Neutrino follow-up analysis of GRB 221009A with the KM3NeT detectors

Juan Palacios González (IFIC - Valencia)
on behalf of the KM3NeT Collaboration
Juan.Palacios@ific.uv.es

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KM3NeT

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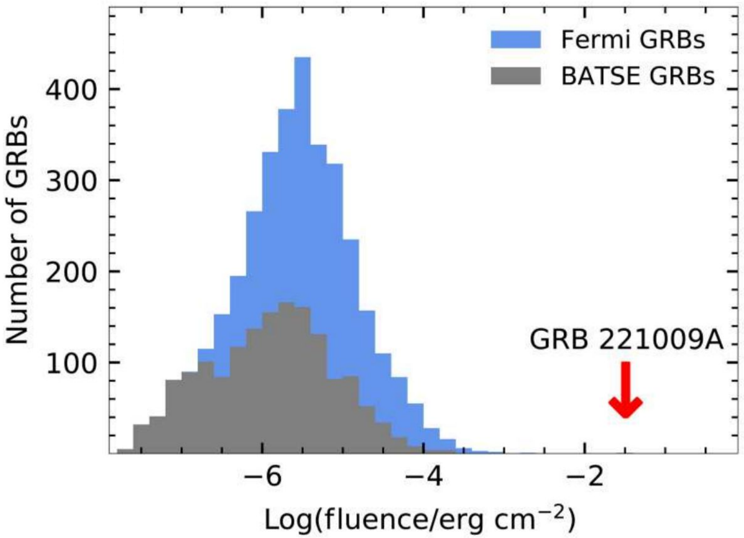
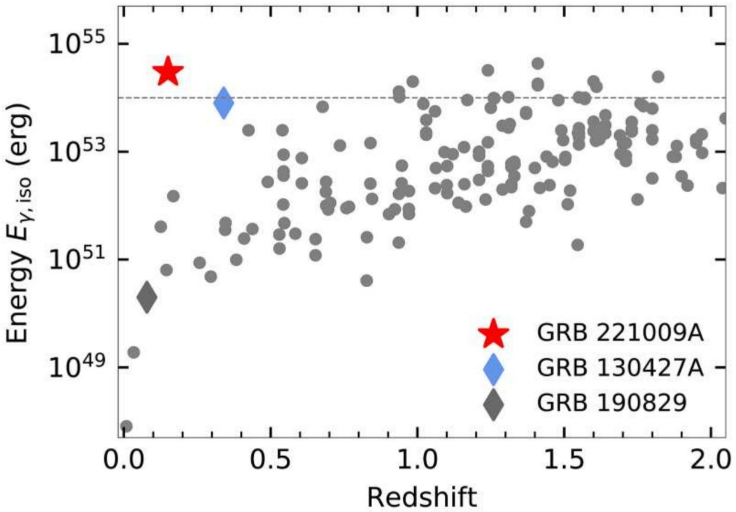
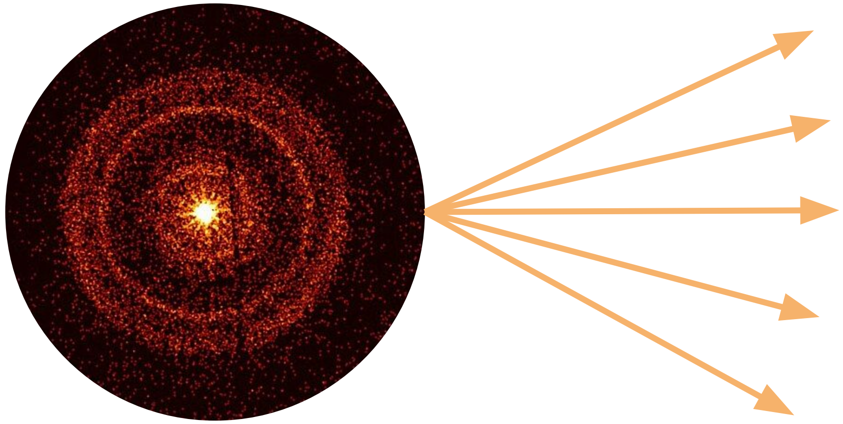
GRB 221009A

- The **BOAT**: ‘Brighest Of All Time’.
- **Location** by *Swift* (0.61’’ 90% CL error):
  - R.A.(J2000) = 288.26452°
  - DEC. (J2000) = + 19.77350°
- **Redshift** z = 0.151
- **Isotropic equivalent E** around $3 \cdot 10^{54}$ erg (among the highest ever).
- $\mathbf{T_{90}}$ estimated to be around 327 s.

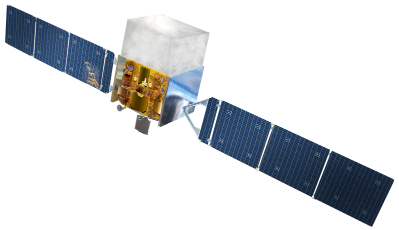




O’Connor et al 2023

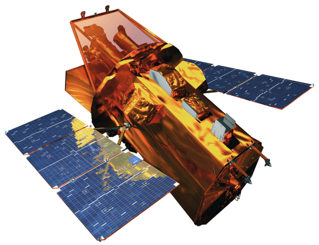


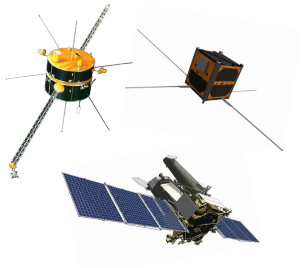
GRB image by Swift



Fermi-GBM
9th October 2022
13:16:59.0 UT

Swift-BAT
9th October 2022
14:10:17.0 UT



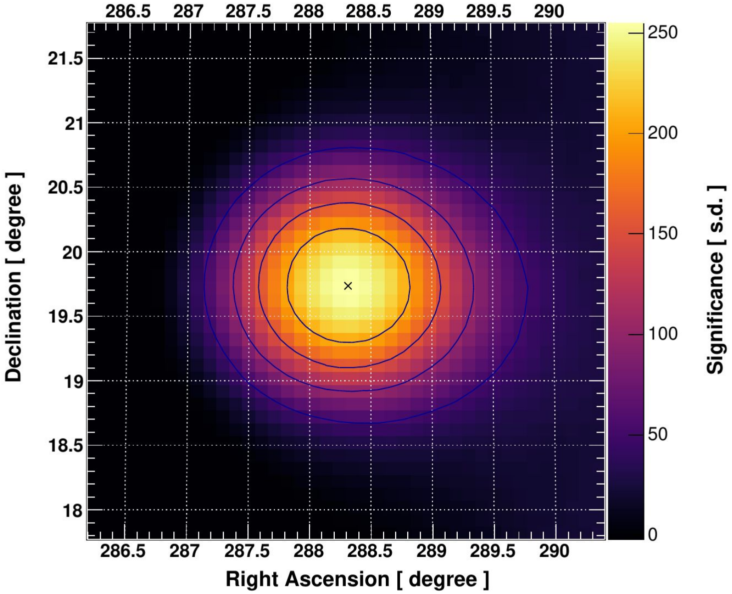


Detection by other multiple satellites (Konus-Wind, SRG, GRBAlpha, etc).

