

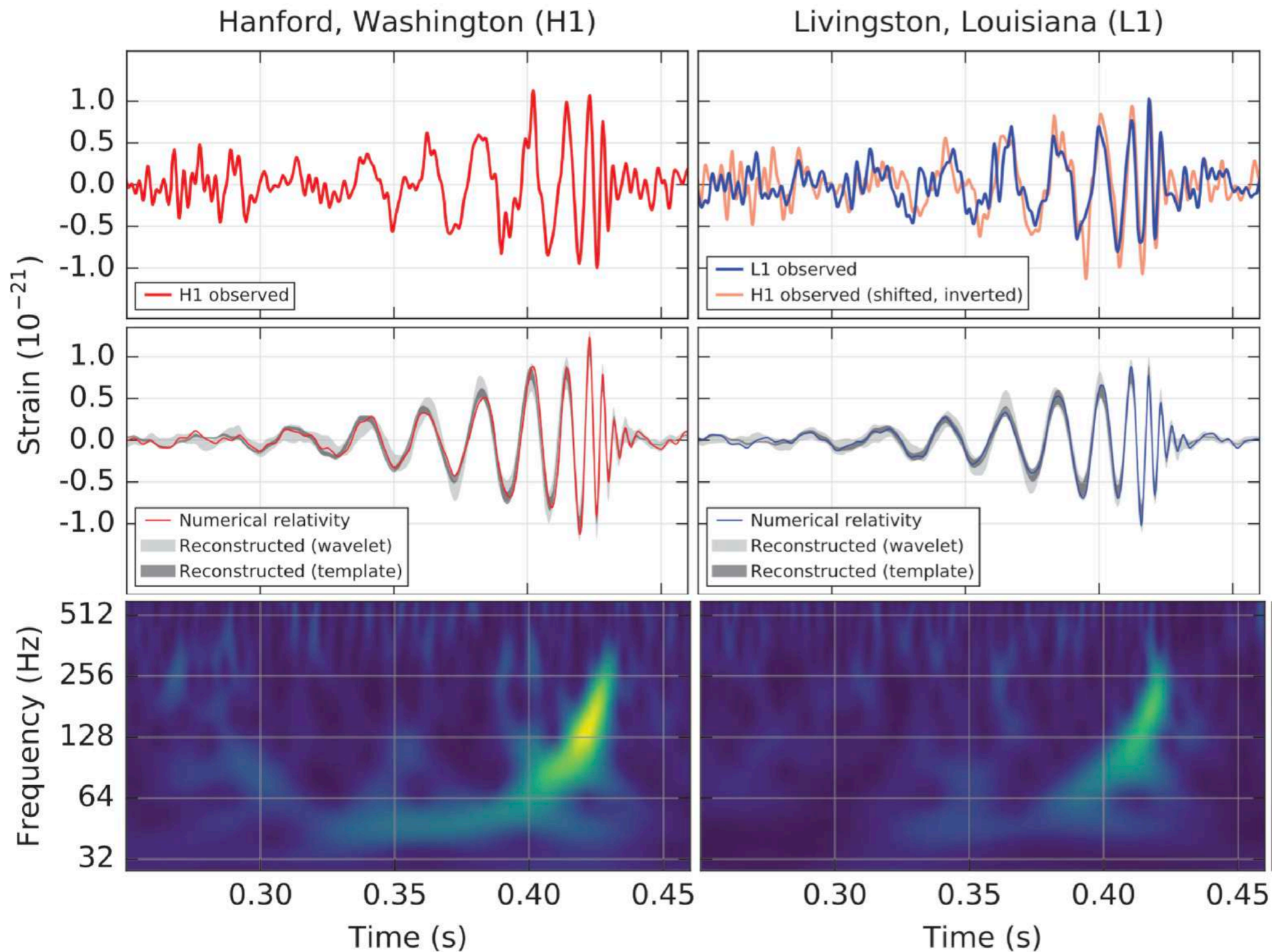
Dense matter in the gravitational wave sky

Chuck Horowitz, Indiana U.
Arizona State, Aug. 2020

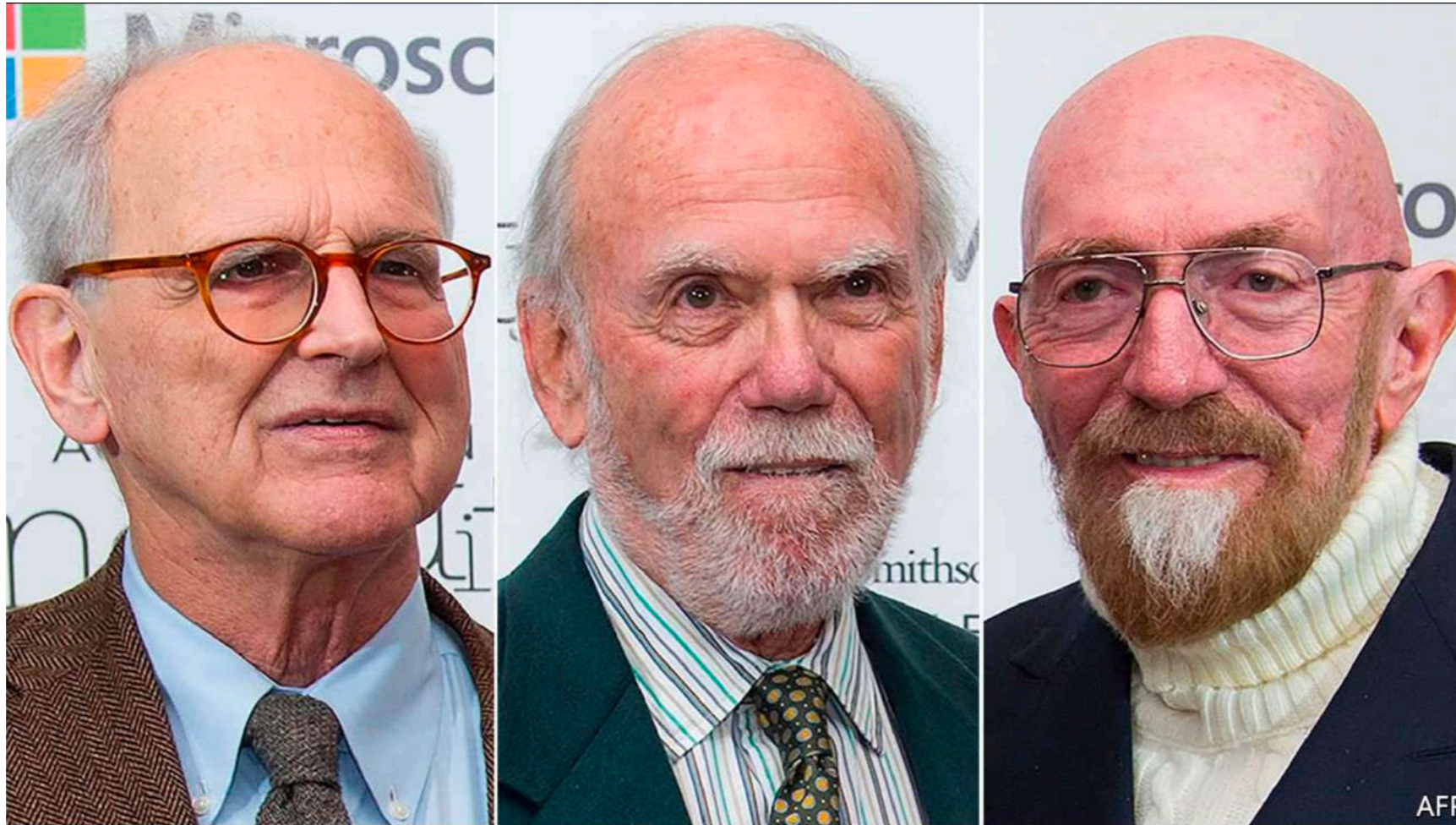


Historic detection of gravitational waves

- Gravitational waves, very small oscillations of space-time predicted by Einstein 100 years ago, were directly observed by LIGO in 2015.



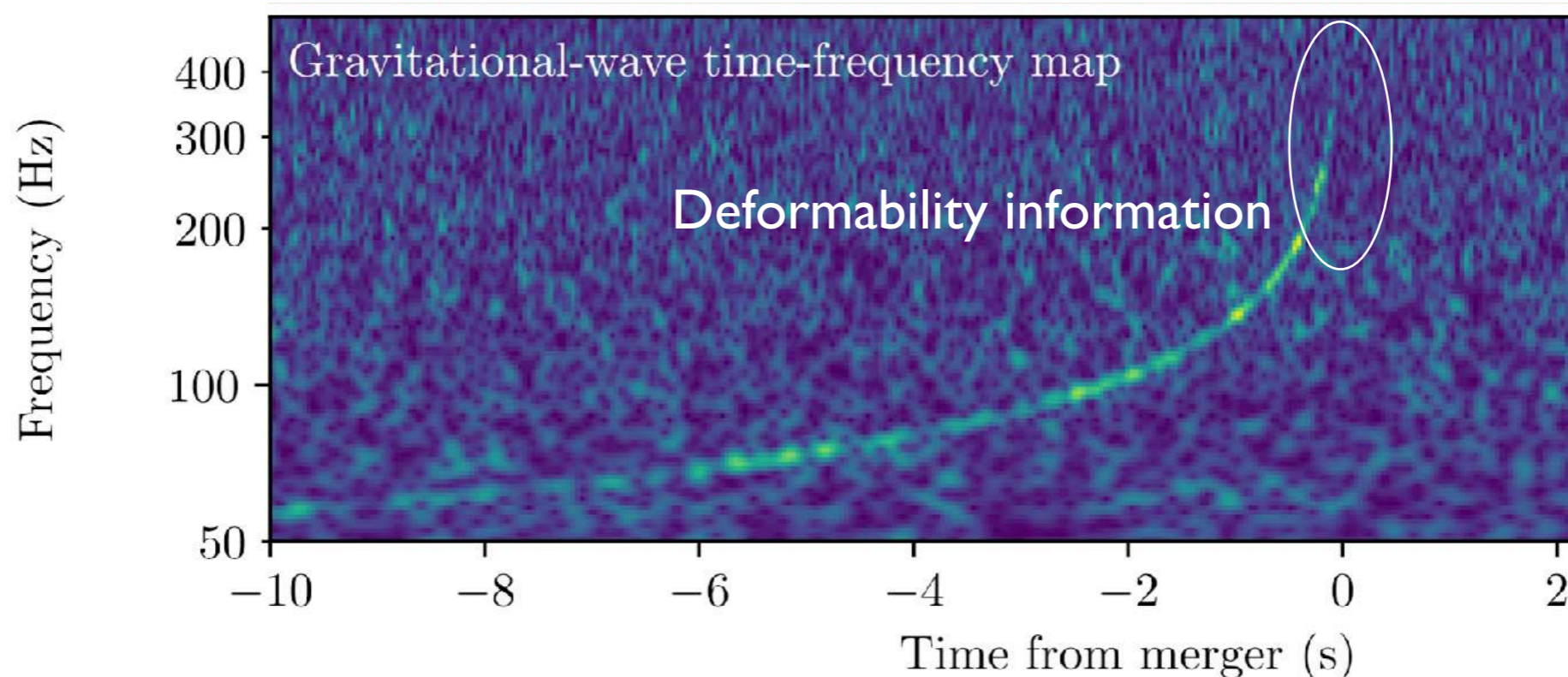
Nobel Prize in Physics 2017



- One half to Rainer Weiss (MIT) and the other half jointly to Barry C. Barish and Kip S. Thorne (Caltech)
- “for decisive contributions to the LIGO detector and the observation of gravitational waves”

