The IceCube Neutrino Observatory: Future Plans

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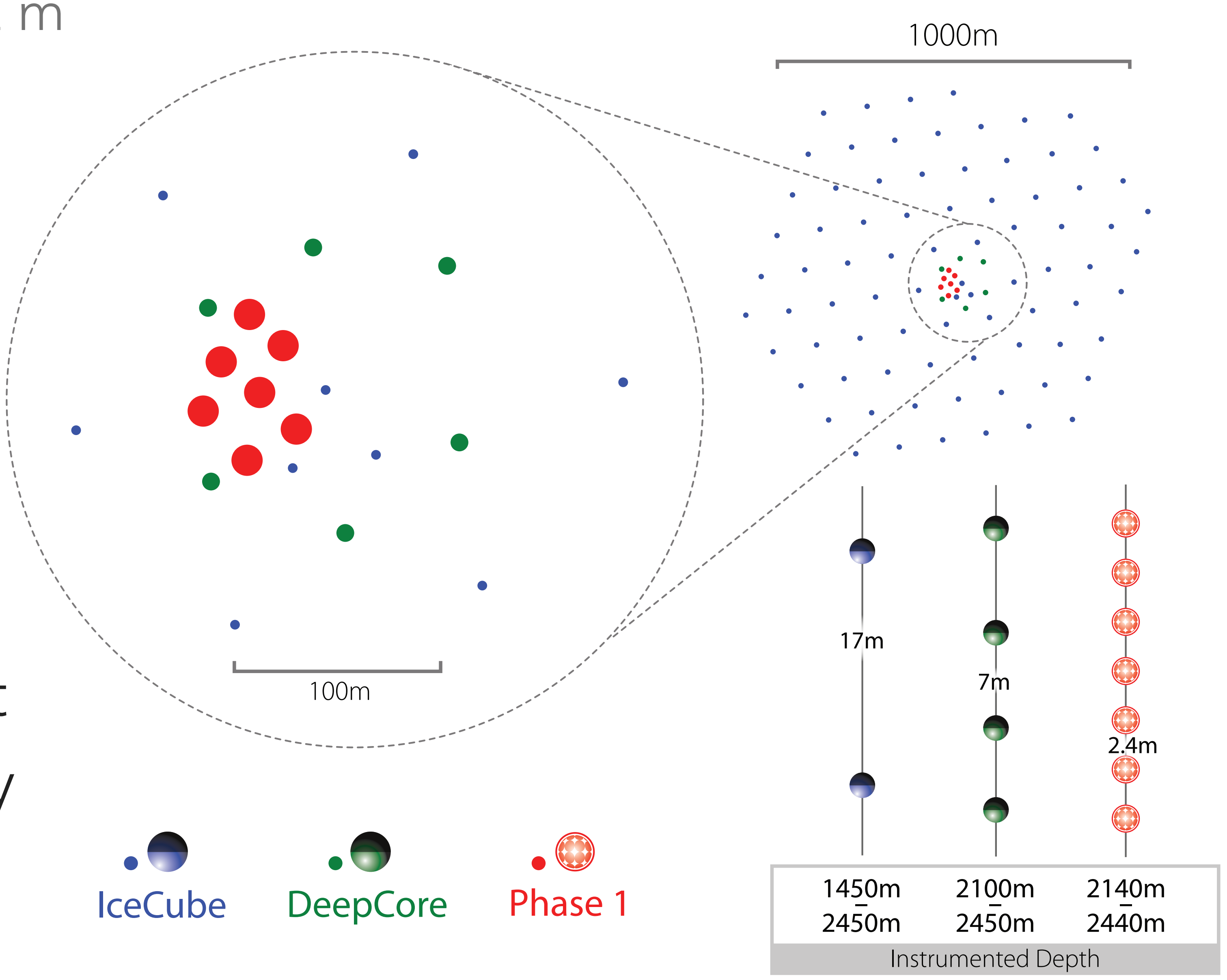
Lake Louise Winter Institute 2018

MICHIGAN STATE
UNIVERSITY

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

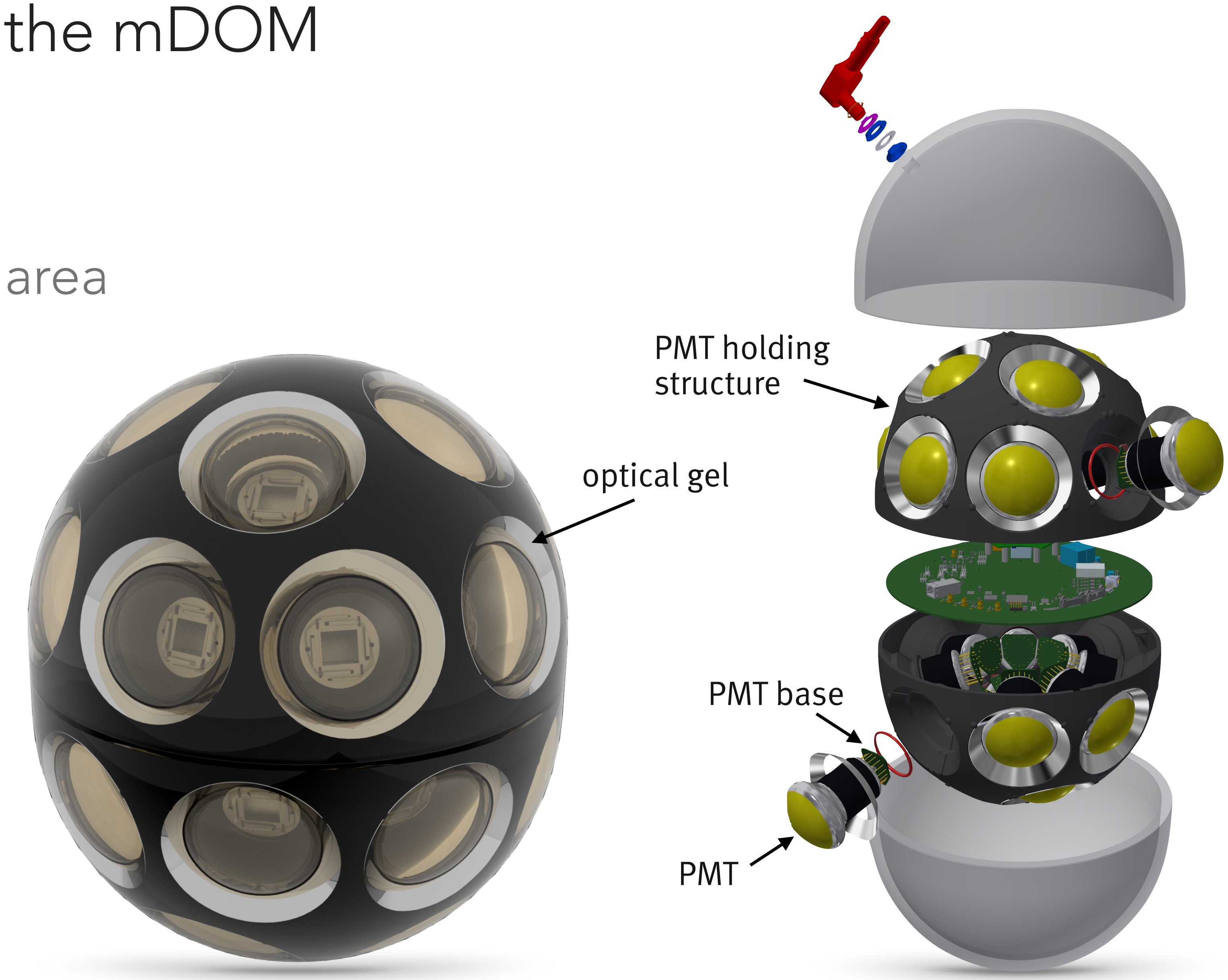
Next Step: the IceCube Upgrade

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy



Multi-PMT Digital Optical Module (mDOM)

- Baseline sensor design is the mDOM
  - 24x3″ PMTs in a 14″ DOM
  - Double the photocathode area of IceCube DOMs
  - Segmentation provides directional information for detected photons
- Onboard LEDs
  - Ice and hole calibration
  - Ability to mimic tau events
  - Also developing camera for local ice calibration

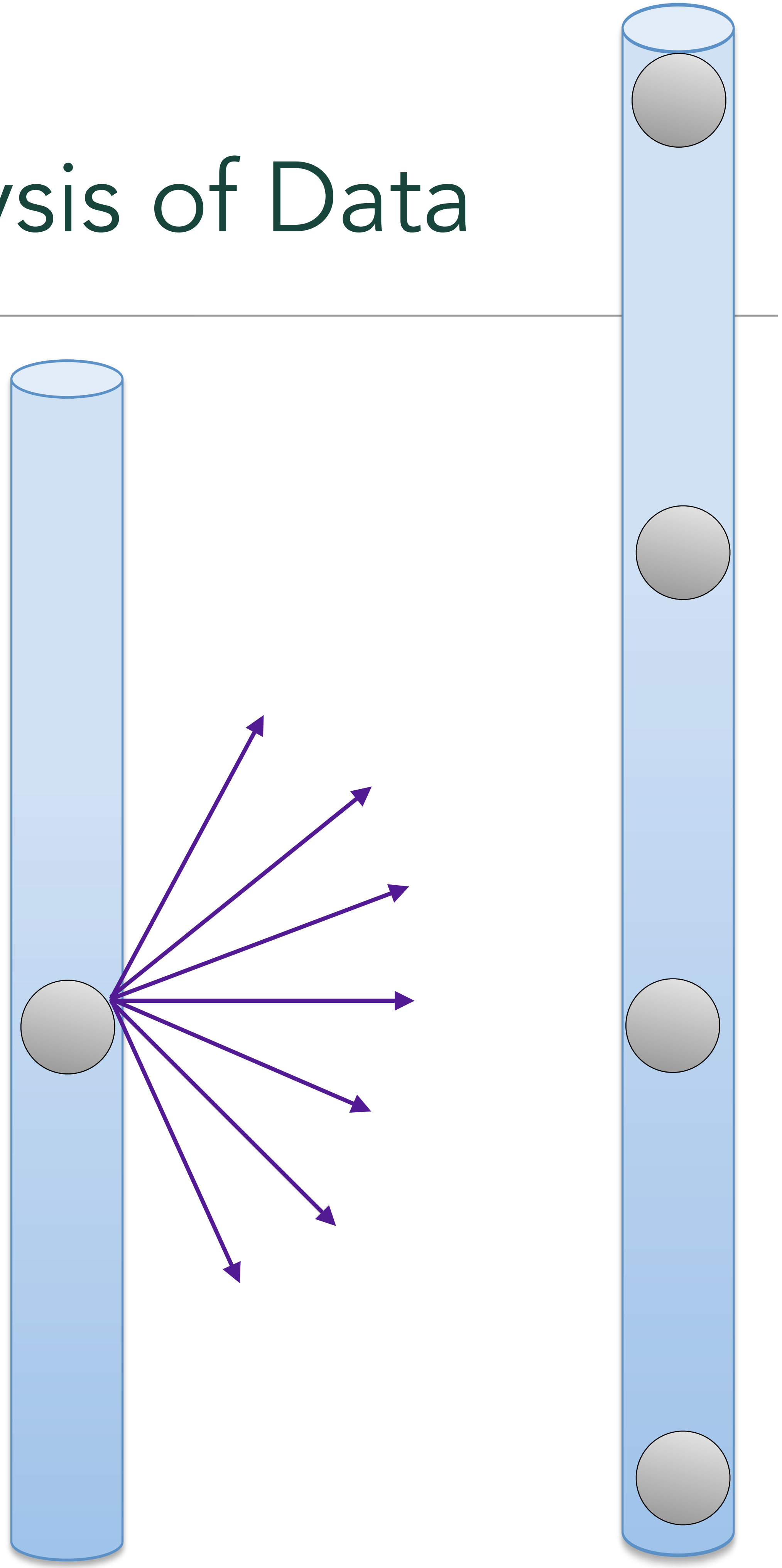


Science Goals

- Neutrino astronomy at high energy with recalibration and reanalysis of existing data
  - Improved angular resolution and veto performance
  - Tau neutrino identification
  - Multi-messenger astronomy
- Neutrino physics at low energy with new instrumentation
  - Tau neutrino appearance and PMNS unitarity tests
  - Precision measurements of $\sin^2 \theta_{23}$ (incl. octant) and Δm^2_{32} at 10-20 GeV

Recalibration and Reanalysis of Data

- Improved devices and closer inter-string spacing permit significant improvement in bulk and hole ice modeling
  - Probe $L < \lambda_{\mathrm{scatt}}^{\mathrm{eff}}$ for first time
  - Wider range of angles accessible to LEDs, especially vertically
  - More precise LEDs, new devices like POCAM, onboard cameras



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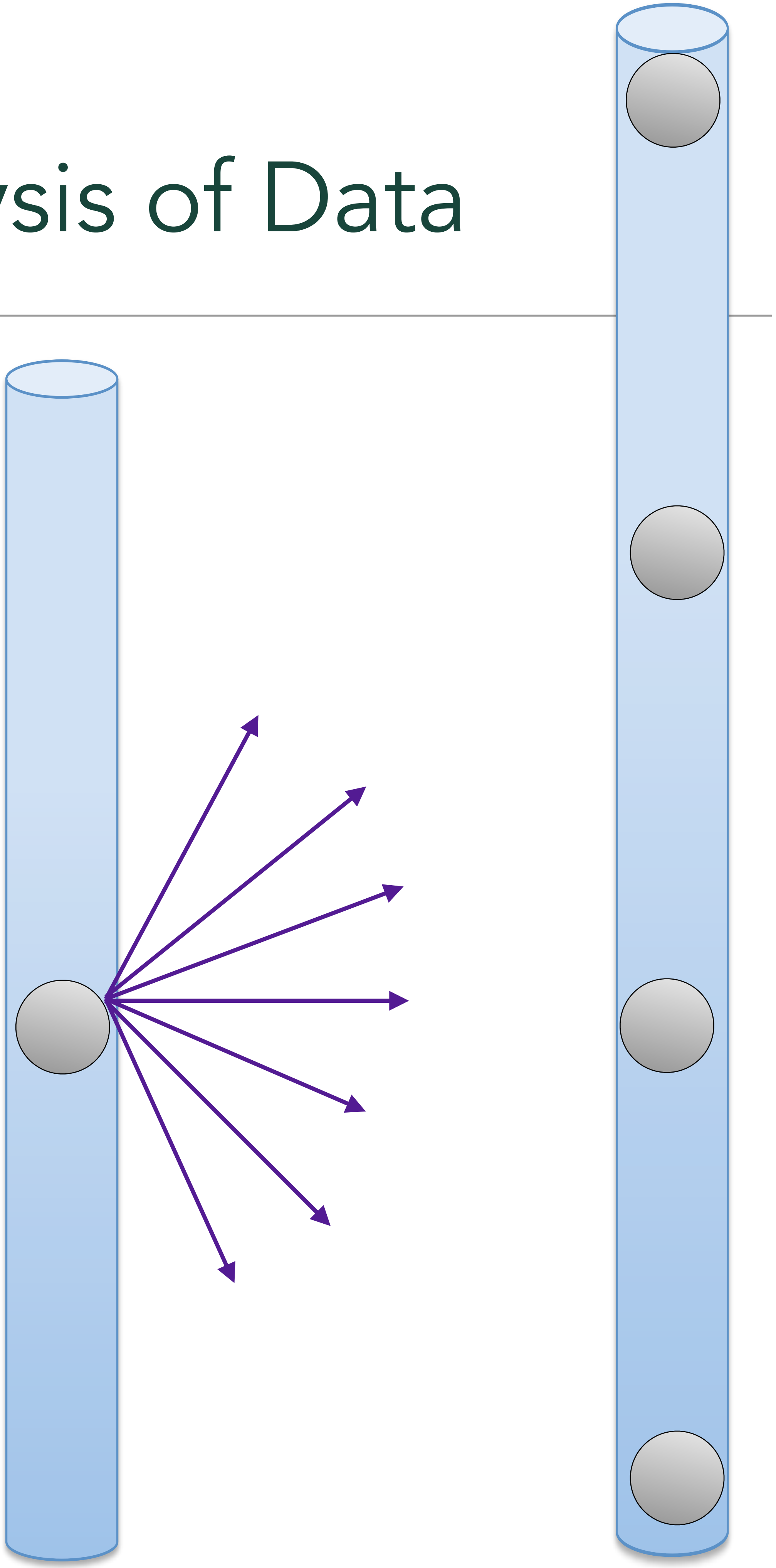
- Extrapolate throughout detector using new DOM calibration methods, ice layer info



