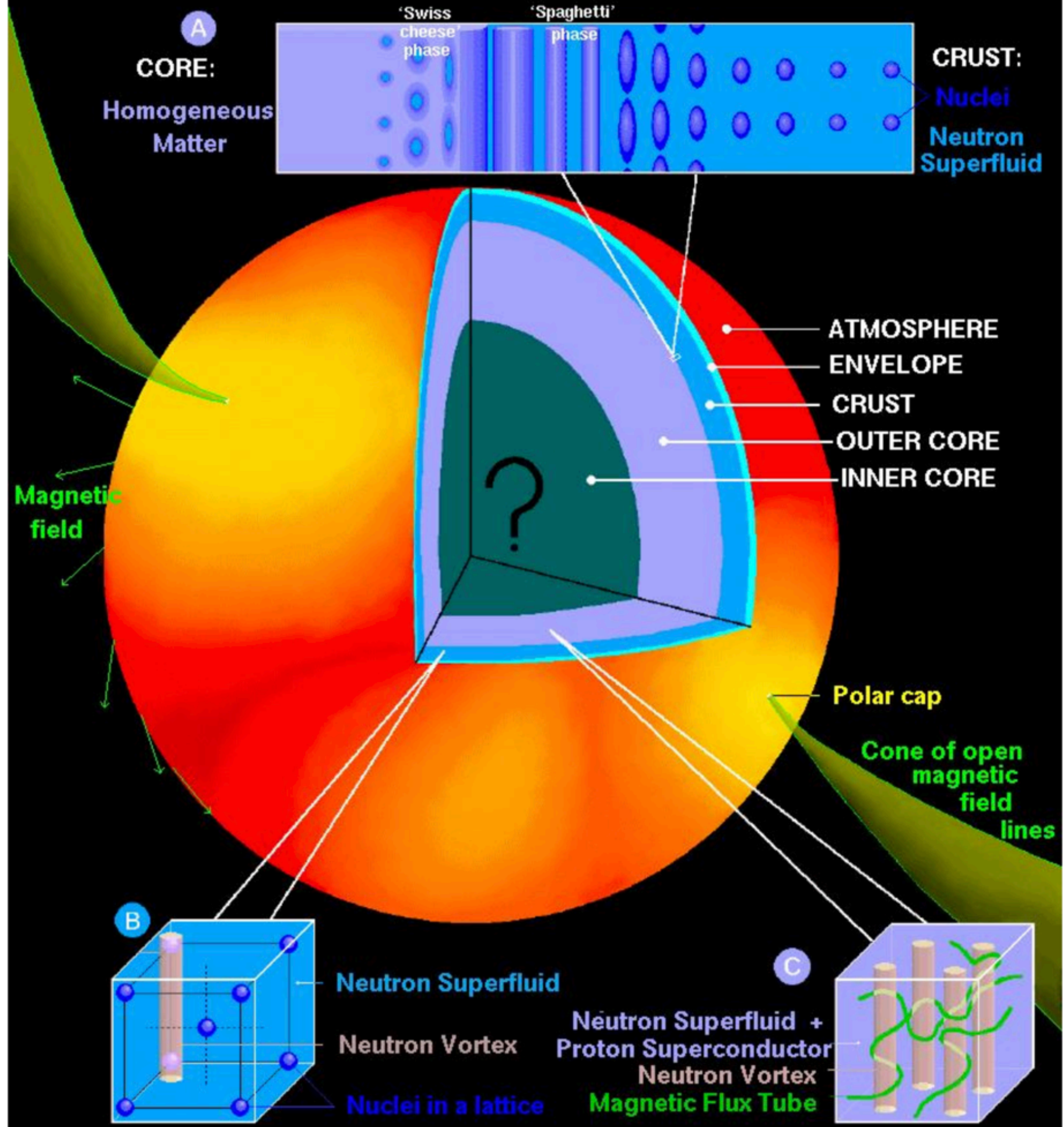


Supernova remnant
Cassiopea A in X-rays



MD simulation of Nuclear
Pasta with 100,000 nucleons

A NEUTRON STAR: SURFACE and INTERIOR



Dany Page

Tolman-Oppenheimer-Volkov Eq.

- Nonrelativistic hydrostatic equilibrium (pressure increases from weight of shell of material)

$$\frac{dp}{dr} = -\frac{G\rho(r)\mathcal{M}(r)}{r^2} \quad \mathcal{M}(r) = 4\pi \int_0^r r'^2 dr' \rho(r') = 4\pi \int_0^r r'^2 dr' \epsilon(r')/c^2$$

- General relativity: replace mass density by energy density/c² and include corrections from curvature of space ...

$$\frac{dp}{dr} = -\frac{G\epsilon(r)\mathcal{M}(r)}{c^2 r^2} \left[1 + \frac{p(r)}{\epsilon(r)} \right] \left[1 + \frac{4\pi r^3 p(r)}{\mathcal{M}(r)c^2} \right] \left[1 - \frac{2G\mathcal{M}(r)}{c^2 r} \right]^{-1}$$

- For Sun $2GM_{\text{sun}}/c^2=3$ km. Relativistic correction for $1.4M_{\text{sun}}$, 12 km star $2GM/c^2R=33\%$
- Need equation of state (EOS) $p=p(\epsilon,T,Y_e)$. Assume $T\sim 0$ and beta equilibrium $Y_e=Y_e(\epsilon)$ from equilibration via electron capture and neutron decay: $p + e \leftrightarrow n + \nu$
- Simple EOS $p=p(\epsilon,0,Y_e(\epsilon))$ or just $p=p(\epsilon)$. EOS that only depends on density is called barotropic.

TOV solution for free Fermi gas (Homework)

