Neutron Star Observations and Dense Matter

Cole Miller

University of Maryland

Plan of Talk

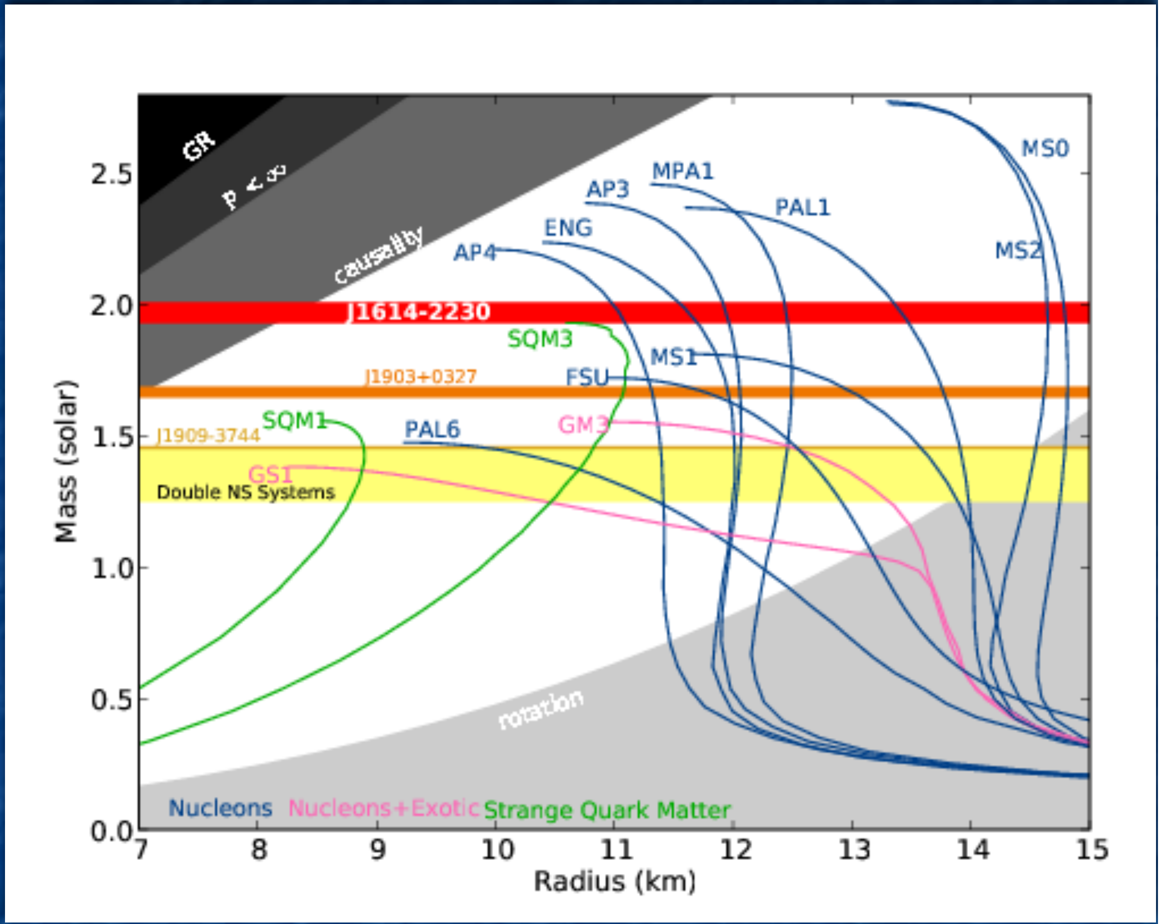
- Astronomical observations and implications for EOS: NS masses, tidal deformabilities, radii
- What do PREX/CREX measurements have to say about neutron star properties?

NICER results from Miller et al. 2019, 2021; see also Riley et al. 2019, 2021 and Raaijmakers et al. 2019, 2021

Grad students: Alex Dittmann, Isiah Holt, Débora Mroczek (UIUC)

NS masses

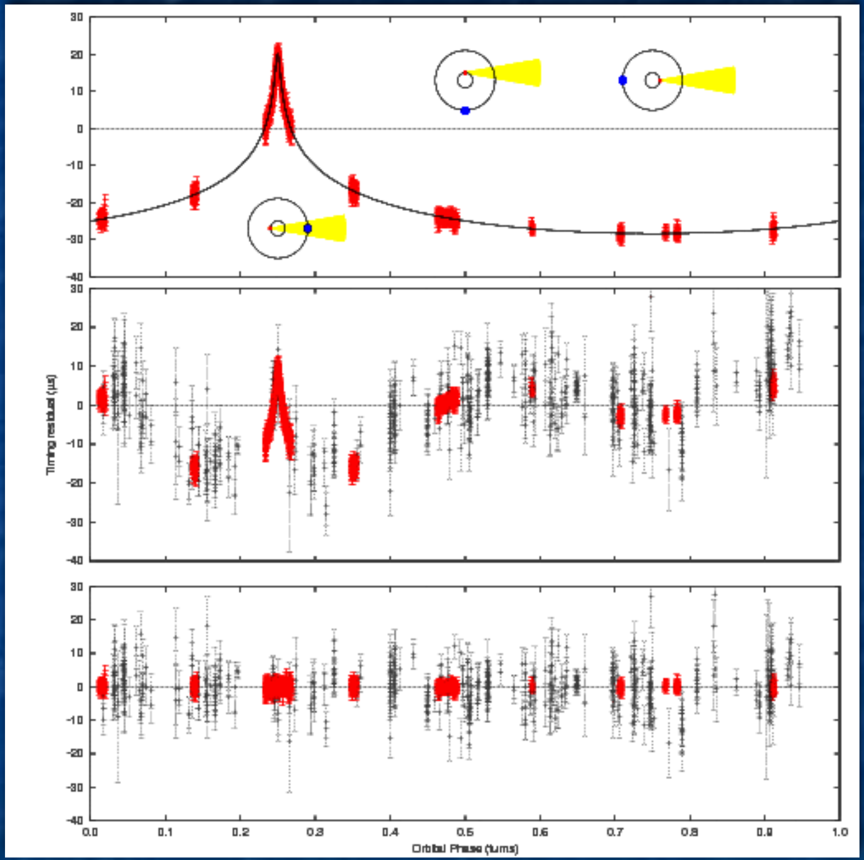
- A given equation of state (EOS) P(ε)
  (P is pressure, ε is total mass-energy density) predicts M(R)
  Assume equilibrium
- Also predicts maximum mass
- Viable EOS must accommodate largest measured mass



Demorest et al. 2010

~2 M_{sun} Neutron Stars

- J1614−2230, 1.937+−0.014
  Demorest et al. 2010
- J0348+0432, 2.01+−0.04 M_{sun}
  Antoniadis et al. 2013
- J0740+6620, 2.08+−0.07
  Cromartie et al. 2019
- Eliminate EOS that are too soft, i.e., whose pressure is too low at the relevant densities



Demorest et al. 2010

No Lutz-Kelker Bias

- Concern that NS masses measured using Shapiro delay could be biased high because delay can't be <0
- But this is incorrect, in theory and practice
- Theory: claim is equivalent to saying you can't sample distributions with boundaries
- Practice: last two NANOGrav updates, 5/9 and then 5/14 *increased* mass

