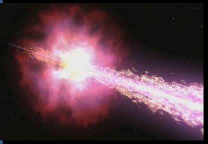
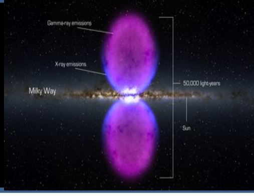
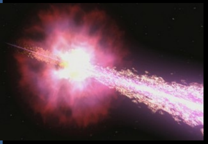


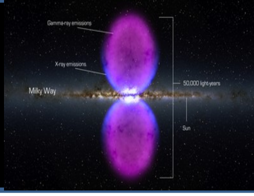


High Energy Neutrino Telescopes
&
The Search for Quantum Gravity

Bruny Baret
APC Paris (CNRS)



Why VHE neutrinos ?

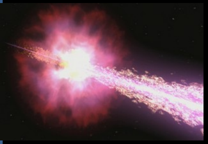


Extremely light → extreme Lorentz factor

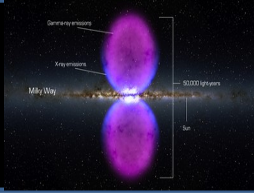
Weak interaction → travel cosmological distances

↓

Accumulate potential spacetime
Interaction effects

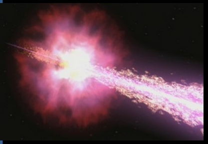


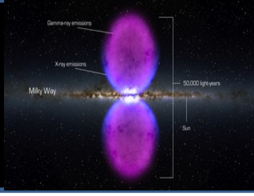
How to search for L.I.V. or D.S.R.

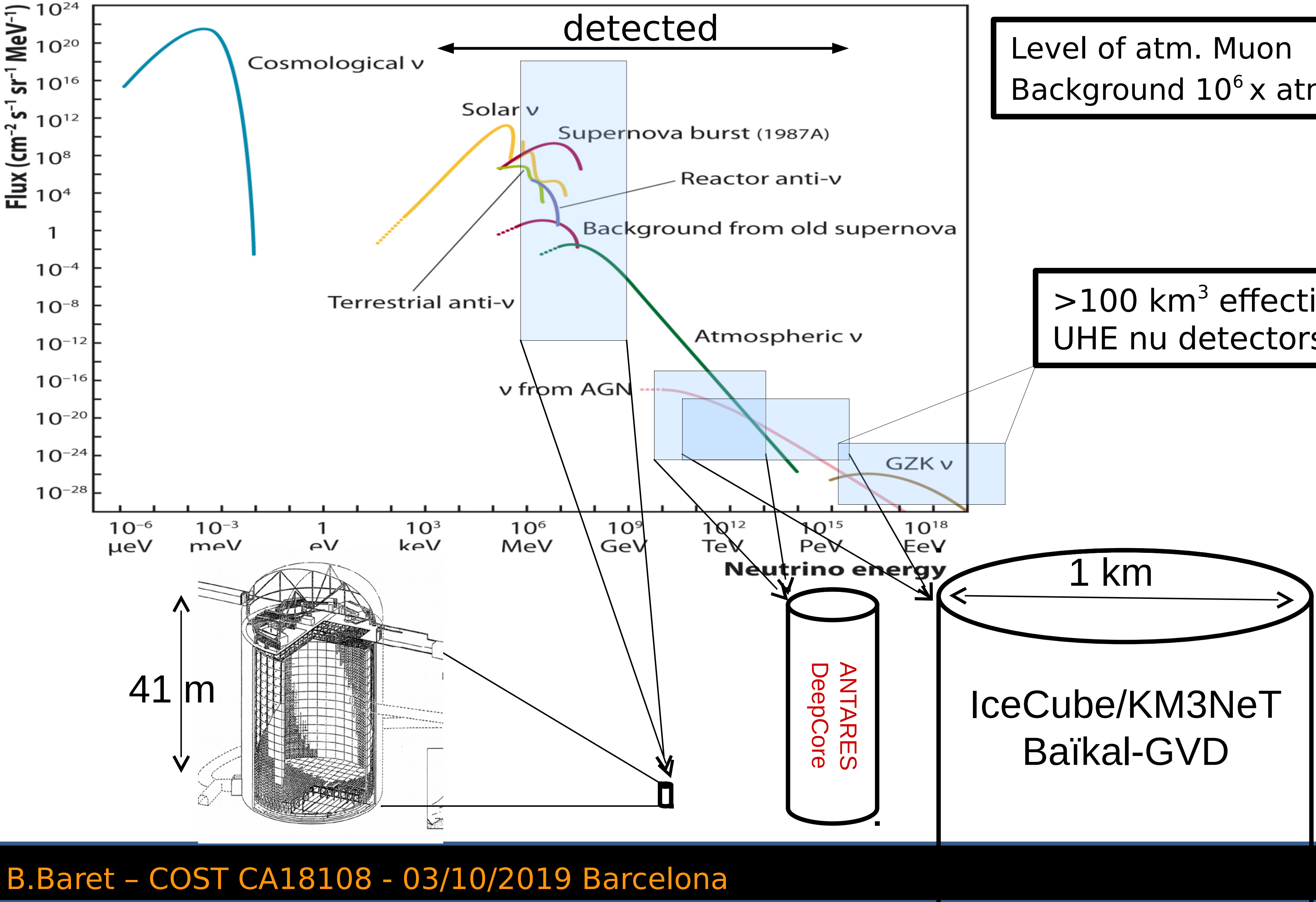


	Gamma-rays	Neutrinos	Sources	
TOF difference	γ @ diff. E	$\nu - \gamma$	AGNs, GRBs	ν telescopes
Evolution of	polarisation	flavor	VHE diffuse	
Flux suppr.	VHE	UHE	"GZK"	UHE ν det

Hard to detect

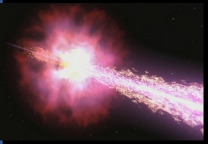




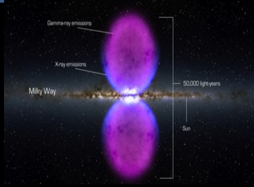


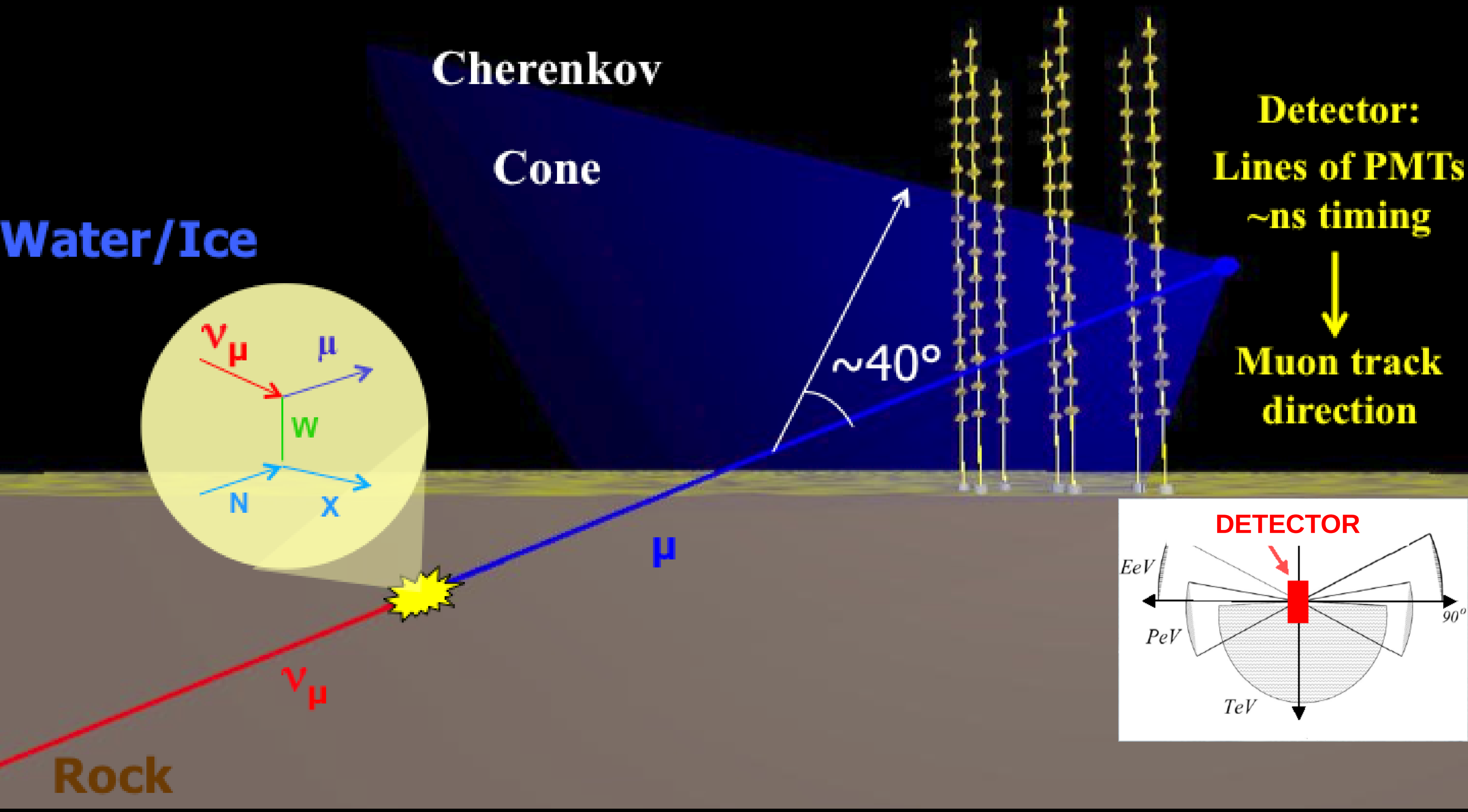
Level of atm. Muon Background 10^6 x atm ν

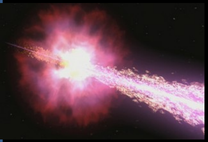
>100 km^3 effective UHE nu detectors



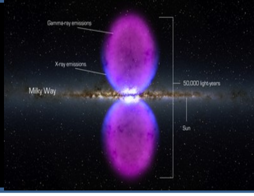
Nu-Telescope pratically: seeing muon tracks

