IceCube

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Neckarzimmern

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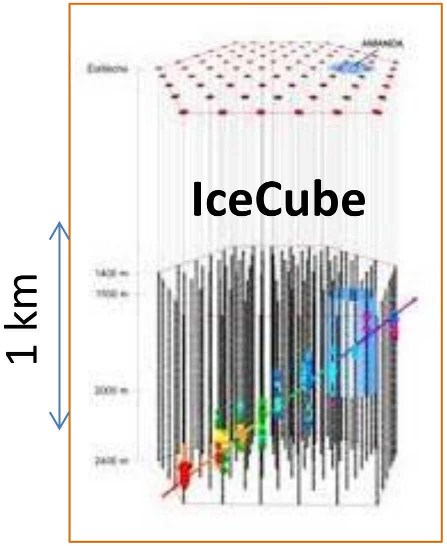
Goal of astroparticle physics: Explore sky outside of visible electromagnetic band

Messengers and their limitations ...

Exploring the Sky with Particles

… sensitivity determined by energy range, effective area …

Type	**Experiment**	**$E_{typical}$ [eV]**	**Effective area**
Satellite based	Fermi-LAT	10^6-10^9	1 m^2
	Hubble	1	5 m^2
Neutrino telescope	**IceCube**	**10^{10}-10^{15}**	**5 m^2**
Cherenkov telescope array	CTA	10^{10}-10^{13}	10^6 m^2
Cosmic air shower array	AUGER	10^{18}-10^{20}	$3x10^9$ m^2



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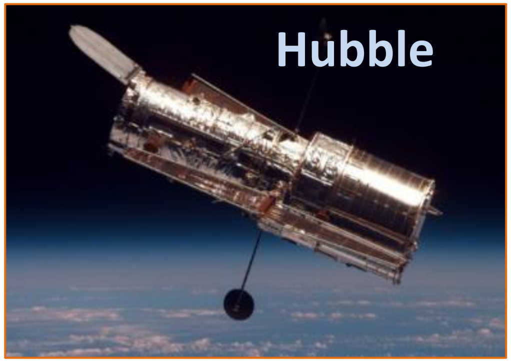
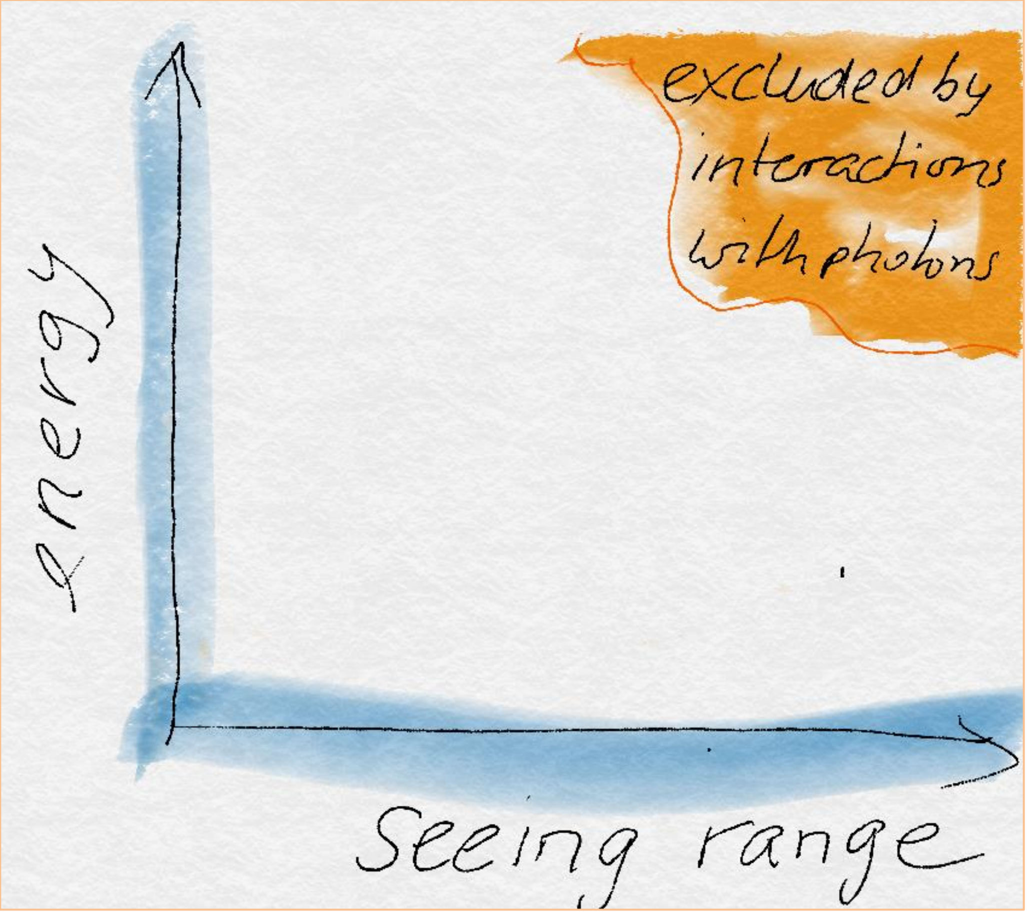
similar effective area but signal flux $\propto 1/E^2$



for a serious comparison, other parameters matter …

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

Transparency of the Universe



photons of all energies abound in universe (3K → visible)

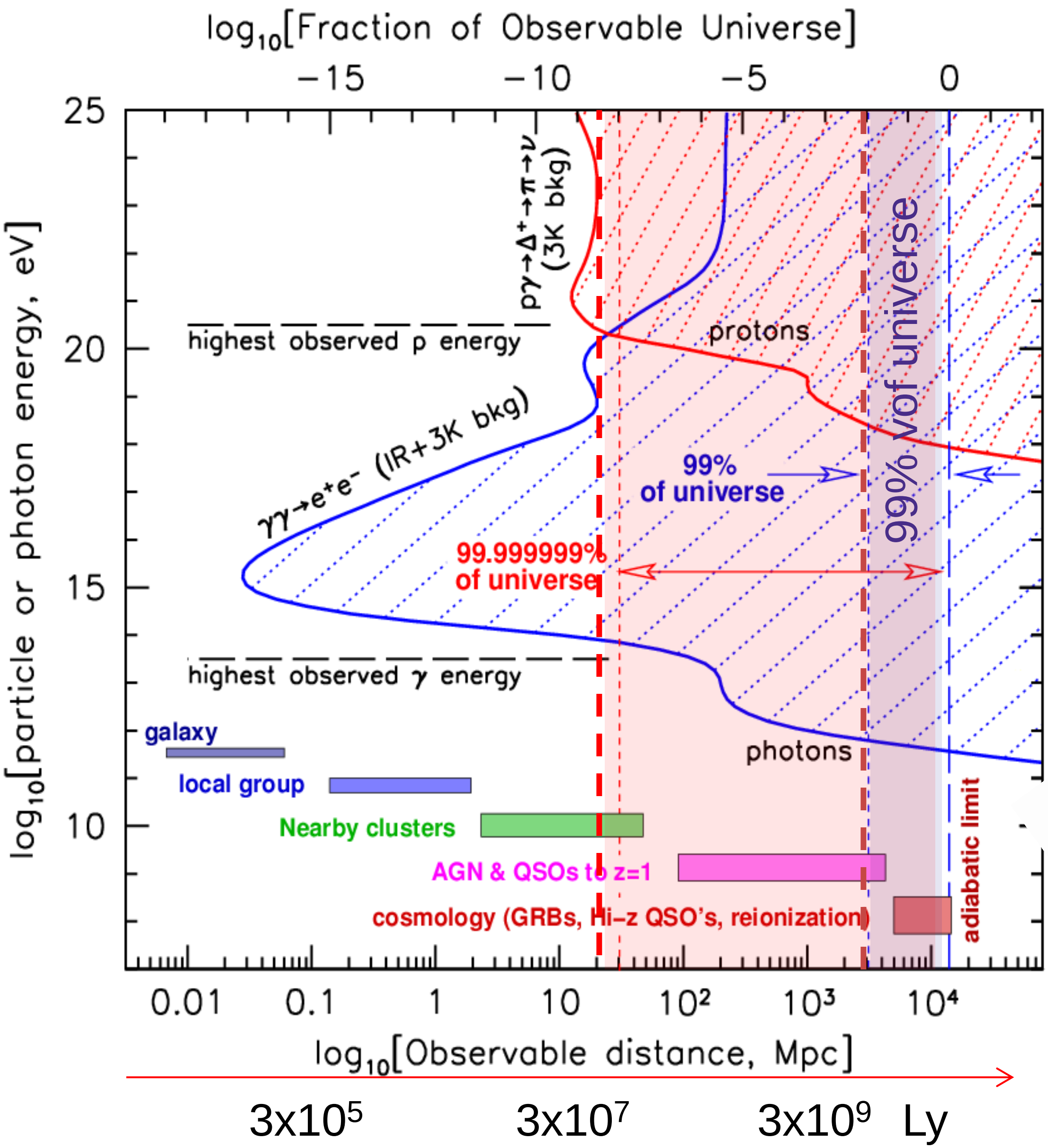
interactions with p and γ:

$p + \gamma(3K) \rightarrow \Delta(1232) \rightarrow p + \pi$

$\gamma + \gamma(IR + 3K) \rightarrow e^+ e^-$

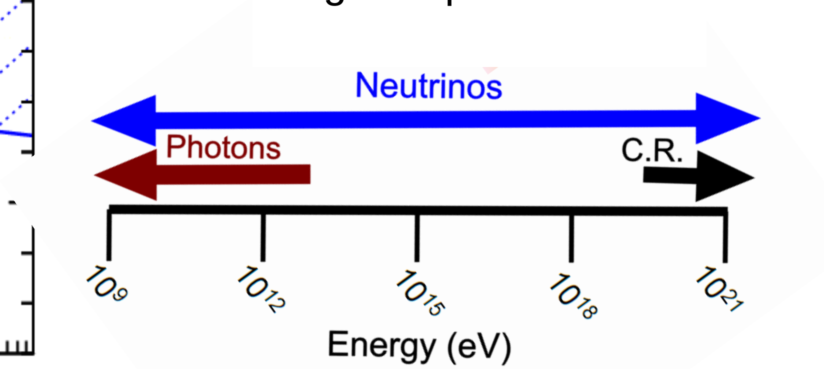
limits „seeing“ range …

…transparency of the Universe

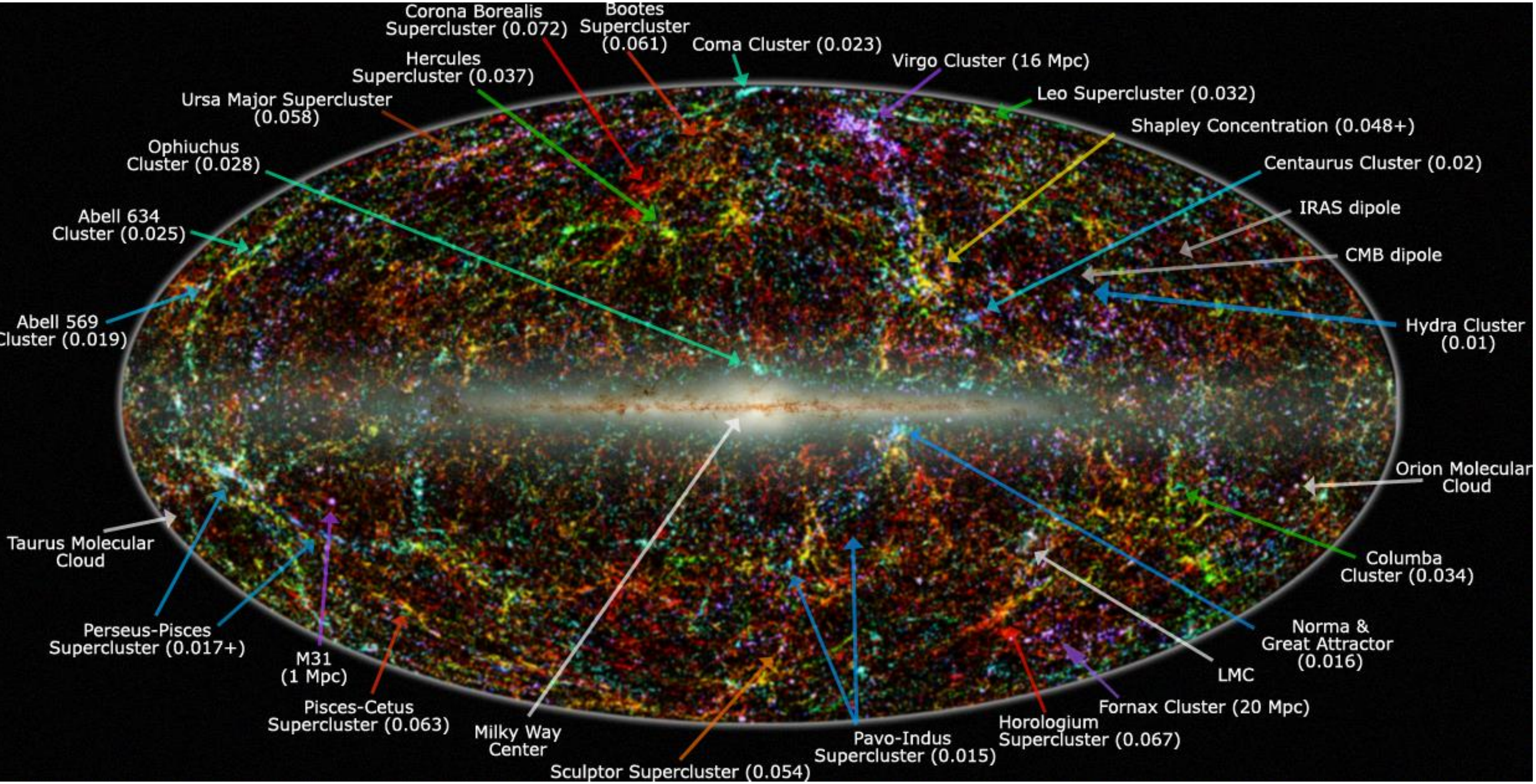


- Only ν's and GW's can "see" beyond local Universe above 100 TeV
- Only ν's and GW's can escape from dense environments
- Only ν's can unambiguously prove hadronic acceleration

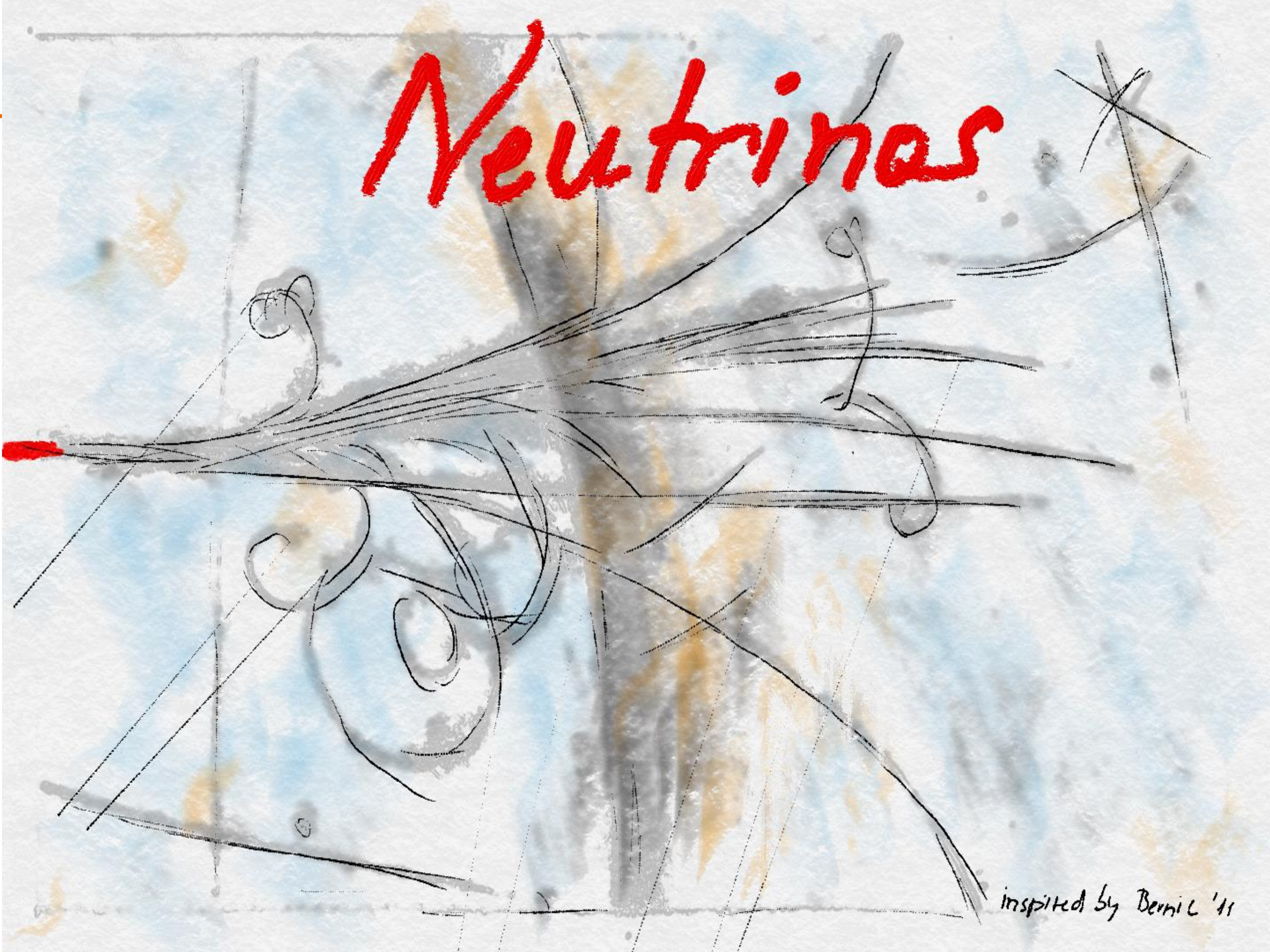
useful range for point searches:



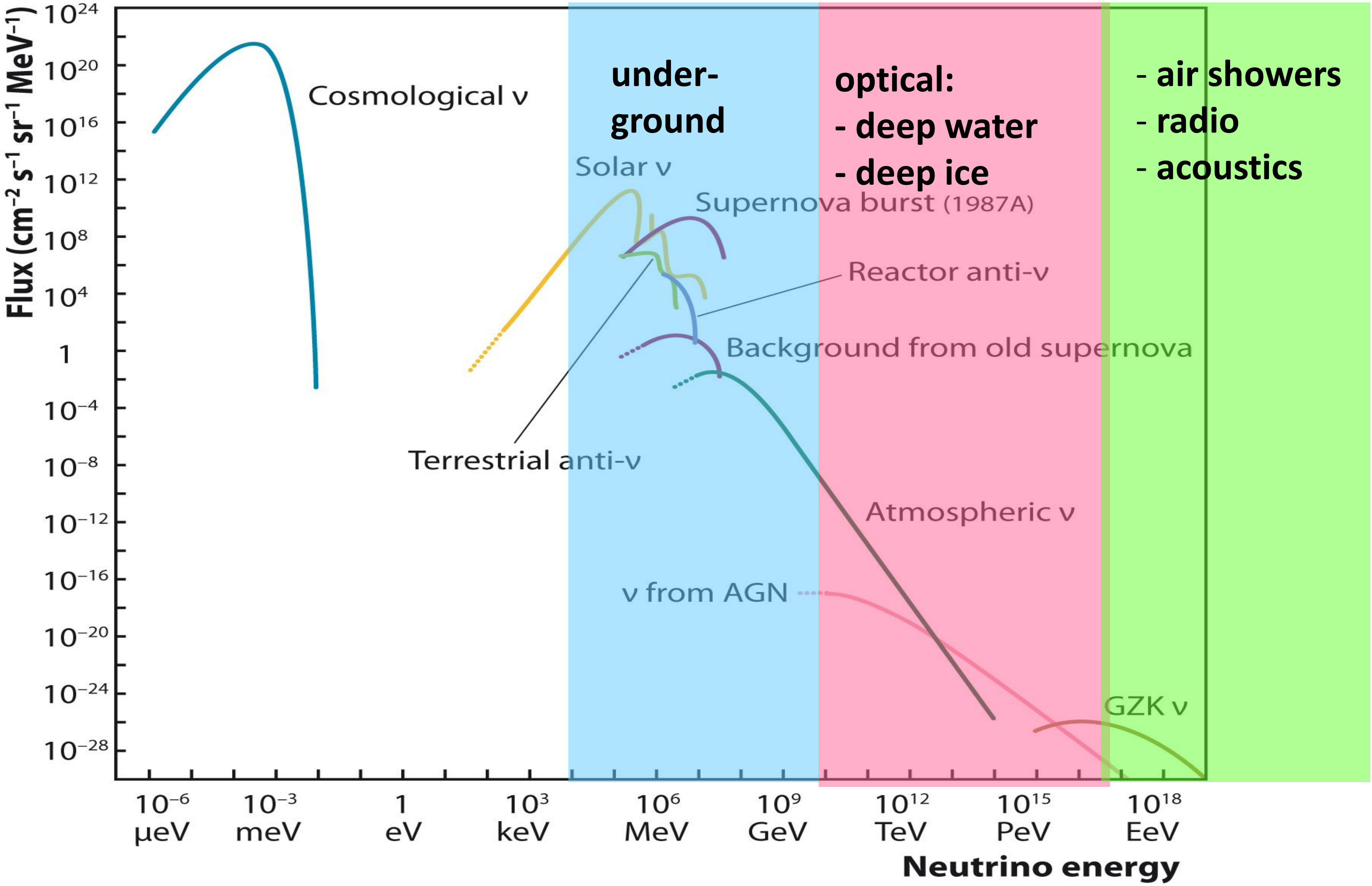
Galaxies and stars within 60 MLy



10^{20} eV p, 100 TeV γ :   seeing range 60 million light years


Neutrinos
inspired by Bernie '11

Fluxes of cosmic neutrinos



under-ground

optical:
- **deep water**
- **deep ice**

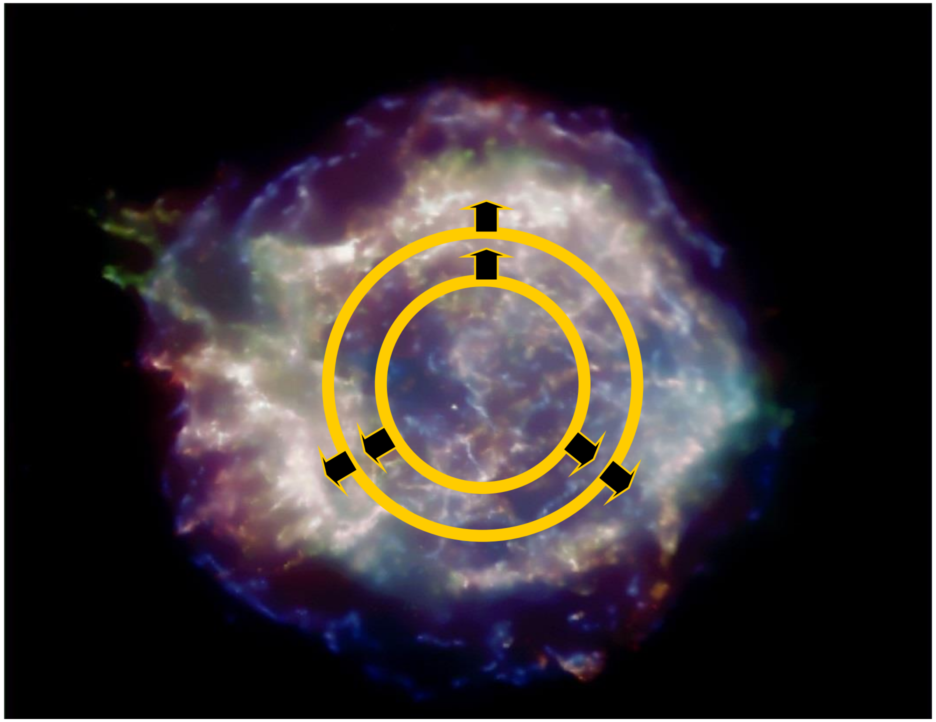
- **air showers**
- **radio**
- **acoustics**

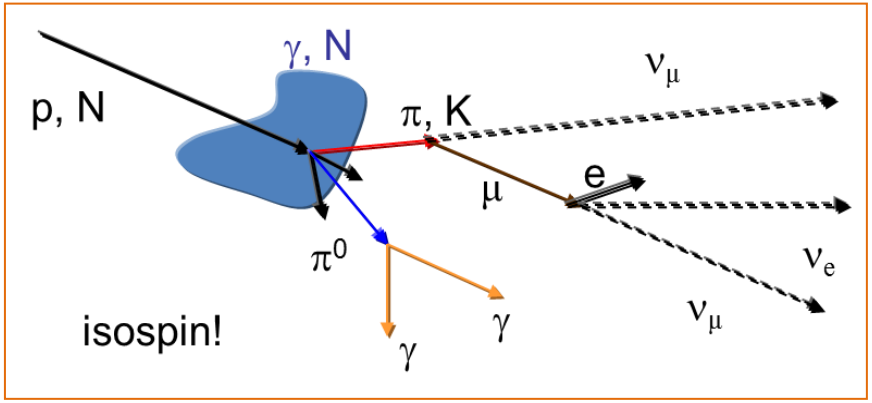
Kamiokande also uses neutrinos from accelerator beams (e.g. T2K)

Production of neutrinos

example: proton acceleration in supernova remnant shock fronts streams O(10^6 m/s)

- *“lucky” particles pass shock fronts frequently, experiencing accelerating “kicks”*
- neutrinos (and gammas) created in beam dump made of gas or photon fields





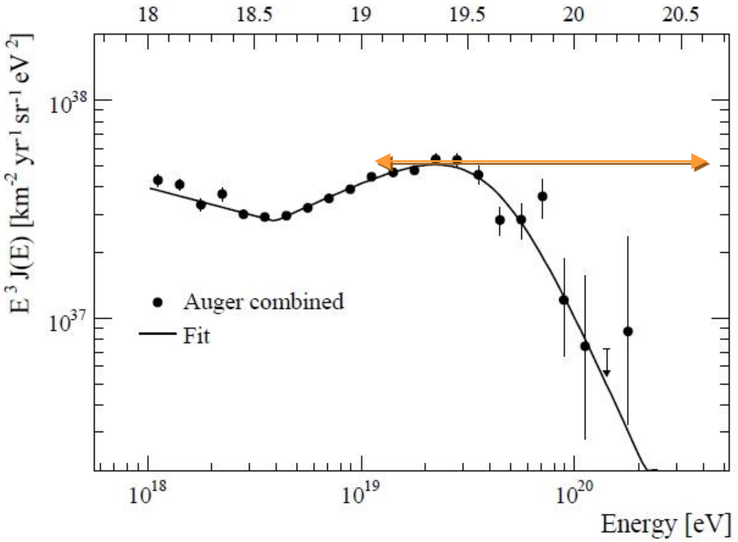
Expect: $\nu_\mu : \nu_e : \gamma = 2 : 1 : 1$
energy distributions different

1 PeV $\upsilon \approx$ 2 PeV $\gamma \approx$ 20 PeV cosmic ray

Electrons: produce bremsstrahlung and synchroton radiation
Protons: interact with γ‘s or protons to produce pions and kaons → Waxman-Bahcall limit

Waxman-Bahcall upper limit

Idea: constrain possible neutrino flux from extragalactic cosmic ray intensity



power required over 10^{10} years to produce measured cosmic ray flux:

$$\dot{\varepsilon} \leq 10^{44} \frac{erg}{Mpc^3 year}$$

Nucleons interacting in surrounding material by pγ (and pp, pn) interaction
→ **pions and kaons → neutrinos**

Assume:

- „optically thin sources“
- E^{-2} flux for extrapolation to lower energy
- Cosmological evolution with maximal rate

Benchmark for building detector

for $p\gamma \rightarrow \Delta^+ \rightarrow \pi^+ n$: $\phi^{p\gamma}_{\bar{\nu}_\mu + \nu_\mu} < \frac{1.9\times10^{-8}}{E_\nu{}^2} \frac{\mathrm{GeV}}{\mathrm{cm^2 s^{-1} sr^{-1}}}$

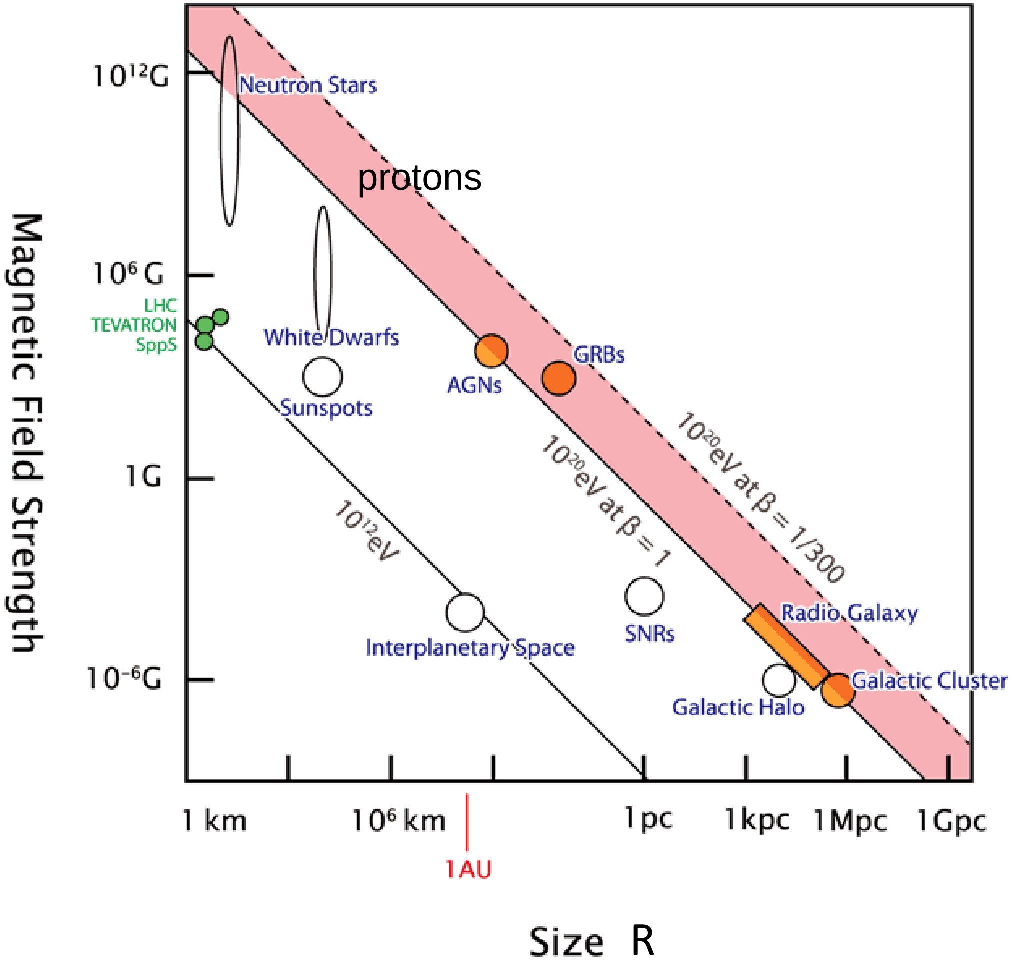
Potential sources of astrophysical neutrinos

- Which object accelerates to what energies?
- Difficult to explain energies >~10^{21} eV for protons
- Easier for heavy nuclei

$$R_{gyro}\ (= \frac{p}{ZqB}) \leq \beta \frac{R}{2}$$

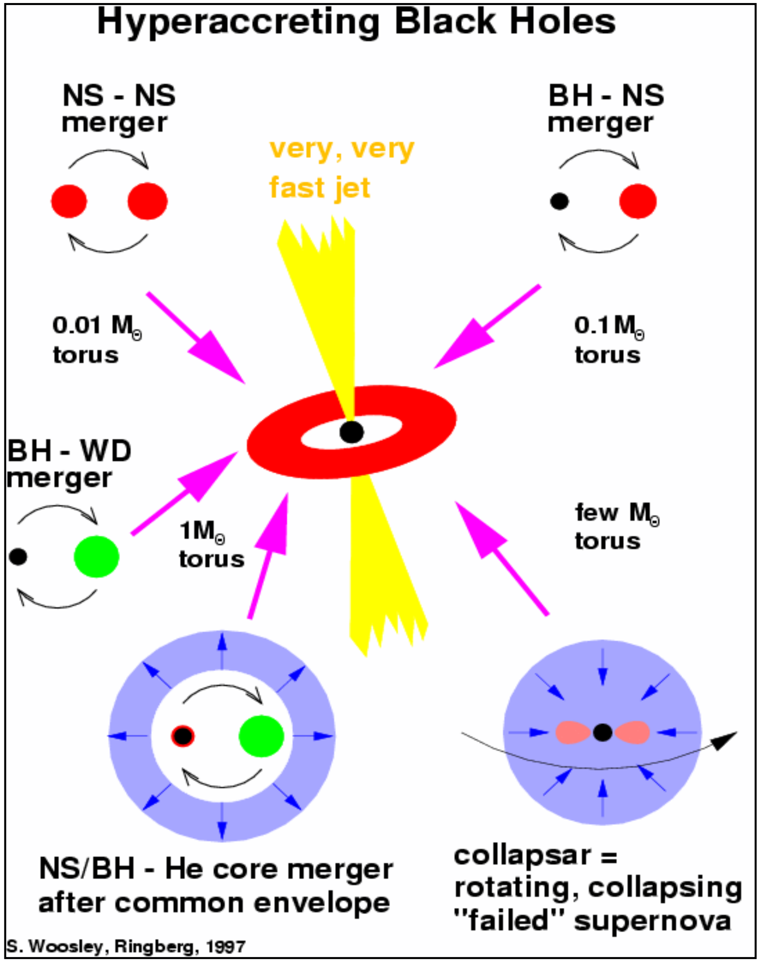
$$p \leq \frac{1}{2} \beta ZqBR$$

$$E \leq \frac{1}{2} c\beta ZqBR$$

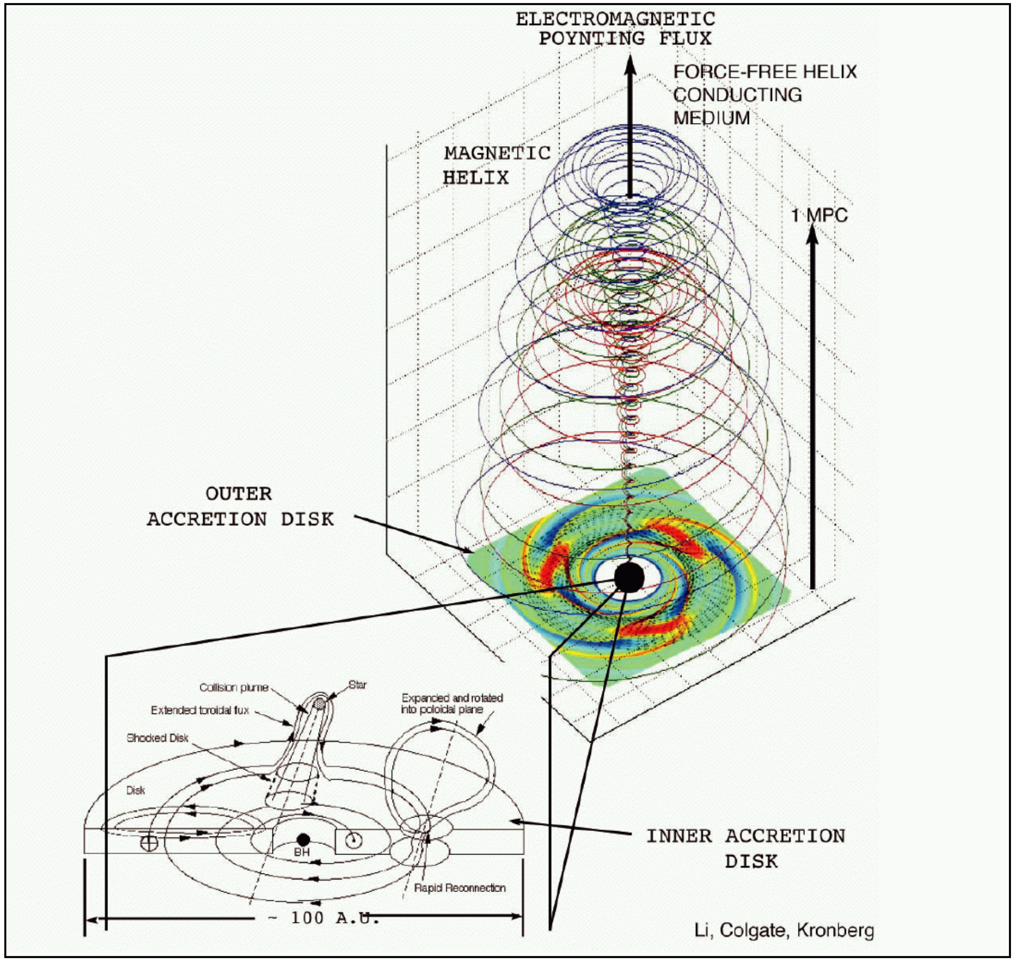


βc: velocity of scattering centers → transforms R< $2R_{gyro}$ →R< $2R_{gyro}/\beta$

Example: Gamma-Ray bursts



S. Woosley, Ringberg, 1997

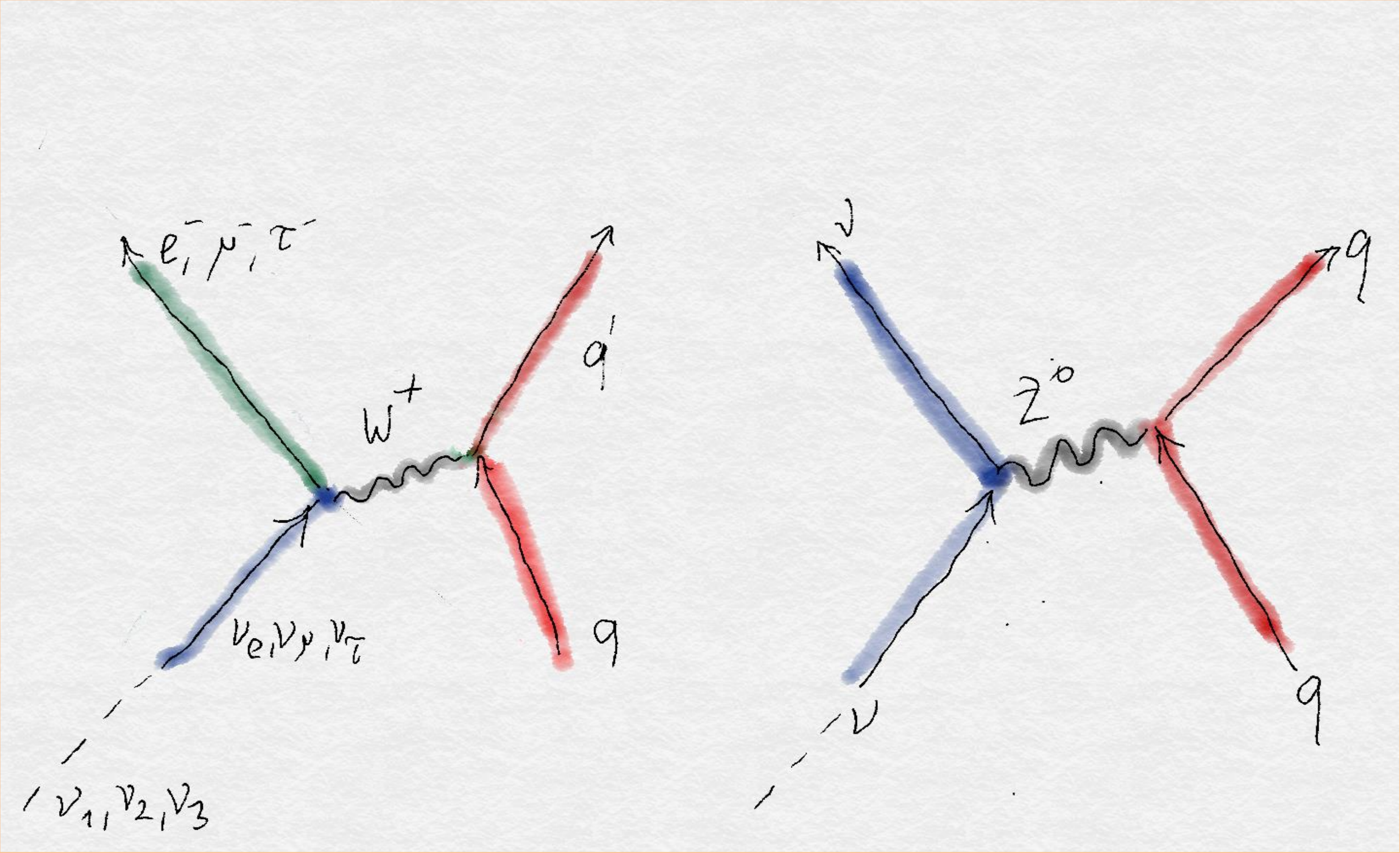


Li, Colgate, Kronberg

~ 80% of stars in Milky Way multiple!

