

Very Large Volume Water Cherenkov High Energy neutrino Telescopes (comment ça marche)

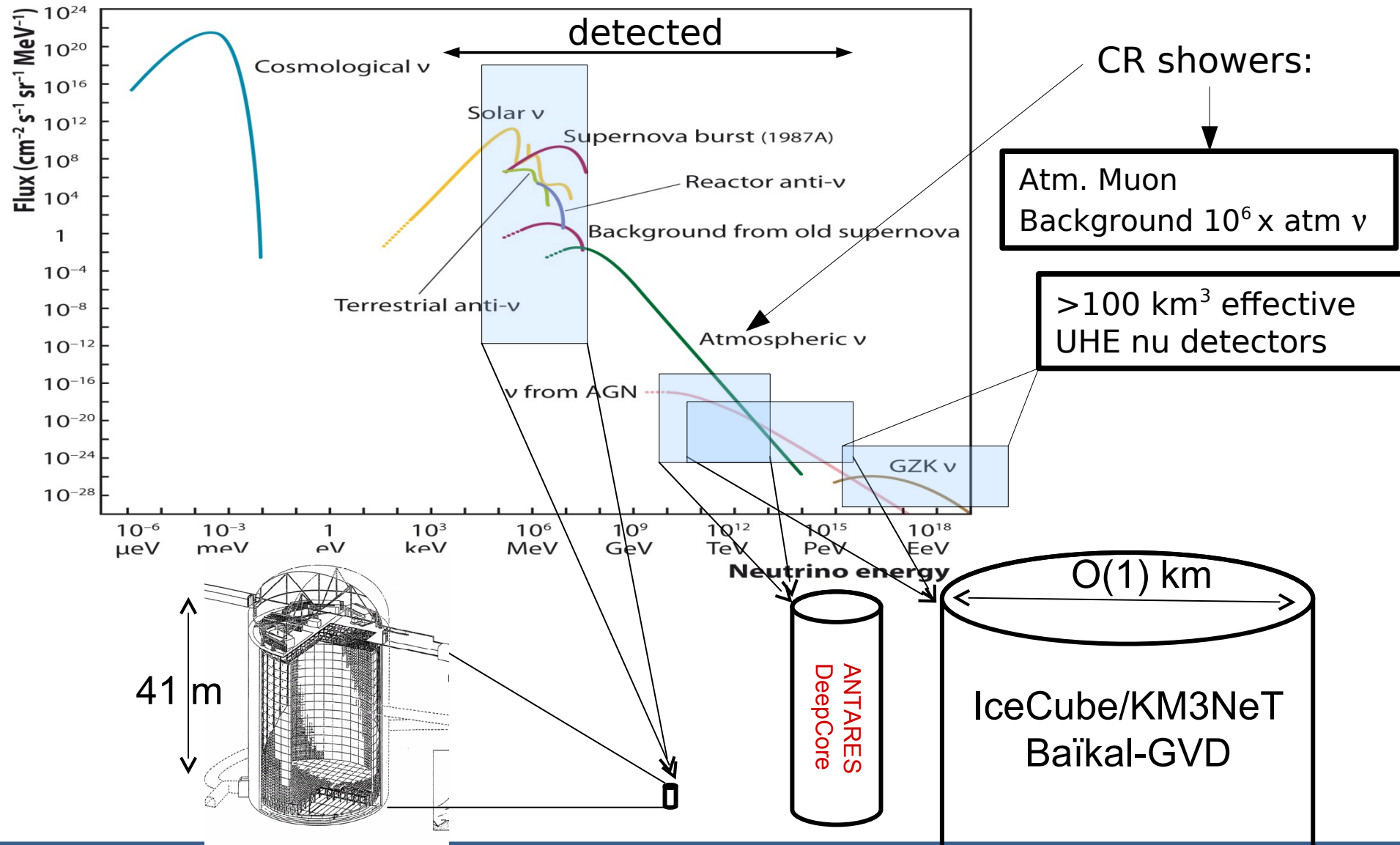
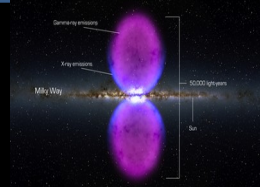
Atelier FRB

IAP Paris – 27-28 Nov 2023

Bruny Baret
Astroparticule & Cosmologie, Paris
baret@in2p3.fr

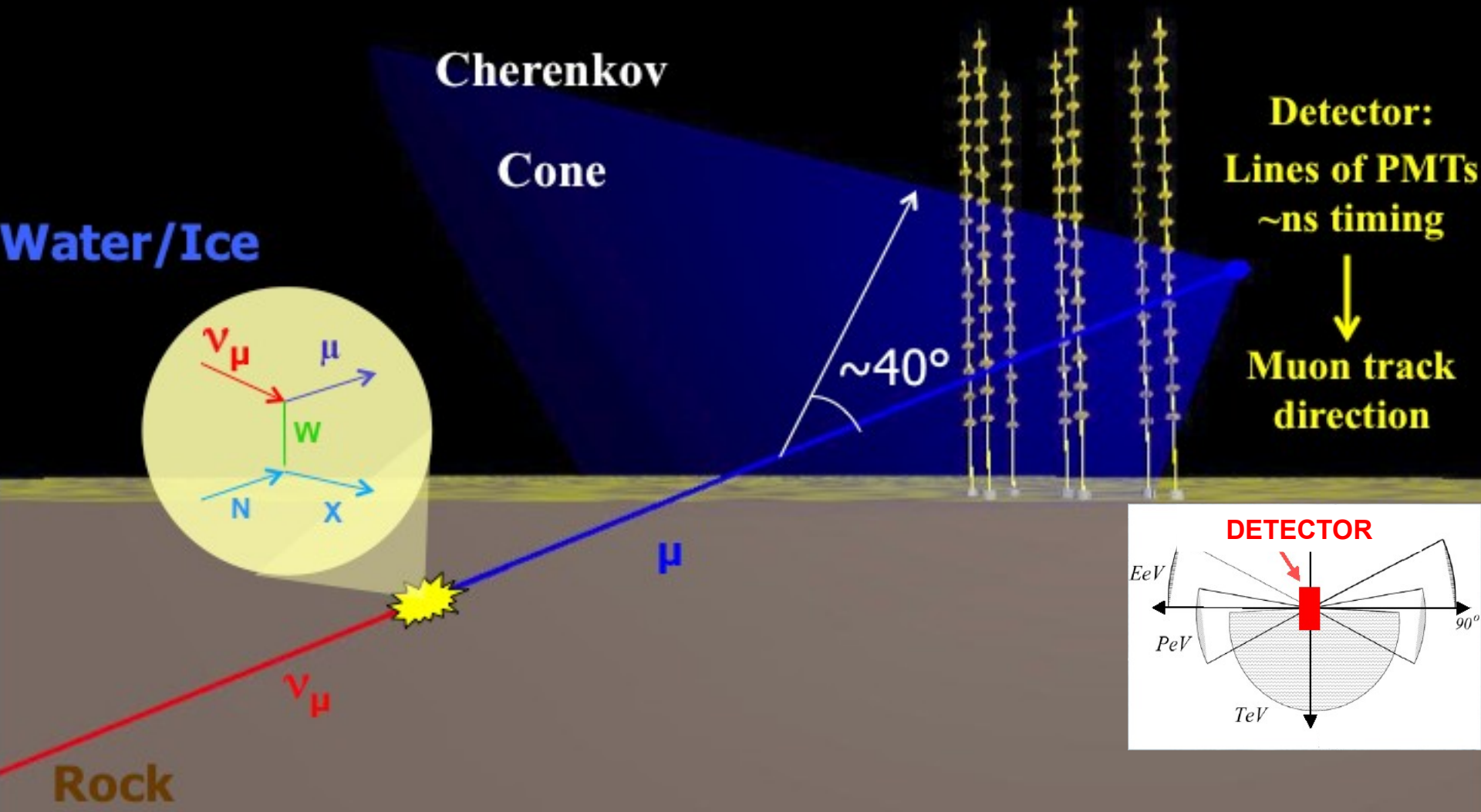
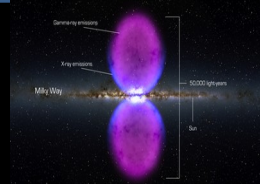


