Title: Perspectives on Matter Effects in GW170817

Speakers: Reed Essick

Series: Strong Gravity

Date: October 17, 2019 - 1:00 PM

URL: http://pirsa.org/19100065

Abstract:

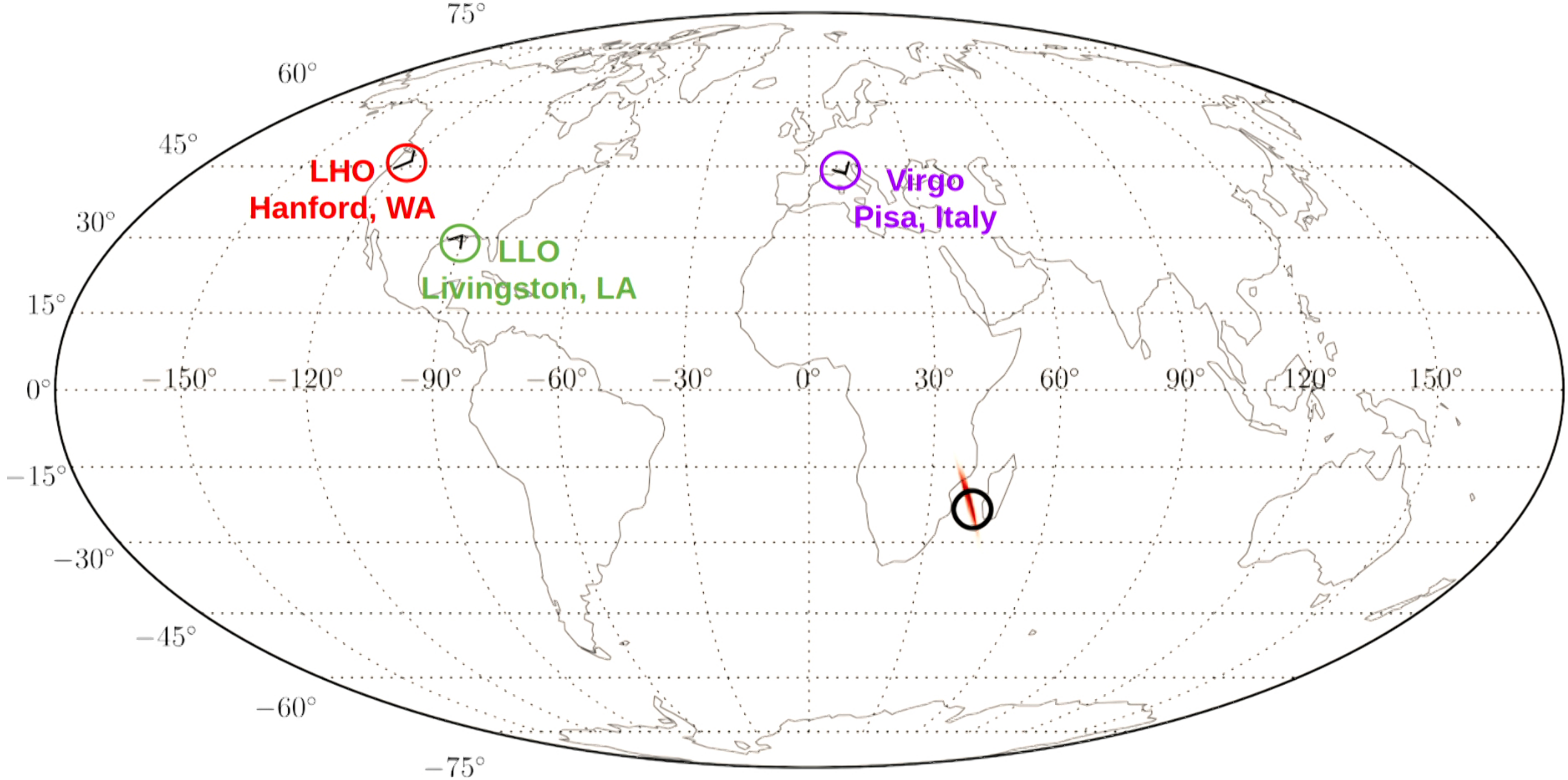
The detection of coalescing neutron stars via gravitational waves (GW170817) has revolutionized our understanding of the equation of state at supranuclear densities. The equation of state determines how neutron stars interact in a variety of astrophysical contexts, from rapidly rotating millisecond pulsars, to accreting X-ray sources, and, of course, coalescing binaries radiating gravitational waves. I will review the state of the field, including commonly adopted parametrizations of the neutron star equation of state in the context of theoretical expectations, before introducing a nonparametric inference scheme based on Gaussian processes. Nonparametric inference provides much greater functional freedom than parametrized analyses, allowing for the direct inference of neutron star composition and the existence of possible phase transtions above nuclear density. Additionally, I will review the search for predicted secular fluid instabilities within neutron star cores and their possible impact on gravitational-wave signals. This instability couples pressure-supported (p-mode) and gravity supported (g-mode) oscillations within the star, and I will show how GW170817 rules out only the most extreme theoretical predictions for how the instability could saturate. As the advanced LIGO and Virgo detectors gear-up for the second half of their third observing run, we will conclude by discussing the outlook for these measurements with future detections and the implications for broader astrophysical populations.

Perspectives on Matter Effects in GW170817

Reed Essick
Kavli Institute for Cosmological Physics
University of Chicago

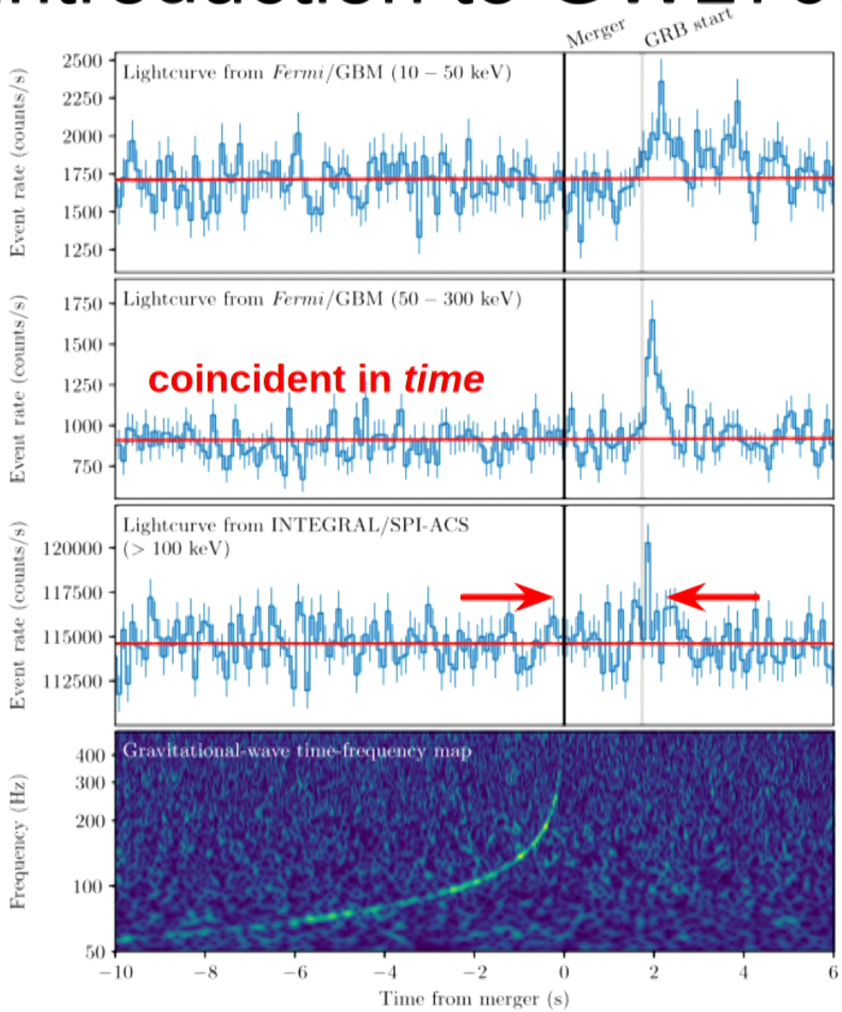
A 60 second Introduction to Gravitational-Wave Detectors and GW170817

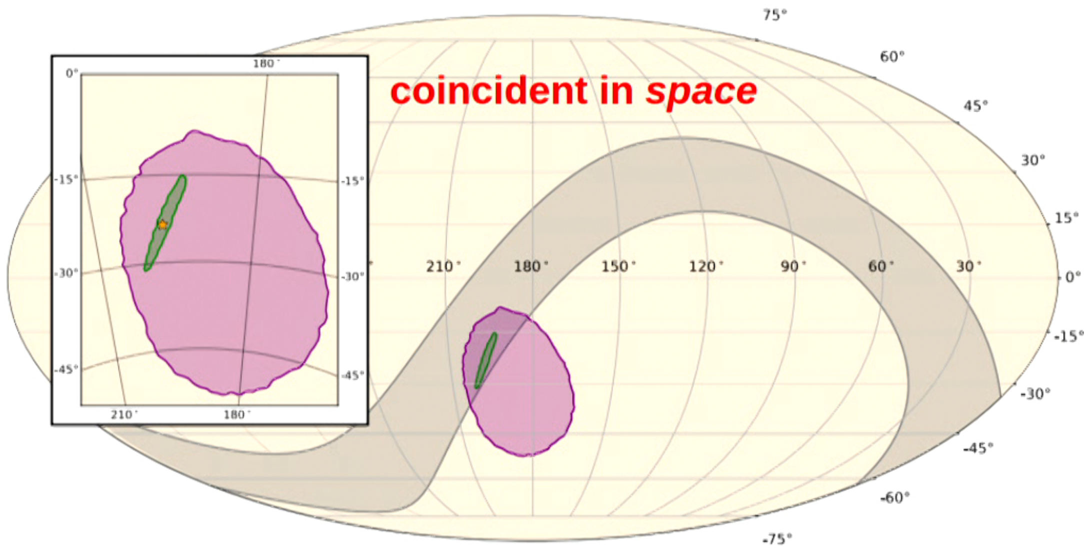
introduction to GW170817



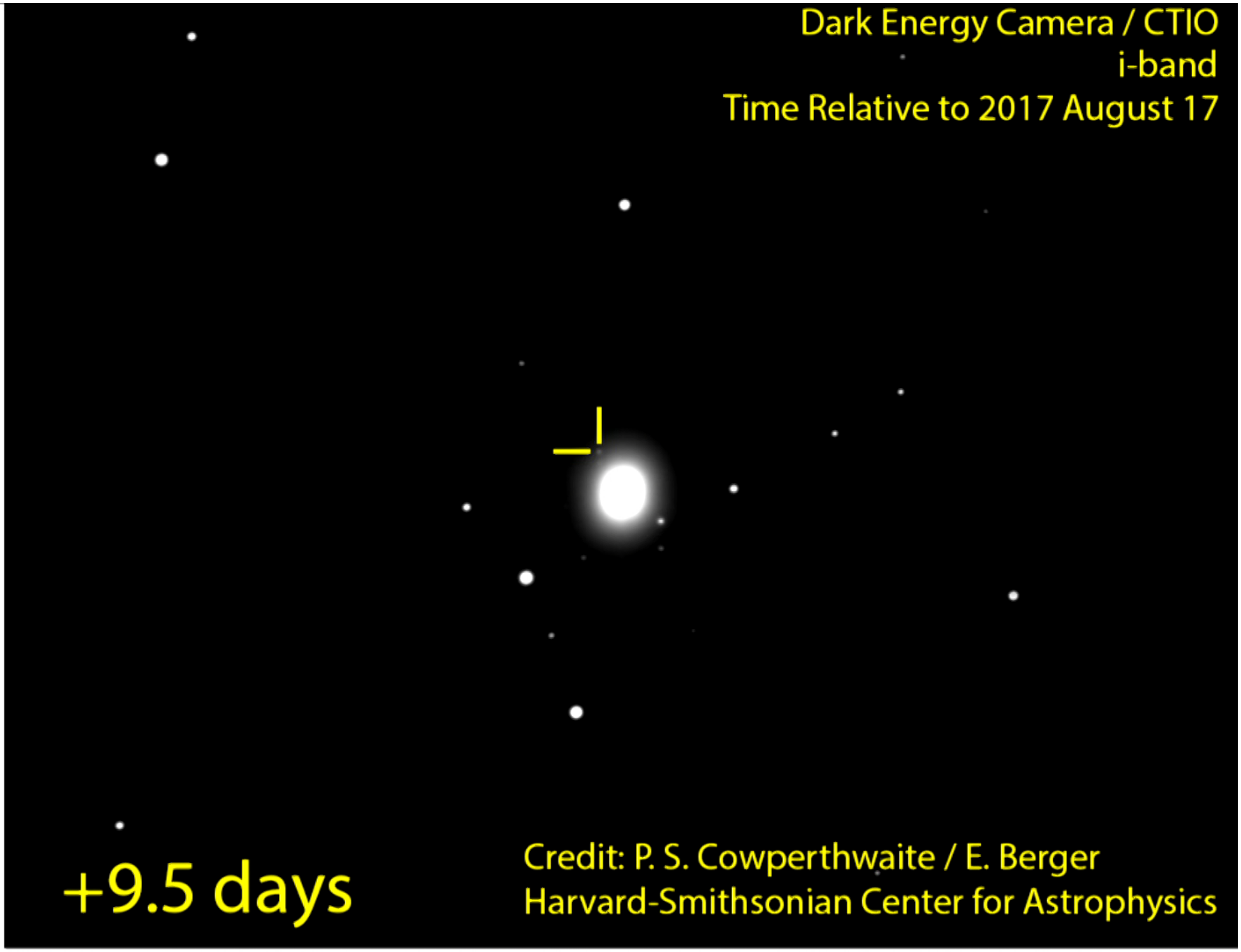
introduction to GW170817

introduction to GW170817





introduction to GW170817



Nonparametric Equation of State Inference with Gravitational Waves

goals

- Self-consistently incorporate information from arbitrary tabulated EOS models
  - condition prior directly on proposed EOS
- Automatically incorporate causality constraints and thermodynamic stability
  - auxiliary variable:

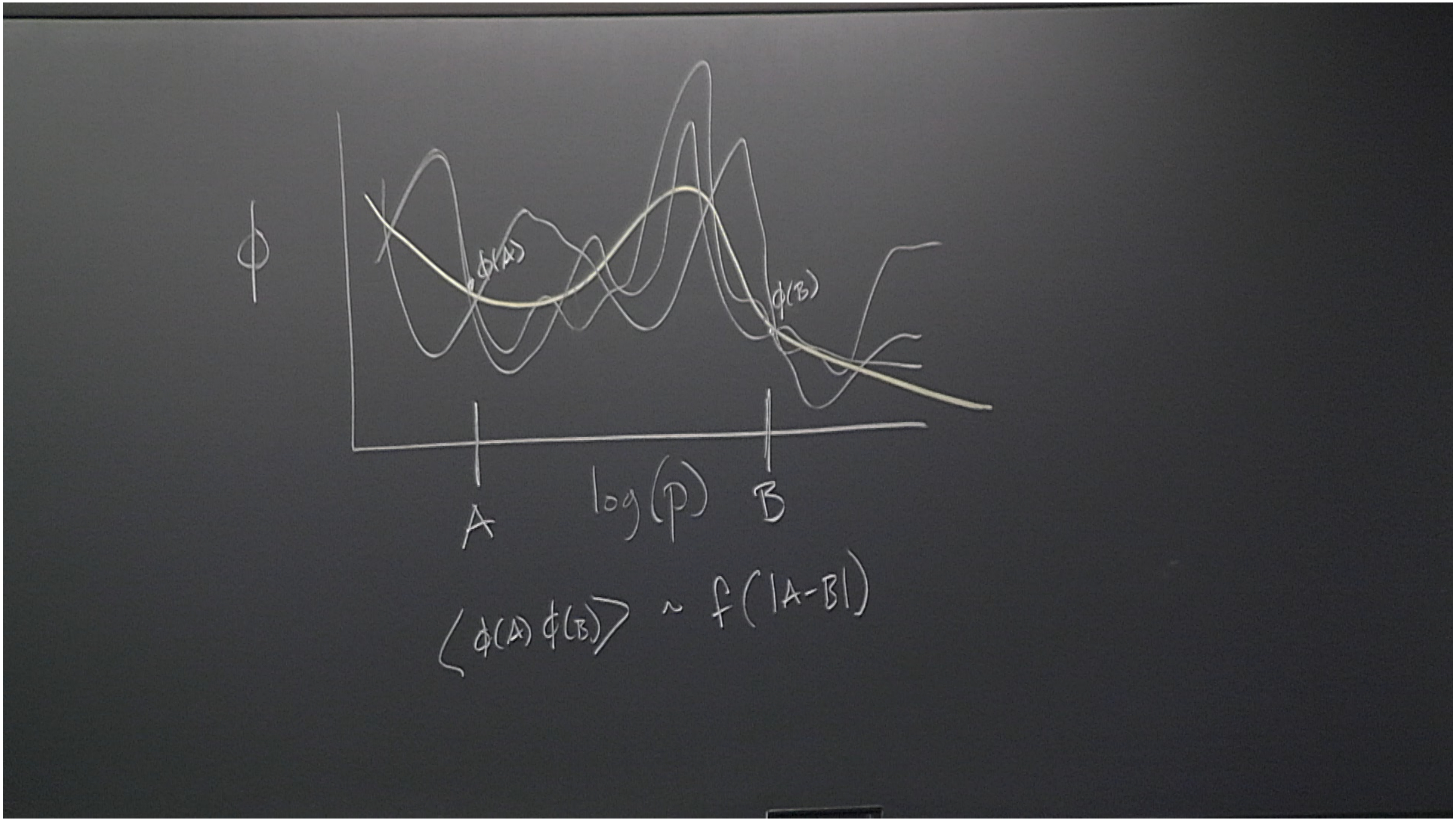
$$\phi = \log\left(c^2 \frac{d\mu}{dp} - 1\right) \qquad 0 \leq dp/d\mu \leq c^2$$

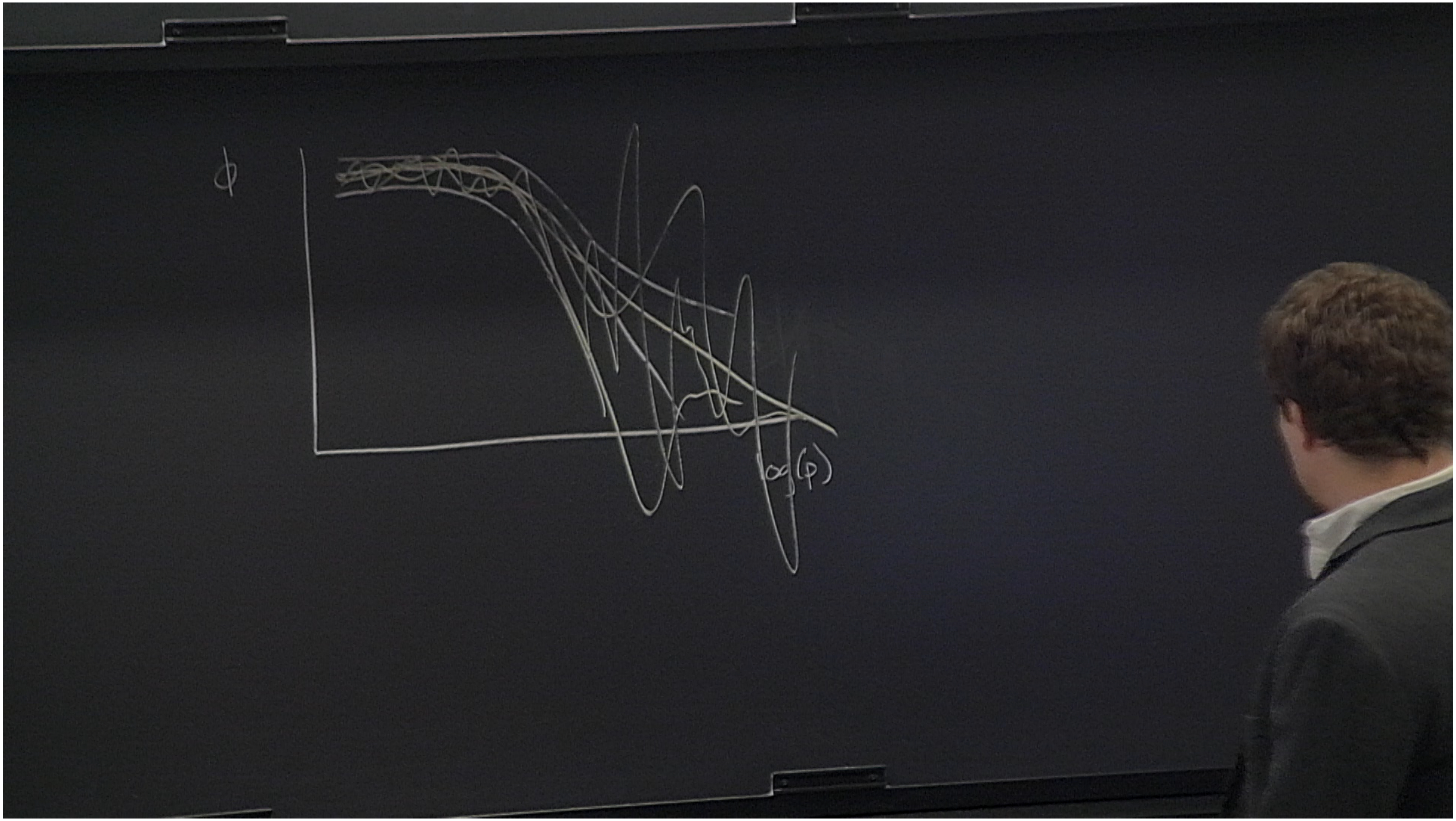
- Allow for large amounts of model freedom
  - Gaussian process formally supports any possible ϕ
- Incorporate transparent priors
  - configurable "confidence" in tabulated EOS
  - different uncertainty at different pressures
    - small uncertainty near the crust
    - large uncertainty near the central core

} determined by the *covariance kernel*

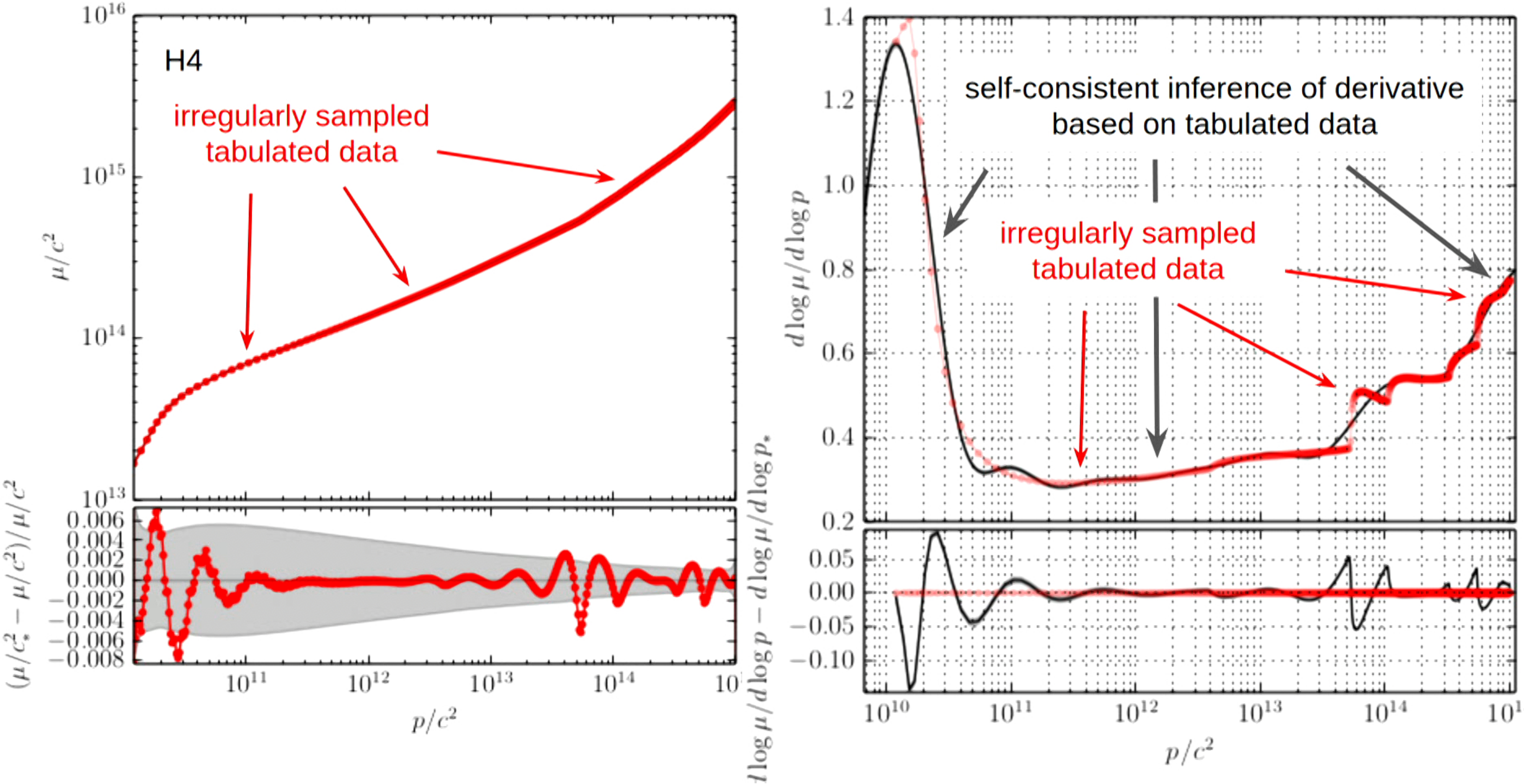
Gaussian processes

BLACKBOARD WORK

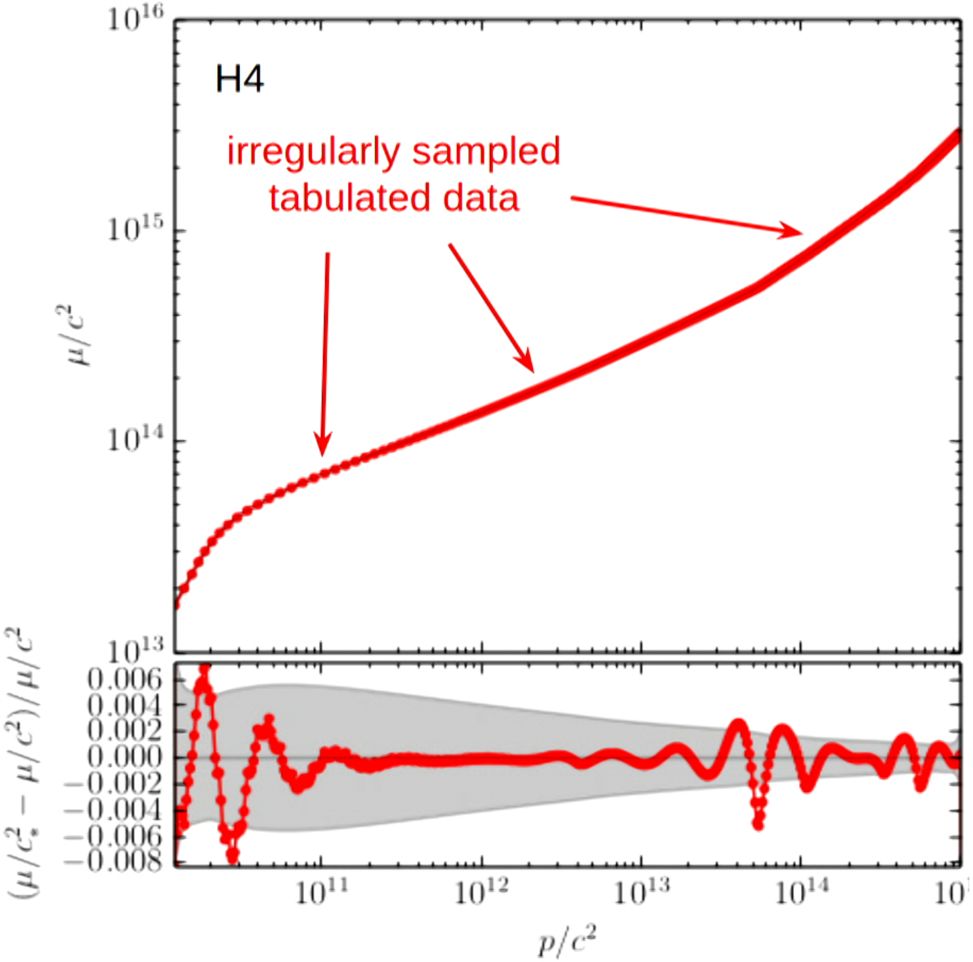

ϕ
ϕ(A)
ϕ(B)
A
log(p)
B
⟨ϕ(A) ϕ(B)⟩ ~ f(|A-B|)