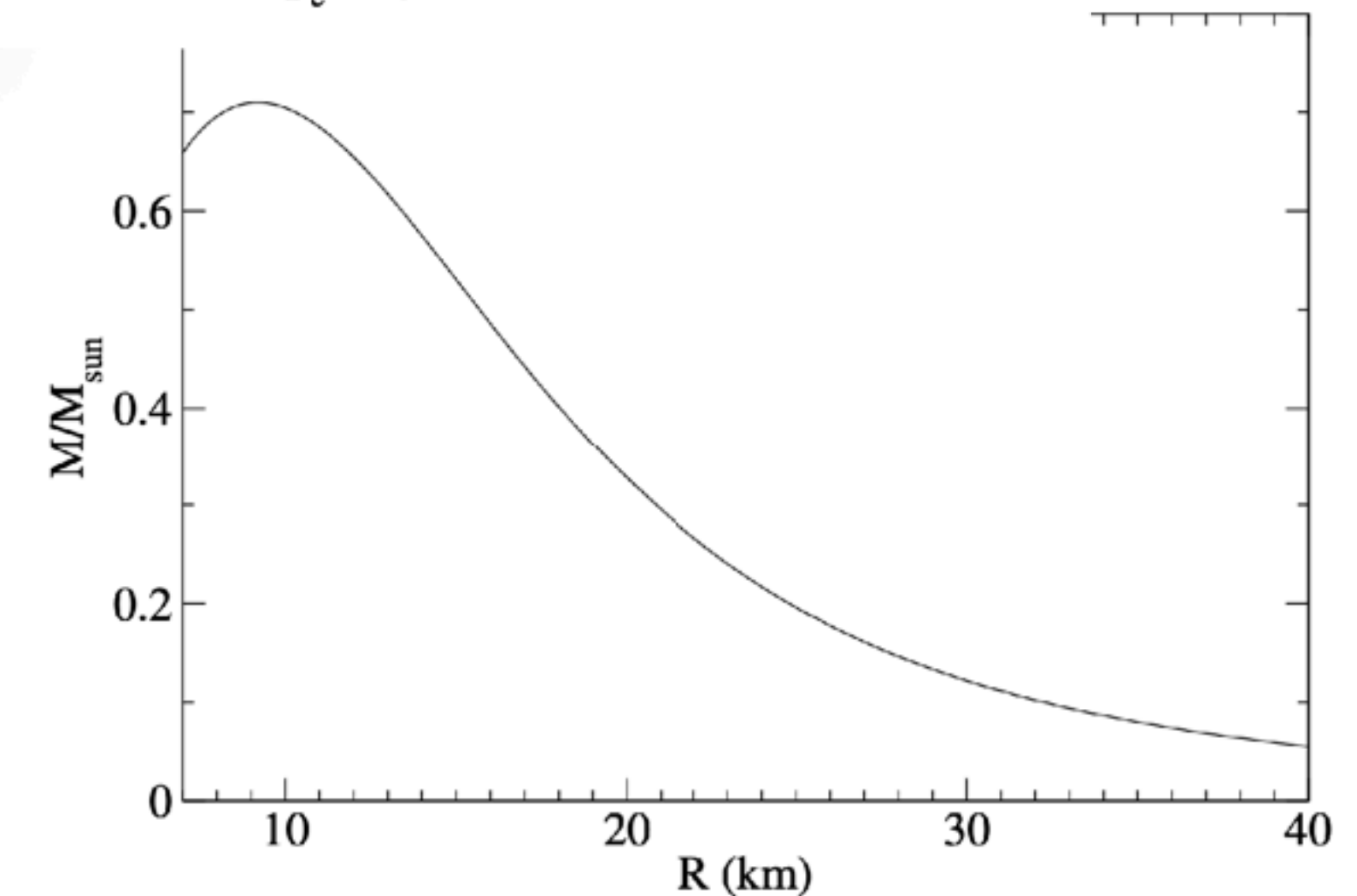
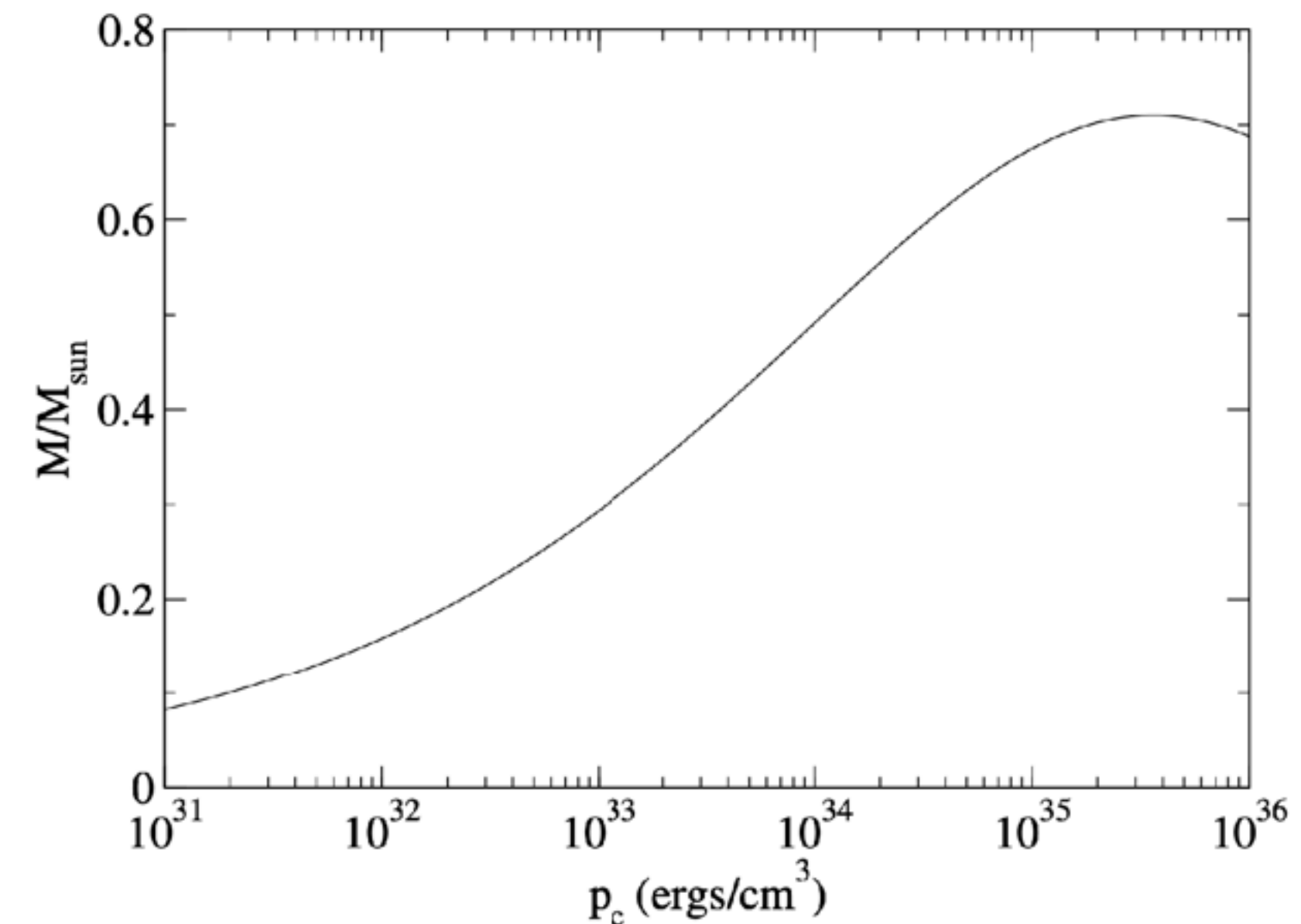
- Free neutron Fermi gas EOS.

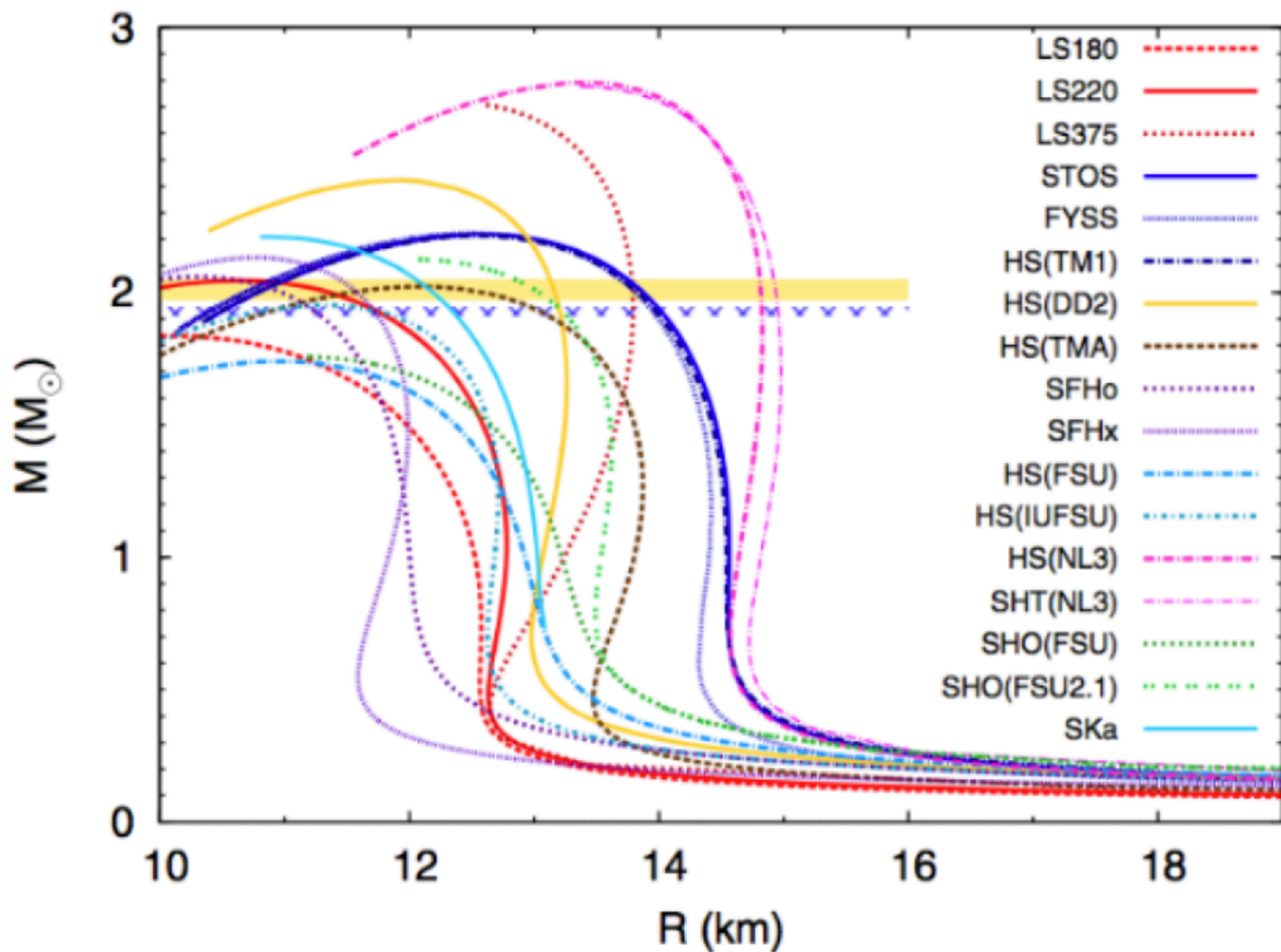
$$p = \frac{5}{24\pi^2} k_f^3 E_f - \frac{1}{8\pi^2} k_f E_f^3 + \frac{m^4}{16\pi^2} \ln \frac{k_f + E_f}{E_f - k_f},$$

$$\epsilon = \frac{1}{8\pi^2} (k_f^3 E_f + k_f E_f^3) - \frac{m^4}{16\pi^2} \ln \frac{k_f + E_f}{E_f - k_f}.$$

Interpolate table to find $\epsilon = \epsilon(p(r))$

- Integrate TOV eq. starting from $r=0$, $p=p_c$ till $p(R)=0$. Gives R and $M=M(R)$



