GW ,EM, GW-EM ADVANCING SEARCHES, THOUGHTS AND ACTIONS

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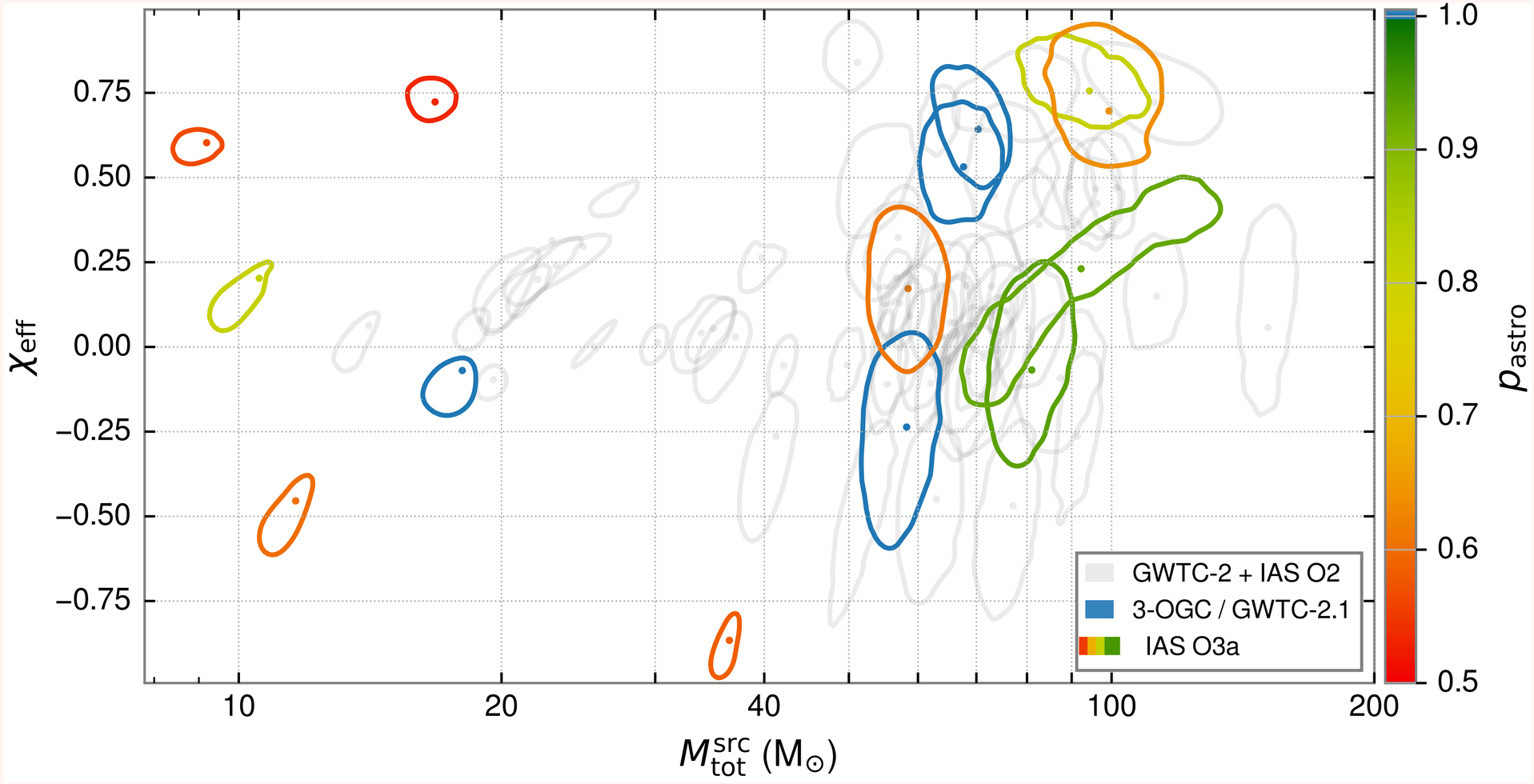
SEARCH PERSPECTIVE ON GW, EM AND GW-EM

- Are we efficient in searching for NSBH? (No, working on it)
- Is optical followup a losing game? (D^10, scale up!)
- Are we efficient in GRB searches? (No, working on it)
- Should we call for making all GRB detector data public?
  (Yes, who wants to lead?)
- What about the GW auxiliary channels? (Have to be public)
- Is archival followup feasible? GRB, Radio?, ZTF/LSST/LAST
- Can we perform Lensing followup for lensed-BBH? (Maybe)

BBH MASSES AND SPINS (O3A)