Source of magnetic field – "dynamo" in accretion disk
Source of jet energy - accretion disk + black hole spin

ν progagation and interaction



Inspired by Nick Berger, Mainz

ν oscillations & decoherence

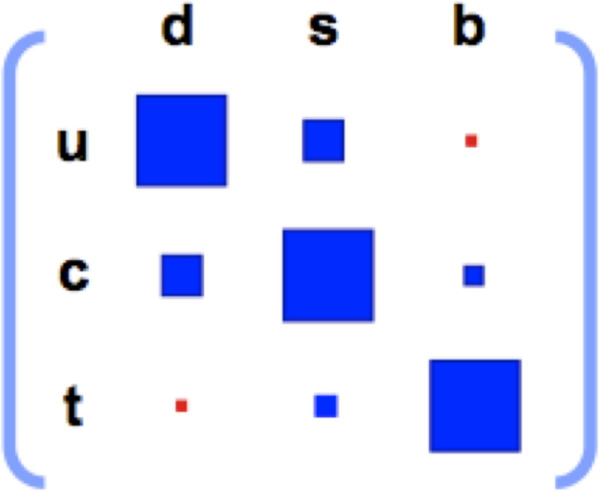
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

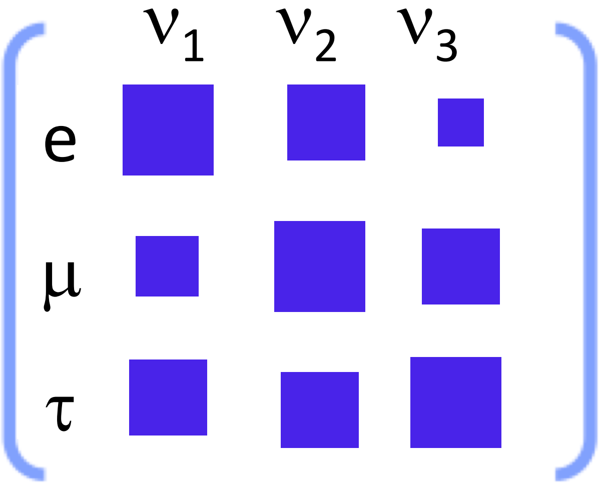
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

weak eigen-states

CKM or
PMNS matrix

mass eigen-states





Neutrino oscillations

ν creation

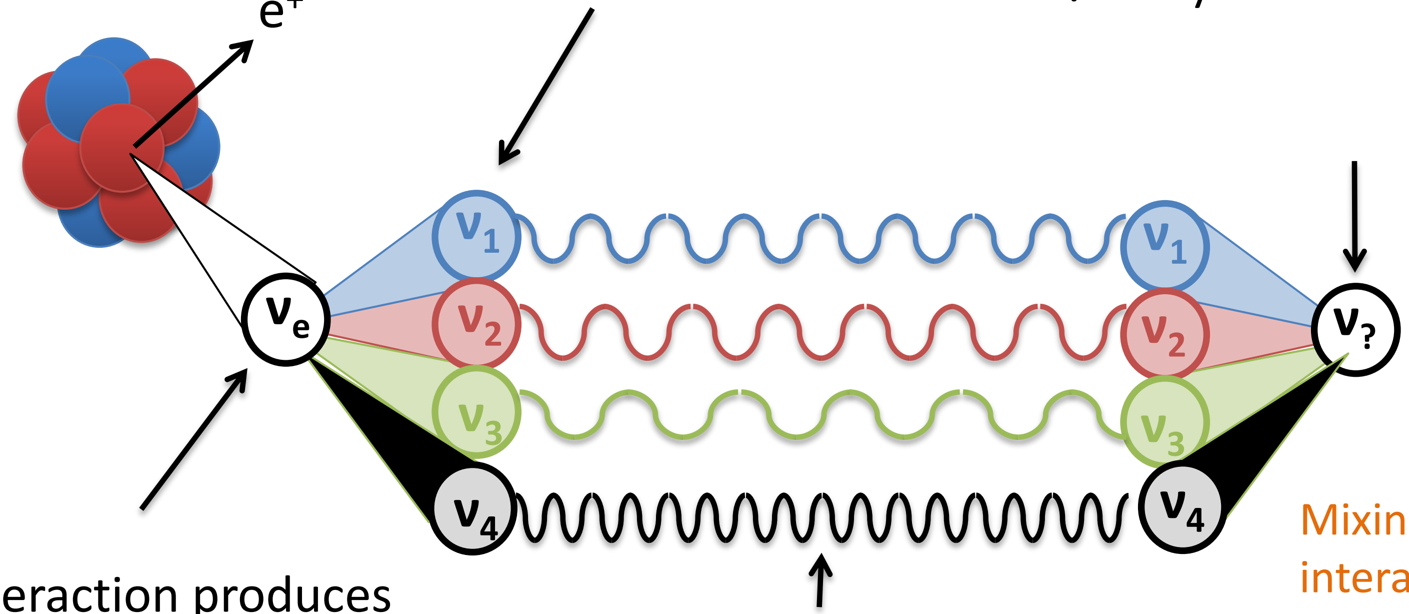
ν propagation

ν detection

z.B. β⁺-Zerfall

propagates as mass eigenstates

different **neutrino flavor** when detected by weak interaction



Weak interaction produces neutrino in **flavor state**

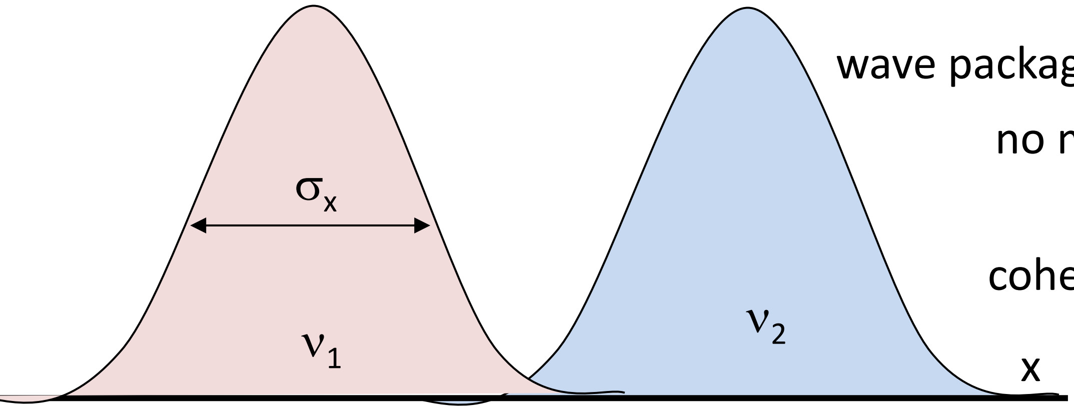
Different masses create time and space dependent **phase differences**

Mixing with non-interacting sterile ν → detected deficit !

$$P_{\alpha\to\beta} = \left|\langle \nu_\beta \left| \nu_\alpha(t) \right\rangle\right|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i}\, e^{-im_i^2 L/2E}\right|^2 = f(\theta_{ji}, (m_j^2 - m_i^2)\frac{L}{E_j})$$

Coherence in propagation

Neutrinos travel as wave package that loose overap due to group velocity differences Δv_{gr} :



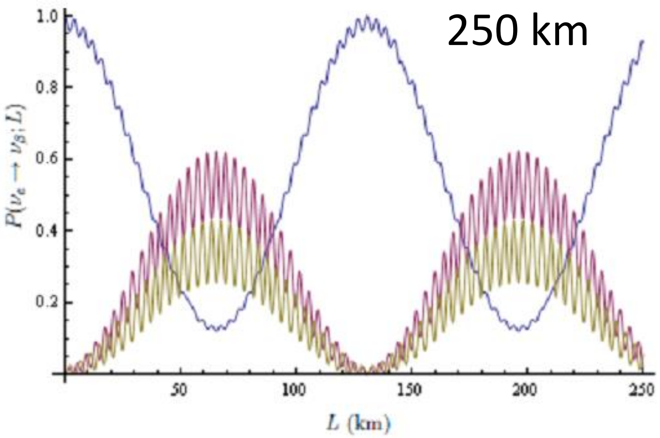
wave package separation: $\Delta v_{gr} L/c$

no more overlap: $\Delta v_{gr} L/c \approx> \sigma_x$

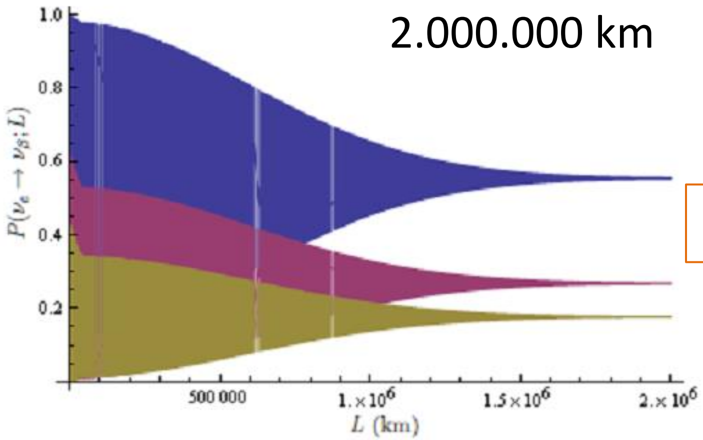
coherence length: $L_{coh} = \sqrt{32}\ \sigma_x\ E^2/(\Delta m^2 c^4)$

… coherence also determined by conditions of creation and detection …

Example 4 MeV neutrinos *http://users.jyu.fi/~jojapeil/thesis/coherence_in_neutrino_oscillations_040211.pdf*



250 km



2.000.000 km

decoherent!!

Neutrinos from far away sources

http://users.jyu.fi/~jojapeil/thesis/coherence_in_neutrino_oscillations_040211.pdf

1. **Which information does a neutrino carry when it is created?**
2. **What happens on the way to detector?**
3. **What can be measured in the detector?**

ad 1: Neutrinos are created as flavor eigenstates ν_α (ν_e, ν_μ ,ν_τ)
identified by energy, momentum, spin direction and neutrino flavor

ad 2:

- Neutrino oscillation length much shorter than travel distance
- Source extension larger than oscillation length
- Broad energy spectrum leads to varying oscillation lengths
- Wave packets separate so that oscillations are no longer possible

What remains is an averaged effect:

$$\boxed{\overline{P}_{\alpha\to\beta} = \sum_i \left|U_{\beta i}\right|^2 \left|U_{\alpha i}\right|^2}$$

ν's from far away sources

$$\boxed{\overline{P}_{\alpha\to\beta} = \sum_i |U_{\beta i}|^2 |U_{\alpha i}|^2}$$

Initially assume that $U_{e3} = \theta_{13} = 0$, $\theta_{23}=45^0$
and $\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$ at source

$$U_{\alpha i} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}\frac{1}{\sqrt{2}} & c_{12}\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ s_{12}\frac{1}{\sqrt{2}} & -c_{12}\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\overline{P}_{e\to e} = \sum_i |U_{ei}|^2 |U_{ei}|^2 = |U_{e1}|^4 + |U_{e2}|^4 = c_{12}^4 + s_{12}^4 = a = 1-2b$$

$$\overline{P}_{e\to\mu} = \sum_i |U_{ei}|^2 |U_{\mu i}|^2 = |U_{e1}|^2 |U_{\mu 1}|^2 + |U_{e2}|^2 |U_{\mu 2}|^2 = s_{12}^2 c_{12}^2 = b$$

$$\overline{P}_{e\to\tau} = \sum_i |U_{ei}|^2 |U_{\tau i}|^2 = |U_{e1}|^2 |U_{\tau 1}|^2 + |U_{e2}|^2 |U_{\tau 2}|^2 = s_{12}^2 c_{12}^2 = b$$

$$\text{trigonometry}: a = 1-2b$$

flux at source: $\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$ flux at Earth: $\nu_e : \nu_\mu : \nu_\tau = 1\text{-}2b : b : b$

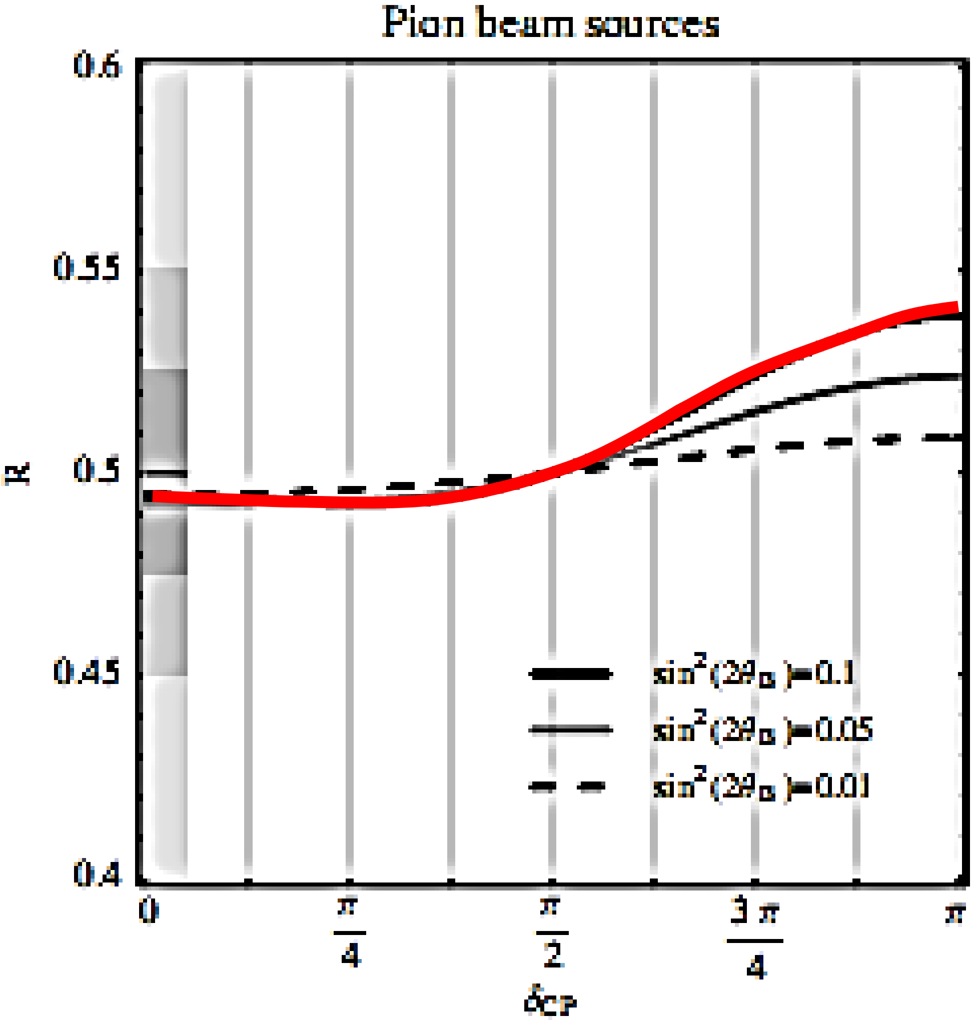
flux at source: $\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0$ flux at Earth: $\nu_e : \nu_\mu : \nu_\tau = b : ½(1\text{-}b) : ½(1\text{-}b)$

flux at source: $\nu_e : \nu_\mu : \nu_\tau = 0 : 0 : 1$ flux at Earth: $\nu_e : \nu_\mu : \nu_\tau = b : ½(1\text{-}b) : ½(1\text{-}b)$

if $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ ($\pi^{+/-}$ decay): **flux at Earth =** 1-2b+2b : b+1-b : b+1-b = **1 : 1 : 1**

Some dependence on θ_{13}, θ_{23} and $\boldsymbol{\delta}_{\mathbf{CP}}$

If one takes measured mixing angles and accounts for possibility of CP violation:



$$R^{\text{Pion beam}} = \frac{2P_{\mu\mu} + P_{e\mu}}{2P_{\mu e} + P_{ee} + 2P_{\mu\tau} + P_{e\tau}}$$

$$\sim \ 0.50 - 0.14\,\theta_{13}\cos\delta_{\text{CP}}$$

In principle: flavor ratio can be used For CP violation studies!

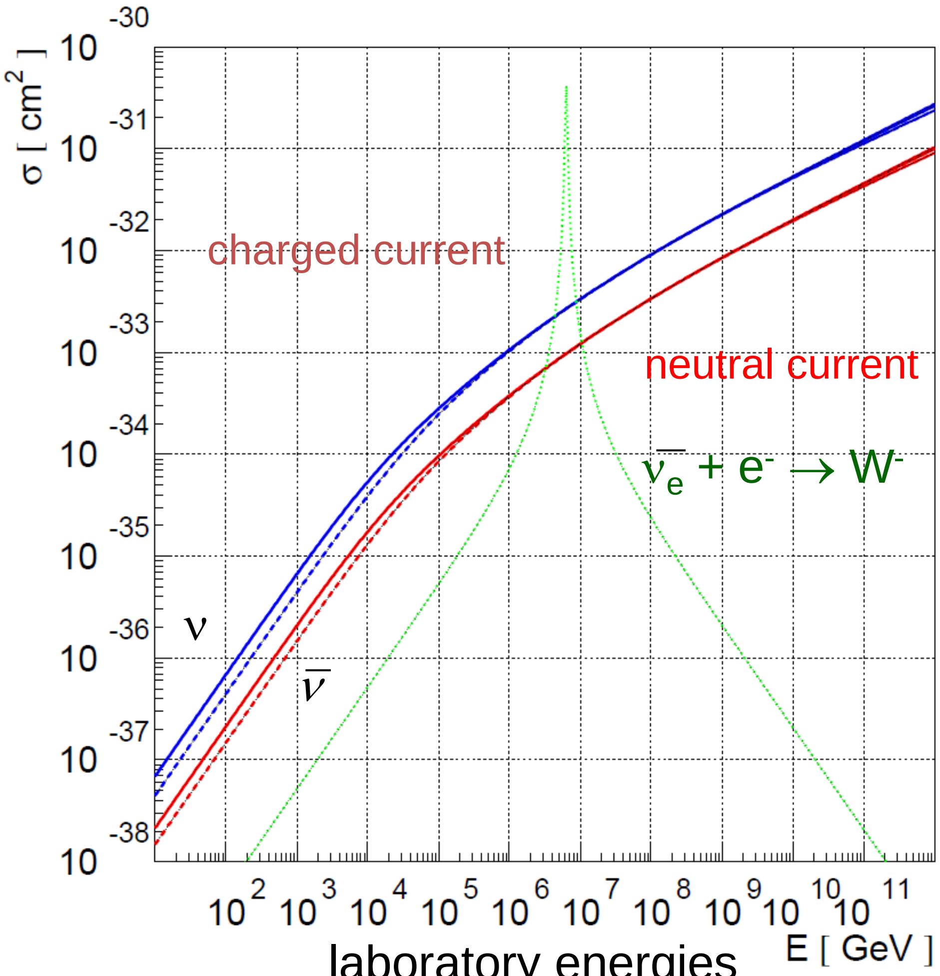
… if production process were known

More later ….

Neutrino cross sections

$s < 10^4$ GeV^2:

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2}{\pi}\, s \left[xd(x) + (1-y)^2 x\bar{u}(x) \right]$$



laboratory energies

x : fraction nucleon momentum carried by q

y : fraction E_ν transferred to final state

xd(x) = momentum distribution of d-type quarks

xu(x) = momentum distribution of u-type anti-quarks

Obvious questions:

- Why is there a kink?
- Why σ(anti-ν) lower?
- Why is there a resonance?

Effect of the W propagator

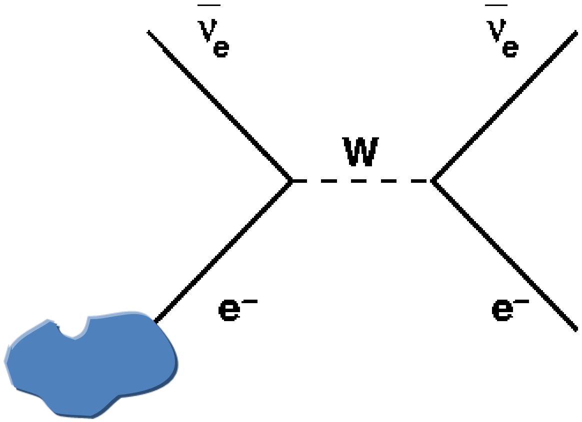
Exchange of massive real W needs to be accounted for energies > 40 TeV

reasonable cross section approximation above W threshold:

$$\sigma_{tot} = 1.2 \times 10^{-32} cm^2 (E_\nu / 10^{18} eV)^{0.40}$$

... no longer ~ E_ν

Glashow resonance: resonant production of real W^- from $\bar{\nu}_e$ hitting ambient electrons



Resonance paramters:

neutrino laboratory energy: 6.7 PeV

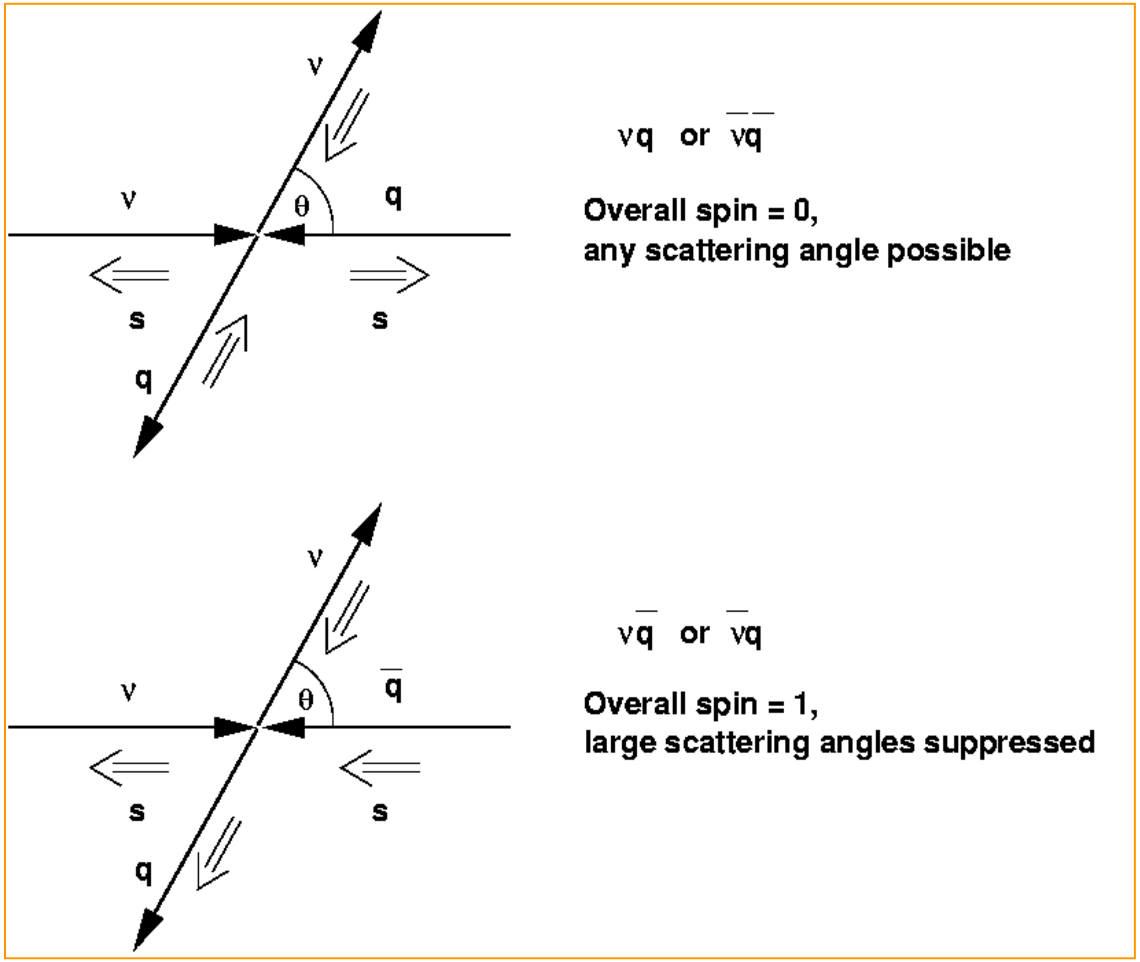
resonance width: ±130 TeV

peak cross section: 5×10^{-35} m^2

„Amplifier“ at very high energies!

Why are $\sigma(\nu q)$ & $\sigma(\bar{\nu} q)$ different?

weak interaction couples to left-handed fermions …



νq or $\bar{\nu}\bar{q}$

Overall spin = 0,
any scattering angle possible

$\nu\bar{q}$ or $\bar{\nu}q$

Overall spin = 1,
large scattering angles suppressed

- neutrino has helicity -½
- quark prefers helicity -½

- spin 0 system has no directional preference

- conservation orf spin gives y-dependence for s=1

- Only seen at low energies: sea quark symmetric betw. quarks and anti-quarks

Absorption length for neutrinos

- average path length L_A for a particle A travelling through medium of particles B with number density ρ_B

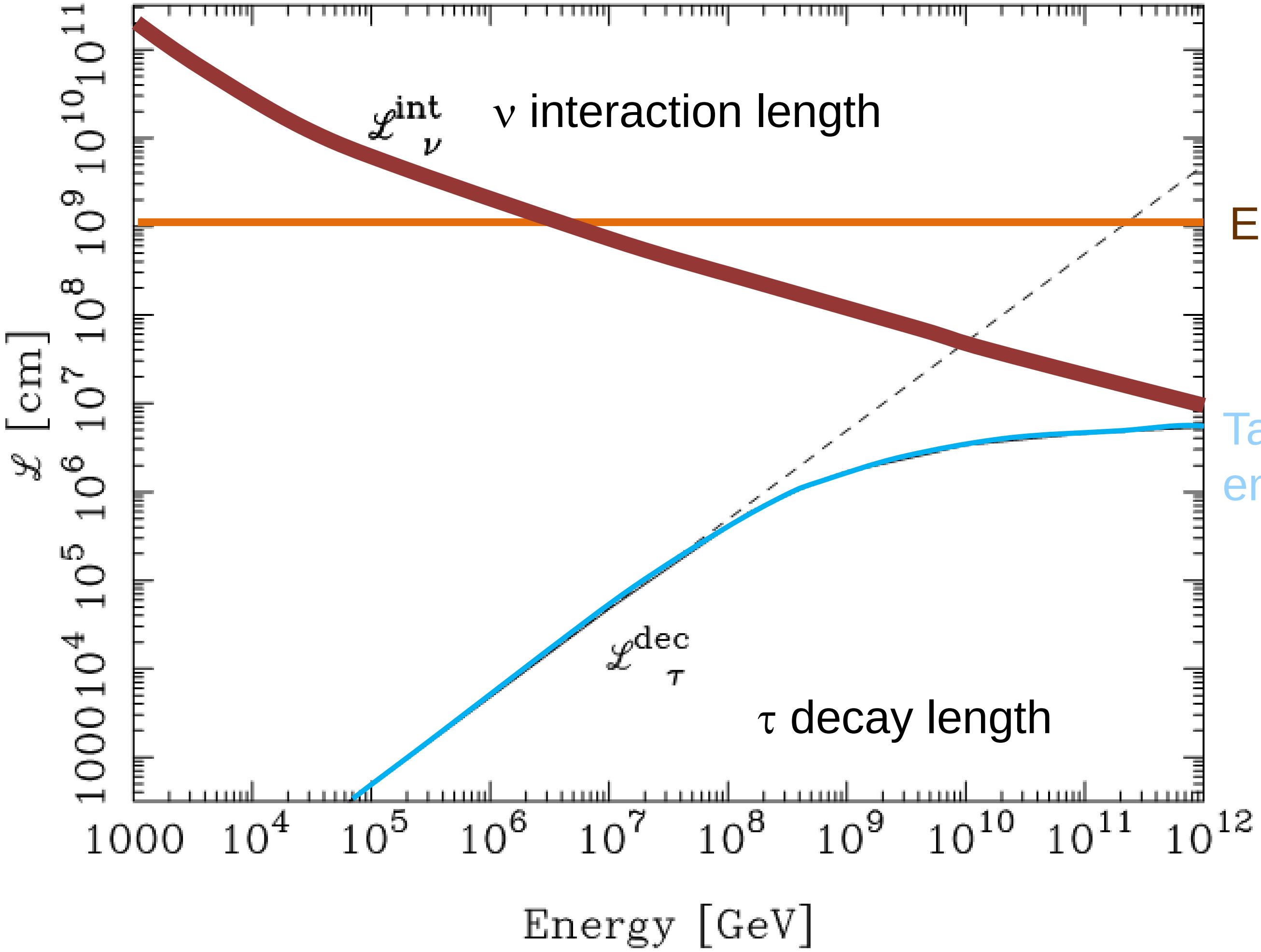
$$L_A = 1 / (\rho_B \, \sigma_{A \to B})$$

example: σ_ν (1 TeV) = 10^{-39} m^2, $\rho = 0.4/cm^3$ → L = 2.5×10^{22} Ly

→ larger than size of universe …

- **Blessing and curse of neutrino astronomy:**
  - neutrinos pass by almost everything … also by the detector

ν interaction length in Earth



ν interaction length

Earth diameter

Tau with elm. energy loss

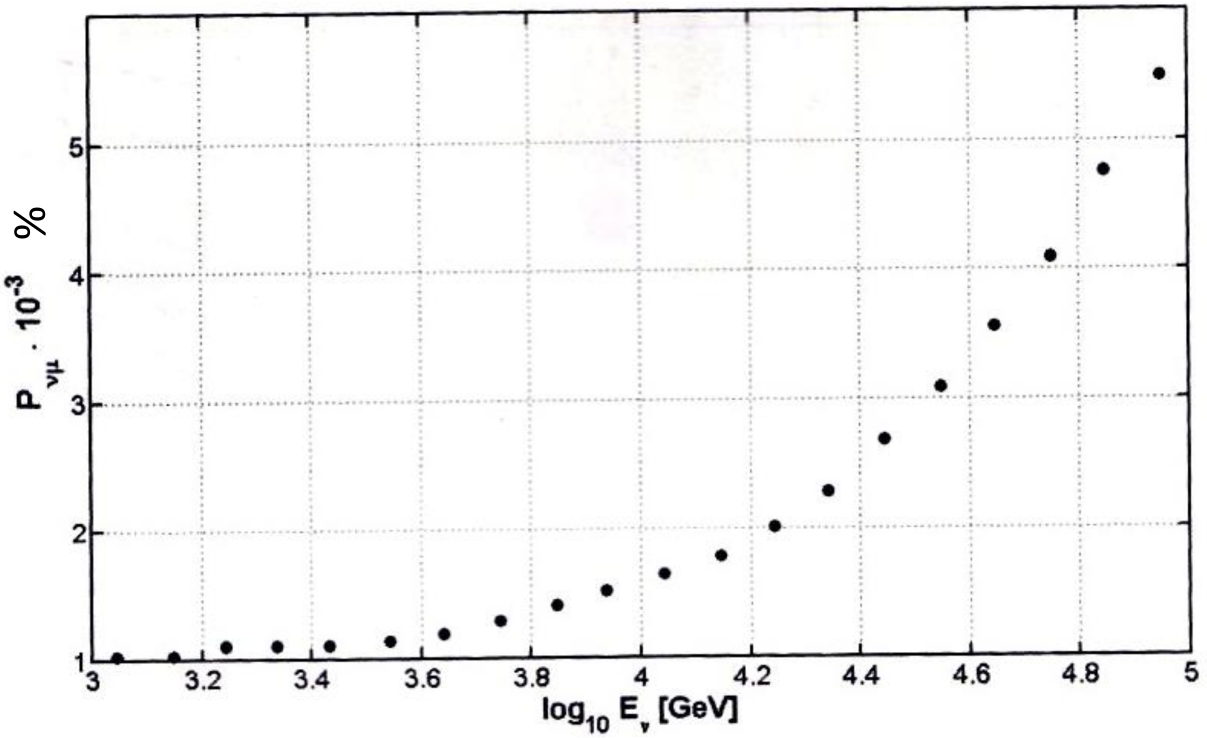
τ decay length

Interesting role of τ neutrinos: regeneration $\nu_\tau \to \tau \to \nu_\tau \to \tau$ ….