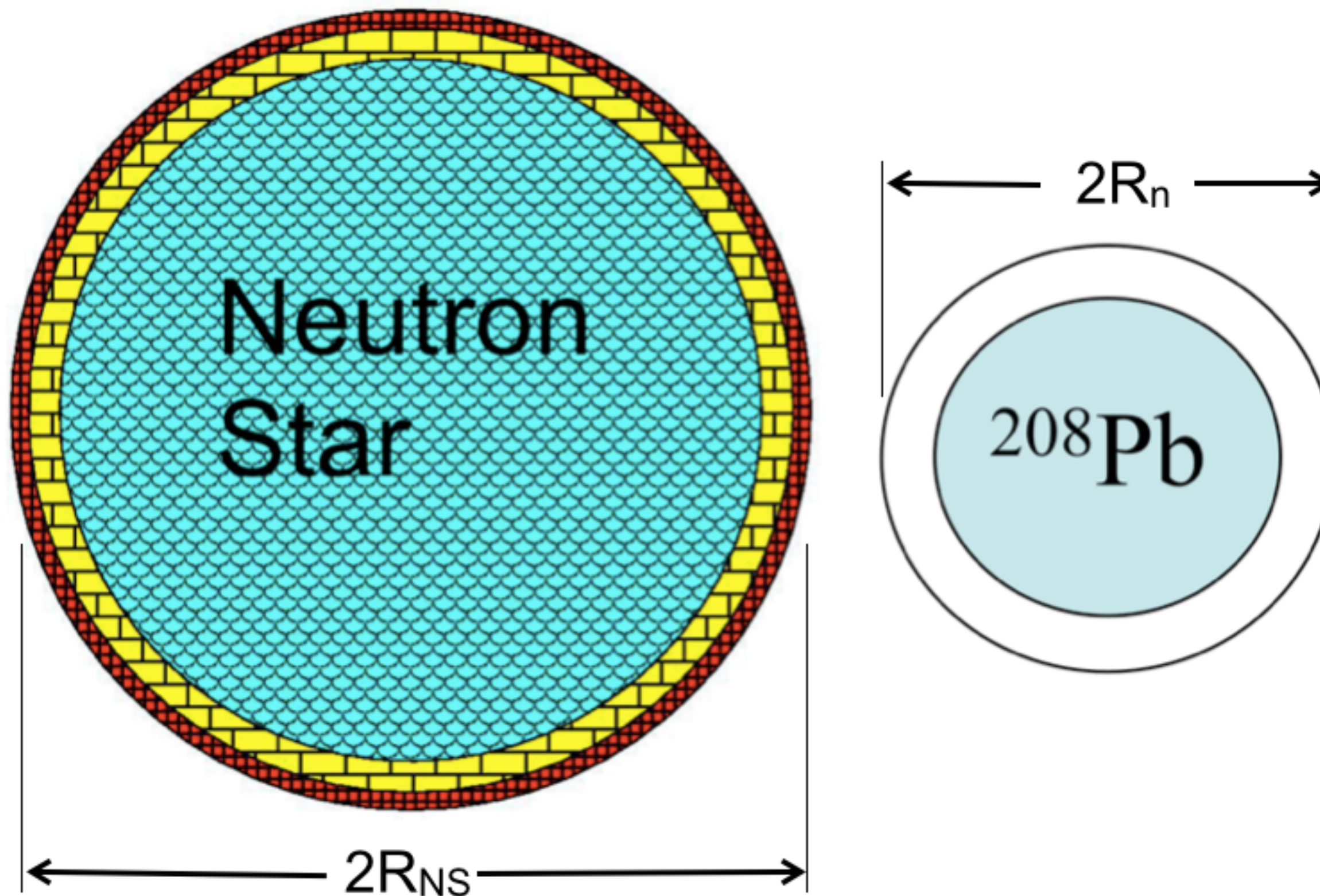


Equation of state of neutron rich matter

- 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 $\sim 3 \times 10^{14}$ g/cm³]
- **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.

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.

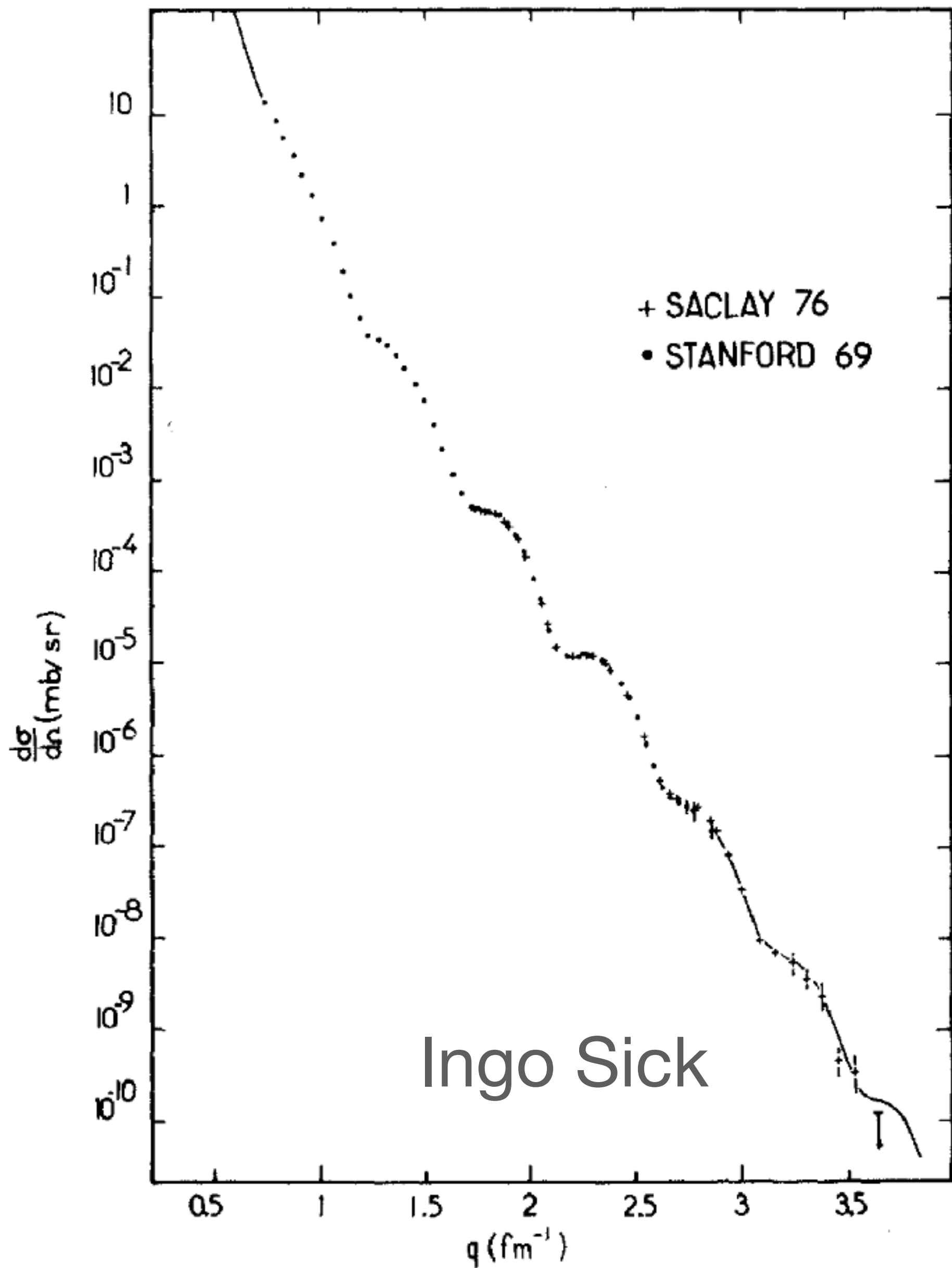


Neutron star is 18 orders of magnitude larger than Pb nucleus but both involve neutron rich matter at similar densities with the same strong interactions and equation of state.

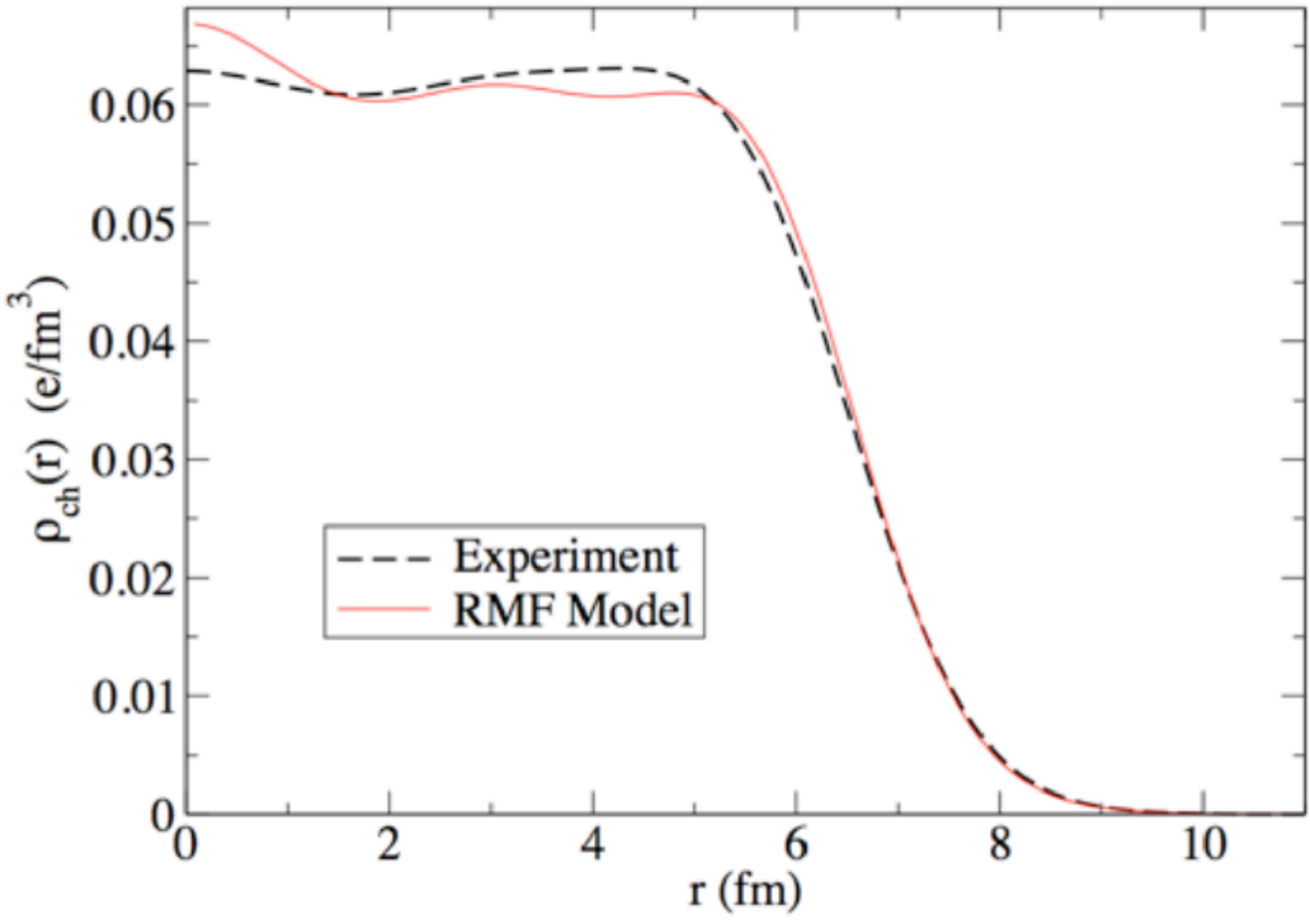
Pressure of neutron rich matter in laboratory