NEW DISCOVERIES IN O3A - MOTIVATING THE INCLUSION OF PRECESSION + HM

Name	Bank	$m_1(\mathrm{M}_\odot)$	$m_2(\mathrm{M}_\odot)$	χ_{eff}	z	$\ln \mathcal{L}_{\max}$	ρ_{H}^2	ρ_{L}^2	IFAR (yr)[a]	p_{astro}
GW190707_083226	(4, 2)	48^{+16}_{-10}	32^{+10}_{-9}	$-0.1^{+0.4}_{-0.6}$	$0.8^{+0.4}_{-0.3}$	40.1	37.0	31.5	23.2	0.94
GW190711_030756	(3, 1)	70^{+50}_{-30}	19^{+11}_{-7}	$0.2^{+0.3}_{-0.6}$	$0.48^{+0.29}_{-0.18}$	49.8	19.8	60.7	11.2	0.93
GW190818_232544	(4, 3)	57^{+22}_{-15}	37^{+13}_{-12}	$0.76^{+0.19}_{-0.27}$	$1.3^{+0.8}_{-0.5}$	40.8	33.0	32.0	3.4	0.81
GW190704_104834	(0, 0)	7^{+6}_{-2}	$3.2^{+1.2}_{-1.1}$	$0.20^{+0.26}_{-0.13}$	$0.10^{+0.03}_{-0.03}$	48.5	47.0	32.1	2.8	0.81
GW190906_054335	(3, 1)	34^{+12}_{-7}	24^{+6}_{-7}	$0.2^{+0.3}_{-0.5}$	$1.1^{+0.5}_{-0.4}$	30.7	23.6	38.1	0.73	0.61
GW190821_124821	(1, 0)	$7.6^{+3.8}_{-1.8}$	$4.0^{+1.0}_{-1.1}$	$-0.45^{+0.32}_{-0.17}$	$0.17^{+0.07}_{-0.05}$	47.9	28.1	49.4	0.71	0.60
GW190814_192009	(5, 4)	Region where PE is unreliable					29.9	33.4	0.65	0.64
GW190910_012619	(1, 1)	34^{+3}_{-3}	$2.9^{+0.3}_{-0.2}$	$-0.87^{+0.19}_{-0.11}$	$0.16^{+0.05}_{-0.03}$	39.4	35.7	32.1	0.65	0.58
GW190920_113516	(0, 0)	$6.0^{+3.2}_{-1.5}$	$3.1^{+1.0}_{-0.9}$	$0.60^{+0.26}_{-0.07}$	$0.13^{+0.06}_{-0.05}$	40.6	26.4	48.0	0.56	0.57
GW190718_160159	(1, 0)	$10.0^{+4.5}_{-1.9}$	$6.6^{+1.5}_{-2.0}$	$0.72^{+0.11}_{-0.18}$	$0.30^{+0.10}_{-0.10}$	39.0	23.5	47.6	0.48	0.53

Red: Events that further challenge the upper mass gap

Blue: Events that challenge the lower mass gap (some may be NSBH)

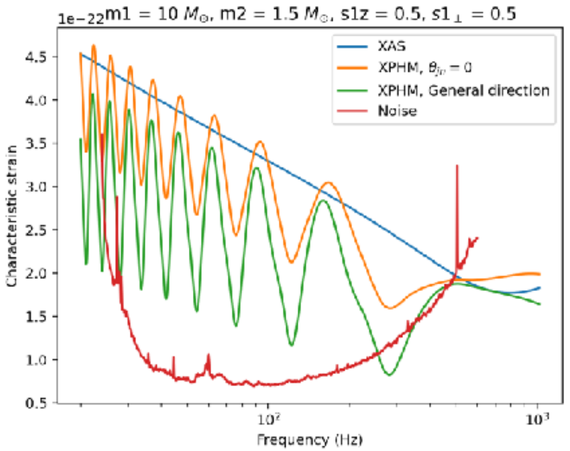
Purple: Events with extreme effective spin, Positive and Negative

Green: Events we expect to rise in significance when including Virgo / HM in the search

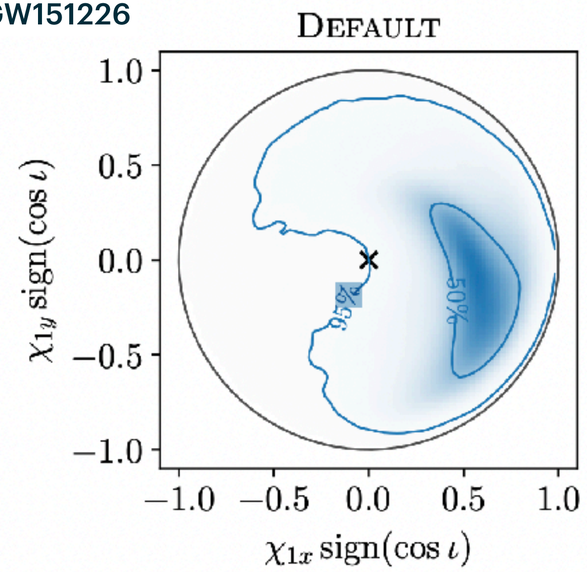
TAKING NSBH SEARCH MORE SERIOUSLY

LIMITATIONS OF CURRENT SEARCHES => NSBH SEARCHES ARE INEFFICIENT

- Higher modes and precession not included.
  - Both become important at high mass ratio (Crucial for NSBH).
  - Can't brute force - Mixing between intrinsic and extrinsic parameters.
- Chicken and egg problem
  - If we don't search we do not find.
  - We then think they do not exist.
- Did we not find?
  - Coordinate system has to be fixed to see this



