Future prospects for distinguishing neutron stars from black holes using only gravitational waves

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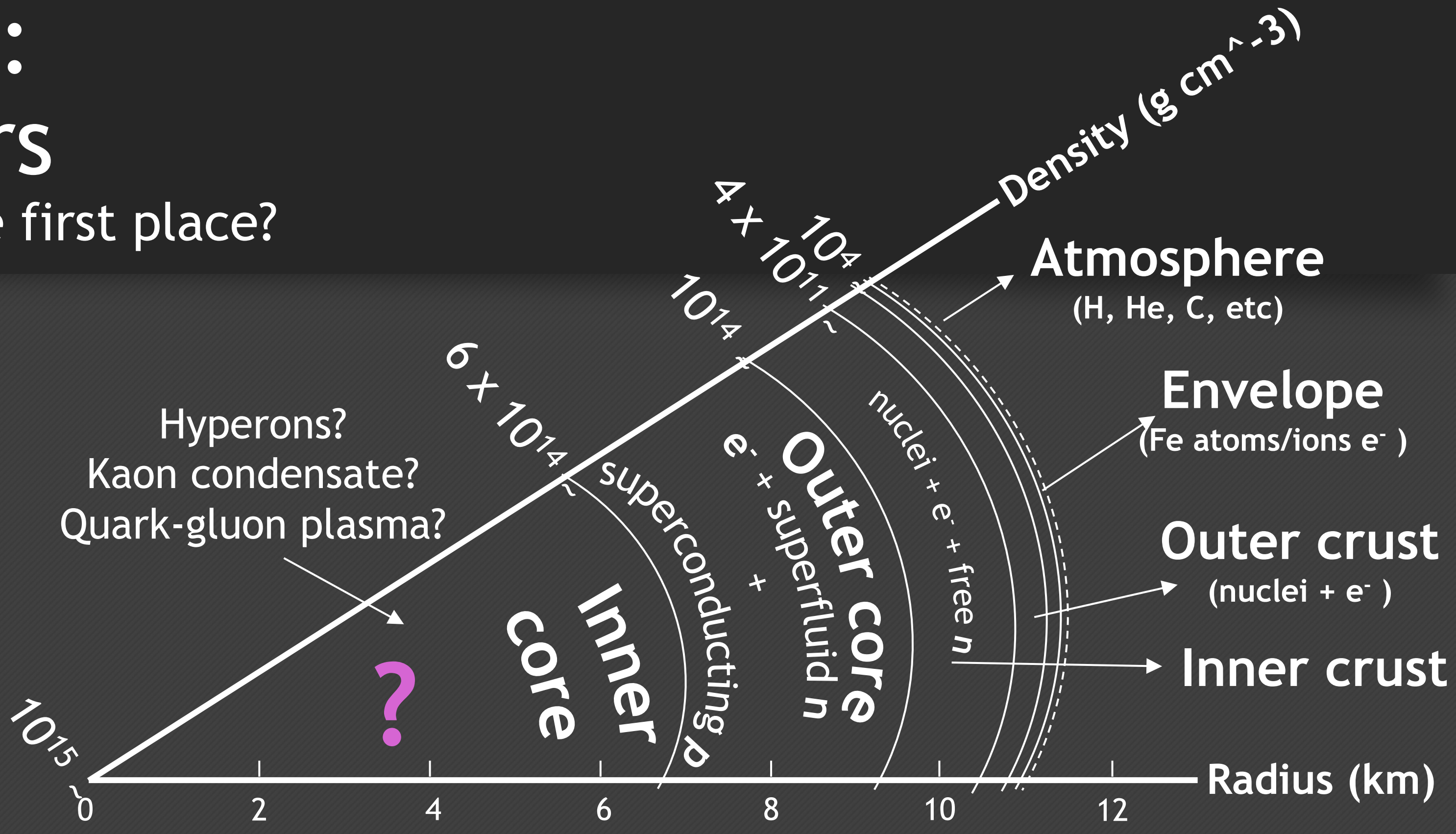
Introduction: Neutron Stars

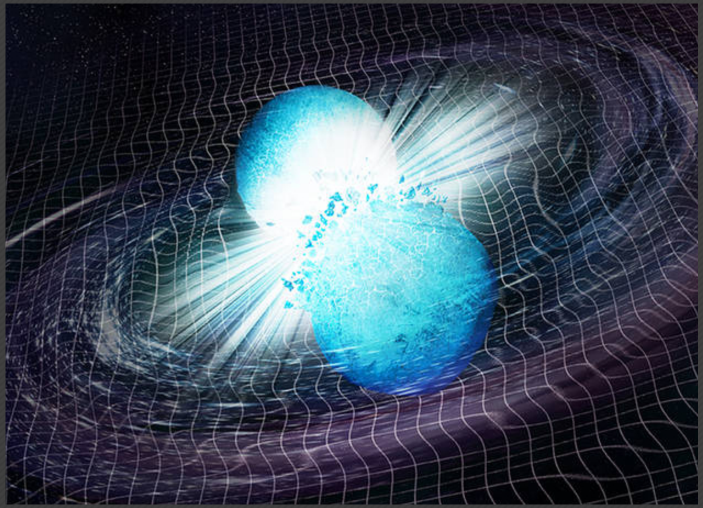
Why do we care in the first place?



- Neutron stars contain ultra-dense matter which makes them unique nuclear physics laboratories
- The exact equation of state (EOS) for nuclear matter is unknown

Nandi, Rana & Bandyopadhyay, Debades. (2012). Magnetised Neutron Star Crusts and Torsional Shear Modes of Magnetars. Journal of Physics Conference Series. 420. 10.1088/1742-6596/420/1/012144.

