Investigating the detection rates and inference of gravitational-wave and radio emission from black hole neutron star mergers

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ABSTRACT

Context. Black hole neutron star (BHNS) mergers have recently been detected through their gravitational-wave (GW) emission. While no electromagnetic emission (EM) has yet been confidently associated with these systems, observing any such emission could provide information on, for example, the neutron star (NS) equation of state (EOS). BHNS mergers could produce EM emission as a short gamma-ray burst (sGRB), and/or an sGRB afterglow upon interaction with the circummerger medium.
Aims. Here, we make predictions for the expected detection rates with the Square Kilometre Array Phase 1 (SKA1) of sGRB radio afterglows associated with BHNS mergers. We also investigate the benefits of a multimessenger analysis in inferring the properties of the merging binary.
Methods. We simulate a population of BHNS mergers, making use of recent stellar population synthesis results, and estimate their sGRB afterglow flux to obtain the detection rates with SKA1. We investigate how this rate depends on the GW detector sensitivity, the primary black hole spin, and the NS EOS. We then perform a multimessenger Bayesian inference study on a fiducial BHNS merger. We simulate its sGRB afterglow and GW emission, as input to this study, using recent models for both and take systematic errors into account.
Results. The expected rates of a combined GW and radio detection with the current generation GW detectors are likely low. Due to the much increased sensitivity of future GW detectors like the Einstein Telescope, the chances of an sGRB localisation and radio detection increase substantially. The unknown distribution of the BH spin has a big influence on the detection rates, however, and it is a large source of uncertainty. Furthermore, for our fiducial BHNS merger we are able to infer both the binary source parameters as well as the parameters of the sGRB afterglow simultaneously, when combining the GW and radio data. The radio data provides useful extra information on the binary parameters such as the mass ratio but this is limited by the systematic errors involved.
Conclusions. The probability of finding an sGRB afterglow of a BHNS merger is low in the near future but rises significantly when the next generation GW detectors come online. Combining information from GW data with radio data is crucial to characterise the jet properties. A better understanding of the systematics will further increase the amount of information on the binary parameters that can be extracted from this radio data.

prospective paper

1. Introduction

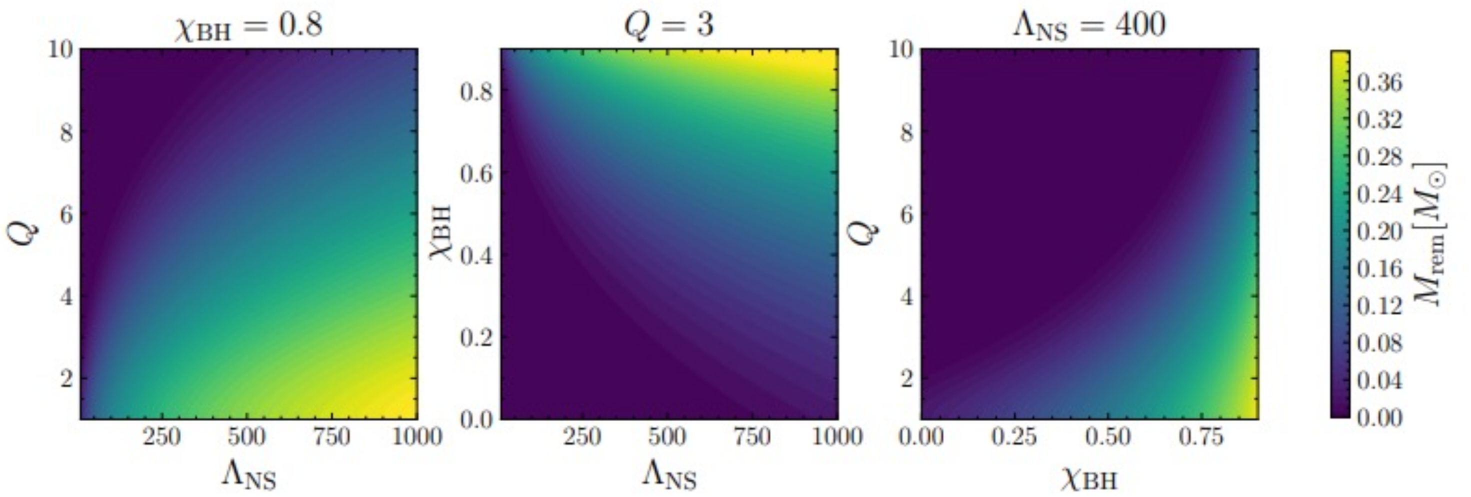
- BH+NS mergers: two detections by LIGO/Virgo (GW200105 and GW200115) but no EM counterpart
- EM expected only if the NS is tidally disrupted and not directly swallowed by the BH
- The fraction of systems where tidal disruption occurs is still uncertain as it depends on unknown distributions of the binary mass ratio, NS compactness, and BH spin.
- Rate expected to be low but rich in infos: NS EOS, BH spin
- Aim of the paper: estimate the GW + radio detection rates with aLIGO/ET + SKA1
  perform a joint analysis of the simulated GW + radio data and
  test a Bayesian method to recover the source parameters: Q = M_{BH}/M_{NS}, $\mathfrak{M}_c$, χ_{BH}, Λ_{NS}, θ_c, i, n_0, ε_B

