Determining the neutrino mass hierarchy with detectors in water and ice

C. Spiering, Prague, May 24, 2013

HELMHOLTZ ASSOCIATION

DESY

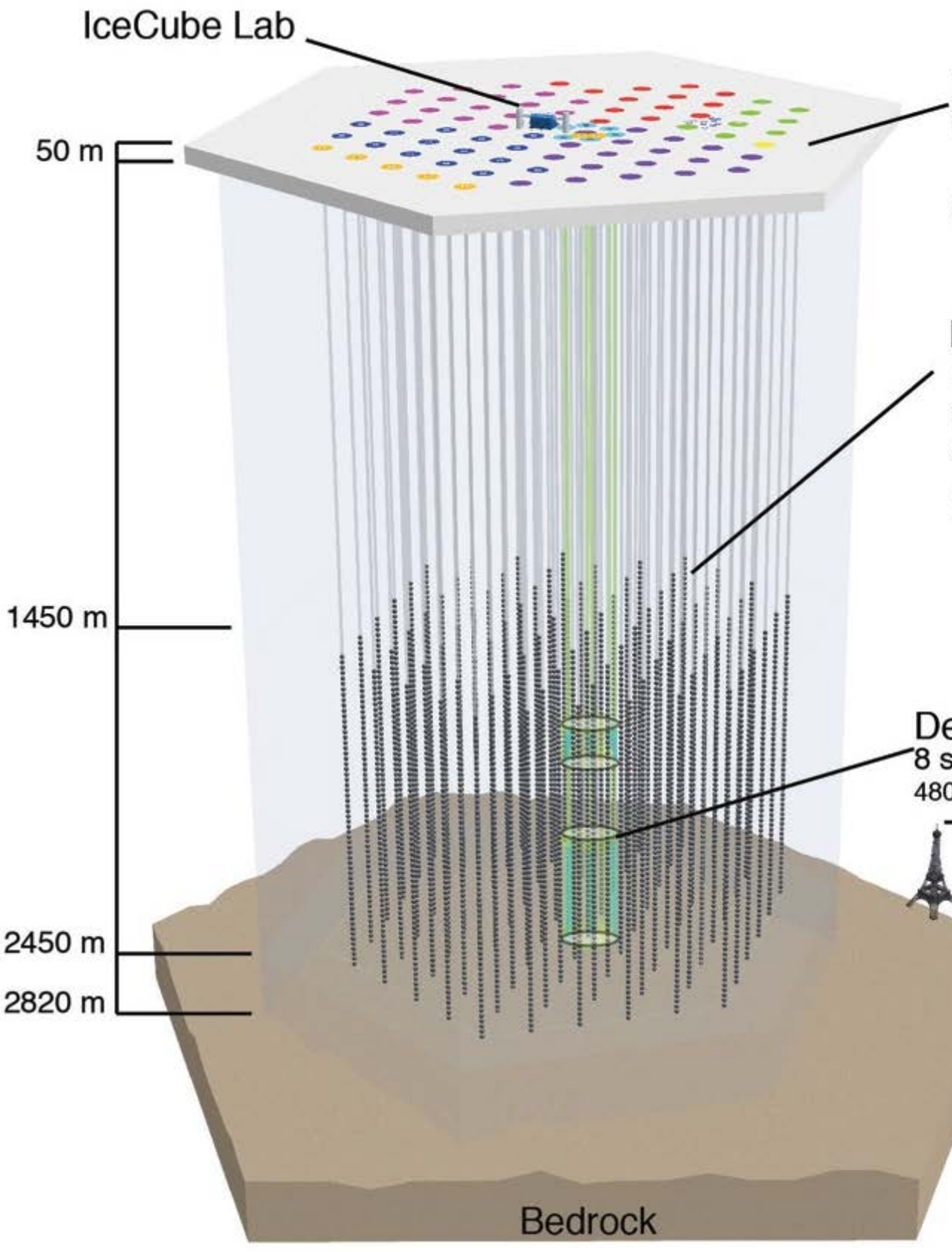
Content

- Present detectors: Antares, IceCube/DeepCore
- Oscillations in Antares and DeepCore
- Measuring the mass hierarchy with PINGU and ORCA
- Status and plans for PINGU
- Protvino → ORCA (J. Brunner, Marseille)

PRESENT DETECTORS:

- ICECUBE/DEEPCORE
- ANTARES

IceCube



IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

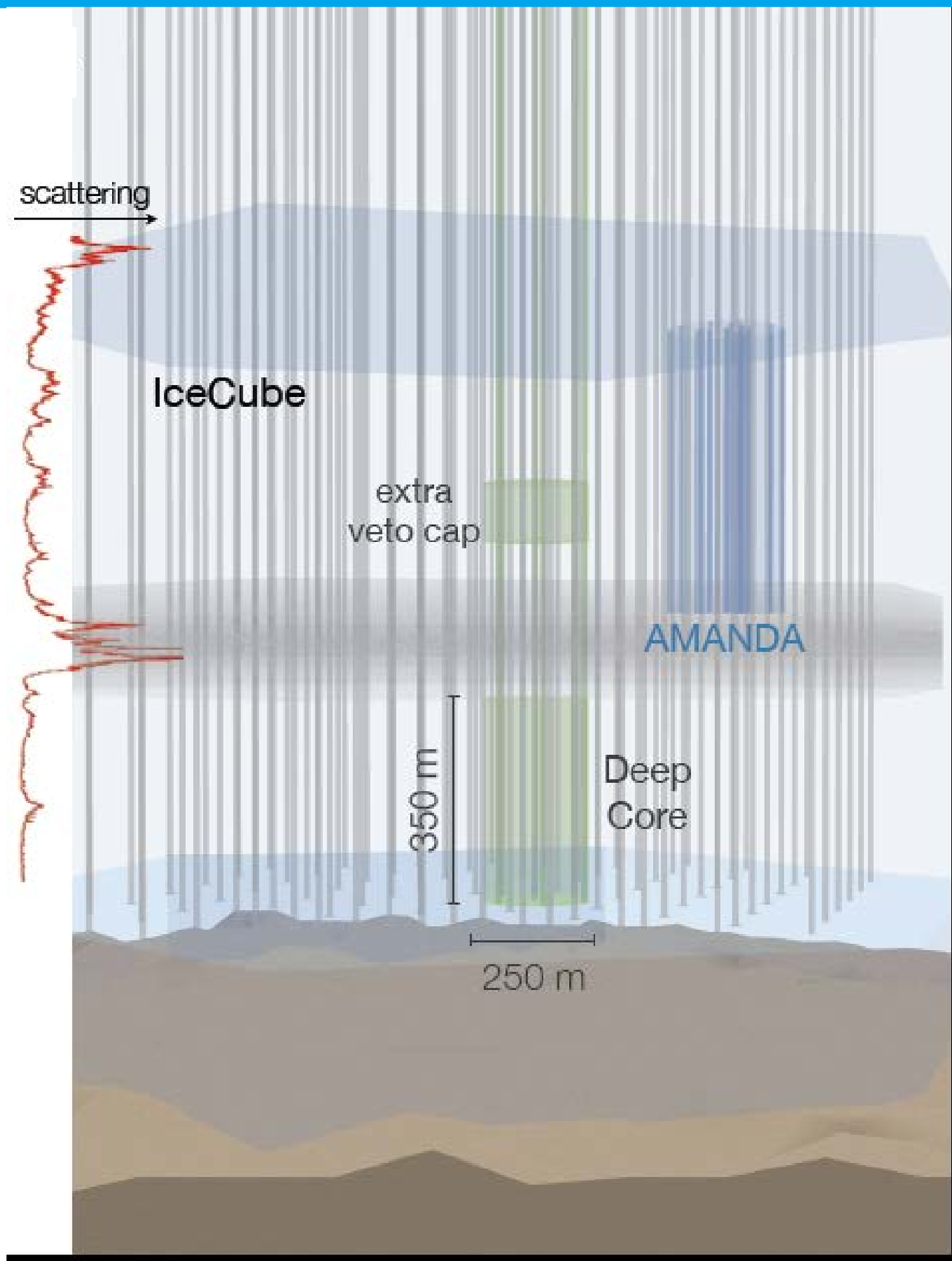
Eiffel Tower
324 m

- ~220 ν/day
- Threshold
  - IceCube ~ 100 GeV
  - DeepCore ~10 GeV

Run 113641 Event 33553254 [6000ns, 9952ns]

DeepCore

- More densily instrumented than IceCube
  - 8 special strings + 12 nearest standard strings
  - Spacing 45 -72 m (IceCube 125 m)
  - Clearest ice (λ_{eff} ~ 45-50 m)
  - High QE PMT (35%)
- Taken alltogether: 5 times better photon collection than standard IceCube



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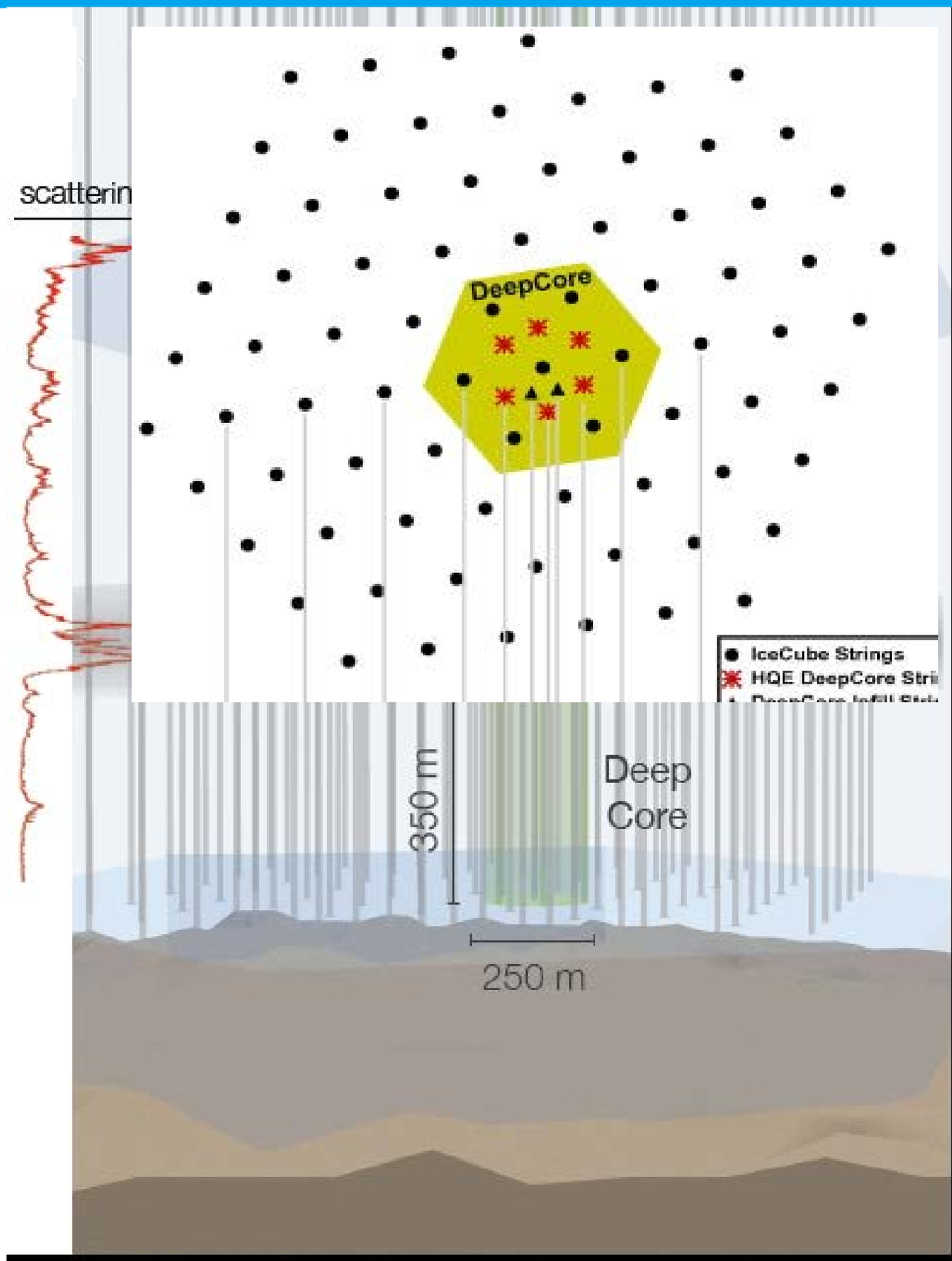

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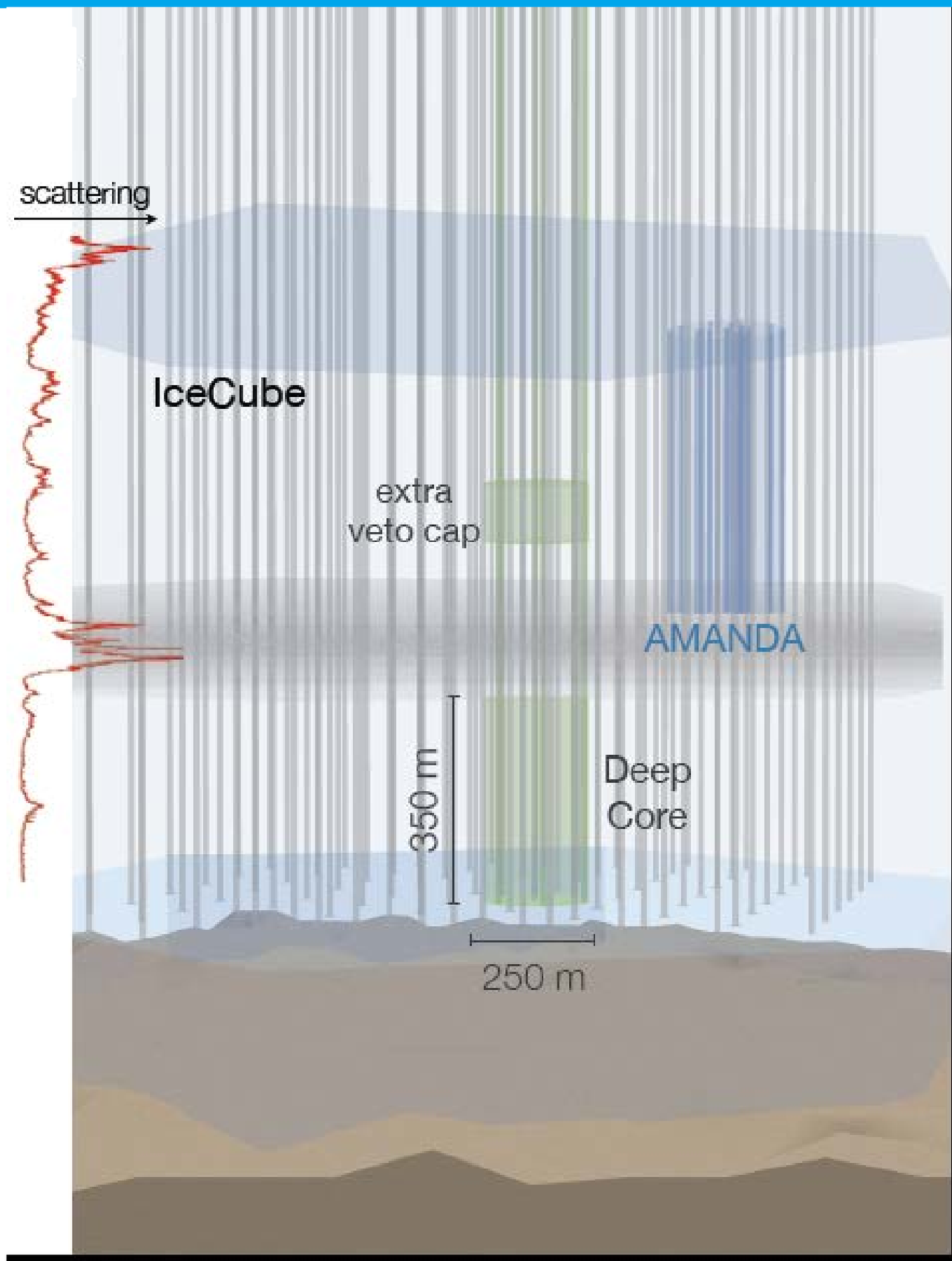
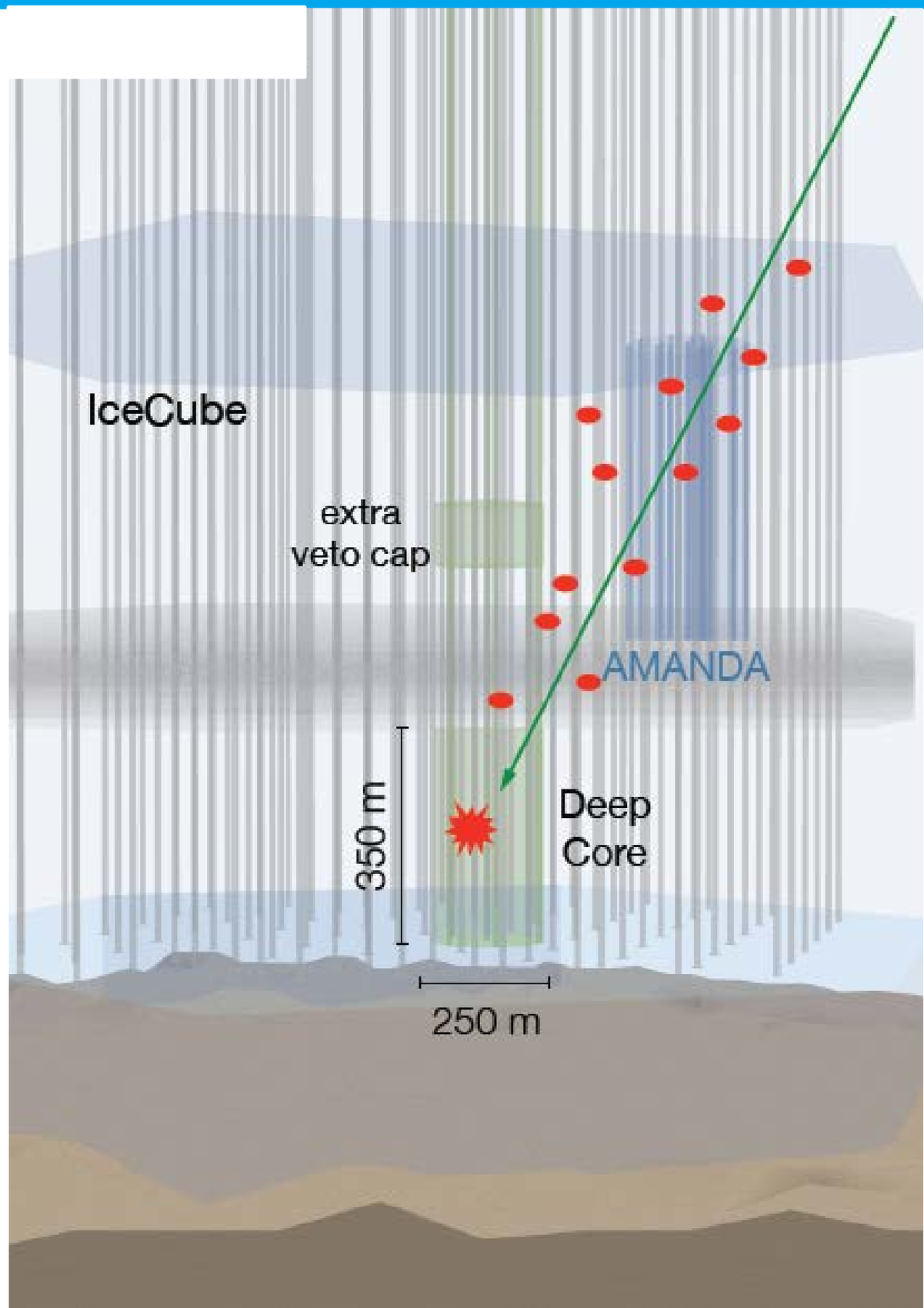


DeepCore

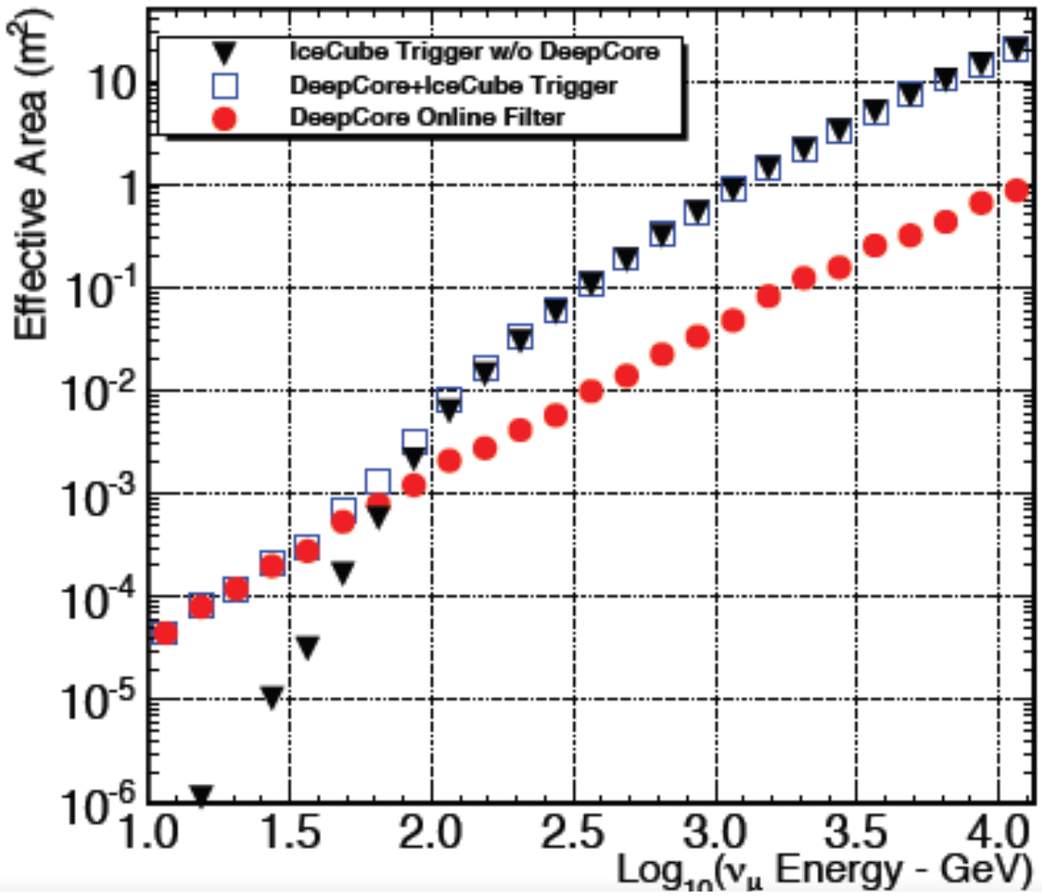
- Depth 2.5 km.w.e.
- Cosmic ray background ~ $10^{5.5}$ of atmospheric neutrinos
- Top and outer layers provide a muon shield
- → effective depth w.r.t. muon background much deeper
- Vetoing algorithms surpass 10^6 rejection level
- Threshold 10-20 GeV