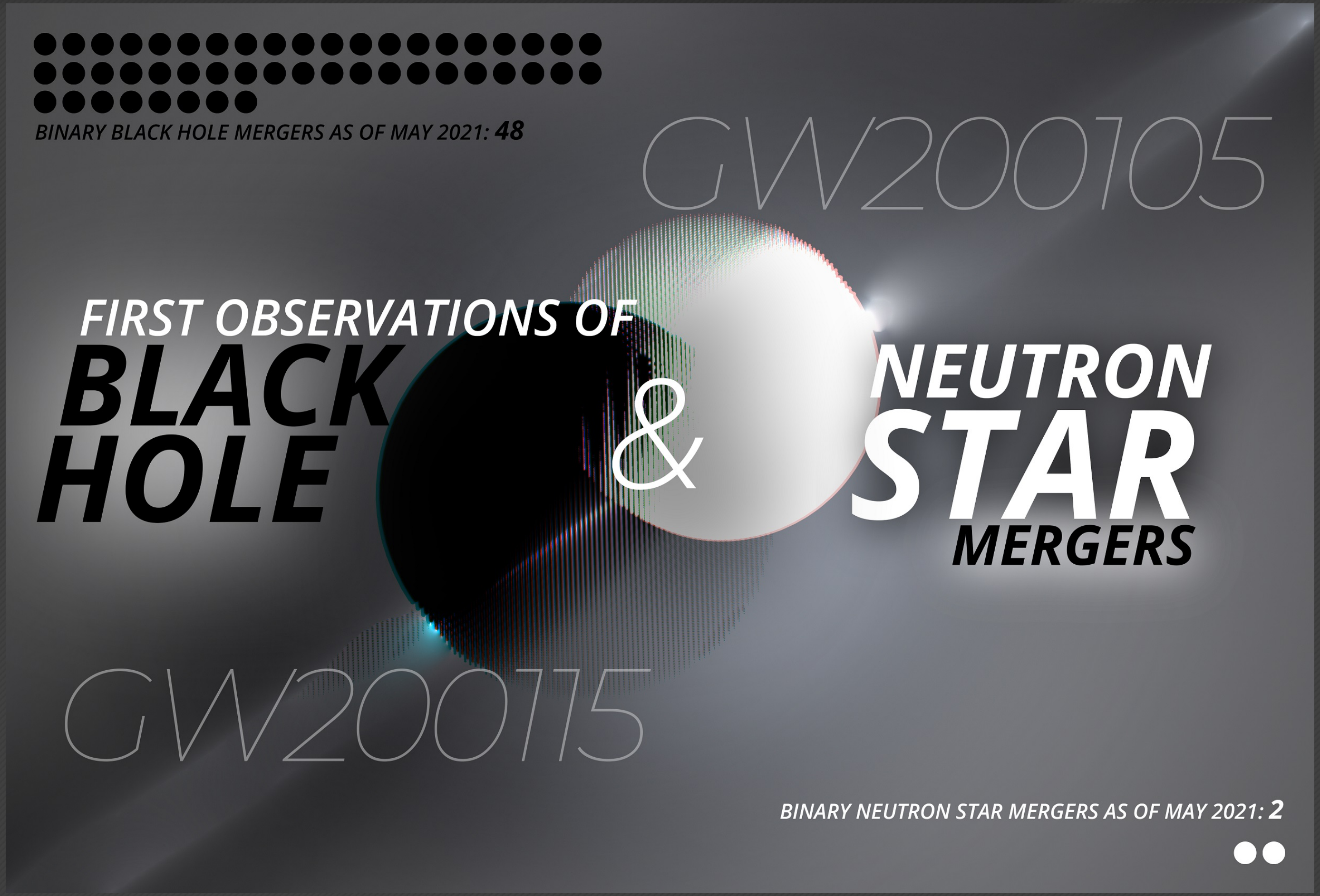
Introduction: Gravitational Waves



- GW170817 opened up a new way study neutron stars
- Gravitational wave data has added to our knowledge of neutron stars
  - Placing upper bound of neutron star radius and tidal deformability
- GW170817 alone could not prove that the event was a BNS and not a BBH
- Coincident GRB 170817A and transient electromagnetic follow-ups provide evidence for the presence of neutron star matter

Neutron Star Black Hole Systems

- In June 2020, the LVC announced detection of two NSBH systems: GW200105 and GW200115
- Only the mass of the smaller object indicates it's a NSBH

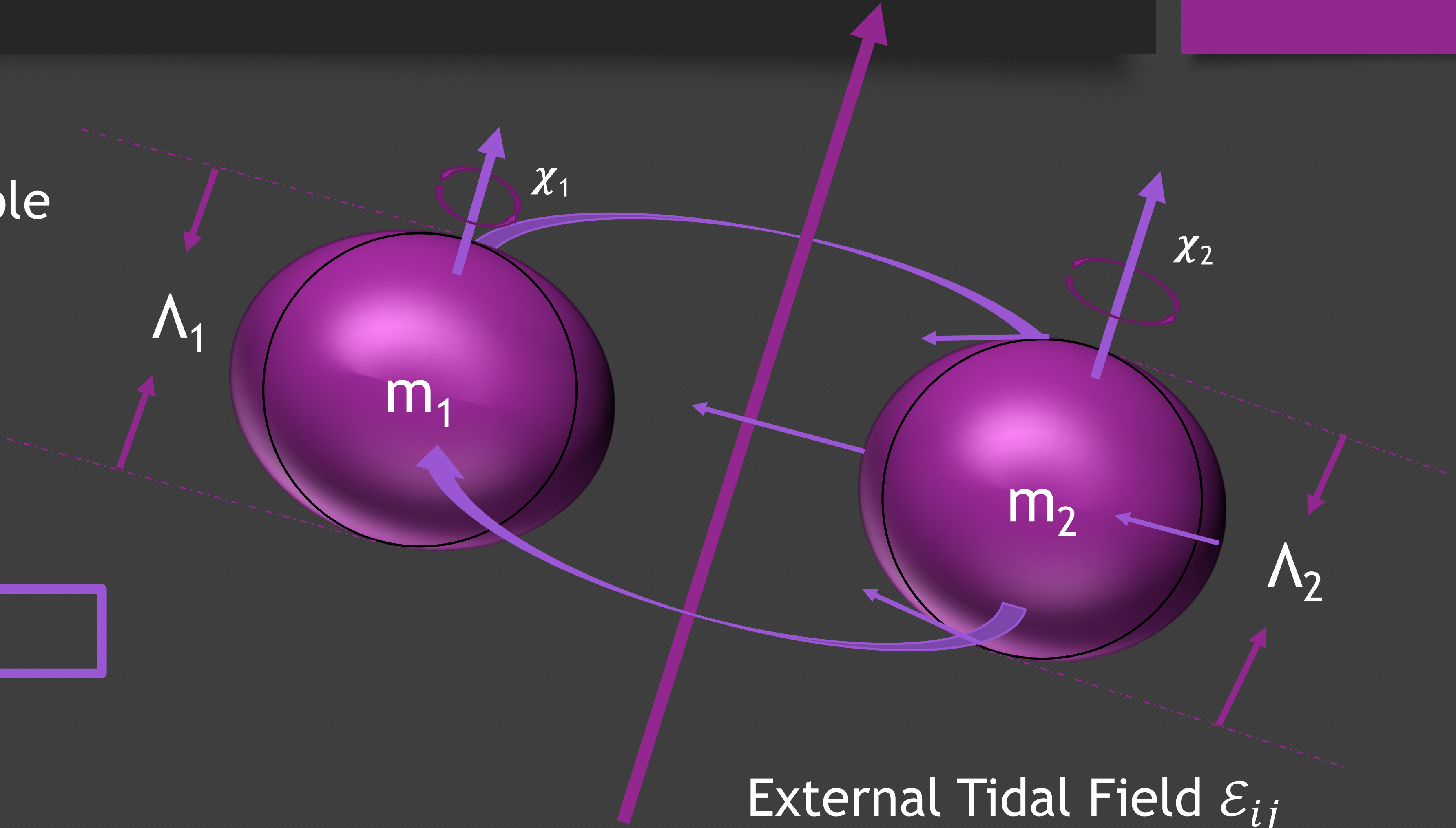


Credit: Carl Knox, OzGrav/Swinburne University.

Introduction: Tidal Deformability?

Internal Multipole Response Q_{ij}

$$Q_{ij} = -\lambda\, \mathcal{E}_{ij}$$



External Tidal Field $\mathcal{E}_{ij}$

QUESTIONS

Under what conditions could gravitational wave data distinguish a neutron star from a black hole in a compact object binary

LIGO-Virgo may not be sensitive enough to do so, what about LIGO A+ or LIGO Voyager? Or 3G detectors?

