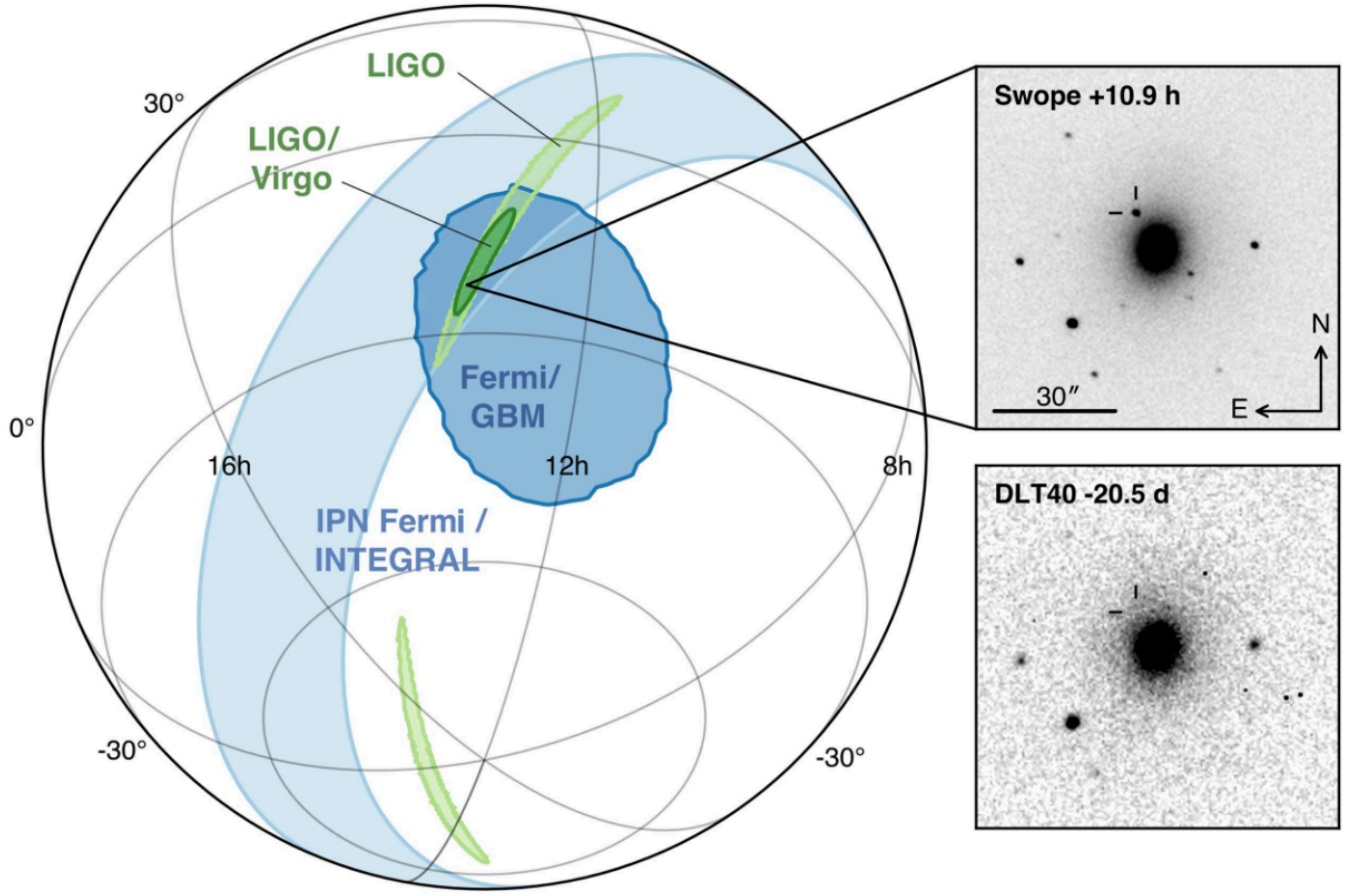
GWSkyNet: a machine learning pipeline for gravitational wave candidate evaluation

Mervyn Chan on behalf of the GWSkyNet team

Outline

- The problem
- GWSkyNet as a solution
- Future upgrade

Multi-messenger astronomy with gravitational waves



The localization of GW170817 by LIGO/Virgo, and the associated gamma-ray burst by Fermi and INTEGRAL. The right are the host galaxy in the Swope optical discovery image and DLT40 pre-discovery image, reproduced from Abbott et al., 2017

Provided insights into fundamental physics, astrophysics and cosmology

Confirmed the association between gamma-ray bursts, kilonovae, and binary neutron star mergers

Enabled an independent measurement of the Hubble constant

Improved understanding of gravity, origin of heavy elements, etc, constraints on neutron star equation of state, etc

Multi-messenger astronomy with gravitational waves

The problem

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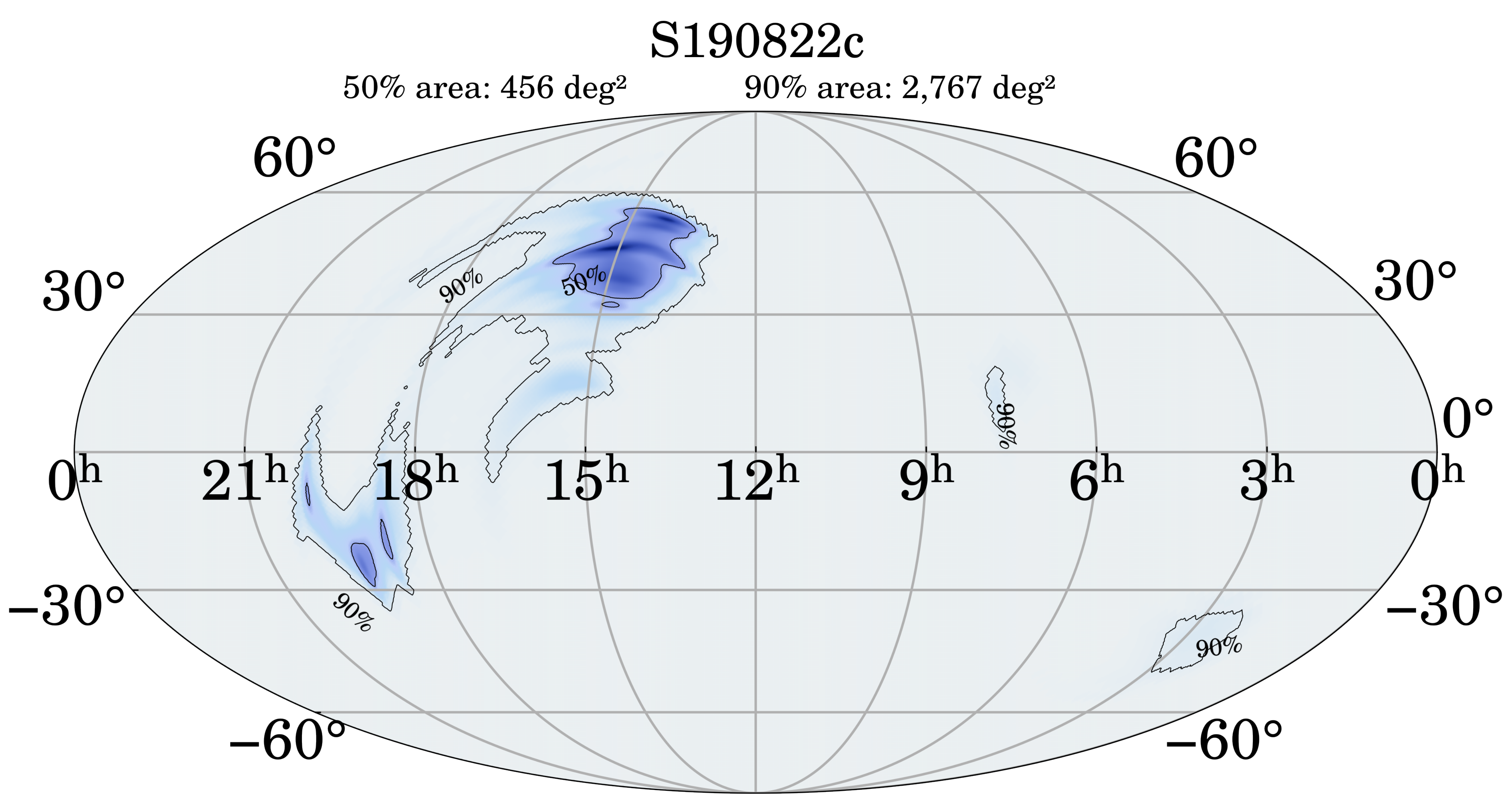
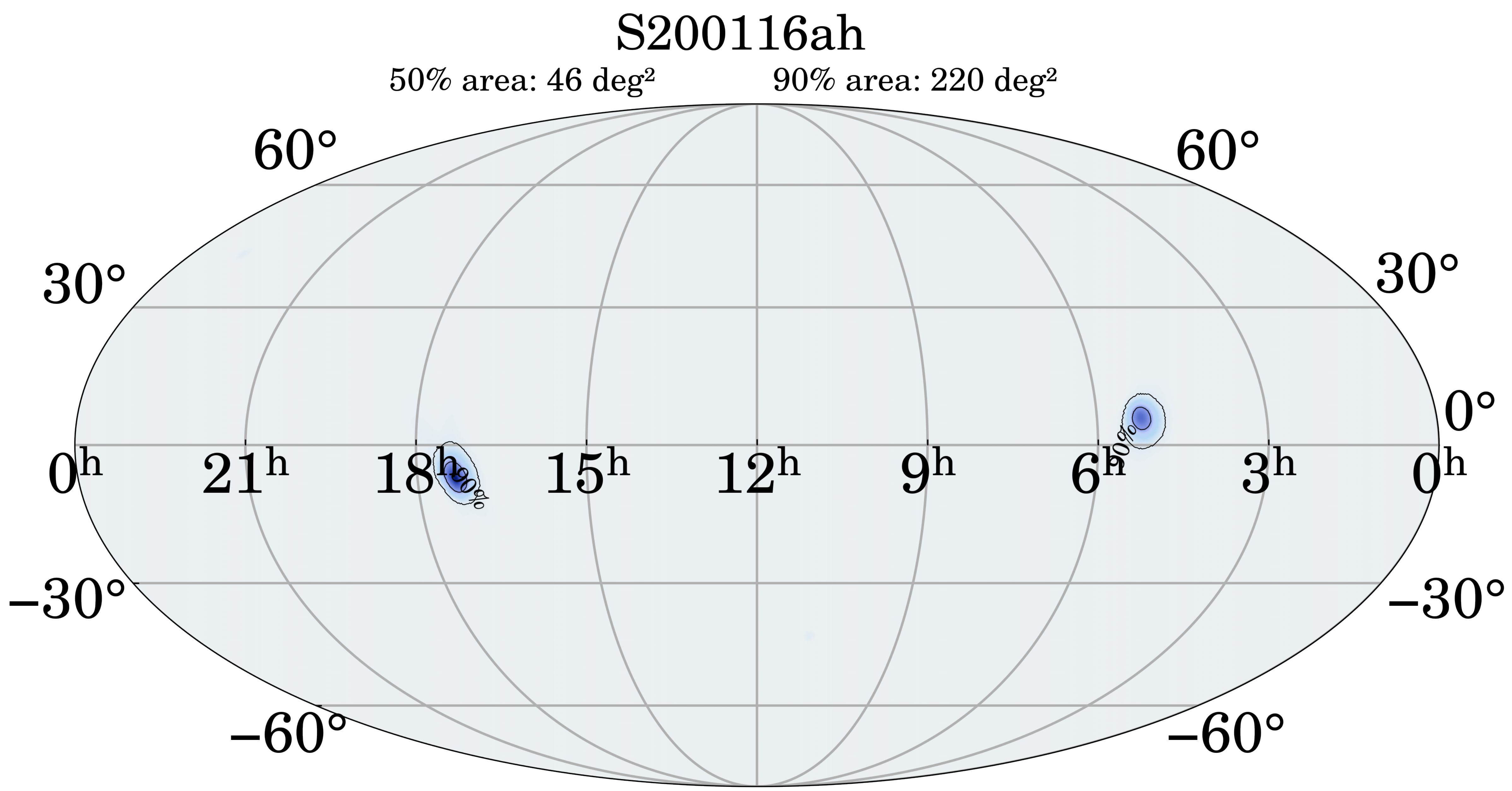


