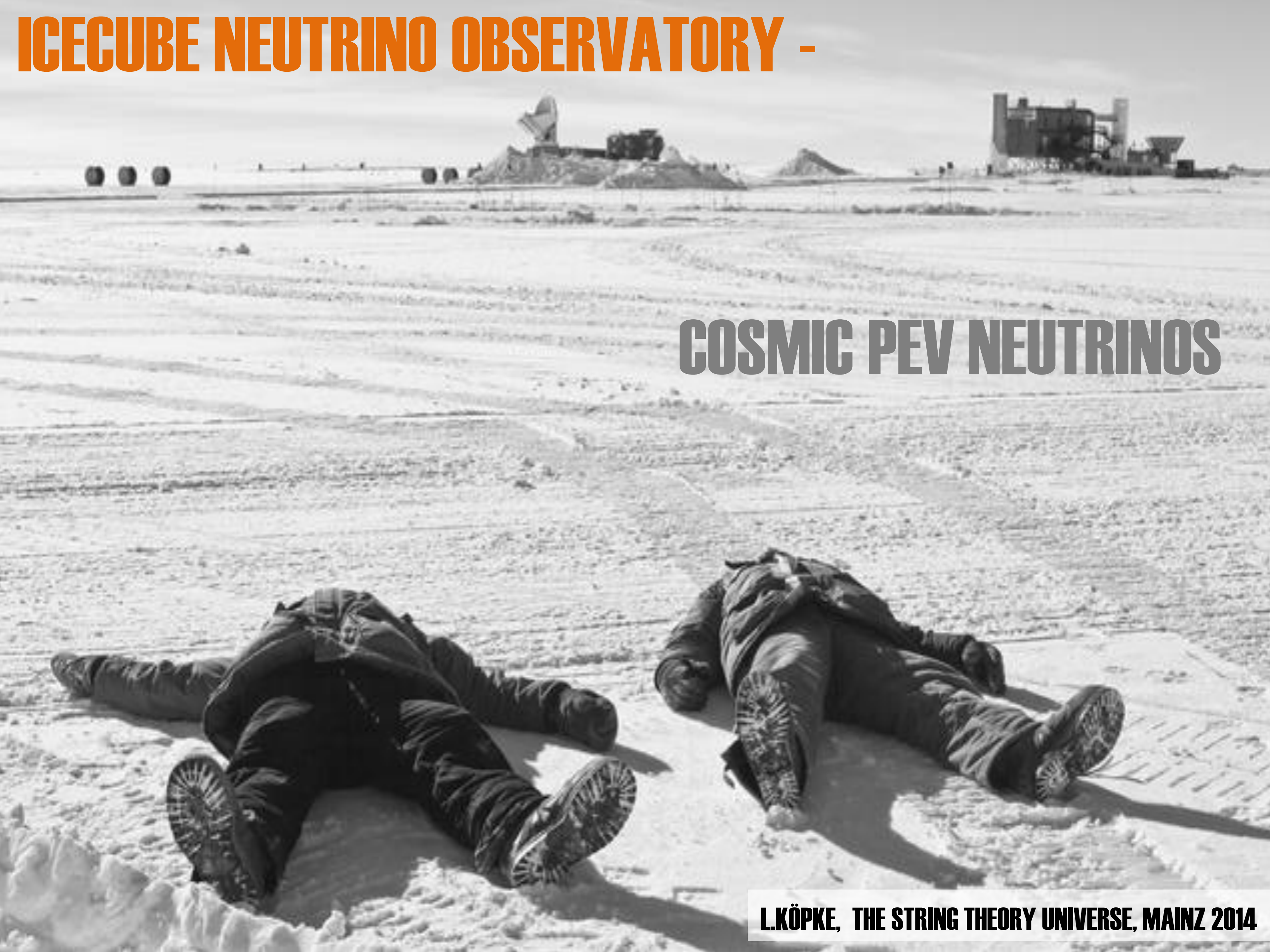
ICECUBE NEUTRINO OBSERVATORY -

COSMIC PEV NEUTRINOS



L.KÖPKE, THE STRING THEORY UNIVERSE, MAINZ 2014

WHAT I WILL TALK ABOUT ...

Neutrino astronomy:

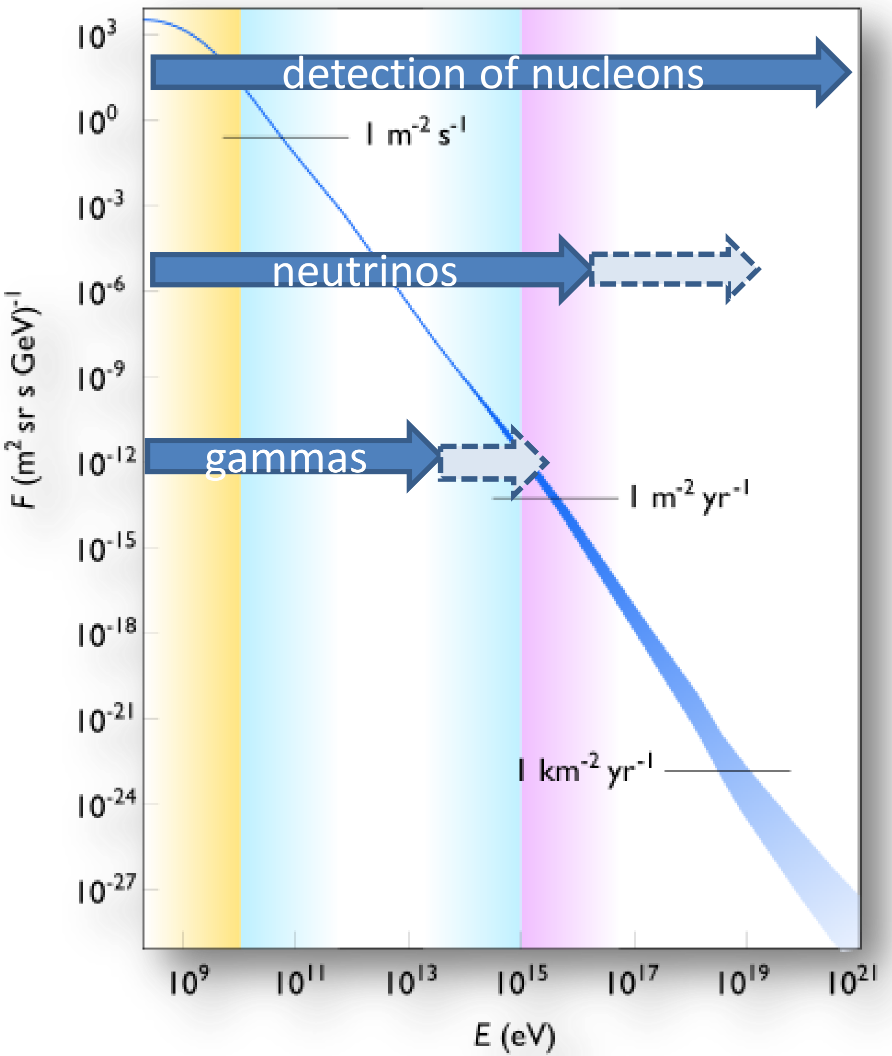
- Cosmic messengers
- Main Goals, detector, challenges, particle sources and methods
- One of the core programs: search for a high energy υ excess
- Experimental approach to pinpoint astrophysical neutrinos
- Why could a string theorist be interested?
- Outlook, new detectors and conclusions

Main studies: origin, composition, interactions of cosmic rays ...
υ physics, dark matter, supernovae, monopoles ...

Real Goal: find something unexpected !

COSMIC MESSENGERS

… cosmic acceleration up to energies of 10^{21} eV



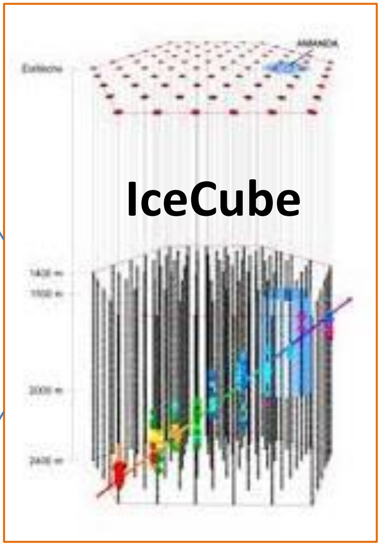
- candidates for cosmic accelerators exist but understanding still partial…
- cosmic cataclysms best observed with highly energetic messengers

EXPLORING THE SKY WITH PARTICLES

… sensitivity determined by energy range, effective area …

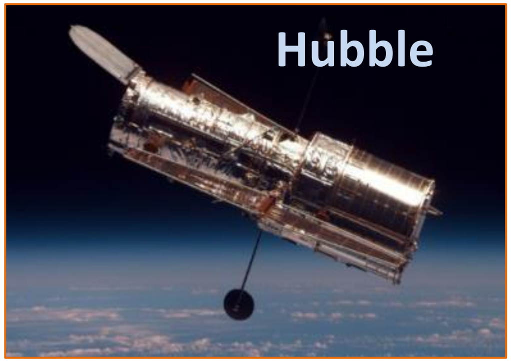
Type	Experiment	$E_{typical}$ [eV]	Effective area
Satellite based	Fermi-LAT	10^6	1 m^2
	Hubble	1	5 m^2
Neutrino telescope	**IceCube**	**10^9-10^{12}**	**5 m^2**
Cherenkov telescope array	CTA	10^8-10^{10}	10^6 m^2
Cosmic air shower array	AUGER	10^{18}-10^{20}	$3x10^9$ m^2

1 km



~

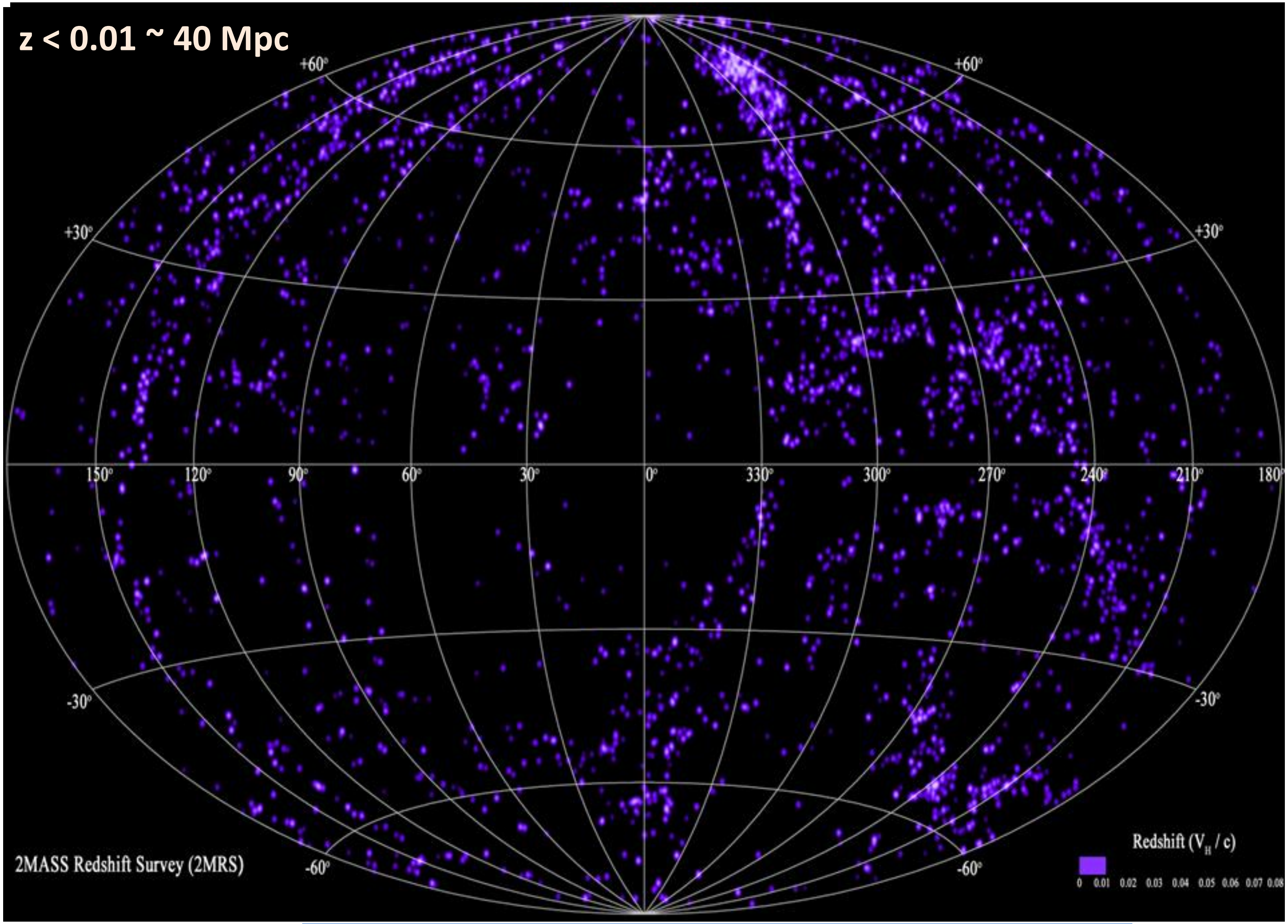
similar effective area
but signal flux $\propto 1/E^2$



for a serious comparison,
other parameters matter …

- angular coverage
- **obstruction by matter**
- magnetic field sensitivity
- backgrounds

VIEWING RANGE

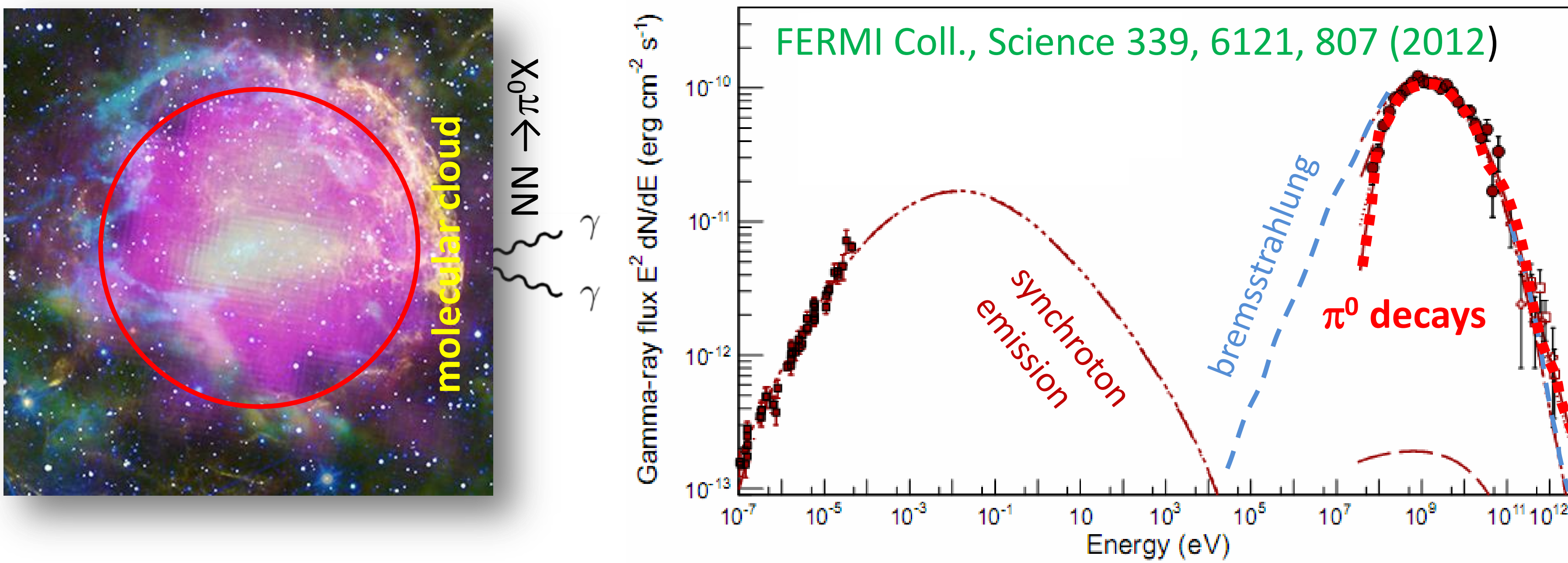


1 PeV υ ≈ 2 PeV γ ≈ 20 PeV cosmic ray

υ's see the whole universe

INDICATIONS FOR HADRONIC ACCELERATION

Gamma telescopes:
- γ rays generated in π^0 decays (67.5 MeV each in rest system)
- minimal energy in boosted system



Cosmic ray arrays:
- Regular/turbulent magnetic fields disturb CR direction for E < O(50 EeV)

TRUE GOAL OF NEUTRINO TELESCOPES

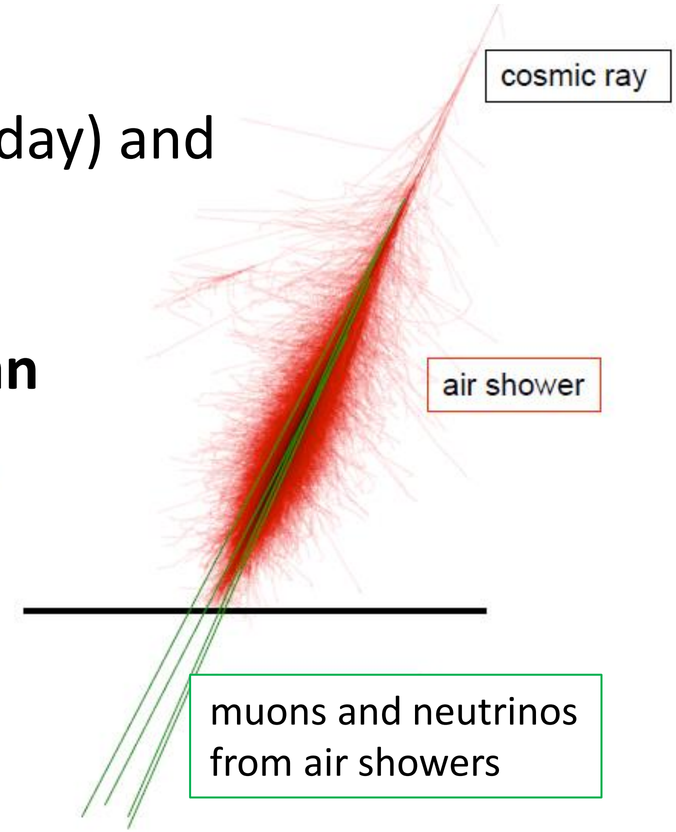
Measure fluxes of

- atmospheric muons (250 million per day) and
- atmospheric neutrinos (> 200 per day)

at higher energies & with better statistics than previous experiments

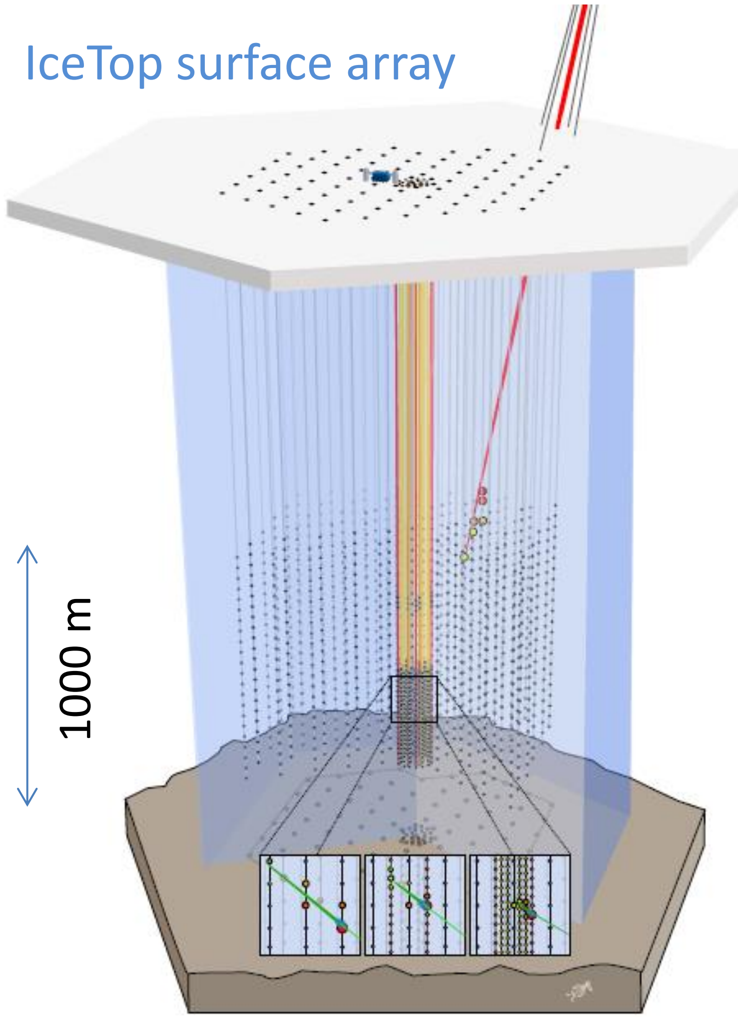
Any deviations from what is expected is new

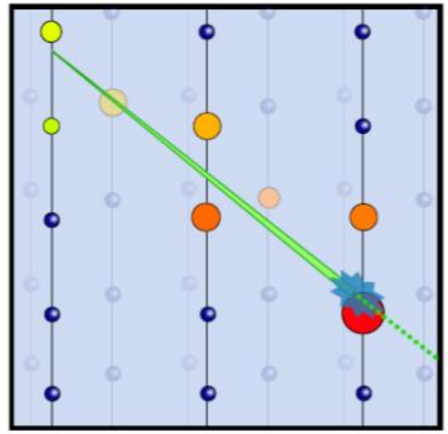
- neutrino physics or
- new astrophysics



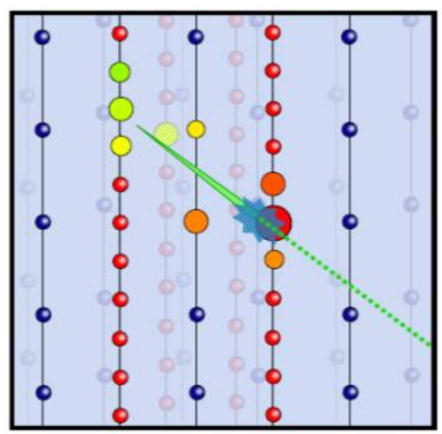
Neutrino telescopes are discovery experiments!