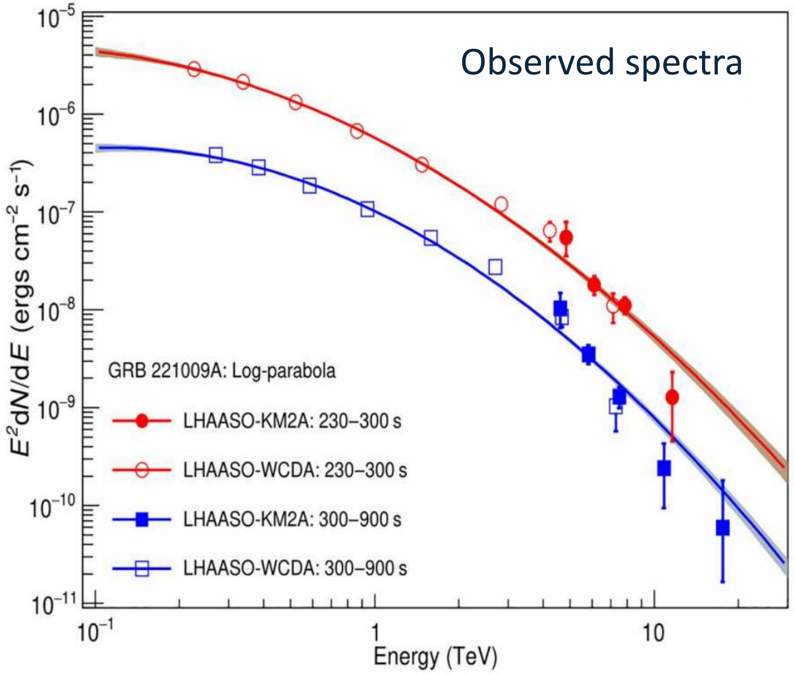
Extensive multi-wavelength ground follow-up campaign

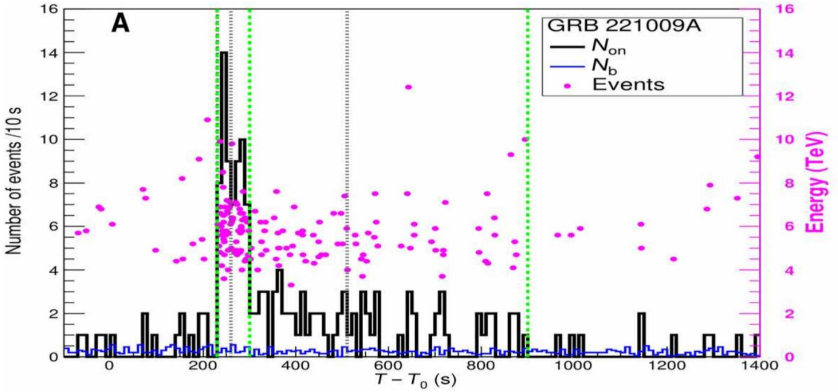
GRB 221009A

- Observation by **LHAASO** of photons up to around 13 TeV: the highest energy ever detected from a GRB event.
- Also highest energy detection by **Fermi-LAT** from a GRB: photons up to about 99 GeV (instrument saturation).
- The most likely origin is a **collapsar event**.
- A GRB as extraordinary as GRB 221009A is expected to occur only **once every ten thousand years**.



Significance map from LHAASO-WCDA observation

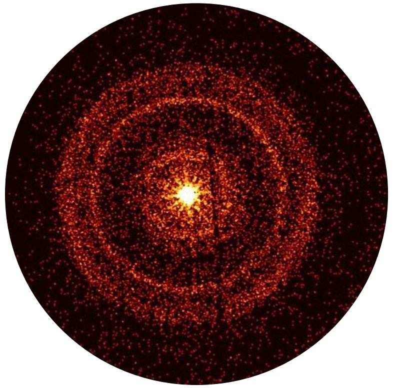




Light curve from LHAASO-WCDA

LHAASO, Science, Vol 9, Issue 46, 2023
DOI: 10.1126/sciadv.adj2778
LHAASO, Science, Vol 380, Issue 6652, 2023
DOI: 10.1126/science.adg9328

Neutrinos from GRBs?



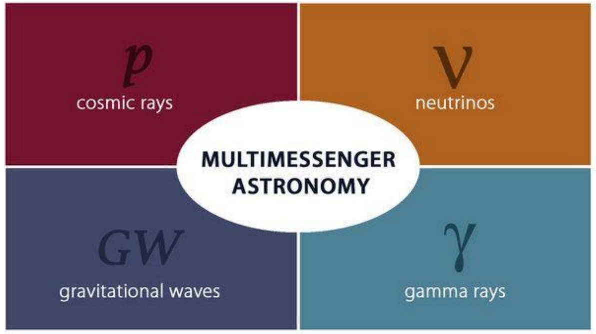
GRB 221009A

ν ?

No neutrino event has ever been correlated to a GRB event.

Many theoretical propositions:

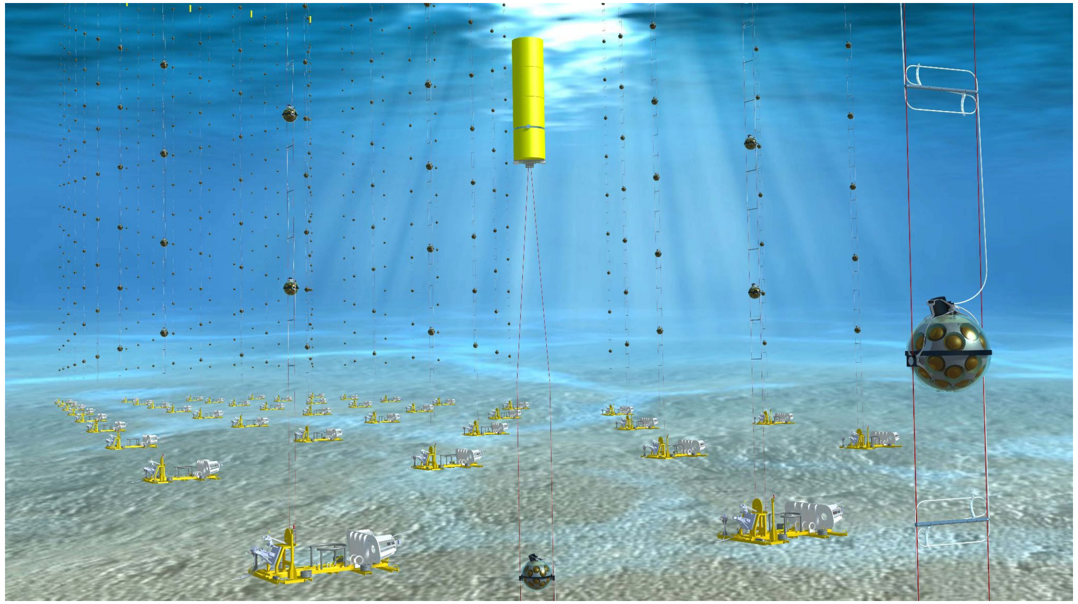
- Photo-meson production.
- Jet propagation processes.
- Subphotospheric production.
- Neutron collisions, etc.