- Pressure is force/area. Measure force with spring and a ruler.
- For pressure of nuclear matter: spring is known surface tension and ruler is the PREX experiment.
- PREX ran at Jefferson Laboratory in Virginia





Charge Density of ^{208}Pb , accurately measured in elastic electron scattering.



Cross section measured over 12 orders of magnitude.

These elastic charge densities **are** our picture of the atomic nucleus!



1961 Nobel Prize
Robert Hofstadter

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

$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-} \approx \frac{G_F Q^2 |Q_W| F_W(Q^2)}{4\pi\alpha\sqrt{2}Z F_{ch}(Q^2)}$$

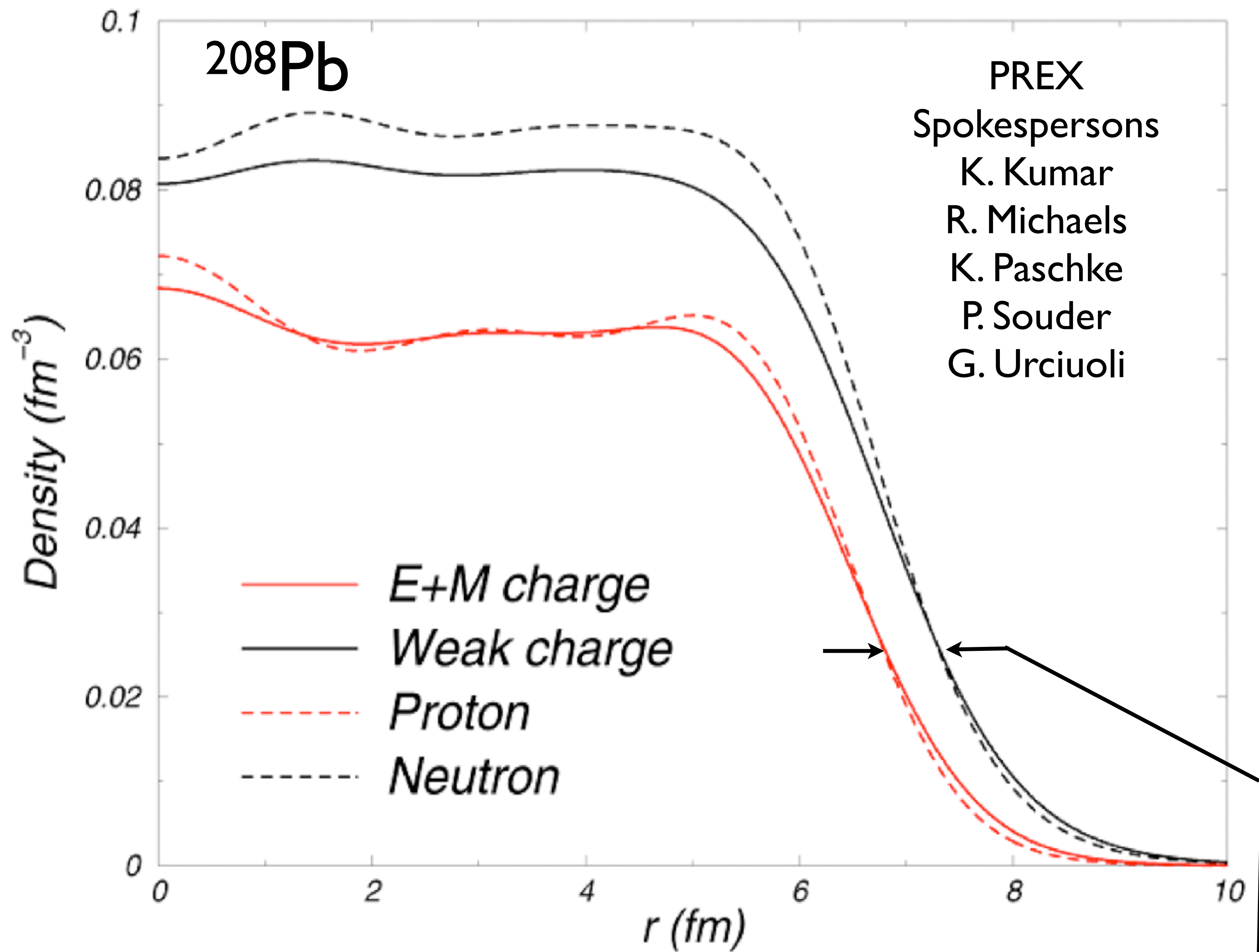
- A_{pv} from interference of photon and Z^0 exchange.

- Determines weak form factor

$$F_W(q) = \frac{1}{Q_W} \int d^3r j_0(qr) \rho_W(r)$$

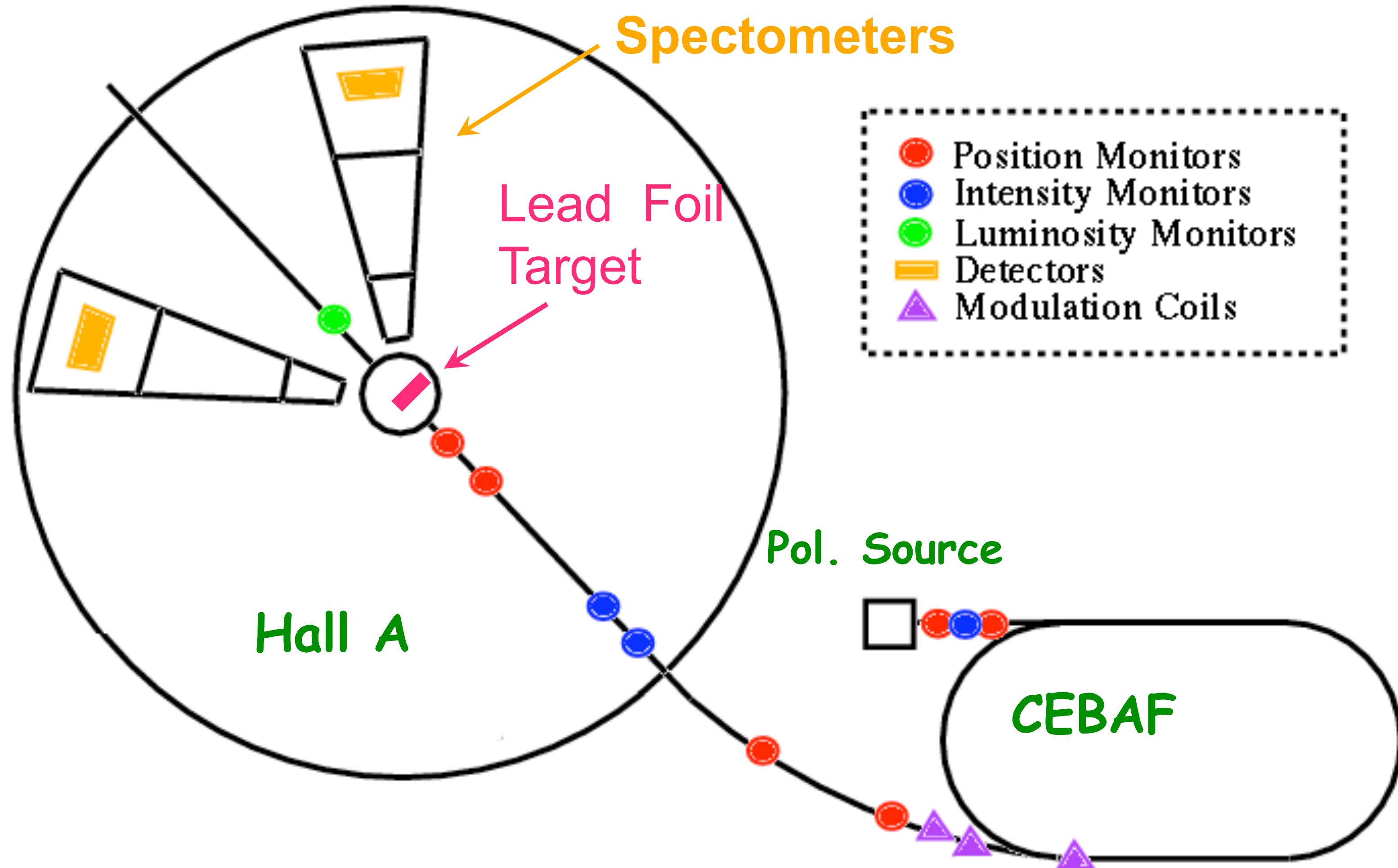
- Model independently map out distribution of weak charge in a nucleus.

