Search for coincident neutrino and gravitational wave emission from binary black hole mergers in the accretion disk of active galactic nuclei

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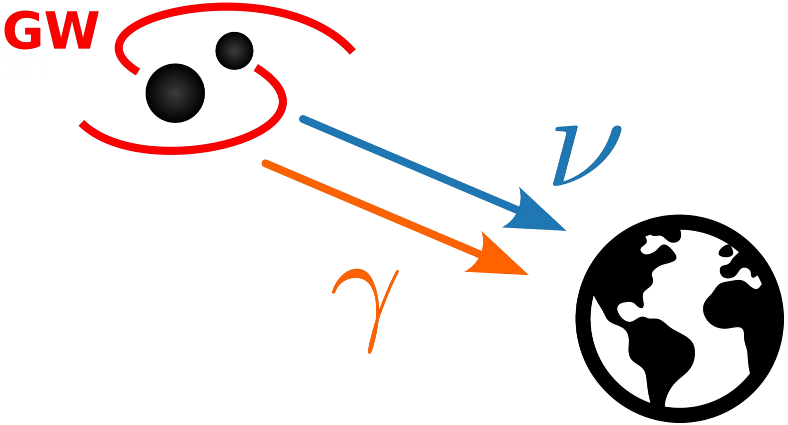
Motivation

Multi-messenger astronomy



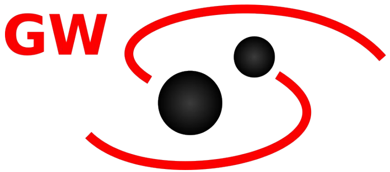
Several such searches already exist!

- ➔ LLAMA analysis (Bayesian)
- ➔ GW Follow-up searches by neutrino observatories (IceCube, KM3Net, SuperK,...)
  - Point-source searches at higher energies
  - Counting analysis at low energies

"General purpose" searches for common source of GW and ν

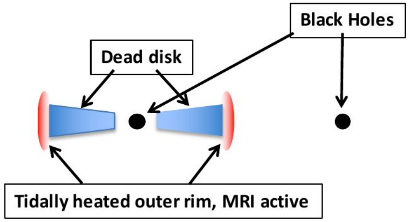
How to get non-GW emission from BBH mergers?

Isolated binaries



✗ No emission

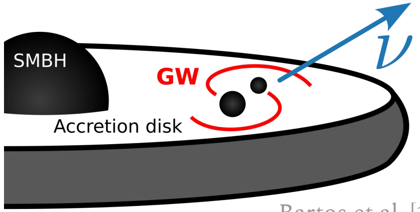
Dead disk



Perna et al. [1602.05140]

√ Remnant disk reactivated

Binaries in AGN accretion disks



Bartos et al. [1602.03831]
McKernan et al. [1907.03746]
Kimura et al. [2103.02461]
Tagawa et al. [2303.02172]
...

√ Many (heavy) black holes
√ Frequent mergers
√ Gas-rich environment

<u>Main take-away:</u>

- *Steal as much as you can from GRB models*
- No clear singular model prediction

BBH mergers in AGN

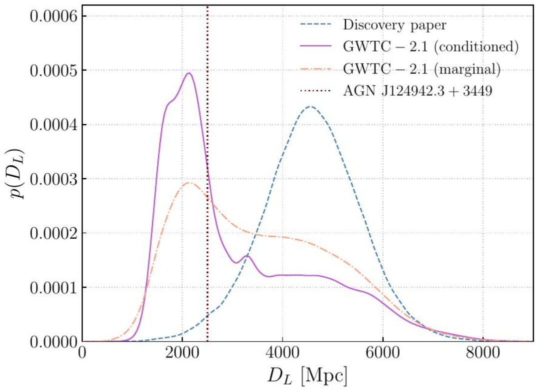
Localization alone can already probe this scenario

➔ "Just" counting AGN

Bartos et al. [1701.02328]
Veronesi et al. [2203.05907]
Veronesi et al. [2306.09415]

GW190521 associated with ZTF19abanrhr from an AGN?