Hard to detect



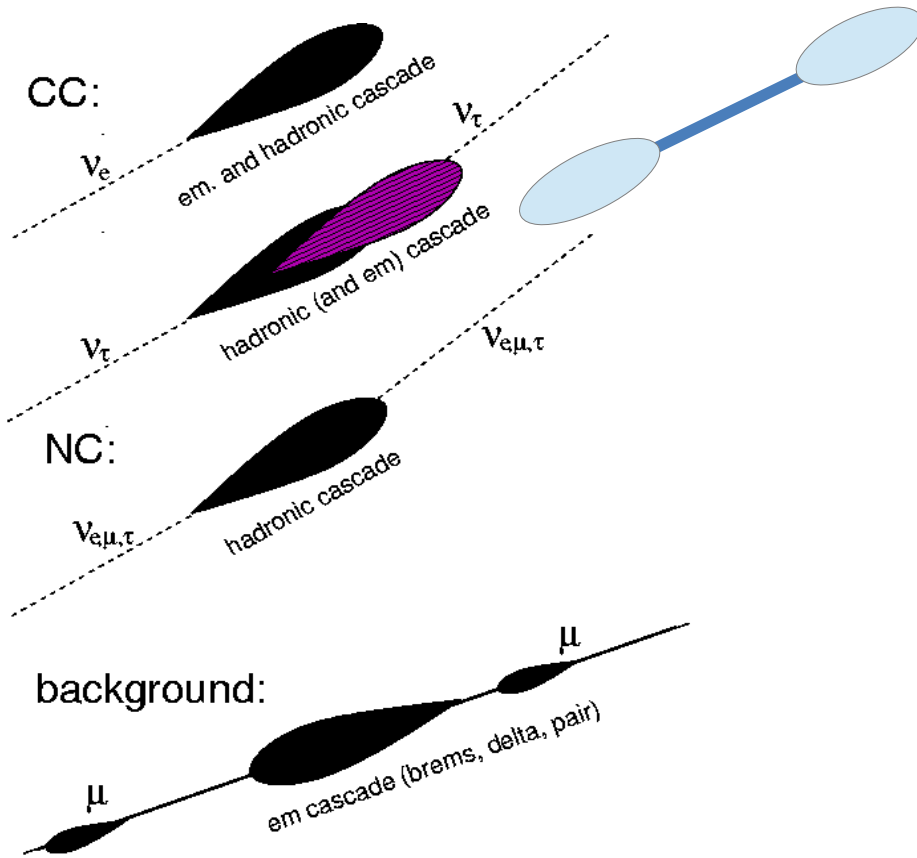
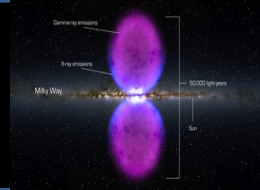


Practically – the muonic channel

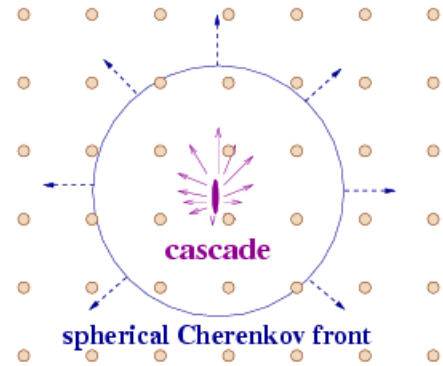




Other channels



“shower” events

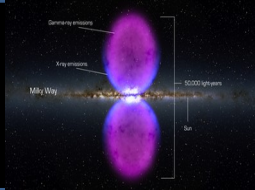


- Contained events ($\sim 10m$) topology
- + energy reconstruction
 - effective volume
 - + identification
 - angular resolution

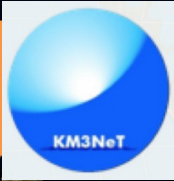
Diffuse flux (and...)



ν -Telescopes today



Antares \rightarrow KM3NeT
0.01 (\rightarrow 1) km³



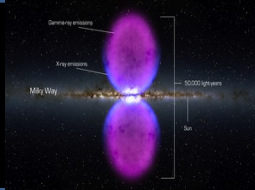
Baïkal GVD-1
0.5 km³



IceCube
1 km³



ν -Telescopes tomorrow (or the day after or...)



KM3NeT phase 3
1- \rightarrow 5 km³



Baïkal GVD
 \sim 1.5+ km³



IceCube Gen2
10km³

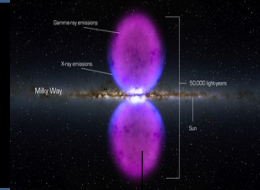


TRIDENT
7.5 km³

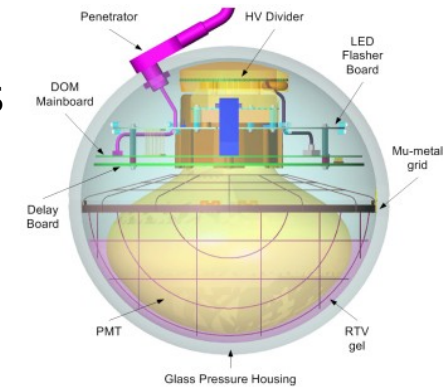
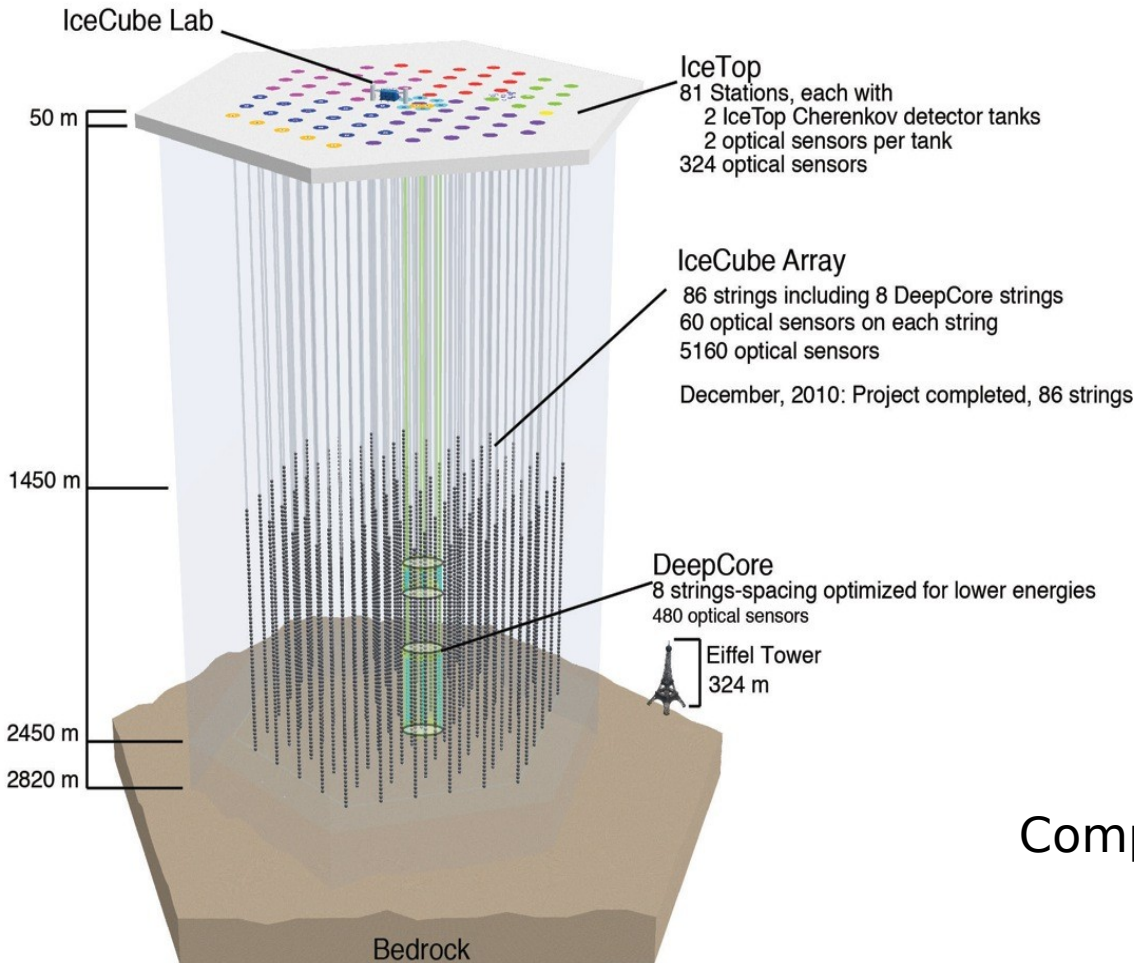
P-ONE
 \sim 1 km³



IceCube



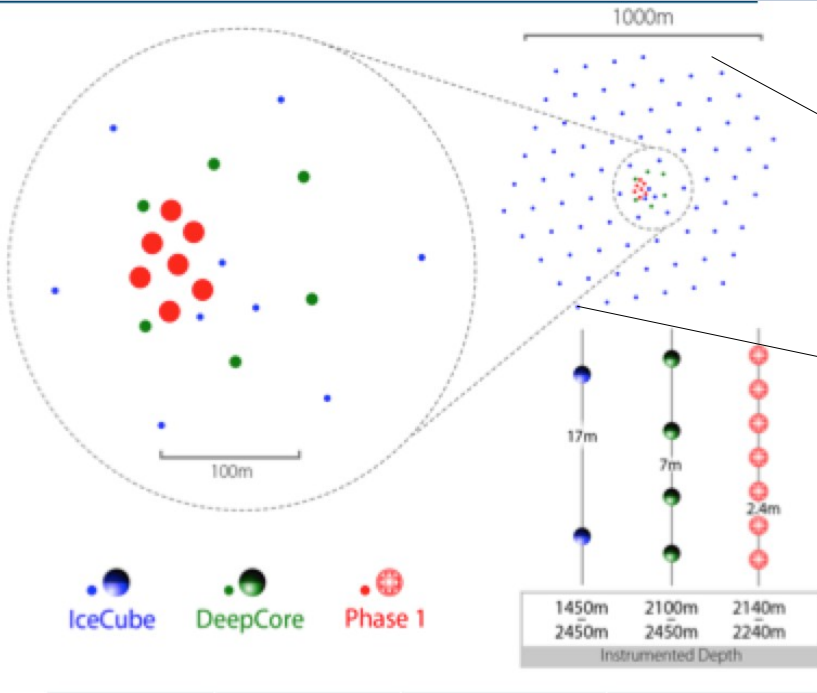
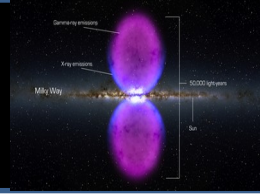
10" PMTs Digitized Waveforms