GW151226



Triggered search that includes precession and HM

Optimal Test Statistic: Bayes Factor (evidence ratio)

$$S(d) = \frac{\mathcal{Z}_1}{\mathcal{Z}_0} = \frac{1}{\mathcal{Z}_0}\int \mathscr{L}(\theta)\Pi(\theta)\mathrm{d}\theta$$

Time consuming with past methods: with lots of effort, can do 100 times

Common Practice in search algorithms:

Matched-Filtering with a template $\boldsymbol{h(\theta)}$

$$S(d) = \underset{\theta}{\mathrm{argmax}} \log\Big(\textbf{Posterior}\ (\theta)\Big) \qquad \theta \in \text{grid}$$

$$\textit{Likelihood} = \mathscr{L}(\theta) \propto \exp\left(\langle d \,|\, h(\theta)\rangle - \frac{1}{2}\langle h(\theta) \,|\, h(\theta)\rangle\right)$$

$$\textit{Prior} = \Pi(\theta)$$

$$\textit{Evidence} = \mathcal{Z} = \int \mathscr{L}(\theta)\Pi(\theta)\ \mathrm{d}\theta$$

$$\textit{Posterior} = \Pr\left(\theta \,\middle|\, d,\ H_1\right) = \frac{\mathscr{L}(\theta)\Pi(\theta)}{\mathcal{Z}_1}$$

Good approximation when posterior is "Gaussian" …

$\textit{Integral} \approx \textit{max+correction}$:

But that's usually not the case in GW Astronomy

Template banks use simplified Physics (no higher modes, no precession)

THE MAGIC INTEGRAL

- **Can factorize the likelihood to:**

$$L(\theta_{\text{int}}, \theta_{\text{ext}}) = \sum_{b,m} A(\theta_{\text{int}})_{b,m} B(\theta_{\text{ext}})_{b,m} C(D, \phi)_m$$

- **Use:**
  - **Precomputed waveforms**
  - **Precomputed extrinsic parameter samples**
  - **Dot => (~10ns per likelihood evaluation)**
- **Result - Evidence integrals in ~10 seconds**
- **Possible use in search!**

Jonathan Mushkin

Javier Roulet

SEARCH DESIGN

Oryna Ivashtenko

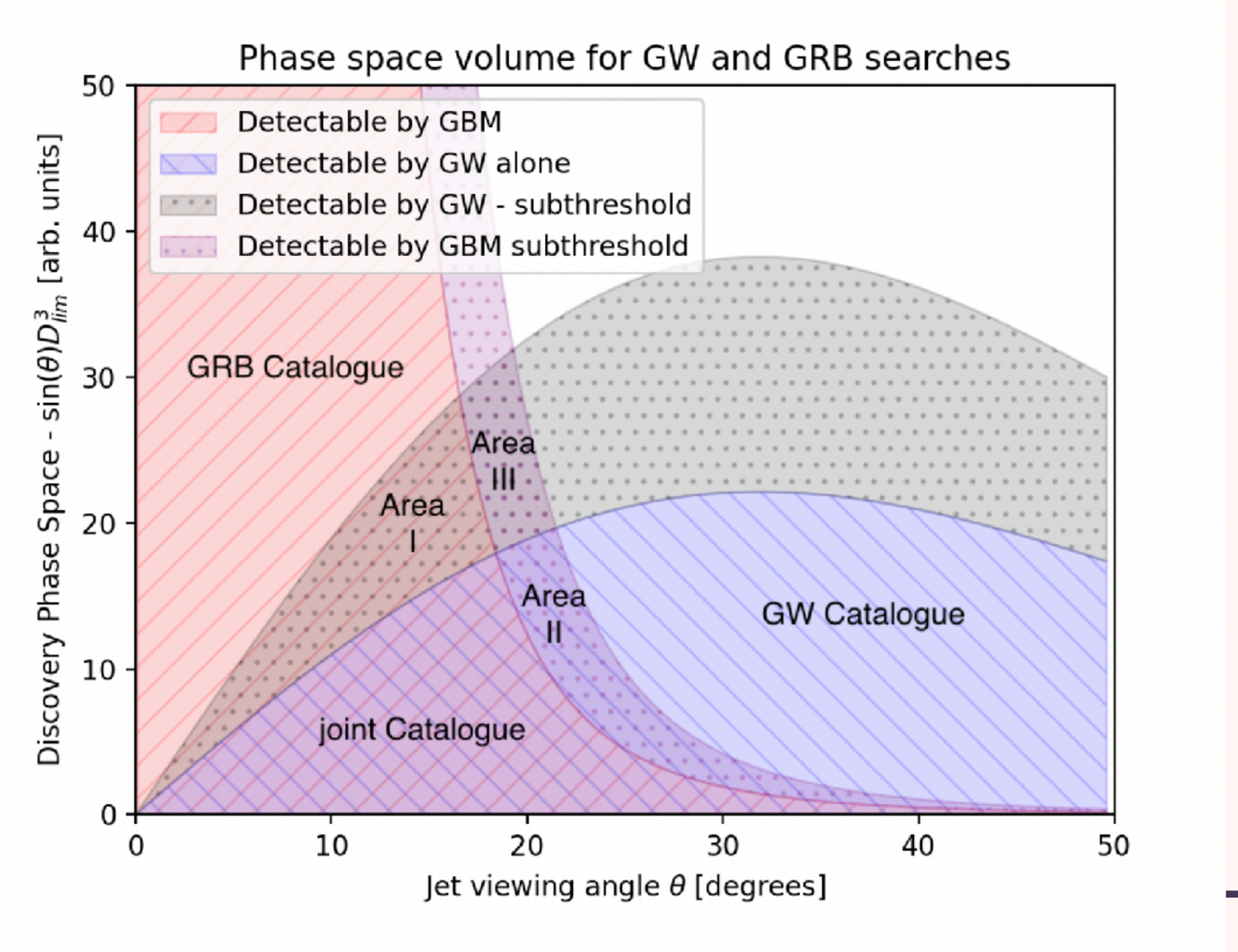
- Precessing waveforms can be written as a sum of 5 “harmonics” (Fairhurst et. Al. 2019)
  - Each waveform (in lower chirp-mass banks) has a unique set of harmonics
  - Combination is intrinsic + extrinsic parameter dependent
  - Use incoherent detection statistic. Passing candidates feed to the “magic integral”.
- An incoherent version of this scheme was recently suggested by (McIsaac et al. 2023)
  => LVK taking it seriously as well.