2. Ejecta outflows of BHNS mergers

Mass of the remnant (disk + dynamical ejecta)

fitting formulae of numerical relativity simulations (Foucart et al, 2018)

In most cases no remnant



Λ_{NS} : deformability of the NS (EOS)
χ_{BH} : dimensionless spin of the BH

2.1 GRB jet

Conditions for the presence and collimation of a jet

A remnant should exist for the jet to form; then:

- initial propagation easier (less "pollution" along the axis)?
- collimation more difficult?

Source of energy:

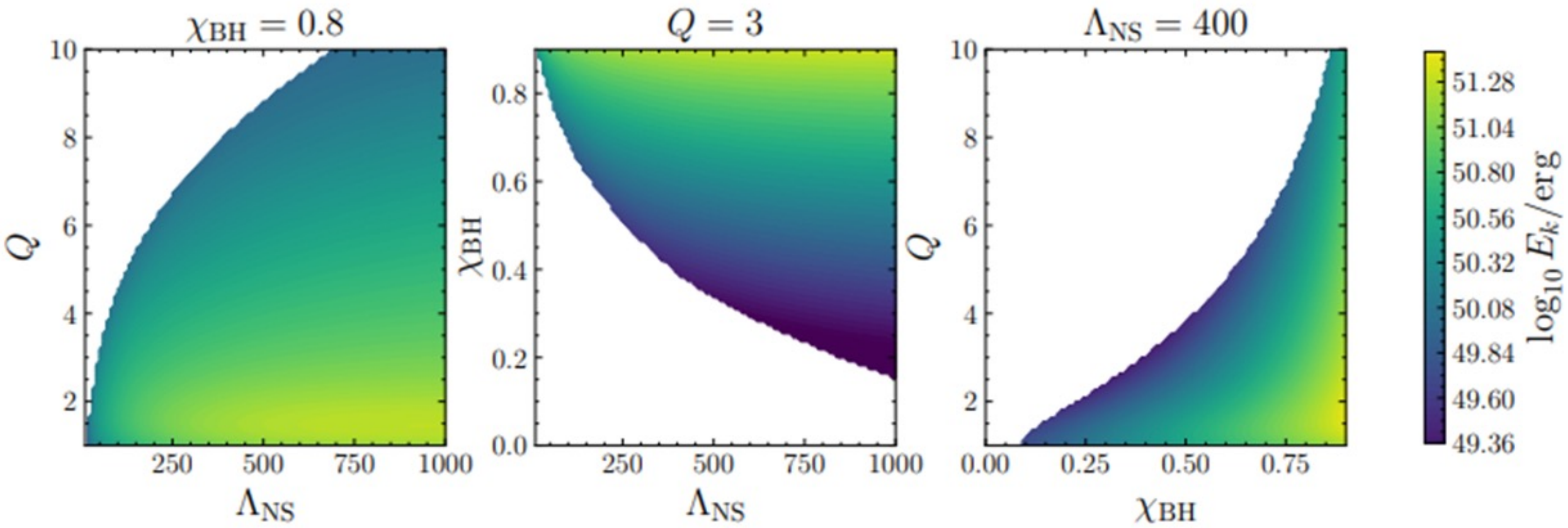
- **BZ mechanism**
- $\nu\bar{\nu}$ annihilation

$$E_k = \frac{1}{2}(1 - f_\gamma)\eta_{BZ} M_{acc} c^2$$

η_{BZ} (BH spin)

M_{acc} (EOS)

$f_\gamma = 0.1$



3. Afterglow detection rates with SKA1

3.1 Population synthesis of BHNS mergers

Finding the detected binaries in GW + EM domains:

- use the results of Broekgaarden et al. (2021) for the component masses

- take a SNR at coalescence ≥ 8 for a detection by aLIGO or ET

- estimate E_k for two EOS ↔ R_{NS} = 11.5 and 13 km and different BH spins χ_{BH} = {0, 0.2, 0.4, 0.6, 0.8}

3.2 sGRB afterglow

At the peak: $F_{p,\nu} \propto E_0\, \theta_c^2\, n_0^{\frac{p+1}{4}}\, \epsilon_e^{p-1}\, \epsilon_B^{\frac{p+1}{4}}\, \nu^{\frac{1-p}{2}}\, d_L^{-2}\, (1+z)^{\frac{3-p}{2}}\, \max\left(\theta_c, \theta_{obs}\right)^{-2p}$.

$\theta_c = 0.1$ rd : opening angle of the jet core

$E_0 = E_k/(1\text{-}\cos\theta_c)$: isotropic kinetic energy

$\varepsilon_e = 0.1$

$[\varepsilon_B\ , n_0]$ log-normal: center 10^{-3} , standard deviation 0.75

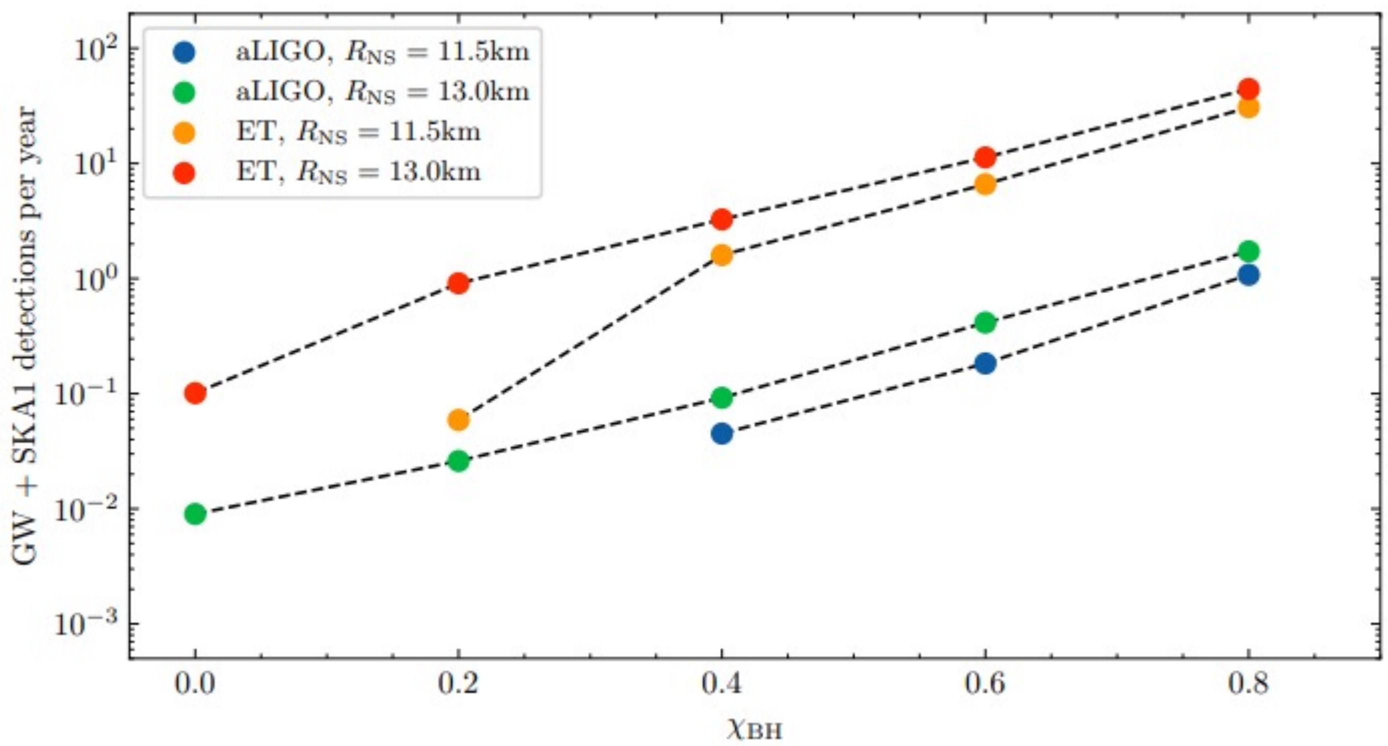
$p = 2.2$: slope of the distribution of the shock accelerated electrons

ν = 1.43 GHz

3.3 Rates

For aLIGO (2G detectors) limited perspective of a GW + EM detection

Situation very much improved with 3G detectors (ET)



Caveats:

- requiring a detection at 10 σ instead of 5 σ lead to the loss of half of the sources
- uncertainties in the population synthesis model, on the minimum disk mass to produce a jet

4. Multimessenger parameter inference

4.1 to 4.5

Beyond estimating the rate is it possible to recover the source parameters?

