Neutrinos and gravitational waves

Matthias Vereecken

Why are we interested in this?

Gravitational waves

Movement of matter

Neutrinos

Interaction of matter
(inside object or with environment)

Complementary information

Power of multi-messenger astronomy: GW170817

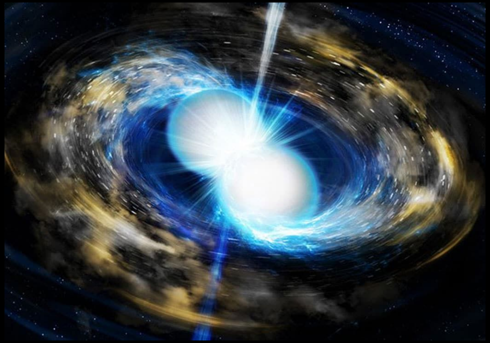
But… no neutrinos seen

Advantage over EM

Escape environment

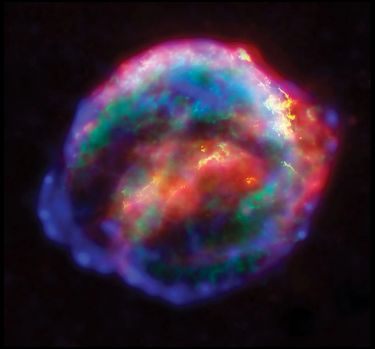
Sources of gravitational waves + neutrinos

Binary neutron star (+NSBH)



Binary black holes

Supernovae



Accretion of matter onto final black hole
Resulting outflow leads to neutrino production

Electron capture during collapse

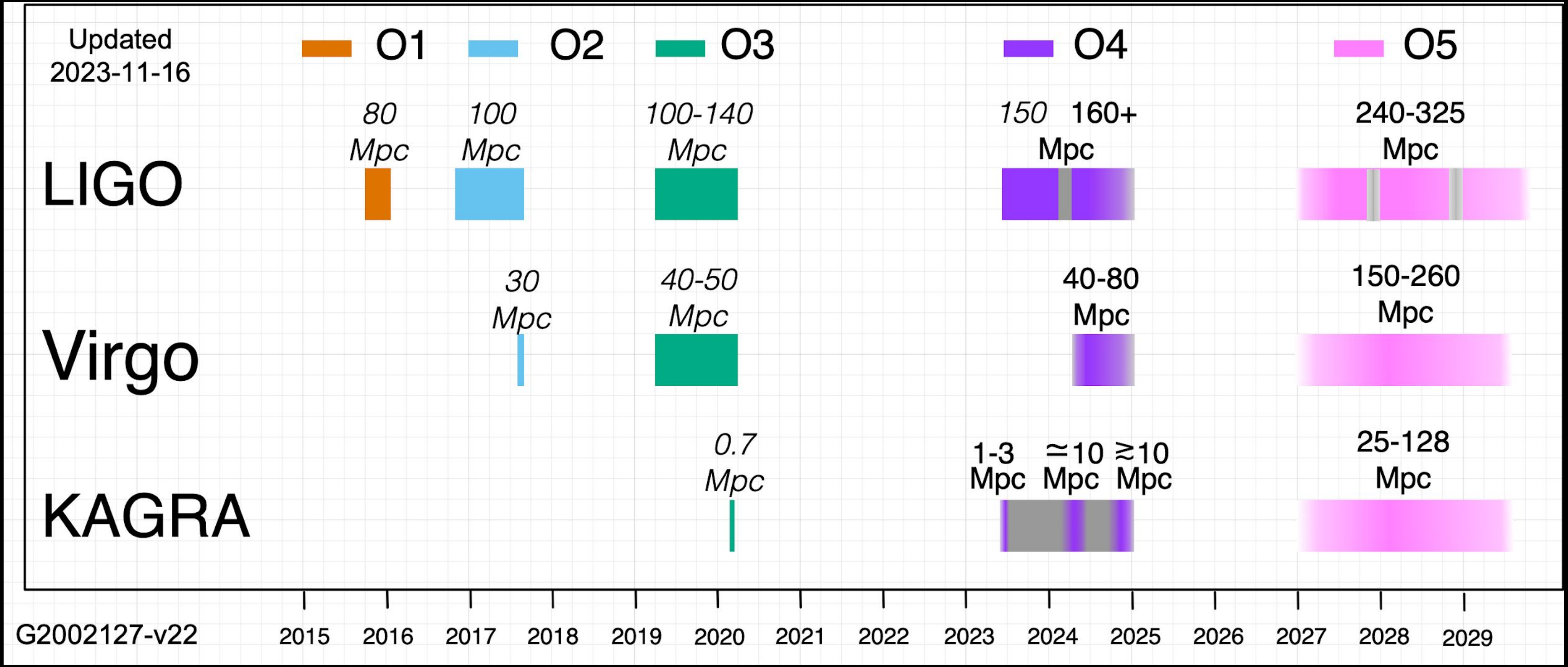
Other: neutrino emission associated to supermassive black hole inspiral De Bruijn et al. [2006.11288]