OPTICAL FOLLOWUP - A LOSING GAME?

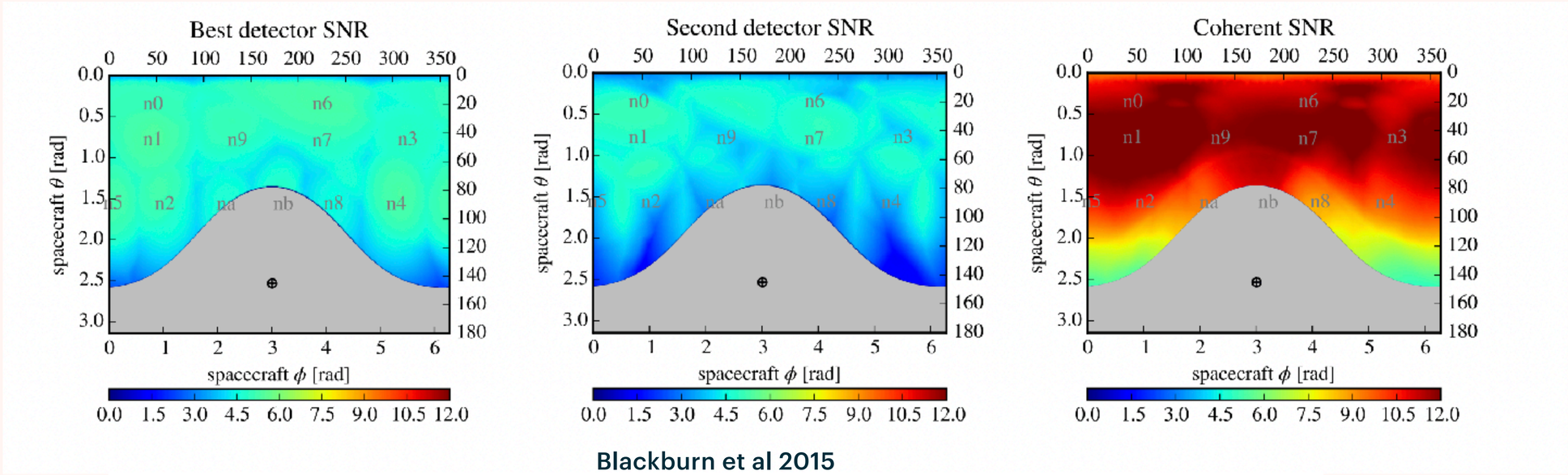
- Imaging scaling:
  - Number of triggers - D^3
  - Exposure time - D^4
- Spectrograph Scaling:
  - Number of triggers - D^3
  - Number of transients for followup - D^3
  - Exposure time per target - D^4
- Solutions:
  - Bigger machines photometry machines - LSST, ULTRASAT
  - Taylor made filters - Can we optimize filters for discriminating SN/AGN from KN?
  - GW detectors in the 0.1Hz range (early warning, ~200 arcsec localization)

