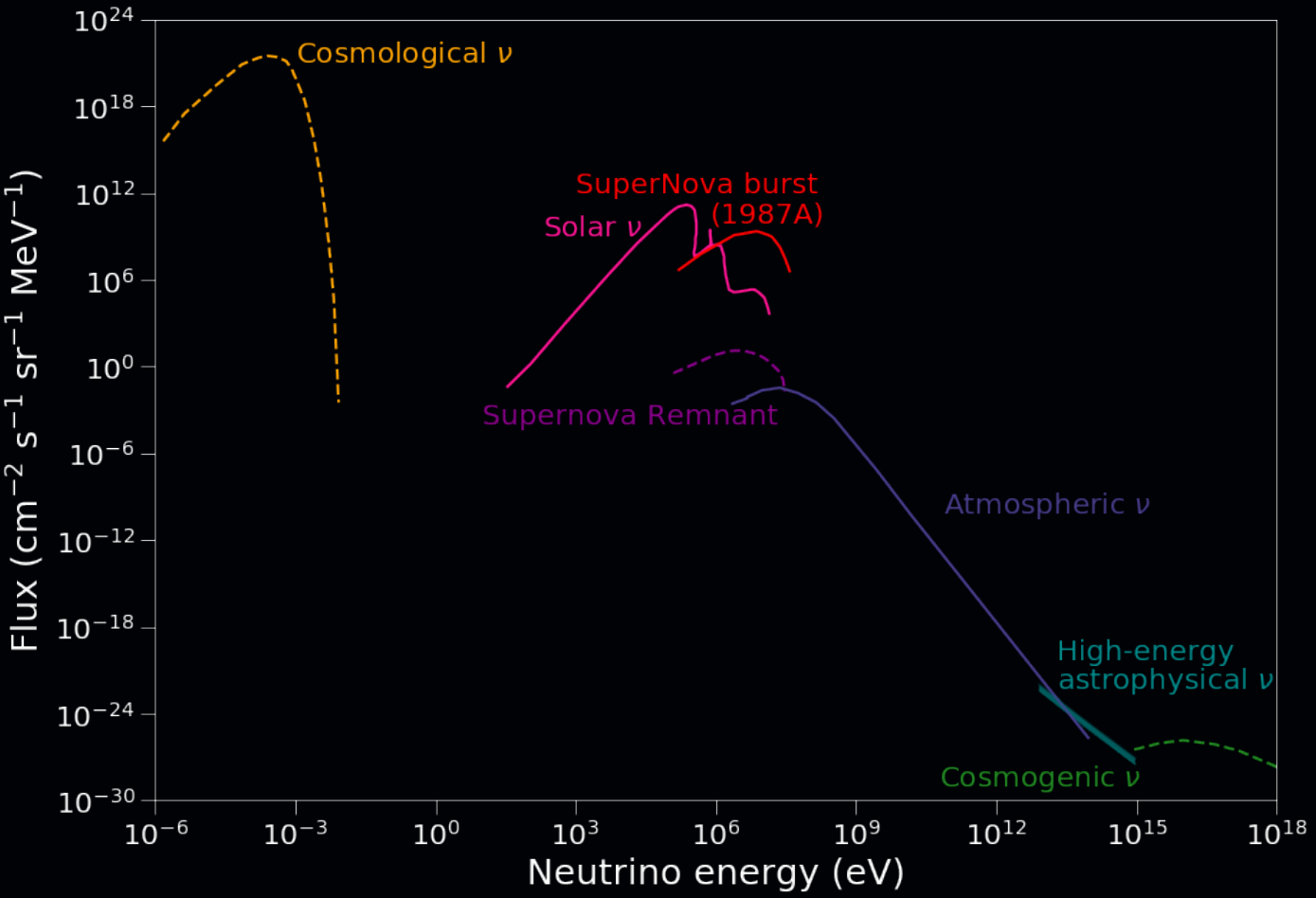
KM3NeT: First results and capabilities for low-energy neutrino events

Gwenhael W De Wasseige

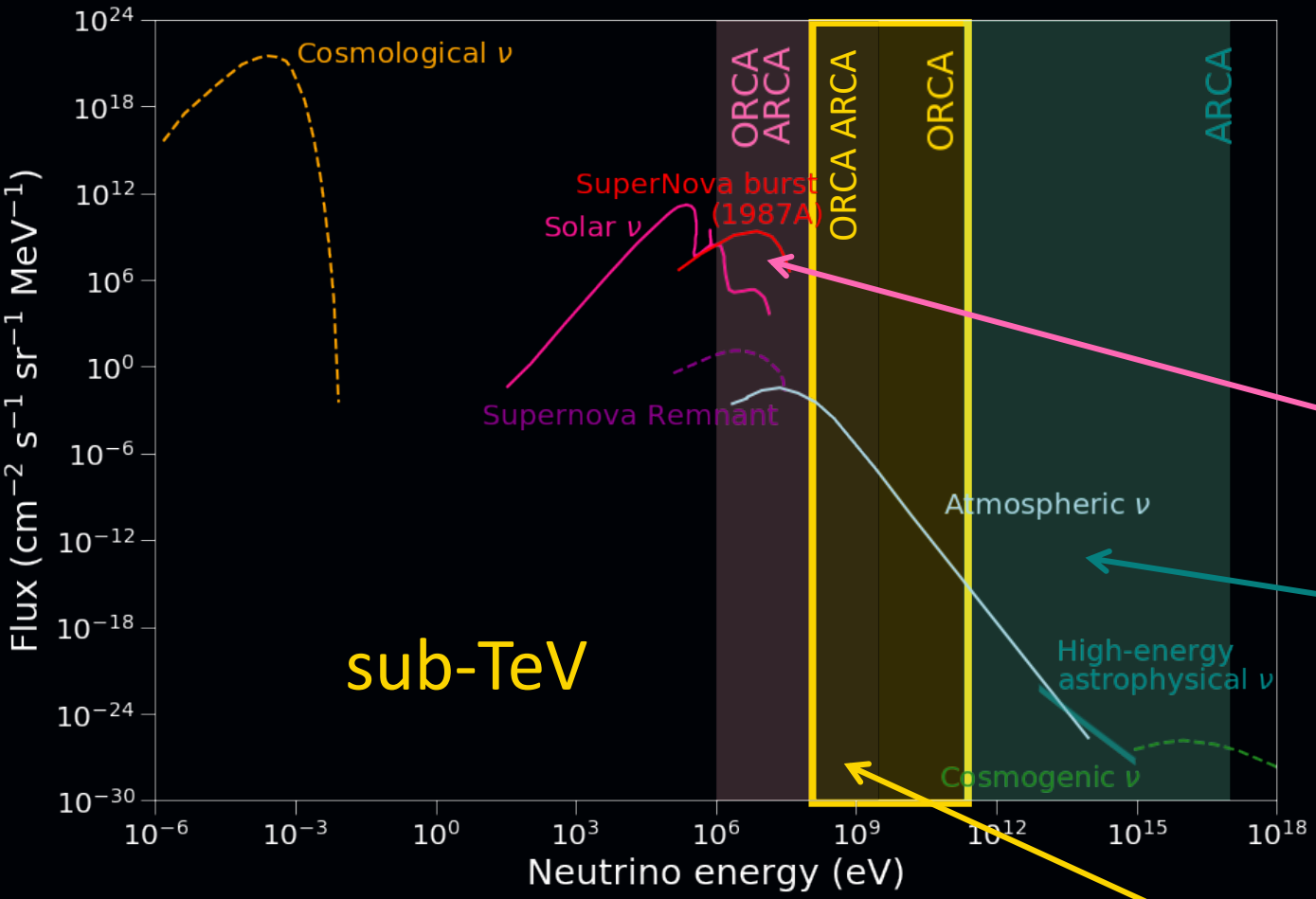
On behalf of the KM3NeT Collaboration

Francqui Foundation

The neutrino sky



The neutrino sky



See talks by:

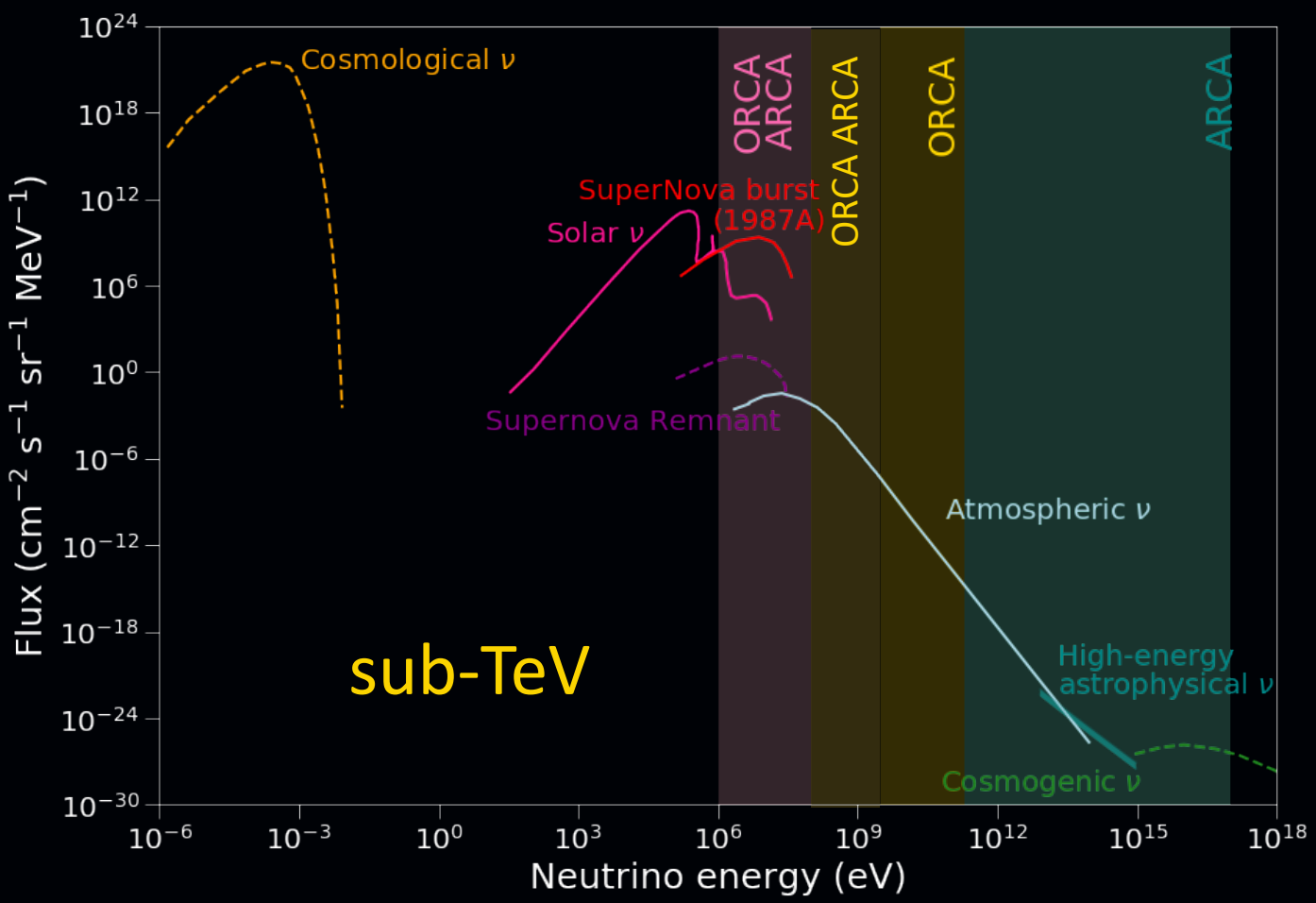
I. Goos

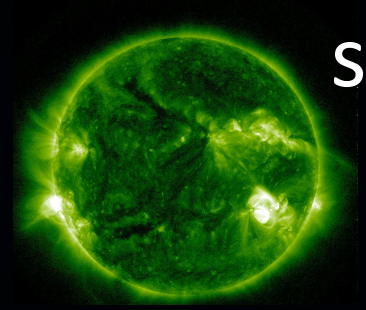
F. Filippini

This talk

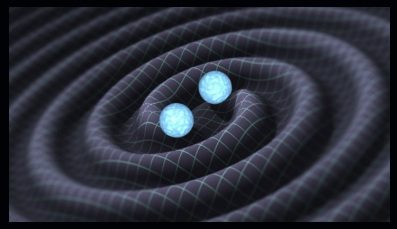
KM3NeT is sensitive to astrophysical neutrinos across a wide energy range

The neutrino sky





Sun



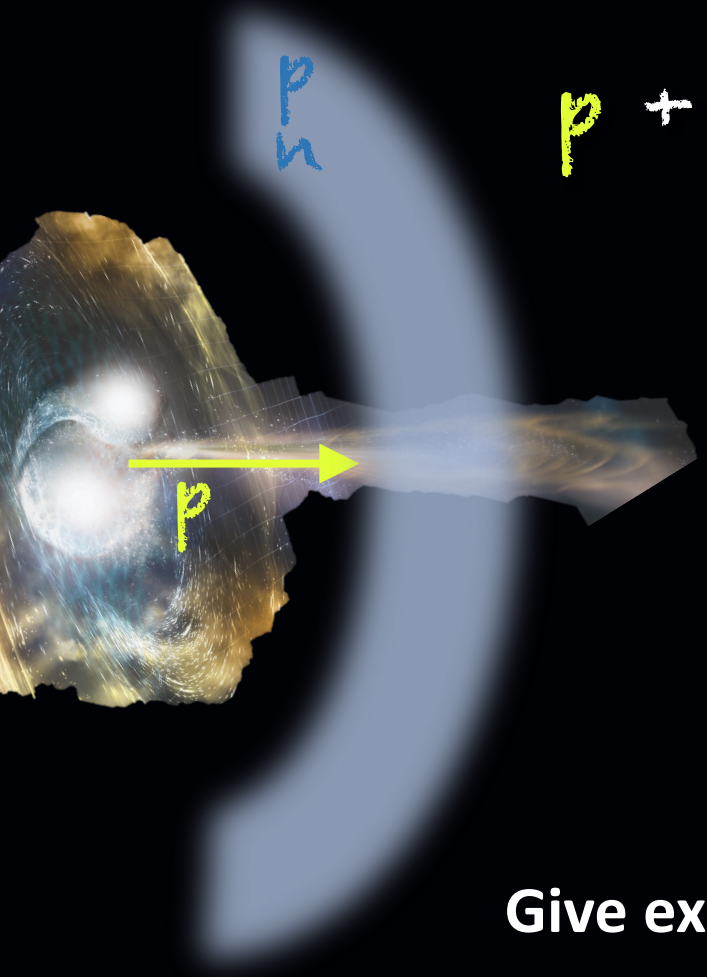
Compact Binary Mergers

GRBs

Novae

Search for an astrophysical transient signal

Why exploring the sub-TeV sky



$$p + p, n \rightarrow \begin{cases} \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \pi^0 \rightarrow 2\,\gamma \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \\ \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \end{cases}$$

Give extra information on source environment

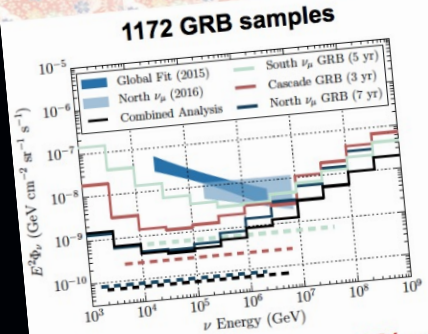
Murase *et al.,* Phys.Rev.Lett. 111 (2013) 131102
Bartos *et al.*, Phys.Rev.Lett. 110 (2013) 241101
Maouloud, GDW, Ahlers, Bustamante, van Elewyck, PoS(ICRC2019)1023

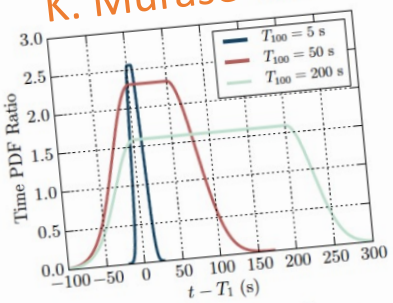
See previous Town Hall meeting!

