Searching for IceCube sub-TeV neutrino counterparts to sub-threshold GW events

Tista Mukherjee *for the IceCube Collaboration*
Karlsruhe Institute of Technology, Germany

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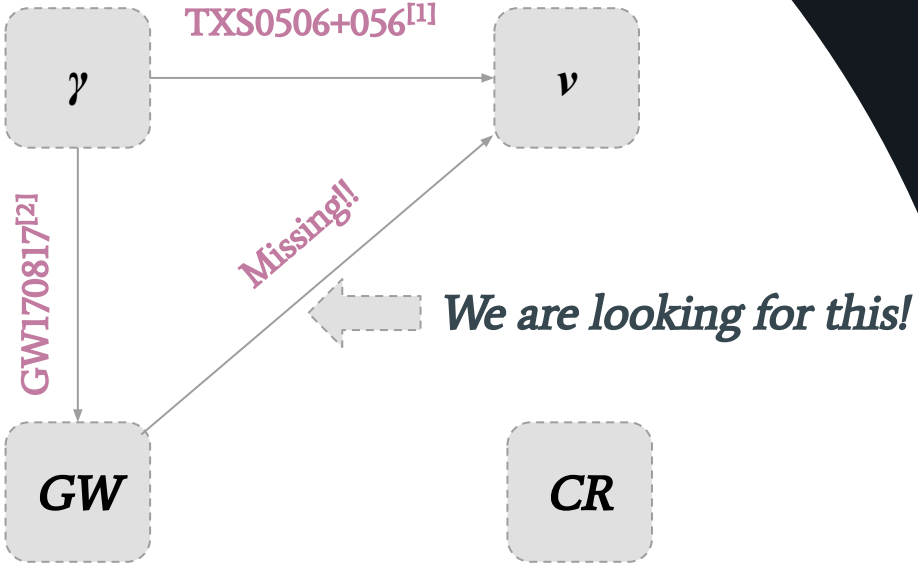
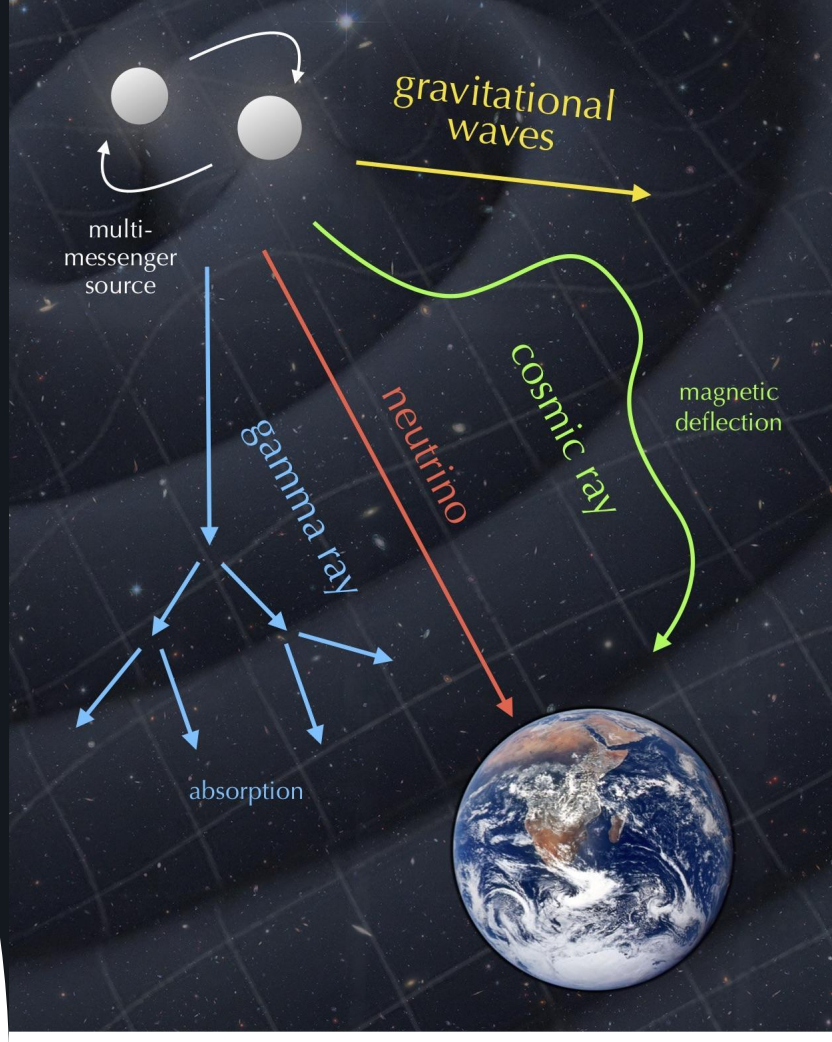
IceCube

