Joint Gravitational Wave and Electromagnetic Observations of Neutron-Star–Black-Hole Coalescing Binaries

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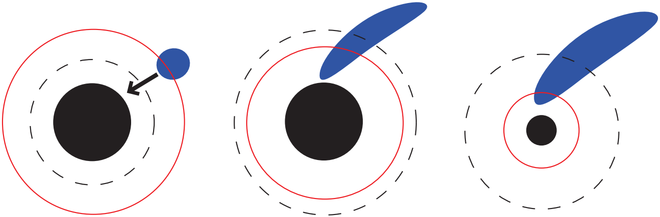
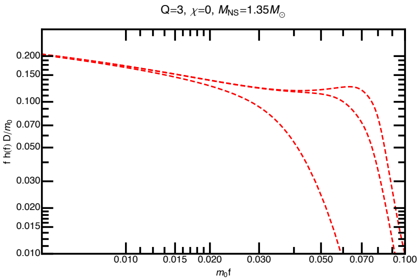
Introduction



[Kyutoku, Okawa, Shibata, Taniguchi (2011)]



[Pannarale, Berti, Kyutoku, Shibata (2013)]

Introduction

The inspiral...

- BH-BH template banks safe enough for NS-BH inspiral searches ($<$ 1% losses)
- Stiff equations of state are marginally distinguishable

[Pannarale, Rezzolla, Ohme, Read (2011)]

...and beyond

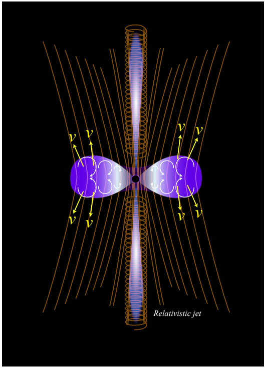
- The tidal deformability $\Lambda = 2k_2 R_{\rm NS}^5/(3M_{\rm NS})^5$ may be extracted at high frequencies

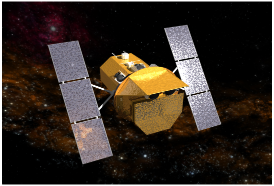
[Lackey, Kyutoku, Shibata, Brady, Friedman (2012)]

- Coherently combining the (small) inspiral and high-frequency matter effects improves the measurability of Λ by a factor ~ 3
- However, incorporating correlations between all the waveform parameters then decreases the measurability of Λ by a factor ~ 3

[Lackey, Kyutoku, Shibata, Brady, Friedman (2014)]

Introduction





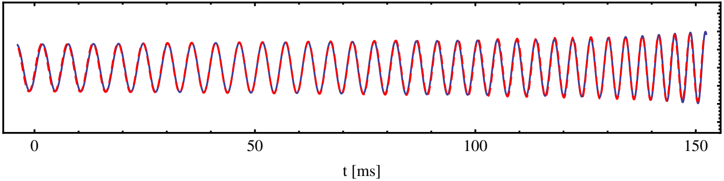
1. Given a GW observation, do we expect an EM counterpart?
2. Given an SGRB trigger, can we improve a GW offline search?
3. Given a *joint* GW+EM observation, can we constrain the NS equation of state (EOS)?

[Pannarale & Ohme, arXiv:1406.6057, ApJL accepted]

Part I: GW measurement

- GW detection will not be able to determine all parameters with high accuracy [Ohme, Nielsen, Keppel, & Lundgren (2013)]

$(1.35 + 5)M_\odot, \chi = 0.3$ $(2.4 + 2.6)M_\odot, \chi = 0.08$



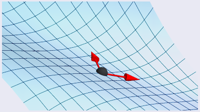
- Understanding the waveform structure throughout the parameter space allows for efficient search strategies and correct interpretations of future observations

Part I: GW measurement

Principal component analysis (PCA)

PCA of post-Newtonian expansion coefficients: computationally cheap and accurate waveform (dis)agreement calculation technique

