PINGU

Sebastian Böser
Neutrino Telescopes | Venice | March 6th 2015

PRISMA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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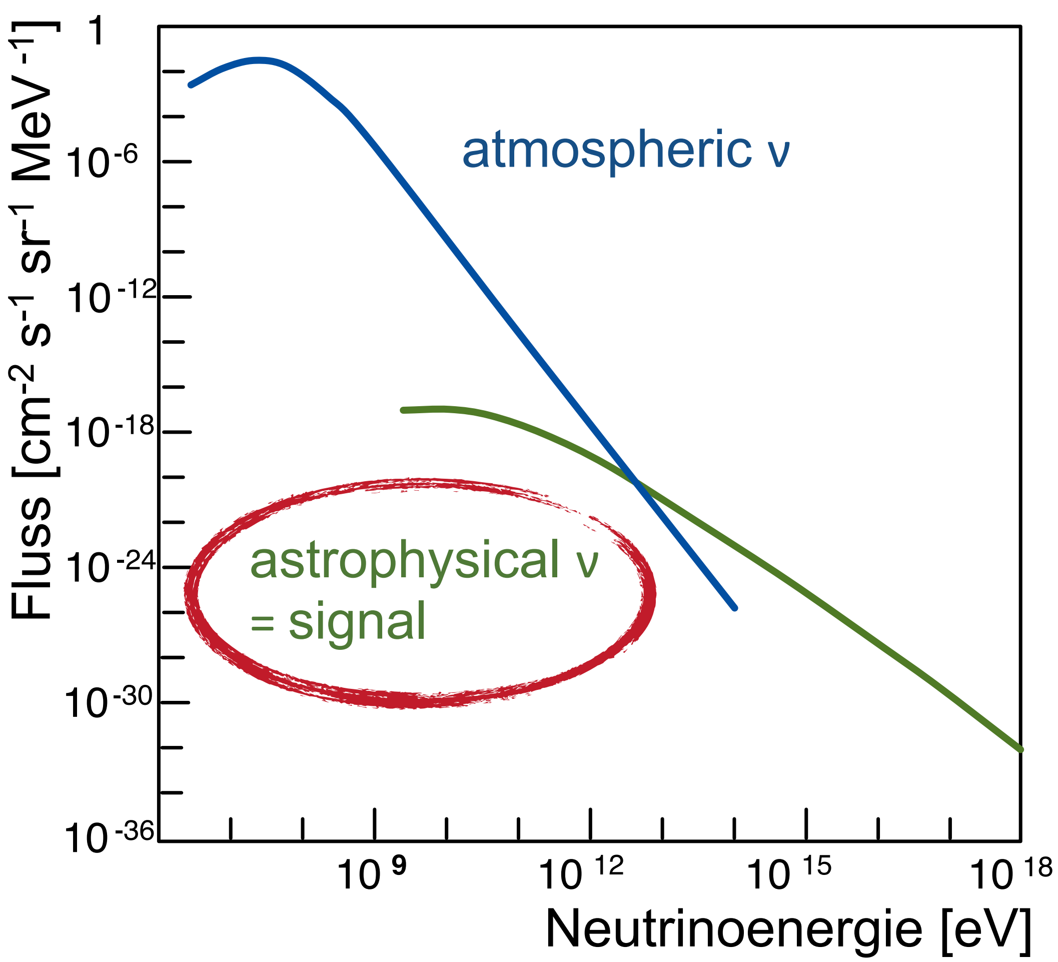
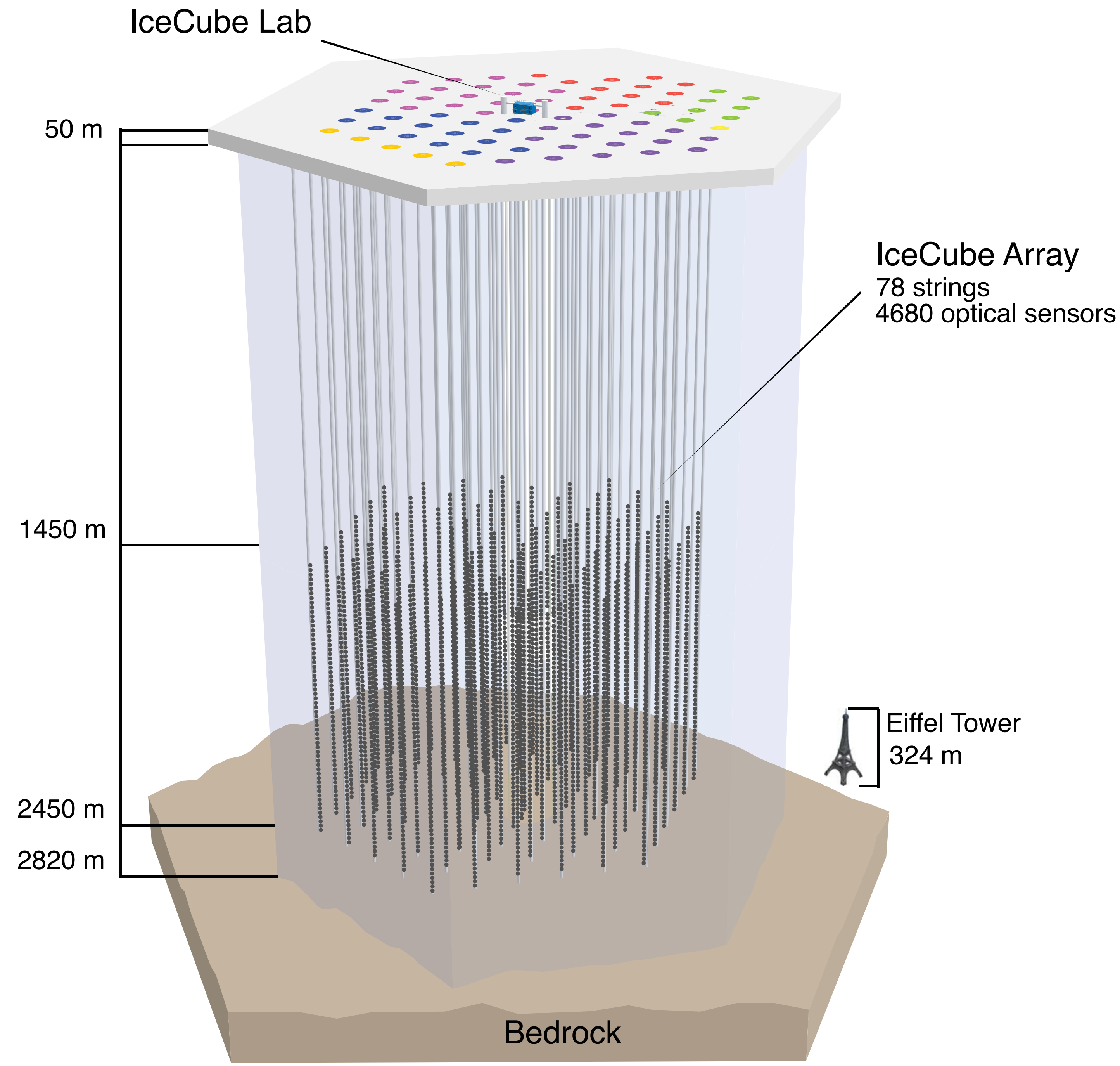
IceCube

IceCube (in operation)

- 78 strings, 125m / 17m spacing
- E_{thresh} ~ 100 GeV
  - optimized for astrophysical CR-sources
  - ▸ discovered!





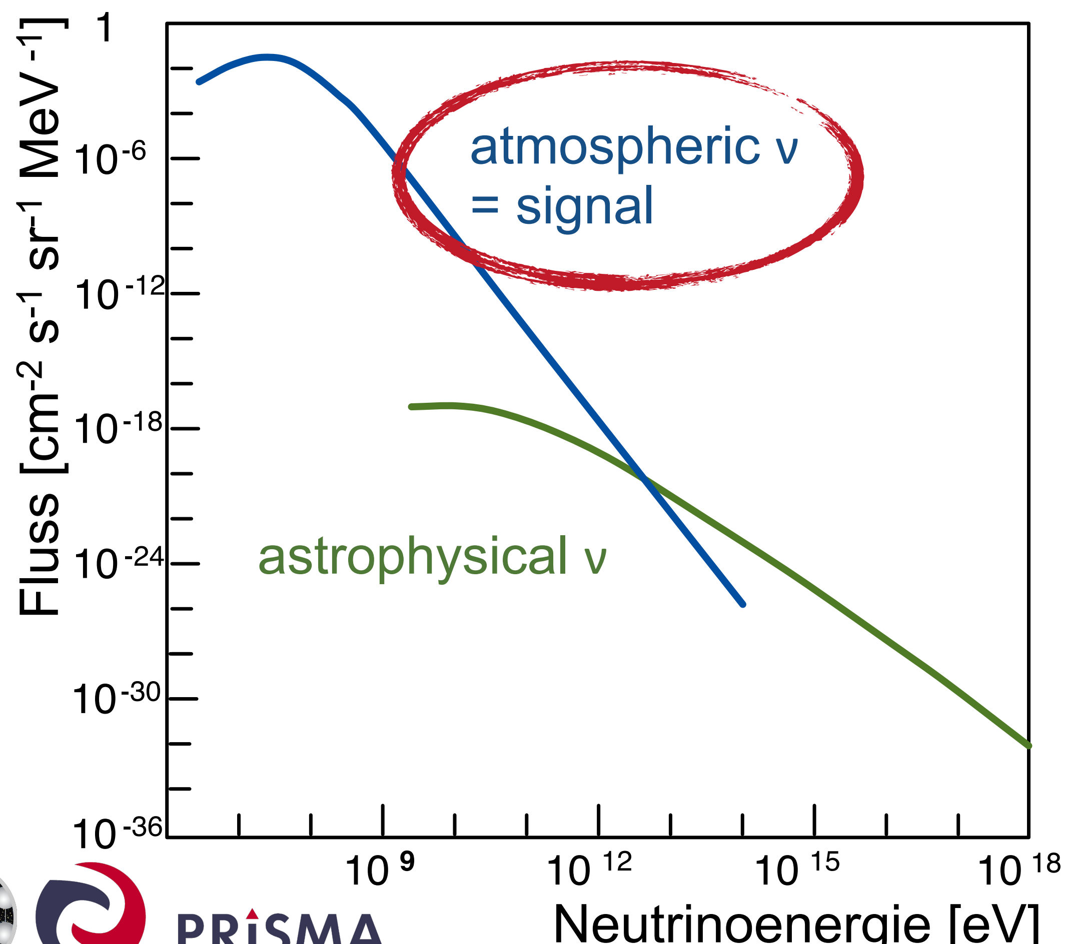
IceCube's low-energy ν detector

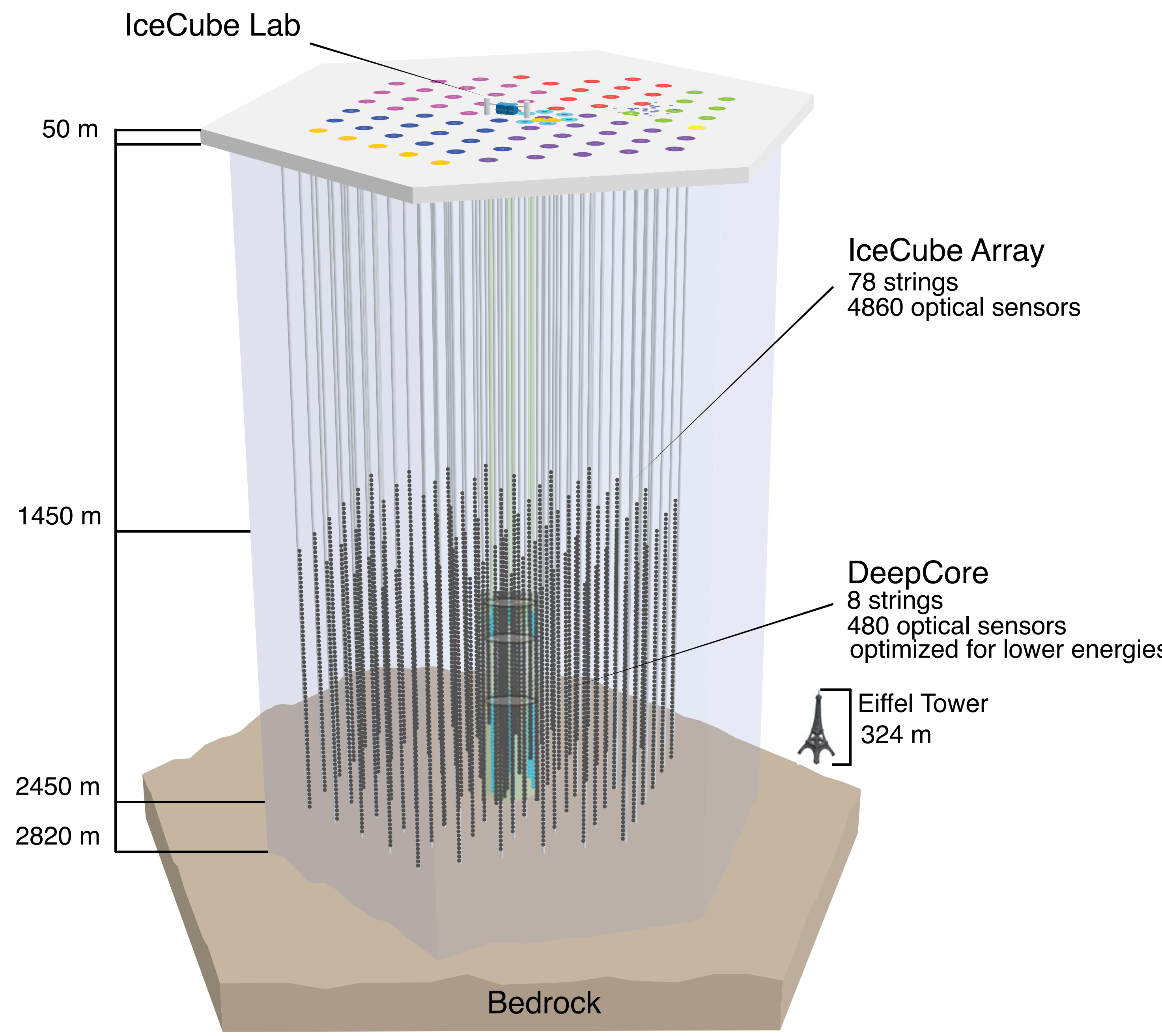
IceCube (in operation)