Graham et al. [2006.14122]

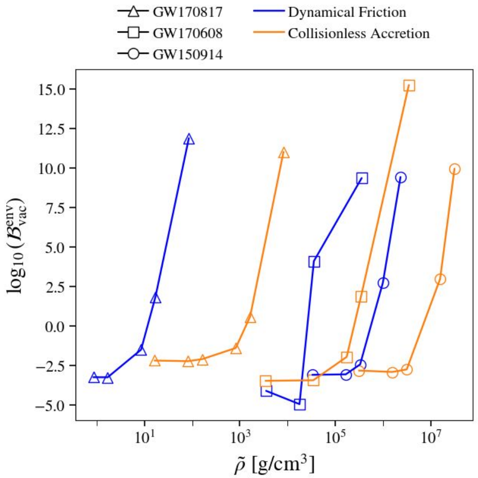


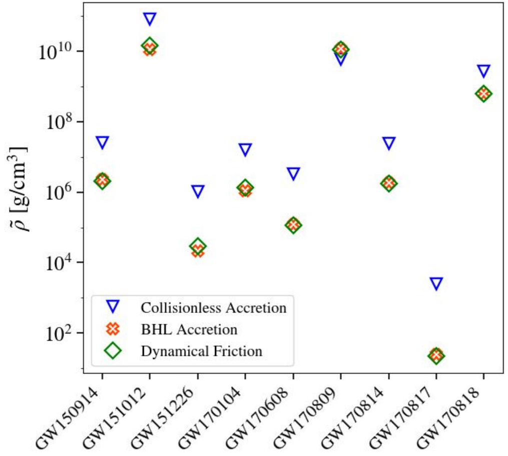
Morton et al. [2310.16025]

Effects on waveform

Effect of gaseous disk environment on waveform

$$\rho \sim 10^{-8} - 0.1(10^5 M_\odot / M_{\rm SMBH})^{7/10} {\rm g/cm}^3$$





Next generation will be able to probe this…

Santoro et al. [2309.05061]

Joint ν-GW search for BBH in AGN disks

Analysis

Given GW event: IceCube ν in a time window T surrounding the event

Compare 2 hypotheses

H_0	**H_1**
ν sky = background	ν sky = background + point source @AGN & GW

Neutrino point-source likelihood

$$\mathcal{L}_{S+B,\nu}(n_s;\hat{x}) = \frac{e^{-(n_s+n_b)}(n_s+n_b)^{N_\nu}}{N_\nu!}\prod_{i=1}^{N_\nu}\frac{n_s\mathcal{S}(\hat{x}_{\nu_i};\hat{x})+n_b\mathcal{B}(\hat{x}_{\nu_i})}{n_s+n_b}$$

$\mathcal{S}(\hat{x}_{\nu_i};\ \hat{x})$ Spatial likelihood signal neutrino

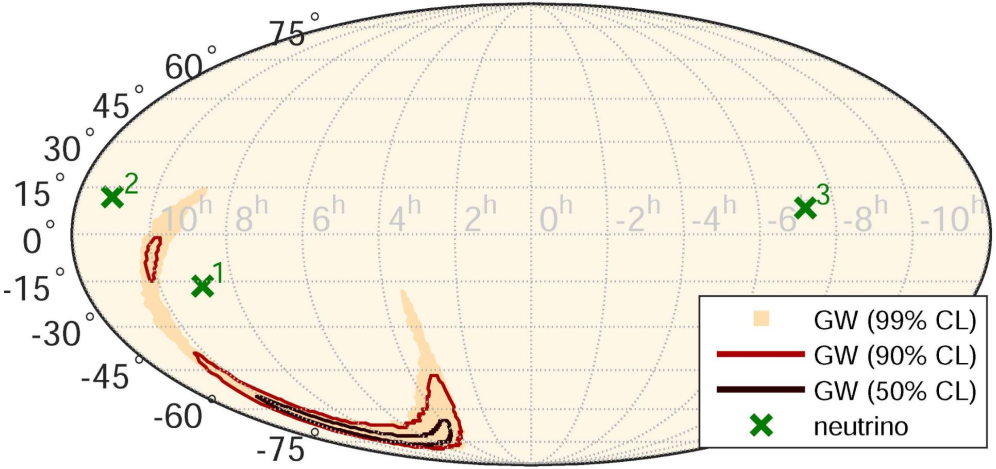
$\mathcal{B}(\hat{x}_{\nu_i})$ Spatial likelihood background