Probability to convert ν into μ

$$P_{\nu\mu} = N_A \int_{E_\mu^{\min}}^{E_\nu} dE_\mu \frac{d\sigma}{dE_\mu} R(E_\mu)$$

$R_{E\mu}$: average muon range
E^{min}: minimal detectable muon energy



$P_{\nu\mu} \sim 1.3 \times 10^{-6} E^{\alpha}$ [TeV]

$\alpha \sim 0.8$ for 1 TeV<E<1 PeV
$\alpha \sim 2.2$ für E<1 TeV

1 TeV: $P_{\nu\mu} \sim 1.3 \times 10^{-6}$
10 TeV: $P_{\nu\mu} \sim 8.2 \times 10^{-6}$
100 TeV: $P_{\nu\mu} \sim 52 \times 10^{-6}$

Some history

High energy neutrino astronomy

Moisei Markov (mid 1950‘s):

proposal for deep underground and underwater neutrino observatories

Markov warned the soviet leaders in 1947 about

„dangerous political-ideological moves that threaten to separate soviet science from the rest“

This was a brave (almost suicidal) move, as he and other scientists were charged of

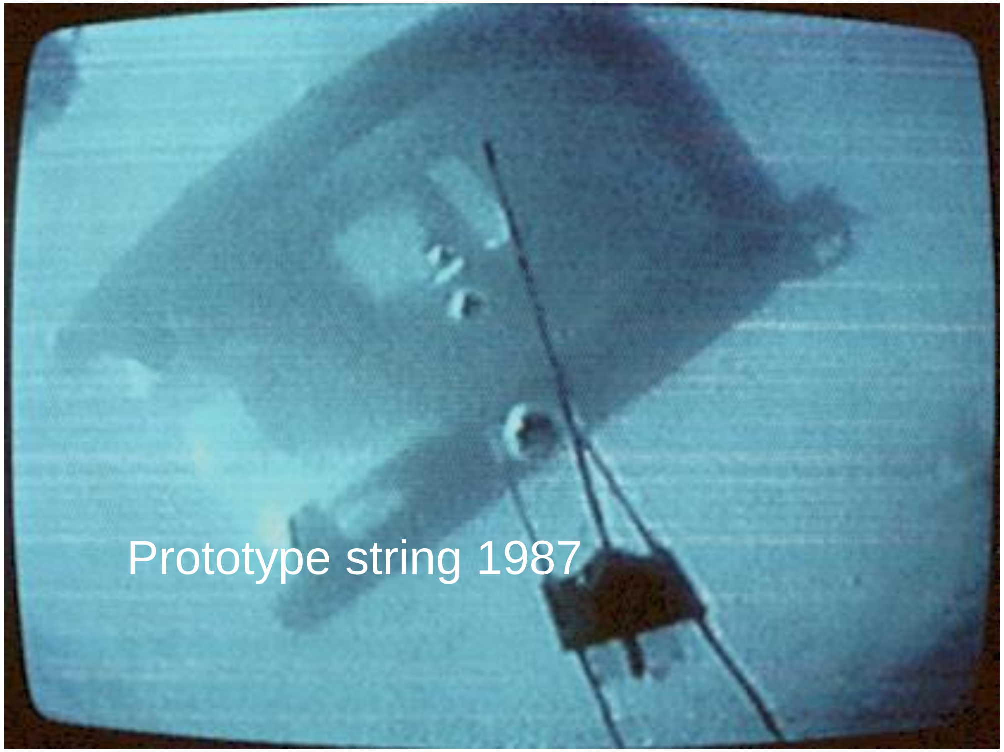
„uncritically receiving western physical theories and propagandizing them in our country“

Stalin, however, „chose the atomic bomb over ideology“

→ *which saved their lives …*

„We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation“ Proc. 1960, ICHEP, Rochester, p. 578

Dumand



Prototype string 1987

1993/94 deployment failed due to leak in penetrator: project (256 PMTs) abandoned

junction box at 4800 m depth sea floor

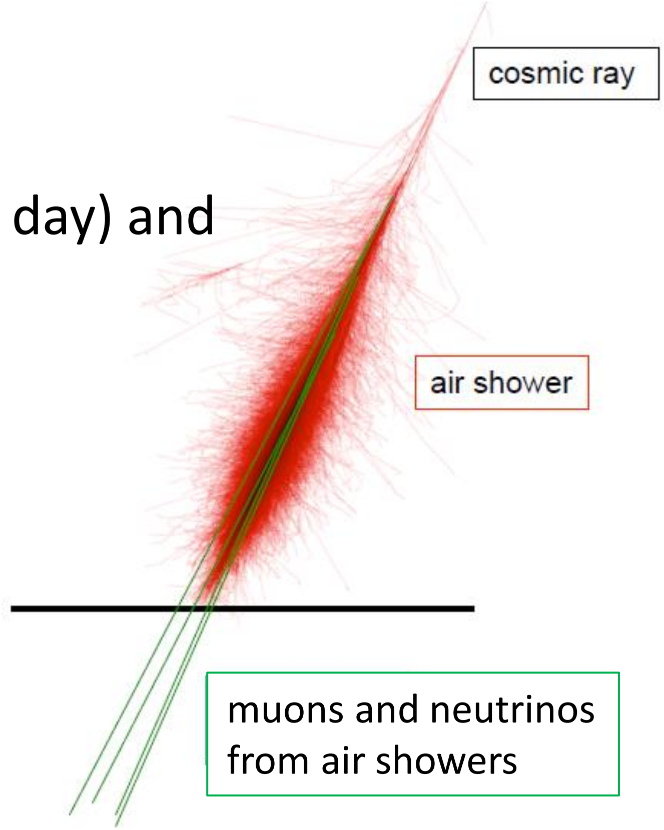
→ Lake Baikal, AMANDA, Antares IceCube, Km3NeT …

Main Goals (of IceCube)

Measure fluxes of

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

at higher energies & with better statistics than ,
previous experiments

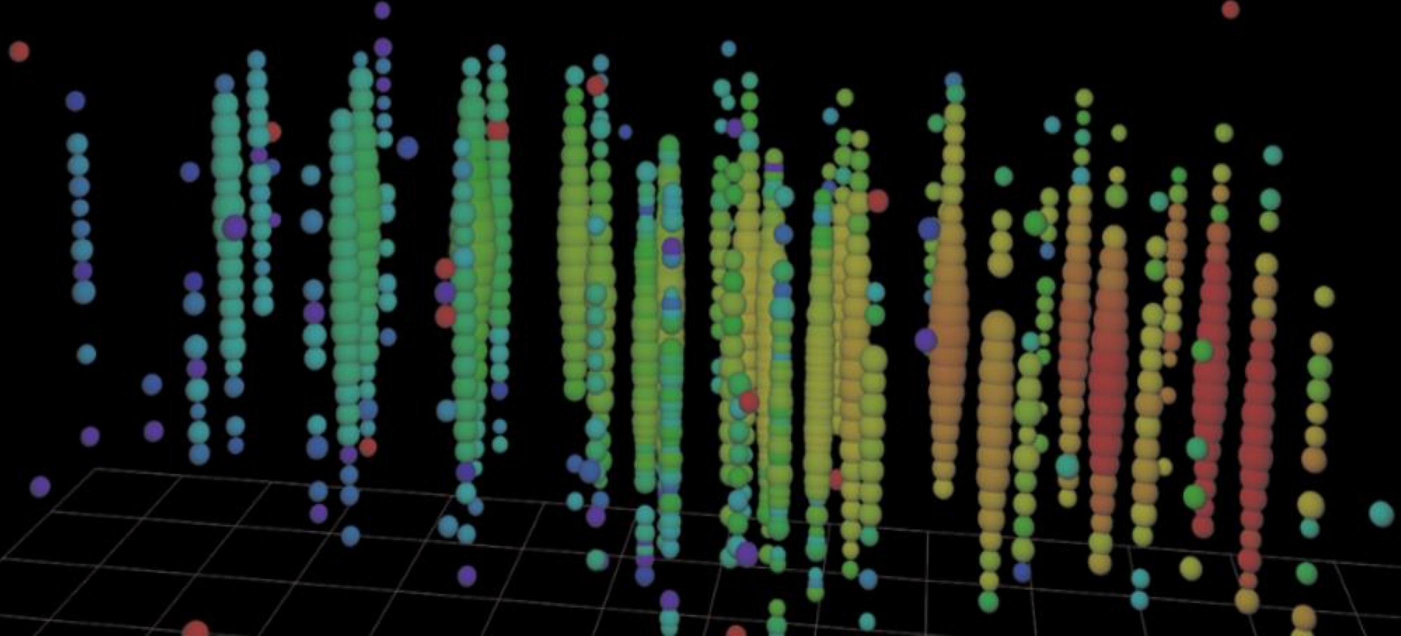


Any deviations from what is expected is new

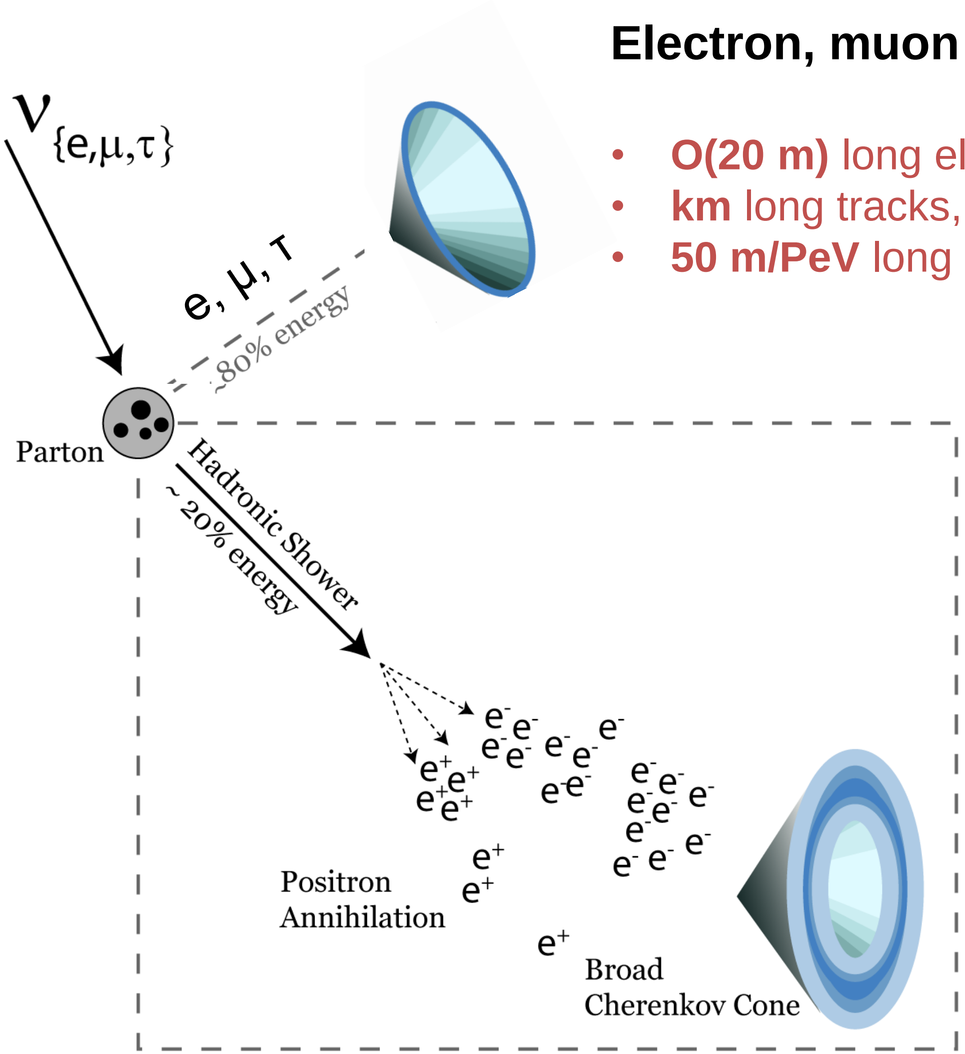
- neutrino physics or
- new astrophysics

Realistic: Understand more about origin, composition and cosmic ray interactions
Dream: Dark matter, new, rare particle interactions, galactic supernovae, etc.

Detection principle



What happens in the detector?



Electron, muon or tauon

- **O(20 m)** long electron showers (except for highest energies)
- **km** long tracks, narrow Cherenkov cone for muons,
- **50 m/PeV** long faint tau tracks, as Bremsstrahlung ~1/m

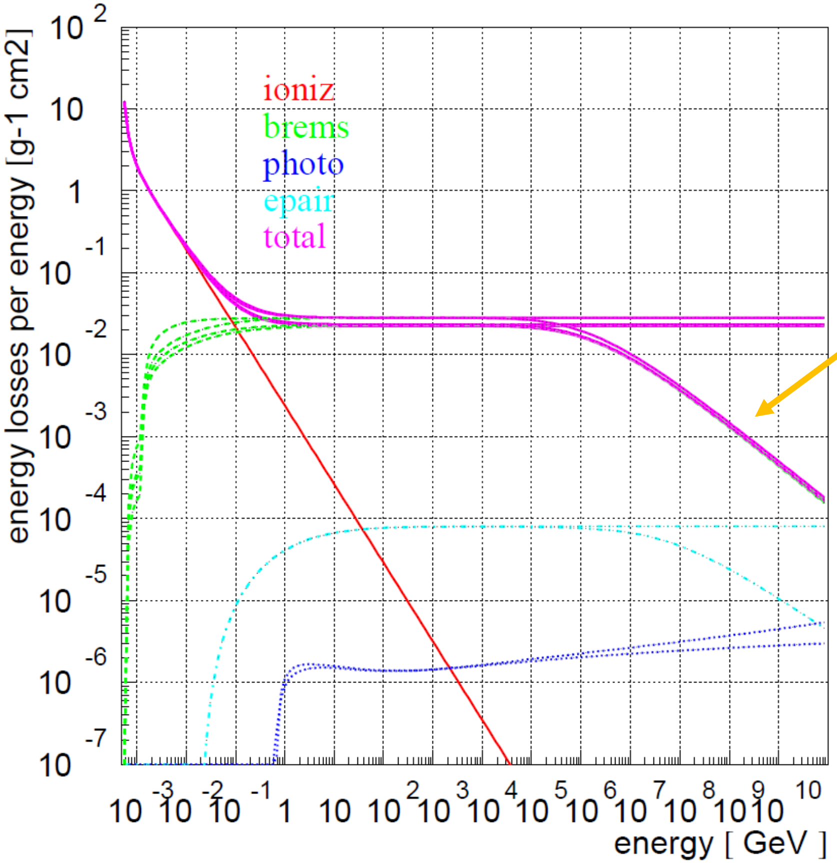
for neutral current interactions:

only hadronic cascade visible!

Let‘s look at the propagation of electrons, muons and tauons …

Electron interactions and propagation

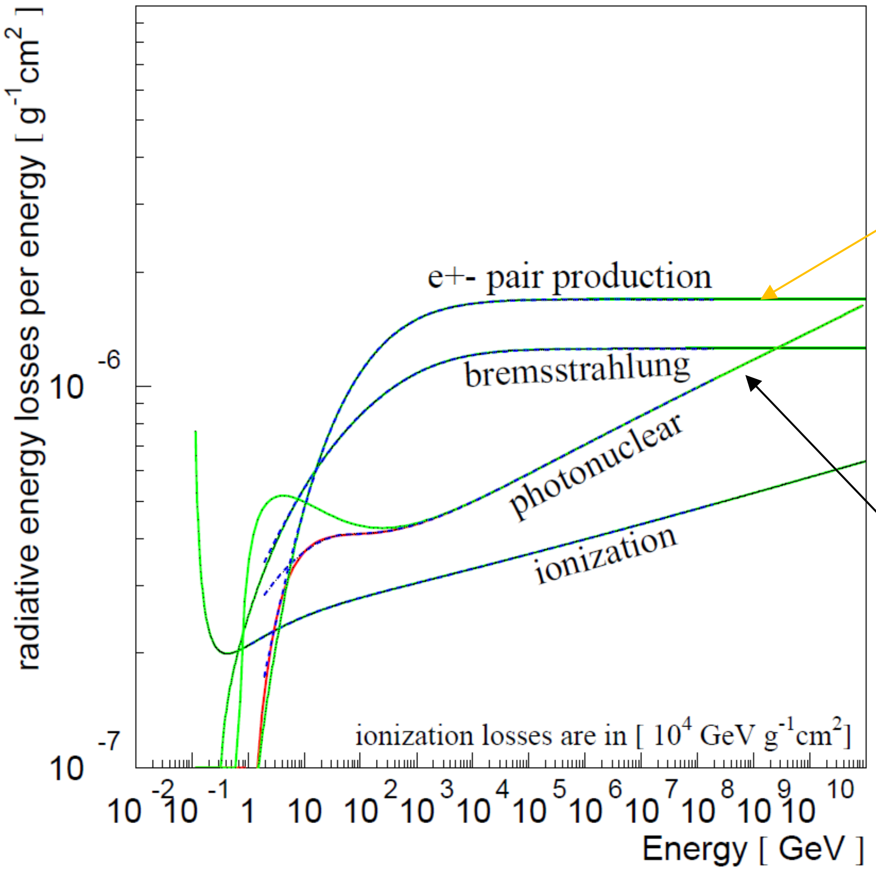
Processes leading to energy loss of electrons:

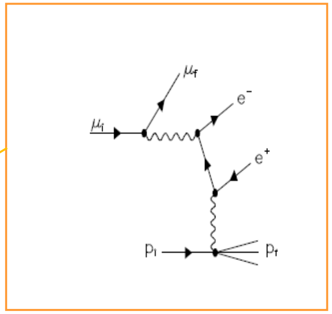


LPM suppression

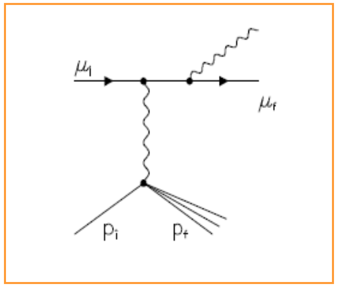
muon energy loss

1/E dE/dx

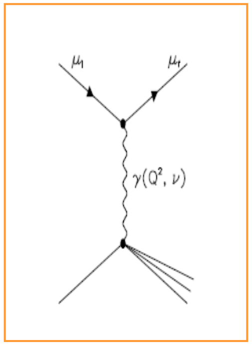




pair creation
dominant!



bremsstrahlung

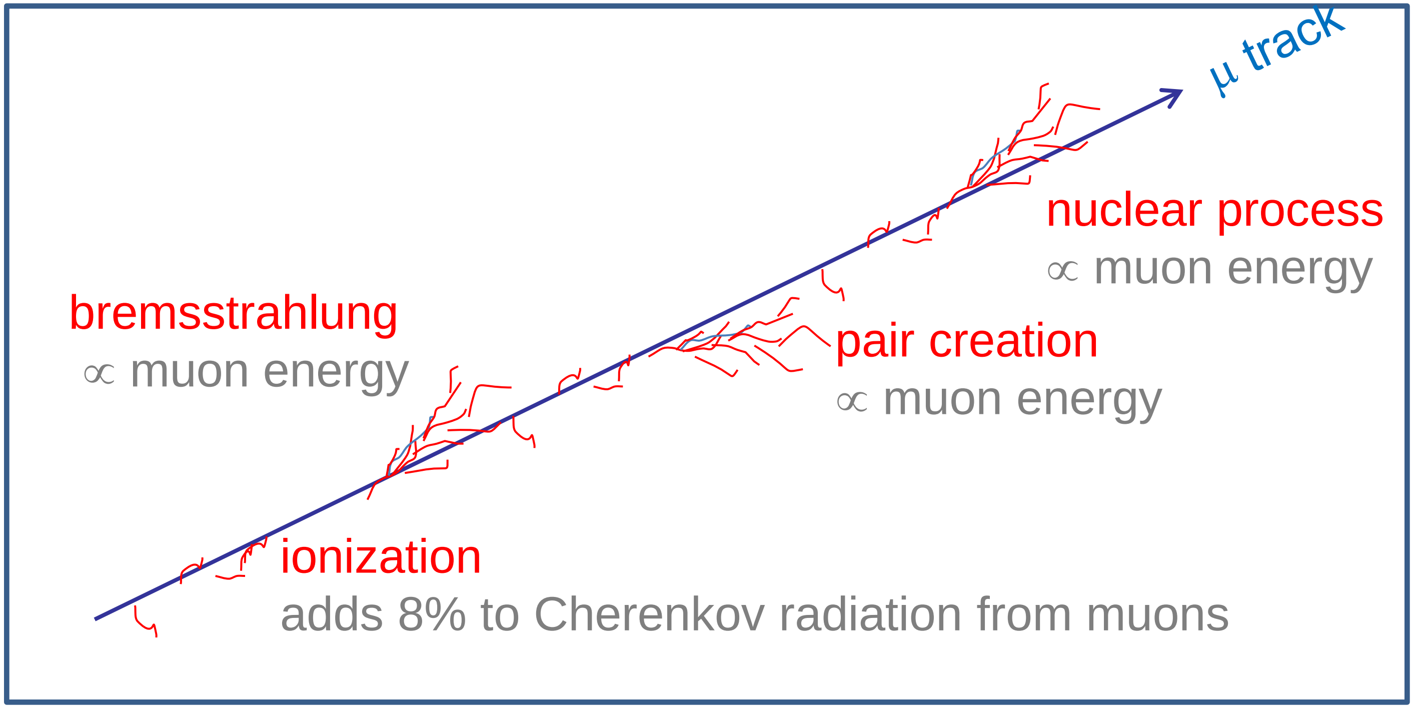


photonuclear

… effect on Cherenkov radiation

Number of Cherenkov photons: $$\frac{dN_\gamma}{d\lambda dx} = \frac{2\pi\alpha^2}{\lambda^2}\left(1-\frac{1}{\beta^2 n_p{}^2}\right) \int_{300\,nm}^{600\,nm} \approx 335/\mathrm{cm}$$

Cherenkov angle: $$\cos\theta_C = \frac{1}{\beta \cdot n_p}$$



μ track

nuclear process

∝ muon energy

pair creation

∝ muon energy

bremsstrahlung

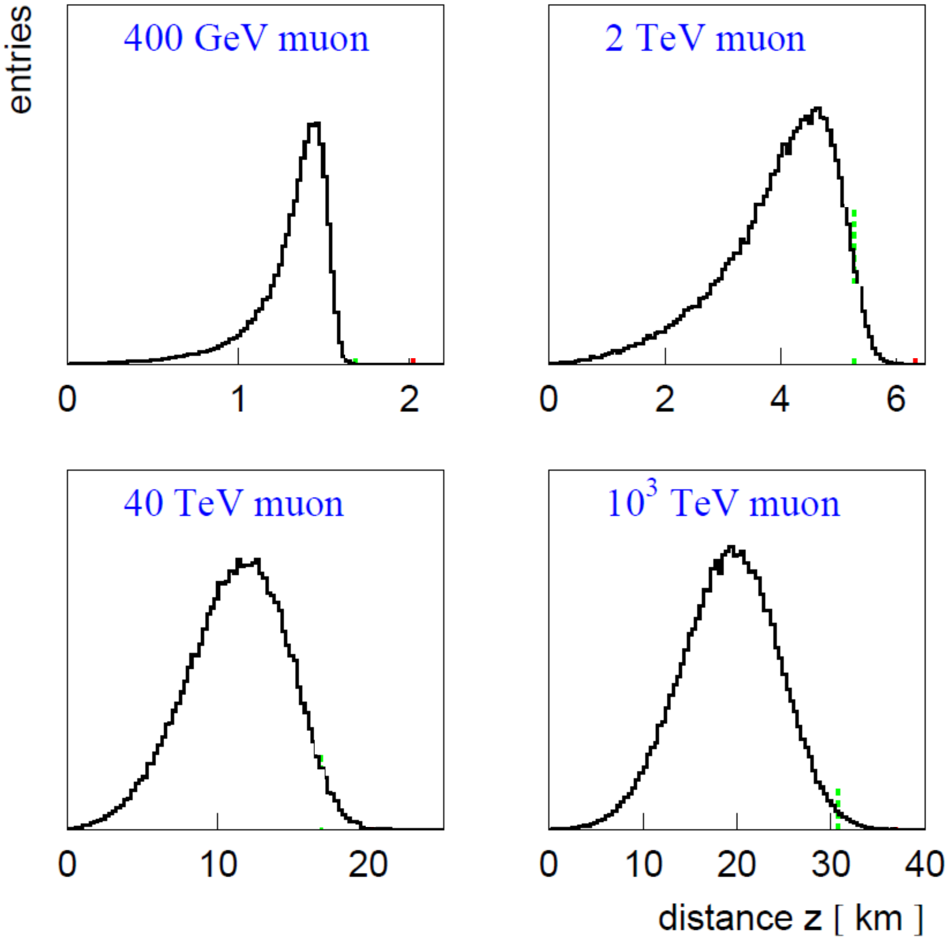
∝ muon energy

ionization

adds 8% to Cherenkov radiation from muons

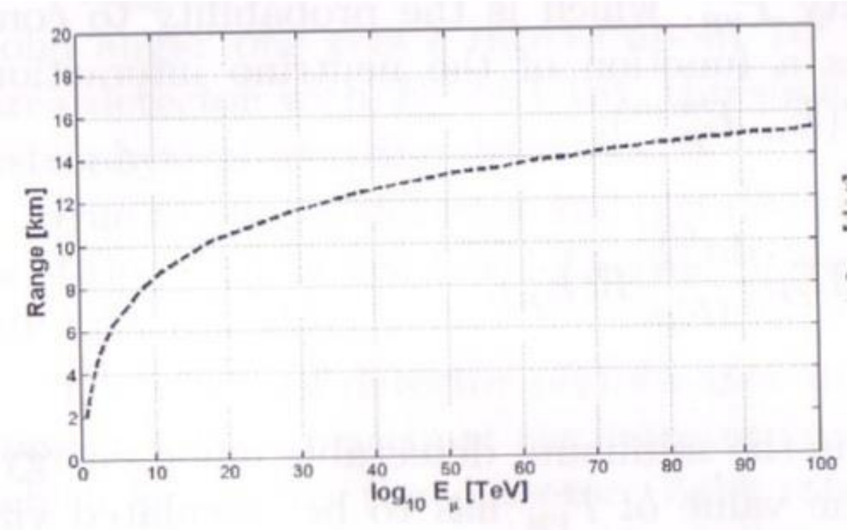
While muon Cherenkov radiation is at fixed angle, widening by showers/ionization

muon range

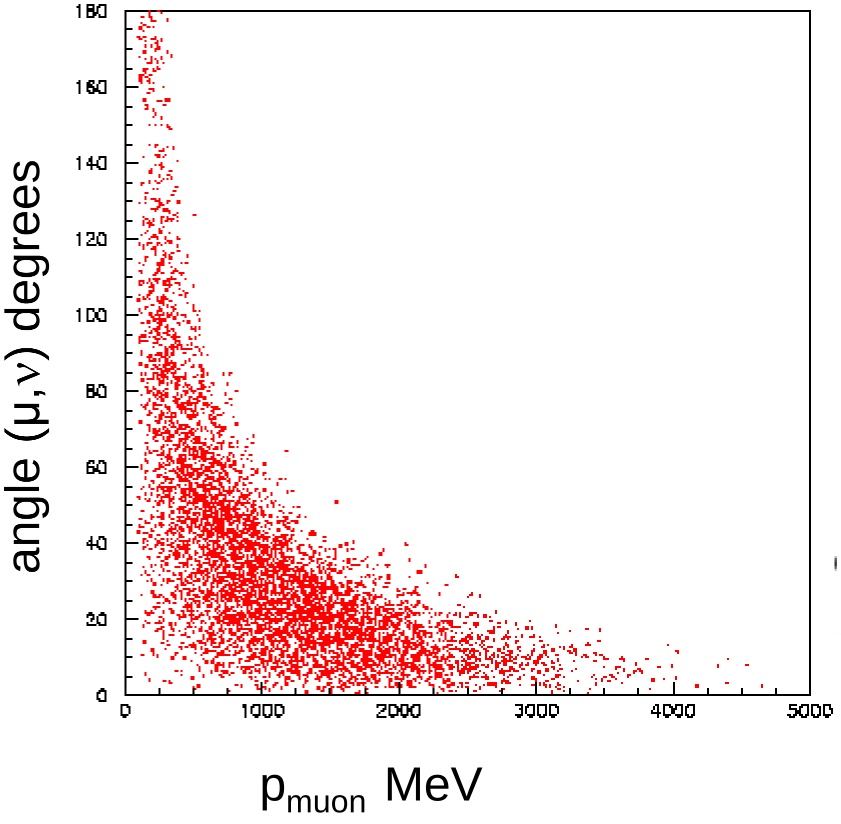


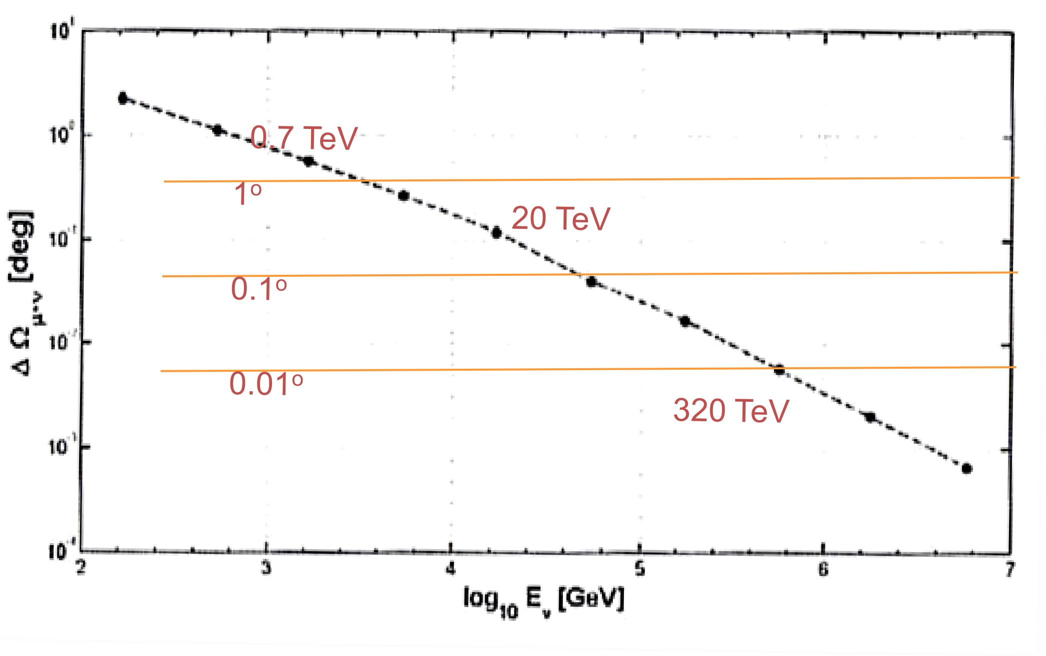
average range R in ice:

$$R = \int_{E_\mu^{\min}}^{E_\mu} \frac{1}{\langle dE/dX \rangle} dE = -\int_{E_\mu^{\min}}^{E_\mu} \frac{1}{a + b \cdot E} = \frac{1}{b} \log \frac{a/b + E_\mu}{a/b + E_\mu^{\min}} \; .$$



muon – neutrino angle



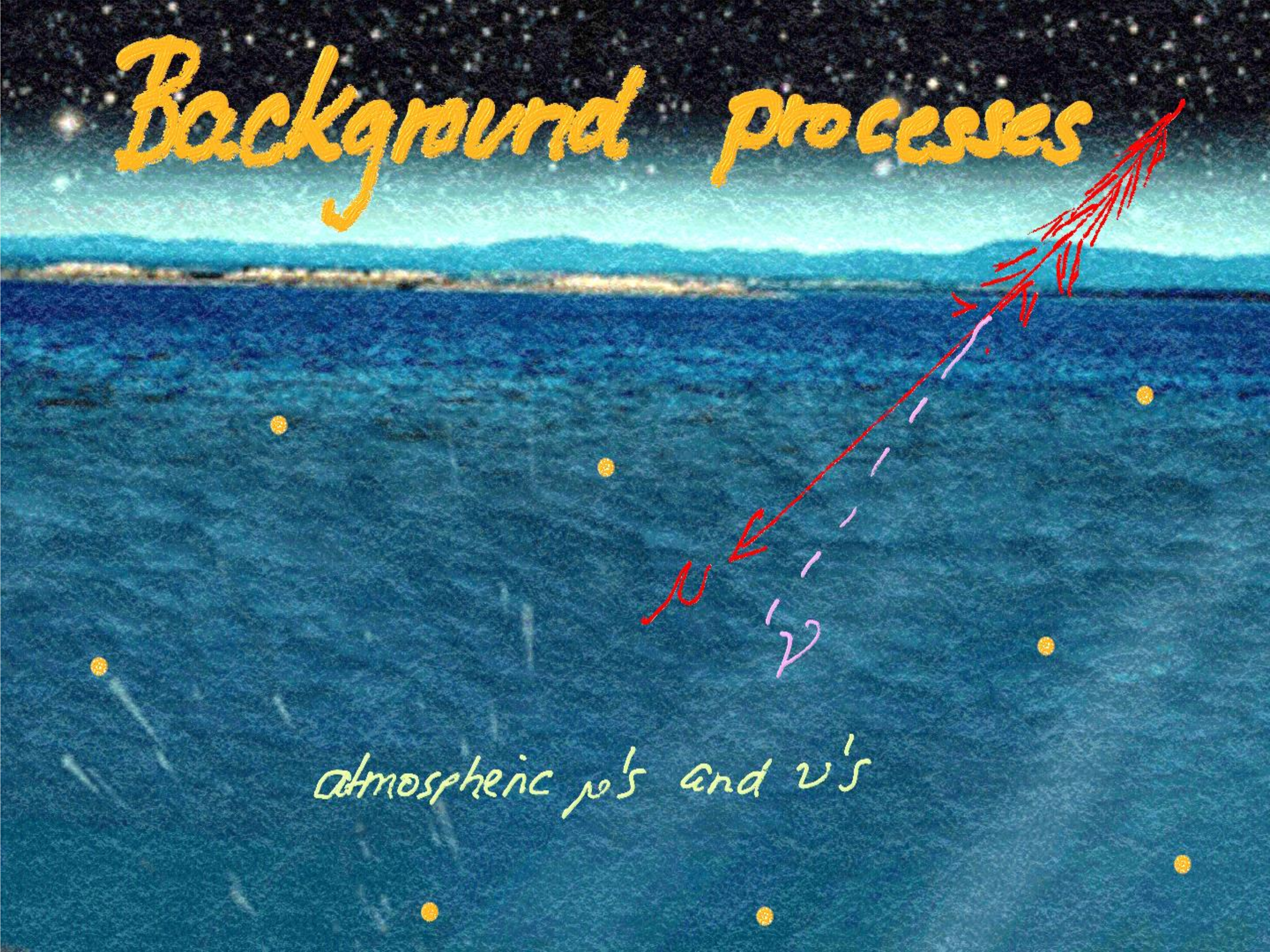


average for high energies:

angle= $0.7^{o} / E[\mathrm{TeV}]^{0.6}$

Sub-degree directional resolution makes sense only for E_{ν} > TeV

Background processes

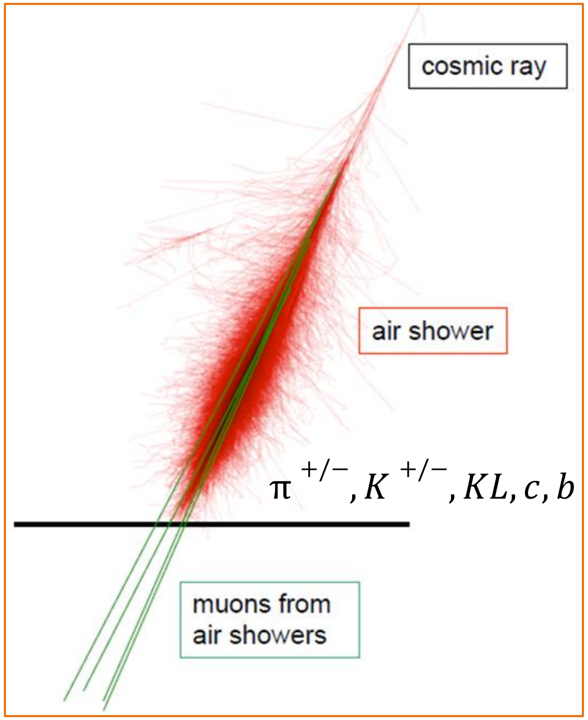


atmospheric μ's and ν's

Atmospheric ν: π and K decays

lightest charged mesons only decay via weak interactions:

$\pi^+ = |ud\rangle \rightarrow \mu^+ + \nu_\mu$ + cc (~100%)
$K^+ = |us\rangle \rightarrow \mu^+ + \nu_\mu$ + cc (63%)



Kinematics: E_ν(from π) < 0.25 x E_π
E_ν(from K) < 0.78 x E_K

Above ~ 100 GeV, interaction length of π and K in atmosphere shorter than their decay length …

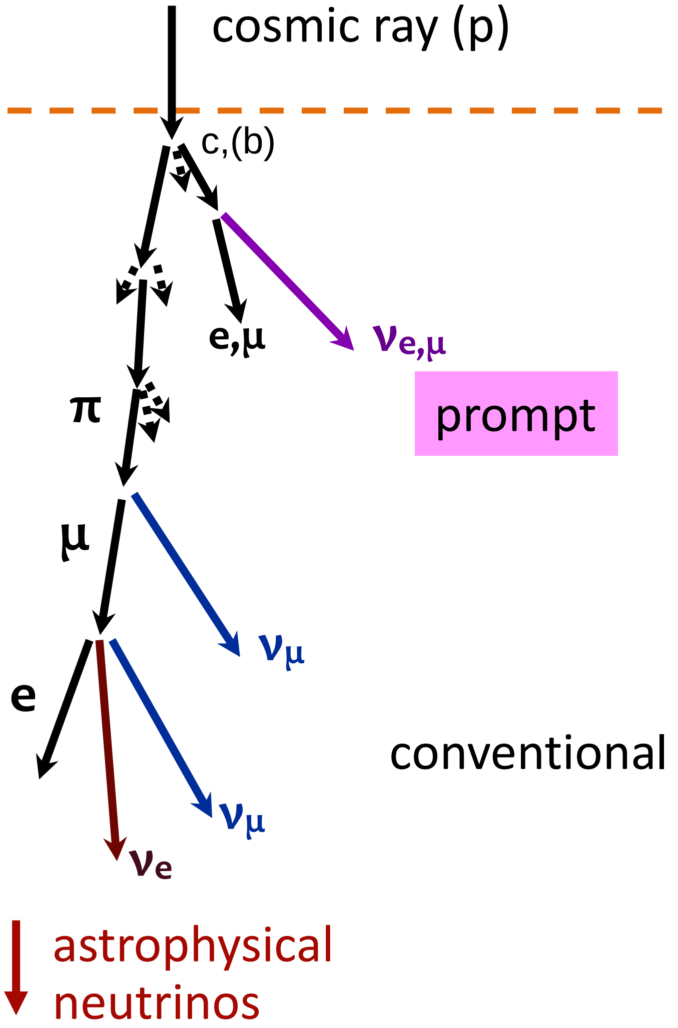
→ ν energy spectrum dN/dE ~ $E^{-3.7}$

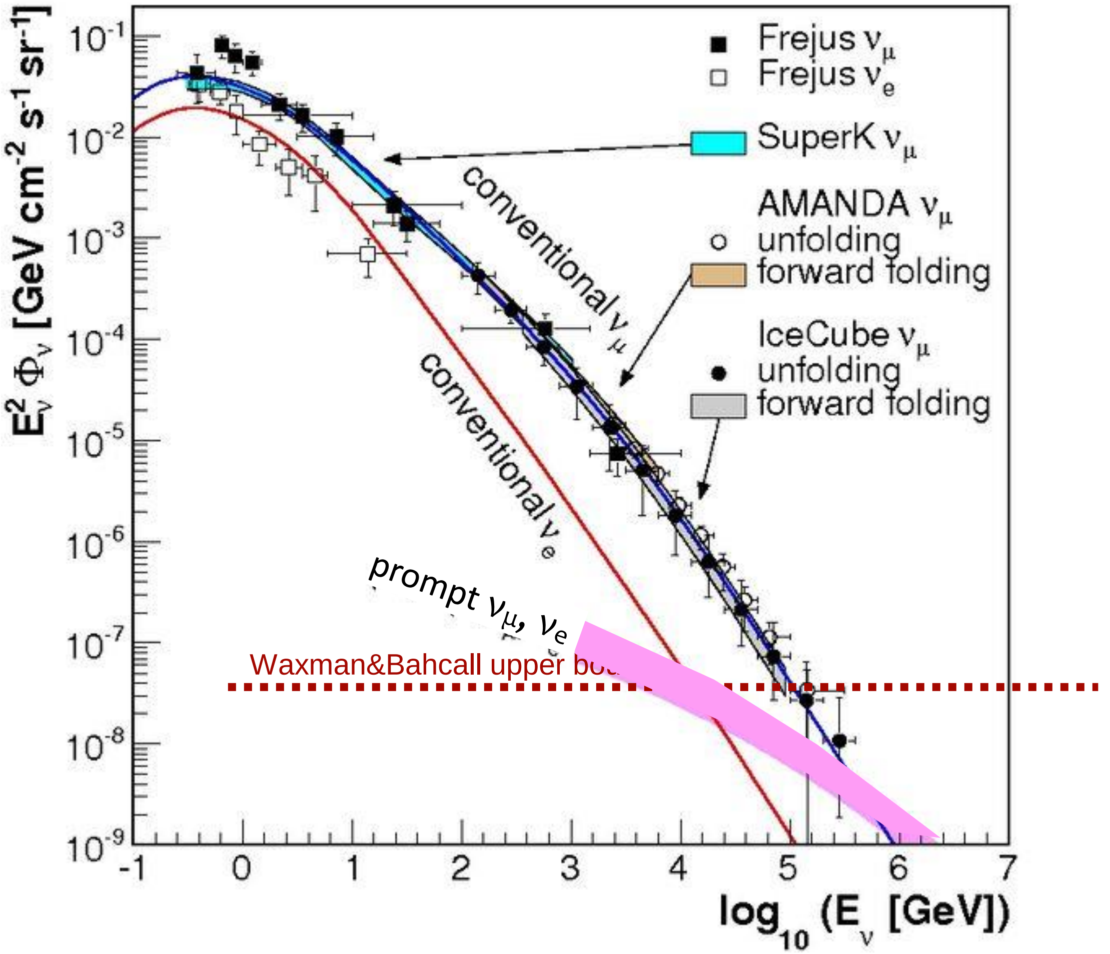
Muons co-produced with neutrinos may decay and produce further neutrinos:

$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$ and $\mu^- \rightarrow e^- + \nu_\mu + \nu_e$

at ~ 1TeV the ν_e / ν_μ flux < 0.1, ν_e flux actually dominated by K^0_L decays

Neutrino fluxes

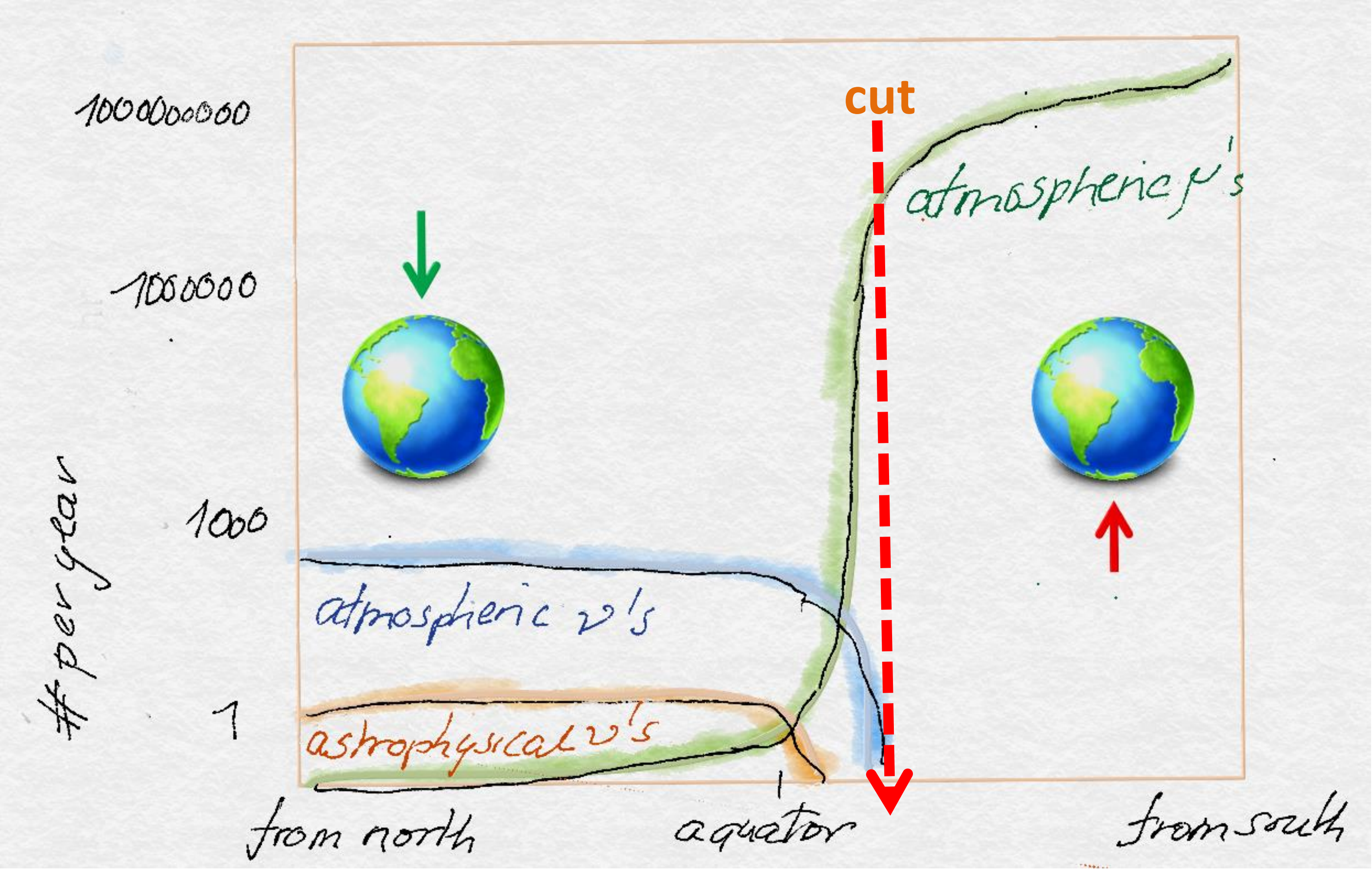




… less background from atmospheric electron neutrinos !!