- 78 strings, 125m / 17m spacing
- E_{thresh} ~ 100 GeV
  - astrophysical CR-sources

DeepCore (in operation)

- +8 strings, 72m / 7m spacing
- E_{thresh} ~ 10 GeV
  - atmospheric neutrinos





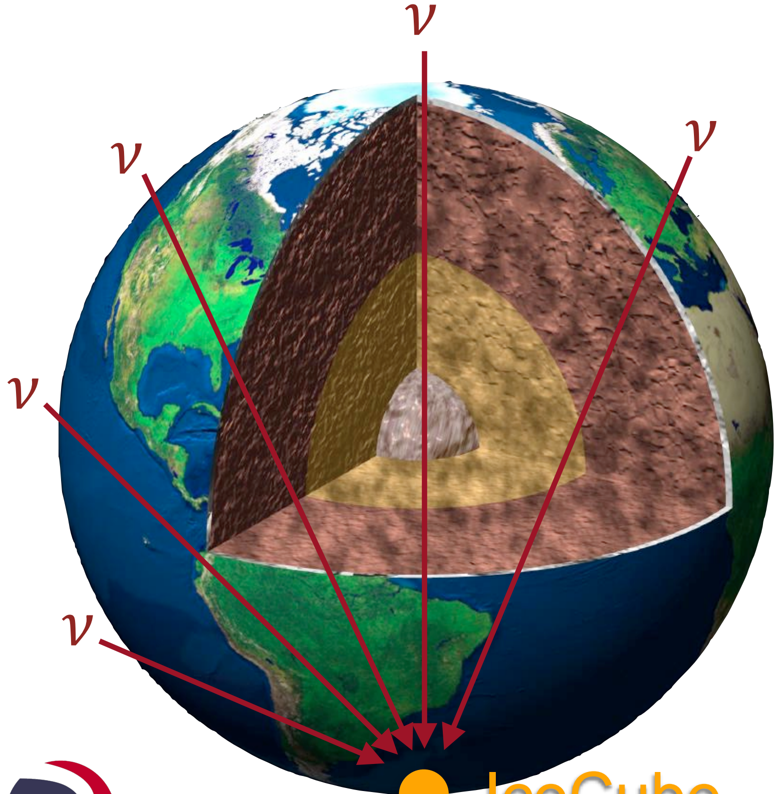
Atmospheric neutrinos

Event rates (trigger level, E≳10 GeV)

