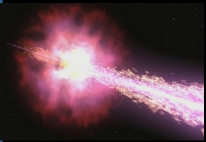
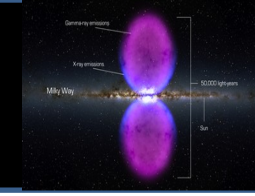
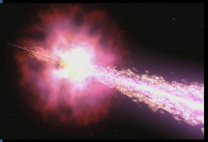




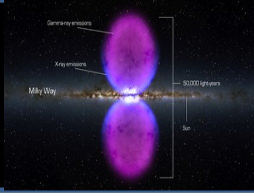
Very Large Volume Water Cherenkov High Energy Neutrino Telescopes (What and How)

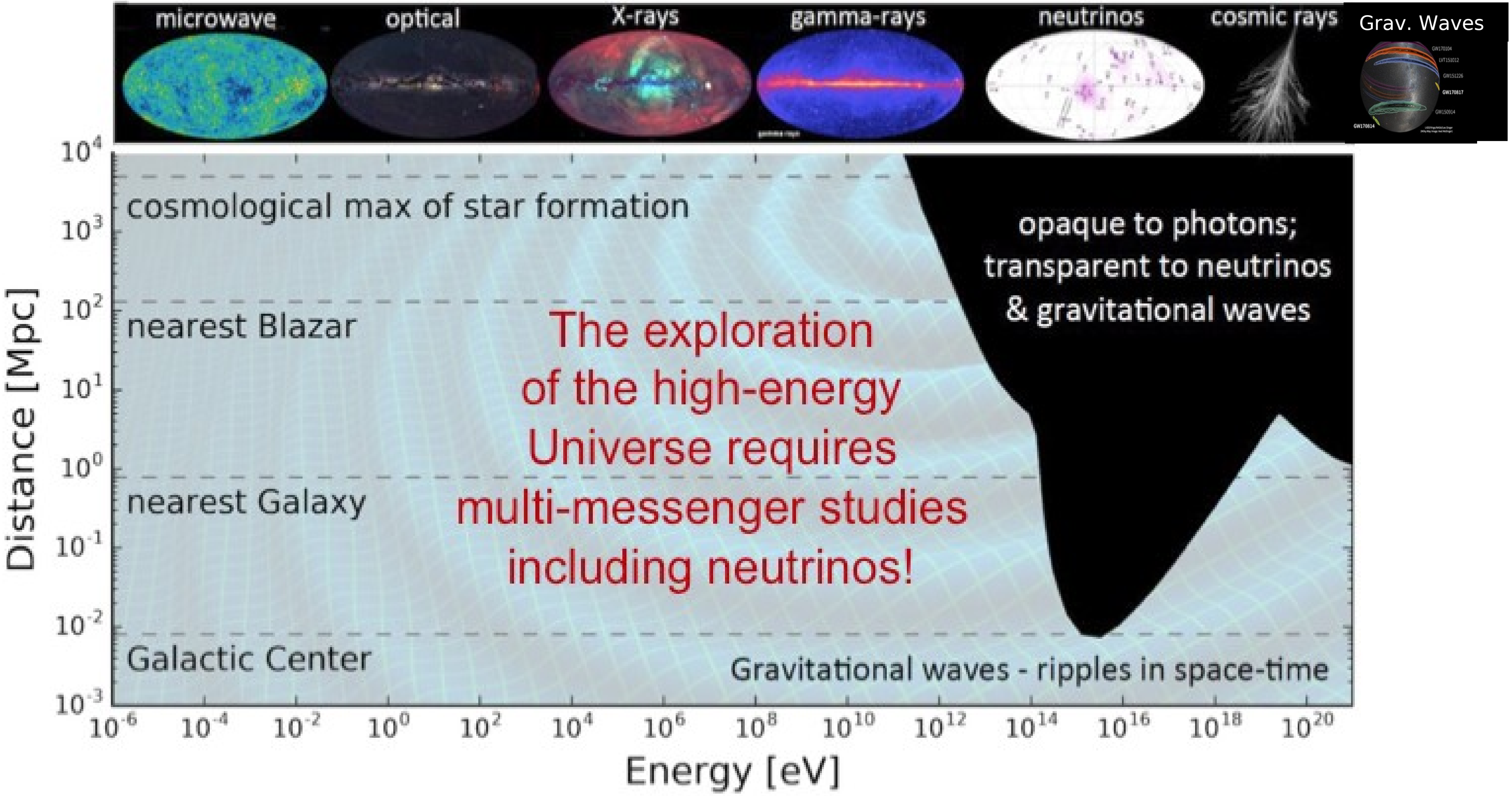
IAP Paris – 06-08 Sept 2023

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



The why





microwave
optical
X-rays
gamma-rays
neutrinos
cosmic rays
Grav. Waves
cosmological max of star formation
nearest Blazar
nearest Galaxy
Galactic Center
opaque to photons;
transparent to neutrinos
& gravitational waves
The exploration
of the high-energy
Universe requires
multi-messenger studies
including neutrinos!
Gravitational waves - ripples in space-time
Distance [Mpc]
Energy [eV]
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-6}
10^{-4}
10^{-2}
10^{0}
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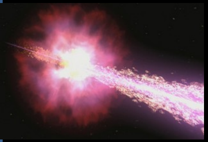
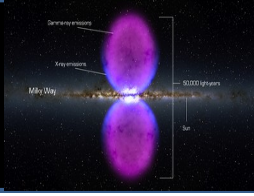
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}



Astrophysical high energiy neutrino sources



Galactic — Extra-galactic

Astrophysical Sources

SN (explosion)

SN (post-expl) Binaries
PWN, TDEs, CRs...

AGN/GRB

UHECR

Energy

0.1-10 MeV

Tev-PeV

>10PeV

Production mechanism

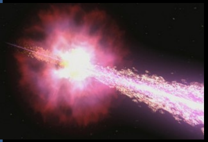
desint. beta
elec. capture

Nuclear reactions

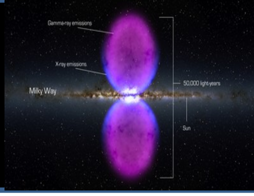
Hadronic interactions

(+top-down ?)

accelerated hadrons
+
dense radiation/matter

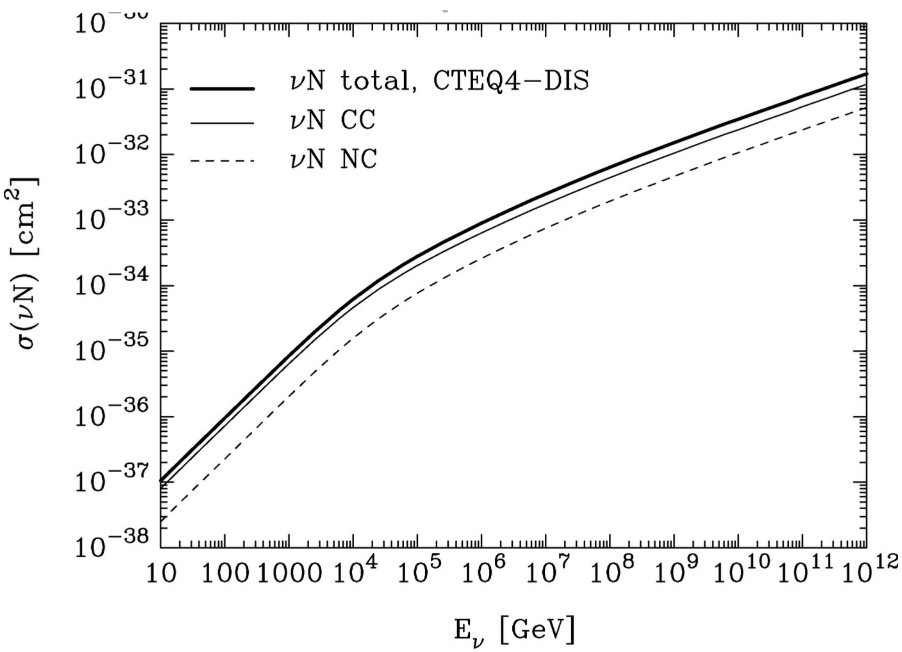


A (very) hard detection



$$\frac{d^2\sigma_{\nu N}}{dx\,dy} = \frac{2G_F^2 m_N E_\nu}{\pi} \frac{M_W^4 x}{(Q^2 + M_W^2)^2}\left[q(x,Q^2) + (1-y)^2\bar{q}(x,Q^2)\right]$$

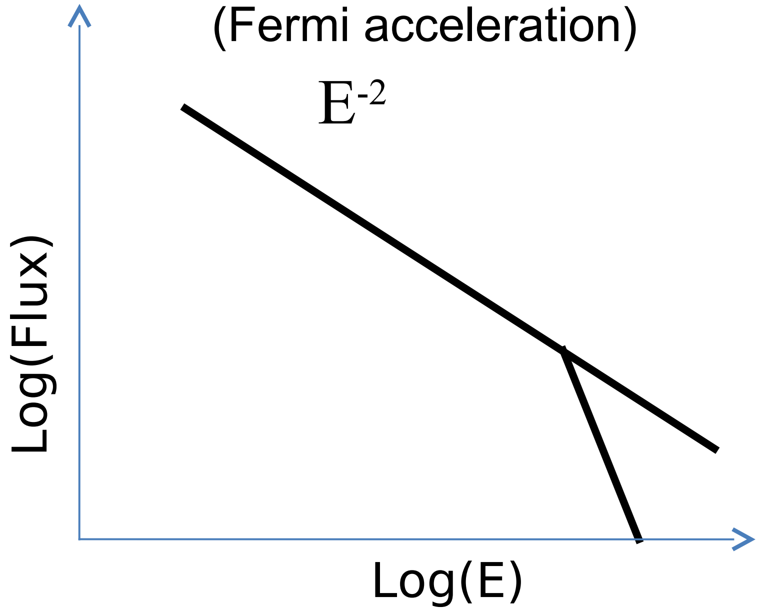
$$\frac{d^2\sigma_{\nu N}}{dx\,dy} = \frac{G_F^2 m_N E_\nu}{2\pi} \frac{M_Z^4 x}{(Q^2 + M_Z^2)^2} \times \left[g_L^2\left(q(x,Q^2) + (1-y)^2\bar{q}(x,Q^2)\right) + g_R^2\left(\bar{q}(x,Q^2) + (1-y)^2 q(x,Q^2)\right)\right]$$