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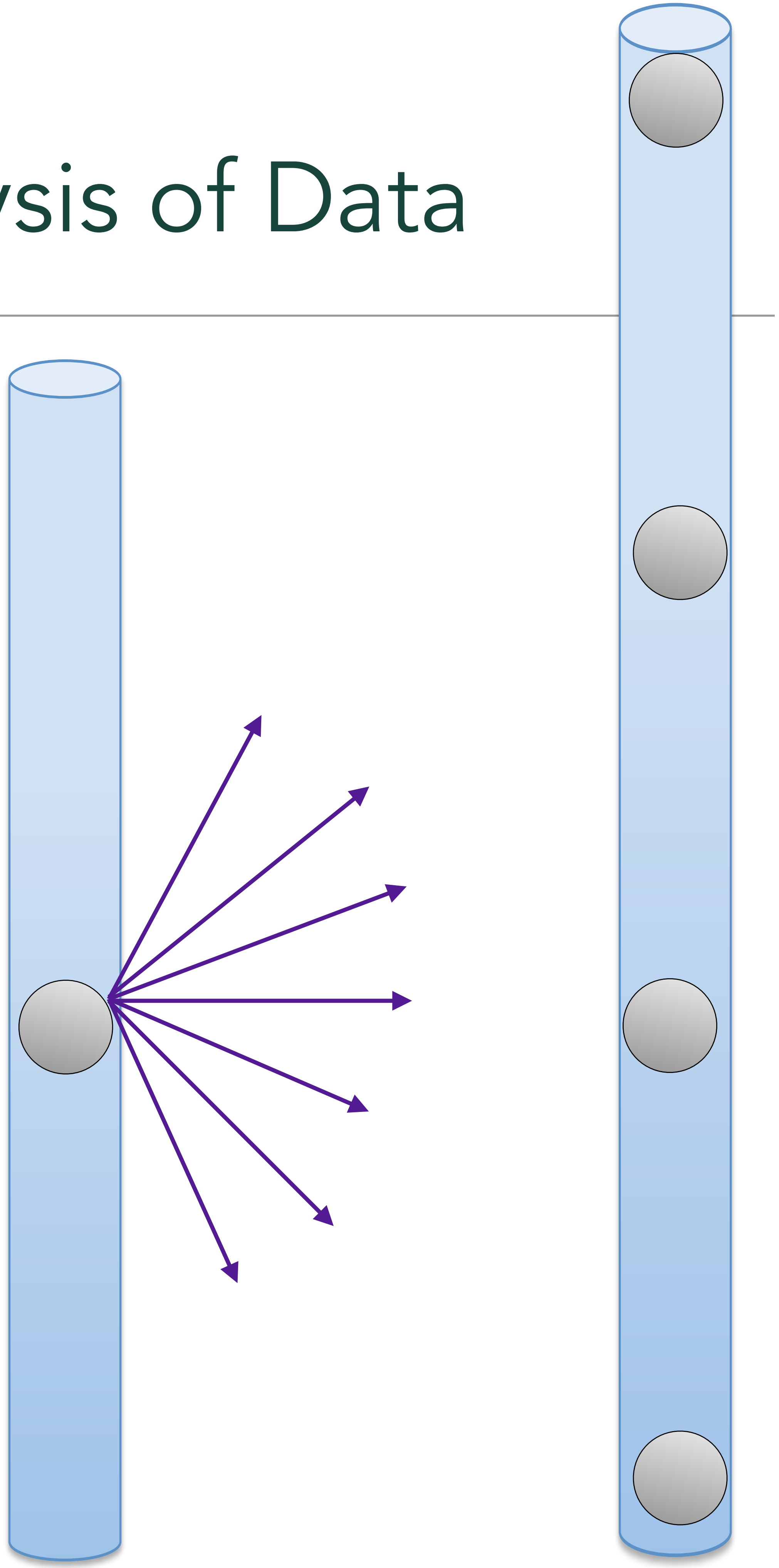
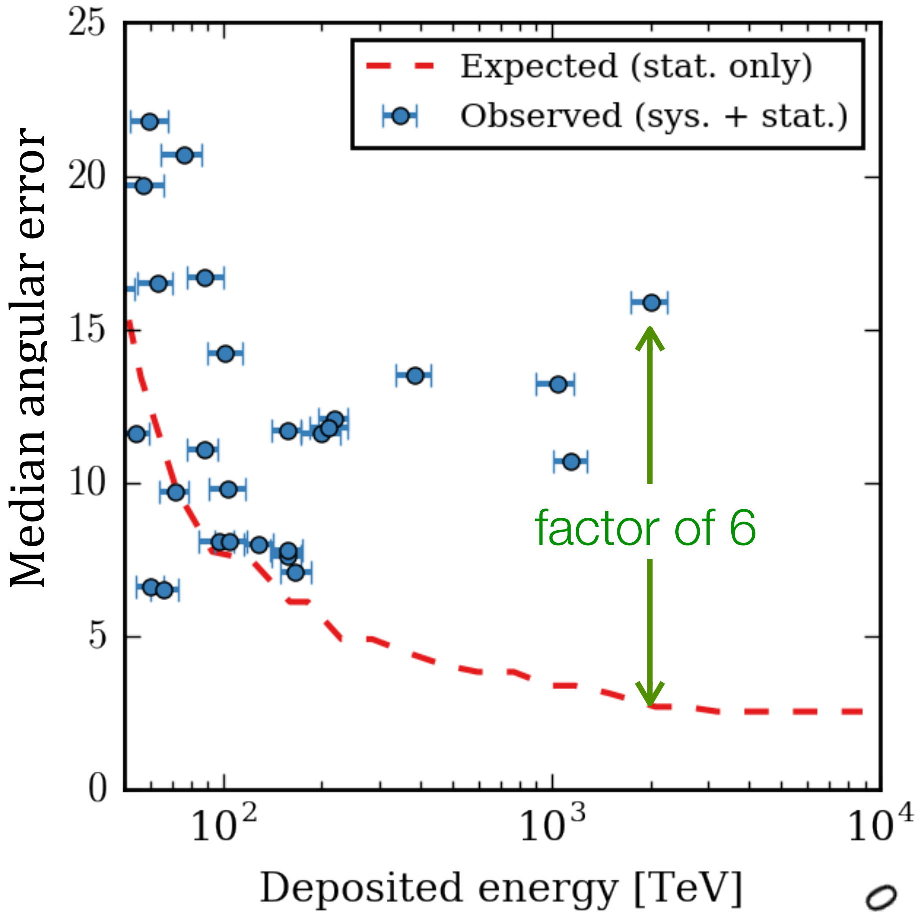
- Improvements can be applied retroactively to existing data: ~km^3·decade of improved data available immediately

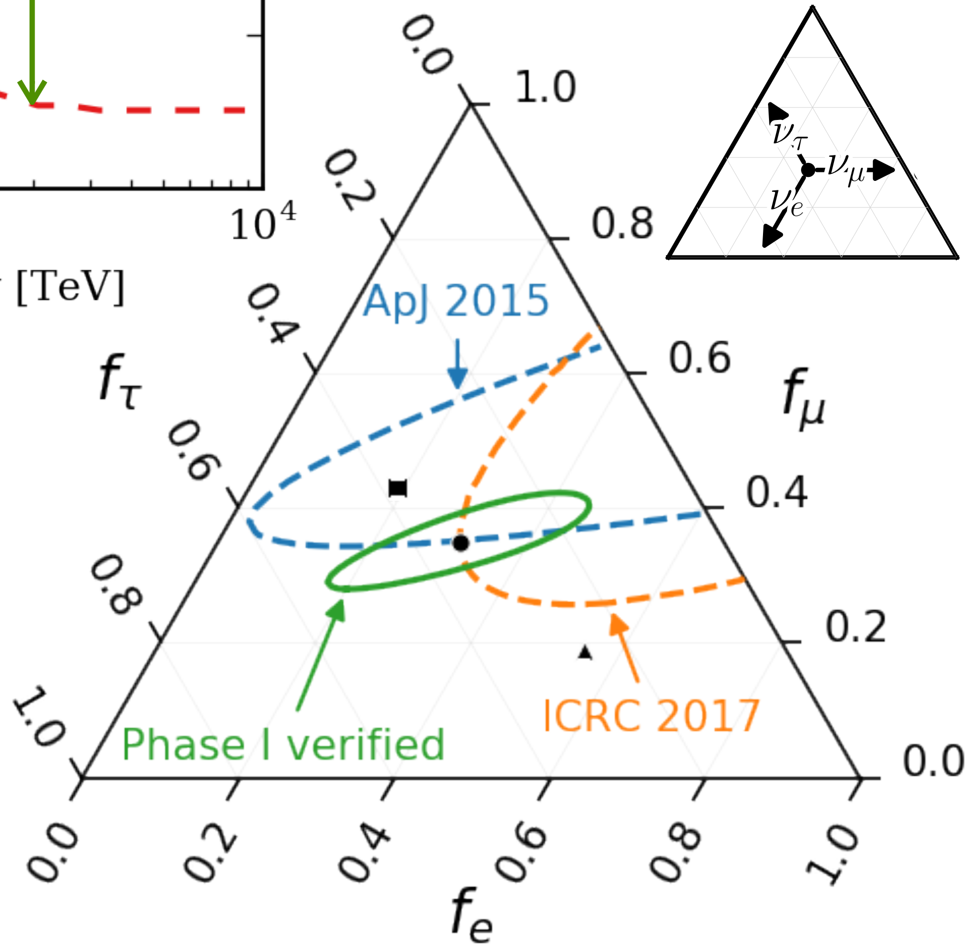


Neutrino Astronomy

- Angular resolution of high energy events dominated by ice optical uncertainties
  - Statistical limit is 0.1-0.2° (ν_μ) and 3-5° (ν_e, ν_τ) rather than 0.5-1°/10-15°
  - Source sensitivity is linear in angular resolution – factor 5 is worth 25x more exposure

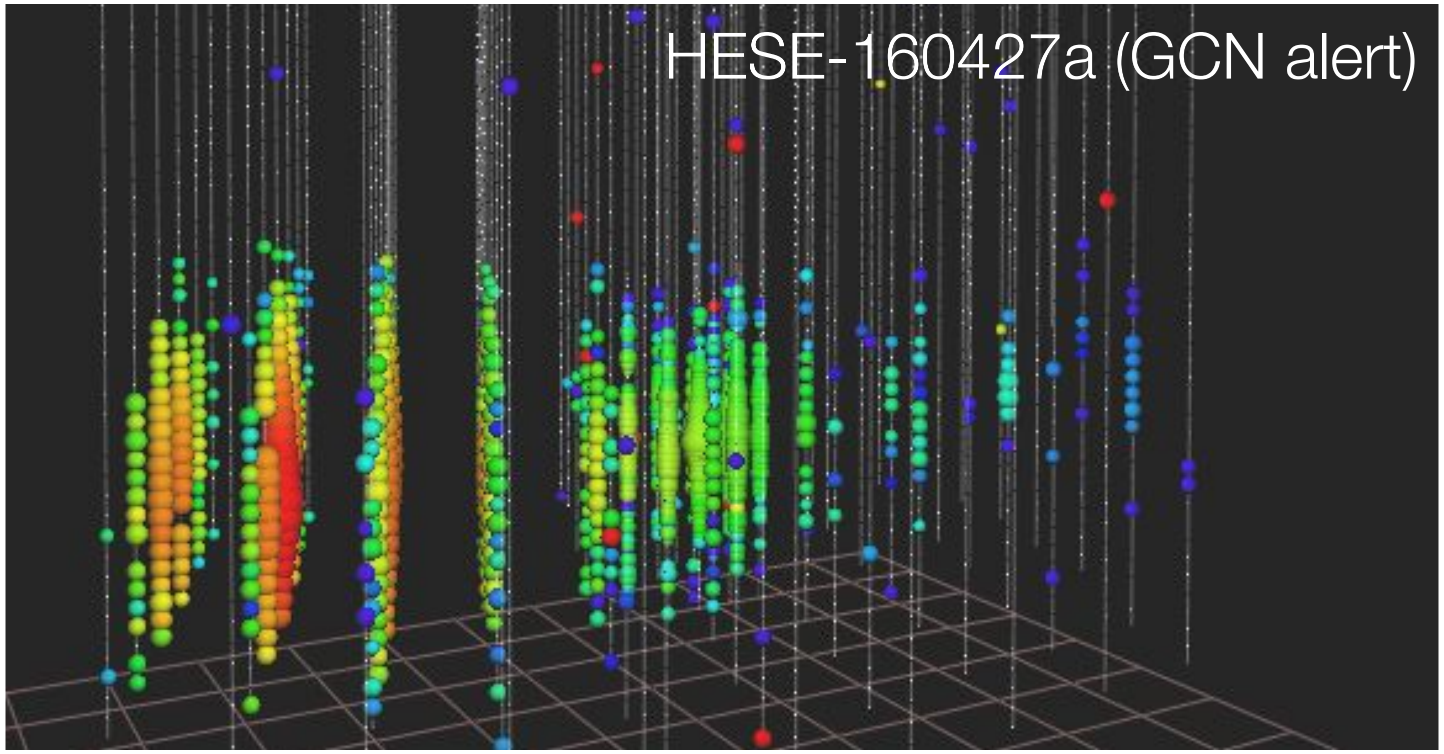


- Ability to identify ν_τ also limited by systematics
- Ice is complex but stable – existing data can be reprocessed with improved calibrations, improvements will be retroactive



Multi-Messenger Follow-Up Observations

- Identification of counterparts limited by angular resolution
    - E.g.: HESE-160427a, ~140 TeV (E_{dep}) track in coincidence with Pan-STARRS SN PS16cgx (p-value 0.3% if type Ic)


HESE-160427a (GCN alert)

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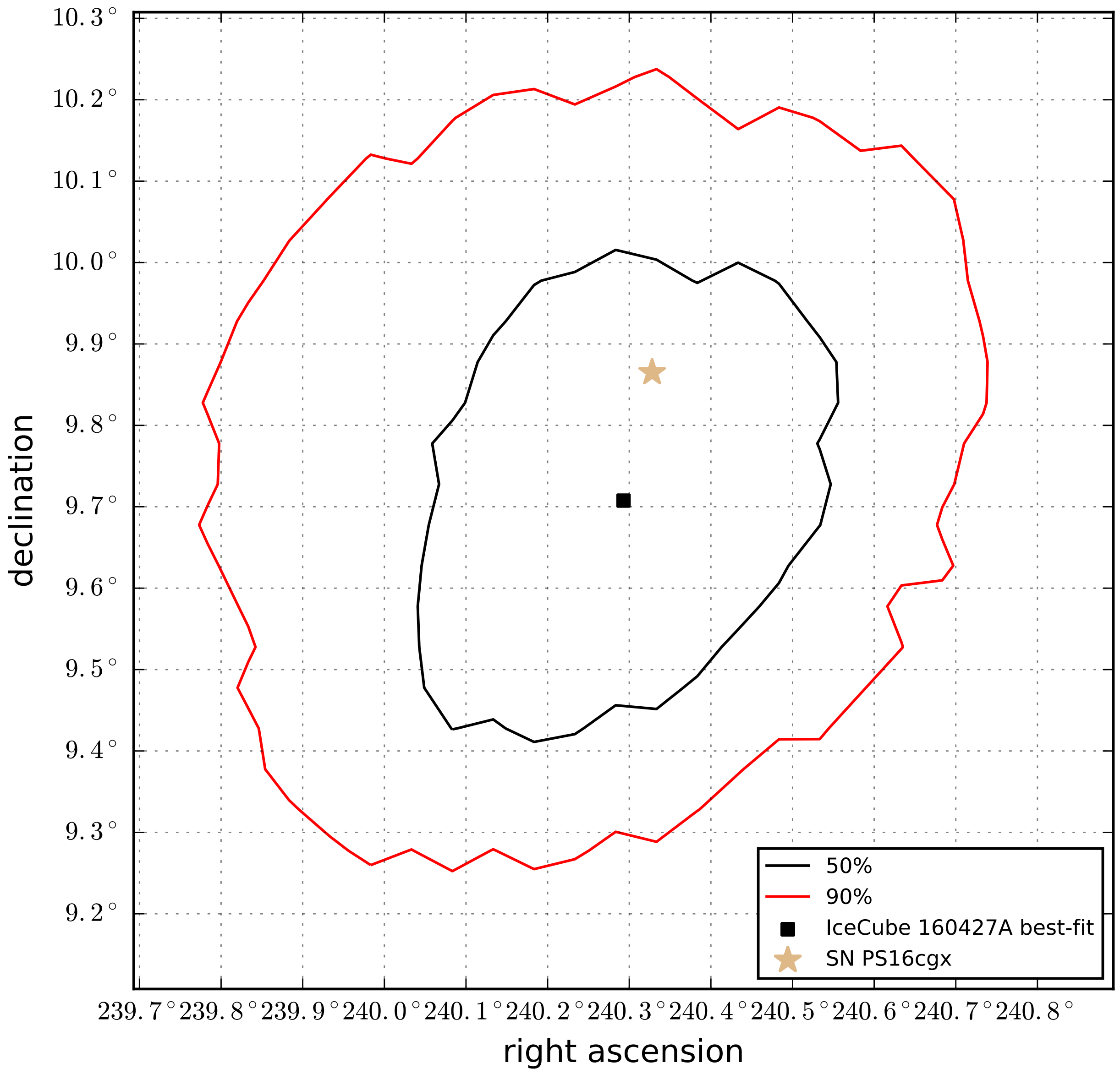

