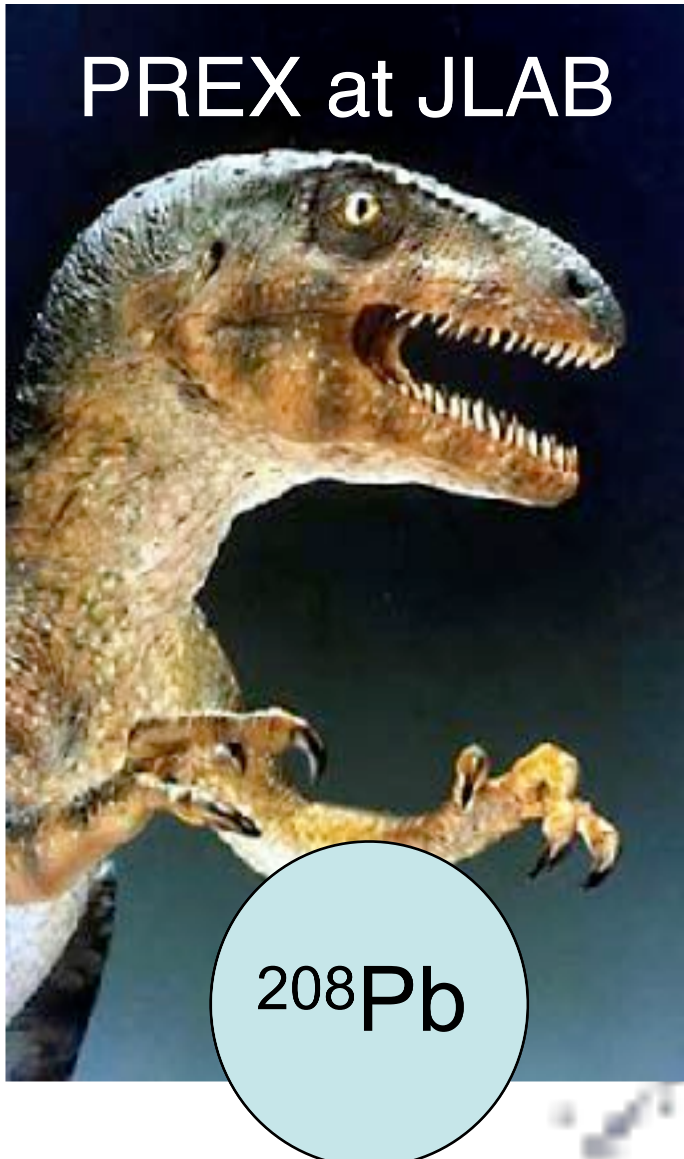
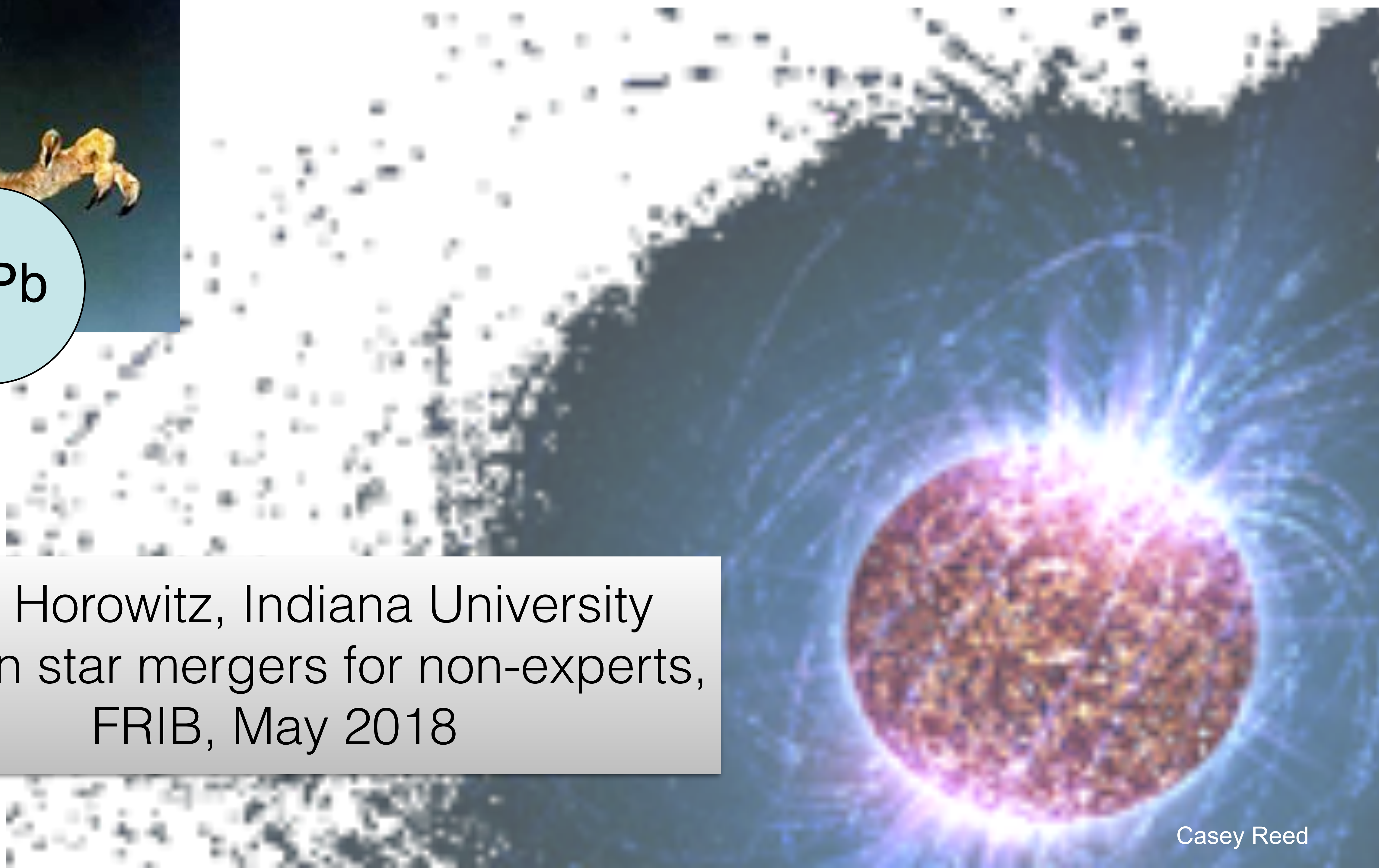


Dense matter and the equation of state

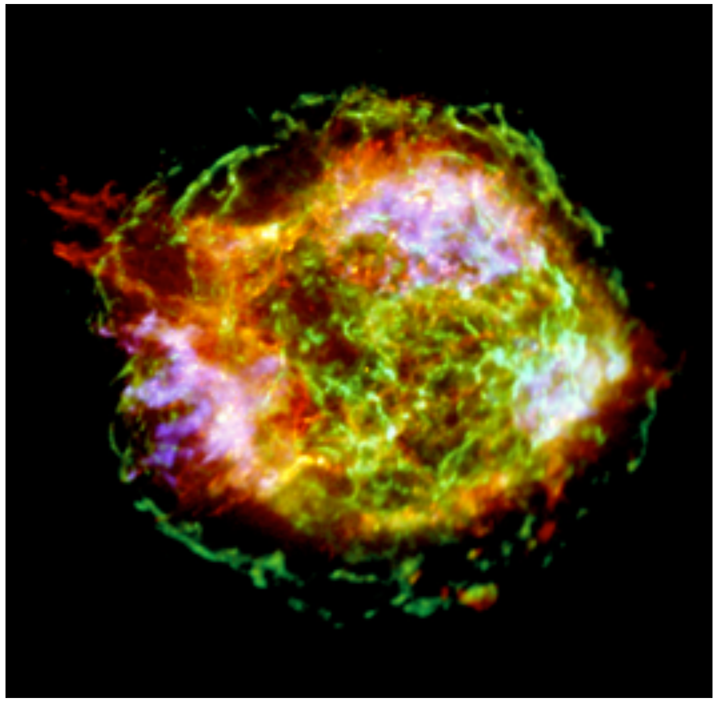


C. J. Horowitz, Indiana University

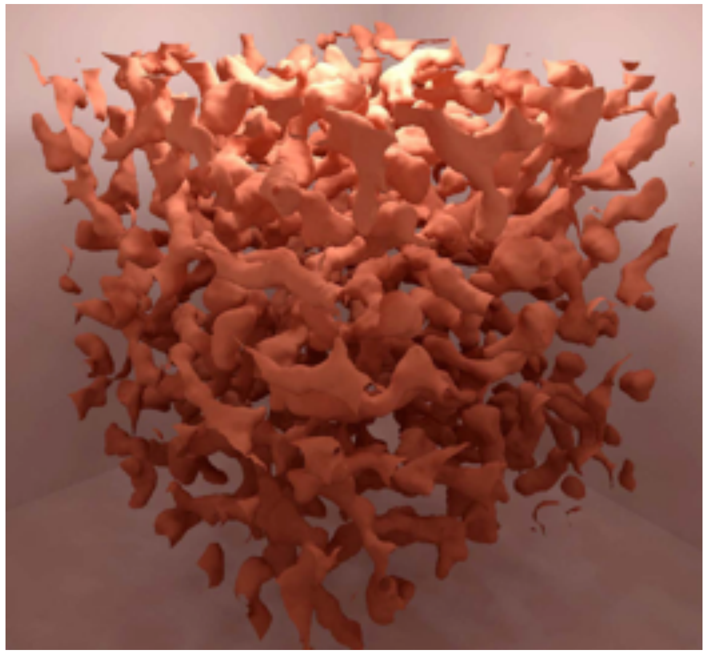
Neutron star mergers for non-experts, FRIB, May 2018

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 the 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, superfluid, color superconductor...*



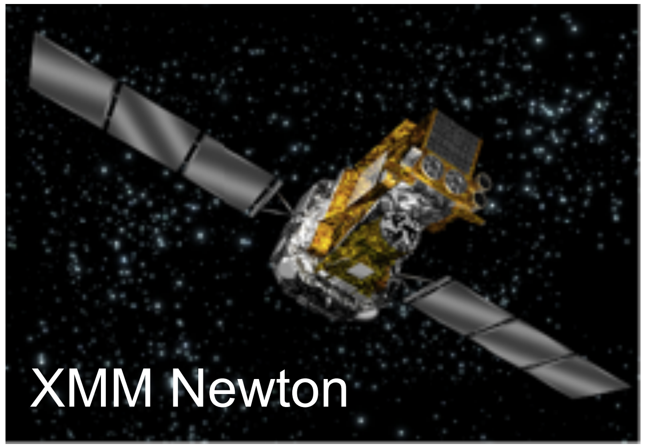
Supernova remanent Cassiopea A in X-rays

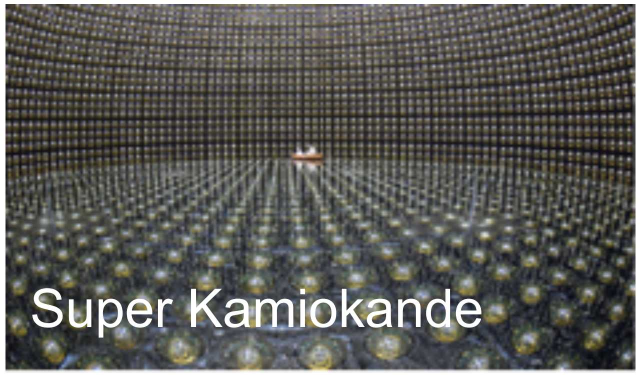


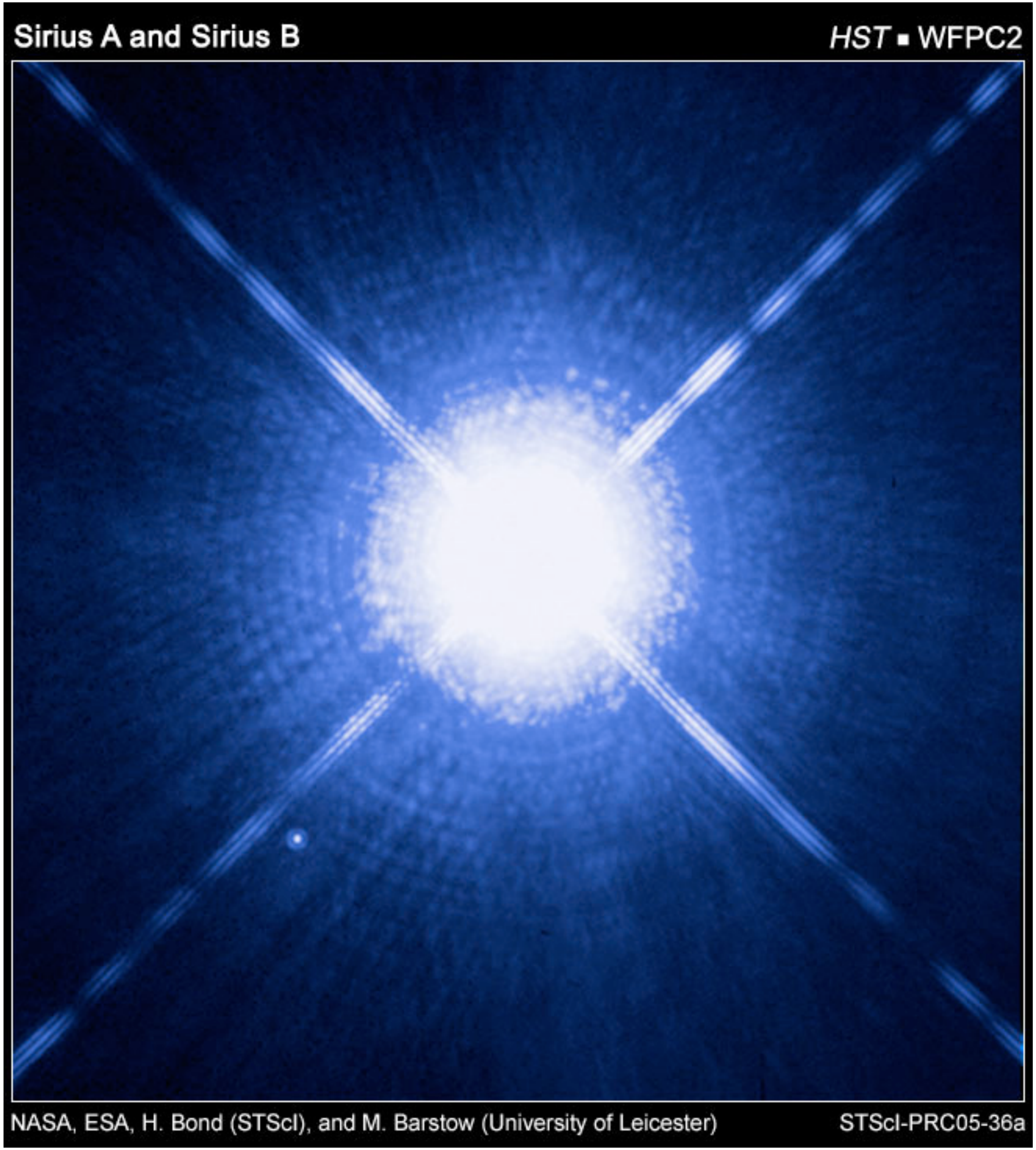
MD simulation of Nuclear Pasta with 100,000 nucleons

Probes of Neutron Rich Matter

- **Multi-Messenger Astronomy:** "seeing" the same event with very different probes should lead to fundamental advances. Often ***photons*** from *solid* neutron star crust, supernova ***neutrinos*** from low density *gas*, and ***gravitational waves*** from energetic motions of *liquid* interior of neutron stars.
- **Laboratory:** Nuclei are liquid drops so most experiments probe liquid n rich matter. However one can also study vapor phase be evaporating nucleons.
  - Electroweak measurements, Heavy ion collisions, Radioactive beams of neutron rich nuclei...
- **Computational:**
  - Chiral effective field theory (and MC calc. with phenomenological NN and NNN forces) depends on important and poorly known *three neutron forces*.
  - Chiral expansion does not converge at high densities. This strongly limits first principle calculations.
- Increases importance of laboratory experiments and astrophysical observations.






