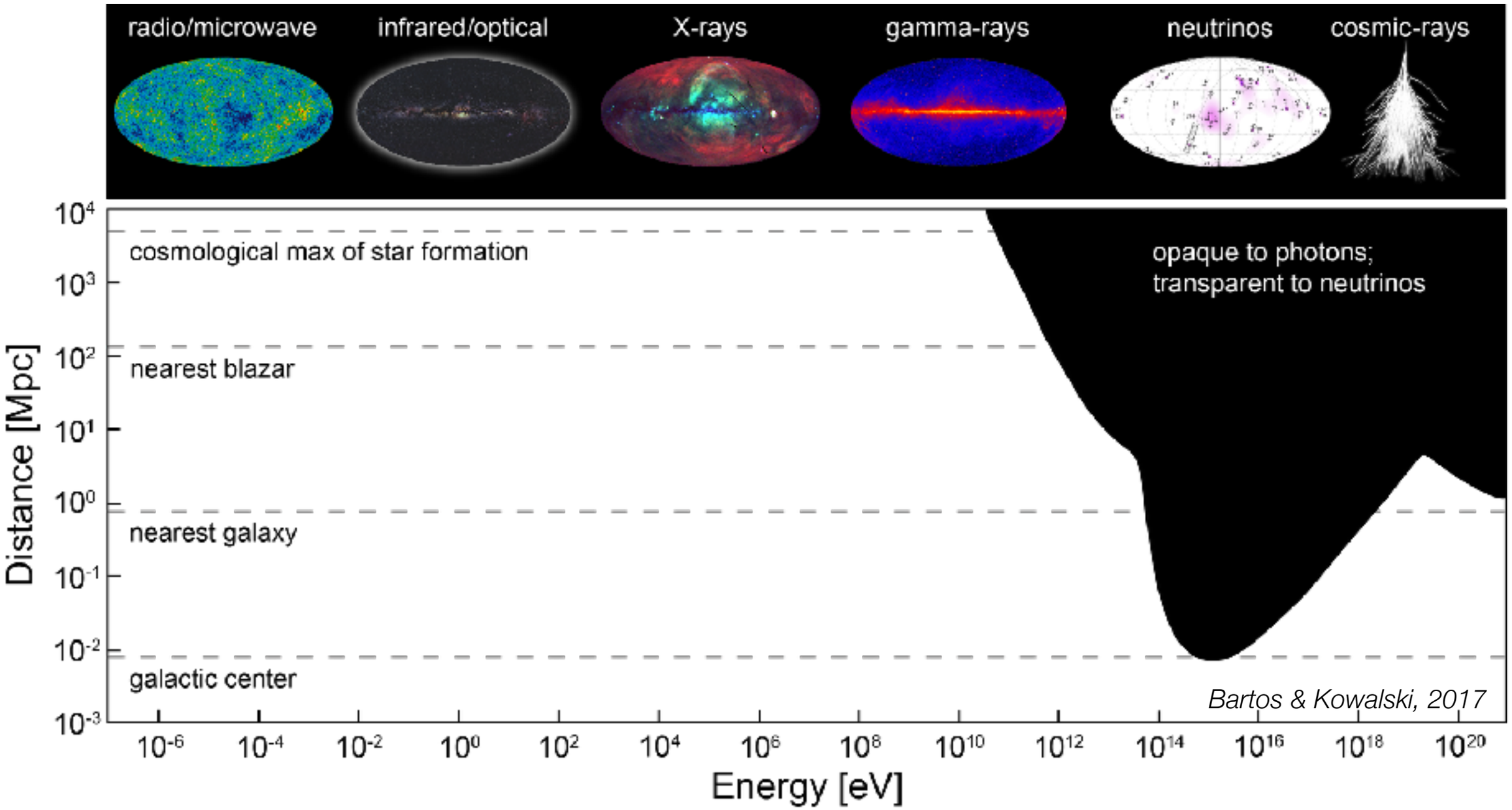
IceCube-Gen2 & IceCube-Upgrade

Marek Kowalski
DESY & Humboldt-University
VLVNT 2018
Dubna

South Pole 2009

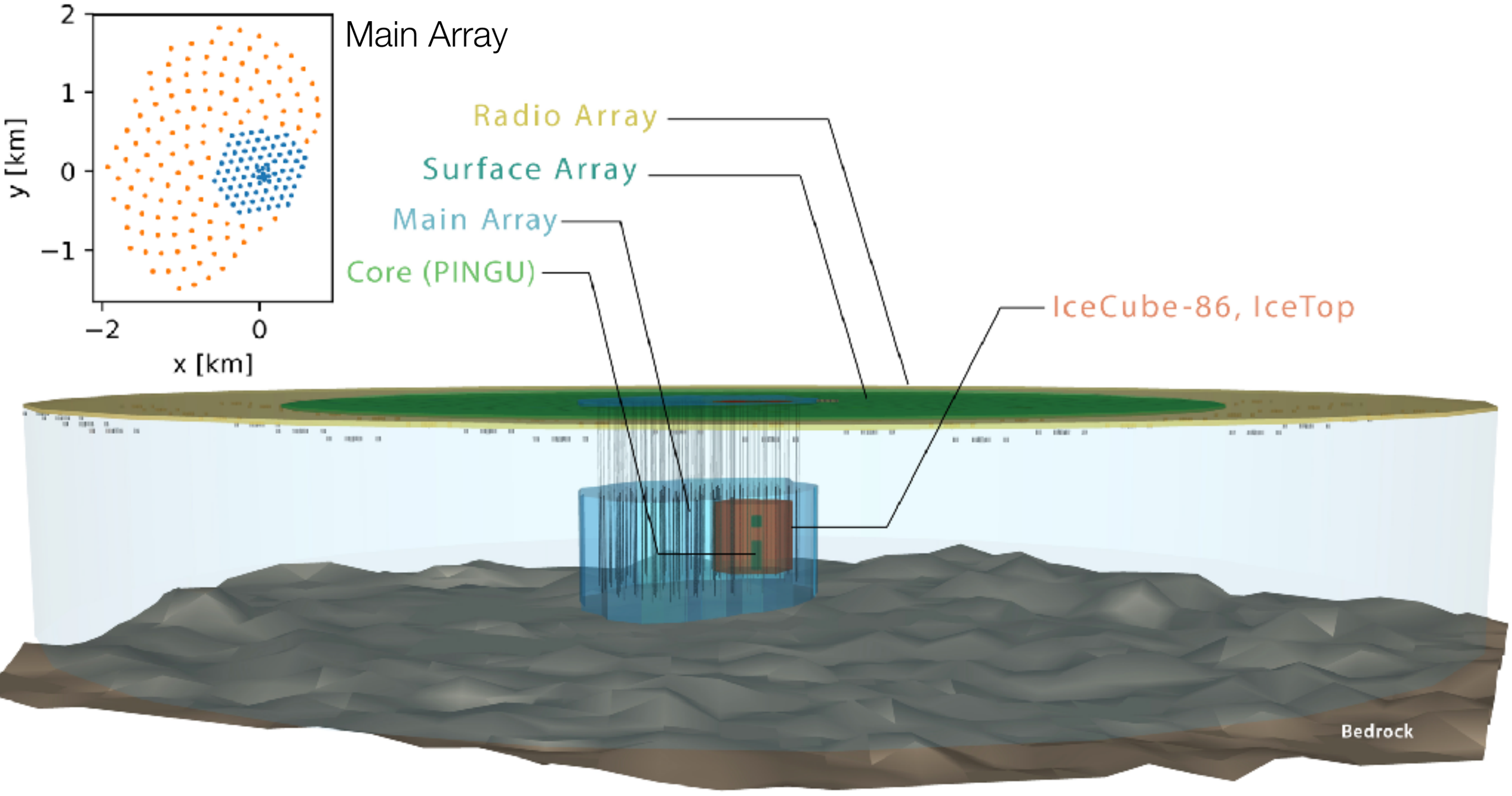
Science driver in a nutshell



The Universe is opaque to EM radiation for ¼ of the spectrum,
i.e. above 10-100 TeV where IceCube sees cosmic neutrinos.
⟹ **explore this mostly uncharted territory with IceCube-Gen2**

IceCube-Gen2 Facility

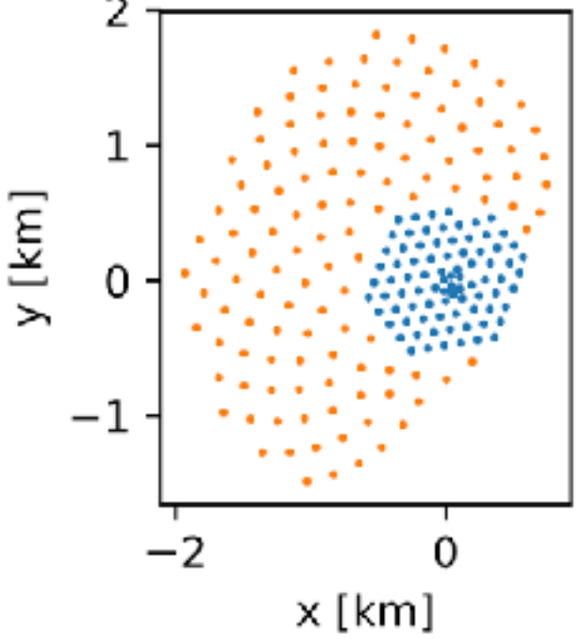
A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

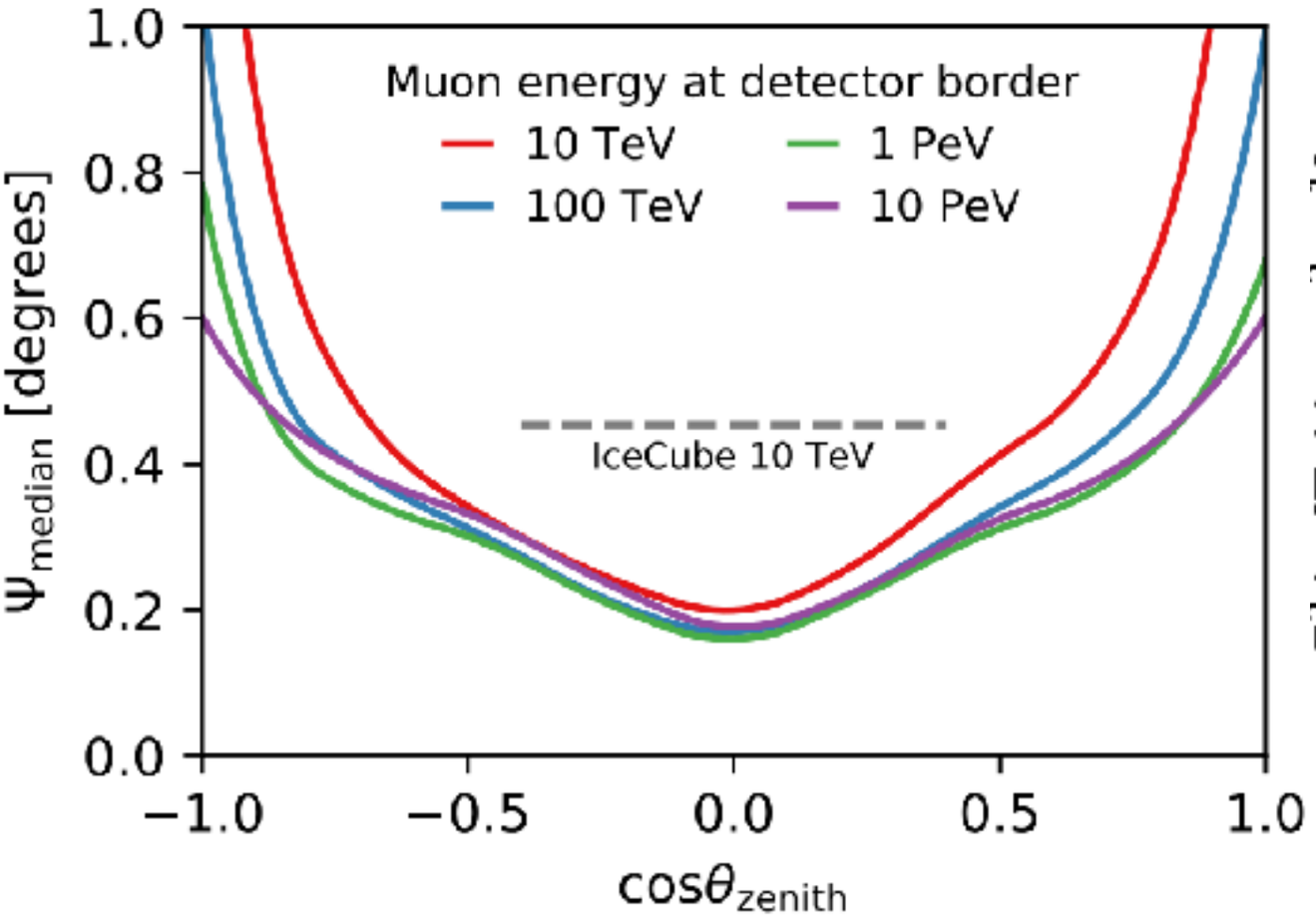


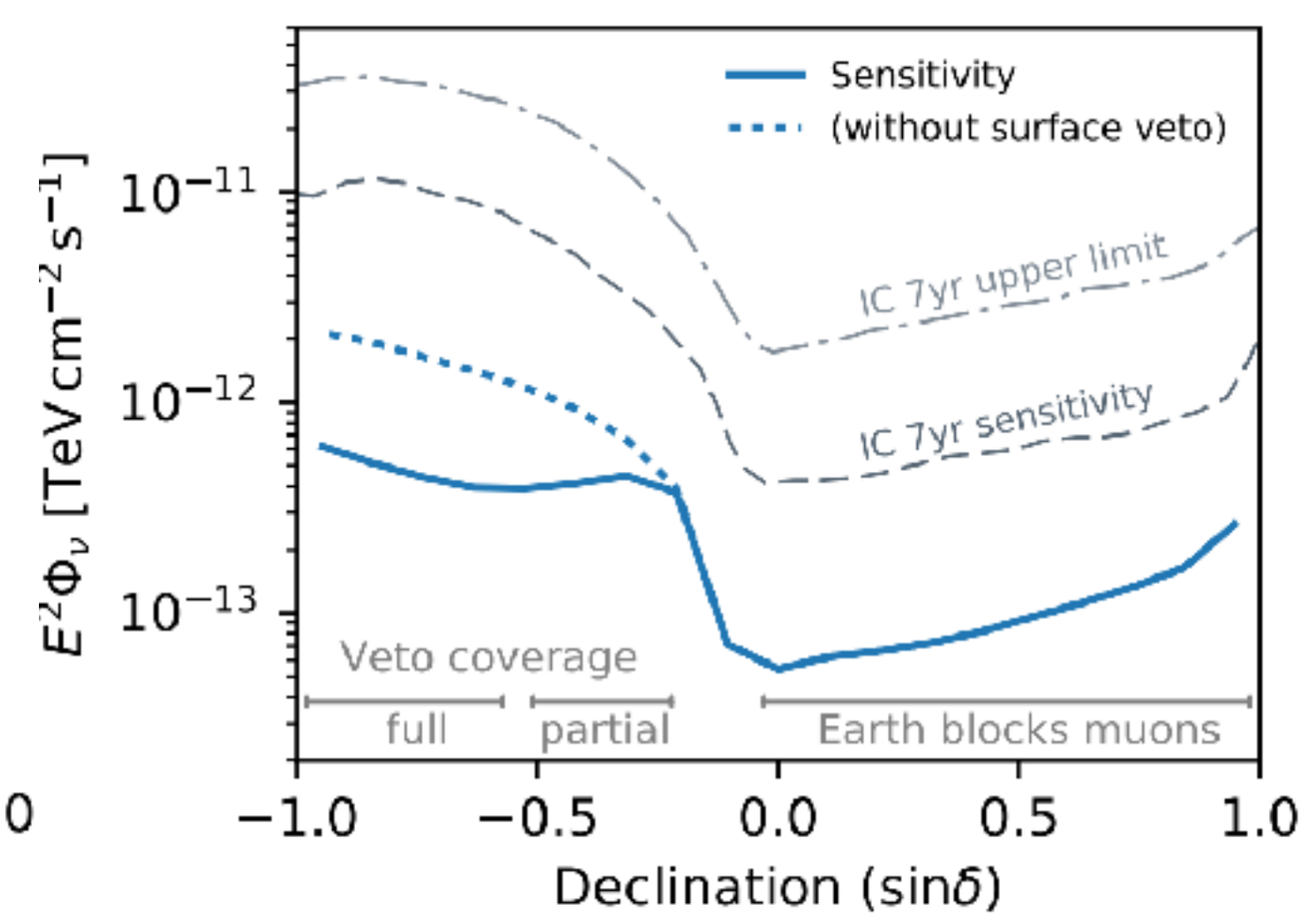
Sensitivity to point sources

Projected sensitivity

- Continuously Improving the angular resolution, better than IC
- Sensitivity shown for 15 y IC86 + 15 y IC-Gen2







