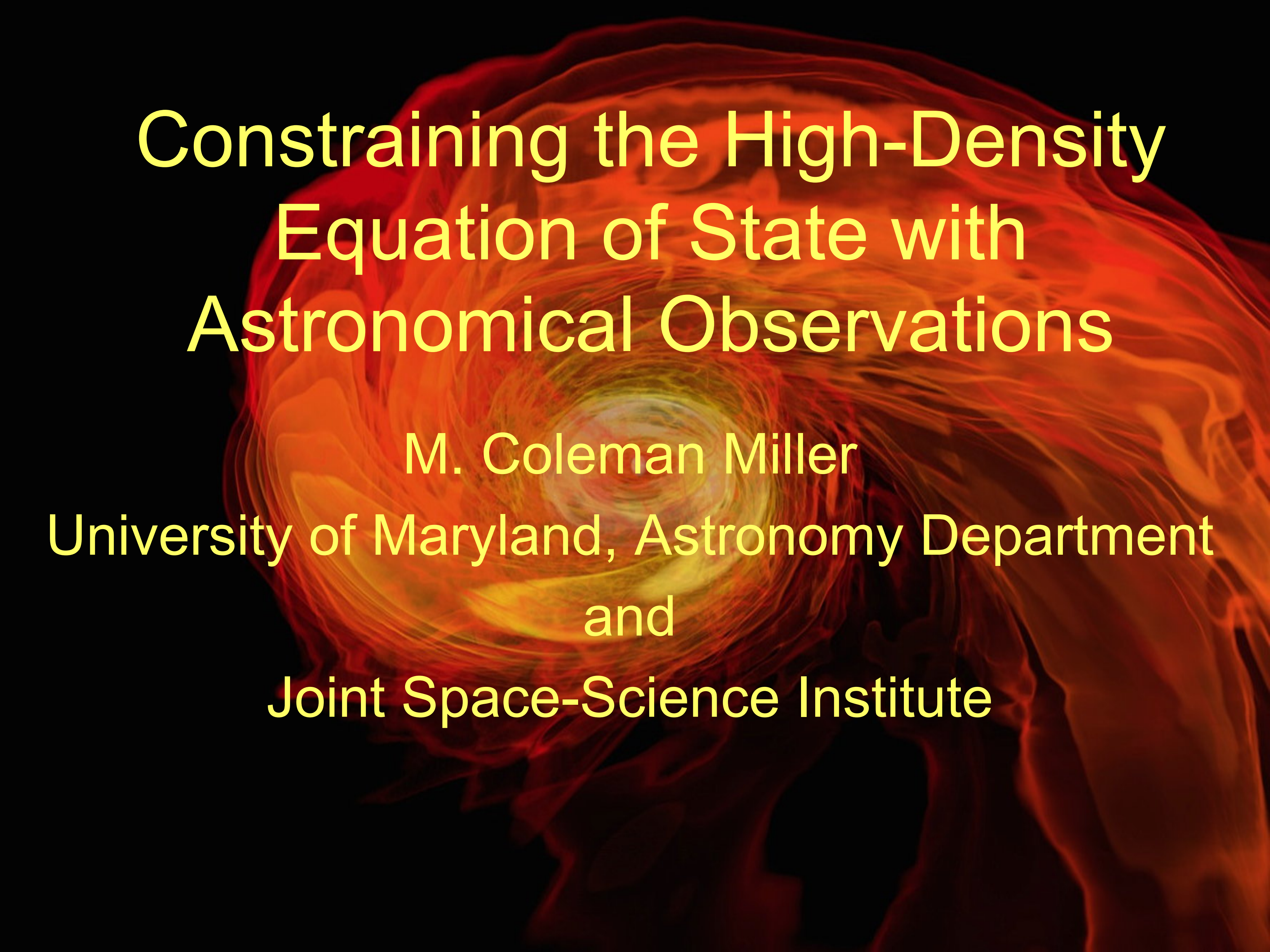


Constraining the High-Density Equation of State with Astronomical Observations

M. Coleman Miller
University of Maryland, Astronomy Department
and
Joint Space-Science Institute

Outline

- Neutron stars and extreme physics
- Current and future measurements
- Putting it all together: Bayesian framework
- Implications for equation of state, mass-radius relation

Based on Miller, Chirenti, Lamb 2019 (arXiv:1904.08907)