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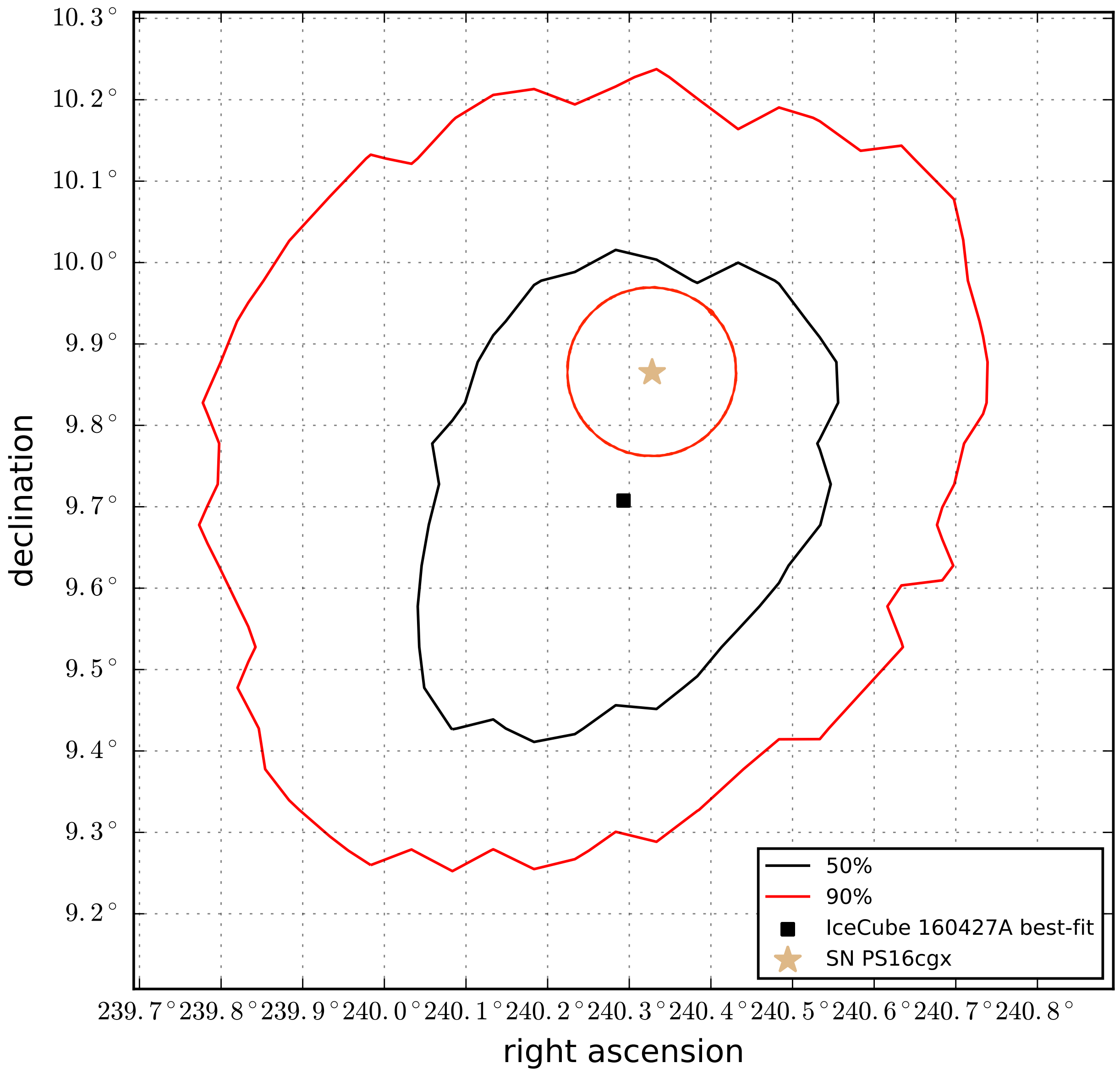
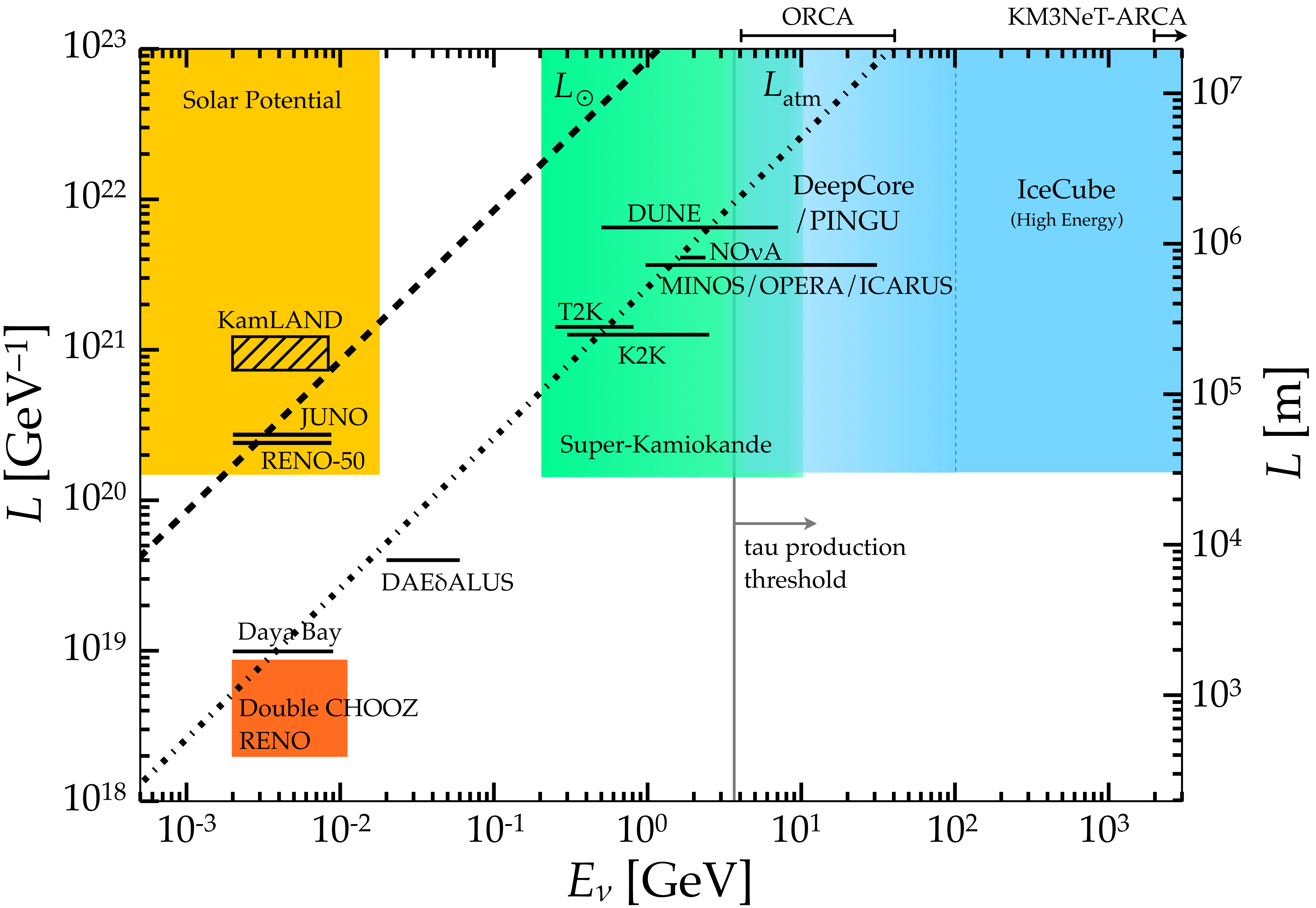
- Identification of counterparts limited by angular resolution
    - E.g.: HESE-160427a, ~140 TeV (E_{dep}) track in coincidence with Pan-STARRS SN PS16cgx (*p*-value 0.3% if type Ic)
- With improved calibration, current ~0.6° error circle could be improved to ~0.1°
- Smaller error circle also facilitates follow-up of cascades as well as tracks
    - E.g., CTA's SC-MST field of view of 8° well matched to cascade resolution of 3°-5°

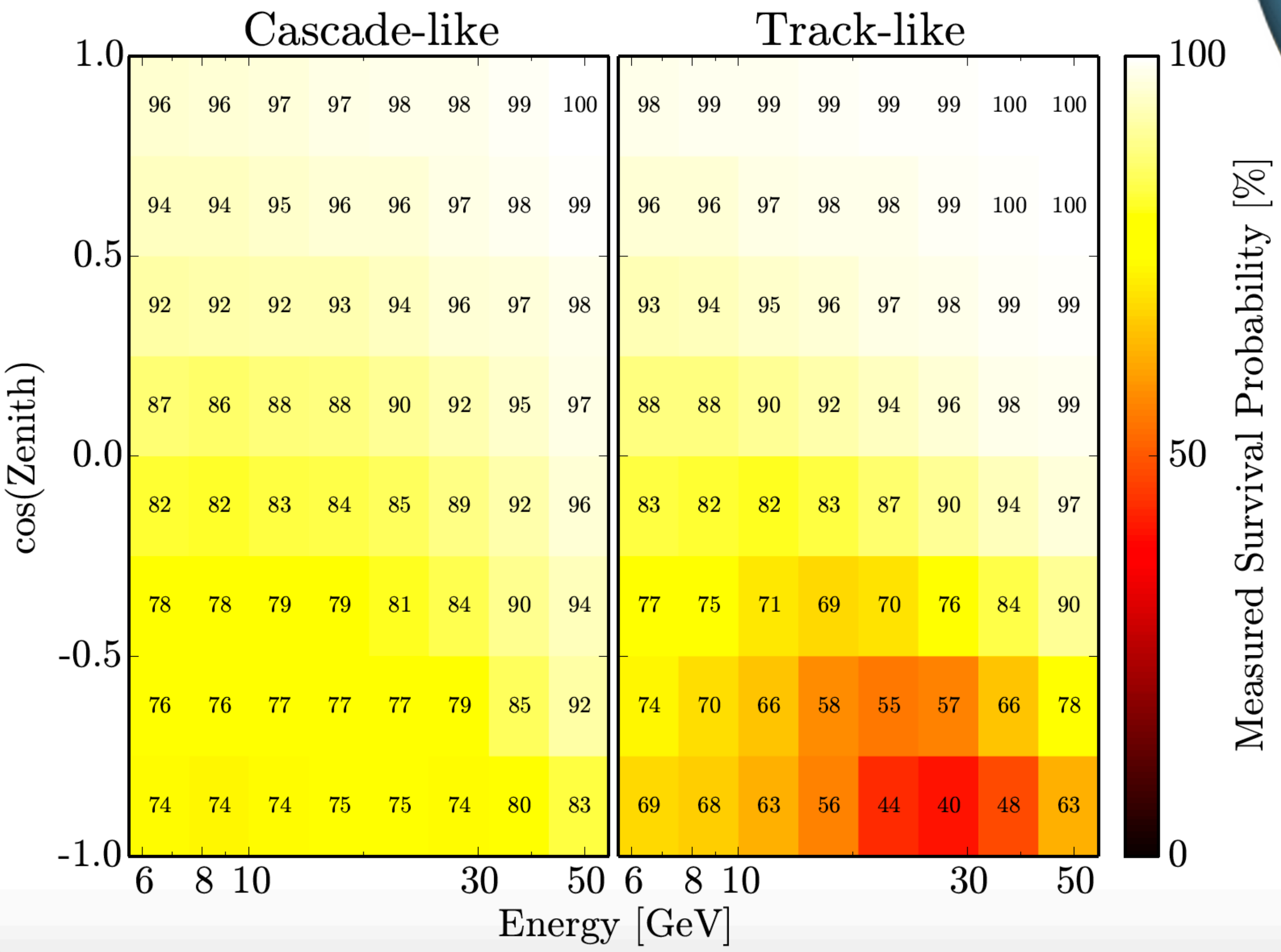




IceCube probes oscillation physics at baselines and energies inaccessible to LBL or reactor neutrino experiments – essential for constraining new physics

Measuring Oscillations

- Exploit high statistics to measure 2D distortions due to oscillations in energy/angle space

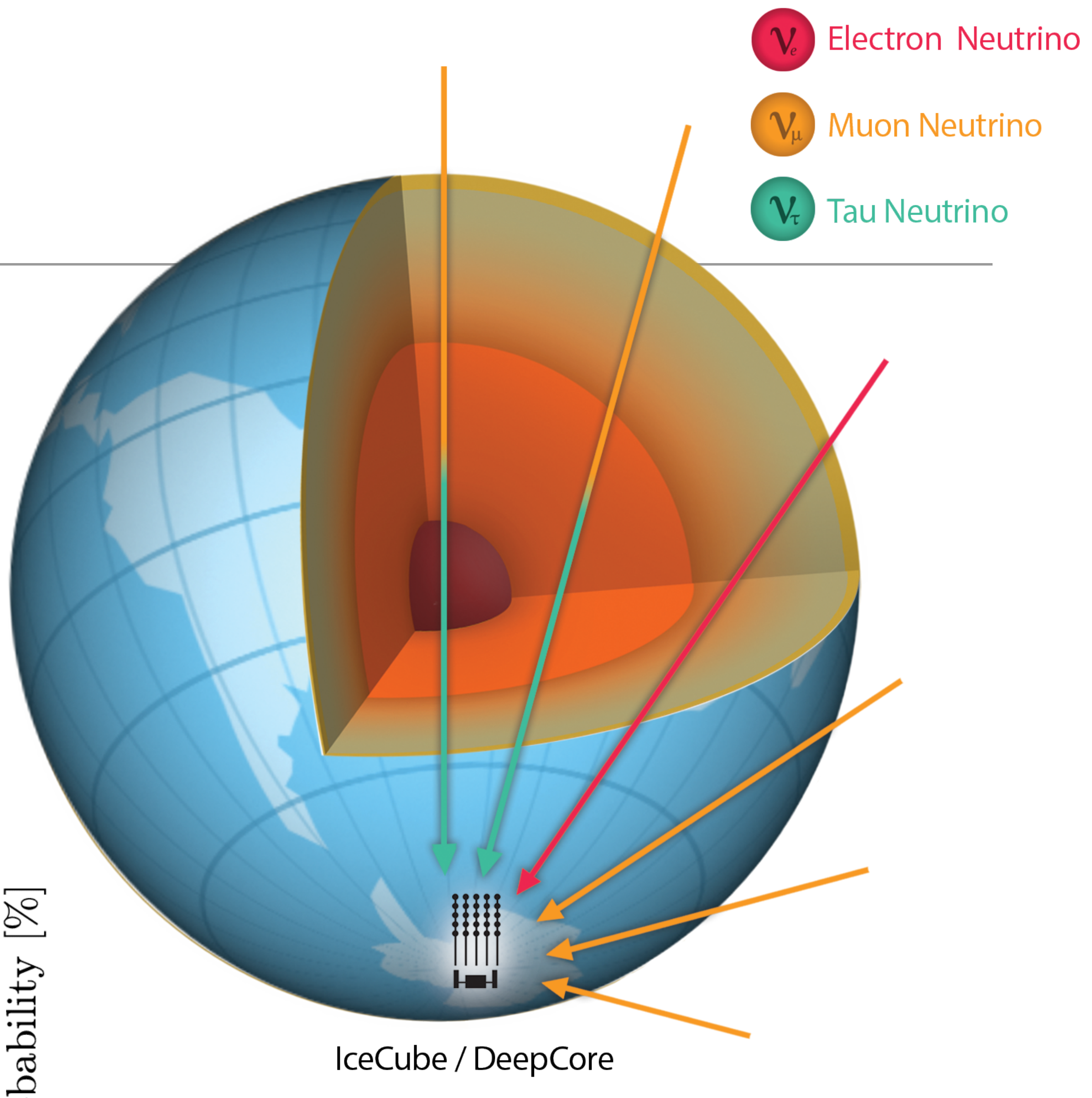


Cascade-like

96	96	97	97	98	98	99	100
94	94	95	96	96	97	98	99
92	92	92	93	94	96	97	98
87	86	88	88	90	92	95	97
82	82	83	84	85	89	92	96
78	78	79	79	81	84	90	94
76	76	77	77	77	79	85	92
74	74	74	75	75	74	80	83

Track-like

98	99	99	99	99	99	100	100
96	96	97	98	98	99	100	100
93	94	95	96	97	98	99	99
88	88	90	92	94	96	98	99
83	82	82	83	87	90	94	97
77	75	71	69	70	76	84	90
74	70	66	58	55	57	66	78
69	68	63	56	44	40	48	63

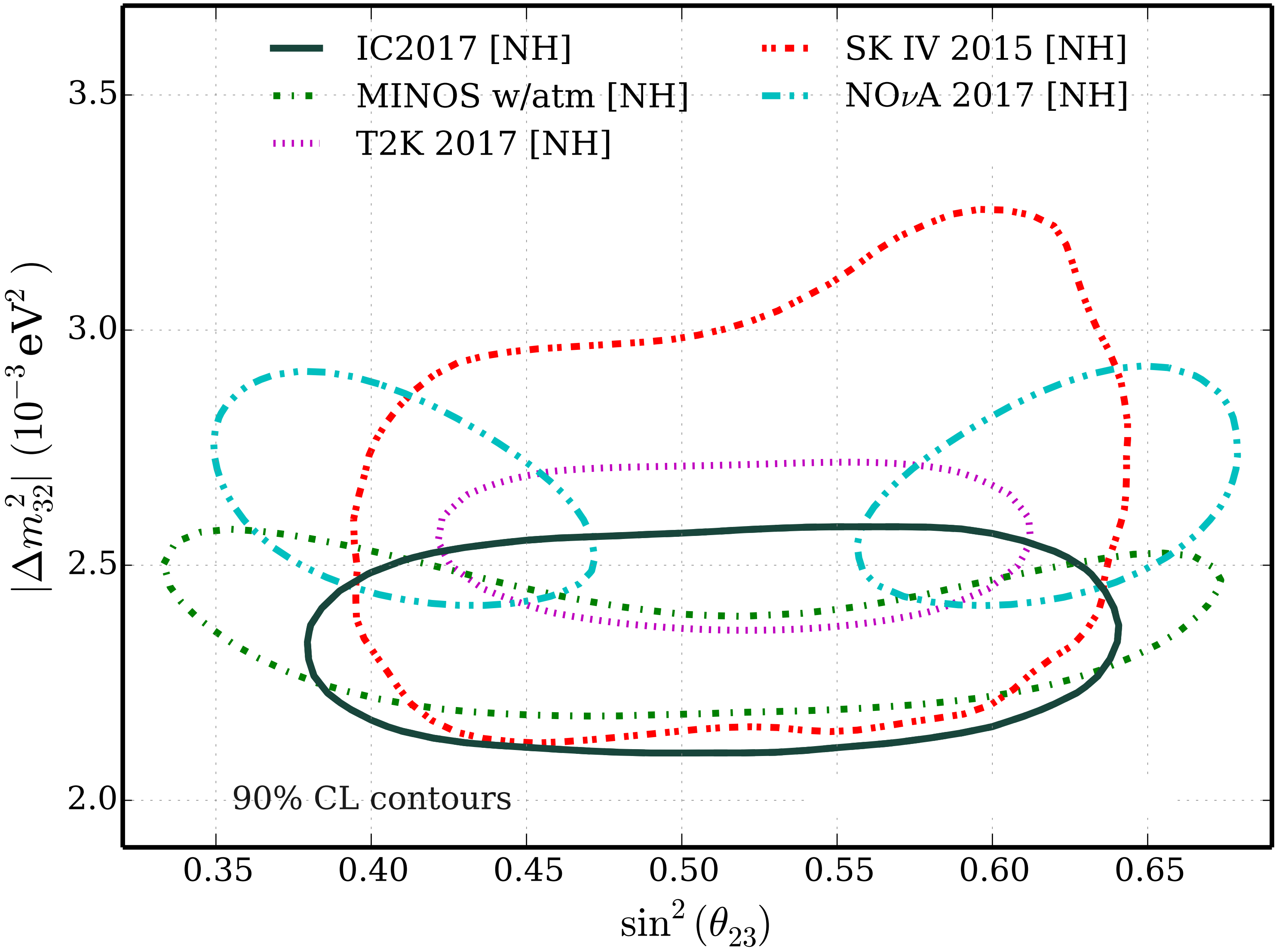


- Broad range of energies and significant matter densities permit searches for a range of new physics (sterile neutrinos, NSI,…)

Atmospheric Oscillation Parameters

- Currently unclear whether $\sin^2 \theta_{23}$ is maximal
    - 3rd mass state made up of equal parts ν_μ, ν_τ
    - Evidence of new symmetry?

arXiv:1707.07081, *Phys. Rev. Lett.* 120, 071801 (2018)



