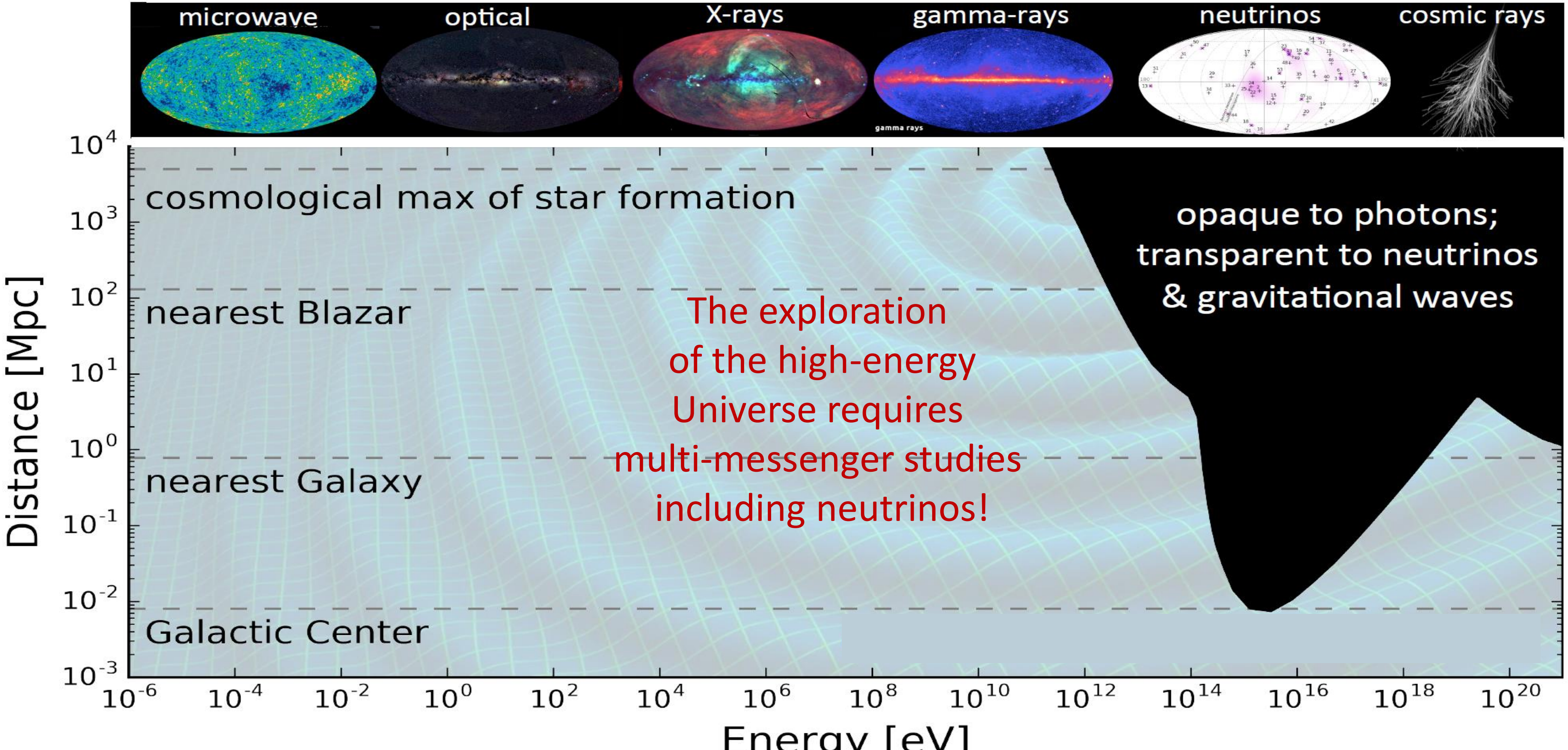
# KM3NeT
# Neutrino astronomy

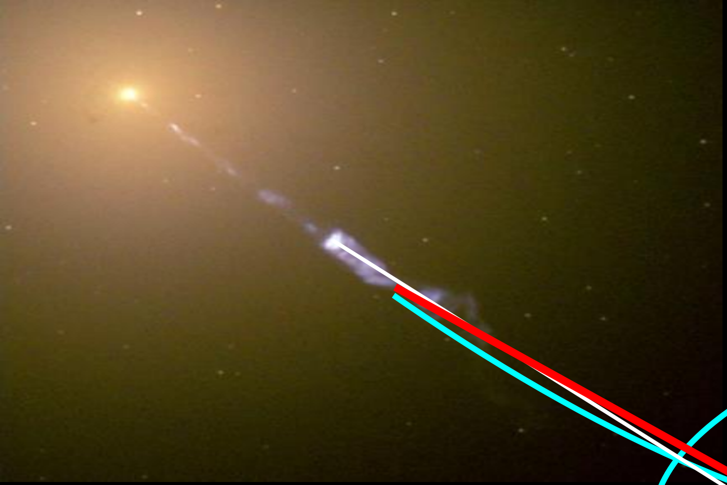
Aart Heijboer

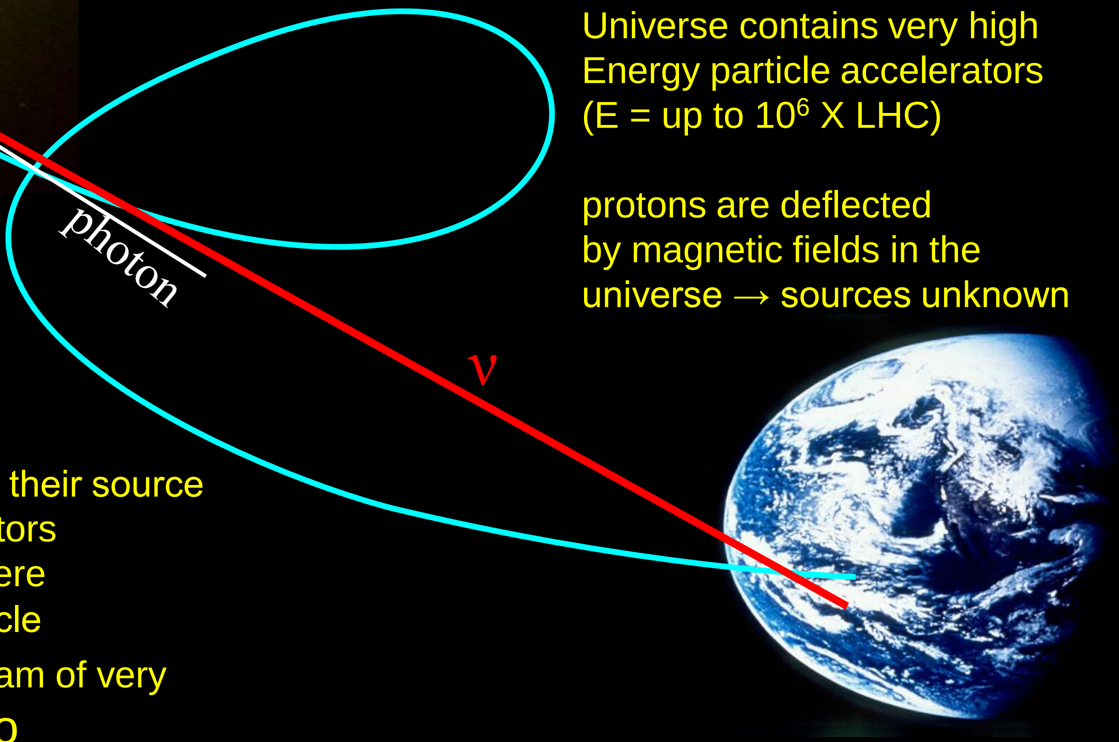
# Neutrino astronomy



high energy

# Neutrino from the Universe






Universe contains very high Energy particle accelerators (E = up to $10^6$ X LHC)

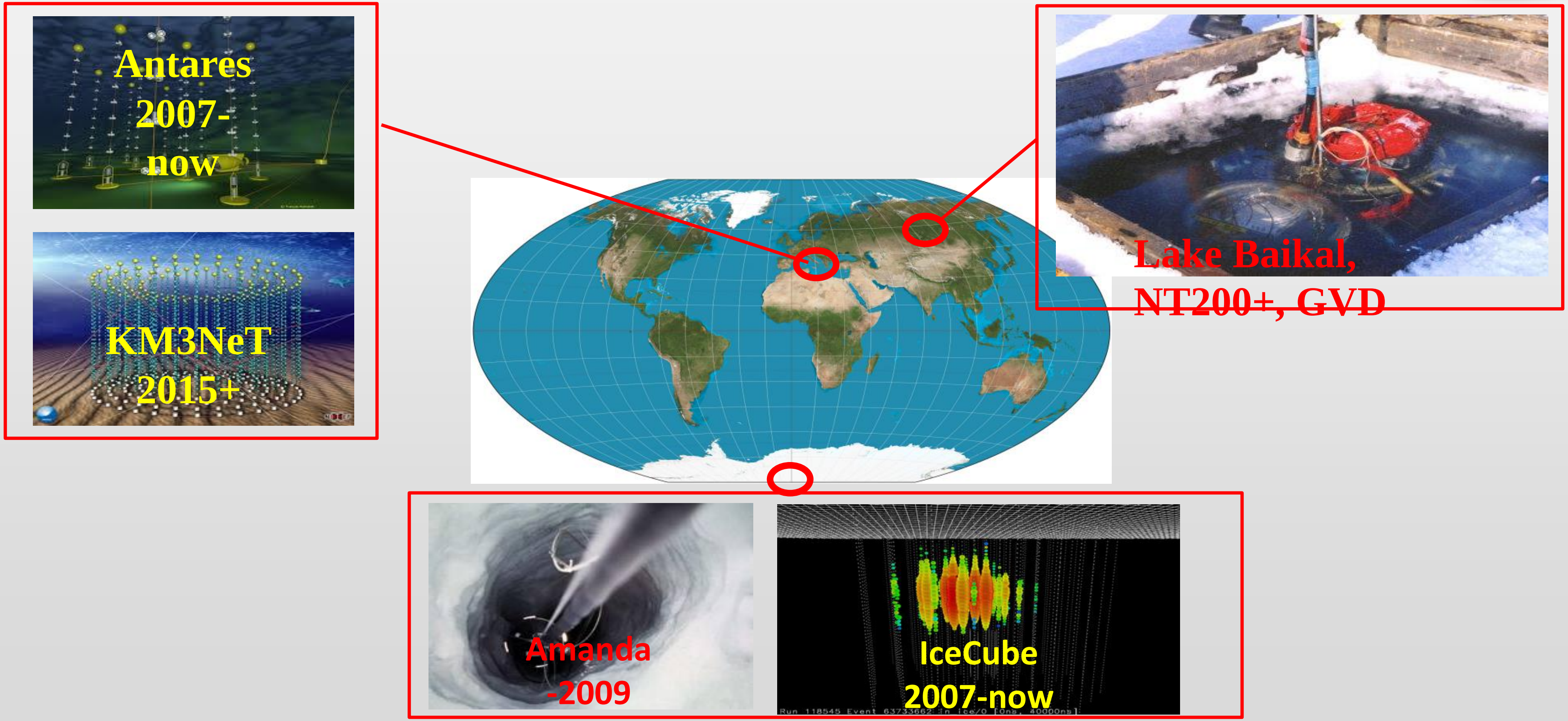
protons are deflected by magnetic fields in the universe → sources unknown

