Hunting for the sources of Neutrinos and Gravitational-Waves in realtime

Marek Kowalski, DESY/Humboldt-University

10.4.2025 Toulouse

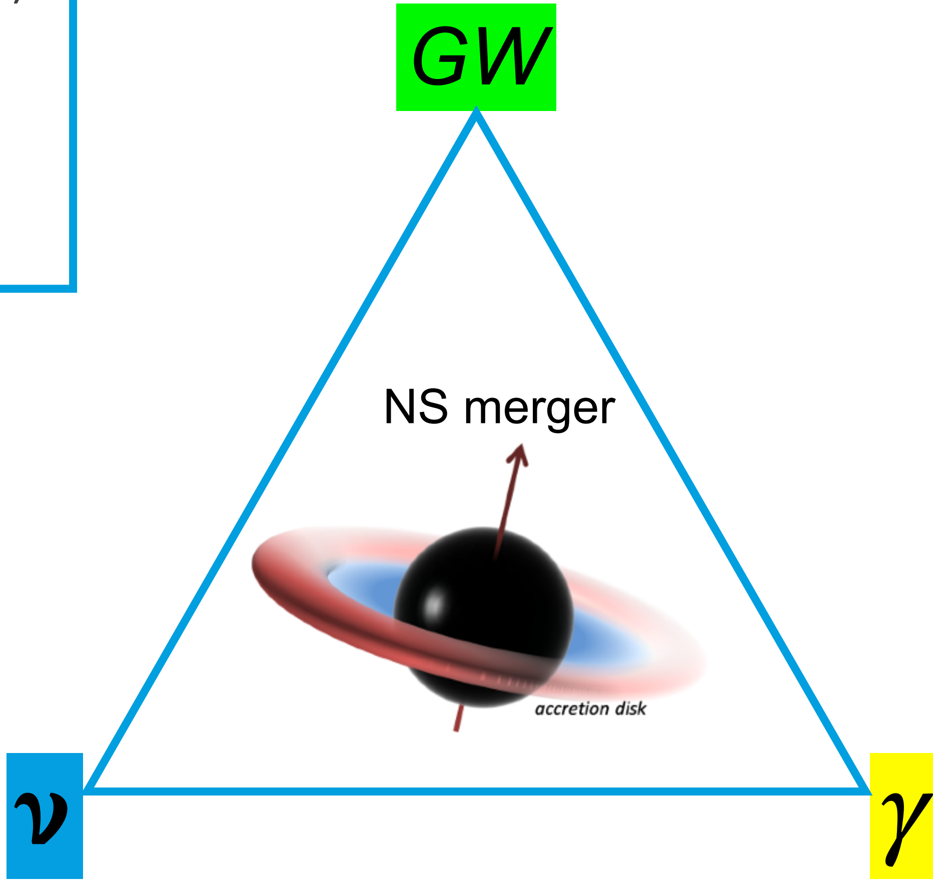
Multimessenger triangle

Explained using the NS merger / Kilonova scenario

Most probable (proposed) GW + ν sources:

- Binary neutron stars (a potential kilonova)
- Binary neutron star-black holes
- Binary black holes with an accretion disc
- Core collapse supernova
- …

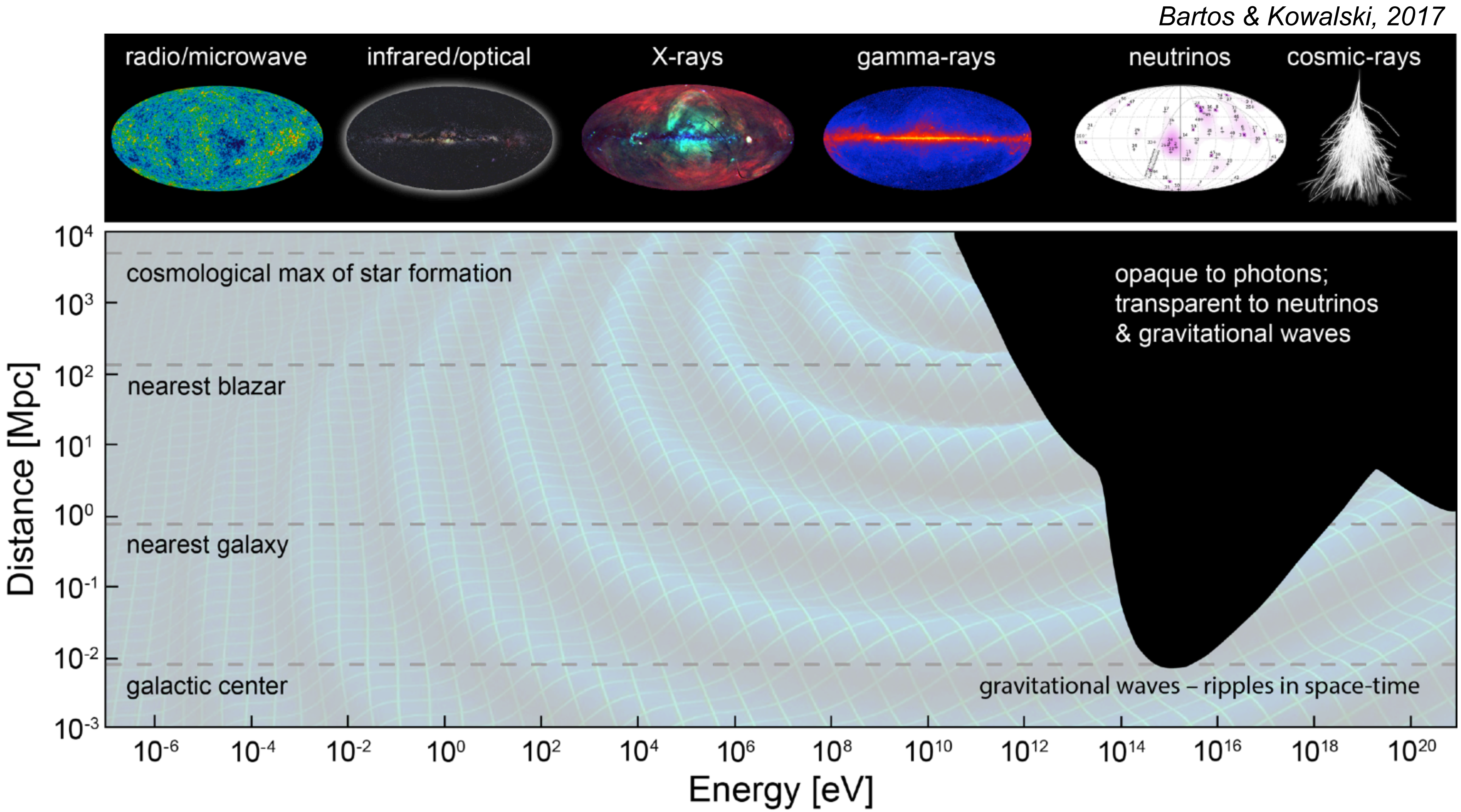
Need a changing quadrupole moment for GW emission



Need of energetic matter / outflows / shocks to produce high-energy neutrinos

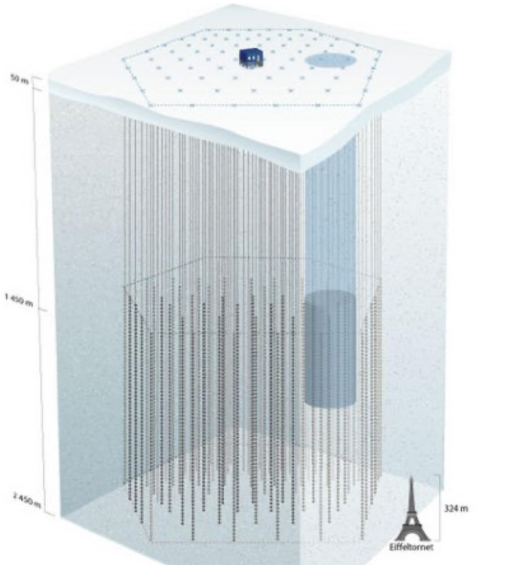
Many channels active for broad multi-wavelength emission. Signatures are known: sGRBs & kilonova

The multi-messenger high-energy frontier

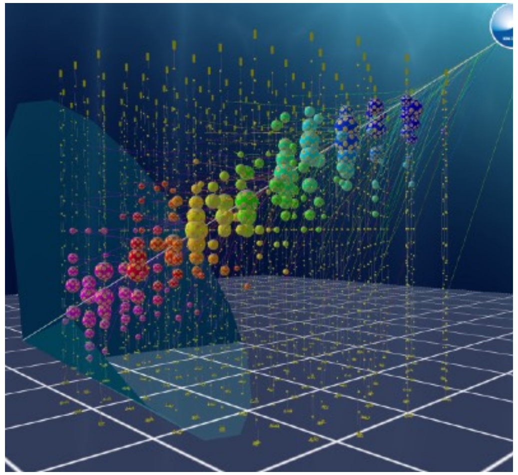


The Universe is opaque to photons for ¼ of the spectrum

Ultra-high energy emission from neutron star mergers?



IceCube



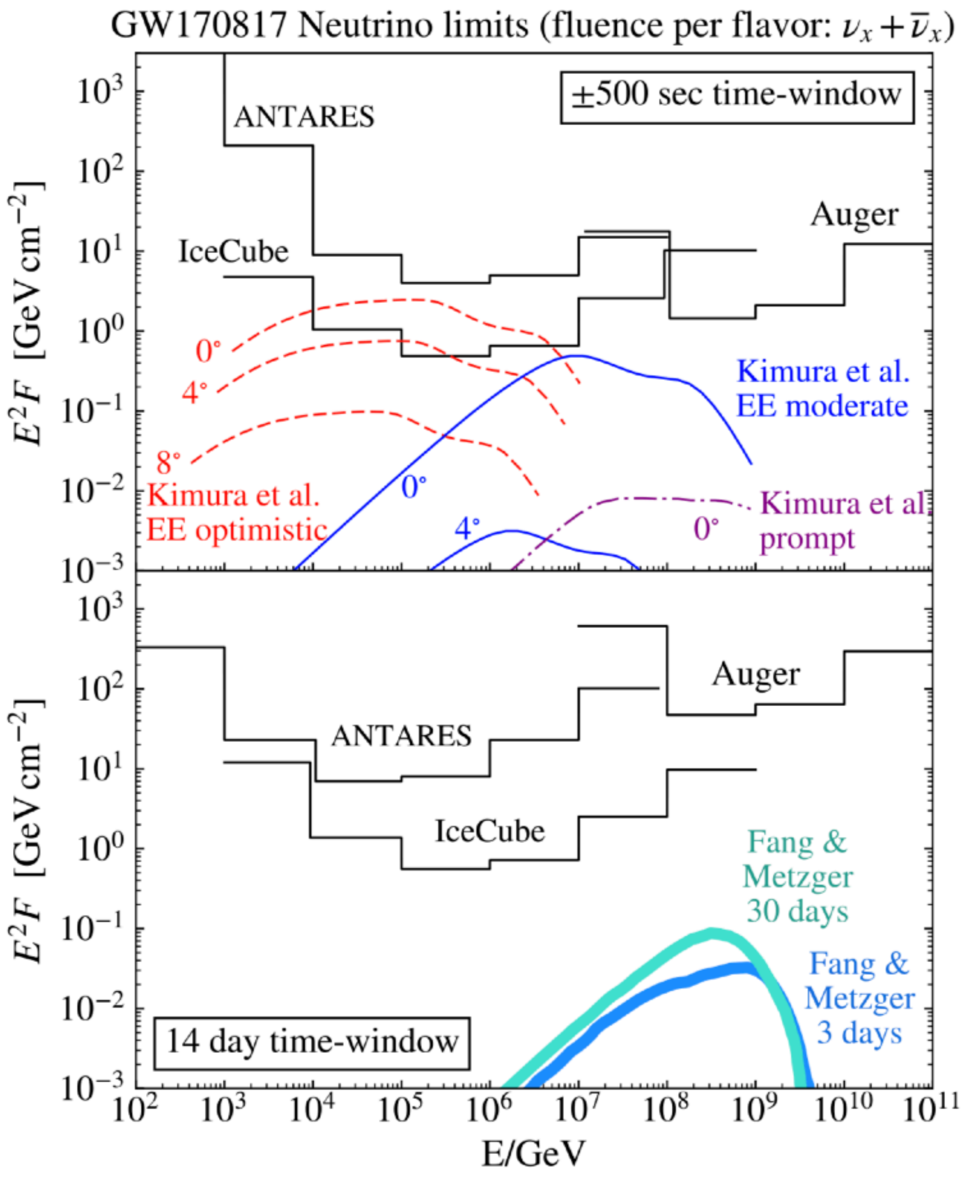
ANTARES / KM3NeT

- High-energy neutrinos:
  - Probe PeV+ particle acceleration
  - All-sky detectors --- rapidly provide precise location
  - ν's can escape environments γ-rays cannot

- High-energy (TeV-PeV) neutrinos could have been detected for on-axis GW170817.