[Tanaka & Tagoshi (2000), Sathyaprakash & Schutz (2003), Pai & Arun (2013), Brown *et al* (2012)]



Eigenvectors μ_i represent *principal directions* ranked by their eigenvalues λ_i

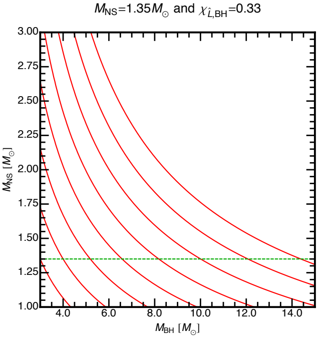
$$\|\Delta h\|^2 = \sum_i \lambda_i (\Delta\mu_i)^2$$

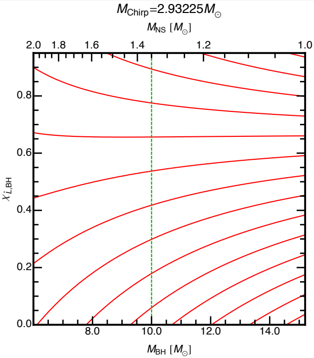
Degeneracies

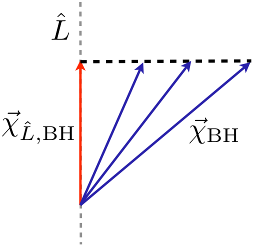
- $\mu_1 \sim M_{\rm Chirp} = (M_{\rm NS} M_{\rm BH})^{3/5}/(M_{\rm NS} + M_{\rm BH})^{1/5}$ (extremely well measurable)
- μ_2 : mass-ratio/spin degeneracy (well constrainable)
- Higher components add less information, neglected here

$\Rightarrow$ GW measurement $\rightarrow$ 1D line in the $M_{\rm BH}$–$M_{\rm NS}$–$\chi_{\hat{\rm L},{\rm BH}}$ space

Part I: GW measurement



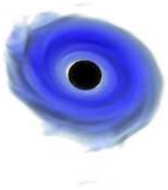


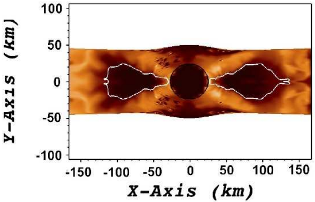


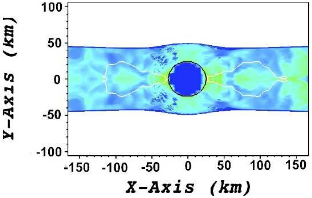
Additional degeneracy

Same $M_{\rm NS}$, $M_{\rm BH}$, and $\chi_{\hat{L},\rm BH}$ $\Rightarrow$ same GW signal

Part II: EM counterparts





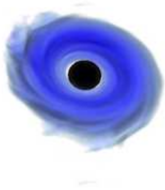


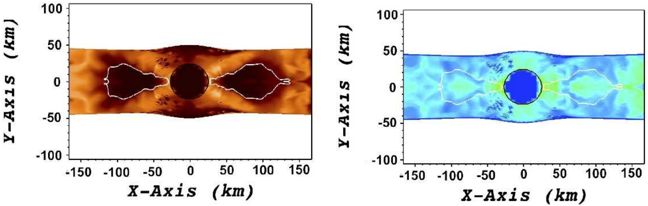
[Foucart *et al* (2014)]

- Disk mass: $10^{-3}-0.1M_{\odot}$
- Size: $10-1000$km
- Density: 10^{8-12}g/cm^3
- Temperature: $>$MeV
- Accretion rate
- Angular momentum distribution
- Magnetic field configuration
- ν cooling
- Composition
- Unbound tidal tails

Use the disk mass as a proxy for EM emission

Part II: EM counterparts





[Foucart *et al* (2014)]