FAR: 1 per 5×10^{9} yrs
BNS merger: 99%
1st follow-up: 23 mins
Retraction: 1.5 hrs



FAR: 1 per 1.5×10^{4} yrs
NSBH merger 99%
1st follow-up: 85s
Retraction: 19 mins

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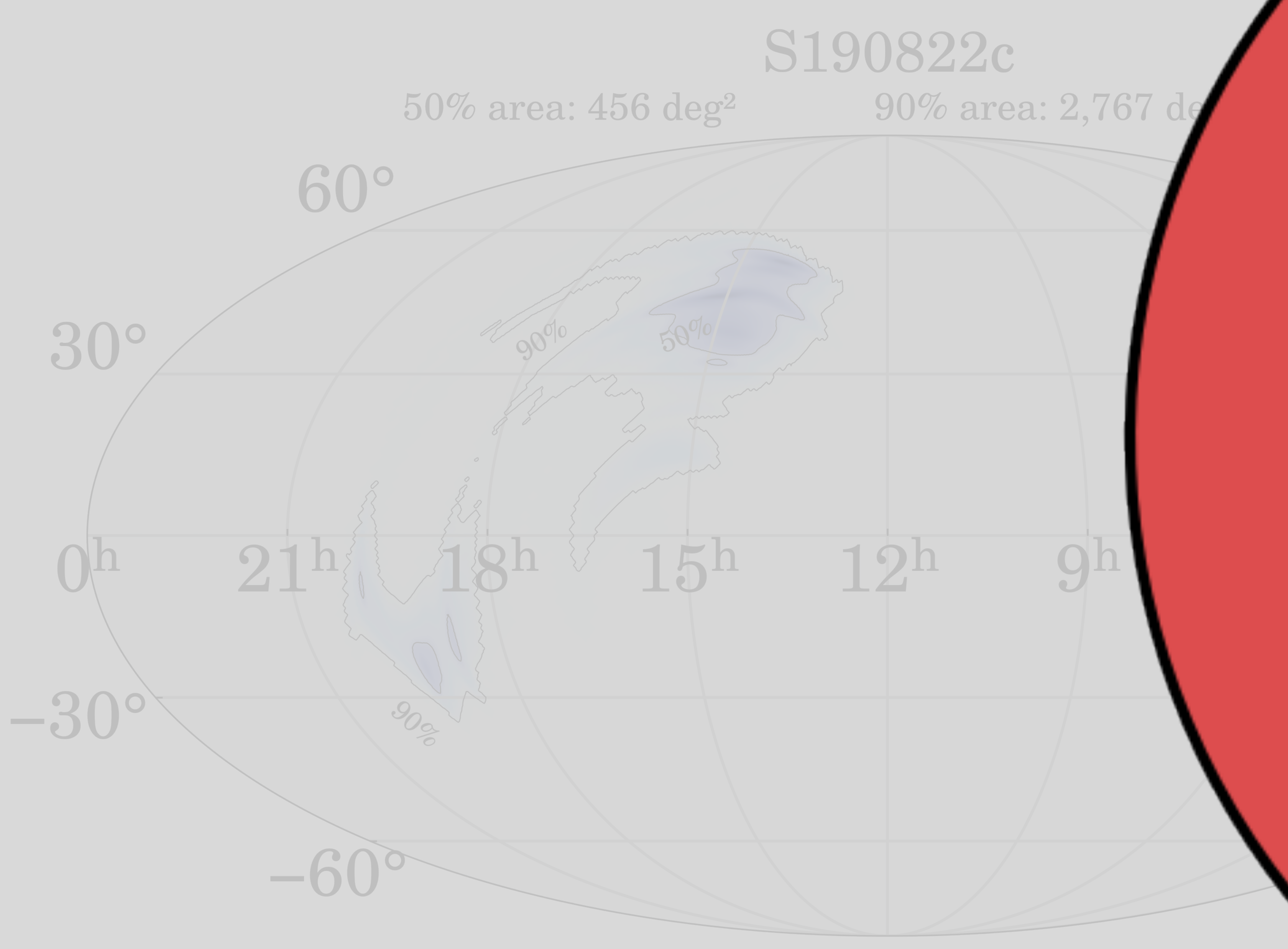

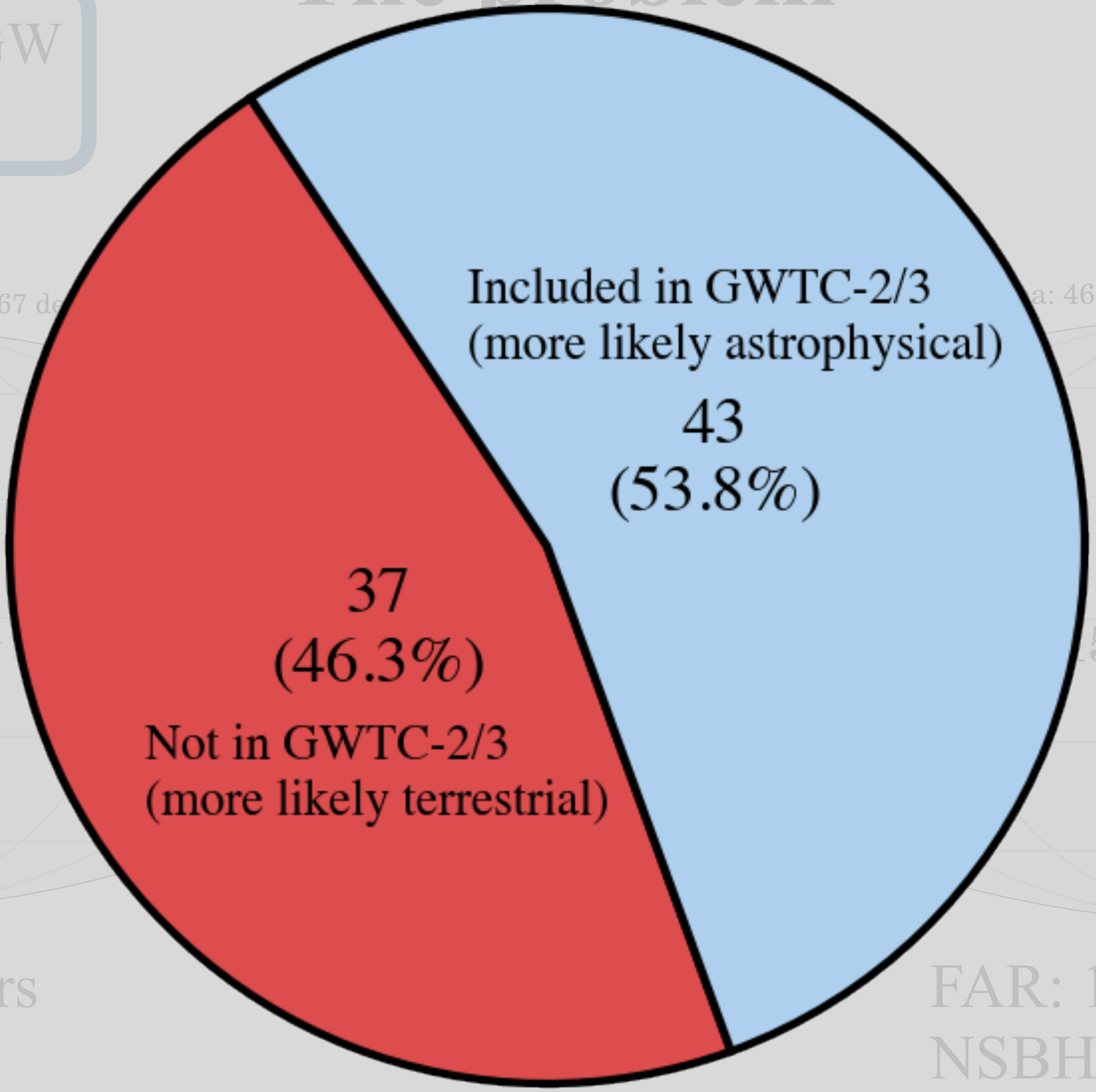

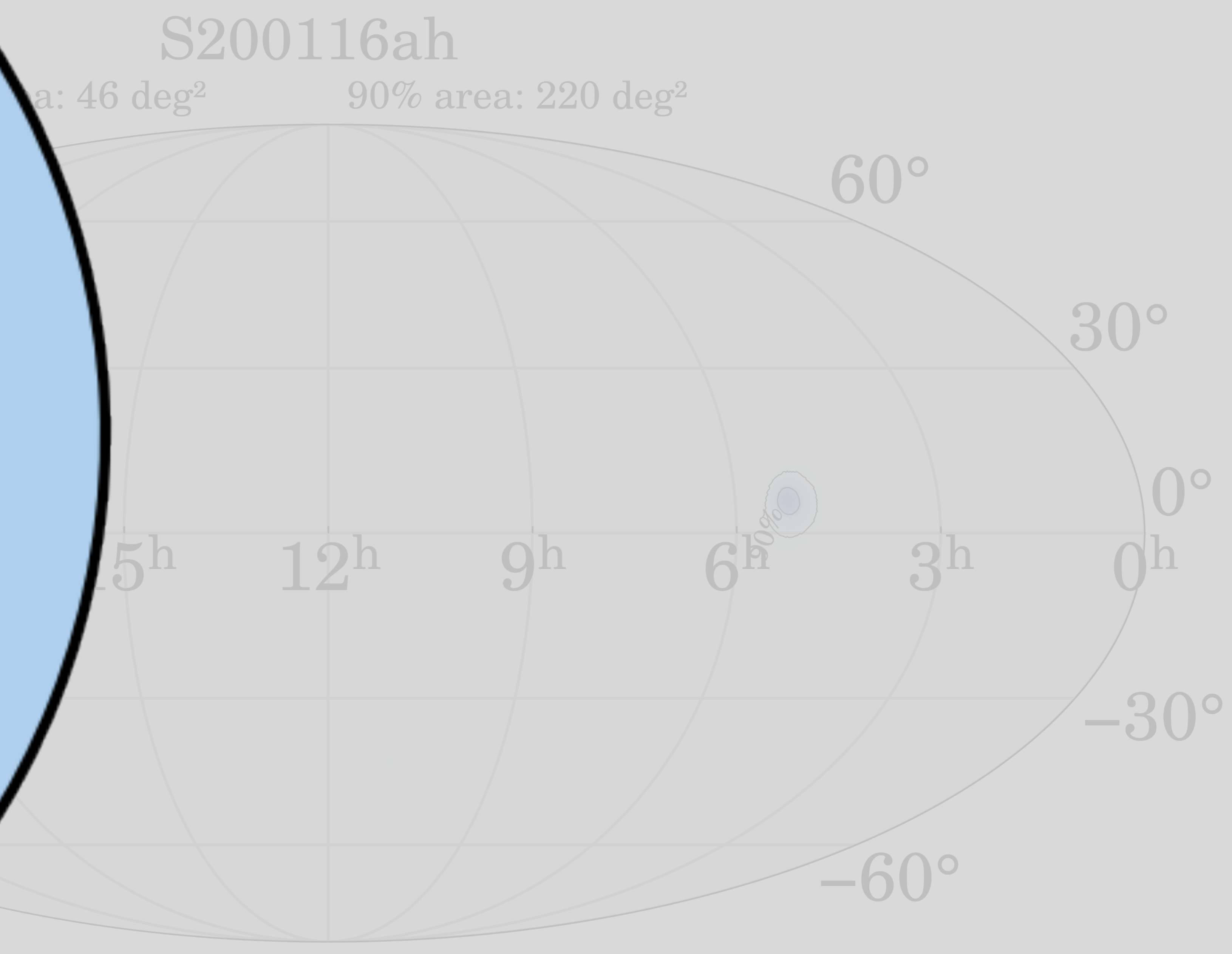

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Retraction: 10 mins

Fraction of gravitational wave alerts from real time searches in O3
that are more likely to be terrestrial in origin according to GWTC-2/3 (Abbott et al., 2021/2023)

The solution

We need a solution!