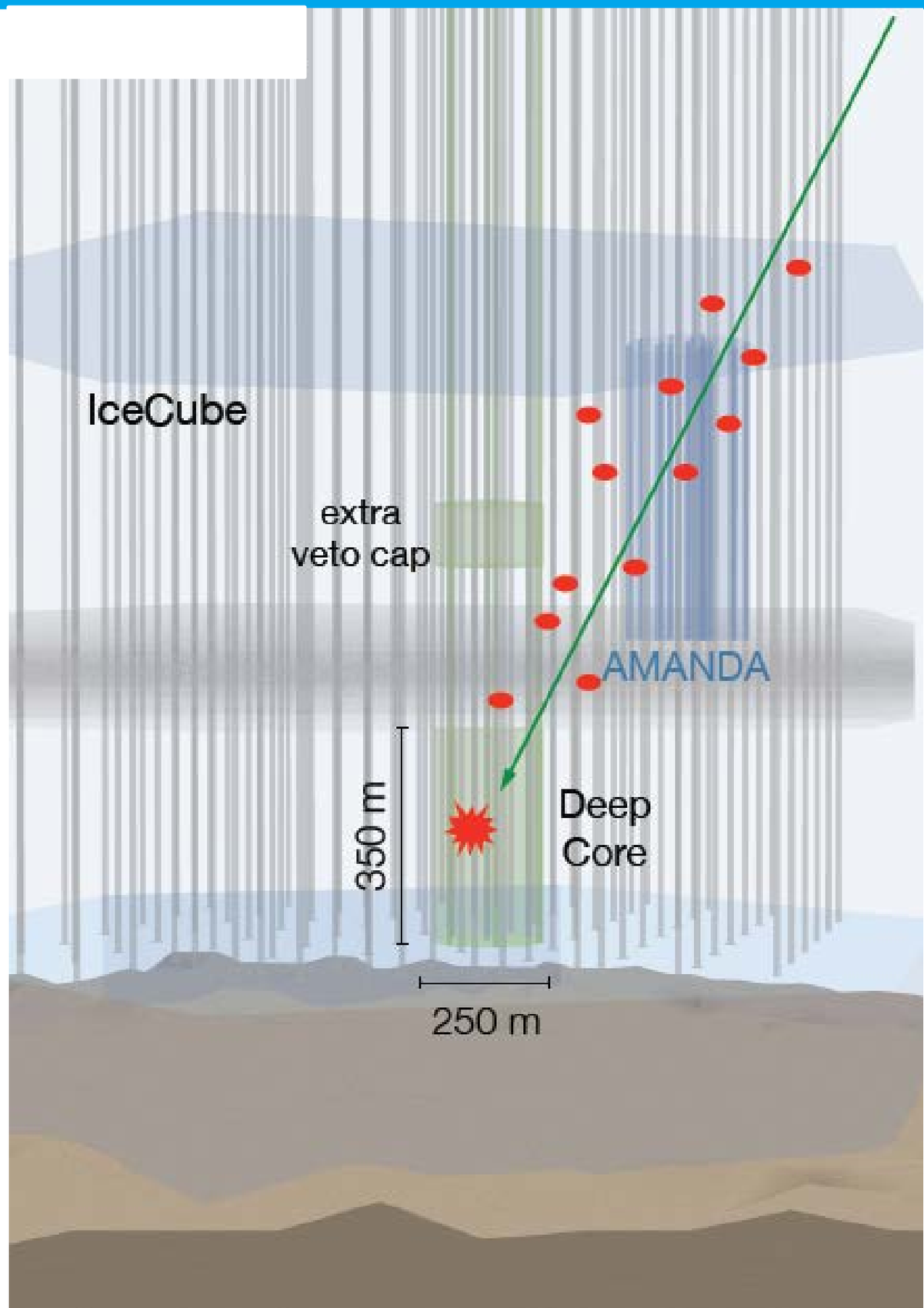
DeepCore

Effective area for ν_μ at trigger level

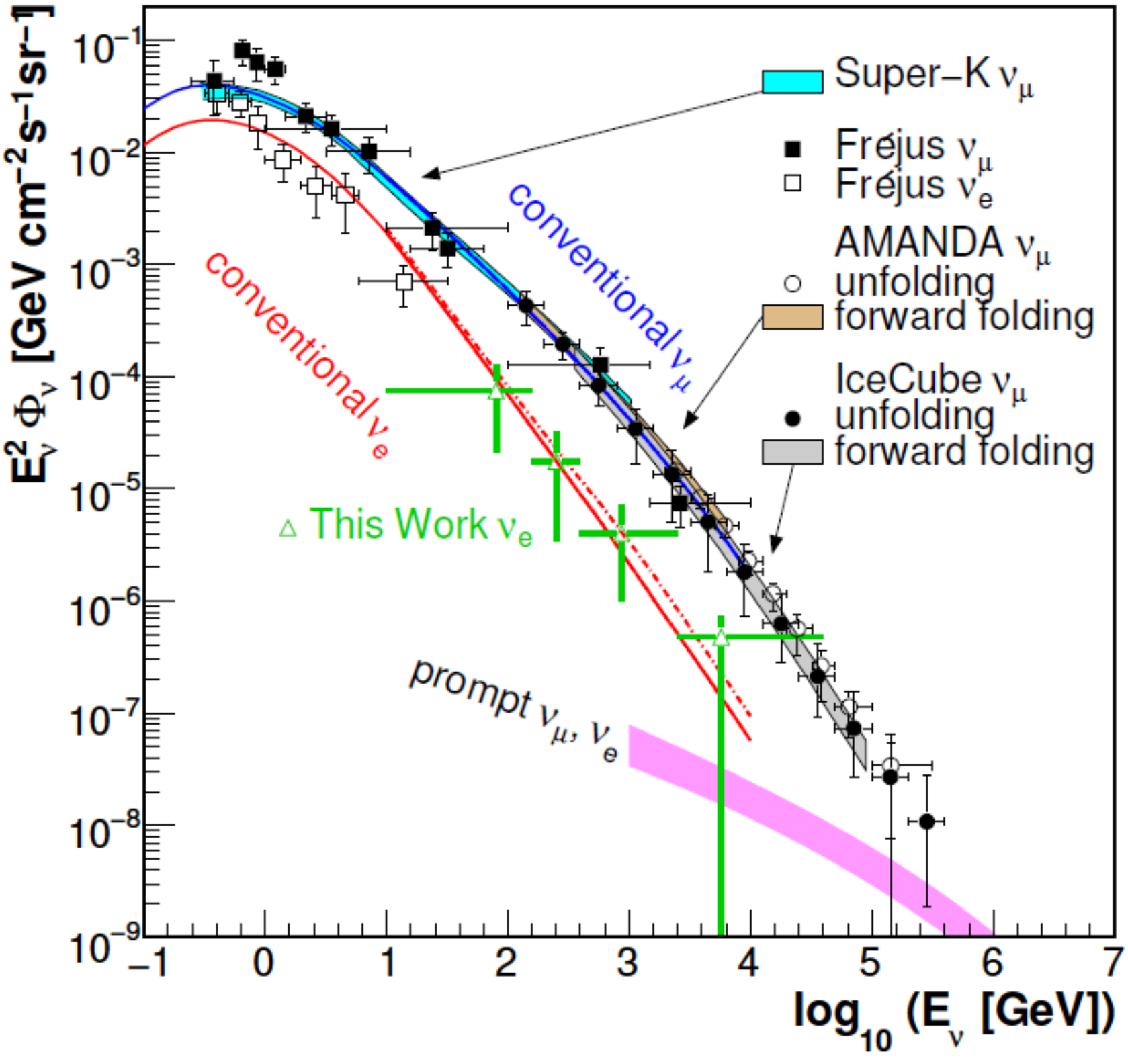
Reconstruction efficiencies not included yet – relative effect likely to increase



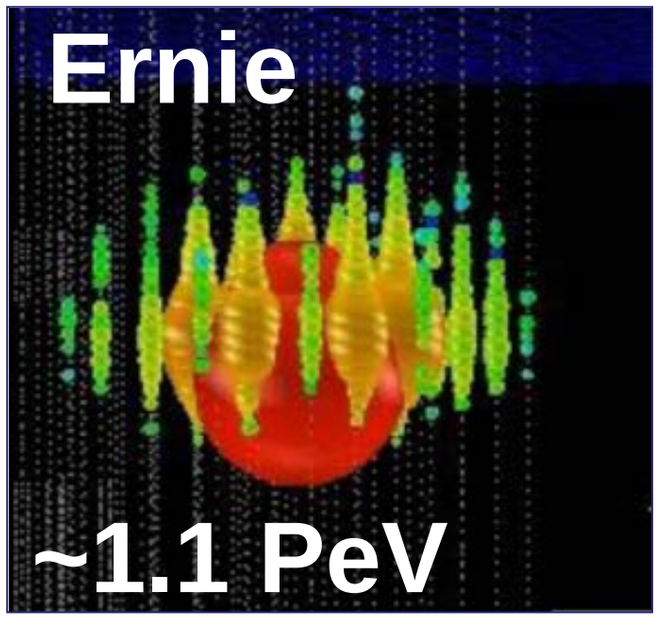
- **Threshold 10-20 GeV**

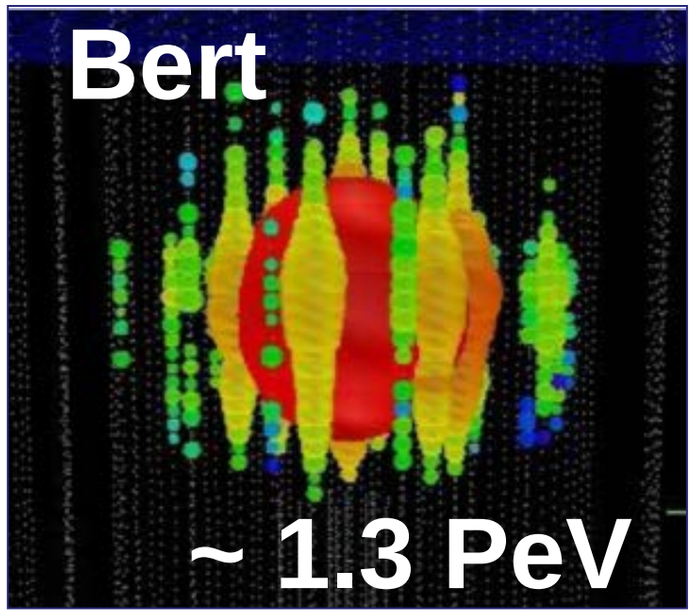


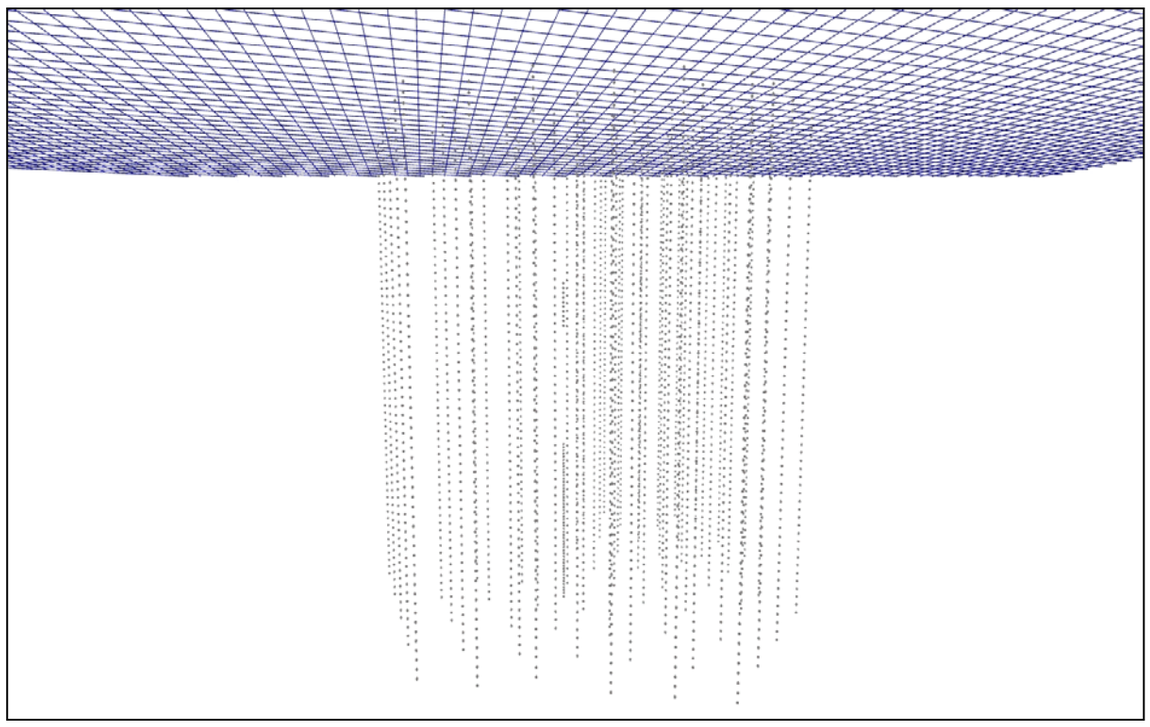
Atmospheric neutrinos in IceCube



Recent IceCube results at the HE frontier



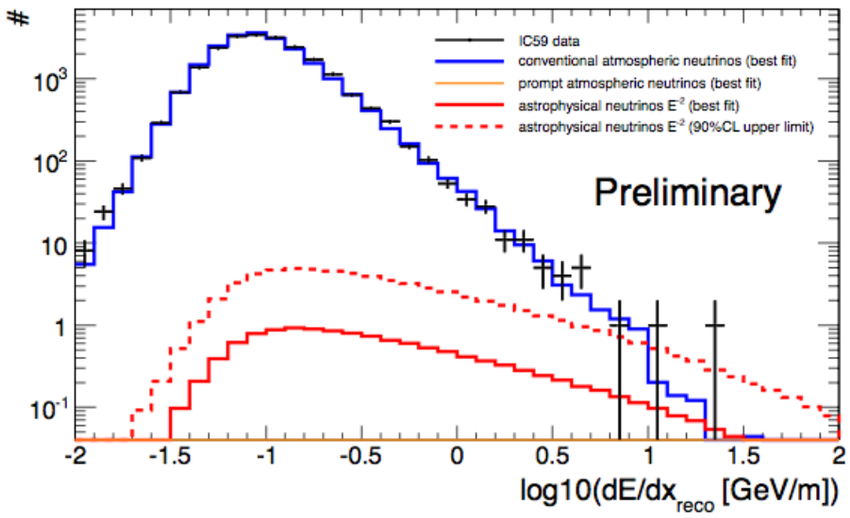


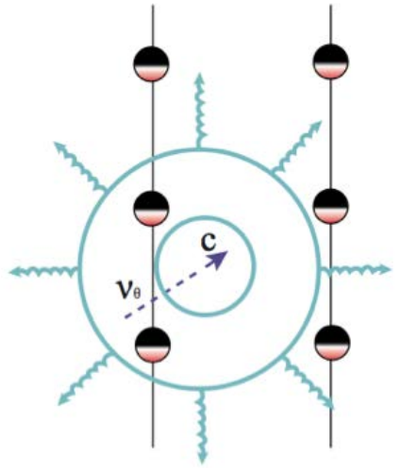


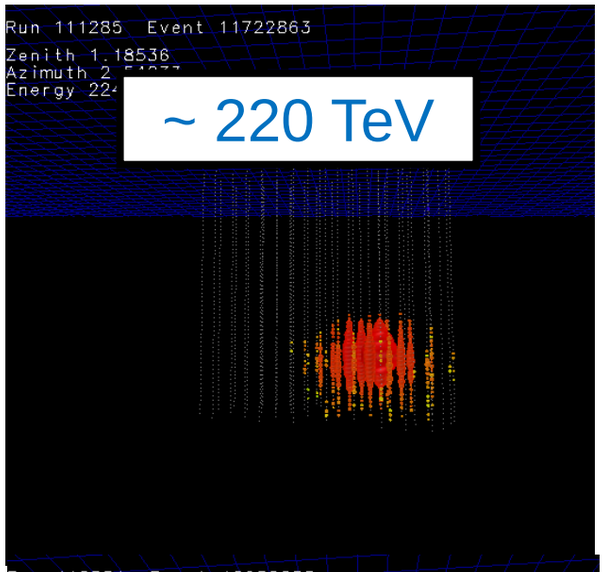
Until last week:

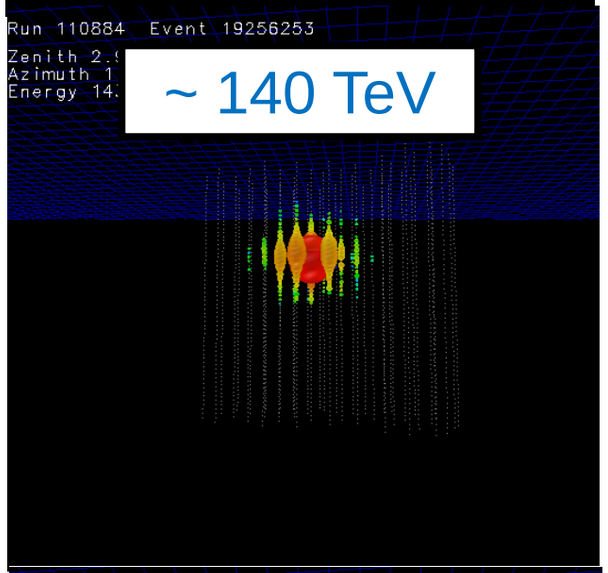
- **Two ~ PeV events**
- **PLUS excesses in the 100-200 TeV range**
  - **Left: muon with ~ 200 TeV**
  - **Also 3 cascade events 140 -200 GeV**
- **Atmospheric neutrinos from charm decay („prompt neutrinos“) or extraterrestrial neutrinos ??**

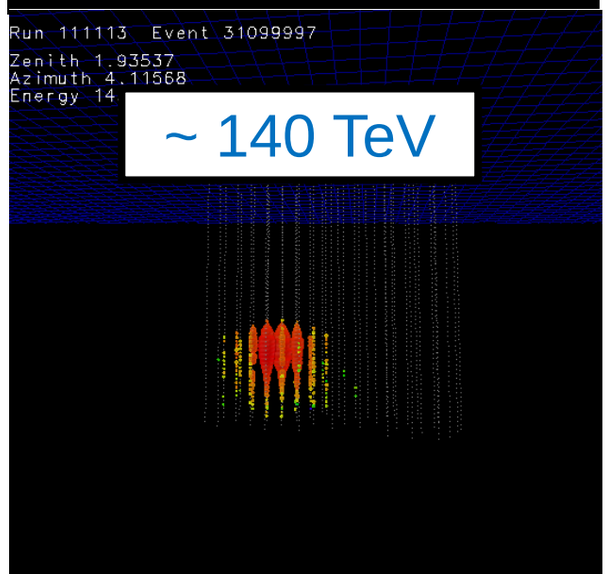
Recent IceCube results at the HE frontier



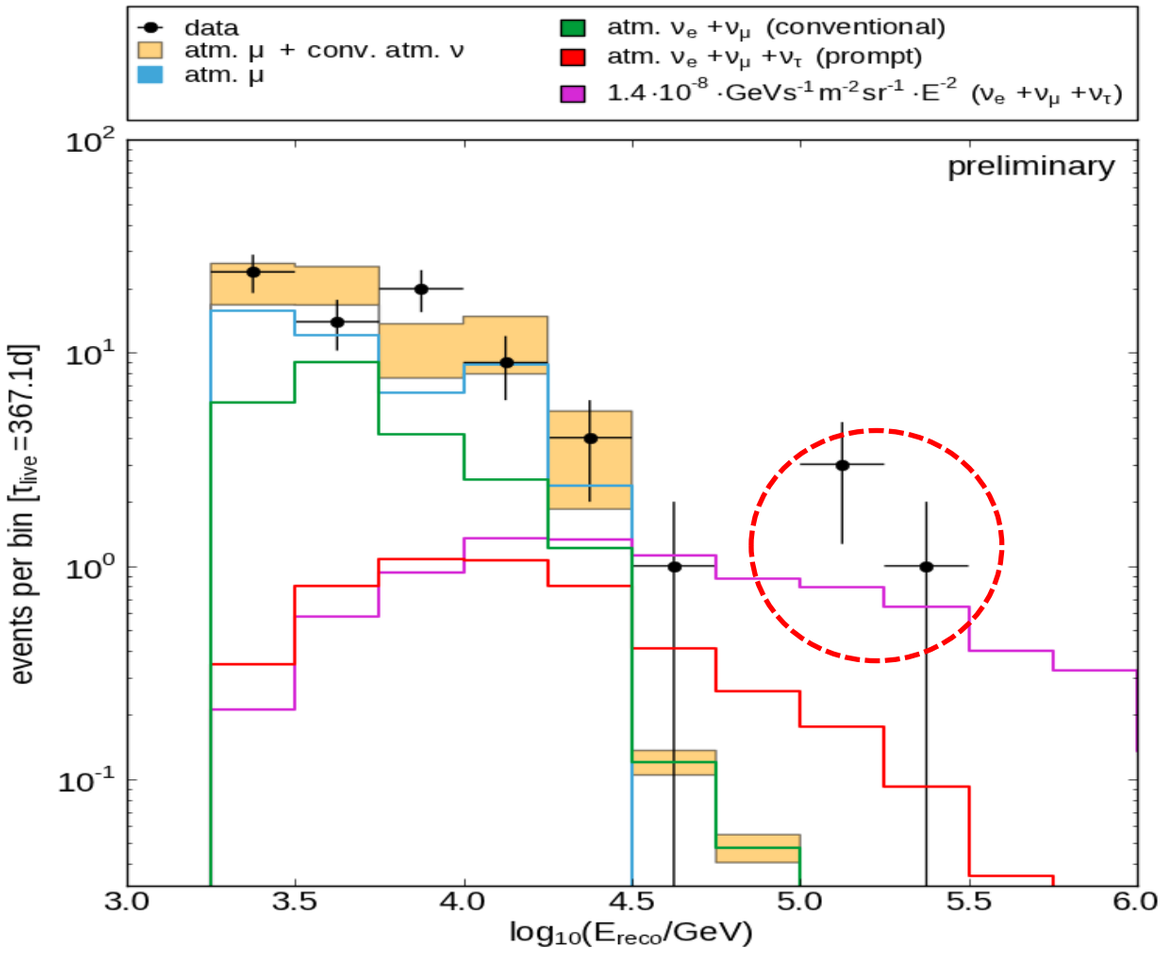








- **Top: the excess of the 200 TeV muon events**

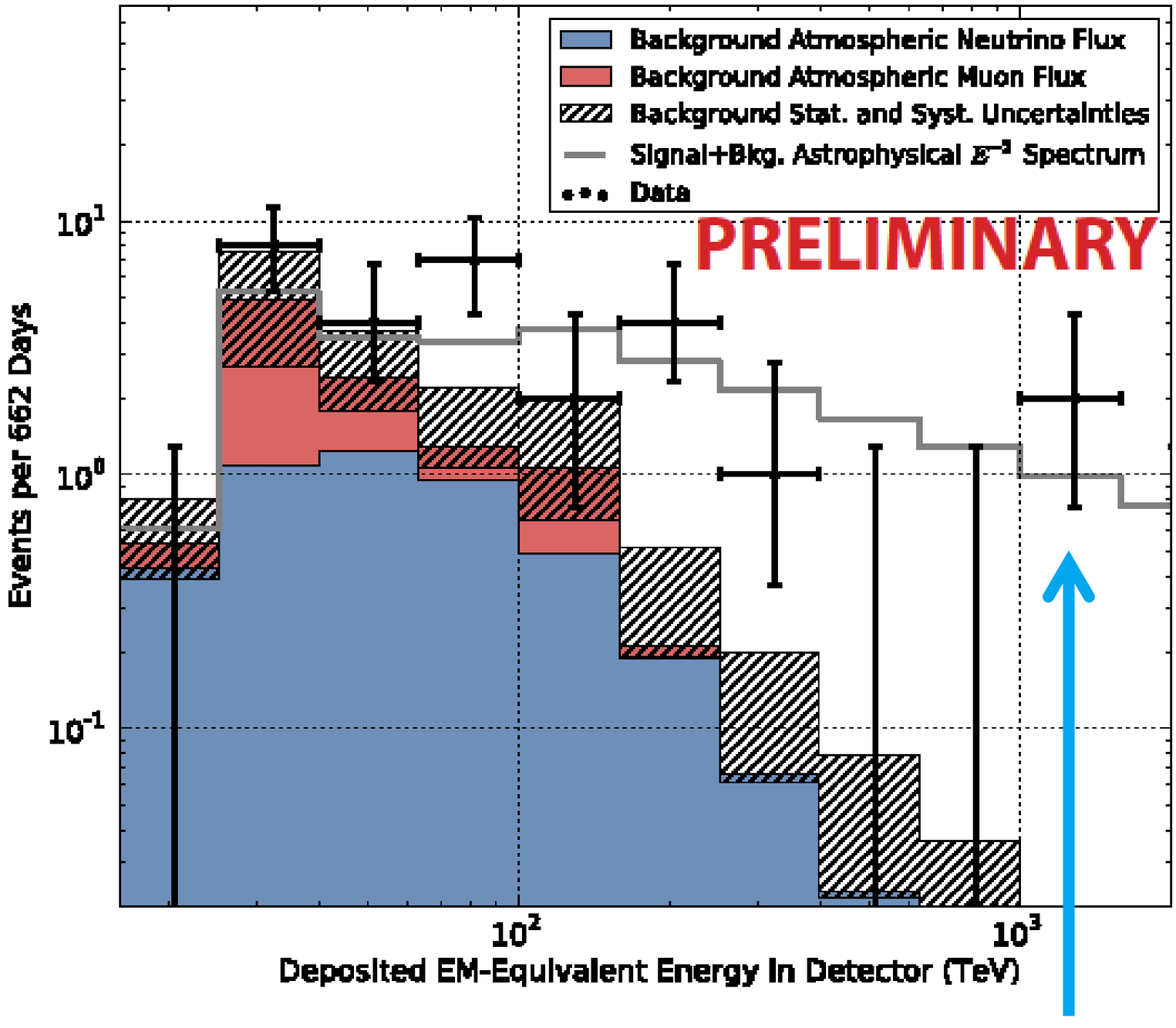


- **Right: the 3 cascade events**

Recent IceCube results at the HE frontier

At present:

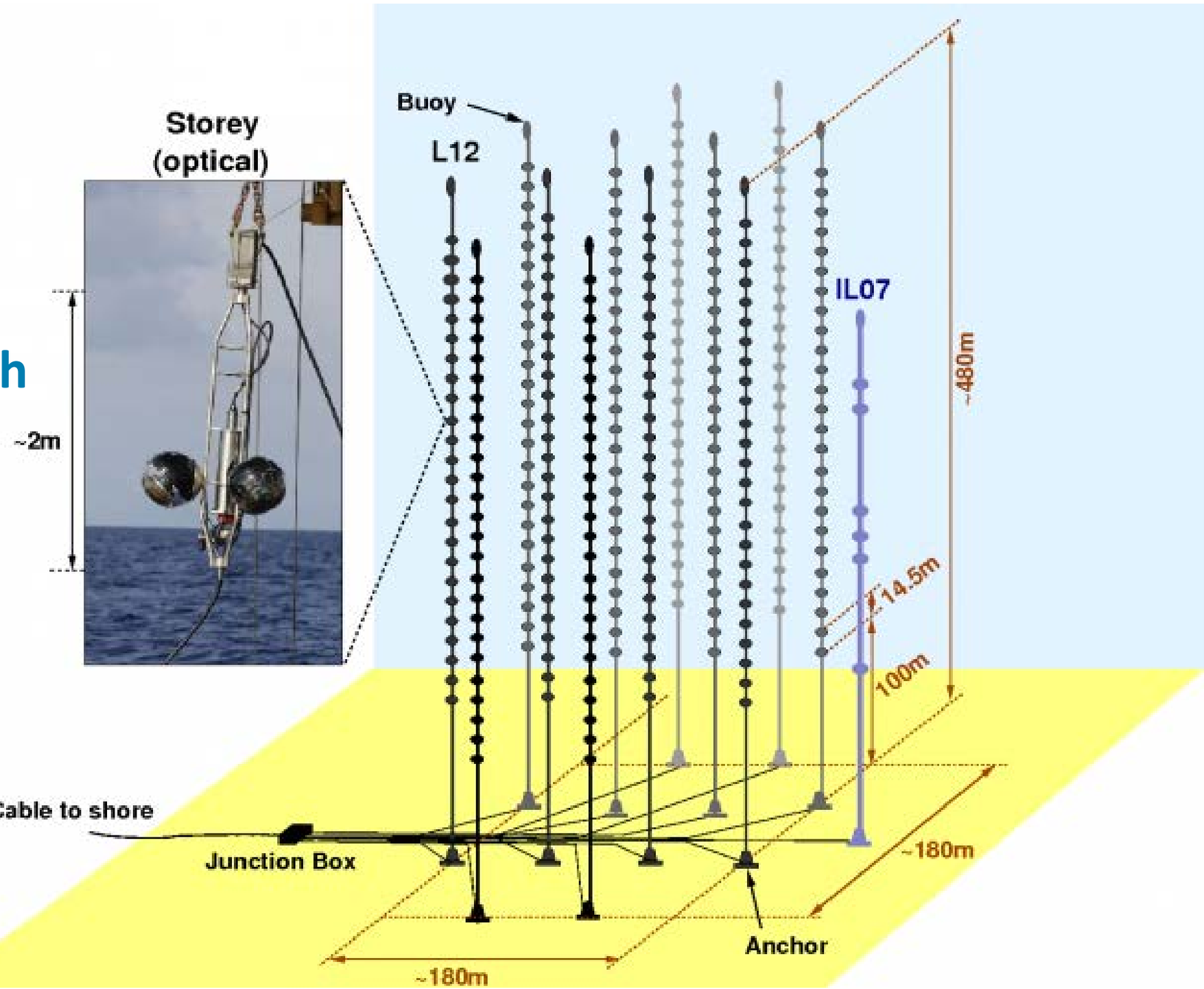
- 26 more events („starting track analysis“)
- Significance of all 28 events 4.3 σ
- More data to be analyzed
- Expect > 5σ at end 2013
- Systematics! (Charm, Energy scale, ...)