Methods

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1: Injections

1. Simulate data with different parameters and detectors
   - Detectors: aLIGO, LIGO A+, LIGO Voyager, Einstein Telescope, Cosmic Explorer
   - Parameters: black hole mass, distance, equation of state

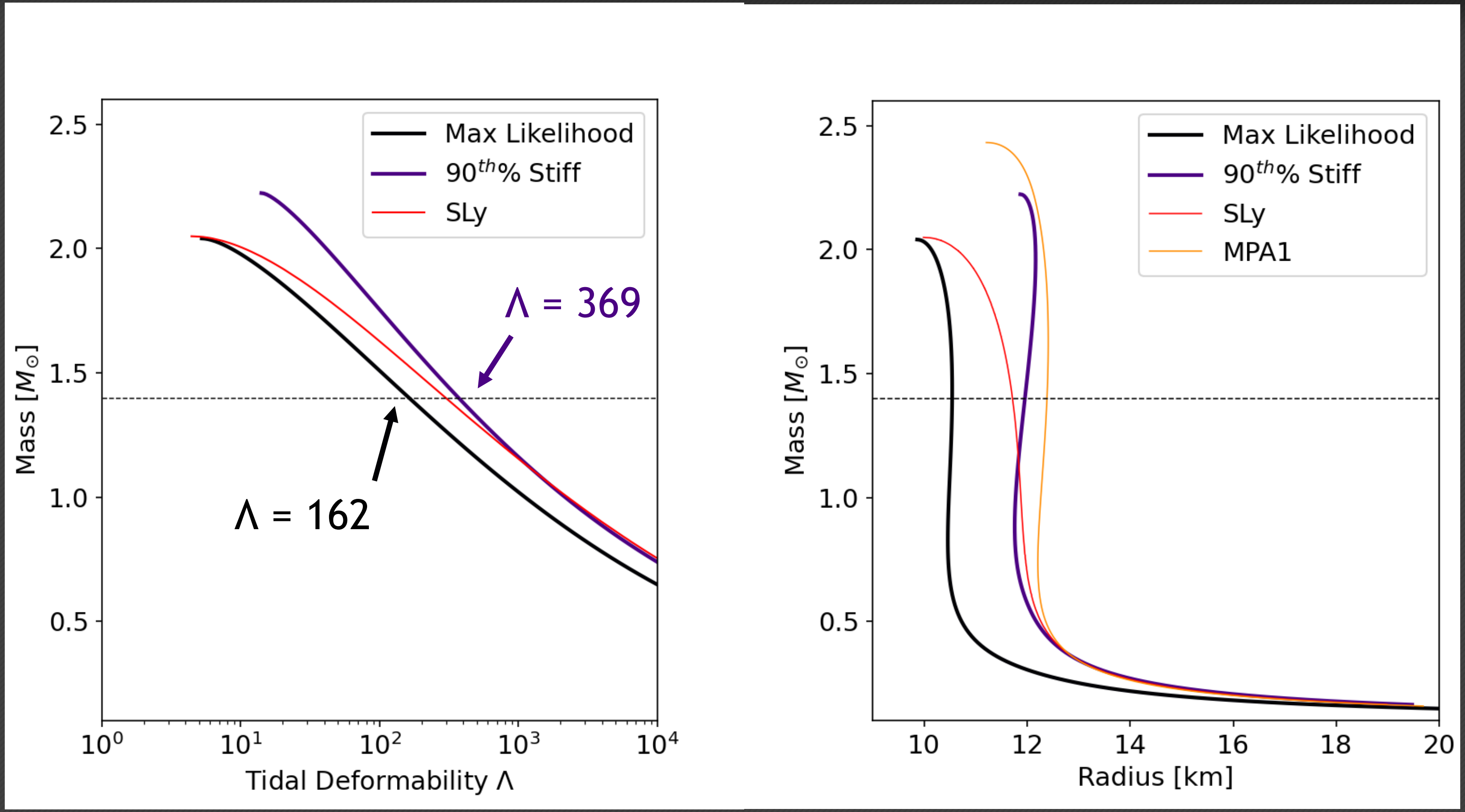
$$d_i(t) = h_i(\vec{\theta}, t) + n_i(t)$$

data

waveform

detector noise

Injections continued

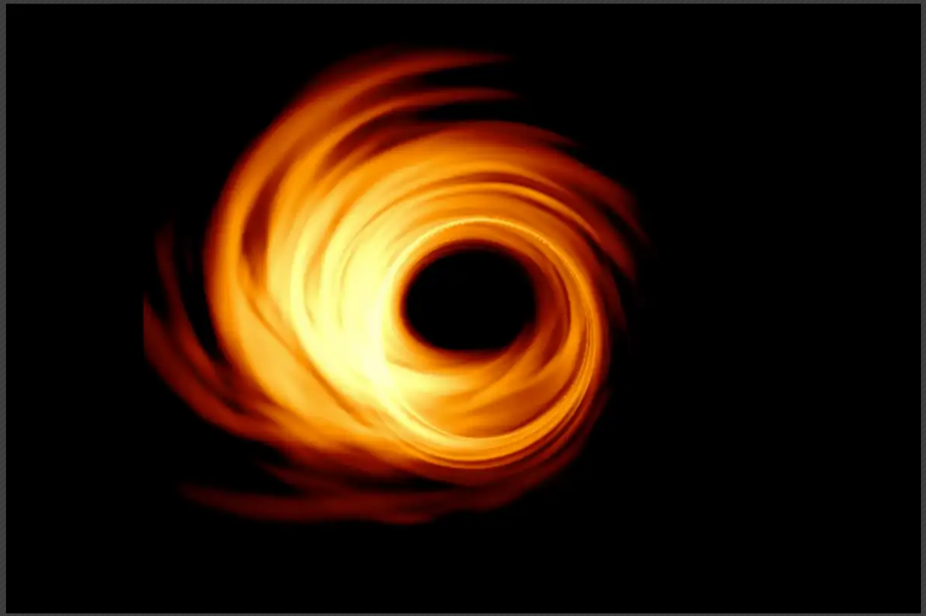


Capano et al 2020

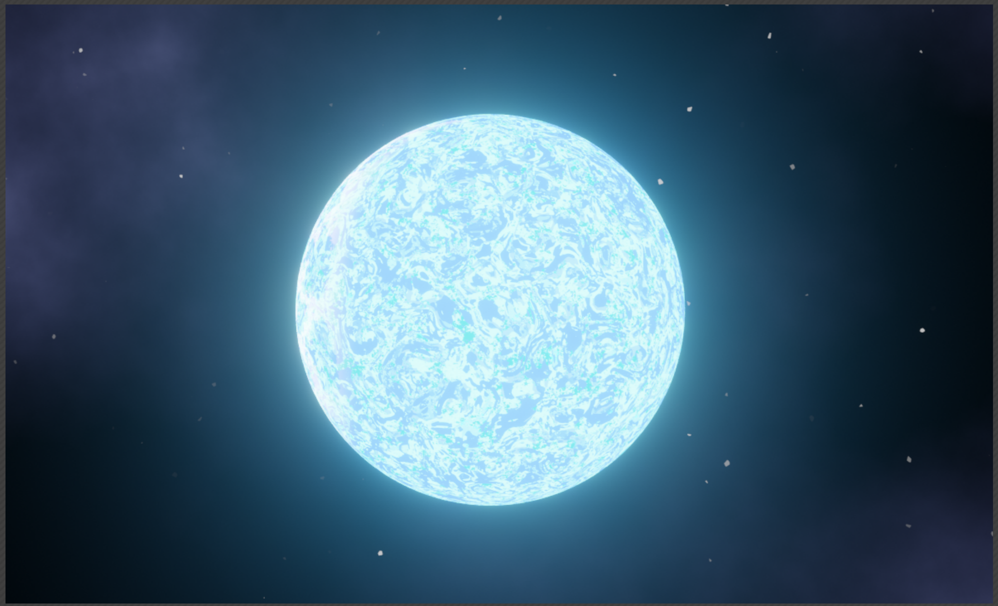
2: Gravitational Wave Data Analysis

Analyze the simulated data twice (once for each model)