TAKING GRB SEARCH MORE SERIOUSLY

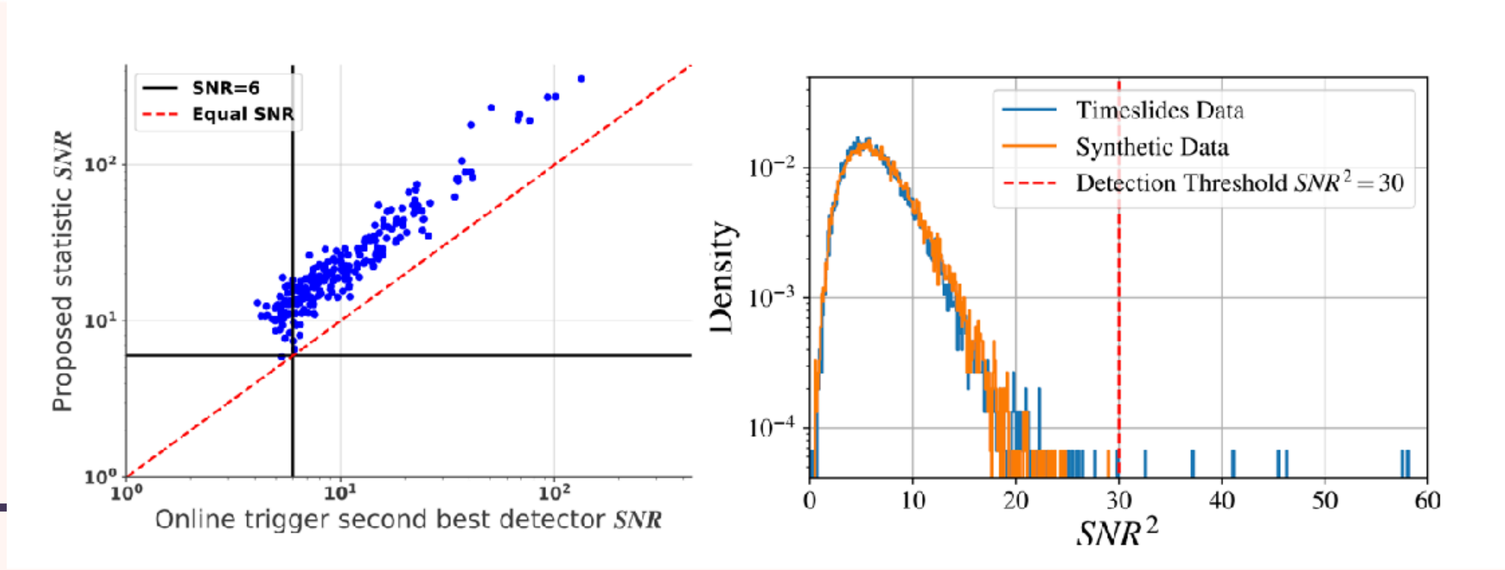
SHOULD WE IMPROVE GRB SEARCHES?