- $\nu_\mu \sim$ 70k / year
- $\nu_e \sim$ 11k / year

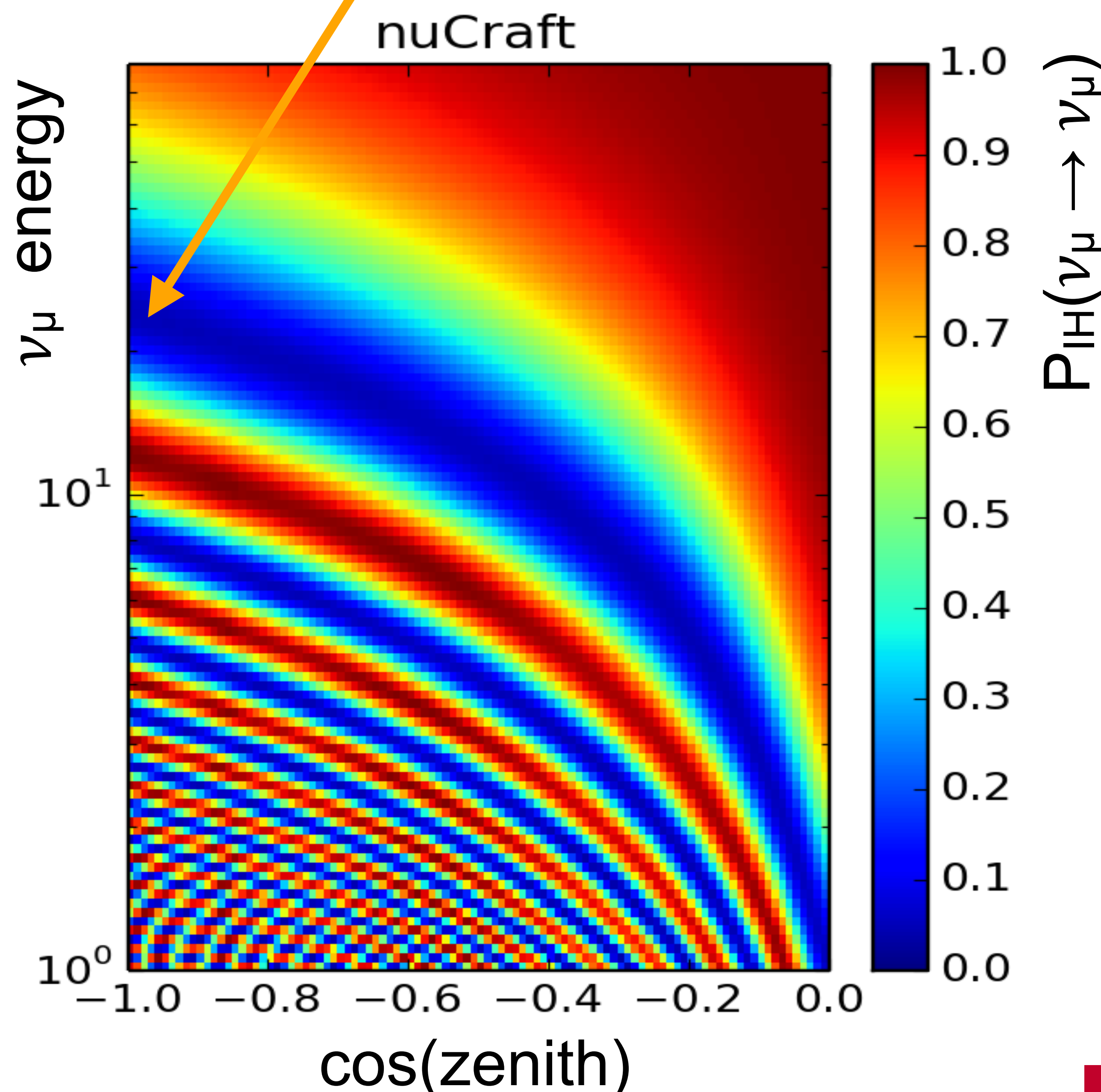
Science goals

- WIMP searches
- ν-oscillation physics
  - wide range of L/E
  - matter effects

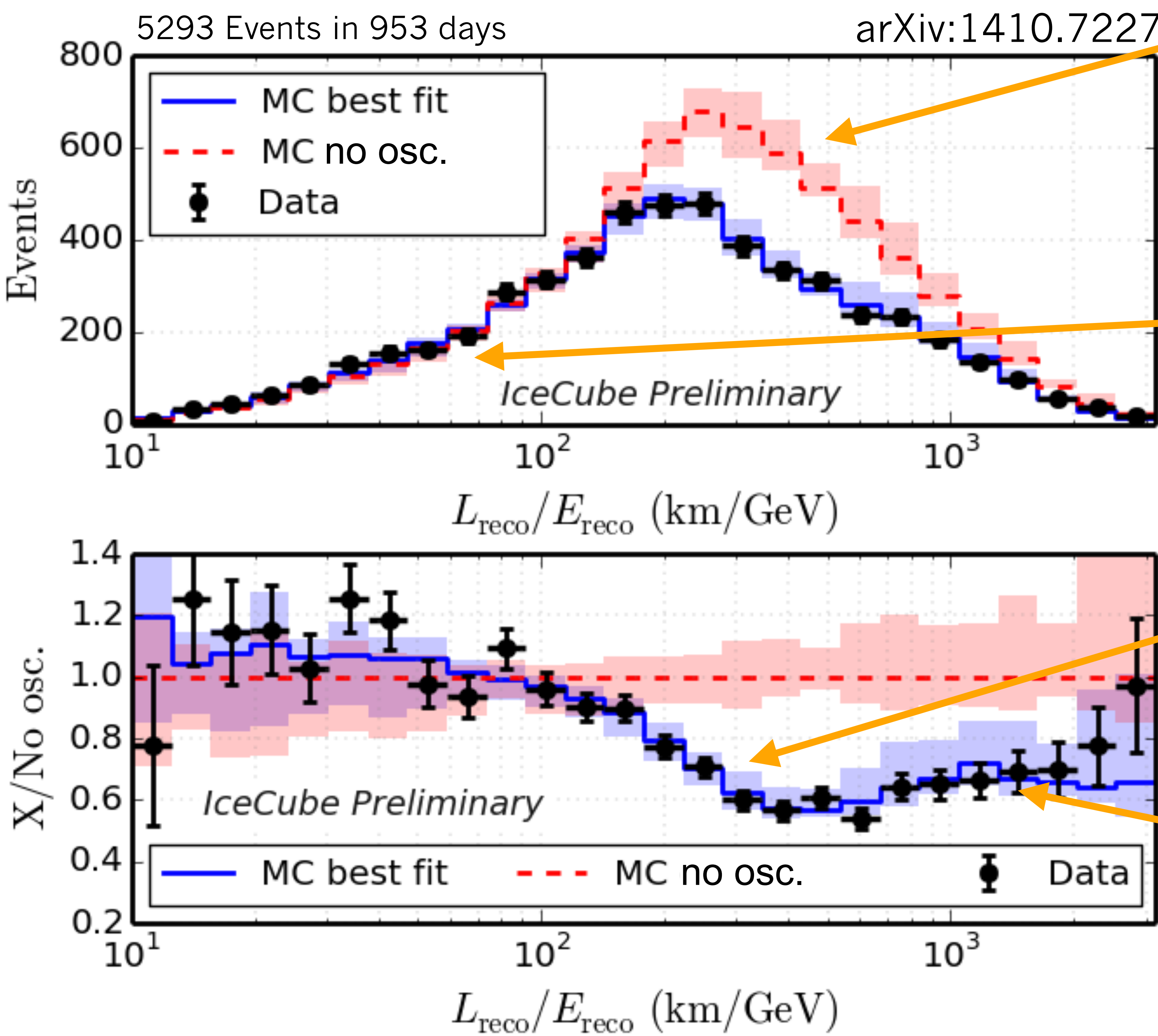


1st oscillation minimum

- $L_{max} = 12\cdot 10^3$ km
- $E_\nu \sim 20$ GeV



Oscillation analysis



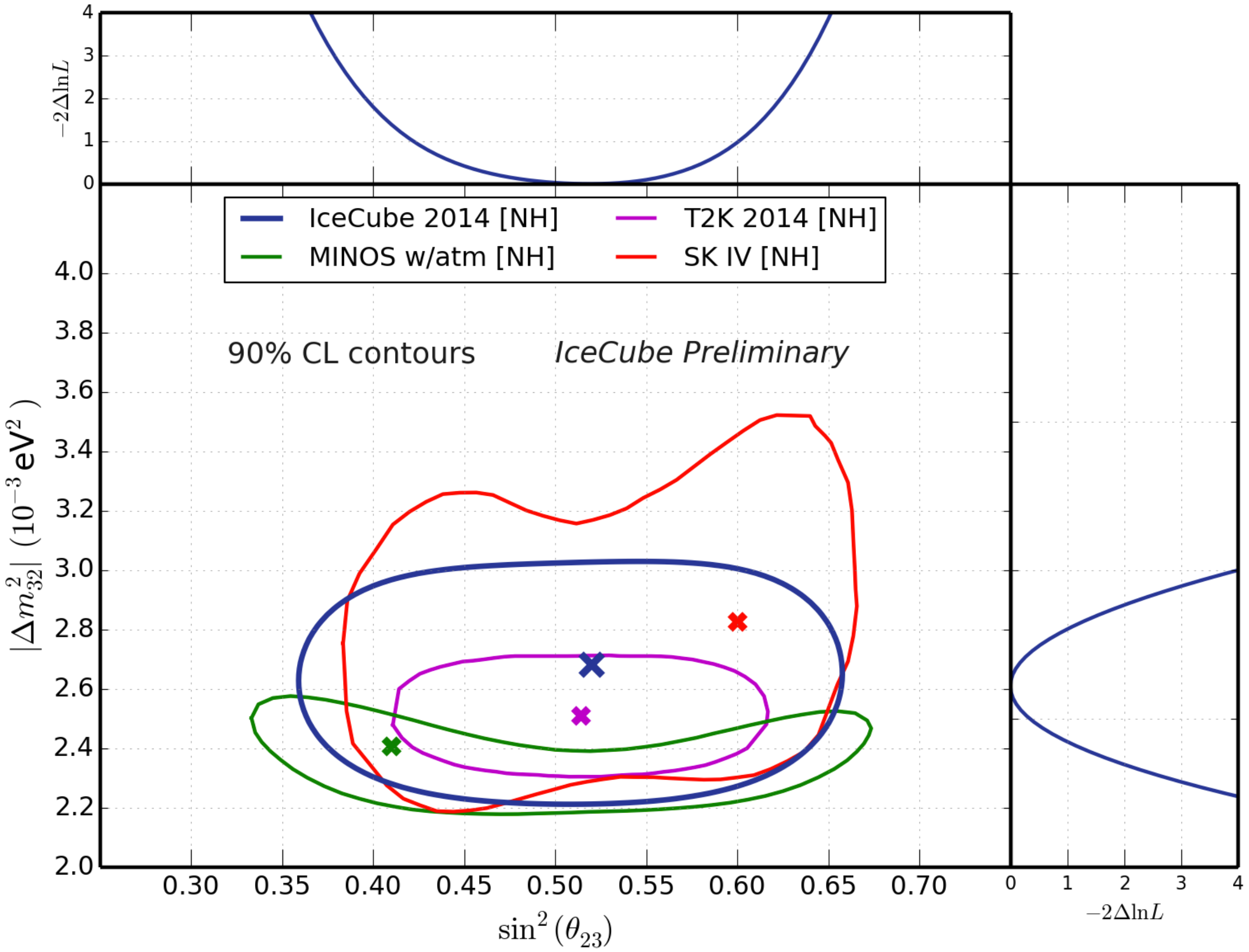
sample peaks at oscillation minimum

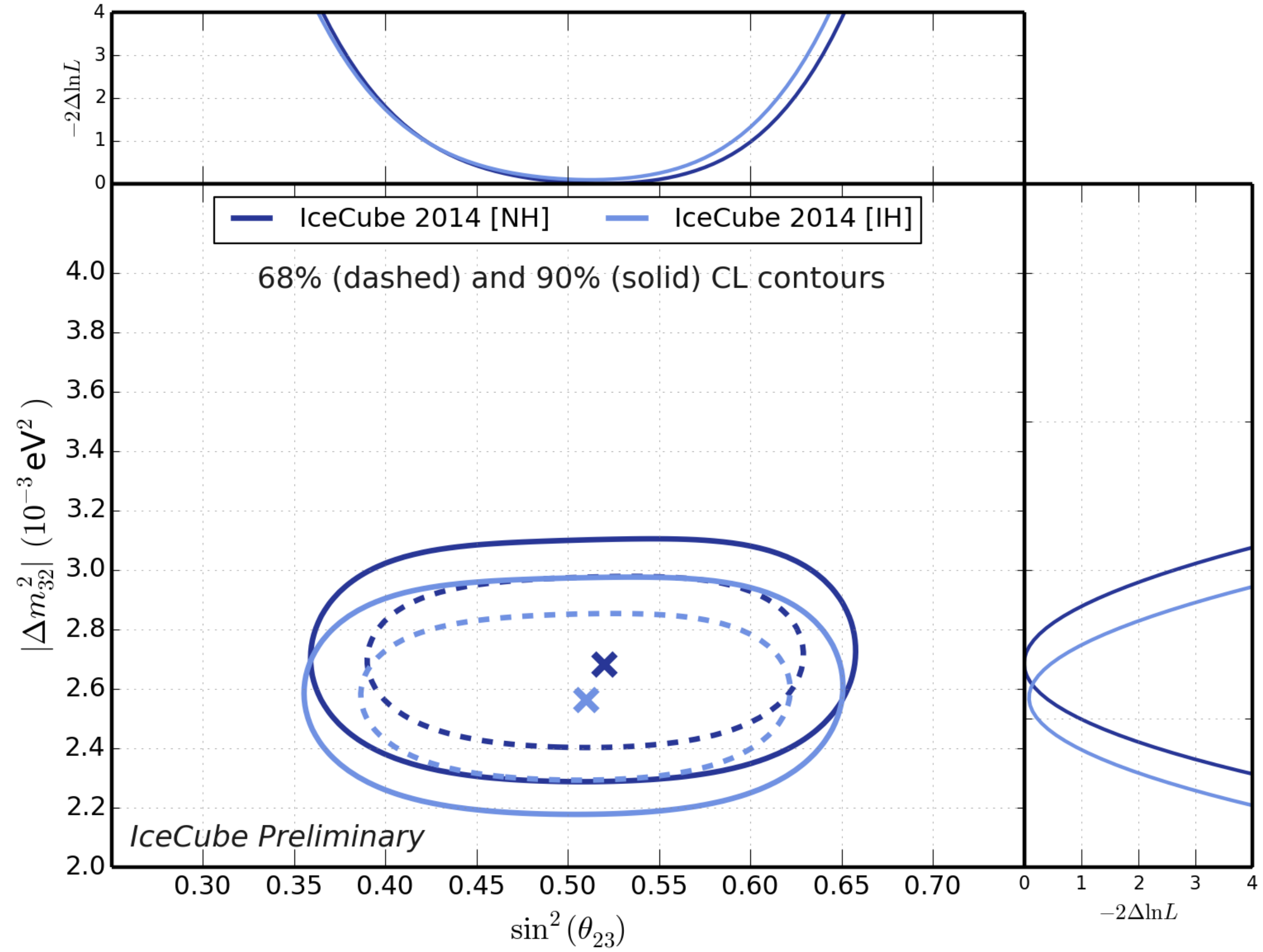
good agreement (limited statistics) in control region

good description of oscillation region

observing oscillation maximum and rise

Oscillation result (arXiv:1410.7227)





- DeepCore delivers competitive oscillation result with 3yrs of data!
- Sensitivity to mass hierarchy through matter effects!

Neutrino Mass hierarchy

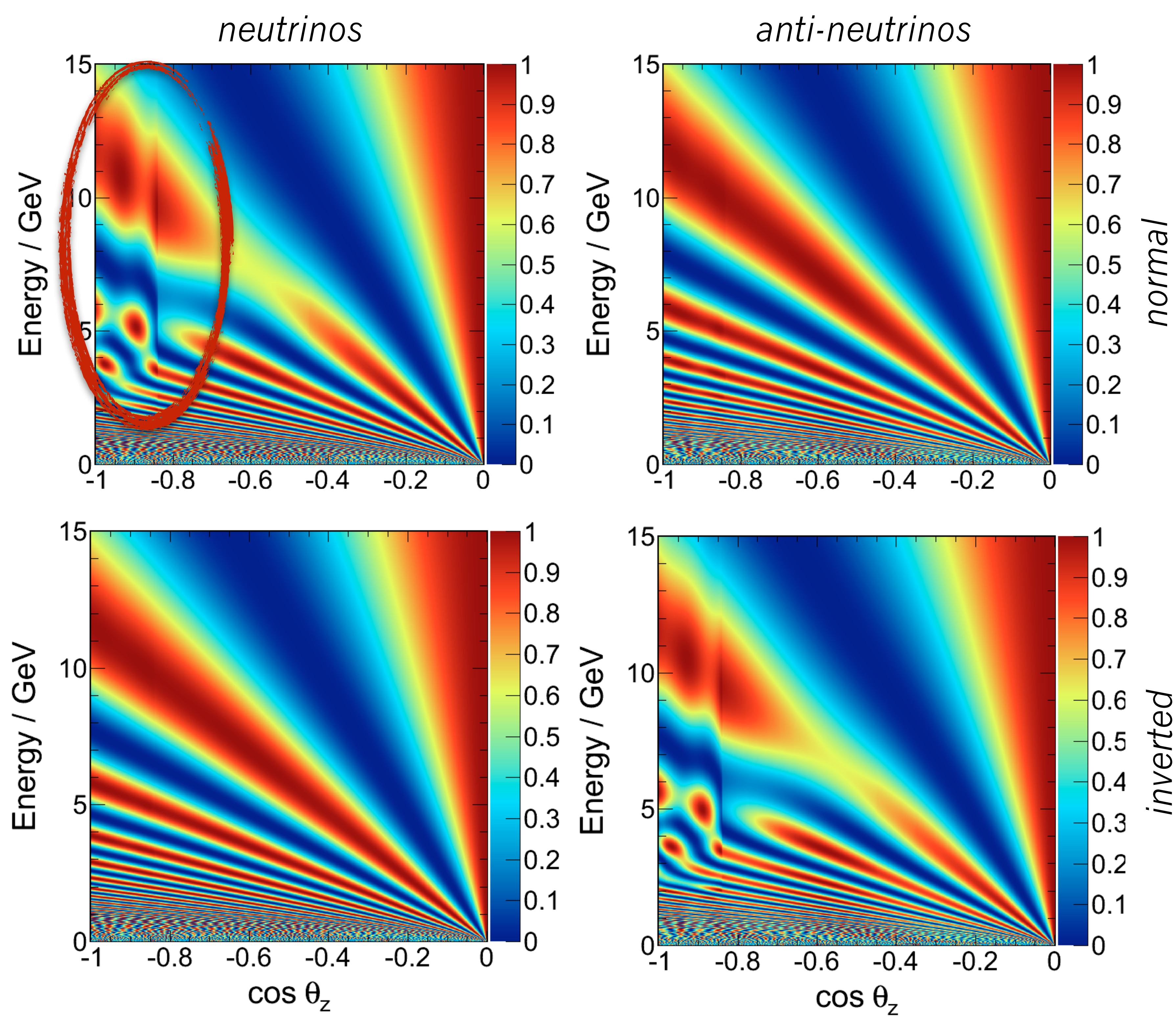
Signal

- matter effects (MSW)
  - impact for tracks through earth core
- *similar* flux from atmosphere
  $\Phi(\nu)/\Phi(\bar{\nu}) \sim 1 \pm 0.1$
- x-sections *differ*
  $\sigma(\nu N)/\sigma(\bar{\nu} N) \sim 2$

→ few % effect

Requirements

- high statistics at E = 1-10 GeV
- very good control of systematic effects



PINGU

Baseline detector (arXiv:1401.2046)

- 40 additional strings
- 60 digital optical modules each
  - deployed inside the DeepCore volume

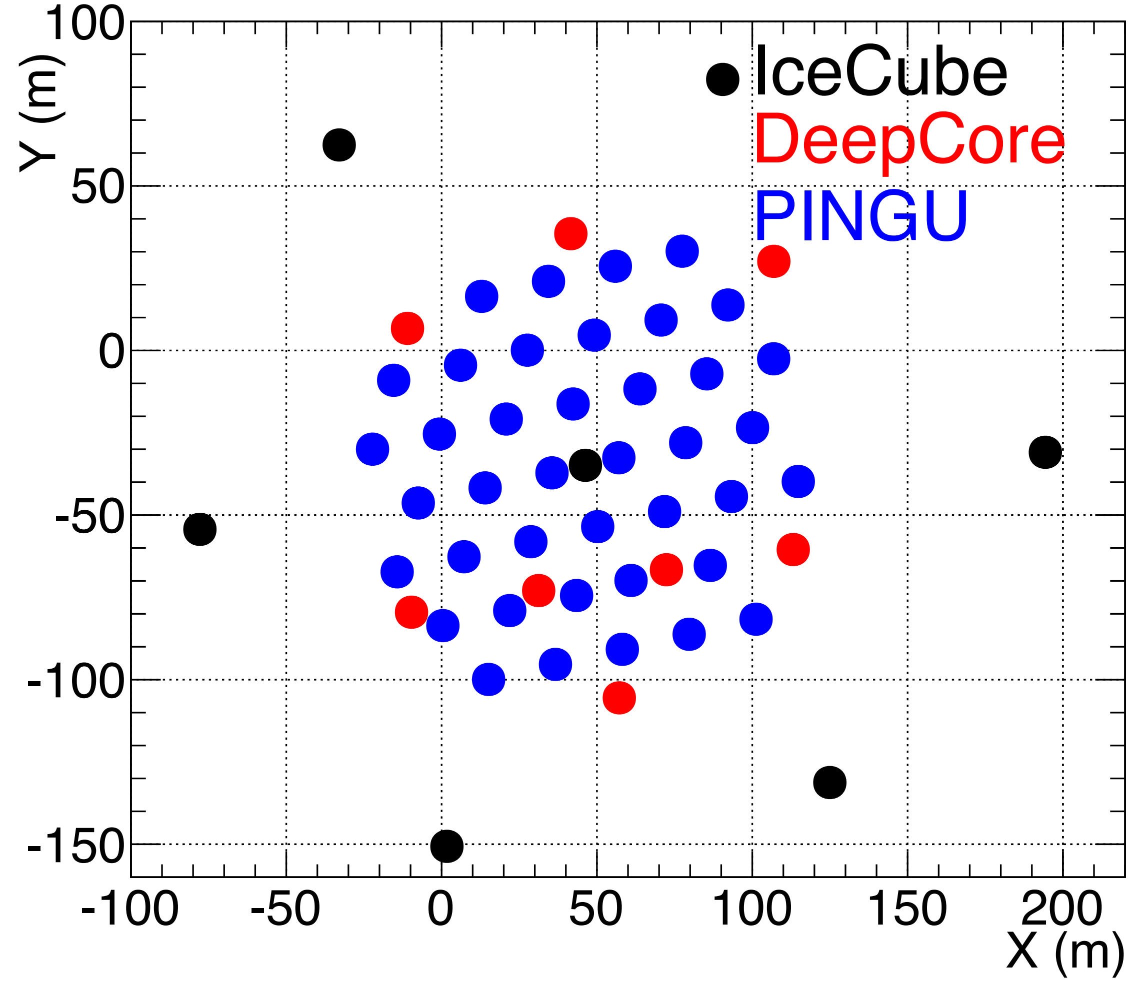
Geometry optimization

- low marginal cost for DOMs
  - likely use 80-96 DOMs/string
- 20-22 m string spacing
  - ~25x higher photocathode density
- additional calibration devices
  - control detector systematics