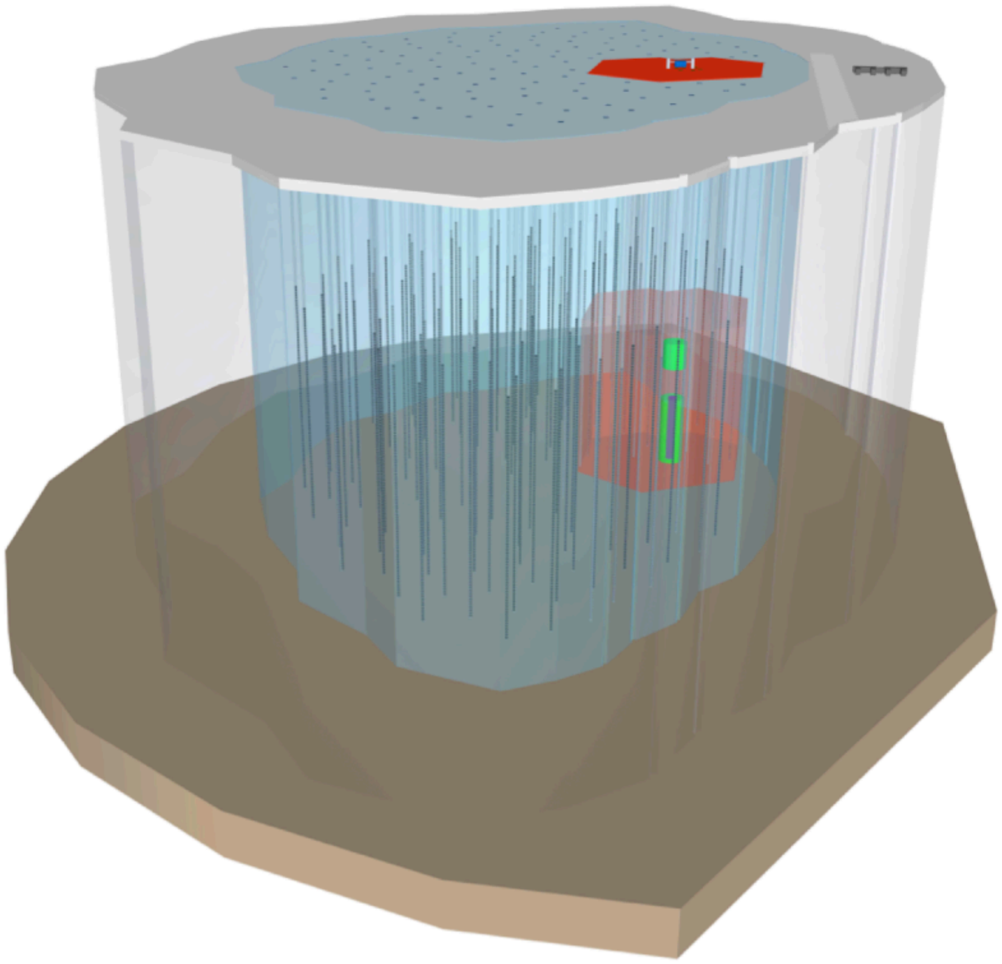
- Relativistic outflow will interact with slower ejecta
  → alter neutrino emission
  → can probe jet structure.

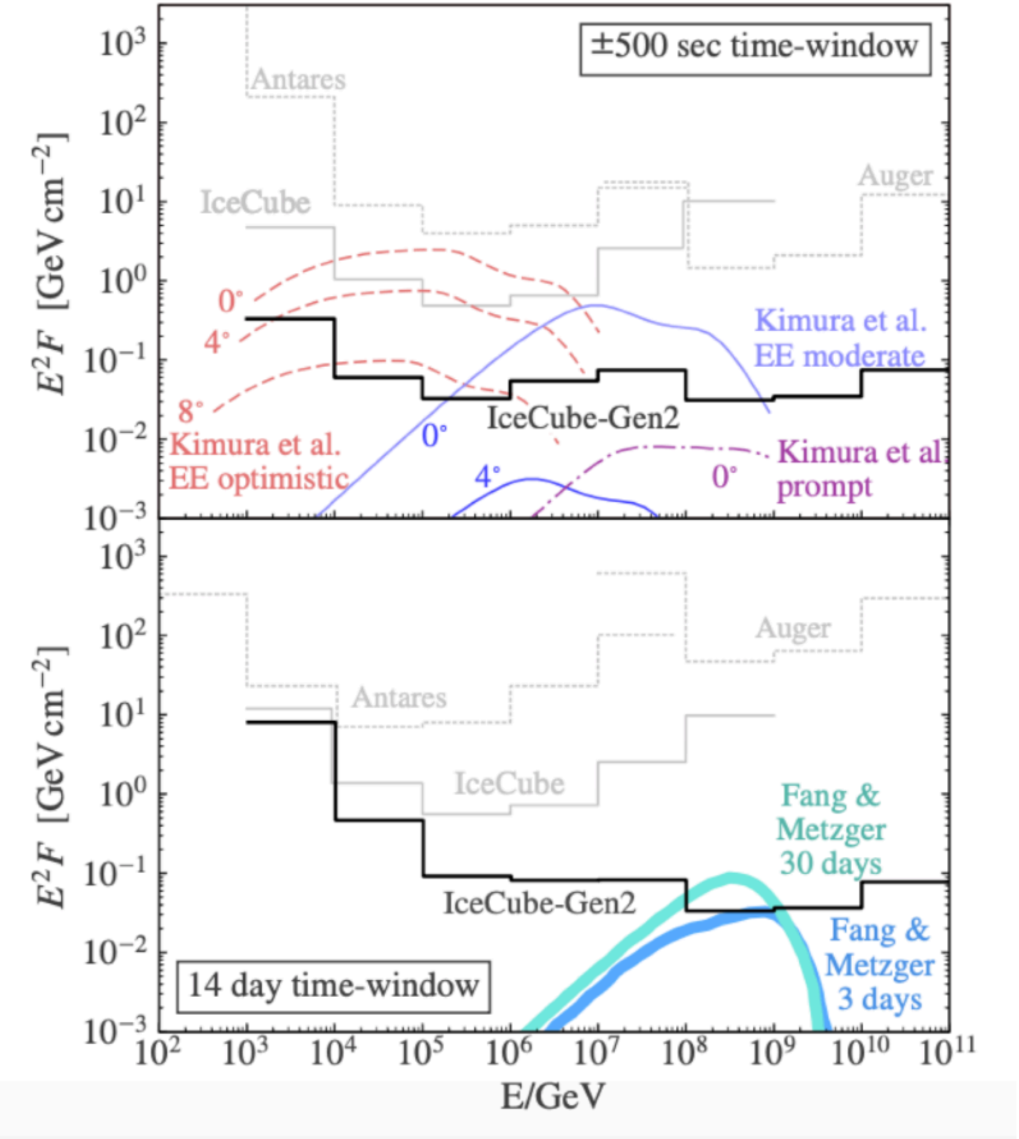
- Typical Search within <u>1000 s</u> and <u>2-week</u> time windows (model motivated).



Magnitude increase in sensitivity for next-gen projects

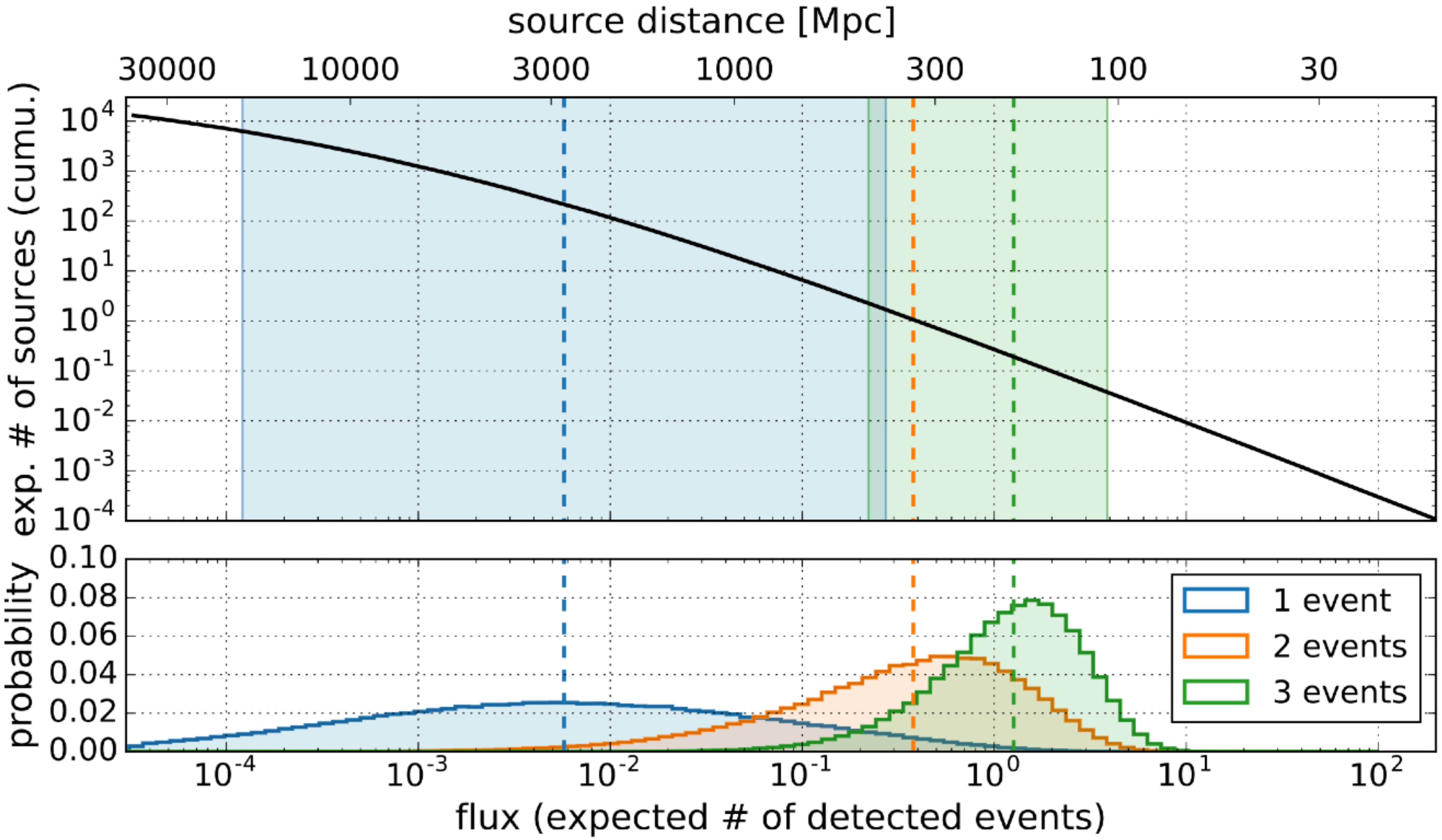
Using IceCube-Gen2 as an example





Technical Design Report

Poisson fluctuation make neutrino astronomy with alerts special



Neutrino event expectation from a simulated distribution of BL-Lacs [Strothjohann, MK, Franckowiak, A&A 2019]

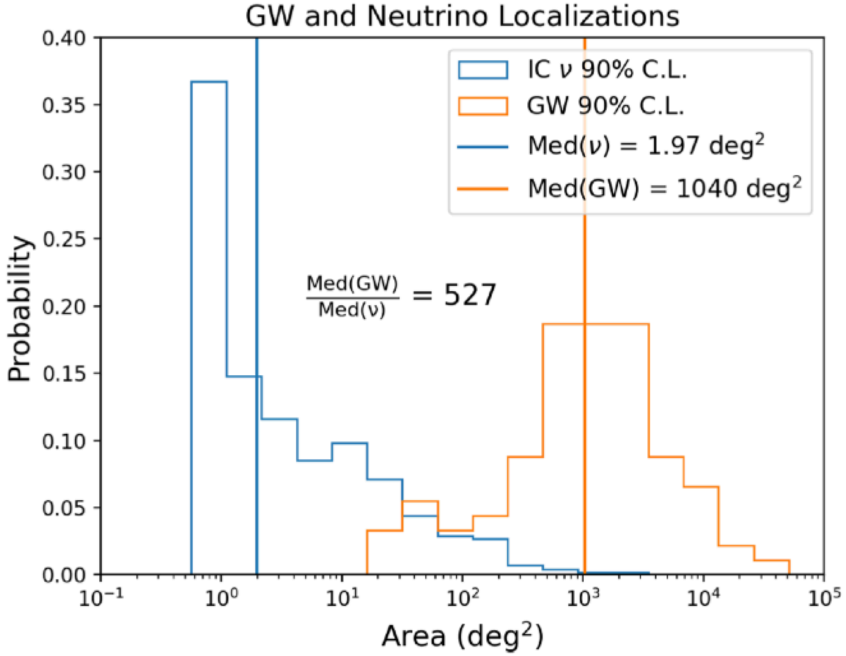
Eddington bias results in sensitivity to faint, distant sources. Detecting the counterpart of single high-energy (>100 TeV) neutrinos essential.