The Earth as a shield

40 billion background muons per year …

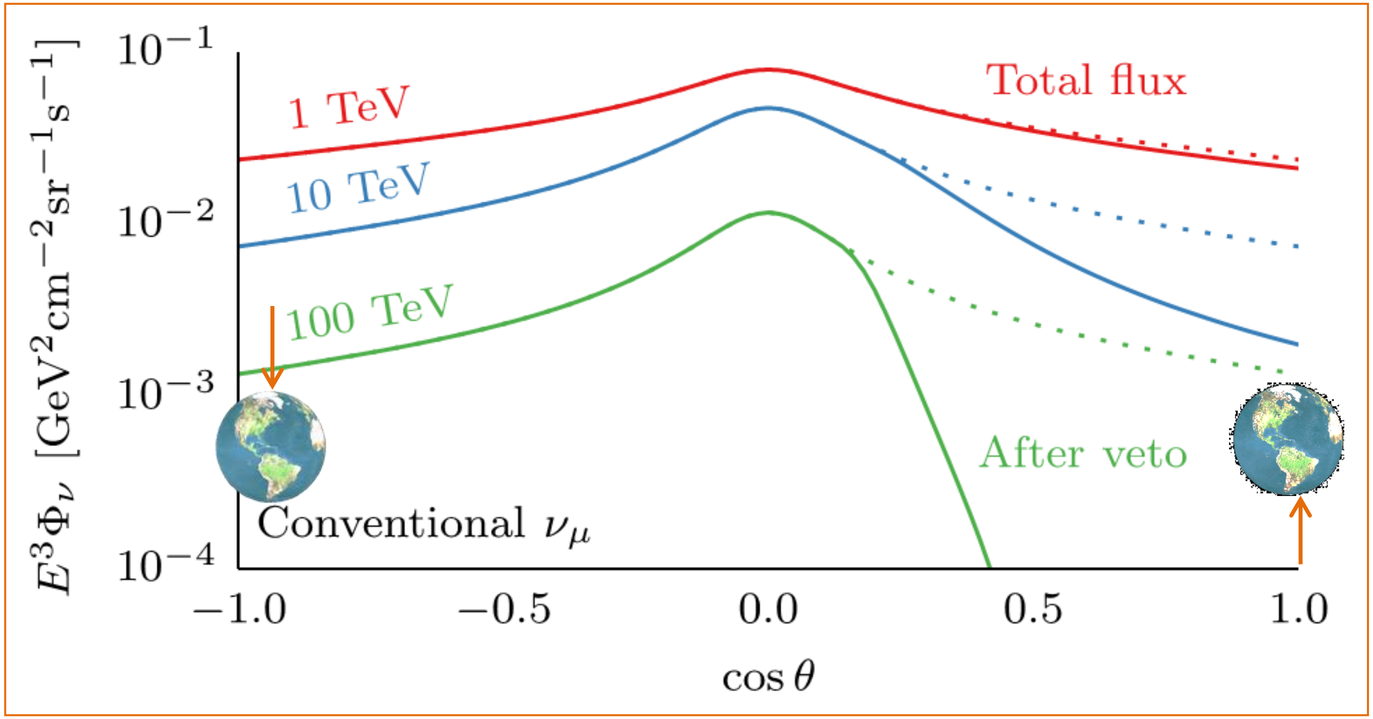


Stupid to see only half of the sky … can one do better?

Can one reduce atmospheric ν's?

Phys. Rev. D.79(4):043009, 2009, Phys. Rev. D 90, 023009, 2014.

atmospheric neutrinos from pion and kaon decays accompanied by muon
Downgoing atmospheric neutrinos can be partly vetoed!!!!



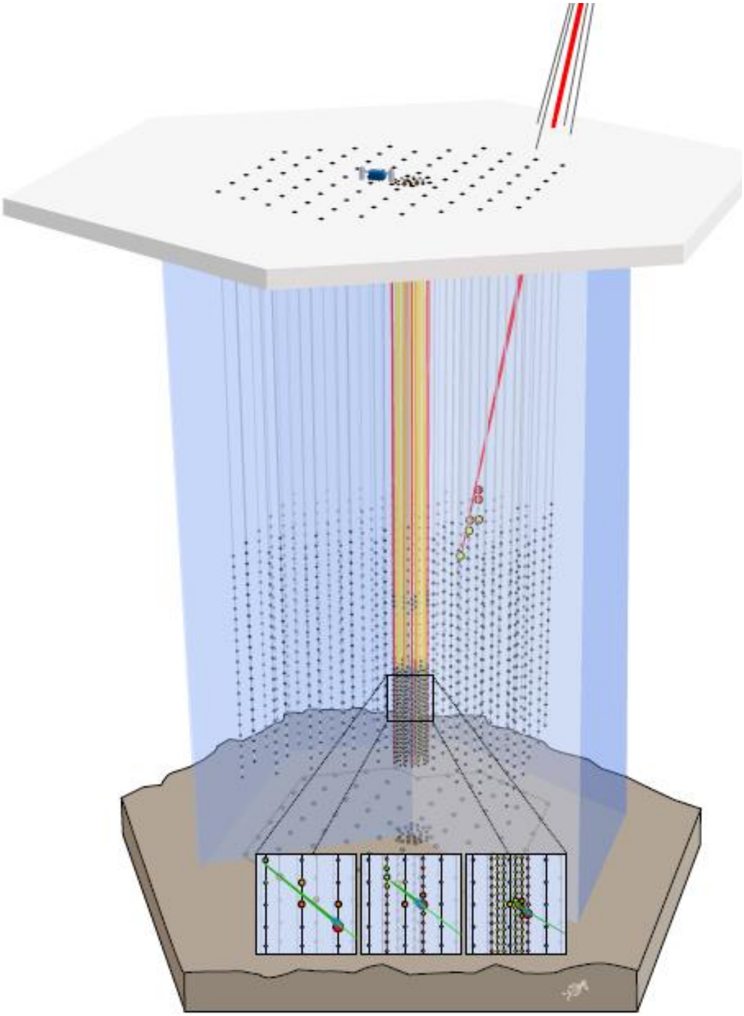
can veto muon with surface detector or in detector boundary

The IceCube observatory

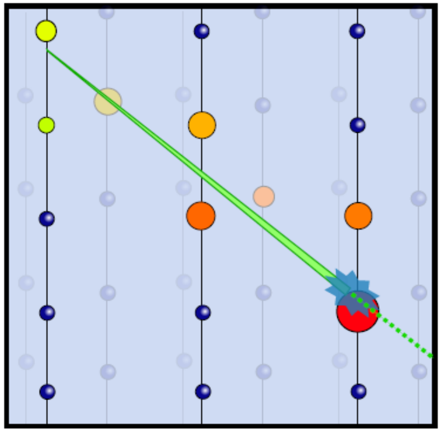
Location: Amundsen-Scott Station
@ geographic South Pole

…data taking with complete detector from May 2011

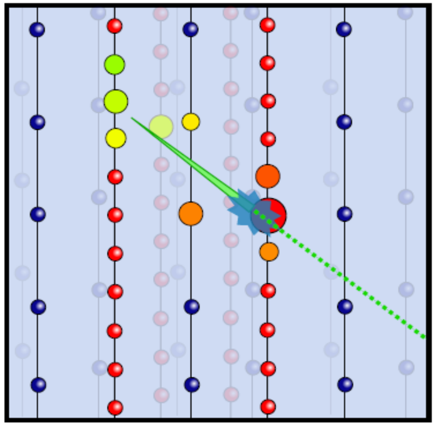
IceCube detector



Plot includes envisaged „Pingu“ low energy extension“



IceCube only



IceCube w/ DeepCore
>few 10 GeV

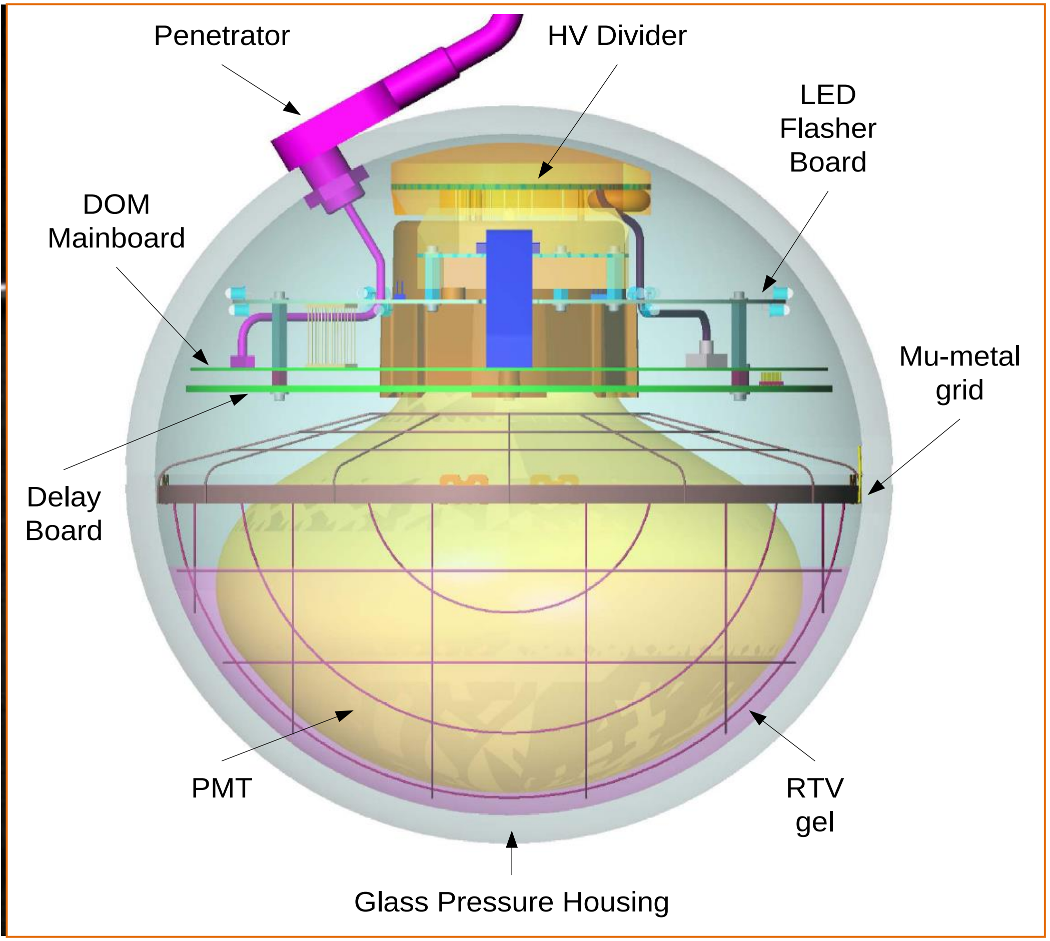
5160 sensors (optical modules) on 86 strings

→ 1 km^3 sensitive volume

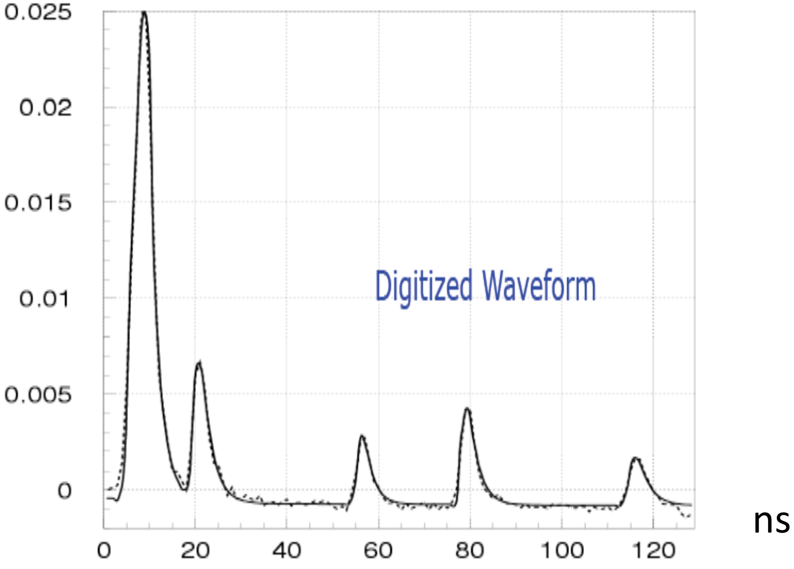
~98% of all sensors working

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

The IceCube Digital Optical Module

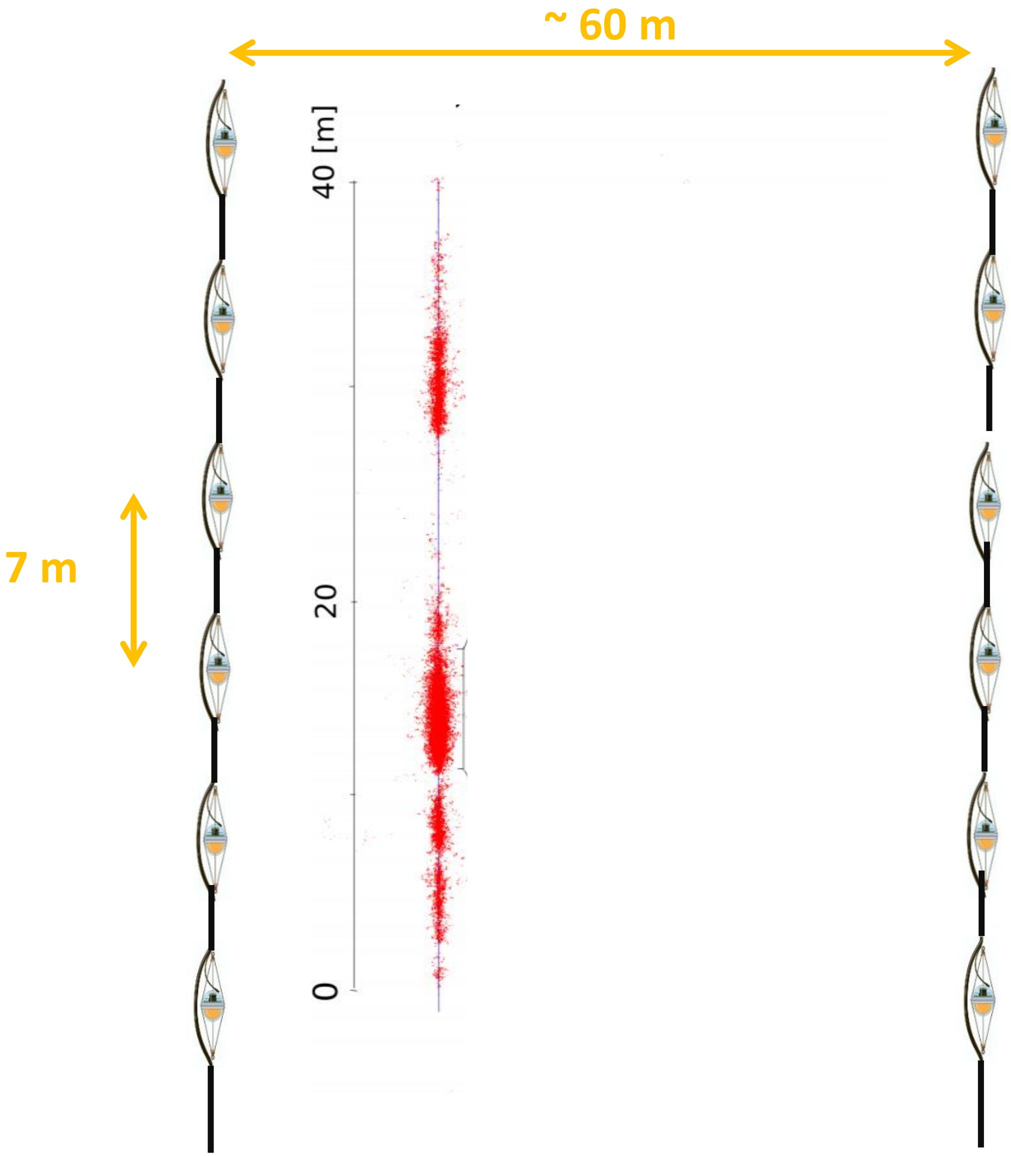


- On board HV, 330 MHz digitization, and rate measurements (1.6ms bins)
- Low power: 3.75 W
- Low noise: ~ 540 Hz
- Fast timing: betw. DOMs: $\Delta t < 5$ ns
- Large dynamic range:
  - 10^3 pe / 10 ns
  - 10^4 pe / 1 µs

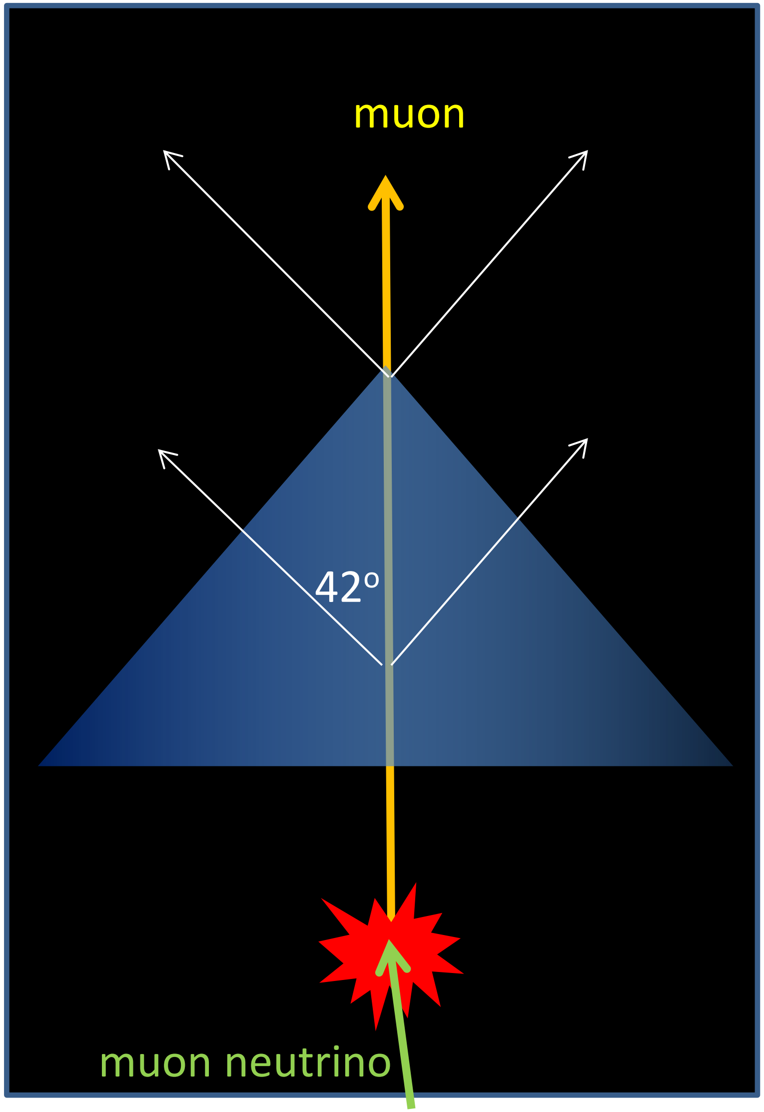


Coarse lattice of DOMs to maximize size
→ essentially no redundance

Coarse detectors to maximize volume



e.g. Antares, DeepCore



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)

Stockholm University
Uppsala Universitet

University of Alberta

University of Oxford

Deutsches Elektronen-Synchrotron
Humboldt Universität
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität München
Universität Bonn
Universität Dortmund
Universität Mainz
Universität Wuppertal

Ecole Polytechnique
Fédérale de Lausanne
University of Geneva

Chiba University

Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls

Université Libre de Bruxelles
Université de Mons
University of Gent
Vrije Universiteit Brussel

University of the West Indies

University of Adelaide

University of Canterbury

International 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)
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)

new station operating at least until 2035

Table of content: Part 2

- Experimental challenges in IceCube
- Point Source searches
- Starting track searches
- Diffuse searches
- Summarizing the results
- The future

Make people trust we see astrophysical ν's

Experimental challenges

Inhomogeneous scattering and little reduncency

Scattering in the ice

Bubble hole column

Camera frozen into the ice

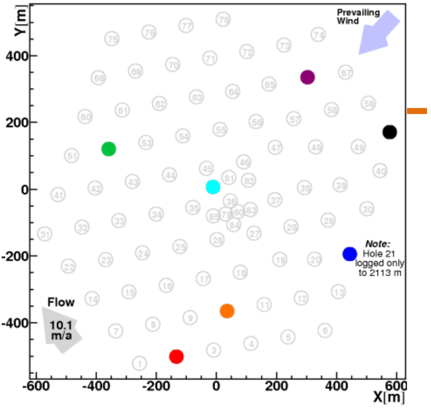
Crux (and fun) of natural media

- no access 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**

Contrary to particle and nuclear physics with > 50 years of experience and many standard tools, understanding is still needs to build up, methods progress…

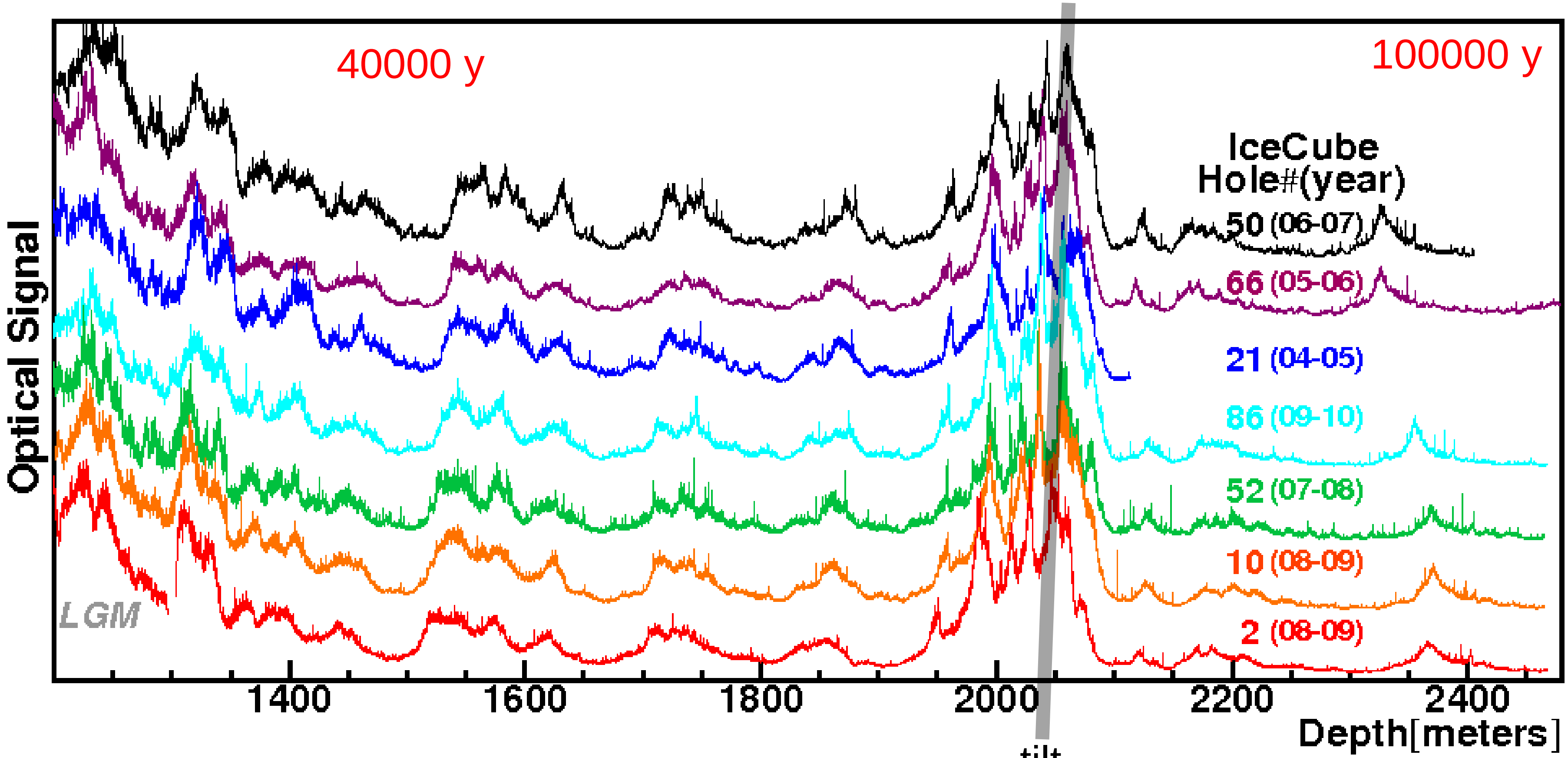
one example for illustration…

The crux of natural media



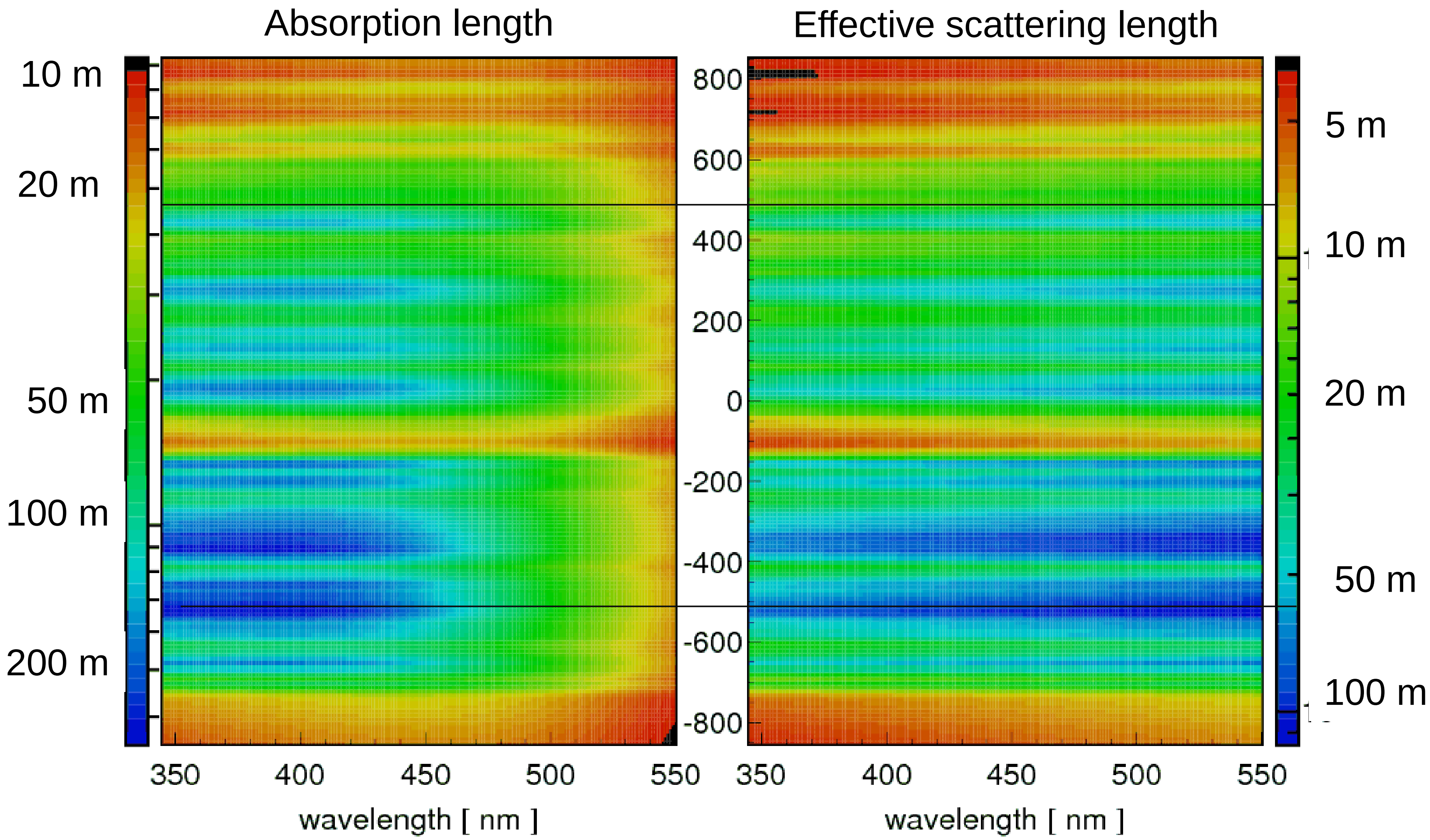
dust layers in the ice with slight tilt along line of prevailing wind

… similar all over Antarctica



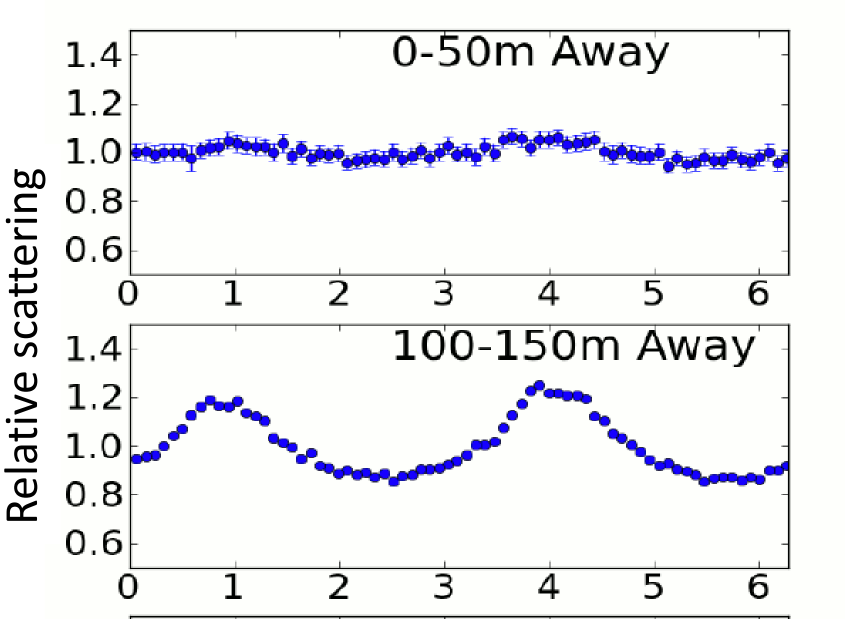
dust causes scattering **and** absorption

Scattering and absorption at Pole



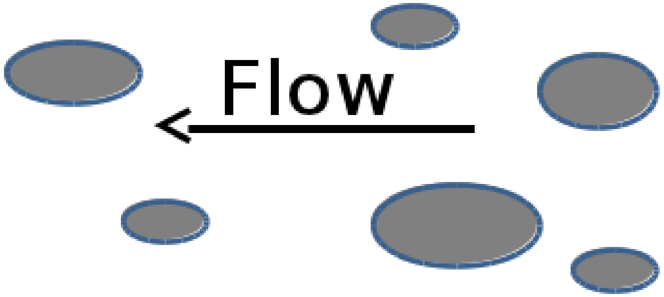
Ice extremely clear but not uniform in depth, wavelength dependent ….

