Nuclear matter EOS constraints from GW

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Outline

- Constraints on EOS using only inspiral GW signal
- Additional constraints in case of known remnant type
- Connection to kilonova observation
- Connection to short gamma ray burst
- Other Avenues

Constraints using GW signal

Inspiral Parameter Space

- Chirp mass

$$M_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

- Mass ratio

$$q = \frac{M_2}{M_1} \leq 1$$

- Effective spin parameter

$$\chi_{\text{eff}} = \frac{M_1 \chi_1^z + M_2 \chi_2^z}{M_1 + M_2} \qquad \text{where} \quad \chi_i = J_i / M_i^2$$

- Spin precession parameter χ_p

Inspiral Parameter Space

Tidal Deformability

- Measures NS quadrupole moment induced by tidal force
- Depends on EOS
- Mainly a function of mass $\Lambda(M)$
- Rapid rotation might complicate picture
- Might need to consider superfluidity

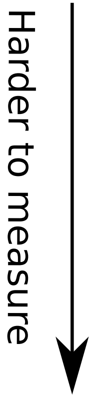
Inspiral Parameter Space

- Effective tidal deformability

$$\tilde{\Lambda} = \frac{16}{13} \frac{(1 + 12q)\,\Lambda_1 + (q + 12)\,q^4 \Lambda_2}{(1 + q)^5}$$

- Negligible impact of $\Lambda_1 - \Lambda_2$ for given $\tilde{\Lambda}$
- Cannot measure individual deformabilities

Impact of Parameters



Chirp mass

Mass ratio, Spin

Precession?

Effective tidal deformability

Spin-Induced Quadrupole?

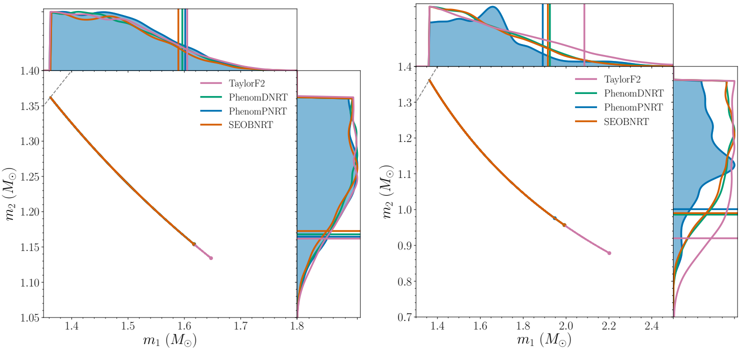
Difference of deformabilties

NS radii do not enter inspiral waveform!

Measurable EOS Aspects

For GW170817 $\Rightarrow$

- Maximum NS mass $\gtrsim 1.36 M_{\odot}$

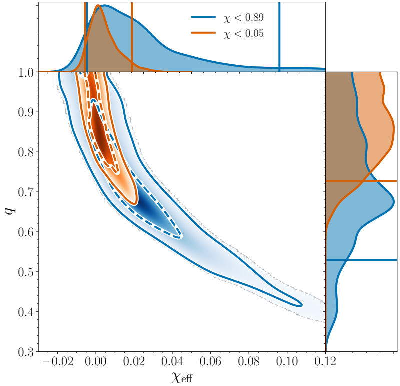


Source: LIGO/Virgo, **Phys. Rev. X 9 (2019)**

Measurable EOS Aspects

For GW170817 ⇒

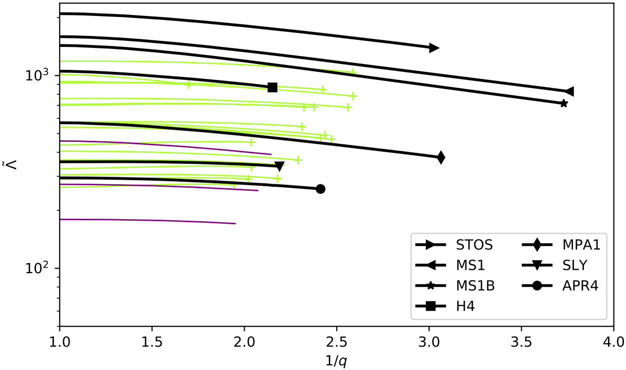
- Maximum NS mass $\gtrsim 1.36 M_\odot$
- Spin compatible with zero, no constraint on EOS