Sirius A and Sirius B
HST ▪ WFPC2
NASA, ESA, H. Bond (STScI), and M. Barstow (University of Leicester)
STScI-PRC05-36a

Sirius B

- Bessel was trying to measure parallax of nearby stars and in 1844 concluded that Sirius was a binary with an unseen companion.

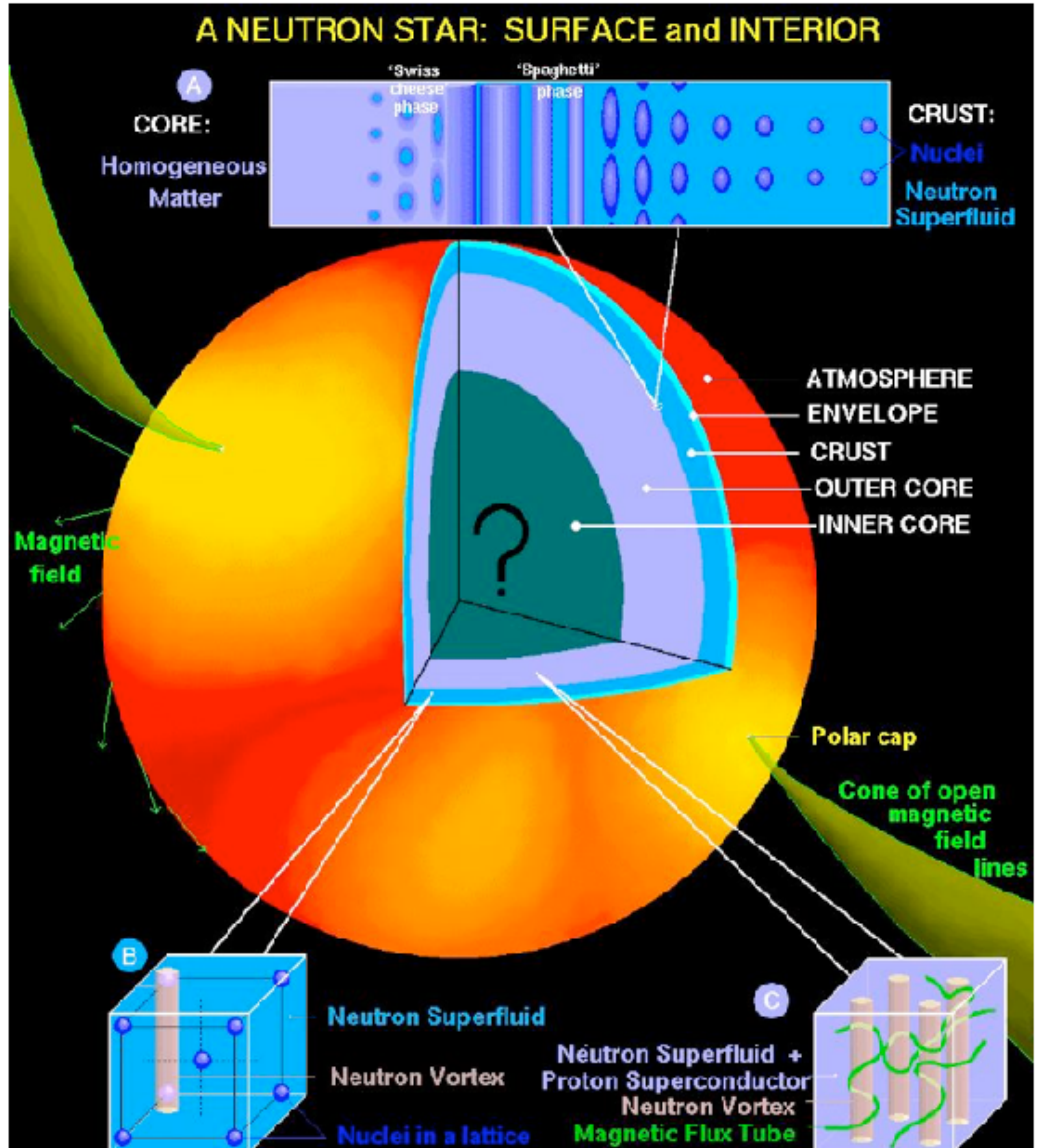
- In 1862 Alvan Clark with a new 18.5” refractor observed Sirius B (which is 10 magnitudes fainter than Sirius A).

- Sirius A $2M_{sun}$ main sequence star 8.7 light years away and 25 times brighter than sun.

- Srius B is in 50 year orbit around A.

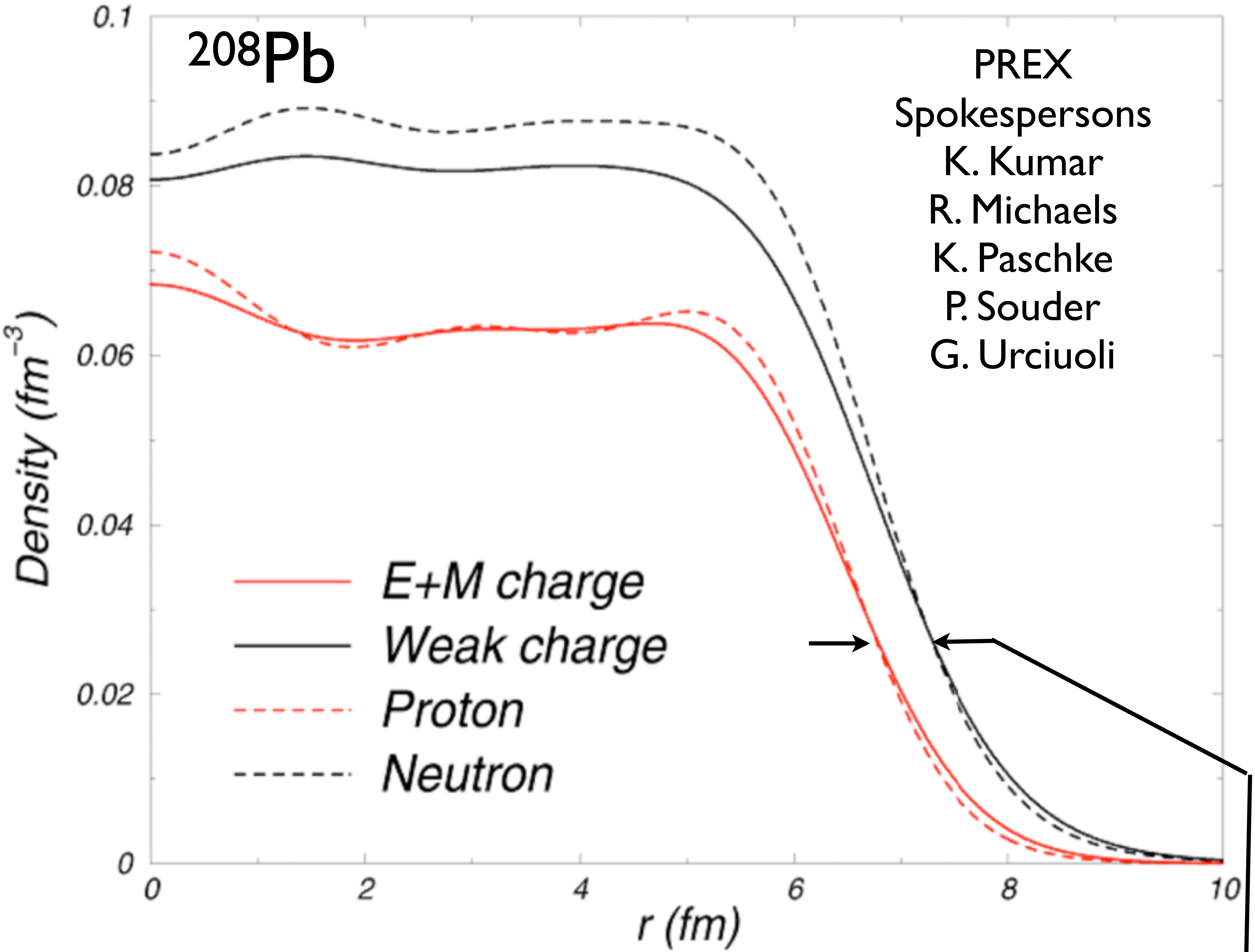
Neutron stars

- Neutron stars are formed from the collapse of a massive star in a supernova explosion.
- Mass ~1.4 M_{sun}, Radius ~10 km
- Solid crust ~ 1km thick (~10^{12} g/cm^3) over liquid outer core of neutron rich matter(~10^{15} g/cm^3).
- Possible exotic phase in center: de-confined quark matter, strange matter, meson condensates, color superconductor...
- Structure determined by Equation of State (pressure vs density) of n rich matter.
- Figure: **Dany Page,** UNAM



Equation of state

- Neutron star structure is determined by the equation of state: pressure as a function of energy density.
- $P = -dE/dV = -d(E/A)/d(V/A) = n^2 d(E/A)/dn$, V=volume.
- Here the baryon density $n=(A/V)$. [particles/fm^3]
- The energy density is $\epsilon=E/V=(E/A)n$. [MeV/fm^3]
- The mass density is $\rho=\epsilon/c^2$. [g/cm^3] Note that E includes rest mass mc^2. (In nonrel. limit $\rho=mn$)
- Calculate both $\epsilon(n)$, $P(n)$ and tabulate **$P=P(\epsilon)$ which is the equation of state.**



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

NS hydrostatic equilibrium

- As you go deeper into a NS pressure p rises because of weight of material above you.

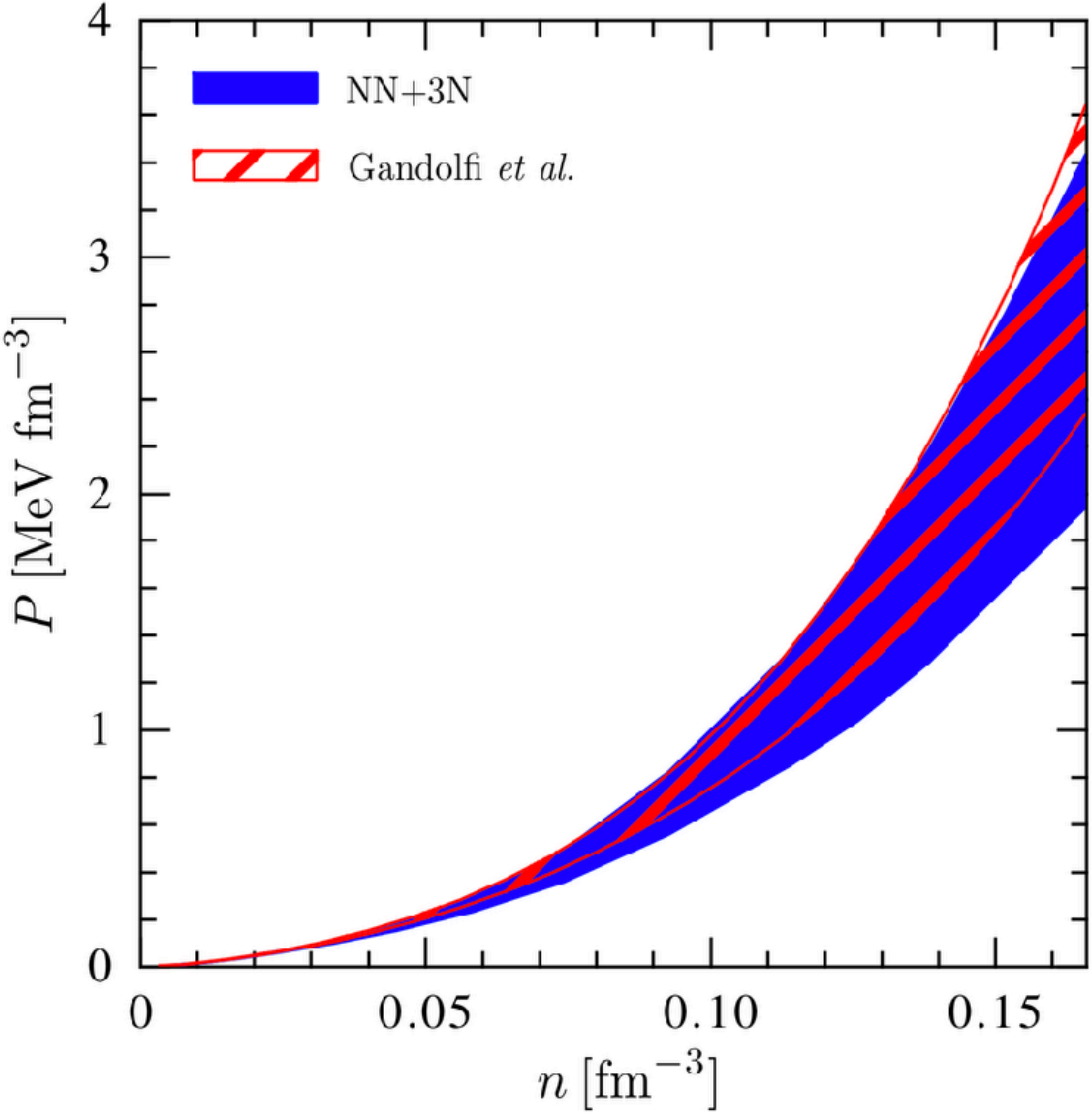
$$\frac{dp}{dr} = -\frac{G\rho(r)\mathcal{M}(r)}{r^2} = -\frac{G\epsilon(r)\mathcal{M}(r)}{c^2r^2}$$
$$\frac{d\mathcal{M}}{dr} = 4\pi r^2\rho(r) = \frac{4\pi r^2\epsilon(r)}{c^2}$$
$$\mathcal{M}(r) = 4\pi\int_0^r r'^2 dr'\rho(r') = 4\pi\int_0^r r'^2 dr'\epsilon(r')/c^2$$

- Above assumes Newtionian gravity. See NS for undergraduates R. R. Silbar, S. Reddy, Am. J. Phys. **72** (2004) 892