IceCube legacy

- engineering solutions
- cost of deployment
- timeline (≥20 strings per season)
  - well understood

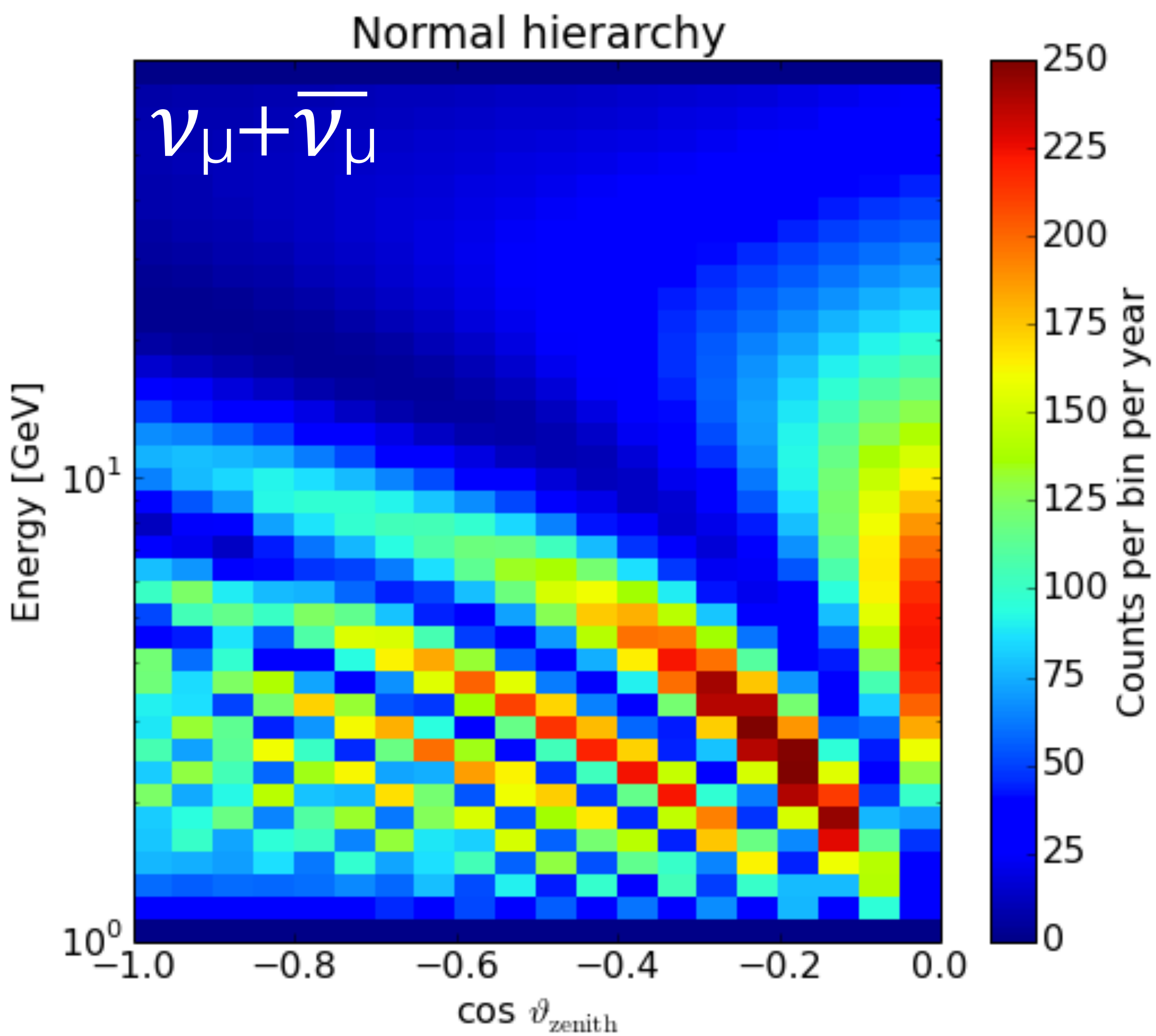
Top view of the PINGU new candidate detector



Signatures in PINGU

Detected events (1-80GeV, after cuts)

- ~50k ν_μ + anti-ν_μ per year
- ~38k ν_e + anti-ν_e per year
  - small but distinct signature



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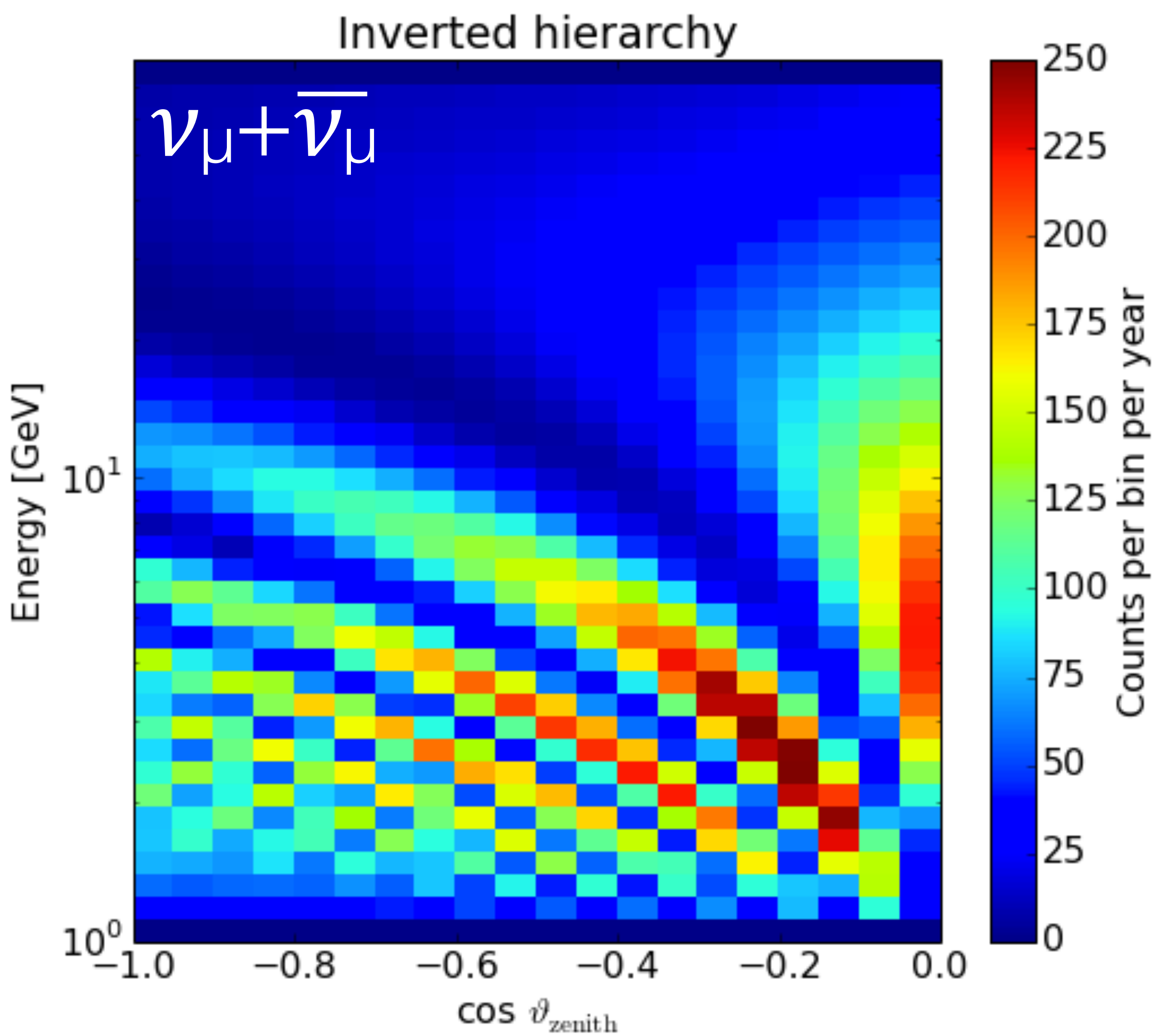

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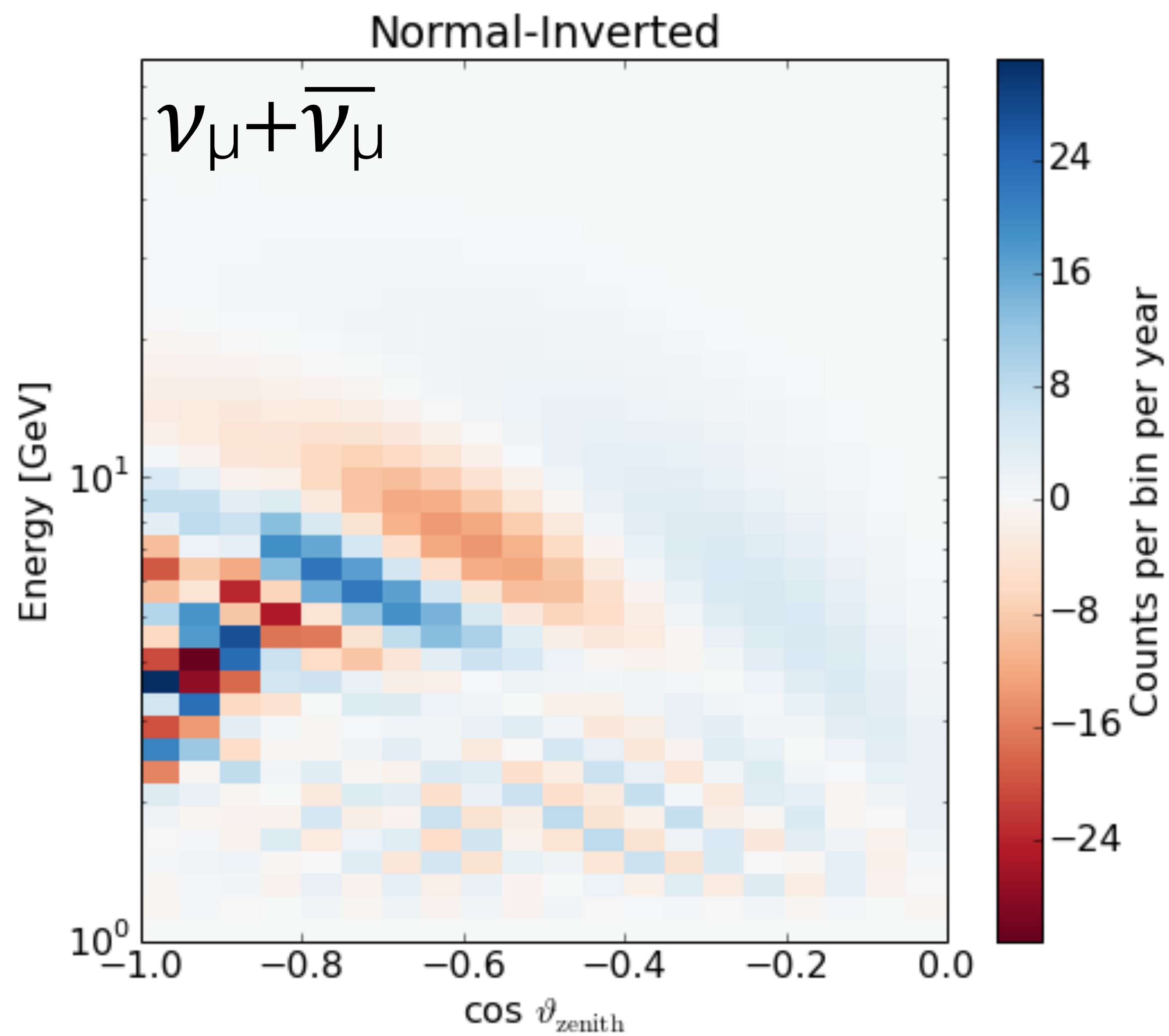

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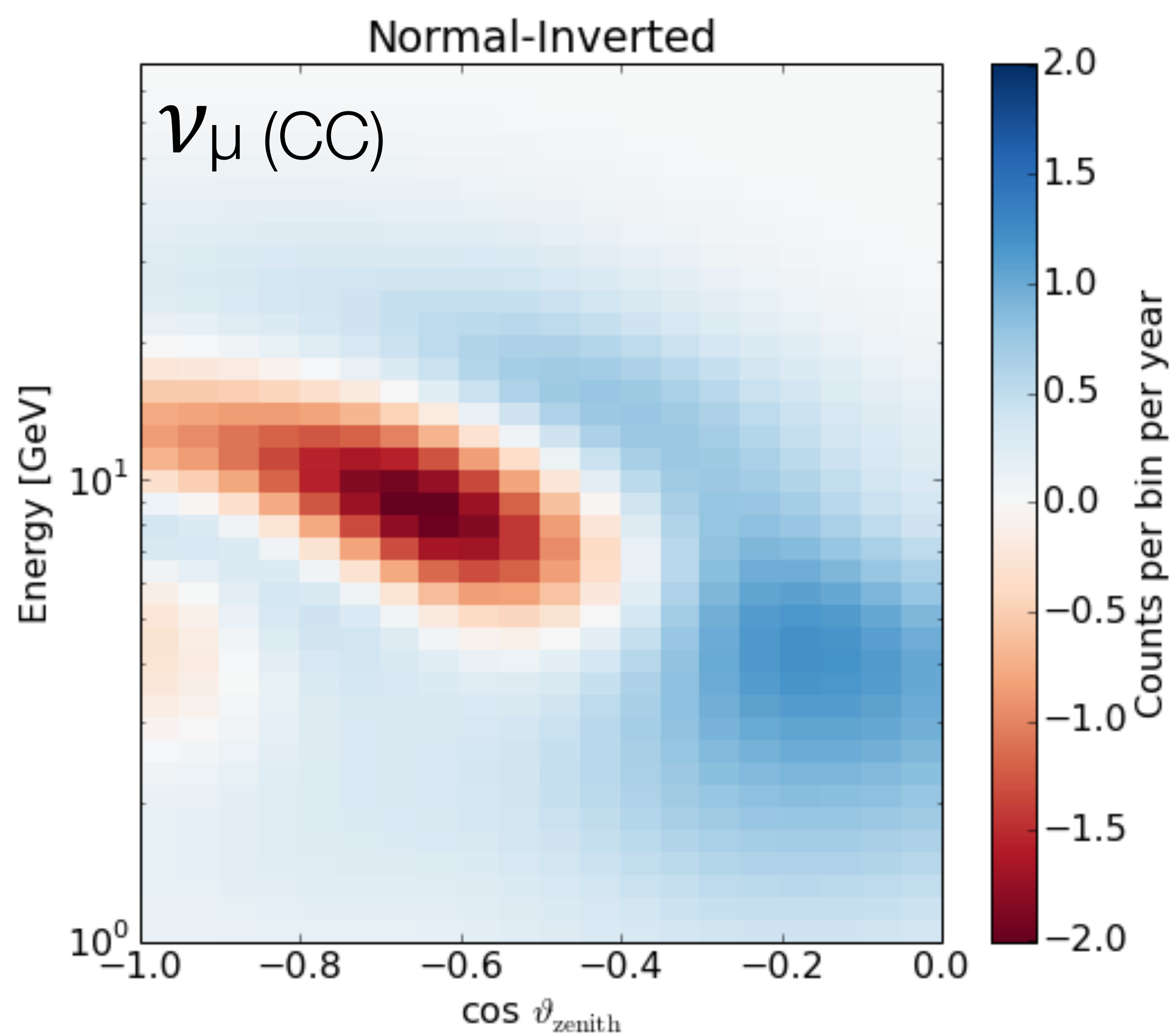
Detector effects