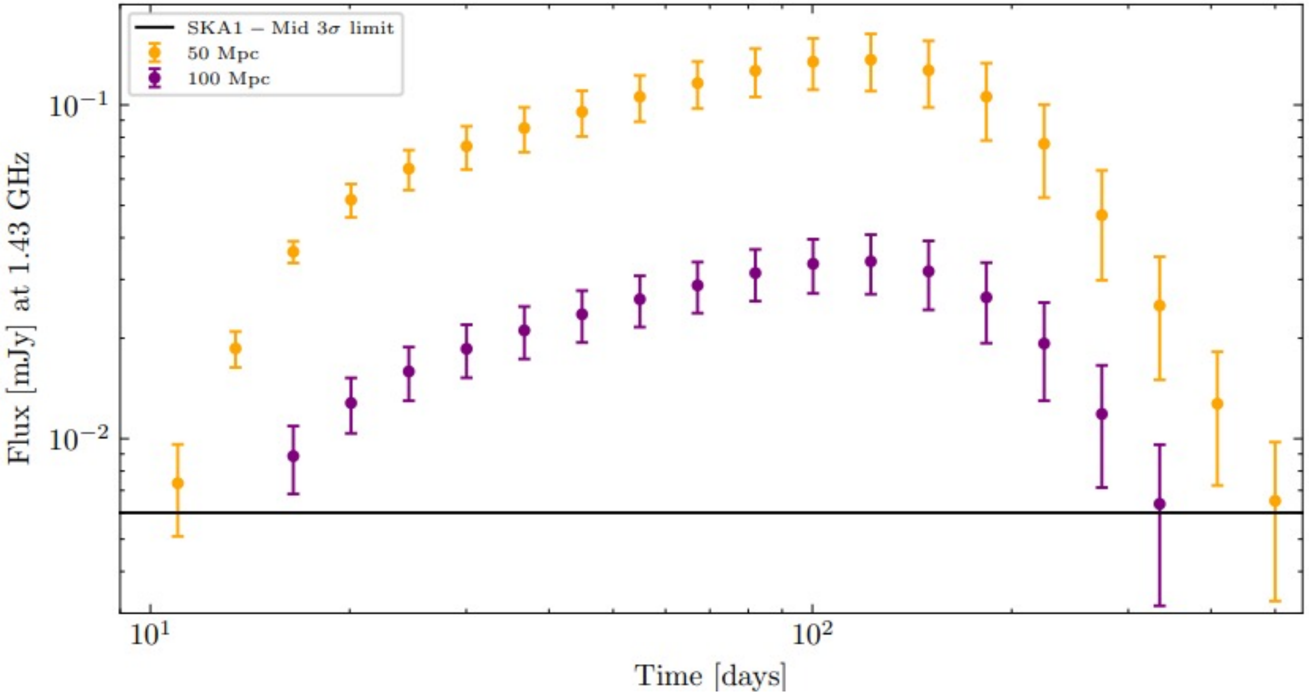
Likelihood estimates from: $\mathscr{L} = \mathscr{L}_{GW} \times \mathscr{L}_{EM}$; parameters $\{\mathcal{M}_c, q, \chi_{BH}, \chi_{NS}, \Lambda_{NS}, i, \psi, \theta_c, \theta_w, b, n_0, \varepsilon_B\}$

4.6 Fiducial BHNS merger

Parameter	Fiducial value	Prior type	Range
M_{BH}	$9.0\ M_\odot$	-	-
M_{NS}	$1.7\ M_\odot$	-	-
$\mathcal{M}_c$	$3.198\ M_\odot$	Uniform	$(2.7, 3.7)$
q	0.189	Uniform	$(0.05, 1.0)$
χ_{BH}	0.7	Uniform	$(-0.9, 0.9)$
χ_{NS}	0.02	Uniform	$(-0.05, 0.05)$
Λ_{NS}	400	Uniform	$(10, 3000)$
ι	0.4 rad	Sine	$(0, \pi/2)$
ψ	2.659 rad	Uniform	$(0, \pi)$
θ_c	0.05 rad	Uniform	$(0, \pi/2)$
θ_w	0.2 rad	Uniform	$(0, 12\theta_c)$
b	6.0	Uniform	$(0, 10)$
n_0	$10^{-3}\ \mathrm{cm}^{-3}$	Log-Uniform	$(10^{-5}, 10^{3})$
ϵ_B	$10^{-3.7}$	Log-Uniform	$(10^{-5}, 1)$
d_L	50, 100 Mpc	-	-