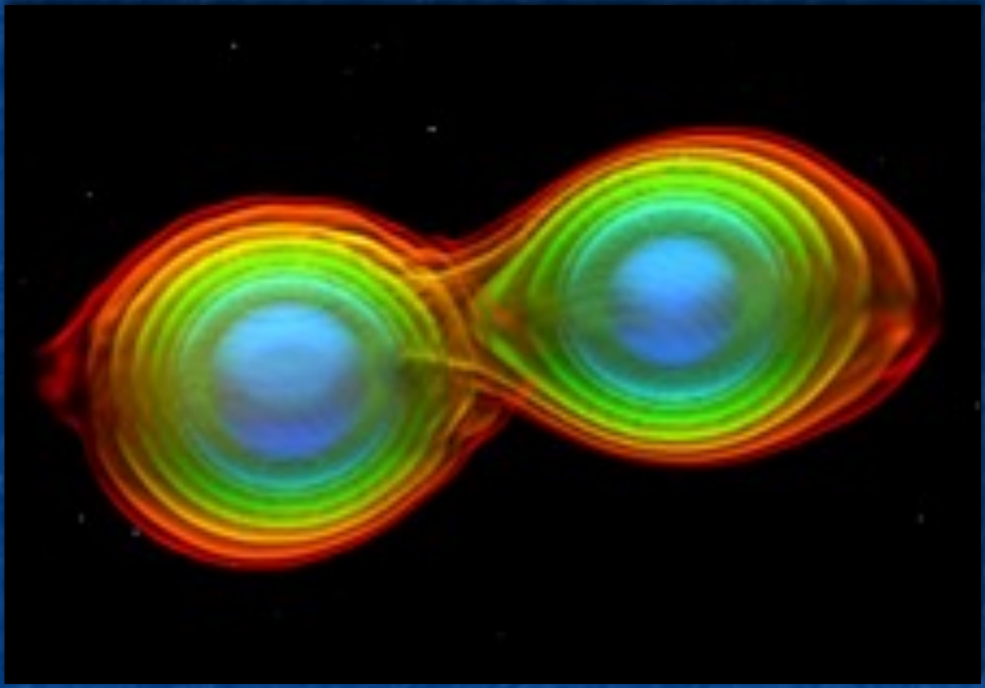
Gravitational Waves and NS

- GW come from mass motions, so bulk of NS is involved
- GW can tell us about cold matter (NS pre-merger) or hot (post-merger, SN)
- Various quantities matter for different GW observations; all depend on the EOS, so this gives us self-consistency checks

Both images from Wikipedia

NS tides from GW

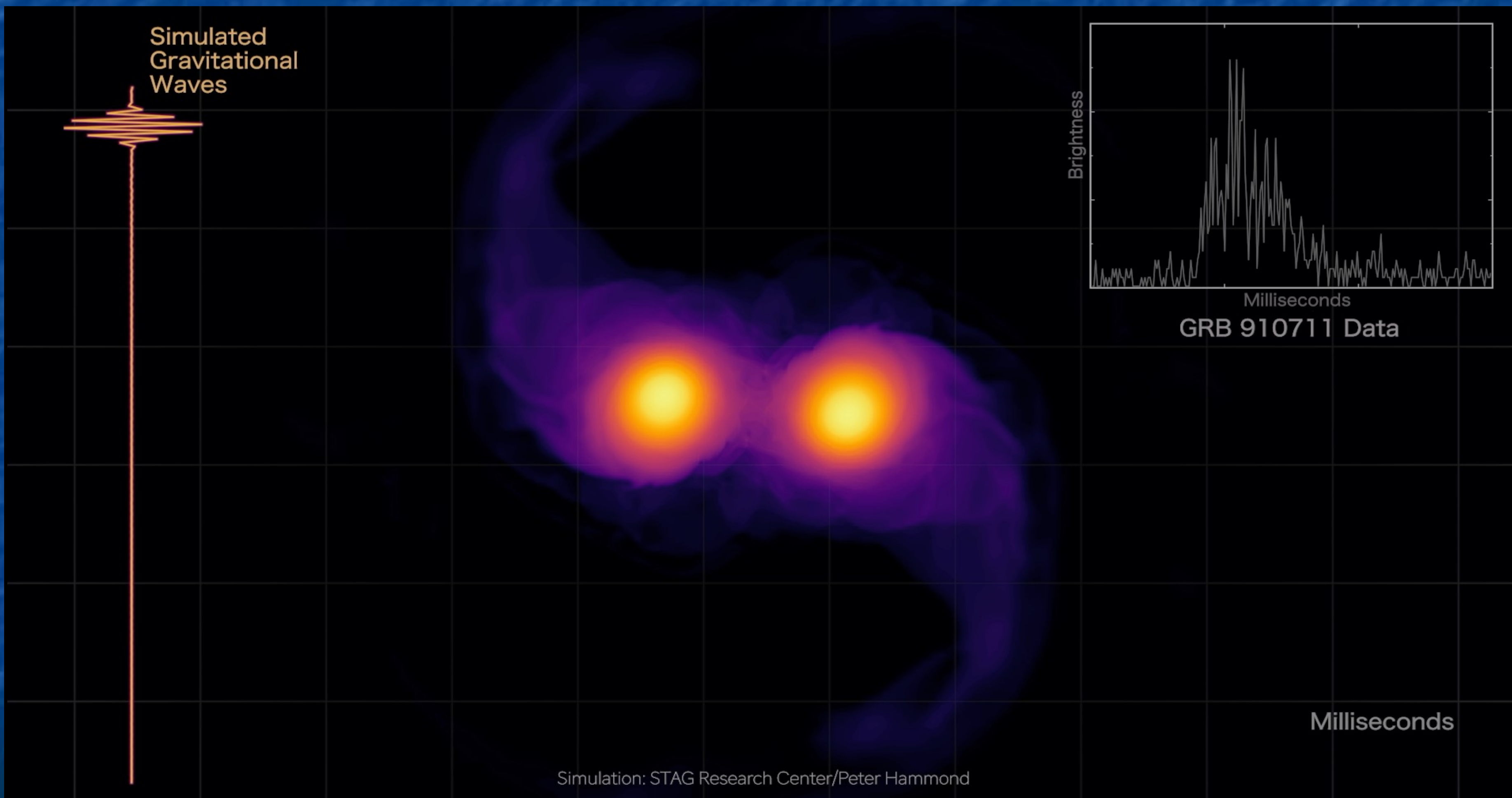
- Tides take energy from orbit
  Changes waveform
- A bigger NS will be deformed more
- Thus measurement of tidal deformability Λ gives insight into structure
- For GW170817, no clear evidence for deformation
  Suggests $R_{1.4}<13.5$ km
  Eliminates hardest EOS



Simulation: T. Dietrich et al. (Albert Einstein Institute)

Post-merger oscillations?

~2600 Hz and ~1000 Hz γ-ray oscillations in two GRBs



Chirenti et al. 2023 (courtesy of Cecilia Chirenti)

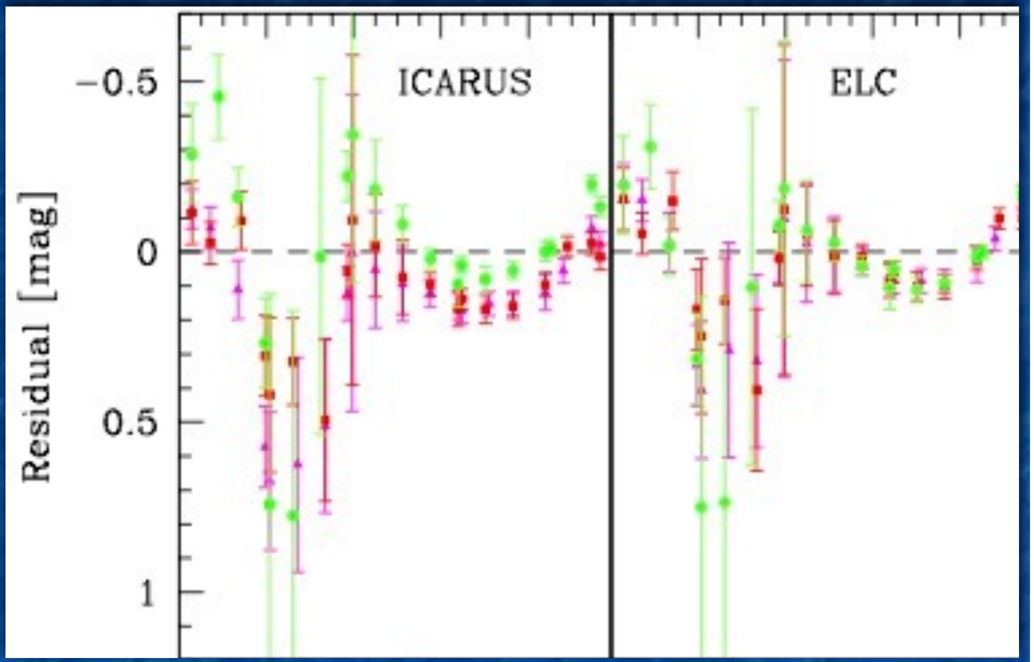
Moment of Inertia?