Figure kindly provided by Anna Watts

Original diagram and concept: Gordon Baym

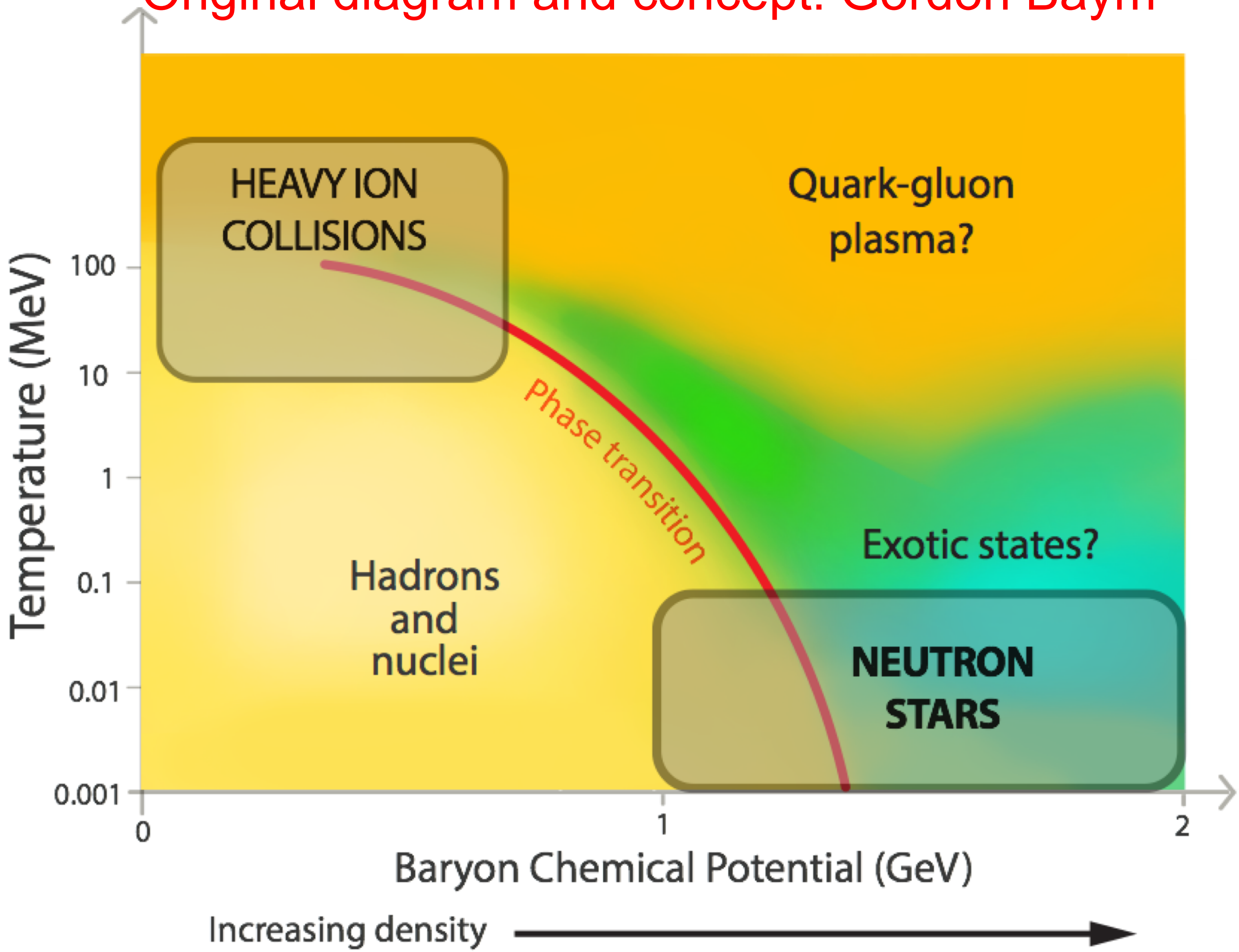


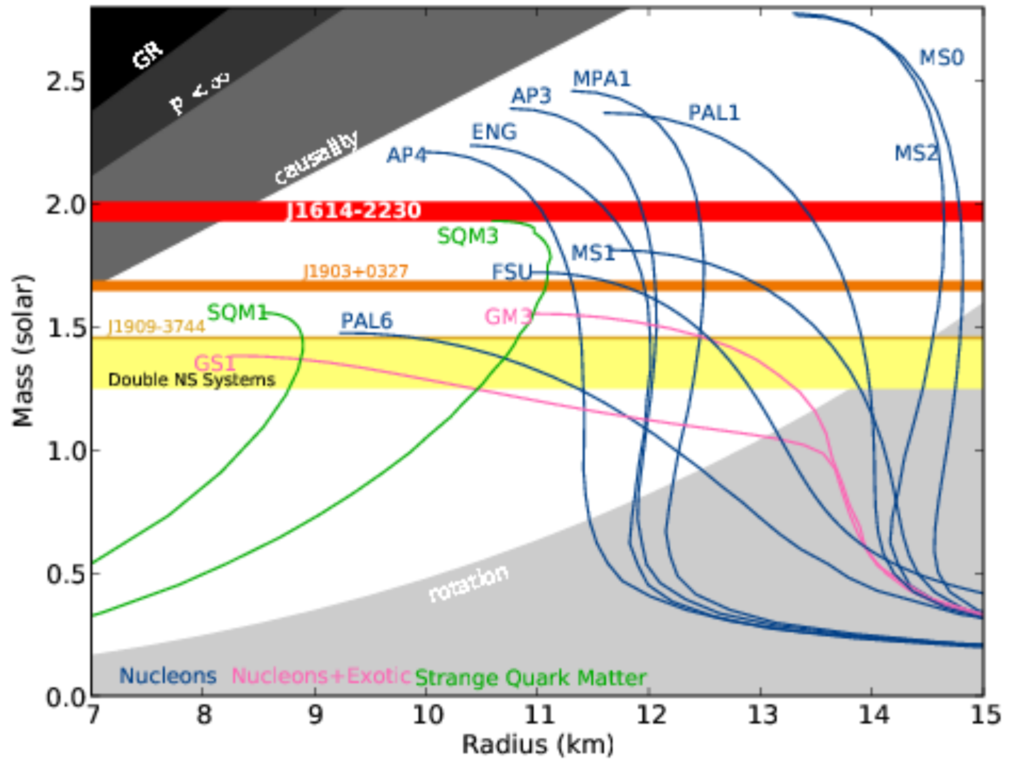
Figure: Watts et al. 2016

The measurements

- What we have now:
  Masses and one tidal deformability
- What we will have soon:
  Radii and masses from NICER
- What we might have if we get lucky:
  NS moment of inertia, binding energy
- Now on to the details!