The solution

Working with data products quickly available

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3D localization information*
coherence information between detectors

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*https://gracedb.ligo.org

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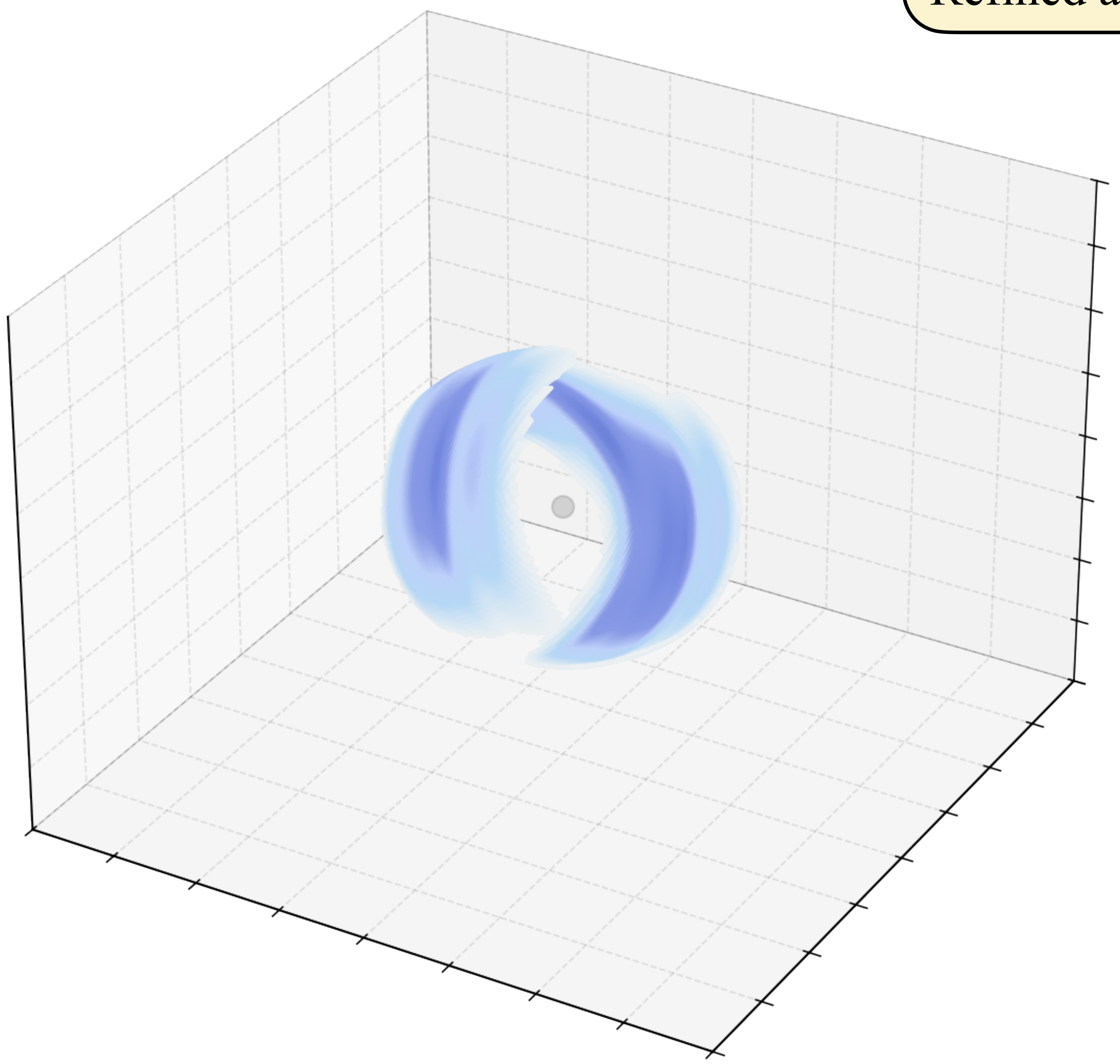
The deep learning algorithm, GWSkyNet, based on convolutional neural network as a solution.

GWSkyNet: how does it work?

For a GW candidate
3D localization information by BAYESTAR
Singer et al. 2015/2016

Prototype by Cabero. et al 2020 arXiv: 2010.11829

Refined and deployed by Chan. et al 2024 arXiv: 2408.06491



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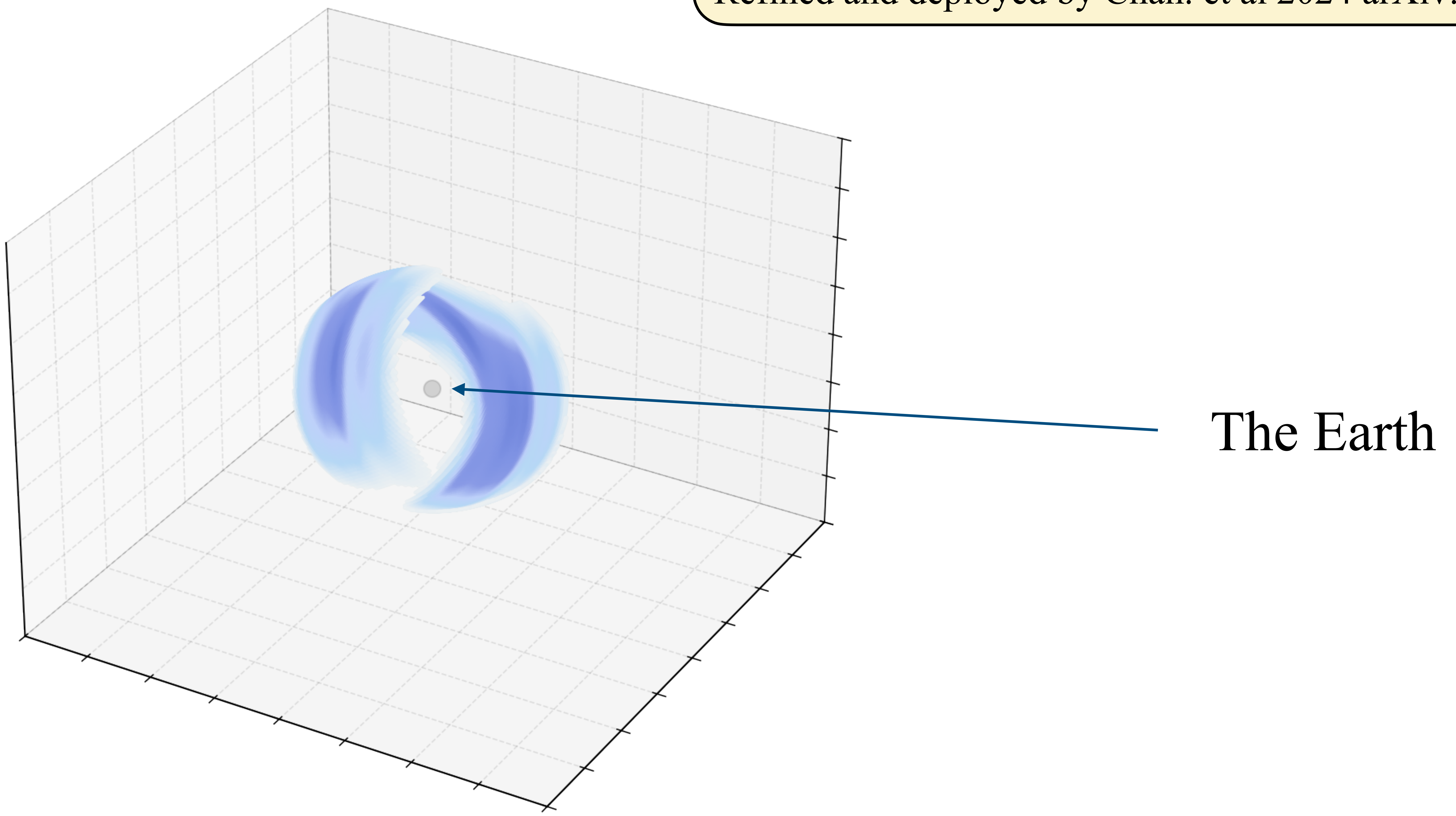

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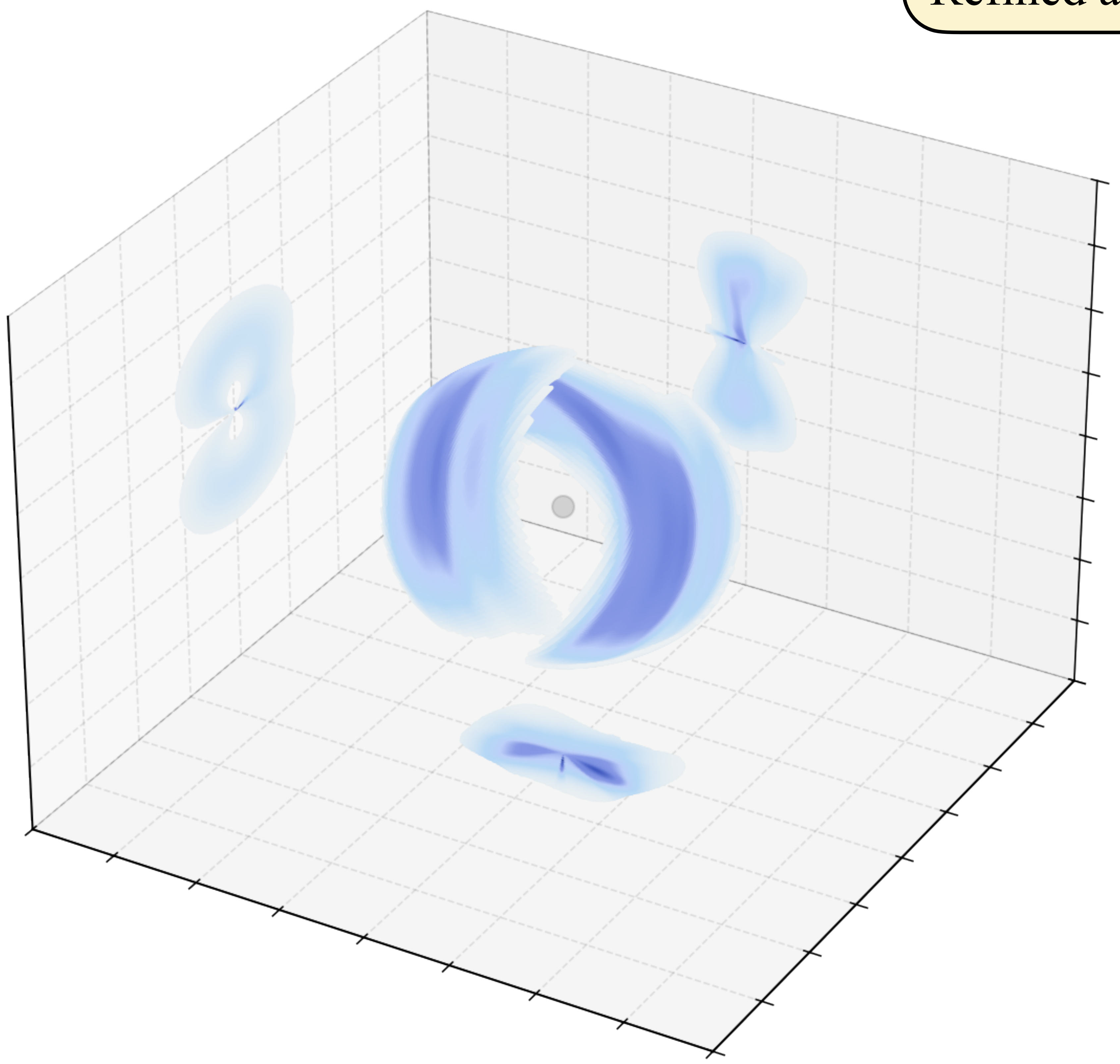

