

# Search for Lorentz Invariance Violation with High Energy Neutrino Telescopes

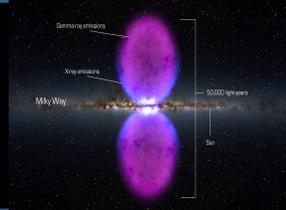
B. Baret APC

Probing quantum spacetime with Astrophysical Sources : the  
CTA era and beyond

LPNHE Paris 30/11/2017



# Why VHE neutrinos ?

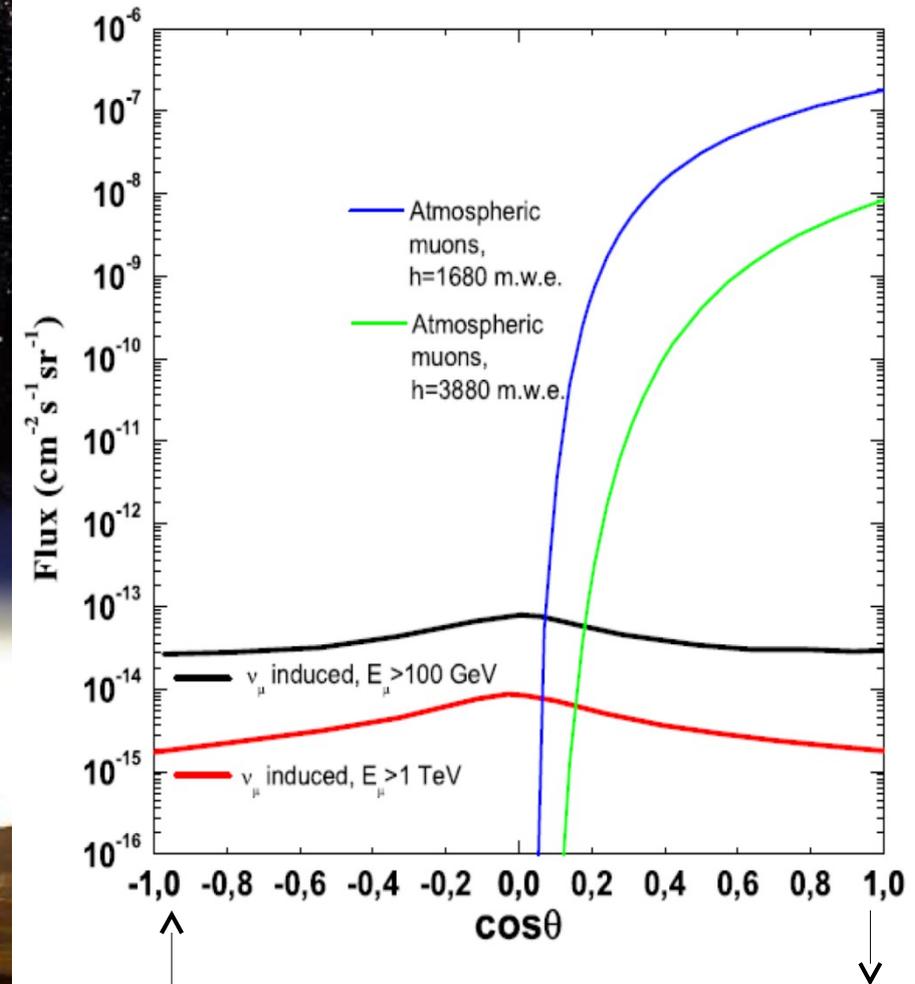
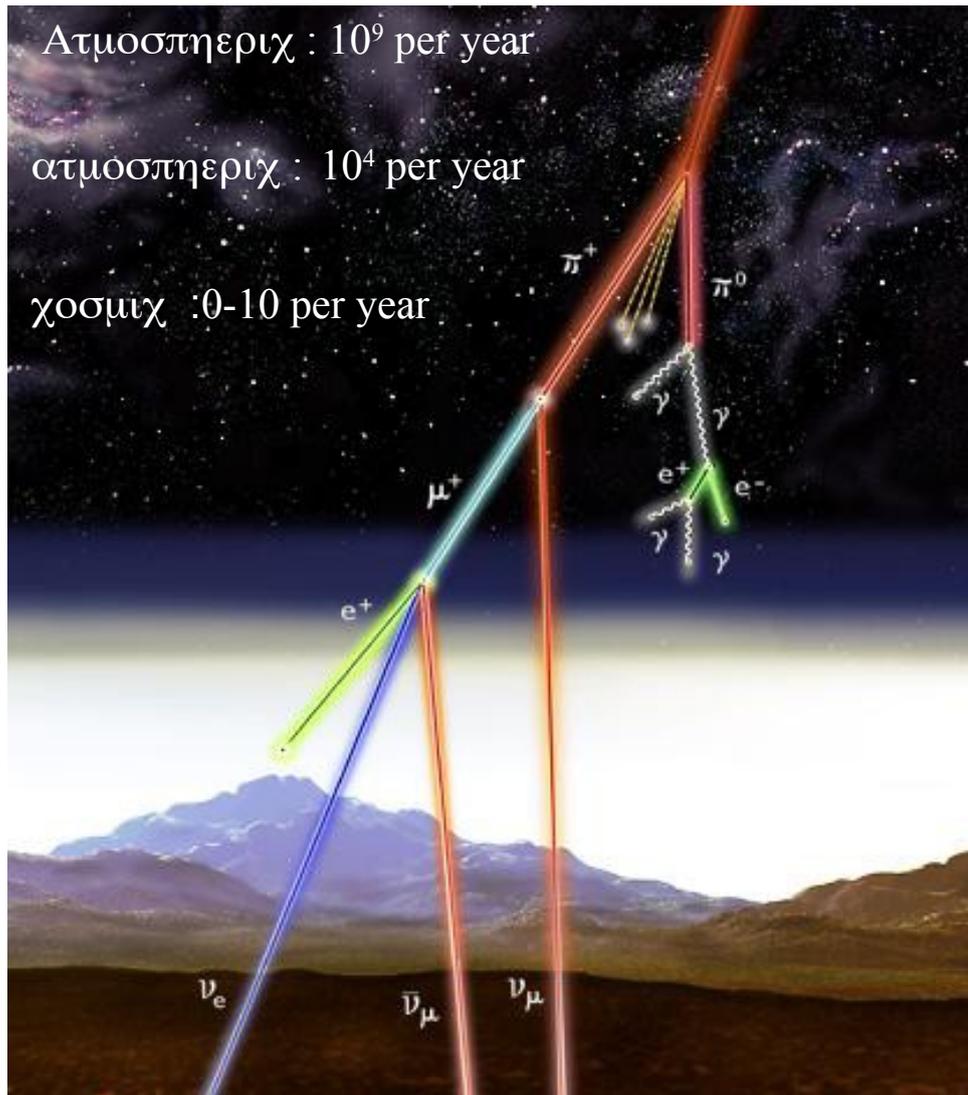
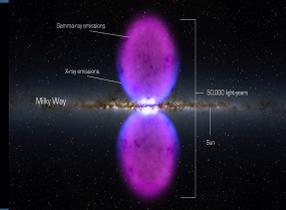


## Because :

- they are very light → they are very relativistic
- they are very weakly interacting → they travel very long distances



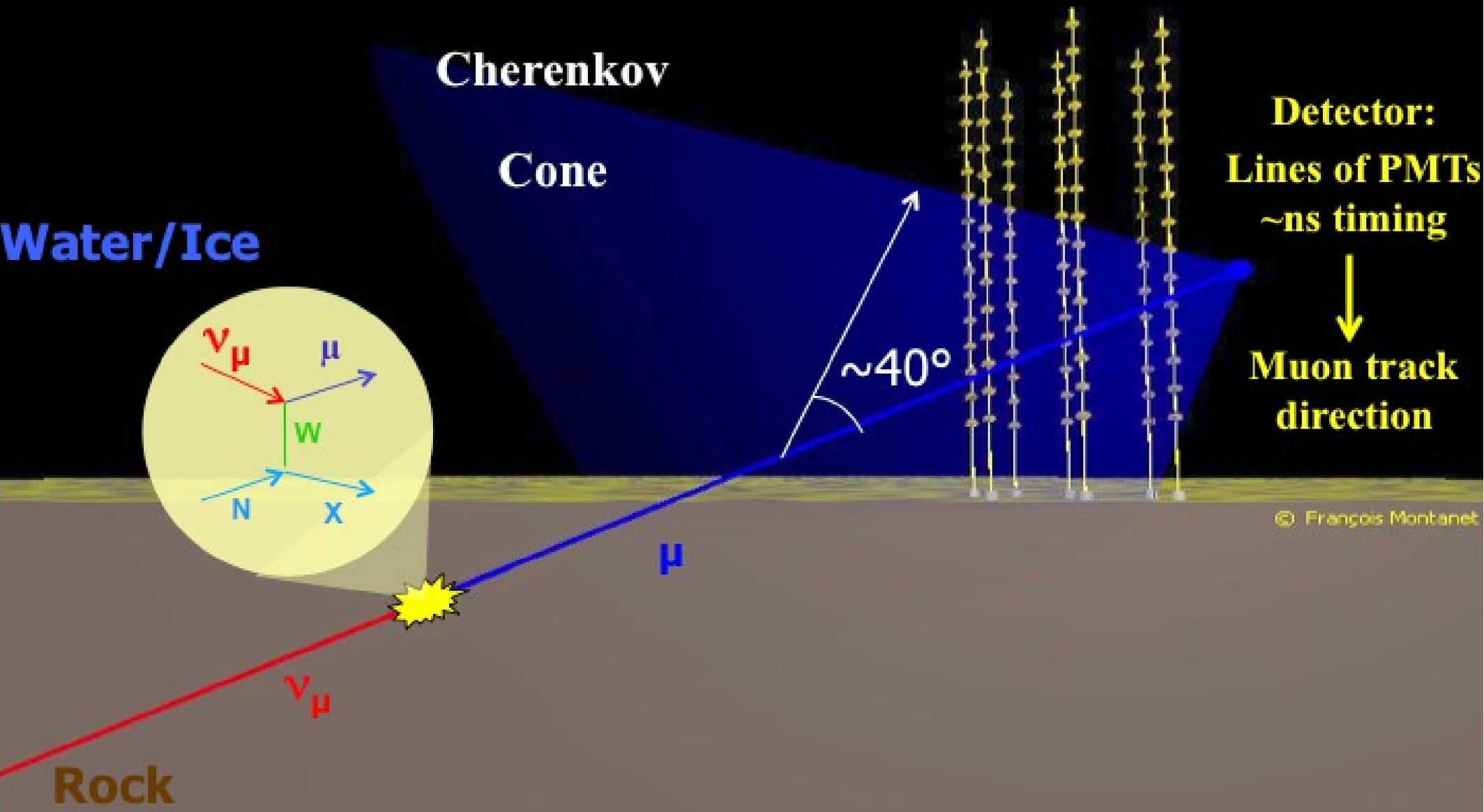
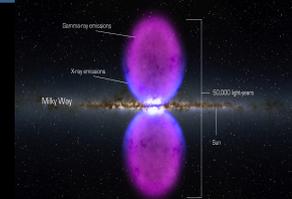
# Physical background



Shield detector and look through the Earth



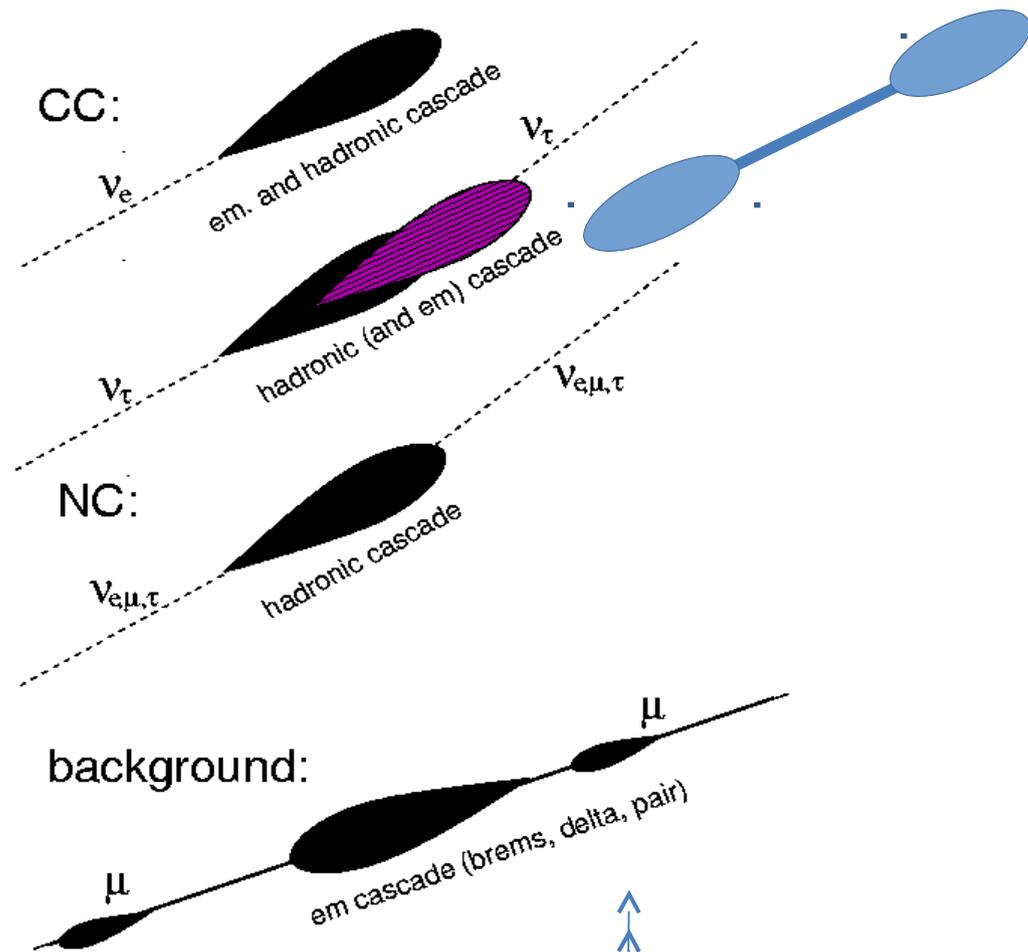
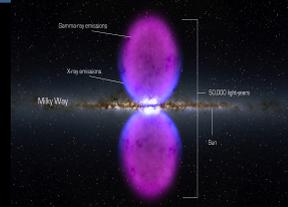
# Practically



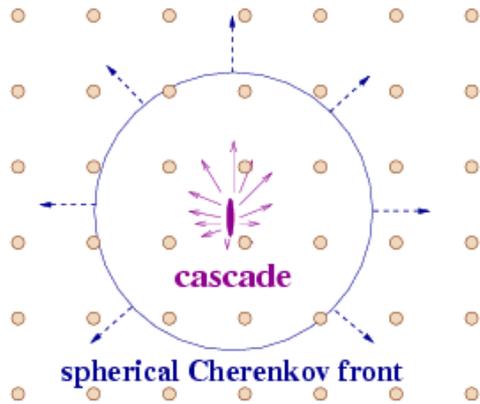
© François Montanet



# Other channels



- “shower” events



Contained events ( $\sim 10m$ )

topology

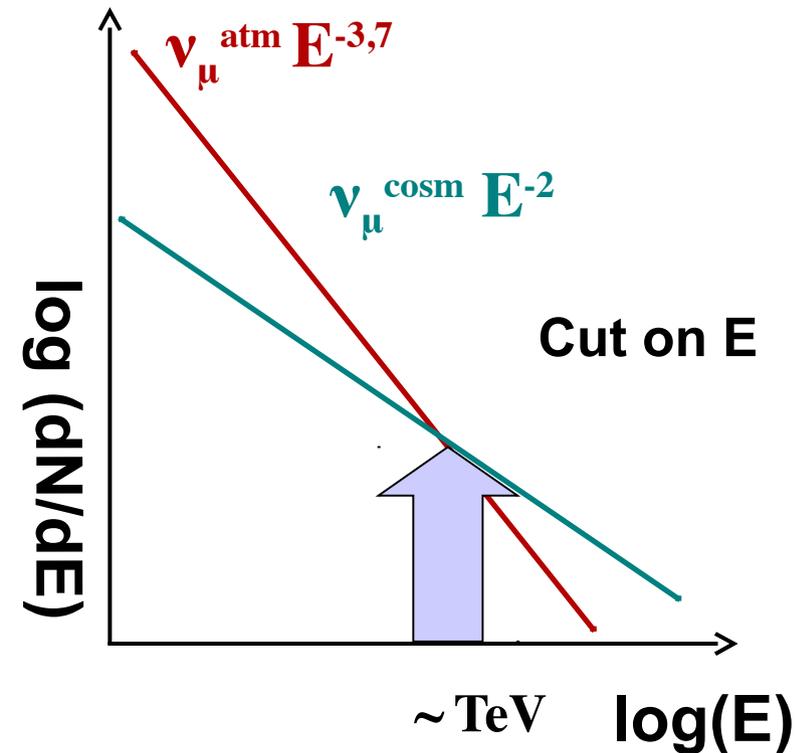
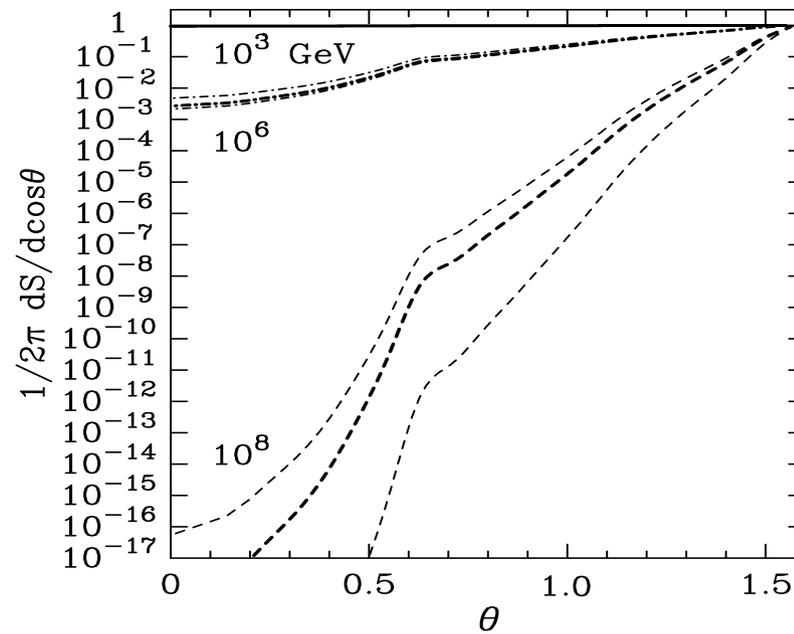
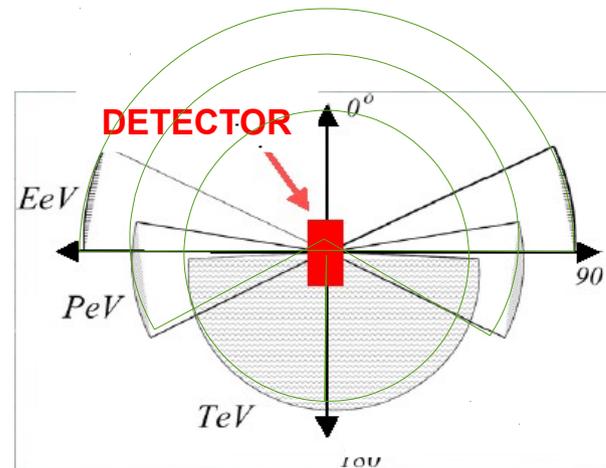
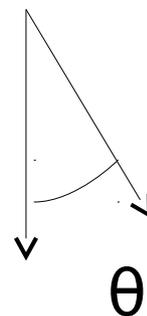
- + energy reconstruction
- effective volume
- + identification
- angular resolution

Diffuse flux (and...)