search intervals

GW: waveform model
EM: afterglow light curve



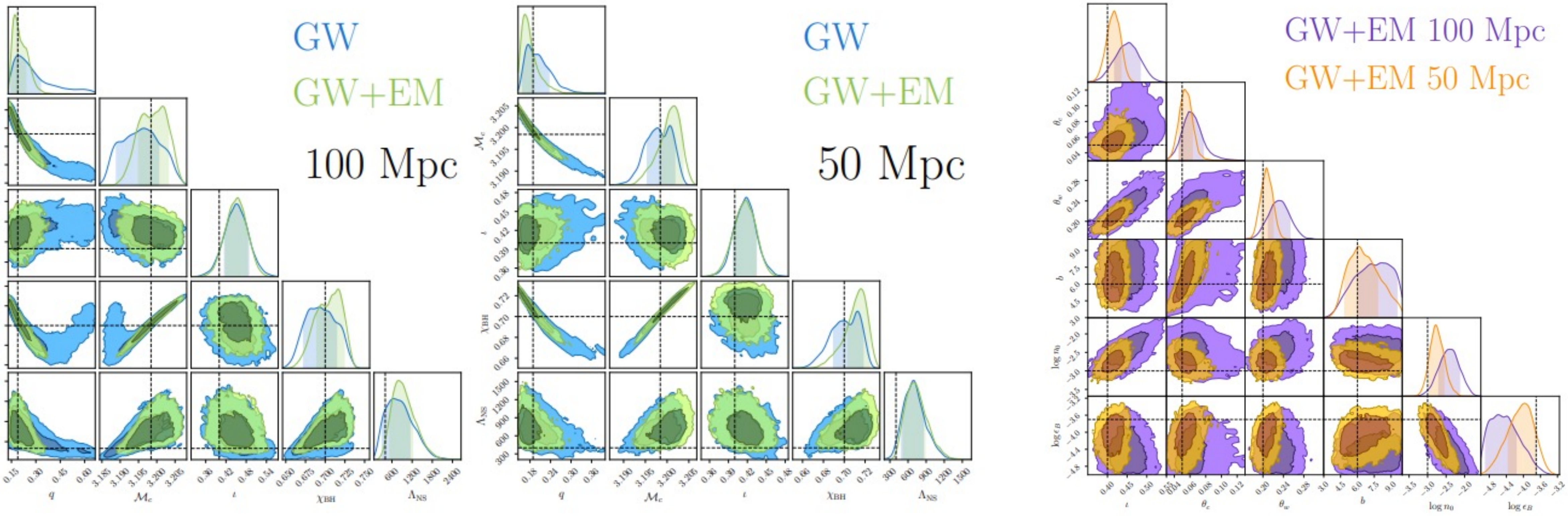
4.7 Setup

Generate a BHNS merger signal with the fiducial parameters

Radio follow-up starts 11 days after the merger until 500 days post-merger: 20 observations equally spaced in Log t

Two distances: d_L = 50 and 100 Mpc

5. Results



Including EM data improves the determination of some parameters (mass ratio)

with little gain on some others (inclination)

6. Discussion

- degeneracy between n_0 and ε_B $\rightarrow$ data at different frequencies to lift the degeneracy $\rightarrow$ improve all parameter estimates
- correlations between parameters: θ_j (other source properties)
- include the kilonova to improve the parameter estimates
- …

7. Summary and conclusion

- combined GW + EM detection not likely with 2G GW detectors (aLIGO)
- about one GW+EM detection/yr with $\chi_{BH} \sim 0.2$ with 3G detectors (ET)
- inferring the source parameters possible from a (nearby) combined detection