ICECUBE OBSERVATORY





IceCube only
>100 GeV



IceCube w/ DeepCore
>few 10 GeV

5160 sensors on 86 strings
→ 1 km^3 sensitive volume
→ higher density DeepCore

~98% of all sensors working

~99% data taking efficiency
.... 365 days of the year

plot includes envisaged „Pingu“ low energy extension“

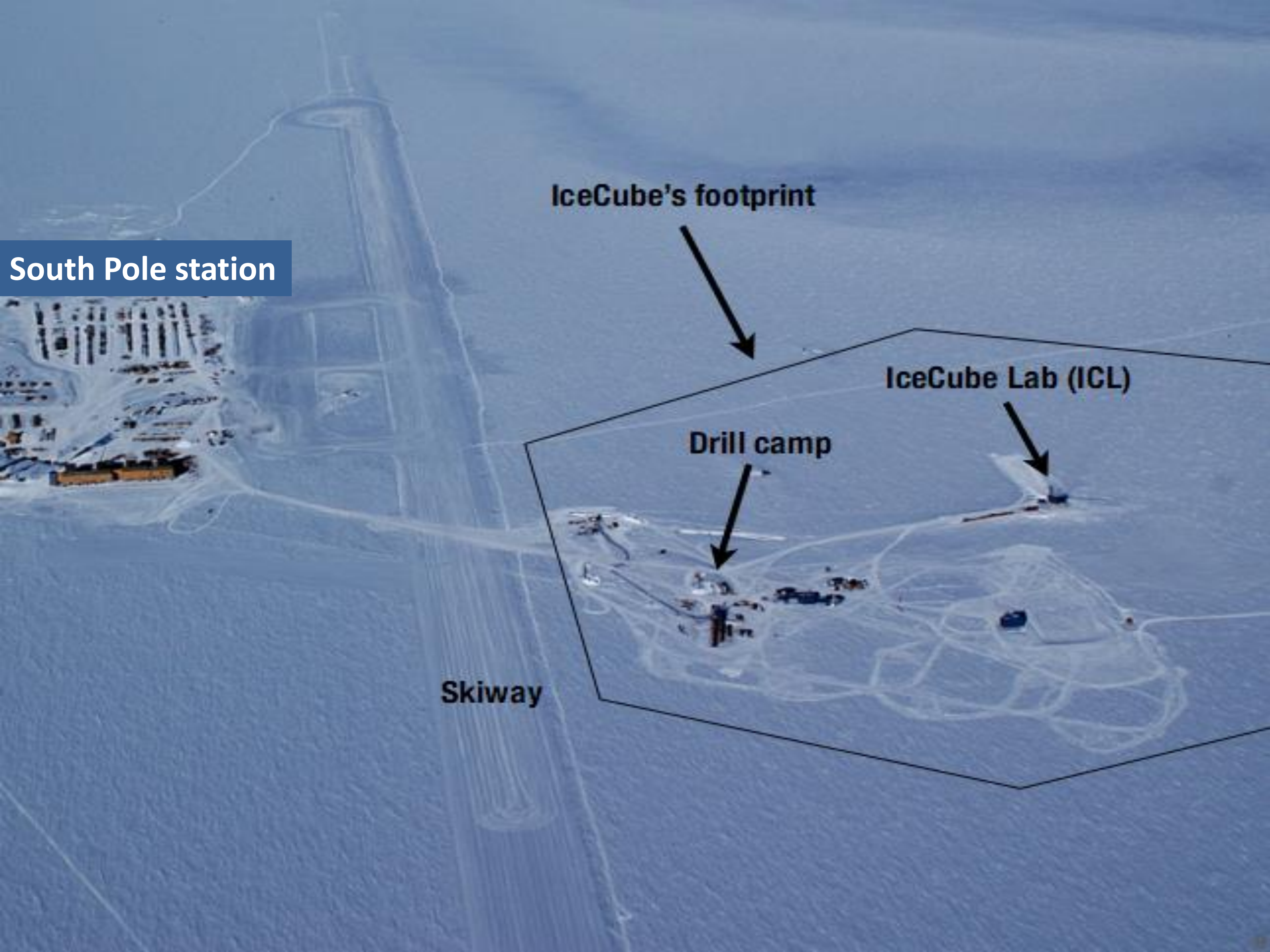
...full data taking started May 2011

The IceCube Collaboration

12 countries, 41 Institutions

Funding Agencies

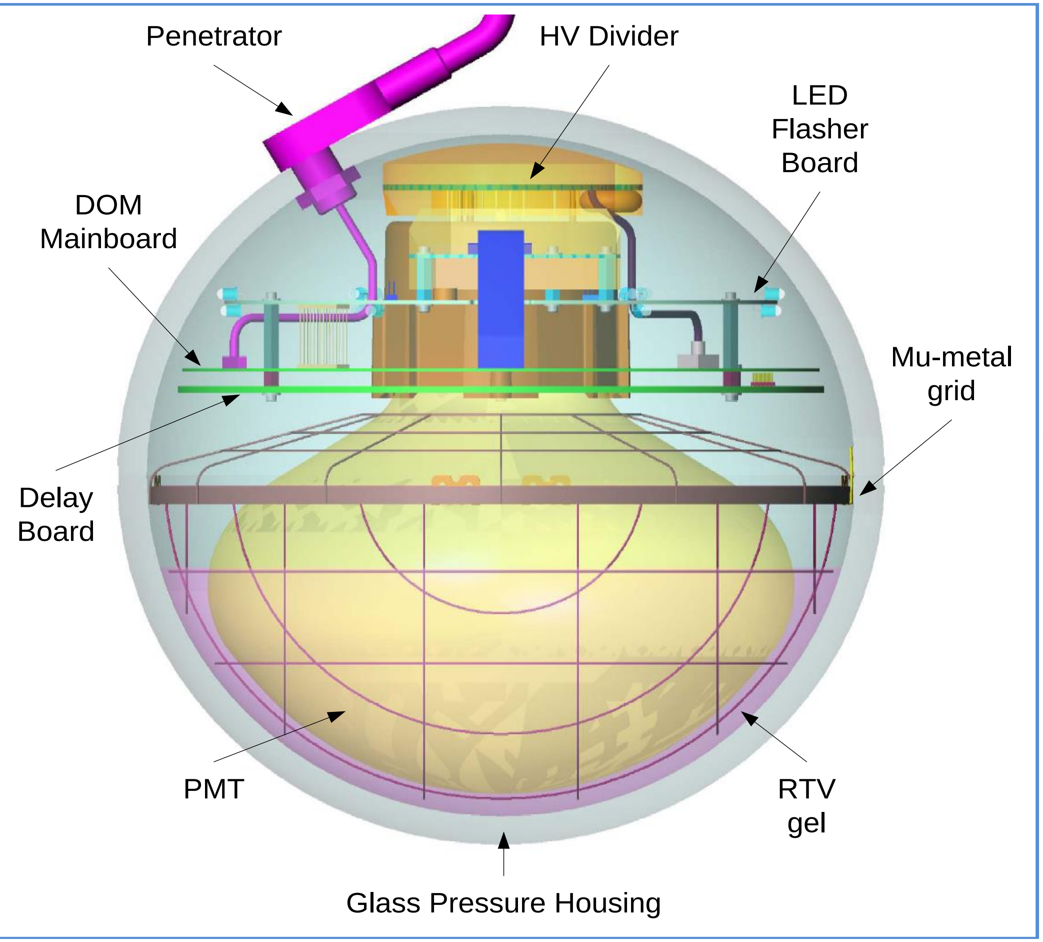
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)


South Pole station
IceCube's footprint
IceCube Lab (ICL)
Drill camp
Skiway

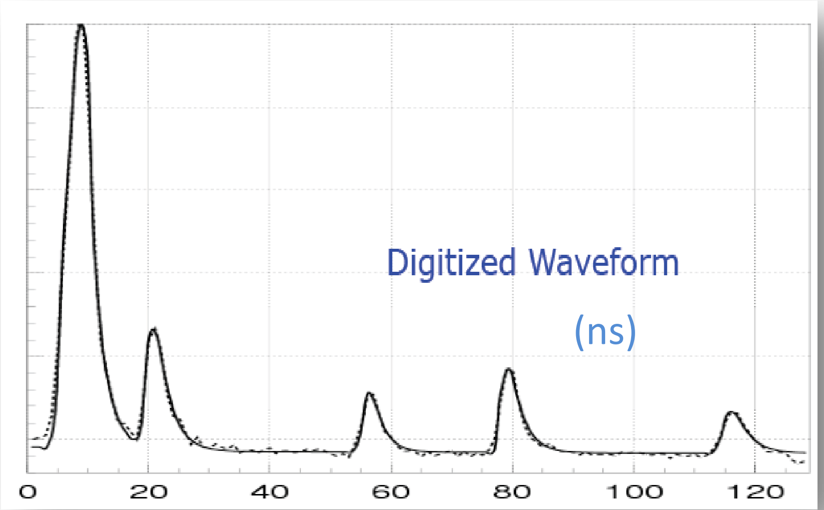
Technical and support issues

~60 kW power to electronics
90 GB/day filtered out and sent on satellite
2 winterovers
summer population (around 5-7 pop Dec - Jan)

THE ICECUBE DIGITAL OPTICAL MODULE



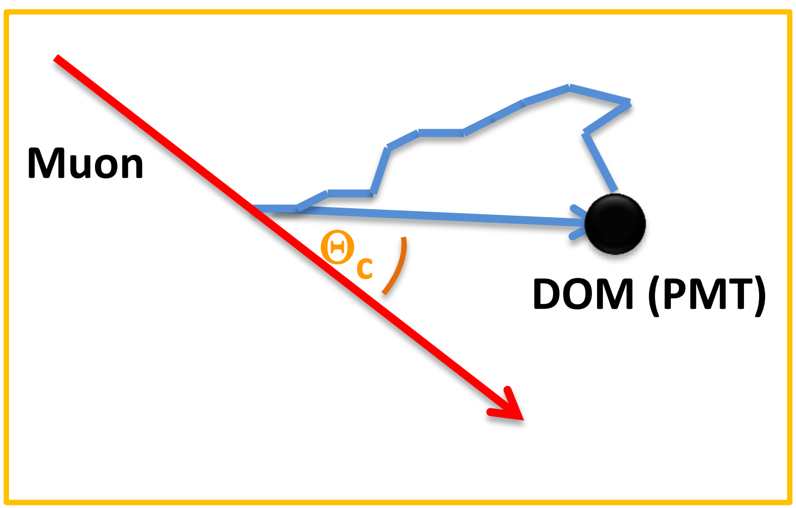
- On-board HV, 330 MHz digitizers
- Low power: 3.75 W
- Low noise: ~ 540 Hz

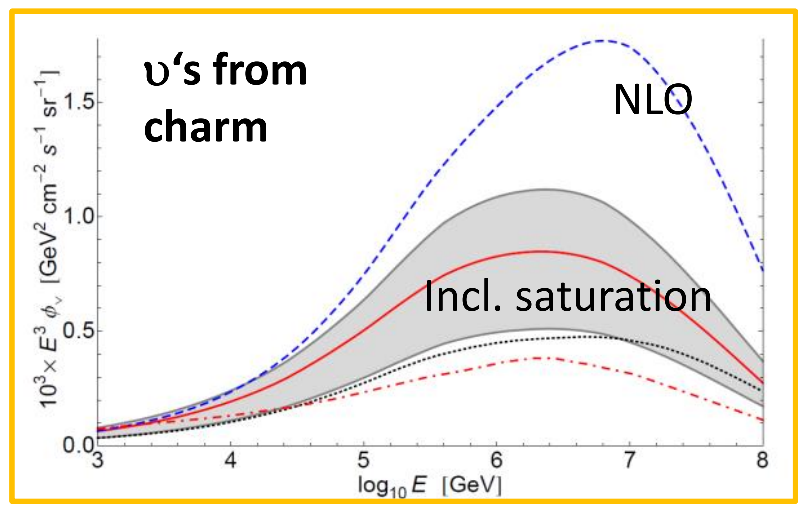


Coarse lattice of DOMs to maximize size → little redundance

THE CRUX OF NATURAL MEDIA AND BEAMS

- no flights to site during Austral winter (no problem)
- special infrastructure / experts needed for drilling (done)
- detector frozen in, can‘t be repaired (no problem)
- **tilted dust layers causing variable scattering and absorption**
- **Uncertainty in atmospheric neutrino fluxes (charm!)**



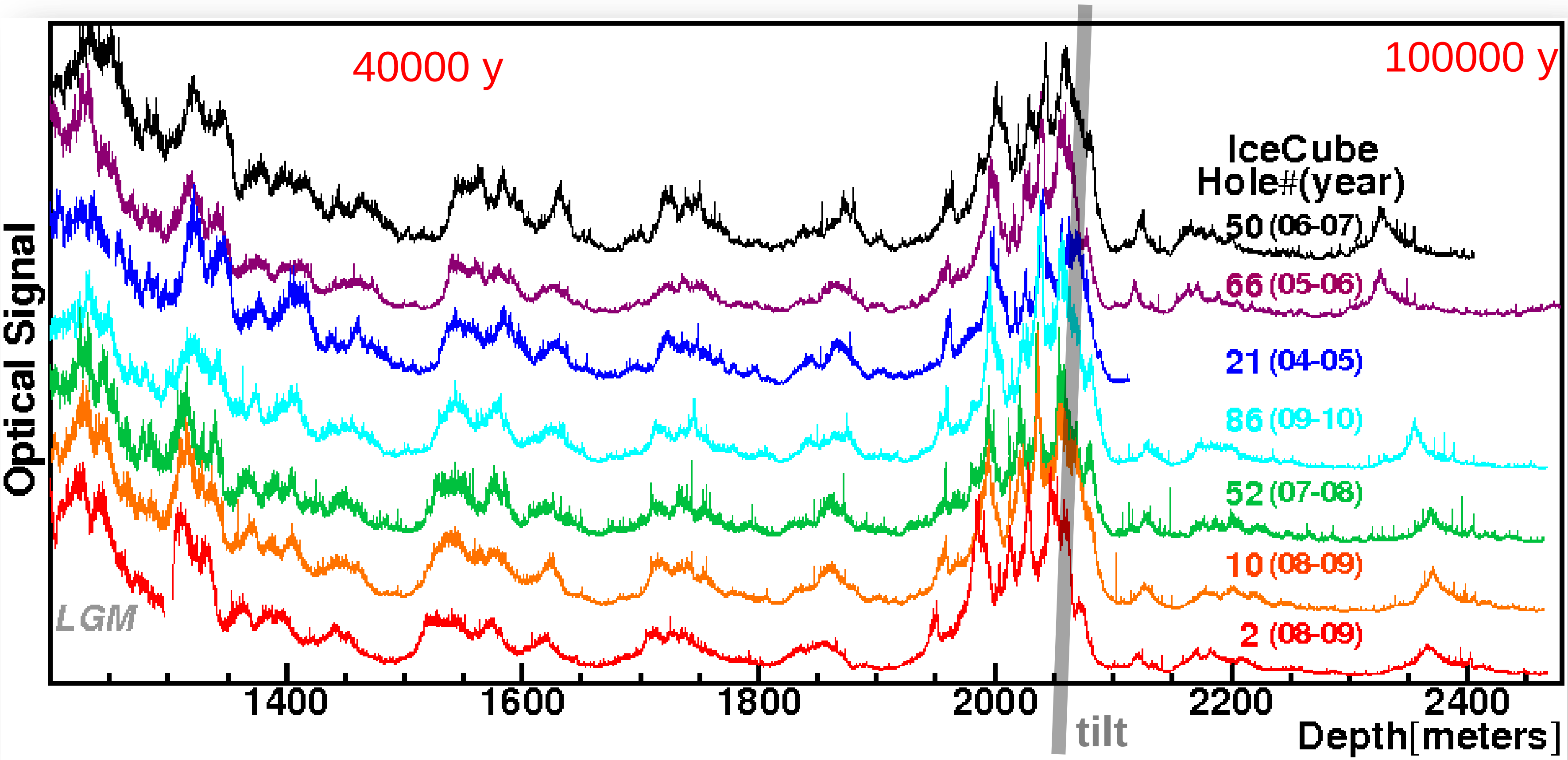


Enberg, Phys. Rev. D 78, 043005 (2008)