- The double pulsar PSR J0737 has highly precise measurements
- Maybe see extra precession due to frame-dragging? Depends on moment of inertia
- Long sought, but many complications
  E.g., dP_b/dt has spindown contribution!
- Currently I_A<3x10^{45} g cm^2 (90%), R<22 km
- Estimate: 11% precision on I_A by 2030

Heavy Black Widows?

- Some “black widow” pulsars might have much higher masses $M>2.4\ M_{sun}$?
- If so, extremely important!
- But worry about heating patterns etc. Romani et al. PSR J0952; better?

PSR J1311-3430

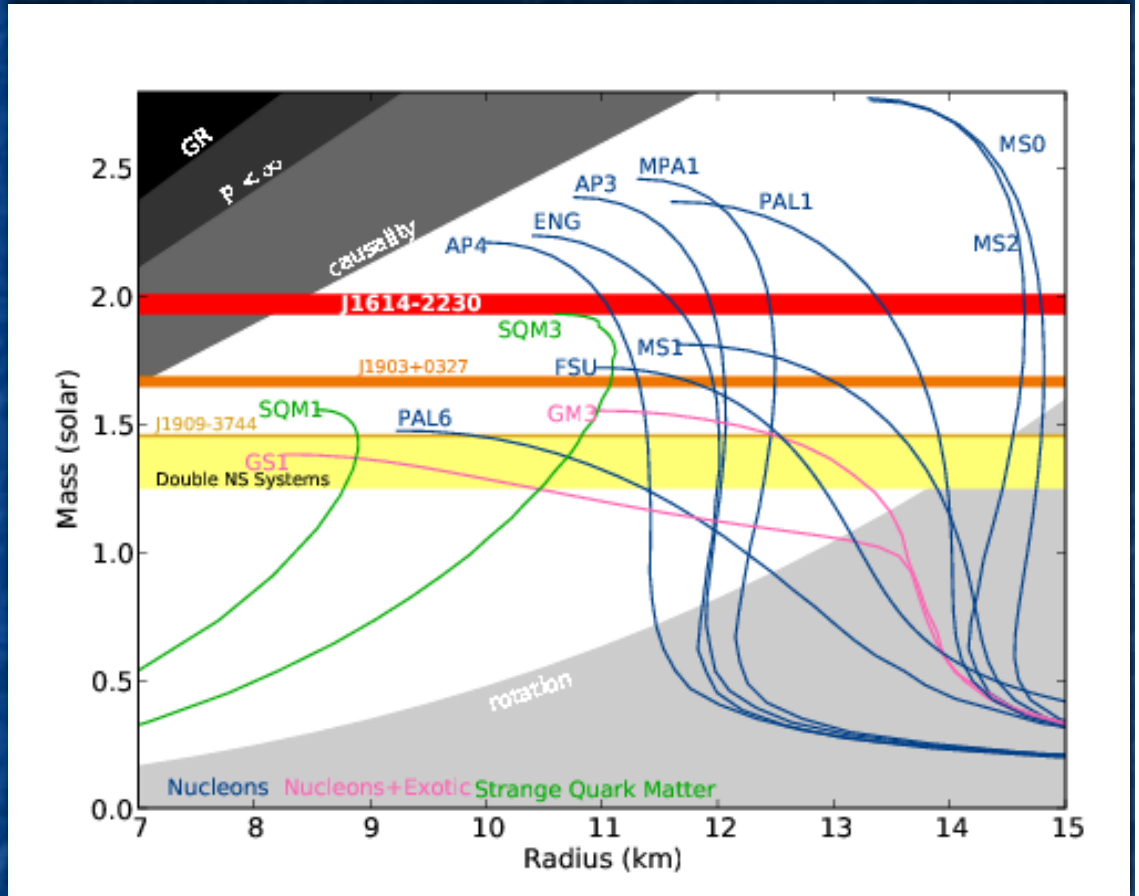


Romani et al. 2015

(ICARUS and ELC are two different fitting codes)

The Importance of Radii

- Radius would provide great EOS leverage
  Wide range in models
- But tough to measure
- Measurements that use just flux and spectra are susceptible to huge systematic error
  One reason: NS atm are fully ionized
- NICER X-ray pulse modeling can help



Demorest+ 2010

NICER Reduces Systematic Errors

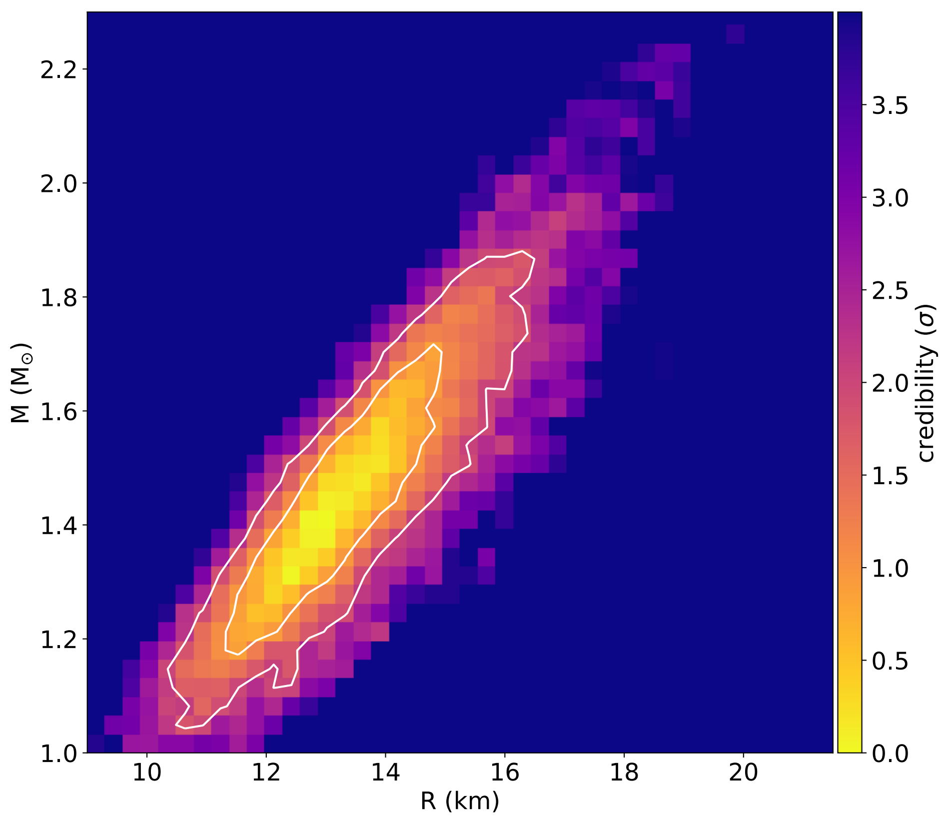
- Extensive work with Fred Lamb (Illinois) suggests that when we fit *rotational-phase dependent* spectra, such as with NICER, systematic errors are minimized
- Current conclusion: if good fit, no significant bias
- More work being done: Isiah Holt, UMd