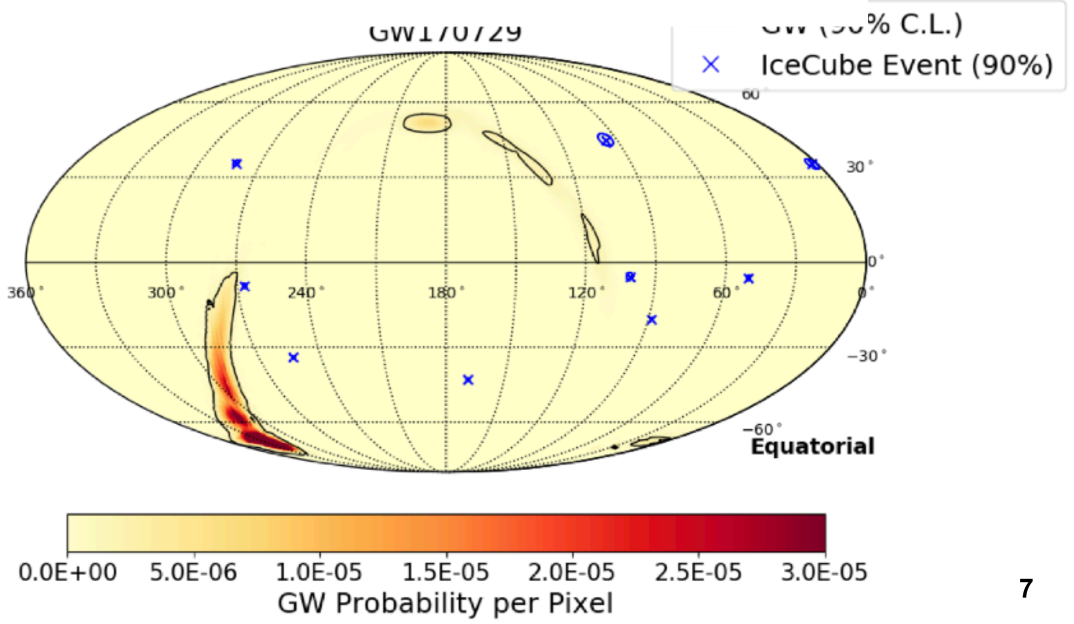
IceCube neutrino follow-up of GW events

What we do in IceCube

Two follow-up methods/algorithms in IceCube:

- a general transient search, using an unbinned maximum likelihood analysis [Abbasi et al. ApJ, 2023]
- a Bayesian search assuming a binary merger scenario [Aartsen et al 2020 ApJL, see also Bartos et al., 2019 PRD].





IceCube neutrino follow-up of GW events

GWν

Realtime information: https://roc.icecube.wisc.edu/public/LvkNuTrackSearch/

Event Name	Merger Time (ISO)	LVK GCN Link	IceCube GCN	Duration (s)	N Coincident Neutrinos	IceCube Sensitivity (E^2 dN/dE, GeV cm^-2)	Neutrino Information
S250401bi-1-Preliminary	2025-04-01 08:06:13.662295	LVK GCN	GCN Notice	1.00e+03	0	[0.028, 1.133]	-
S250401bi-2-Preliminary	2025-04-01 08:06:13.662295	LVK GCN	GCN Notice	1.00e+03	0	[0.028, 1.133]	-
S250401av-1-Preliminary	2025-04-01 06:43:08.401609	LVK GCN	GCN Notice	1.00e+03	0	[0.028, 1.060]	-
S250401av-2-Preliminary	2025-04-01 06:43:08.401609	LVK GCN	GCN Notice	1.00e+03	0	[0.028, 1.060]	-
S250401an-1-Preliminary	2025-04-01 04:04:49.066895	LVK GCN	GCN Notice	1.00e+03	2	[0.028, 0.543]	here
S250401an-2-Preliminary	2025-04-01 04:04:49.066895	LVK GCN	GCN Notice	1.00e+03	2	[0.028, 0.552]	here
S250331cv-1-Preliminary	2025-03-31 22:20:26.434591	LVK GCN	GCN Notice	1.00e+03	0	[0.028, 0.552]	-
S250331cv-2-Preliminary	2025-03-31 22:20:26.415283	LVK GCN	GCN Notice	1.00e+03	0	[0.028, 0.584]	-
S250331af-1-Preliminary	2025-03-31 08:52:38.002316	LVK GCN	GCN Notice	1.00e+03	0	[0.028, 0.830]	-
S250331af-2-Preliminary	2025-03-31 08:52:37.998779	LVK GCN	GCN Notice	1.00e+03	0	[0.028, 0.830]	-

IceCube neutrino follow-up of GW events

GWν

Realtime information: https://roc.icecube.wisc.edu/public/LvkNuTrackSearch/

IceCube Follow-up: S250329fl-2-Preliminary

Page generated (UTC): 2025-03-29 15:30:20

Home

Analysis Results

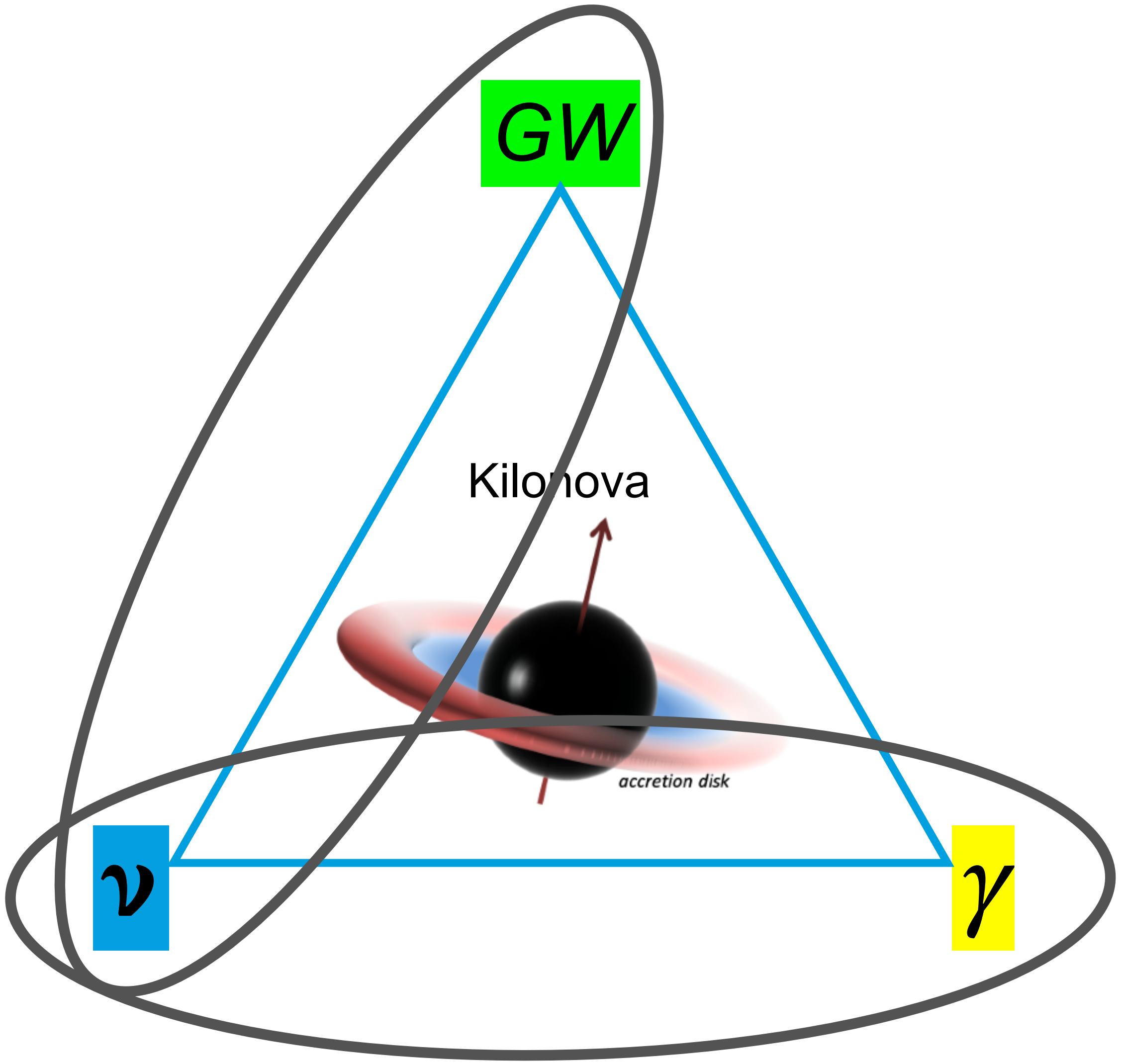
Note: These p-values measure the consistency of the observed track-like events with the known atmospheric backgrounds for this single map (not trials corrected for multiple GW events). The most probable direction is the maximum probability RA, decl. found in the generic transient search (reported when the p-value for that search is less than 10%).

Name:	S250329fl-2-Preliminary
Start time (UTC):	2025-03-29T14:58:44.288Z
Stop time (UTC):	2025-03-29T15:15:24.288Z
N Coincident Events	2
p-value (generic transient):	None
p-value (Bayesian):	5.1e-05
Most probable direction:	N/A