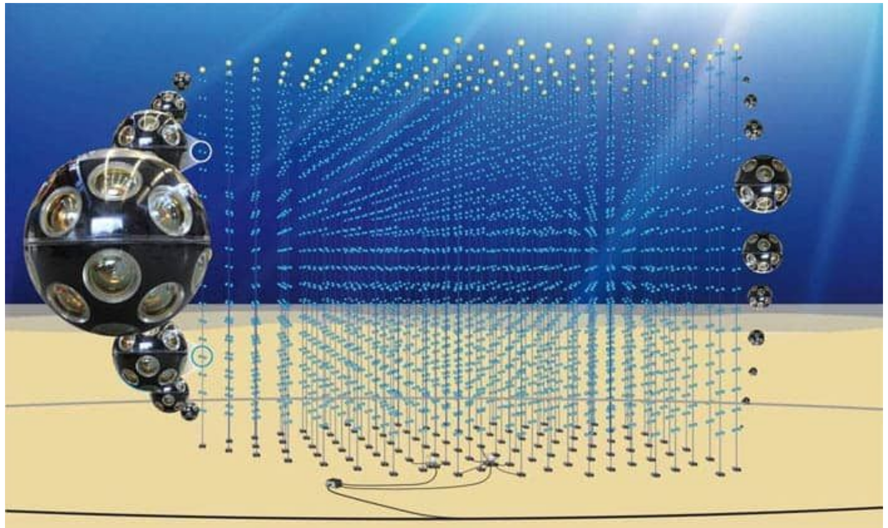
See the talk by V. Cecchini!

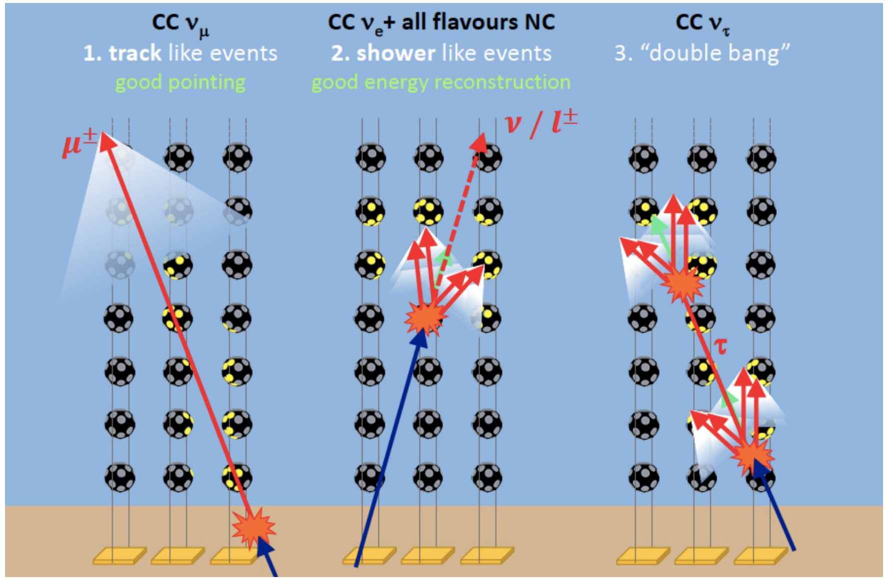
How do we detect cosmic neutrinos in the GeV to PeV energy range?

We need **large structures in a transparent media** (like the Mediterranean Sea).



KM3NeT

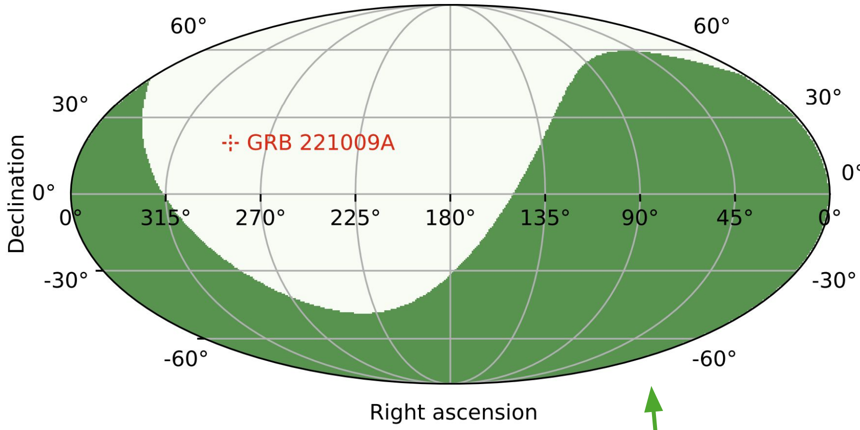




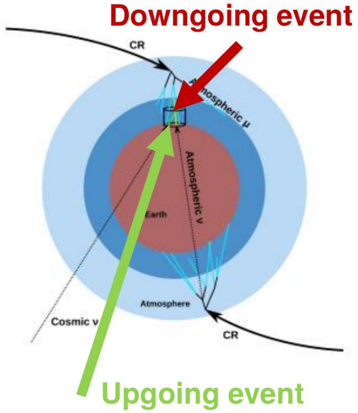
- Array of photomultipliers tubes (PMTs) to detect the **Cherenkov radiation** induced by neutrino interactions.
- **KM3NeT-ORCA:**
  - 40 km offshore **Toulon (France)**, 2450 m depth.
  - DOM spacing: 20 m x 9 m.
  - Sensitive to the **GeV-TeV energy range**.
  - Currently taking data with 23 lines (20% of the full detector).
- **KM3NeT-ARCA:**
  - 100 km offshore **Sicily (Italy)**, 3450 m depth.
  - DOM spacing: 90 m x 36 m.
  - Sensitive to the **TeV-PeV energy range**.
  - Currently taking data with 28 lines (12% of the full detector).
- **MeV neutrinos** can also be detected through a global increase in the PMT coincide rate in single DOMs.
- At the time of GRB 221009A, ARCA and ORCA were taking good-quality data with **21 and 10 detection units** respectively.