PoS (ICRC2017) 991

Identifying the sources of IC's neutrinos

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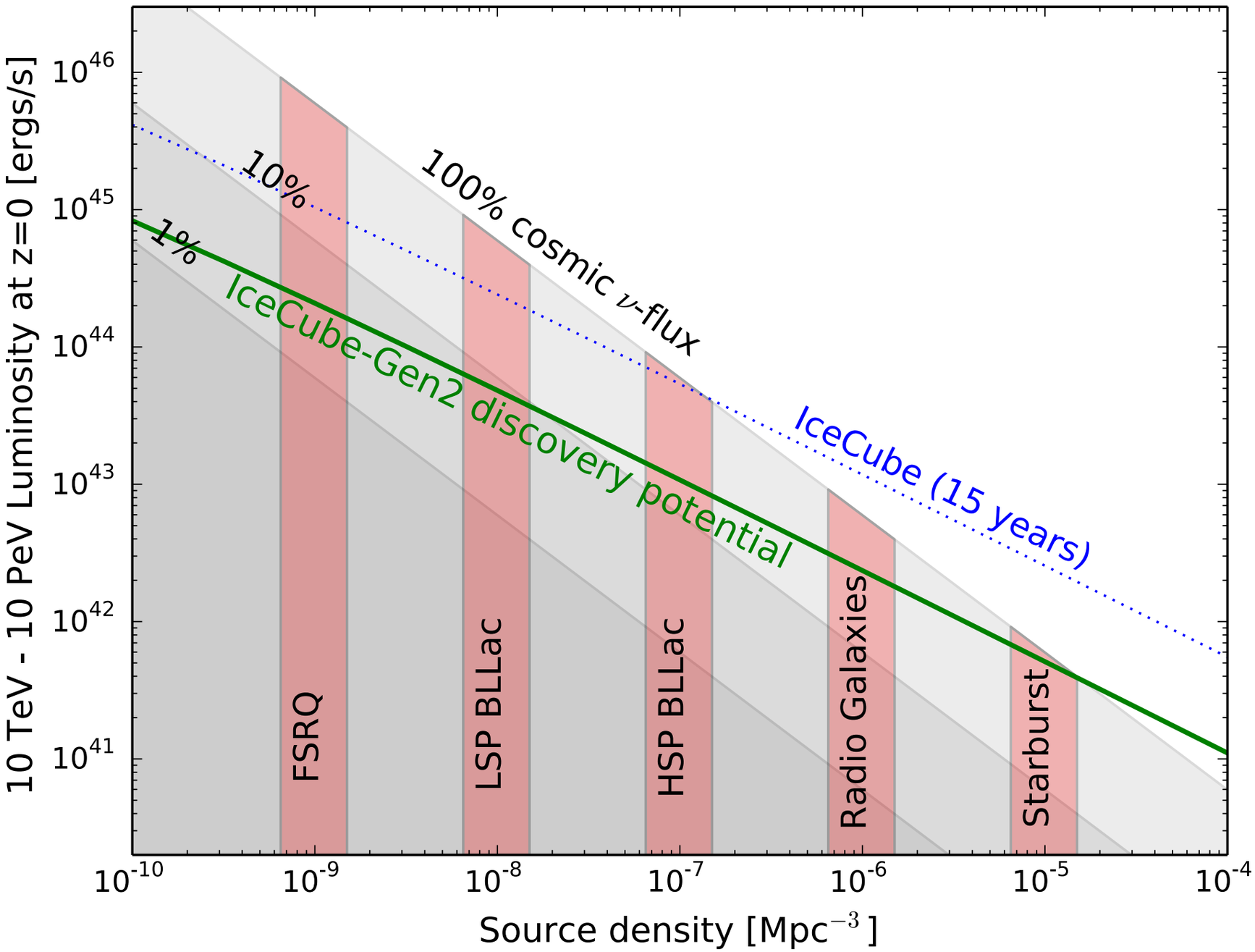
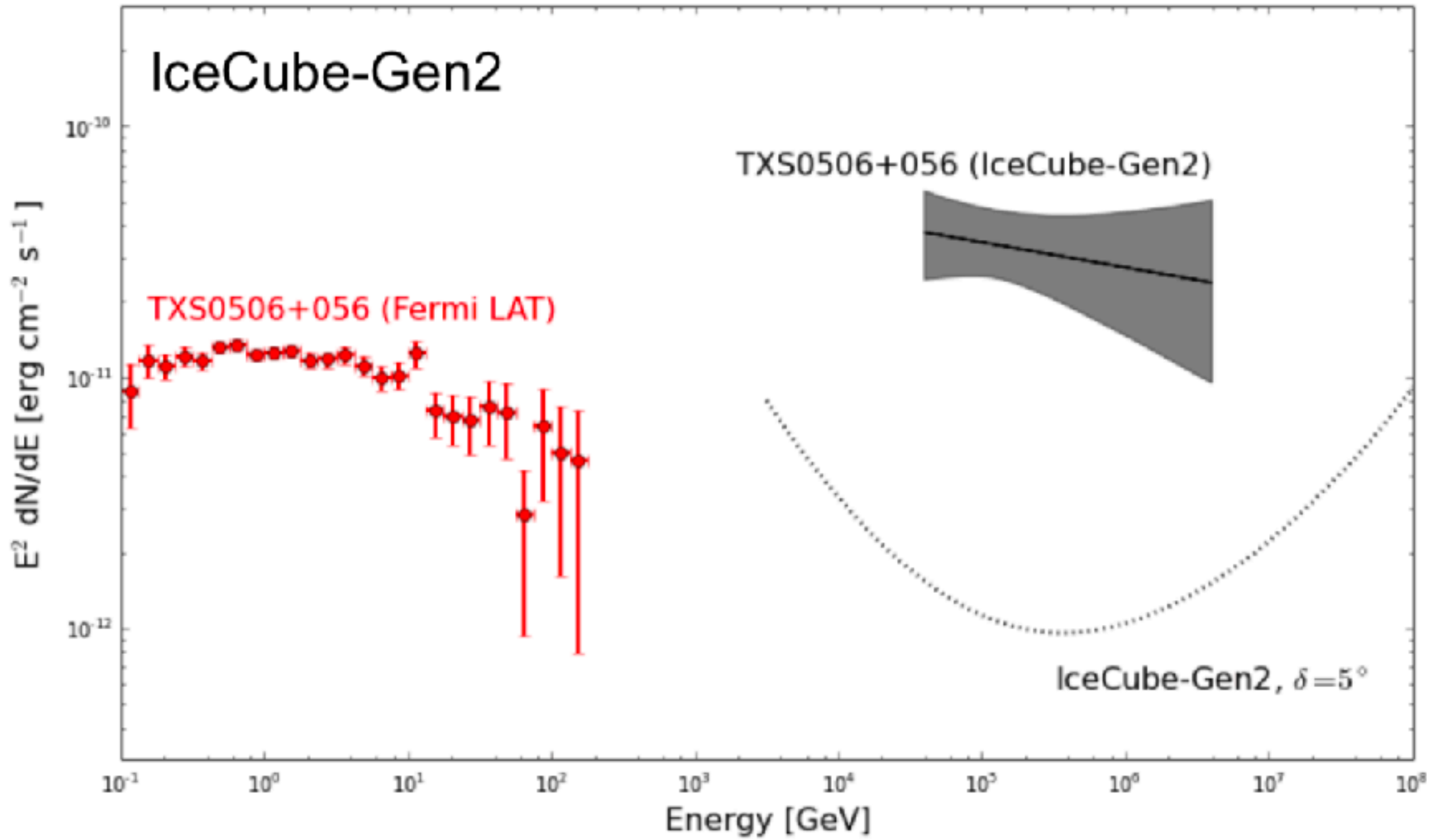


Five times IceCube's point source sensitivity to detect any reasonable source scenario

*Sensitivity for source catalog search

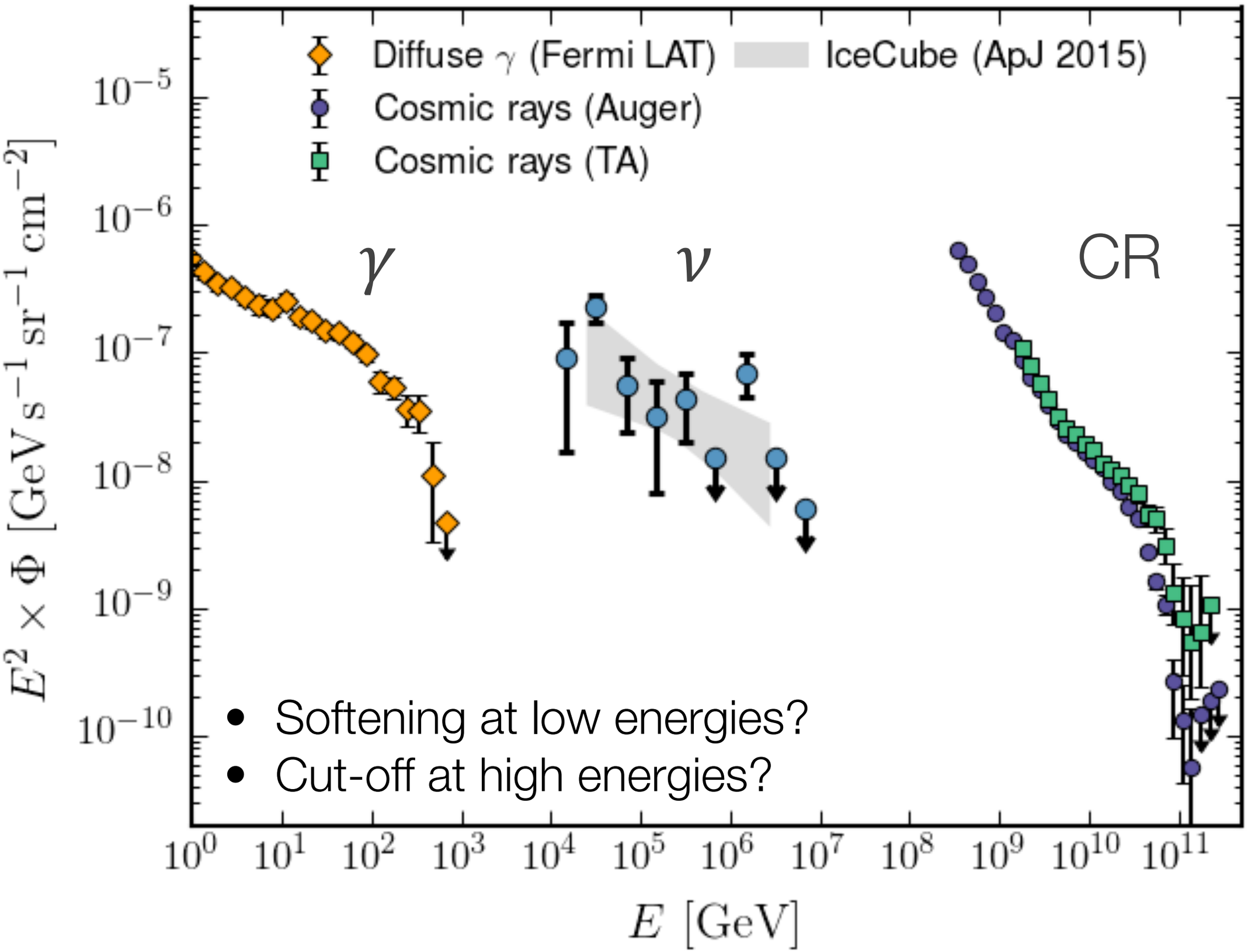
Sensitivity to point sources

Example: TXS0506+056-like source observed with Gen2



- **Order of magnitude increase of # TXS0506+056-like flares observable with Gen2**

Resolving the mysteries of the UHE Universe



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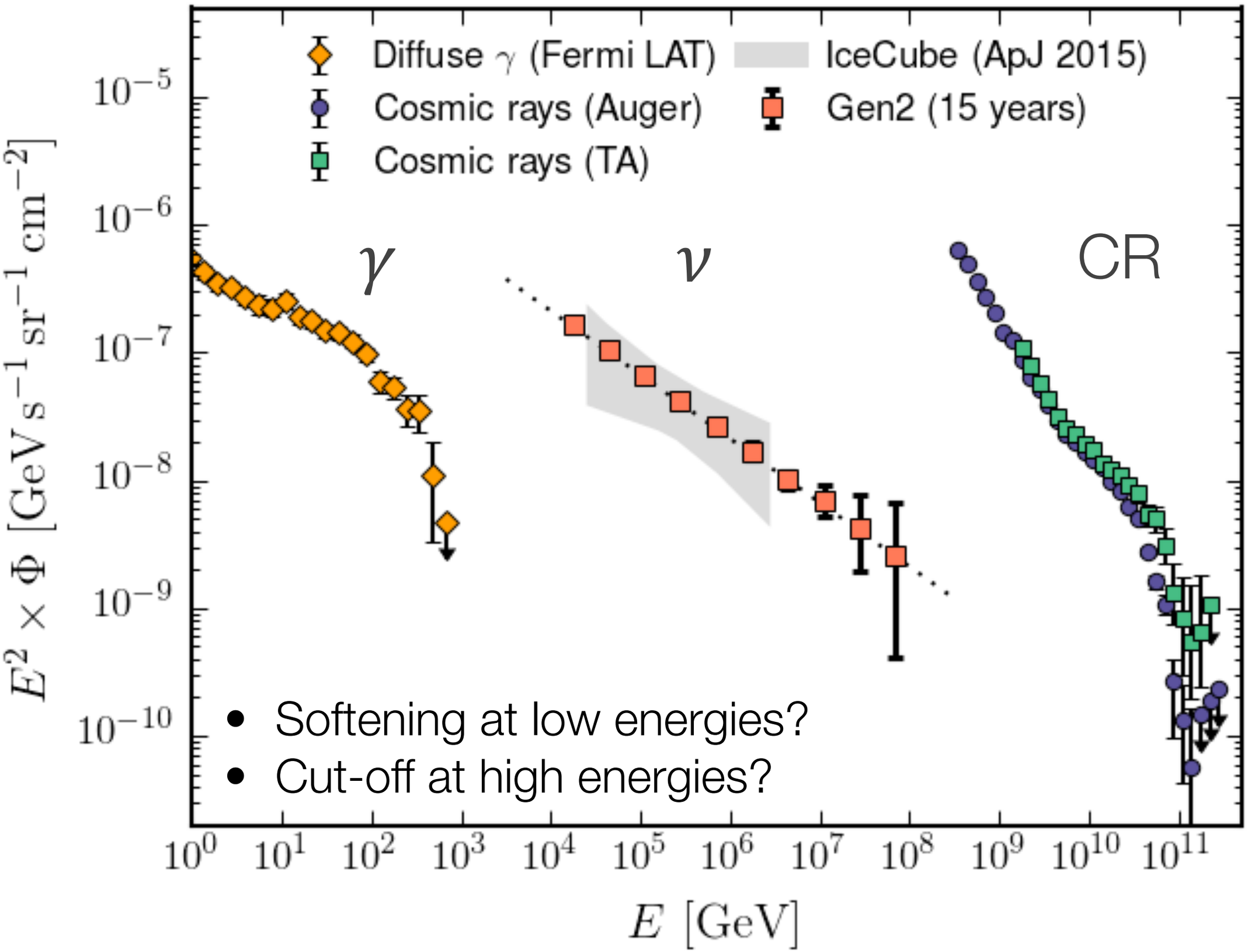

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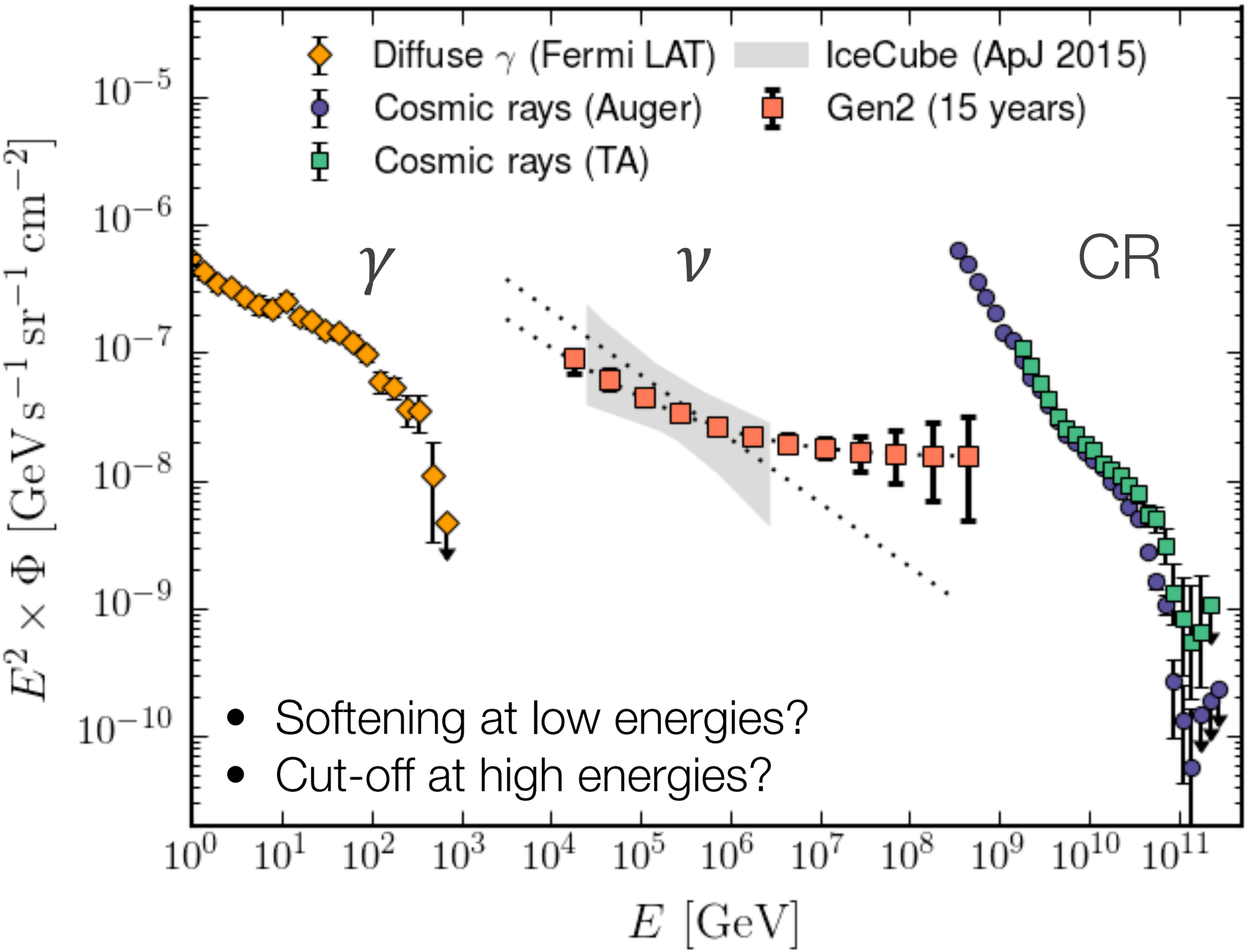


- Softening at low energies?
- Cut-off at high energies?

