Gravitational Wave Follow-Up with the Super-Kamiokande detector

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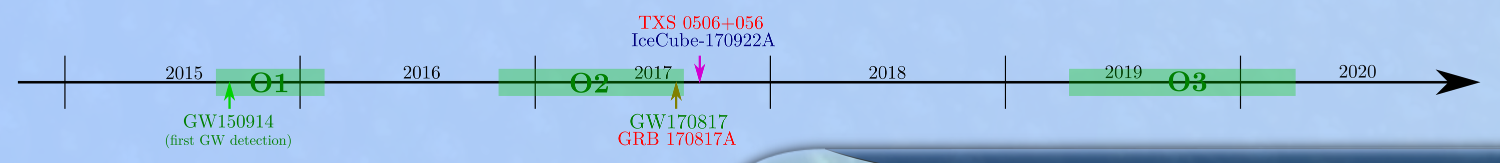
Multi-messenger astronomy

■ Gravitational Waves (GW) were first discovered in 2015. In 2017, neutrinos (IceCube-170922A) and GWs (GW170817) were both observed in coincidence with an electromagnetic (EM) counterpart.
→ beginning of the multimessenger era

■ But there is no evidence yet of an astrophysical source emitting both GW and neutrinos.

■ Such detection will significantly improve the localization of the source with respect to the GW-only case, making EM follow-up observations much faster and prompt to identify a source.

■ It will also provide important inputs to understand the environment and the dynamics of the source.



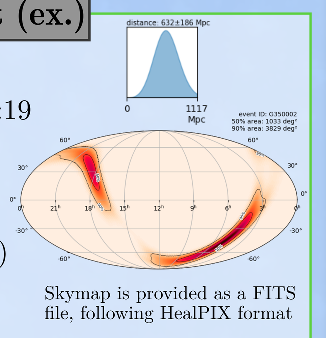
GW and LIGO-Virgo

■ Gravitational waves are detected in LIGO and Virgo by interferometry.

■ Advanced LIGO and Virgo have performed several observing runs since 2015. O3 is the first where GW alerts are sent publicly in realtime.

Content of realtime alert (ex.)

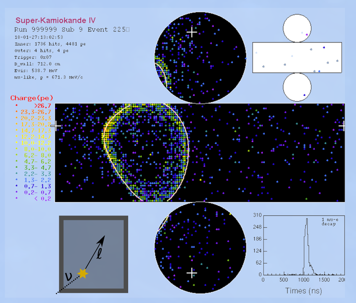
ID: S190910d
Event UTC: 2019-09-10 01:26:19
Instruments: H1,L1
Source classification:
BBH (0%) BNS (0%)
NSBH (98%) MassGap (0%)
Terrestrial (2%)



Skymap is provided as a FITS file, following HealPIX format

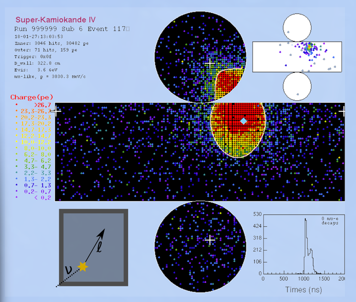
Samples

Three main samples separated by event topology and Outer Detector information



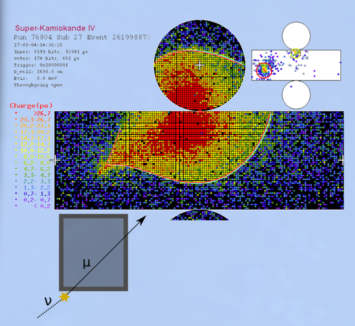
Fully-Contained (FC) **events**

FULL-SKY COVERAGE
Typical energies: 0.1-10 GeV
Expected background:
0.112 events/(1000 seconds)
Possible topologies: 1 ring or multi-ring (e-like/μ-like)



Partially-Contained (PC) **events**

FULL-SKY COVERAGE
Typical energies: 0.1-100 GeV
Expected background:
0.007 events/(1000 seconds)
Possible topologies: same as FC



Upward-going muons (UPMU)

COVERING ONLY BELOW THE HORIZON
Typical energies: few GeV - TeV
Expected background:
0.016 events/(1000 seconds)
Possible topologies: throughgoing or