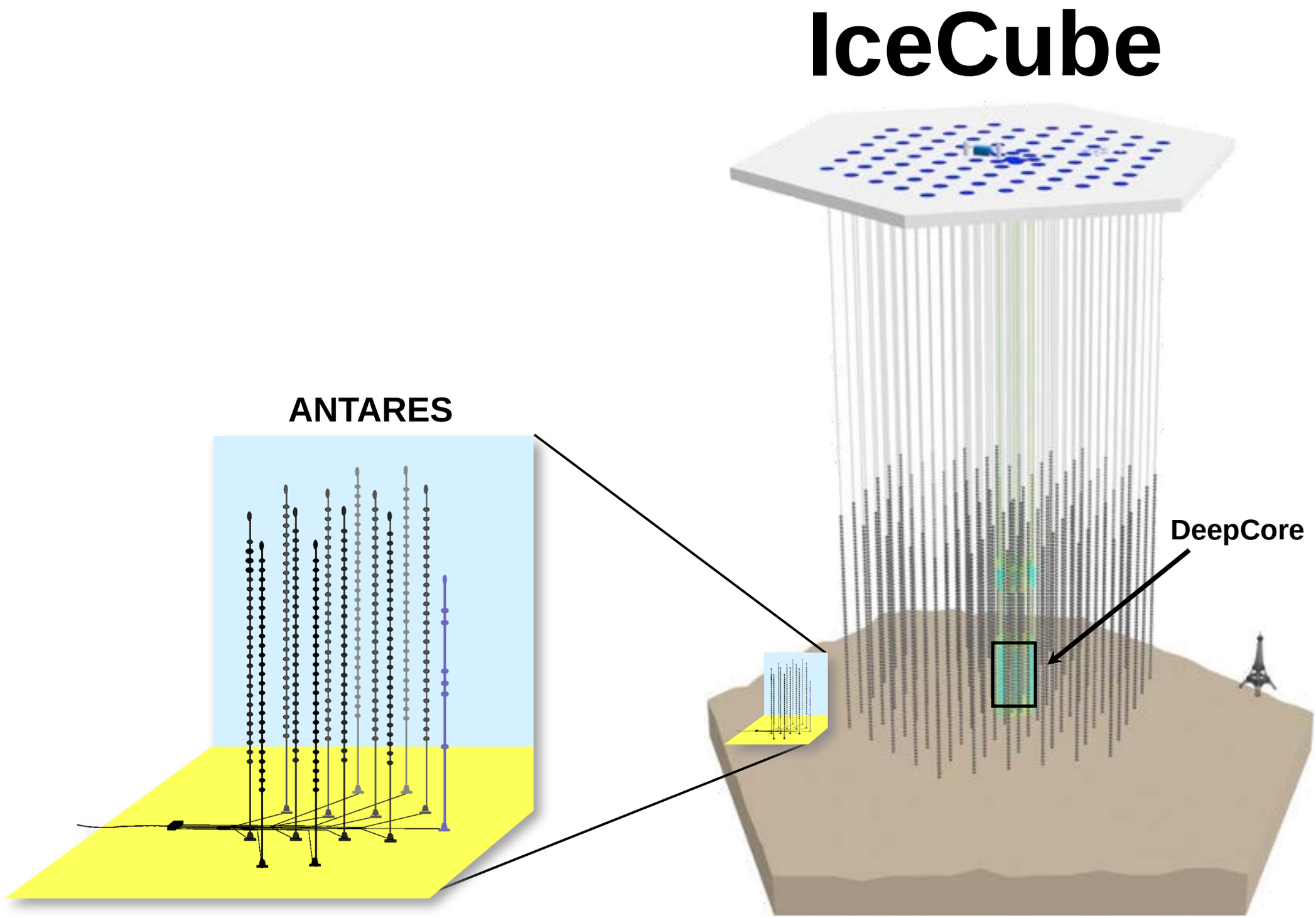
Ernie and Bert

ANTARES

- Mediterranean Sea close to Toulon
- Depth ~2475 km
- Volume ~0.01 km³
- 12 strings, each with 25 PMT triplets
- Operating in final configuration since 2008



Scales

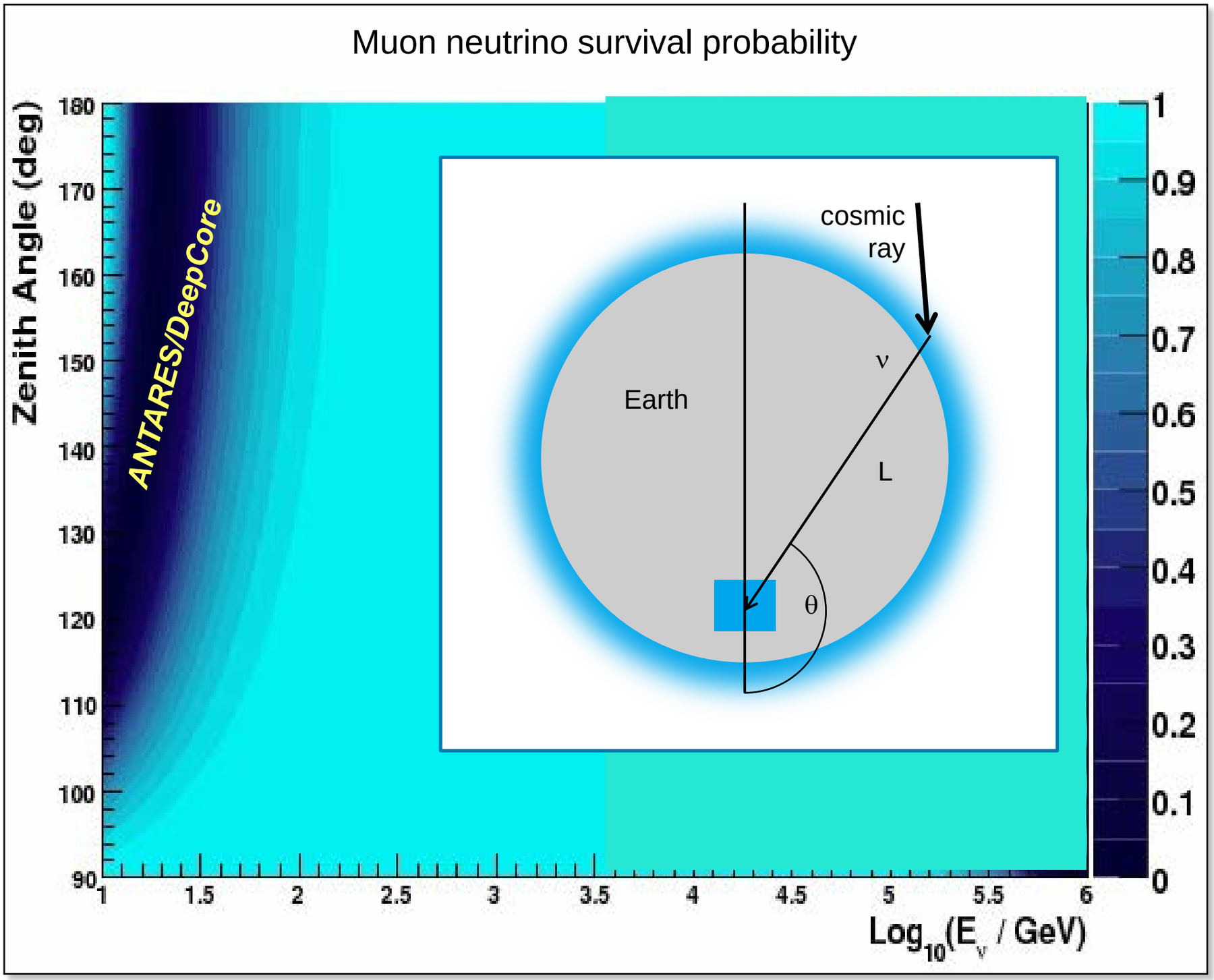


OSCILLATIONS IN ANTARES AND DEEPCORE

Oscillations of atmospheric neutrinos

Vertically upward

Horizontal



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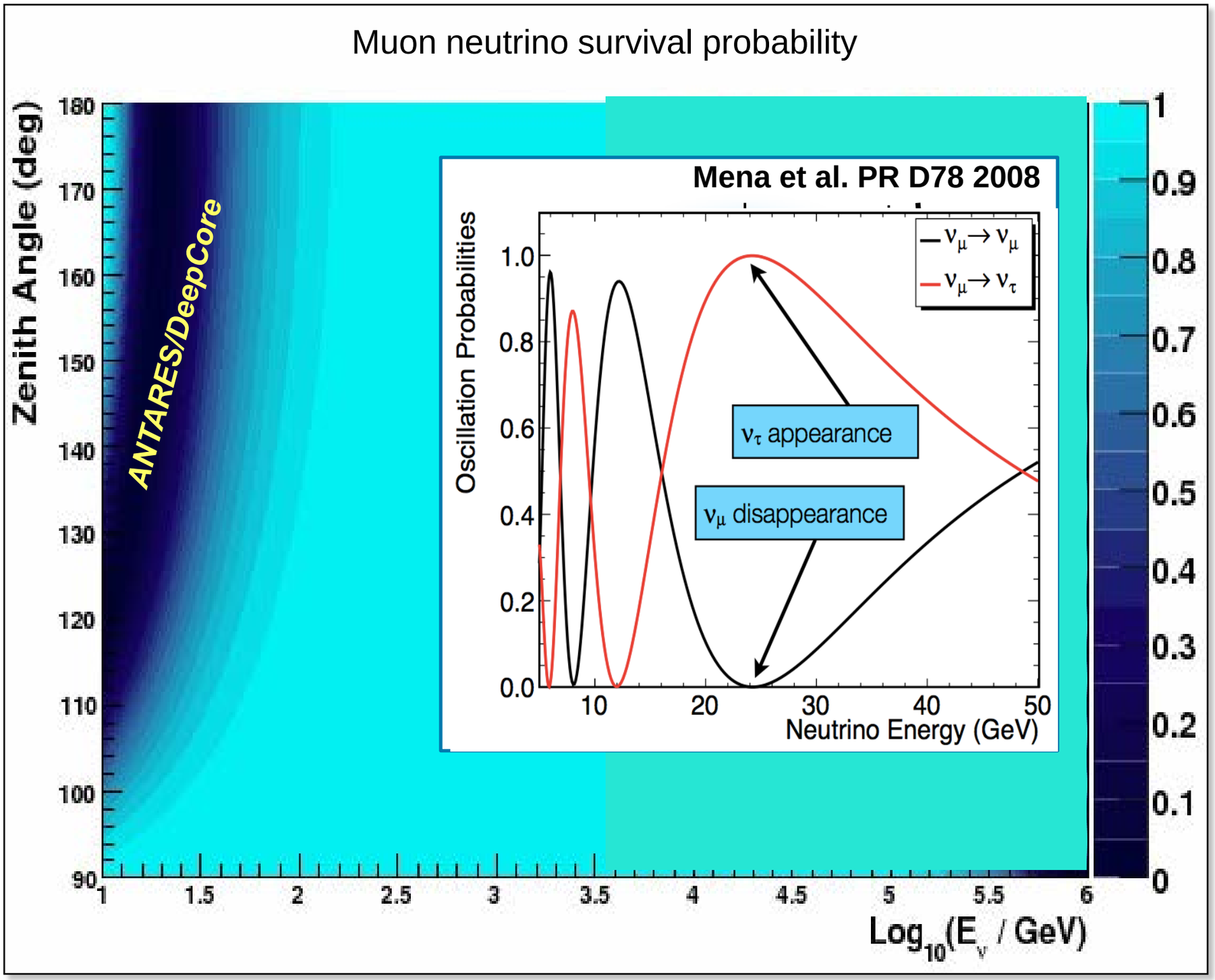

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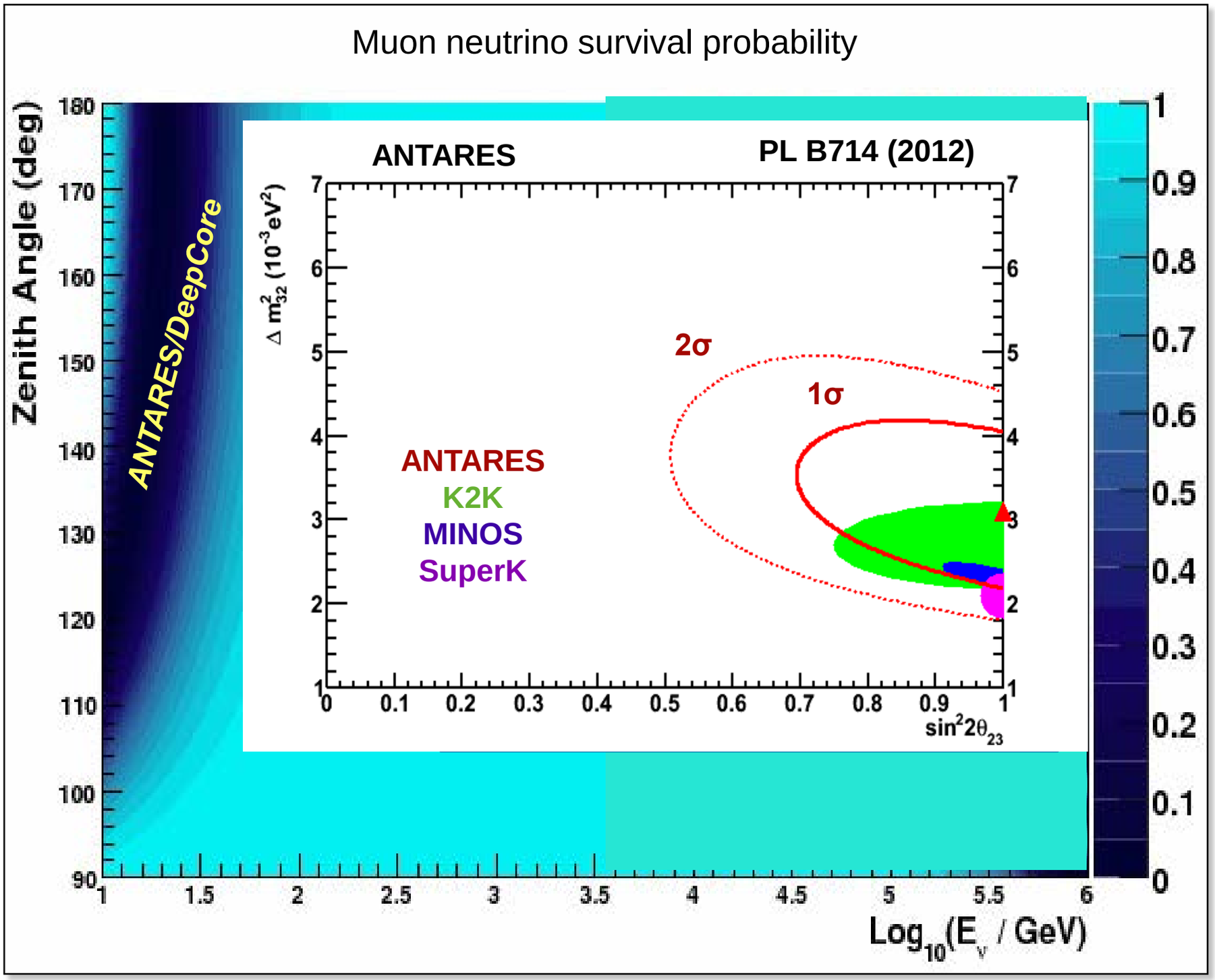
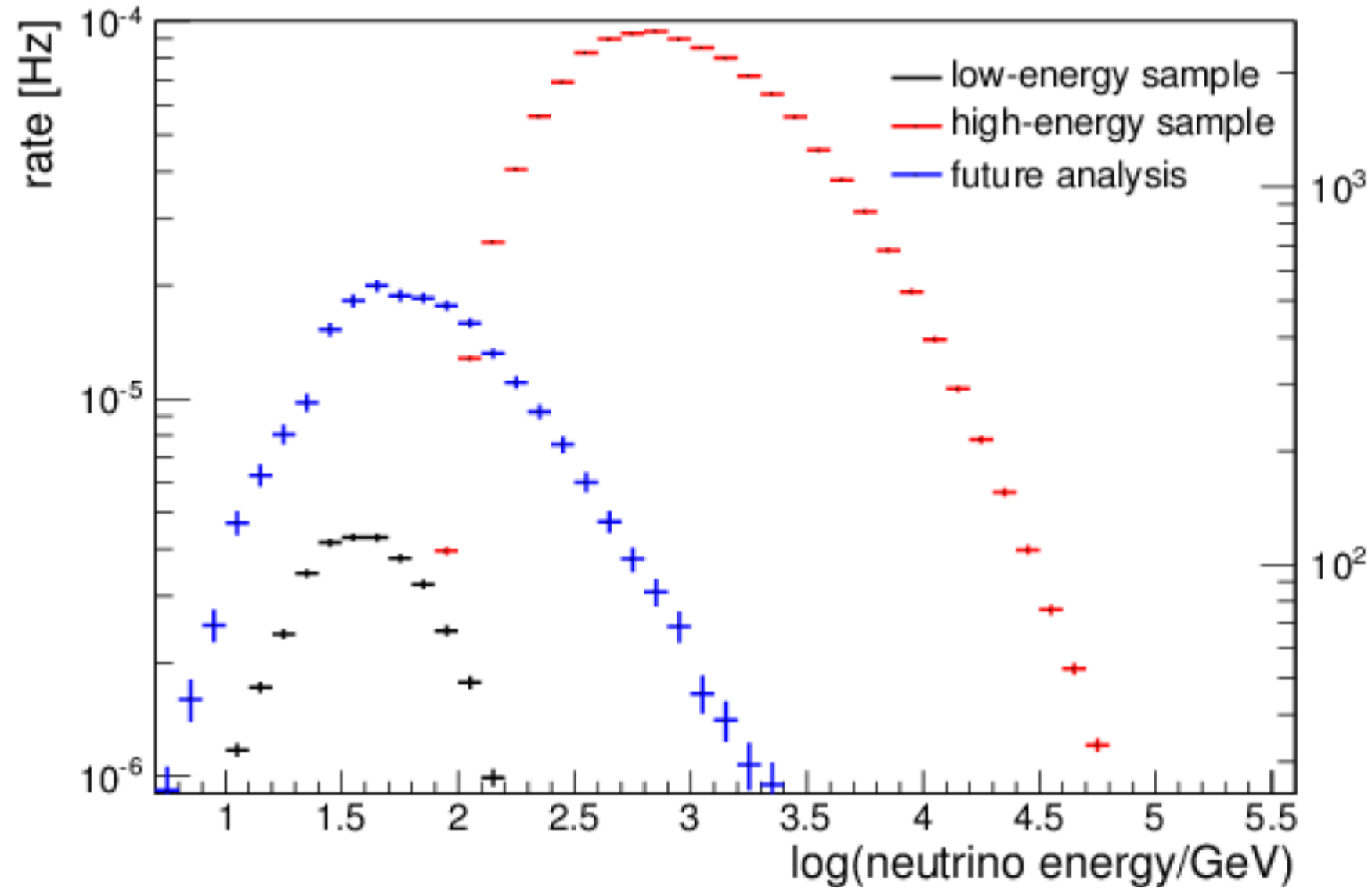


DeepCore result (IC79)

- **Low energy sample: DeepCore**
- **High Energy sample: full IceCube (control sample which should not reveal any effect of oscillation)**



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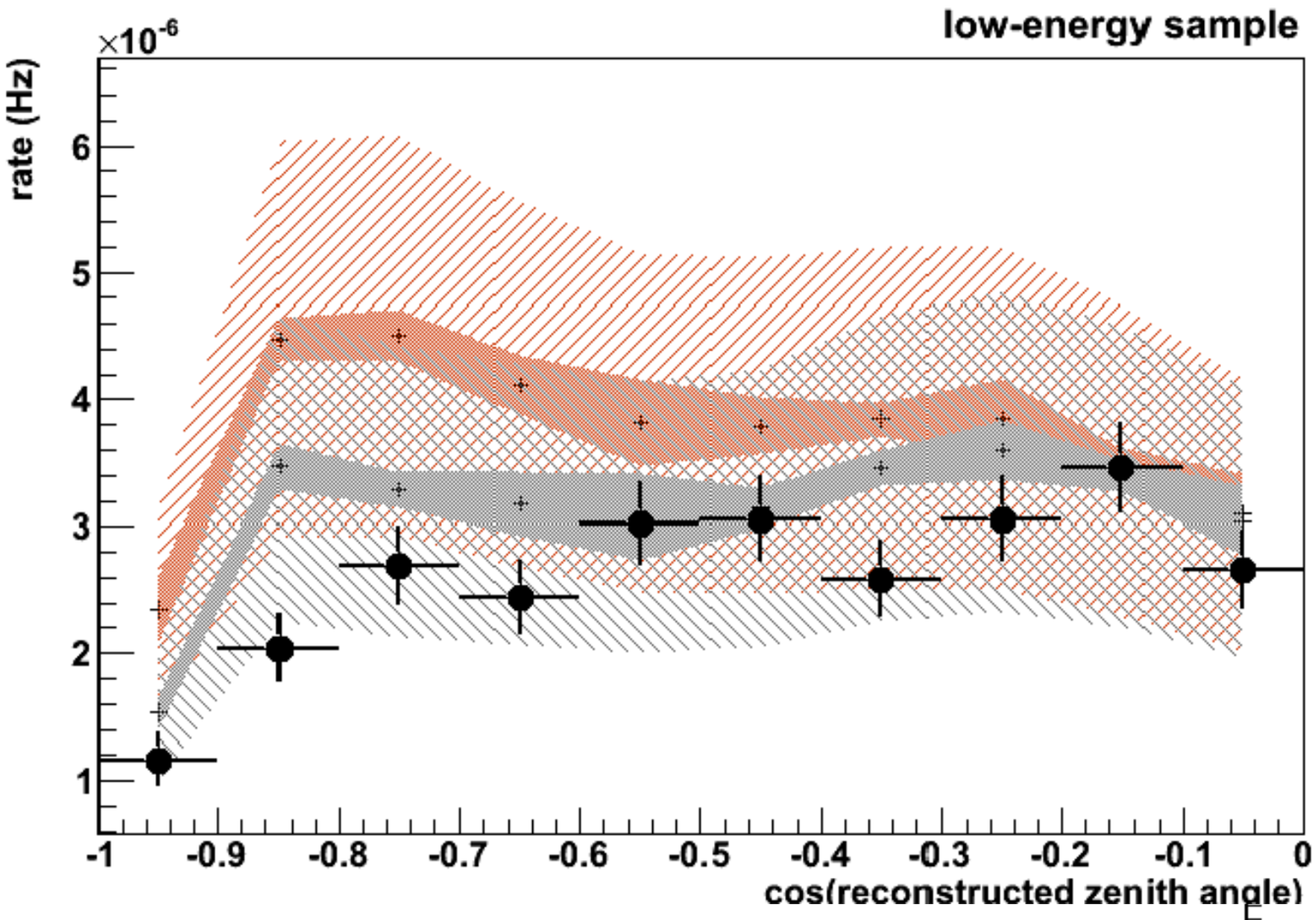
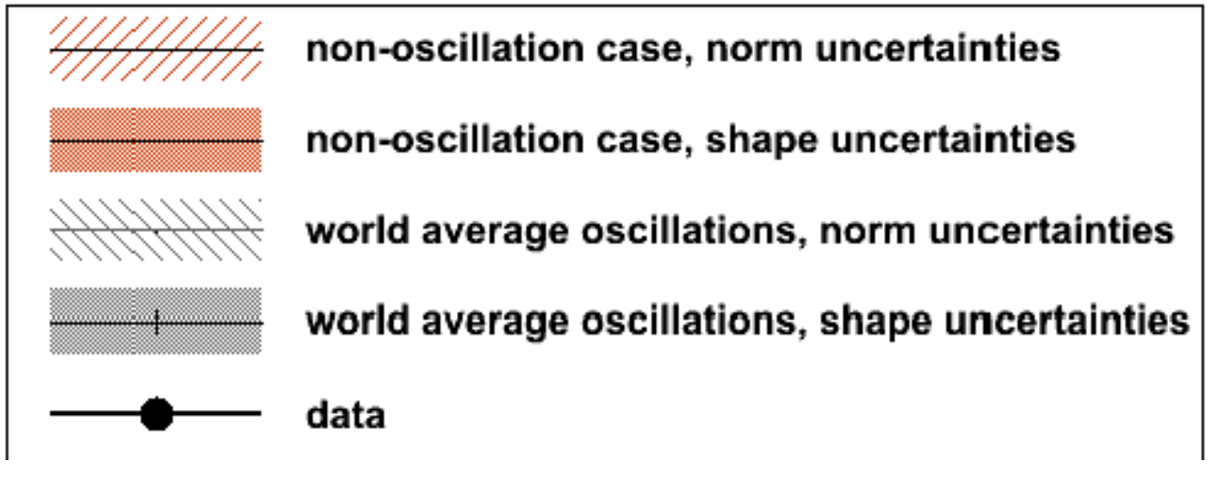
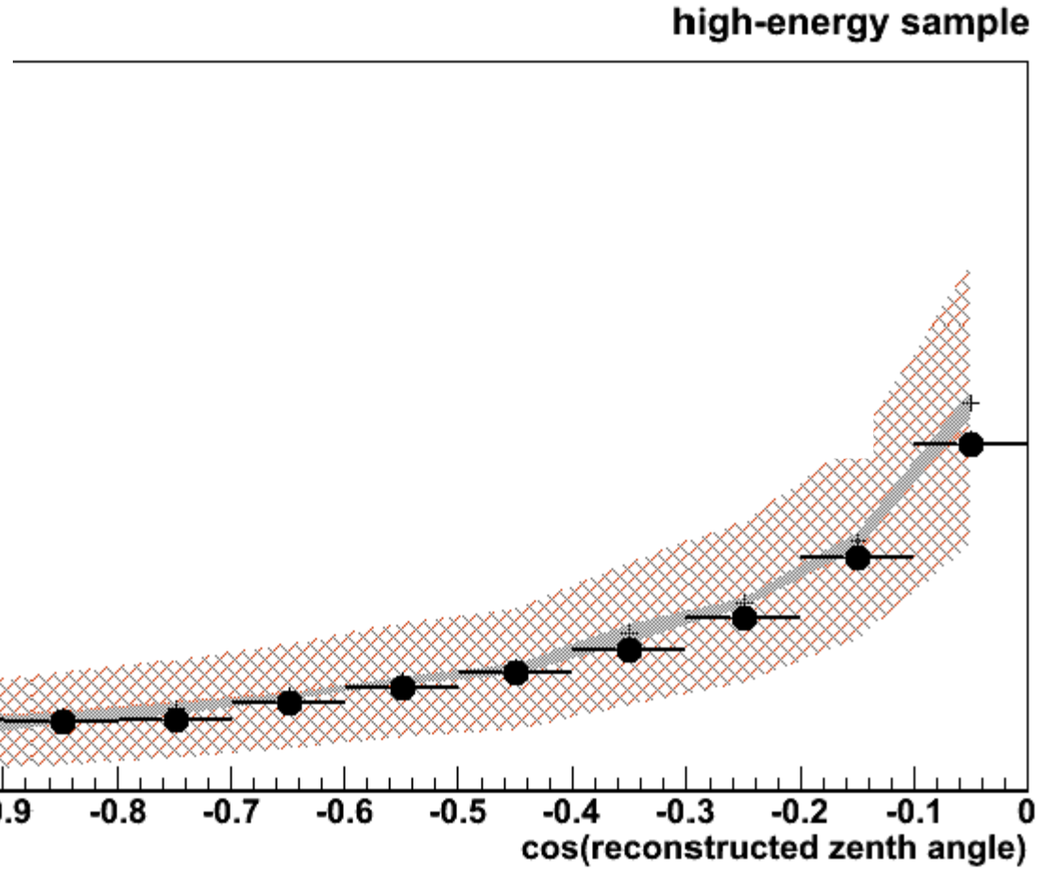