Questions

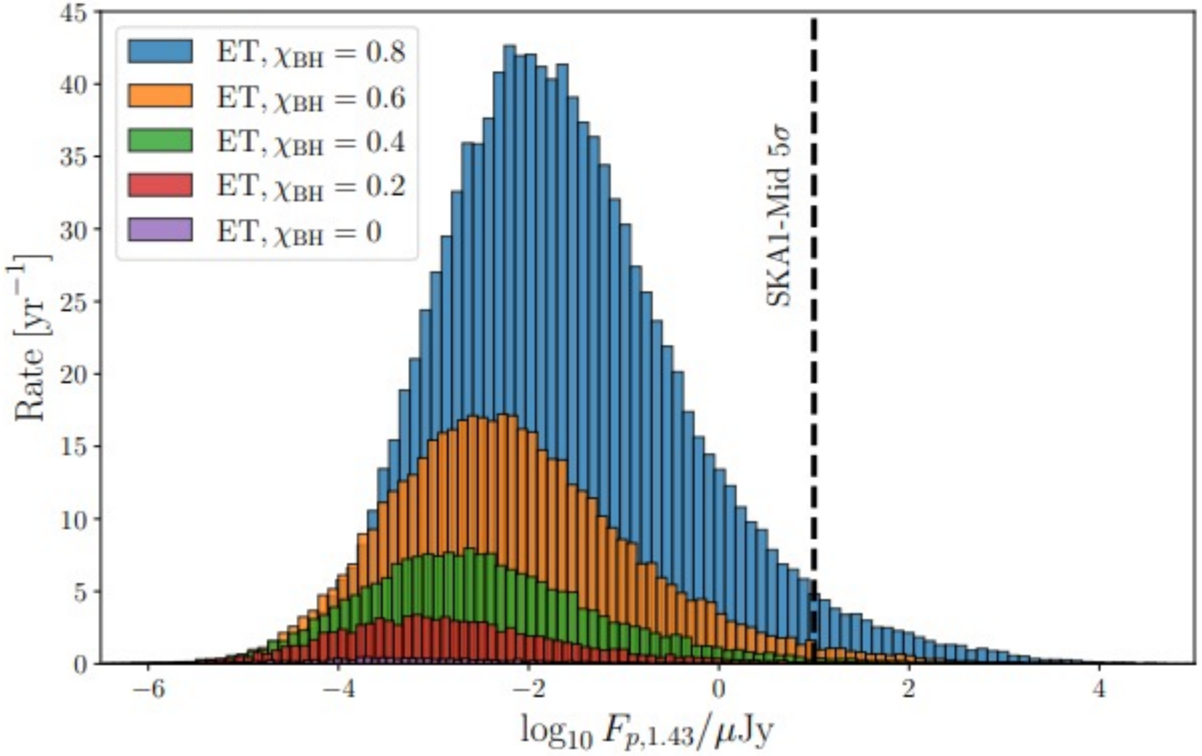
Detections at $d_L \lesssim 100$ Mpc (condition for a good AG lightcurve and reliable parameter estimates) : how frequent ?

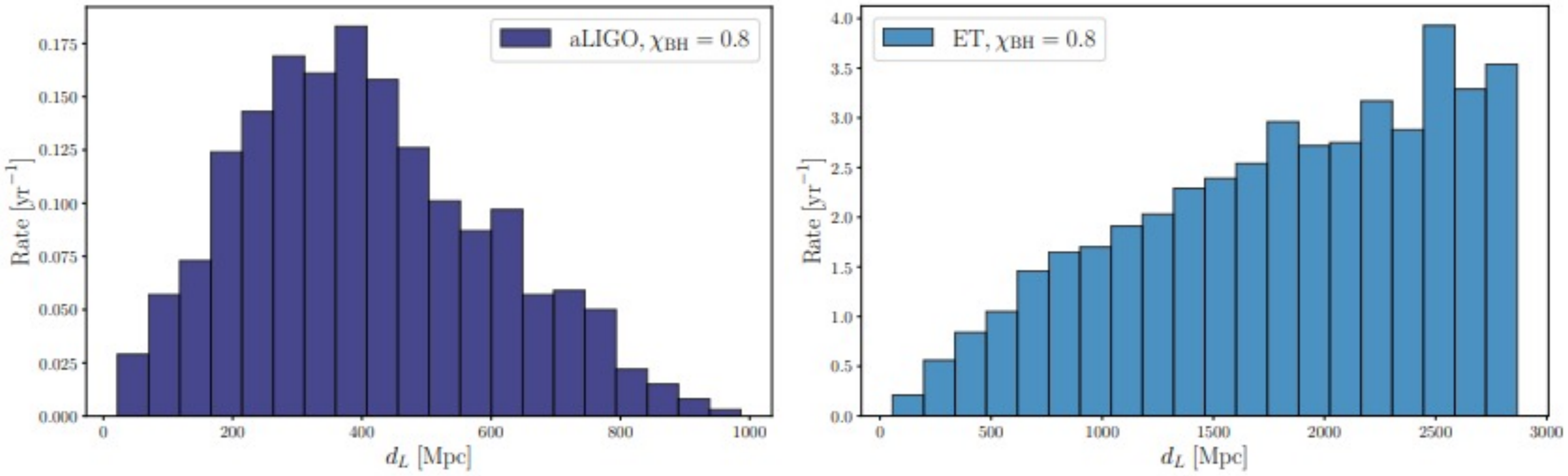
$$\tau = \frac{4\pi}{3} \times {d_L}^3 \times r \times f_{ej} \times (1 - \cos\theta_v)$$