Super-Kamiokande

■ *Usual acronym:* SK or Super-K

■ Detector running since 1996

■ Located under the peak of Mt Ikeno (Kamioka city, Gifu prefecture, Japan)

■ 1000 m of rock (2700 m.w.e) overburden

■ 50 kton of water (22.5-27.2 kton fiducial)

■ Optically separated into:

► Inner Detector: 11146 PMTs (50 cm Ø)

► Outer Detector: 1885 PMTs (20 cm Ø)

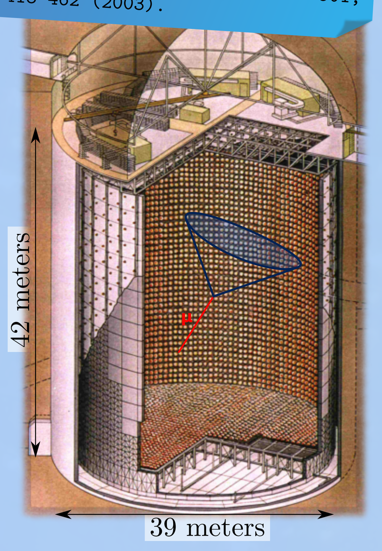
■ Neutrinos detected using Cherenkov light emitted by produced charged particles

Different phases

Start		End
	SK-I	
04/1996	-	07/2001
	SK-II	
10/2002	-	10/2005
	SK-III	
07/2006	-	09/2008
	SK-IV	
09/2008	-	06/2018
	SK-V	
01/2019	-	ongoing

transition to the Gadolinium loaded phase (SK-Gd)

Fukuda et al. NIM Phys. Res. 501, 418-462 (2003).



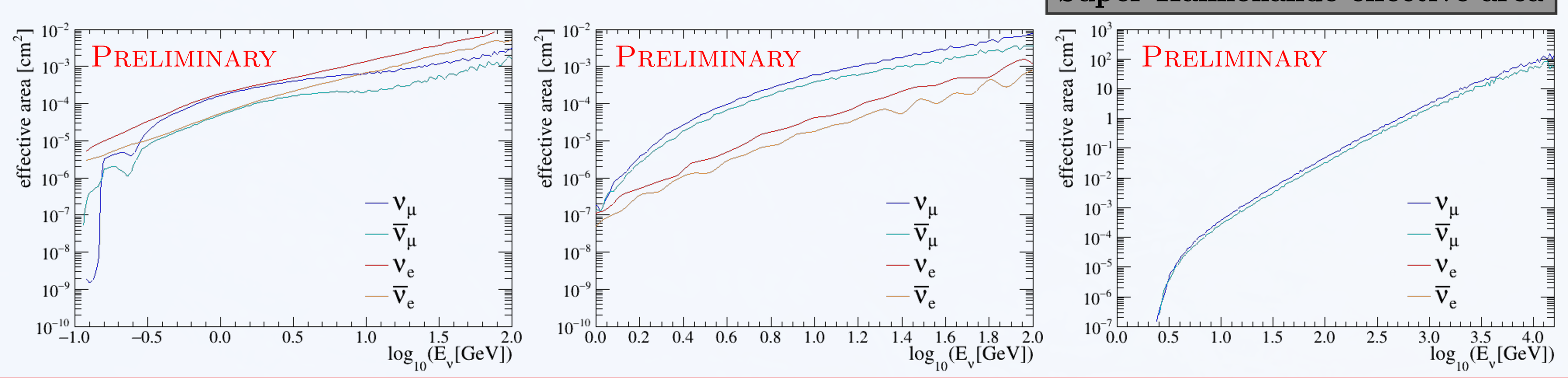
For each sample:

$$N_{\text{signal}} = \int \underbrace{\boxed{A_{\text{eff}}(E,\Omega)}}_{\text{effective area}} \times \underbrace{\frac{dn(E)}{dE}}_{\text{incoming neutrino flux}} \times dE$$

$$N_{\text{expected}} = N_{\text{background}} = \underbrace{T}_{\text{size of time window}} \times \underbrace{\text{rate}}_{\text{atmospheric background rate}}$$