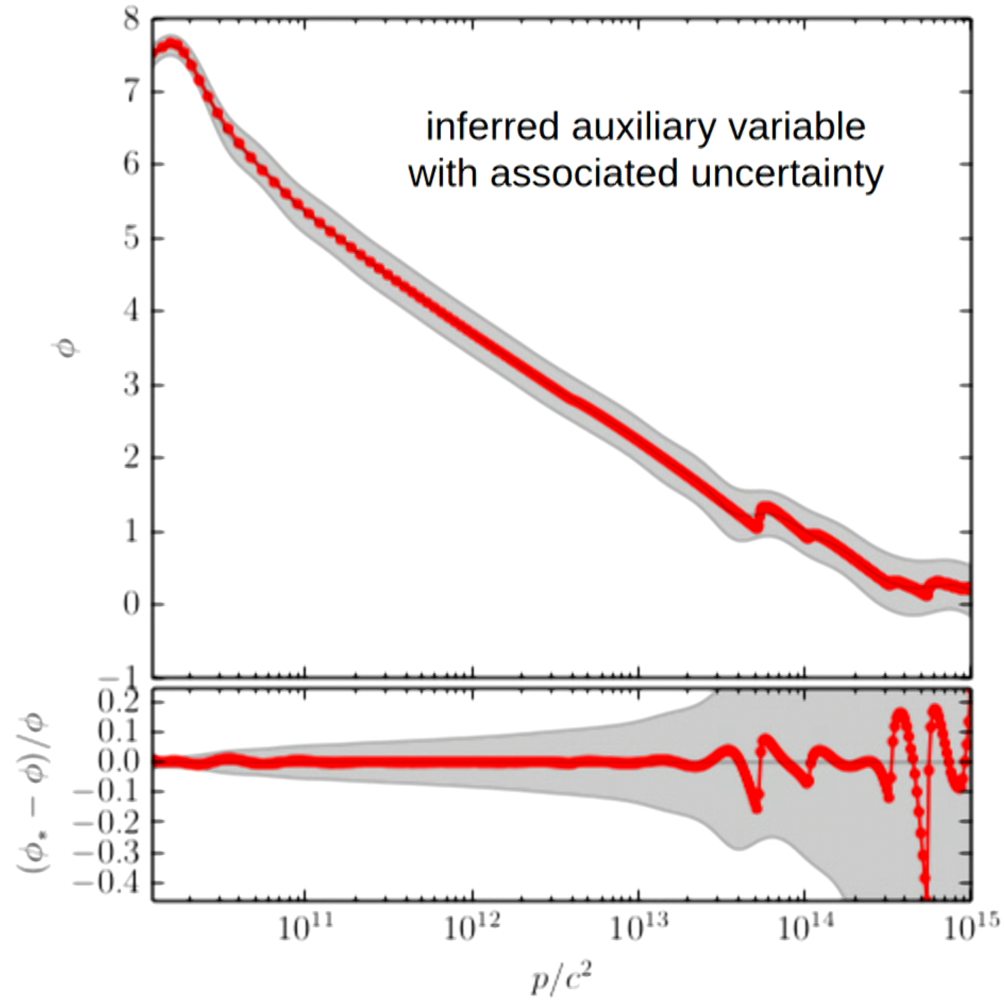

ϕ
log(ϕ)

conditioning

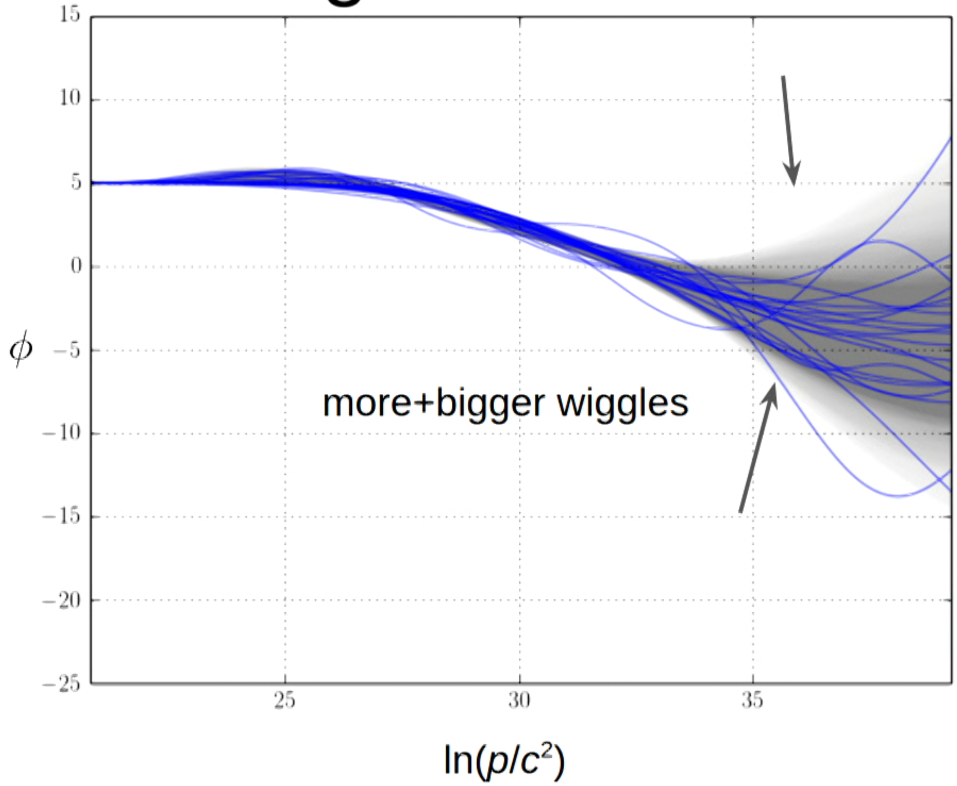


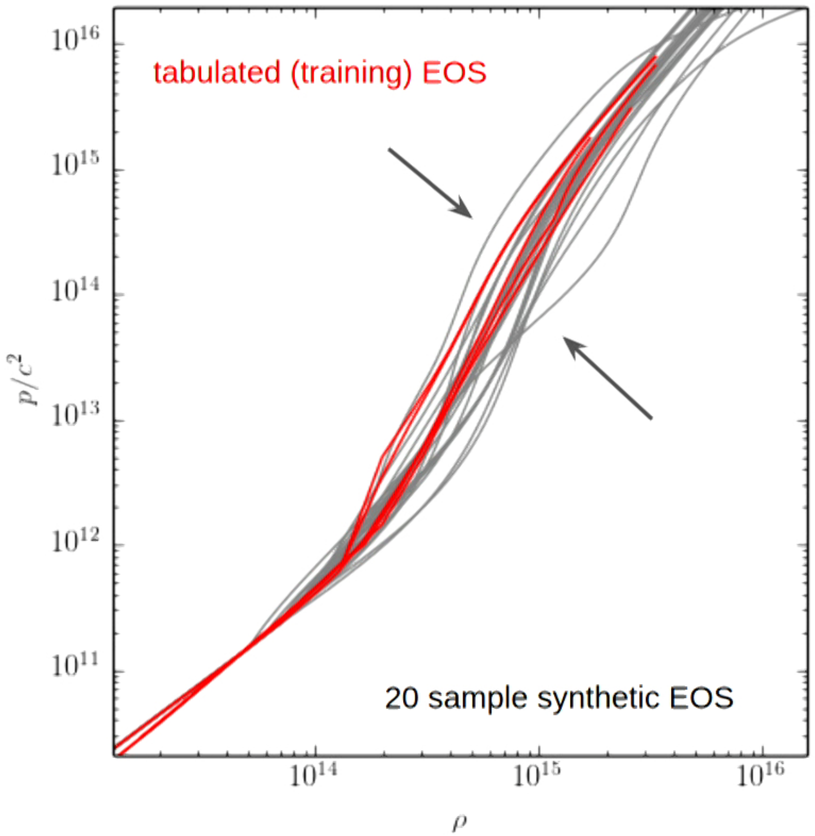
conditioning





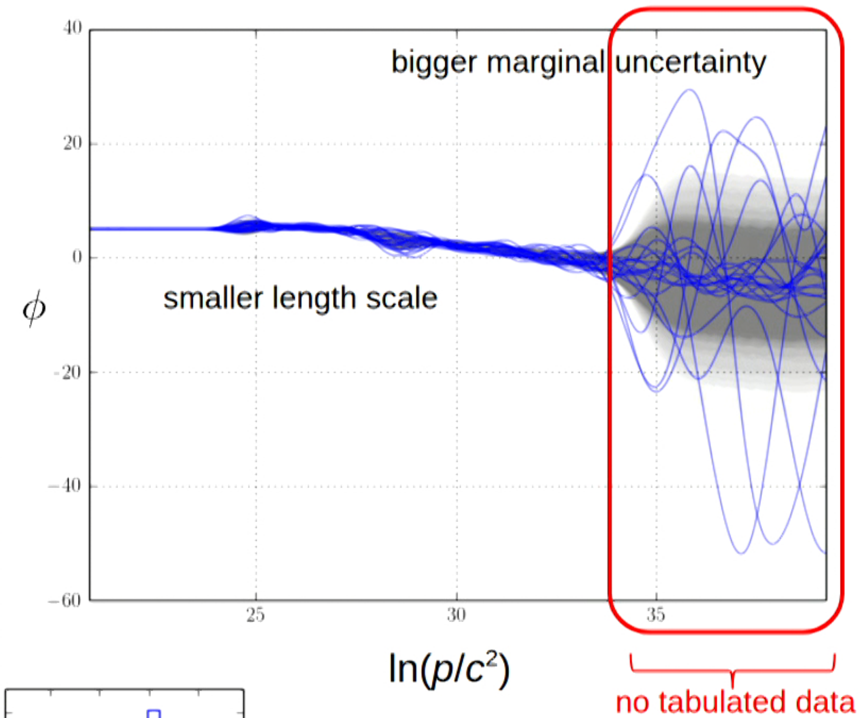
conditioning

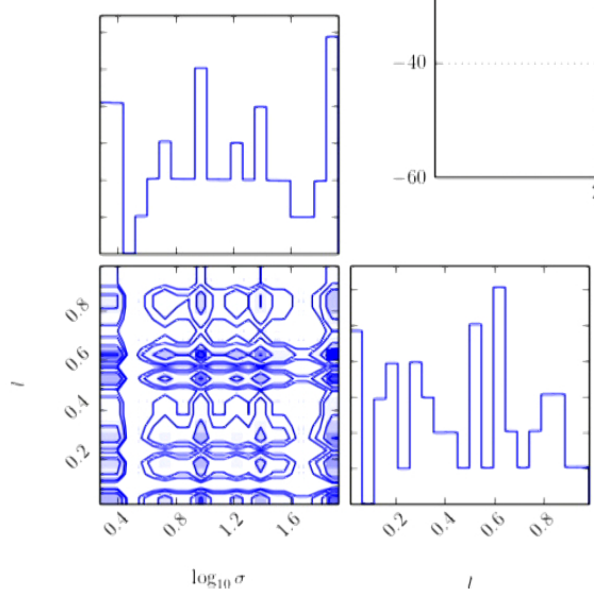


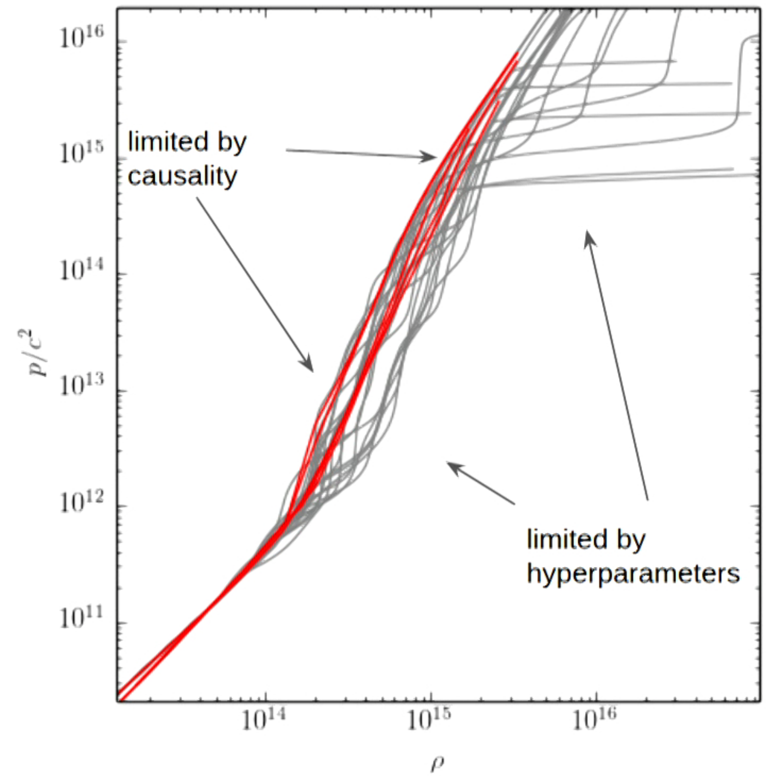


marginalizing over wider hyperprior with
“flat” likelihood allows for “arbitrary” behavior