Source: LIGO/Virgo, **Phys. Rev. X 9 (2019)**

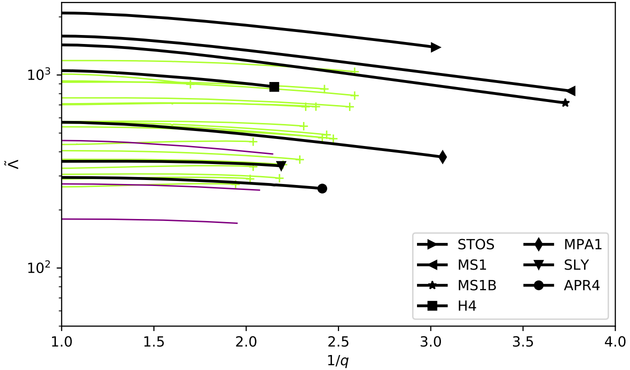
Measurable EOS Aspects

- Single, ideal detection yields data point $(M_c, \tilde{\Lambda}, q)$
- EOS determines function $\tilde{\Lambda}(M_c, q)$



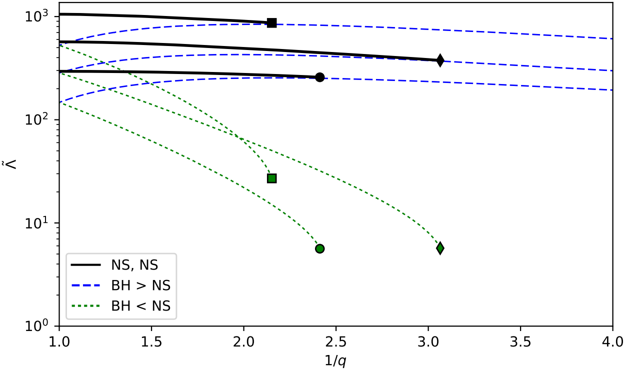
Measurable EOS Aspects

- Different EOS can pass through same data point
- Maximum mass can vary strongly

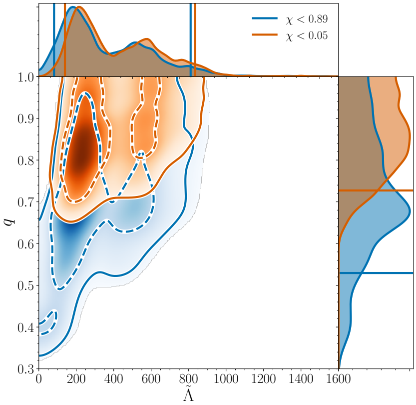


Measurable EOS Aspects

- Different EOS can pass through same data point
- Maximum mass can vary strongly
- NS-BH and NS-NS can have same $\tilde{\Lambda}$ for different EOS



Model-Agnostic Study

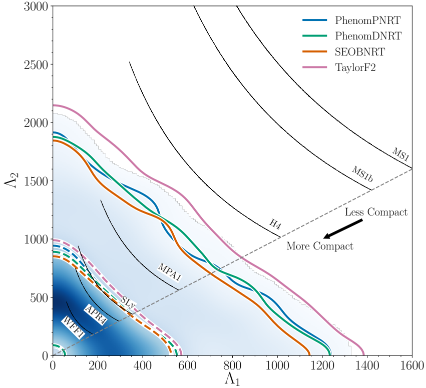


Assumptions

- Arbitrary objects type
- No correlation Λ and M
- Uniform prior in Λ_1, Λ_2

Source: LIGO/Virgo, **Phys. Rev. X 9 (2019)**

Model-Agnostic Study



Source: LIGO/Virgo, **Phys. Rev. X 9 (2019)**

Assumptions

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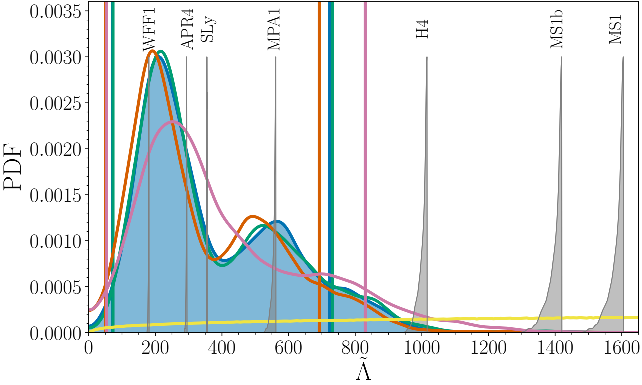
Model-Agnostic Study