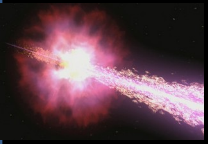


X

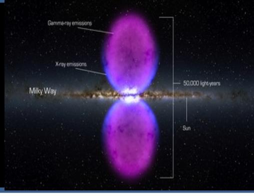
Expected cosmic flux

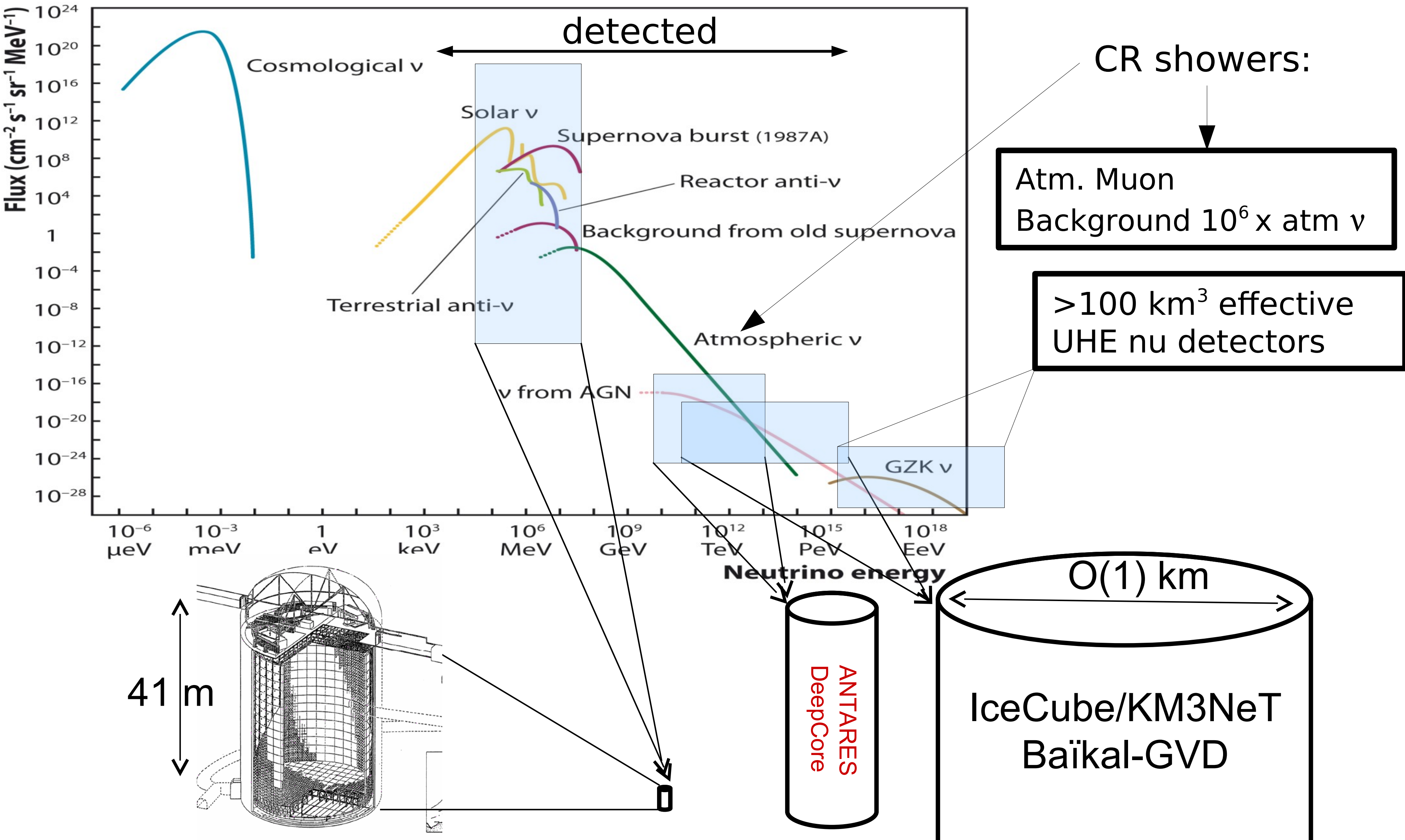
(Fermi acceleration)

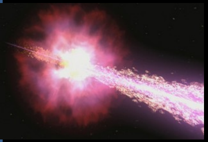




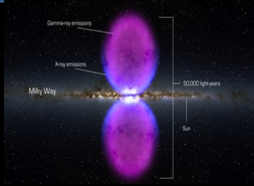
Hard to detect

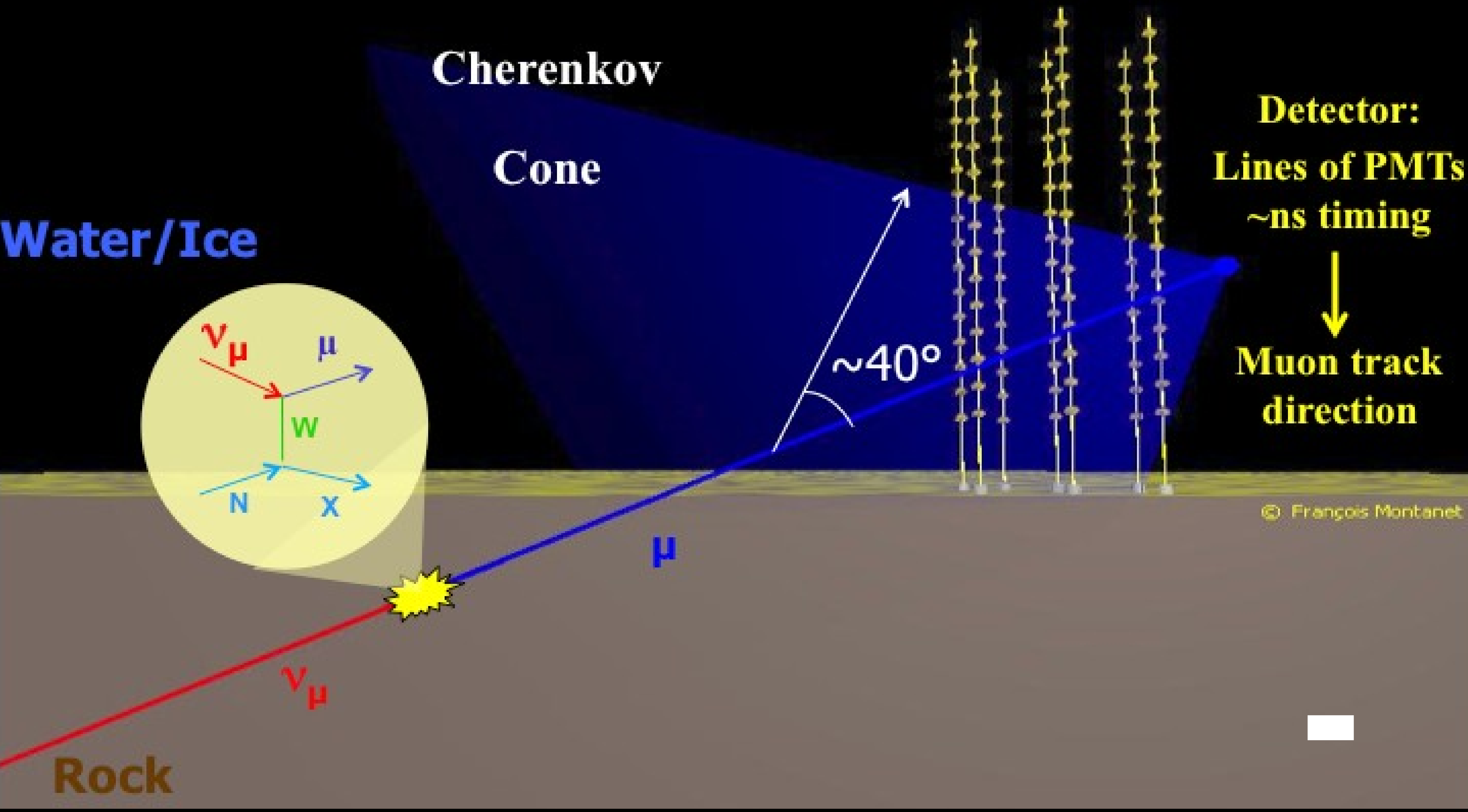


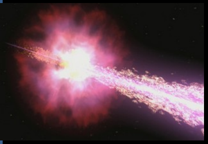




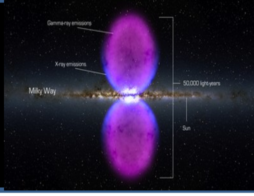
Practically – the muonic channel







Some consequences

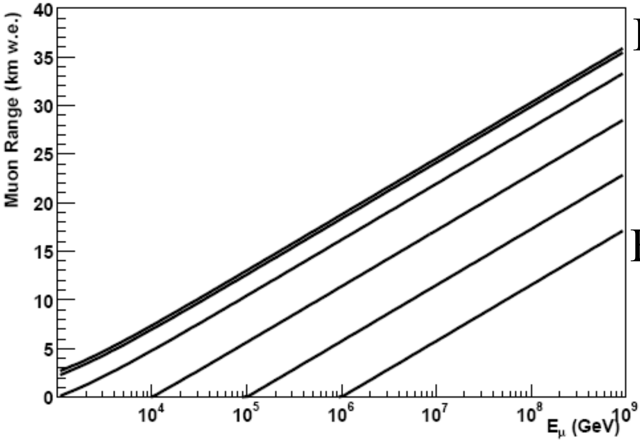


Muons energy losses:

$$dE_\mu/dx = \alpha(E_\mu) + \beta(E_\mu)\cdot E_\mu$$

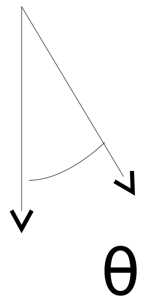
"Muon range" :

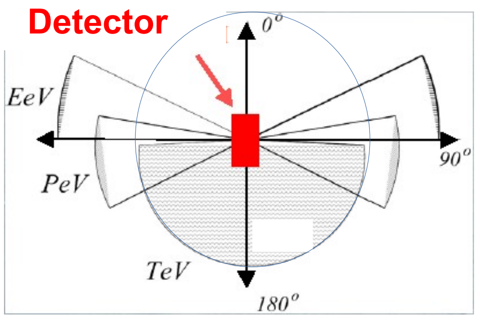
$$R_\mu(E_\mu, E_{thr}) = \int_{E_{thr}}^{E_\mu} \frac{1}{dE_\mu/dx}dE \approx \frac{1}{\beta}ln\frac{(\alpha/\beta)+E_\mu}{(\alpha/\beta)+E_{thr}}$$