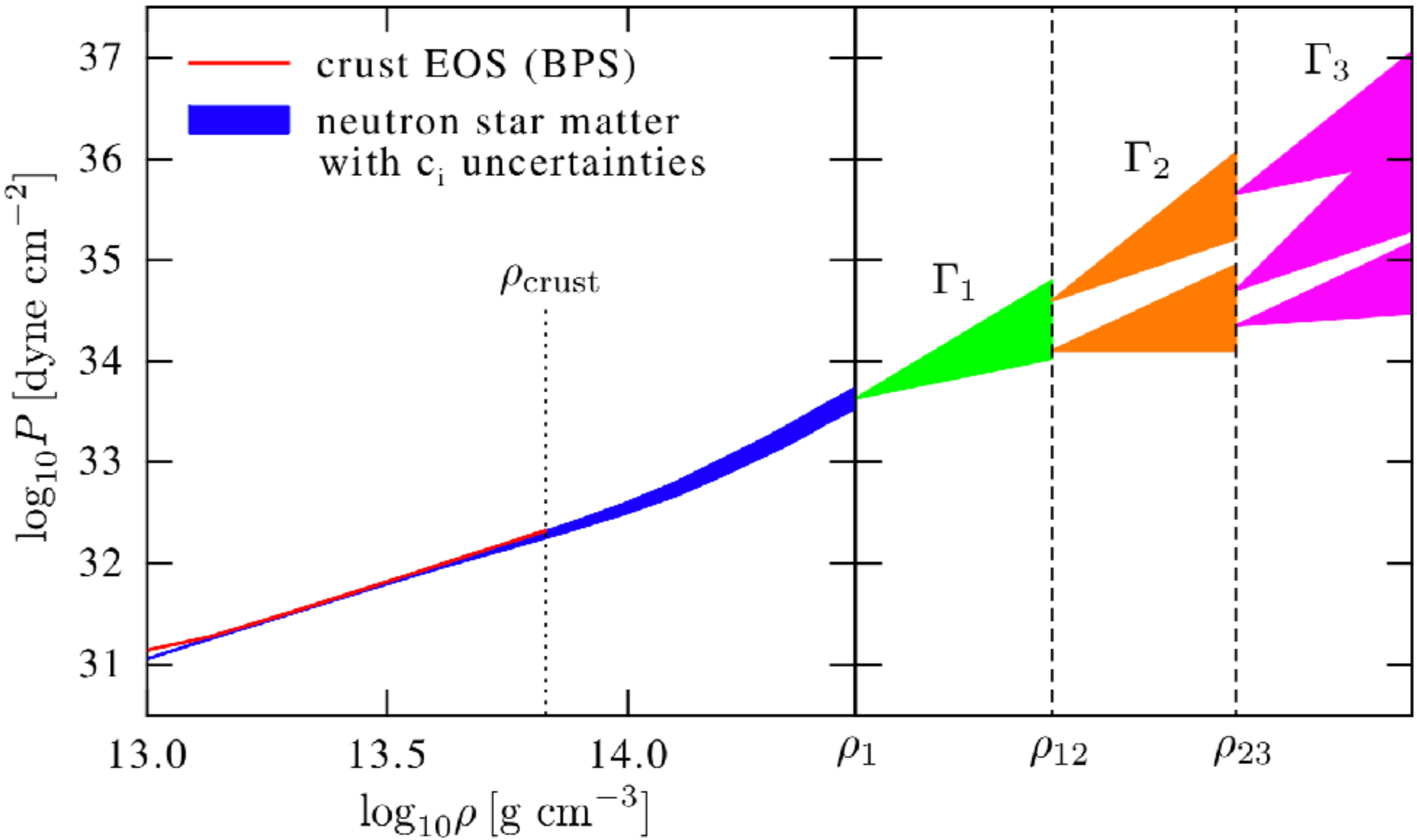
TOV Equation

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

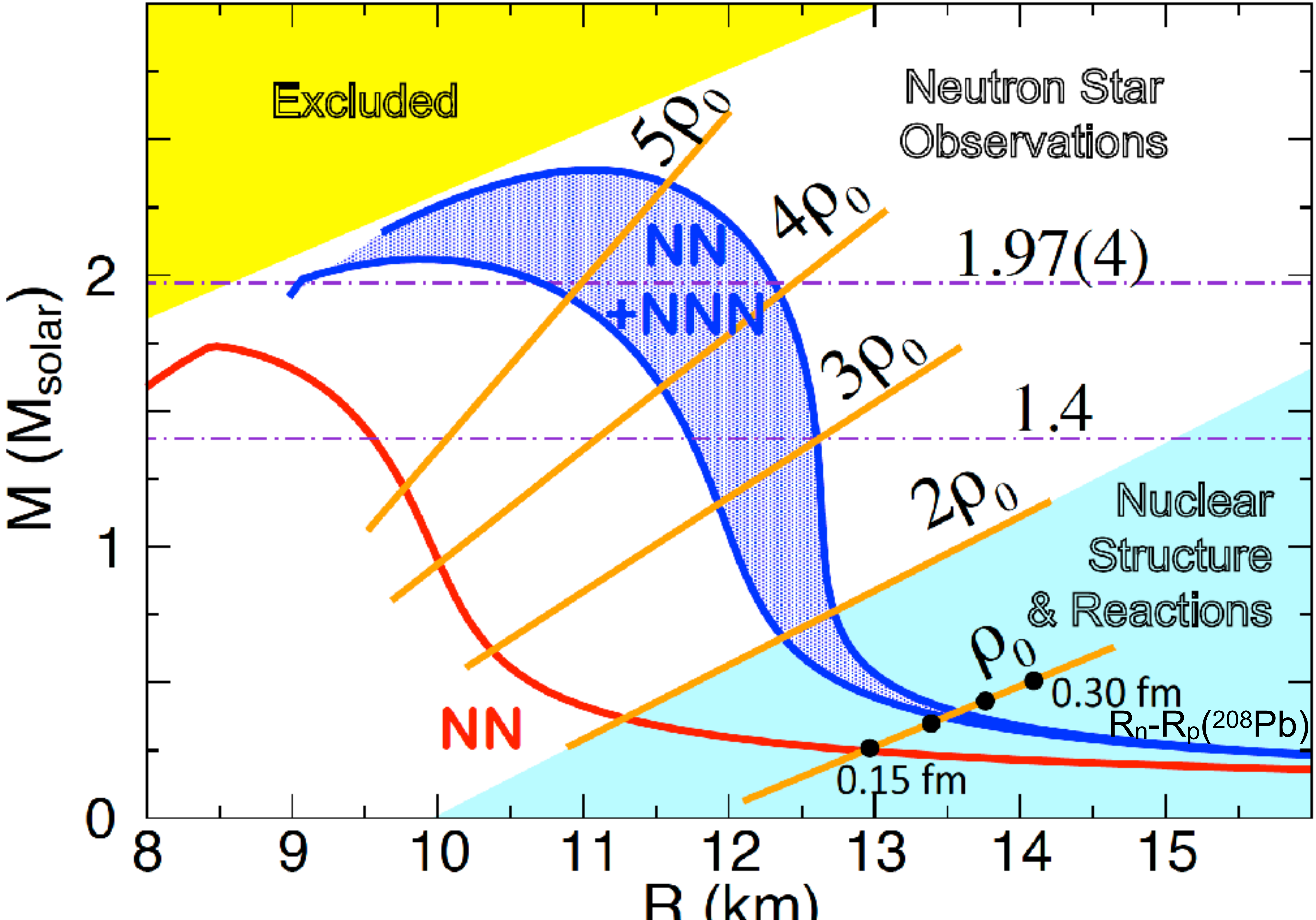
- First two terms in brackets are special relativistic corrections while last term is a GR correction from the curvature of space.
- All three terms act to increase p in star. Effects are nonlinear, eventually gravity wins and star will collapse to black hole —> maximum mass for NS.
- For given EOS p=p(ϵ) guess central p and ϵ(p). Integrate p outward from r=0 until p=0. This gives radius and mass of star. Repeat for different central p to determine mass of NS as a function of radius.



NN+3N
Gandolfi et al.
4
3
2
1
0
0.05
0.10
0.15
P [MeV fm^{-3}]
n [fm^{-3}]



crust EOS (BPS)
neutron star matter
with c_i uncertainties
ρ_{crust}
Γ_1
Γ_2
Γ_3
$\log_{10} P$ [dyne cm^{-2}]
$\log_{10} \rho$ [g cm^{-3}]
37
36
35
34
33
32
31
13.0
13.5
14.0
ρ_1
ρ_{12}
ρ_{23}

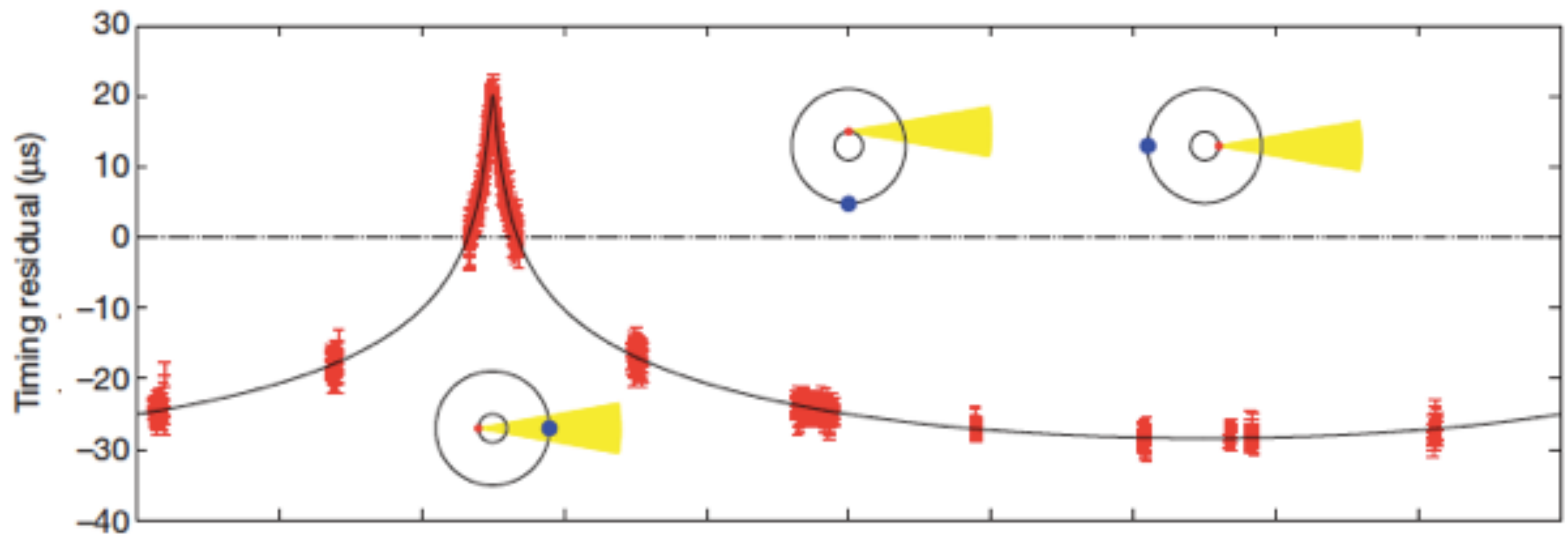


Gandolfi, Carlson, Reddy

Discovery of $2M_{sun}$ Neutron Star

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

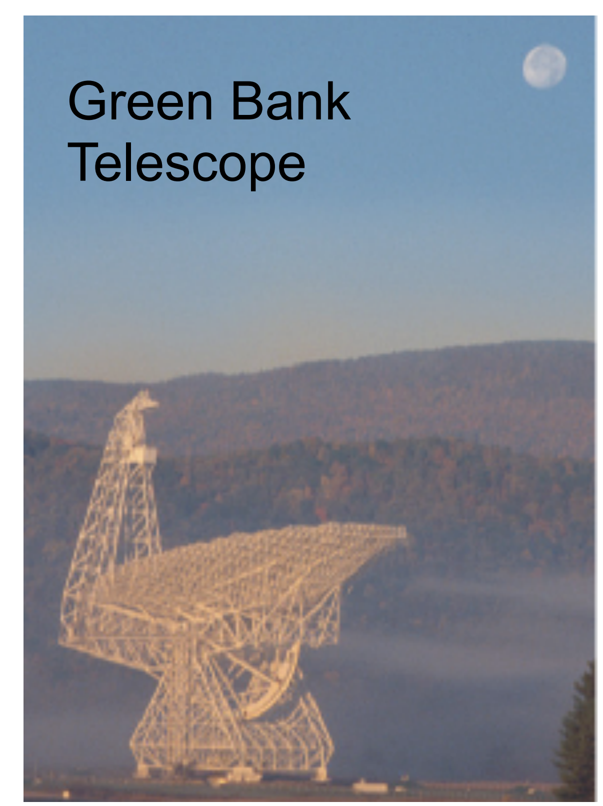
Delay in pulse arrival



NS + White Dwarf Binary

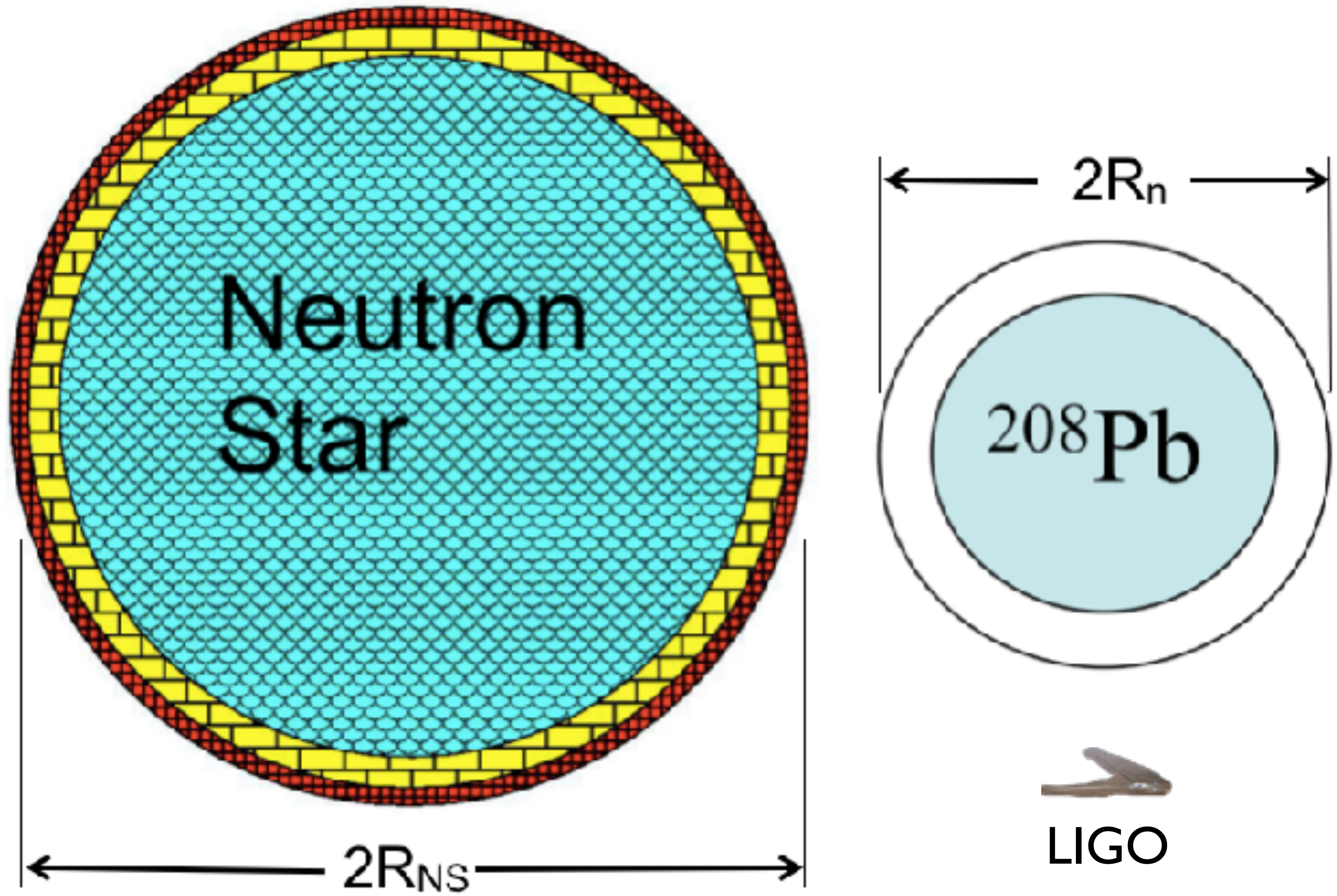
Orbital phase

- 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.*



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.