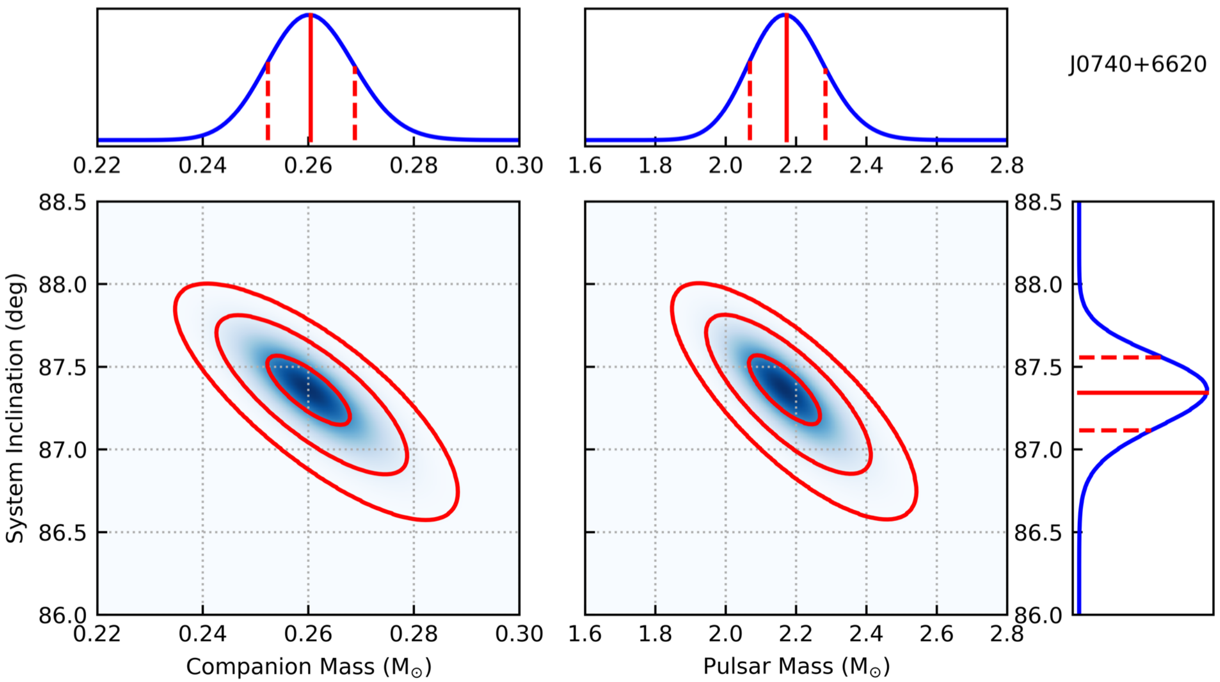
Measurement 1: NS masses

- A given equation of state 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

New mass: $2.17^{+0.11}_{-0.10}$ M_{sun}

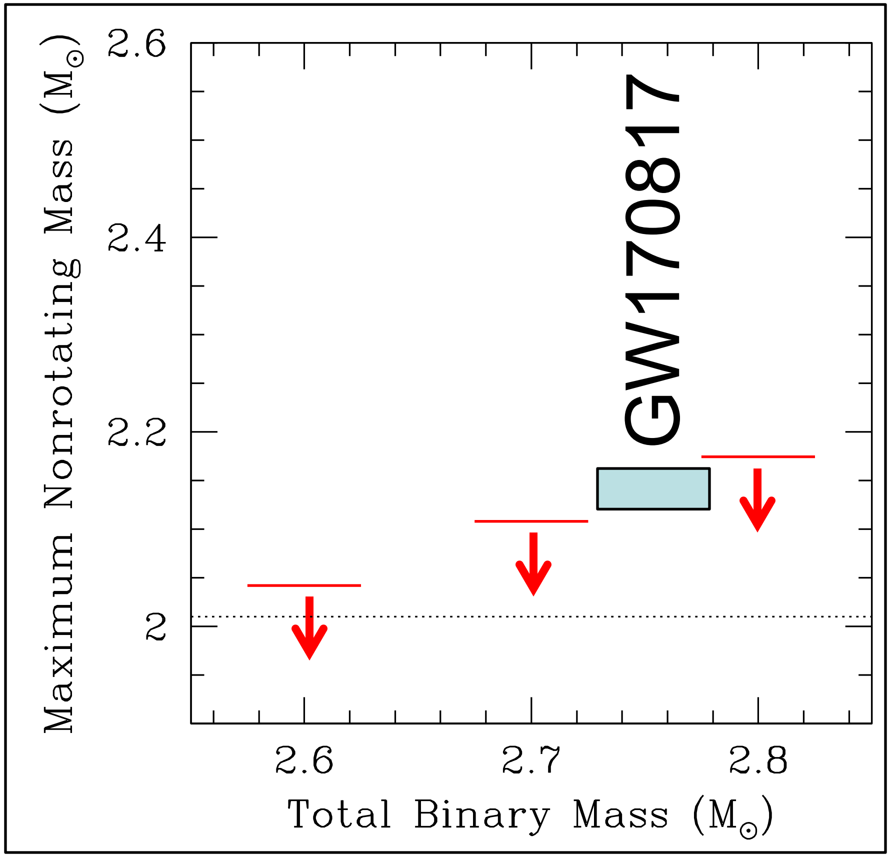


Cromartie+, 2019

- Other high masses: 2.01+-0.04 M_{sun}, 1.908+-0.016 M_{sun} ~2.4 M_{sun} for BW?
- Eliminates soft equations of state

Upper Limit to NS M_{max}?