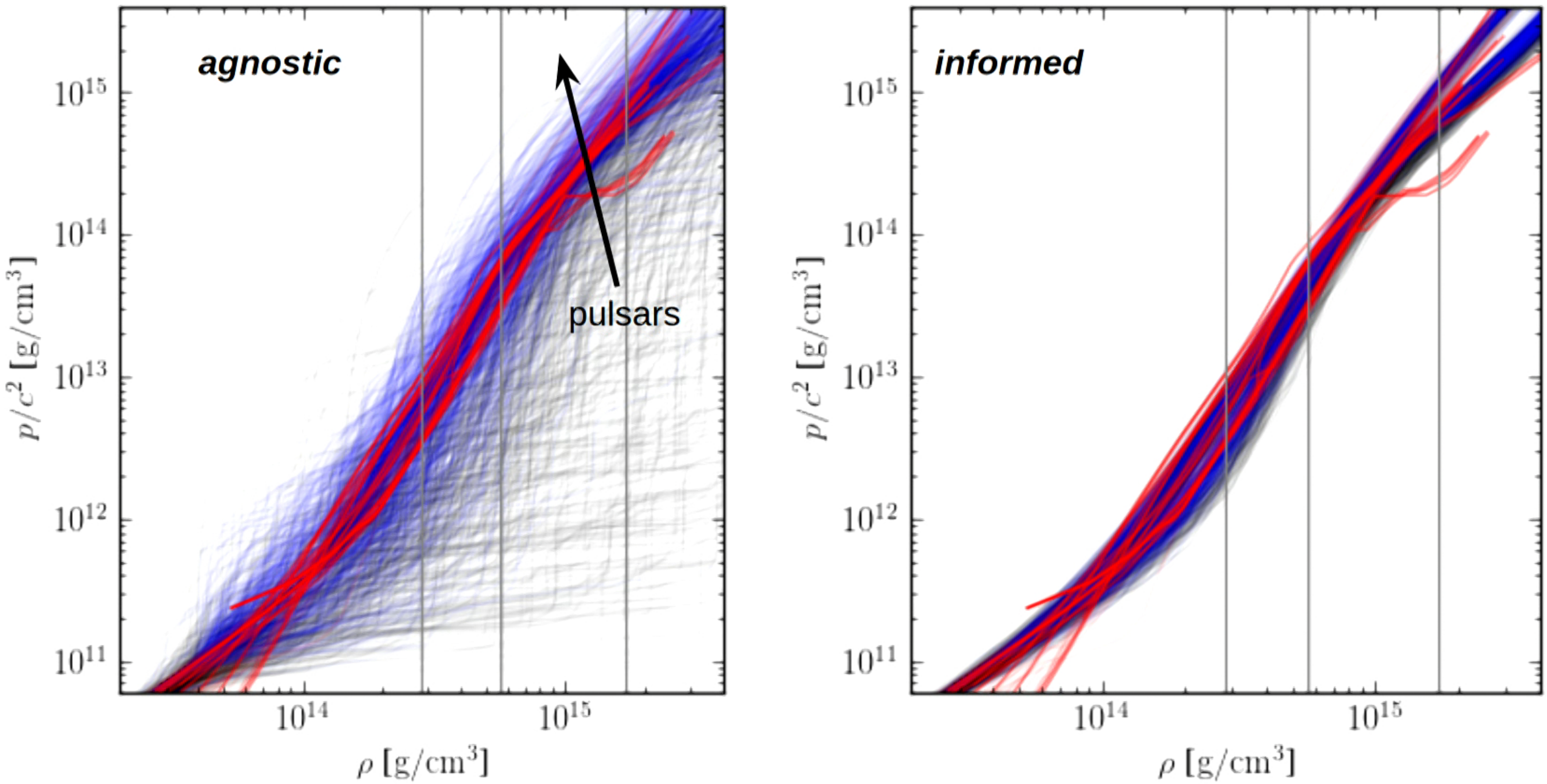
conditioning



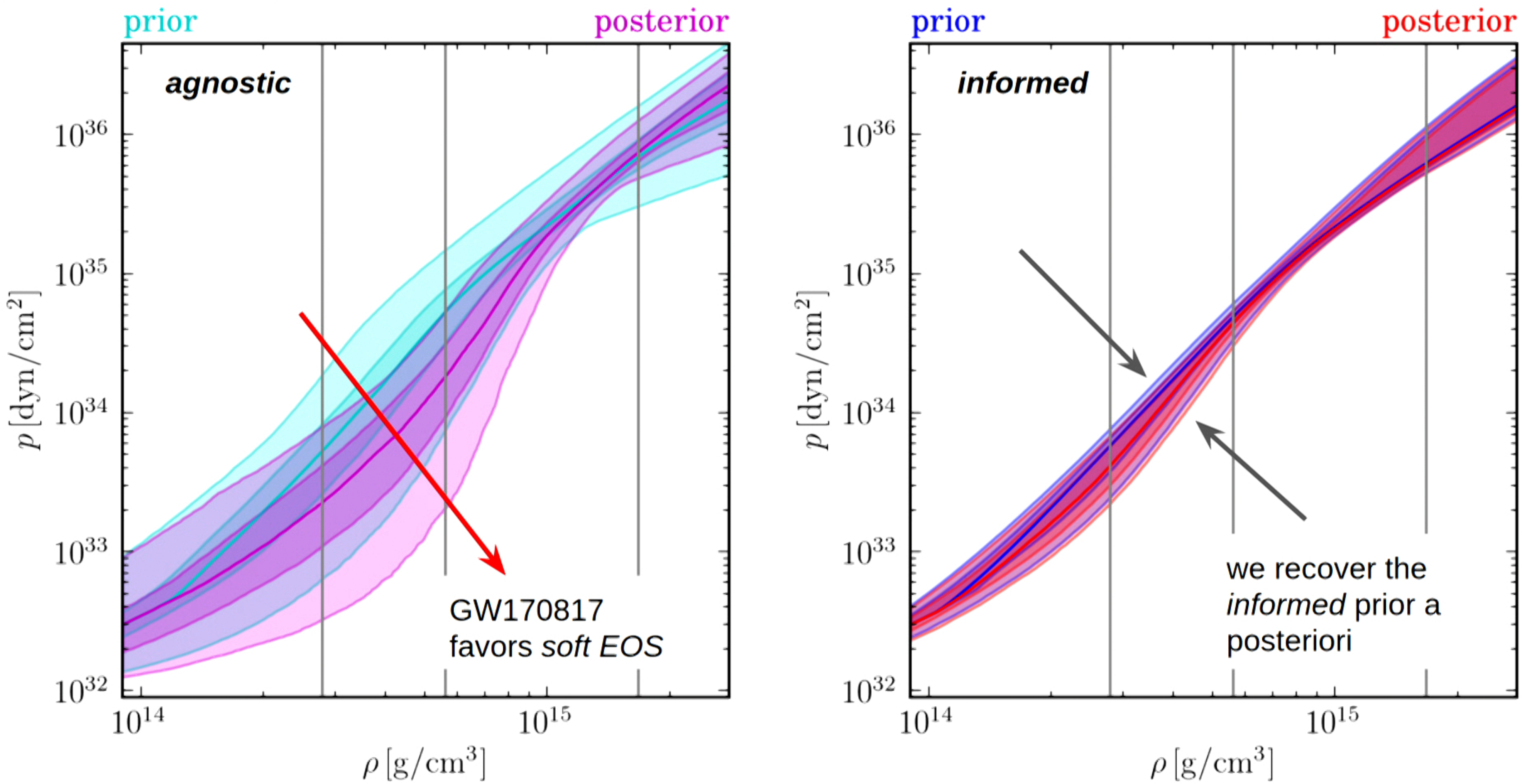




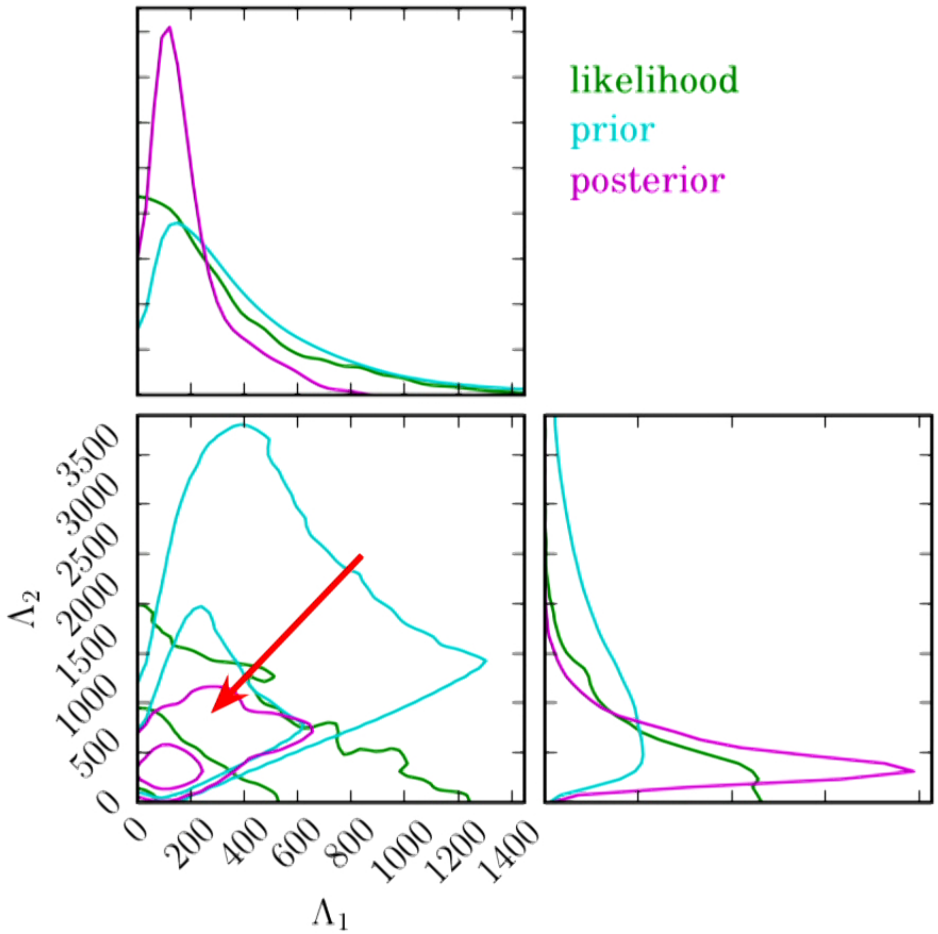
prior processes

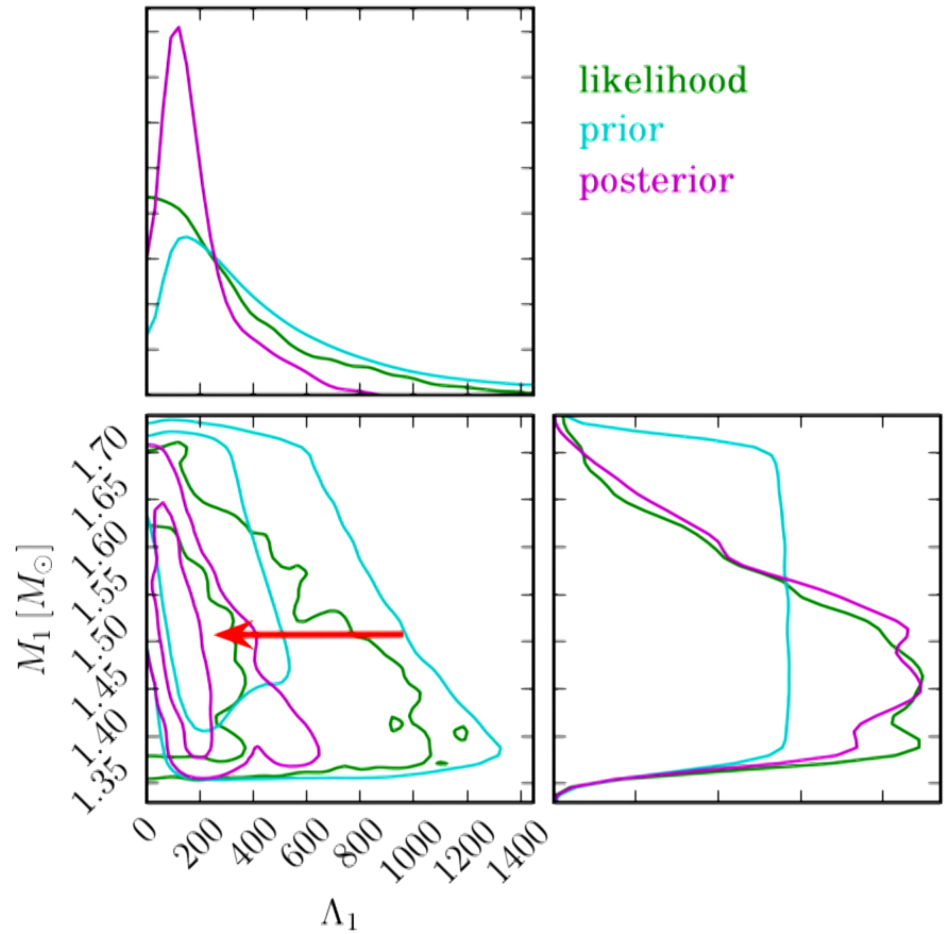


posterior processes

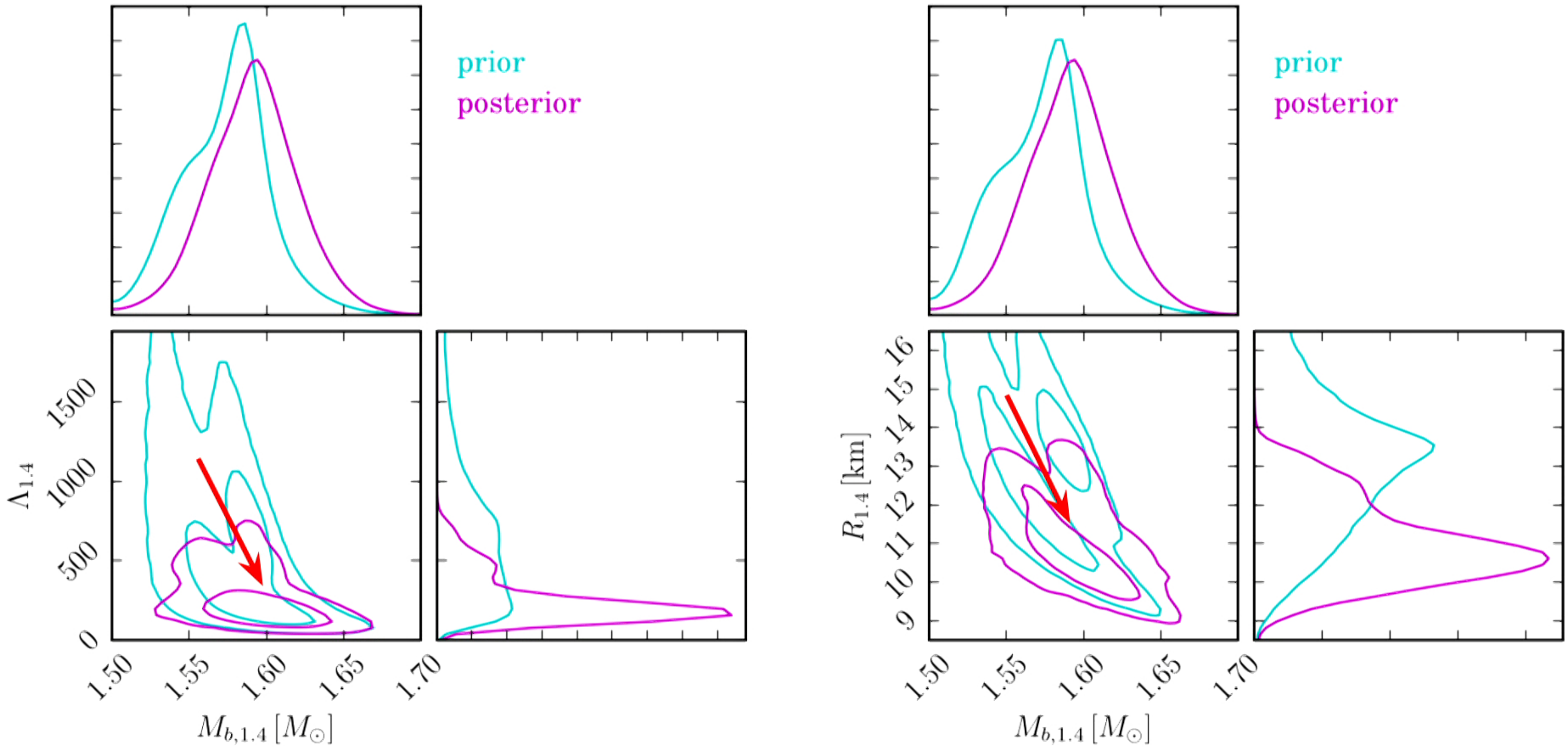


GW170817 components

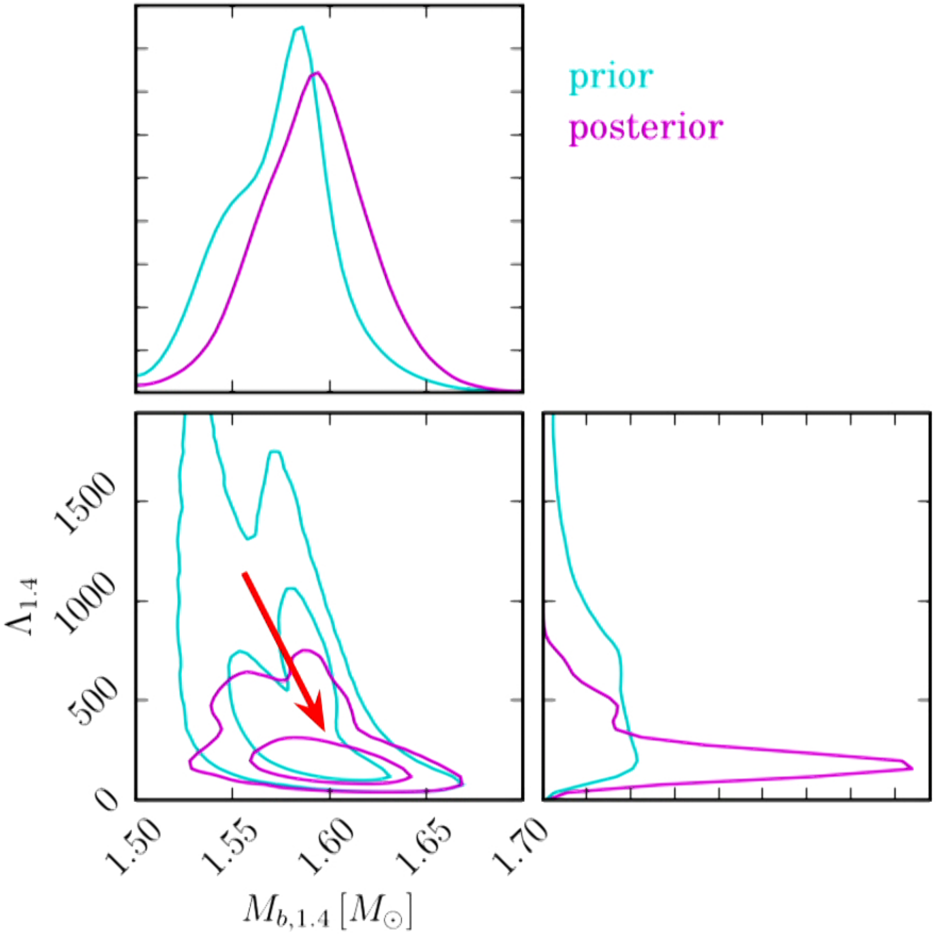




