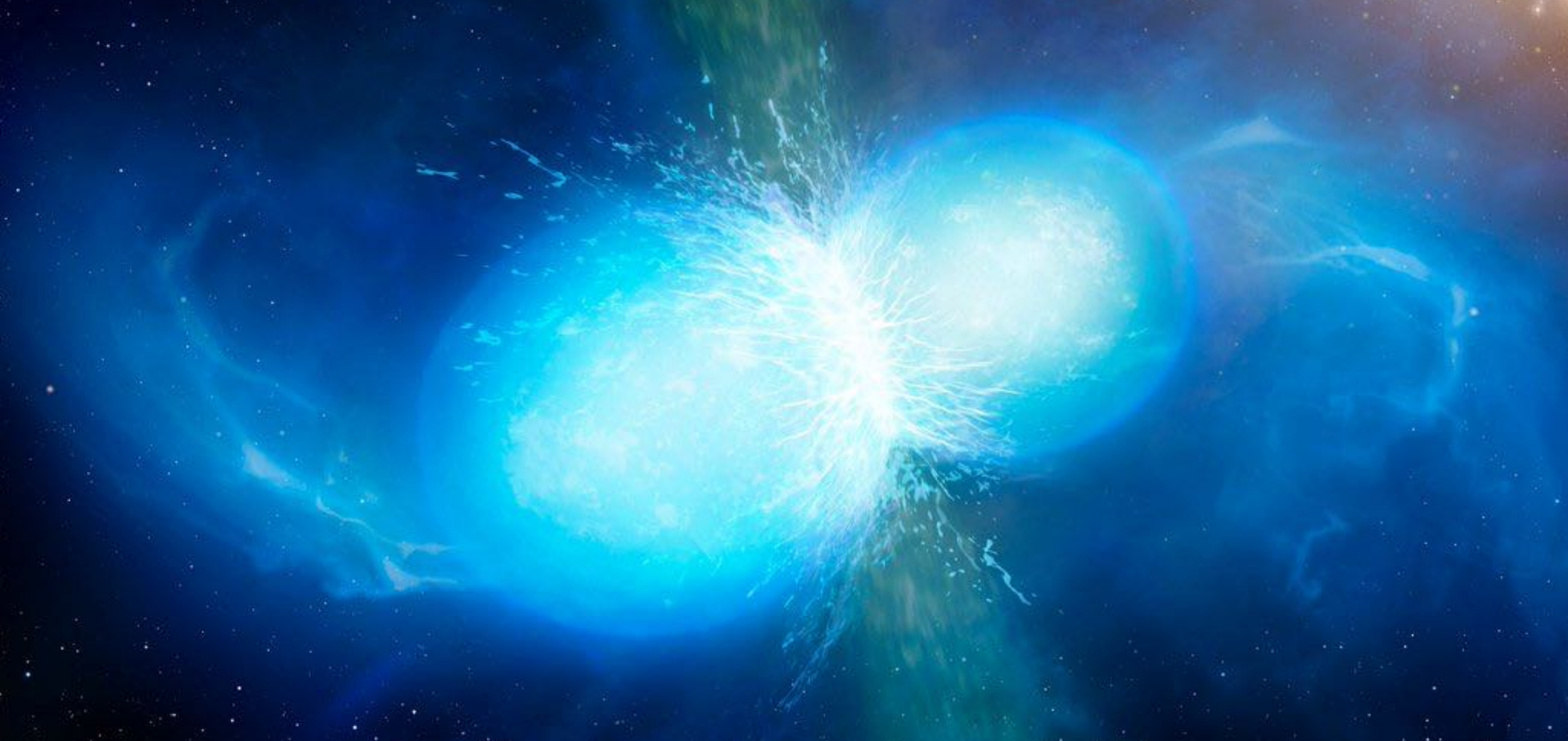
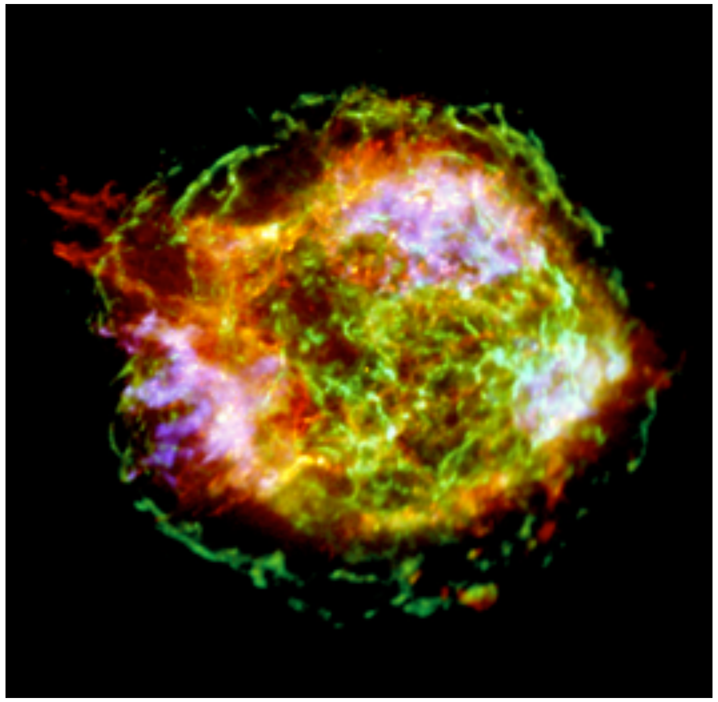
Gravitational waves and the dense matter equation of state



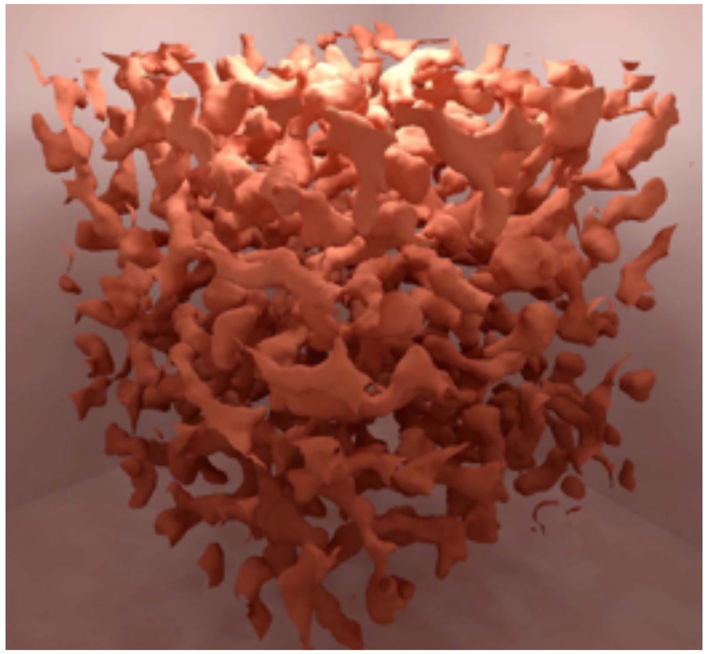
Chuck Horowitz, Indiana U., IHIC, Tsinghua, Beijing, Apr. 2018

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 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} K!), superfluid, color superconductor...*