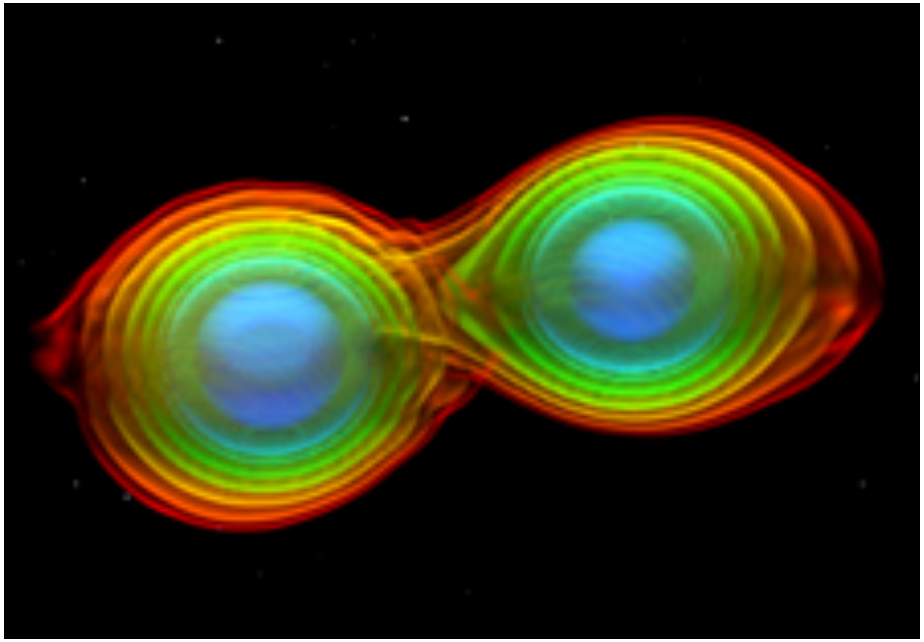
- Bauswein+13; Fryer+15; Lawrence+15
- For GW170817, we would find a limit of ~2.15 M_{sun} Margalit & Metzger 2017 find M_{max}=2.17 M_{sun}
- But we don't have clear evidence of collapse
- Similar model-dependent upper limits suggested from GRMHD simulations



Adapted from Lawrence et al. (2015)

Meas. 2: NS tides from GW

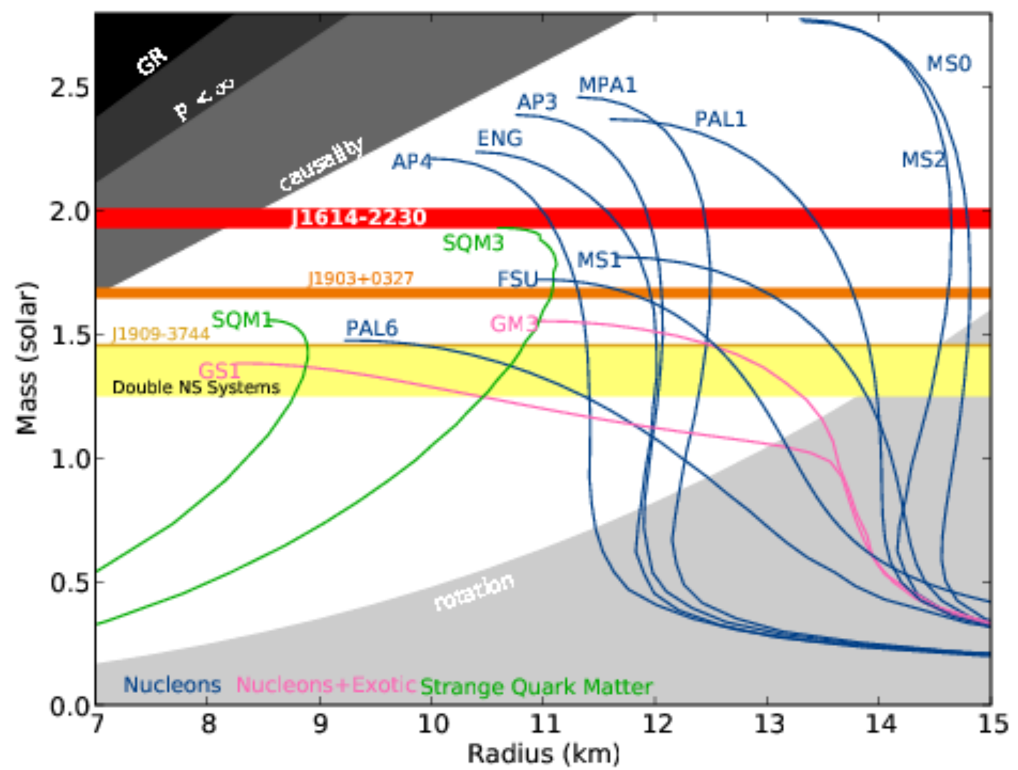
- Tides take energy from orbit   See Read talk
  Changes waveform
- A bigger NS will be deformed more
- Thus measurement of tidal deformability Λ gives insight into structure
- GW170817: ~soft EOS



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

Future Meas. 1: R and M

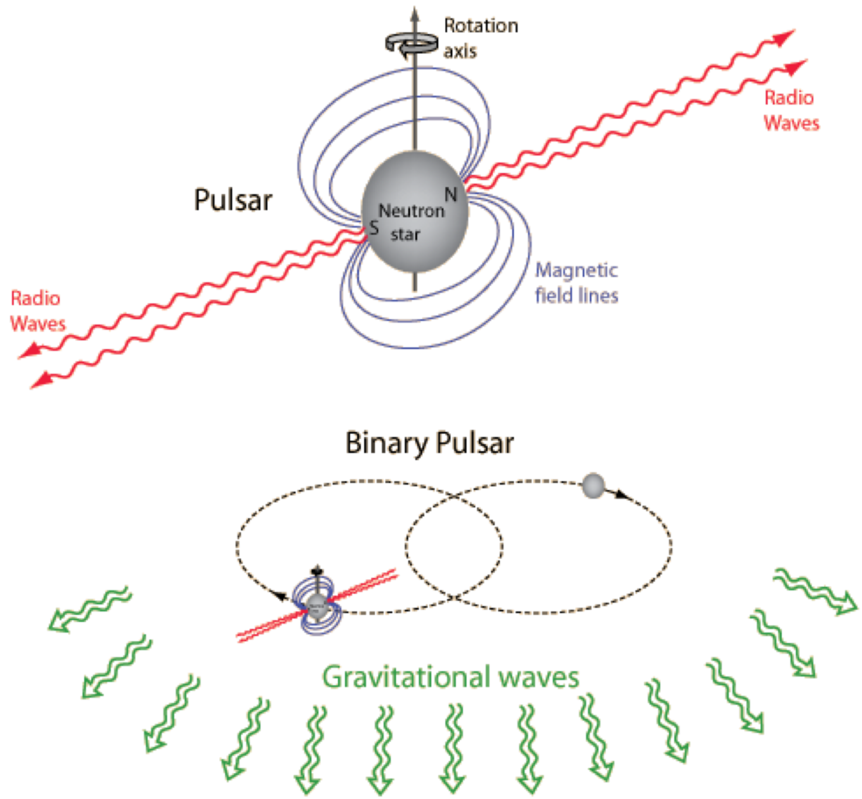
- Radius would provide great leverage
  Wide range in models
- But tough to measure
- All current published measurements are susceptible to huge systematic error
- NICER pulse profile modeling can help