one example for illustration…

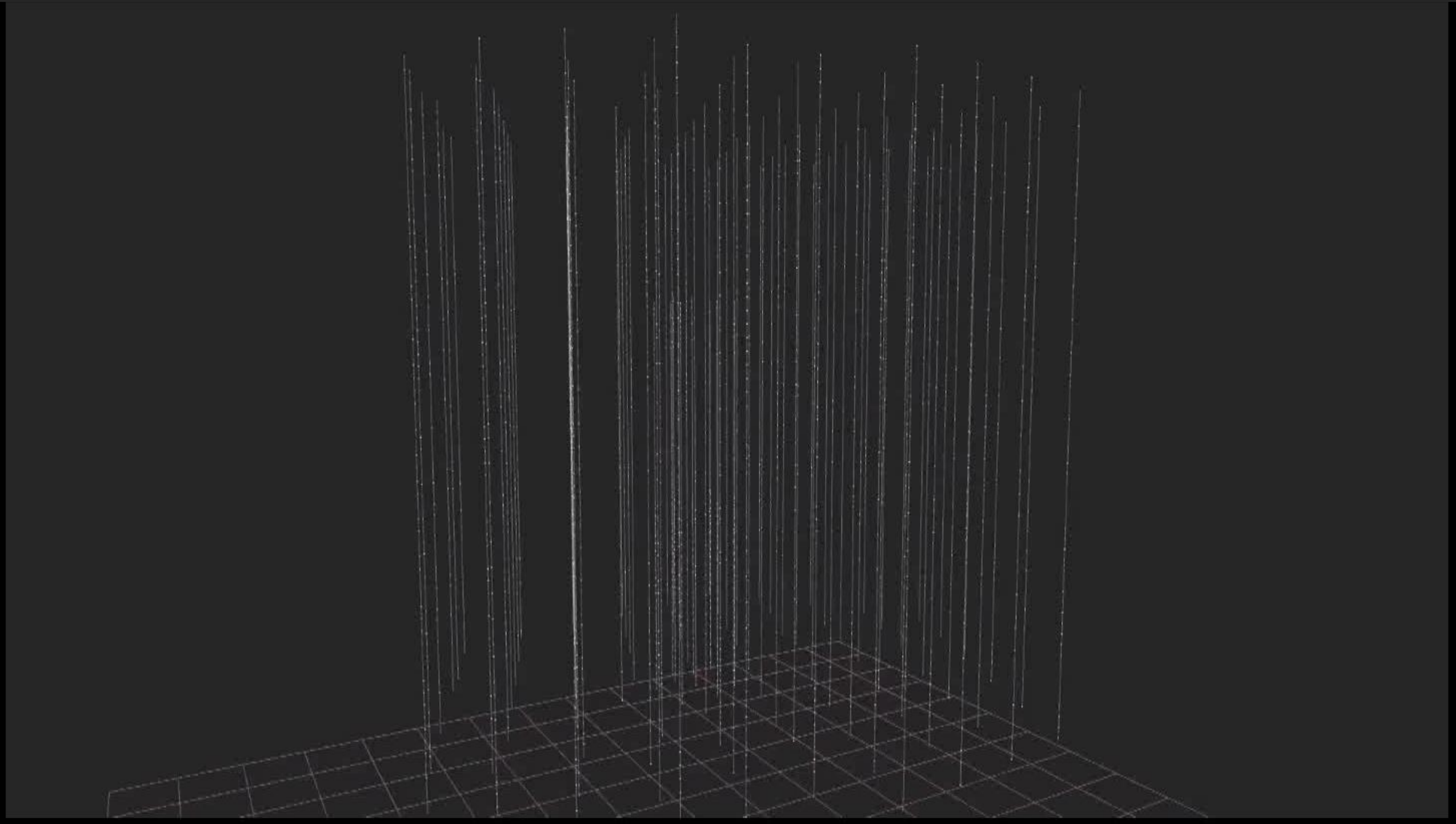
..... THE CRUX OF NATURAL MEDIA

dust layers in the ice with slight tilt along line of prevailing wind



dust causes ice flow dependent scattering **and** absorption

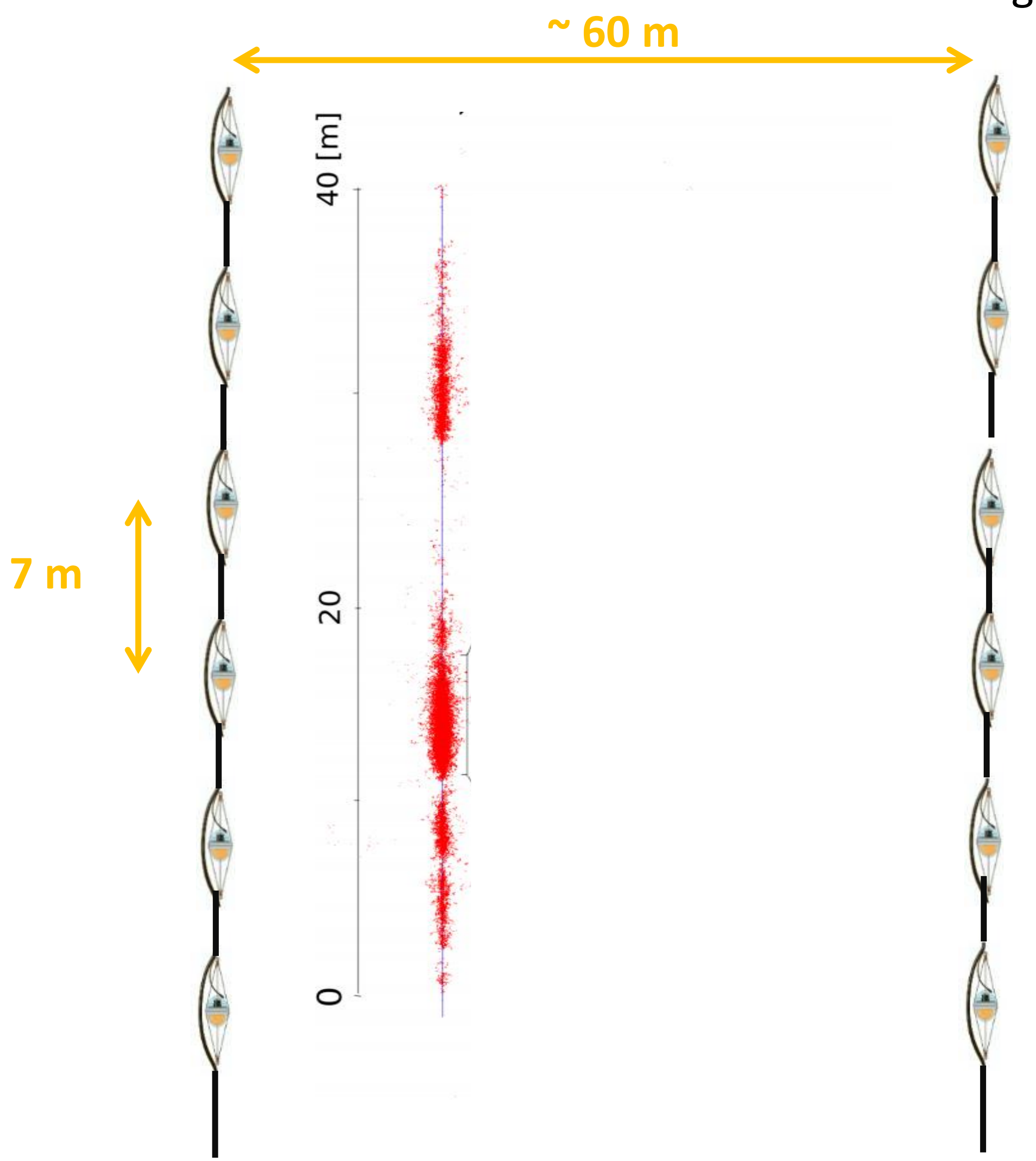
CHERENKOV PHOTONS FROM MUON



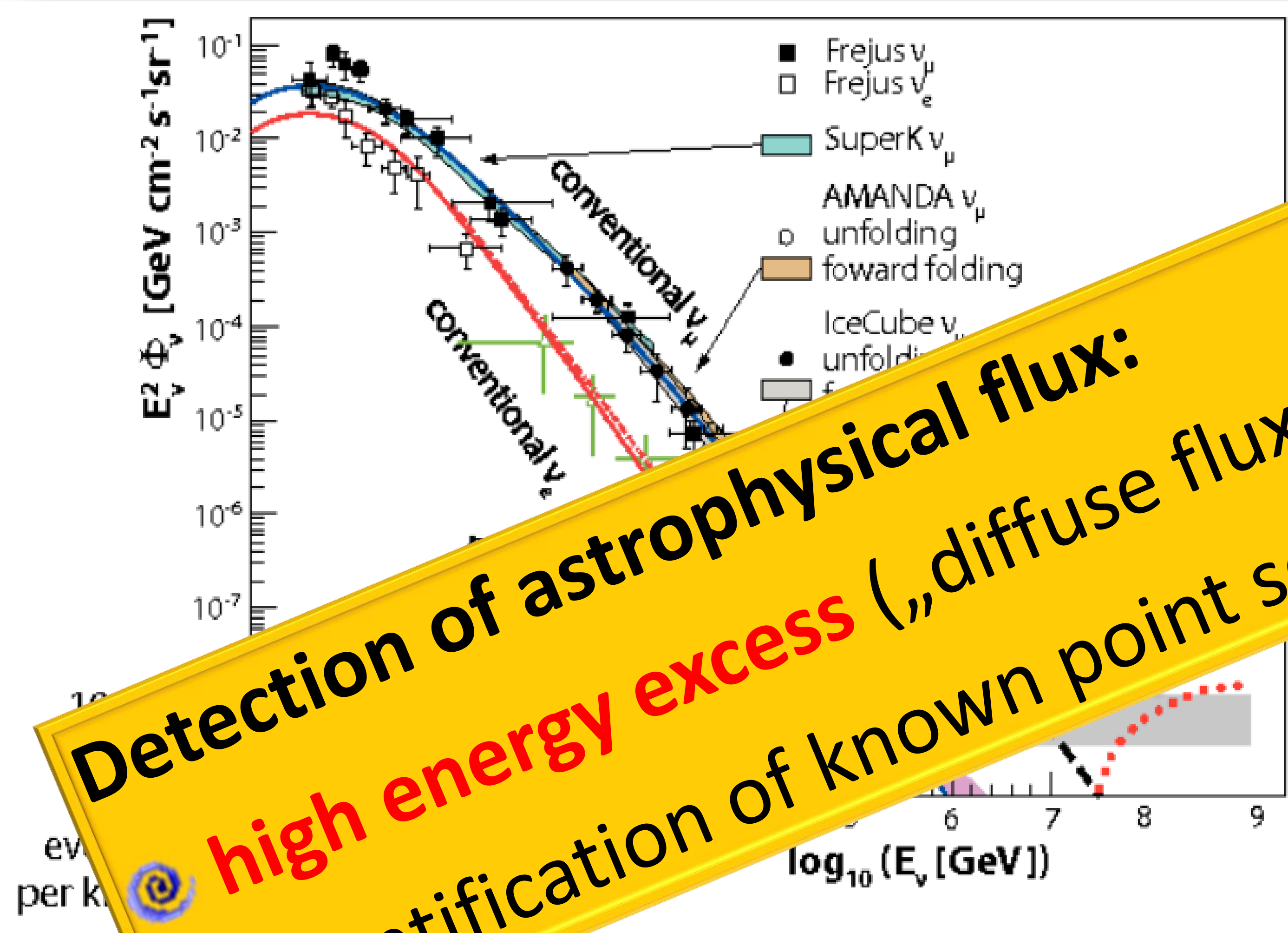
CHERENKOV PHOTONS FROM ELECTRON (CASCADE)

COARSE DETECTOR TO MAXIMIZE VOLUME

e.g. Antares, DeepCore



EXPECTED NEUTRINO FLUXES



astrophysical
... s

ν

υ's from
π, K decay

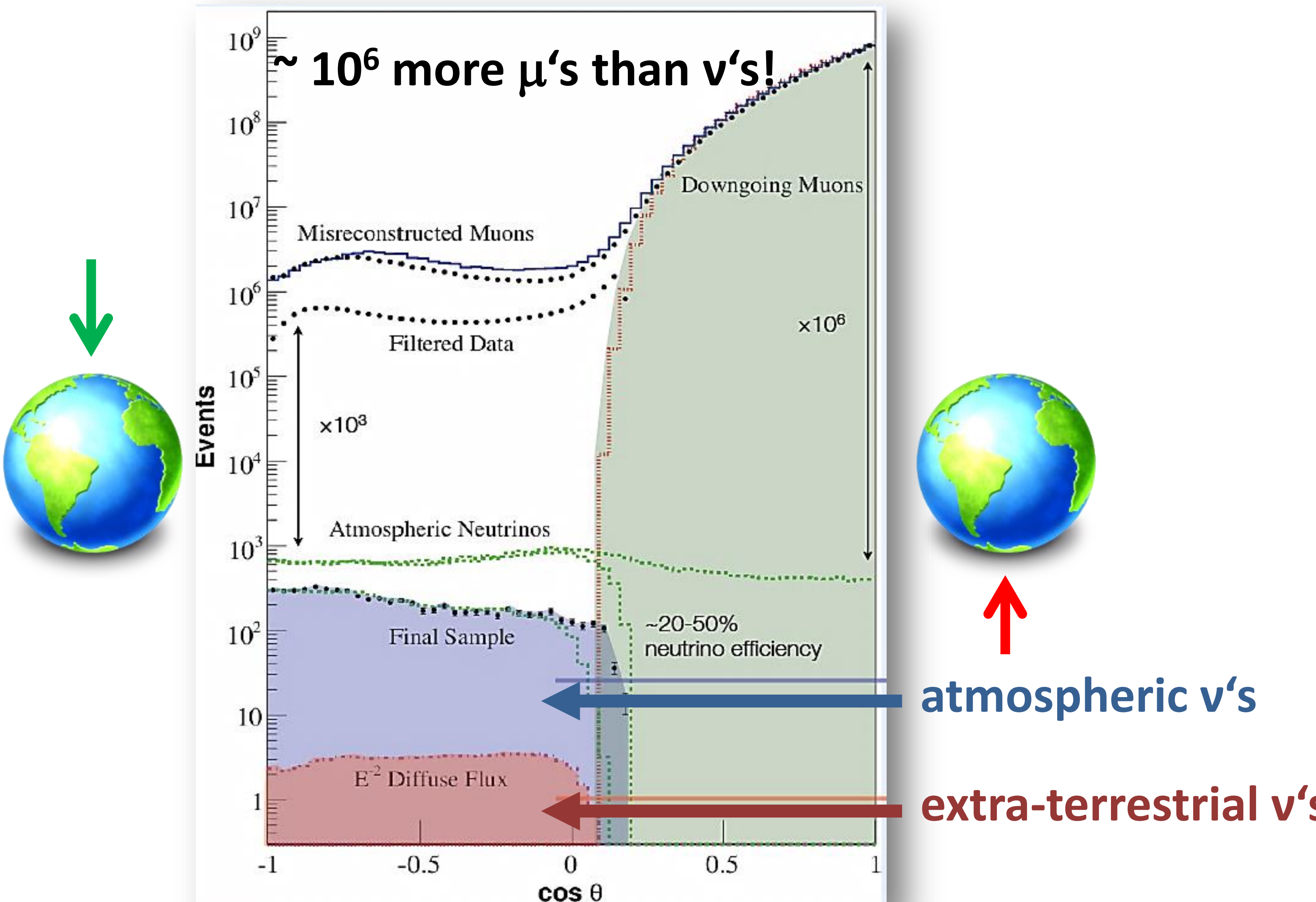
ν_e : ν_μ : ν_τ
1 : 1 : 1

~ E^{-2}

Detection of astrophysical flux:

- **high energy excess** („diffuse flux“), υ_τ flux
- identification of known point sources

Most analyses so-far used use Earth as shield against cosmic ray muons:



SHIFT OF VIEW

Why not try to fight against muon background and look upwards?

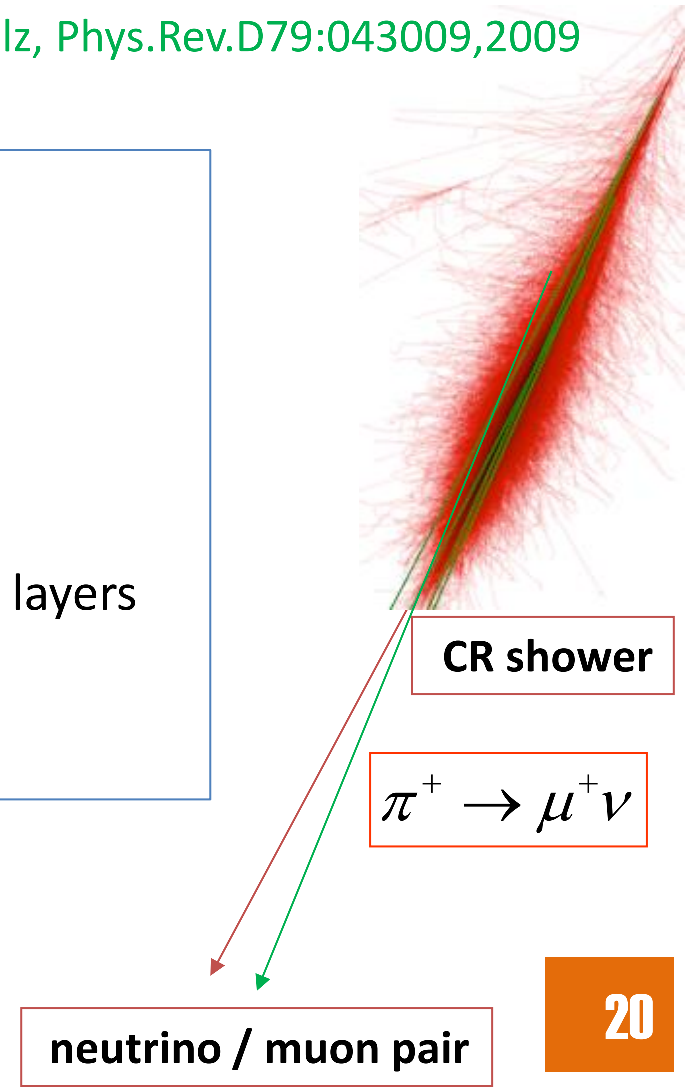
Schönert, Gaisser, Resconi, Schulz, Phys.Rev.D79:043009,2009

Advantage:

- **Suppress atmospheric neutrino background !!**
- No absorption in Earth at very high (PeV) energies

How can one study upgoing events?

- Veto muons either on surface or in outer detector layers
- **Use cascades rather than muons**
- Study very high energies …



SEARCH FOR CASCADES

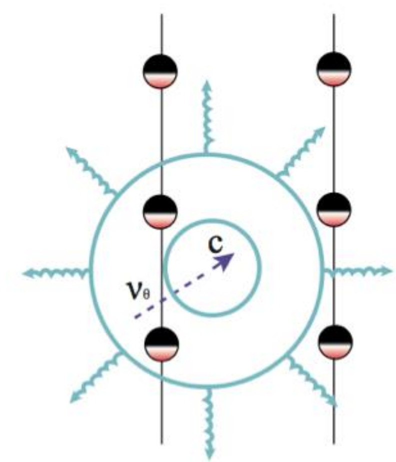
Cascades: synonym for ν_e, ν_τ or neutral current interactions

Advantages:
little direct background from atmospheric muons
order of magnitude less background from atmospheric neutrinos
better neutrino energy resolution (10-15 %)
more signal events (expect $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$)

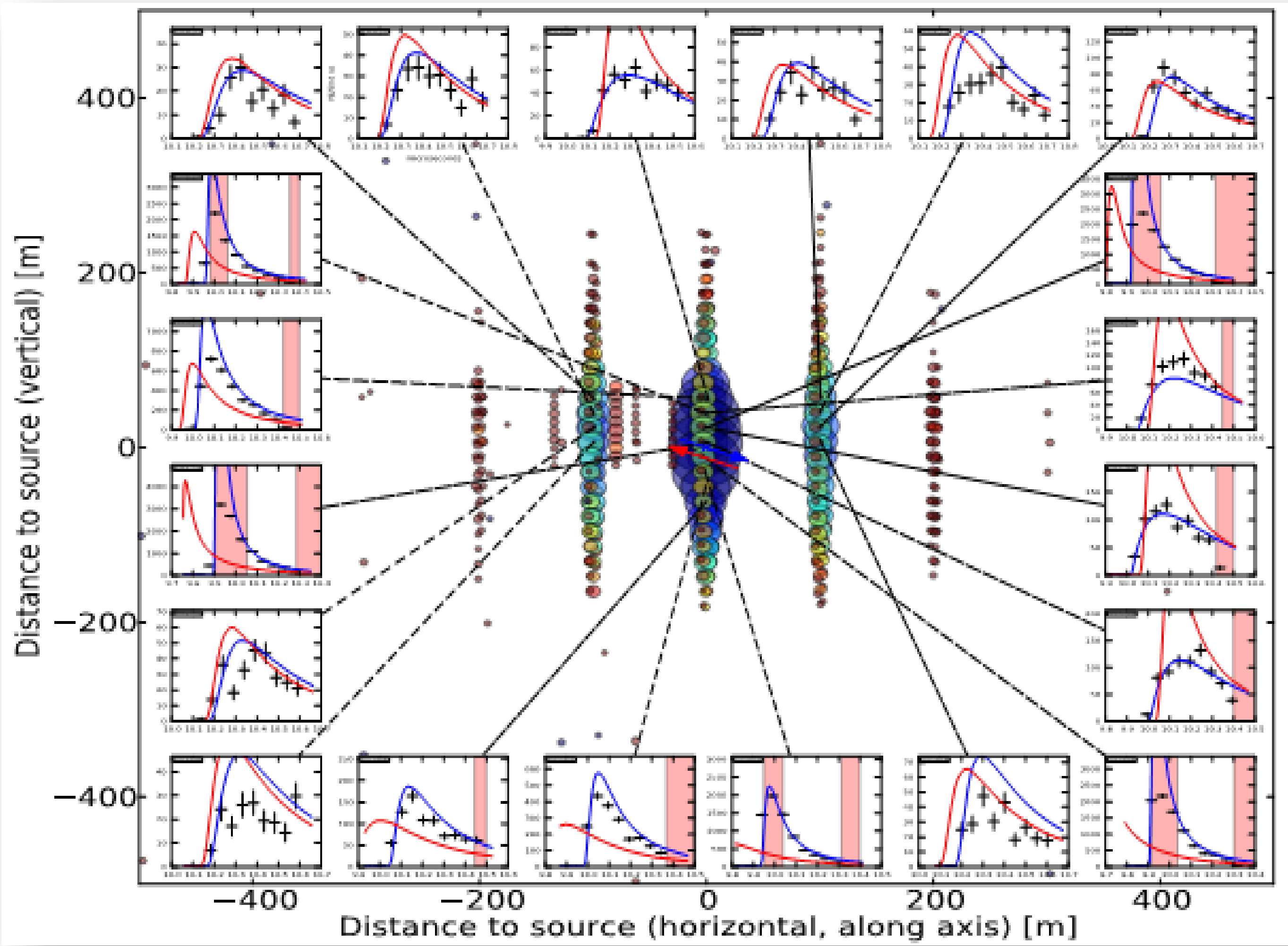
Disadvantages:
almost spherical shower, direction resolution O(10-15°) at high E_υ
detection volume < instrumented volume

Challenging analysis, particularly at low energies, requires sophisticated, time consuming likelihood reconstruction

→ only unscattered photons carry direction information
→ depends strongly on ice properties



DIRECTIONALITY OF SHOWERS



Time residual distributions

best cascade fit

reversed orientation for illustrative purpose

WHAT WOULD BE A CONVINCING ANALYSIS?