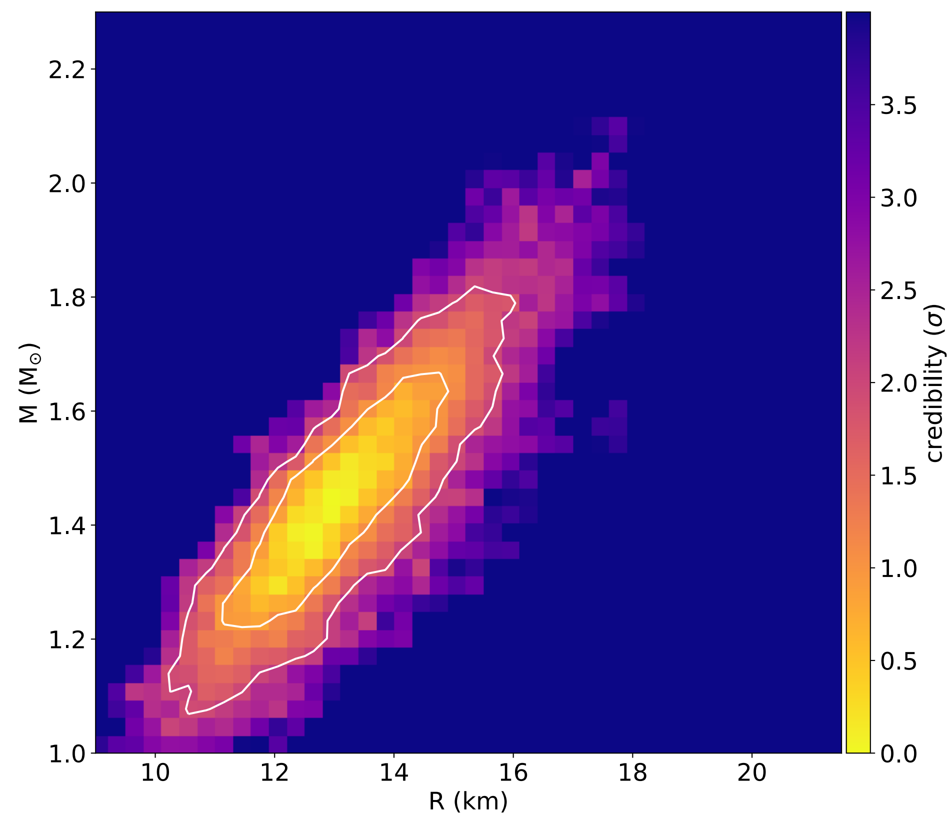
The NICER Idea in Brief

Alex Dittmann, UMd

Bayesian fits: trace rays from hot spots on NS surface, compare with energy-dep waveform

Mass-Radius Posteriors for J0030

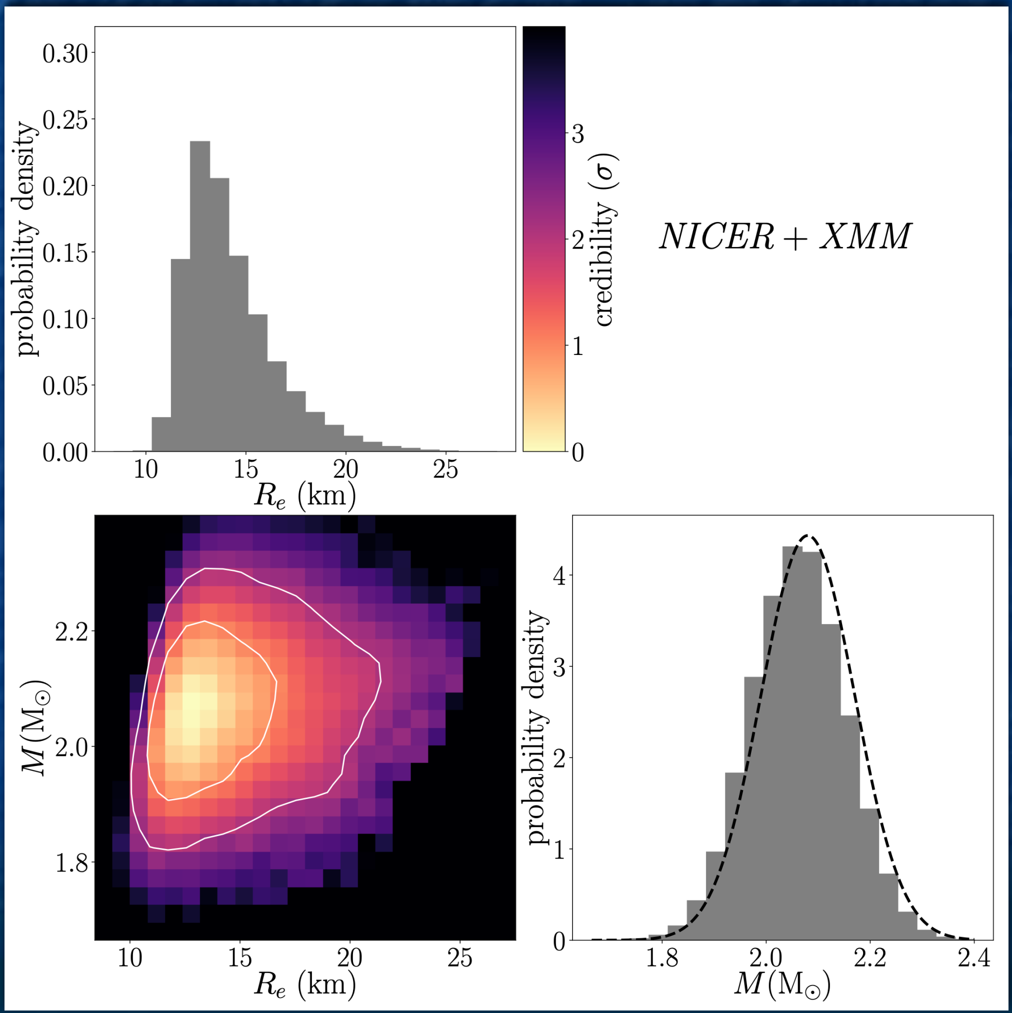




Left: M-R posterior for NICER J0030 data, two ovals
Right: M-R posterior for NICER J0030 data, three ovals

J0740 NICER+XMM: M and R

10x fainter than J0030; need radio, XMM data as well



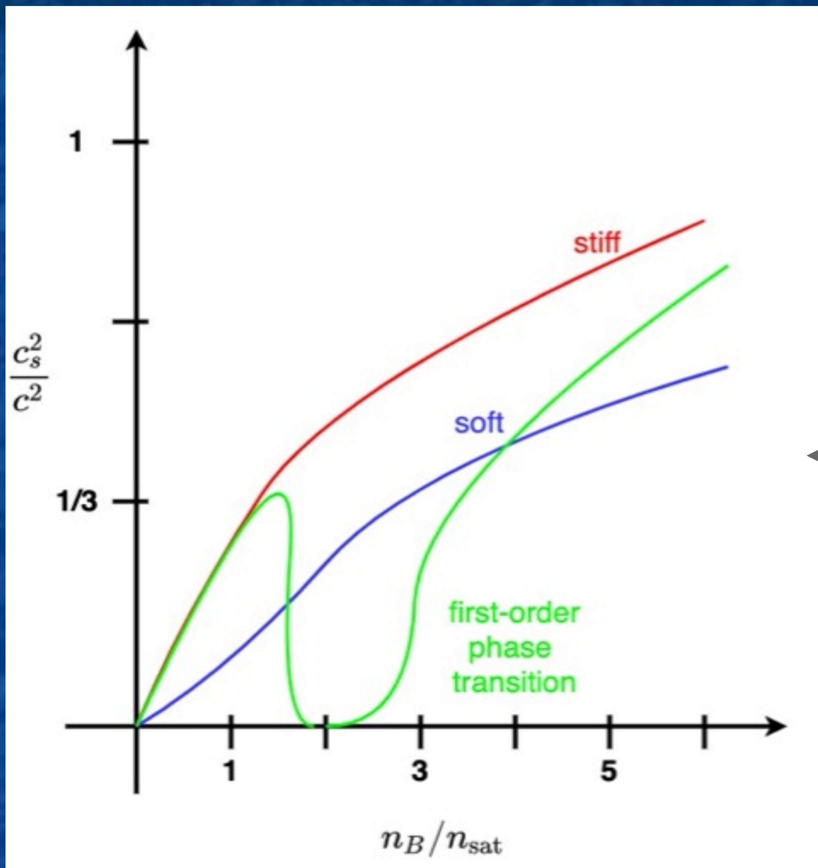
Radius of PSR J0740+6620: $13.7^{+2.6}_{-1.5}$ km (1σ)