Demorest+ 2010

Future Meas. 2: Inertial Moment

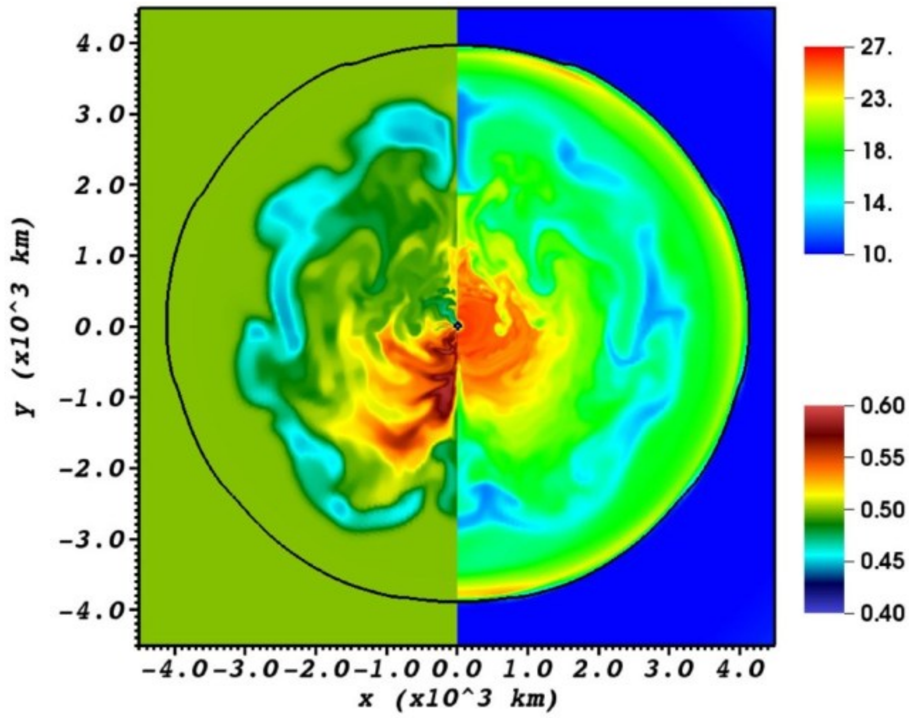
- Binary pulsars
  First evidence of GW!
- Highly precise masses
- Rotation of NS drags spacetime with it
  Extra precession
- Precession depends on angular momentum, and thus on I for known Ω
- Maybe measure in 10 yr?



http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/imgast/binpulse.gif

Future Meas. 3: Binding Energy

- If we know baryonic rest mass M_{bary} and grav mass M, we know NS binding energy
- Suggestion: NS from e^- capture supernovae might have known M_{bary} Nomoto, Podsiadlowski
- Difficulty: can we identify which NS?



electron capture SN
Müller et al. 2017

Putting it all together

- There are a wide variety of measurements, of different stars, which relate in different ways to $P(\varepsilon)$
- Putting them together requires a rigorous but practical Bayesian framework
- This is the focus of Miller, Chirenti, and Lamb 2019 (arXiv:1904.08907)

The setup

- Pick a parametrized equation of state
  Any will do; we use the spectral parametrization of Lindblom (2010, 2018)
- For some constraints, no marginalization is needed (example: maximum mass)
- For others, need to marginalize (example: if have M,R likelihood, need to integrate over central densities)
  We use uniform prior on central density