See also, https://gcn.nasa.gov/circulars/39928

…but likely a glitch in LVK

If the EM signatures of a GW source are known, one can directly look for them

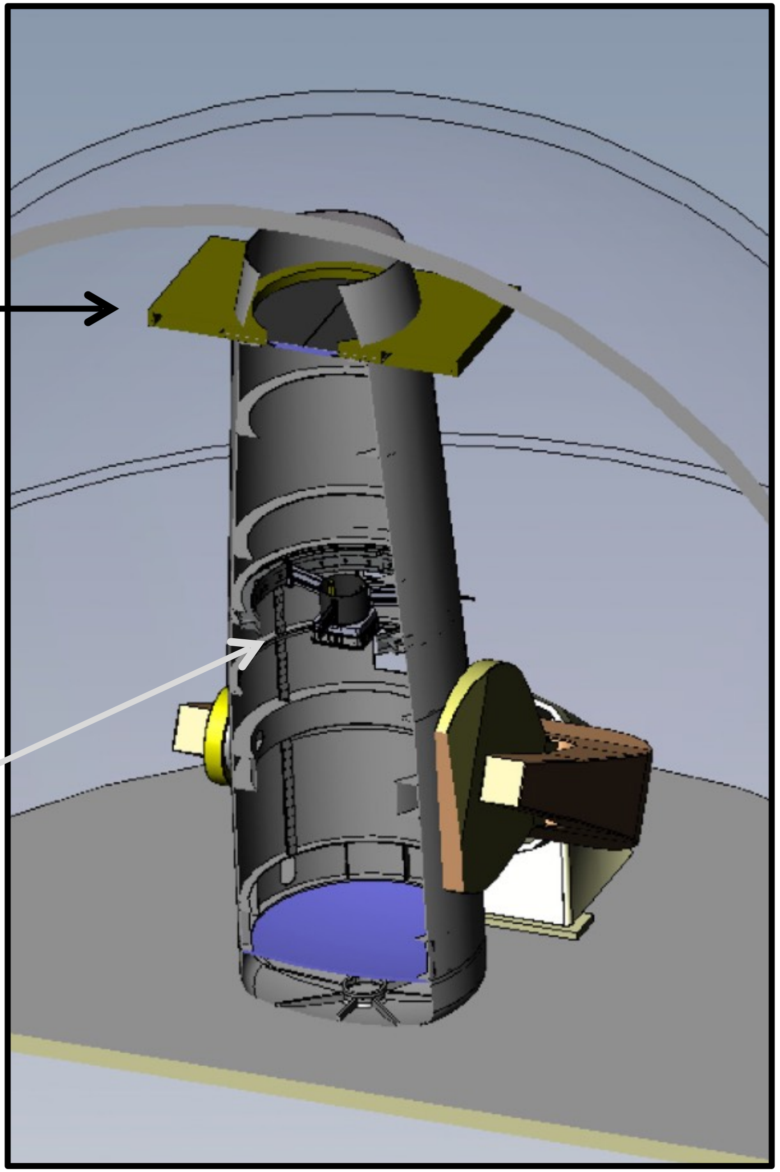


The Zwicky Transient Facility

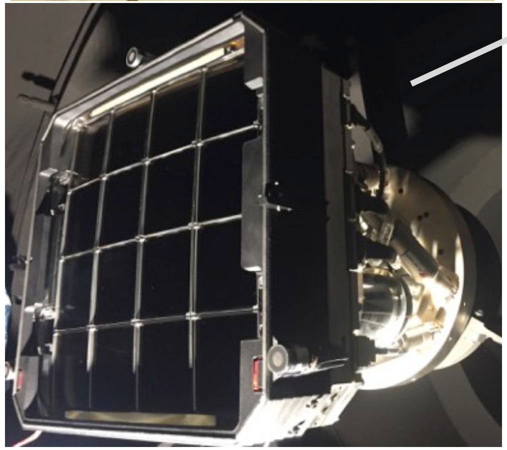
A Multimessenger search engine

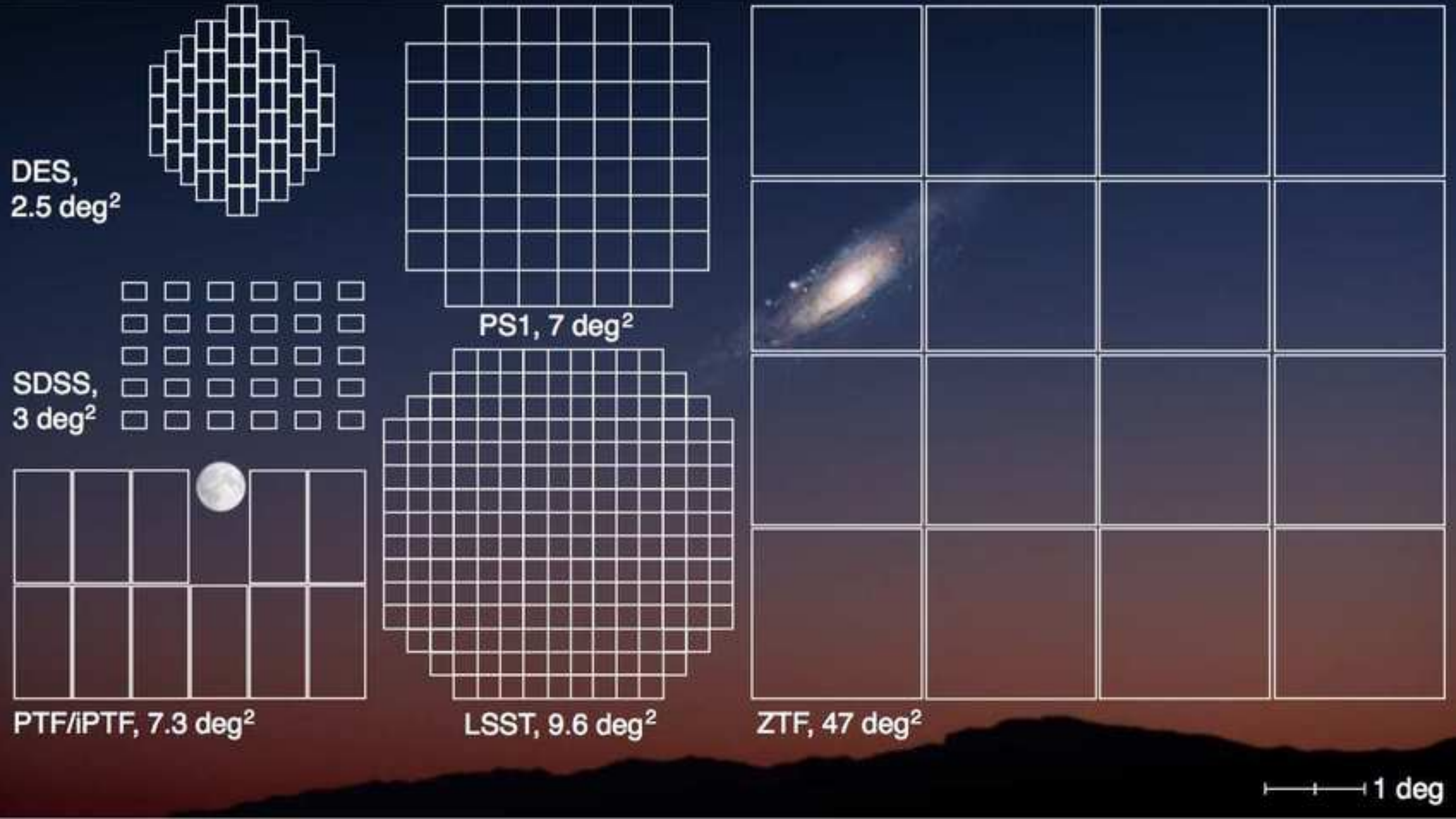
The Zwicky Transient Facility

Largest shutter
ever build
(DESY/Bonn)



47deg^2 FoV,
576 Mpixels

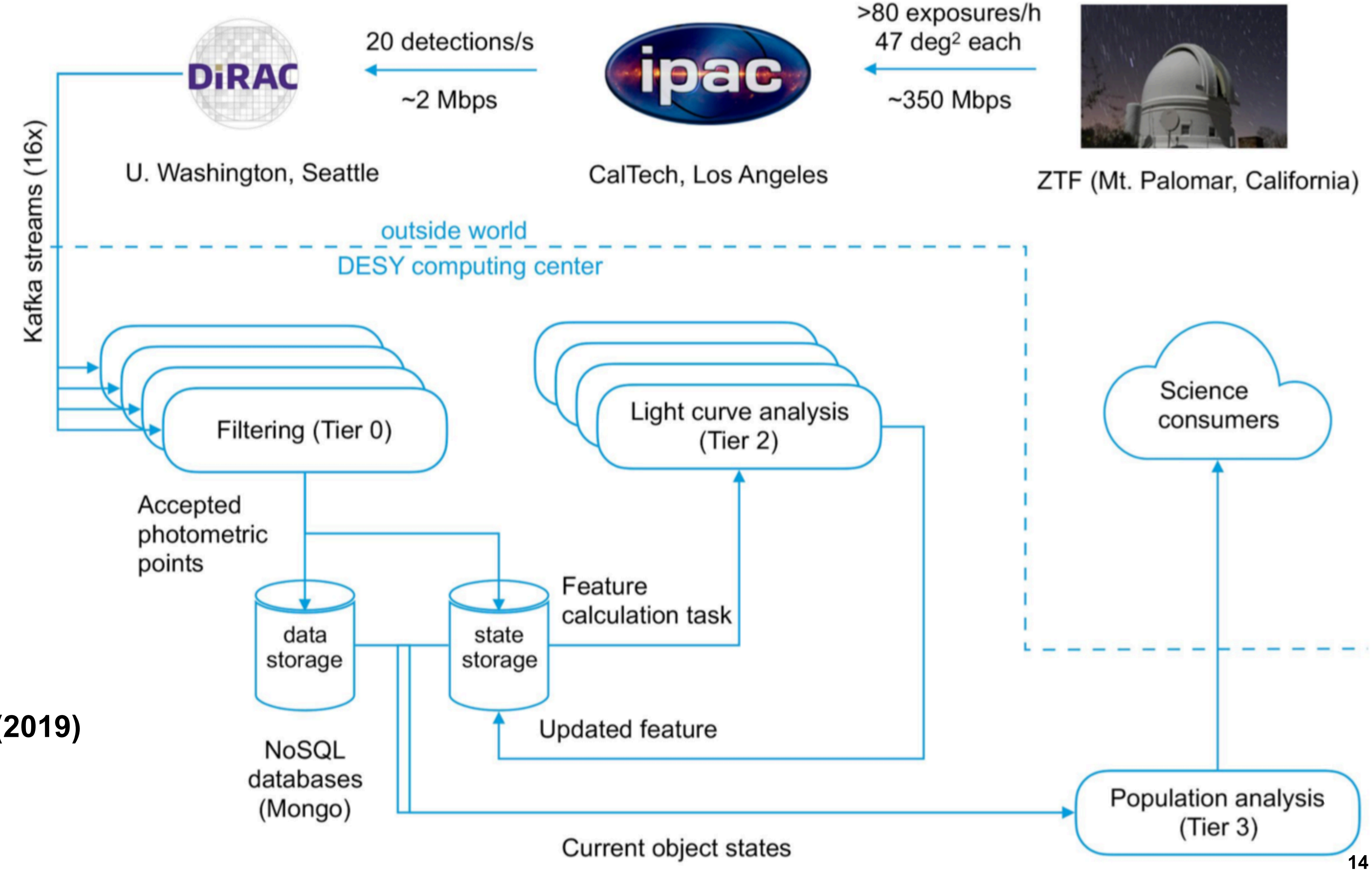



DES,
2.5 deg^2
PS1, 7 deg^2
SDSS,
3 deg^2
PTF/iPTF, 7.3 deg^2
LSST, 9.6 deg^2
ZTF, 47 deg^2
1 deg

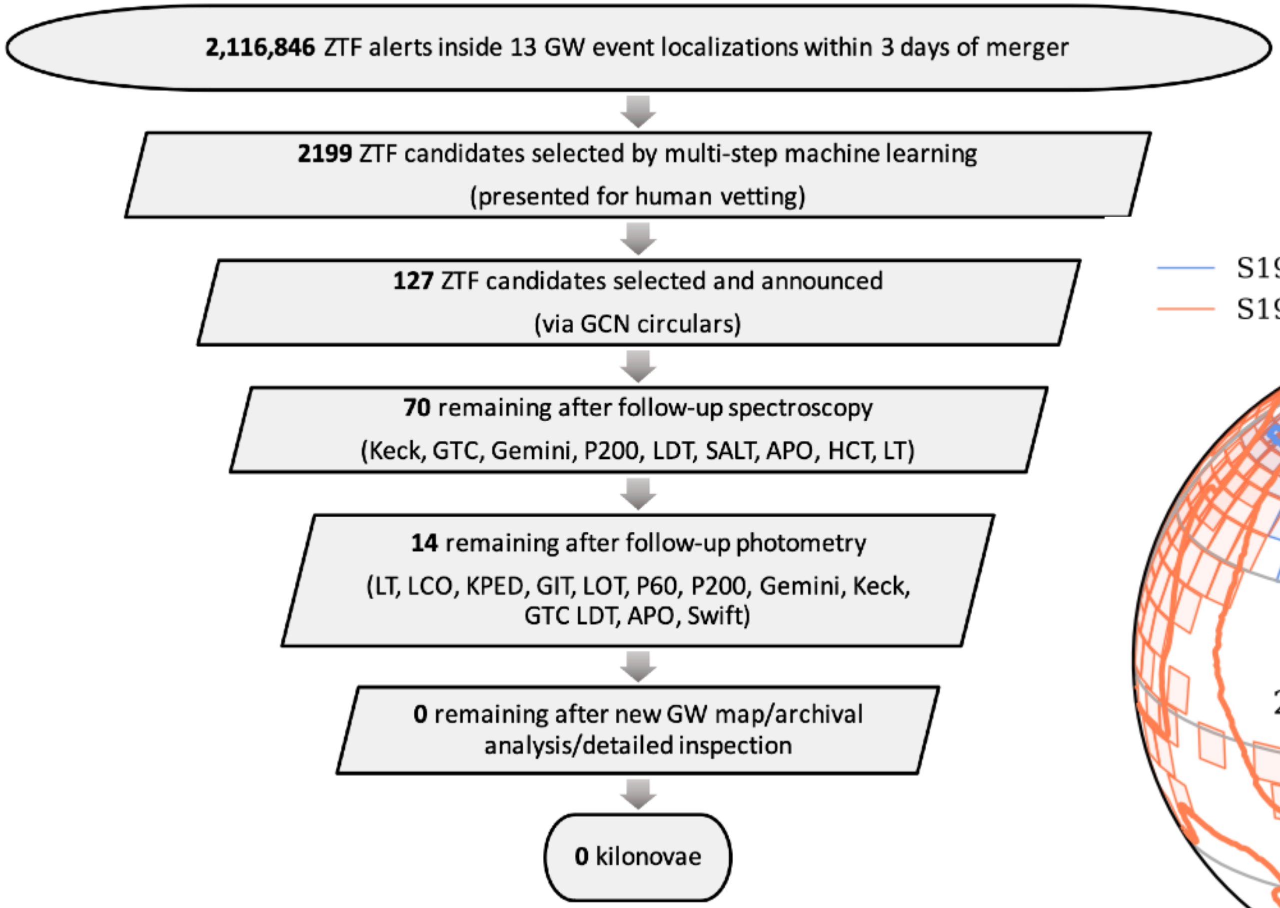
Transient detections with ZTF and AMPEL

AMPEL
Real-time analysis framework running 24/7 @ DESY

J. Nordin et al. A&A (2019)

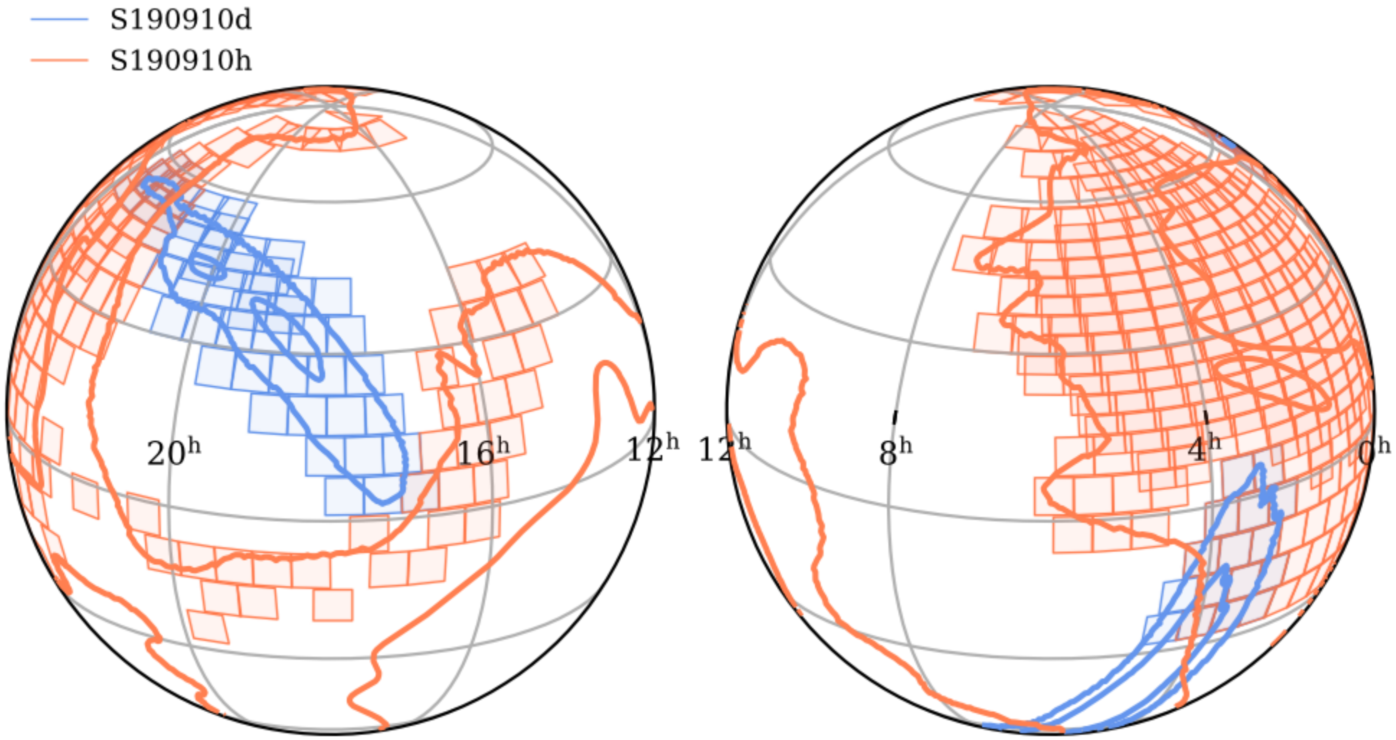


ZTF: Search for Kilonovae as counter parts of GW events



joint probability of zero detections is <10%
for AT2017gfo / GW170817-like Kilonova
-> constrain the luminosity function