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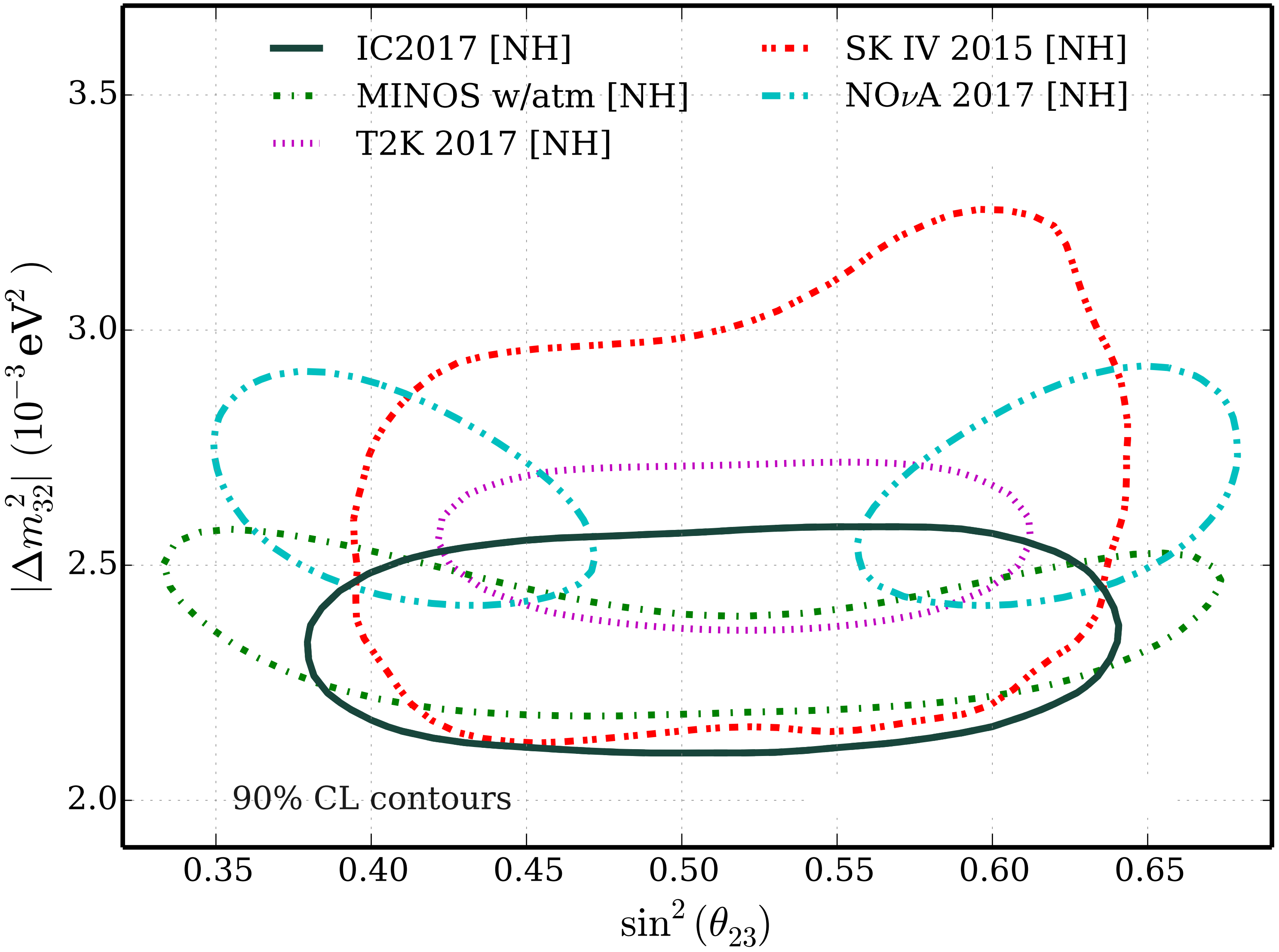

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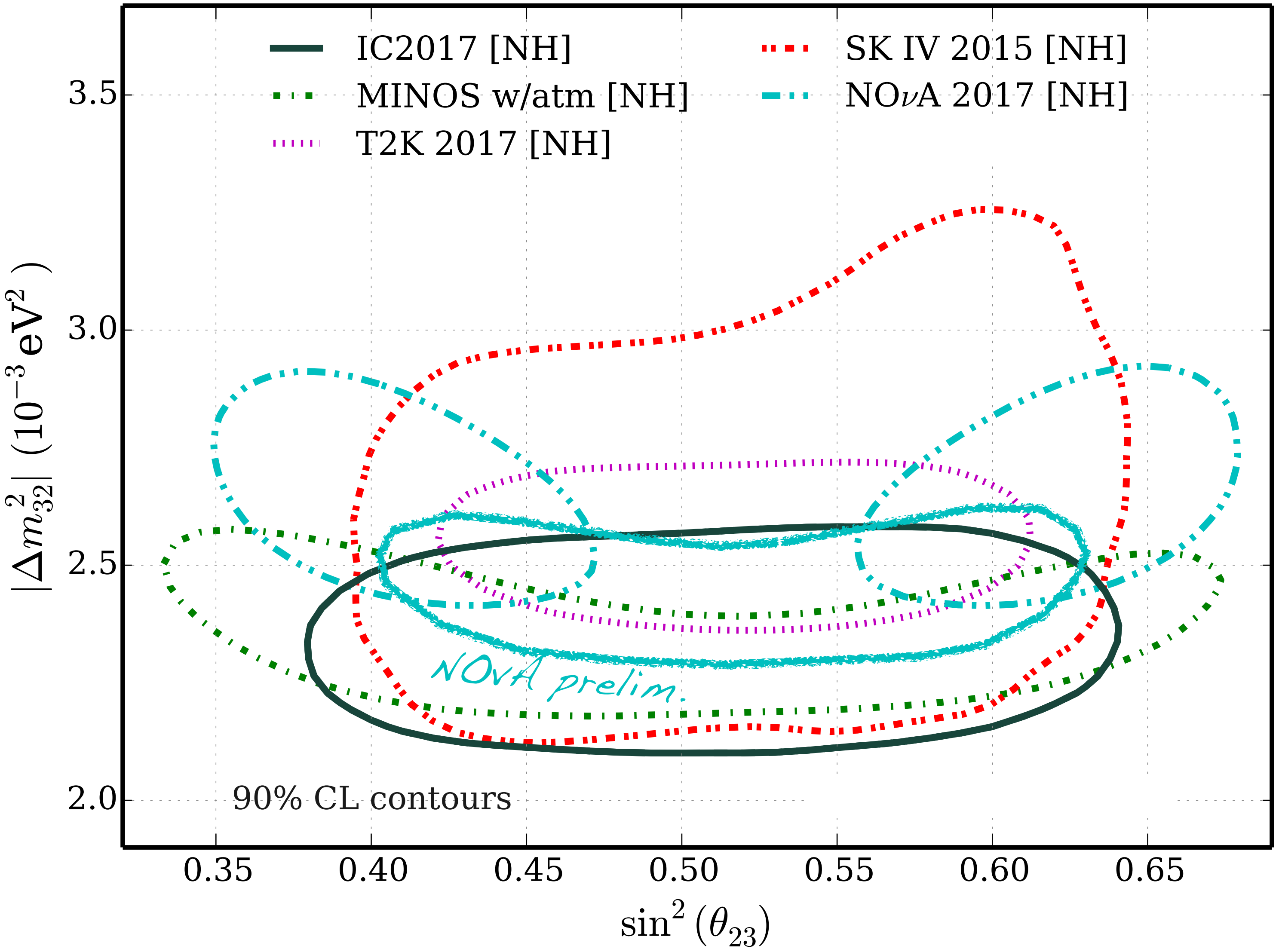

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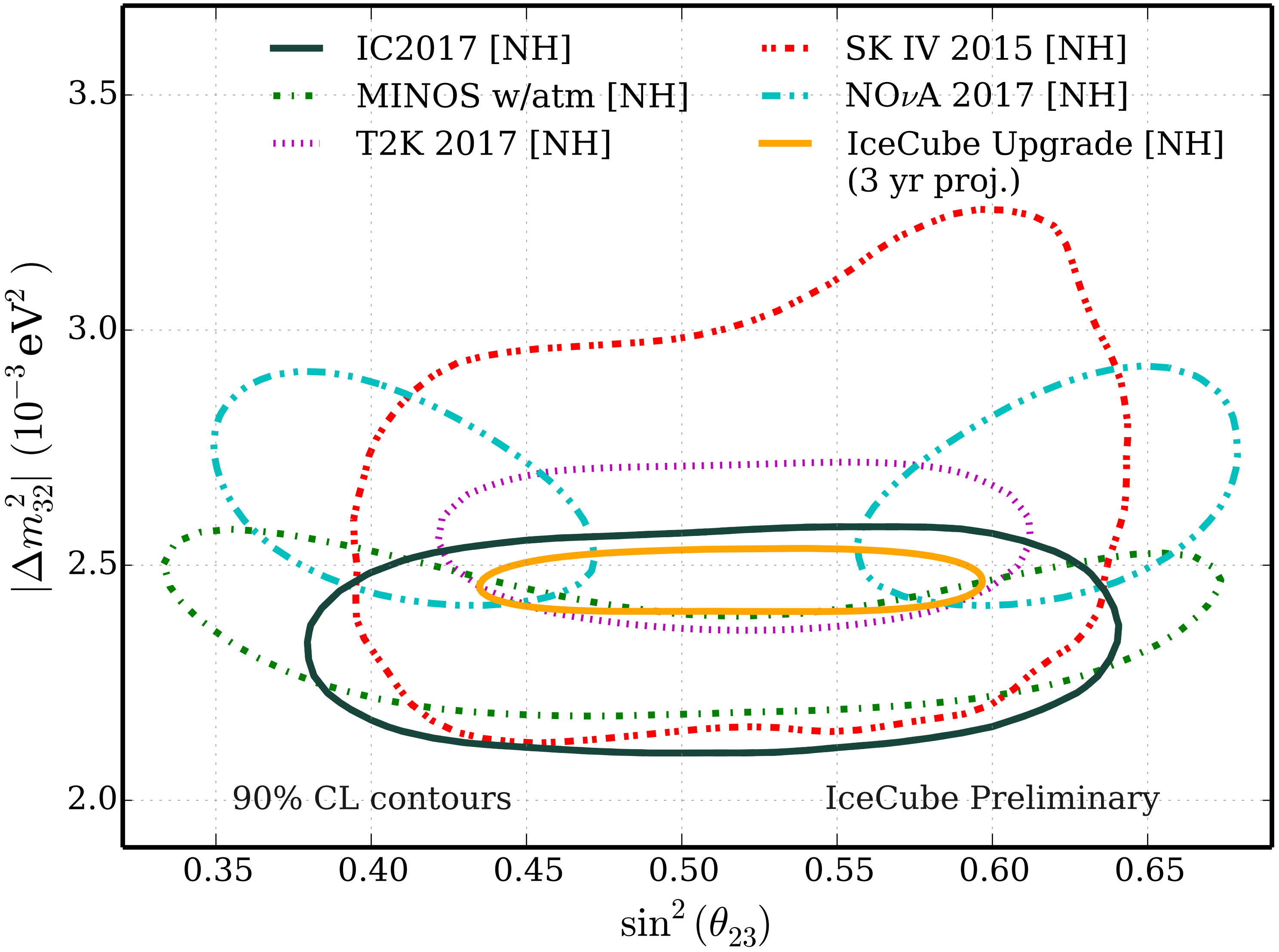

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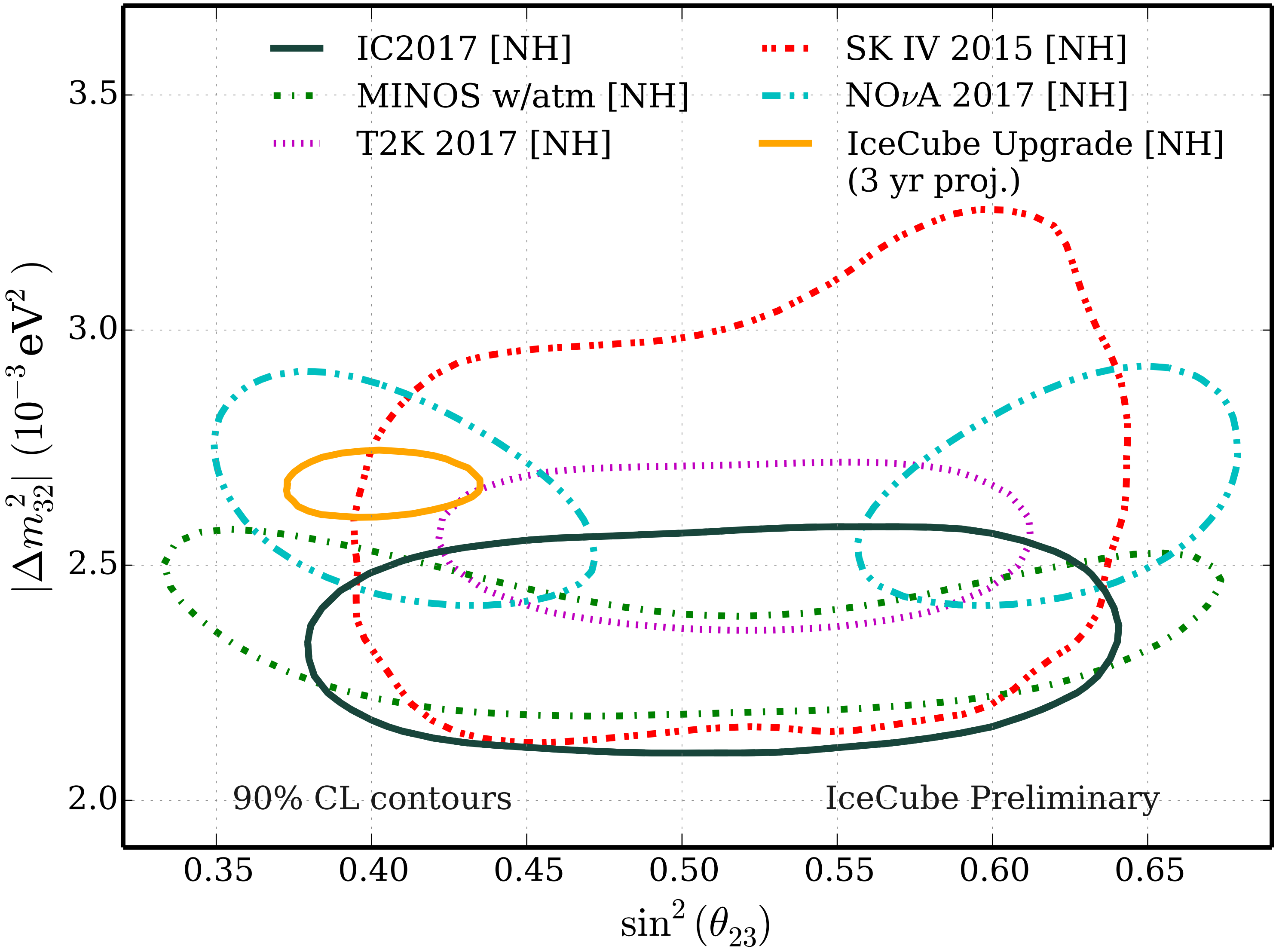
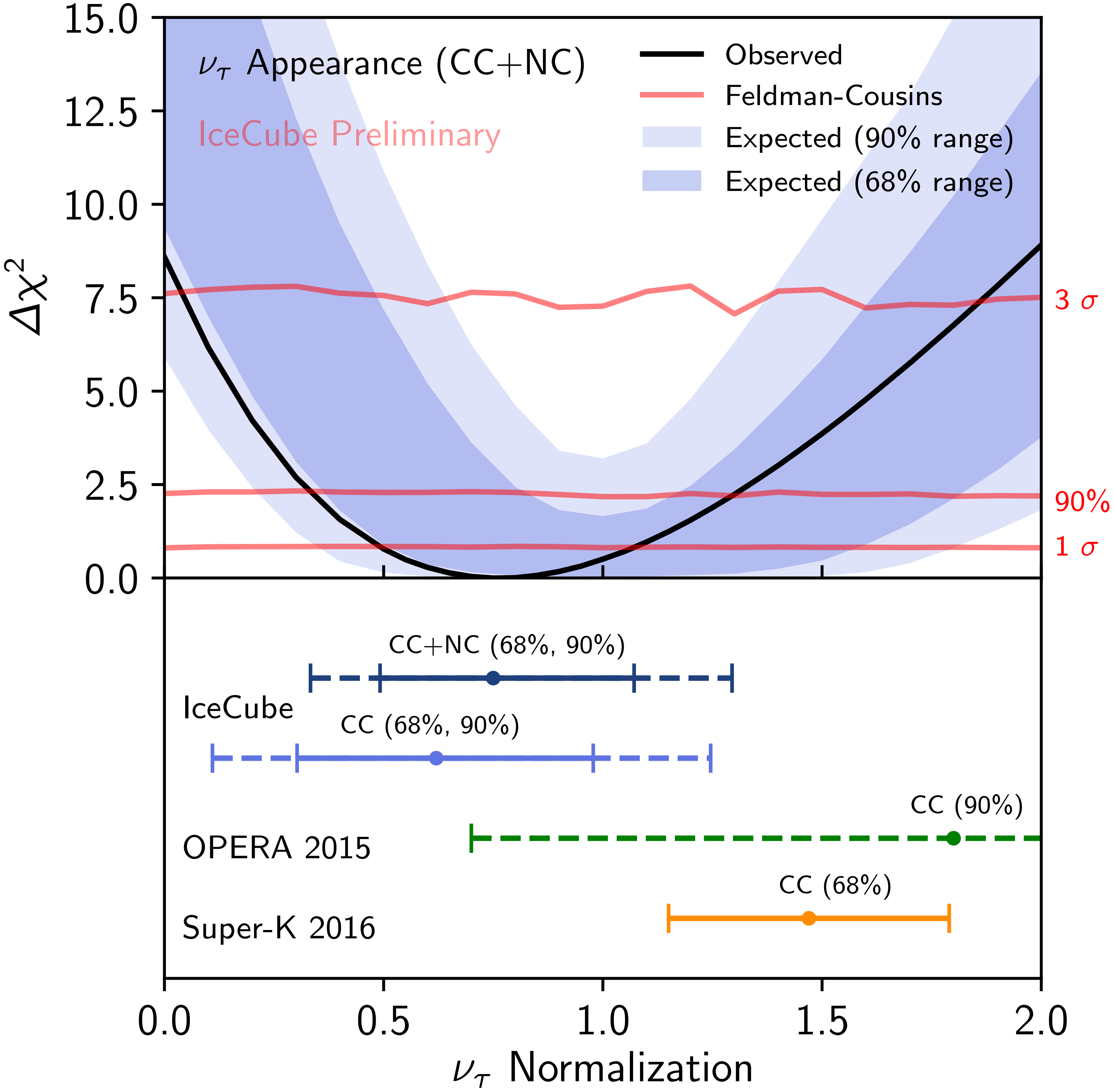


- Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)

Tau Appearance and PMNS Unitarity

- 3-yr DeepCore result competitive with 15-yr Super-K measurement
  - Analysis improvements and additional data will improve precision
- IceCube Upgrade will achieve ±7% in 3 years
  - ~10% precision needed for real tests of unitarity of PMNS mixing matrix