Why exploring the sub-TeV sky

Implications of GRB Stacking Search

K. Murase IceCube 2017 ApJ

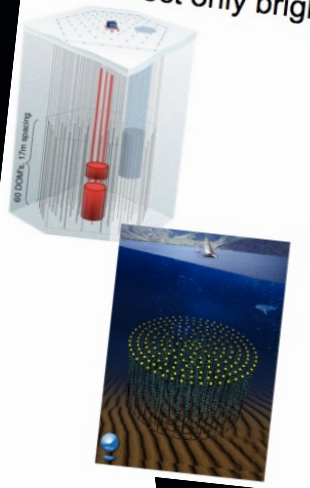


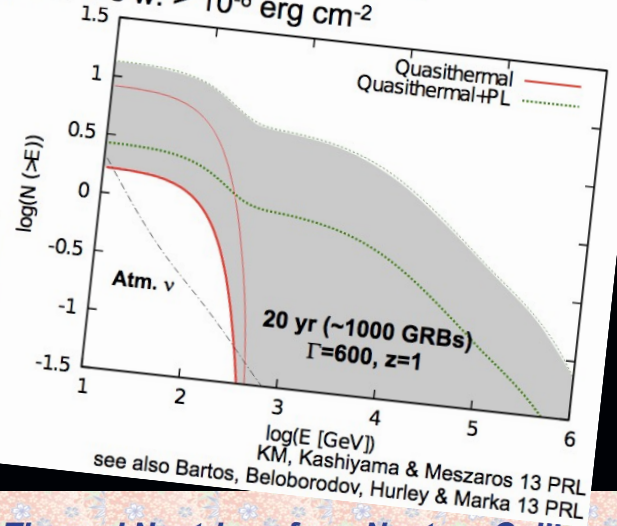


- Classical GRB: <~1% of the diffuse IceCube flux
- DO NOT overinterpret results:
  - Constraints are much weaker at EeV (ex. ν afterglow models)
  - Constraints are much weaker at GeV-TeV (ex. sub-photospheric models)
  - Constraints are weaker for longer-lasting emission (ex. flares/afterglows)
  - Not applied to other transients (ex. low-luminosity GRBs, choked jets)

Prospects for IceCube & KM3Net

- Dedicated searches **below 100 GeV:** crucial (DeepCore,ORCA)
- Reducing atmospheric ν background is essential
  → select only bright GRBs w. > 10^{-6} erg cm^{-2}

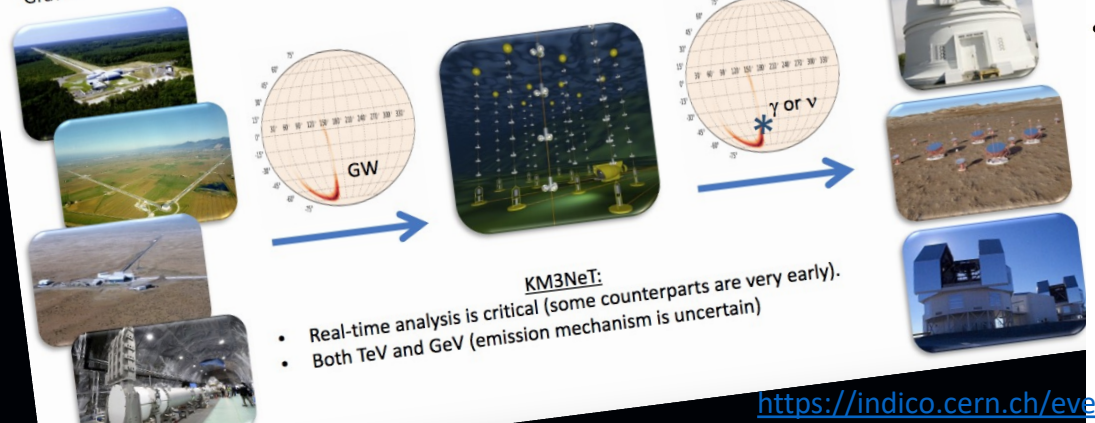




KM, Kashiyama & Meszaros 13 PRL
see also Bartos, Beloborodov, Hurley & Marka 13 PRL

Multi-messenger follow-up

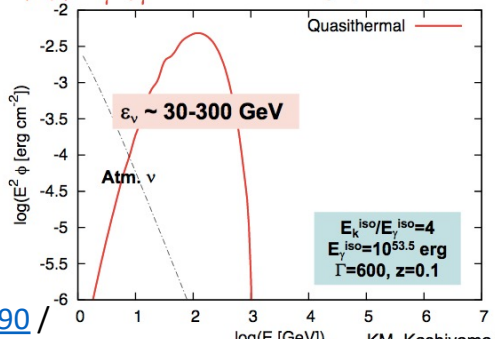
I. Bartos



KM3NeT:
- Real-time analysis is critical (some counterparts are very early).
- Both TeV and GeV (emission mechanism is uncertain)

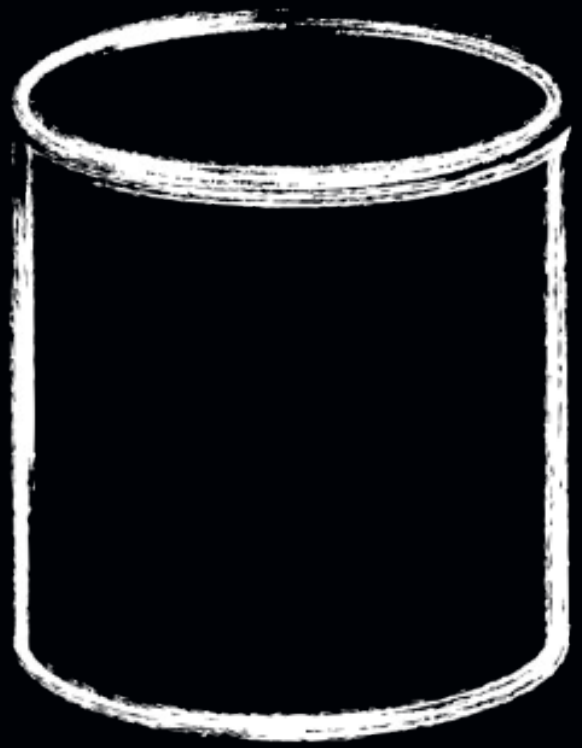
Quasi-Thermal Neutrinos from Neutron Collisions

- Quasithermal (nonthermal CRs unnecessary)
  ν energy: $\varepsilon_\nu \sim 0.1\Gamma\Gamma_{rel} m_p c^2 \sim 100$ GeV$(\Gamma/500)(\Gamma_{rel}/2)$
- Efficient π production (inelastic dissipation of ns)
  ν flux: $\varepsilon_\nu^2 \phi_\nu \sim \varepsilon_\gamma^2 \phi_\gamma$: calibrated by prompt emission



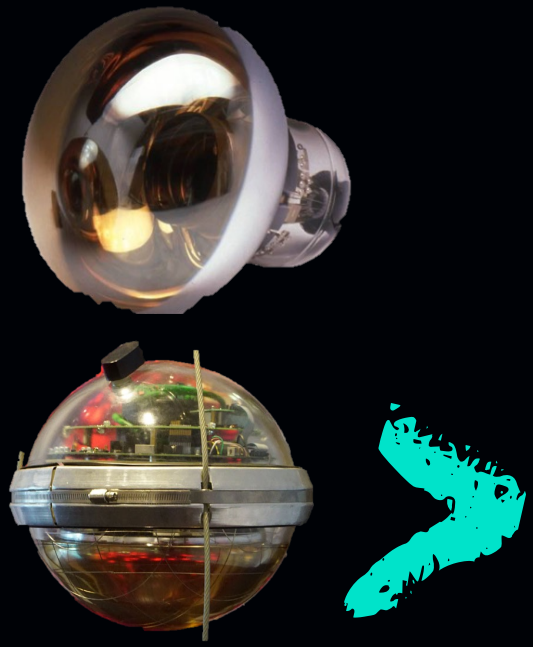
https://indico.cern.ch/event/848390 /

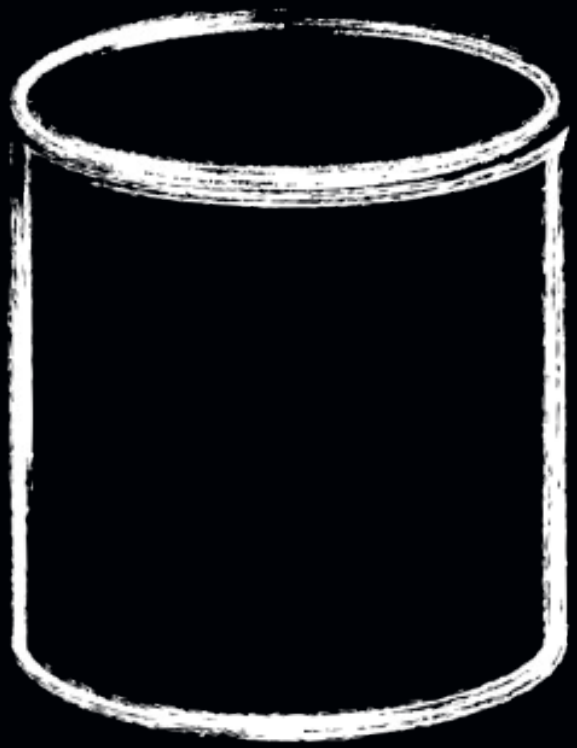
What do we need to detect low-energy neutrinos



Large detection volume

What do we need to detect low-energy neutrinos

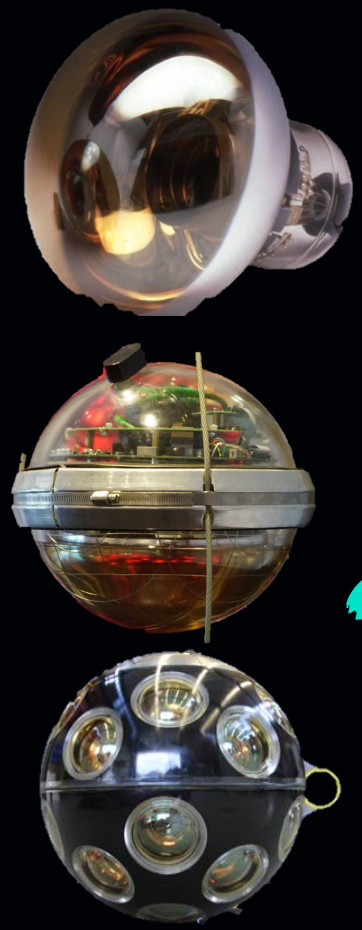




Densely instrumented volume

Large detection volume

What do we need to detect low-energy neutrinos



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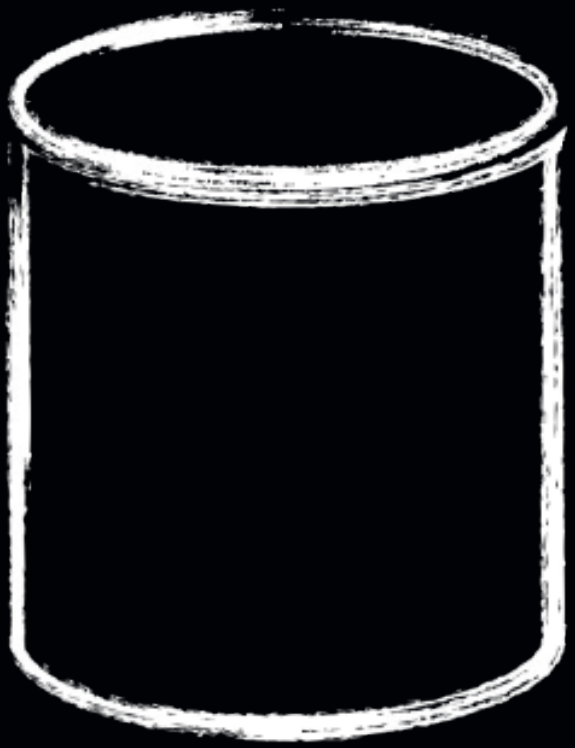
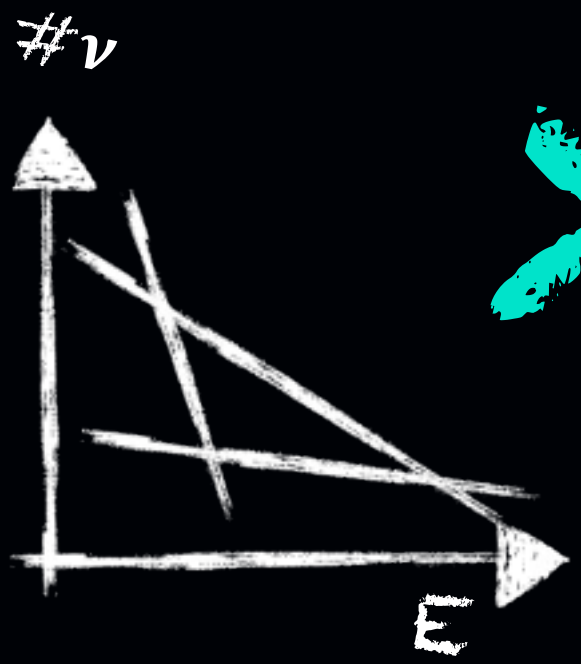