Black Hole $\Lambda = 0$



Neutron Star $\Lambda \neq 0$



Bayesian Parameter Estimation

likelihood

prior

$$p(\vec{\vartheta}|\vec{d}(t),h) = \frac{p(\vec{d}(t)|\vec{\vartheta},h)\,p(\vec{\vartheta}|h)}{p(\vec{d}(t)|h)}$$

posterior

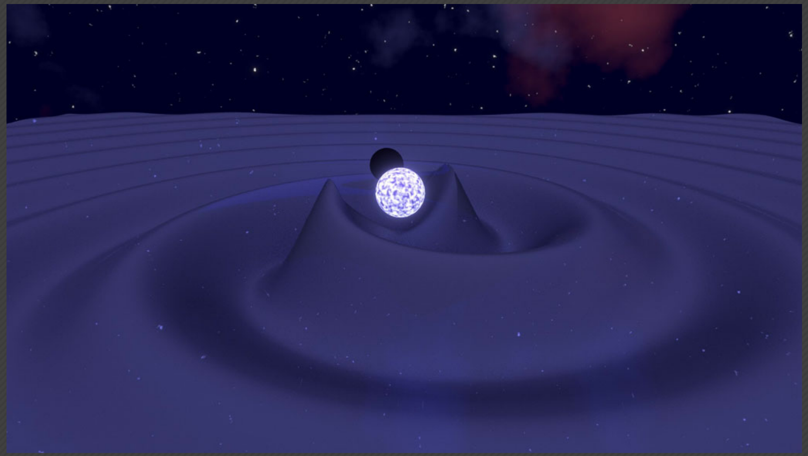
evidence

3: Bayes Factors

$$\mathcal{B} = \frac{p(\boldsymbol{d}|H_{NSBH})}{p(\boldsymbol{d}|\boldsymbol{H}_{\boldsymbol{BBH}})}$$

$\mathcal{B} < 1$

OR



$\mathcal{B} > 1$

Results

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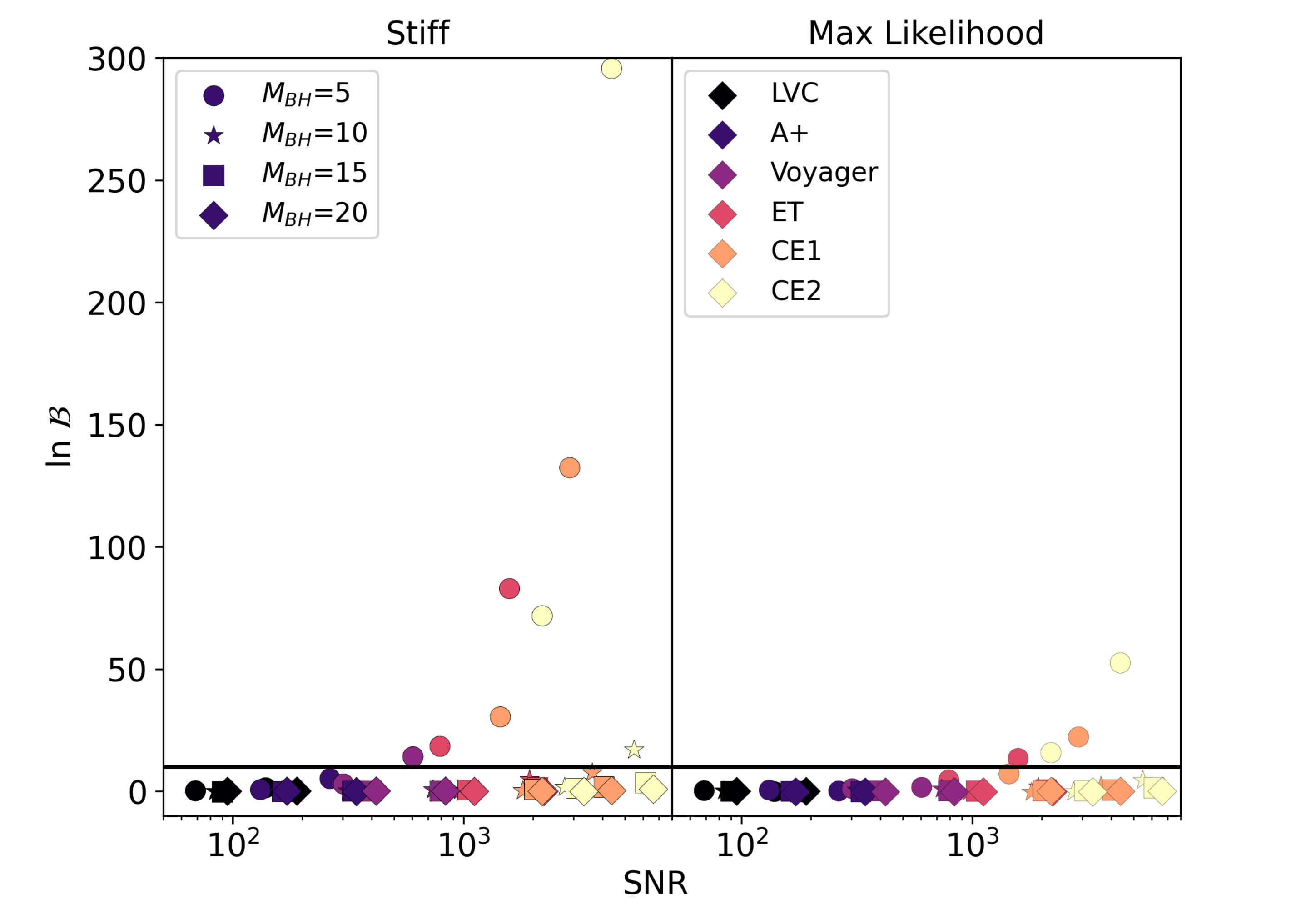
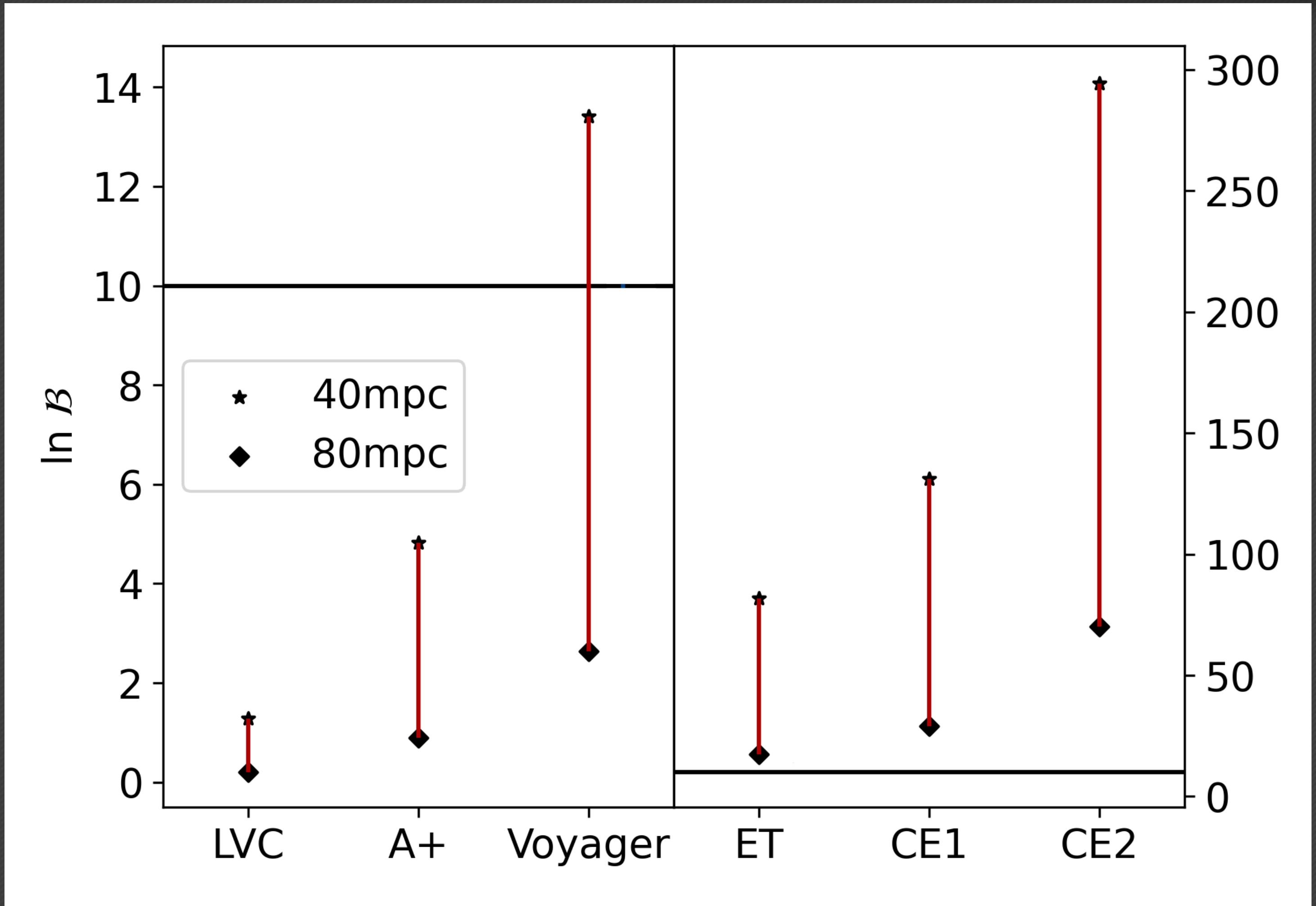
Summary