Flavor Physics with Astrophysical Neutrinos

Flavor ratio constrain:

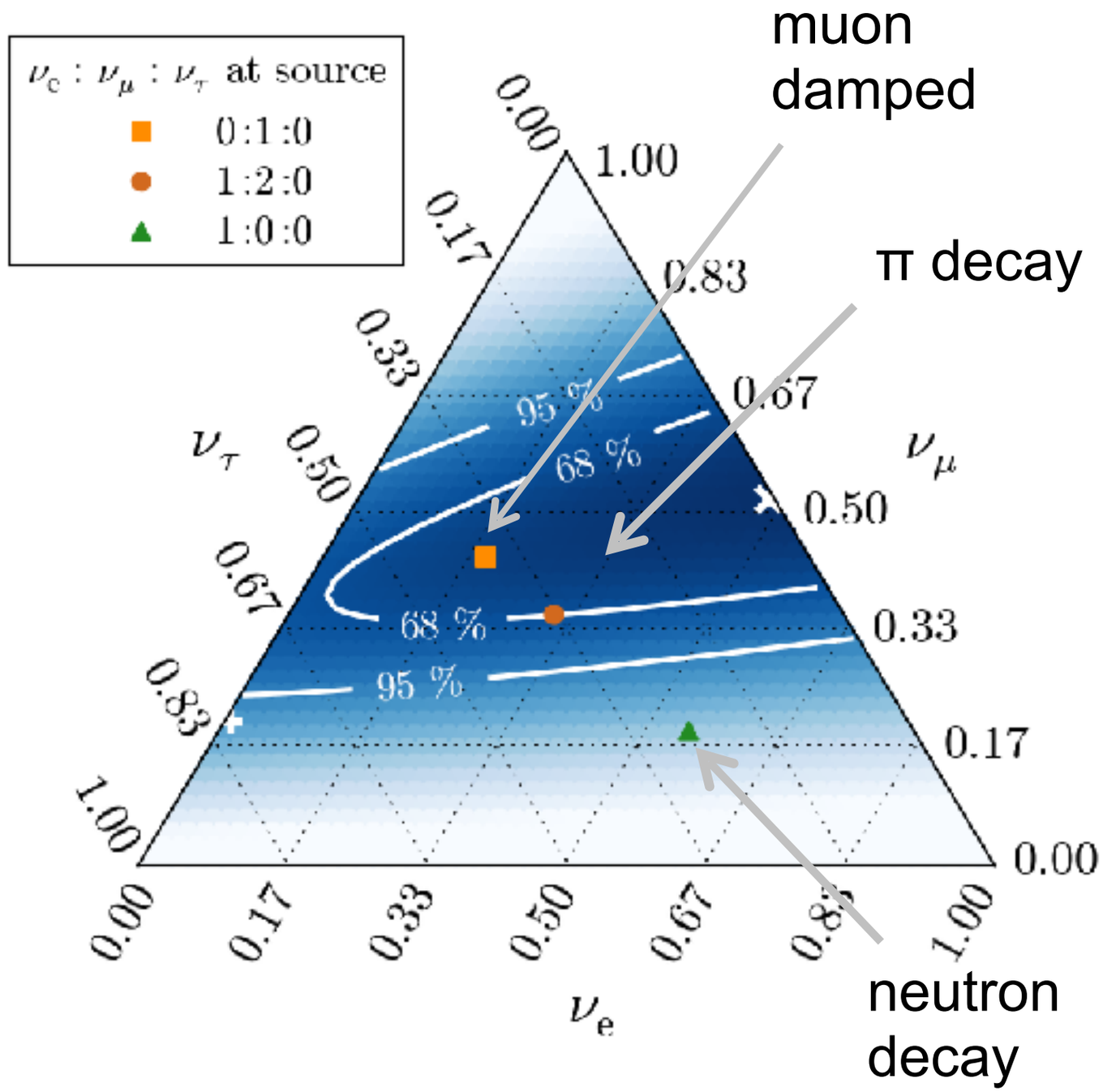
- conditions at source
  e.g. magnetic fields

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \bar{\nu} + \nu$$

1:2:0

- neutrino physics, e.g. decay or new operators
  (e.g. Bustamante et al. PRL 2015, Argüelles et al., PRL 2015 Rasmussen et al, PRD 2017)



IceCube, **ApJ 2015**, see also PRL2015

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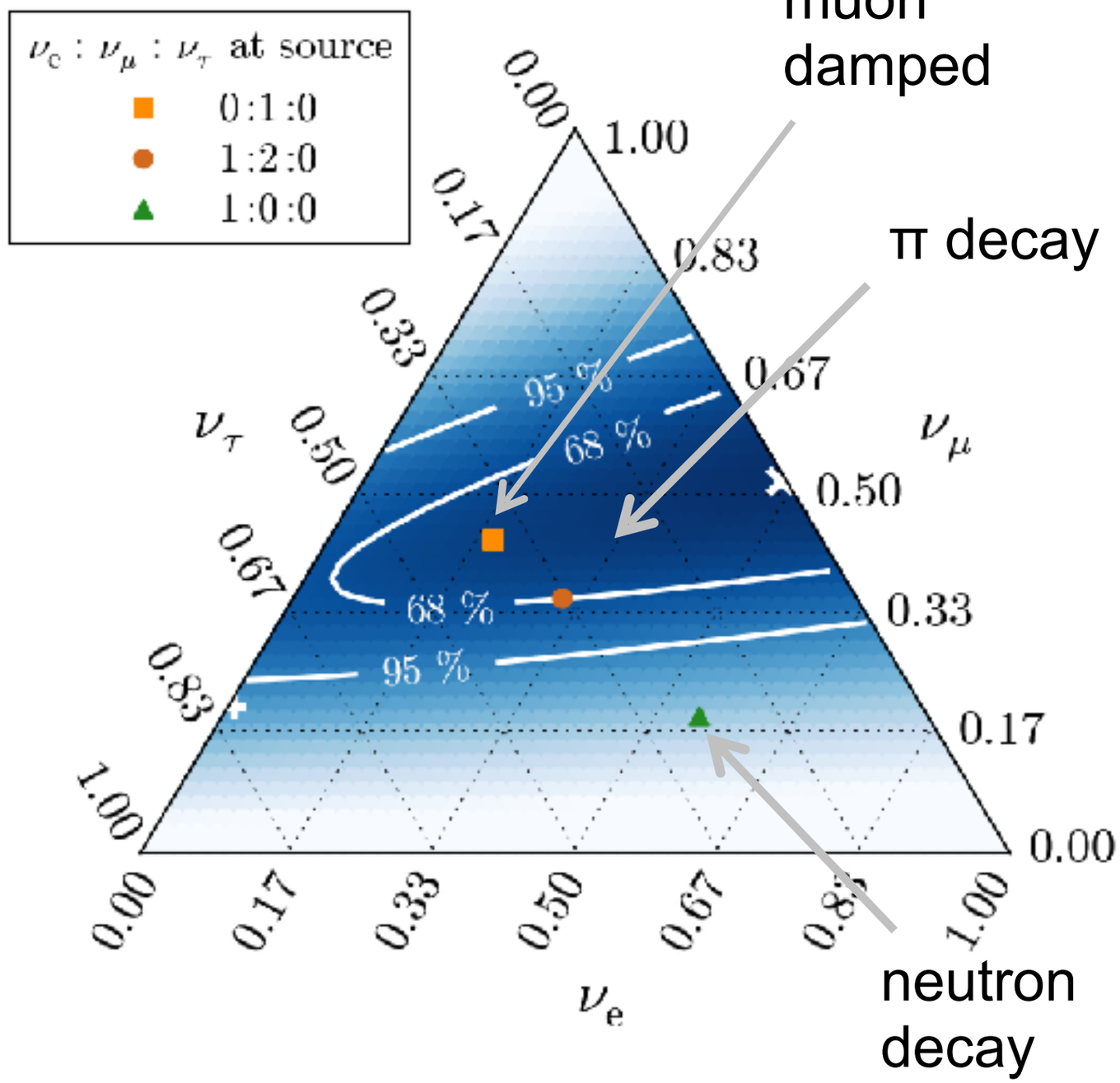

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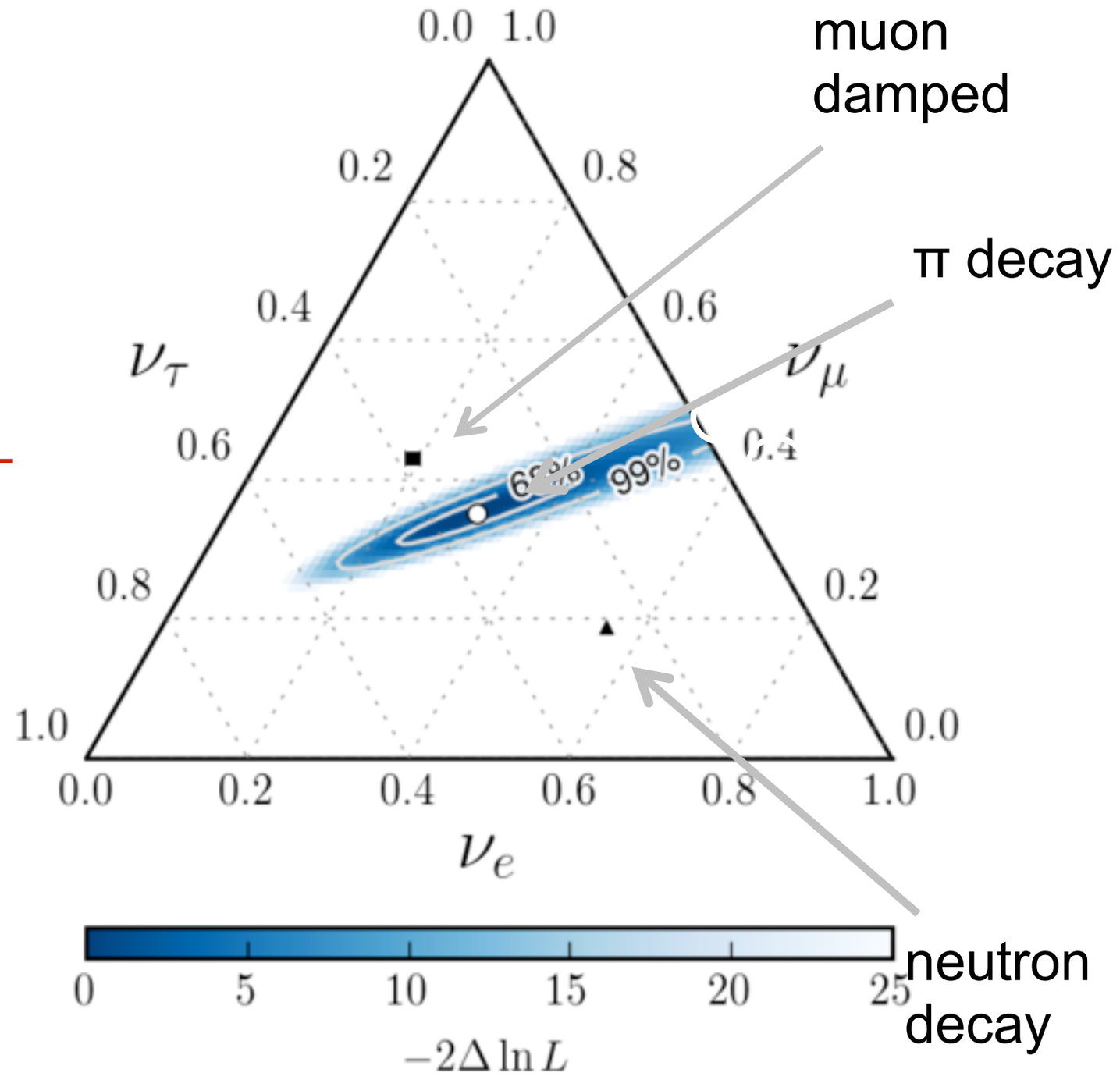
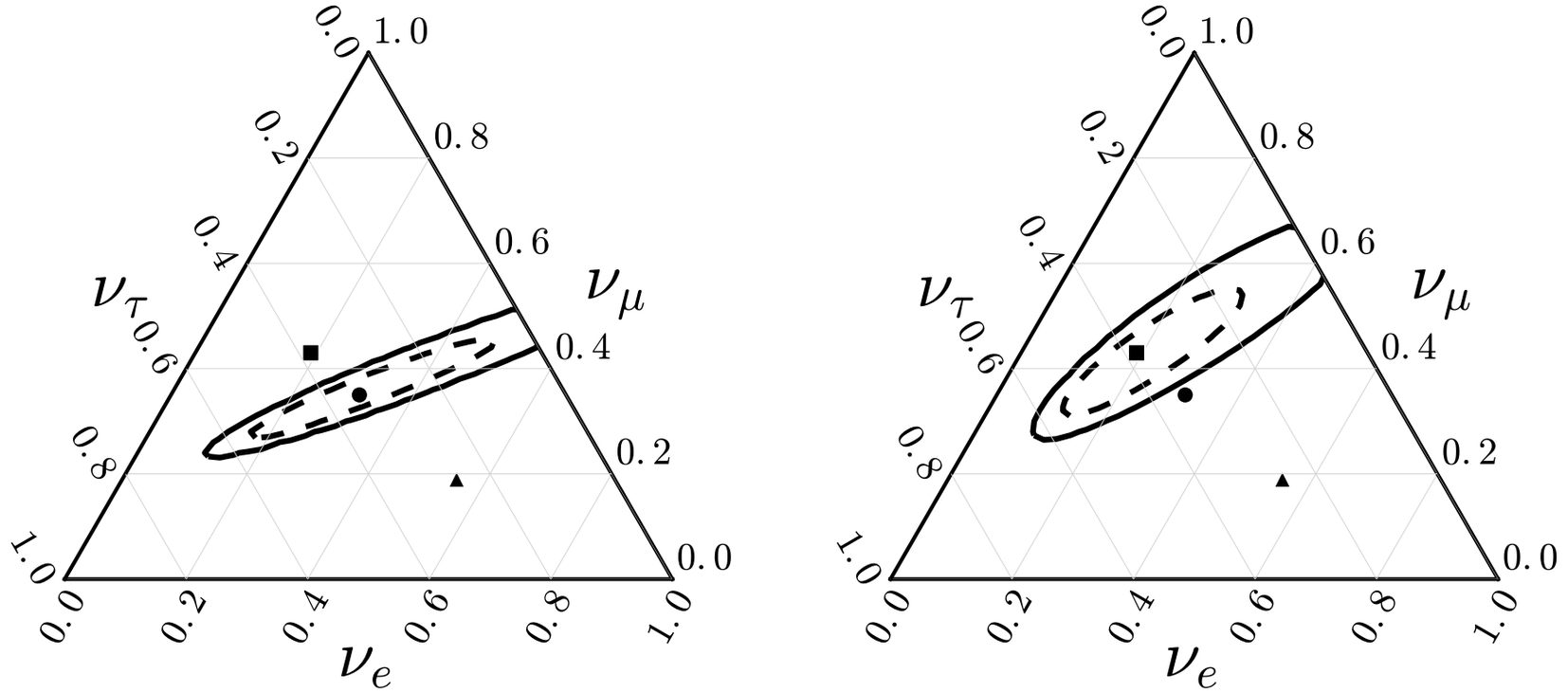
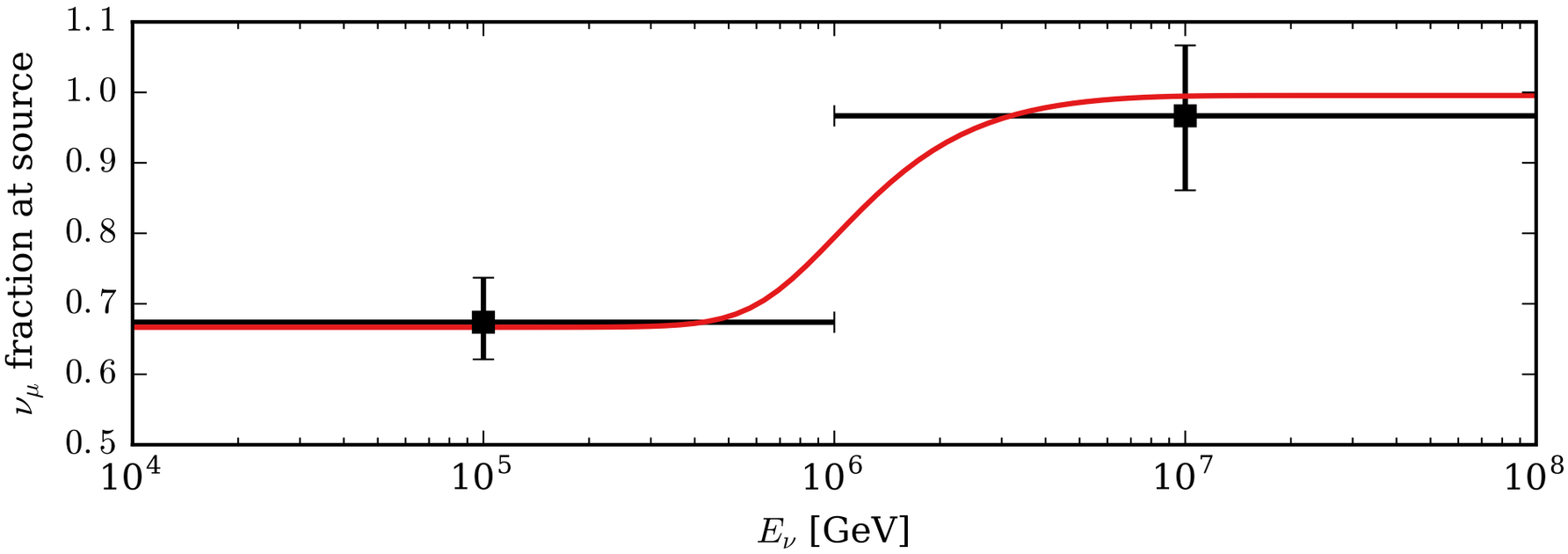


Gen2 (15 yrs)

Flavor Physics - Energy Dependence

Muon damping as a test of source magnetic fields

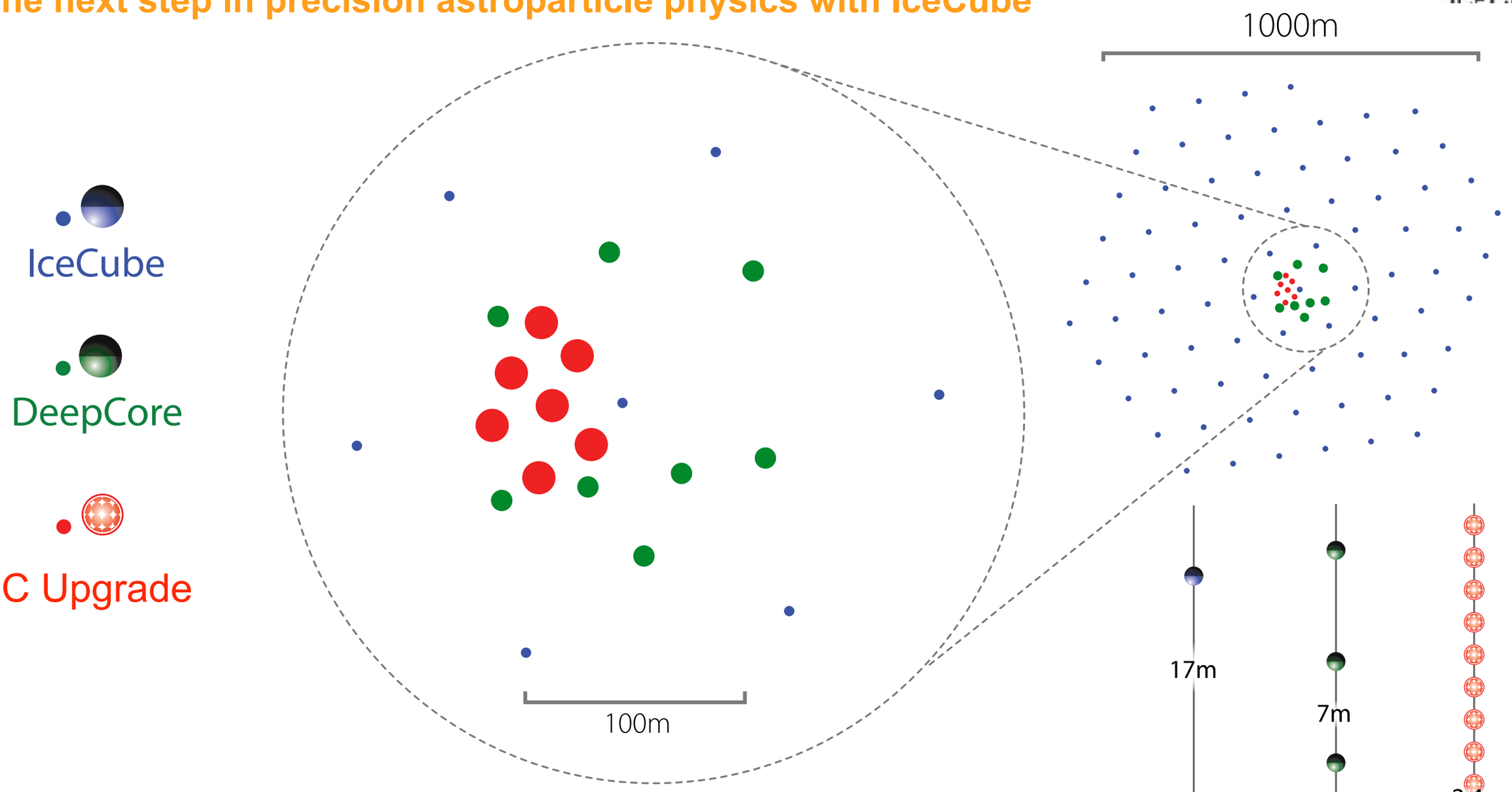




Sensitivity to source populations (Kasthi, Waxman 2005)