Karlsruhe Institute of Technology

Motivation

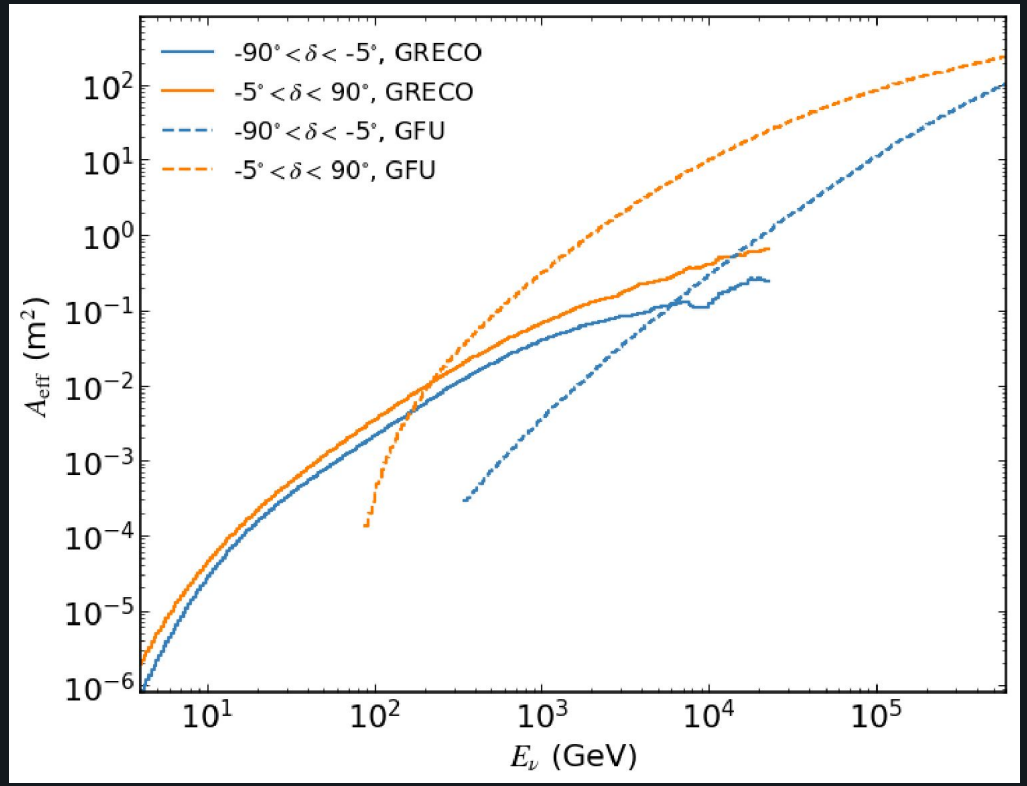
With multi-messenger studies, we access *maximum information* that we get from nature to unveil the unknowns of the Universe.





Ref: [1]IceCube collaboration, *Science 361 (2018)* [2]LV collaboration, *PhRvL 119, 161101 (2017)*

Existing resources: sub-TeV neutrinos from IceCube



- The dataset: **G**eV **R**econstructed **E**vents with **C**ontainments for **O**scillations (*GRECO*).
- *All flavour* dataset with *stable event rate*.
- *Complimentary effective-area* coverage to high-energy tracks.
- *Suitable for transient follow-up.*

Ref:
IceCube Collaboration, *ApJ 953, 160 (2023).*

Existing resources: Gravitational Wave Transient Catalogue (GWTC)

- Existing GW events: 90
  - GWTC-1: 11 events from LVC O1 + O2
  - GWTC-2.1: updated 44 events from LVC O3a
  - GWTC-3: 35 events from LVC O3b

Realtime and archival follow-up by IceCube

Ref:
IceCube Collaboration, *ApJL 898, L10 (2020)*
IceCube Collaboration, *ApJL* 946, L26 (2023)
IceCube Collaboration, *arXiv:2303.15970 (2023)*

- Threshold criteria for GWTC-2.1 & 3:
  - *FAR* [1] *< 2 per year*
  - p_{astro} [2] > 0.5 ➡ GWTC-3 specific

CBC analysis pipelines:
- GstLAL
- MBTA
- PyCBC
- PyCBC-highmass

[1] False alarm rate [2] Probability of being astrophysical

Sub-threshold candidates from GWTC-2.1 & -3

- Existing GW candidates:
  - GWTC-2.1: 1201 candidates
  - GWTC-3: 1048 candidates

No realtime information was received. No neutrino follow-up.

Ref.:
LVK collaboration, *arXiv:2108.01045 (2021)*
LVK collaboration, *arXiv:2111.03606 (2021)*

- Sub-threshold selection criteria:
  - *FAR < 2 per day*

CBC analysis pipelines:
- GstLAL
- MBTA
- PyCBC
- PyCBC-highmass

Take Home Messages

- No O3 sub-threshold GW candidate was followed in real-time or archival studies.
  - We want to do archival studies with these candidates to look for neutrino counterparts.

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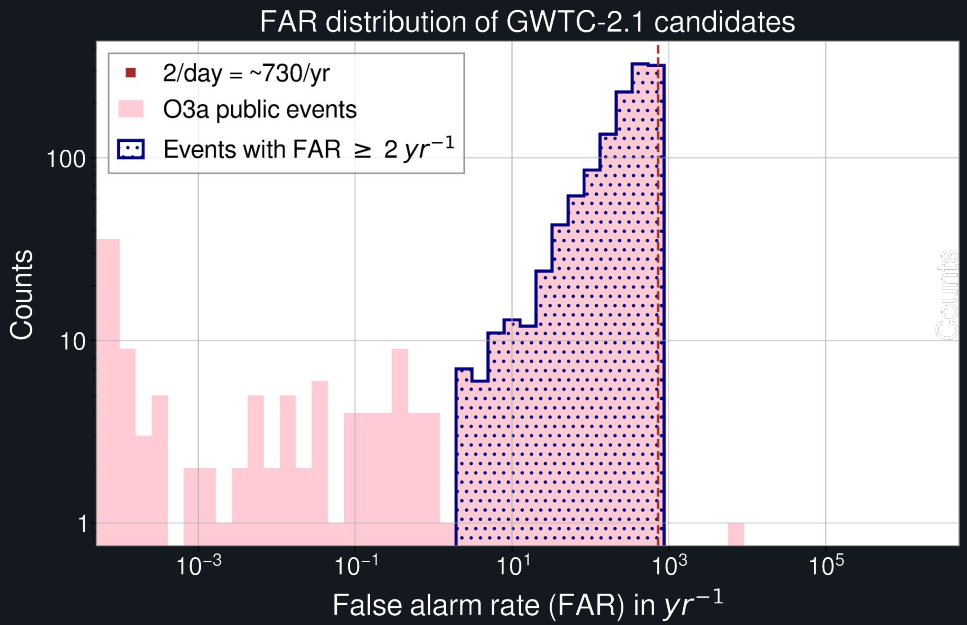
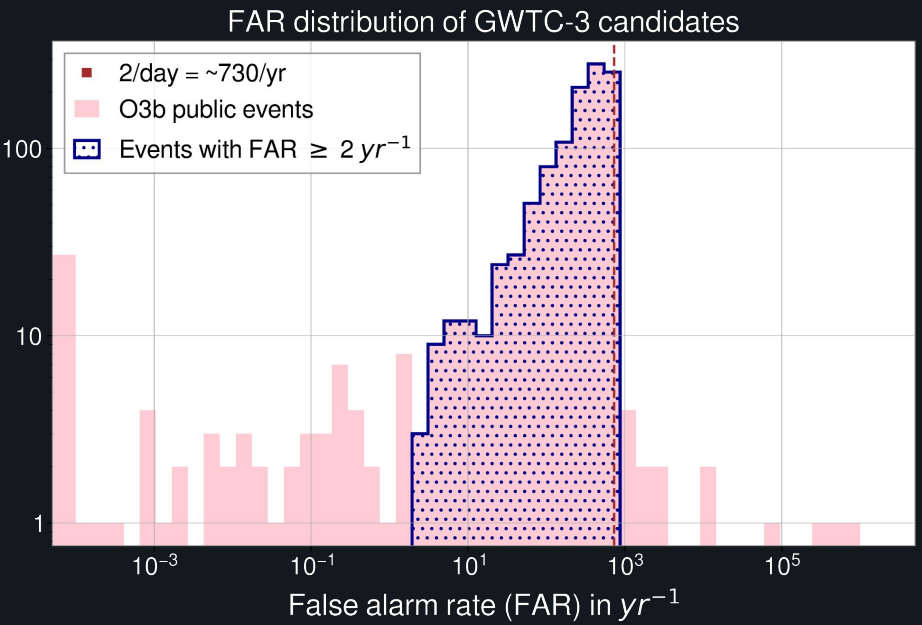
- The knowledge we can gain from sub-threshold candidates is crucial for planning future real-time campaigns.
  - We can improve our understanding about the ‘threshold’ for GW detection, helping future detectors.