canonical NS properties



canonical NS properties

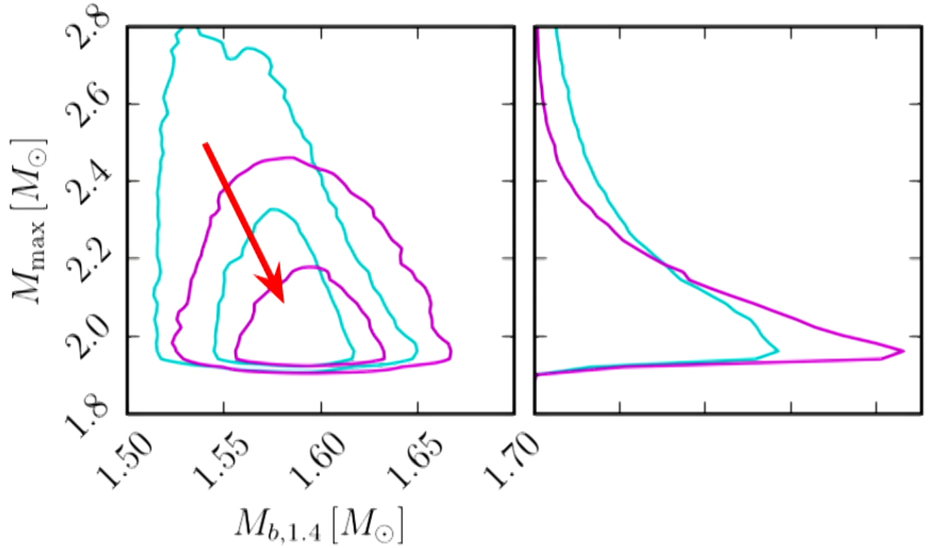


agnostic $M_{\rm max} \leq 2.32\, M_\odot$

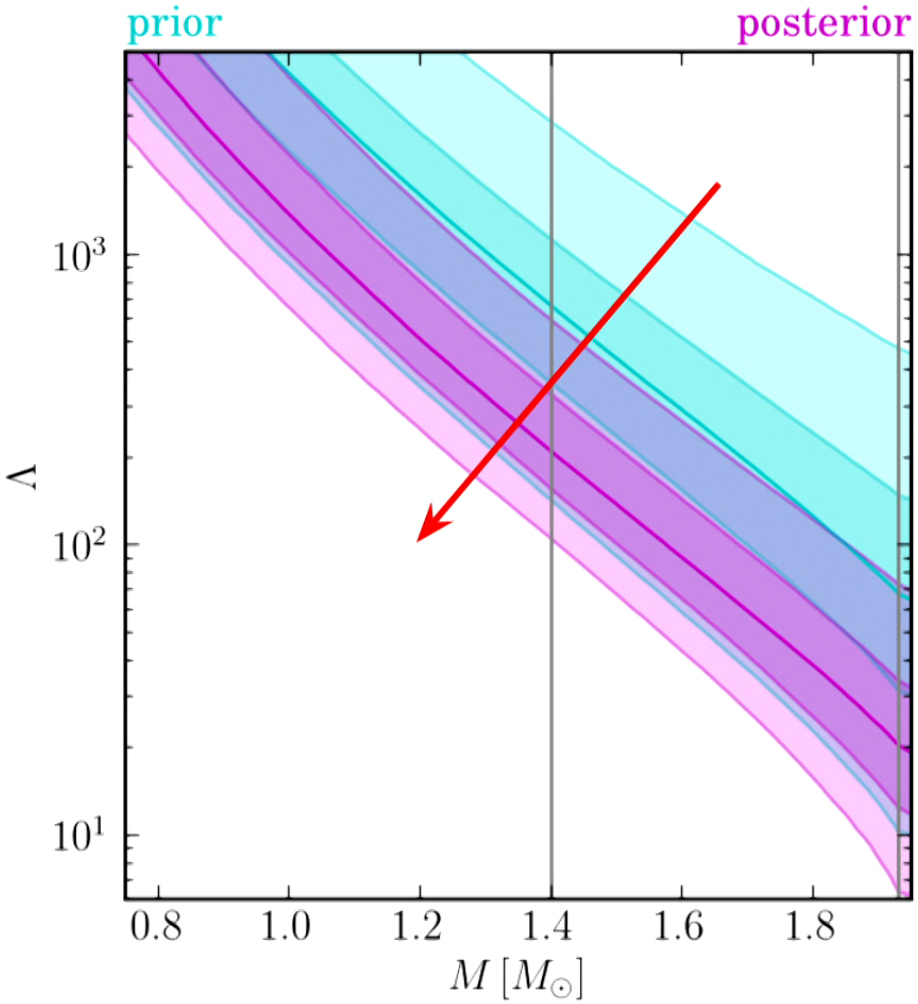
informed $M_{\rm max} \leq 2.26\, M_\odot$

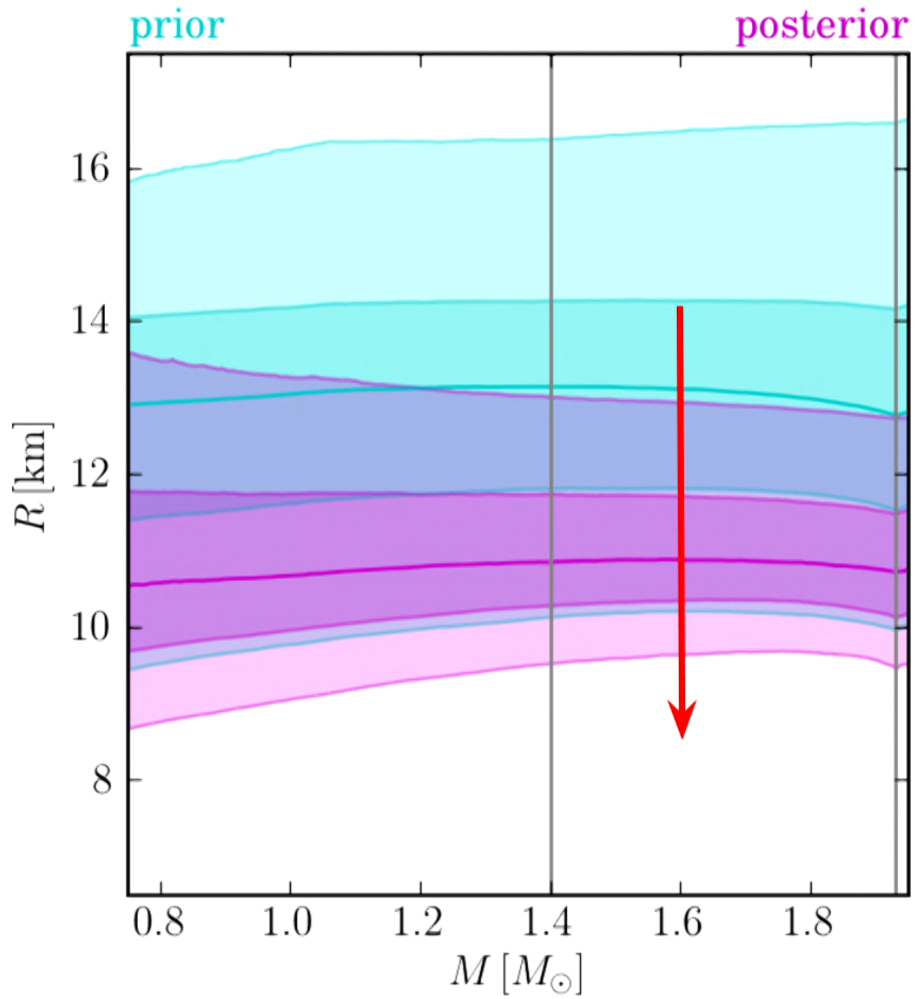
compare to [Cromartie+(2019)]