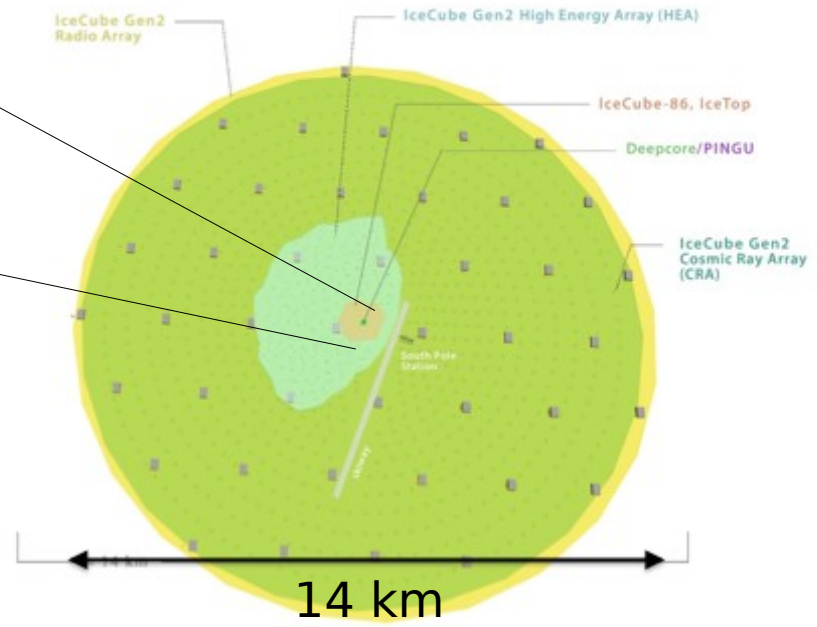
Complete since Dec. 2010



IceCube GEN 2



The IceCube Gen2 Facility



mDOM



Inspired by KM3NeT
 24x3" PMTs
 Borosilicate glass
 Baseline design

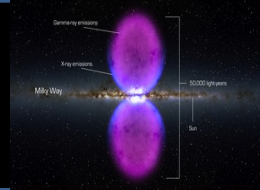
D-Egg



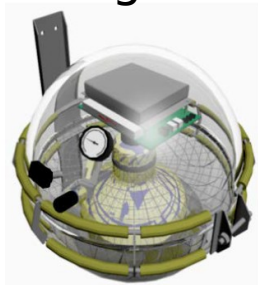
Developped by japanese groups
 2 x 8" PMTs
 UV-transparent glass



Baikal GVD

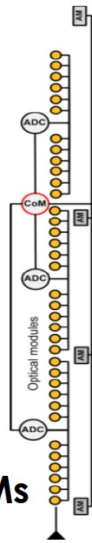


10" PMTs
digitized charge

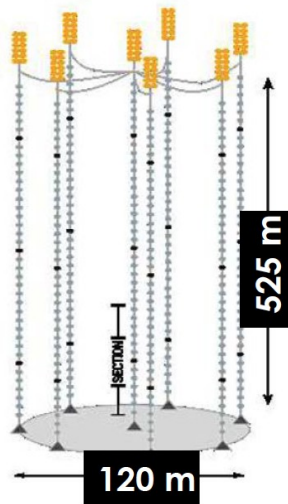


Optical module

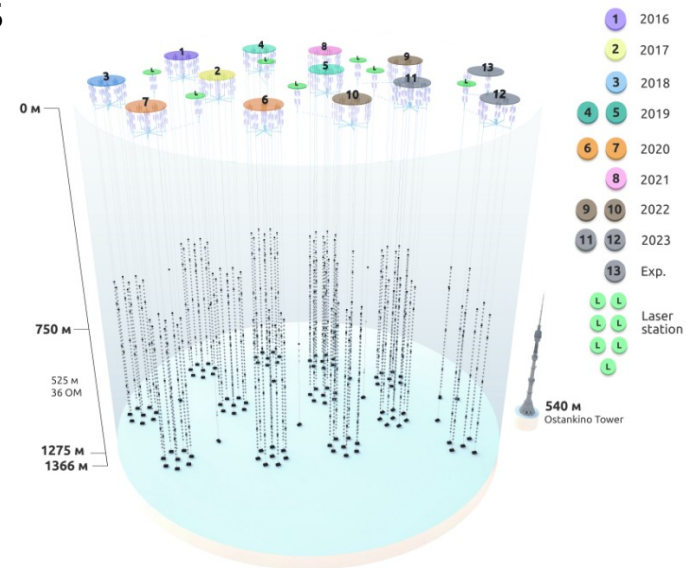
String: 36 OMs



today: 12 clusters



Cluster: 8 strings

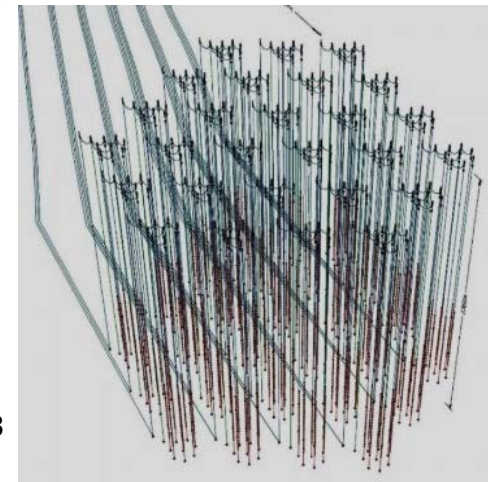


GVD-1: 8 clusters

1-2 clusters deployment per season (winter)

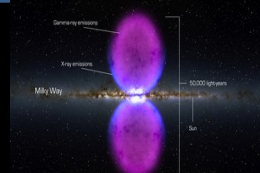


Final goal:
27 clusters: 1.5 km³





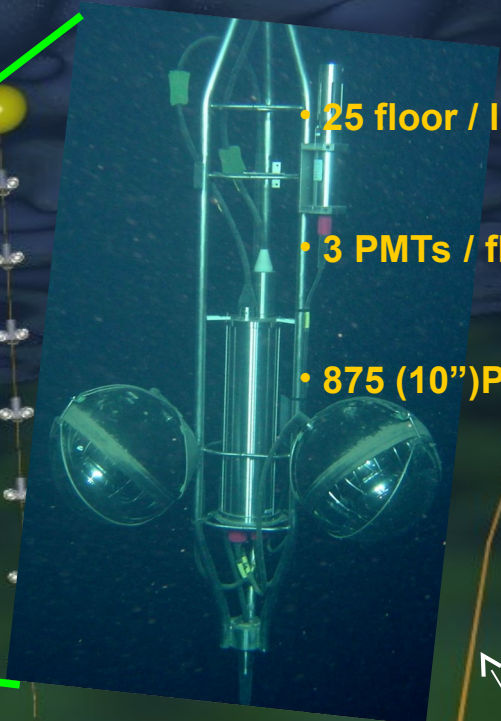
ANTARES



Complete since June 2008
Unplugged on Feb 2022

350 m
100 m
~70 m

14.5 m



- 12 lines
- 25 floor / line
- 3 PMTs / floor
- 875 (10") PMTs

40 km from coast

Junction box

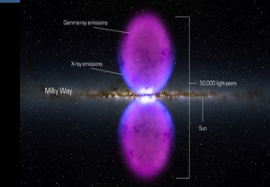
Anchor/line socket

Interlink cables

-2450m

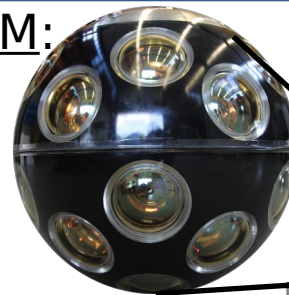


KM3NeT ARCA & ORCA



1 block=115 D.U.