**high energy neutrinos:**

- travel in straight lines → point to their source
- are produced in proton accelerators
- are not absorbed on their way here
  - → “ideal” messenger particle
  - free very-long baseline beam of very

high energy neutrino

# neutrino telescopes

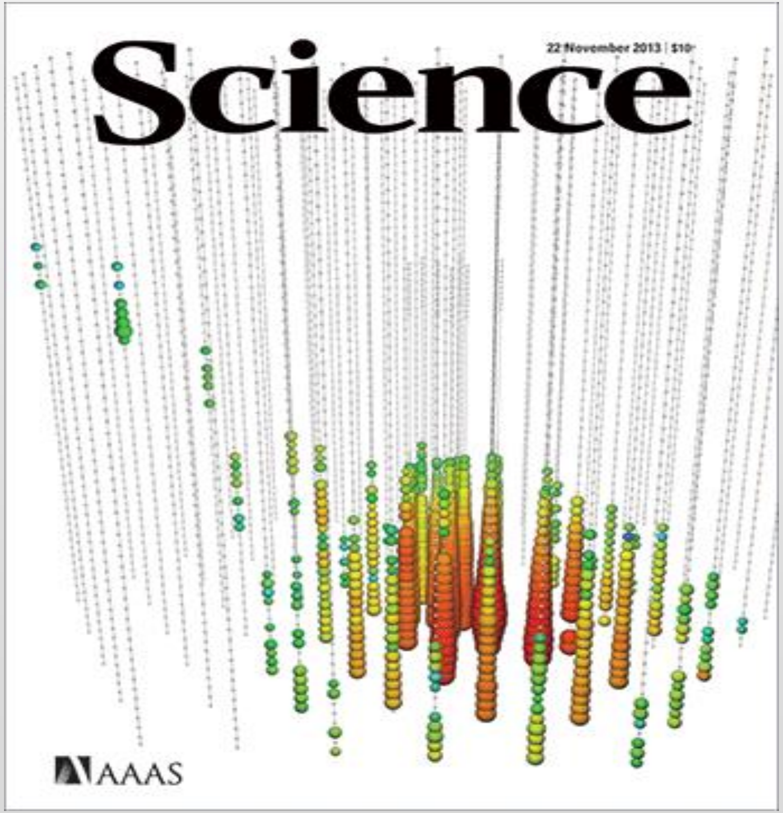


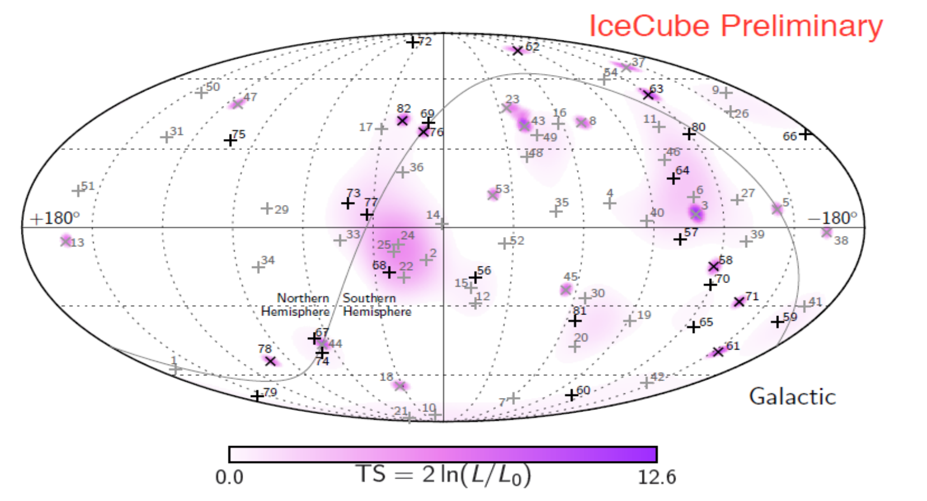

http://www.cherenkov.nl/aa3d/?f=../aa3d_files/numucc_8.js.gz


http://www.cherenkov.nl/aa3d/?f=../aa3d_files/nuecc_3.js.gz


http://www.cherenkov.nl/aa3d/?f=../aa3d_files/taux_evt_8.js.gz

# Cosmic neutrinos observed!

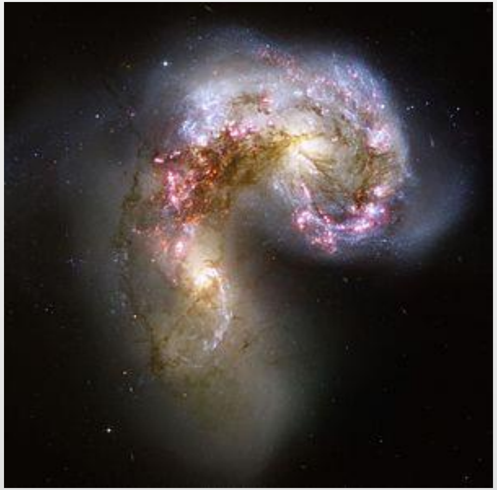


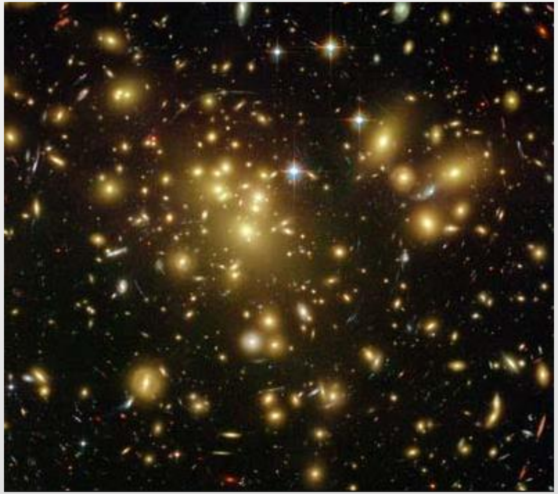

- Cosmic  neutrinos seen with Icecube.
- Energies: PeV
- Most are electron- and tau neutrinos
  - Bad resolution
  - Sources unknown

# Sources of IceCube neutrinos?

AGN and BLAZARS



(SNR inside)
Starburst Galaxies

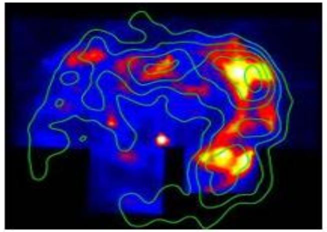


(SNR inside)
Galaxy Clusters

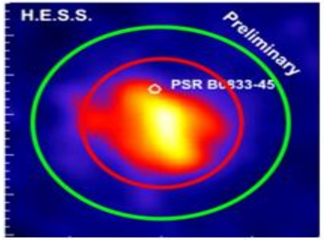
[ and/or Galactic component, heavy dark matter decay, new physics?]

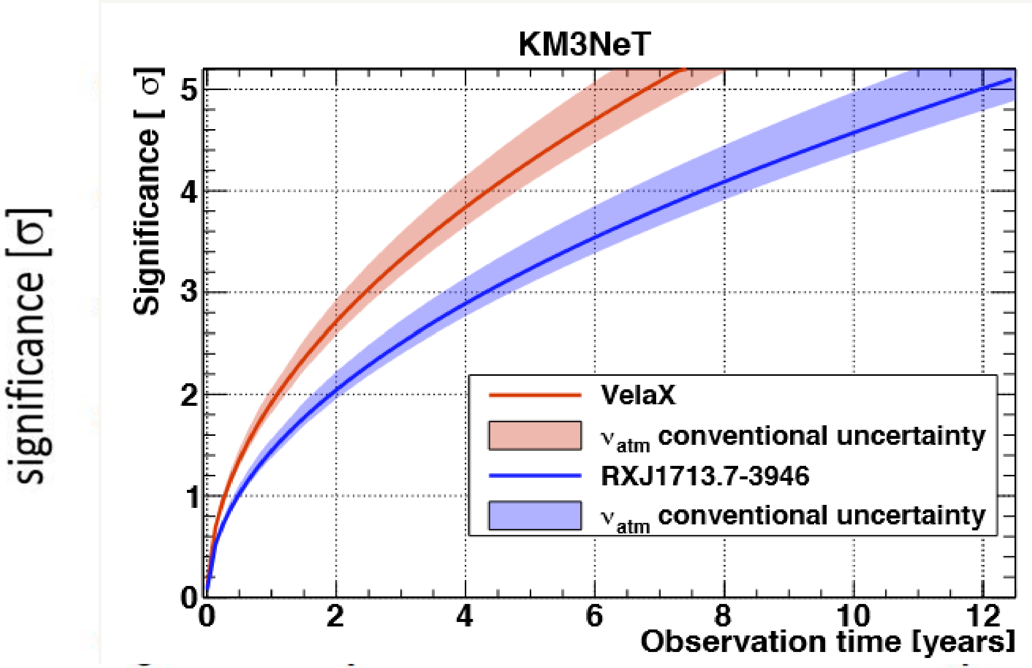
# Galactic Supernova Remnants – if hadronic