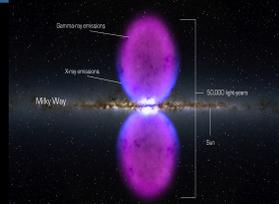


# Look at high energies

tracks  
showers



# $\nu$ -telescopes today



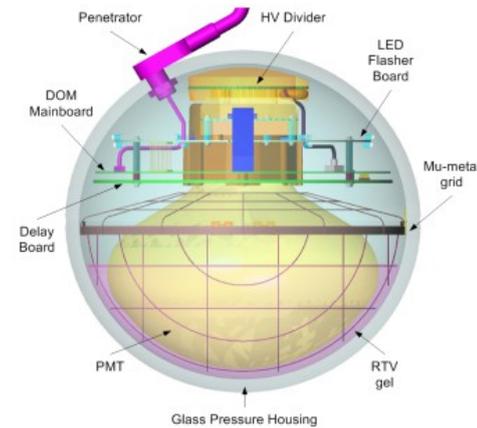
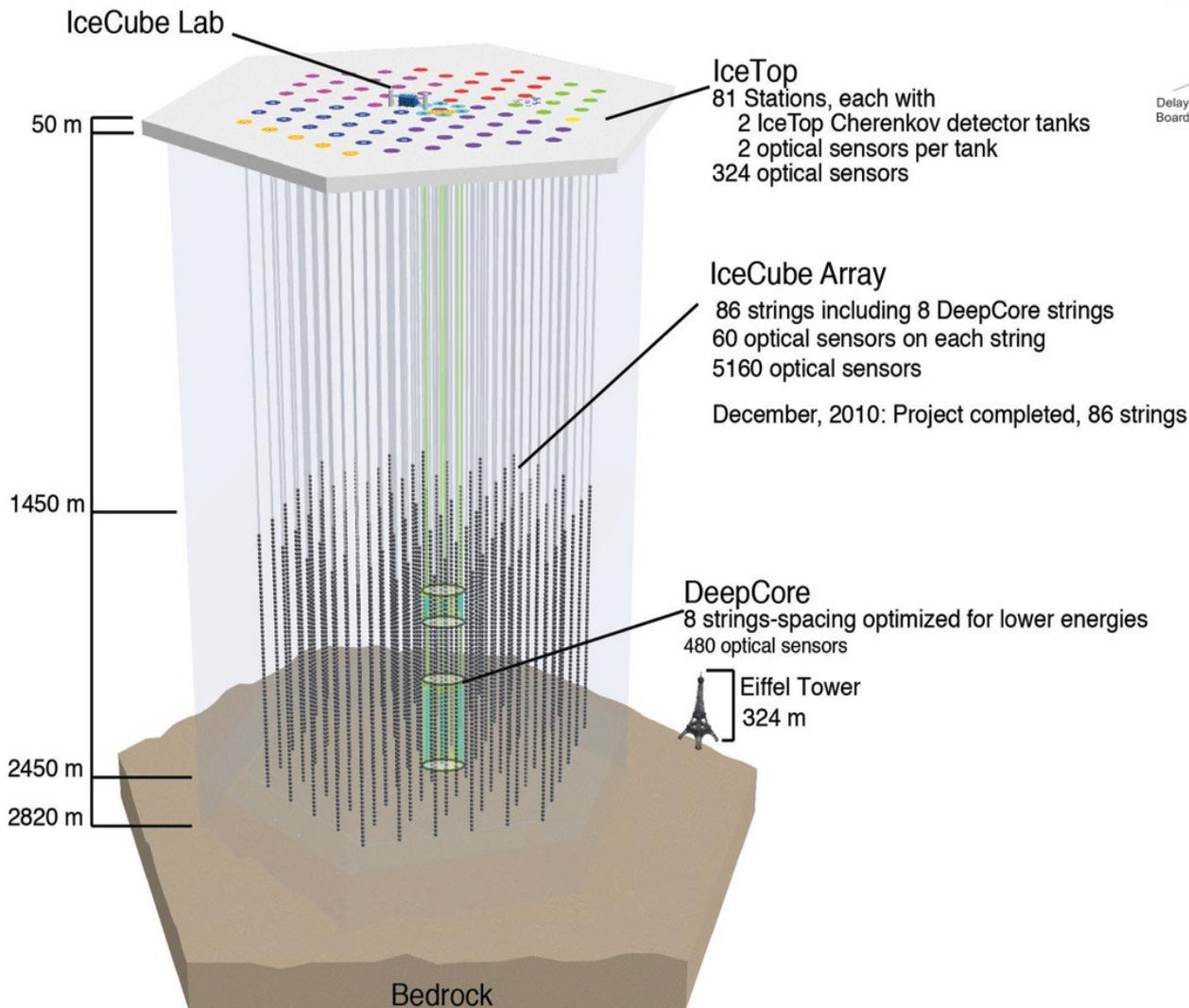
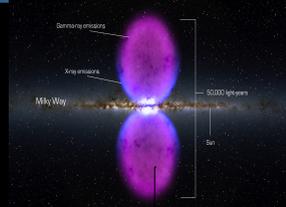
Antares/KM3NeT  
0.01km<sup>3</sup> growing (1 → 6)

Baikal GVD  
0.005 km<sup>3</sup> growing (~1)

IceCube  
1km<sup>3</sup>

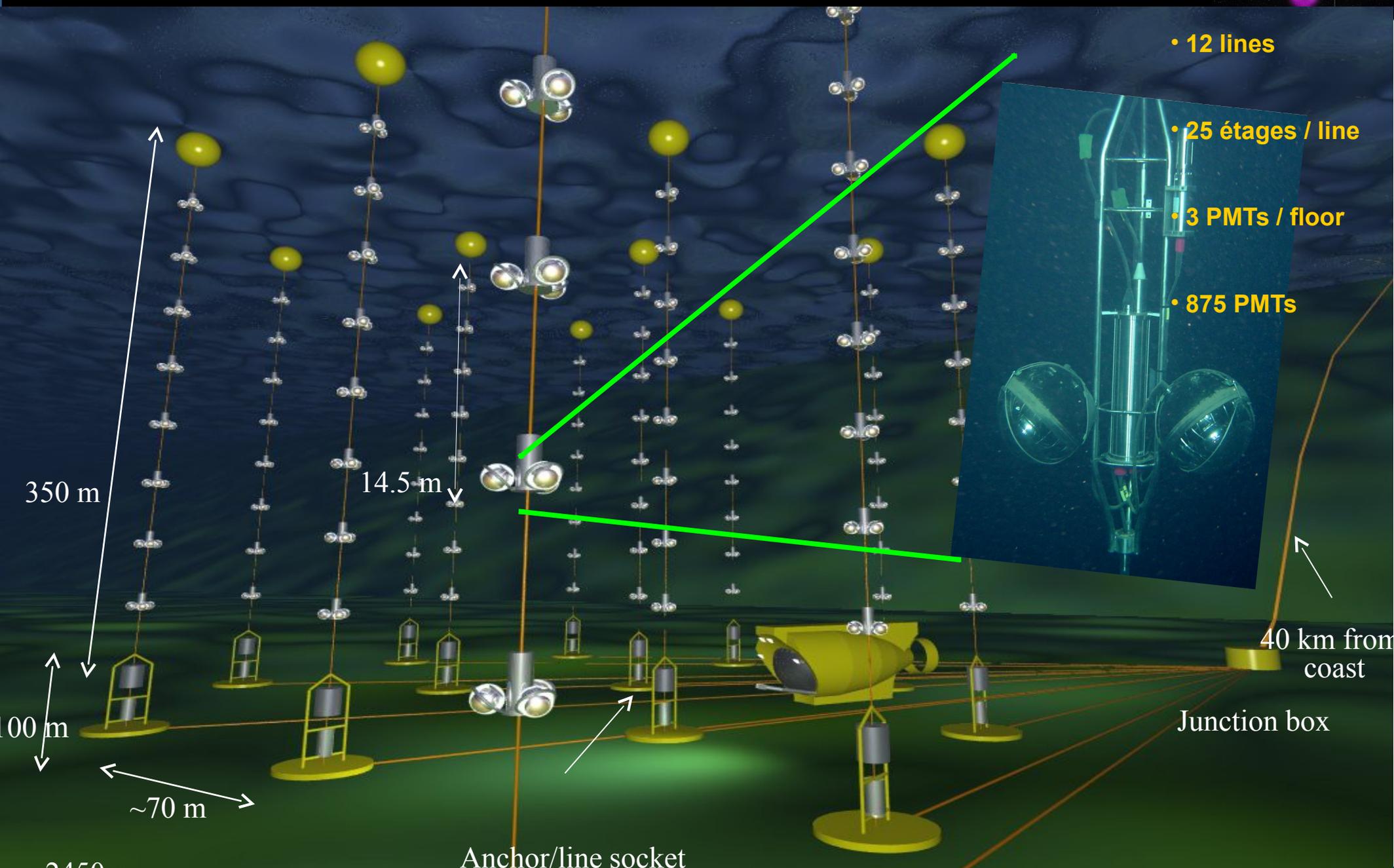
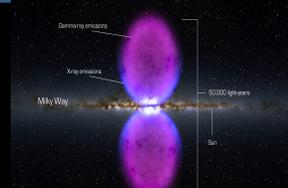


# IceCube



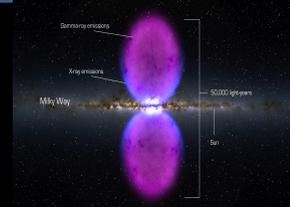


# ANTARES





# Mediterranean / South Pole



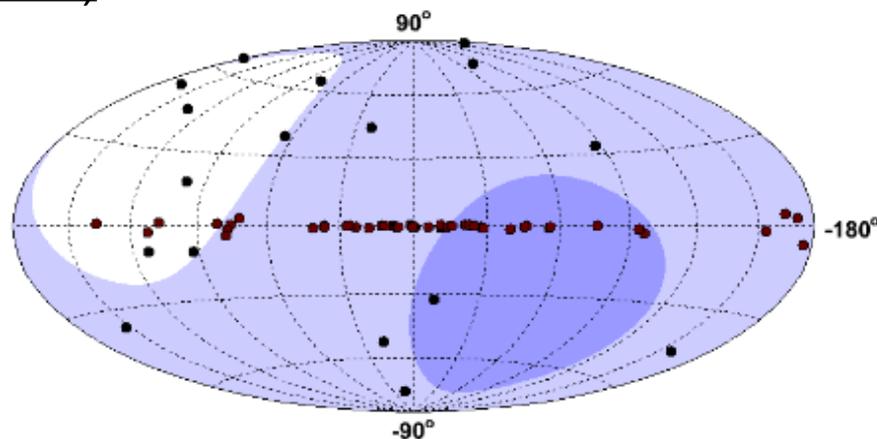
## ▶ Complementary coverage ( $\mu$ channel)

gal. center / extragal. sources

overlap:

0.5  $\pi$  sr instantaneous

1.5  $\pi$  sr integrated



ANTARES

- > 75%
- 25% – 75%
- < 25%

TeV  $\gamma$ -Sources

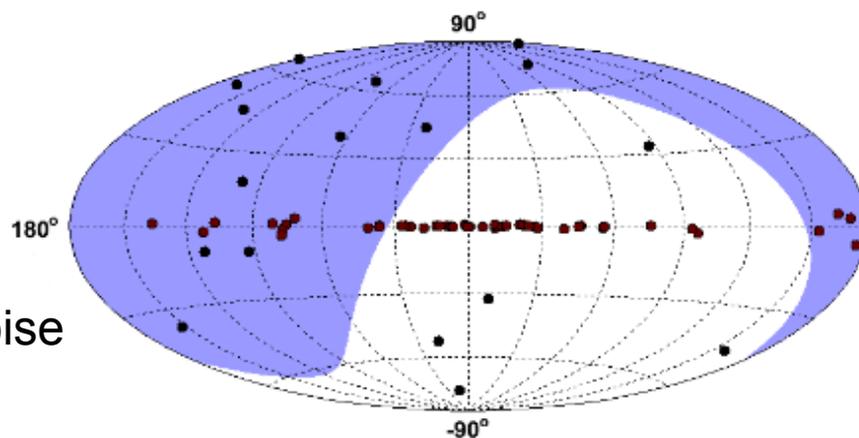
- galactic
- extragalactic

## ▶ Water v.s. Ice

Optical noise (biolum) / no noise

absorption / diffusion

pointing / calorimetry

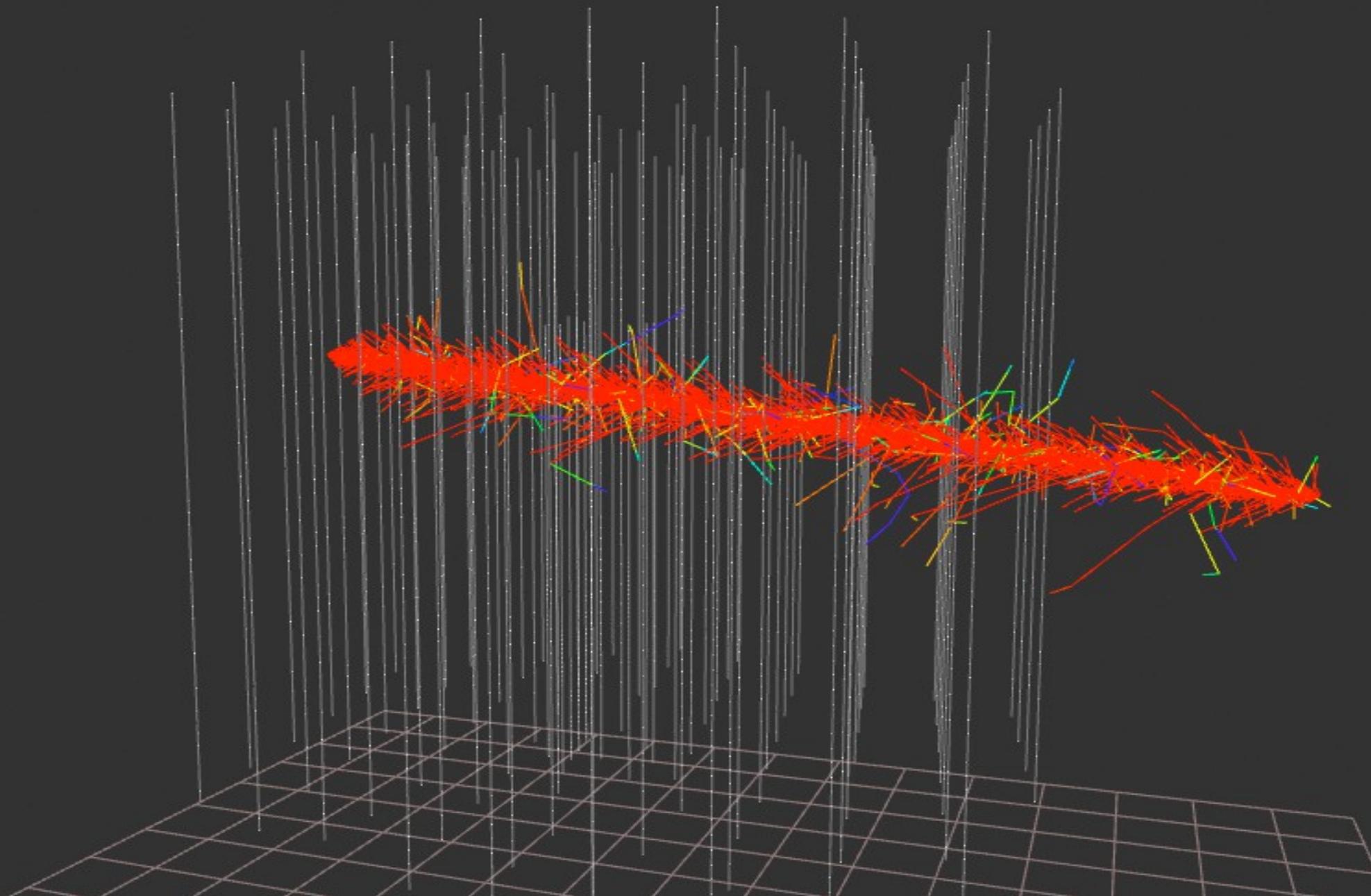
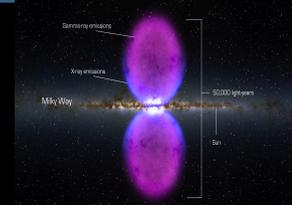