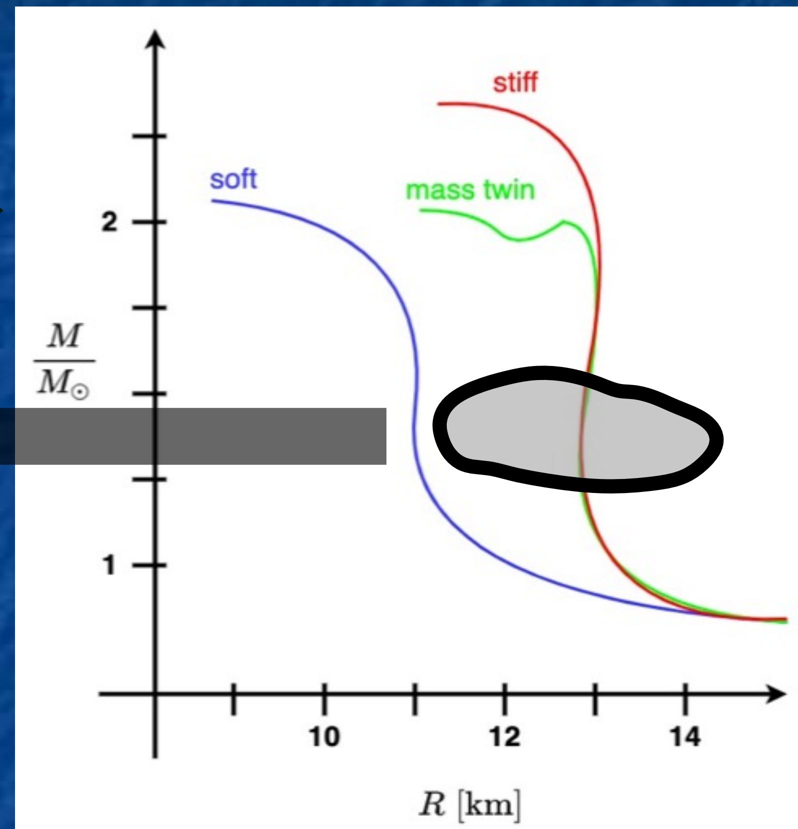
Dashed line: prior on mass from NANOGrav and CHIME/Pulsar data

Information about the EOS

- Many recent sources of information about dense matter
- Binding energy of nuclei (~n_{sat}~0.15-0.16 fm^{-3})
- PREX/CREX (isospin asymmetry near n_{sat})
- cEFT (up to ~1.5-2 n_{sat})
- Radius, tidal deformability of 1.4 M_{sun} NS (~2 n_{sat})
- Existence, radius of ~2 M_{sun} NS (~4-6 n_{sat})
- pQCD (down to ~40 n_{sat}; influence at NS den?)

From R to EOS

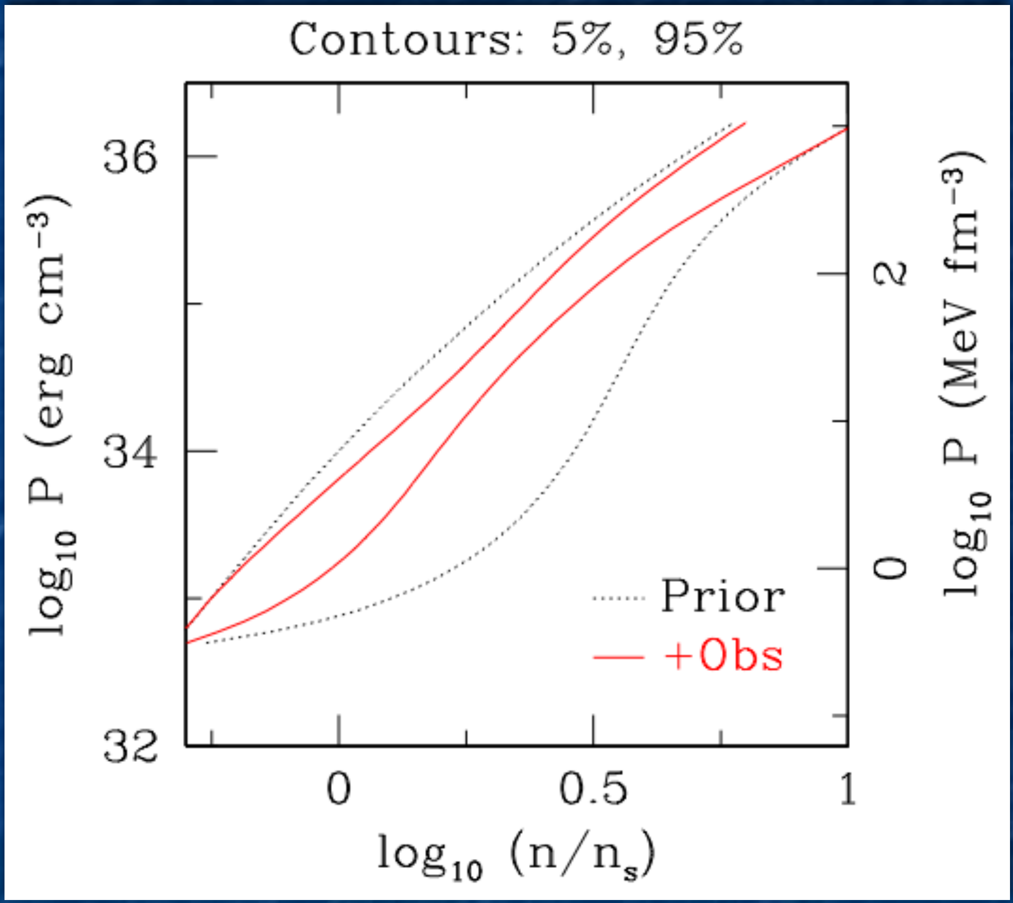




Adapted from: Yunes, Miller, Yagi. Nature Rev.Phys (2022)