EM counterpart production condition (SGRB ignition)

$$M_{\rm b,disk} > M_{\rm b,Threshold} \gtrsim 0.01 M_\odot$$

Fit to numerical-relativity results

$$M_{\rm b,disk} = \frac{0.296 r_{\rm tide} - 0.171 r_{\rm ISCO}}{R_{\rm NS}} M_{\rm b,NS}$$ [Foucart (2012)]

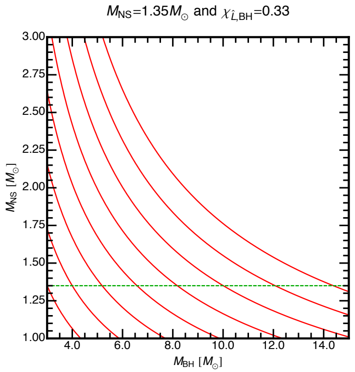
Generalized to misaligned mergers [Stone, Loeb, Berger (2013)]

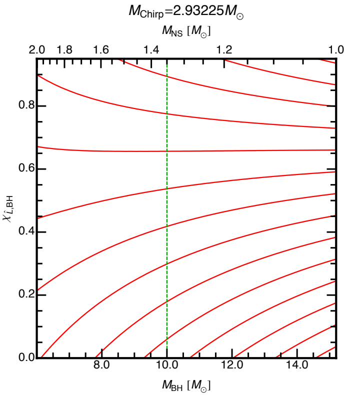
Part III: Combining the information

Algorithm

1. Pick a class of target systems ($\chi_{\rm BH} = 0.998$ to maximize $M_{\rm b,disk}$)
   (A) Constant chirp mass, as accurately determined by GW measurement.
   (B) Systems degenerate with $M_{\rm NS} = 1.35 M_\odot$, $\chi_{\hat{\rm L},\rm BH} = \rm const.$
2. Perform PCA, identify GW degeneracies through constant principal components (Advanced LIGO ZDHP, 15 Hz cutoff)
3. Pick an equation of state
4. Calculate $M_{\rm b,disk}$ for each point along the GW degeneracy
5. Regions with $M_{\rm b,disk} > M_{\rm b,Threshold} = 0.03 M_\odot$ are EM loud
6. Overlay GW degeneracies with EM loud parameter space regions

Part IV: Results





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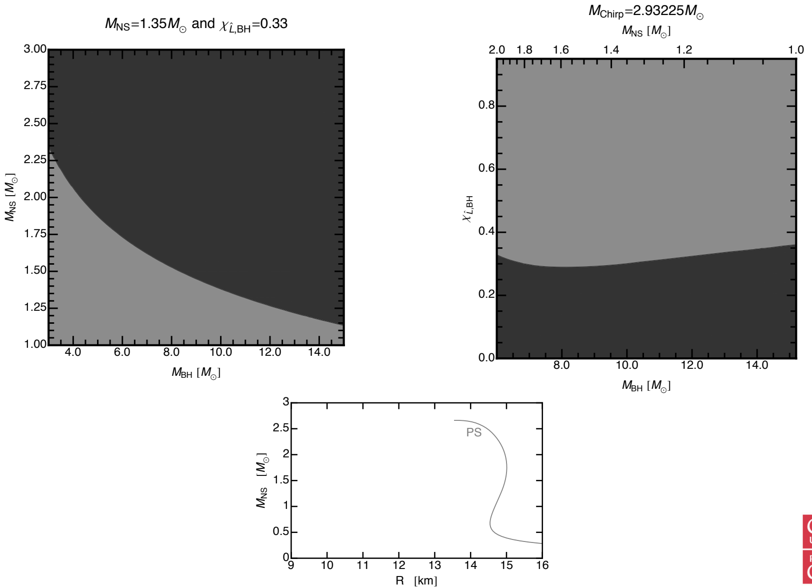