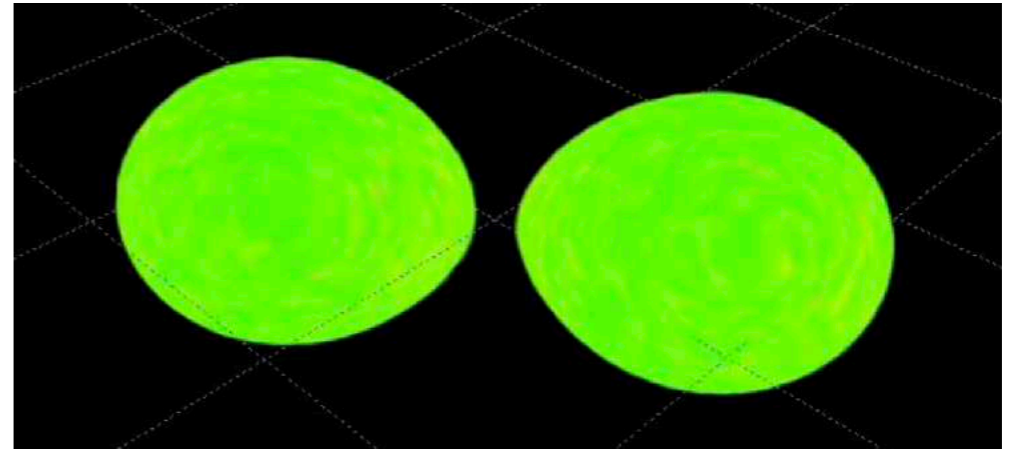
Spectacular event GW170817

- On Aug. 17, 2017, the merger of two NS observed with GW by the LIGO and Virgo detectors.
- 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.



Merger GW170817: deformability of NS

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

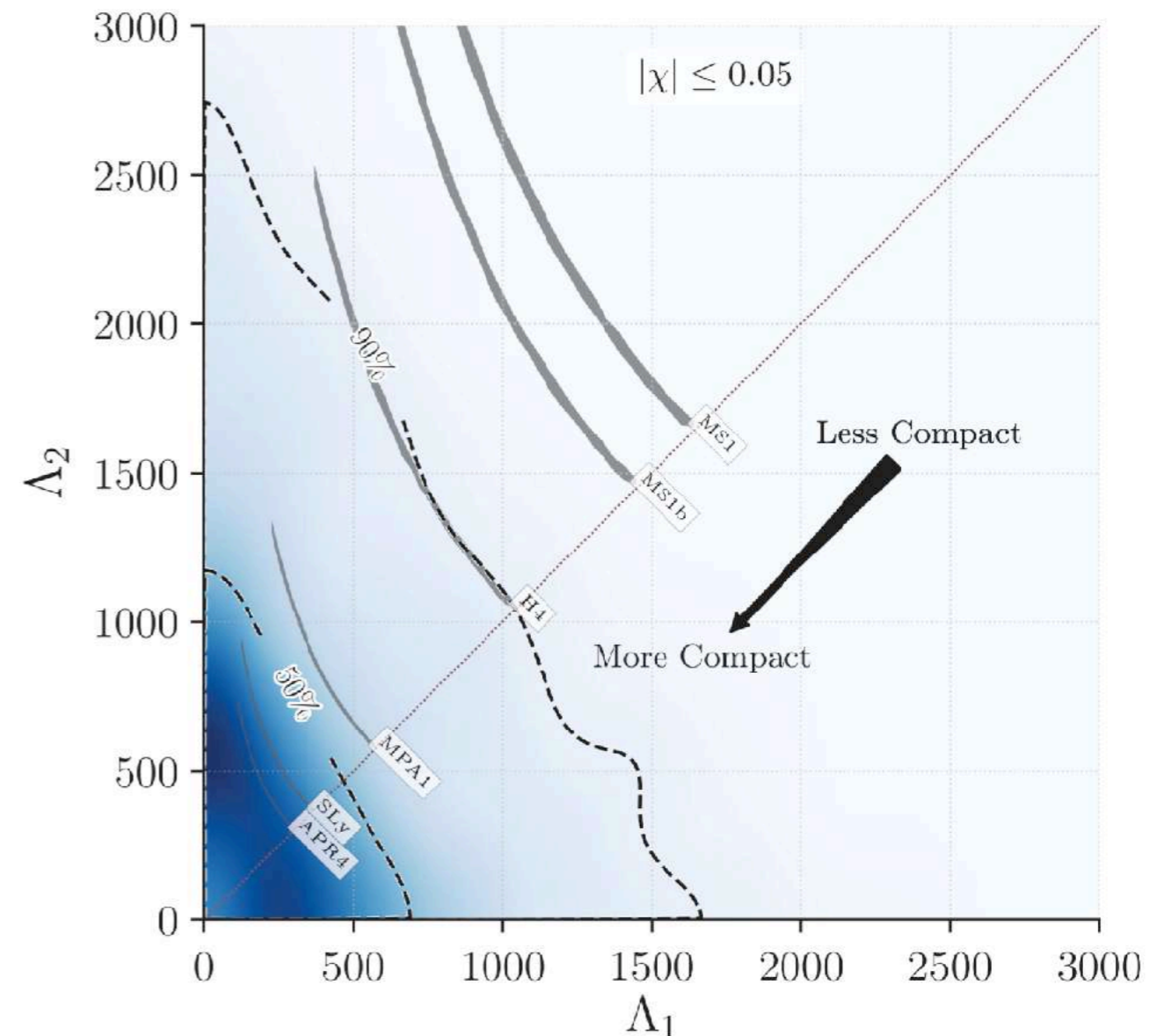


$$\kappa = \sum_f \frac{|\langle f | r Y_{10} | i \rangle|^2}{E_f - E_i} \propto R^3$$

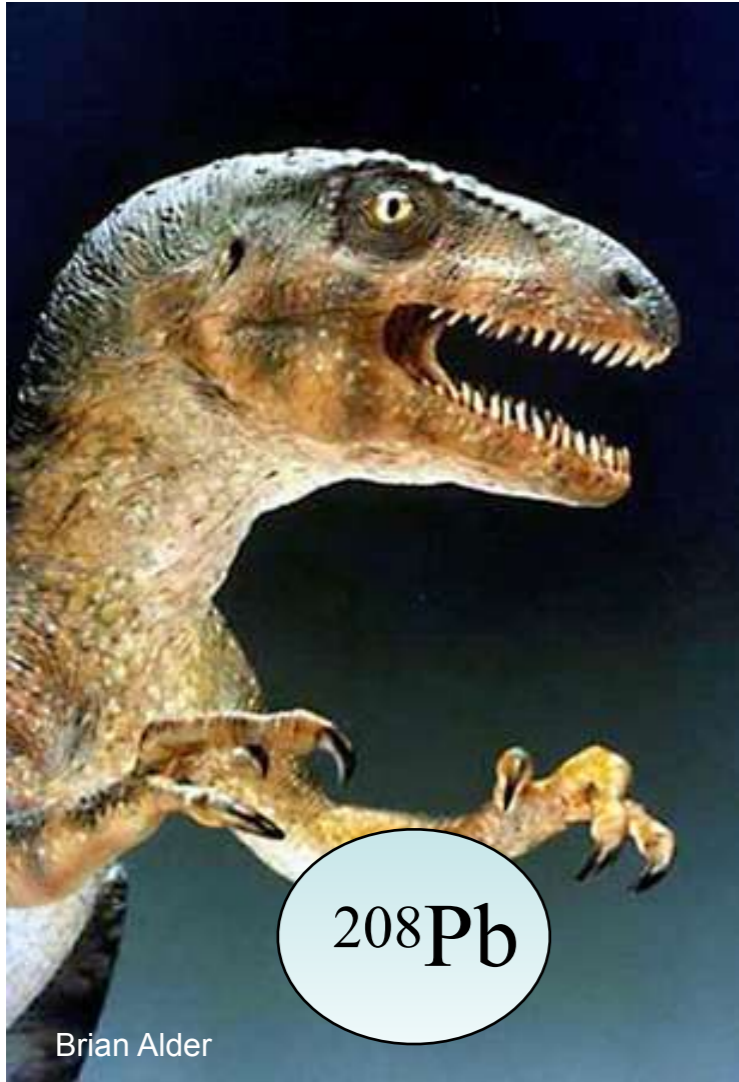
- Tidal deformability (or mass quadrupole polarizability) of a neutron star scales as R^5 .

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

- GW170817 observations set upper limits on Λ_1 and Λ_2 .



Cold dense matter in the laboratory

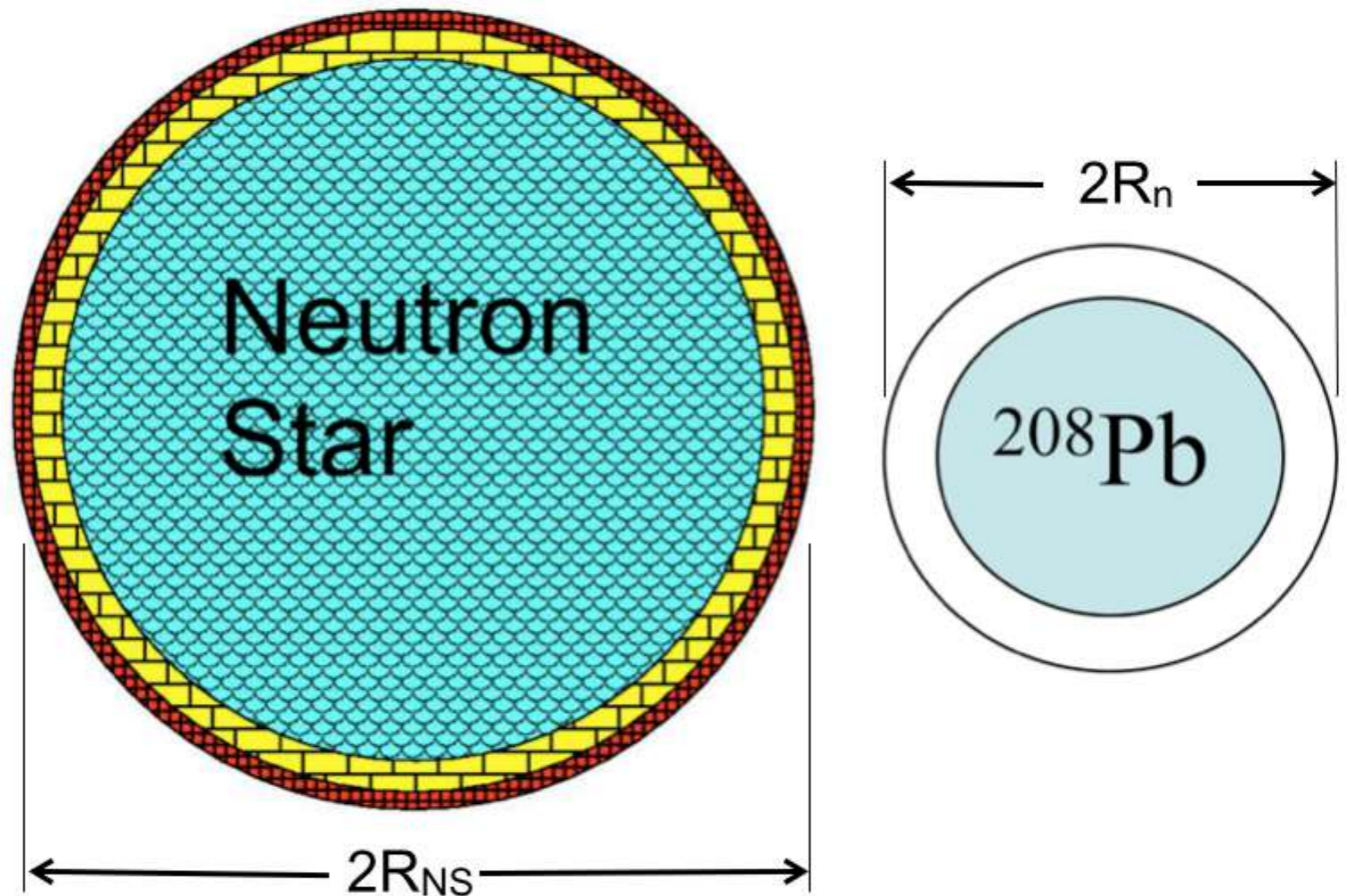


PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb .

This has important implications for neutron rich matter and astrophysics.

Radii of ^{208}Pb and Neutron Stars

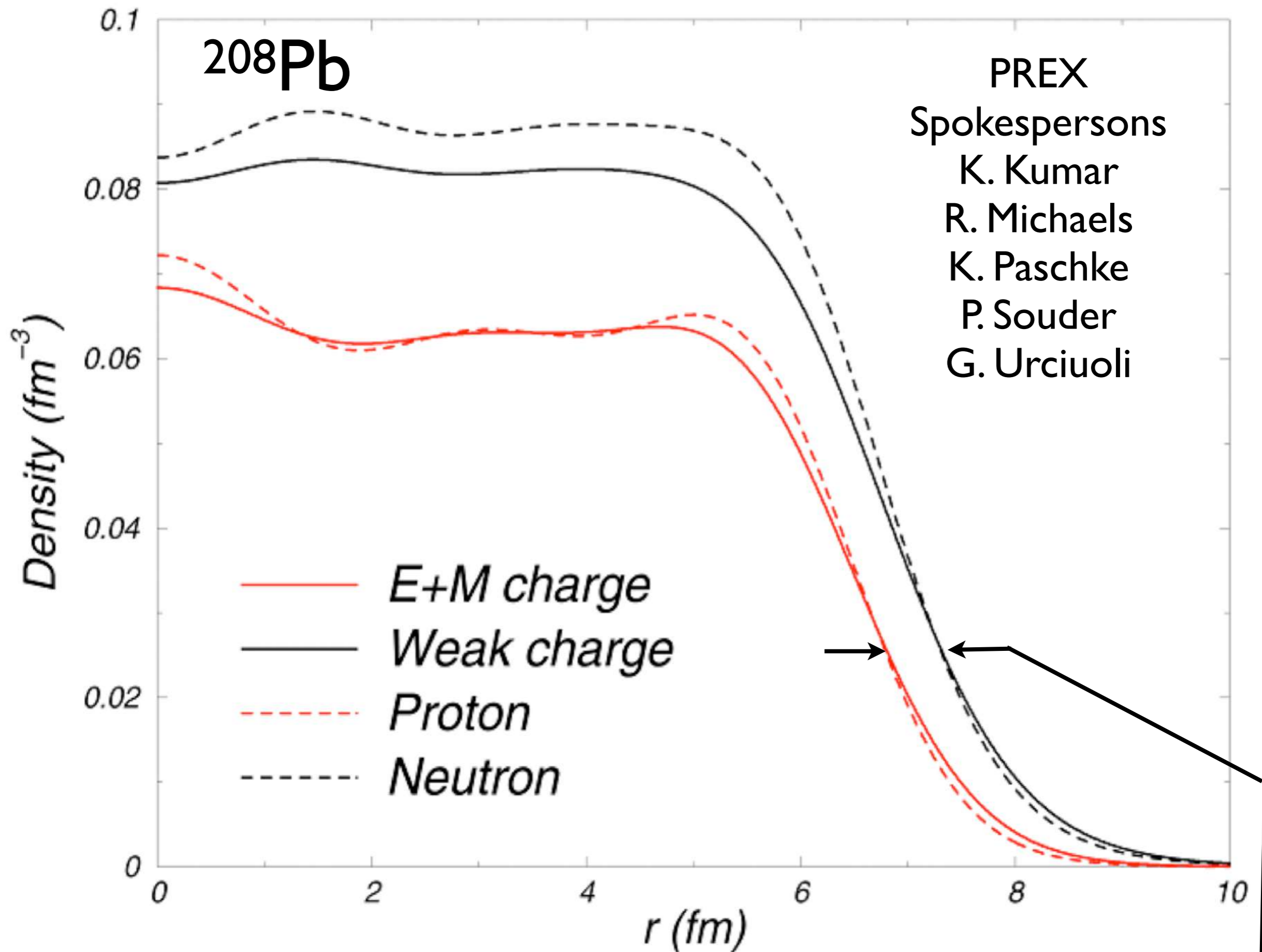
- Pressure of neutron matter pushes neutrons out against surface tension $\implies R_n - R_p$ of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of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



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

Surface tension barometer

- Measure a force with a spring and a ruler. The spring constant is calibrated by the known surface tension of nuclei (from the surface energy of the semi-empirical mass formula).
- The ruler is PREX measuring the neutron skin thickness of ^{208}Pb .
- Divide measured force by surface area to deduce pressure of neutron rich matter at nuclear density.



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

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

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

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

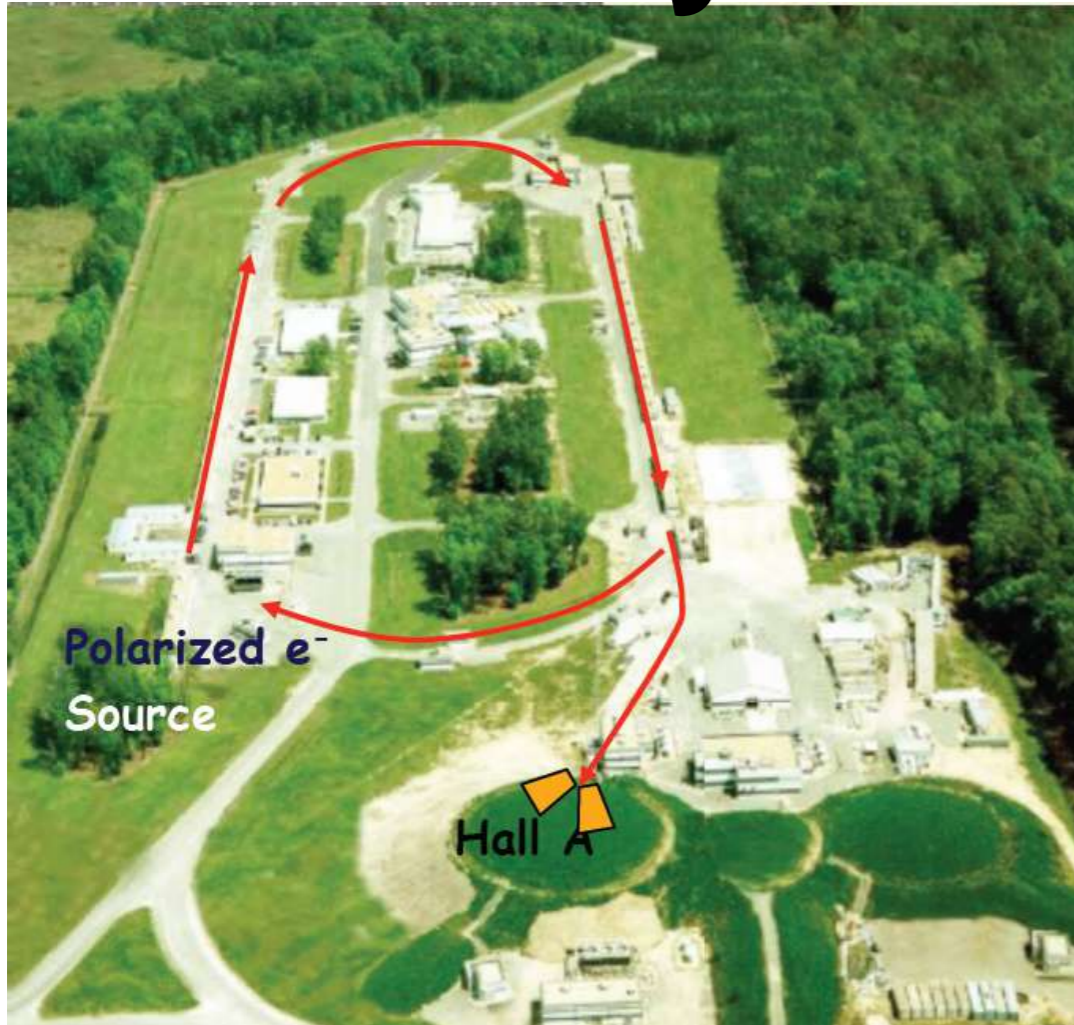
$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

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

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

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

PREX at Jefferson Lab in Virginia



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

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

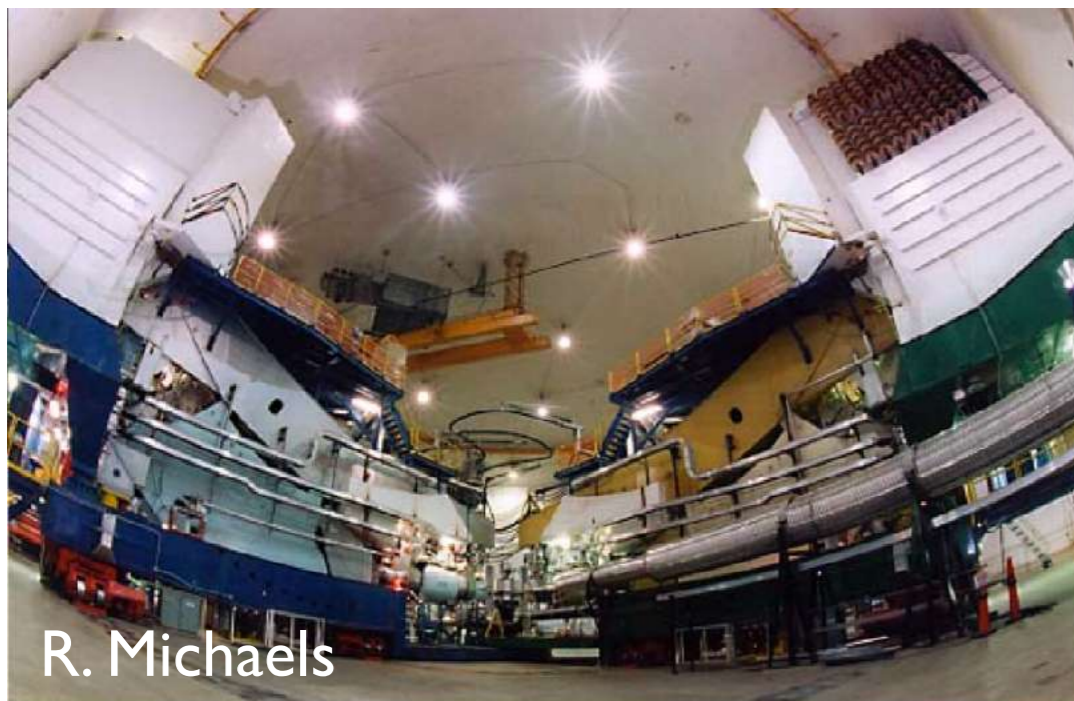
- From A_{PV} I inferred neutron skin:
 $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm.

- Next measurements:

- **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*.