RXJ1713[¶]



Vela X[§]

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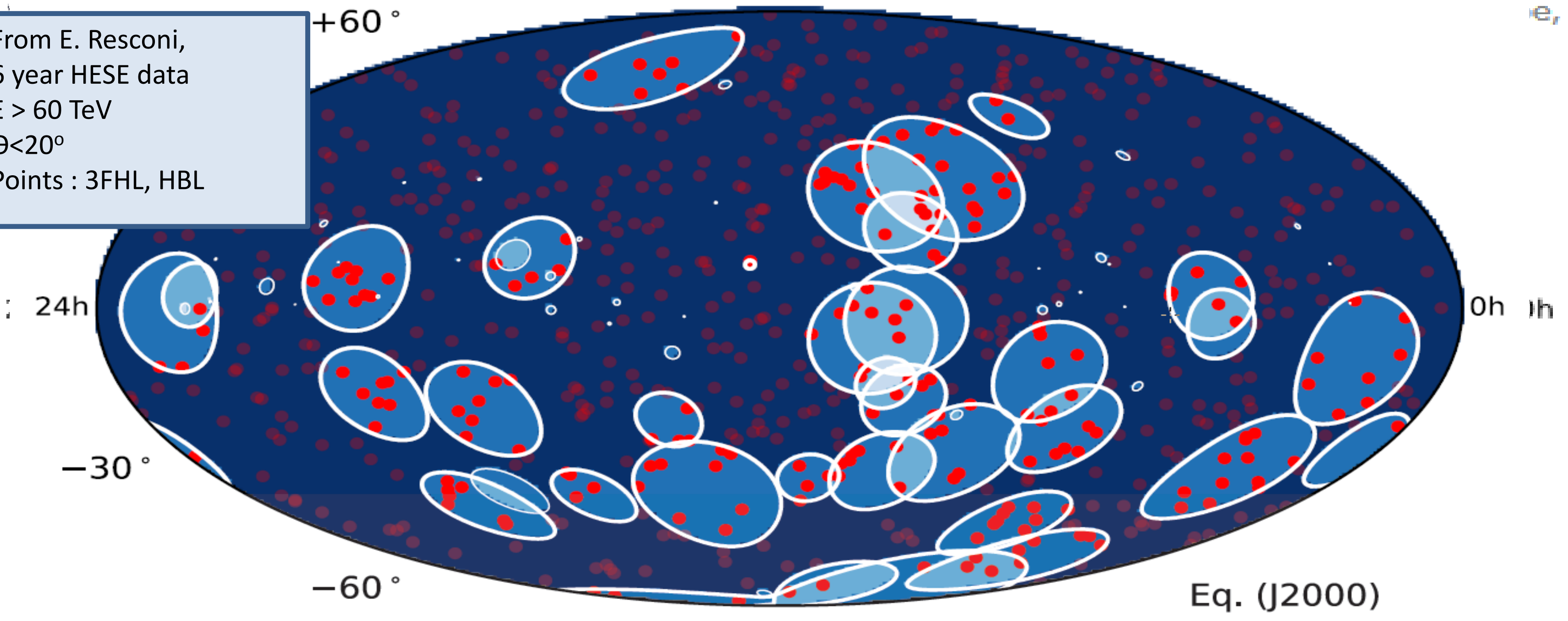
¶ S.R. Kelner, *et al.*, Phys. Rev. D 74 (2006) 034018.
§ F.L. Villante and F. Vissani, Phys. Rev. D 78 (2008) 103007.

# Resolution is key

From E. Resconi,
6 year HESE data
E > 60 TeV
Θ<20º
Points : 3FHL, HBL

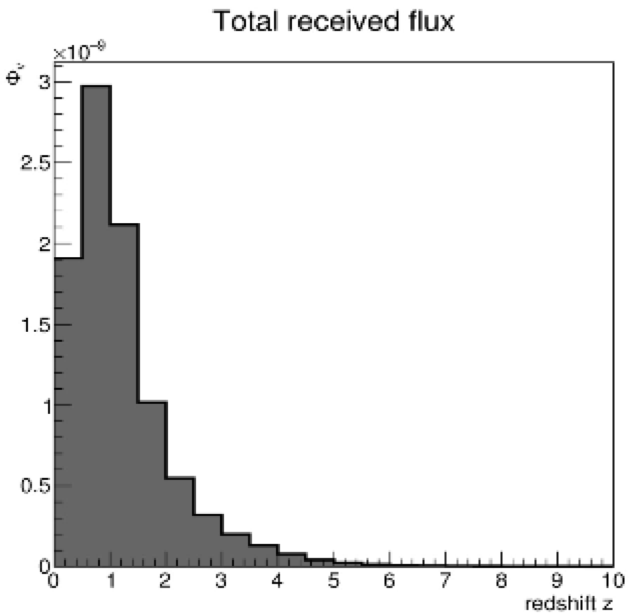



Resolution for $\nu_e$
ANTARES
KM3NeT

Resolution for $\nu_\mu$
ANTARES
KM3NeT

Resolution of key importance for catalogue searchers

# Catalog searches : explorative studies




- Neutrinos reach us from too far away -> many neutrinos, but also many sources.

## Results for Blazars

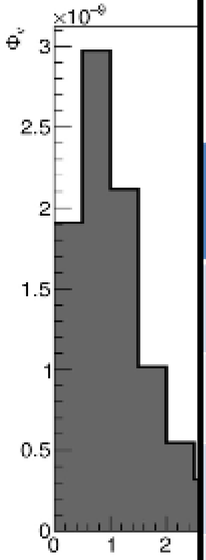
$(\mathcal{H}_0 = 10^{-9}\ \mathrm{Mpc}^{-3})$

| n_signal_nu | fraction_from_catalog | catalog_size | resolution | search_cone | n_random_hits | n_signal_hits | significance |
|---|---|---|---|---|---|---|---|
| 100 | 0.01 | 0.004881 | 0.1 | 0.2404 | 2.148e-06 | 0.9818 | 4.689 |
| 100 | 0.02 | 0.03853 | 0.1 | 0.2356 | 1.629e-05 | 1.957 | 6.346 |
| 100 | 0.04 | 0.3141 | 0.1 | 0.2302 | 0.0001268 | 3.899 | 8.442 |
| 100 | 0.08 | 2.59 | 0.1 | 0.2241 | 0.0009903 | 7.753 | 11.05 |
| 100 | 0.16 | 21.79 | 0.1 | 0.2167 | 0.007788 | 15.38 | 14.2 |
| 100 | 0.32 | 187.2 | 0.1 | 0.2076 | 0.06142 | 30.39 | 17.78 |
| 100 | 0.64 | 1661 | 0.1 | 0.1961 | 0.4867 | 59.55 | 21.41 |

B. Jongewaard

Blazars are among the rarest objects (per Mpc3)

# Catalog searches : explorative studies




## Optimal settings

For $\mathcal{H}_0 = 10^{-9}$ Mpc$^{-3}$

Message: Resolution just as important as acceptance.

| $N_\nu$ | ψ | β | $f_\nu$ | $N_{src}$ | random hits | signal hits | CL (σ) |
|---|---|---|---|---|---|---|---|
| 100 | 0.1° | 0.190° | 0.8194 | 4193 | 1.154 | 75.243 | **22.128** |
| 100 | 0.5° | 0.844° | 0.5198 | 856 | 4.646 | 44.777 | **12.011** |
| 500 | 0.5° | 0.844° | 0.5160 | 837 | 22.701 | 222.25 | **26.849** |
| 500 | 0.1° | 0.211° | 0.2680 | 108 | 0.182 | 127.85 | **> 35** |

> many

| _signal_hits | significance |
|---|---|
| .9818 | 4.689 |
| .957 | 6.346 |
| .899 | 8.442 |
| .753 | 11.05 |
| 5.38 | 14.2 |
| 0.39 | 17.78 |
| 9.55 | 21.41 |

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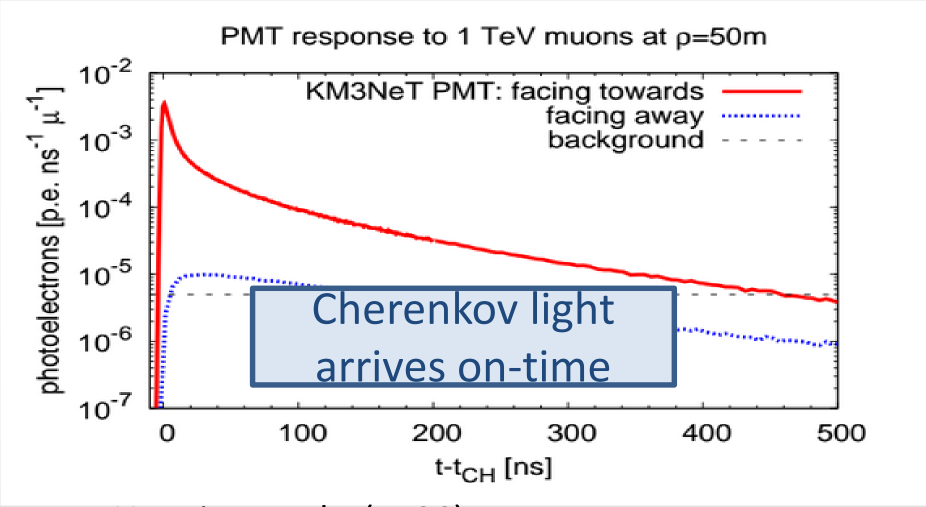
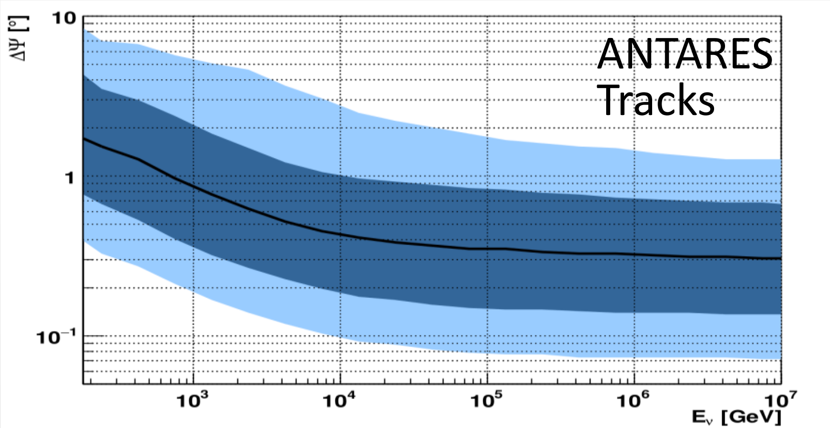
# Sea water as detection medium