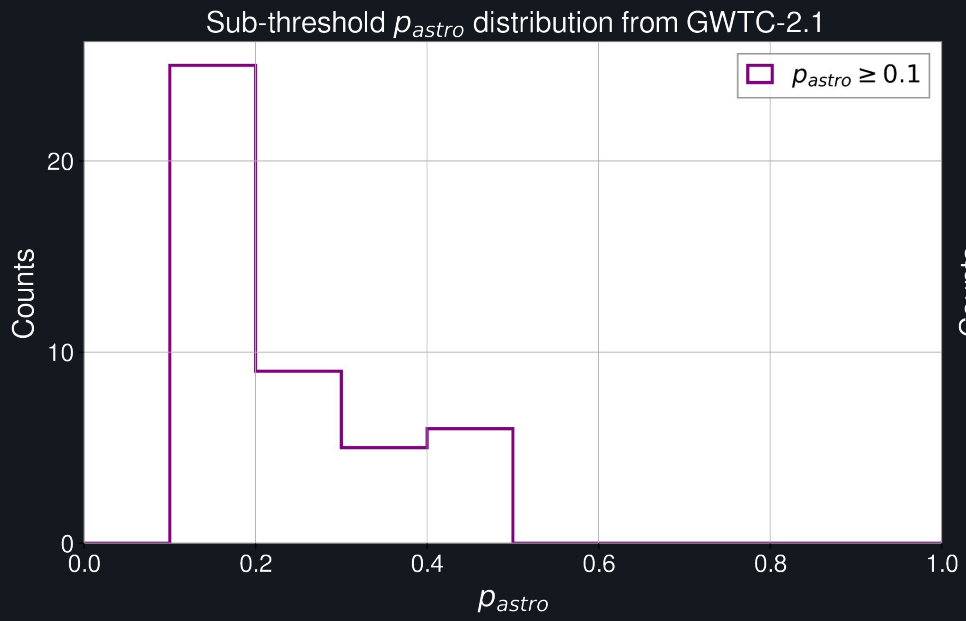
Sub-threshold candidate selection

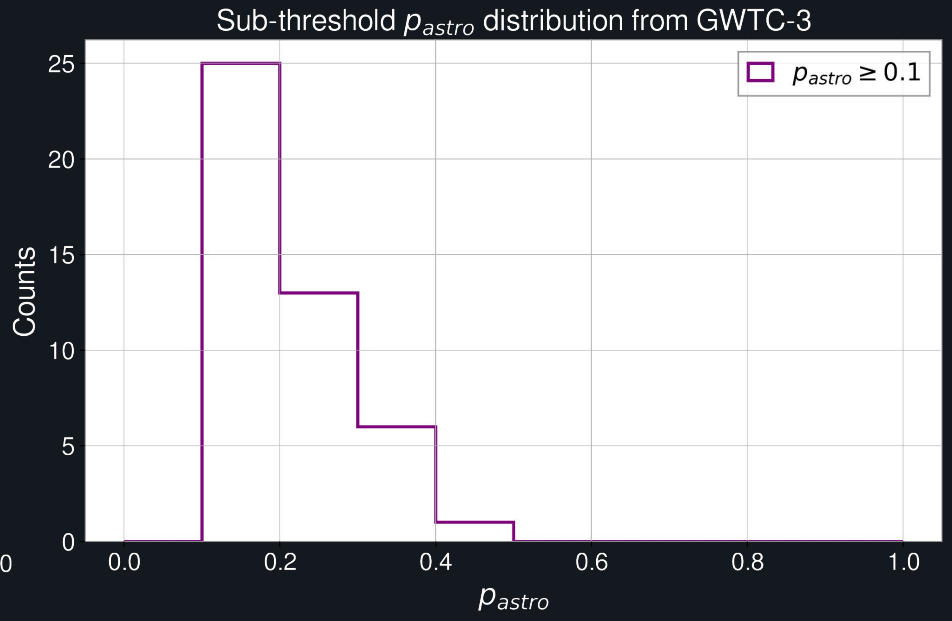




Ref: **IceCube Collaboration,** T. Mukherjee et al, *arXiv: 2308.06102(2023)*

p_{astro} distribution

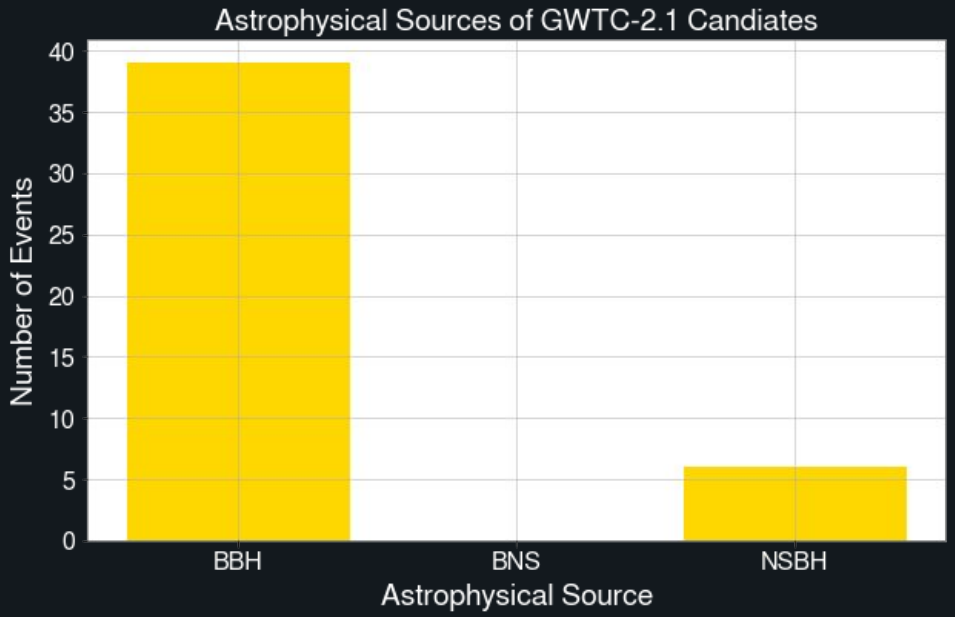