- **Electroweak reaction free from most strong interaction uncertainties.**

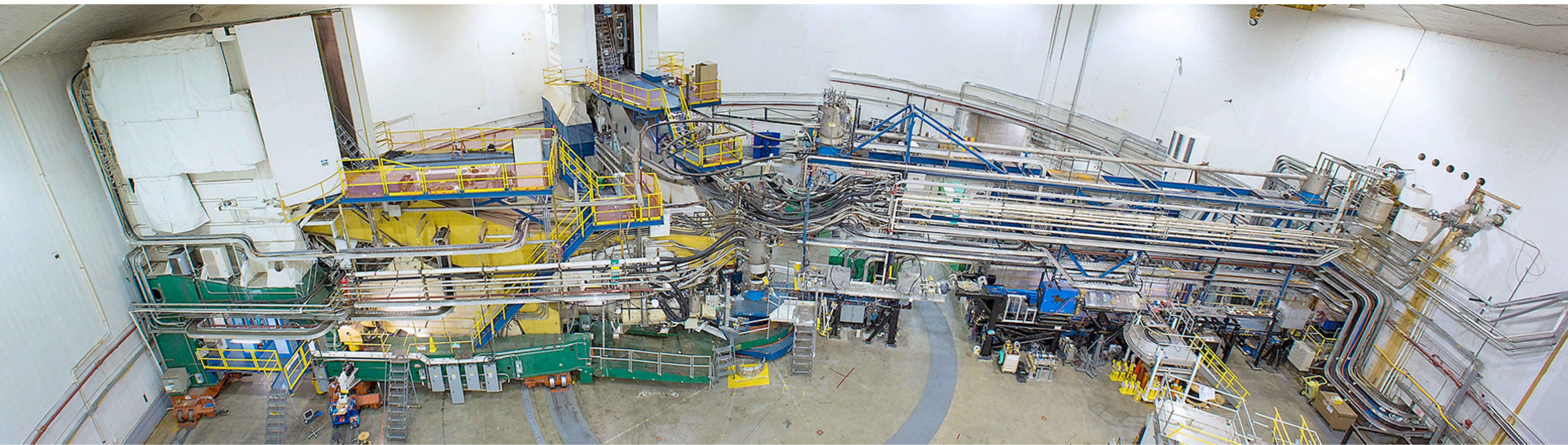


- PREX measures how much neutrons stick out past protons (neutron skin).

