Astrophysical and Atmospheric Neutrinos in Neutrino Telescopes

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1 Introduction Neutrino astronomy

2 Astrophysical neutrinos

- Cosmic sources
- Neutrino relation to cosmic rays and gamma ray
- Flavor distribution

3 Atmospheric Neutrinos

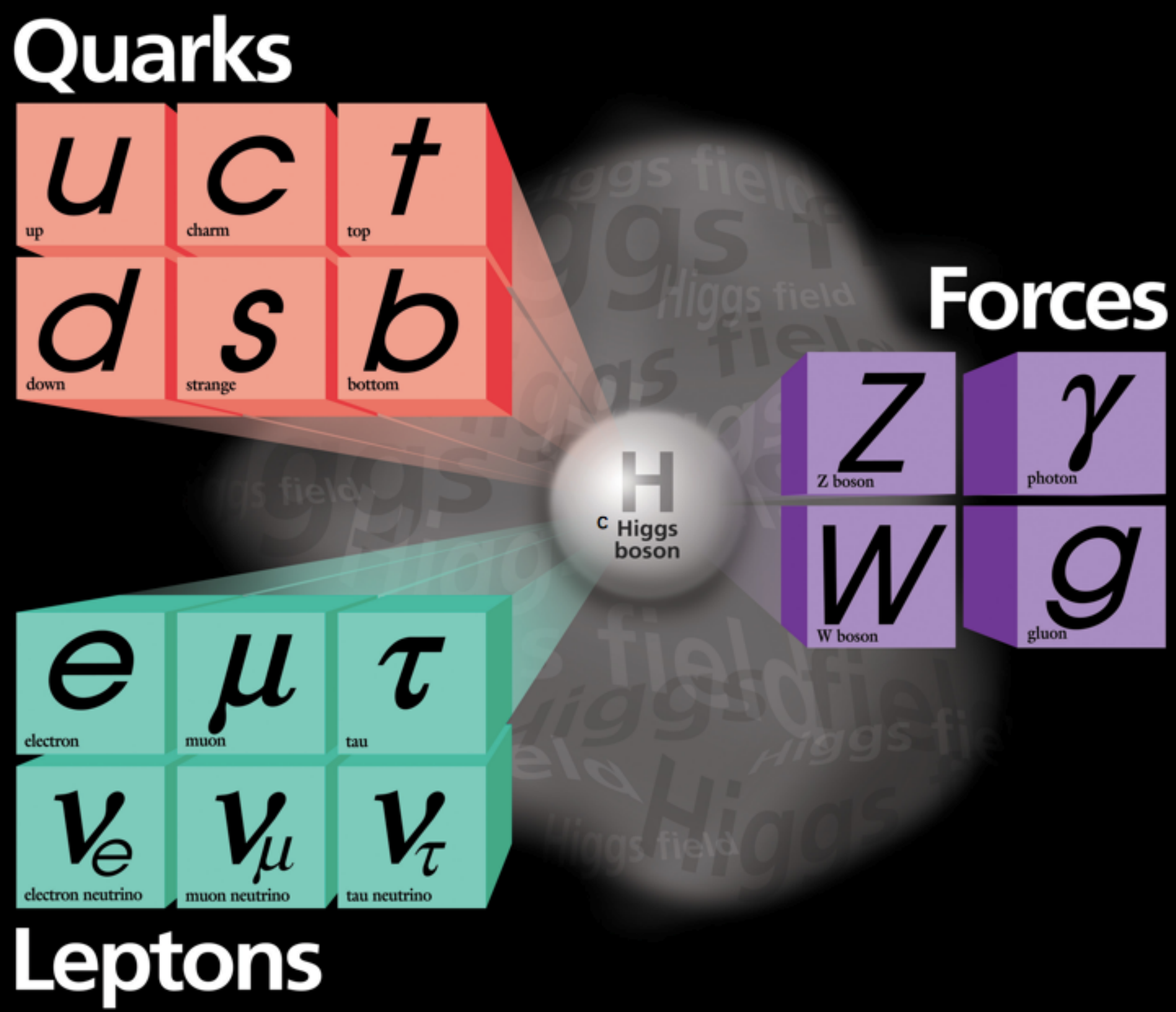
- Neutrino production in the atmosphere

4 Neutrino telescopes

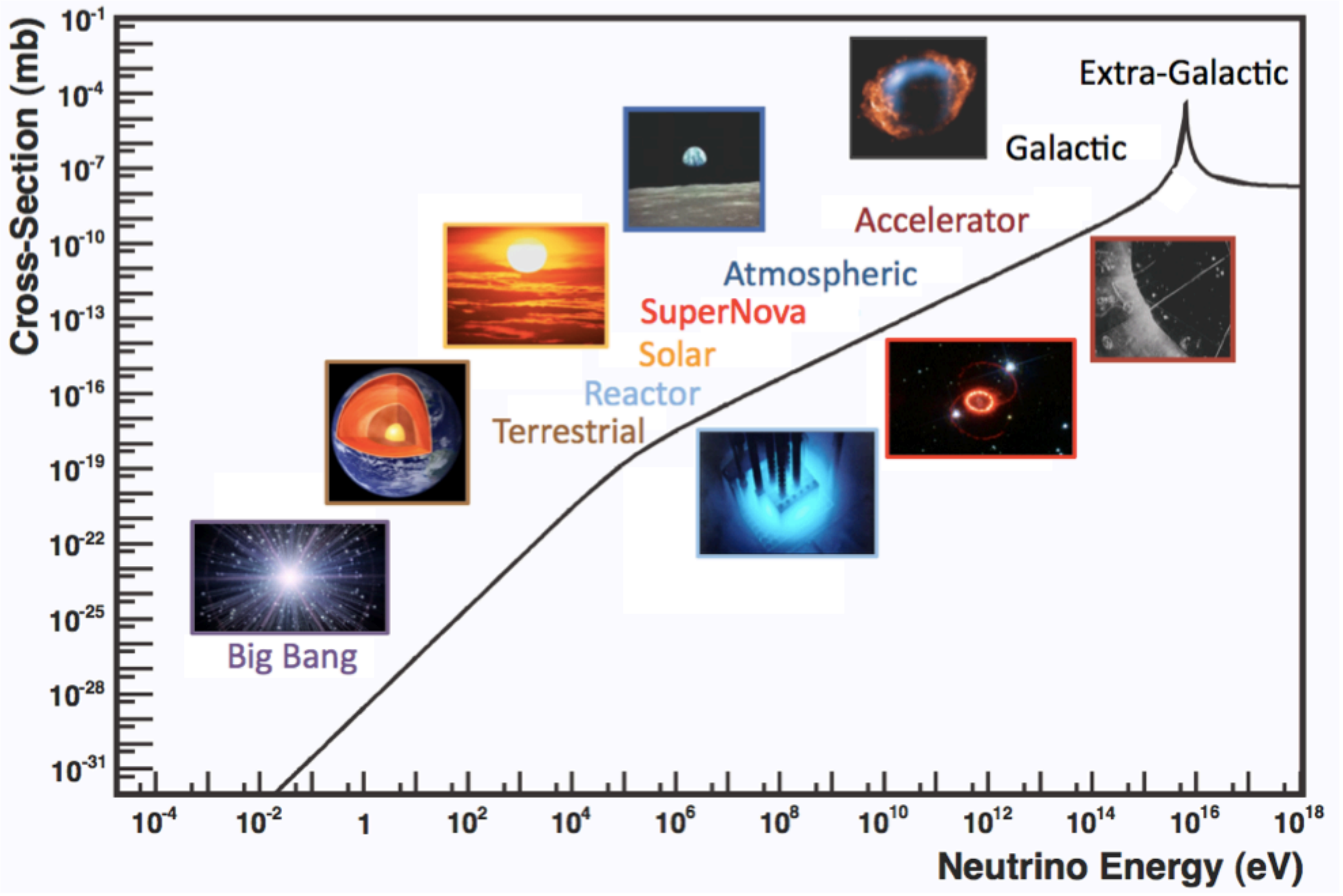
- Detection principles
- Baikal/IceCube/ANTARES/KM3NeT

5 Measurement challenges and prospects

- Atmospheric neutrino flux
- Point source searches
- IceCube detection of Cosmic Neutrinos
- Multimessenger observations
- Transient sources
- Dark Matter
- Neutrino oscillations & New Physics

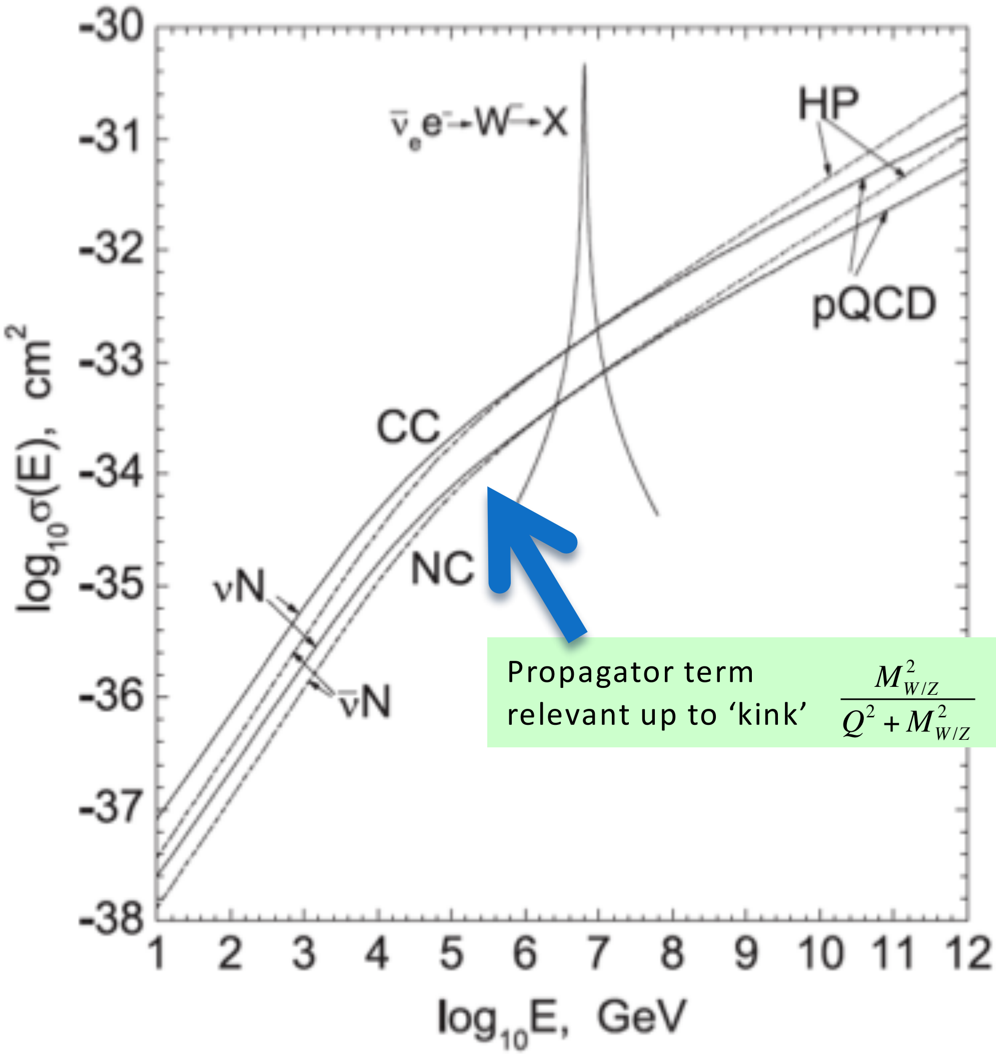

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Higgs field

Where do we get neutrinos from?



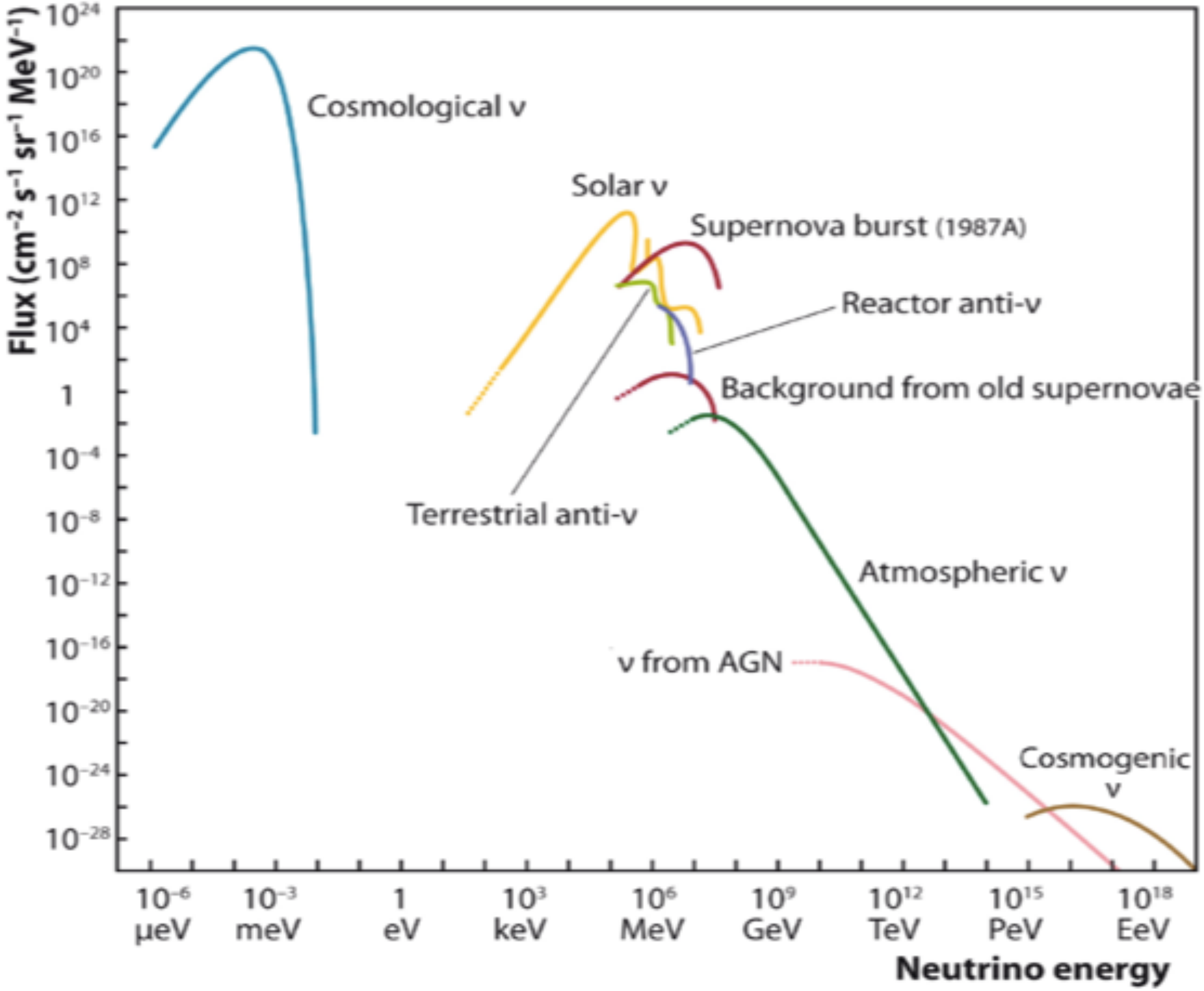
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012)

Neutrino cross section



Propagator term relevant up to 'kink' $\frac{M_{W/Z}^2}{Q^2 + M_{W/Z}^2}$

Gazizov, Kowalski Comput. Phys. Commun. 172 (2005)



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^24
10^20
10^16
10^12
10^8
10^4
1
10^-4
10^-8
10^-12
10^-16
10^-20
10^-24
10^-28
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^-6 μeV
10^-3 meV
1 eV
10^3 keV
10^6 MeV
10^9 GeV
10^12 TeV
10^15 PeV
10^18 EeV
Neutrino energy

Science for Neutrino Telescopes

Astrophysics

Neutrinos can surpass dense media and long distances -> new information

Multimessenger information (combine with electromagnetic/gravitational wave/cosmic ray observations)

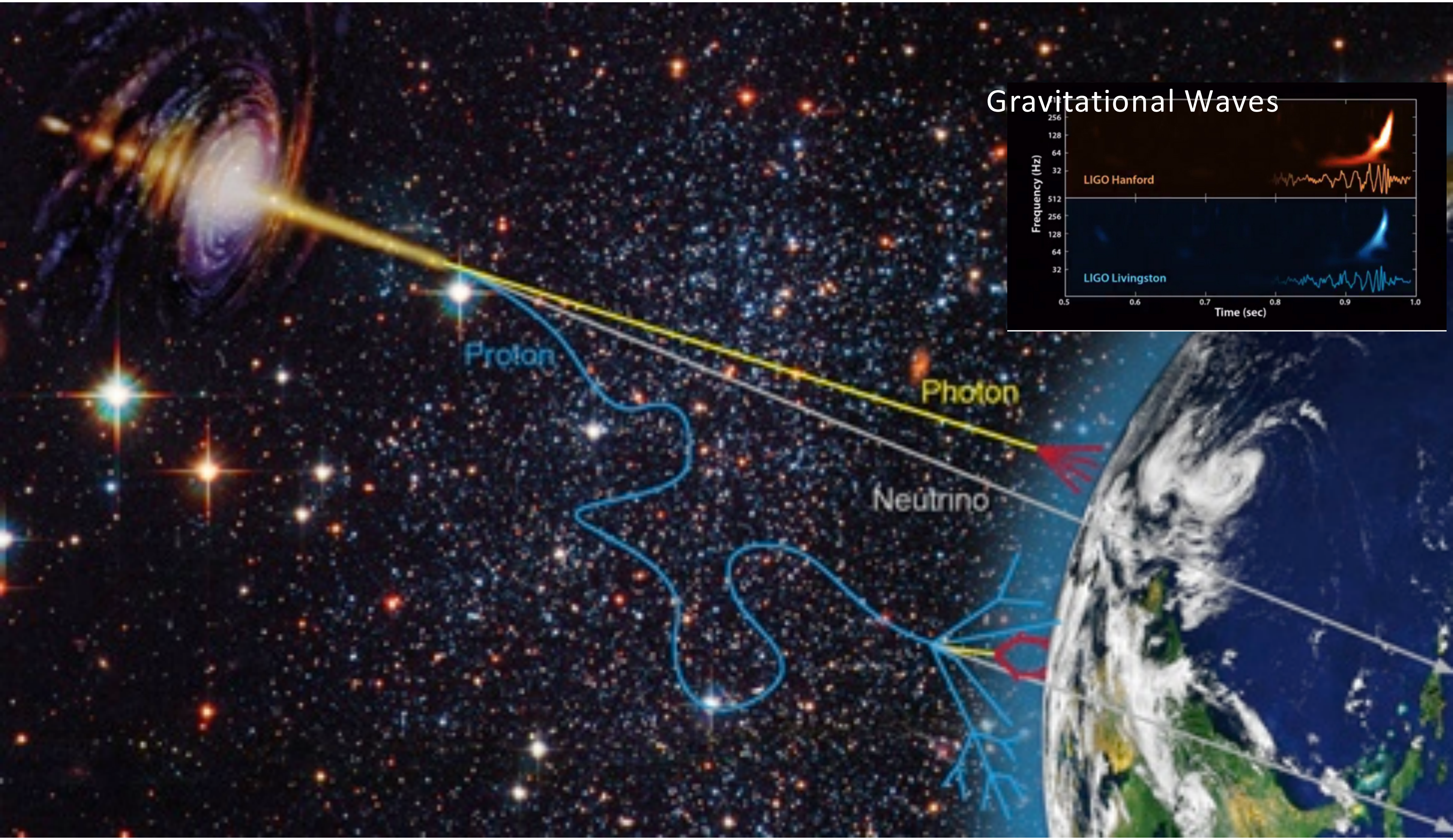
Particle Physics

Dark Matter annihilation products possibly visible

Potential new physics signatures in rates/flavor ratios

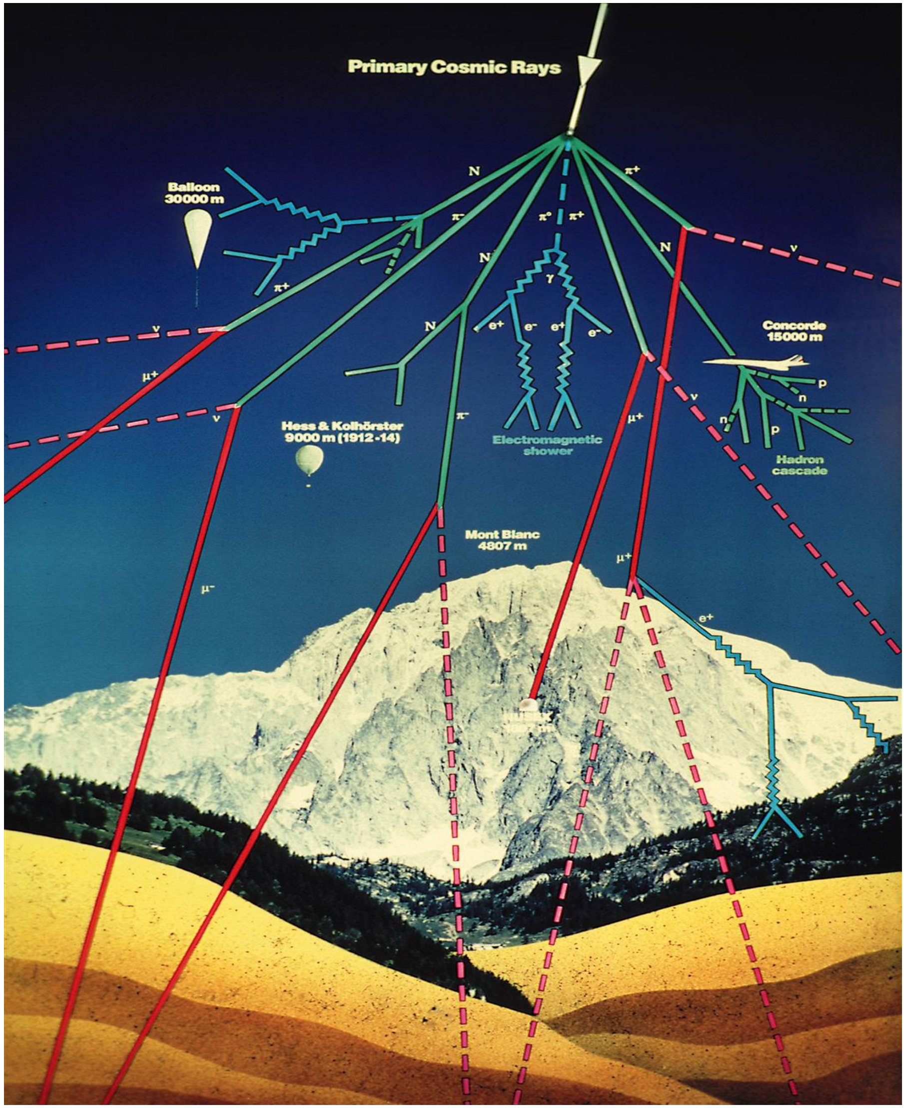
Atmosphere acts as ‘beam dump‘ for cosmic rays
=> neutrinos for oscillation studies

Different Messengers

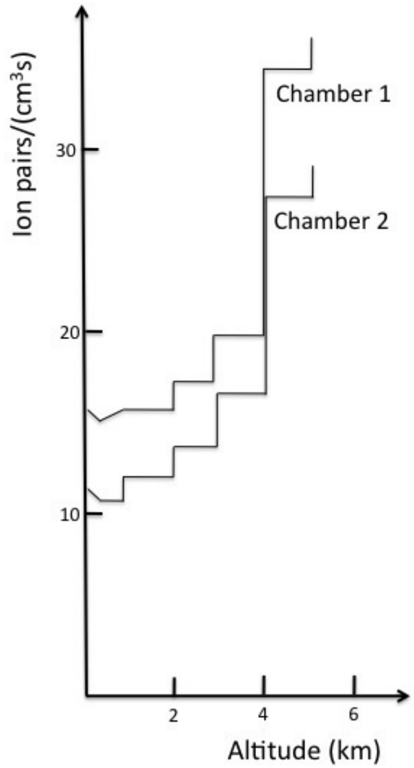


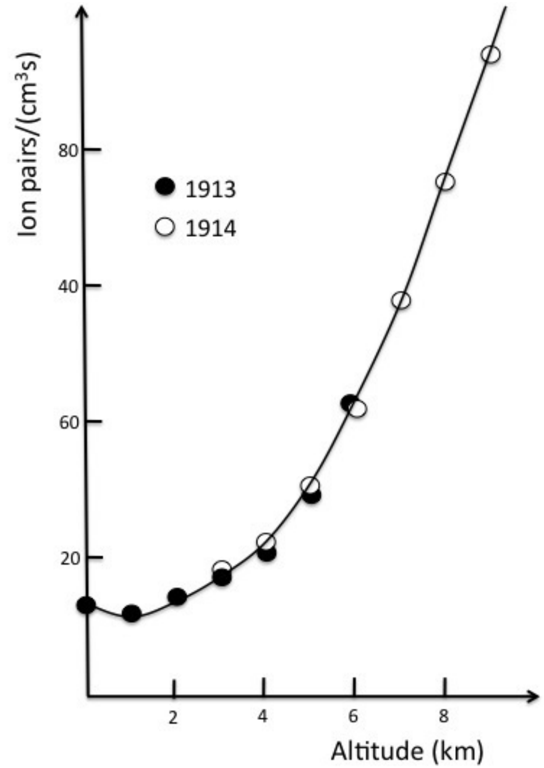
Neutrinos from galactic and extragalactic sources (supernovae, gamma ray bursts, active galactic nuclei…)

Neutrino beam 'for free': Showers from cosmic ray interactions in the atmosphere



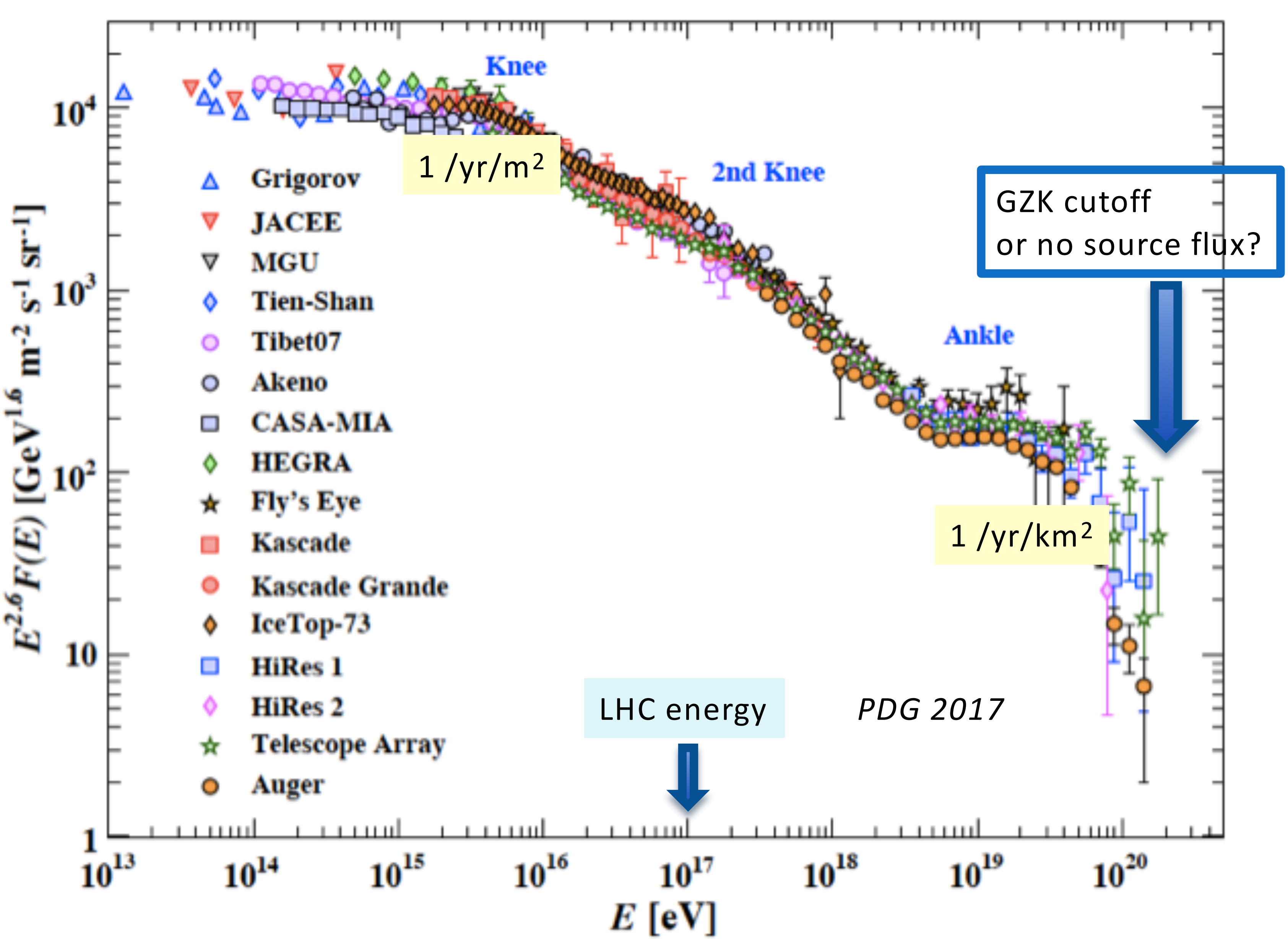
1936 Nobelprize for Victor Francis Hess (1883-1964)





The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."

High energy cosmic ray spectrum



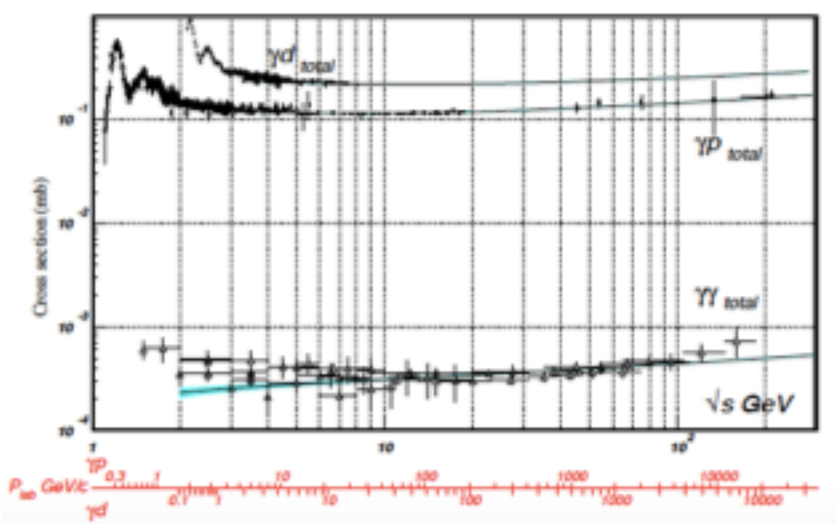
Note: Several measurements before LHC => far extrapolations used in the data evaluation for hadronic interaction

Greisen Zatsepin Kuzmin (GZK) cutoff:

Energy limit in cosmic rays from protons interacting with cosmic background photons
Average energy for CMB photon **~6.4 10^{-4} eV**

$$p + \gamma \rightarrow \Delta^{+} \begin{cases} \rightarrow p + \pi^{0} \\ \rightarrow n + \pi^{+} \end{cases}$$

pγ Cross section



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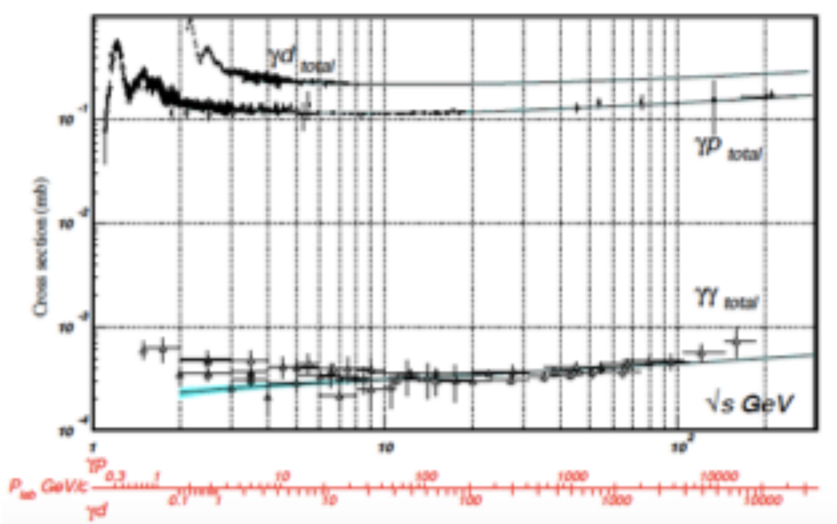
$$\pi^{0} \rightarrow \gamma\gamma$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\hookrightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$

pγ Cross section



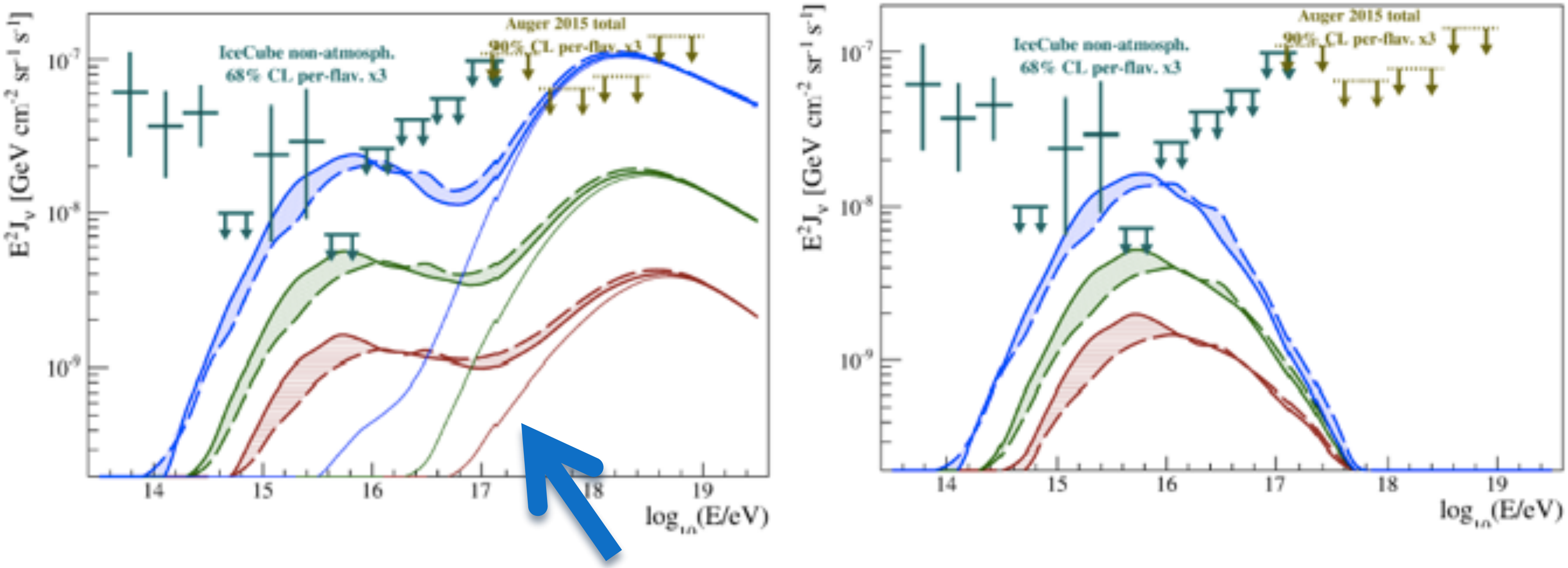
$$n \rightarrow e^{-} + p + \bar{\nu}_{e}$$

Neutron lifetime: 881 s

Energy 10^{18} eV -> long flight path

⇒ Expectation of very high energetic neutrinos (cosmogenic neutrinos)

Cosmogenic neutrino spectra (left proton assumption, right nuclei)
Colors show different source evolution models (bottom: no evolution over time)

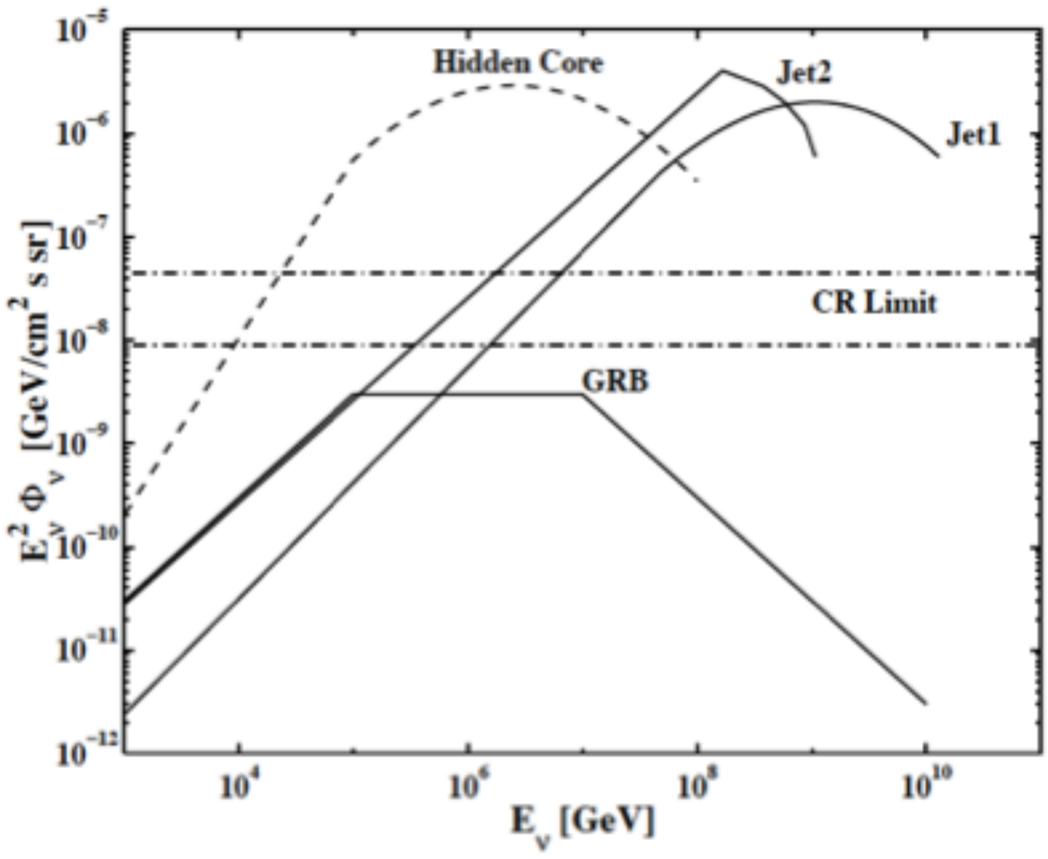


Only scattering on CMB (not Extragalactic Background Light)

Aloisio, JCAP 10 (2015) 006

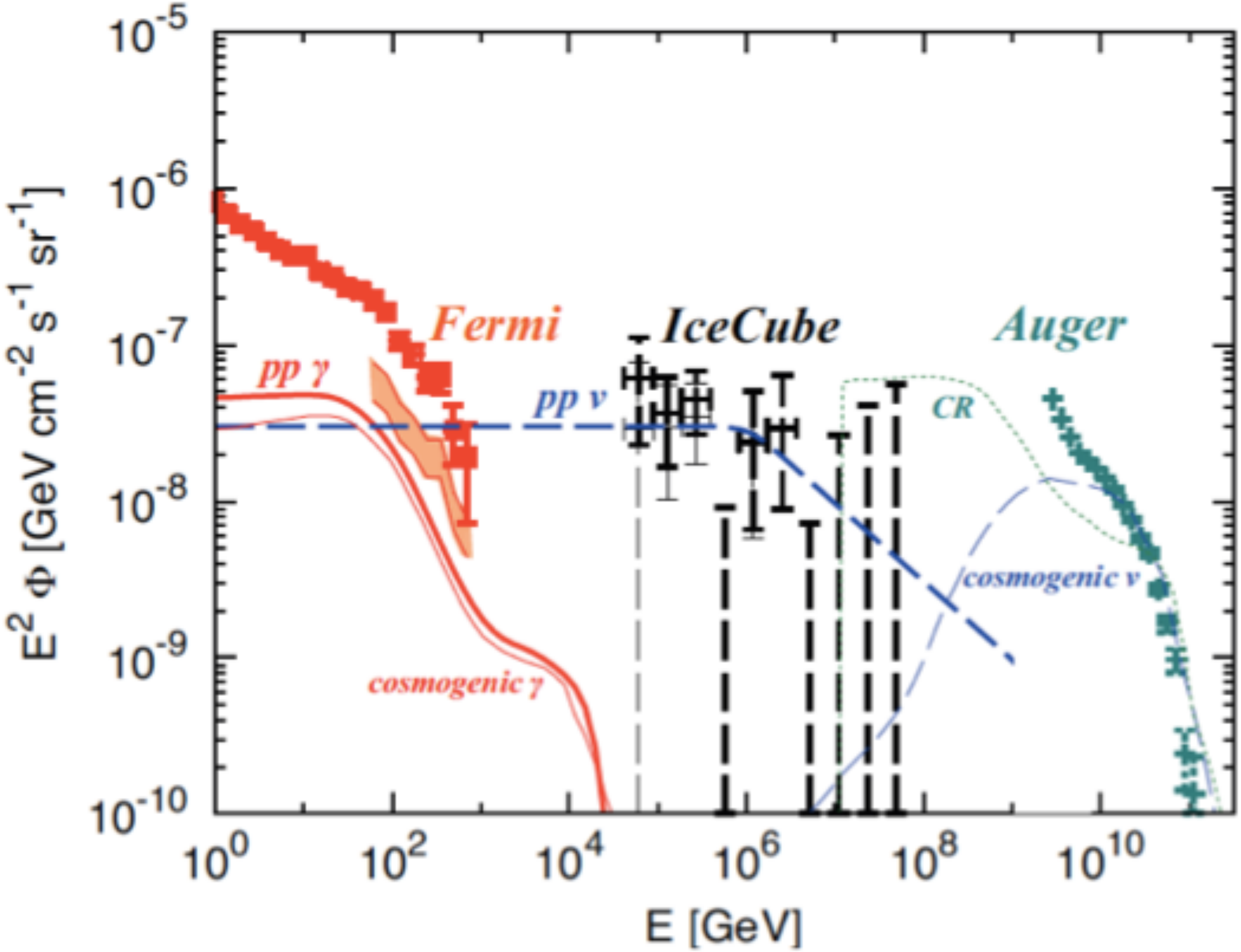
Waxman Bahcall Bound

Use measured Cosmic Ray spectrum
=> Constraint on neutrino flux (optically thin sources)



Waxman & Bahcall 1998

Photons – Neutrinos - Protons



Murase & Waxman 2016

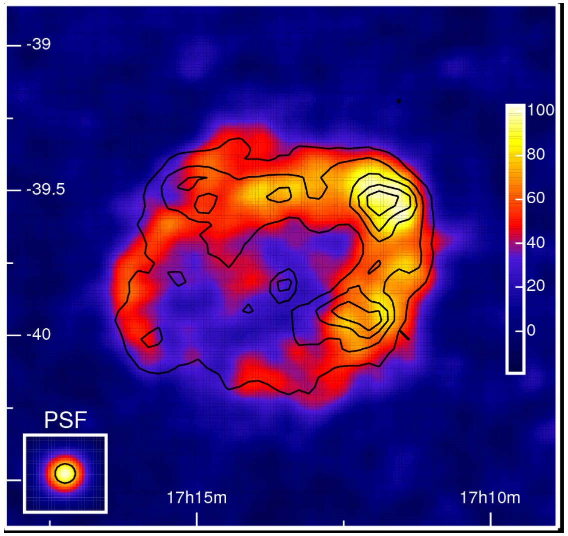
Cosmic particle accelerators

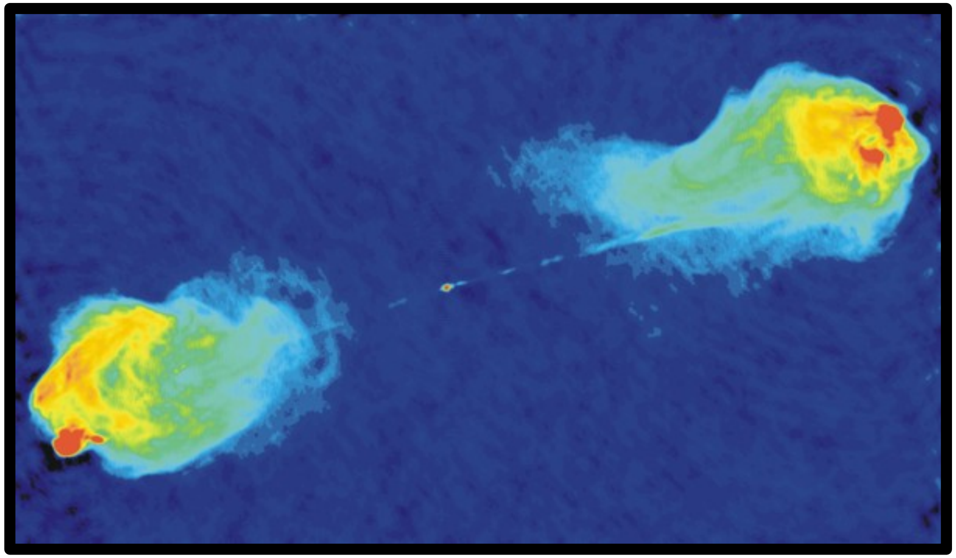
Galactic

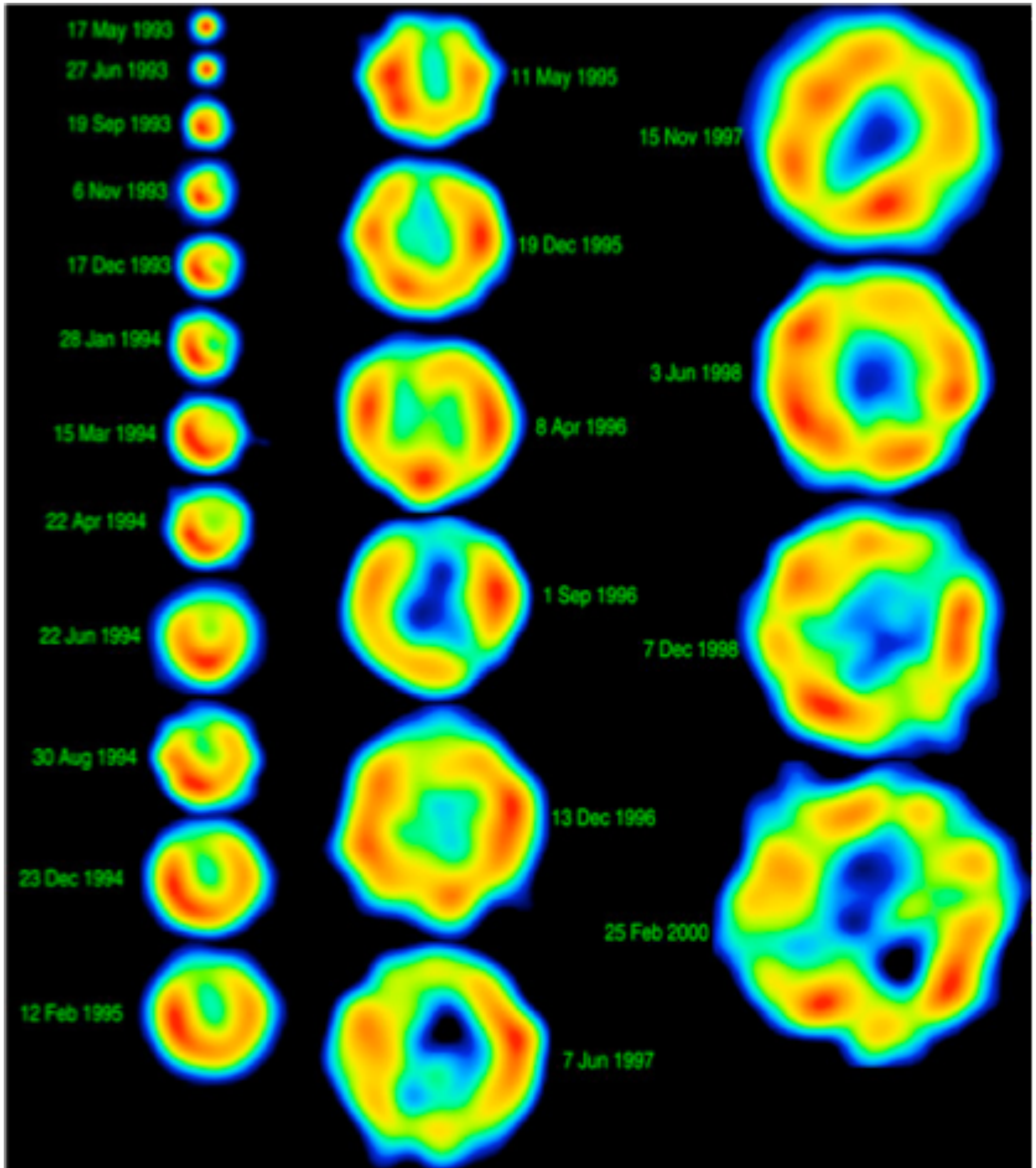
e.g. Supernova remnants

Extra-galactic

e.g. Active Galactic Nuclei







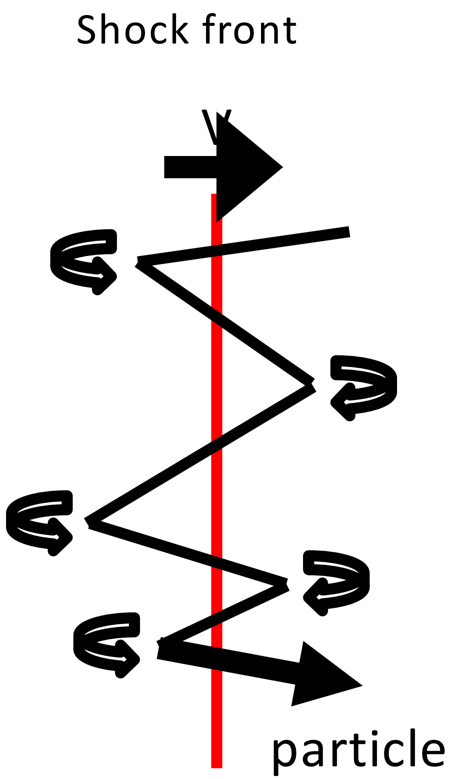
SN 1993J radio observations of 7 years

~10 Mly away

Starting with ~20000km/s expansion

Image courtesy of NRAO/AUI and N. Bartel, M. Bietenholz, M. Rupen, et al

Fermi Acceleration



Acceleration: $\Delta E = \alpha E$
Probability: $P = \beta$

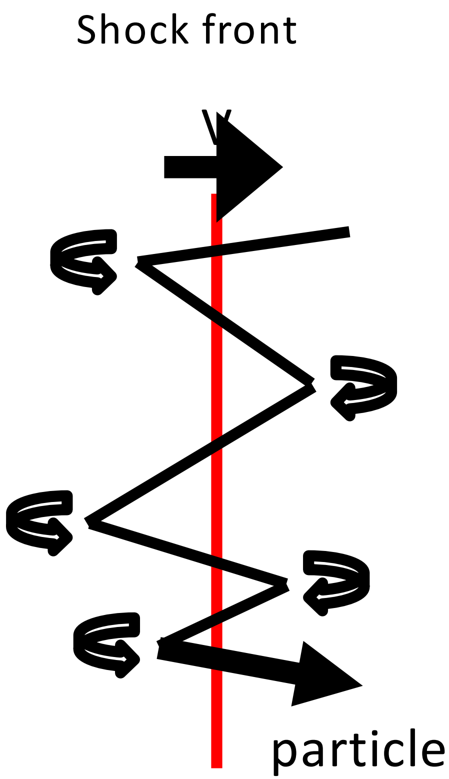
k Iterations:

$$E = E_0 (1+\alpha)^k$$

$$N = N_0 (\beta)^k$$

α,β determined by shock dynamics, relativity
=> Power Law E^{-2} expected

Fermi Acceleration



Acceleration: $\Delta E = \alpha E$

Probability: $P = \beta$

k Iterations:

$E = E_0 (1+\alpha)^k$

$N = N_0 (\beta)^k$

$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\frac{\ln(\beta)}{\ln(1+\alpha)}} \qquad \frac{dN}{dE} \propto E^{\frac{\ln(\beta)}{\ln(1+\alpha)}-1}$$

α, β determined by shock dynamics, relativity

=> Power Law E^{-2} expected

Extragalactic sources

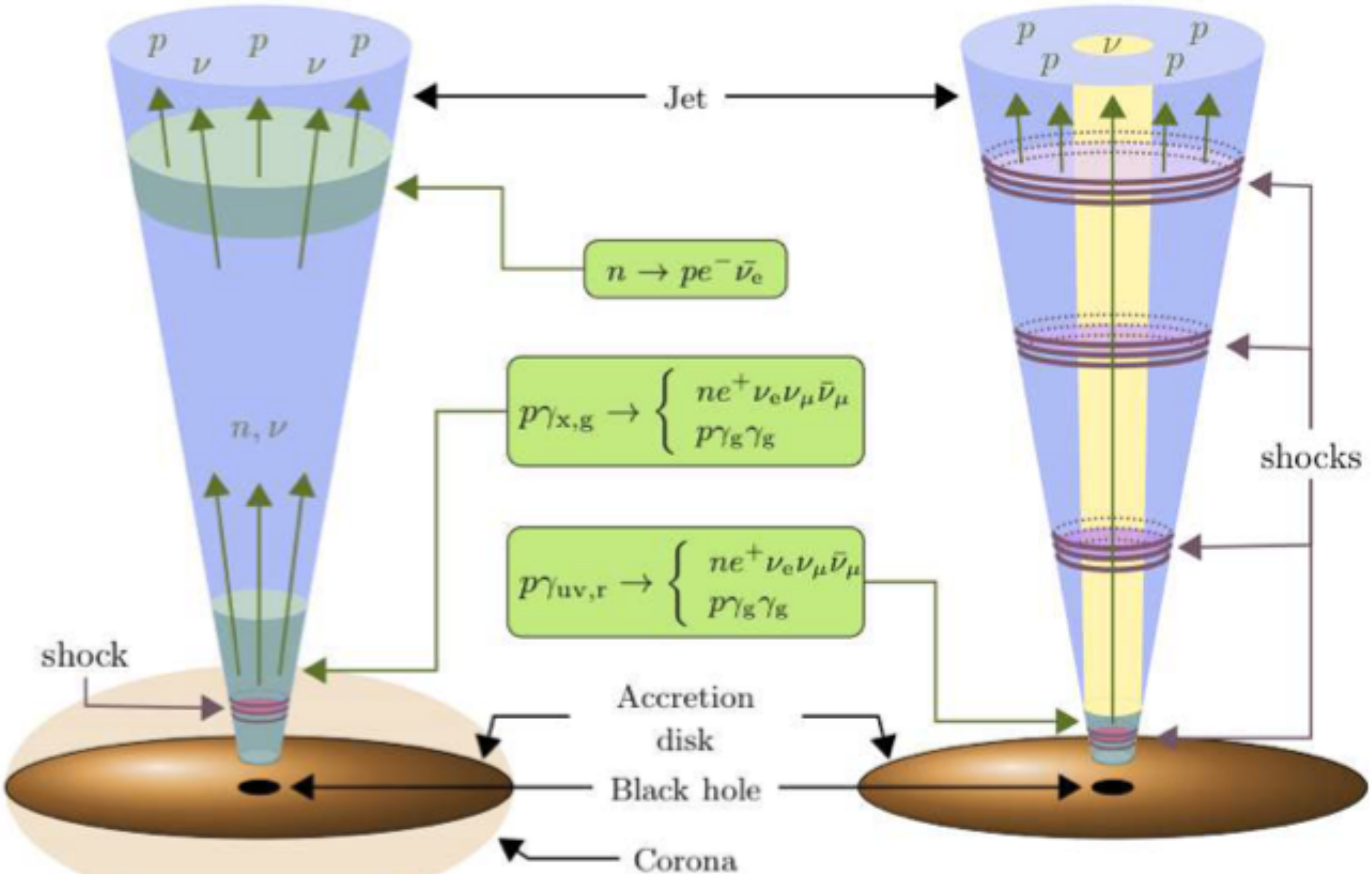
Blazars
(subclass of Active Galactic Nuclei - **AGN**)

Radio-loud active galactic nuclei with relativistic jets pointing towards Earth
-> **Flat Spectrum Radio Quasars** (**FSRQ**, strong/broad optical emission lines)
-> BL Lacertae (weak optical emission lines)

Also classified according to synchrotron peak position (associated to the energy of the accelerated electrons)
-> high synchrotron peaked (**HSP**)
-> low and intermediate synchrotron peaked (**LSP**)

HSP BL Lacs (rare) very powerful γ emitters

Different blazar models



10^6-10^9 solar masses
massive black hole accreting

Jacobsen et al, MNRAS 451, 4 *2015*

Intense γ ray flashes first detected 1967 (US military satellites)
-> published only 1973

Short Gamma Ray Bursts

Likely NS-NS mergers, less energetic

Long Gamma Ray Bursts

Core collapse of massive star to black hole

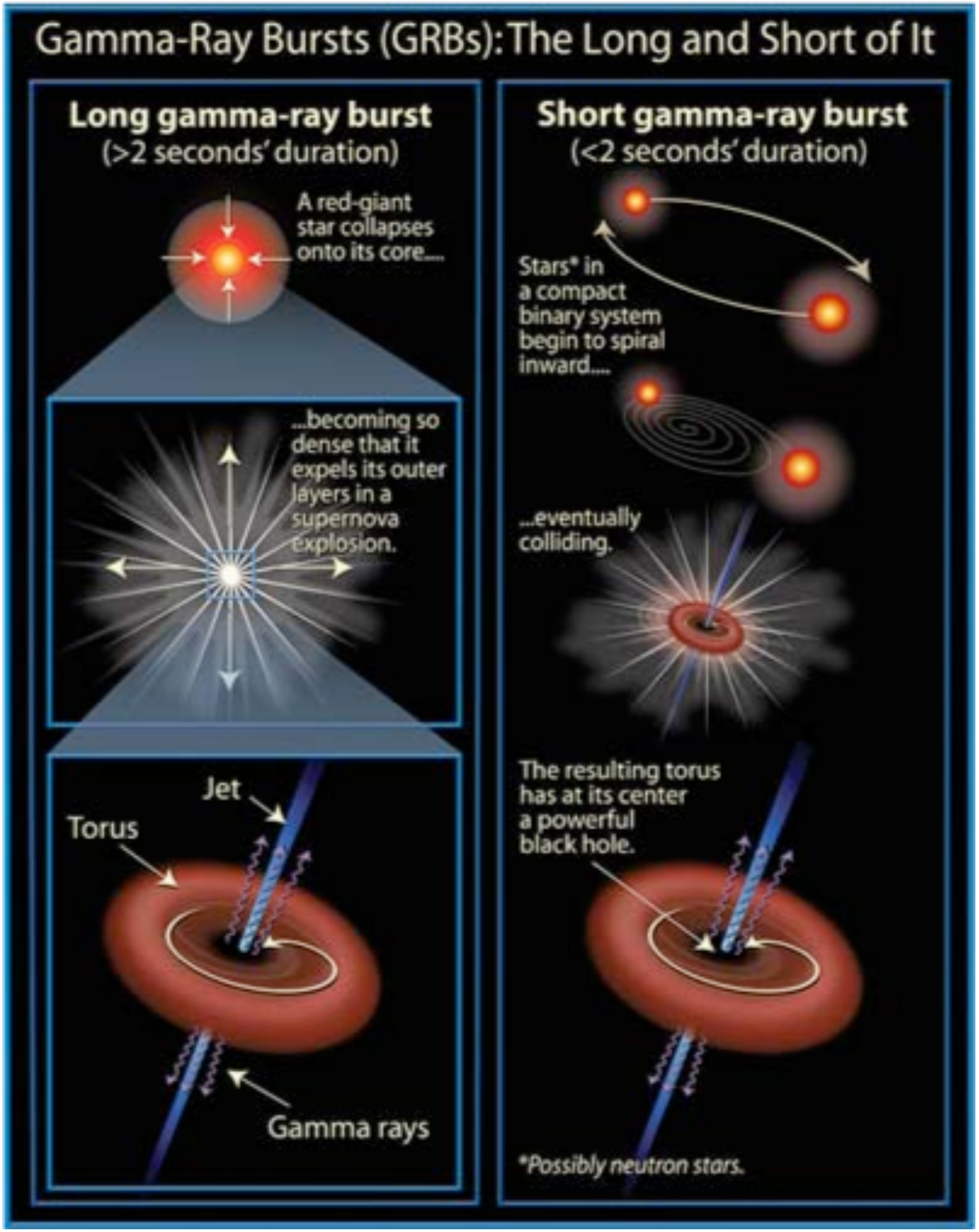
Seen up to z~8

Luminosities 10^{53}-$3*10^{54}$ erg/s

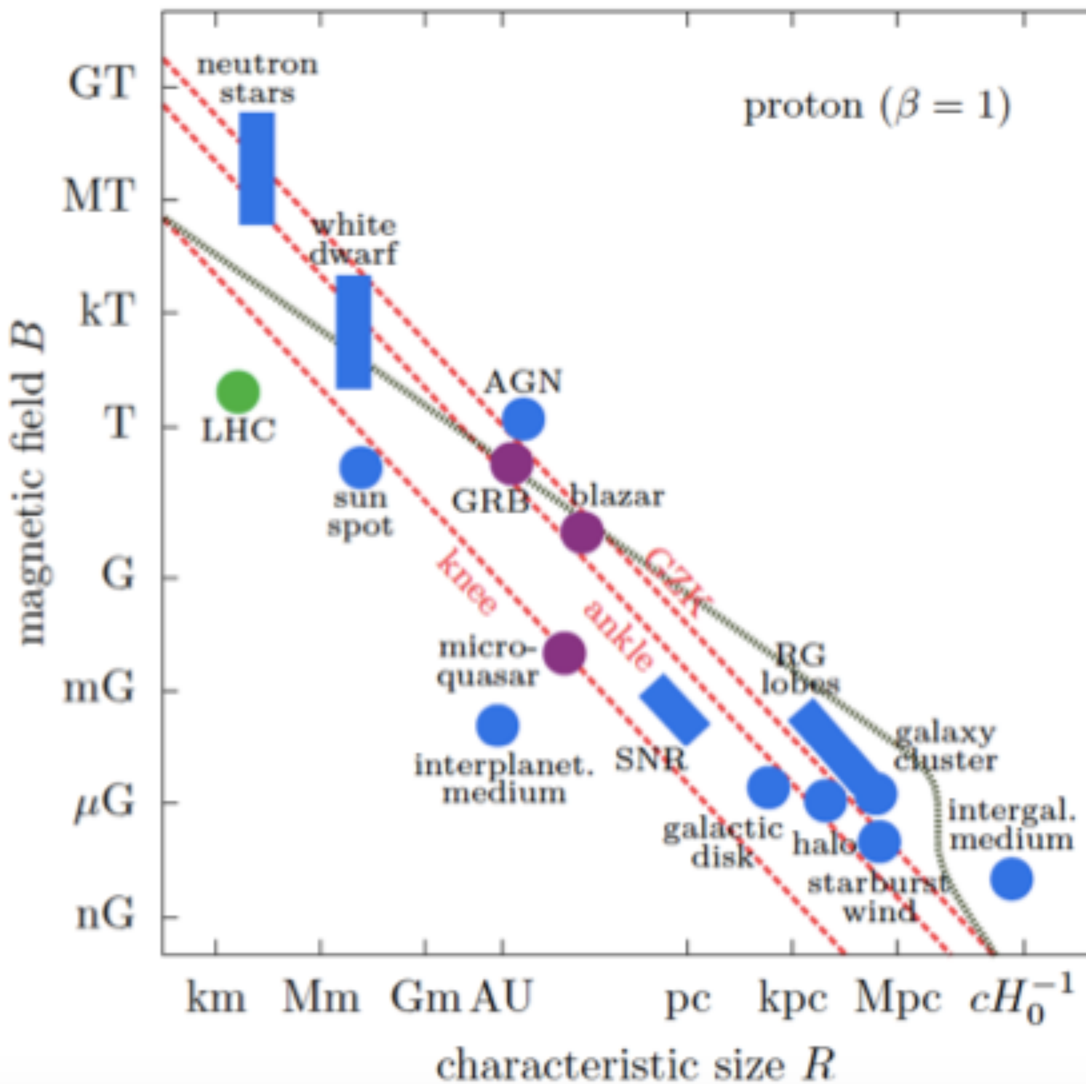
10^{-7}/yr/galaxy

Highly relativistic outflows

Γ factors >=100



http://www.daviddarling.info/encyclopedia/G/gamma-ray_burst.html



Confinement constraints for cosmic particle accelerators:

Magnetic field as function of size of sources

$$E_{\max} \cong 0.9 \beta Z \frac{B}{\mu G} \frac{R}{kpc} EeV$$

R: Accelerator size

B: Magnetic field strength

Red line: GZK energies

Grey line: synchrotron losses in the sources

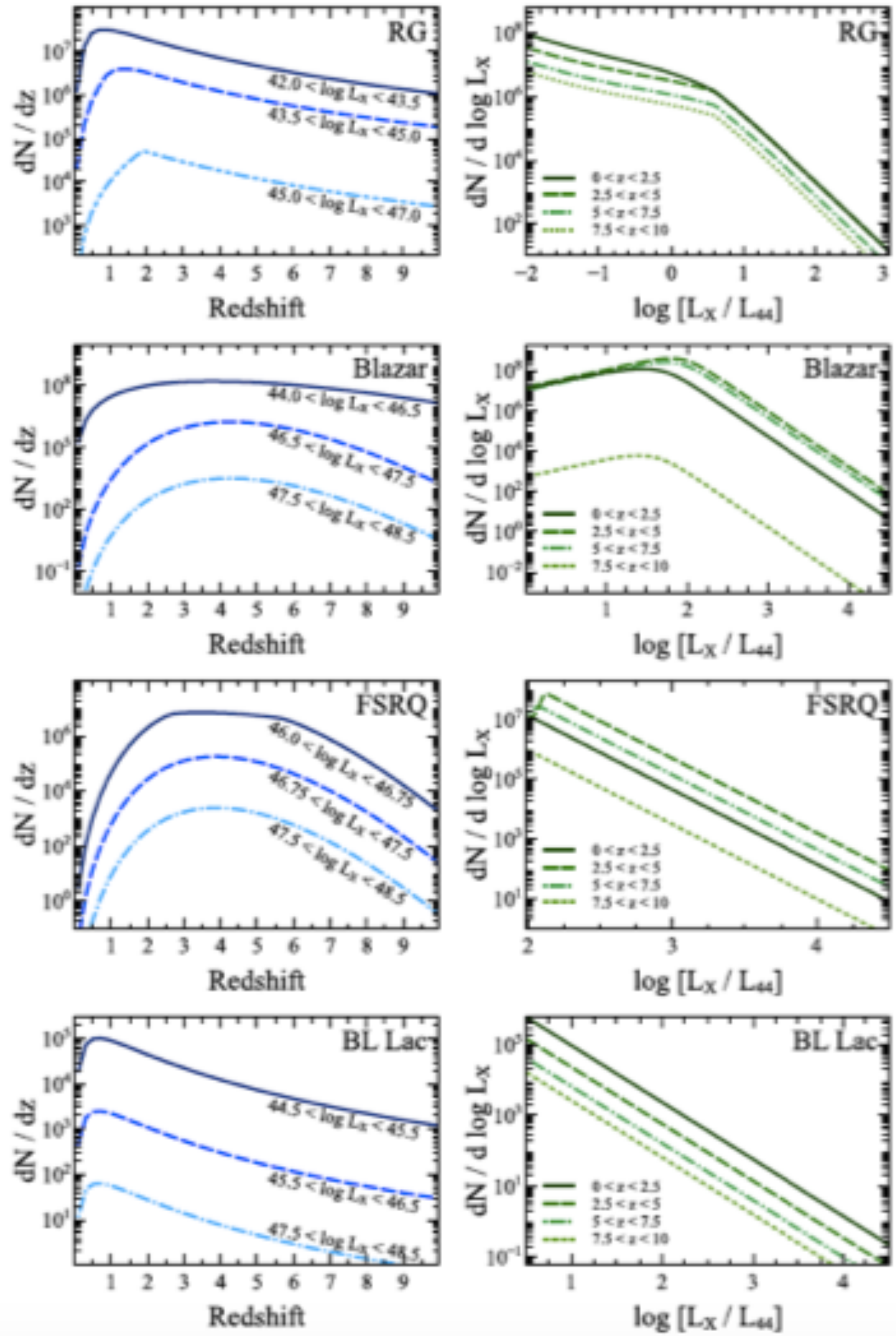
Aartsen et al, arXiv 1701.03731

Active Galactic Nuclei:

Source and luminosity evolution with redshift

-> Different redshifts z contribute differently to neutrino yield

Jacobsen et al, MNRAS 451, 4 *2015*



Neutrino connection with γ rays

Highly energetic particle acceleration needed to explain observed cosmic ray energy spectrum, expect then:

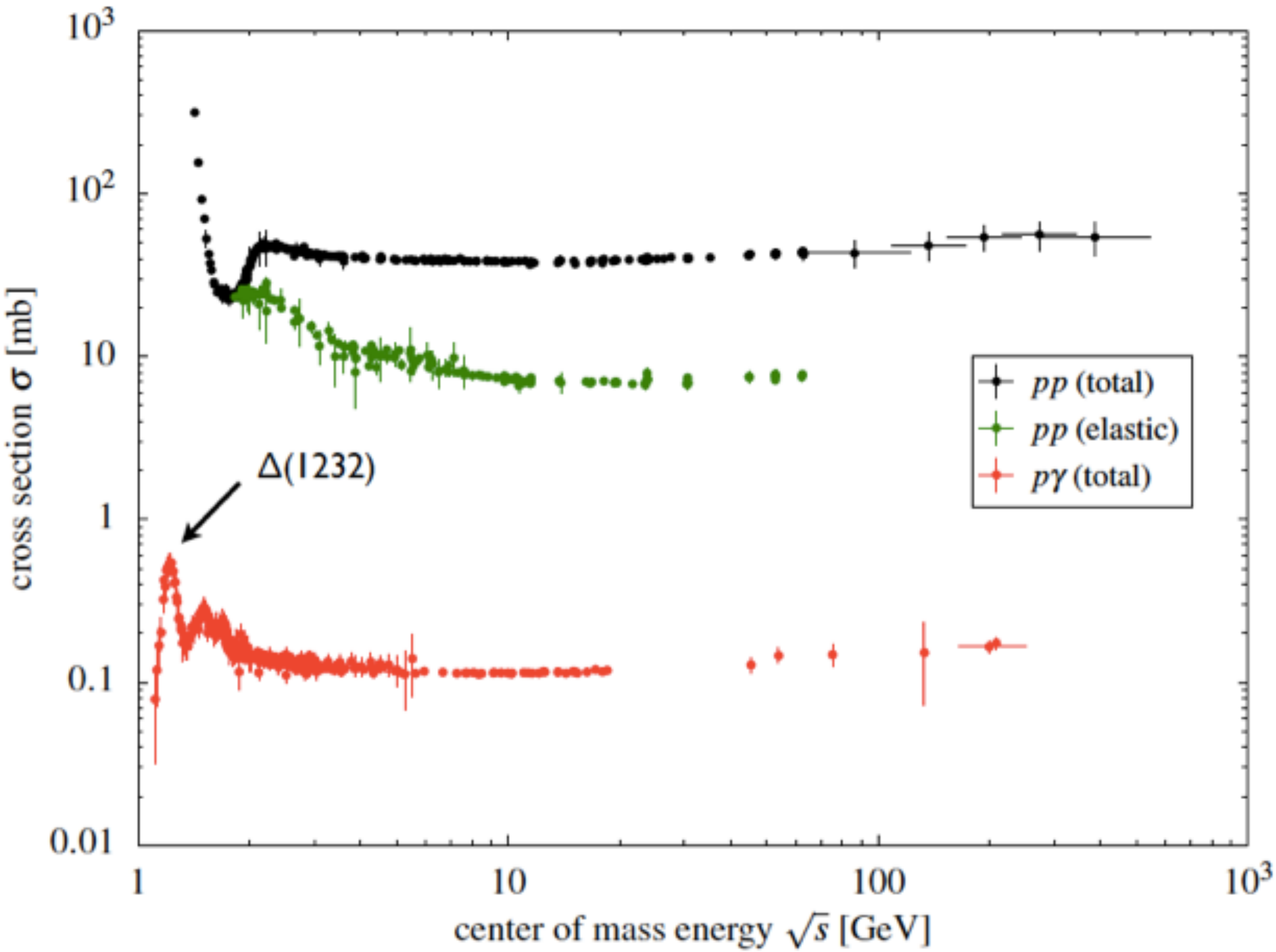
- γ from inverse Compton scattering
- γ from synchrotron radiation of electrons, Bremsstrahlung
- γ from pion decay

Neutrino fluxes can be derived from γ emission by assuming pion decay as origin of γ

$\Rightarrow$ Neutrino detection unambiguous proof of hadron acceleration in source

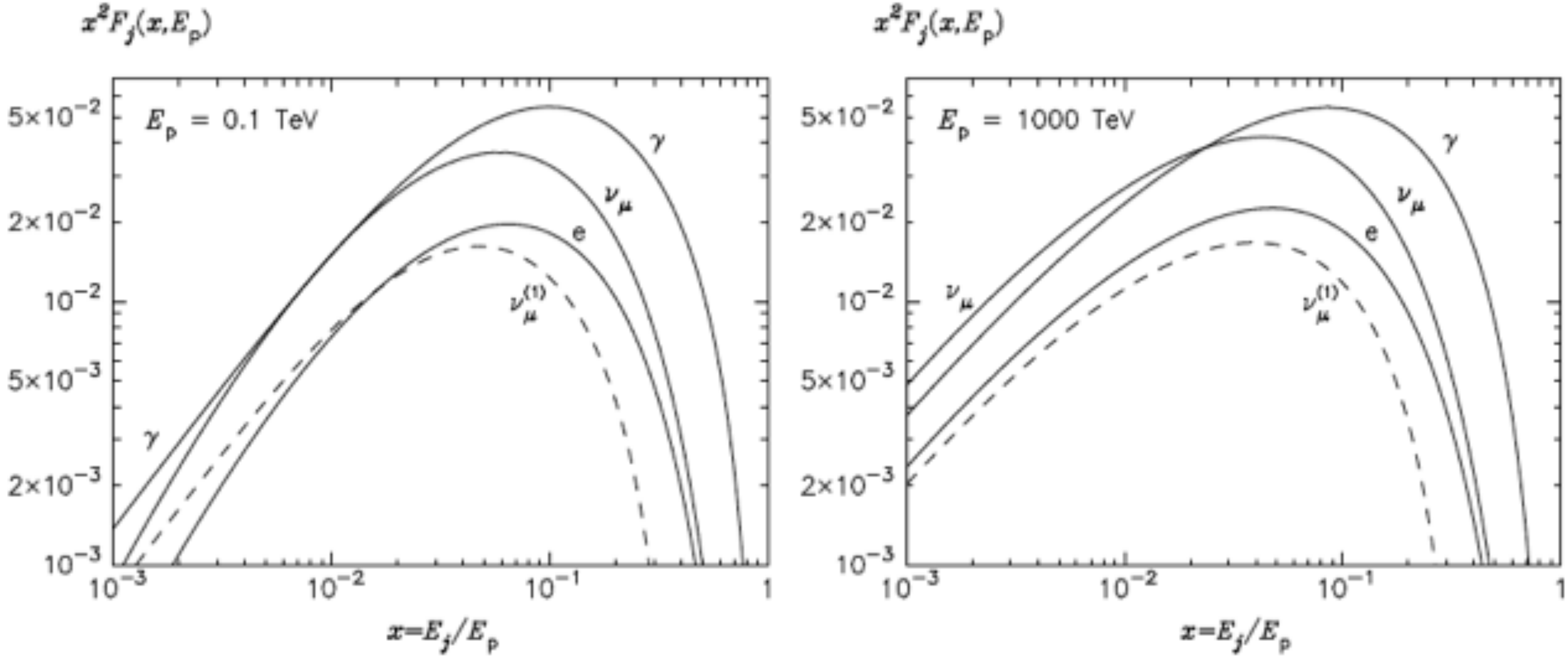
$$p + p/\gamma \dashrightarrow X + \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \end{cases}$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



Data PDG (plot: Ahlers)

Energy distribution of photons/neutrinos from pp interactions



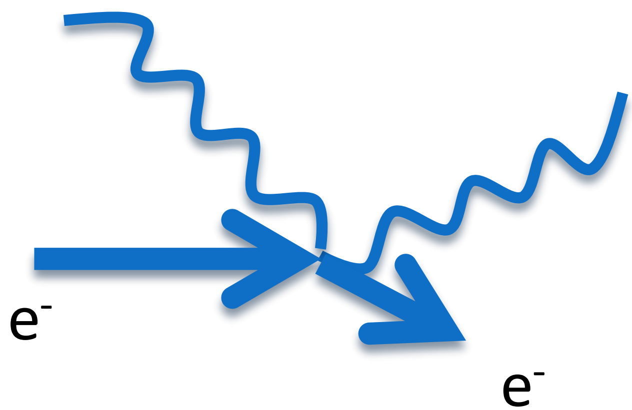
E_{proton}	:	E_γ	:	E_ν
1	:	0.1	:	0.05

Kelner, F. A. Aharonian, V.V. Bugayov, 2006

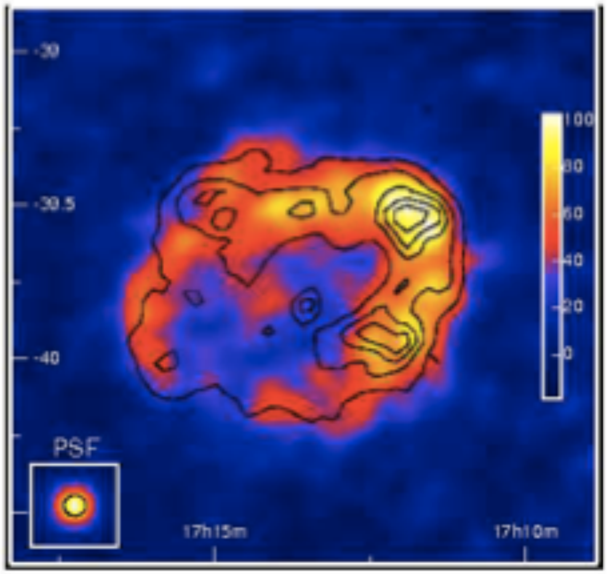
Inverse Compton Scattering:

Relativistic electrons in astrophysical sources (Γ ~ 100-1000)
Interact in source radiation fields

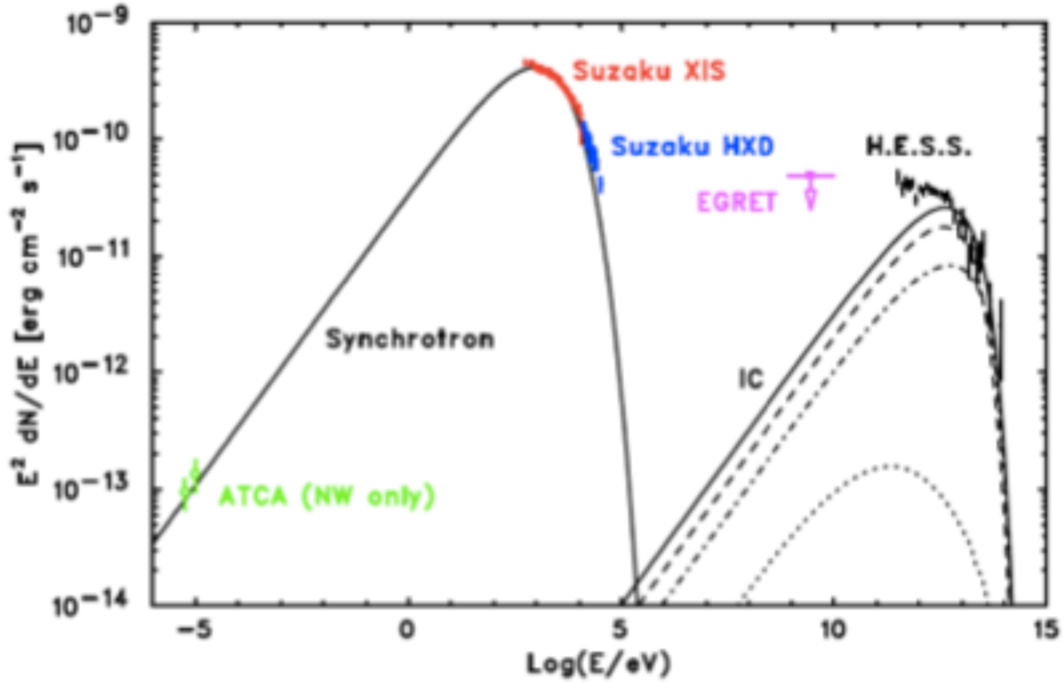
Waveband	**Scattered Waveband**
Radio	UV
Far-infrared	X rays (100eV – 100keV)
Optical	γ rays (GeV-TeV)



Supernova remnant RX J1713.7-3946



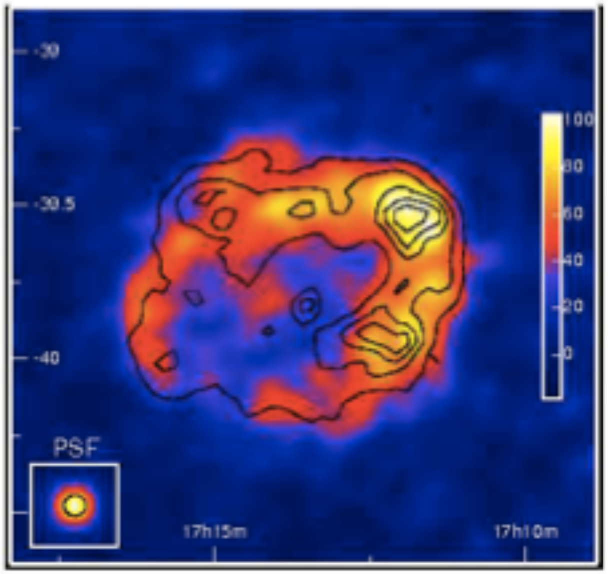
Color: TeV (HESS), contour: keV (ASCA)



Gabici, 2008

Leptonic scenario: All spectra from synchrotron, bremsstrahlung, IC
Hadronic scenario: γ rays from π^0 decay (>~70 MeV, sharp peak)

Supernova remnant RX J1713.7-3946



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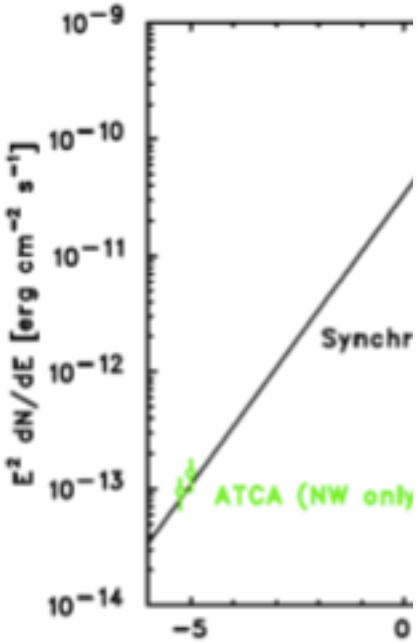
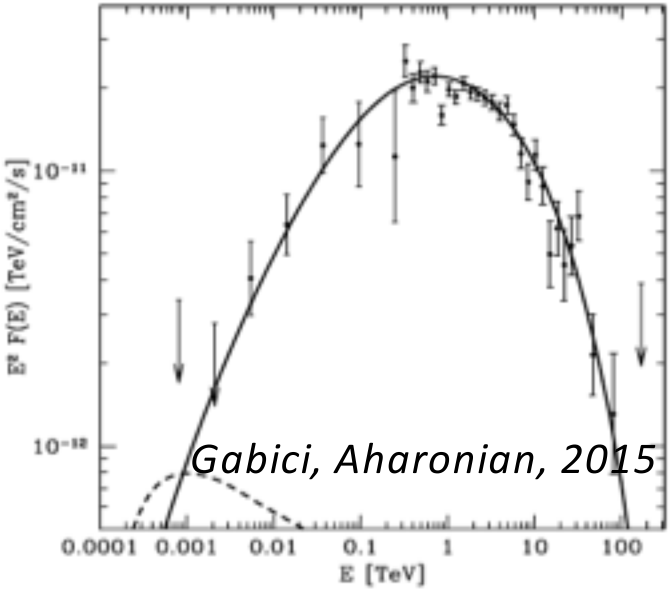
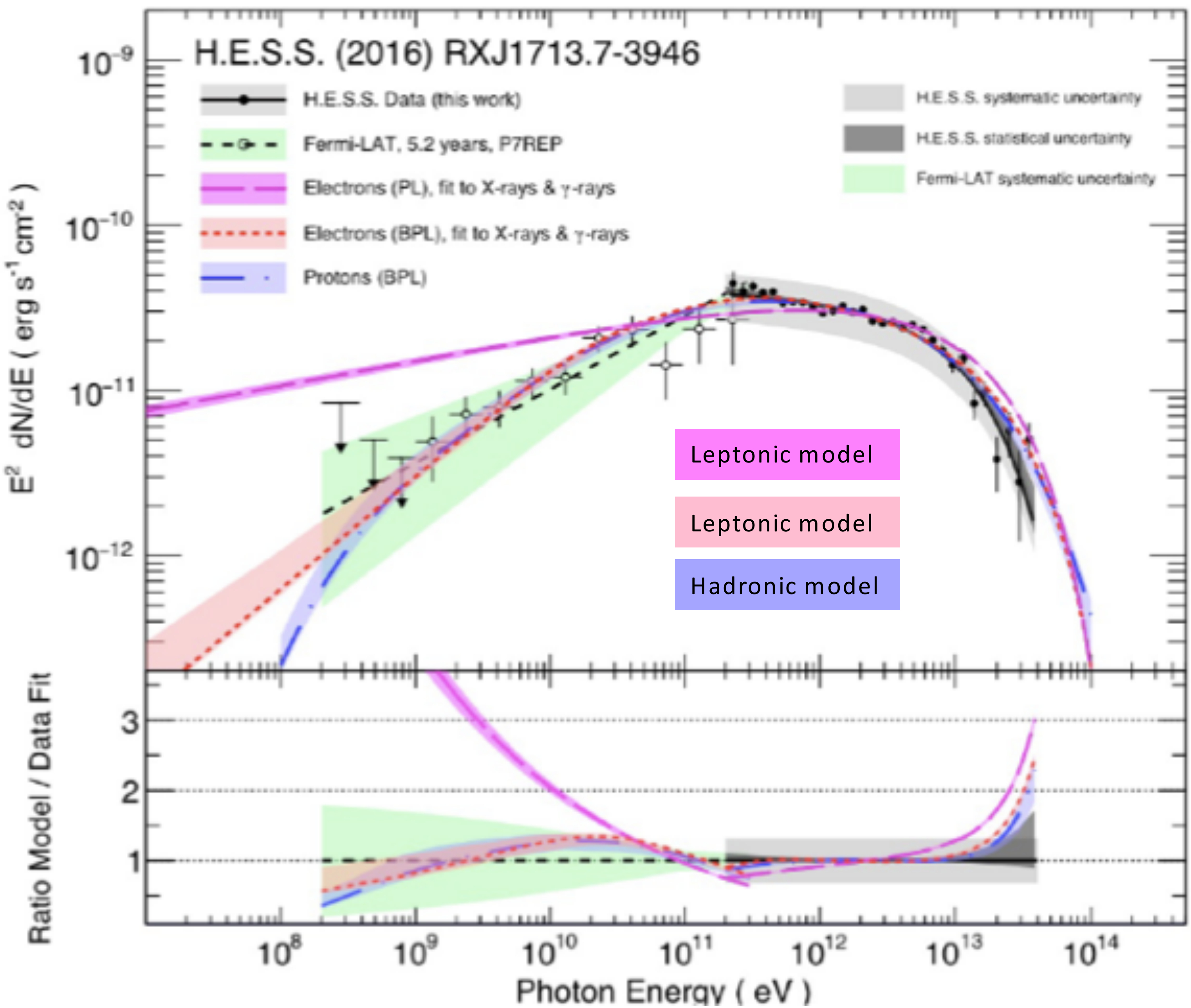




Gabici, Aharonian, 2015

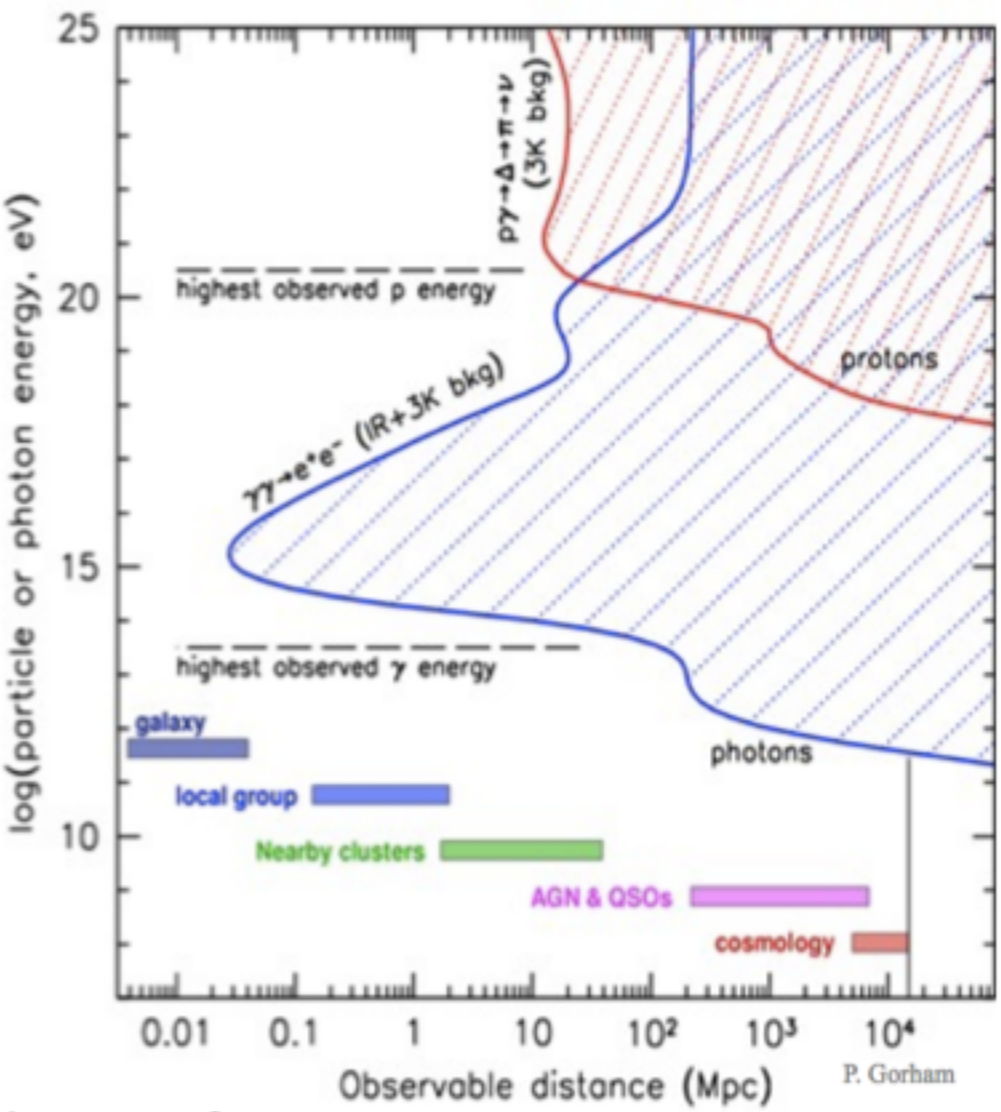
Leptonic scenario: All spectra from synchrotron, bremsstrahlung, IC
Hadronic scenario: γ rays from π^0 decay (>68 MeV, sharp peak)


H.E.S.S. (2016) RXJ1713.7-3946
H.E.S.S. Data (this work)
Fermi-LAT, 5.2 years, P7REP
Electrons (PL), fit to X-rays & γ-rays
Electrons (BPL), fit to X-rays & γ-rays
Protons (BPL)
H.E.S.S. systematic uncertainty
H.E.S.S. statistical uncertainty
Fermi-LAT systematic uncertainty
Leptonic model
Leptonic model
Hadronic model
E² dN/dE (erg s⁻¹ cm⁻²)
Ratio Model / Data Fit
Photon Energy (eV)

Path lengths for particles & photons

$\gamma + \gamma_{\text{background}} \to e^+e^-$
$p + \gamma \to \Delta^+$

Large part of the Universe can not be observed with high energetic protons/photons



Neutrino Oscillations

Flavor eigenstates are not equal to mass eigenstates

Flavor eigenstate		Mass eigenstate
νe		$\nu 1$
$\nu \mu$	→	$\nu 2$
$\nu \tau$		$\nu 3$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{CP}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{CP}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{CP}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{CP}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{CP}} & c_{23} c_{13} \end{bmatrix}.$$

Neutrino Oscillations

- Neutrino is created in single flavor eigenstate
  (superposition of different mass eigenstates)

- Propagation of the different mass eigenstates depends on energy and **mass**

=> Leads to differences in the composition of the superposition

=> Leads to flavor changes, depending on
travel length/energy/**mass differences**

Flavor changes ONLY if neutrinos have mass

Oscillation pattern determined by mass differences (thus no mass measurement)

Flavor distribution at astrophysical source is different from detected flavors on Earth

Diffferent source scenarios

$$p+\gamma \rightarrow \Delta^{+} \begin{cases} \rightarrow p+\pi^{0} \\ \rightarrow n+\pi^{+} \end{cases}$$

$$\pi^{0} \rightarrow \gamma\gamma$$

$$\pi^{+} \rightarrow \mu^{+}+\nu_{\mu}$$

$$\hookrightarrow e^{+}+\bar{\nu}_{\mu}+\nu_{e}$$

$$n \rightarrow e^{-}+p+\bar{\nu}_{e}$$

Neutron lifetime: 881 s

$$p+p \rightarrow \pi^{\pm}+X$$

$$\hookrightarrow \mu^{\pm}+\nu_{\mu}(\bar{\nu}_{\mu})$$

$$\hookrightarrow e^{\pm}+\bar{\nu}_{\mu}(\nu_{\mu})+\nu_{e}(\bar{\nu}_{e})$$

Different source scenarios

$$\nu_e : \nu_\mu : \nu_\tau$$

'Standard '

-> charged pion decay, muon decay

1 : 2 : 0

Muon damped source

-> strong magnetic fields, muon decay suppressed
-> pion decay dominant

0 : 1 : 0

Neutron beam source

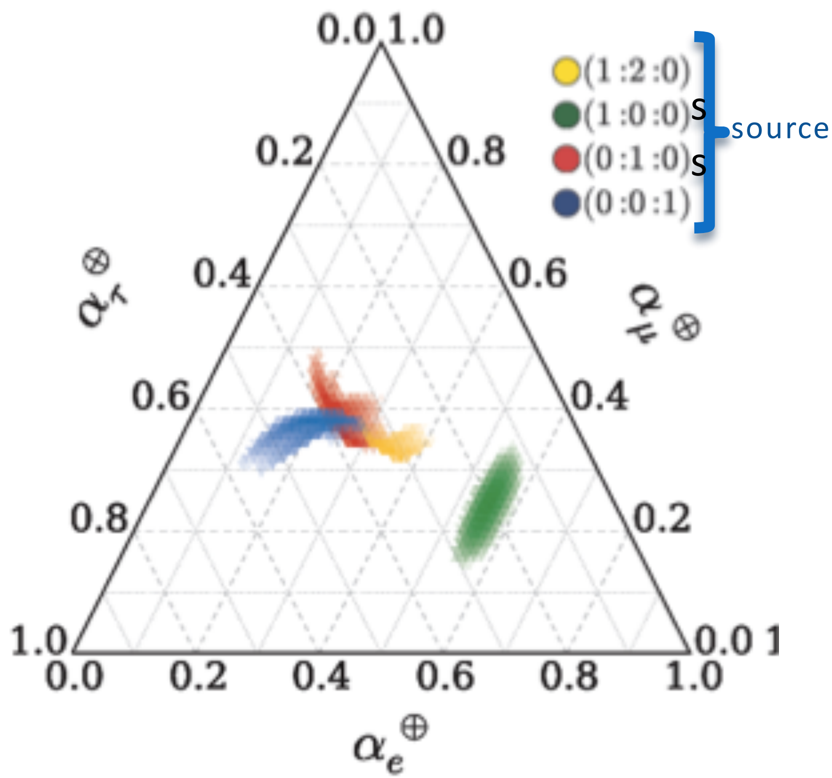
-> extremely strong magnetic field
-> cosmic rays heavy nuclei

1 : 0 : 0

Note: Also different neutrino/antineutrino ratios

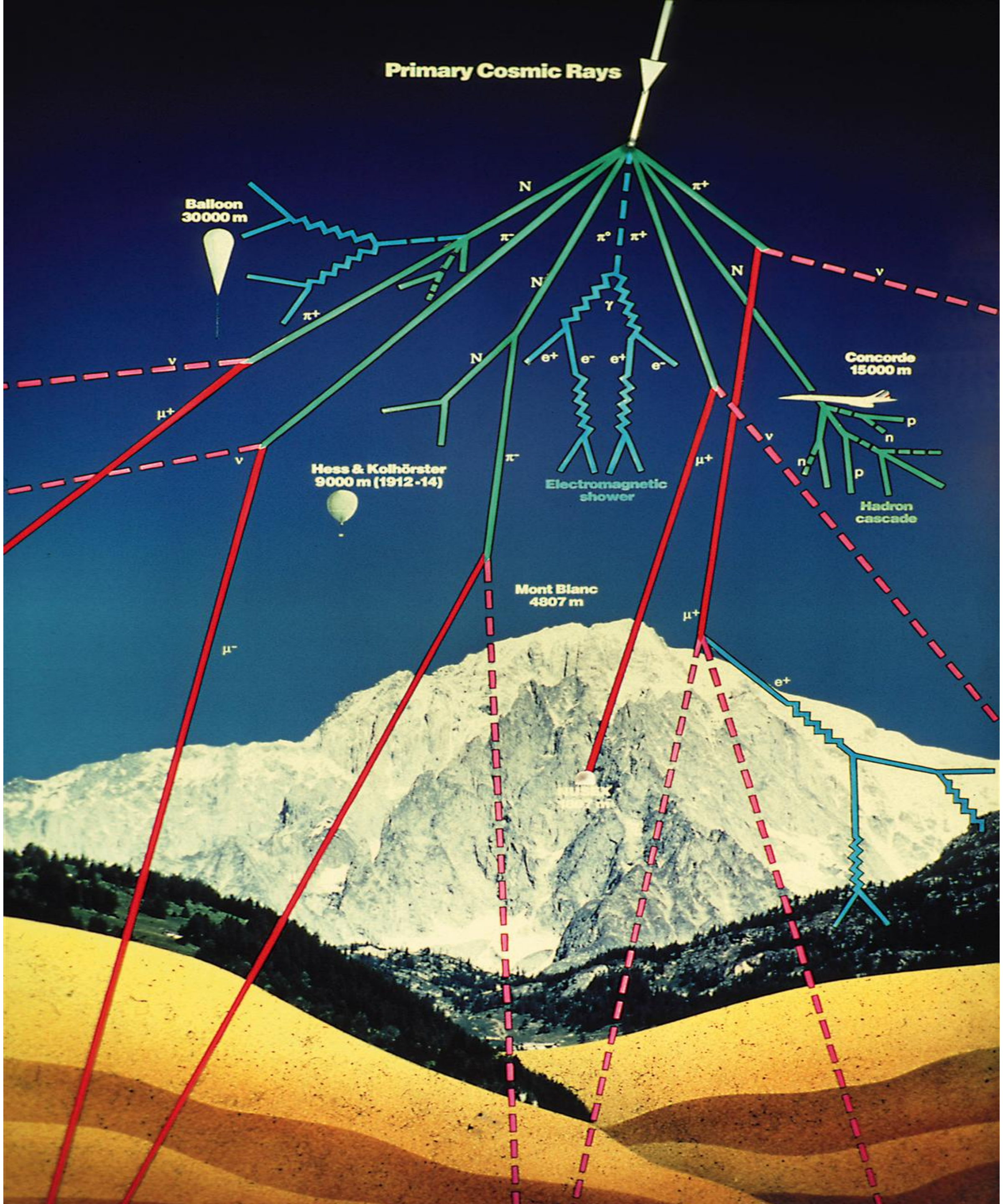
Neutrino flavor ratio at Earth

'Standard' phase space
-> Deviations indicate new physics



C. Arg?uelles, T. Katori and J. Salvado, Phys.Rev.Lett. 115 (2015) 161303

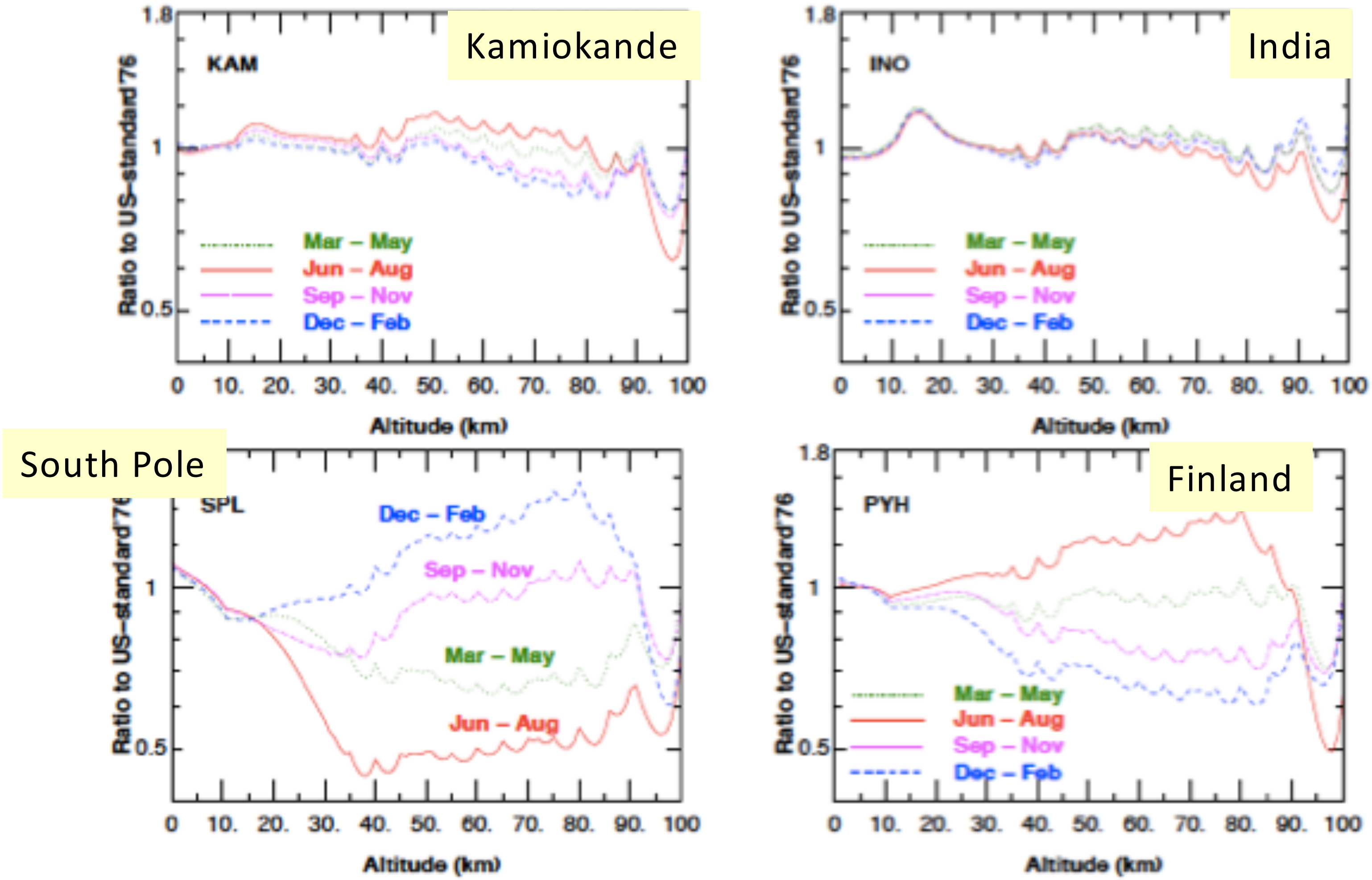
Atmospheric Neutrinos



Primary Cosmic Rays
Balloon 30000 m
Hess & Kolhörster 9000 m (1912 -14)
Mont Blanc 4807 m
Concorde 15000 m
Electromagnetic shower
Hadron cascade

‘Moving’ Target: The Atmosphere
Air density profile

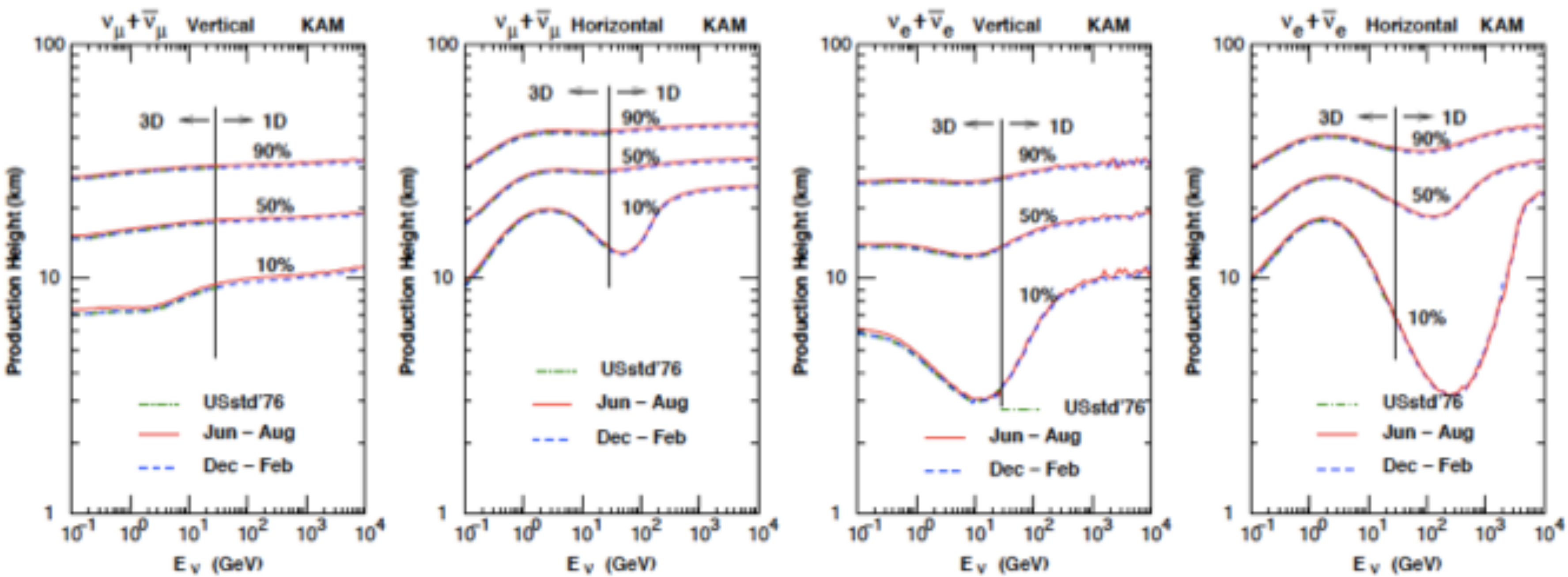
Air density profile compared to ‘reference’ constant model
Changing mostly at pole region



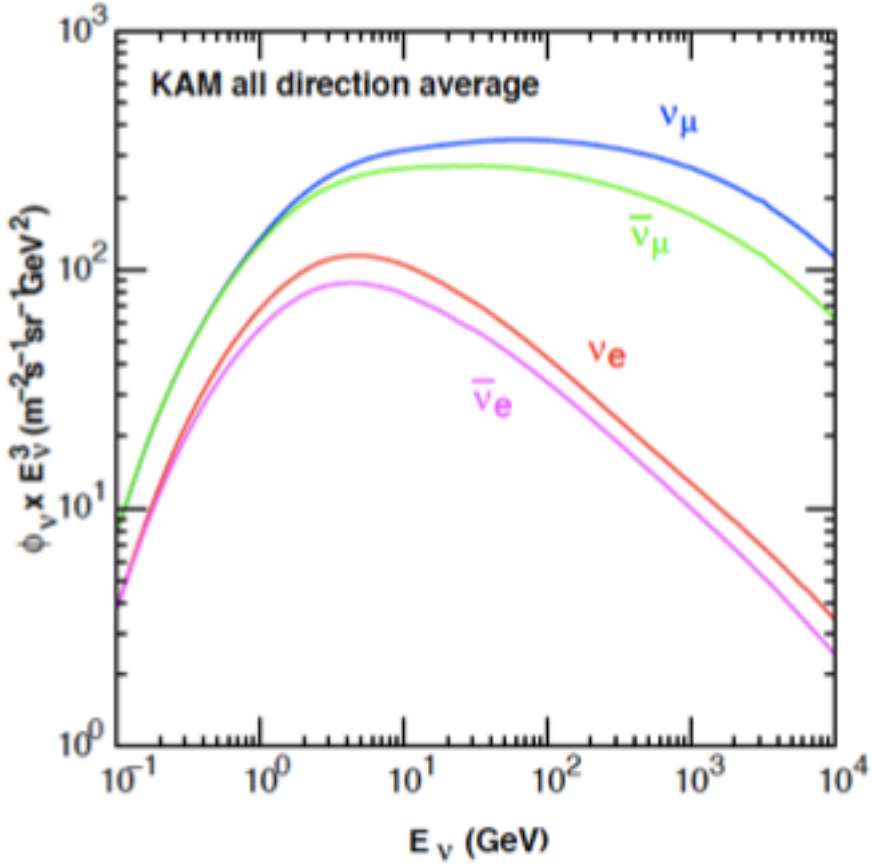
Honda et al, Phys. Rev. D83 (2011) 123001

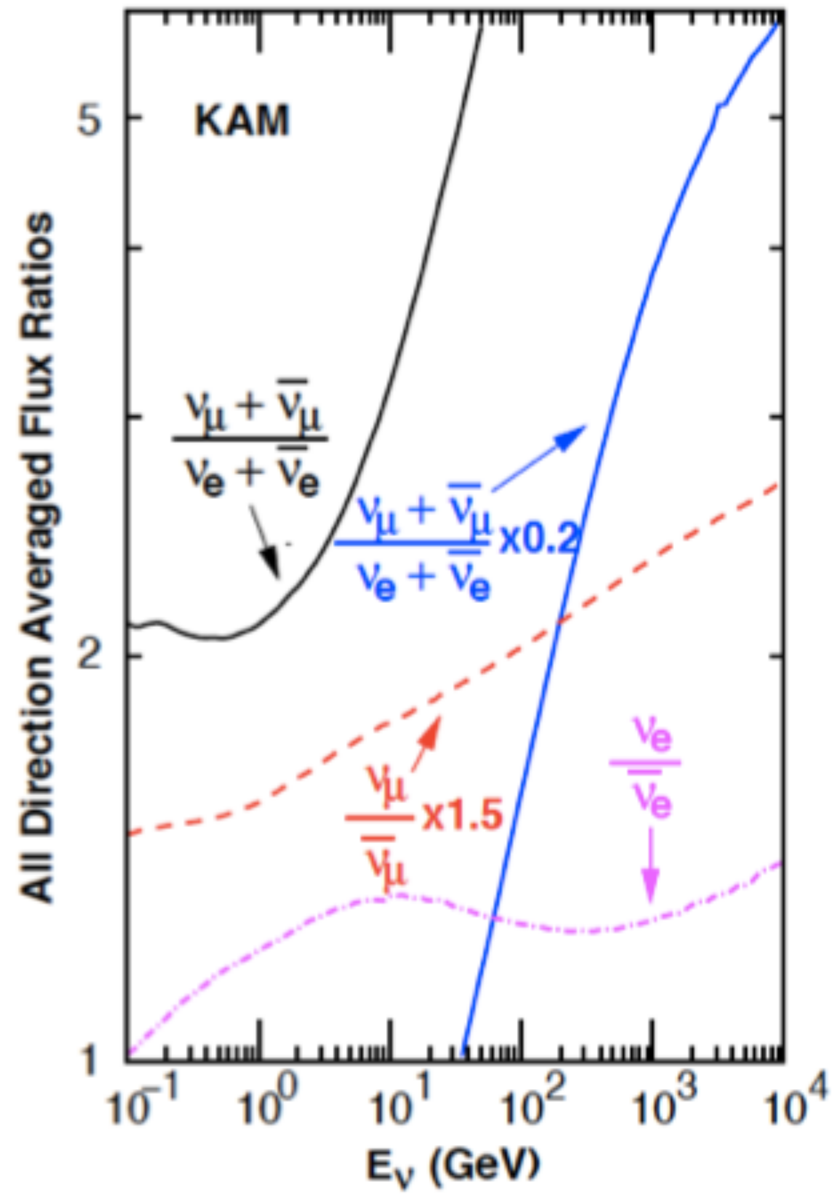
Collisions of primary cosmic rays with atmosphere (N, O, C …)
-> pions, kaons, … -> decay -> neutrinos

Production height distribution at the site of Superkamiokande



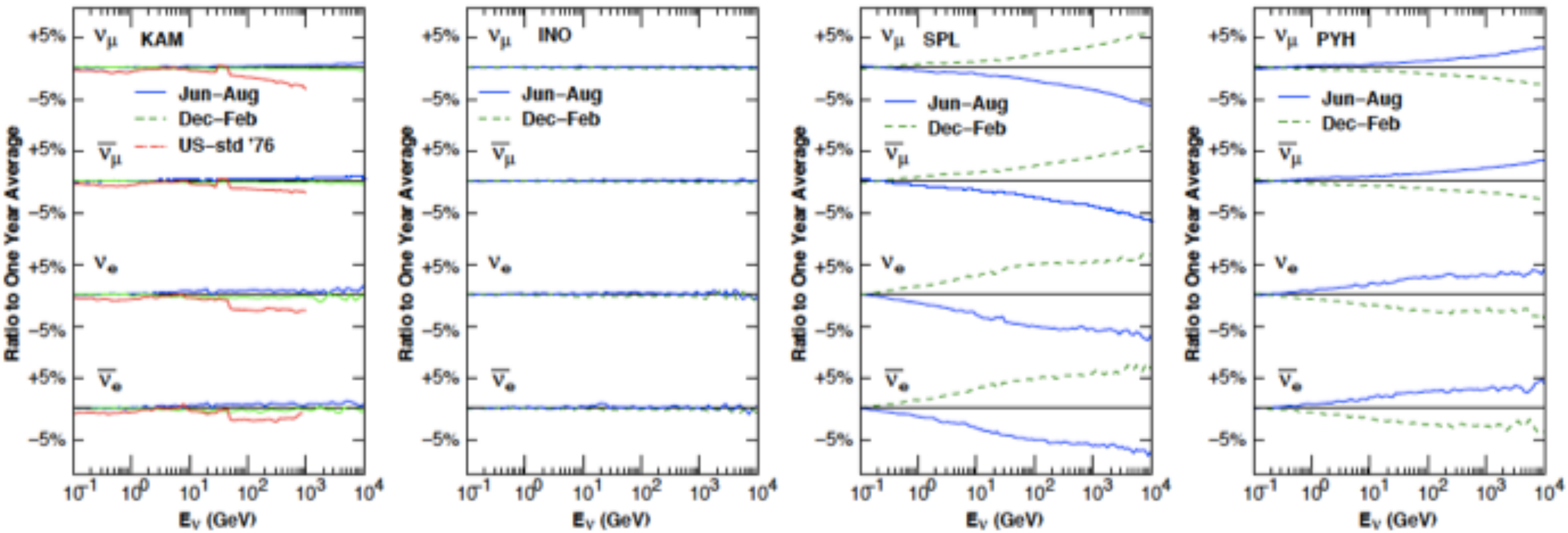
Flavors and neutrino/antineutrinos





Honda et al, Phys. Rev. D92 (2015) 023004

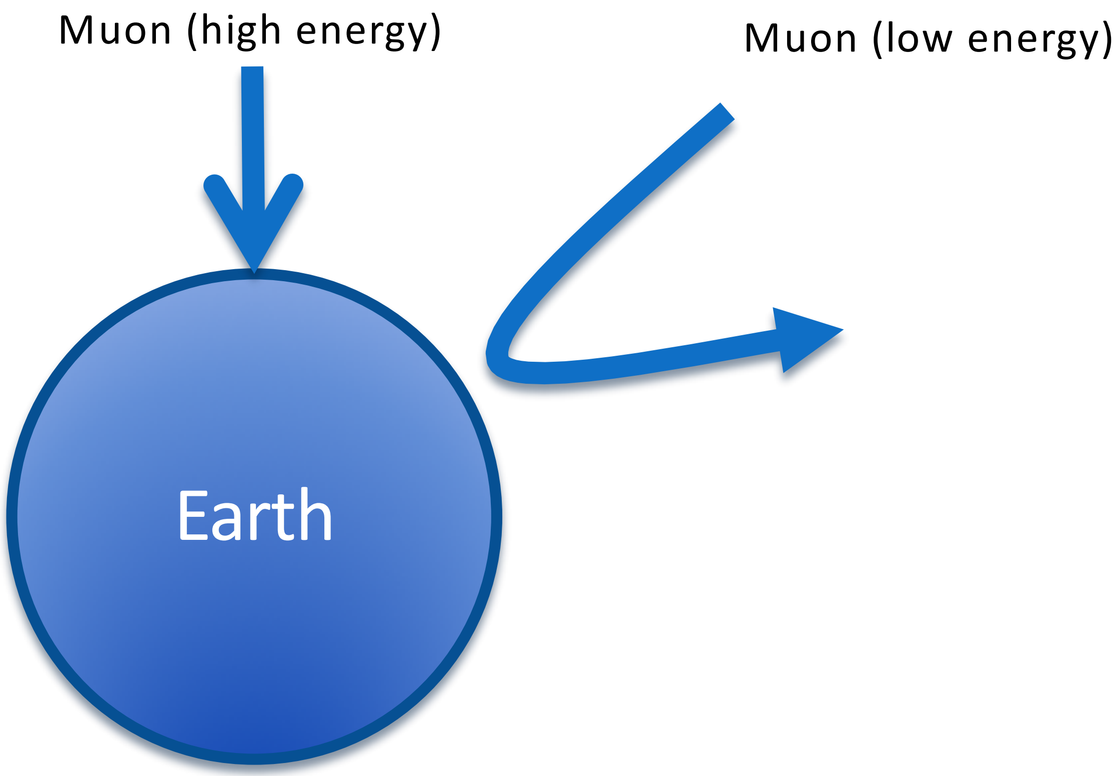
Seasonal Variations



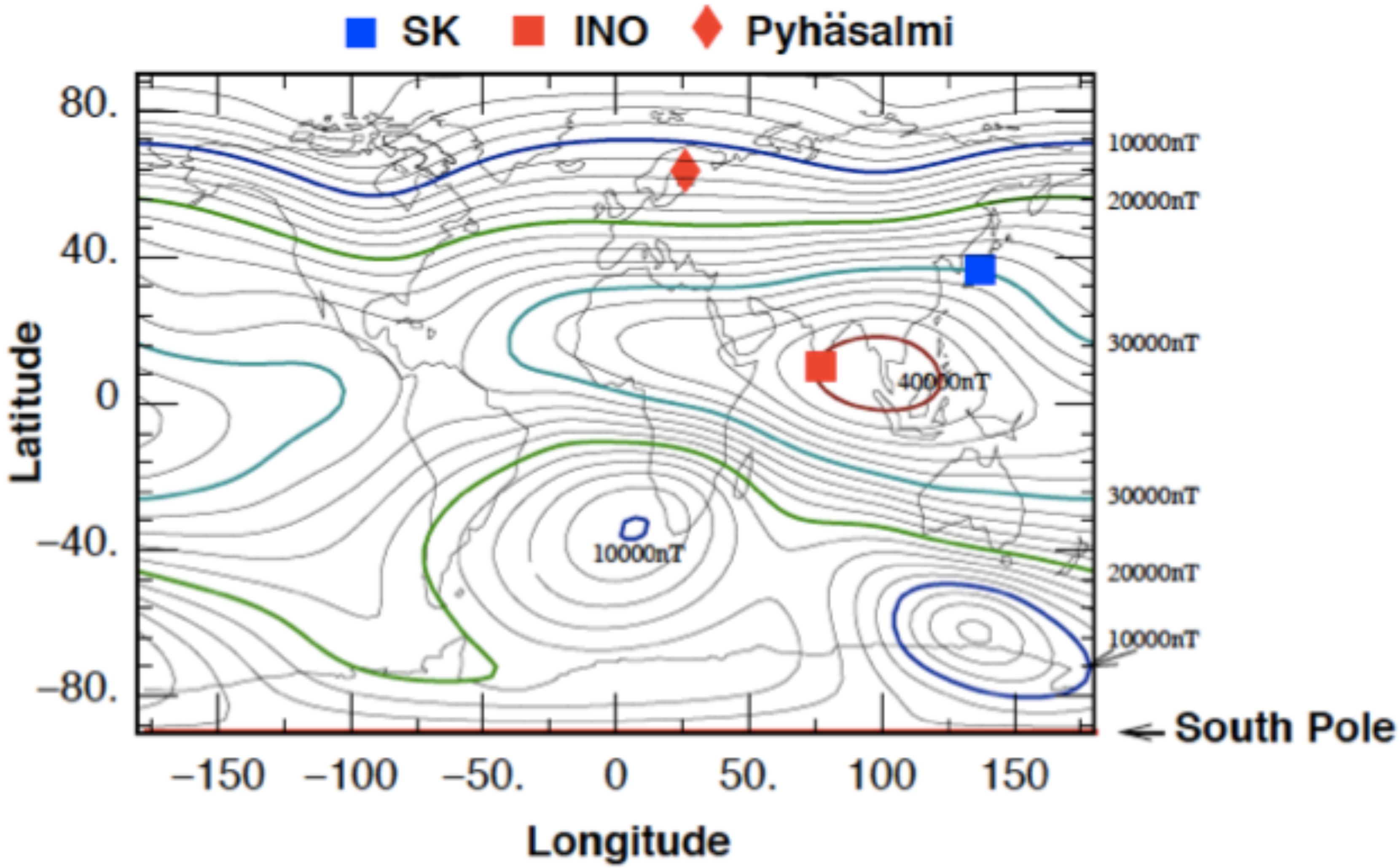
Regions close to poles:

- \>100 GeV: Air density at high altitudes higher
  -> shorter interaction length (pions, >100 GeV)
- \>10 GeV: Muons created at lower altitudes, hit faster rock
  -> very low energetic neutrinos

