The neutrino telescope

ANTARES

(antares.in2p3.fr)

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Thomas Eberl
for the ANTARES collaboration

Fermi and Jansky Meeting
St. Michaels, November 12th, 2011

Friedrich-Alexander-Universität Erlangen-Nürnberg

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Neutrino Astronomy

A new window to the Universe

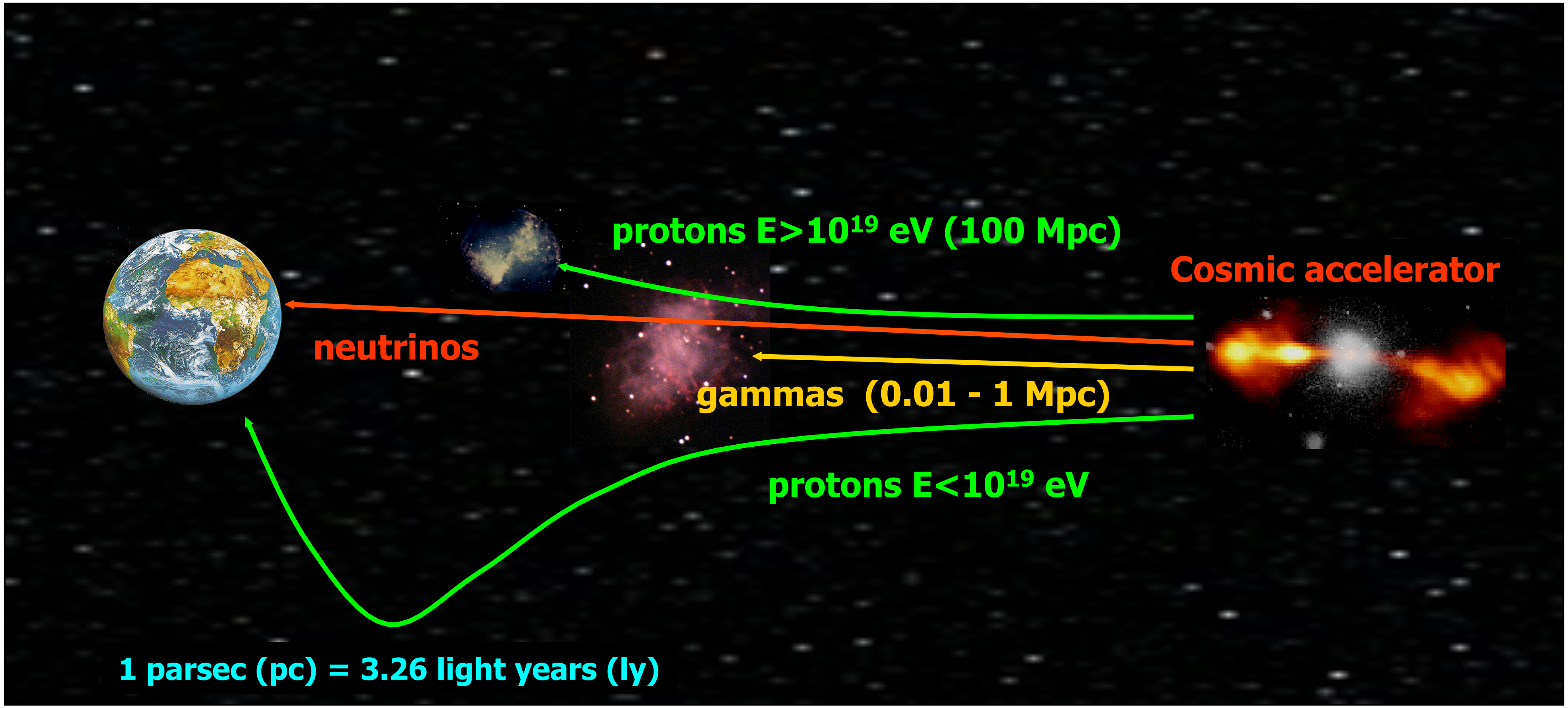
Why high-energy neutrino astronomy?

- Neutrinos point back to the source
- Neutrinos travel cosmological distances
- Neutrinos escape from optically thick sources
- Neutrinos are a clear sign for hadron acceleration

→ Understand origin and acceleration of HE hadronic CRs

→ Neutrinos provide complementary information to gamma-rays and protons

Neutrinos are unique cosmic messengers!



Photons: absorbed on dust and radiation
Protons/nuclei: deflected by magnetic fields, reactions with radiation (CMB)

High-energy neutrino production in the Universe

- CR (hadron) accelerators
- Shock fronts (Fermi acceleration)
- Strong magnetic fields up to 10^{15} Gauss (pulsars, magnetars)

- Beam dump (secondary particle production)
- Interaction with photon field, matter, interstellar medium
- Protons: pion decay gives photon <-> neutrino connection

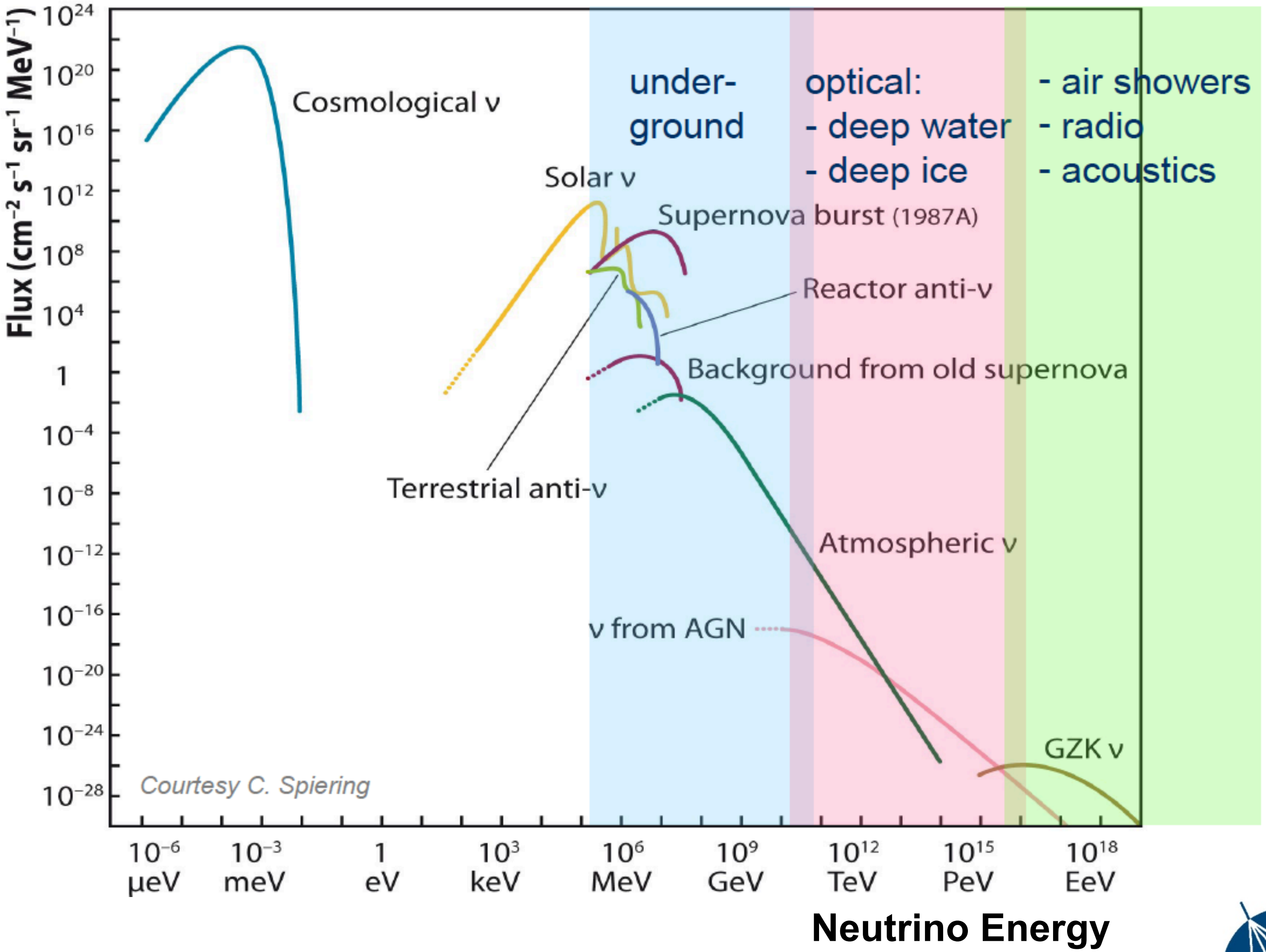
$$p + p(\gamma) \rightarrow \pi^{\pm} + X$$
$$\hookrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_\mu + \nu_e$$

$$p + p(\gamma) \rightarrow \pi^{0} + X$$
$$\hookrightarrow \gamma + \gamma \text{ (TeV)}$$

→ Many diffuse and point source flux predictions available

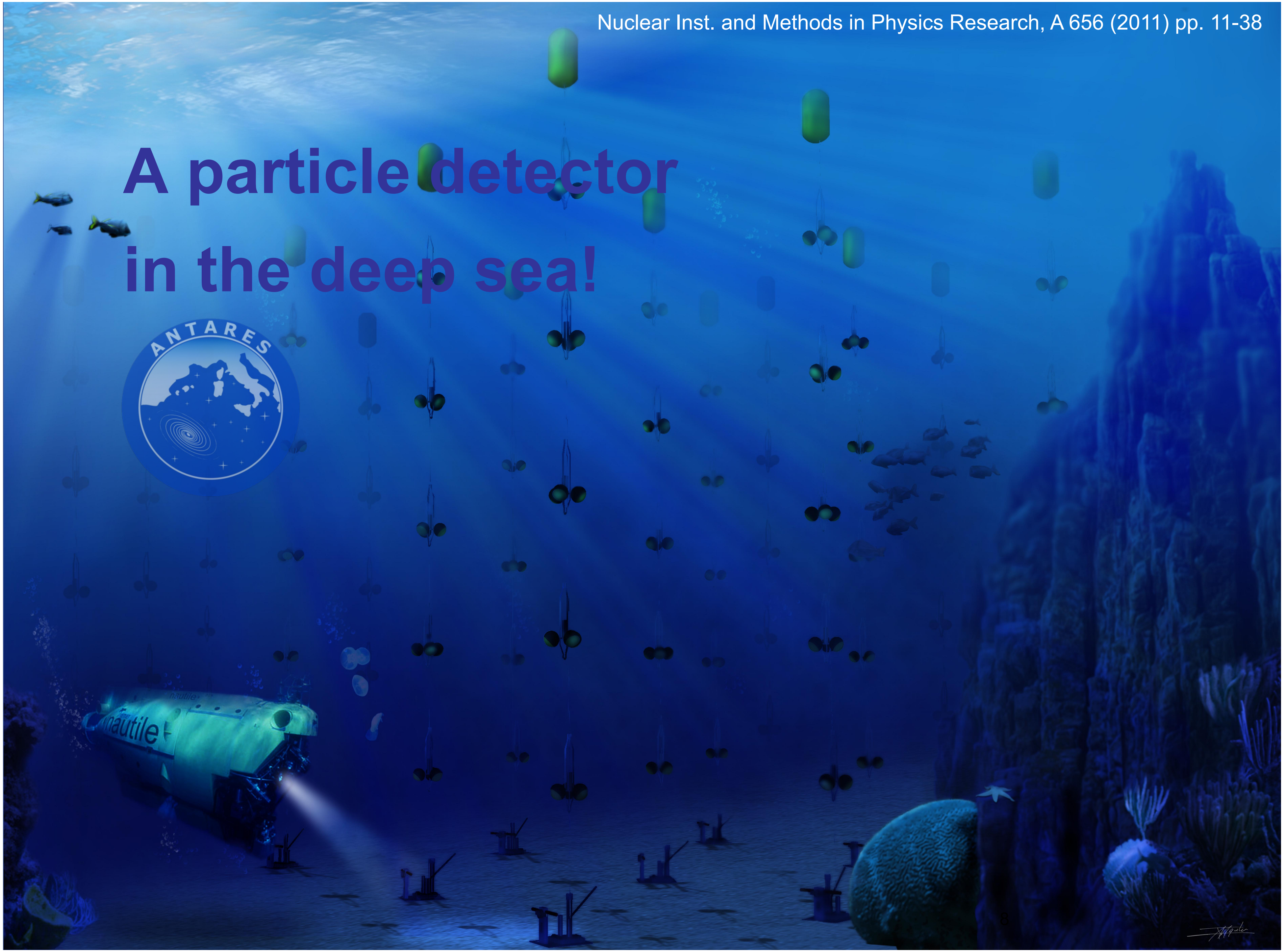
see e.g. reviews Becker 2008 Phys. Rep., Chiarusi et al. 2010 EPJ C, Anchordoqui 2010, Ann. Rev. Nucl. Part. Sci

Neutrino fluxes: overview

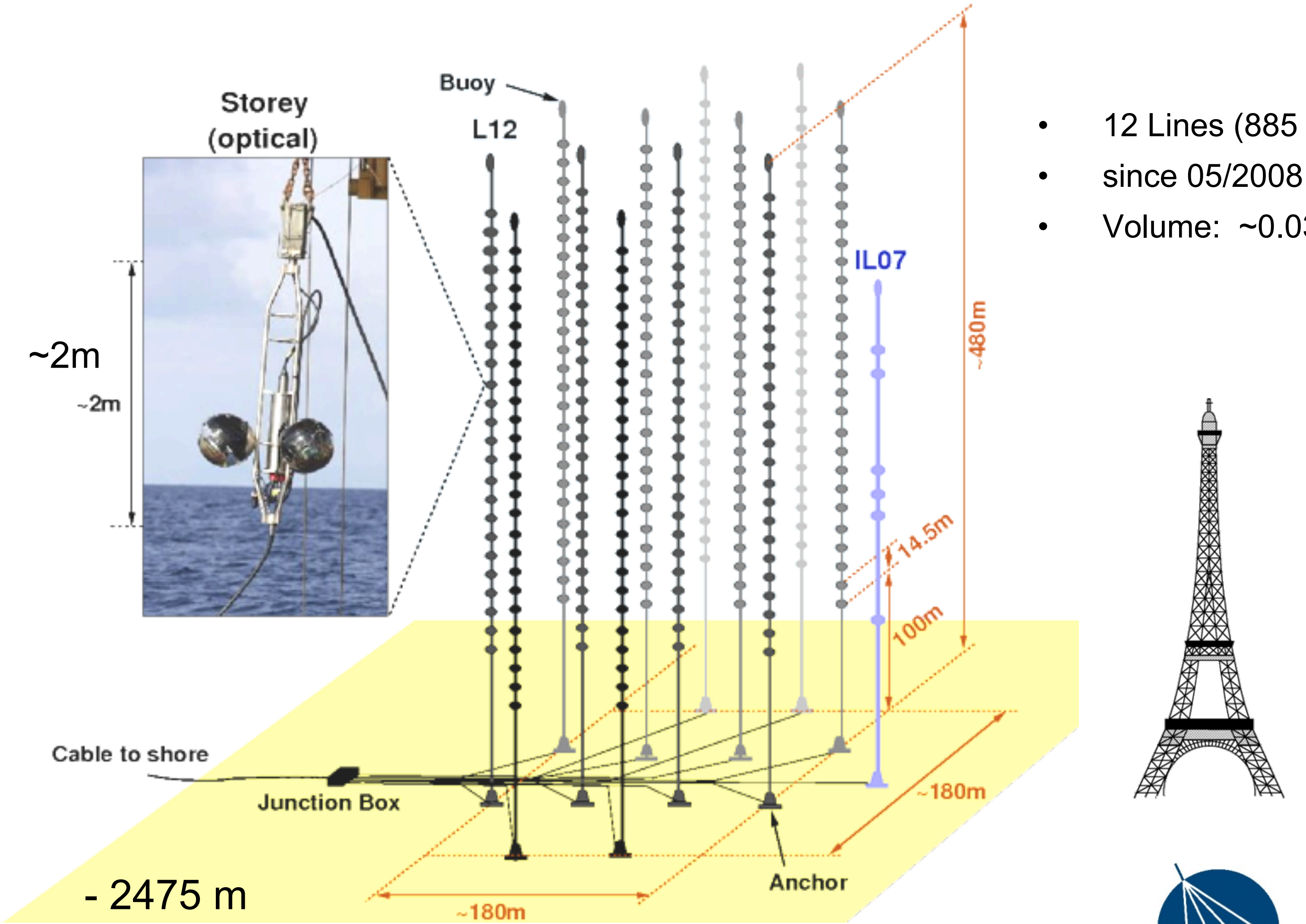


Physics with neutrino telescopes

- **Galactic sources**
  (Supernova remnants, Binary systems, Pulsar Wind Nebulae . . .)
- **Extra-Galactic sources**
  (Gamma-ray Bursts, Active Galactic Nuclei …)
- **Dark Matter**
  (WIMPs)
- **Cosmogenic neutrinos**
  (GZK, Top-down, . . .)
- Supernovae (MeV neutrinos)
- Neutrino oscillations (atmospheric neutrinos 10 - 100 GeV)
- Cosmic-ray anisotropy (atm. muons)
- Exotic physics
  (Lorentz violation, monopoles, . . .)

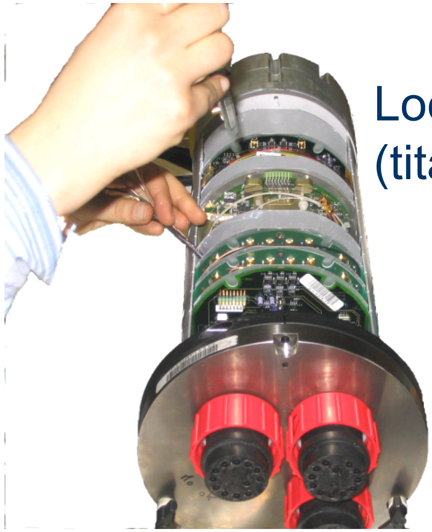

Nuclear Inst. and Methods in Physics Research, A 656 (2011) pp. 11-38
A particle detector
in the deep sea!
ANTARES
nautile

ANTARES

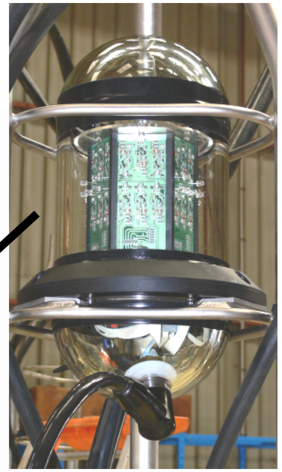


- 12 Lines (885 PMTs)
- since 05/2008
- Volume: ~0.03 km^3

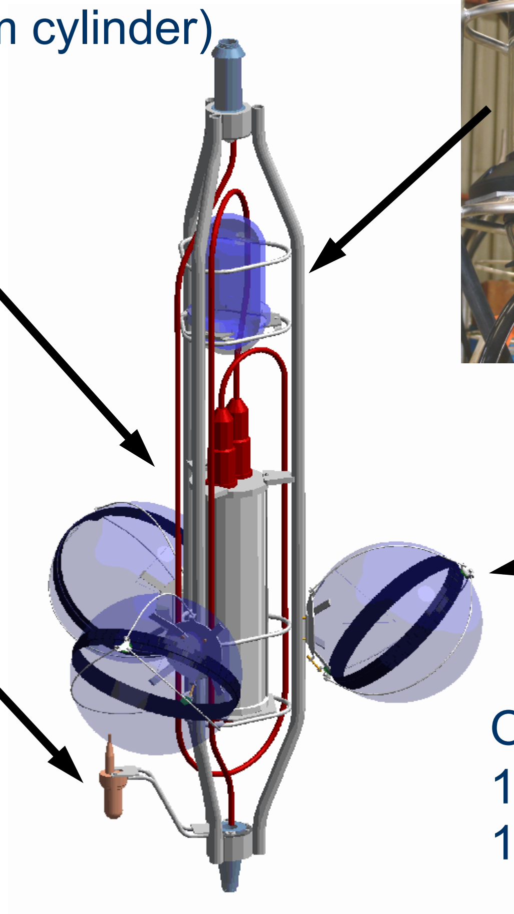
A Storey: The Basic Detector Element

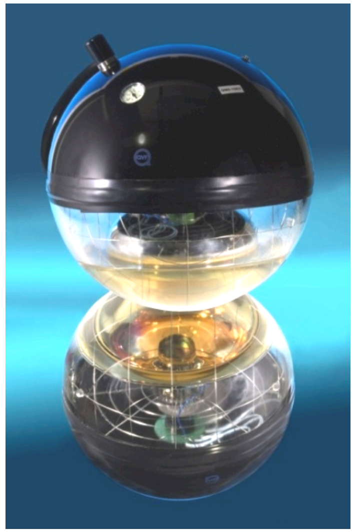


Local Control Module
(titanium cylinder)



LED Optical Beacon
timing calibration
(4 per line)