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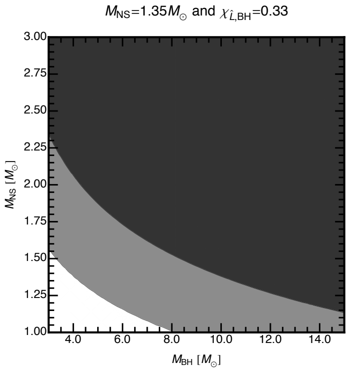

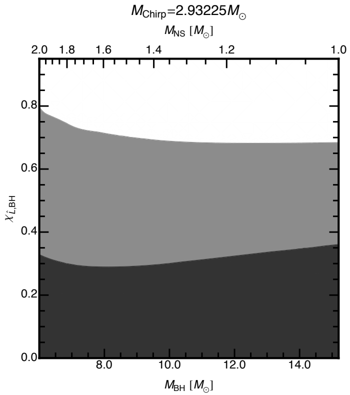

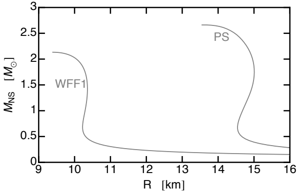

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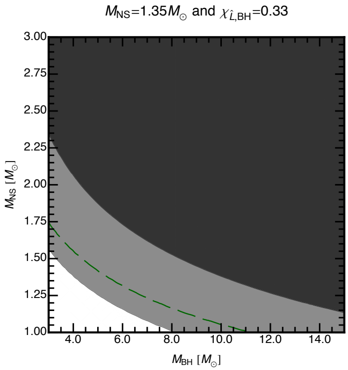

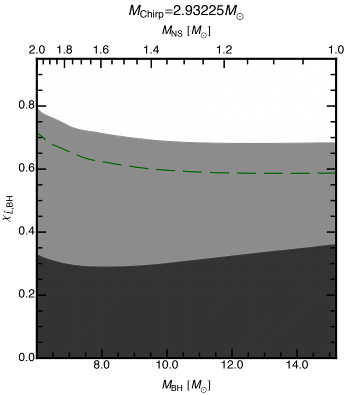

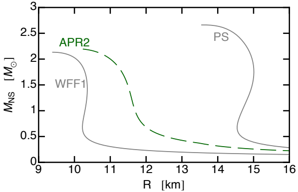

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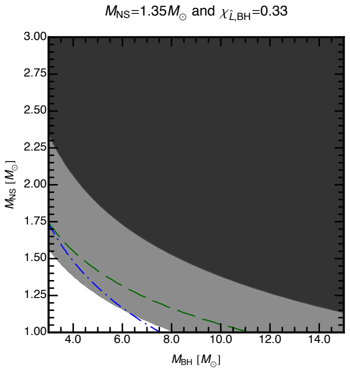

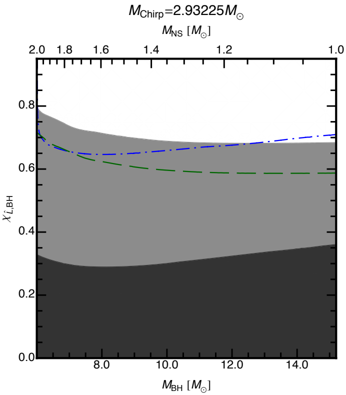

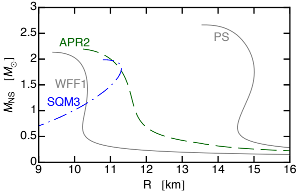

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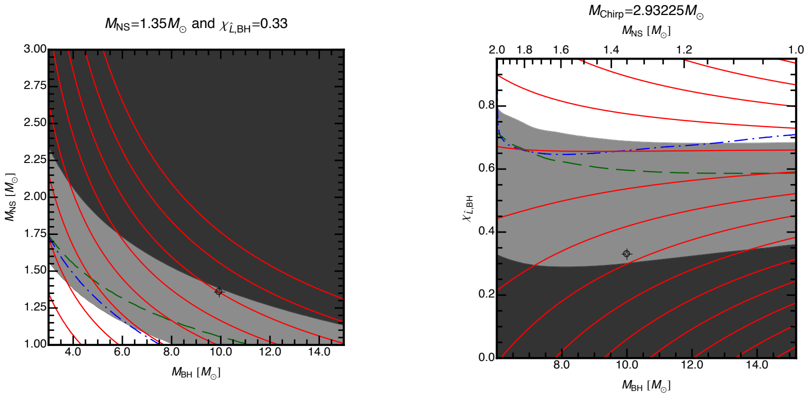