- energy resolution
  - ~20% above 10GeV
- directional resolution
  - improving with E



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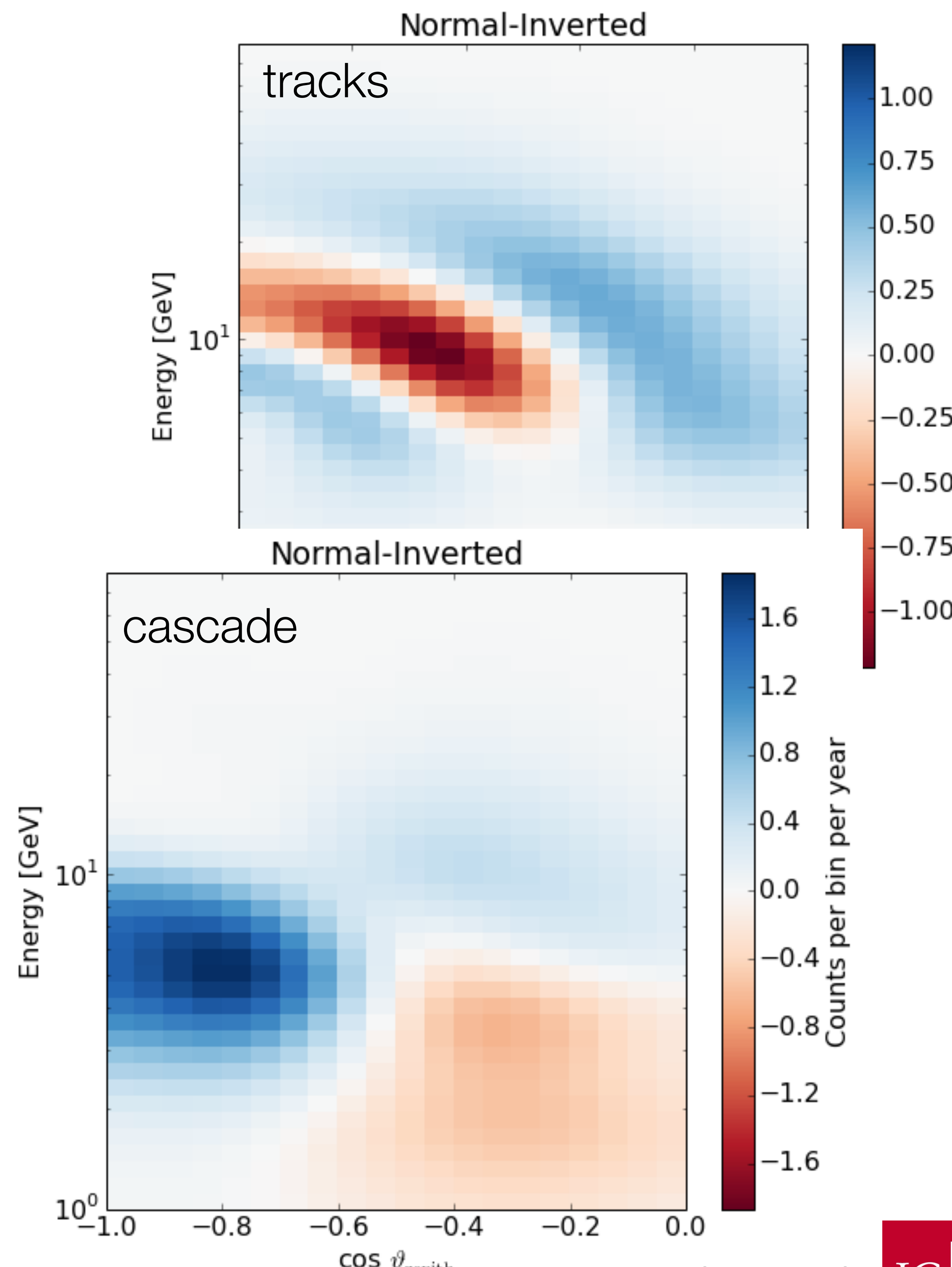
Particle identification

- ν_μ(CC) = *tracks*
  - ~90% purity
- ν_e (CC) + ν_X (NC) = *cascades*
  - quite distinct

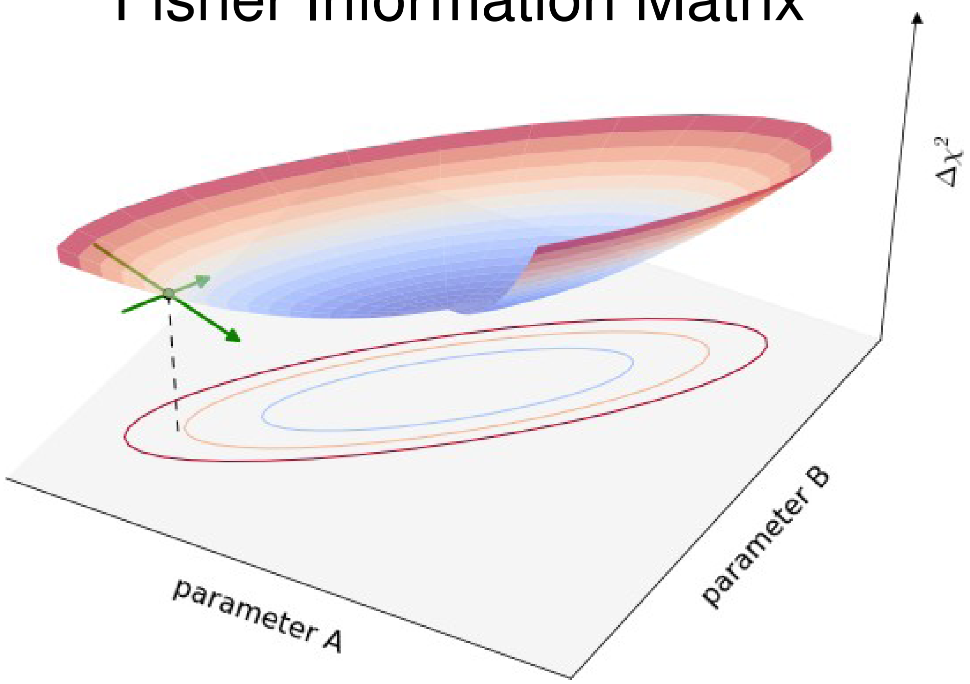


Estimating Sensitivity to the Mass Hierarchy

Mass hierarchy templates

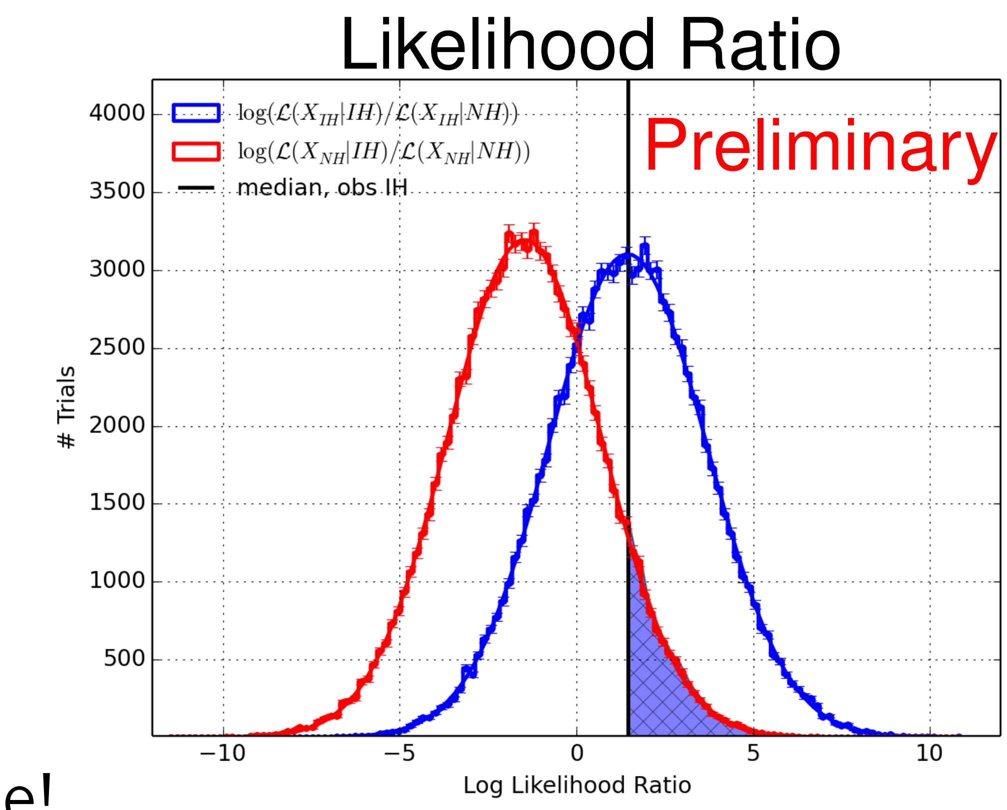
- factorize
  - flux $\otimes$ oscillations $\otimes$ detector
- time-consuming MC generation
  - parametrize detector response for quick studies

Fisher Information Matrix



- use gradients in parameter space to determine covariance matrix
  - fast but requires approx. Gaussian errors

Likelihood ratio analysis



- pseudo-data sets ensemble
  - slower, includes fewer systematics

For common set of systematics the methods agree!

Systematic uncertainties (arXiv:1401.2046)

Oscillation parameters

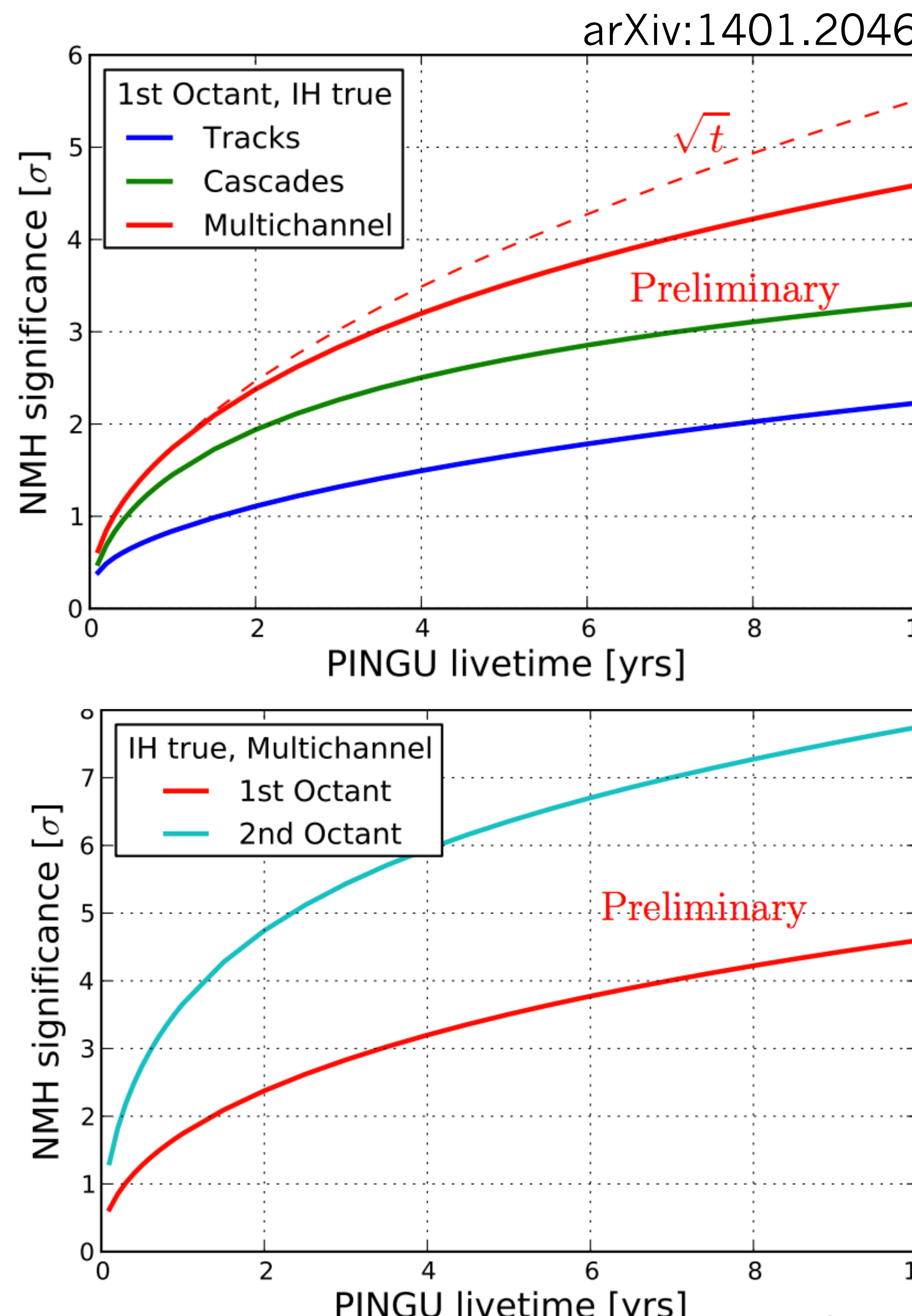
- mass splittings
- mixing angles
- CP-phase