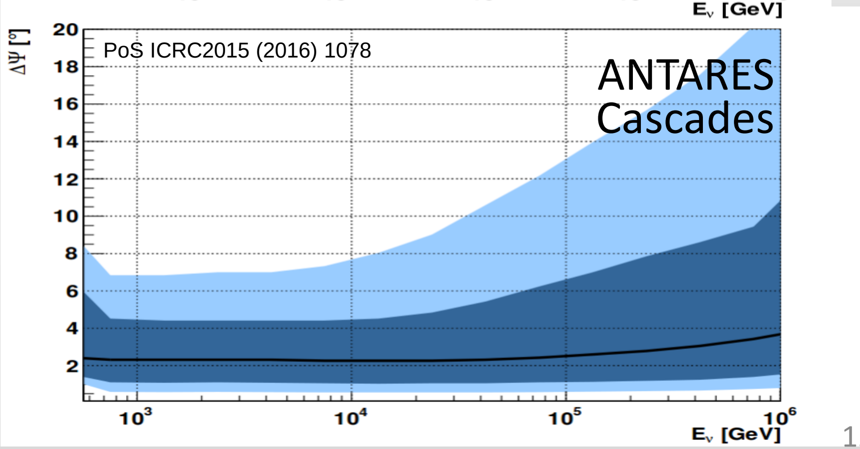

Upgoing tracks ($\nu_\mu$CC)

- Angular resolution <0.4° for $E_\nu$>10 TeV




Upgoing cascades($\nu_e/\nu_t$ CC, NC)

- Angular resolution < 3°
- Energy resolution for $\nu_e$ : 5%



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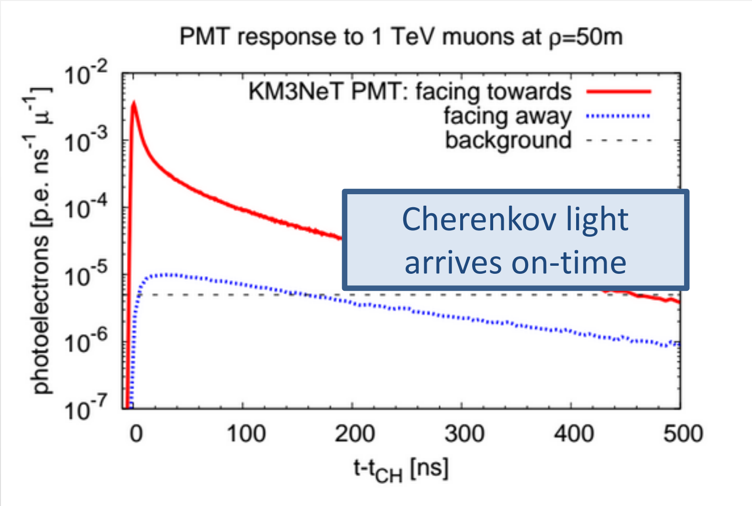
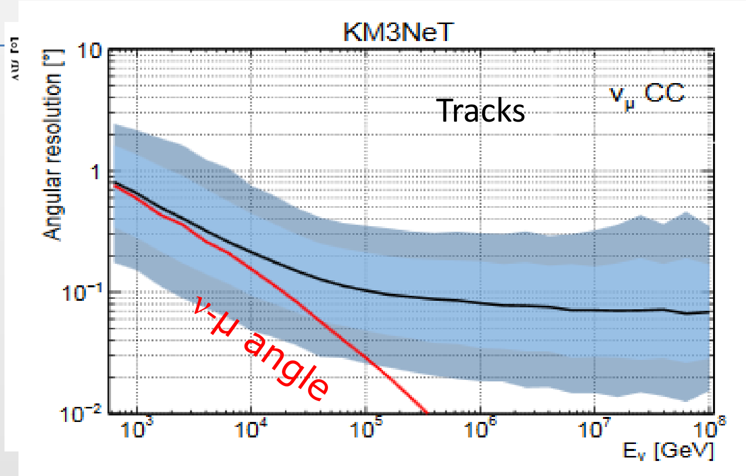
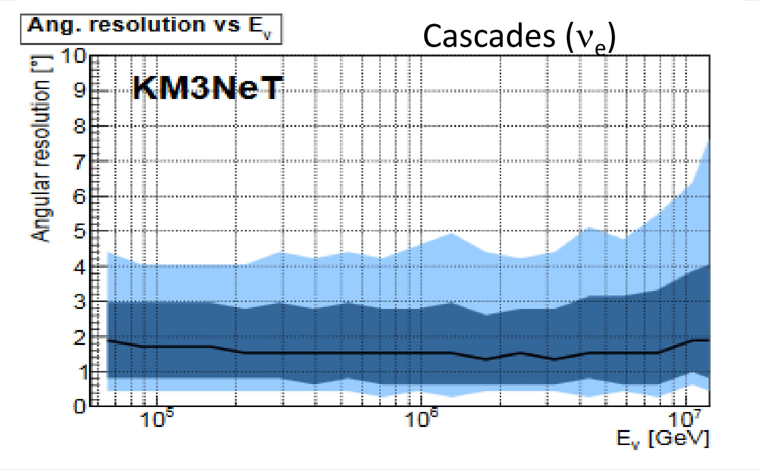


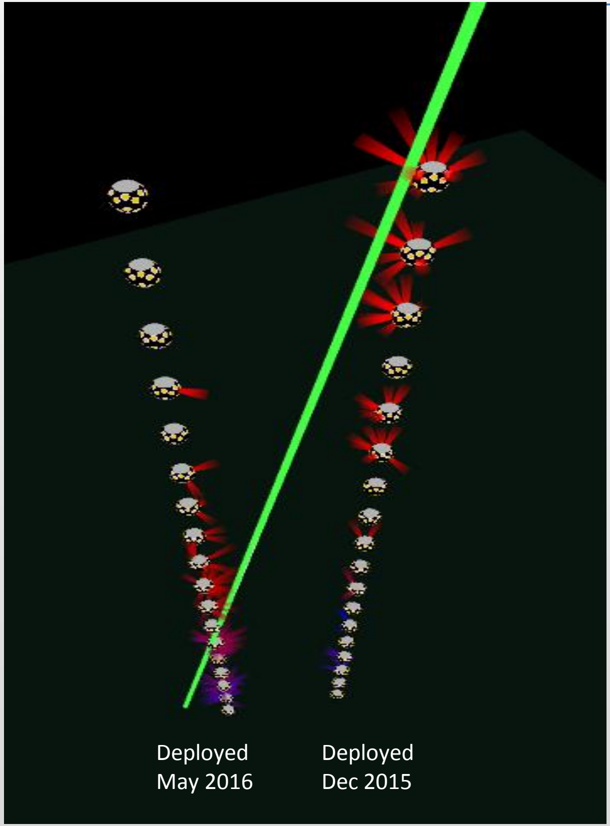

Track s ($\nu_{\mu}$CC)

- Angular resolution <0.1° for Eν>100 TeV

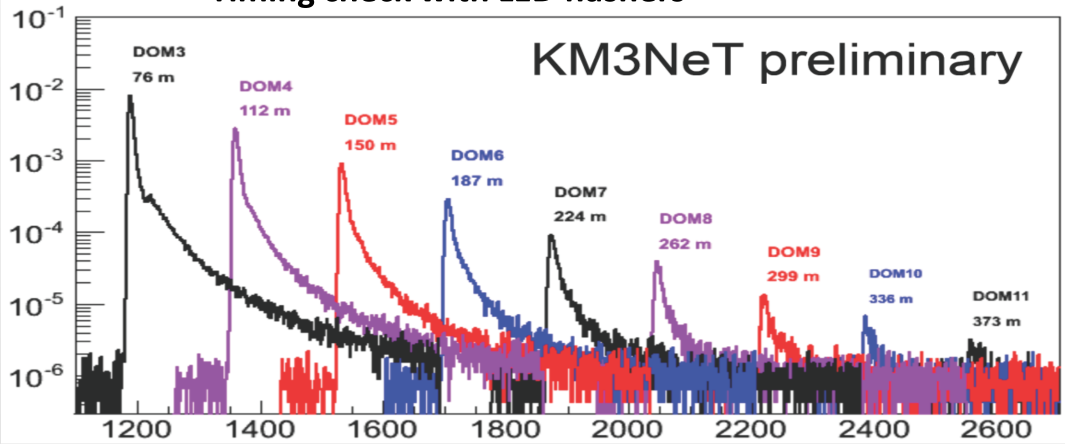
Cascade events ($\nu_{e}$/$\nu_{t}$ CC, NC)