Polarizability of giant nuclei

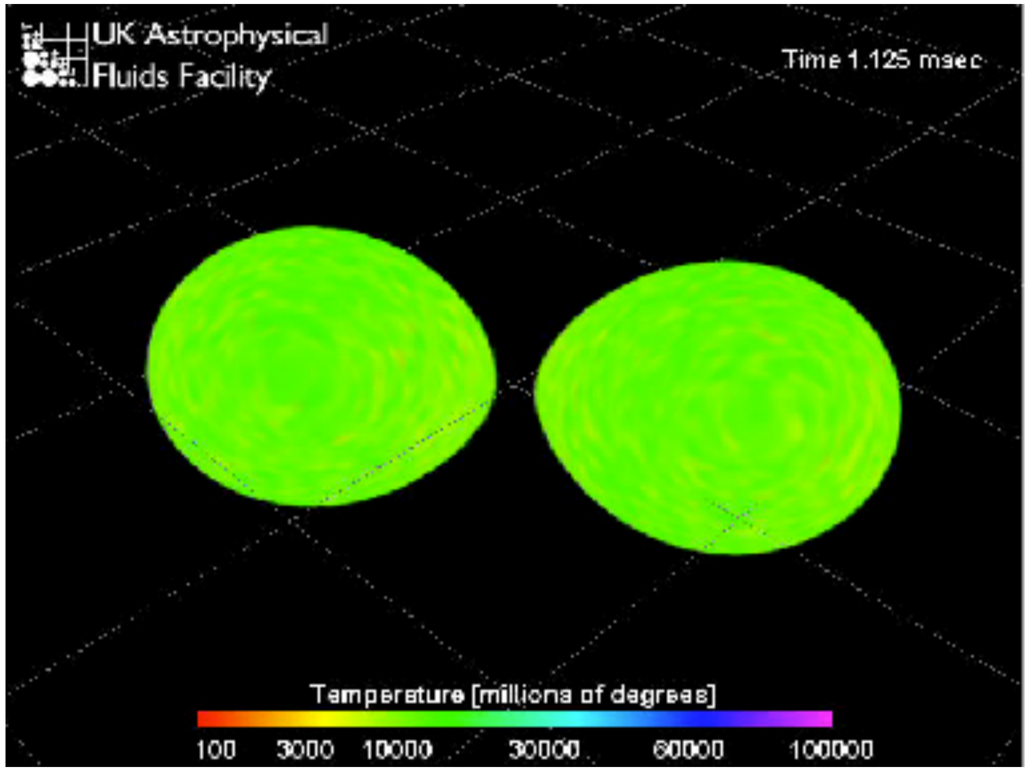
- Electric dipole polarizability of an atom scales as R^3.

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

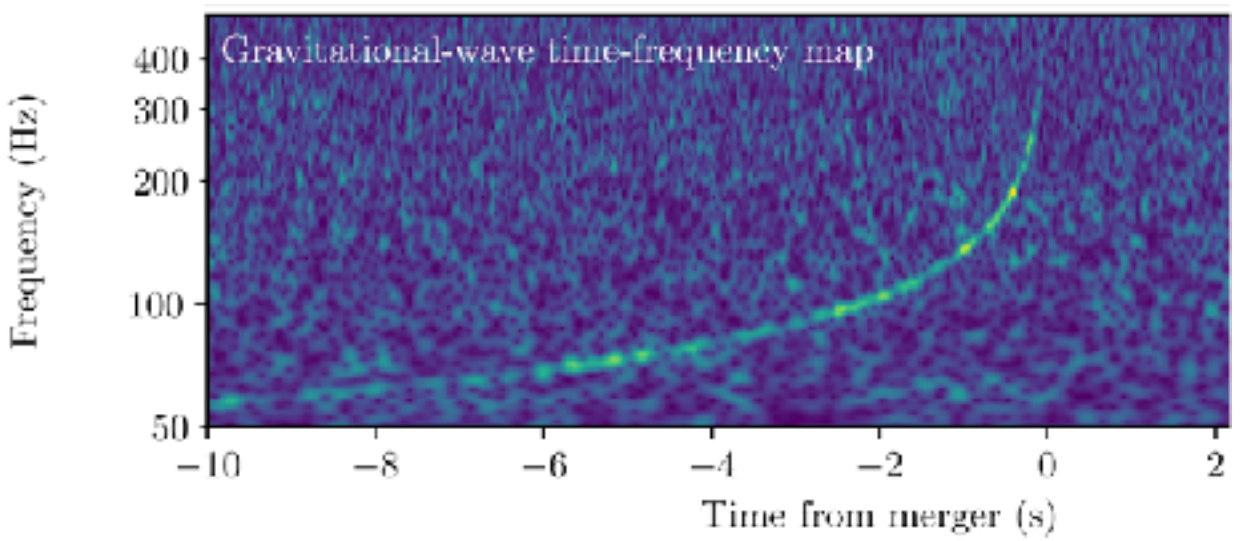
- Mass quadrupole polarizability of a neutron star scales as R^5.

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

- 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.



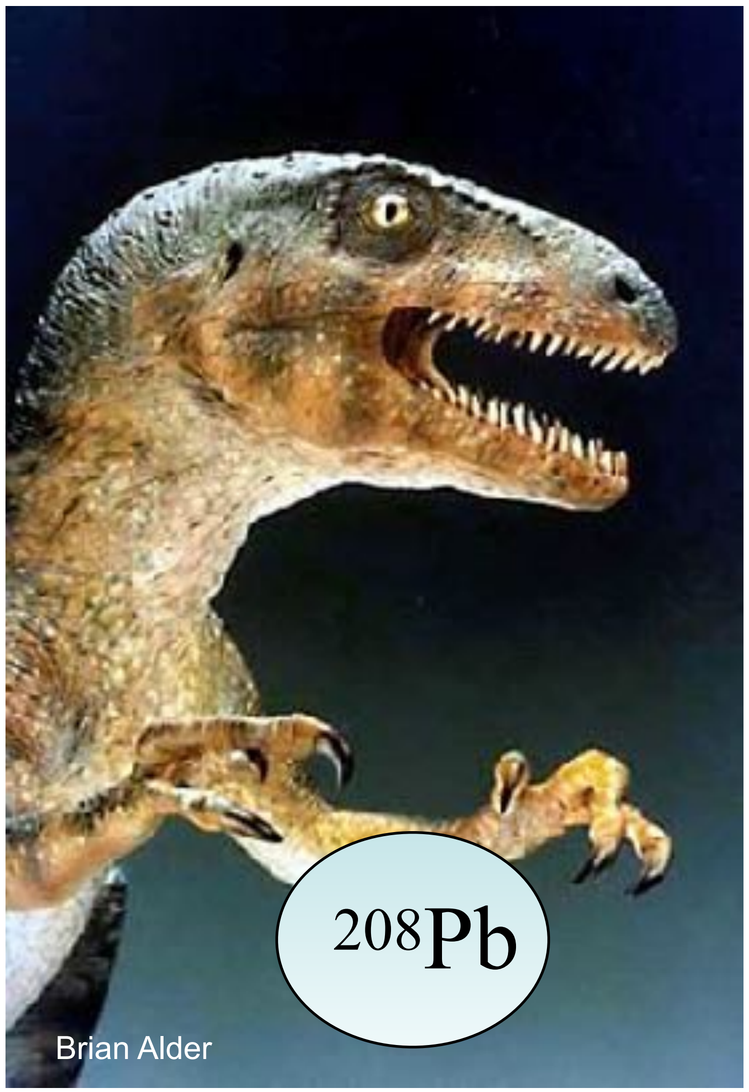
Stephan Rosswog, Richard West



Both the laboratory and the heavens are made of the same materials

- For Newton the material was mass. In 19th century it was chemical elements. Observation that spectral lines are the same in lab and in outer space created astrophysics.
- Today the material is neutron rich matter. In astrophysics and in the laboratory it has the same neutrons, the same strong interactions, and the same equation of state.
- A measurement in one domain (astronomy or the lab) has important implications in the other domain.

Laboratory probe 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

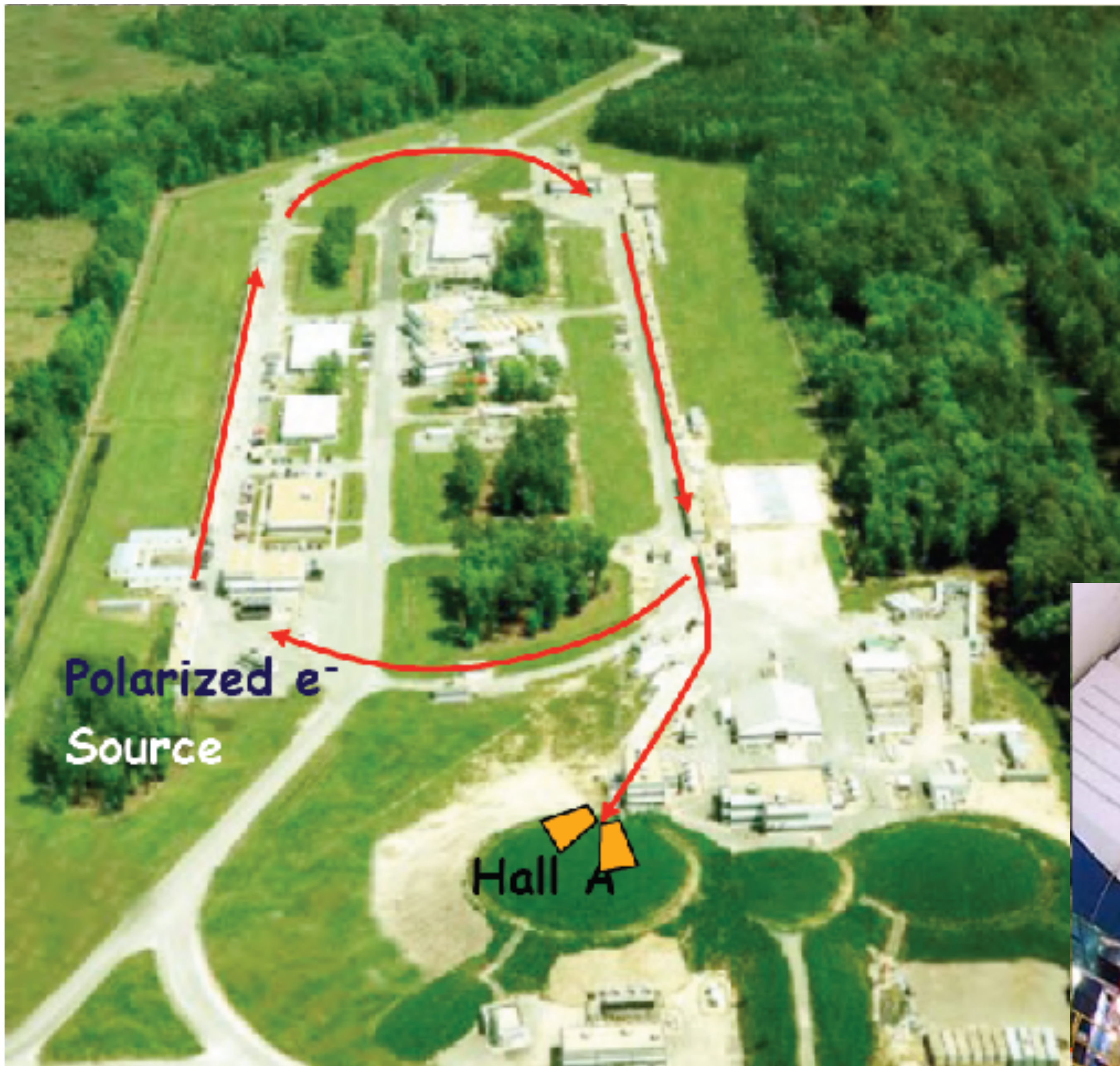
$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\rm ch}(Q^2)}$$

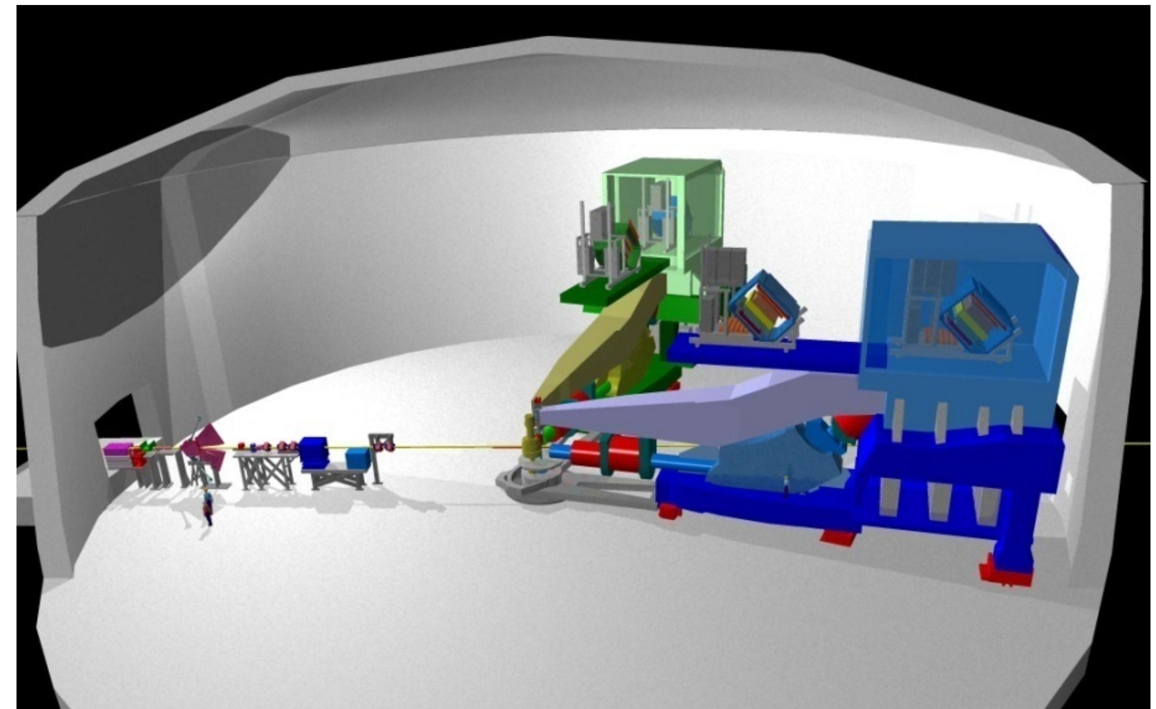
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