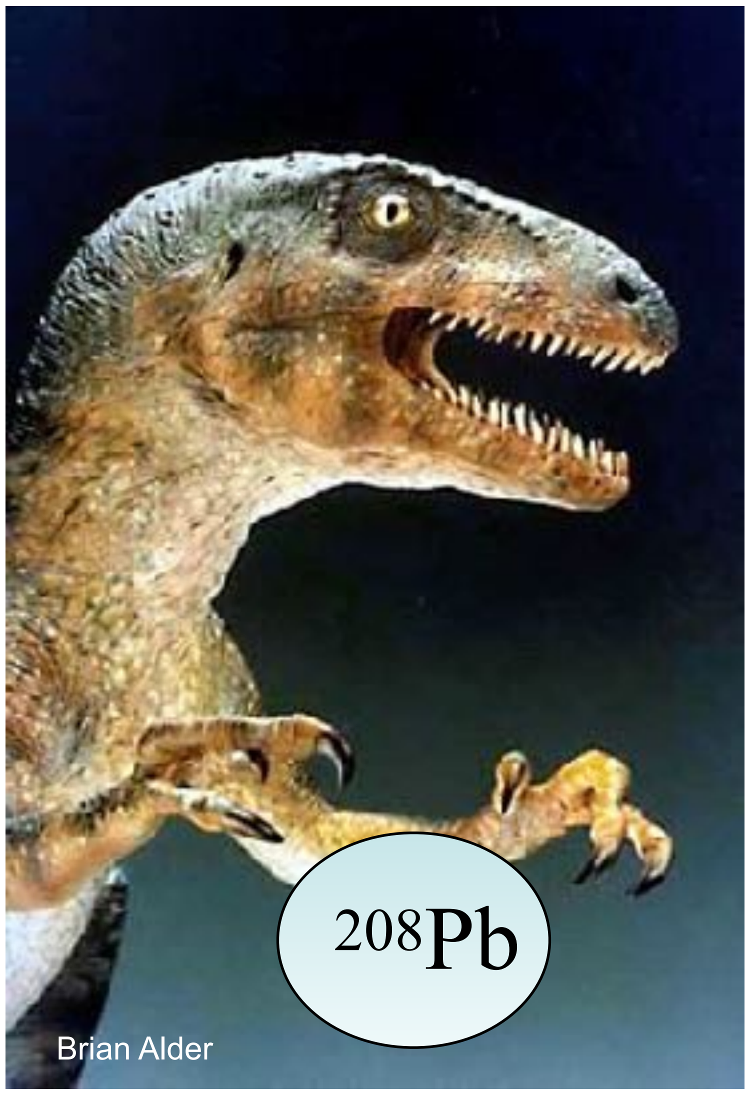


Supernova remanent Cassiopea A in X-rays



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

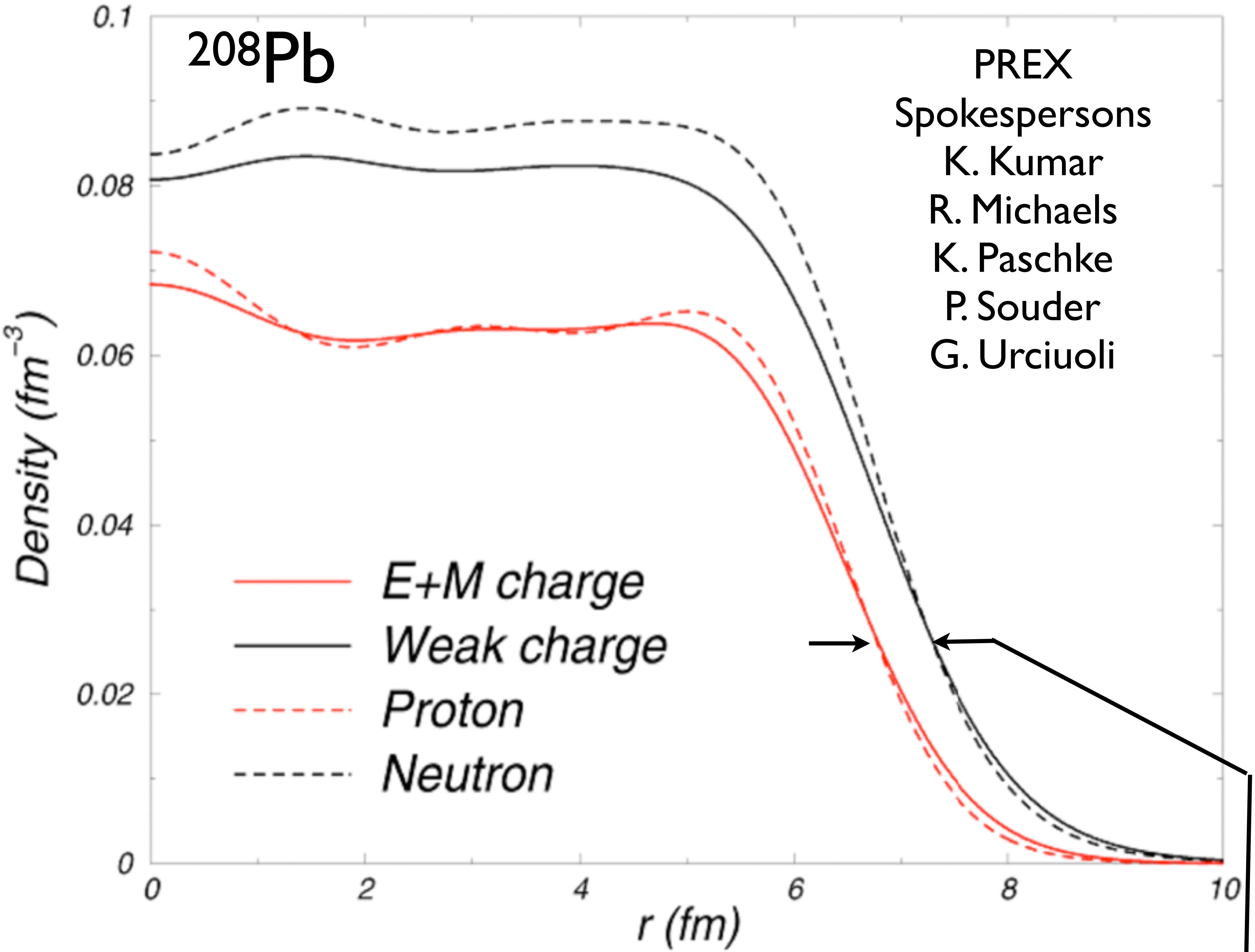
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

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

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

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

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

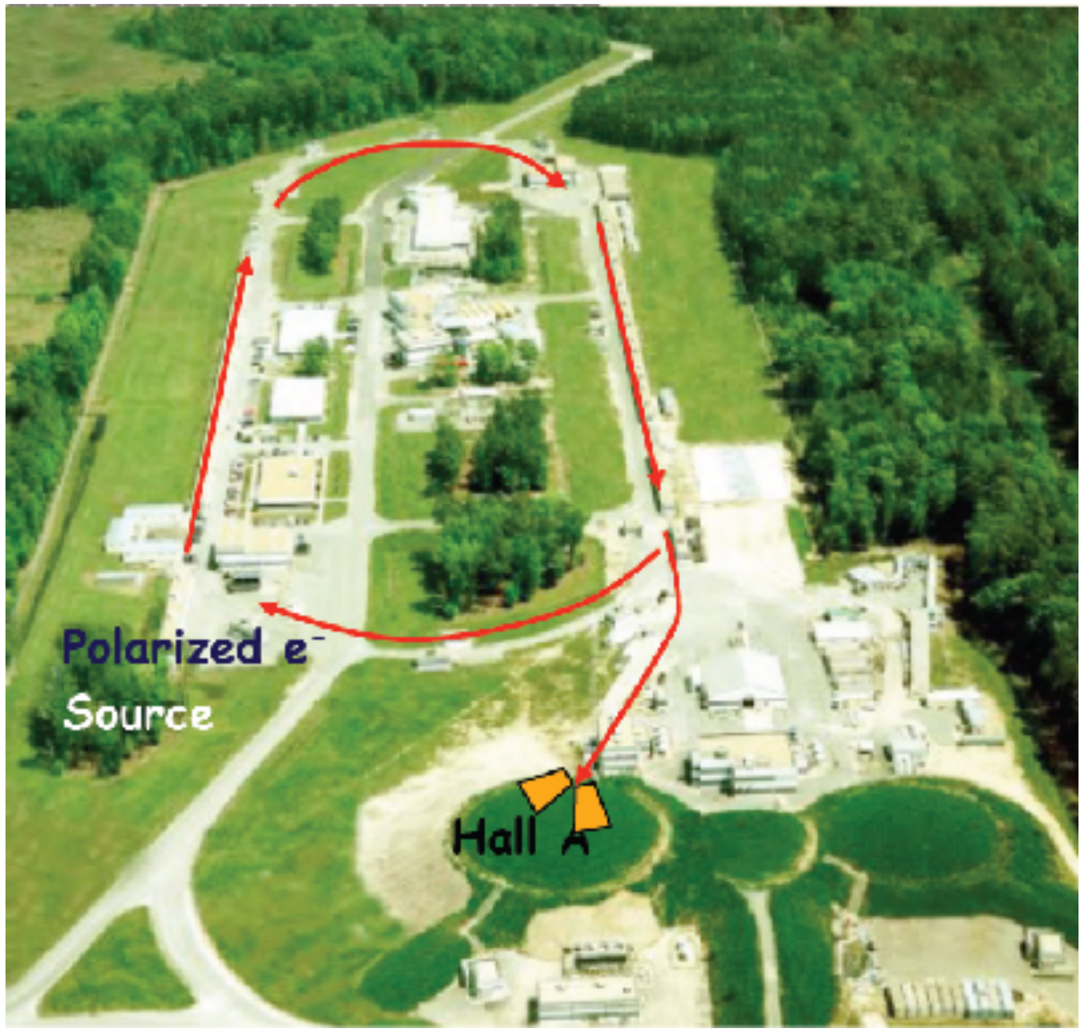


^{208}Pb

PREX
Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli

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

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.