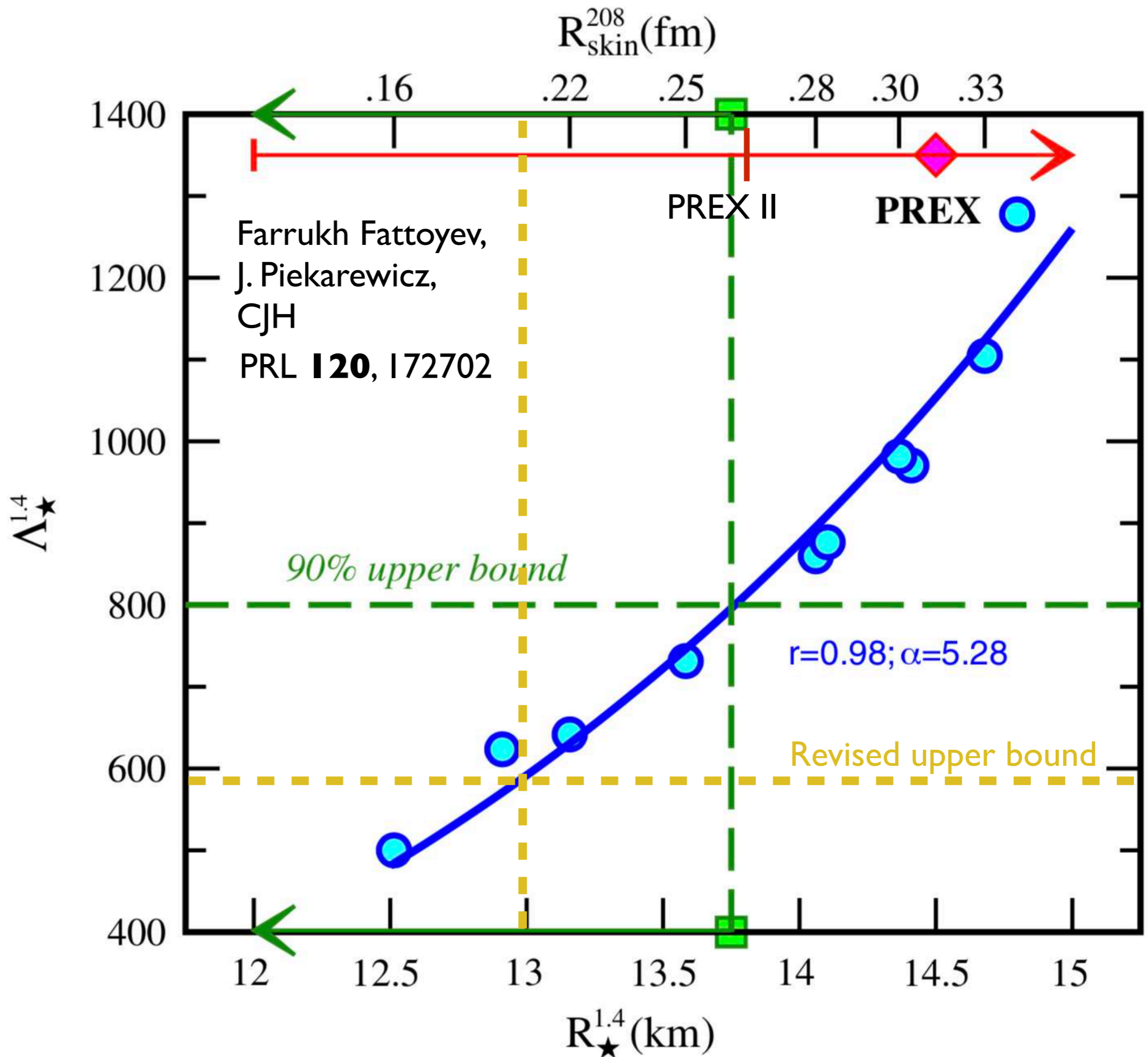
- PREX II ran last Summer. CREX is running now.



LIGO VS PREX

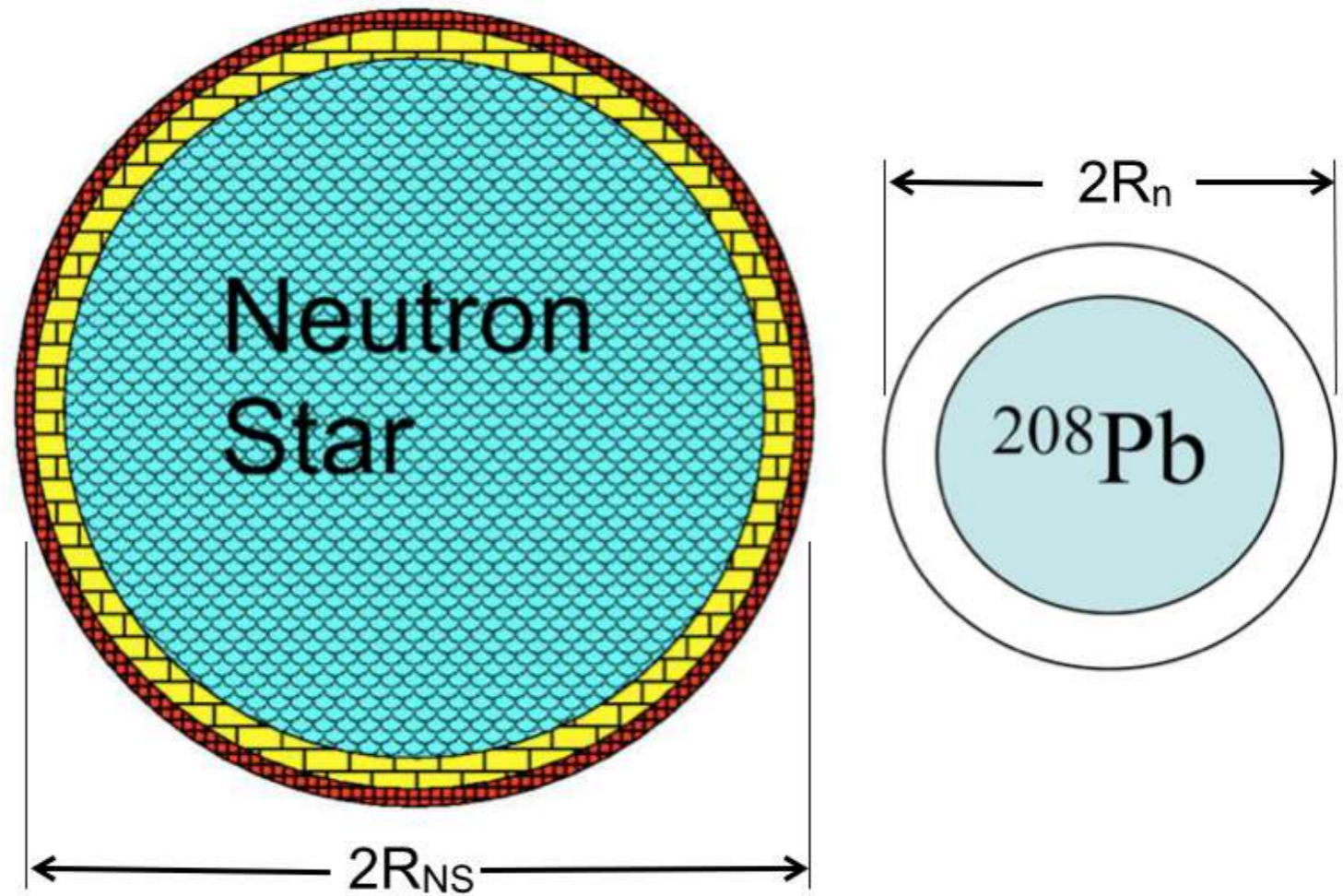
Deformability Λ
of $1.4M_{\text{sun}}$ NS
now less than 590
(Yellow dashed).
ArXiv:1805.11581

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



Density Dependence of EOS

- Pressure of neutron matter pushes neutrons out against surface tension $\Rightarrow R_n - R_p$ of ^{208}Pb determines P at **low densities** $\sim 0.7\rho_0$
- Radius or deformability Λ of ($\sim 1.4M_{\text{sun}}$) NS depends on P at **medium densities** $\sim 2\rho_0$.
- Maximum mass of NS depends on P at **high densities** (fate of merger remnant).
- Three measurements constrain density dependence of EOS.

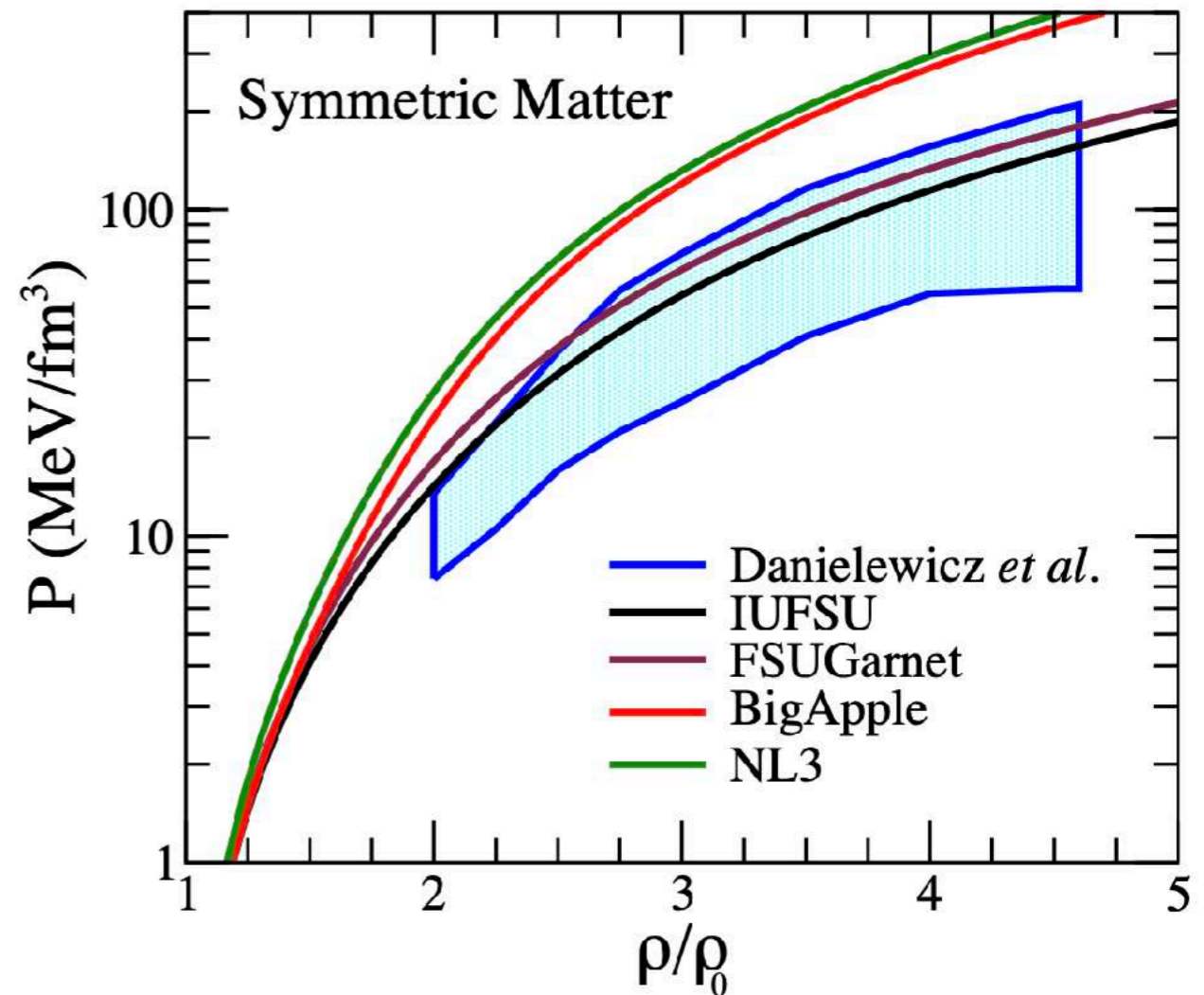


If PREX II finds a thick ^{208}Pb skin and high pressure, while NS radius or deformability appears small: this could suggest a softening of the EOS (lowering of P with increasing density) from a phase transition — perhaps from hadronic to quark matter.