- Prior disfavors low $\tilde{\Lambda}$
- To derive EOS constraints, prior was modified
- Divided by marginalized $\tilde{\Lambda}$ prior
- Results in flat marginalized $\tilde{\Lambda}$ prior
- Does not correspond to common EOS assumption.
- Ad-hoc modification instead discussion of prior impact

Model-Agnostic Study



Source: LIGO/Virgo, **Phys. Rev. X 9 (2019)**

Universal Relations Studies

Motivation

- Assume BNS with common EOS
- Without assuming specific EOS
- Same mass should yield same deformability

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Approach

- Use phenomenological relations to compute
  - Individual deformabilities from effective one
  - Radii from deformabilities
- Describes many EOS models within a certain error

[LIGO/Virgo, **PRL 121, 091102 (2018)**]
[De et al, **PRL 121, 161101 (2018)**]

Universal Relations Studies

- Re-parametrise

$$\Lambda_s = (\Lambda_1 + \Lambda_2)/2 \qquad \Lambda_a = (\Lambda_2 - \Lambda_1)/2$$

- Expand Λ_a as

$$\Lambda_a(\Lambda_s, q) = \Lambda_s F_n(q) \frac{1 + \sum_{l=1}^{3} \sum_{k=1}^{2} b_{lk} q^k \Lambda_s^{-l/5}}{1 + \sum_{l=1}^{3} \sum_{k=1}^{2} c_{lk} q^k \Lambda_s^{-l/5}}$$

$$F_n(q) = \frac{1 - q^{10/(3-n)}}{1 + q^{10/(3-n)}}$$

Universal Relations Studies

- Calibrate coefficients using a few EOS models

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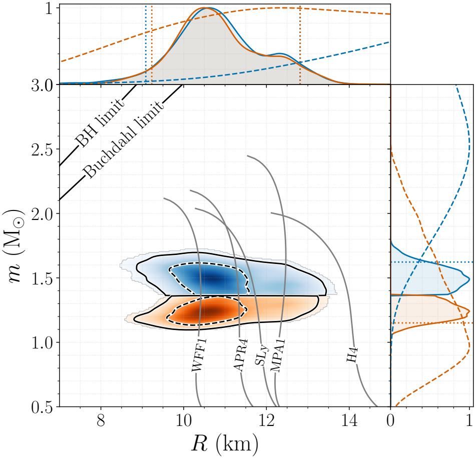
- Used in range forbidden by the EOS models!

Universal Relations Studies

- Calibrate coefficients using a few EOS models
- Used in range forbidden by the EOS models!
- No quark stars
- No phase transitions
  [Han and Steiner, Phys. Rev. D 99 (2019)]

Universal Relations Studies

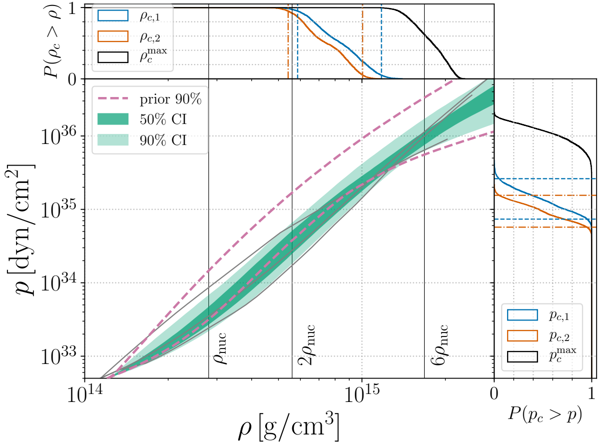


- **Infer** mass-radius posteriors
- Radii are **not** measured
- Model-dependent