The IceCube Upgrade

The next step in precision astroparticle physics with IceCube

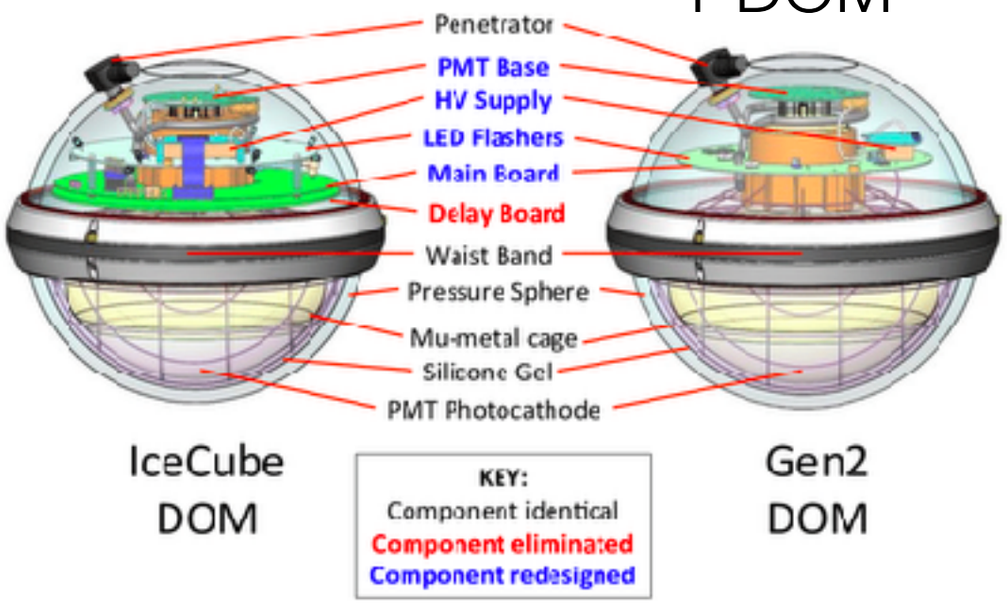


- 7 strings with ~20 m spacing
- 2 m vertical spacing of 125 modules / string
- Located inside of IceCube-DeepCore

The IceCube Upgrade - R&D

In-situ testing of new optical modules

PDOM



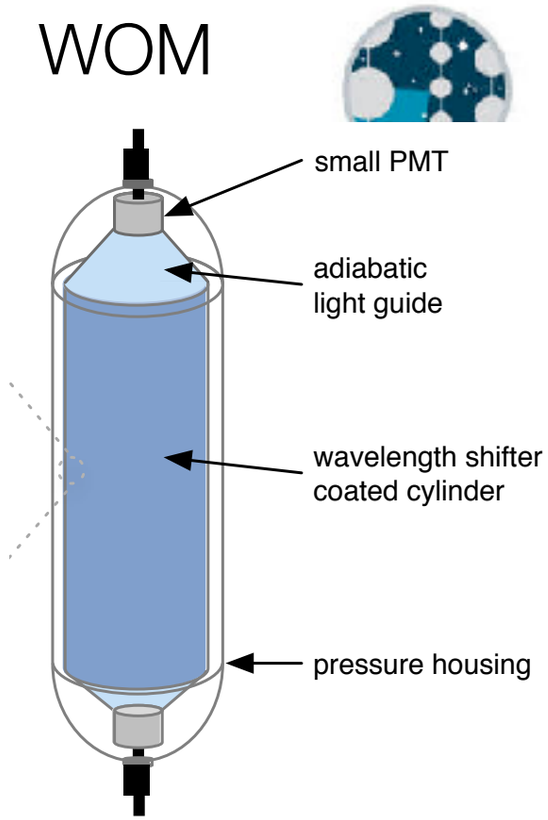
D-Egg

30 cm

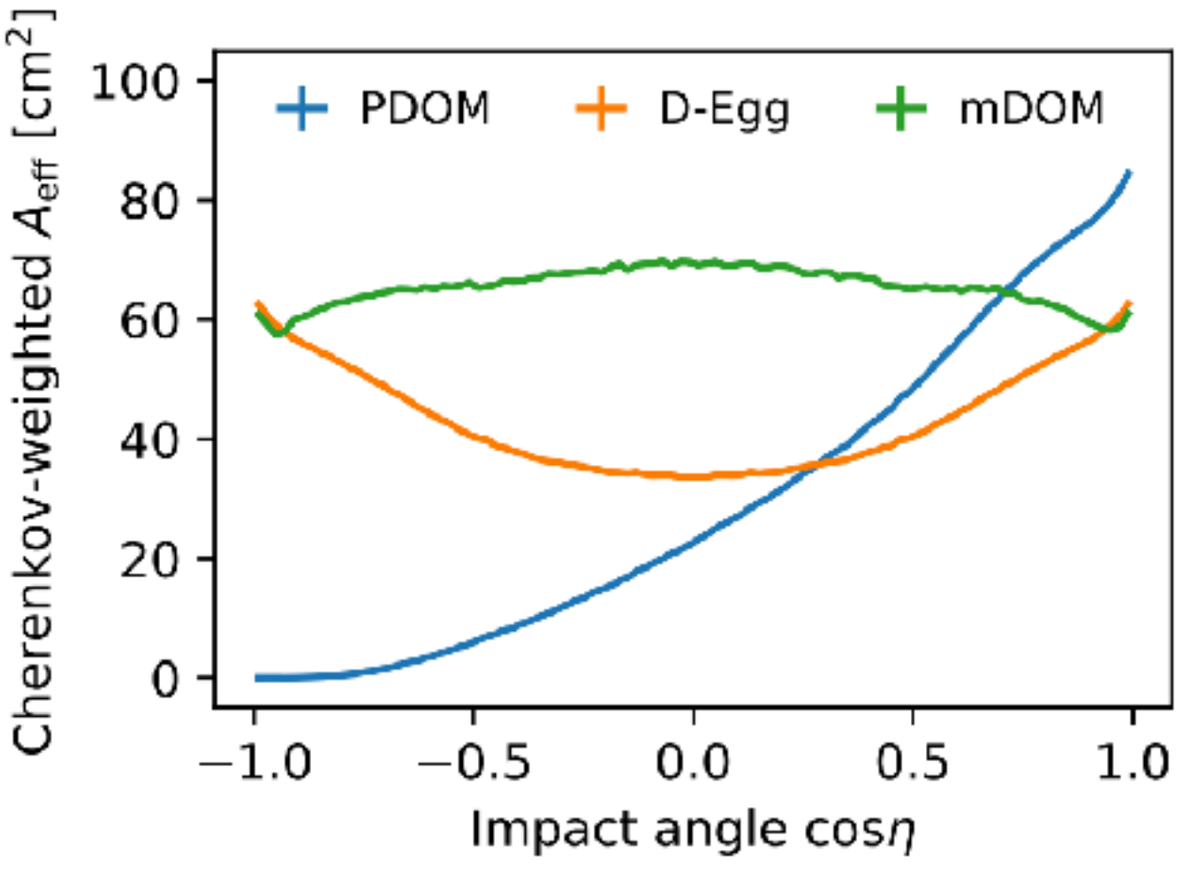
mDOM

36 cm

WOM



11 cm



New sensor designs will incorporate one or more of the following:

- Upgraded electronics
- Smaller diameter
- Increased UV acceptance
- Larger and/or pixelated effective area

The IceCube Upgrade - Calibration

Deployment of new devices at better distances

Integrated devices

- LED flashers
- Acoustic sensors
- Optical cameras

Stand-alone light sources

- Precision Optical Calibration Module (POCAM)
- “Movable” sub-ns pulsed LEDs with small opening angle

Reduce primary systematic uncertainties

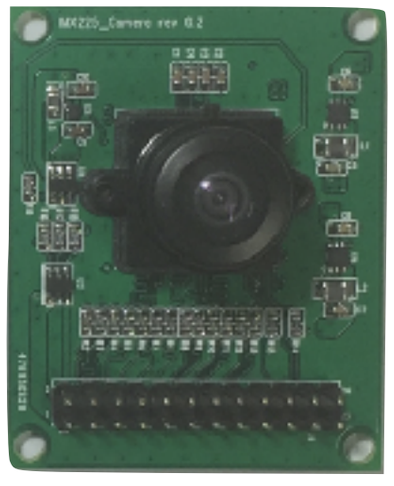
- Better calibration of new and existing sensors
- Improved knowledge of glacial ice

Piezo-module[1]

POCAM[3]

CCD[2]

CMOS[2]



[1] https://doi.org/10.1051/epjconf/201713506003

[2] https://doi.org/10.22323/1.301.1040

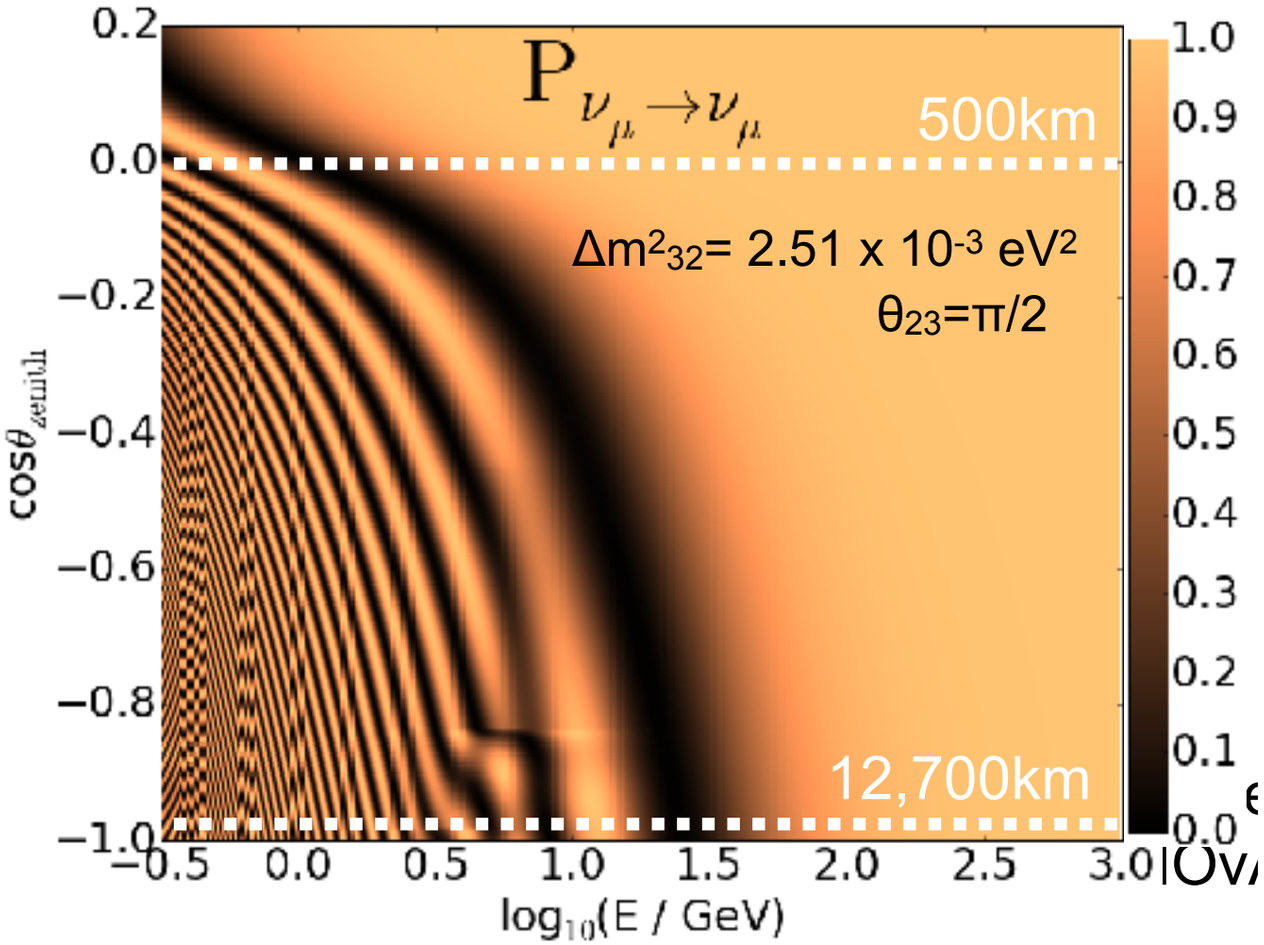
[3] https://doi.org/10.22323/1.301.0934

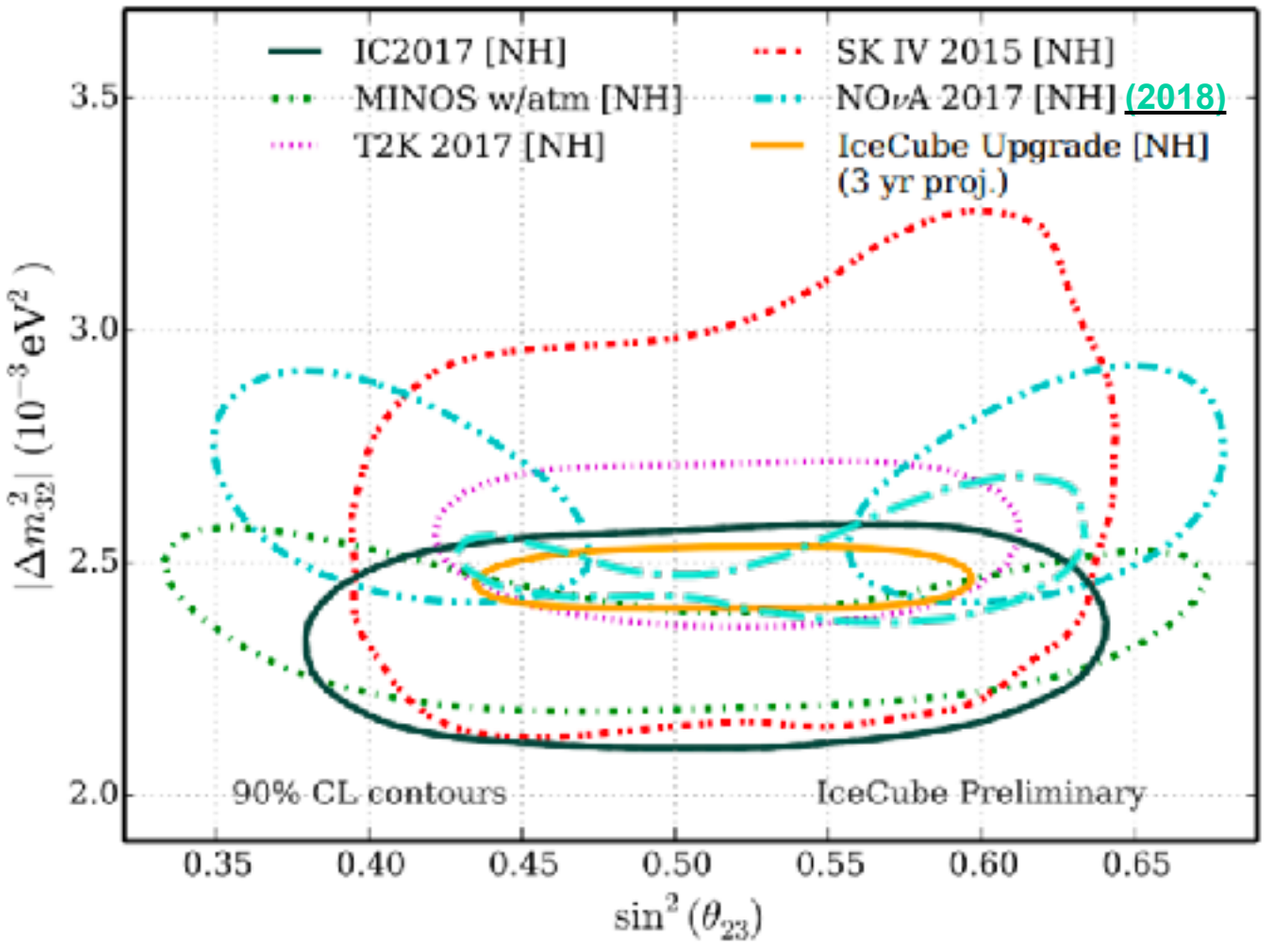
The IceCube Upgrade - Science

Precision atmospheric oscillation measurements

Similar physics program to DeepCore, just better!