Anisotropy of scattering



- Alignment of ice crystal grains and impurities intimately related

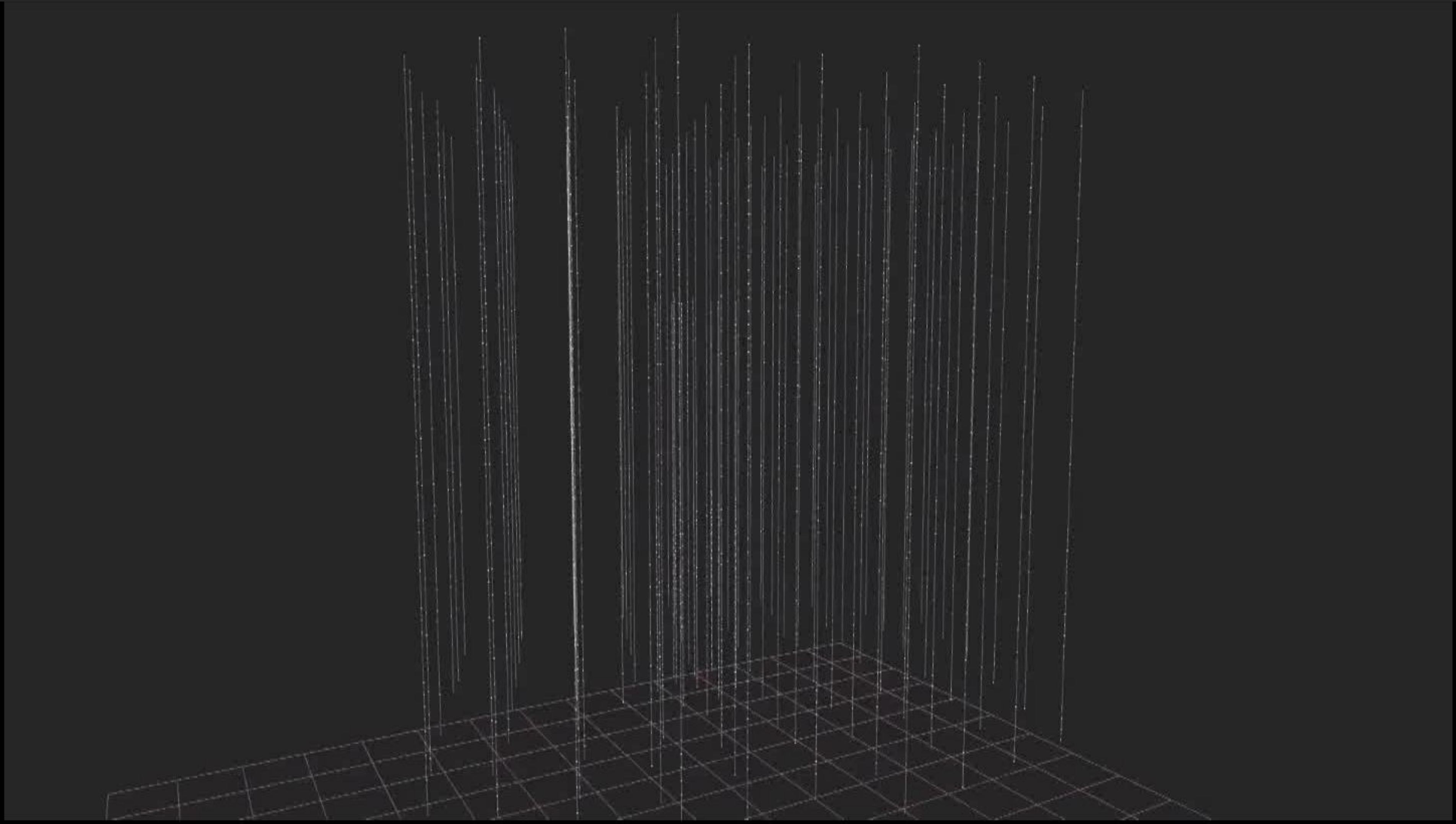
- Ice undergoes vertical compression and longitudinal externsion along flow



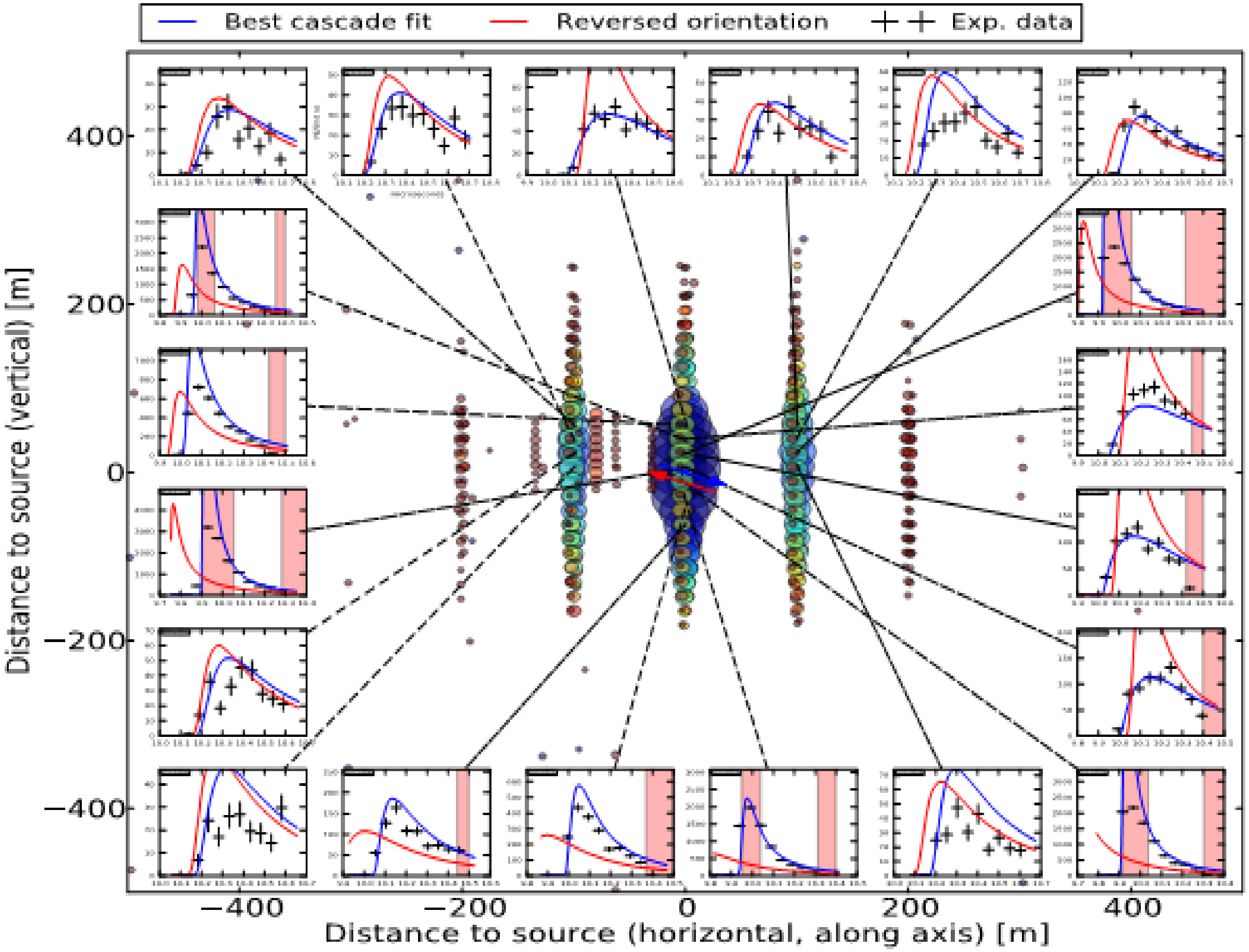
Important at larger distances … particularly for showers and $\upsilon_e / \upsilon_\tau$ distinction …

Cherenkov photons from electron

Cherenkov photons from muon



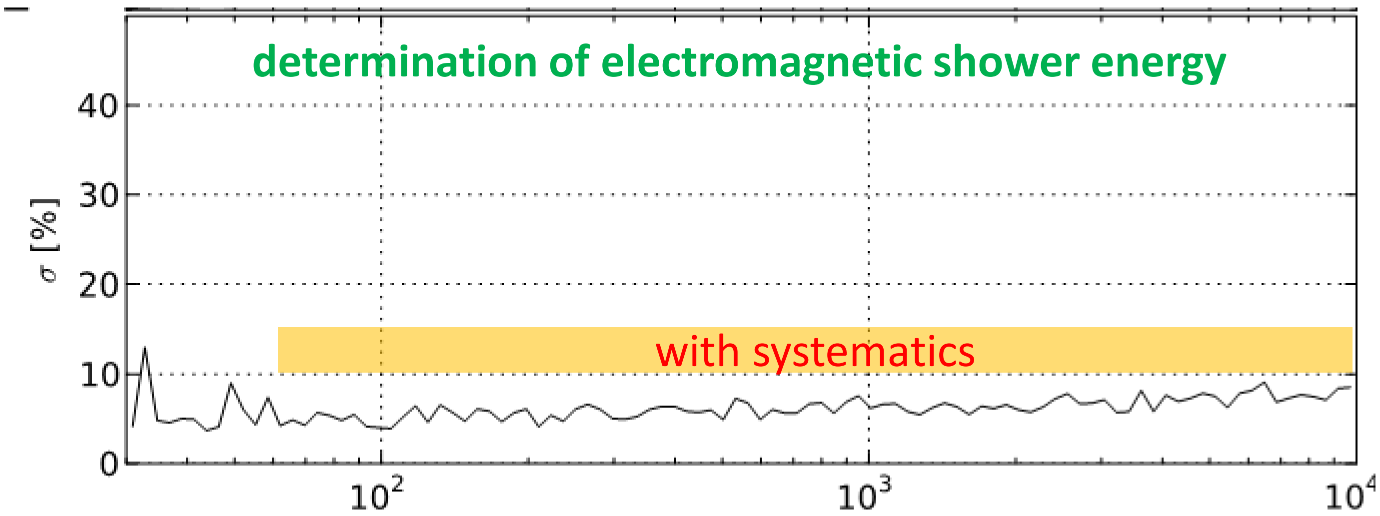
Directionality of showers

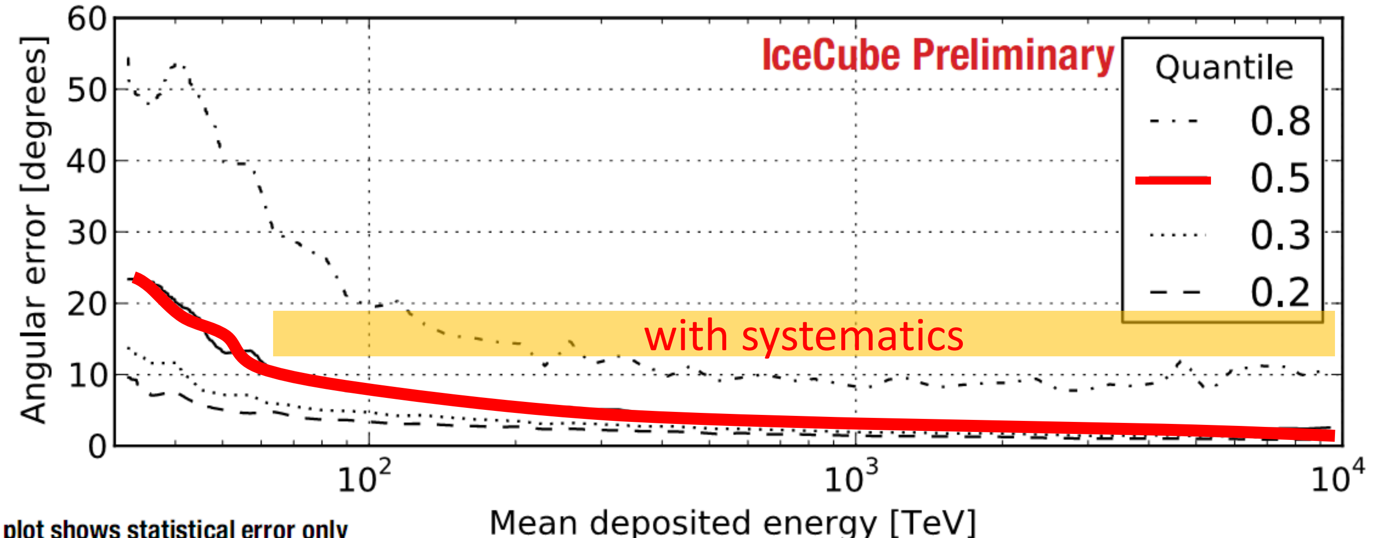


…. at high energies, angular resolutions of 10-15% achievable ….

Energy and direction uncertainties

Muon neutrino energy resolution ~ 0.35 log(E_ν/1 TeV) lousy for throughgoing tracks





plot shows statistical error only

Systematics:

hadronic energy from Interaction vertex etc

σ(E) ~ 10-15%

Knowledge of depth dependent ice Properties

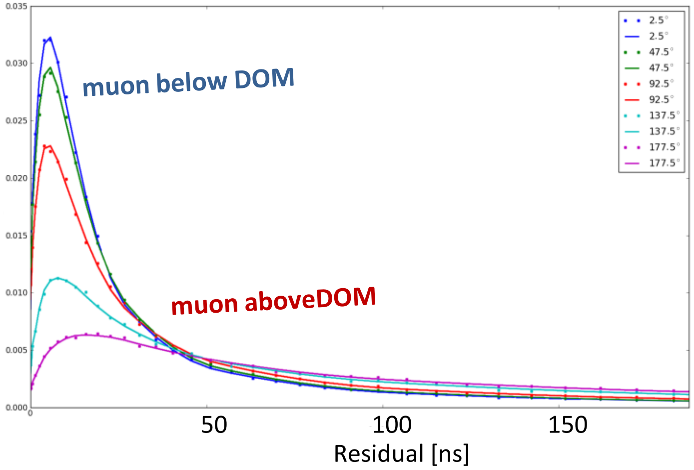
σ(ψ) ~ 10°-15°

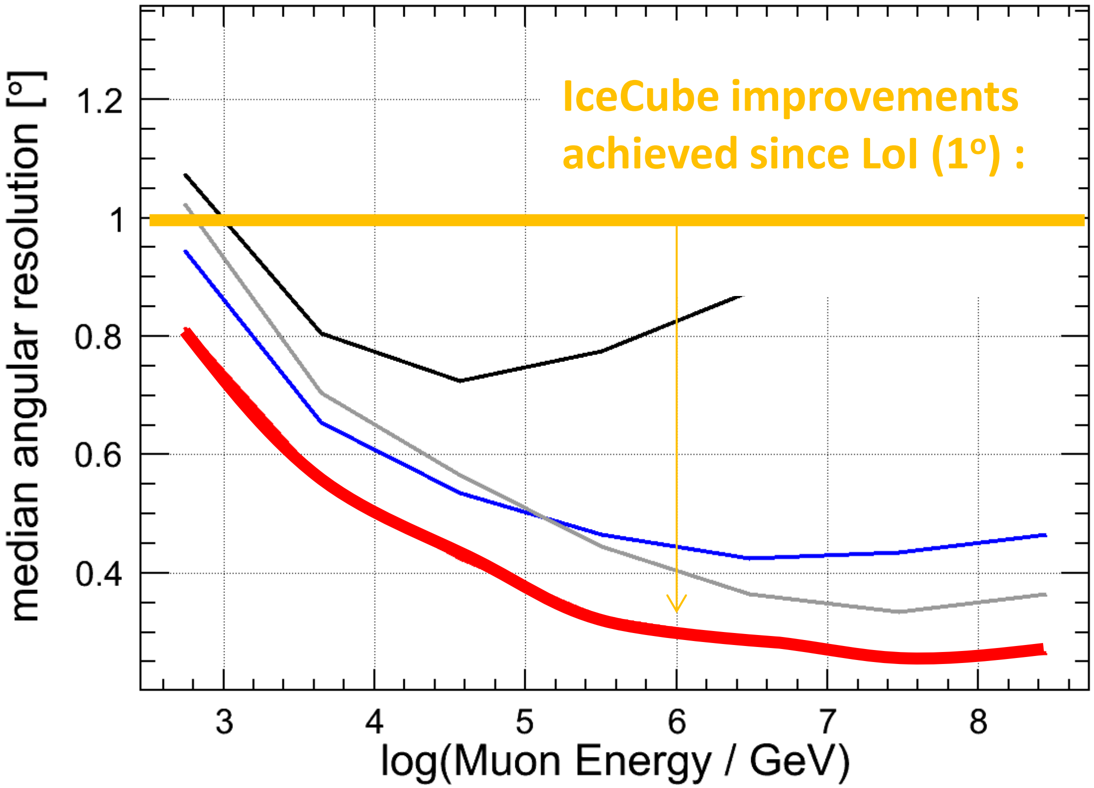
(depends on position)

track reconstruction

… photons delayed by depth and angle dependent scattering in ice layers

→ propagate photons using GPUs
→ store results in 2 billion tables
→ fit results with spline surface





IceCube improvements achieved since LoI (1°) :

IceCube: < 0.3° at high energies
(like running Antares)

Km3Net: < 0.1° at high energies
only phase 1 financed

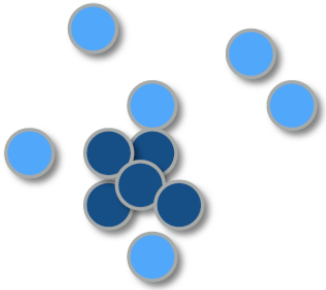
…further improvements possible

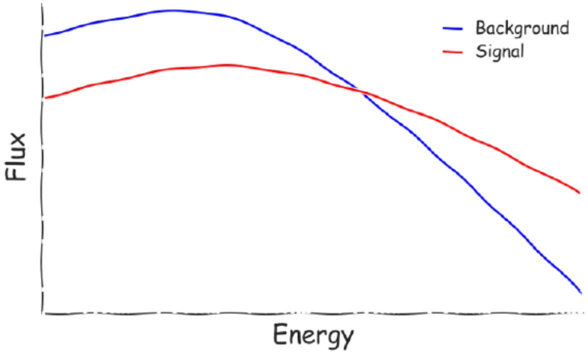
Point sources

Likelihood method

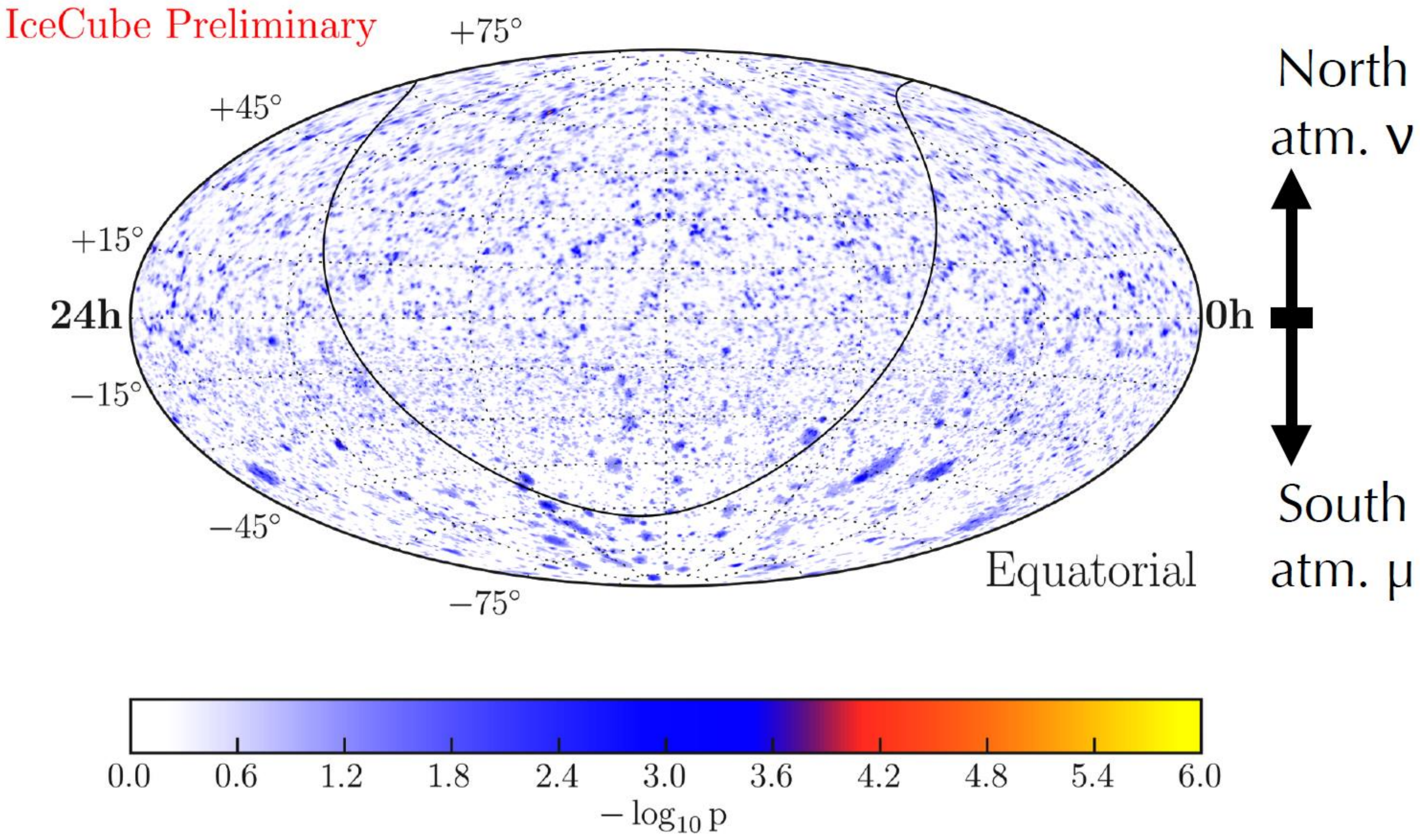
$$\mathcal{L} = \prod_i \left(\frac{n_s}{N} \mathcal{S}\left(\Delta\Psi_i, \sigma_i, E_i; \gamma\right) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}\left(\delta_i, E_i\right) \right)$$

- Use unbinned clustering likelihood to search for steady sources
- Signal S: Gaussian clustering around source location
- Background B: Distributed homogeneously around source
- Energy: Signal at higher energies (~E^{-2}) than background (~$E^{-3.7}$)
  - Fit for spectral index ɣ



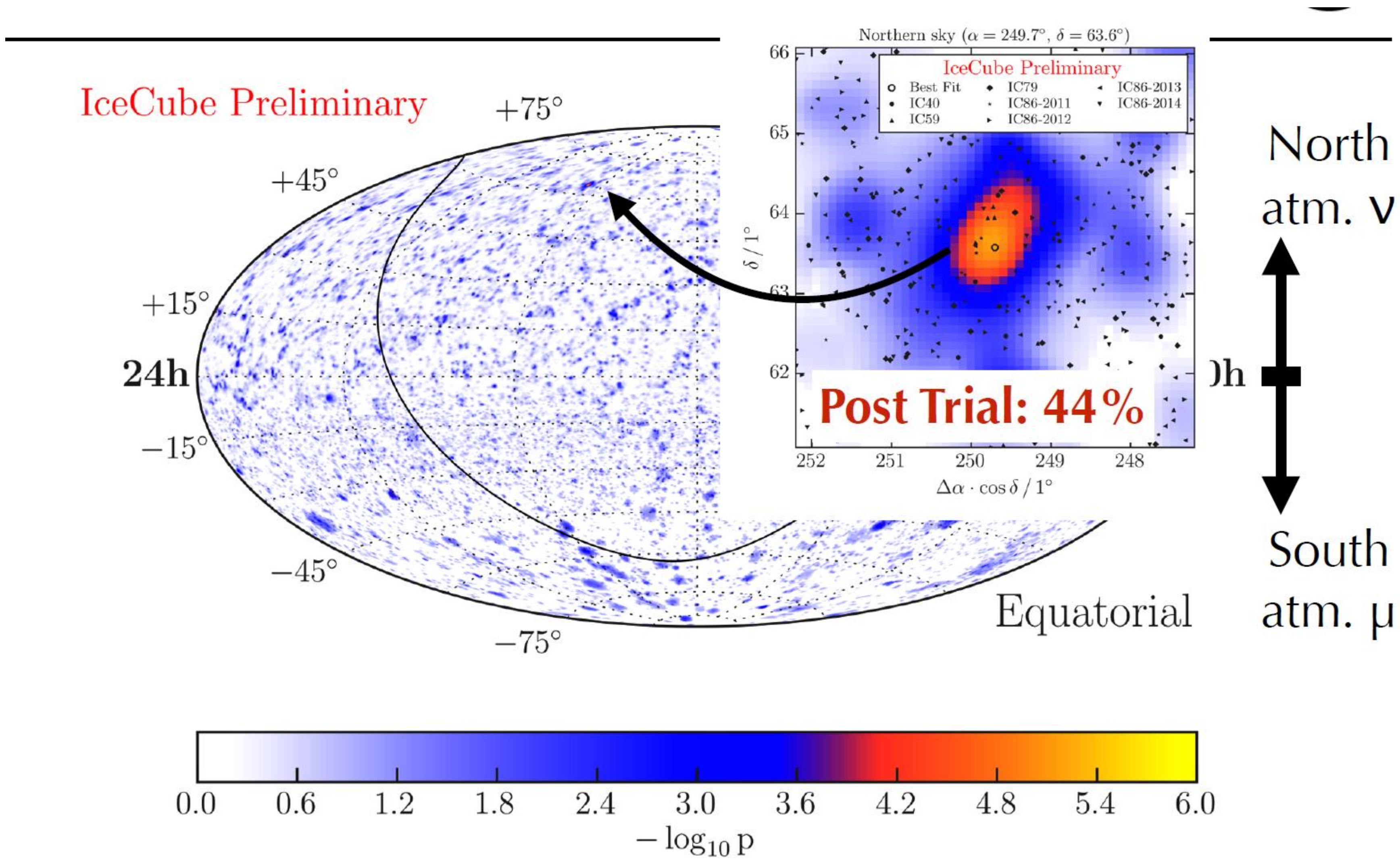


7 year search for point sources



Full sky clustering search 2008-2015 (700000 events)

… hottest spots

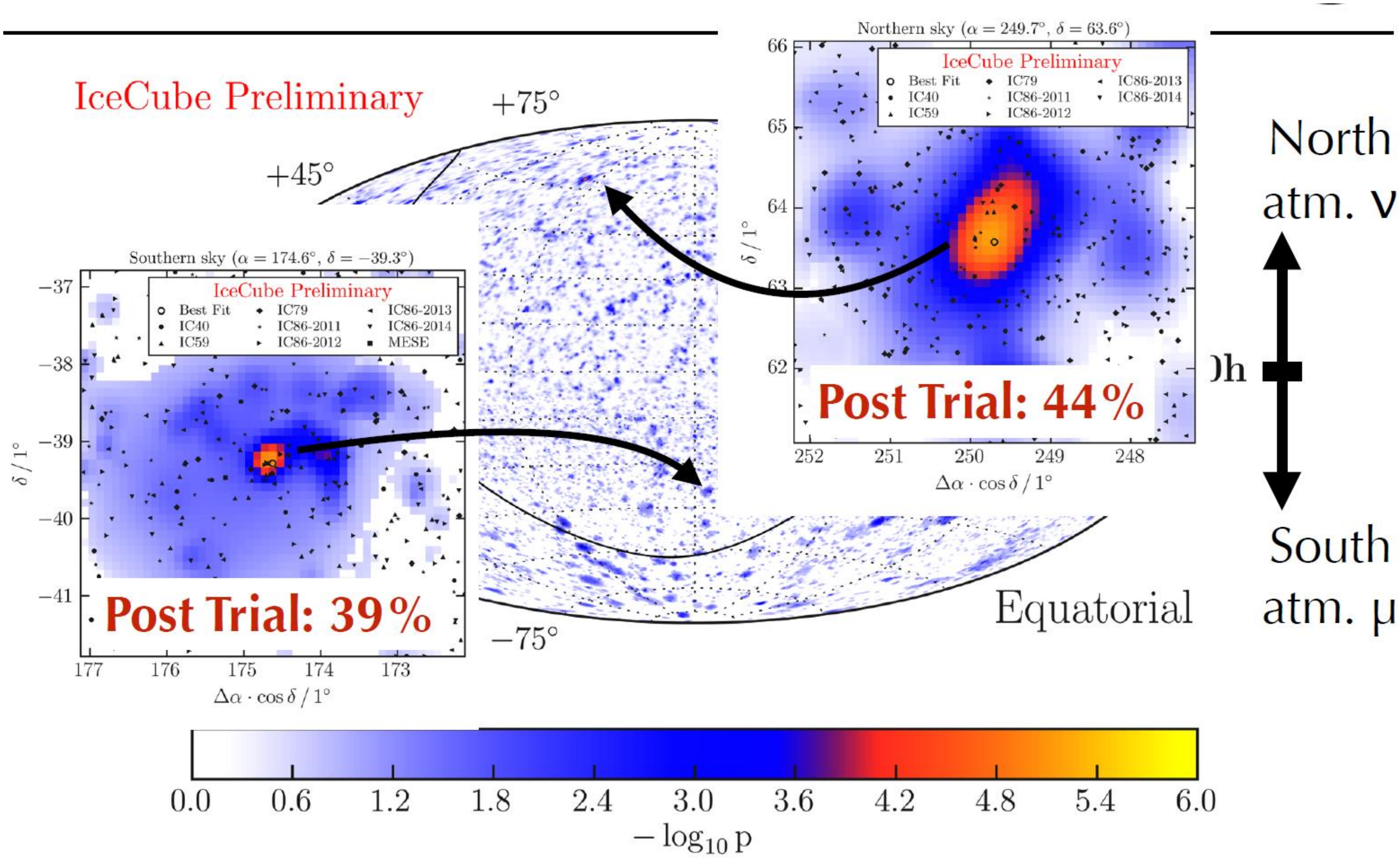


Post Trial: 44%

North
atm. ν

South
atm. μ

... hottest spots



North

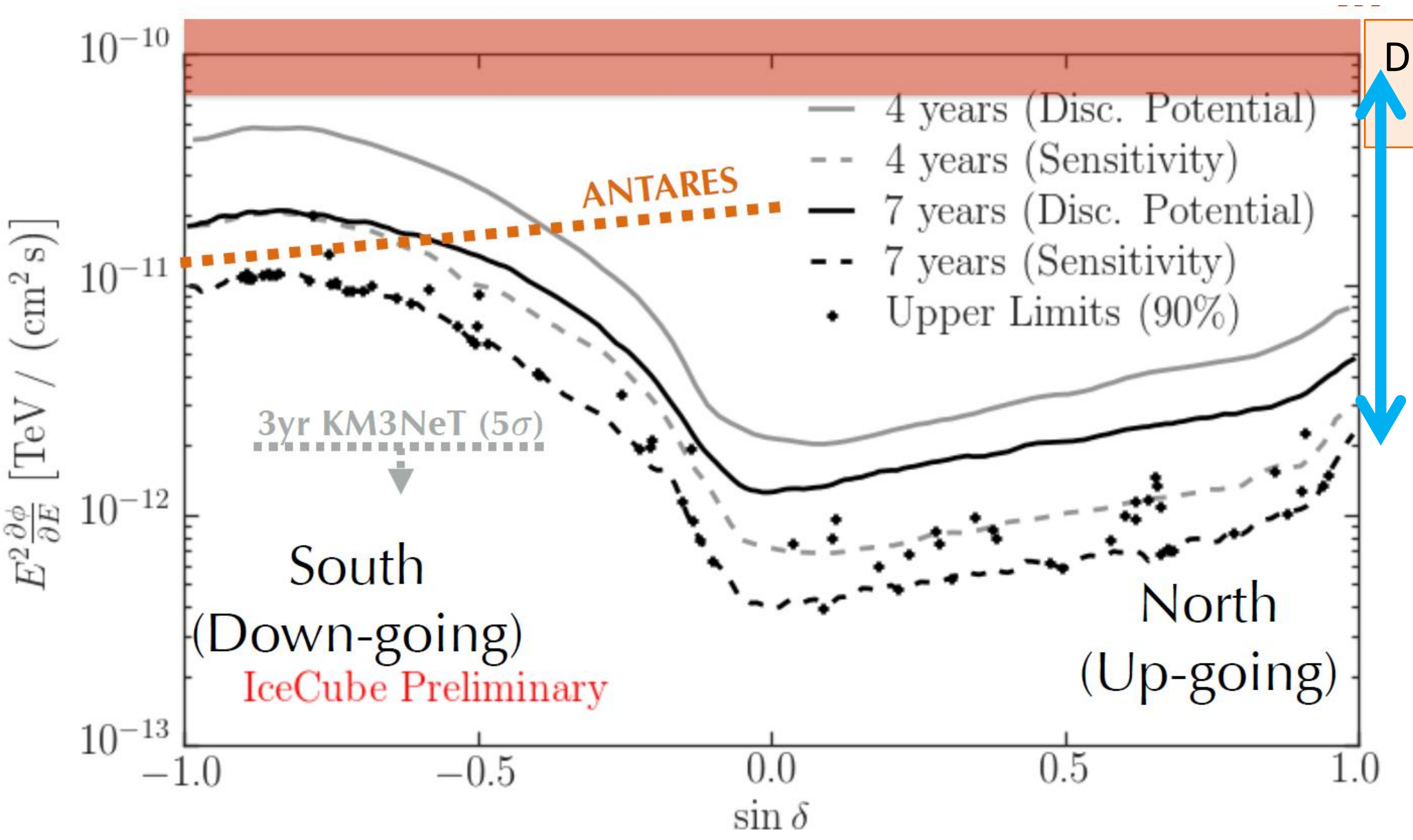
atm. ν

South

atm. μ

Flux sensitivity

Despite of a factor of 1000 improvement in sensitivity: **no point source yet identified**



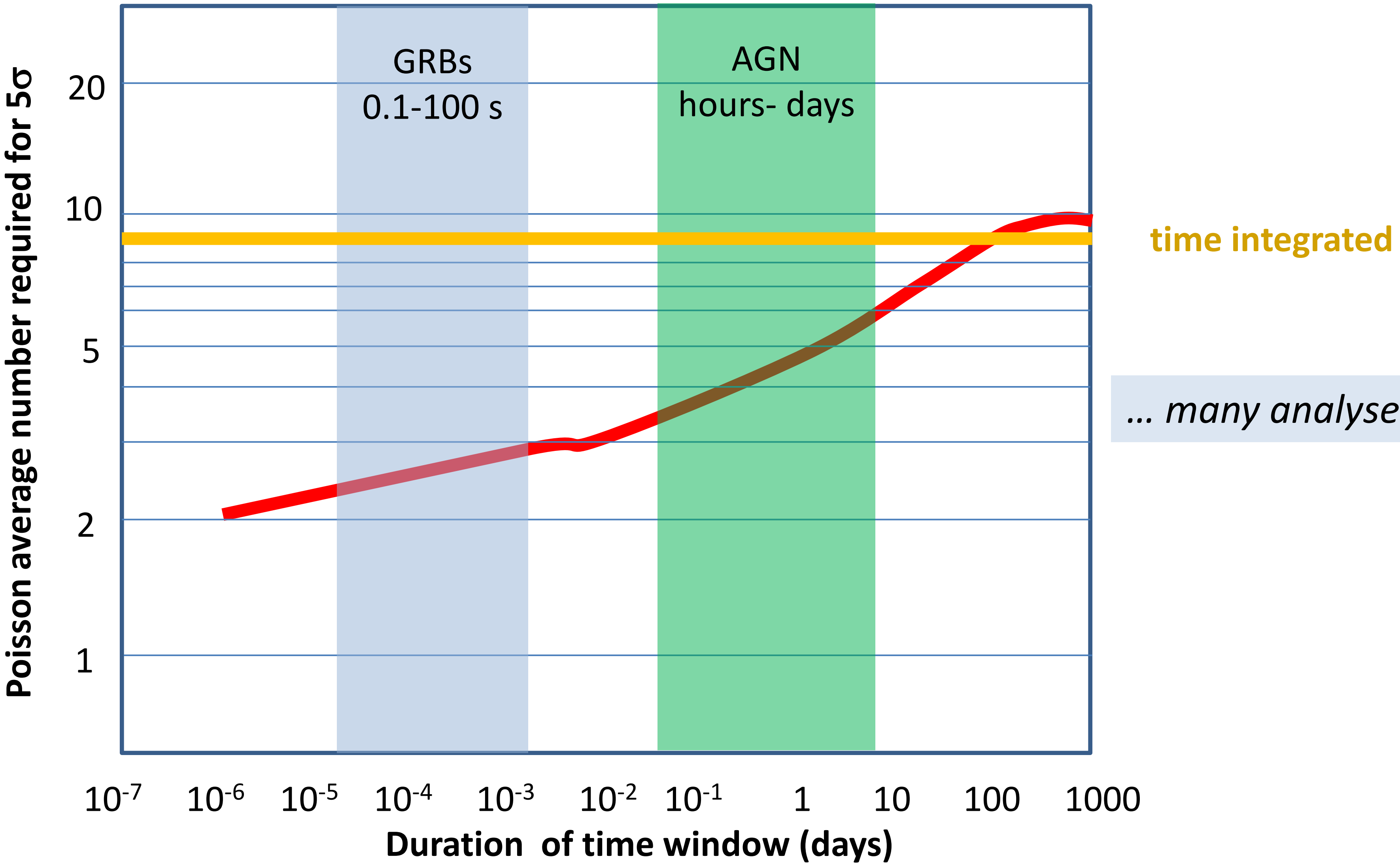
Diffuse Waxman-Bahcall flux

Need at least 100 weak sources to explain flux

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

Required # events for discovery

… just an example



… many analyses

Methods to improve sensitivity

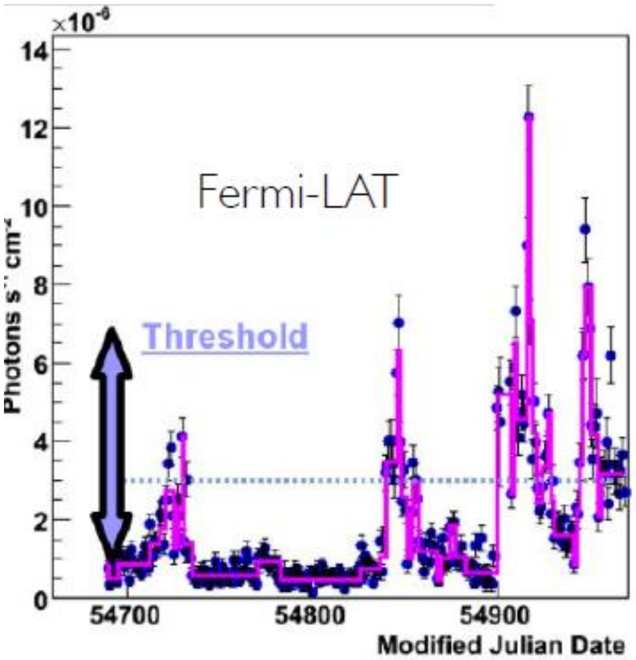
***biggest problem:** too many background events ….*

- **Non-stationary sources using external information** (gain factor ~5)

  Gamma Ray bursts (satellites)
  Cherenkov gamma telescopes , x-ray

- **Stacking of sources** (gain factor < ~10)
- **Duplets/Triplets** (in space and time)
- **Veto atmospheric muons**

  currently limited (1 km^2 IceTop)

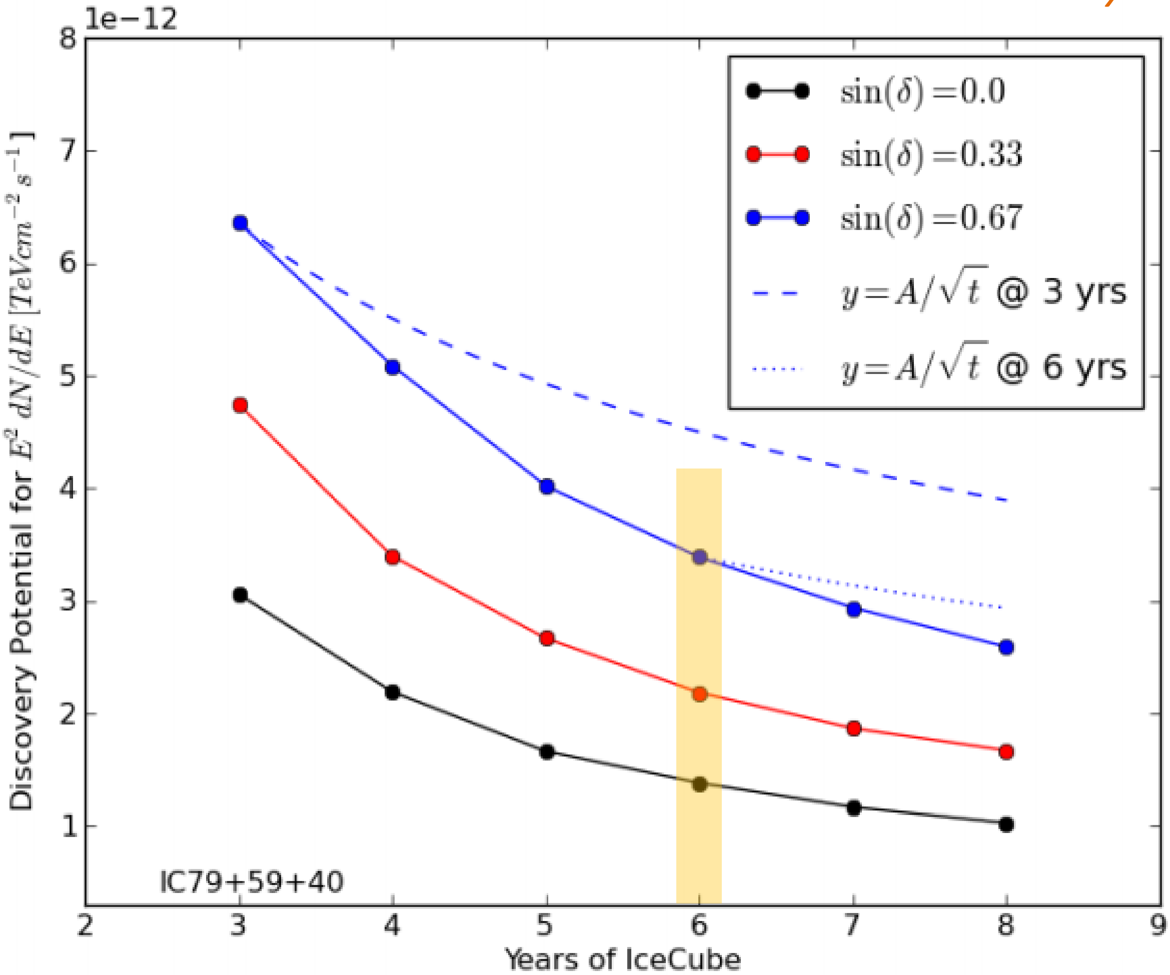


….of course, more data,

improved resolutions always help …

Future Point source analyses …

… not yet in 1/√time regime …



2016

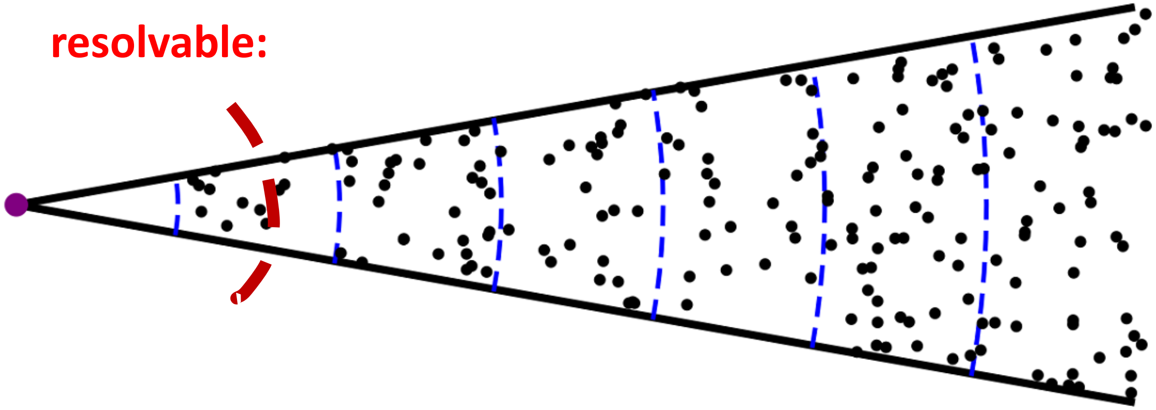
expect Icecube to run at least until 2022, longer if extensions are built …

Still … are we on the wrong track?

$$\boxed{\phi_{\text{inclusive}} = \sum_{\text{all sources}} \phi_{\text{single source}}}$$

Argument by Paolo Lipari (2005)

resolvable:



dominated by large distances …

Olbers paradox:
Why is the night sky dark?