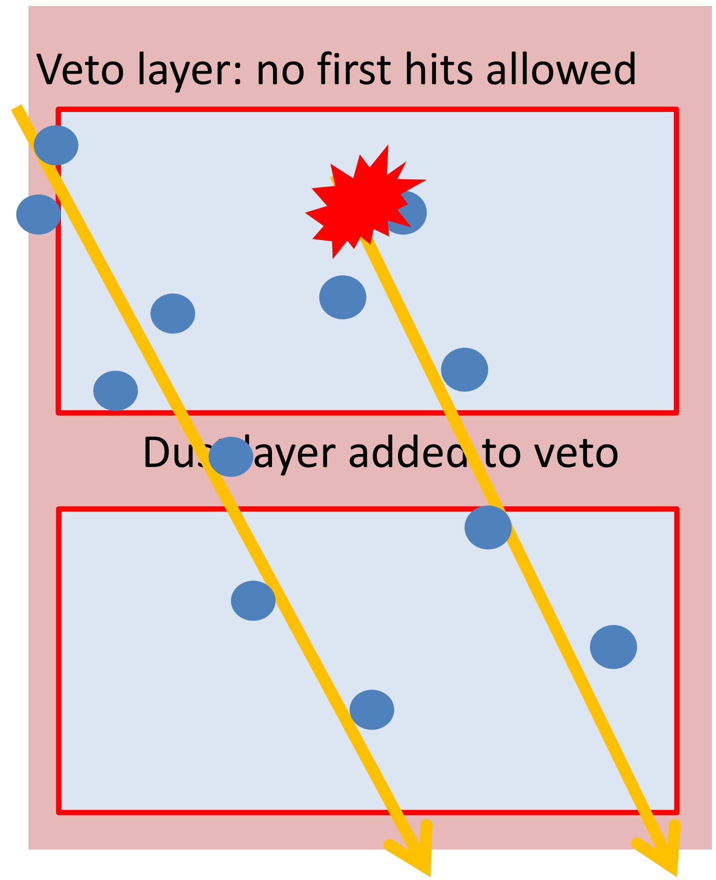
Try simple cut experiment based analysis ...

- Only study very high energies (> 4000 photo-electrons)
- Only use well reconstructable contained events
- Veto atmospheric μ\`s and υ‘s
- Calculate backgrounds from data

  (define second inner veto layer)
- Like always: blind analysis

420 Mton fiducial mass (~1/3)

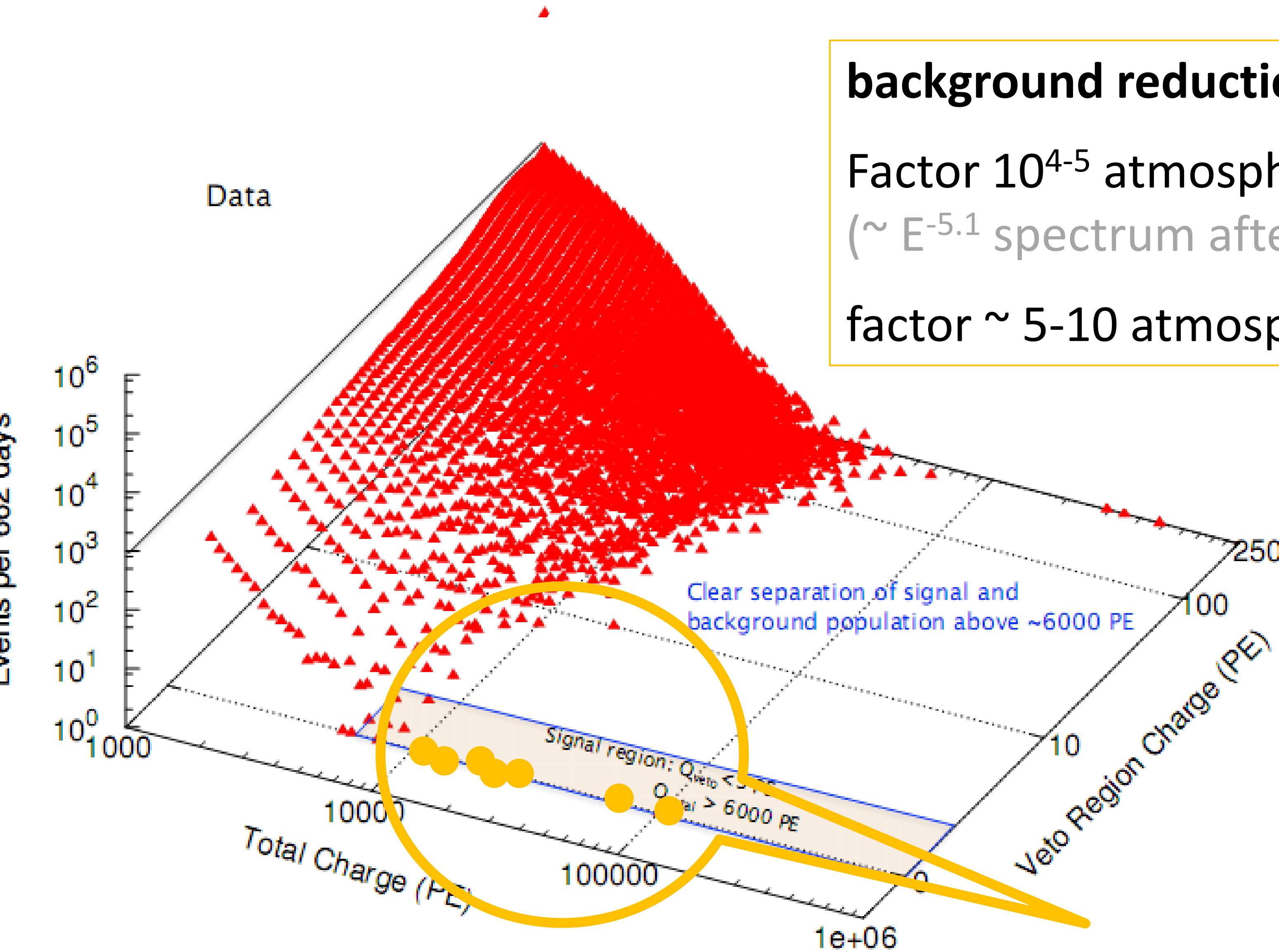
all flavor 4π sensitivity > 50 TeV for contained events



High energy contained events?

SIGNAL EXTRACTION BY VETO CRITERION

Events events appear at zero veto charge:



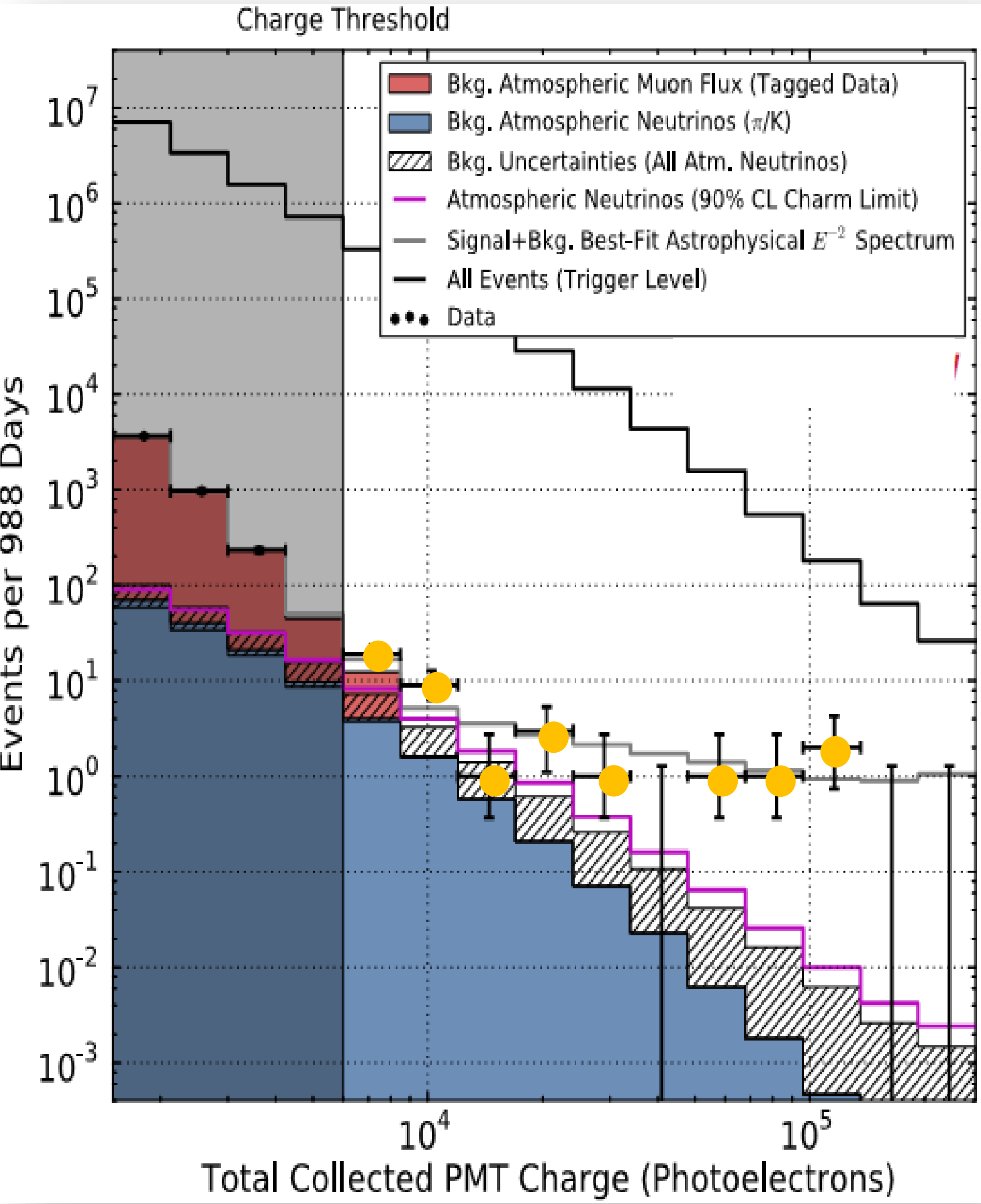
background reduction by veto:

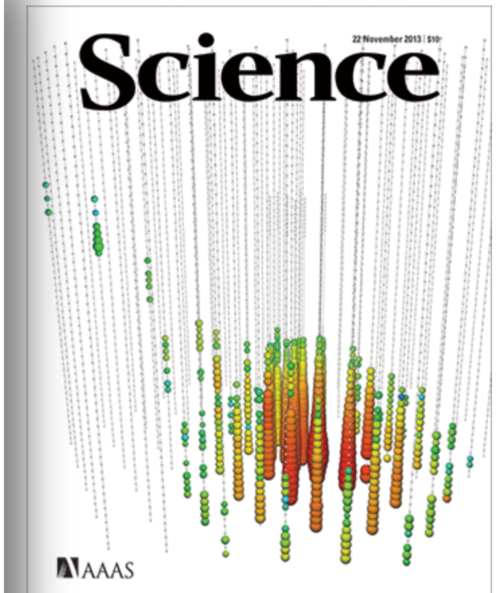
Factor 10^{4-5} atmospheric muons

(~ $E^{-5.1}$ spectrum after veto)

factor ~ 5-10 atmospheric υ's

COLLECTED SPECTRUM OF PHOTOELECTRONS





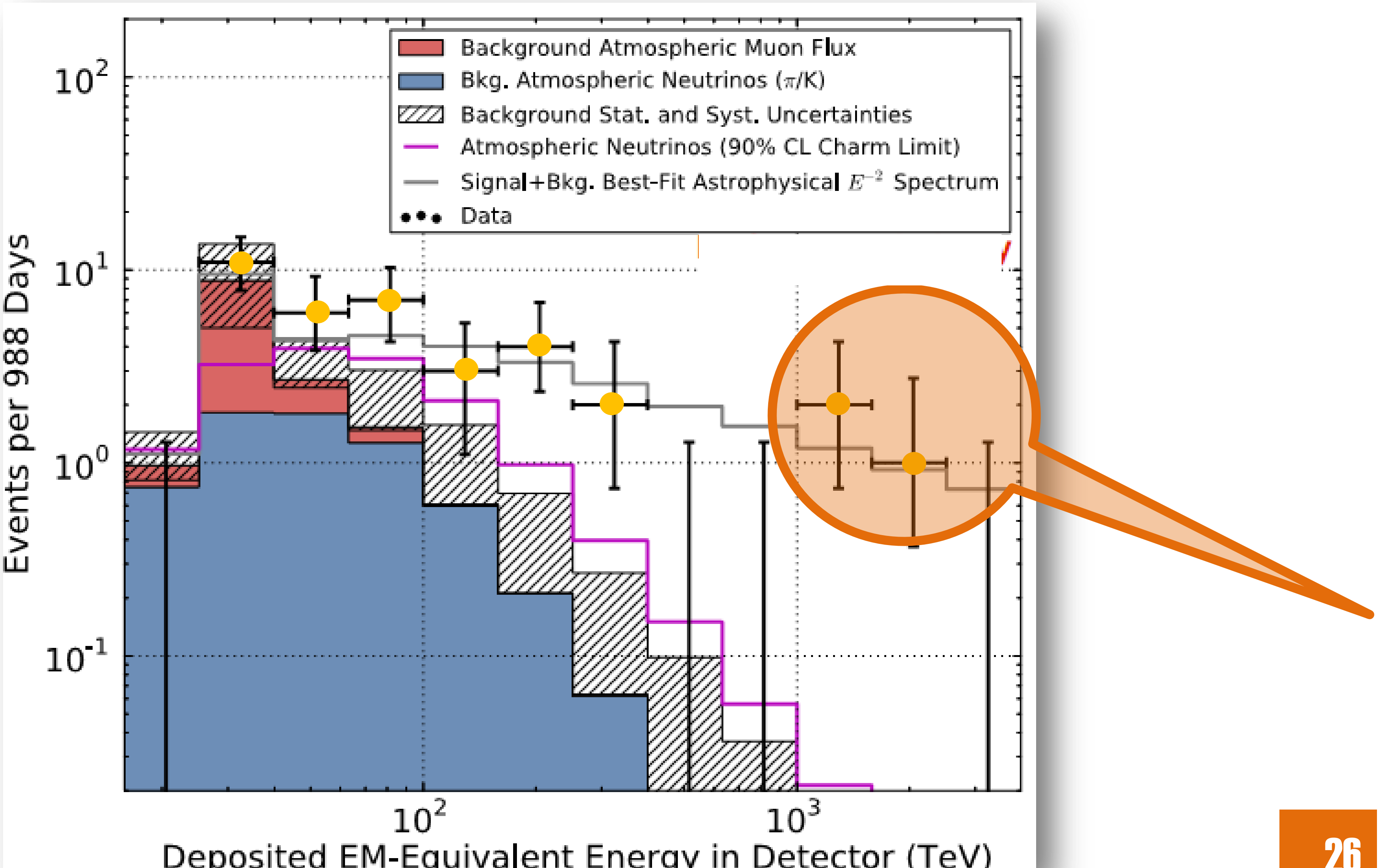
Nov. 22, 2013:
Vol. 342 no. 6161

physics world
BREAKTHROUGH OF THE YEAR
2013

Phys. Rev. Lett. 113, 101101, 2014

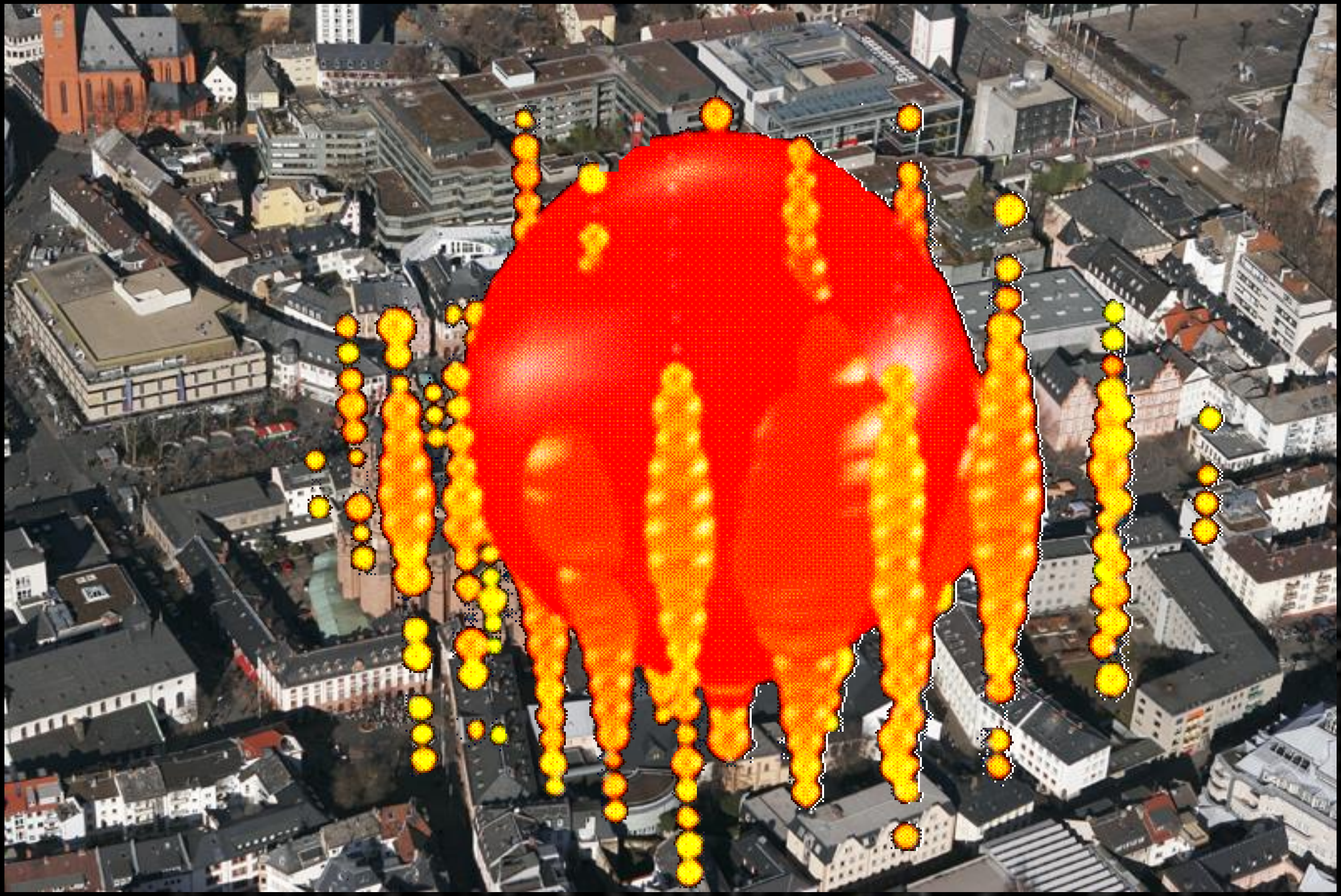
3 years (soon 4) of data:
36 events
μ background 8.4 ± 4.3
υ background 6.6 $^{+5.9}_{-1.6}$