In practice

GW-triggered neutrino searches

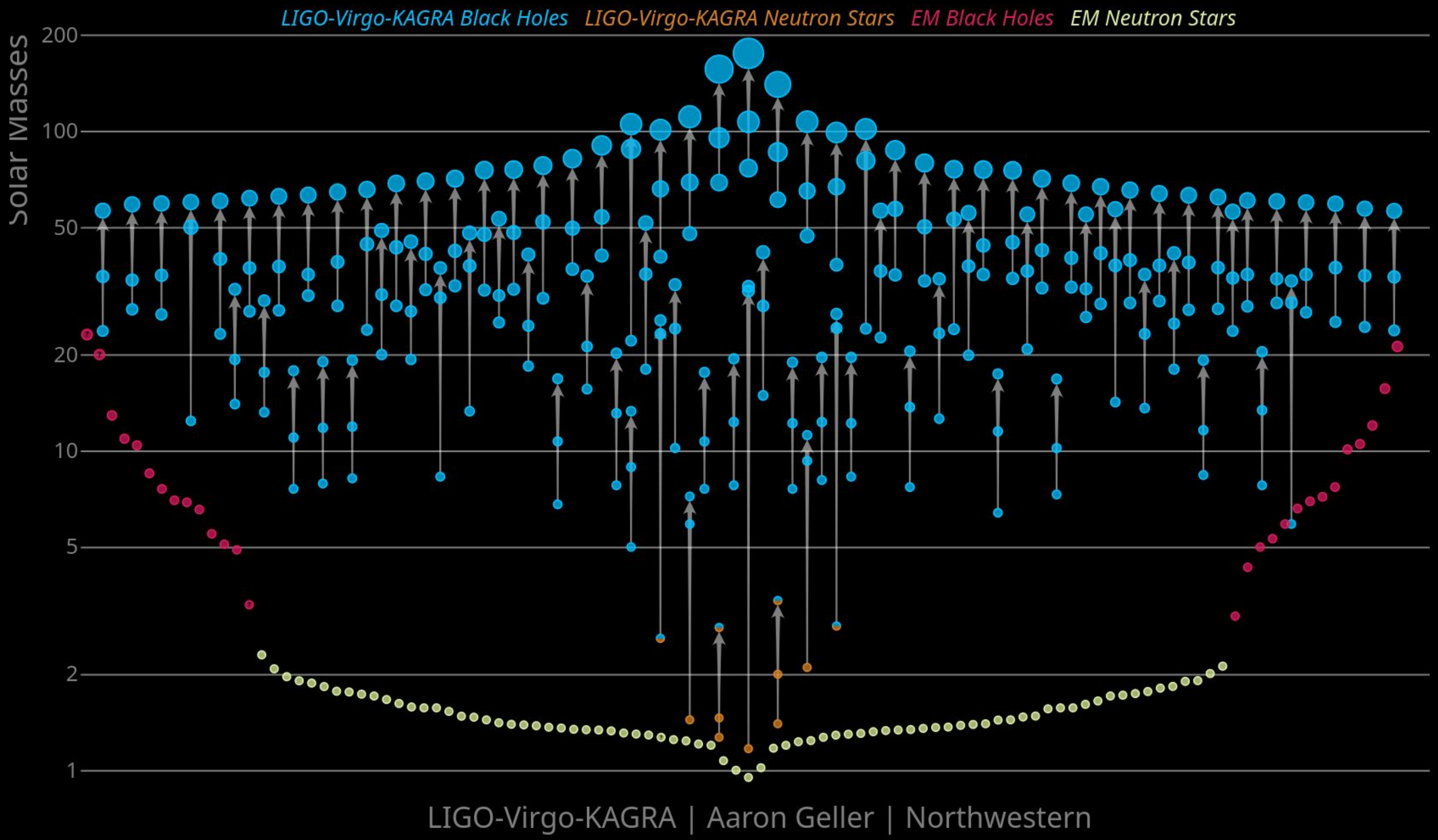
Mostly...
At this time...