PRELIMINARY



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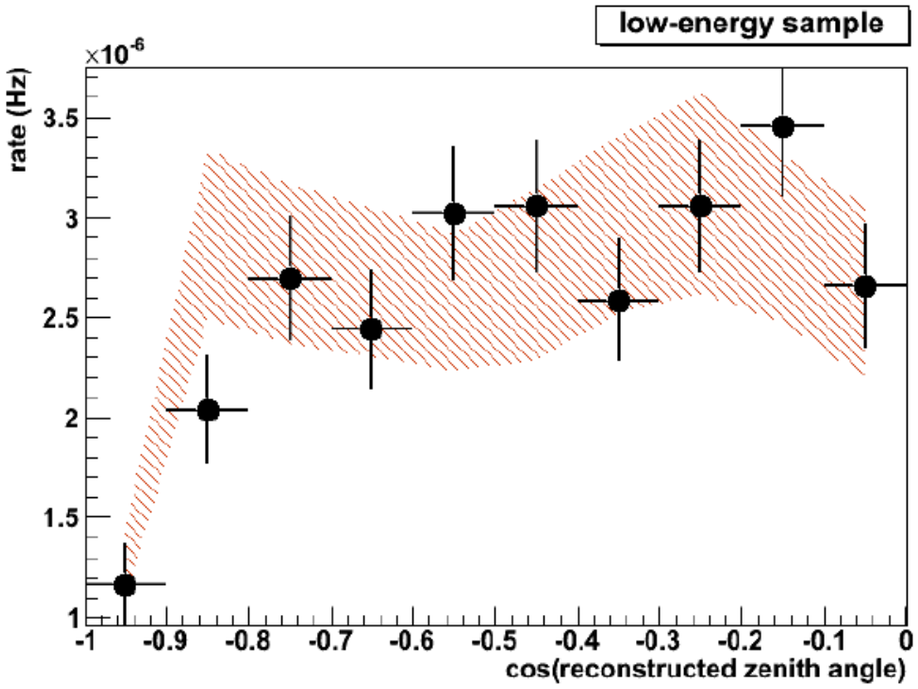
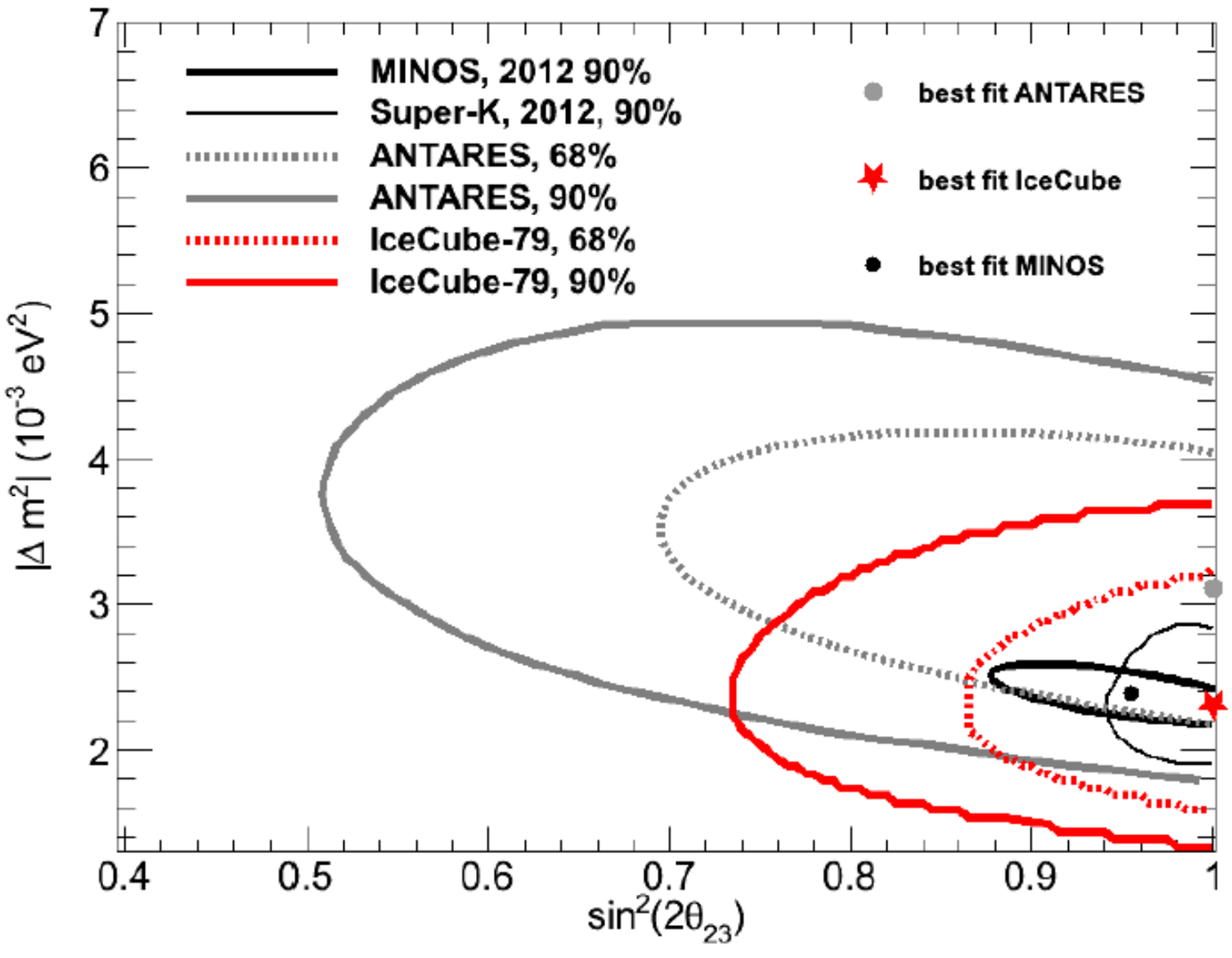


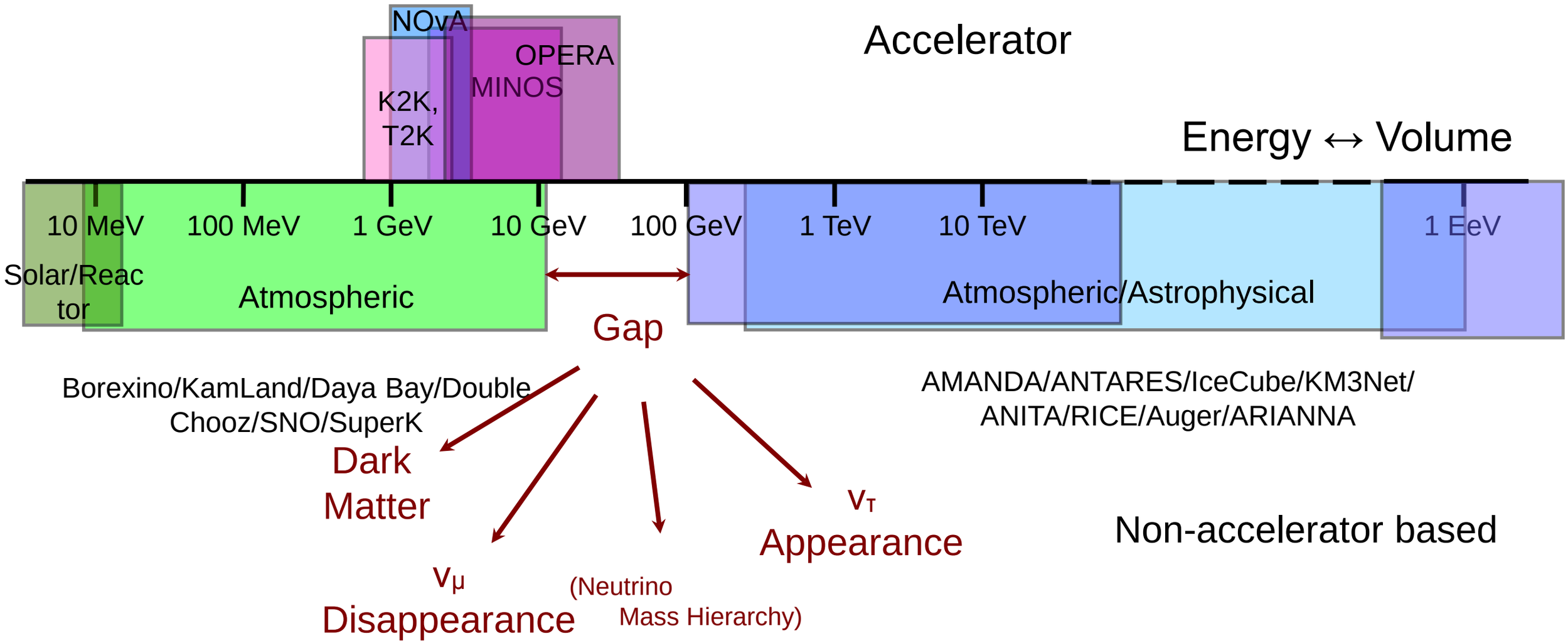
- Submitted to Journal
- Can do precicsion measurements with DeepCore
- DeepCore, 86-string data being analyzed
- Improved reconstruction methods
- Expect considerably tighter constraints to osc. parameters very soon

PRELIMINARY



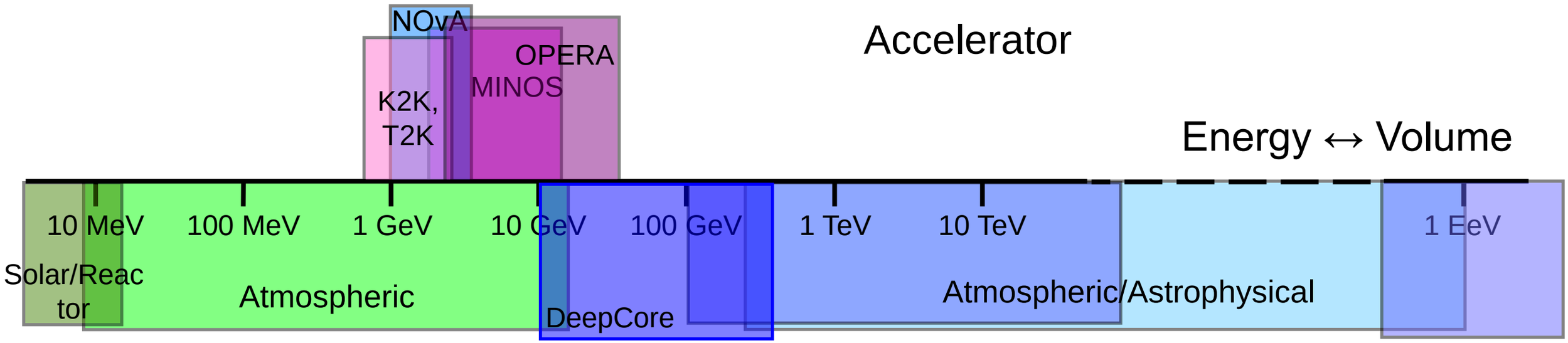
PINGU AND ORCA

The Neutrino Detector Spectrum



** boxes select primary detector physics energy regimes and are not absolute limits*

The Neutrino Detector Spectrum



Borexino/KamLand/Daya Bay/Double Chooz/SNO/SuperK

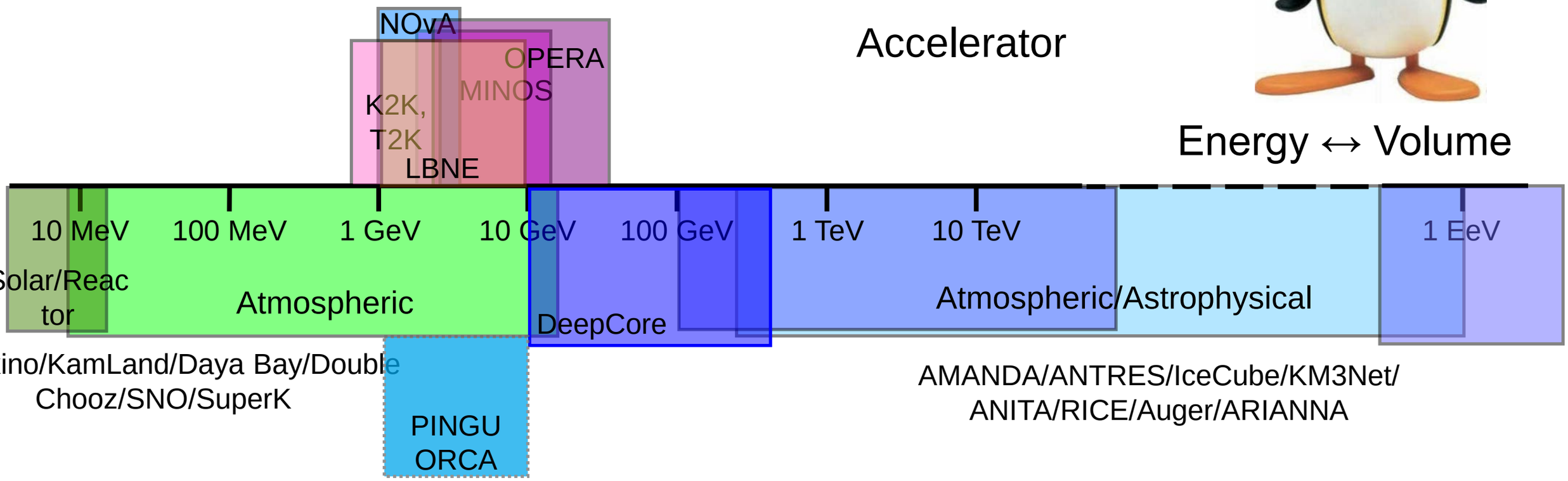
AMANDA/ANTARES/IceCube/KM3Net/ ANITA/RICE/Auger/ARIANNA

Non-accelerator based

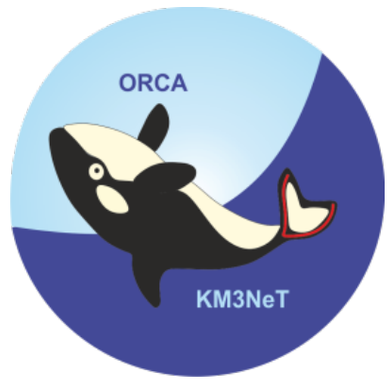
** boxes select primary detector physics energy regimes and are not absolute limits*

The Neutrino Detector Spectrum

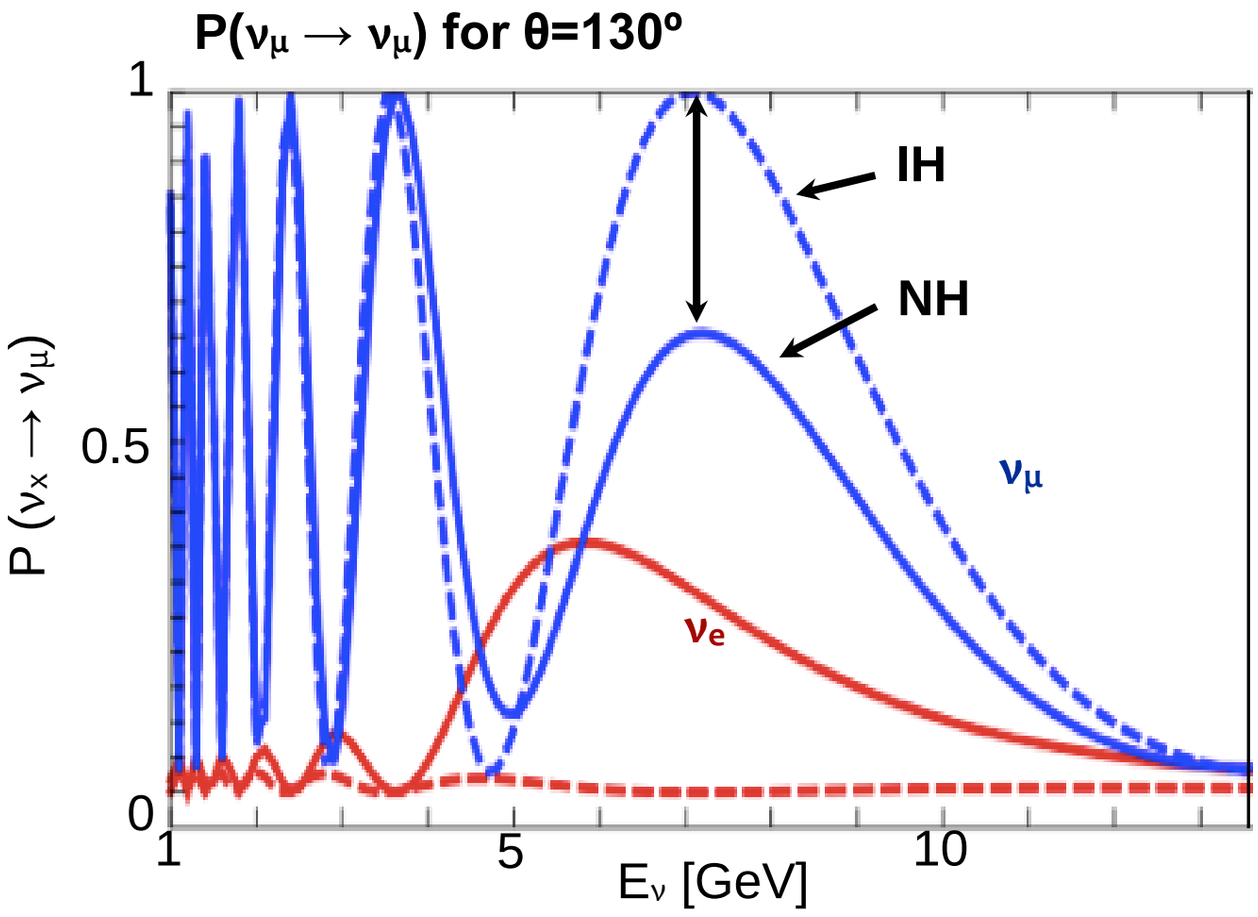
PINGU (Precision IceCube Next Generation Upgrade)



ORCA (Oscillation Research with Cosmics in the Abyss)



Future: Matter Oscillations and Mass Hierarchy



Akhmedov et al., arXiv:1205.7071

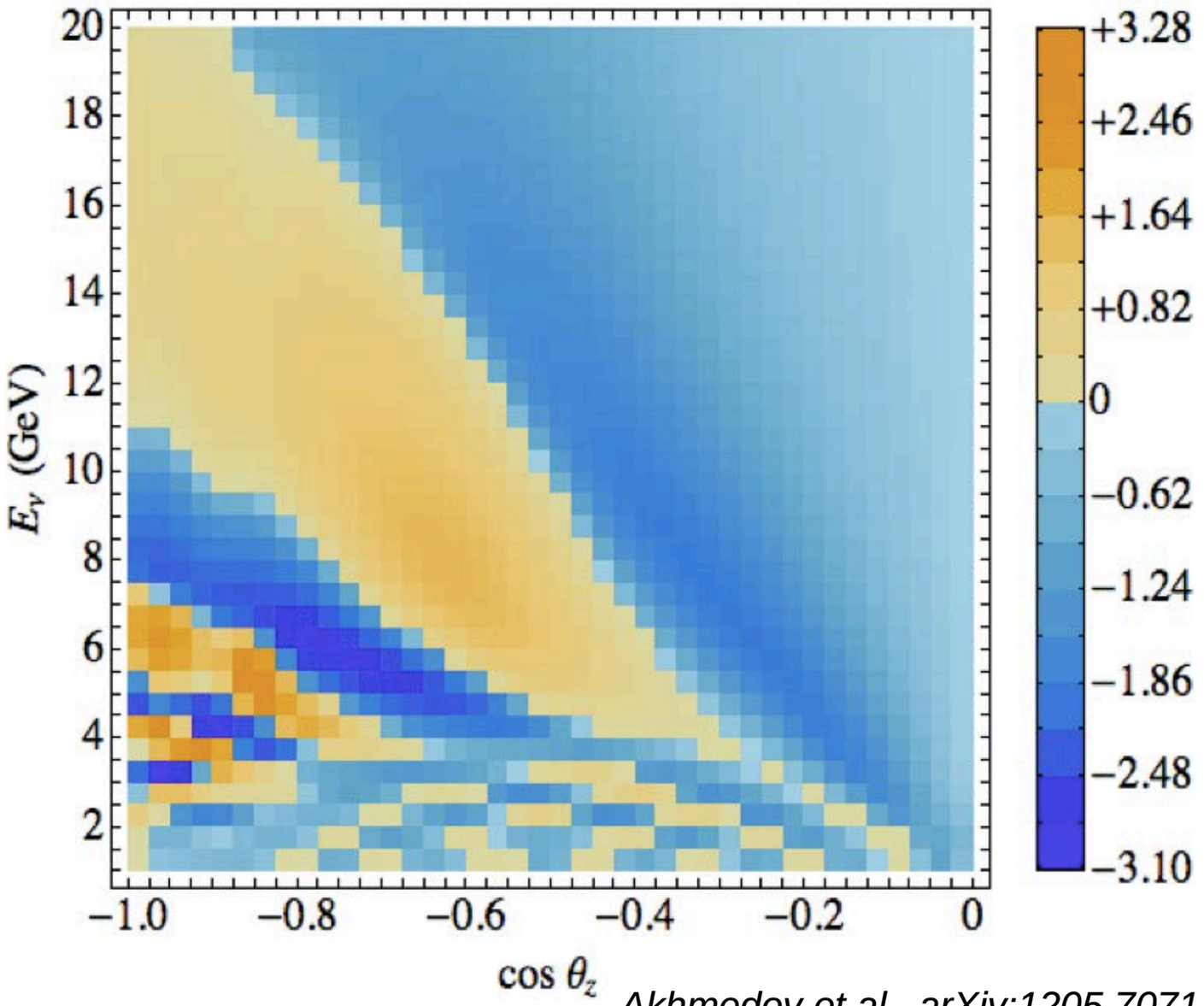
- **Maximum difference NH ↔ IH for θ = 130° at 7 GeV**
- **For anti-ν, NH and IH are approximately swapped → effect cancels if ν and anti-ν have equal fluxes and cross sections and if the detector cannot distinguish μ^+ and μ^-**
- **However: flux of atm.ν ~ 1.3 × flux of atm. anti -ν**

  and σ(ν) ~ 2 × σ(anti-ν) at low energies
- **→ Count $N_\mu(\theta, E)$ from $\nu_\mu + N \rightarrow \mu + X$ and compare with NH/IH predictions**

Pattern from matter oscillations

ΔN(IH-NH) / √N(NH) [PINGU 1 yr, 10% sys.]

Perfect resolution



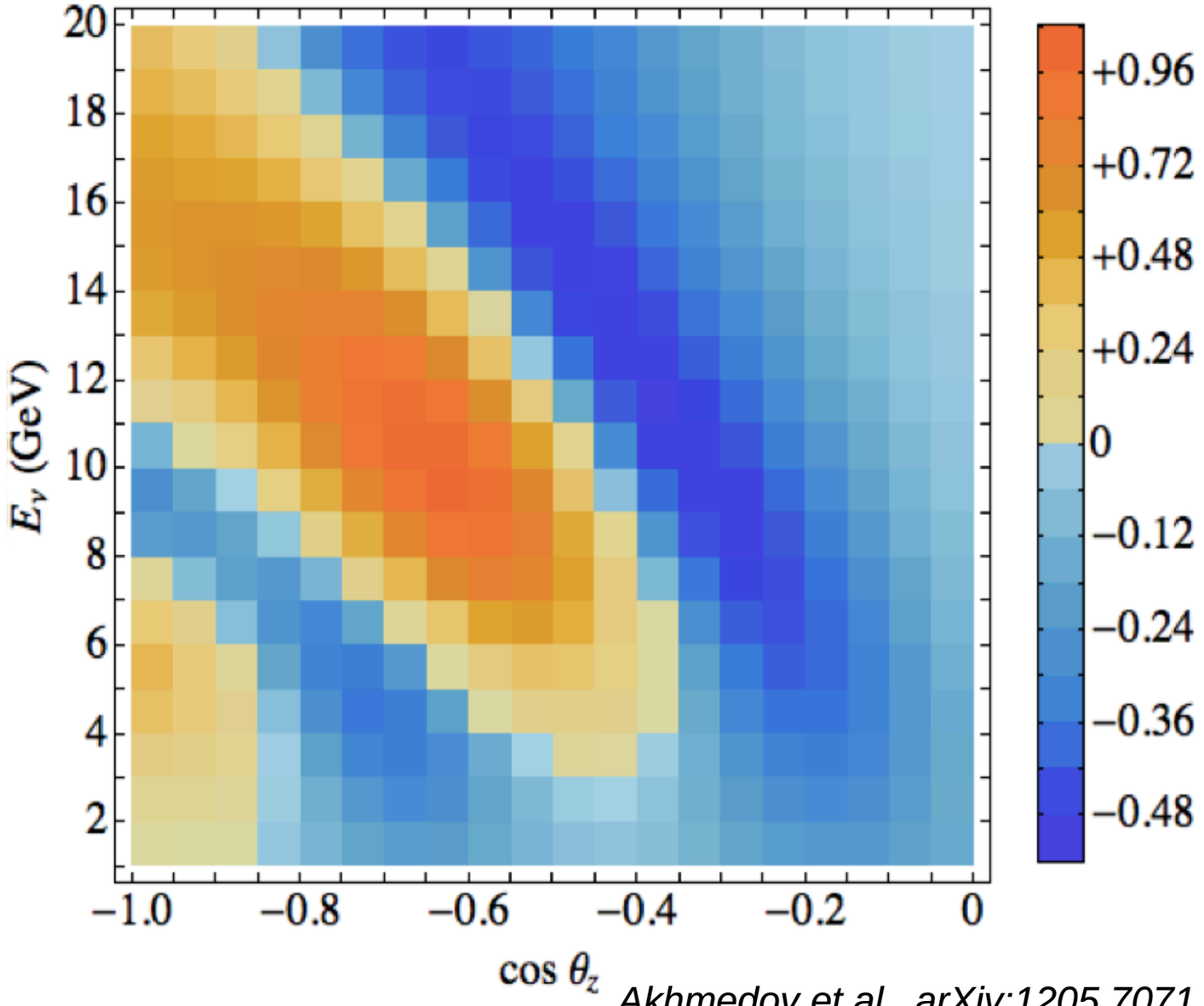
Akhmedov et al., arXiv:1205.7071

Importance of resolution and systematics

- Feasibility depends on
  - Angular resolution
  - Energy resolution
  - Particle ID
  - Systematic effects

ΔN(IH-NH) / √N(NH) [PINGU 1 yr, 10% sys.]