Geomagnetic effect

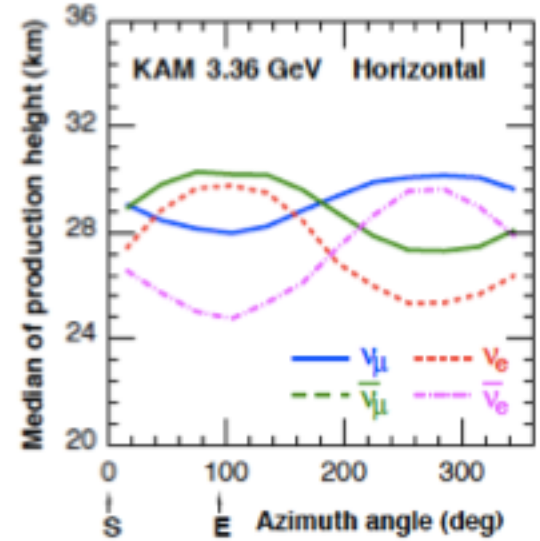


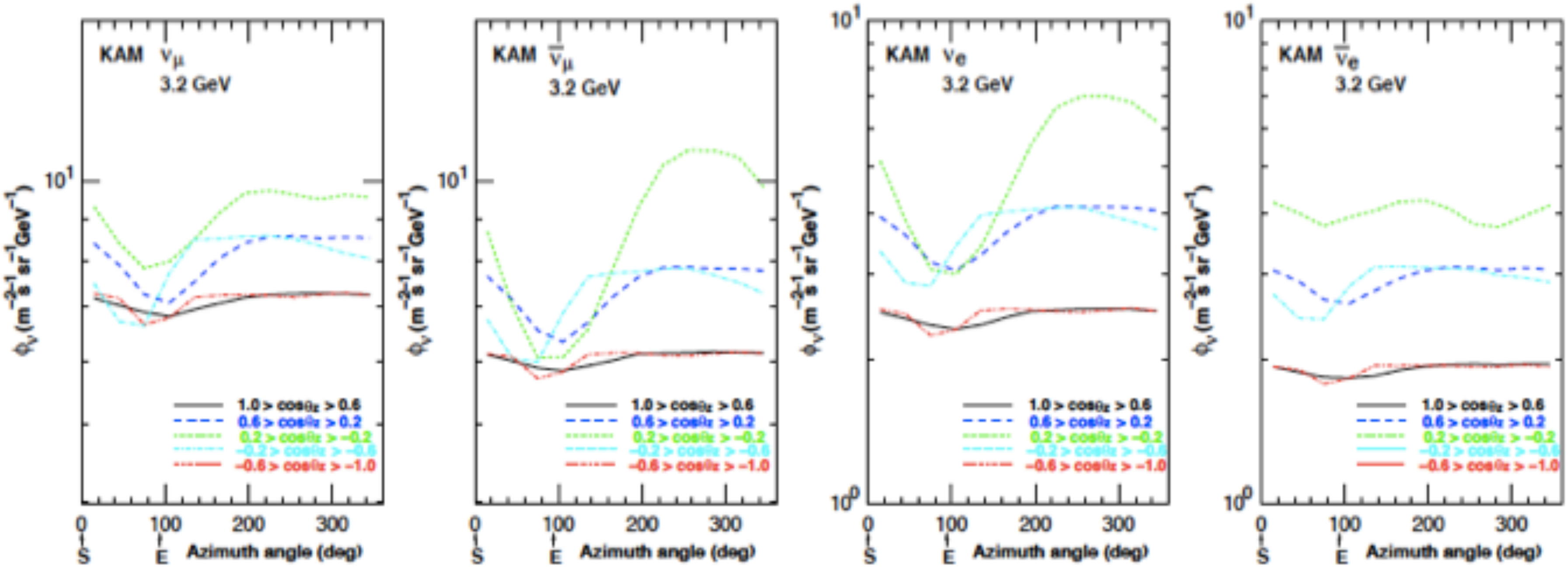
Geomagnetic effect



Azimuthal asymmetries

Noticable asymmetries for low energetic neutrinos

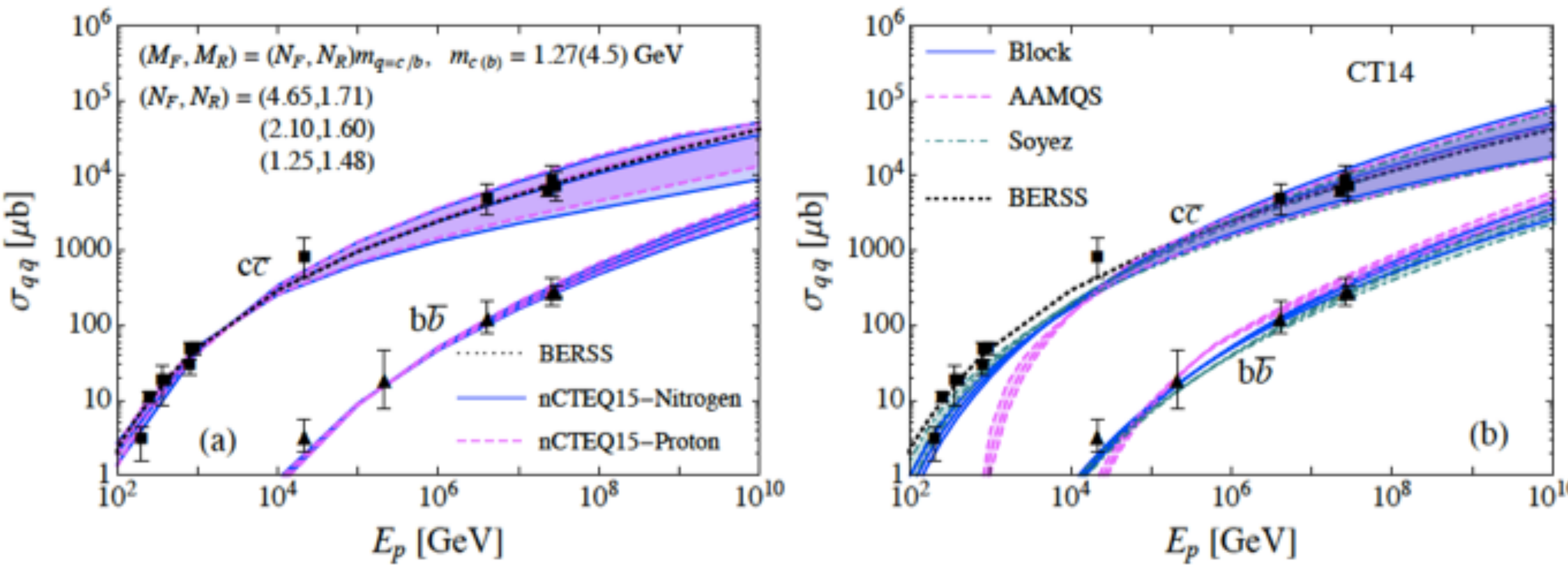




Prompt atmospheric neutrino flux

Neutrinos from $D^{\pm}$ ($B^{\pm}$) decays
Fast decay, no energy loss in interactions
-> hard energy spectrum -> background to astrophysical neutrinos

Total cross sections $c\bar{c}$ and $b\bar{b}$
Bands indicate modelling uncertainties



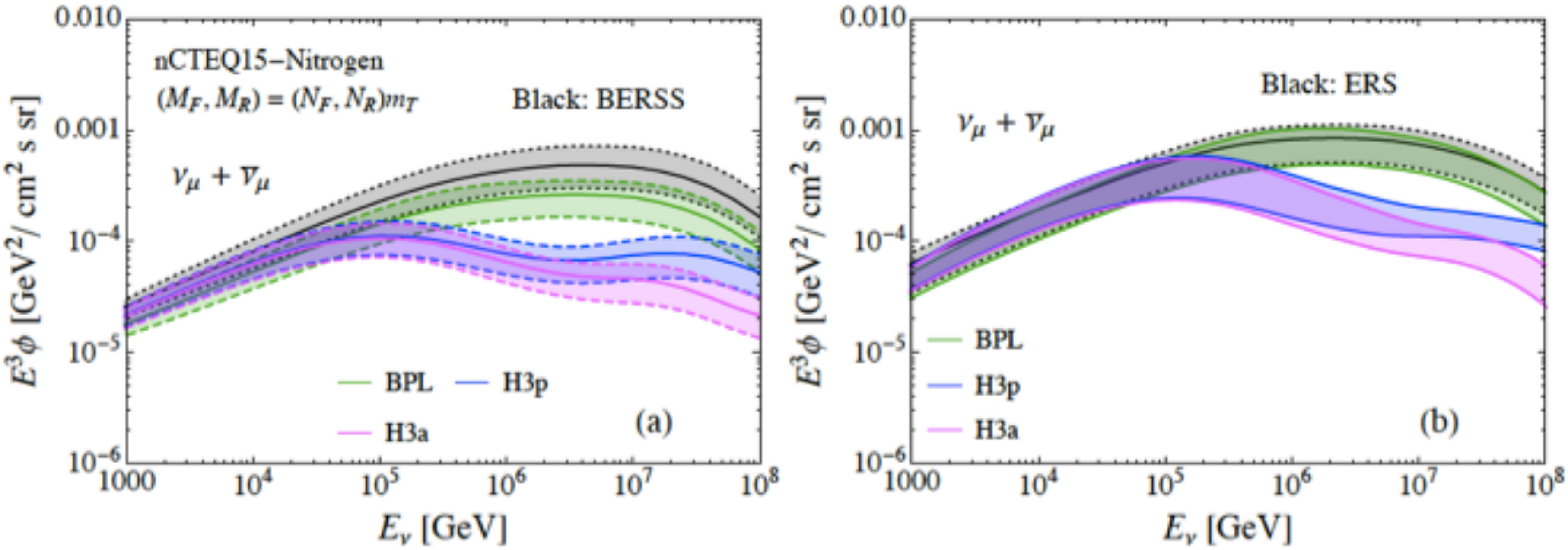
Left, right: Different models

Jeong et al, arXiv 1611.05120

Prompt atmospheric neutrino flux

Neutrinos from $D^{\pm}$ ($B^{\pm}$) decays
Fast decay, no energy loss in interactions
-> hard energy spectrum, background to astrophysical neutrinos

Energy spectrum

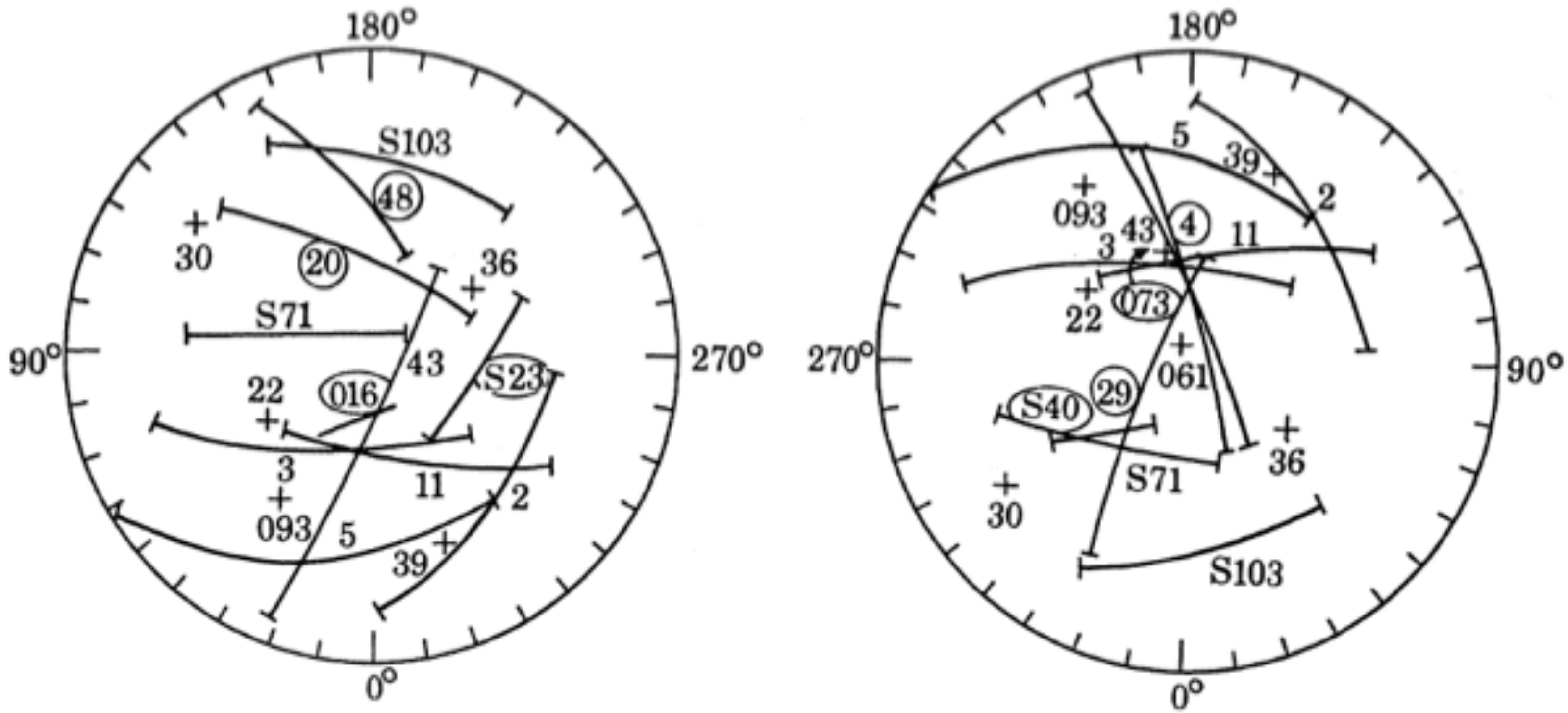


Jeong et al, arXiv 1611.05120

Neutrino telescopes

First neutrino sky map (1971)

Kolar Gold Field (India)



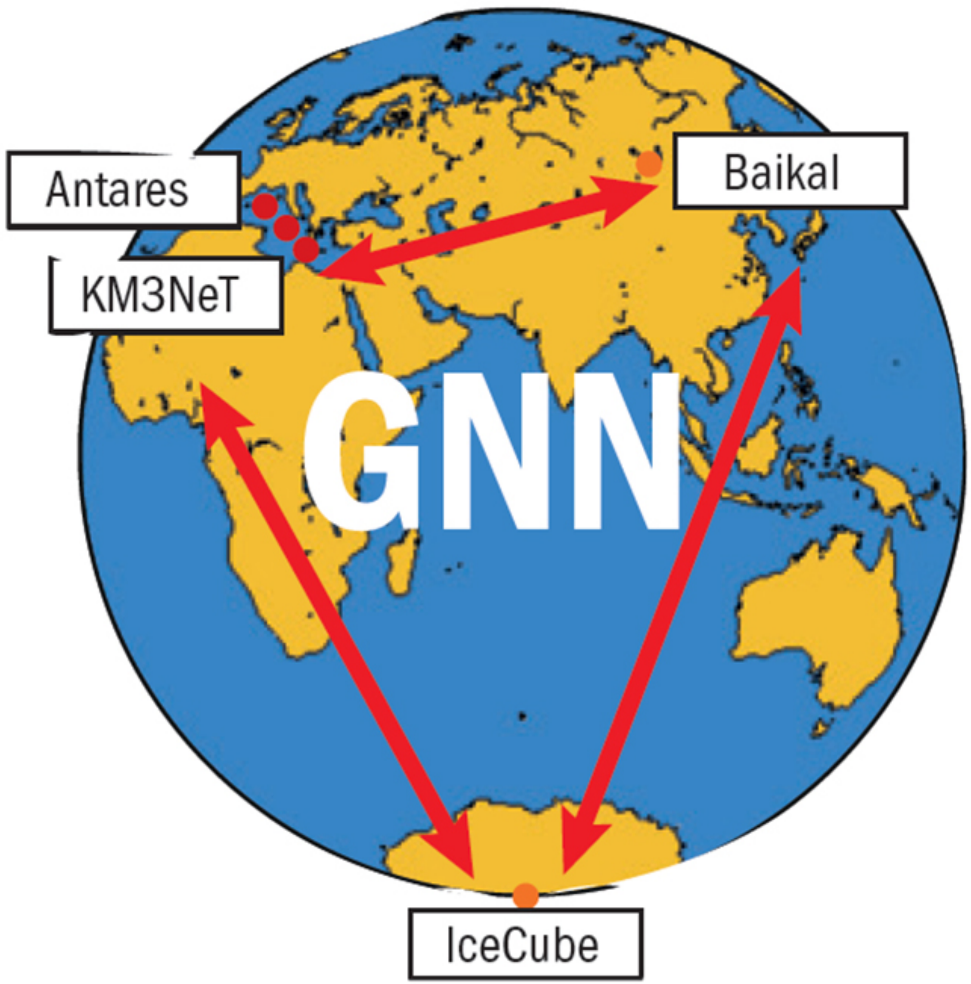
(a) Northern Celestial Hemisphere   (b) Southern Celestial Hemisphere

~GeV neutrinos from cosmic ray interactions in the atmosphere

Search for cosmic sources:
Probability of 4 arches crossing: 10^{-3},
no cosmic ray source (strong radio/pulsar) closeby identified

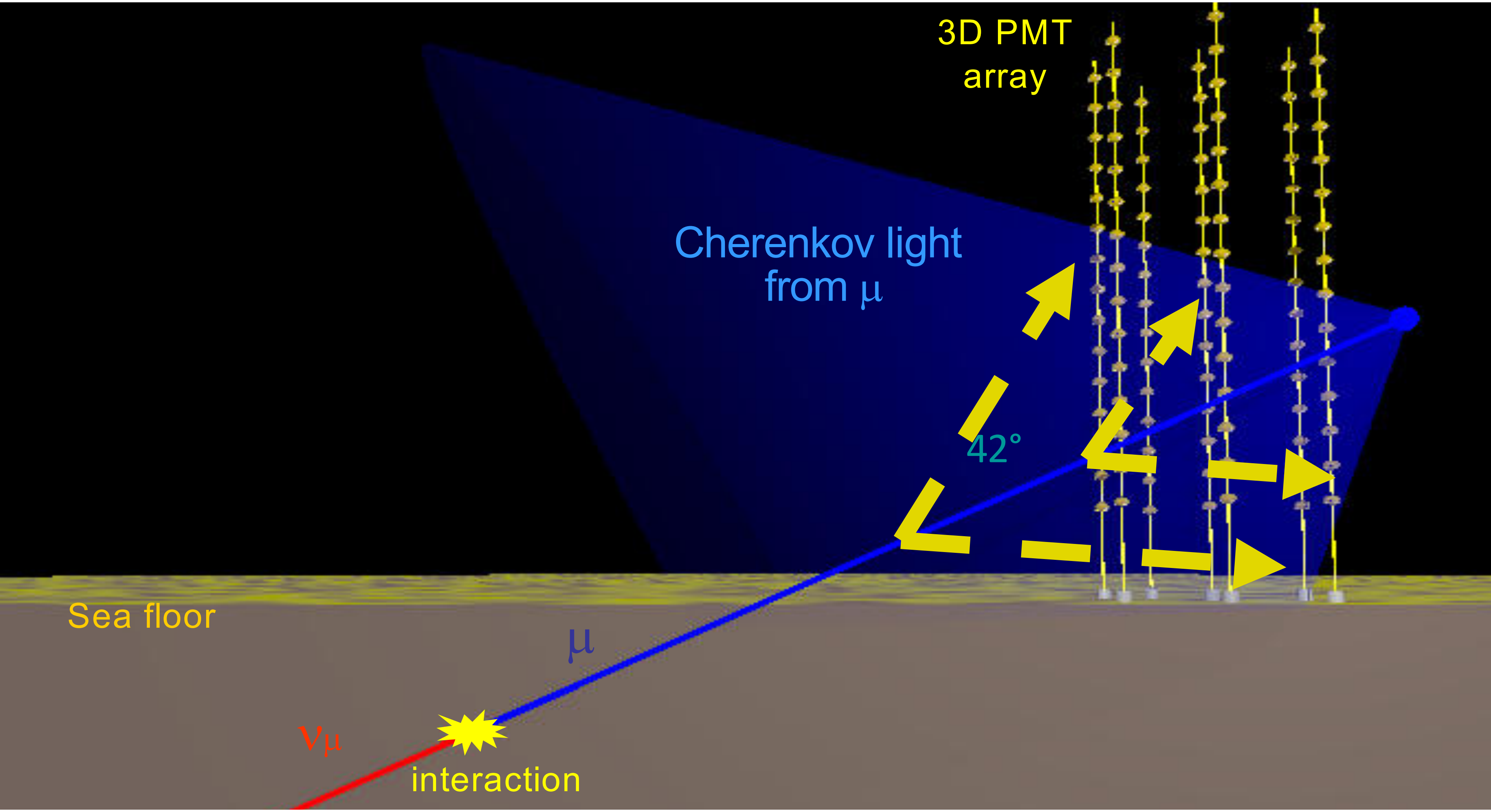
Krishnaswamy et al, Proc. R. Soc. Lond. A 1971 323, 489

GNN
The Global Neutrino Network

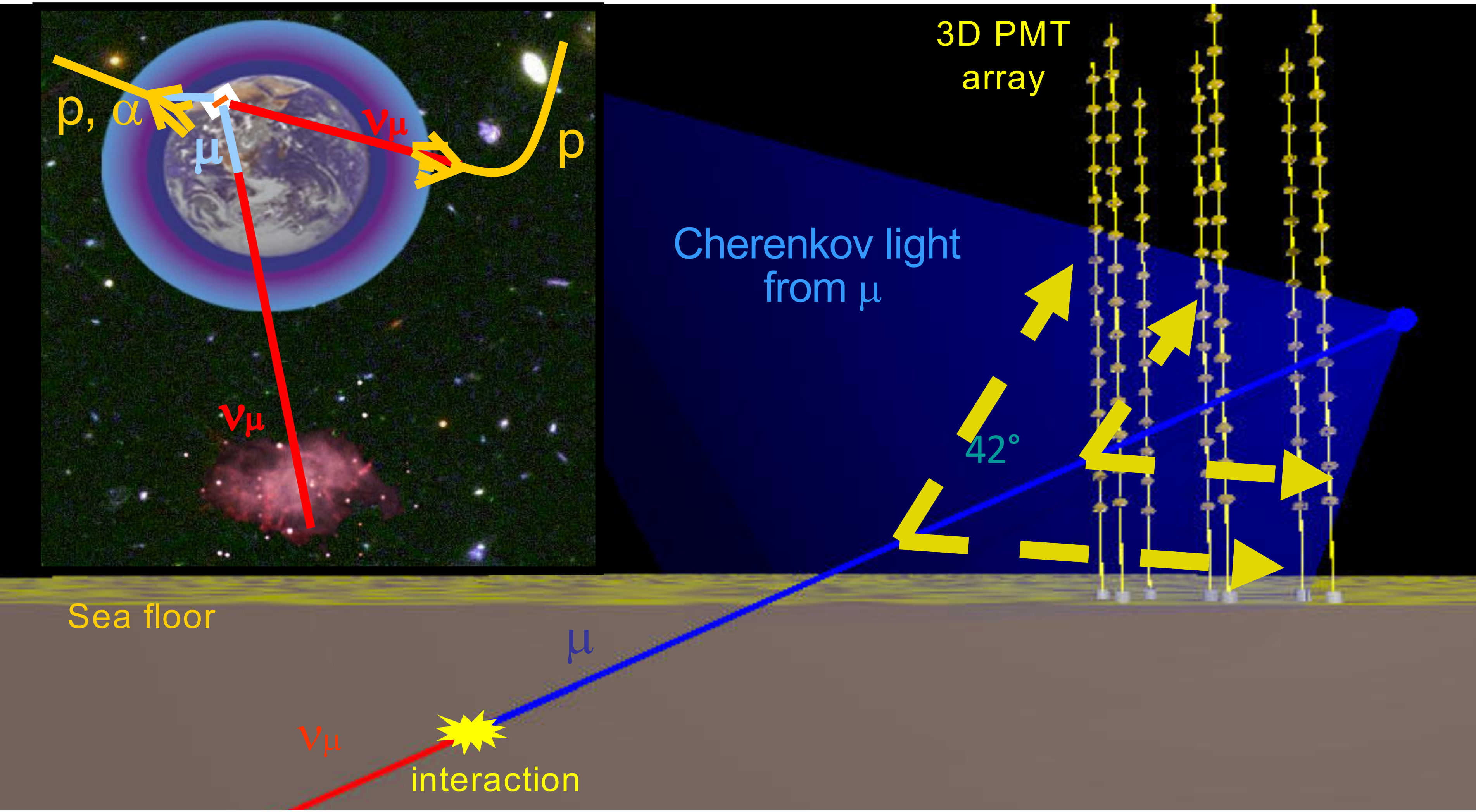


https://www.globalneutrinonetwork.org

Small interaction probability -> Huge detectors -> Use natural resources (ice, water)



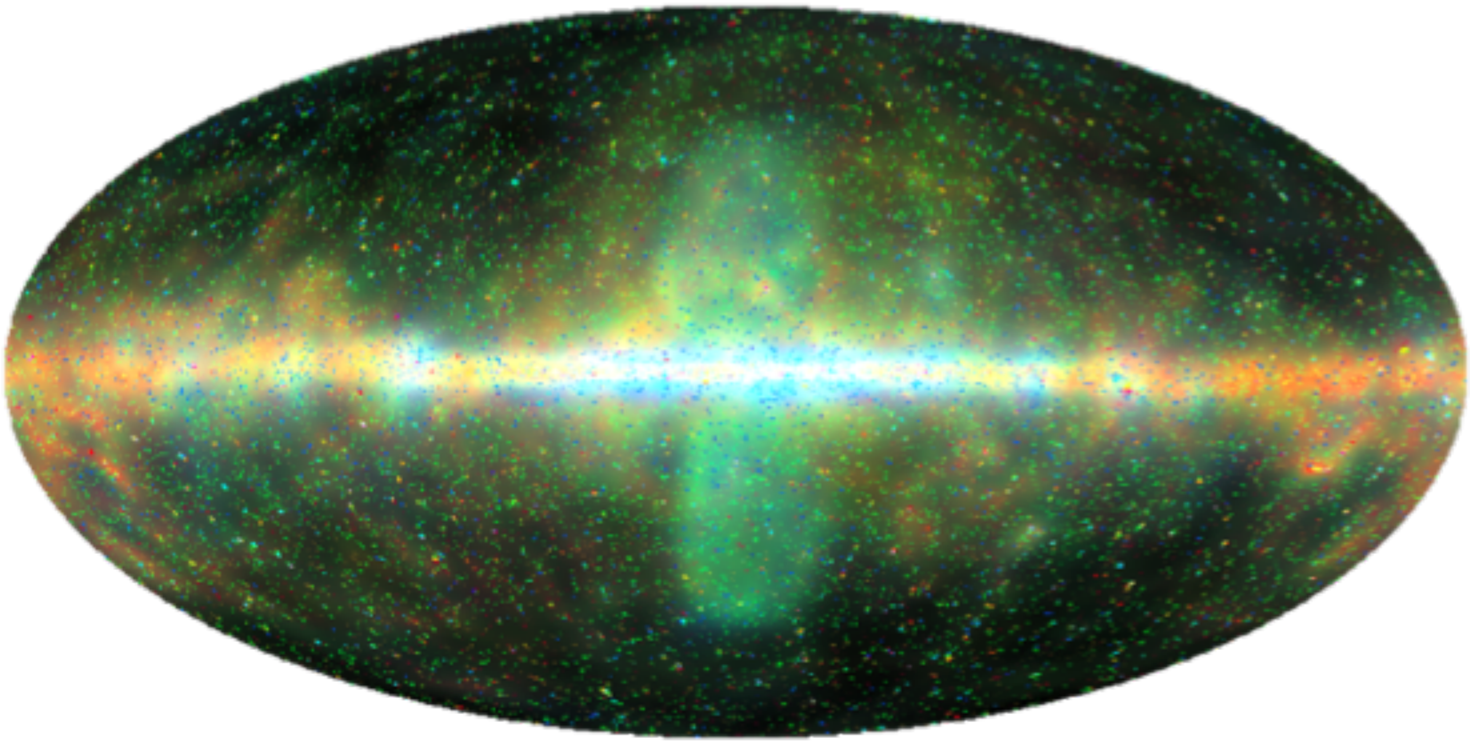
(Muon) Neutrino CC interaction in Earth
=> Muon passes detector



Cosmic rays interact with atmosphere
=> Background showers,
-> muons passing downwards
-> neutrinos from all directions

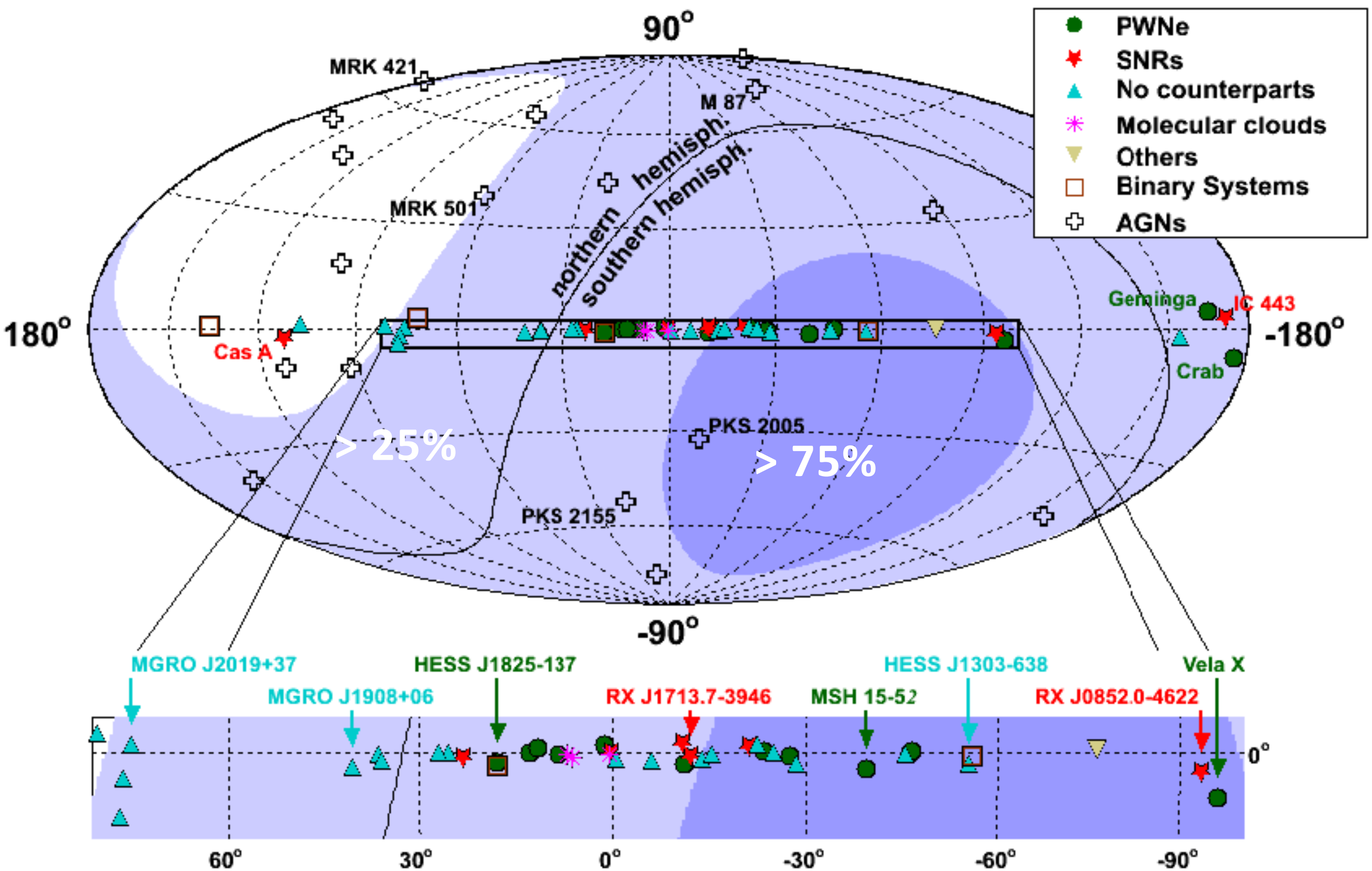
(Muon) Neutrino CC interaction in Earth
=> Muon passes detector

The sky seen in gamma rays (galactic coordinates)



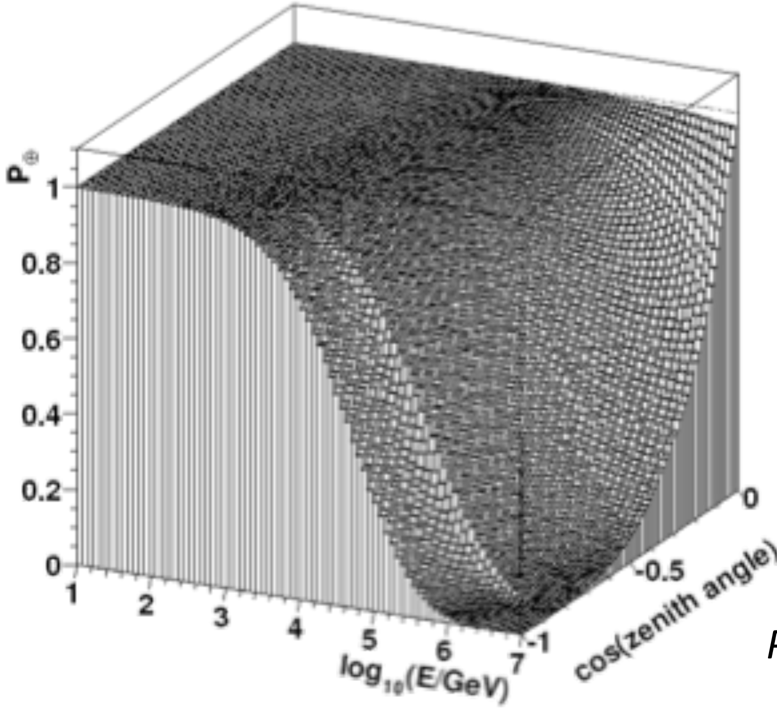
Rolf Bühler, ICRC 2015, Den Haag

Field of view for medium latitude site (ANTARES)



Absorption in the Earth

Probability to transverse the Earth as function of energy and zenith

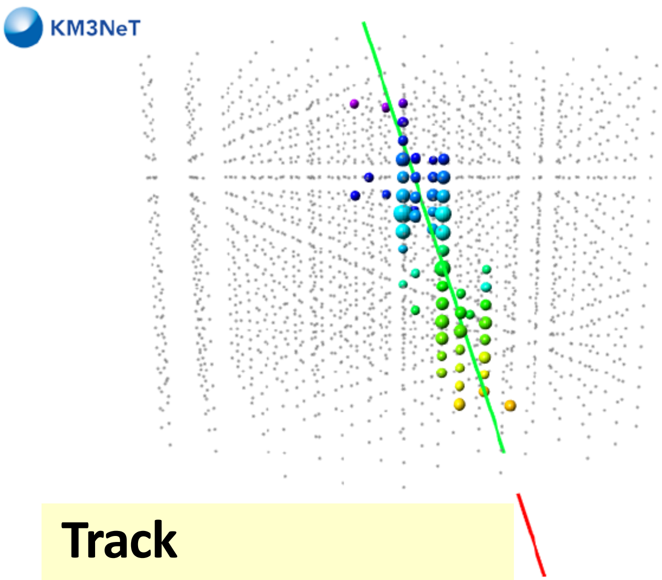


PhD thesis, Heijboer

Cross section rises with energy -> Earth becomes opaque for high energy neutrinos

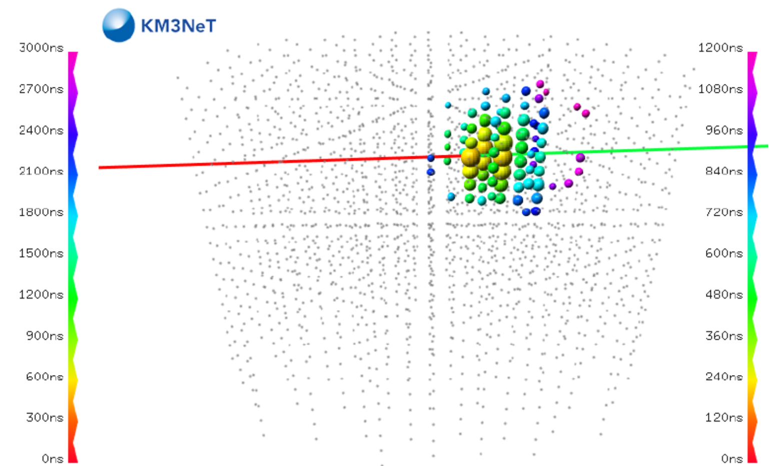
Exception: Tau neutrinos (regeneration: τ^- --> $\mu^- + \nu_\mu + \nu_\tau$)

Neutrino interaction signatures



Track

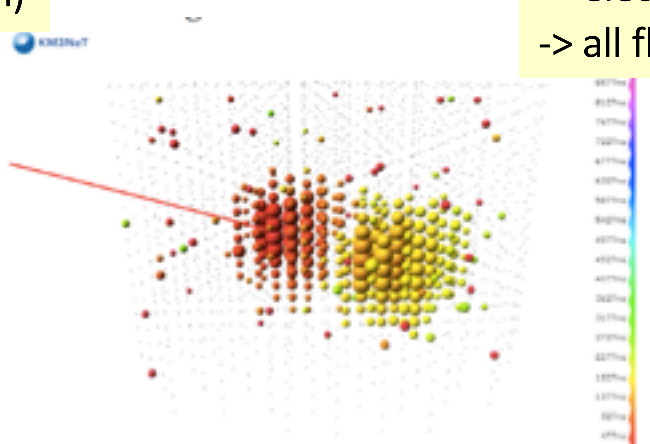
-> muon (ν_μ interaction)



Shower

-> electron (CC ν_e interaction)

-> all flavors (NC ν_e / ν_μ / ν_τ interactions

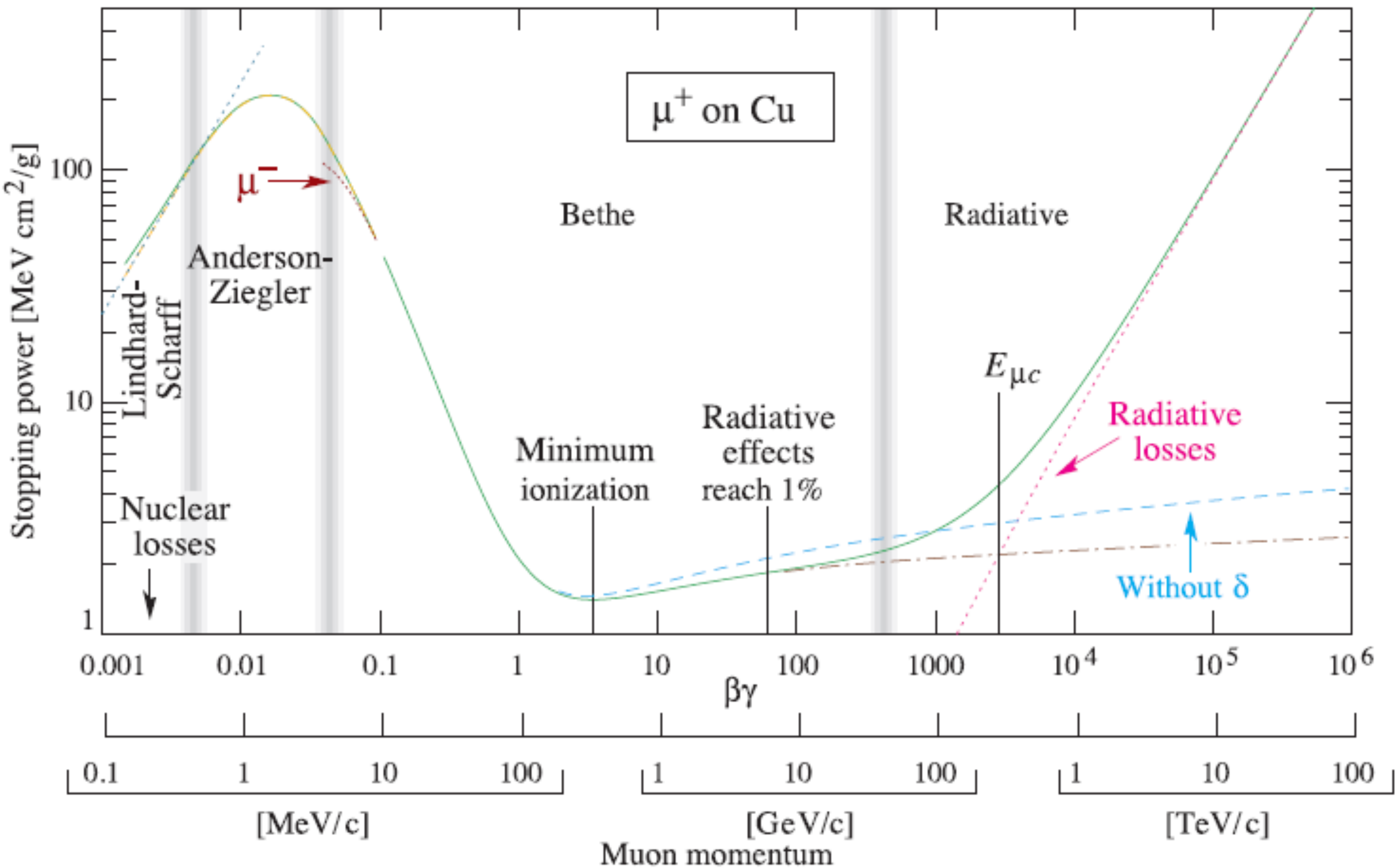


'Double Bang'

-> from high energetic tau (ν_τ interaction)

'long' τ lifetime (10^{-13}s)-> 50m/PeV (visible for very high energies)

Energy loss of muons



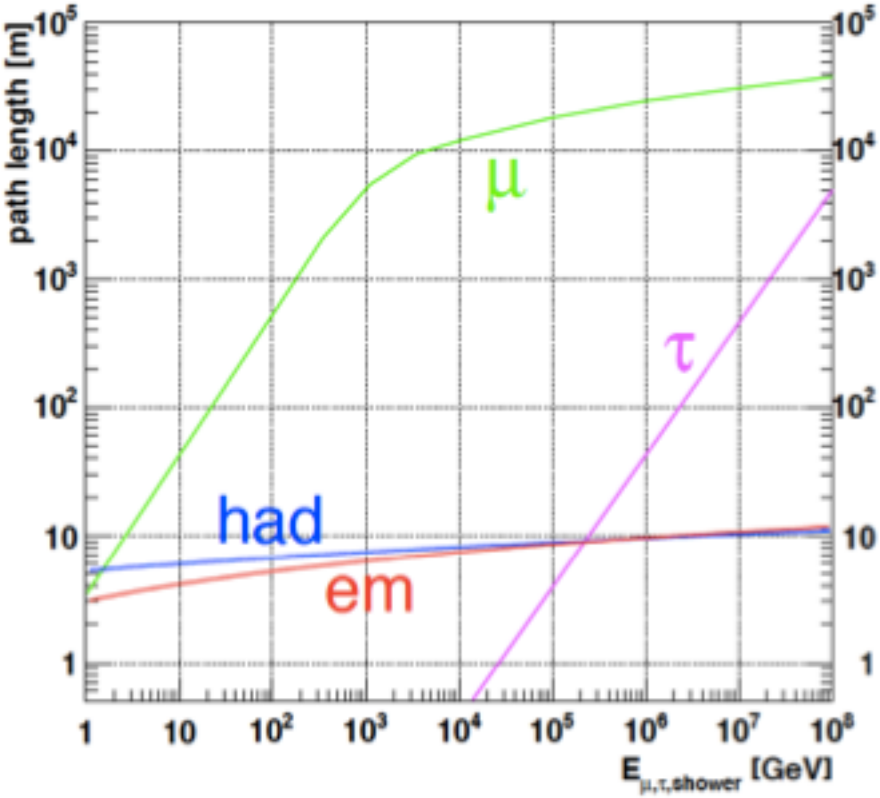
PDG 2017

Range of μ,τ and showers in water

Energy loss dE/dx ~ a + b*E

-> a, b slightly dependent on energy
a ~ 2 MeV/cm

-> TeV muons travel several kilometers in water



Chiarusi, Spurio, 2009

Cherenkov Light

$$\frac{dN_\gamma}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

$\Rightarrow$ 3.5 * 10^4 photons emitted between 300-600nm per meter of a muon track

$\Rightarrow$ Transparency of detector housing relevant

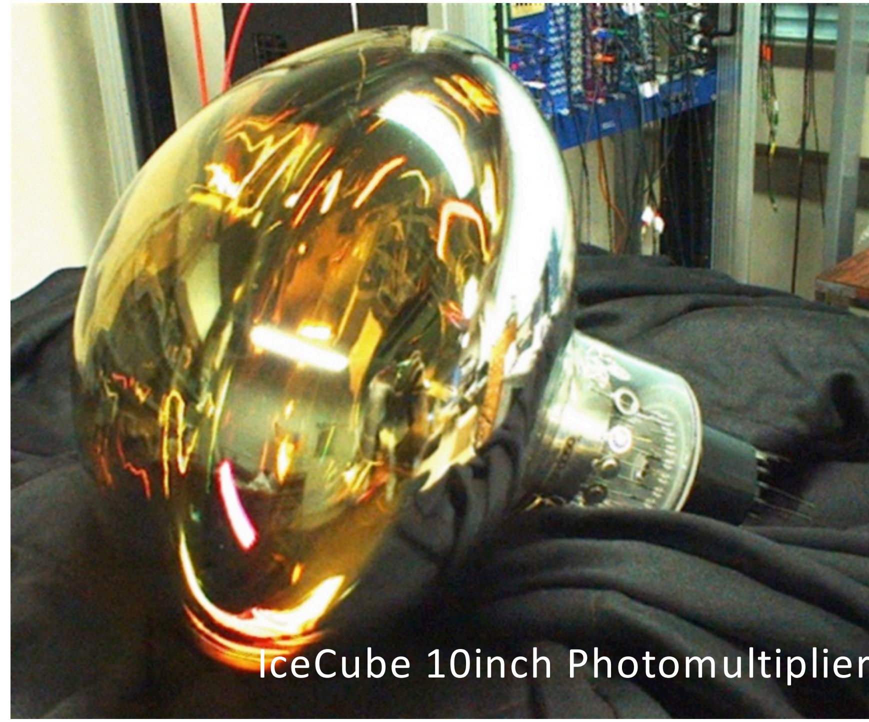
Photomultipliers

Relevant characteristics:

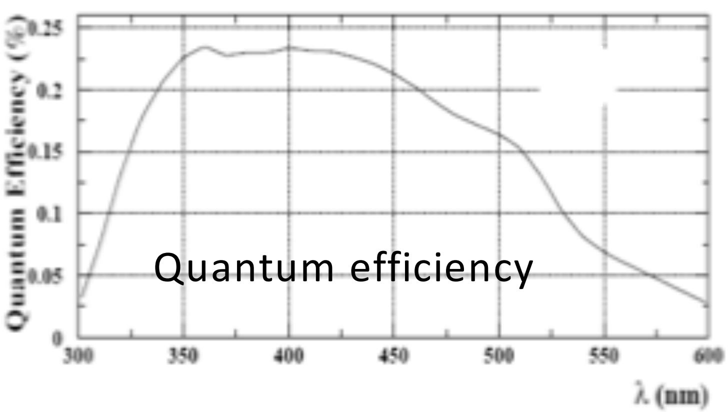
- Quantum Efficiency
- Dark Count
- Time spread

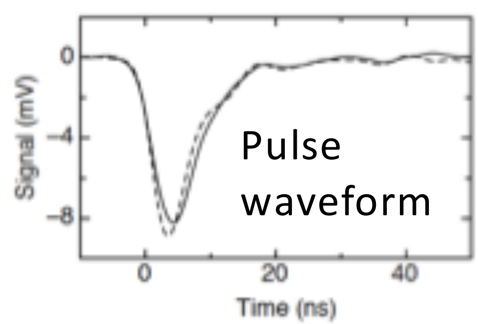
Glass sphere surrounds PMTs as pressure housing

Large PMTs require also shielding from Earth magnetic field
-> mu metal grid



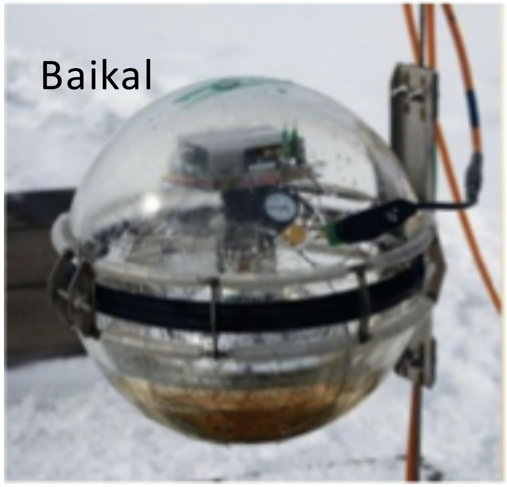
IceCube 10inch Photomultiplier

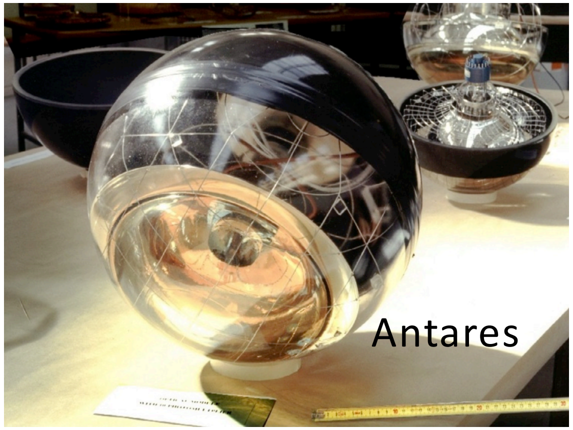




Typical gain 10^7
Quantum efficiency ~25%
Noise rate ~500Hz
~2ns time precision

Optical Modules

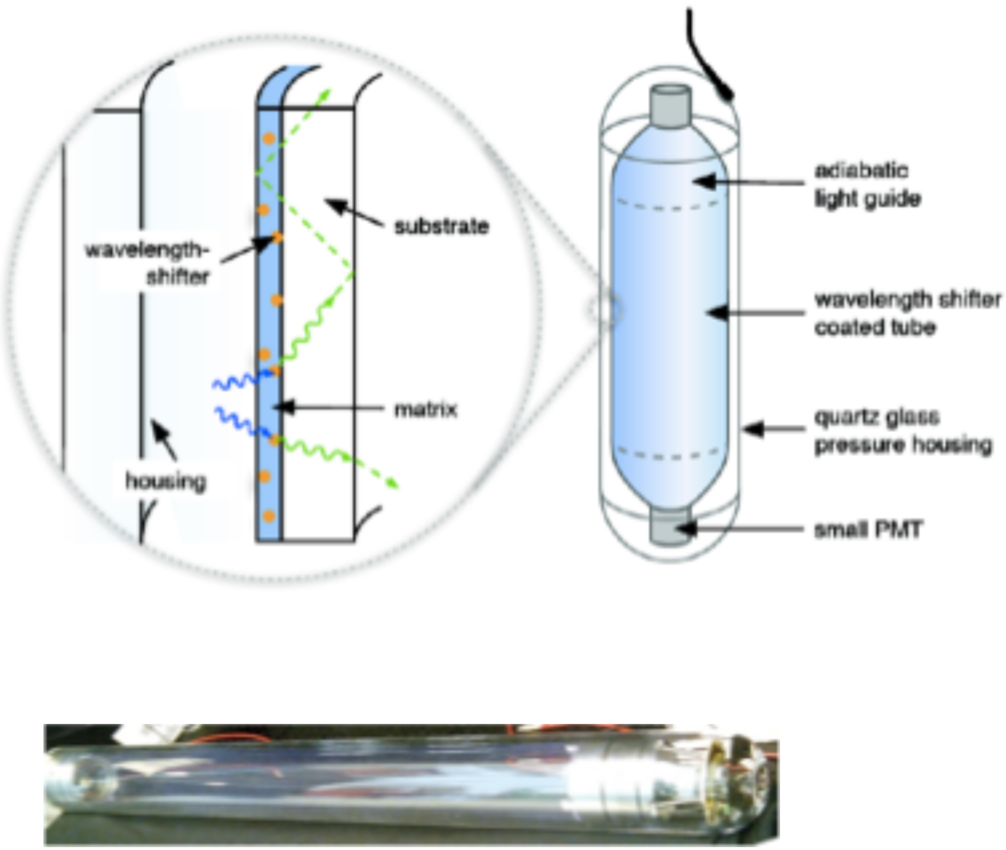




Small PMTs:
-> Photon counting
-> Directional resolution

Further developments

Wavelength-shifting module



Higher efficiency, lower noise

D-Egg module

Smaller radius
Upwards sensitivity
Glass with improved UV transparency

Baikal: NT200(+) -----> **G**igaton **V**olume **D**etector (GVD)

Lake with 1.3km depth

1981: Start of first underwater neutrino telescope in the Baikal Lake (1 string)

Since 1998 NT200 (8 strings)

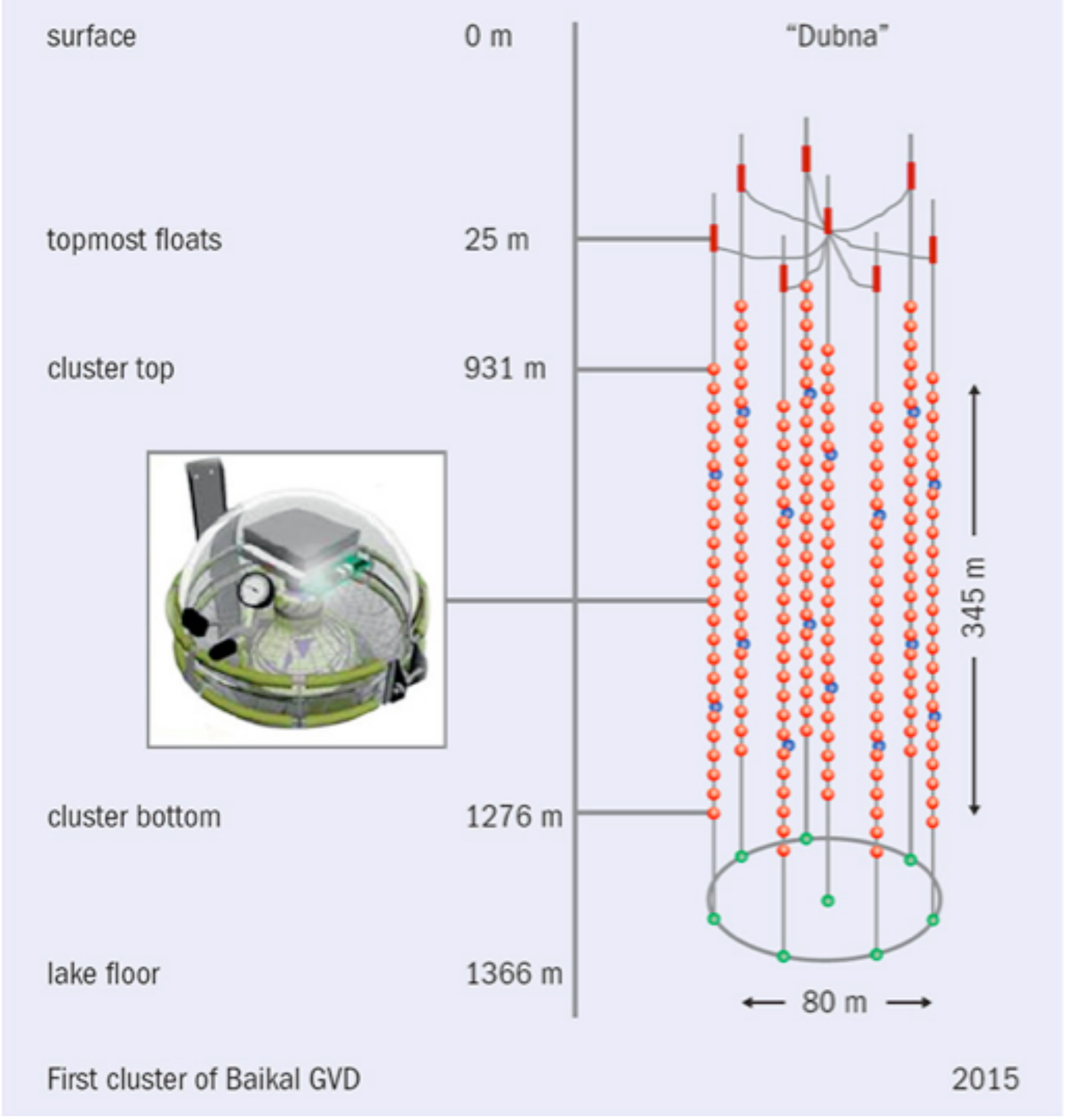
2005: +3 strings (NT200+)

Since 2011: Upgrade to GVD

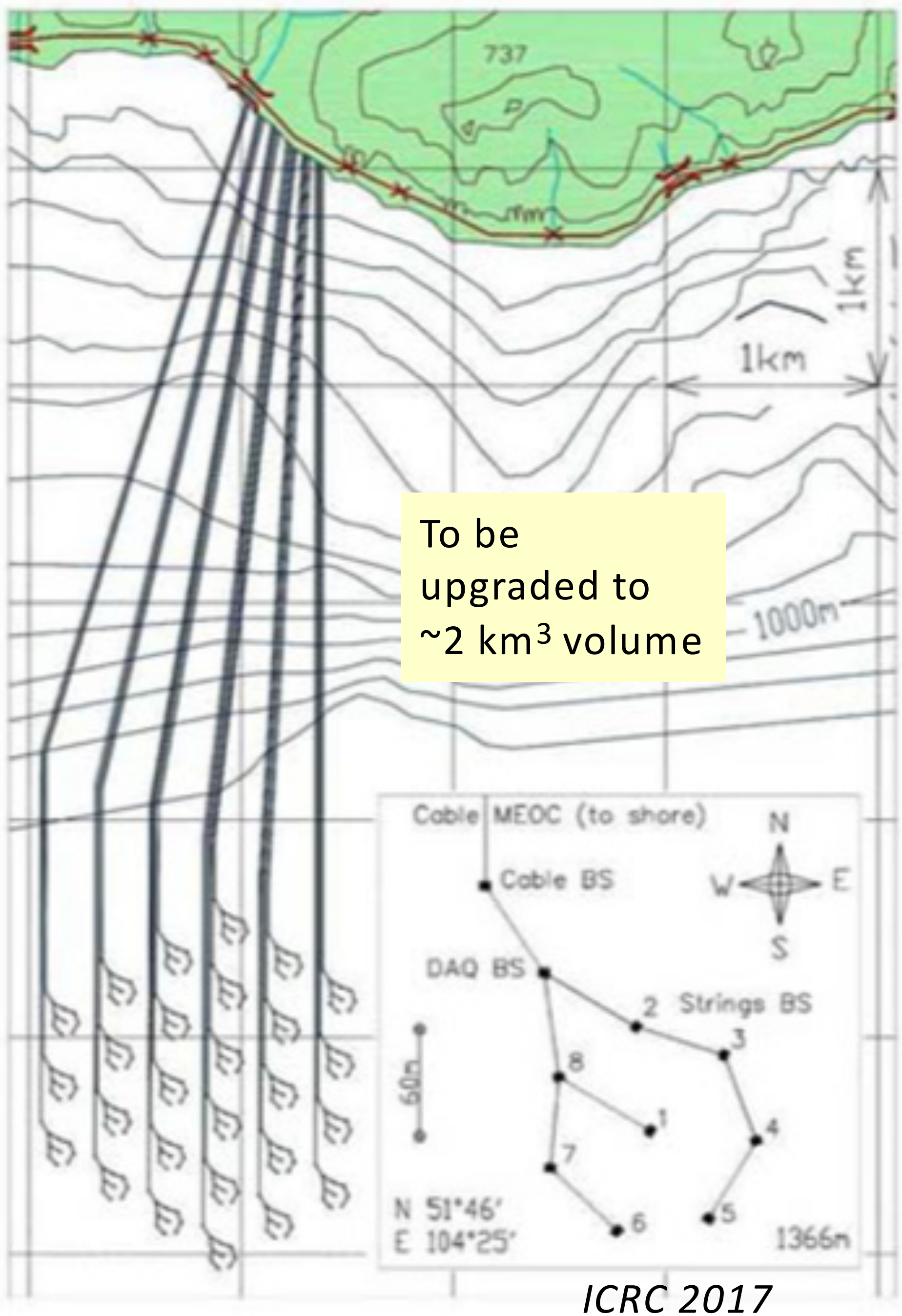
Picture: Cern Courier 2005

Cern Courier 2015

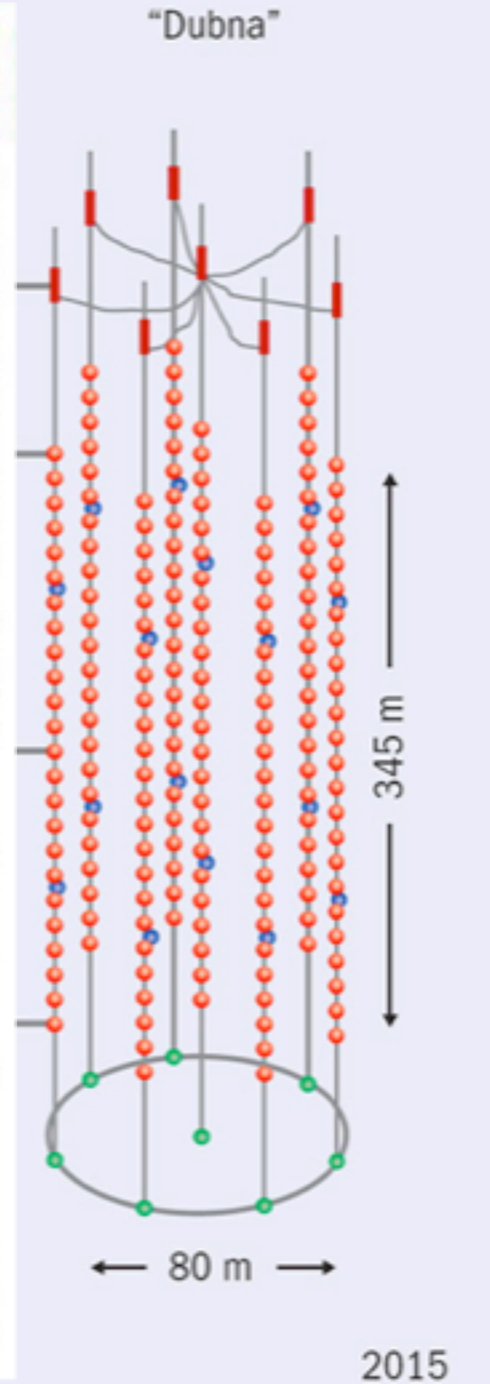
- First of 8 clusters
- in total 0.4 km^3 volume
- to be deployed til 2020