$$M = 2.14^{+0.10}_{-0.09}\, M_\odot$$

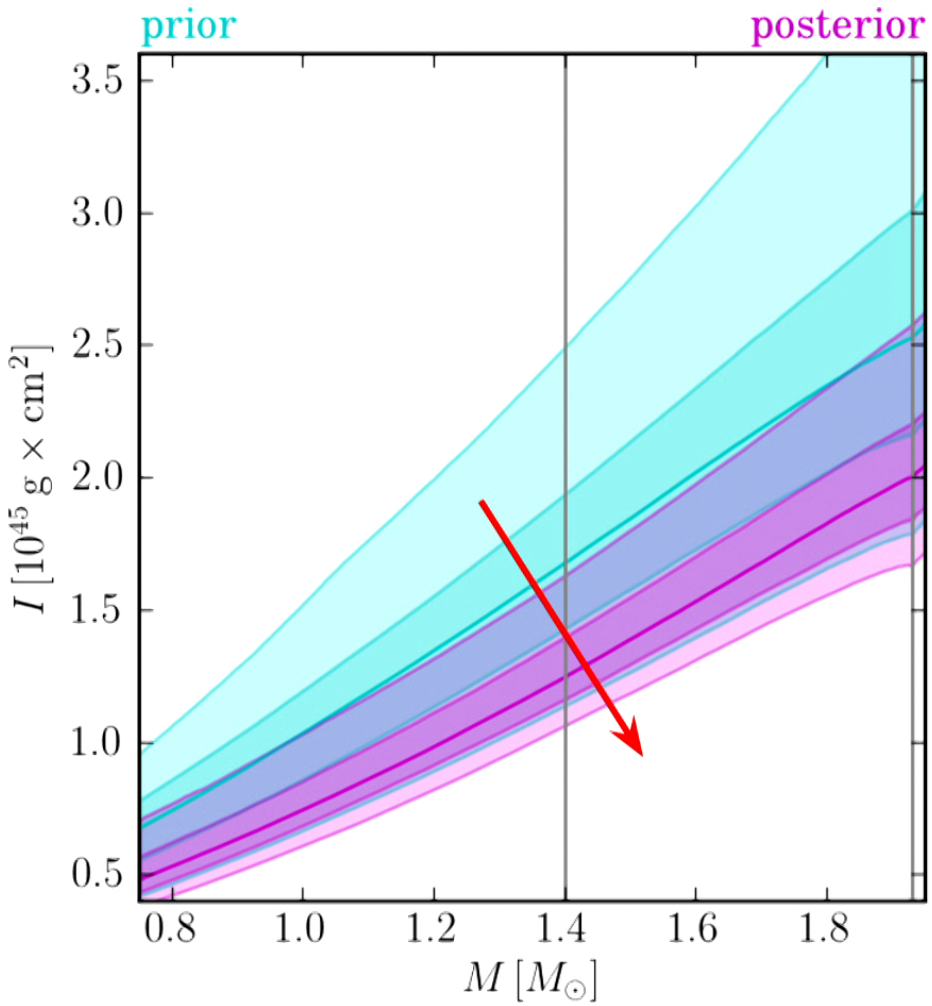


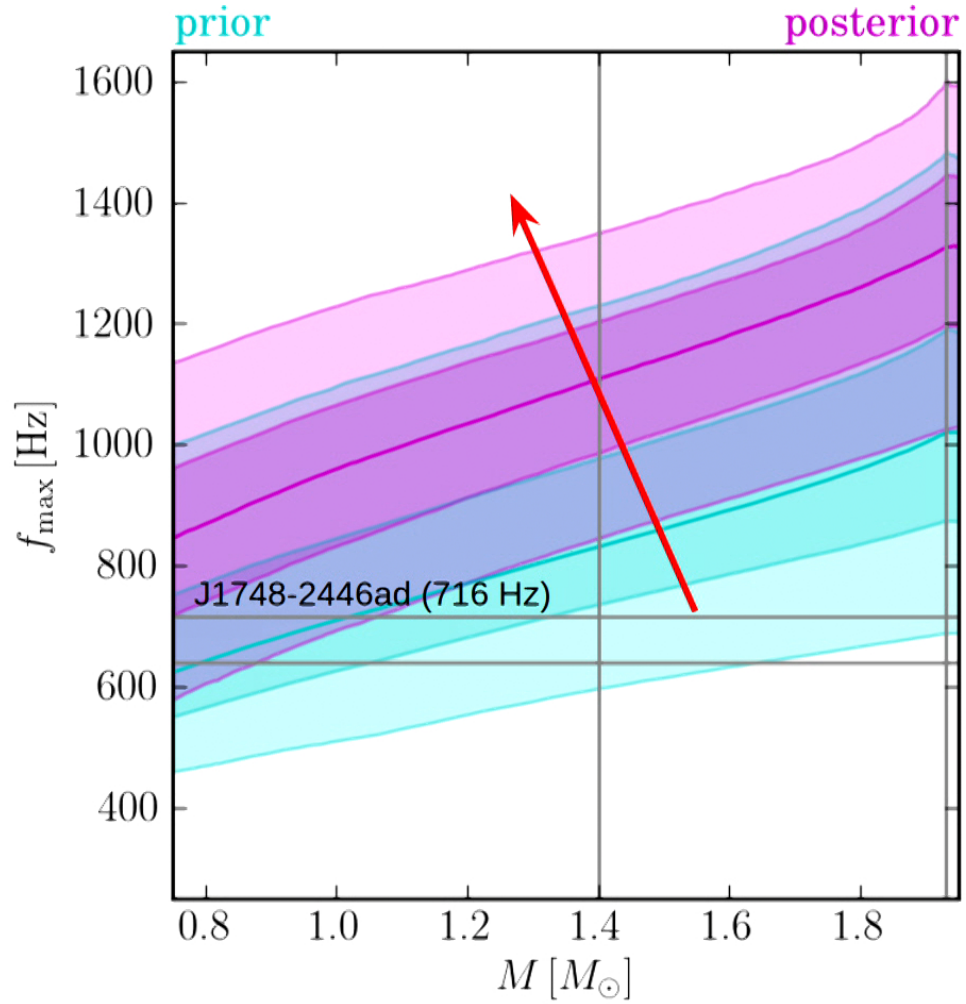
generic NS observables





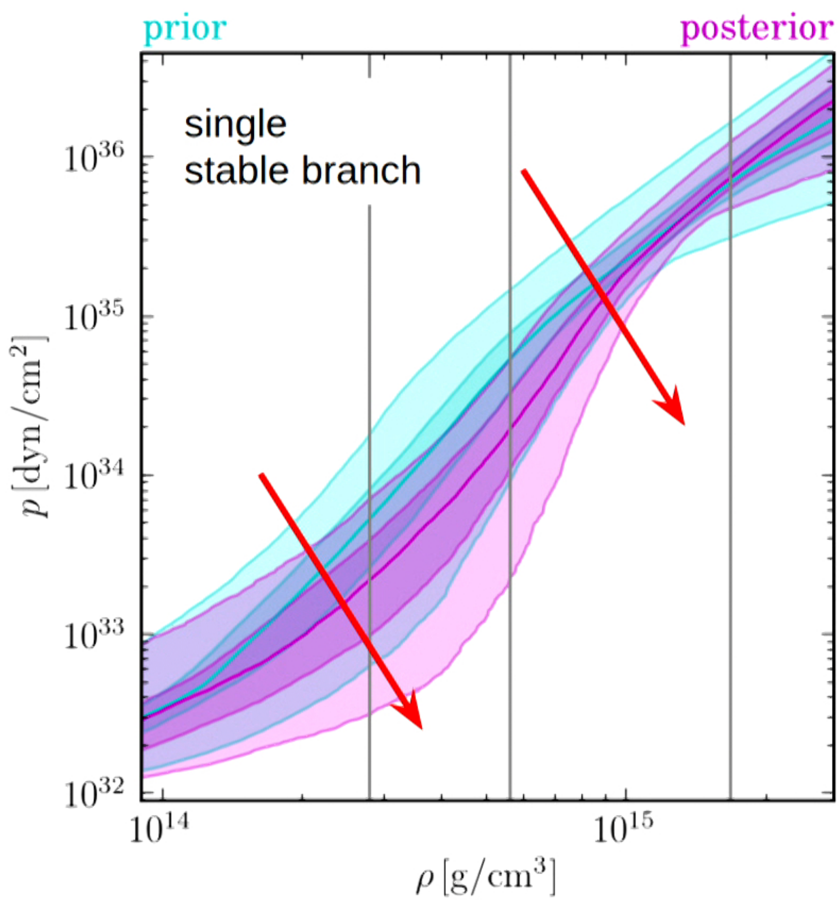
generic NS observables

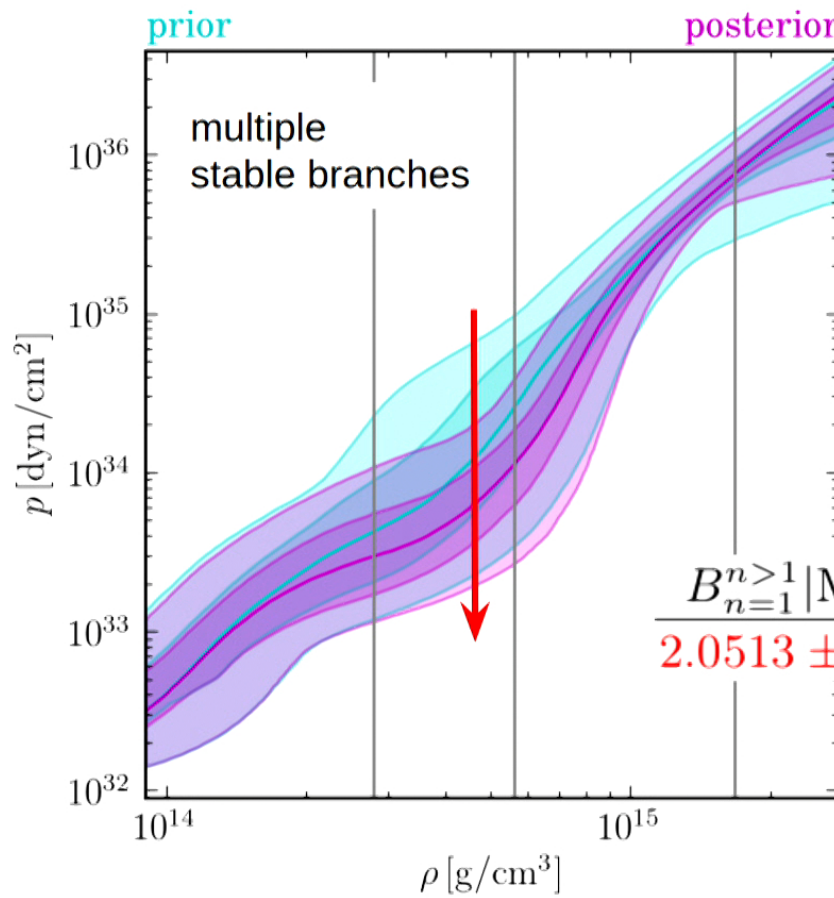




NS composition

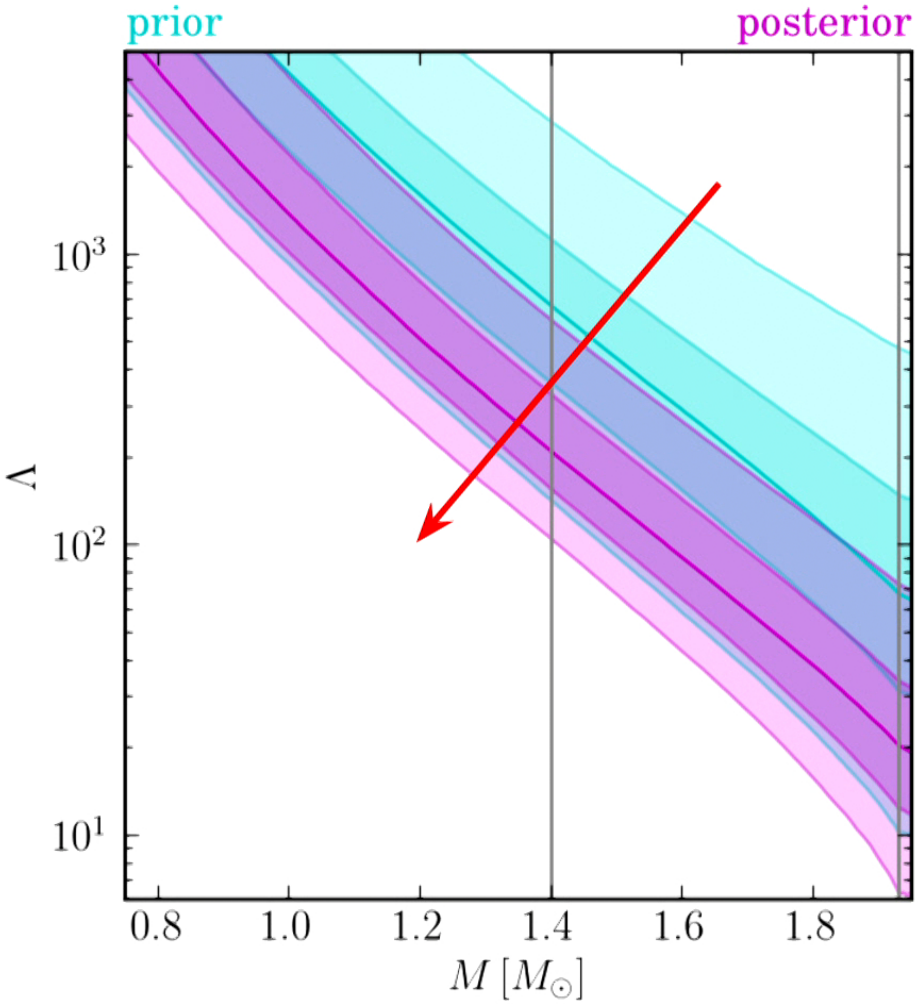
$P(\text{Hadronic}\|\text{data})$	$P(\text{Hyperonic}\|\text{data})$	$P(\text{Quark}\|\text{data})$
28%	16%	56%

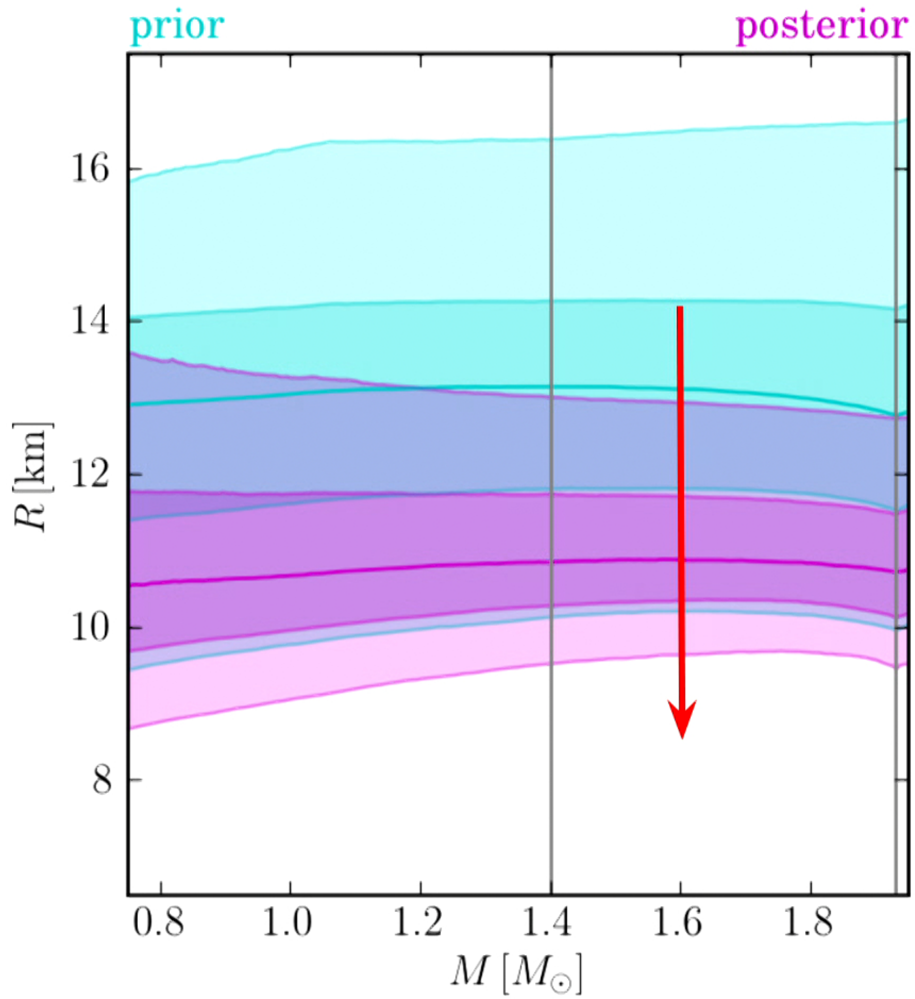




$B^{n>1}_{n=1}\|\text{Marginalized}$
$2.0513 \pm (9.5 \times 10^{-3})$

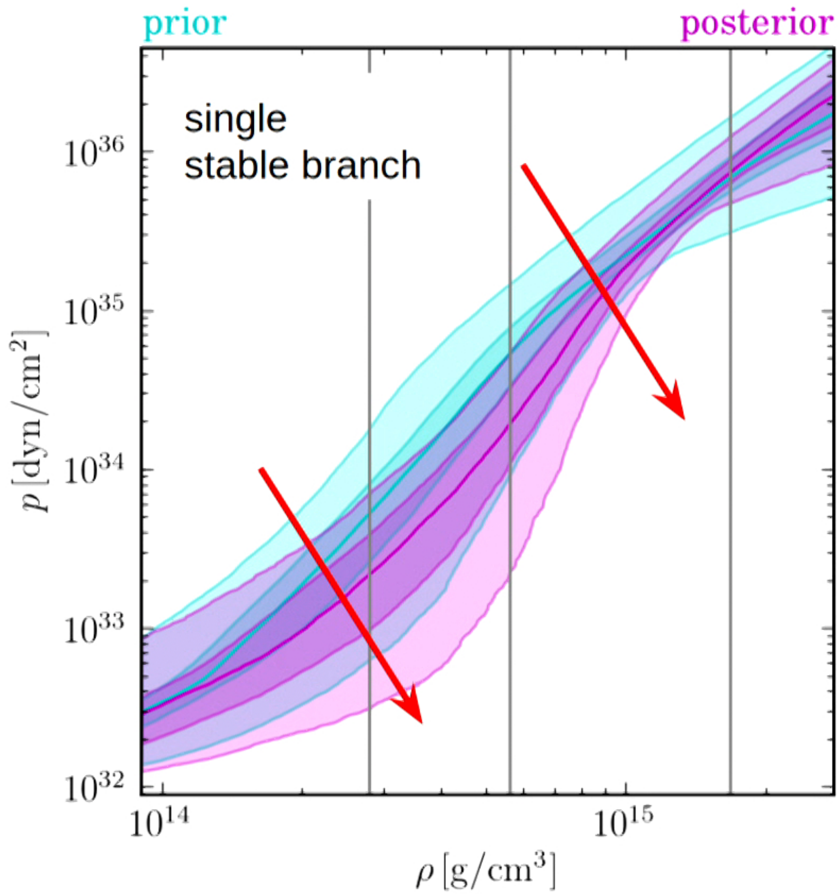
generic NS observables

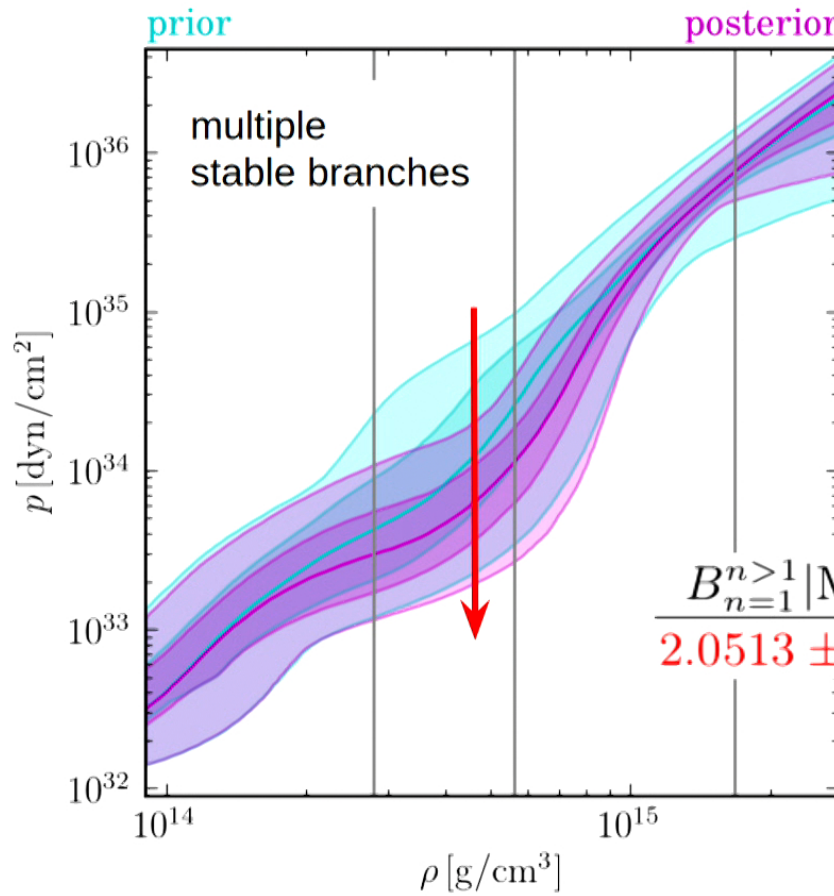




NS composition

$P(\text{Hadronic}\|\text{data})$	$P(\text{Hyperonic}\|\text{data})$	$P(\text{Quark}\|\text{data})$
28%	16%	56%