σ_θ = 11° σ_E = 2 GeV → Σ=7σ



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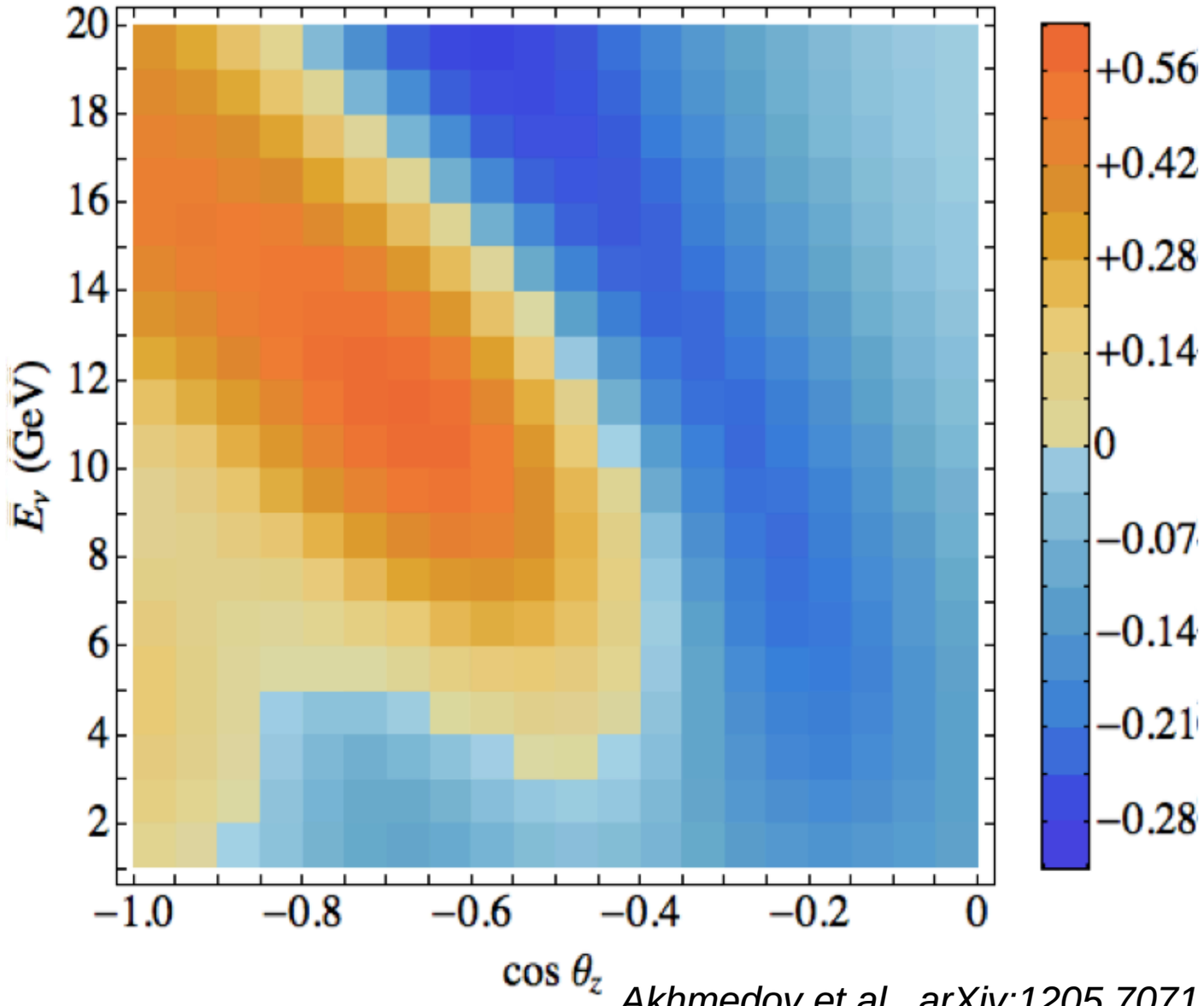
ΔN(IH-NH) / √N(NH) [PINGU 1 yr, 10% sys.]

$\sigma_\theta = 15^o$ $\sigma_E = 3$ GeV → Σ=5σ



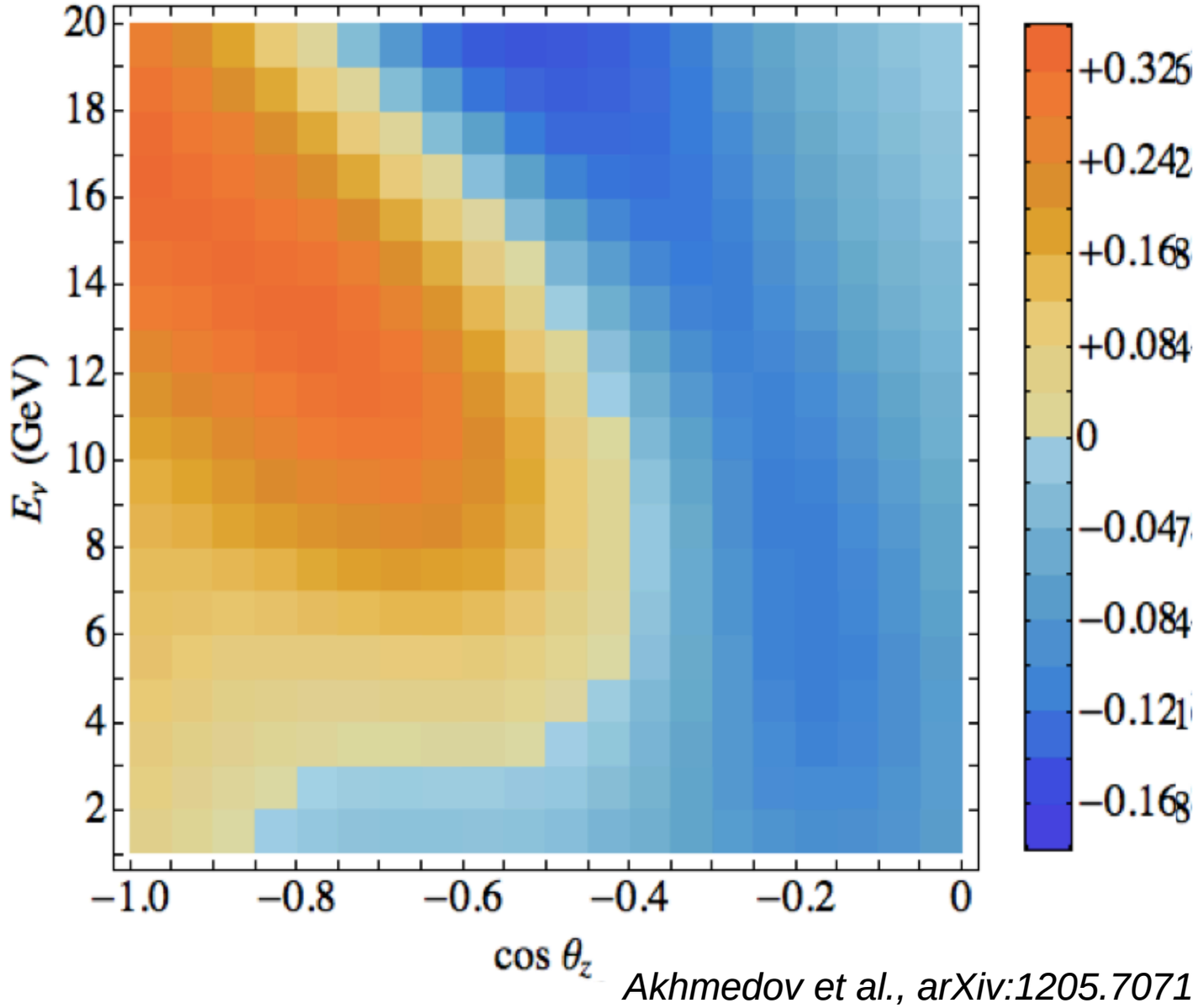
Akhmedov et al., arXiv:1205.7071

Importance of resolution and systematics

- Feasibility depends on
  - Angular resolution
  - Energy resolution
  - Particle ID
  - Systematic effects

ΔN(IH-NH) / √N(NH) [PINGU 1 yr, 10% sys.]

σ_θ = 23° σ_E = 4 GeV → Σ=3σ



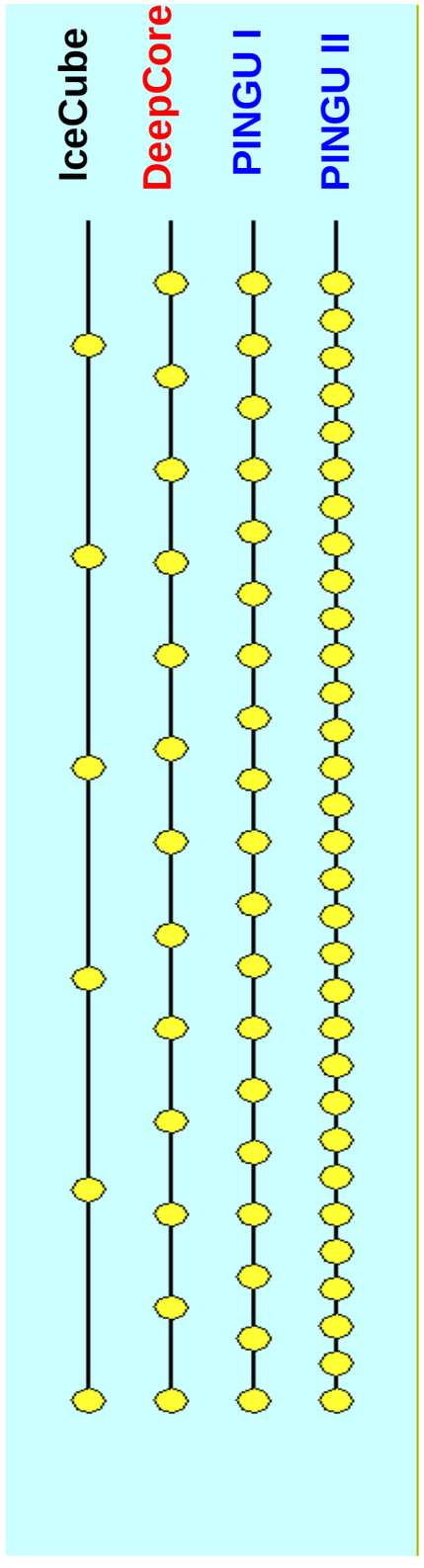
Akhmedov et al., arXiv:1205.7071

PINGU

- **Goals:**
  - Determine neutrino mass hierarchy
  - low mass WIMP search
  - improved sensitivity to SN burst neutrinos

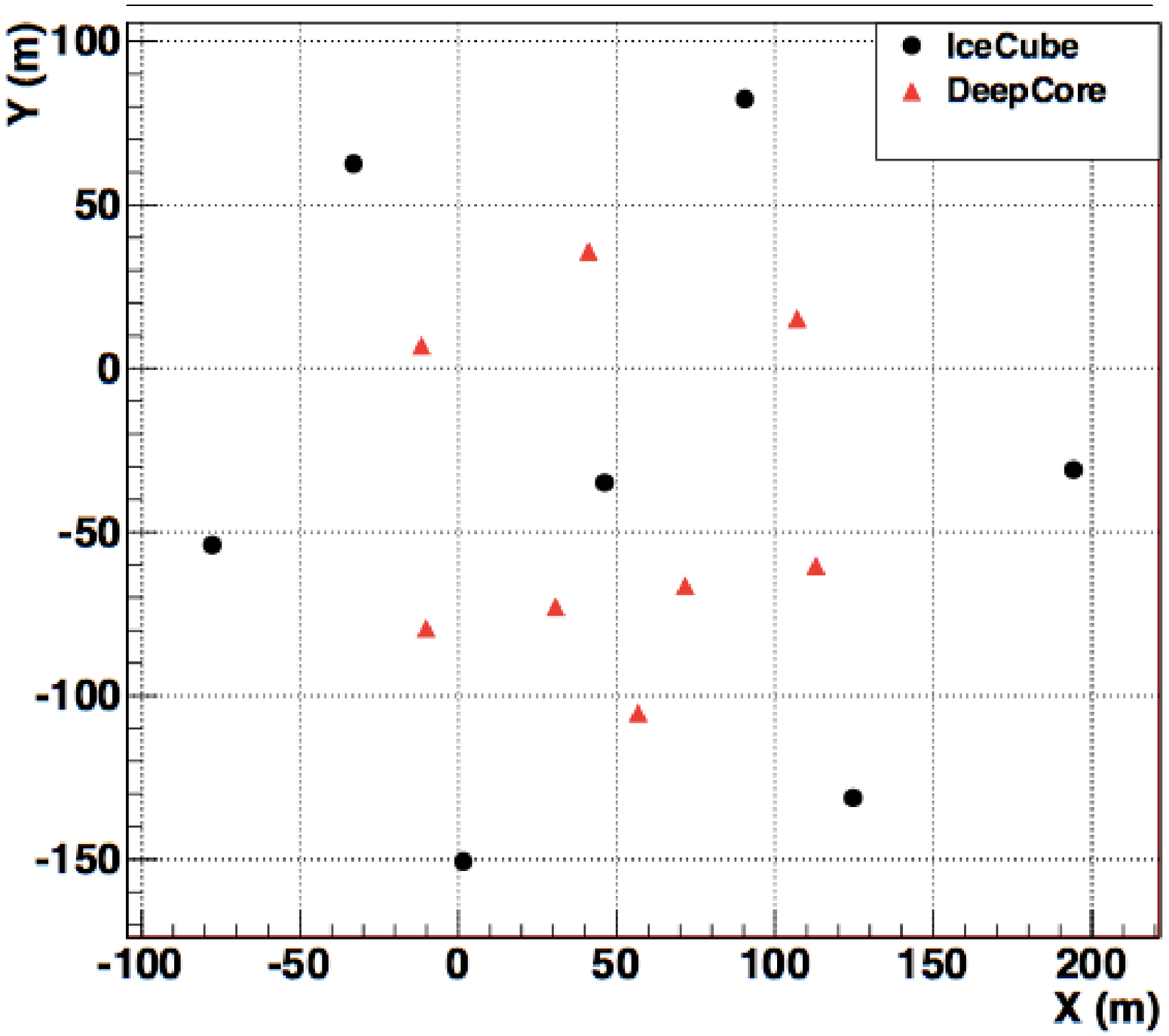
  → must reach energy threshold of < 5 GeV

- **Add infill strings to DeepCore**
- **More optical modules per string** →
- **Improve veto capabilities**
- **Co-deploy calibration devices optimized for low energy**
- **Simplify optical modules**
- **Improve quality of refrozen hole ice**



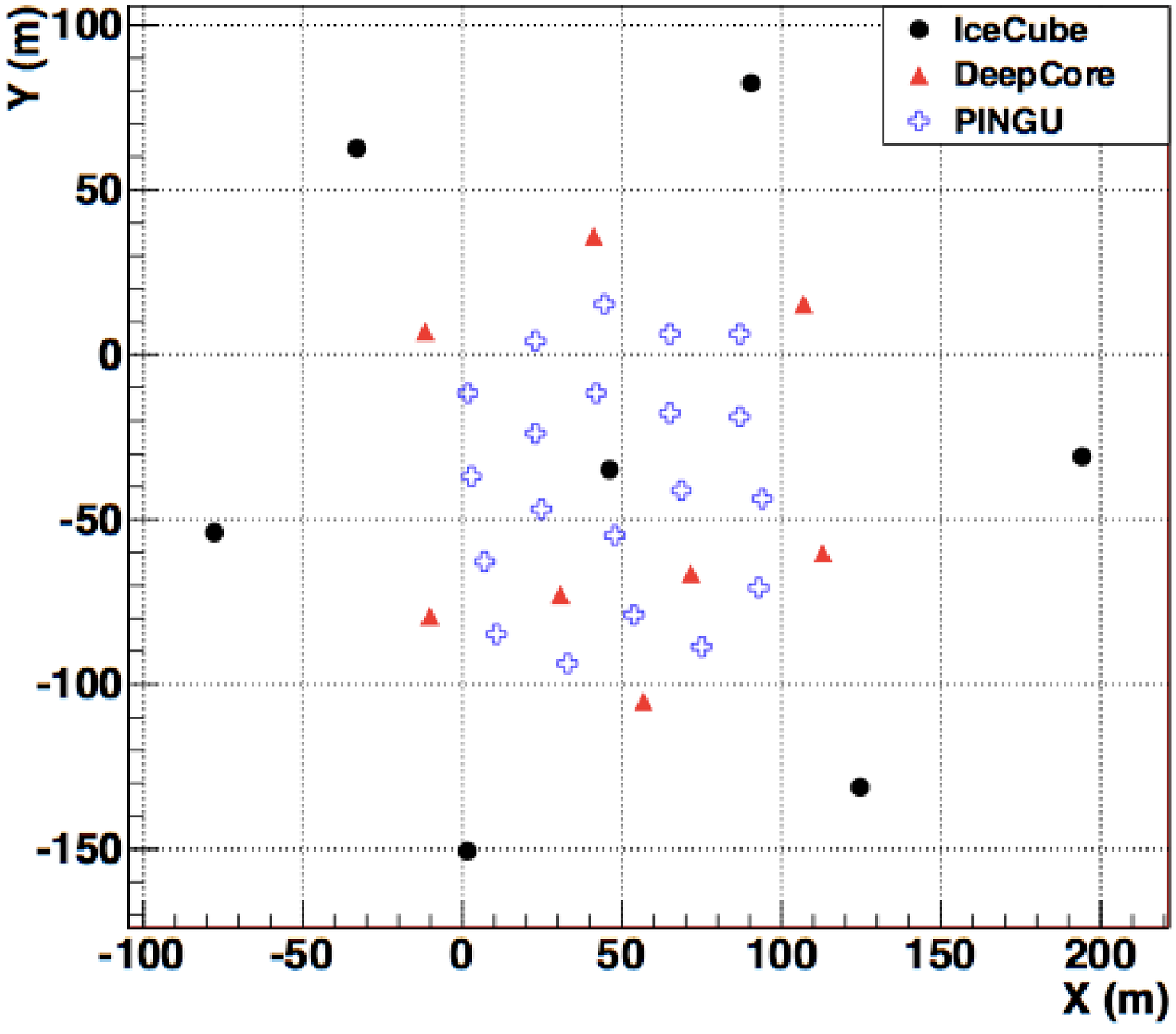
Configurations

- DeepCore



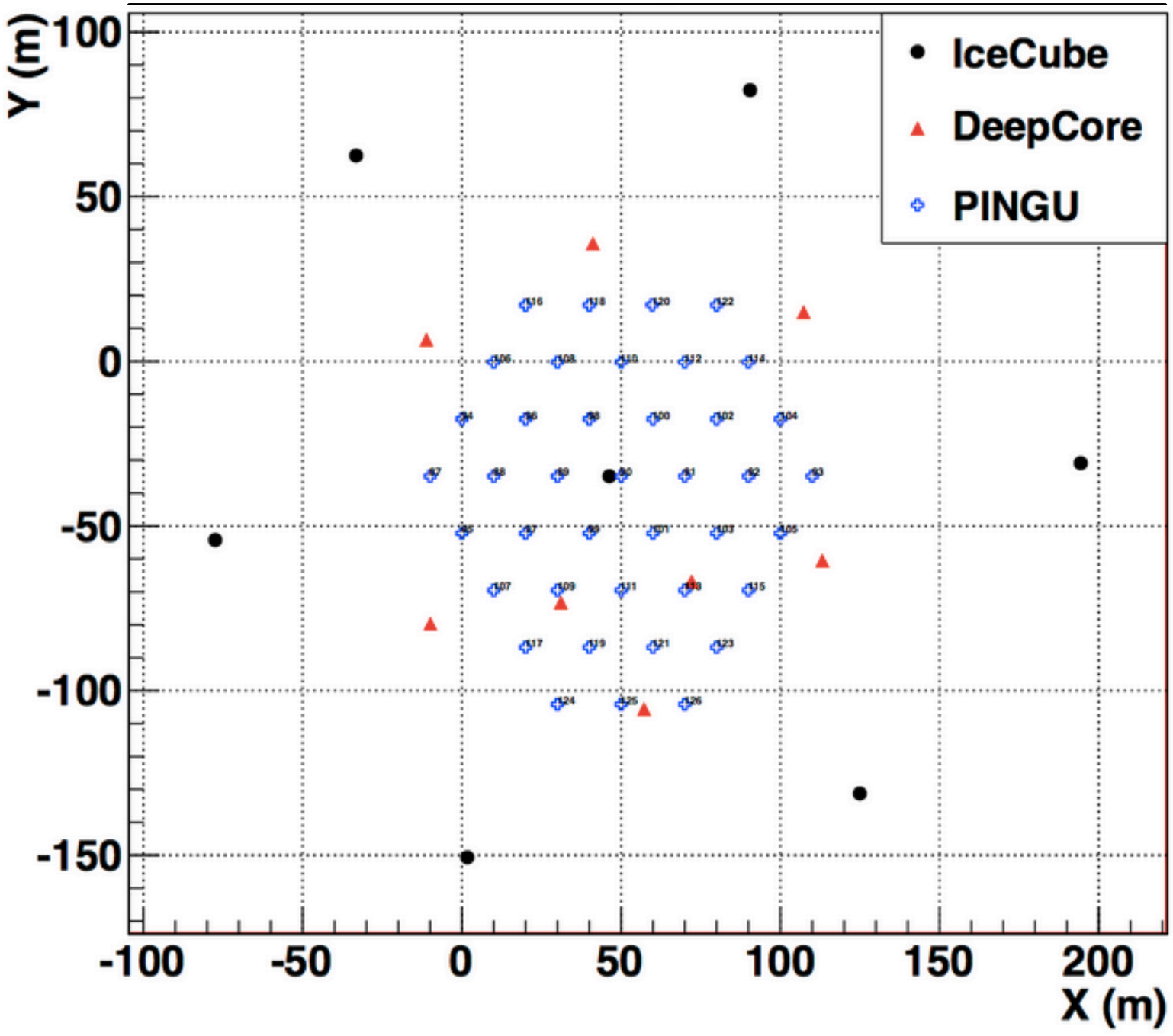
Configurations

- **PINGU**
  - Minimal option
  - 20 more strings
  - 26 m spacing
  - 60 DOMs per string
  - 5 m spacing
  - Need 2 seasons to deploy



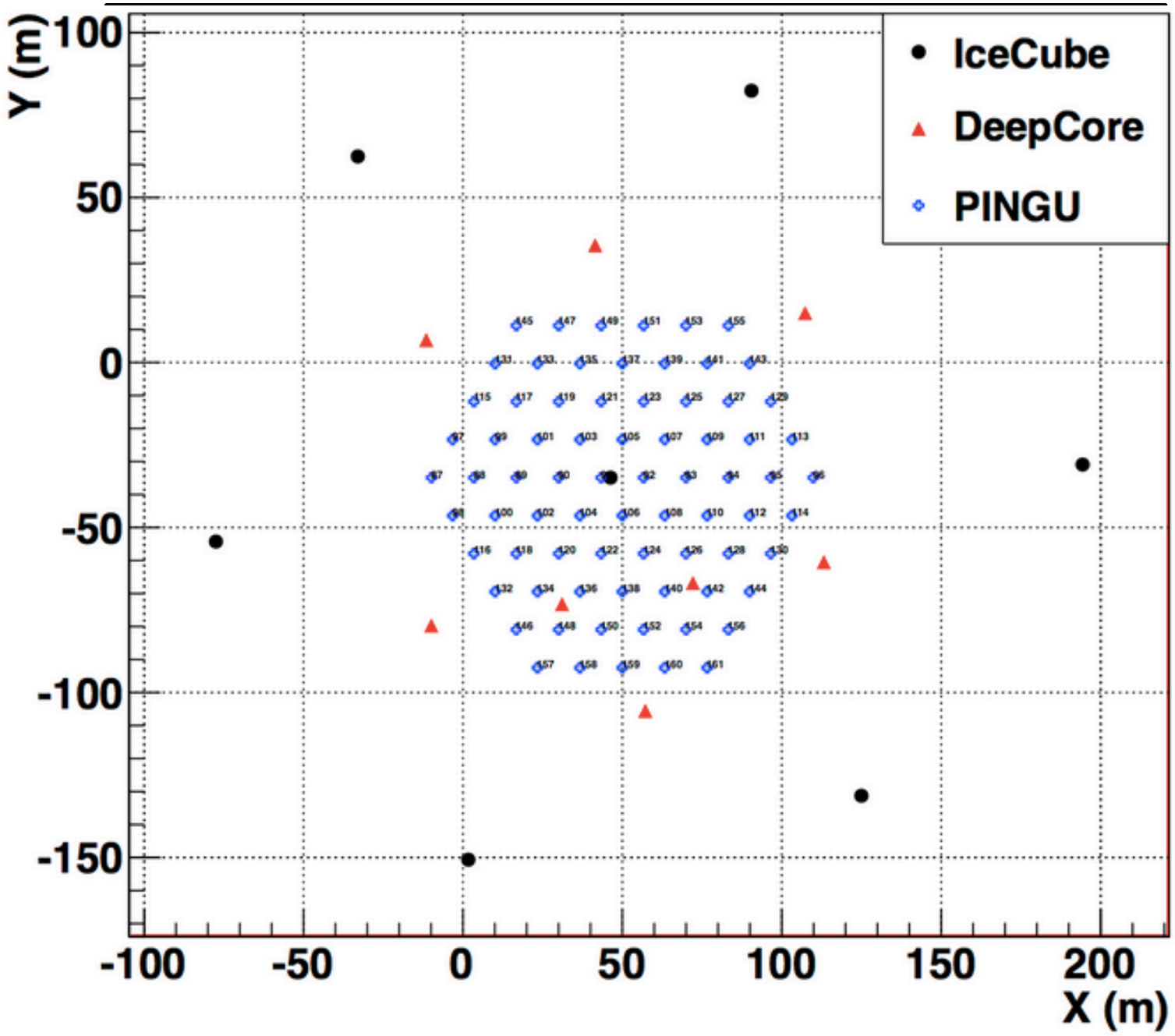
Configurations

- **PINGU**
  - Medium option
  - 40 more strings
  - 20 m spacing
  - 60-120 DOMs per string
  - 2.5-5 m spacing
  - Need 3 seasons to deploy