- First of 8 clusters
- in total 0.4 km^3 volume
- to be deployed til 2020



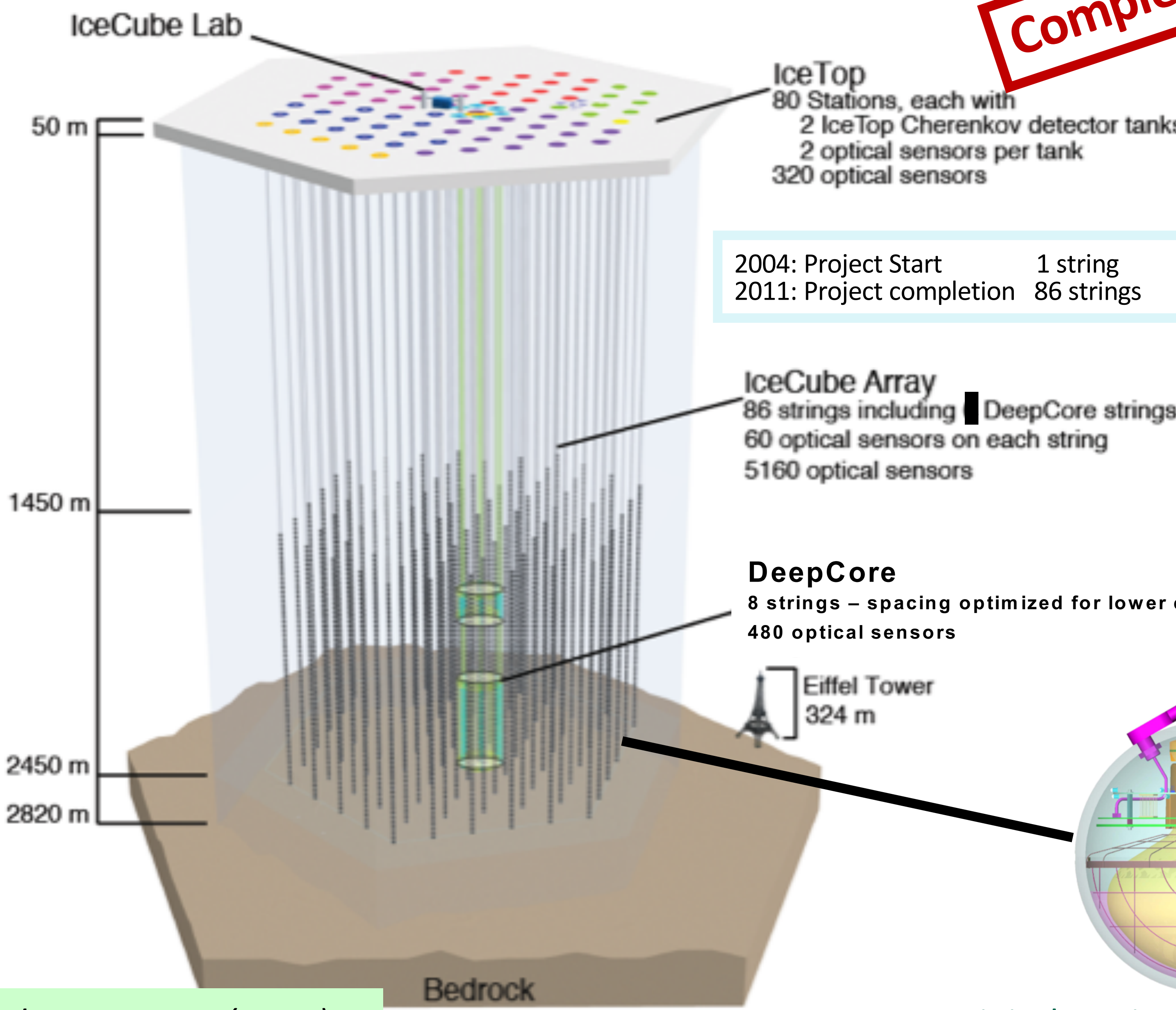
To be upgraded to ~2 km^3 volume



ICRC 2017

The IceCube Neutrino Observatory

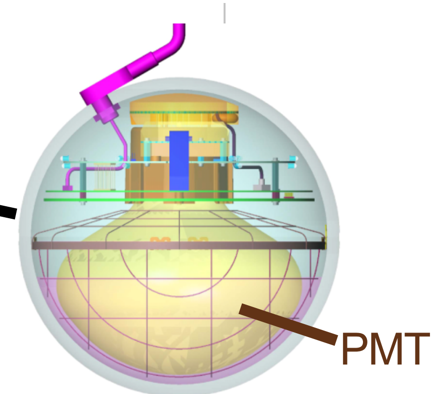
Completed: Dec 2010



2004: Project Start 1 string
2011: Project completion 86 strings

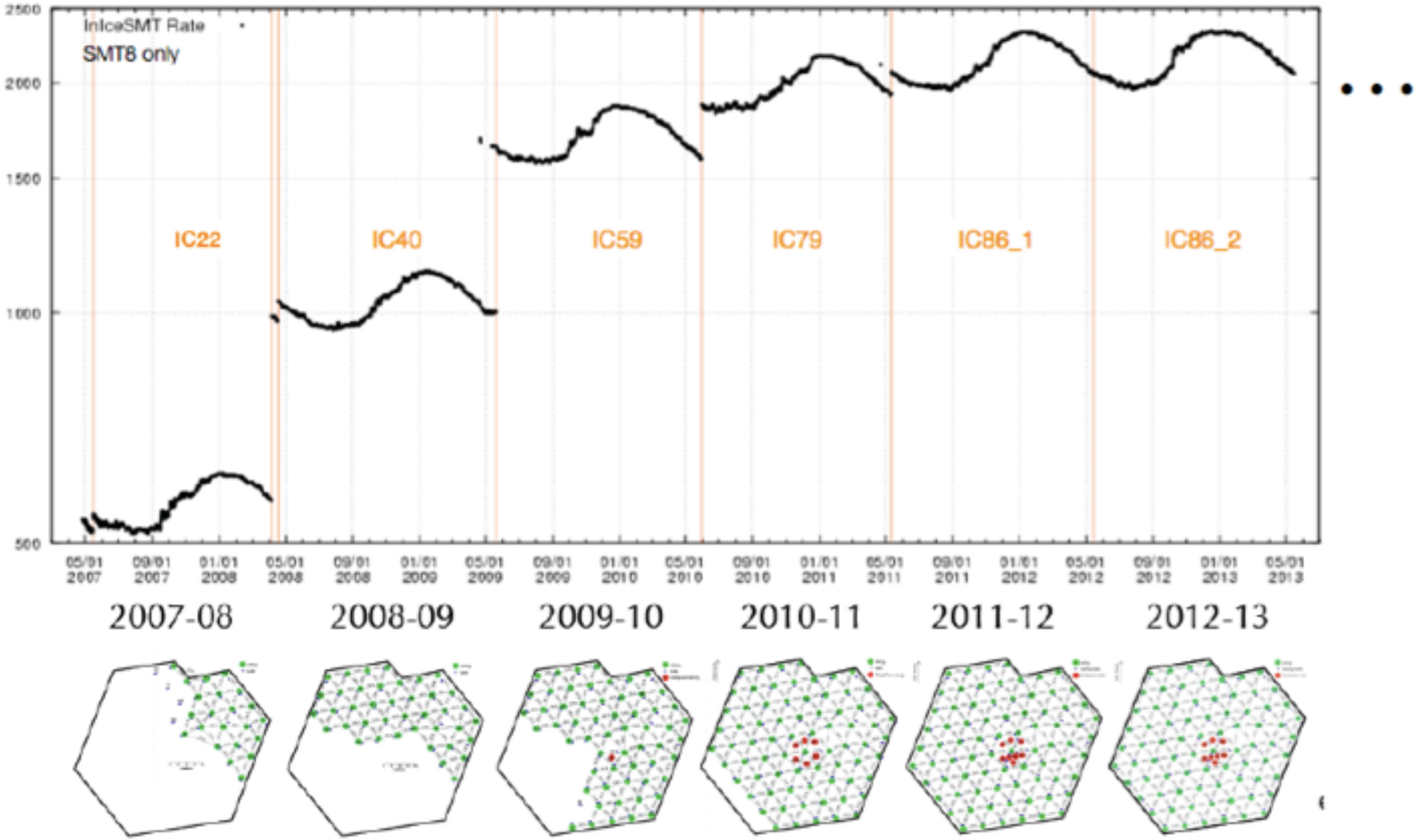
Configuration chronology

2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86



Digital Optical Module (DOM)

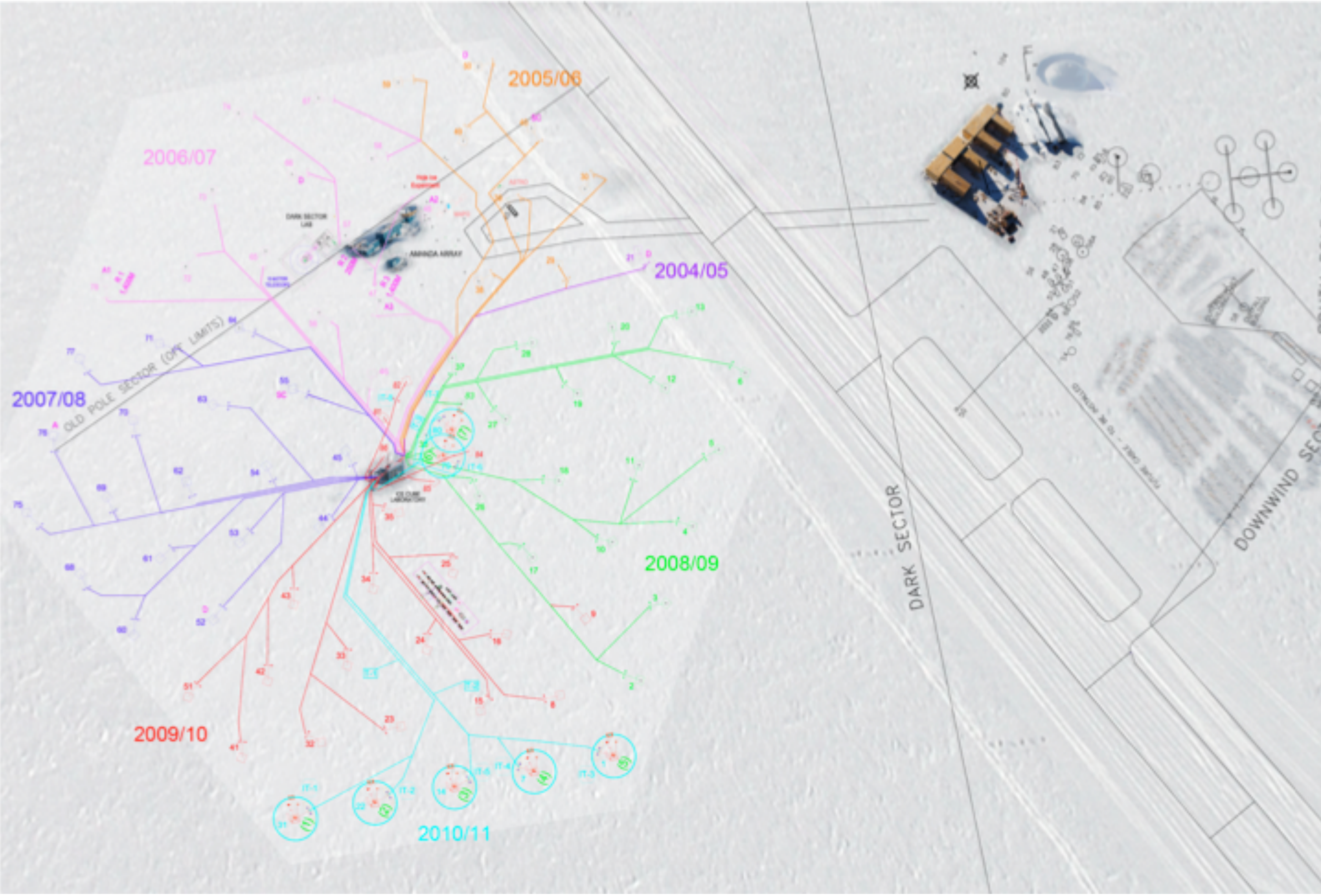
Woschnagg 2011 (SLAC)

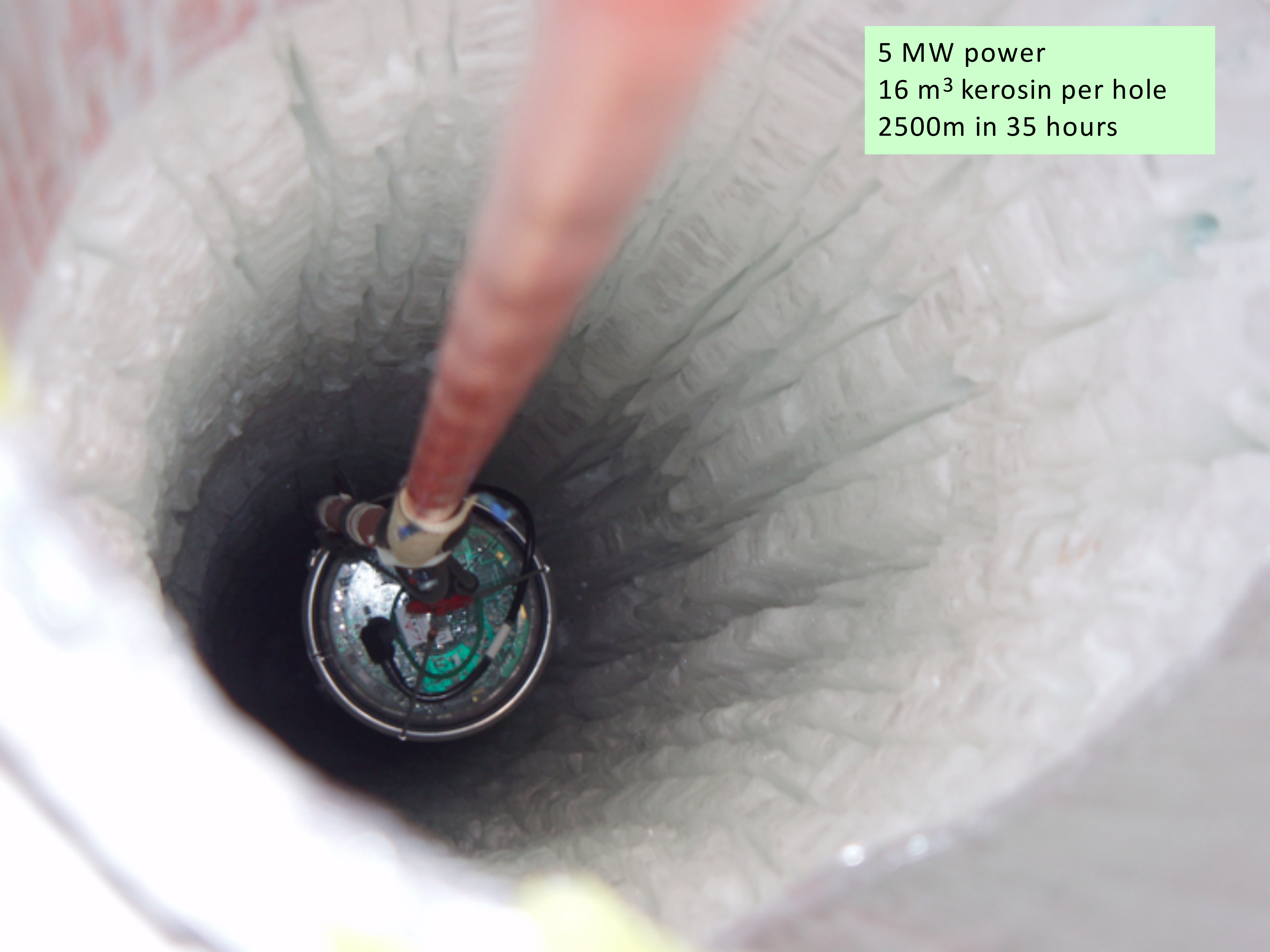


IceCube Operations

Full detector in operation since 2011 (now in IC86-V)
Stable behavior except for seasonal variations,
equilibration of DOM noise levels after installation

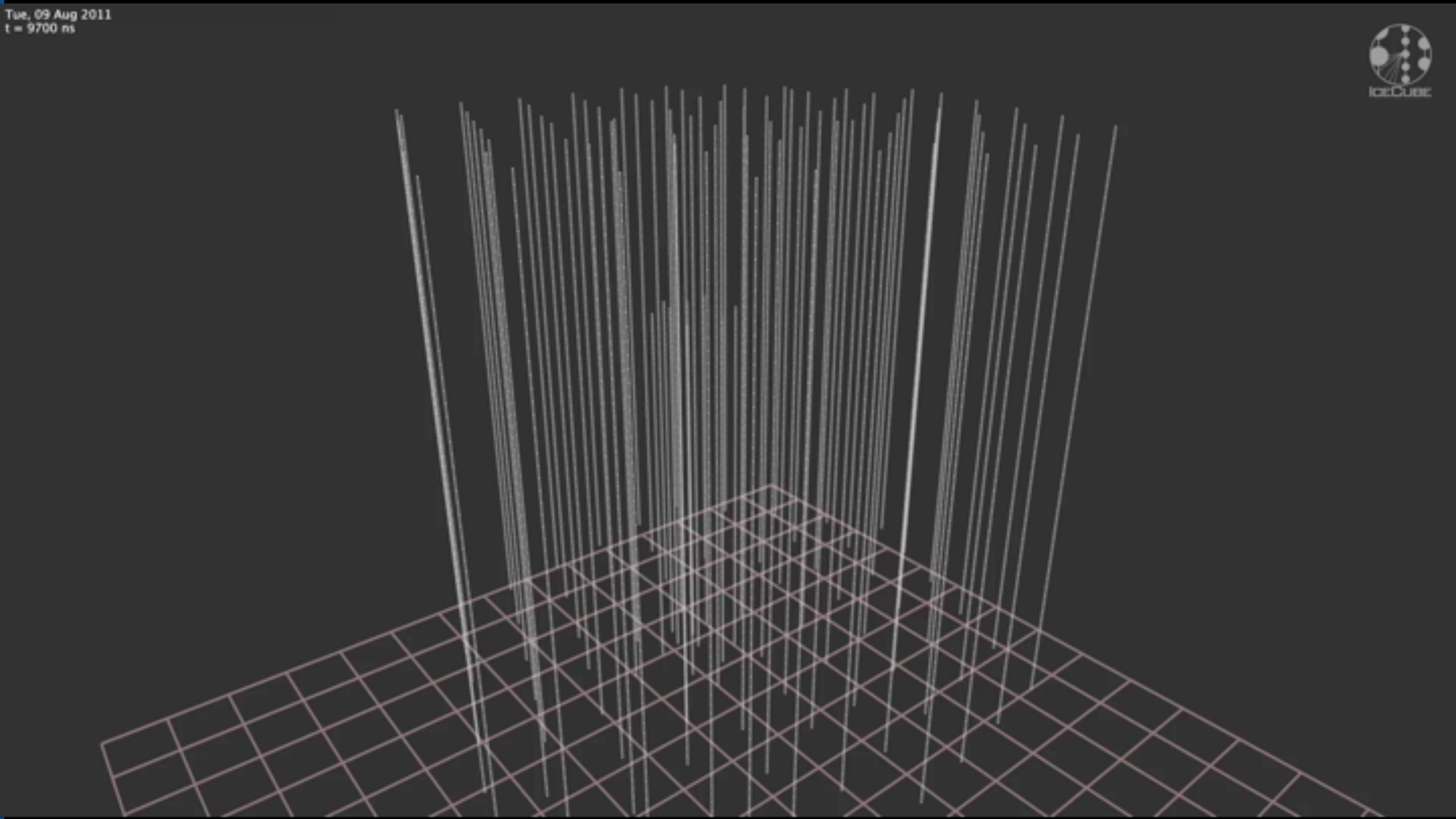
DeYoung, VLVNT205


2005/06
2006/07
2004/05
2007/08
OLD POLE SECTOR (OFF LIMITS)
2008/09
2009/10
2010/11
DARK SECTOR
DOWNWIND SEC



5 MW power
16 m^3 kerosin per hole
2500m in 35 hours

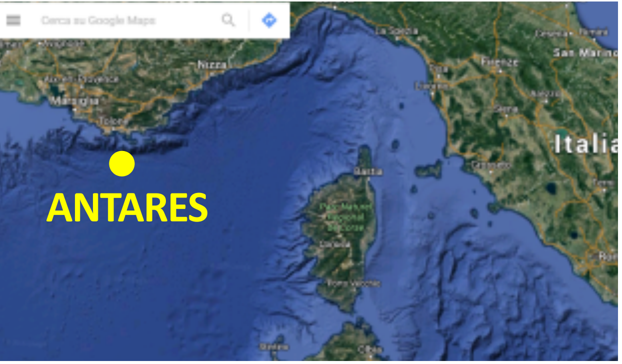
1.14 PeV shower (‘Ernie’)



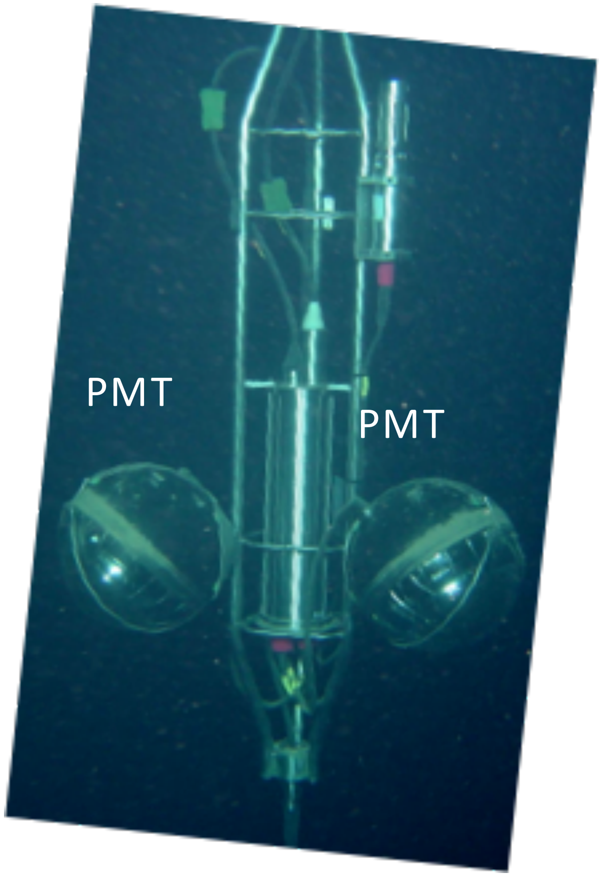
One of the extraterrestrial neutrino events in IceCube - moved to Paris

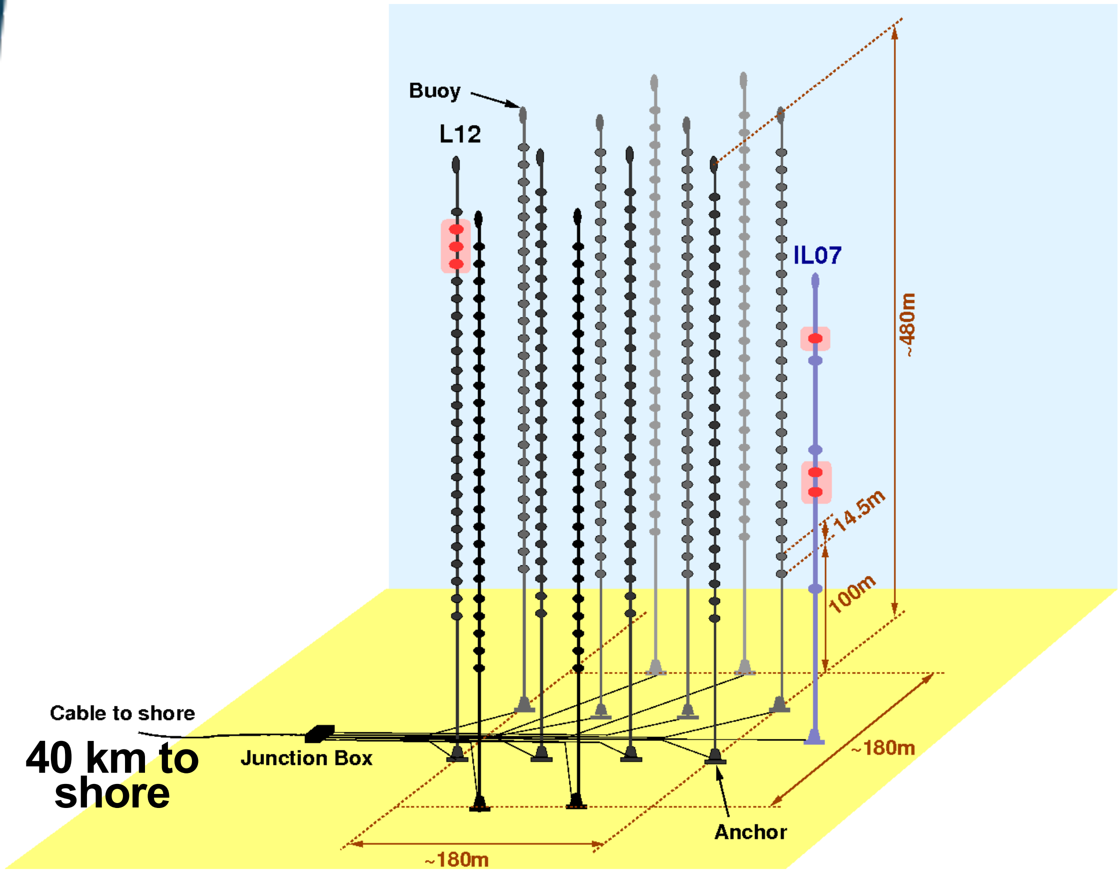
Picture by Doug Cowen, Rencontres de Blois 2013

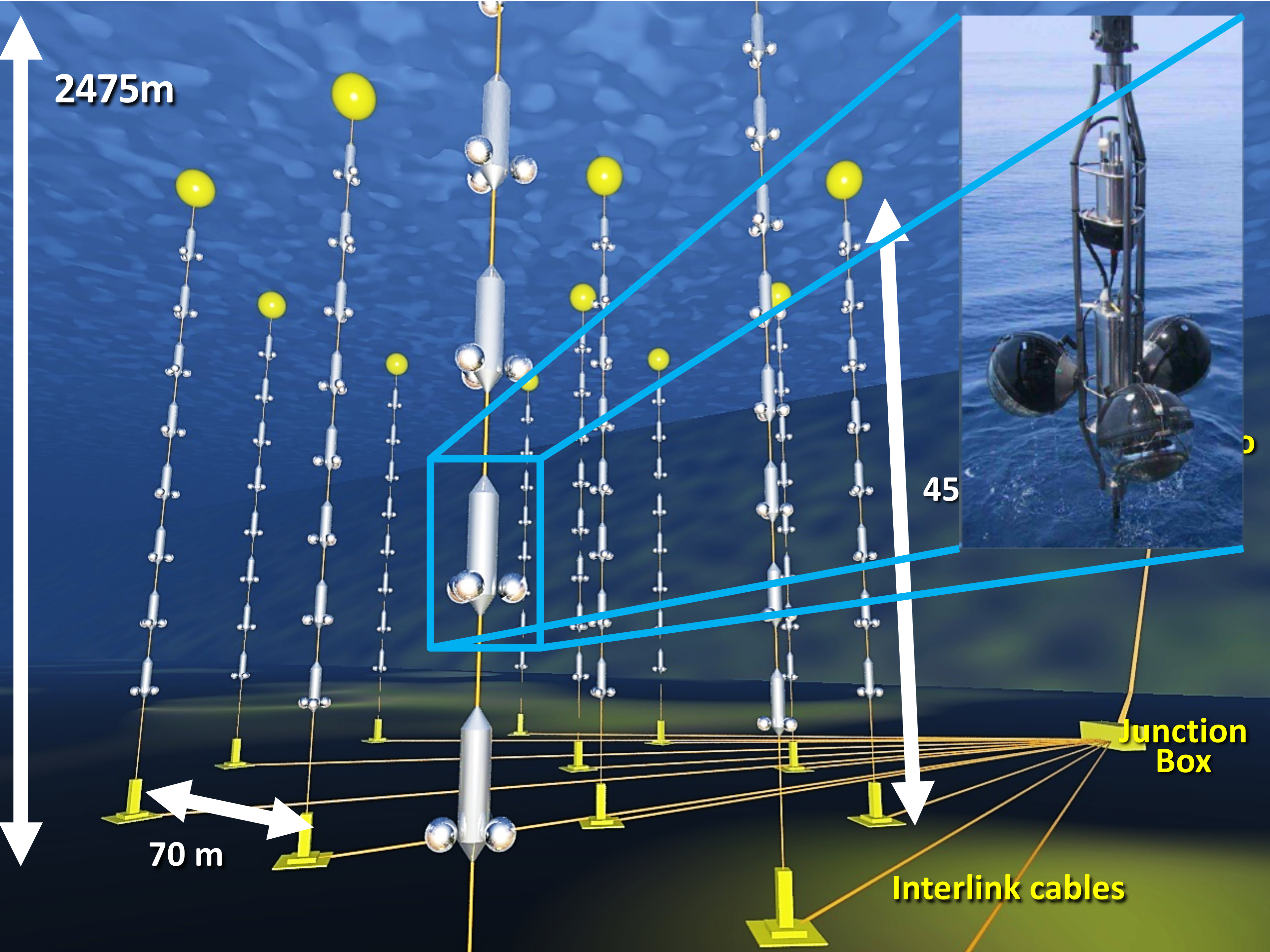
ANTARES



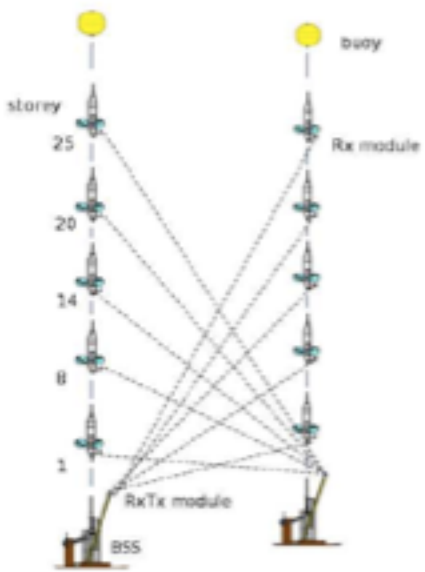
- Running since 2007 at 2475m depth
- 885 10" PMTs
- 12 lines
- 25 storeys/line
- 3 PMTs / storey



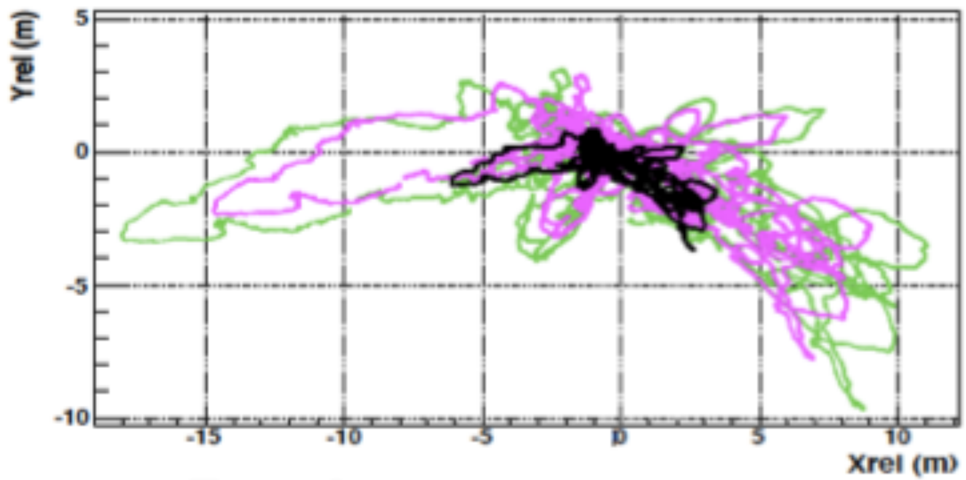


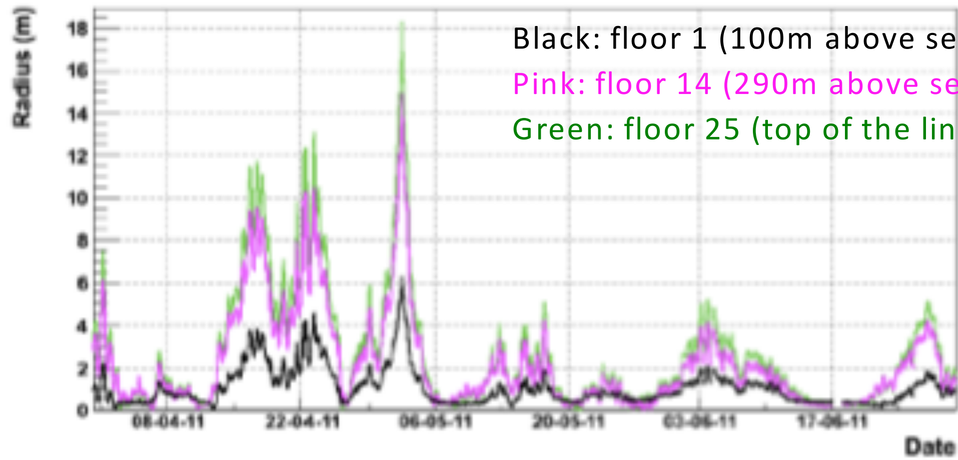

2475m
45
Junction Box
70 m
Interlink cables

Acoustic positioning system



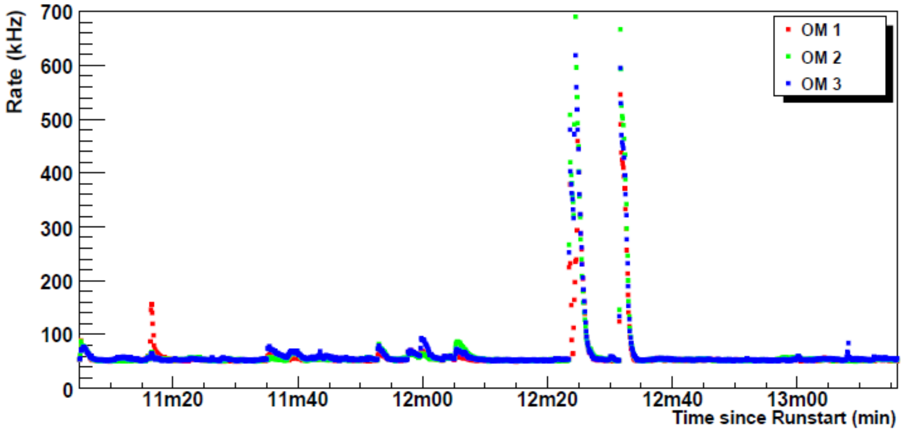
Line movements in 3 months period





Typical sea currents <7cm/s
Monitoring every 2 minutes

Optical backgrounds in the Sea

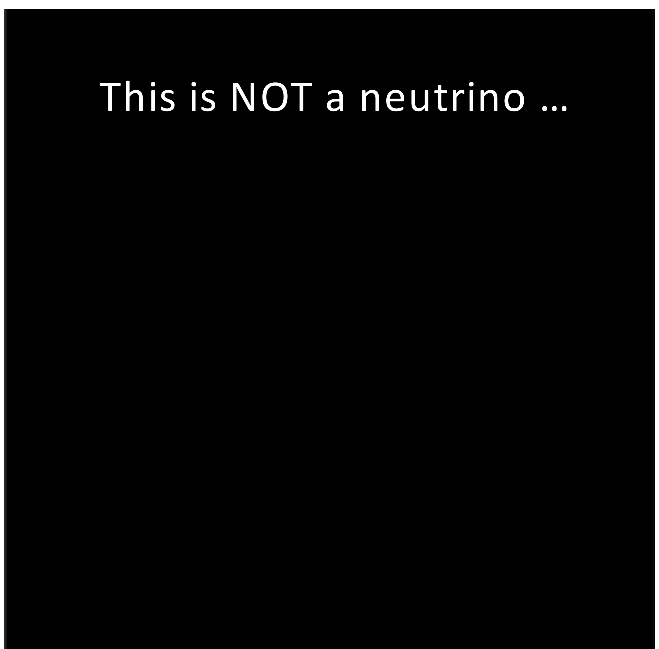


Optical background due to

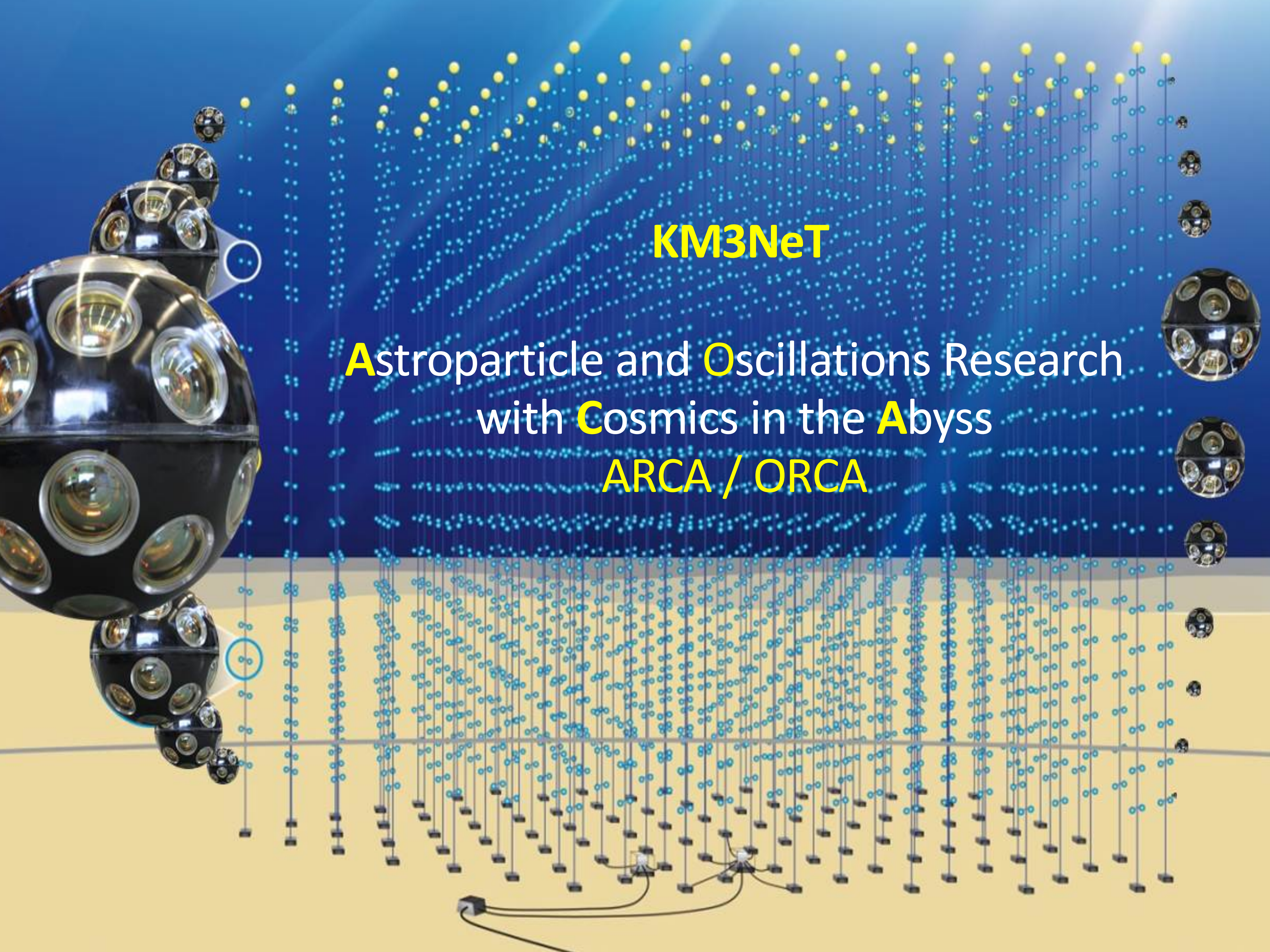
- ^{40}K decay (salt in water)
  -> can be used for calibration

- bioluminescent organisms
  (e.g. megaplankton, pyrosoma, size 0.2-2000mm)

Baseline hit rate 50-120kHz
Short bursts/flashes with higher rates



Video from biocam installed 2010

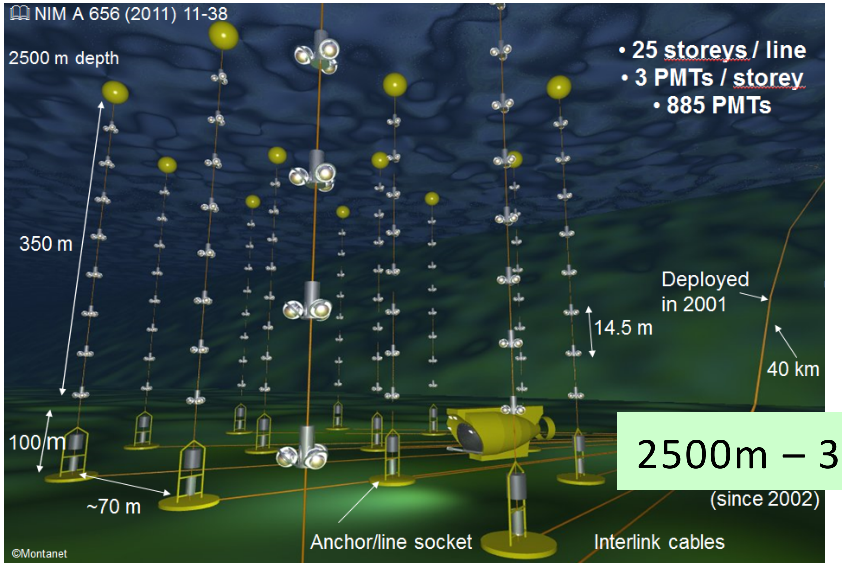

KM3NeT
Astroparticle and Oscillations Research
with Cosmics in the Abyss
ARCA / ORCA

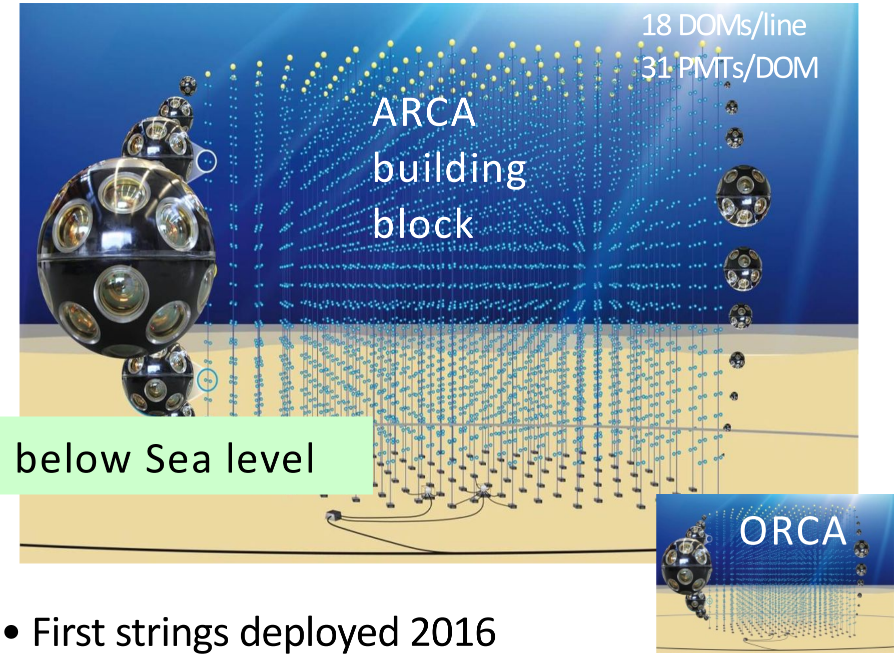
New telescope will be 'second biggest structure created by mankind' after Great Wall of China

- Detector uses 'towers' taller than Burj Khalifa in Dubai
- 'Watches' for light flashes in 2.2 billion kg of water
- Detects tiny, fast-moving particles which usually pass straight through matter

By ROB WAUGH
UPDATED: 10:58 GMT, 27 December 2011

The ANTARES/KM3NeT Neutrino Telescopes





2500m – 3500m below Sea level

- Running since 2007
- 40km from French coast
- 12 lines, 885 10" PMTs

- First strings deployed 2016
- 2x115 strings (128k 3" PMTs) Italian site (ARCA)
- 1x115 strings (64k 3" PMTs) French site (ORCA)

ORCA	ANTARES	ARCA
Low energy	Medium energy	High energy
3 GeV – 50 GeV	10 GeV < E < 1 TeV	E >> 1 TeV

Earth and Sea sciences: Oceanography, Biology, Geology, Climate monitoring

Atmospheric neutrinos
Neutrino oscillations
Neutrino mass ordering

Dark Matter
Exotics

Cosmic Sources

Status of ARCA/ORCA

ARCA

- 2 strings operated til April 2017, interruption, attempt to repower again later this year
- Full restoration of sea-bed network by mid-2019

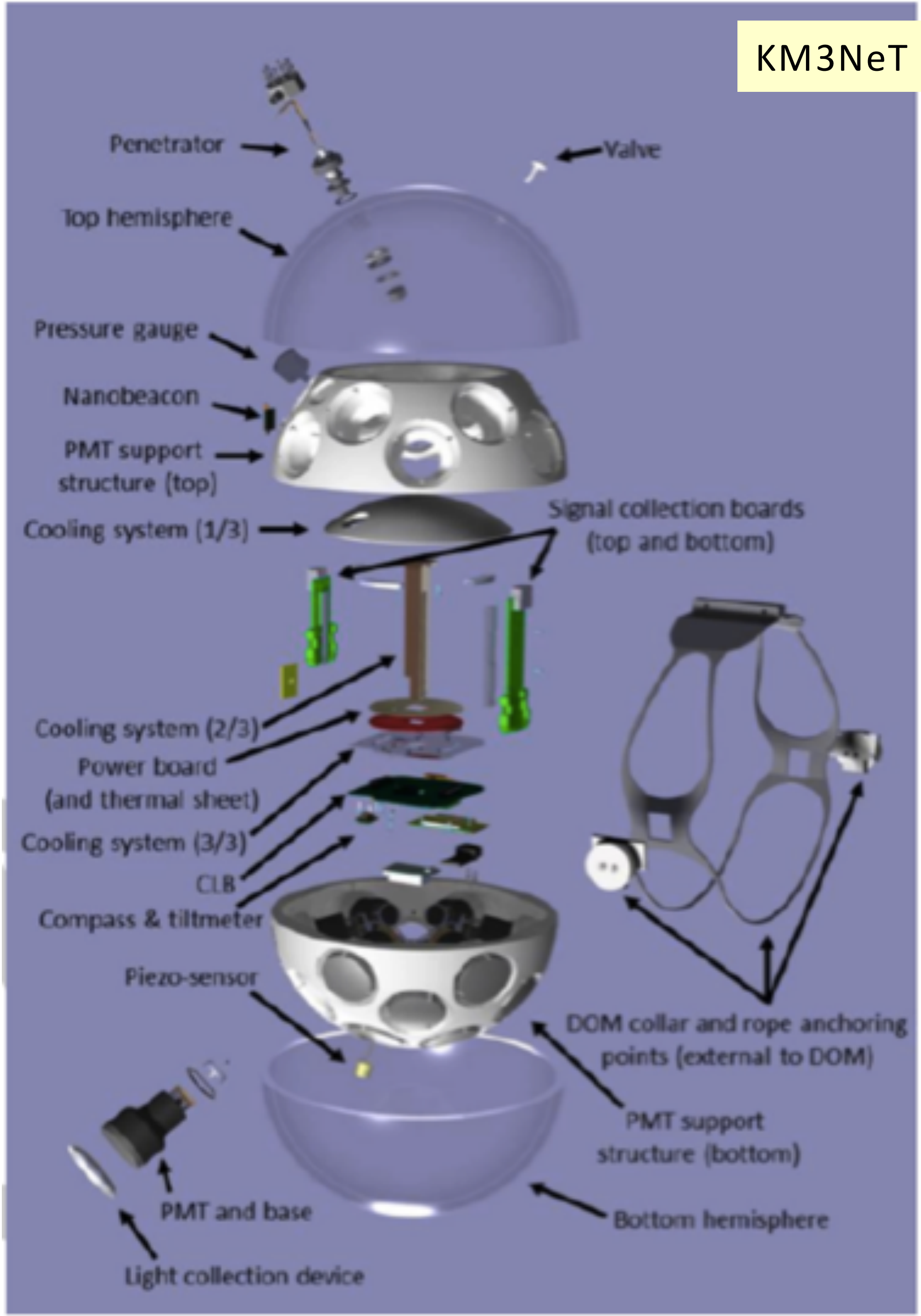
ORCA

- Successful deployment & operation of first string (Sept 2017)
- Cable problem, replacement in summer 2018, resume operations thereafter

Construction

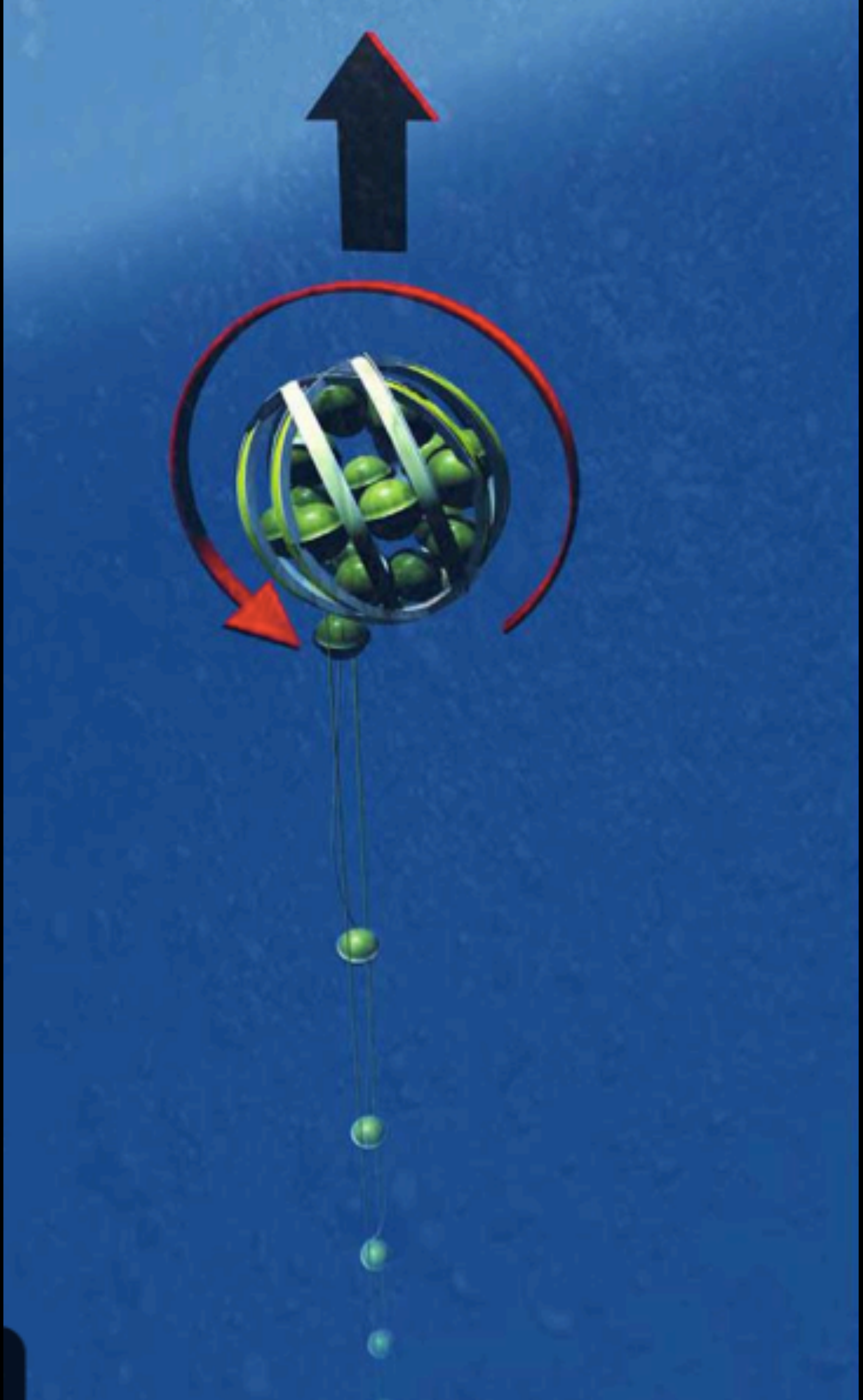
- DOM and detector string assembly proceeding
- Construction & Deployment feasible til -2023 (depending on funds)

KM3NeT Digital Optical Module




DOM 117
DOM 109
9161
TOP 9265
DOM 116
9262
9264
TOP
BOT
DUMMY DOM
Cooling mushroom


150 KG

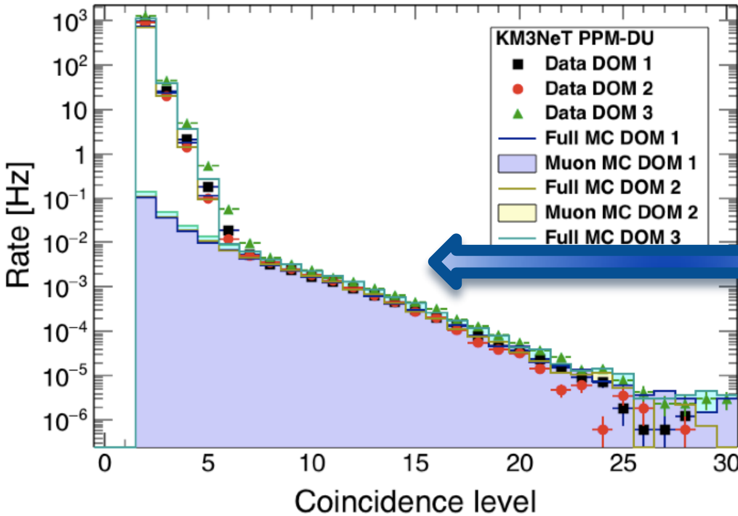


Deployment

ARCA deployment

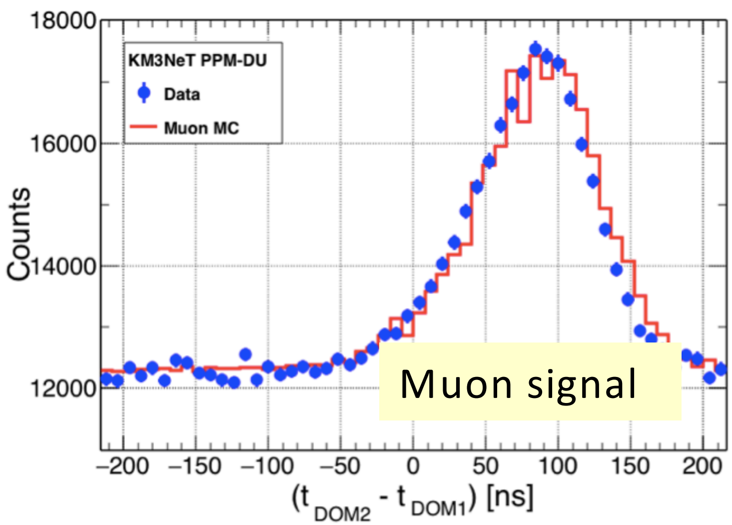
Multifold coincidences

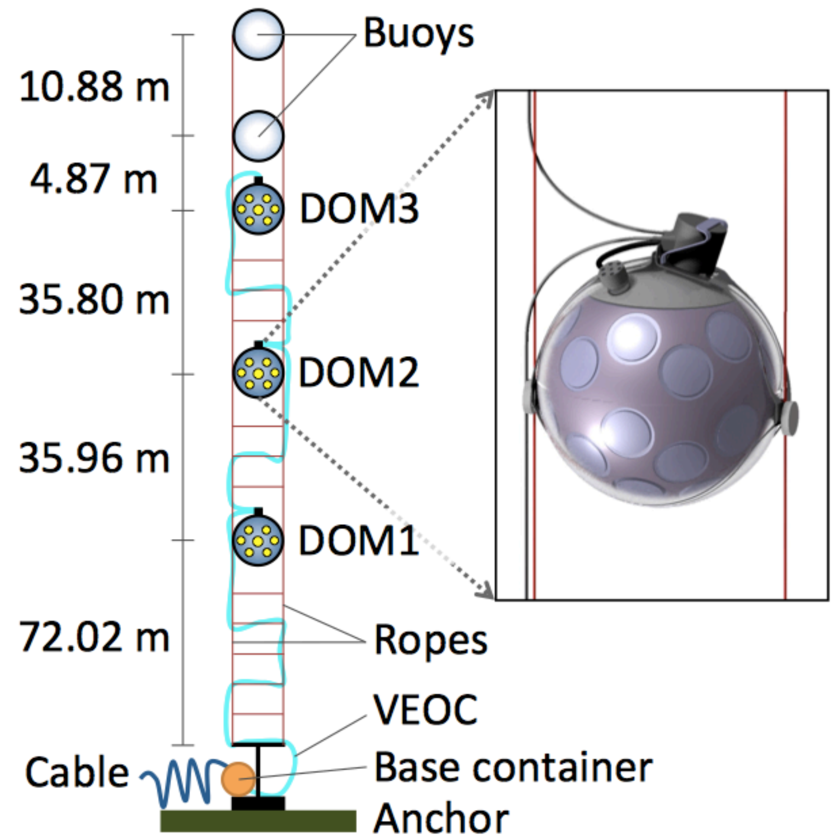
First results from mini-string with 3 DOMs



Muon identification with a single DOM (high multiplicity of coincident signals)

Signal time differences between 2 DOMs



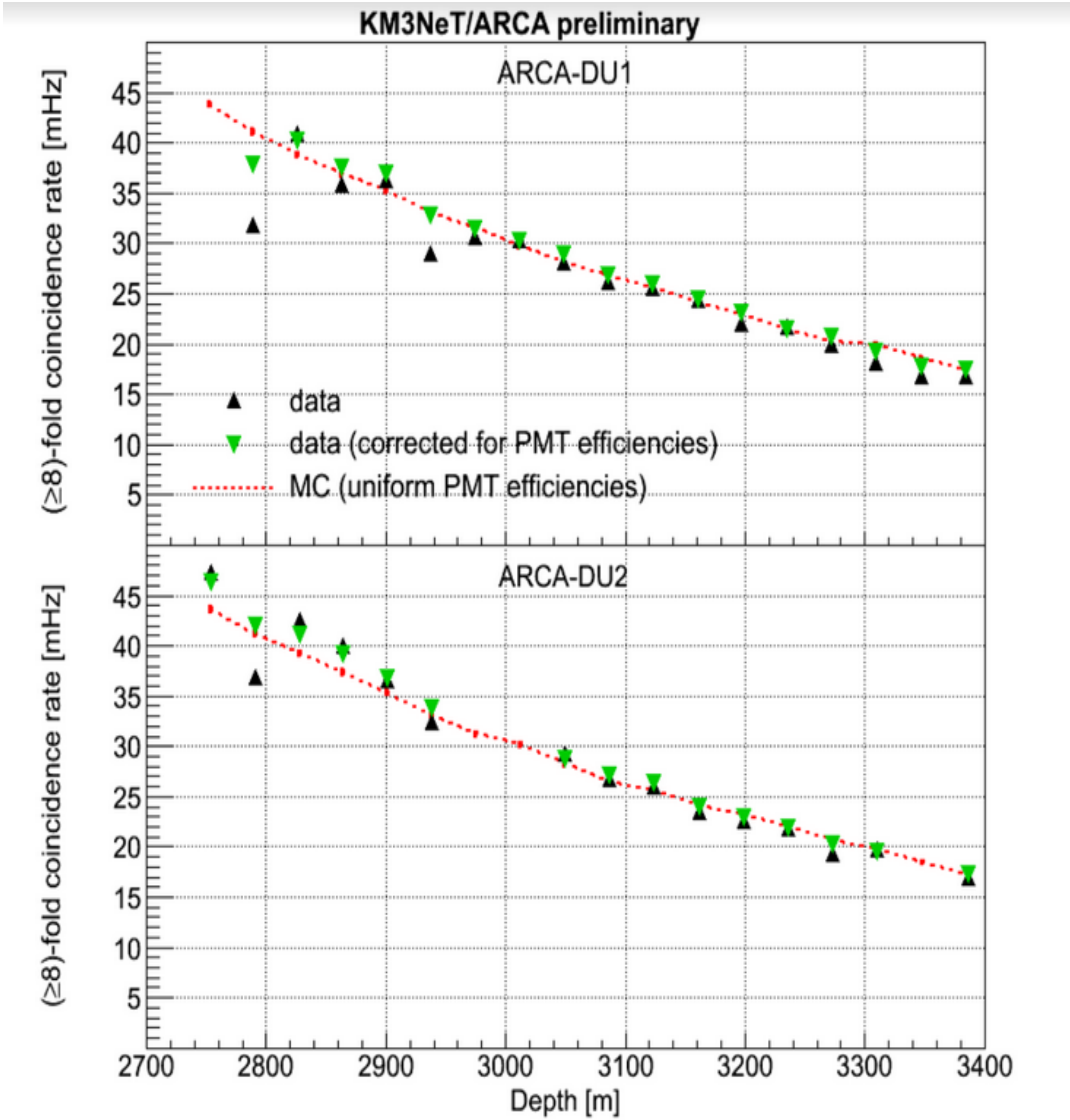


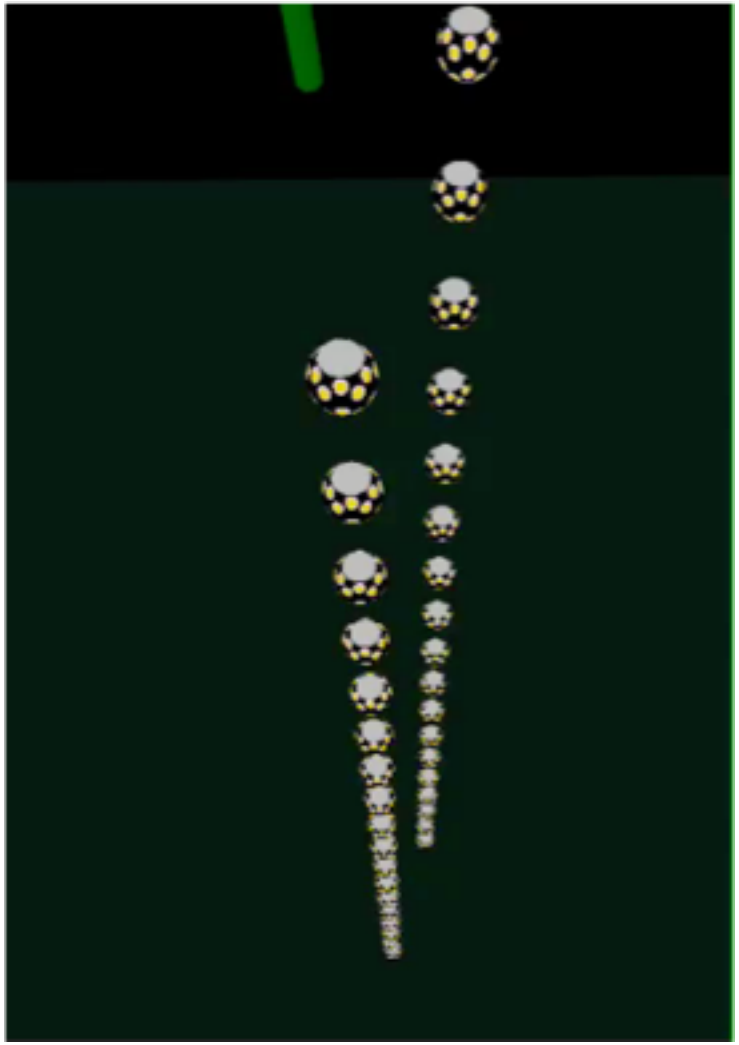
Results from 2 full ARCA strings

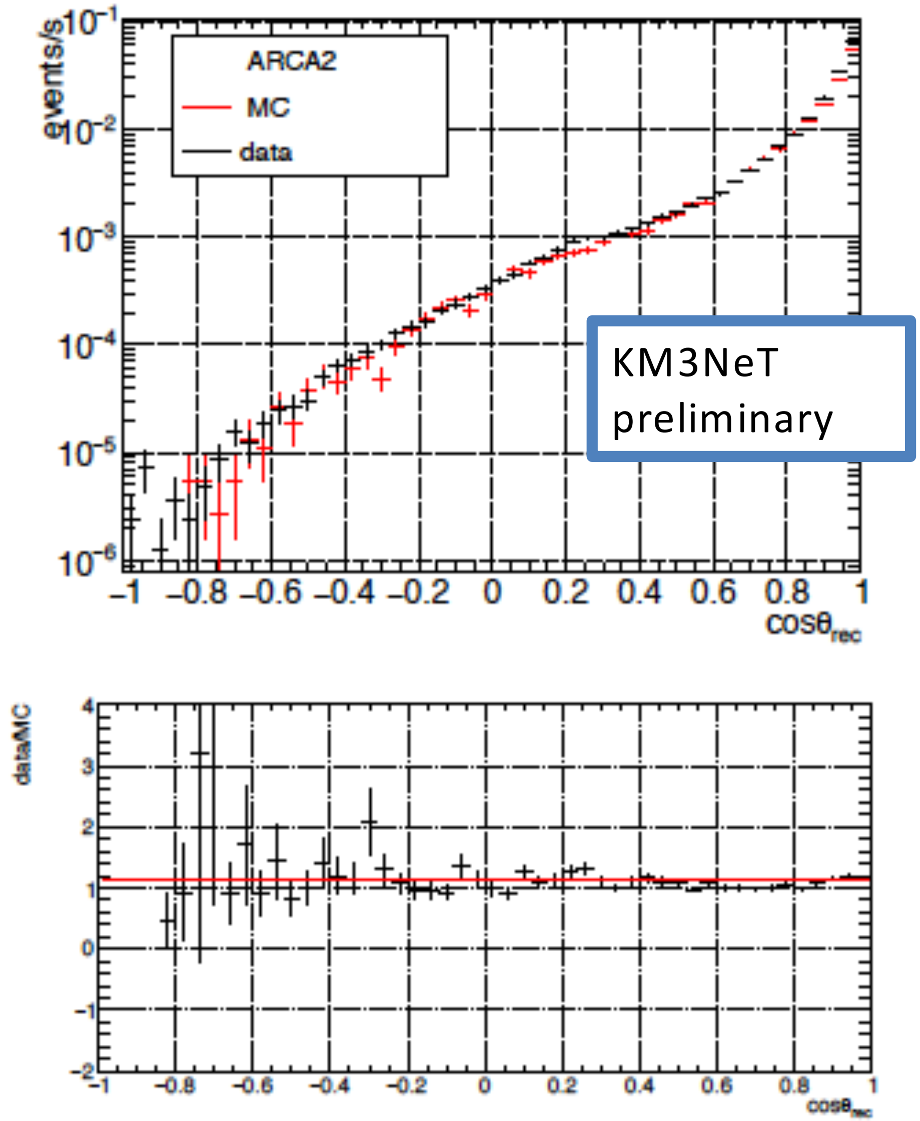
Muons identified by high multiplicity on single DOMs