- Regions in which EM follow-ups are favourable/unfavourable
- Increasing(decreasing) the target $\chi_{\hat{L},BH}$(M_{Chirp}) enhances the chances of having an EM counterpart

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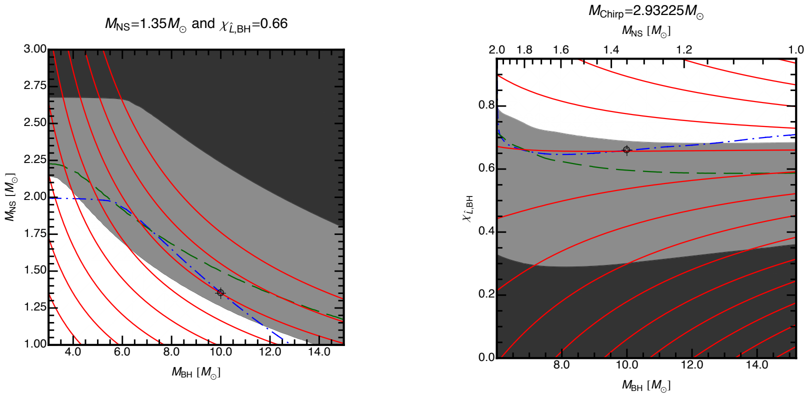

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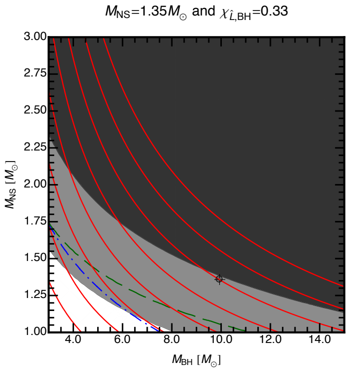

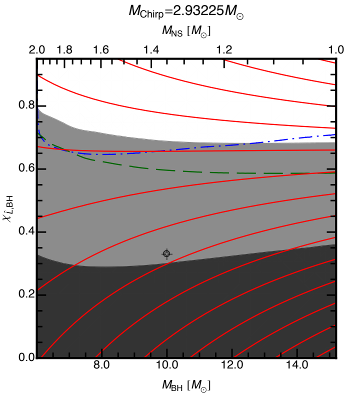

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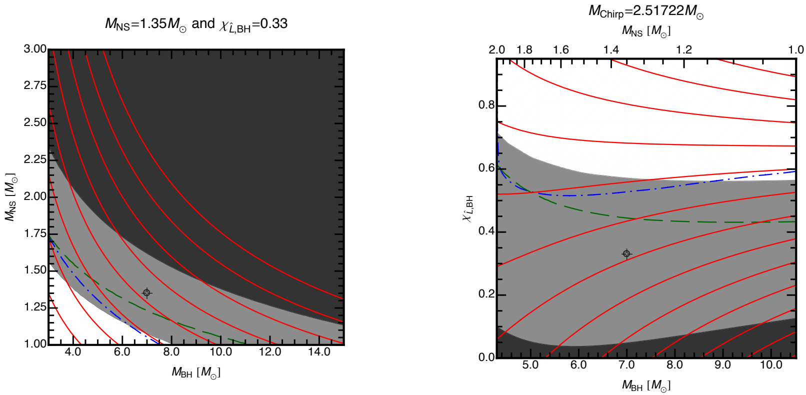