GW observing runs



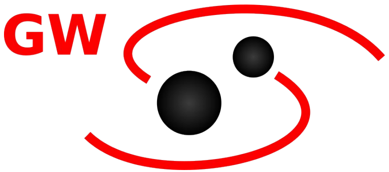
https://observing.docs.ligo.org/plan/

Masses in the Stellar Graveyard



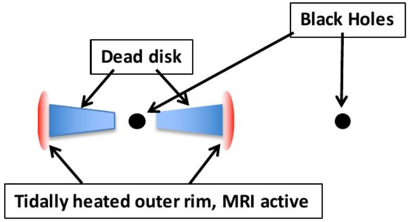
How to get non-GW emission from BBH mergers?

Isolated binaries



✗ No emission

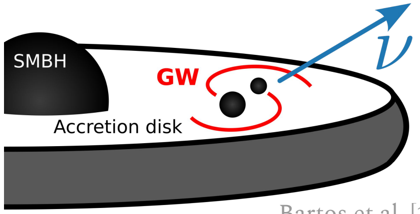
Dead disk



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

Quantifying limits on neutrino flux

Limits from individual events

$$E_\nu^{\mathrm{iso}}$$

Note: beaming effects complicate limits

Sometimes re-expressed in terms of

$$f_\nu^E = \frac{E_\nu^{\mathrm{iso}}}{E_{\mathrm{GW}}} \quad \text{or} \quad f_\nu^M = \frac{E_\nu^{\mathrm{iso}}}{M_{\mathrm{tot}}}$$

Population/stacking limits

assuming all mergers have same E_ν^{iso}, f_ν^E, or f_ν^M

Limits on neutrino flux

Motivation for f_ν^E or f_ν^M?

Large variation of BBH masses = need to assume *some* scaling

Physical models have f_ν^E, $f_\nu^M < 1$

If universal: strong limits from diffuse flux $f_\nu^E < 10^{-5}$

Compared to typical per-event limit from IceCube of $f_\nu^E \sim 10^{-2}$

Conclusion: significant individual detection = exceptional event

De Vries et al. [1612.02648]

Neutrino search methods

➔ *Cut-and-count*

Number of ν from GW direction

➔ *Unbinned maximum likelihood + spatial prior*

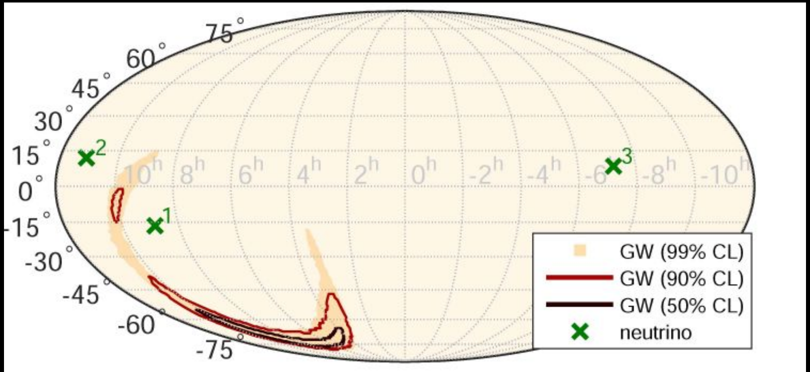
$$TS = \max 2 \ln \left(\frac{\mathcal{L}_{S+B,\nu}(\vec{x};n_s)}{\mathcal{L}_{B,\nu}(\vec{x};n_s=0)} \times p_{\mathrm{GW}}(\vec{x}) \right)$$