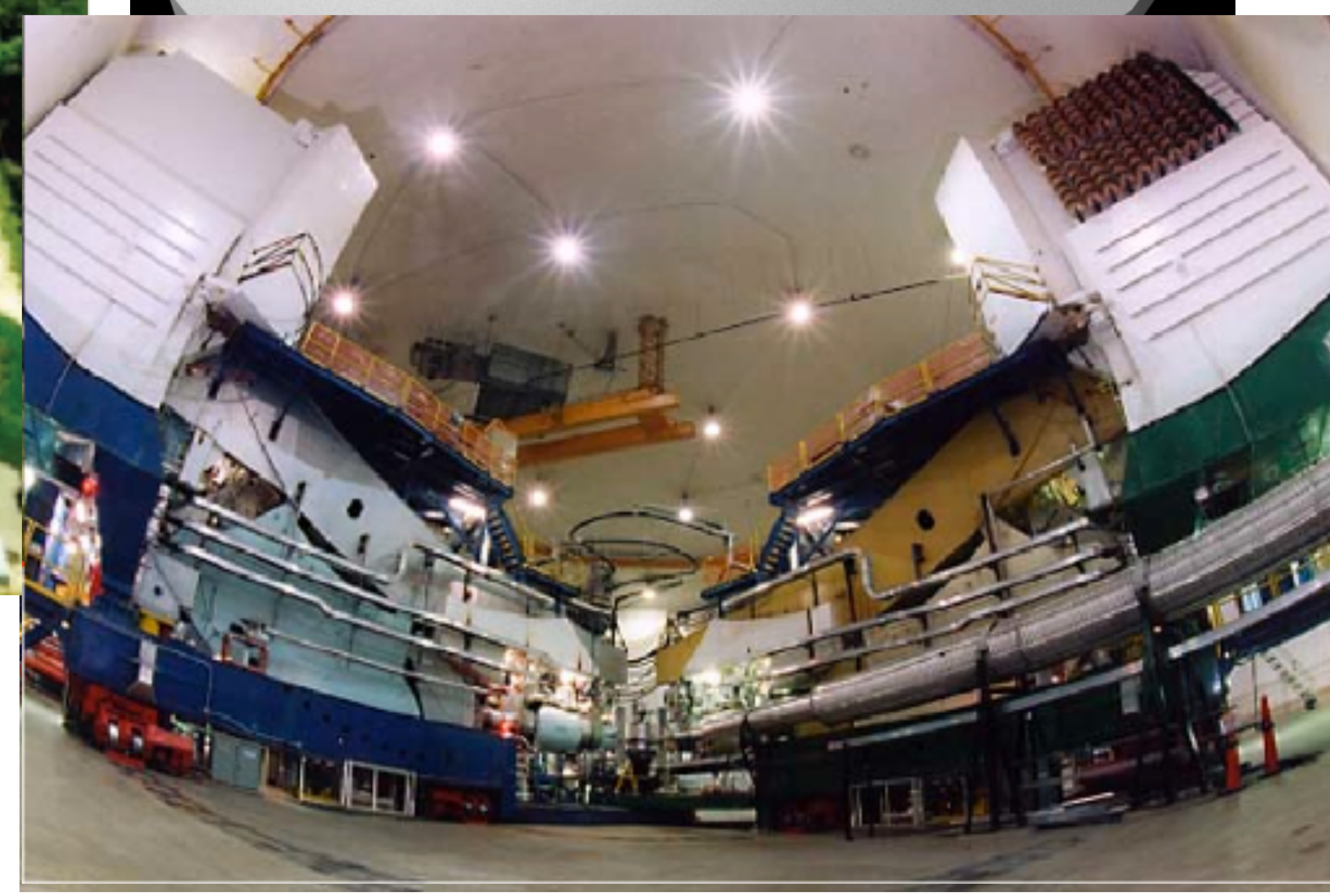
- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**

–Donnelly, Dubach, Sick

Hall A at Jefferson Lab







R. Michaels, JLAB

Parity violating neutron radius experiments

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

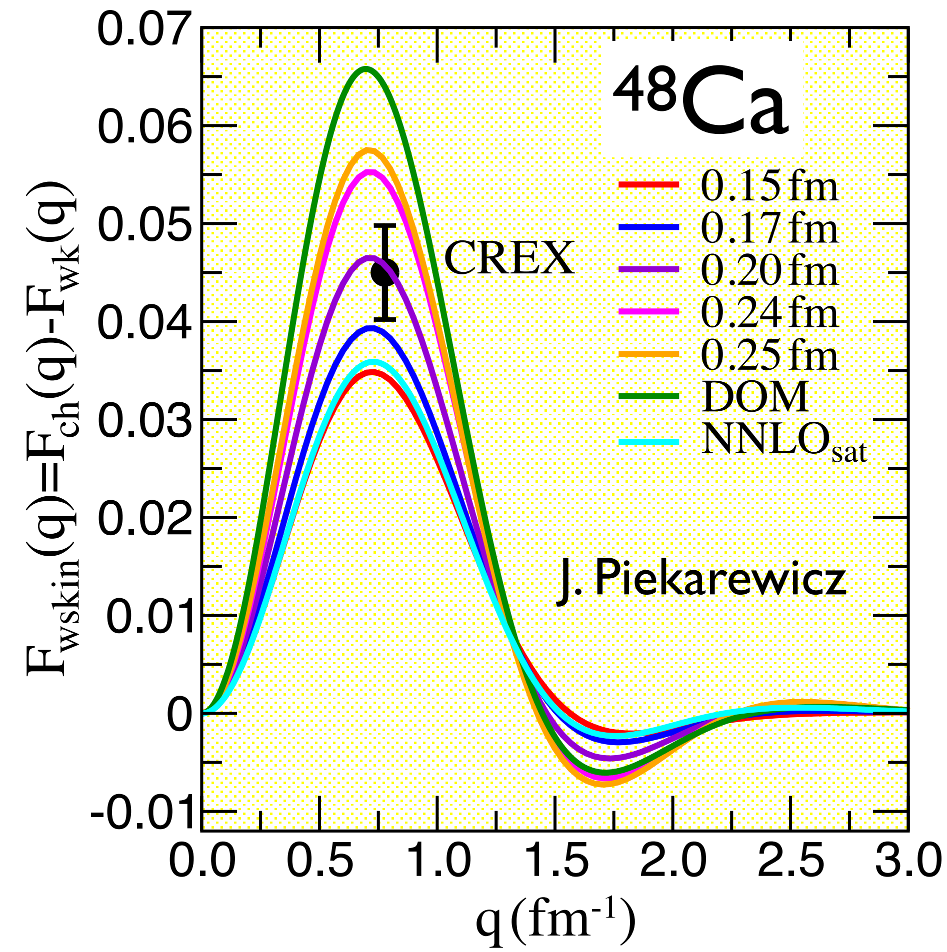
  A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sym) ppm

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

- Next runs (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*.

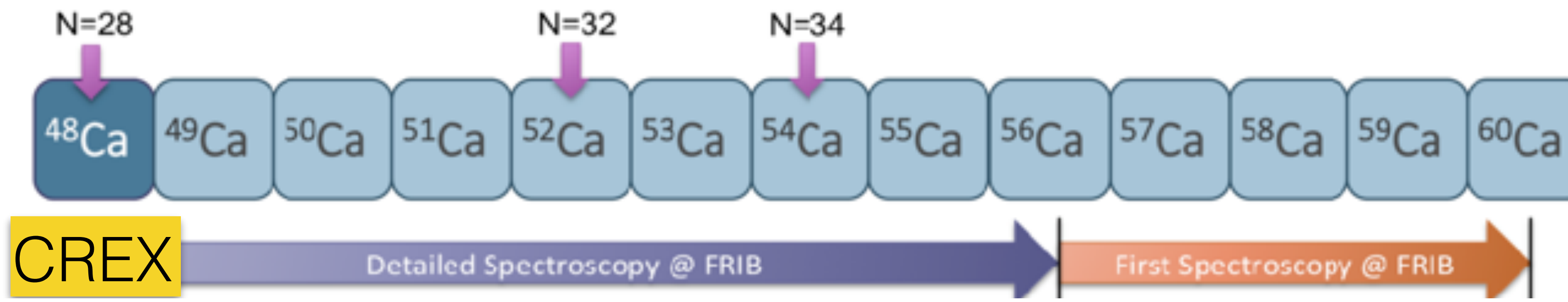


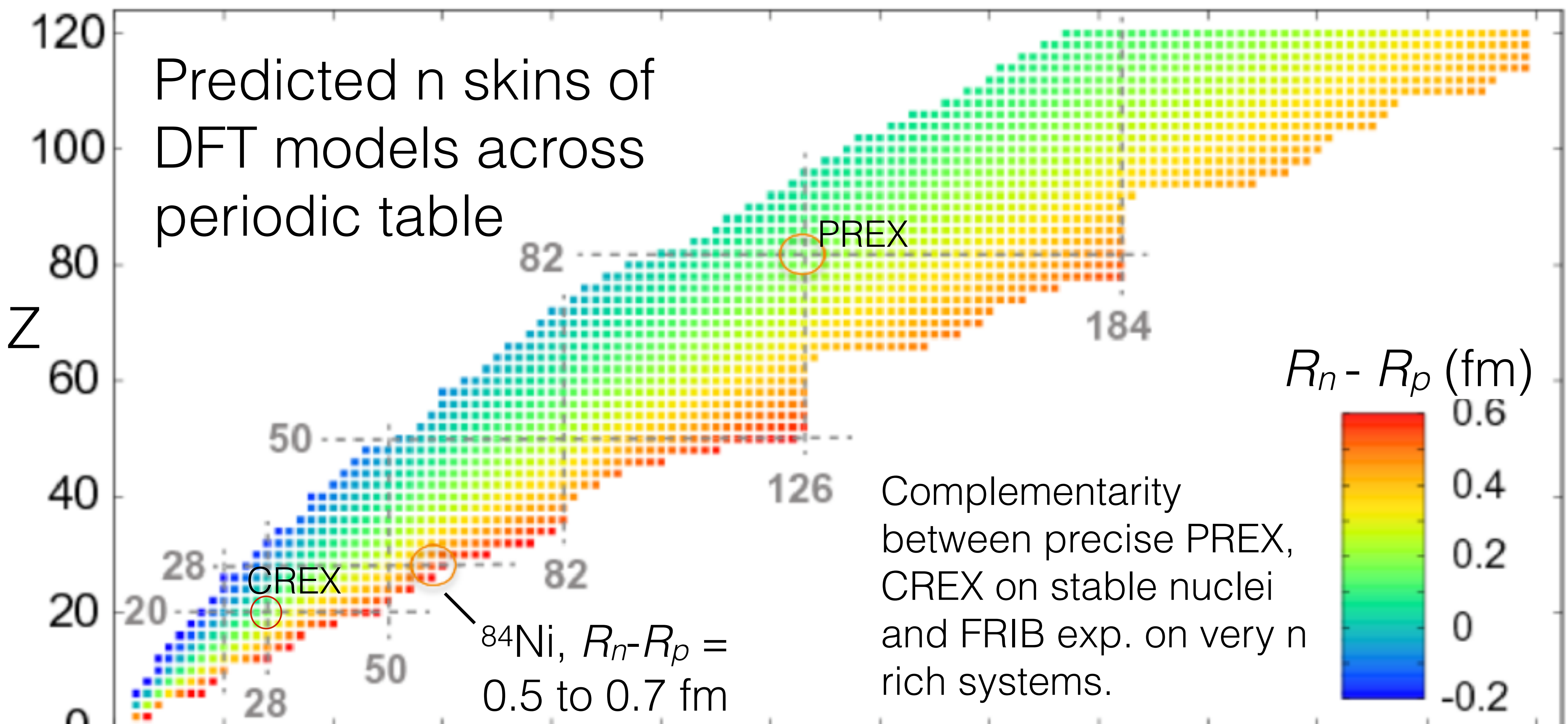
- Microscopic coupled cluster calculations for ^{48}Ca make sharp prediction R_n-R_p=0.135±0.015 fm using chiral interaction $NNLO_{sat}$ [Nature Physics **12** (2016) 186].

- Many DFT calc. have larger skins, and dispersive optical model (DOM) gives R_n-R_p=0.25±0.02 fm.

Study more n rich nuclei at FRIB

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

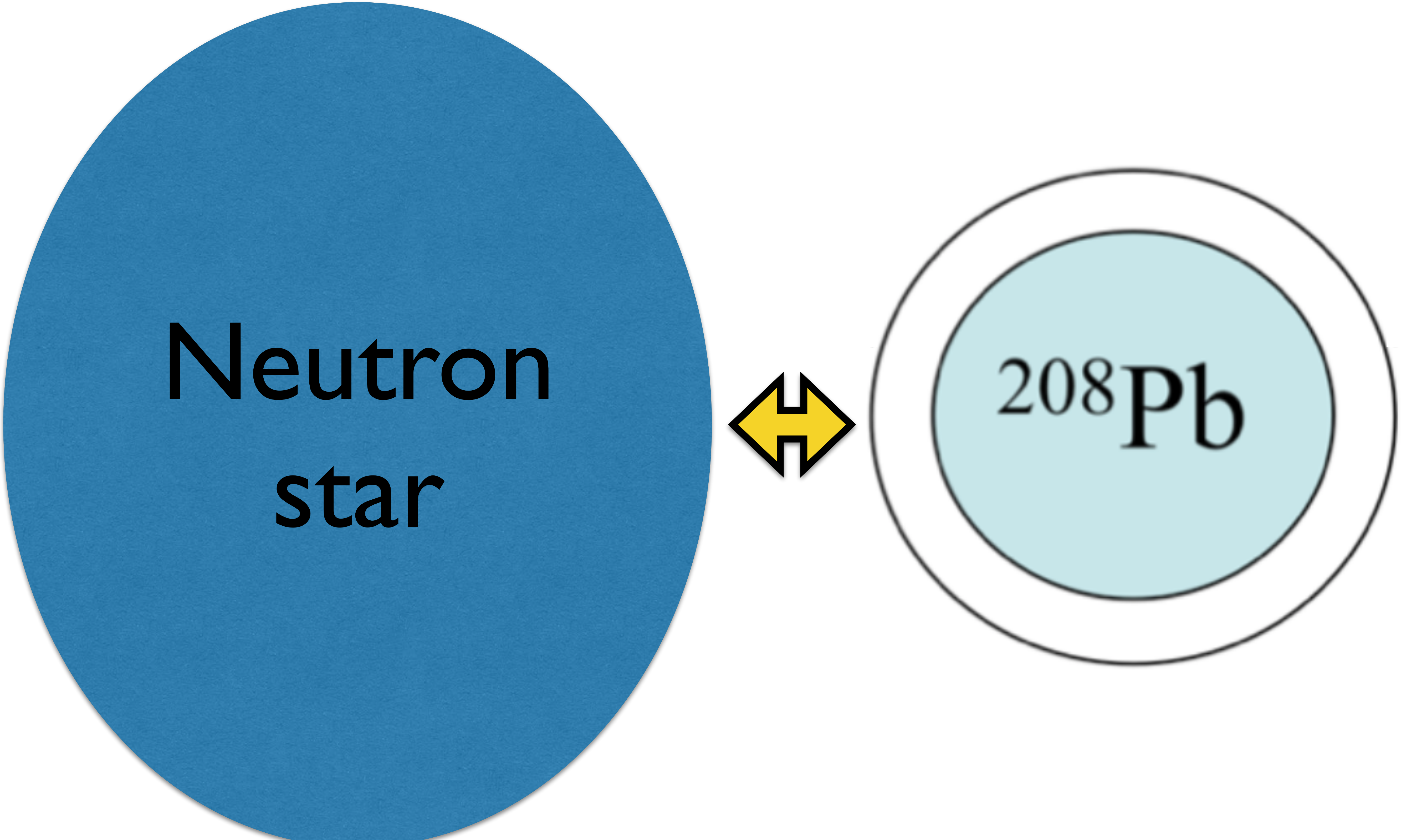




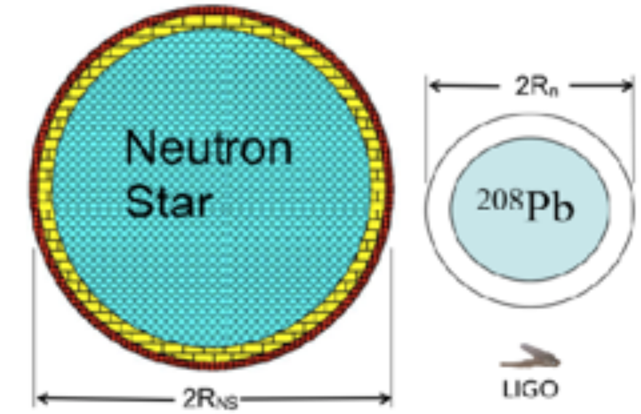
Predicted n skins of DFT models across periodic table