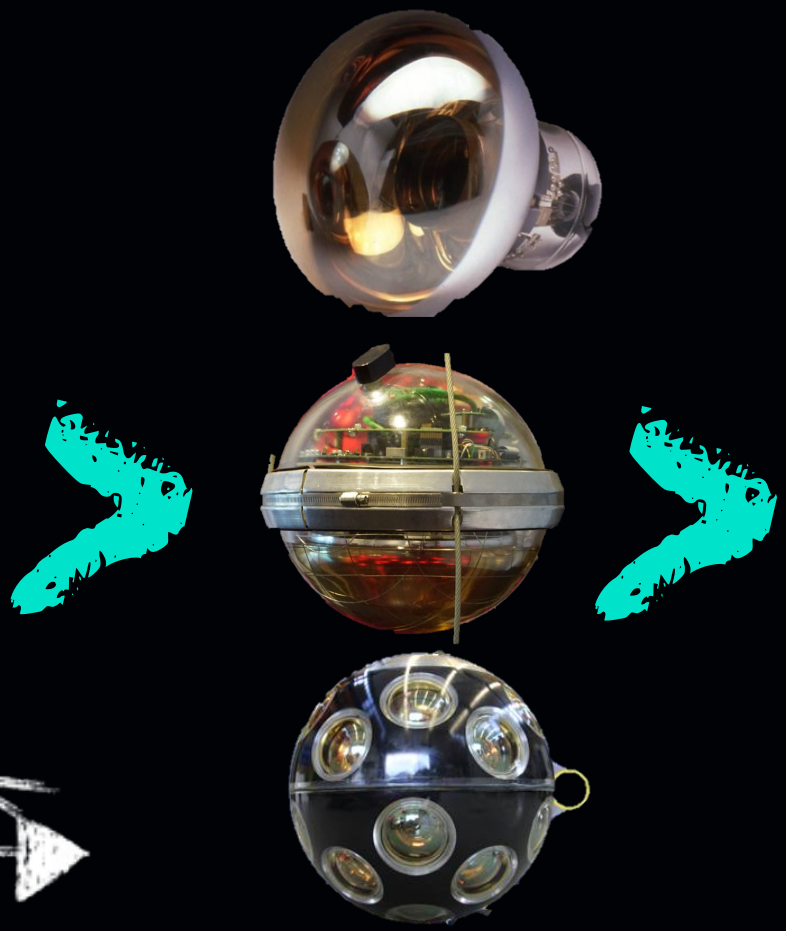
Large detection volume

What do we need to detect low-energy neutrinos

Atmospheric muons
Atmospheric neutrinos
Bioluminescence
Afterpulses
Thermal noise
Radioactive decay
Luminescence
…



Ingenuity



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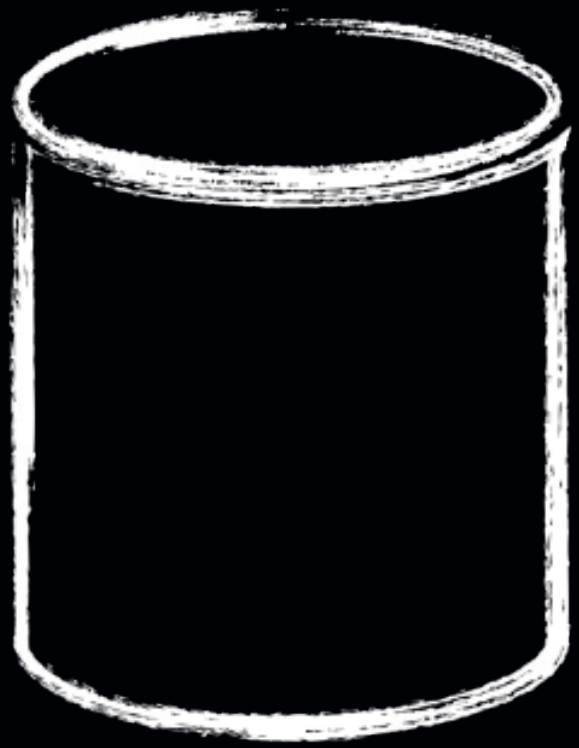

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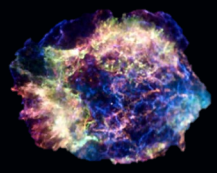
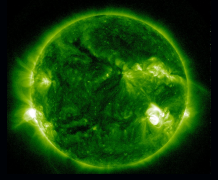
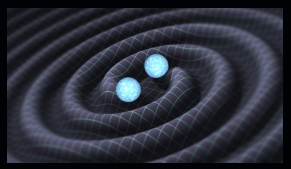
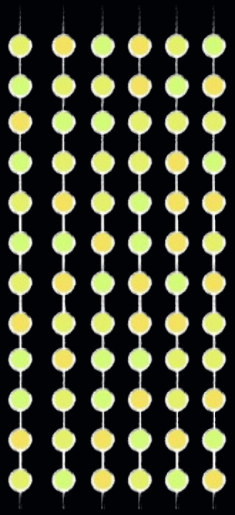
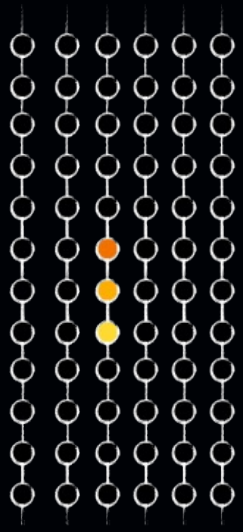



Energy

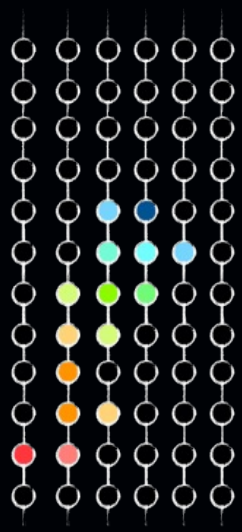


- No single event reconstruction possible
- Search for a transient increase in the overall detector rate
- Triangulation for source localization
- Estimate of the mean energy



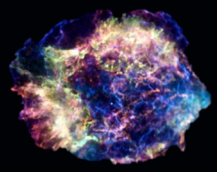
- Neutrino interactions trigger data taking
- No angular reconstruction possible at the moment
- Search for an increase in the rate during the astrophysical transient

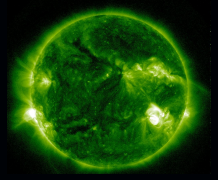
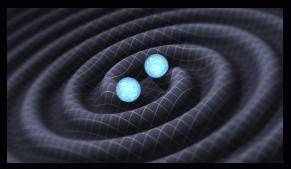
Phys. Rev. D 103, 102001



- Approach similar to what is done in high-energy searches
- Still enough hits to reconstruct the direction of the events

arXiv:2011.05096

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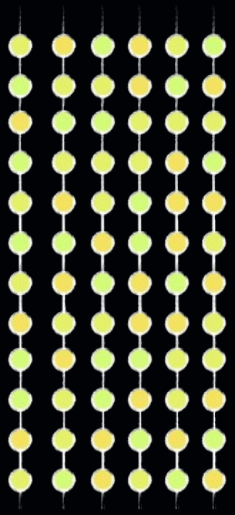

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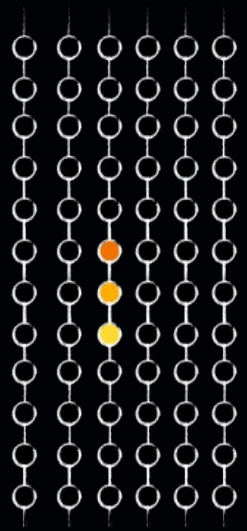
See I. Goos talk



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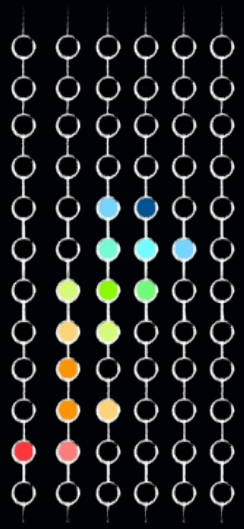

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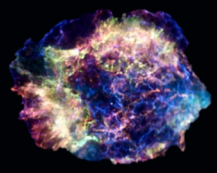

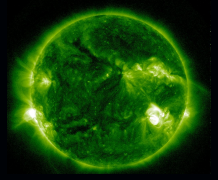
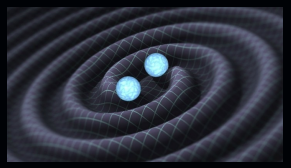


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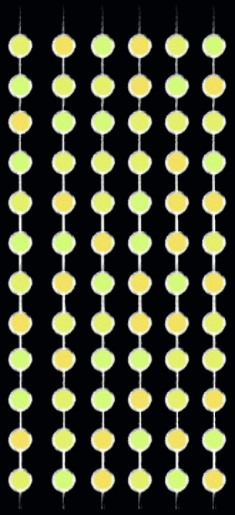
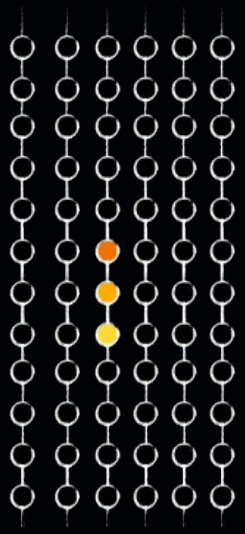
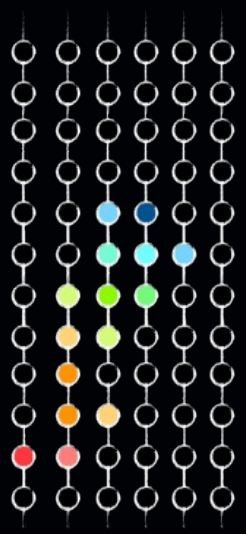
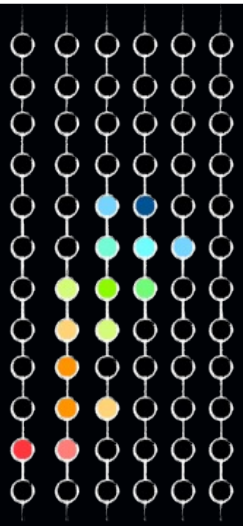
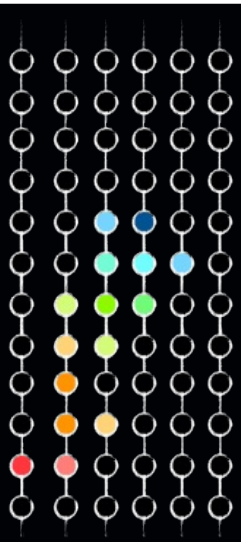
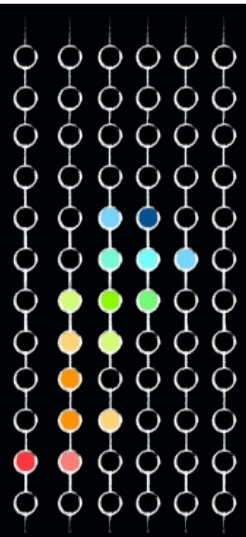
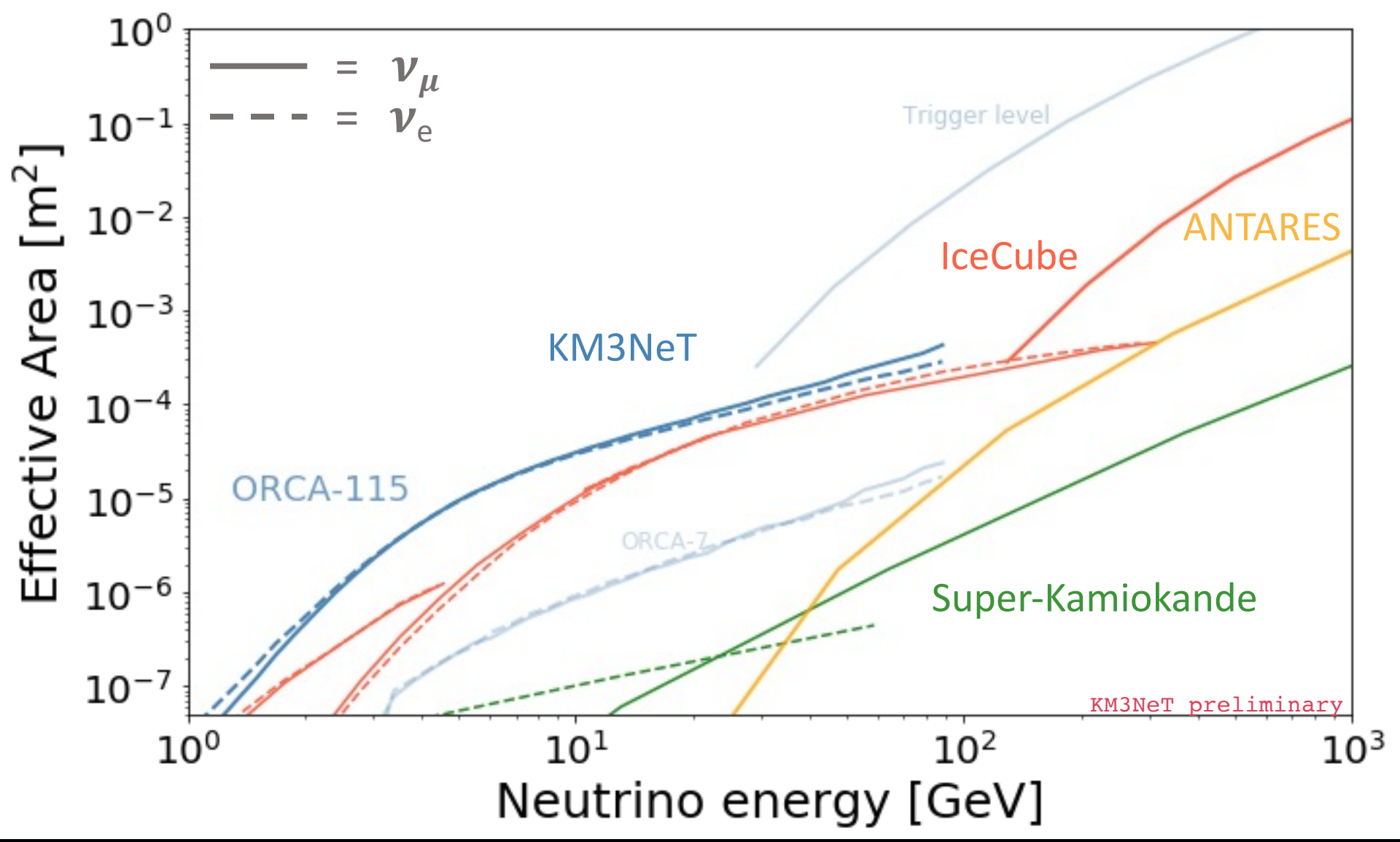