Stiff
Max Likelihood
300
250
200
150
100
50
0
ln $\mathcal{B}$
M_{BH}=5
M_{BH}=10
M_{BH}=15
M_{BH}=20
LVC
A+
Voyager
ET
CE1
CE2
10^2
10^3
10^2
10^3
SNR

M_{BH} = 5 $M_{\odot}$, Stiff

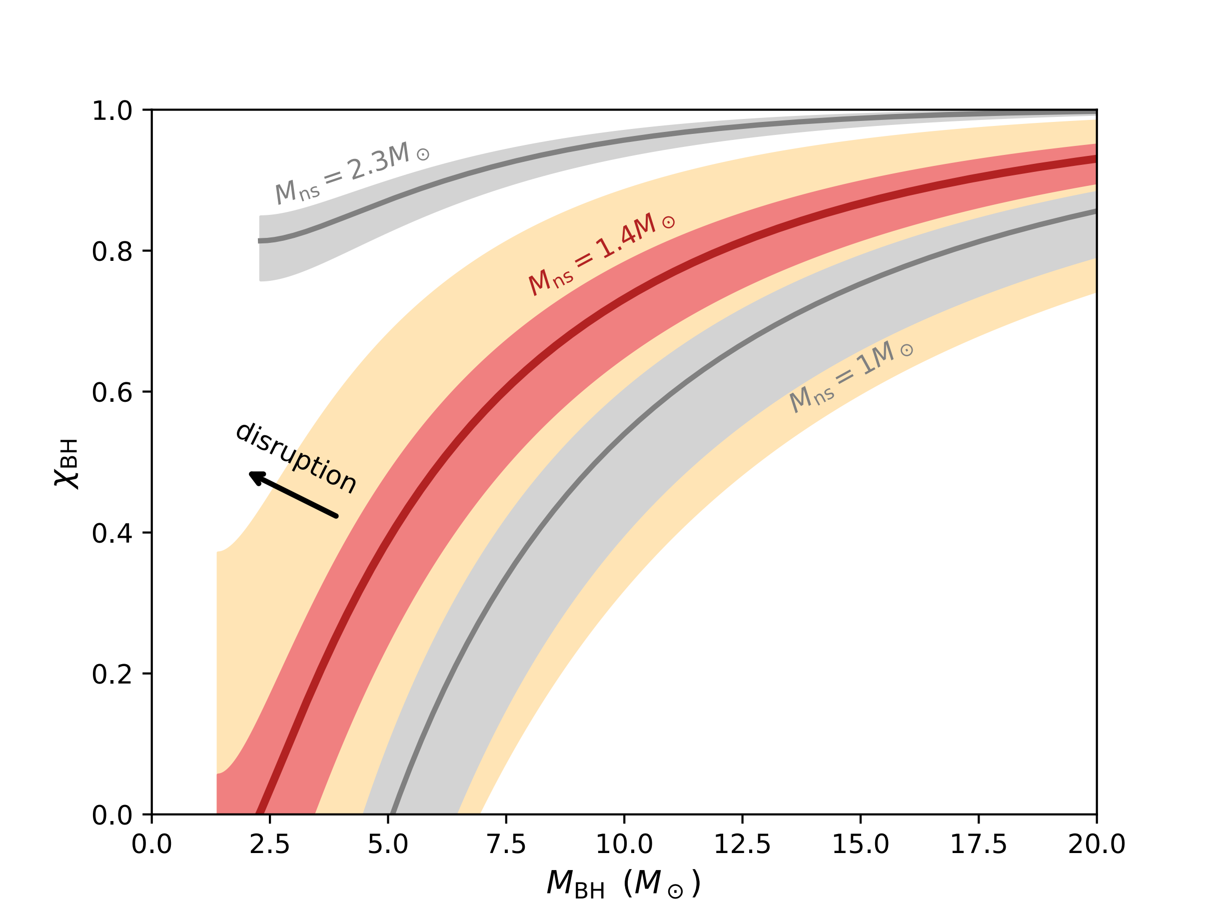


Result Summary

- We find that LIGO-Virgo and its upgrades have very little chance of distinguishing NSBH systems without EM follow up.
- 3G detectors are critical for studying neutron star-black hole mergers without EM counterparts.
- Given that the analysis of GW170817 suggests that NSBH mergers are unlikely to be disrupted by black holes with low to no spin, we find that events like GW190814 with objects in the mass gap will remain a mystery until we have better detectors.

Neutron Star Black Hole systems

- GW confirmation of the existence of neutron matter may especially important for neutron star black hole binaries
- Results GW170817 suggest that average mass neutron stars are unlikely be disrupted
- For mass gap objects (such as GW190814), we would have to rely on the GW signal to tell what sort of object it is



Published as

- Brown, S.M., Capano, C.D., Krishnan, B. Using Gravitational Waves to Distinguish Between Neutron Stars and Black Holes in Compact Binary Mergers. Astrophys J 2022.