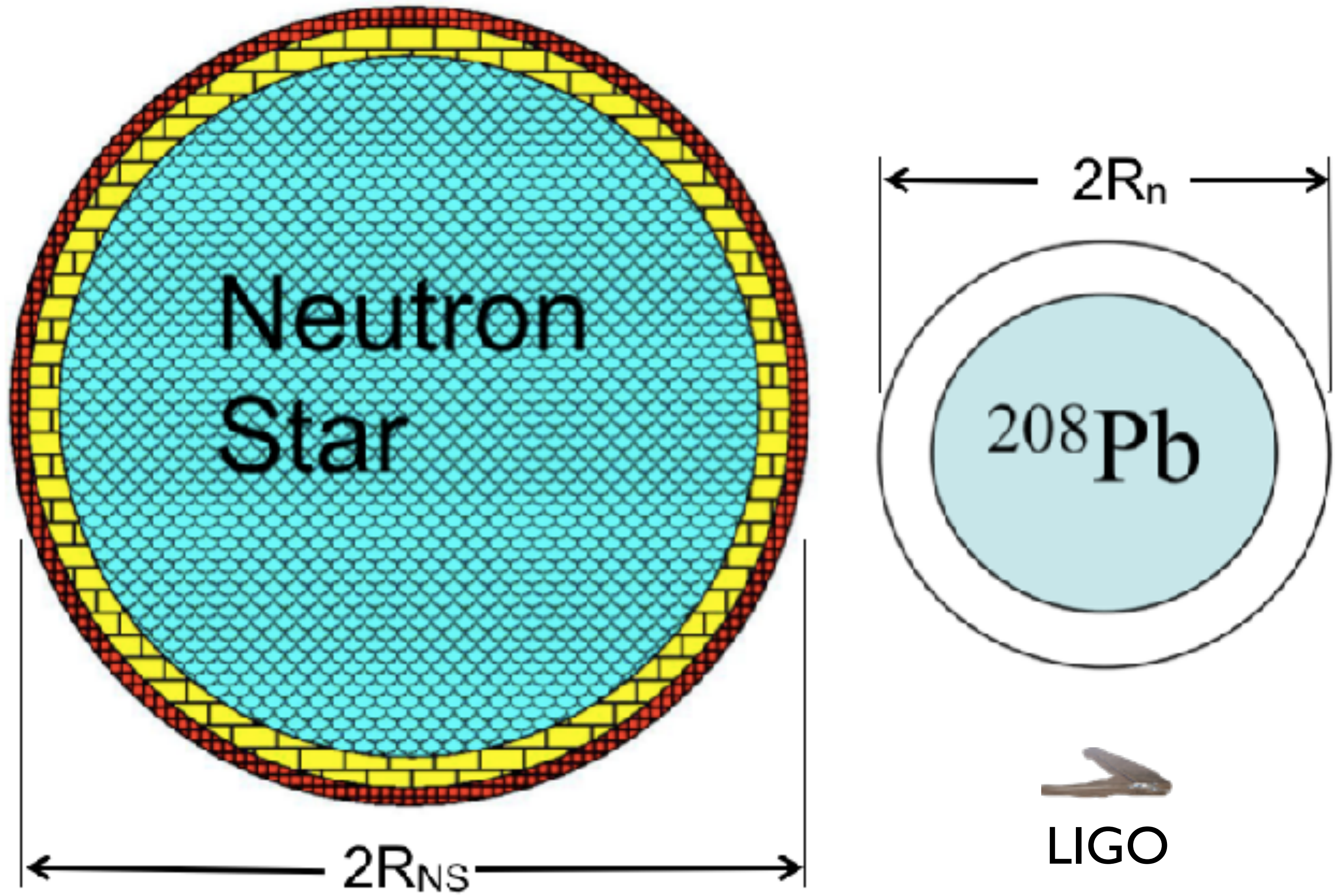
- Next run (plan is 2019)

- **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*.

Radii of ^{208}Pb and Neutron Stars

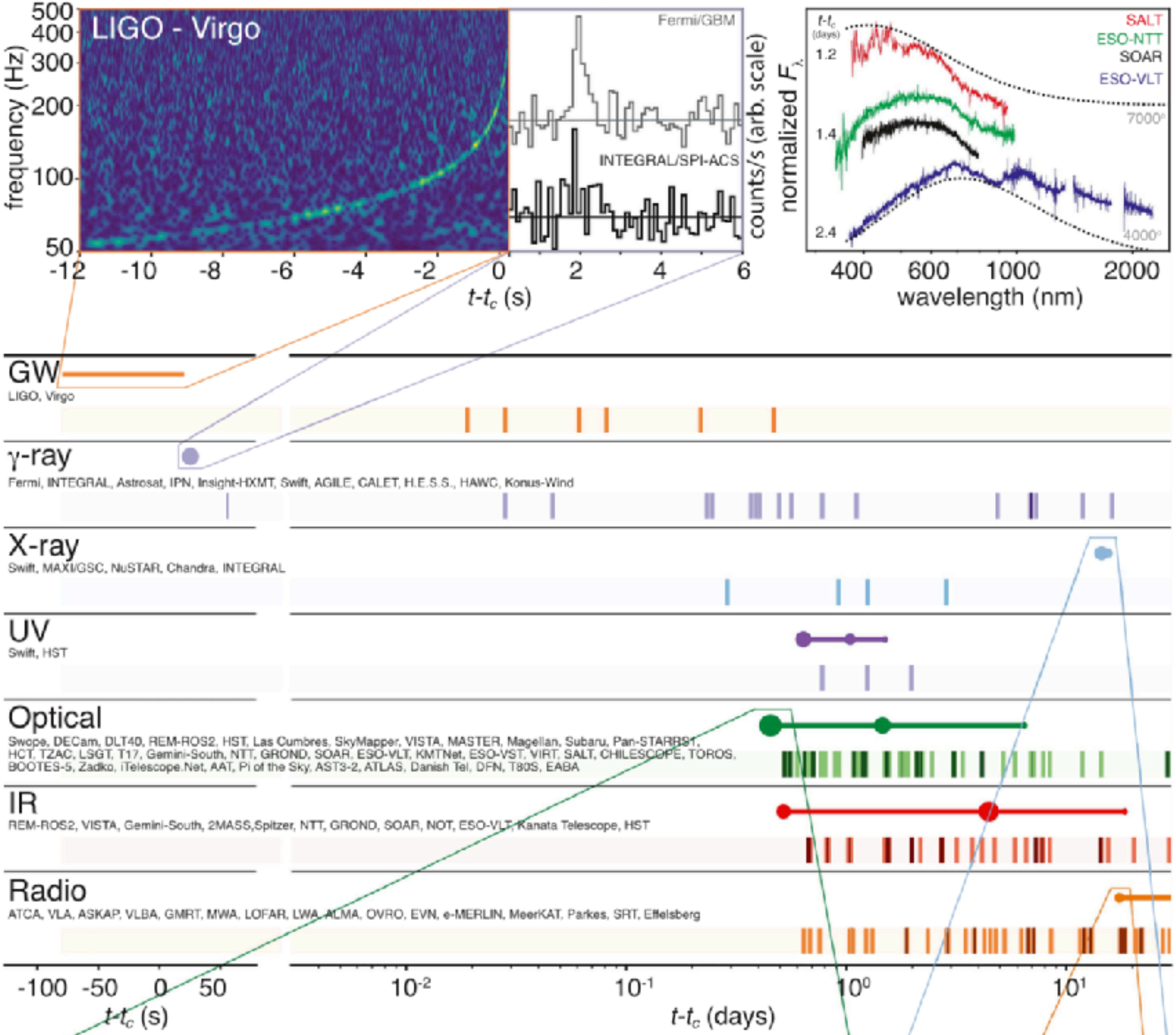
- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