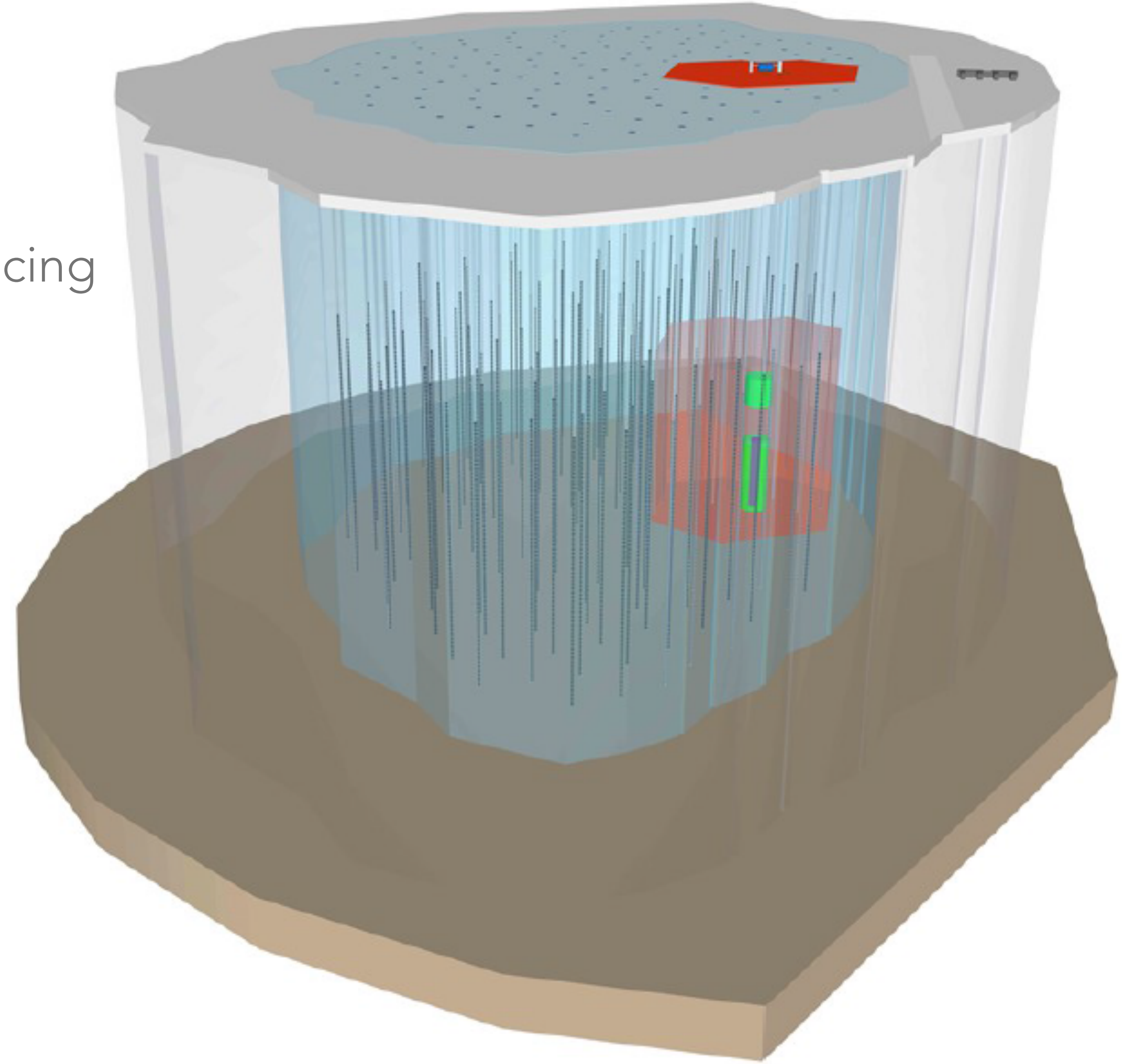


IceCube Upgrade Status

- Proposals pending with NSF (PHY mid-scale) and foreign partners
  - $22.7M US plus $12.8M from foreign partners
- Significantly enhanced detector performance for ~10% incremental investment
  - Improved performance *retroactively* for reanalysis of 10 $\mathrm{km}^3 \cdot$year IceCube data set
- Project-driven timeline:
  - Final engineering and design reviews in 2018-19
  - mDOM, DAQ electronics and cable production in 2020
  - Drill integration and firn drilling at South Pole in 2020/21
  - Deep drilling and deployment in 2021/22
  - Commissioning and integration in 2022

The Future: IceCube-Gen2

- High Energy Array
  - 120 strings x 80 sensors/string
  - ~8 km^3 volume, wider string spacing
- PINGU
  - Low energy infill
  - 26 strings (incl. IC Upgrade)
- Also investigating surface arrays, UHE radio detection
- Cost scale similar to IceCube



Thanks for your attention!

Calibration with the Upgrade

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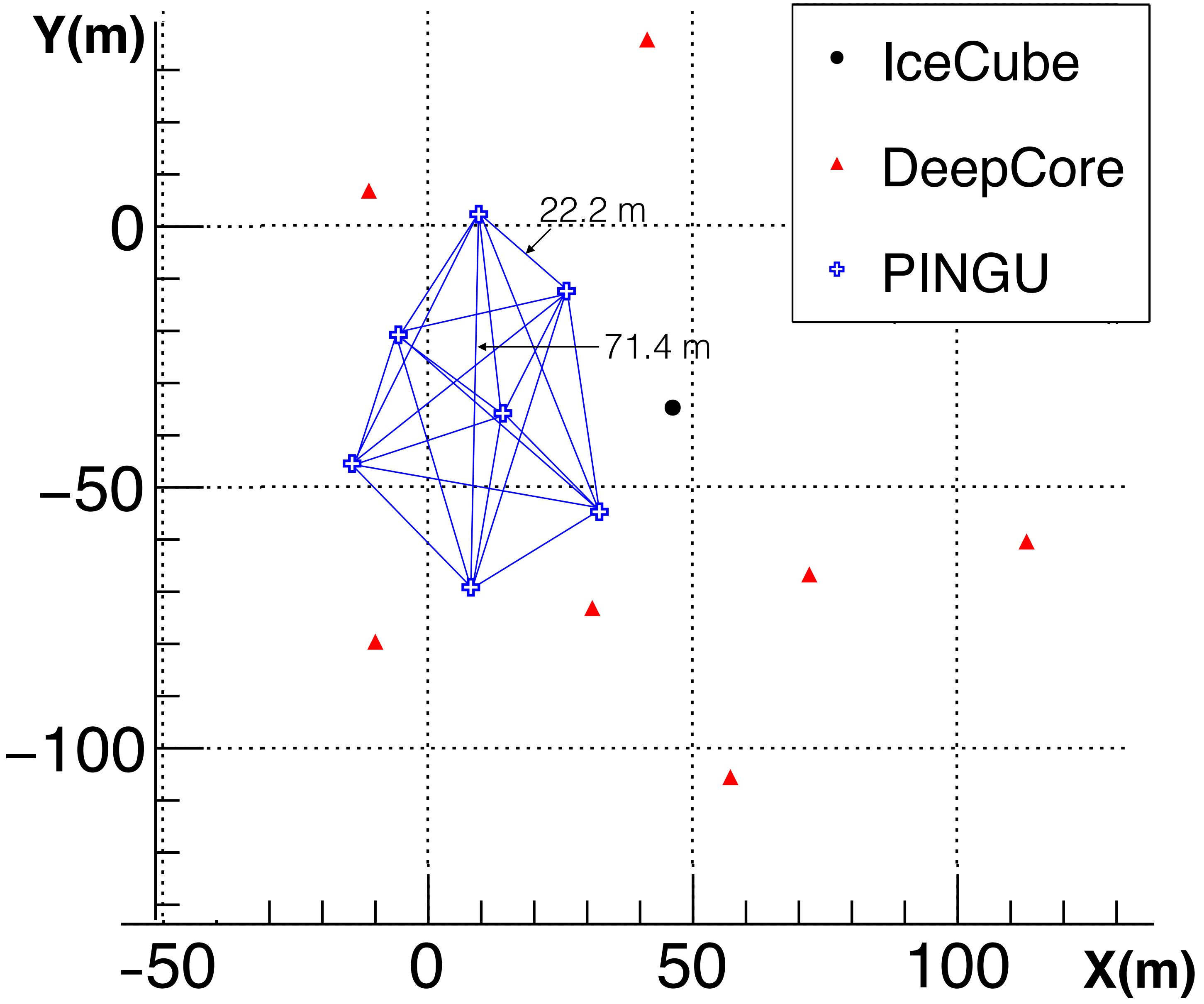
  - Wider range of angles accessible to LEDs – both horizontally and vertically
  - Probe $L < \lambda_{\mathrm{scatt}}^{\mathrm{eff}}$ for the first time



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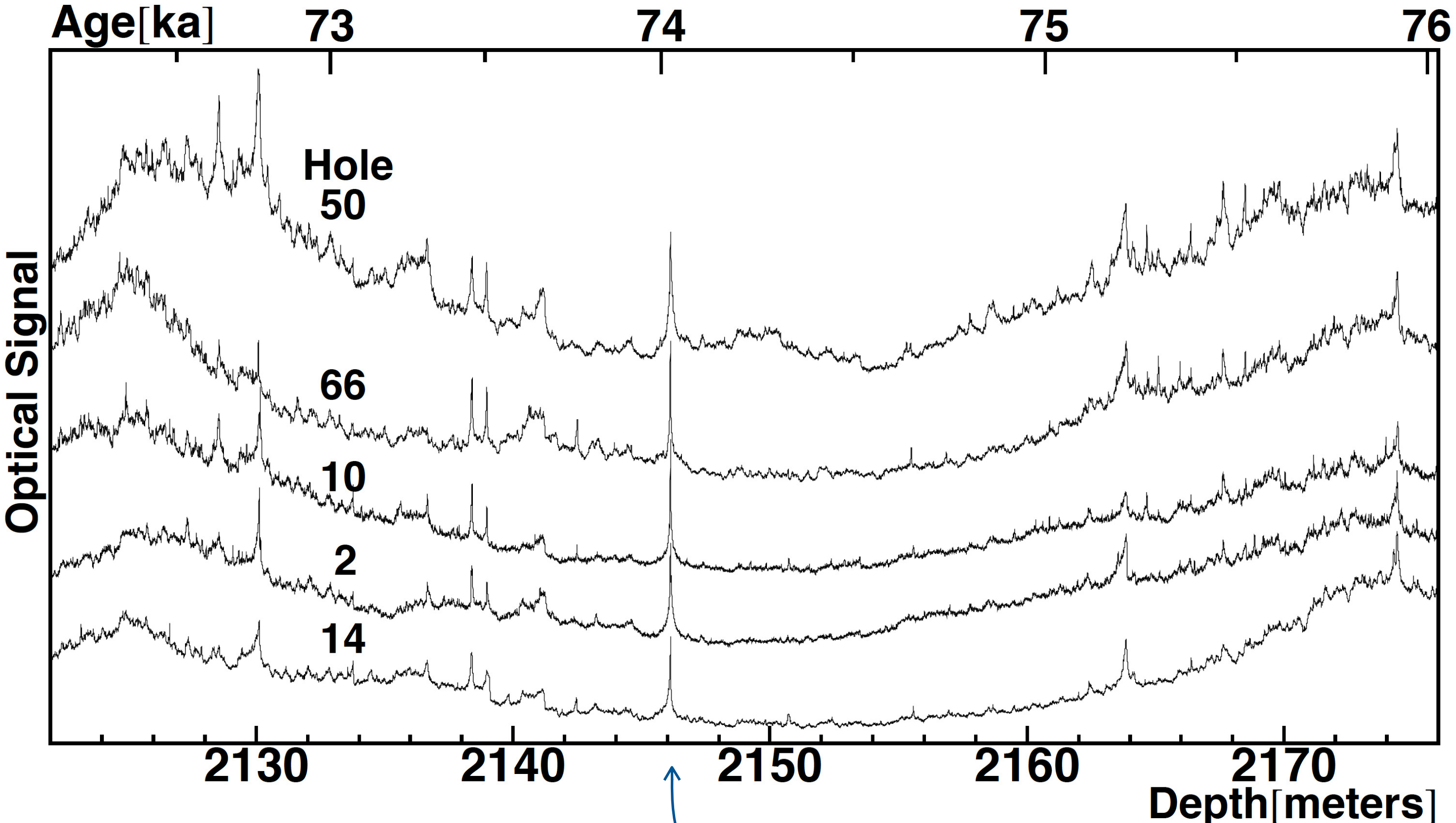
  - Wider range of angles accessible to LEDs – both horizontally and vertically
  - Probe $L < \lambda_{\text{scatt}}^{\text{eff}}$ for the first time
- More precise LEDs, fundamentally new devices like POCAM

POCAM v1-g being deployed at Lake Baikal

Bulk Ice Characterization

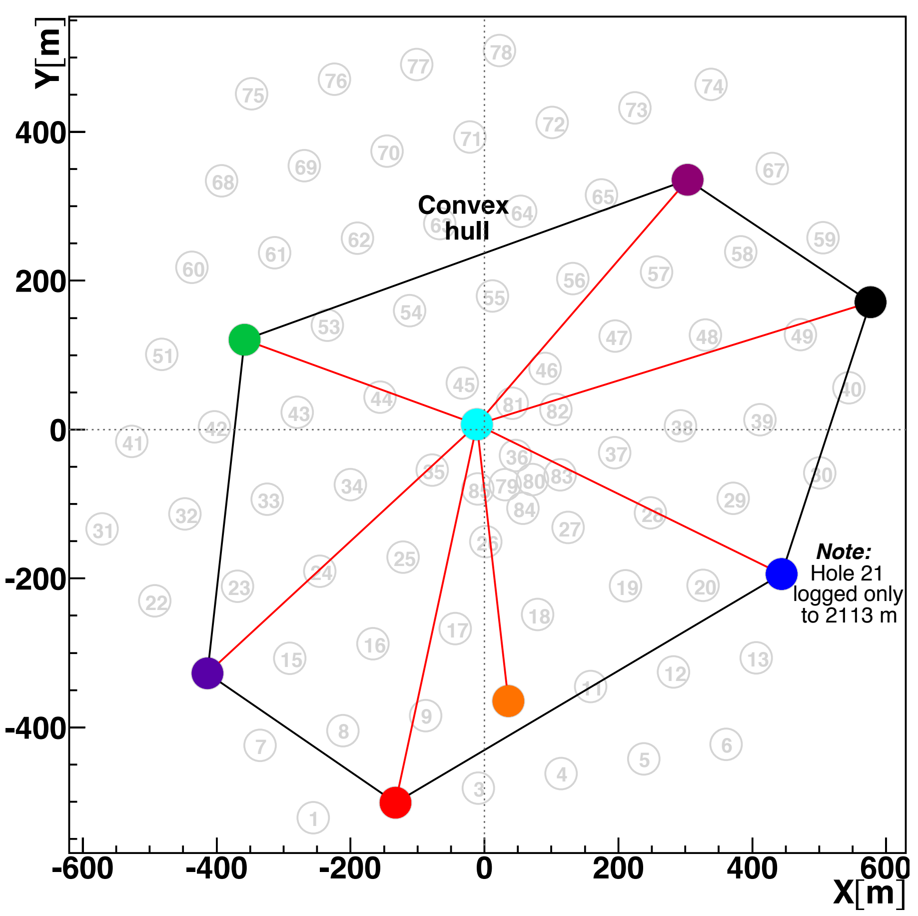
- Optical properties of the bulk ice are determined by varying amount of dust grains
  - Current uncertainties on absorption, effective scattering at ~10% level
  - Also: anisotropy, scattering angle distribution



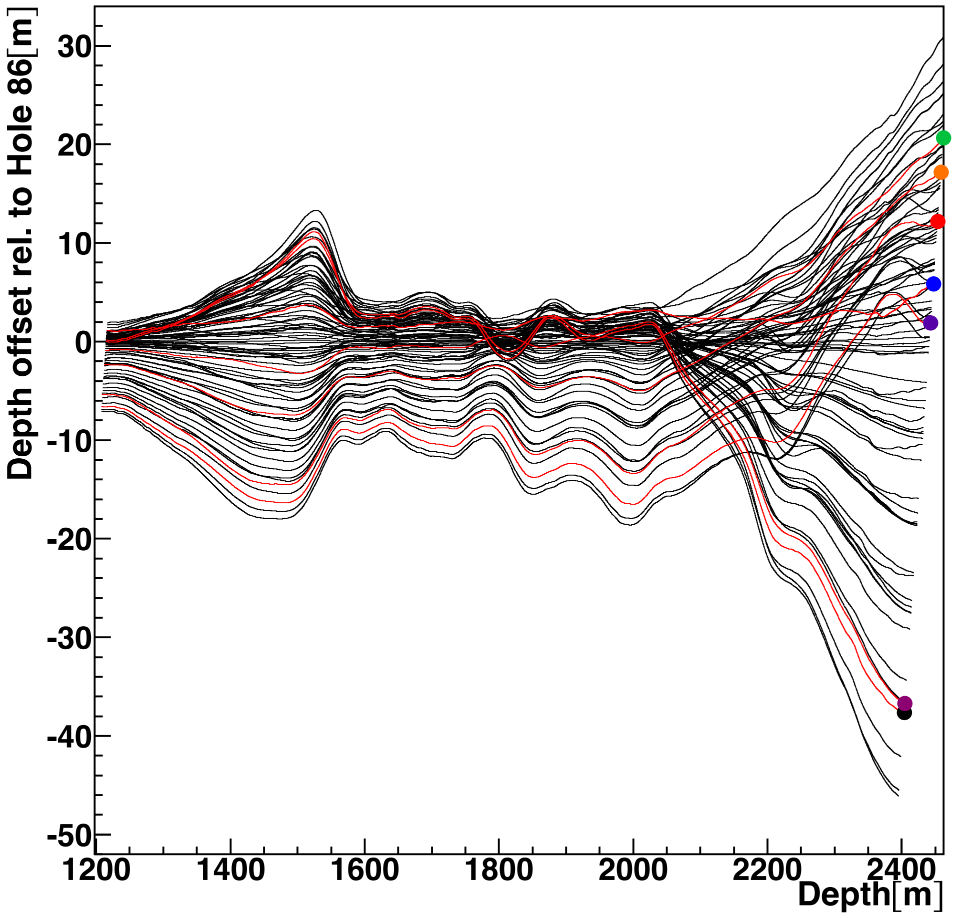
Toba eruption

- Dust logger data taken during construction provides an incredibly detailed map of the ice – the issue is conversion to optical properties