Thank you

Questions?

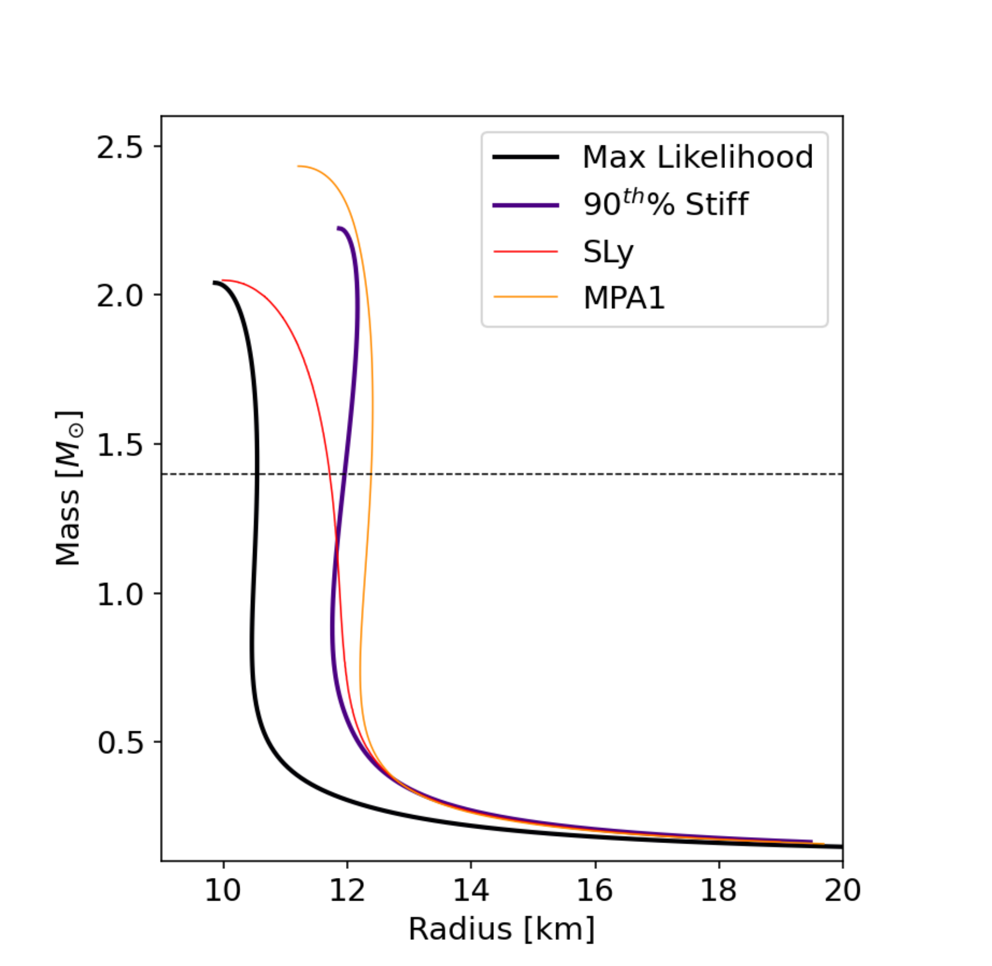
Additional Slides

Injections

- The parameters explored are mass, distance, and equation of state (as a proxy for tidal deformability)
  - All other parameters (such as skyloc) are the same as those for GW170817
- Distance: 40 and 80 Mpc
- Mass
  - Neutron star mass: 1.4 $M_{\odot}$
  - Blackhole mass: 5, 10, 15, and 20 $M_{\odot}$

Injections continued

- Two equations of state are explored. Both are from an analysis of GW170817 in Capano et al.
  - One is the maximum likelihood EOS
  - One is the stiffest equation of state in the 90th percentile credible region.

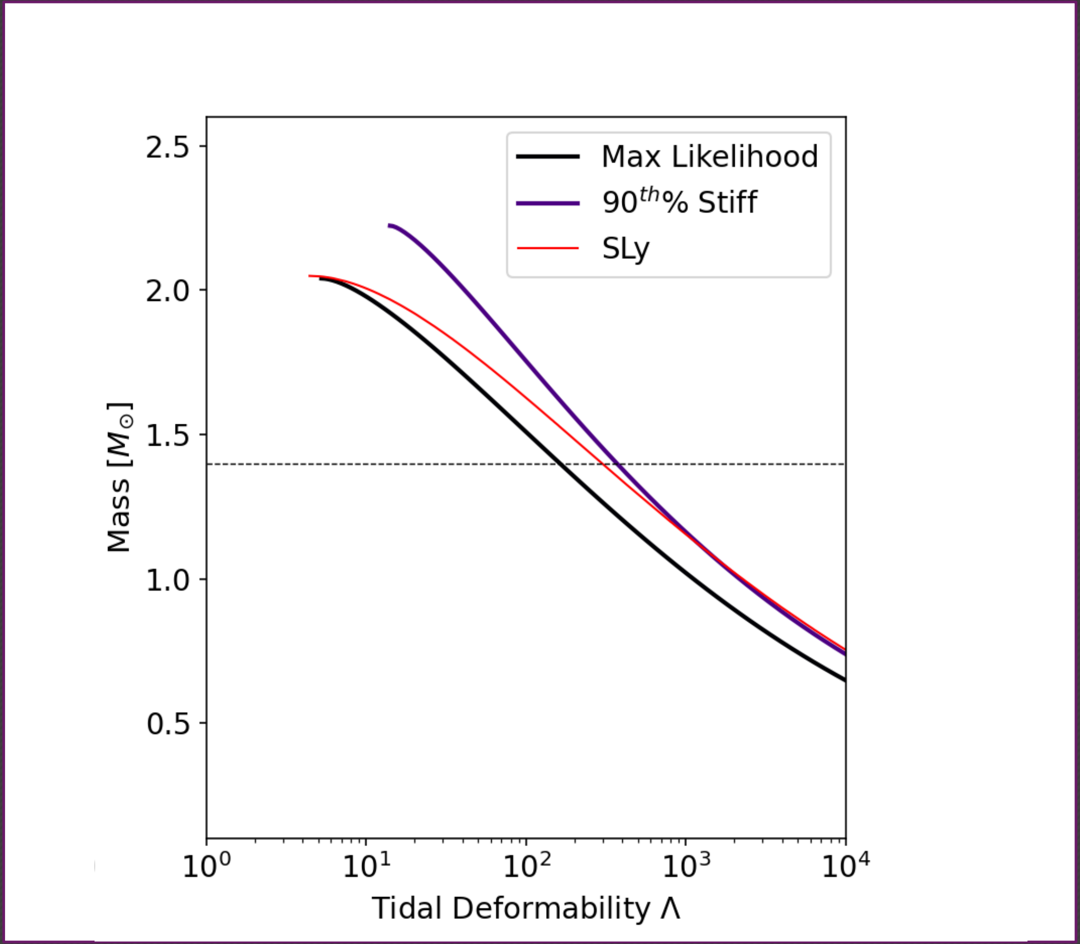


Chiral EFT

- State-of-the-art nuclear physics model
  - uses the most general Lagrangian possible
    - consistent with fundamental theories of nuclear interactions
    - includes pions and nucleons
  - allows for a reliable estimation of theoretical uncertainties