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

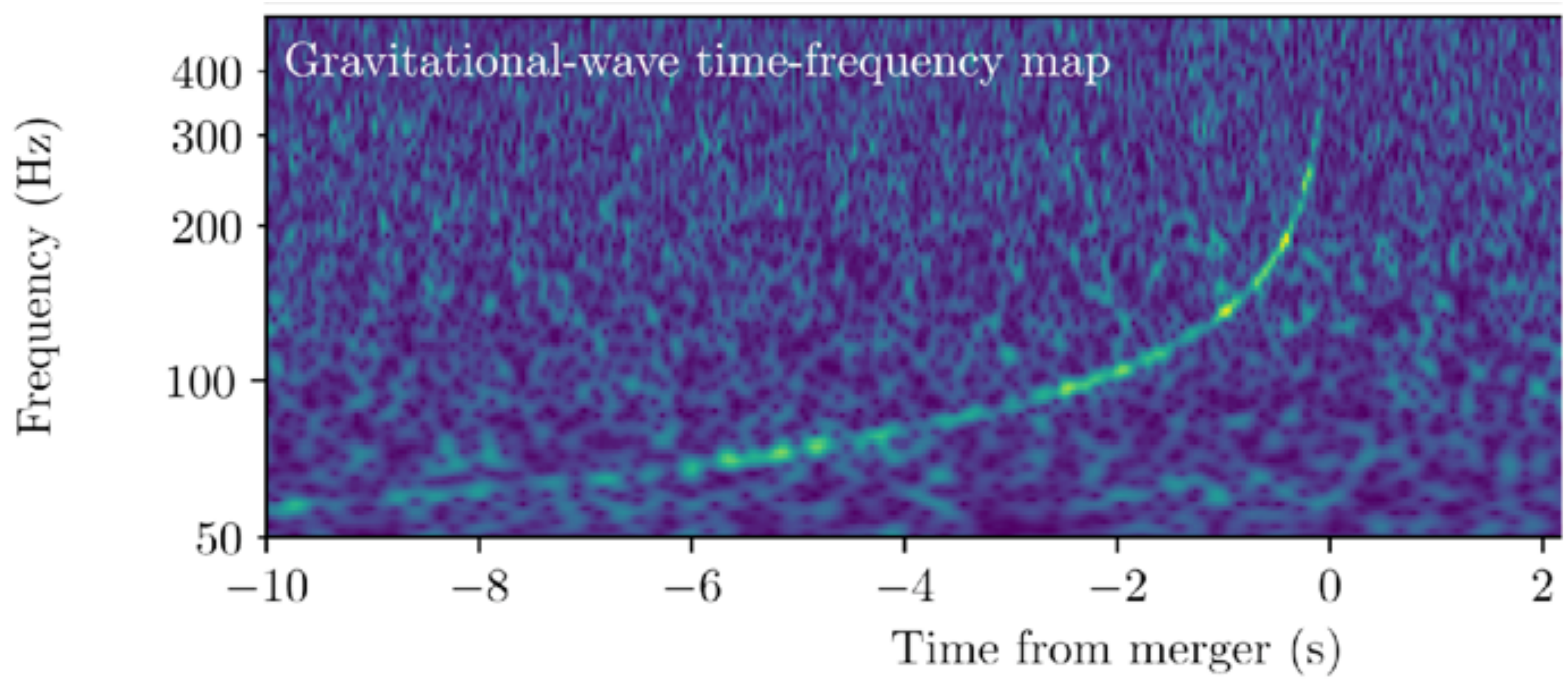
Spectacular event GW170817

- On August 17, 2017, the merger of two neutron stars was observed with gravitational waves (GW) by the LIGO and Virgo detectors.
- The Fermi and Integral spacecrafts independently detected a short gamma ray burst.
- Extensive follow up observations detected this event at X-ray, ultra-violet, visible, infrared, and radio wavelengths.
- Focus here on implications for equation of state of neutron rich matter and r-process.



LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
t-t_c (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-t_c (s)
10^{-2}
10^{-1}
10^{0}
10^{1}
t-t_c (days)

Chirp signal from GW170817



- "Chirp mass" depends on orbital frequency f from Kepler's laws and df/dt from GW radiation:
  $M_{chirp} = (M_1 M_2)^{3/5} / (M_1 + M_2)^{1/5} = 1.188^{+0.004}_{-0.002}\ M_{sun}$.
- Chirp mass too low for a binary black hole system.
- Total mass determined less accurately: $\sim 2.75\ M_{sun}$.

Polarizability of giant nuclei

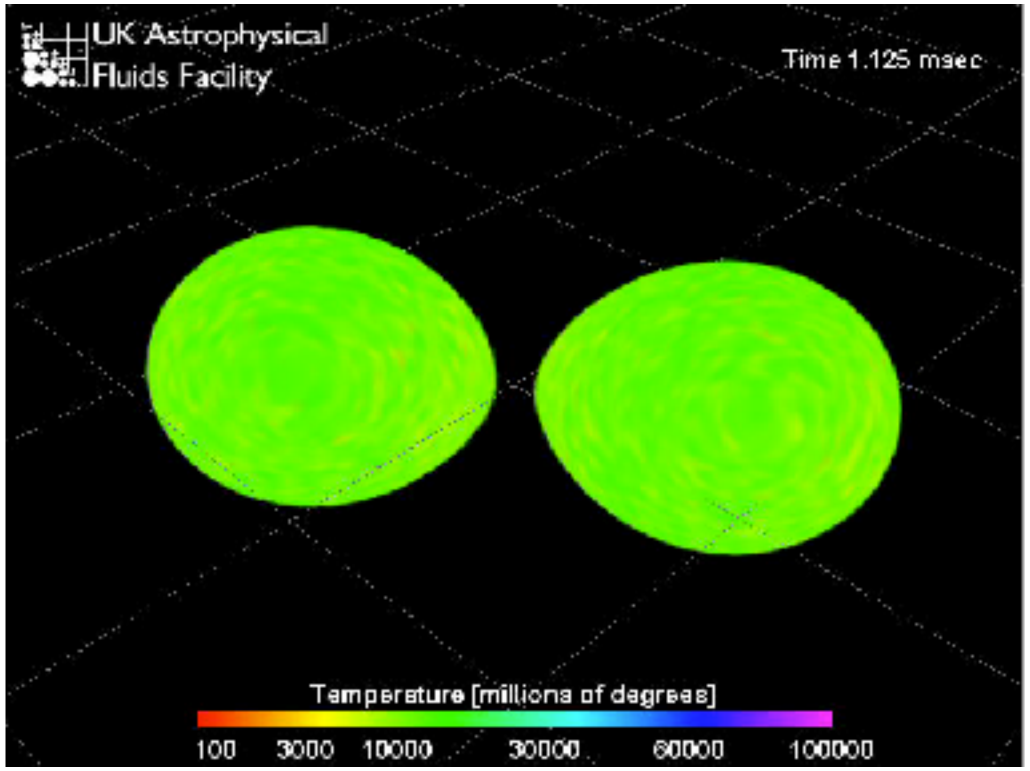
- Electric dipole polarizability of an atom scales as R^3.

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

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

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

- 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.