$B^{n>1}_{n=1}\|\text{Marginalized}$
$2.0513 \pm (9.5 \times 10^{-3})$

goals

- Self-consistently incorporate information from arbitrary tabulated EOS models
  - condition prior directly on proposed EOS

- Automatically incorporate causality constraints and thermodynamic stability
  - auxiliary variable:

$$\phi = \log\left(c^2 \frac{d\mu}{dp} - 1\right) \qquad 0 \leq dp/d\mu \leq c^2$$

- Allow for large amounts of model freedom
  - Gaussian process formally supports any possible ϕ

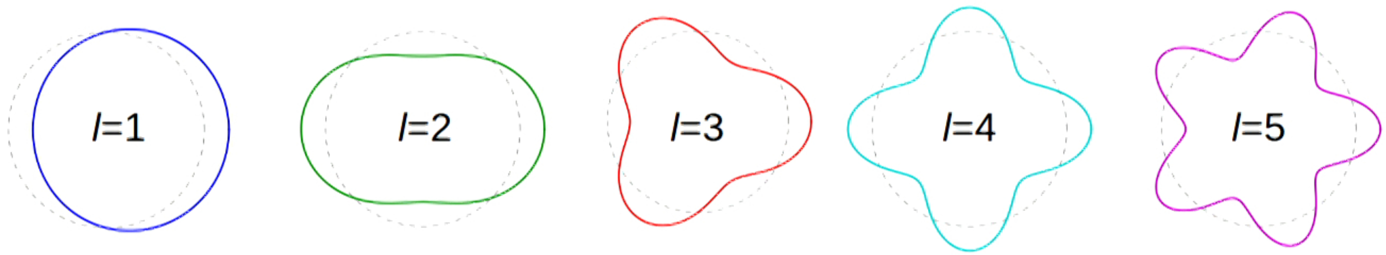
- Incorporate transparent priors
  - configurable “confidence” in tabulated EOS
  - different uncertainty at different pressures
    - small uncertainty near the crust
    - large uncertainty near the central core

  } determined by the *covariance kernel*

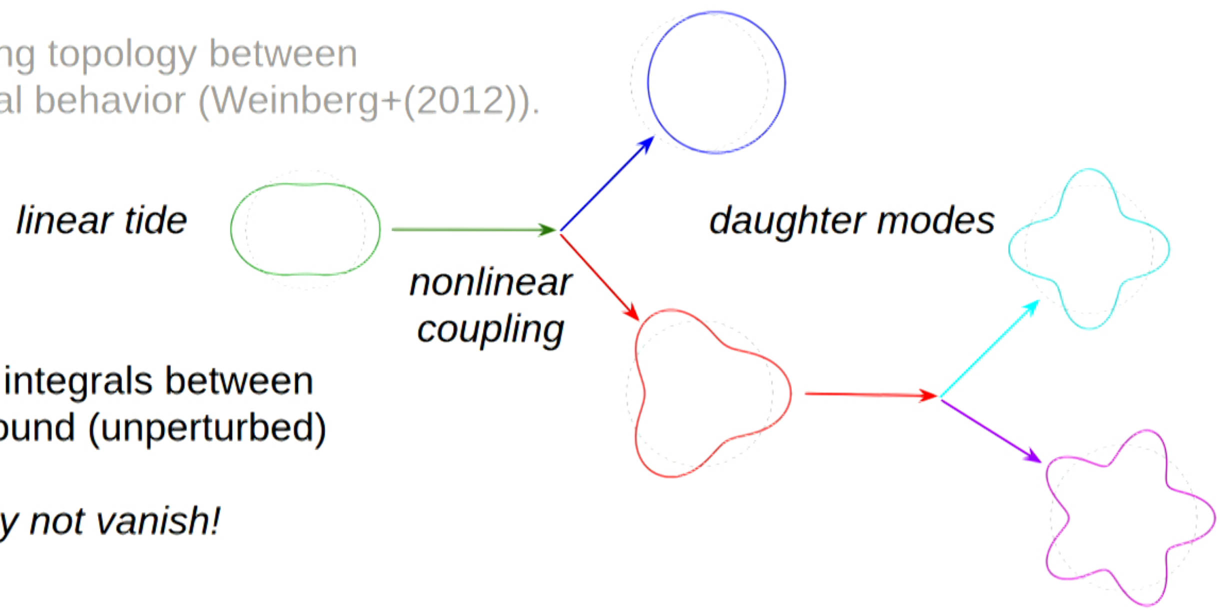
Constraining Nonresonant Fluid Instabilities in Degenerate Stars with Gravitational Waves

multi-mode interactions

equations of motion for mode amplitudes can be described via a Galerkin decomposition based on the linear eigenmodes.



generally produces a complicated coupling topology between modes, which can produce rich dynamical behavior (Weinberg+(2012)).



coupling strength determined by overlap integrals between mode shapes with respect to the background (unperturbed) stellar structure.

- *integrals over 3+ mode shapes may not vanish!*

survey of dynamical tidal effects

(nonresonant) *p-g* secular instabilities

- instability of the *linear tidal bulge* coupled to a *high-frequency p-mode* and a *low-frequency g-mode* (Weinberg+(2012)).
- present in degenerate stars because *p*- and *g*-mode propagation regions overlap significantly.
  - coupling coefficients in the Galerkin decomposition can be large.
  - could be important for compact systems containing *either* Neutron Stars or White Dwarfs.
- *nonresonant* and active whenever the linear tidal perturbation is above some threshold.
  - equivalently, when orbital separation is below some threshold or when orbital frequency is above some threshold.
  - 4-mode couplings are also important (Venumadhav+(2016)) and can dynamically cancel part of the instability, but an instability still exists for dynamical tidal fields.
  - finite-frequency and other non-adiabatic effects on mode shapes spoil the cancellation between 3- and 4-mode interactions, resulting in smaller but still possibly relevant growth timescales (Weinberg (2016)).
- *difficult to simulate*
  - spatial grid required to resolve high-order *g*-modes is prohibitively expensive.
  - larger number of relevant coupled modes makes Galerkin amplitude equations difficult to simulate.

survey of dynamical tidal effects

(nonresonant) *p-g* secular instabilities

- phenomenological model
  - dissipation by *p-g* instability modifies orbital evolution and Gravitational-Wave phase (Essick+(2016)).

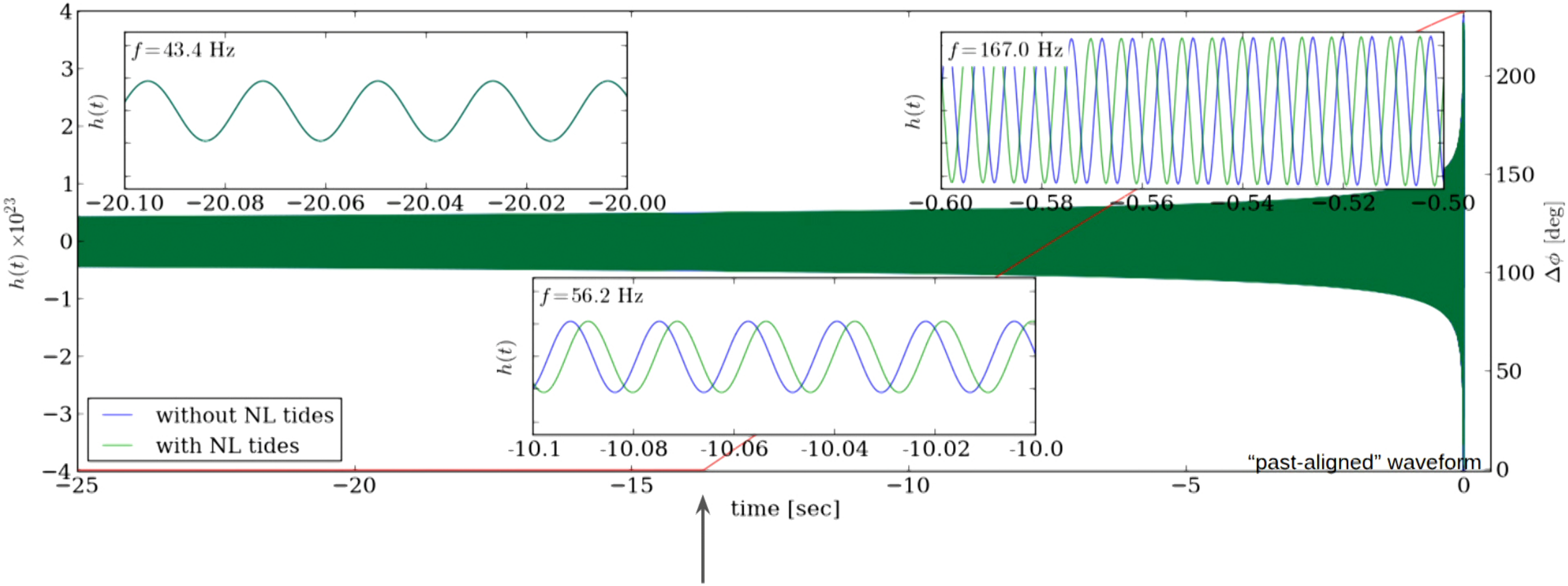
A_0: overall amplitude of induced phase shift

f_0: saturation frequency ~ instability threshold *assuming modes grow quickly*

n_0: scaling of energy dissipated as a function of frequency

survey of dynamical tidal effects

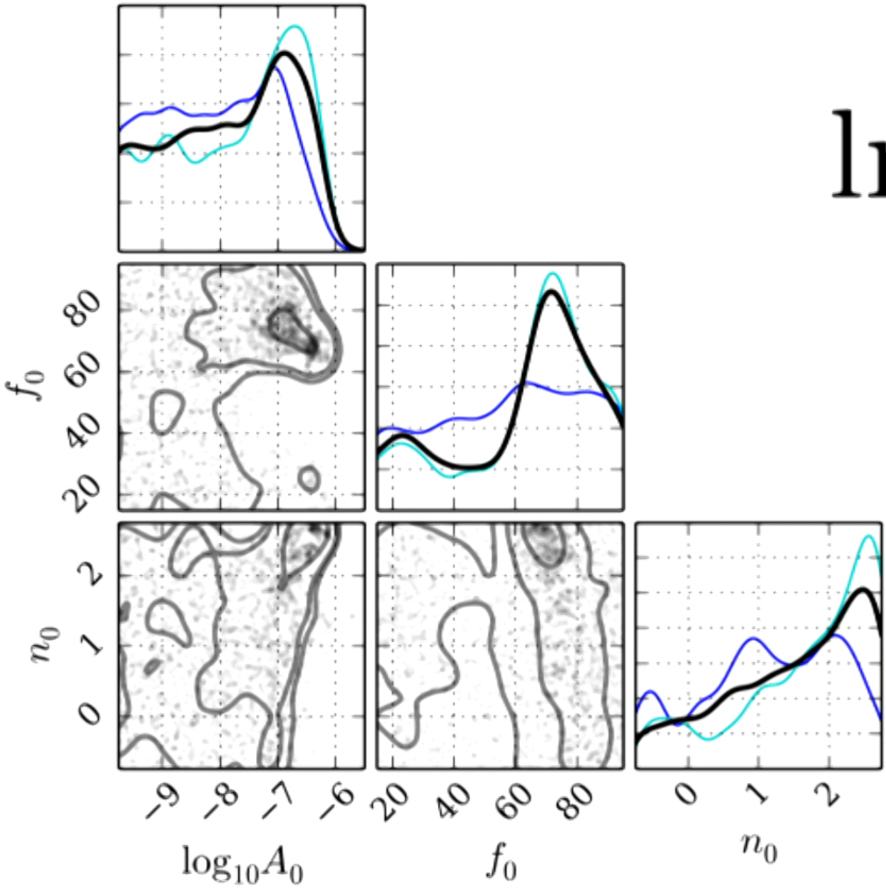
(nonresonant) *p*-*g* secular instabilities