Determine n_s using maximum-likelihood fit

Direction prior (GW skymap)

$$p\left(\hat{x}_{\rm AGN}\,|{\rm GW}\right)$$

GW150914

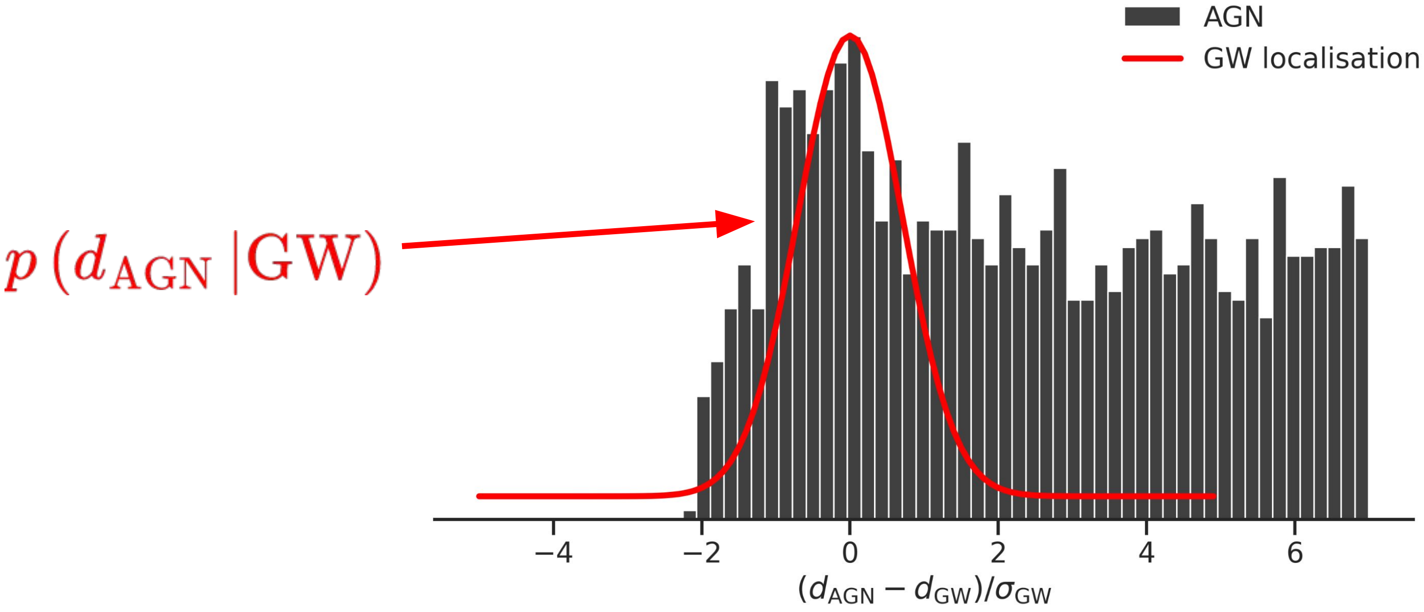


LIGO and Virgo Collab. [1602.03837]
The IceCube Collab. [1602.05411]