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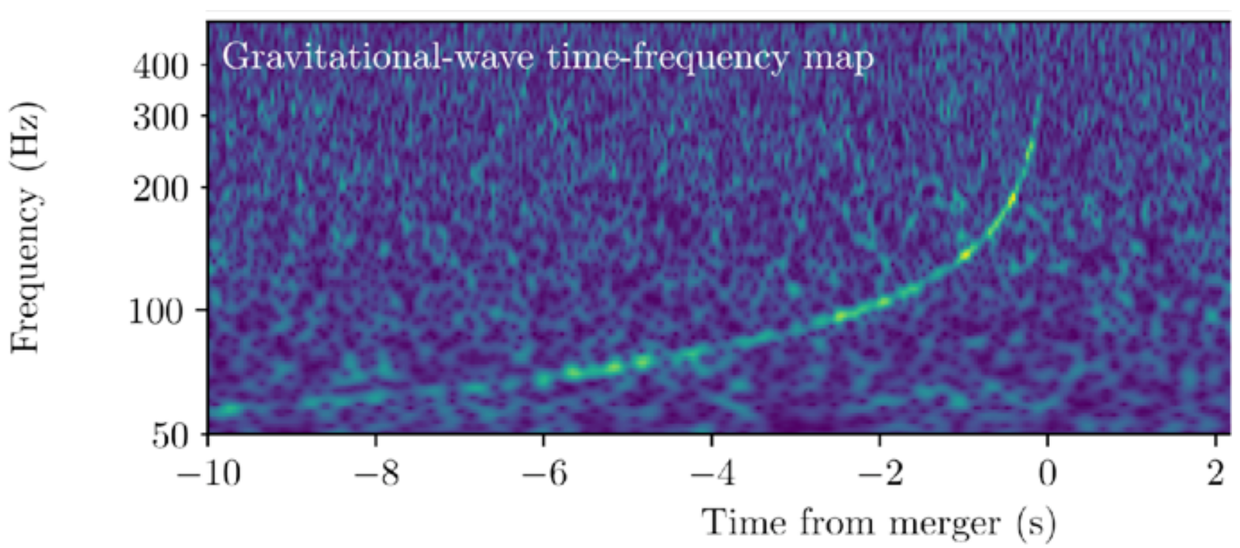
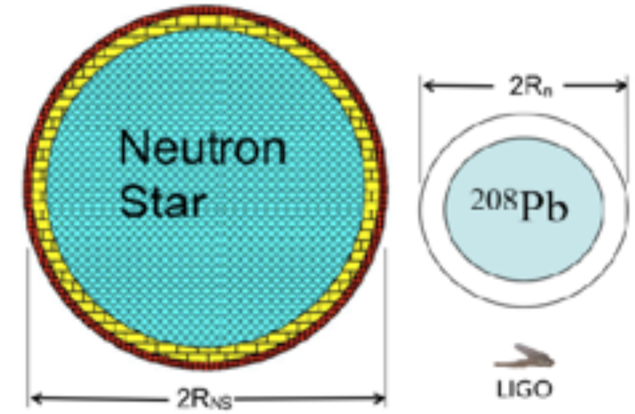
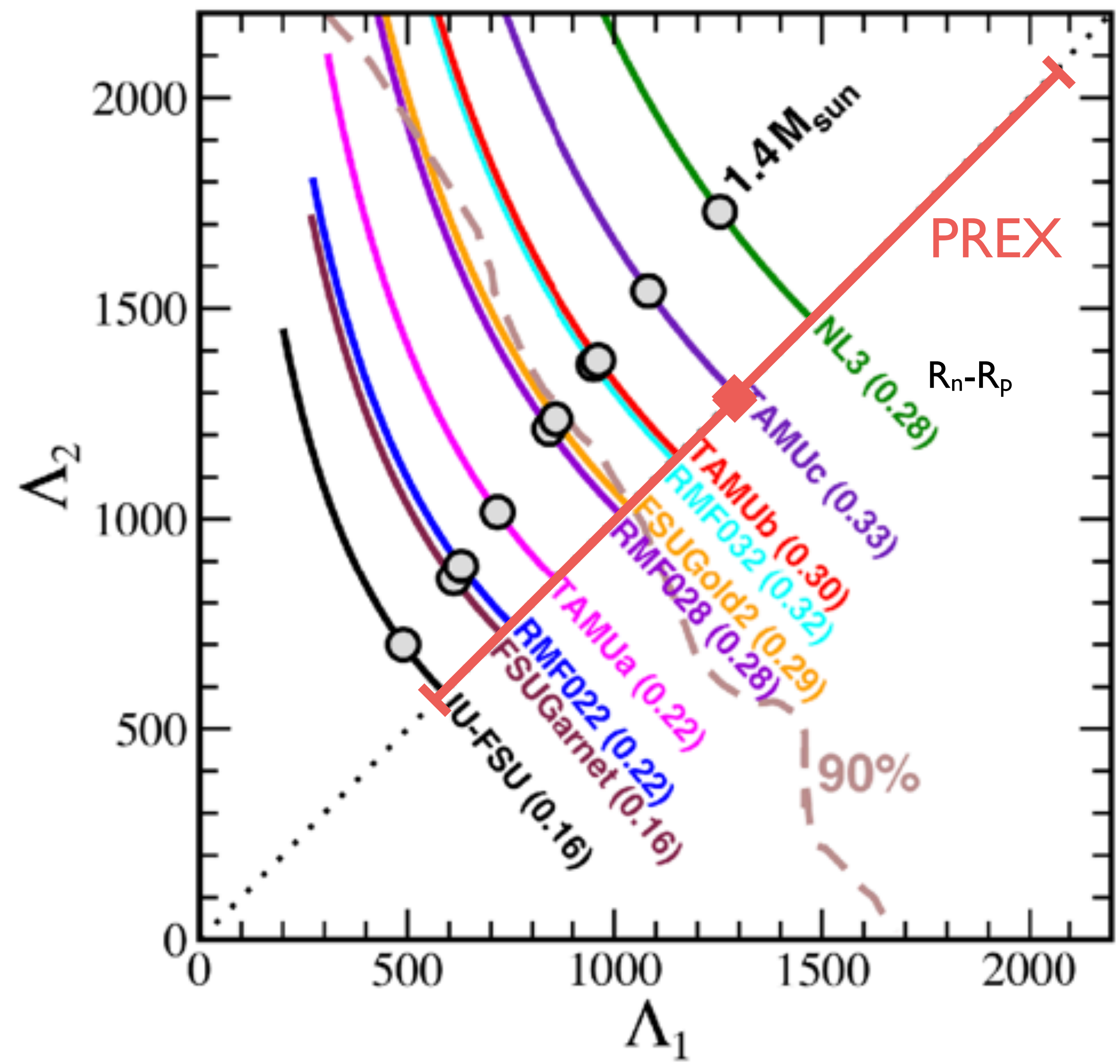