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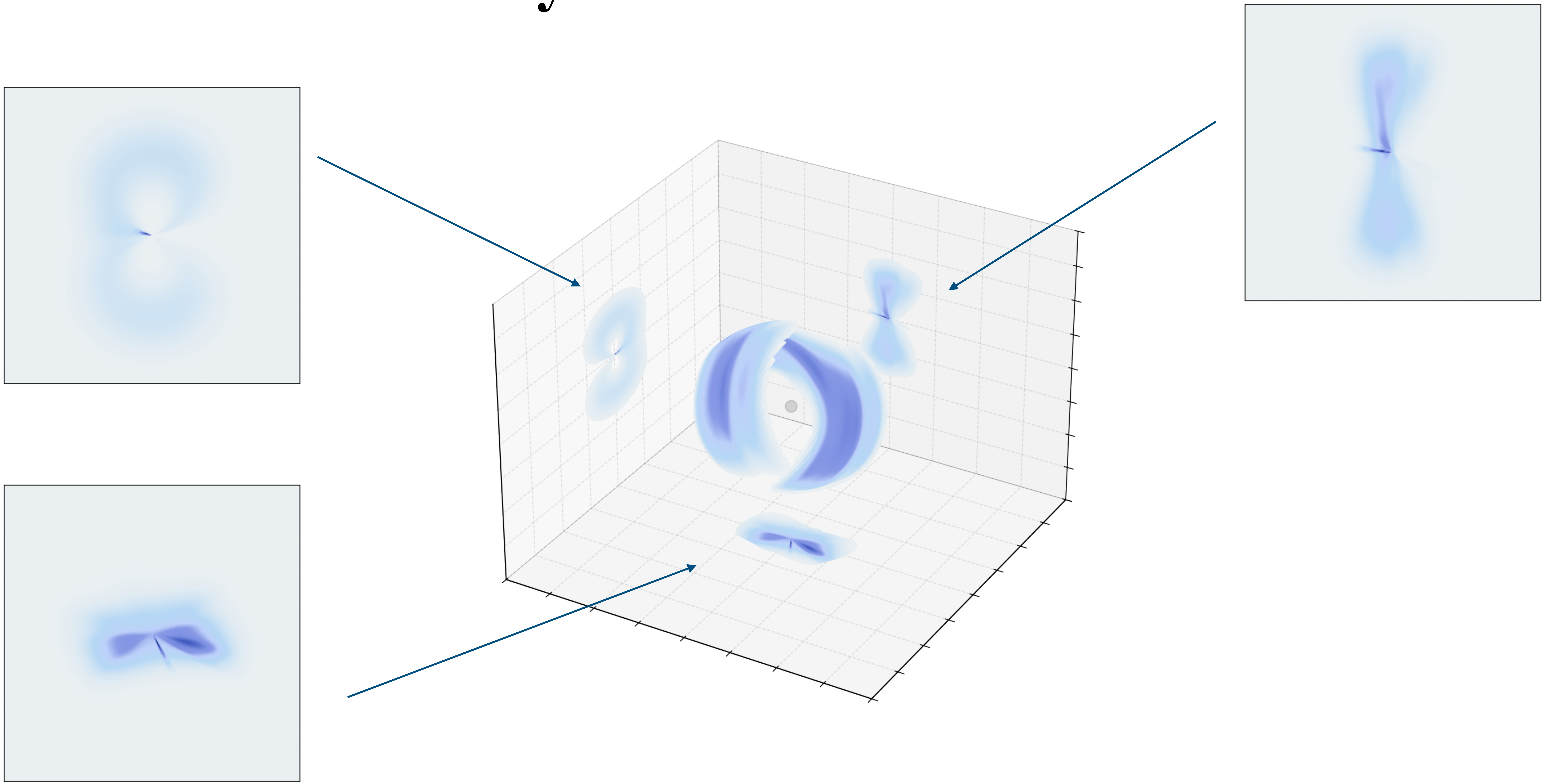

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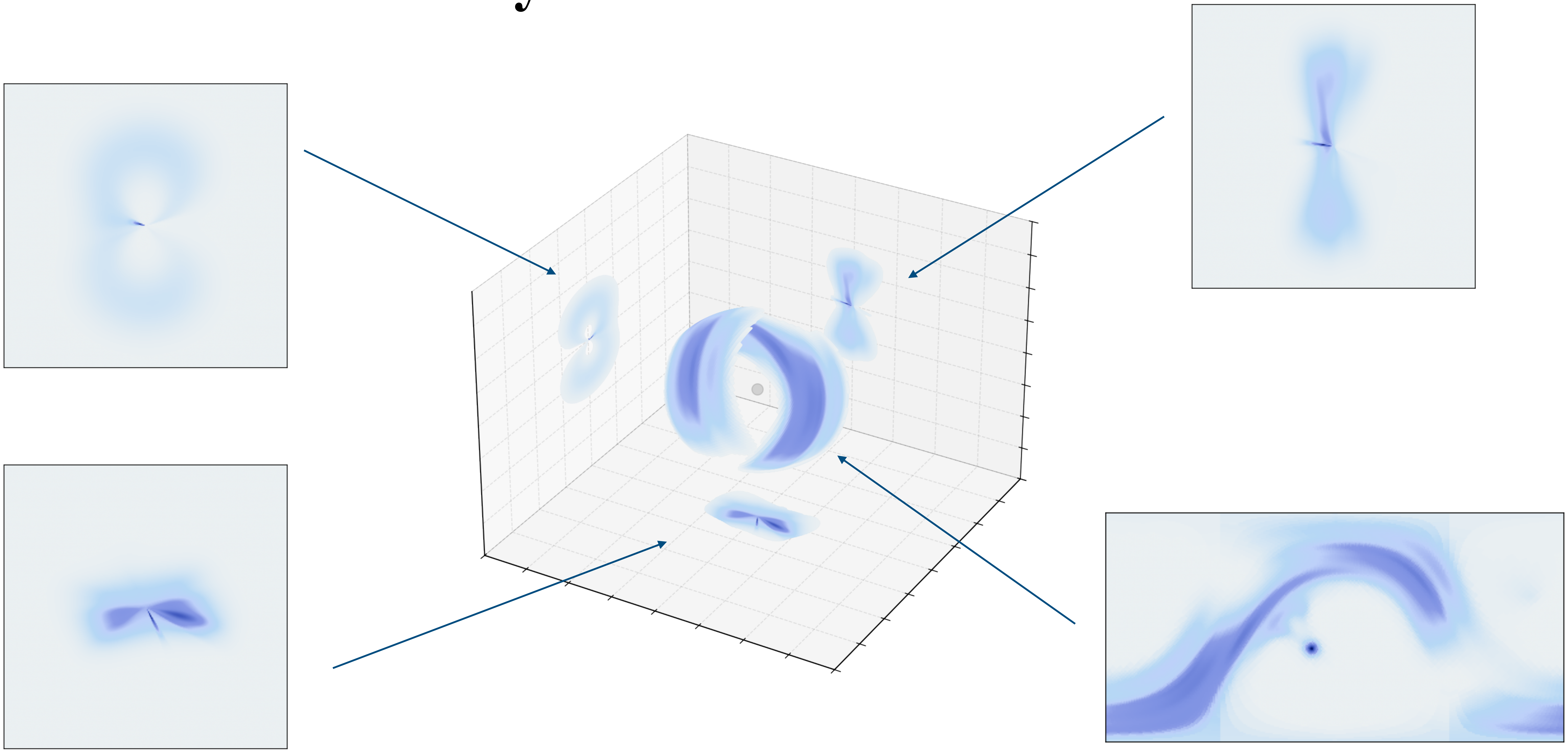

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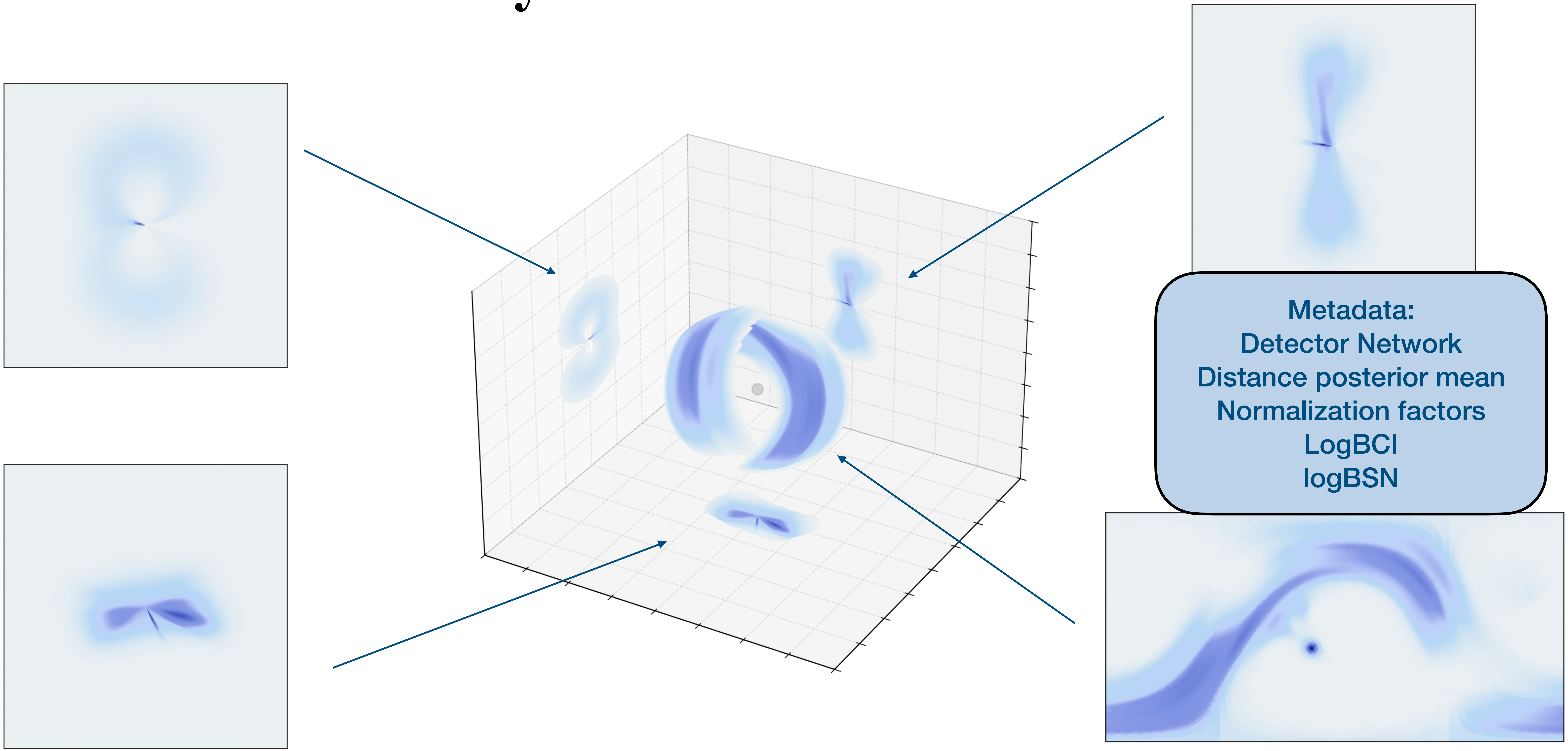