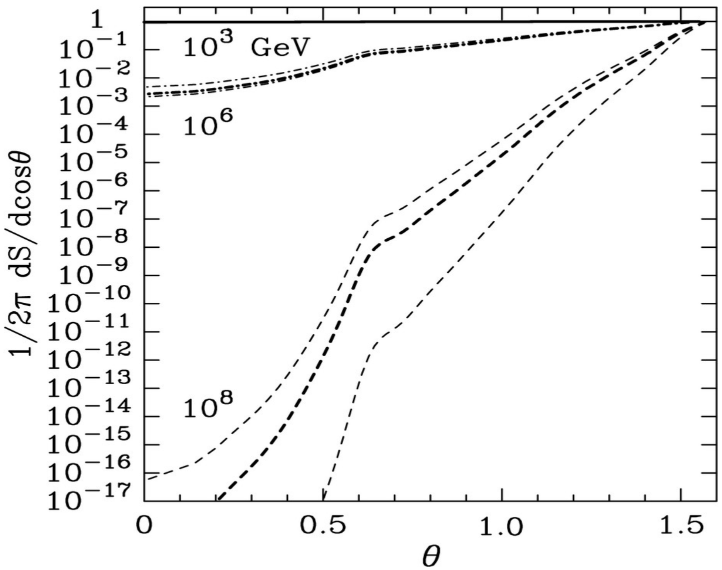


E_{thr}=1 GeV

E_{thr}=10^6 GeV

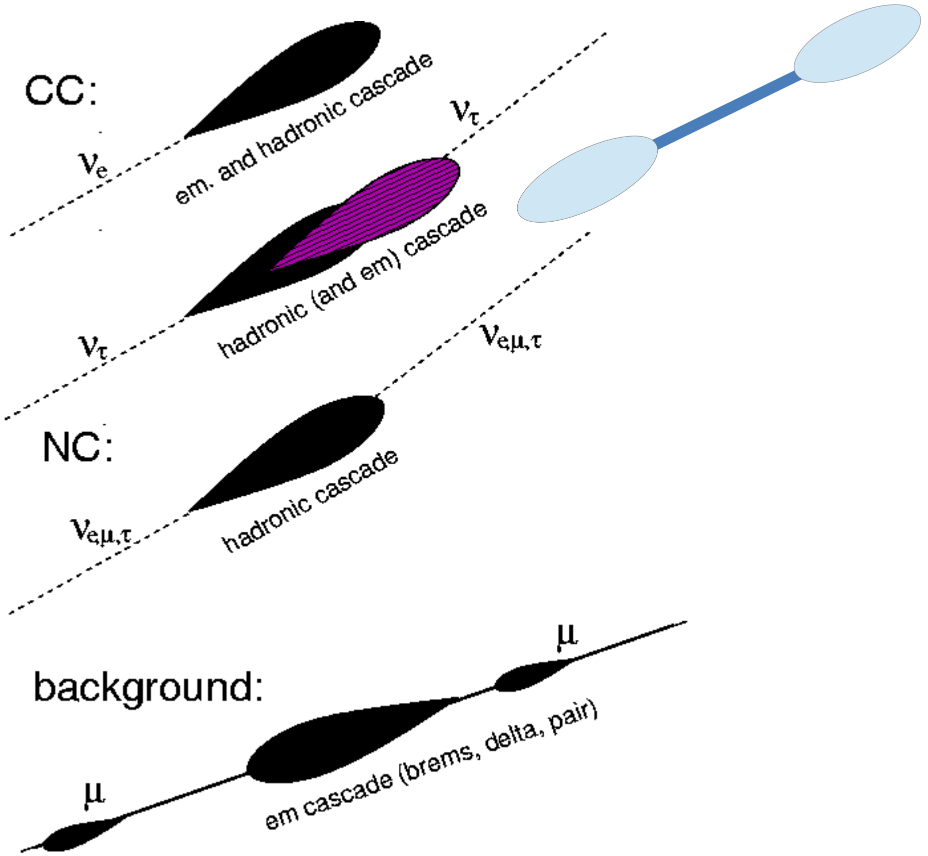




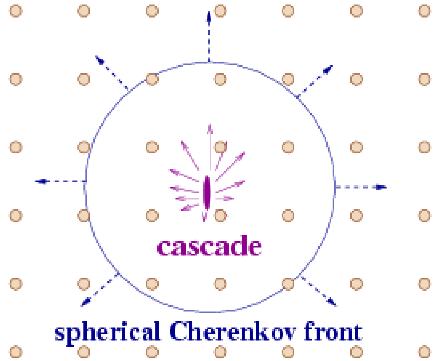


Muon tracks

Effective volume >> instrumented volume



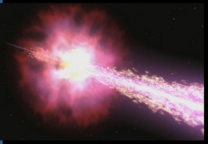
"shower" events



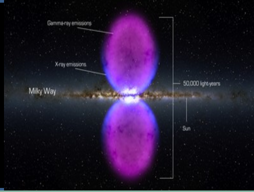
Contained events (~10m)
- + energy reconstruction
- - effective volume

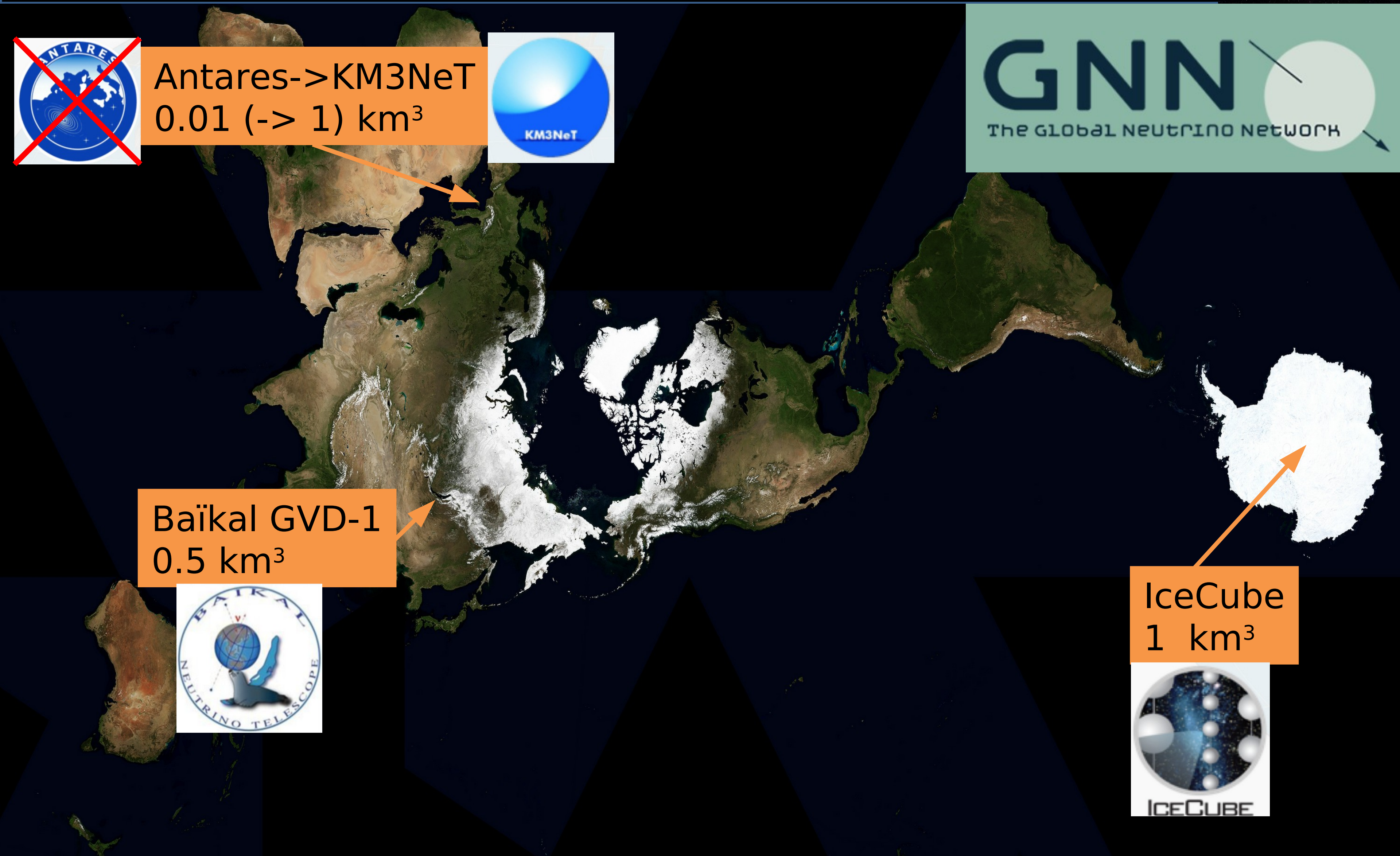
topology
- + identification
- - angular resolution

Diffuse flux (and...)

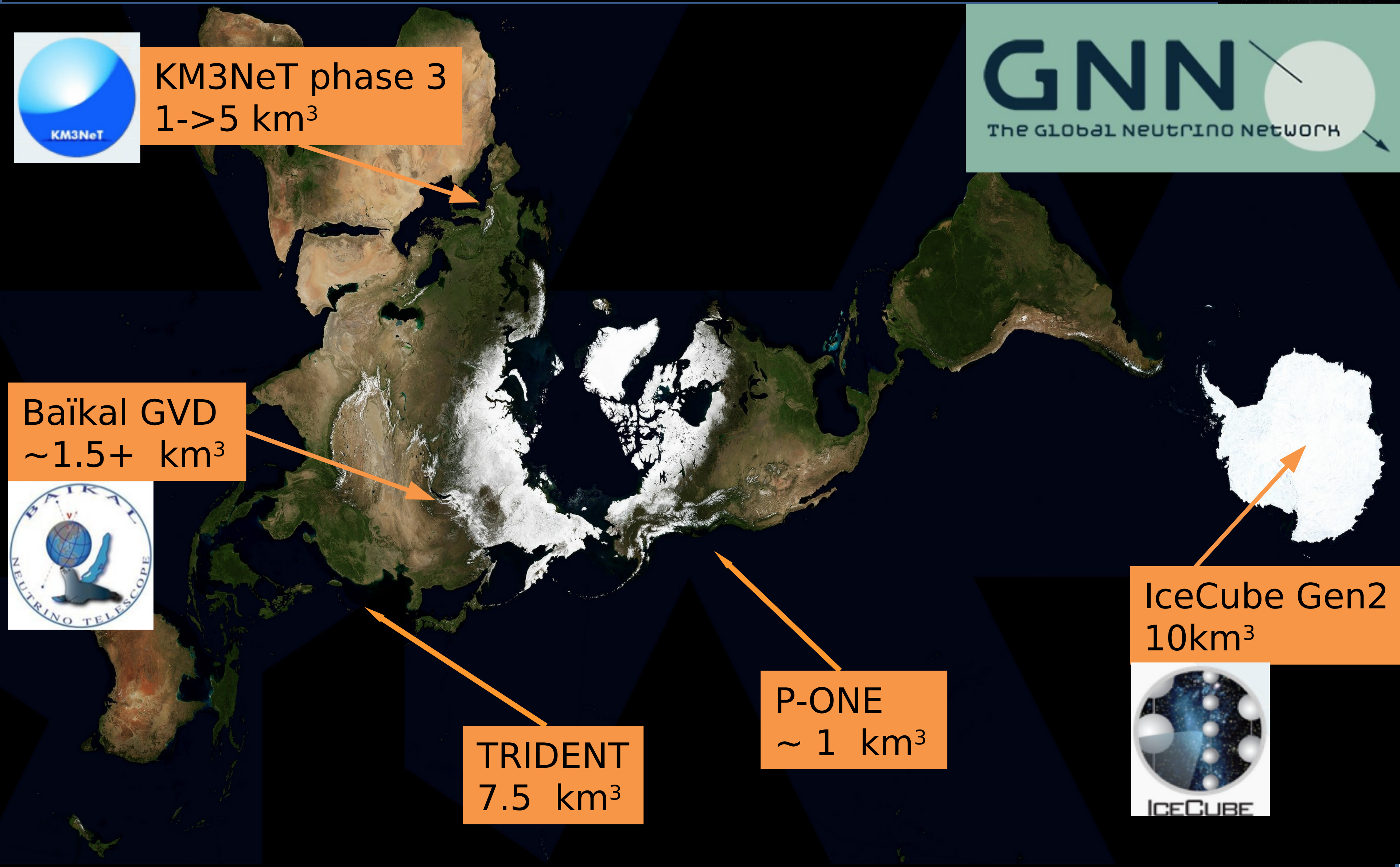


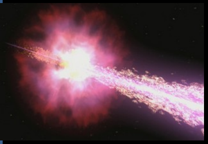
ν-Telescopes today



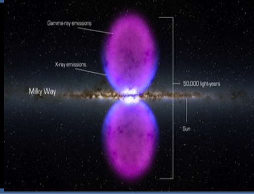


ν-Telescopes tomorrow (or the day after or...)