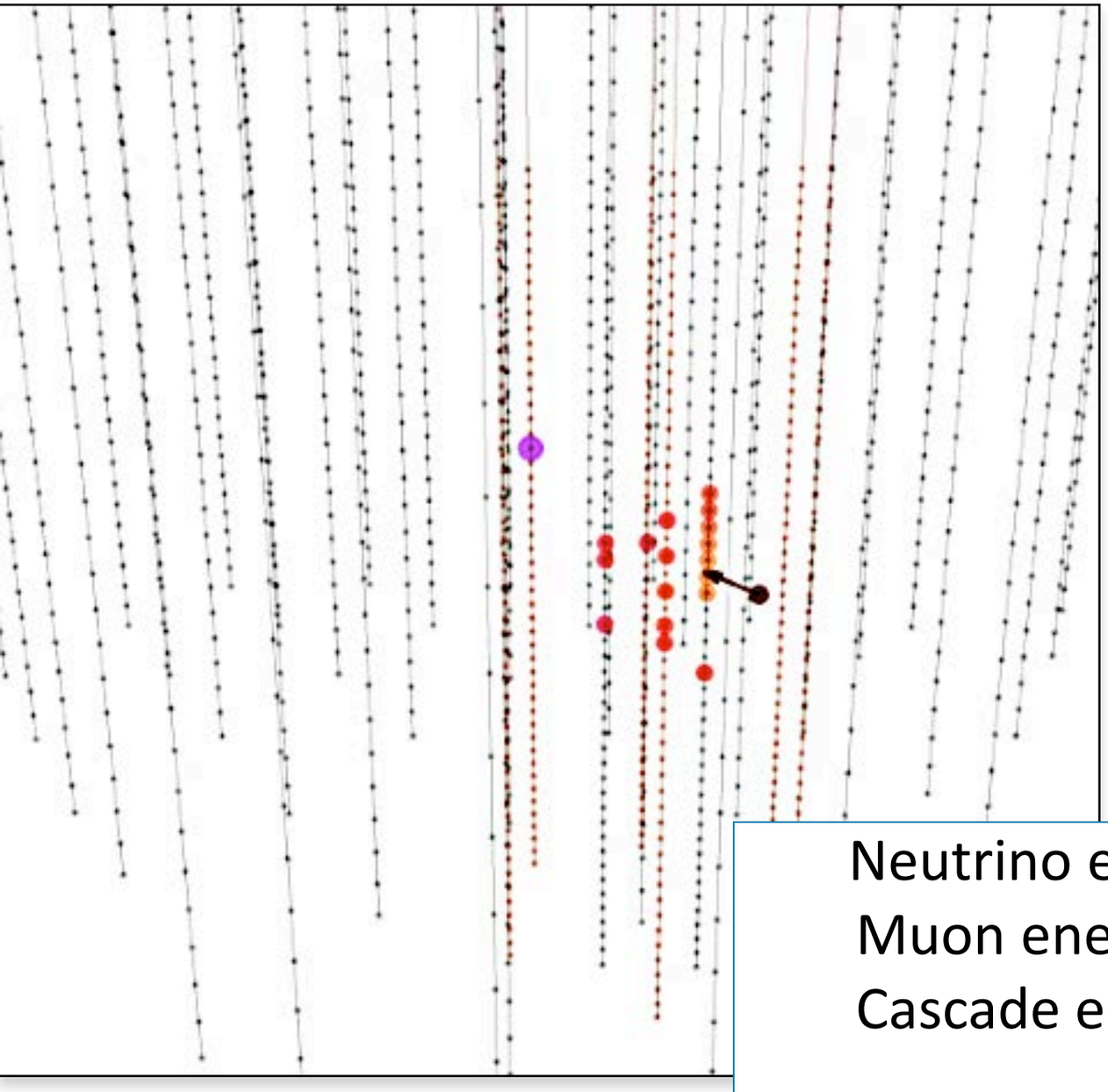
Configurations

- **PINGU**
  - Maximum (?) option
  - 75 more strings
  - 13 m spacing
  - 60-120 DOMs per string
  - 2.5-5 m spacing
  - Need 4 seasons to deploy

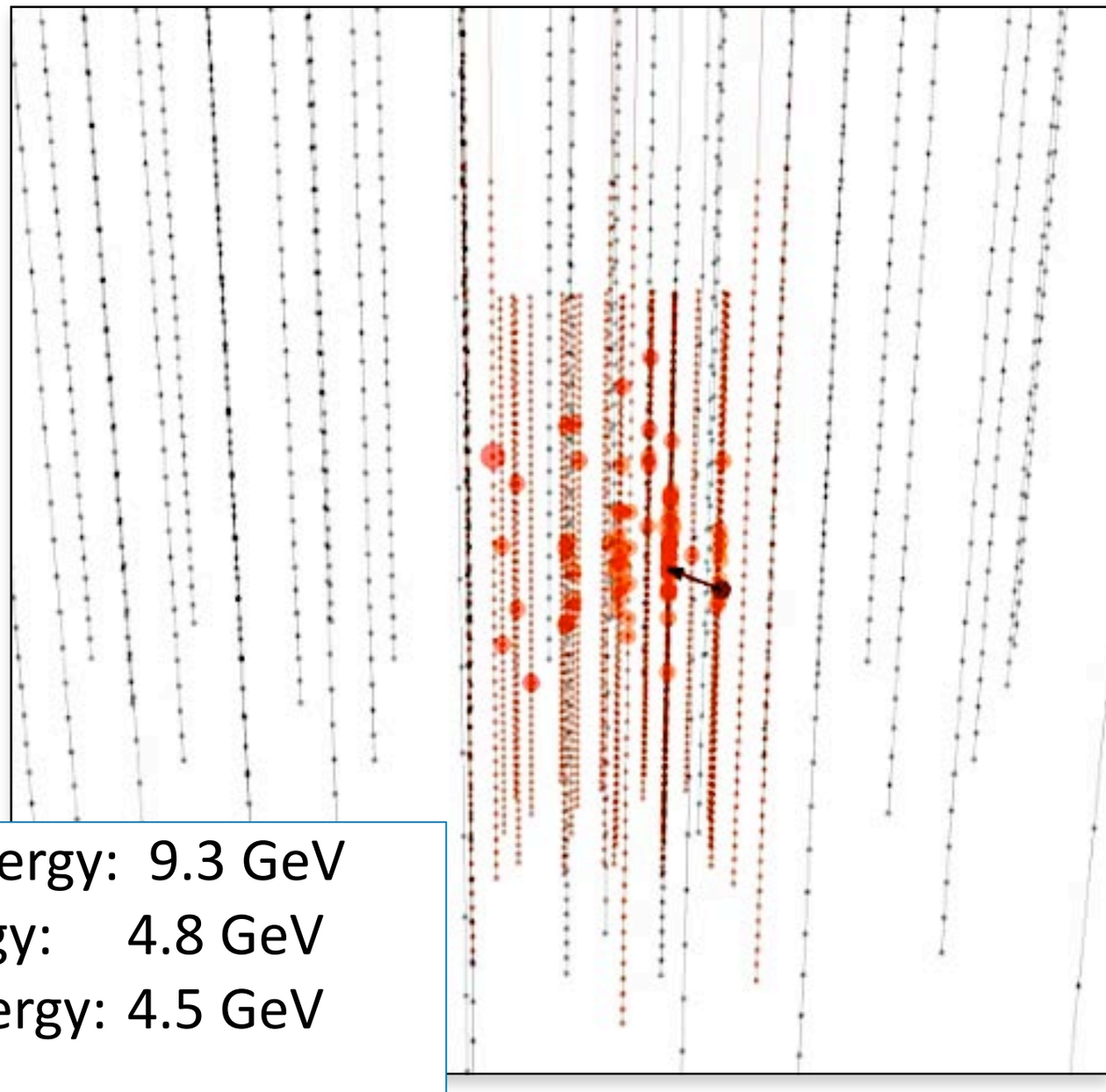


A 9-GeV neutrino event (PINGU 20 strings)

DeepCore



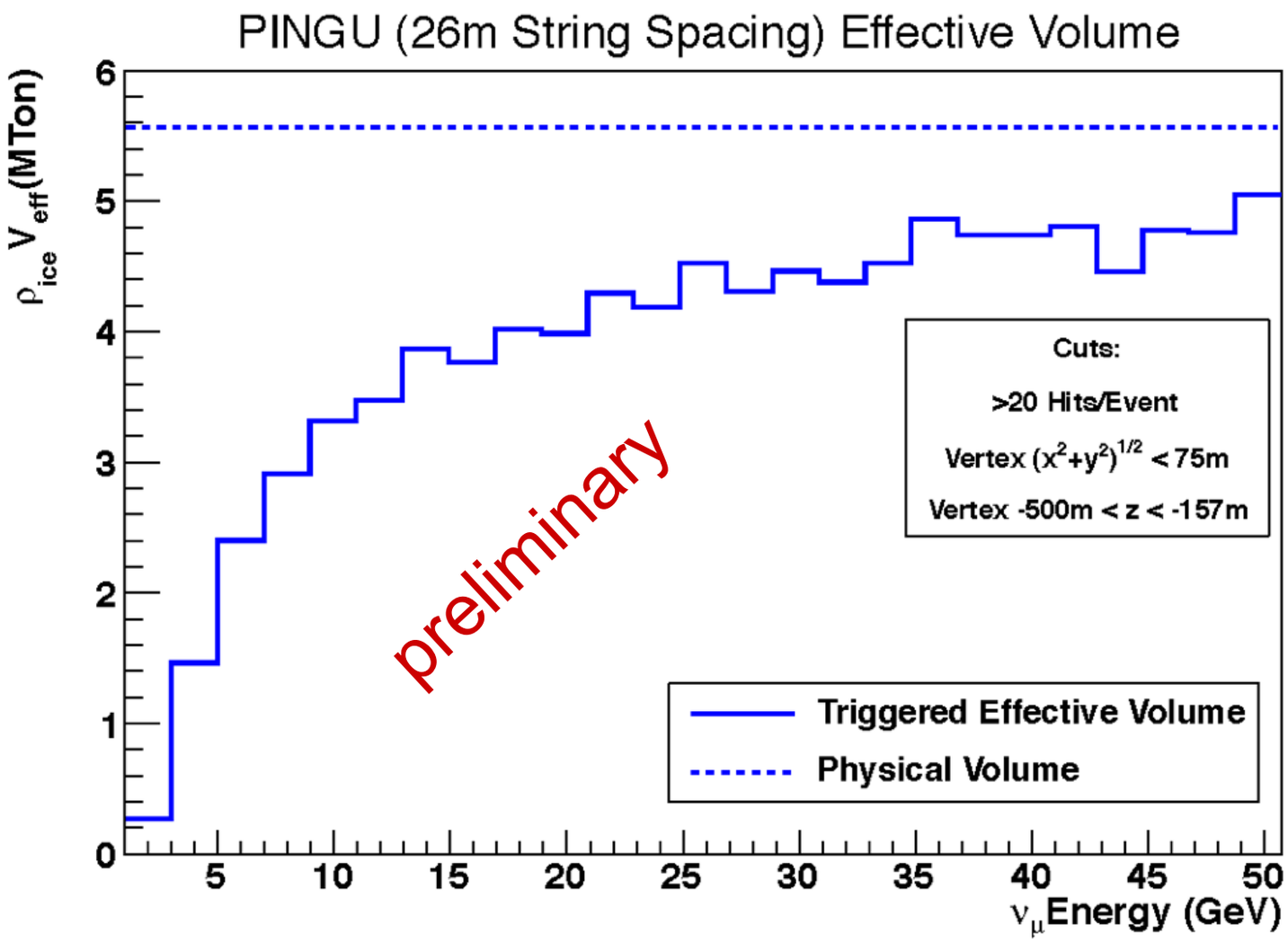
DeepCore + PINGU



Neutrino energy: 9.3 GeV
Muon energy: 4.8 GeV
Cascade energy: 4.5 GeV

Hit modules:
20 (DC) → ~50 (DC + PINGU)

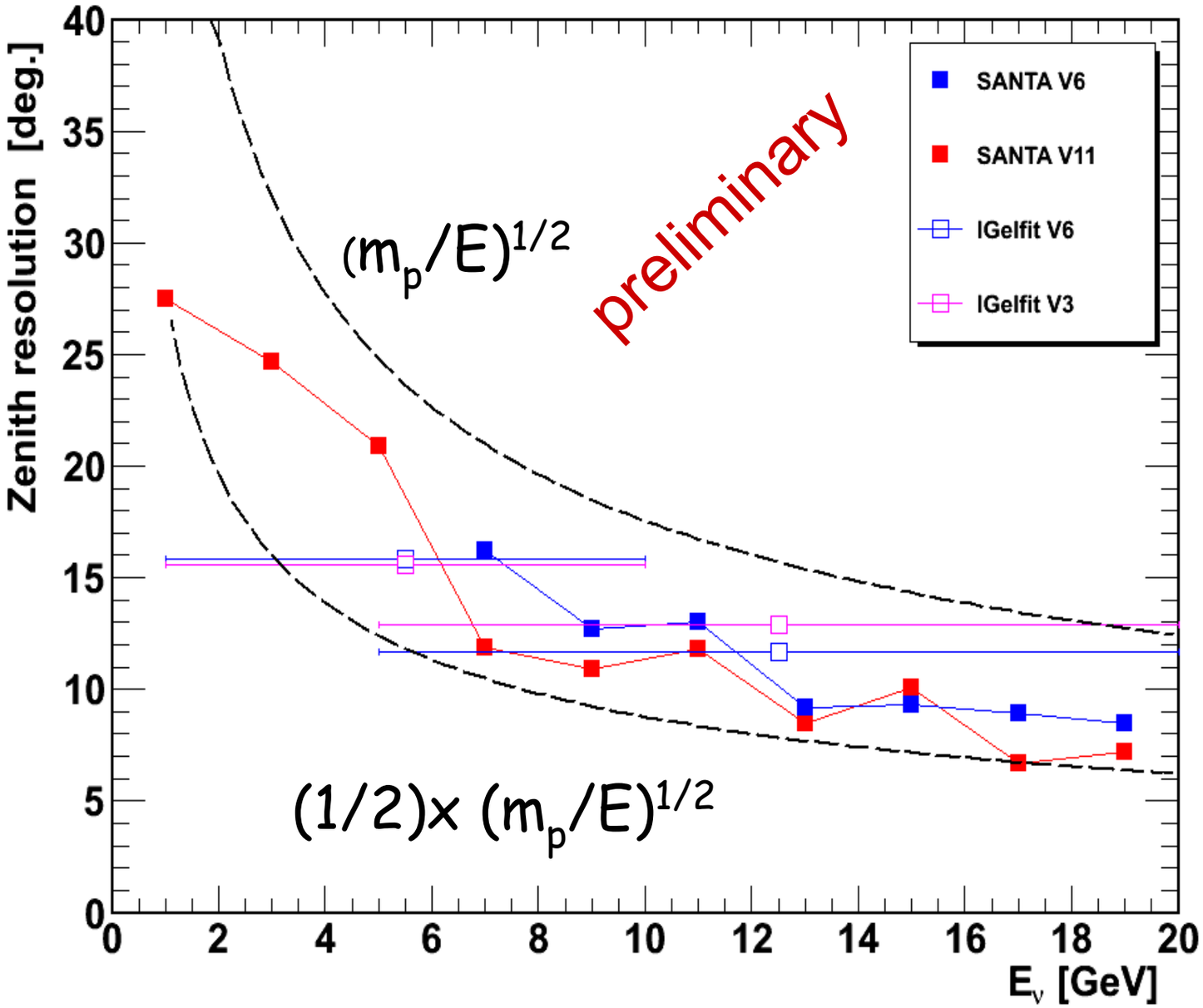
Effective volume



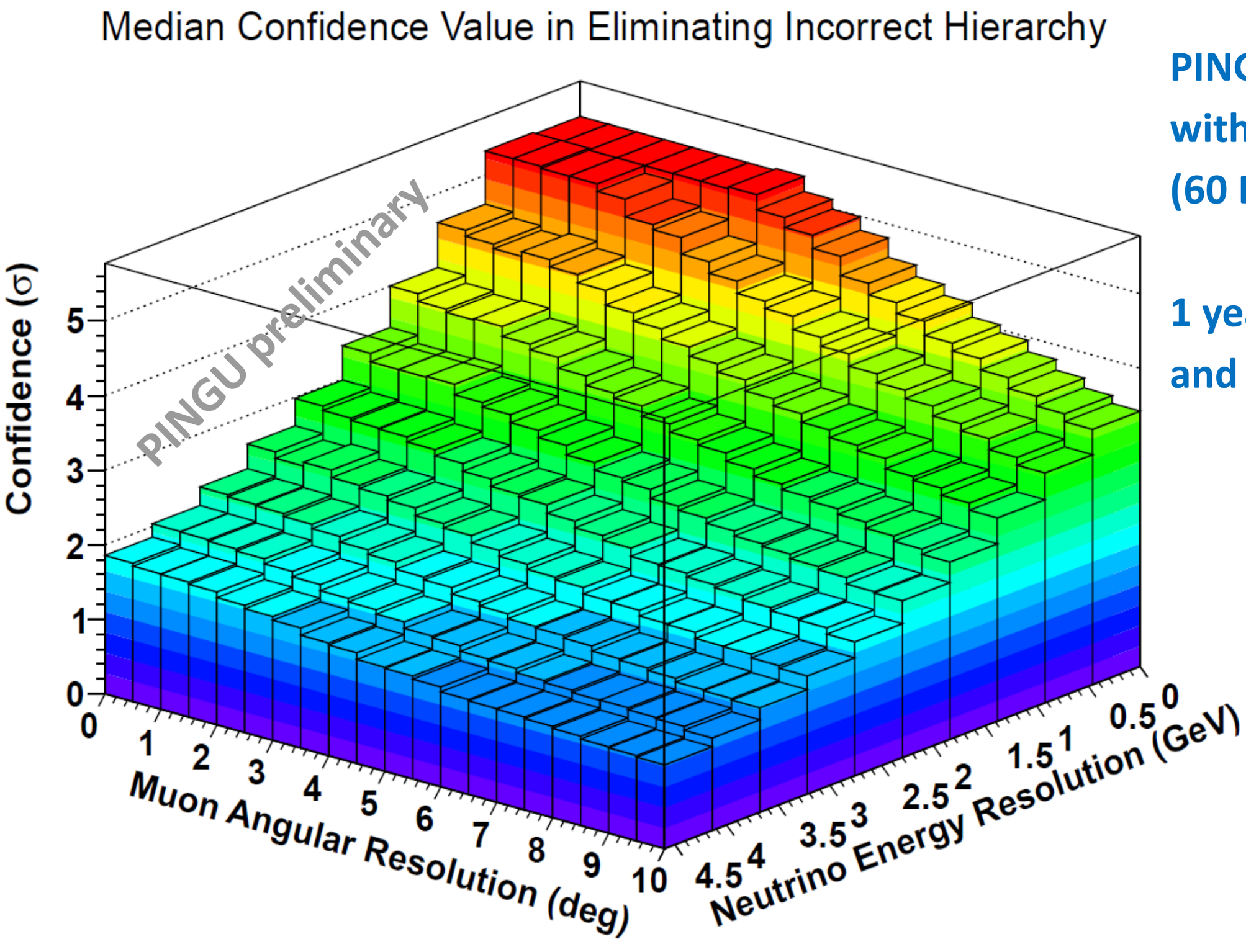
- For „maximum configuration“ the effective (> 20 hits) volume at 3-4 GeV increases by more than a factor 2
- This does not mean that we will have sufficiently good angular and energy resolution and flavor identification. These aspects are under investigation. They will lead to a substantial reduction of the real effective volume

Angular resolution

- Trying different algorithms
  - using only non-scattered photons (SANTA)
  - LLH fit with grid-search strategy (Igelfit)
  - Reco of CC events with 8 parameters (interaction vertex and time, direction, length and cascade energy)
- Figure: examples for different configurations and fit-algorithms
- Resolution in relevant energy range~ 10 degree



Statistical analysis for the NMH sensitivity

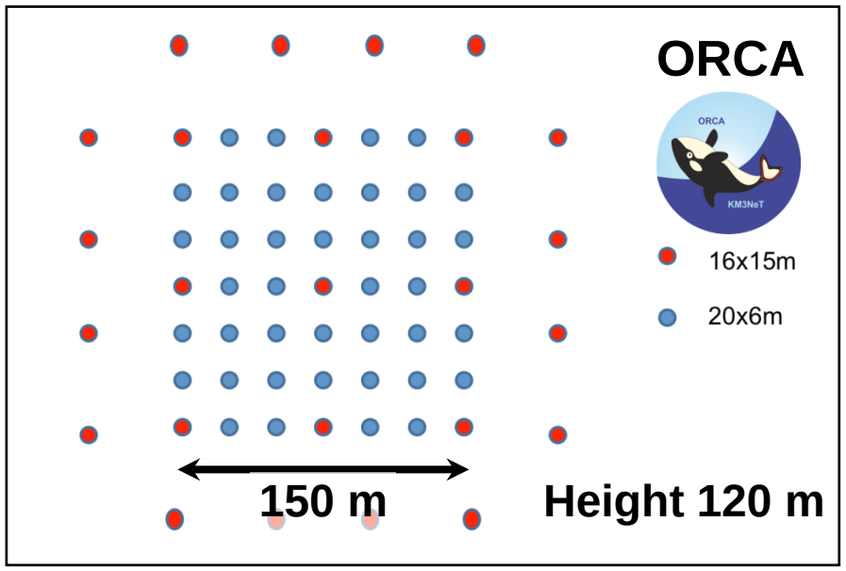


PINGU configuration with 20 strings (60 DOM/string)

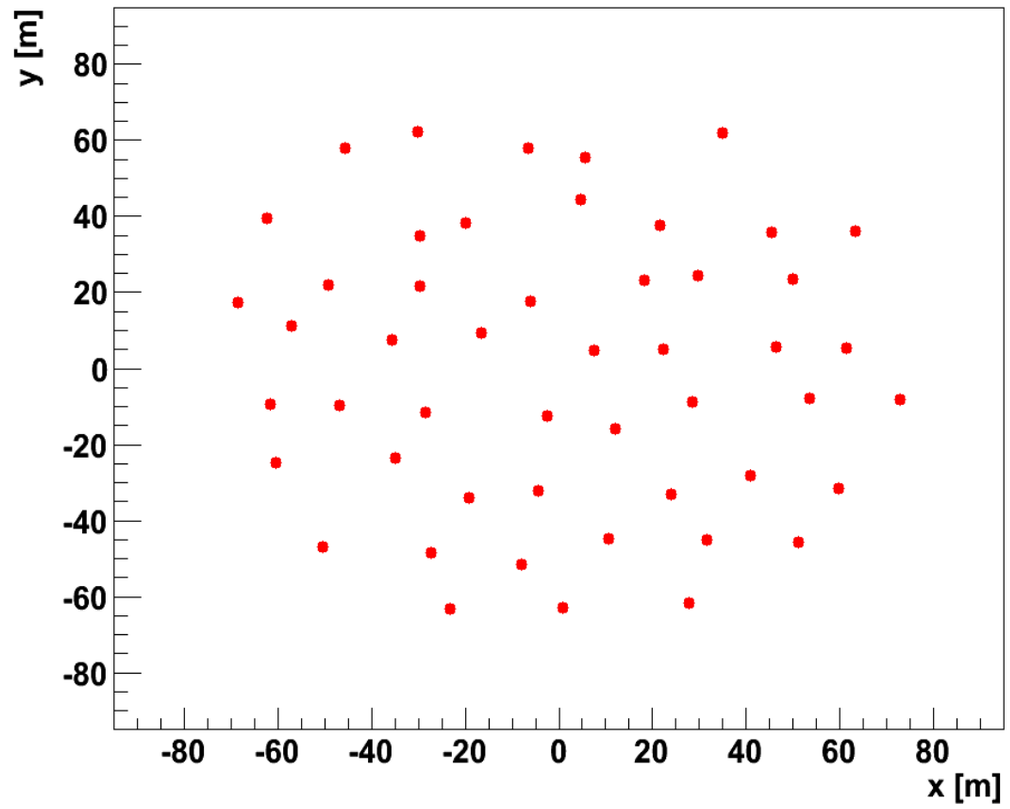
1 year of data and N_{hit}>20

ORCA

- Shown are 2 example configurations, for instance



- 50 strings, 20 OMs each
- KM3NeT design:
  31 3-inch PMTs / OM
- 20 m horizontal distance
- 6 m vertical distance
- instrumented volume: 1.75 Mton water



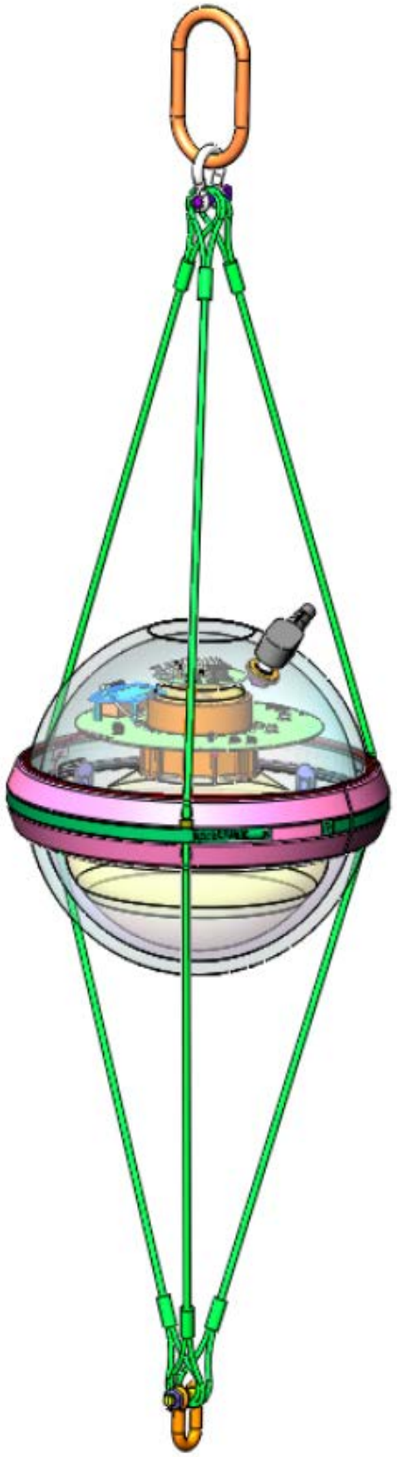
STATUS AND PLANS FOR PINGU

First of all:

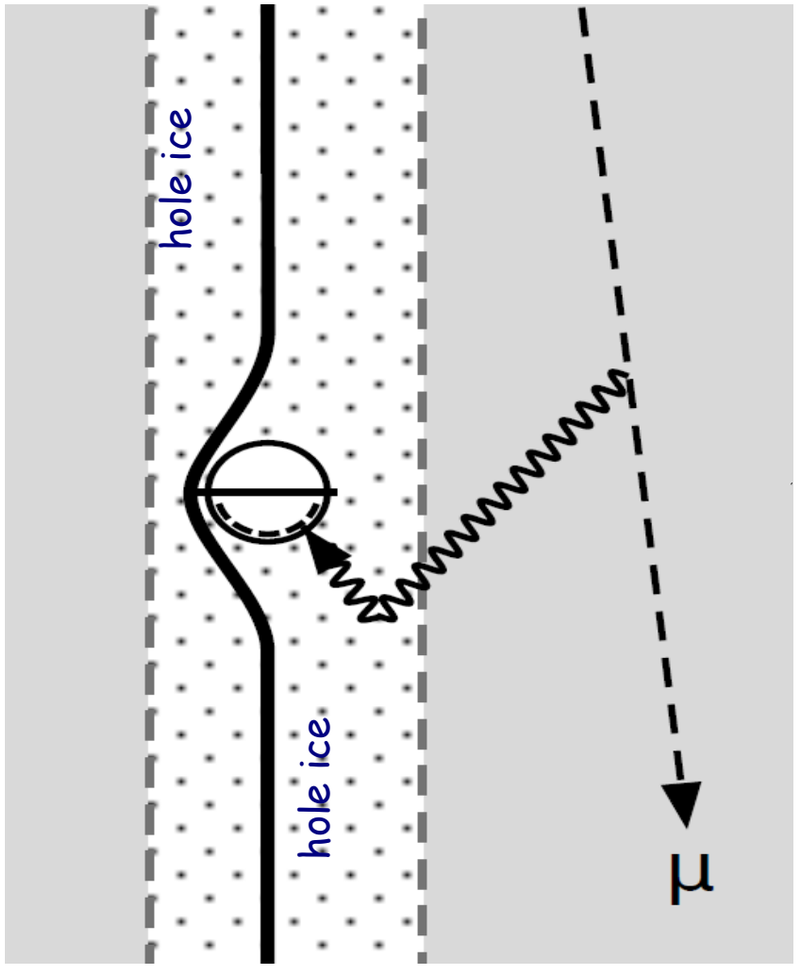
- **Confirm feasibility (DeepCore as test bed, MC studies, improve reconstruction) !**

- **Which energy resolution can be achieved?**
- **Which angular resolution can be achieved?**
- **How well works flavor identification?**
- **Are there non-understood systematic effects?**

Optical Module and hole ice



- Reduced ADC time window
- Reduced dynamical range
- Simplified control circuity
- Simplified support solution
- Modified coincidence circuitry



Upgrade drilling system

- Cleanliness – Filter water, Replace hose
- Minimize Bubbles – Circulate de-gassed water at hole bottom
- Crack Free – limit refreeze pressure

Timeline (the optimist´s view)

- **April 18, 2013:** advanced LoI for SAC Meeting at UW Madison
- **October 2013:** proposal to US finding agencies (NSF)

If proposal approved in March/April 2013: ← ???