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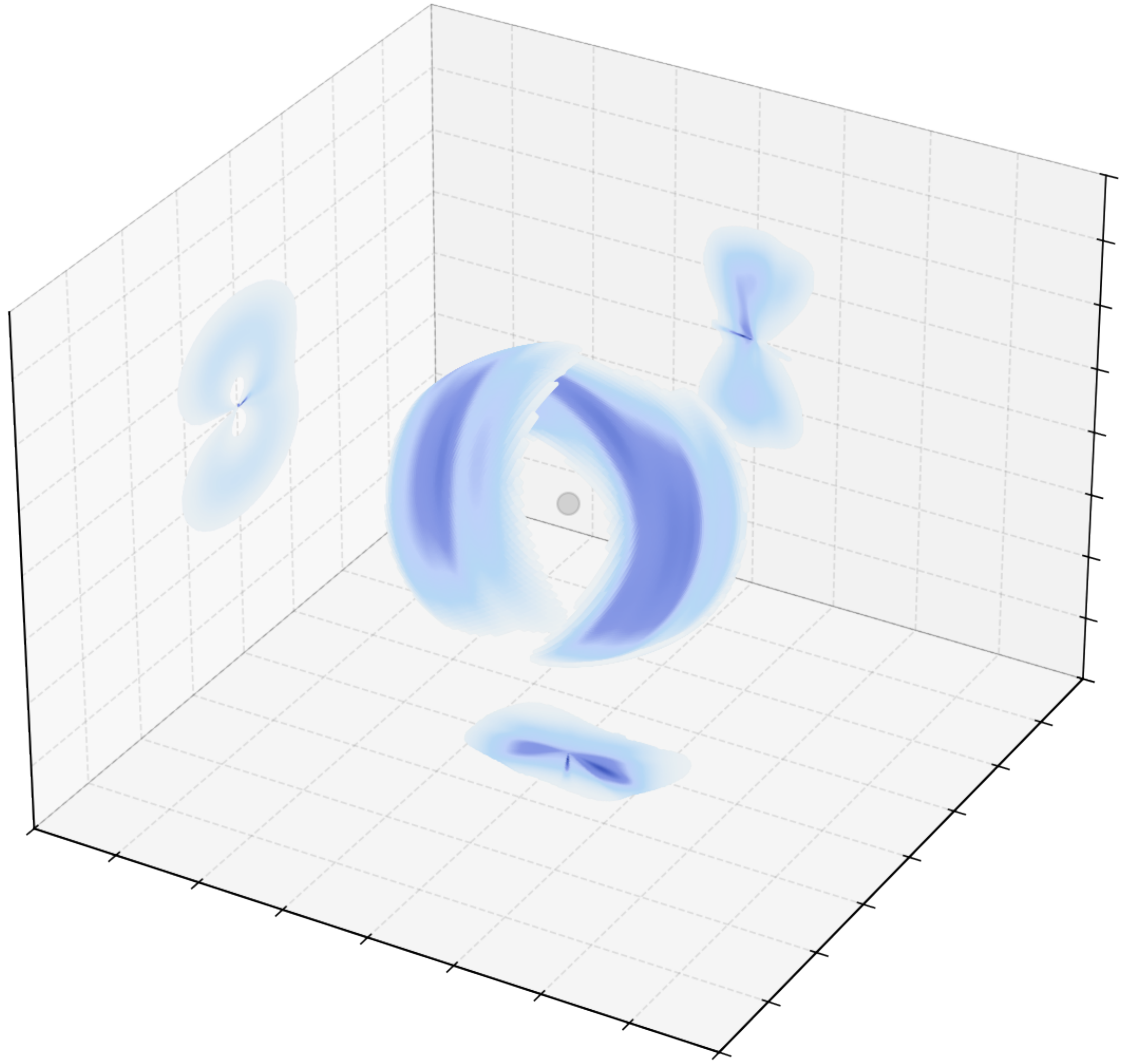

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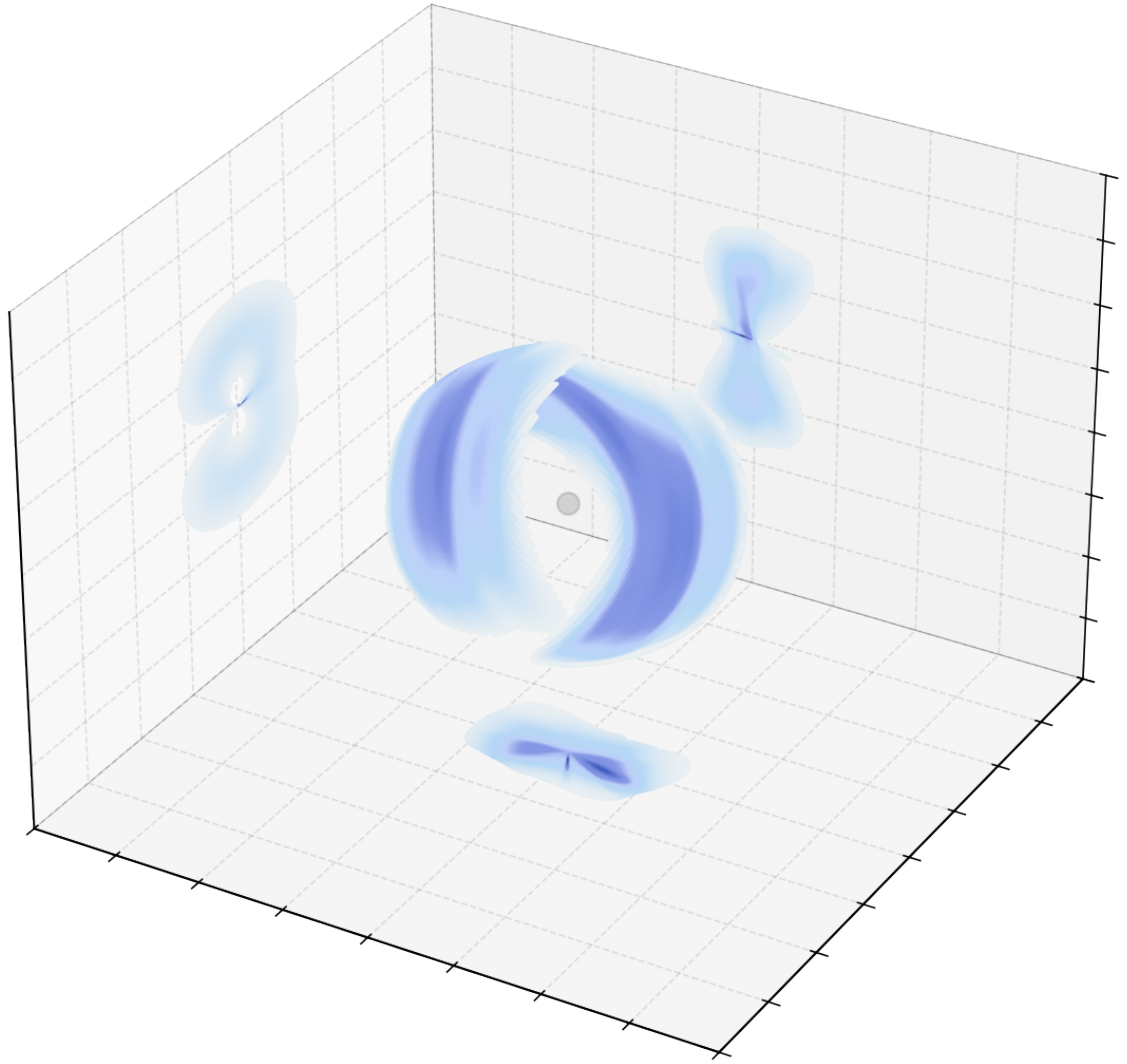