“expansion of Universe cuts summation“

inclusive search is up to 100 times more sensitive than single source flux

… of course, background is much higher …

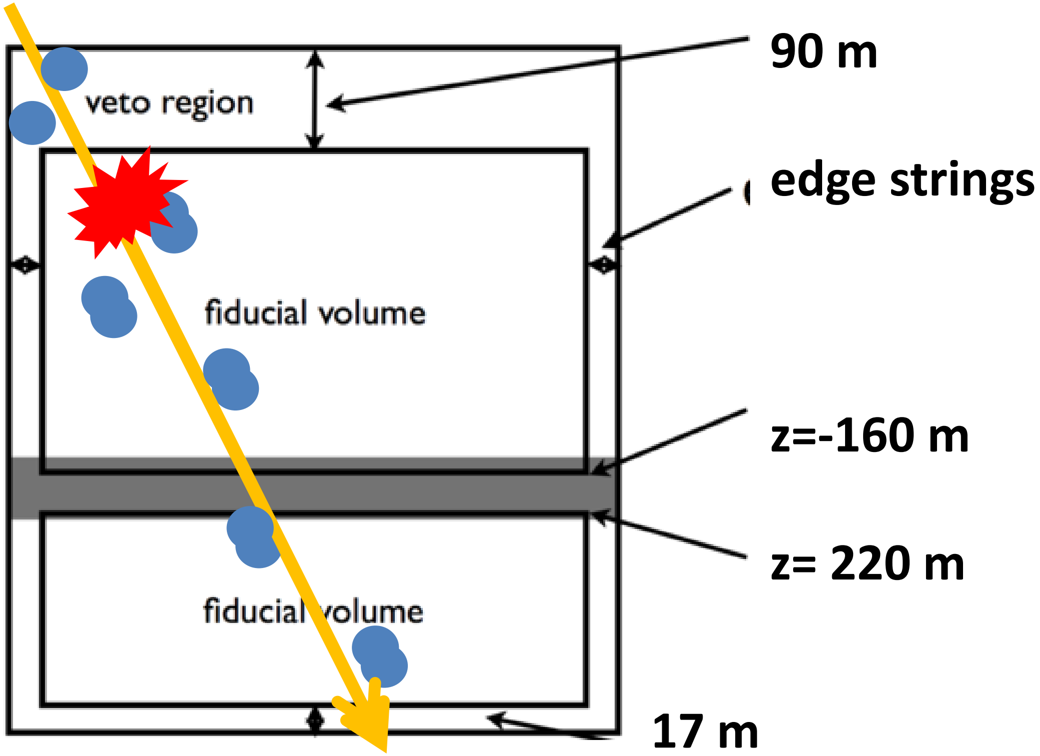

Starting events

What would be a convincing analysis?

Try clear-cut experiment based analysis

- **Only study very high energies (> 4000 photo-electrons)**
- **Only use well reconstructable contained events (tracks start in fiducial volume)**
- **Use veto to reject atmospheric muons and neutrinos**
- **Calculate all backgrounds from data**
- **Like always, do blind analysis**

- 420 Mton fiducial mass (~1/3)
- all flavor 4π sensitivity > 50 TeV for contained events



Signal extraction by veto criterion

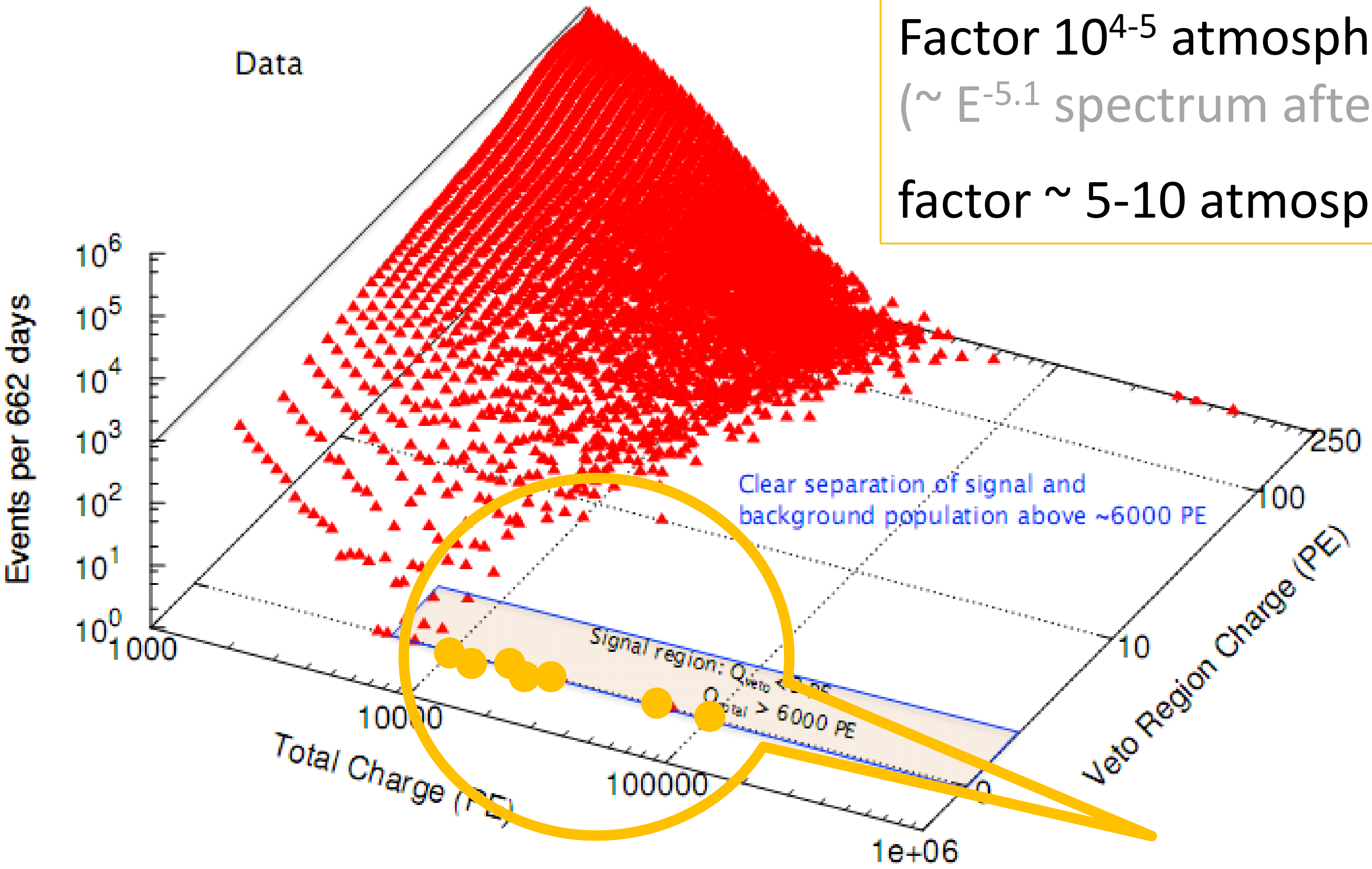
Events events appear at zero veto charge:

background reduction by veto:

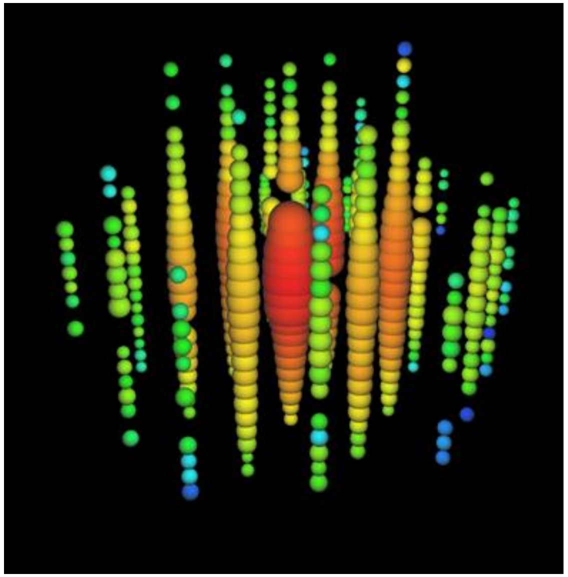
Factor $10^{4\text{-}5}$ atmospheric muons

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

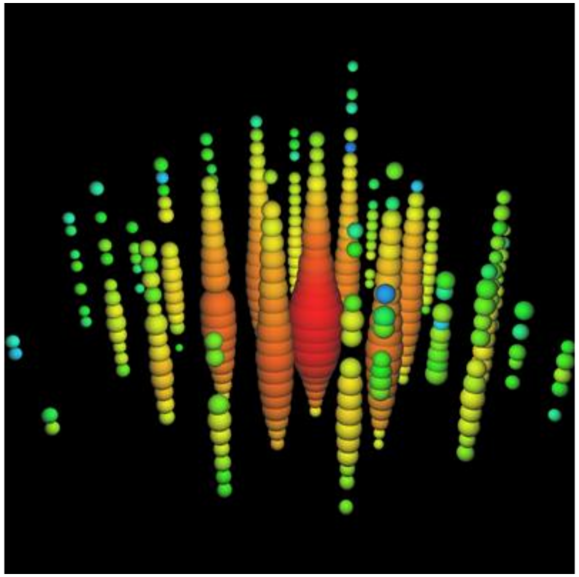
factor ~ 5-10 atmospheric υ‘s



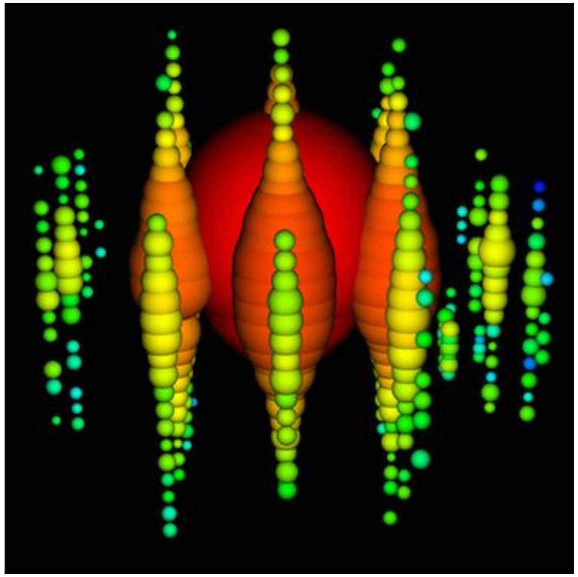
The highest energy events



1 PeV (Bert)



1.1 PeV (Ernie)



2.2 PeV (Big Bird)

Collected photo-electrons

Fix background from data:

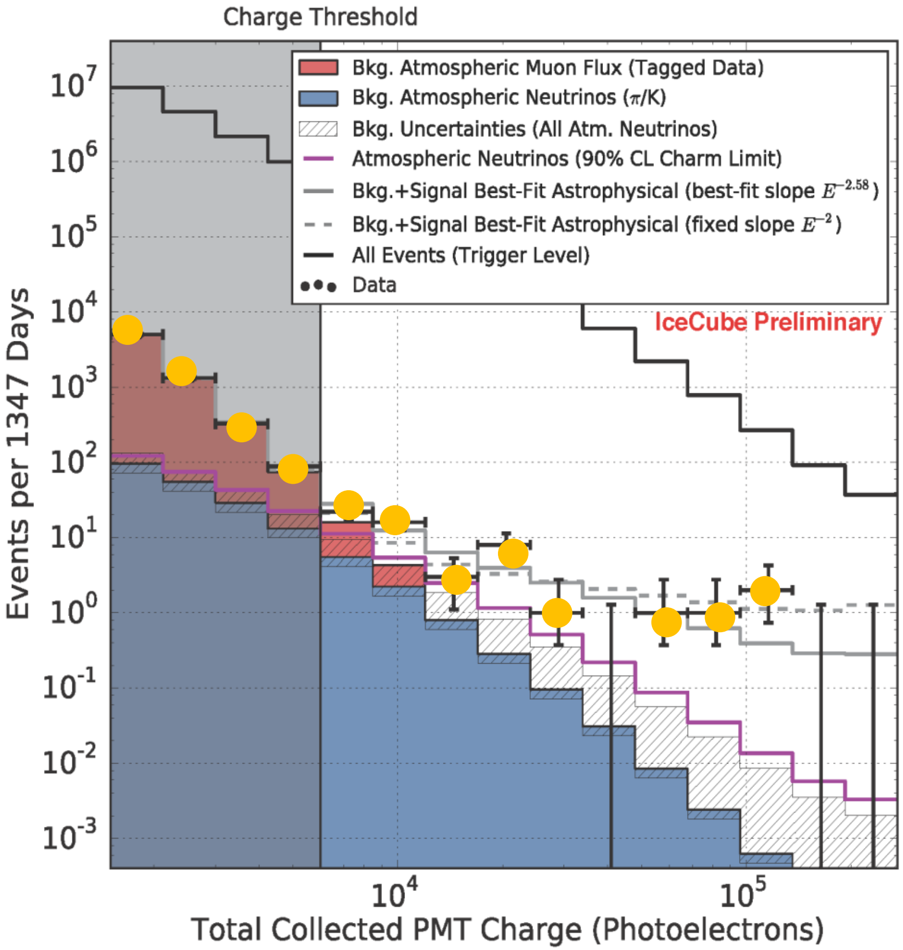
- Define second veto layer to determine atmospheric muon background
- Fix atmospheric υ background uncert. (prompt and charm) from υ_μ analysis

Reduce background by veto:

- factor 10^4-10^5 atmospheric muons ($E^{-5.1}$ energy spectrum after veto)
- factor ~ 5-10 atmospheric υ‘s

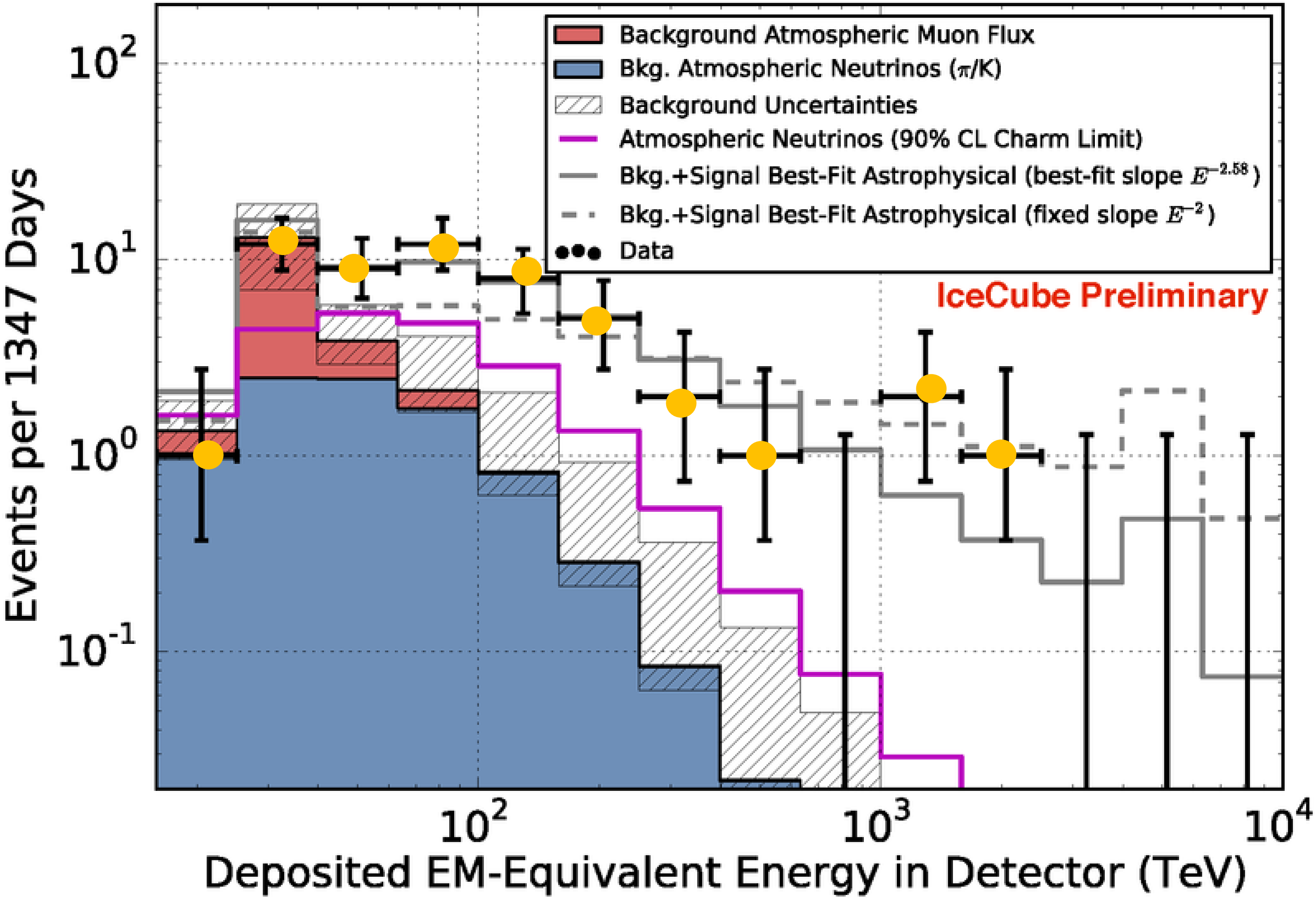
Excess of 41 events !!

Est. background 12.6 events

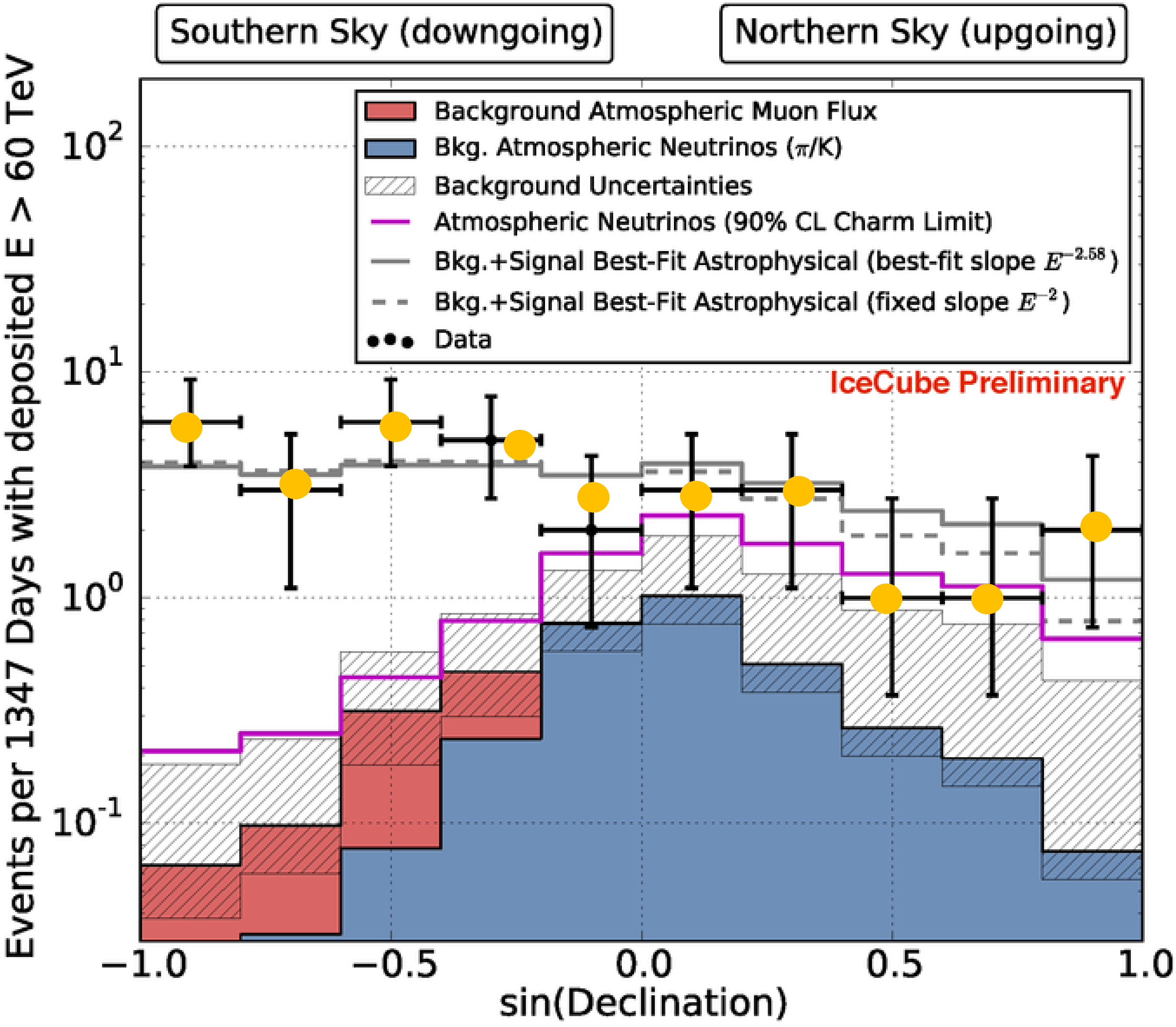


HESE 4 year

Deposited energy *(underestimates energy of muon neutrinos)*

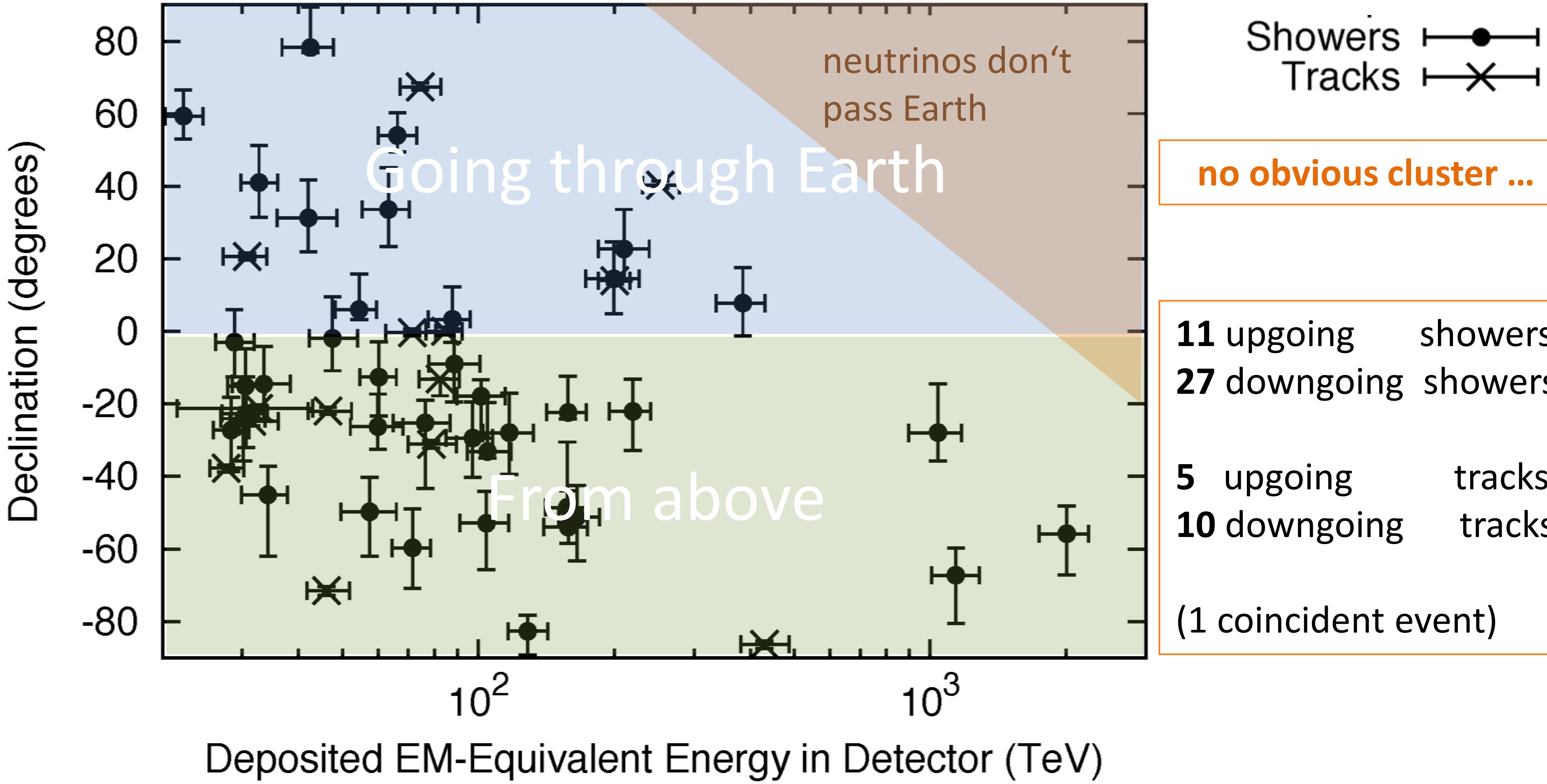


Angular distribution



Topology of events

54 events expected background from atmospheric sources: 12.6 events



no obvious cluster …

11 upgoing showers
27 downgoing showers

5 upgoing tracks
10 downgoing tracks

(1 coincident event)

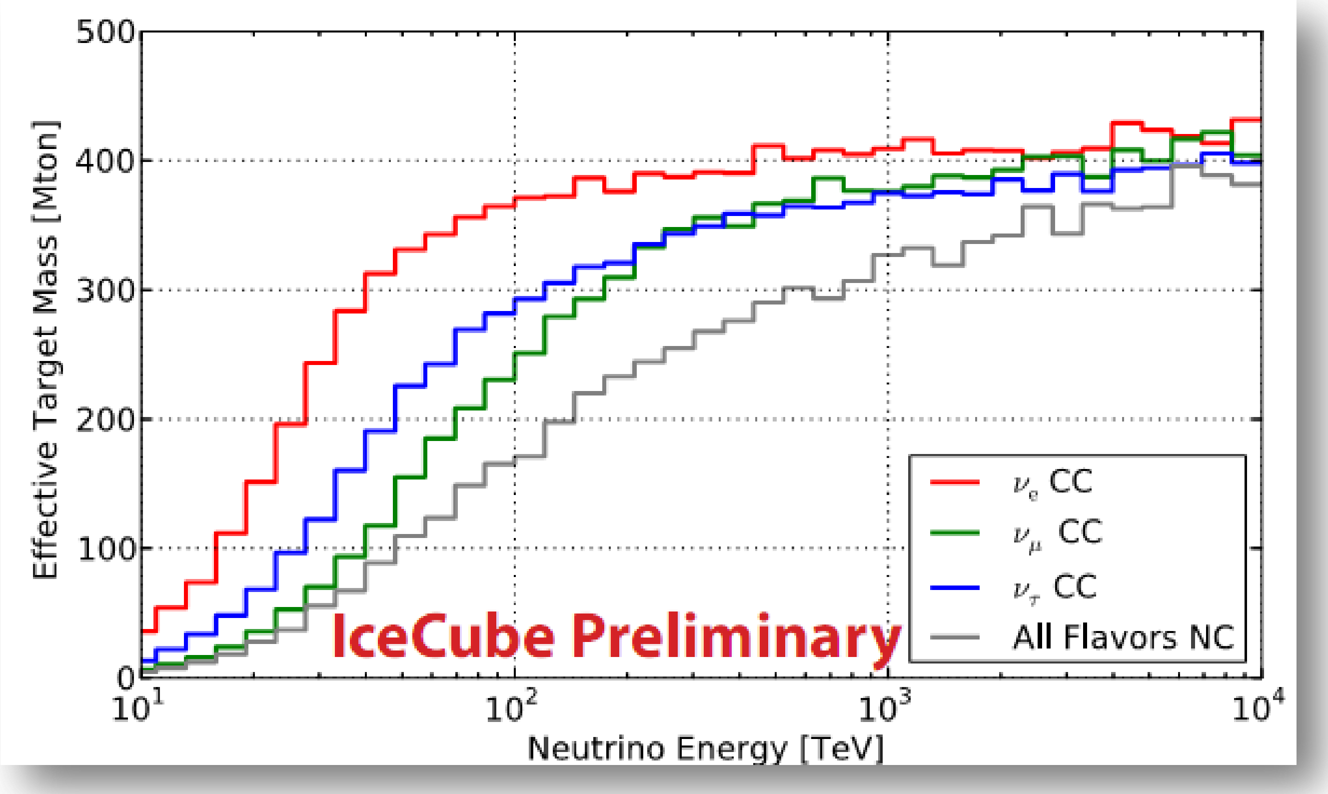
Ratio cascade to tracklike events

From 54 clean events seen:

15 events	with muon topology
38 events	shower like topology

Hint?

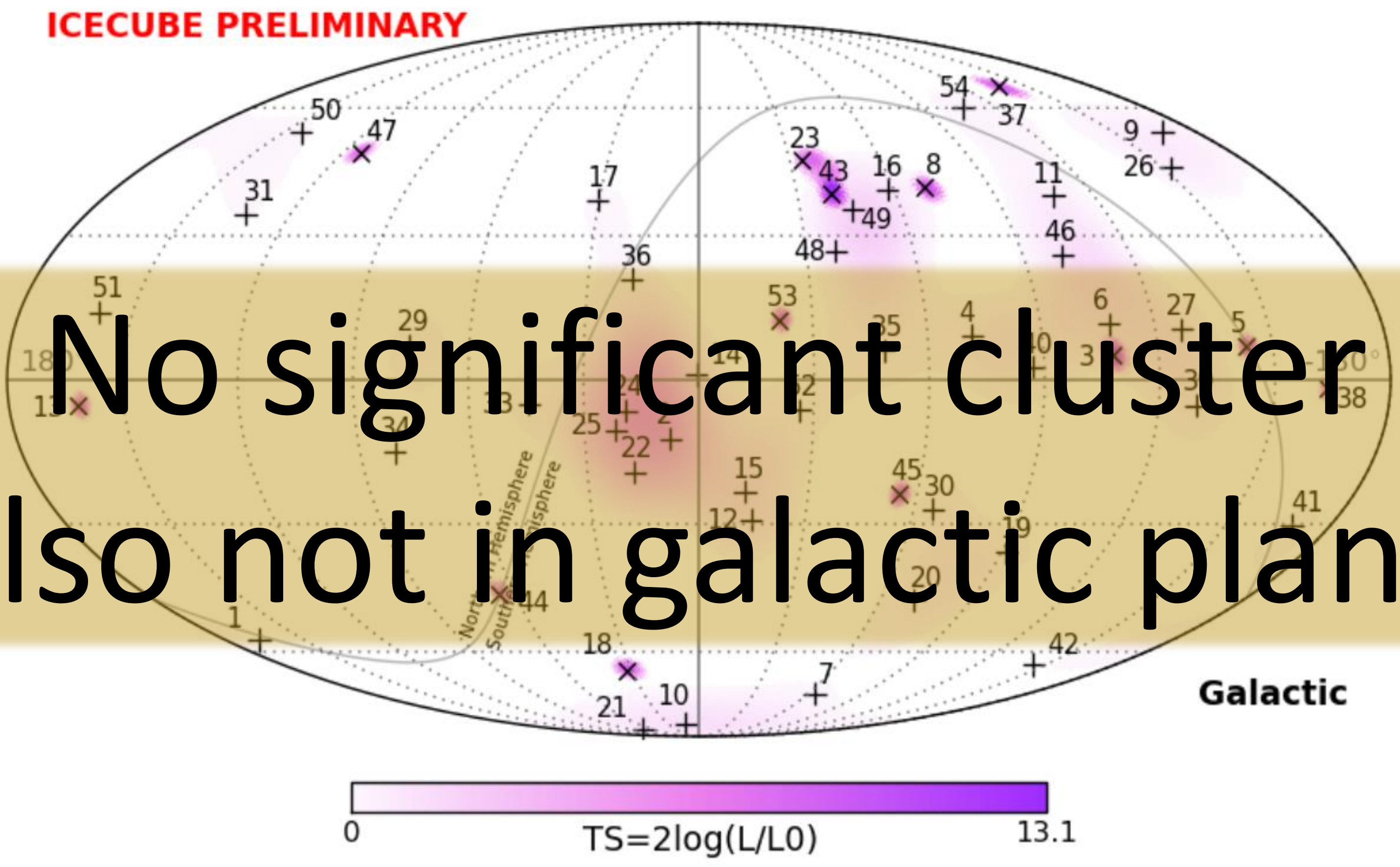
Effective Mass M_{eff}



$m_{eff}(\text{track-like}) = m_{eff}(\nu_\mu) < m_{eff}(\nu_\tau) < m_{eff}(\nu_e) \ll m_{eff}(\text{shower-like})$

…for $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ → astrophysical flux 81 % shower-like !!