⇒ Muon rate as function of depth

Efficiency correction from K40 calibration



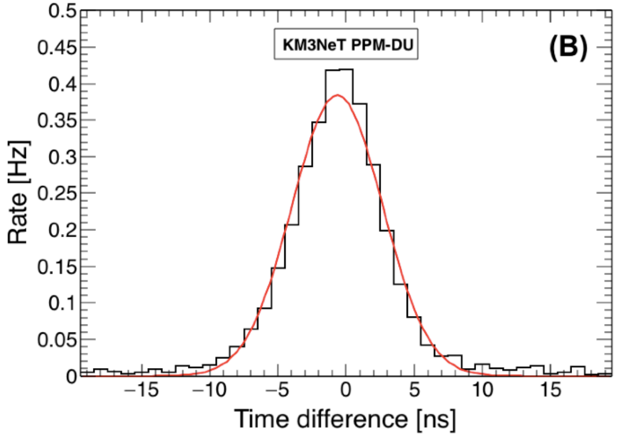




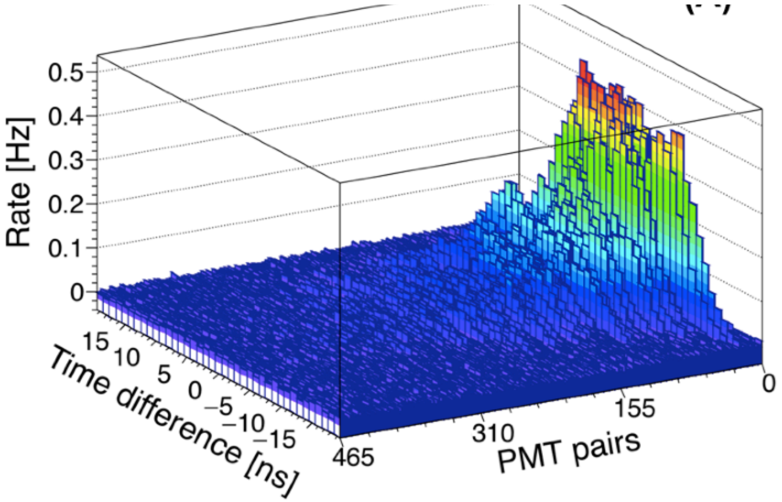
events/s
ARCA2
MC
data
cosθrec
data/MC
KM3NeT
preliminary

Calibration using potassium decay in sea water

Hit time differences from a PMT pair



Hit time differences – all pair combinations



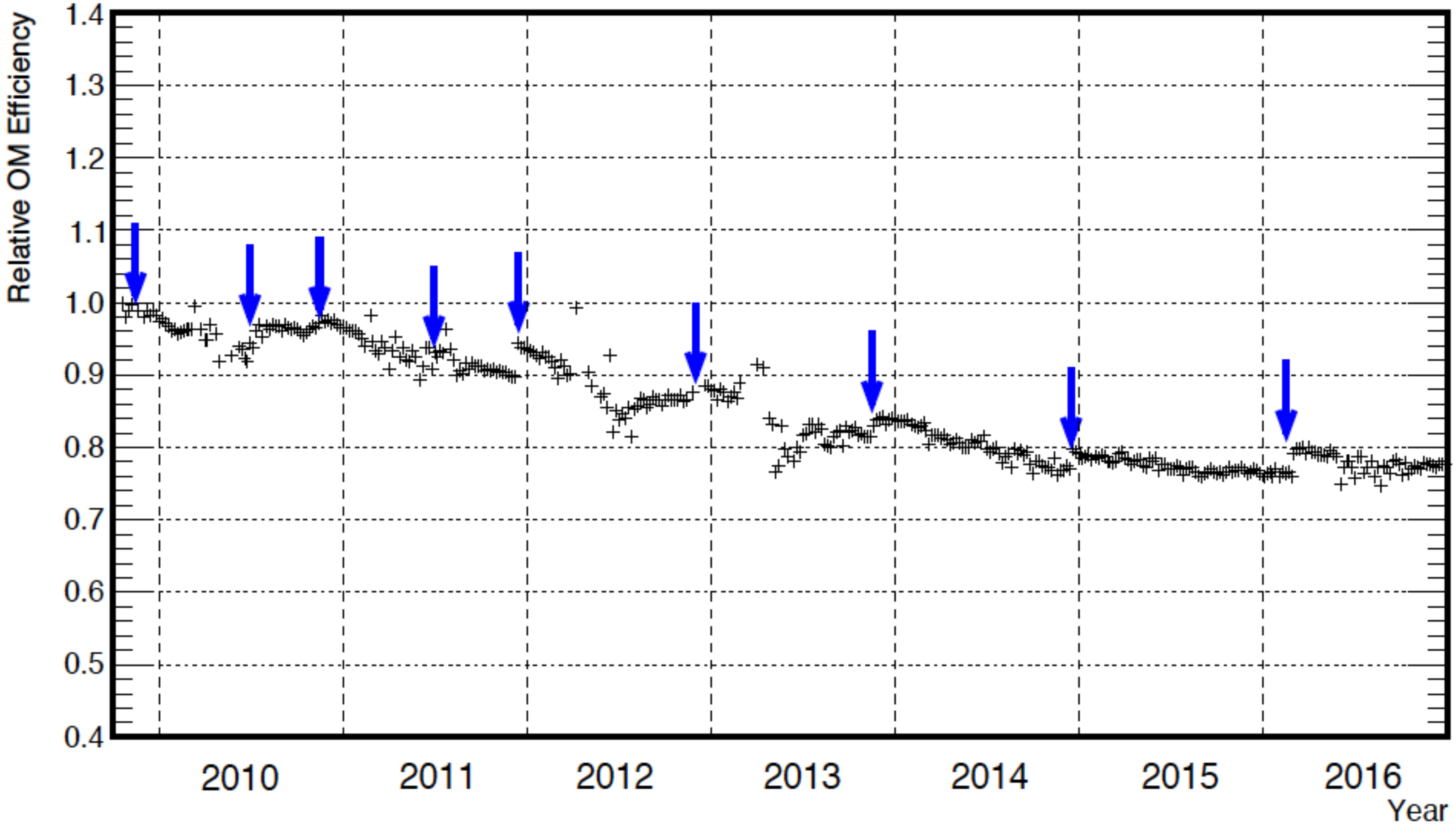
^{40}K beta - decay (salt in seawater) -> light signal can be used for calibration

Correlated signal between PMT pairs:

- Height => Efficiency determination
- Position => Time calibration (nanosecond accuracy)
- Width => Time spread of PMT

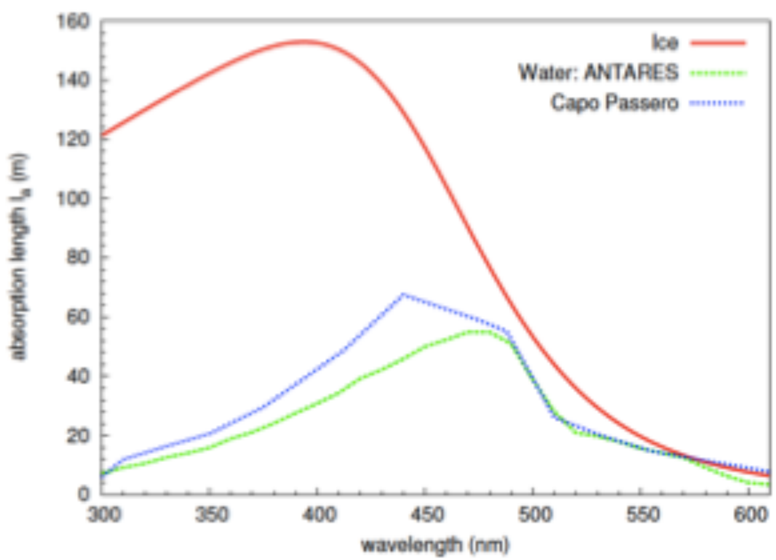
Antares K40 measurements

- After 7 years, 20% efficiency drop (blue : HV tuning)
- Long-term operation in deep sea possible

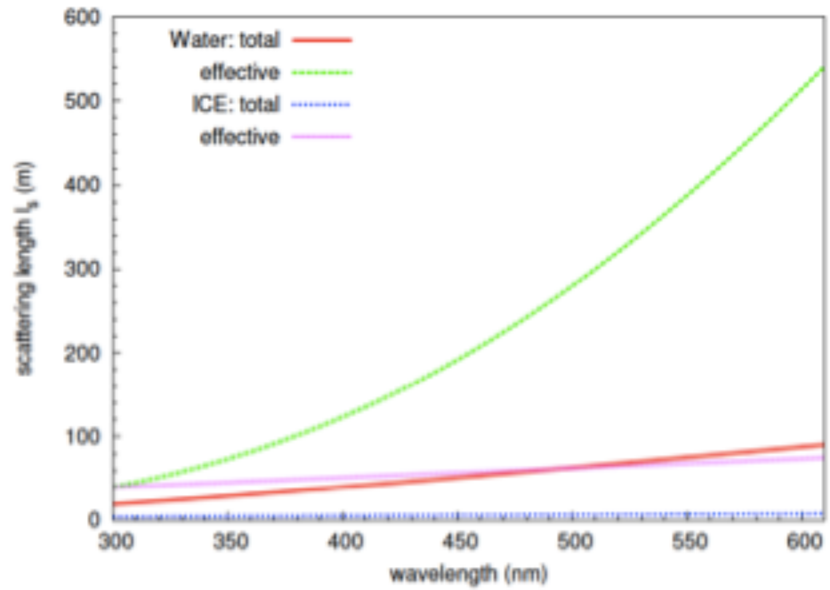


Different absorption/scattering properties at the different sites

absorption



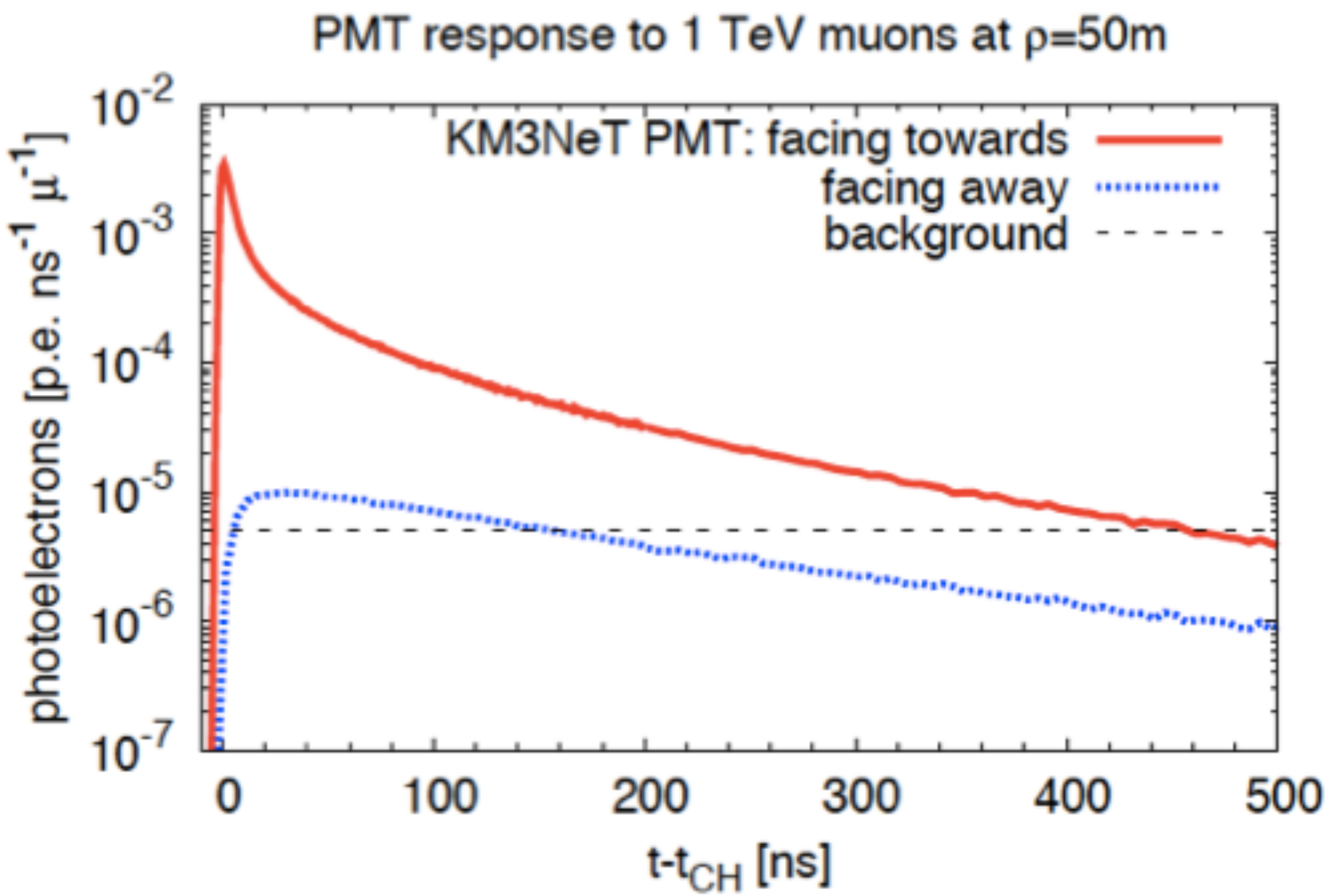
scattering



For Ice properties are depth dependent
-> different dust layers

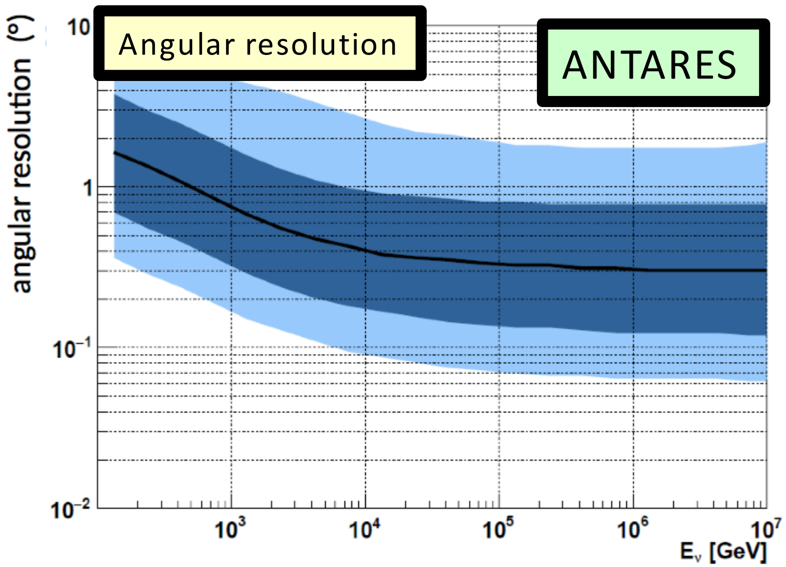
For Lake Baikal significantly lower absorption/scattering lengths than in Mediterranean water (~20m)

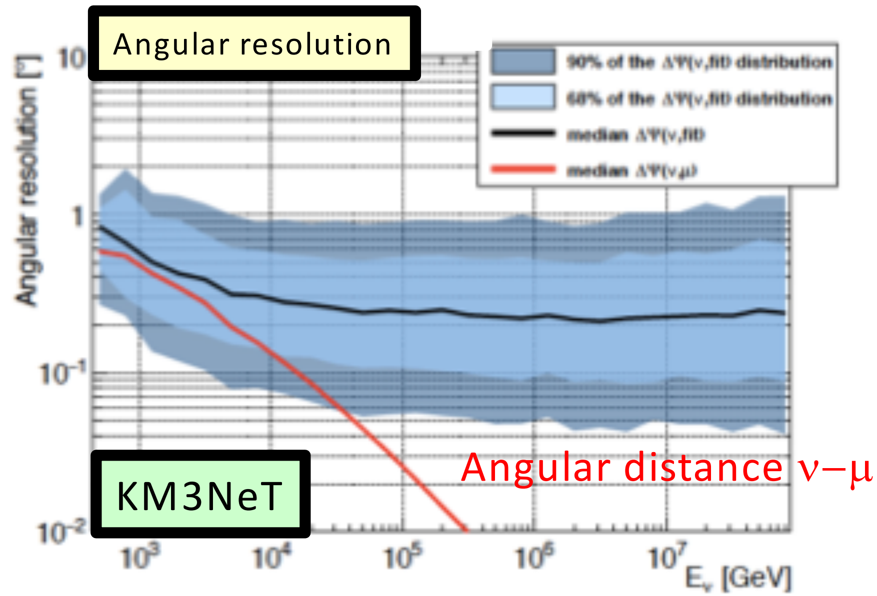
Time residual distribution for signals from a muon in water

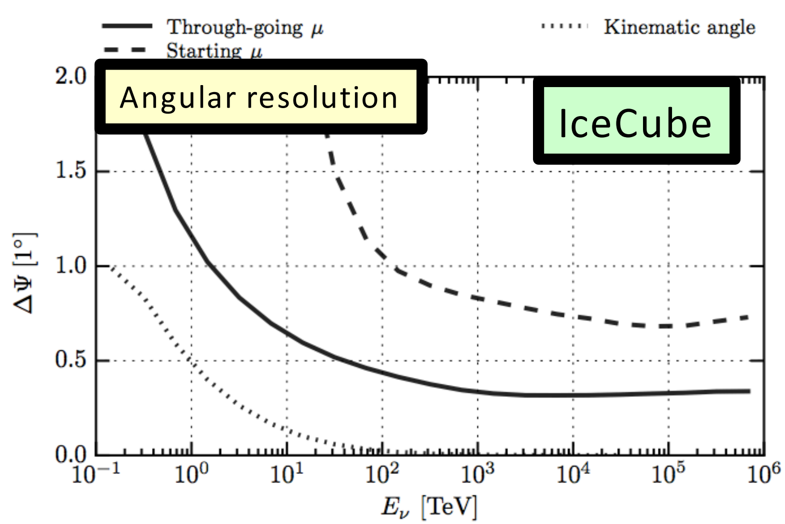


Large scattering length => at 50m still extremely precise time information

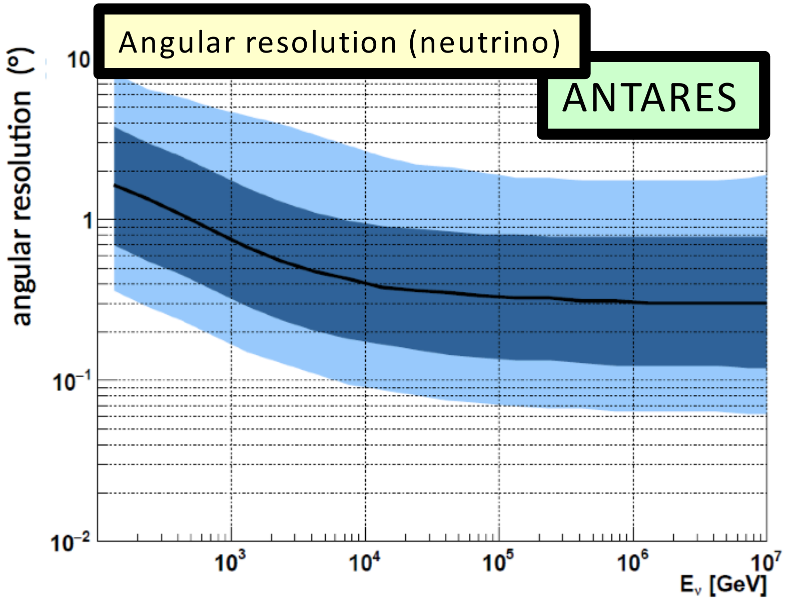
Track reconstruction performance

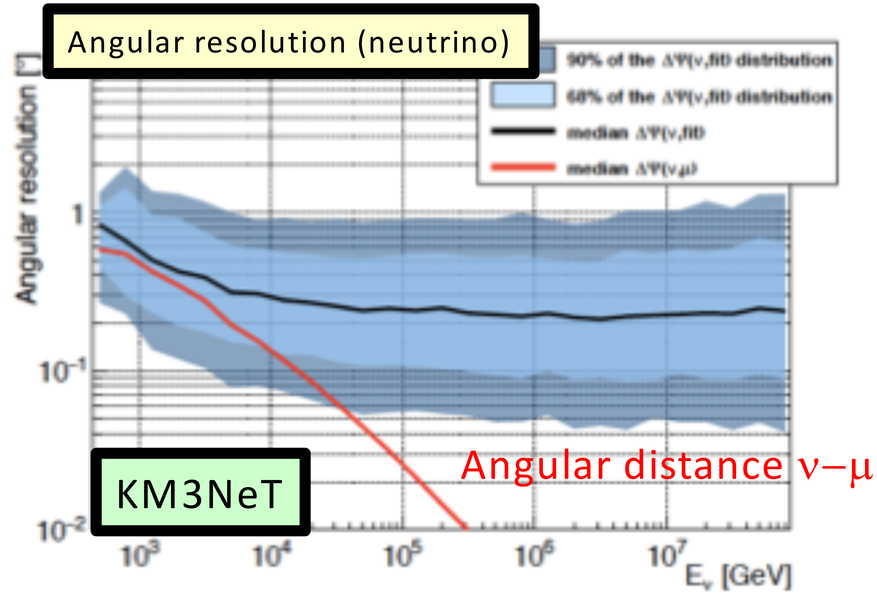


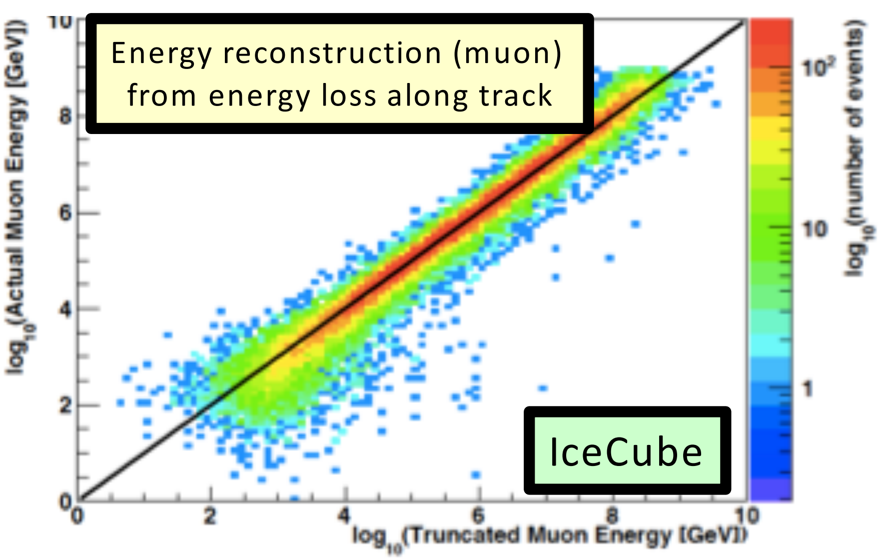


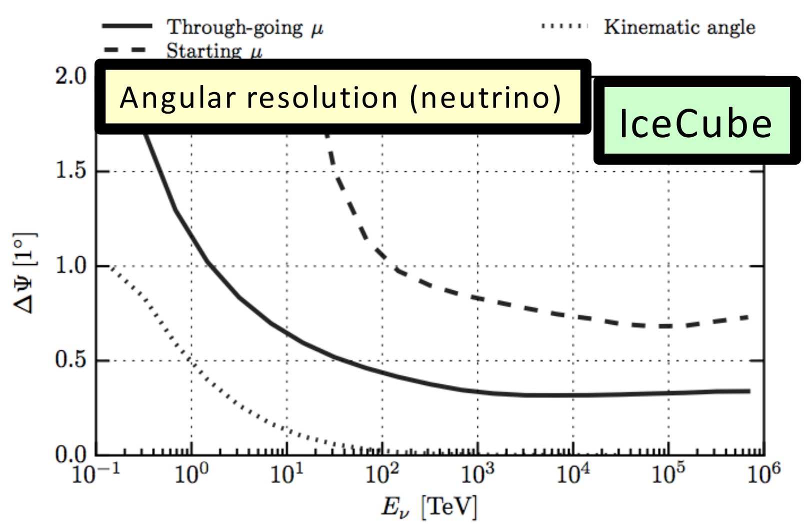


Track reconstruction performance



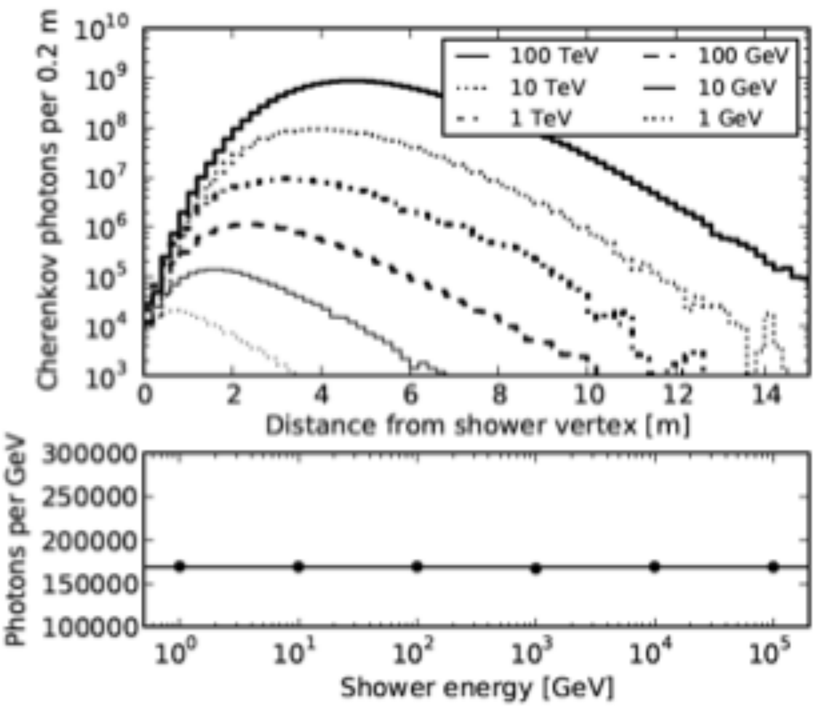




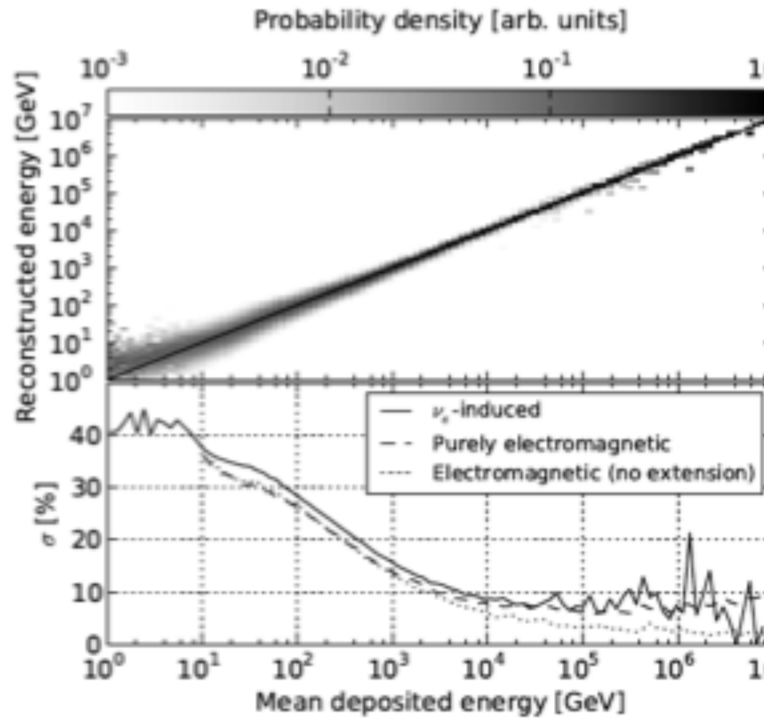


Shower reconstruction performance

Photon yield as function of distance



Energy reconstruction



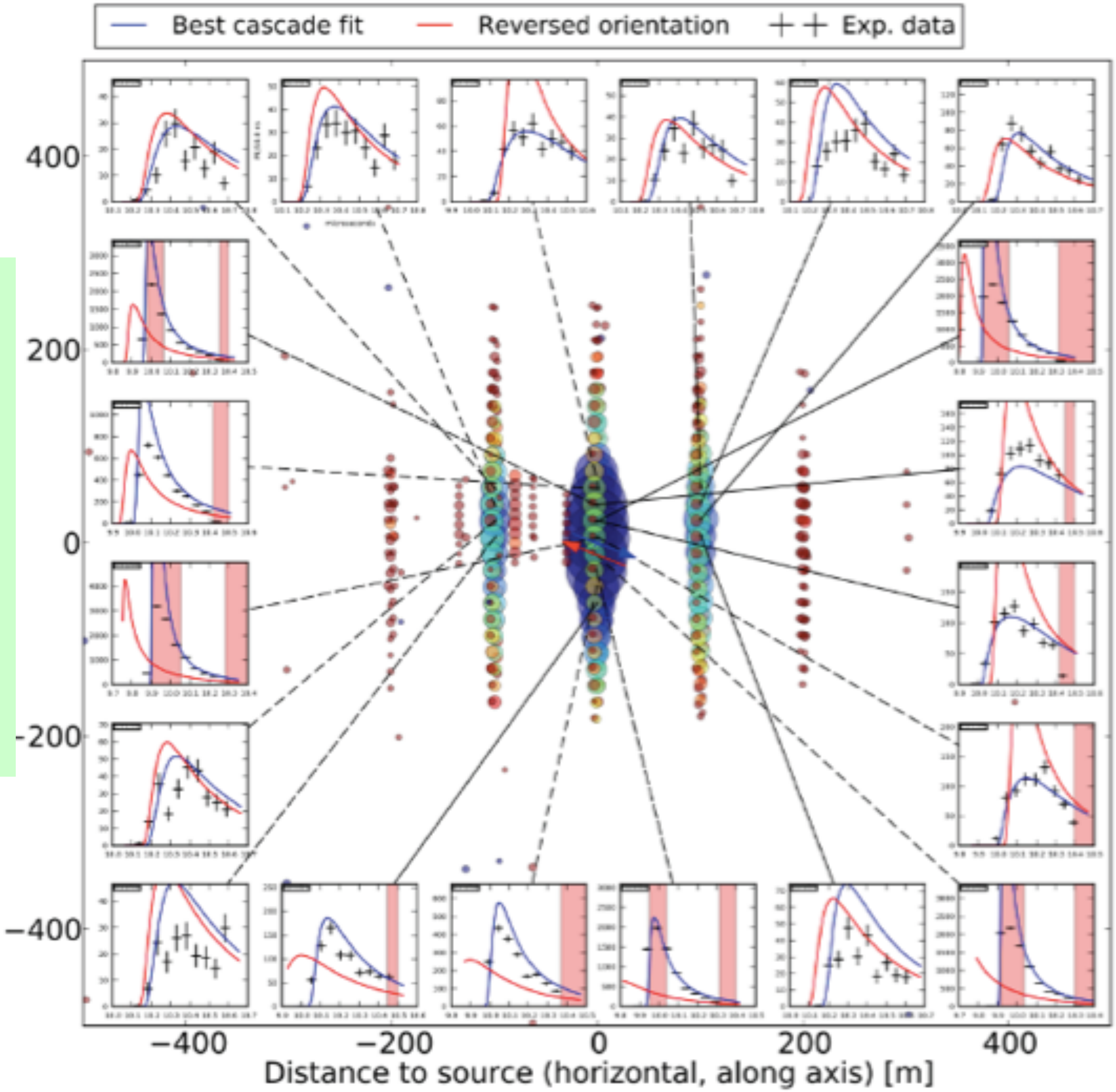
IceCube, JINST 9 (2014), P03009

IceCube
High energy
cascade 'Bert'

Likelihood fit on the waveforms

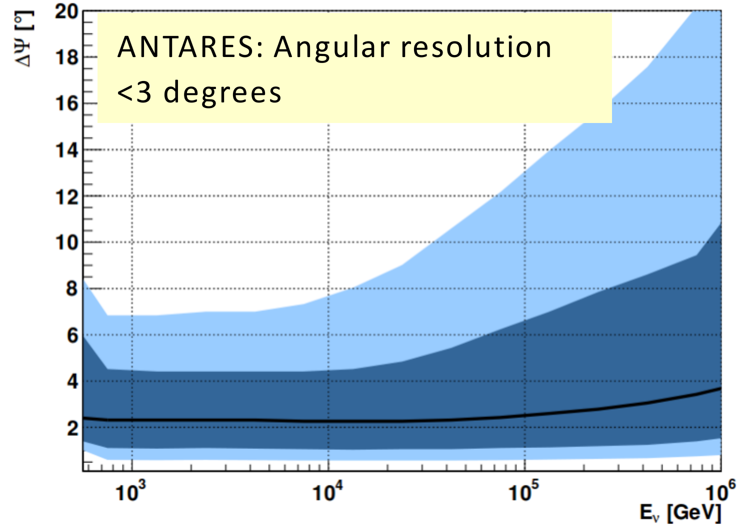
Shaded areas disregarded (saturation/ Systematics)

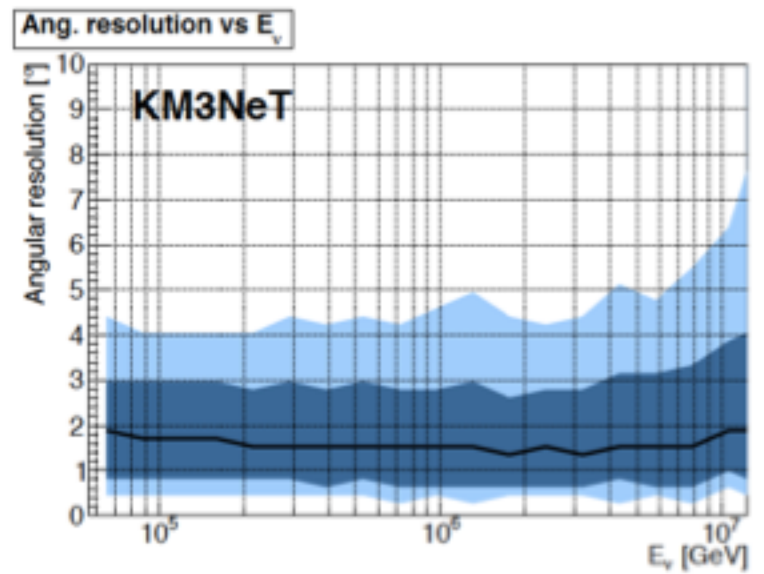
High energy events direction resolution 7-25 degrees

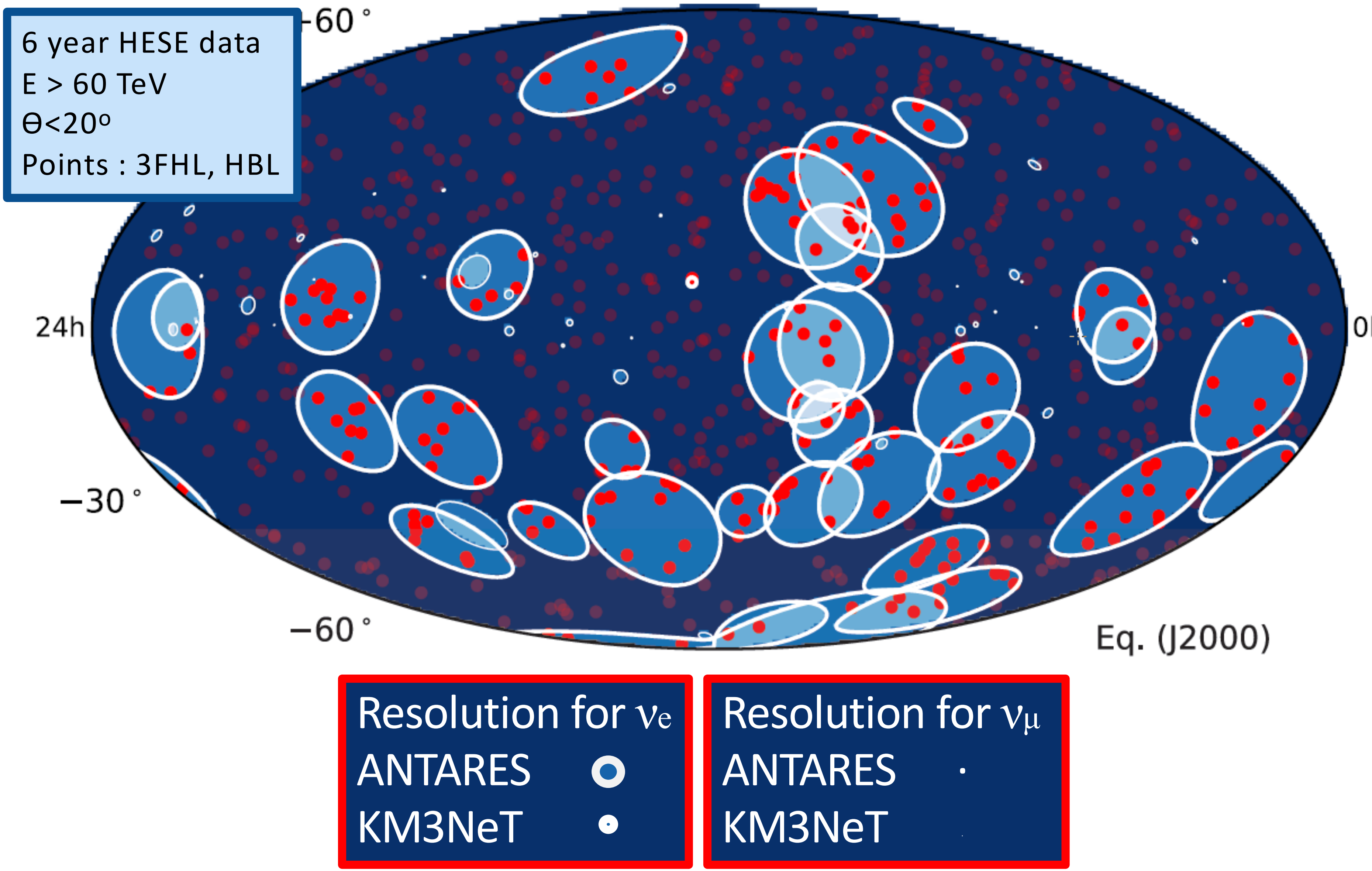


Shower reconstruction performance

Shower light contains directional information
-> little scattering in water
-> angular resolution ~2 degrees





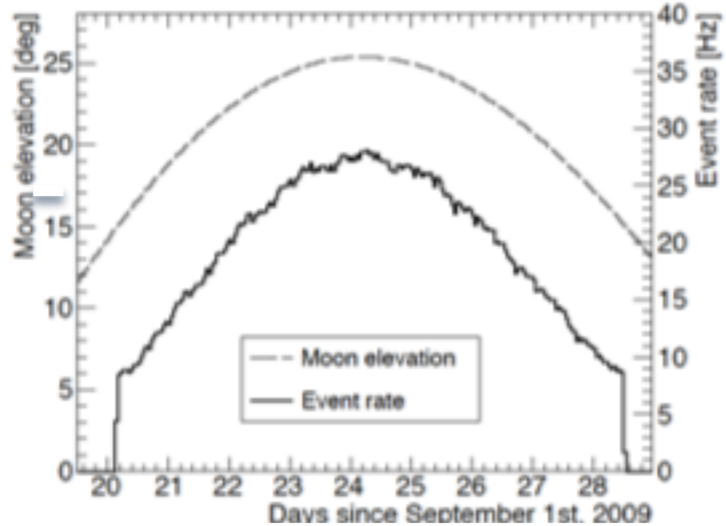


From Resconi/Heijboer ICRC 2017

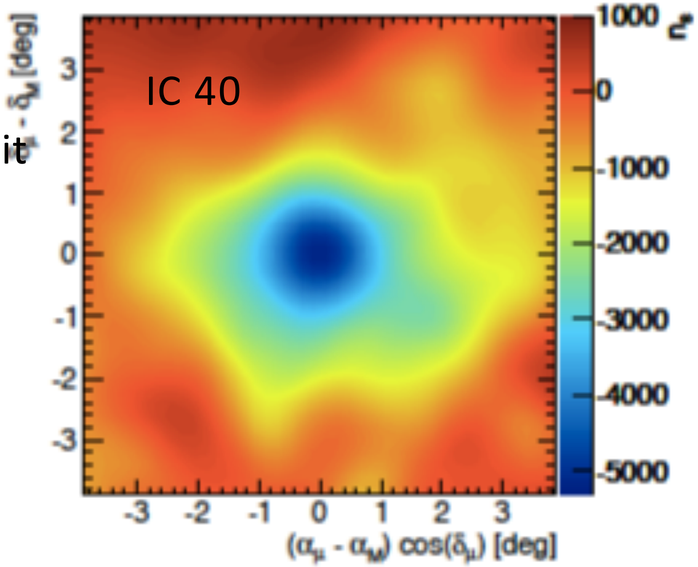
Pointing: Only calibration source: The Moon (Sun)

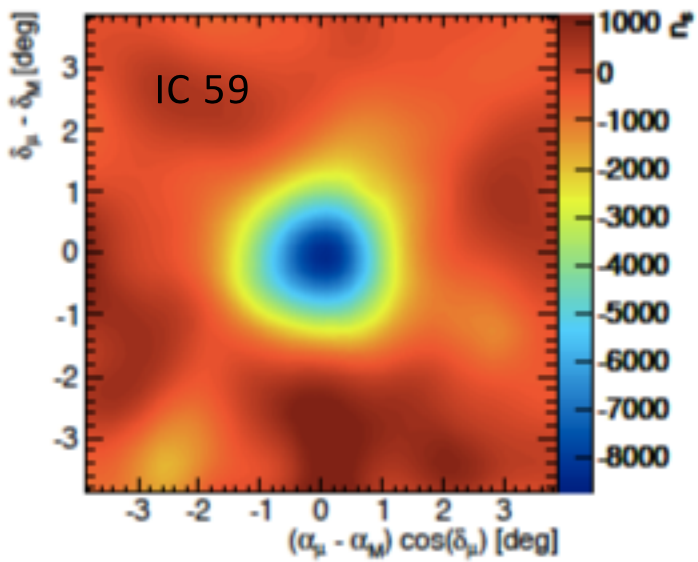
Cosmic ray ‘hole’ in direction of moon
-> look at downward going muons

IceCube measurement of the moon
-> cross check of pointing,
angular resolution



Fitted deficit events





A. CPU performance requirements of major current and future astroparticle physics projects

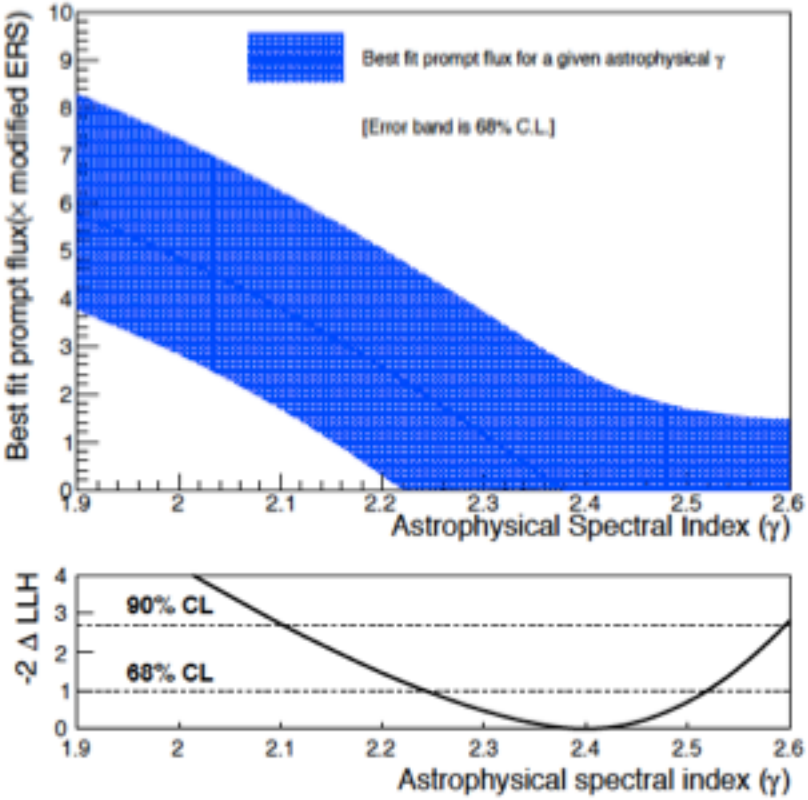
Unit is HS06

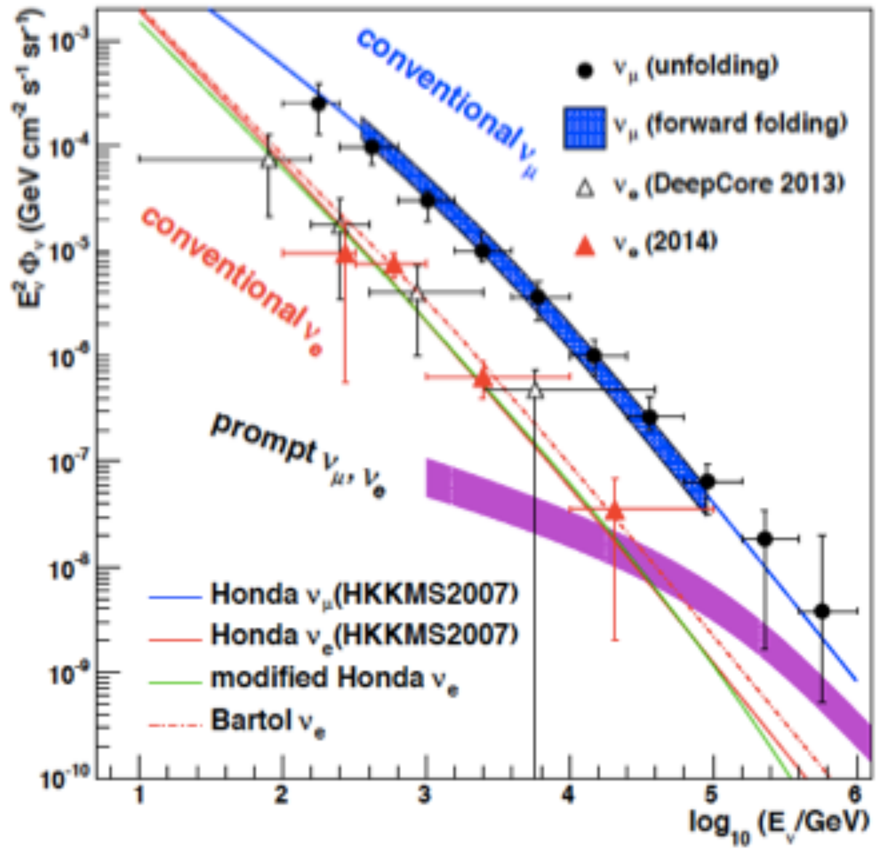
Towards a Model for Computing
In European Astroparticle Physics
arXiv 1512.00988

		2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
data with event-like structure	AUGER (total)	1,4	2,2	2,6	3,5	4,6	4,6	4,6	4,6	4,6	4,6
	HESS	1,6	2,0	10	14	16	16	16			
	MAGIC	0,8	0,8	8,0	8,0	8,0	8,0	8,0			
	CTA	10	10	10	10	10	10	24	30	40	50
	ANTARES	1,6	2,9	5,7	5,7	5,7					
	KM3NeT			0,5	0,5	3,0	10	20	50	100	200
	IceCube	15	15	15	15	15	15	15	15	15	15
	FERMI	15	15	15	15	15	15	15			
	AMS	2,3	9,0	30	50	60	70	80	90	100	110
	subtotal	*48*	*57*	*97*	*122*	*137*	*149*	*183*	*190*	*260*	*380*
data with signal-like structure	VIRGO	2,0	2,3	3,0	8,0	12					
	advanced VIRGO						30	50	80	90	90
	LIGO			80	80	80					
	advanced LIGO						750	1200	1200	1200	1200
	subtotal	*2,0*	*2,3*	*83*	*88*	*92*	*780*	*1250*	*1280*	*1290*	*1290*
data with image-like structure	PAU	10	40	110	90	90	90	90	90	90	90
	SNLS	1,0	1,0	1,0	1,0	1,0					
	EUCLID			0,2	0,5	6,2	13	19	25	31	38
	LSST			0,2	0,5	6,2	14	28	43	57	152
	subtotal	*11*	*41*	*111*	*92*	*103*	*117*	*137*	*158*	*178*	*280*
	Other	2	2	2	2	2	2	2	2	2	2
	CPU (kHS06) total	**63**	**102**	**293**	**304**	**335**	**1047**	**1572**	**1629**	**1730**	**1951**
	LHC Tier-0(2012)	0,096	0,16	0,45	0,47	0,51	1,6	2,4	2,5	2,7	3,0

(Selected) Measurements

Atmospheric flux measurement



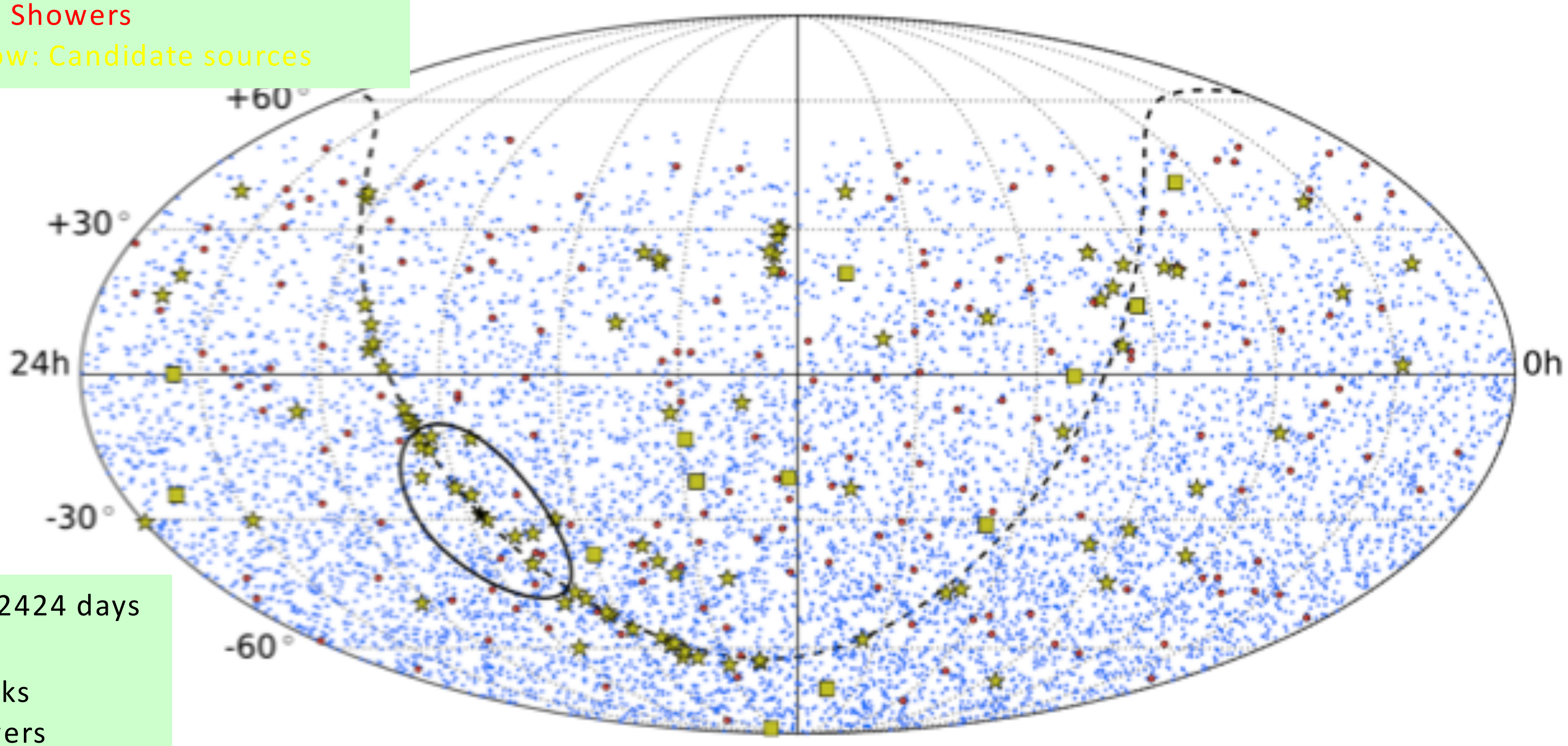


Neutrino sky seen by Antares
(9 years, equatorial coordinates)

Antares
~10^6 atmospheric muons per day
~3 atmospheric neutrinos per day
IceCube
~10^8 atmospheric muons per day
~300 atmospheric neutrinos per day

Quality important to eliminate misreconstructed muon signals

Blue: Tracks
Red: Showers
Yellow: Candidate sources

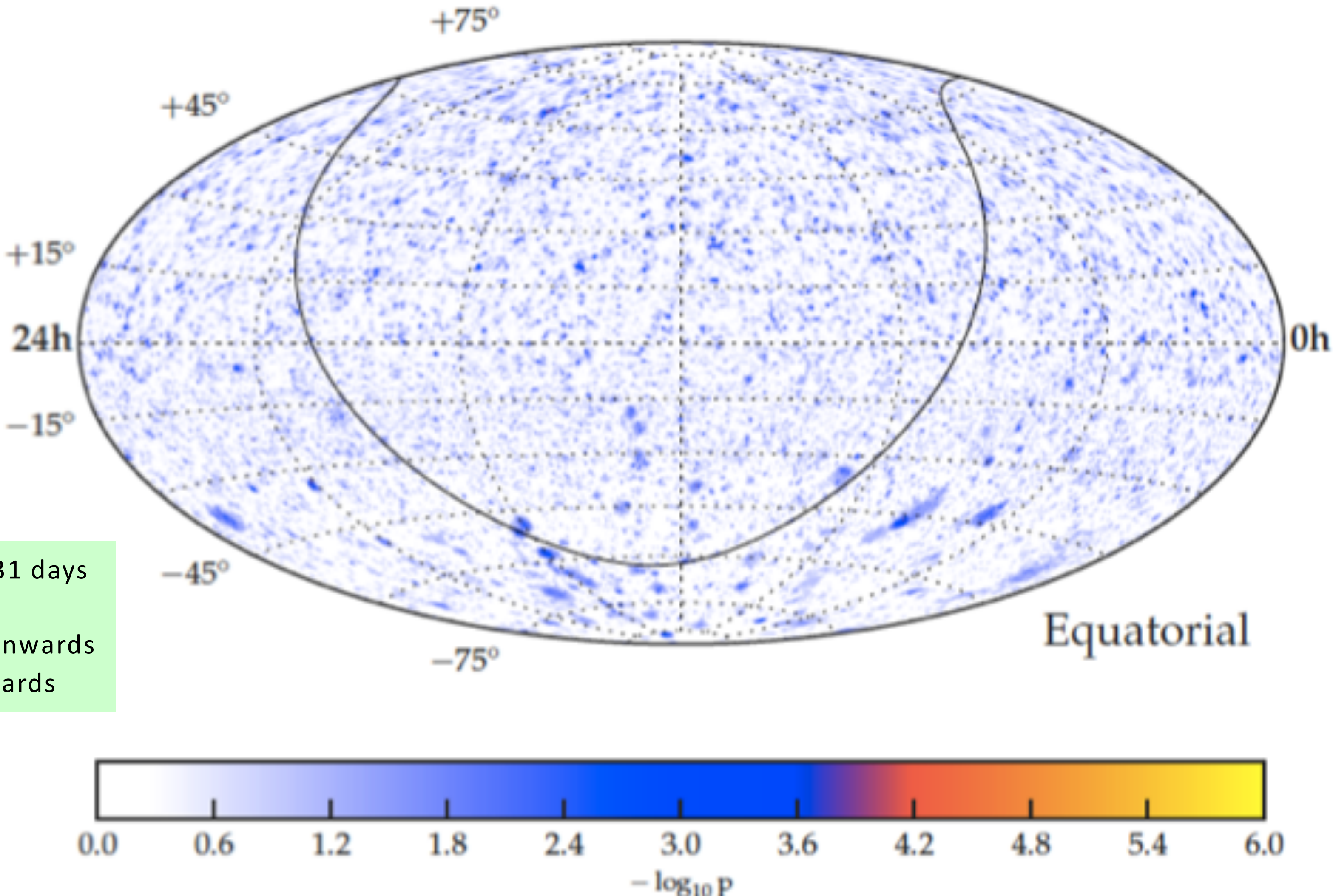


Livetime 2424 days
Events:
7629 tracks
180 showers

IceCube 7 year Skymap (probabilities)

Spatial clustering and energy evaluated for signal and background hypothesis

$$\log \Lambda = 2 \log \frac{\mathcal{L}(n_S, \gamma)}{\mathcal{L}(n_S = 0)}$$



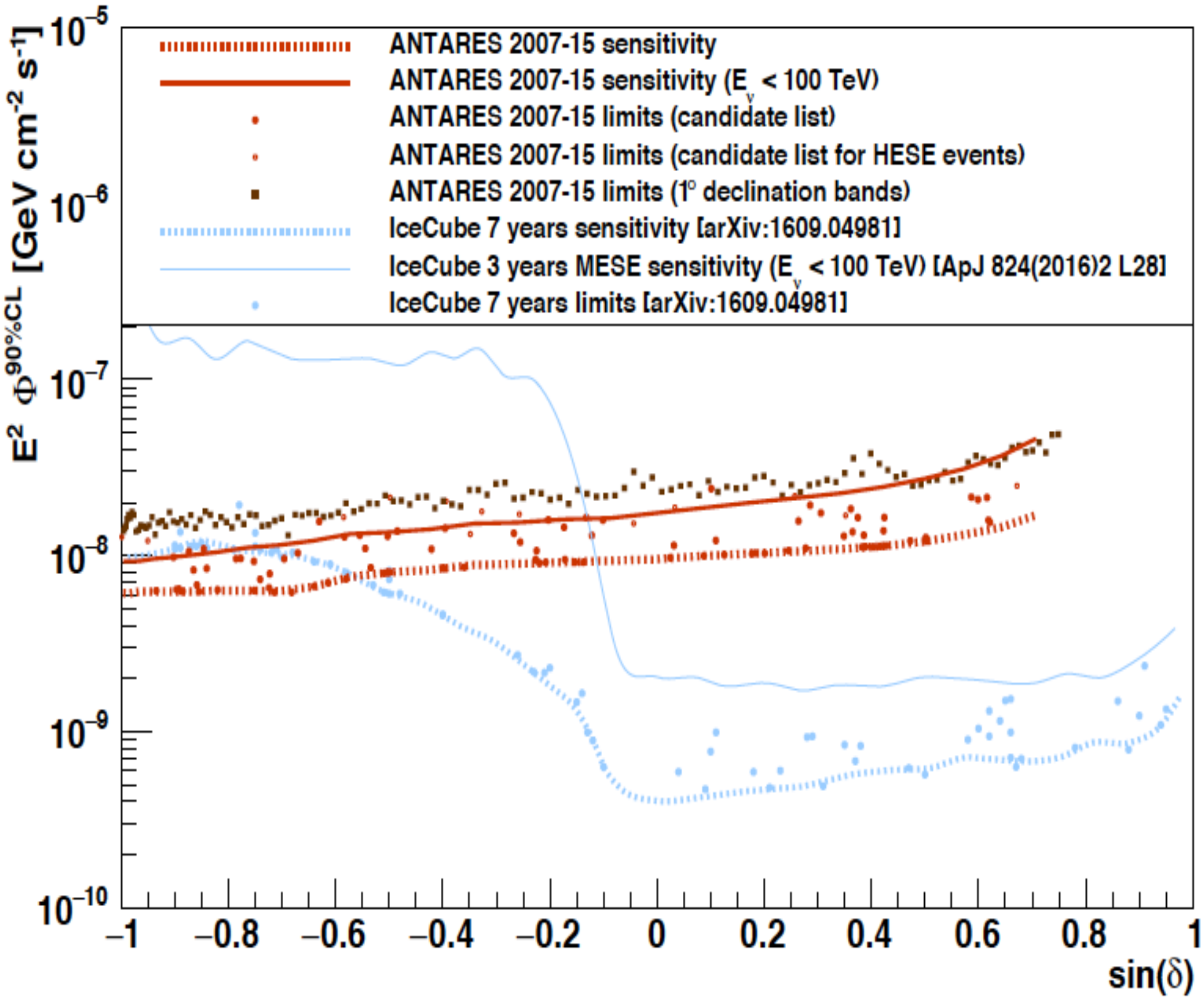
Livetime 2431 days
Events:
289078 downwards
422791 upwards

No significant excess -> Upper limits on point source fluxes

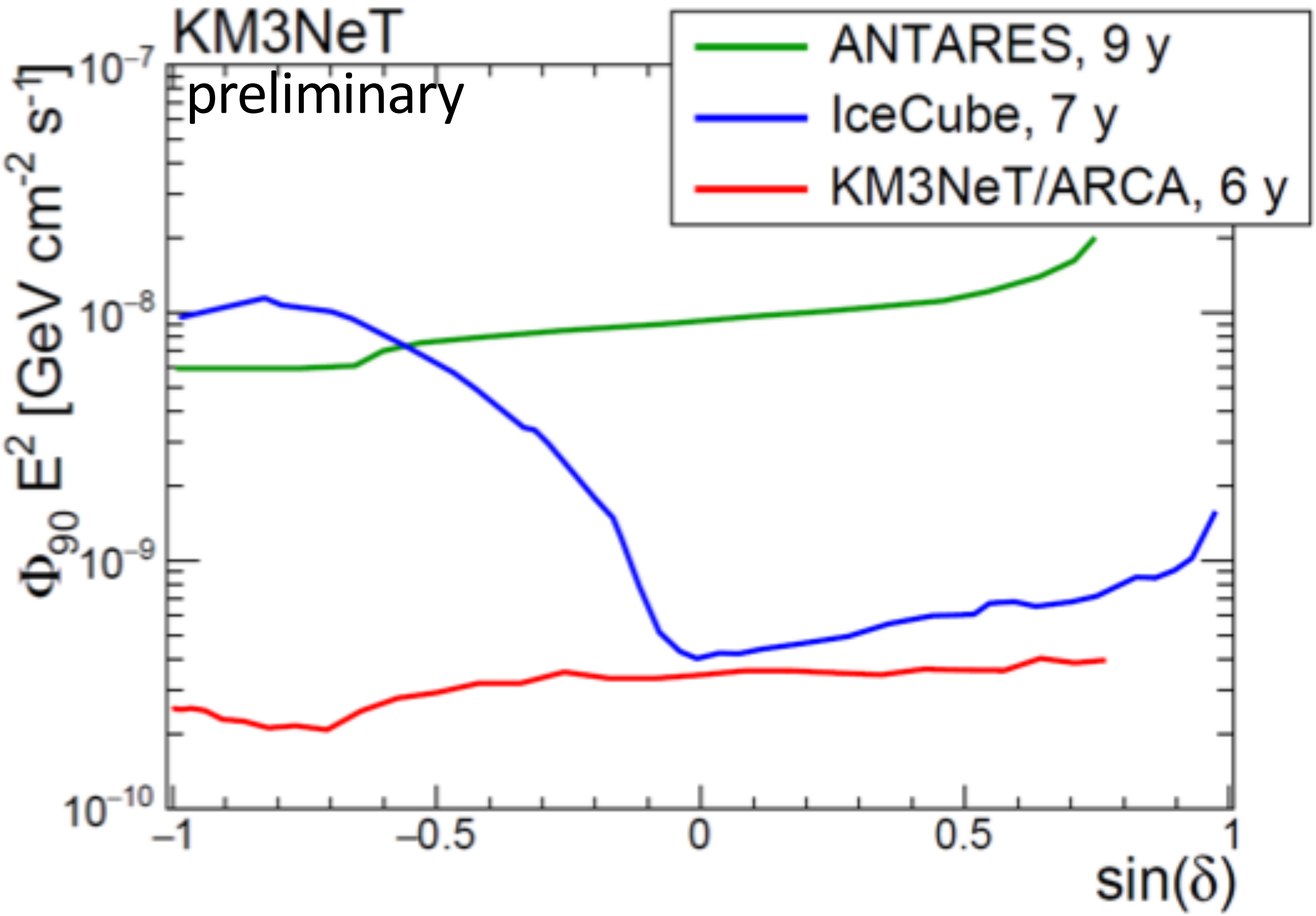
IceCube most sensitive
In Northern Sky

ANTARES most sensitive
at low energies in Southern Sky

Common analysis can improve limits in the Southern Hemisphere

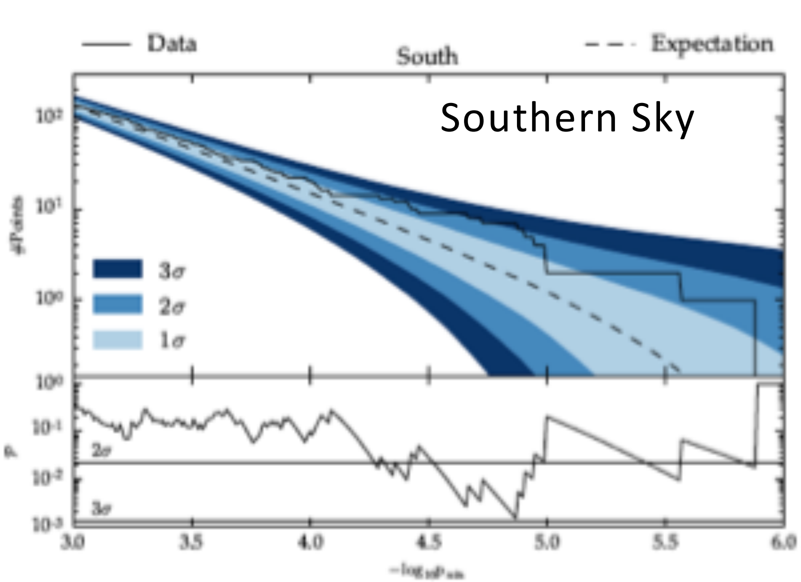


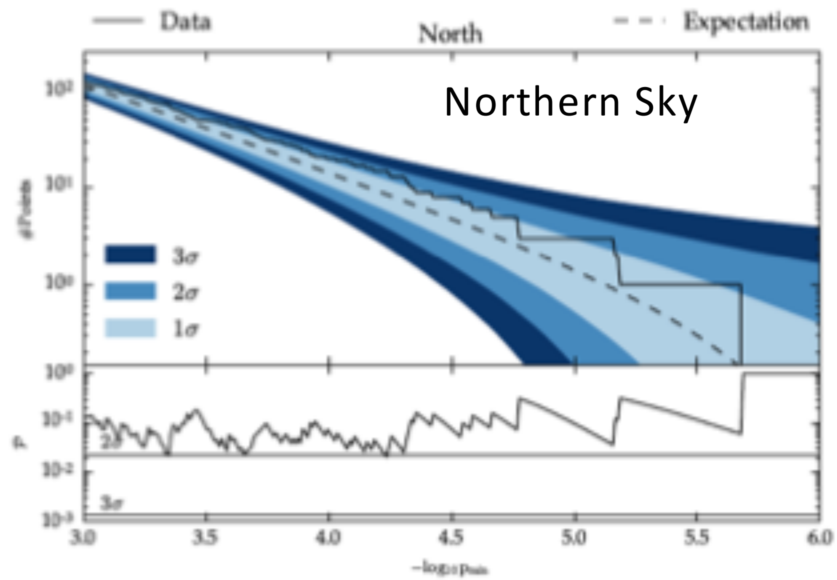
Prospects for KM3NeT



Excess in number of ‘warm’ spots?