ICECUBE

KM3NeT

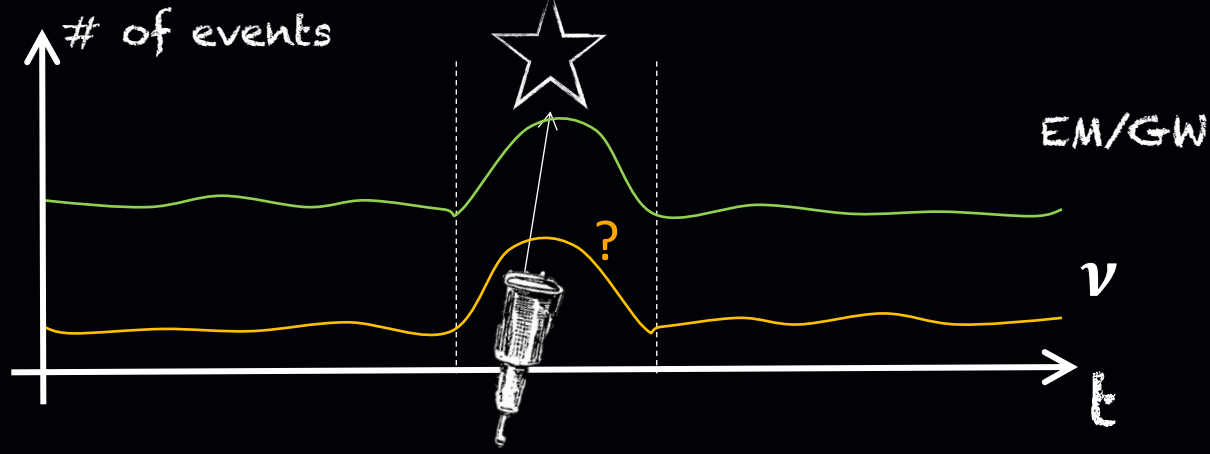
SUPER K

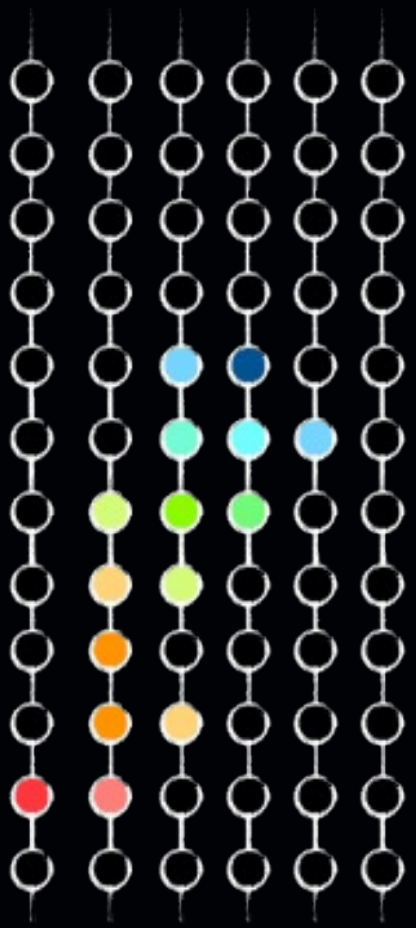


https://arxiv.org/pdf/2011.05096.pdf
https://arxiv.org/abs/1612.06028

Neutrino2020, poster 161
Neutrino2020, poster 280

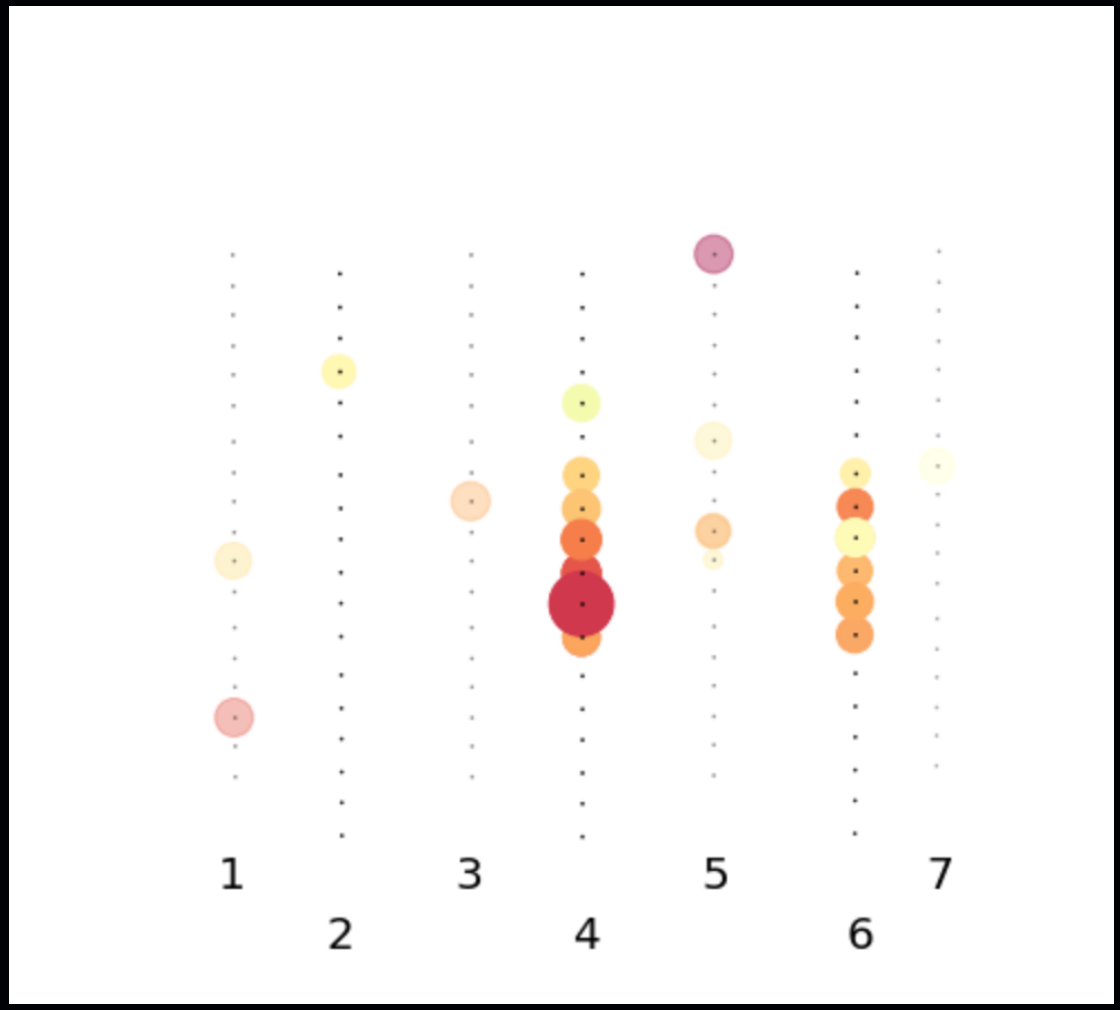
https://arxiv.org/abs/1601.07459
PoS(ICRC2019)934





- Approach similar to what is done in high-energy searches
- Still enough hits to reconstruct the direction of the events
- <u>Mean angular resolution</u>

In degrees @ 30 GeV	Tracks	Cascades
IceCube	20	40
KM3NeT/ORCA	5	5
SK	< 2	5-10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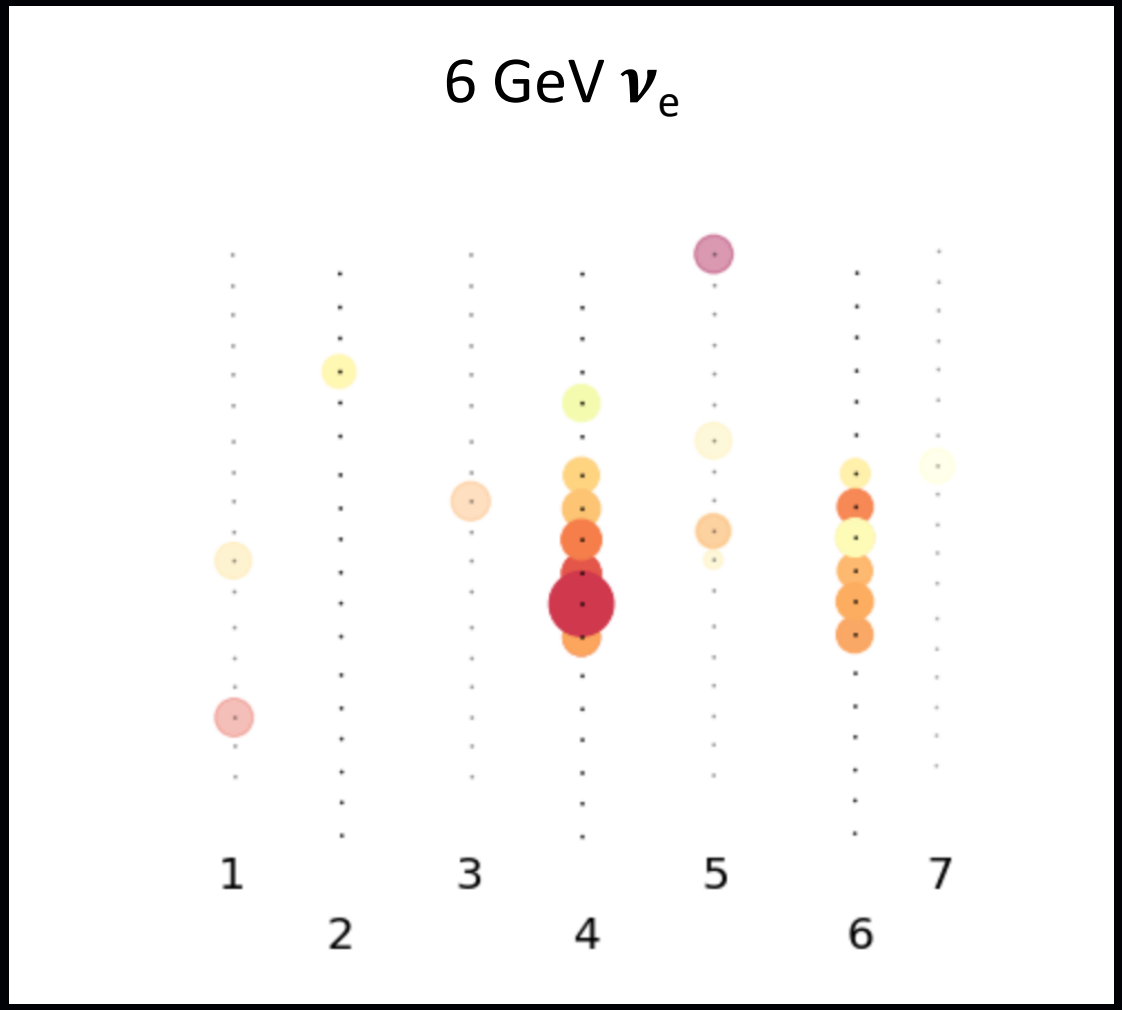
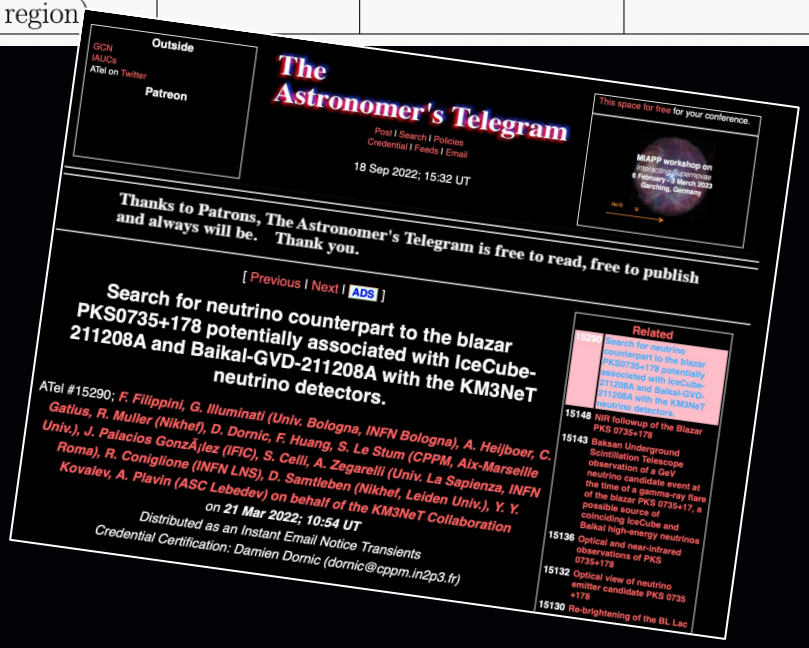


ORCA can be used for neutrino astronomy!