Distance prior

Pixel-dependent GW distance probability

E.g. using Véron-Cetty AGN catalogue



Analysis

Best-fit = AGN which maximises TS

$$TS_{\mathrm{AGN}} = 2\ln\left(\frac{\mathcal{L}_{\nu,\mathrm{S+B}}(n_s;\hat{x}_{\mathrm{AGN}})}{\mathcal{L}_{\nu,B}} \times p\left(\hat{x}_{\mathrm{AGN}}\,|\mathrm{GW}\right) \times p\left(d_{\mathrm{AGN}}\,|\mathrm{GW}\right)\right)$$

Similar to existing ν-GW unbinned ML TS

New

Significance:

➔ Perform trials with scrambled neutrino data

➔ Compare obtained TS-distribution with observed TS

AGN catalog

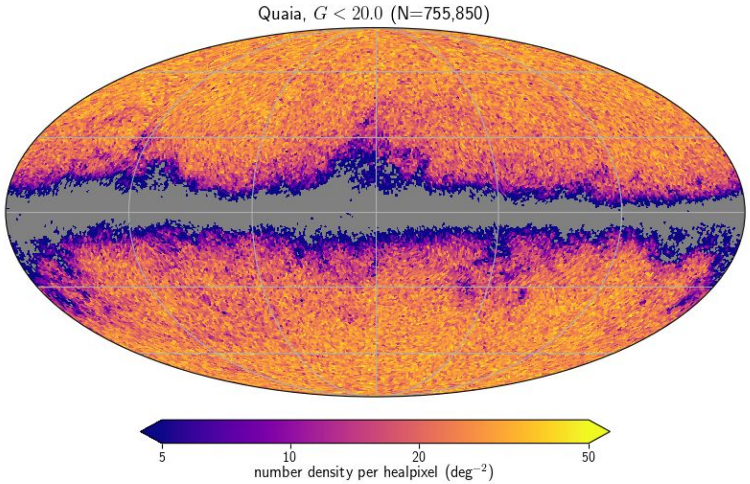
Requirements

- ➔ Number of AGN
  - Too few AGN = miss coincidences
  - Too many AGN = lose sensitivity advantage
- ➔ Uniformity (cover full sky with similar depth)
- ➔ Completeness

Quaia catalog

Quaia = Gaia DR3 quasar candidates (6.6M) ⊗ unWISE (2B+)

- ➔ 755 850 quasars with magnitude G < 20
- ➔ 200 000 up to z<=1
- ➔ G<19, z<=1 only 70k for improved purity



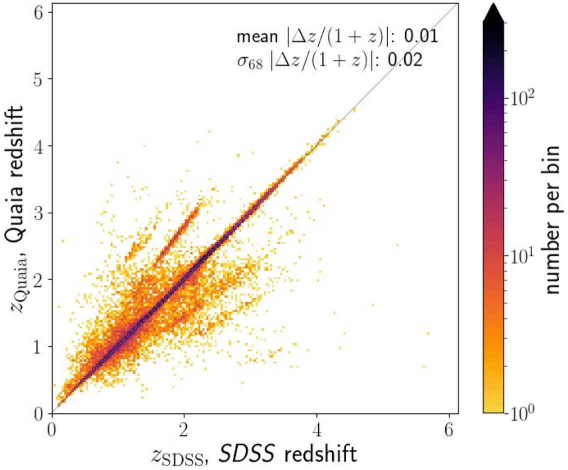
Storey-Fisher et al. [2306.17749]