PREX II analysis now and results to be announced at Fall DNP meeting

GW190814: demise of “Big Apple”

- GW190814 had massive BH and $2.6M_{\text{sun}}$ compact object.
- **Big Apple:** Relativistic energy functional with $2.6M_{\text{sun}}$ NS that fits many nuclear properties and has deformability of 717 for $1.4M_{\text{sun}}$ that (almost) fits NS merger GW170817. But pressure of symmetric matter too high for HI flow data.
—> $2.6M_{\text{sun}}$ object is lightest observed BH.



Farrukh Fattoyev, Jorge Piekarewicz, B. Reed and CJH, arXiv:2007.03799

Studying dense matter with gravitational waves

- What are neutron stars made of? Nucleons? Quarks? **What is nature of dense matter?**
 - Much richer than what is EOS? [Why EOS bias?]
 - Also need transport properties: thermal cond., neutrino emissivity... For example, NS cooling data may be important.
 - How does cold dense matter in NS compare to dense laboratory matter at RHIC, FRIB ...?
 - RHIC found hot dense matter to be strongly interacting QGP—> NS matter also likely strongly interacting.

The gravitational wave sky

Galileo's Sky

Moons of Jupiter
Mountains on moon
Phases of Venus
Sun spots
Saturn's rings...

Gravitational Wave Sky

Black hole-BH mergers
NS -NS mergers
BH-NS merger
What else? ...



H. Detouche

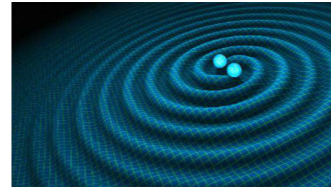
- These are historic times with the opening of the GW sky. ***What else could be out there?***

E+M bias in GW astronomy



E+M: Measure intensity, frequency, (polarization)

- Infer: Temperature, Composition (spectral lines), Velocity
- Not observed: Mass, Density, Shape, Distance



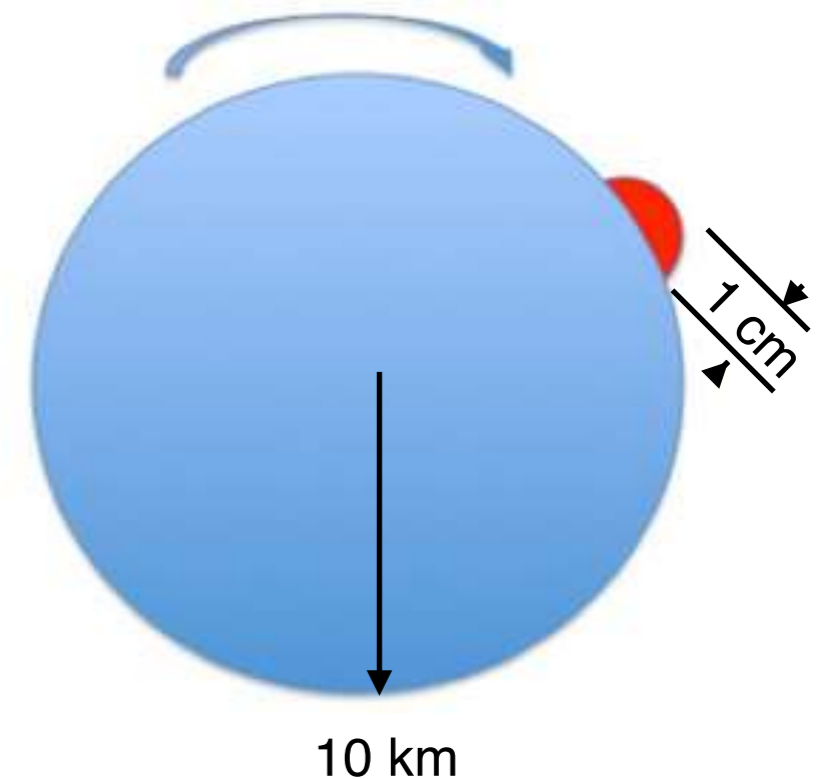
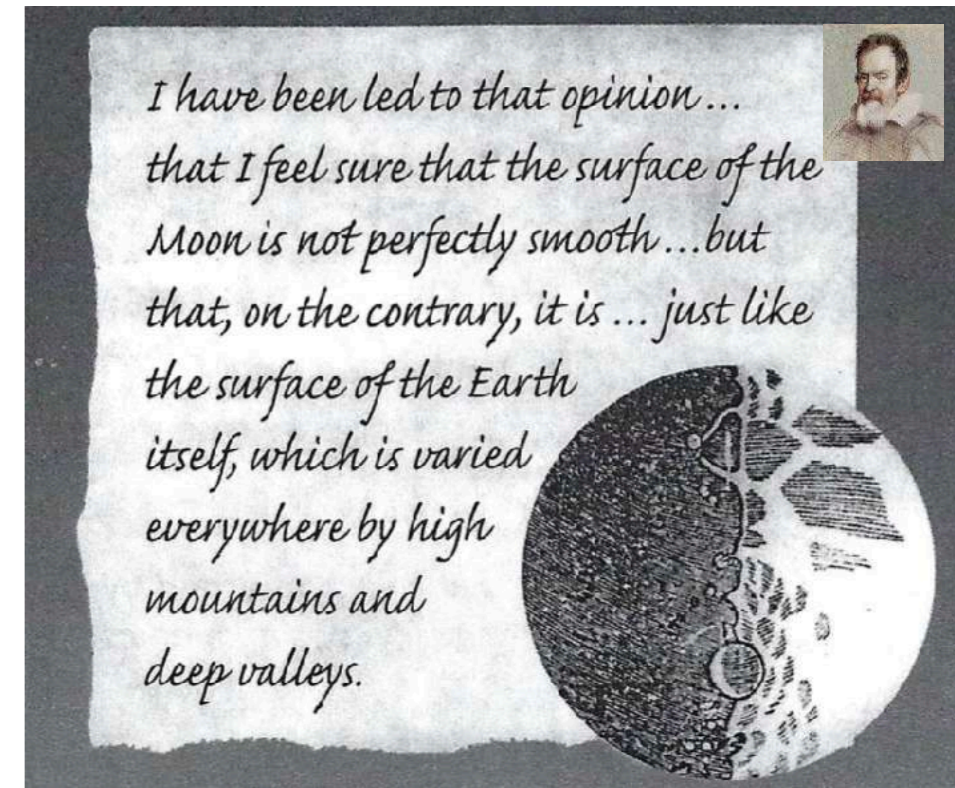
GW: Measure amplitude, frequency, polarization (+,x)

- Infer: Chirp mass, Density (lower limit), Shape (quadrupole), Luminosity distance
- Not observed: Composition!, Temperature

-
- LIGO only sensitive to high densities: $f \sim (G\rho)^{1/2} > 10\text{Hz}$
—> $\rho > 10^{10} \text{ g/cm}^3$. Only *known* sources NS and BH!
 - Discovery potential at low chirp mass: a single well measured event with a low chirp mass would be revolutionary.

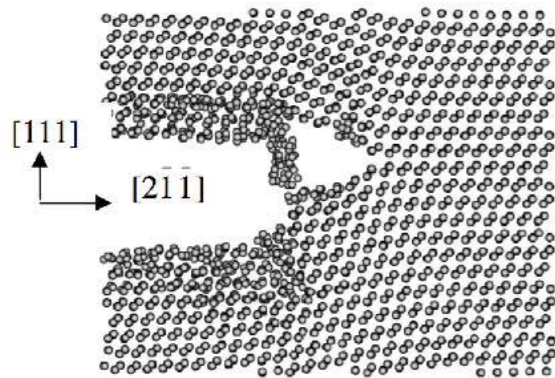
“Mountains” on neutron stars and continuous gravitational waves

- Consider a large mountain (red) on a rapidly rotating neutron star. Gravity from the mountain causes space-time to oscillate, radiating gravitational waves. Fundamental question: *how do you support the mountain?*
- Mountains on rotating star involve large mass undergoing large accelerations and efficiently radiate GW.
- Strong GW source (at LIGO frequencies) places extraordinary demands on dense matter.
 - Put a mass on a stick and shake vigorously.
 - Need both a large mass and a strong stick.
 - Let me talk about the strong stick.



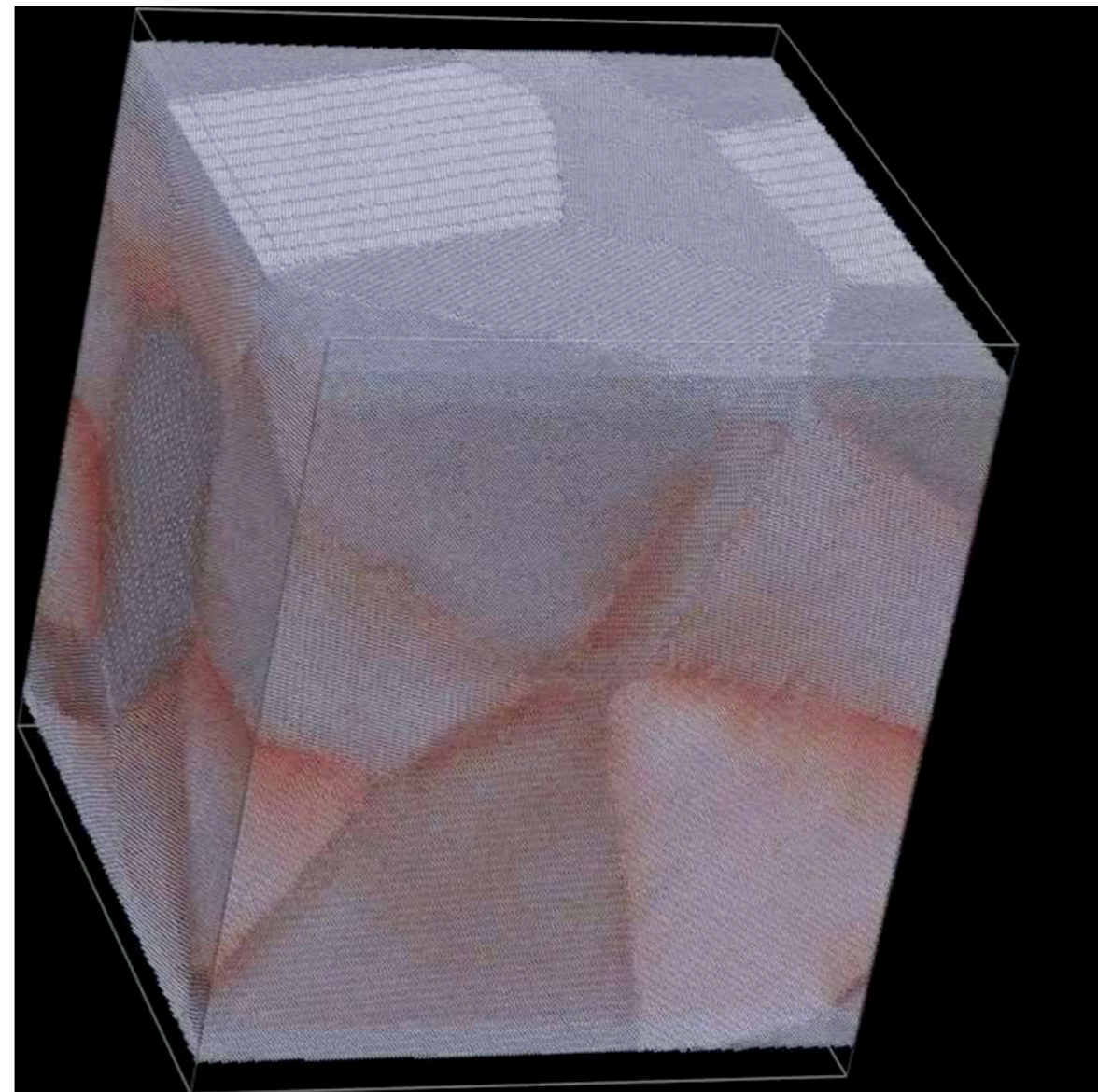
Crust Strength and Neutron Star Mountains