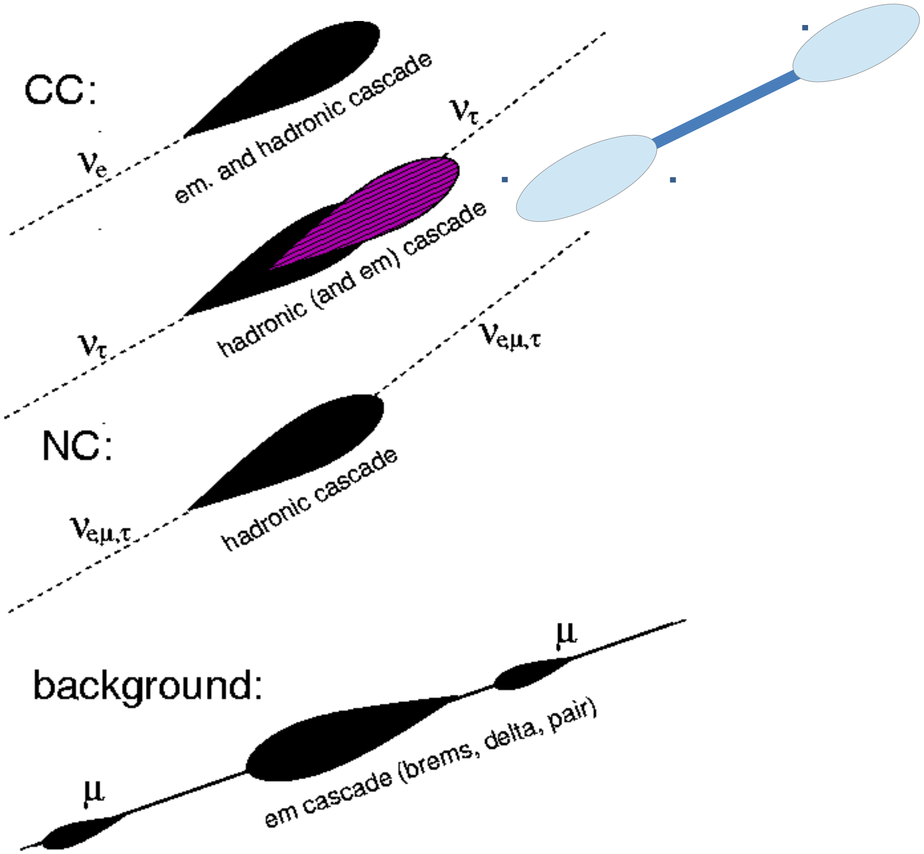




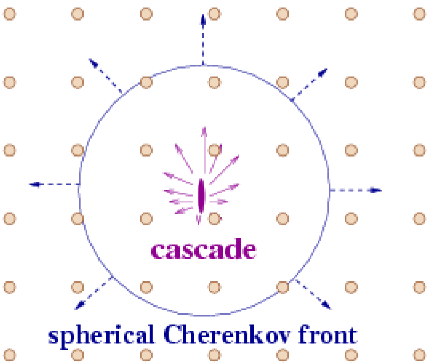


Other channels





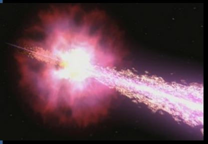
“shower” events



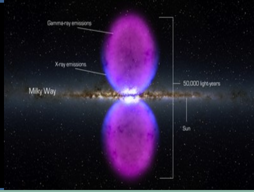
Contained events (~10m)
+ energy reconstruction
- effective volume

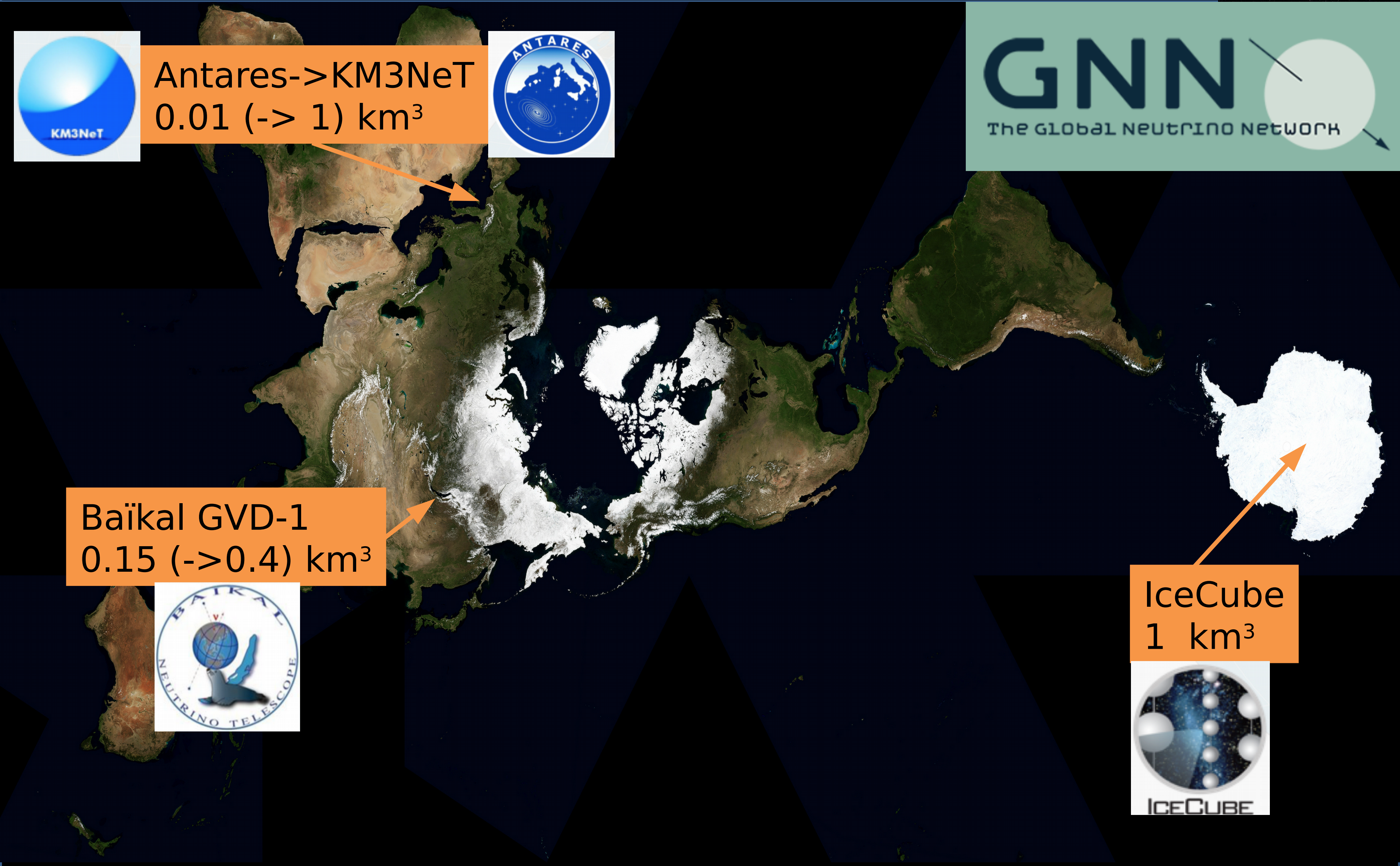
topology
+ identification
- angular resolution

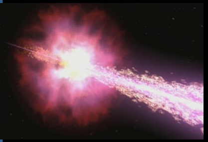
Diffuse flux (and...)