ENERGY IN DETECTOR



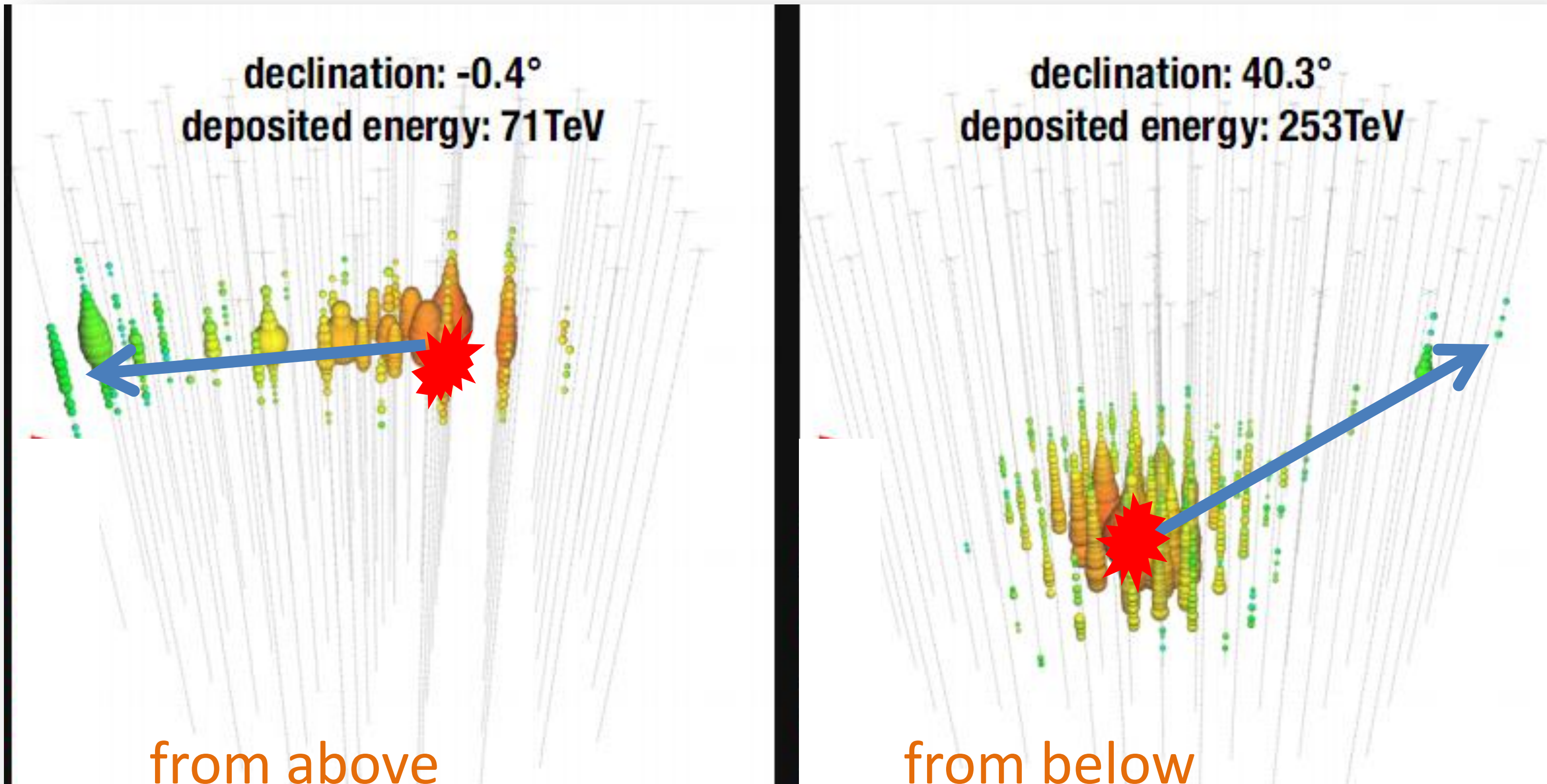
HIGHEST ENERGY EVENTS

Big Bird: $2.0^{+0.26}_{-0.24}$ PeV



TRACK-LIKE EVENTS

red: early hits; green: late hits



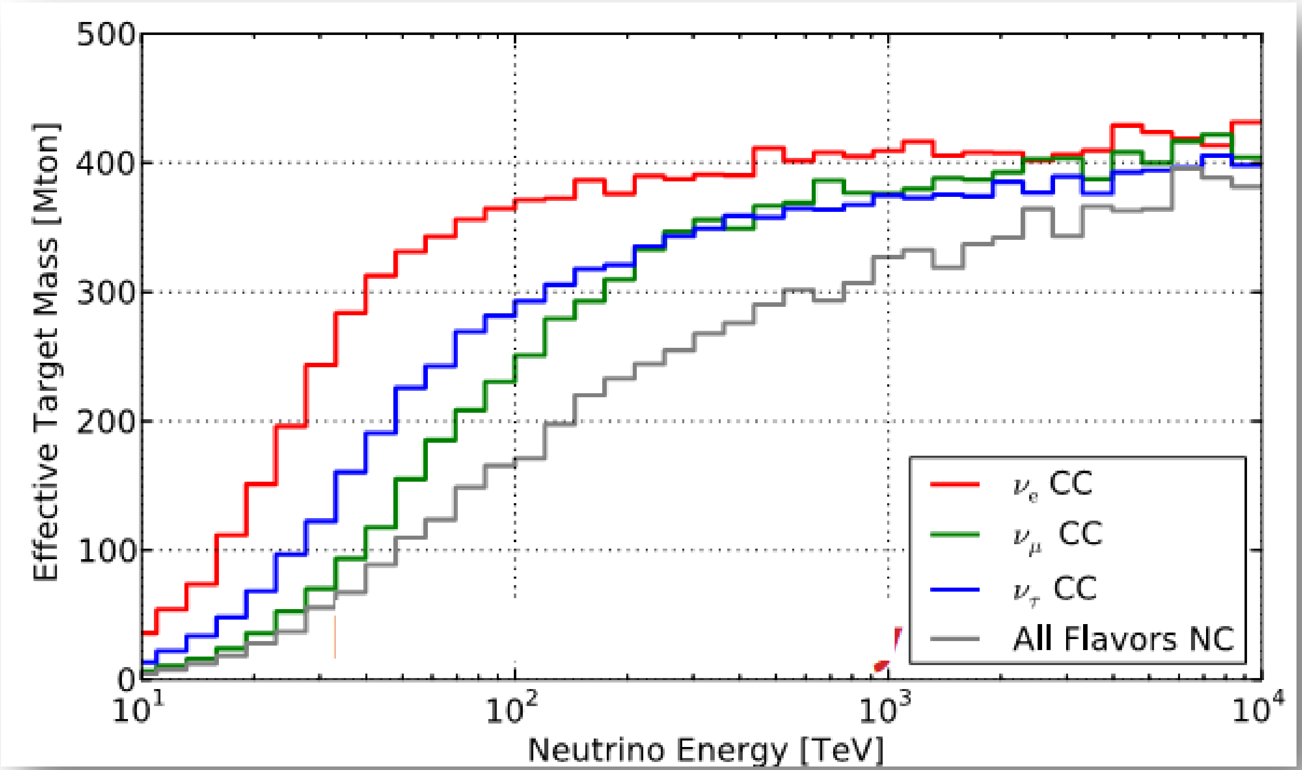
76 % showers
75% downgoing from South (69 % expected)

RATIO OF CASCADE TO TRACK-LIKE EVENTS

From 36 clean events seen:

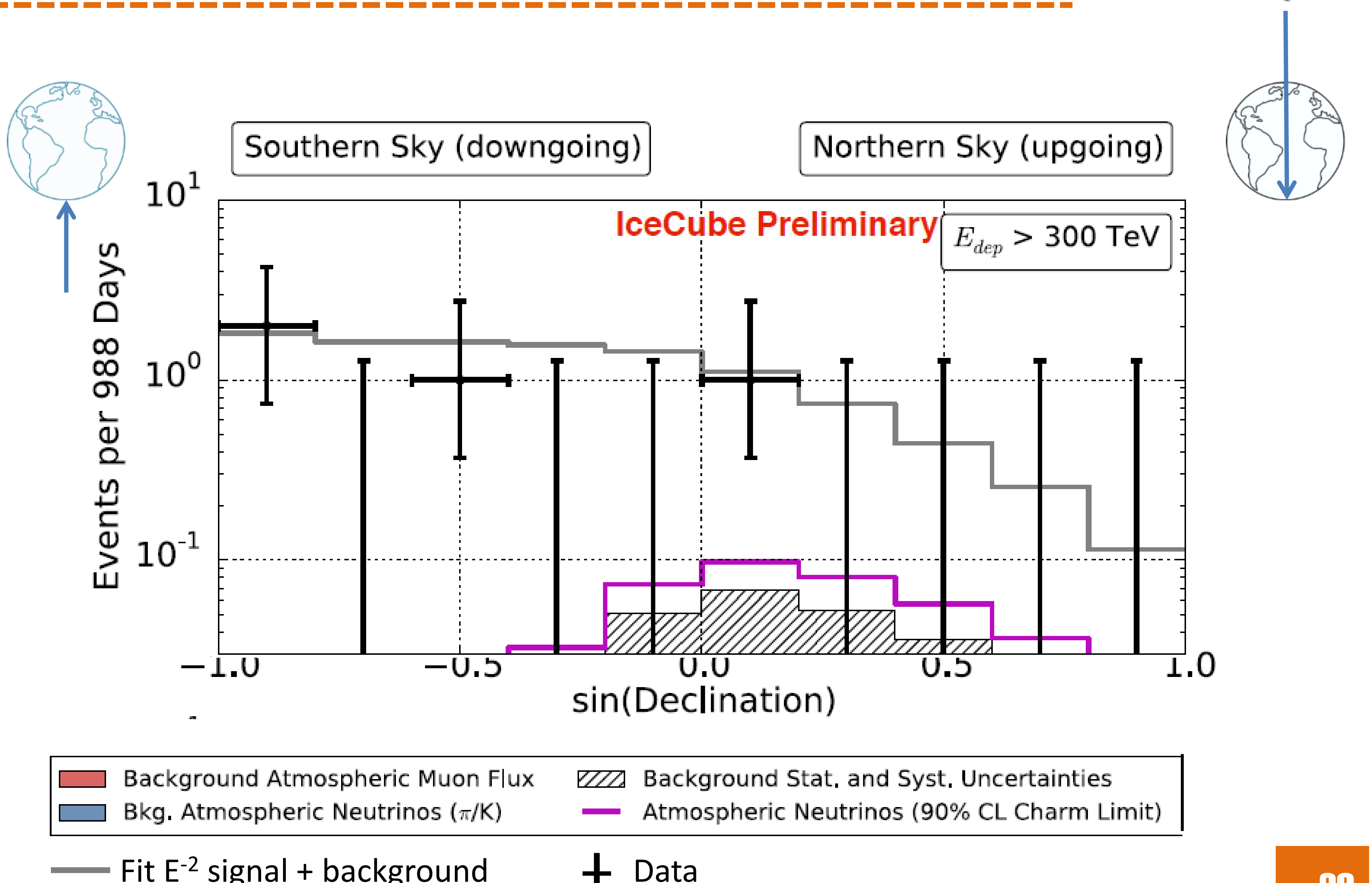
8 events	with muon topology
28 events	shower like topology

Effective Mass M_{eff}



...for $\nu_e : \nu_\mu : \nu_\tau = 1:1:1 \rightarrow$ astrophysical flux 81 % shower-like

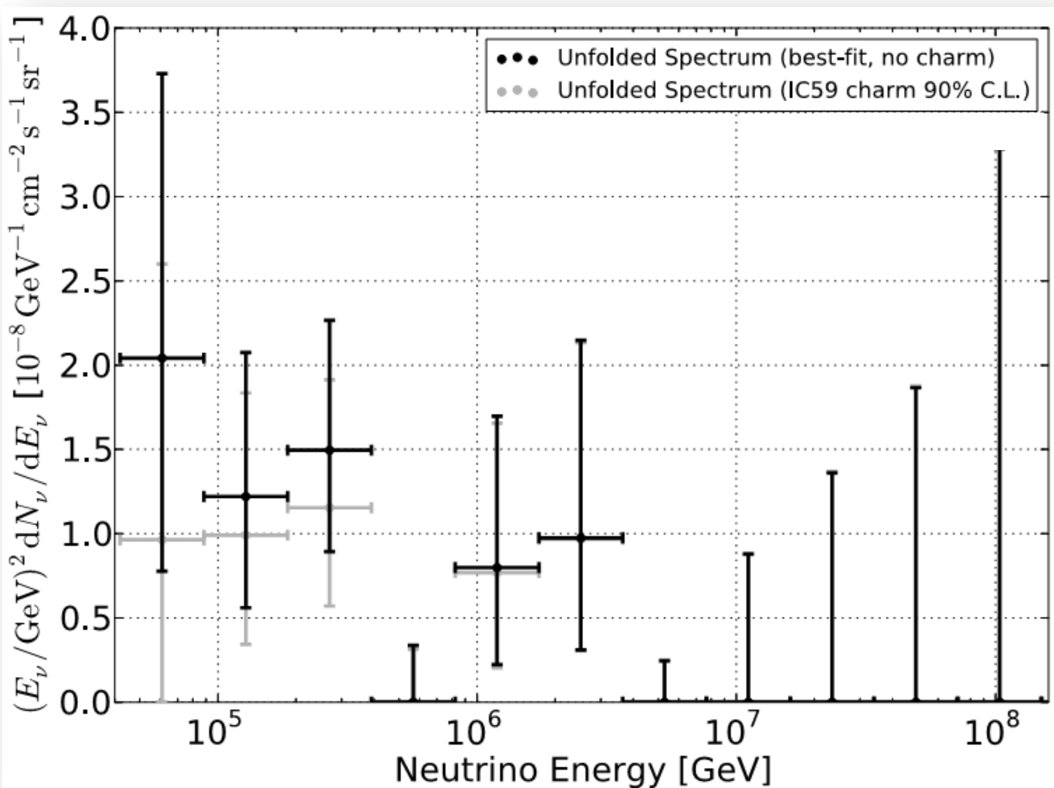
ANGULAR DISTRIBUTION OF EVENTS



FLUX & SIGNIFICANCE DETERMINATION

Profile likelihood fit above 60 TeV (< 1 atmospheric μ track expected):
components free floating, Gaussian penalty for μ background

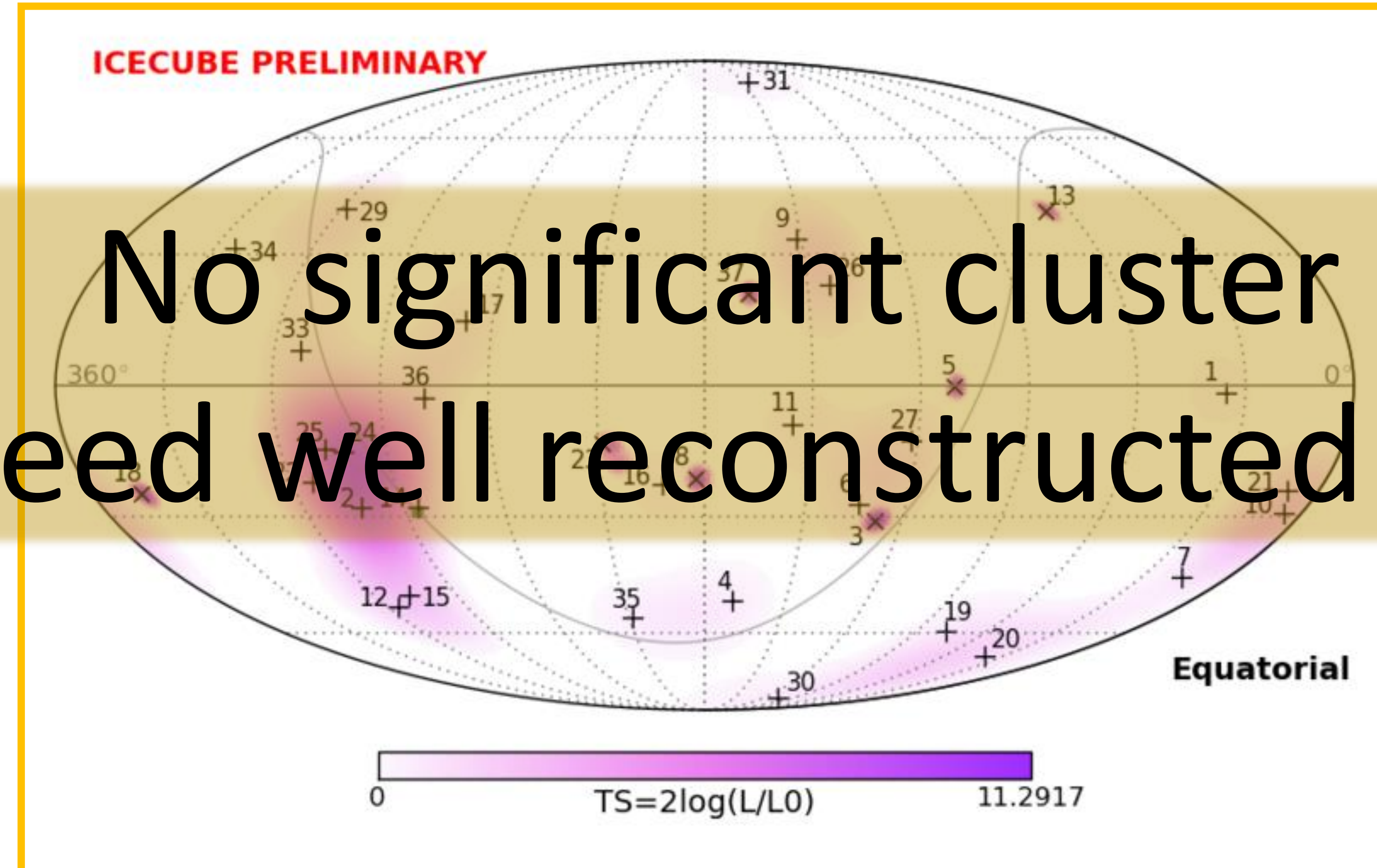
- $E^2\Phi(E)_{\text{per flavor}} = (0.95 \pm 0.3) \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
- Best fit spectral index -2.3 ± 0.3
- **Null hypothesis of no astrophysical flux rejected by 5.7 σ**



hint that spectrum is softer than E^{-2}

SKYPLOT OF 36 EVENTS

…also searches for galactic plane cluster and time clustering …



No significant cluster

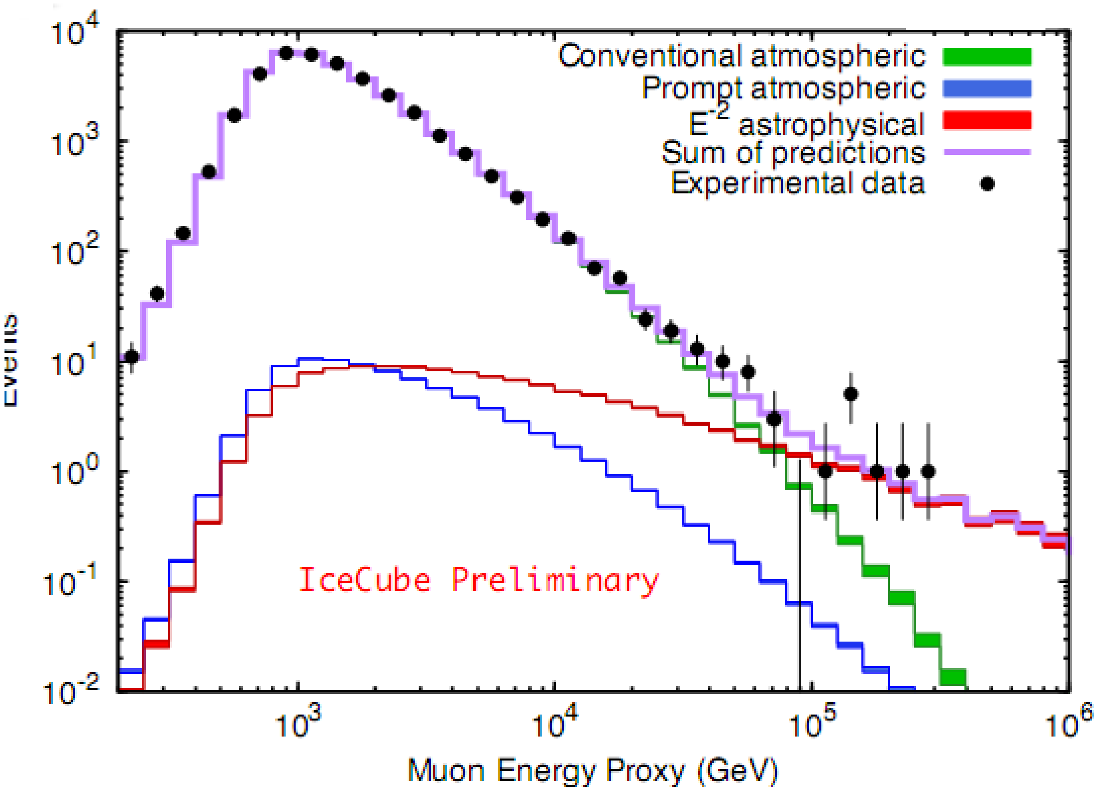
Need well reconstructed ν_μ

angled crosses are neutrino-induced **muons**

vertical crosses **cascades**

CHARGED CURRENT $\nu_\mu N \rightarrow \mu + X$

….now excess also seen with through-going muons!