IceCube

- 100%
- 0%

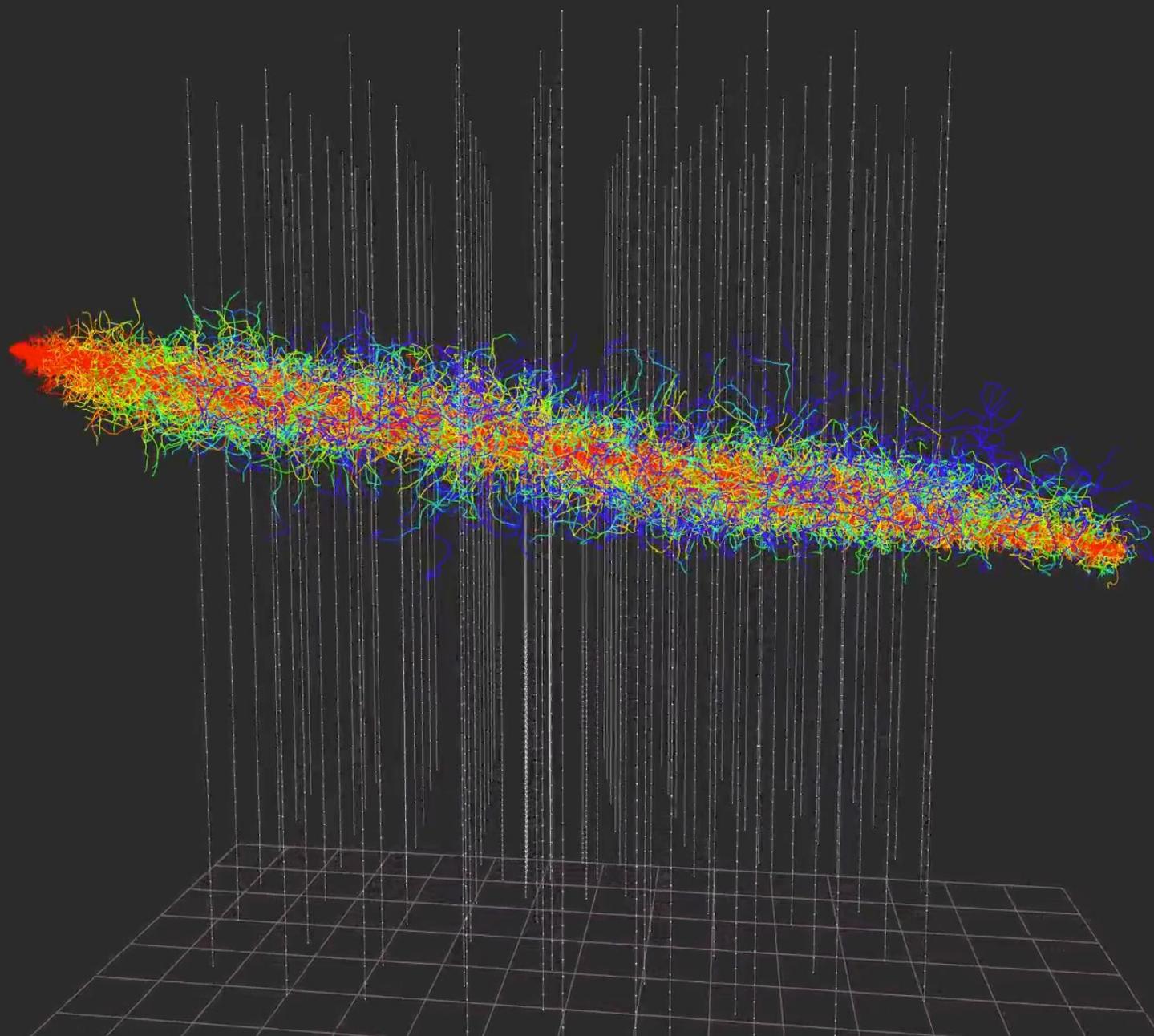
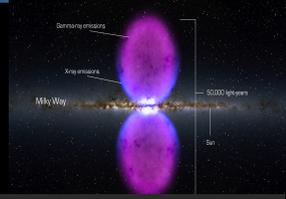


# A $\mu$ in water

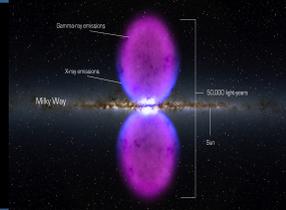




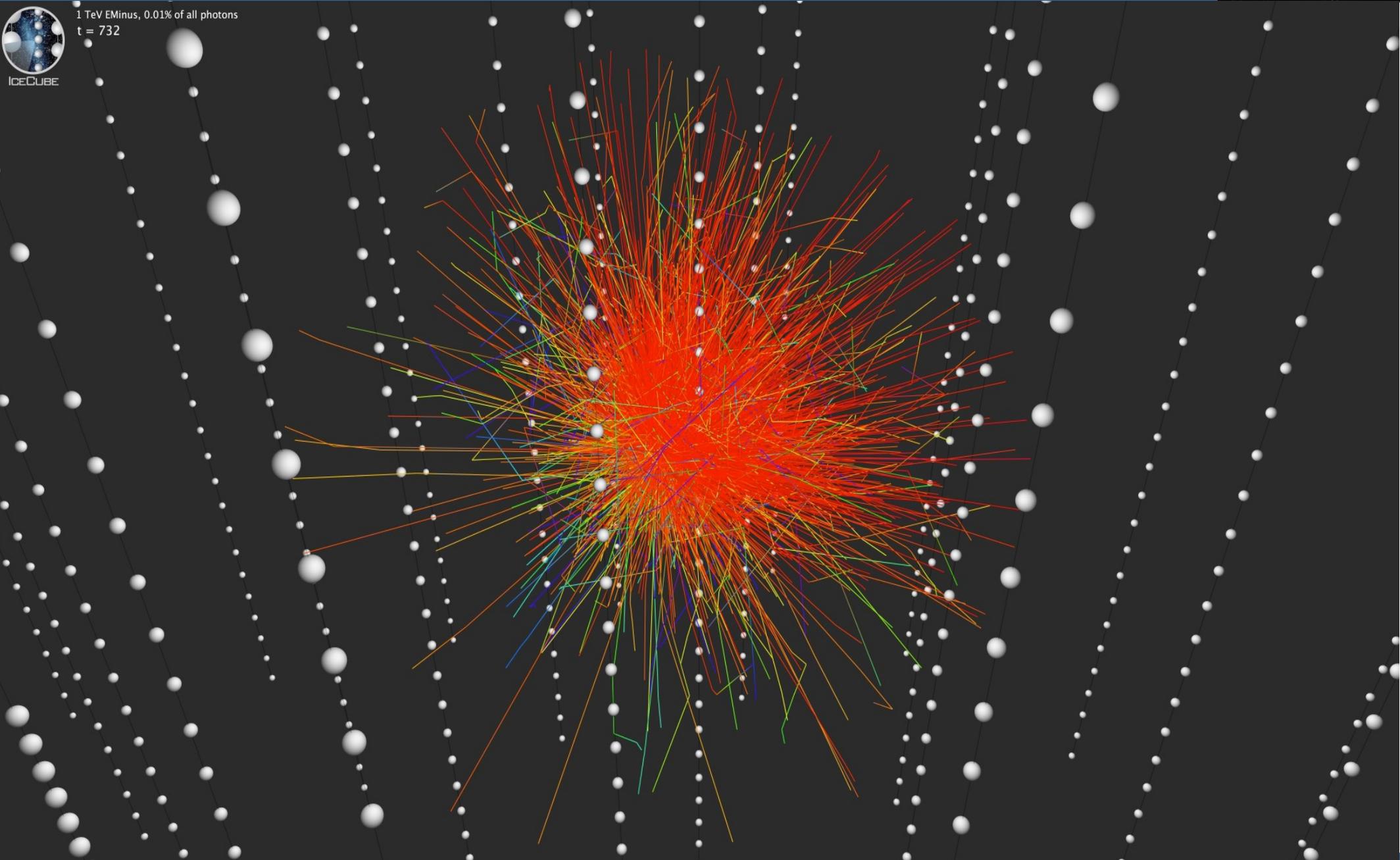
# A $\mu$ in ice



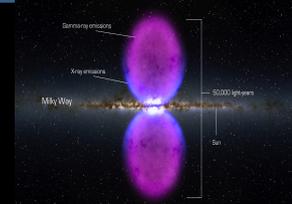
# A shower in water



1 TeV EMinus, 0.01% of all photons  
 $t = 732$

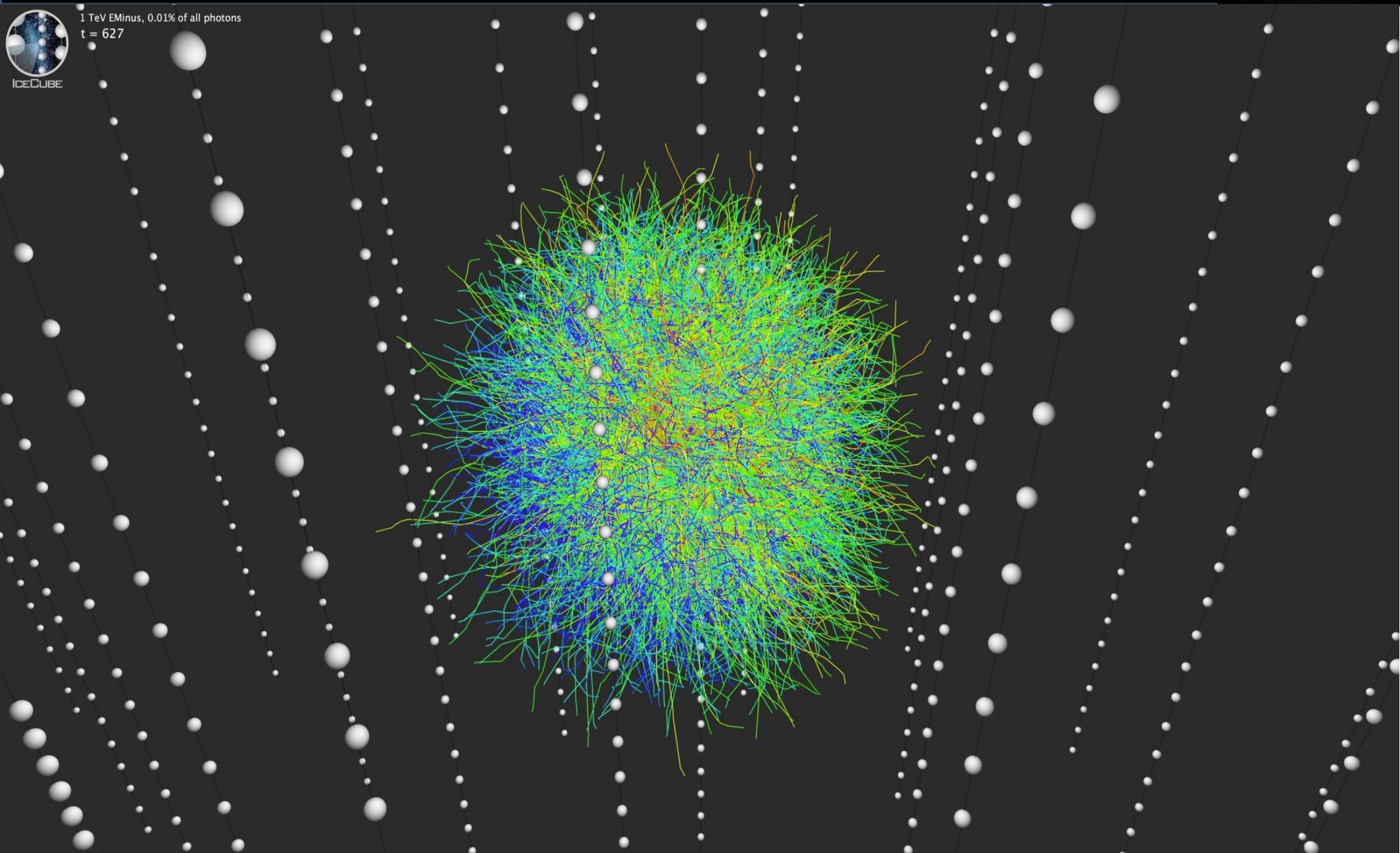


# A shower in ice



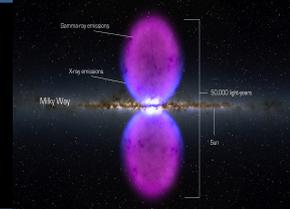
1 TeV EMinus, 0.01% of all photons  
 $t = 627$

ICECUBE





# Angular resolution



Size of some astrophysical objects :

RXJ1713 (SNR):  $1^\circ$

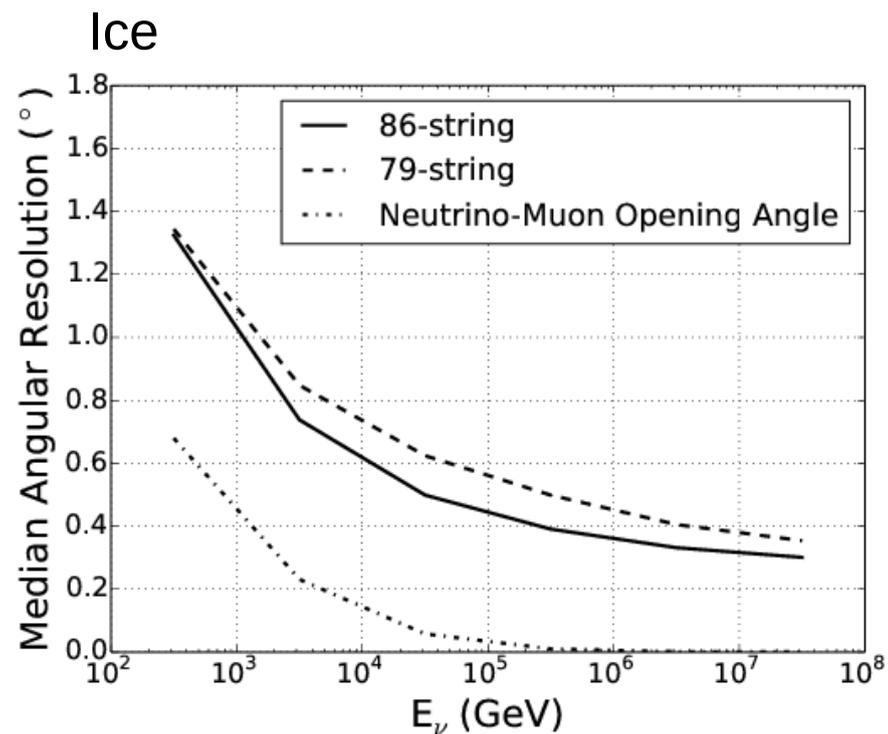
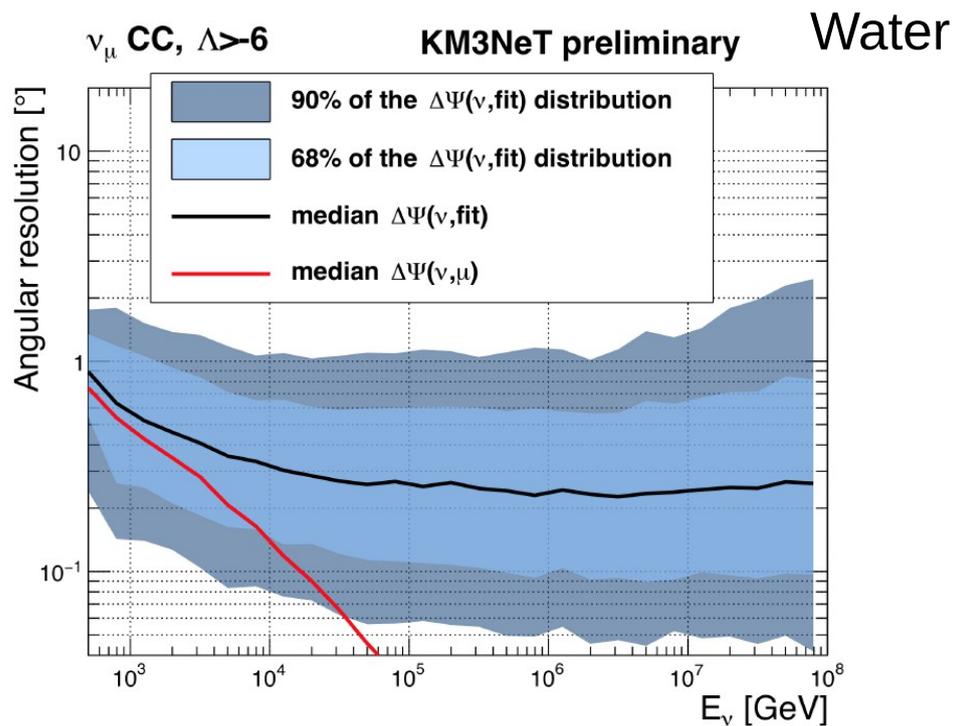
Sun, Moon :  $0.5^\circ$