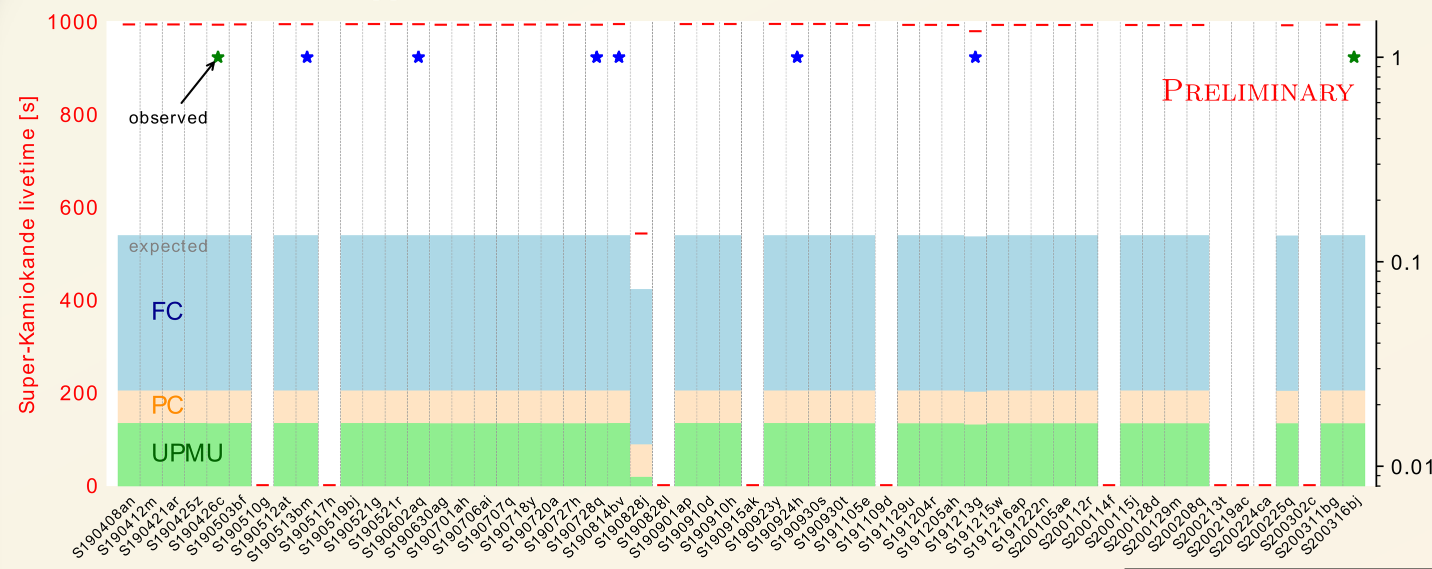
The effective area encodes effects related to neutrino cross sections, detector geometrical acceptance and efficiency, Earth shadowing...
Estimated using Monte Carlo simulations (with known spectrum).

Super-Kamiokande effective area



O3 results...

56 confirmed GW triggers in O3, **46** with SK livetime, **8** with SK events in time coincidence

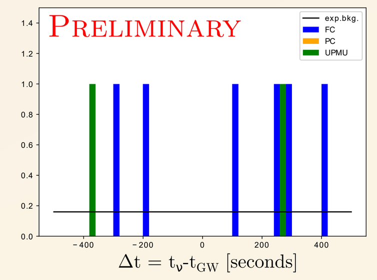


SUMMARY OF THE RESULTS

PRELIMINARY

Sample	Total observed	Total expected	Poisson p-value (%)
FC	6	5.06	39.48
PC	0	0.33	100.00
UPMU	2	0.74	16.98

No important excess with respect to the background expectation, no particular feature in the event time distribution.