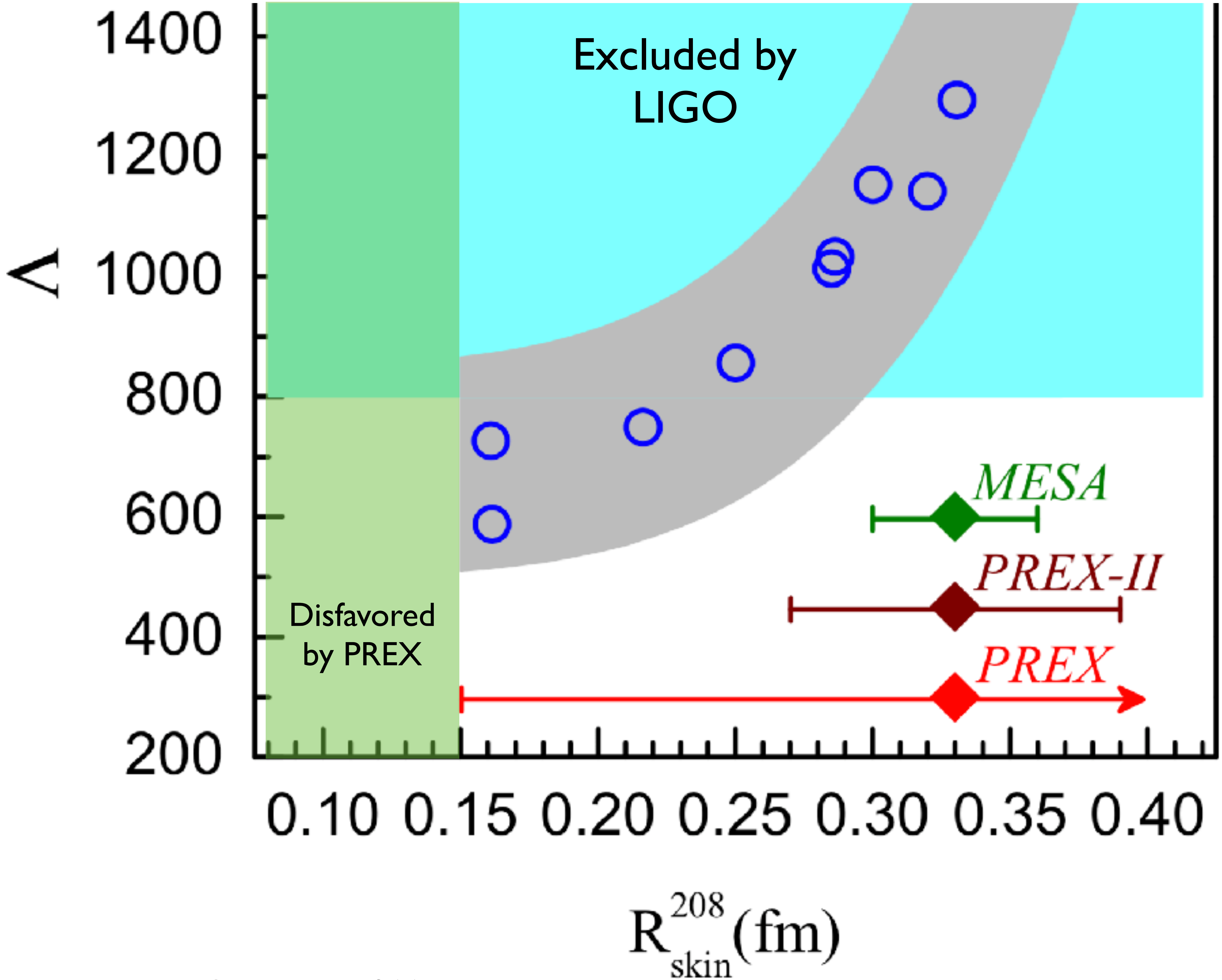
NS deformability and neutron skin of ^{208}Pb



- 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.*



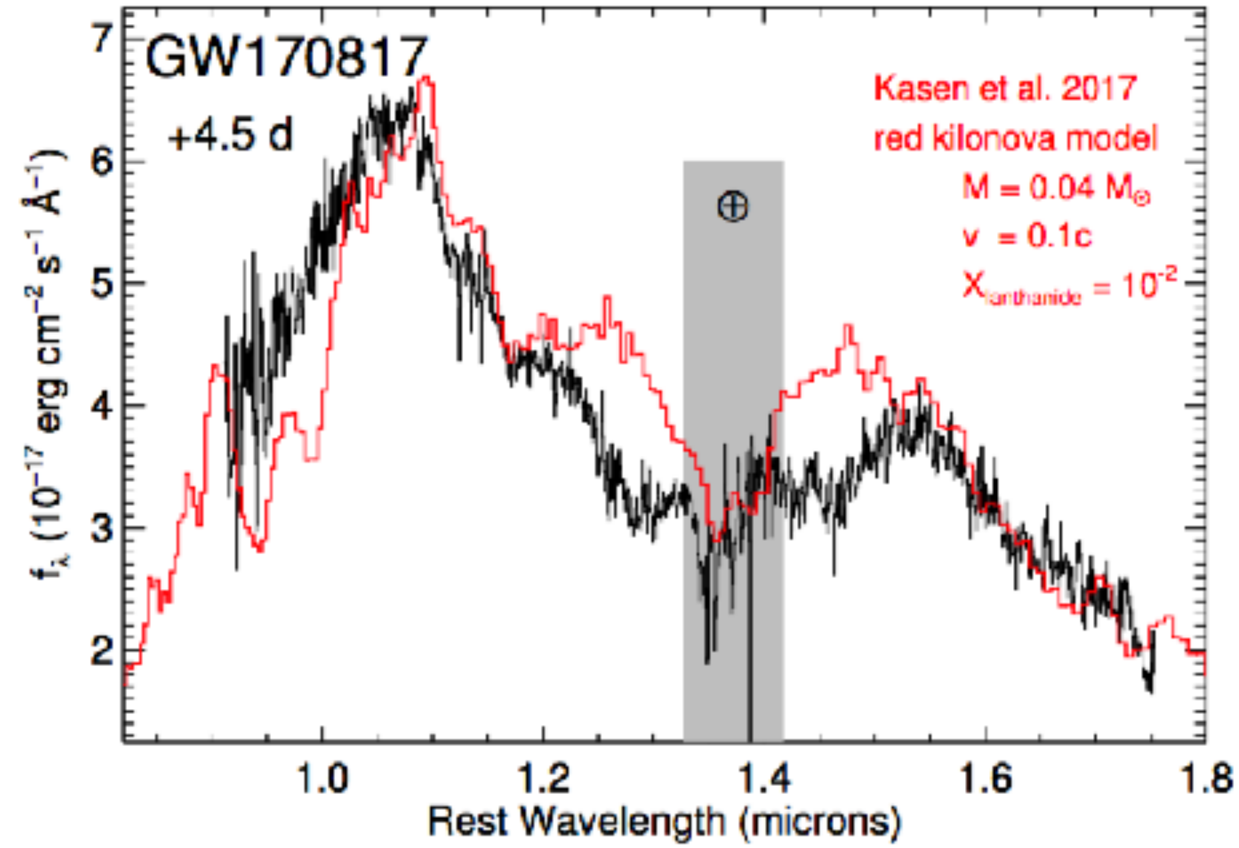
GW170817 allowed region to lower left of 90% line. F. Fattoyev et al. ArXiv: 1711.06615



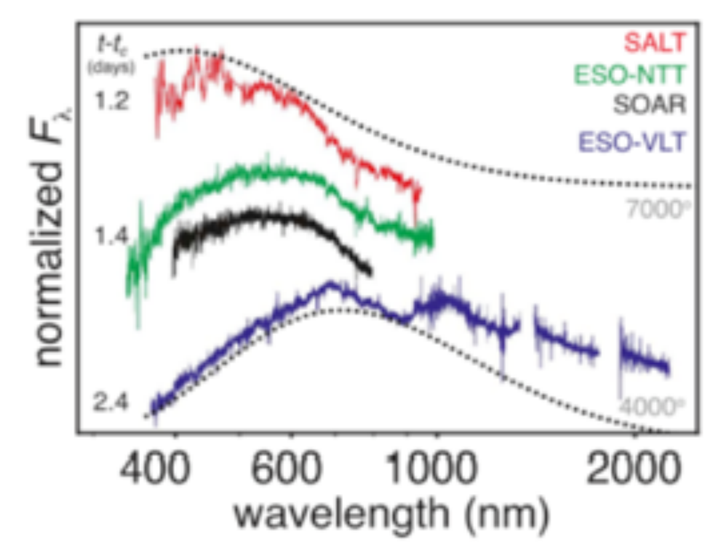
F. Fattoyev et al. ArXiv:1711.06615

Kilonova and r-process

- Some of the ejecta is very n rich, while neutrino interactions can raise proton fraction Y_P above 0.25 in other material.
- Ejecta with $Y_P<0.25$ undergo main r-process and produces heavy r-process elements.
- Radioactive heating produces a Kilonova. If main r-process elements such as Lanthanides are produced, expect very large optical opacity so spectrum is red and peaks in the infrared.
- GW170817 observed to have both blue and red components. Brightness of red component shows NS mergers are an important site of the main r-process and mergers can explain galactic inventory.