- Oscillations, non-standard interactions, sterile neutrinos, dark matter…





- Enable atmos. mixing param. measurements with precision competitive with projected final T2K/NOvA results, but different systematics and energy range

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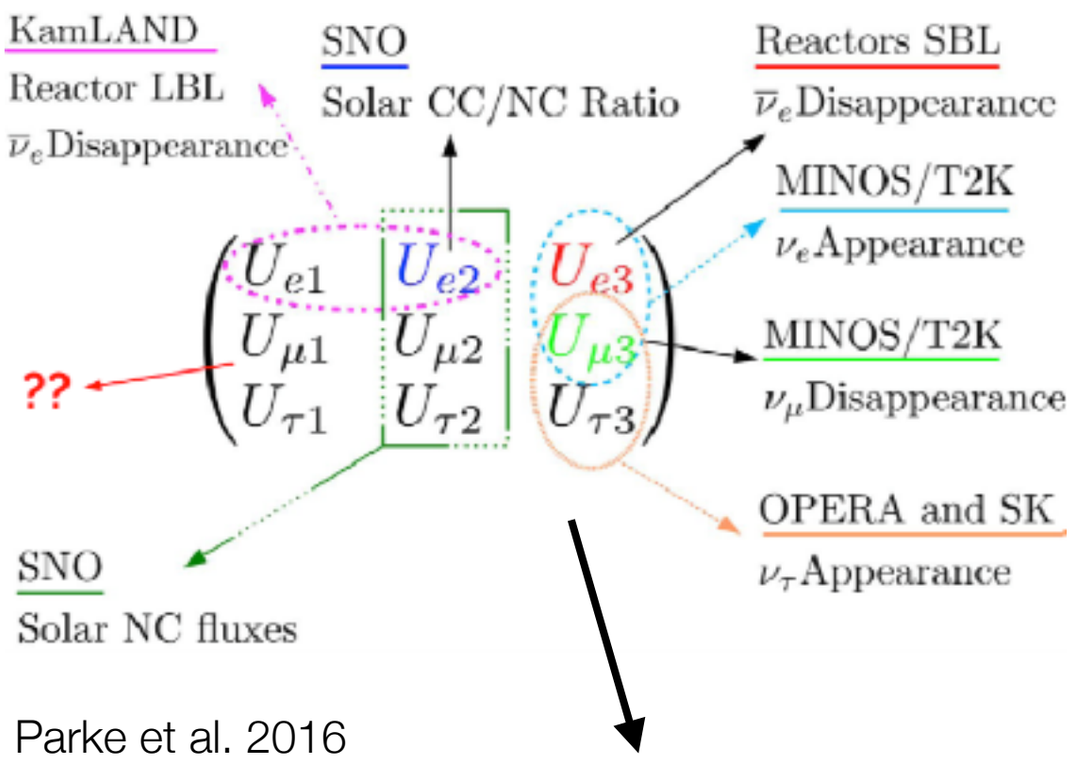
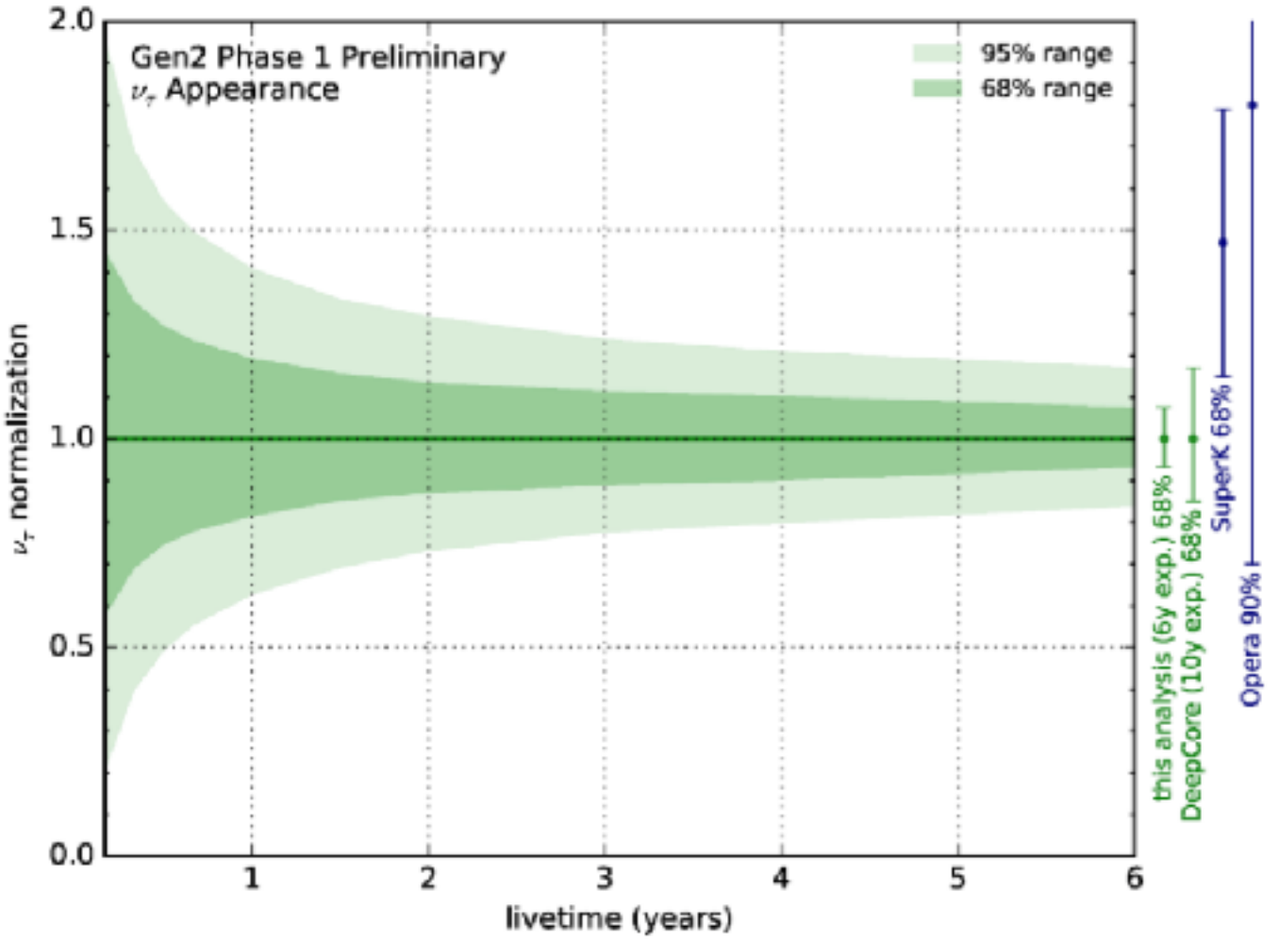


Parke et al. 2016

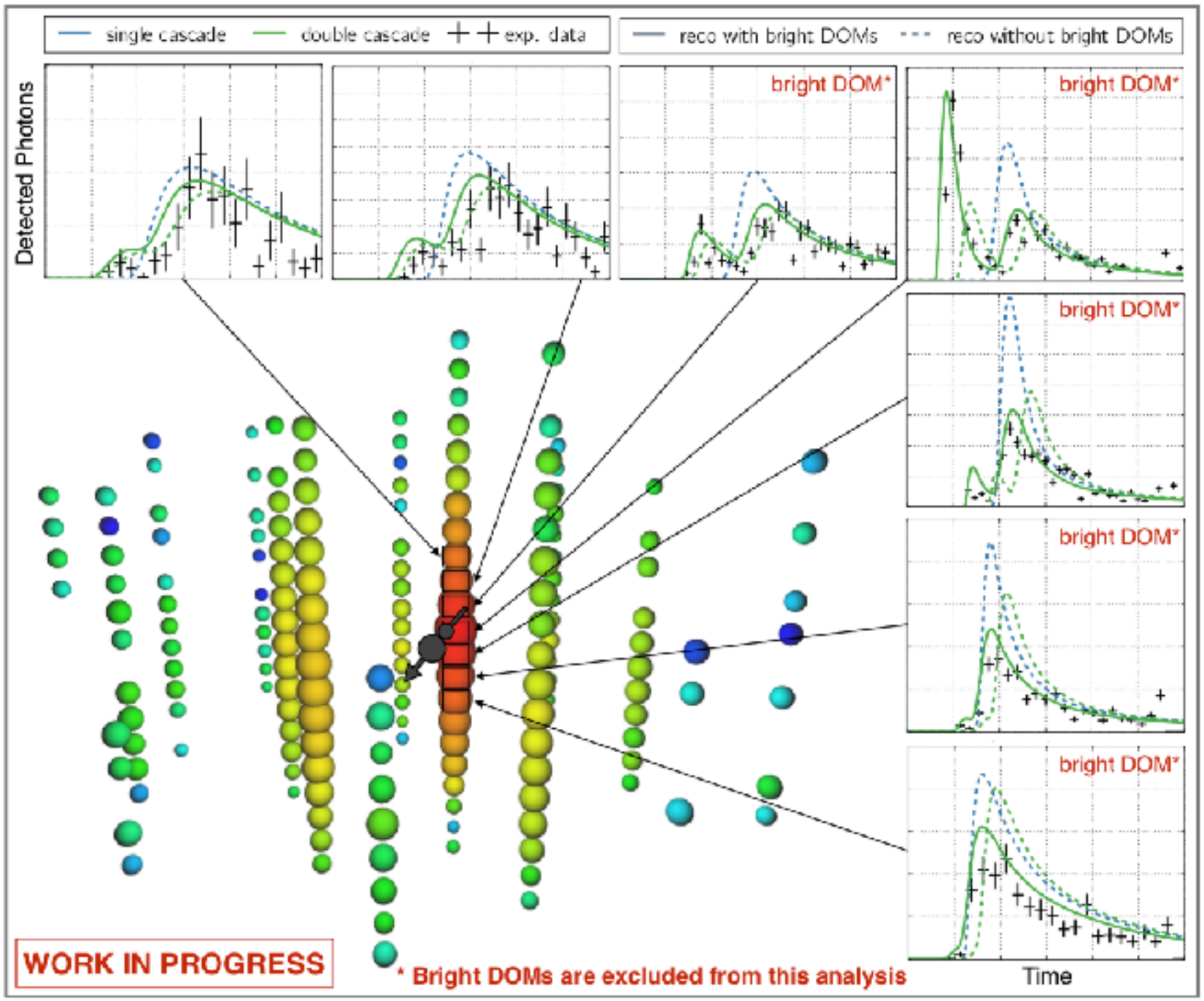


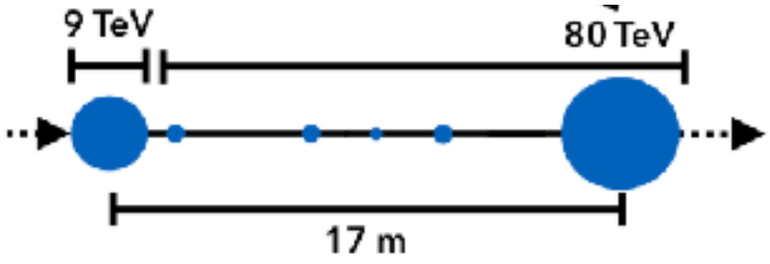
poorest constrained element
targeted directly with IC Upgrade

- World best constraints on tau appearance / Unitarity triangle

Recap: High-Energy Tau Neutrino Candidate

One of two events in the HESE 7.5 year identified by tau neutrino search





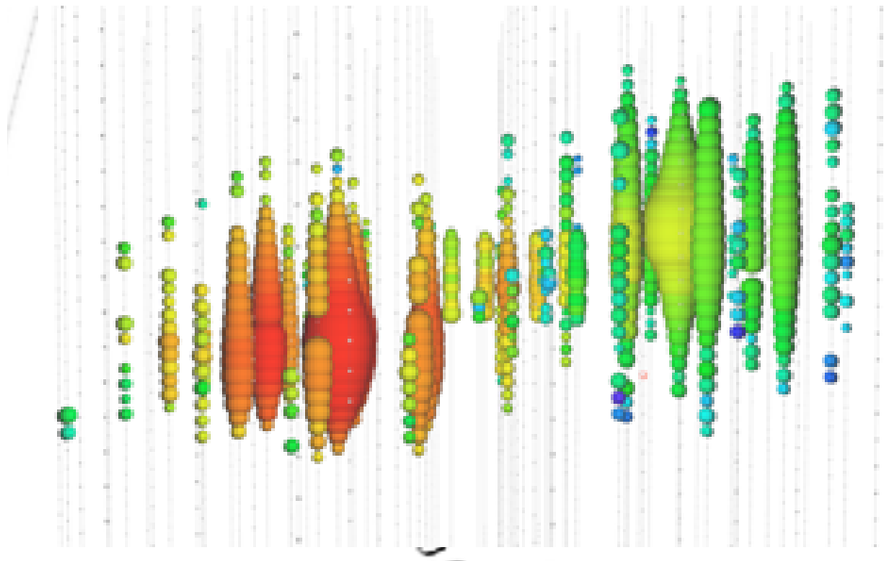
- observed light arrival pattern clearly favors double cascade hypothesis

Stachurska et al, VLVNT 2018

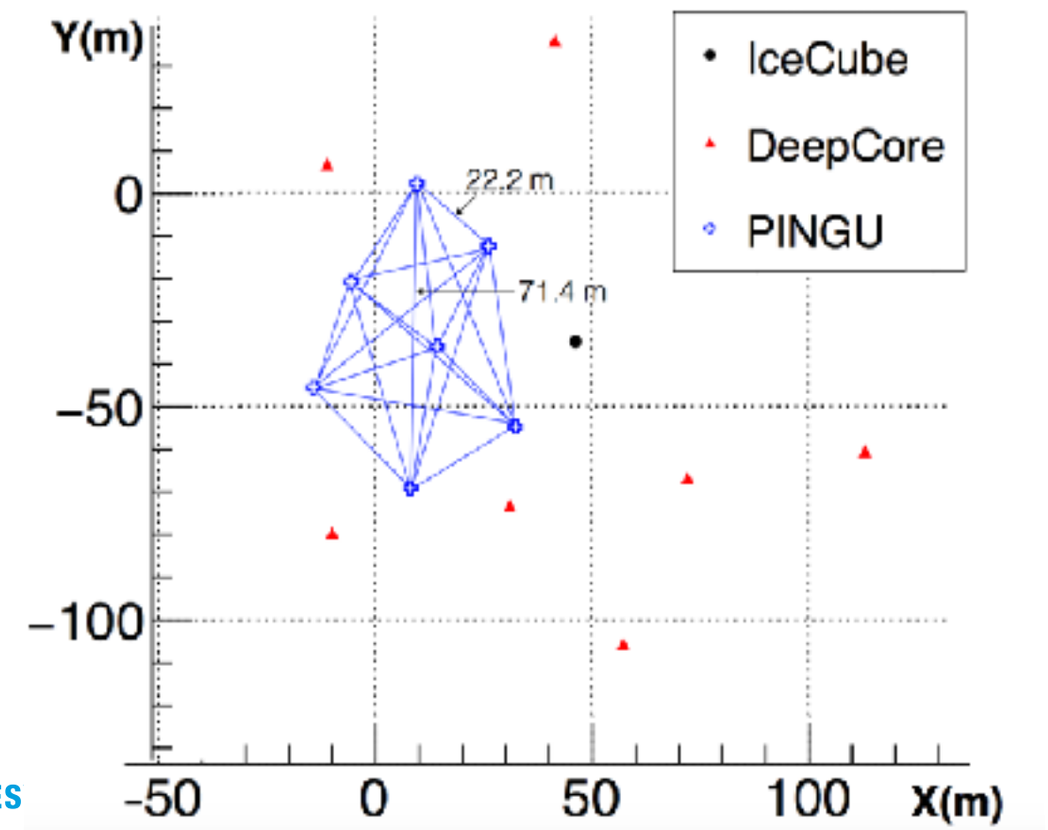
The IceCube Upgrade - Science

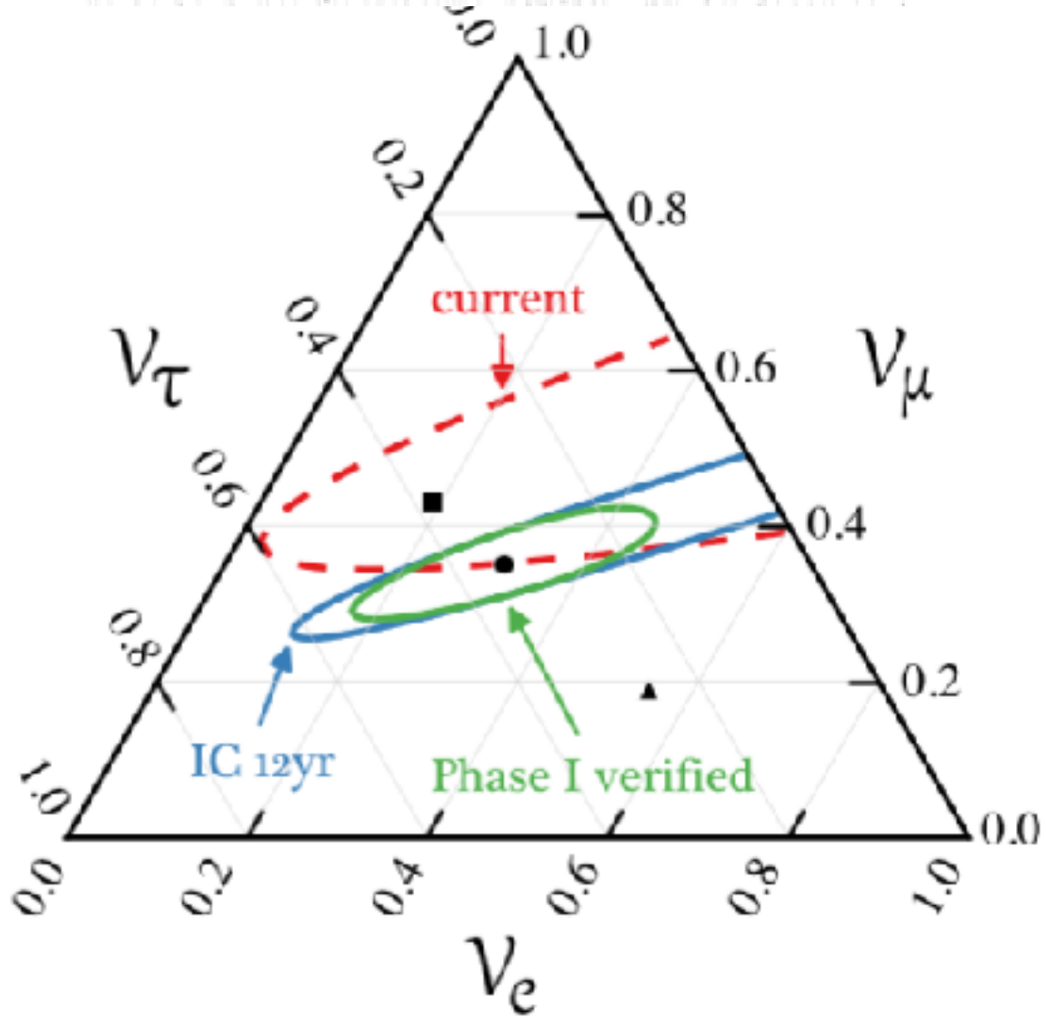
New calibration devices inside IceCube enhance HE science