Higher ν background than with cascades and starting tracks

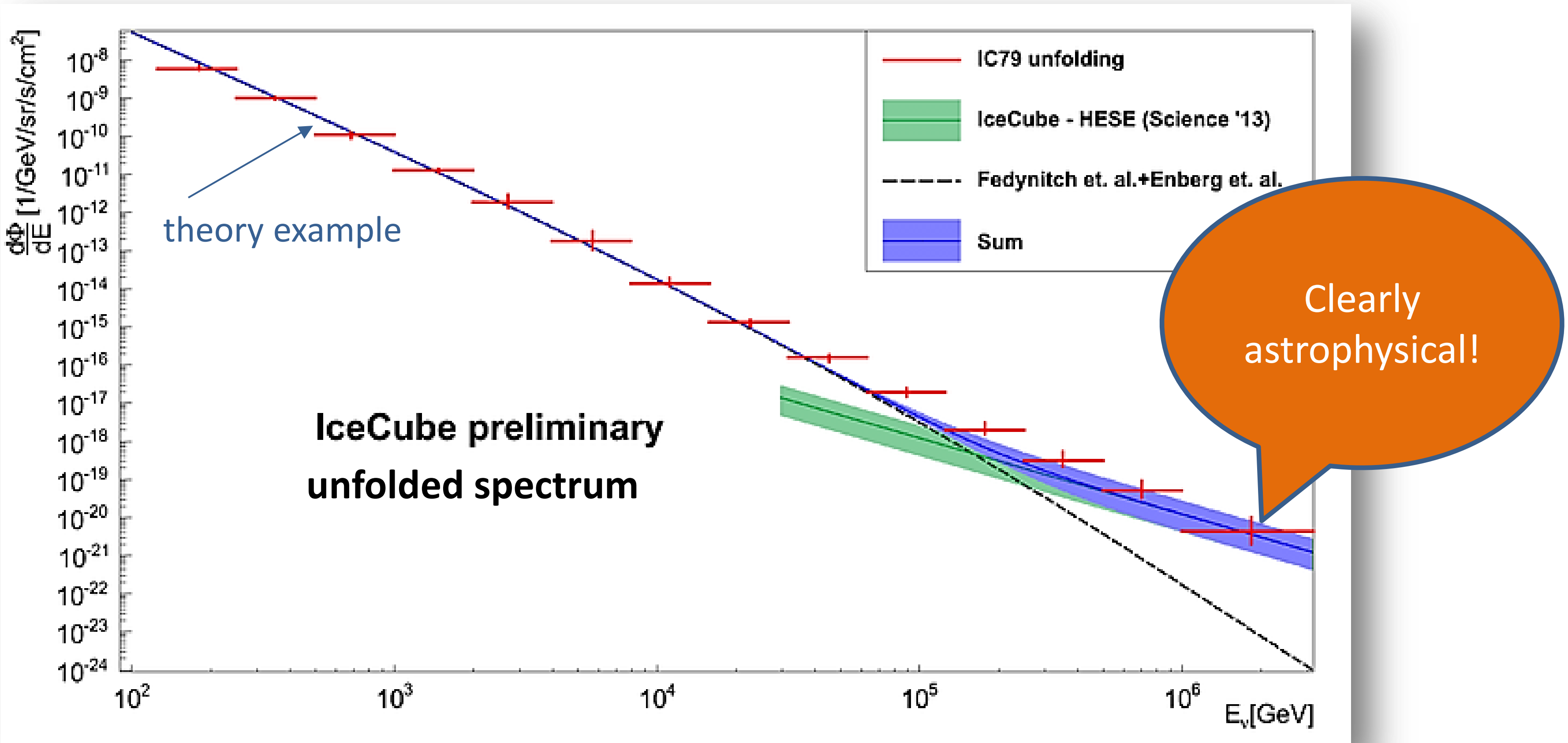
… but < 0.4° muon angular resolution for E > 10^4 GeV

Atmospheric only hypothesis disfavored at 3.9 sigma

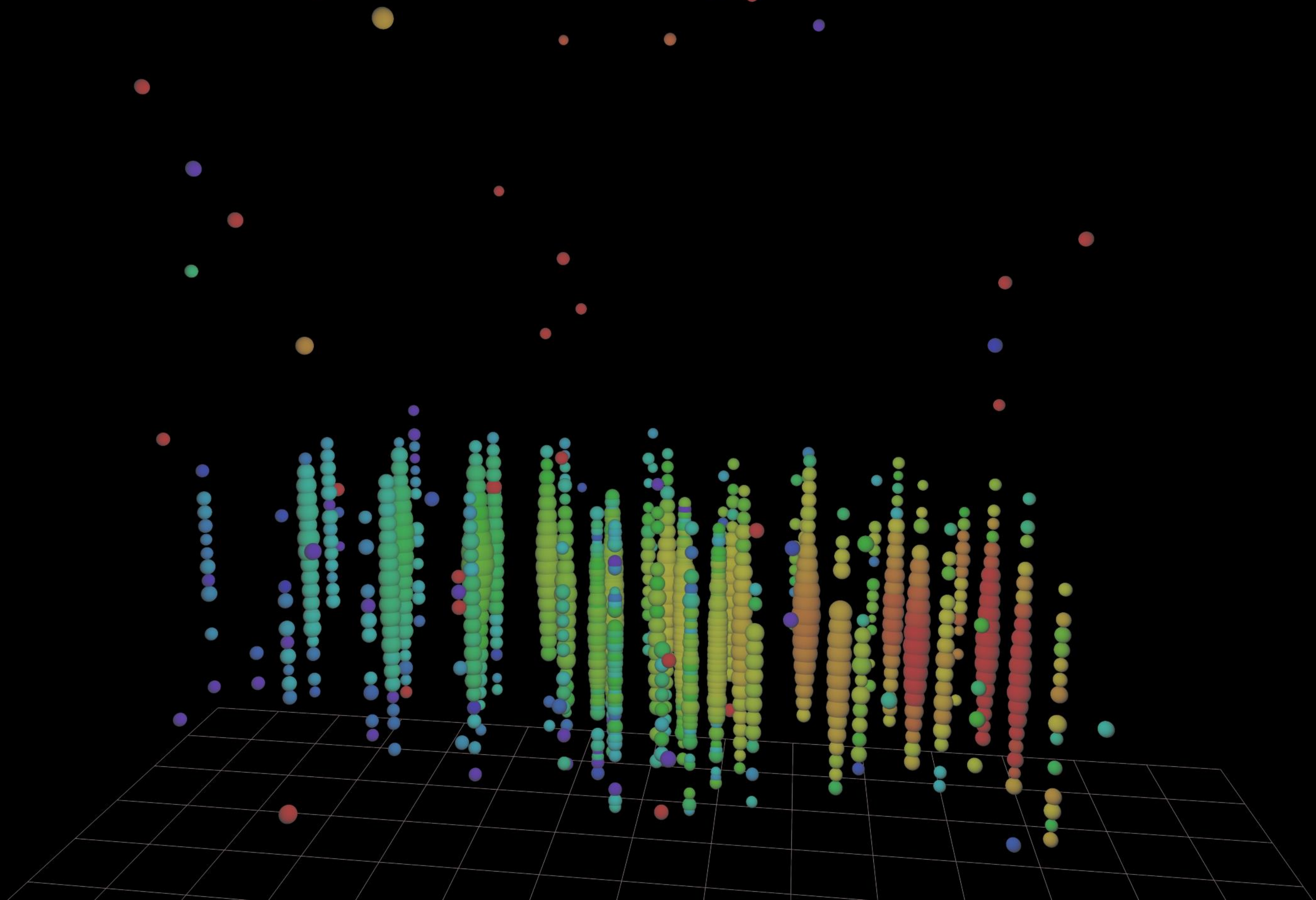
- Flux close to that measured with starting events
- Supports 1:1:1 flavor ratio expected from oscillations

THROUGH-GOING MUONS

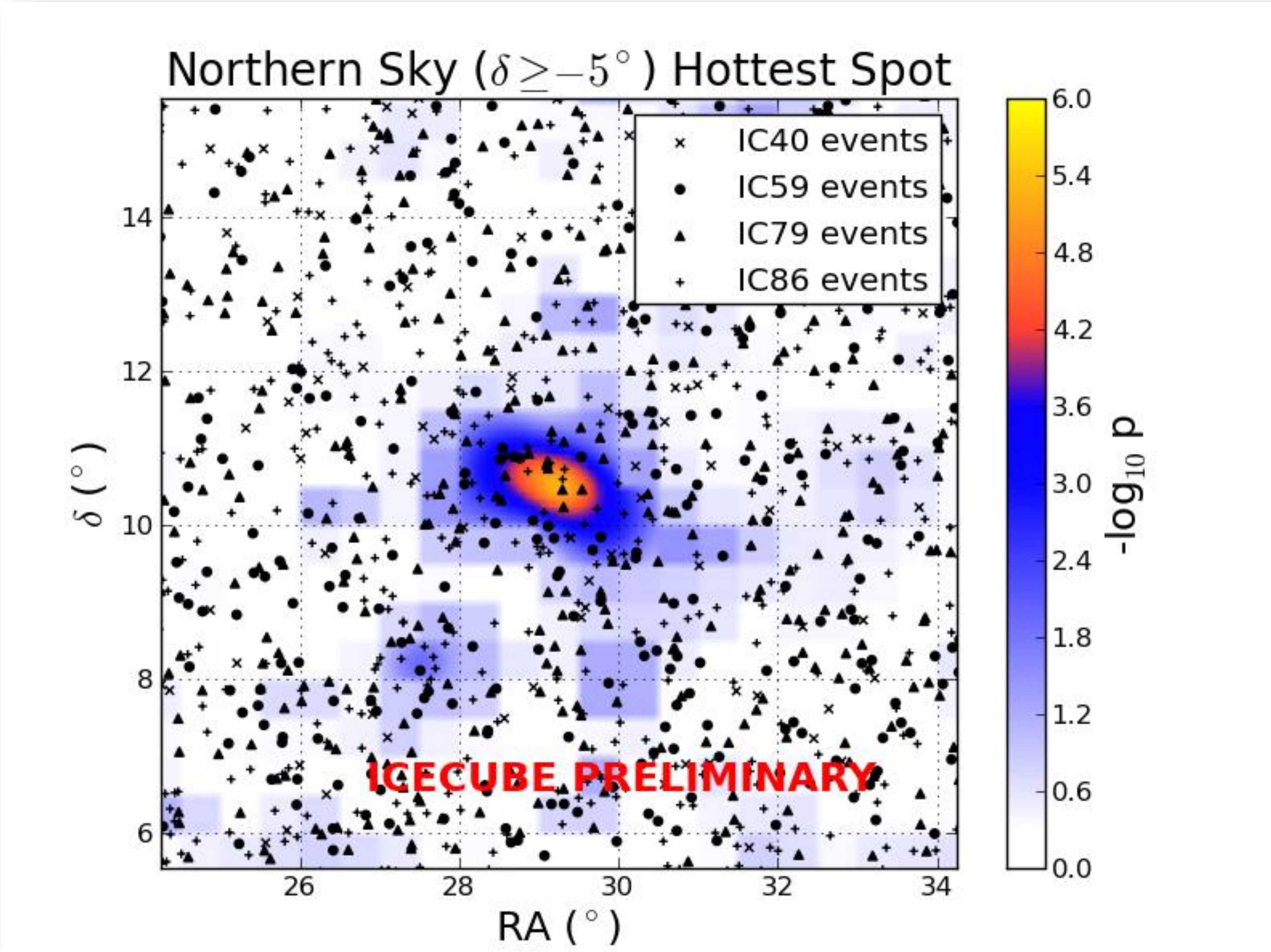
Needs unfolding to estimate original neutrino energy:



CAN WE IDENTIFY SOURCES ?



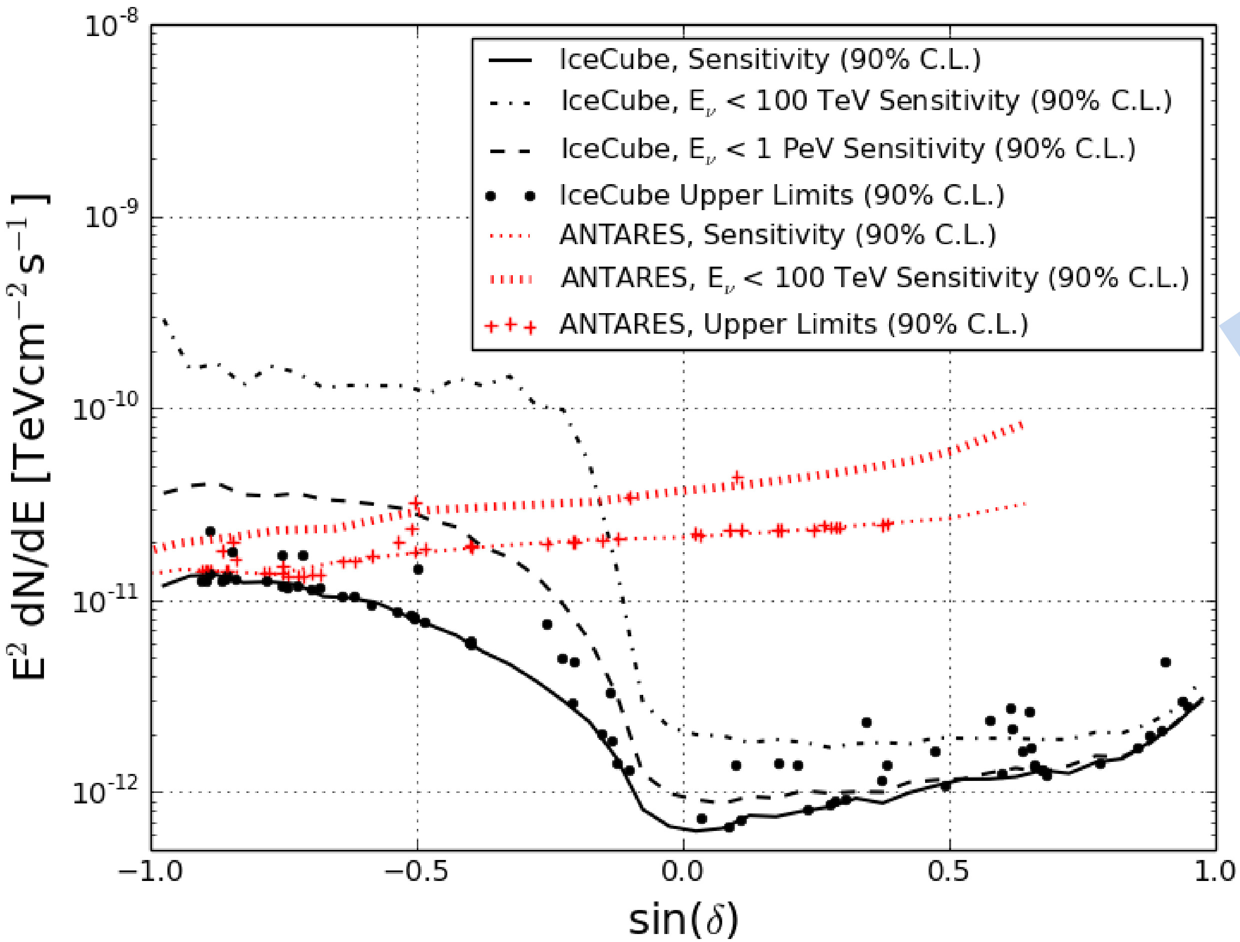
NO POINT SOURCES YET (4 YEARS)



UPPER FLUX LIMITS FOR POINT SOURCES

PRiSMA IceCube

4 π acceptance (in Southern sky limited to high energies)



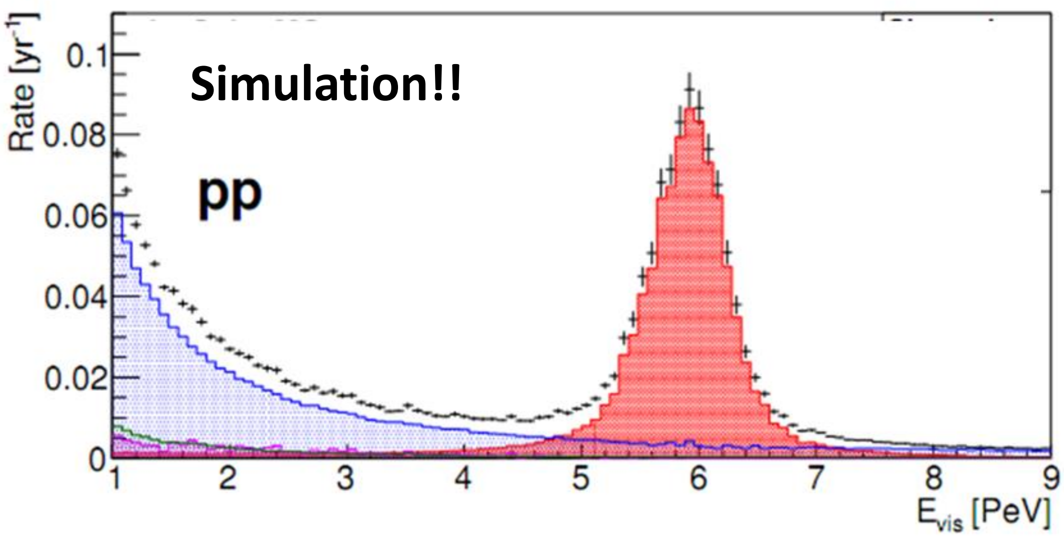
Work continuing by adding statistics and improving resolutions

Sensitivity can be improved by stacking source candidates or studying flaring objects as well as short time phenomena …

NEXT STEPS WITH ASTROPHYSICAL NEUTRINOS

… many improvements on the way: lower energy threshold by better vetos or using cascades, increase effective area at high energies, high-energy muons …

- Detailed understanding of flux and flavor ratios
  - spectral index, spectral cut-off?
  - pp or pγ production … 1:1:1 flavor ratio?
- Identify υ_τ
- Search for anisotropies, point sources, determine source classes



„Magnifiying glass“ Glashow resonance :

$$\bar{\upsilon}_e + e^- \rightarrow W^{real} \rightarrow \bar{\upsilon}_e + e^-, qq$$

We are looking at so-far untested energies!