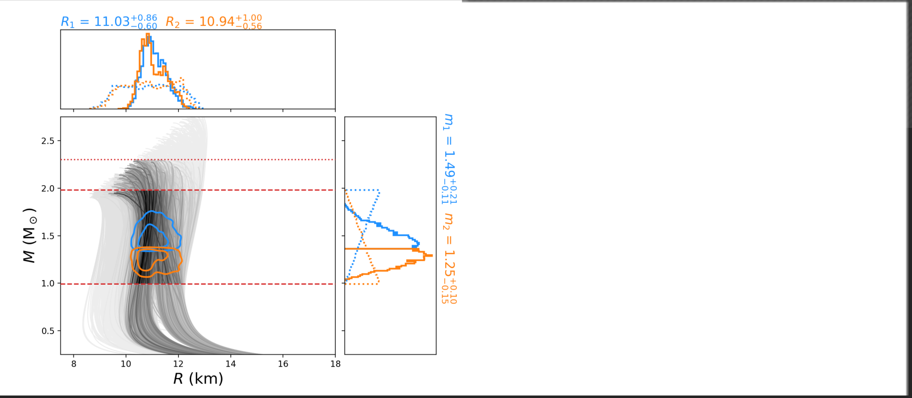
EOS Continued

- For a 1.4 M Neutron star
  - Λ = 162
  - Λ = 369

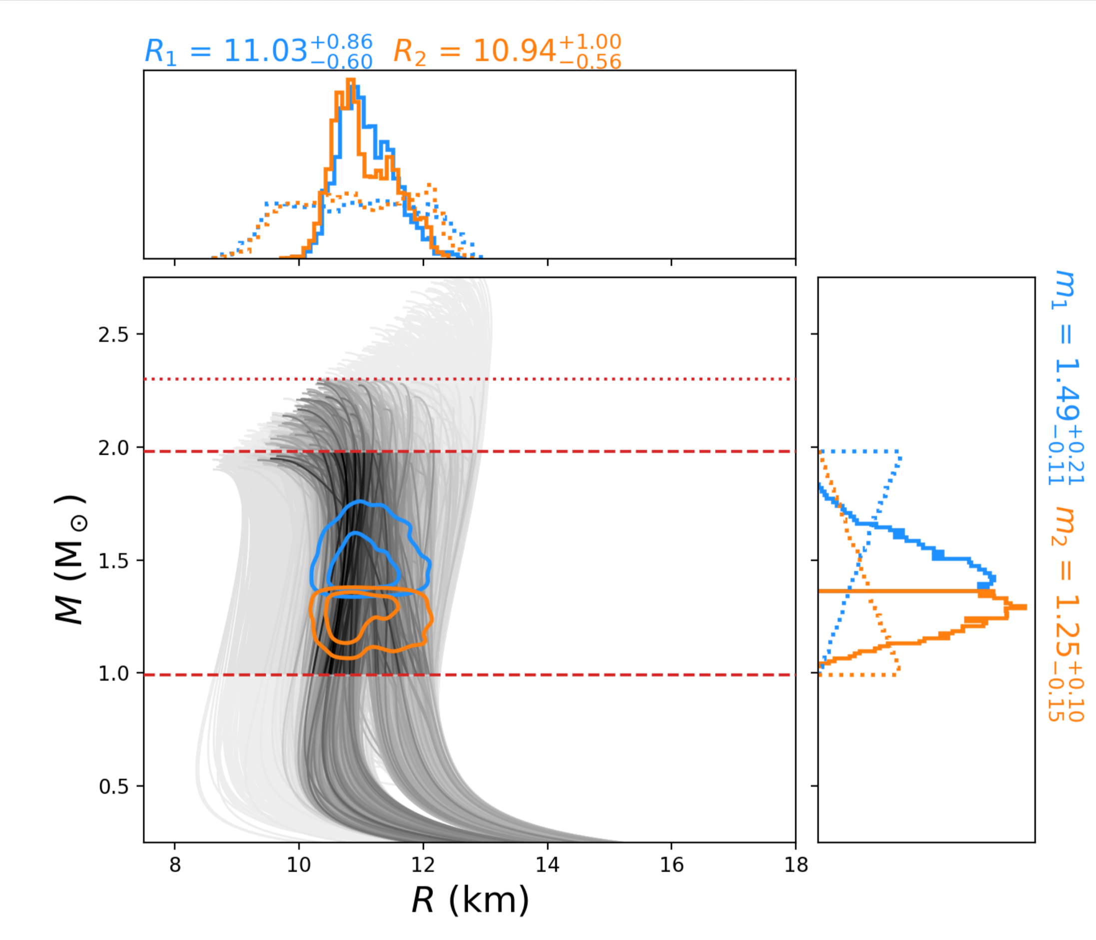


Model 1: Neutron Star Black Hole

- Neutron Star parameter estimation method is the same as Capano et al 2020 (presented here before)
- Available on arxiv: 1908.10352
- I use the same method, so I will review quickly



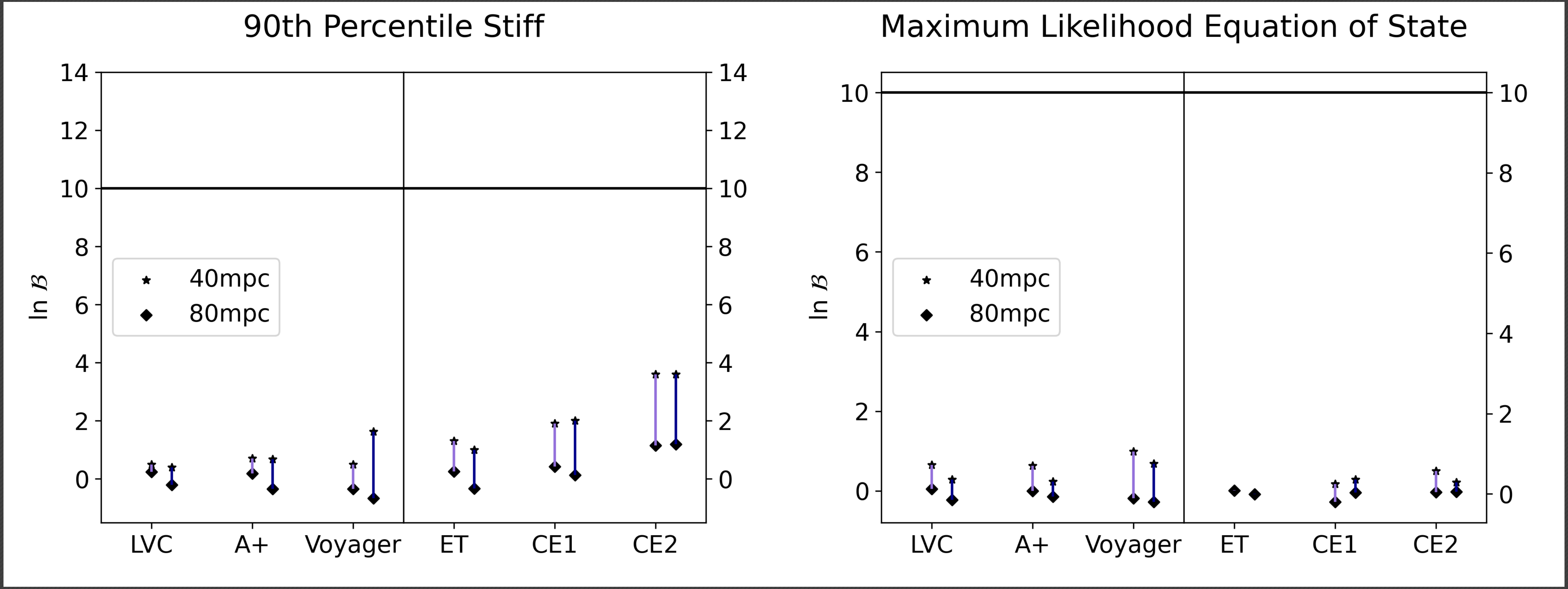
- Sampled EOS space directly in our parameter analysis
- EOS are defined by Chiral EFT up to a transition density. Above that density the EOS are constrained only by the requirement that they are causal, stable, and able to support a neutron star of mass $1.9M_\odot$.
- These equations are designed to be as general as possible and include phase transitions