- better control of systematics
- applicable to all IceCube data



IceCube Upgrade permits to generate double cascades with baselines of ~20 m

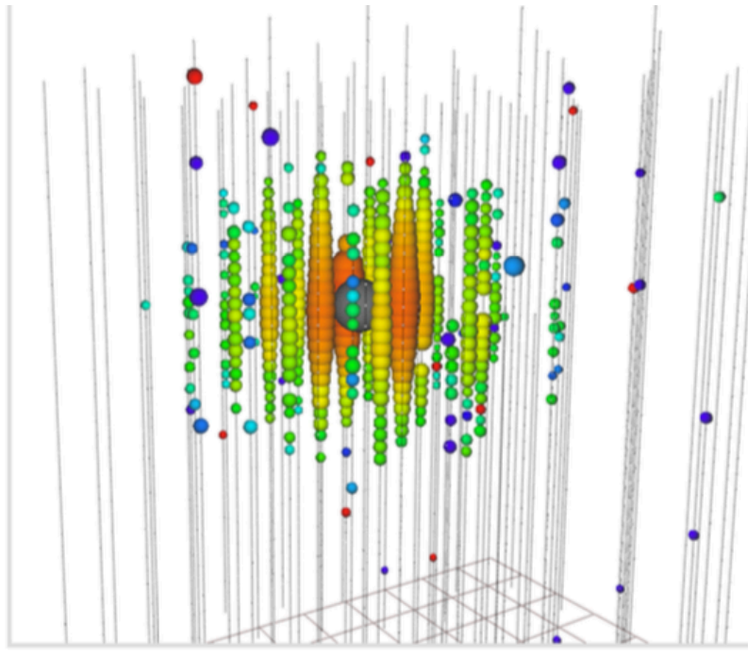


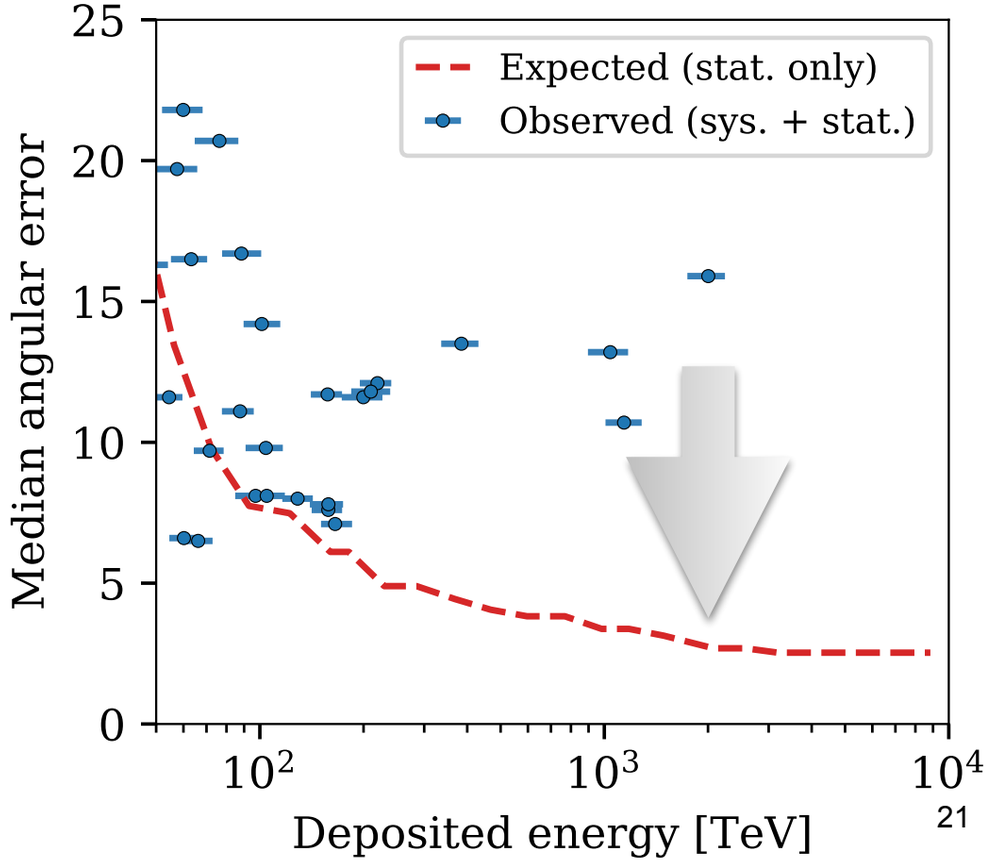


The IceCube Upgrade - Science

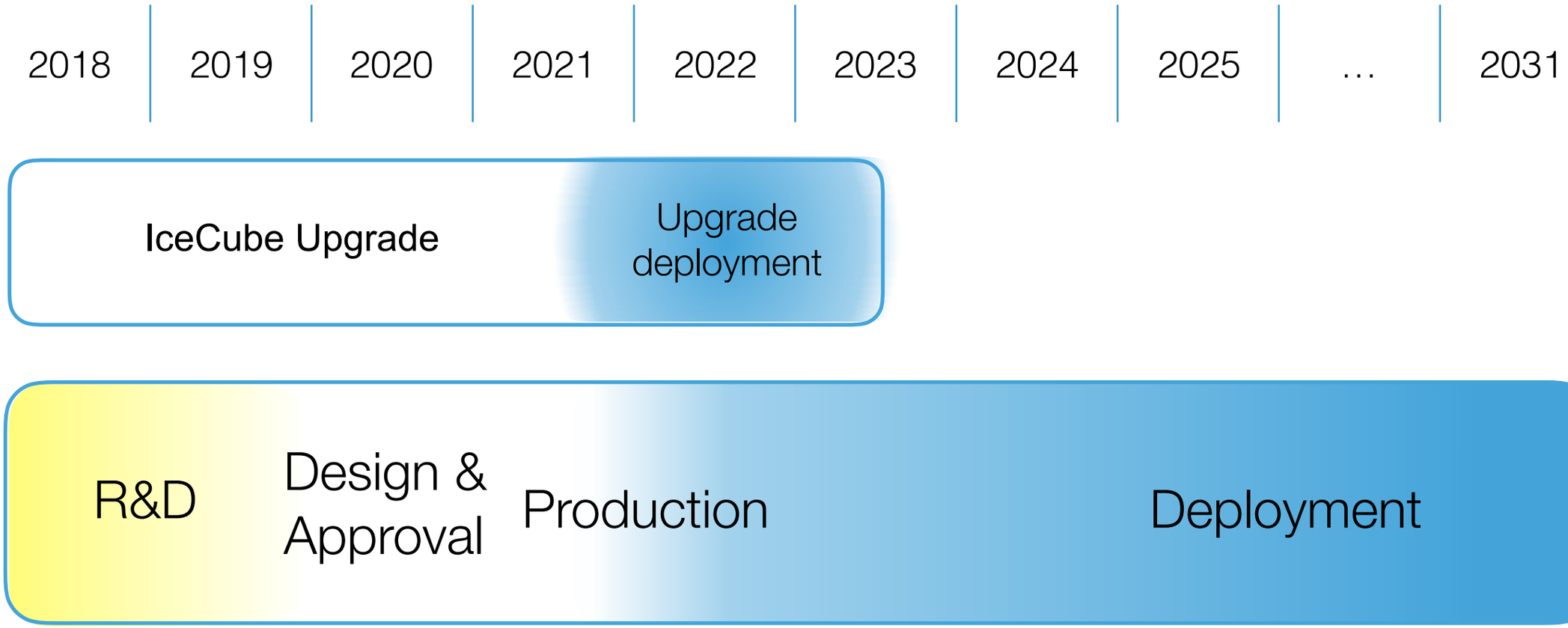
New calibration devices inside IceCube enhance HE science

- better control of systematics
- applicable to all IceCube data
- improved reconstruction





Project-driven IceCube-Gen2 Timeline



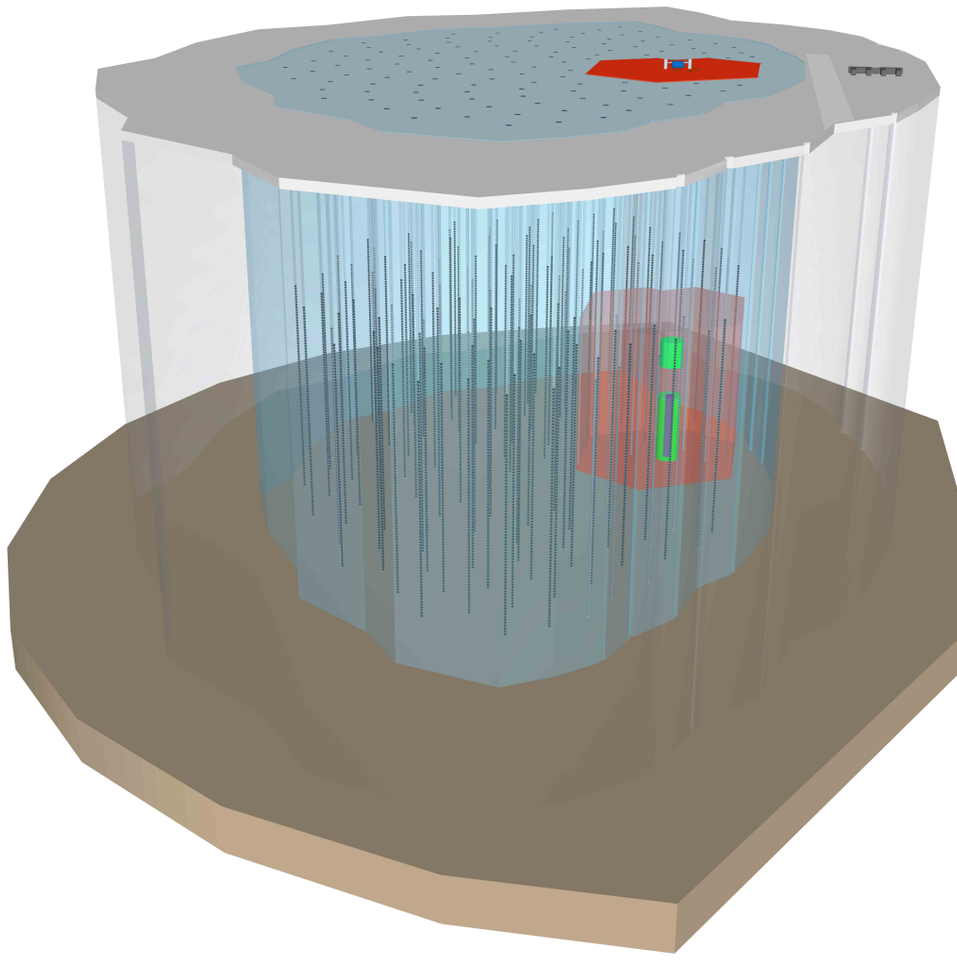
Conclusions

- IceCube-Gen2 sensitivity to address questions raised by IceCube, expanding its energy reach by several orders of magnitude and order of magnitude more astro. neutrinos

- Complementary to KM3NeT/ARCA in hemisphere, targeting higher energy. Its also in an earlier project phase

- Gen2 costs comparable to that of IceCube

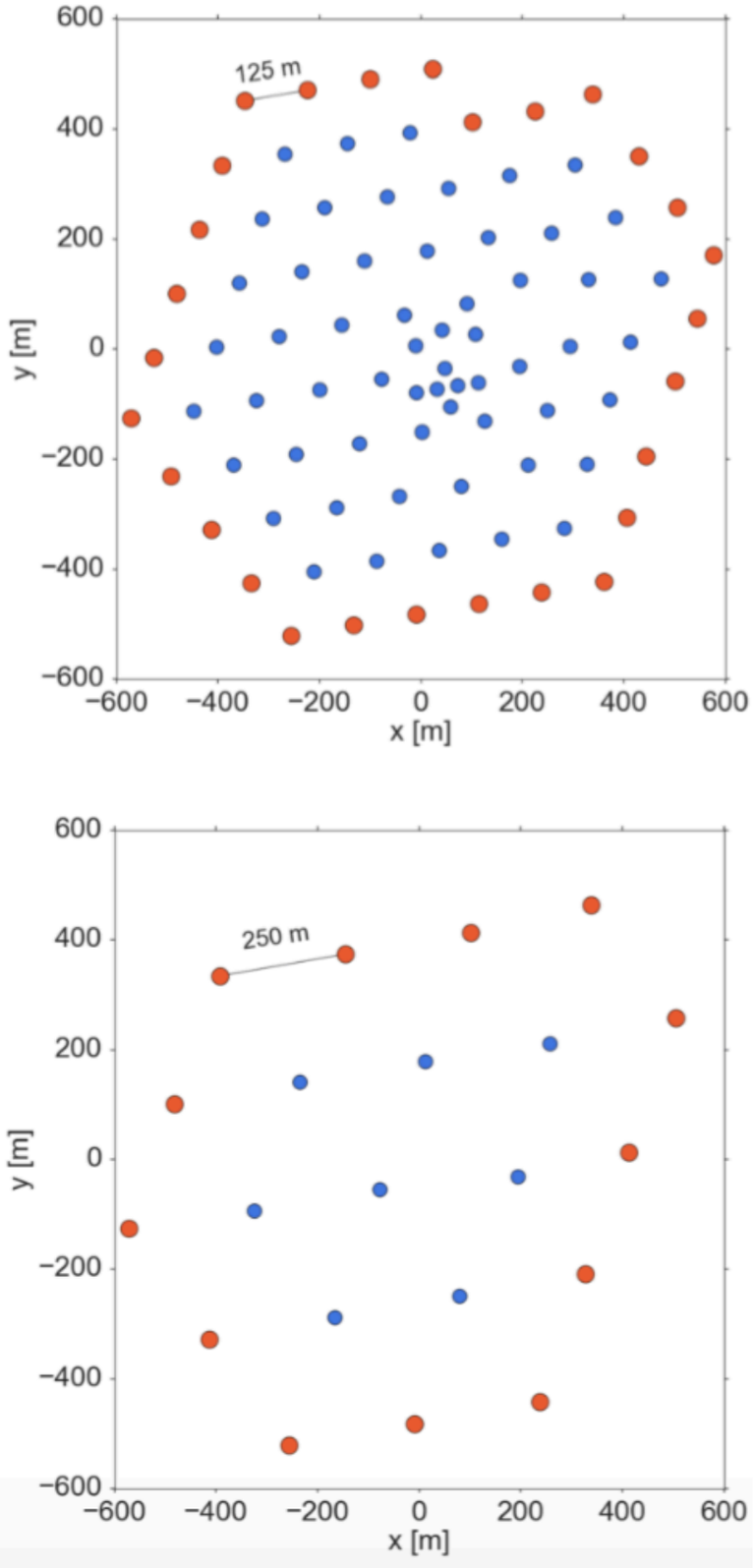
- IceCube Upgrade, now funded, has a compelling science case on its own while being the first step towards Gen2

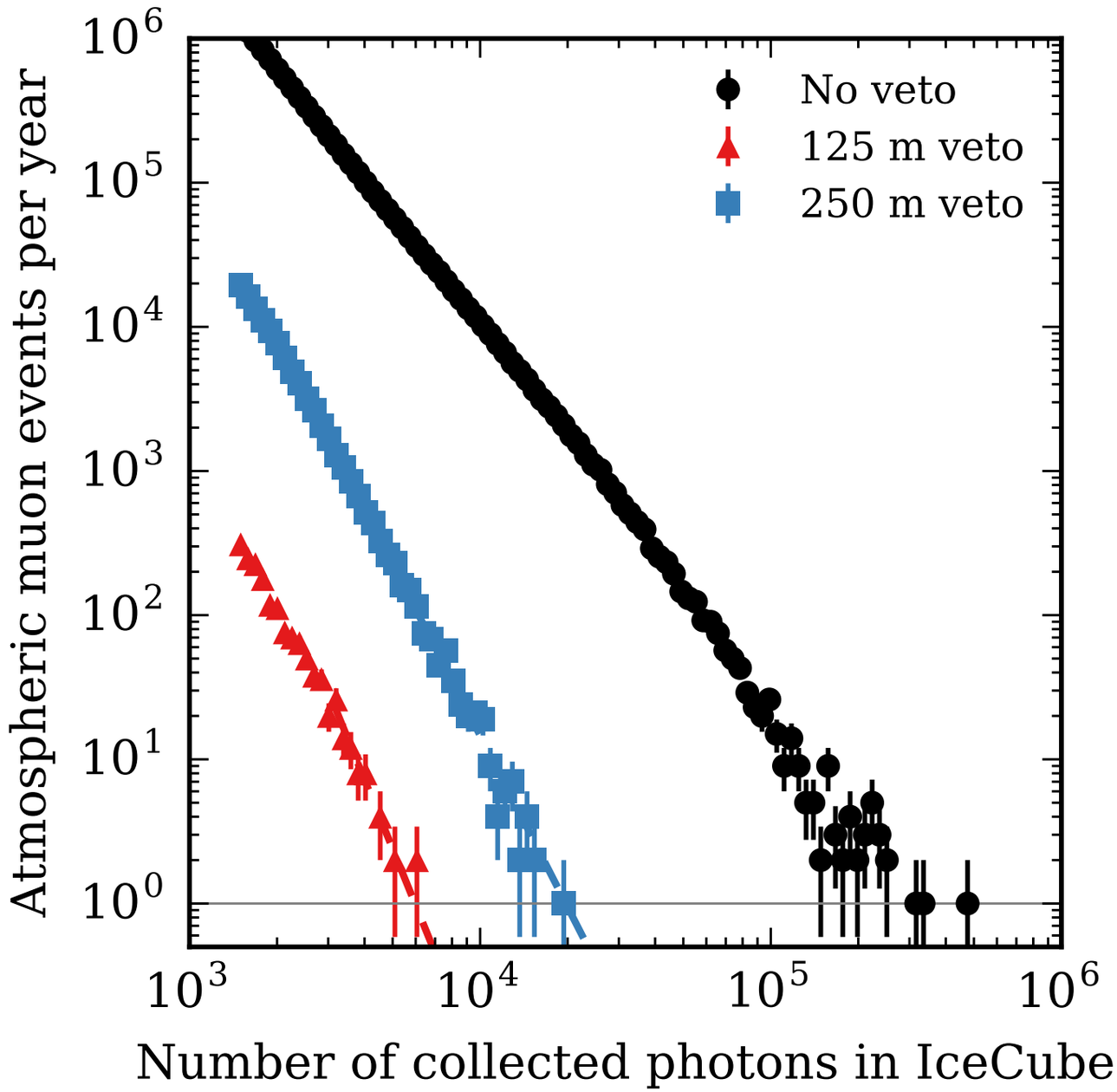


Backup

Vetoing atmospheric events: HESE for Gen2

Evaluation of the veto passing rate from real data

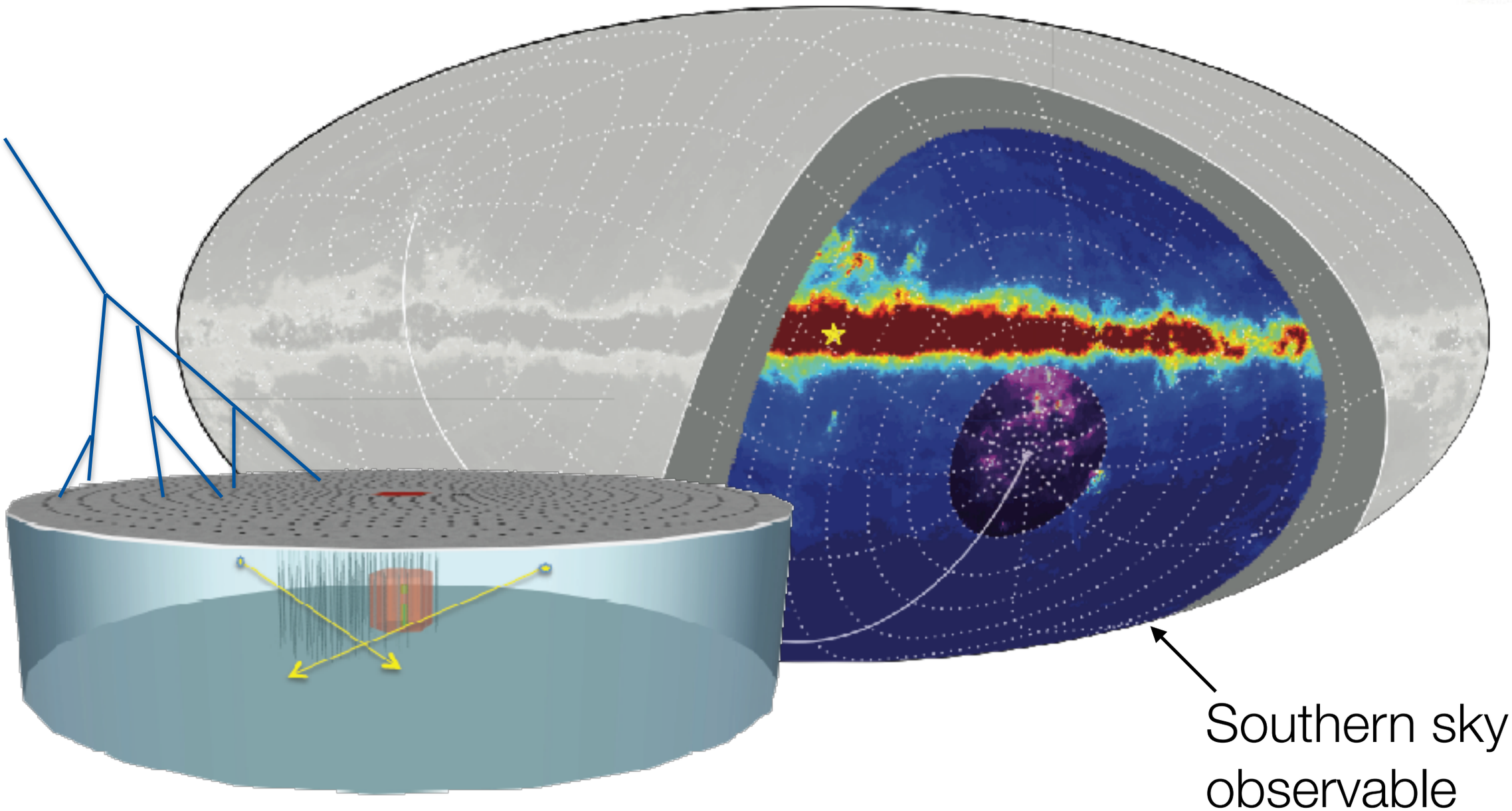




Vetoing atmospheric events works just like in IceCube!