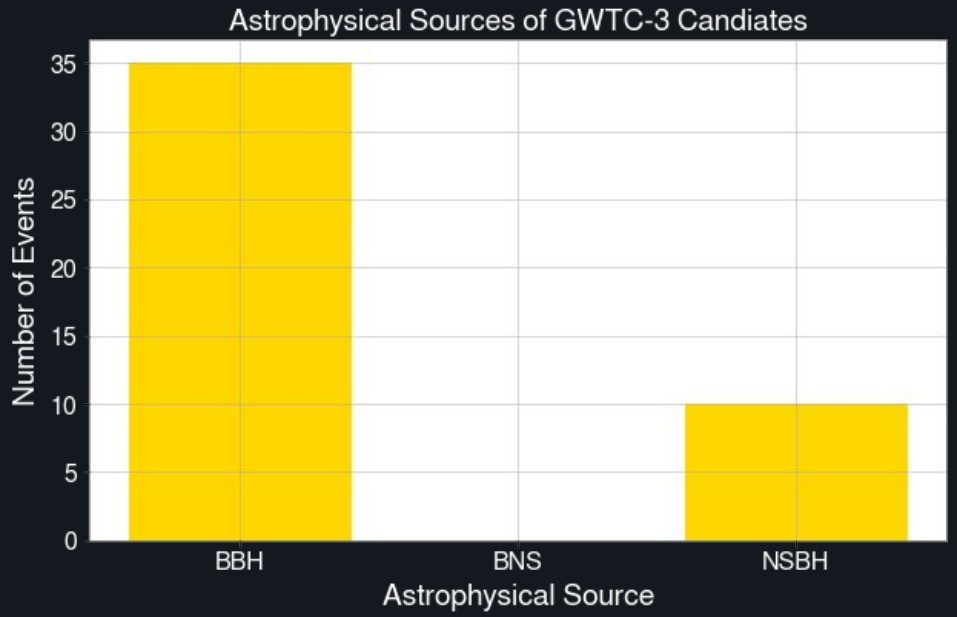


We have 90 CBC candidates from GWTC-2.1 & -3 with $p_{astro} \geq 0.1$

Ref: **IceCube Collaboration,** T. Mukherjee et al, *arXiv: 2308.06102(2023)*

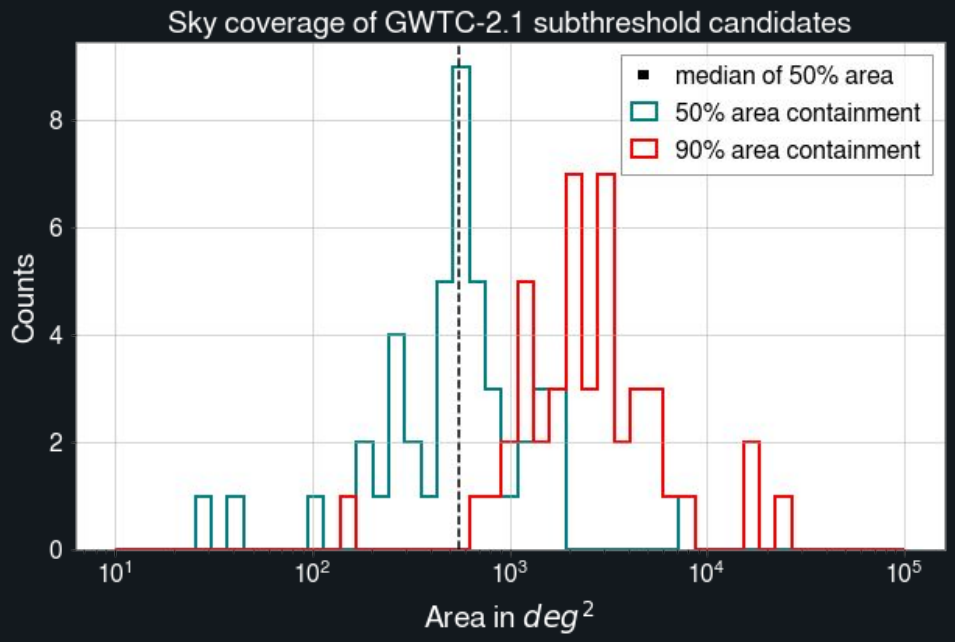
What kind of sources to we have?