Cen A (AGN) :  $0.3^\circ$

Point sources search:

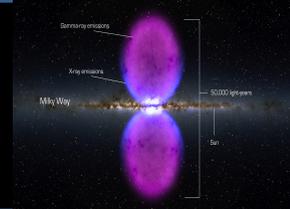
Signal/Noise :  $1/\Delta\Omega^2$

Muons:





# Angular resolution



Size of some astrophysical objects :

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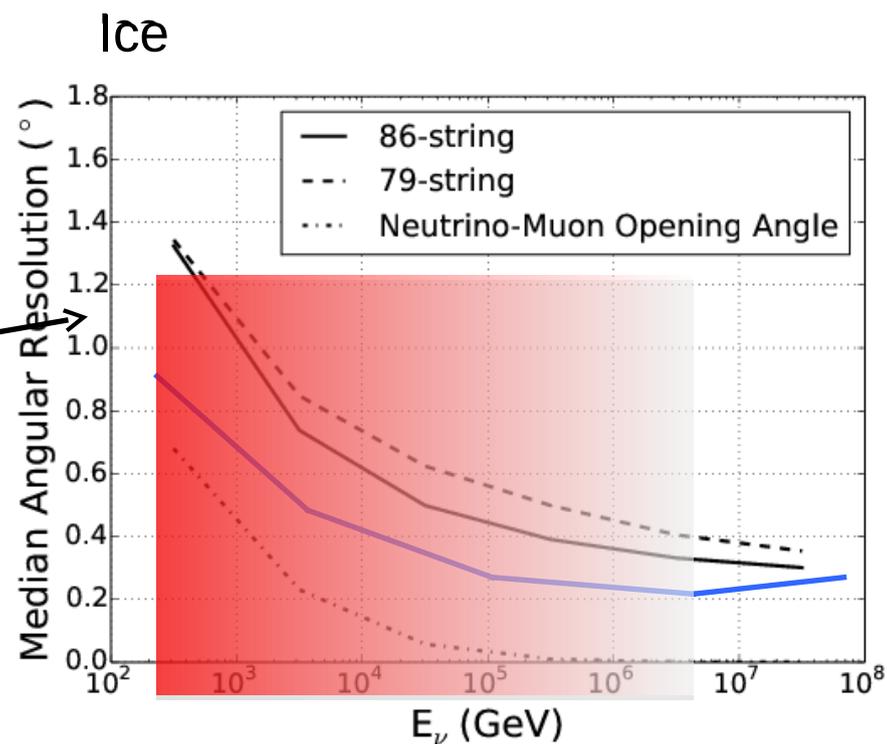
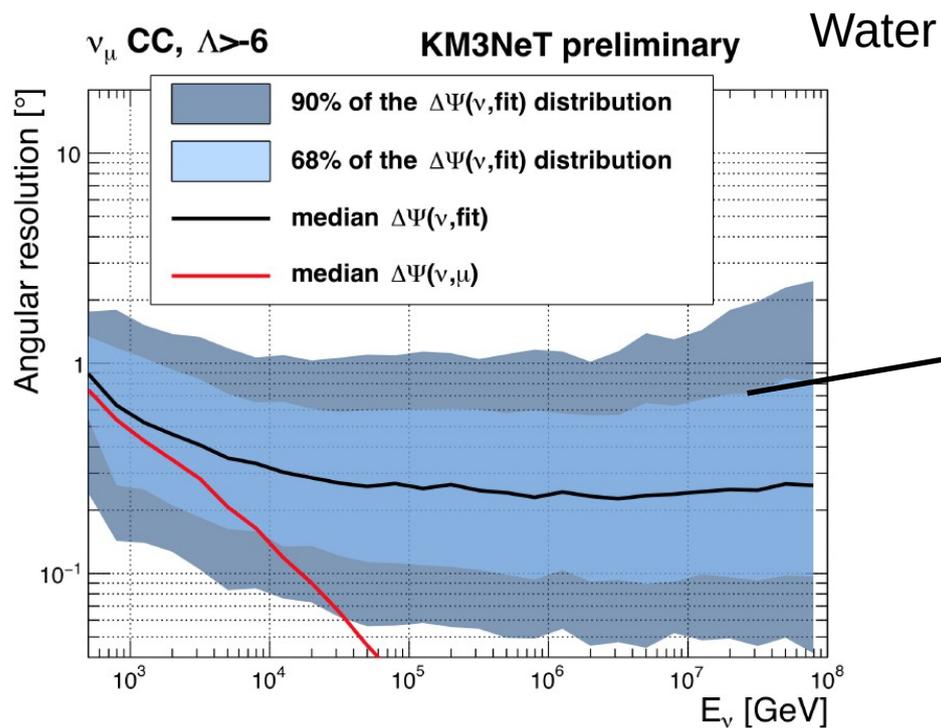
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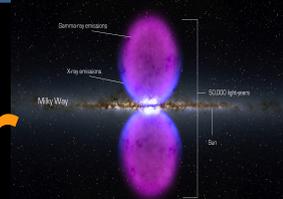
Signal/Noise :  $1/\Delta\Omega^2$

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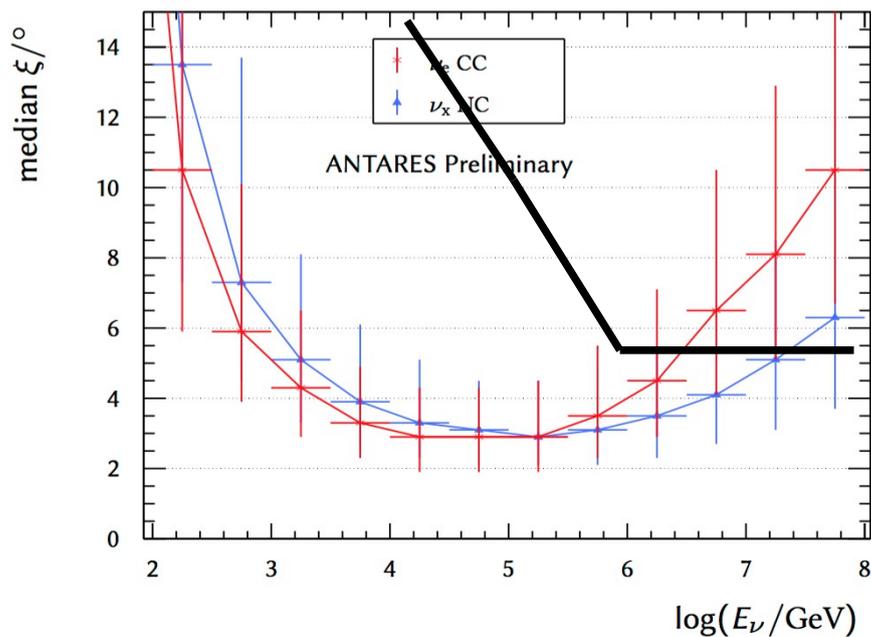
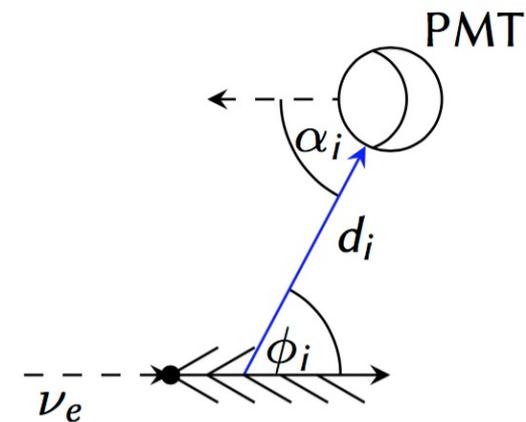




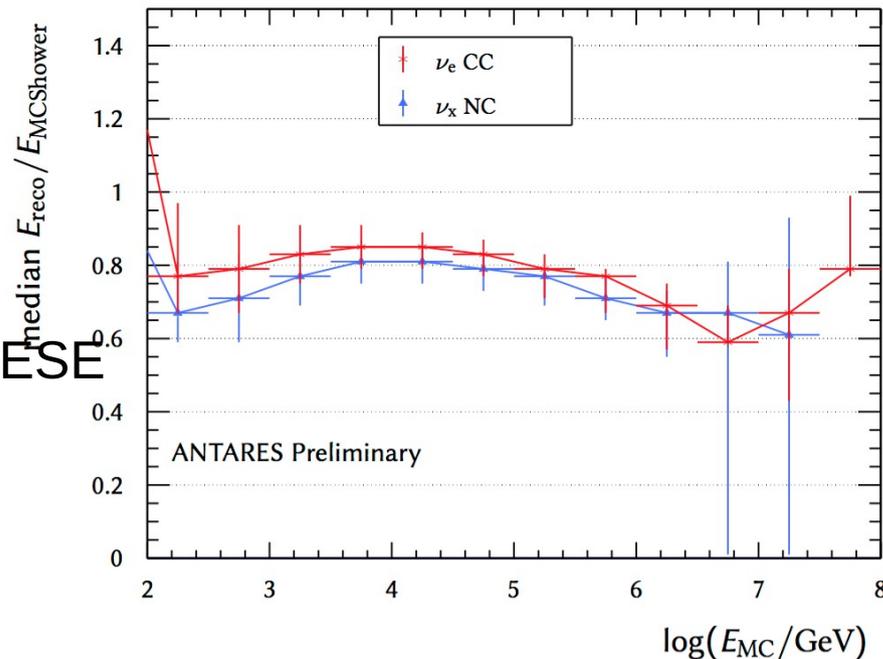
# Shower reconstruction in water



$$\mathcal{L} = \sum_{i=1}^{N_{\text{selected Hits}}} \log \{ P_{q>0}(q_i | E_\nu, d_i, \phi_i, \alpha_i) + P_{\text{bg}}(q_i) \} + \sum_{i=1}^{N_{\text{unhit PMTs}}} \log \{ P_{q=0}(E_\nu, d_i, \phi_i) \}$$



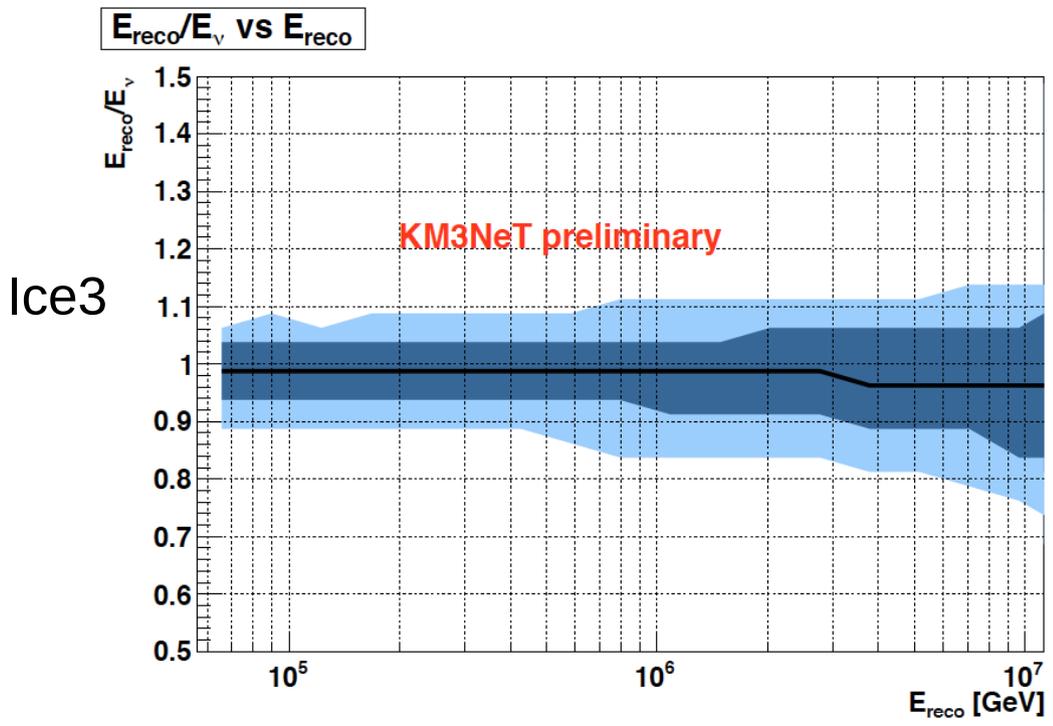
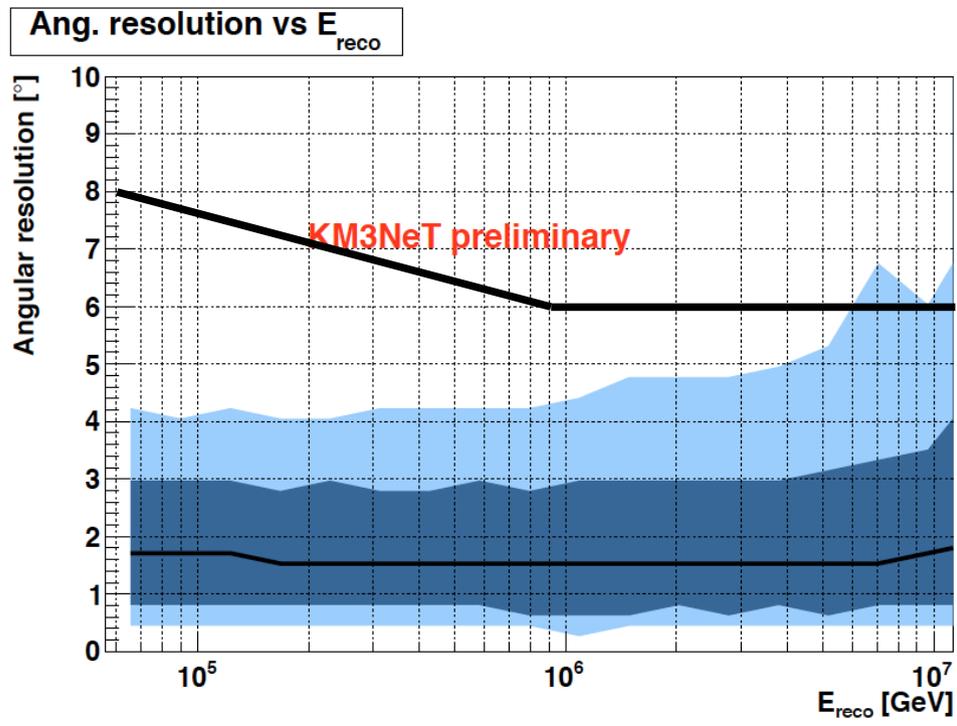
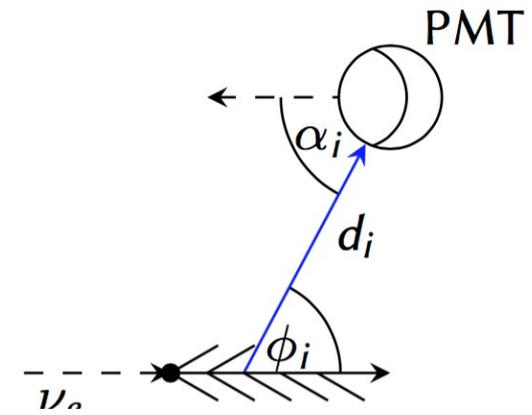
Ice3 HESE