Multi-PMT DOM:
31 x3" pmts
ToT



N CENT IOPART

~ 600 m

102 m

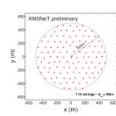
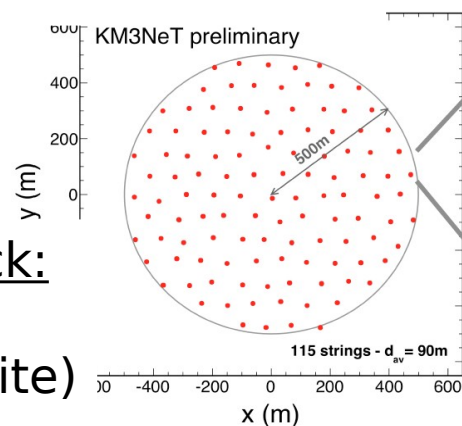
ICRC 2015

ARCA Block:

-3200m
90m/36m v./h. Spacing
TeV-PeV

ORCA block:

-2450m
(Antares site)
20m/9m v./h. Spacing
GeV+



Phase-1:
24 ARCA DUs
6 ORCA DU

Phase-2:
2 ARCA blocks
1 ORCA block

Phase-3:
6(+1) blocks



KM3NeT 2.0 Letter of Intent:
arXiv:1601.07459 and
J.Phys. G43 (2016) 084001



KM3NeT Status



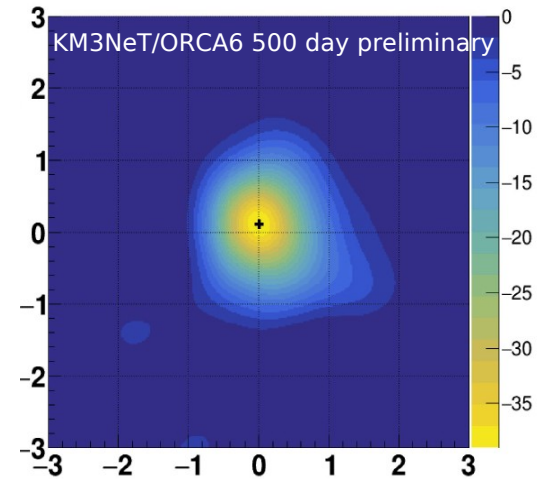
ARCA:

- 28 strings deployed

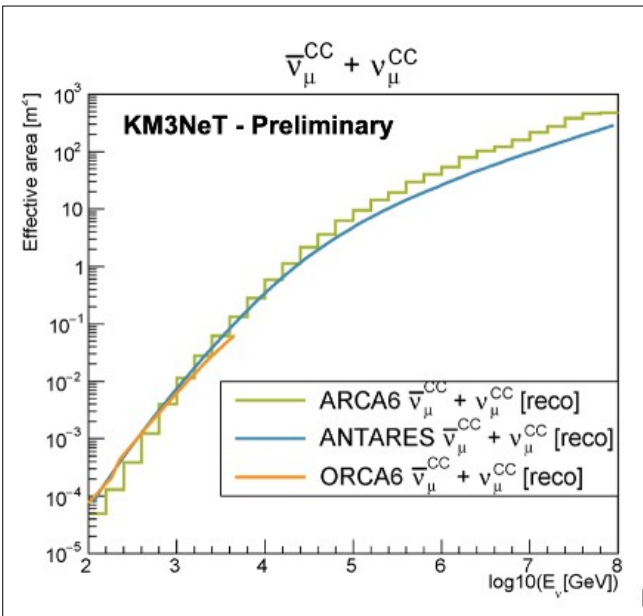
>2 x ANTARES
Photocathode area

ORCA:

- 18 strings deployed
24 soon



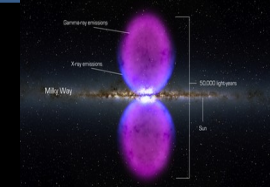
	Sun	Moon
Significance	6.0 σ	2.4 σ
Amplitude	1.42 \pm 0.38	0.70 \pm 0.29
Resolution	0.68° \pm 0.12°	0.54° \pm 0.16°



Effective area bigger than ANTARES

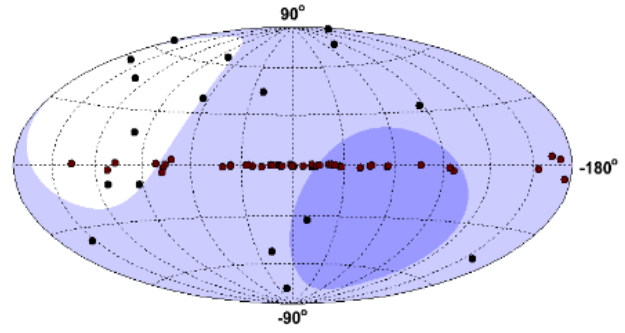
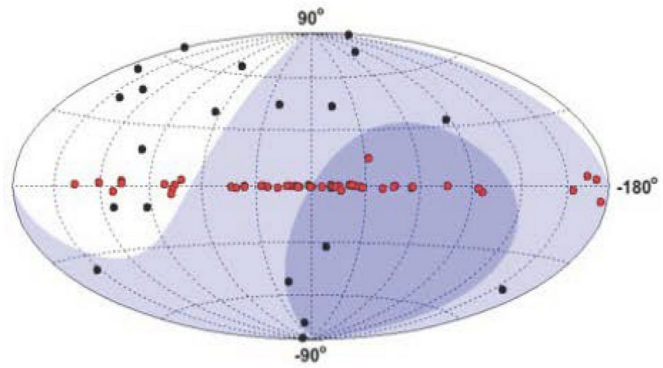


Mediterranean / South Pole



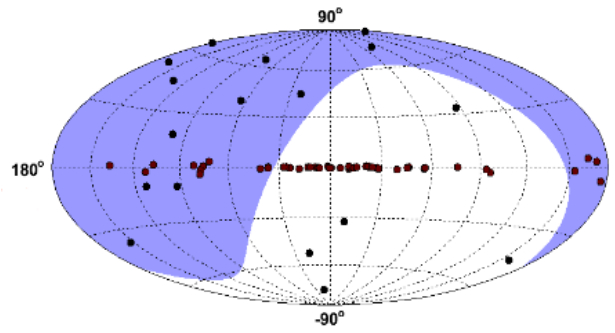
Complementary coverage (μ channel)

- Lake Baikal
- > 75%
 - 25% – 75%
 - < 25%



- KM3NeT
- > 75%
 - 25% – 75%
 - < 25%

- TeV γ -Sources
- galactic
 - extragalactic



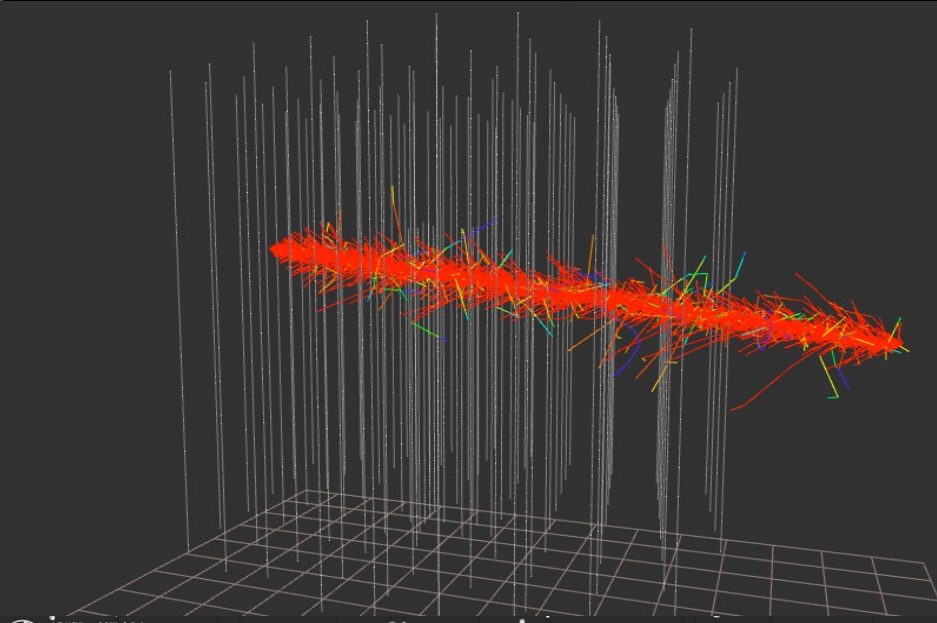
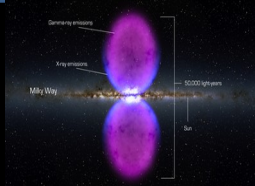
- IceCube
- 100%
 - 0%