Parameter Estimation: Priors

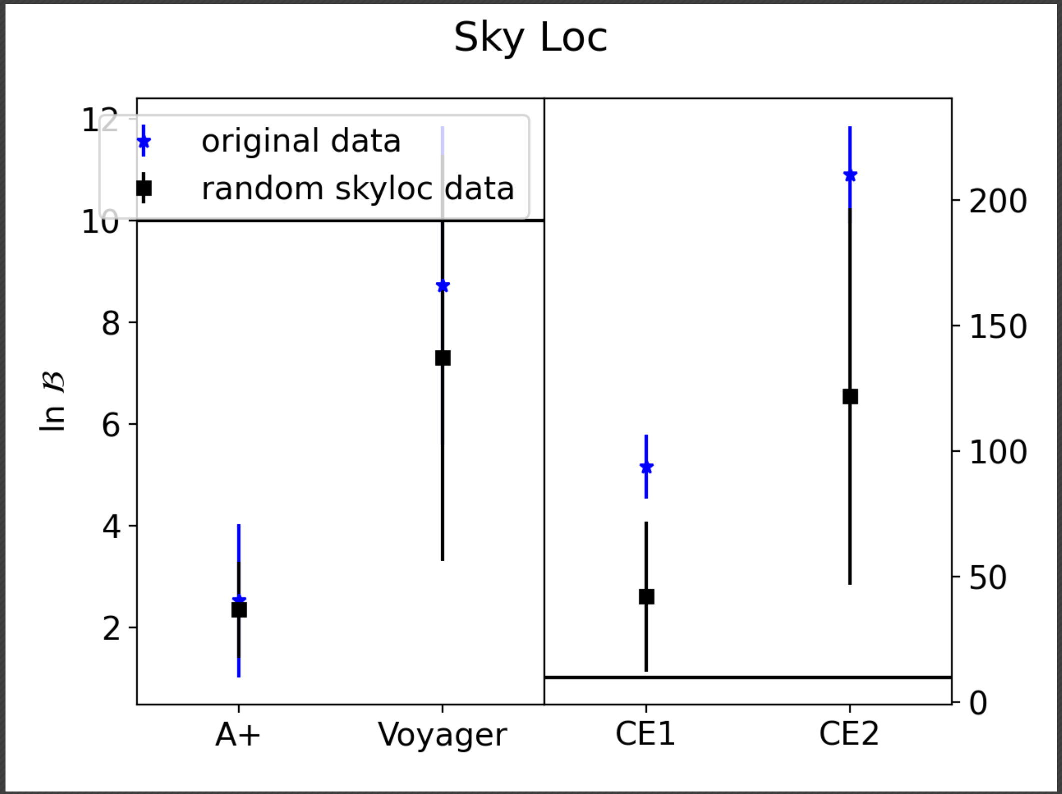
- Uniform prior
  - Neutron star: uniform (1,2)
  - Black Hole: uniform (m_{bh}-2,m_{bh}+2)
- Low Spin prior is $\chi_{1,2}$ ~ U(-0.05,0.05)
- Polarization: $\psi \in [0,2\pi)$
- Inclination: $\cos\iota \in [0, 1)$
- Coalescence time: $t_c \in t_0 \pm 0.1$ s

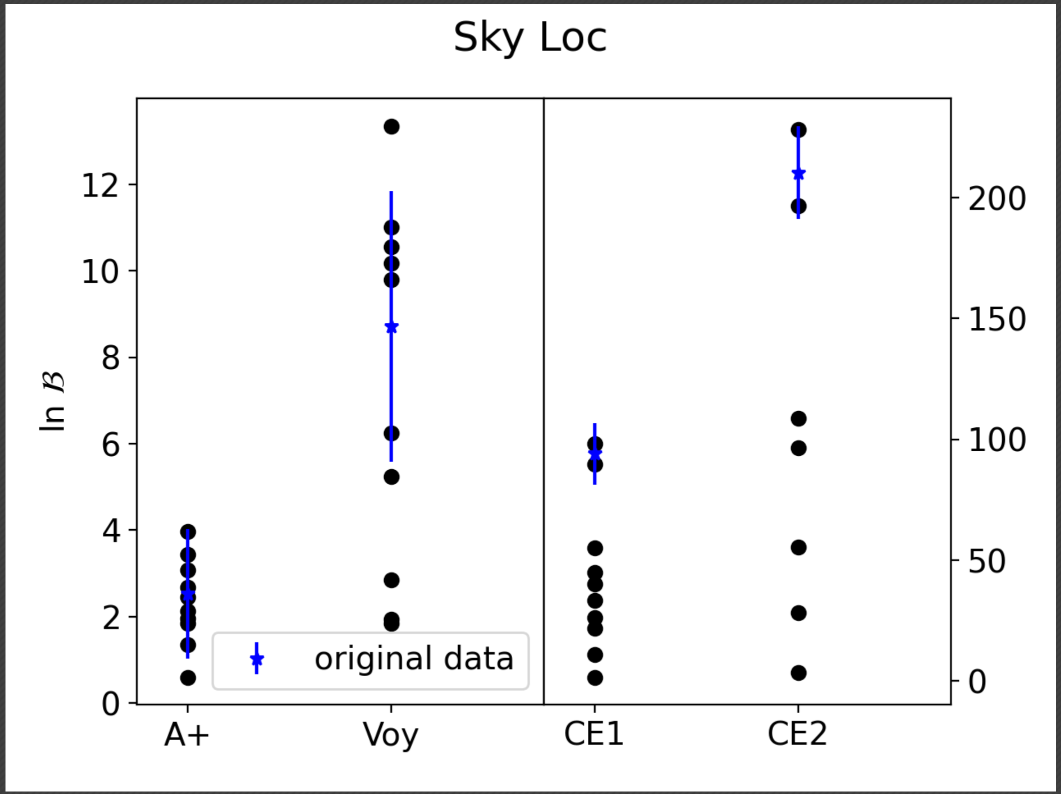
10M Black Hole



Sky Location

- The sky location was chosen to be the same as GW170817
- Of course, an event could take place anywhere in the sky
- To take this into account we selected a few points and did runs at randomly chosen sky locations.
- As GW170817 was in a very advantageous sky location, the Bayes factor for a randomly selected sky location is on average lower, even up to half.


Sky Loc
original data
random skyloc data
ln $\mathcal{B}$
A+
Voyager
CE1
CE2


Sky Loc
original data
ln $\mathcal{B}$
A+
Voy
CE1
CE2