but with 3 x higher energy threshold

Extended surface veto



Potential gain for e.g. 75 km² veto:

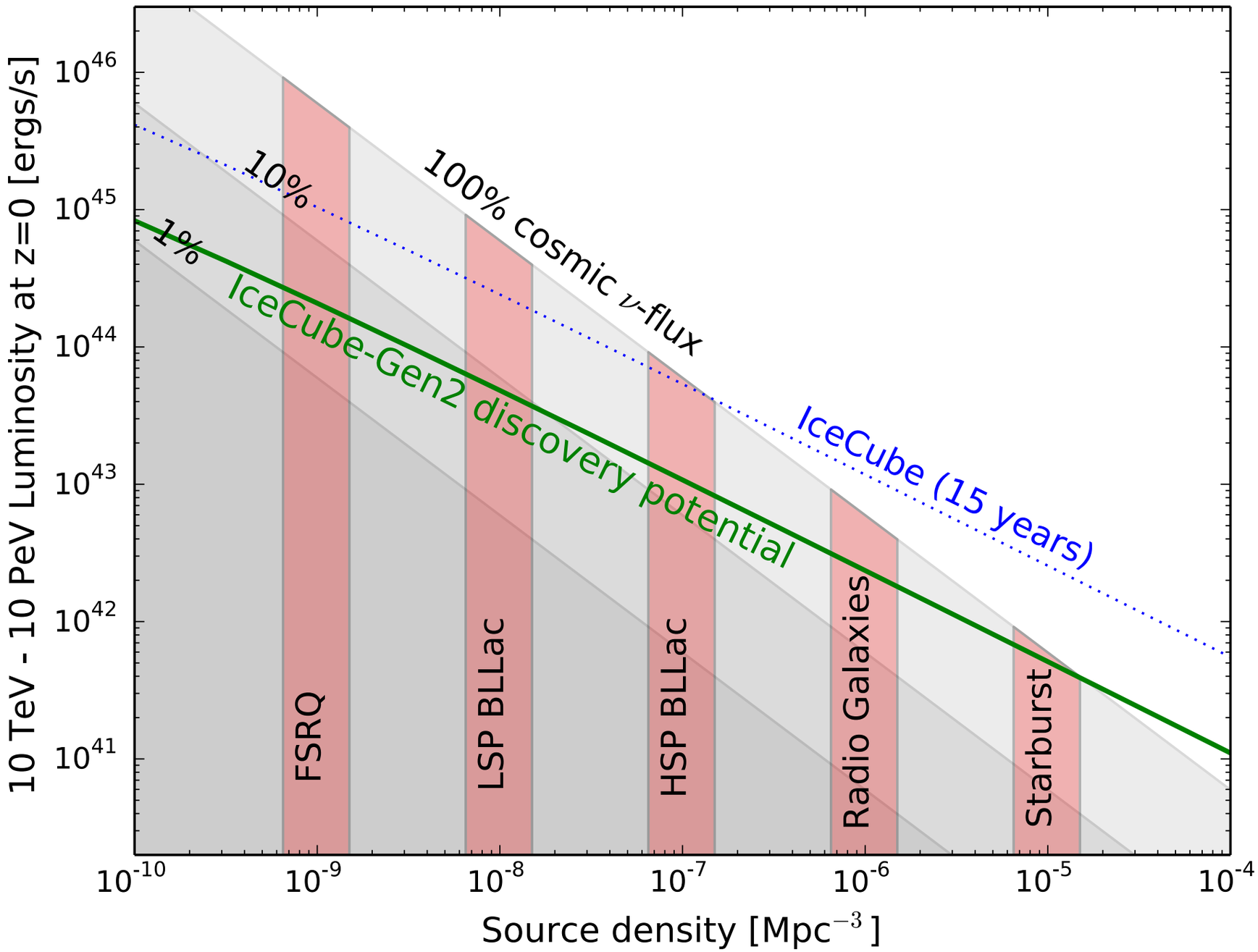
~2x number of PeV tracks

Event statistics

Event type	Number of events per year in Gen2 (IceCube)			
	10–100 TeV	0.1–1 PeV	1–10 PeV	>10 PeV
Contained cascades	0 (2.6)	20 (4.4)	15 (1.6)	2 (0.2)
Surface vetoed μ	0 (0)	9.7 (0.12)	4.8 (0.053)	1.2 (0.014)
Upgoing μ	100 (37)	55 (16)	11 (3.2)	1.6 (0.47)

Table 2: Number of neutrino events per decade of neutrino energy expected per year in IceCube and Gen2, assuming an astrophysical neutrino flux of $\Phi_\nu = 0.95 \times 10^{-18} \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-2.13} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ per flavor. Surface vetoed μ are muon tracks that pass through the footprint of a $75\,\mathrm{km}^2$ veto array above Gen2, or the $1\,\mathrm{km}^2$ IceTop array in the case of IceCube, and reach the detector with more than 100 TeV.

Identifying the sources of IceCube's neutrinos



Five times IceCube's point source sensitivity required to detect any reasonable source scenario

*Sensitivity for source catalog search

New sensor designs for improved performance

mDOM

36

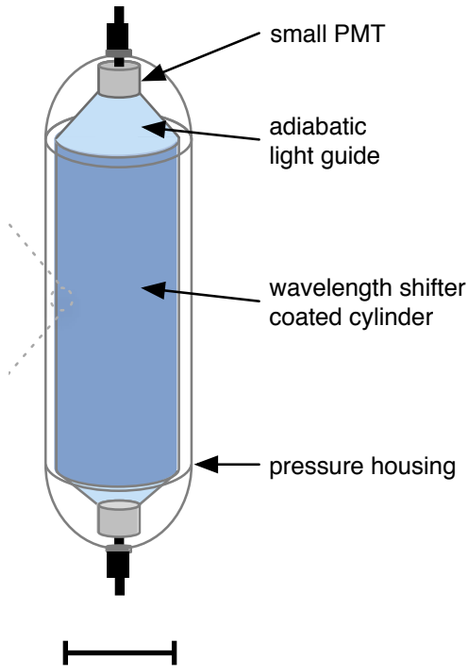
- Directional information
- More sensitive area per module

D-Egg

30

- Directional information
- More sensitive area per module
- Smaller geometry

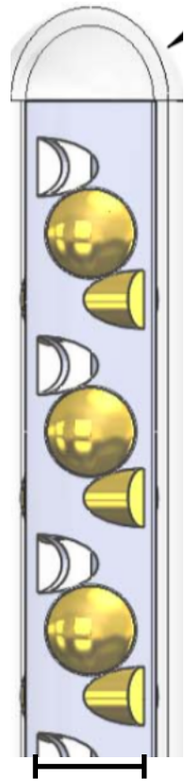
WOM



11

- more sensitive area per $
- Small diameter
- Lower noise rate

LOM



13

- Small diameter
- Directional info.
- More area per module

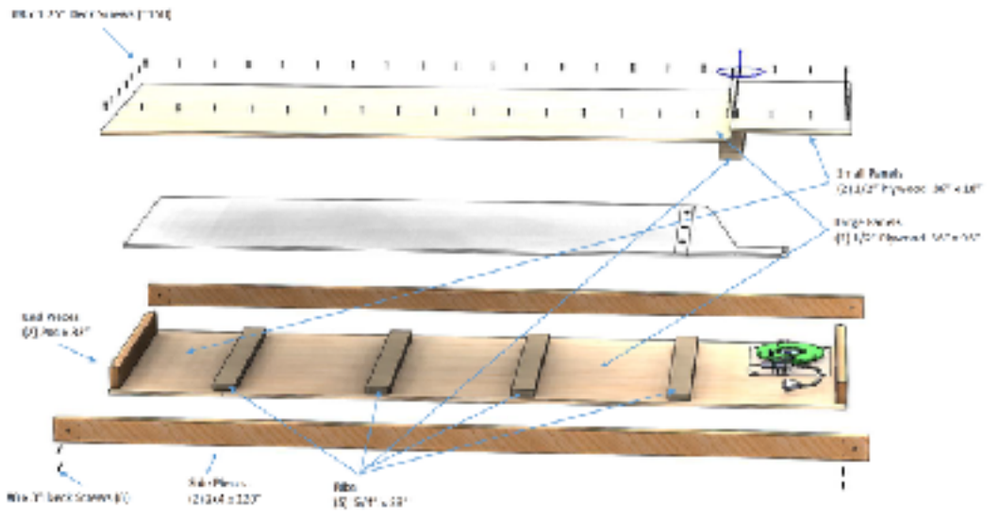
Surface veto technologies under considerations

IceTop tanks

1.8 m

- Good CR detectors
- Operated at South Pole since 2007
- Deployment requires effort at Pole

Scintillator panels



3 m

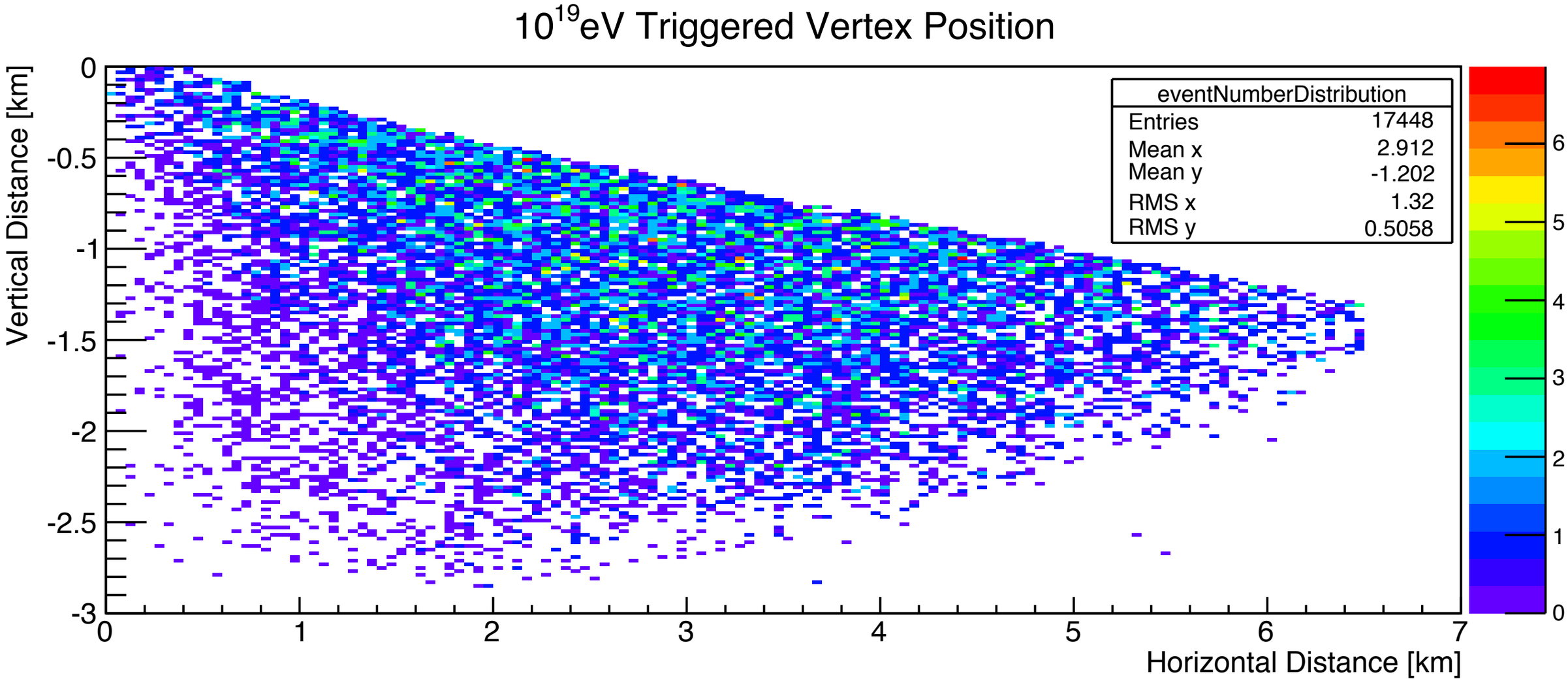
- Easier deployment
- Low cost (cheap materials and SiPMs)

Additional concepts (ACTs, radio)

1 m

- Reduced energy threshold
- Add resolution, particle ID,…

Radio detection of neutrinos at the South Pole



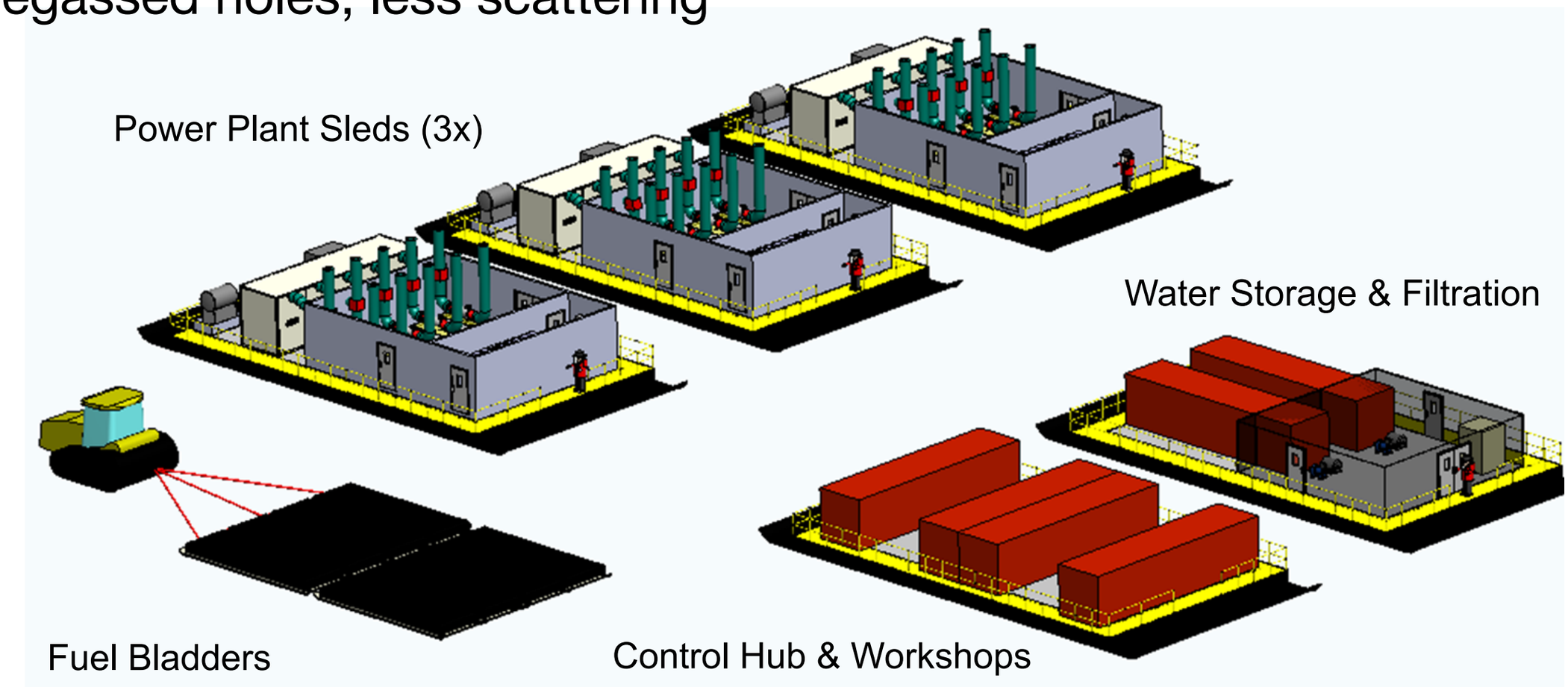
Simplified logistics & improved performance

Simplified logistics:

- Equipment and fuel delivered to Pole via single traverse instead of air
- Reduced logistical footprint at Pole; smaller crew

Improved performance:

- New sensors allow for narrower holes ⟹ large fuel savings
- Faster drilling
- Degassed holes, less scattering



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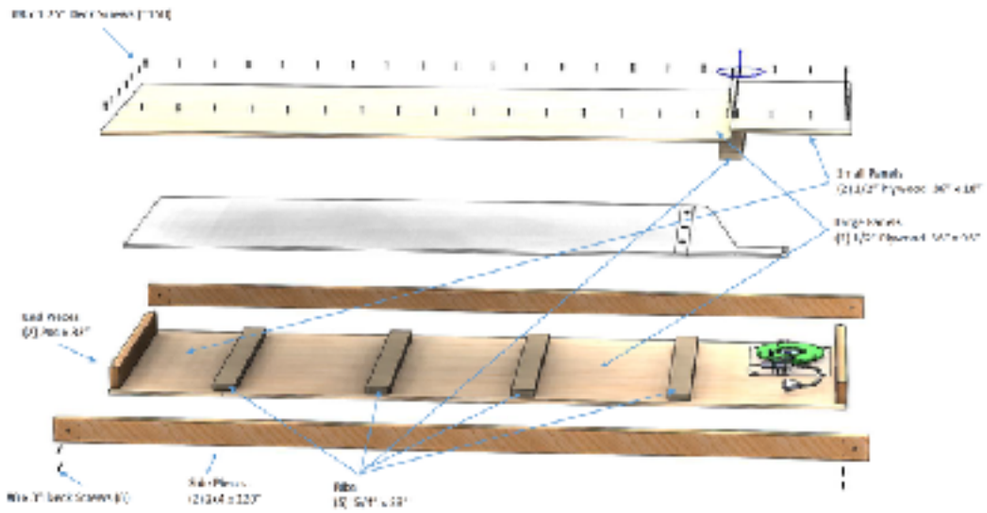

3 m

- Easier deployment
- Low cost (cheap materials and small PMTs)

Additional concepts (ACTs, radio)