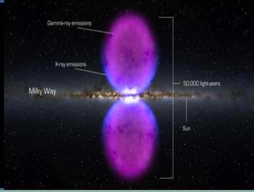
ν-Telescopes today

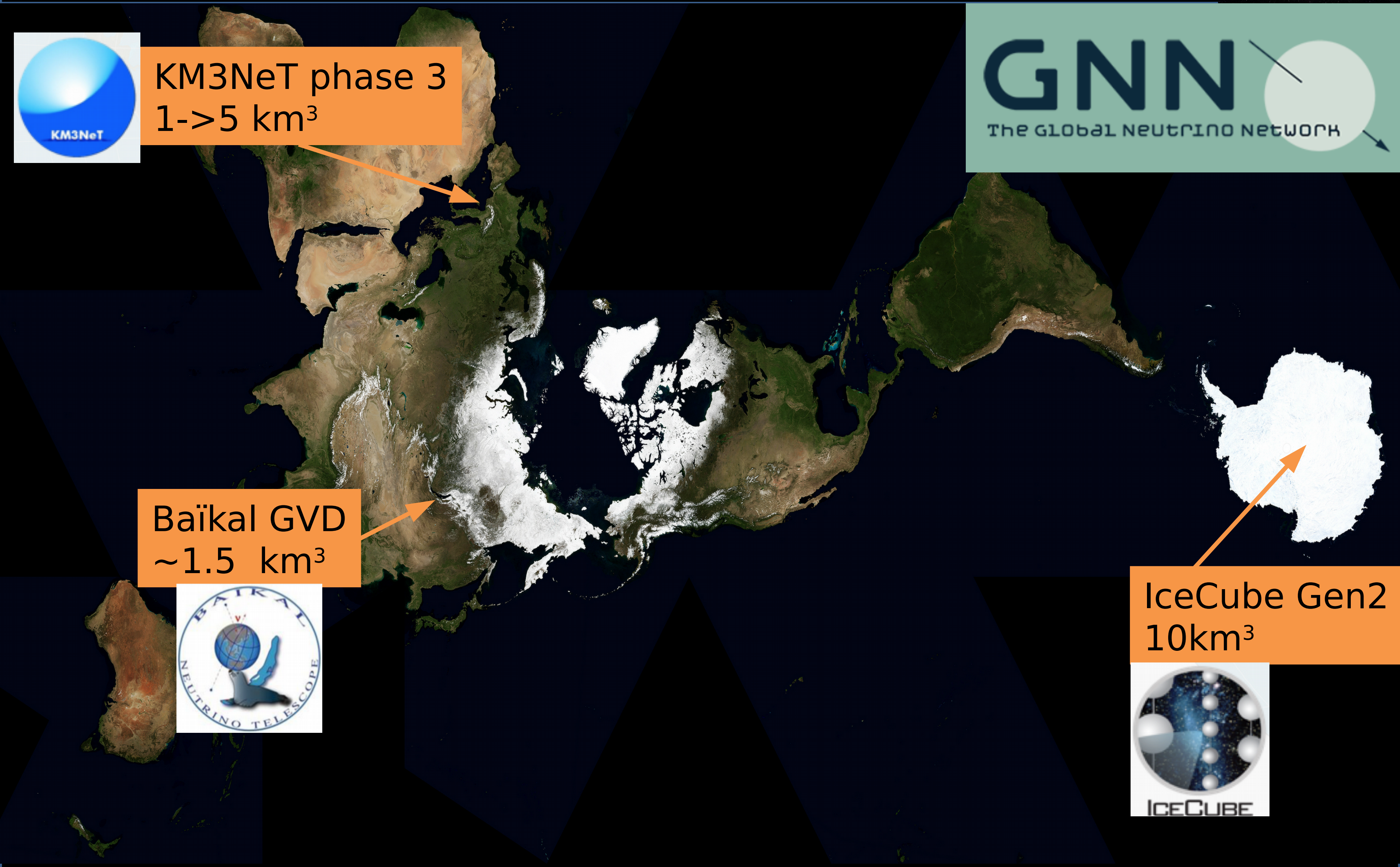






ν-Telescopes tomorrow



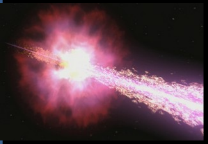


KM3NeT phase 3
1->5 km^3

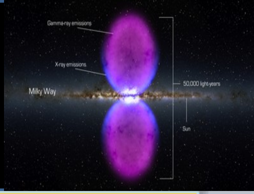
Baïkal GVD
~1.5 km^3

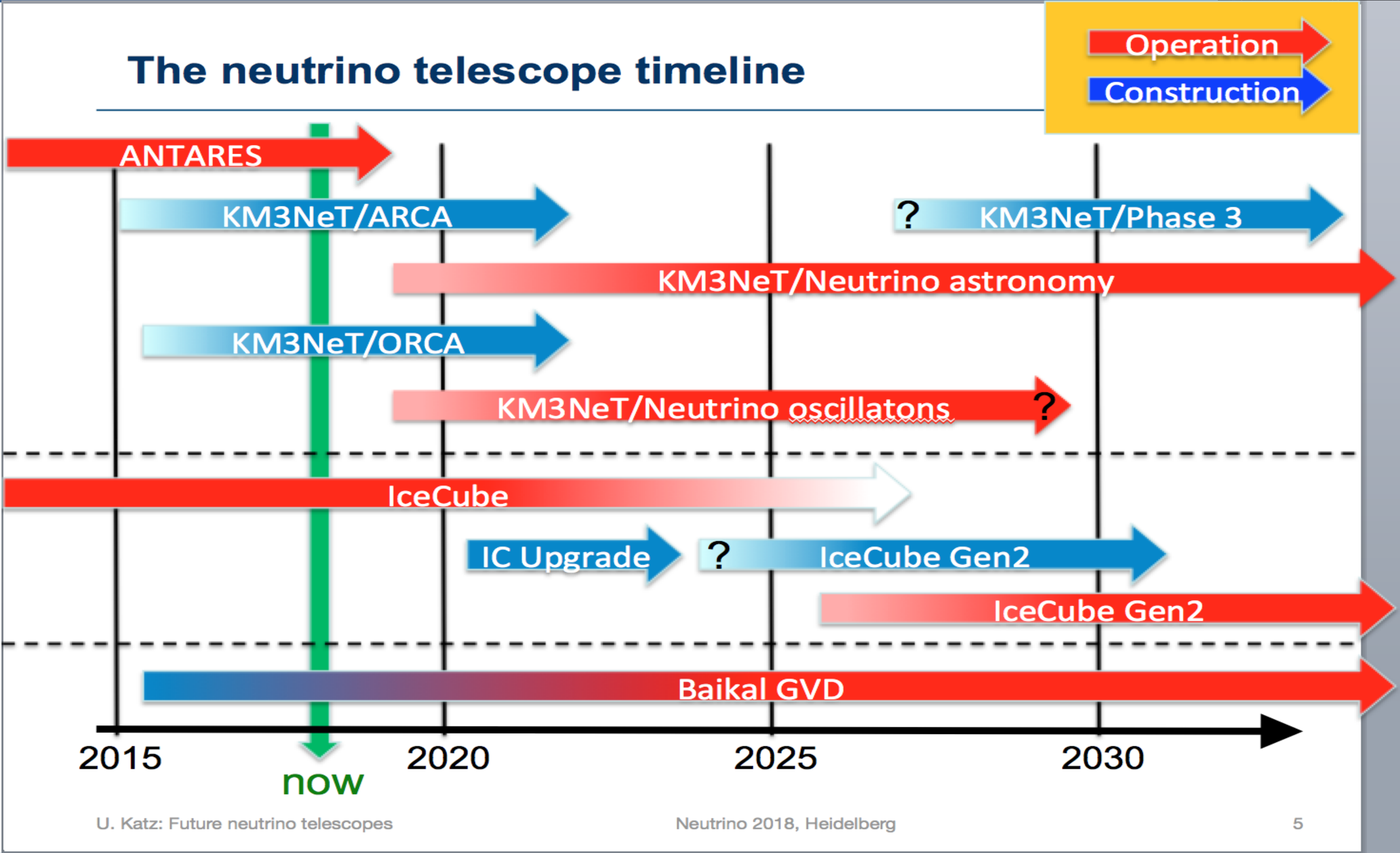
IceCube Gen2
10km^3

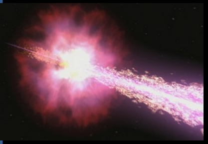
GNN
The Global Neutrino Network



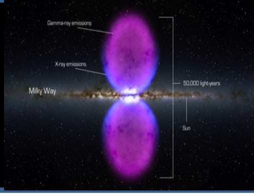
Timeline



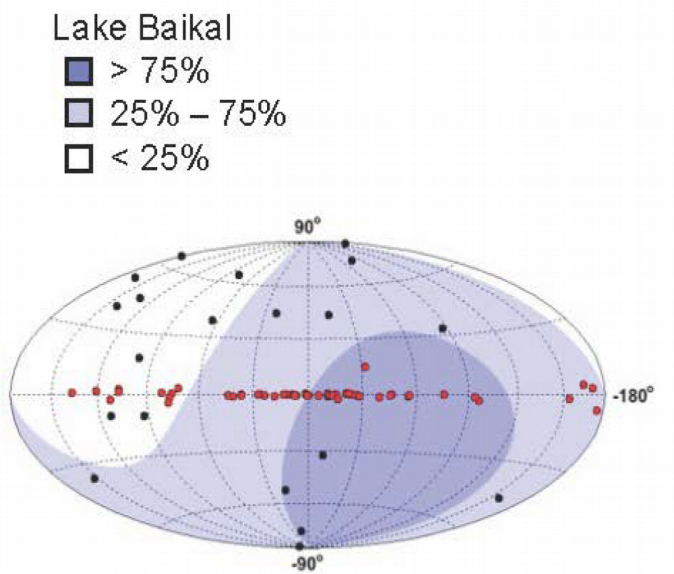

The neutrino telescope timeline
Operation
Construction
ANTARES
KM3NeT/ARCA
?
KM3NeT/Phase 3
KM3NeT/Neutrino astronomy
KM3NeT/ORCA
KM3NeT/Neutrino oscillatons
?
IceCube
IC Upgrade
?
IceCube Gen2
IceCube Gen2
Baikal GVD
2015
now
2020
2025
2030
U. Katz: Future neutrino telescopes
Neutrino 2018, Heidelberg
5