Example of flux limits for S190412m

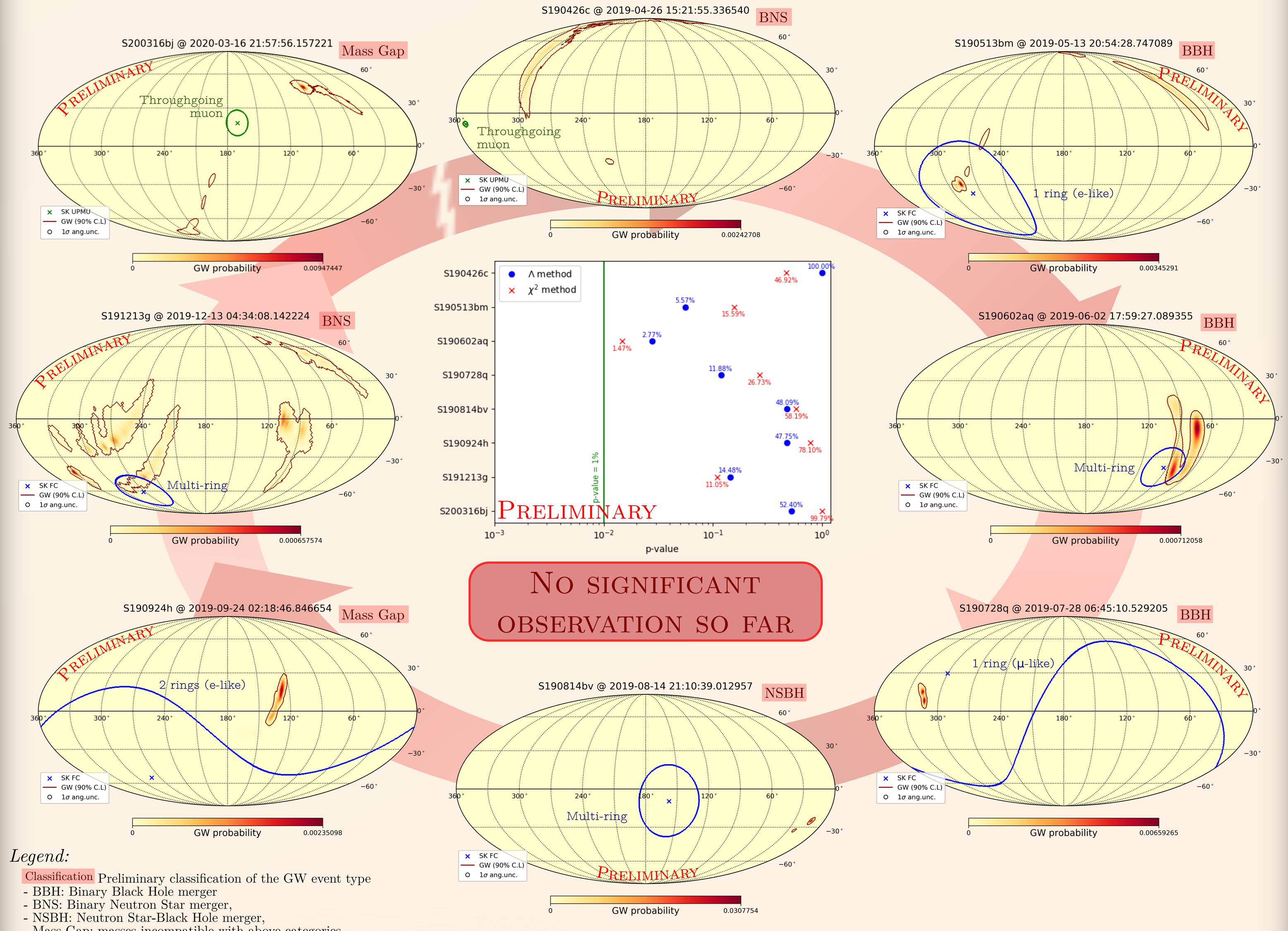
PRELIMINARY

Sample	Observed	Expected	range of 90%UL on $E^2\frac{dn}{dE}$ [GeV.cm^{-2}] ν_μ	ν_e	$\overline{\nu_\mu}$	$\overline{\nu_e}$
FC	0	0.111	$5.40 - 5.44 \cdot 10^3$	$3.93 - 4.02 \cdot 10^3$	$1.53 - 1.55 \cdot 10^4$	$1.03 - 1.05 \cdot 10$
PC	0	0.007	$1.08 - 1.09 \cdot 10^4$	$8.12 - 9.79 \cdot 10^4$	$1.85 - 1.93 \cdot 10^4$	$2.09 - 2.47 \cdot 10$
UPMU	0	0.016	$3.17 - 3.74 \cdot 10^1$	-	$3.67 - 4.53 \cdot 10^1$	-

Limits using Λ test statistic:

$$\left(E^2\frac{dn}{dE}\right)_{\nu_\mu} < 3.16 - 4.58 \cdot 10^1\ \text{GeV.cm}^{-2}$$

Such numbers are derived for all GW triggers independently.