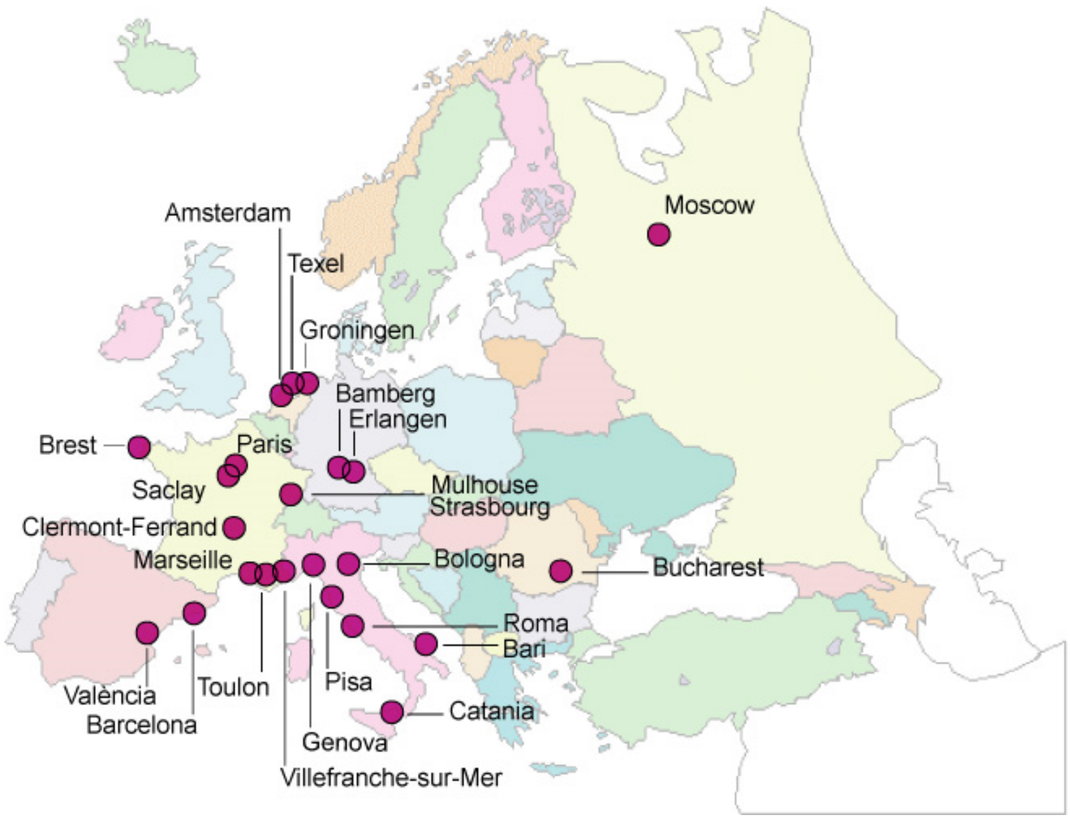




Optical Module:
17” glass sphere
10” PMT Ham. R7081-20

Hydrophone RX
(5 per line)

The ANTARES Collaboration



27 institutes in 7 European countries

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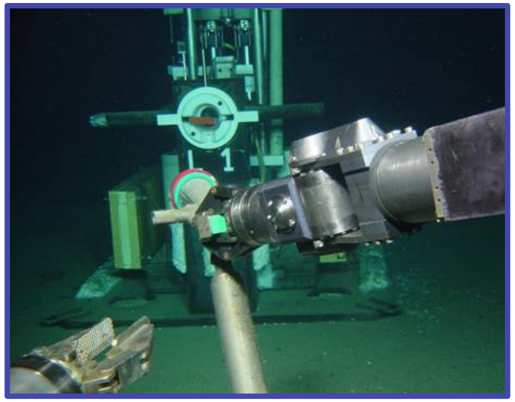
11

ANTARES deployment



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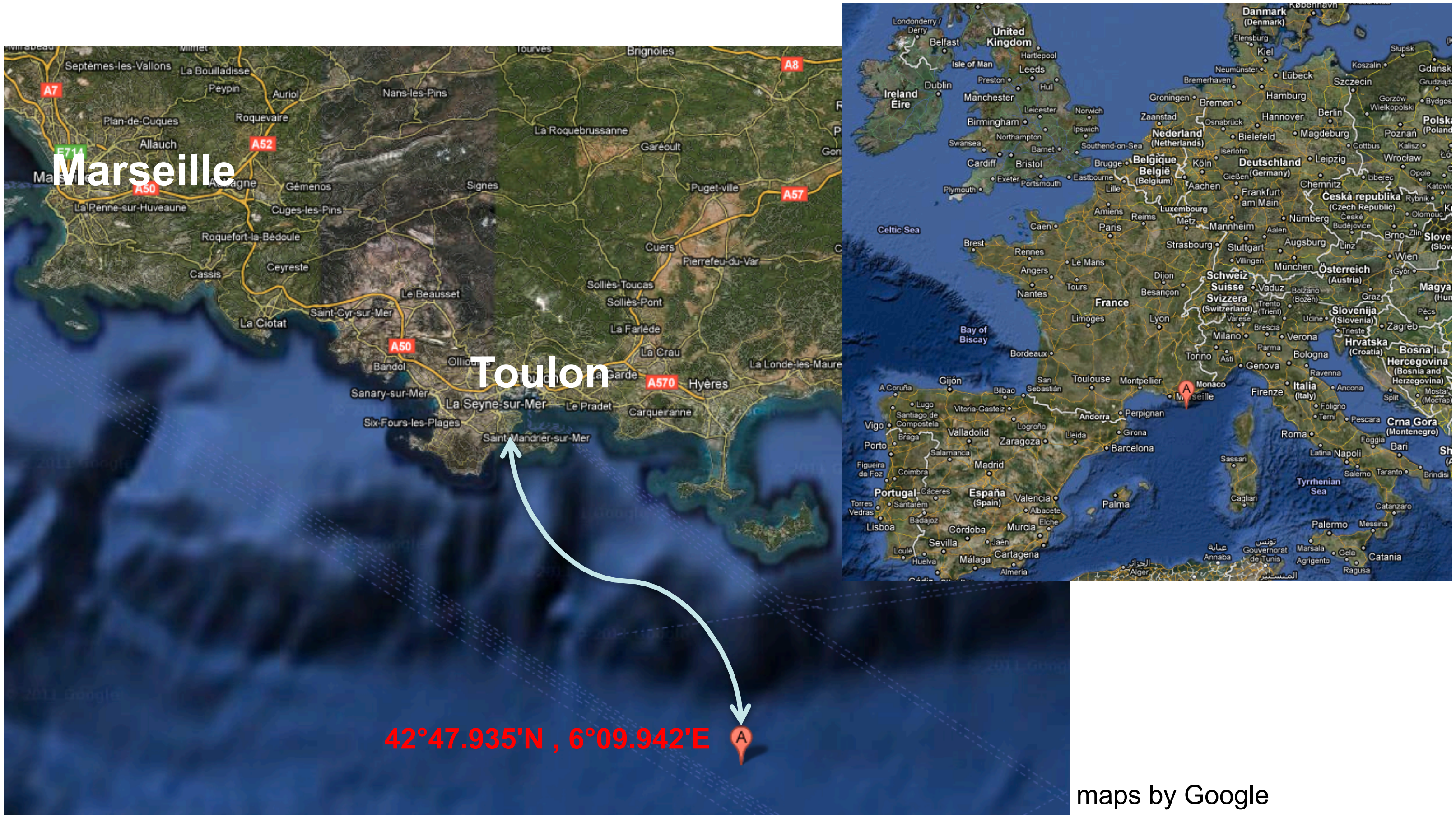
FOR ASTROPARTICLE
PHYSICS

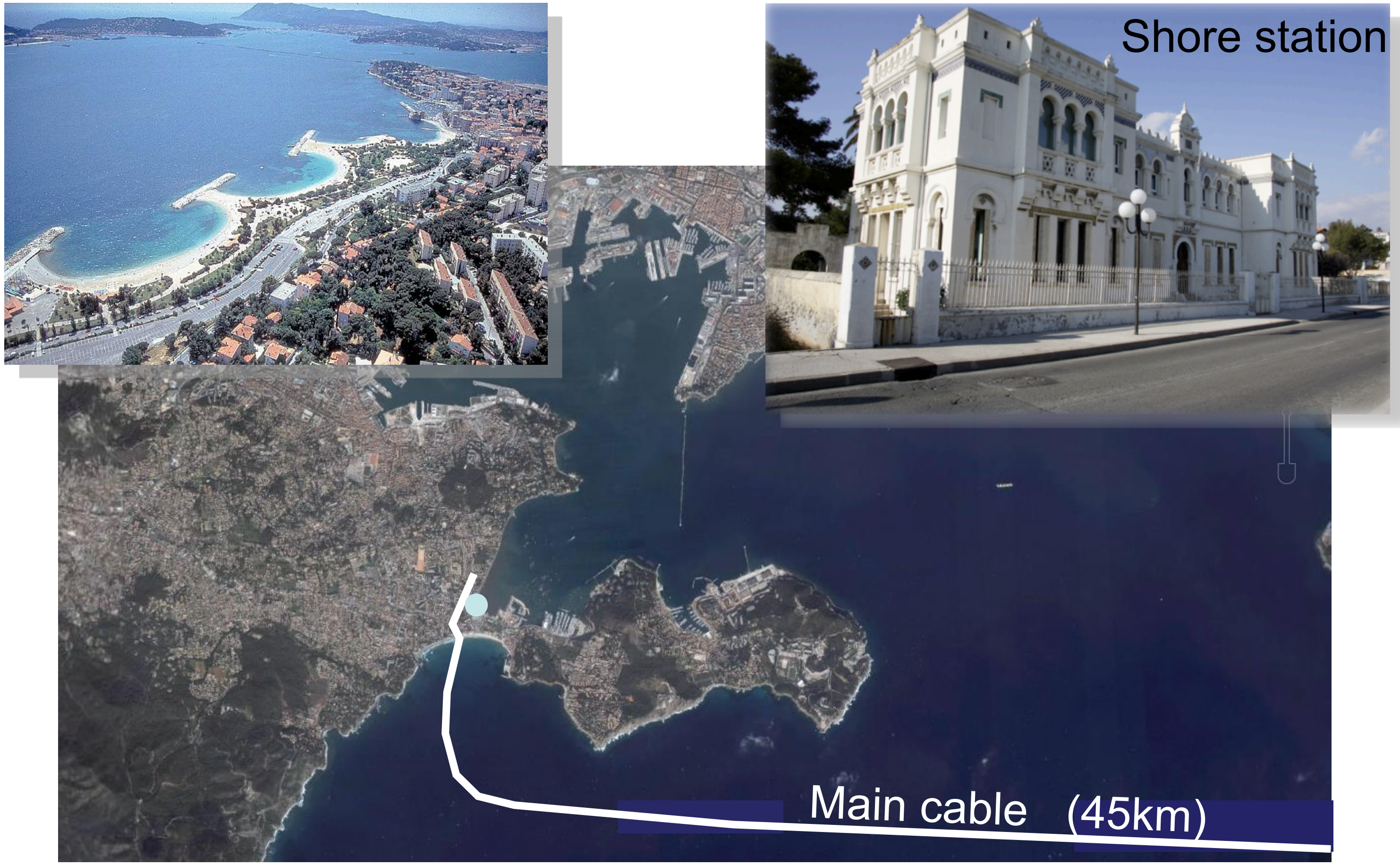
ANTARES in the Mediterranean Sea



maps by Google

La Seyne-sur-Mer, near Toulon, France

ANTARES in the Mediterranean Sea



La Seyne-sur-Mer, near Toulon, France

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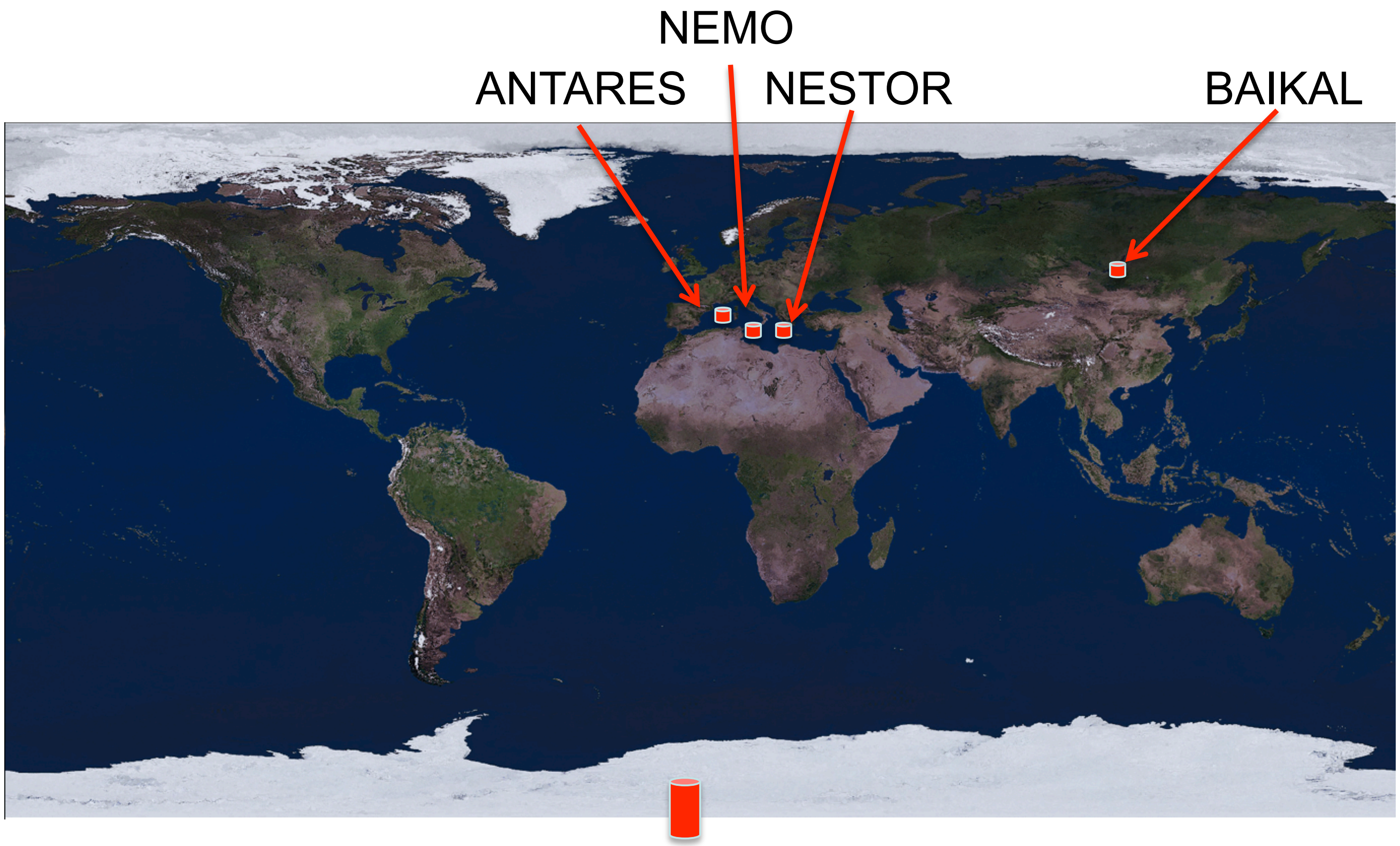
High-energy Neutrino Telescopes 2011



IceCube
V ~ 1 km^3 since 12/2010

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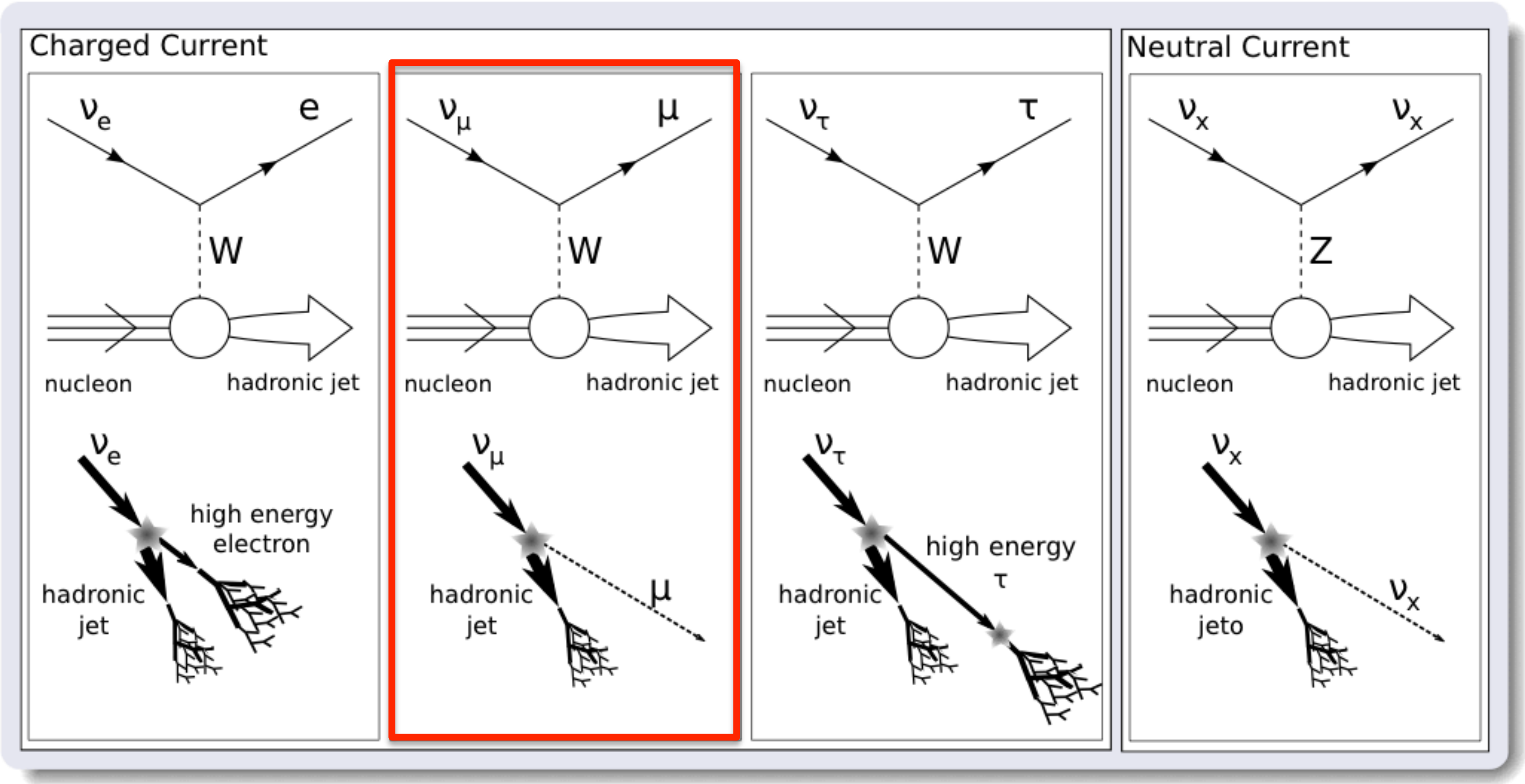
The Telescope:

principle and performance

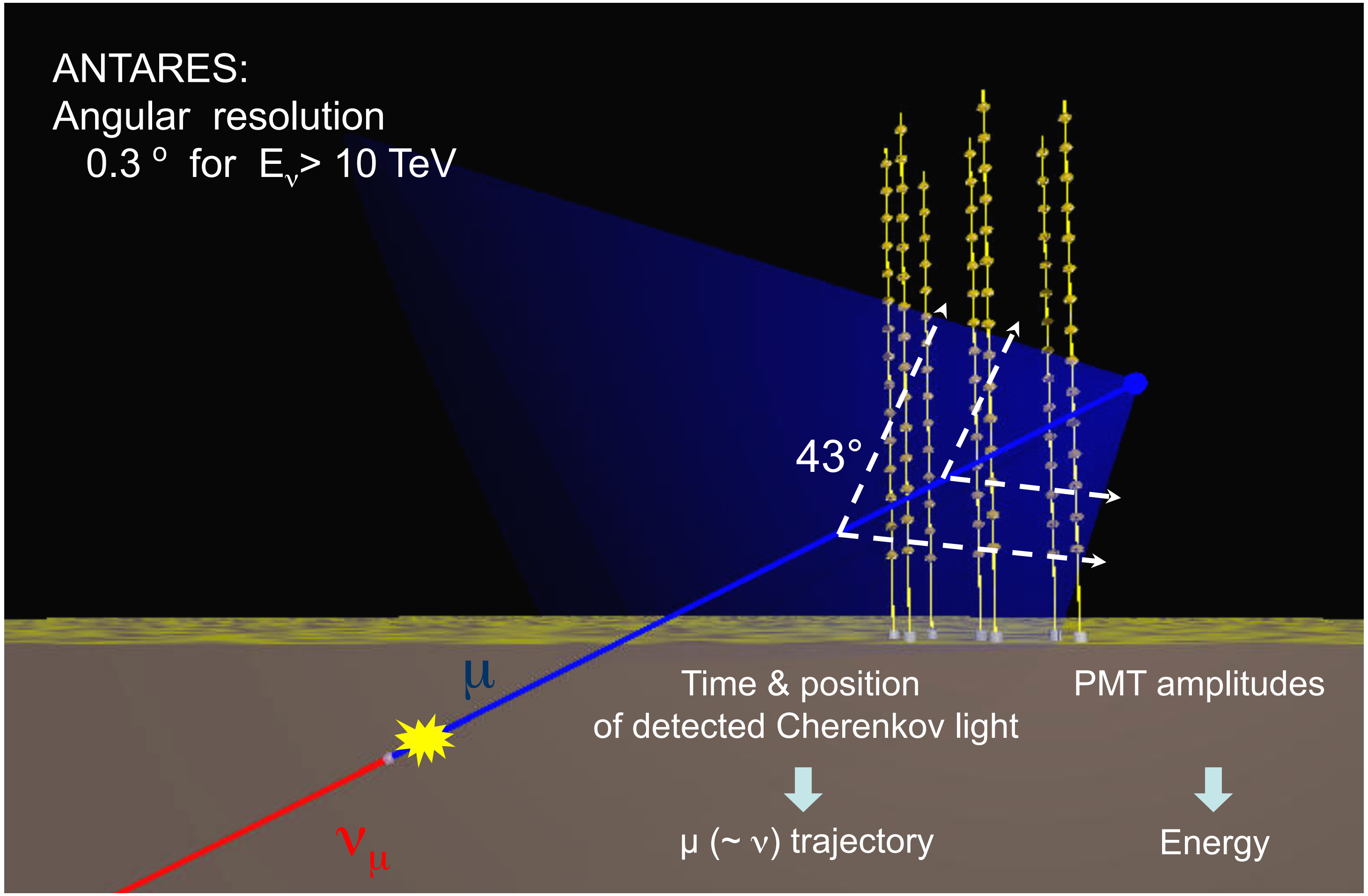
Neutrino nucleon interactions



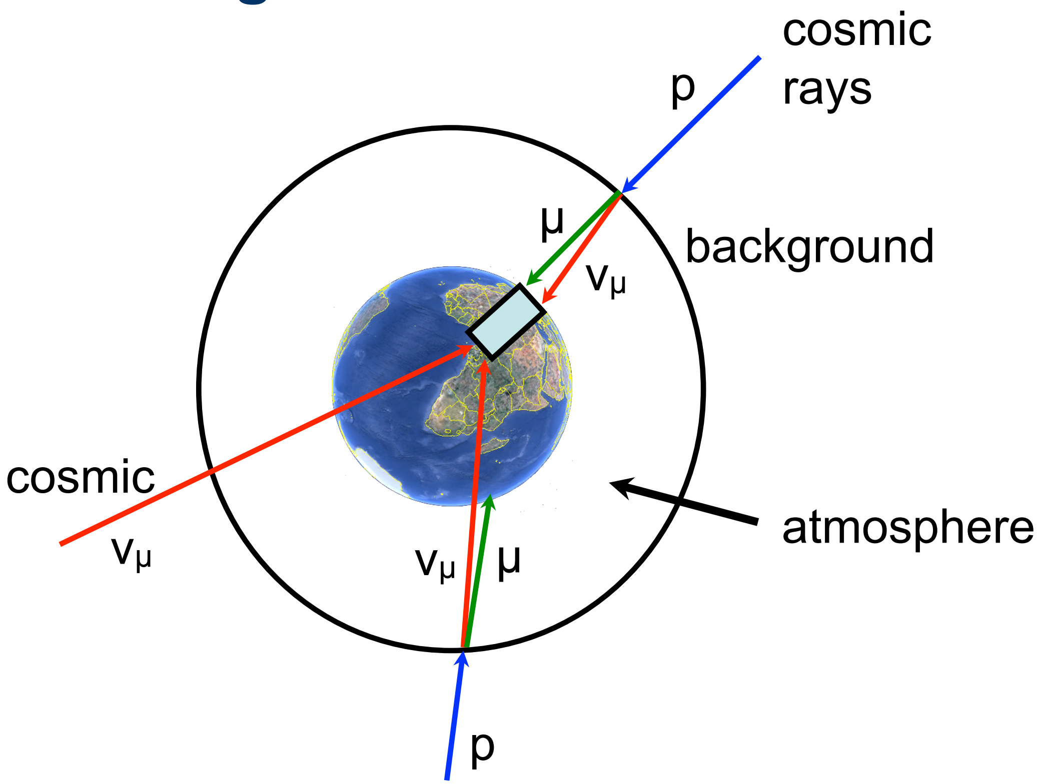
"golden" channel
for astronomy

J. Tiffenberg, NUSKY11

Principle of (muon) neutrino detection

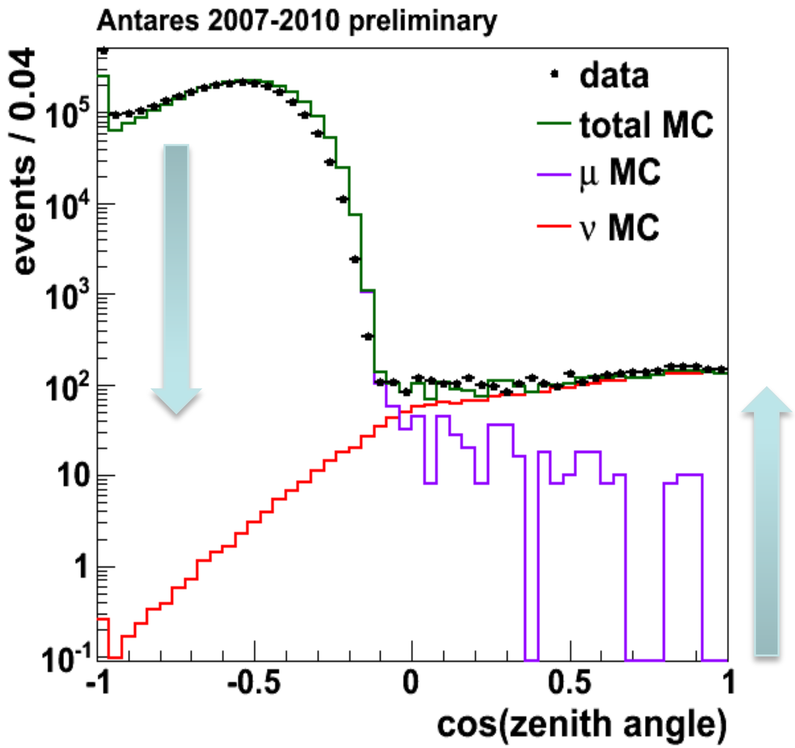


Particle background: atm. muons and neutrinos

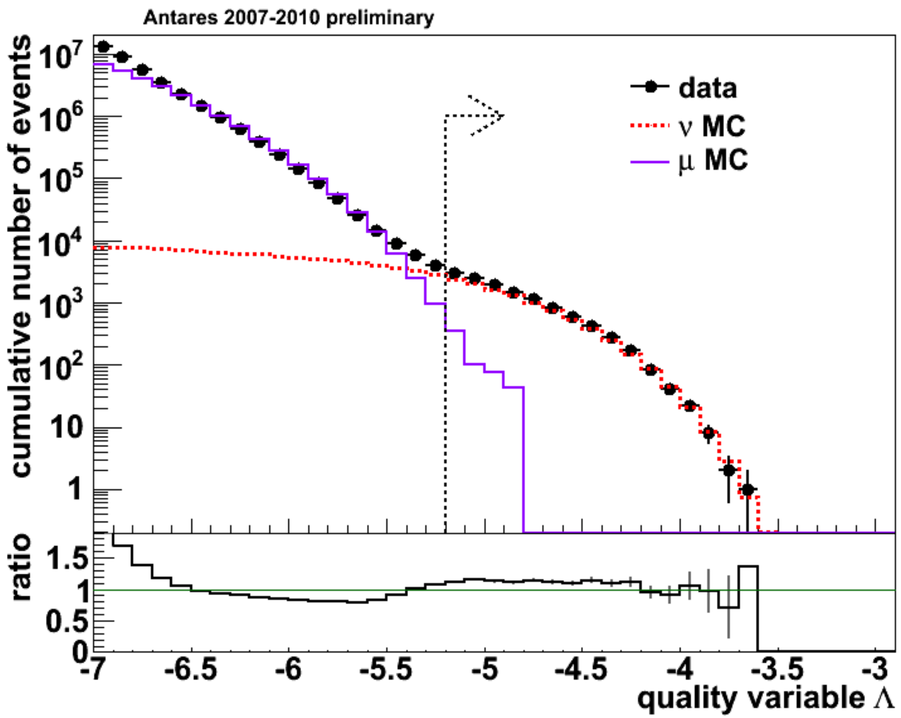


- Flux from above dominated by atmospheric muons
- Neutrino telescopes optimised to be sensitive to neutrinos from below

Muon background suppression

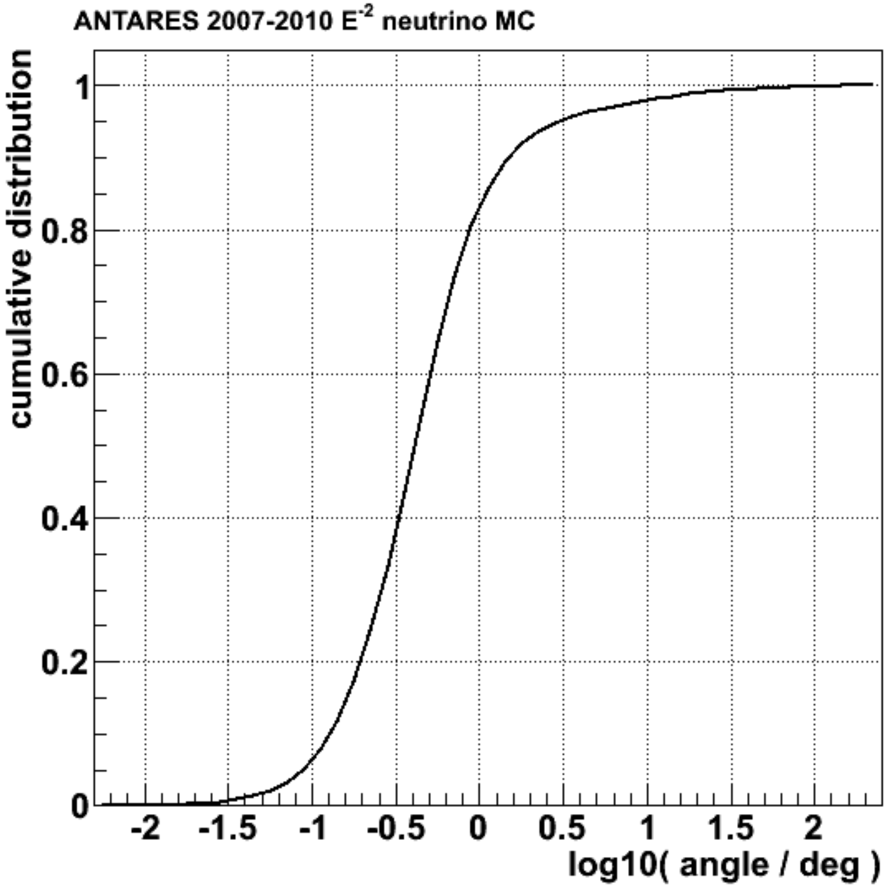


tracking quality parameter



Good Data – MC agreement!

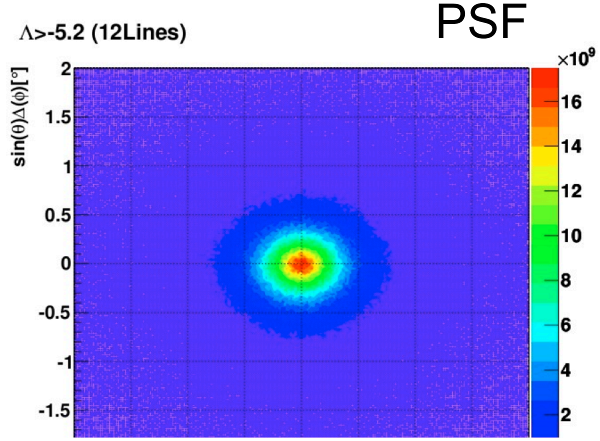
Angular resolution (from MC)



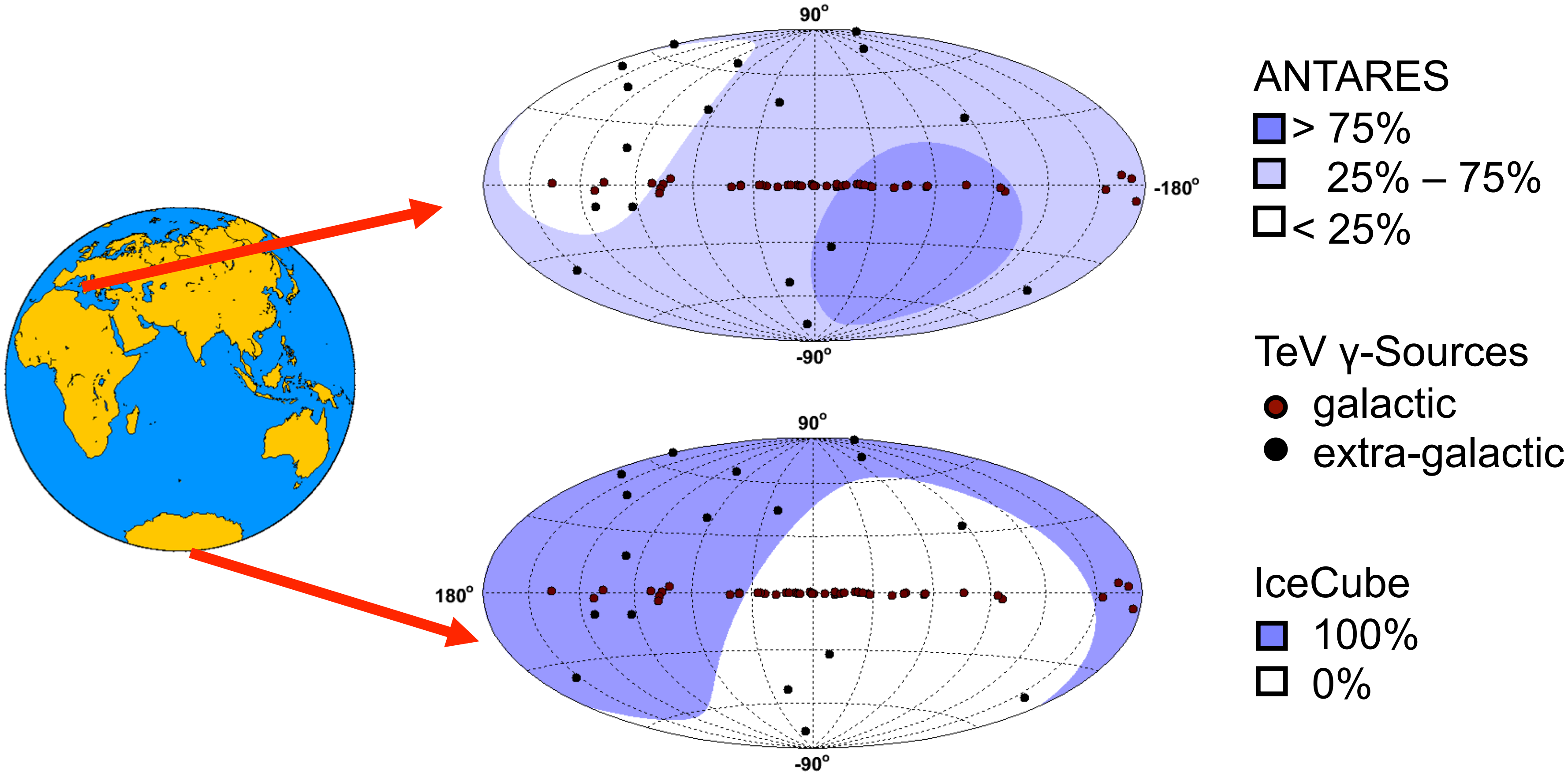
median ang. res. **0.46 deg** (2007-2010 data)

absolute pointing **~0.1 deg**

PSF



Sky coverage

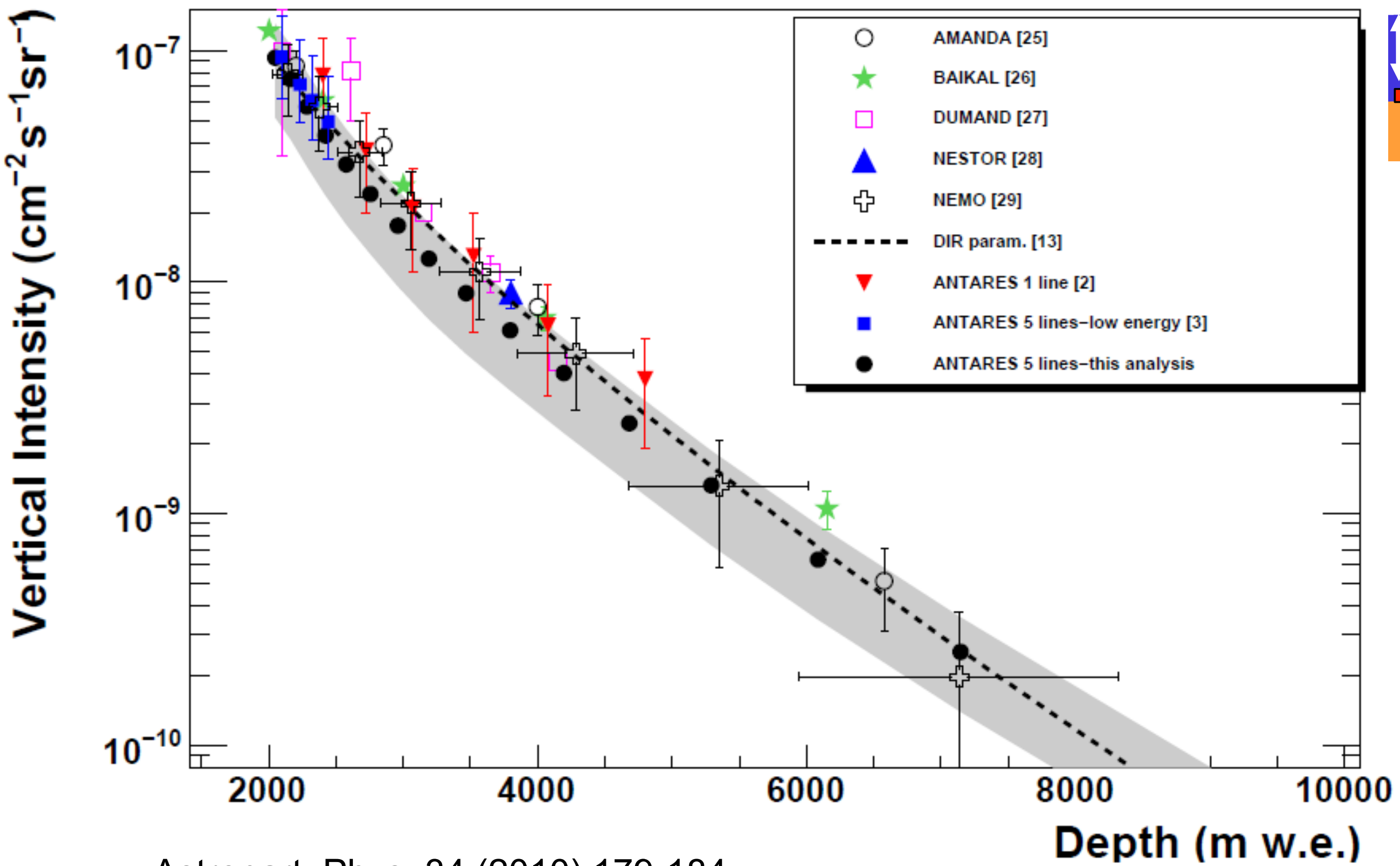


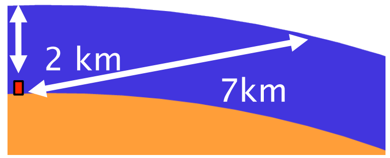
0.5 π sr instantaneous common view

1.5 π sr common view per day

First Results

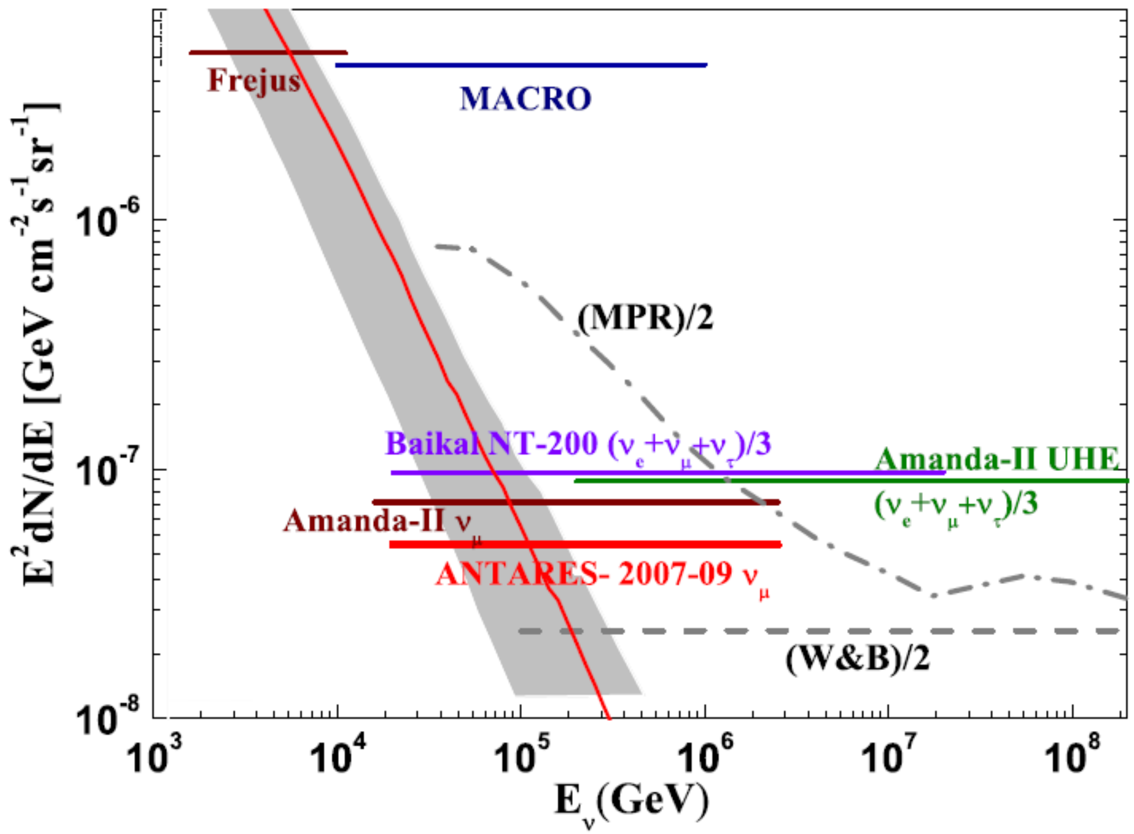
Atmospheric muon flux:
depth-intensity relation with 5 Lines