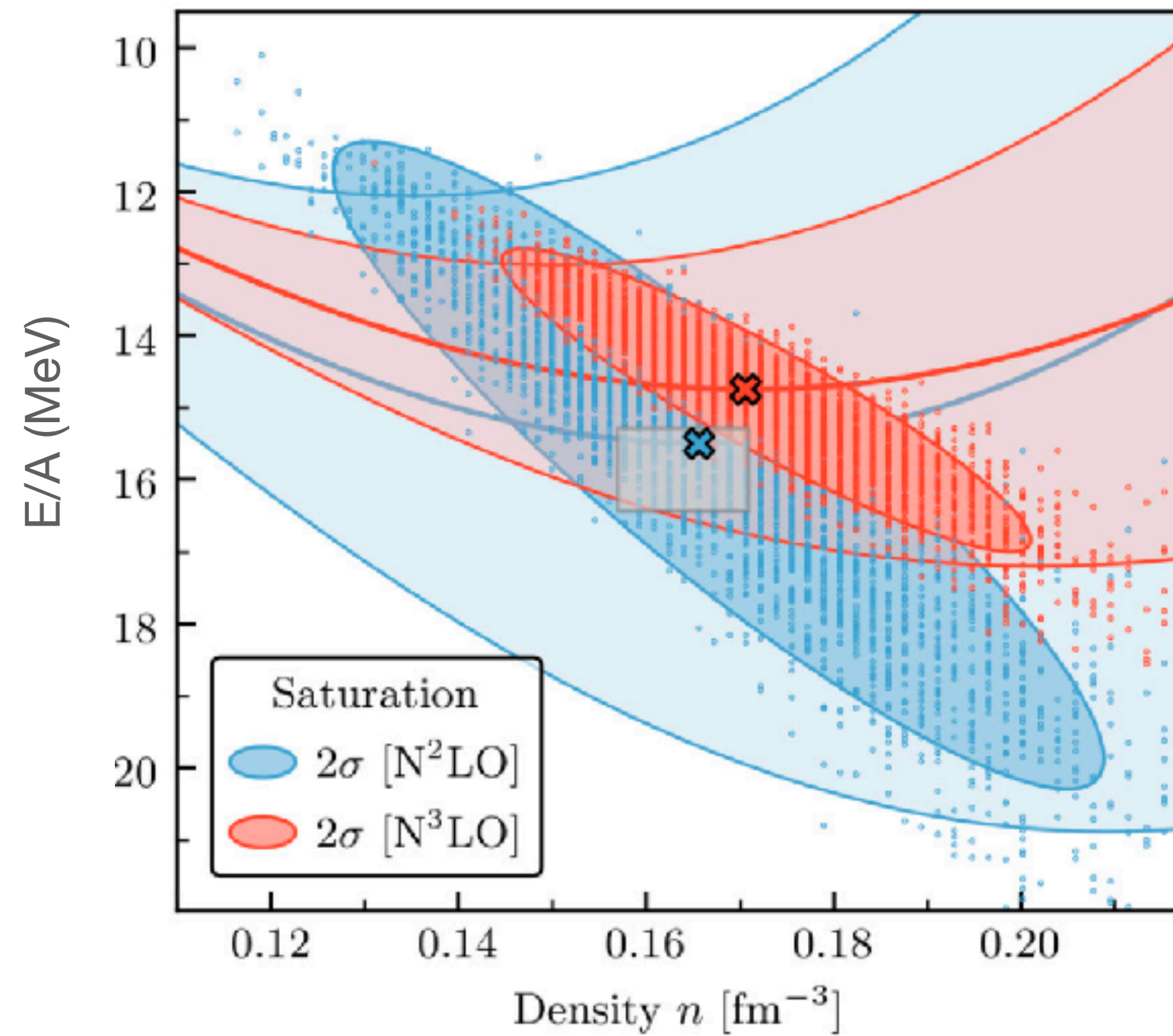
PREX in Hall A at JLab



R. Michaels



High Resolution Spectrometers in Hall A at Jefferson LAB



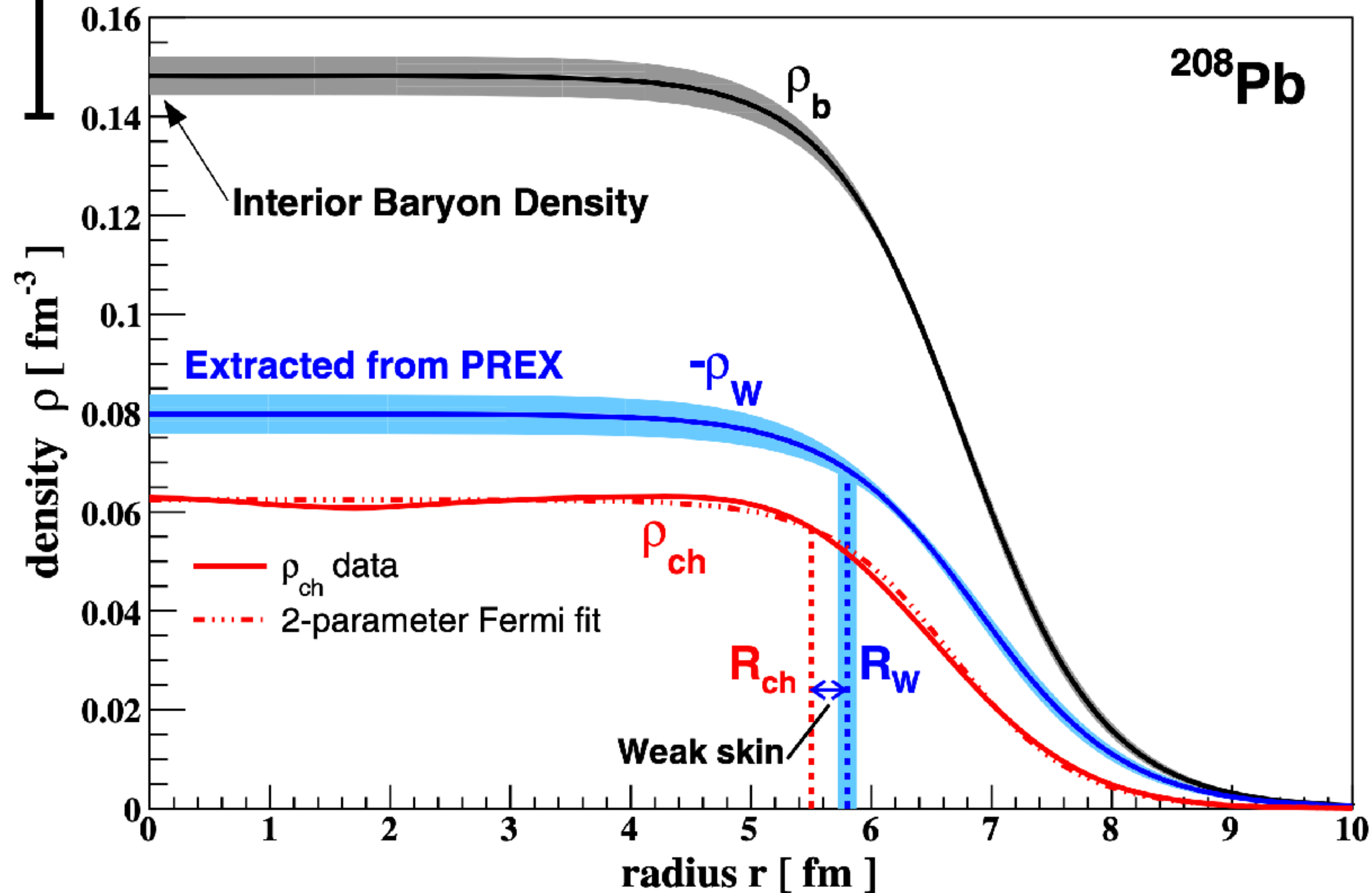
PREX results

$$R_W = 5.800 \pm 0.075 \text{ fm}$$

$$R_{ch} = 5.503 \text{ fm}$$

$$R_n - R_p = 0.283 \pm 0.071 \text{ fm}$$

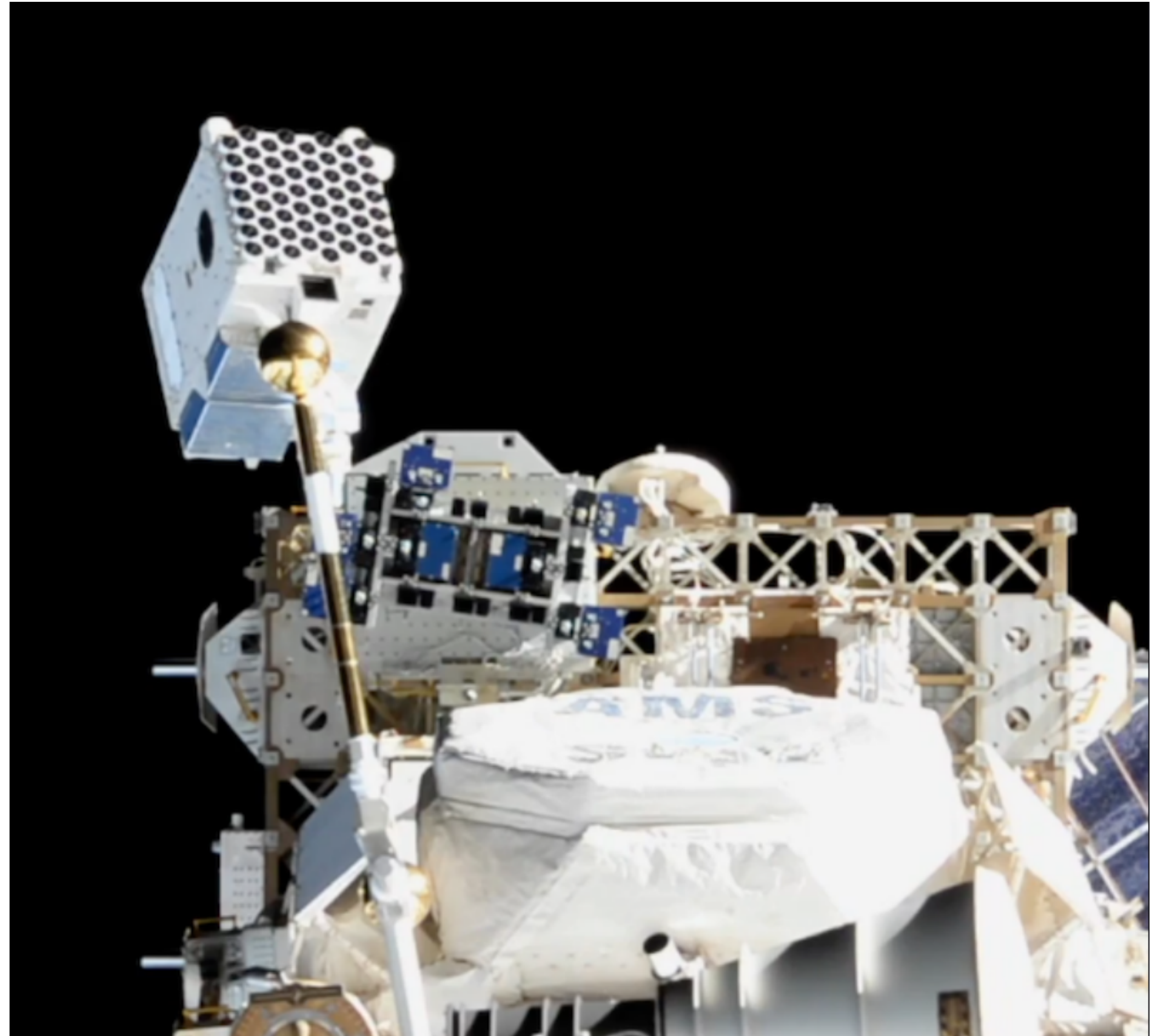
Drischler et al Chiral EFT calculation of nuclear density PRC 102, 054315