Source: LIGO/Virgo, **Phys. Rev. L. 121 (2018)**

Parametrized EOS Studies

- Parametrized EOS allows Bayesian analysis of parameters
- LVC study using causal spectral representation



Source: LIGO/Virgo, **Phys. Rev. L. 121 (2018)**

Parametrized EOS Studies

- Parametrized EOS allows Bayesian analysis of parameters
- LVC study using causal spectral representation
- EOS parameter space multi-dimensional
- Measurable space 1-dimensional ($\tilde{\Lambda}$)
  $\Rightarrow$ Degenerate subspace unconstrained by data
- Impact of prior in degenerate subspace unclear.
- Impact of prior in general unclear.

Evidence for Tidal Effects?

- GW data analysis based on Bayesian statistics
- Posterior is combination of prior and observational data
- Need to investigate impact of prior
- Low Λ have small impact on signal
- Expect larger impact of prior on lower limits
- Published lower limits could be entirely based on prior [Kastaun,Ohme, in preparation]

Evidence for Tidal Effects?

- Need to consider impact of waveform models
- Estimated by repeating analysis with different models
- Waveform model irrelevant if lower limits prior-based
- Systematic error possibly under-estimated
- Cross check error estimate by comparing waveforms
- Limits below $\tilde{\Lambda} \approx 200$ questionable
  [Kastaun,Ohme, in preparation]

EOS Model Selection Study

- Credible intervals do not exclude models per se
- Shape of posterior matters, e.g. Gaussian
- Ambiguous choice: symmetric two-sided, upper limits, HPD
- Credible intervals depend on prior and parameter space volume

EOS Model Selection Study

- Credible intervals do not exclude models per se
- Shape of posterior matters, e.g. Gaussian
- Ambiguous choice: symmetric two-sided, upper limits, HPD
- Credible intervals depend on prior and parameter space volume
- More direct: compare models using Bayes factors
- Relative probability that noisy data contains different signals.

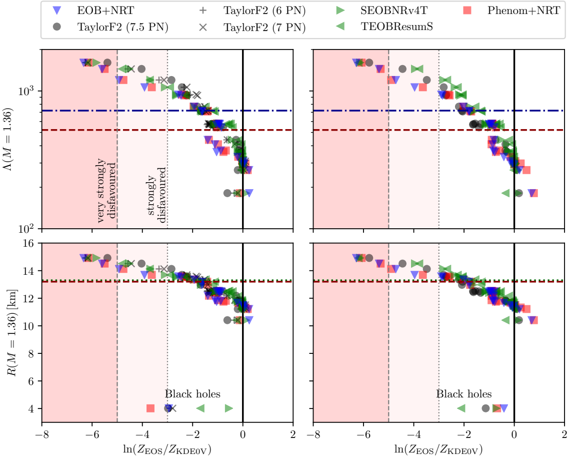
EOS Model Selection Study

New study of GW170817 [LIGO/Virgo, `arXiv:1908.01012`]

- Performed model comparison between 24 different EOS: `APR4, BHF_BBB2, H4, KDE0V1, MPA1, MS1, SK255, SKI2, SKI4, SKI6, SKOP, SLY2, SLY9, WFF1, HQC18, KDE0V, MS1B, RS, SK272, SKI3, SKI5, SKMP, SLY230A, SLY`
- `HQC18` is a Quark-Hadron EOS
- Each using 5 different waveform models
- Two priors:
  - Wide spins, wide component masses
  - Slow rotation, narrow component masses
    Gaussian at $= 1.33\, M_\odot$, width of $0.09\, M_\odot$