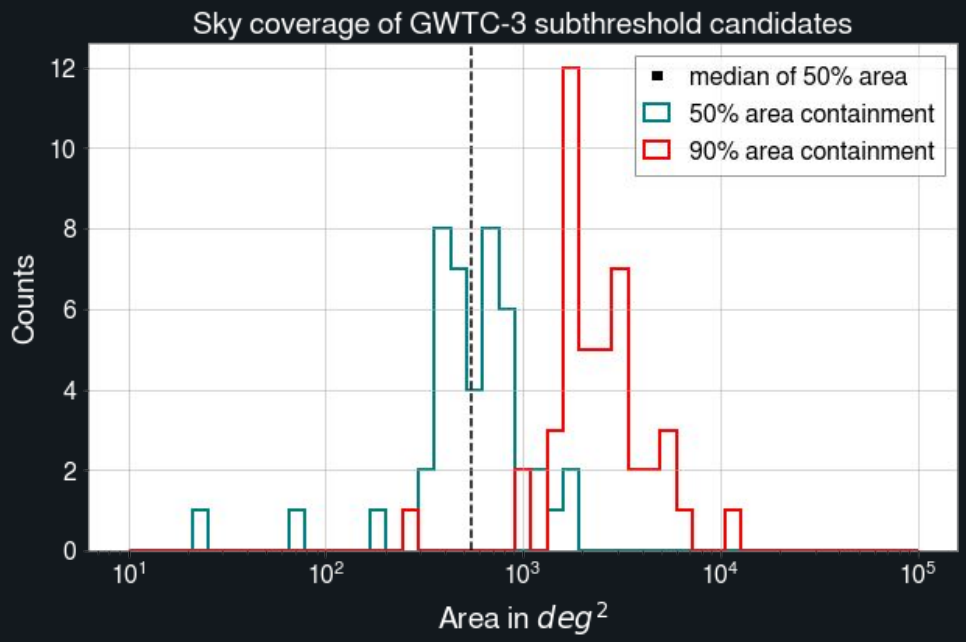




We have 16 NSBH candidates from GWTC-2.1 & -3

Sky area coverage of sub-threshold candidates





The localisation of these sub-threshold candidates can significantly improve with neutrino counterparts!

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- The knowledge we can gain from sub-threshold candidates is crucial for planning future real-time campaigns.
  - We can improve our understanding about the ‘threshold’ for GW detection, helping future detectors.
- A selection of sub-threshold candidates has been made for archival studies with sub-TeV neutrinos.
  - The CBC candidates have $2 \leq \mathrm{FAR} < 730\ \mathrm{yr}^{-1}$ and $0.1 \leq p_{\mathrm{astro}} \leq 0.5$
  - We are looking for sub-TeV neutrino counterparts within 1000 s time-window

The Methodology: Unbinned Maximum Likelihood (UML) analysis

Define a likelihood to maximise its value

$$\mathcal{L}(n_{\mathrm{s}}(\gamma)) = \frac{(n_{\mathrm{s}} + n_{\mathrm{b}})^{N}}{N!} \mathrm{e}^{-(n_{\mathrm{s}}+n_{\mathrm{b}})} \prod_{i=1}^{N} \left(\frac{n_{\mathrm{s}} S_{\mathrm{i}}}{n_{\mathrm{s}} + n_{\mathrm{b}}} + \frac{n_{\mathrm{b}} B_{\mathrm{i}}}{n_{\mathrm{s}} + n_{\mathrm{b}}} \right).$$

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Spectral index

Poisson term

Signal term

Background term

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We can find the maximum likelihood by maximising the Test Statistic.

Maximum TS value = Maximum likelihood

$$TS = \max\left[2\,\ln\left(\frac{\mathcal{L}_{\mathrm{k}}(n_{\mathrm{s}}(\gamma))\cdot\omega_{\mathrm{k}}}{\mathcal{L}_{\mathrm{k}}(n_{\mathrm{s}}=0)}\right)\right] = \mathrm{TS}_{\mathrm{PS}} + 2\,\ln\,(w_{k})$$

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Define a likelihood to maximise its value

$$\mathcal{L}(n_s(\gamma)) = \frac{(n_s + n_b)^N}{N!} e^{-(n_s+n_b)} \prod_{i=1}^{N} \left(\frac{n_s S_i}{n_s + n_b} + \frac{n_b B_i}{n_s + n_b} \right)$$