Bulk Ice Characterization



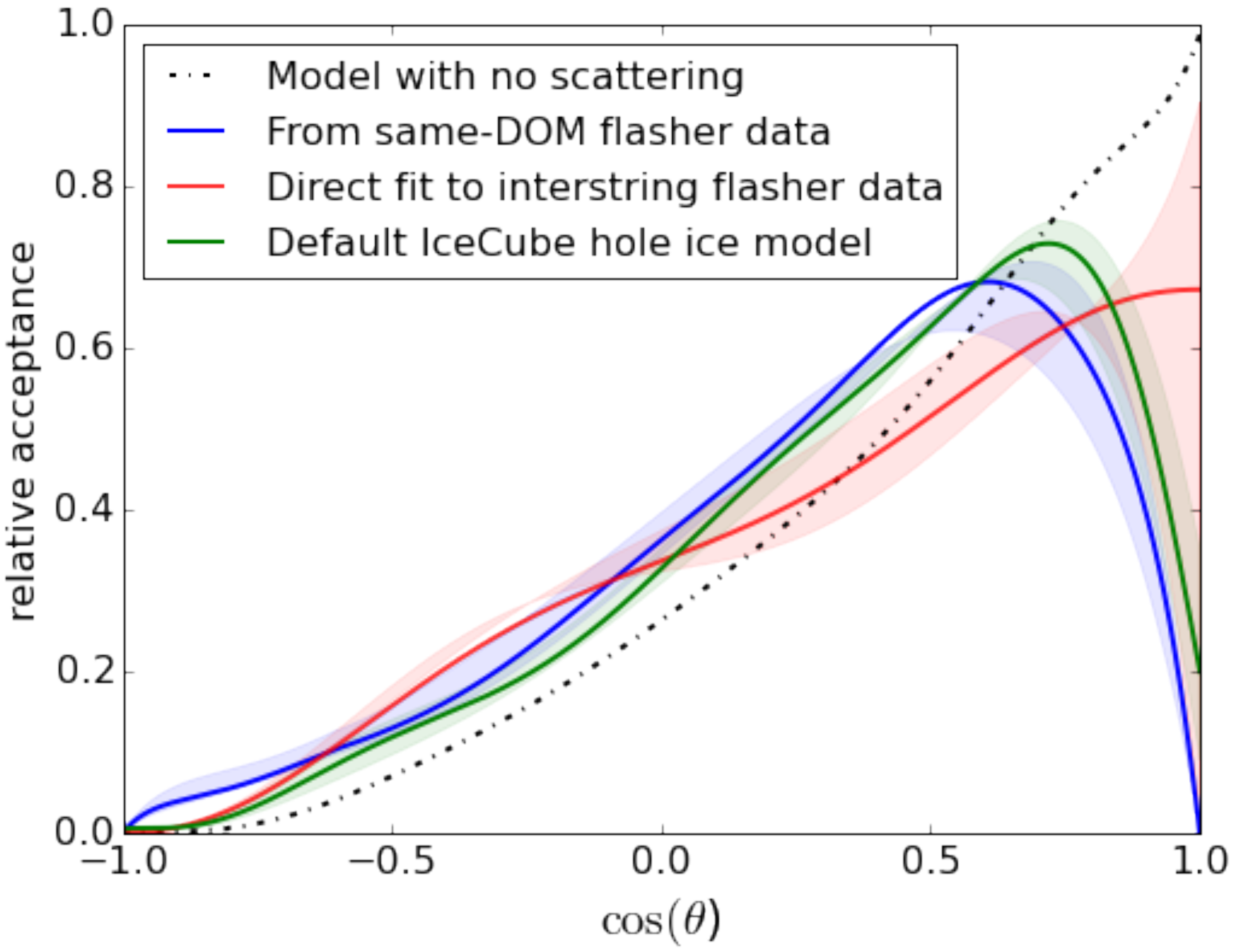
Note: Hole 21 logged only to 2113 m



- Precision measurements in the Phase 1 region can be applied throughout the array, using our existing 3D map of the dust layers

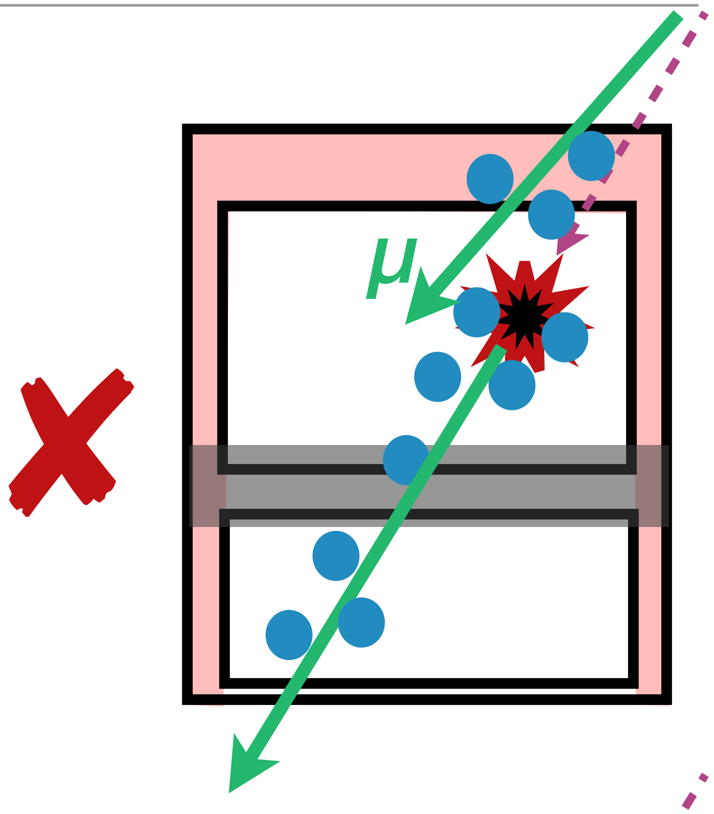
Local Effects on DOM Response

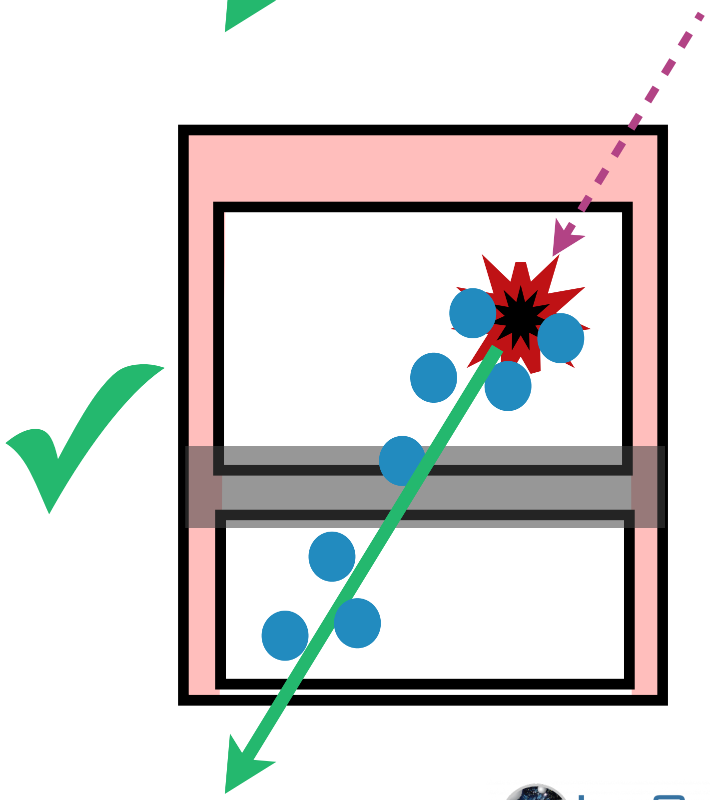
- Sensitivity of DOMs in situ is modified by cable shadow and bubbles in the refrozen ice
  - Leading systematic for low energy analyses
  - Limits angular resolution for high energy events
- Closer strings, POCAMs, and better LEDs will enable us to map the DOM angular response directly



High Energy Cascade Veto

- Original contained event searches (HESE, MESE) make no use of neutrino event information
  - Search entire veto volume for muon traces: maximal robustness, (nearly) equal flavor sensitivity





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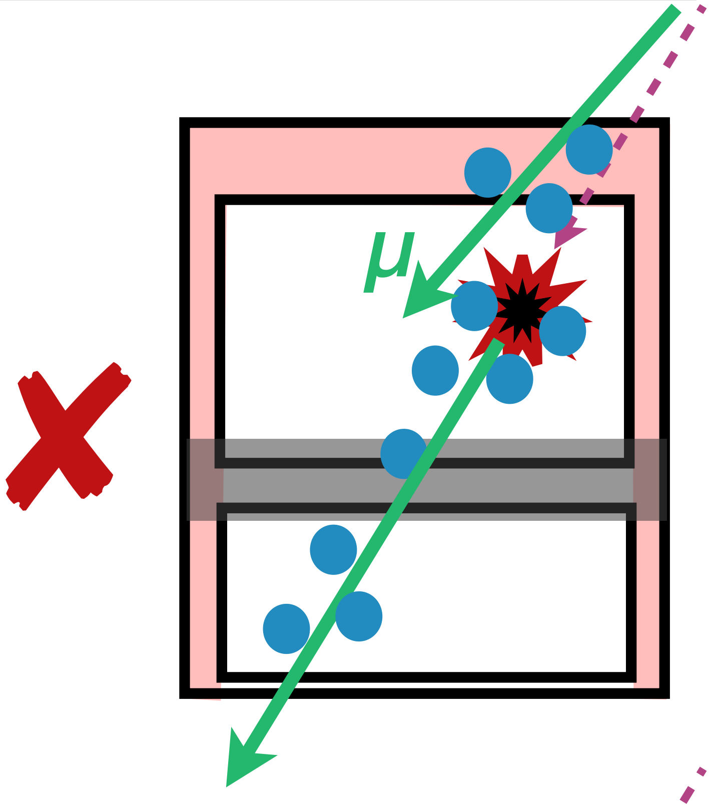

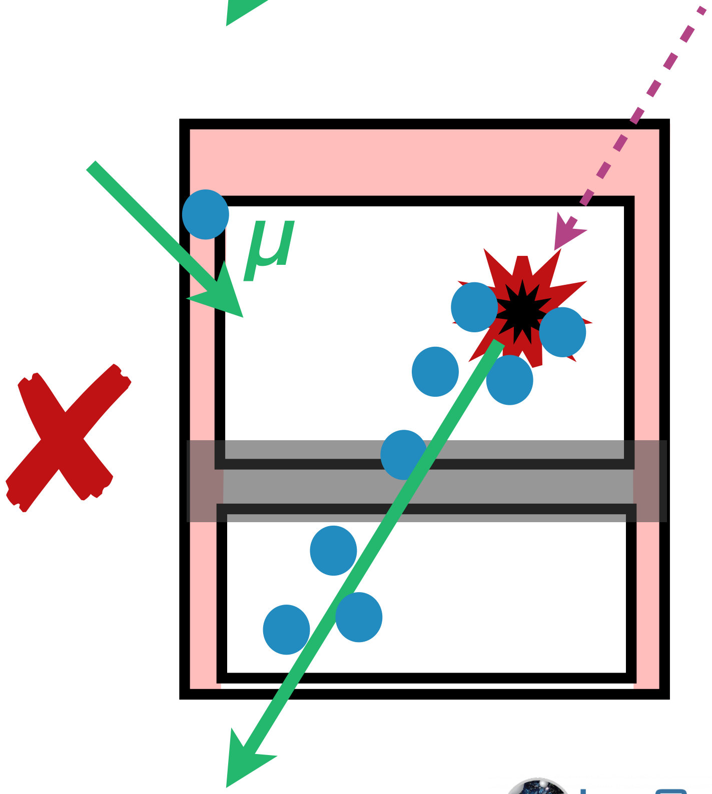

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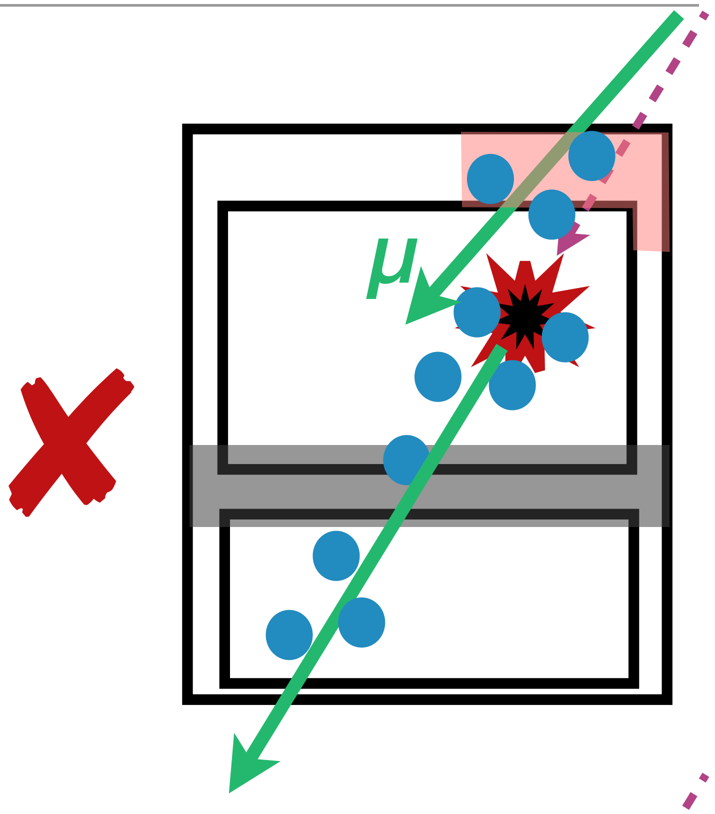
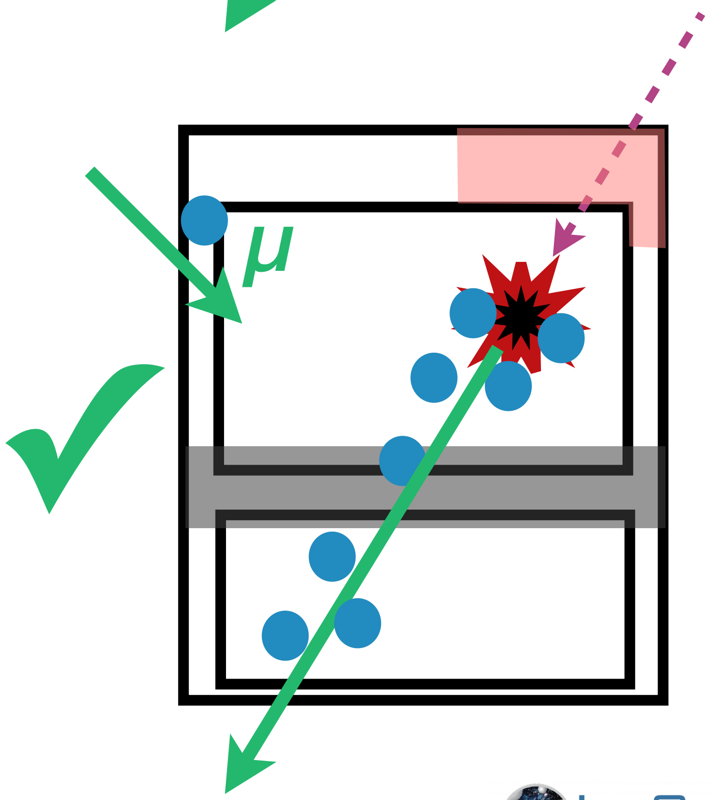
    - Uses event reconstruction to determine veto region: lower effective energy threshold, reduced false-positive rate





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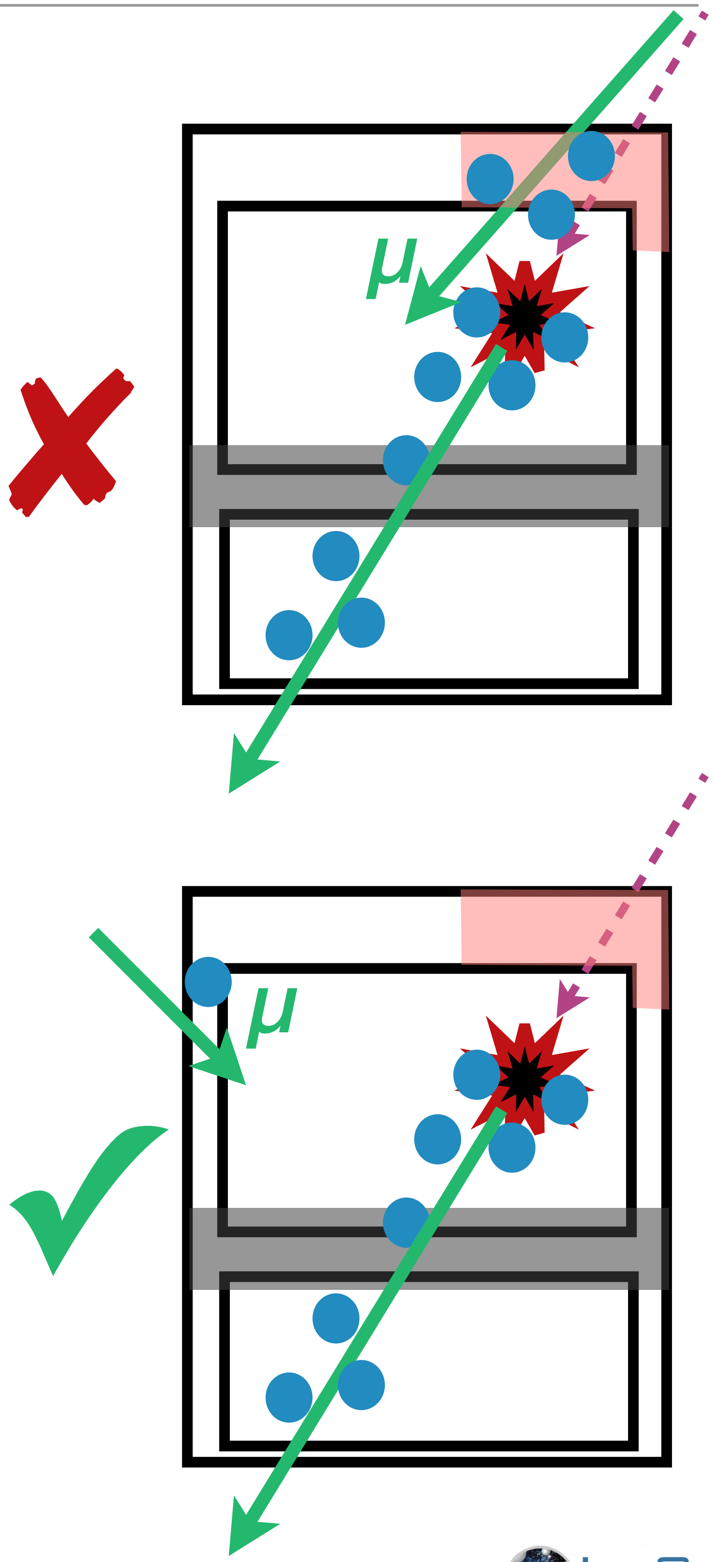
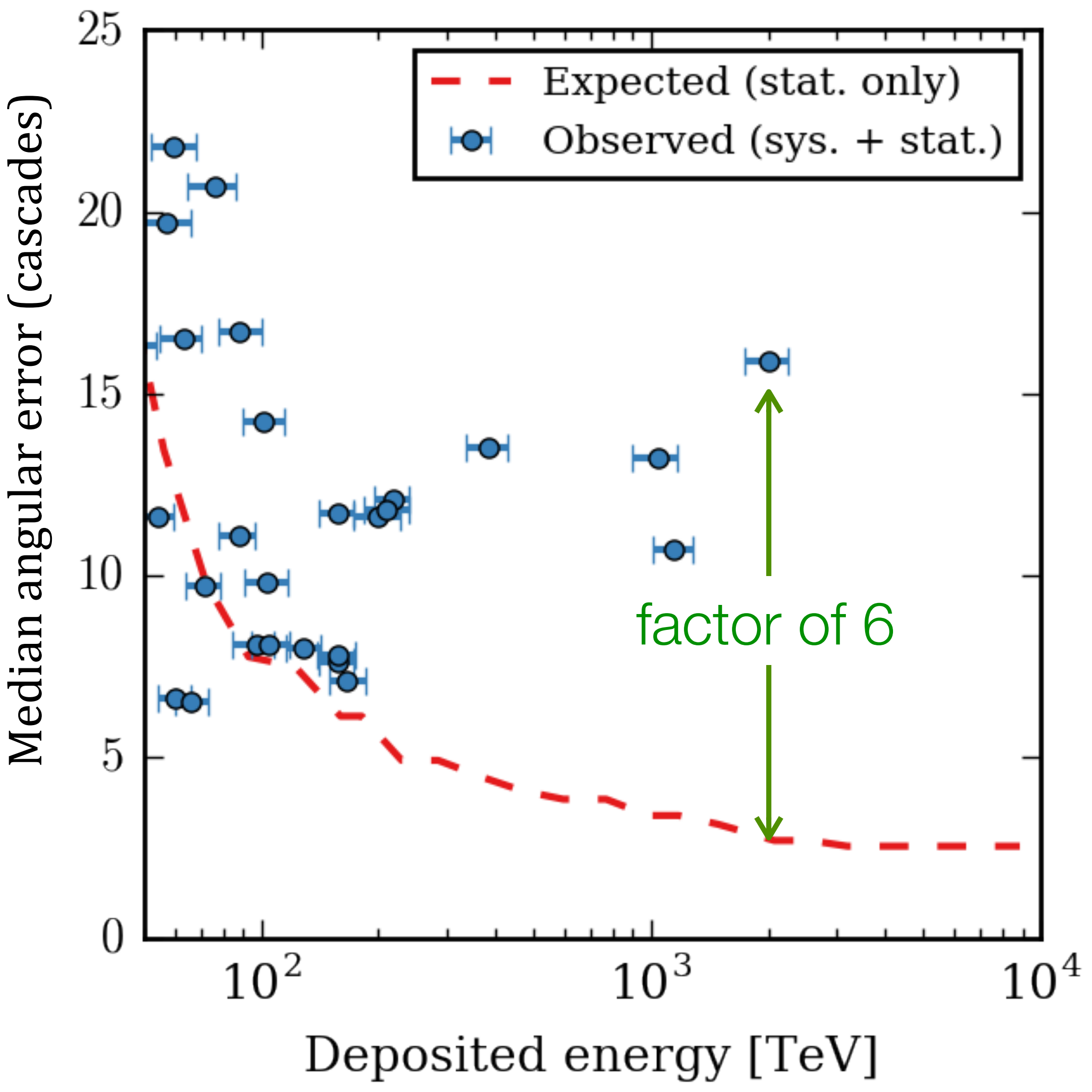
- Better reconstruction will permit similar gains for cascades
  - Slightly worse pointing, but can also use particle ID to reject background (atmospheric muons)