EOS Model Selection Study

- Clear trend disfavoring large radii/deformabilities



Source: LIGO/Virgo, **arXiv:1908.01012 (2019)**

EOS Model Selection Study

- Clear trend disfavoring large radii/deformabilities
- Only `MS1`/`MS1B` strongly disfavored
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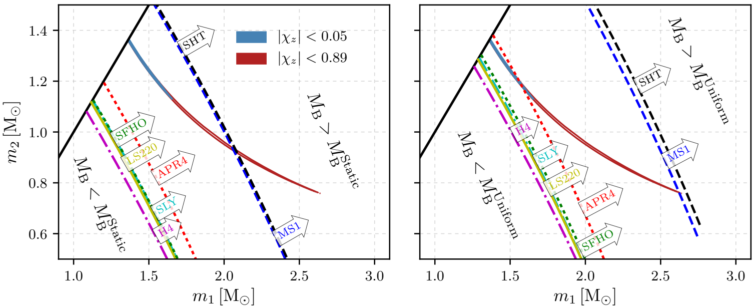
EOS Model Selection Study

- Clear trend disfavoring large radii/deformabilities
- Only `MS1`/`MS1B` strongly disfavored
- Cannot rule out BBH or mixed cases
- Remnant lifetime essentially unconstrained
- Indefinitely stable remnants disfavored
- For some specific EOS, prompt collapse ruled out

Implication of Remnant Type

- Inspiral provides upper limit for mass of remnant
- Remnant lifetime related to mass and EOS
- Hypermassive: short-lived, Supramassive: long-lived
- BH formation would constrain maximum TOV mass
- Tighter constraint if assuming remnant is hypermassive



Source: LIGO, Virgo, Fermi GBM, INTEGRAL, **Astrophys. J. Lett. 848 (2017)**

Implication of Remnant Type

Newest estimate by [LIGO/Virgo, `arXiv:1908.01012`]

- Limit on maximum nonrotating NS baryonic mass $\hat{M}_b$ and gravitational mass $\hat{M}_g$
- If remnant mass above stable range for true EOS: $\hat{M}_b < 3.05 M_\odot$ and $\hat{M}_g \lesssim 2.65 M_\odot$
- If remnant mass in hypermassive range for true EOS: $\hat{M}_b < 2.67 M_\odot$ and $\hat{M}_g \lesssim 2.32 M_\odot$
- Limits for wide spin prior less tight

Implication of Remnant Type

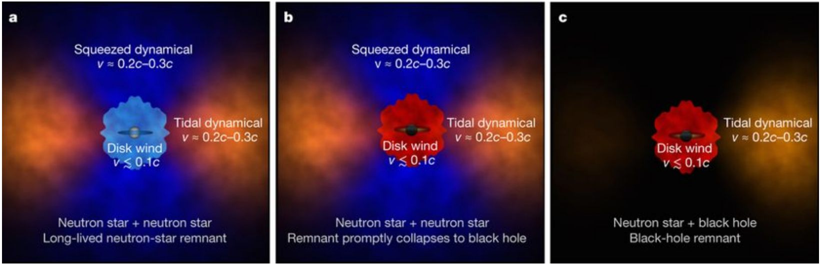
Recent analysis [Shibata et al, **Phys. Rev. D 100 (2019)**]

- Less assumptions
- Uses trends from numerical simulations
- Also considers angular momentum balance
- Similar limit $\hat{M}_g \lesssim 2.3 M_\odot$

Kilonova

Mass ejection

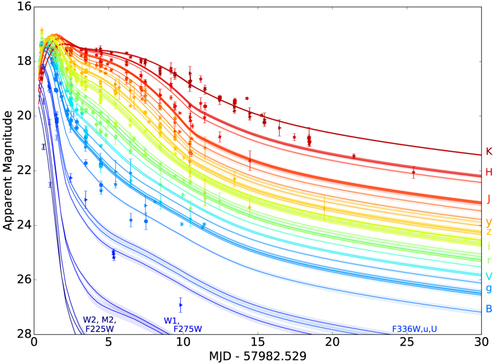
- Different types of matter ejection
- Tidal ejection during merger
- Shock-driven ejection during merger
- Winds from disk
  - By-product of accretion process
  - Magnetically driven



Source: Kasen, Metzger et al, **Nature 551 (2017)**

Kilonova Modeling

- Detailed models for spectral and luminosity evolution
- Depends on ejecta mass, velocity, and Lanthanide fraction
- Can infer parameters of different components