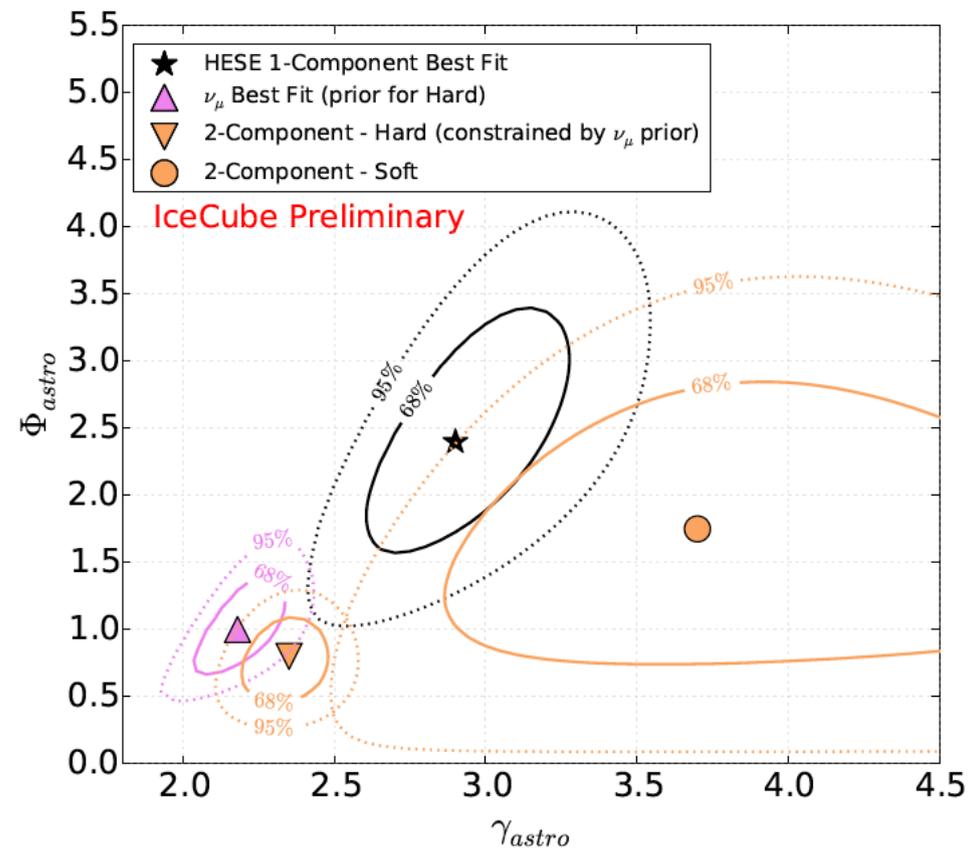
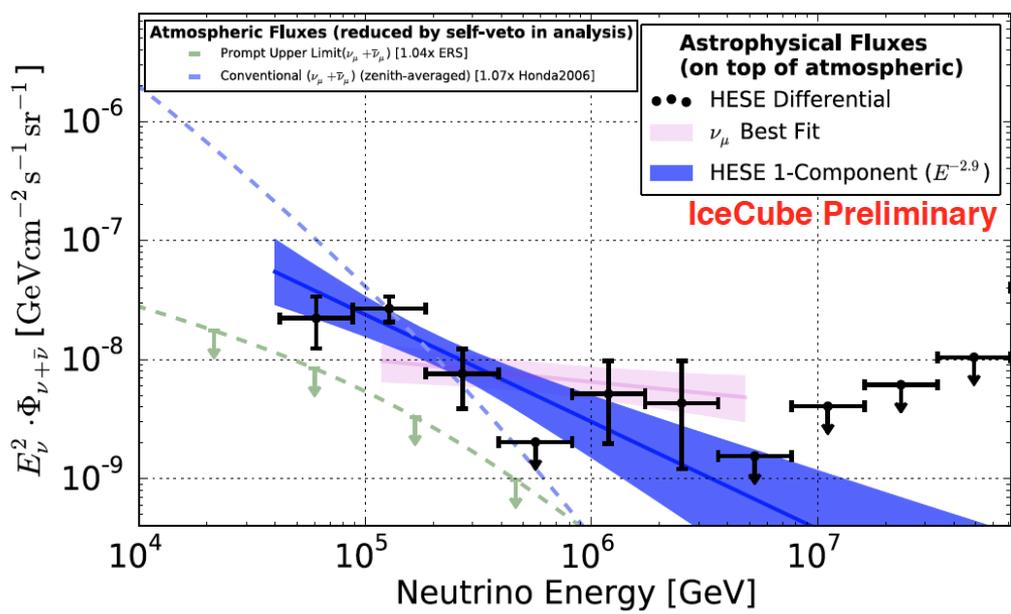
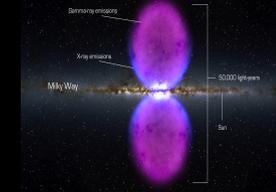
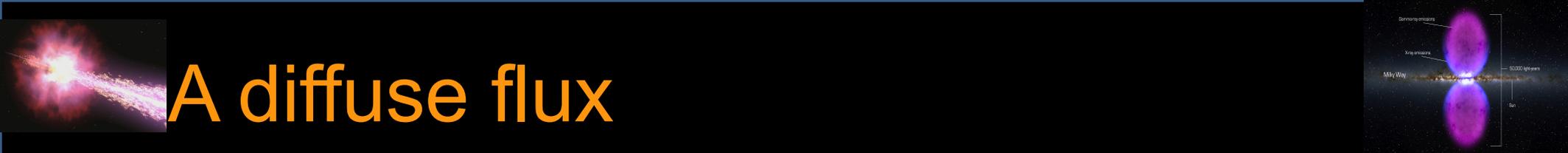
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Ice3





So far :  
 purely diffuse  
 no extended emission  
 no inhomogeneities  
 no point sources  
 no transients  
 no new physics  
 (no fun?)...yet !

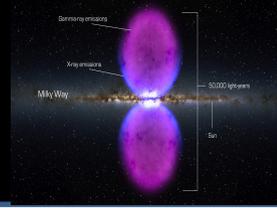
**IceCube:**  
[arXiv:1710.01207](https://arxiv.org/abs/1710.01207)  
[arXiv:1710.01201](https://arxiv.org/abs/1710.01201)  
[arXiv:1710.01197](https://arxiv.org/abs/1710.01197)  
[arXiv:1710.01194](https://arxiv.org/abs/1710.01194)  
[arXiv:1710.01191](https://arxiv.org/abs/1710.01191)  
[arXiv:1710.01179](https://arxiv.org/abs/1710.01179)

**Antares :**  
[arXiv:1711.01251](https://arxiv.org/abs/1711.01251)  
[arXiv:1711.01486](https://arxiv.org/abs/1711.01486)  
[arXiv:1711.01496](https://arxiv.org/abs/1711.01496)

**KM3NeT :**  
 well... google it



# GRBs and neutrinos as L.I.V. probes



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

- Theories of Quantum Gravity (deformed relativity, LQG, non-commutative 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 :

$$E^2 - p^2 c^2 = \pm E^2 \cdot (E / M_{\text{LIV}})^n + \cancel{m_\nu^2 \cdot c^4}$$

sizeable effect : n=1

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

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

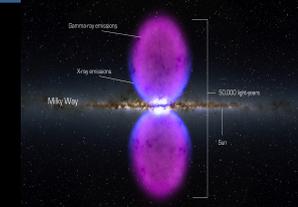
$$v = \partial E / \partial p$$

U. Jacob and T. Piran, JCAP 0801 (2008)

G. Amelino-Camelia et al., Astrophys. J. 806(2), 269 (2015)

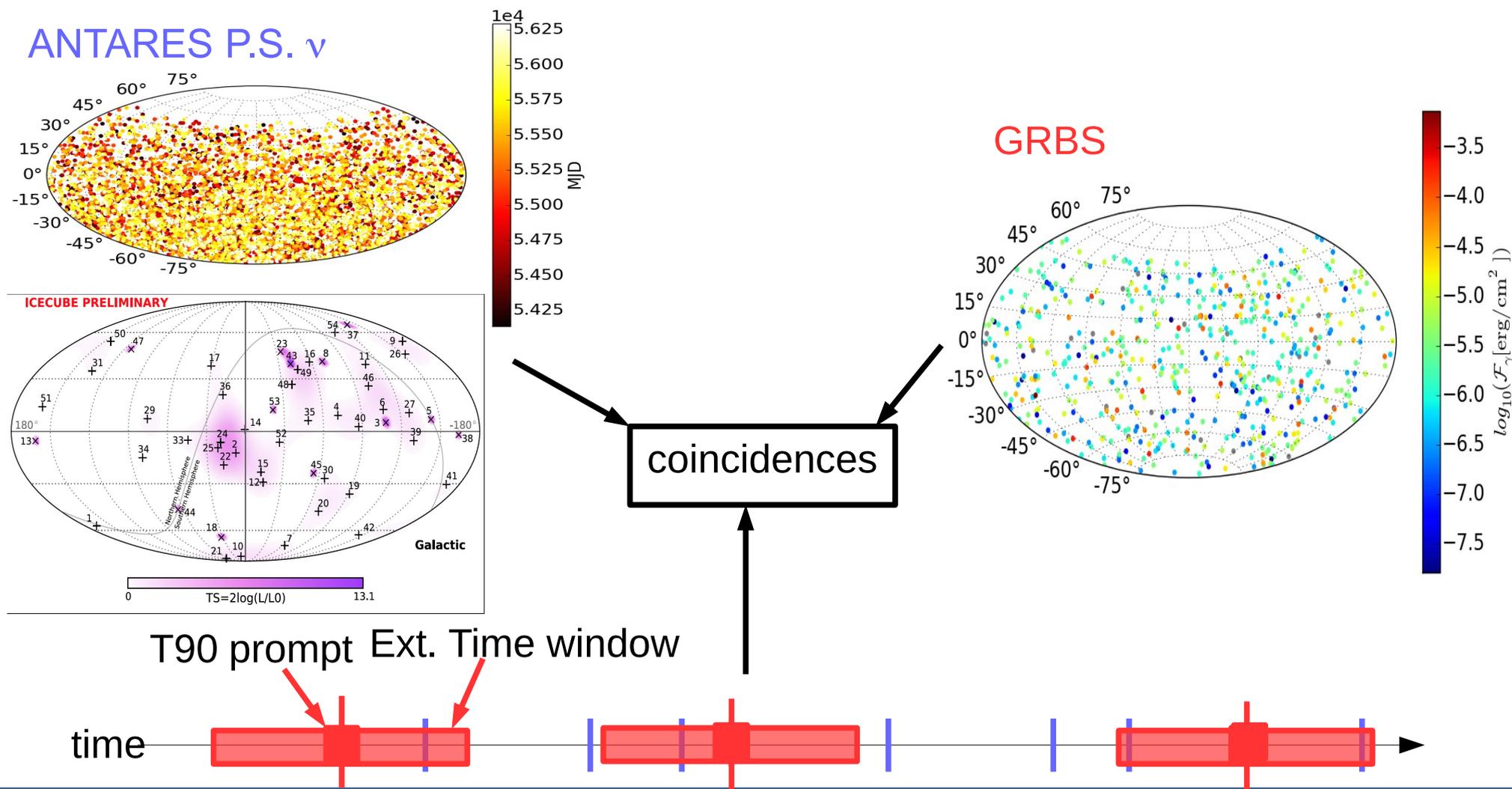


# GRBs and neutrinos as L.I.V. probes



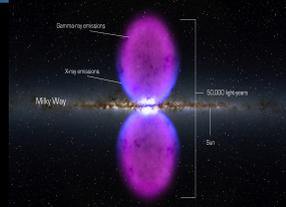
## Search for:

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





# IceCube: a hint ? ( « naïve analysis » )



Amelino-Camelia et al (2015):

track channel data -> 2010 : 2 low significance events 2-3x10<sup>3</sup> s before 2 GRBS

Amelino-Camelia et al (2016) arXiv:1605.00496v1:

cascade channel data 2010-> 2014

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

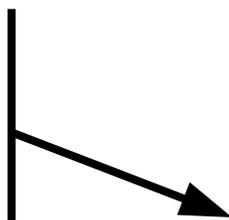
$$\Delta t^* = \eta \frac{E}{M_P} D(1) \pm \delta \frac{E}{M_P} D(1)$$

• Directional coincidence:  
Within 2σ of instrument resolution

• Time coincidence: <6 days

• Energy: 60-500TeV

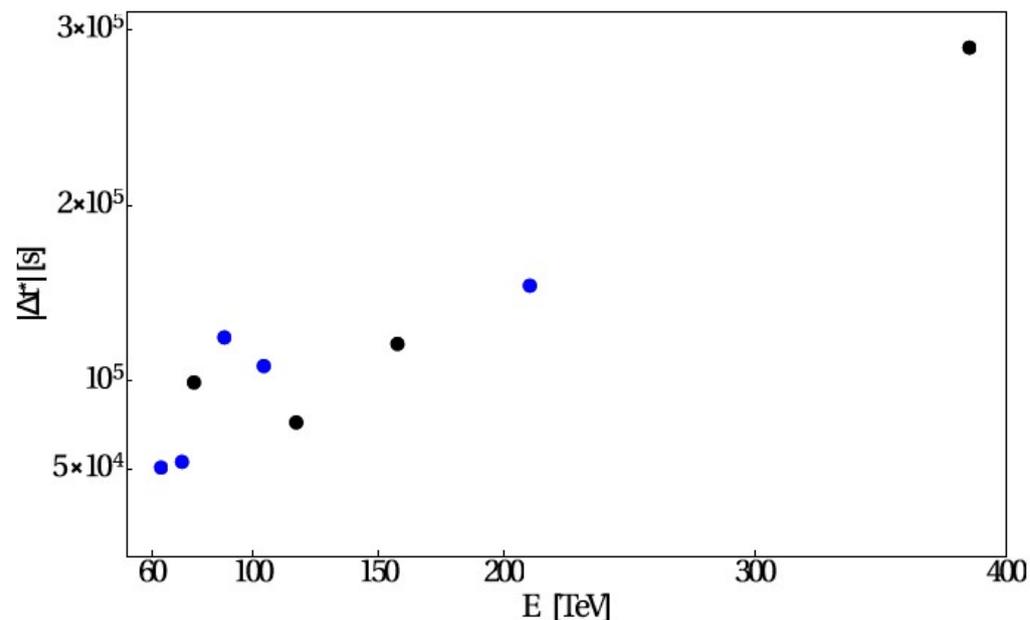
• Unknown z -> default values



Avoid multiple coincidences

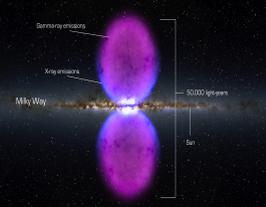
Correlation=0.8-0.95

p-value=1%





# GRB extended time stacking search with ANTARES



## Stacked variables :

$$\begin{aligned} \tau_{\text{obs}} &= t_{\nu} - t_{\text{GRB}} && \text{Generic time delay} \\ \tau_z &= \tau_{\text{obs}} / (1 + z) && \text{Fixed delay at the source} \\ \tau_{\text{LIV}} &= \frac{\tau}{E_{\text{est}} \cdot D(z)} && \text{L.I.V. effects} \end{aligned}$$

## Test Statistic :

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

- Maximum time delay 42 days:

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

## Directional coincidence:

$$\delta_{\text{cut}} = 1.58 \cdot \max(\sigma_{\nu}, \min(\Delta_{\text{err}}, \Delta_{\text{err}}^{\text{max}})) \quad \# \text{ coinc. } (\Delta_{\text{err}}^{\text{max}}) < 10 \# \text{ coinc. } (\sigma_{\nu})$$

maximise Sig/Bgd

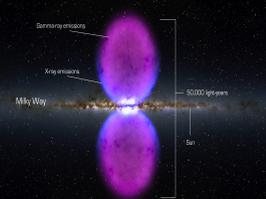
$\nu$  resolution

GRB error box

Compute z dependent quantities for measured z only.