Kasliwal et al, ApJ, 2020



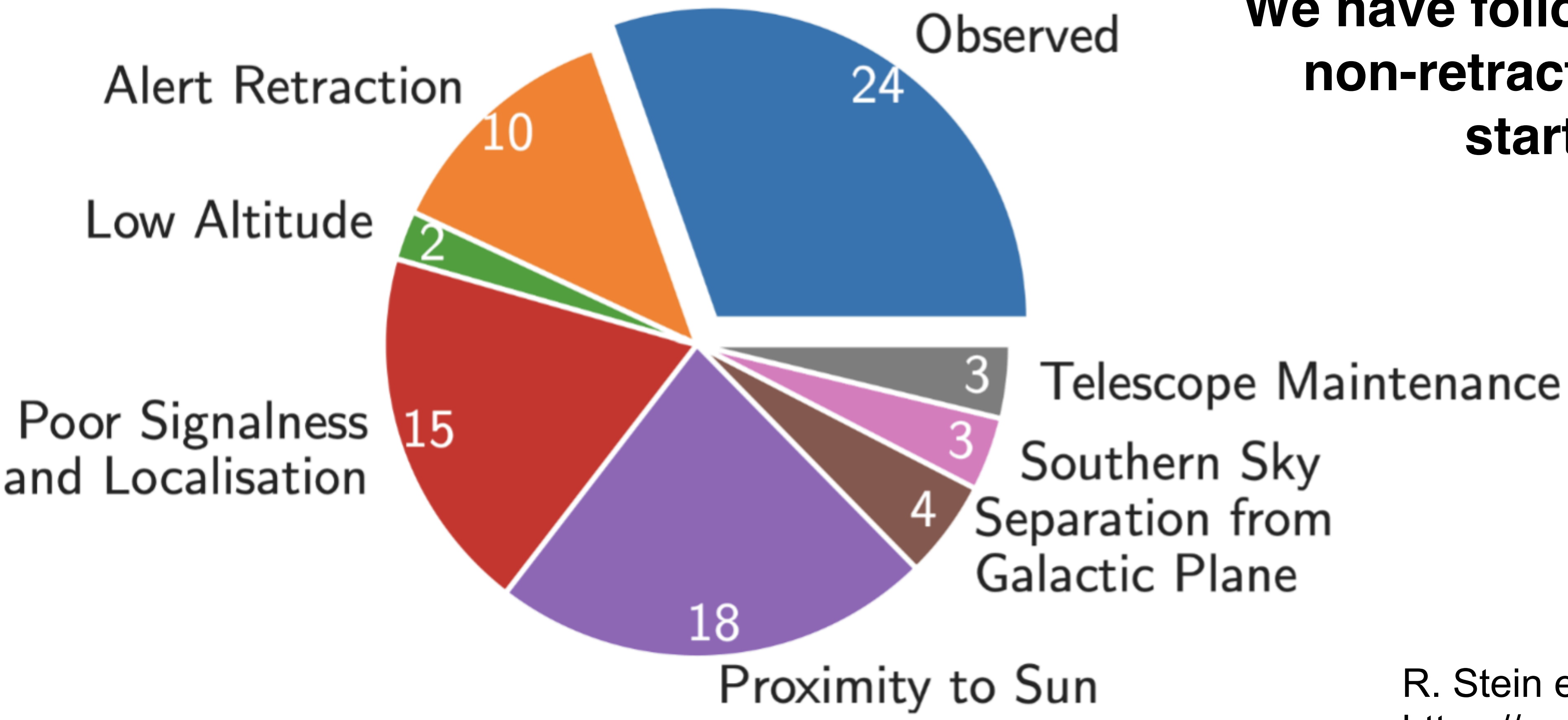
(O4 produced so far also no counterparts)

ZTF: Neutrino-Optical coincidences

Systematic follow-up of IceCube high-energy neutrino alerts

What is the origin of IceCube high-energy neutrinos?

We have followed up 35% of non-retracted alerts since start of ZTF in 2018



R. Stein et al, https://arxiv.org/abs/2203.17135

ZTF: Neutrino-Optical coincidences

ZTF follow-up of IceCube neutrinos identified a SNe Ibn

GCN Circular 34797 — Neutrino alert

Subject
IceCube-231004A - IceCube observation of a high-energy neutrino candidate track-lik
event
Date
2023-10-04T15:46:15Z (6 months ago)
From
Massimili
bochum.d

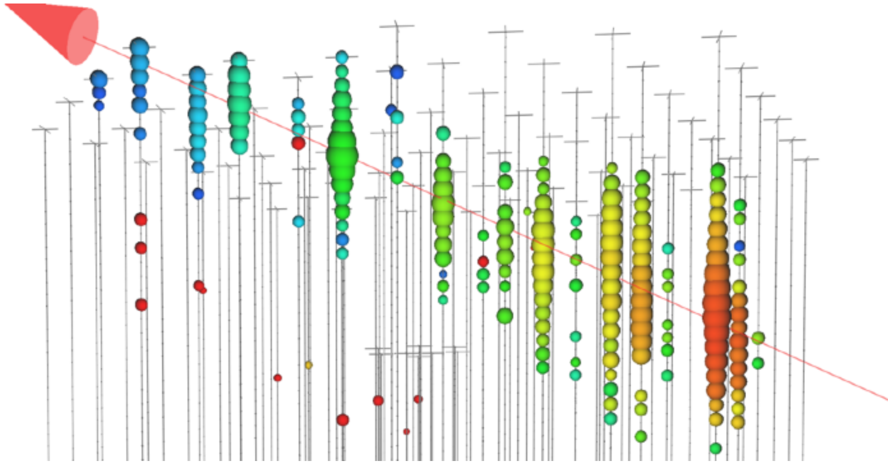
GCN Circular 34810 — Counter part

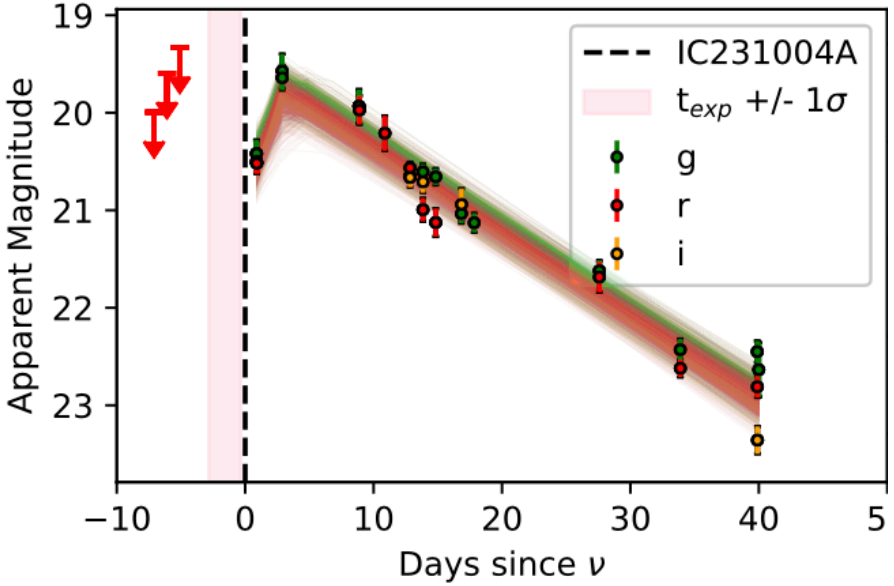
Subject
IceCube-231004A: One Candidate Counterpart from the Zwicky Transient Facility
Date
2023-10-10T17:57:45Z (5 months ago)
From
Simeon Reusch at DESY <simeon.reusch@desy.de>

GCN Circular 34837 — Classification

Subject
IC231004A: Classification of AT2023uqf/ZTF23abidzvf as a rapidly-evolving supernova with CSM interaction
Date
2023-10-18T23:57:27Z (5 months ago)
From
Robert Stein at Caltech <rdstein@astro.caltech.edu>

A **SNe Ibn** (stripped core collapse SNe interacting with circumstellar medium) in coincidence (p=2.510^{-3}) with IceCube neutrino — **Publication**

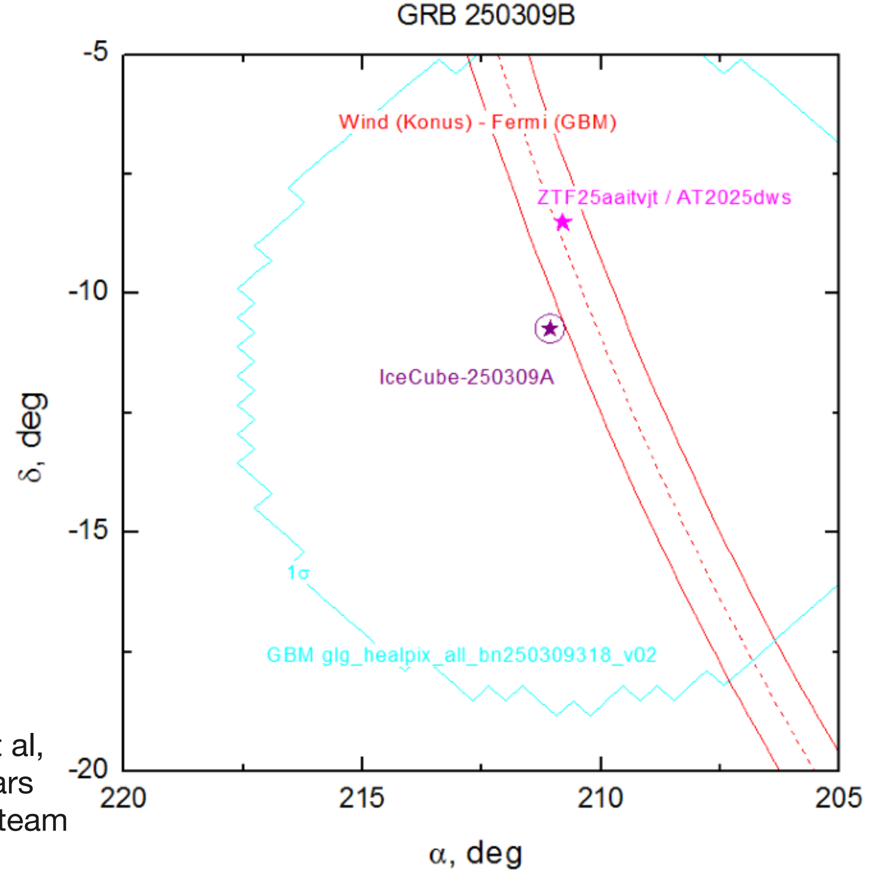




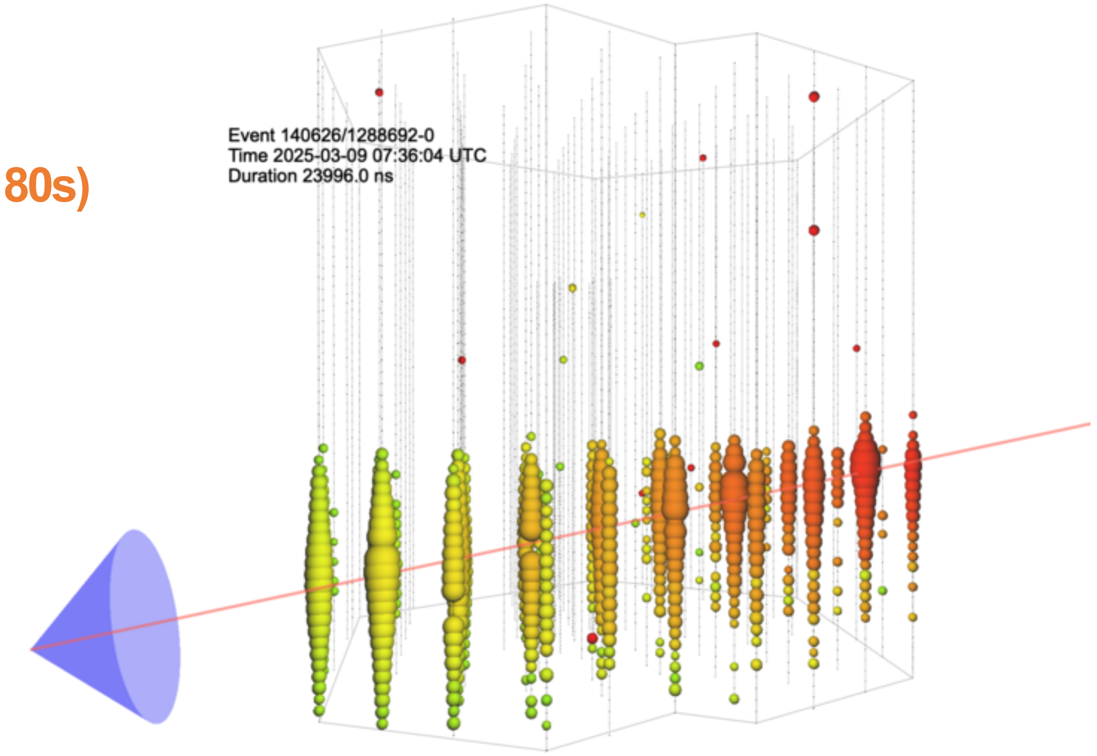
R. Stein et al. (submitted)