- With Material Scientist Kai Kadau (LANL), we simulated breaking stress of NS crust including impurities, dislocations, grain boundaries... We find NS crust is the strongest material known ~ ten billion times stronger than steel.
- **Material Science:** Defects, impurities, dislocations, grain boundaries... can nucleate cracks. Often material fractures at a strain (fractional deformation) $\sigma \ll 0.1$



MD simulation of crack propagation (fracturing) in Silicon. Neutron star crust does not fail this way.

- **Astromaterial Science:** High pressure in compact stars prevents void formation and fractures. Long range Coulomb interactions provide many redundant bonds. Breaking strain very large $\sigma \sim 0.1$ M. E. Caplan and CJH, Rev. Mod. Phys. **89** (2017) 041002.
- **Strong crust can support large detectable mountains (cm high)!**



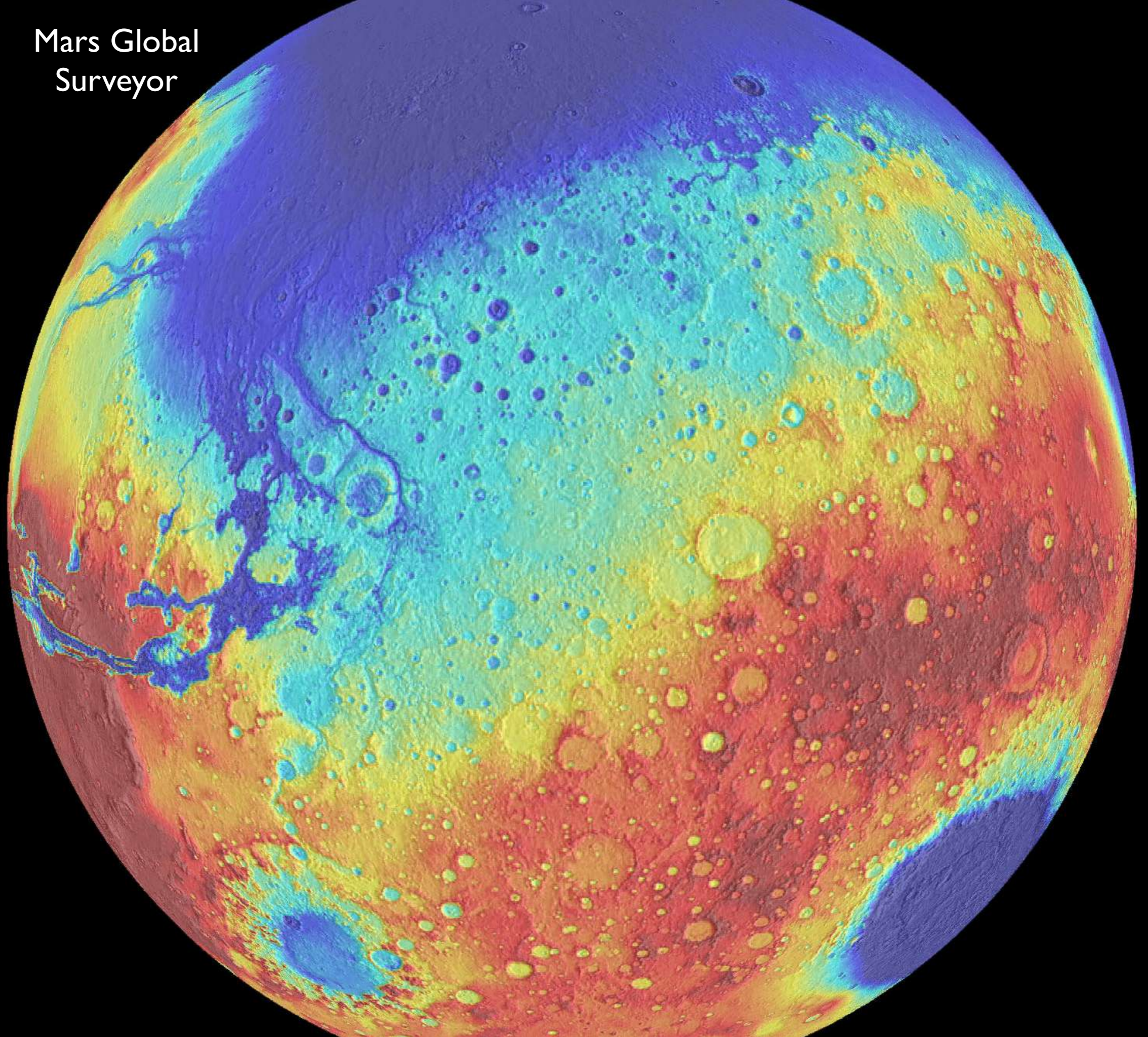
MD simulation of crust breaking, with 13 million ions. Red color indicates deformation of bcc lattice. Phys. Rev. Let. **102**, 191102 (2009)

Ellipticity is difference in moments of inertia: $\epsilon = (I_1 - I_2) / I_3 < \text{few} \times 10^{-6}$

How big are mountains on neutron stars?

- **Maximum possible mountain:** depends on strength of the crust. I find a strong crust that can support up to $\epsilon < \text{few} \times 10^{-6}$. Simple(?)“(astro)material science” question.
- **Mountain building mechanisms:** does nature actually build big mountains on a given star?? Hard astrophysical, planetary science ... problem.