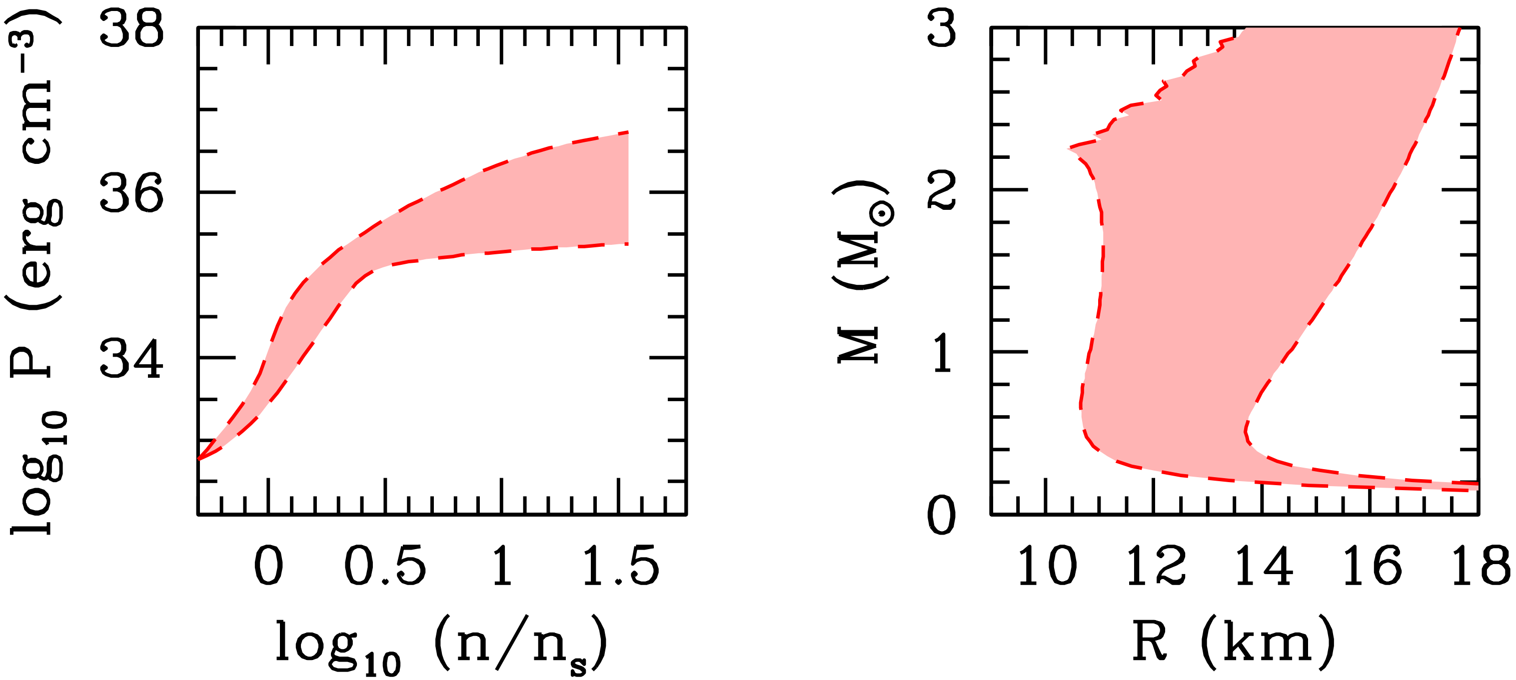
An example of a subtlety

- How should we incorporate a high measured mass in our constraints?
- Method used by almost everyone is to set a strict lower bound
  Often: if $M_{max}<1.97\ M_{sun}$ for an EOS parameter combination, that combination is ruled out; otherwise, acceptable
- But what we recommend is to use the full mass posterior

The Results

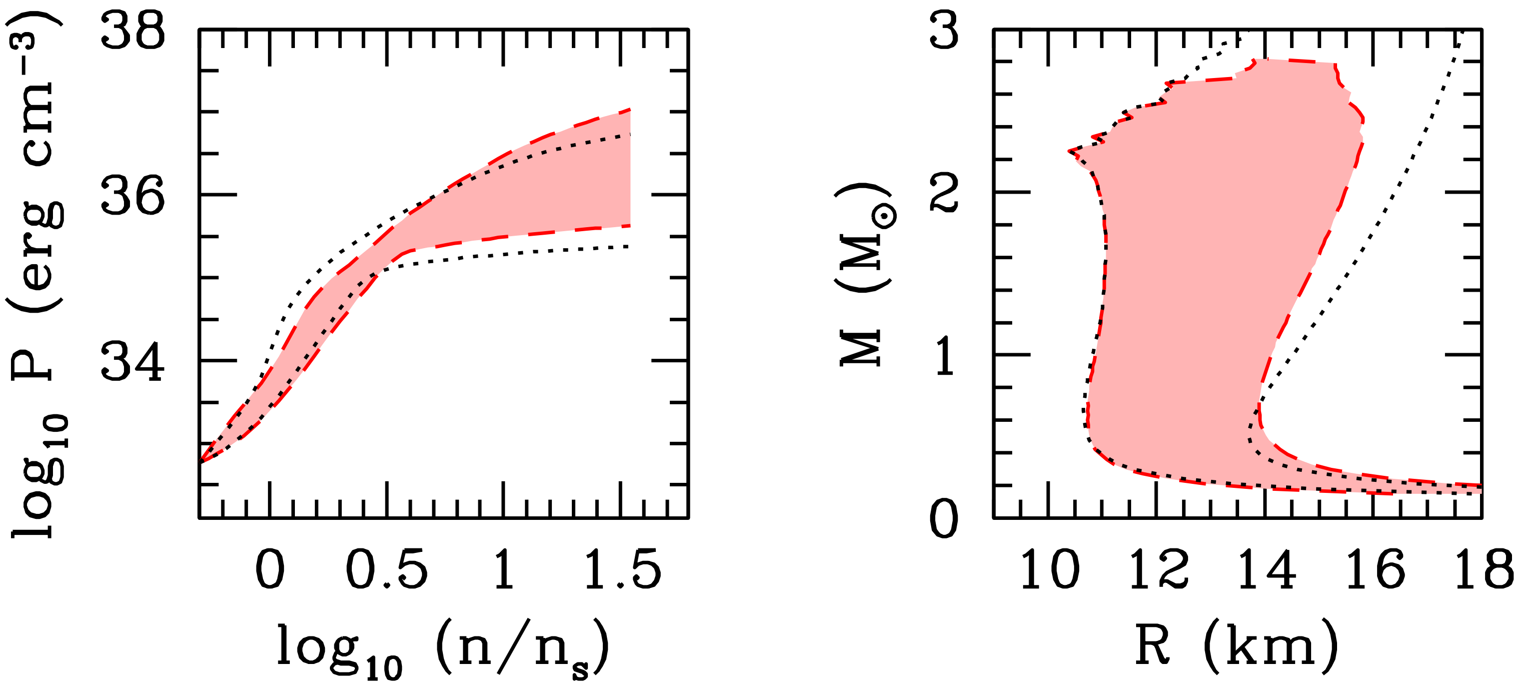
- In the following figures, we will show the 5% to 95% credible region for pressure (represented as a function of number density, n, defined as ρ/m_n), and radius as a function of mass, given progressive incorporation of:
  Mass, tidal deformability (in hand)
  (M,R) for one star (expected from NICER)
  Moment of inertia (10 years?)
  Binding energy (optimistic)