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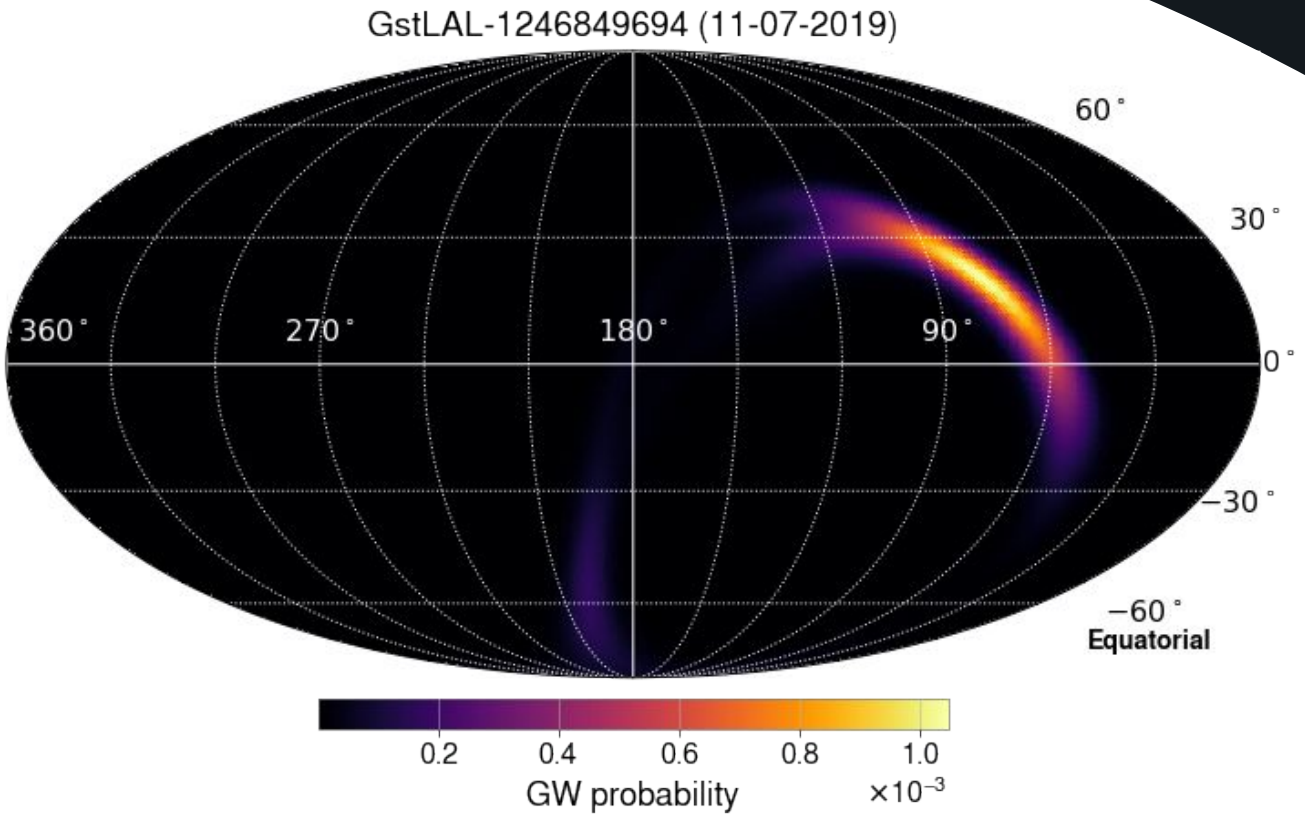
Spatial penalty, zero for best-fit GW source location, otherwise increasingly negative

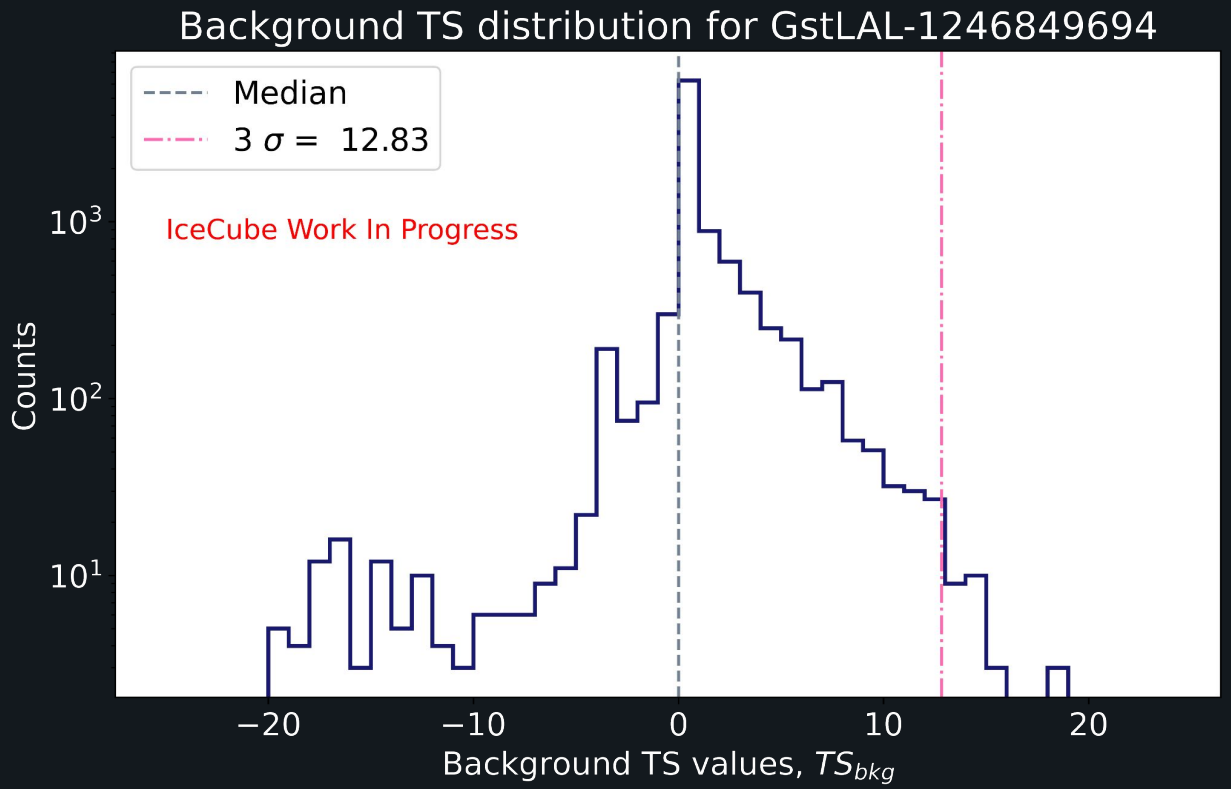
Example case: GstLAL-1246849694



GW skymap for a sub-threshold candidate with $p_{astro} = 0.35$

Background TS distribution: an example

- Generating 10,000 independent background events by time-scrambling the GRECO dataset