- **Summer 2014:** start construction project
- **2014-16:** design, manufacture and test hardware
- **Season 2015/16:** drill preparation
- **2016:** first cables/DOMs shipped to Antarctica
- **Season 2016/17:** first deployment
- **Season 2017/18:** second deployment

Summary on PINGU

- **PINGU offers a fast, low cost solution to determine the mass hierarchy with atmospheric neutrinos**
- **PINGU feasibility remains still to be demonstrated**
- **PINGU construction cost including drilling: 40-50 M$**
- **PINGU start data taking**
  - **approval Spring 2014, 20 strings: 2018**
  - **approval late 2014 or 2015, 40 strings: 2020**

References

- O. Mena, I. Mocioiu, S. Razzaque, Phys. Rev. D78(2008), 093003 [arXiv:0803.3044]

  Neutrino mass hierarchy extraction using atmospheric neutrinos in ice

  First calculation for DeepCore, assuming $\sin^2(2Q_{13}) = 0.1$, d=0

- E.Kh. Akhmedov, S.Razzaque and A.Yu. Smirnov, JHEP 1302(2013),082 [arXiv:1205.7071]

  Mass hierarchy, 2-3 mixing and CP-phase with Huge Atmospheric Neutrino Detectors

- S. K. Agarwalla, T. Li, O. Mena, and S. Palomares-Ruiz, arXiv:1212.2238

  Exploring the Earth matter effect with atmospheric neutrinos in ice

- M.Ribordy and A. Yu. Smirnov, arXiv:1303.0758

  Improving the neutrino mass hierarchy identification with inelasticity measurement in PINGU and ORCA

- T. Ohlsson, H. Zhang and S. Zhou, arXiv: 1303.6130

  Effects of non-standard neutrino interactions at PINGU

- D.Franco et al., arXiv: 1301.4332

  Mass hierarchy discrimination with atmospheric neutrinos in large volume ice/water Cherenkov detectors

BEAM PHYSICS WITH UNDERWATER DETECTORS

Jürgen Brunner, Marseille

See: J. Brunner „ Counting Electrons to Measure the Neutrino Mass Hierarchy “ arXiv:1304.6213

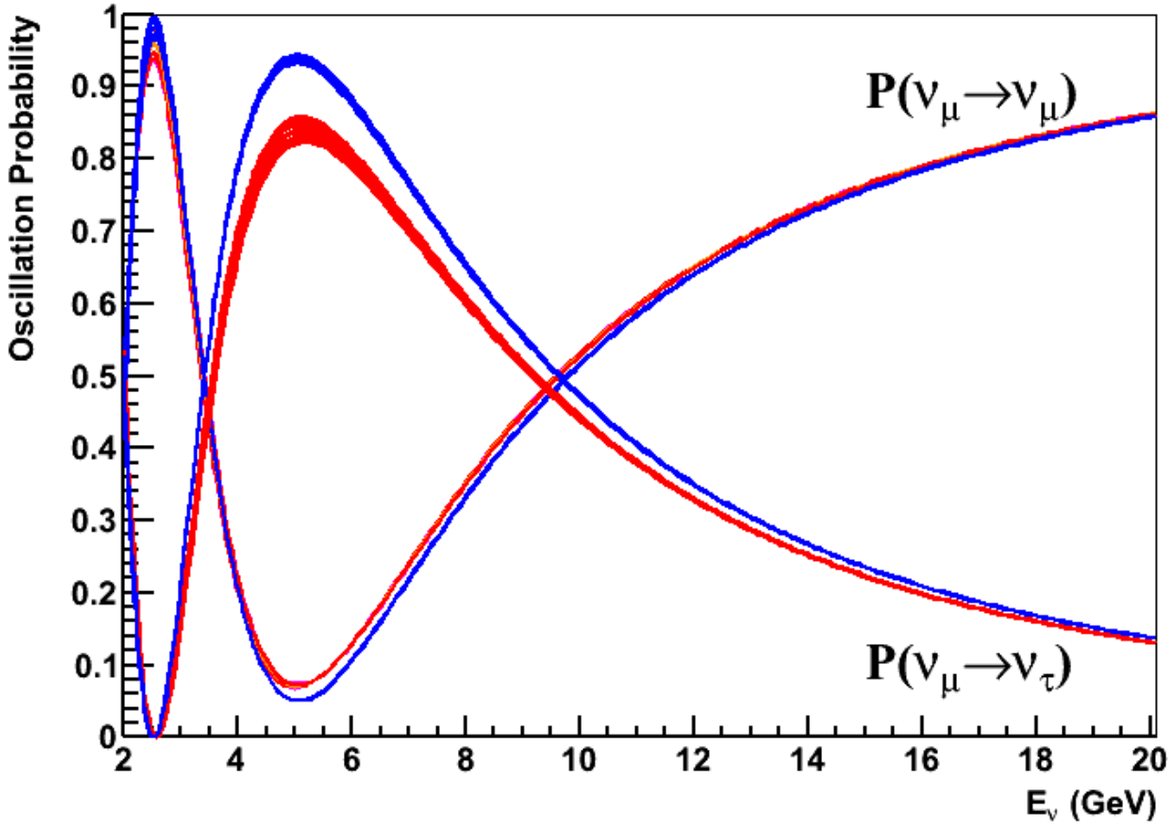
Slides based on a talk of J. Brunner at APC

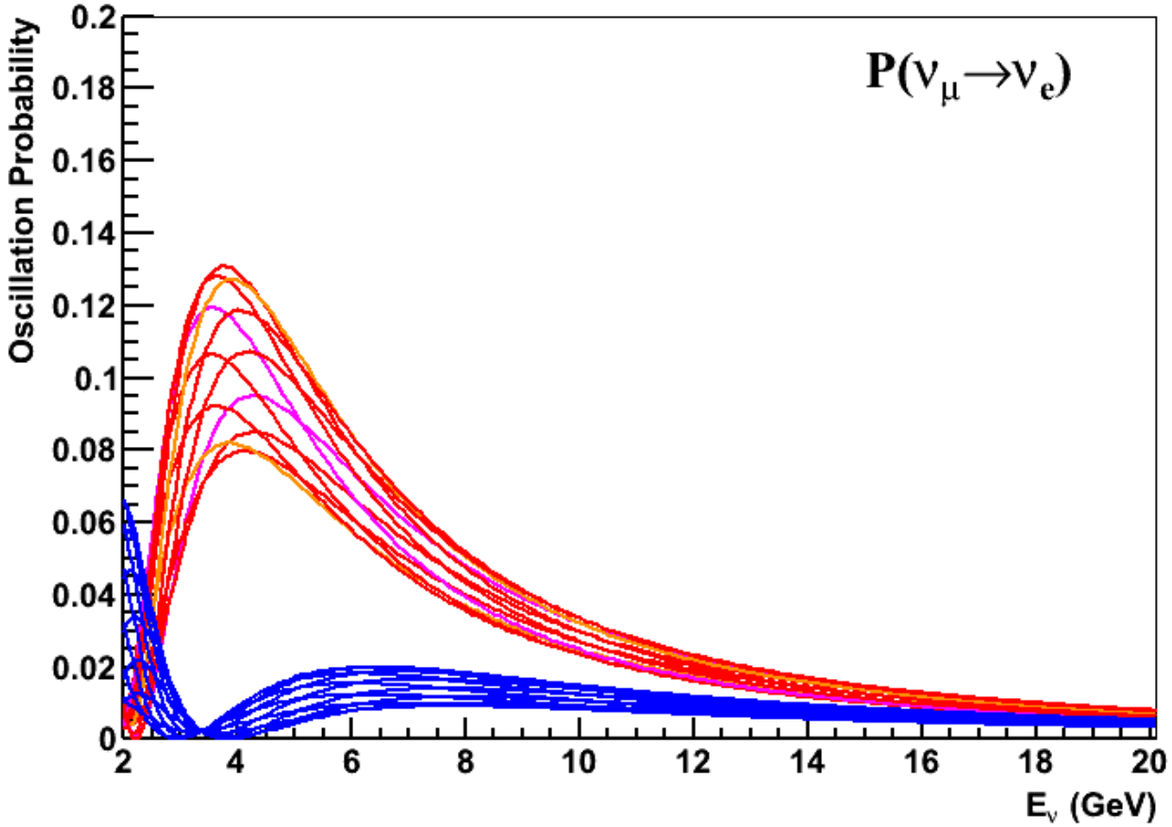
Oscillation Probabilities

- GLOBES for Baseline of 2600km (neutrinos)
- CP phase in steps of 30 degree
- Full 3-flavor treatment

red: NH, blue: IH

NH/IH = 5/1

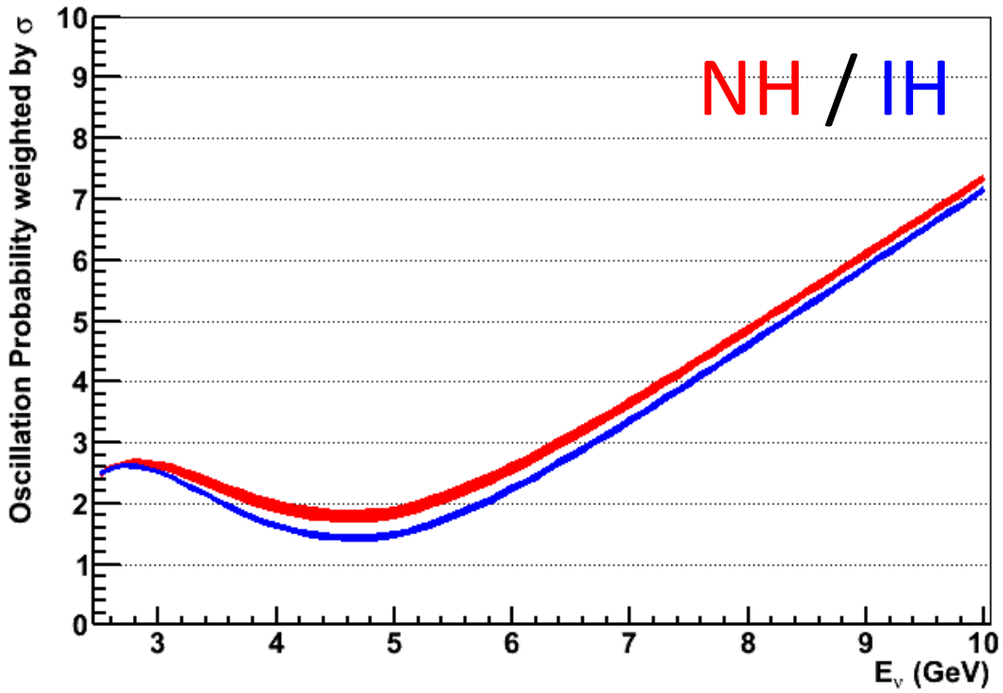


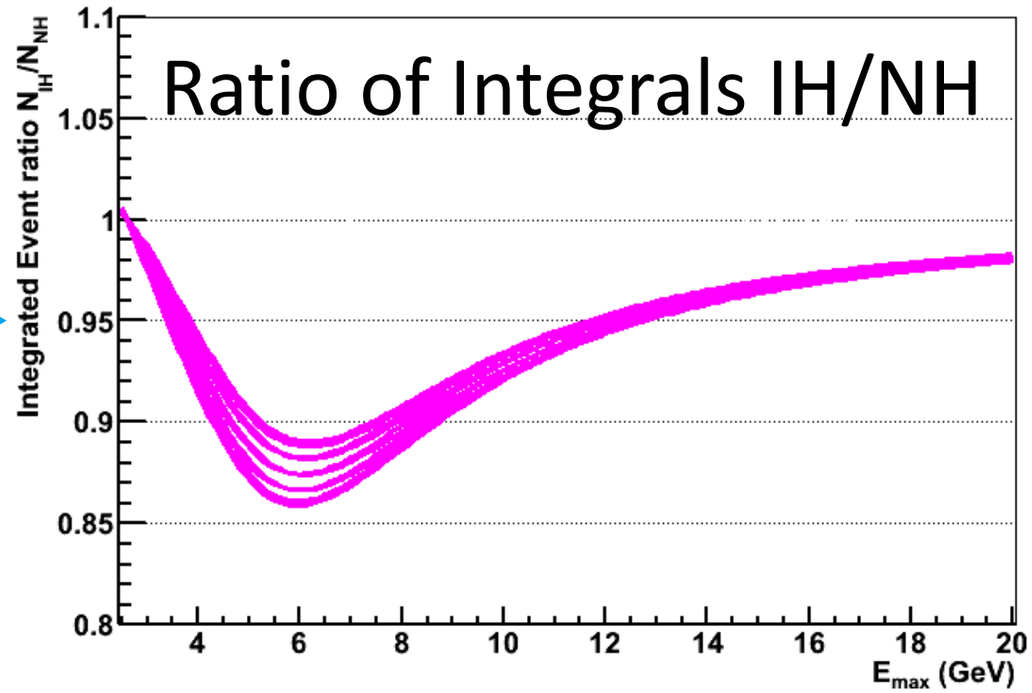


Cross Section Weighted P_{osc}

- Allows to find optimal energy range for MH determination
- No flavour tagging or CC/NC separation used
- Kinematical suppression of ν_τ exploited

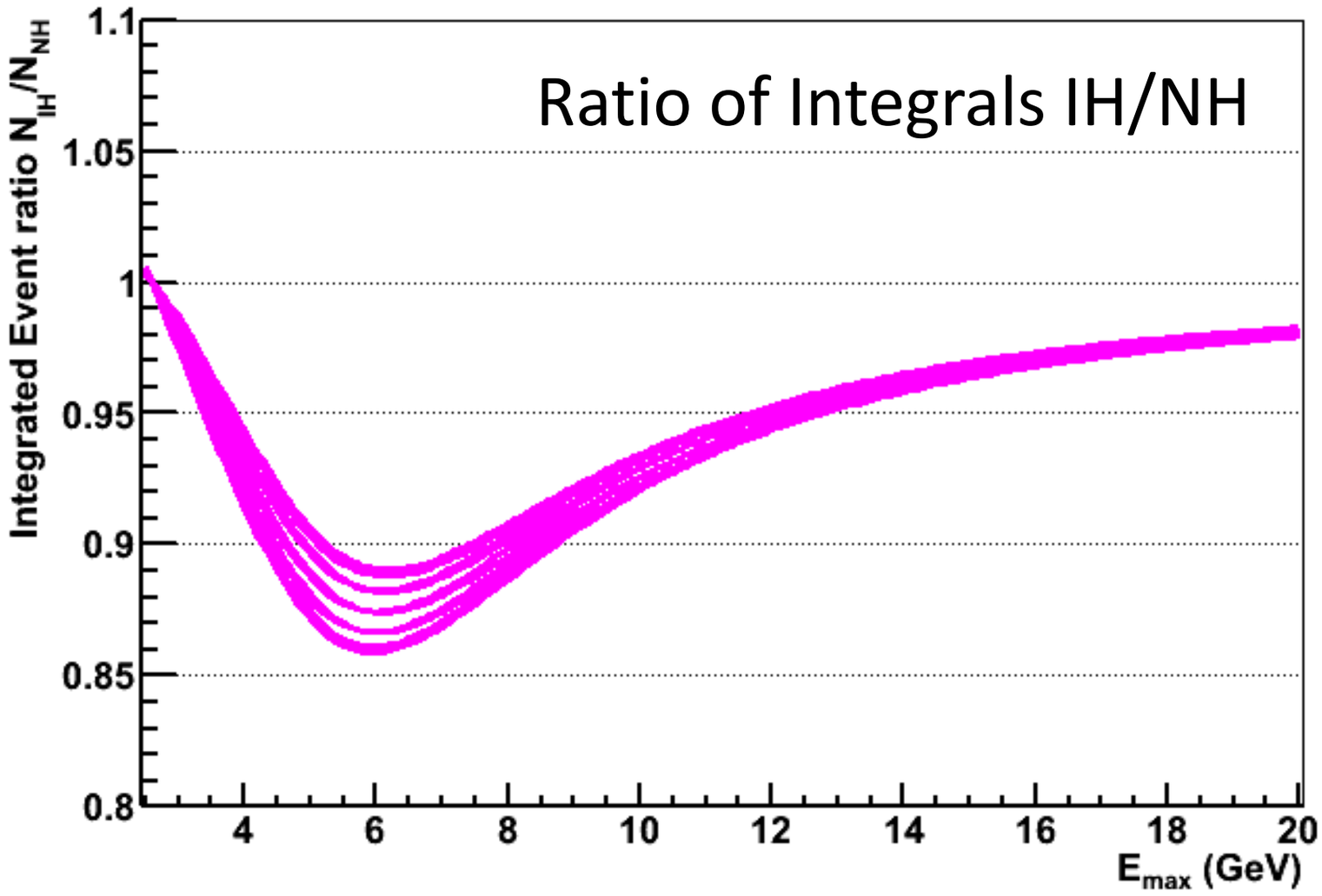
$$P_\mu^\sigma(E_\nu) = \frac{1}{\left[\sigma_{\nu_\mu}^{CC} + \sigma_\nu^{NC}\right](E_0)} \sum_\alpha \left[P(\mu \to \alpha)\sigma_{\nu_\alpha}^{CC} + \sigma_\nu^{NC}\right](E_\nu)$$



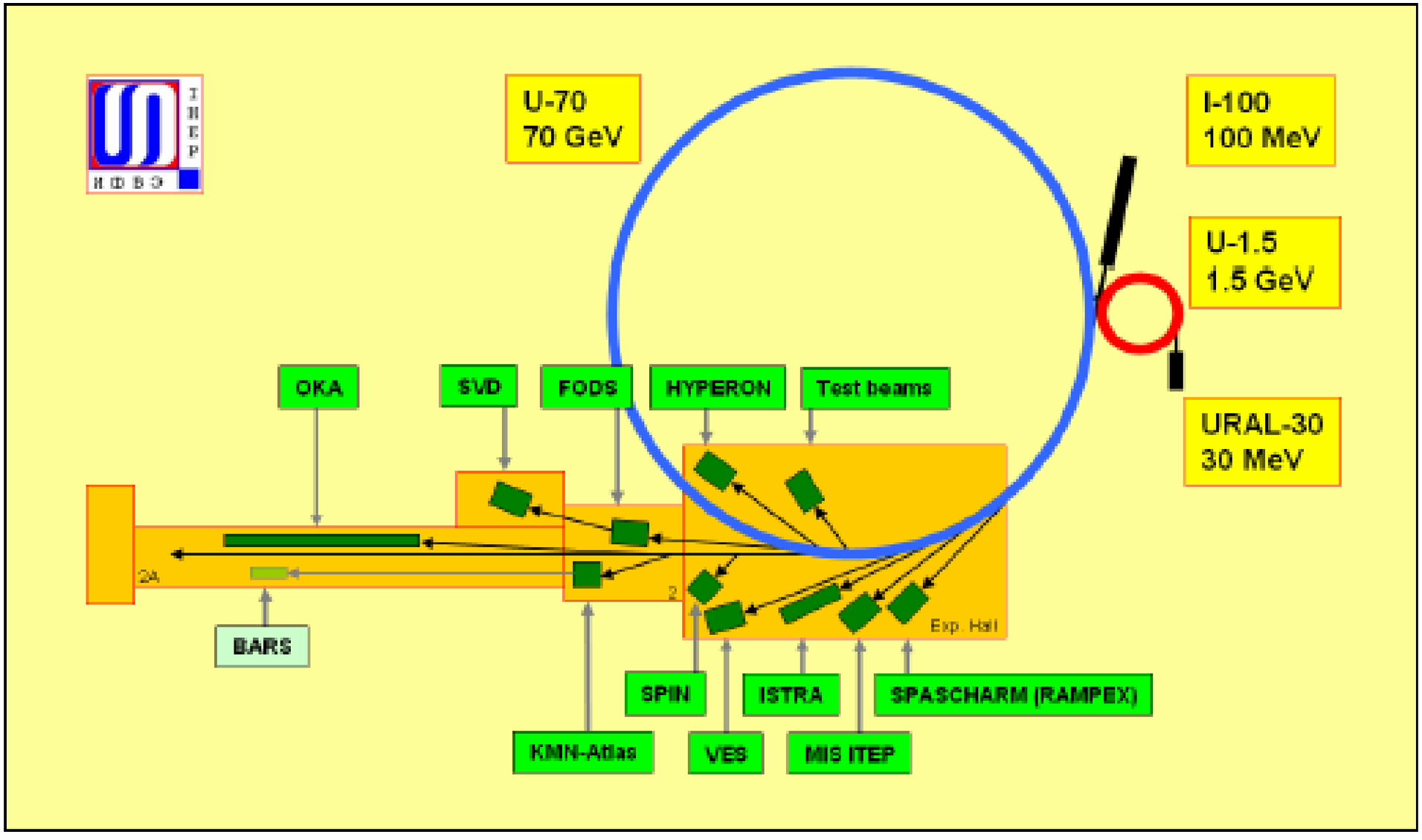


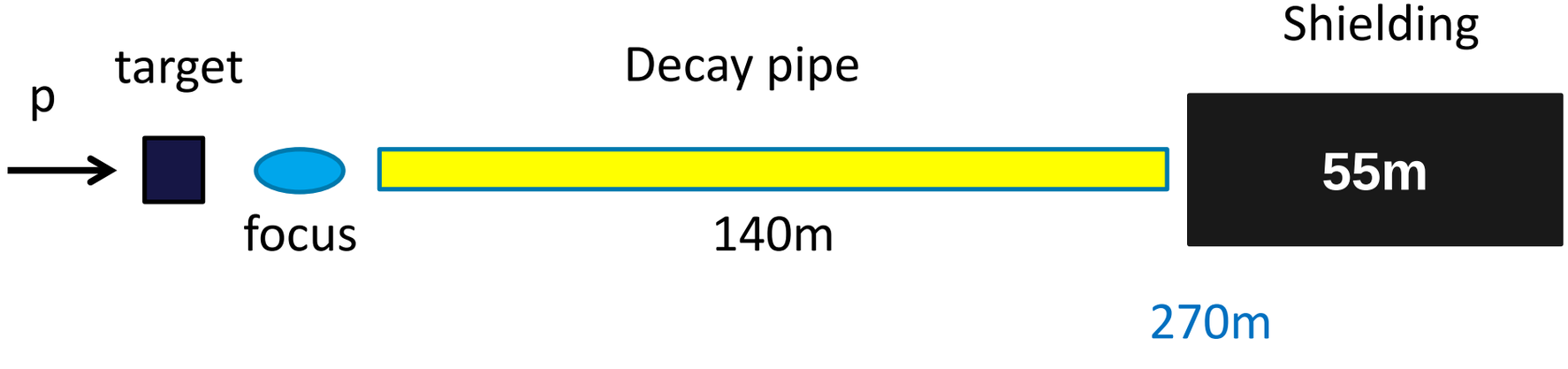
Cross Section Weighted P_{osc}

- Optimal energy range for “event counting” 4-7 GeV
- 11-14% suppression of IH w.r.t. NH