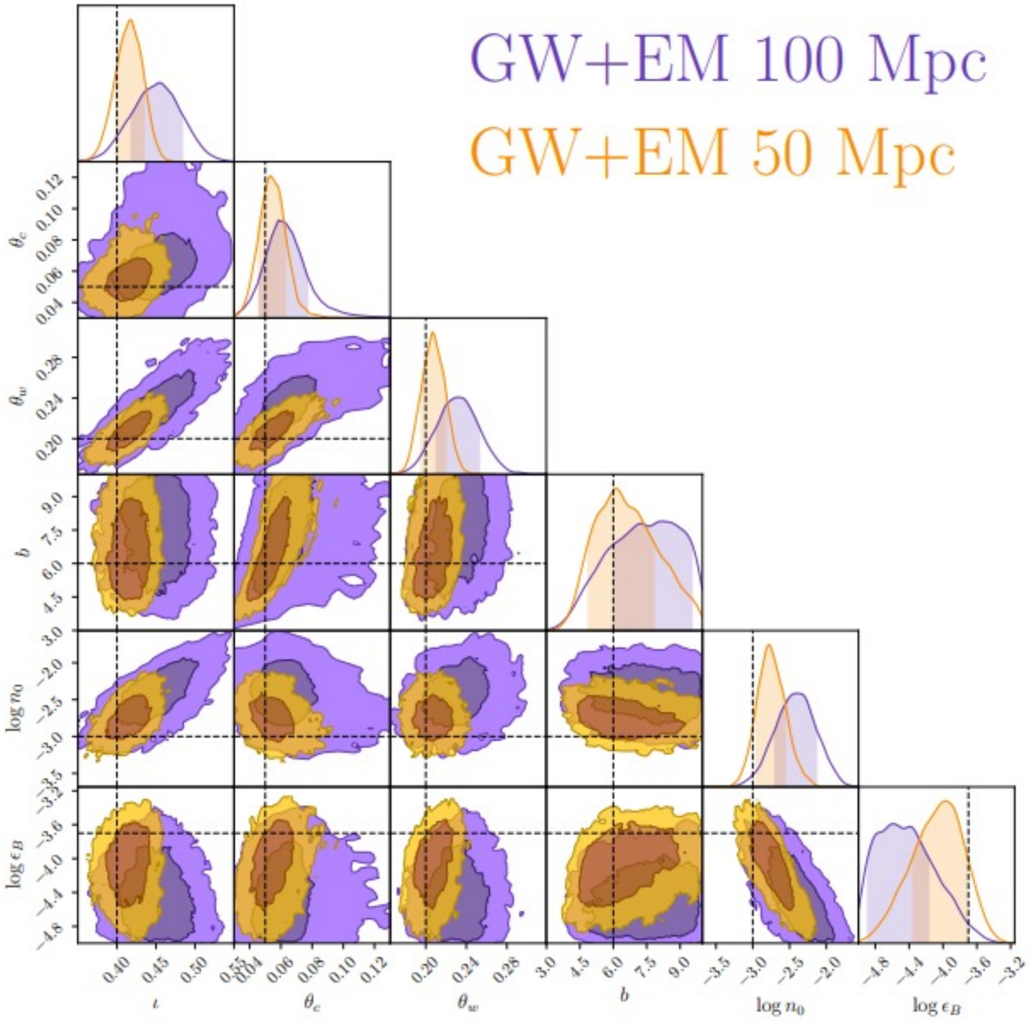
$$r = 4 - 830 \text{ Gpc}^{-3}$$

$\rightarrow$ 1 every 30 years for $d_L = 100$ Mpc, $r = 300$ Gpc^{-3}, $f_{ej} = 0.3$, $\theta_v = 0.4$ rd !