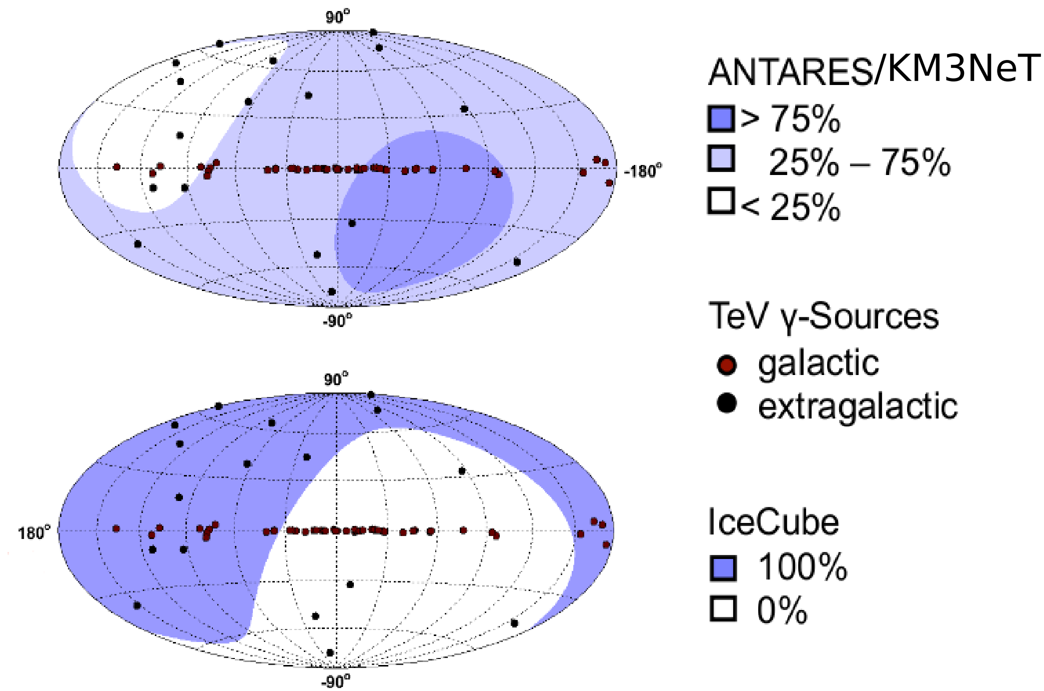


Water V.S. Ice



- <u>Complementary coverage (μ channel)</u>



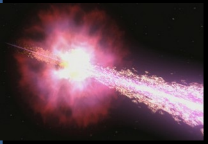


- <u>Water v.s. Ice</u>

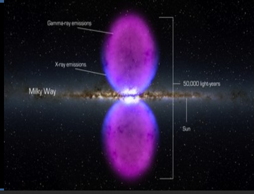
  Optical noise (biolum) / no noise

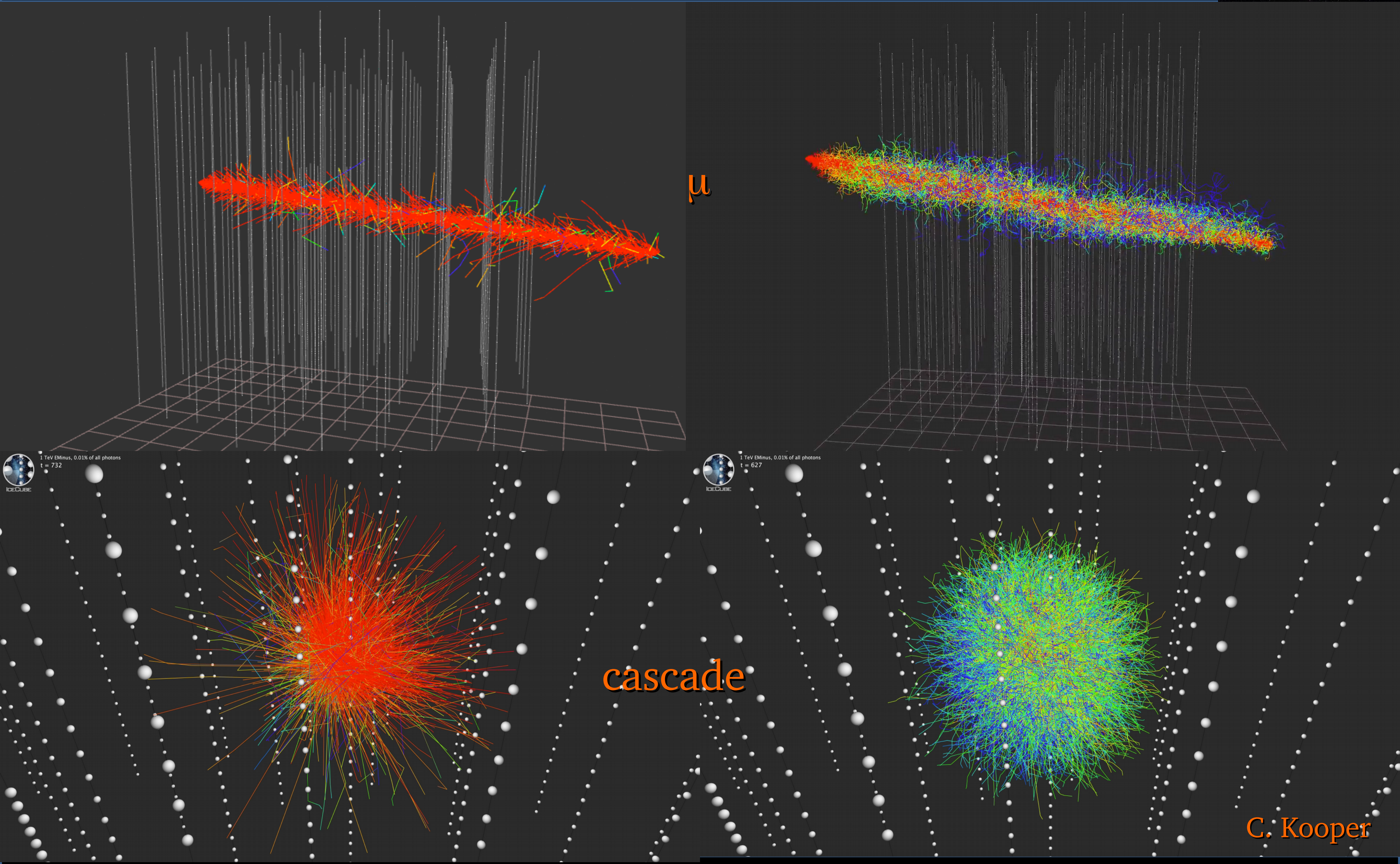
  absorption / diffusion

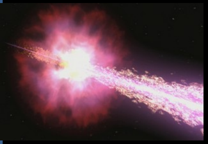
  pointing / calorimetry



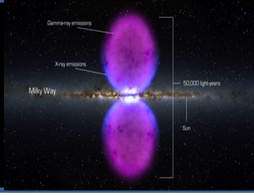
Water V.S. Ice (Monte Carlo Simulations)



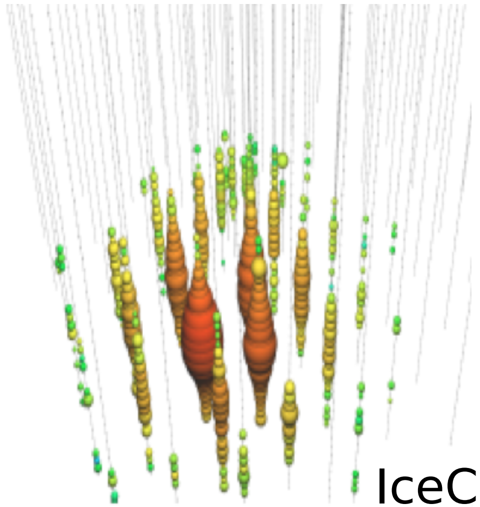




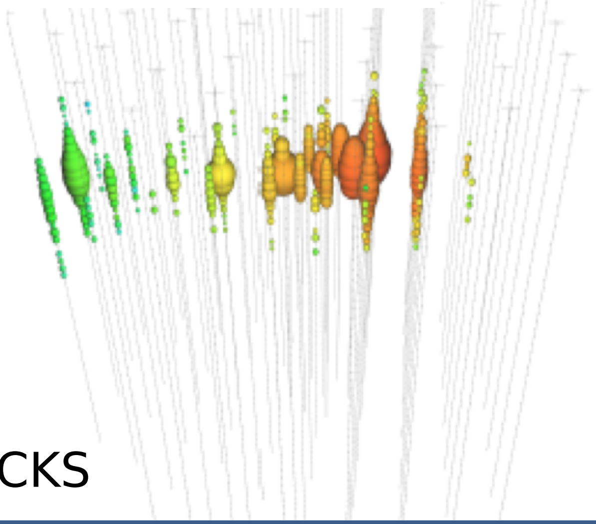
Water V.S. Ice (in real life)



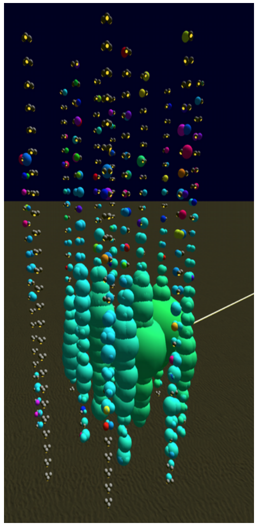
Cascades



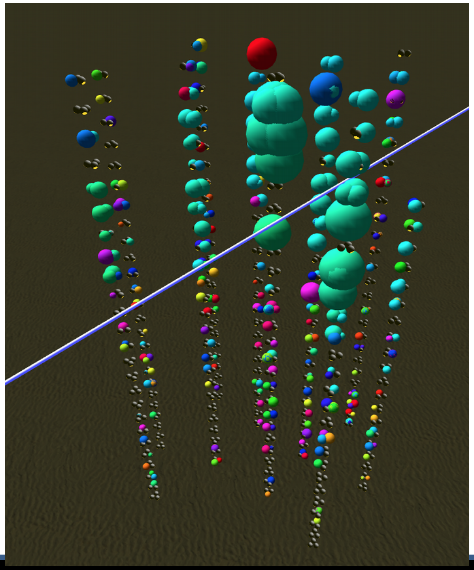
IceCube



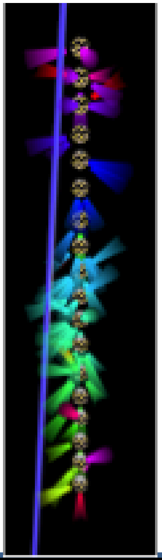
TRACKS

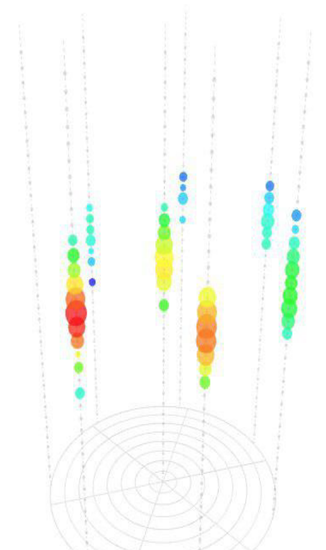


Antares

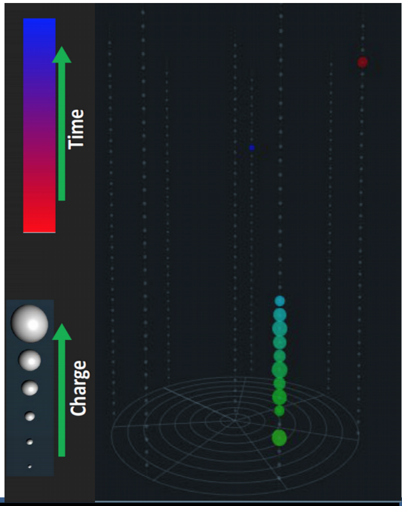


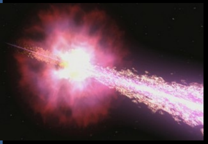
ORCA

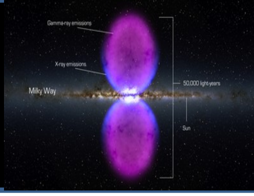




Baikal-GVD







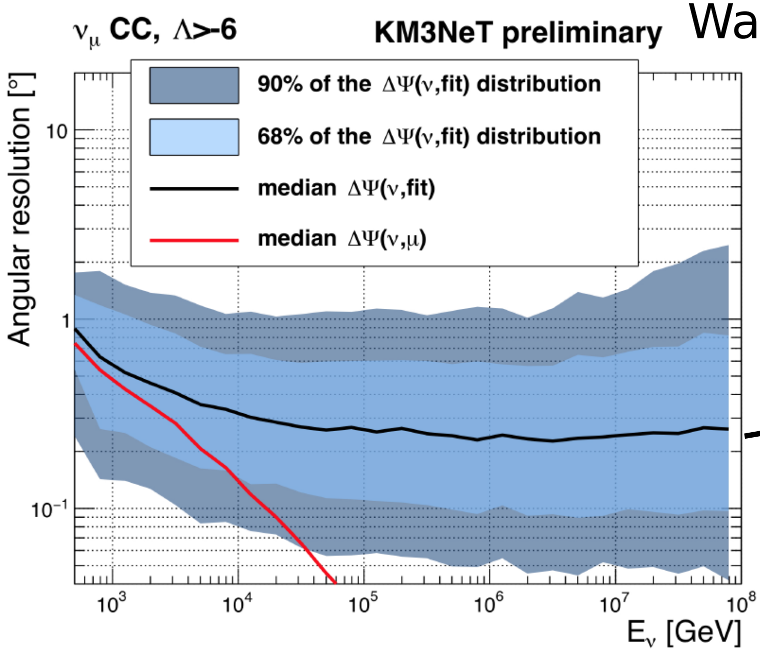
Size of some astrophysical objects :
RXJ1713 (SNR):1°
Sun, Moon : 0.5°
Cen A (AGN) : 0.3°