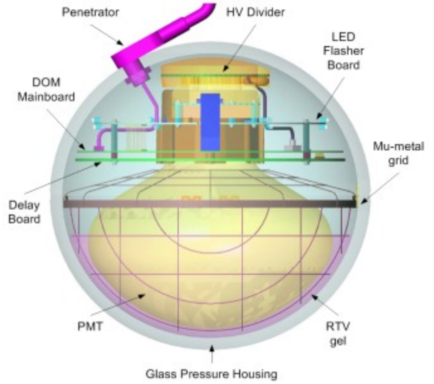


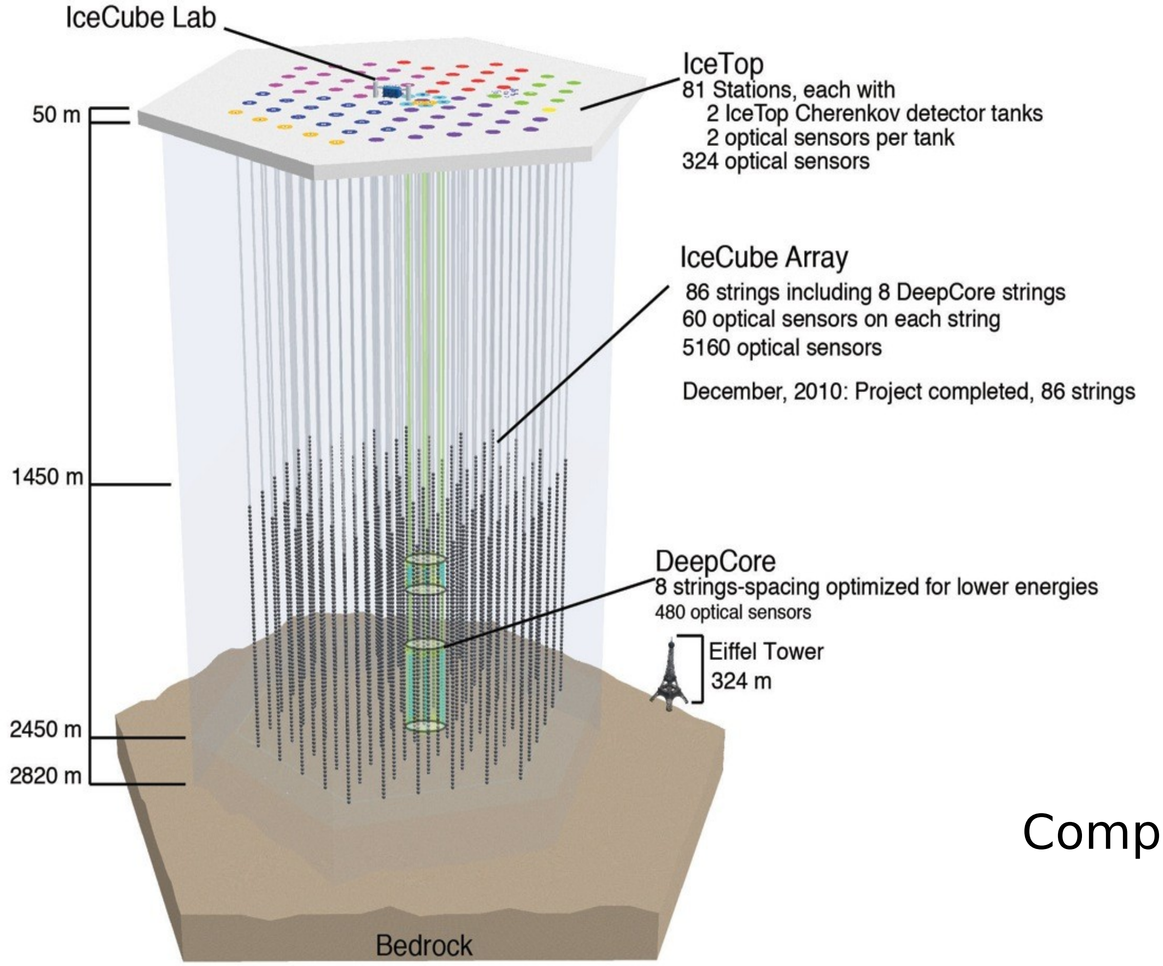


IceCube



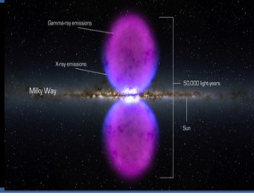
10” PMTs
Digitized Waveforms

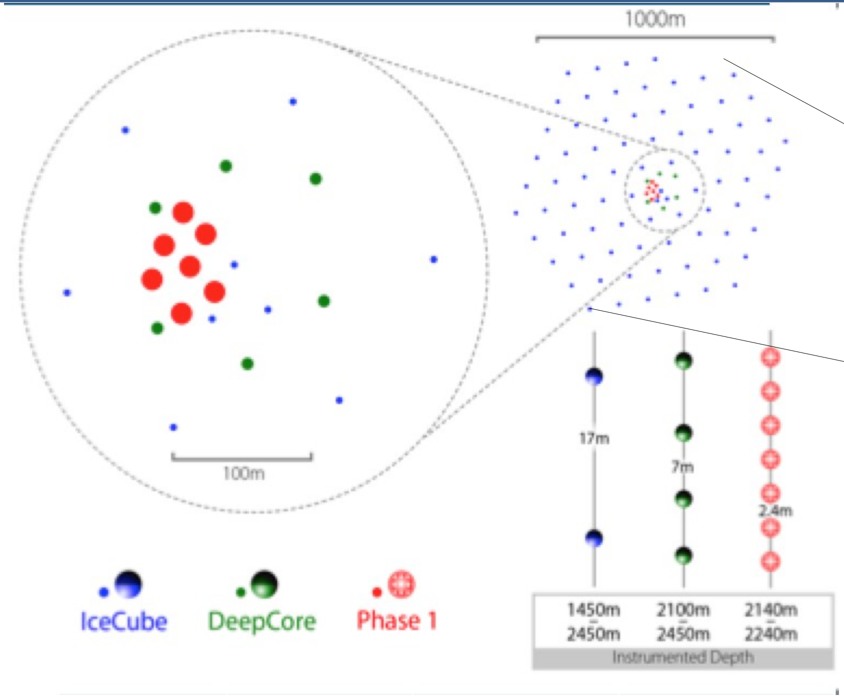


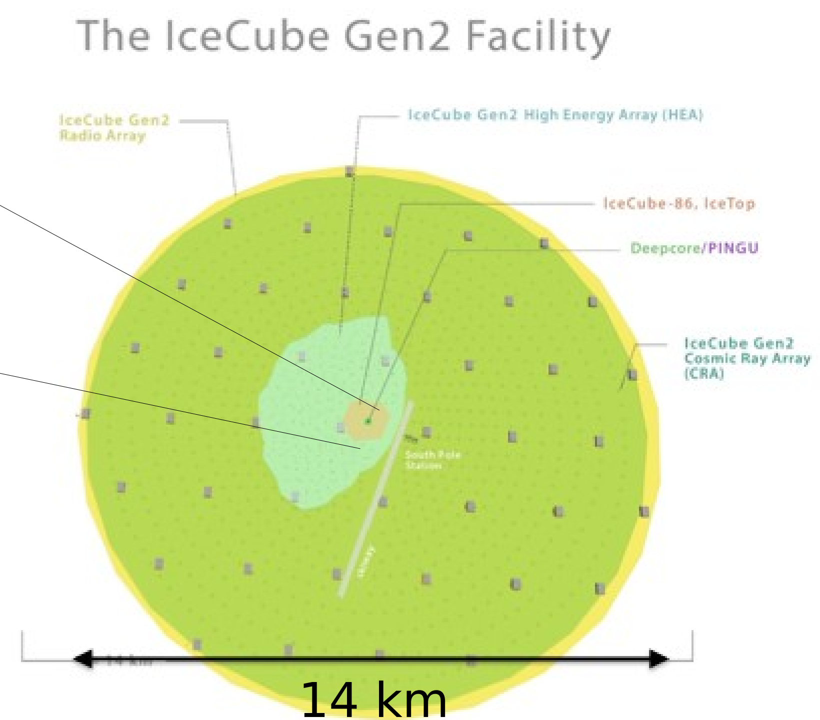


Complete since Dec. 2010

IceCube GEN 2





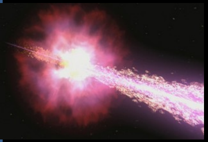


mDOM

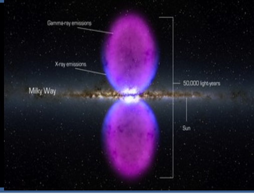
Inspired by KM3NeT
24x3” PMTs
Borosilicate glass
Baseline design

D-Egg

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

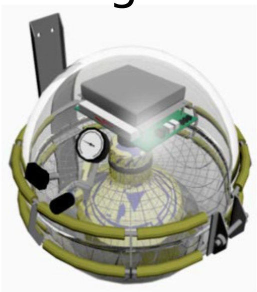


Baïkal GVD

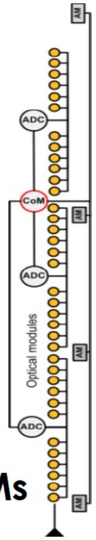


10” PMTs
digitized charge

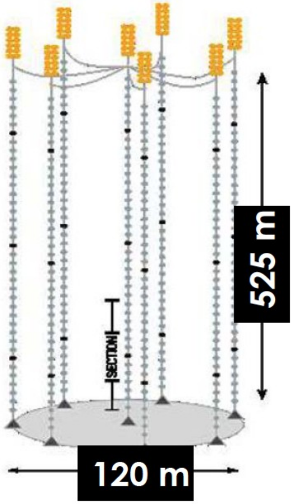
today: 12 clusters



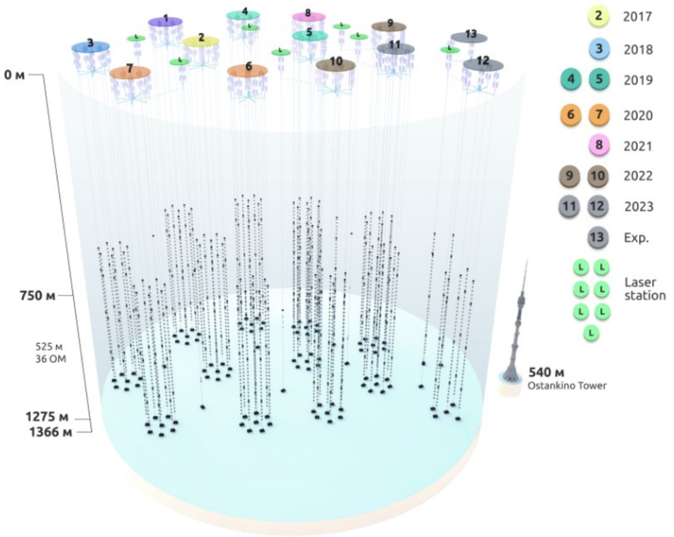
Optical module



String: 36 OMs



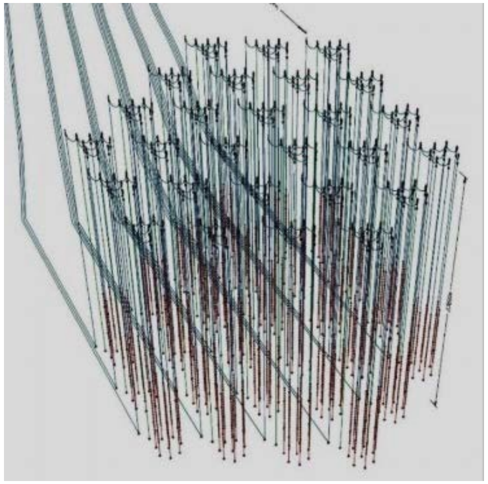
Cluster: 8 strings

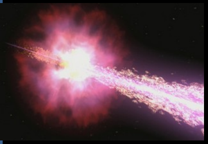


GVD-1: 8 clusters

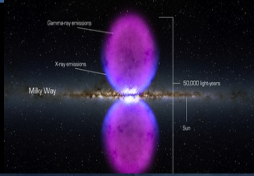
1-2 clusters deployment per season (winter)