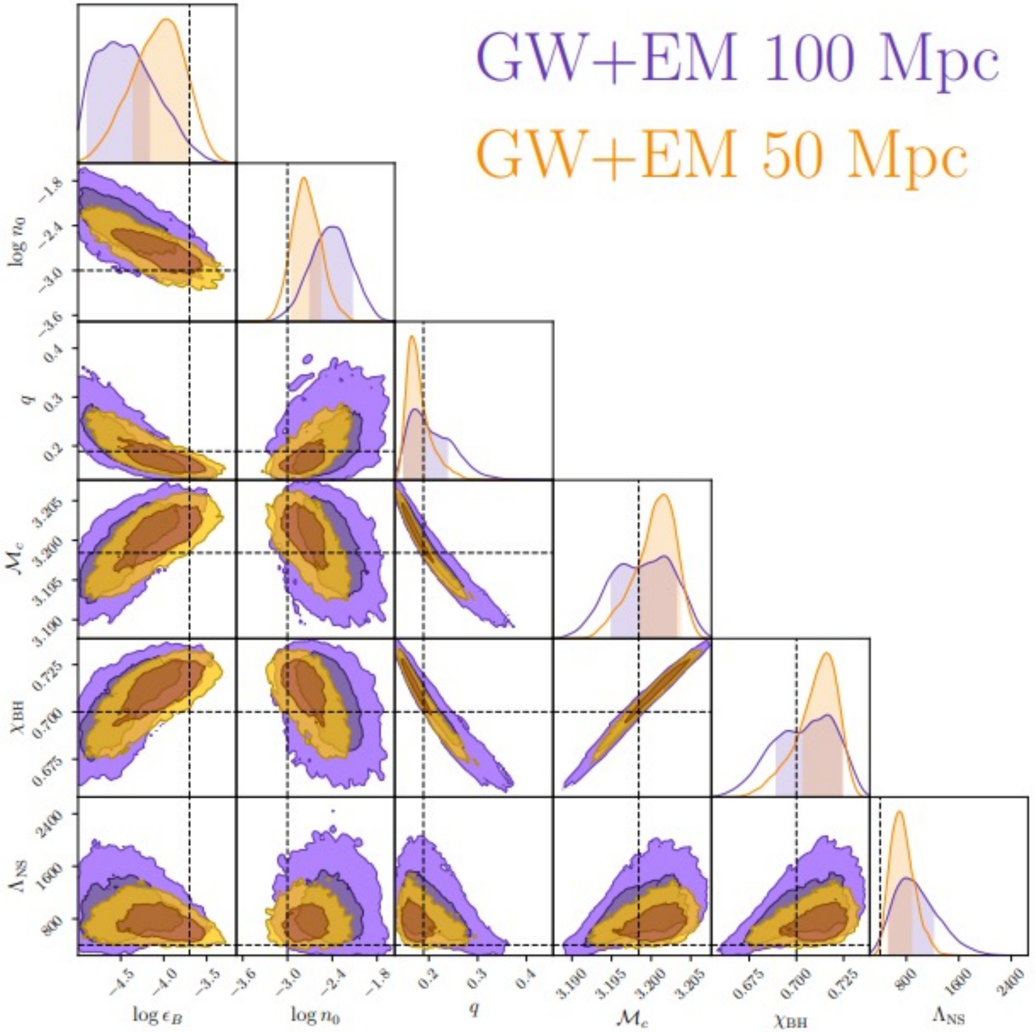
What can we learn from the “tip of the iceberg” lightcurve of a more distant event?


ET, $\chi_{BH} = 0.8$
ET, $\chi_{BH} = 0.6$
ET, $\chi_{BH} = 0.4$
ET, $\chi_{BH} = 0.2$
ET, $\chi_{BH} = 0$
SKA1-Mid 5σ
Rate [yr^{-1}]
$\log_{10} F_{p,1.43}/\mu$Jy
0
5
10
15
20
25
30
35
40
45
−6
−4
−2
0
2
4


aLIGO, $\chi_{BH} = 0.8$
Rate [yr^{-1}]
d_L [Mpc]
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0
200
400
600
800
1000
ET, $\chi_{BH} = 0.8$
Rate [yr^{-1}]
d_L [Mpc]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
500
1000
1500
2000
2500
3000



GW+EM 100 Mpc
GW+EM 50 Mpc
θ_c
θ_w
b
$\log n_0$
$\log \epsilon_B$
ι



GW+EM 100 Mpc
GW+EM 50 Mpc
$\log n_0$
q
$\mathcal{M}_c$
$\chi_{\rm BH}$
$\Lambda_{\rm NS}$
$\log \epsilon_B$