Effective uncertainties

- overall efficiency
  - energy dependent
- energy scale
- x-section uncertainty

Result

- ~3σ in 3-4 years
- strong dependence on octant of θ_{23}
  - assume worse case for now



Analysis improvements

Simulation

- fixed bug in noise simulation for PINGU DOMs ✓
- improved treatment of atmospheric muon background •••

Systematic uncertainties

- DOM-by-DOM calibration error ✓
- Optical properties of South Pole ice ✓
  - e.g. anisotropy in scattering
- ν-N interaction uncertainties ✓
  - via GENIE parameters
- atmospheric flux uncertainties •••
  - detailed model instead of overall scaling

Analysis

- incorporating full suite of systematic uncertainties into likelihood-ratio •••
- update priors on new and existing uncertainties •••

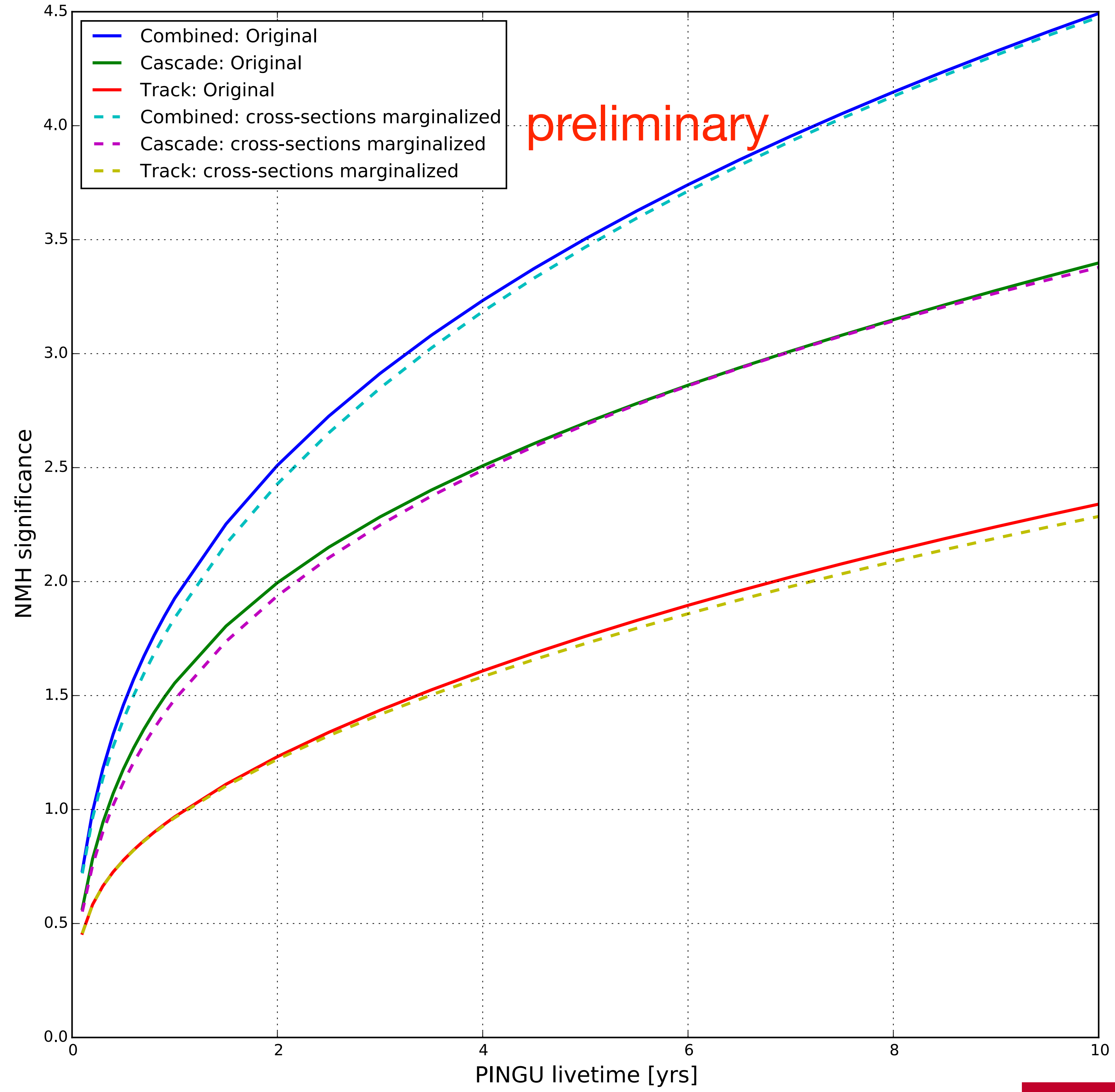
Neutrino Interaction Uncertainties

GENIE parameters

- biggest effects from uncertainty in:
  - Bodek-Yang higher twist parameters
  - axial mass term for hadron resonance production
- ad hoc scalings still included
  - may be over-counting

Result

- small additional effect to effective x-section uncertainties



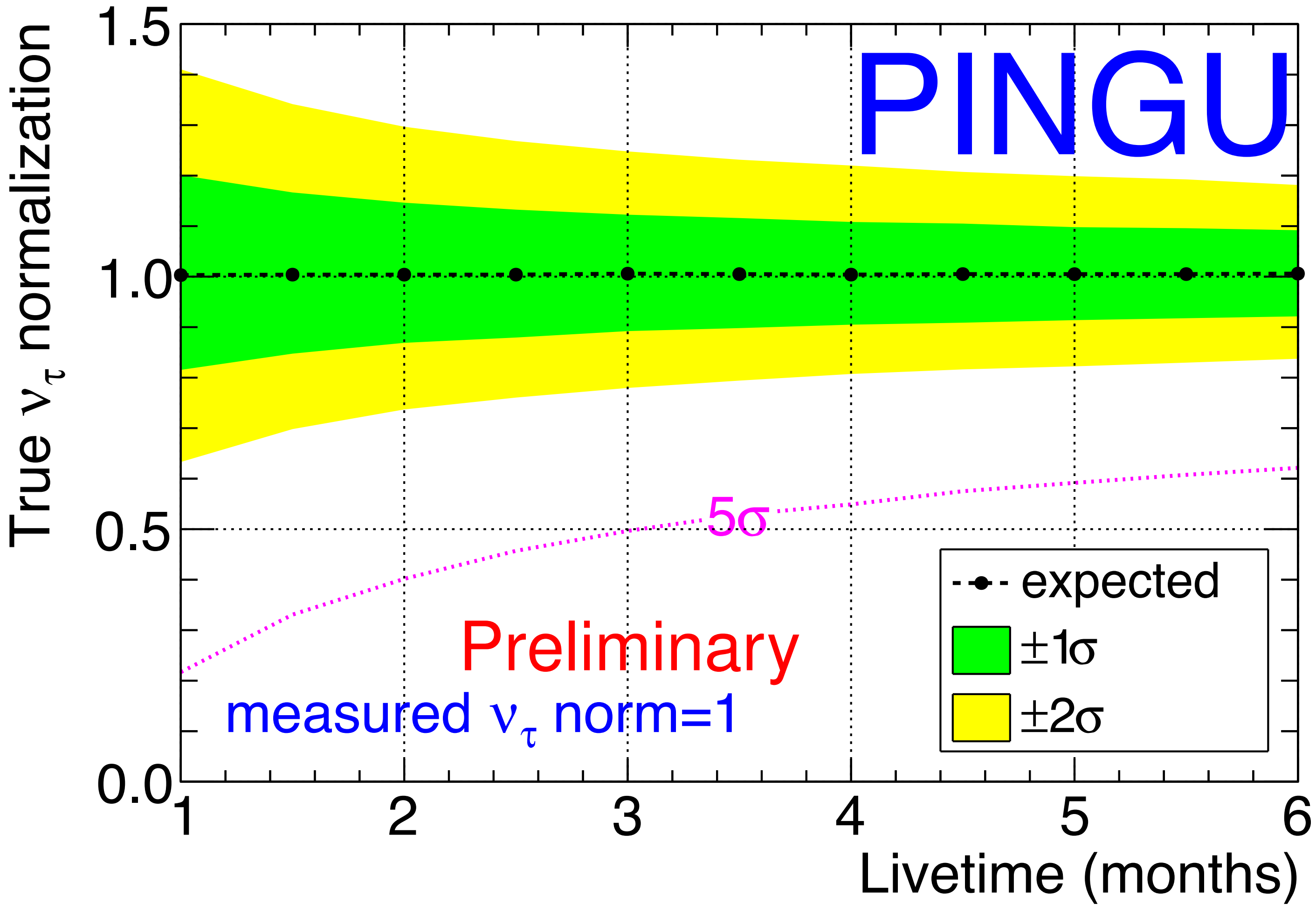
Further oscillation studies

Oscillation parameters

- θ_{23} and Δm_{atm} precision
  - expect competitive results to T2K and NOVA

Tau neutrino appearance

- PINGU energy range
  - ~3.5k ν_τ / year
- ν_τ appearance
  - characteristic distortion of cascade distribution



Test of unitarity of 3x3 neutrino mixing

- Direct probe of $U_{\tau 3}$
- 10% precision on ν_τ appearance rate within a year