Angular Resolution

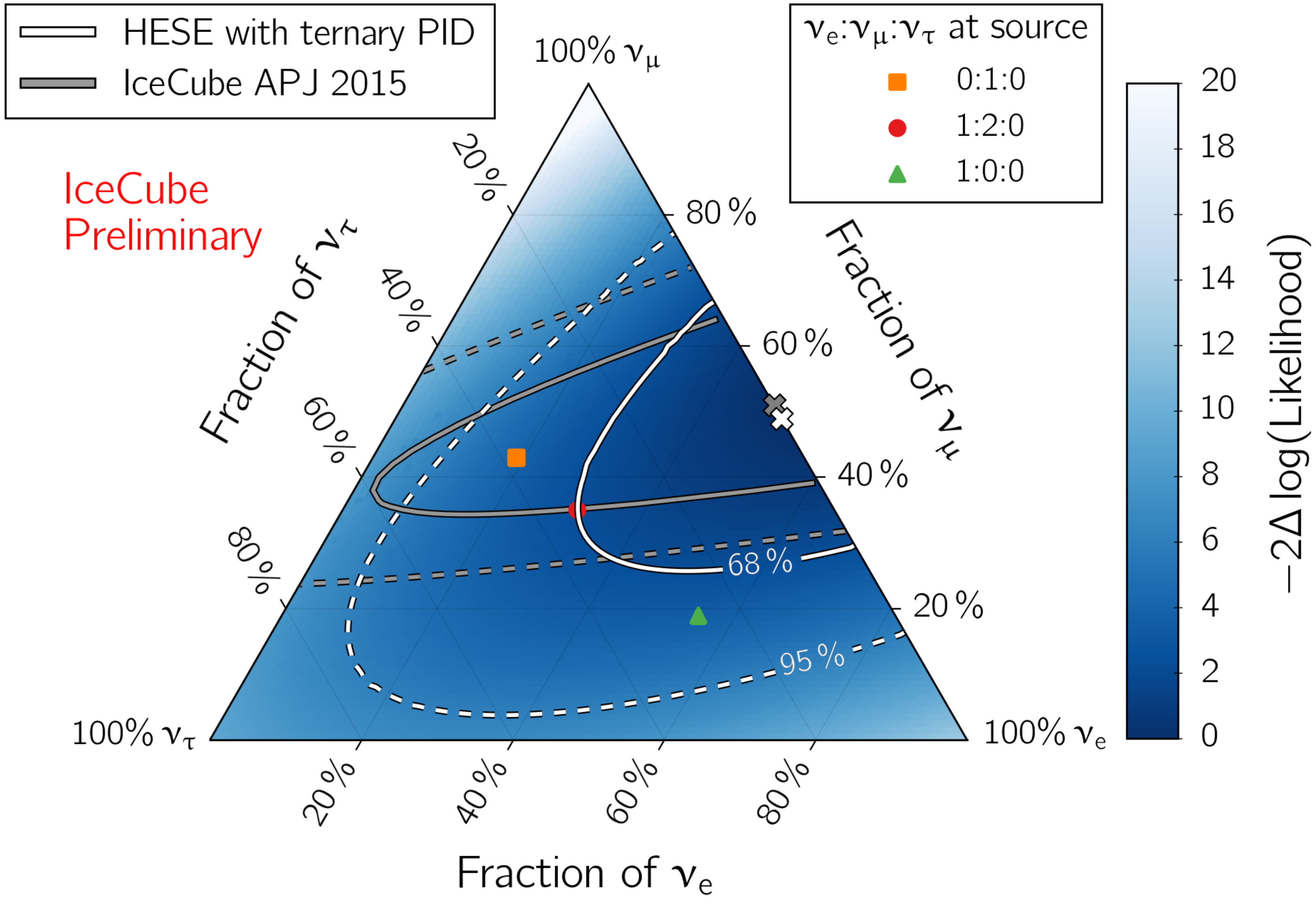
- Reconstruction of tracks and cascades limited by systematics above ~100 TeV
    - Uncertainties in detailed scattering of Cherenkov photons in bulk ice and in immediate vicinity of DOMs (cable shadow, bubbles in refrozen ice)
    - DOMs closest to the event must be omitted from fit to avoid strong pulls



- Resolutions as low as 0.1°-0.2° (muons), 3°-5° for cascades possible in the absence of systematic uncertainties
    - Better resolution also enables targeted veto – up to 2x yield for cascades at 10-100 TeV

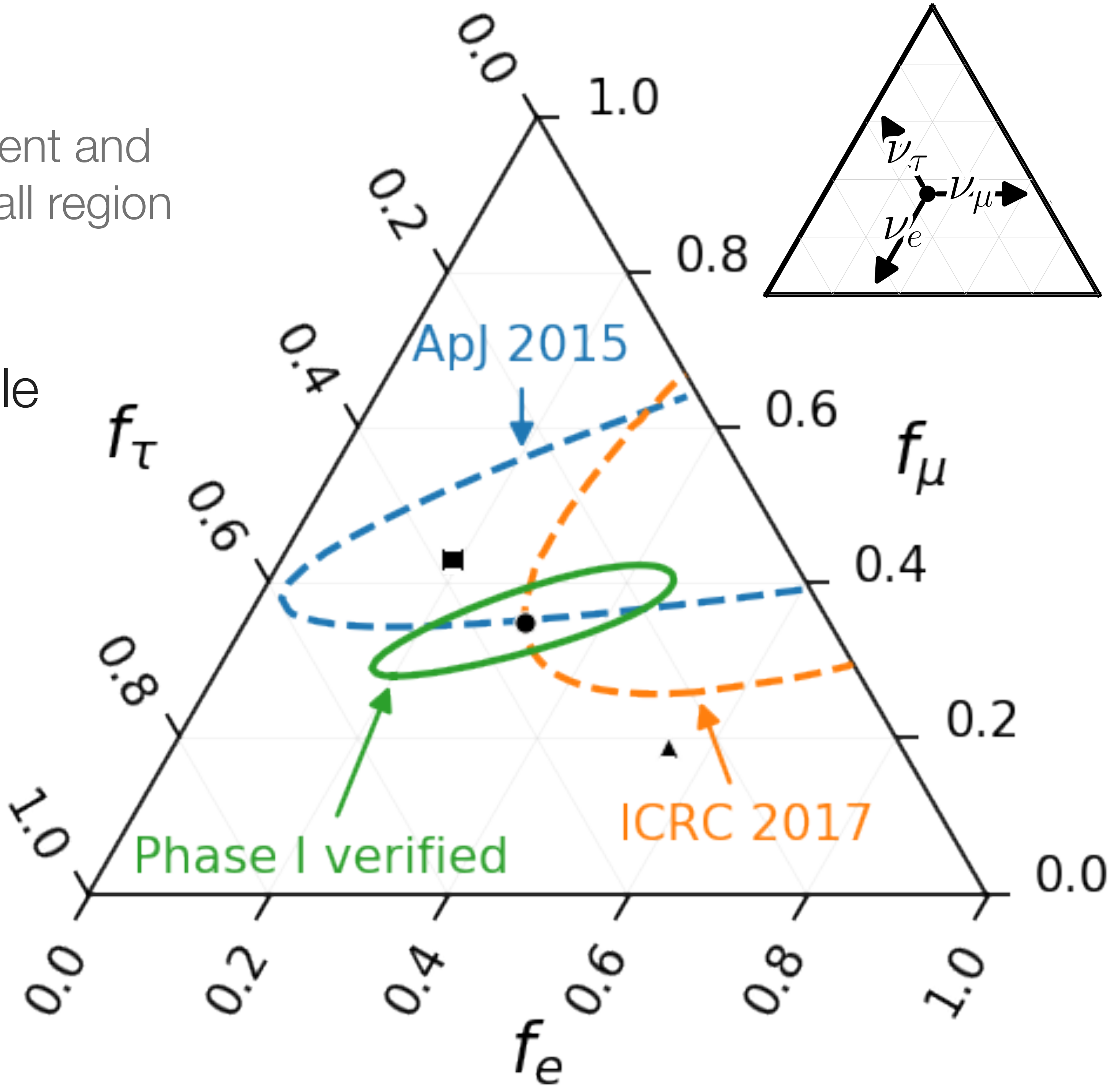
Flavor Ratio Measurements

- No tau neutrinos yet identified
  - Difficult to tag below ~PeV; only 2 expected so far assuming equal flavors (9% probability of observing zero events)



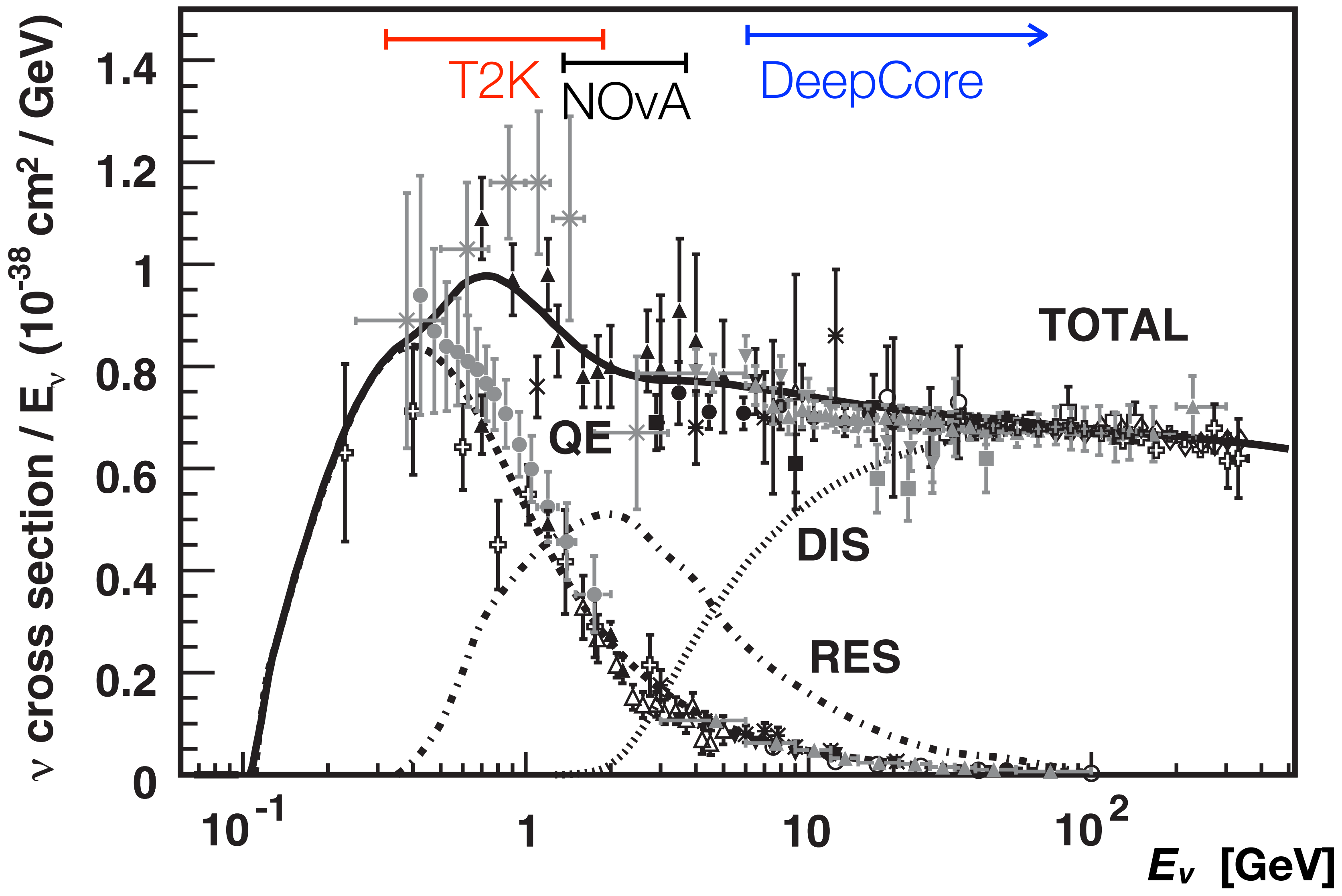
Tau Neutrino Identification

- For standard PMNS oscillations, 1/3 of cosmic neutrinos should arrive as ν_τ
  - Depends weakly on source environment and oscillation parameters, but only a small region of flavor triangle is allowed in SM
- Primary detection channel is "double bang:" ν_τ interaction followed by τ lepton decay
  - Anisotropic Cherenkov photon propagation can give double image of single cascade (cf. birefringence)
  - New LEDs will enable controlled injection precisely timed light pulses – direct calibration