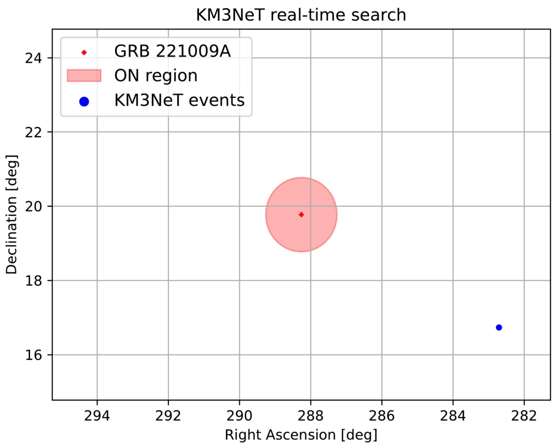
‘Online’ neutrino search

- KM3NeT reported **real-time results**: GCN #32741
- The event was **above the local horizon of KM3NeT** (a.k.a. downgoing) at T_0.
- Search time window: [T_0 - 50 s, T_0 + 5000 s].
- **No track-like candidate neutrino event found.**
- A MeV search was also conducted in real-time with no significant detection.
- IceCube also reported real-time results (GCN #32665) with no candidate neutrino event.



Visibility below the horizon (a.k.a. upgoing)





TITLE: GCN CIRCULAR
NUMBER: 32741
SUBJECT: GRB 221009A: search for neutrinos with KM3NeT
DATE: 22/10/13 18:57:37 GMT
FROM: Damien Dornic at CPPM,France <dornic@cppm.in2p3.fr>

The KM3NeT Collaboration (https://www.km3net.org/) reports:

Using the data from the online fast processing chain, the KM3NeT Collaboration has performed a dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A (Dichiara et al. GCN 32632 (Swift); Veres et al. GCN 32636 (Fermi-GBM)). The search covers the time range of [T0-50s, T0+5000s], with T0 being the trigger time reported by Fermi-GBM (T0=2022-10-09 13:16:59.00 UTC), during which both KM3NeT detectors were collecting good quality data. However, the GRB location was above the KM3NeT horizon (mean elevation of about ~40deg) during the search time window, significantly reducing the point-like source sensitivity. In both detectors, zero events were observed in the search window, while o(0.1) were expected from the background. The online fast processing uses preliminary calibrations and detector alignment, which will be superseded in a future elaborated analysis.

A parallel search has been performed in the MeV range (Eur.Phys.J.C 82 (2022) 4, 317) without any significant neutrino coincidence.

KM3NeT is a large undersea (Mediterranean Sea) infrastructure hosting two neutrino detectors, sensitive to burst of supernova neutrinos in the MeV range and to astrophysical neutrinos in the GeV-PeV energy range: ARCA at high energy and ORCA at low energy. A total of 21 and 11 detection lines are currently in operation in ARCA and ORCA, respectively.

‘Offline’ neutrino search

Later, a refined search is done including:

- The use of **Monte Carlo simulations** to improve the event selections and to compute upper limits.

- Addition of **systematic effects**:

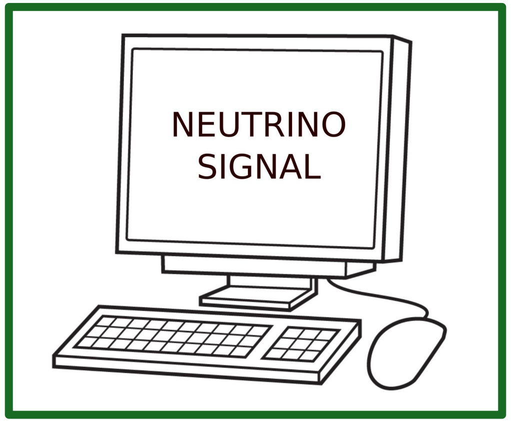
    - Data recalibrated including **dynamical positioning** of the detection units by acoustic methods.

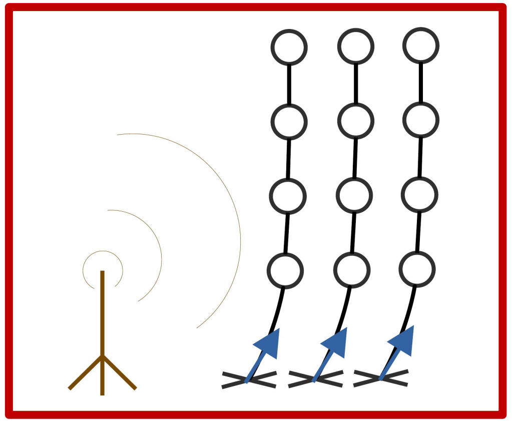
    - Evaluation of the **Point Spread Function**:

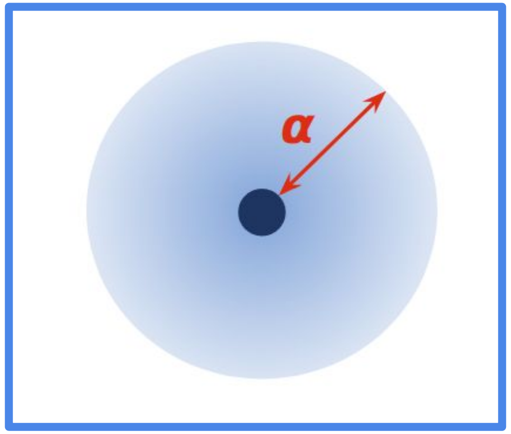
        - ARCA21: 0.8° median value for E^{-2} spectrum.
        - ORCA10: 1.2° median value for E^{-2} spectrum.

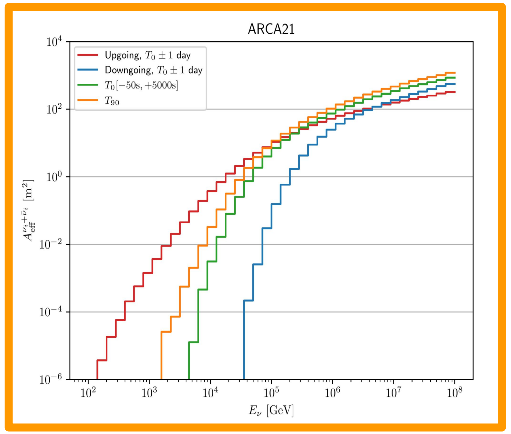
    - Estimation of the systematics on the **effective area** (~30% impact) due to:

        - Seawater properties: light absorption length, etc.
        - PMT quantum efficiency, etc.