p-*g* instability turns on at

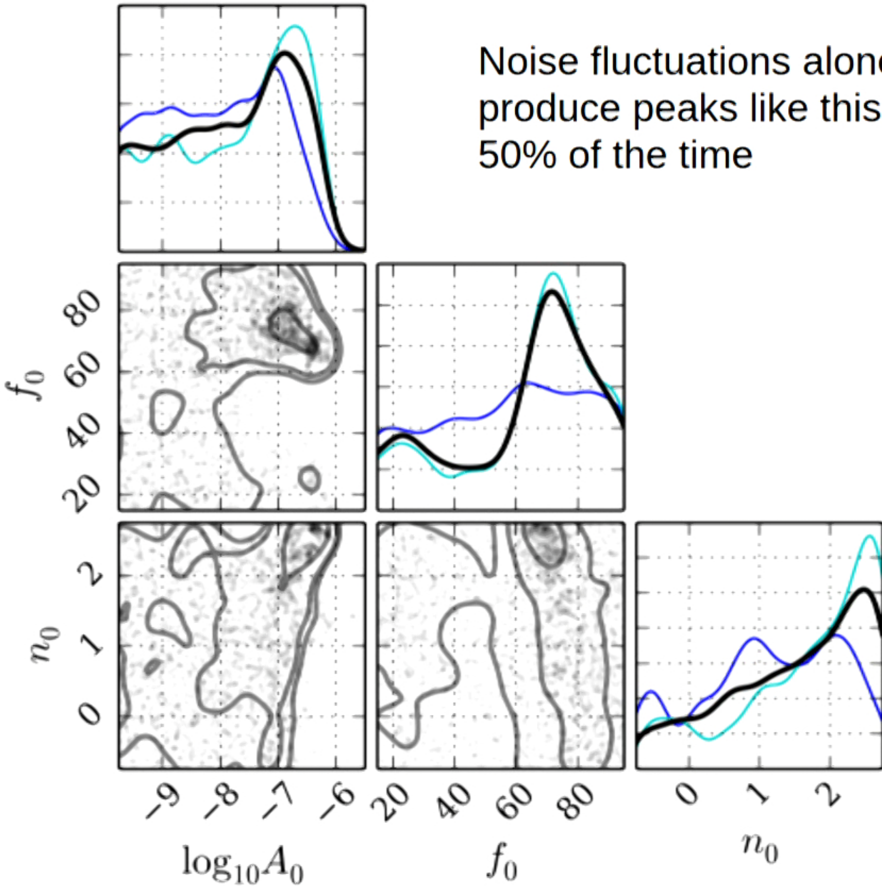
f_{GW} ~ 50 Hz

p-*g* instabilities with GW170817

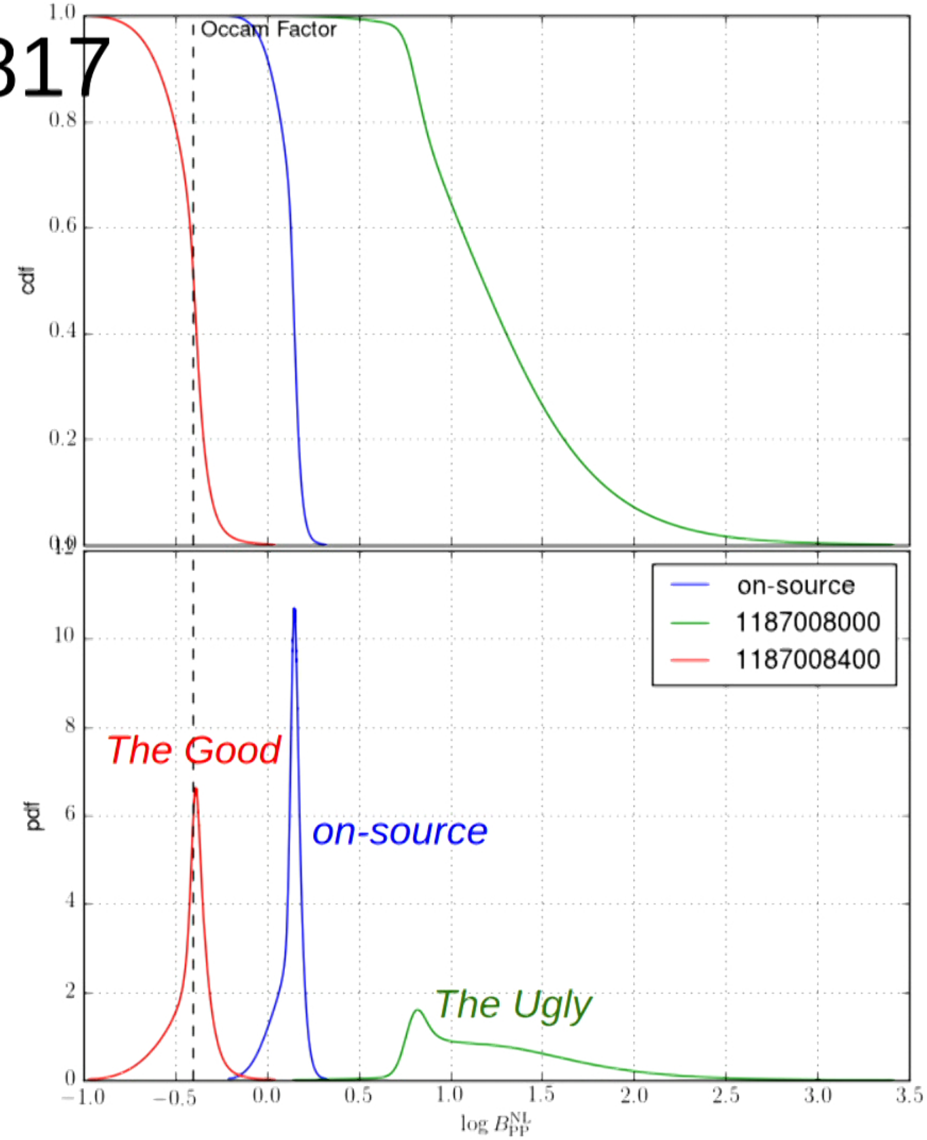


$$\ln B^{pg}_{!pg} = 0.03^{+0.70}_{-0.58}$$

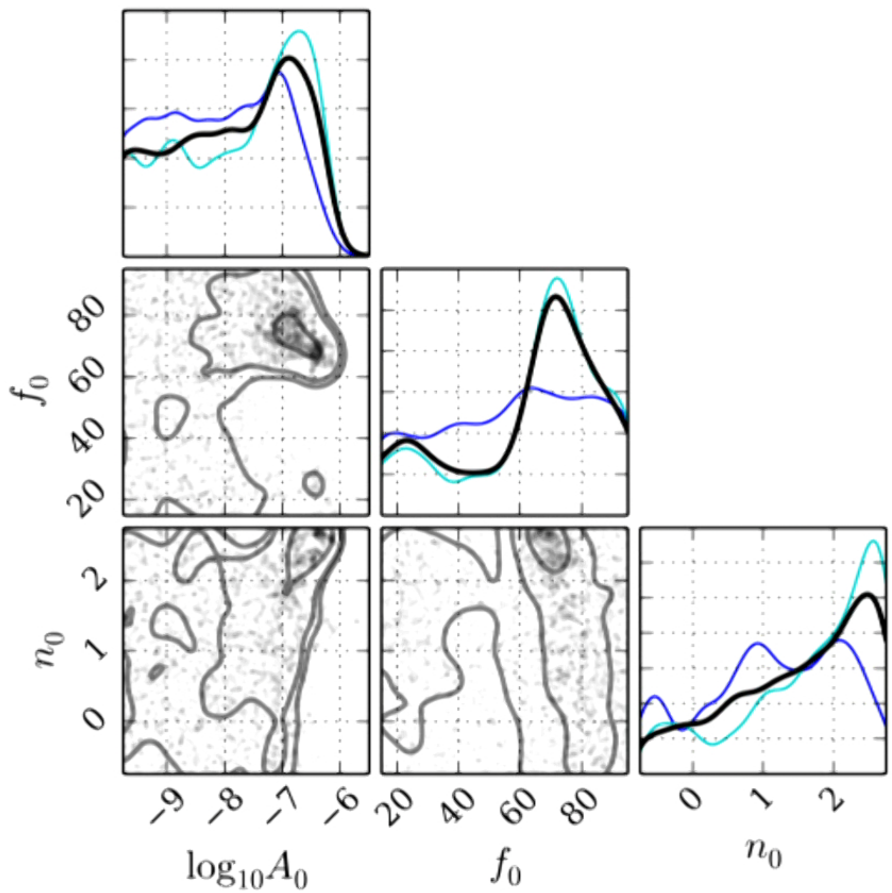
p-*g* instabilities with GW170817

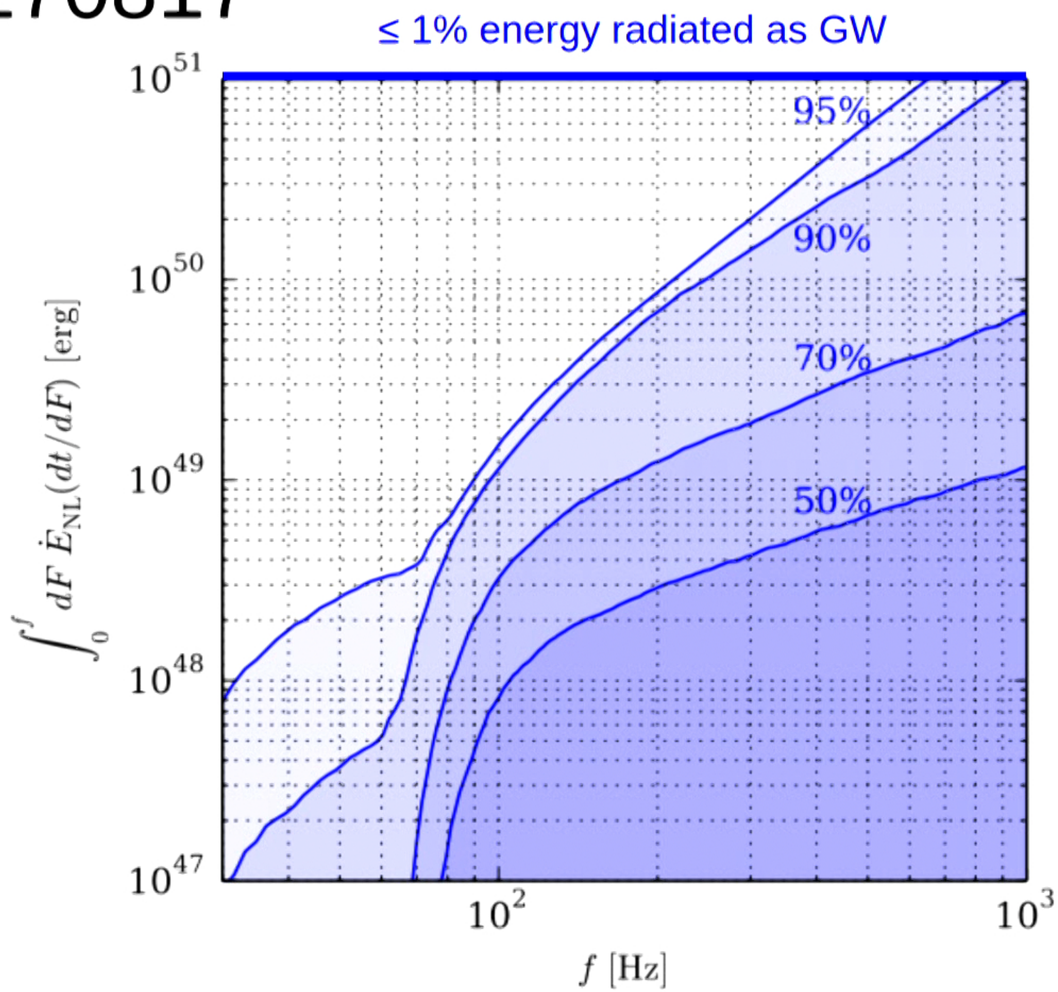


Noise fluctuations alone will produce peaks like this roughly 50% of the time



p-g instabilities with GW170817





survey of dynamical tidal effects

where does this leave (nonresonant) *p-g* secular instabilities?

With GW170817, **log*B* > 0**

- "Peaks in posteriors" occasionally line up in the single-IFO runs

Result appears **completely consistent with GR + Gaussian noise**

- There are peaks in the posterior, which are occasionally large
  - these occur due to Gaussian Noise as well

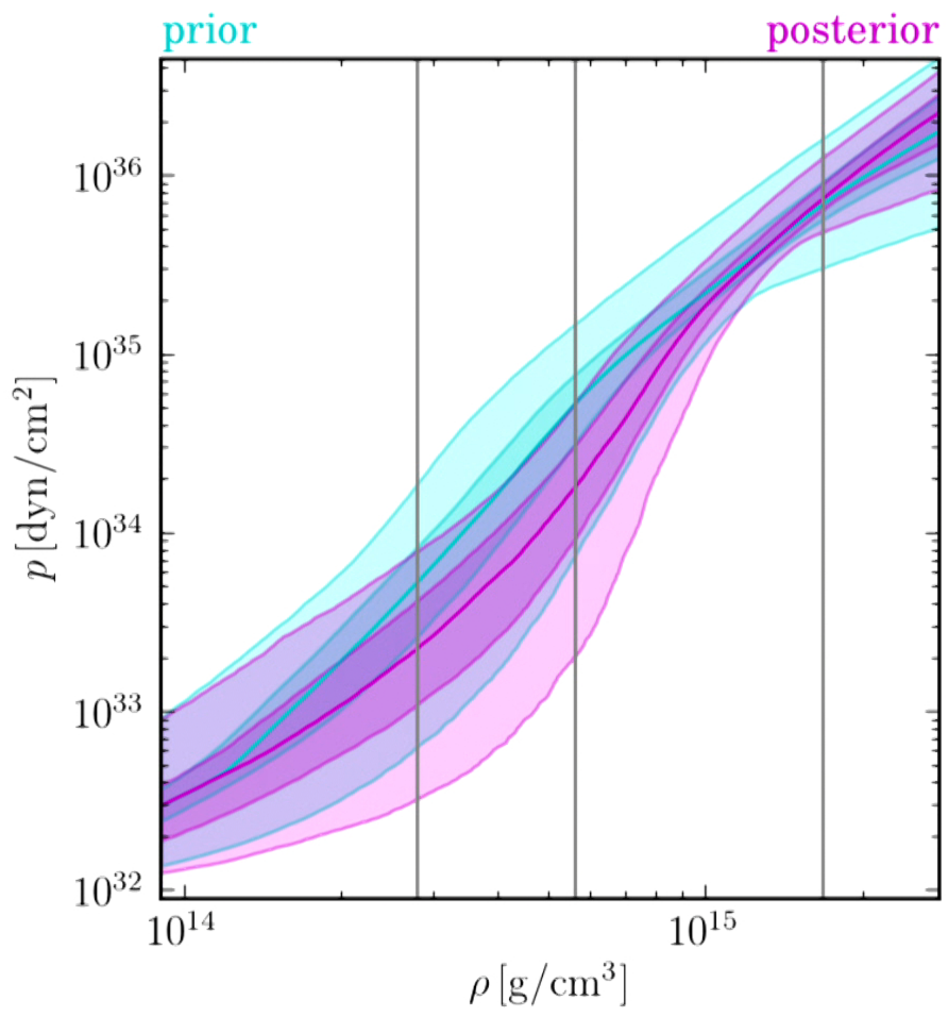
Constraints on the amount of energy dissipated by the *p-g* instability

- Results are **still consistent with a wide range of NL parameters**
  - We haven't really constrained the theory space all that much…

can EOS constraints help?

linear resonant tides

- *yes!*
- knowledge of the EOS specifies the mode spectra and shapes.
- but these effects are likely to be negligible anyway...



References

LVC. *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*. PRL **119**, 161101 (2017).

R. Essick. *Detectability of dynamical tidal effects and the detection of gravitational-wave transients with LIGO*. PhD Thesis, MIT (2017).

LVC and N. Weinberg. *Constraining the p-mode--g-mode Tidal Instability with GW170817*. PRL **122**, 061104 (2019).

P. Landry and R. Essick. *Nonparametric Inference of the Neutron Star Equation of State from Gravitational Wave Observations*. PRD **99**, 084049 (2019).

Appearing soon!

R. Essick, P. Landry, and D. Holz. *Nonparametric Inference of Neutron Star Composition, Equation of State, and Maximum Mass with GW170817*.

I also work on GW data quality/detector characterization with machine learning, detector calibration using astrophysical sources, and population inference with many (multi-messenger) sources. Ask me about any of this or general GW stuff at any time!