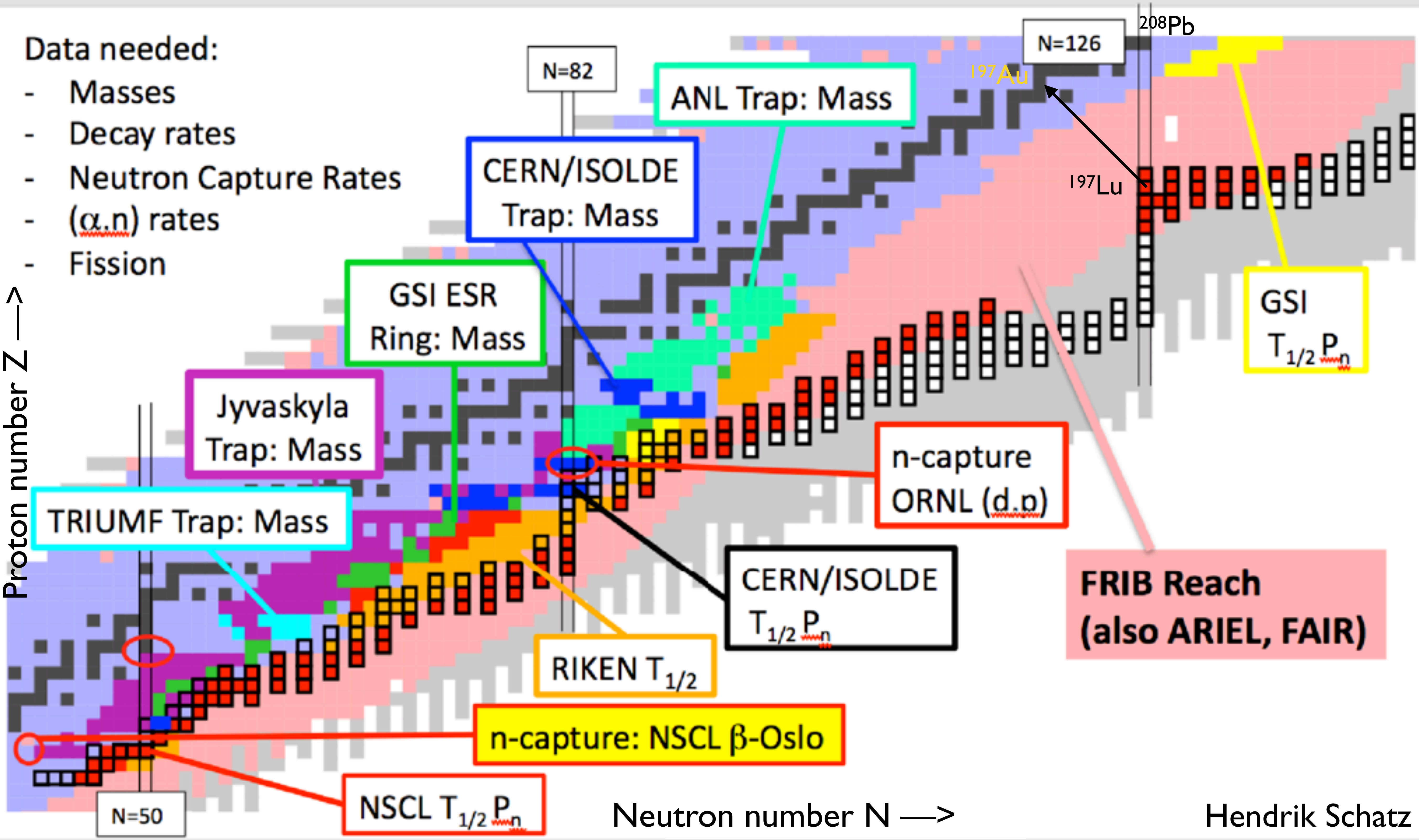
Gemini S. near IR spectrum (black) 4.5 days after merger compared to Kilonova model with lanthanides (red) arXiv:1710.05454



Experiments have reached the r-process
New Generation of Facilities Cover Much of the R-process

Data needed:

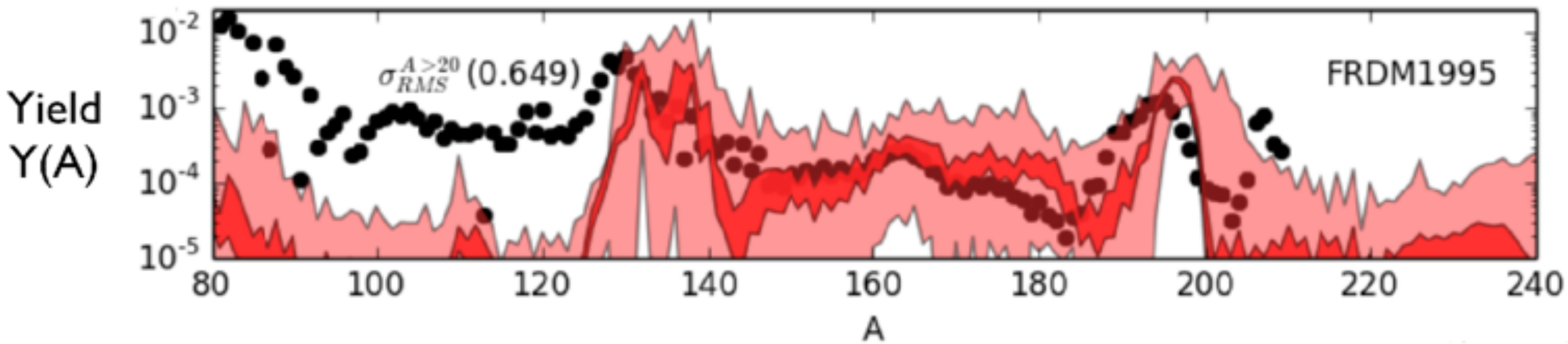
- Masses
- Decay rates
- Neutron Capture Rates
- (α,n) rates
- Fission



Hendrik Schatz

From LIGO to FRIB

- Do simulations of the r-process in GW170817 ejecta reproduce solar r-process abundances? We do not know. It is possible.



- There are still major nuclear physics uncertainties such as the masses and half-lives of very n rich heavy nuclei. These uncertainties will soon be significantly reduced by laboratory measurements at FRIB and other radioactive beam facilities.

- If merger simulations then agree with solar abundances, we can use this to advance galactic chemical evolution and cosmology.

- If not it could suggest an important missing ingredient such as nonstandard neutrino interactions.

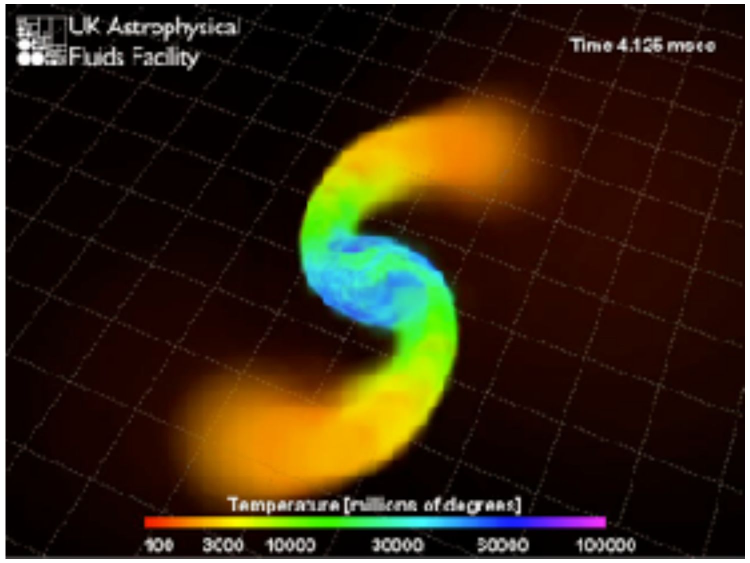
Fate of Remnant and EOS

- **Prompt collapse** to black hole (BH): Ruled out because too little mass would be ejected to provide E+M fireworks. —> A. Bauswein et al. say Λ> 250

- **Hypermassive NS** (HMNS): supported by differential rotation against collapse to BH. System collapses after 10s of ms as viscosity removes differential rotation. Likely the case for GW170817.

- **Supermassive NS** (SMNS): supported by rigid body rotation and lasts longer time before angular momentum radiated away. Margalit and Metzger argue that SMNS will transfer too much of its 10^{53} ergs of rotational energy to ejecta which were observed to have only 10^{51} ergs.

- **Stable NS**: very stiff EOS can support full mass of binary system. Merger would form ***Magnetar.*** Now ruled out by upper limit on deformability Λ.