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

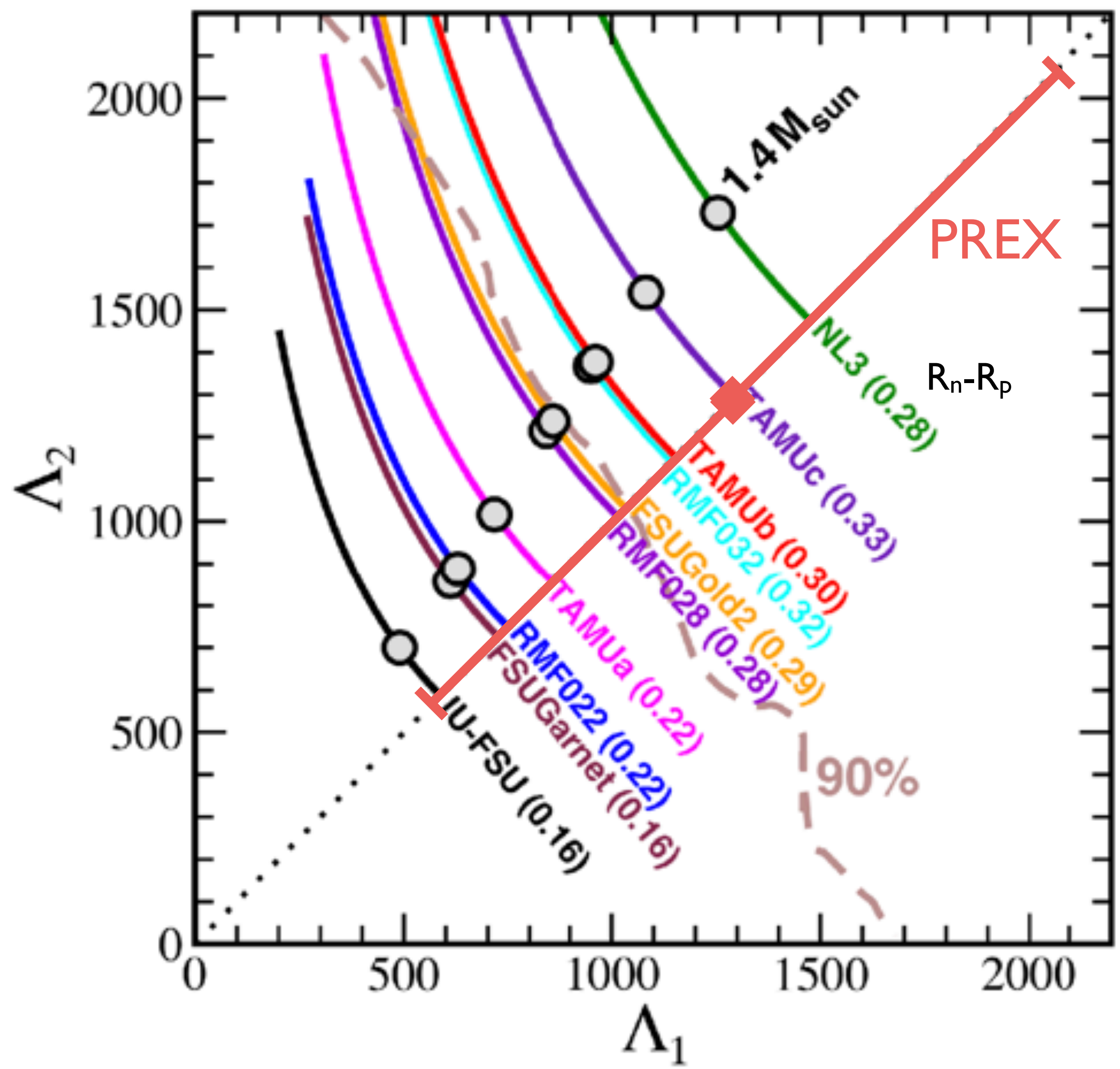
Kortelainen, M. et al. Phys.Rev. C88 (2013)


Neutron star
^{208}Pb

NS deformability and neutron skin of ^{208}Pb



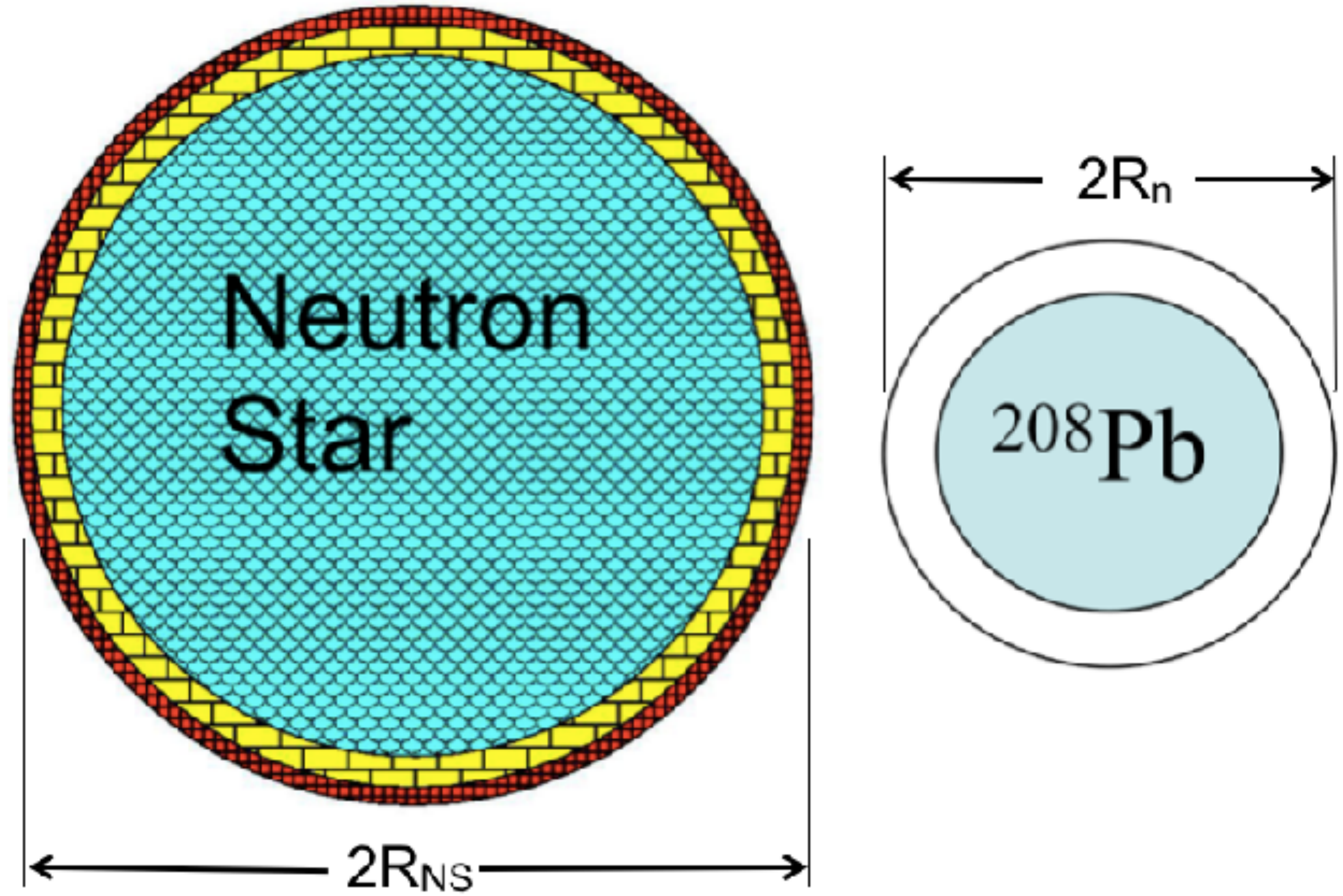
- EOS with high pressure give thick n skin for ^{208}Pb and large deformability for a NS.
- Several relativistic mean field EOS curves with R_n-R_p (^{208}Pb) listed in fm.
- GW170817 rules out stiff EOS with neutron skins greater than about 0.29 fm.
- PREX R_n-R_p= $0.33^{+0.16}_{-0.18}$ fm. Central 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. Phys. Rev. Lett. **120**, 172702 (2018)

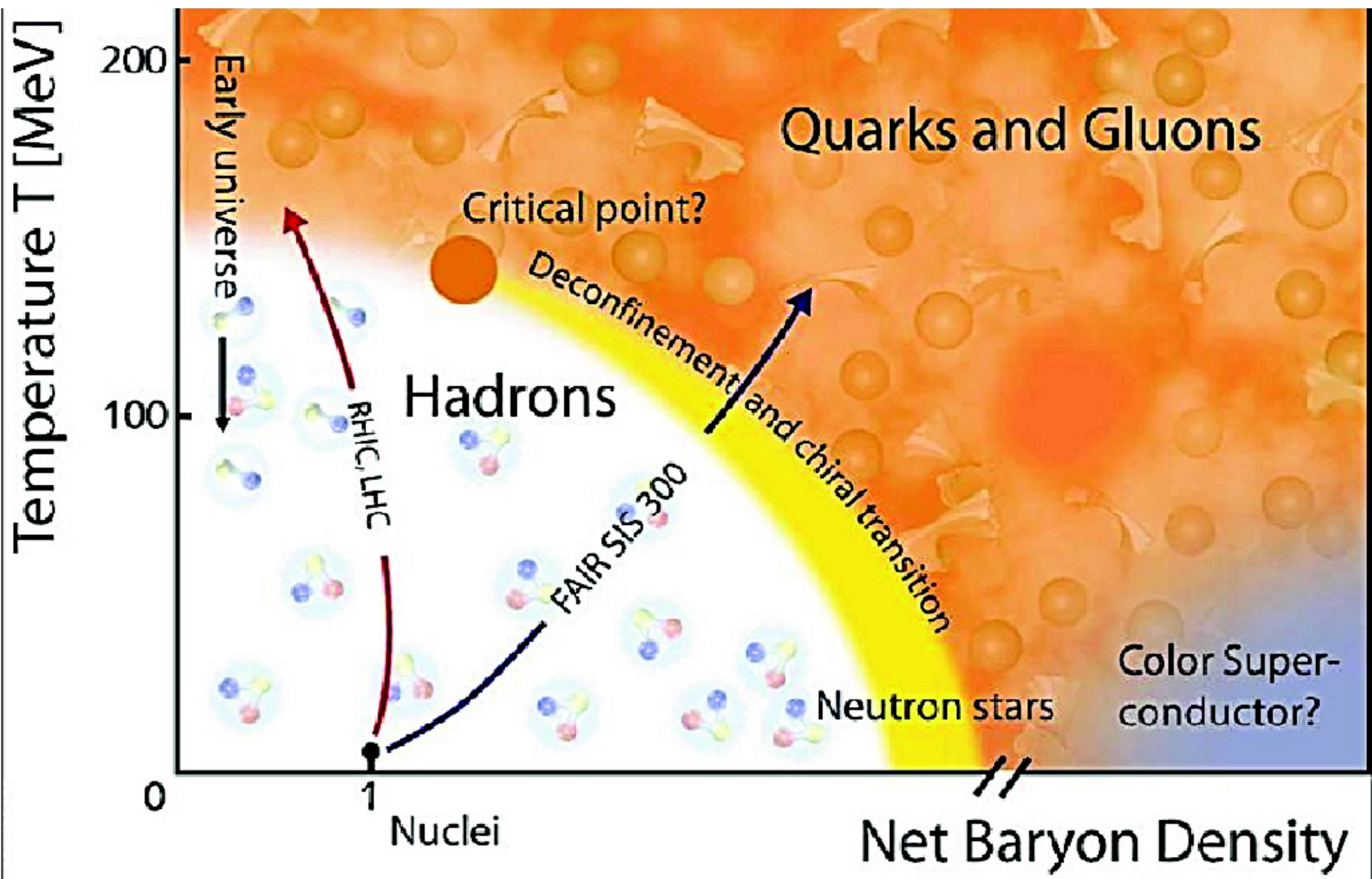
Density Dependence of EOS

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb determines P at low densities ~0.7ρ_0
- Radius of (~1.4M_{sun}) NS depends on P at medium densities ~2ρ_0.
- Maximum mass of NS depends on P at high densities (fate of merger remnant).
- Three measurements constrain density dependence of EOS.



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

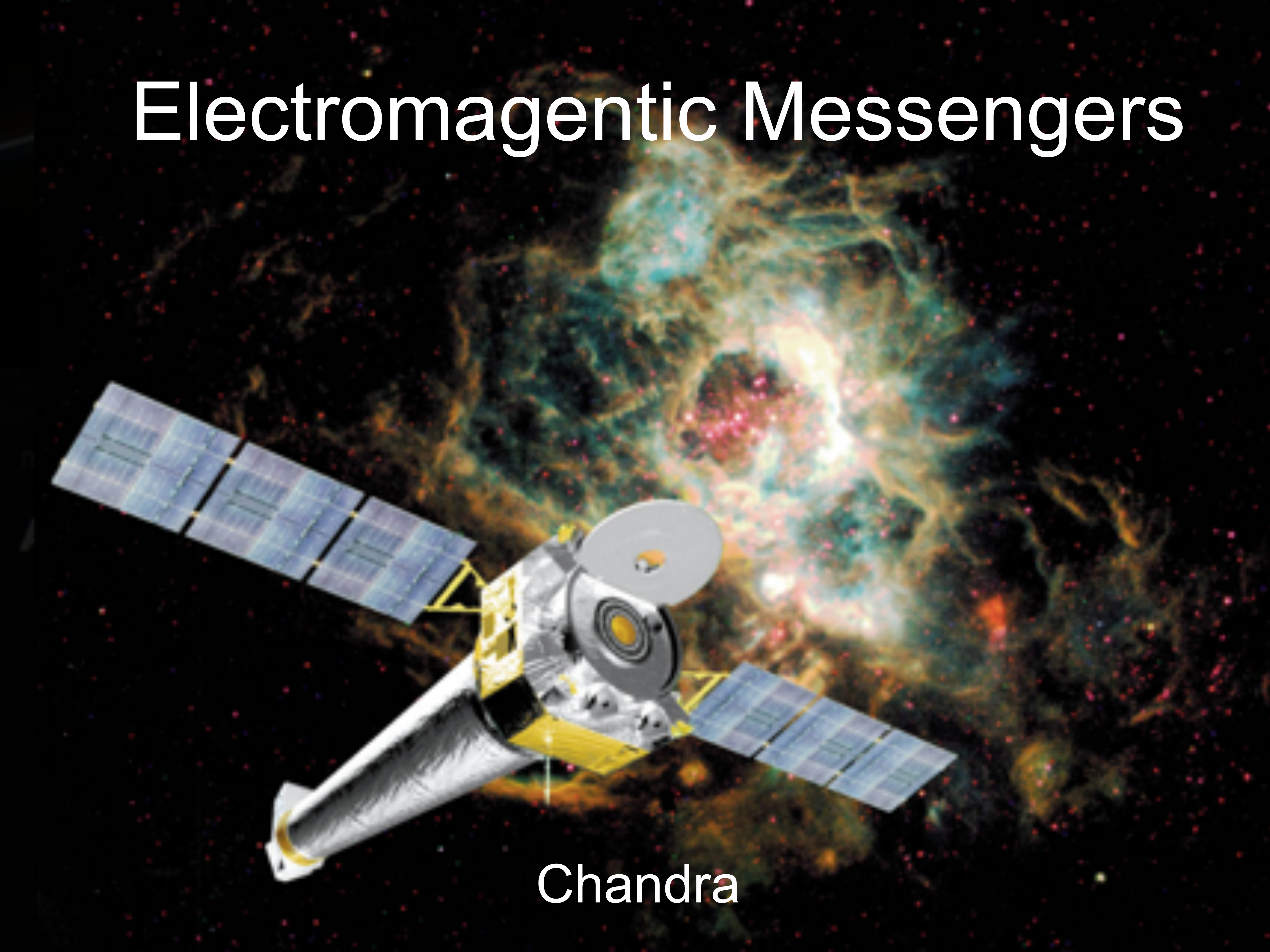
PREX II: R_n(^{208}Pb) to ±0.06 fm
CREX: R_n(^{48}Ca) to ±0.02 fm


Temperature T [MeV]
200
100
0
Early universe
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
RHIC, LHC
FAIR SIS 300
Neutron stars
Color Super-
conductor?
1
Nuclei
Net Baryon Density

What are NS made of?