Astropart. Phys. 34 (2010) 179-184

Upper limit on diffuse flux of cosmic HE ν



0.83 * 2π sr

monitored for

334 days

with
reduced detector setup
during
construction phase

$$E^2\ \Phi(E)_{90\%CL} = 5.3^{+2}_{-1} \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

Physics Letters B 696 (2011) 16-22

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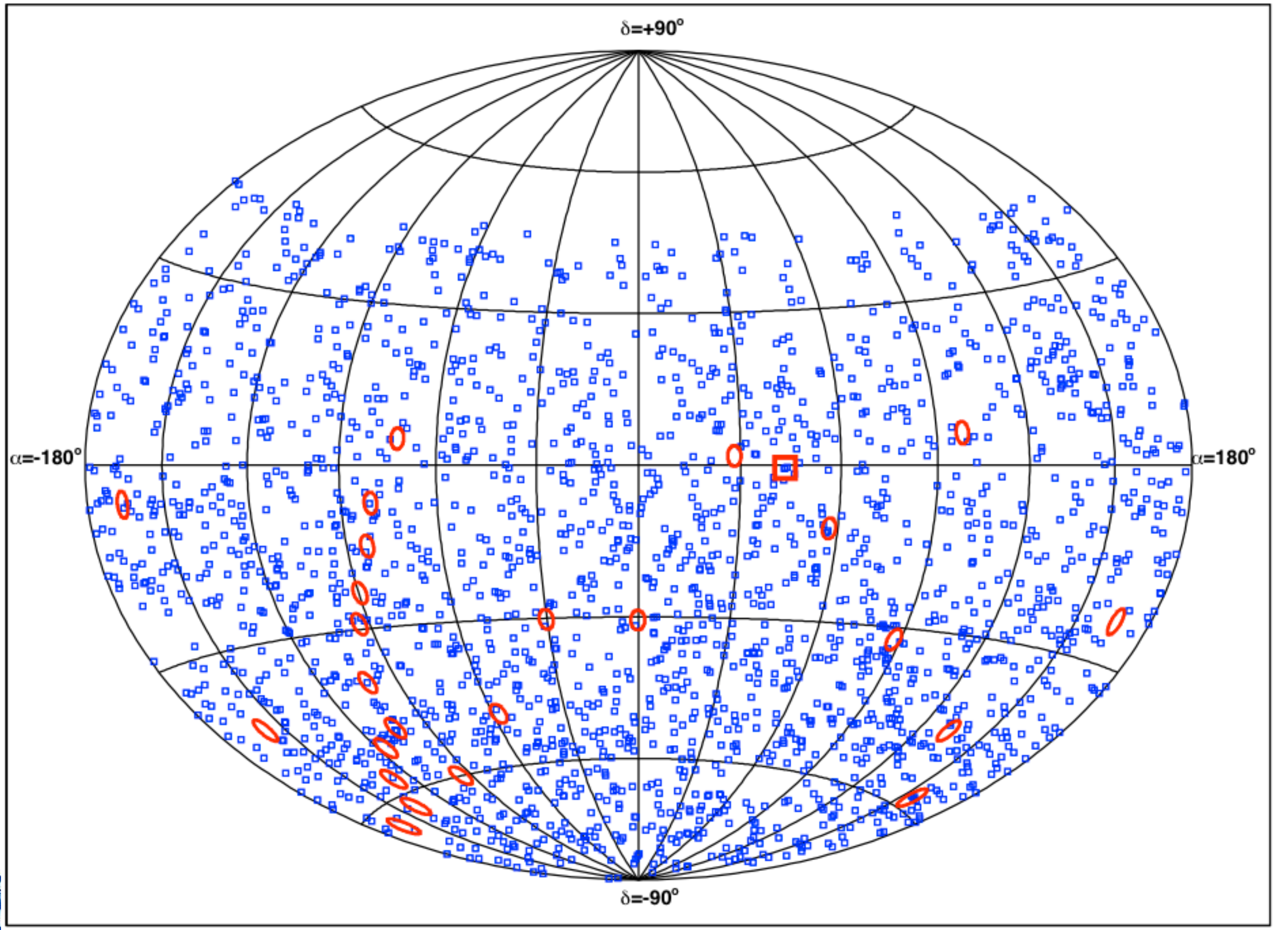
First neutrino sky map, 2007-2008 data

Submitted to Astrophysical Journal Letters [preprint: arXiv:1108.0292v1]

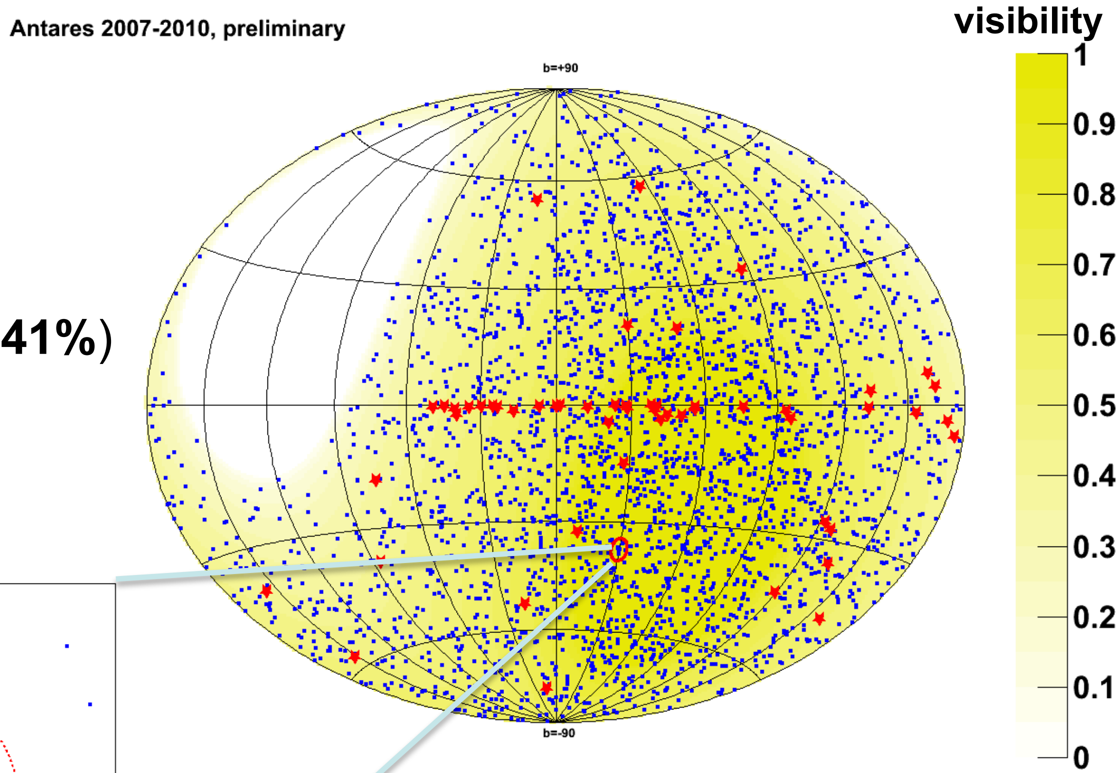


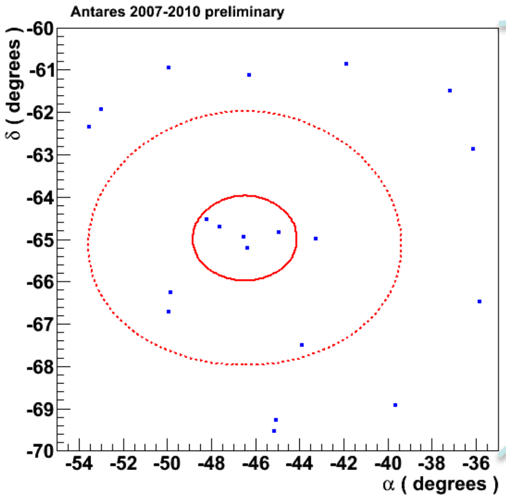
objects for candidate list search

Updated sky map, 2007-2010 data, prelim.

3058 neutrino events

Candidate list search
(51 candidate sources,
best HESS J1023-575,**p=41%**)





All-sky search
p-value: **2.6%**
not significant

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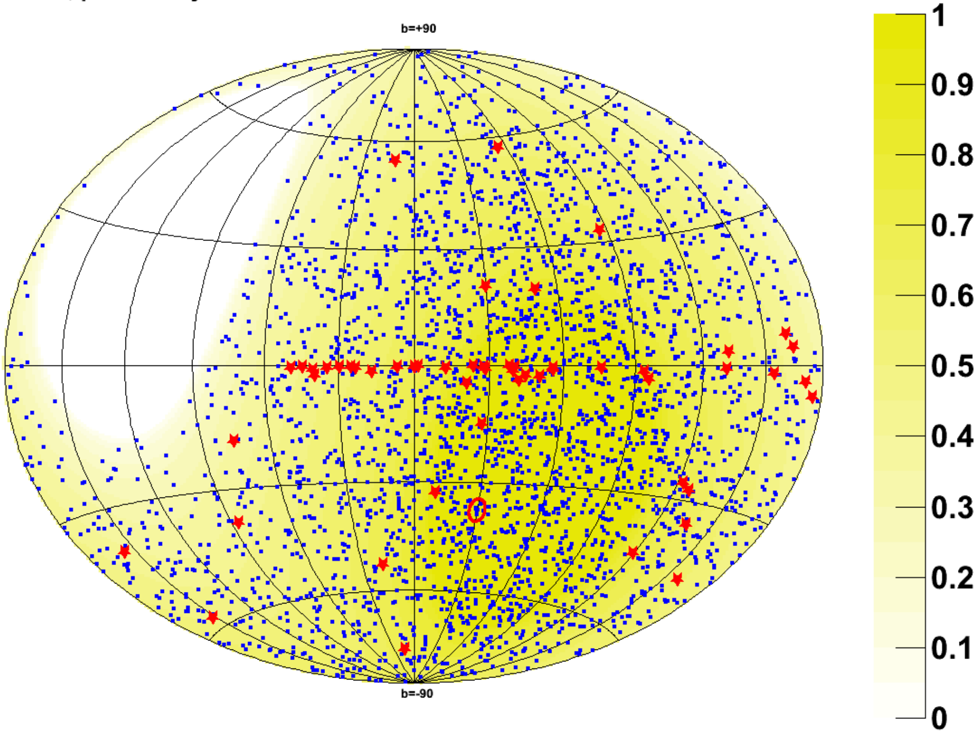
Antares 2007-2010, preliminary



Method: unbinned search with likelihood ratio

$$\log \mathcal{L}_{\rm s+b} = \sum_i \log[\mu_{\rm sig} \times \mathcal{F}(\beta_i(\delta_s, \alpha_s)) \times \mathcal{N}(N_{hits}^{i,sig}) + \mathcal{B}_i \times \mathcal{N}(N_{hits}^{i,bkg})] + \mu_{\rm tot},$$

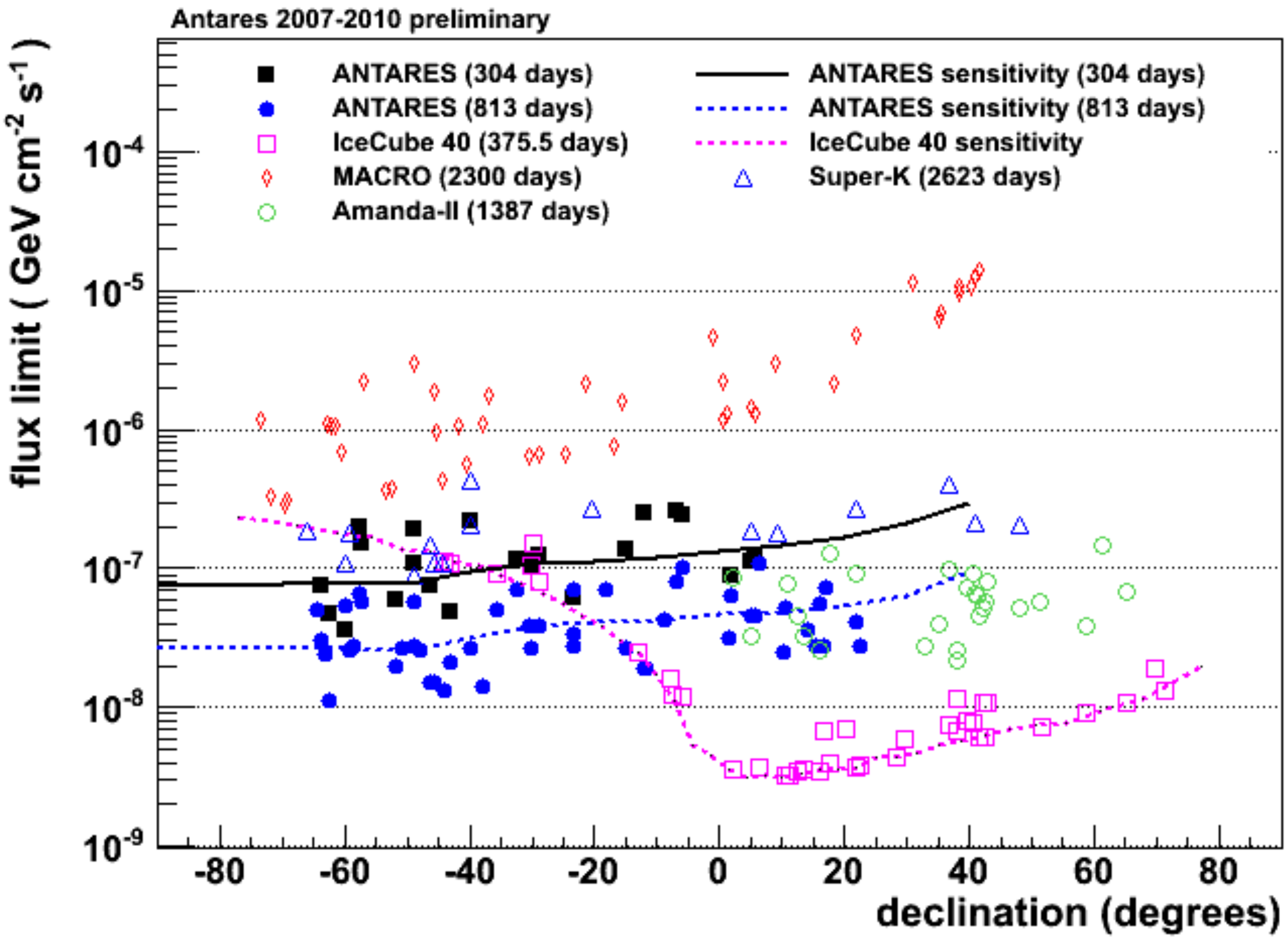
test statistic: $\mathcal{Q} = \mathcal{L}_{s+b}^{max} - \mathcal{L}_b$

C. Bogazzi et al., ICRC '11 proceedings

source	$\alpha_s(^\circ)$	$\delta_s(^\circ)$	p	$\phi^{90\%CL}$
HESS J1023-575	155.83	-57.76	0.41	6.6
3C 279	-165.95	-5.79	0.48	10.1
GX 339-4	-104.30	-48.79	0.72	5.8
Cir X-1	-129.83	-57.17	0.79	5.8
MGRO J1908+06	-73.01	6.27	0.82	10.1
ESO 139-G12	-95.59	-59.94	0.94	5.4
HESS J1356-645	-151.00	-64.50	0.98	5.1
PKS 0548-322	87.67	-32.27	0.99	7.1
HESS J1837-069	-80.59	-6.95	0.99	8.0
PKS 0454-234	74.27	-23.43	1.00	7.0
IceCube hotspot	75.45	-18.15	1.00	7.0
PKS 1454-354	-135.64	-35.67	1.00	5.0
RGB J0152+017	28.17	1.79	1.00	6.3
Geminga	98.31	17.01	1.00	7.3
PSR B1259-63	-164.30	-63.83	1.00	3.0
PKS 2005-489	-57.63	-48.82	1.00	2.8
HESS J1616-508	-116.03	-50.97	1.00	2.7
HESS J1503-582	-133.54	-58.74	1.00	2.8
HESS J1632-478	-111.96	-47.82	1.00	2.6
H 2356-309	-0.22	-30.63	1.00	3.9
MSH 15-52	-131.47	-59.16	1.00	2.6
Galactic Center	-93.58	-29.01	1.00	3.8
HESS J1303-631	-164.23	-63.20	1.00	2.4
HESS J1834-087	-81.31	-8.76	1.00	4.3
PKS 1502+106	-133.90	10.52	1.00	5.2
SS 433	-72.04	4.98	1.00	4.6
HESS J1614-518	-116.42	-51.82	1.00	2.0
RX J1713.7-3946	-101.75	-39.75	1.00	2.7
3C454.3	-16.50	16.15	1.00	5.5
W28	-89.57	-23.34	1.00	3.4
HESS J0632+057	98.24	5.81	1.00	4.6
PKS 2155-304	-30.28	-30.22	1.00	2.7
HESS J1741-302	-94.75	-30.20	1.00	2.7
Centaurus A	-158.64	-43.02	1.00	2.1
RX J0852.0-4622	133.00	-46.37	1.00	1.5
1ES 1101-232	165.91	-23.49	1.00	2.8
Vela X	128.75	-45.60	1.00	1.5
W51C	-69.25	14.19	1.00	3.6
PKS 0426-380	67.17	-37.93	1.00	1.4
LS 5039	-83.44	-14.83	1.00	2.7
W44	-75.96	1.38	1.00	3.1
RCW 86	-139.32	-62.48	1.00	1.1
Crab	83.63	22.01	1.00	4.1
HESS J1507-622	-133.28	-62.34	1.00	1.1
1ES 0347-121	57.35	-11.99	1.00	1.9
VER J0648+152	102.20	15.27	1.00	2.8
PKS 0537-441	84.71	-44.08	1.00	1.3
HESS J1912+101	-71.79	10.15	1.00	2.5
PKS 0235+164	39.66	16.61	1.00	2.8
IC443	94.21	22.51	1.00	2.8
PKS 0727-11	112.58 -	11.70	1.00	1.9

Table 1: Results of the candidate source search. The source coordinates and the p-values (p) are shown as well as the limits on the flux intensity $\phi^{90\%CL}$; the latter has units $10^{-8}\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Sensitivity: best limits for the southern sky!