Sunday, March 9th, 2025

A 4 PeV neutrino event coincident with a GRB (within 180s)



Svinkin et al, HEND/Mars Odyssey team



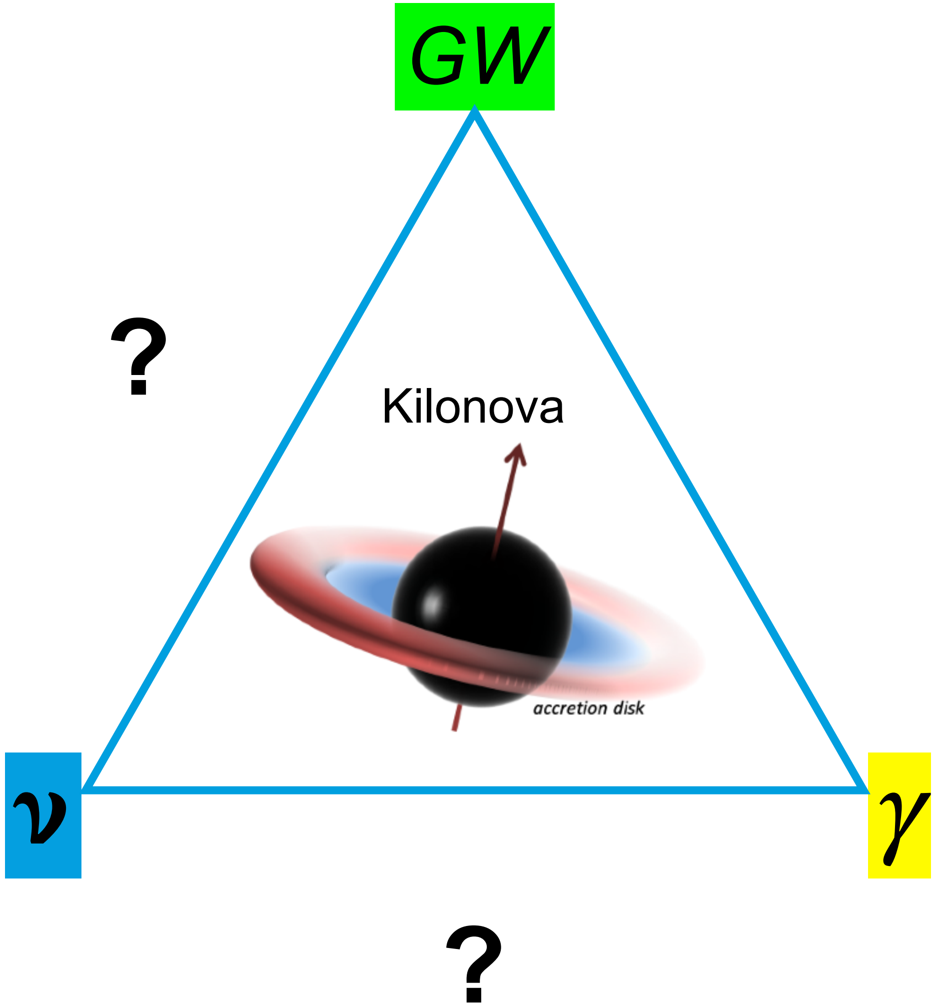

```
TITLE:   GCN CIRCULAR
NUMBER:  39639
SUBJECT: GRB250309B: One candidate counterpart from the Zwicky
Transient Facility
DATE:    25/03/09 18:25:09 GMT
FROM:    Robert David Stein at JSI &lt;rdstein@umd.edu&gt;

Robert Stein (JSI), Tomas Ahumada (Caltech), Jannis Necker, Akshay
Eranhalodi (DESY), and Anna Franckowiak (Ruhr University Bochum),
Jesper Sollerman (Stockholm) report:
```

Follow-up with ZTF identified the afterglow, which was then confirmed in X-rays. Unfortunately, this source was 2.24 degrees away from the neutrino, and therefore inconsistent.

https://gcn.nasa.gov/circulars/39639.txt

Projecting into the future: which approach has the largest sensitivity?



Projecting into the future: deep-stacking GW and neutrinos

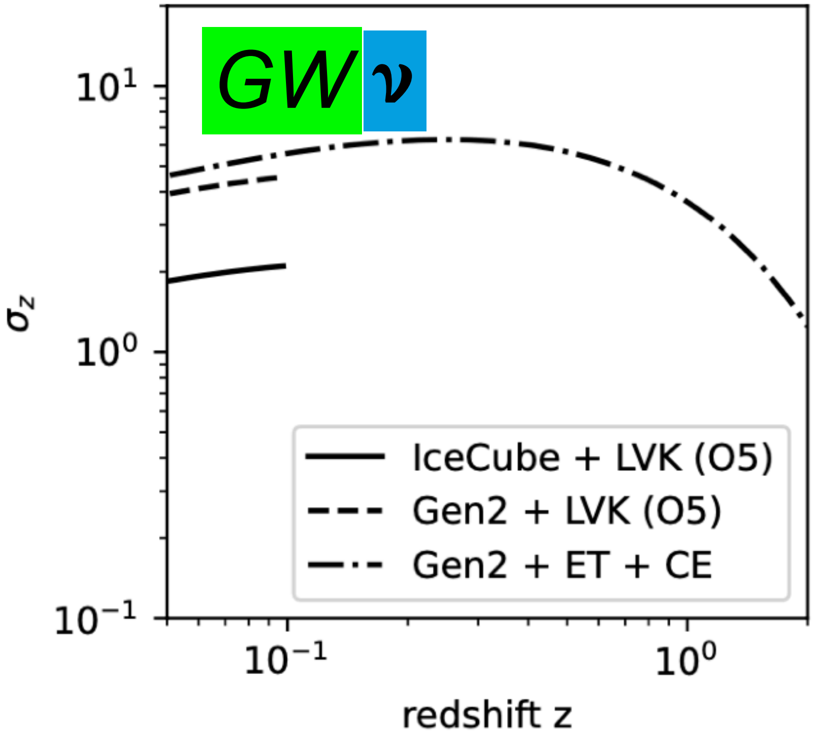
Based on Asimov data we have developed a formalism that allows to estimate the sensitivity to stacking of entire populations of sources. [MK, Baros, Ackermann, arxiv:2501.10213].

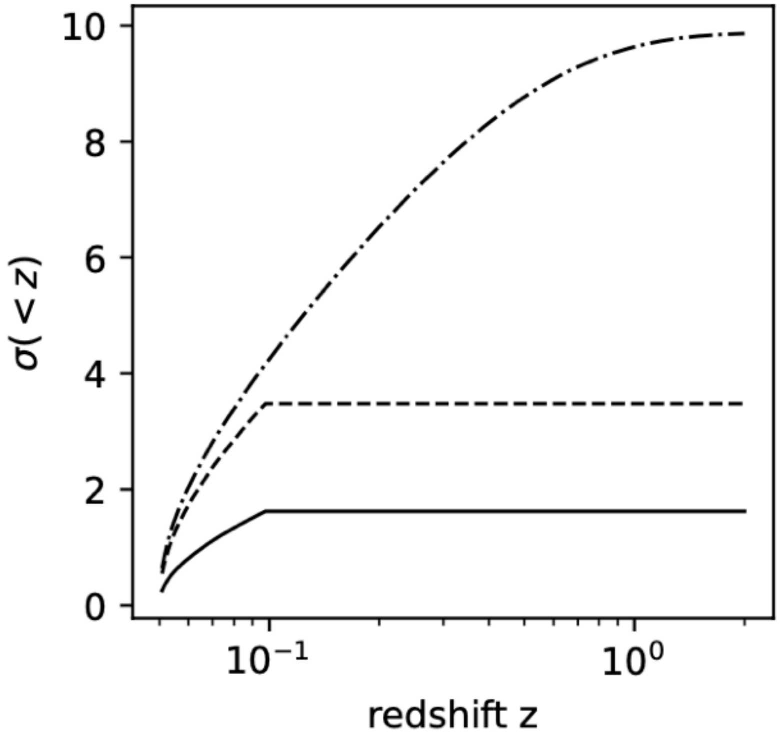
We take into account account backgrounds and signal, as well as cosmological distribution of sources.

“moderate” model prediction of Kimura et al. 2017 ApJL 848 L4 can be detected at >5-10σ significance.

$$\sigma_z := \left[z \frac{d\sigma^2_{\mathrm{tot}}}{dz} \right]^{1/2}$$

$$\sigma(< z) := \int_0^z \frac{d\sigma^2_{\mathrm{tot}}}{dz'} dz'$$





IceCube + LVK. vs IceCube-Gen2 + ET +CE

Bartos & Kowalski, in prep

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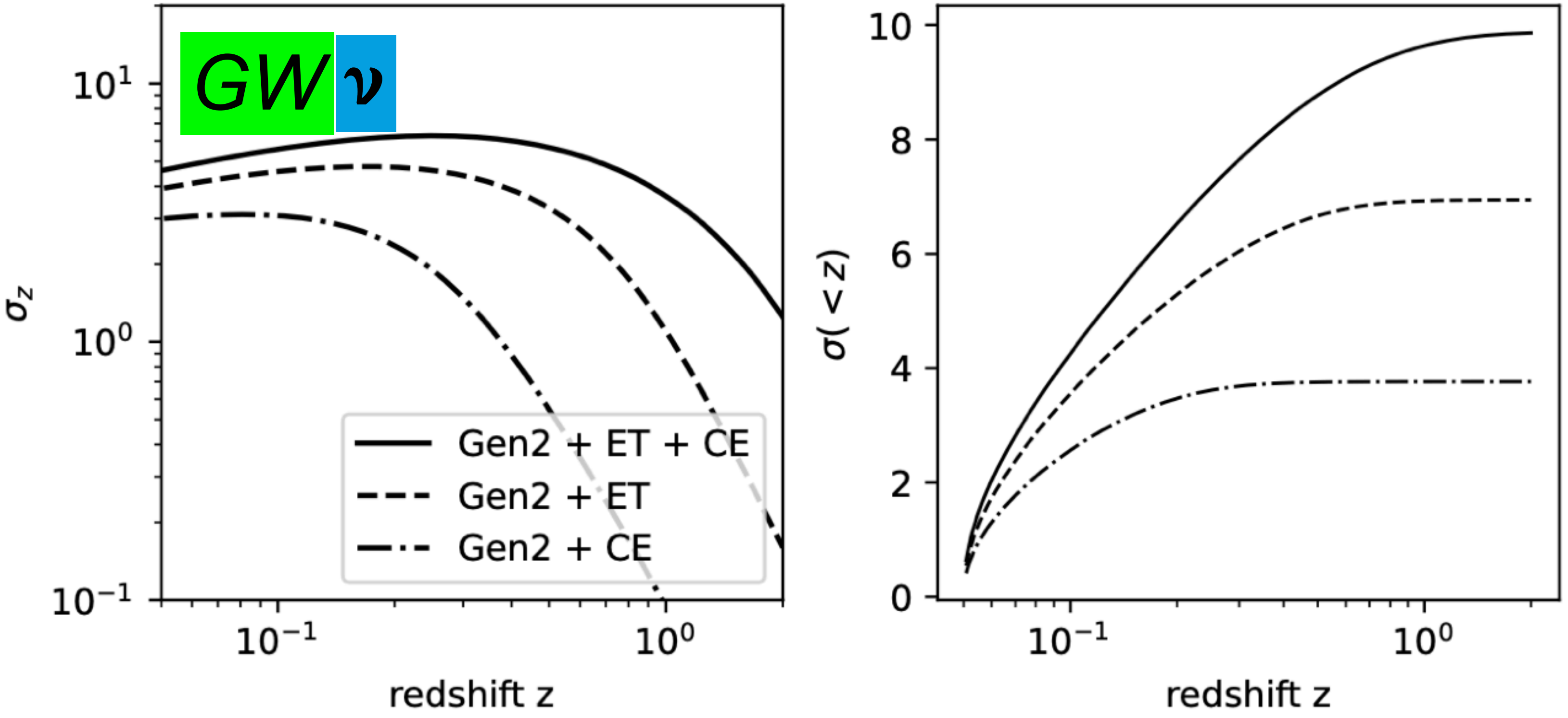

Pointing of GW detectors matters!