Débora Mroczek, UIUC

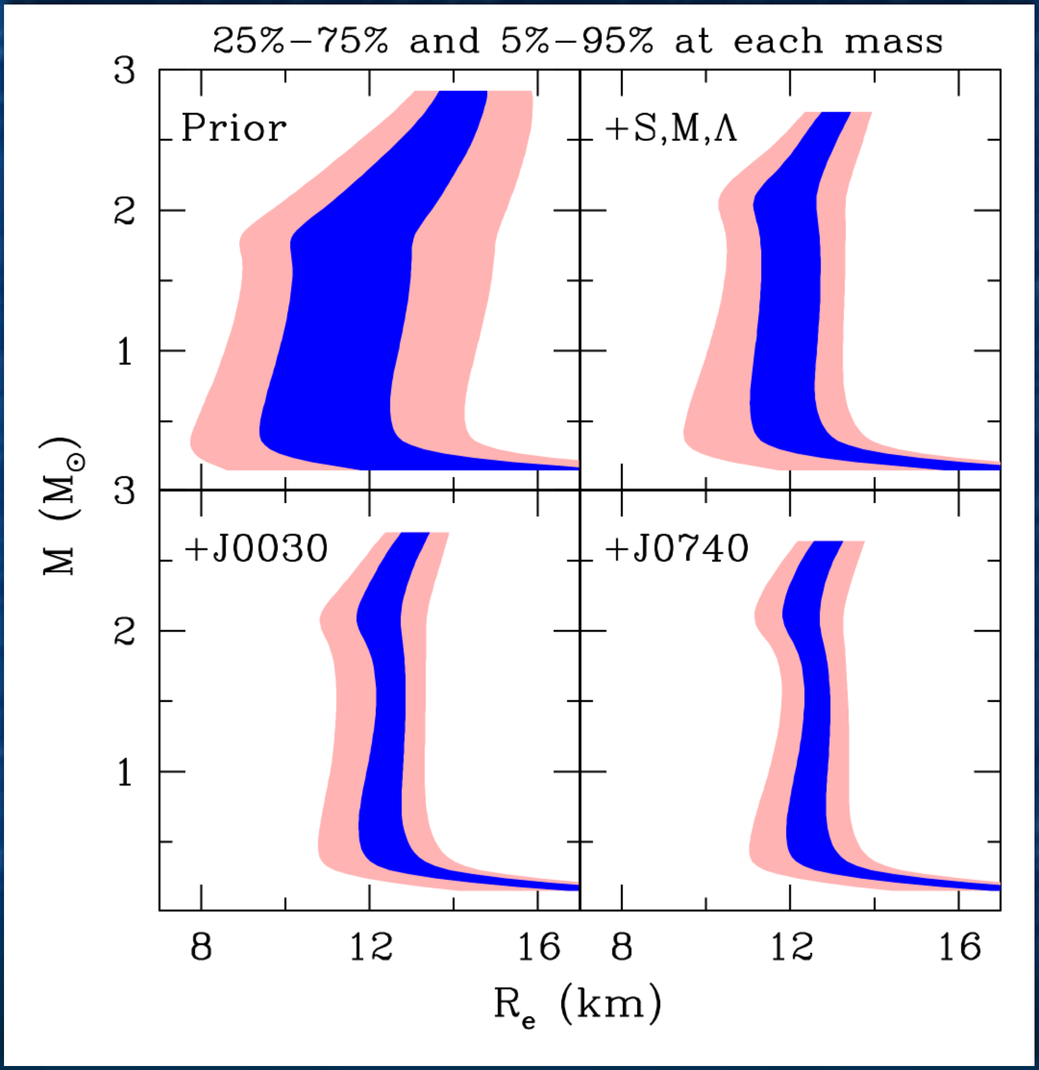
J0030, J0740, Other Measurements Provide Tight EOS Constraints



Assume knowledge of EOS to half nuclear saturation density, extrapolate using Gaussian processes. Other extrapolations give similar answers.

Good EOS convergence in ~ 1.5 – 5 ρ_{sat} range

Tight Mass-Radius Constraints



Sequence:

- Priors
- Pre-NICER observations
- +PSR J0030+0451
- +PSR J0740+6620

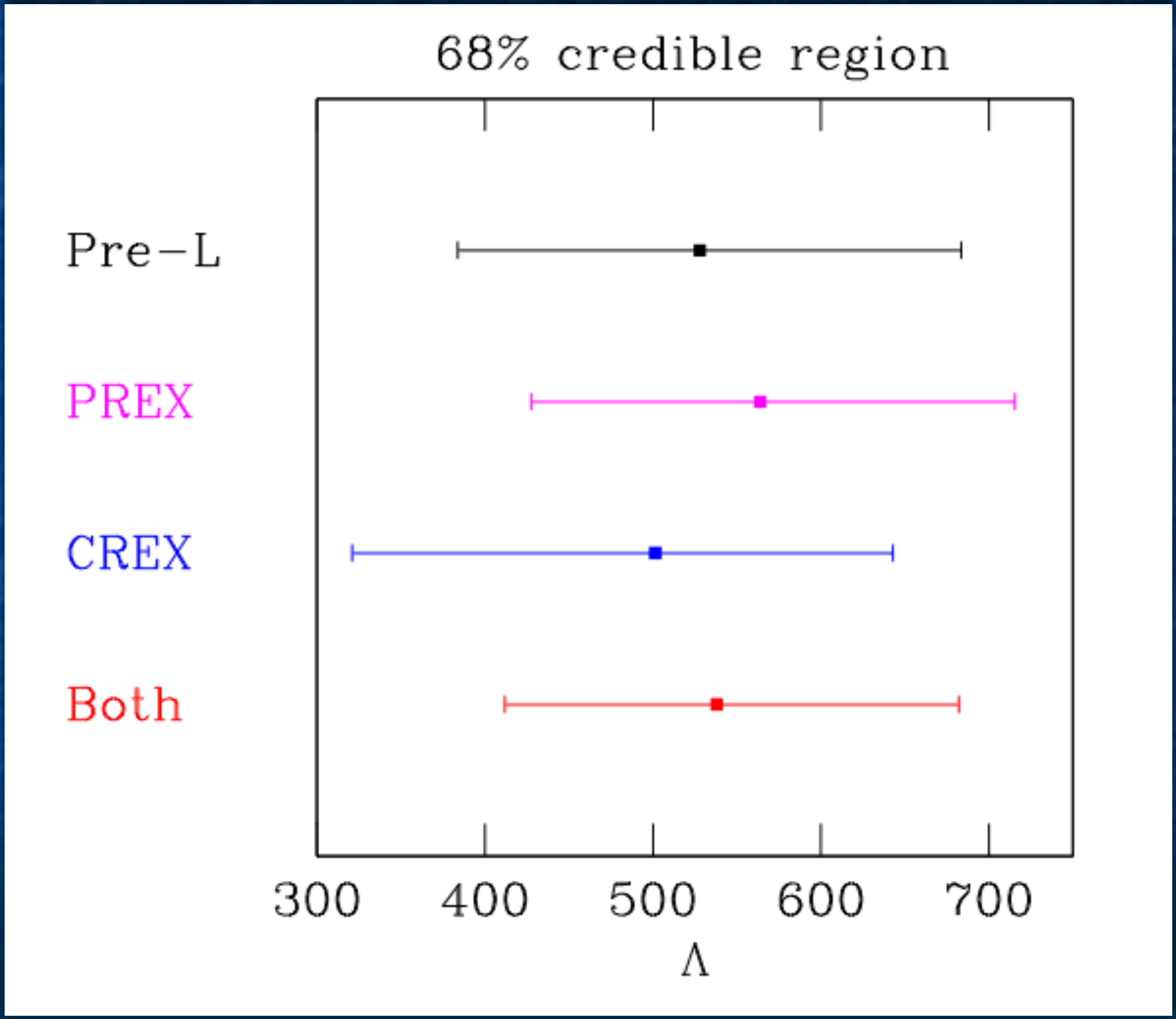
1σ radius: 11.8 – 13.1 km for 1.4 M_{sun} spanning all three EOS models.

+− 5%   Pretty impressive!