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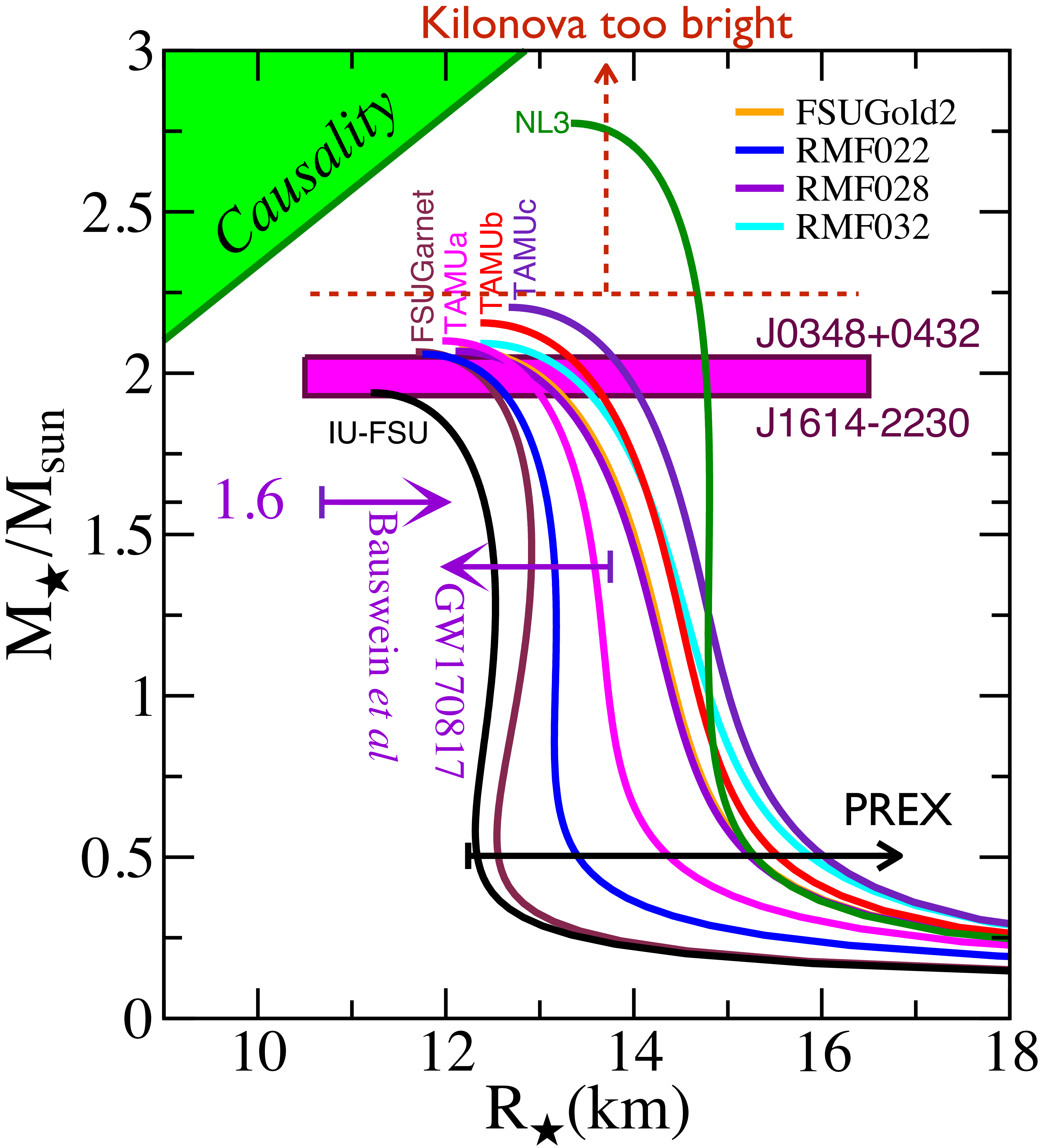
- 1) If maximum mass above 2.2 Msun remnant lives too long and transfers too much rotational E to kilonova.
- 2) If R_{NS}< 10.5 km collapses too fast to black hole with too little ejected mass.
- 3) If R_{NS}>13.7 km deformability too large.
- 4) If $R(0.5M_{sun})$<12.2 km, 208Pb neutron skin too small for PREX

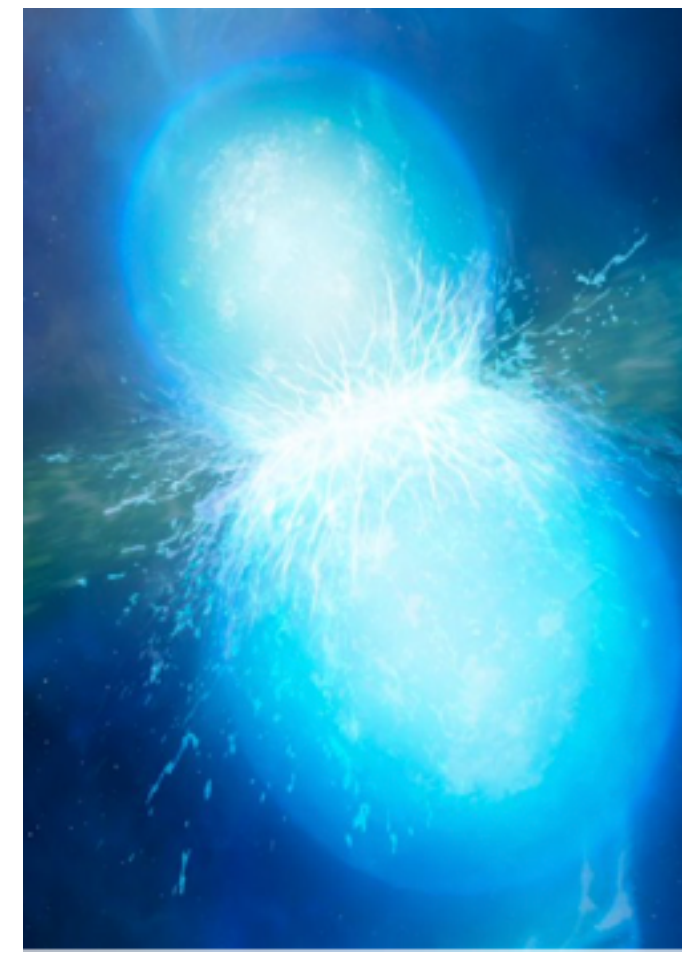


NS merger zoo

- **Multi-messenger astronomy may have started with a bang, but it is just getting going!**
- Expect observation of many more NS mergers when LIGO reaches full design sensitivity.
- Other mergers may be different from GW170817 (~2.75M_{sun})
- Merger of massive NS (say 1.6+1.6 M_{sun}?) could lead to a prompt collapse and little ejected mass. Perhaps a "dud" with out much nucleosynthesis or E+M fireworks.
- Merger of low mass NS (say 1.2+1.2 M_{sun}?) could produce longer lived SMNS and very bright E+M fireworks??
- Merger observed at different viewing angles may have stronger or no short gamma ray burst and different ratios of red and blue optical components…

FRIB TA Summer school: "Neutron star mergers for non-experts: GW170817 in the multi-messenger astronomy and FRIB eras"

- The FRIB Theory Alliance will offer a summer school May 16-18, 2018 at the Facility for Rare Isotope Beams (FRIB) in East Lansing, MI.
- The school is intended for an inclusive audience of graduate students, post docs, and more senior researchers working in nuclear physics, astrophysics, astronomy, and related areas.
- Lecturers: Brian Metzger (Columbia), C. J. Horowitz (Indiana), Katerina Chatziioanno (CITA), David Radice (Princeton), Luke Roberts (MSU), Hendrik Schatz (MSU).
- Remote participation possible: https://indico.fnal.gov/event/15789/



Hold similar school in China?

Gravitational waves and the dense matter equation of state

- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke…
- NS deformability vs ^{208}Pb skin: **Farrukh Fattoyev**, J. Piekarewicz.
- Graduate students: Zidu Lin (2018), Hao Lu (Astronomy), Jianchun Yin, Zack Vacanti, Matt Caplan (2017)

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Nuclear Computational Low-Energy Initiative

OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

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