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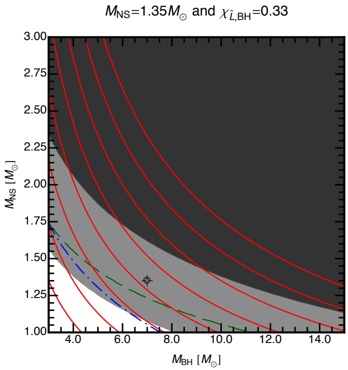

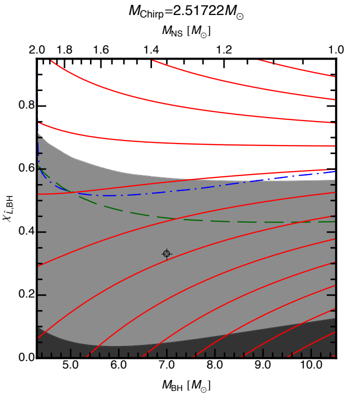

- GW degeneracies hardly intersect with EOS thresholds
- Joint GW+EM detection $\rightarrow$ lower bound on the NS EOS stiffness
- Low $\chi_{\hat{L},BH}$ $\rightarrow$ exclude soft EOSs (possibly strange quark matter) for most M_{Chirp} values

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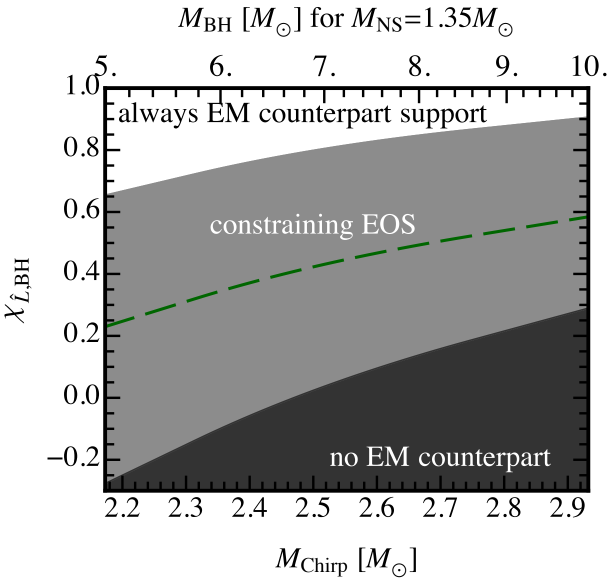

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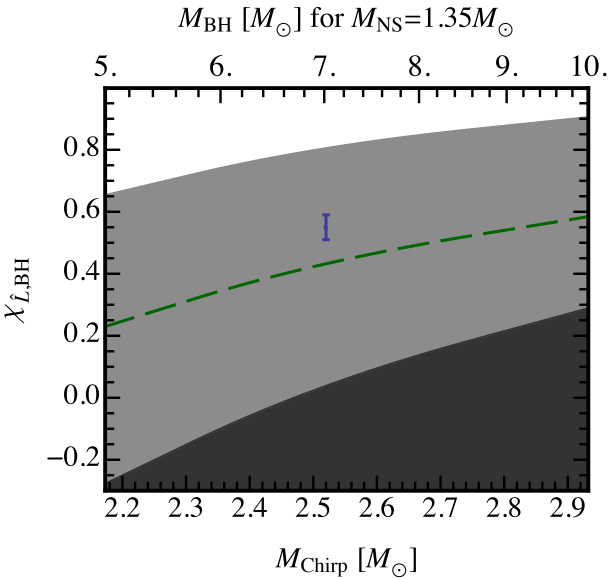