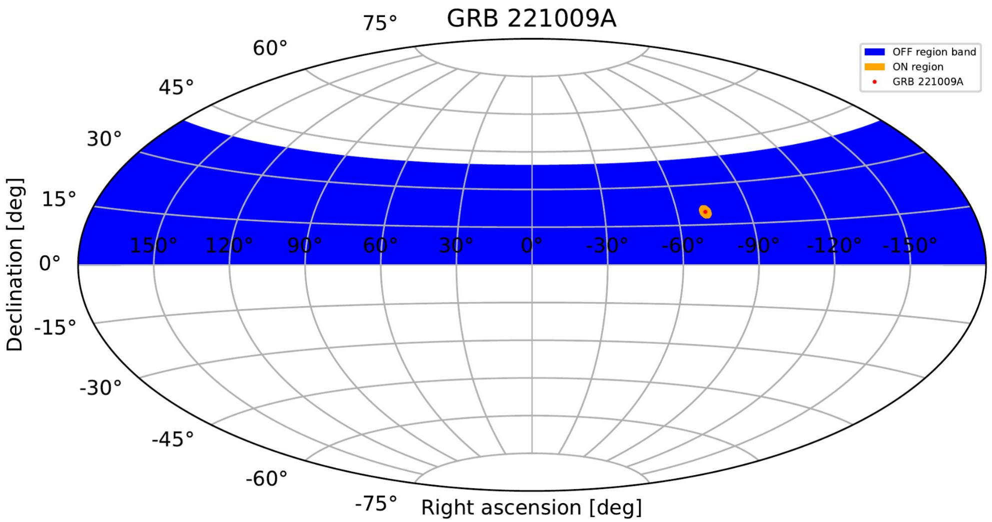




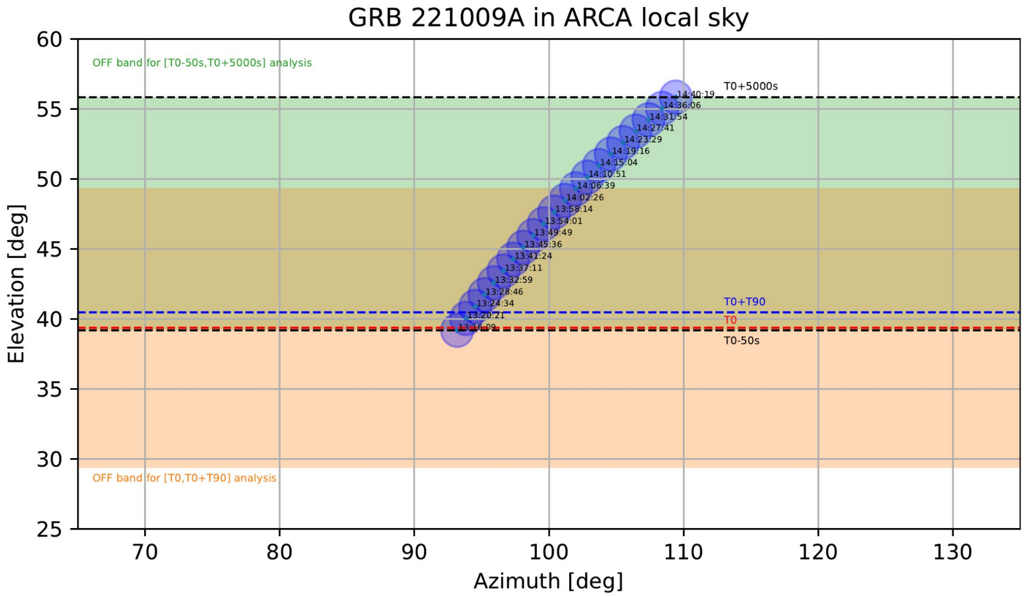


Search method

Equatorial coordinates



Local coordinates



- **ON region:** where the **signal** is expected. Circular area region optimized for each analysis.

- **OFF region**: band in the local/equatorial sky used to compute the **expected background**:

$$n_{\mathrm{bckg}} = \frac{T_{\mathrm{ON}}}{T_{\mathrm{OFF}}} \times \frac{\Omega_{\mathrm{ON}}}{\Omega_{\mathrm{OFF}}} \times N_{\mathrm{OFF}}$$

- **Time windows** analysed (both ARCA and ORCA):
  - Above the day range (equatorial coordinates):
    - $T_0 \pm 1$ day upgoing selection. (the integrated visibility in one day is 45%).
    - $T_0 \pm 1$ day downgoing selection.
  - Below the day range (local coordinates):
    - $[T_0 - 50\text{ s}, T_0 + 5000\text{ s}]$ downgoing selection.
    - $[T_0, T_0 + T_{90}]$ downgoing selection.

Event selection

- Optimization procedure:

  1. Reduce the background so that **one event in the ON region** is enough to reach 3**σ** significance.

  2. Maximize the expected signal (from MC simulations).

- A differential neutrino flux proportional to E^{-2} is assumed.

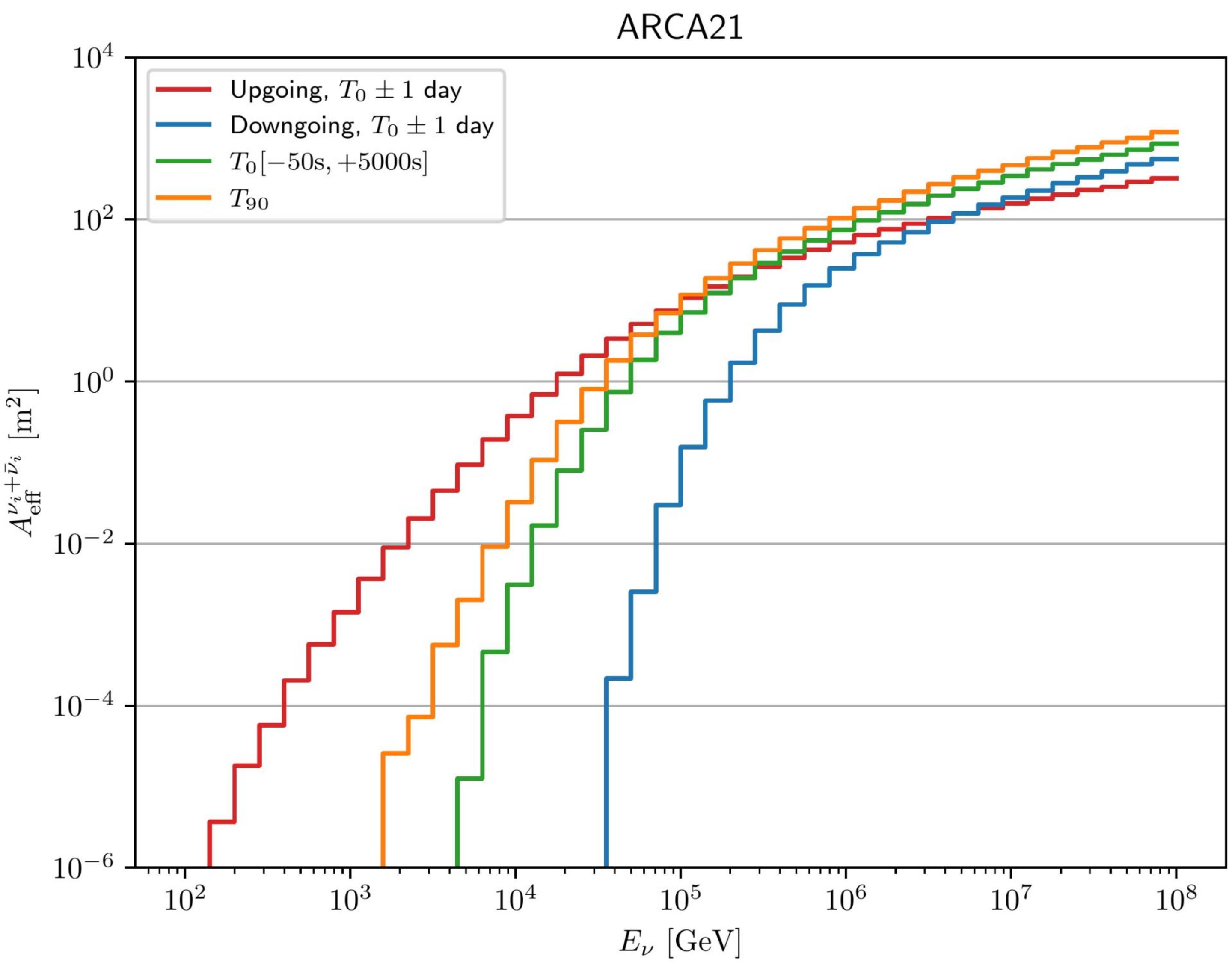
$$N_{\mathrm{s}} = \int dt \int dE \cdot \Phi(E) \cdot A^{\delta}_{\mathrm{eff}}(E)$$