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

➔ *LLAMA pipeline with Bayesian odds ratio*

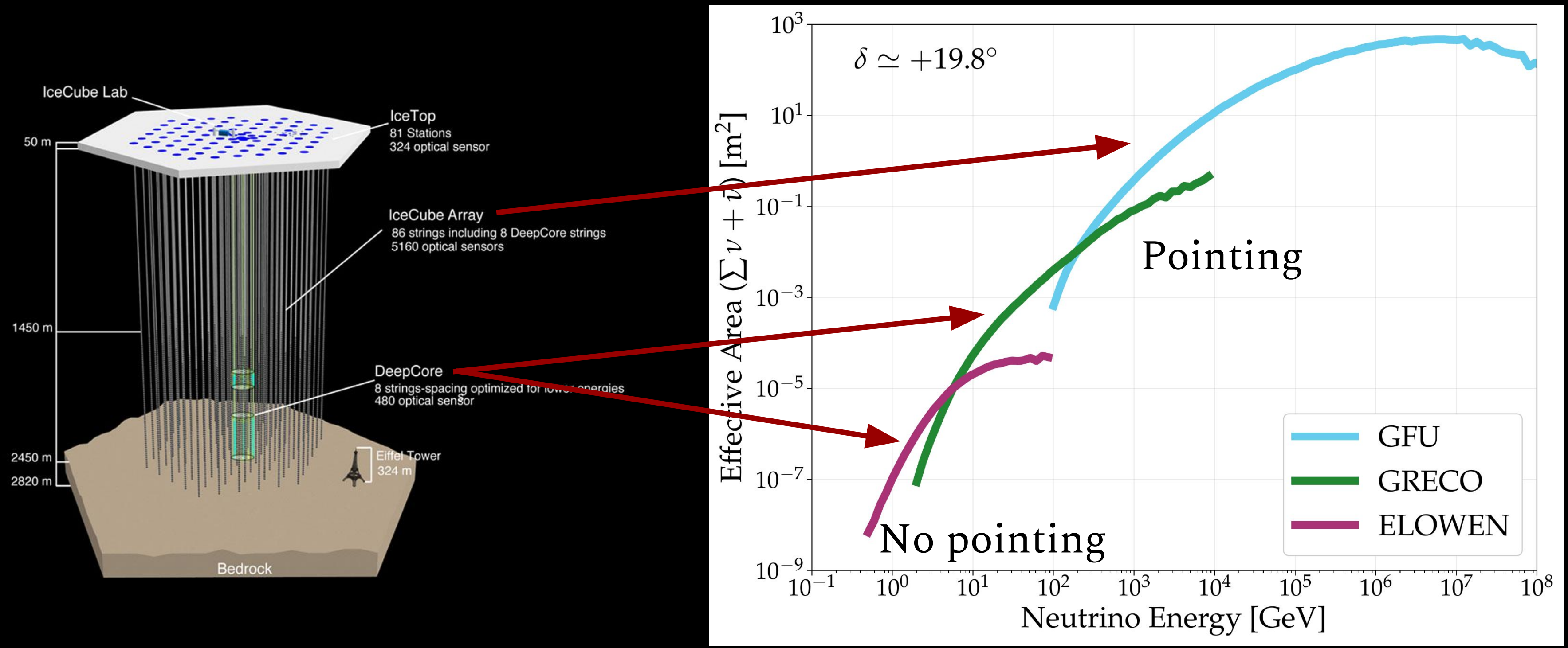
Considering all combinations of signal/background hypotheses

GW150914 skymap



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

IceCube searches



The IceCube Collab. [2302.05459]

IceCube GWTC-3 follow-up

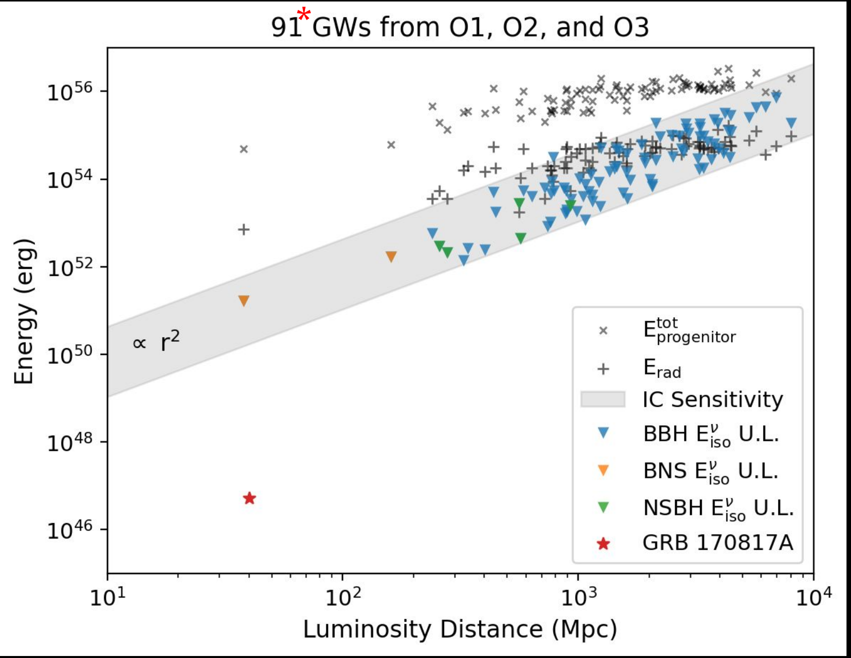
GFU

- Unbinned maximum likelihood
- LLAMA

Online + offline

Time windows:

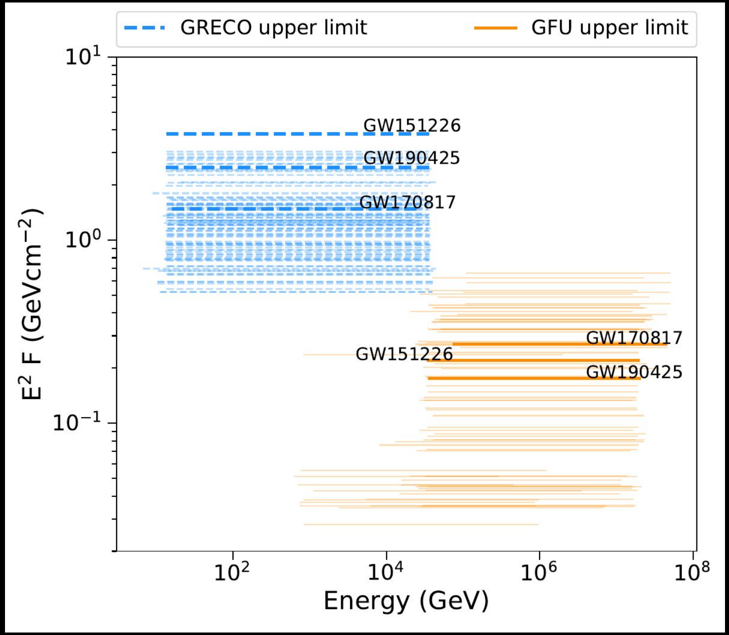
- 1000 s
- 2 weeks if neutron star
- Custom for GW190521 with ZTF association



The IceCube Collab. [2208.09532]

* 90 confident events from GWTC-3 + GW200105_162426 a NSBH candidate with p_{astro}<0.5

IceCube GWTC-3 follow-up



GRECO

Unbinned maximum likelihood

The IceCube Collab. [2303.15970]

Also search for associations with sub-threshold gw events

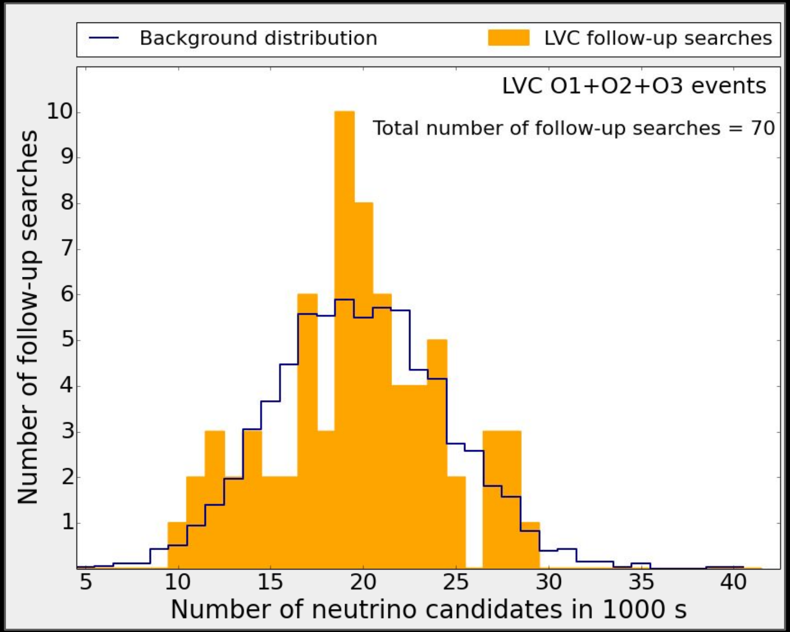
The IceCube Collab. [2308.06102]

IceCube GWTC-3 follow-up

<u>ELOWEN</u>

No pointing so Poisson counting analysis

0.5-5 GeV energy range probes different emission regime

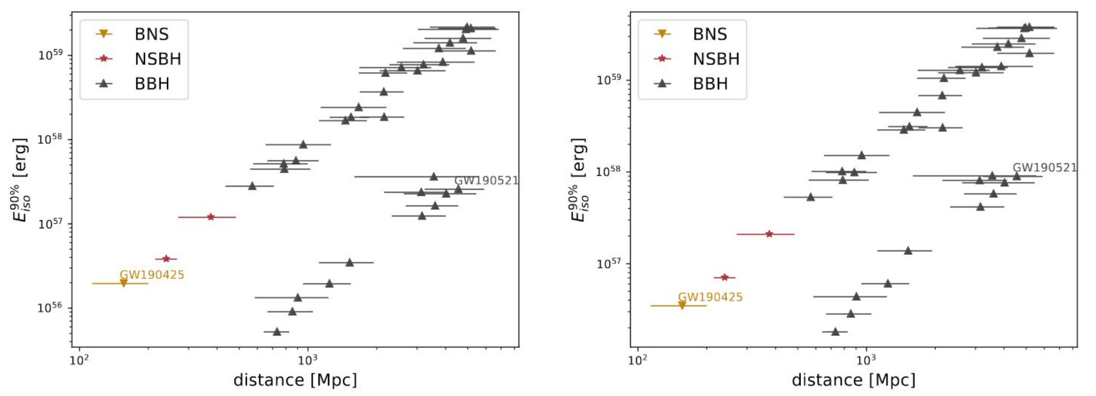


The IceCube Collab. [2105.13160]