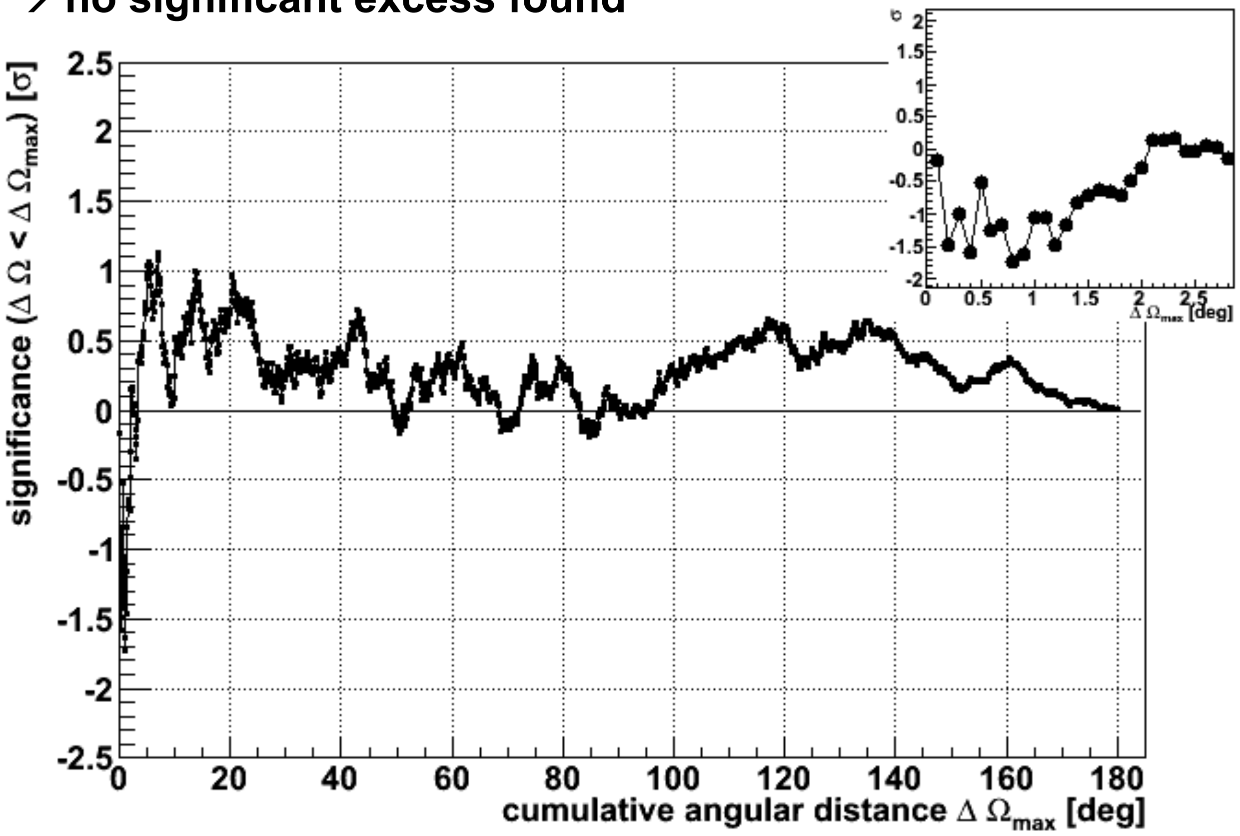


Auto-correlation: 2007-2008

search for deviations from isotropy in neutrino sky

• cumulative number of neutrino pairs in increasing ang. bins compared to mean randomized sky

→ **no significant excess found**



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First time dependent analysis

• use "high-state" time information from other experiments:
  e.g. Fermi, H.E.S.S., Swift etc.

• Idea: space and time coincidences reduce background

• improve discovery potential over time-integrated searches

• Method in the following:
  - unbinned search using likelihood ratio
  - optimization: min. flux for 5 sigma discovery

• **Search for flaring Fermi-LAT blazars in Sept. – Dec. 2008**

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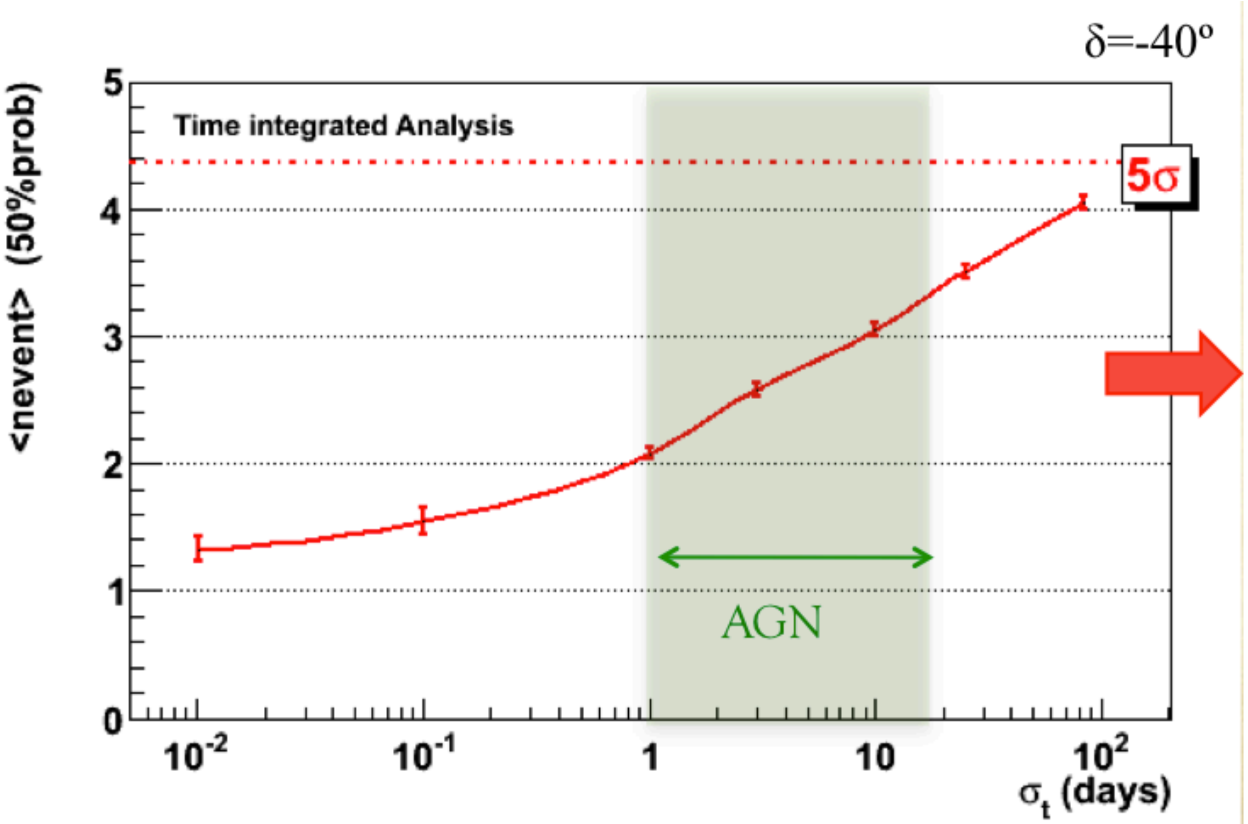
Potential of time dependent analysis

Average number of events per source required for 5 sigma discovery (50% probability) as function of the flare period width.



factor 2 – 3 improvement compared to time-integrated analysis

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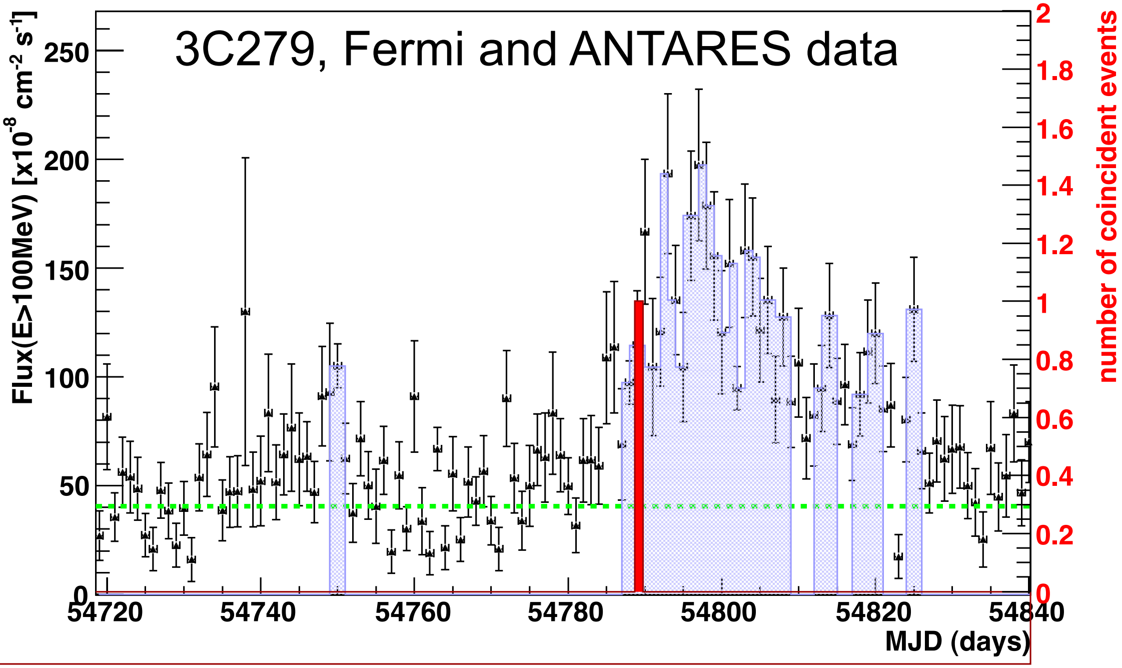
Blazar coincidence searches

- identify flare period for 10 gamma sources, search for neutrino coincidence
- 1st year Fermi cat + LBAS → 6 FSRQs+4 BL Lacs, only 4 seen by IACTS
- 1 coincidence found for 3C279, 0 for the other 9 objects

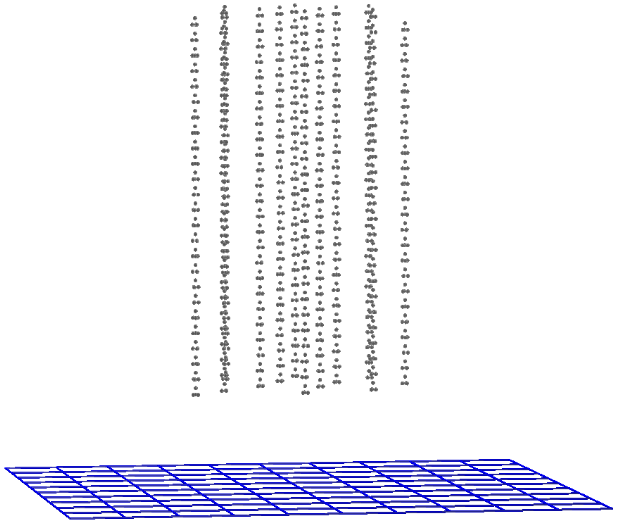
Source	visibility	timePDF (MJD+54000)	Live time (day)	N(5σ)	Nobs	Fluence U.L. GeV/cm^2
3C279	0.53	749-51, 787-809, 812-5, 817-21, 824-6	13.8	5.0	1	8.2



Neutrino search result for 3C279

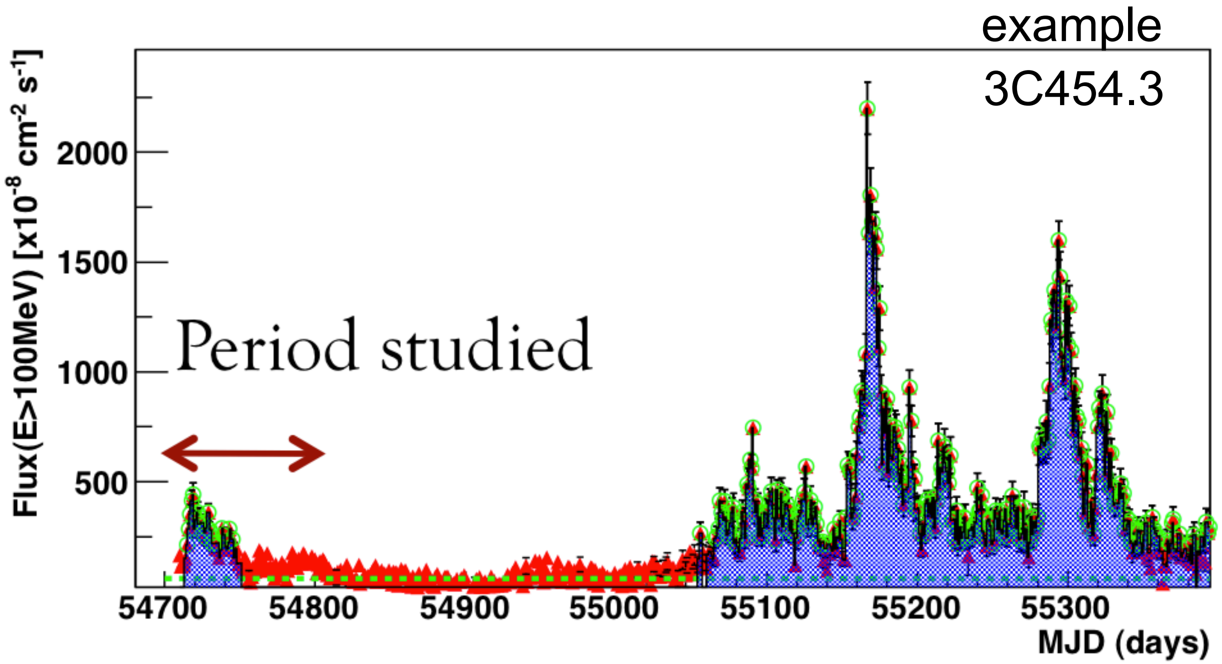
- 61 days live-time of ANTARES data from Sept. – Dec. 2008 used
- 1 neutrino compatible with time range of flare
  and with coordinates of 3C279 (ang. distance 0.56 degrees)
- post-trial probability of 10%
  → compatible with atmospheric background fluctuation

- energy of event not yet used

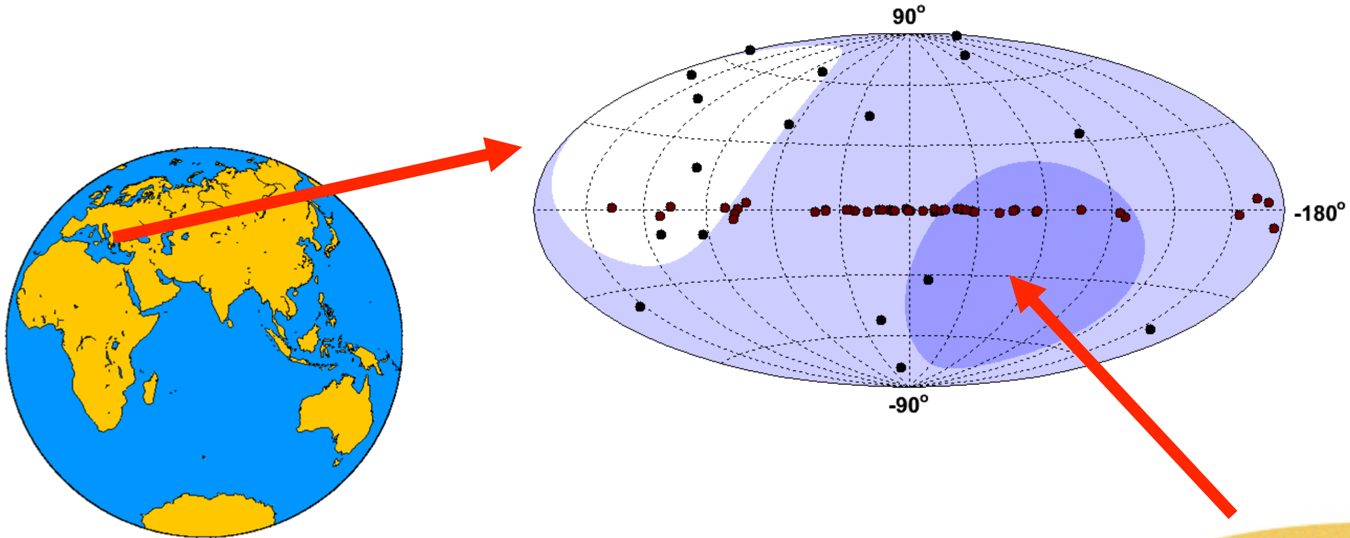


Outlook on time dependent analysis

• Several thousand neutrino candidates recorded since start of 2008, data analysis in progress



Outlook on ANTARES & TANAMI



ANTARES visibility
- > 75%
- 25% – 75%
- < 25%

TANAMI

Idea: develop a dynamical blazar ν-candidate list, based on the variable GeV Fermi sky and the jet-production activity as revealed by TANAMI.

→ work in progress:
C. Müller, M. Kadler, U. Fritsch, K. Fehn, TE, …
(ECAP and U. Würzburg).

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Recent ANTARES publications … much more to come

- **First search for point sources of high energy cosmic neutrinos with the ANTARES neutrino telescope**
  J.A.Aguilar et al.
  Submitted to Astrophysical Journal Letters [preprint: arXiv:1108.0292v1]

- **Acoustic and optical variations during rapid downward motion episodes in the deep north-western Mediterranean Sea**
  H. van Haren et al.
  Deep-Sea Research I 58 (2011) 875–884

- **ANTARES: the first undersea neutrino telescope**
  J.A. Aguilar et al.
  Nuclear Inst. and Methods in Physics Research, A **656** (2011) pp. 11-38 [arXiv:1104.1607v1]

- **A Fast Algorithm for Muon Track Reconstruction and its Application to the ANTARES Neutrino Telescope**
  J.A. Aguilar et al.
  To be published in Astroparticle Physics []

- **Time Calibration of the ANTARES neutrino Telescope**
  J.A. Aguilar et al.
  Astroparticle Physics 34 (2011) 539-549 [arXiv:1012.2204]

- **Search for a diffuse flux of high energy n_μ with the ANTARES neutrino telescope**
  J.A. Aguilar et al.
  Phys. Letter B 696 (2011) 16-22 [arXiv:1011.3772]

- **AMADEUS - The Acoustic Neutrino Detection Test System of the ANTARES Deep-Sea Neutrino Telescope**
  J.A. Aguilar et al.
  Nucl. Instr. and Meth. A 626-627 (2011)128-143 [arXiv:1009.4179]

- **Zenith distribution and flux of atmospheric muons measured with the 5-line ANTARES detector**
  J.A. Aguilar et al.
  Astroparticle Physics 34 (2010), pp. 179-184 [arXiv:1007.1777]

- **Performance of the front-end electronics of the ANTARES Neutrino Telescope**
  J.A. Aguilar et al.
  Nucl. Instr. and Meth. A 622 (2010) 59-73, [arXiv:1007.2549]

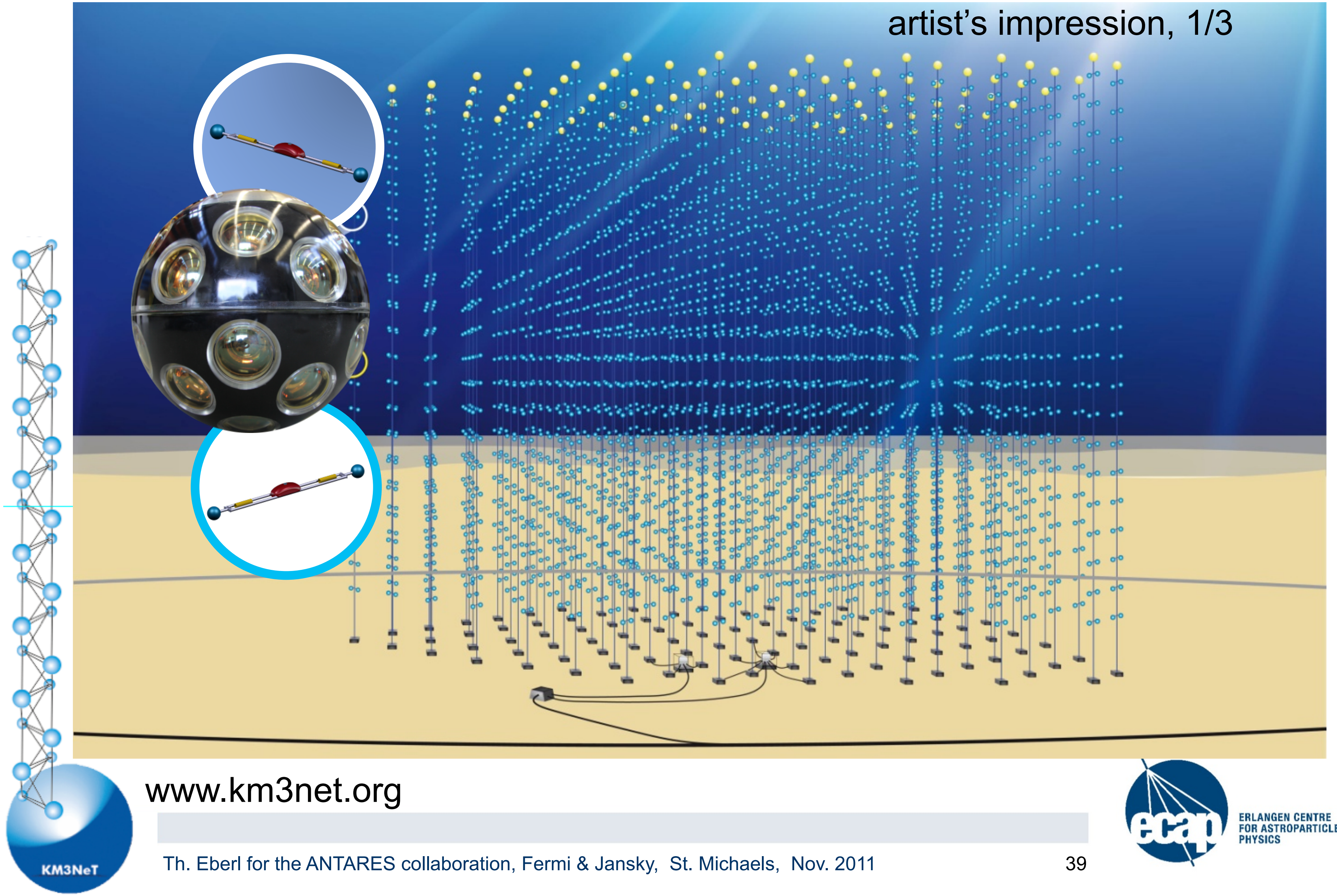
- **Measurement of the atmospheric muon flux with a 4 GeV threshold in the ANTARES neutrino telescope**
  J.A. Aguilar et al.
  Astroparticle Physics 33 (2010) pp. 86-90
  (erratum published in Astroparticle Physics 34, 3 (2010) pp.185-186) [arXiv:0910.4843]

- **Performance of the First ANTARES Detector Line**
  M. Ageron et al.
  Astroparticle Physics 31, 4 (2009) pp.277-283 [arXiv:0812.2095]

No time to talk about …

- TATOO: Fast optical follow up program
- GRB analyses
- Dark matter searches
- Neutrino oscillations
- Joint analyses with VIRGO/LIGO and Pierre Auger
- Exotics: limits on nuclearites and monopoles
- CR composition studies
- AMADEUS: Acoustic neutrino detection feasibility study
- ***… but some words about the future: KM3NeT***

The Future: KM3NeT



www.km3net.org

KM3NeT: What & why?