- Extended datasets used to estimate the background:

  ARCA21: around 70 days.

  ORCA10: around 40 days.

- Only track-like events used.



MeV search

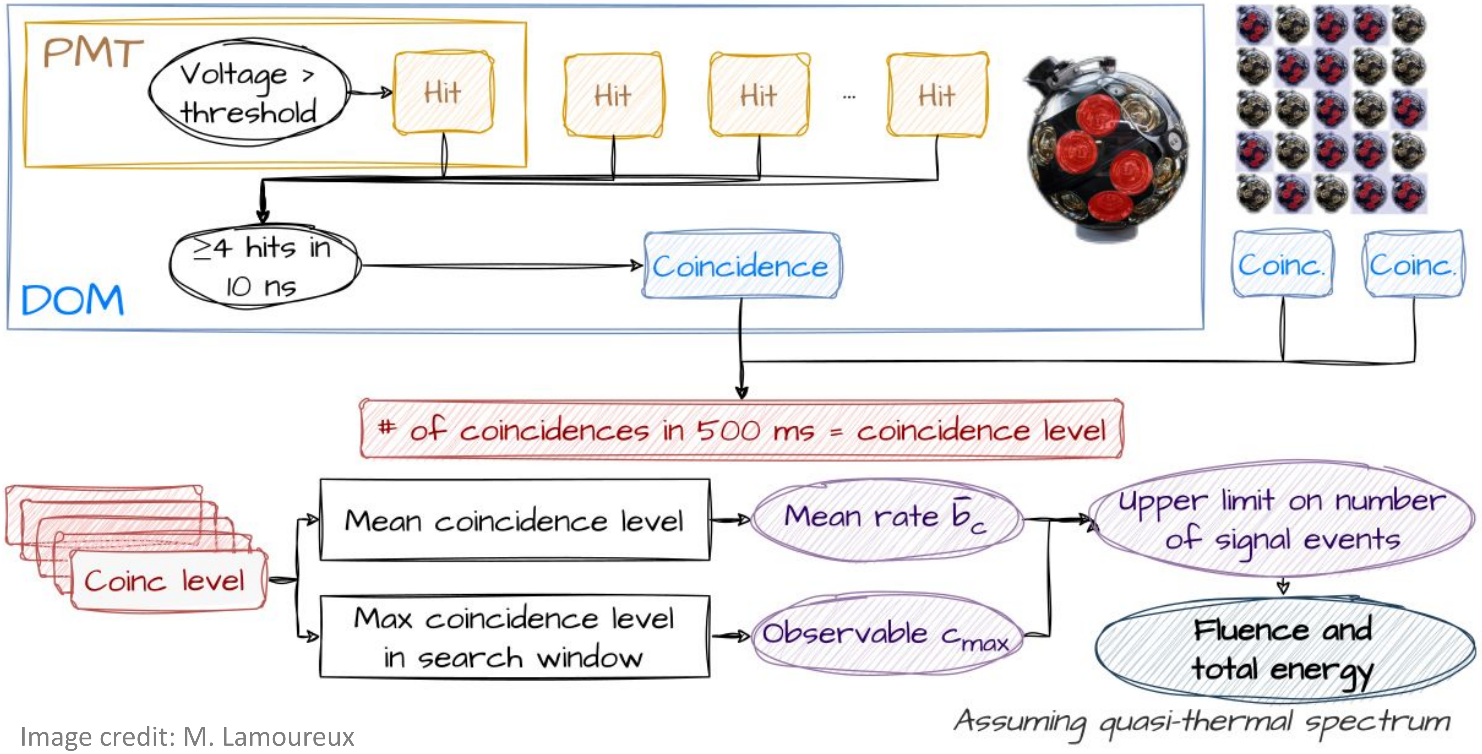


Image credit: M. Lamoureux

Results for quasi-thermal neutrino flux
$F_{\bar{\nu}_e}(E) \propto E^2 \exp(-3E/\langle E \rangle)$ at $\langle E \rangle = 15\,\mathrm{MeV}$

	T_{90}	$T_0[-50\,\mathrm{s}, +5000\,\mathrm{s}]$
Maximum coincidence level	27	32
Expected background	29	33
pvalue	0.99	0.79
Total $\bar{\nu}_e$ flux [cm^{-2}]	2.5×10^9	4.8×10^9
$E^{\mathrm{iso},90\%}_{\mathrm{tot},\nu}$ [erg]	5.1×10^{62}	6.7×10^{62}

- Identification of a **burst of electron** $\bar{\nu}$ through a global increase in the PMT coincidence rate.
- Sensitive energy range: 5 - 30 MeV.
- Time windows inspected: [T_0, T_0 + T_{90}] and [T_0 - 50 s, T_0 + 5000 s].
- **No significant excess observed.** Determination of upper limits on the total time-integrated neutrino flux and on the total energy emitted in isotropically distributed MeV neutrinos by the source.

Results

- **No candidate events found within the ON region**.
- **Upper limits** on the ν emission:

$$\Phi_0^{\rm UL} = \frac{\mu_{90}^{\rm FC}(n_b)}{\int dt \int dE \cdot (E/E_0)^{-\gamma} \cdot A_{\rm eff}^{\delta}(E)}$$

- The most restrictive results are those for the **upgoing searches**.
- E_{min}(E_{max}): 5% (95%) quantiles of the energy range for the neutrino flux.
- Fluence: per-flavour neutrino flux integrated in energy and time:

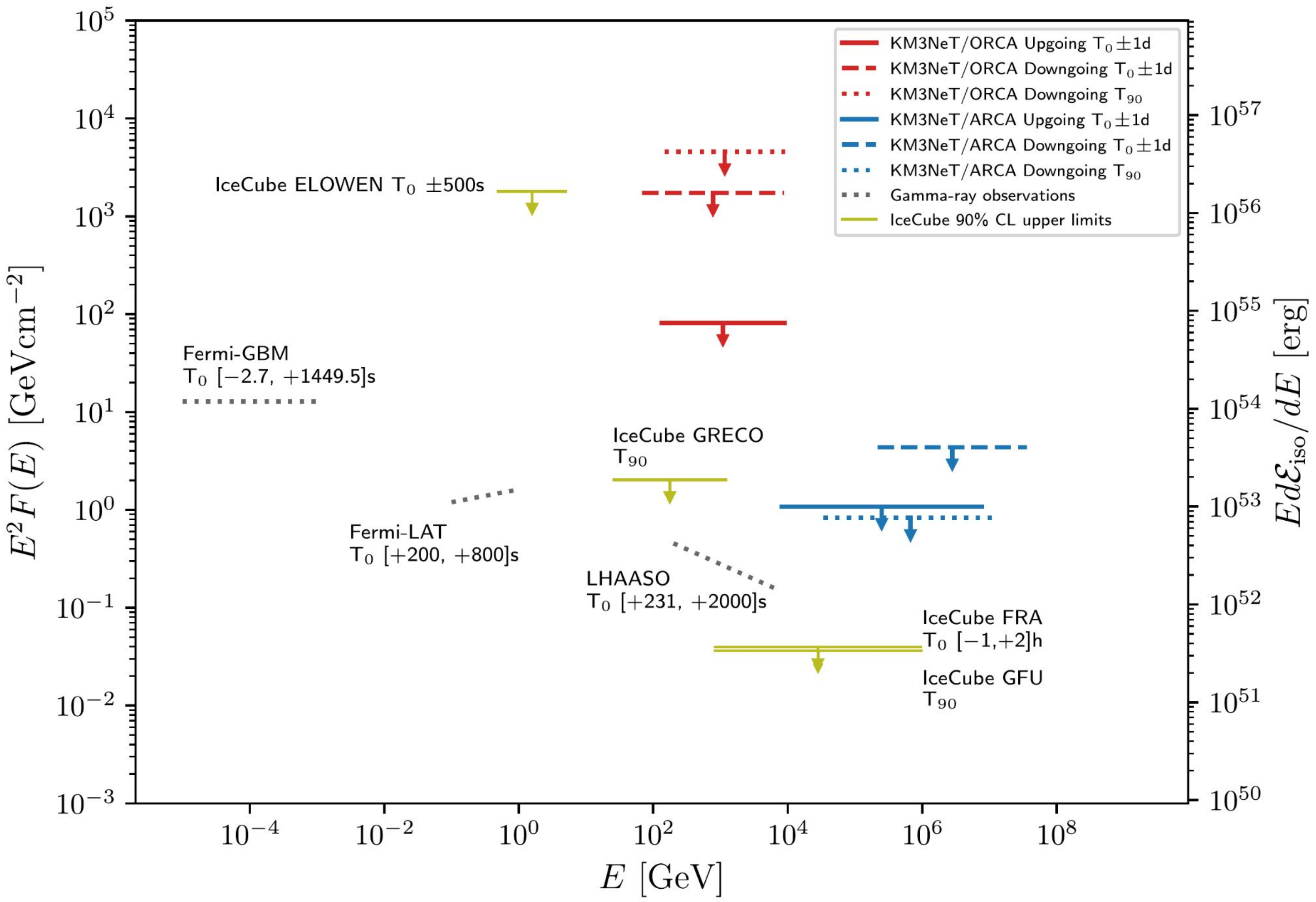
$$\mathcal{F}^{\rm UL} = \Delta T \int_{E_{\rm min}}^{E_{\rm max}} dE \cdot E \cdot \Phi_0^{\rm UL} \cdot \left(\frac{E}{E_0}\right)^{-\gamma}$$

SEARCH	KM3NeT 90% CL upper limits on neutrino emission from GRB 221009A						
	Results for neutrino flux $\Phi(E) = \Phi_0(E/E_0)^{-2}$ at $E_0 = 1\,\mathrm{GeV}$						
ARCA (TeV–PeV)	RoI radius	Expected background ($\times 10^{-3}$)	Φ_0 UL [$\mathrm{GeV^{-1}\,cm^{-2}\,s^{-1}}$]	$E_{\rm min}$ [TeV]	$E_{\rm max}$ [PeV]	Fluence $\mathcal{F}$ UL [$\mathrm{GeV\,cm^{-2}}$]	$E^2F(E)$ UL [$\mathrm{GeV\,cm^{-2}}$]
T_{90}	2.1°	2.64 ± 0.02	2.5×10^{-3}	34	13	4.9	0.83
$T_0[-50\,\mathrm{s}, +5000\,\mathrm{s}]$	1.1°	2.53 ± 0.04	2.8×10^{-4}	110	27	7.9	1.4
$T_0\pm$1d downgoing	1.0°	2.6 ± 0.1	2.5×10^{-5}	220	36	22	4.4
$T_0\pm$1d upgoing	1.7°	2.7 ± 0.2	6.2×10^{-6}	8.1	7.7	7.4	1.1
	Results for neutrino flux $\Phi(E) = \Phi_0(E/E_0)^{-2}$ at $E_0 = 1\,\mathrm{GeV}$						
ORCA (GeV–TeV)	RoI radius	Expected background ($\times 10^{-3}$)	Φ_0 UL [$\mathrm{GeV^{-1}\,cm^{-2}\,s^{-1}}$]	$E_{\rm min}$ [GeV]	$E_{\rm max}$ [TeV]	Fluence $\mathcal{F}$ UL [$\mathrm{GeV\,cm^{-2}}$]	$E^2F(E)$ UL [$\mathrm{GeV\,cm^{-2}}$]
T_{90}	2.0°	2.61 ± 0.04	14	150	9.1	1.9×10^4	4.5×10^3
$T_0[-50\,\mathrm{s}, +5000\,\mathrm{s}]$	5.4°	2.6 ± 0.2	1.9	54	8.7	4.9×10^4	9.6×10^3
$T_0\pm$1d downgoing	1.0°	2.7 ± 0.3	1.0×10^{-2}	68	8.8	8.5×10^3	1.7×10^3
$T_0\pm$1d upgoing	1.2°	2.7 ± 0.3	4.7×10^{-4}	130	9.8	3.5×10^2	81
	Results for quasi-thermal neutrino flux $F_{\bar{\nu}_e}(E) \propto E^2 \exp(-3E/\langle E\rangle)$ at $\langle E\rangle = 15\,\mathrm{MeV}$						
MeV search	Maximum coincidence level	Expected background	p-value	$E_{\rm min}$ [MeV]	$E_{\rm max}$ [MeV]	Total $\bar{\nu}_e$ flux [$\mathrm{cm^{-2}}$]	$E_{\rm tot,\nu}^{\rm iso,90\%}$ [erg]
T_{90}	27	29	0.99	5	30	2.5×10^9	5.1×10^{62}
$T_0[-50\,\mathrm{s}, +5000\,\mathrm{s}]$	32	33	0.79			4.8×10^9	9.7×10^{62}

Results

- **E²F(E)**: per-flavour energy-scaled time-integrated neutrino flux.
- **Multi-messenger plot:** KM3NeT limits + IceCube limits + some gamma-ray measurements for comparison.
- For KM3NeT, GRB 221009A happened in the non-visible region, unlike IceCube.
- About a 15% improvement in sensitivity is expected upon detector completion.
- Future analyses will also incorporate cascade events.