Super-Kamiokande O3a

Low-energy analysis

- 7-100 MeV
- Inverse beta-decay (ν_e) and elastic scattering (all ν)
- Poisson counts



(a) Limits on $E_{\rm iso}^{\nu_\mu}$ (b) Limits on $E_{\rm iso}^{\rm all-flavors}$

High-energy analysis

- 0.1-1e5 GeV
- ν_e and ν_μ
- Spatial likelihood x time likelihood

Super-Kamiokande Collab. [2104.09196]

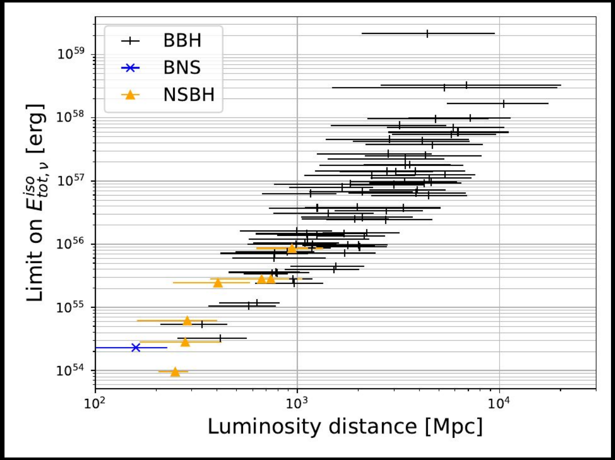
ANTARES O3

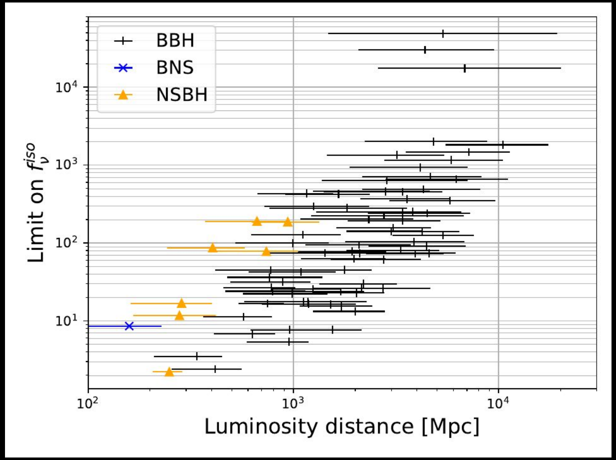
Cut-and-count analysis

- Tracks and showers
- From 90% GW skymap + buffer angle

ANTARES Collab. [2302.07723]

Also stacking analysis $f_\nu^E < 0.15$





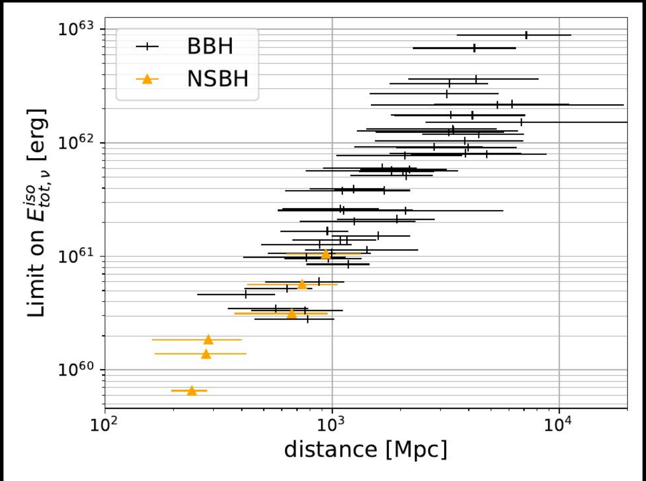
KM3Net O3

Partial detectors: ORCA4 and ORCA6

KM3Net Collab. [2311.03804]