WHAT I HAVEN'T TALKED ABOUT …

PRiSMA ICECUBE

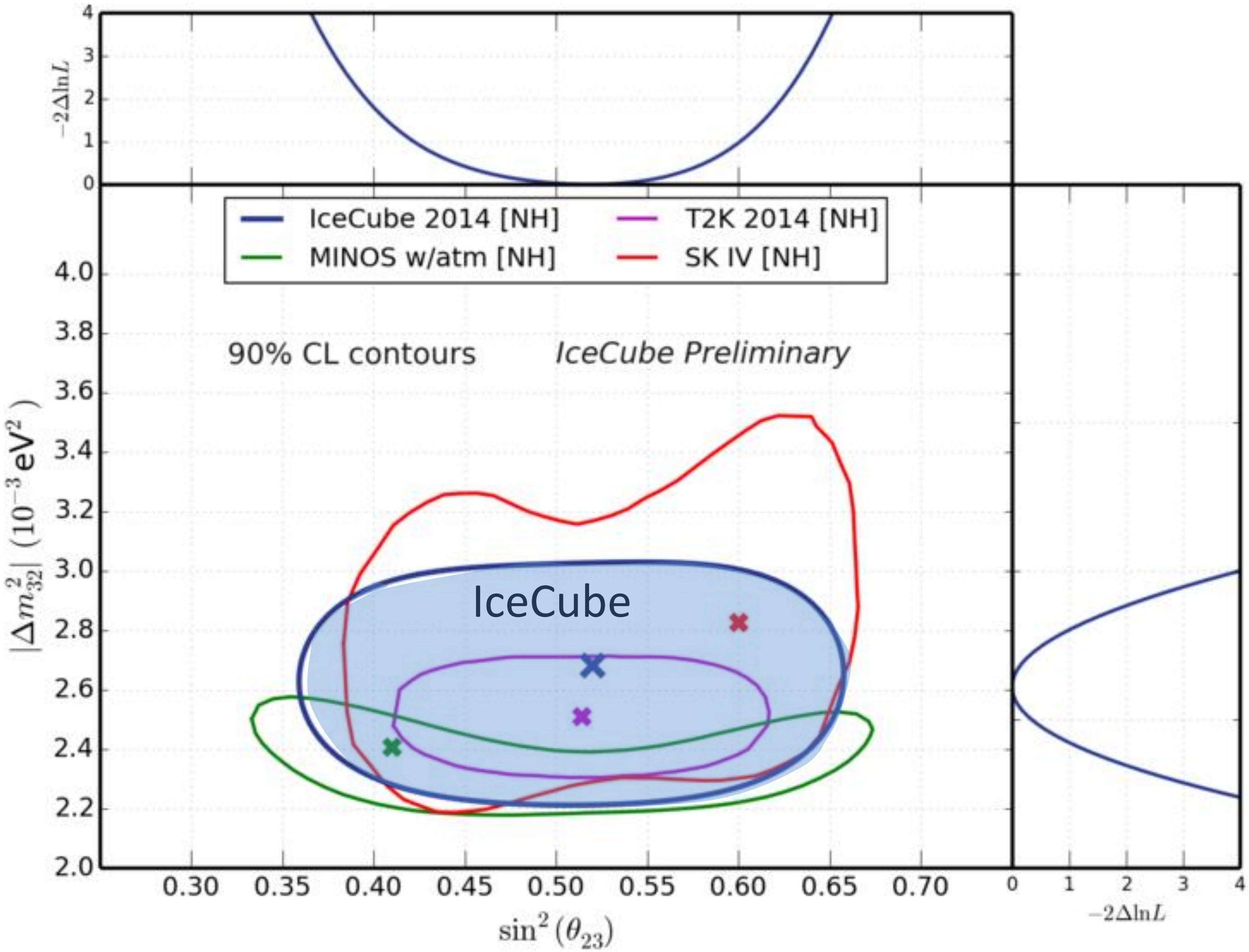
Neutrino observatories offer quite a range of topics:

- excellent cosmic ray (IceTop+IceCube) detector [Phys Rev D 88, 042004]
- highest statistics detector for close supernovae [A&A 535 (2011) A109]
- **very competitive for determining Θ_{23} , Δm^2_{23}** [arXiv:1309.7008]
- world's best sensitivities for
  - spin-dependent WIMP cross sections [Phys.Rev.Lett. 110 (2013)]
  - monopoles [EPJC 74, 7]
  - Top-down scenarios, fundamental tests
  - ….

…. Let's pick one example: neutrino oscillations

EXAMPLE: NEUTRINO-OSCILLATIONS

… based on 3 years of data with full detector:



More data to come!

WHAT MAY A STRING PHYSICIST BE INTERESTED?

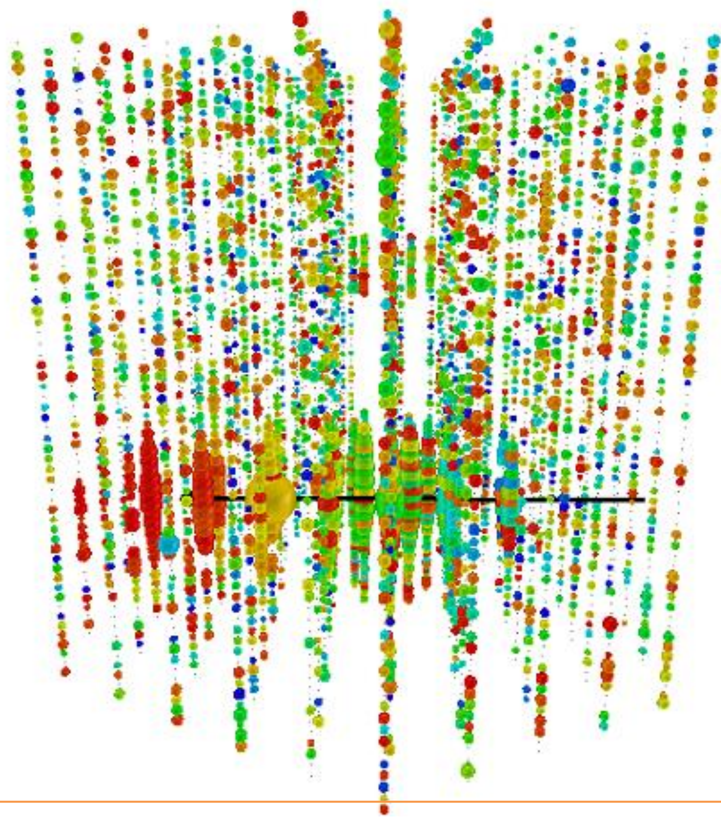
Untested energy regime with neutrinos … giga-ton detector for rare phenomena ….

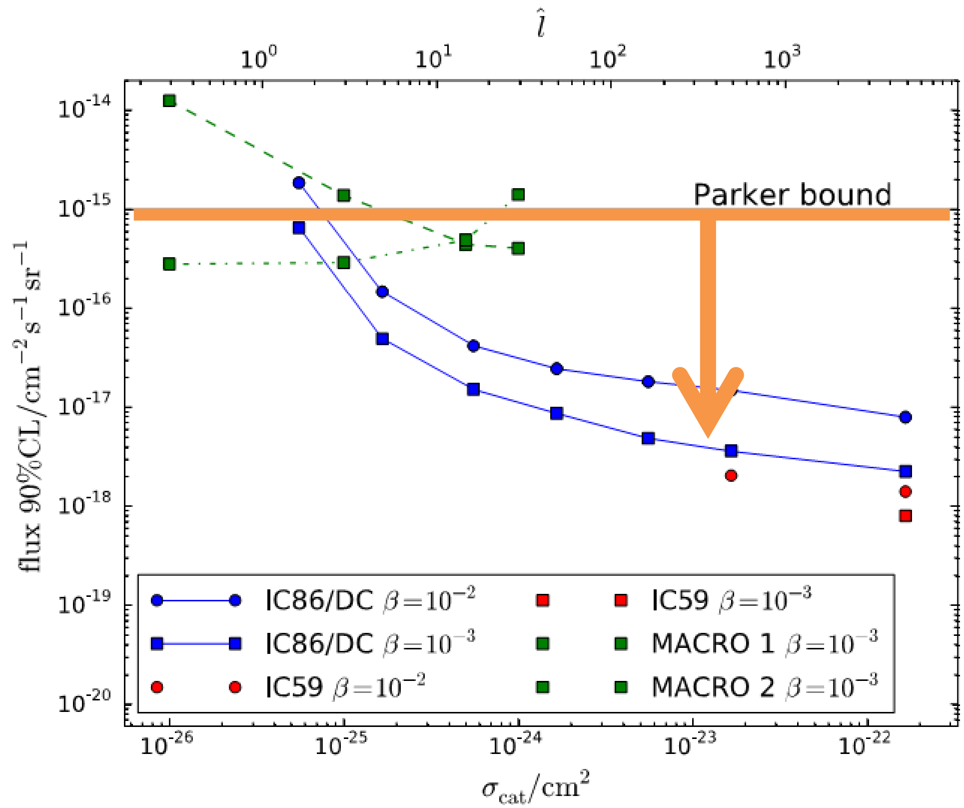
- Search for new, rare particles (e.g. **magnetic monopoles**)
- Many publications suggesting top-down scenarios / fundamental tests, e.g:
  - Decaying, boosted, self-interacting or super-heavy dark matter
  - [1405.7370, 1303.7320, 1308.1105,1312.0797,1408.5471 …]
  - **Superluminal neutrinos** [1306.6095 ,1404.7025 …]
  - Lorentz invariance tests / CPT [1211.7129 , 1303.5843, 1401.2964 …]
  - Quantum spacetime [1303.1826 …]
  - Neutrino mass mechanism [1408.3799 …]
  - Probing large extra dimensions [1409.3502]
  - …..

But note: we are dealing with natural, probably complex astrophysical sources!

EXAMPLE 1: SEARCH FOR MAGNETIC MONOPOLES

Example: slowly moving magnetic monopole catalyzing proton decay:





v ~ c/1000, 10 ms data, special trigger
Strong signal above integrated noise

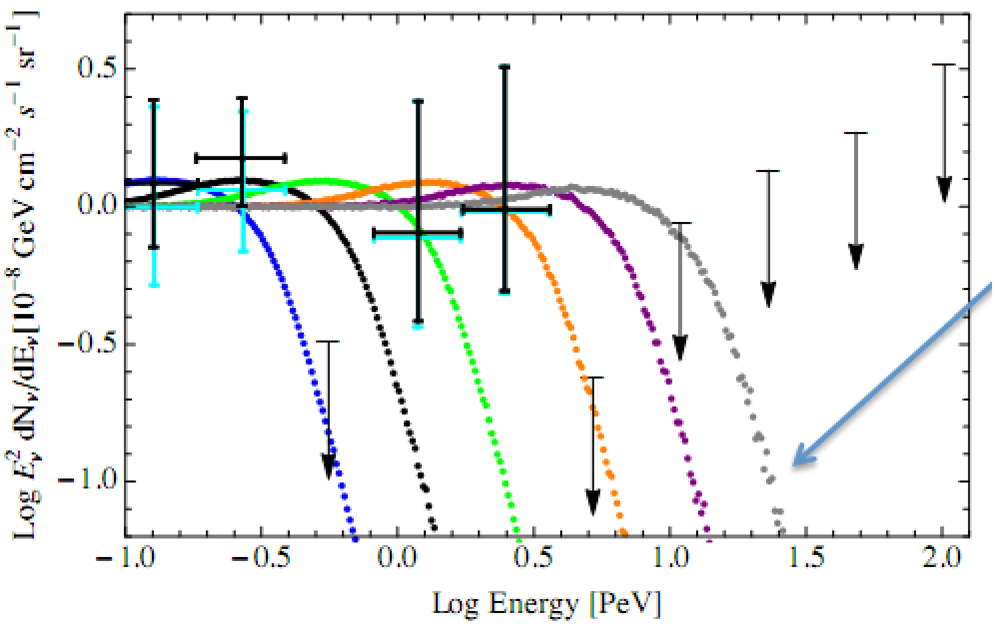
EPJC 74, 7 (cover print)

IceCube: good search tool for rare particle with strong signals

EXAMPLE 2: LIMITS ON SUPERLUMINAL VELOCITY

S. Stecker & S. Scully, arXiv:1404.7025

Existence of high energy neutrinos limits on superluminal velocity:



δ_υ-δ_e < 5.2 x 10^{-21}

Pair-production threshold of 10 PeV required for consistency with IceCube

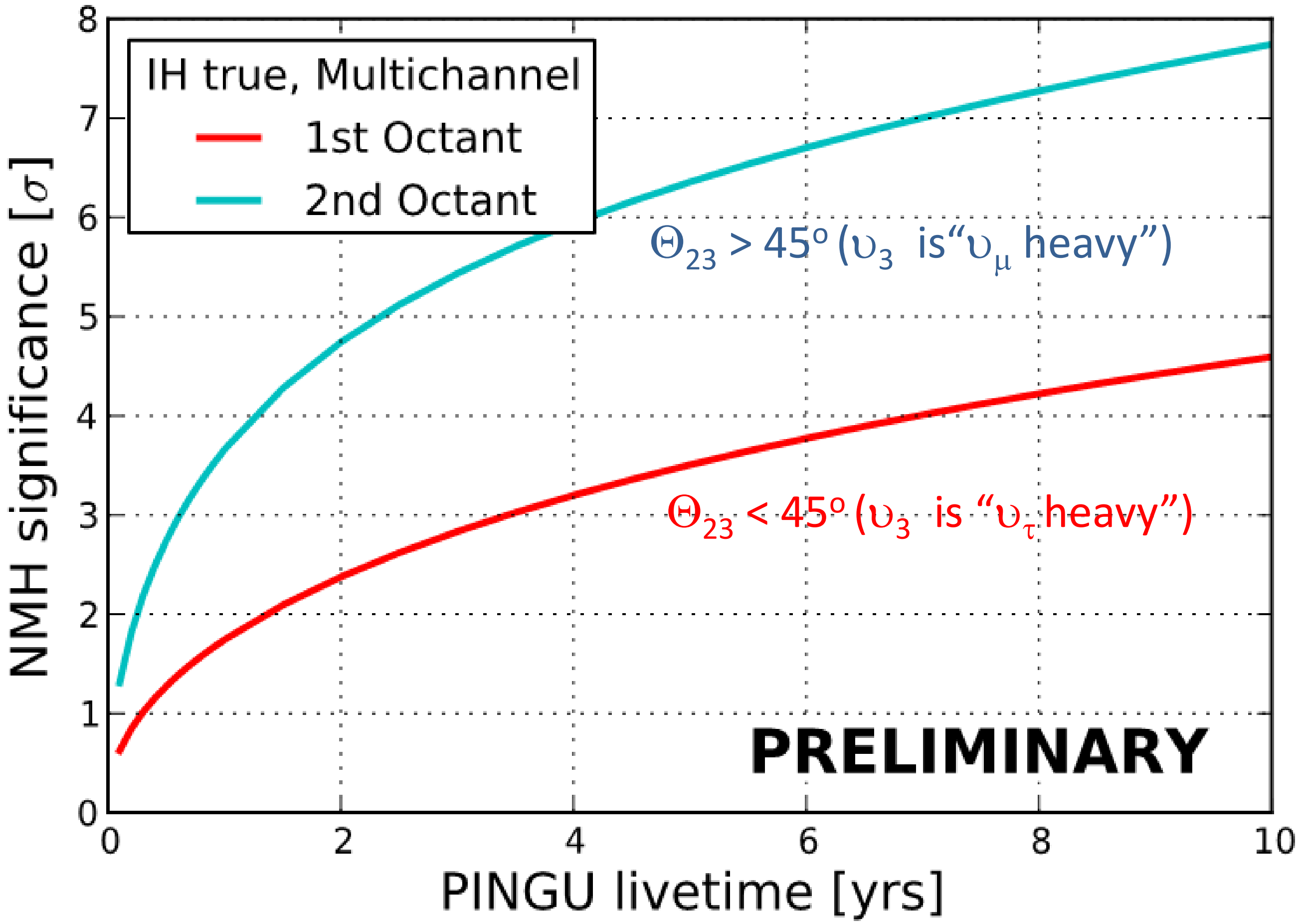
Reason for cut-off could be vacuum pair emission (astrophysics more likely …)

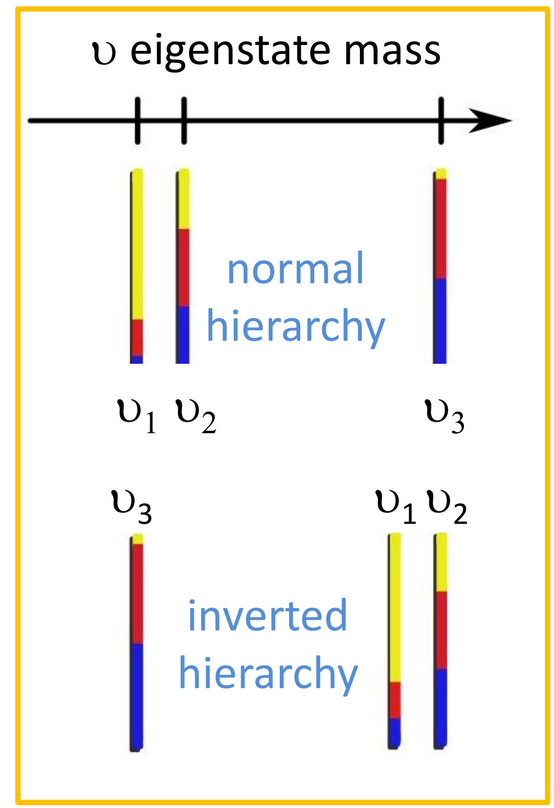
…almost done: 2 slides on future options …

PINGU (ORCA IN MEDITERRANEAN)

Letter of Intent for PINGU: arXiv:1401.2046

Main goal: determine neutrino mass hierarchy with atmospheric neutrinos

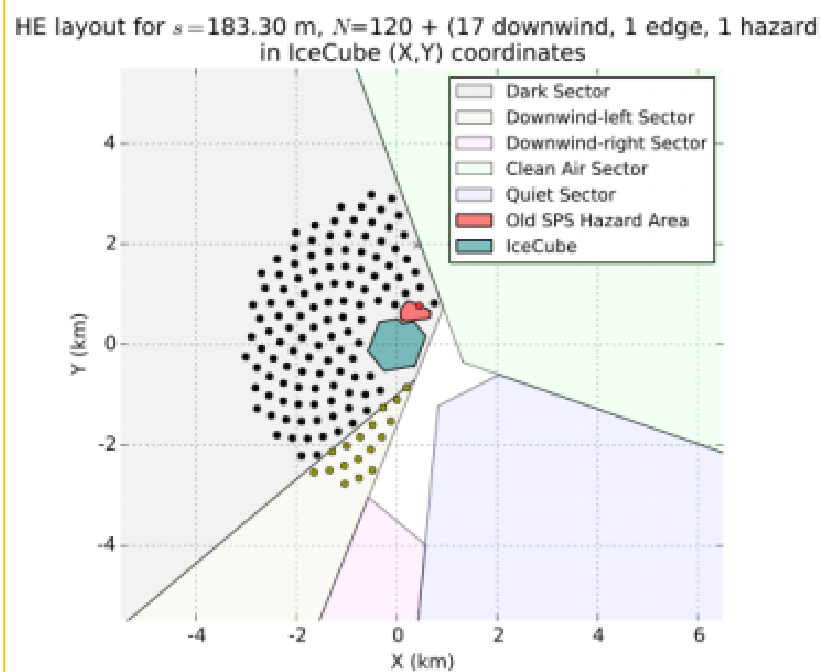




ICECUBE EXTENSION AND SURFACE VETO

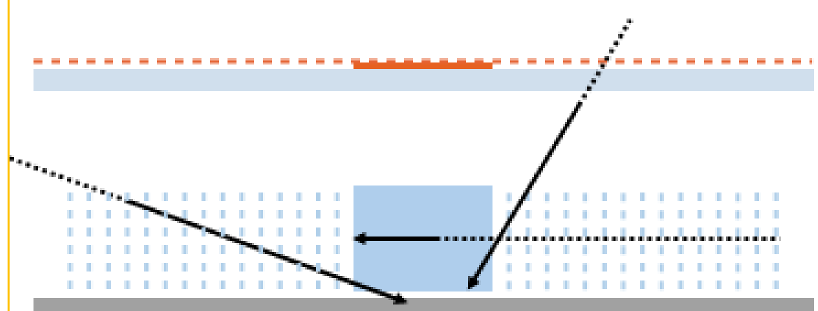
High energy extensions O(100) strings

O(10 TeV) threshold “ok”
→ larger string-spacing
→ **Up to 10 times larger area**



~ 1000 veto tanks (> 100 km²)

- „background free pointing“
  for > 10 TeV in Southern sky
- cosmic ray physics ….



SUMMARY AND OUTLOOK

- **Full IceCube data taking from May 2011**
  - ~ [obscured]% round-the-clock available, working smoothly
  - D[obscured]ded technical goals

- **Ice[obscured] astrophysical importance**
  - [obscured]
  - [obscured] [obscured]gh-going)
  - + many mo[obscured]

5.7 sigma evidence for astrophysical ν's

- **Many future options**
  - KM3NeT in Mediterranean (~3 times IceCub[obscured]
  - PINGU low energy extension (υ mass hierarchy)
  - On surface 100 km^2 veto
  - IceCube extension (~5-10 times IceCube volume at higher energies)

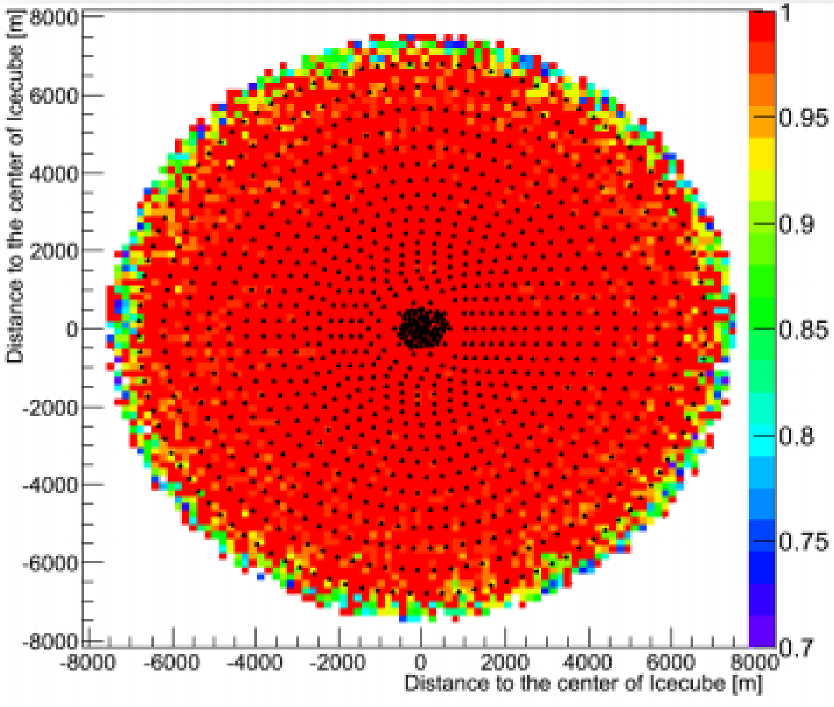
combined proposal?