- Angular resolution < 1.5°
- Energy resolution for $\nu_{e}$ ~5%

# First detection lines



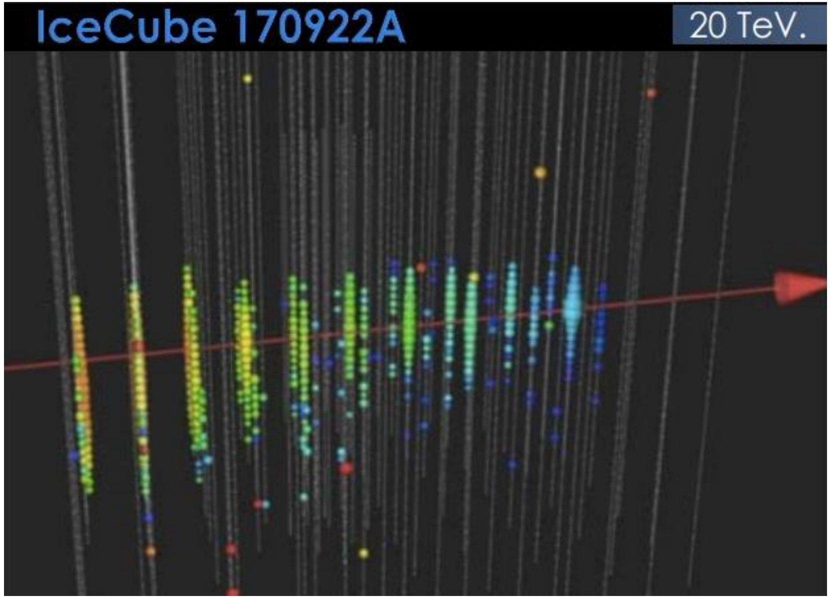

**Timing check with LED flashers**

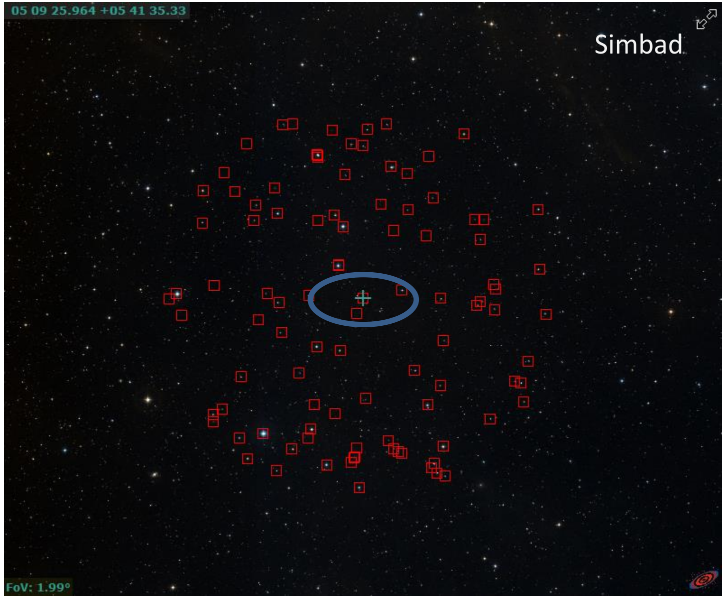



**Time after flash (ns)**

- Nanobeacon analysis confirms simulations:
- Light signals maintain timing information even after hundreds of meters

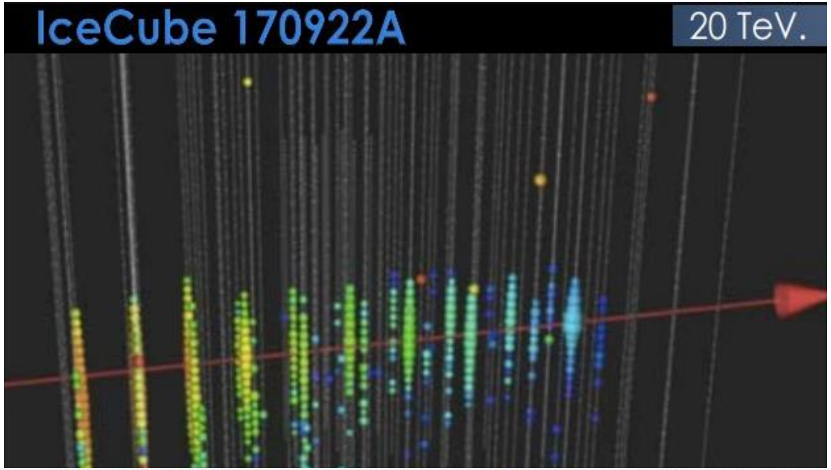
# IceCube-170922A / TXS 0506+056

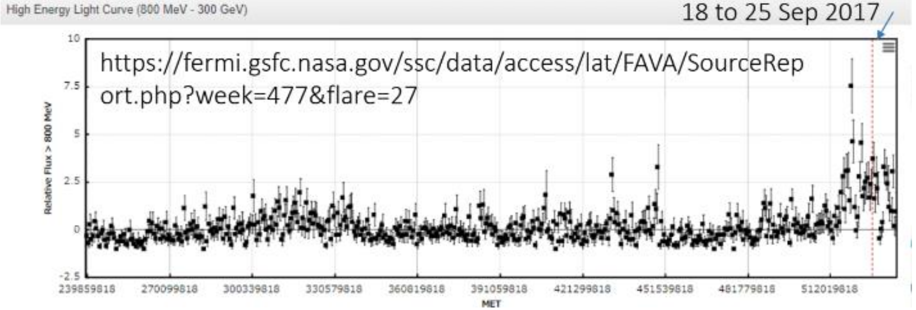


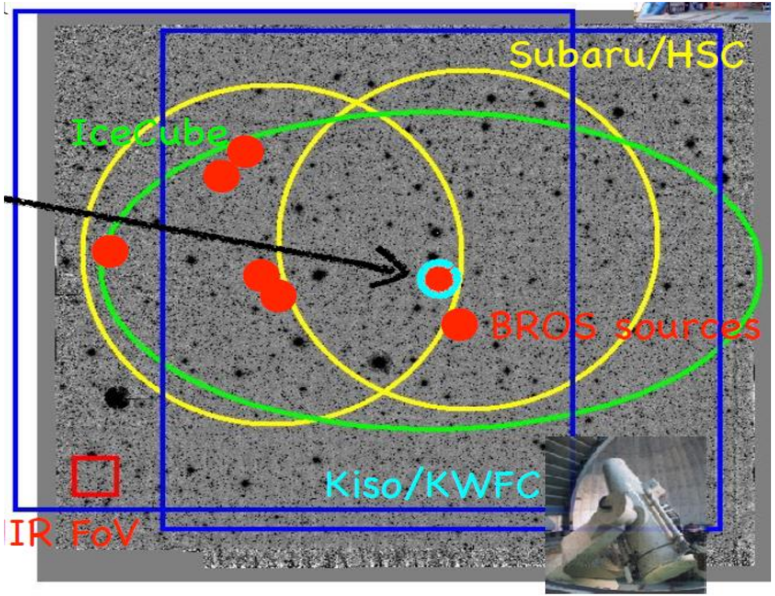




Notice horizontal track

# IceCube-170922A / TXS 0506+056



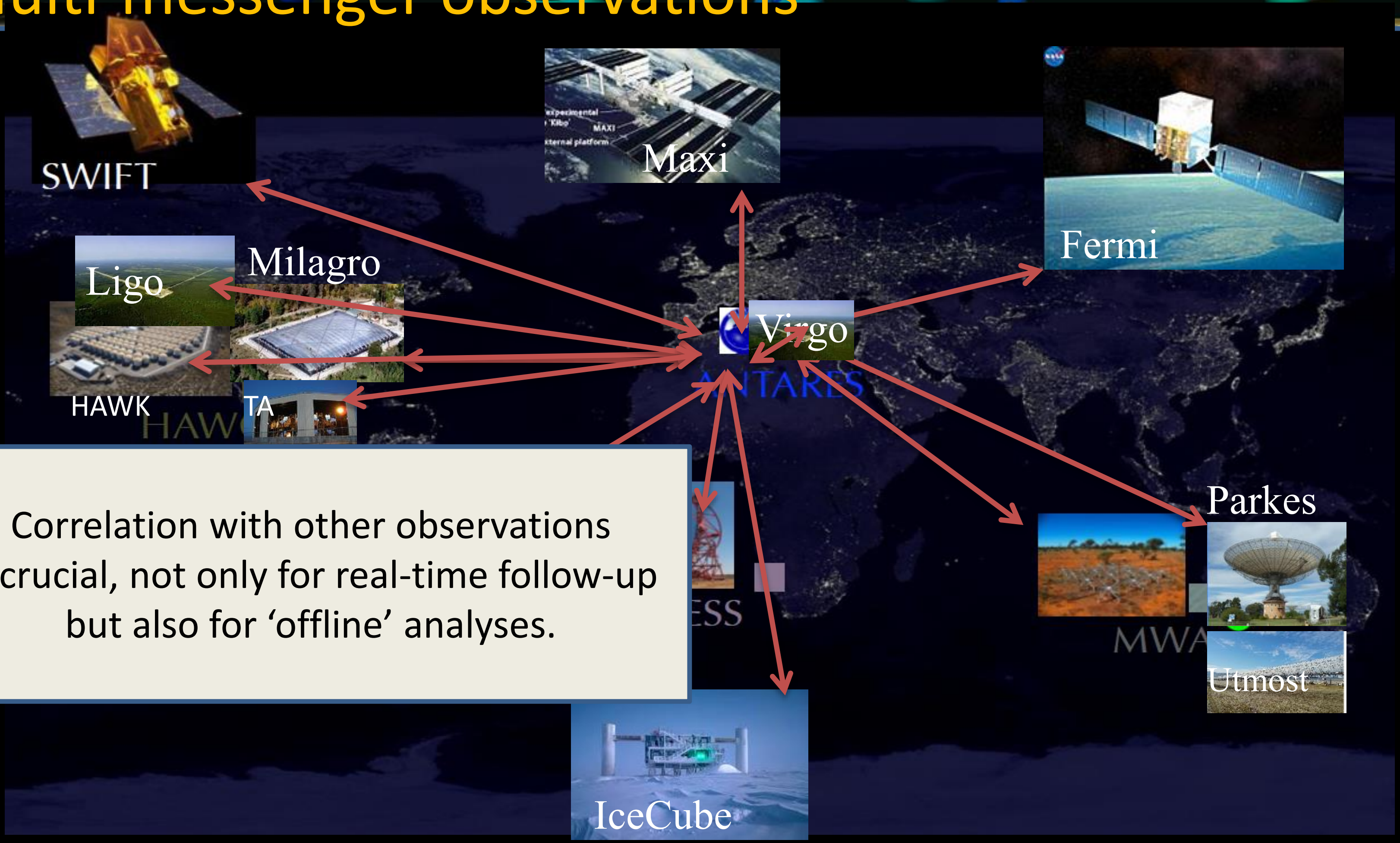




Specialized blazar candidate catalog (BROS):
6 more blazar candidates in error box.