Point sources search:
Signal/Noise : $1/\Delta\Omega^2$

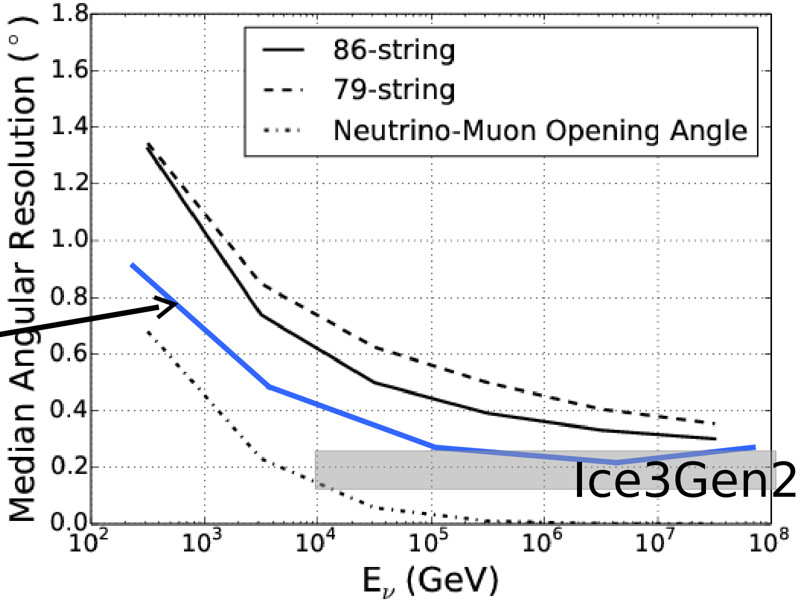
Based on photons time and position likelihood

Muons:

Water

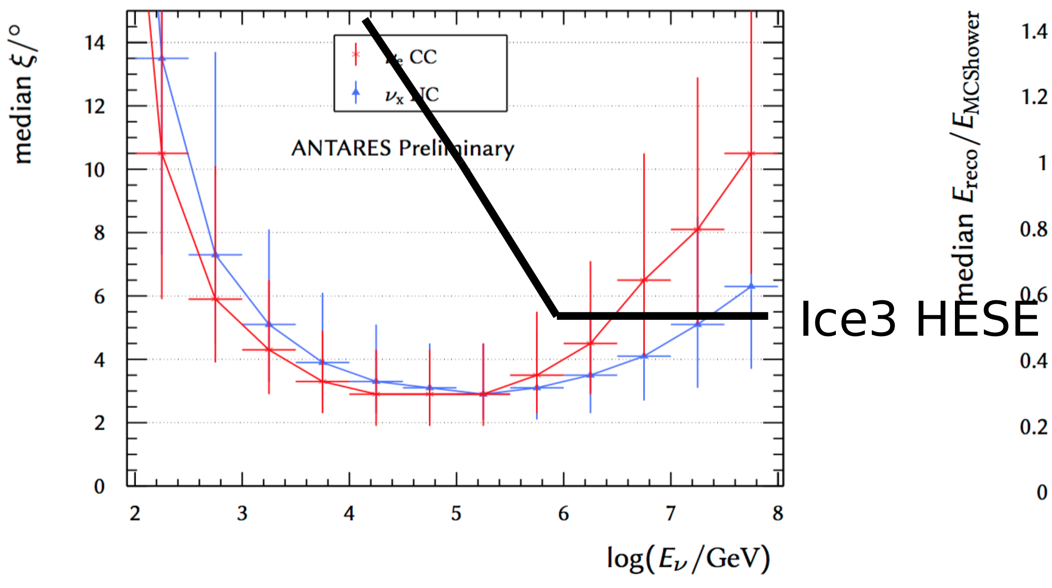


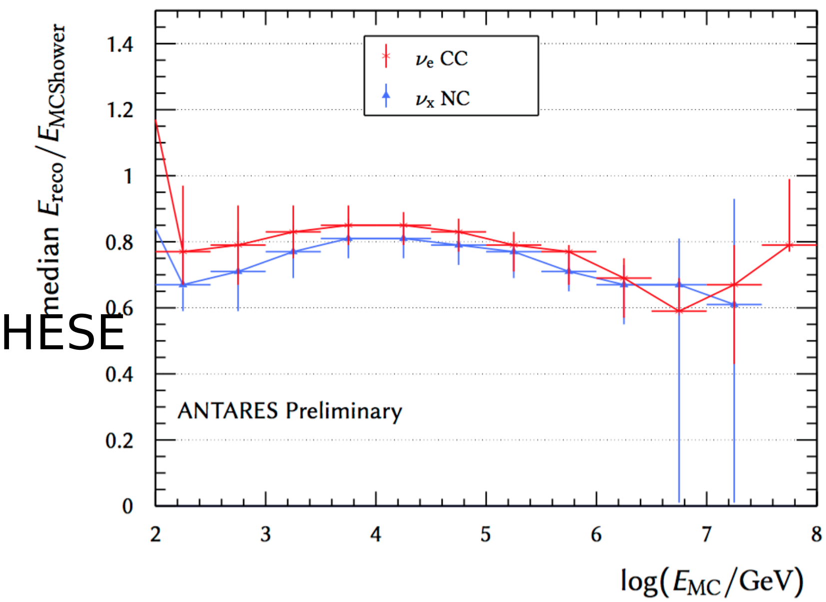
Ice

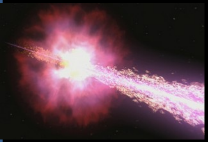


Based on photons number and position likelihood

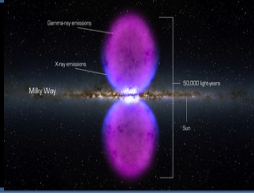
ANTARES & GVD: similar resolutions



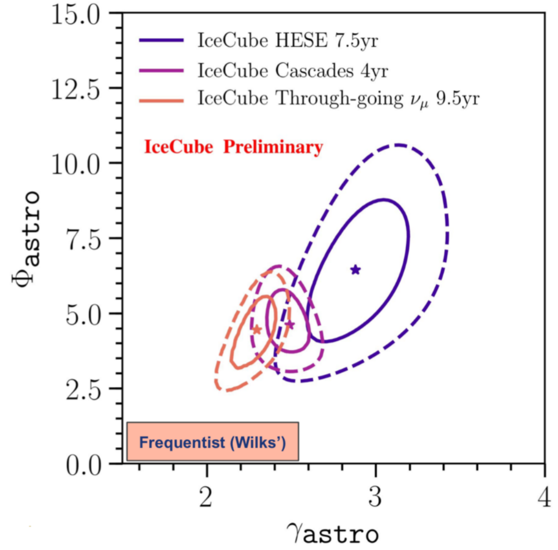


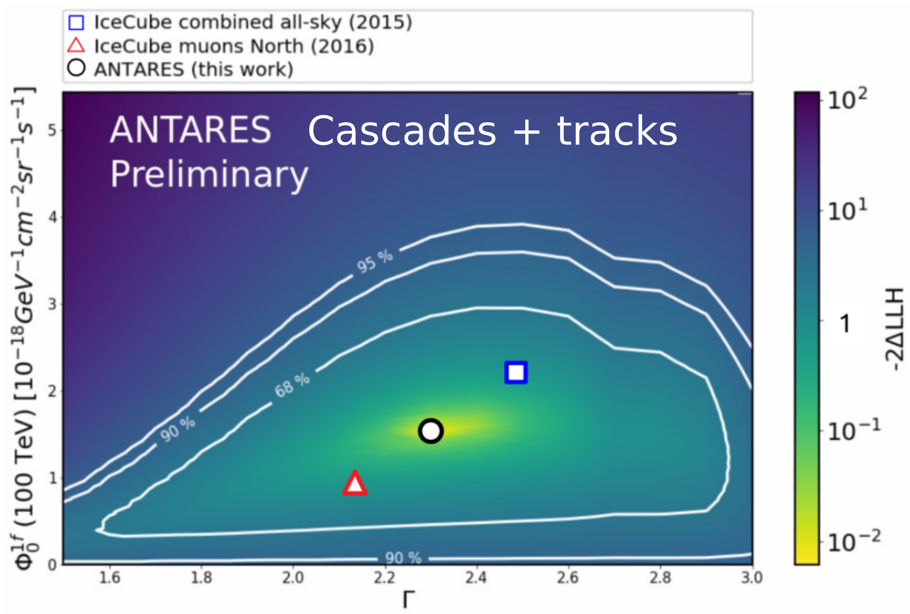


A Diffuse Flux

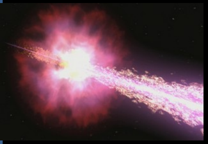


$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{\mathrm{astro}} \left(\frac{E_\nu}{100\mathrm{TeV}} \right)^{-\gamma_{\mathrm{astro}}} \cdot 10^{-18} \, [\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$$

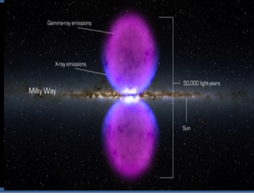




Name	Approx. Neutrino Energy	Direction	Dominant Flavor	Unbroken Spectral Index
HESE	50 TeV - 5 PeV	All-sky	e, μ, τ	2.89
Cascades	5 TeV - 5 Pev	All-sky	e, τ	2.48
NuMu	50 TeV - 10 PeV	Northern sky	μ	2.28

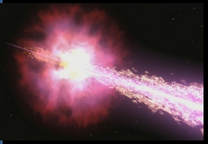


Where from?

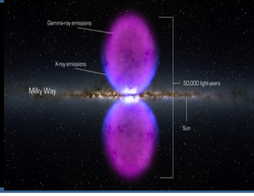


- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
    [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - association with diffuse γ-ray background [Murase, MA & Lacki'13]
    [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
  - active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
    [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
    [Padovani & Resconi'14; Petropoulou, Dimitrakoudis, Padovani, Mastichiadis & Resconi'15]
  - gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
  - galaxies with intense star-formation
    [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13]
    [Murase, MA & Lacki'13; Anchordoqui, Paul, da Silva, Torres& Vlcek'14]
    [Tamborra, Ando & Murase'14; Chang & Wang'14; Liu, Wang, Inoue, Crocker& Aharonian'14]
    [Senno, Meszaros, Murase, Baerwald & Rees'15; Chakraborty & Izaguirre'15]
  - galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
  - . . .