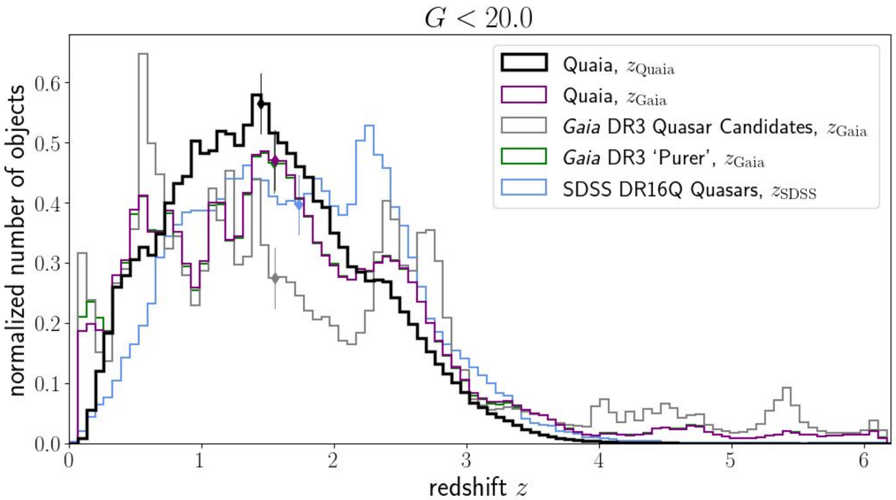

Quaia
SDSS DR16Q
4
3
2
1
0
redshift z

AGN catalog - redshift information

Photometric redshift, inherently less precise...

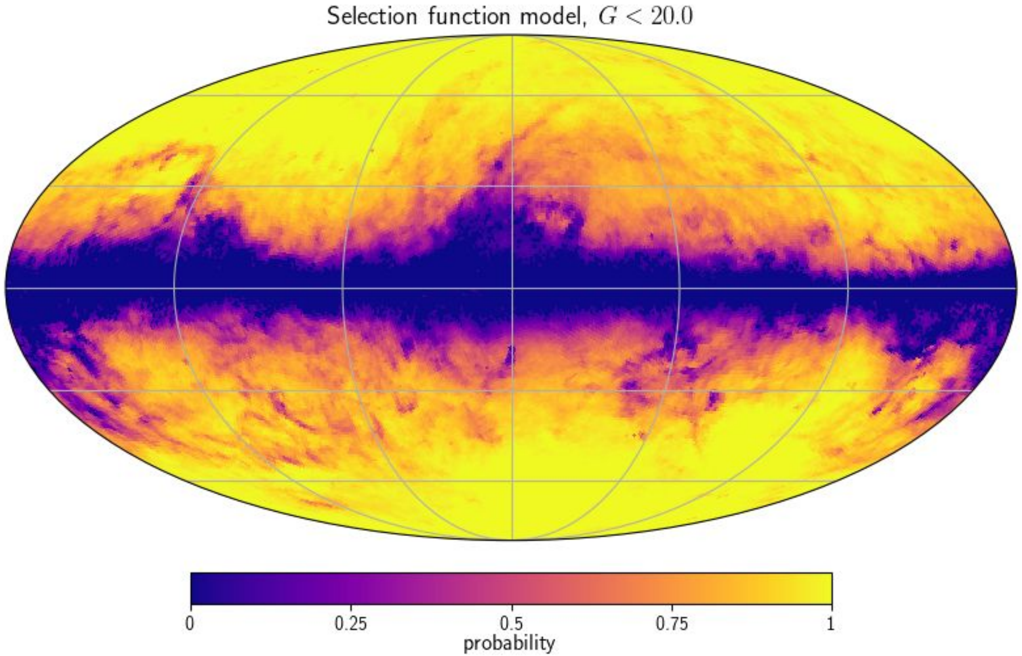
But error on redshift provided!





AGN catalog - Selection function

Measure of completeness provided



Next steps

- ➔ Neutrinos
  - Decide on time window (standard 1000 s)
  - Start with high-energy neutrino sample (100 GeV - ~PeV)
  - Add lower-energy samples in future:
    - GRECO (10 GeV - 100 GeV)
    - ELOWEN (1 GeV - 10 GeV)?
    - Hitspool (raw data, potentially even lower energy)?
- ➔ Gravitational waves
  - Add subthreshold GW - do we add new term to likelihood?
- ➔ AGN Catalog
  - Once analysis is designed, go back and evaluate properties of catalog