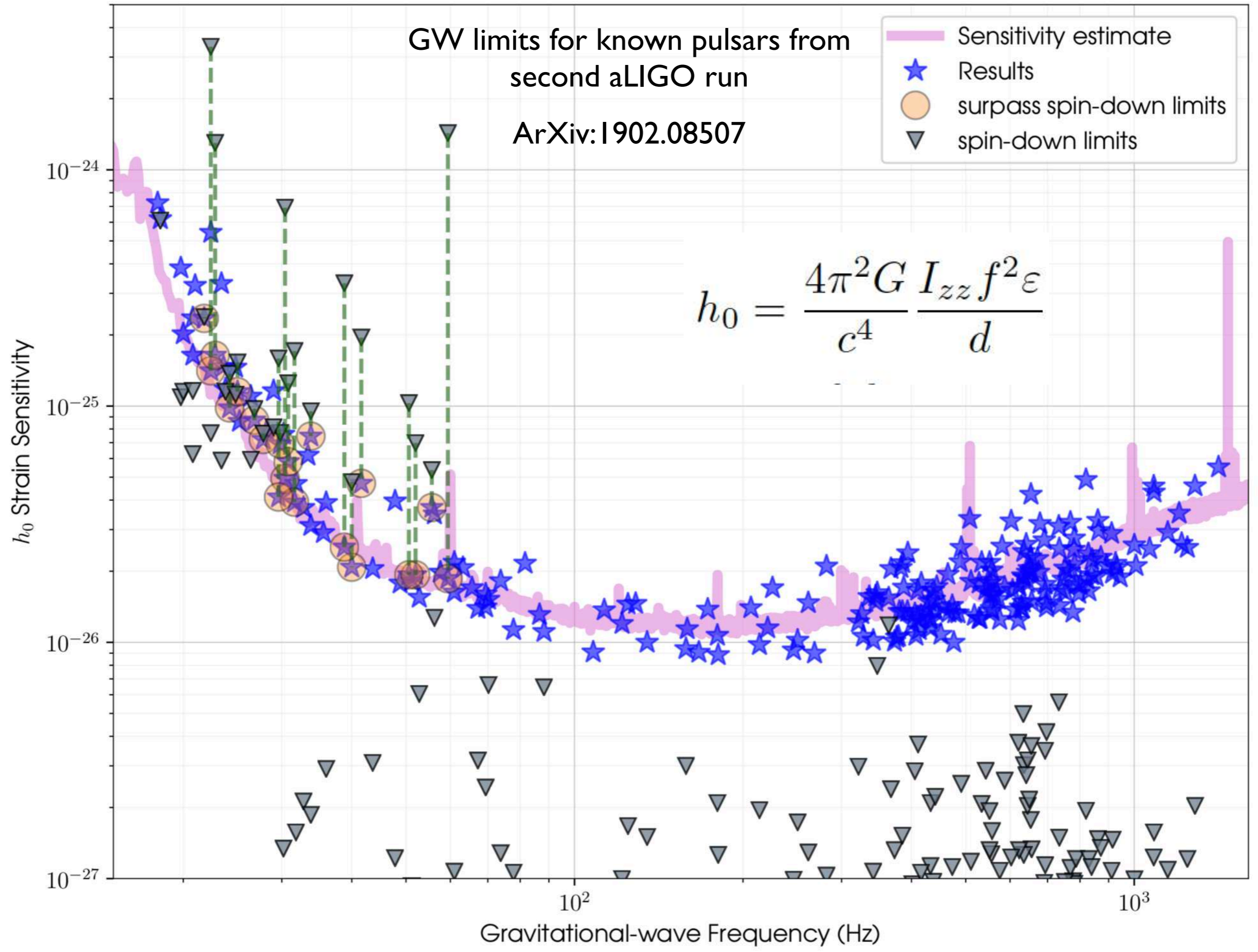
Mars Global
Surveyor

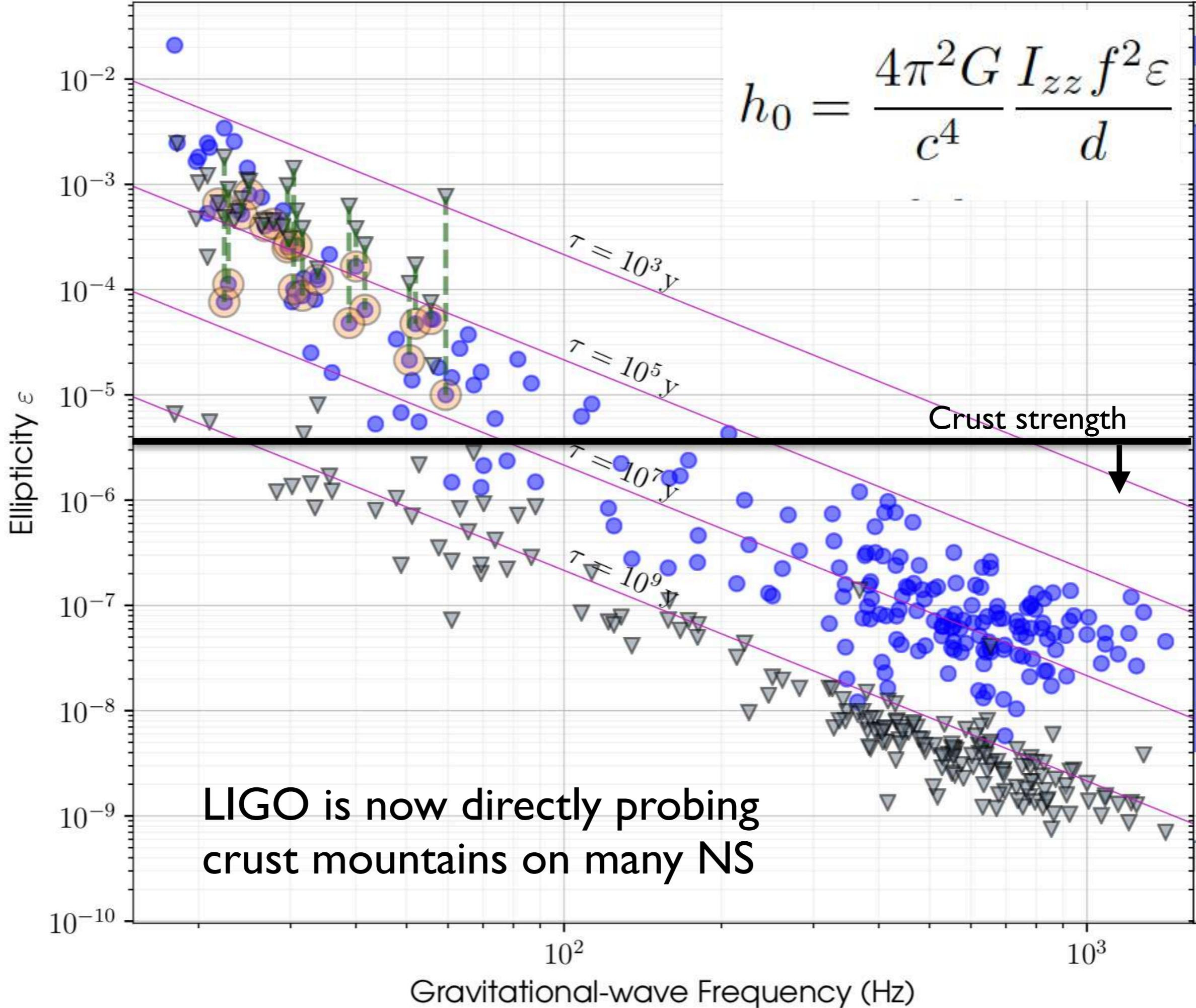


GW limits for known pulsars from
second aLIGO run
ArXiv:1902.08507

- Sensitivity estimate
- Results
- surpass spin-down limits
- spin-down limits

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f^2 \epsilon}{d}$$





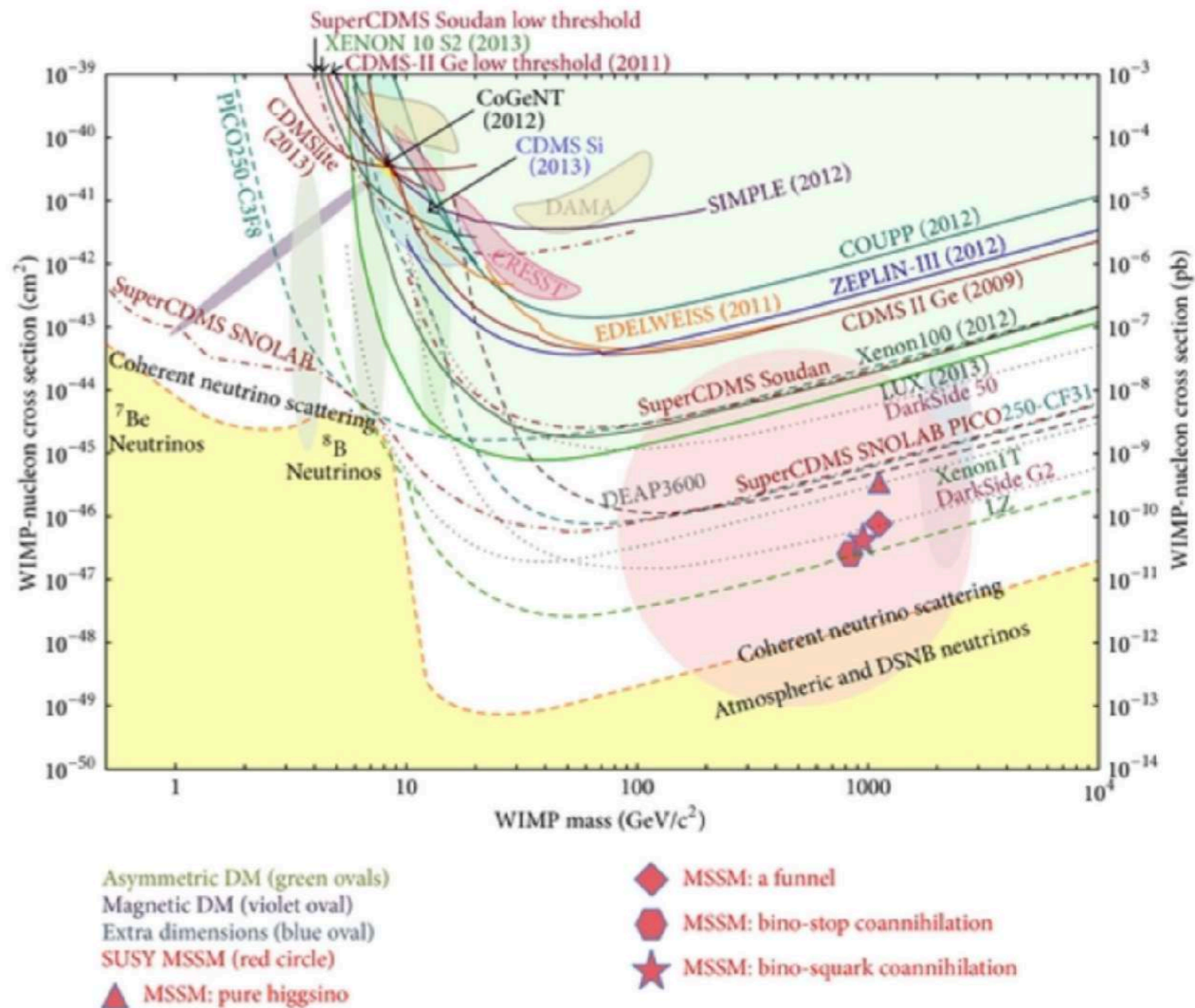
Roundest objects known

- To help define kilogram, two 93.75 mm ^{28}Si spheres were machined to ± 60 or 70 nanometers at large scales.
- Roundest objects in world with $\Delta r/r \sim 10^{-6} \sim$ ellipticity ϵ .
- Gravity probe B gyros have similar ϵ ??
- Best O2 run ellipticity limit: J0636, $\epsilon < 5.8 \times 10^{-9}$. Direct GW obs. show some NS are at least 100 times rounder than what we can machine.
- Many ms pulsars have spin down limits $\epsilon \sim 10^{-9}$. E+M timing demonstrates that some NS are at least 1,000 times rounder than what we have machined. **Minimum ϵ can't be zero!**



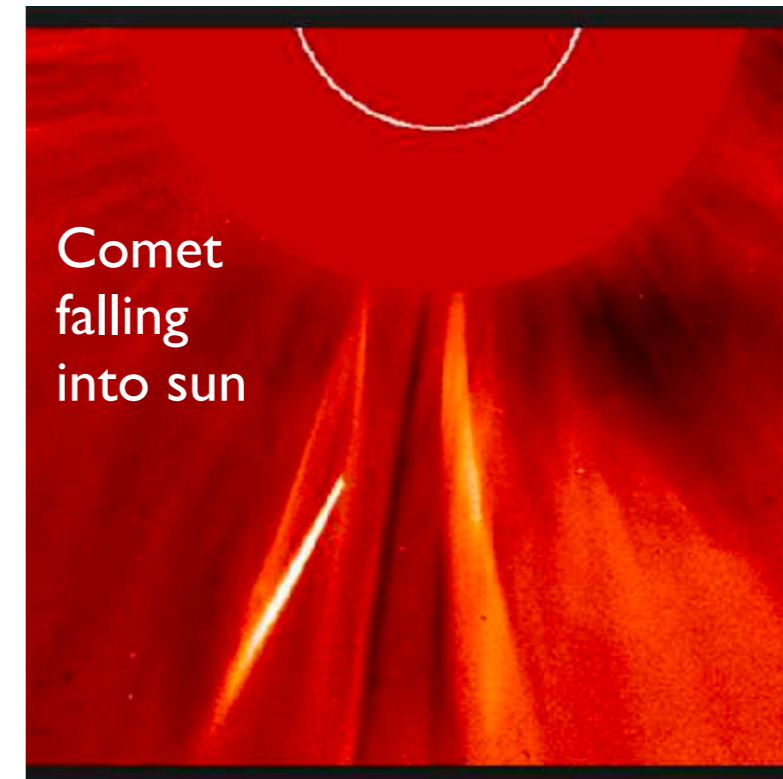
Much of Universe is unknown dark matter

- Many (so far empty) searches for weakly interacting massive particles (WIMPs).
- Attractive to search for dark matter with GW instead since dark matter is known to have gravitational interactions.



Compact dark objects

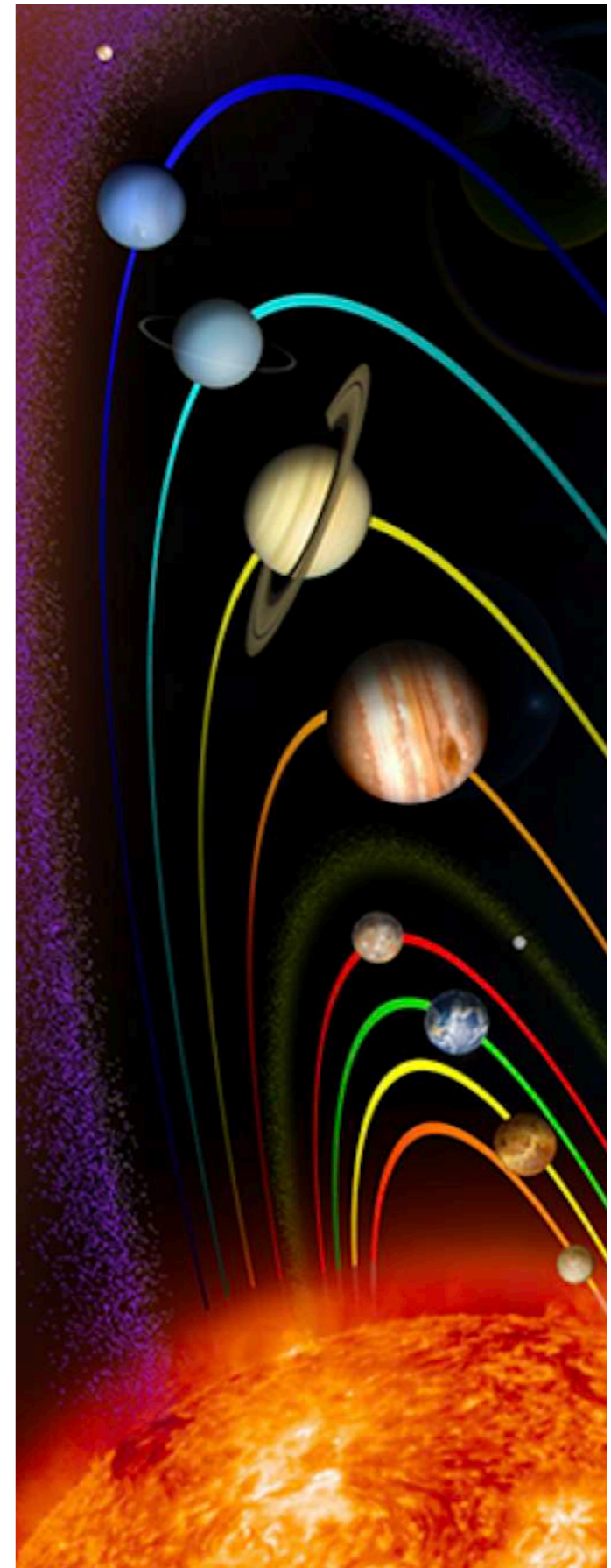
- Dark matter could come in compact dark objects or CDOs for example if self-interactions bind dark matter particles together into macroscopic objects.
- Some possibilities or names for CDOs include Boson Stars, Dark Blobs, asymmetric dark matter nuggets, Exotic Compact Objects, Ultra Compact Mini Halos (UCMH), and Macros.
- Let us not talk about primordial black holes (although popular dark matter model) to avoid destroying solar system bodies.
- CDOs could enter the sun and continue to orbit inside.