# GRB extended time stacking search with ANTARES



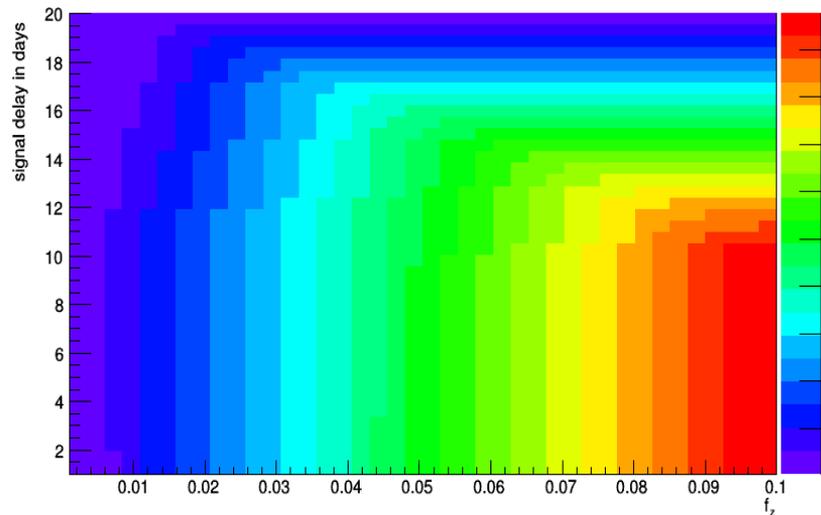
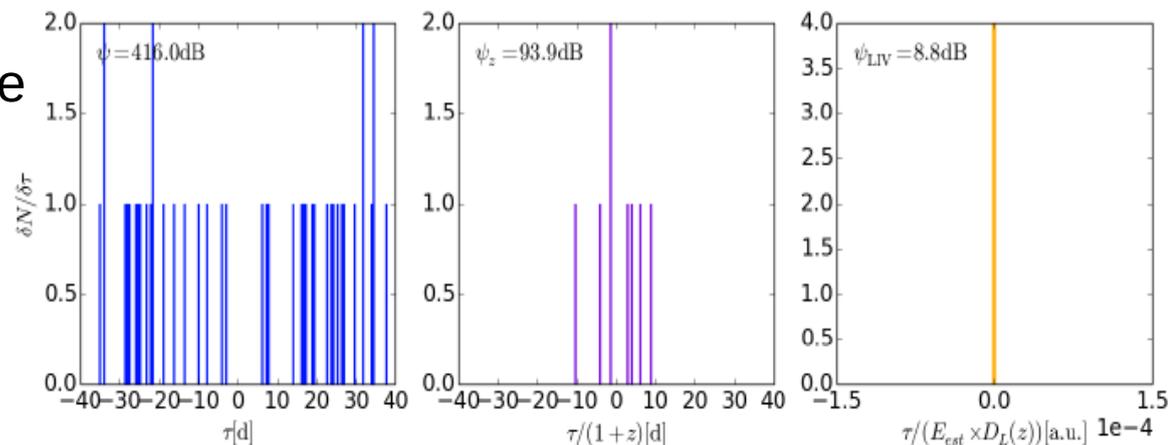
## Results:

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

$\nu$ telescope data	$\tau_{\text{tot}}$ (d)	$N_{\text{events}}$	$m(\delta)$ ( $^\circ$ )	$\delta_{\text{max}}$ ( $^\circ$ )	$\tau_{\text{max}}$ (d)	$N_{\text{GRB}}$	$N_{\text{GRB},z}$	$n_{\text{coinc}}$ (uncorrelated)	$n_{\text{coinc},z}$	Meas.		P-value	
										w.z	w.o.z		
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):

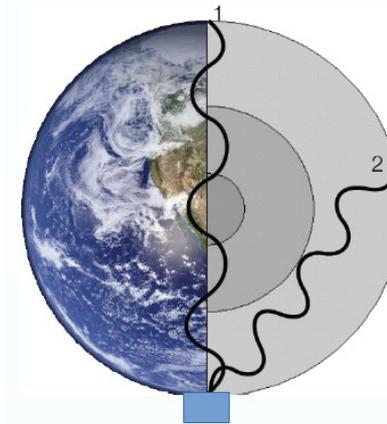
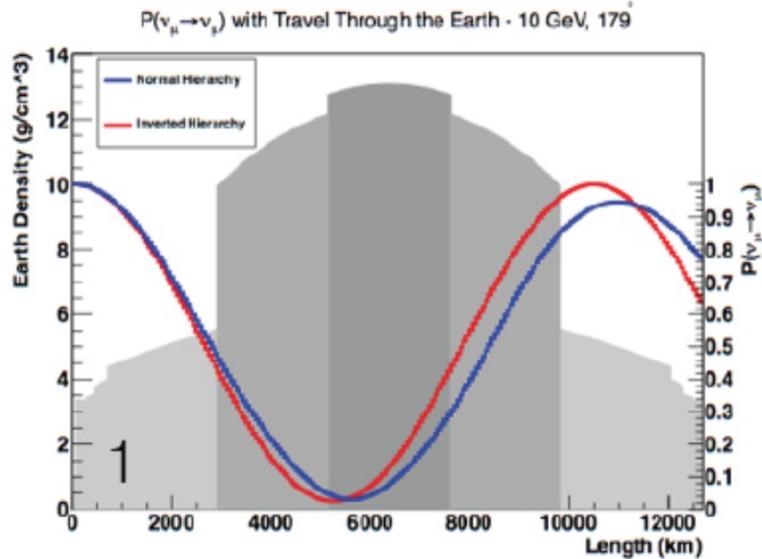
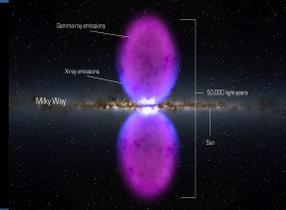
Signal delayed of 5 days at the source



Test Statistic	Sensitivity at 90% CL		Sensitivity at 99% CL		$MDP$ $3\sigma$		$MDP$ $5\sigma$	
	$f_{\text{all}}$	$f_z$	$f_{\text{all}}$	$f_z$	$f_{\text{all}}$	$f_z$	$f_{\text{all}}$	$f_z$
$r$	0.8%	3%	1.5%	5.5%	2.4%	9%	4.5%	17%
$\psi$	0.6%	2.2%	1.3%	5%	1.3%	5%	2.4%	9%
$\psi_z$	0.3%	1.1%	0.8%	3%	0.6%	2.3%	1.2%	4.5%
$\psi_{\text{LIV}}$	0.3%	1.1%	0.8%	3%	1.5%	5.5%	3%	12.5%



# Oscillation from atm. nu



Include matter effects (MSW)

$$P[\nu_a \rightarrow \nu_b] = \sin^2 2\theta \sin^2 \left[ 1.27 \frac{\Delta m^2 L}{E} \right]$$

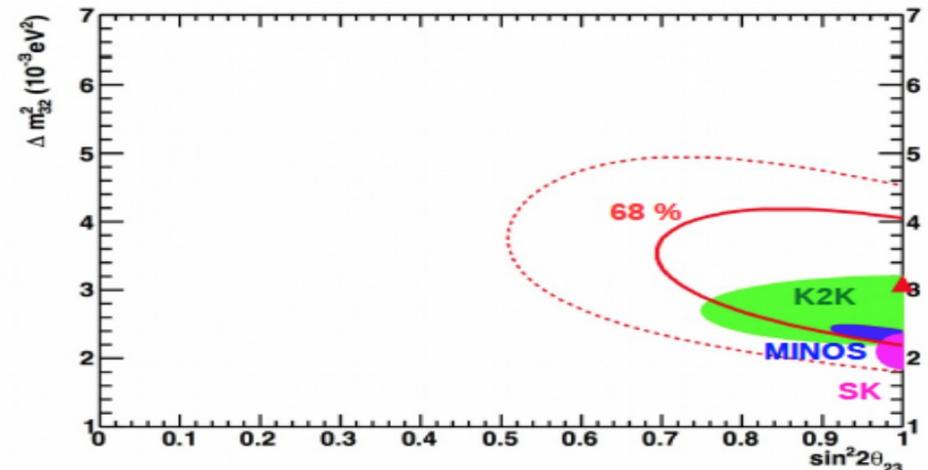
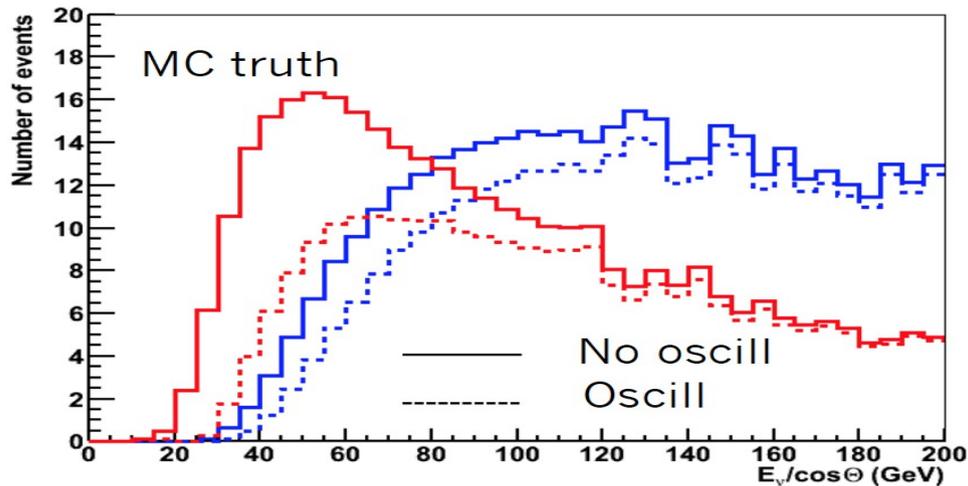
$$E/L \propto E/\cos(\theta)$$

$$1\text{GeV} < E < 100\text{GeV}$$

Single line events

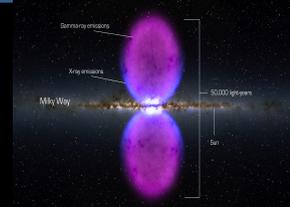
Multi line events

S. Adrian-Martinez et al. Phys. Lett. B 714 (2012) 22.



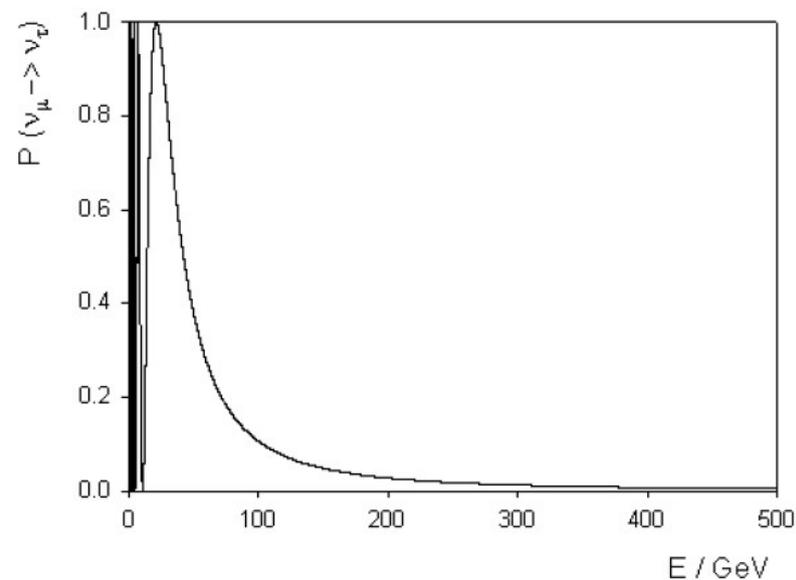
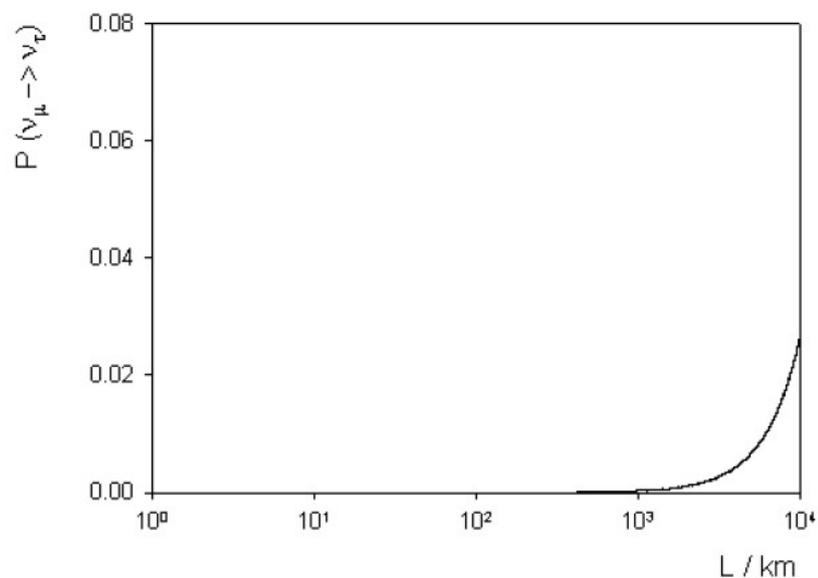


# L.I.V oscillation patterns



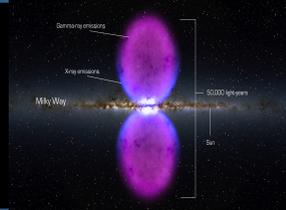
$$E^2 = p^2 + m^2 + \eta p^2 \left( \frac{E}{E_p} \right)^\alpha \quad \longrightarrow \quad P[\nu_a \rightarrow \nu_b] = \sin^2 2\theta \sin^2 \left[ 1.27 \frac{\Delta m^2 L}{E} + 1.27 \times 10^{9(n+1)} \Delta \eta E^n L \right]$$

No L.I.V.



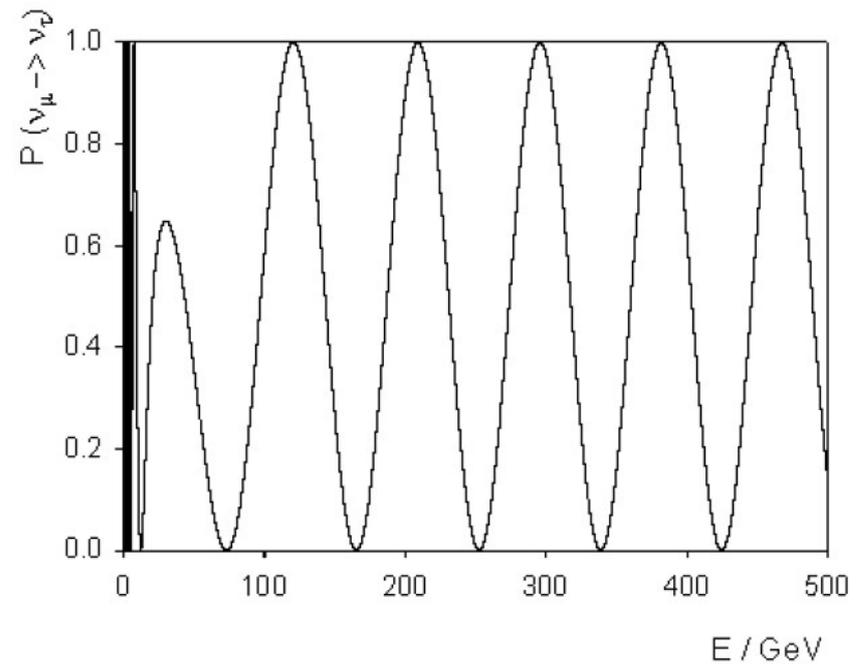
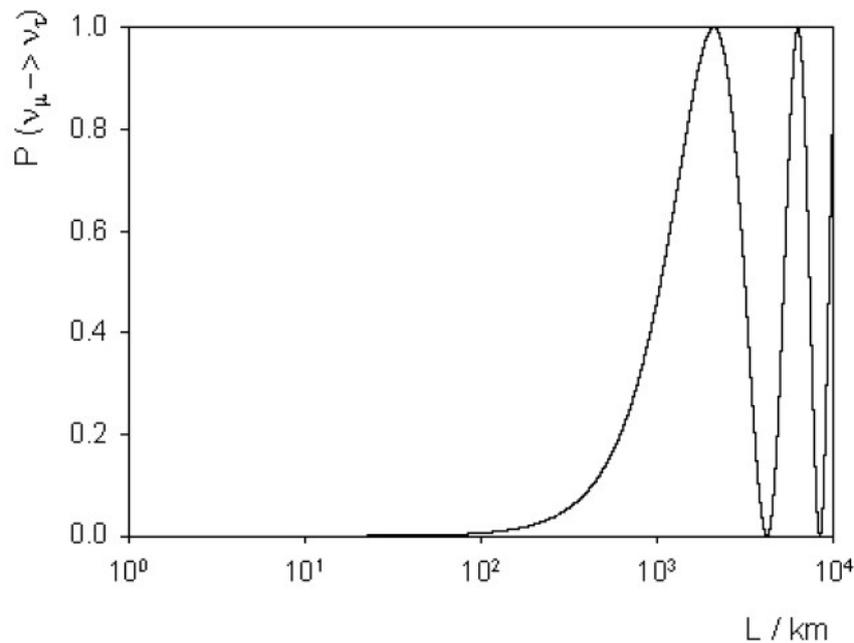


# L.I.V oscillation patterns



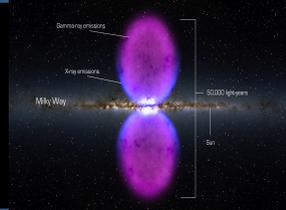
$$E^2 = p^2 + m^2 + \eta p^2 \left( \frac{E}{E_p} \right)^\alpha \quad \longrightarrow \quad P[\nu_a \rightarrow \nu_b] = \sin^2 2\theta \sin^2 \left[ 1.27 \frac{\Delta m^2 L}{E} + 1.27 \times 10^{9(n+1)} \Delta \eta E^n L \right]$$

n=1



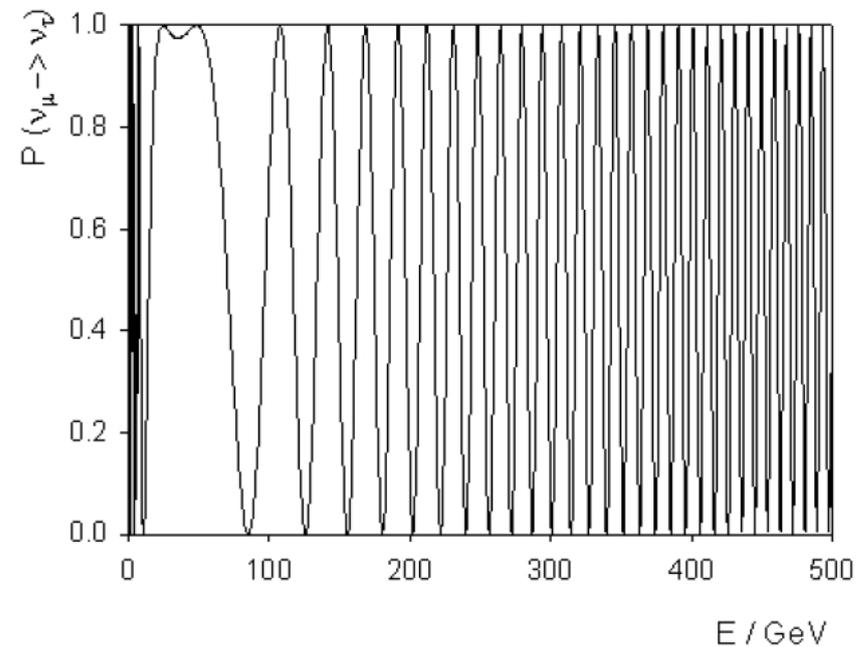
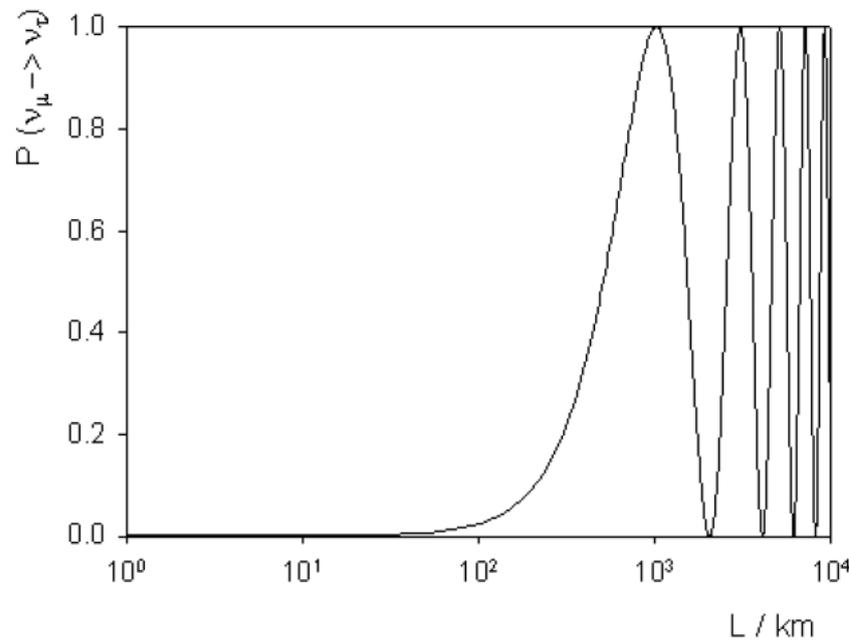