NO SIGNIFICANT OBSERVATION SO FAR

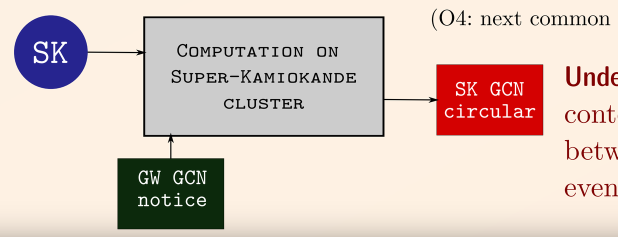
Legend:
Classification Preliminary classification of the GW event type
- BBH: Binary Black Hole merger
- BNS: Binary Neutron Star merger,
- NSBH: Neutron Star-Black Hole merger,
- Mass Gap: masses incompatible with above categories

... and beyond

Switching to real-time follow-up for O4

(O4: next common GW Observation period scheduled for late 2021)

Ongoing work to speed up real-time data processing for prompt follow-up

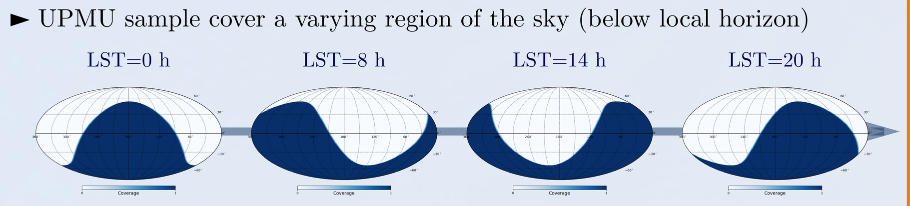


Under discussion within collaboration: content of the alert and criteria to separate between non-observation and interesting event (in terms of p-value)

Sample-by-sample considerations

► Visible energy in SK is a good estimator of E_ν for FC/PC. But the reconstructed energy for UPMU is only a lower limit on E_ν.
► The pointing capability is limited due to the neutrino-muon scattering angle (~20° at 1 GeV and ~6° at 10 GeV with FC/PC)

► UPMU sample cover a varying region of the sky (below local horizon)



UPMU sample is used only if the GW contour is at least partially below horizon.

Statistical analysis

How likely is it that a given observation in Super-Kamiokande comes from atmospheric background?

■ Define a likelihood and test statistic to separate between signal (point-source) and background:

$$\underbrace{\mathcal{L}_\nu^{(s)}}_{\text{sample}}(\underbrace{n_S^{(s)}}_{\text{signal events}}, \gamma; \underbrace{\vec{x_S}}_{\text{direction of source}}) = \frac{e^{-(n_S^{(s)}+n_B^{(s)})}(n_S^{(s)} + \overbrace{n_B^{(s)}}^{\text{expected background}})^{N^{(s)}}}{\underbrace{N^{(s)}}_{\text{observed events}}!} \underbrace{\prod_{i=1}^{N^{(s)}}}_{\text{product on selected events}} \frac{n_S^{(s)} \overbrace{\mathcal{S}^{(s)}(\vec{x_i}, E_i; \vec{x_S}, \gamma)}^{\text{signal pdf}} + n_B^{(s)} \overbrace{\mathcal{B}^{(s)}(\underbrace{\vec{x_i}, E_i}_{\text{event direction/energy}})}^{\text{background pdf}}}{n_S^{(s)} + n_B^{(s)}}$$

Hussain et al. arXiv:1908.07706
Aartsen et al. arXiv:2004.02910

$$TS = \underbrace{\max_{\vec{x_S}}}_{\text{best-fit position}} [\Lambda(\vec{x_S})] \text{ with } \Lambda(\vec{x_S}) = 2\sum_s \ln\left[\frac{\mathcal{L}_\nu^{(s)}(\overbrace{\widehat{n_S^{(s)}}, \widehat{\gamma^{(s)}}}^{\text{values maximising the likelihood}}; \vec{x_S})}{\mathcal{L}_\nu^{(s)}(n_S^{(s)} = 0; \vec{x_S})}\right] + 2\ln \underbrace{w_L(\vec{x_S})}_{\text{GW probability distribution}}$$