Bartos & Kowalski, in prep

Projecting into the future: deep-stacking GW and neutrinos

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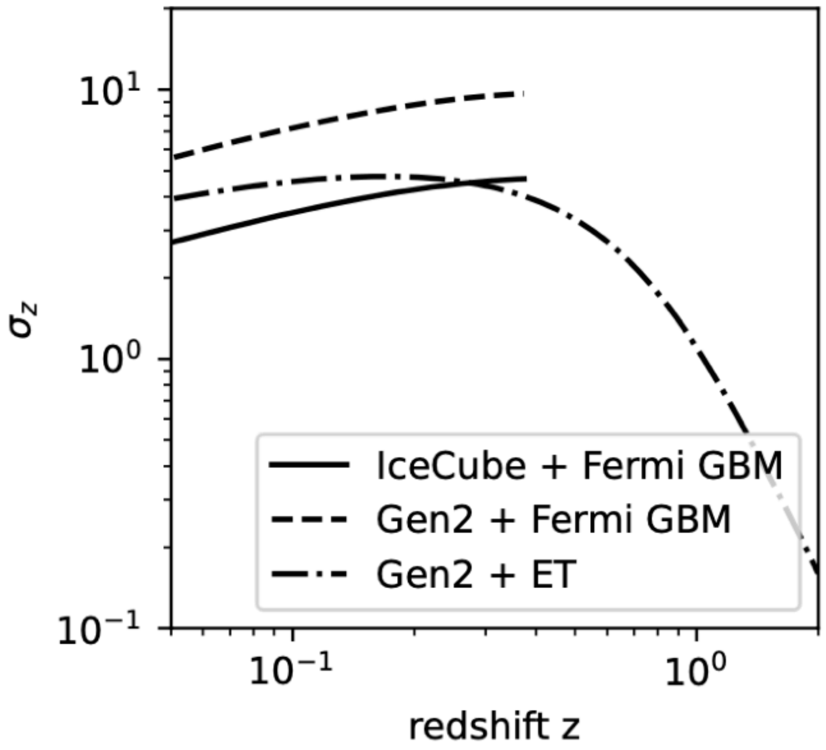
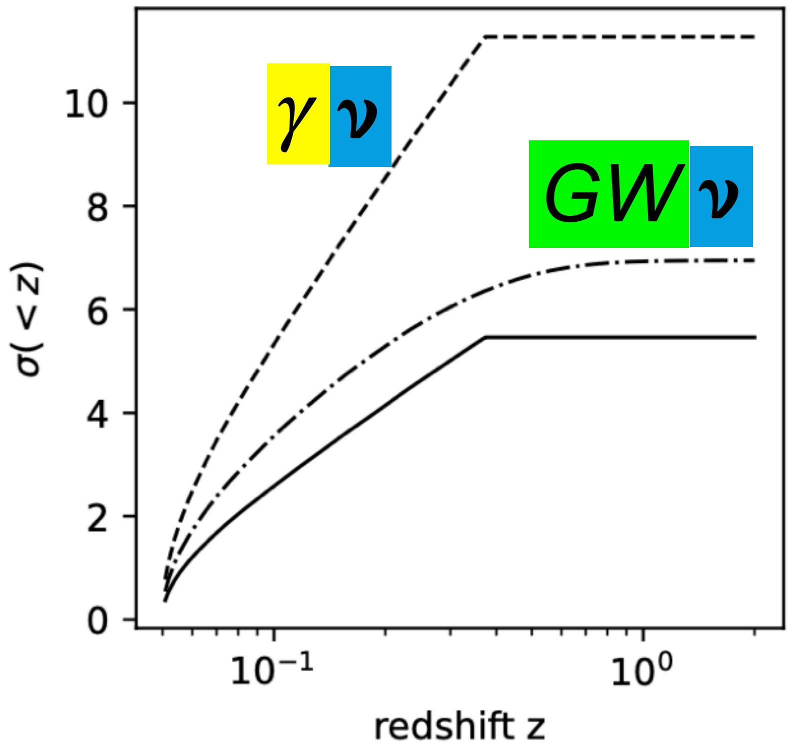
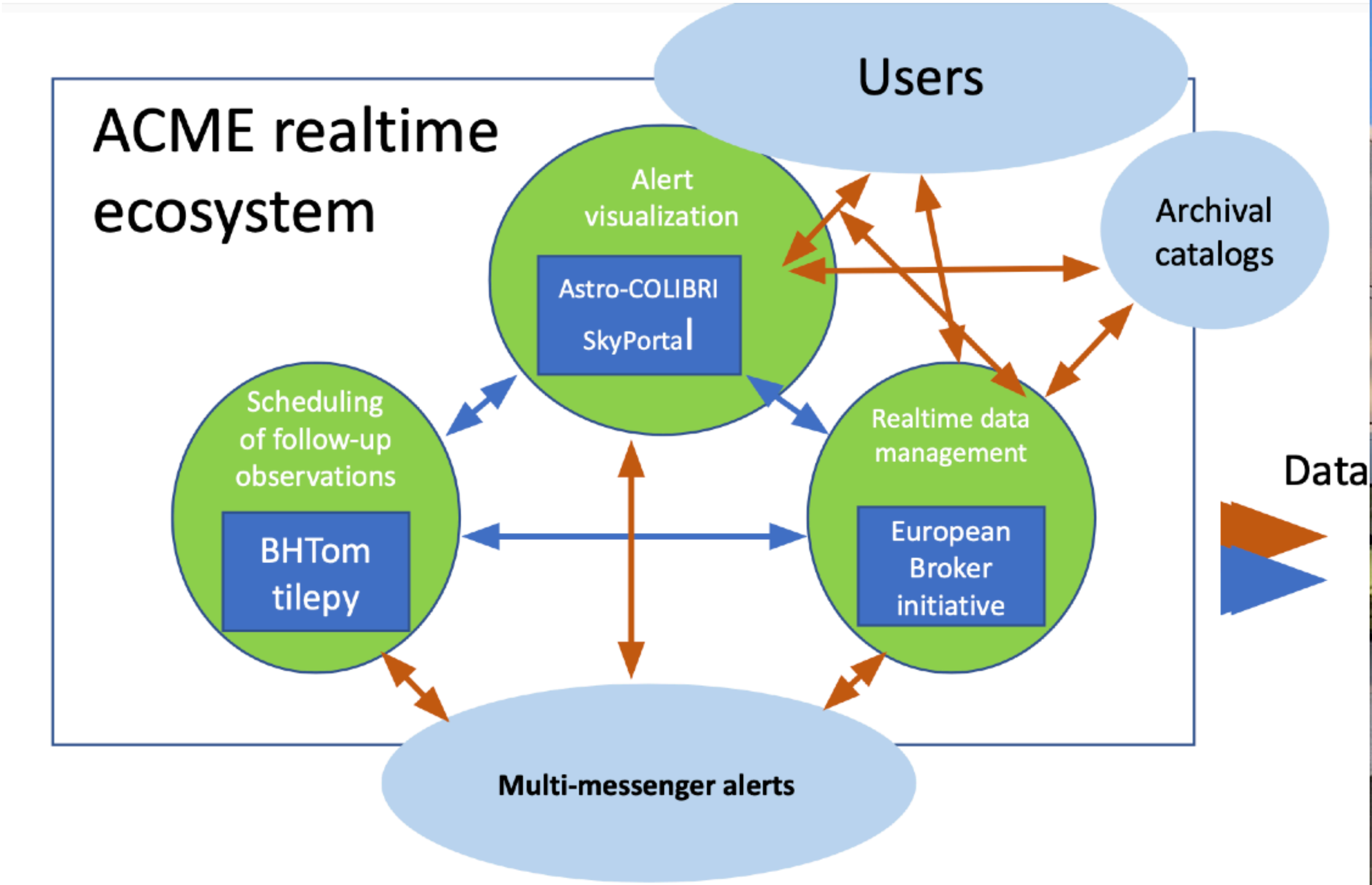




Neutrino+EM follow-up offers excellent sensitivity

Bartos & Kowalski, in prep

Software is key for real time multimessenger astronomy - join us in WP5!



WP5 face-to-face meeing
June 12-13th, DESY Zeuthen

Conclusions

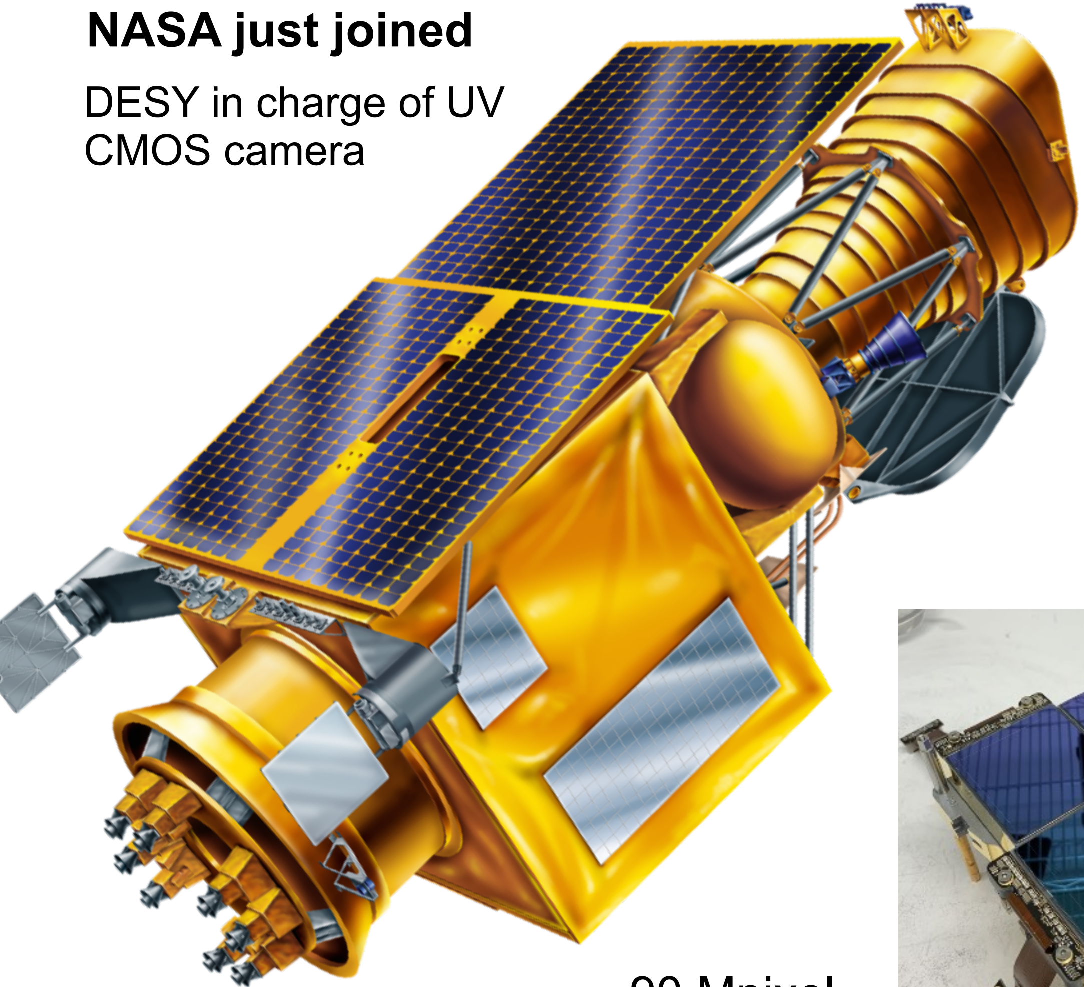
- Neutrinos allow to explore the highest energy part of the spectrum
- IceCube has been operating a cubic-kilometer detector since 2011, KM3NeT is catching up.
- Several multimessenger routes to search for the neutrinos from GW sources
- So far we have not found a significant GW / neutrino coincidence.
- So far we have not found a significant GRB / neutrino coincidence.
- Diverse data to be combined in near realtime. Dedicated software essential.
- Combination of next generation detectors will allow to probe “moderately” optimistic models.

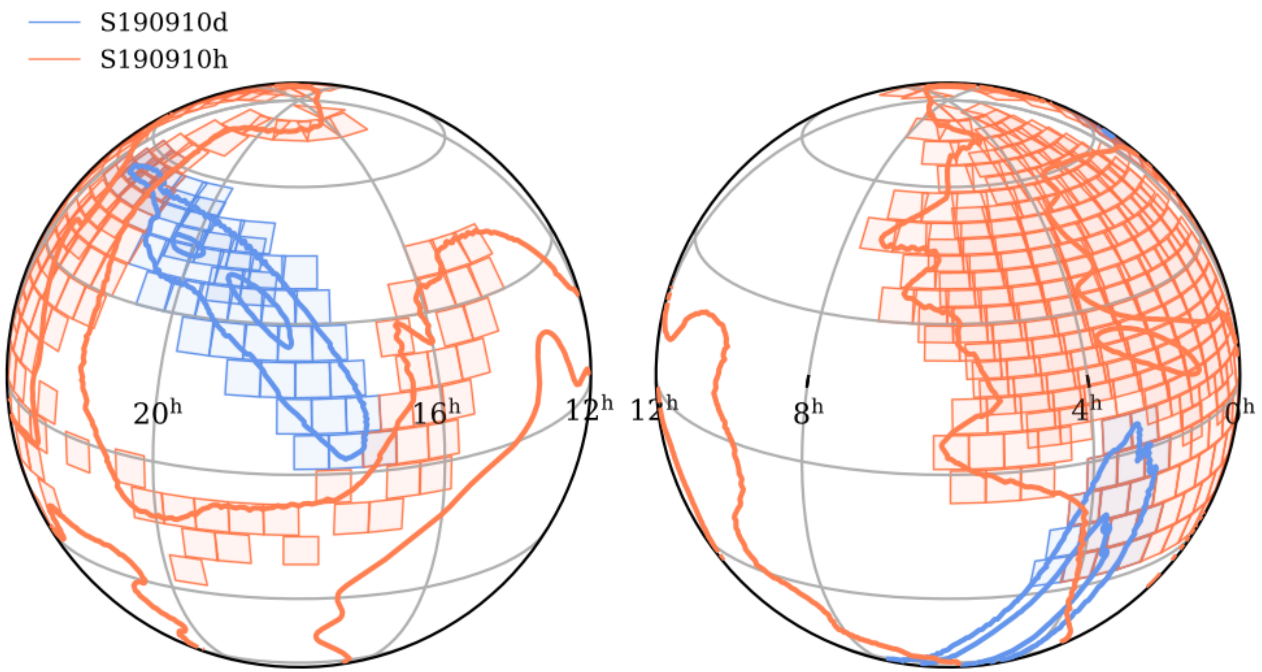
Outlook 1: Time domain astronomy in the UV: ULTRASAT