- Large deep-sea infrastructure in the Mediterranean Sea
  - next generation neutrino telescope: ***multi - km³ size***
  - cabled observatories for Earth & Sea sciences

- Science
  - discovery of sources of (high-energy) cosmic neutrinos
  - continuous and long-term measurements in the areas of oceanography, geophysics and marine biological sciences

KM3NeT: Scientific focus

- Geographical location

  Field of view includes Galactic centre

- Optical properties of deep-sea water

  Excellent angular resolution

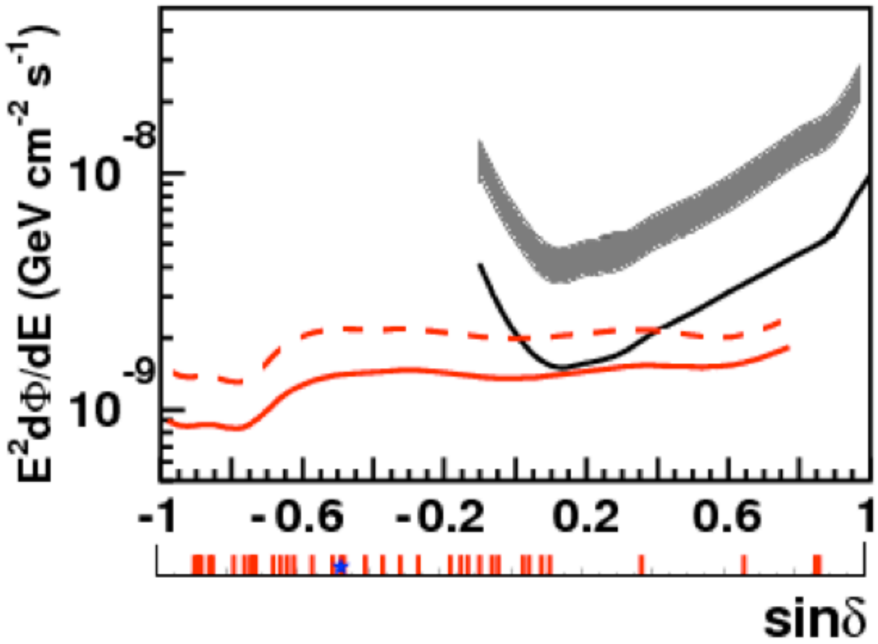
- Envisaged budget 220–250 M€

  Large effective neutrino area

Observe Supernova Remnants in our Galaxy

Fermi & Jansky …. & Pauli ?

Sensitivity of KM3NeT (TDR) to neutrino point sources



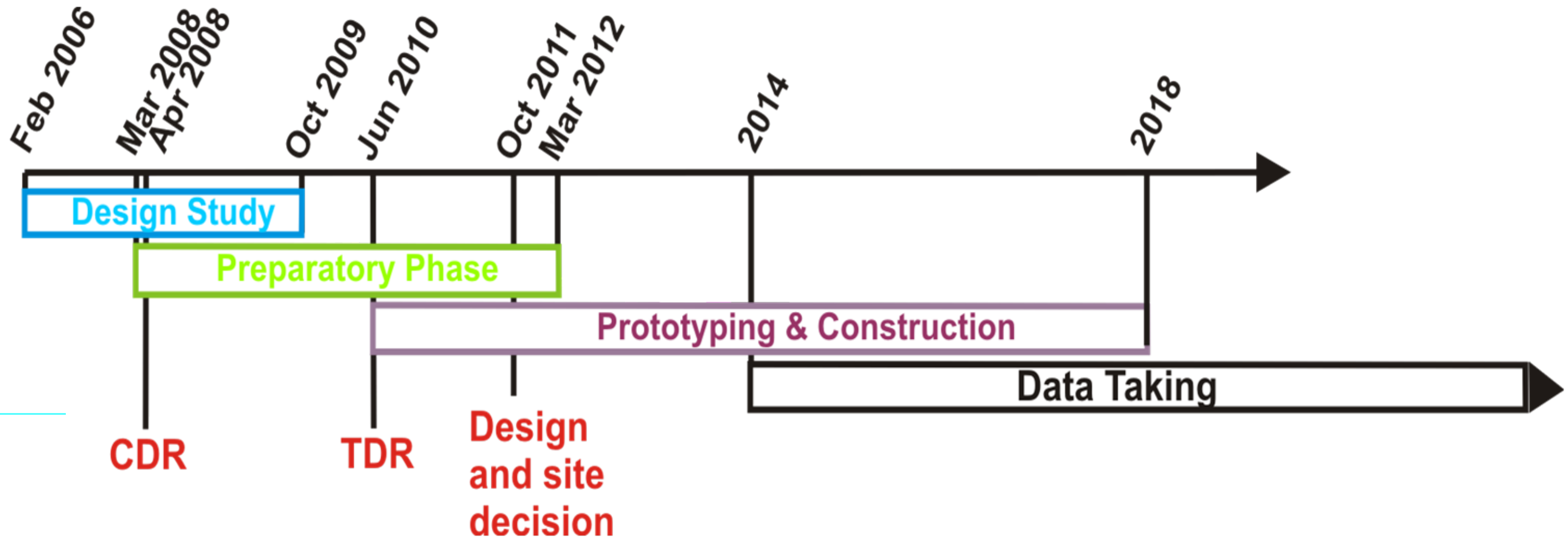
IceCube

KM3NeT

~ 100x ANTARES

Figure 6-10: Sensitivity of the full KM3NeT detector to neutrino point sources with an E^{-2} spectrum for one year of observation, as a function of the source declination. The red lines indicate the flux sensitivity (90% CL;full line) and the discovery flux(5σ, 50% probability; dashed line). Both are estimated with the binned analysis method. The black line is the IceCube flux sensitivity for one year, estimated with the unbinned method [2] (full line). IceCube's discovery flux (5σ, 50% probability) is also indicated (shaded band, spanning a factor 2.5 to 3.5 above the flux sensitivity). The red ticks at the bottom of the horizontal axis show the positions of Galactic gamma ray sources [3]; the position of the Galactic Centre is indicated by a blue star.

KM3NeT: Timeline from TDR



Conceptual Design Report. 2008. ISBN 978-90-6488-031-5
Technical Design Report. 2011. ISBN 978-90-6488-033-9

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

Summary and Conclusions

ANTARES …

- is a pilot project in the MedSea and takes data for 4.5 years now
- proves feasibility of deep sea concept for KM3NeT
- FOV and excellent angular resolution allow to complement IceCube
- has a broad (particle and astro-) physics program
- determines sensitive upper limits on HE diffuse ν flux and on fluxes from Galactic and Extra-Galactic point sources
- makes use of multi-messenger information to increase sensitivity

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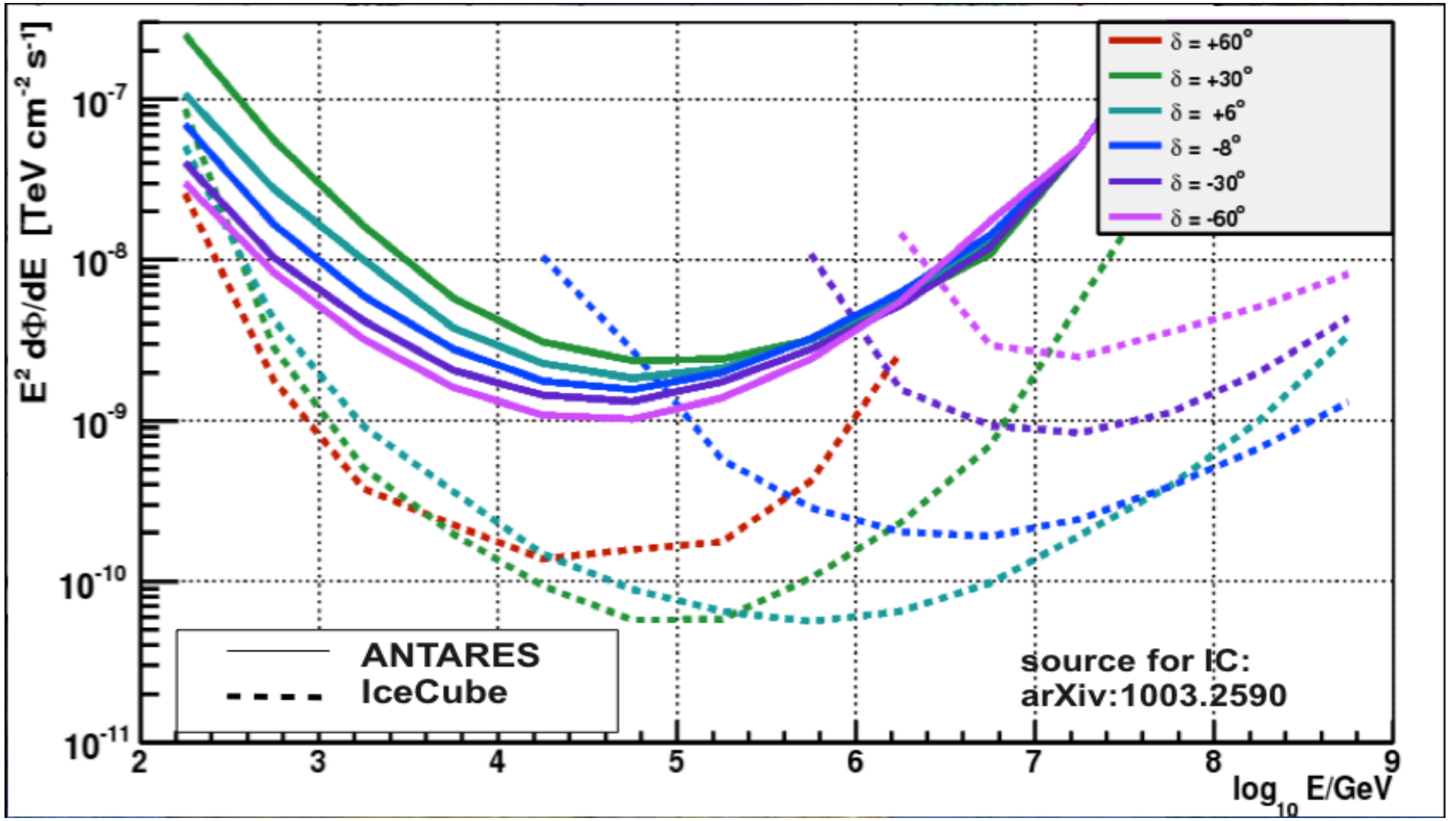
Backup slides

Fermi sources for time dependent analysis

Name	OFGL name	Class	RA [^{o}]	Dec [^{o}]	Redshift
PKS0208-512	J0210.8-5100	FSRQ	32.70	-51.2	1.003
AO0235+164	J0238.6+1636	BLLac	39.65	16.61	0.940
PKS0454-234	J0457.1-2325	FSRQ	74.28	-23.43	1.003
OJ287	J0855.4+2009	BLLac	133.85	20.09	0.306
WComae	J1221.7+28.14	BLLAc	185.43	28.14	0.102
3C273	J1229.1+0202	FSRQ	187.28	2.05	0.158
3C279	J1256.1-0548	FSRQ	194.03	-5.8	0.536
PKS1510-089	J1512.7-0905	FSRQ	228.18	-9.09	0.36
3C454.3	J2254.0+1609	FSRQ	343.50	16.15	0.859
PKS2155-304	J2158.8-3014	BLLac	329.70	-30.24	0.116

ANTARES vs IceCube: 5σ discovery flux



• Combined data analysis of ANTARES with IceCube in progress

ANTARES: 295d (2007-2008), IC40: 375d (2008-2009)

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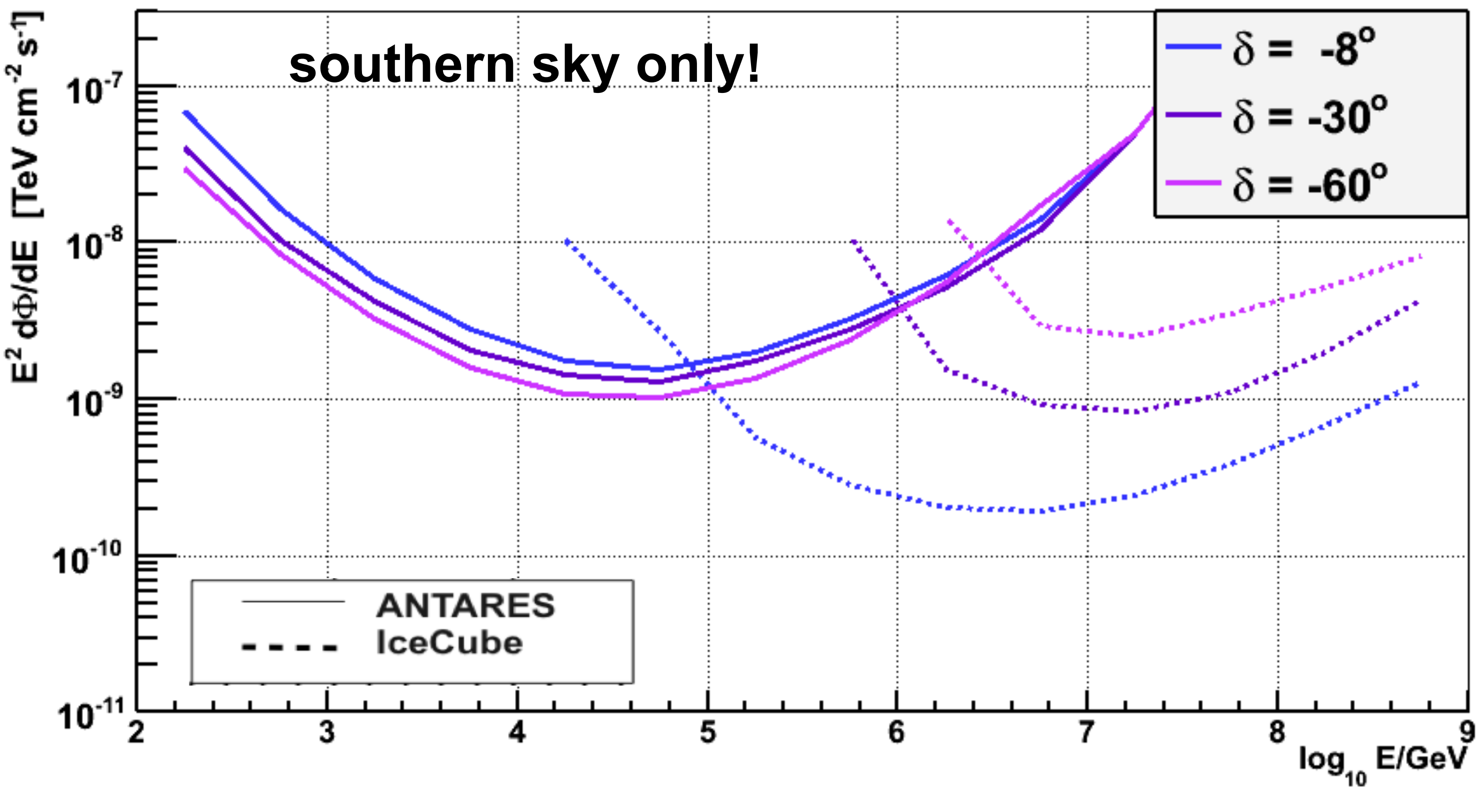
ANTARES vs IceCube: 5σ discovery flux



- ANTARES adds sensitivity at δ < 0 at E ~ 10TeV: Galactic sources!
- Very different energy ranges!!!

ANTARES: 295d (2007-2008), IC40: 375d (2008-2009)

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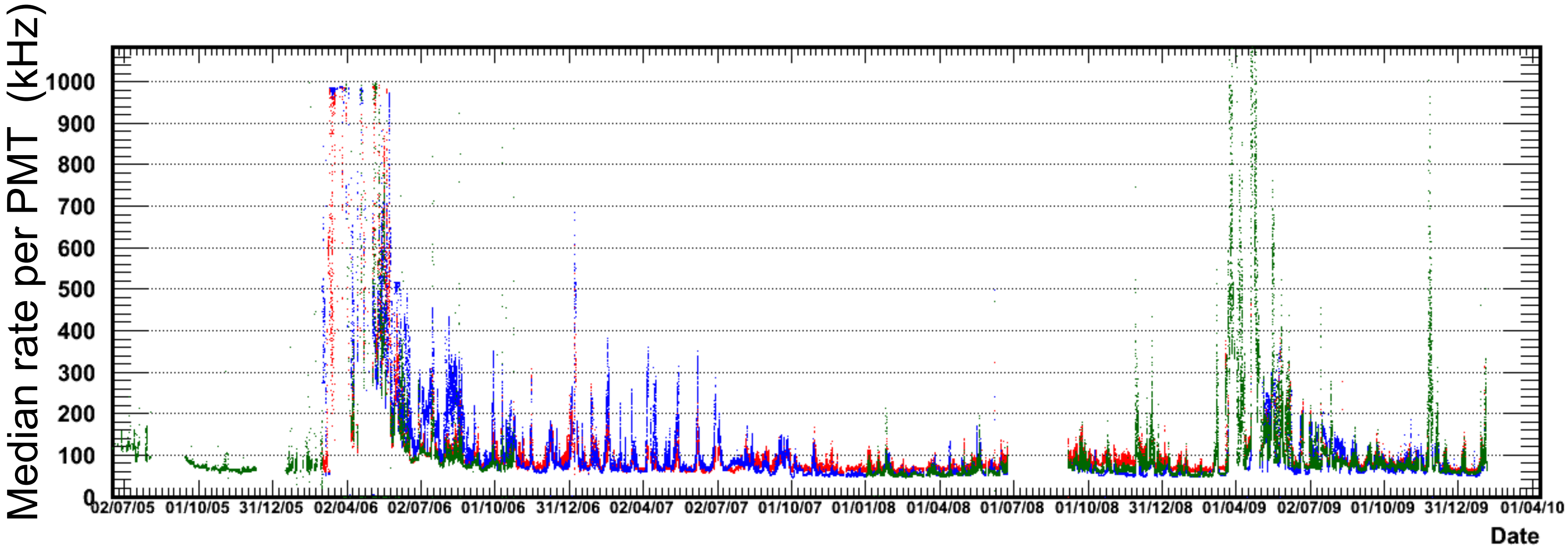
Optical Background: the deep sea is not dark !!!