Mass only



Use all three high-mass neutron stars; n_s=0.16 fm^{-3}
Red region: 5% to 95% at each n, M.
Requirement of high masses pushes P and R high

Mass and tidal deformability

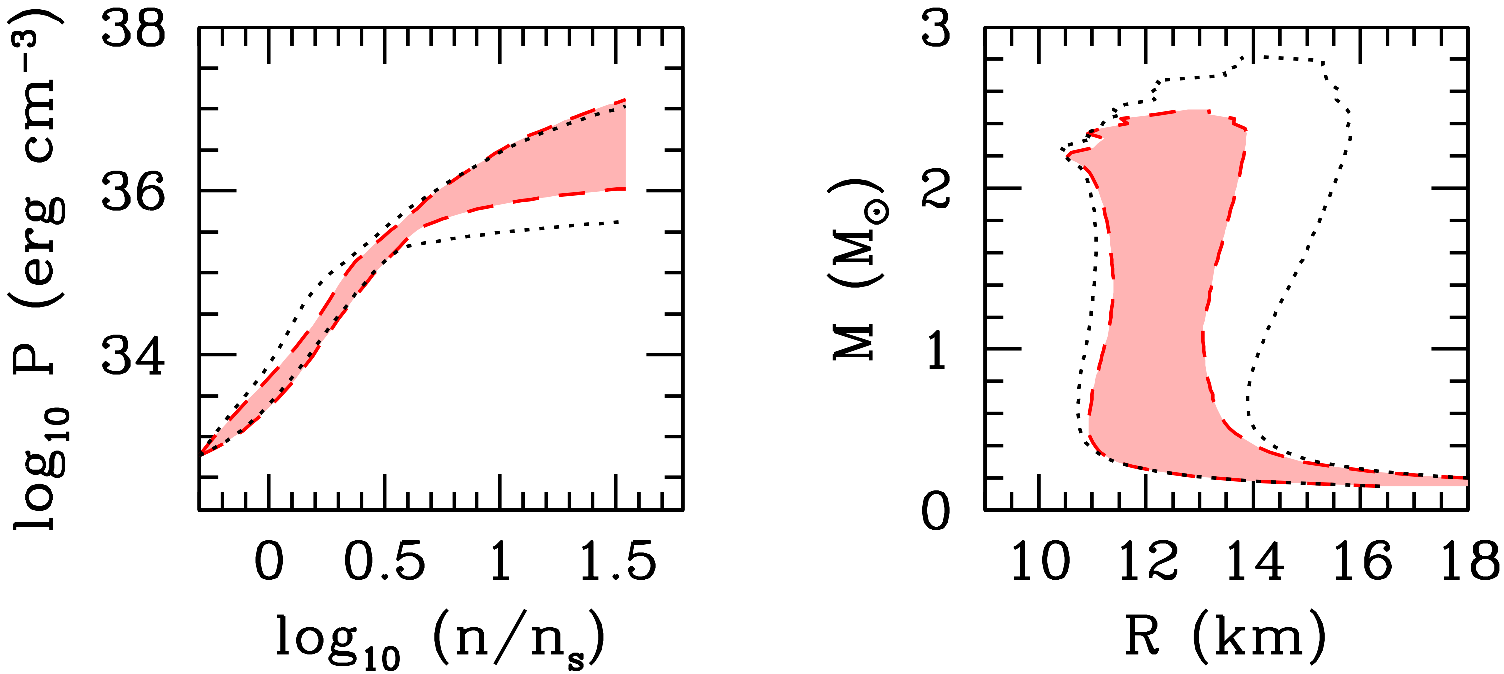


Include LIGO GW170817 Λ measurement

Dotted lines are mass-only 5%, 95% credible regions

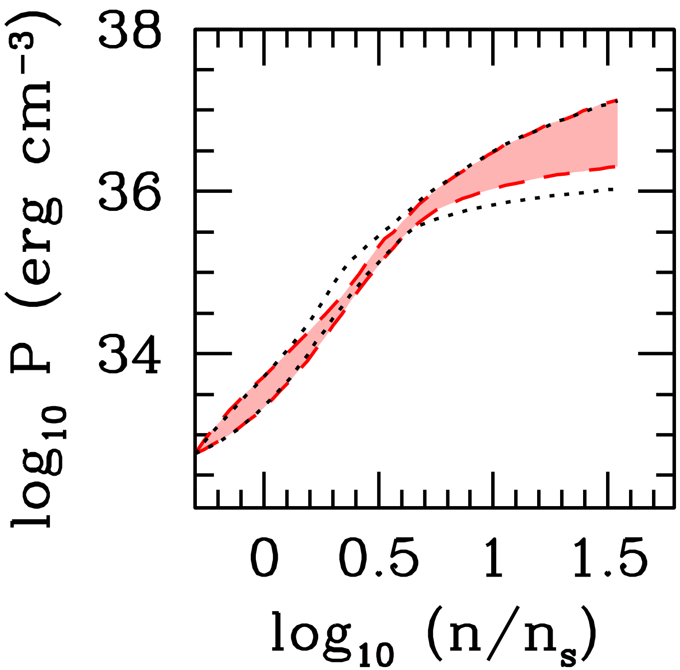
Low Λ pushes P lower for low n, pushes R lower