Finding Gravitational Wave and neutrino counterparts in the UV

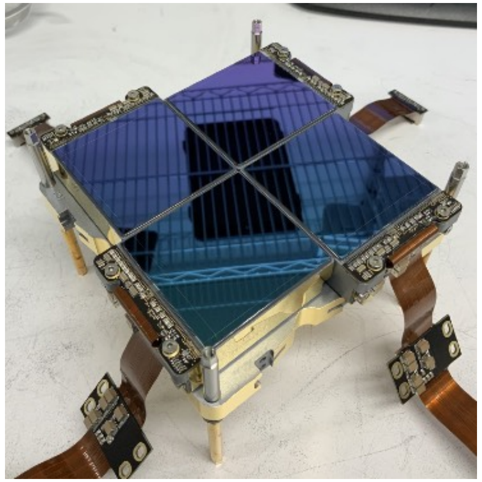
Israel / DESY collaboration
NASA just joined

DESY in charge of UV CMOS camera





90 Mpixel test sensor



UV-Satellite ULTRASAT
204 sq deg field (230-290 nm) optimized for e.g. detection of gravitational wave counterparts starting 2027.

arXiv:2304.14482

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Finding Gravitational Wave and neutrino counterparts in the UV

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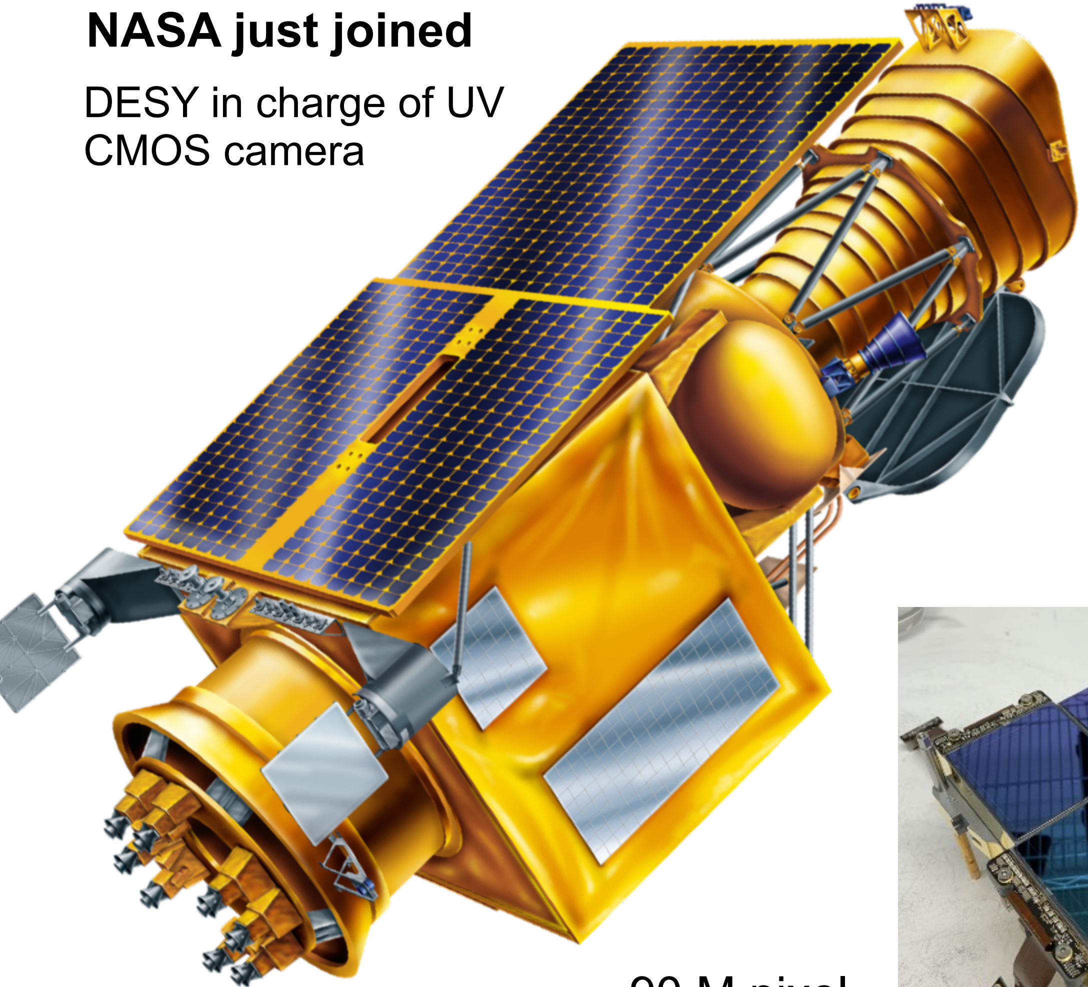
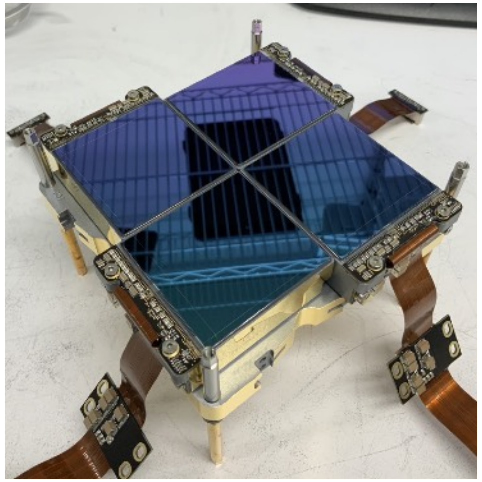
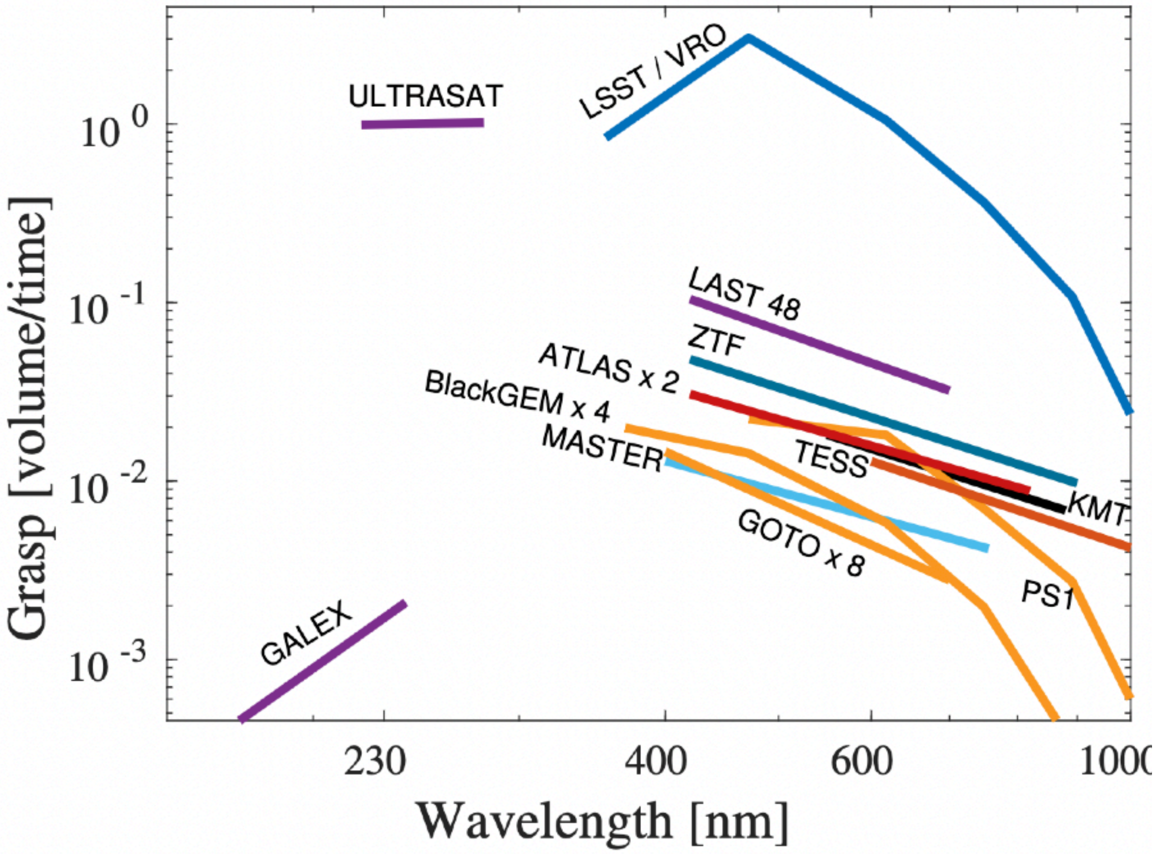
DESY in charge of UV
CMOS camera



90 M pixel
test sensor





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204 sq deg field (230-290 nm) optimized for e.g. detection of gravitational wave counterparts starting 2027.

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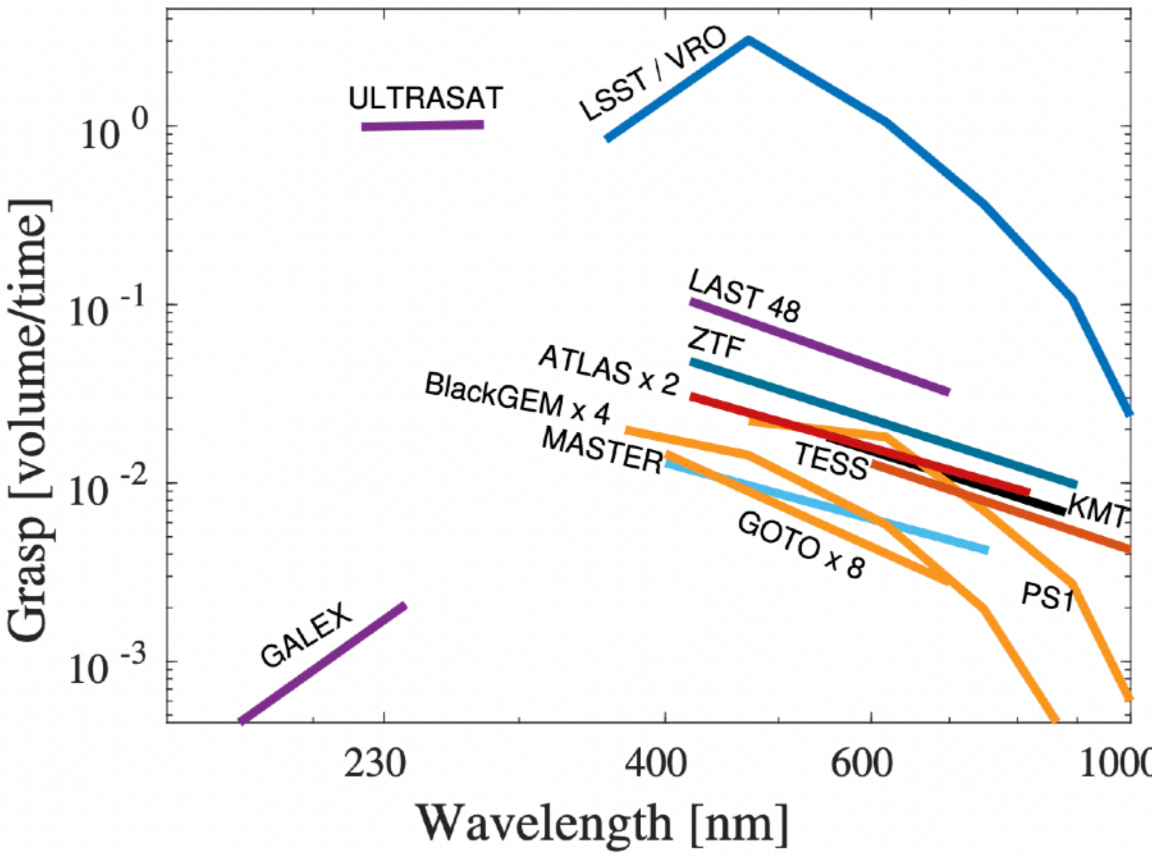
Outlook 1: Time domain astronomy in the UV: ULTRASAT

Survey & Statistics

- High-cadence survey: 204 deg2 with 5 min cadence
- Low-cadence survey: ~8000 deg2 with 4 day cadence
- ToO: >50% of sky accessible within 15min

Some numbers on the expected sensitivity:

- Kilonova/AT 2017gfo-like events up to 240 Mpc (15min ex
- TDEs: 10^3 - 10^4 TDEs per year, depending on redshift evolution and TDE temperature, up to z~1



- **We are missing an LSST-like survey in the North.**
- **We are missing photometric follow-up resources**
- **We are missing spectroscopic follow-up resources (mostly in North)**

We are discussing with the project if access can be broadened. Talk to David Berge or me if interested.

Outlook 2: Small-aperture Optical Telescope Arrays (OTA)

Off-the-shelf technology & serialization allows for costs reduction

GOTO, imaging survey @ La Palma
8 telescopes per mount,

LAST imaging survey @ Negev, IL
12 x 4 telescopes per mount,
wide-field polarimetry prototype

MARCOT Pathfinder @ Calar Alto
Spectroscopy

Diverse science case from transient astronomy, AGN monitoring, stellar astronomy to planetary science, see splinter session (slides) from last AG Meeting.

Conclusion

- Multimessenger astronomy has recently delivered spectacular breakthroughs, e.g. the first detection of counterparts of GWs and cosmic neutrinos
- Existing and upcoming all sky surveys, such as ZTF, LSST and ULTRASAT, combined with advanced detection pipelines, increase the discovery rates of transients by orders of magnitude
- To channel neutrino / GW data into a stream of multi-messenger discoveries requires large sky coverage and highly connected multi-wavelength observatories