IceCube: Probabilities for number of high-probability clusters





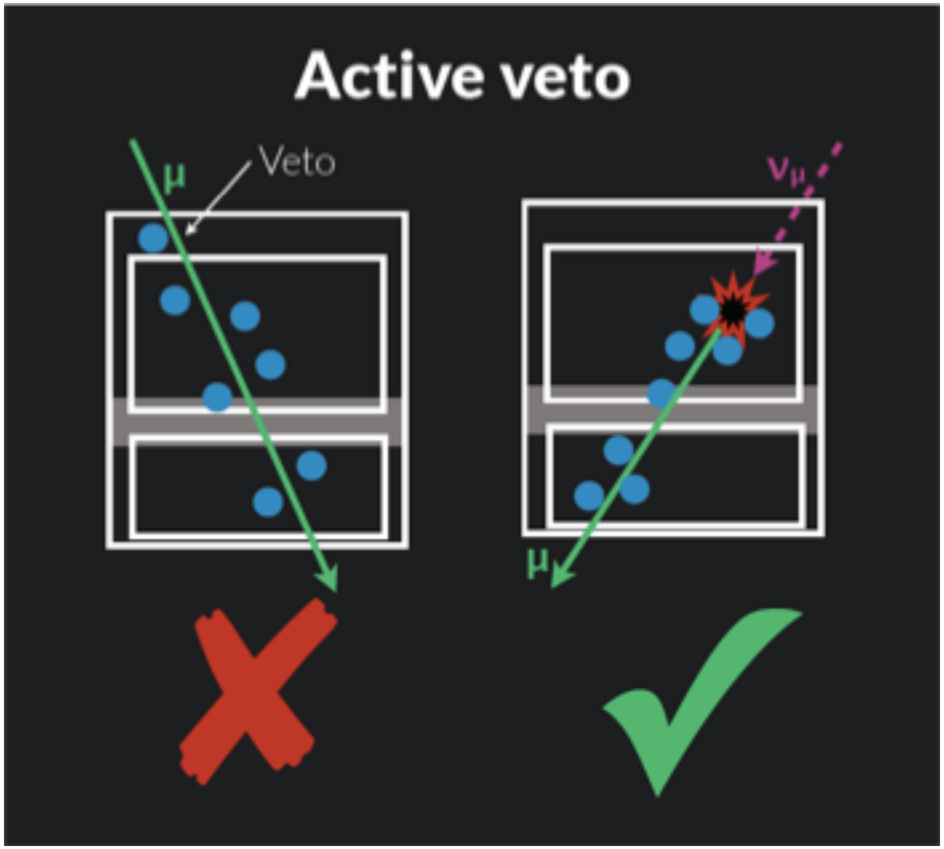
No significant excess identified

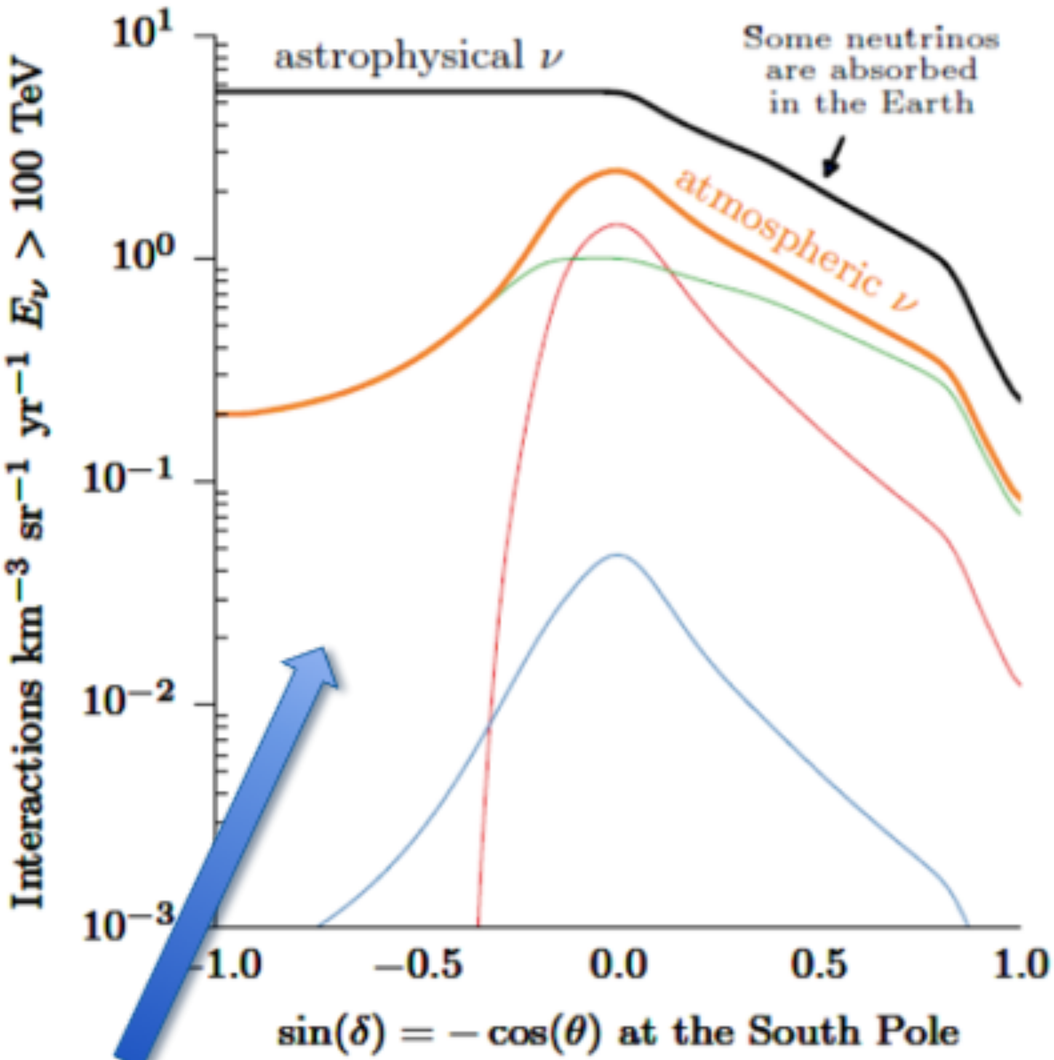
Cosmic neutrino detection by IceCube

2013: IceCube reports detection of
two ~PeV energy cascades
('Ernie & Bert')
-> no atmospheric background

2013++: Reducing atmospheric
background with veto in
top of the detector
-> **H**igh **E**nergy **S**tarting **E**vents (HESE)

-> Access to Southern Hemisphere





prompt flux
atmospheric ν_μ
atmospheric ν_e

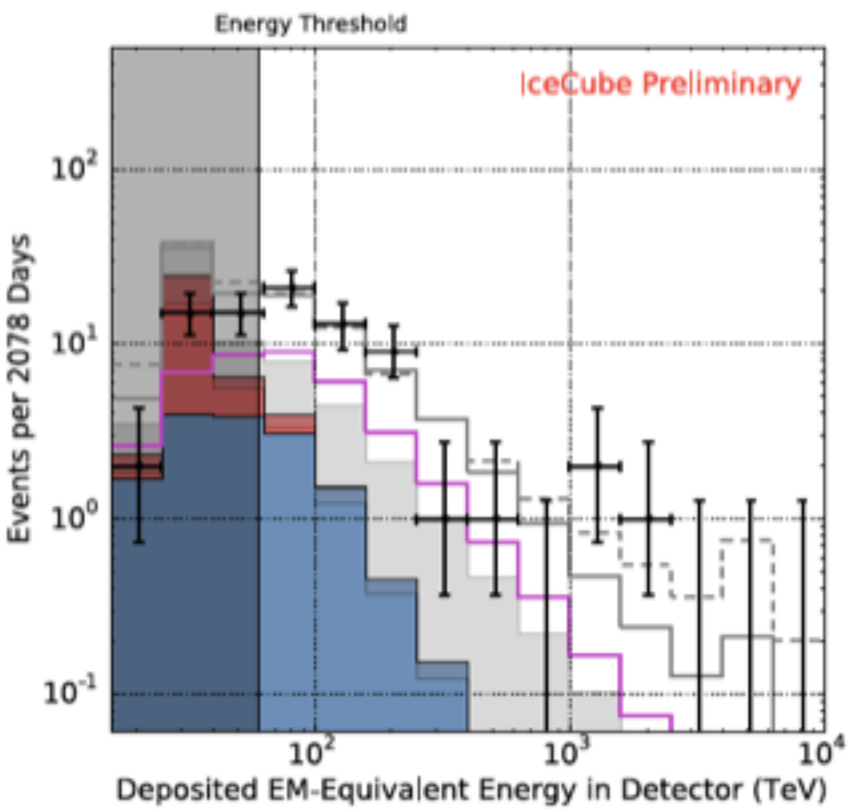
Atmospheric downward going neutrino background reduced with veto

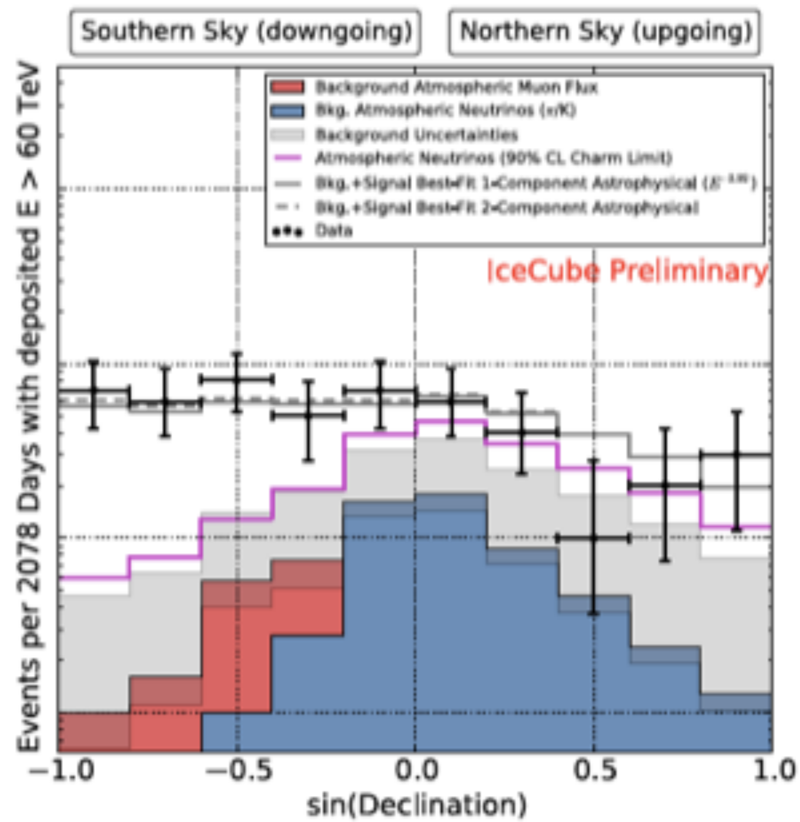
J. v. Santen, 2017

HESE Energy distribution 6 years

2 yrs 28 evts $4.1\ \sigma$
3 yrs 37 evts 5.9σ
4 yr 54 evts $\sim 7\sigma$
6 yr 82 evts

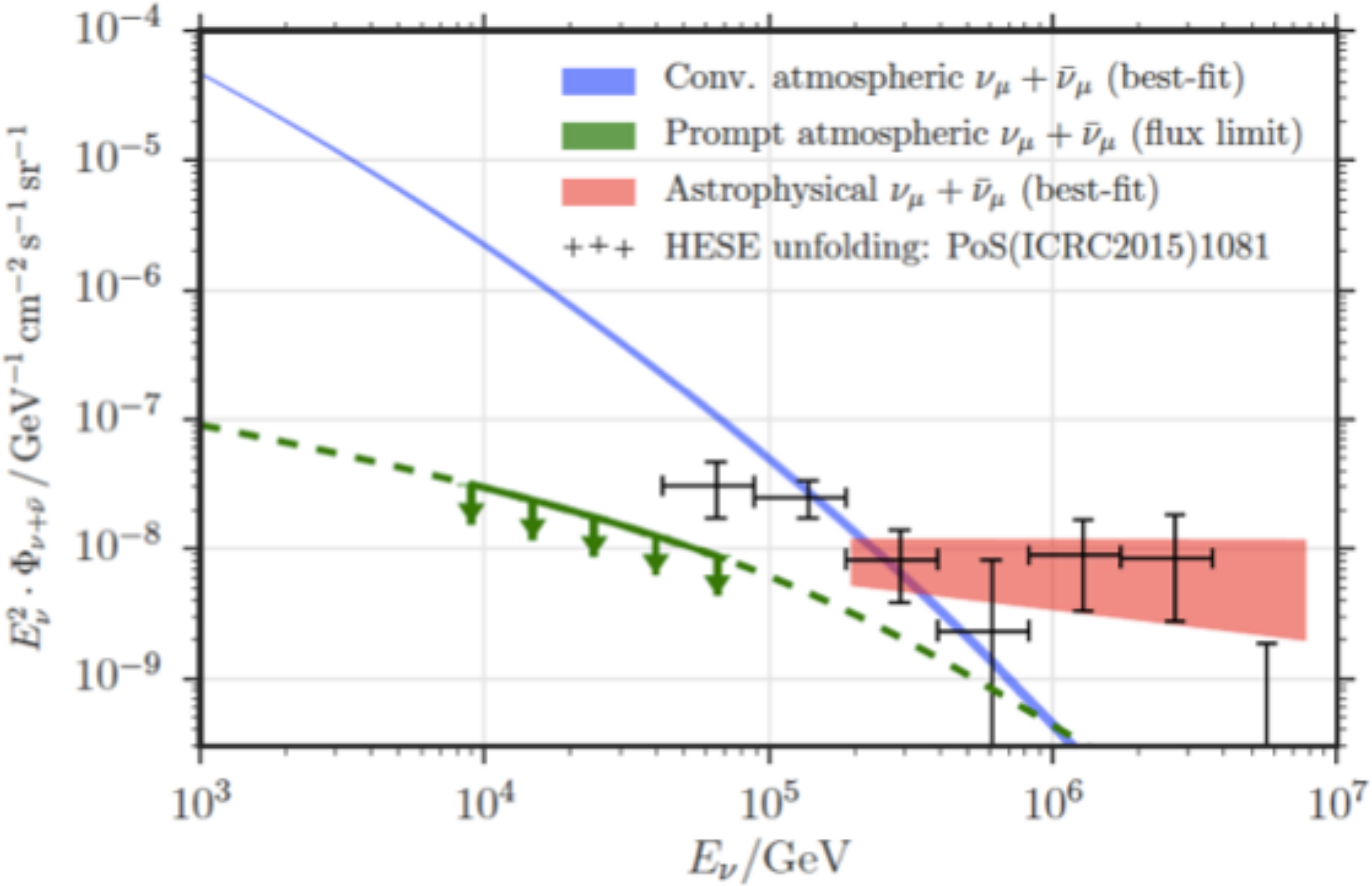
6 year analysis with 10 TeV threshold





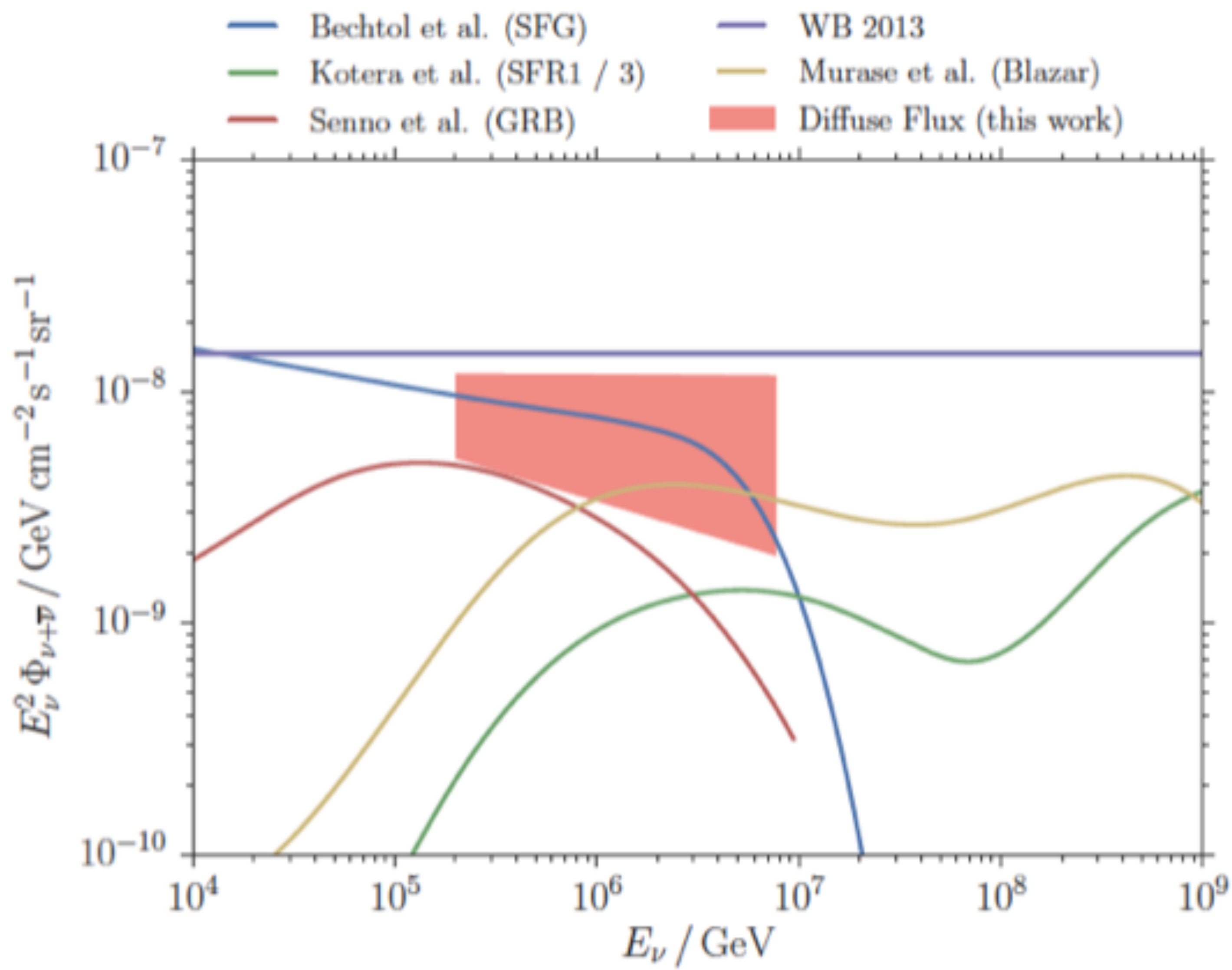
Kopper, ICRC 2017

IceCube Diffuse flux analysis using throughgoing muons

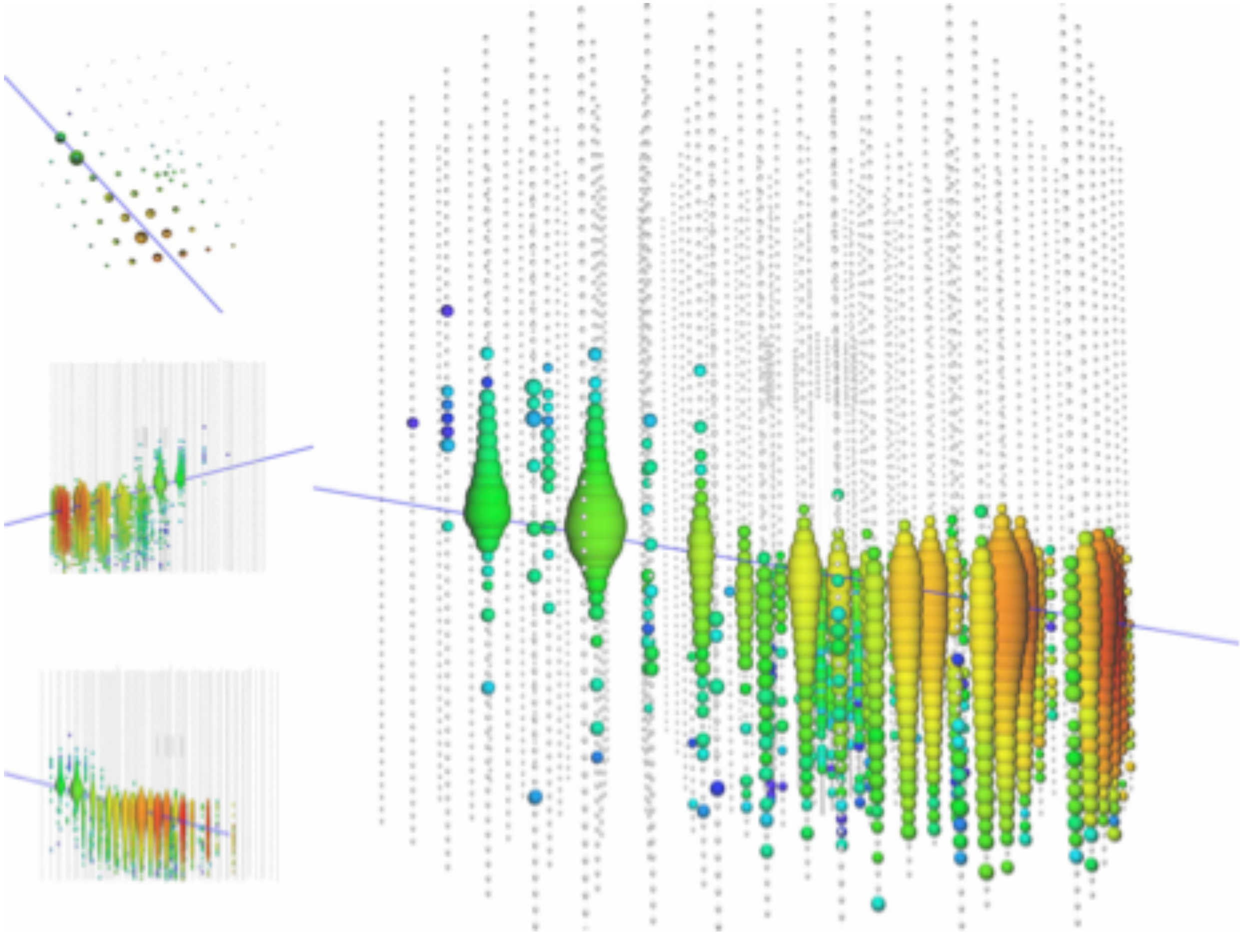


IceCube, Astrophys.J. 833 (2016) no.1, 3

Comparison of different models



The highest energy event (track)

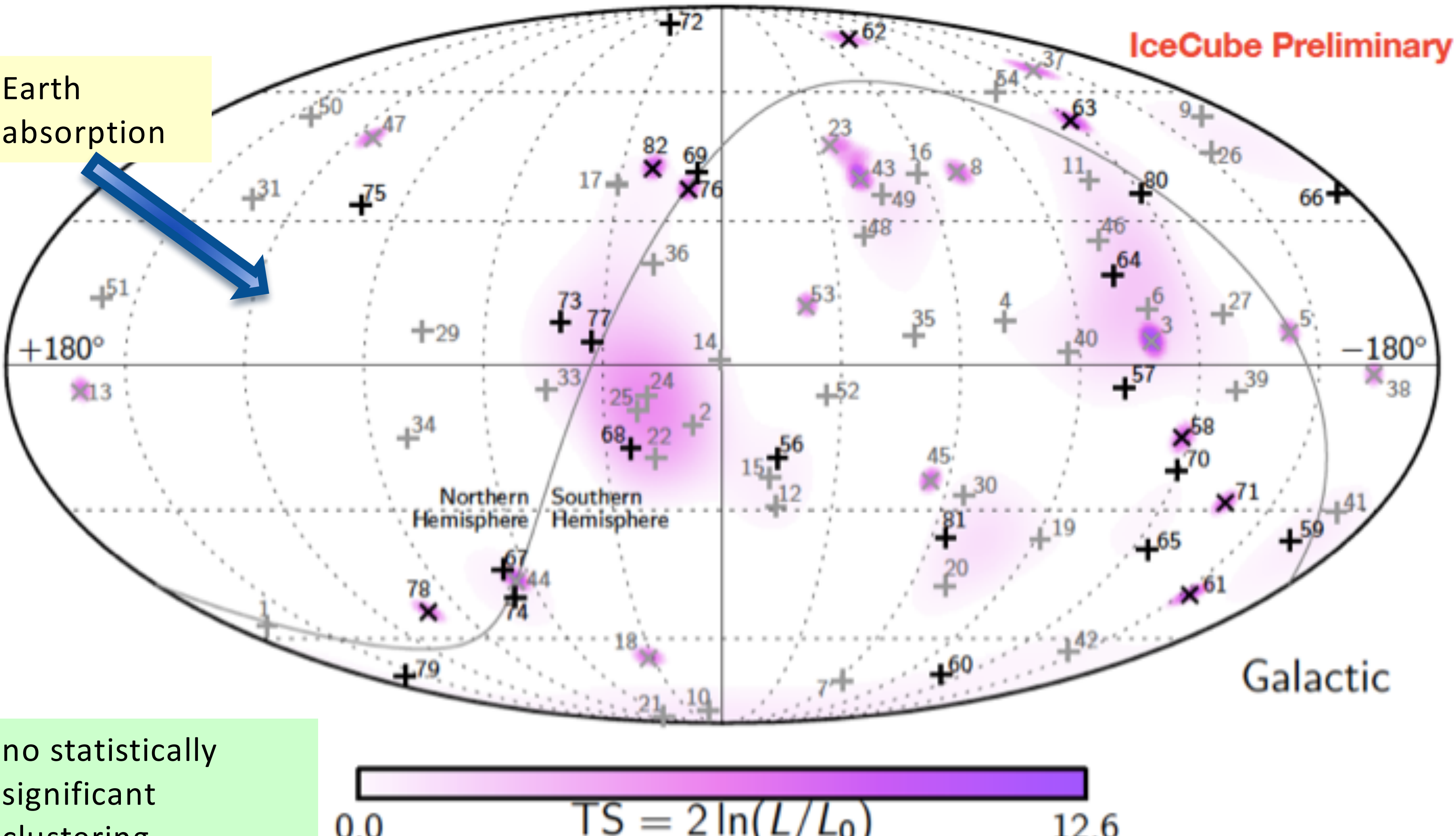


Deposited energy 2.6+-0.3 PeV

Most probable ν energy ~ 7PeV

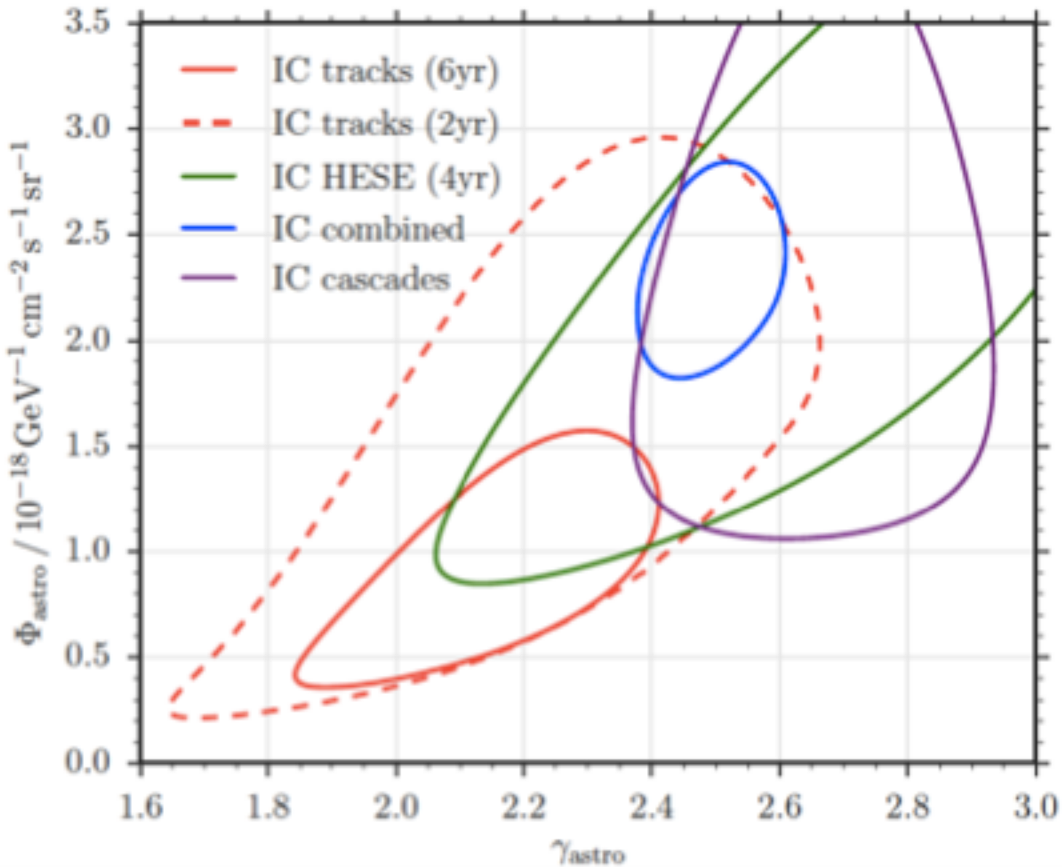
Skymap for high energy neutrinos (IceCube, ICRC 2017)

Earth absorption



no statistically significant clustering
-> isotropic
-> extragalactic

Kopper, ICRC2017

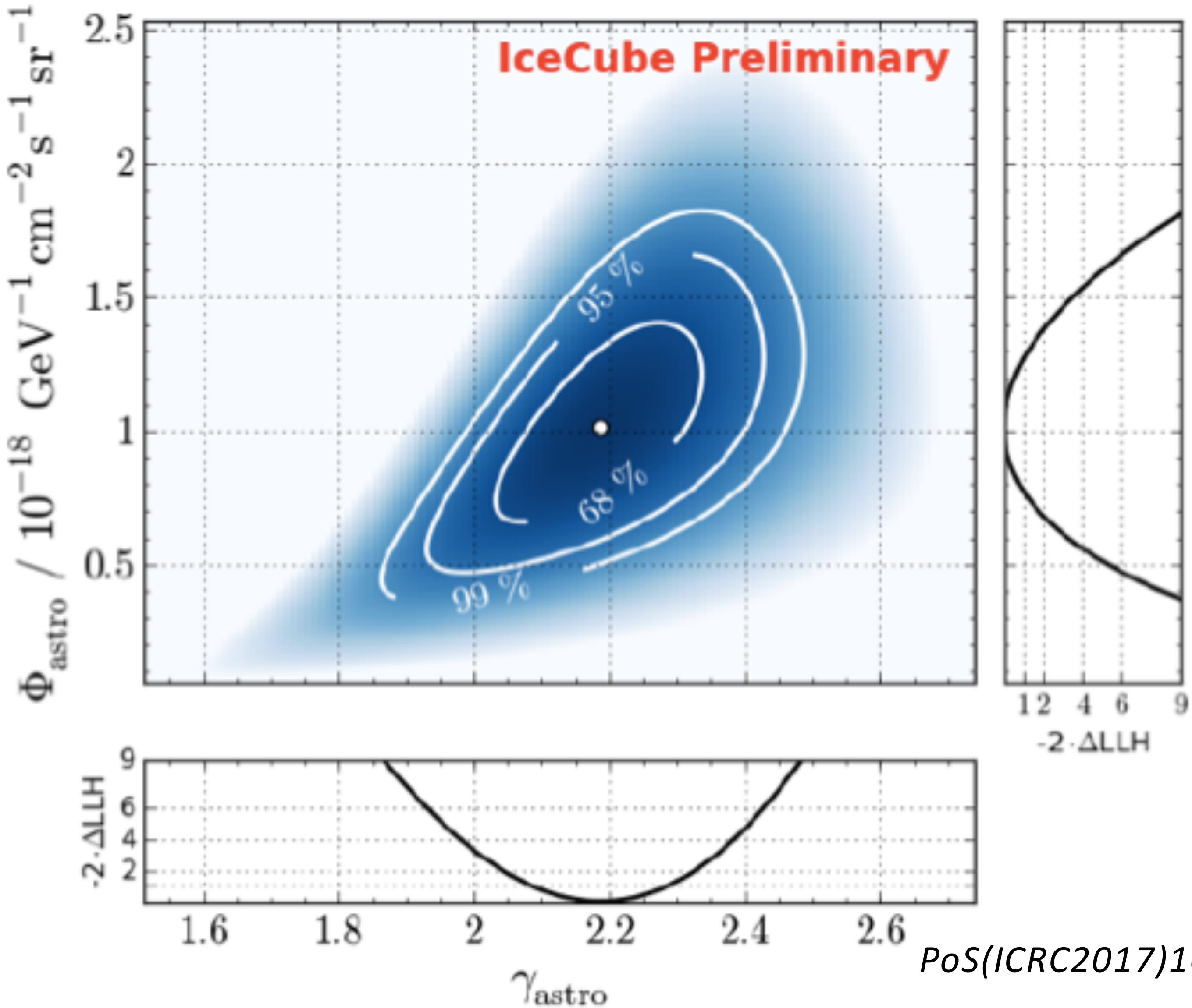


Single Power Law in 3.3 σ tension
between HESE events and throughgoing muons

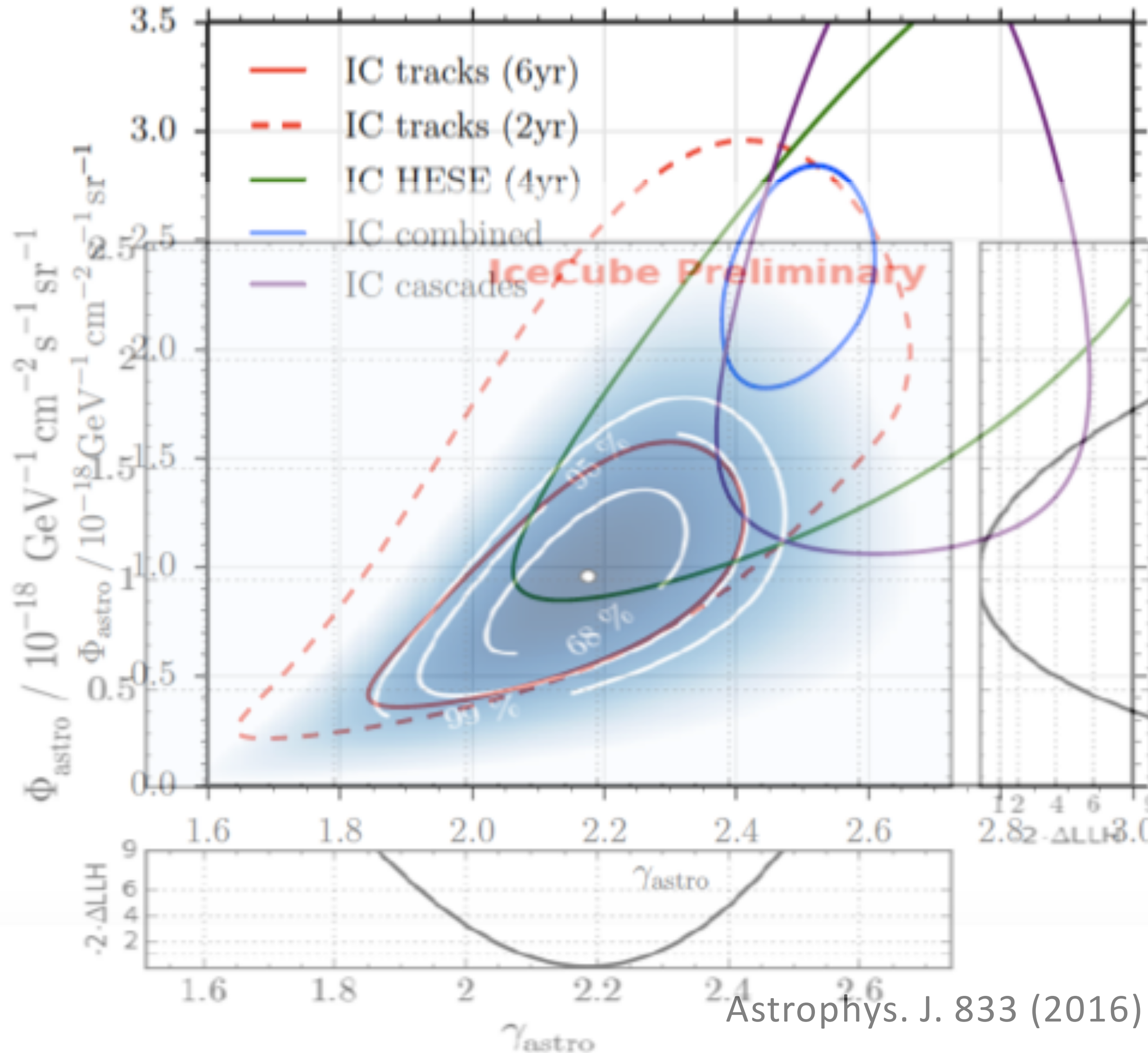
Astrophys. J. 833 (2016) 3

Could be e.g. explainable by
- the different energy ranges of the two event samples (assuming broken power law)
- the different sky coverage of the two event samples (different impact of galactic or other non-isotropic emission

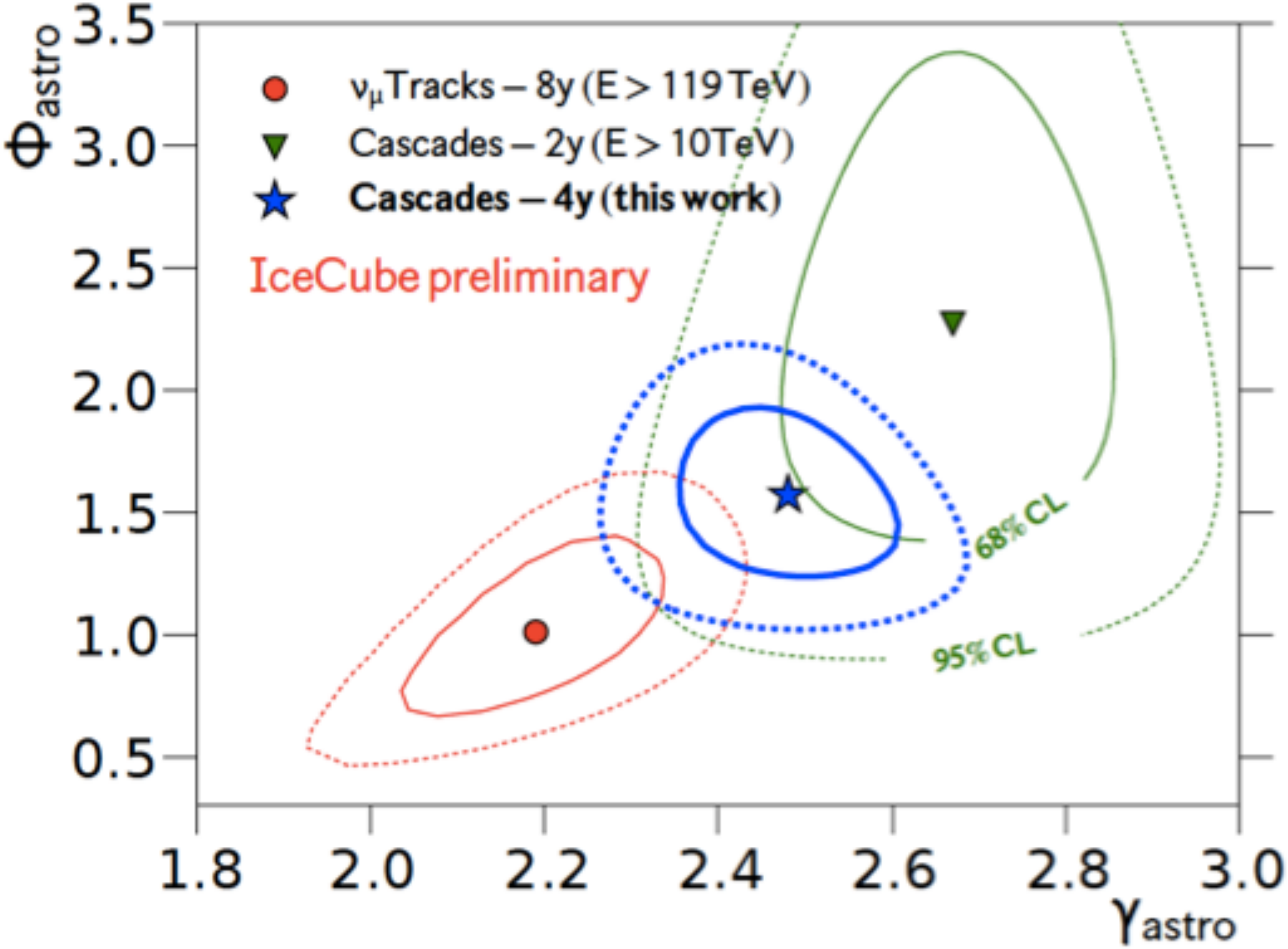
Recent 8 year track analysis



PoS(ICRC2017)1005



Astrophys. J. 833 (2016) 3

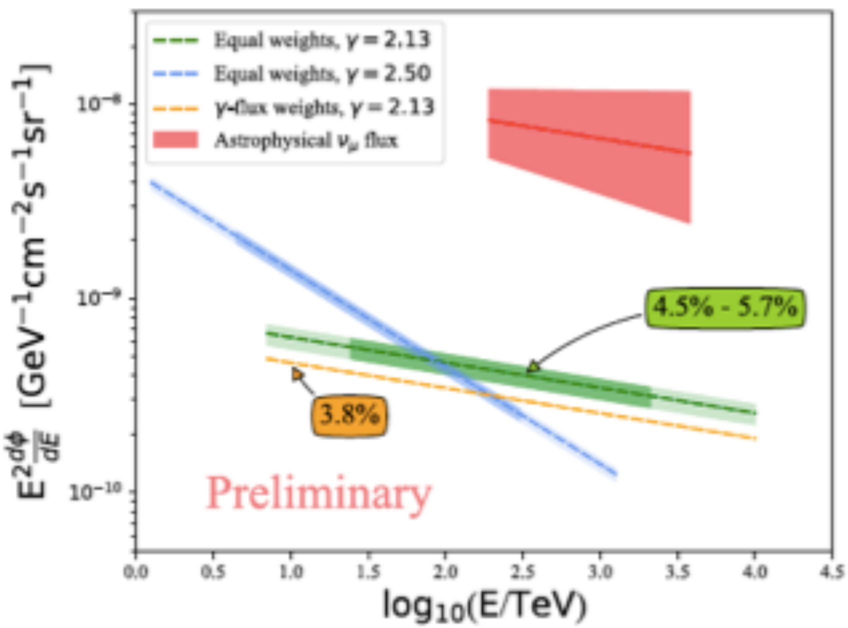


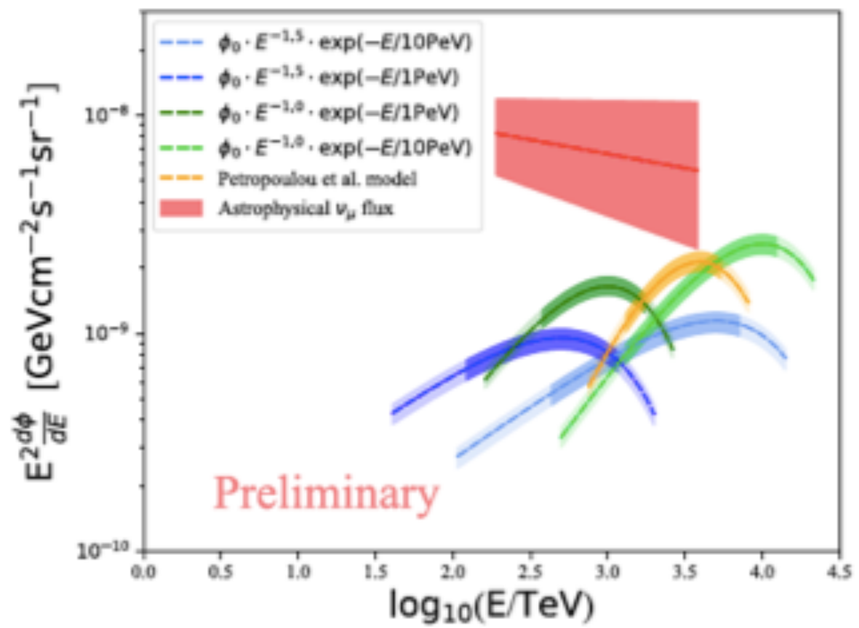
Tension already reduced (p=0.04)

PoS(ICRC2017)968

Checking on source classes

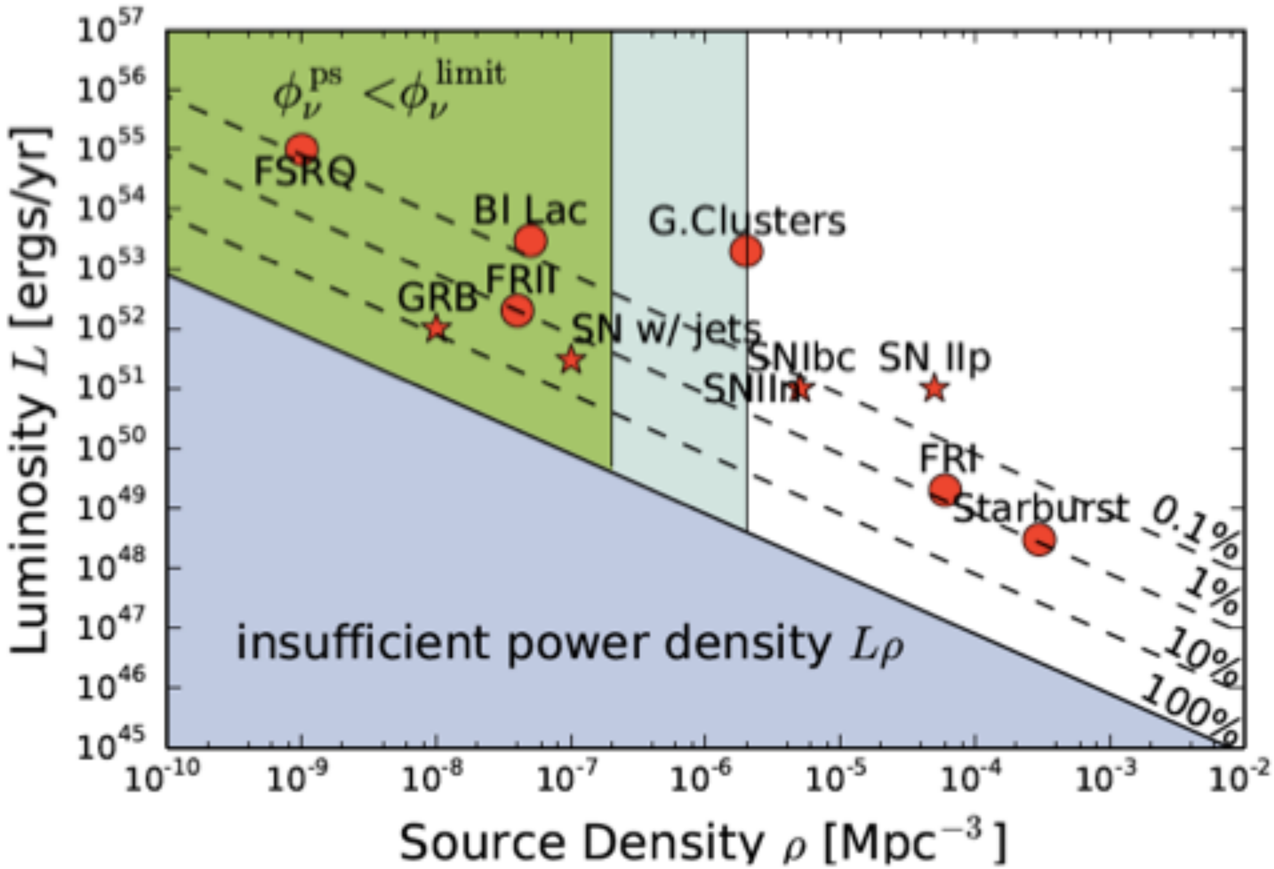
Example 7 year of IC data, stacking of Blazars from Fermi 2FHL HBL catalogue





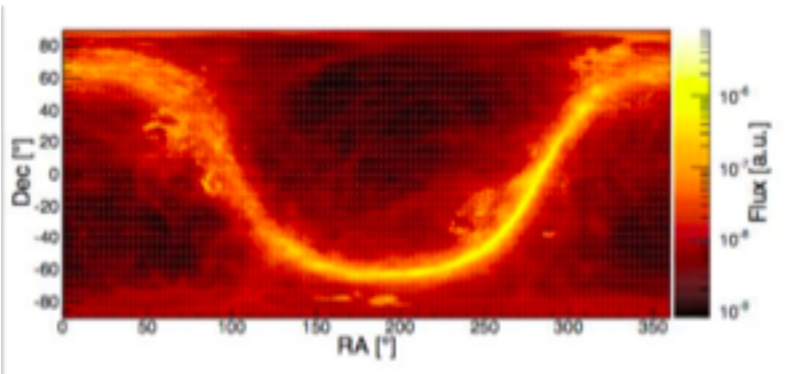
Huber, Krings, PoS(ICRC2017) 994

Constraints on contributions of different source populations

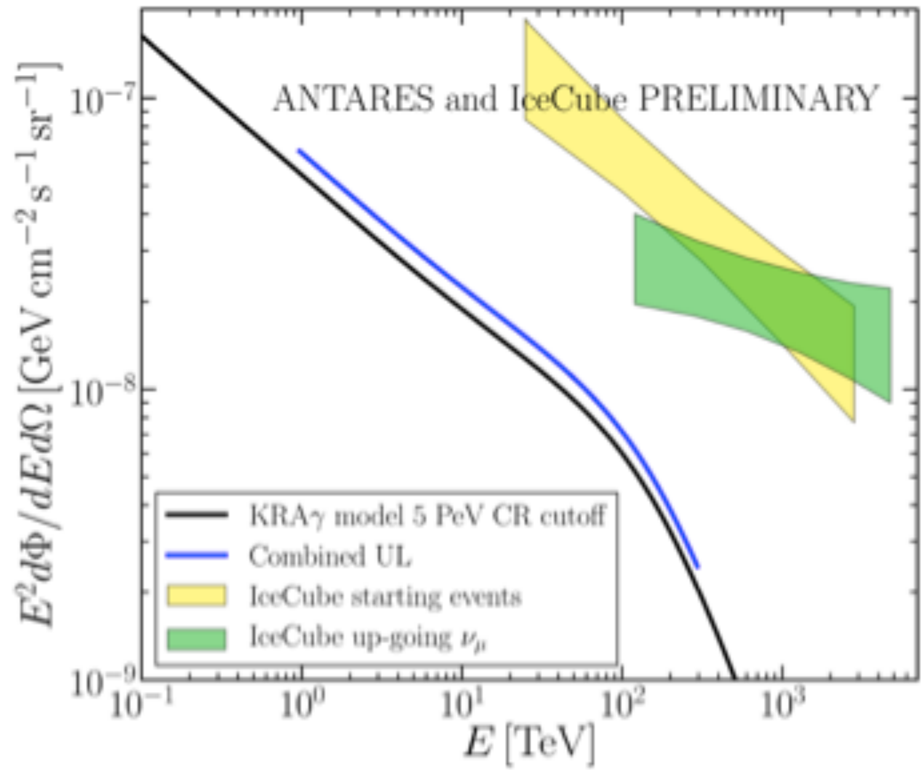


Kowalski, 2014

Constraints on the flux from Galactic Plane (IceCube and ANTARES common analysis)



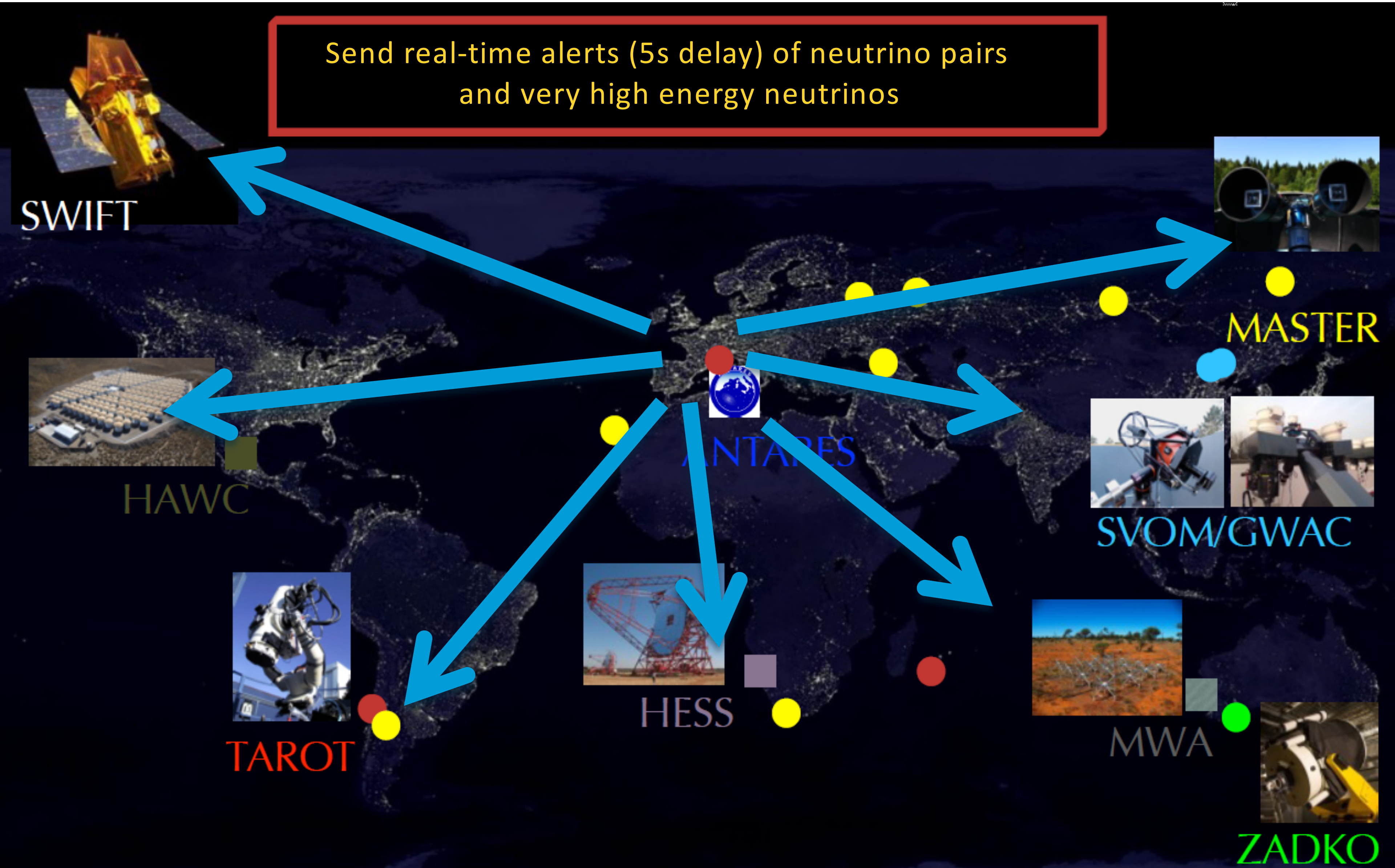
(a) KRA-γ (50 PeV cutoff) template



KRA model describes cosmic ray interactions with interstellar medium => corresponding neutrino flux