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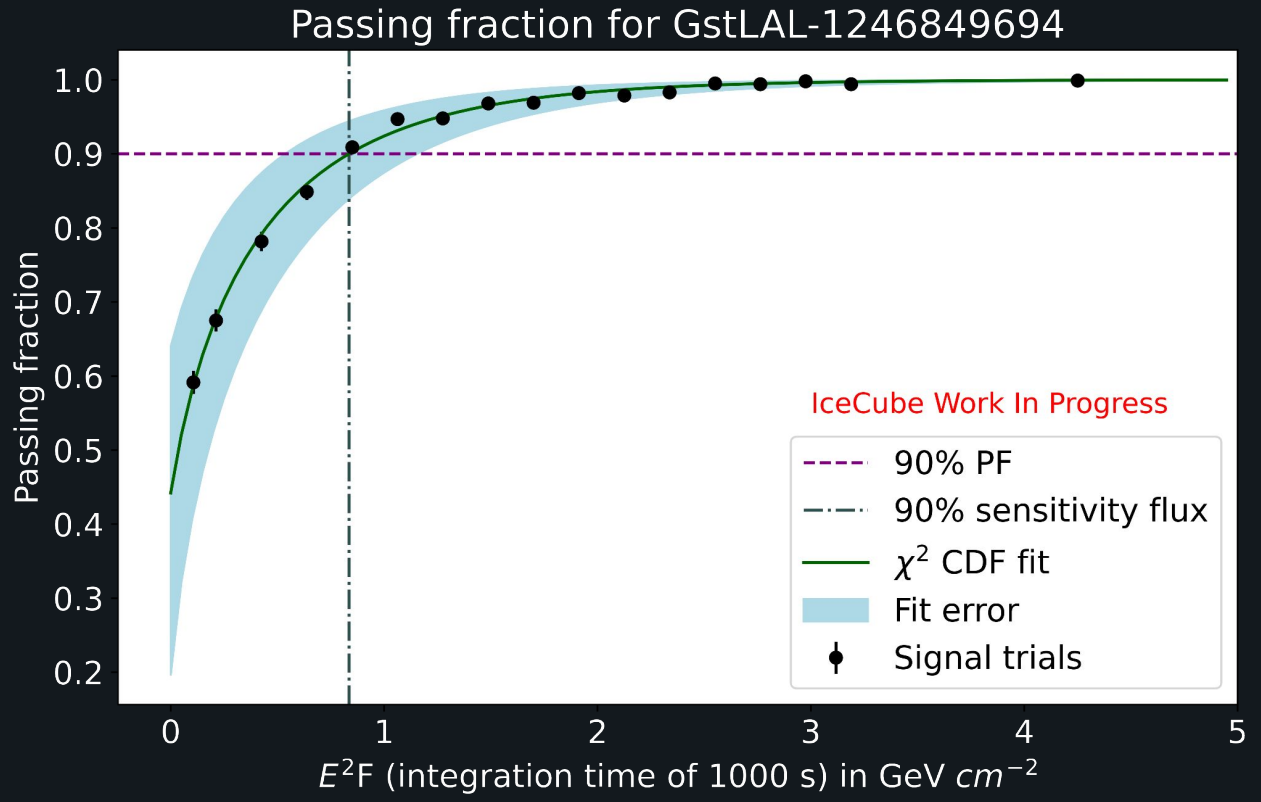
Sensitivity studies: an example

- Per-flavour sensitivity flux at a reference energy of 1 GeV at 90% C.L.
- The sensitivity is comparatively better for candidates in the Northern Hemisphere.