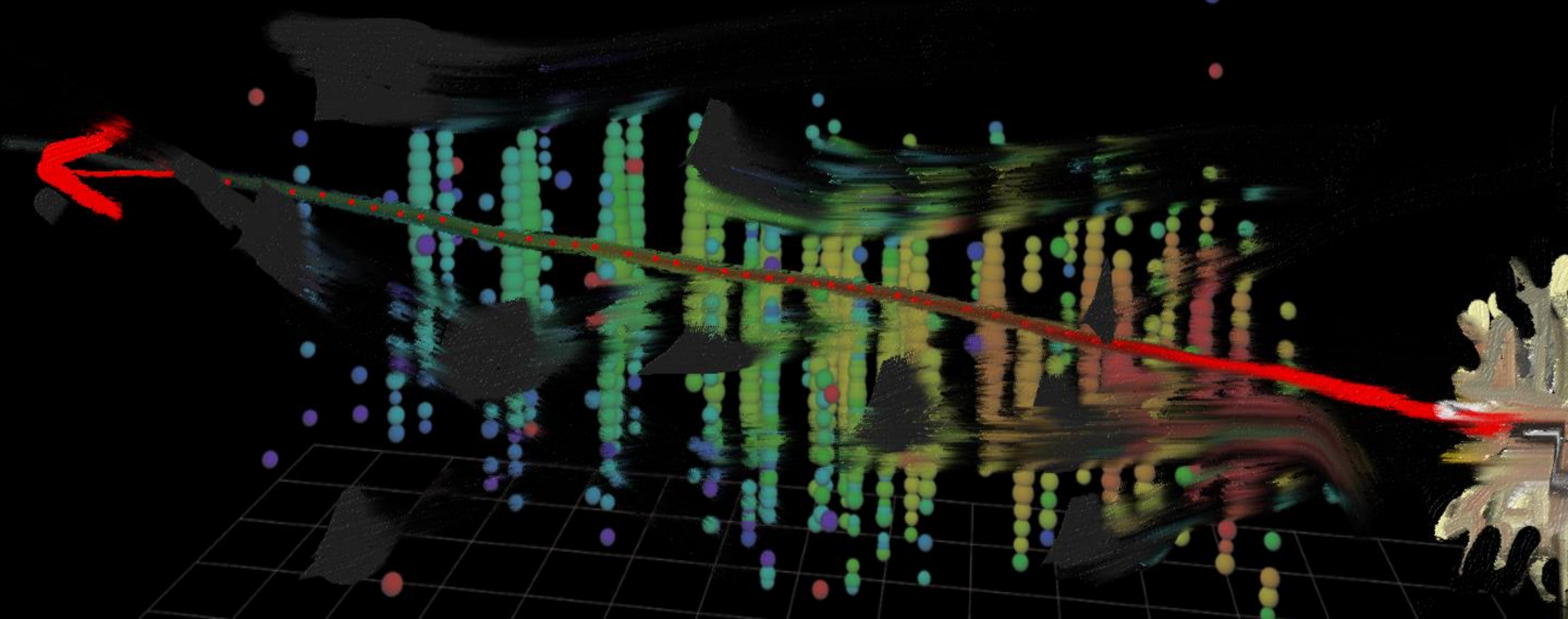
Skyplot



No significant cluster also not in galactic plane

angled crosses are neutrino-induced **muons**
vertical crosses are **cascades**

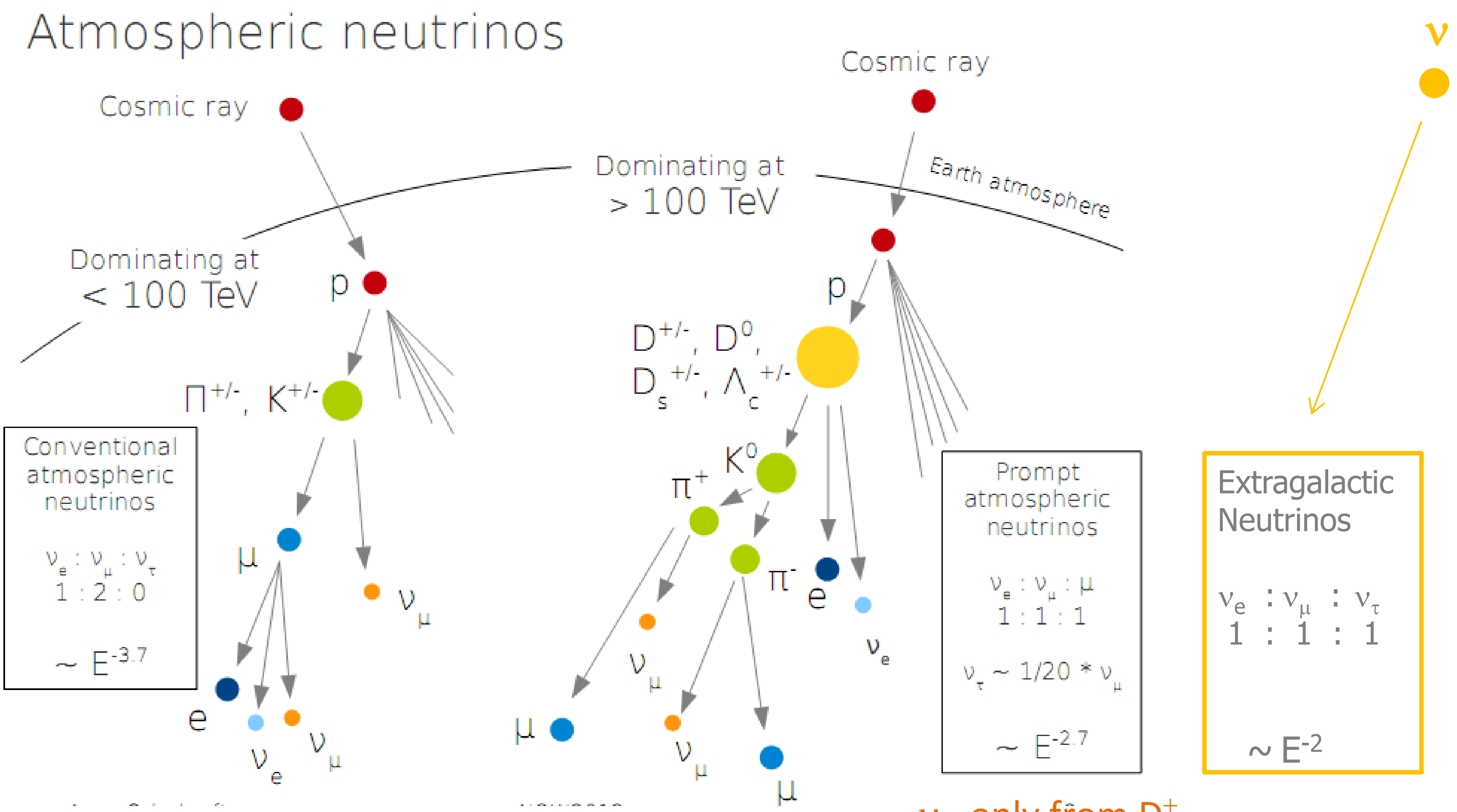
Diffuse ν_μ search



inclusive („diffuse“) searches

Reminder:

©Anne Schukraft



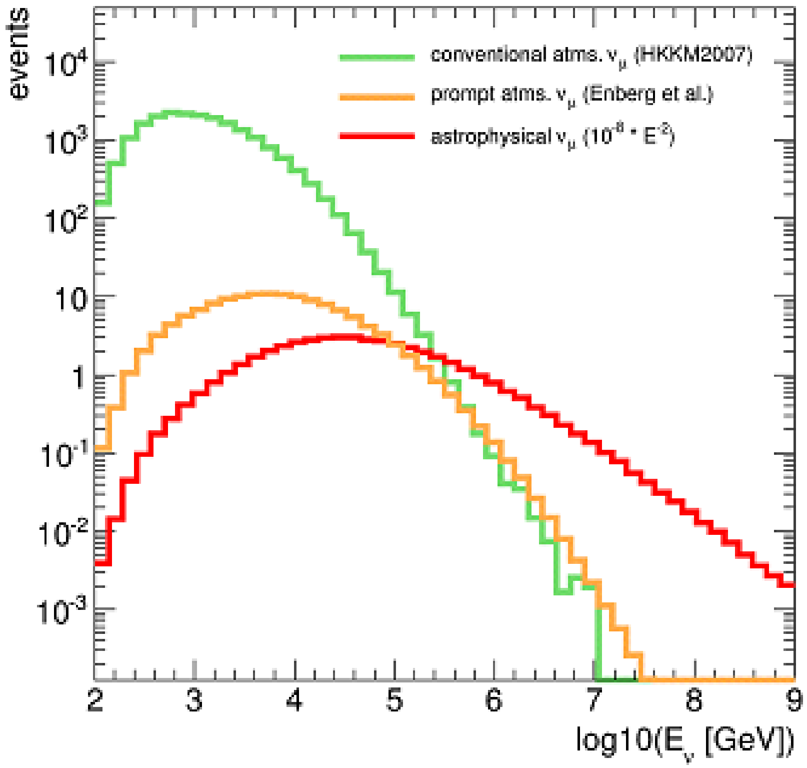
ν_τ only from $D^{\pm}_s$

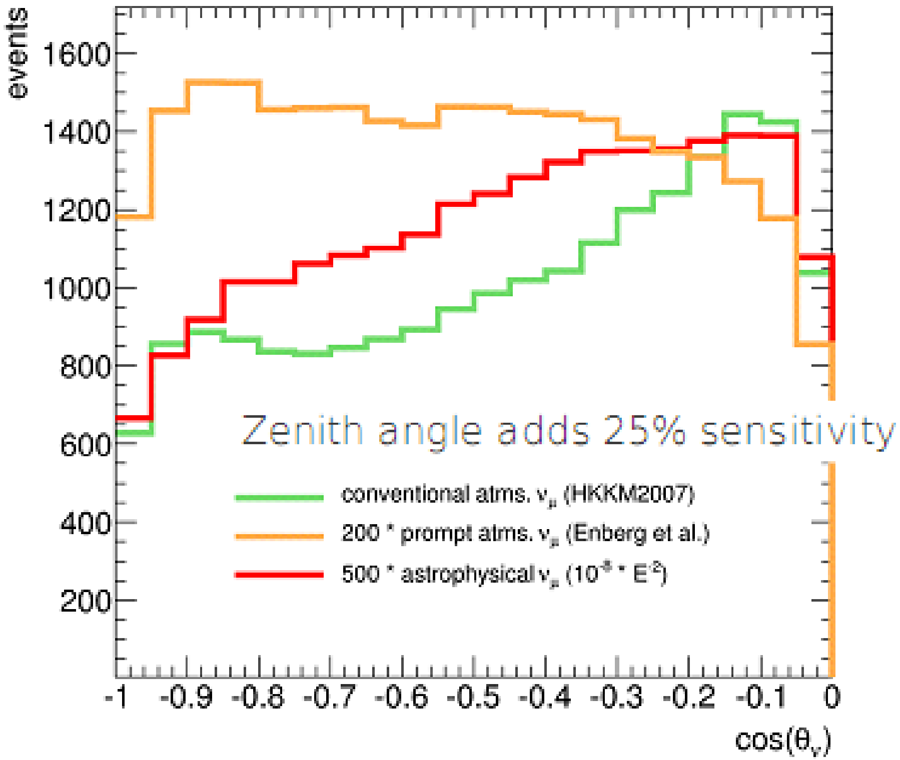
prompt flux very badly known (LHC!)

Different energies, flavor ratios, angles …

Signatures for υ_{μ}

… components can be distinguished statistically by energy and angular distribution





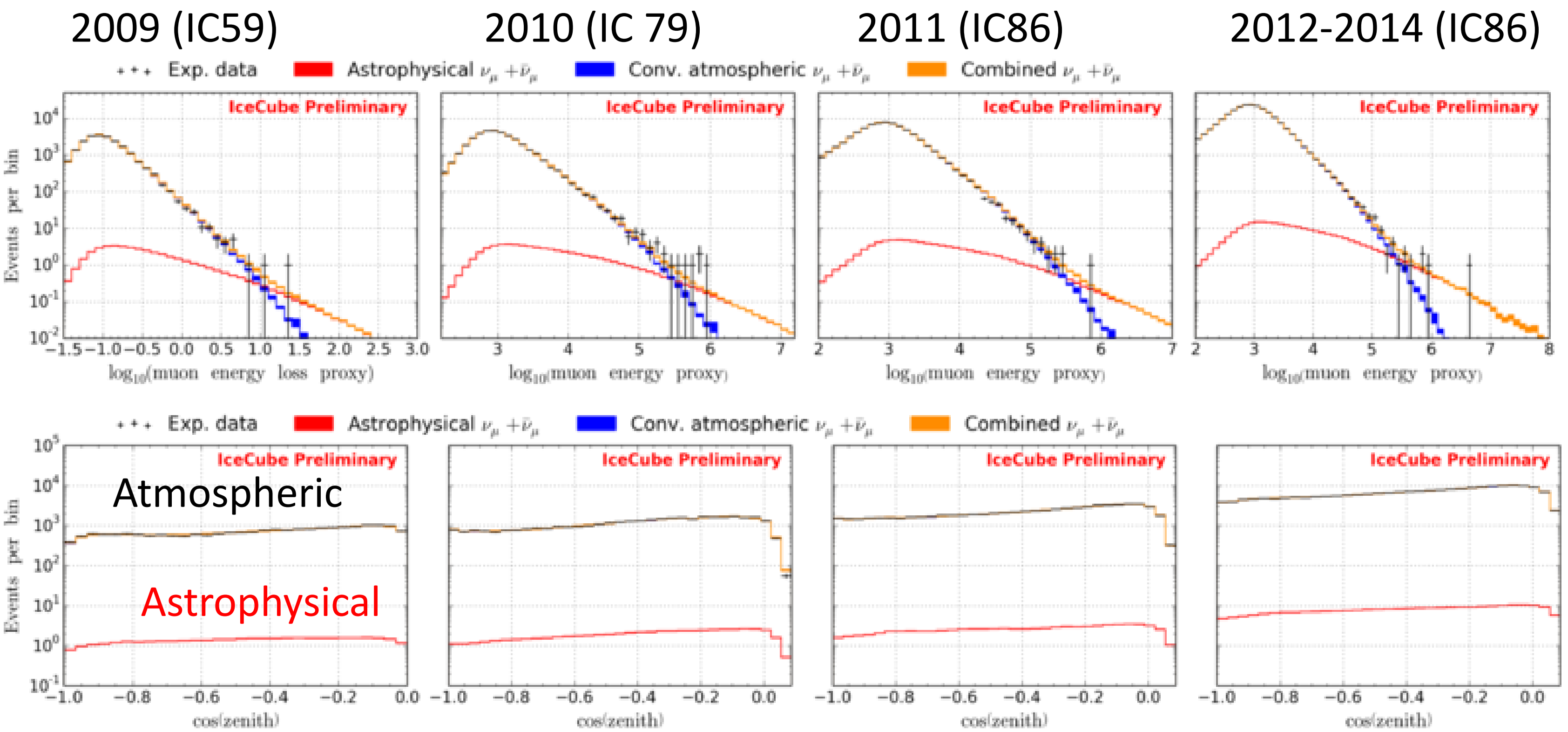
Zenith angle adds 25% sensitivity

At high energies, cosmic ray beam, cross sections (e.g. charm at x~10^{-6}) carry large uncertainties

… perform likelihood analysis to determine fluxes from data …

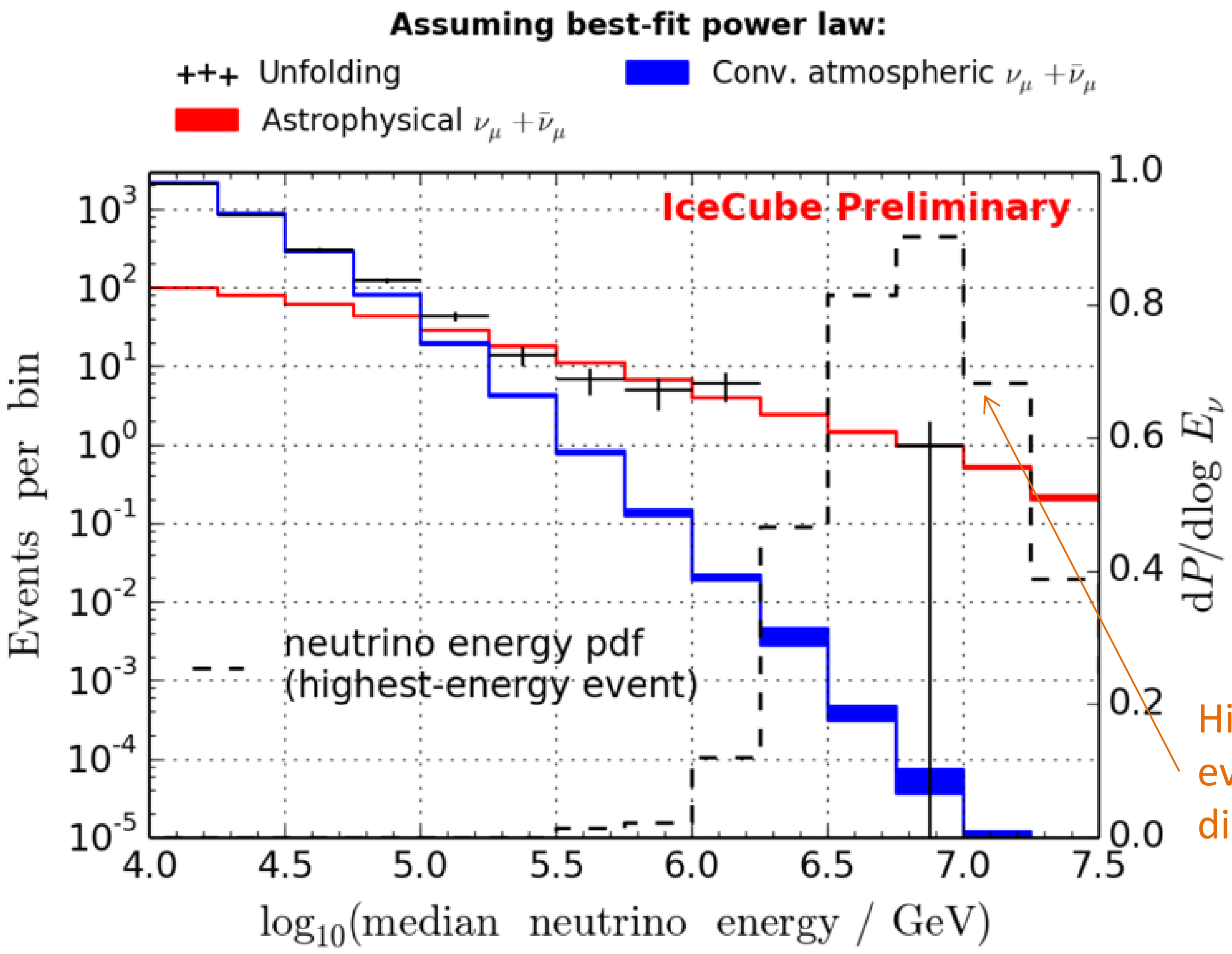
Diffuse muon neutrinos

Select essentially background free upgoing neutrino samples:



Consistent overshoot at high energies ….

Unfolded spectrum

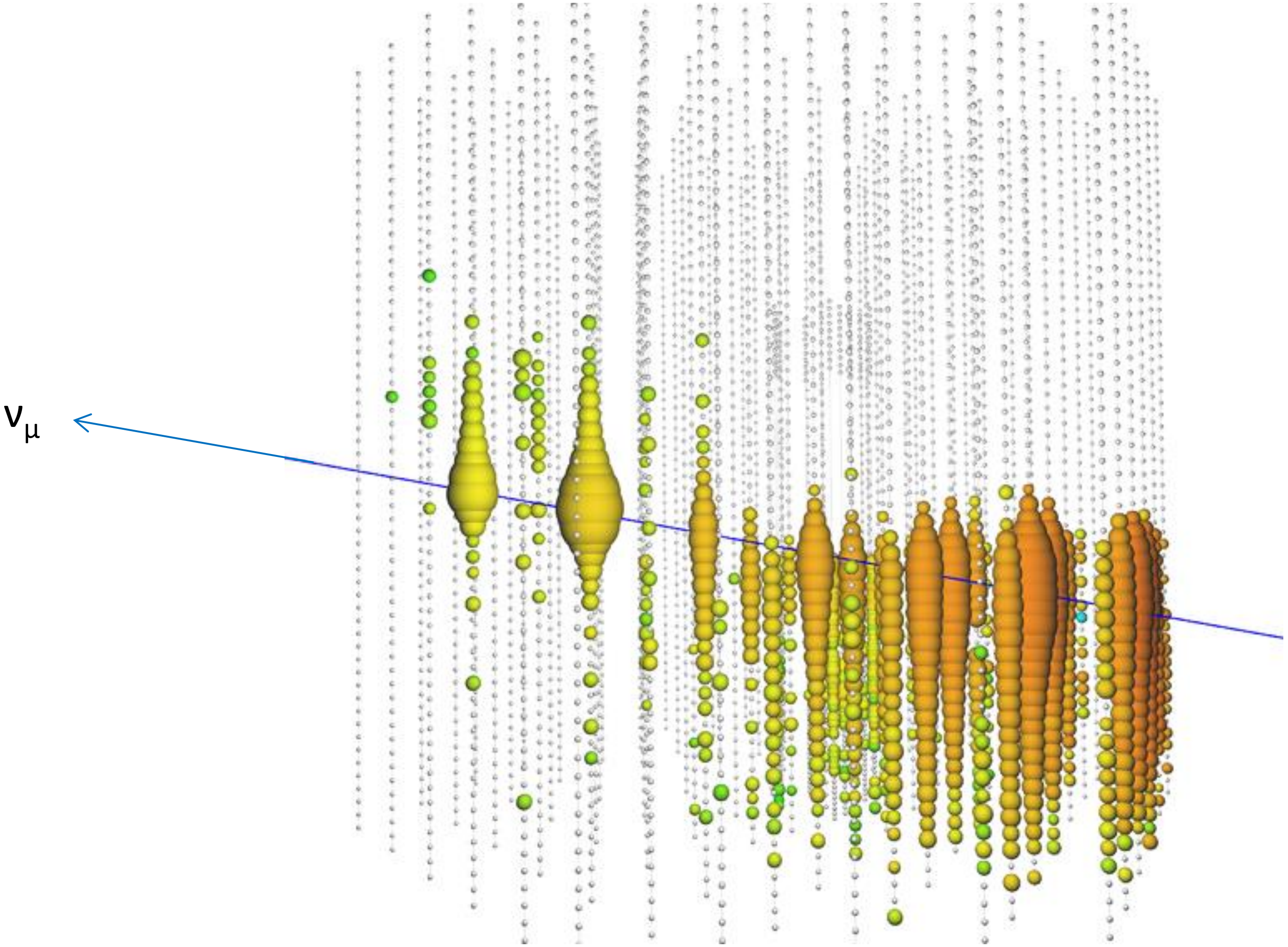


Highest energy event probability distribution

Highest energy neutrino so far

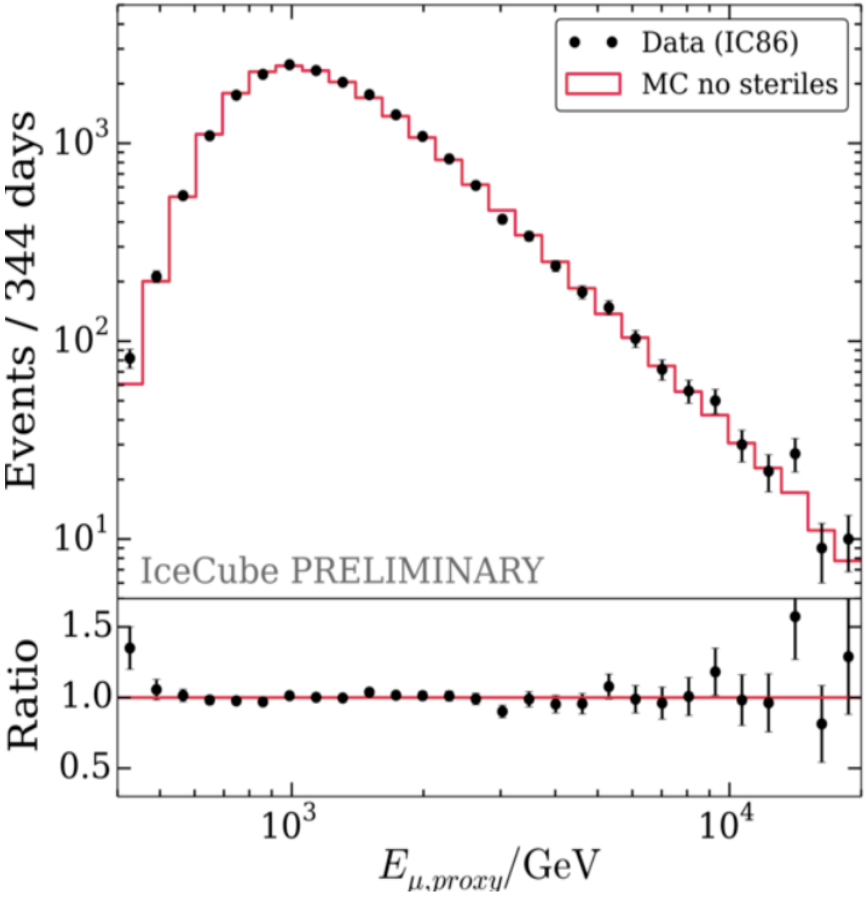
Highest energy neutrino event seen: 2.6+- 0.4 PeV deposited energy

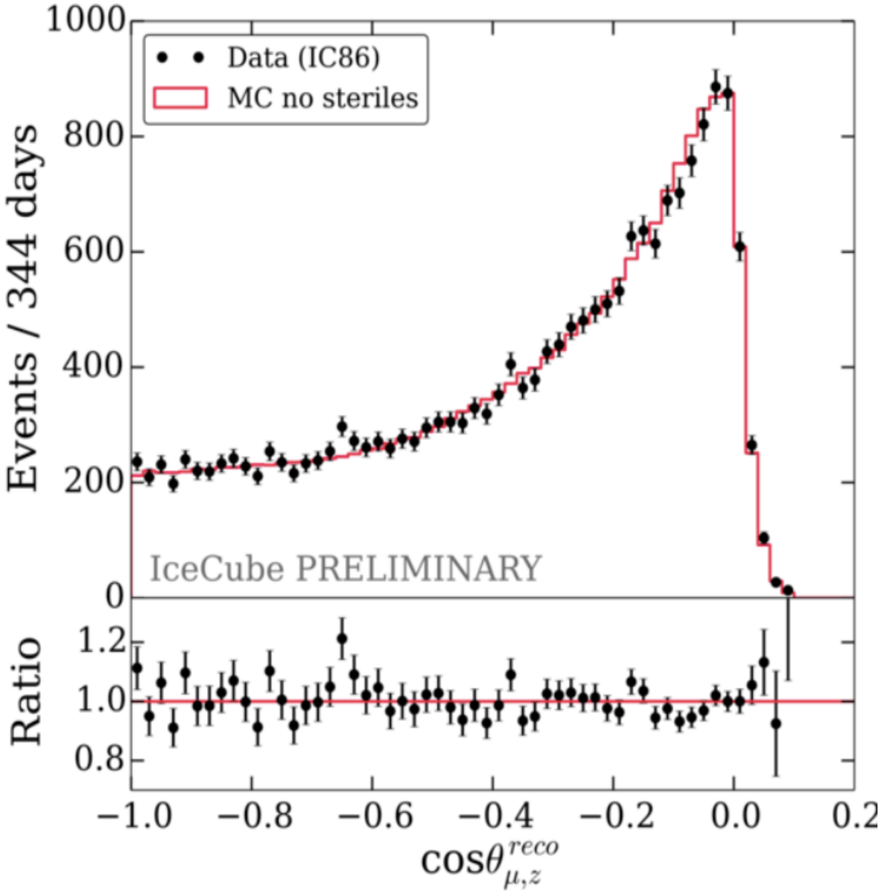
Estimated neutrino energy: ≈ 10 PeV



Search for sterile neutrinos

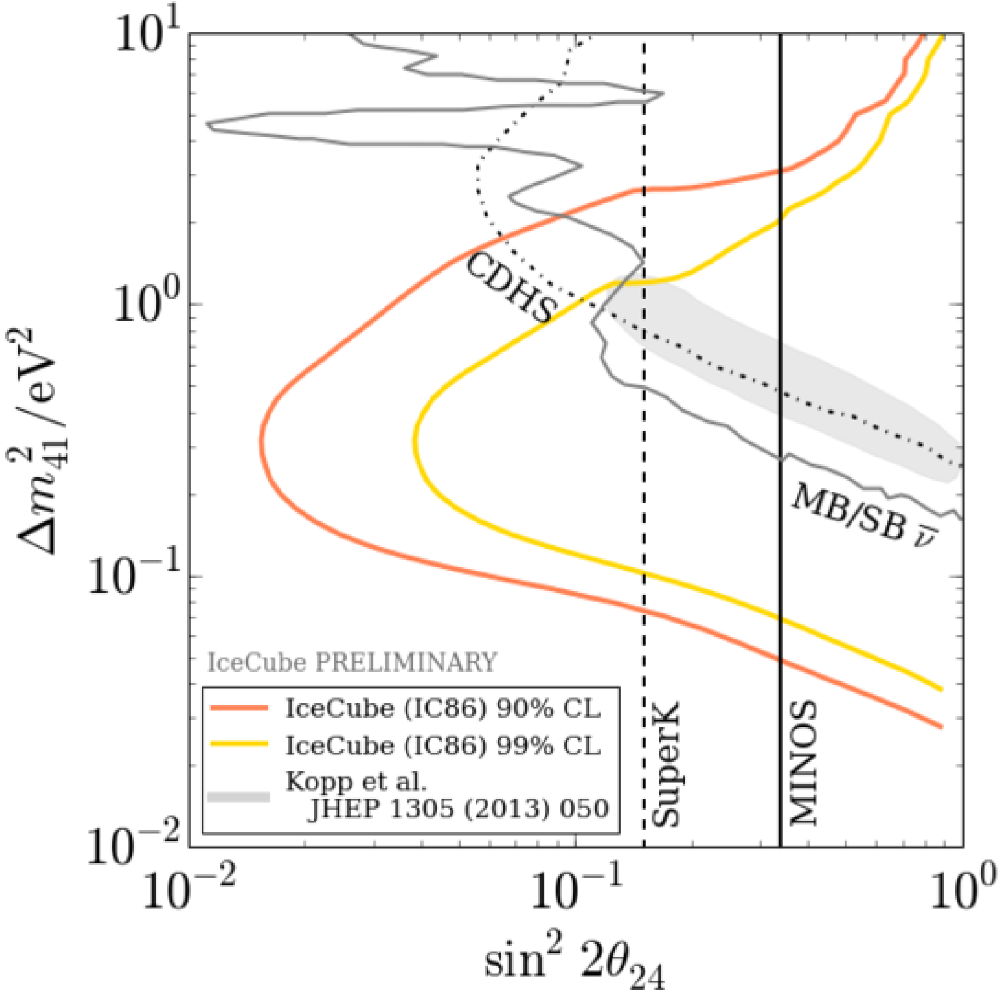
Are there any features in the atmospheric neutrino spectrum?





Disappearance search: expect (matter enhanced deficit)

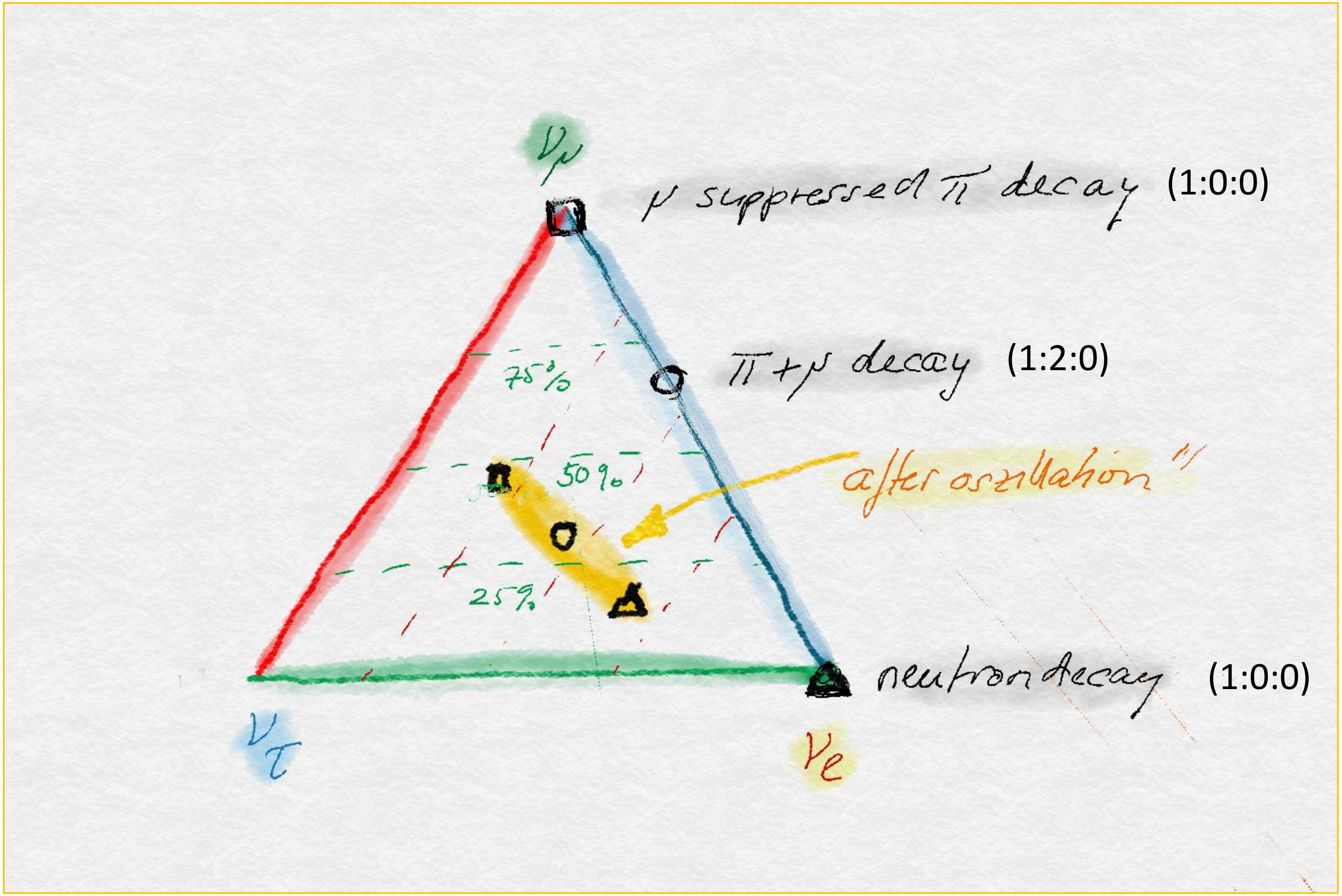
…sterile neutrino sensitivity



SK:	arXiv:1410.2008ed
MINOS:	arXiv:1104.3922
Kopp et al. :	arXiv:1303.3011

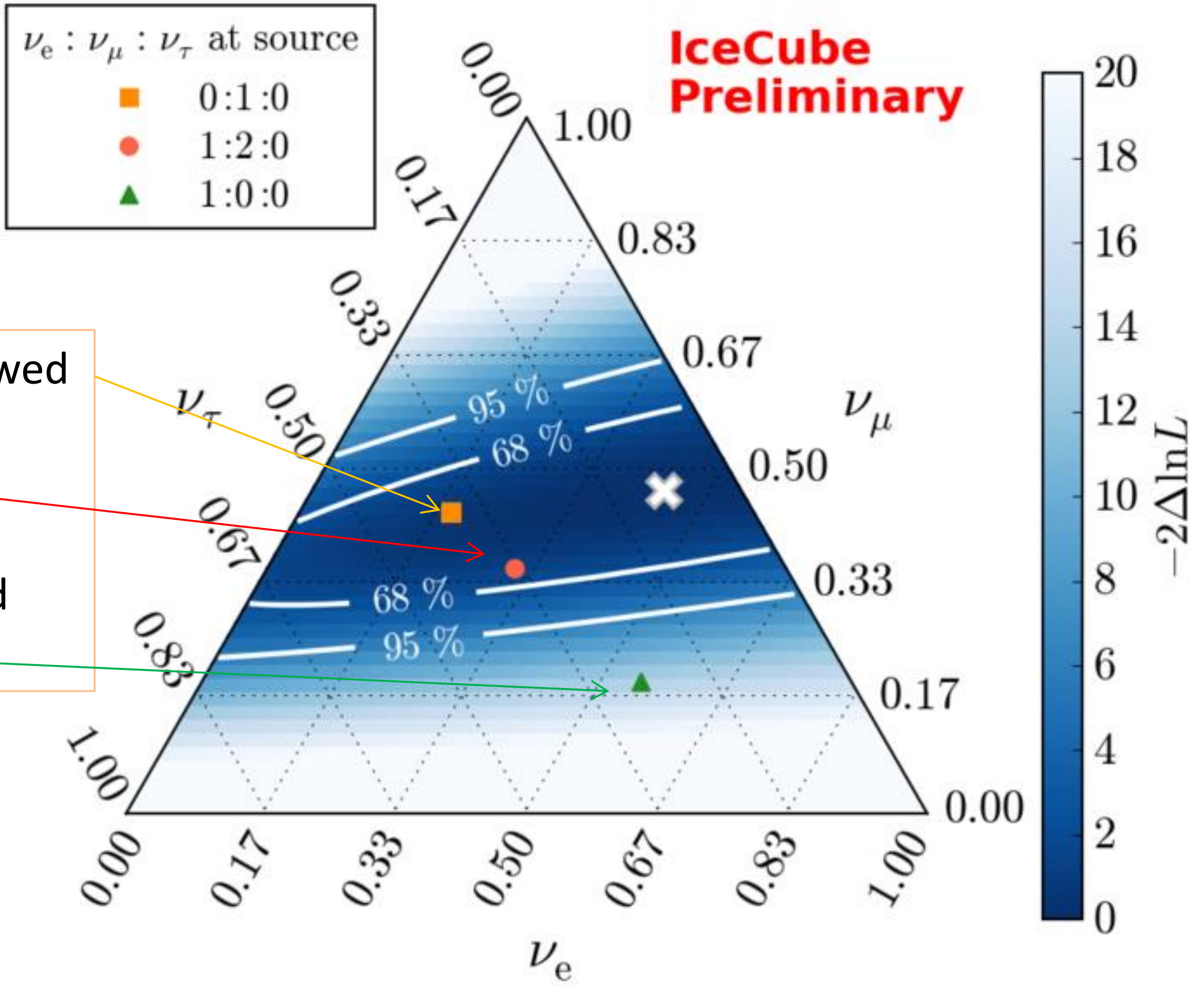
- No sign of energy spectum distortion
- Strong bounds by IceCube

Flavor ratios (ν_e,ν_μ,ν_τ)



Ratio after oscillations depend on production, mixing angles and CP violation phase

Global fit – flavor ratios



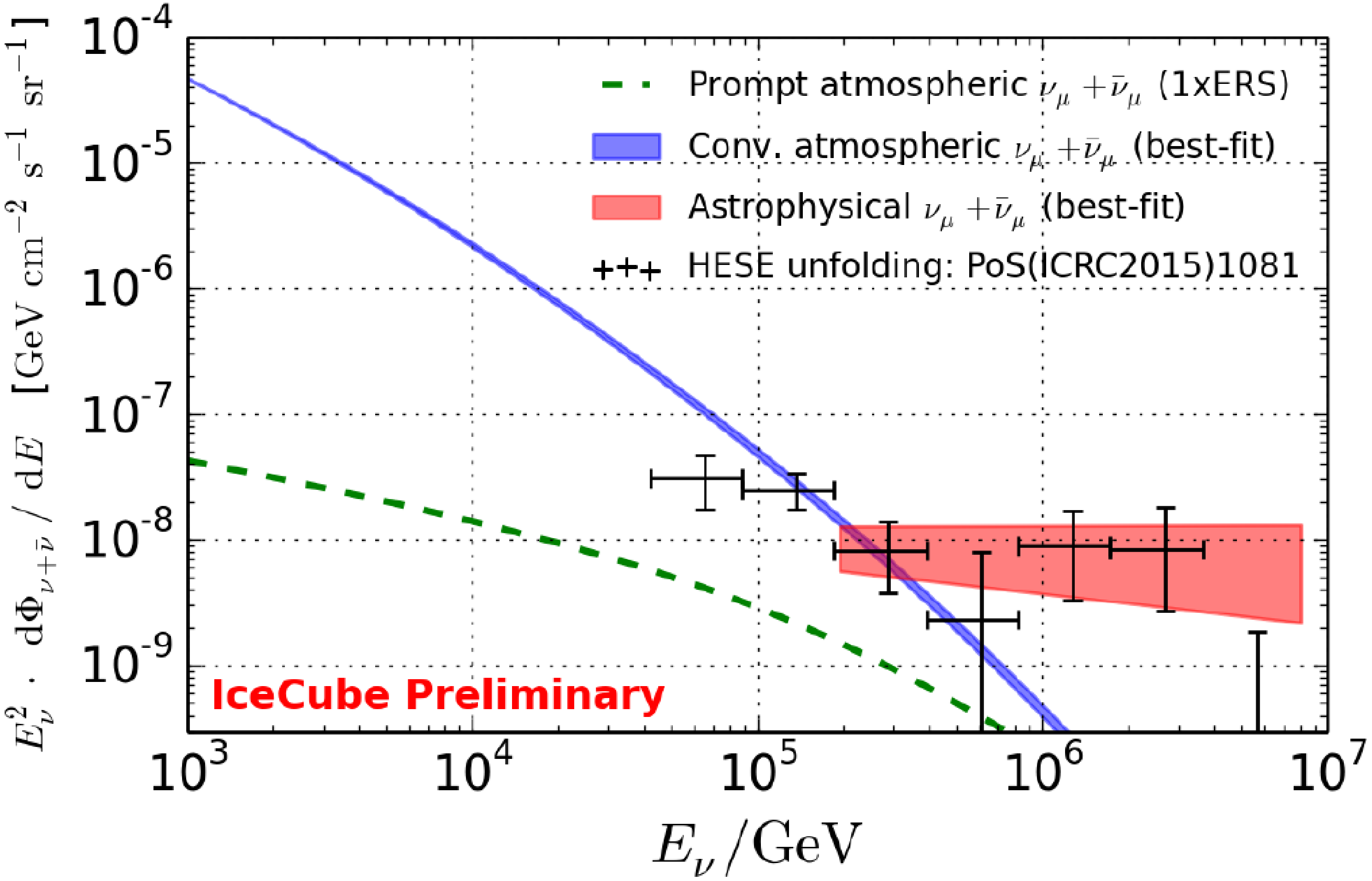
Muon damped π decay allowed

π decay allowed

Pure neutron decay rejected at 3.7 σ

Contribution of ν_τ so far unconstraint … dedicated searches are under way

Summary fluxes

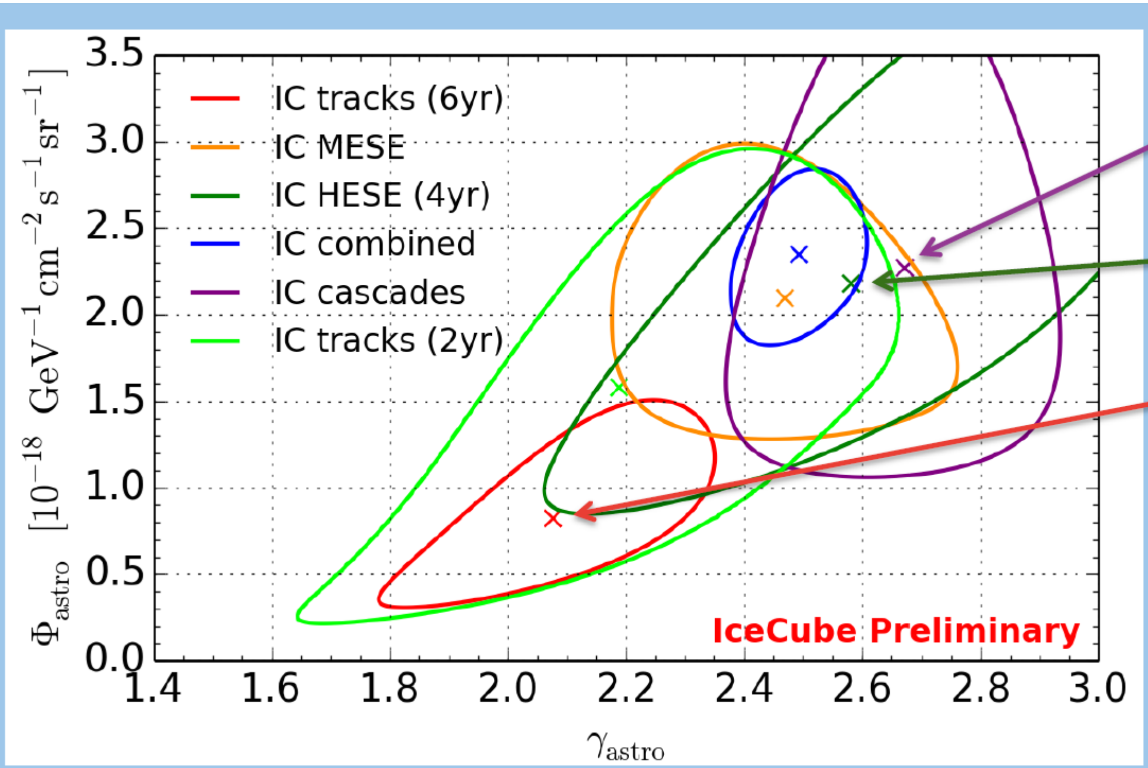


At first sight: good agreement of fluxes for starting and throughgoing events

$$\Phi(E_\nu) = (2.2^{+0.7}_{-0.7}) \cdot 10^{-18} \cdot \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{(-2.58\pm0.25)}$$

$$\Phi(E_\nu) = (0.66^{+0.4}_{-0.3}) \cdot 10^{-18} \cdot \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{(-1.91\pm0.20)}$$

energy/direction dependence?