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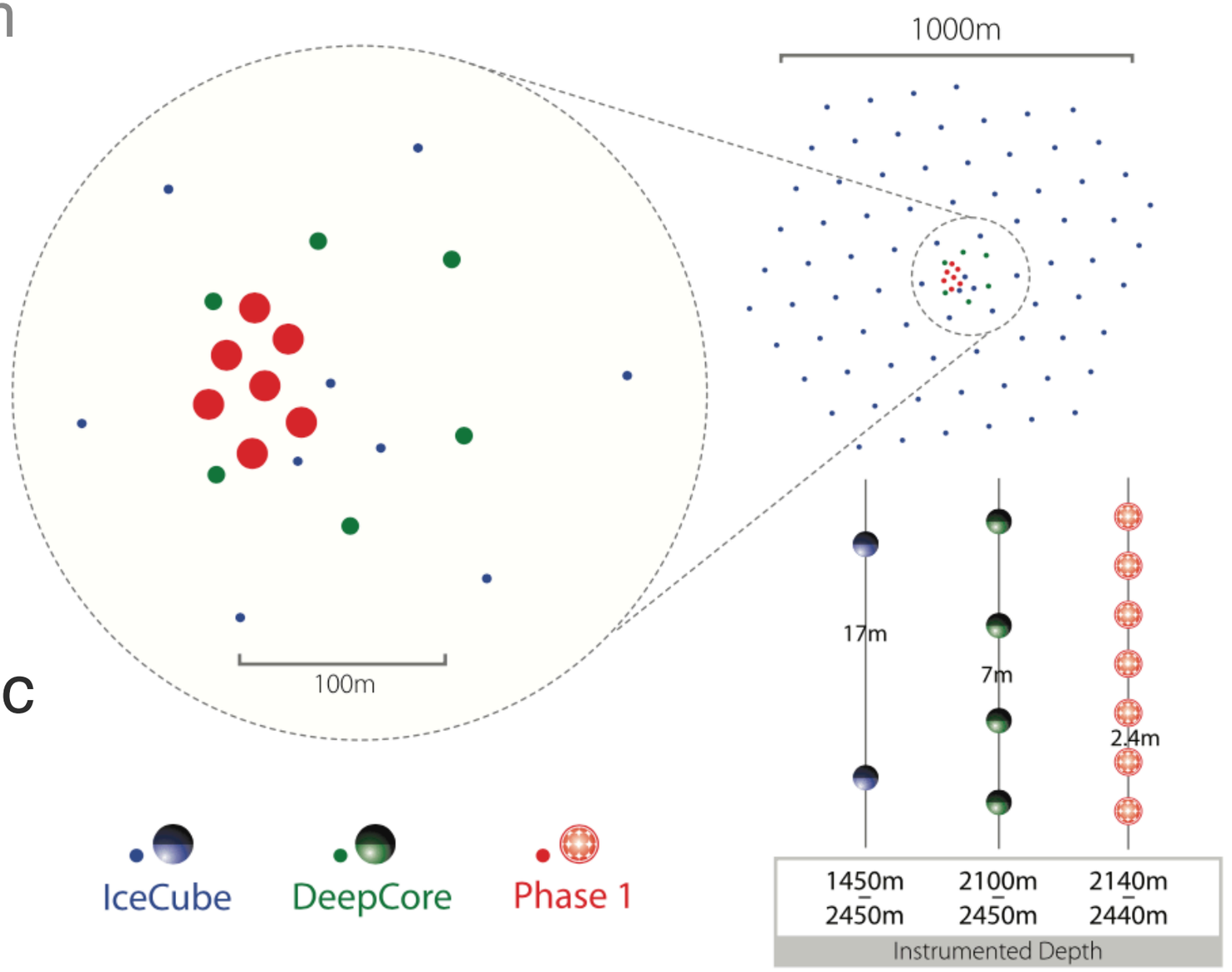
- Add resolution, particle ID,…

Gen2-Phase I

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- New calibration devices, incorporating lessons learned from a decade of IceCube calibration efforts
- Enhance IceCube's scientific of capabilities at both high and low energy



Flavor Physics with Astrophysical Neutrinos

$\nu_e:\nu_\mu:\nu_\tau$ at the source

pion decay: 1:2:0

$$\pi \rightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_e + \nu_\mu$$

muon damping: 0:1:0

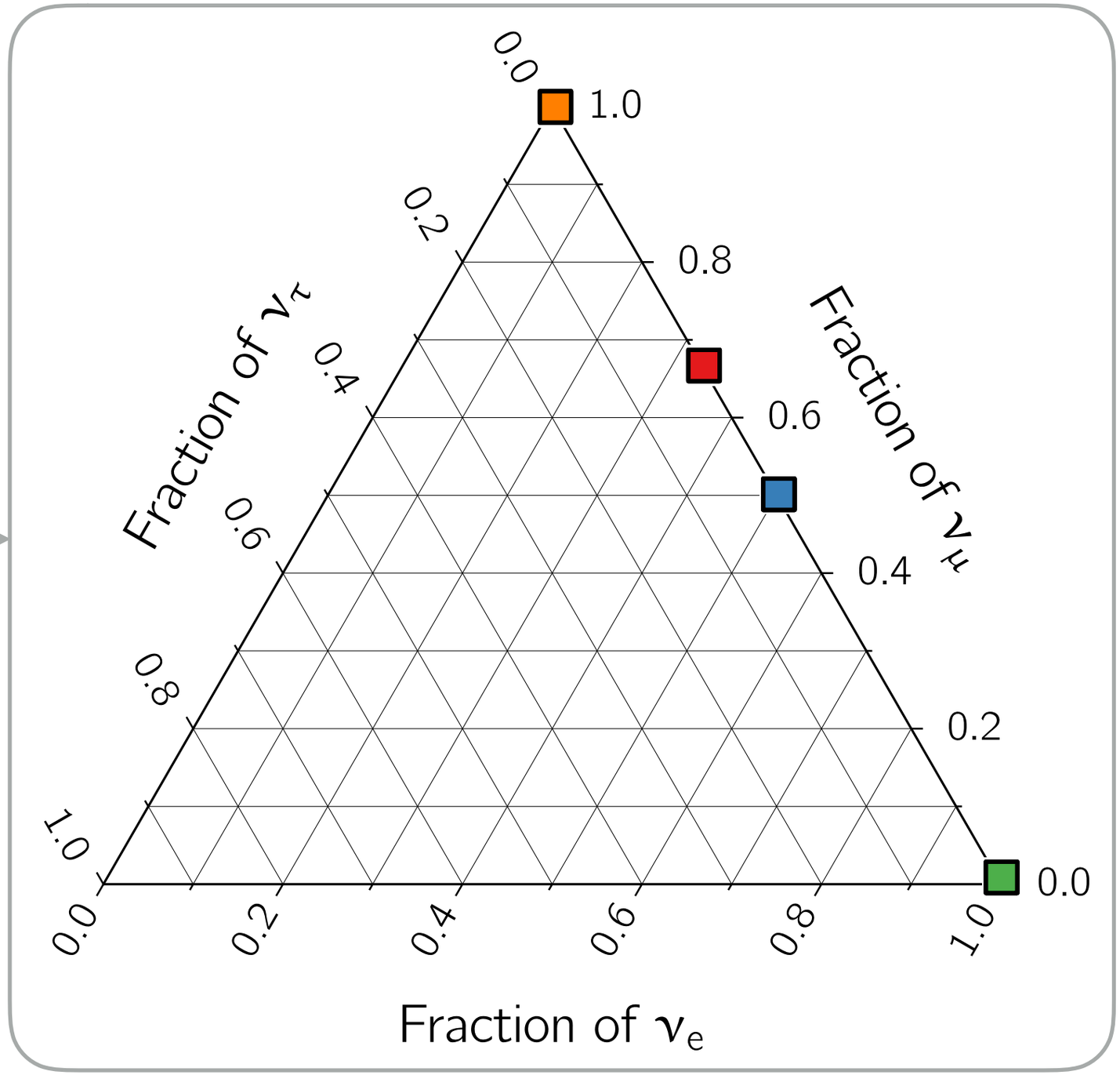
$$\pi \rightarrow \mu + \nu_\mu$$

neutron decay: 1:0:0

$$n \rightarrow p + e + \nu_e$$

charm decay: 1:1:0

$$D \begin{cases} \rightarrow X + e + \nu_e \\ \hookrightarrow X + \mu + \nu_\mu \end{cases}$$



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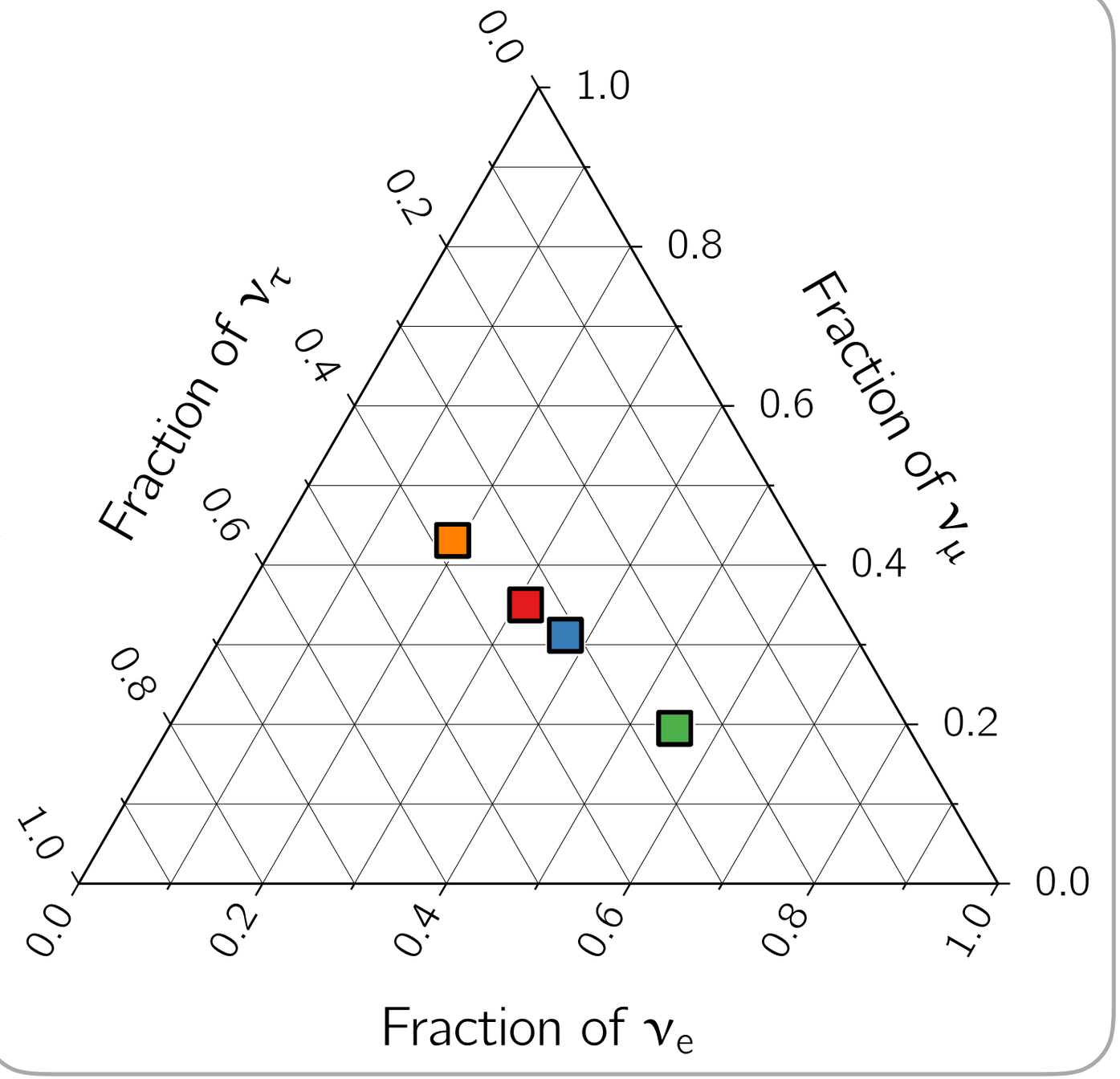
$$D \to X + \mu + \nu_\mu$$

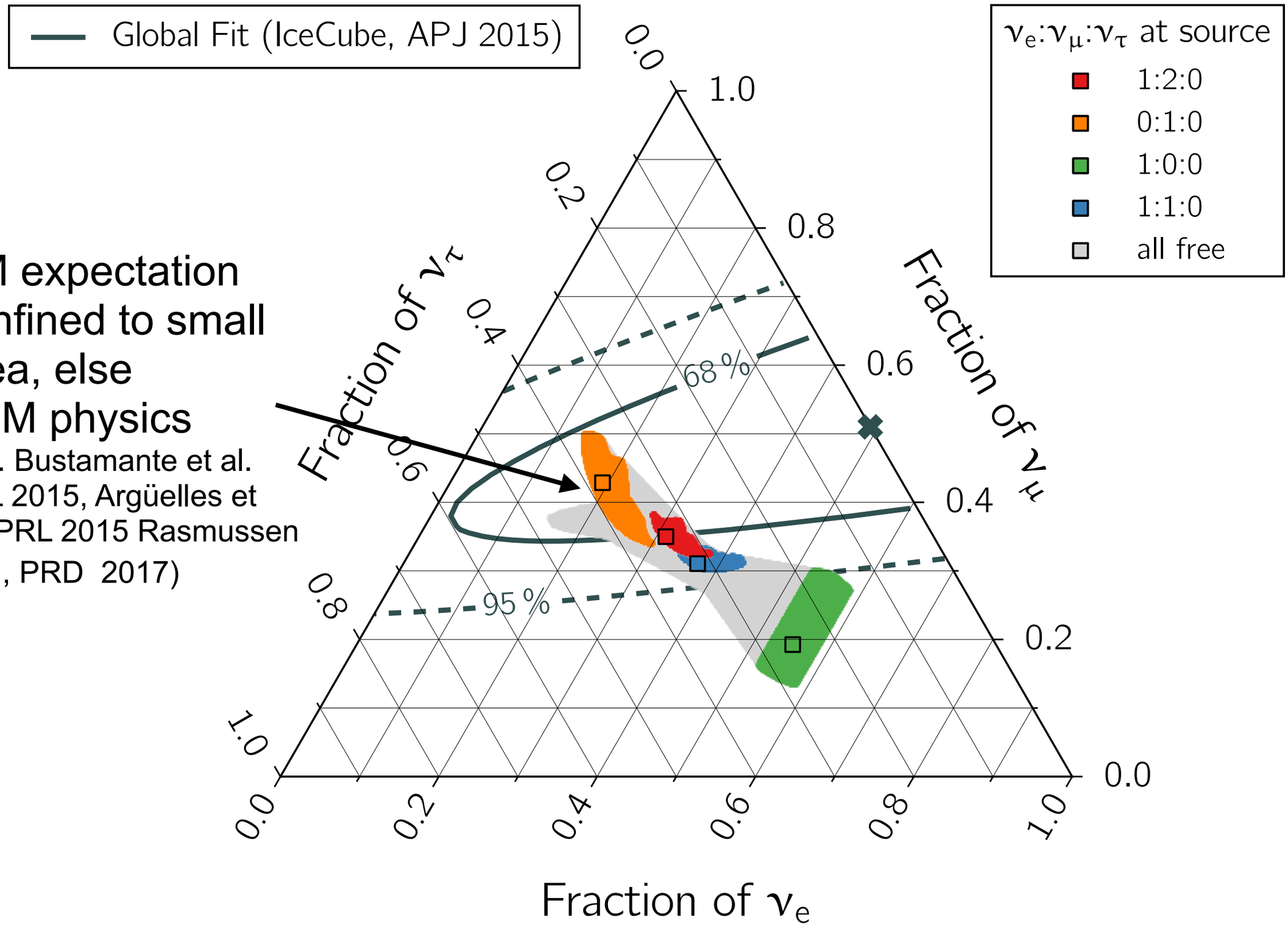
cosmic baseline neutrino oscillations

$\nu_e:\nu_\mu:\nu_\tau$ at Earth



adapted from M. Usner, PhD thesis 2018

Flavor Physics with Astrophysical Neutrinos

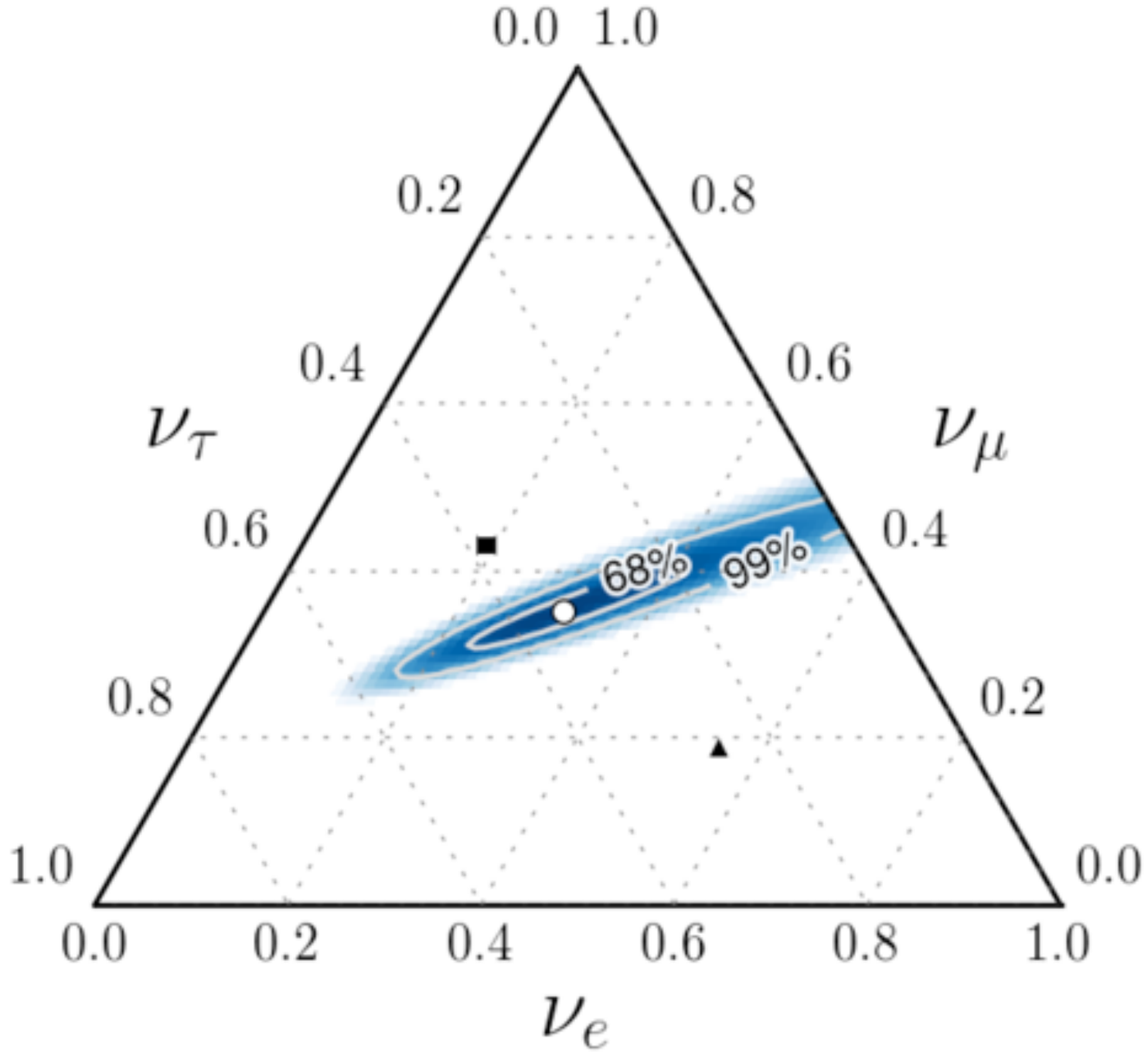


SM expectation confined to small area, else BSM physics

(e.g. Bustamante et al. PRL 2015, Argüelles et al., PRL 2015 Rasmussen et al, PRD 2017)

adapted from M. Usner, PhD thesis 2018

Flavor Physics with Astrophysical Neutrinos



Gen2 (15 yrs)