NOTE: Plot updated with the latest results reported by IceCube , check (2023, ApJL, 946, L26).



Conclusions

- Multiple searches for neutrinos coming from **GRB 221009A** have been performed with the KM3NeT detectors.

- **No coincident neutrino events** found.

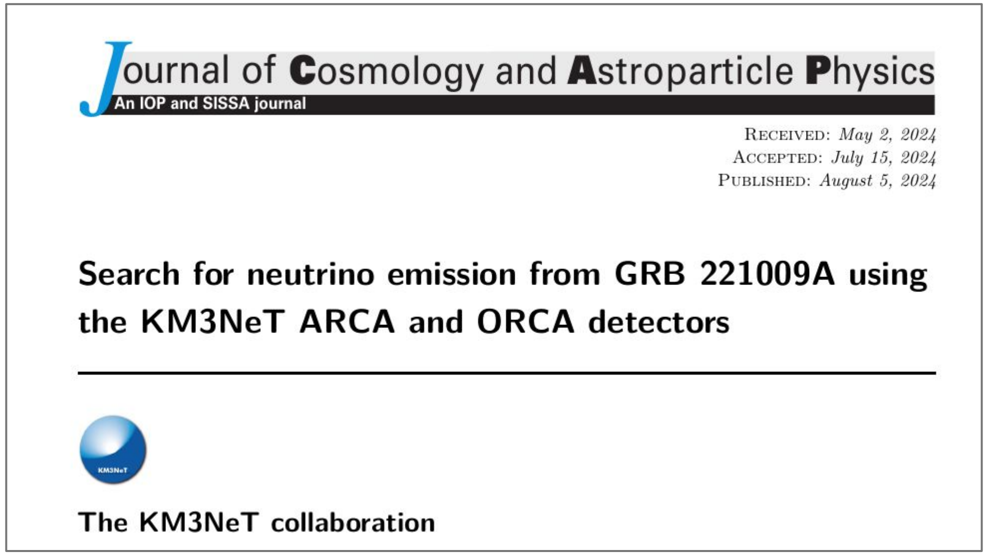
- **Upper limits** on the neutrino emission have been determined. These are limited by:

    - Visibility of the event.
    - Current (partial) detector configuration.

- For future GRBs, these results will improve with larger detector configurations and the addition of cascade-like events.

- The **Online Platform of KM3NeT** continues searching for GRB-neutrino correlations, while the detector size is growing.

- More information at the JCAP publication.



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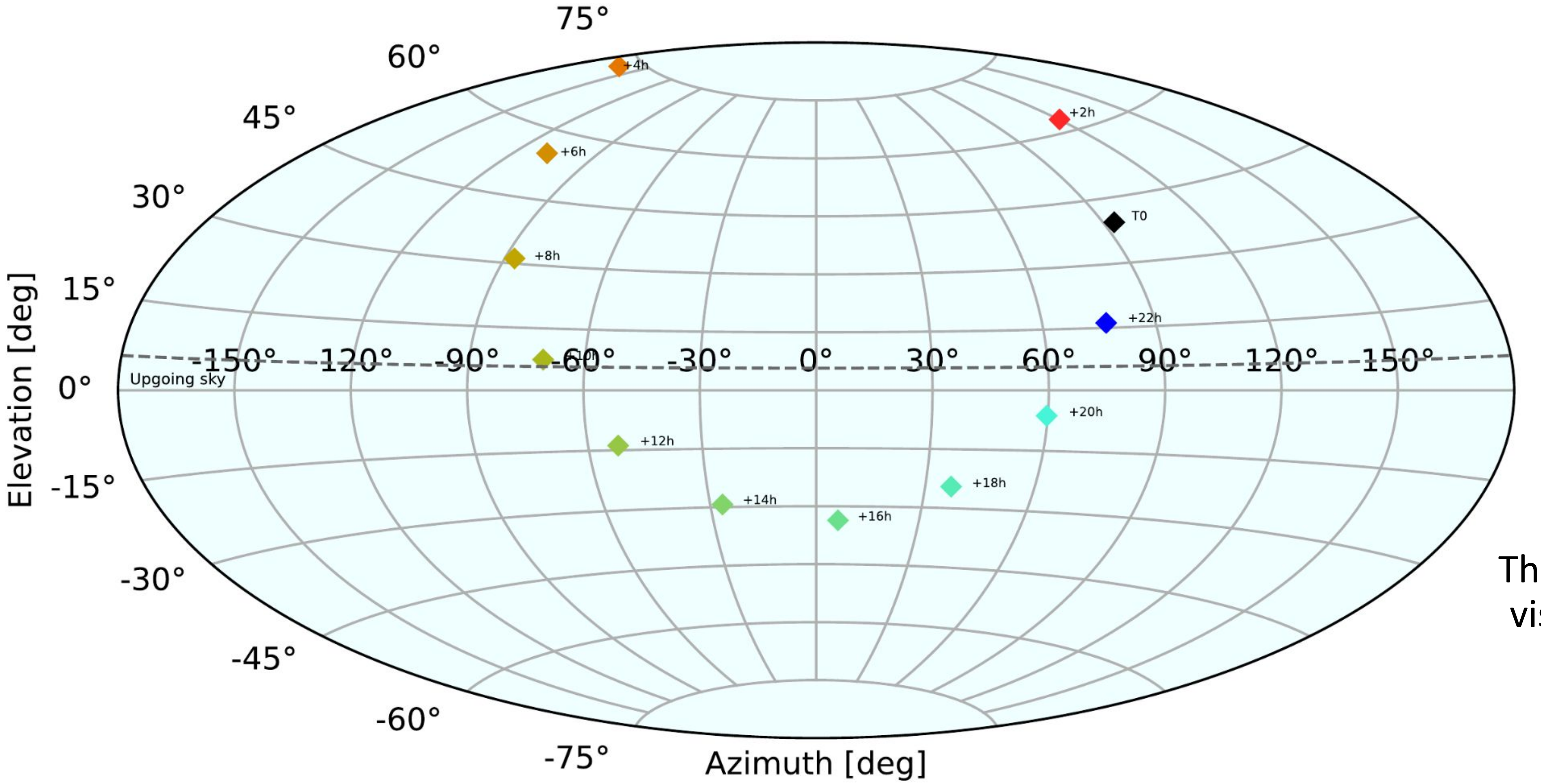
Search for neutrino emission from GRB 221009A using the KM3NeT ARCA and ORCA detectors

The KM3NeT collaboration

Backup

Local sky movement



The integrated upgoing visibility is 45% in one day.

Movement of GRB 221009A in the local sky of KM3NeT/ARCA.

Field of view