Water v.s. Ice

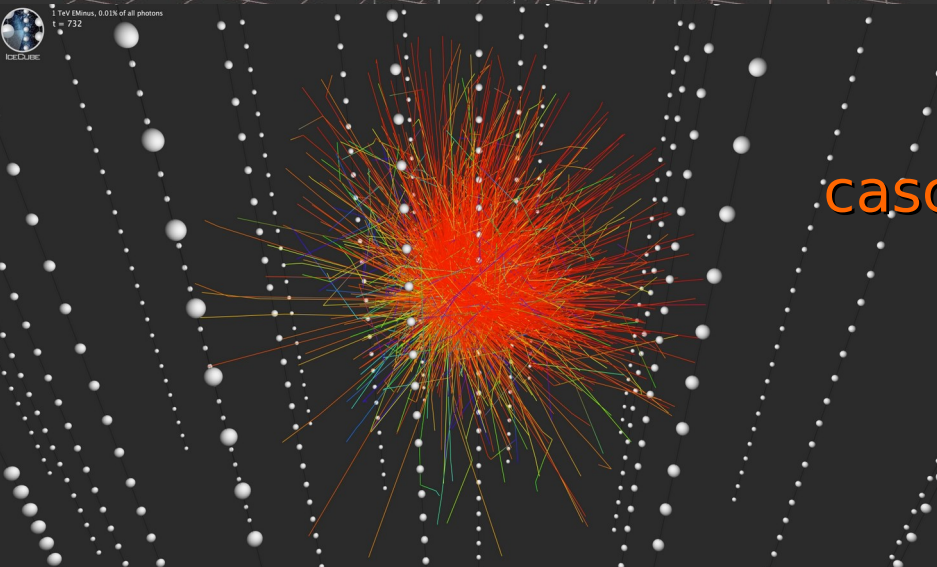
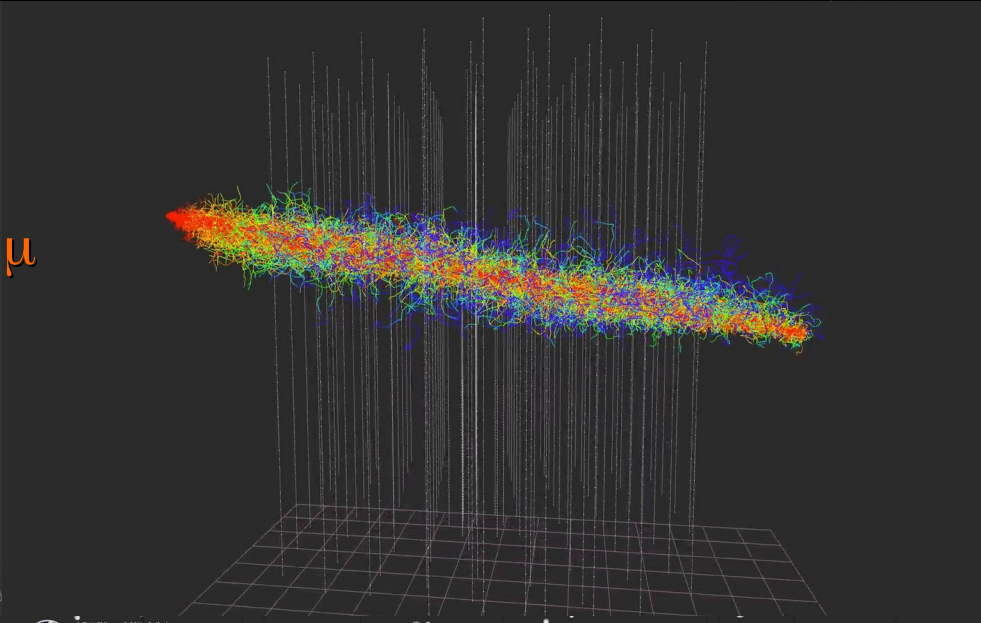
Optical noise (biolum) / no noise
 absorption / diffusion
 pointing / calorimetry



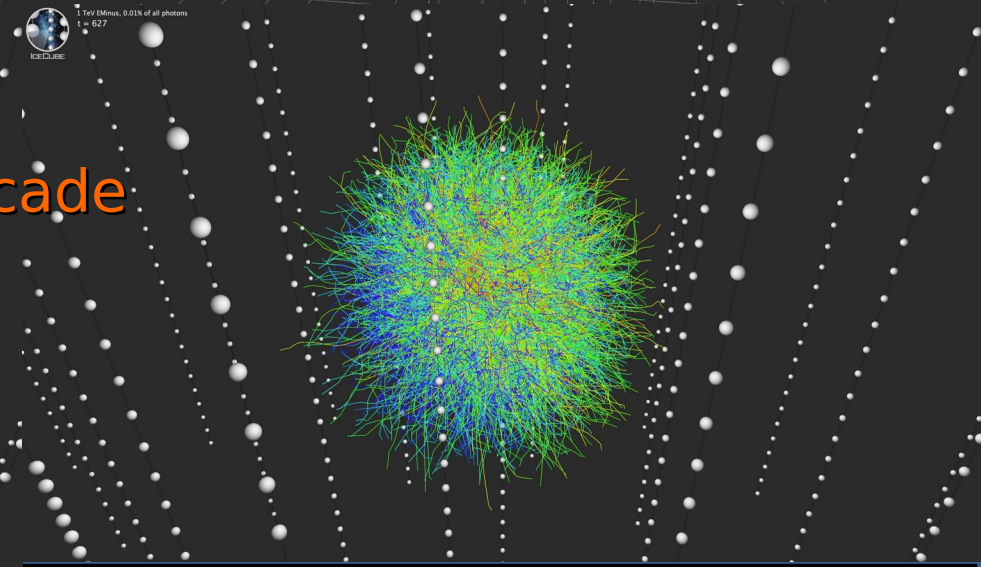
Water v.s. Ice (MC)