# Multi-messenger observations

# Multi-messenger observations




Correlation with other observations
is crucial, not only for real-time follow-up
but also for 'offline' analyses.

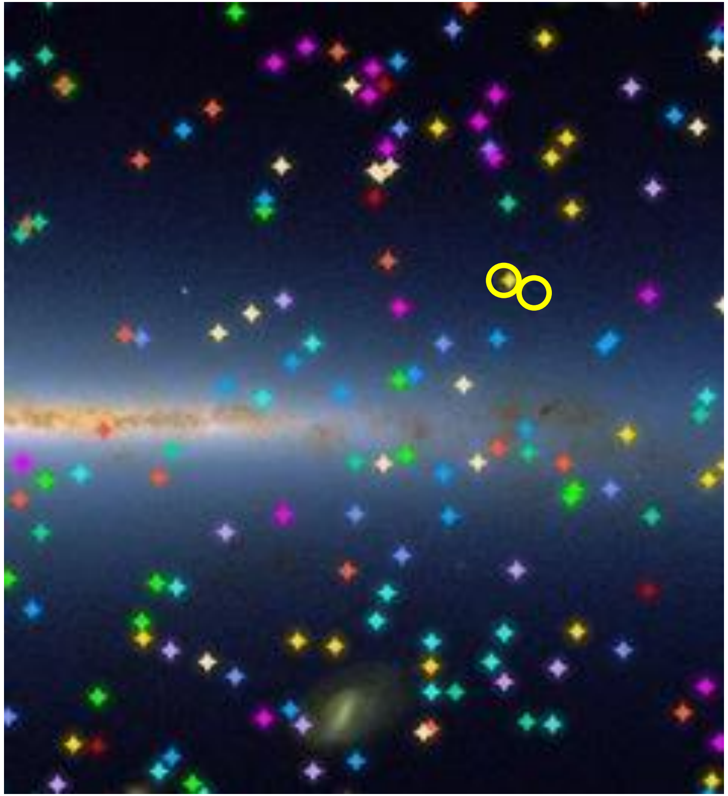
# Collecting signal

Source will be discovered by:
- High energy track (nm) events
- Time correlation
- Correlation with known object

Next:
- Once a neutrino source is established
- Identify compatible
  - Low energy tracks
  - Shower-events
  - Tau neutrinos
- Understand flavour composition

-> sample of long-baseline neutrinos

# Collecting signal



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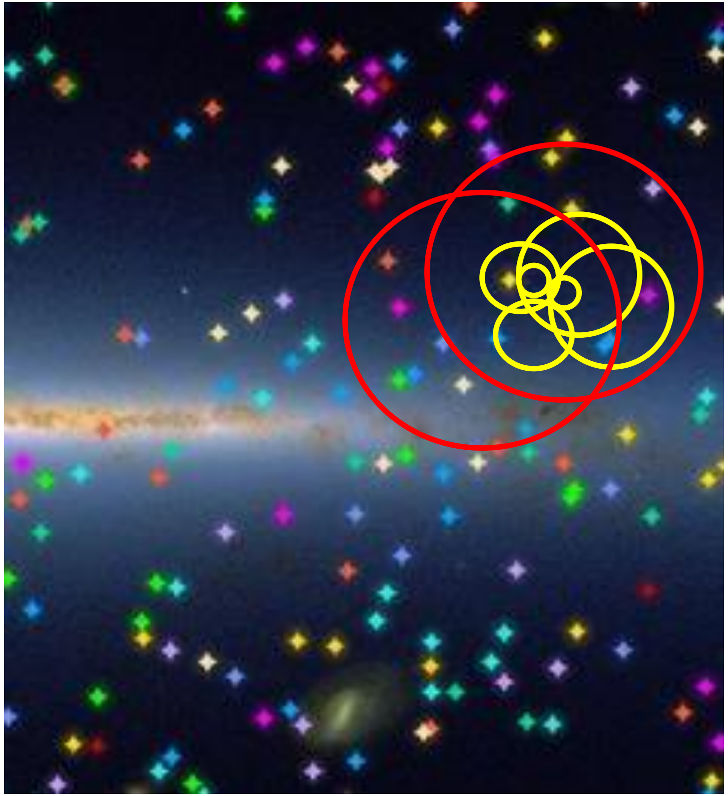

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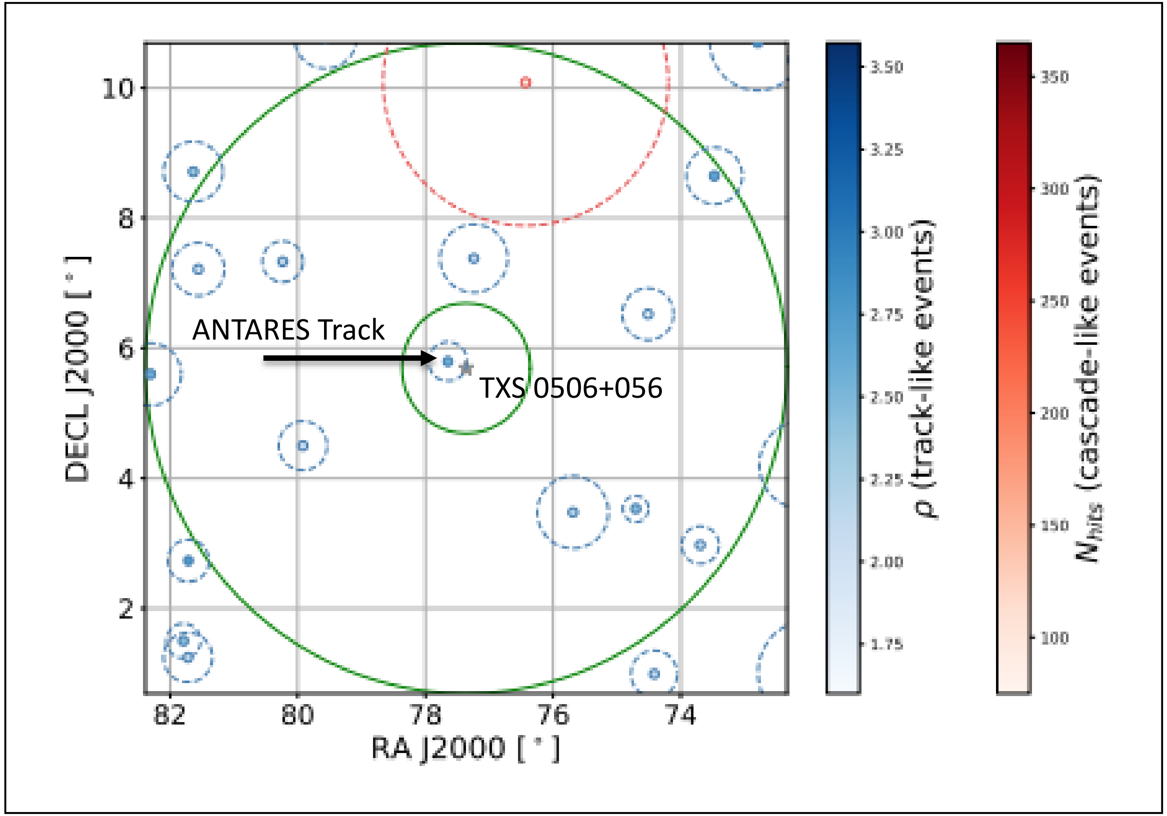
-> sample of long-baseline neutrinos

# Towards a sample of neutrinos




If you believe TX 0506+056 Is a neutrino source, it's quite likely this is a signal track.

(similar signal is rumoured to be present in Icecube Track data).

# Thoughts

- Angular resolution is absolutely key.

- With KM3NeT: can do better, especially for electron- and tau-neutrinos

- Strong sources may give multiple events (case for TXS 0506+056)

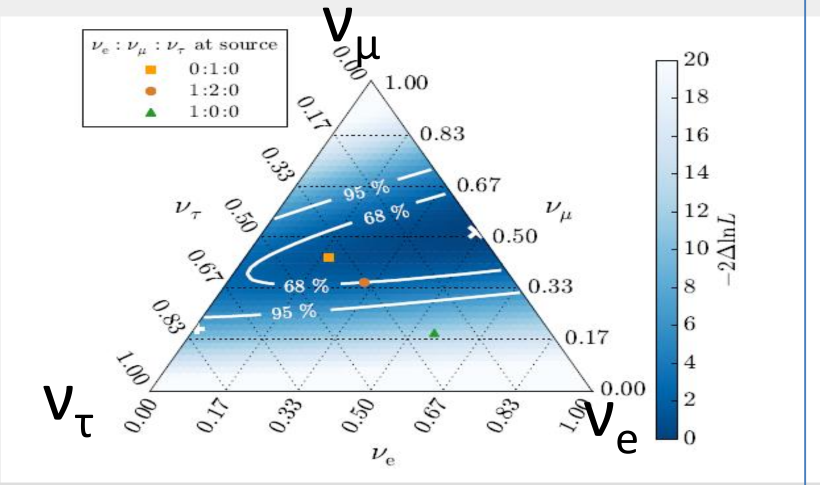
- Time dependence (flaring) is important
    - Activity in the Netherlands? Or simply send alerts?
    - Optical, radio, gamma ?