# L.I.V oscillation patterns



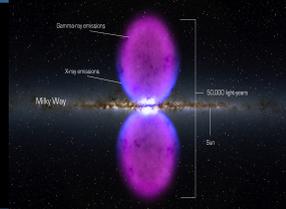
$$E^2 = p^2 + m^2 + \eta p^2 \left( \frac{E}{E_p} \right)^\alpha \quad \longrightarrow \quad P[\nu_a \rightarrow \nu_b] = \sin^2 2\theta \sin^2 \left[ 1.27 \frac{\Delta m^2 L}{E} + 1.27 \times 10^{9(n+1)} \Delta \eta E^n L \right]$$

n=2



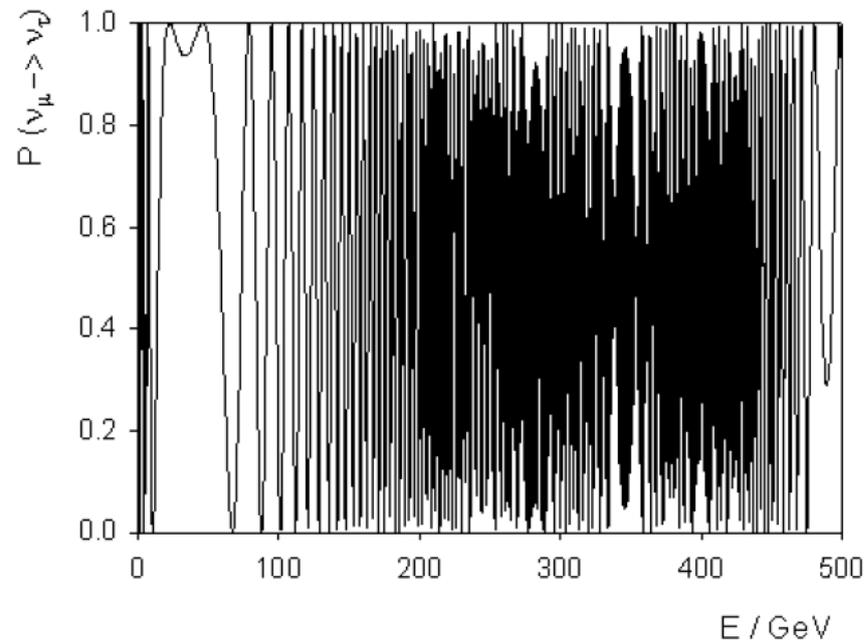
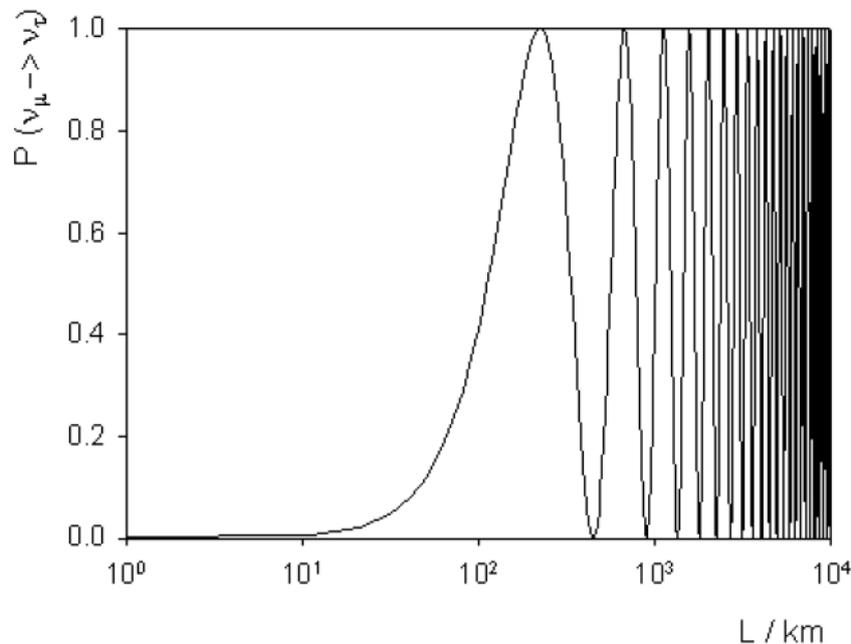


# L.I.V oscillation patterns



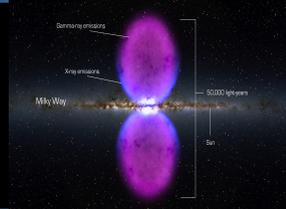
$$E^2 = p^2 + m^2 + \eta p^2 \left( \frac{E}{E_p} \right)^\alpha \quad \longrightarrow \quad P[\nu_a \rightarrow \nu_b] = \sin^2 2\theta \sin^2 \left[ 1.27 \frac{\Delta m^2 L}{E} + 1.27 \times 10^{9(n+1)} \Delta \eta E^n L \right]$$

n=3





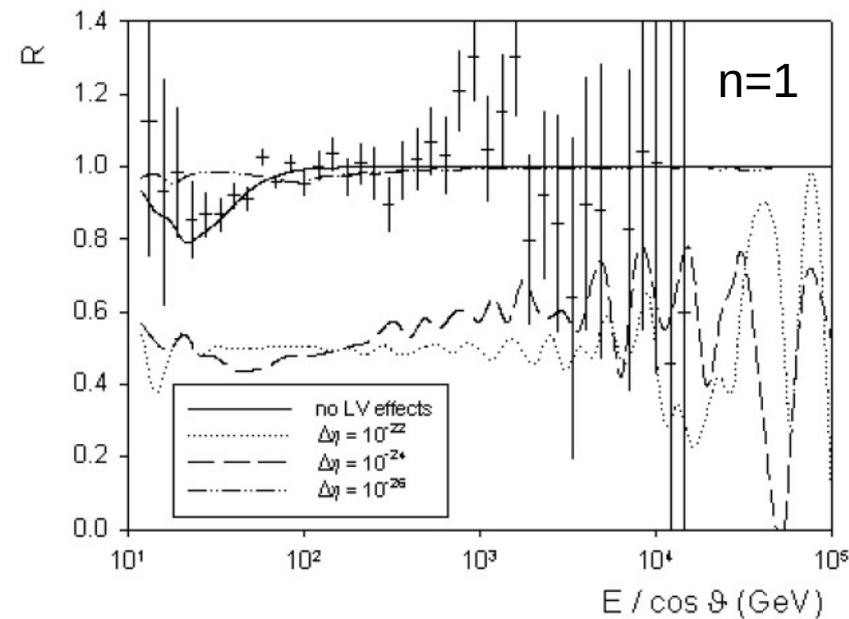
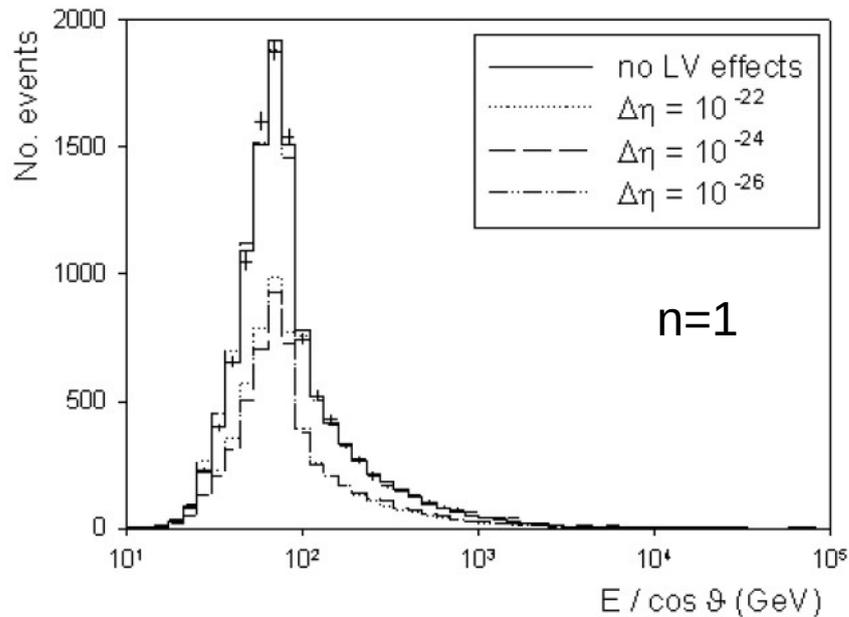
# Sensitivity estimate with ANTARES



Morgan et al, *Astropart.Phys.* 29 (2008) 345-354

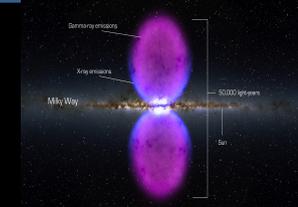
Sensitivity for  
 3 yrs  $\nu_\mu$  data taking (MC)  
 $100 \text{ GeV} < E < 1 \text{ TeV}$

n	$\Delta\eta \text{ (eV}^{-n+1}\text{)}$
1	$2.9 \cdot 10^{-24}$
2	$2.9 \cdot 10^{-35}$
3	$6.9 \cdot 10^{-46}$





# Latest Ice3 search



More general theoretical framework :

Ice3 coll., arXiv:1709.03434

$$H \sim \frac{m^2}{2E} + \hat{a}^{(3)} - E \cdot \hat{c}^{(4)} + E^2 \cdot \hat{a}^{(5)} - E^3 \cdot \hat{c}^{(6)} \dots$$

A. Kostelecky et al. , Phys. Rev.D85 (2012)  
096005.  
[arXiv:1112.6395](https://arxiv.org/abs/1112.6395),

Focuses on CPT even coefficients (  $c^{(2n)}$  ) and (  $\nu_\mu \rightarrow \nu_\tau$  ) oscillations

$$\hat{c}^{(6)} = \begin{pmatrix} \hat{c}_{\mu\mu}^{(6)} & \hat{c}_{\mu\tau}^{(6)} \\ \hat{c}_{\mu\tau}^{(6)*} & -\hat{c}_{\mu\mu}^{(6)} \end{pmatrix} .$$

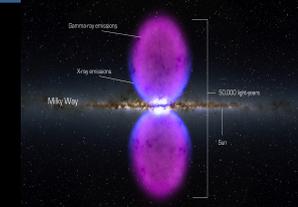
eigenvalues  $\lambda$  of  $H$

$$\begin{aligned} \lambda_1, \lambda_2 &= \frac{1}{2} \left[ (A_1 + A_3) \pm \sqrt{(A_1 - A_3)^2 + 4A_2^2} \right] \\ A_1 &= \frac{1}{2E} (m_2^2 \cos^2 \theta + m_3^2 \sin^2 \theta) + E^{d-3} (\hat{a}_{\mu\mu}^{(d)} - \hat{c}_{\mu\mu}^{(d)}) \\ A_2 &= \frac{1}{2E} \cos \theta \sin \theta (m_2^2 - m_3^2) + E^{d-3} (\hat{a}_{\mu\tau}^{(d)} - \hat{c}_{\mu\tau}^{(d)}) \\ A_3 &= \frac{1}{2E} (m_2^2 \sin^2 \theta + m_3^2 \cos^2 \theta) - E^{d-3} (\hat{a}_{\mu\mu}^{(d)} - \hat{c}_{\mu\mu}^{(d)}) . \end{aligned}$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \frac{4A_2^2}{(\lambda_2 - \lambda_1)^2} \sin^2 \left( \frac{\lambda_2 - \lambda_1}{2} L \right)$$



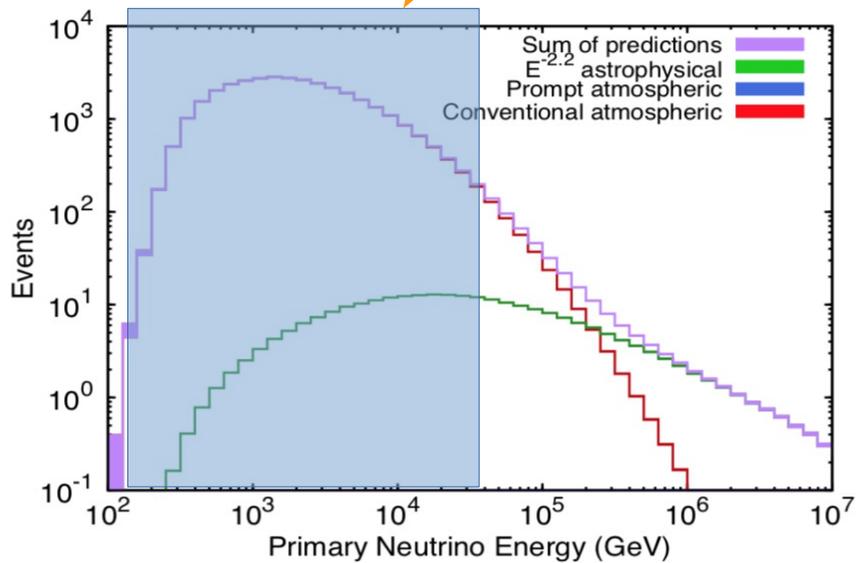
# Improvements



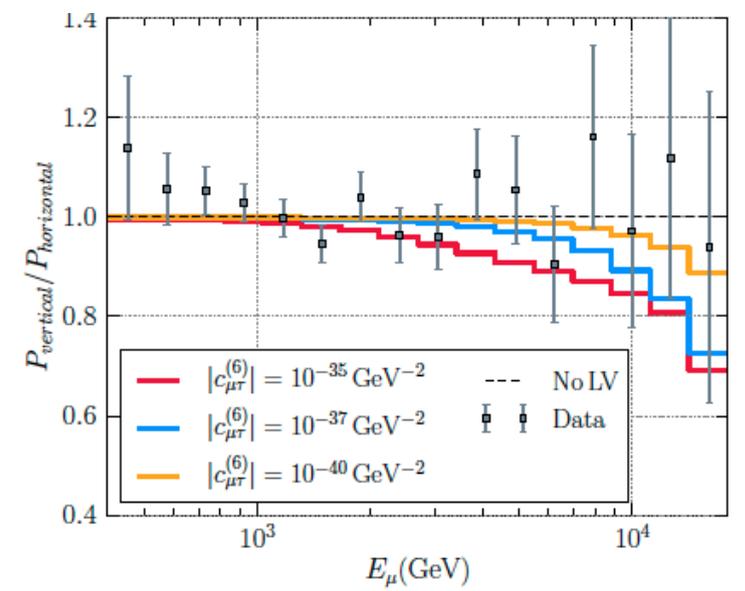
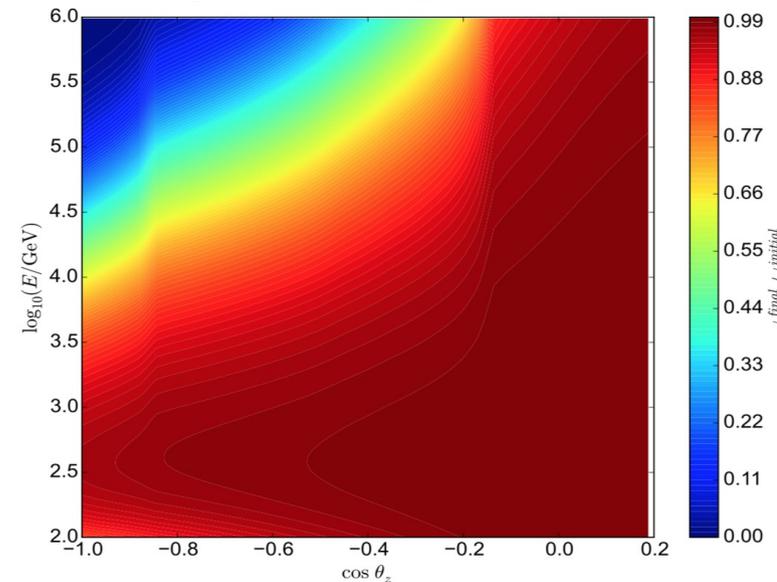
Stat\*20