μ

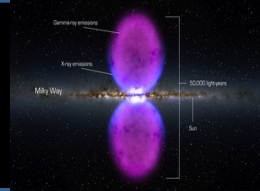


cascade

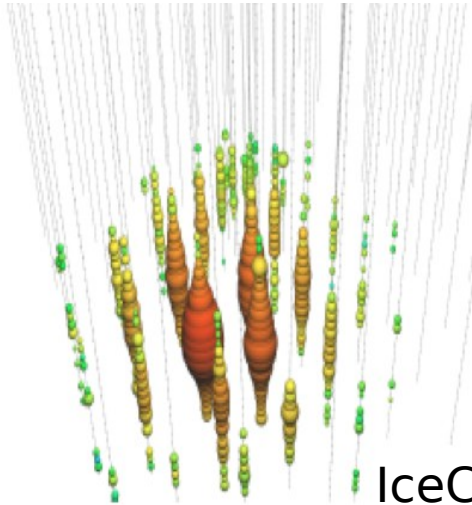




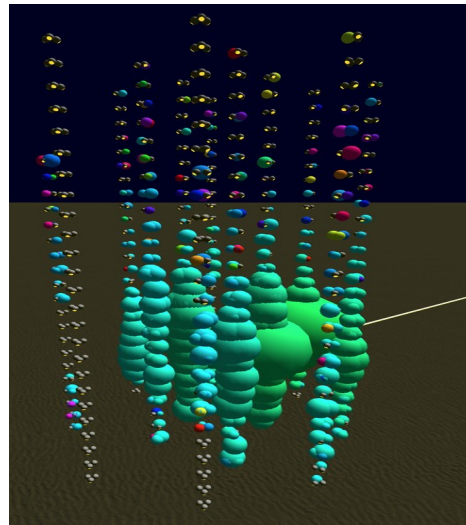
In real life



Cascades

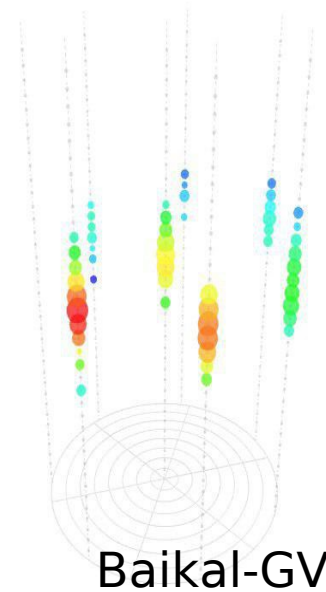


IceCube



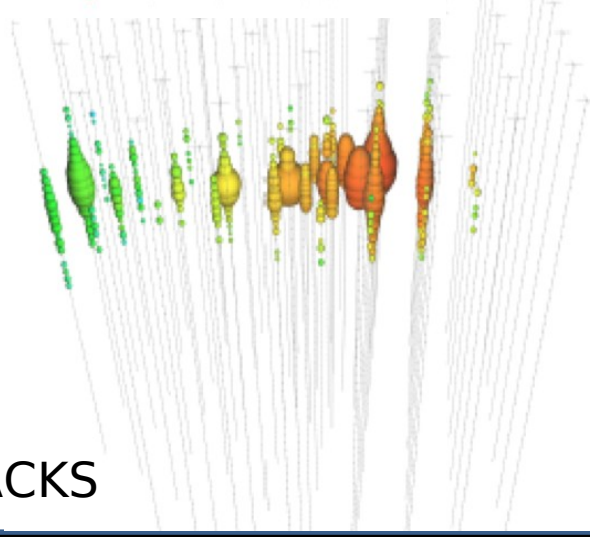
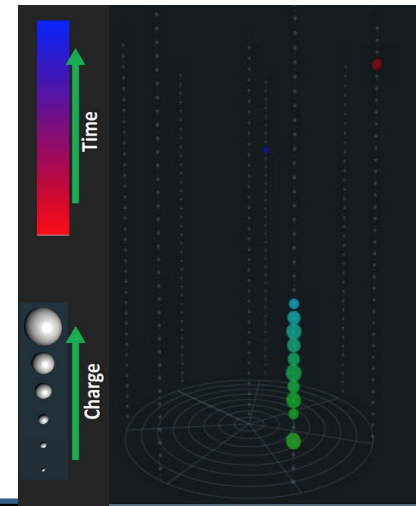
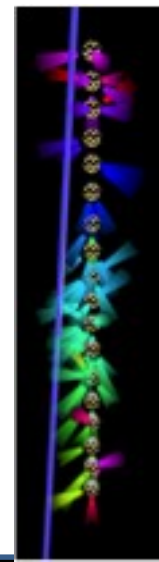
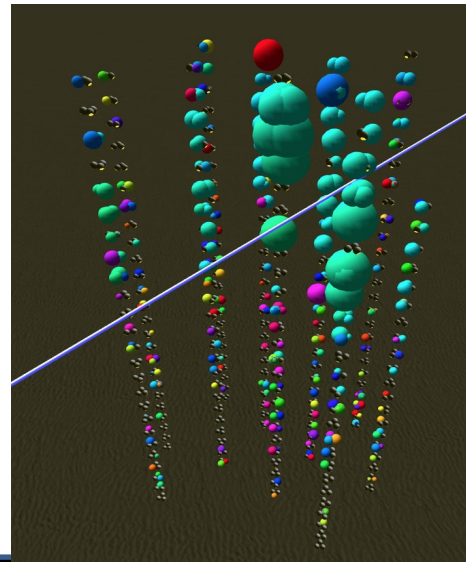
Antares

ARCA



Baikal-GVD

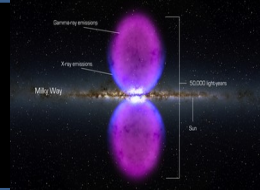
ORCA



TRACKS



Angular resolution with tracks



Size of some astrophysical objects :

RXJ1713 (SNR): 1°

Sun, Moon : 0.5°

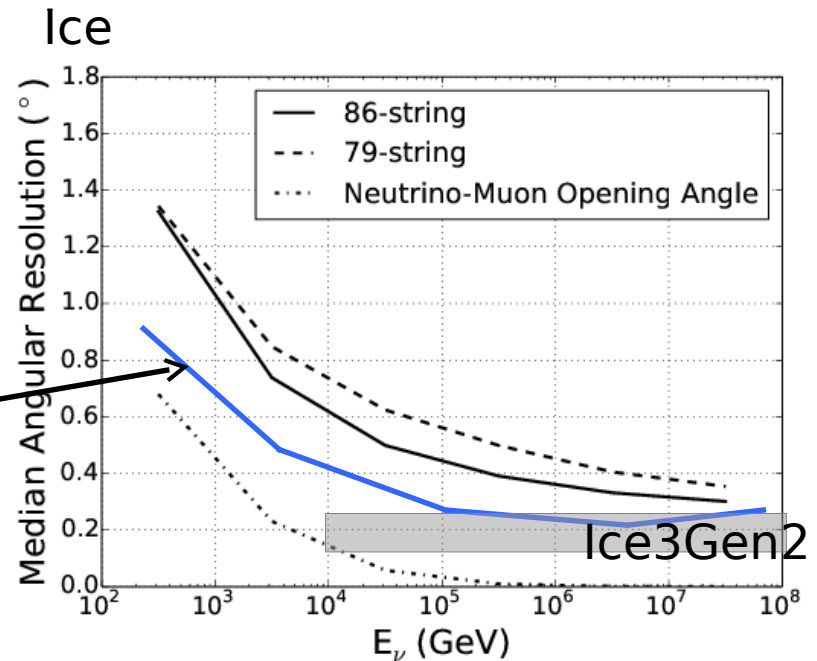
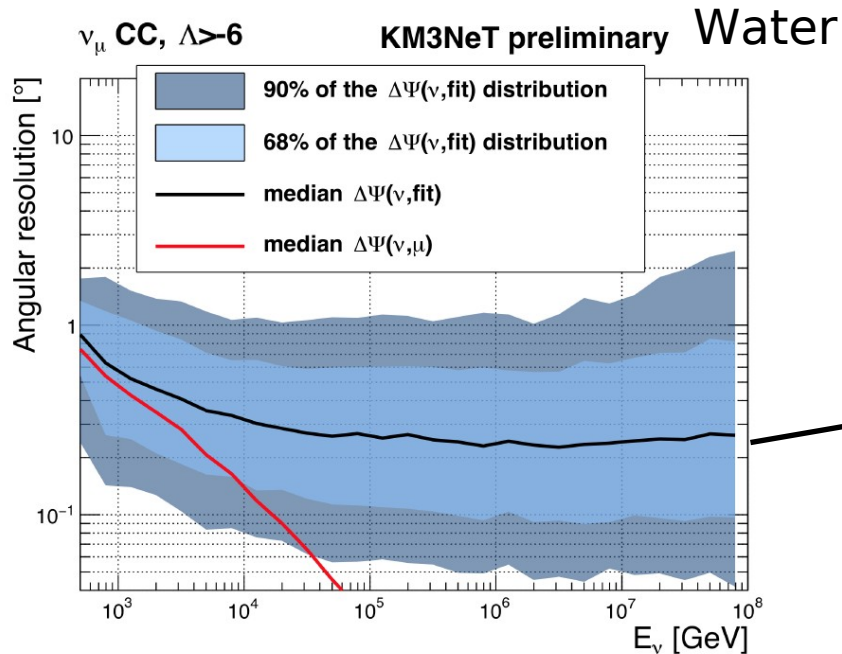
Cen A (AGN) : 0.3°

Point sources search:

Signal/Noise : $1/\Delta\Omega^2$

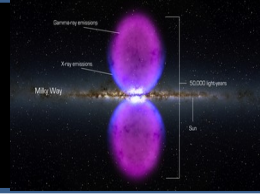
Based on photons time and position likelihood

Muons:



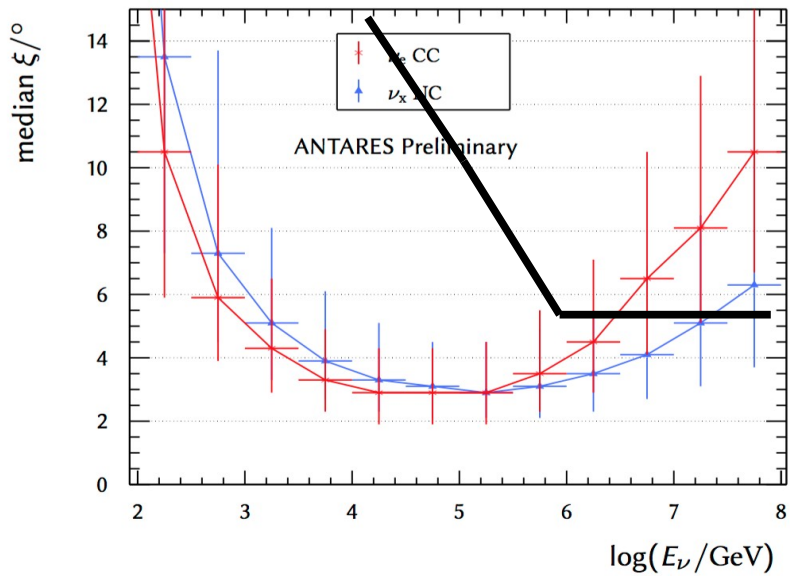


Shower reconstruction in water

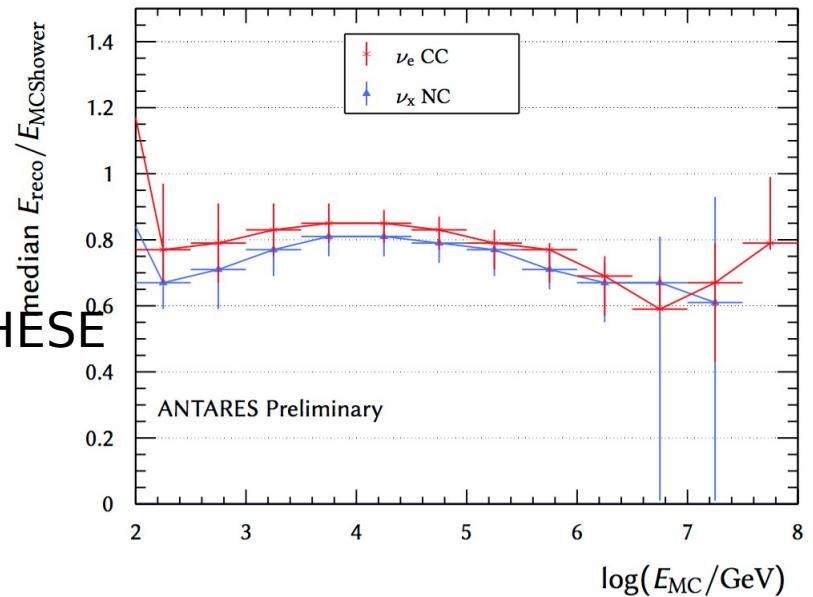


Based on photons number and position likelihood

ANTARES & GVD: similar resolutions

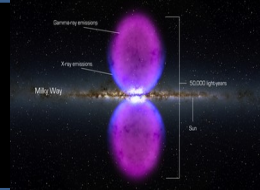


Ice3 HESE

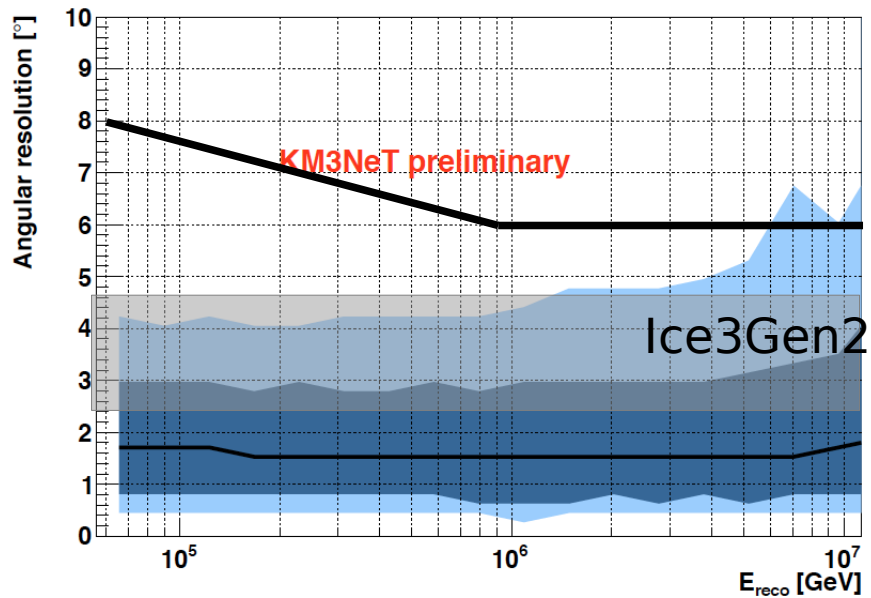




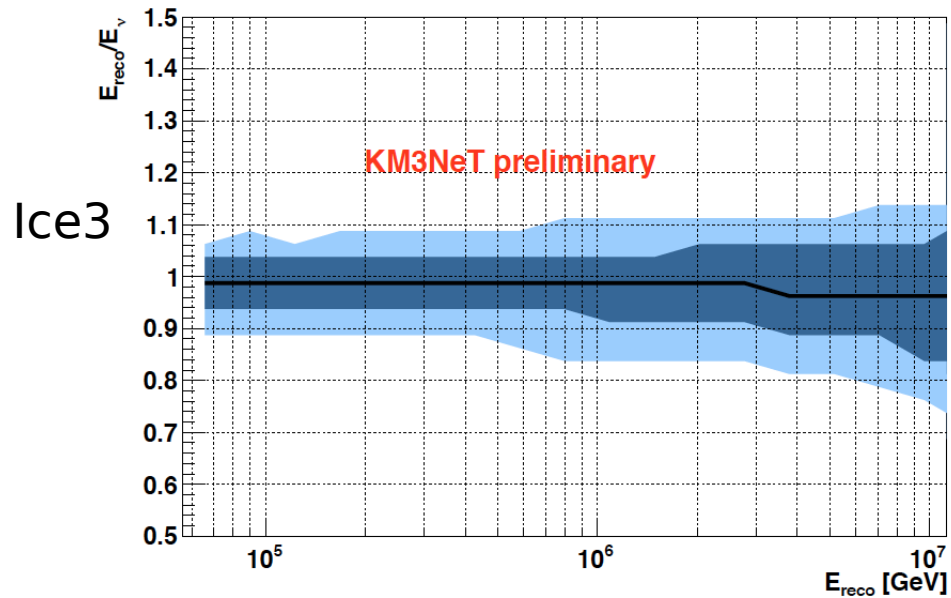
Shower reconstruction prospects



Ang. resolution vs E_{reco}

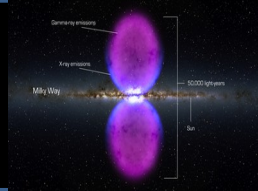


E_{reco}/E_{ν} vs E_{reco}





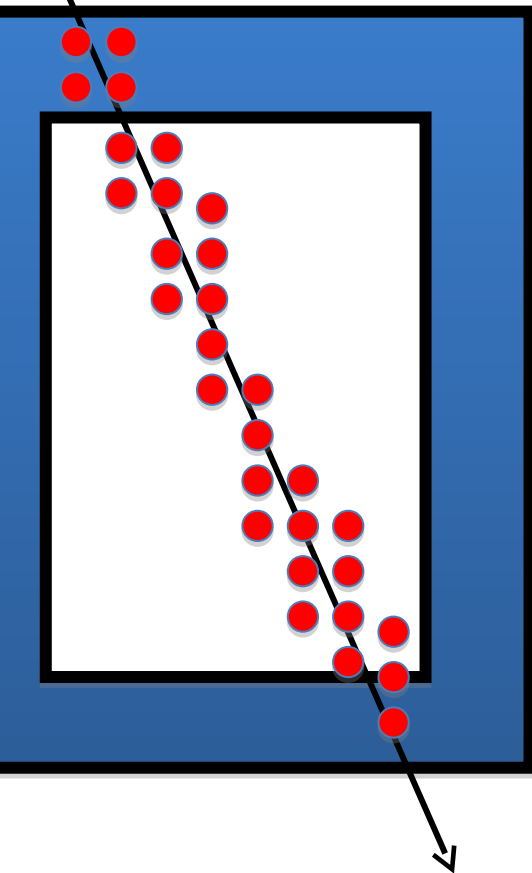
Another strategy : « HESE »



High Energy Starting Events

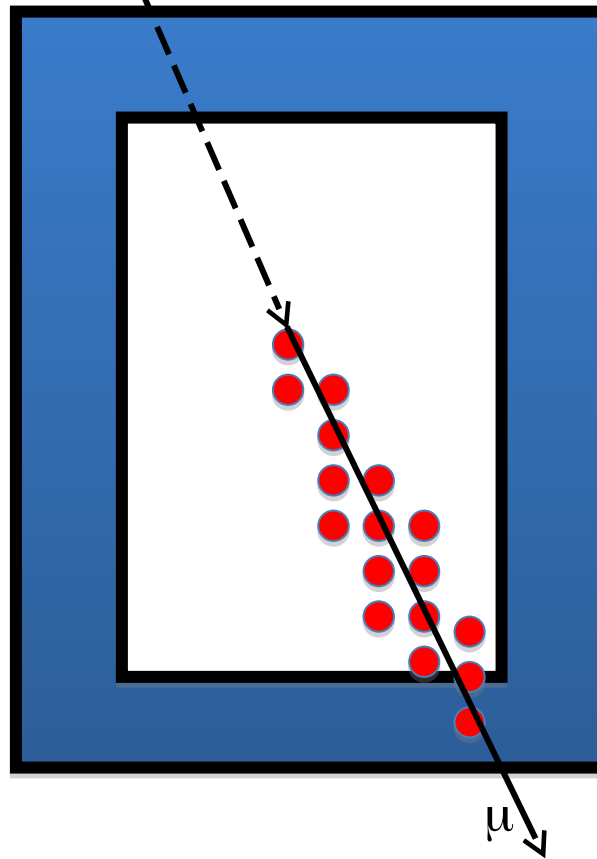
VETO

μ



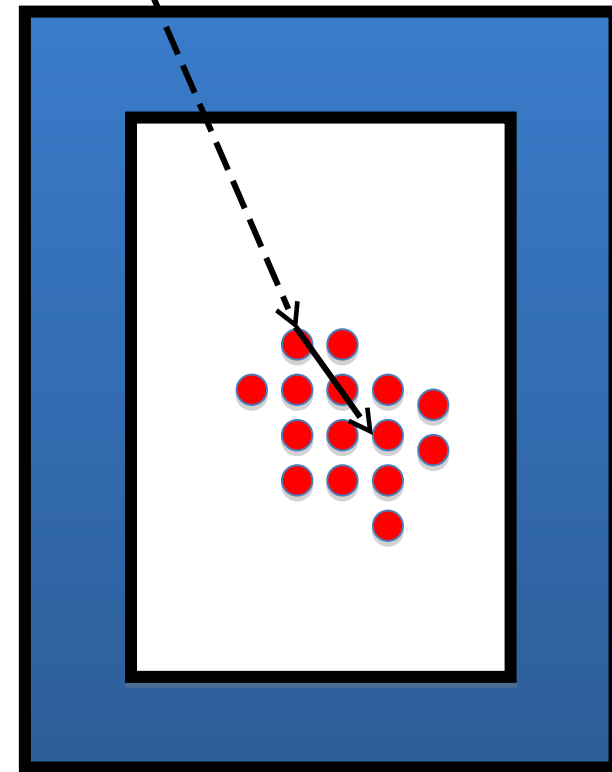
OK

ν_{μ}



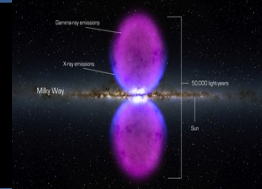
OK

$\nu_{e,\mu,\tau}$





Existing Data Samples Characteristics



Sample	Ang. Res.	Energy Res.	Stat.
IceCube trck Up-going Down-going	$O(0.3)^\circ$	$0.3 \times \text{Log}(E)$	HE ν tracks, $\sim 10\text{k}$ evt/yr VHE μ tracks $\sim 5\text{k}$ evt/y
Antares trck Up-going	$O(0.3)^\circ$	$0.3 \times \text{Log}(E)$	HE ν tracks a few k evt/yr
IceCube Casc (up+down- going)	$\sim 5\text{-}15^\circ$	1-10%	$O(10)$ evt/yr
Antares Casc. (up-going)	$2.5\text{-}10^\circ$	10%	1-10 evt/yr
Baikal cascades	4.5°	30%	5 evt/yr ($>100\text{TeV}$)