Source: Villar, Guillochon et al, **Astrophys. J. Lett. 851 (2017)**

Kilonova Modeling

- Detailed models for spectral and luminosity evolution
- Depends on ejecta mass, velocity, and Lanthanide fraction
- Can infer parameters of different components
- Complications
  - Need to consider interaction via radiation transport
    [Kawaguchi et al, Astrophys. J. Lett. 865 (2018)]
  - Energy input from long-lived remnant?
    [Yu et al, Astrophys. J. 861 (2018)]

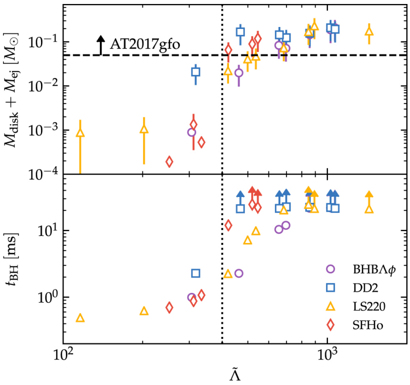
Constraints from Kilonova

- Numerical simulations show dynamical ejecta insufficient
- Kilonova modeling ejecta mass $\gtrsim 0.05\,M_\odot$
- Velocity and composition also at tension
- Need contribution from disk winds
- Difficult to model expelled fraction
- Hard upper limit by total disk mass

Modeling the Disk

- Simulations provide density distribution for given model
- Gradual transition from remnant to disk
- Definitions of disk mass ambiguous
  [Endrizzi, Logoteta et al, PRD 98 (2018)]
- Remnant keeps expelling matter into disk
  [Kastaun et al, PRD 94 (2016)]
- Magnetic effects might expel more matter from remnant
  [Ciolfi, Kastaun et al, PRD 100 (2019)]
- Final disk mass difficult to model accurately

Constraints from Kilonova



Source: Radice, Perego et al, **Astrophys. J. Lett. 852 (2018)**

- Postulated correlation disk mass ↔ deformability
- NS masses not restricted to GW170817 range
- Few EOS models
- Fraction of disk mass expelled unknown
- Outliers reported in [Endrizzi et al (2018)]
- Systematic study discovered larger spread [Kiuchi et al (2019)]

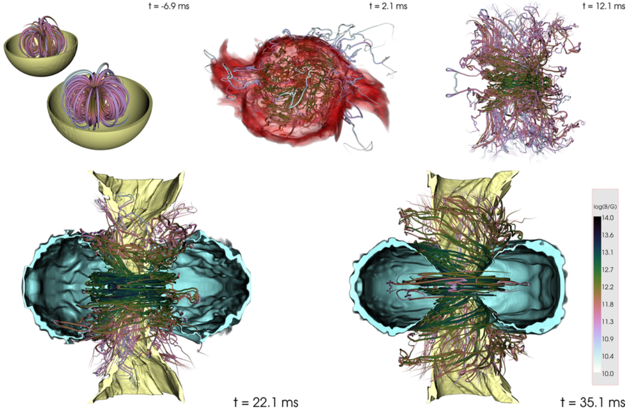
Short Gamma Ray Burst

Short Gamma Ray Burst Models

- Important question: Does SGRB require BH?
- SGRB Scenario 1: BH + disk + B-field
- SGRB Scenario 2: Magnetar + disk

Numerical Simulations

- No SGRB ever emerged in simulations
- Some potential precursors for BH case



Source: Kawamura, Giacomazzo, Kastaun et al, **PRD 94 (2016)**

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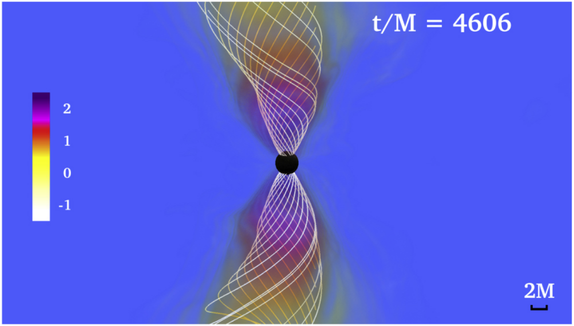