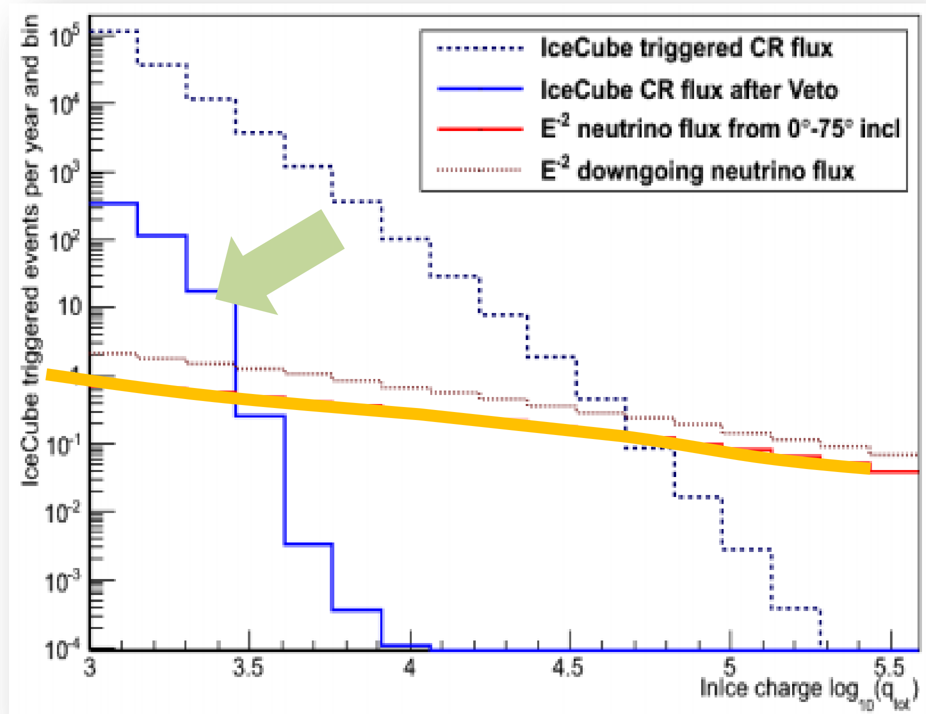

THE END

LARGE COSMIC RAY SOUTHERN SKY VETO

… cosmic ray veto demonstrated with IceTop in limited angular range

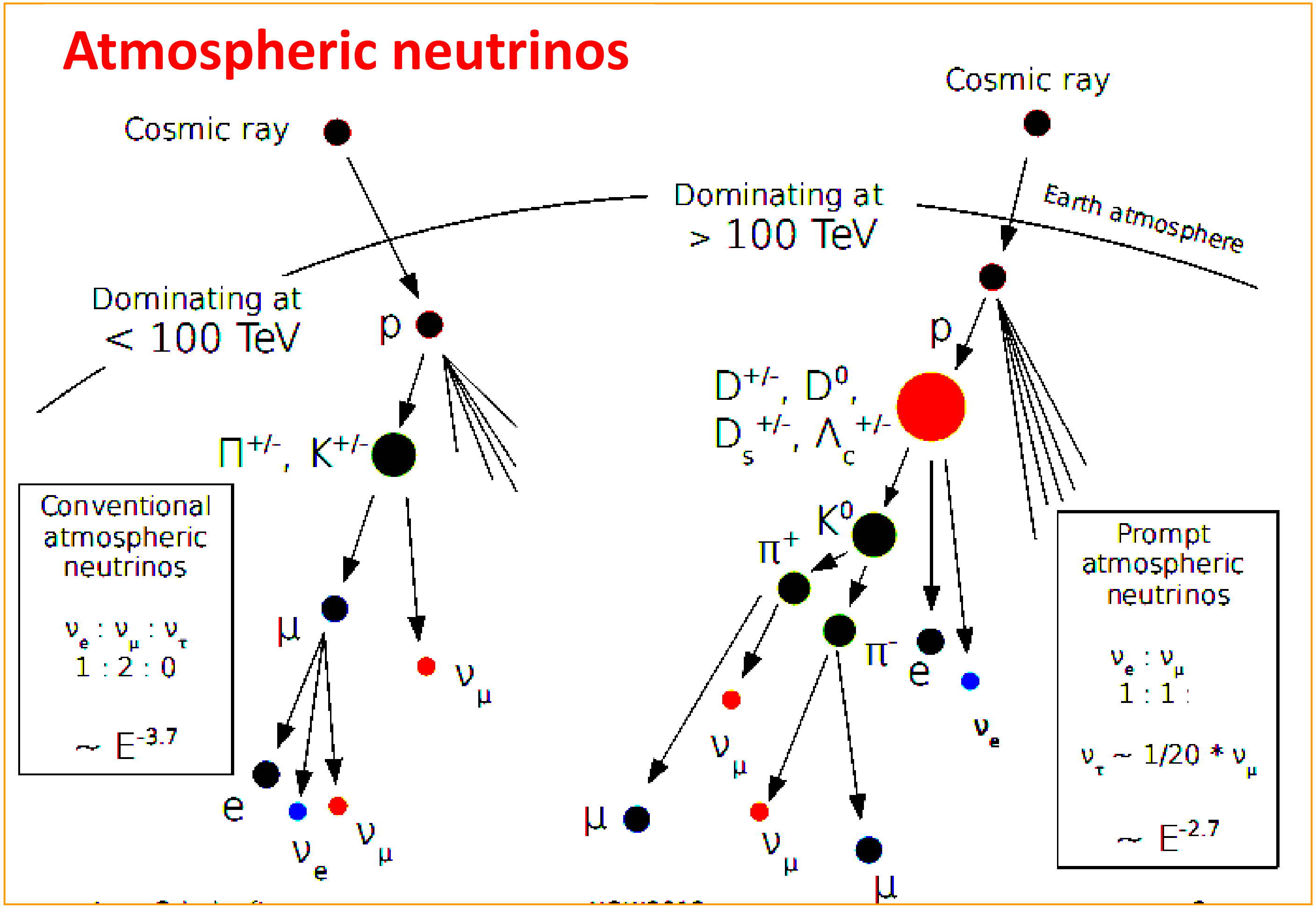
- Southern sky is interesting → more galactic sources …
- ~ 1000 veto tanks (> 100 km^2)

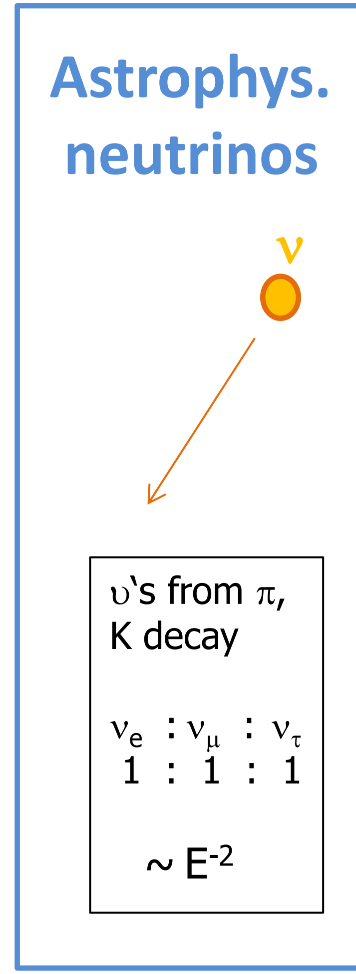




- „background free pointing" for > 10 TeV in Southern sky
- cosmic ray physics ….

LETS DO INCLUSIVE ("DIFFUSE") SEARCHES



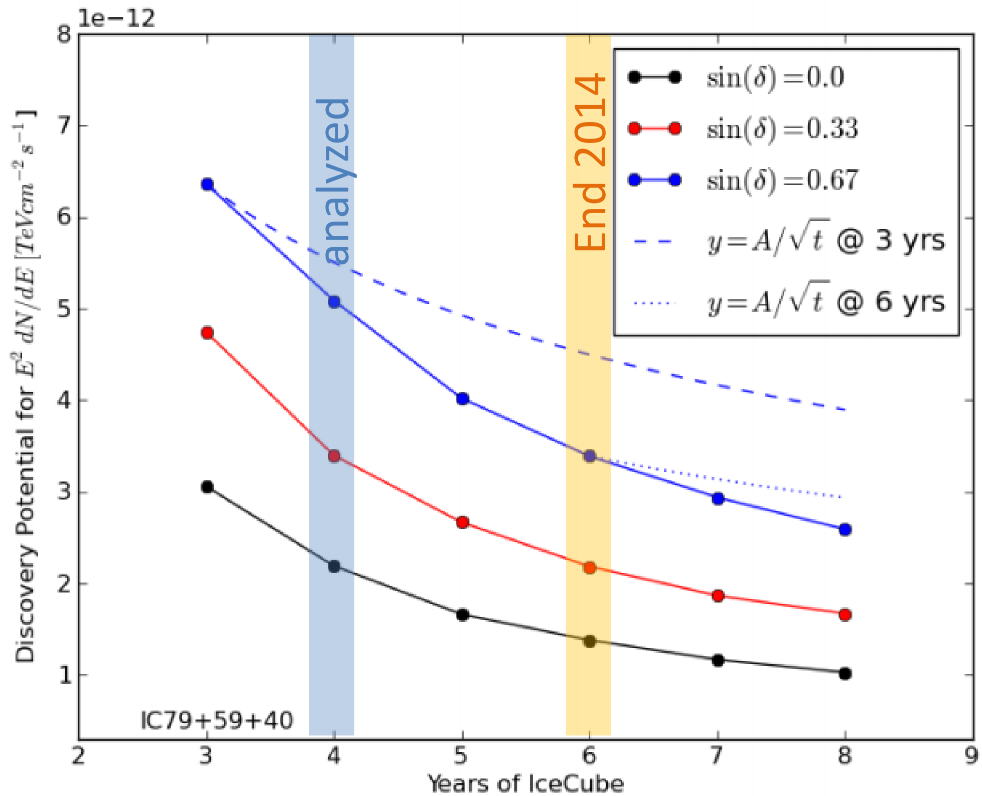


ν_τ only from $D^{\pm}_s$, help from LHC to constrain prompt flux?

METHODS TO IMPROVE SENSITIVITY

***Limitation:** background events ….*

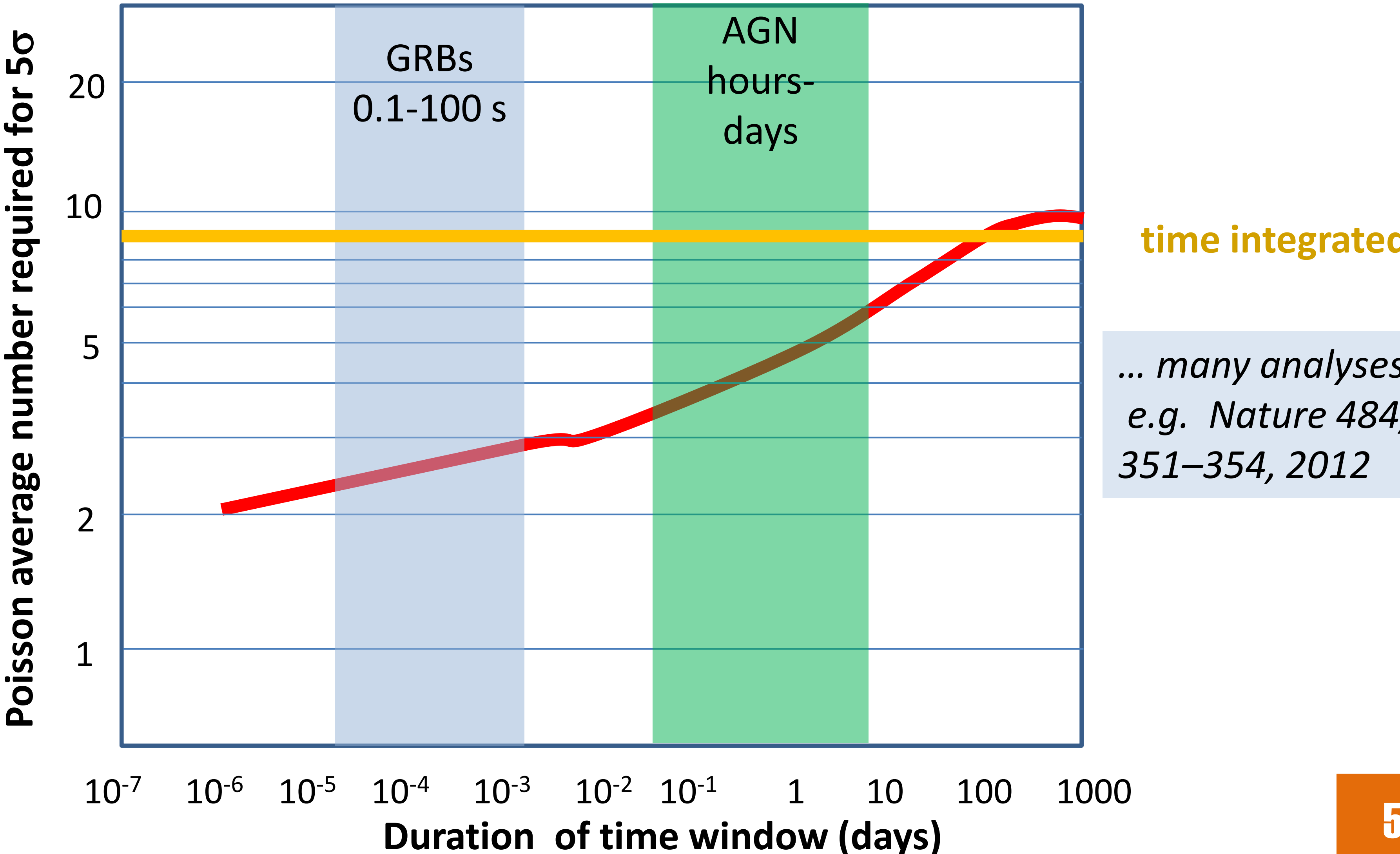
- **Non-stationary sources using external information** (gain factor ~5)
  Gamma Ray bursts (satellites), Cherenkov telescopes , x-ray …
- **Stacking of sources**
  (gain factor < ~10)
- **Improve angular resolution**
  (now ~0.4° @ 10 TeV for υ_μ)



… of course, more data always help ..

... REQUIRED EVENTS FOR DISCOVERY

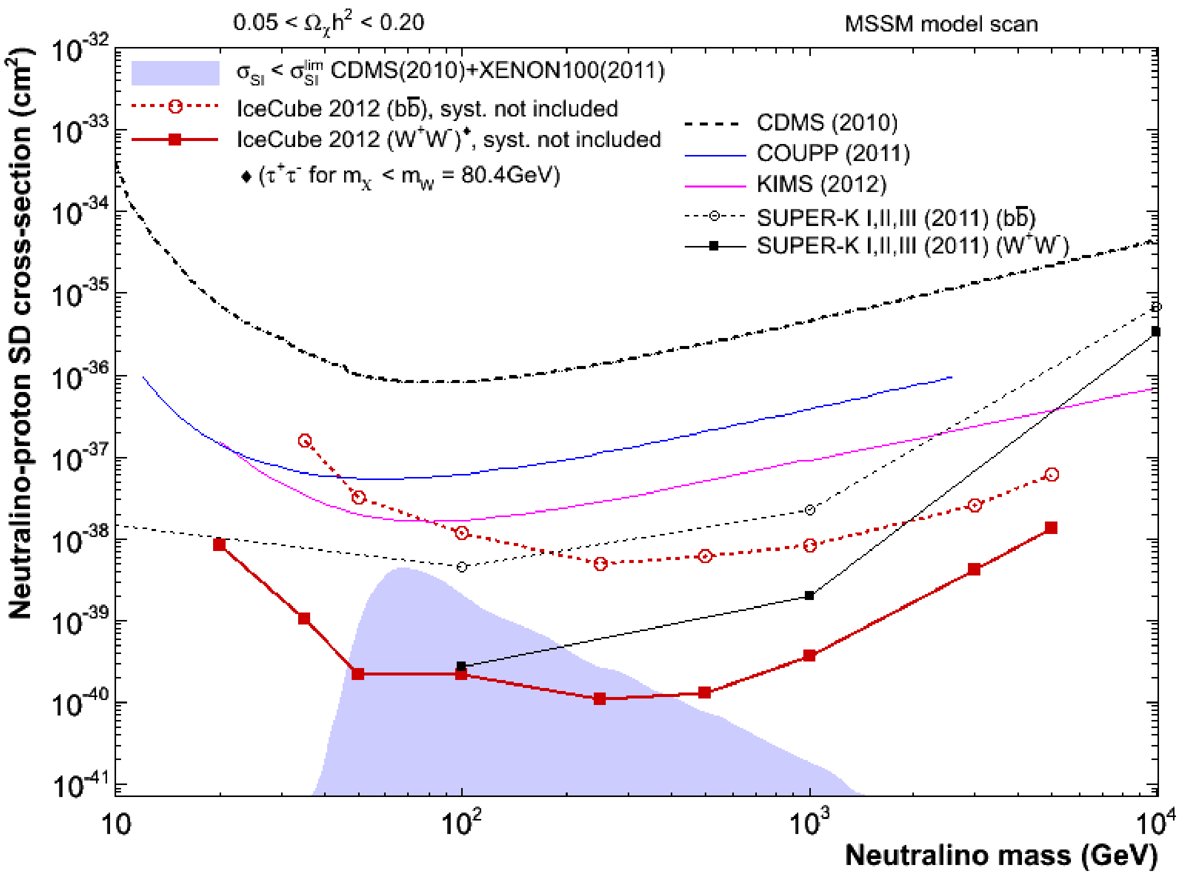
... just an example

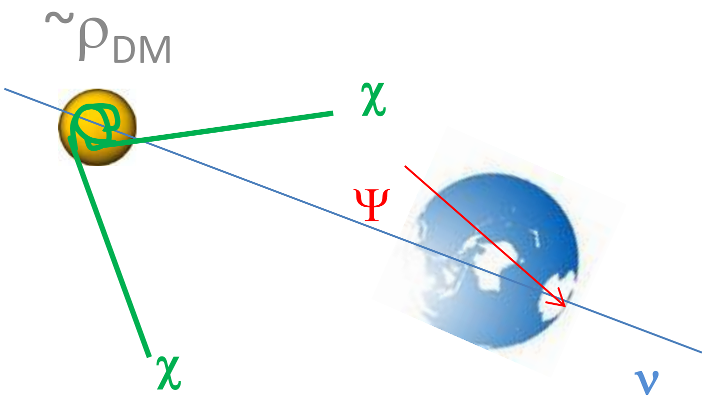


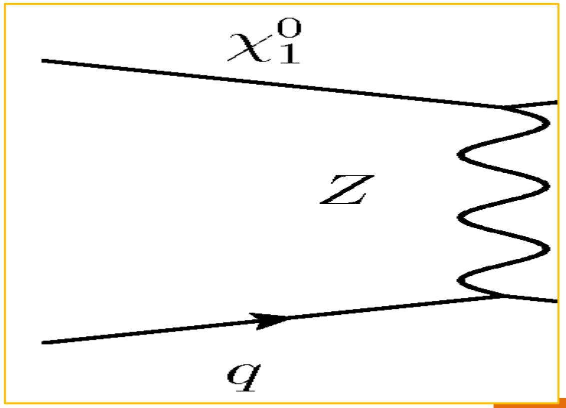
... many analyses e.g. Nature 484, 351–354, 2012

$\chi\chi$ ANNIHILATION IN SUN

… worlds most sensitive measure of spin-dependent χp cross section







ANALYTIC CALCULATION OF VETO