Final goal:
27 clusters: 1.5 km^3

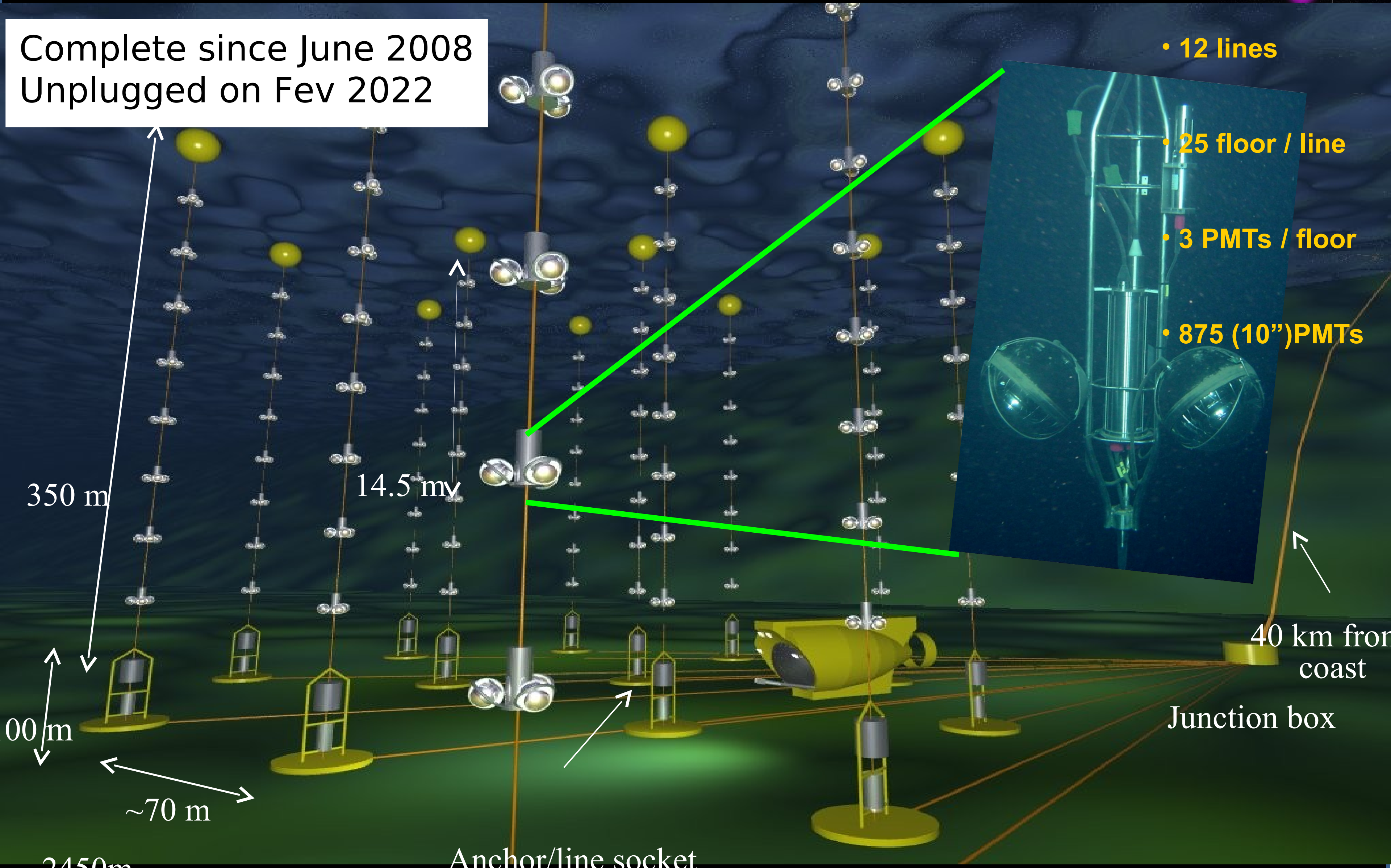




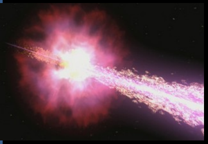
ANTARES



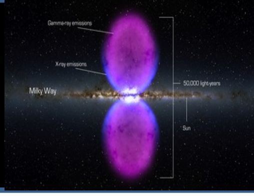
Complete since June 2008
Unplugged on Fev 2022



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



KM3NeT ARCA & ORCA



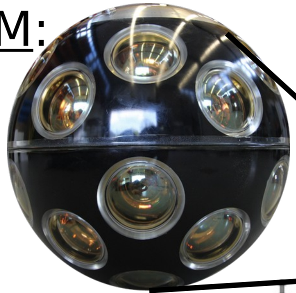
1 block=115 D.U.

Phase-1:
24 ARCA DUs
6 ORCA DU

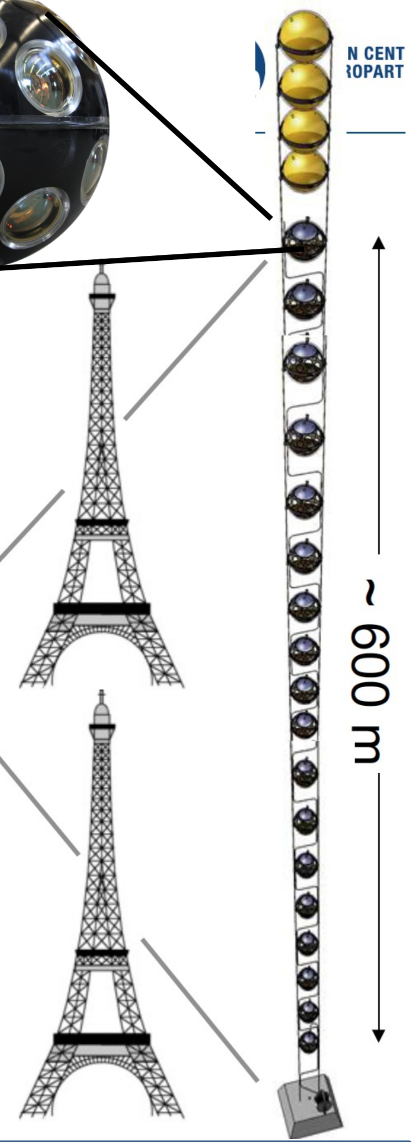
Phase-2:
2 ARCA blocks
1 ORCA block

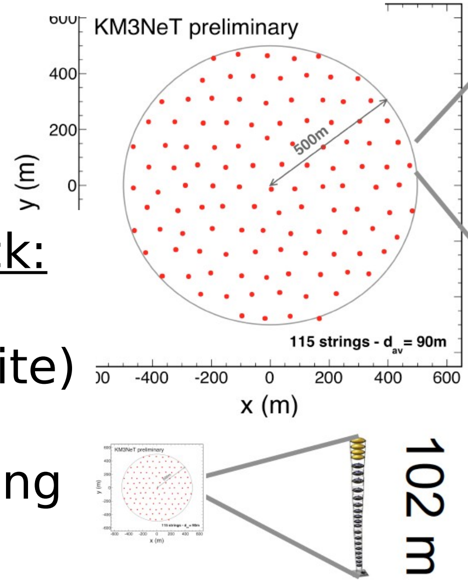
Phase-3:
6(+1) blocks

Multi-PMT DOM:
31 x3" pmts
ToT



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

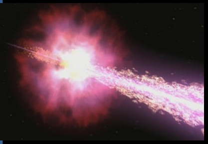




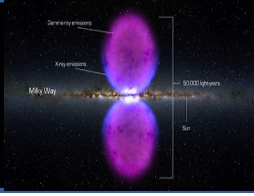
, ICRC 2015

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

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



KM3NeT Status

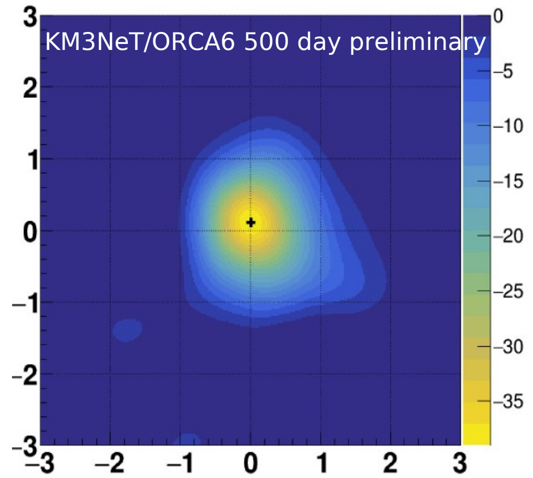


<u>ARCA:</u>
- 21 strings deployed → 2 x ANTARES Photocathode area

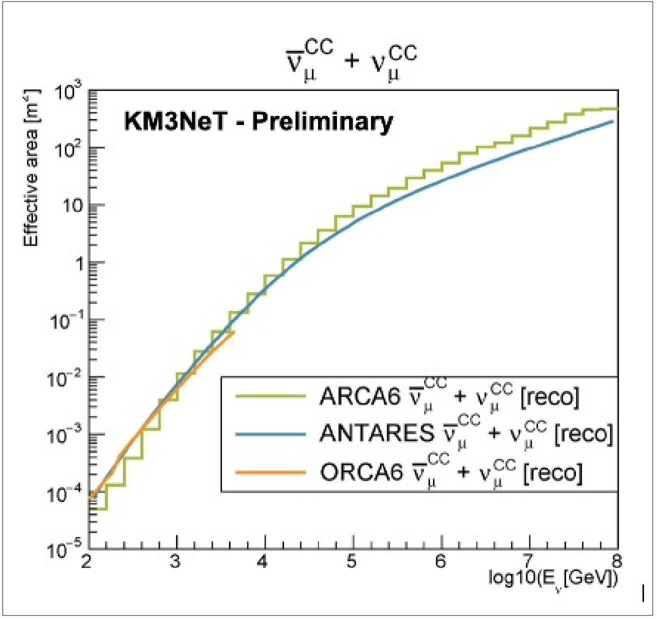
  31 in Dec.

<u>ORCA:</u>
- 18 strings deployed

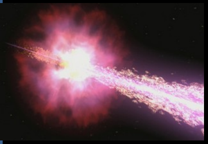
  24 in Dec.



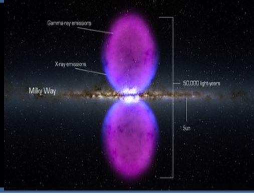
	Sun	Moon
Significance	6.0 σ	2.4 σ
Amplitude	1.42 ± 0.38	0.70 ± 0.29
Resolution	0.68° ± 0.12°	0.54° ± 0.16°