Most sensitive region at about > 5*10^4 GeV

Most sensitive region at about > 10^5 GeV

Most sensitive region at about > 2*10^5 GeV

Slight trend:

- With the energy of the sensitive region shifting to higher energies the fitted spectral index increases
- Might be a first hint for features in the astrophysical neutrino flux

Summary so far

- **No single strong source**; need at least 100 weak sources to explain diffuse flux

- **Stacking of sources show that there are many different kinds of sources**

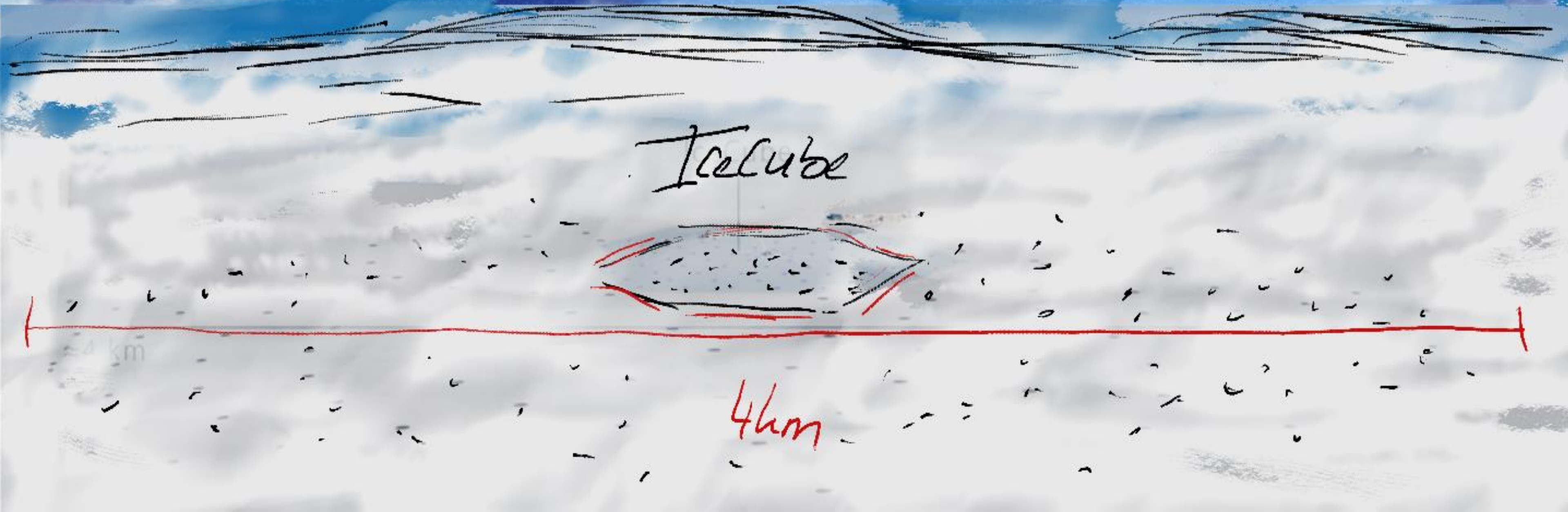
Blazars	< 17% (preliminary)
Nearby Starburst Galaxy	< 8% (preliminary)
Young galactic supernova remnants	< 5% (preliminary)
Galactic Plane	< 14% (preliminary)

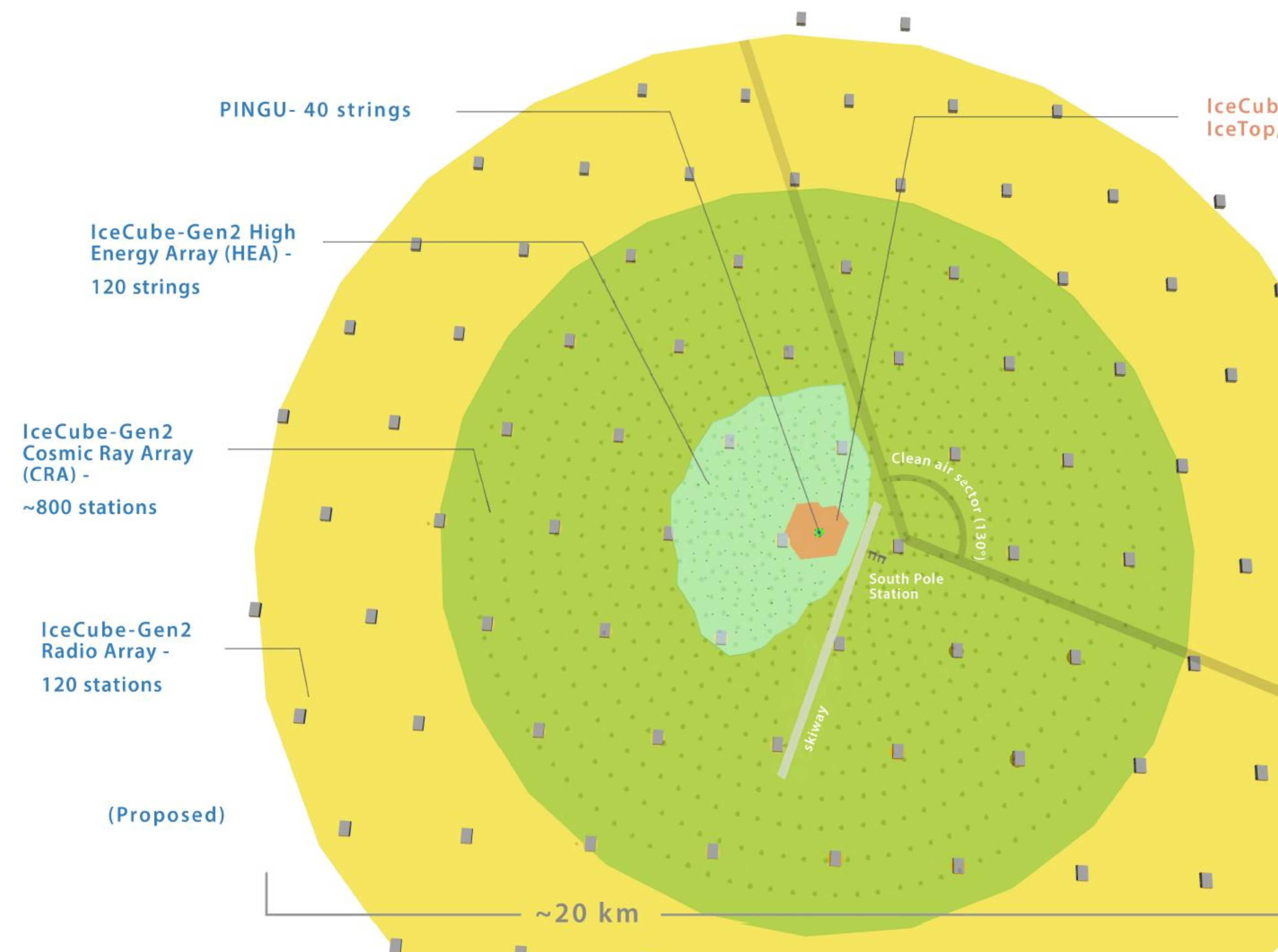
- **80% of sources with redshift > 0.5** (7 Billion light years) arXiv:1602.06625

- Discovery limit not yet $1/\sqrt{\text{time}}$ dependent, **chance to see galactic source**
- Chance to identify υ_τ interactions
- **Indication of break in spectrum & spectral index / flux differences** north/south

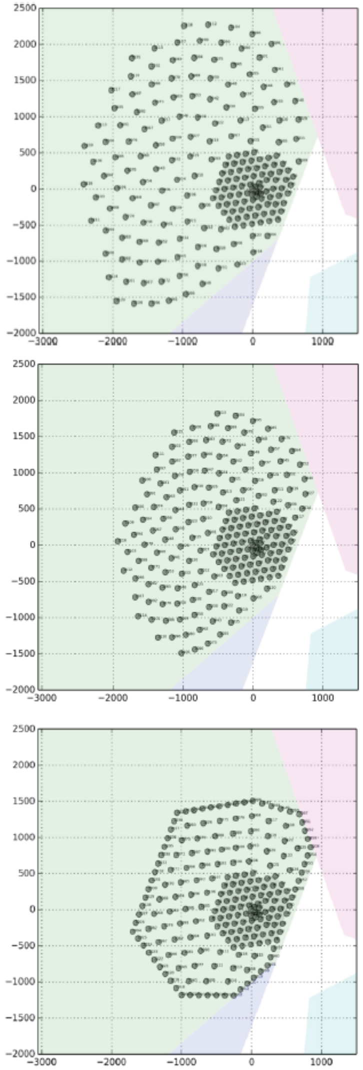
Need more data and a bigger detector !

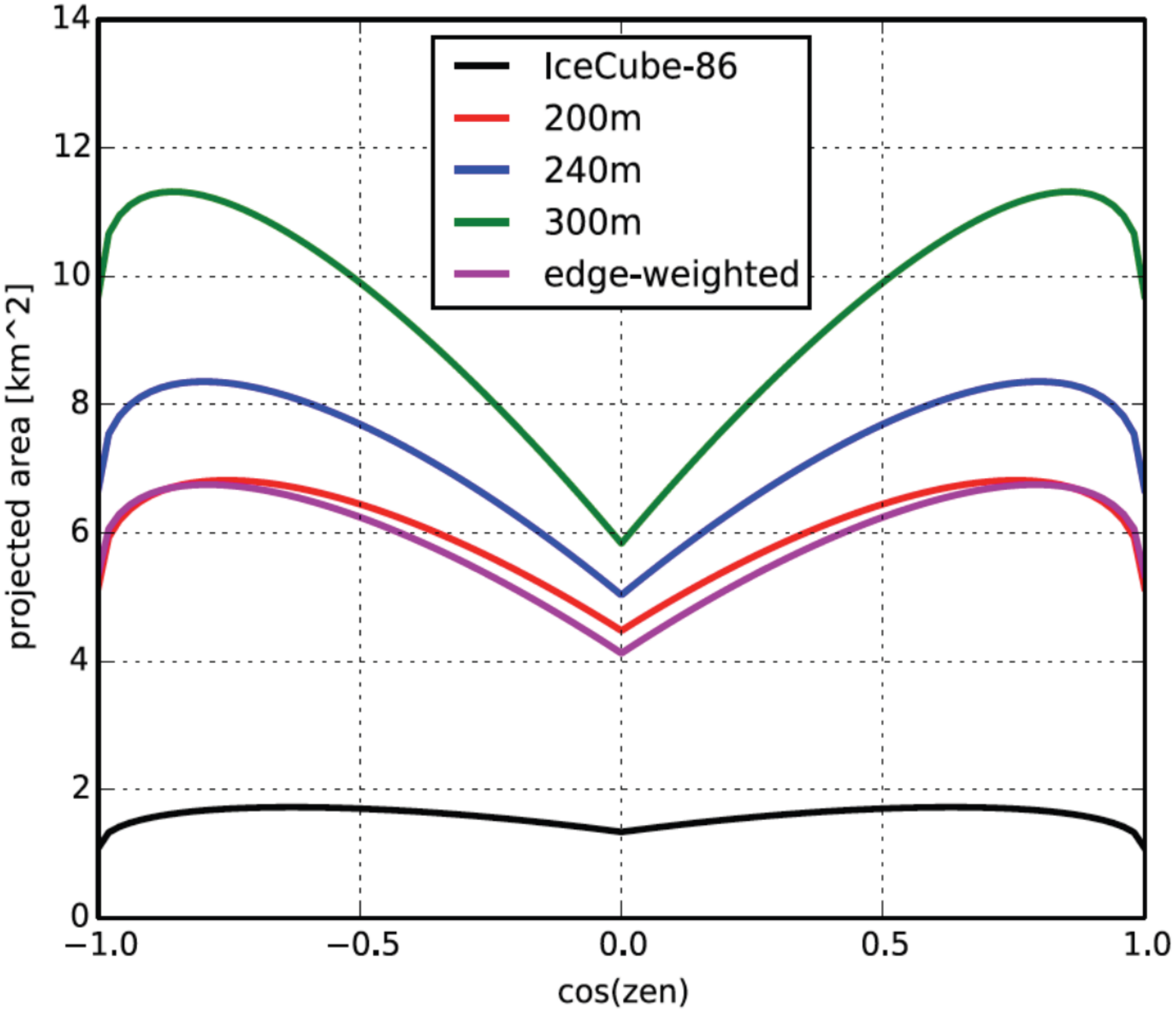
IceCube Gen2




PINGU- 40 strings
IceCub
IceTop/
IceCube-Gen2 High Energy Array (HEA) -
120 strings
IceCube-Gen2 Cosmic Ray Array (CRA) -
~800 stations
IceCube-Gen2 Radio Array -
120 stations
Clean air sector (130°)
South Pole Station
skiway
(Proposed)
~20 km

Geometry studies

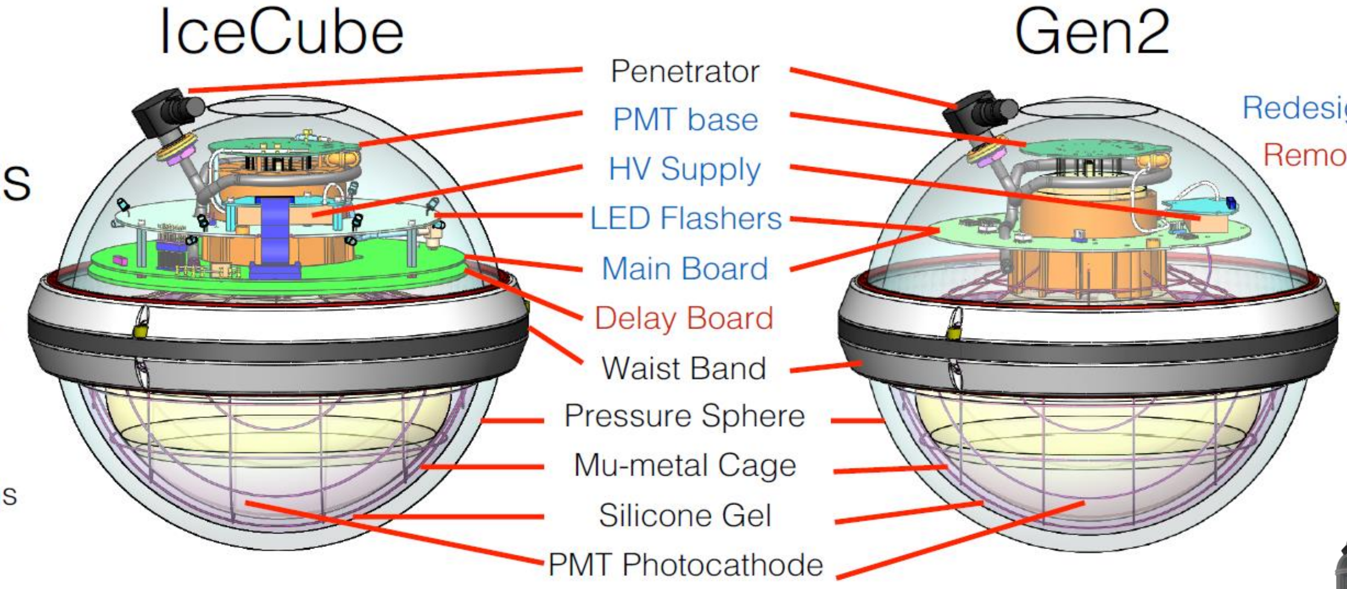




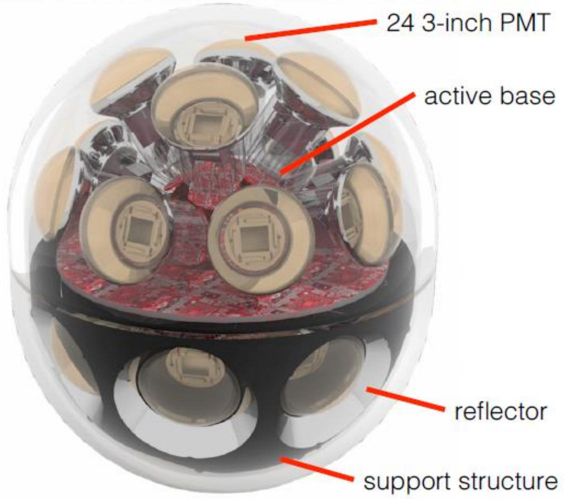
Detector designs for Gen2

Improvements on known technology

New ADC front-end
New firmware
Improved communications

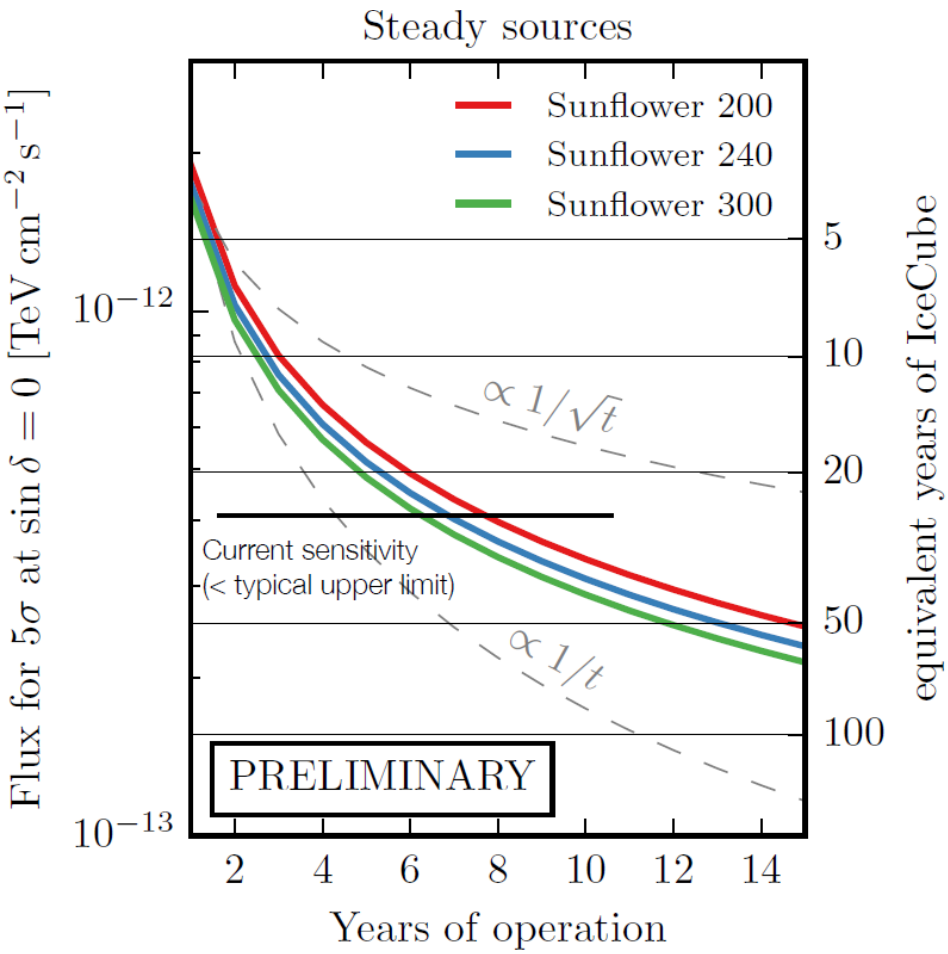


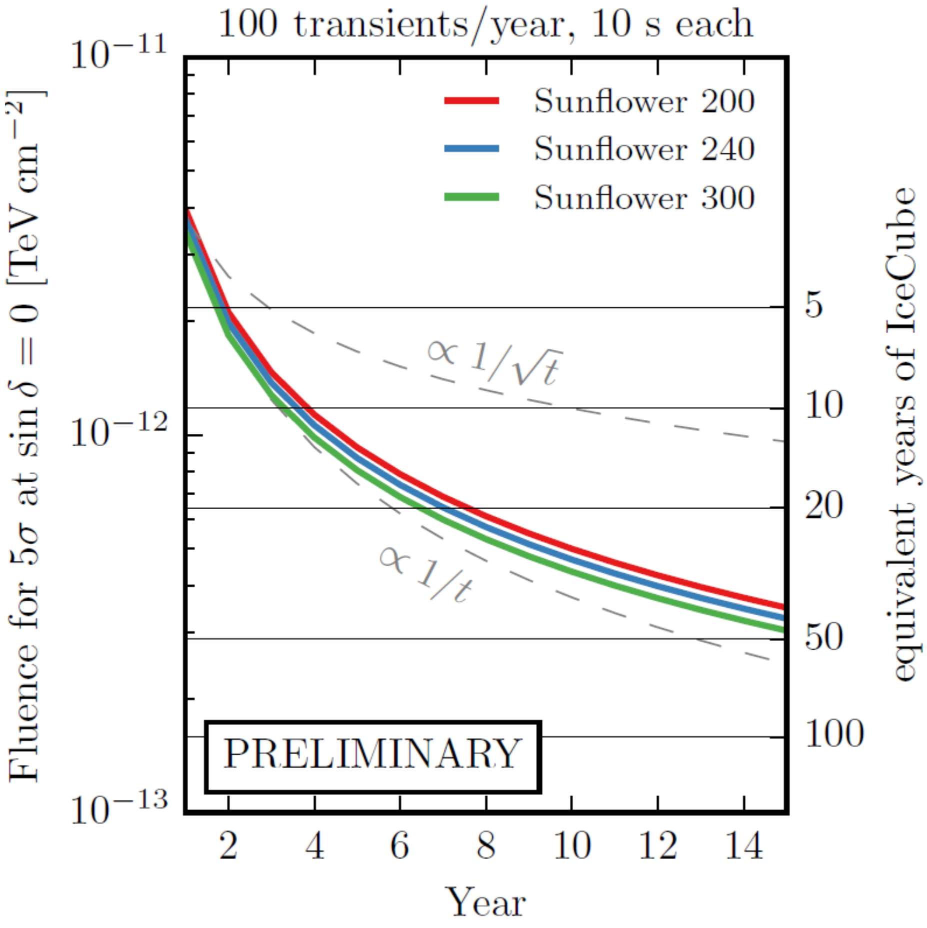
other designs being considered:



Wavelength-shifting optical module

Sensitivity to point sources





Not in 1/ √time regime yet…

Next steps with astrophysical ν's

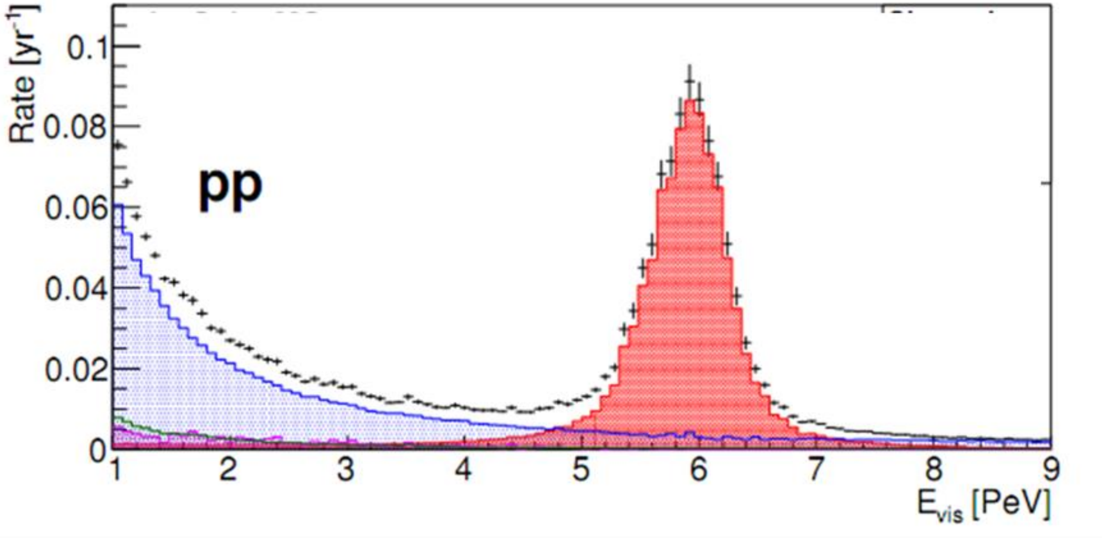
Just one example for additional reach with Gen2:

„magnifiying glass“
Glashow resonance :

$\upsilon_e + e^- \rightarrow W^{real} \rightarrow \upsilon_e + e^-$, qq

Expect 0.88 (**7.2**) events/year with IC86 **(Gen2)**

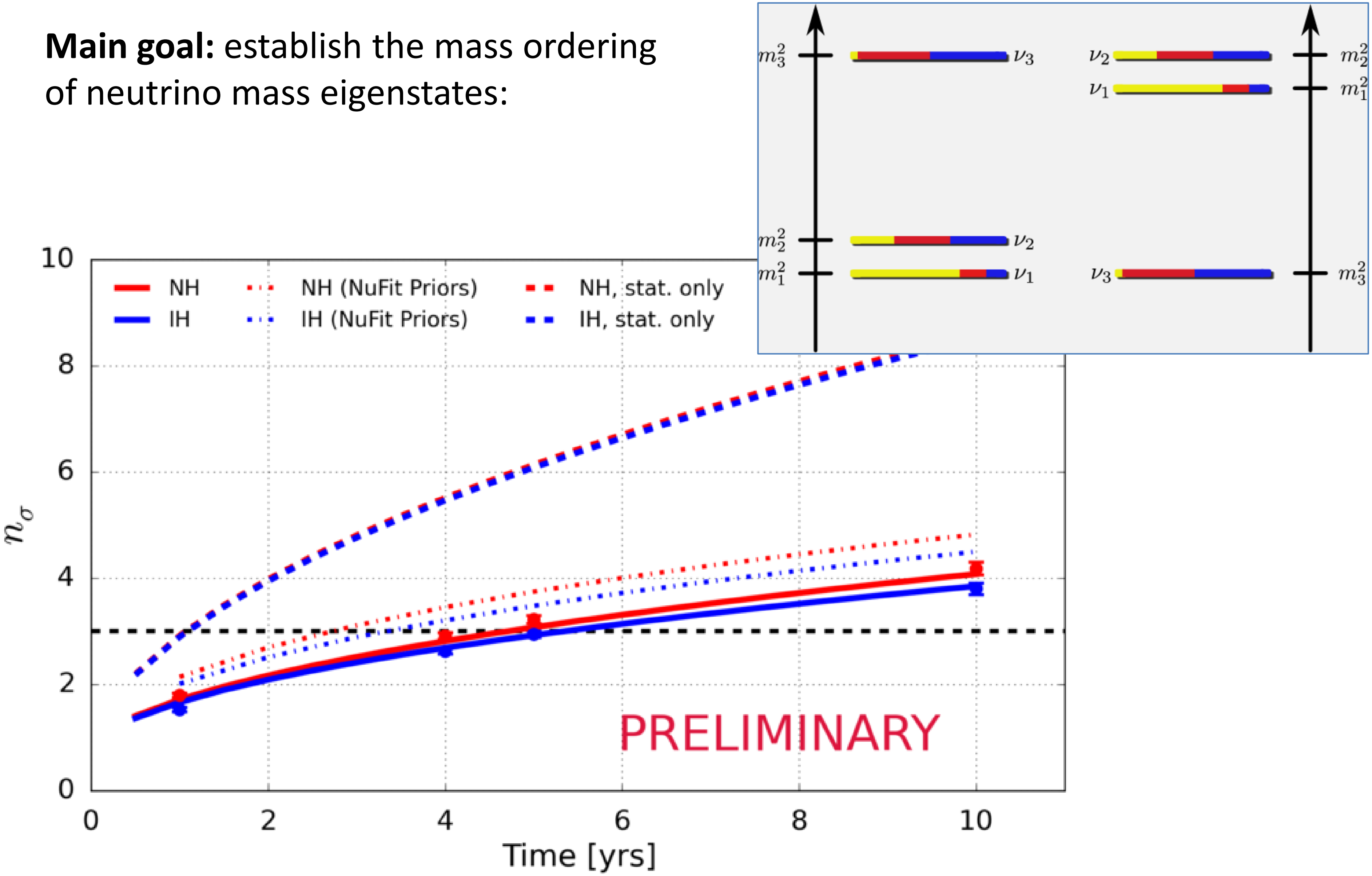
(~10 % background)



Remember: we are looking at so far untested energies

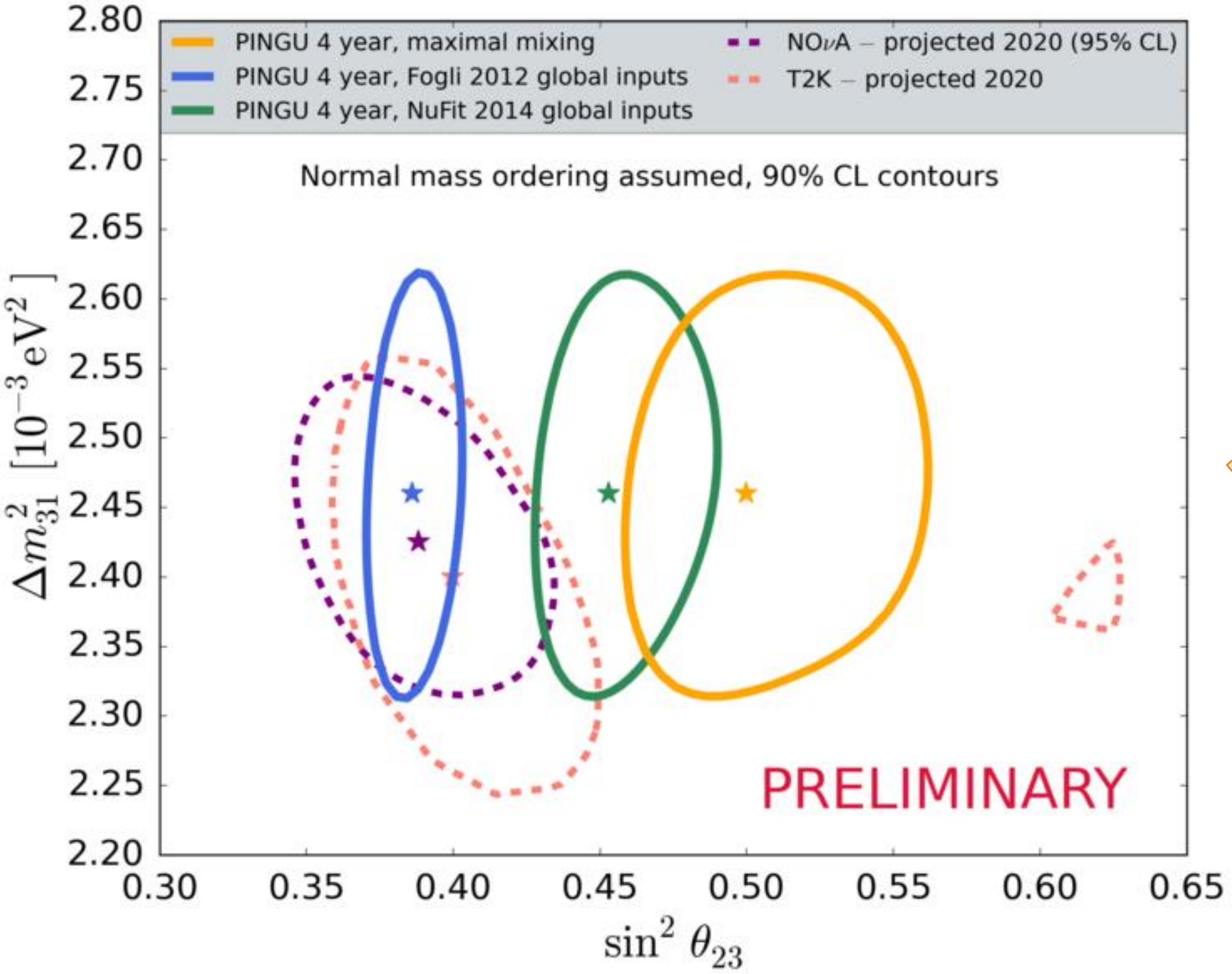
Pingu LOI V2

Main goal: establish the mass ordering of neutrino mass eigenstates:



PINGU LOI V2

Also other neutrino parameters measurable with much improved precision:



Competitive with Accelerator experiments

Summary and outlook

- **Full IceCube data taking from May 2011 (~ 99% of the time available)**
- **IceCube rather „multi-purpose“ for an astroparticle experiment …**
  - by factor ~30 largest detector for atmospheric and astrophysical neutrinos
  - excellent cosmic ray detector
  - highest statistics supernova detector
  - best sensitivities for spin-dependent WIMP cross sections, monopoles and other exotics
  - competitive for determining θ_{23} and Δm^2_{23}
- **IceCube reaching sensitivity of astrophysical importance**
  - 1000 x sensitivity compared to 1995)
- **Many future options**
  - Km3Net in Mediterranean (phase 1 funded) (Phase 2: 3-5 x IceCube volume)
  - IceCube Gen2 (5-10 times IceCube volume at higher energies) + PINGU

The End