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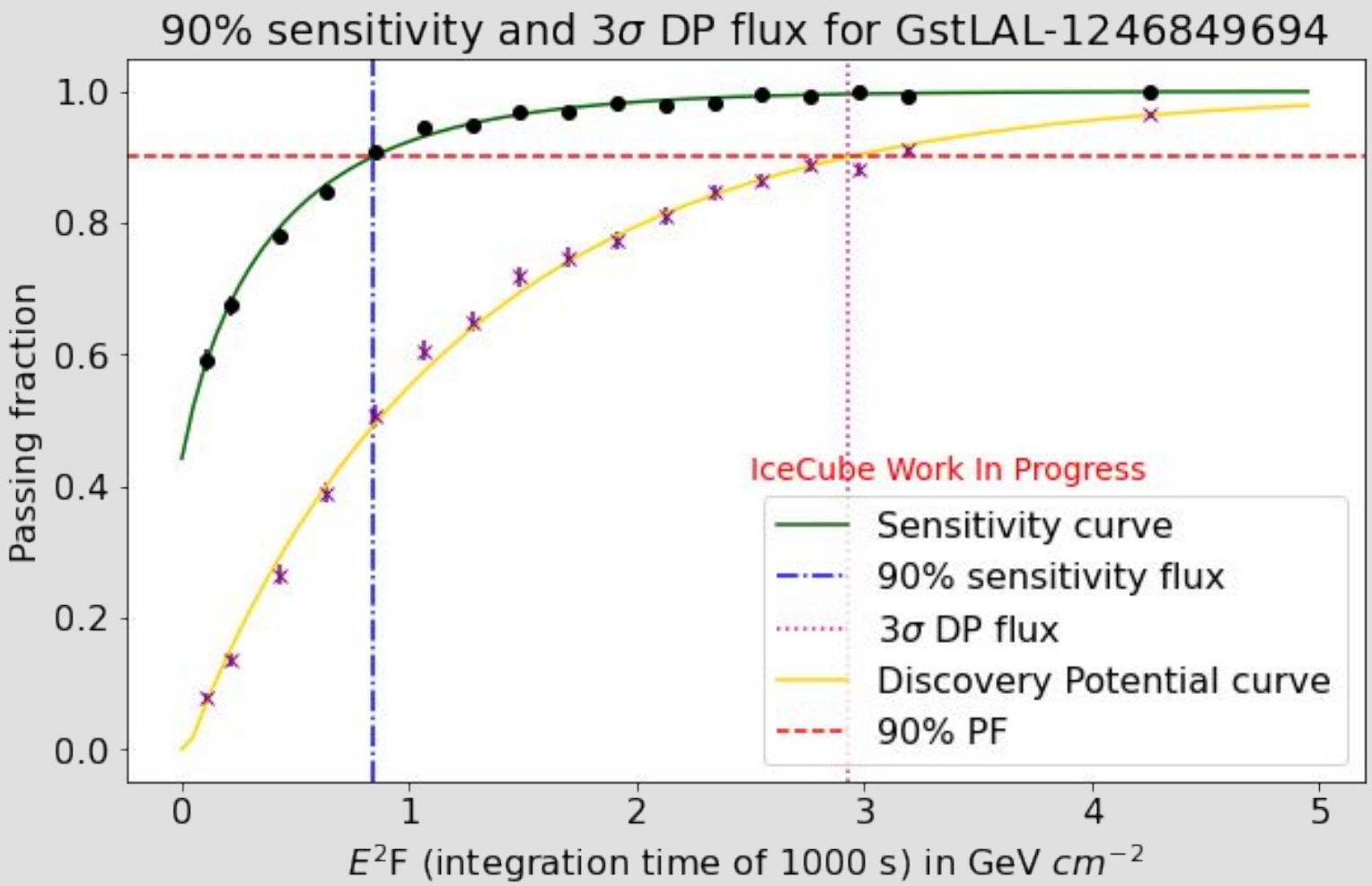
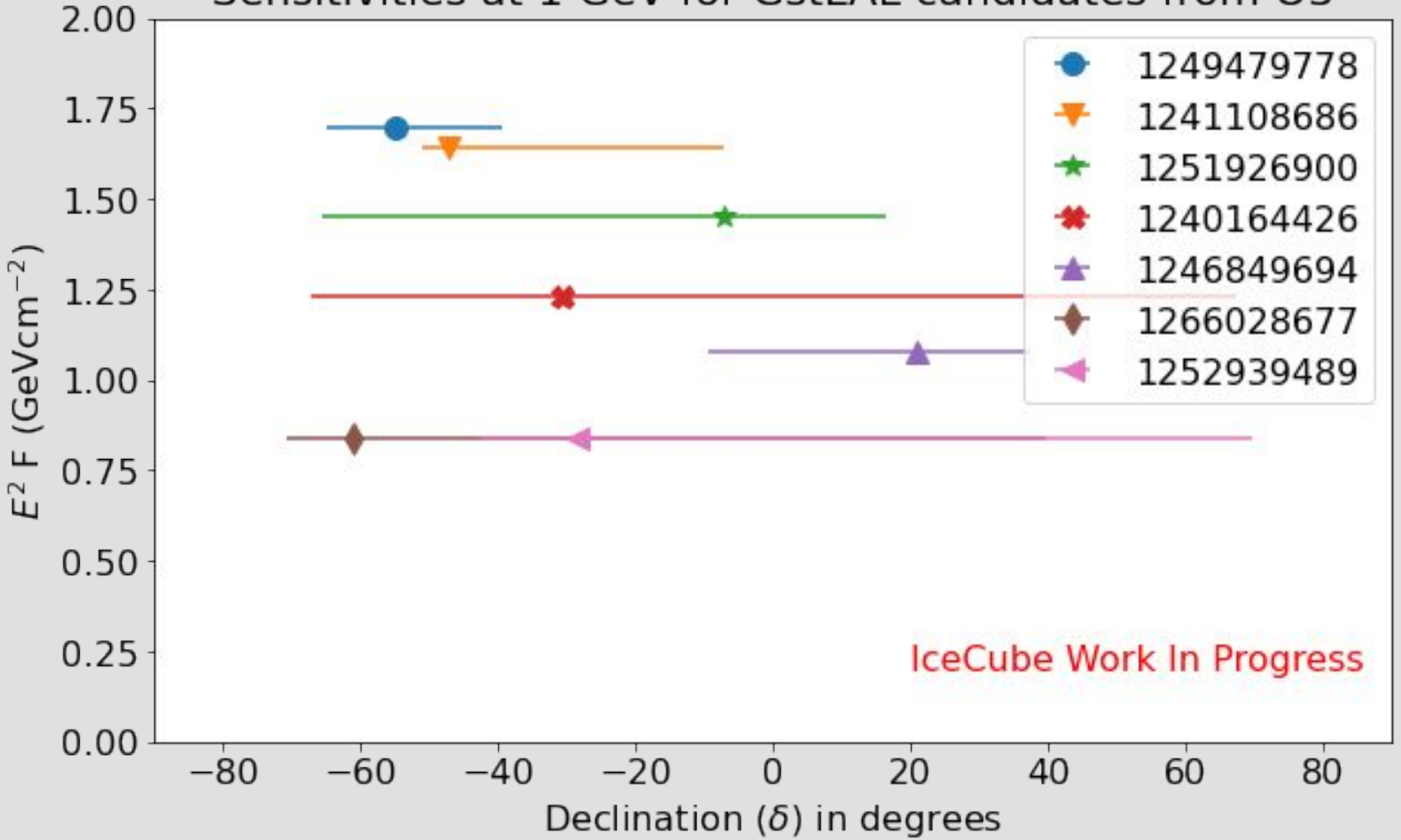
  - We are looking for sub-TeV neutrino counterparts within 1000 s time-window
- Studies on the sensitivities have been completed for GWTC-2.1. Work with GWTC-3 candidates is ongoing.
- After finalising the studies, we will request for unblinding the IceCube data.
- Eventually, we want to move the analysis to real-time.


Thank you!!

Back-up


90% sensitivity and 3σ DP flux for GstLAL-1246849694
Passing fraction
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
E^2F (integration time of 1000 s) in GeV cm^{-2}
IceCube Work In Progress
Sensitivity curve
90% sensitivity flux
3σ DP flux
Discovery Potential curve
90% PF


Sensitivities at 1 GeV for GstLAL candidates from O3
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
E^2 F (GeVcm^{-2})
−80
−60
−40
−20
0
20
40
60
80
Declination (δ) in degrees
1249479778
1241108686
1251926900
1240164426
1246849694
1266028677
1252939489
IceCube Work In Progress