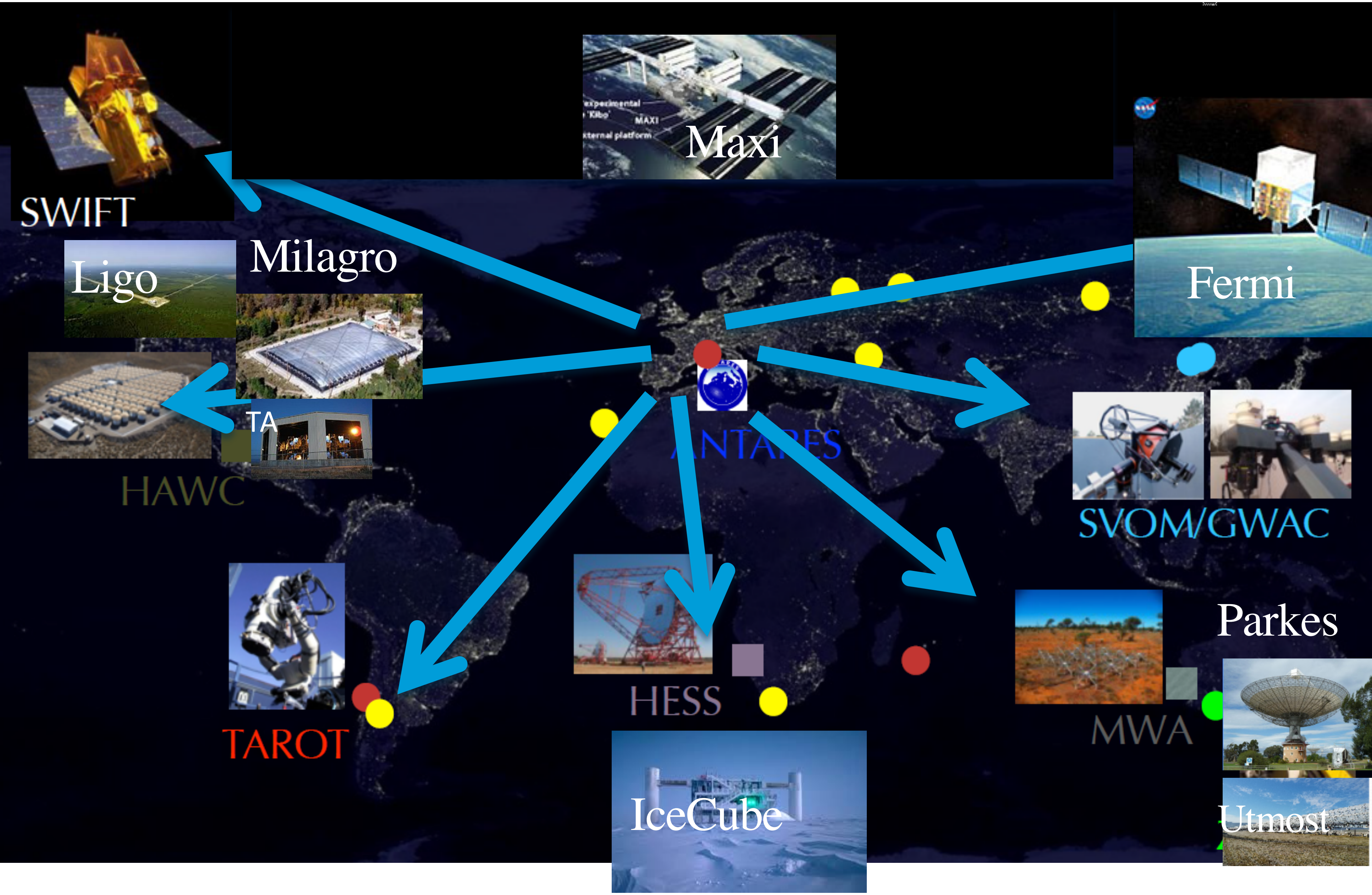
Limits close to the model expectation

Multi-messenger connections (online and offline)



Shown for ANTARES, similar for IceCube

Multi-messenger connections (online and offline)



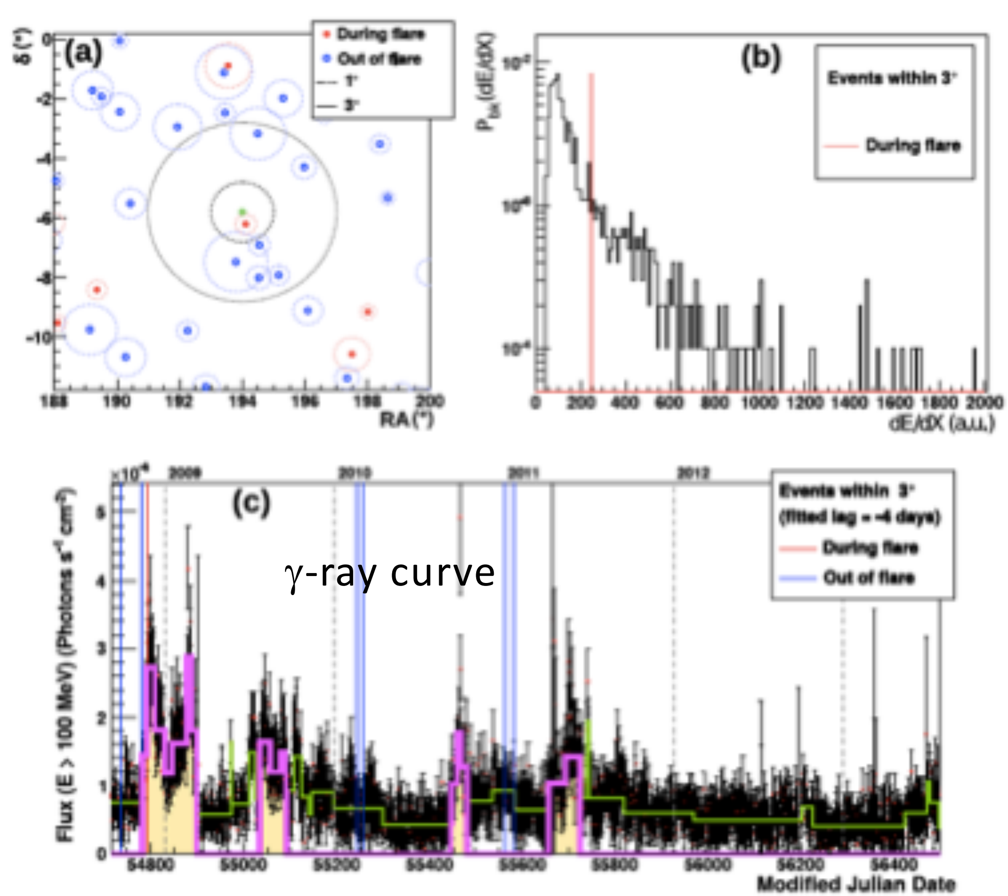
Transient studies: Example of flare analysis (ANTARES)

Most significant correlation with blazar 3C 279
1 event in spatial/temporal neighbourhood
3.3% probability (post-trial probability 67%)

Both IceCube and ANTARES:

No significant correlation seen with X-ray / gamma-ray flares of selected sources

No significant flare in all sky



ANTARES, JCAP 1512 (2015)

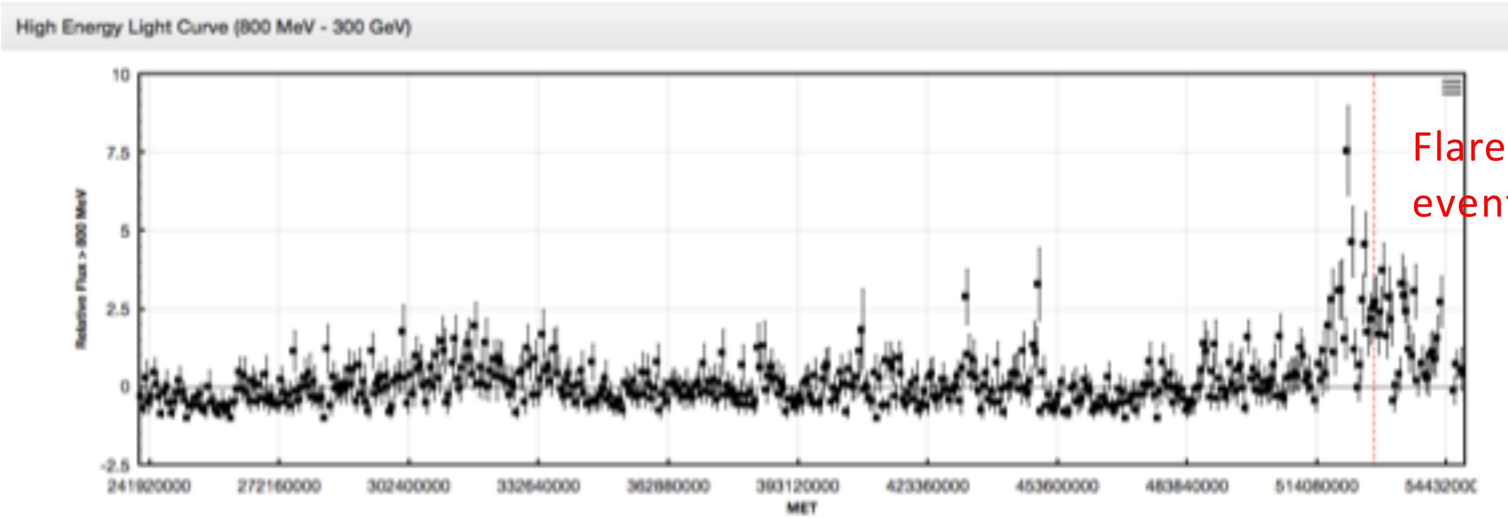
IceCube high energy alerts

April 2016-End of 2017:
6 EHE alerts, 8 HESE alerts (1 overlapping event)

Interesting Alert 22 September 20:55 EHE-170922A

Followup:

Integral, ANTARES, HAWC, HESS: no detection
SWIFT XRT: 9 X-ray emitters
FERMI: increased gamma-ray activity of TXS 0506+56
MAGIC: detection of VHE gamma rays
.... Many more observatories followed

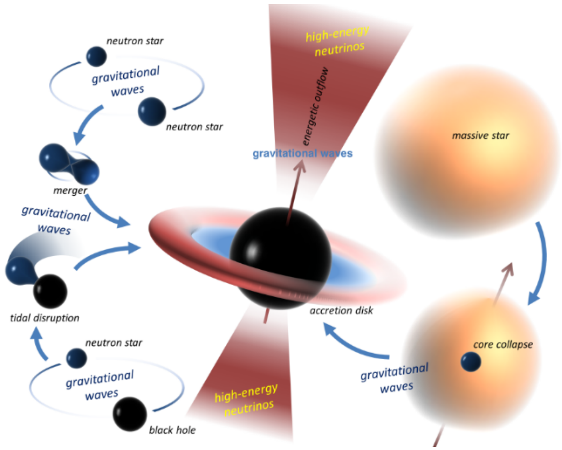


Flare with neutrino event closeby

Neutrino follow-up of GW150914, GW151226, LVT151012

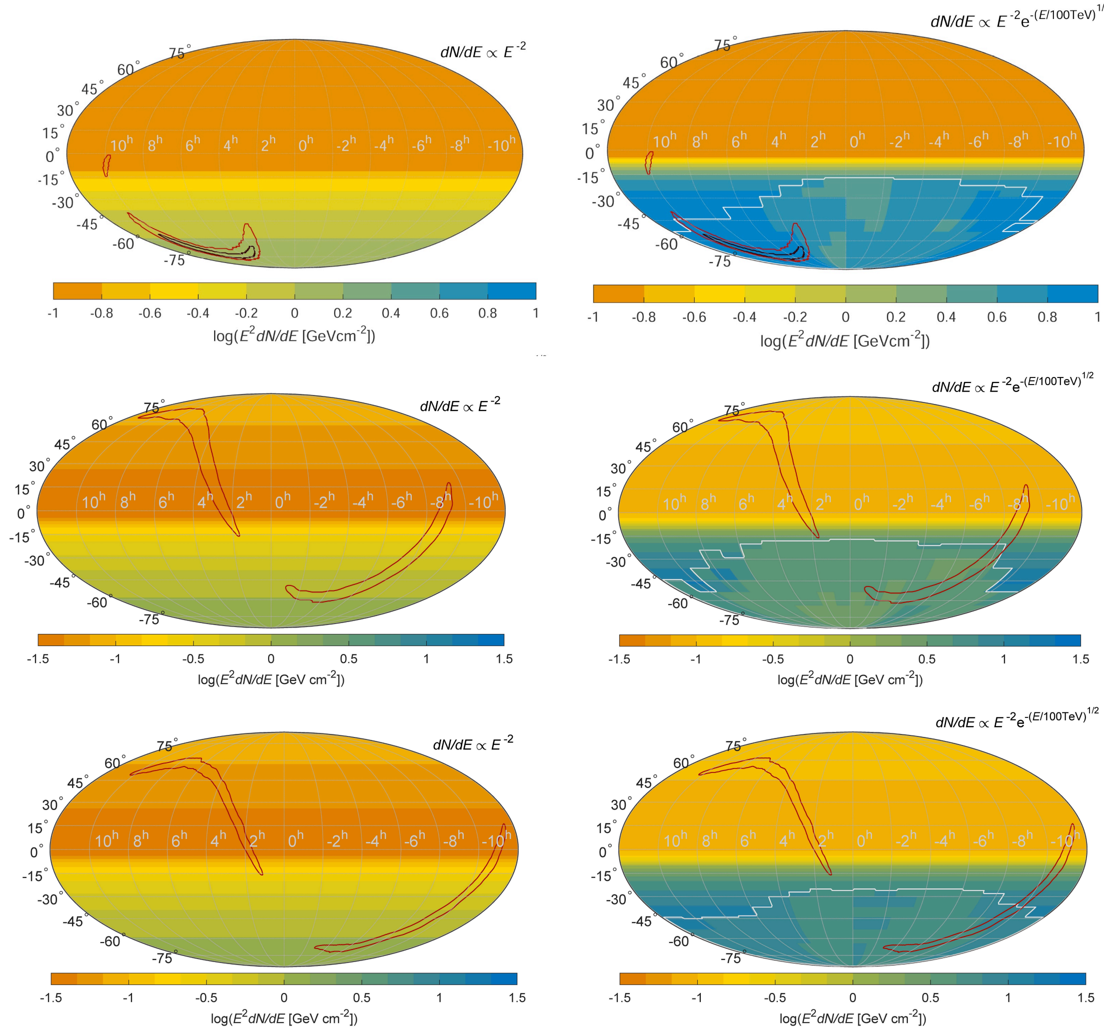
joint ANTARES/IceCube/LigoSC/Virgo.

Phys.Rev. D93 (2016), 122010, Phys.Rev. D96 (2017), 022005

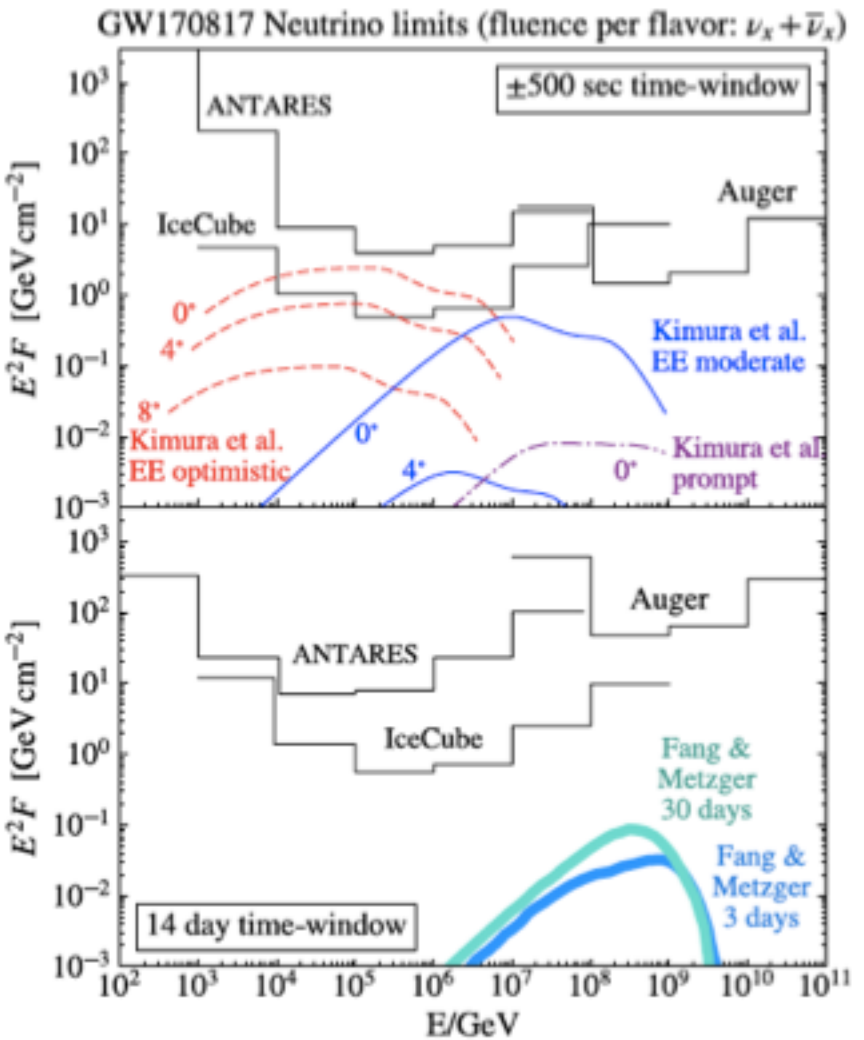


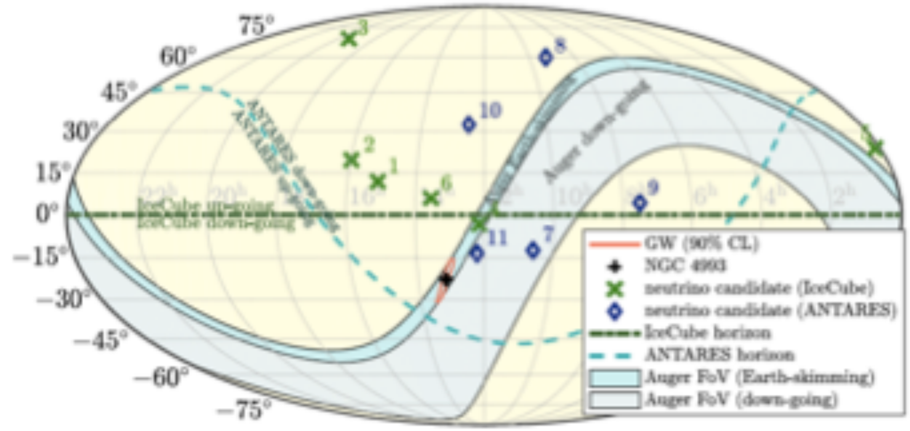
- From binary black hole mergers in a few environments neutrino emission expected -> could pinpoint source
- Within ±500 s detected amount of events compatible with background:
- IC/ANTARES events: 0/3 (GW150914), 2/1 (GW151226), 4/0 (LVT151012)
- Limits from ANTARES dominate for $E\nu < 100$ TeV

Limits for E^{-2} | Limits for $E^{-2}\, e^{-(E/100\,\mathrm{TeV})^{1/2}}$



Search for neutrinos from GW170817

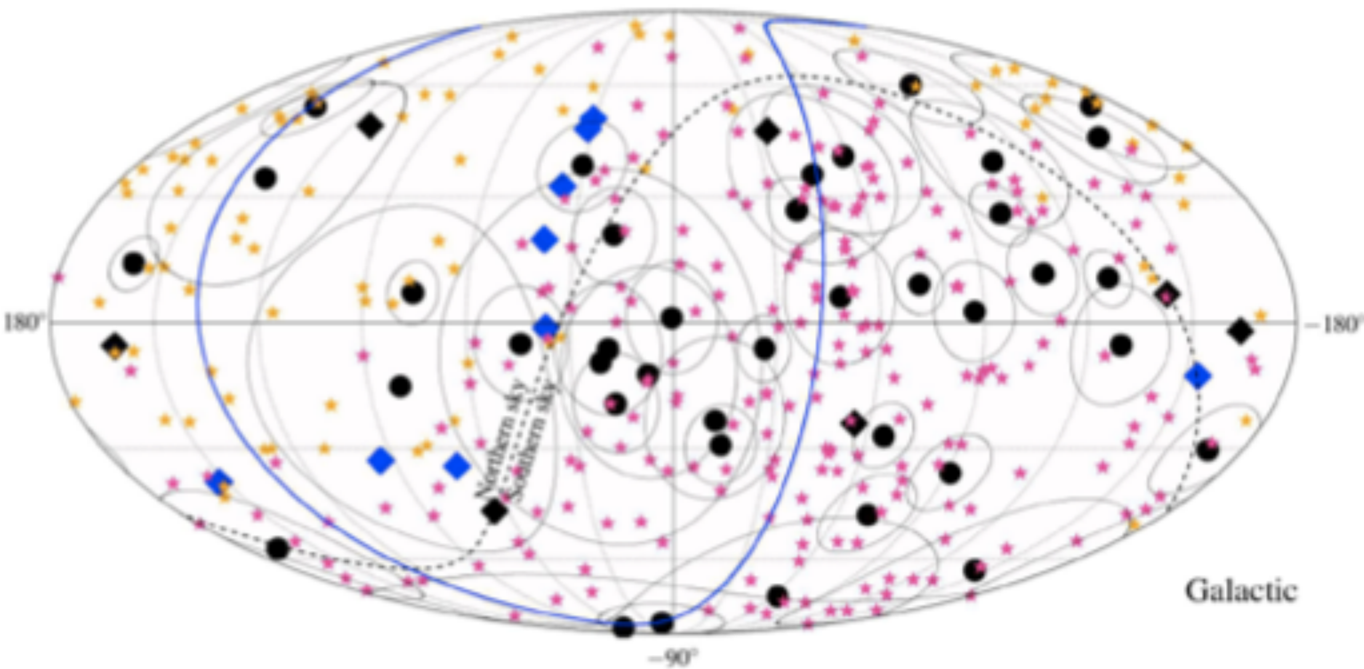




No events detected

Model predictions vary largely
-> consistent with expectation

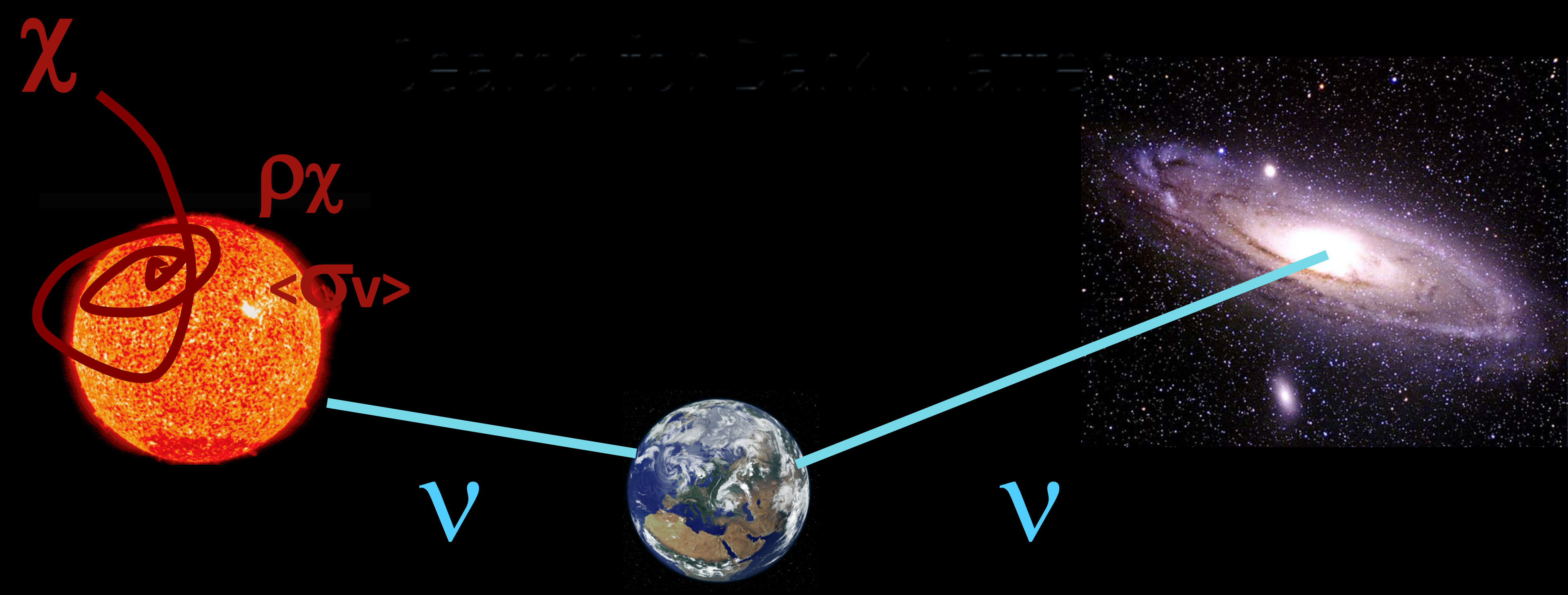
Search for event correlations IceCube-Pierre Auger-TA



IceCube cascades (dots)
IceCube HESE tracks (diamonds)
IceCube throughgoing tracks (diamonds)
Pierre Auger
Telescope Array

No significant correlations found

Most significant correlation for IC cascades with UHECR



- Dark Matter WIMPs accumulate in heavy objects (Sun, Galactic Center, Earth)
- Capture/Annihilation in equilibrium at the Sun core

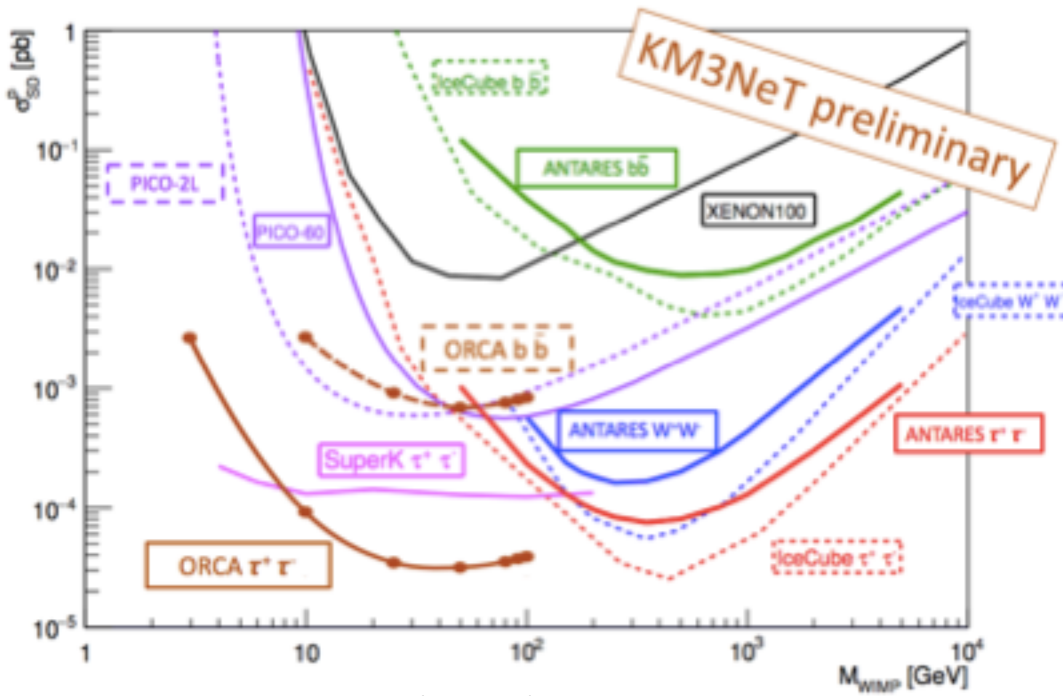
Dark Matter in the Sun

Accumulation and annihilation in massive objects

$$X_{\mathrm{WIMP}}\bar{X}_{\mathrm{WIMP}} \rightarrow b\bar{b}, W^{-}W^{+}, \tau^{-}\tau^{+}, \mu^{-}\mu^{+}, \nu\bar{\nu}$$

=> Look for excess in the direction of the Sun
=> Selection cuts tuned separately for different channels and WIMP masses

Spin dependent cross section



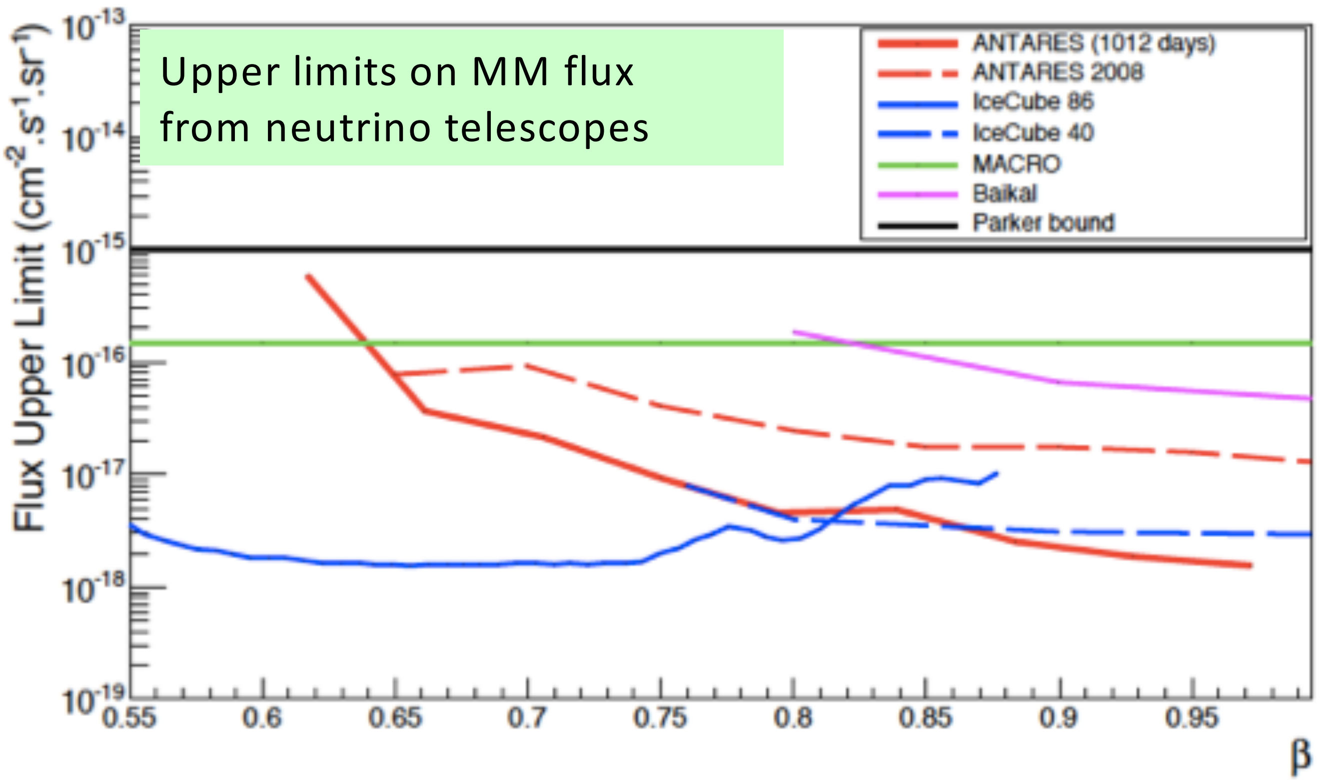
ANTARES results: PLB 759 (2016), 69

Search for Magnetic Monopoles

MM produces significantly more light than a muon in the detector

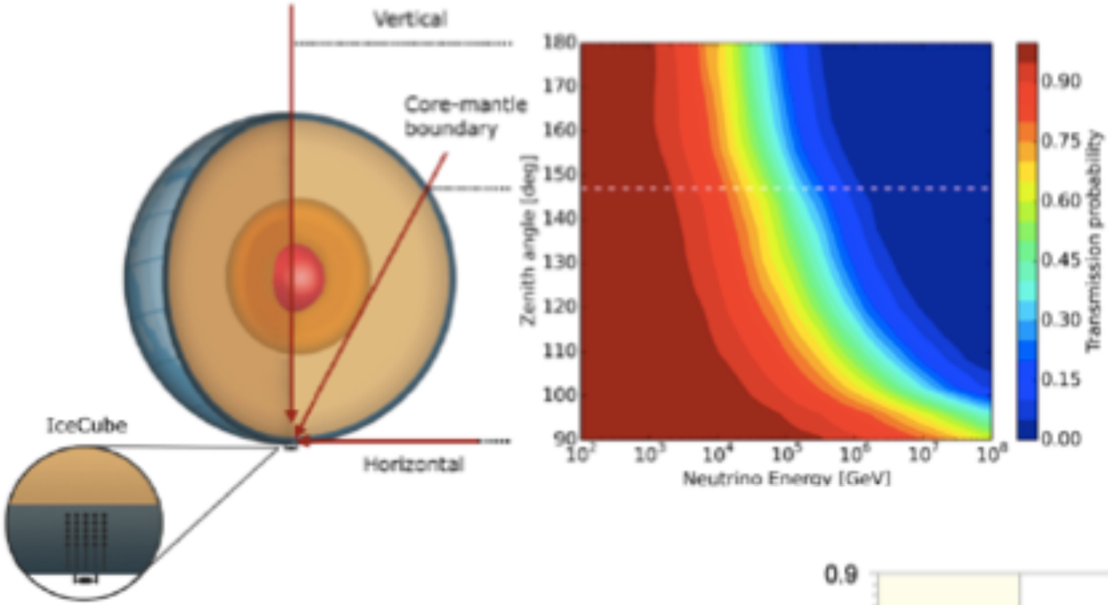
=> Scan data for bright events

Upper limits on MM flux from neutrino telescopes



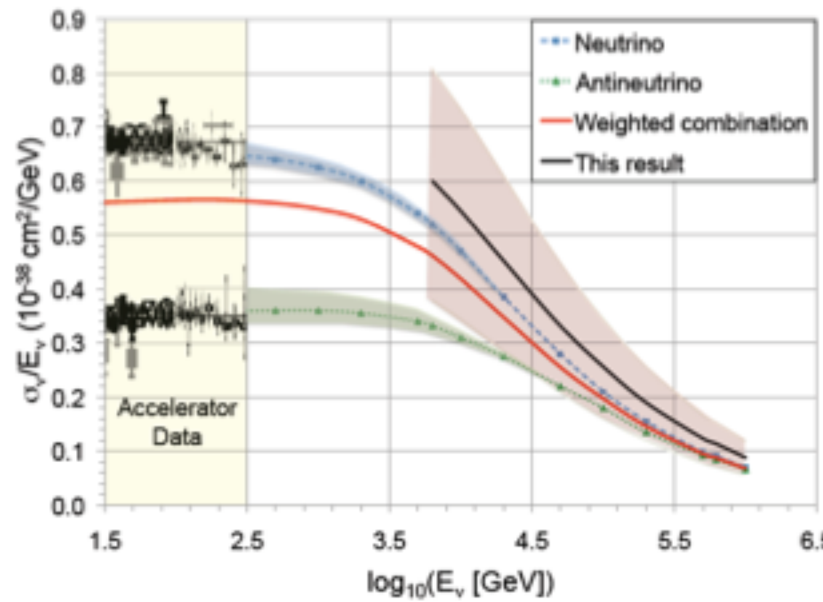
J. High Energ. Phys. (2017) 2017: 54

Cross section at high energies



IceCube

Fit to the expected absorption depending on the zenith angle and energy



Nature 551, 596–600 (30 November 2017)

Neutrino Oscillations – IceCube DeepCore measurements

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

'Sweet spot' around 20GeV

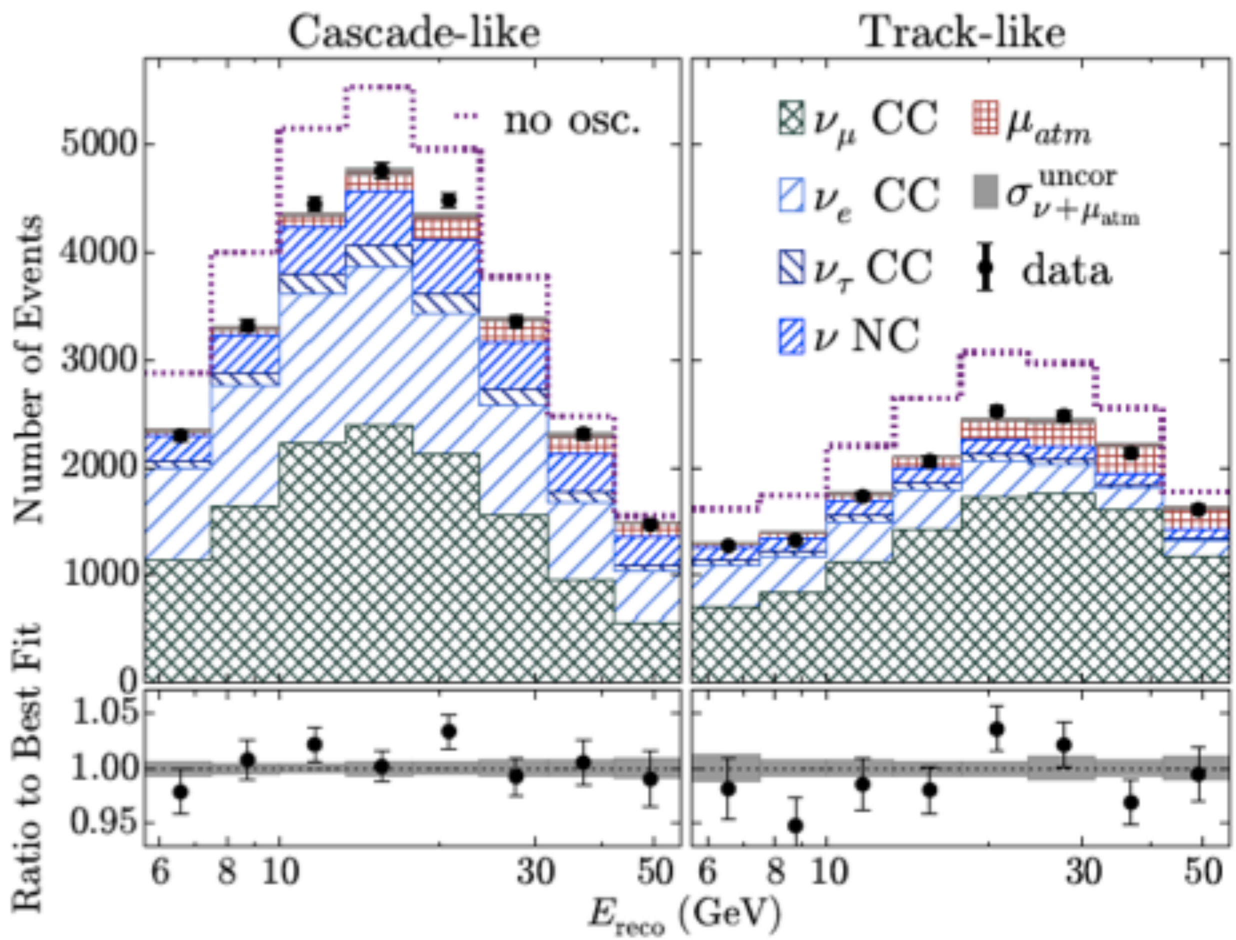
Events contained within DeepCore selected

Zenith resolution:

10 (16) degrees @10 GeV

Energy resolution:
24% (29%) @10 GeV

for Tracks (Cascades)



Phys. Rev. Lett. 120, 071801 (2018)

Neutrino Oscillations – IceCube DeepCore measurements

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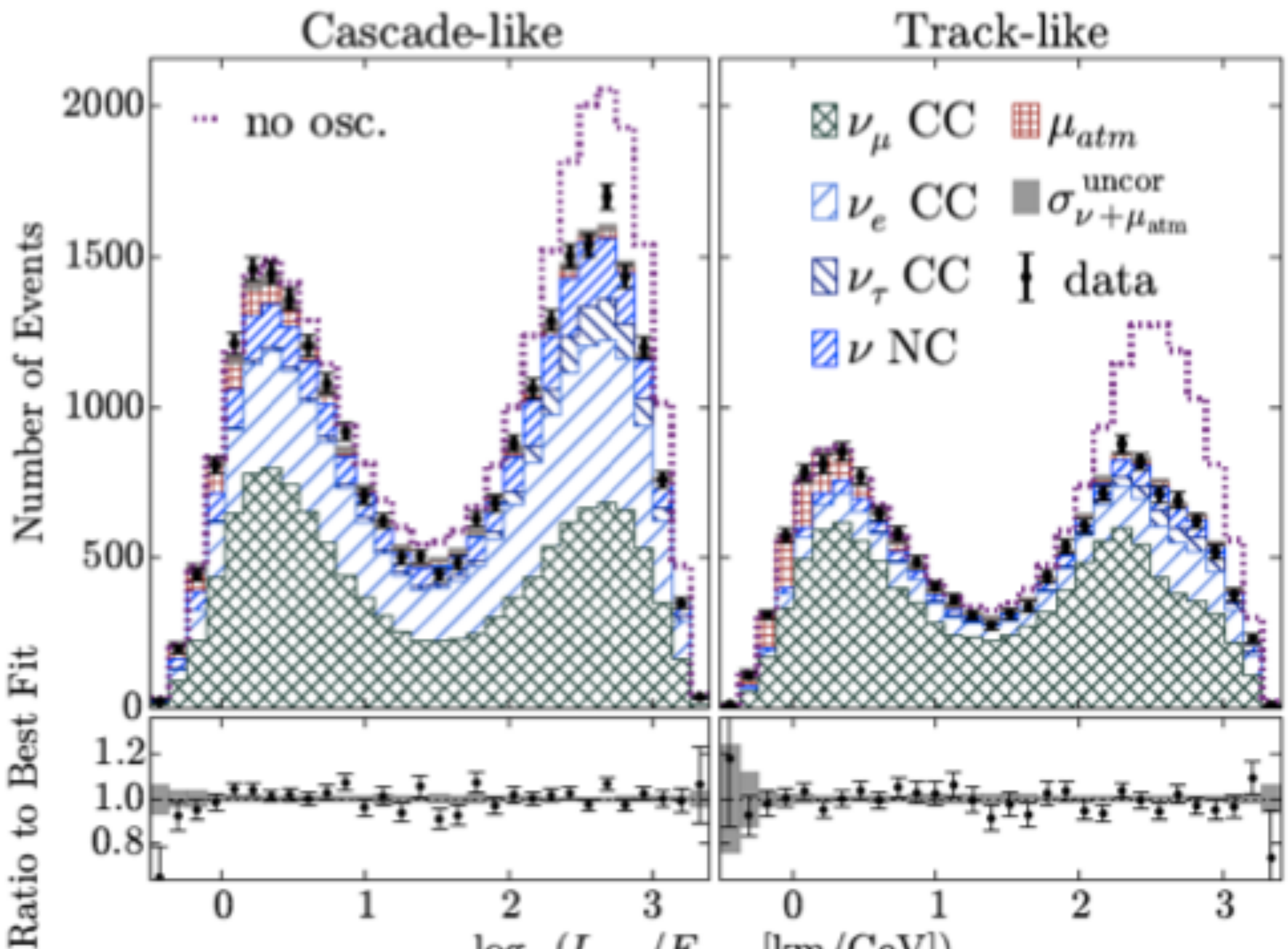
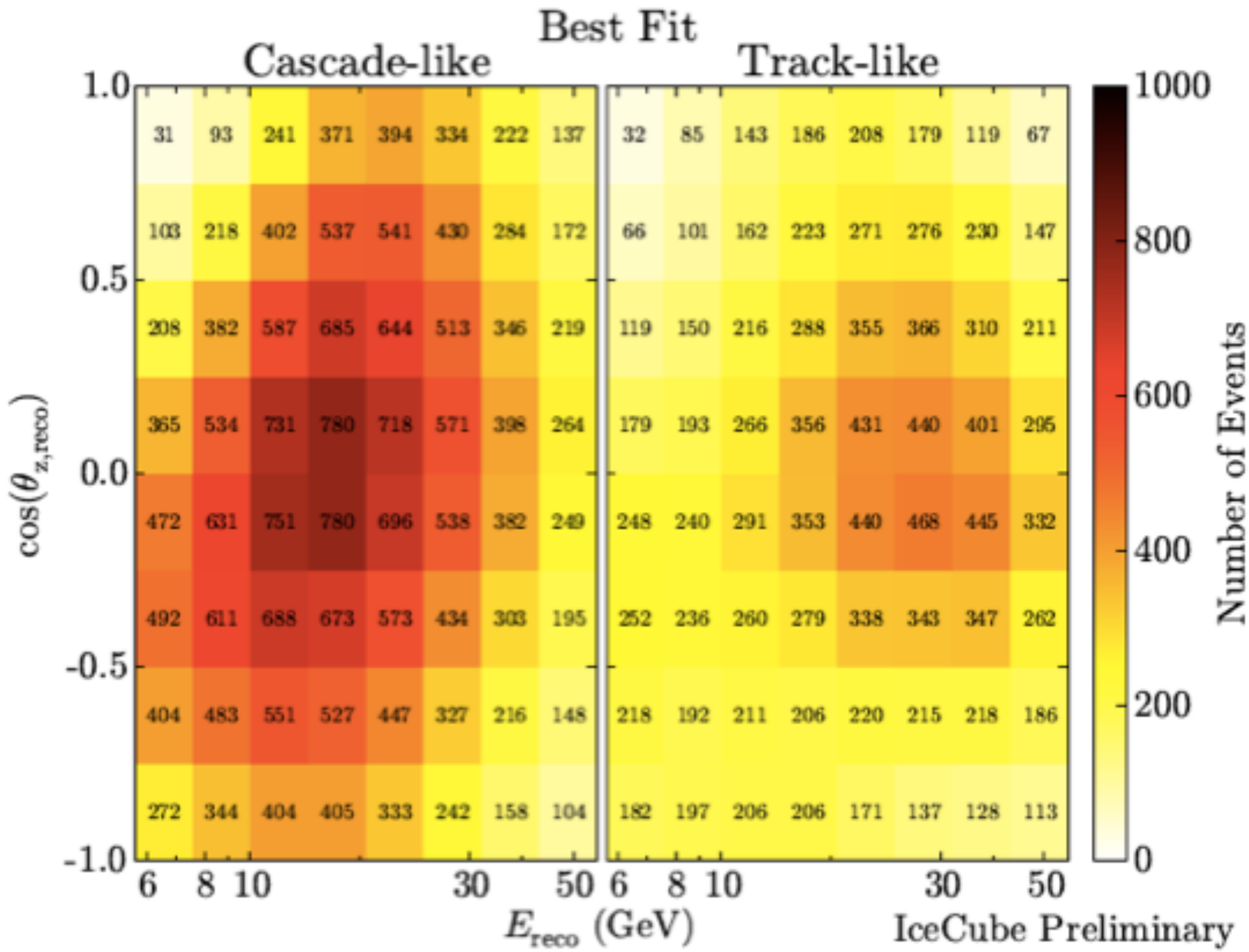
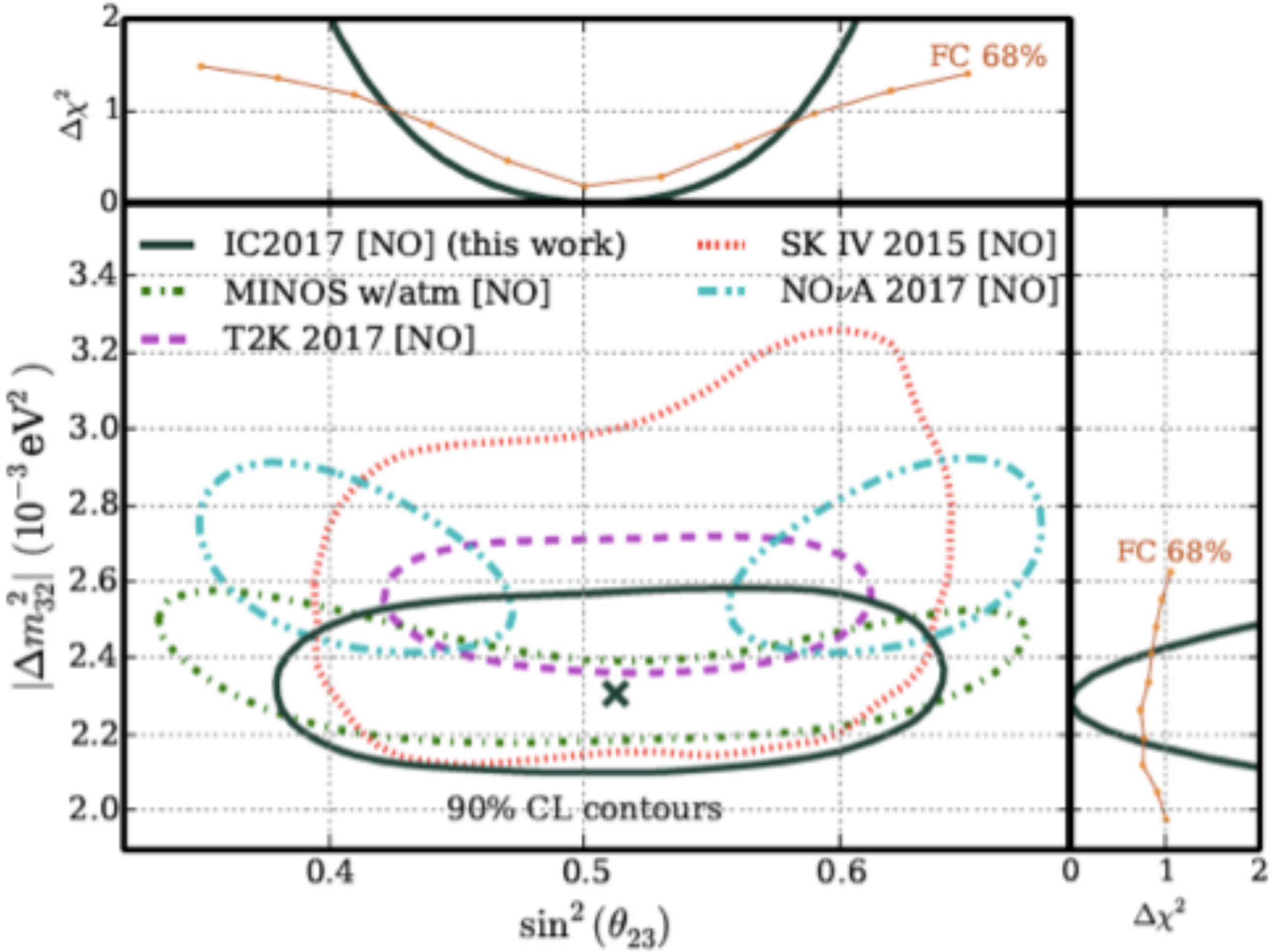
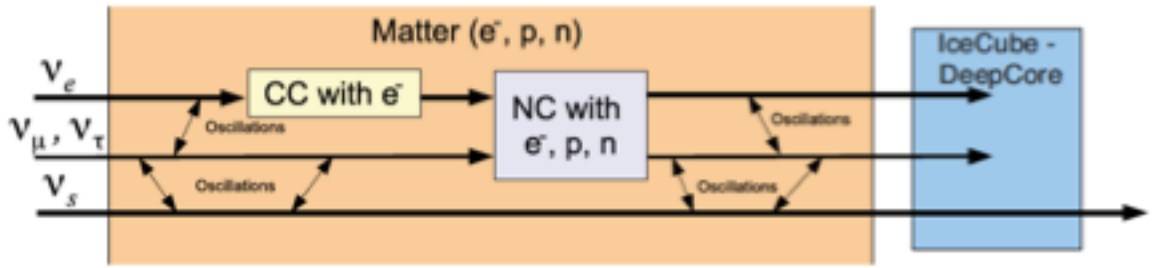


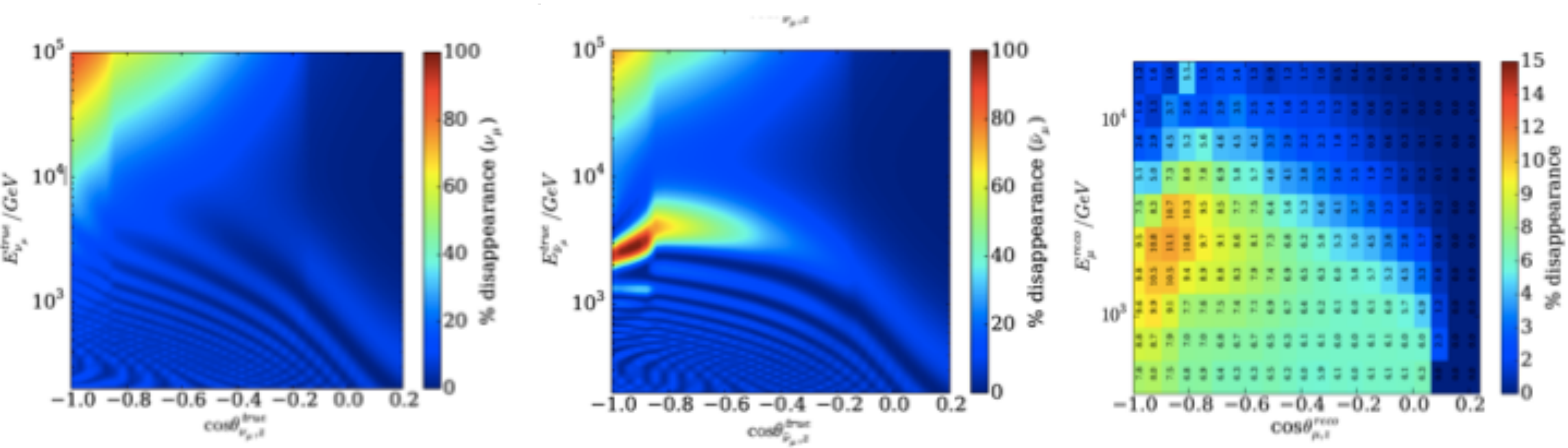

Best Fit
Cascade-like
Track-like
cos($\theta_{z,reco}$)
E_{reco} (GeV)
Number of Events
IceCube Preliminary
1.0
0.5
0.0
-0.5
-1.0
6
8
10
30
50
1000
800
600
400
200
0
31 93 241 371 394 334 222 137
103 218 402 537 541 430 284 172
208 382 587 685 644 513 346 219
365 534 731 780 718 571 398 264
472 631 751 780 696 538 382 249
492 611 688 673 573 434 303 195
404 483 551 527 447 327 216 148
272 344 404 405 333 242 158 104
32 85 143 186 208 179 119 67
66 101 162 223 271 276 230 147
119 150 216 288 355 366 310 211
179 193 266 356 431 440 401 295
248 240 291 353 440 468 445 332
252 236 260 279 338 343 347 262
218 192 211 206 220 215 218 186
182 197 206 206 171 137 128 113

Constraints on oscillation parameters



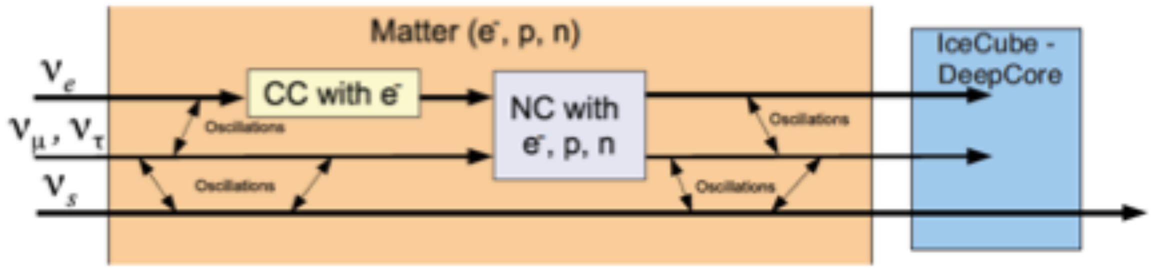
Sterile neutrinos

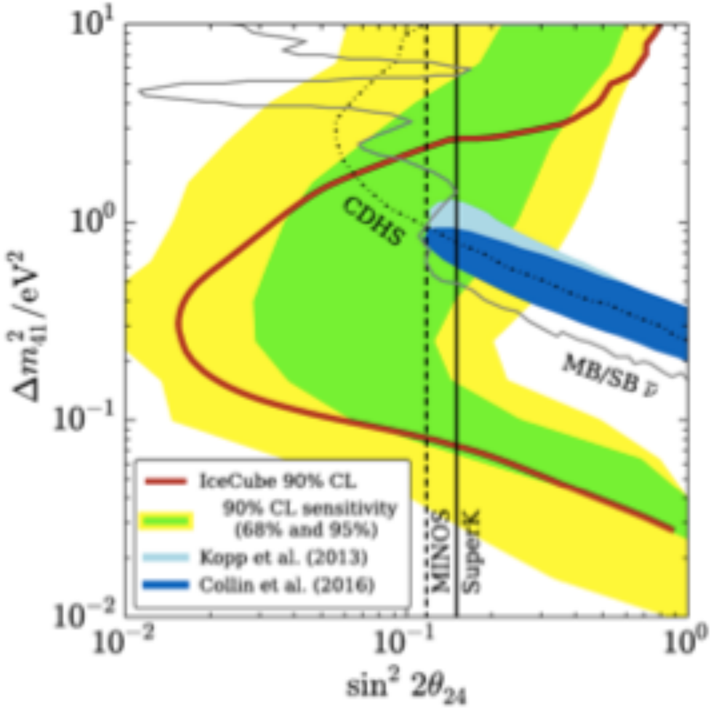




IceCube, Phys. Rev. Lett. 117, 071801 (2016)

Sterile neutrinos

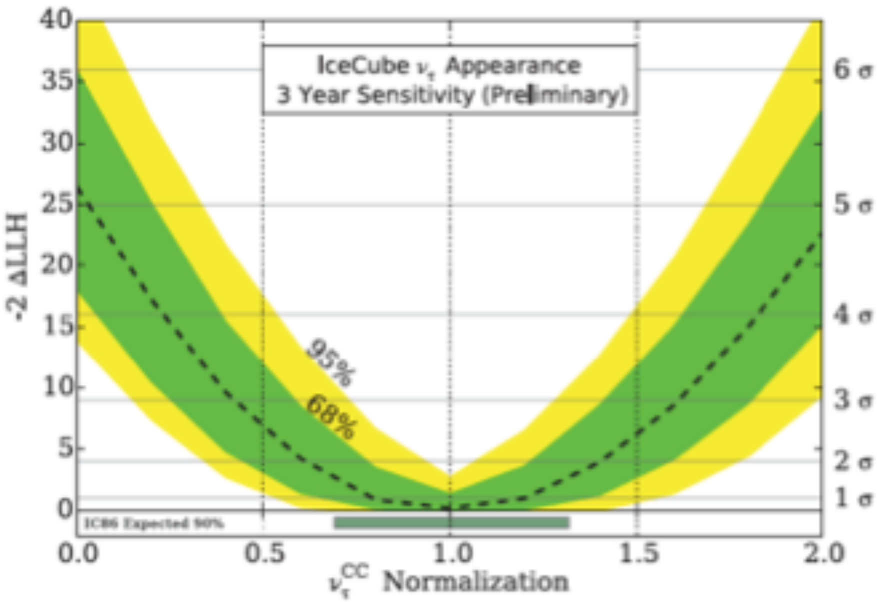


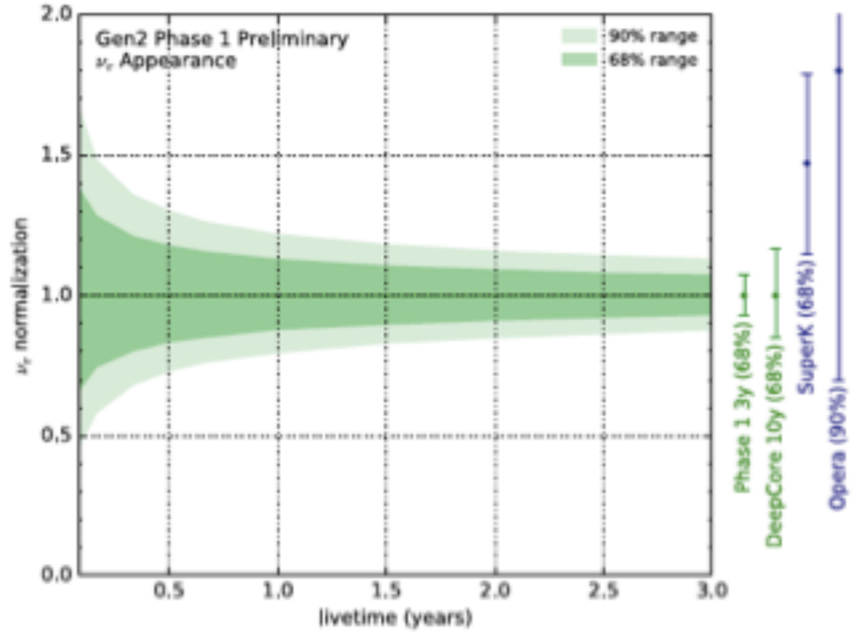


ν_τ appearance

$\nu_\mu \to \nu_\tau$ measurement valuable to check unitarity of PMNS matrix

Prospects for IceCube/Deepcore and Phase-1



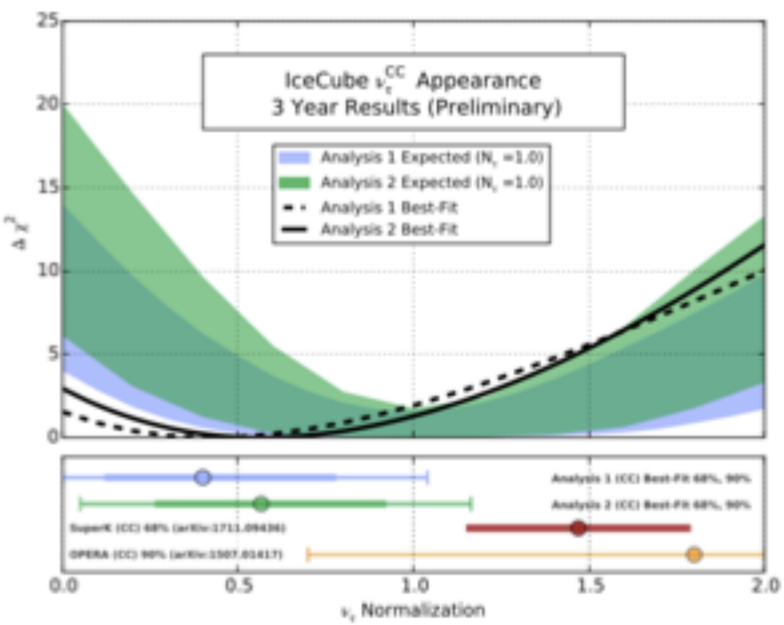


Koskinen (NEUTRINO 2016)