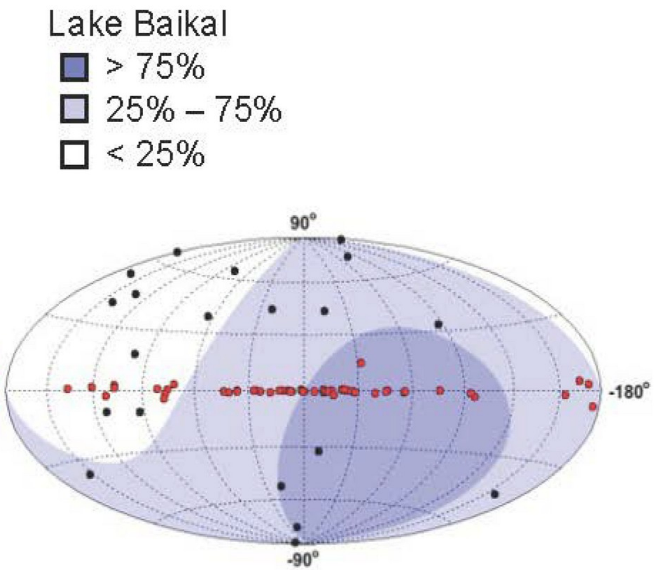
Effective area bigger than ANTARES

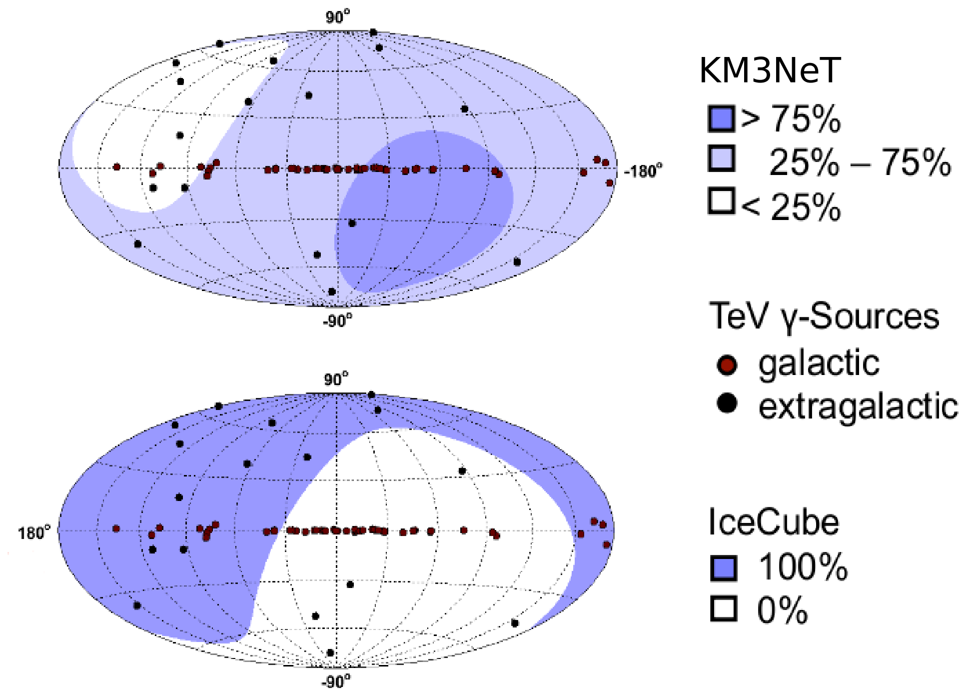


Mediterranean / South Pole



- **Complementary coverage (μ channel)**



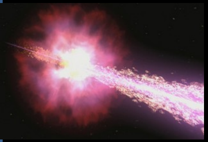


- **Water v.s. Ice**

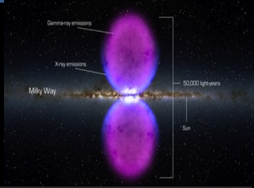
  Optical noise (biolum) / no noise

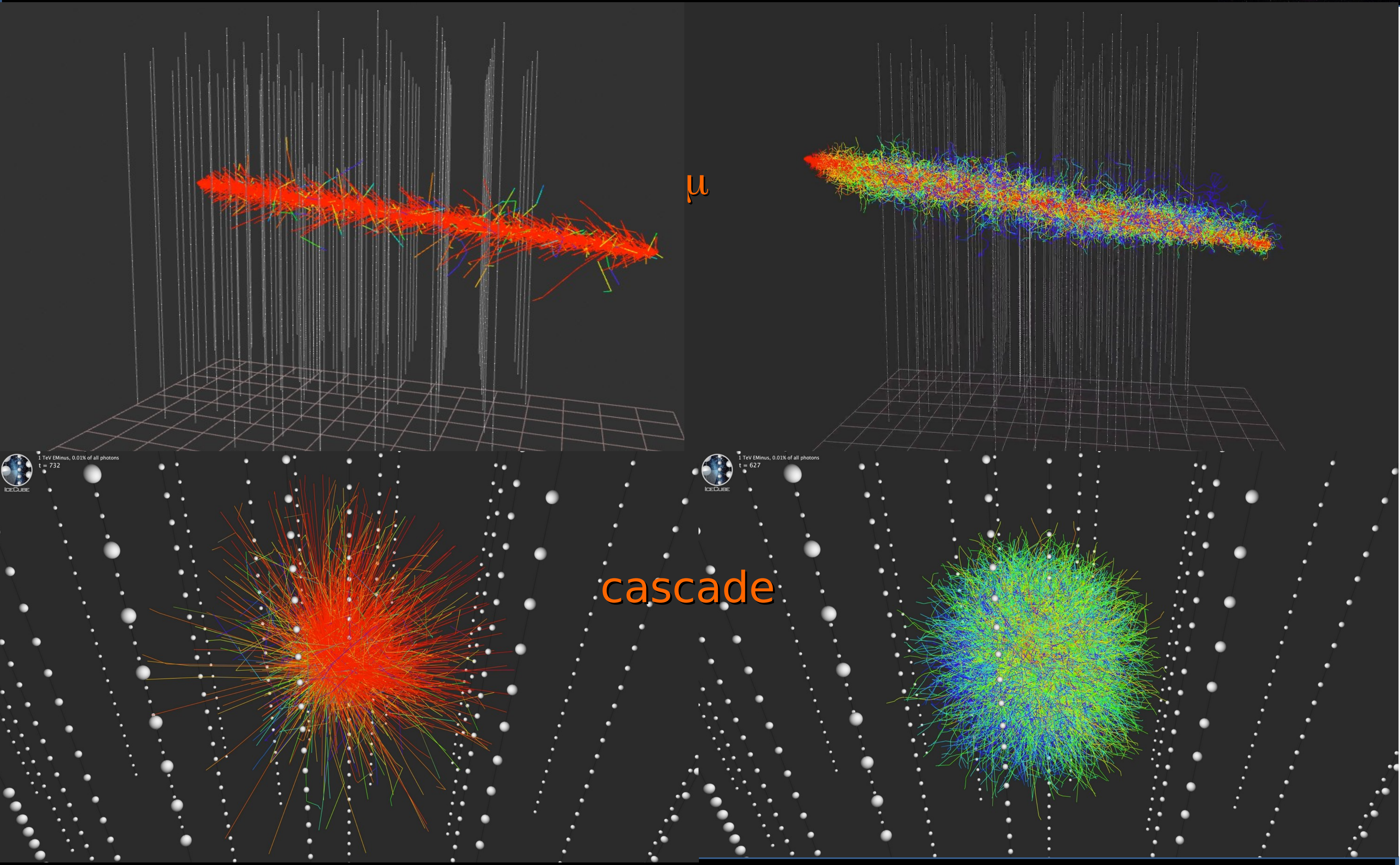
  absorption / diffusion

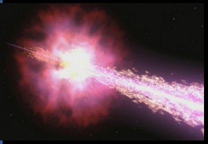
  pointing / calorimetry



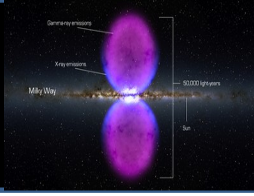
Water v.s. Ice (MC)



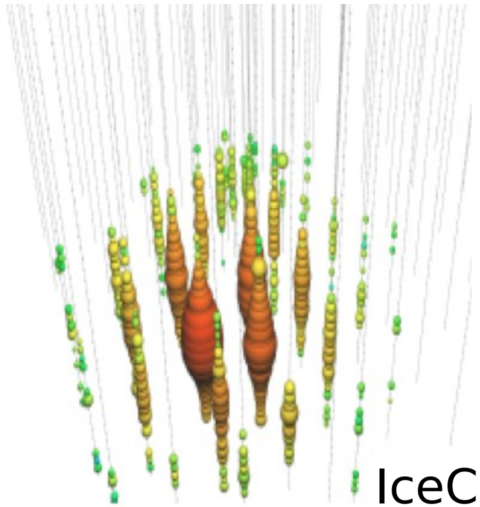


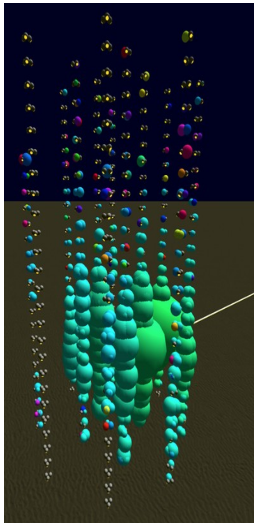


In real life

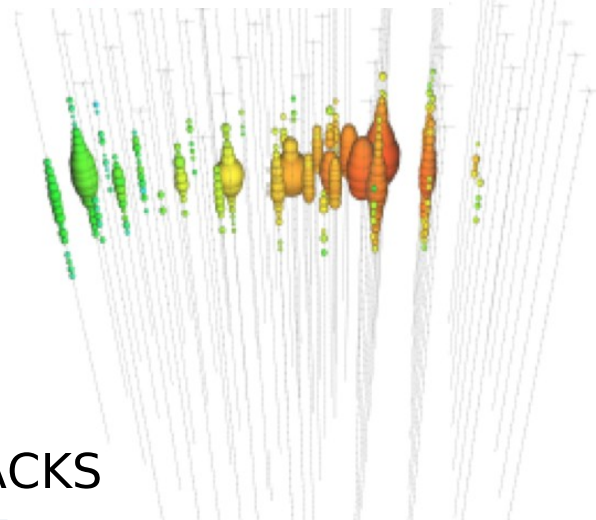


Cascades



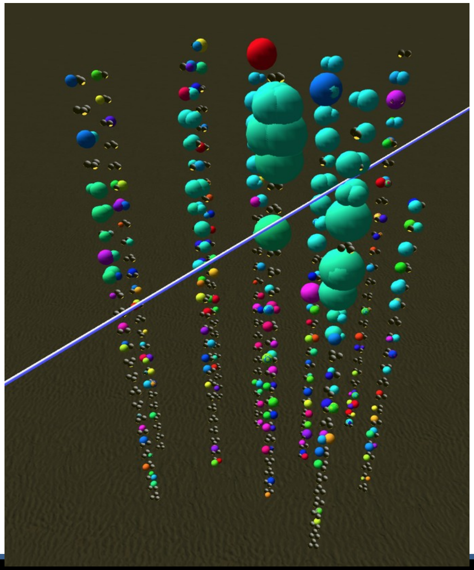


IceCube

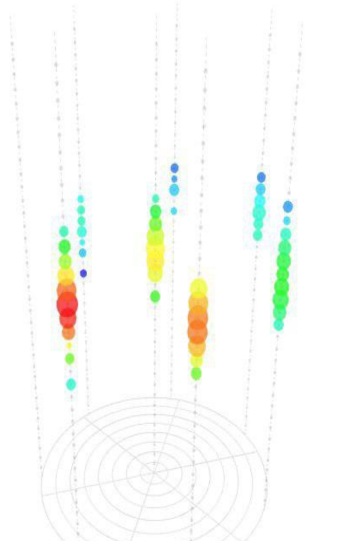


TRACKS

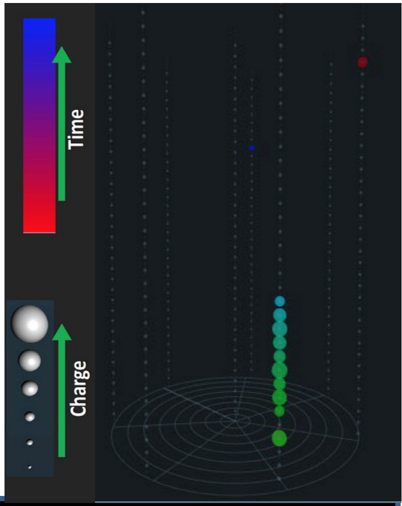
Antares



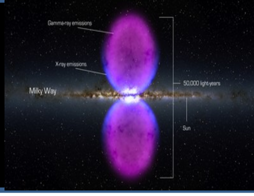
ORCA



Baikal-GVD



Angular resolution with tracks



Size of some astrophysical objects :