Solar and Heliospheric Observatory

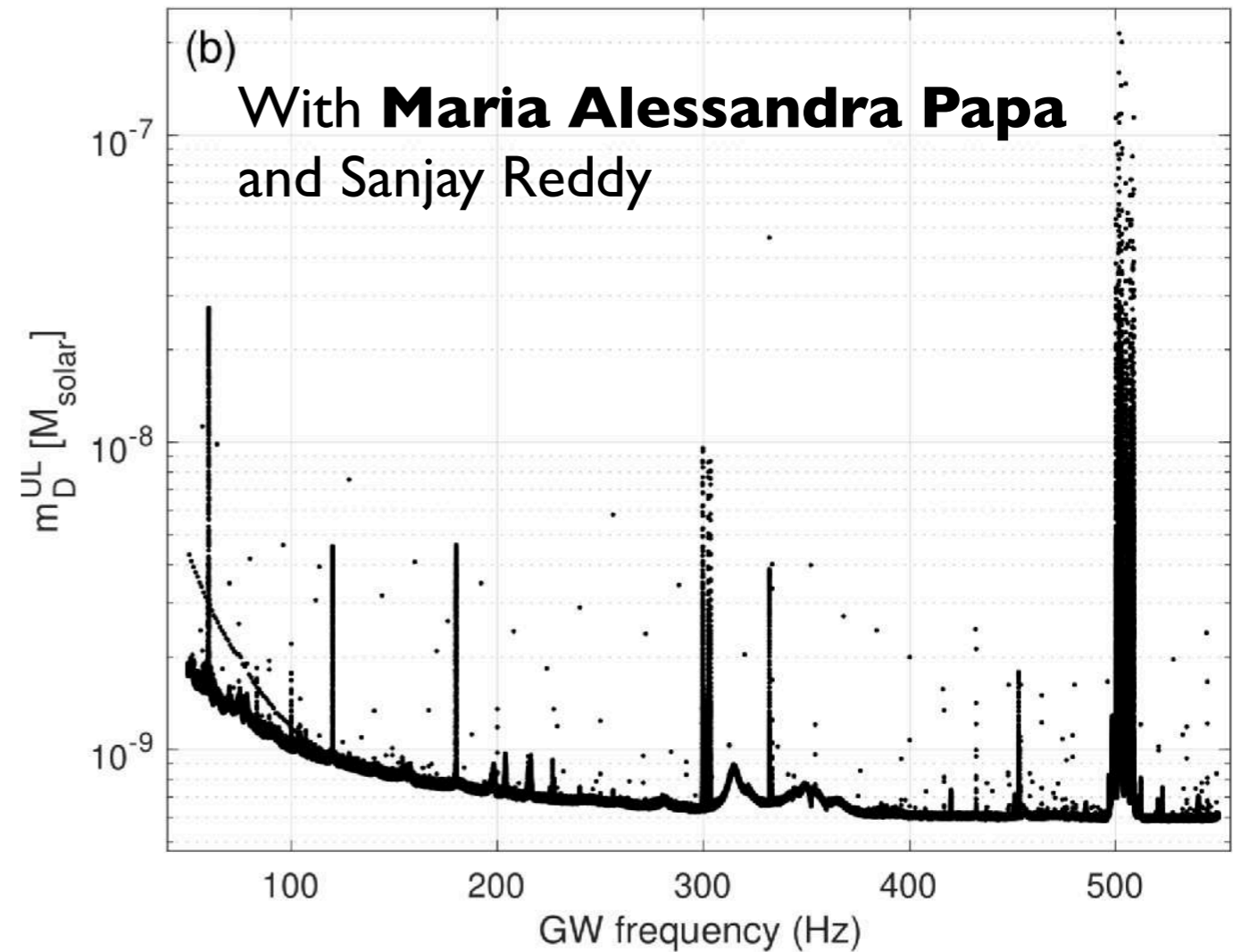
Kepler's Third Law inside the Sun

- Object of mass m in circular orbit of radius r about an enclosed mass $M(r)$ has angular frequency ω : $GM(r)m/r^2 = mr\omega^2$.
- Enclosed mass: $M(r)=4\pi\rho r^3/3$.
- Orbital frequency: $\nu = \omega/(2\pi) = [G\rho/(3\pi)]^{1/2}$
- $\nu \sim 1\text{mHz}$ determined by known central density of Sun 150 g/cm^3 . [Not determined by dark matter m or r]. Too low for LIGO ($2\nu > 10\text{Hz}$).



CDO binaries in solar system

- A close binary of CDOs in the solar system can be a very loud source of GW.
- We have carried out a search using data from first aLIGO observing run.
- Binaries near center of sun with masses above curve ($\sim 10^{-9} M_{\text{sun}}$) and orbiting at 1/2 GW frequency are ruled out.



Phys. Rev. Lett. **122** (2019) 071102

Phys. Lett. B **800** (2020) 135072

Philosophy

- Try to obtain sensitivity to lowest possible CDO masses.
- Try to minimize assumptions about CDO properties.
- A lower CDO mass likely implies a larger number density and the nearest one may be closer to you.
- Look for CDOs orbiting *inside* the earth.
- Now so close one can just look for Newtonian gravity instead of GW.

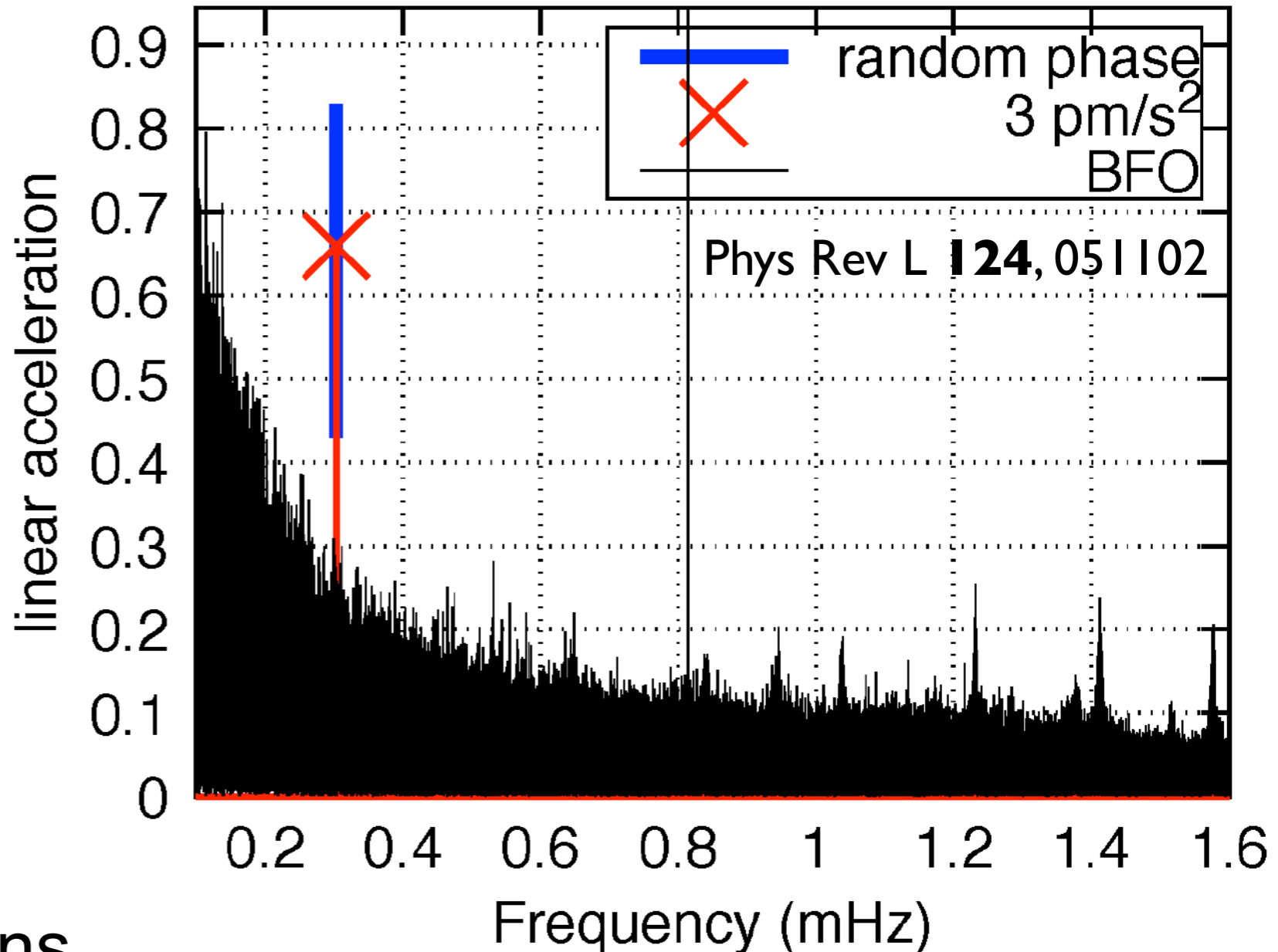
Gravimeter in Abandon Silver Mine



With Rudolf Widmer-Schnidrig

Superconducting Gravimeter Results

- Seven years of data from Black Forest Observatory.
- Upper bound:
 $\Delta g(\nu=0.3 \text{ mHz}) < 3 \text{ pm/s}^2$.



- Atmospheric fluctuations above gravimeter dominant background.
- Product of CDO mass m_D times orbit radius a bounded

$$m_D a < 1.2 \times 10^{-13} M_{\oplus} R_{\oplus}$$

If $a \sim 0.1 R_E$ then $m_D < 1.2 \times 10^{-12} M_E$ or $7 \times 10^{12} \text{ kg}$



H. Detouche

- These are historic times with the opening of the GW sky. What else could be out there?

Dense matter in the gravitational wave sky

- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke, G. Urciuoli...
- NS deformability vs ^{208}Pb skin: **Farrukh Fattoyev**, Jorge Piekarewicz.
- Compact dark objects in Sun: **Maria Alessandra Papa**
- Gravimeter: **Rudolf Widmer-Schnidrig**
- Graduate students: Zidu Lin (2018), Brendan Reed, Jianchun Yin, Matt Caplan (2017), Tomoyo Namigata ...