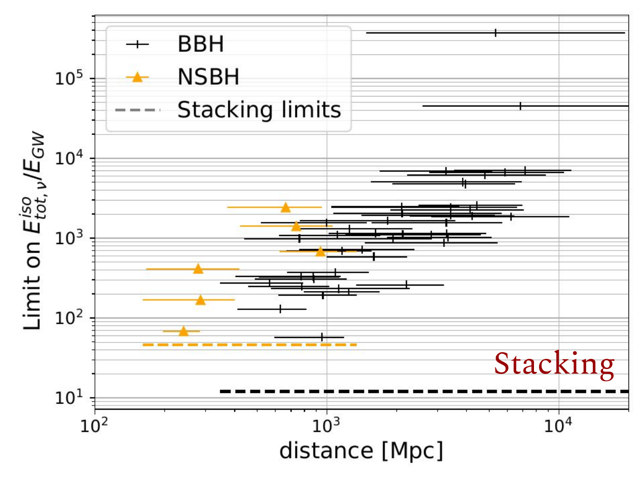
<u>Low-energy search</u>

- MeV neutrinos
- Inverse beta-decay
- Global rate in 2s time window

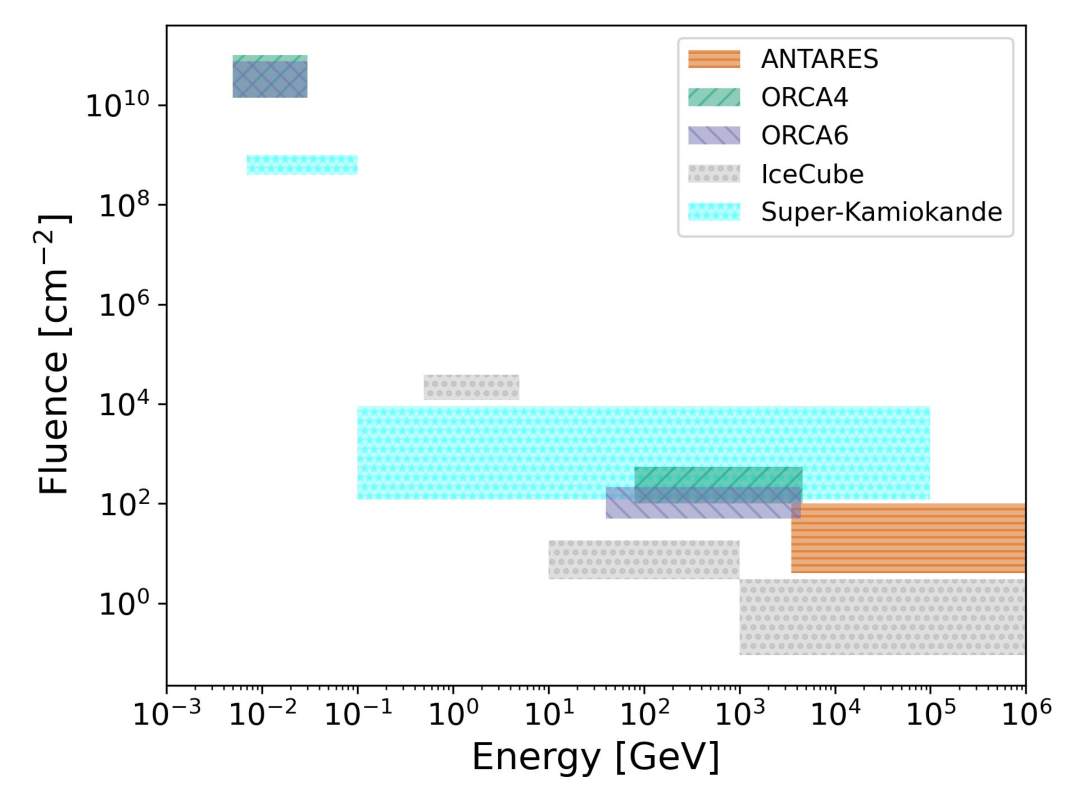


<u>High-energy search</u>

- Upgoing tracks from GW skymap + buffer
- 1000 s time window
- Cut-and-count



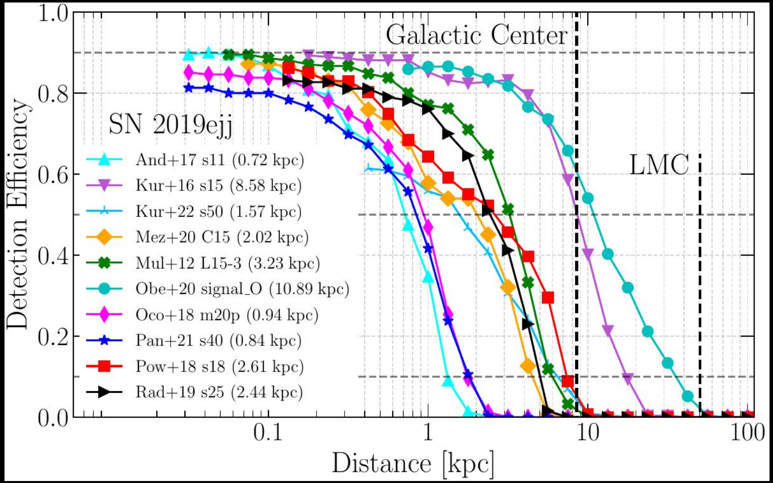
Summary of searches



KM3Net Collab. [2311.03804]