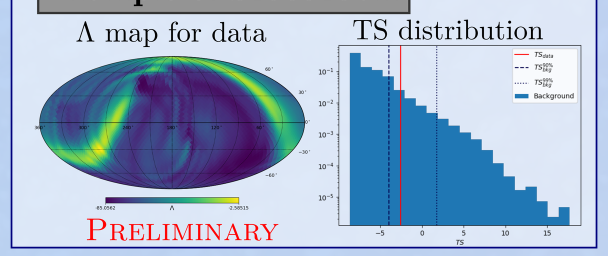
A complementary method was implemented using the likelihood from [Albert et al. arXiv:1810.10693], The p-value (p_{χ^2}) is computed with similar method.

■ The background distribution of TS is obtained using time-scrambled neutrinos and p-value is:

$$p_\Lambda = \int_{TS_{\text{data}}}^{\infty} P_{\text{bkg}}(TS)\,\mathrm{d}TS$$

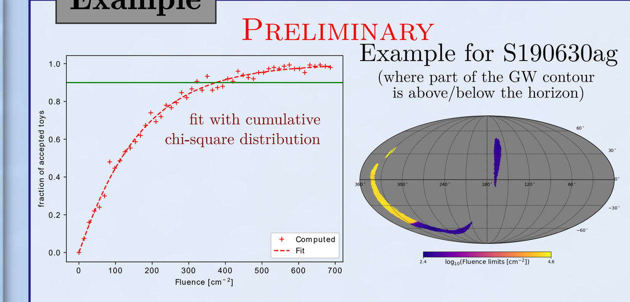
Background TS is computed using toys with at least one observed event → p-value is interpreted as the probability for background to raise an observation at least as extreme as the data, **given that** at least one event was observed.

Example of S190513bm



Above test statistic can be used to compute neutrino fluence limits:
■ inject fake signal of fluence Φ at position consistent with GW skymap
■ compute TS for each of signal injections and compute the fraction R of them with $p_\Lambda < 10\%$
■ find minimal fluence Φ to inject such that R > 0.90
■ repeat for all pixels in GW 90% contour

Example



Flux limits

The neutrino flux from a point-source is:

$$\frac{dn}{dE_\nu} = \underbrace{\Phi^f}_{\text{fluence}} \times \underbrace{\lambda(E_\nu)}_{\text{shape function}}$$

For E^{-2} spectrum: $\frac{dn}{dE_\nu} = \phi_0 E_\nu^{-2}$ with $\phi_0 = \Phi^f \times (E_{\min}^{-1} - E_{\max}^{-1})$ (minimum-maximum of the integration range)

For a given sample s (FC, PC or UPMU):
■ expected background B_{exp} is known
■ observed number of event N_{obs} is known
■ 90% upper limit on number of signal events can be extracted using Poisson statistic (noted $N_{up,90}$)
■ limits on fluence (assuming E^{-2} spectrum):

$$\Phi^{s,f}_{up,90}(\theta) = \frac{N^{\text{signal}}_{up,90}}{\int_{E_{\min}}^{E_{\max}} dE_\nu A^{s,f}_{\text{eff}}(E_\nu,\theta)\lambda(E_\nu)} [\text{cm}^{-2}]$$

Value depends on θ; we compute it for all directions in 90% GW contour and quote min-max values.

or equivalently:

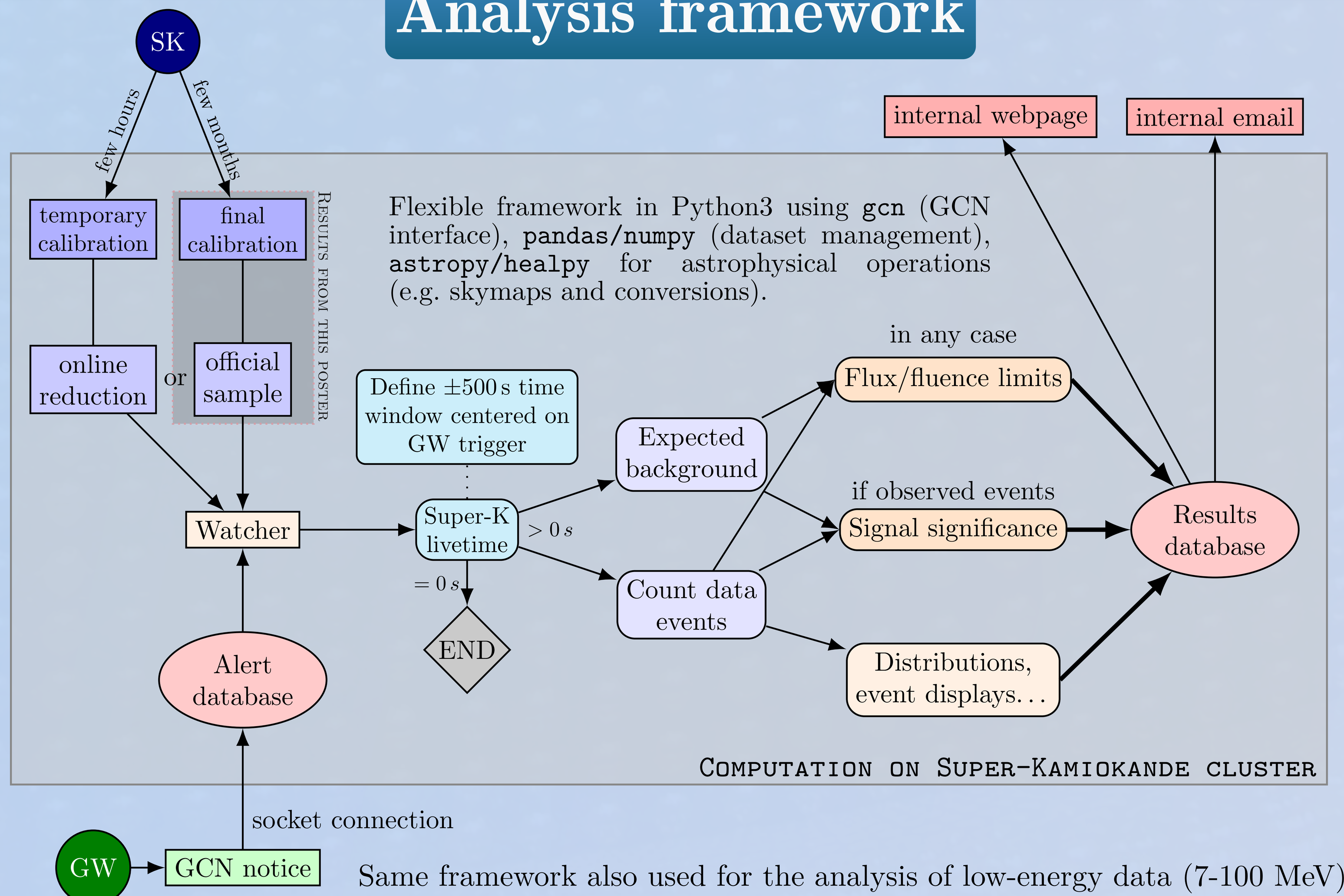
$$E_\nu^2 \frac{dn}{dE_\nu} < \Phi_{up,90} \times \left(E_{\min}^{-1} - E_{\max}^{-1}\right)^{-1} [\text{GeV.cm}^{-2}]$$

Computation output

One range of fluence limits per flavour, per sample

Sample	ν_μ	$\bar\nu_\mu$	ν_e	$\bar\nu_e$	$E_{\min} - E_{\max}$ [GeV]
FC	✔	✔	✔	✔	0.1 – 10
PC	✔	✔	✔	✔	0.1 – 100
UPMU	✔	✖	✔	✖	1.6 – 10^5

Analysis framework



Flexible framework in Python3 using `gcn` (GCN interface), `pandas/numpy` (dataset management), `astropy/healpy` for astrophysical operations (e.g. skymaps and conversions).

Same framework also used for the analysis of low-energy data (7-100 MeV) and for other types of external triggers (e.g. IceCube Golden/Bronze alerts or GRBs) **(not presented in this poster)**.

Choice of time window size

The ±500 s time window was derived for GW and ν emission from Gamma-Ray Bursts (GRB).
This is now widely used as a conservative coincidence time window in many GW+ν sources searches.

Baret et al. Astropart. Phys. 35, 1-7 (2011)

NEUTRINO 2020