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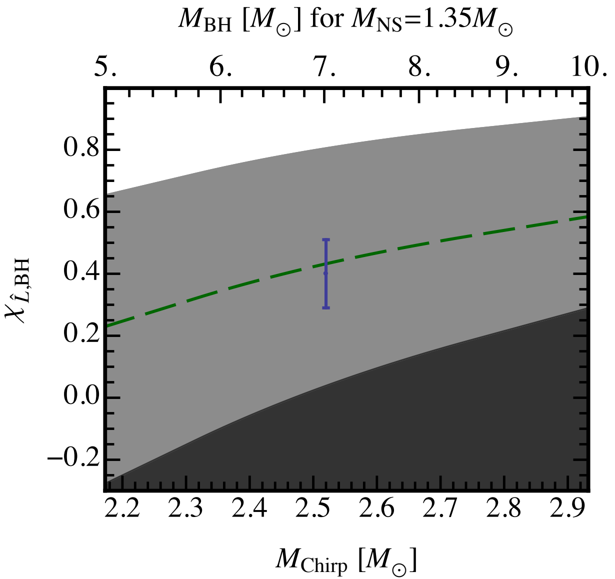

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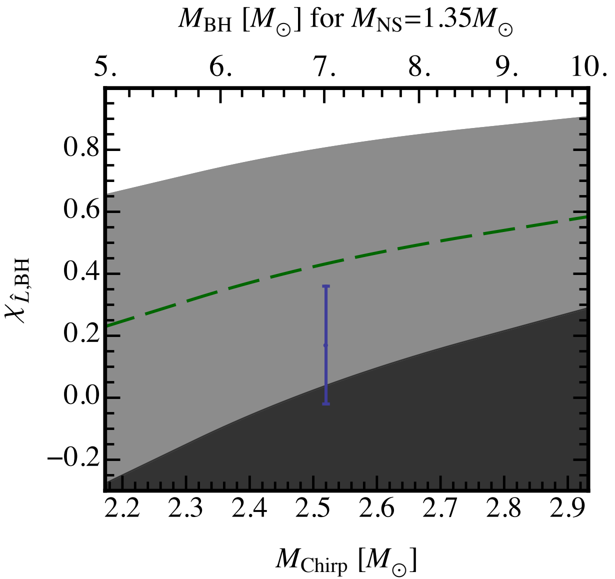


Part V: Improving offline searches

An SGRB is detected and it triggers and offline NS-BH GW search:

- $M_{\rm NS} \in [1, 2.8]M_\odot$, $M_{\rm BH} \in [3, 15]M_\odot$, $\chi_{\hat{\rm L},\rm BH} \in [-0.95, 0.95]$

Conservatively estimate the size of parameter space where an SGRB counterpart cannot be ignited:

- $\chi_{\rm BH} = 0.998$
- 2H 2-piecewise-polytrope $\to$ high $M_{\rm NS}^{\rm Max} \sim 2.8M_\odot$ and large $R_{\rm NS}$
- No SGRB counterpart for $M_{\rm b,disk} = 0M_\odot$

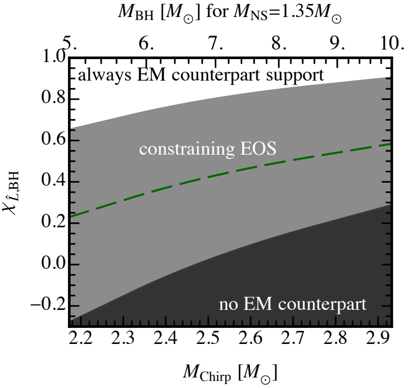
$\Rightarrow$ At most 35%(25%) of the parameter space is useful in following up an SGRB trigger

$\Rightarrow$ 43%(48%) of the templates cover the SGRB silent region

$\Rightarrow$ Increase in speed and sensitivity

Conclusions

- Conventional wisdom (high $\chi_{\rm BH}$, low $M_{\rm BH}$ favour SGRBs) translated into quantitative predictions for CBC searches
- Joint GW+EM detection potentially places lower bound on EOS stiffness
- Developed framework to assess the importance of an EM follow-up



- Can easily be turned into an add-on for search/parameter-estimation pipelines
- Potential speed-up in offline GW searches following SGRB triggers