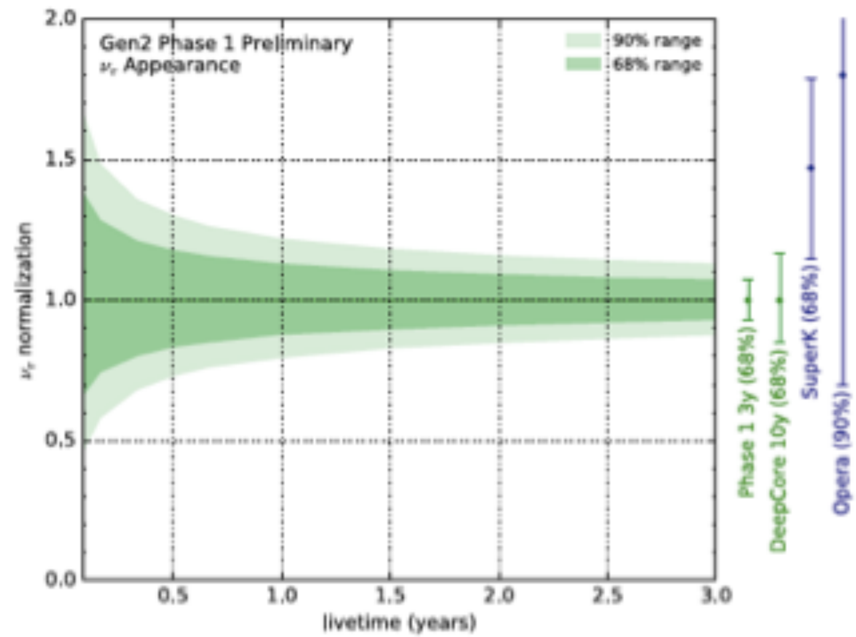
ν_τ appearance

$\nu_\mu \to \nu_\tau$ measurement valuable to check unitarity of PMNS matrix

Deepcore result and prospects for Phase-1



Deepcore result presented in Moriond 2018

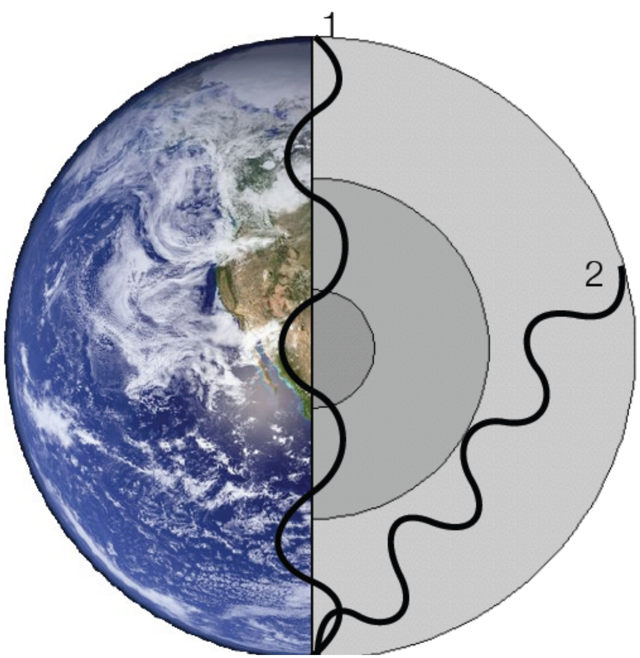


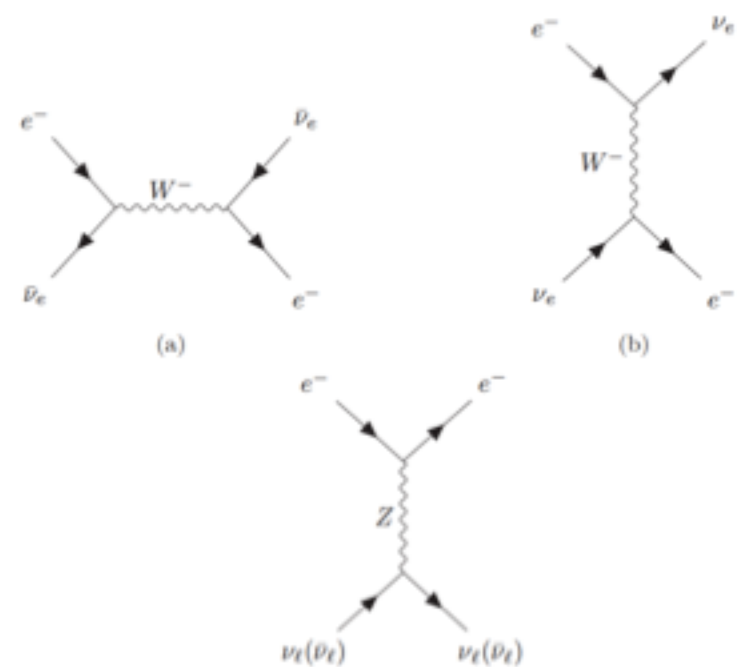
Koskinen (NEUTRINO 2016)

Neutrino oscillations in matter

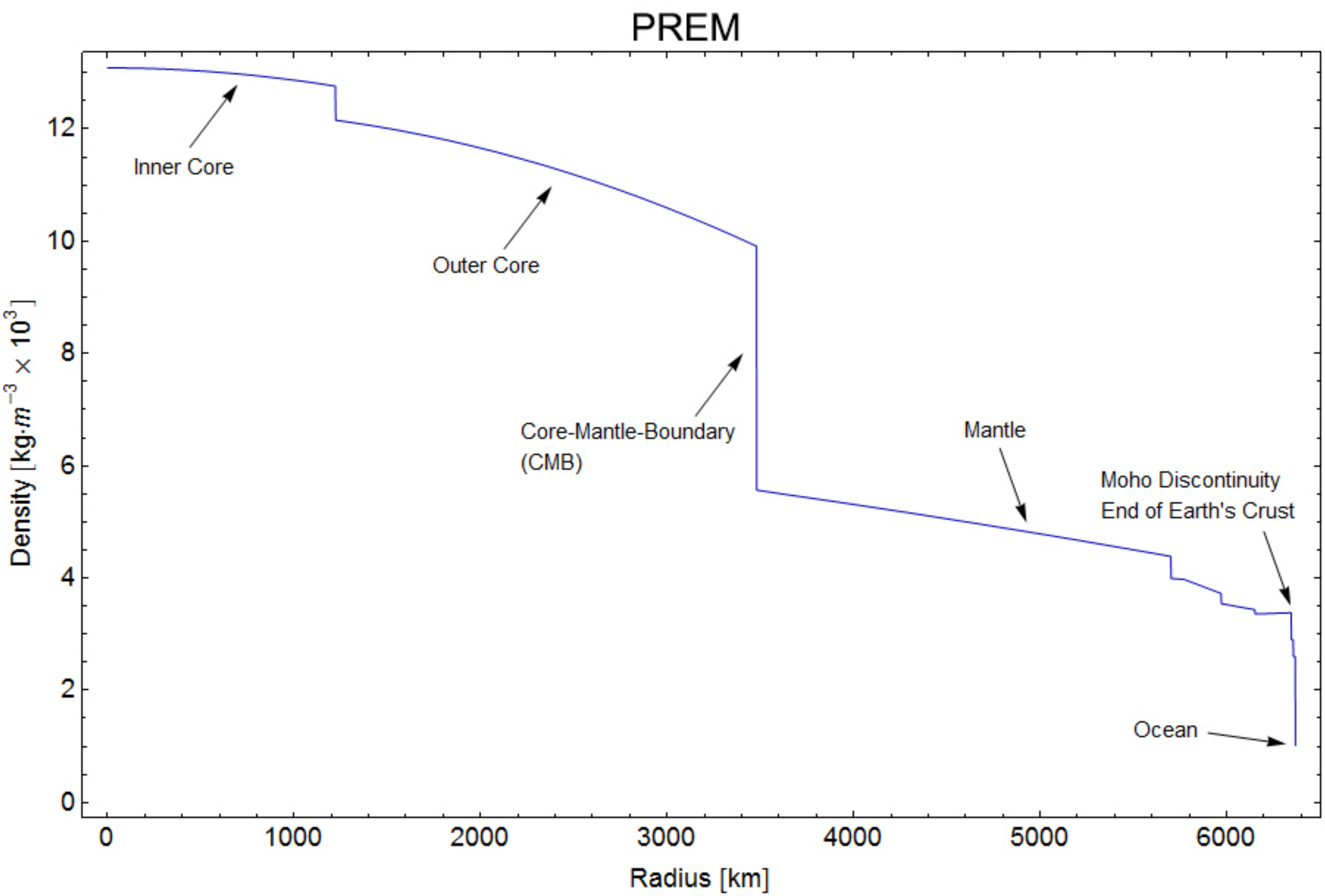
Propagation of electron (anti-)neutrinos in the Earth affected
(Mikheyev-Smirnov-Wolfenstein effect)

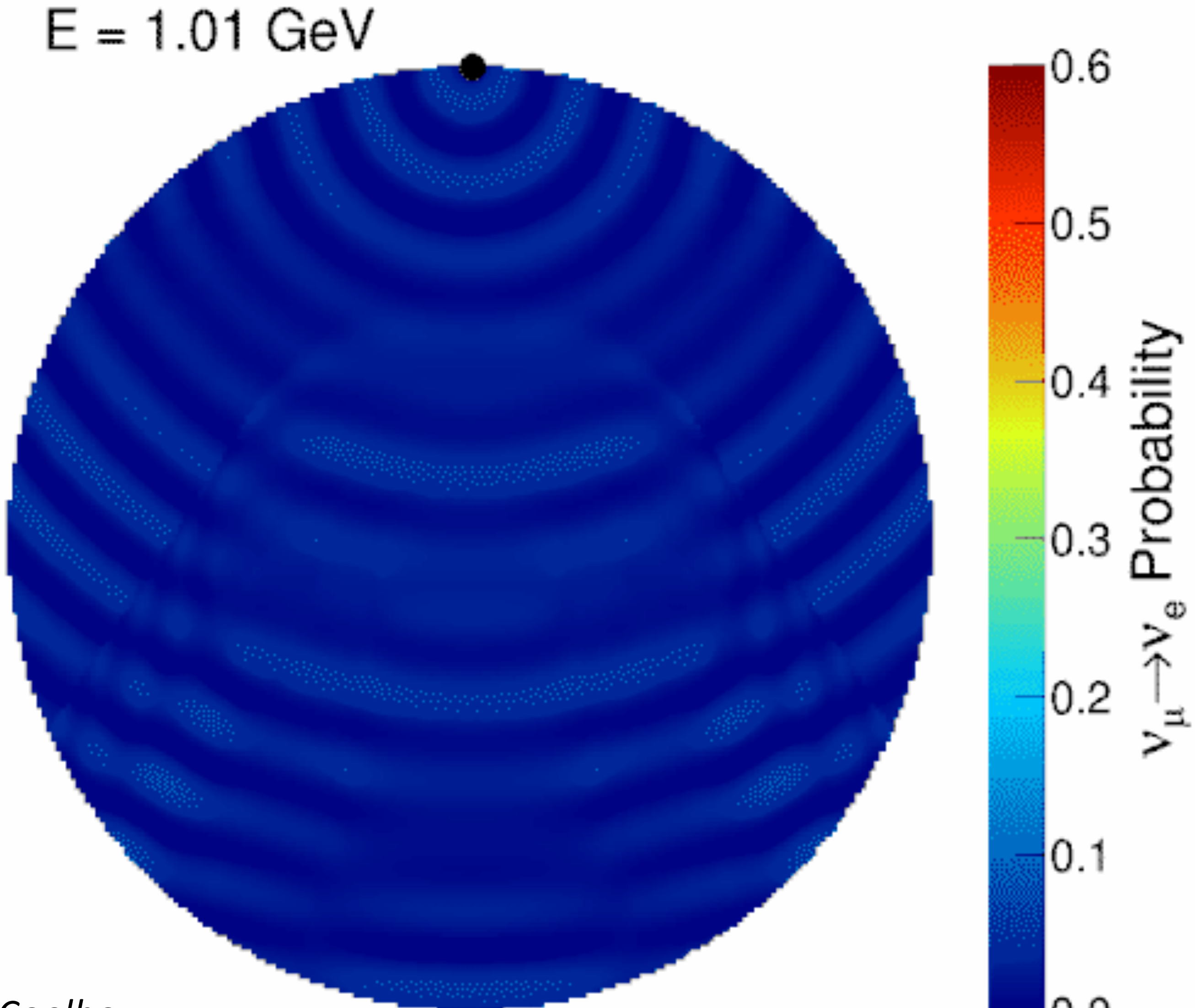
=> Sensitive to Neutrino Mass hierarchy





Earth reference model



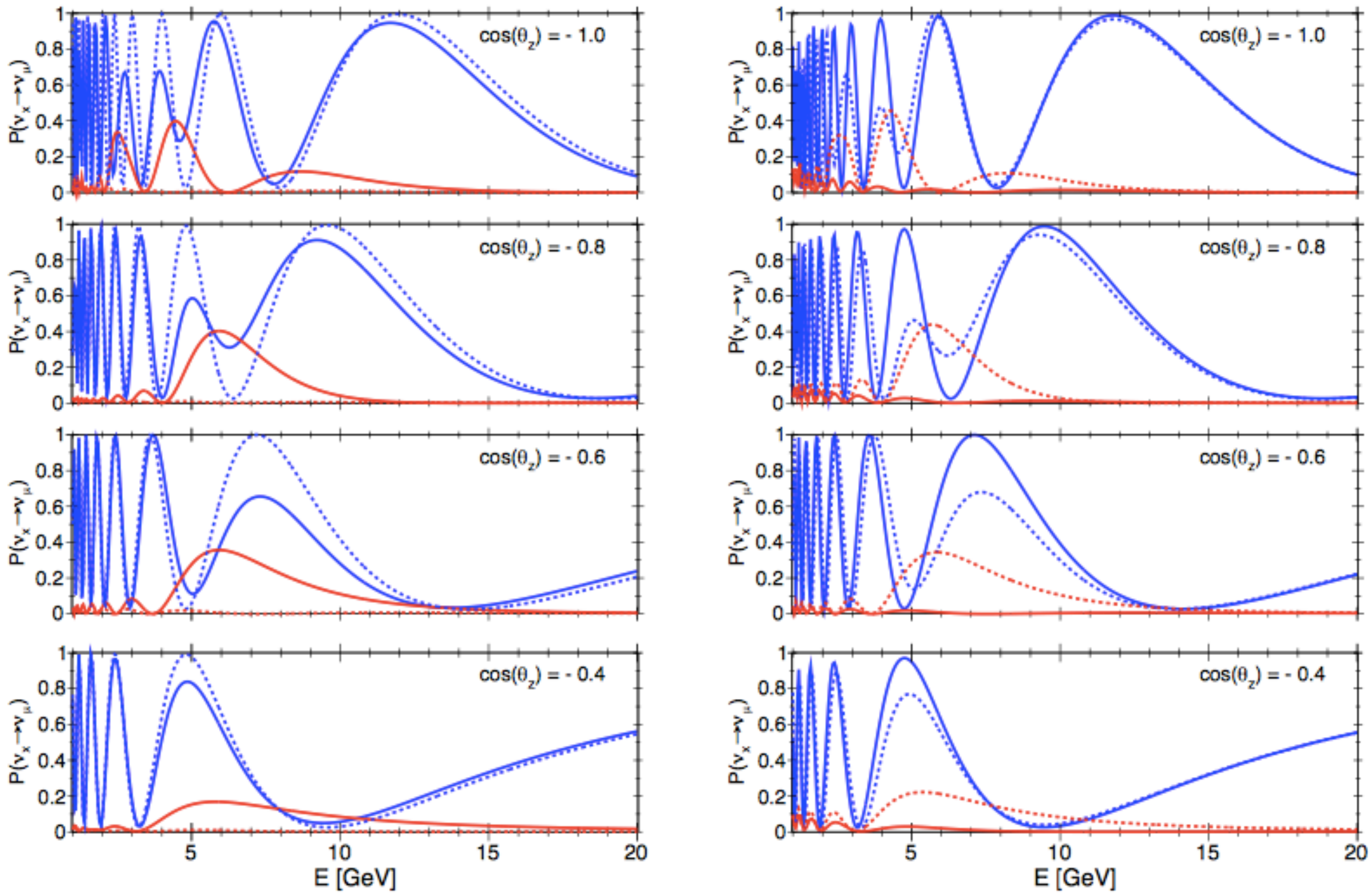


Animation J. Coelho

http://www.apc.univ-paris7.fr/Downloads/antares/Joao/animations/

Neutrinos

Antineutrinos



νμ -> νμ

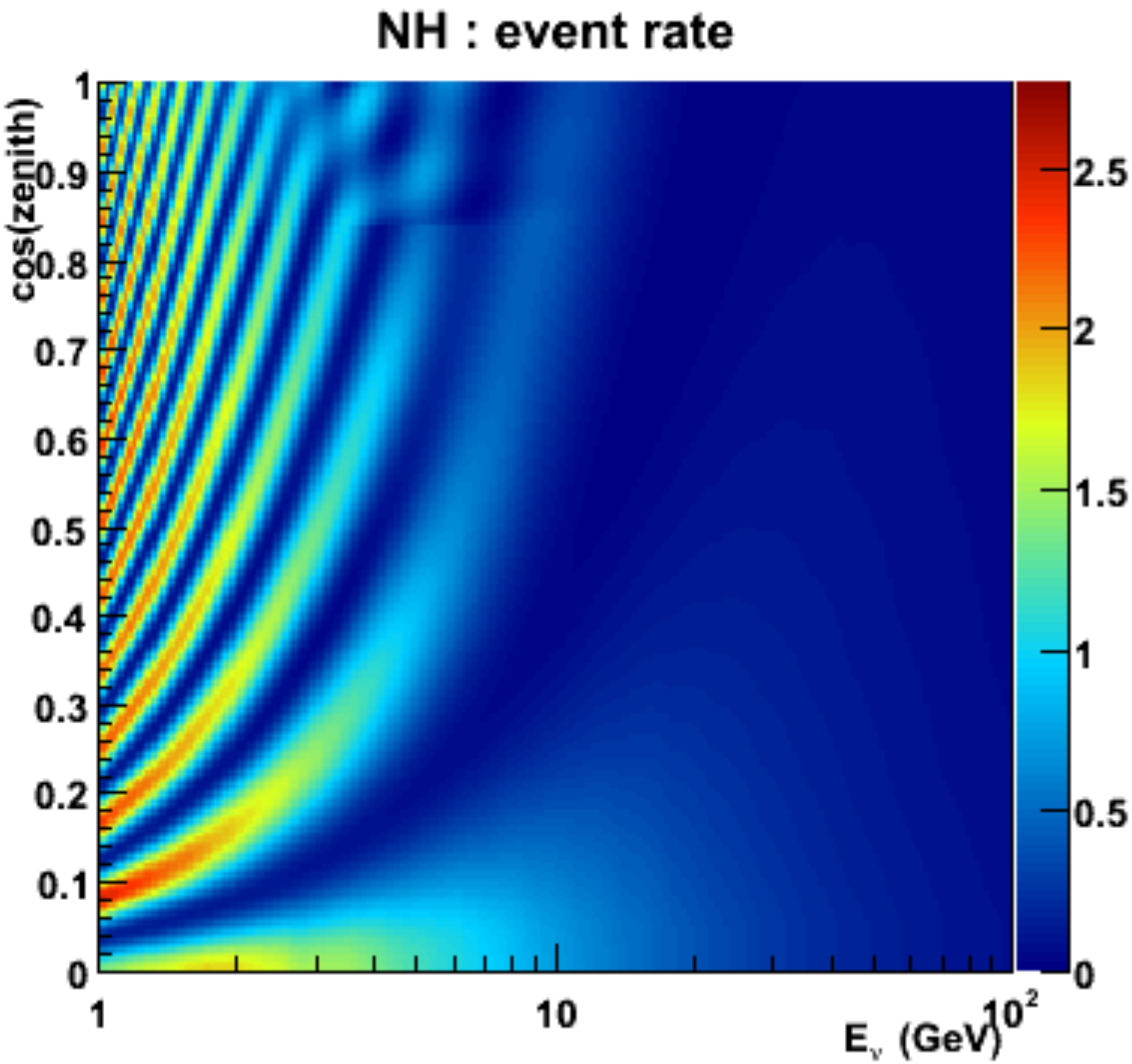
νe -> νe

Solid: NH
Dashed: IH

Neutrinos IH pattern corresponds to antineutrinos NH

⇒ Effect would cancel with equal neutrino/antineutrino rates

Normal hierarchy

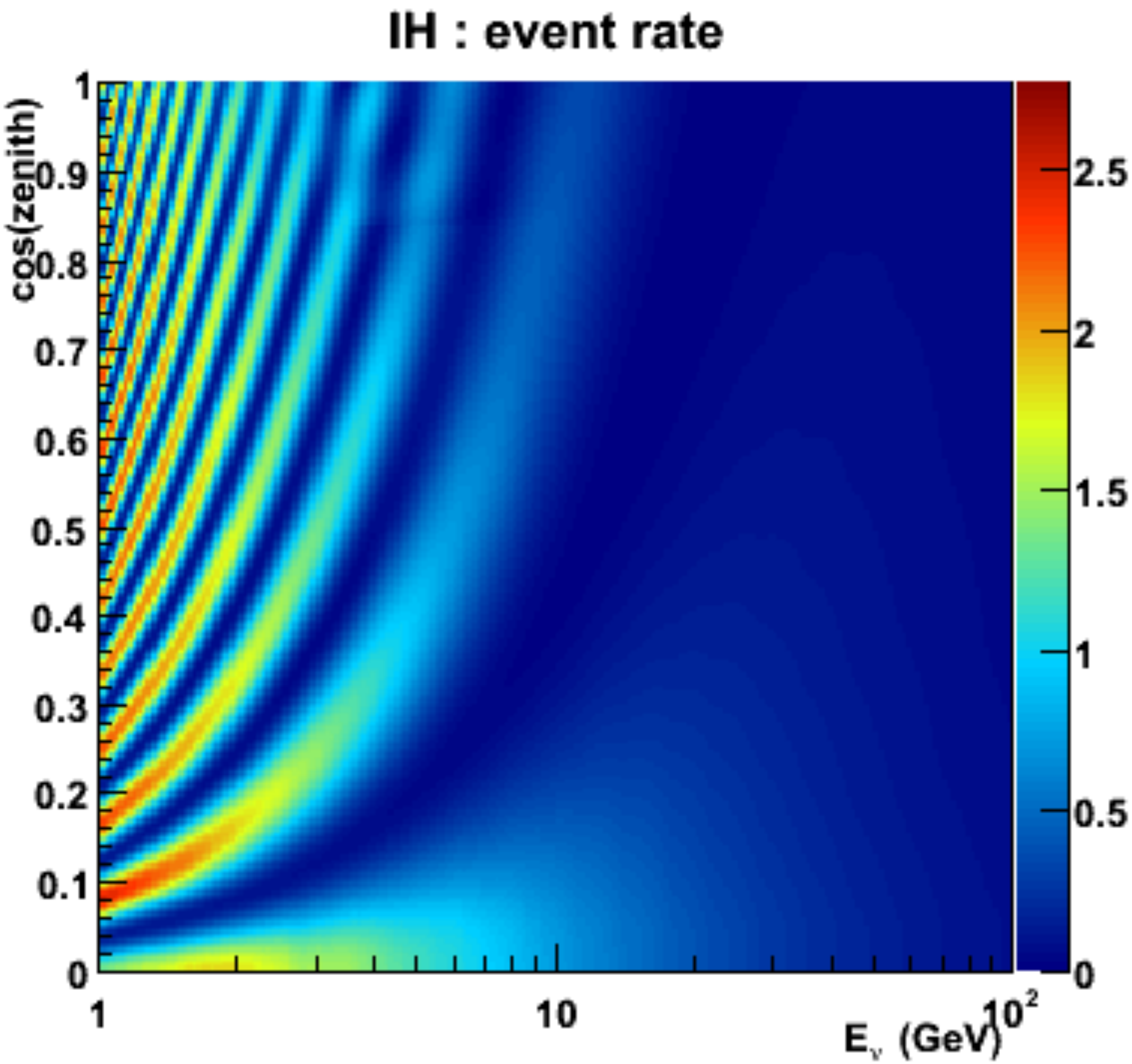


Ideal measurement
Muon channel

Event rate as function of energy and direction (zenith)

by Aart Heijboer, Nikhef

Inverted hierarchy

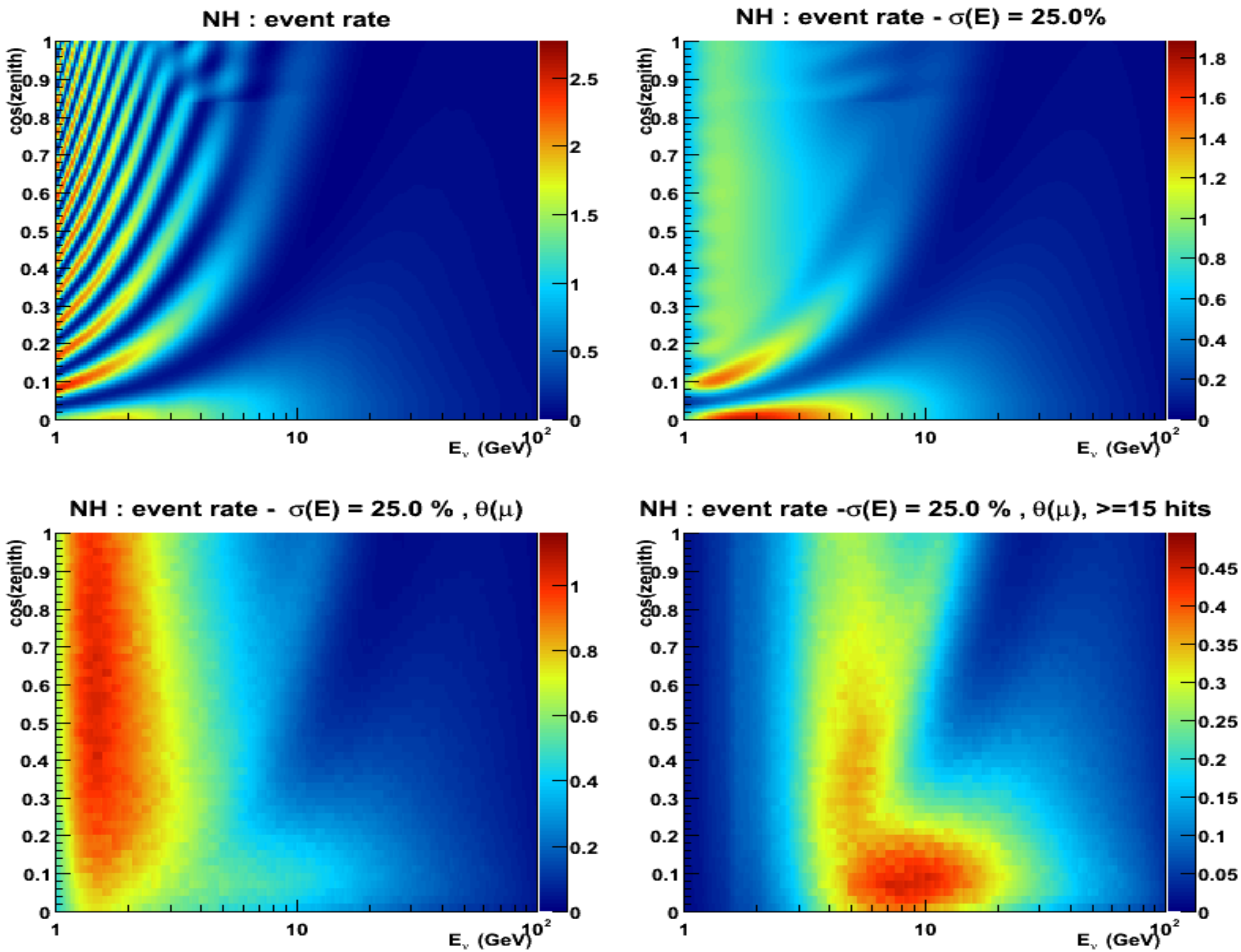


Ideal measurement
Muon channel

Event rate as function of energy and direction (zenith)

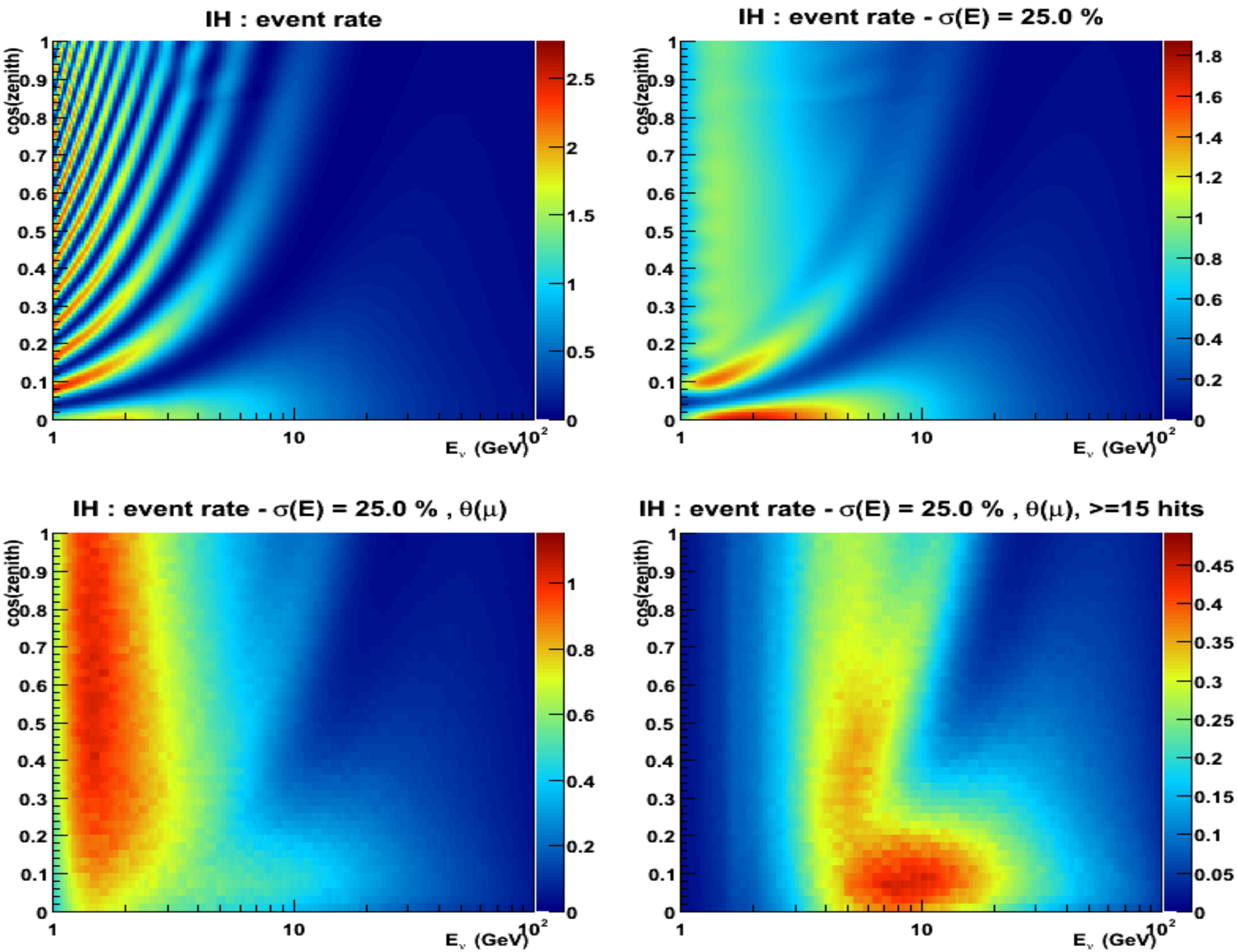
by Aart Heijboer, Nikhef

Adding realistic smearing for energy and angular resolution

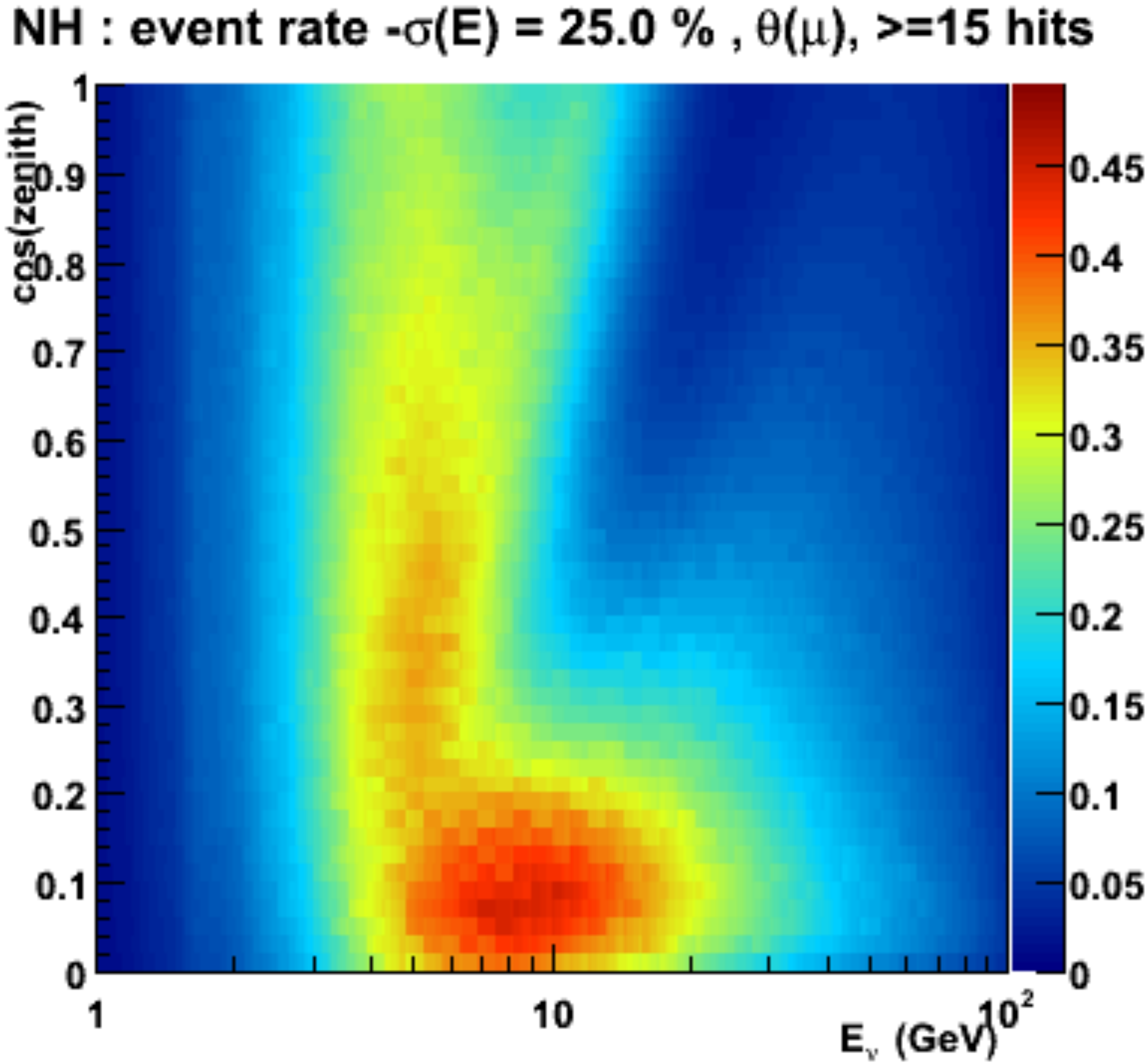


by Aart Heijboer, Nikhef

Adding realistic smearing for energy and angular resolution



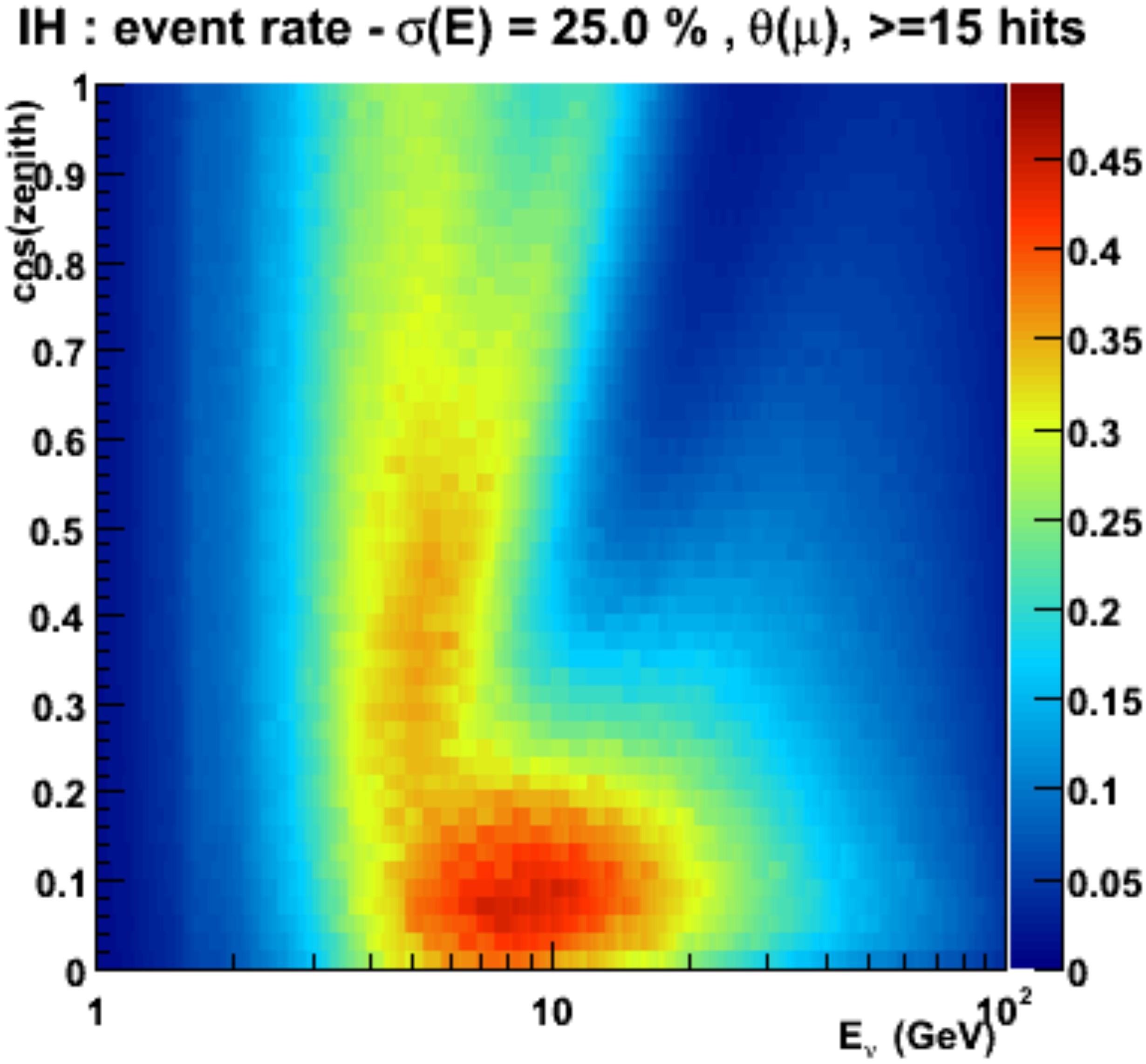
by Aart Heijboer, Nikhef



Realistic resolutions

Event rate as function of energy and direction (zenith)

by Aart Heijboer, Nikhef

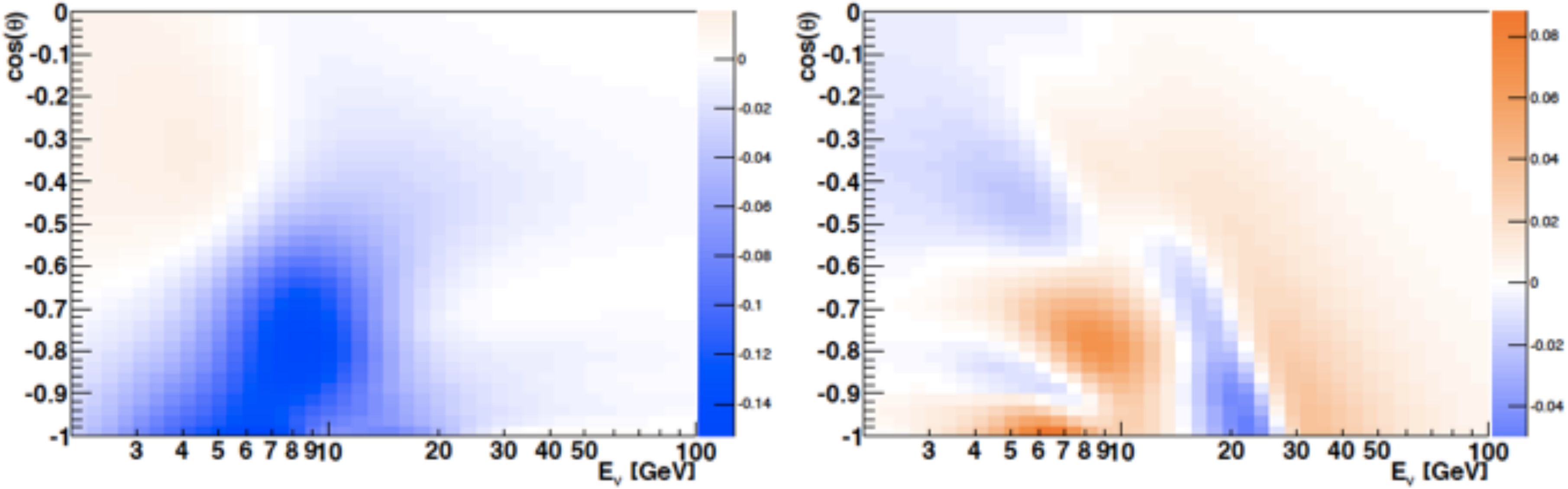


Realistic resolutions

Event rate as function of energy and direction (zenith)

by Aart Heijboer, Nikhef

Asymmetry between pattern of normal and inverted hierarchy: $(N_{IH} - N_{NH}) / N_{NH}$

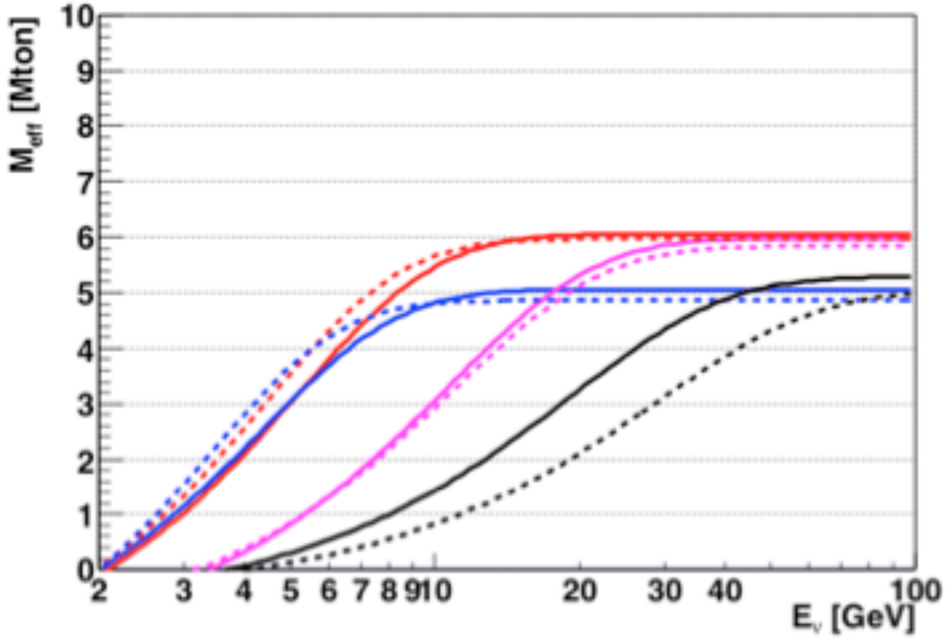


Small differences in pattern

-> large statistics needed
-> good control of systematics
-> energy/angular resolution crucial
-> flavor identification crucial

Evaluation of prospects for KM3NeT/ORCA

Effective mass



Events/yr (atm):

ν_eCC: 17300

ν_μCC: 24800

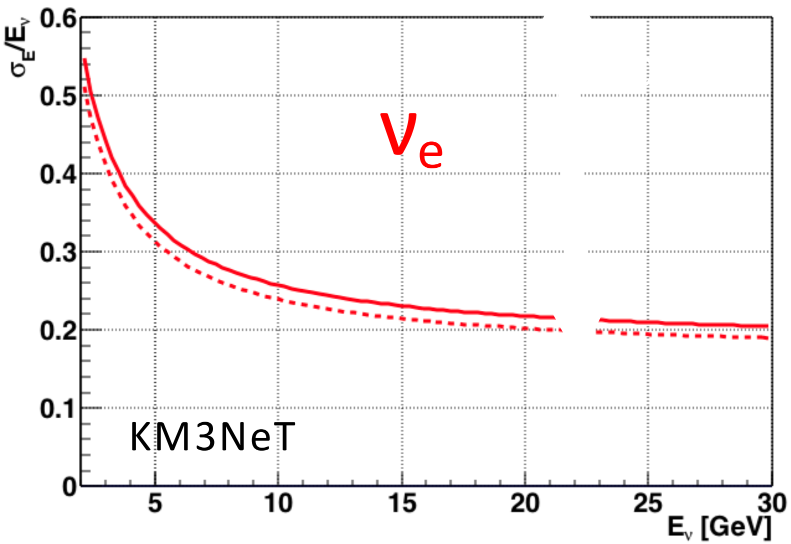
ν_τCC: 3100

NC: 5300

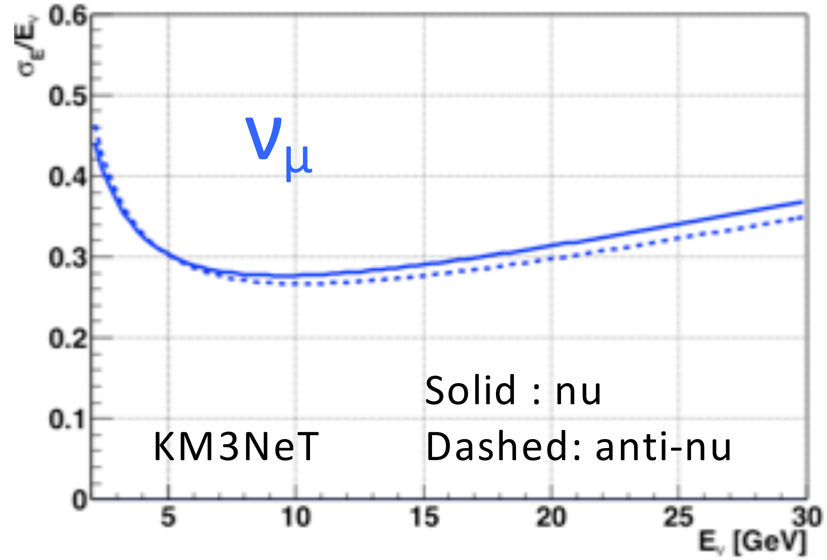
Low energy turn-on determined by DOM spacing
-> optimization of distances (design now 9m)

Energy Resolution

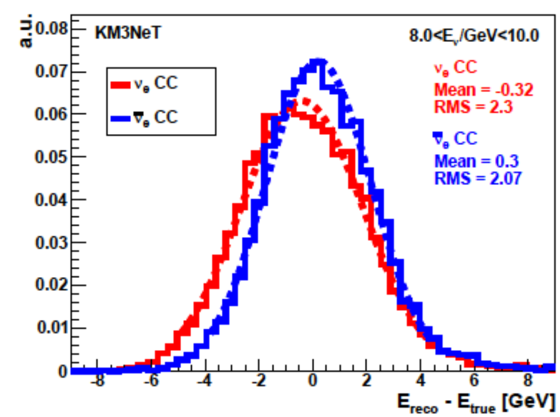
Shower



Track

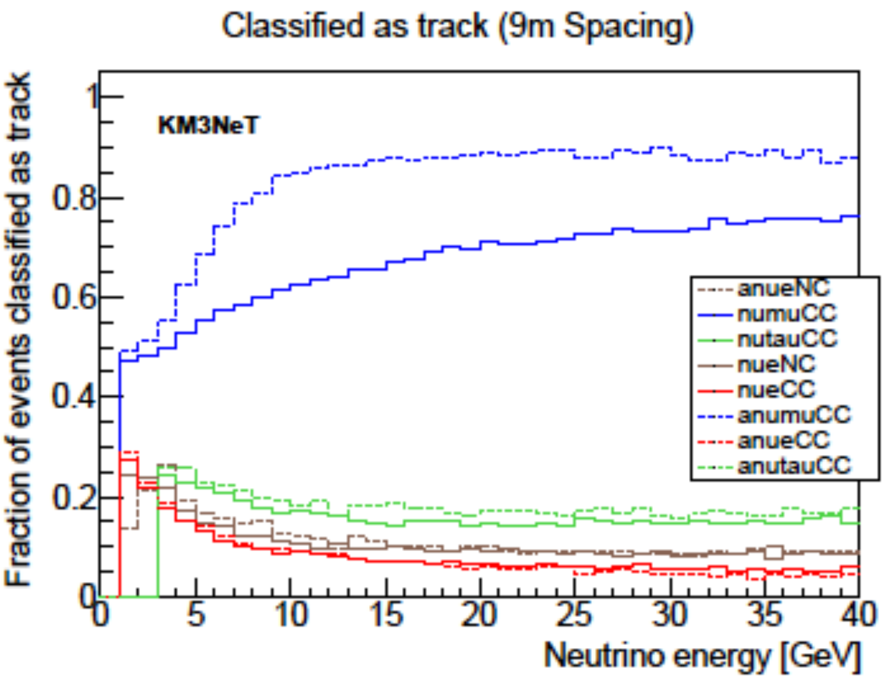


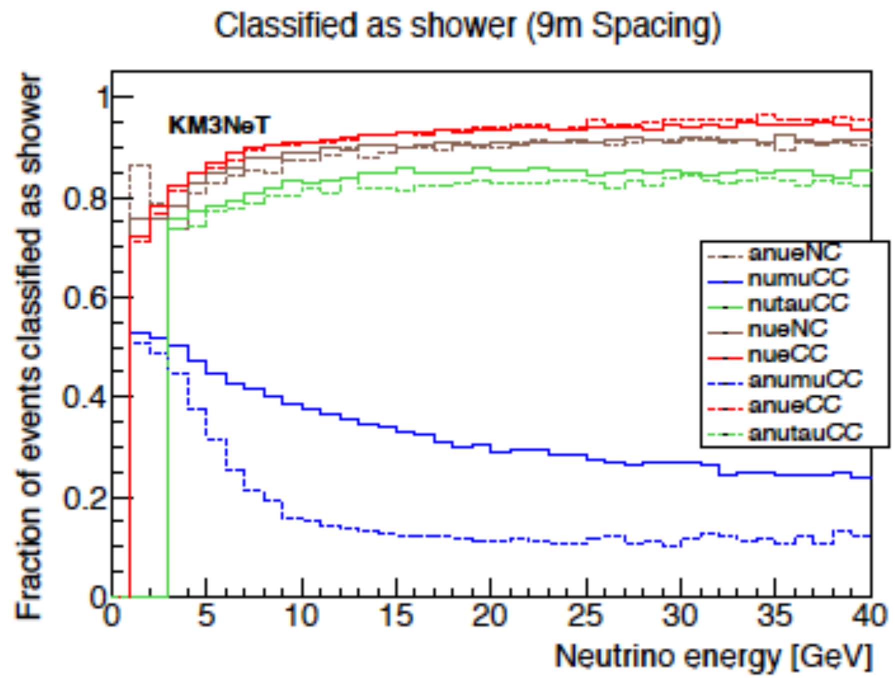
- Energy resolution better than 30% in relevant range
- Close to Gaussian



Flavor identification

Discrimination of track-like and shower-like events via Random Decision Forest





At 10 GeV:

- 90% correct identification of ν_e^{CC}
- 70% correct identification of ν_μ^{CC}

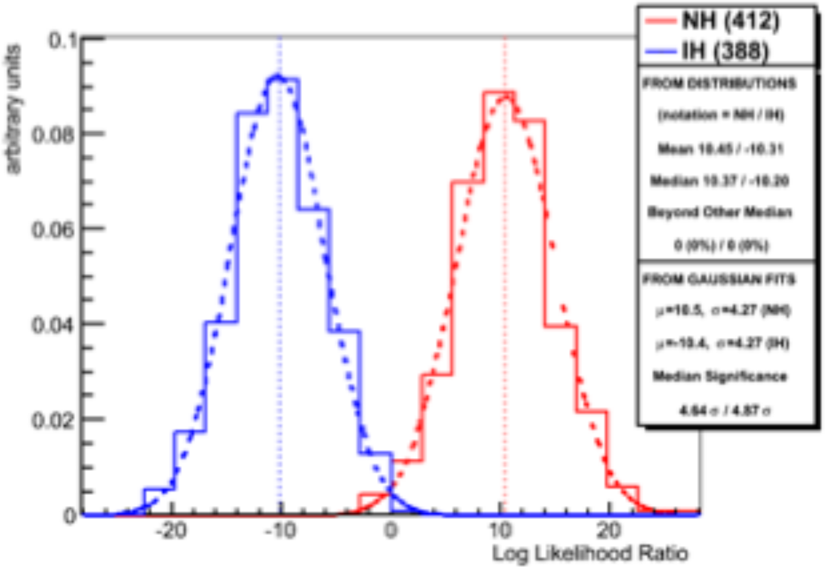
Sensitivity determination

Pseudo-experiments created using as input

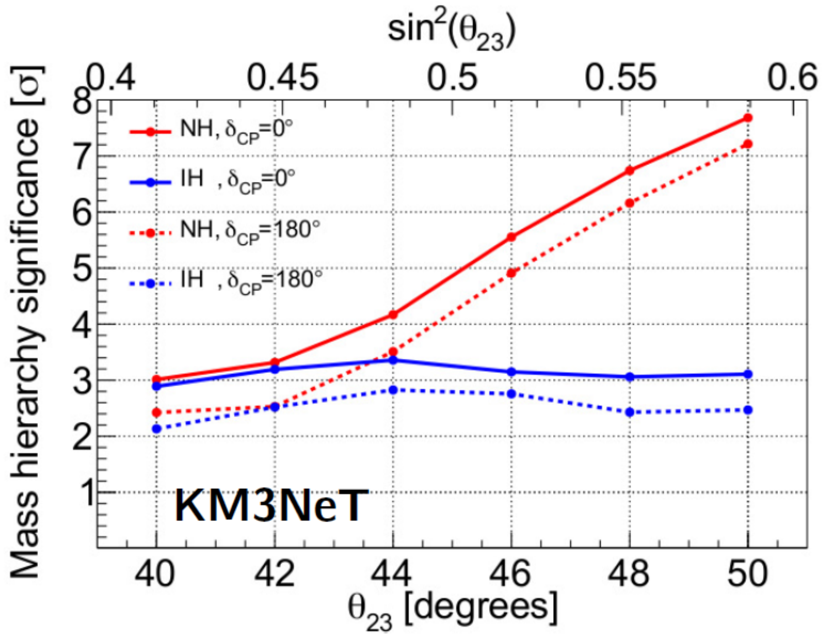
- atmospheric neutrino flux
- neutrino cross sections
- 3-flavour earth matter oscillations
- track vs shower event classification
- full MC detector efficiency / resolution response matrices including misidentified and NC events
- atmospheric muon contamination

To optimally distinguish between IH and NH:
likelihood ratio test with nuisance parameters

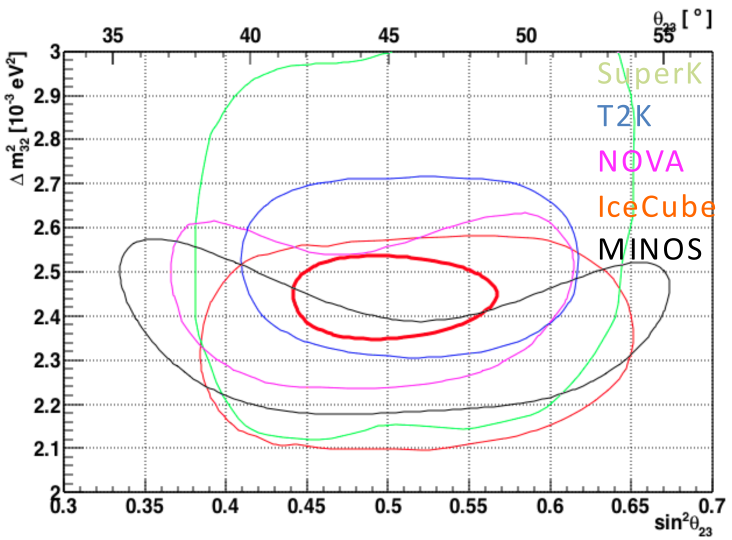
1) Fit parameters assuming NH
2) Fit parameters assuming IH
3) Compute $\Delta \log L = \log(L(NH)/L(IH))$



Sensitivity (3 years) for different θ23



Expected parameter constraints



90% CL contours (3 years)

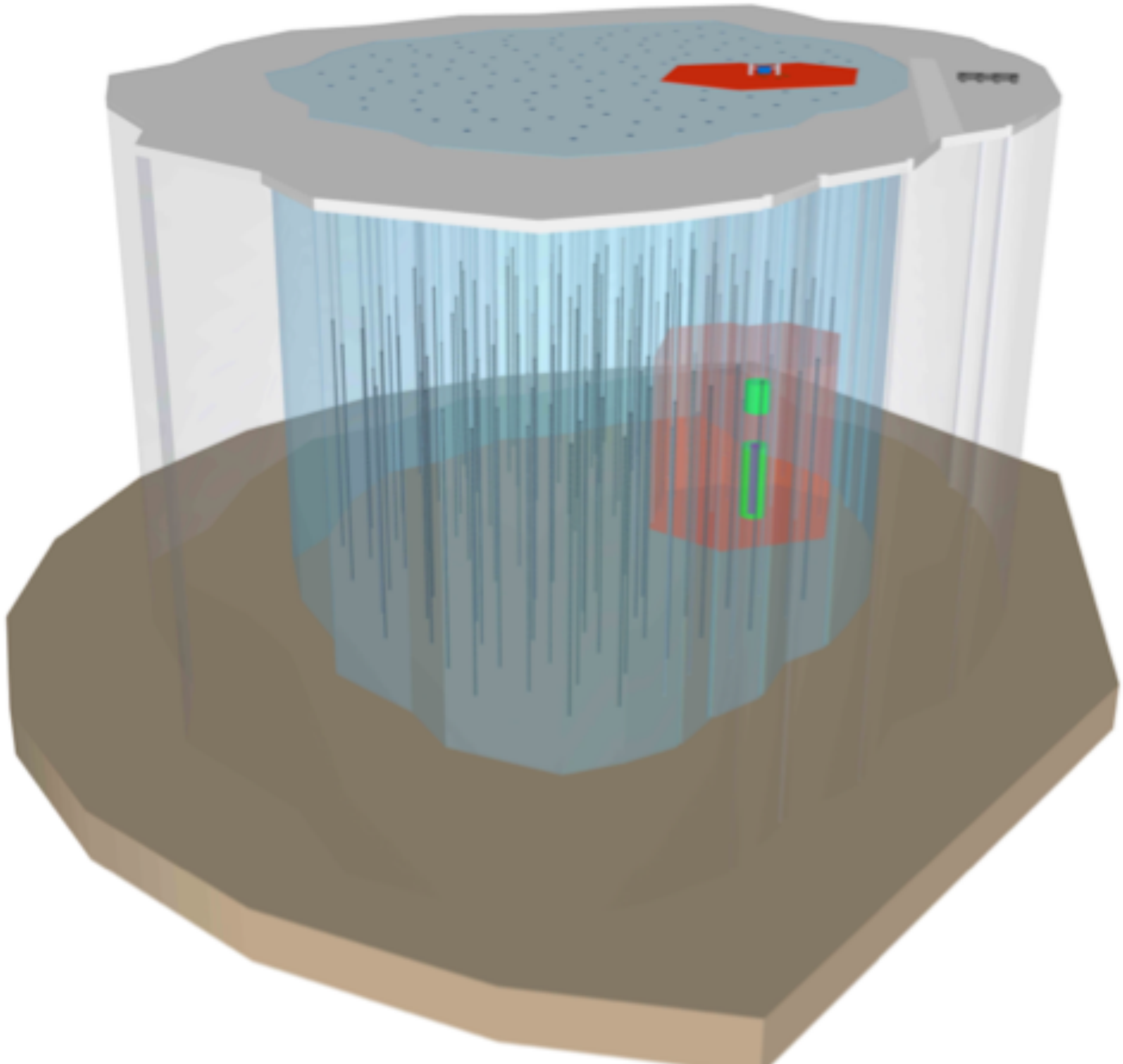
IceCube Gen2

Plans for extending IceCube with sparse array (2025-31)

250m string distances

$10km^3$ volume

-> Increased high energy sensitivity




CASTOR 02
ORCA's friends:
Pilot whale escort!
After the successful deployment of
the first ORCA string