RXJ1713 (SNR):1°

Sun, Moon : 0.5°

Cen A (AGN) : 0.3°

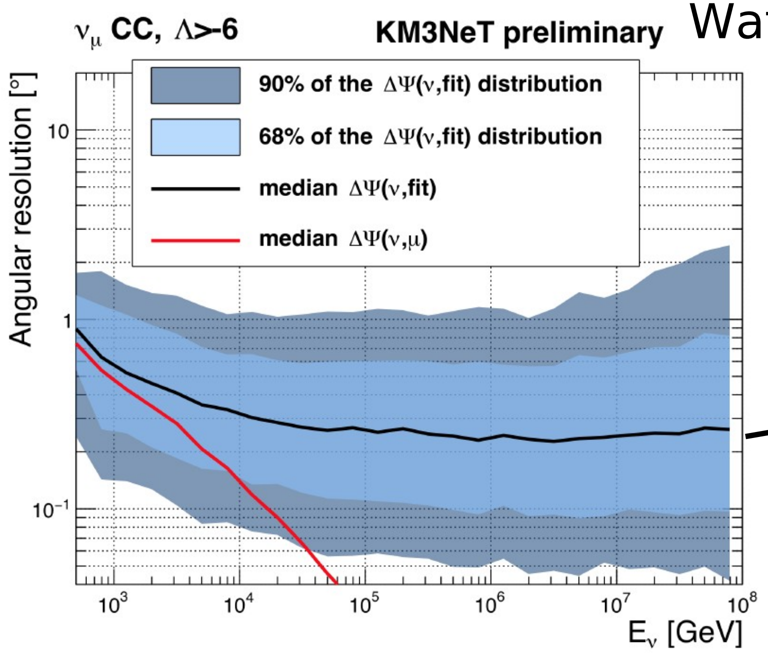
Point sources search:

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

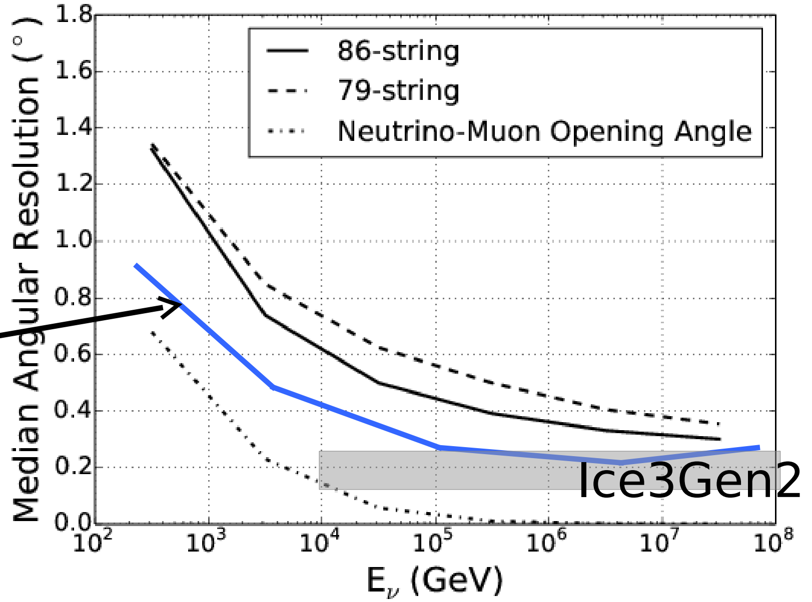
Based on photons time and position likelihood

Muons:

Water

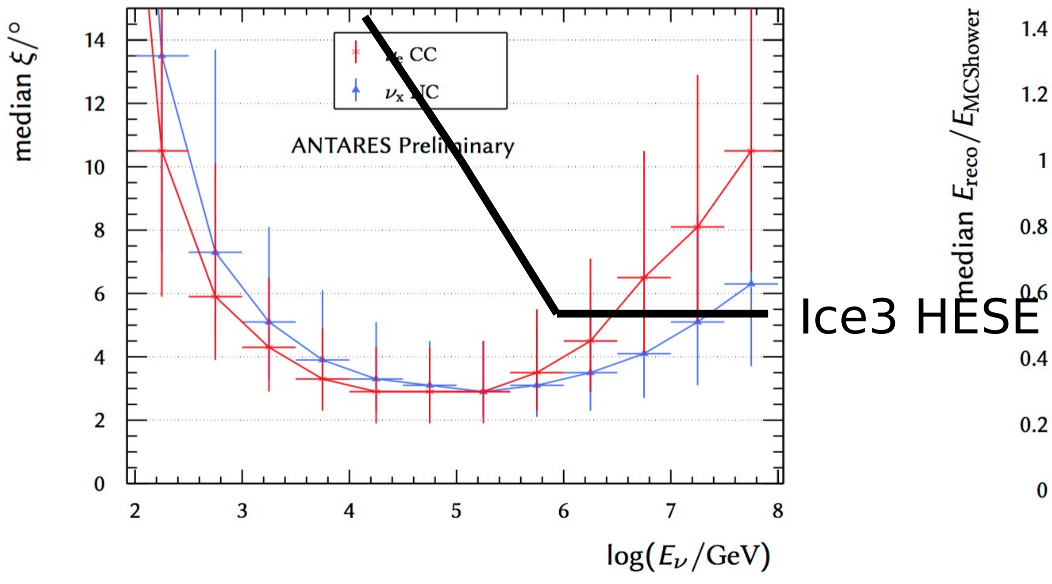


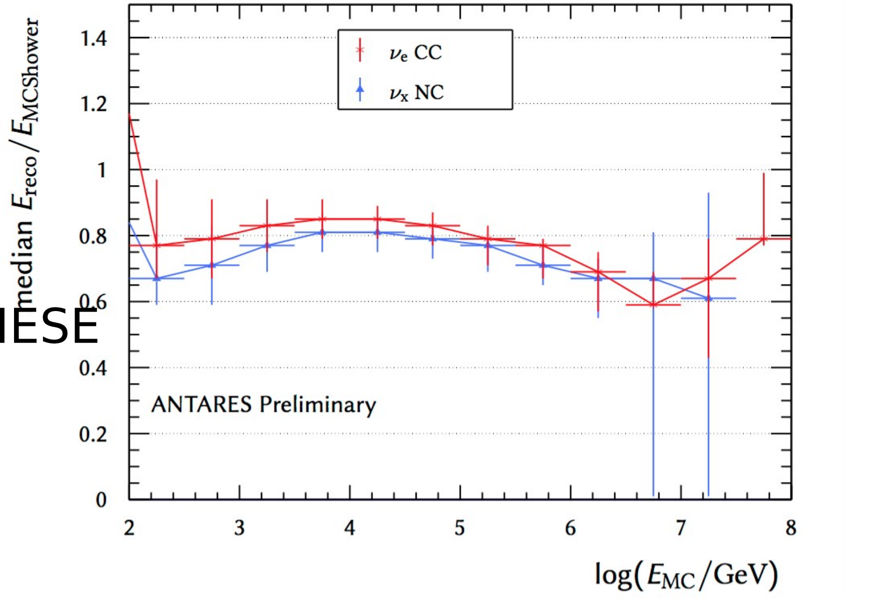
Ice

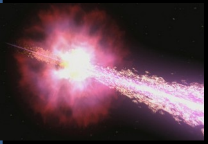


Based on photons number and position likelihood

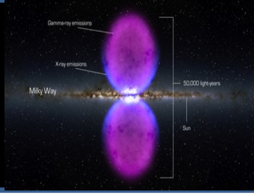
ANTARES & GVD: similar resolutions

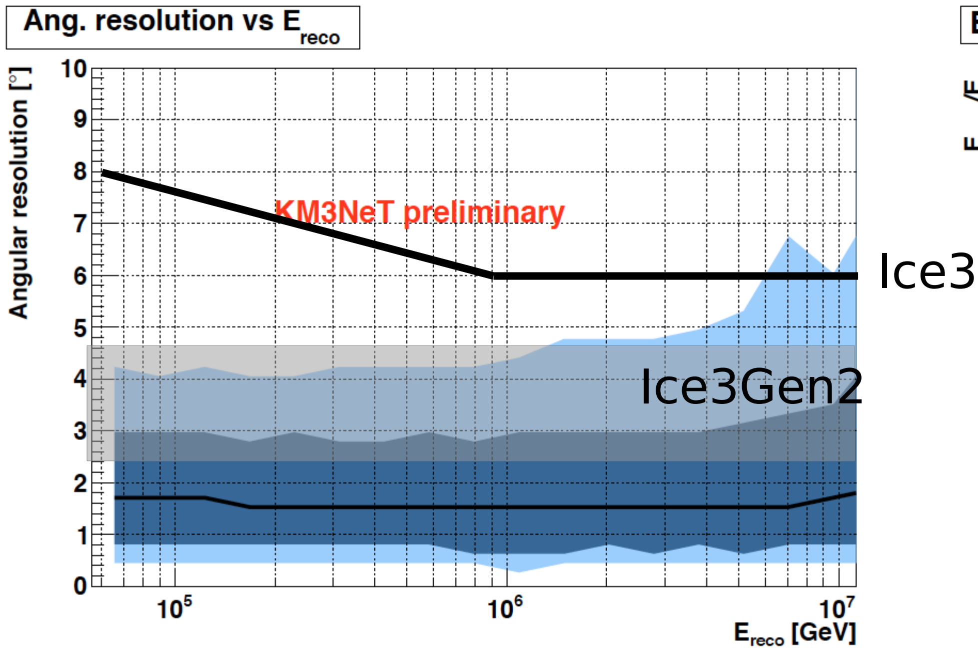


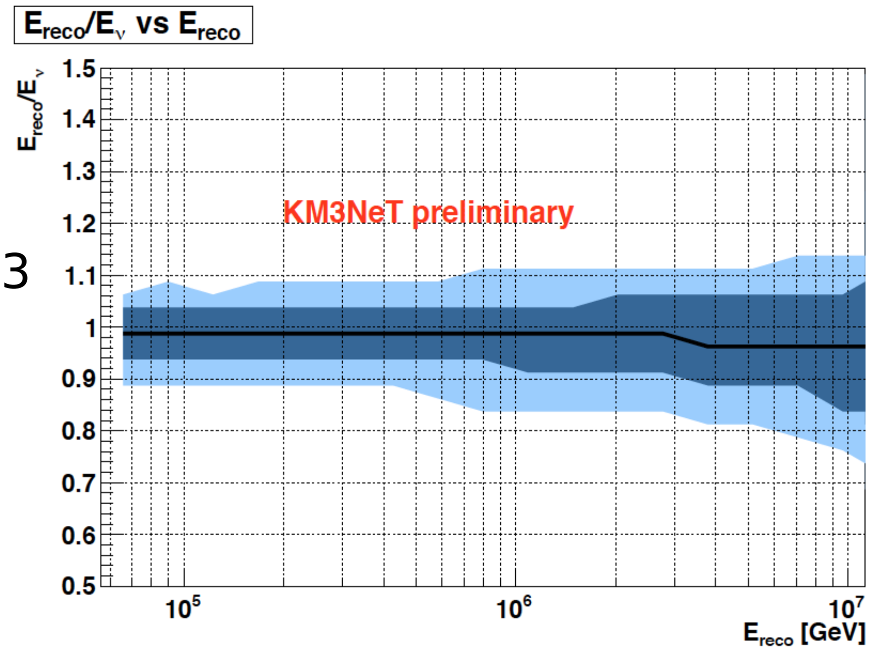


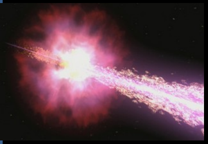


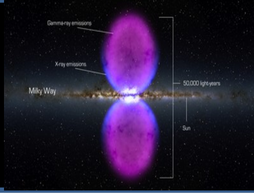
Shower reconstruction prospects



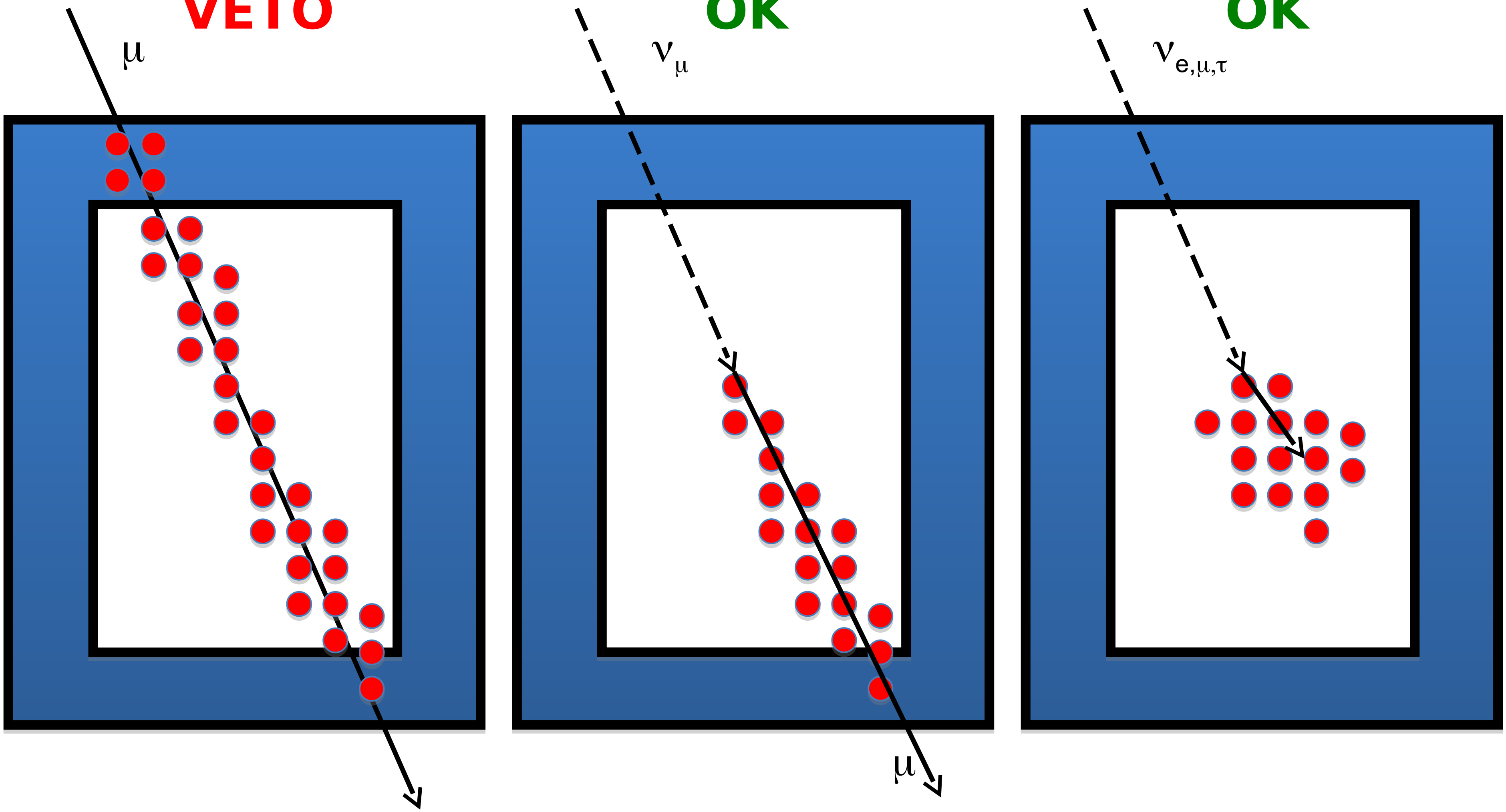


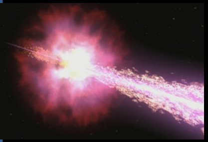




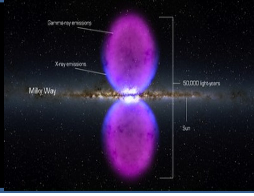


High Energy Starting Events





Existing Data Samples Characteristics

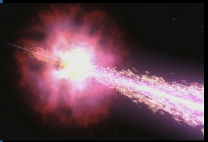


Sample	Ang. Res.	Energy Res.	Stat.
IceCube trck Up-going Down-going	O(0.3) °	0.3xLog(E)	HE ν tracks, 80k evt/yr VHE μ tracks 35k evt/y
Antares trck Up-going	O(0.2)°	0.3xLog(E)	HE ν tracks a few k evt/yr
IceCube Casc	~5-15°	1-10%	O(10) evt/yr
Antares Casc.	2.5-10°	10%	1-10 evt/yr
Baïkal cascades	4.5°	30%	5 evt/yr (>100TeV)

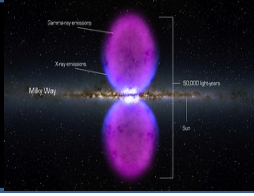
Potential μ contamination up to ~10%

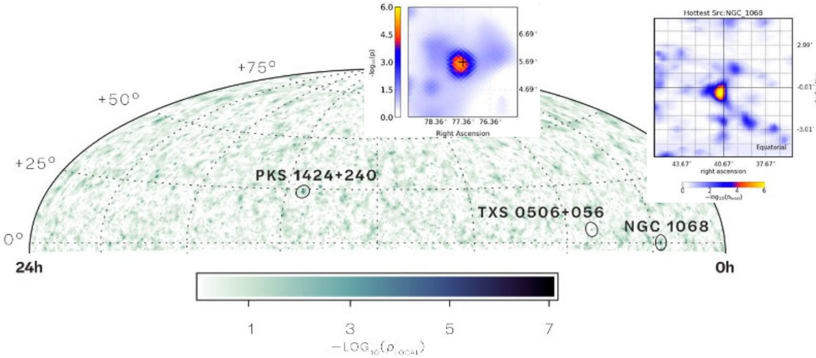
Available “Open samples”:
HESE and HE Alerts
~10/yr >50%, “signalness”
(i.e. 1-atm.pro.)

PS search samples (I3 trcks, Ant. trks+casc.)
high statistics/overwhelming atm. background
Searched signal dependent selection



Observed signals

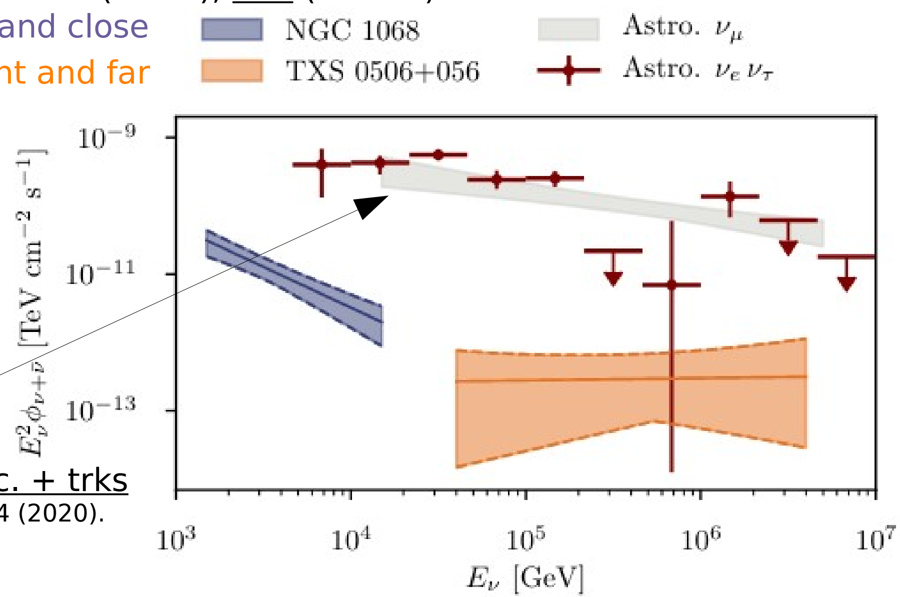




Point sources (AGNs), trks (+casc.)

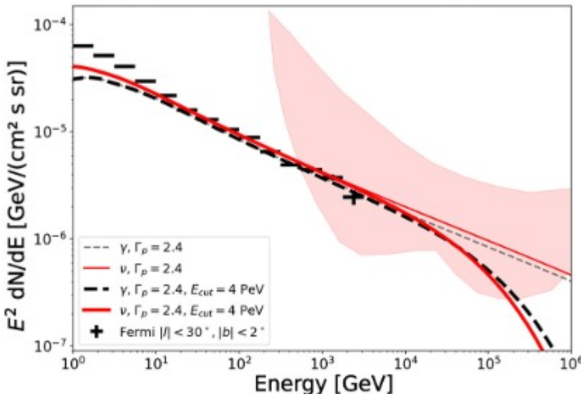
Steady and close

Transient and far



Ice3 Diffuse flux casc. + trks

Phys. Rev. Lett.125, 121104 (2020).



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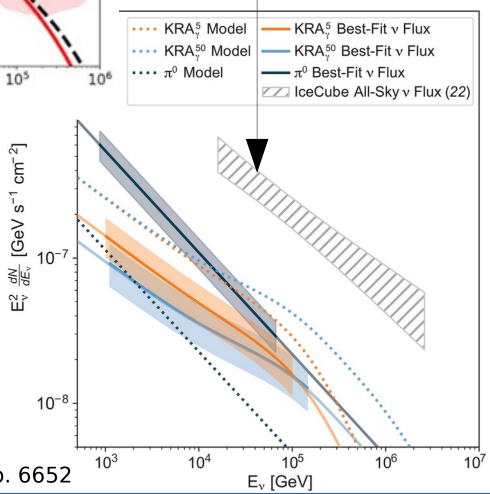
Phys. Let. B, Volume 841, (2023) 137951

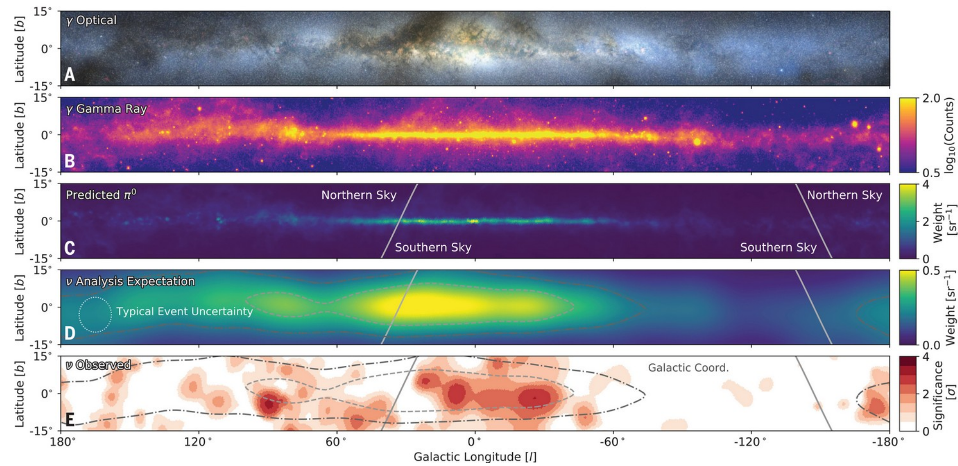
Extended source:

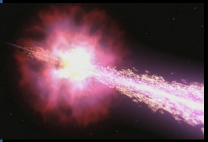
Galactic ridge, casc. (+trks)



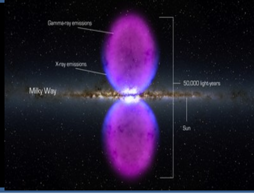
IceCube:

Science Vol. 380, No. 6652





Summary & Perspectives



- Hard to detect, Gigaton detector needed, hard environment (2000+m deep)

- Second generation telescopes now running or in construction:
  technology is mature and detectors big enough

- HE neutrino astronomy is born, even if not many/strong confirmed sources yet

<u>Take home message:</u>

- Several types of events w. differentf characteristics
  => different types of searches and analyses

- Complementatrity of existing projects w.r.t. pointing and energy reconstructon resolutions, instantaneous and integrated sky coverage
  => important for MM offline searches and online follow-up

- KM3NeT on its way, will confirm IceCube and dig in galactic sources