0: consistent with noise

1: consistent with GW signal

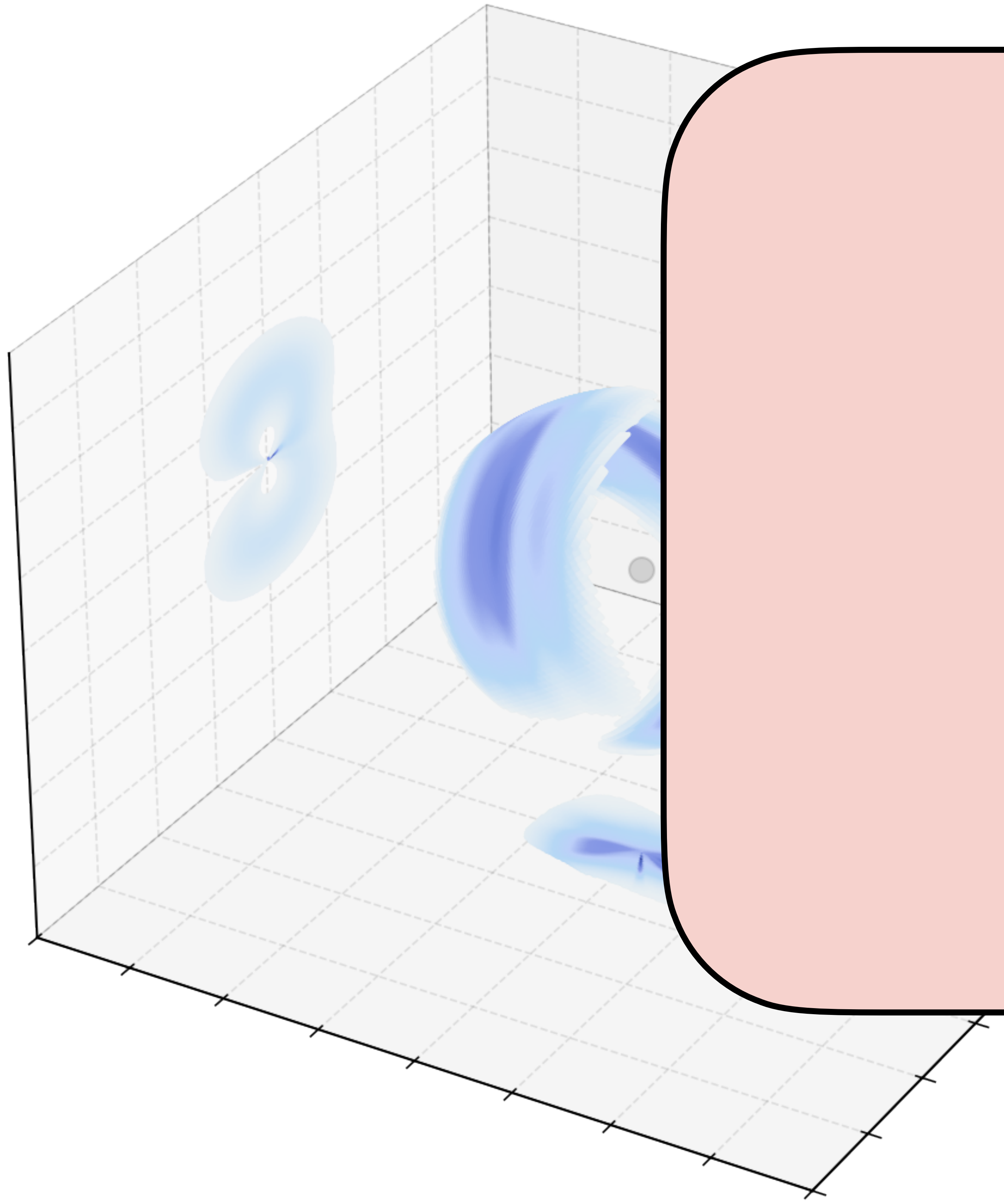
GWSkyNet score

False alarm probability:
the fraction of noise events at or above a candidate's GWSkyNet score

False negative probability:
the fraction of astrophysical events at or below a candidate's GWSkyNet score

LVK GWSkyNet output guide

GWSkyNet: how does it work?



1: consistent with GW signal

re

~93% accuracy on testing data

~90% on O3 public alerts

Evaluation time a matter of a minute

Chan. et al 2024 arXiv: 2408.06491

ility:
ndidate's GWSkyNet score

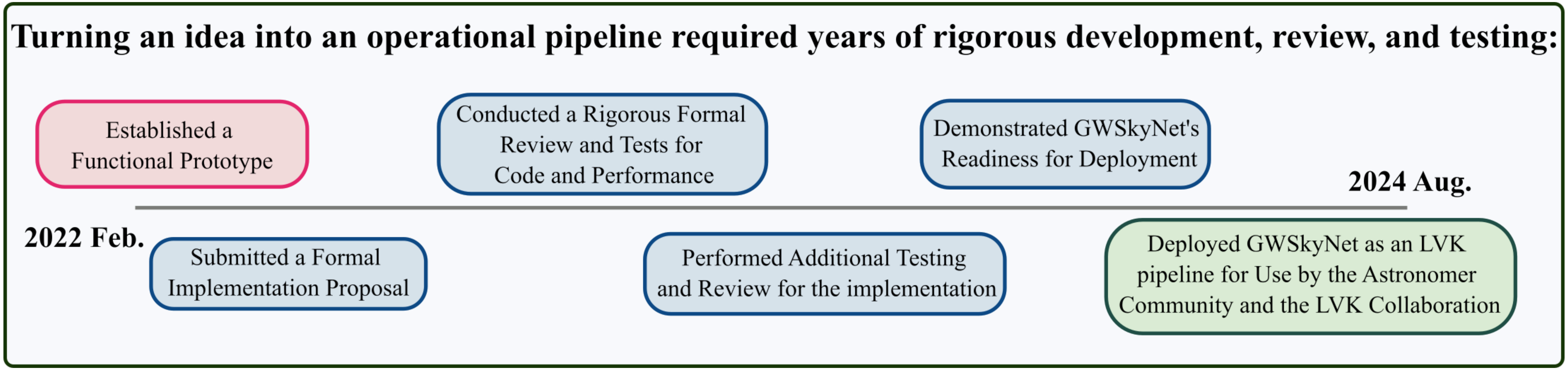
False negative probability:
the fraction of astrophysical events at or below a candidate's GWSkyNet score

LVK GWSkyNet output guide

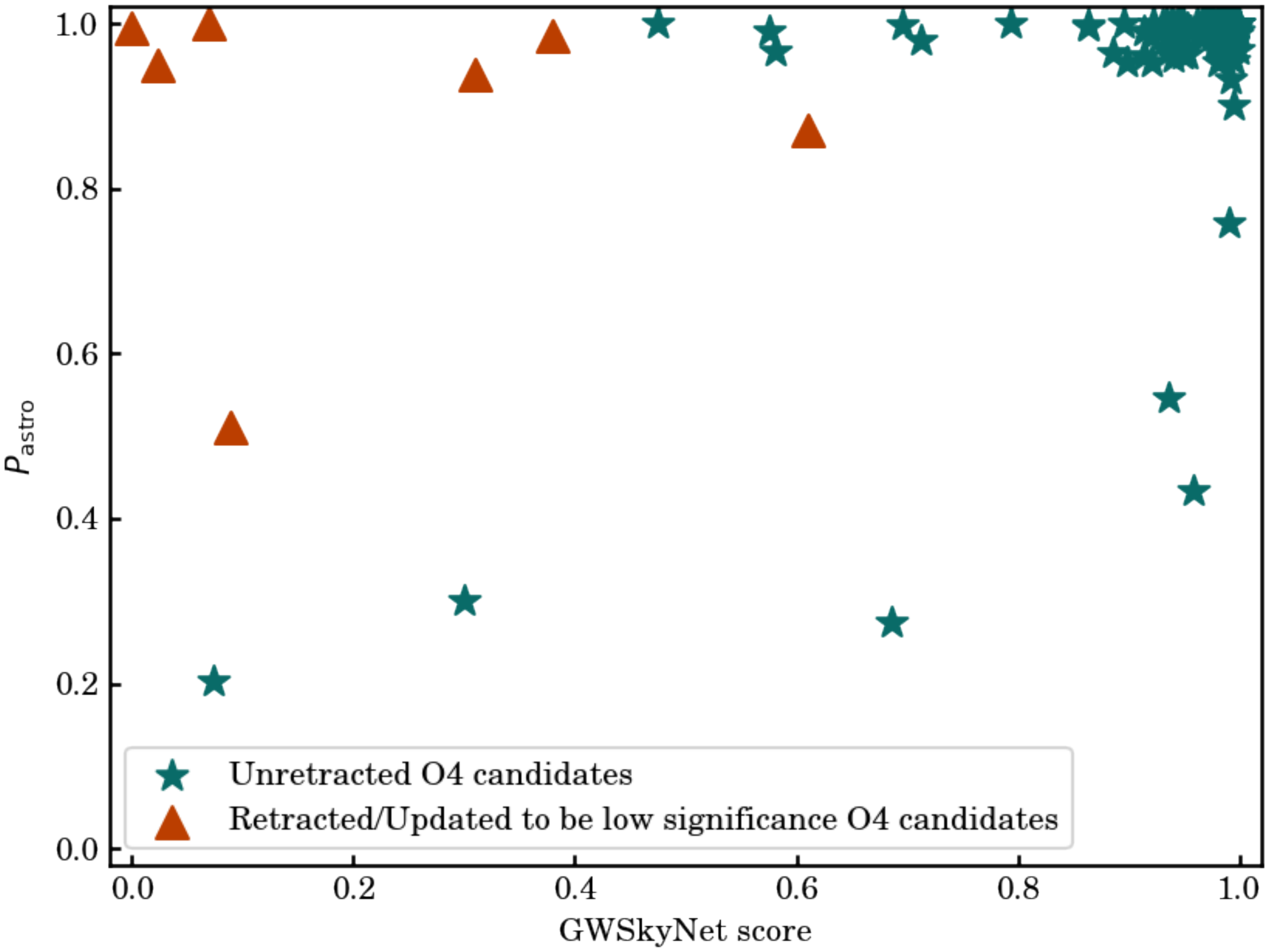
GWSkyNet itself is only half the solution

However, a tool is useful only if it is put to good use.

To facilitate electromagnetic followup observations, the GWSkyNet team has led years of effort to integrate the GWSkyNet pipeline into the LVK's low-latency infrastructure.