GRB SEARCH WITH RIGOR



Blackburn et al 2015

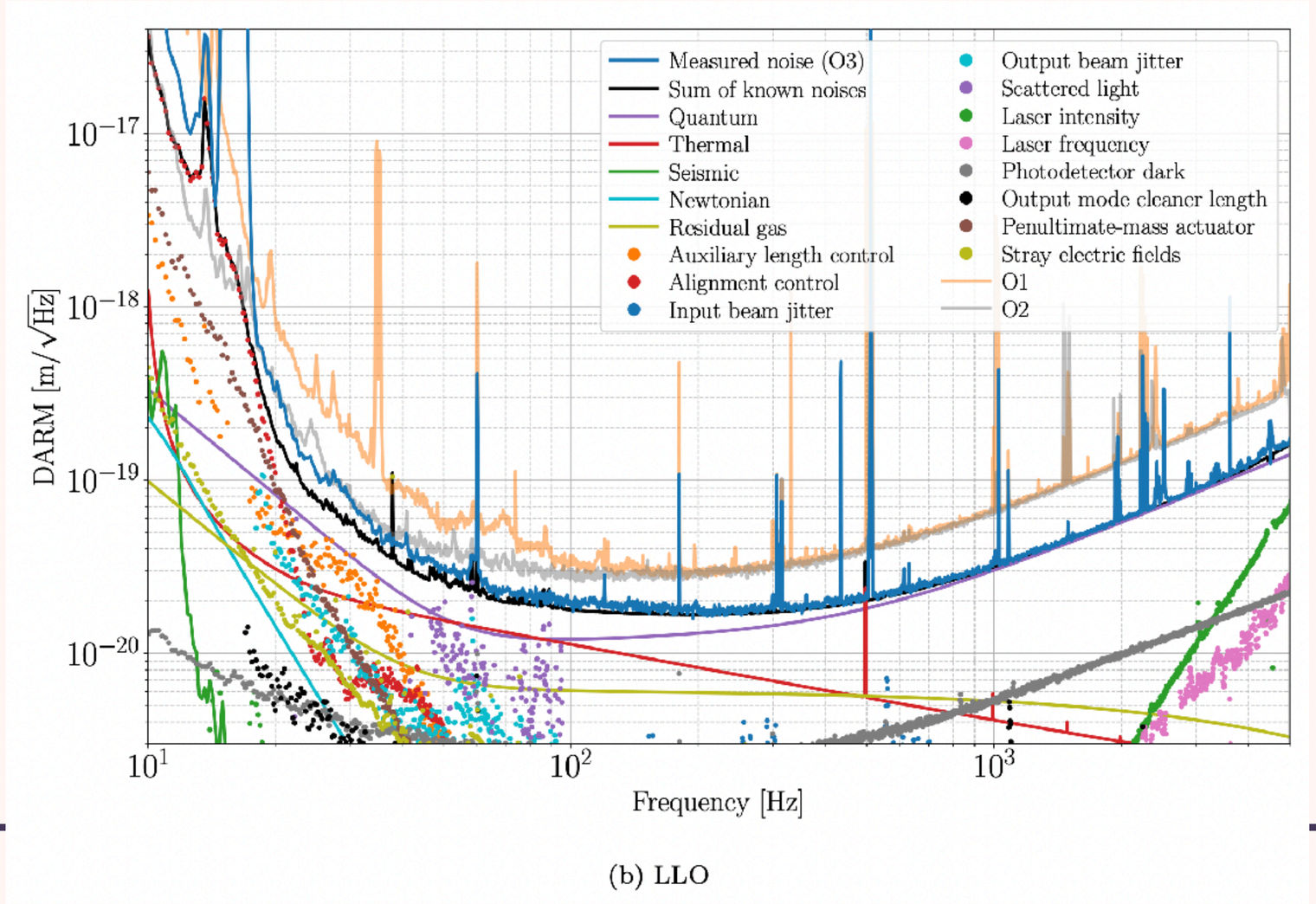


SHARING GRB DATA?

- Fermi-GBM - Data is public
- Swift - Data is public, but requires external triggers (Tohuvavohu et al, 2020)
  - Offline analysis with Nitrates is much better (DeLaunay and Tohuvavohu, 2021)
  - Can we take Nitrates up to SWIFT?
- Integral, (Other?)
- We can combine information! (Reduce false alarm, increase effective area)
- What about all the new missions?
  - SVOM, GECAM, IPN, (more?)

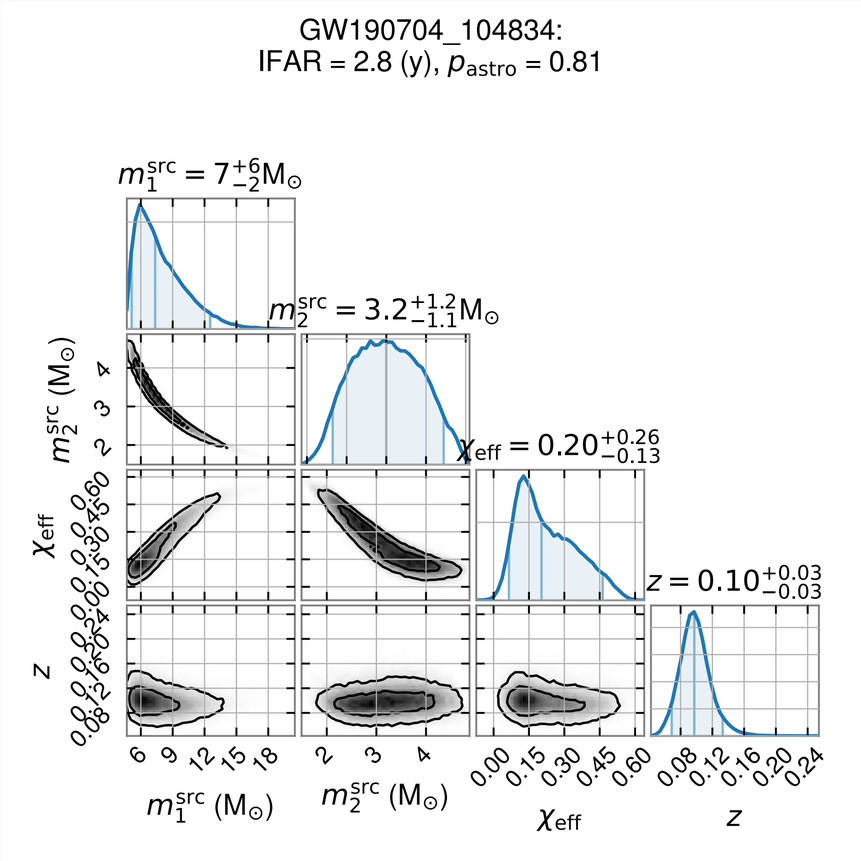
WHAT ABOUT THE GW AUXILIARY CHANNELS?