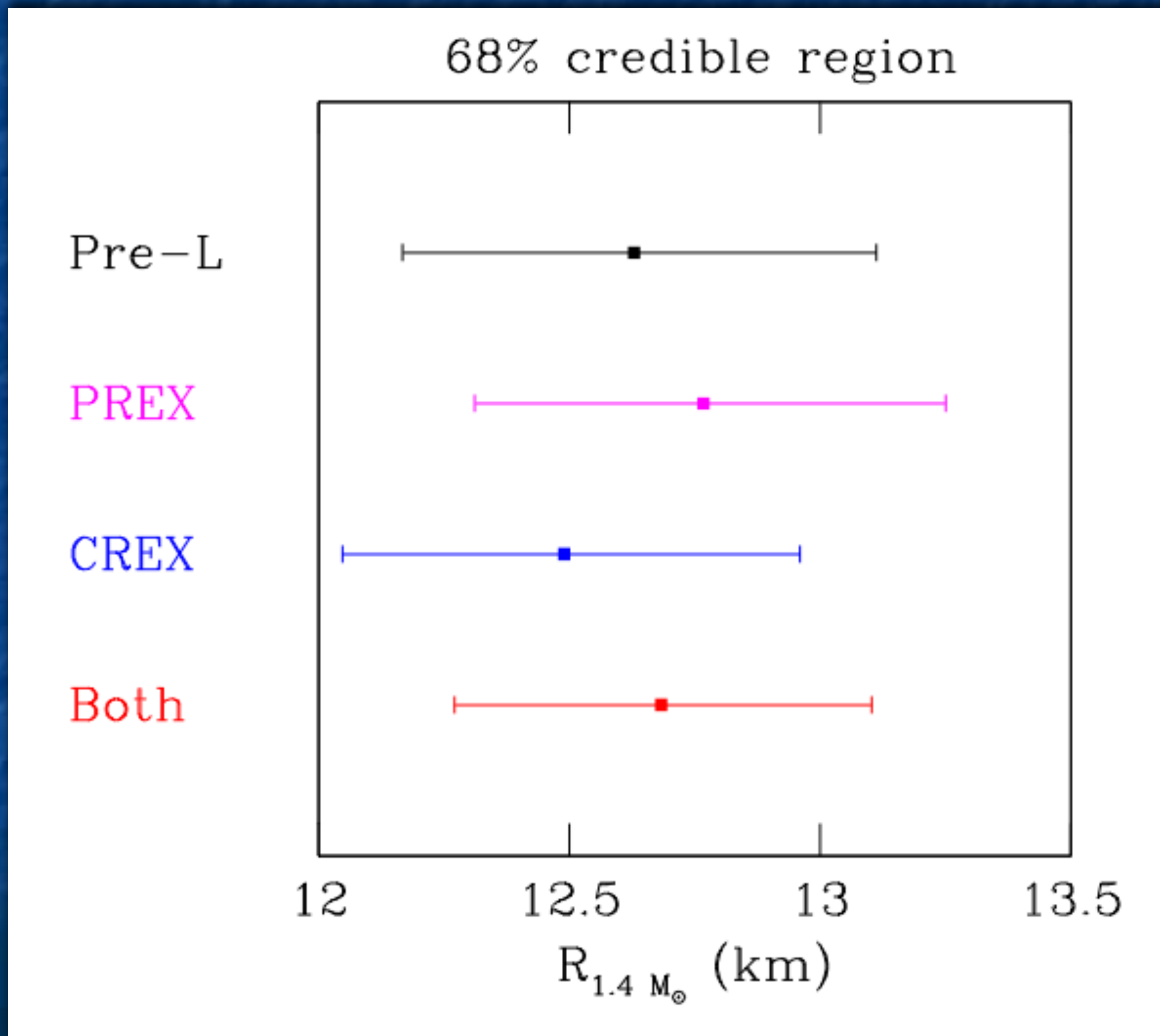
Impact of PREX/CREX

- How do the PREX/CREX measurements affect our understanding of NS?
- In the following we show +−1σ range for several quantities. As a proxy, we use the inferred slope of symmetry energy $L(n_{sat})$ (Lattimer 2022). L=121+−47 MeV from PREX; −5+−40 MeV from CREX; 53+−13 MeV when both are combined