Online follow-ups

KM3NeT preliminary

	ARCA			ORCA				
ALERT	IC211208A ±1 day	IC211208A Month time window	IC220205B ±1 day	IC211208A ±1 day	IC211208A Month time window	IC220205B ±1 day	IC220225A ±1 day	IC220304A ±1 day
RoI radius	1.4°	1.4°	1.9°	4.2°	2.3°	3.6°	4.0°	4.0°
Expected signal	$8.9{\cdot}10^{-3}$	$1.2{\cdot}10^{-1}$	$9.7{\cdot}10^{-3}$	$8.6{\cdot}10^{-4}$	$1.0{\cdot}10^{-2}$	$6.7{\cdot}10^{-4}$	$6.5{\cdot}10^{-4}$	$6.3{\cdot}10^{-4}$
Expected background (using MC)	$4.9{\cdot}10^{-2}$	$6.7{\cdot}10^{-1}$	$5.2{\cdot}10^{-2}$	$8.0{\cdot}10^{-2}$	$2.8{\cdot}10^{-1}$	$8.0{\cdot}10^{-2}$	$8.0{\cdot}10^{-2}$	$8.0{\cdot}10^{-2}$
Expected background (using data)	$(4.7{\pm}0.7){\cdot}10^{-2}$	$(6.6{\pm}0.3){\cdot}10^{-1}$	$(4.9{\pm}0.9){\cdot}10^{-2}$	$(9{\pm}2){\cdot}10^{-2}$	$(2.3{\pm}0.2){\cdot}10^{-1}$	$(9{\pm}1){\cdot}10^{-2}$	$(8{\pm}1){\cdot}10^{-2}$	$(9{\pm}1){\cdot}10^{-2}$
Number of events in ON region for 3σ	2	5	2	2	3	2	2	2
Signal events (ON region)	0	1	0	0	0	0	0	0

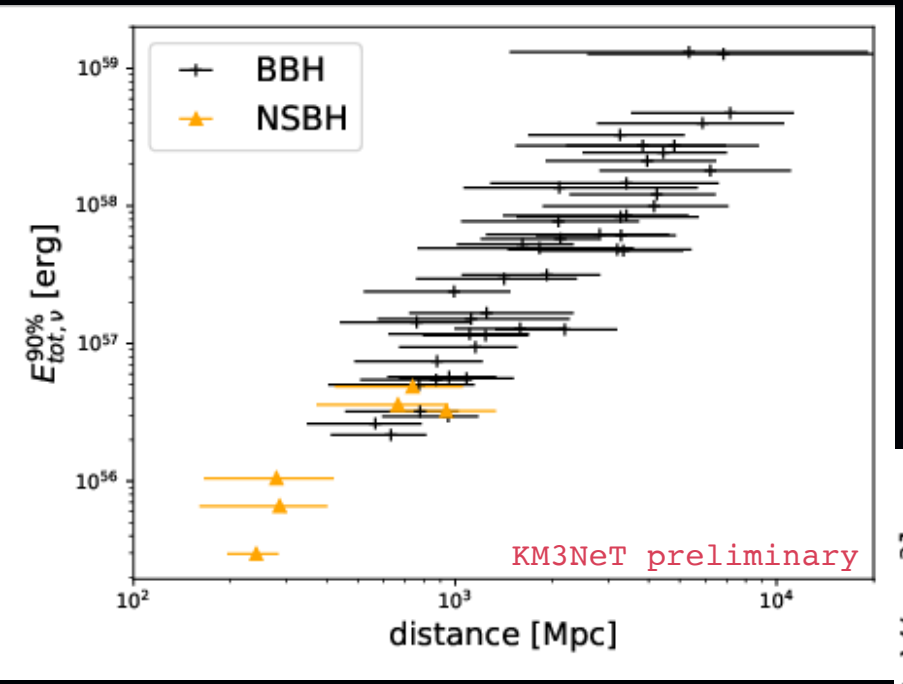


See the Alert session on Thursday!

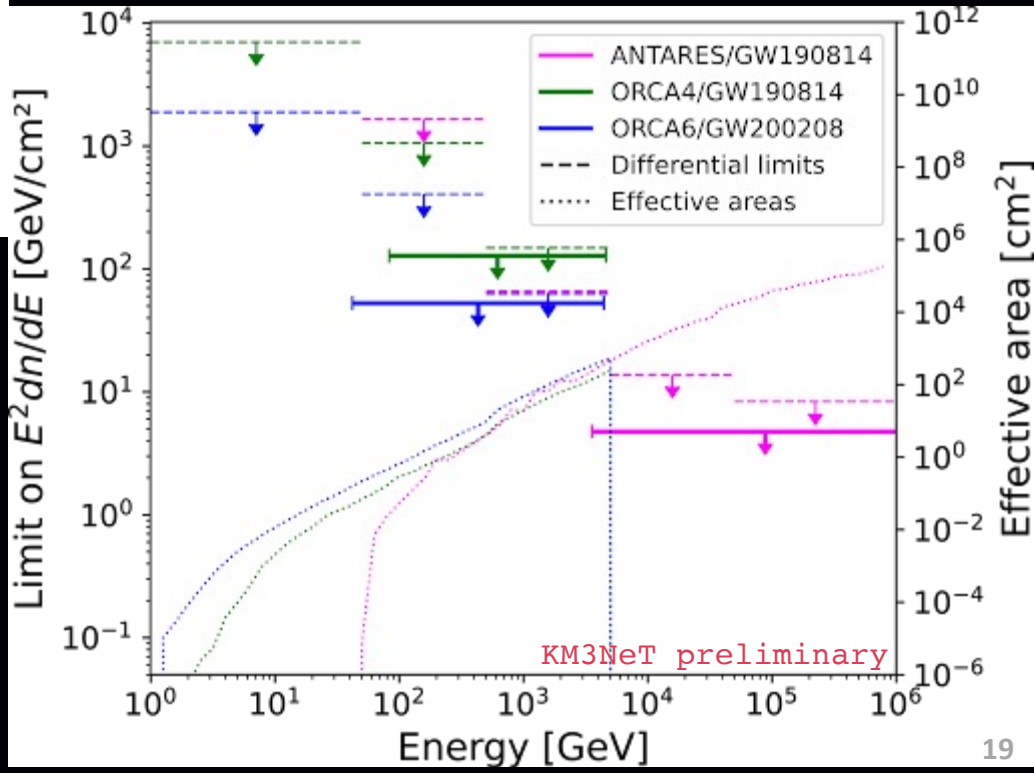
See Neutrino2022 contributions
P0739
P0536

https://www.astronomerstelegram.org/?read=15290

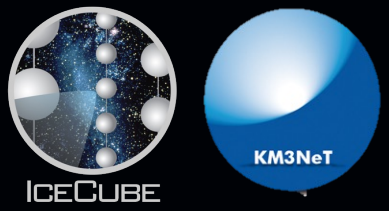
Gravitational wave follow-ups



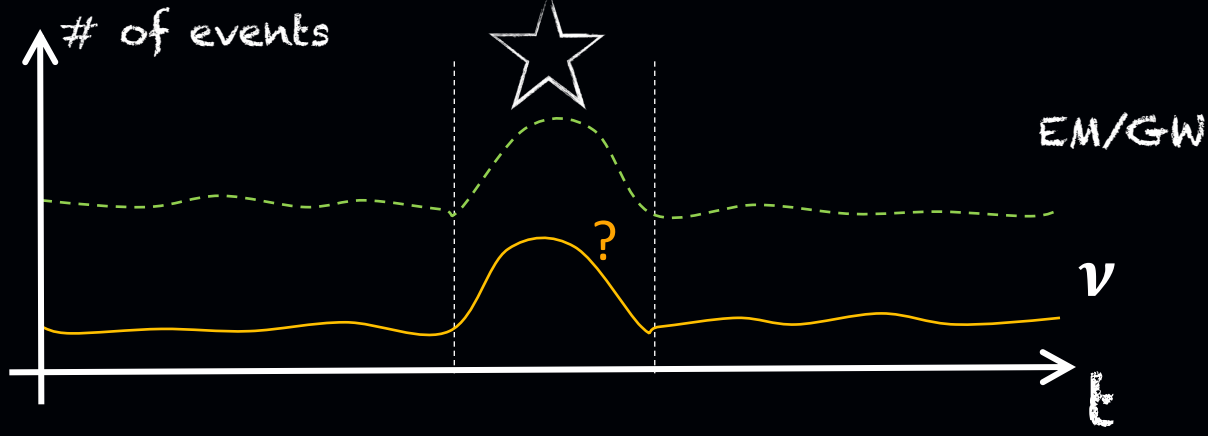
- Follow-up searches of O3 events with 4 and 6 DUs
- Getting ready for O4 real-time follow-up searches

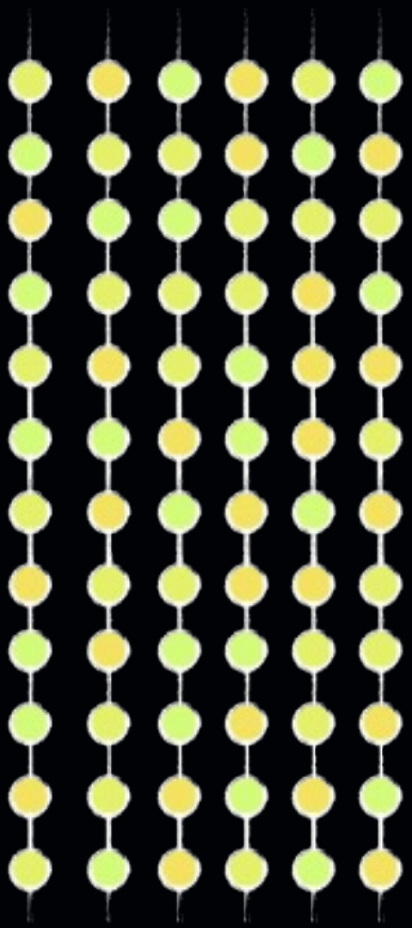


See Neutrino2022 contribution P367



See I. Goos' talk





- No single event reconstruction possible
- Search for a transient increase in the overall detector rate
- Triangulation for source localization
- Estimate of the mean energy

Gravitational wave follow-ups

- First GCN sent by KM3NeT during LVC O3!

- Follow-up searches of O3 events withx 4 and 6 DUs

TITLE: GCN CIRCULAR
NUMBER: 26751
SUBJECT: LIGO/Virgo S200114f: Constraints on a CCSN origin from KM3NeT MeV neutrino search.
DATE: 20/01/14 22:22:57 GMT
FROM: Alexis Coleiro at APC/U. Paris Diderot <coleiro@apc.in2p3.fr>

M. Colomer (APC, Universite de Paris), M. Lincetto (Aix Marseille Univ, CNRS/IN2P3, CPPM), A. Coleiro (APC, Universite de Paris), D. Dornic (Aix Marseille Univ, CNRS/IN2P3, CPPM), V. Kulikovskiy (INFN - Sezione di Genova), report on behalf of the KM3NeT Collaboration:

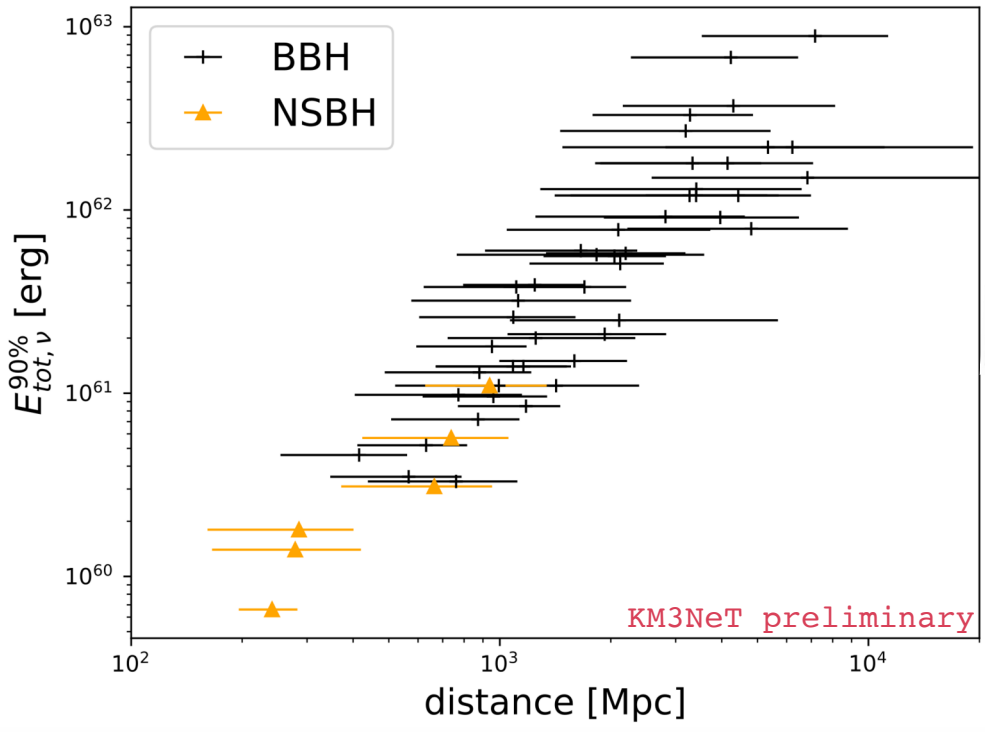
Using online data from the KM3NeT ORCA detector, we have performed a follow-up analysis of the recently reported gravitational-wave (GW) burst candidate S200114f (GCN #26734) to investigate the possibility that this burst was emitted by a core-collapse supernova (CCSN) event.

KM3NeT can detect ~10 MeV neutrinos from a Galactic CCSN through a collective rise of the photomultiplier (PMT) detection rates on top of the noise, due to the Cherenkov light produced by the interaction of electron antineutrinos through inverse beta decay. This is expected mostly during the CCSN accretion phase (lasting a few hundred ms) where most of the electron antineutrinos are supposed to be emitted [1].

Two events were observed with the CCSN trigger in the KM3NeT/ORCA online infrastructure during a 400 ms time-window starting at the time of the GW trigger while 1.4 events are expected on average from the background at trigger time (p-value = 40.1%). KM3NeT/ARCA, due to a programmed upgrade of the on-shore station in Capo Passero, is off temporarily.

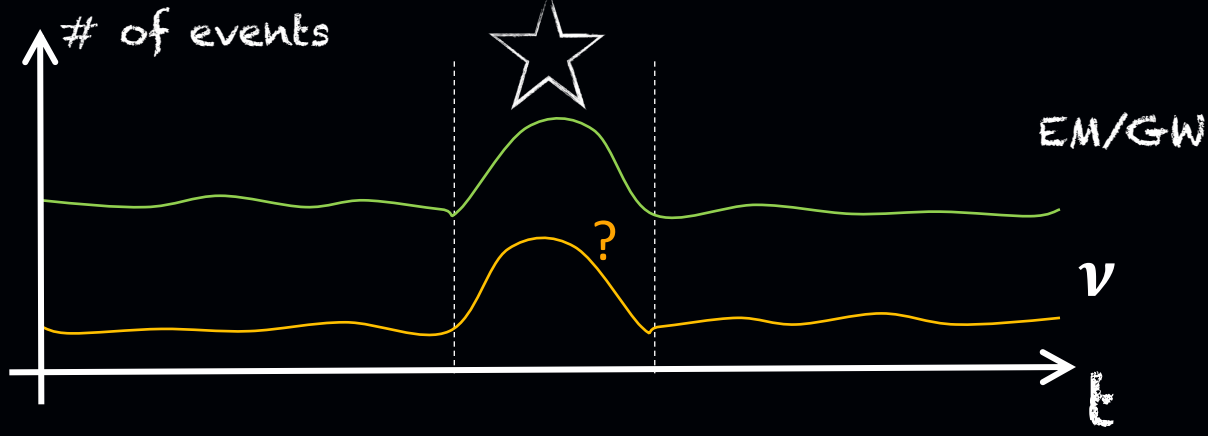
Using the Feldman and Cousins approach, a 90% confidence level upper limit on the number of signal events is estimated. Assuming two progenitor models from the Garching group [2] with masses of 27 Msun and 11.2 Msun, we derive a lower limit on the distance of the potential source of 11.5 kpc and 6.1 kpc respectively.