Potential μ contamination up to $\sim 10\%$

~ 10 yrs of data

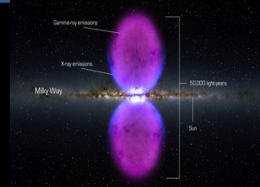
Event time precision: $< 1 \mu\text{s}$
(GeV rate rise for SN $\sim \text{ns}$)

Available "Open samples":
HESE and HE Alerts
 $\sim 10/\text{yr}$ $>50\%$, "signalness"
(i.e. $\sim S/(S+B)$)

PS search samples (13 trcks, Ant. trks+casc.)
high statistics/overwhelming atm. background
Searched signal dependent selection



Sample <-> Search type



Cut & count

Likelihood (+c.&c.)

Transient

Alerts

Catalogue Search

Subthreshold

PAS VU

Cascades
energy

Tracks
Pointing, Stat.

Steady
Or
Slow var.

diffuse

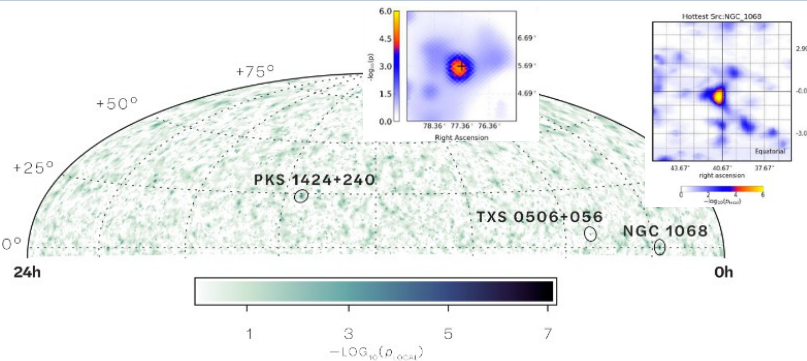
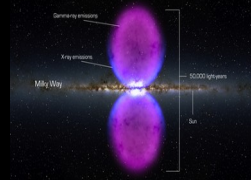
extended

Point Sources

VU

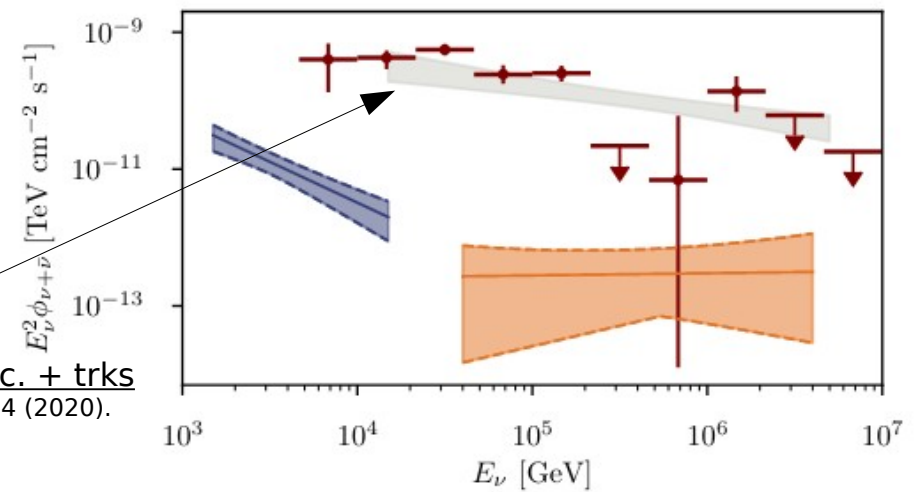


Observed signals

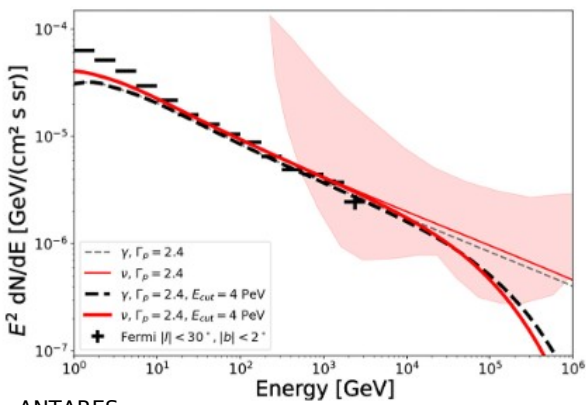


Point sources (AGNs), trks (+casc.)
 Steady and close
 Transient and far

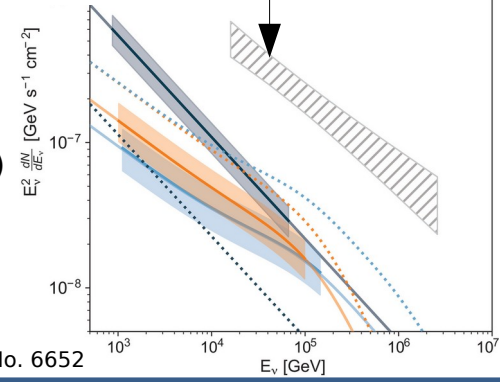
- NGC 1068
- TXS 0506+056
- Astro. ν_μ
- ✦ Astro. $\nu_e \nu_\tau$



Ice3 Diffuse flux casc. + trks
 Phys. Rev. Lett.125, 121104 (2020).



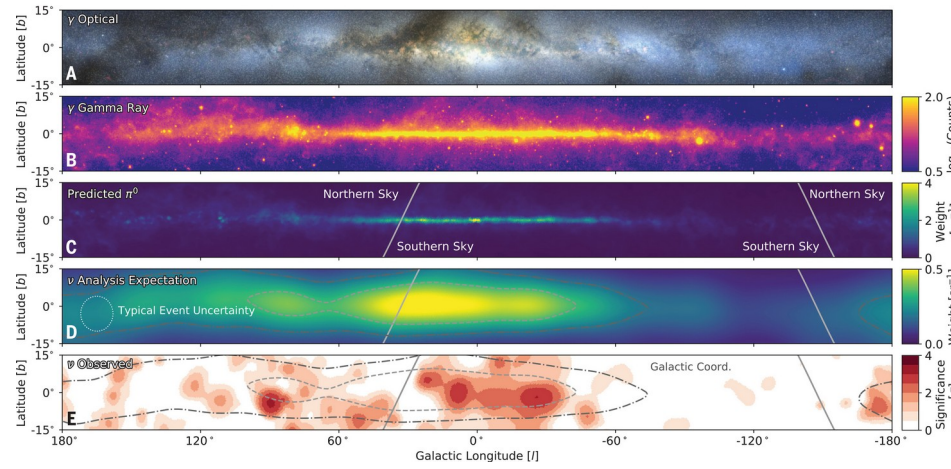
- KRA⁵ Model
- KRA⁵⁰ Model
- π^0 Model
- KRA⁵ Best-Fit ν Flux
- KRA⁵⁰ Best-Fit ν Flux
- π^0 Best-Fit ν Flux
- ▨ IceCube All-Sky ν Flux (22)



ANTARES
 Phys. Let. B, Volume 841, (2023) 137951

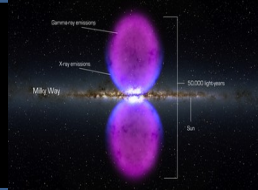
Extended source:
 Galactic ridge, casc. (+trks)

IceCube:
 Science Vol. 380, No. 6652





Summary & Perspectives



- HE neutrino astronomy is born, even if not many/strong confirmed sources yet
- Second generation telescopes techn mature and big enough
- Several types of event w. Diff charac => different analyses
- Complementarity of existing projects w.r.t. pointing and E reco resolutions, instantaneous and integrated sky coverage
 - KM3NeT => galactic sources