The outcome: all O4 retracted events correctly identified



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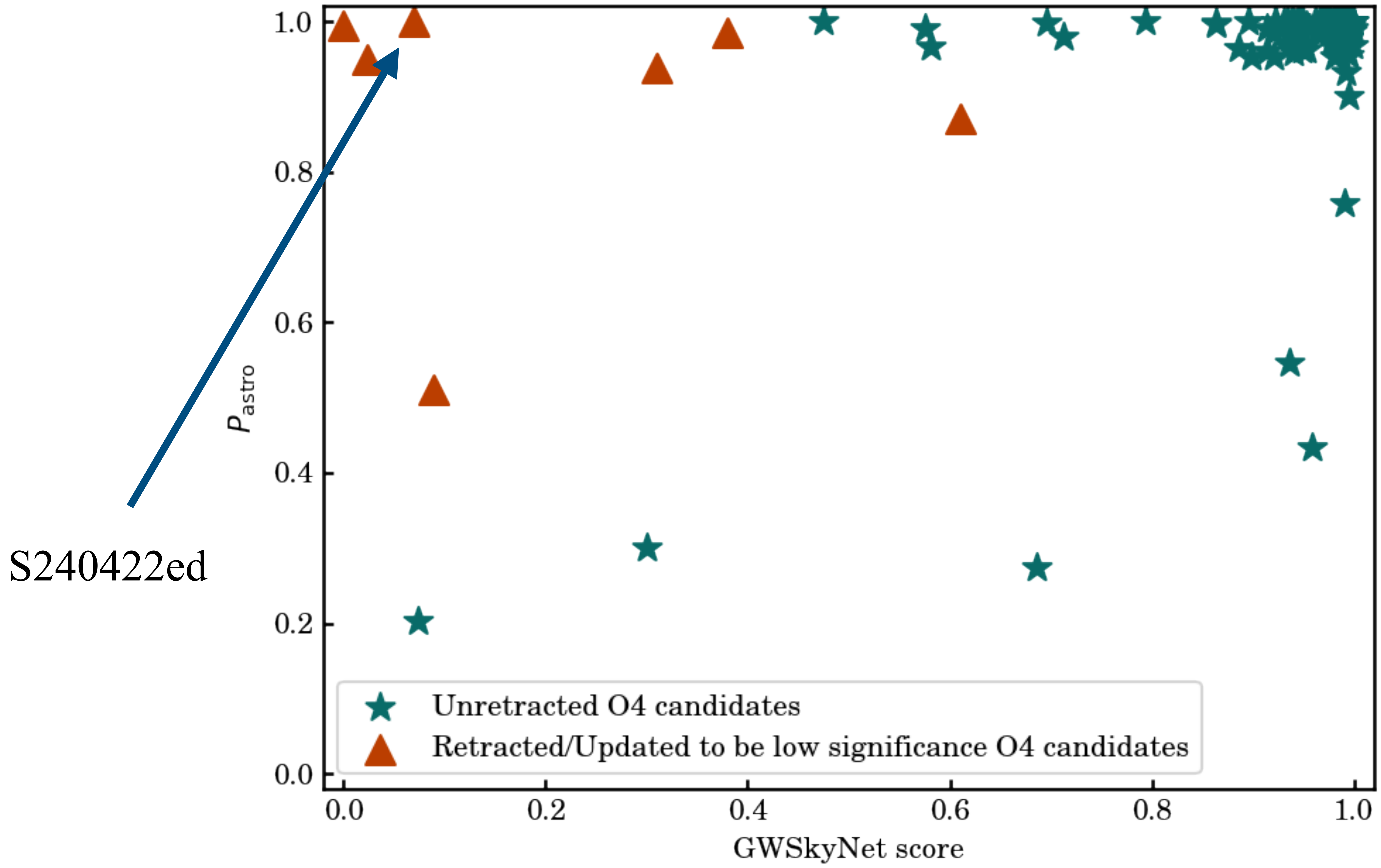
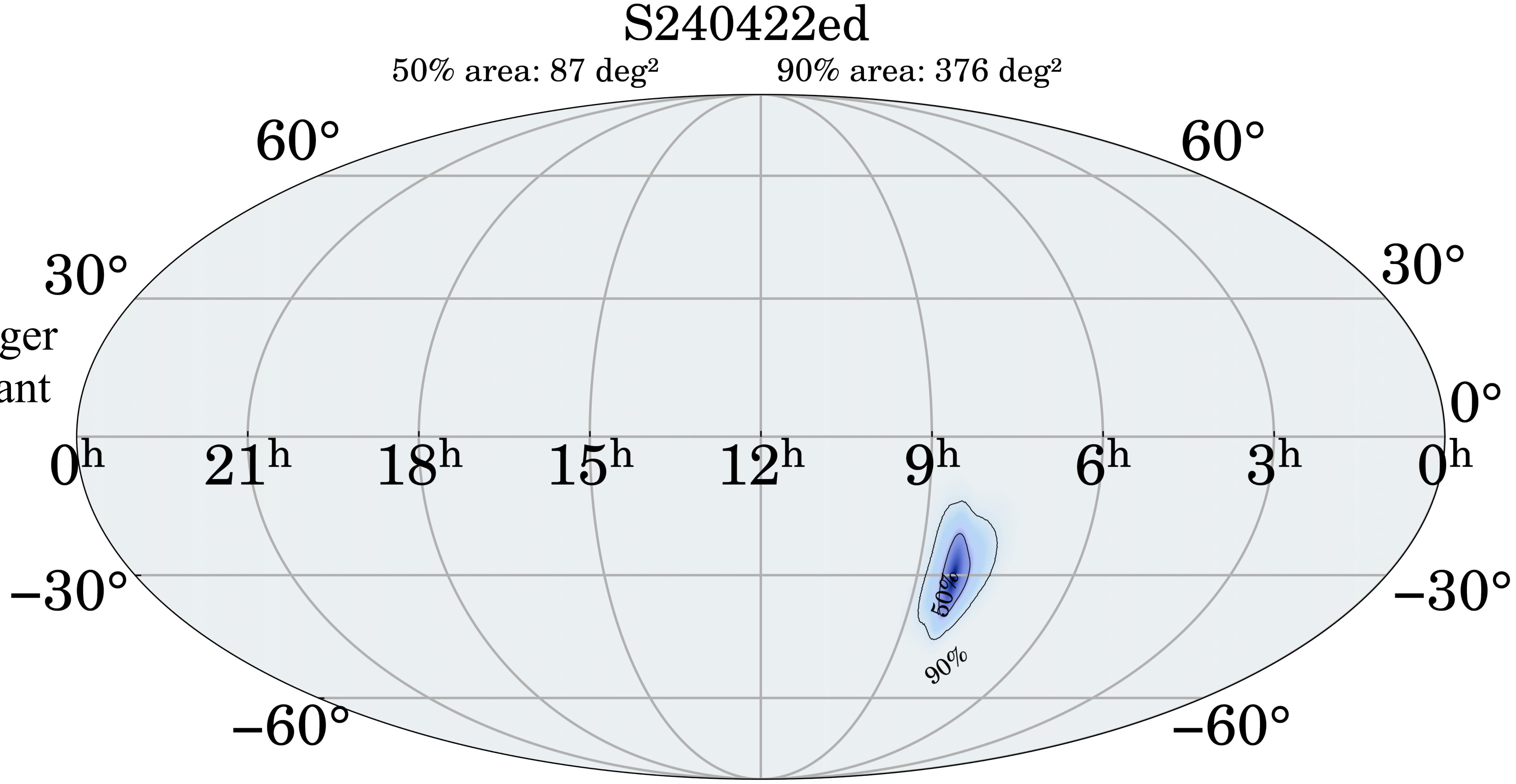


The outcome: an example O4 alert - S240422ed

- 99% neutron star black hole merger
- 100% has neutron star and remnant
- FAR: 1 per 1.0×10^5 years



GCN Circular 36812

Subject LIGO/Virgo/KAGRA S240422ed: Updated significance estimate
Date 2024-07-03T15:49:54Z (7 months ago)
From Ryan Magee at LVC <ryan.magee@ligo.org>
Via Web form

The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration report:

We have conducted further analysis of the LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) data, obtaining an improved estimate for the significance of compact binary merger (CBC) candidate S240422ed (GCN Circular 36236) by including information from subsequent data in the background model.

The updated background estimate from the GstLAL [1] pipeline results in a reduced significance of the candidate. As a result, the highest significance estimated for this candidate is now a false alarm rate of 3.269e-07 Hz, or about one in thirty five days, which was obtained by the PyCBC Live analysis in low latency. Both GstLAL [1] and PyCBC Live [2] analyses now find this event as a low-significance candidate. The MBTA [3] low-latency analysis finds the false alarm rate of the candidate to not pass the low-significance threshold.

The updated classification of the candidate, in order of descending probability, is Terrestrial (93%), BNS (5%), NSBH (2%), or BBH (<1%).

Note that future offline analyses may infer a different terrestrial probability and/or false alarm rate.

For further information about analysis methodology and the contents of this alert, refer to the LIGO/Virgo/KAGRA Public Alerts User Guide https://emfollow.docs.ligo.org/.

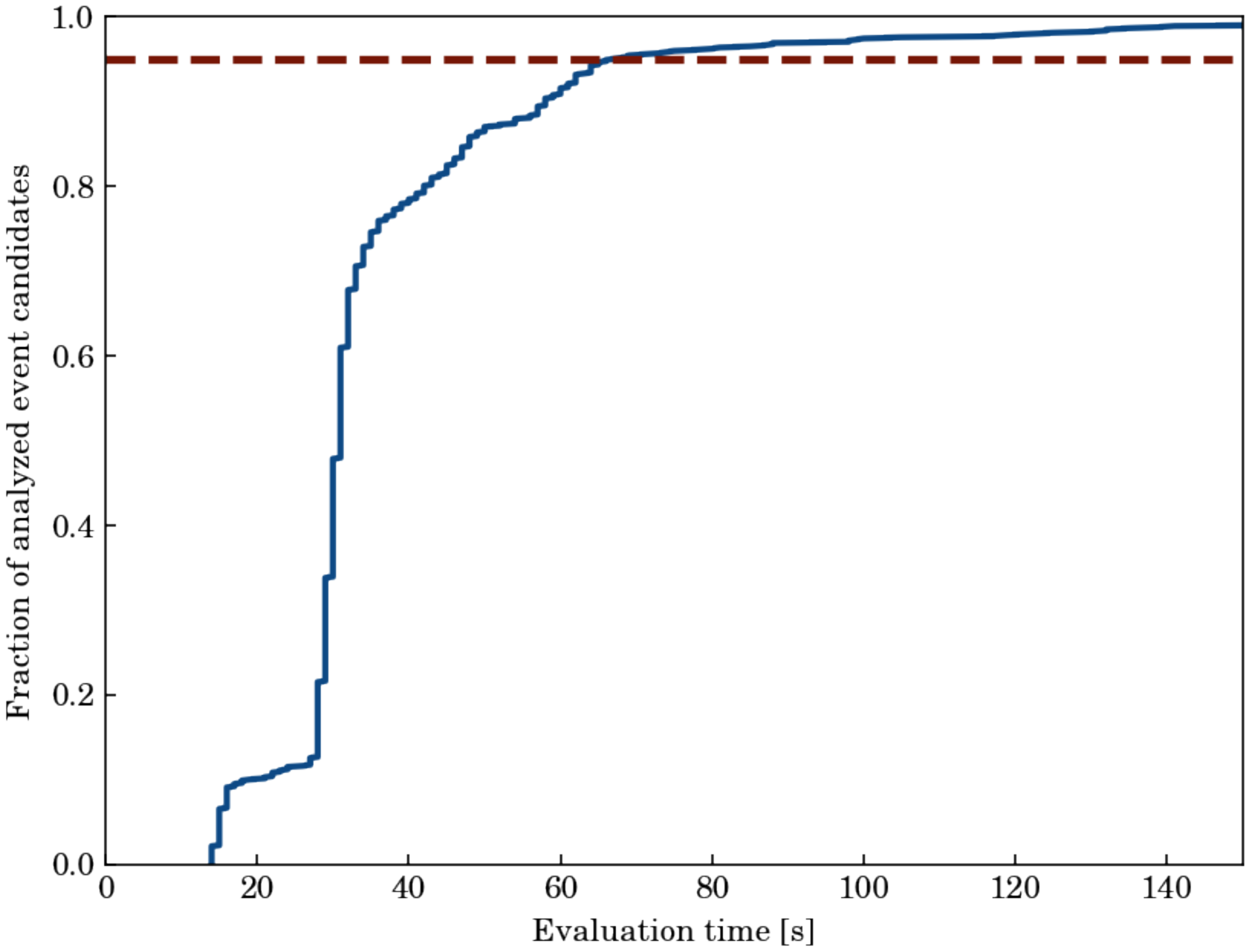
[1] Tsukada et al. PRD 108, 043004 (2023) doi:10.1103/PhysRevD.108.043004 and Ewing et al. (2023) arXiv:2305.05625
[2] Dal Canton et al. ApJ 923, 254 (2021) doi:10.3847/1538-4357/ac2f9a
[3] Aubin et al. CQG 38, 095004 (2021) doi:10.1088/1361-6382/abe913

GWSkyNet score: 0.069
FAP: 0.729, FNP: 0.004

72 days (2.4 months) earlier!