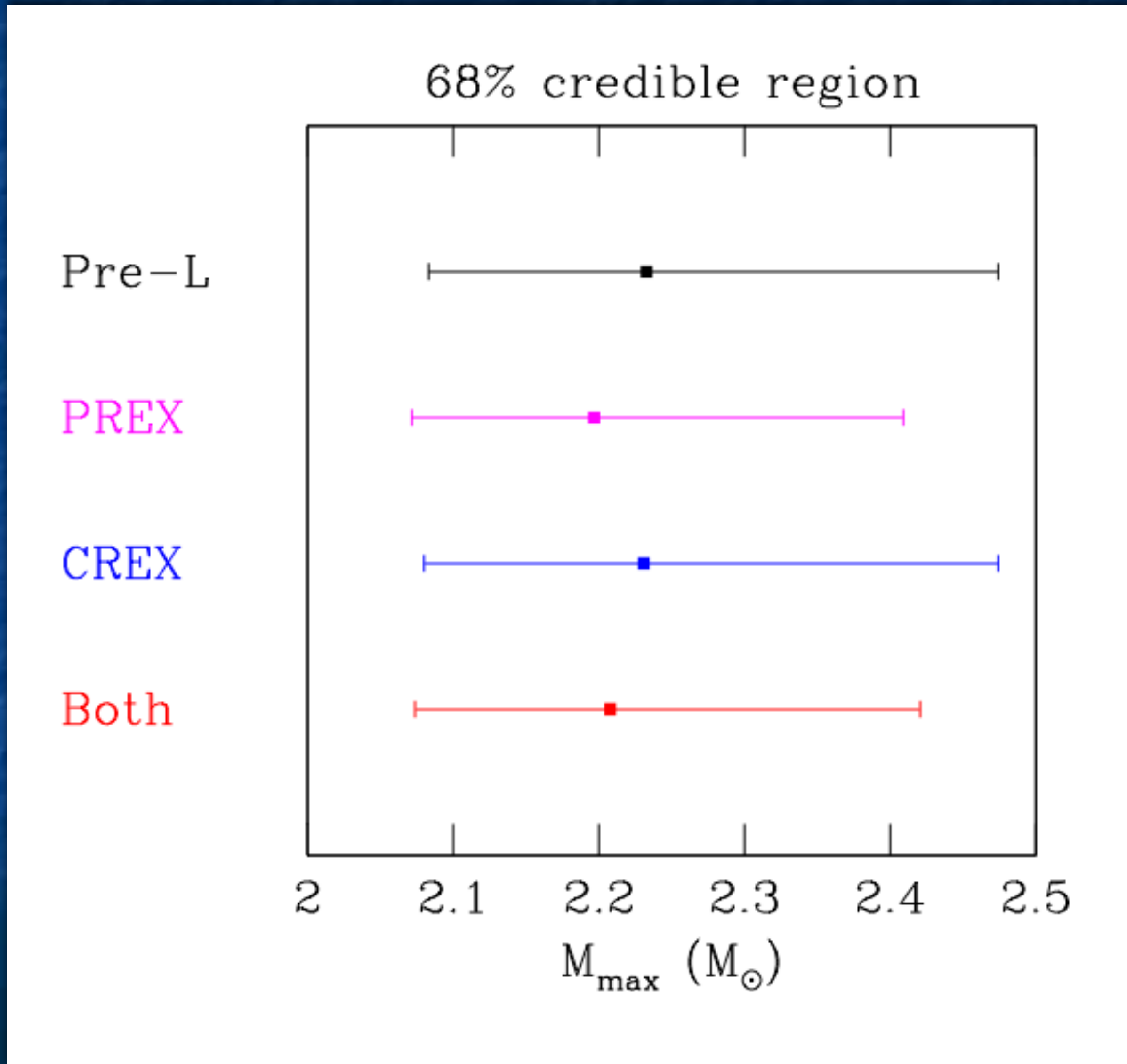
Tidal Deformability at $M=1.4M_{sun}$



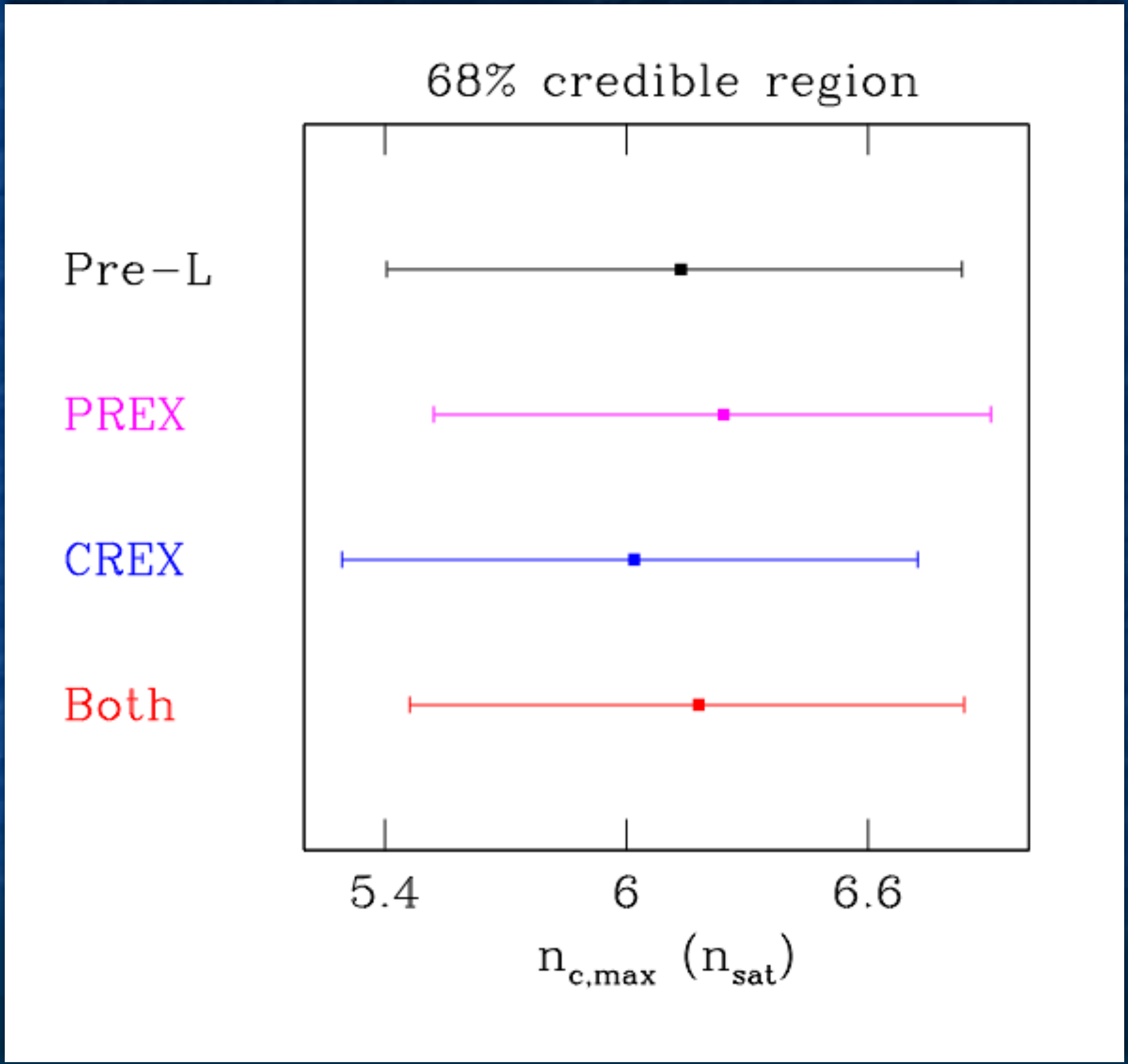
Radius at M=1.4 M_{sun}

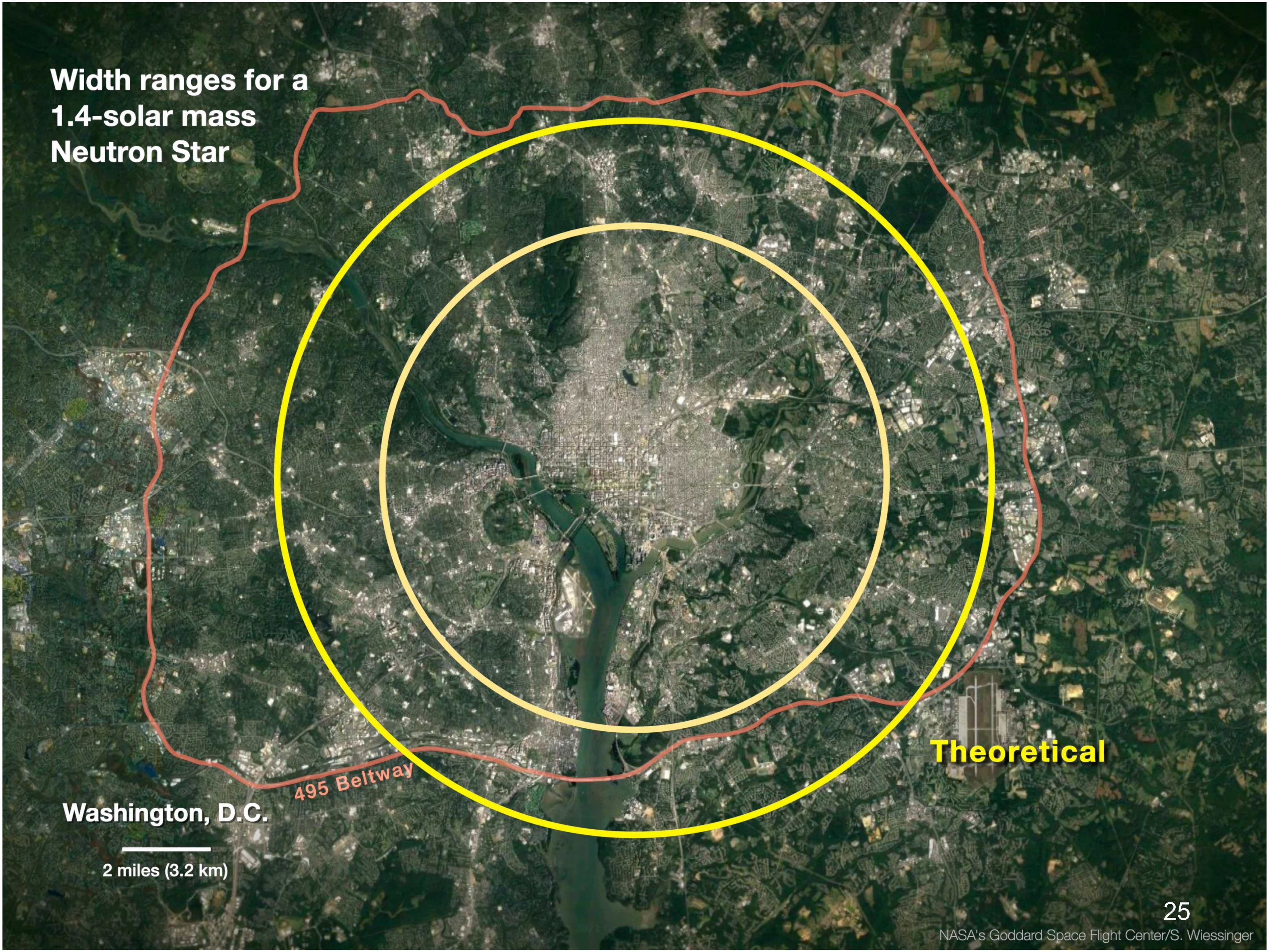


Maximum Mass



Maximum Central Density




Width ranges for a
1.4-solar mass
Neutron Star
Theoretical
495 Beltway
Washington, D.C.
2 miles (3.2 km)
NASA's Goddard Space Flight Center/S. Wiessinger

Conclusions and Future Work

- Many recent developments in studies of cold dense matter
- Future astronomical prospects: more tidal deformabilities (LIGO O4 run started in May); better NICER measurements
- Future nuclear prospects: you tell me! I'm excited for the astro/nuclear partnership