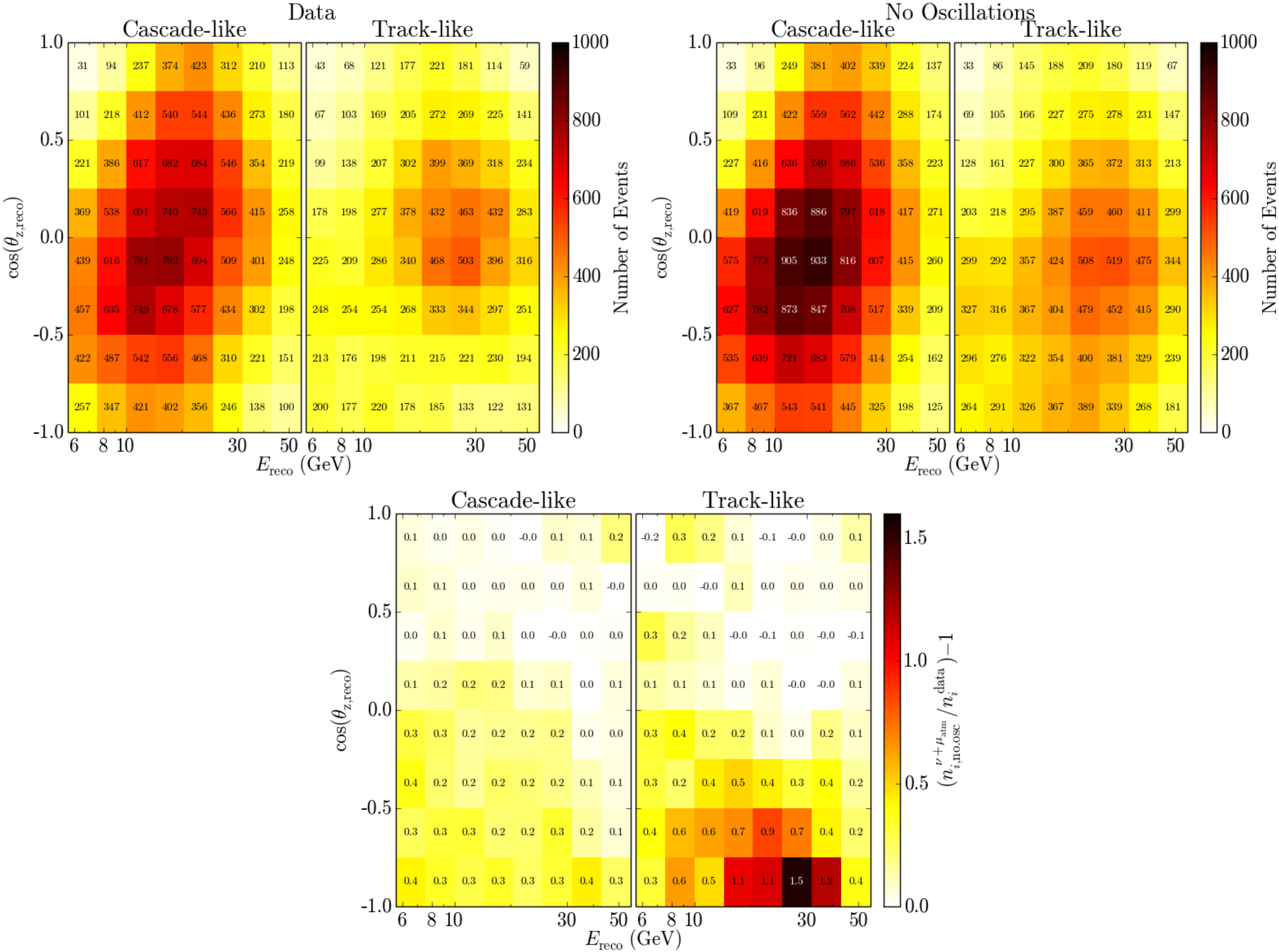


Experimental Uncertainties

Formaggio and Zeller 2012

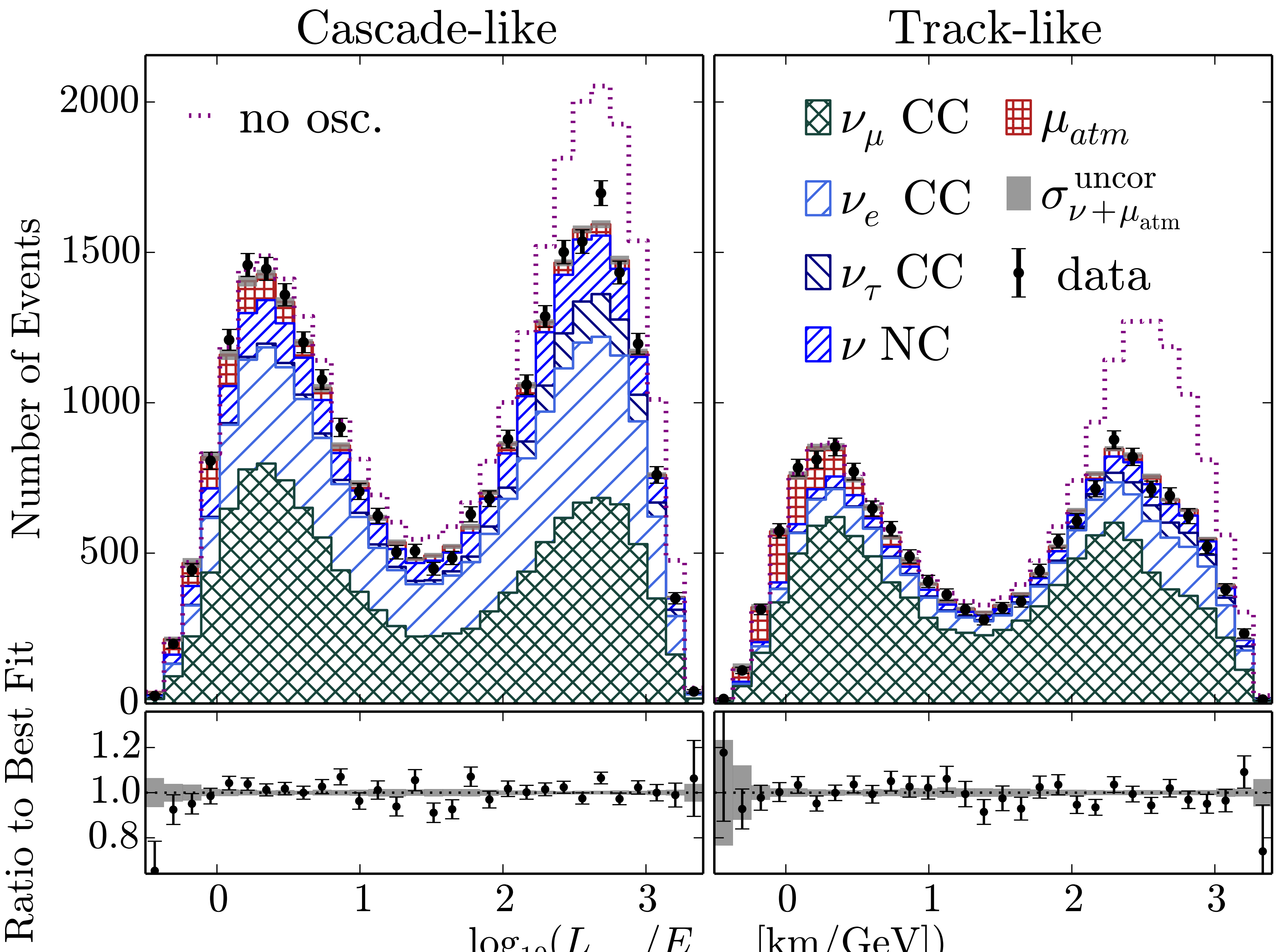


- Neutrino-nucleon interactions dominate long-baseline systematics
  - Nuclear physics effects can have a significant impact at lower energies – IceCube complementary from the experimental perspective, as well as theoretical

Data
Cascade-like
Track-like
31 94 237 374 423 312 210 113
101 218 412 540 544 436 273 180
221 386 617 682 684 546 354 219
369 538 691 740 743 566 415 258
439 616 781 792 694 509 401 248
457 635 749 678 577 434 302 198
422 487 542 556 468 310 221 151
257 347 421 402 356 246 138 100
43 68 121 177 221 181 114 59
67 103 169 205 272 269 225 141
99 138 207 302 399 369 318 234
178 198 277 378 432 463 432 283
225 209 286 340 468 503 396 316
248 254 254 268 333 344 297 251
213 176 198 211 215 221 230 194
200 177 220 178 185 133 122 131
1.0
0.5
0.0
-0.5
-1.0
$\cos(\theta_{\mathrm{z,reco}})$
6
8
10
30
50
E_{reco} (GeV)
1000
800
600
400
200
0
Number of Events
No Oscillations
Cascade-like
Track-like
33 96 249 381 402 339 224 137
109 231 422 559 562 442 288 174
227 416 636 740 686 536 358 223
419 619 836 886 797 618 417 271
575 773 905 933 816 607 415 260
627 782 873 847 708 517 339 209
535 639 721 683 579 414 254 162
367 467 543 541 445 325 198 125
33 86 145 188 209 180 119 67
69 105 166 227 275 278 231 147
128 161 227 300 365 372 313 213
203 218 295 387 459 460 411 299
299 292 357 424 508 519 475 344
327 316 367 404 479 452 415 290
296 276 322 354 400 381 329 239
264 291 326 367 389 339 268 181
1.0
0.5
0.0
-0.5
-1.0
$\cos(\theta_{\mathrm{z,reco}})$
6
8
10
30
50
E_{reco} (GeV)
1000
800
600
400
200
0
Number of Events
Cascade-like
Track-like
0.1 0.0 0.0 0.0 -0.0 0.1 0.1 0.2
0.1 0.1 0.0 0.0 0.0 0.0 0.1 -0.0
0.0 0.1 0.0 0.1 0.0 -0.0 0.0 0.0
0.1 0.2 0.2 0.2 0.1 0.1 0.0 0.1
0.3 0.3 0.2 0.2 0.2 0.2 0.0 0.0
0.4 0.2 0.2 0.2 0.2 0.2 0.1 0.1
0.3 0.3 0.3 0.2 0.2 0.3 0.2 0.1
0.4 0.3 0.3 0.3 0.3 0.3 0.4 0.3
-0.2 0.3 0.2 0.1 -0.1 -0.0 0.0 0.1
0.0 0.0 -0.0 0.1 0.0 0.0 0.0 0.0
0.3 0.2 0.1 -0.0 -0.1 0.0 -0.0 -0.1
0.1 0.1 0.1 0.0 0.1 -0.0 -0.0 0.1
0.3 0.4 0.2 0.2 0.1 0.0 0.2 0.1
0.3 0.2 0.4 0.5 0.4 0.3 0.4 0.2
0.4 0.6 0.6 0.7 0.9 0.7 0.4 0.2
0.3 0.6 0.5 1.1 1.1 1.5 1.2 0.4
1.0
0.5
0.0
-0.5
-1.0
$\cos(\theta_{\mathrm{z,reco}})$
6
8
10
30
50
E_{reco} (GeV)
1.5
1.0
0.5
0.0
$(n_{i,\mathrm{no.osc}}^{\nu+\mu_{\mathrm{atm}}}/n_i^{\mathrm{data}})-1$

Muon Neutrino Disappearance: *L/E*

arXiv:1707.07081, *Phys. Rev. Lett.* 120, 071801 (2018)



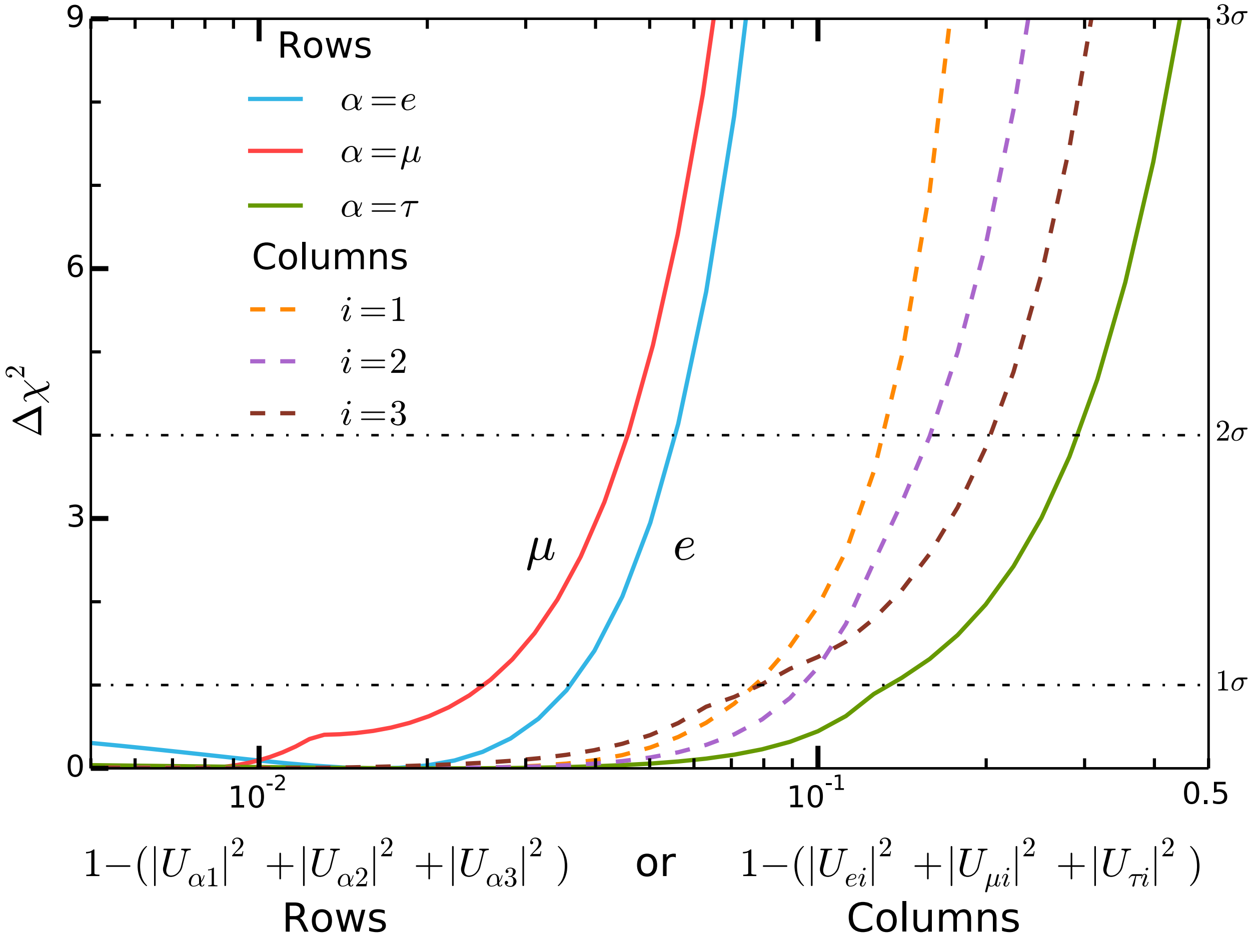
Tau Neutrino Appearance and Unitarity

- Direct tests of unitarity of the PMNS mixing matrix are limited by imprecision of tau neutrino appearance data
  - 30% deviations in tau row allowed at 2σ CL by world data
- Tau lepton mass suppresses CC cross section – appearance measurements difficult in long-baseline experiments

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

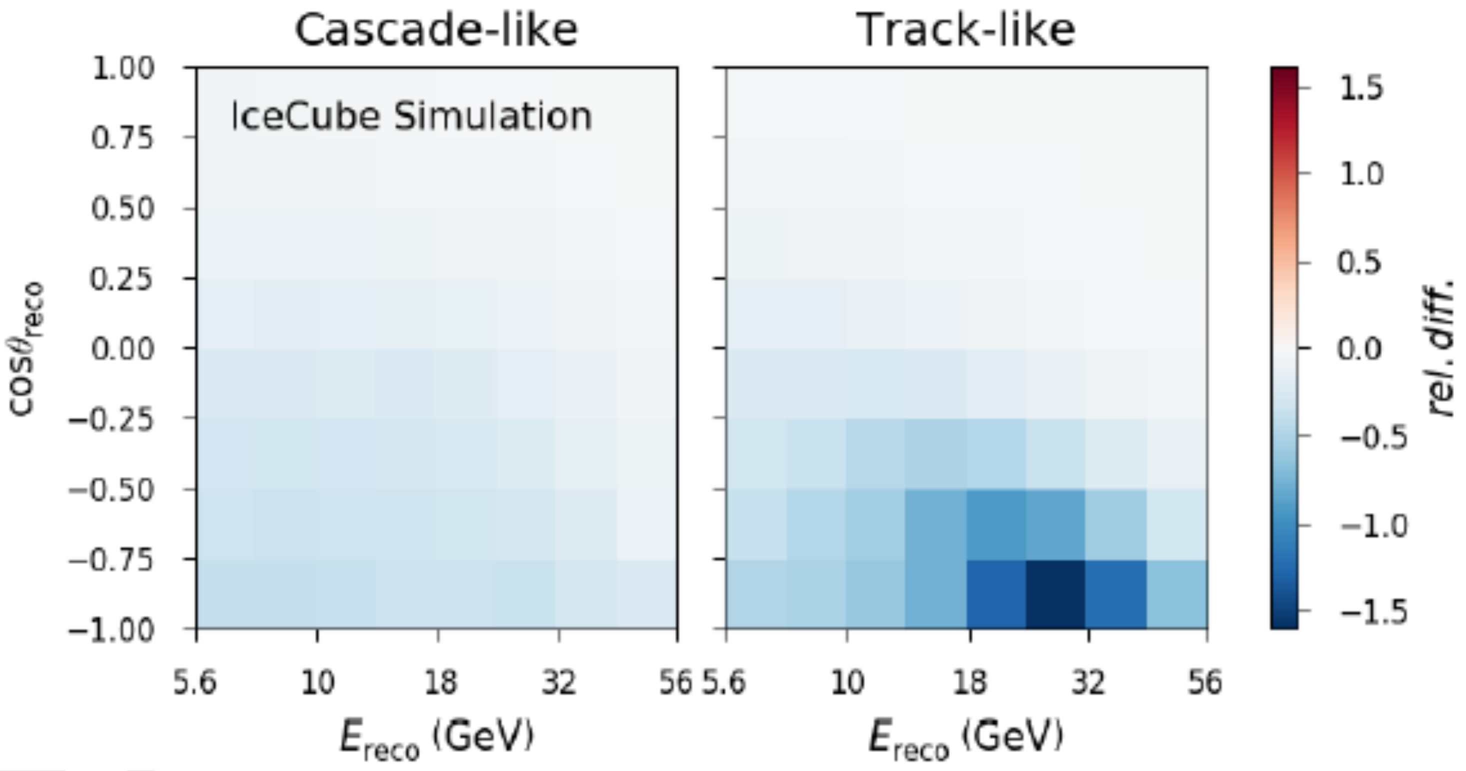
Parke and Ross-Lonergan 2016

Normalisations



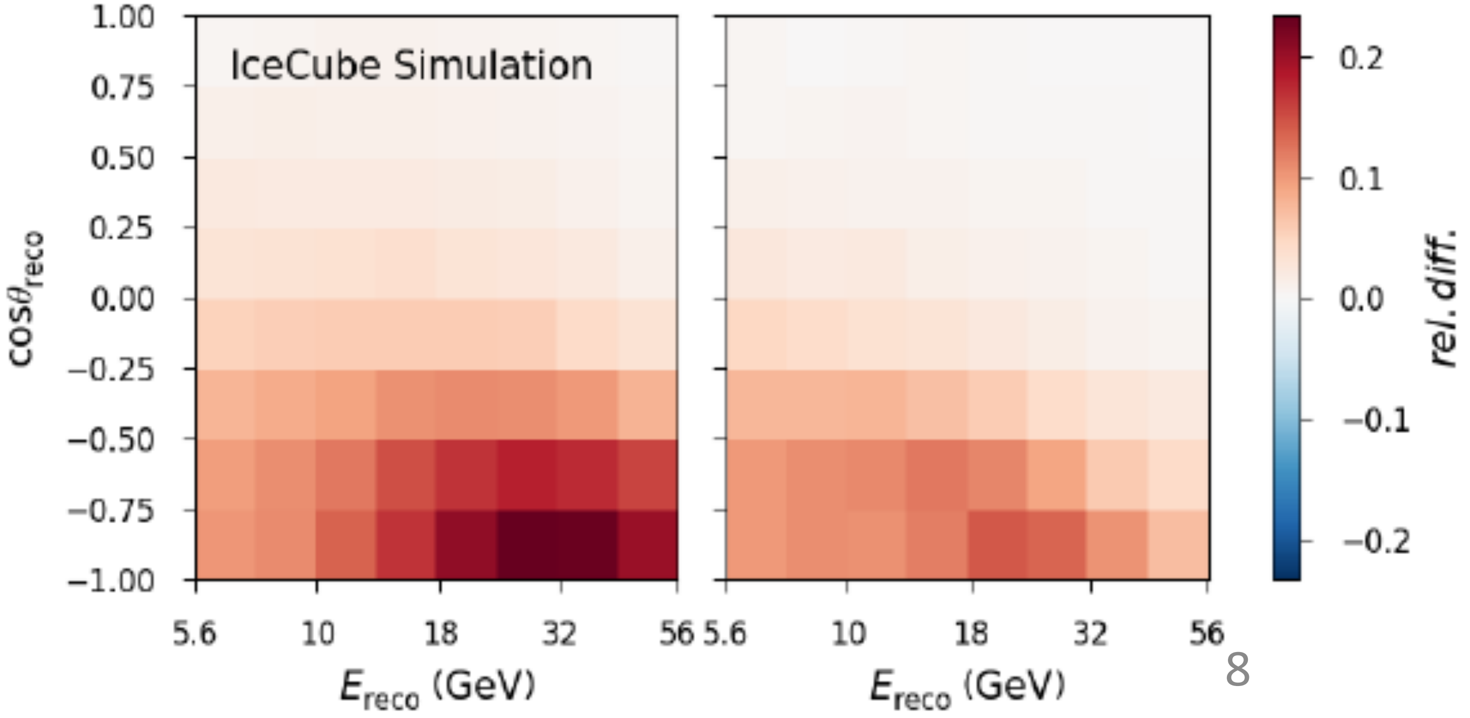
Oscillation Signatures

- Different oscillation effects have different characteristic distortions of data set
  - NSI, steriles, etc. also have characteristic signatures



ν_μ disappearance

ν_τ appearance



- Systematic uncertainties are constrained by sidebands – untangled from oscillations by broader impact on data