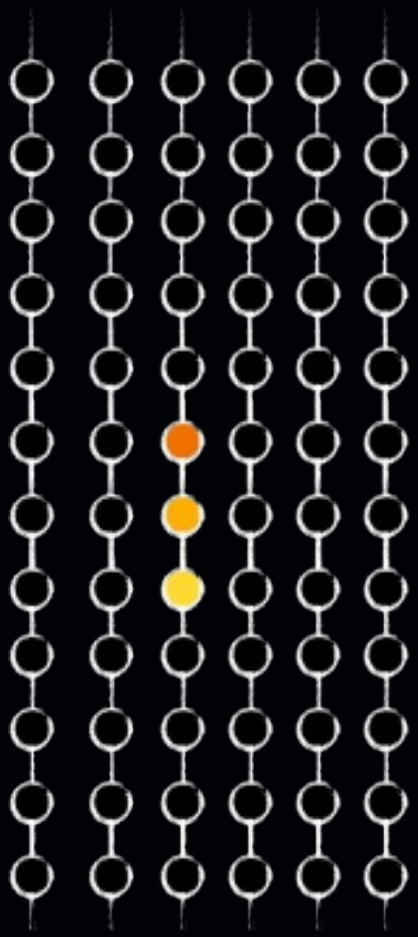
Moreover, assuming a quasi-thermal neutrino spectrum as in [2] with a spectral pinching parameter value of 3 and a mean neutrino energy of 15 MeV and assuming that 70% of the energy is released in the 400 ms, we estimate the total energy emitted into neutrinos from this GW burst candidate to be E < 2.9e53 erg at 10 kpc.



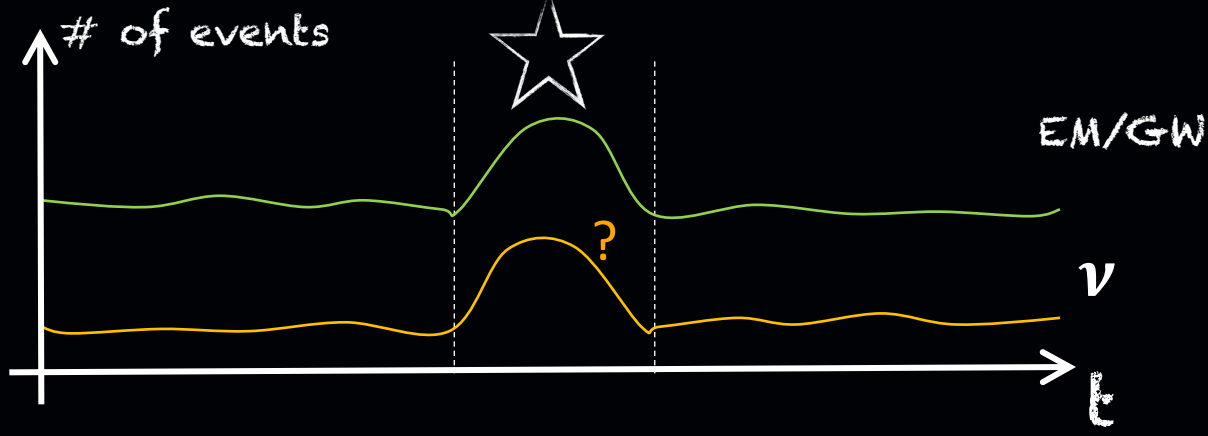
See Neutrino2022 contribution P367

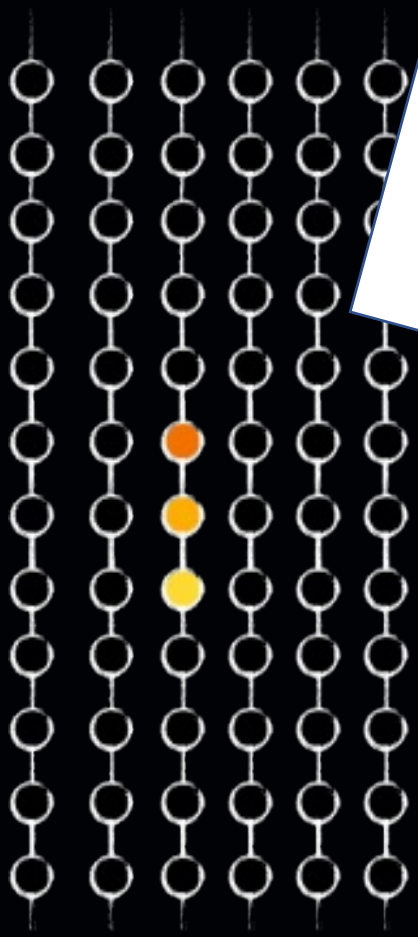
https://gcn.gsfc.nasa.gov/gcn3/26751.gcn3





- Neutrino interactions trigger data taking
- No angular reconstruction possible at the moment
- Search for an increase in the rate during the astrophysical transient





ino interactions trigger data taking

ible at the moment

KM3NeT has the same potential!

- Search for an increase in the rate during the astrophysical transient

Feasible in KM3NeT?

Dominant background in this energy range expected to come from the environment (bioluminescence + K-40 decay)

Exploratory analysis

Can we develop new trigger conditions to save sub-GeV neutrinos?

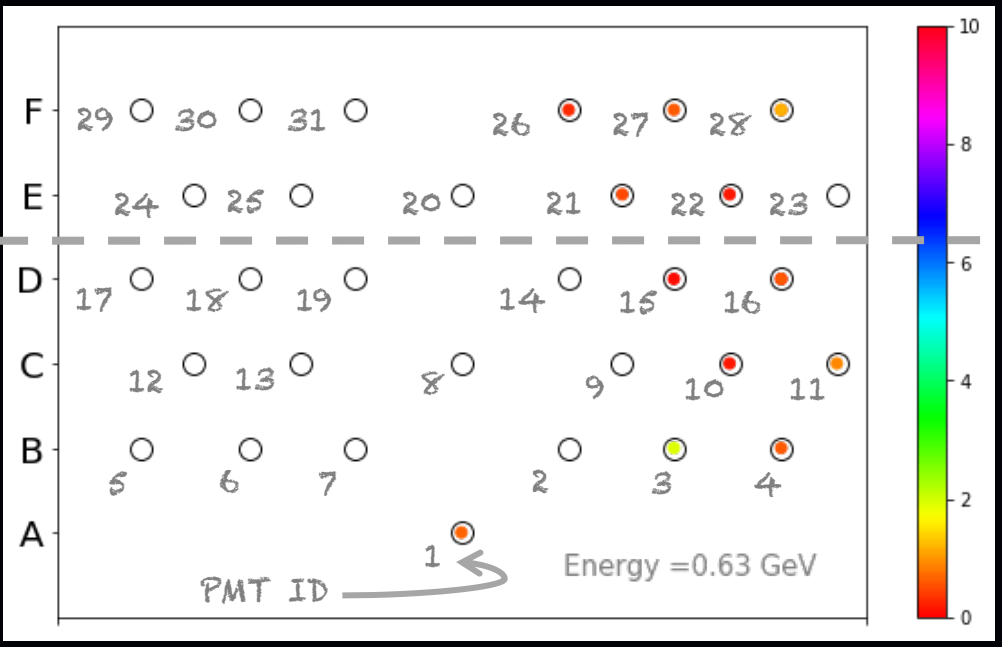
Need to characterize the environment signature to disentangle it from GeV neutrino signature

https://www.zooniverse.org/projects/reinforce/deep-sea-explorers

REINFORCE
REsearch INfrastructures FOR Citizens in Europe

List of original variables

Unfolded DOM



Number of hits in EF PMTs

Number of hits on the DOM

Mean PMT ID on the DOM

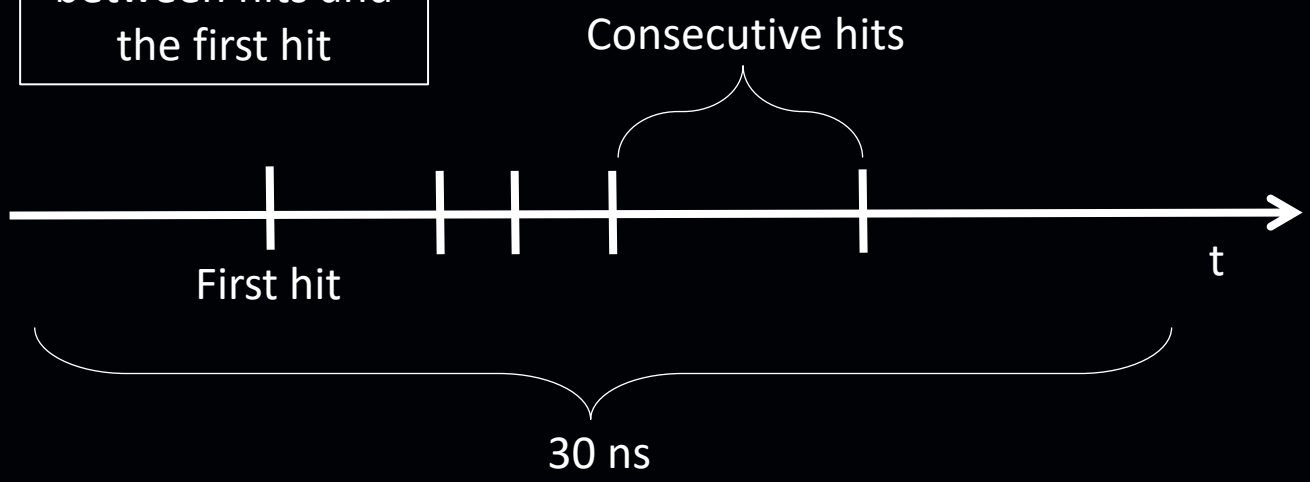
Number of hits in ABCD PMTs

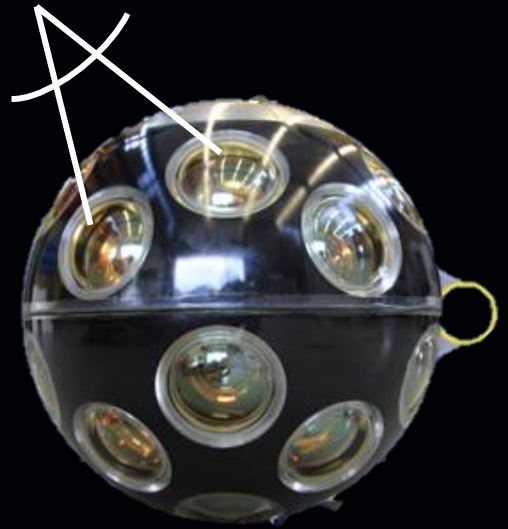
Total *time over threshold* on the DOM

Mean + std of PMT IDs between consecutive hits

Mean + std of angle between consecutive hits

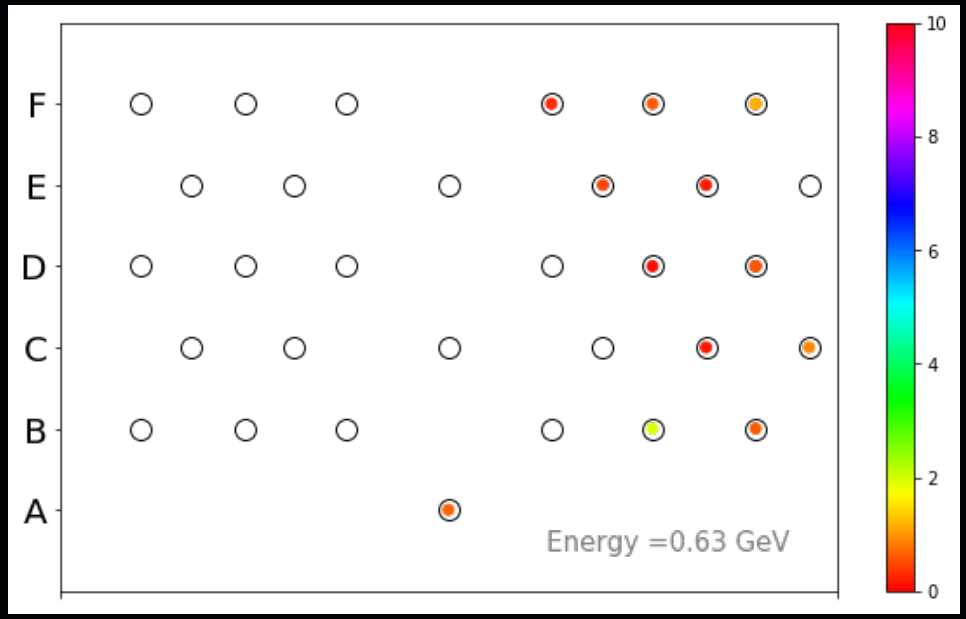
Mean + std delay between hits and the first hit





Chosen approach

Unfolded DOM

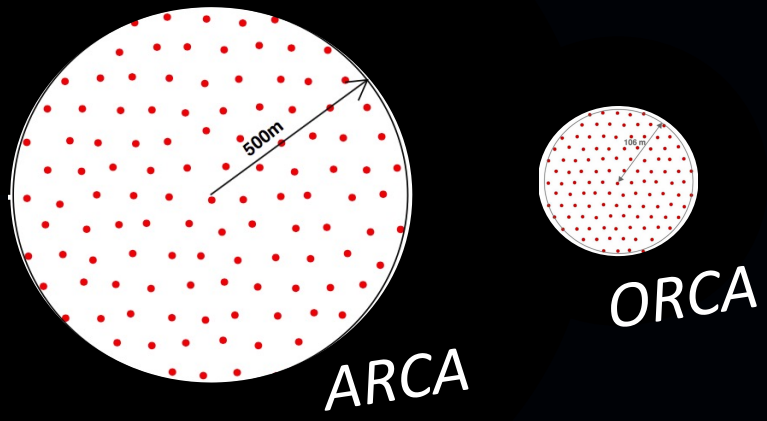


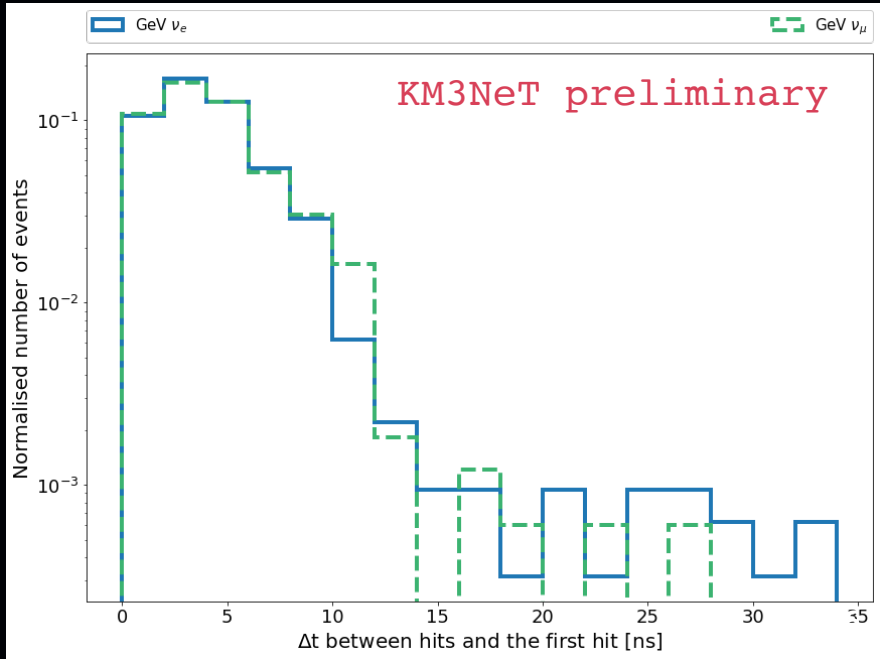
[Single DOM analysis]