- Measurements of mass and radius or GW constrain equation of state (P vs density).
- This dose not determine composition.
- $2M_{sun}$ NS says interactions are strong at high densities. Could be strongly interacting neutrons or quarks.
- NS cool by neutrino emission from high density interior. This can shed light on composition.

Electromagentic Messengers



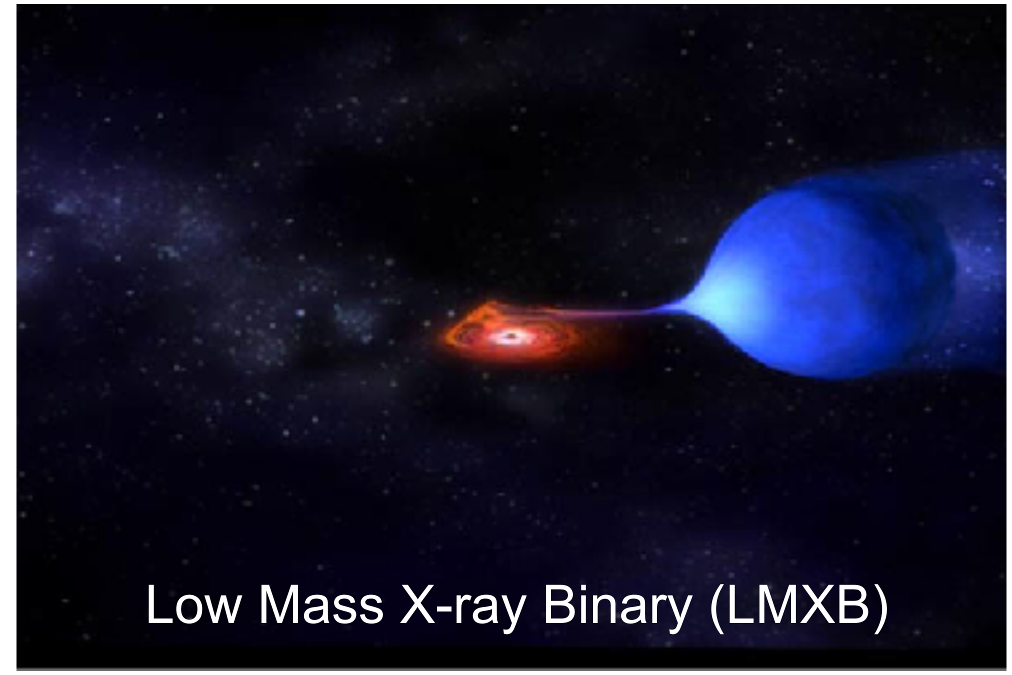
Chandra

X-ray observations of NS radii, masses

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

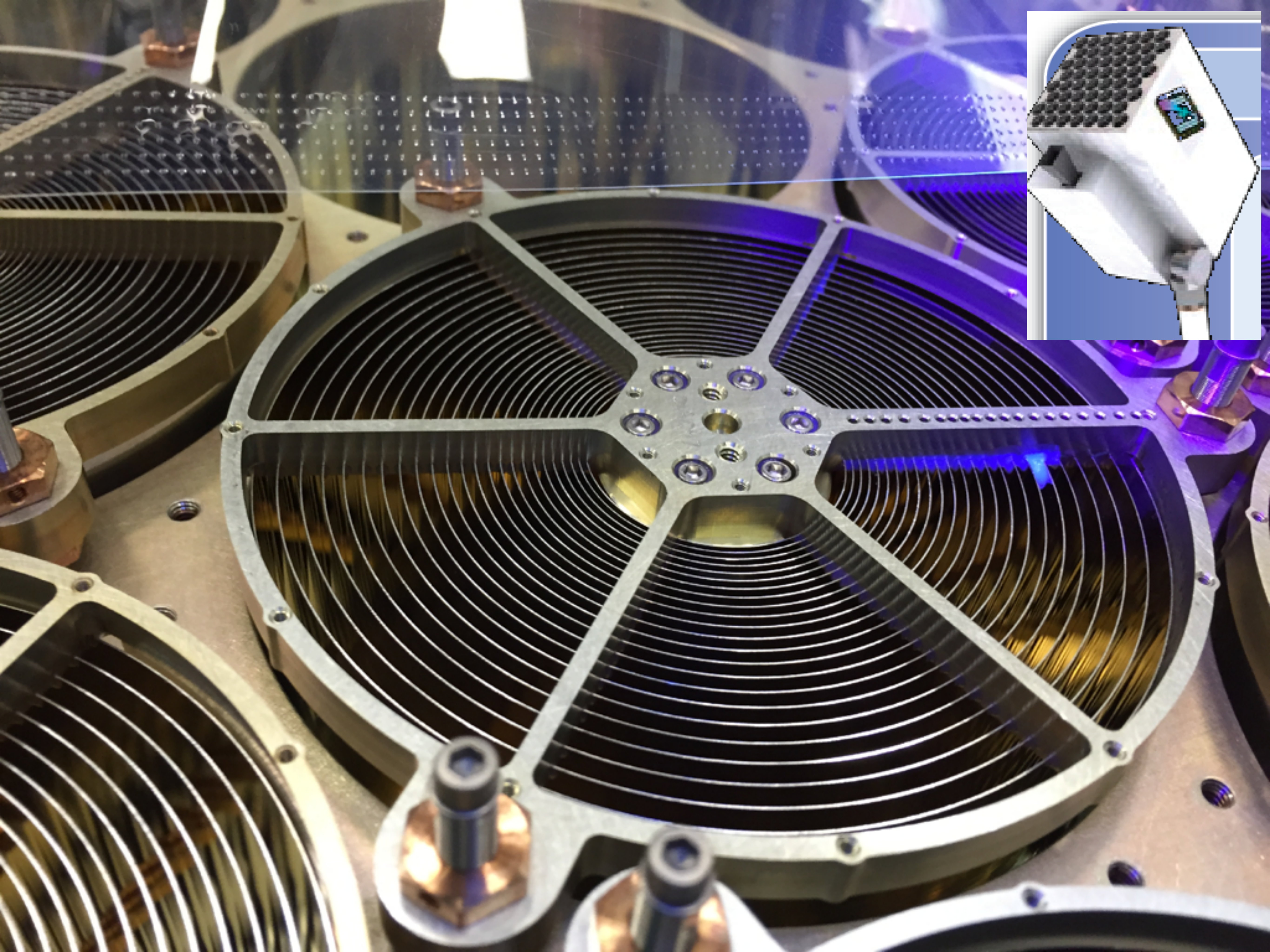
$$L_\gamma = 4\pi R^2 \sigma_{\mathrm{SB}}\, T^4$$

- 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.
- 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!
- Steiner, Lattimer, Brown combine X-ray observations --> 1.4 M_{sun} star has ~ 12 km radius.
- However important uncertainties may remain in extracted radii. Suleimanov and Poutanen use more sophisticated atmosphere models and find larger radii.

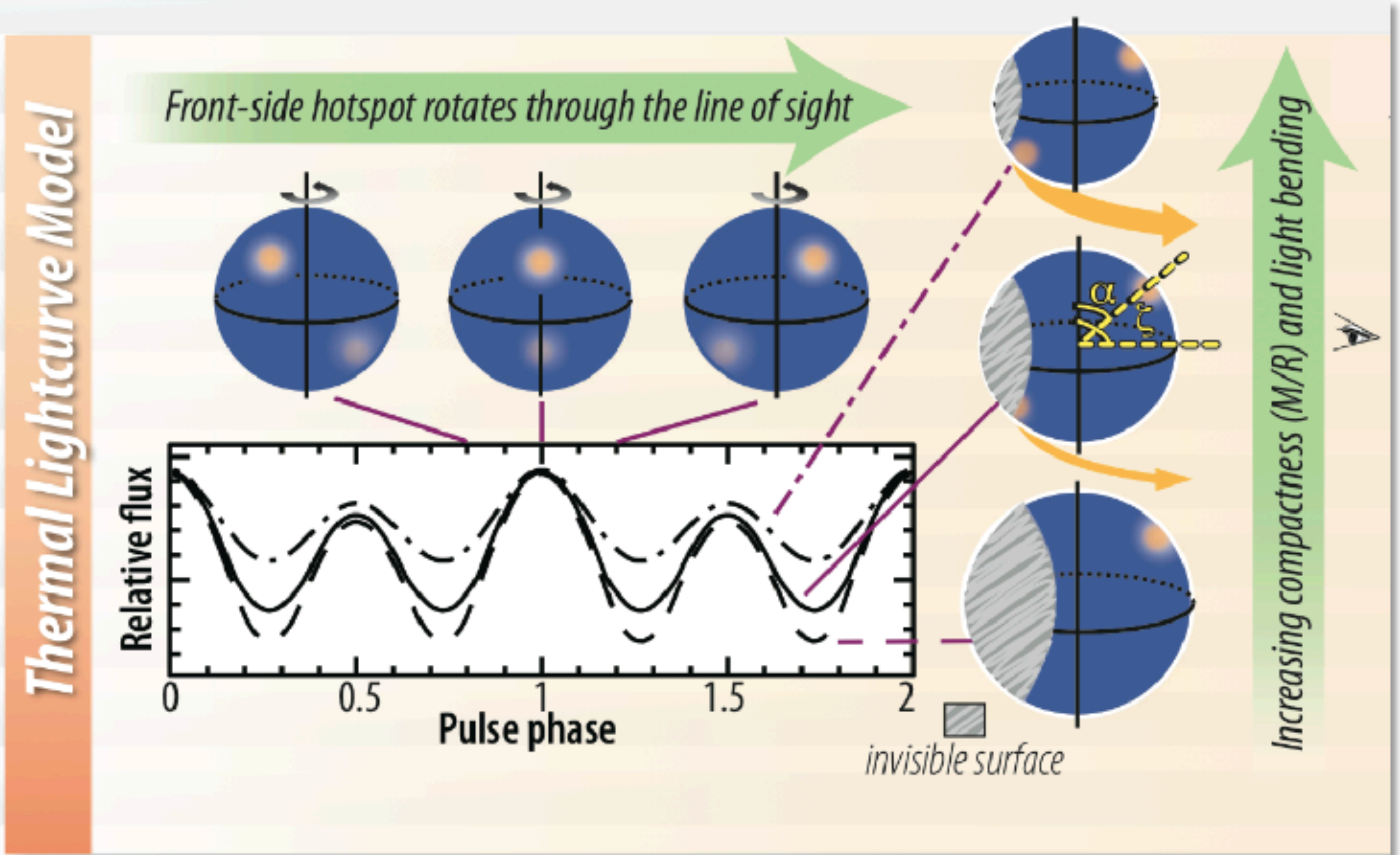

NICER
Neutron star Interior Composition ExploreR
Keith Gendreau, NASA GSFC
Principal Investigator
NASA
GSFC
MIT KAVLI
INSTITUTE



Science Measurements

NICER

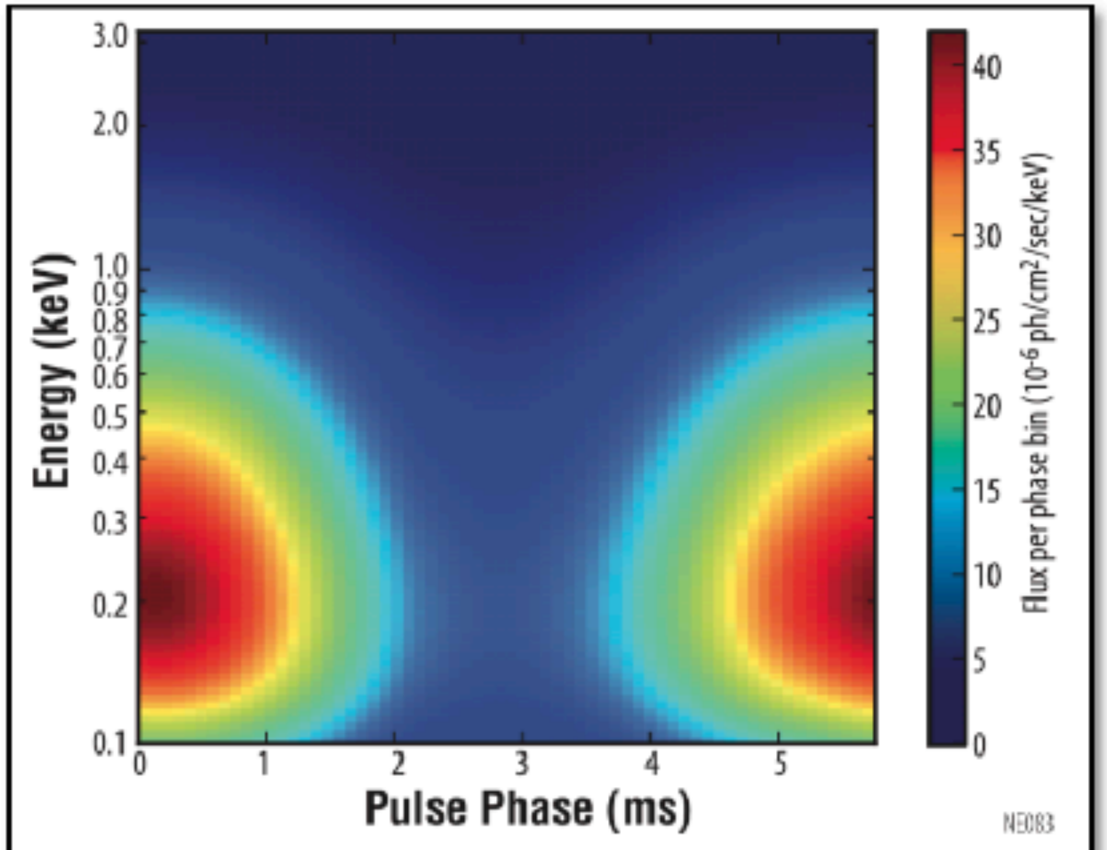
Reveal stellar structure through lightcurve modeling, long-term timing, and pulsation searches