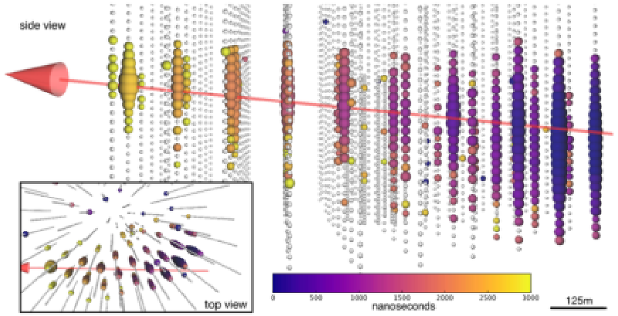
Adapted from M. Ahlers

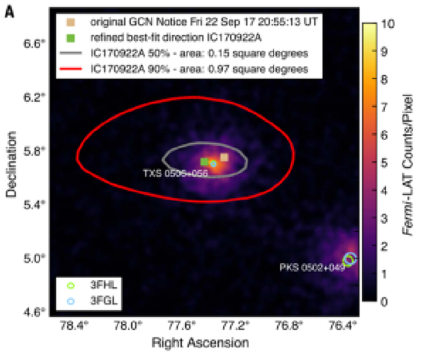


TXS 0506+056



Sept. 22, 2017:
A neutrino in coincidence with a blazar flare



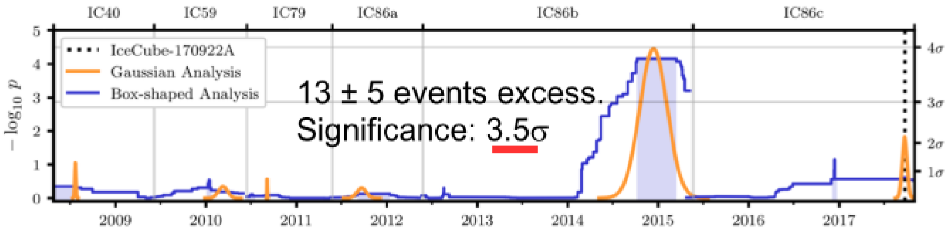


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

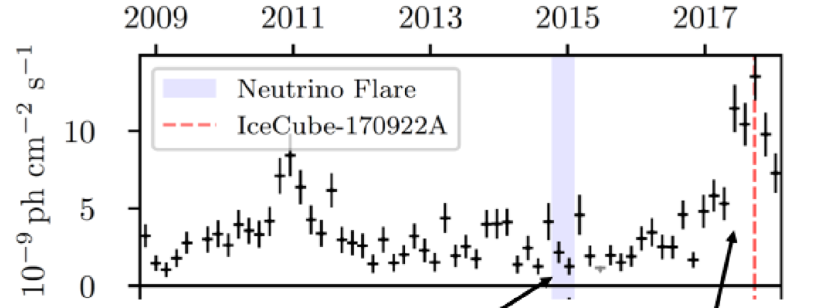
Science 361 (2018) no. 6398, eaat1378

2014-2015: A (orphan) neutrino flare found from the same object in historical data



Science 361 (2018) no. 6398, eaat2890

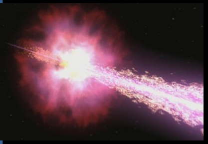
Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192



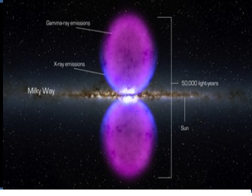
At 2014-15 neutrino flare

The 2017 flare

Adapted from A. Kappes



Back to QG searches



T. Jacobson et al. Ann. Phys. 321, 150 (2006),

- Theories of Quantum Gravity (deformed relativity, LQG, non-communtative geometry, some string theories...
-> Lorentz Invariance Violation at the Planck scale

- Some QG can be effectively parametrized at “low energy”

G. Amelino-Camelia, et al., Nature 393, 763 (1998).
D. Colladay et al. Phys. Rev. D 55, 6760 (1997),
V. A. Kosteleck´y et al. Phys. Rev. D 80, 015020 (2009)

Propagation dispersion relation :

$$E^2 - p^2c^2 = \pm E^2 \cdot (E/M_{\mathrm{LIV}})^n + m_\gamma^2 \times c^4$$

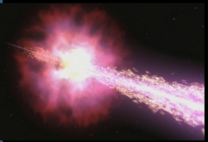
$$v = \partial E/\partial p$$

sizeable effect : n=1

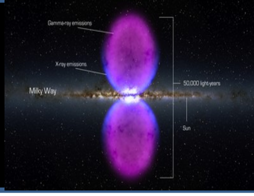
$$\Delta t_{\mathrm{LIV}} = (\pm 1) \cdot E/M_{\mathrm{LIV}} \cdot D(z)/c$$

$$D_{\mathrm{LIV}}(z) = \frac{c}{H_0} \int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

U. Jacob and T. Piran, JCAP 0801 (2008)
G. Amelino-Camelia et al., Astrophys. J. 806(2), 269 (2015)



TOF with TXS 0506-056



J. Ellis et al. Phys.Lett. B789 (2019) 352-355:

IceCube – MAGIC detections: delay of 10 days, distance of 4 Gl.y.

E(IC170922A)=200TeV, E(MAGIC) negl. ,

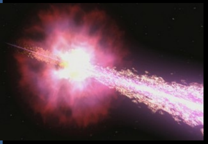
$$M_1 = (M_{1,\gamma} \times M_{1,\nu})/(M_{1,\gamma} - M_{1,\nu})$$

or

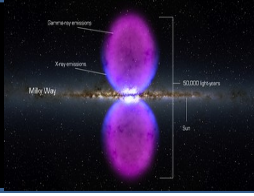
$$M_1 \to \text{the smaller of } M_{1,\gamma} \text{ and } M_{1,\nu}$$

$$\Delta v_{\nu\gamma} = -E/M_1 \longrightarrow M_1 \gtrsim \frac{H_0^{-1}}{\Delta t} E \int_0^{z_{\rm src}} \frac{(1+z)}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \approx 3 \times 10^{16} \text{ GeV}$$

$$\Delta v_{\nu\gamma} = -E^2/M_2^2 \longrightarrow M_2 \gtrsim \left[\frac{3}{2} \frac{H_0^{-1}}{\Delta t} E^2 \int_0^{z_{\rm src}} \frac{(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \right]^{1/2} \approx 10^{11} \text{ GeV}$$

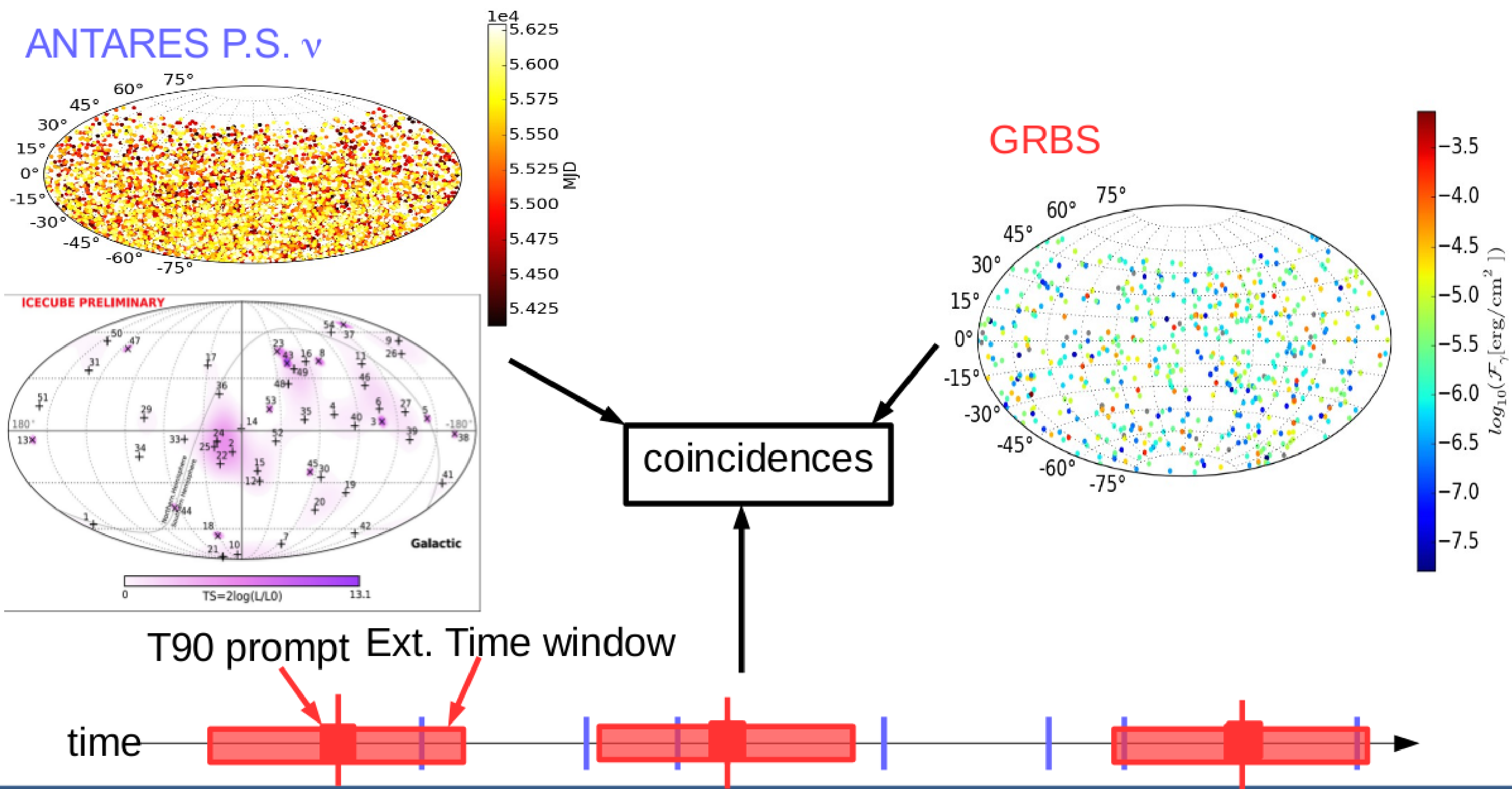


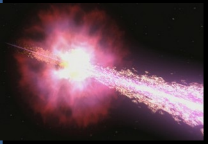
Using GRBs and time of flight



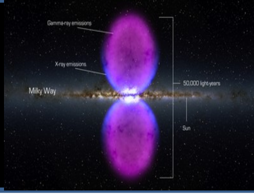
Search for:

- neutrinos shifted w.r.t. the prompt emission out of the T90 time window
- Correlation between time shift and energy





Hints? (theorist view)



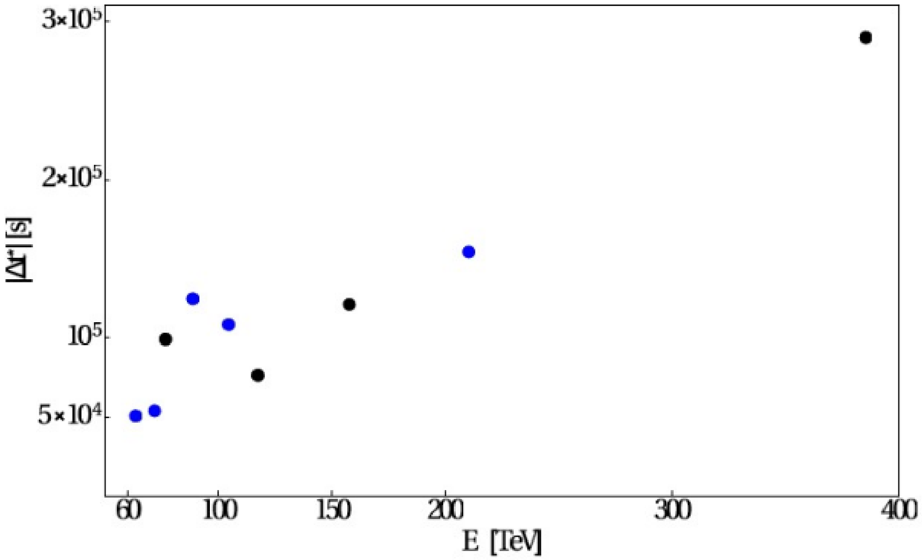
Amelino-Camelia et al (2015):
track channel data -> 2010 : 2 low significance events 2-3x10^3 s before 2 GRBS