- Weak sources : < 1 event can be studied on statistical bases
  -> catalog searches

# Neutrino physics at a PeV

# Flavour ratios contain (astro) physics

IceCube flavour ratio fit

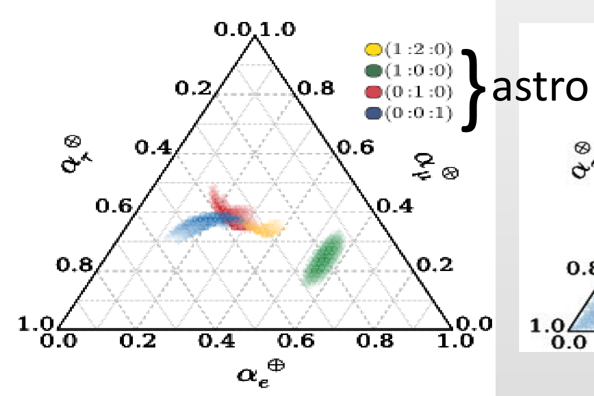



Fit to IceCube data consistent with 1:1:1

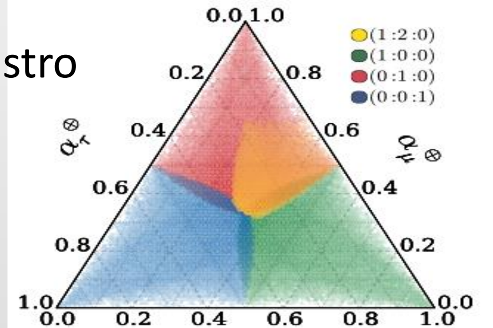
More data to come

Phys.Rev.Lett. 115 (2015) 161303

**SM**

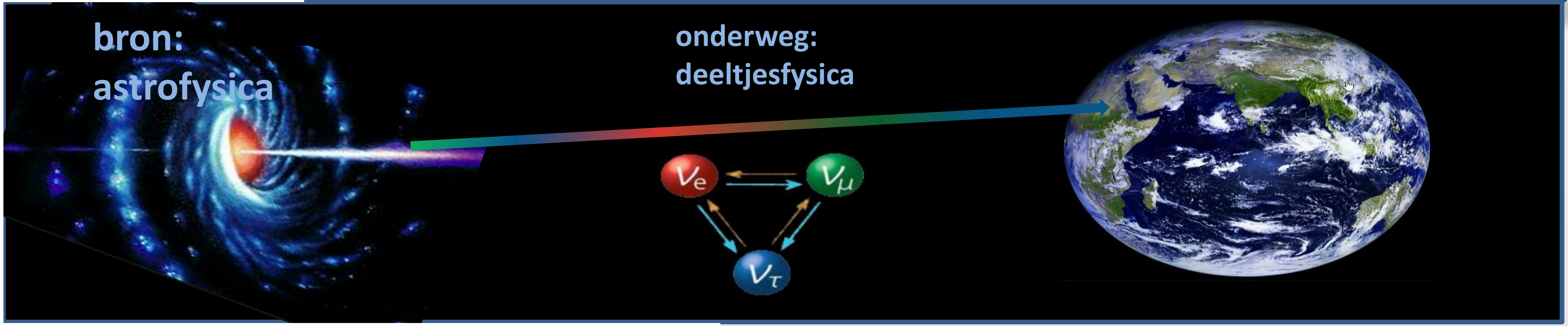



**New Physics**



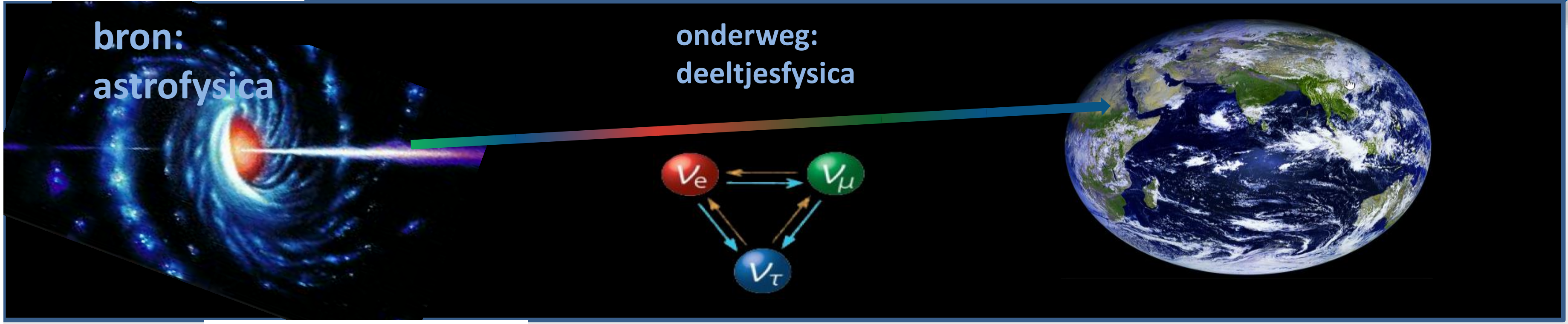

- Oscillations affect flavour ratios of cosmic neutrinos.
- non-standard interaction, Lorentz-invariance violation, ν-decay, steriles…
- Works better when sources are understood (and then, **can even probe $\delta_{cp}$**)
- *KM3NeT will contribute a lot here*

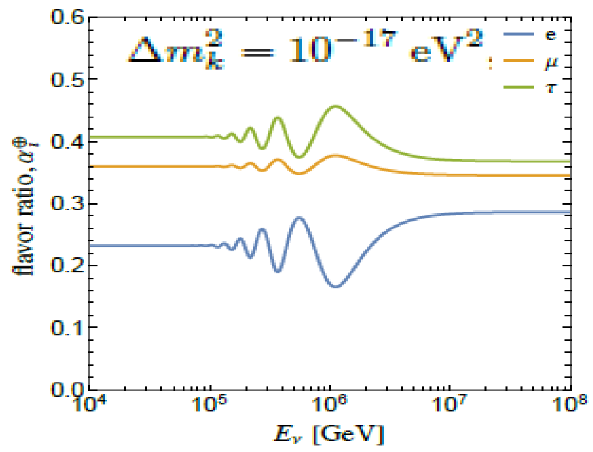
# PeV Neutrino physics




- **Flavour ratio's** probe both astro- , but **also particle-** physics
- energy (100 x LHC) and baseline : completely new domain
- Probe exotic scenarios of mass generation
- measure $\delta_{CP}$ (requires lots of statistics)

# PeV Neutrino physics



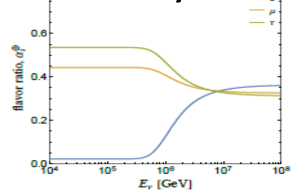

Pseudo-dirac neutrinos:

See-saw with very light Majorana mass -> right handed neutrinos have tiny mass difference with left handed neutrinos.

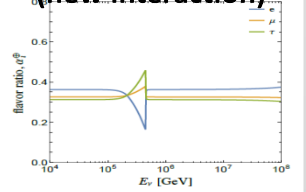
Phys. Rev. D 93, 085004 (2016)

Oscillations over *huge* lengths

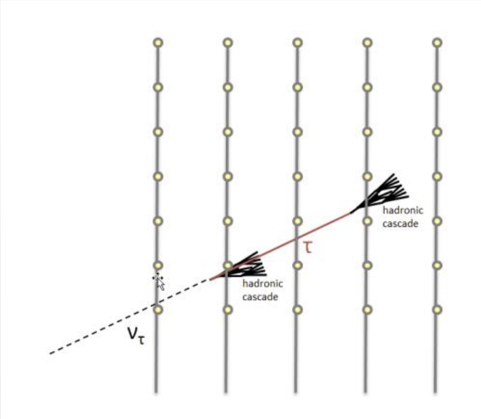
decay




Scattering on CvB (new interaction)



# Can we improve angular resolution?



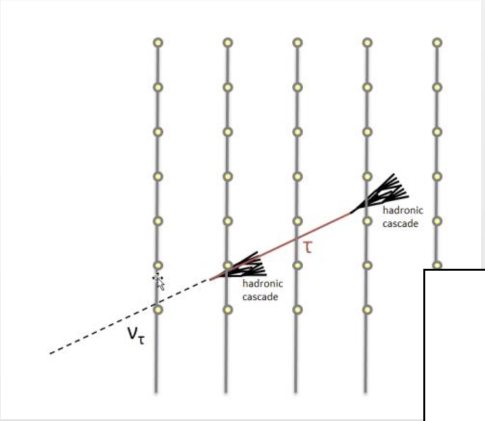


Tau neutrinos :
- precisely reconstruct position of each bang (likelihood-fit of hit times) -> angular resolution

Cascades:
- including timing information in direction-fit (don't know about the gain)

Tracks:
- At highest energies, can we do better? (difference with IC seems not so large)
- There is one class of events….