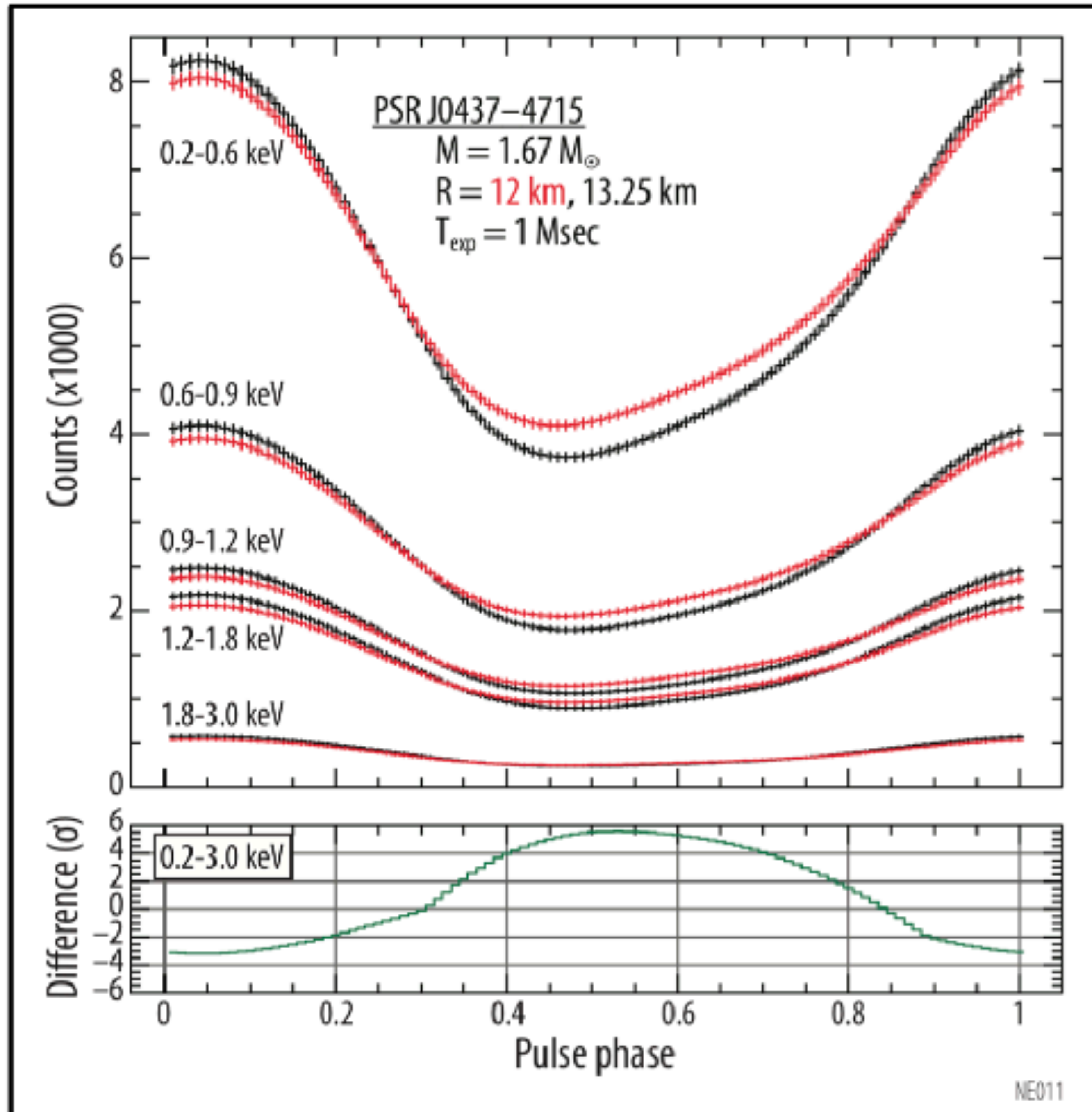


Lightcurve modeling constrains the compactness (*M/R*) and viewing geometry of a non-accreting millisecond pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots, thanks to gravitational light-bending…

Science Measurements (cont.)

NICER





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

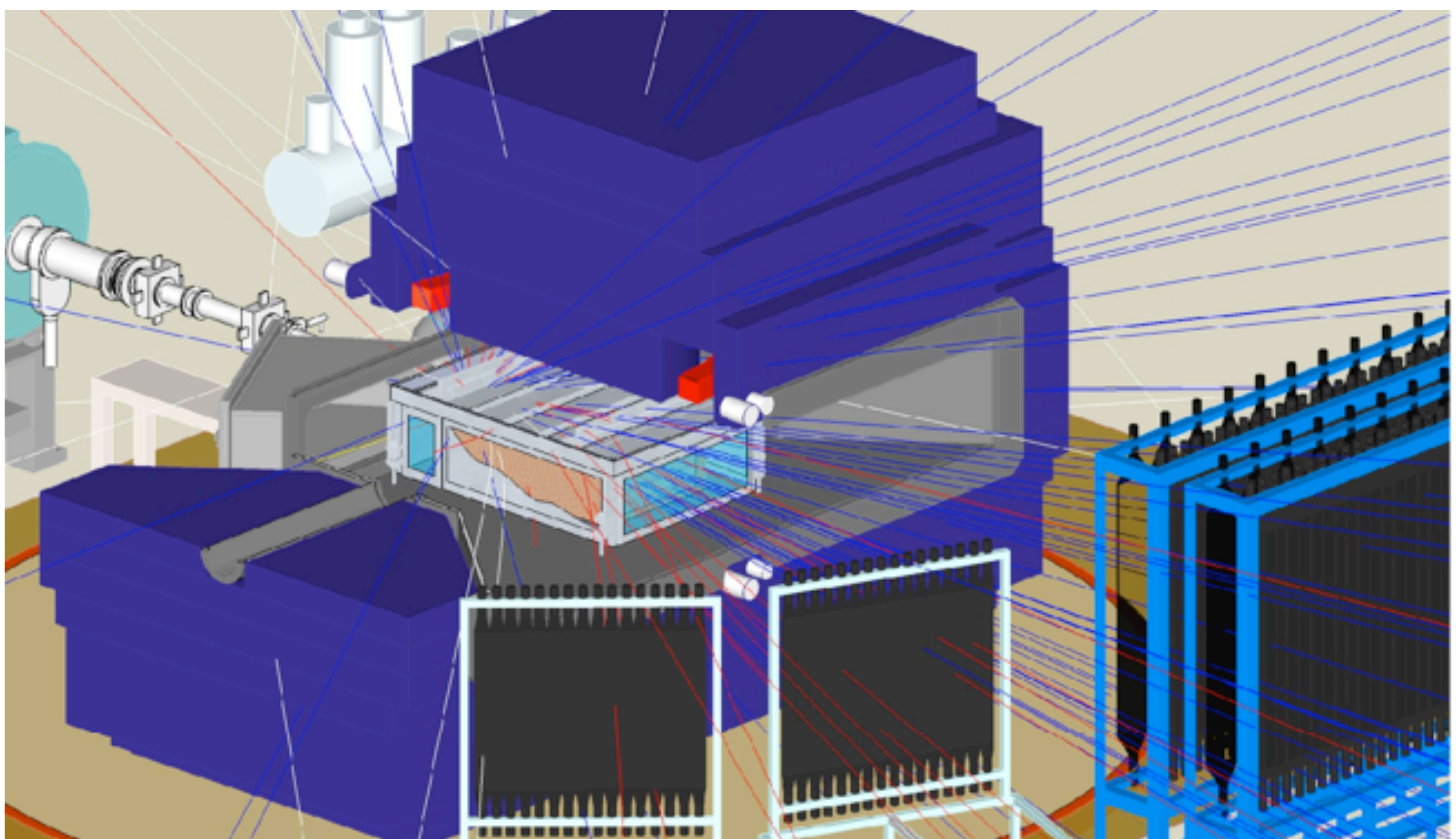
NICER launched June 3 and was installed June 13-14, 2017

Symmetry Energy S(ρ)

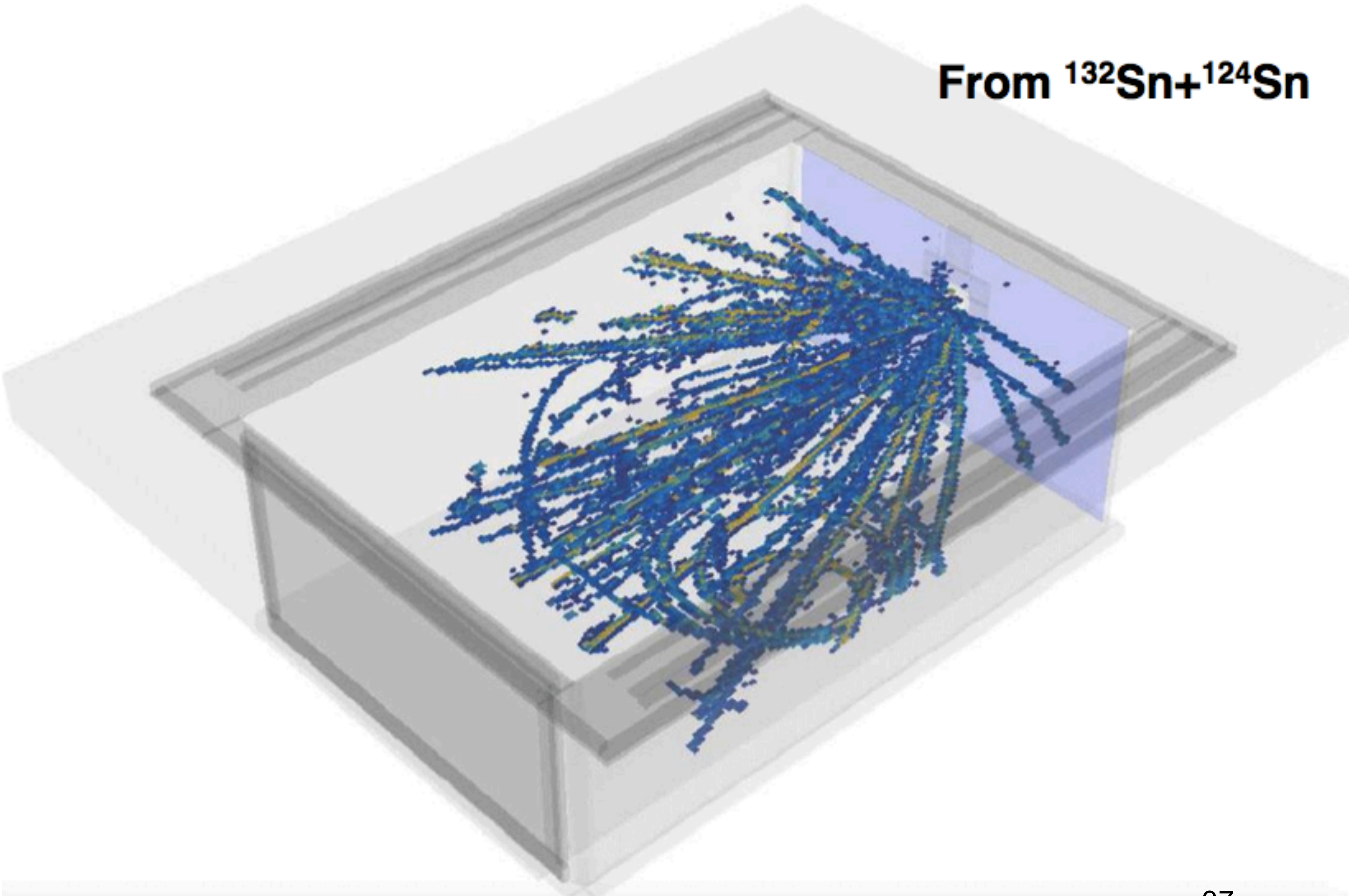
- Describes how energy of nuclear matter rises with increasing neutron excess.
- Important for extrapolating laboratory measurements to very neutron rich systems in astrophysics.
- *S(ρ) at high densities ($\rho > \rho_0$) is the single laboratory observable most closely related to the structure of neutron stars.*
- Heavy ion collisions, with radioactive beams, can produce high density n rich matter in the laboratory.

Samurai TPC and $S(\rho)$ at $\rho>\rho_0$

- Determining $S(\rho)$ from HI exp. may depend on transport models. Look at pion production and π^+/π^- ratios, n/p flow…
- Experimental program underway at RIKEN RIBF using SAMURAI magnet and time projection chamber (TPC). Exp. with ^{108}Sn, ^{132}Sn beams 2016

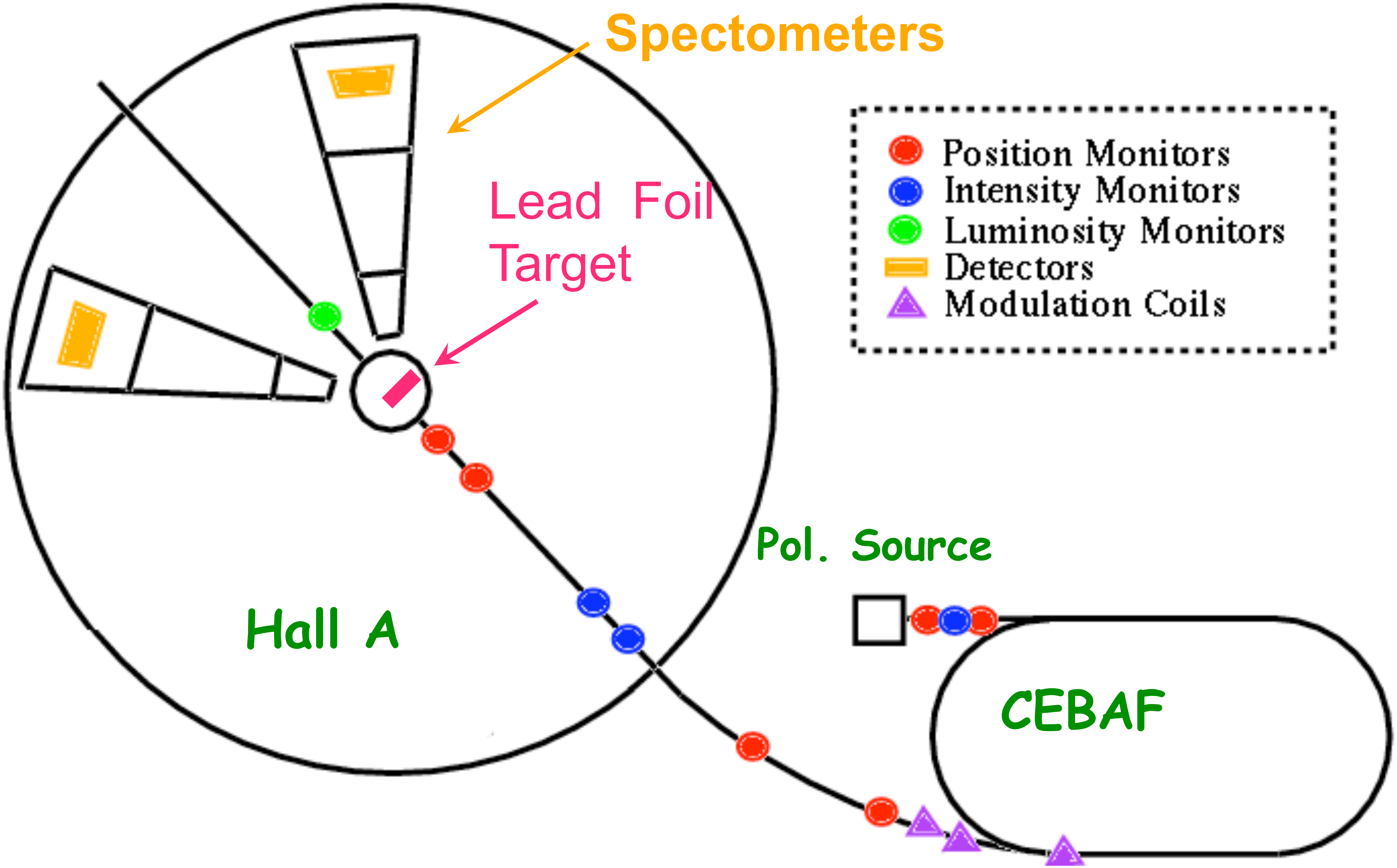


First results in a year



Event from Tetsuya MURAKAMI talk

PREX in Hall A at JLab



R. Michaels