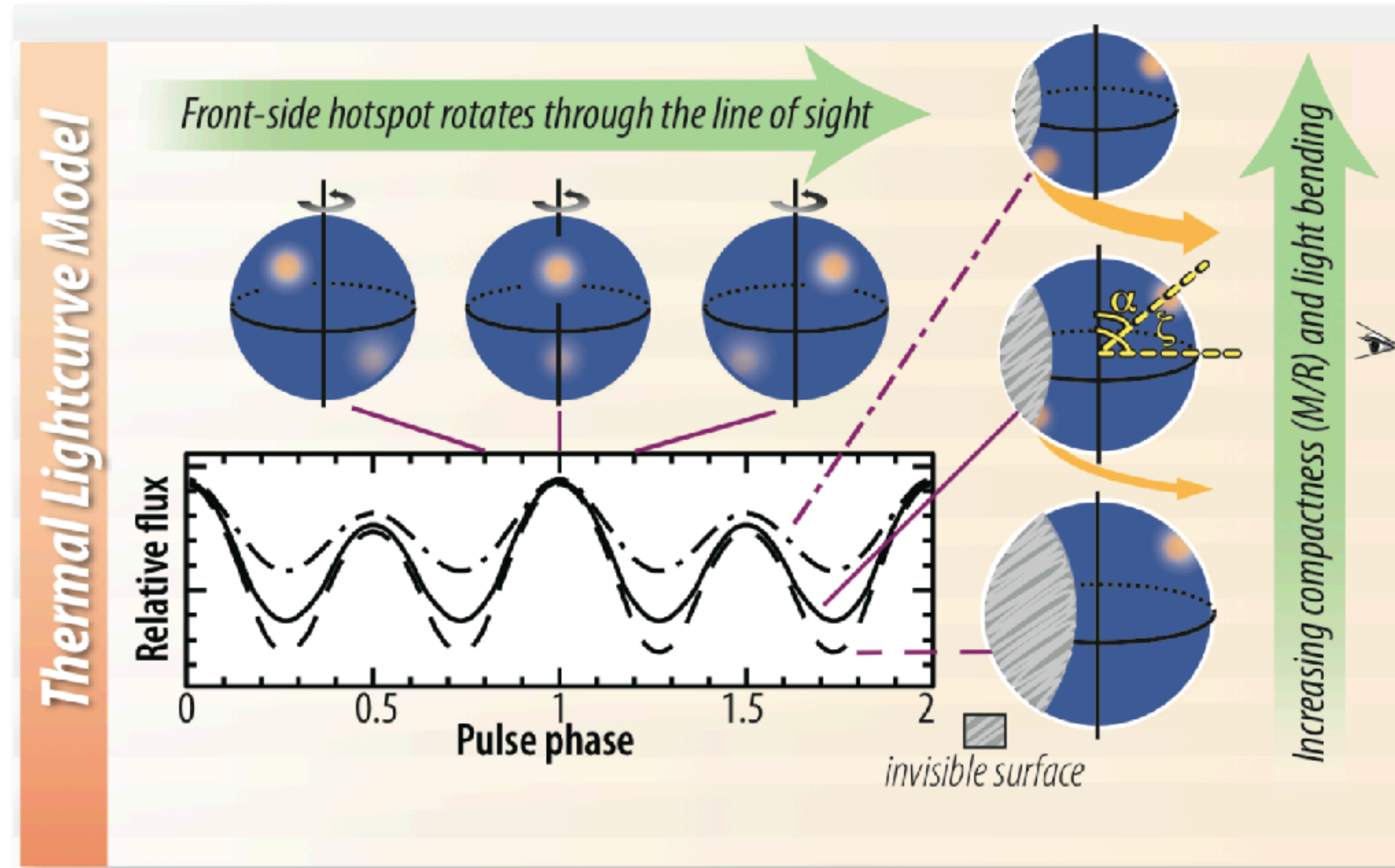
Measuring neutron star radii



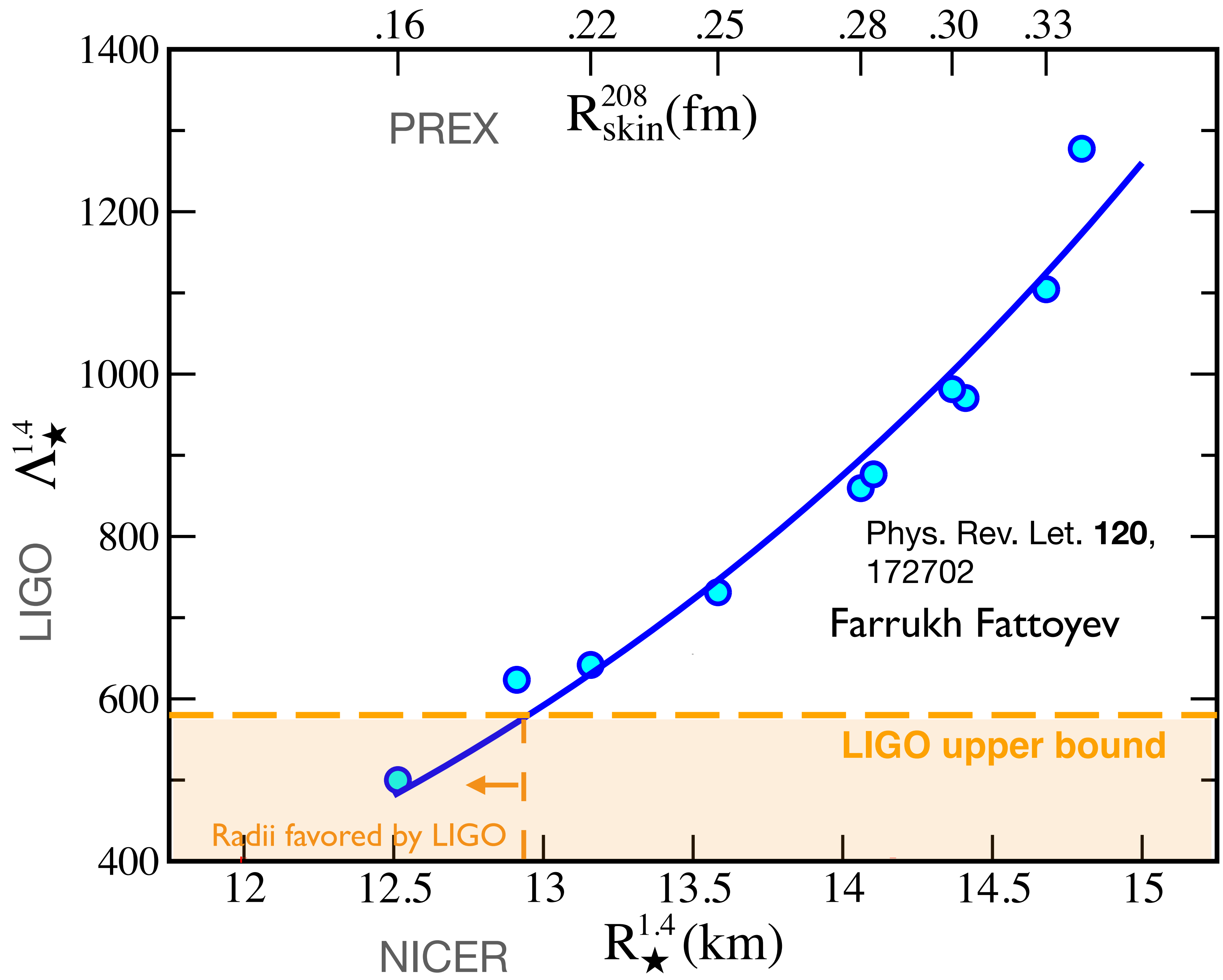
NICER X-ray telescope

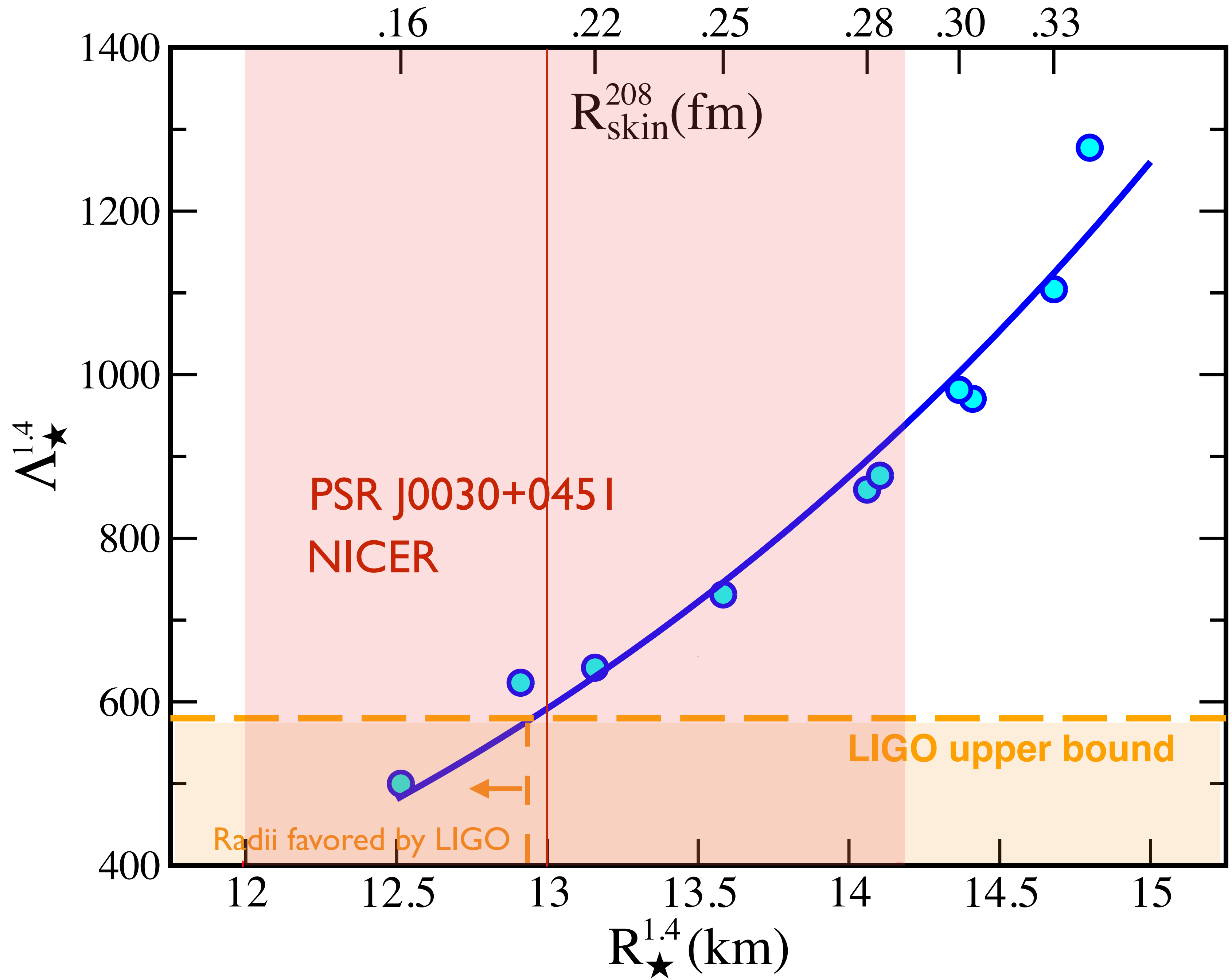


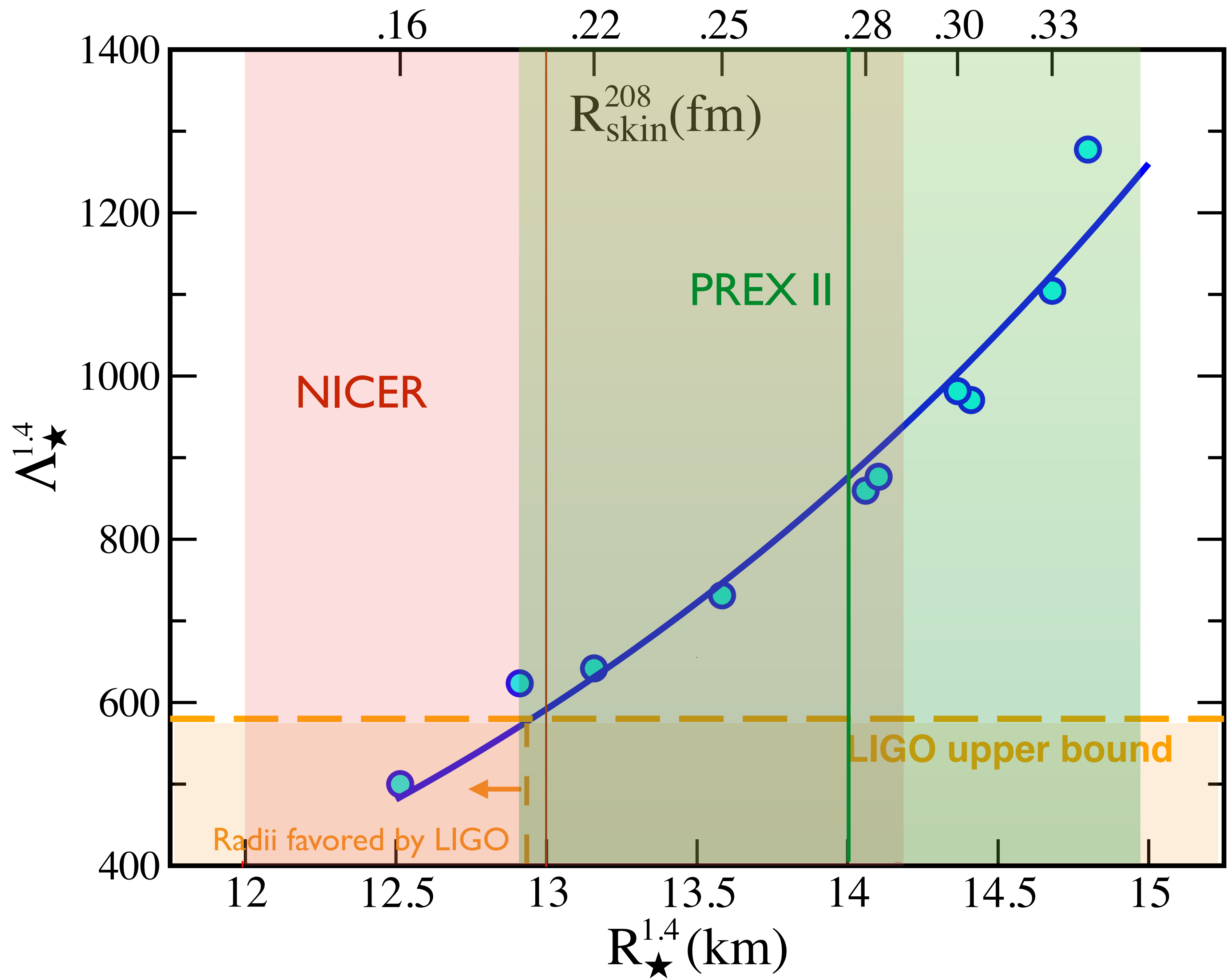
Reveal stellar structure through lightcurve modeling, long-term timing, and pulsation searches



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**...







Nature of dense matter

- NS masses, and radii determine EOS not deg. of freedom.
- What are neutron stars made of?
- How are quarks and gluons organized in NS interior?
- What are effective degrees of freedom (quark or hadron)?
- **Transport properties** such as viscosity, thermal conductivity, neutrino emissivity may provide important additional information. \Rightarrow NS cooling
- EOS is an important beginning of the search, not the end.

Experiment, theory, observation

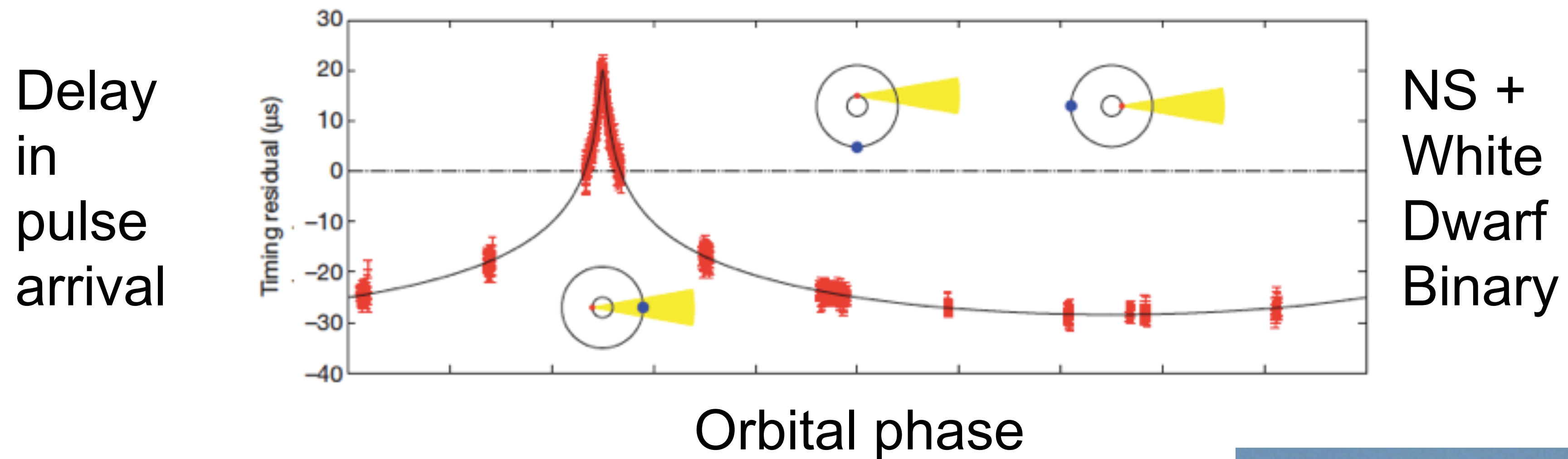
- In last 20 years what observational, experimental, or theoretical development has taught us the most about cold dense matter?
- **Theory:** Development of Chiral EFT with many nuclear structure and nuclear matter successes.
- **Observation:** Opening of GW astronomy with GW170817 and great promise for future.