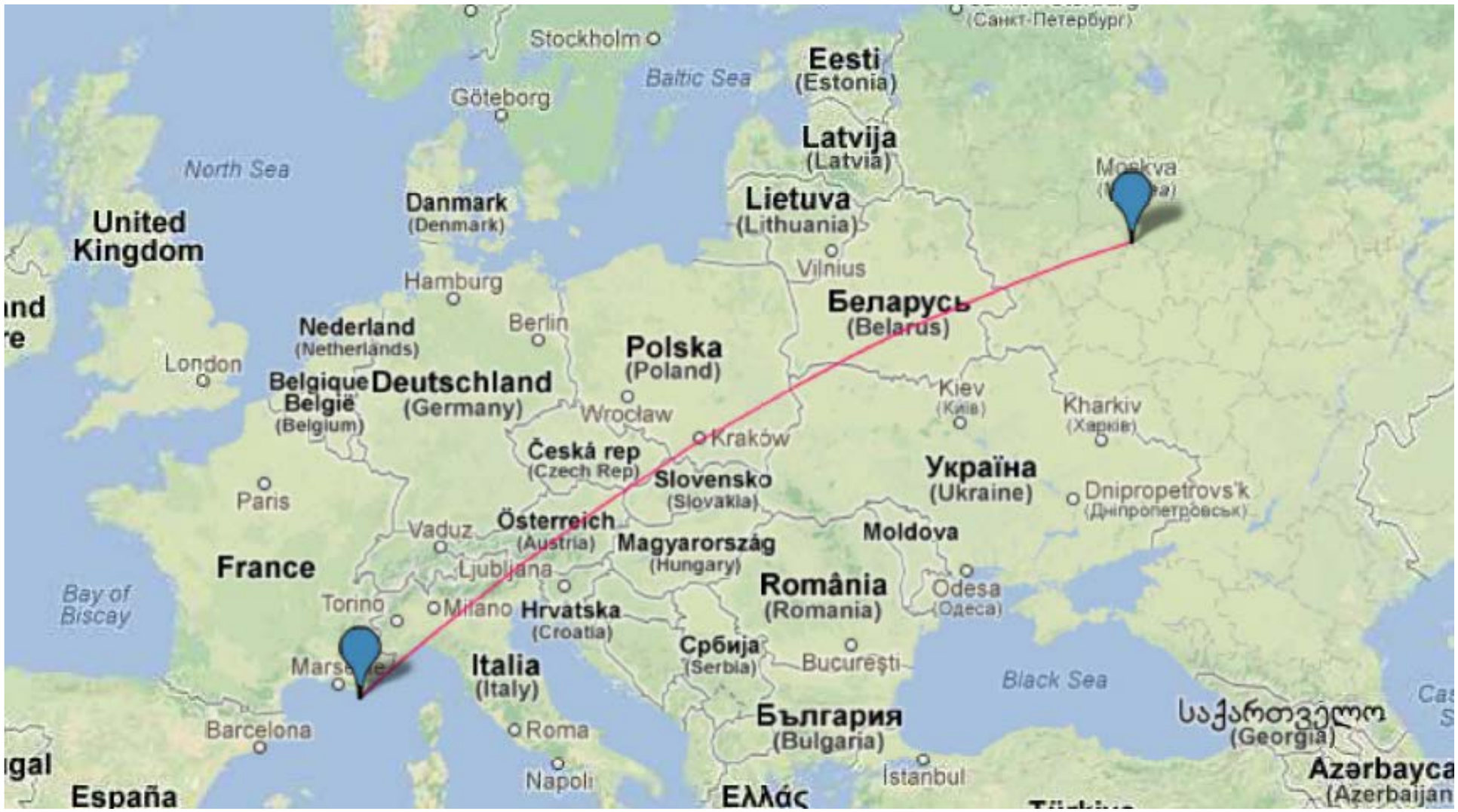
U-70 and neutrino beam in Protvino





Protvino - Toulon

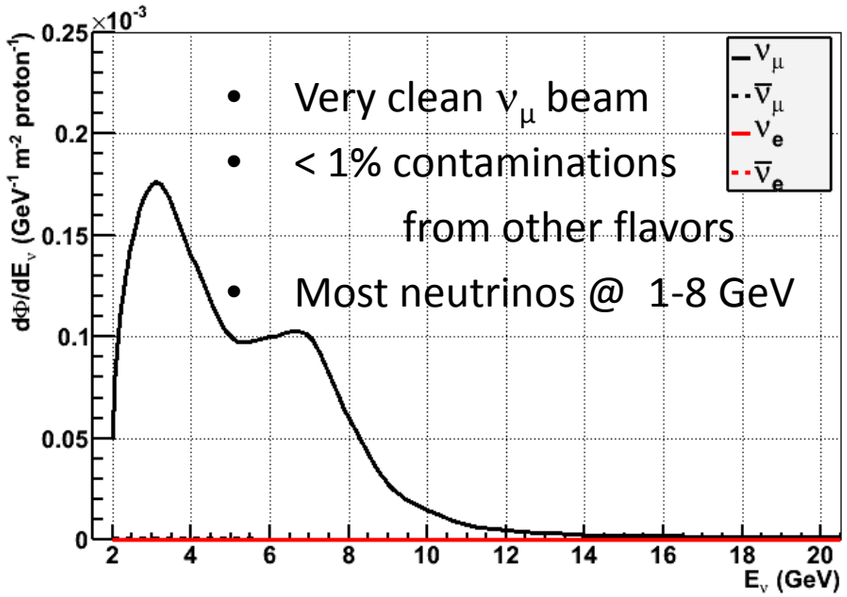
- Baseline 2588km ; beam inclination : 11.7˚ ($\cos\theta = 0.2$)
- Similar distance to Fréjus : 2400km
- Deepest point 134 km : 3.3 g/cm^3
- With upgrade 10^{21} p.o.t. in 3 years might be feasible



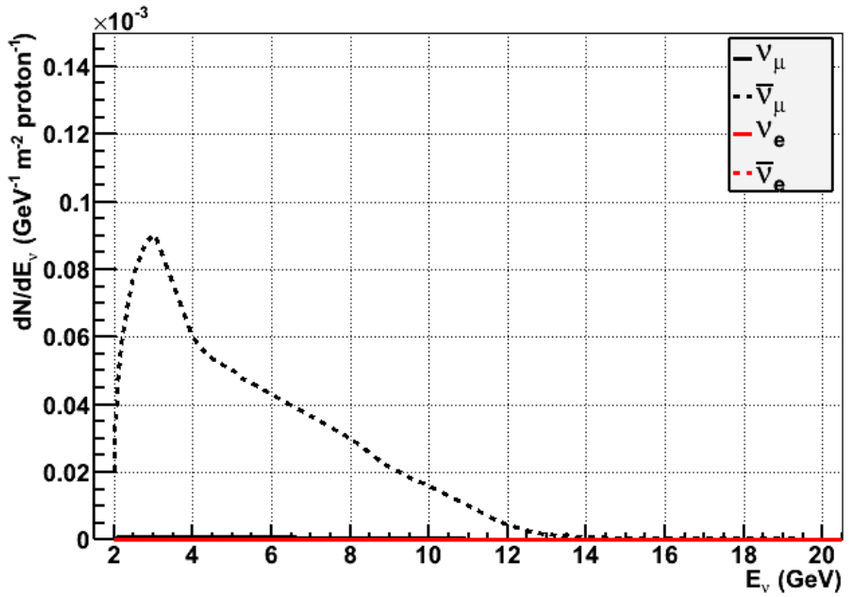
Beam parametrisation (1988)

Scaling to ANTARES site $(0.245/2600)^2$

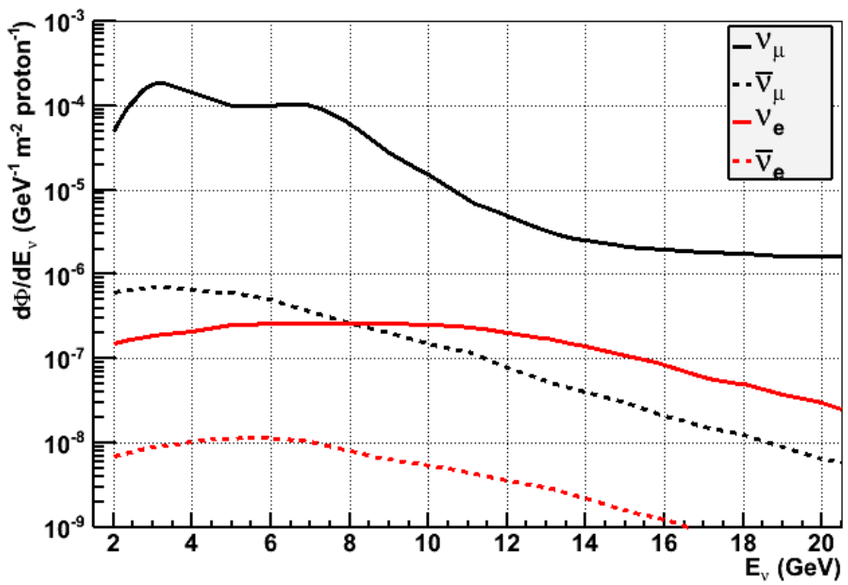
- **Neutrino Focus**

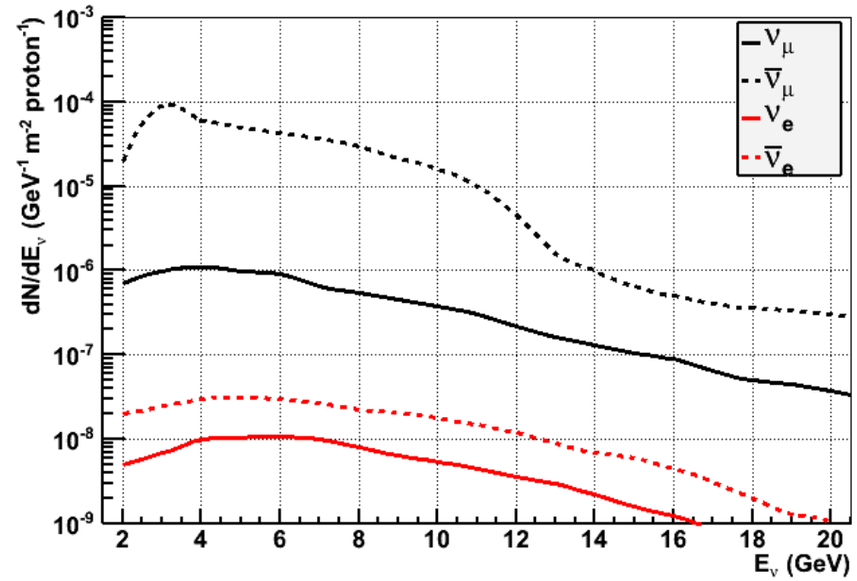


- **Anti-Neutrino Focus**



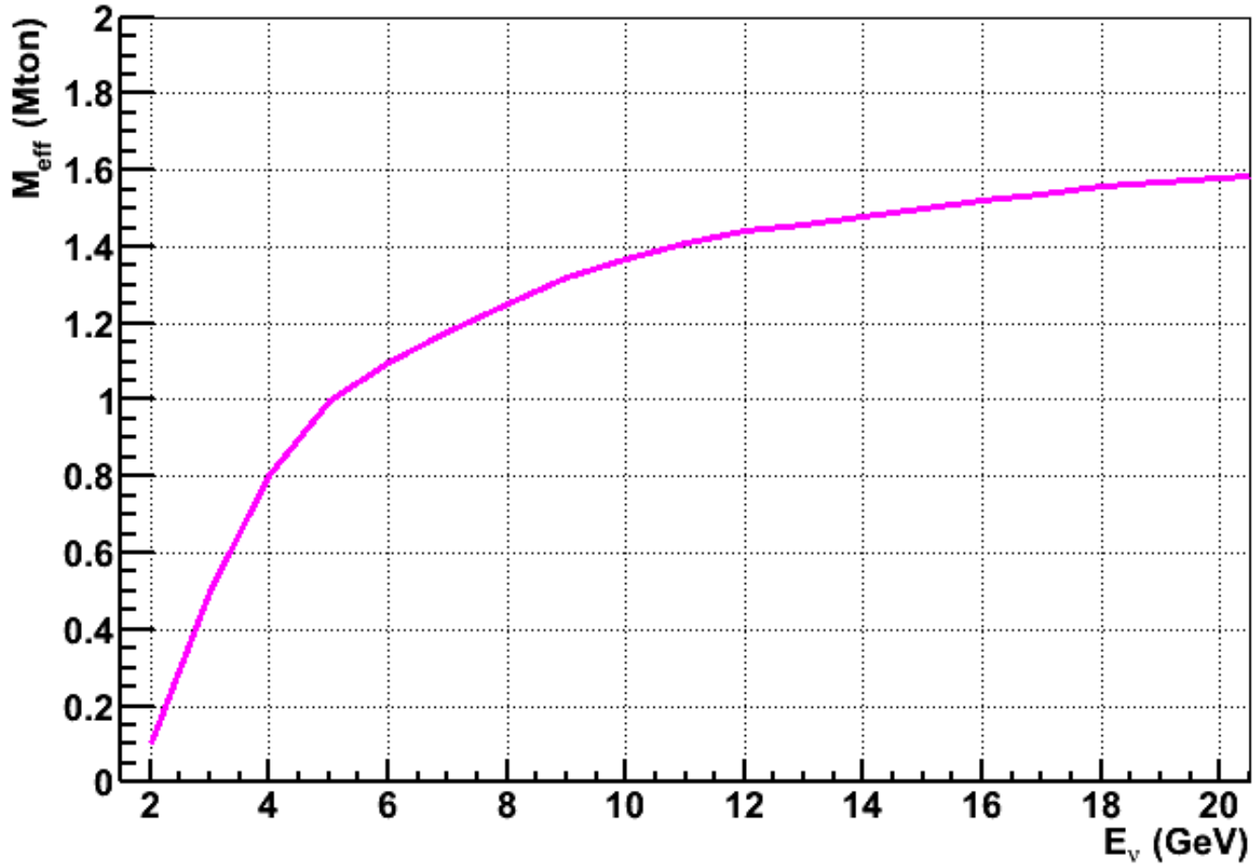
Z. Phys. C 40 (1988) 487





ORCA Effective Mass, event simulation

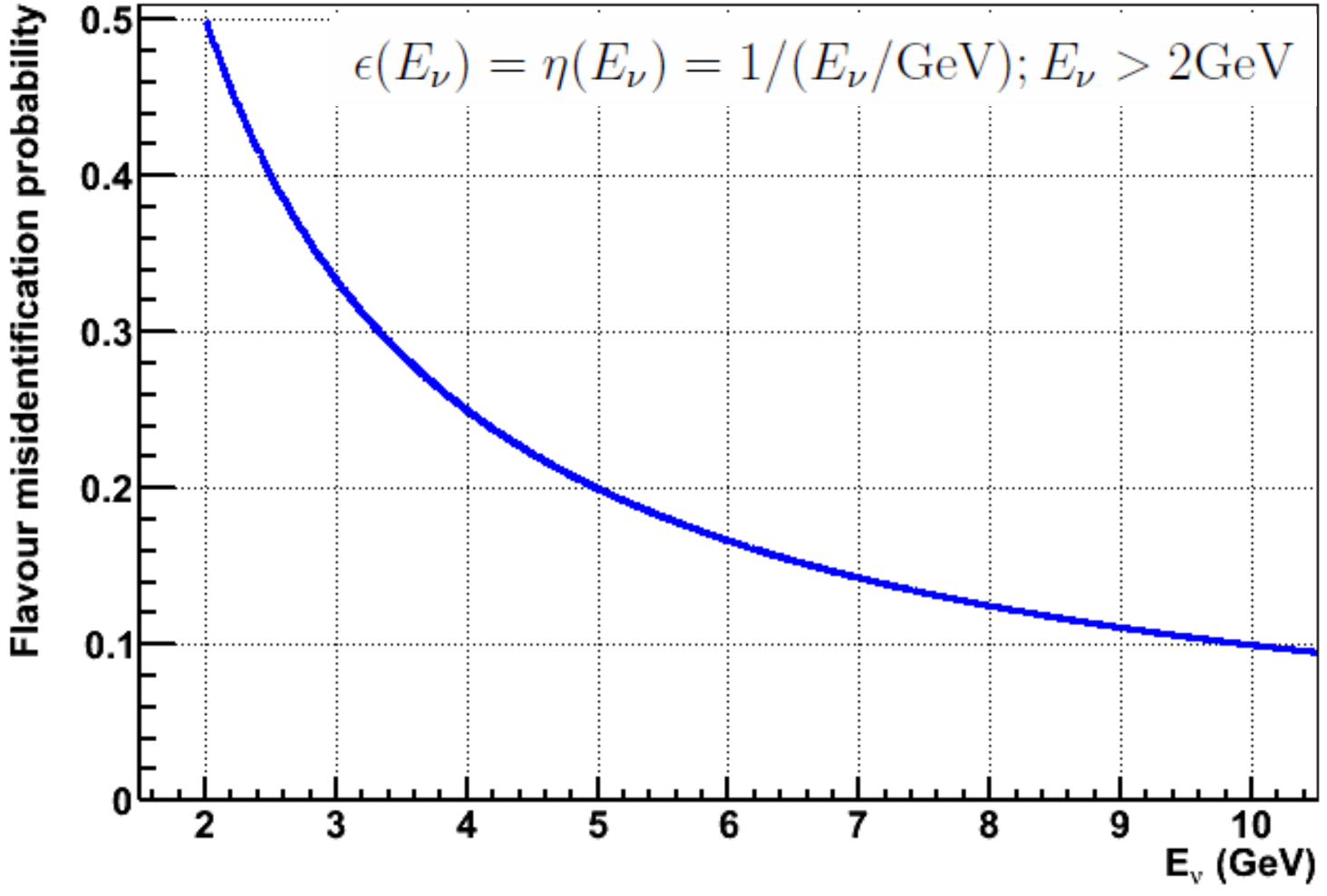
- From study of A. Trovato for “default” ORCA detector
- Vertex in instrumented volume
- Reconstruction Quality cut
- beam direction known, no background from atmospherics



- Same function used for all CC interactions
  - Same light output for ν_μ and ν_e
  - Conservative for ν_τ due to escaping neutrinos
- NC evaluated at E/2

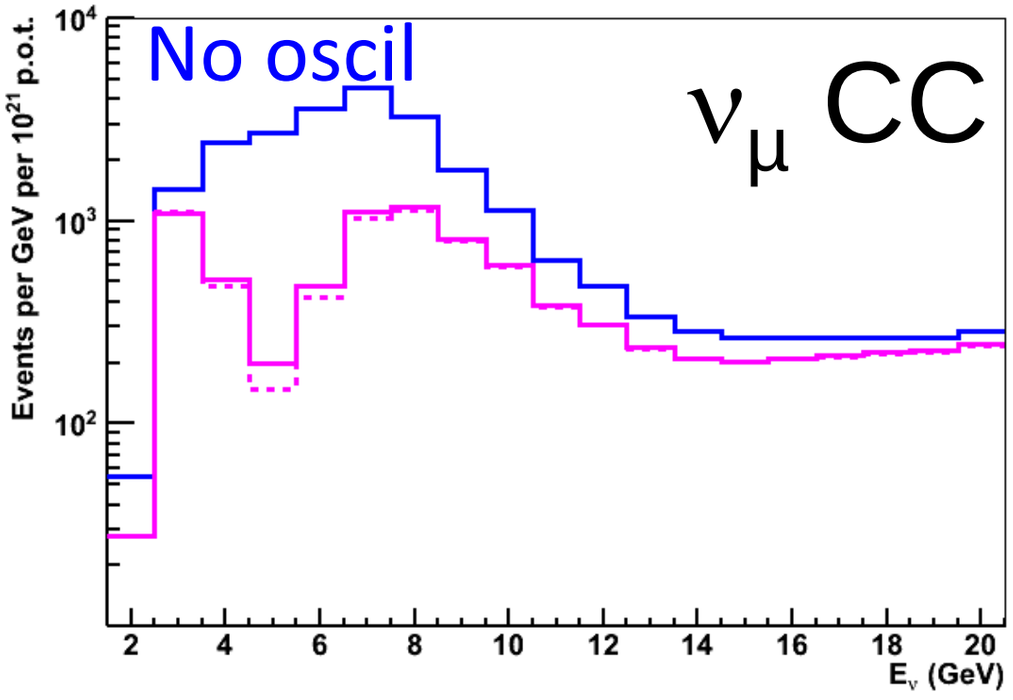
Flavour identification

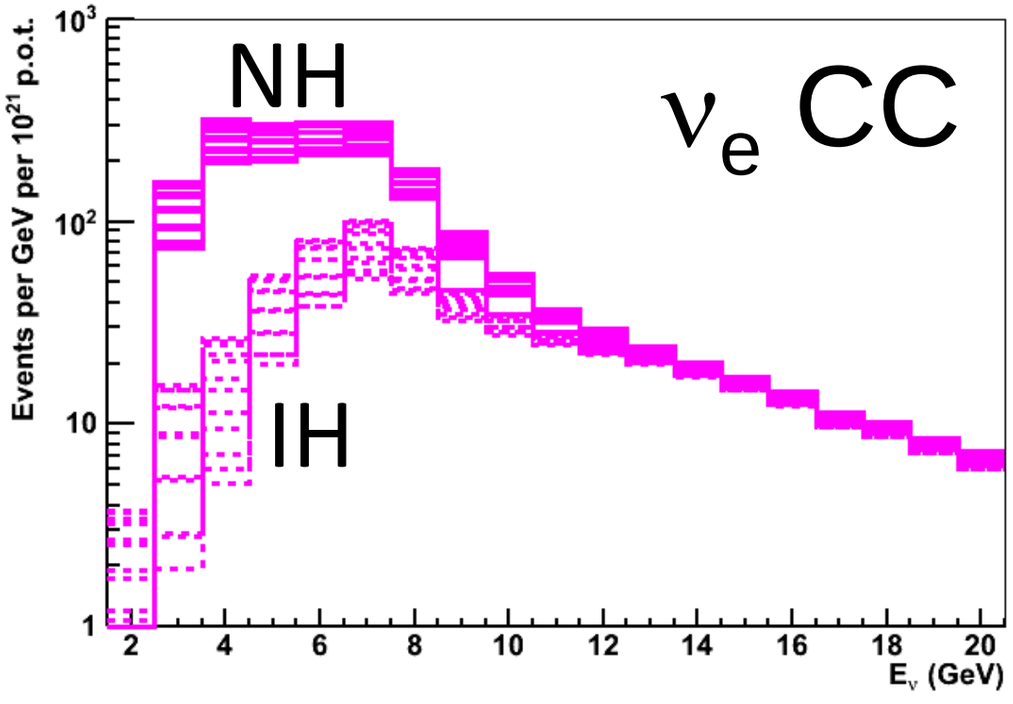
- **Misidentification probability :**
  - **assume same for both directions**
- **50% at 2 GeV → random ; 20% at 5 GeV ; 10% at 10 GeV**



Event rates, flavor specific

- **Event numbers for 1.5 10^{21} pots**
  - **NH : 1621 +/- 255 (CP-phase variations)**
  - **IH : 497 +/- 100 (CP-phase variations)**
- **20 sigma statistical separation of both Mass Hierarchy hypotheses from signal**
- **10000 muon events for beam normalisation**





Event rates, topology specific

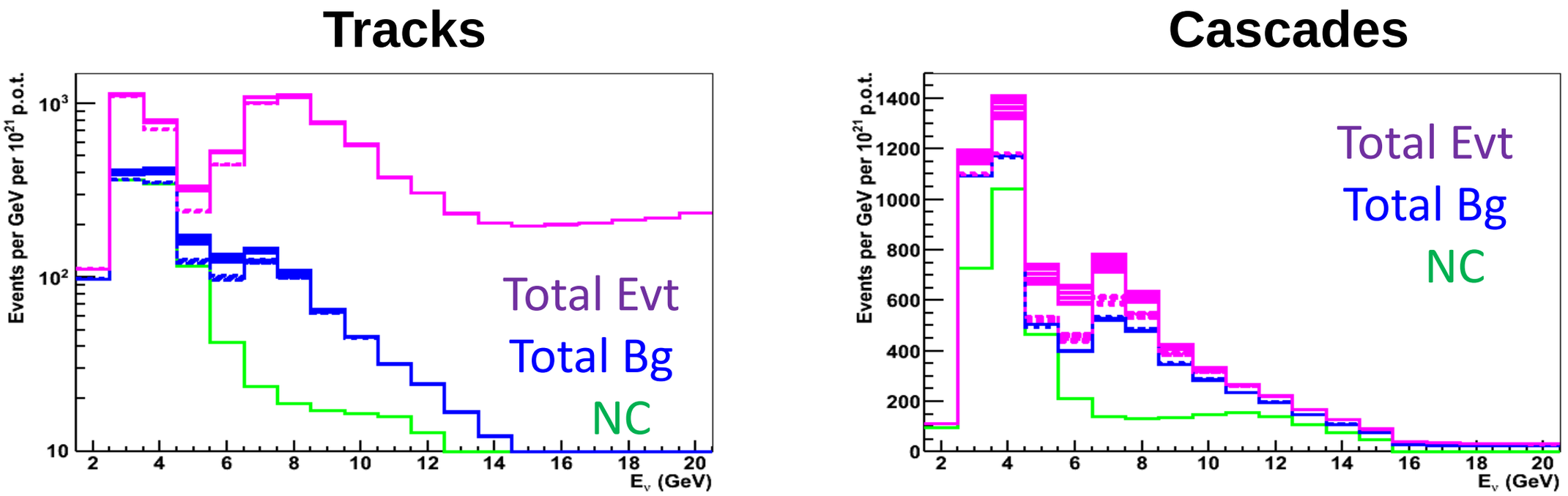
- **Event numbers for 1.5 10^{21} pots**

Channel	Tracks NH	Tracks IH	Cascades NH	Cascades IH
No oscil	26315		—	
Signal	8990	8735	1134-1547	350-519
Misreco	232-329	47-79	1326	1280
ν_τ	324-332	351-355	978-998	1057-1068
NC	1092	1092	3640	3640
BG Total	1655-1745	1494-1522	5944-5964	5977-5988
Total	10645-10736	10229-10257	7099-7491	6338-6496

- **9-18% difference for NH/IH**
- **7 sigma statistical separation of MH hypotheses**
- **With 3-4% syst. uncertainty still 3 sigma for MH test**
- **No assumption on energy reconstruction !**
- **Background largely independent from MH (& CP)**

Event rates, topology specific

- **Event numbers for 1.5 10^{21} pots**



- **9-18% difference for NH/IH**
- **7 sigma statistical separation of MH hypotheses**
- **With 3-4% syst. uncertainty still 3 sigma for MH test**
- **No assumption on energy reconstruction !**
- **Background largely independent from MH (& CP)**

Systematic Uncertainties

- Detector Response
- Water parameters
  - Extensively studied in ANTARES
- Neutrino flux
  - Can be monitored with muon events
- Neutrino Cross Section
  - Ongoing and planned short baseline Experiments
- Oscillation parameters
  - ORCA with atmospheric neutrinos

Summary on Protovino-ORCA

- **Upgraded proton accelerator at Protvino well suited for LBL towards Mediterranean Sea.**
- **Beam with 10^{21} pot realistic in a short time?**
- **Complementary to measurement with atmospheric neutrinos. Much less uncertainties due to known direction, small background and better defined energy band. 3-4% systematical error realistic?**
- **Preliminary performance figures of ORCA encouraging: High significance determination of Mass Hierarchy after few years of data taking**
- **Cost: HL beam (~ X(?)00 M€) + detector (30-40 M€)**
- **However: ORCA not the priority option of KM3NeT collaboration**
- **$\rightarrow$ No time line**

END