Non-oscillation studies

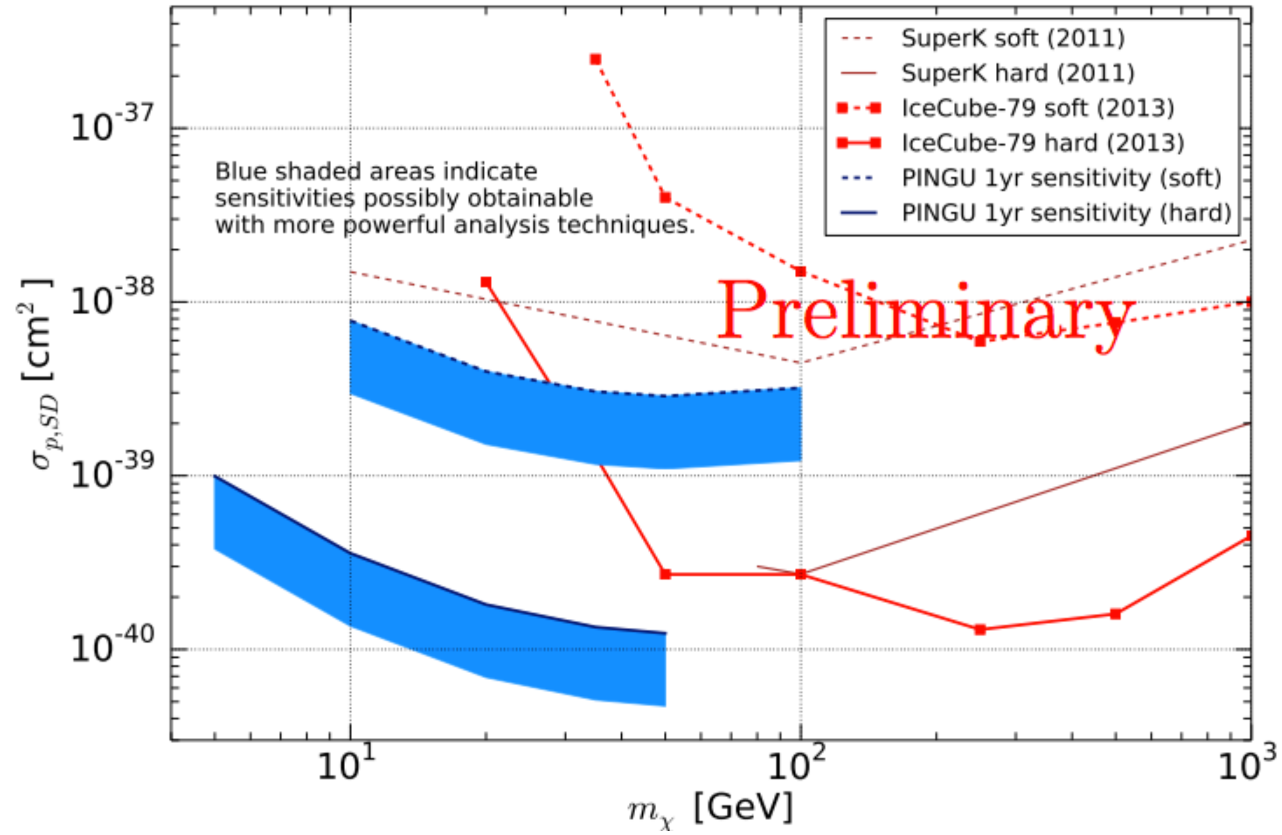
WIMPs

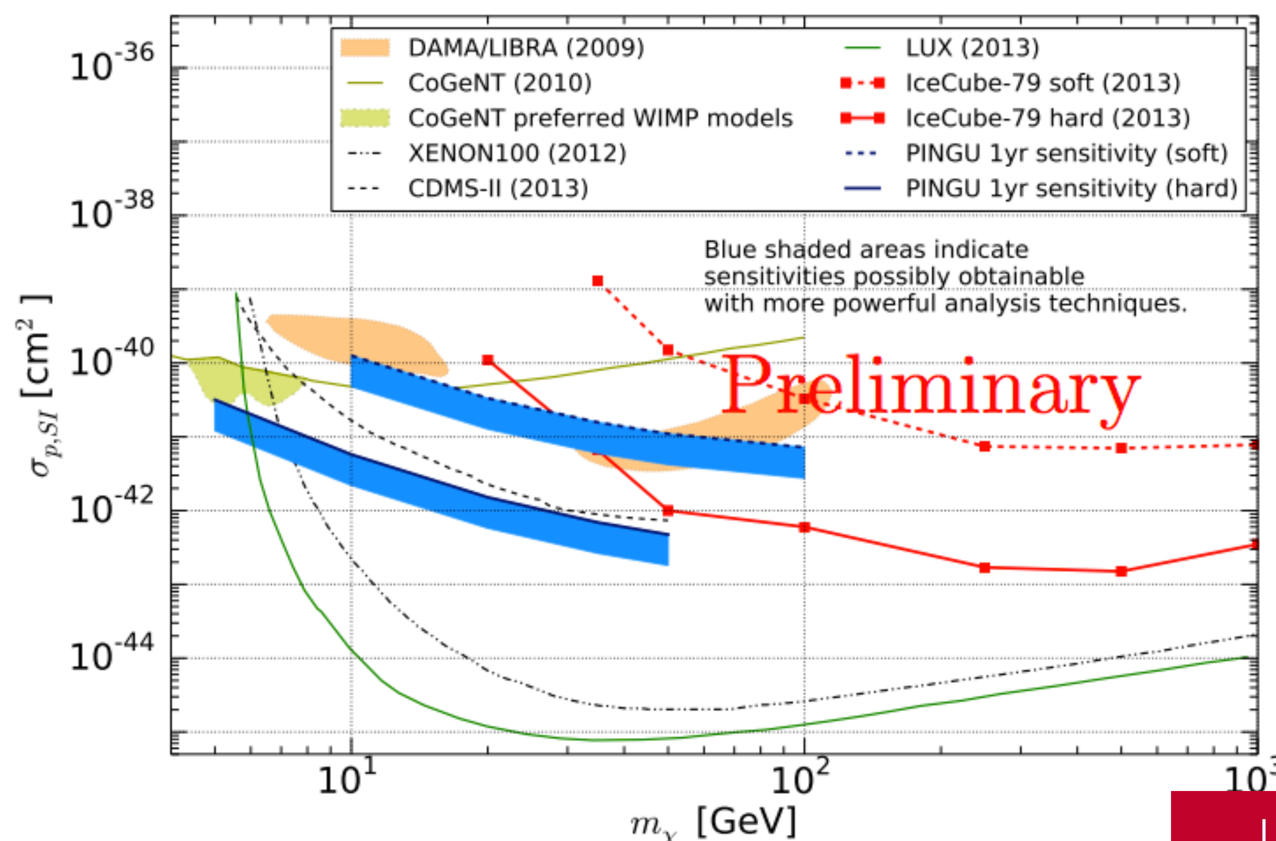
- indirect detection from $\chi\bar{\chi}$-annihilation in the sun
  - soft channel: $\chi\bar{\chi} \rightarrow b\bar{b}$
  - hard channel: $\chi\bar{\chi} \rightarrow \tau^{+}\tau^{-}$
- highest sensitivity for spin-dependent interactions

Other studies

- earth tomography
- supernova neutrinos
- ...

Will provide *updated performance paper* this year!





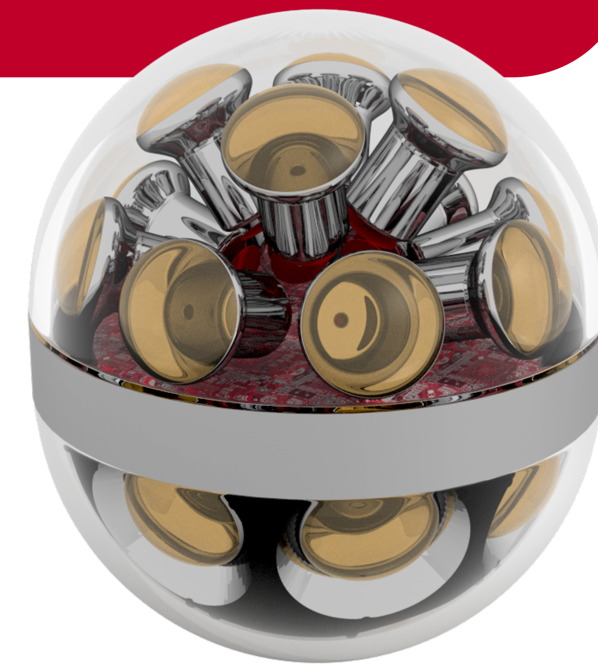
Towards the PINGU detector

Optical modules

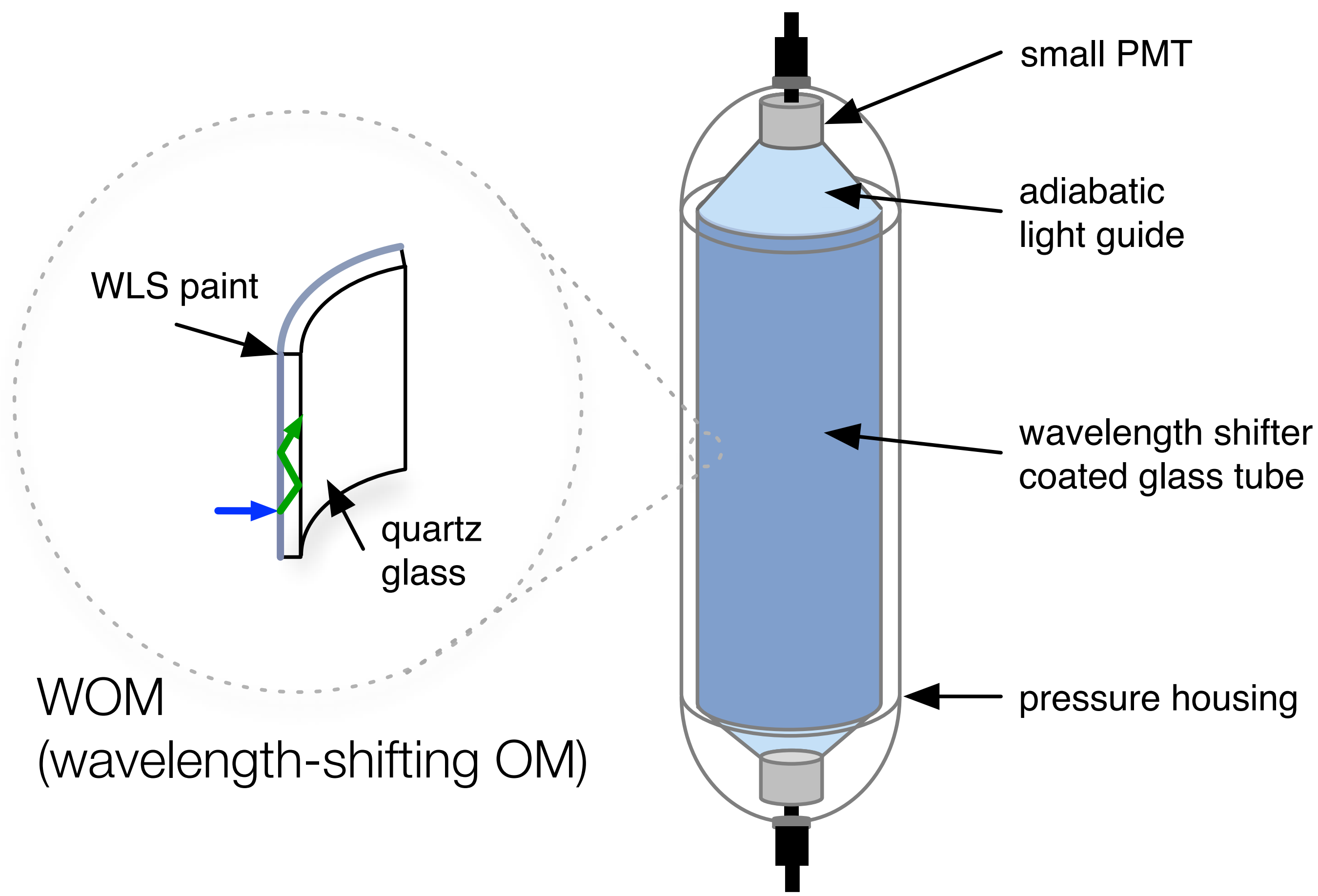
- baseline design
  - electronics upgrade on IceCube DOM
- exploratory designs
  - larger photosensitive area
  - lower noise
  - directional sensitivity

Calibration devices

- calibrated light sources
- digital cameras
  - hole ice studies



mDOM
(multi-PMT DOM)



WOM
(wavelength-shifting OM)

Schedule and cost

Timeline

- ramp-up for IceCube-Gen2
  - first component
- if technically limited
  - completion possible by early 2021 or 2022

Cost

- part of IceCube-Gen2
  - marginal cost 88 M$
  - aiming for substantial european contribution

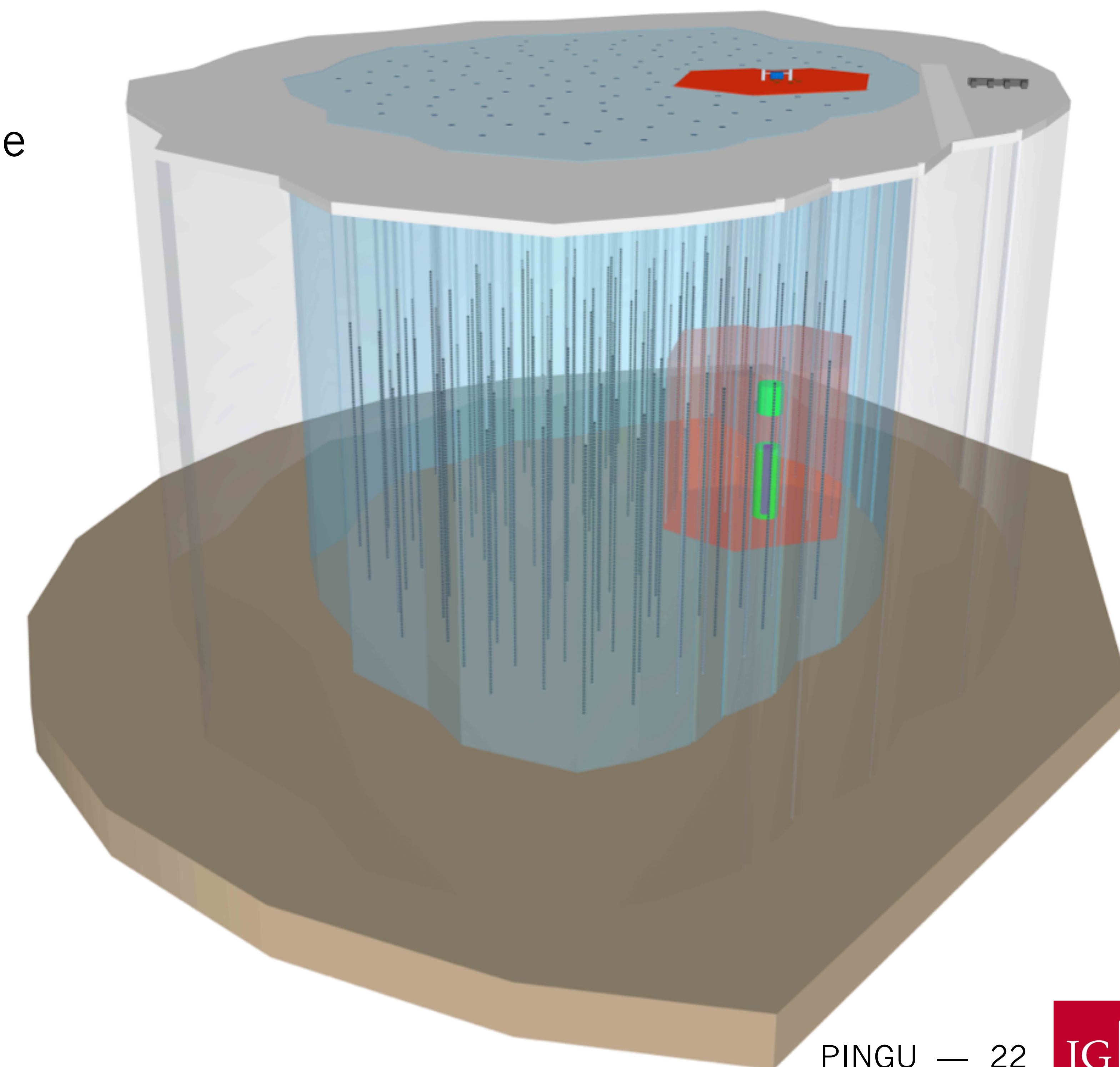
Cost of PINGU component

Hardware	48 M$
Logistics	23 M$
Contingency	16 M$
Total (US accounting)	88 M$

IceCube-Gen2

Bigger vision

- multipurpose facility leveraging the experience and investment in IceCube
  - high-energy array
  - surface extension
  - low-energy array = PINGU