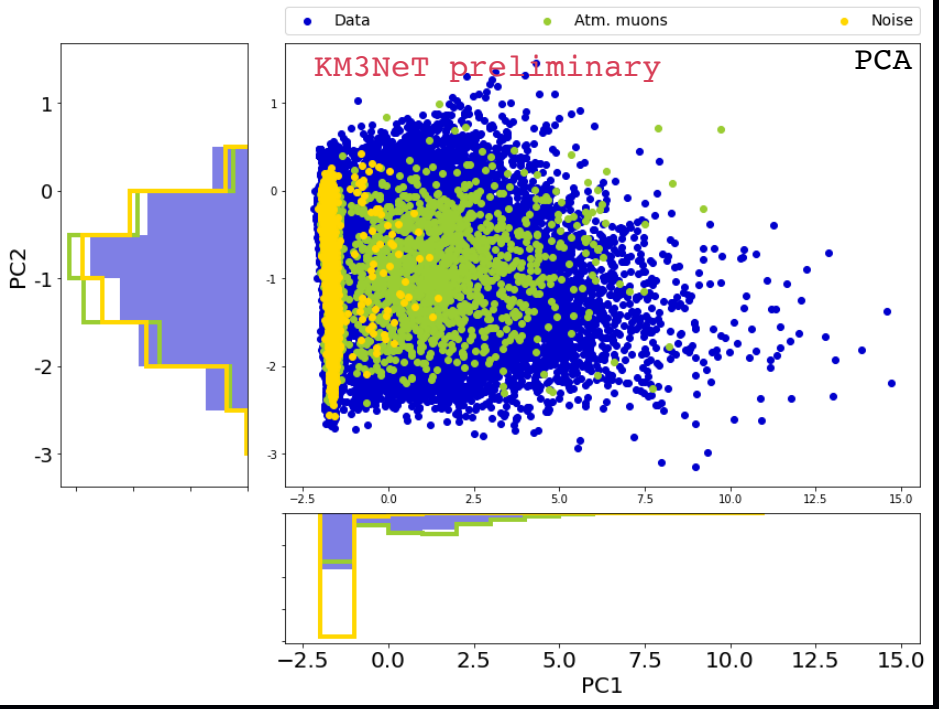
→ Search for specific pattern (t,x,y,z) in multi-PMT DOMs in minimum bias data

Focus on 30 ns time window

Developed to be applied to ARCA and ORCA data







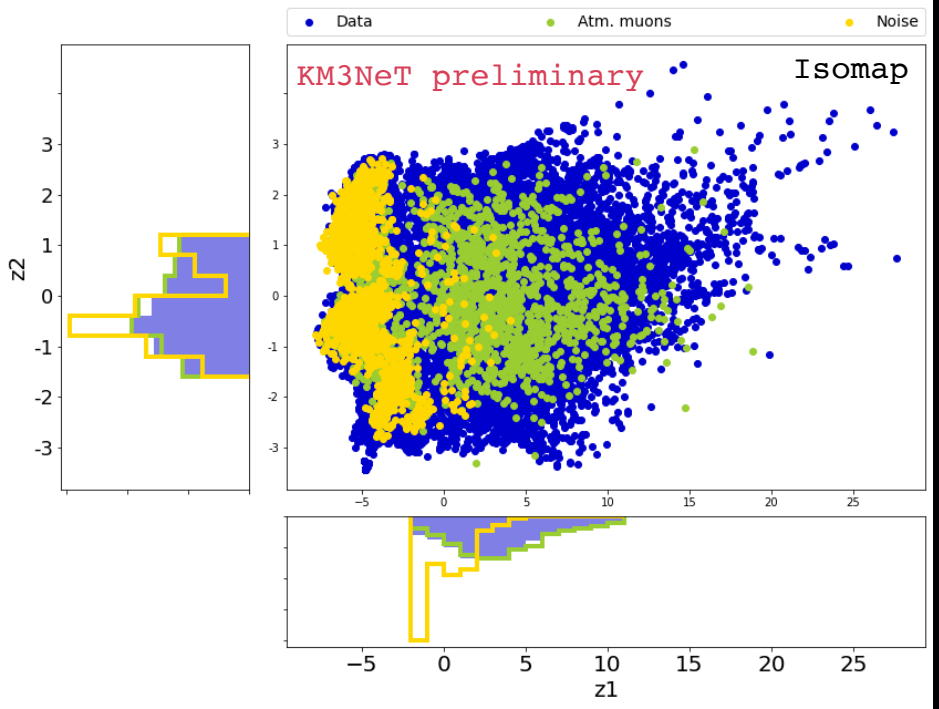
Do we have a good data/MC agreement?

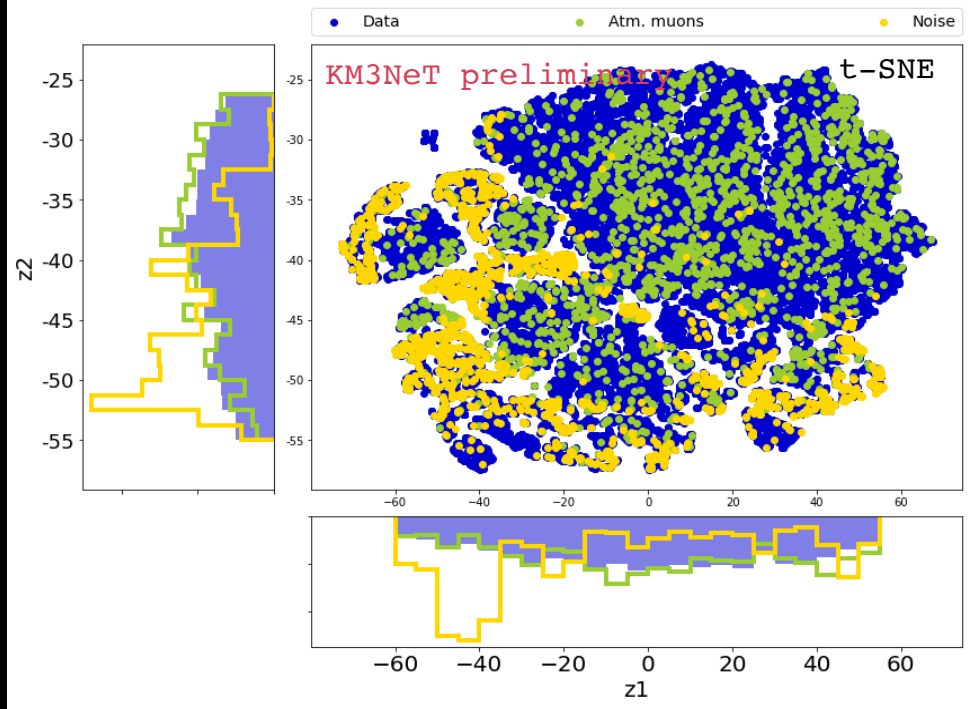
Data

Atm.μ

Noise

We also have a very good data/MC

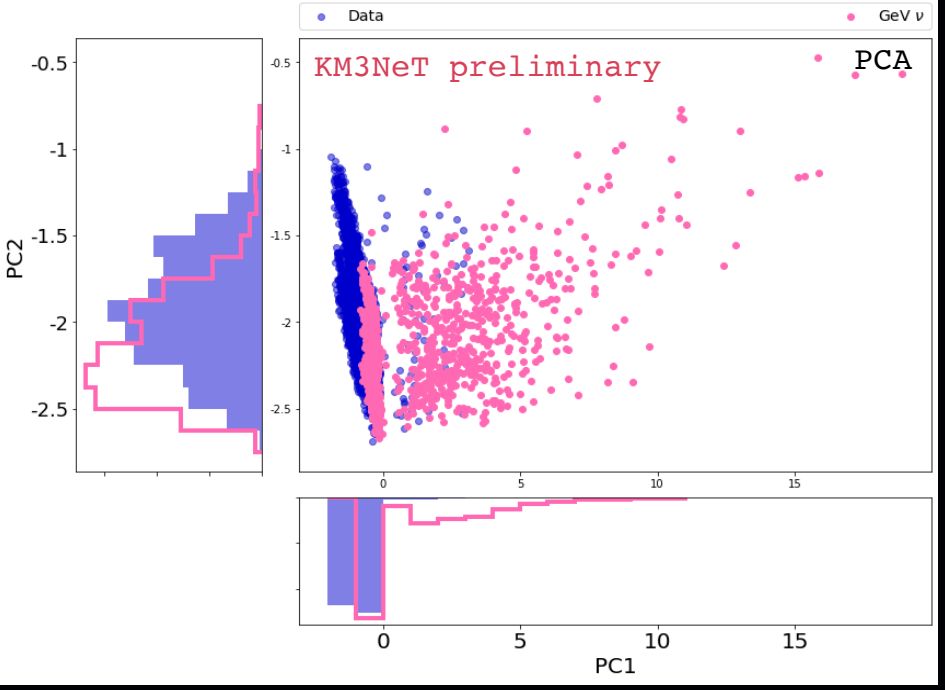


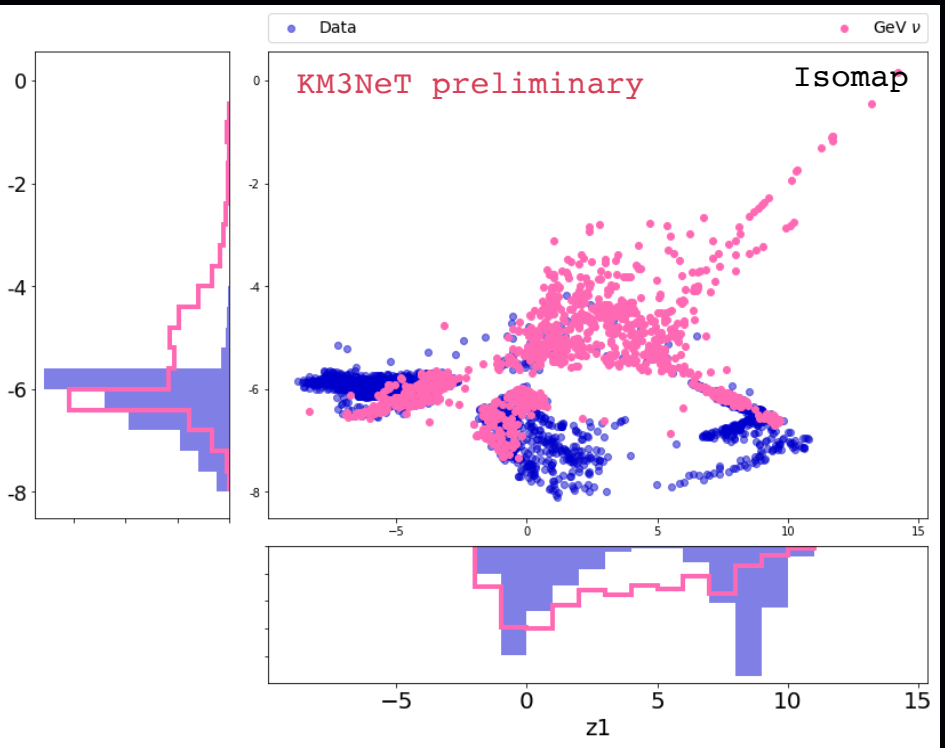


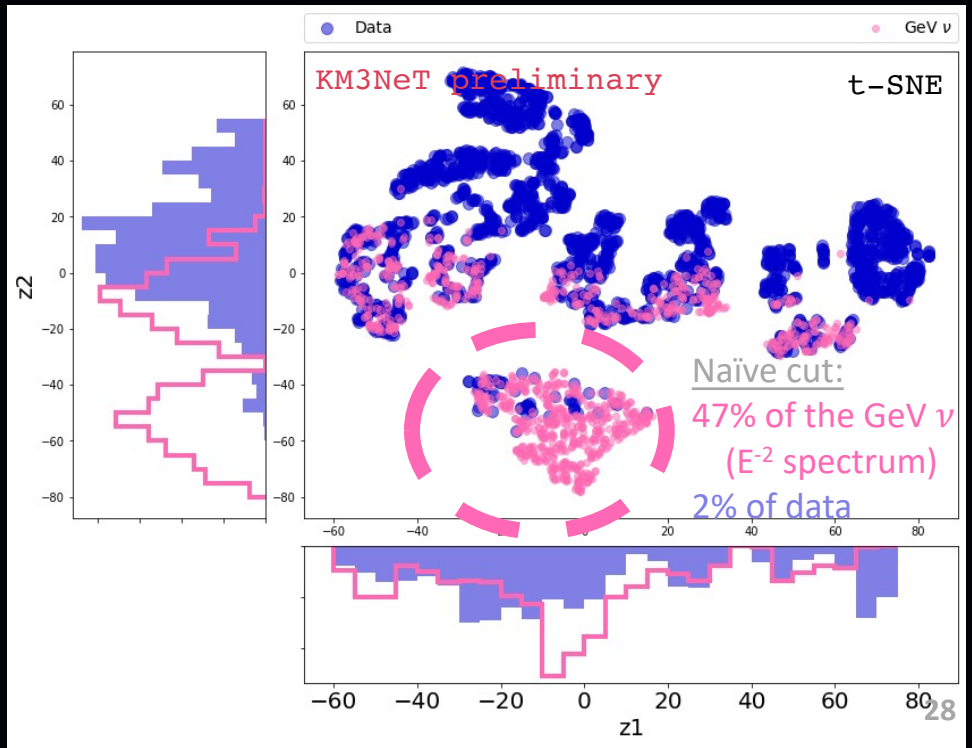
Can we extract GeV neutrinos?