- 99% neutron star b
- 100% has neutron
- FAR: 1 per 1.0 × 1

The outcome: GWSkyNet's time efficiency



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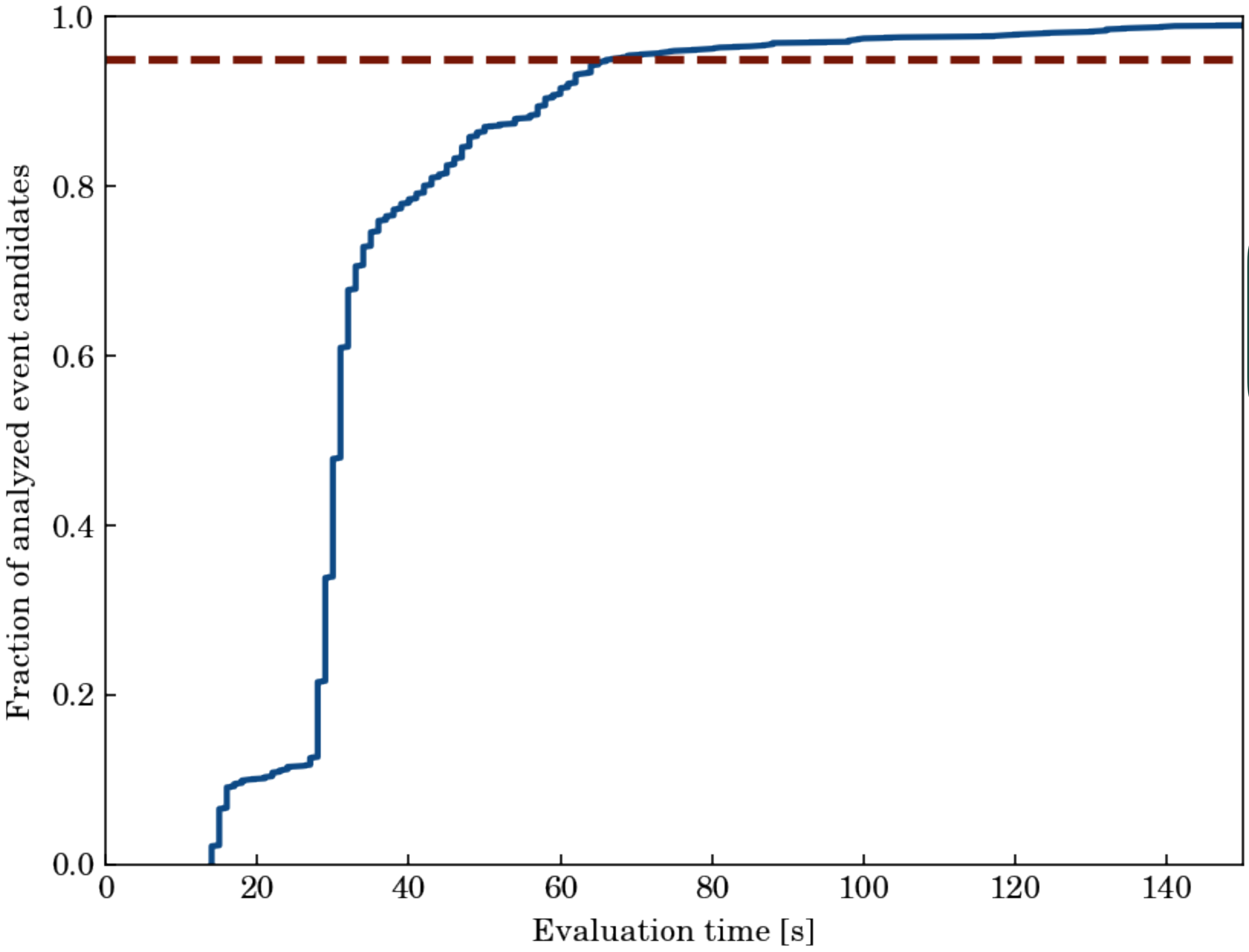

95% GW candidates analyzed within 66 seconds

The outcome: community impact

- GWSkyNet's accurate performance has already made an impact since it was deployed in summer 2024
  - It has been used by the LVK Collaboration and by astronomers
  - For example, the Gravitational-Wave Optical Transient Observer (GOTO)*
    - incorporates GWSkyNet's automatic outputs in their follow-up algorithm

*An international team of astronomers for gravitational wave follow-up observations

https://goto-observatory.org/

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Our team also reveals the physical features GWSkyNet has learned by applying explainability techniques

Raza et al. 2024 arXiv: 2308.12357

Please talk to me about this if you are interested!

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GWSkyNet: next level

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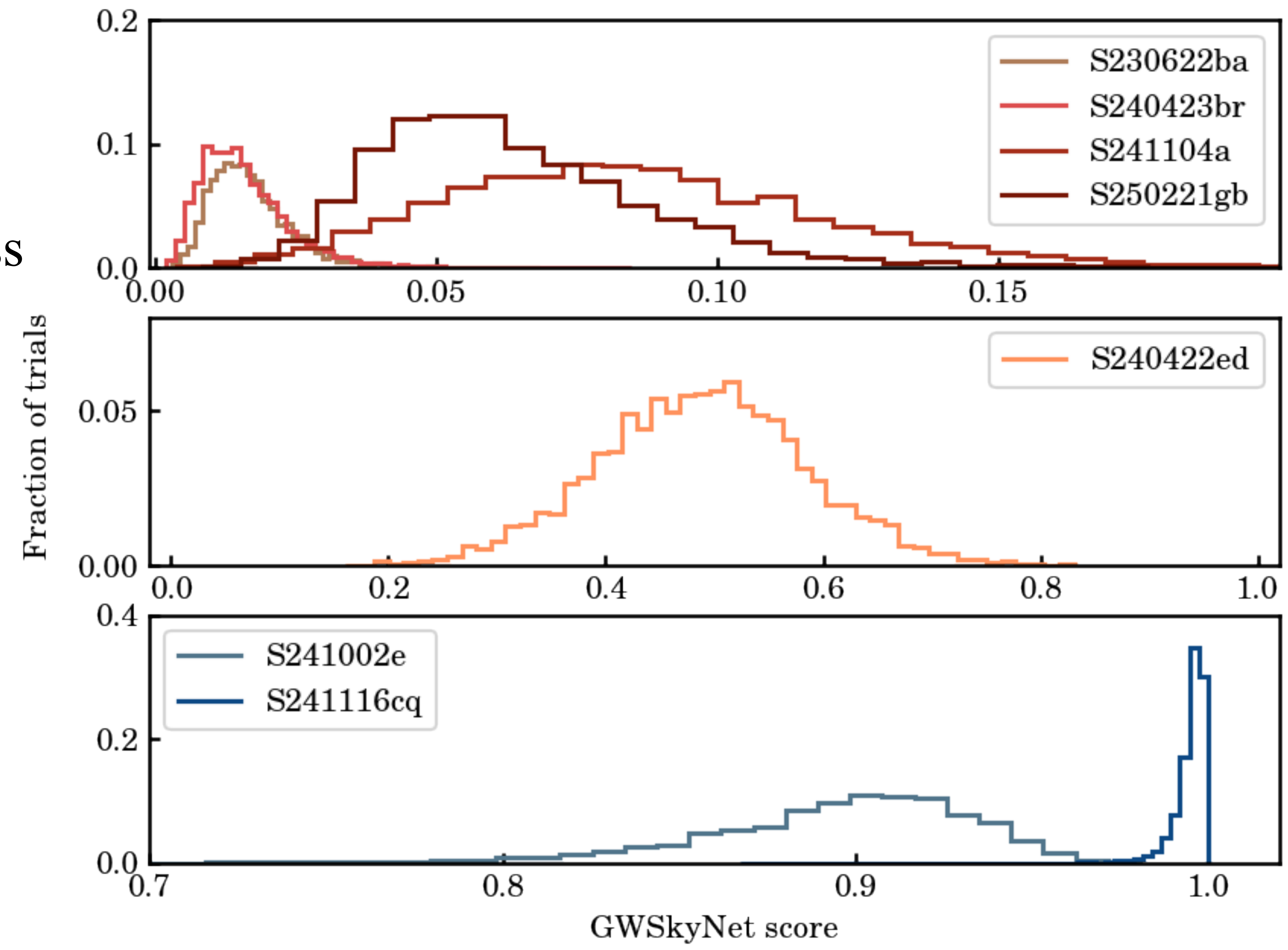

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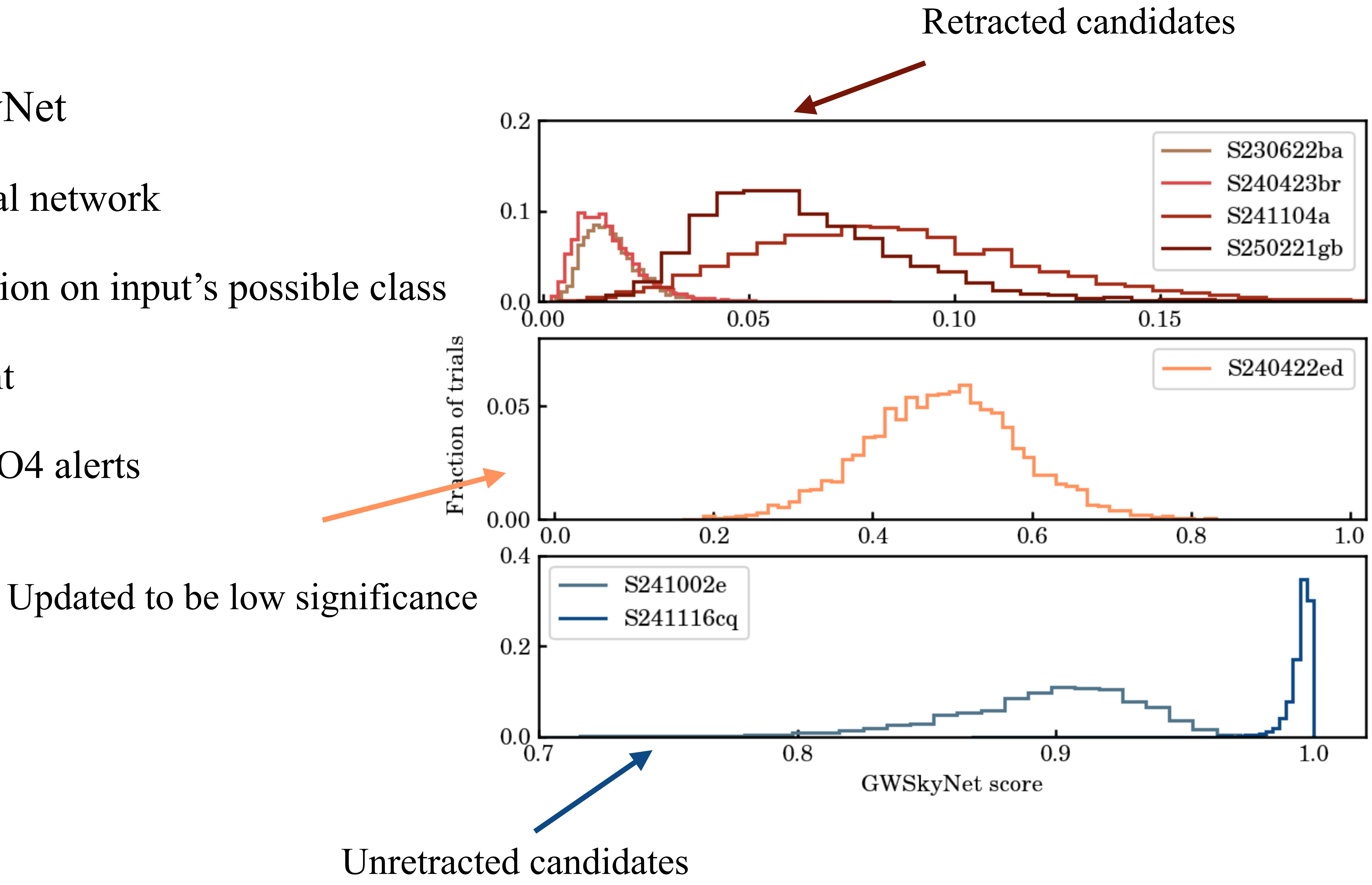

Conclusion

- GWSkyNet is a deep learning solution
  - To address the problem of false alarms with real-time GW searches
  - Led by the UBC LIGO group, and collaborators from across Caltech, McGill University and the LVK
  - Deployed since the summer last year
  - Excellent accuracy already made an impact on astronomer community
  - New upgrade to address problems inherent with convolutional neural networks on the way