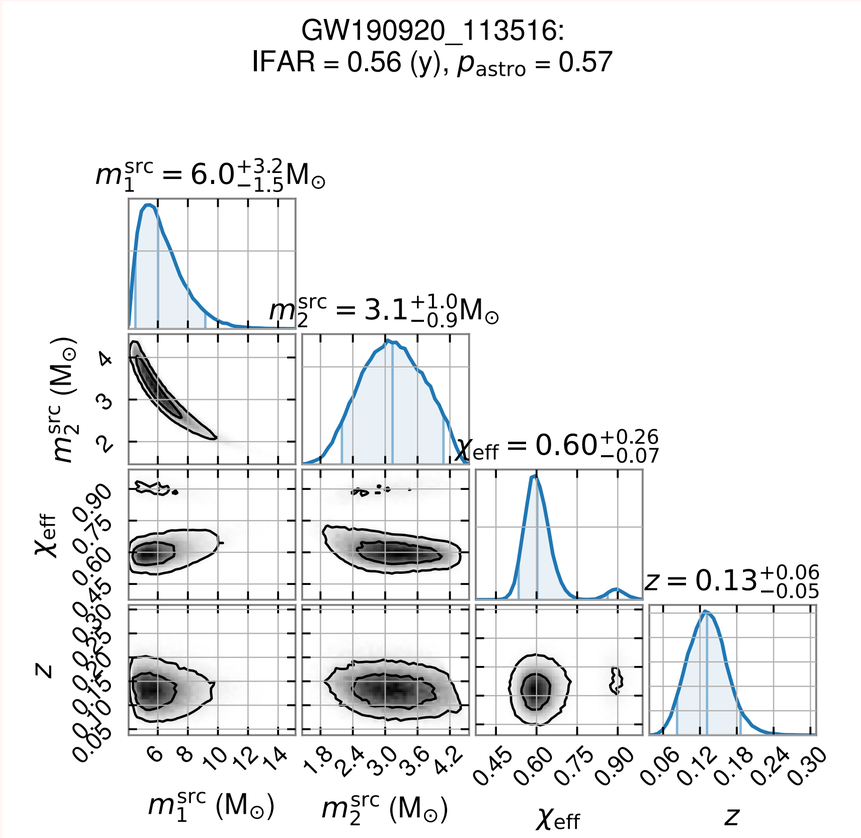
THE POTENTIAL OF THE AUXILIARY CHANNELS



(b) LLO

ARCHIVAL FOLLOWUP OF NSBH?





ARCHIVAL MULTI-MESSENGER SEARCHES?

- **GW170814**
- **GW170104**
- **GWC170620**

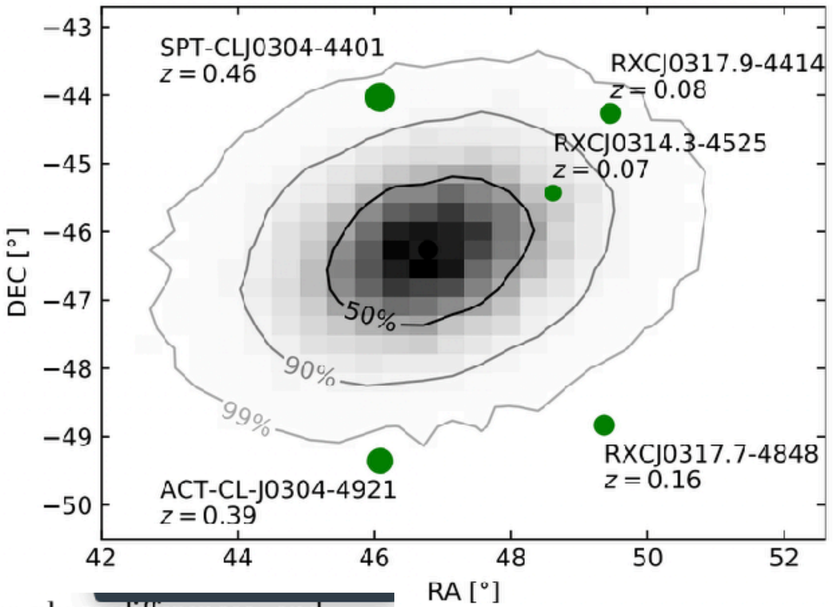


TABLE I: Summary of derived significance and inferred physical parameters. Time delays, Morse phase differences, and magnification ratios are quoted for the three events GW170104, GWC170620 and GW170814 ordered according to the event date.