Source: Ruiz, Lang et al, **Astrophys. J. Lett. 824 (2016)**

Numerical Simulations

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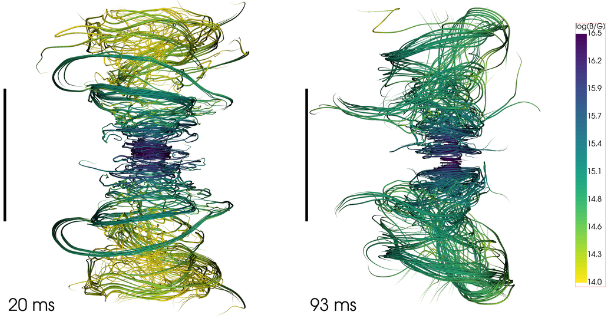
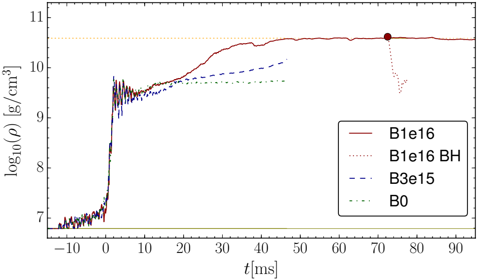
- Some potential precursors for BH case
- Recent magnetar simulation discouraging



Source: Ciolfi, Kastaun et al, **Phys. Rev. D 100 (2019)**

Numerical Simulations

- No SGRB ever emerged in simulations
- Some potential precursors for BH case
- Recent magnetar simulation discouraging
- Baryon pollution would choke jet

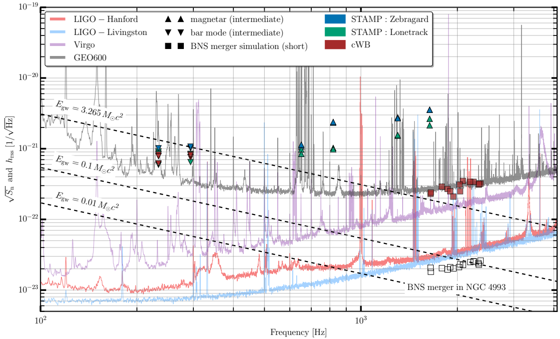


Source: Ciolfi, Kastaun et al, **Phys. Rev. D 100 (2019)**

Other Avenues

Post-Merger Signal

- Nothing expected, nothing found
- Upper limits > 10 times too large to be useful



Source: LIGO/Virgo, **Astrophys. J. Lett. 851 (2017)**

Searching p-g effects

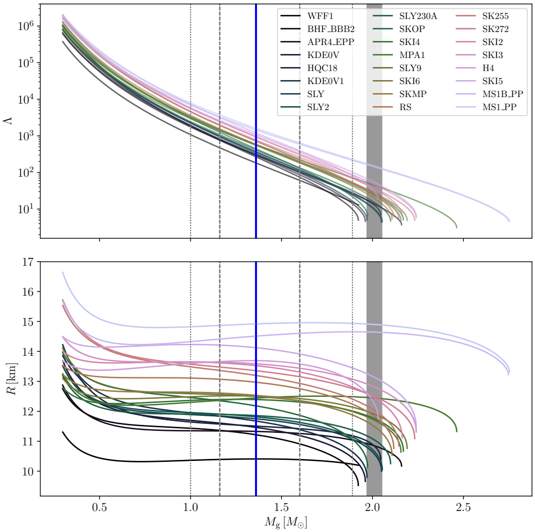
- Tidal forces can excite NS oscillation modes
- Not enough time for resonant mode excitation
- Search for non-resonant, nonlinear instability
- Involves coupling of different mode types
  - Pressure modes (p modes)
  - Buoyancy driven modes (g-modes)
- Orbital energy dissipated

Searching p-g effects

- Phenomenological models used
- Saturation amplitude unknown, free parameter
- Two studies
  - [Essick and Weinberg, PRL 122 (2019)]
  - [Reyes and Brown, arXiv:1808.07013]
- No evidence for p-g modes found
- Evidence against p-g modes based on error
- Large upper limit on saturation amplitude
- No constraints on EOS