# Can we improve angular resolution?




Tau neutrinos :
- precisely reconstruct position of each bang (likelihood-fit of hit times) -> angular resolution

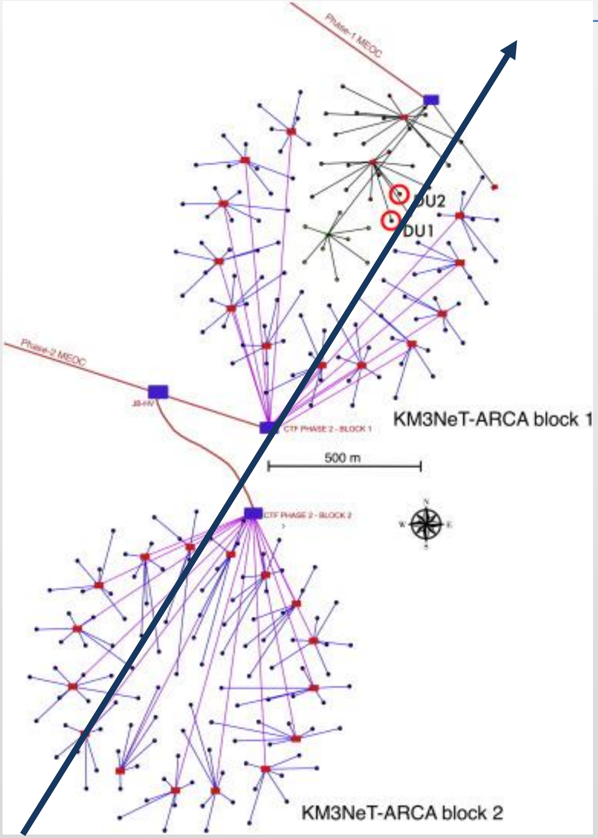

FERMILAB-PUB-17-287-T, IFT-UAM/CSIC-17-071

## Double Bangs from New Physics in IceCube

Pilar Coloma,[1,*] Pedro A. N. Machado,[1,†] Ivan Martinez-Soler,[2,‡] and Ian M. Shoemaker[3,§]
[1]*Theory Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*
[2]*Instituto de Fisica Teorica UAM-CSIC, Calle Nicolas Cabrera 13-15, Universidad Autonoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[3]*Department of Physics, University of South Dakota, Vermillion, SD 57069, USA*
(Dated: July 28, 2017)

A variety of new physics models allows for neutrinos to up-scatter into heavier states. If the incident neutrino is energetic enough, the heavy neutrino may travel some distance before decaying. In this work, we consider the atmospheric neutrino flux as a source of such events. At IceCube, this would lead to a "double-bang" (DB) event topology, similar to what is predicted to occur for tau neutrinos at ultra-high energies. The DB event topology has an extremely low background rate from coincident atmospheric cascades, making this a distinctive signature of new physics. Our results indicate that IceCube should already be able to derive new competitive constraints on models with GeV-scale sterile neutrinos using existing data.

# Can we improve?




Tracks going through both building blocks

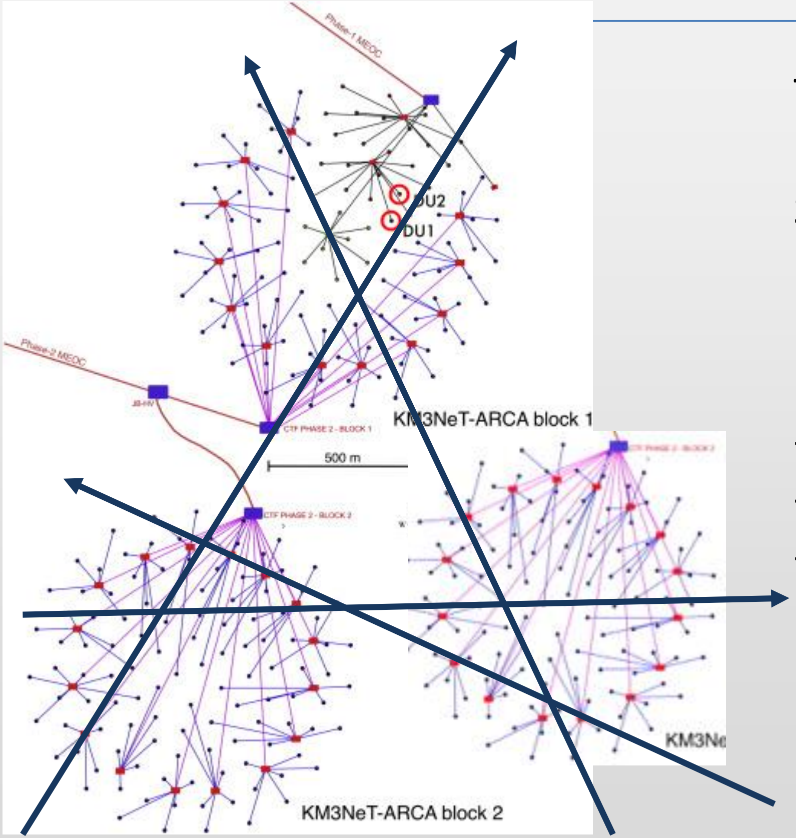
Should have extremely good resolution

Horizontal tracks : good for very high energy

- What is the resolution?
- Interesting region in the sky?
- May make good case for 3rd building block….

(idea for master project)

# Can we improve?

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Should have extremely good resolution

Horizontal tracks : good for very high energy

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- Interesting region in the sky?
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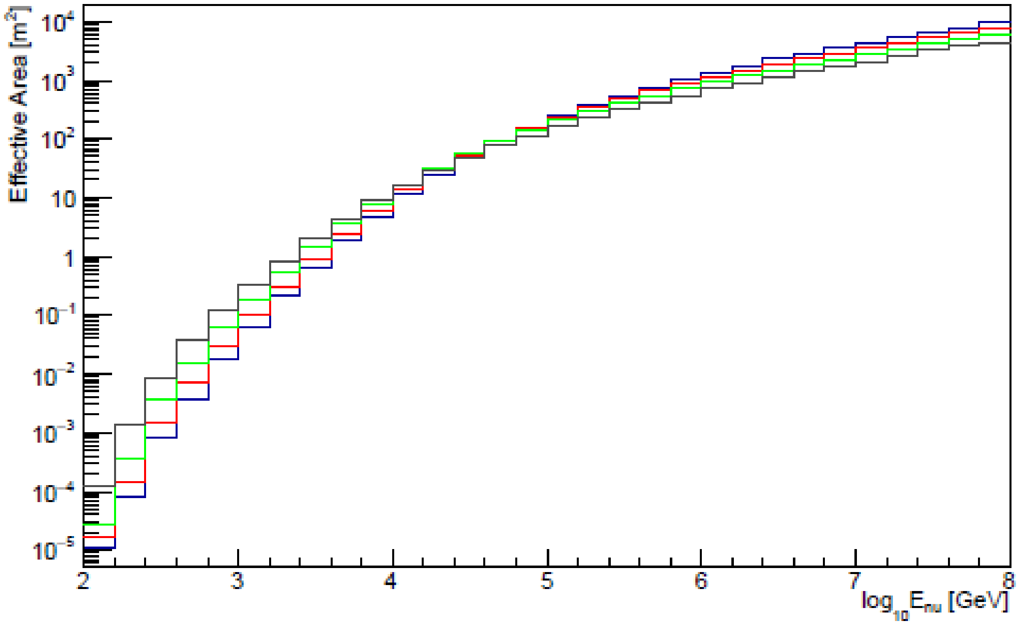
(idea for master project)

# The end

# Sample of signal-like neutrinos



# Library of new physics

FERMILAB-PUB-17-287-T, IFT-UAM/CSIC-17-071

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## Heavy decaying dark matter and IceCube high energy neutrinos

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[1]*Institutt for fysikk, NTNU, Trondheim, Norway*
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**Abstract**

We examine the hypothesis of decaying heavy dark matter (HDM) in the context of the IceCube highest energy neutrino events and recent limits on the diffuse flux of high-energy photons. We consider DM particles $X$ of mass $10^6 \leq M_X \leq 10^{16}$ GeV decaying on tree-level into $X \to \nu\bar{\nu}$, $X \to e^+e^-$ and $X \to q\bar{q}$. The full simulation of hadronic and electroweak decay cascades and the subsequent propagation of the decay products through the interstellar medium allows us to determine the permitted values of $M_X$. We show that for leptonic decay channels it is possible to explain the IceCube highest energy neutrino signal without overproducing high-energy photons for $M_X \lesssim 5.5 \cdot 10^7$ GeV and $1.5 \cdot 10^8 \lesssim M_X \lesssim 1.5 \cdot 10^9$ GeV, while hadronic decays contradict the gamma-ray limits for almost the whole range of $M_X$ values considered. The leptonic hypothesis can be probed by operating and planned gamma-ray observatories: for instance, the currently upgrading Carpet experiment will be capable to test a significant part of the remaining parameter window within one year of observation.

**Keywords:** dark matter, neutrino, gamma-ray.

## NEUTRINOS FROM CHOKED JETS ACCOMPANIED BY TYPE-II SUPERNOVAE

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ABSTRACT

The origin of the IceCube neutrinos is still an open question. Upper limits from diffuse gamma-ray observations suggest that the neutrino sources are either distant or hidden from gamma-ray observations. It is possible that the neutrinos are produced in jets that are formed in the core-collapsing massive stars and fail to break out, the so-called choked jets. We study neutrinos from the jets choked in the hydrogen envelopes of red supergiant stars. Fast photo-meson cooling softens the neutrino spectrum, making it difficult to explain the PeV neutrinos observed by IceCube in a one-component scenario, but a two-component model can explain the spectrum. Furthermore, we predict that a newly born jet-driven type-II supernova may be observed to be associated with a neutrino burst detected by IceCube.
*Keywords:* neutrinos – stars: jets – stars: massive – supergiants – supernovae: general

## Seeking leptoquarks in IceCube

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ABSTRACT: We investigate the sensitivity of IceCube(-Gen2) to a scalar leptoquark scenario with couplings only to heavy quark flavors which may be connected to solving discrepancies in $B$-meson semileptonic decays. We take into account, for the first time, the non-negligible neutrino-gluon cross section induced by leptoquarks, and we systematically account for indirect and direct constraints which have been overlooked in previous studies. We conclude that IceCube(-Gen2) can only probe the light LQ regime, already disfavored by the combination of flavor physics constraints, electroweak precision data and the direct searches at the LHC.

KEYWORDS: *Beyond Standard Model, Leptoquarks*