Item	Value	Reference
Catalog FAP (GW170104, GW170814)	1.1×10^{-2}	Section II
Existence of GWC170620 (GPS time: 1181956460)	1.3×10^{-2}	Section II
Time delays (relative to GW170104)	0, 166.63 days, 222.01 days	Section IV
Morse phase differences (relative to GW170104)	$0, \pi, \pi$	Section III
Magnification ratios (relative to GW170814)	$0.401 \pm 0.08, 0.0719 \pm 0.0024, 1$	Section III
Apparent luminosity distance of GW170814	$D_L^{\mathrm{GW170814}}/\sqrt{\mu_{\mathrm{GW170814}}} = 577^{+159}_{-216}$ Mpc	Section III
Expected number of lensed events in O2	10^{-2}–10^{-3}	[5–9, 20][a]

LET’S CHAT ABOUT

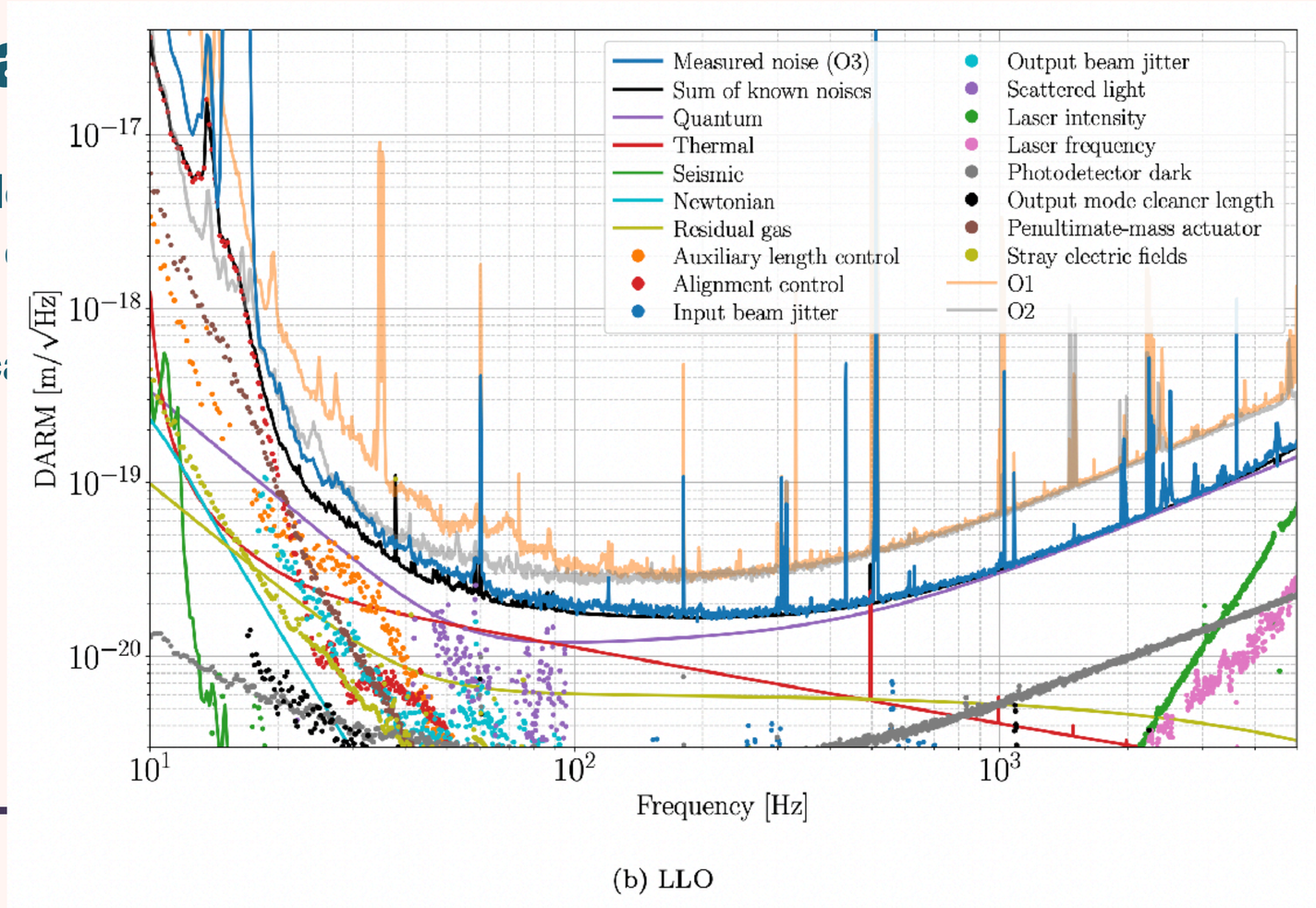
- Can we see both afterglow and KN? (Not sure)
- What about spinning BNS mergers?
- Should we search for sub-solar neutron stars?
- Suppose we see lone KN, will we ever have a way to connect the GW to the EM?

FUTURE PLANS

- Include HM + Precession in the search coherently.
  - Easier said than done, but a few key components are within reach:
    - Fast PE with HM and precession (see Teja's talk tomorrow)
    - Template bank with HM (Jay Wadekar)
- Analyze the GRB-GBM data with the same rigor as we do GW (See Aaron's talk next week for a similar work on Swift-BAT)
- Try and improve h(t) using auxiliary data.
  - Barrier for further improvements in low-frequency?
- Lensing search

DISCUSSION (2)

- **Auxili**
  - **We shoul** **of the data is in public**
  - **Affects c**



(b) LLO