GW from supernovae

Both GW and neutrino observatories perform SN searches



Supernova	Type	Host Galaxy	Distance [Mpc]	t_1 [UTC]	t_2 [UTC]	Δt [days]	OSW Method	$T_{\rm coinc}$ [days]
SN 2019ehk	IIb	NGC 4321	16.1	2019 Apr 23.10	2019 Apr 24.50	1.40	2	0.41 (29%)
SN 2019ejj	II	ESO 430-G20	15.7	2019 Apr 23.28	2019 Apr 30.86	7.58	3	1.25 (16%)
SN 2019fcn	II	ESO 430-G20	15.7	2019 May 03.02	2019 May 07.56	4.54	3	2.51 (55%)
SN 2019hsw	II	NGC 2805	28.2	2019 Jun 05.14	2019 Jun 13.14	8.00	1	5.08 (64%)
SN 2020oi	Ic	NGC 4321	16.1	2020 Jan 02.48	2020 Jan 06.18	3.70	2	2.56 (69%)
SN 2020cxd	IIP	NGC 6395	20.9	2020 Feb 16.53	2020 Feb 22.53	6.00	1	4.58 (76%)
SN 2020dpw	IIP	NGC 6952	22.3	2020 Feb 21.08	2020 Feb 25.08	4.00	1	3.06 (77%)
SN 2020fqv	IIb	NGC 4568	17.3	2020 Mar 22.00	2020 Mar 28.00	6.00	1	4.06 (68%)

Szczepańczyk et al. [2305.16146]

Back to BBH mergers in AGN

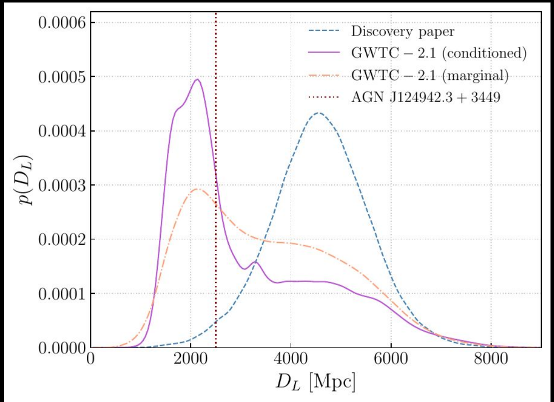
Localization alone can already probe this scenario

➔ "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]



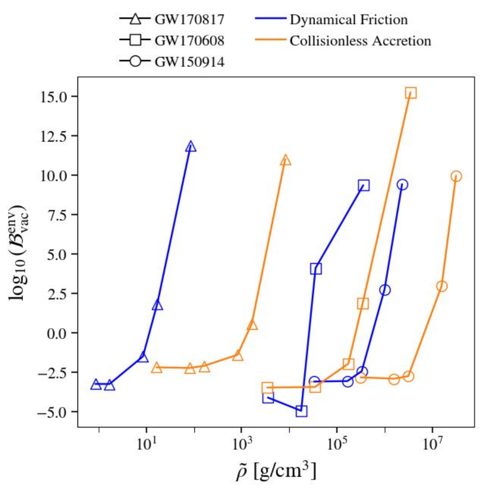
Updated localisation compatible with this hypothesis

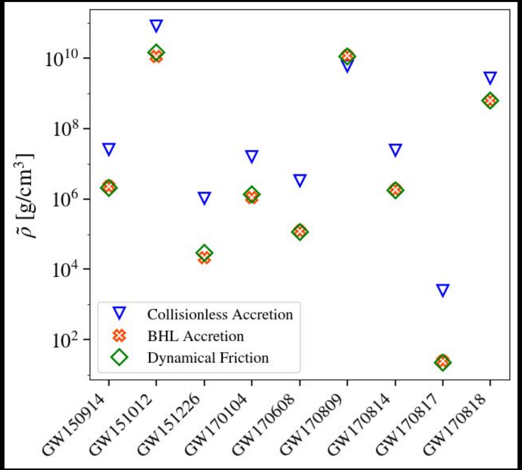
Morton et al. [2310.16025]

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 detectors will be sensitive to this!

Santoro et al. [2309.05061]

Conclusion

- Many experimental searches for GW+neutrino coincidences
- Vanilla models don't predict such emission from BBH mergers
- *But* many models have appeared in recent years that do
- So far no detection
- Future GW observatories will be able to observe all BBH mergers in the universe, but neutrino telescopes sensitivity remains limited