Appendix

NS properties



Source: LIGO/Virgo, **arXiv:1908.01012 (2019)**

Claim of Anti-Chirp

- Claim of extended emission in GW spectrum [VanPutten, Della Valle, MNRAS 482 (2019)]
- Decreasing frequency
- Indication for spinning-down NS remnant?
- Rebuttal [Oliver et al, MNRAS 485 (2019)]
  - Custom data analysis method controversial
  - Even ideal matched filter not sensitive enough
  - Energy output too high

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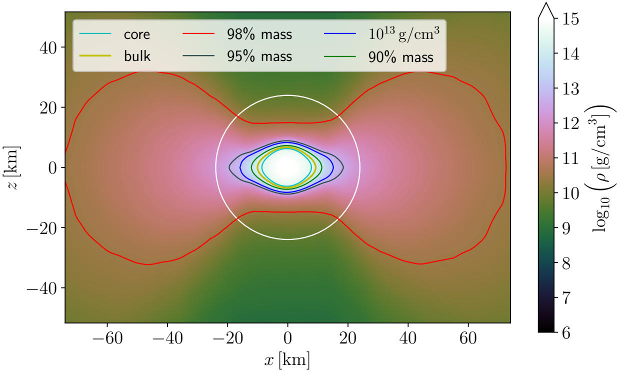
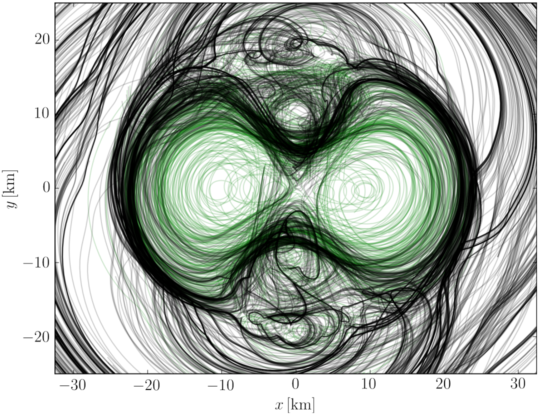


Source: Endrizzi, Logoteta et al, **Phys. Rev. D 98 (2018)**

Modeling the Disk

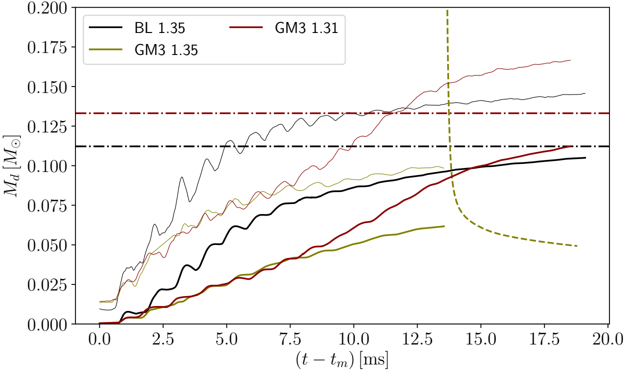
- Remnant keeps expelling matter into disk



Source: Kastaun et al, **Phys. Rev. D 94 (2016)**

Modeling the Disk

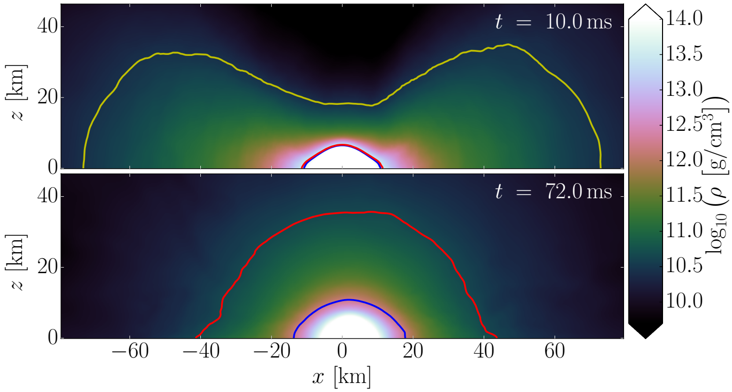
- Remnant keeps expelling matter into disk
- Final disk masses possibly under-estimated



Source: Endrizzi, Logoteta et al, **Phys. Rev. D 98 (2018)**

Modeling the Disk

- Magnetic effects might expel more matter from remnant
- Very difficult to model



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