- **Experiment:** Discovery of nearly perfect fluid at RHIC. Hot matter is strongly interacting QGP \longrightarrow Cold dense matter likely also strongly interacting.

What development in theory, experiment or observation, in last 20 years, has told us the most about dense matter?

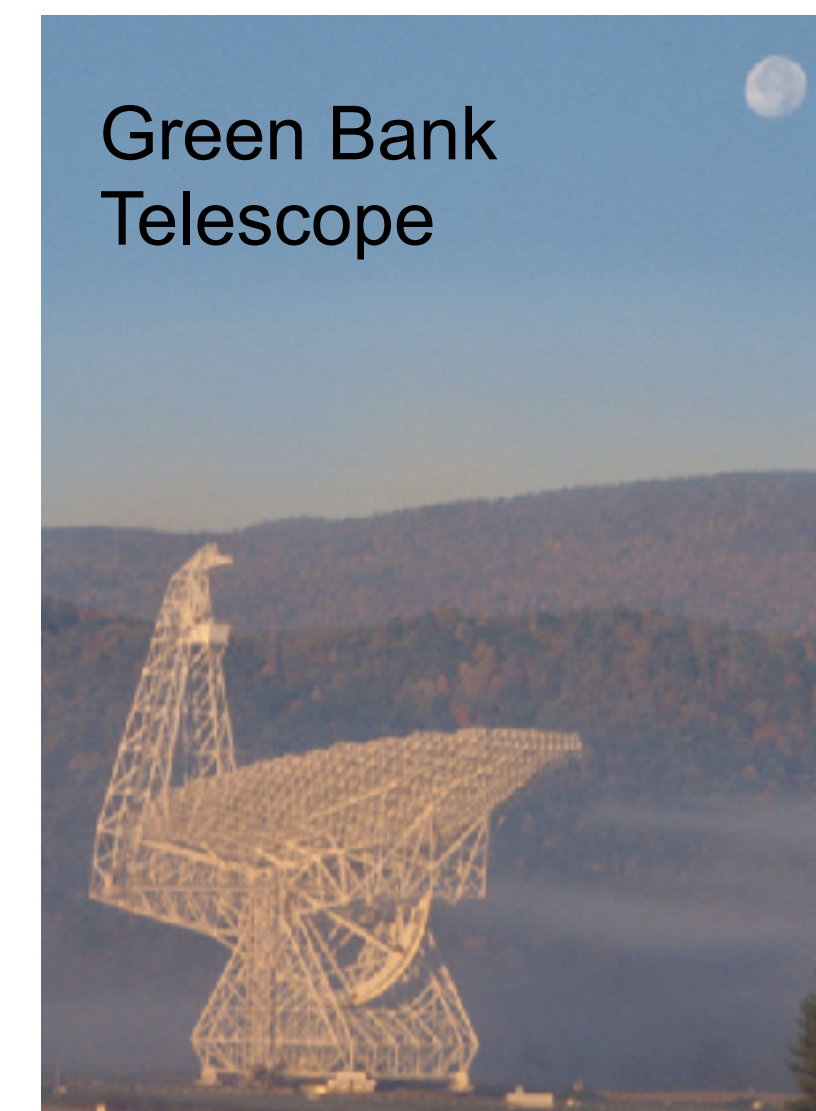
- And the winner is...

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

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



- 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.*



What holds up $2M_{\text{sun}}$ NS?

- Interaction of nucleon “hard cores”
- Omega mesons: Massive spin one vector meson exchange between like baryon charges is strongly repulsive. “Heavy photon” exchange between like charges.
- Strong repulsive vector interaction between quarks in NJL models...

Questions

- When and how does Chiral EFT break down at high ρ ?
- What holds up a $2M_{\text{sun}}$ NS?
- What is nature of dense matter? Is it organized in terms of quarks or hadrons?
- What are neutron stars made of?

Lecture II Supernovae and neutrinos

Lecture III Neutron star mergers and gravitational waves

End

Questions? Feel free to email horowitz@iu.edu. Thanks so much!