Data

GeV neutrinos







Take-home message

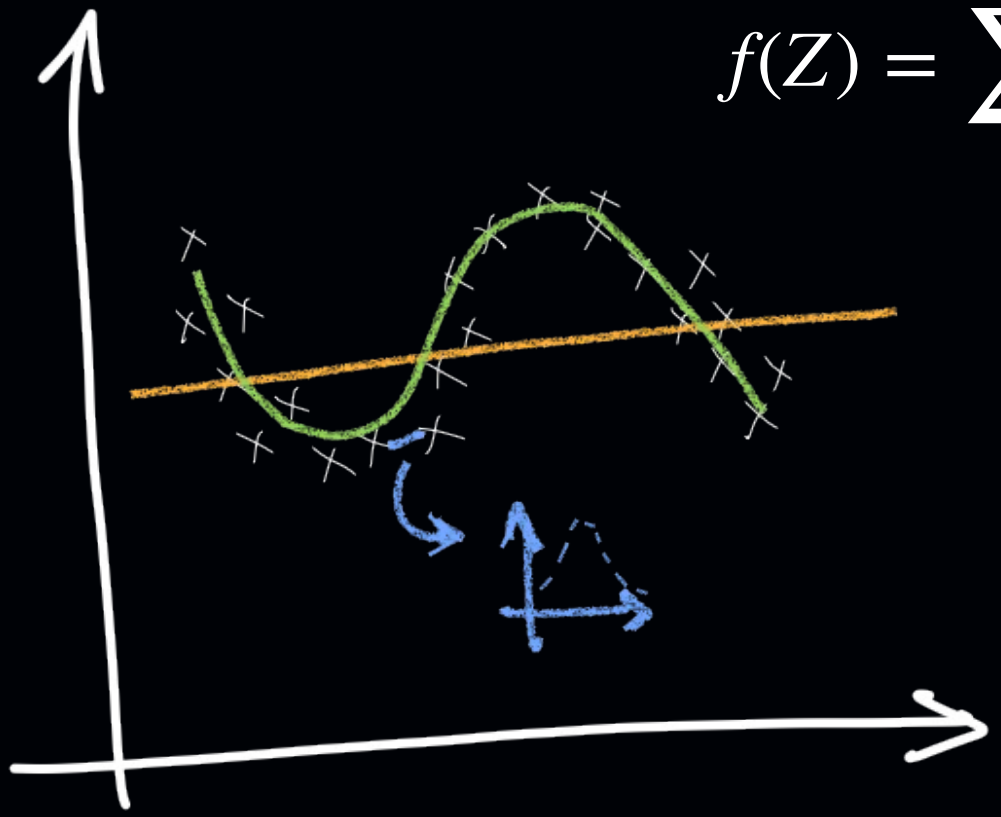
- KM3NeT can probe astrophysical neutrino emission over almost 10 orders of magnitude in energy
- We are sensitive (and have already results!) in the sub-TeV range
- Running analyses in the MeV and >5 GeV range
- Ongoing efforts to cover the energy gap

Every additional DOM in the sea is enhancing our sensitivity

Construction of new variables

- Principal Component Analysis (PCA)
- Isomap
- Stochastic neighbor embedding method (t-SNE)

$$f(Z) = \sum_i \sum_j d_3(d_2(z_i, z_j) - d_1(x_i, x_j))$$

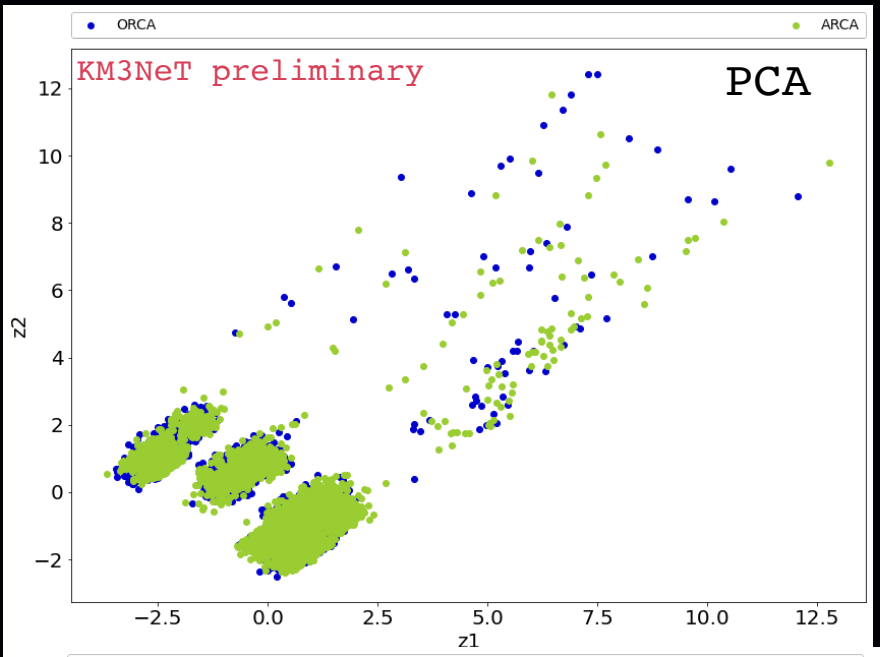


PCA

Isomap

t-SNE

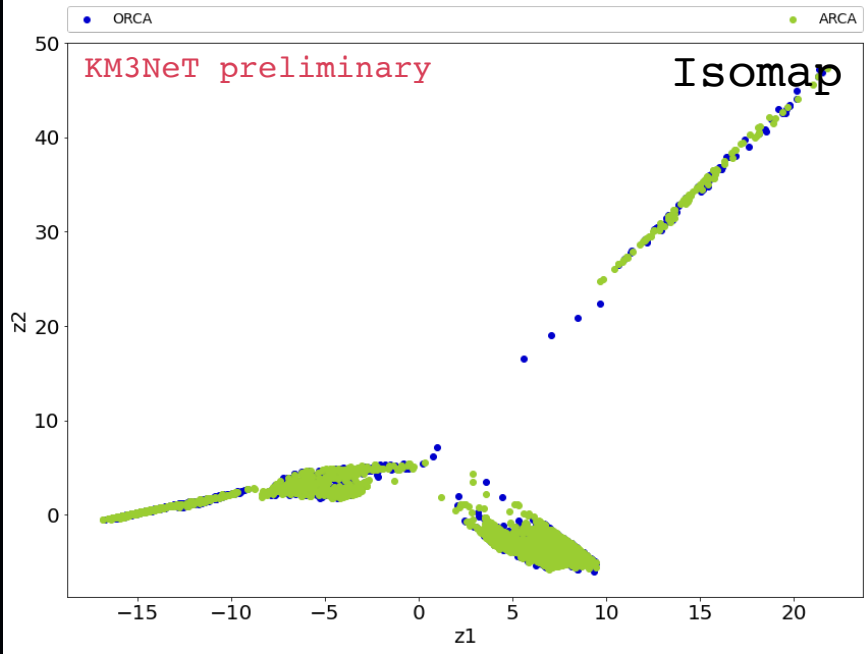
Are the new variables sensitive to ORCA/ARCA data?

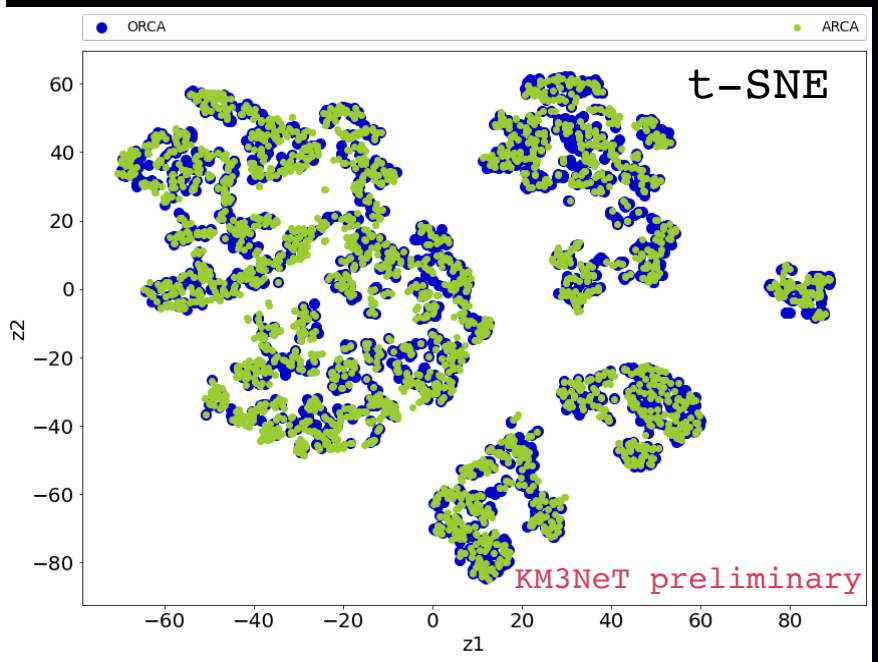


Considered detector

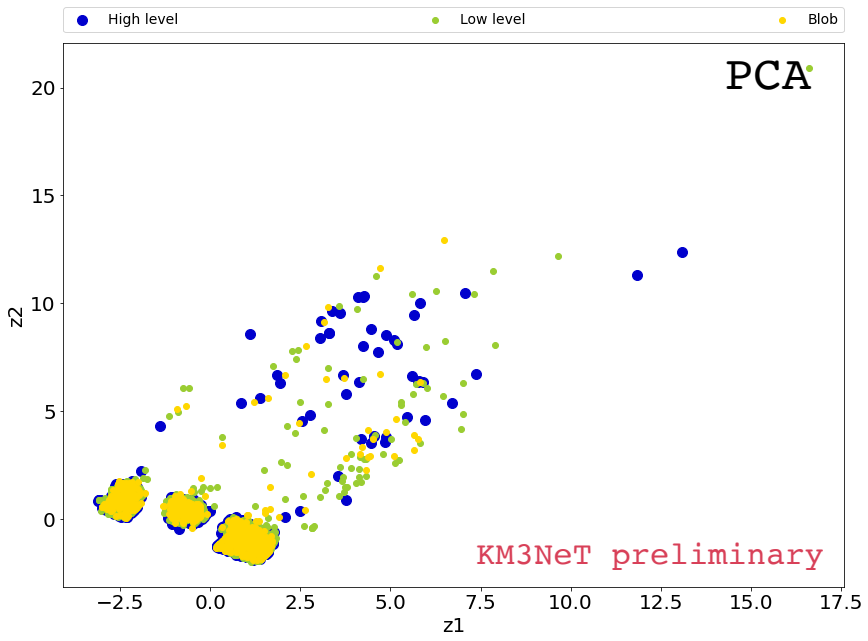
ARCA

ORCA



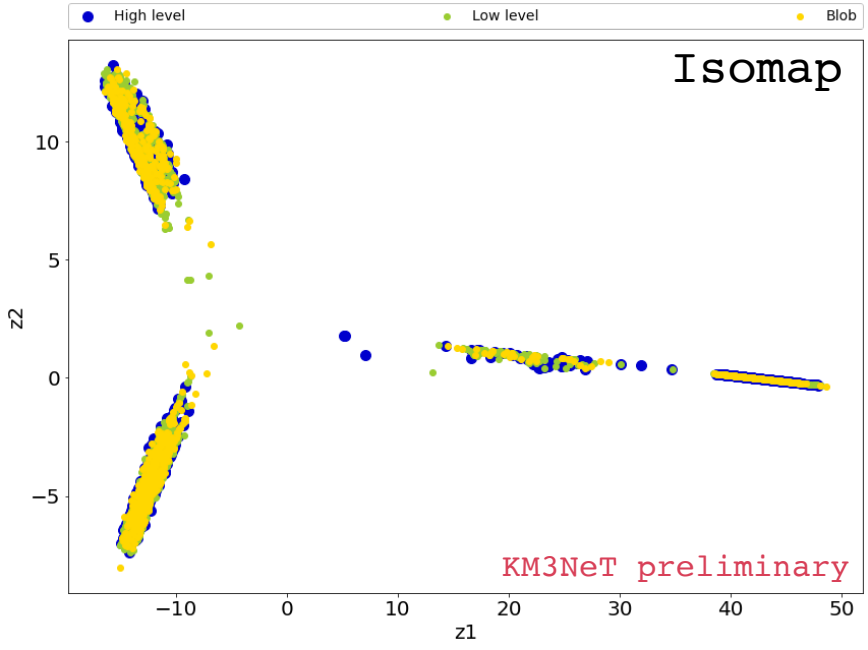


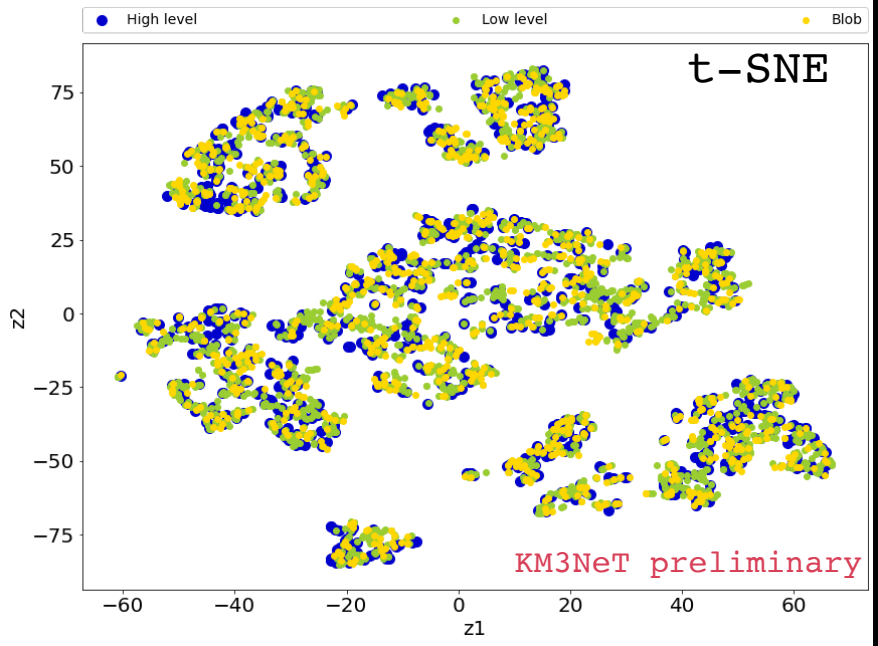
Are the variables sensitive to low/high level of activity in the detector?



Activity level in the detector

- Low
- High
- "Blob"





Do we understand the classification in terms of the original variables?