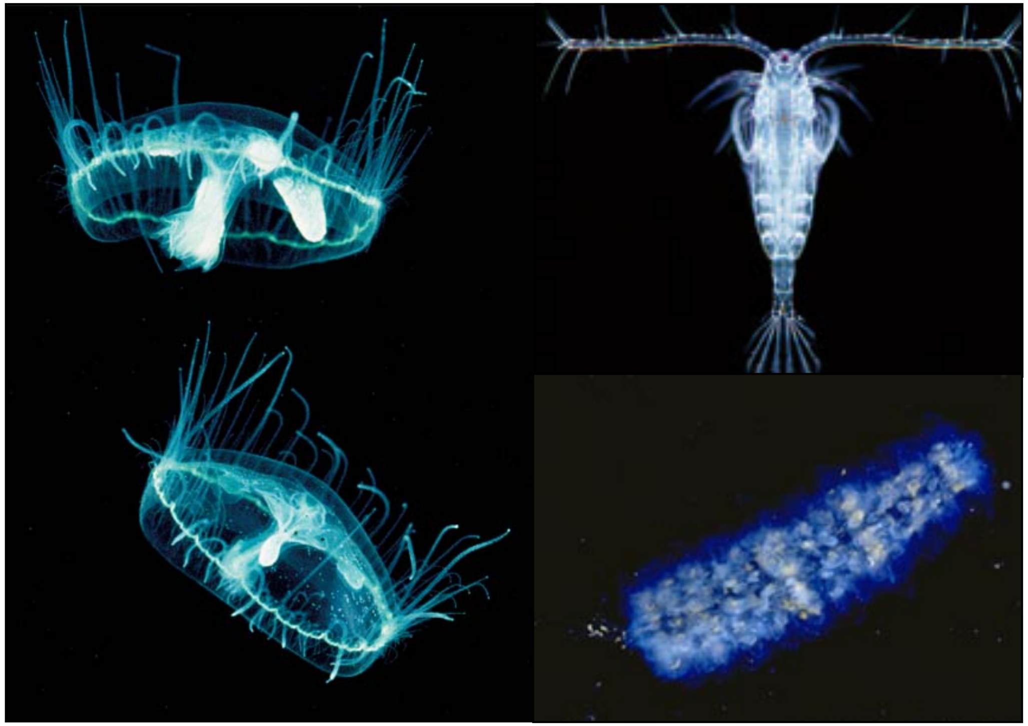
July'05 July'06 July'07 July'08 July'09

Optical background due to ^{40}K-decay and bioluminescence

- Typical rates per PMT 60-120 kHz
- Additional short bursts and periods with higher rates

Bioluminescent Sources

- Bacteria: steady baseline source of light (30kHz in 10'' PMT)
- Macro-organisms: short flashes (up to MHz)



(J. Craig, Univ. Aberdeen, VLVNT 08)

e.g.
large colonial organisms such as pyrosomes (megaplankton)

size range:
0.2 - 2000 mm

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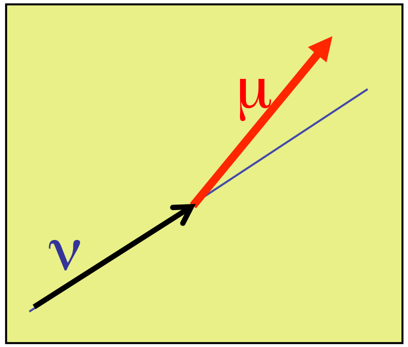
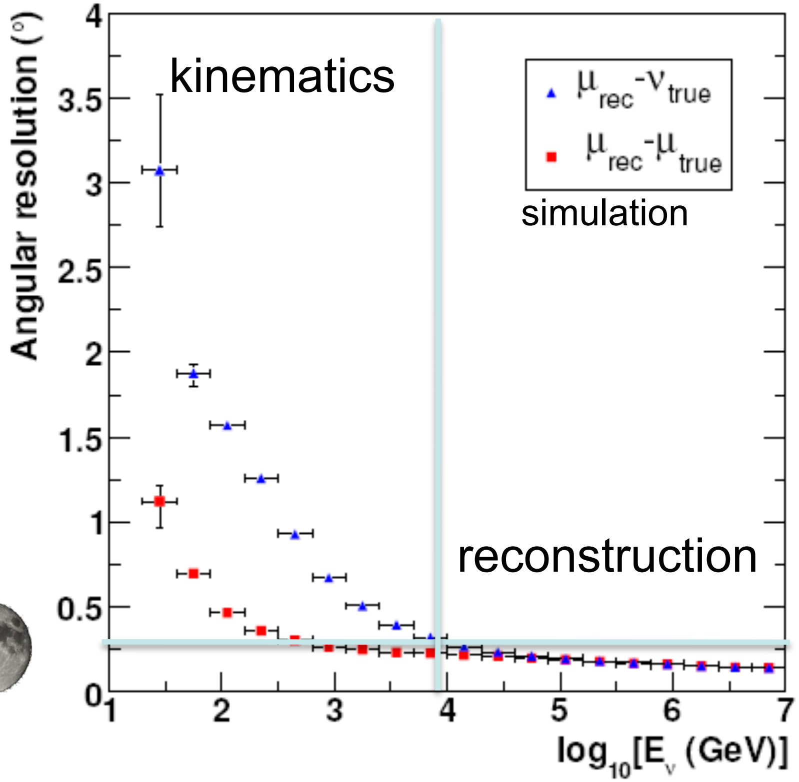
Angular resolution





size of the moon

angular resolution < 0.3° for E_ν > 10 TeV

tracking accuracy limited by timing resolution:

- Light scattering σ ~ 1.0 ns
- TTS in PMT σ ~ 1.3 ns
- time calibration σ < 0.5 ns
- OM position σ < 10 cm (↔ σ< 0.5 ns)

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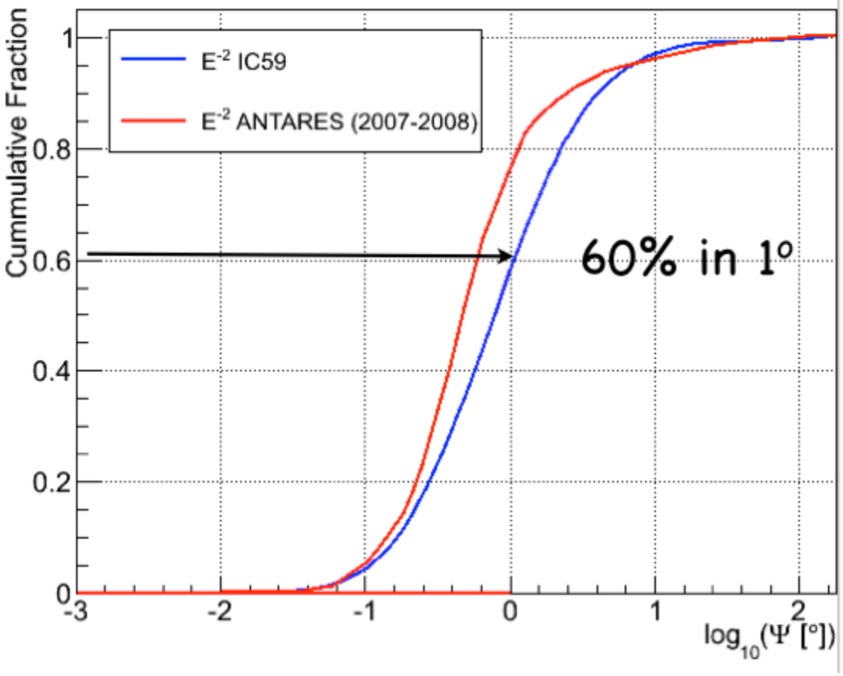
Angular resolution compared to IceCube



T. Montaruli, NUSKY11

advantage of water over ice:

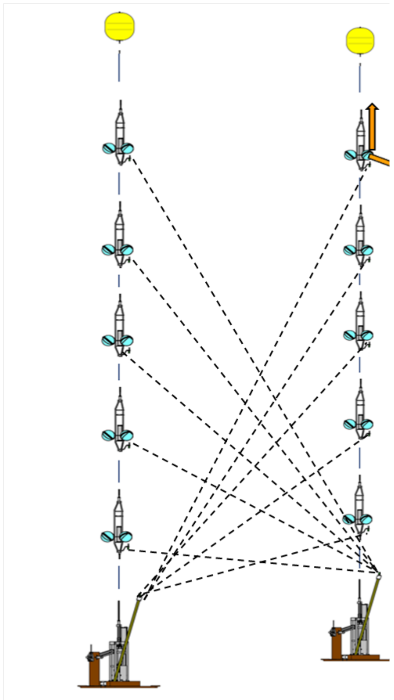
less light scattering
-> better angular resolution

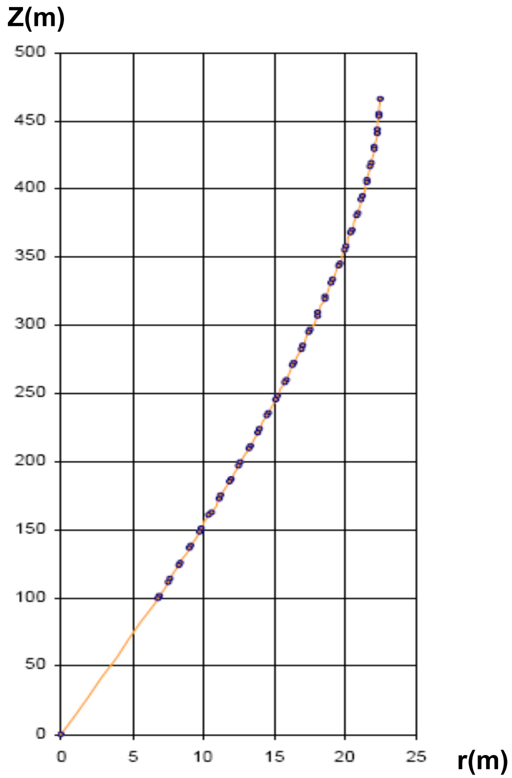
ANTARES: 80% in 1 deg
IceCube : 60% in 1 deg

expectation for KM3NeT:
50% better than 0.1 deg
(longer lever arm!)

Detector positioning

- Acoustic system
  - 1 emitter(+ receiver)
    at each line socket
  - 5 receivers along each line
- Compass and Accelerometer
  - 1 Compass at each storey
  - 1 Acc. at each storey



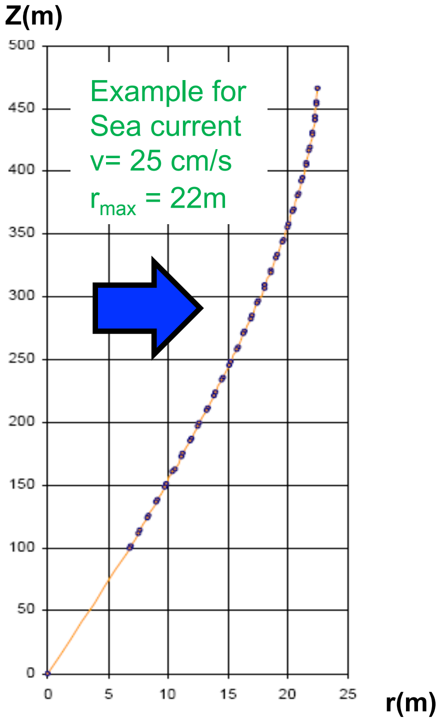


- Measure every 2 min
  - Acoustics: **distance** sockets - receivers
  - Compass: **heading**
  - Accelerometer: **tilt**

} Line shape

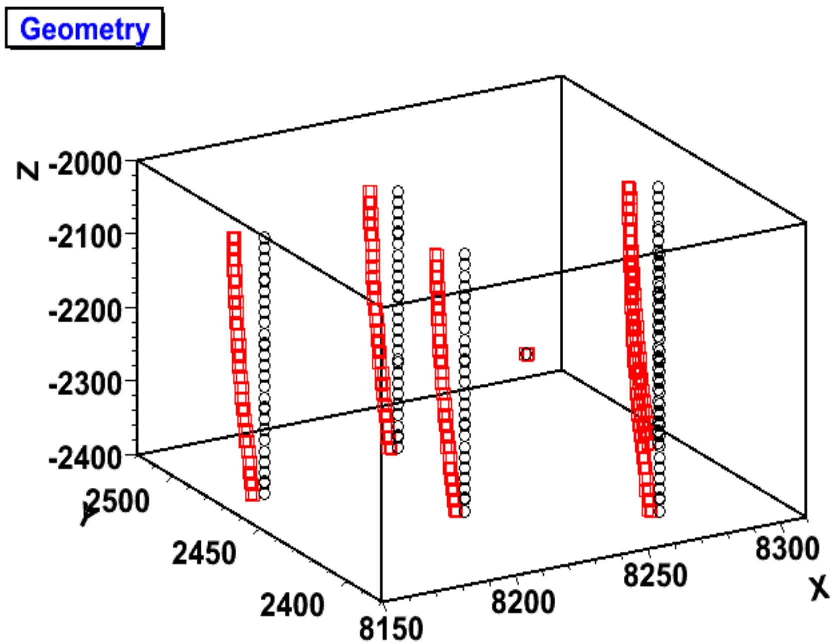
Detector positioning

typical line shape

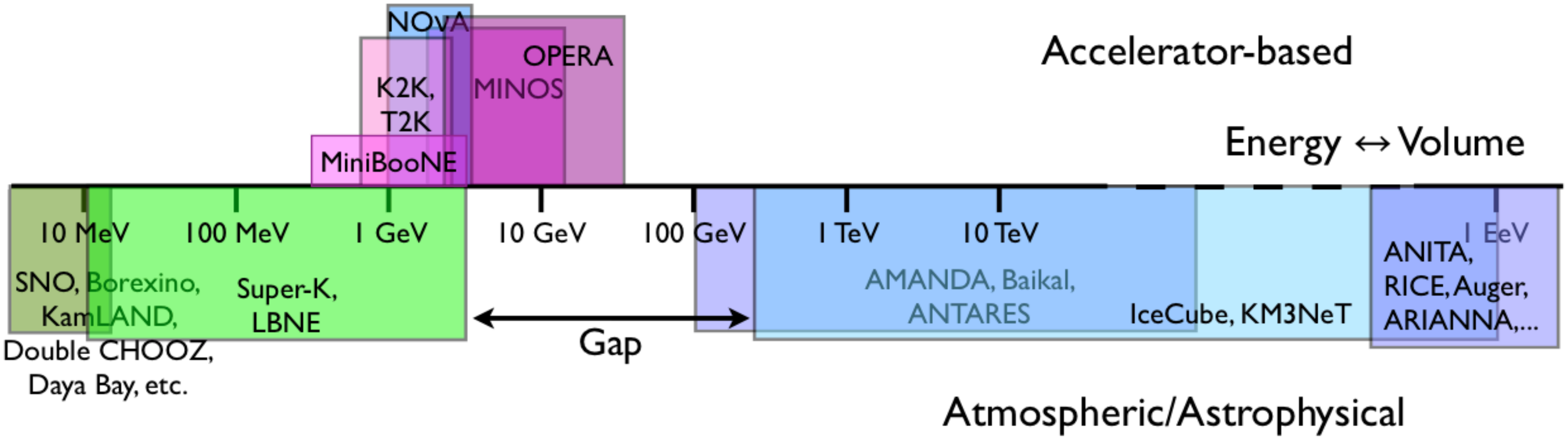


$$r = (a\,z - b\ \ln[1-cz]\,)\,v^2$$

mostly coherent movement of lines



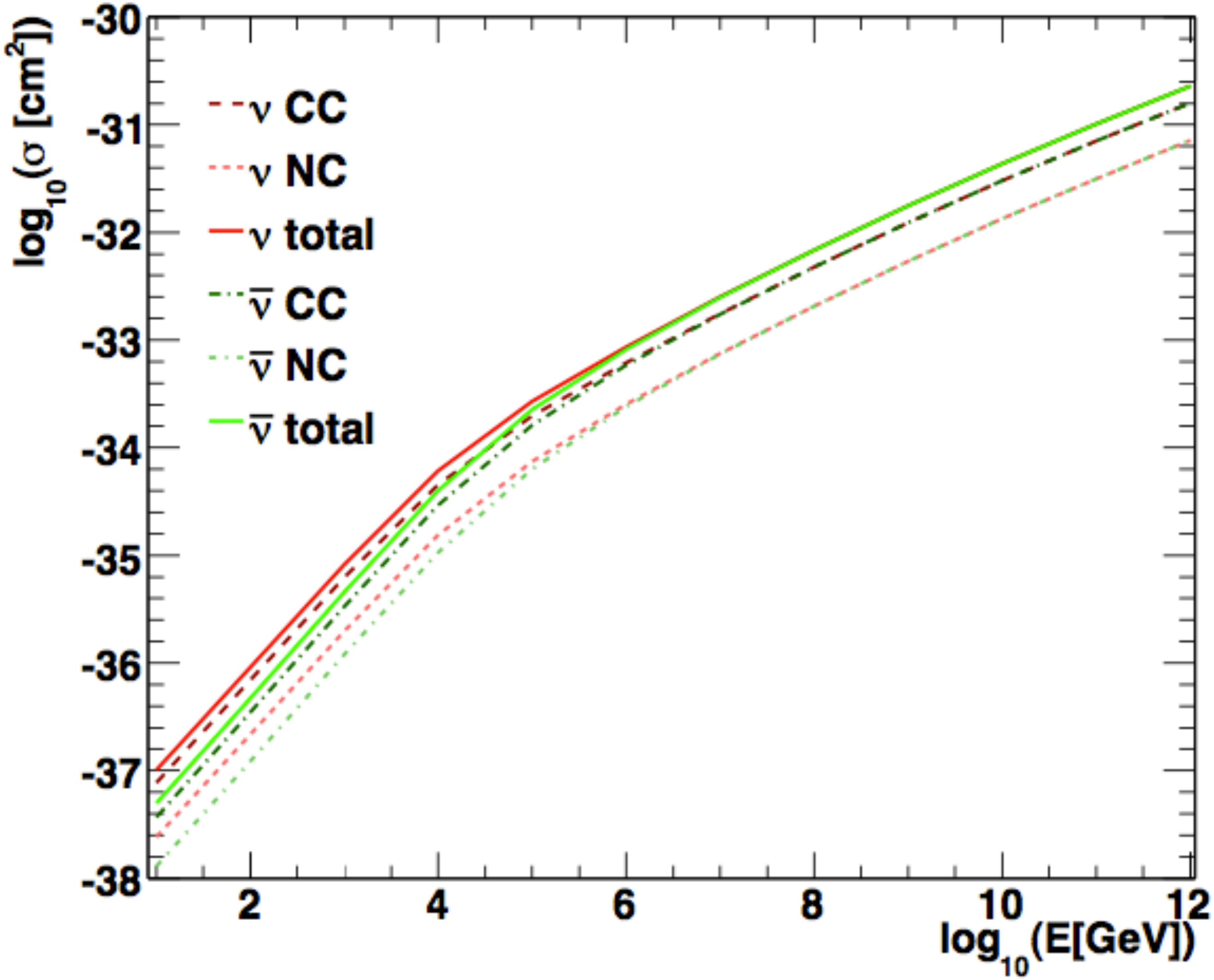
Neutrino Detector / Energy Spectrum



T. deYoung, MANTS2011

Neutrino – nucleon cross sections

PhD thesis O. Schulz



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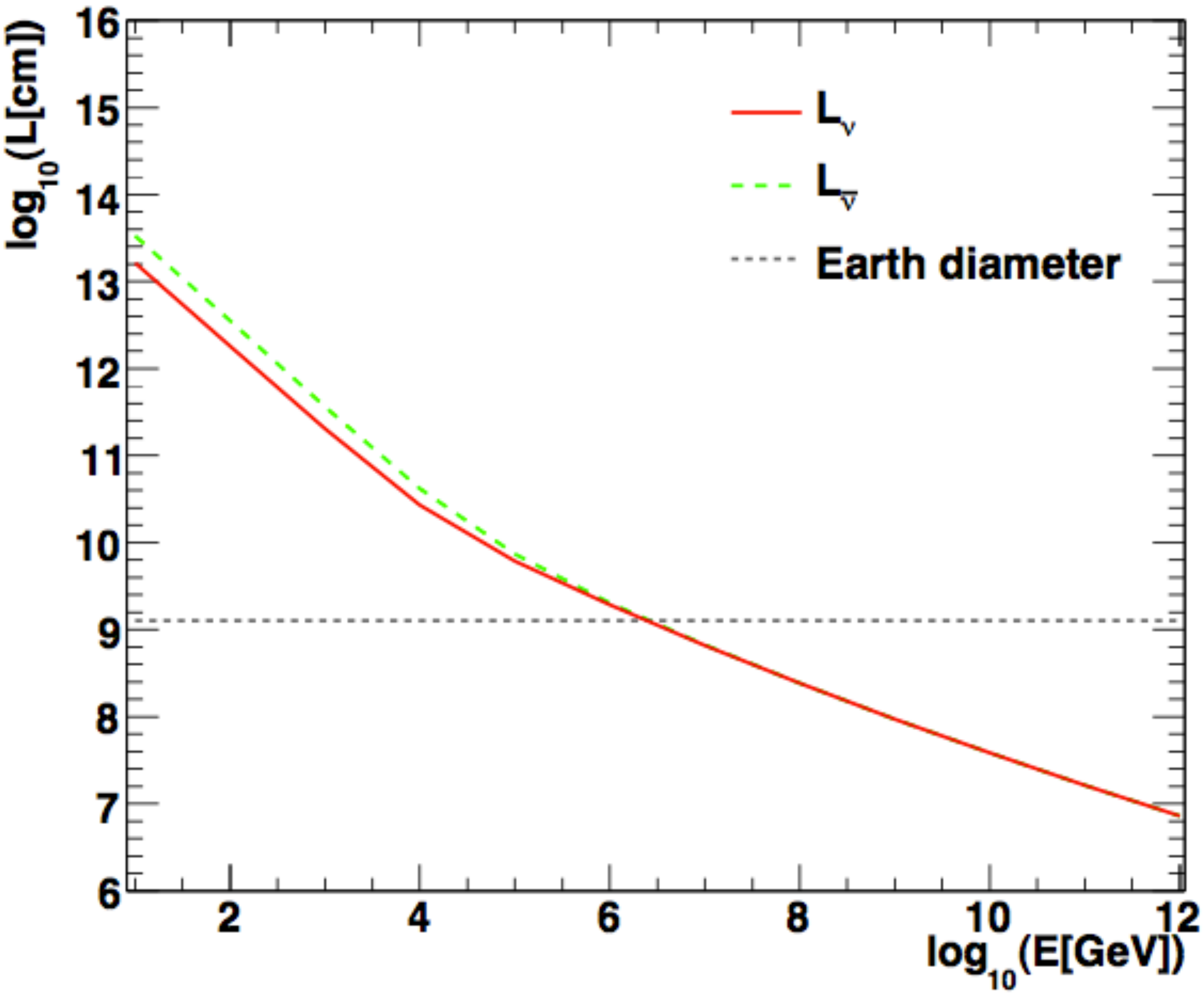
Neutrino mean free path in water

PhD thesis O. Schulz



Why we need a km3 array?