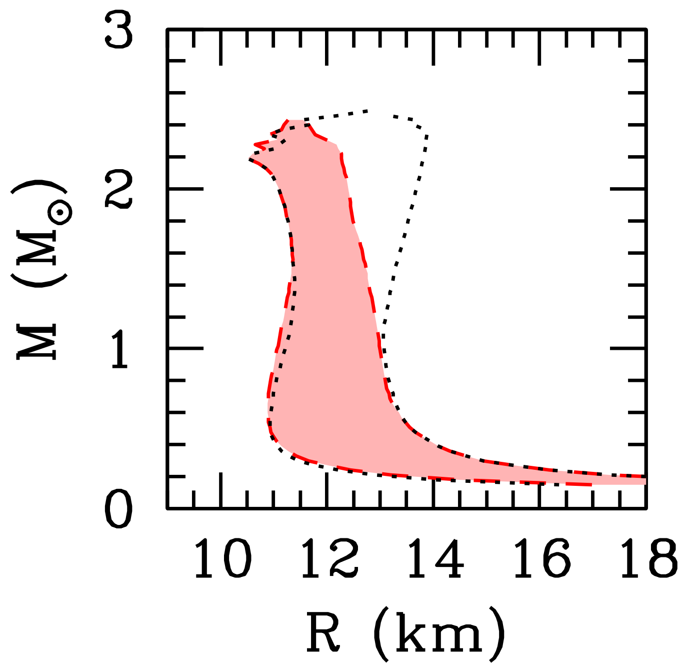
M, Λ, and (R,M)



Assume 5% precision on (12 km,1.4 M_{sun}) for one star
Dotted lines are M+Λ 5%, 95% credible regions
(M,R) measurement naturally tightens R

M, Λ, (R,M), and I



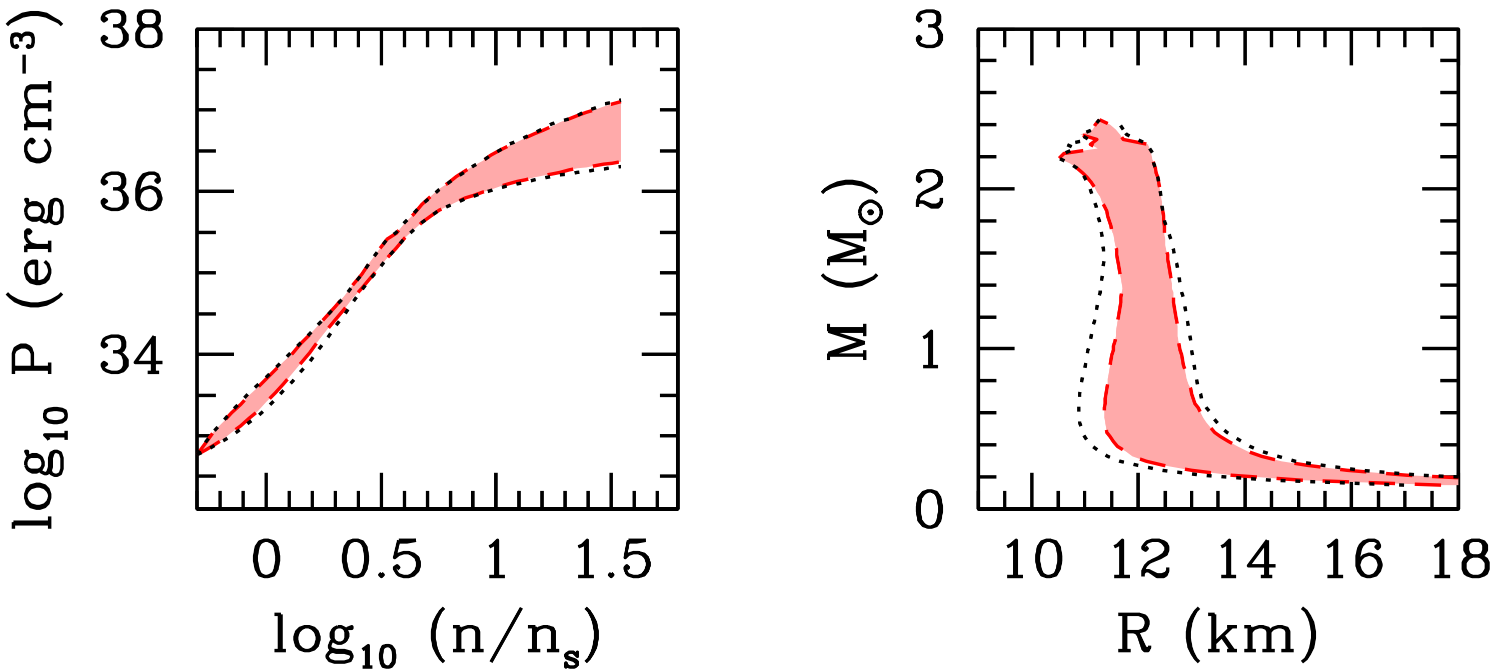


Assume 10% fractional precision on one 1.338 M_{sun} star

Dotted lines are M+Λ+(R,M) credible regions

I measurement tightens EOS, R(M) significantly

M, Λ, (R,M), I, and E_{bind}



Assume ΔM_{bary}=0.005 M_{sun} for measured M=1.249 M_{sun}
Dotted lines are M+L+(R,M)+I credible regions
E_{bind} measurement reduces low-n uncertainty

Conclusions

- High neutron star masses and low tidal deformabilities are already squeezing allowed equation of state
- Mass and radius measurements from NICER will be crucial
- Succession of NS-NS events seen in GW will give us enormous information
- Finally, a data-rich era for NS interiors!