Scientific potential

- see white paper (arXiv:1412.5106)
  - collaboration being formed

~~The end~~ – the beginning

USA
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
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
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Yale University

Canada
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Chiba University
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Belgium
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Université de Mons
Universiteit Gent
Vrije Universiteit Brussel

Niels Bohr Institutet, Denmark

Sweden
Stockholms universitet
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Germany
Deutsches Elektronen–Synchrotron
Friedrich–Alexander–Universität Erlangen–Nürnberg
Humboldt–Universität zu Berlin
Max–Planck–Institut für Physik
Ruhr–Universität Bochum
RWTH Aachen
Technische Universität München
Technische Universität Dortmund
Universität Mainz
Universität Wuppertal

Université de Genève, **Switzerland**

University of Adelaide, **Australia**

University of Canterbury, **New Zealand**

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)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

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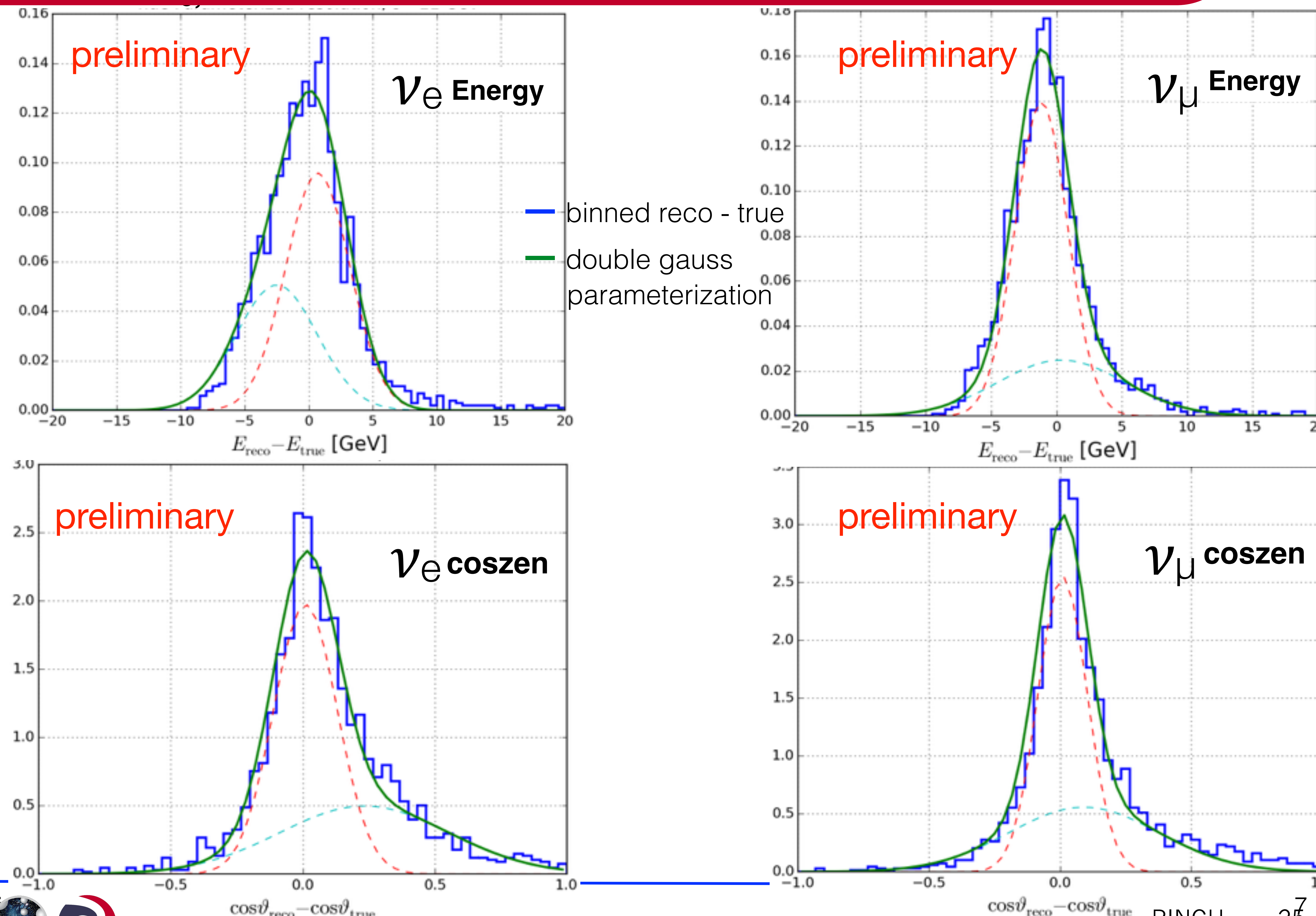
Relative Impact of Systematics

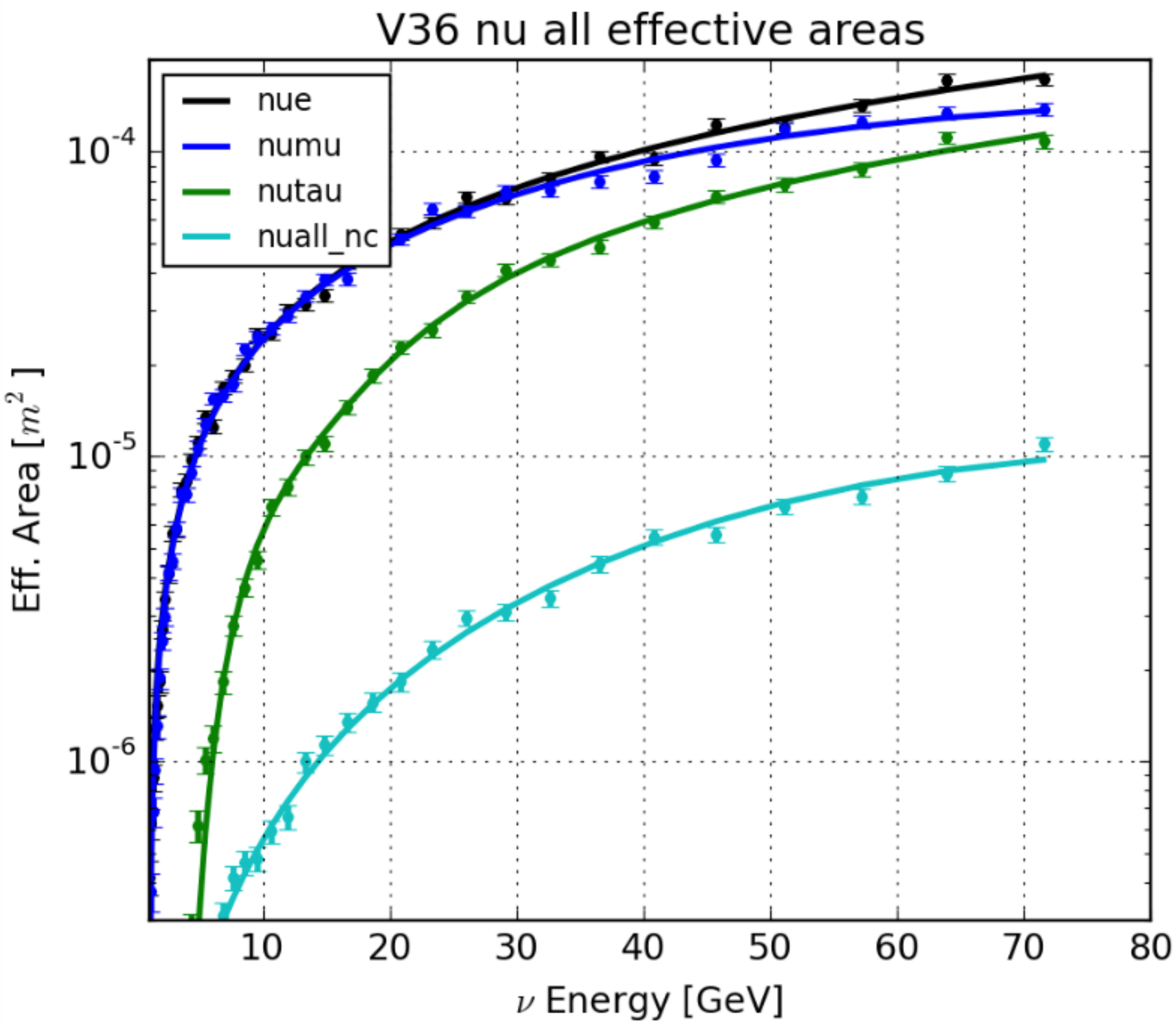
Parameter	Total (%)	Cascades (%)	Tracks (%)
hierarchy	100.0	100.0	100.0
Δm_{31}	13.9	10.4	32.6
$\overline{\nu}$ xsec scale	12.2	4.2	0.1
higher-twist BY	10.3	6.9	12.3
MaCCRES	8.1	2.7	5.2
θ_{13}	5.4	2.0	5.2
Cν-BY	5.1	0.8	10.2
θ_{23}	5.0	10.5	16.4
energy scale	1.0	2.0	3.8
ν xsec scale	0.8	4.5	0.2
MaCCQE	0.6	3.2	1.7
effective area scale	0.1	1.6	1.0

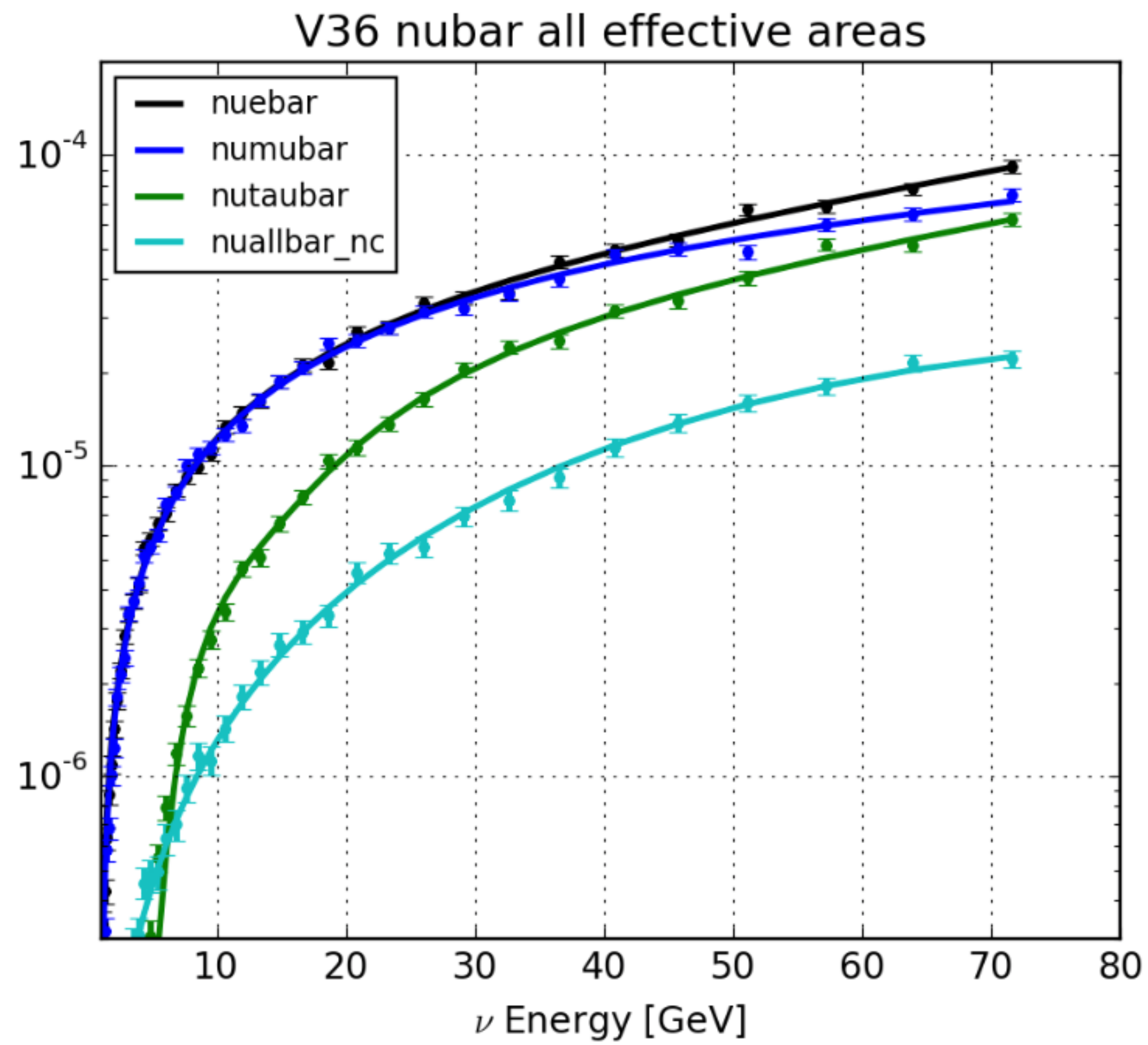
preliminary

Resolutions: 9-11 GeV



Effective area





Tau Appearance with PINGU

Higher energy range of PINGU vs. OPERA, Super-K substantially improves appearance rate

- Reduced kinematic suppression due to tau lepton mass

Tau appearance visible as distortion of cascade energy-angle distribution

- Preliminary studies suggest 5σ observation of ν_τ possible with around 1 month of PINGU data