2D likelihood

Emax\*10

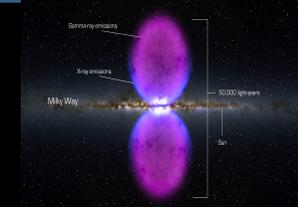


C. Agueles Delgado

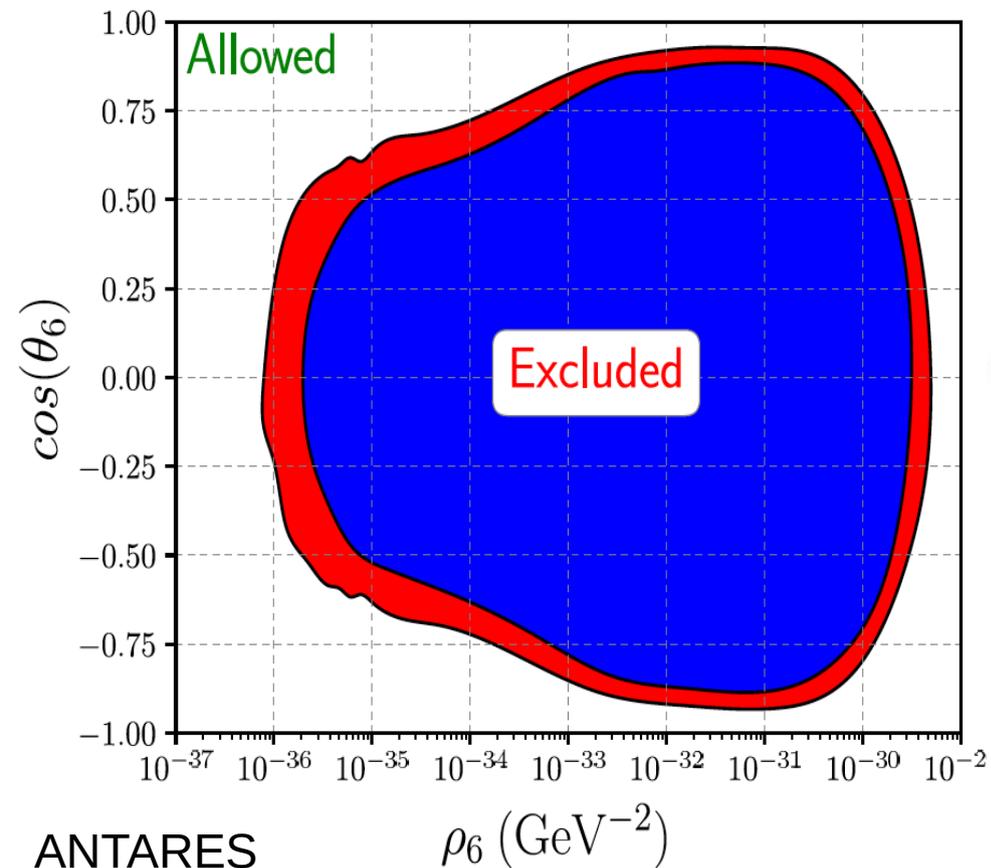




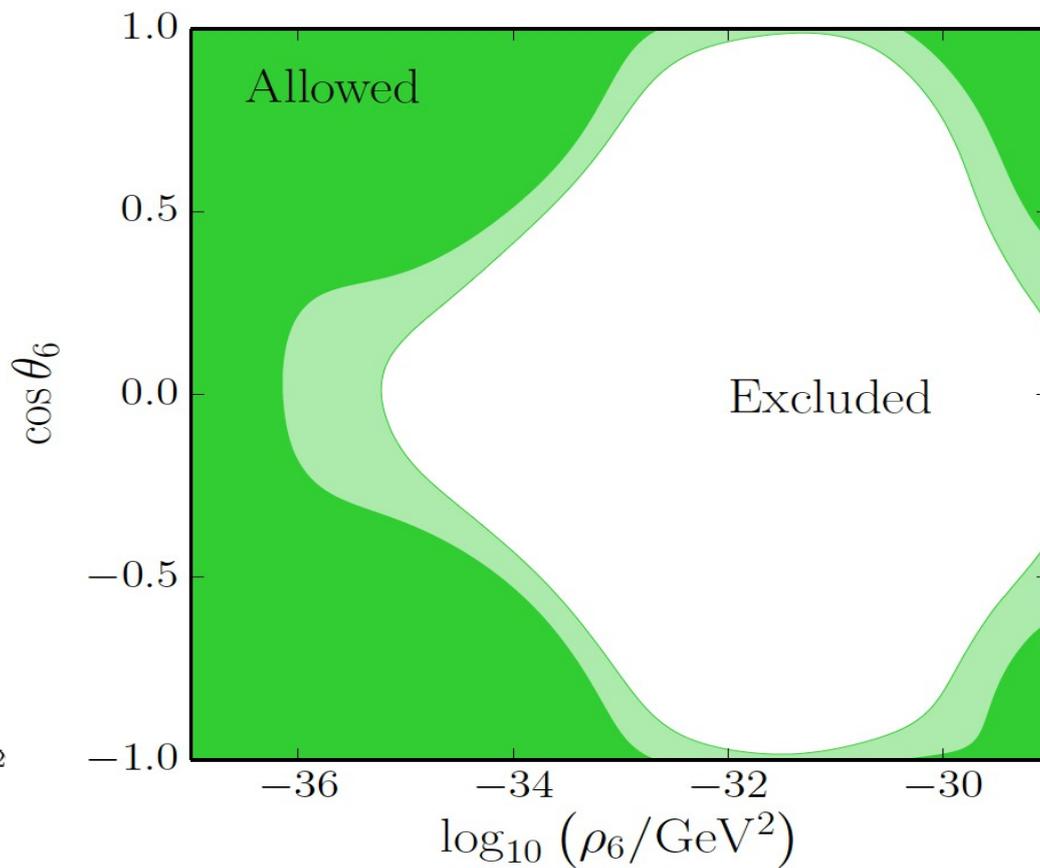
# Constrains



Likelihood minimisation



Markov Chain Monte Carlo



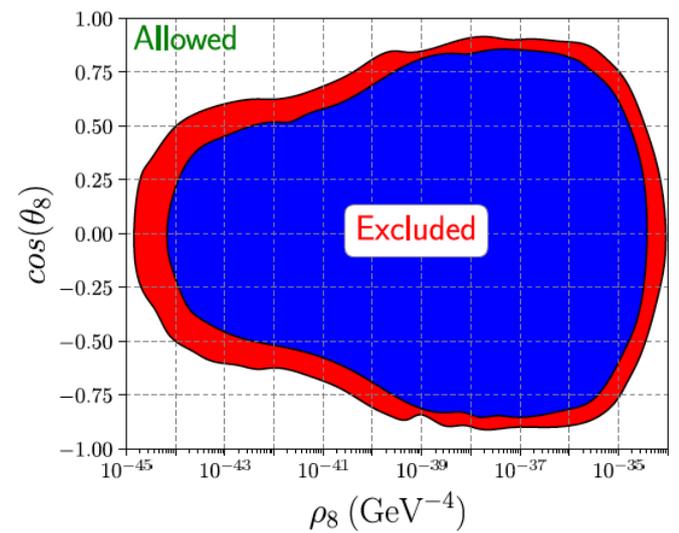
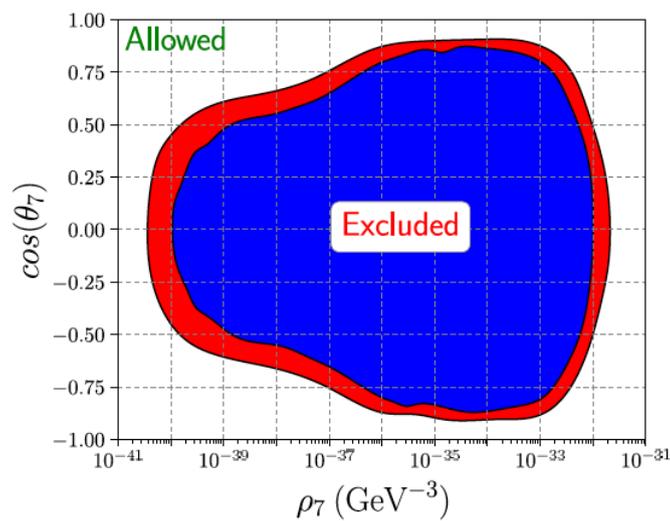
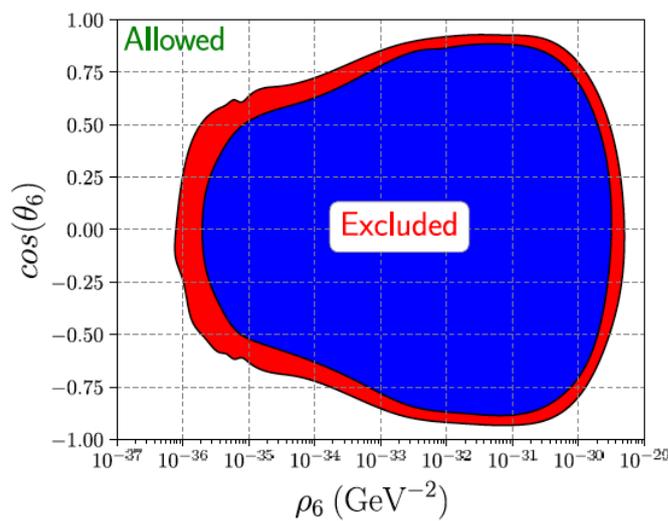
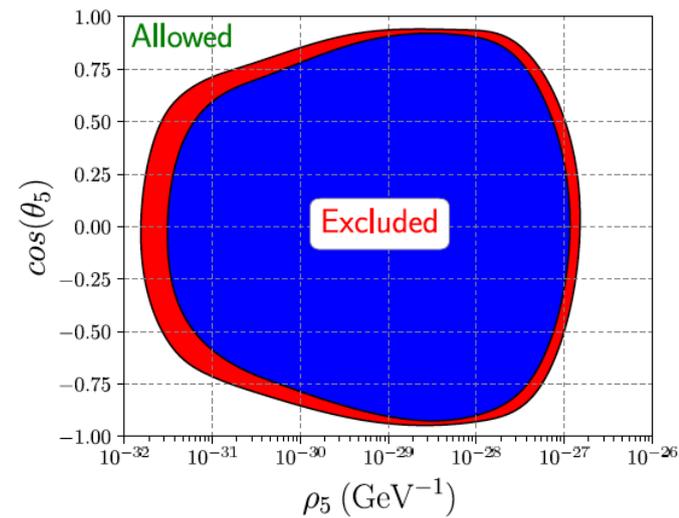
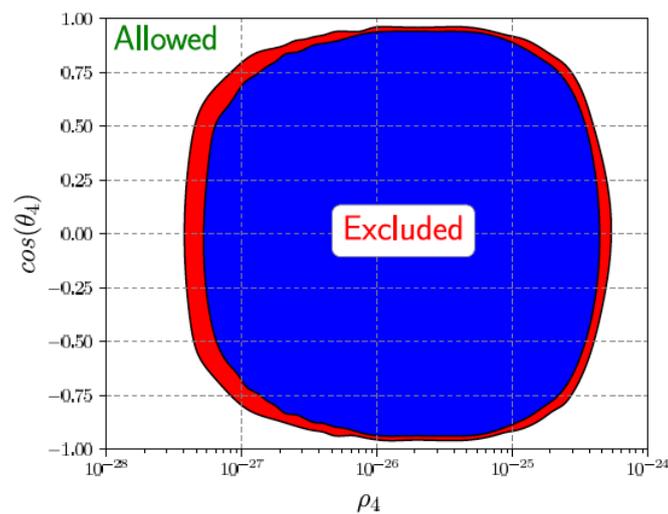
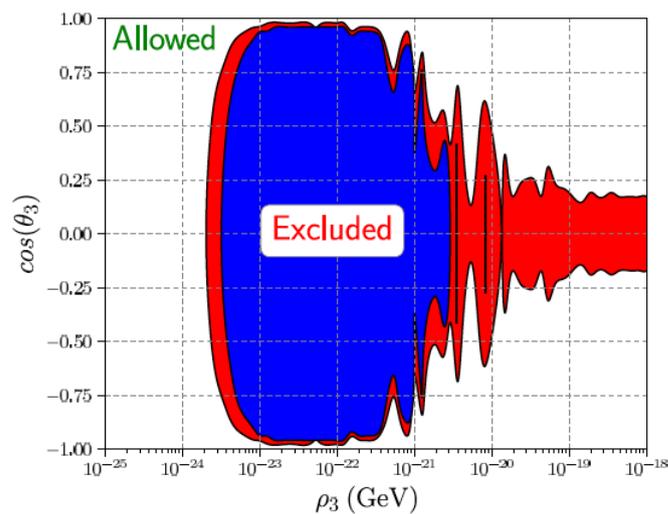
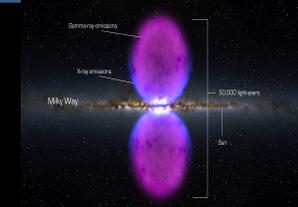
n	$\Delta\eta$ ( $\text{GeV}^{-n+1}$ )
1	$2.9 \cdot 10^{-24}$
2	$2.9 \cdot 10^{-26}$
3	$6.9 \cdot 10^{-28}$

$$\cos \theta_6 \equiv \hat{c}_{\mu\mu}^{(6)} / \rho_6$$

$$\rho_6 \equiv \sqrt{(\hat{c}_{\mu\mu}^{(6)})^2 + \text{Re}(\hat{c}_{\mu\tau}^{(6)})^2 + \text{Im}(\hat{c}_{\mu\tau}^{(6)})^2}$$

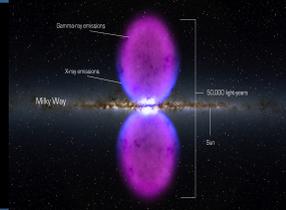


# Constrains





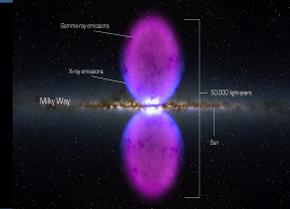
# Constraints



dim.	method	type	sector	limits	ref.
3	CMB polarization	astrophysical	photon	$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron	$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron	$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon	$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$ \text{Re}(\hat{a}_{\mu\tau}^{(3)}) ,  \text{Im}(\hat{a}_{\mu\tau}^{(3)})  < 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon	$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon	$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron	$\sim 10^{-29}$	[11]
	trapped $\text{Ca}^+$ ion	tabletop	electron	$\sim 10^{-19}$	[14]
neutrino oscillation	atmospheric	neutrino	$ \text{Re}(\hat{c}_{\mu\tau}^{(4)}) ,  \text{Im}(\hat{c}_{\mu\tau}^{(4)})  < 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work	
5	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-34}$ GeV $^{-1}$	[7]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-22}$ to $10^{-18}$ GeV $^{-1}$	[9]
	neutrino oscillation	atmospheric	neutrino	$ \text{Re}(\hat{a}_{\mu\tau}^{(5)}) ,  \text{Im}(\hat{a}_{\mu\tau}^{(5)})  < 2.3 \times 10^{-32}$ GeV $^{-1}$ (99% C.L.) $< 1.5 \times 10^{-32}$ GeV $^{-1}$ (90% C.L.)	this work
6	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-31}$ GeV $^{-2}$	[7]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-42}$ to $10^{-35}$ GeV $^{-2}$	[9]
	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-31}$ GeV $^{-2}$	[15]
	neutrino oscillation	atmospheric	neutrino	$ \text{Re}(\hat{c}_{\mu\tau}^{(6)}) ,  \text{Im}(\hat{c}_{\mu\tau}^{(6)})  < 1.5 \times 10^{-36}$ GeV $^{-2}$ (99% C.L.) $< 9.1 \times 10^{-37}$ GeV $^{-2}$ (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-28}$ GeV $^{-3}$	[7]
	neutrino oscillation	atmospheric	neutrino	$ \text{Re}(\hat{a}_{\mu\tau}^{(7)}) ,  \text{Im}(\hat{a}_{\mu\tau}^{(7)})  < 8.3 \times 10^{-41}$ GeV $^{-3}$ (99% C.L.) $< 3.6 \times 10^{-41}$ GeV $^{-3}$ (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-46}$ GeV $^{-4}$	[15]
	neutrino oscillation	atmospheric	neutrino	$ \text{Re}(\hat{c}_{\mu\tau}^{(8)}) ,  \text{Im}(\hat{c}_{\mu\tau}^{(8)})  < 5.2 \times 10^{-45}$ GeV $^{-4}$ (99% C.L.) $< 1.4 \times 10^{-45}$ GeV $^{-4}$ (90% C.L.)	this work



# Summary and perspectives



- VHE neutrinos very good LIV probes
- Time of flight : need a GRB neutrino  
→ time stacking
- Oscillations : quite competitive and versatile
- KM3NeT growing  
→ complement and surpass Ice3