Putting things together: the $1km^3$ estimate

Waxman-Bahcall flux limit

$E^2\Phi = 2*10^{-8}$ GeV cm^{-2} s^{-1}

Should produce several neutrinos per year

Use muon flux:

$\Phi_\mu = \Phi_\nu * \sigma * P_{earth}$ *muon range

Then

Integral(Φ_μ dE)*1yr*A=O(1-10)

This results in A ~ 1 km²

Then same area for all directions ~ $1km^3$

Estimated neutrino fluxes (SNR)

- Photon ↔ neutrino connection:

$p + p \rightarrow \pi^0 + X$
↳ $\gamma + \gamma$

$p + p \rightarrow \pi^\pm + X$
↳ $\mu + \nu_\mu$
↳ $e + \nu_\mu + \nu_e$

- Observed from RX J1713.7–3946:
  - γ-rays up to several 10 TeV

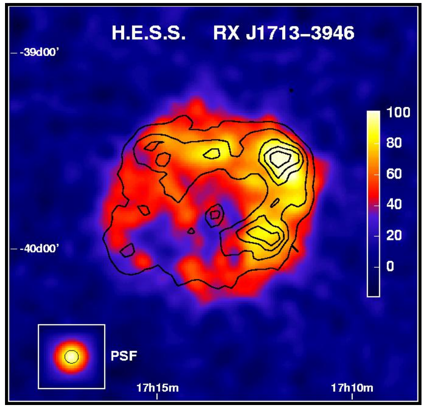
    → particle acceleration up to 100 TeV and above

- Calculated neutrino fluxes:

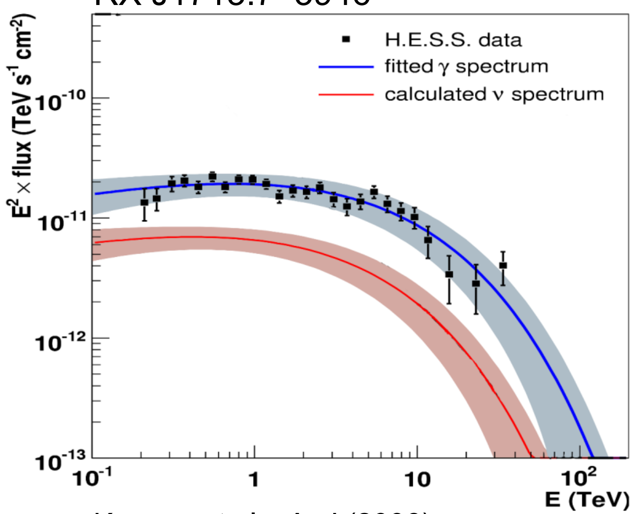
  For strong sources:

  10^{-12}–10^{-11} TeV^{-1} cm^{-2} s^{-1} @ 1 TeV

  Kappes et al., ApJ (2006)
  Halzen et al., PRD (2008)
  Kistler, Beacom, PRD (2006)
  . . .

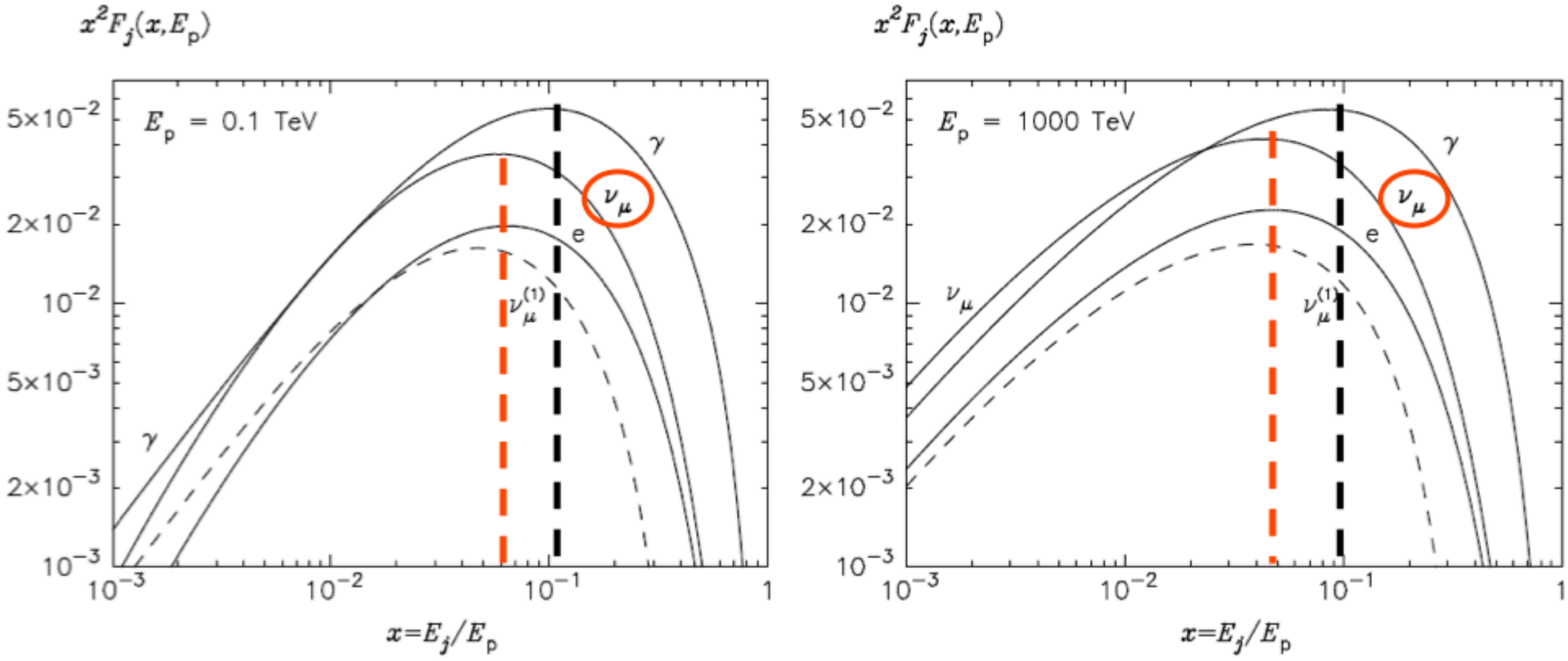


RX J1713.7–3946



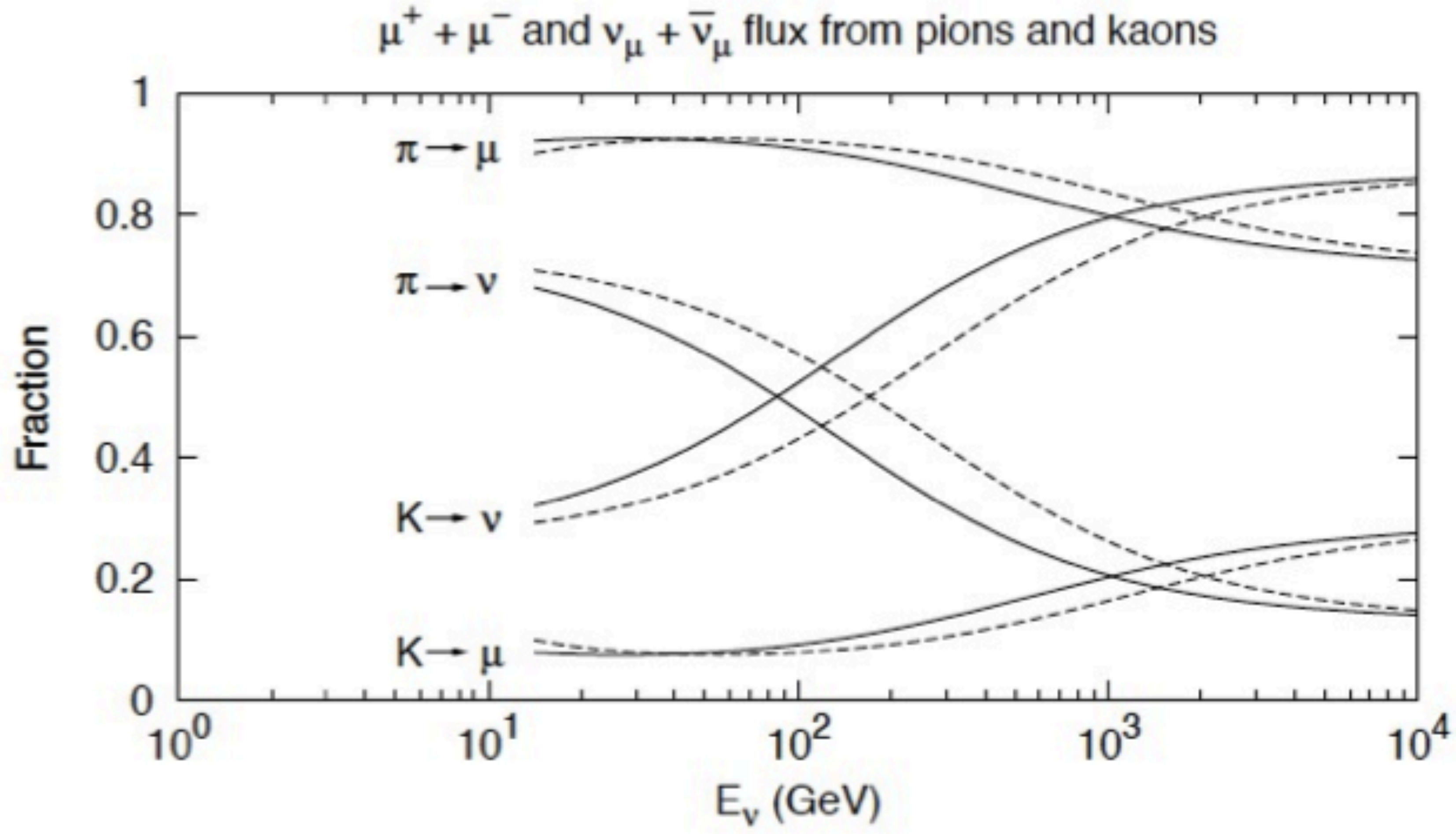
Kappes et al., ApJ (2006)

pp interactions, E spectra, decay products



Kelner et al, PhysRev D74, 2006

Atmospheric neutrino sources



Gaisser et al., Ann. Rev. Nucl. Part. Phys., 52, 2002

Atmospheric neutrino sources

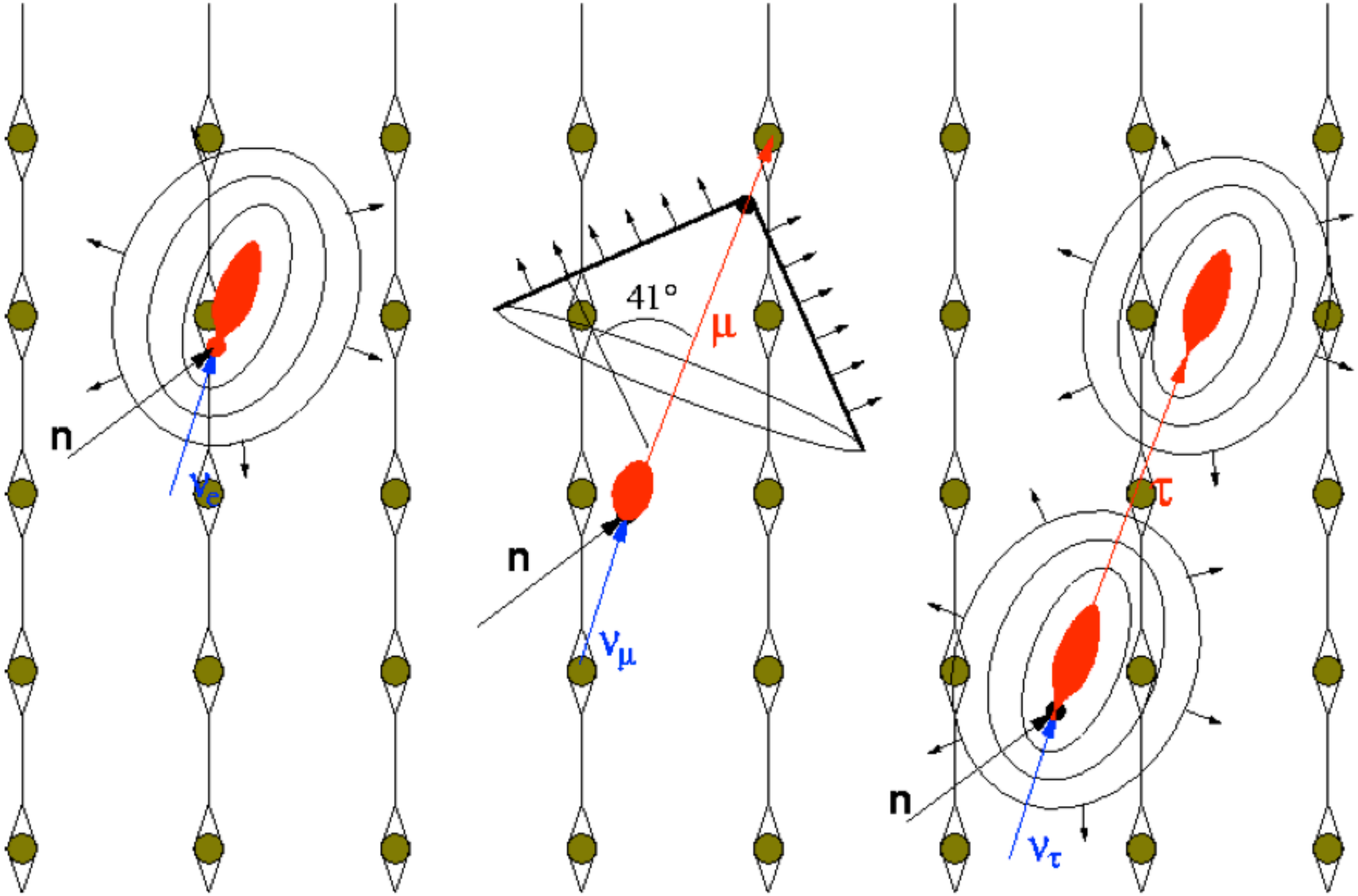
$$\pi^\pm \to \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$$
$$\hookrightarrow e^\pm + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$$

If all particles decay then:

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2, \qquad \nu_\mu/\bar{\nu}_\mu \sim 1 \quad \text{and} \quad \nu_e/\overline{\nu}_e \sim \mu^+/\mu^-.$$

Muons with energy of several GeV and above reach the ground before decaying

Neutrino interaction signatures



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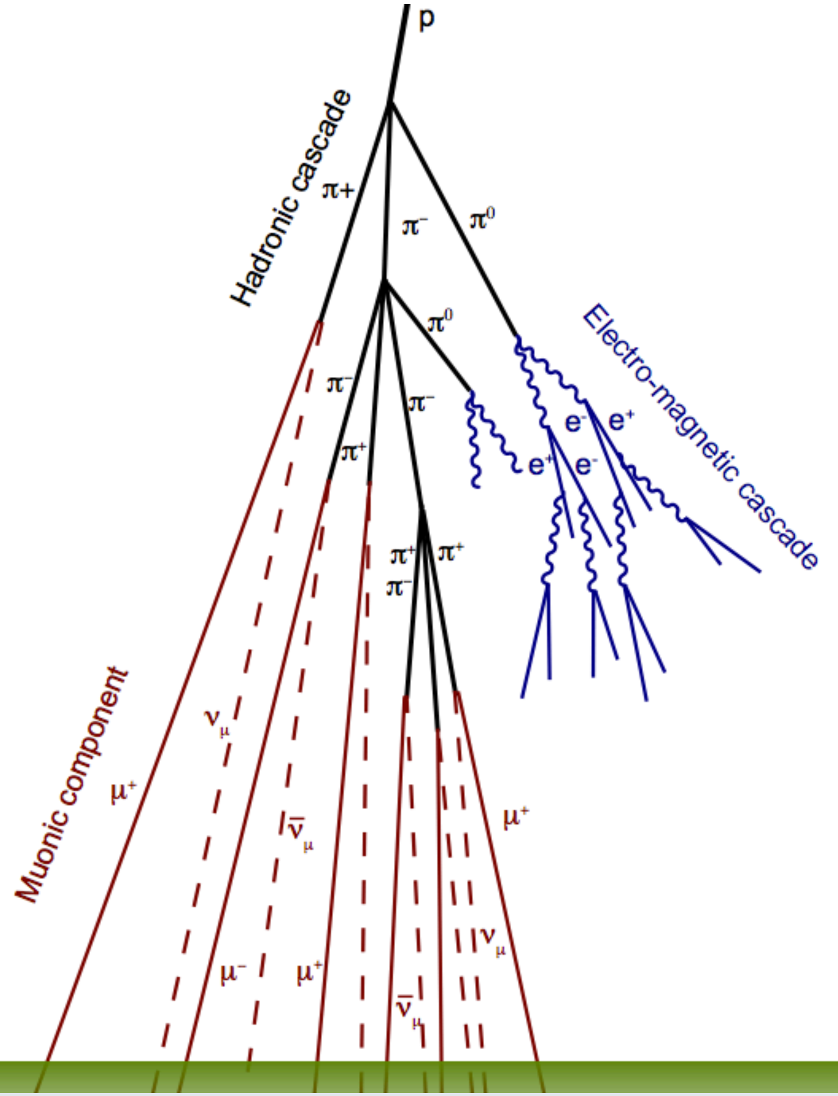
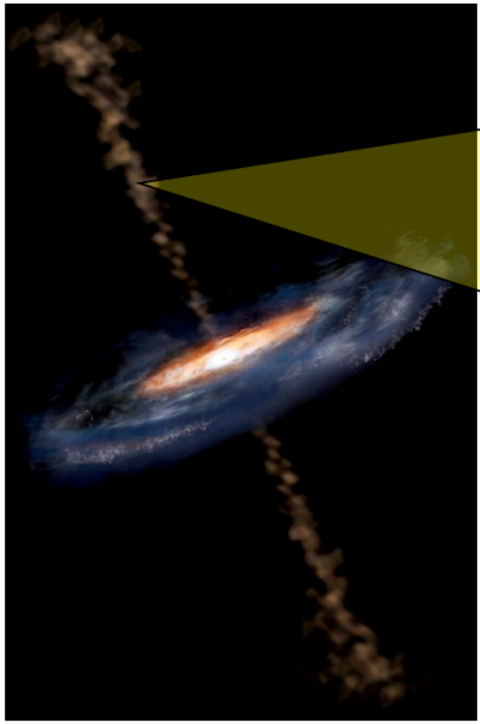
CR air shower

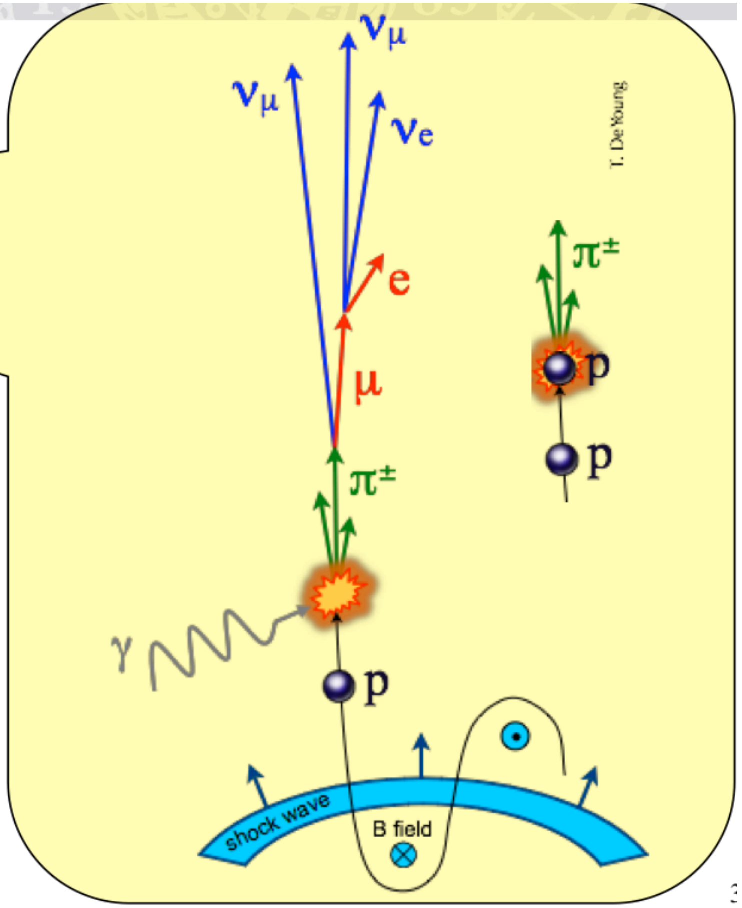


PhD thesis O. Schulz

HE neutrino production



Example: Active galaxy
(Halzen, Venice 2009)



Hadronic jets as possible HE neutrino sources