Amelino-Camelia et al (2016) arXiv:1605.00496v1:
cascade channel data 2010-> 2014

Correlation=0.8-0.95 p-value=1%

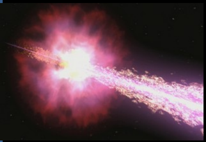
$$\Delta t^* \equiv \Delta t \frac{D(1)}{D(z)}$$

$$\Delta t^* = \eta \frac{E}{M_P} D(1) \pm \delta \frac{E}{M_P} D(1)$$

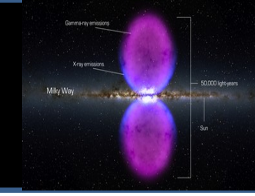


- Directional coincidence:
Within 2σ of instrument resolution
- Time coincidence: <6 days
- Energy: 60-500TeV
- Unknown z -> default values

Avoid multiple coincidences



Hints? (theorist view)



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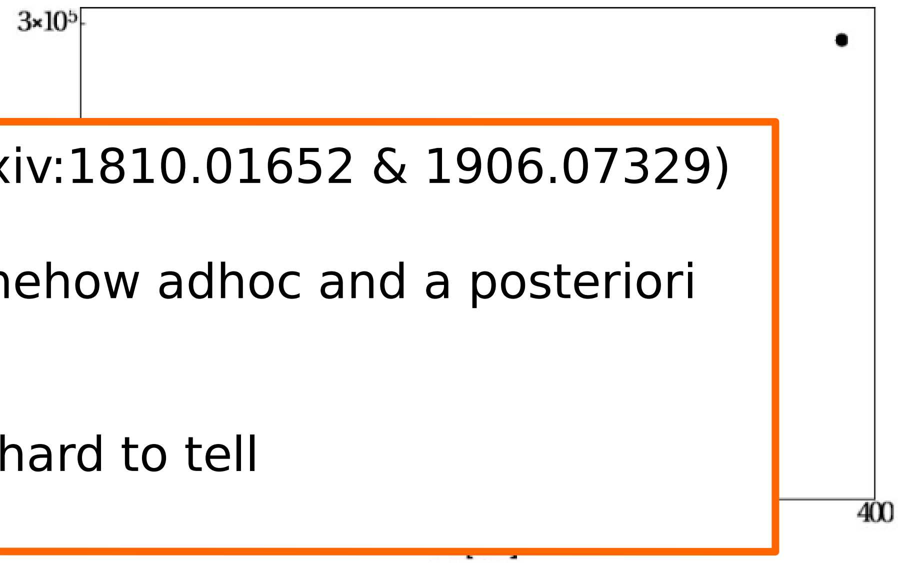


$$\Delta t^* \equiv \Delta t \frac{D(1)}{D(z)}$$

$\Delta t^* = \eta$ …

- Direc…
Within …

- Time…

Update by Yanqi Huang et al. (arxiv:1810.01652 & 1906.07329)

However, selection criteria somehow adhoc and a posteriori

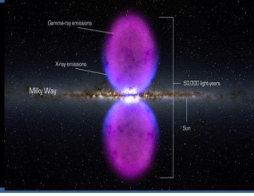
Significance hard to tell

- Energy: 60-500TeV

- Unknown z -> default values

Avoid multiple coincidences

Time stacking (experimentalist view)



Blind selection of GRBs

Stacked variables :

$$\tau_{obs} = t_\nu - t_{GRB}$$ Generic time delay

$$\tau_z = \tau_{obs}/(1+z)$$ Fixed delay at the source

$$\tau_{LIV} = \frac{\tau}{E_{est} \cdot D(z)}$$ L.I.V. efffects

Test Statistic :

$$\psi = -10 \log_{10} p(D|H,I)$$
$$= -10 \left[\log_{10} n! + \sum_{k=1}^{m} n_k \log_{10} p_k - \log_{10} n_k! \right]$$

- Maximum time delay 42 days:

set by maximum expected L.I.V. shift (other effects shorter OR arbitrarily long)

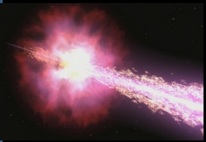
Directional coincidence:

$$\delta_{cut} = 1.58 \cdot \max(\sigma_\nu,\ min(\Delta_{err}, \Delta_{err}^{max}))$$

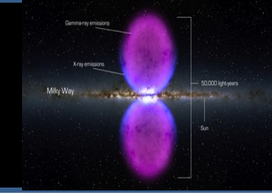
coinc. Δ_{err}^{max}) < 10 # coinc. σ_ν)

maximise Sig/Bgd — ν resolution — GRB error box

Compute z dependent quantities for measured z only. ⟵ Avoid bias



Results



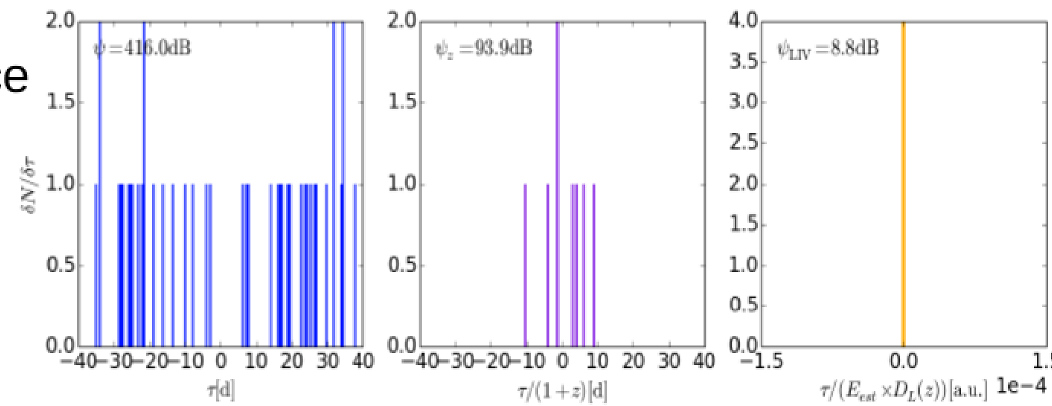
Results:

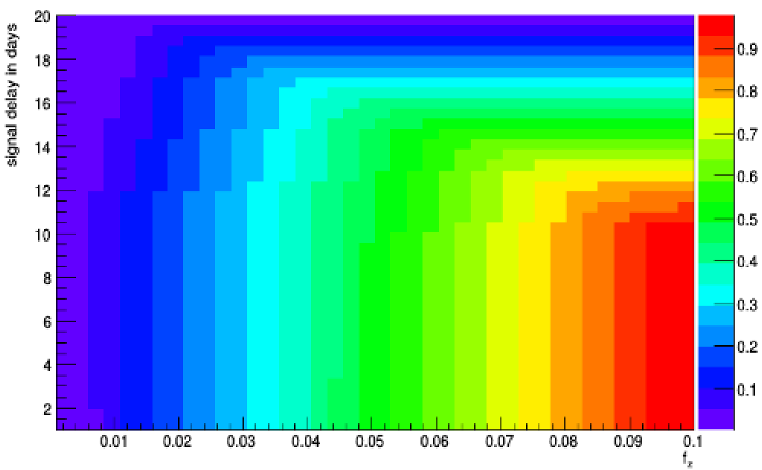
Eur.Phys.J. C77 (2017) no.1, 20

ν telescope data	τ_{tot} (d)	N_{events}	$m(\delta)$ (°)	δ_{max} (°)	τ_{max} (d)	N_{GRB}	$N_{GRB,z}$	n_{coinc} (uncorrelated)	$n_{coinc,z}$ (uncorrelated)	Meas. w. z	Meas. w.o. z	P-value	P-value
ANTARES (07-12)	2154	5516	0.38	0.51 – 1.59	40	563	150	3.9	0.7	0	0	1.2%	51.4%
IC40 (08-09)	408	12876	0.70	0.95 – 2.99	40	60	12	35.0	4.0	42	8	13.5%	5.1%

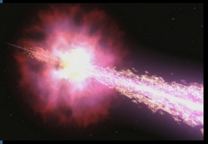
Sensitivity (Antares):

Signal delayed of 5 days at the source

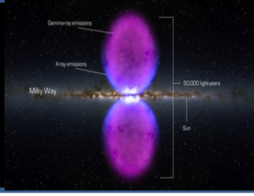




Test Statistic	Sensitivity at 90% CL f_{all}	Sensitivity at 90% CL f_z	Sensitivity at 99% CL f_{all}	Sensitivity at 99% CL f_z	$\mathcal{MDP}$ 3σ f_{all}	$\mathcal{MDP}$ 3σ f_z	$\mathcal{MDP}$ 5σ f_{all}	$\mathcal{MDP}$ 5σ f_z
r	0.8%	3%	1.5%	5.5%	2.4%	9%	4.5%	17%
ψ	0.6%	2.2%	1.3%	5%	1.3%	5%	2.4%	9%
ψ_Z	0.3%	1.1%	0.8%	3%	0.6%	2.3%	1.2%	4.5%
ψ_{LIV}	0.3%	1.1%	0.8%	3%	1.5%	5.5%	3%	12.5%



Results



Eur.Phys.J. C77 (2017) no.1, 20

Results:

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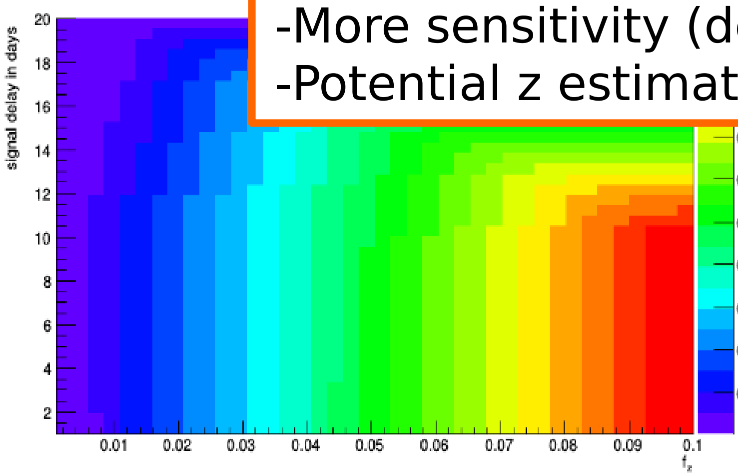
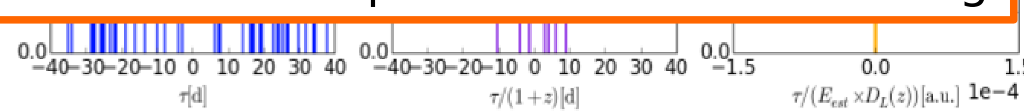
IC40 (08-09)	408	12876	0.70	0.95 – 2.99	40	60	12	35.0	4.0	42	8	13.5%	5.1%

Sensitivity

Signal del

UPDATE soon with:
-More data (2007-2018 => x 2)
-More flavors (adding cascades, signal x 1.2)
-More sensitivity (dedicated “cuts”=> sensitivity x 1.5)
-Potential z estimation from other GRB parameters when missing





Test Statistic	Sensitivity at 90% CL f_{all}	Sensitivity at 90% CL f_z	Sensitivity at 99% CL f_{all}	Sensitivity at 99% CL f_z	MDP 3σ f_{all}	MDP 3σ f_z	MDP 5σ f_{all}	MDP 5σ f_z
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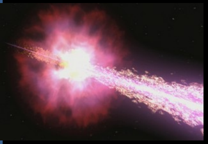
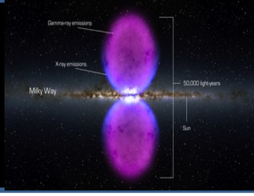
ψ	0.6%	2.2%	1.3%	5%	1.3%	5%	2.4%	9%
ψ_z	0.3%	1.1%	0.8%	3%	0.6%	2.3%	1.2%	4.5%
ψ_{LIV}	0.3%	1.1%	0.8%	3%	1.5%	5.5%	3%	12.5%



Using flavor composition of cosmic flux

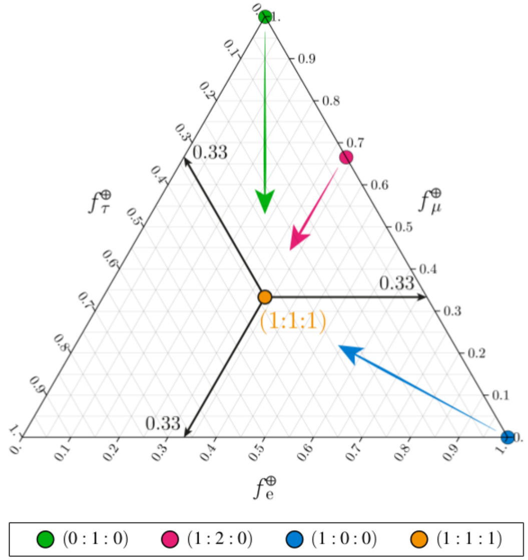


$$H = \frac{1}{2E} U M^2 U^\dagger + \sum_{d>3} \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger$$

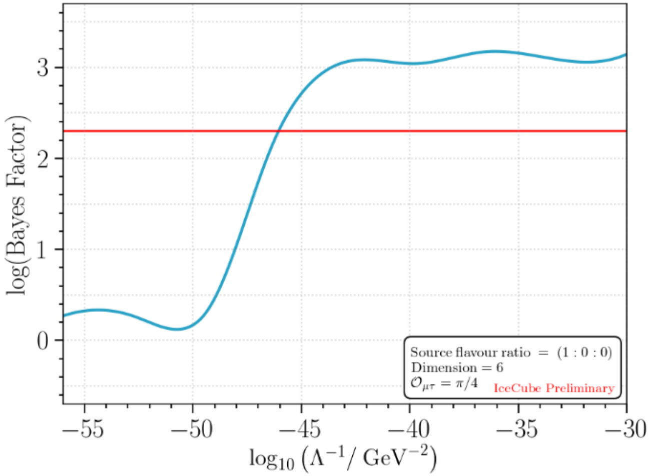
C. Arguelles et al.
ICRC2019
ArXiv:1908.07602

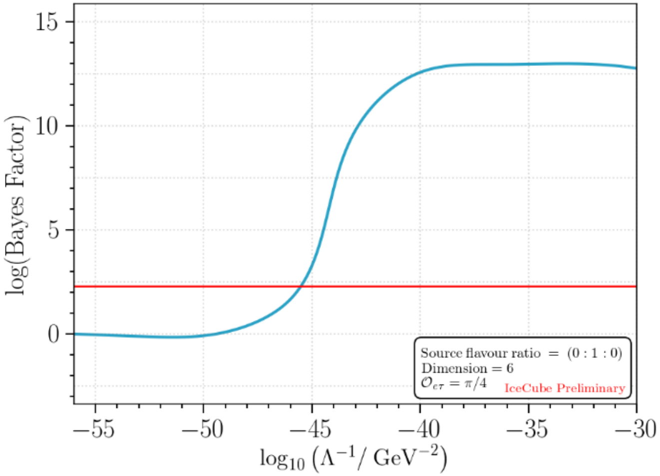
7yrs IceCube HESE

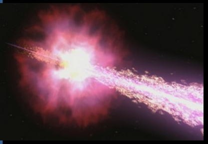
Markov Chain Monte Carlo
Of sources and propagation



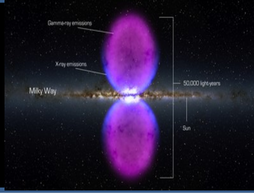
$$B = \frac{P(D|\Theta_1)}{P(D|\Theta_0)}$$



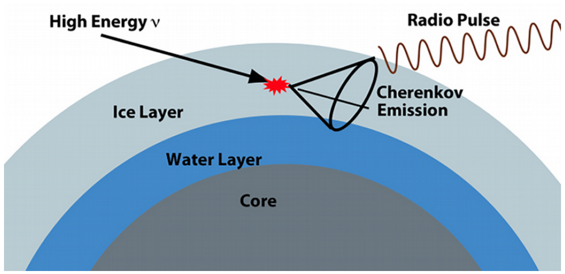




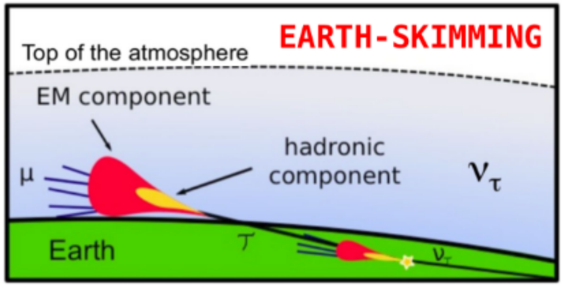
UHE detection (search for flux suppression)

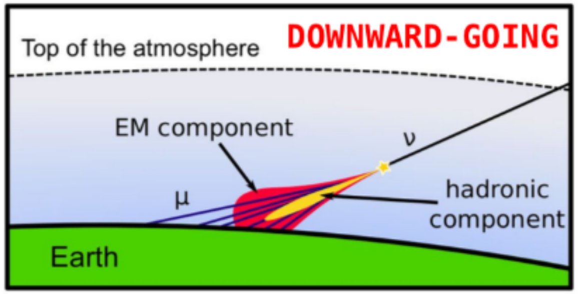


So far, no unambiguous detection

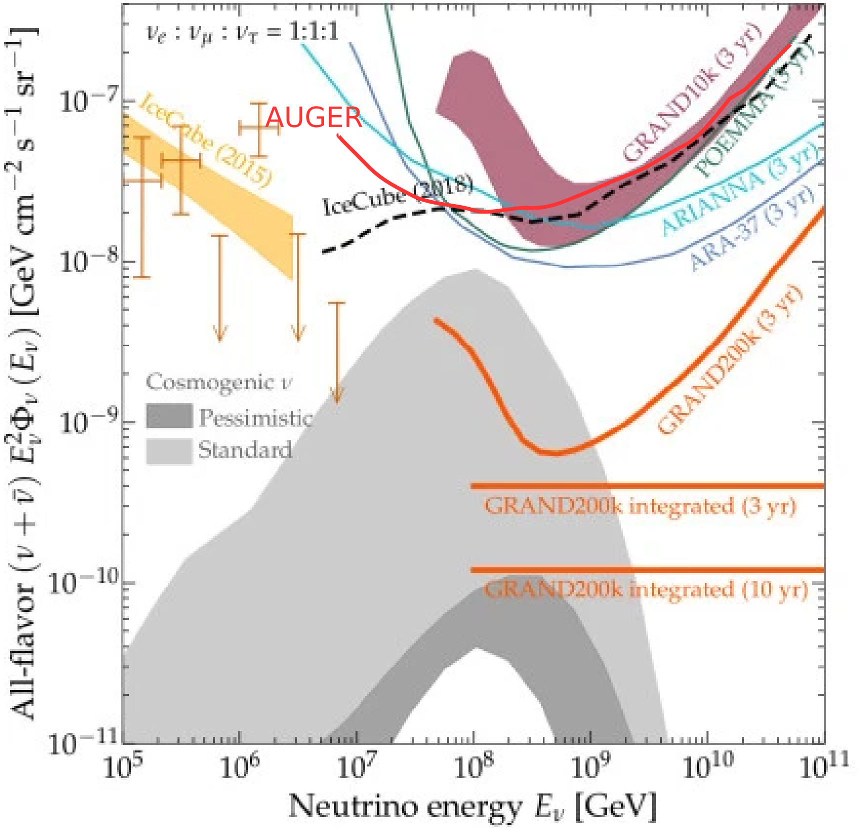


Radio
ARA, ARIANNA, ANITA
(GRAND, ...)



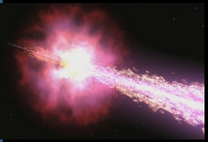


Fluorescence
&
Cherenkov
AUGER, (POEMMA,...)

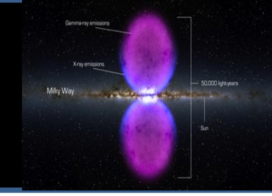


Adapted from GRAND White paper

& MAGIC from selected transient sources



In conclusion



Neutrinos are “ideal” QG probes

But a nighmare to detect (and data not trivial)

So far one (low significance) transient VHE source for TOF
 => statistical approach on GRBs and AGNs flares
 still a lot to learn/understand about sources
 more km3+ detectors comming on line
 => higher statistics is comming

VHE diffuse flavor analysis promissing

UHE “GZK” diffuse flux far away but individual sources maybe less
 =>many new projects

No need to say theorist and experimentalist need to work together ab initio...