

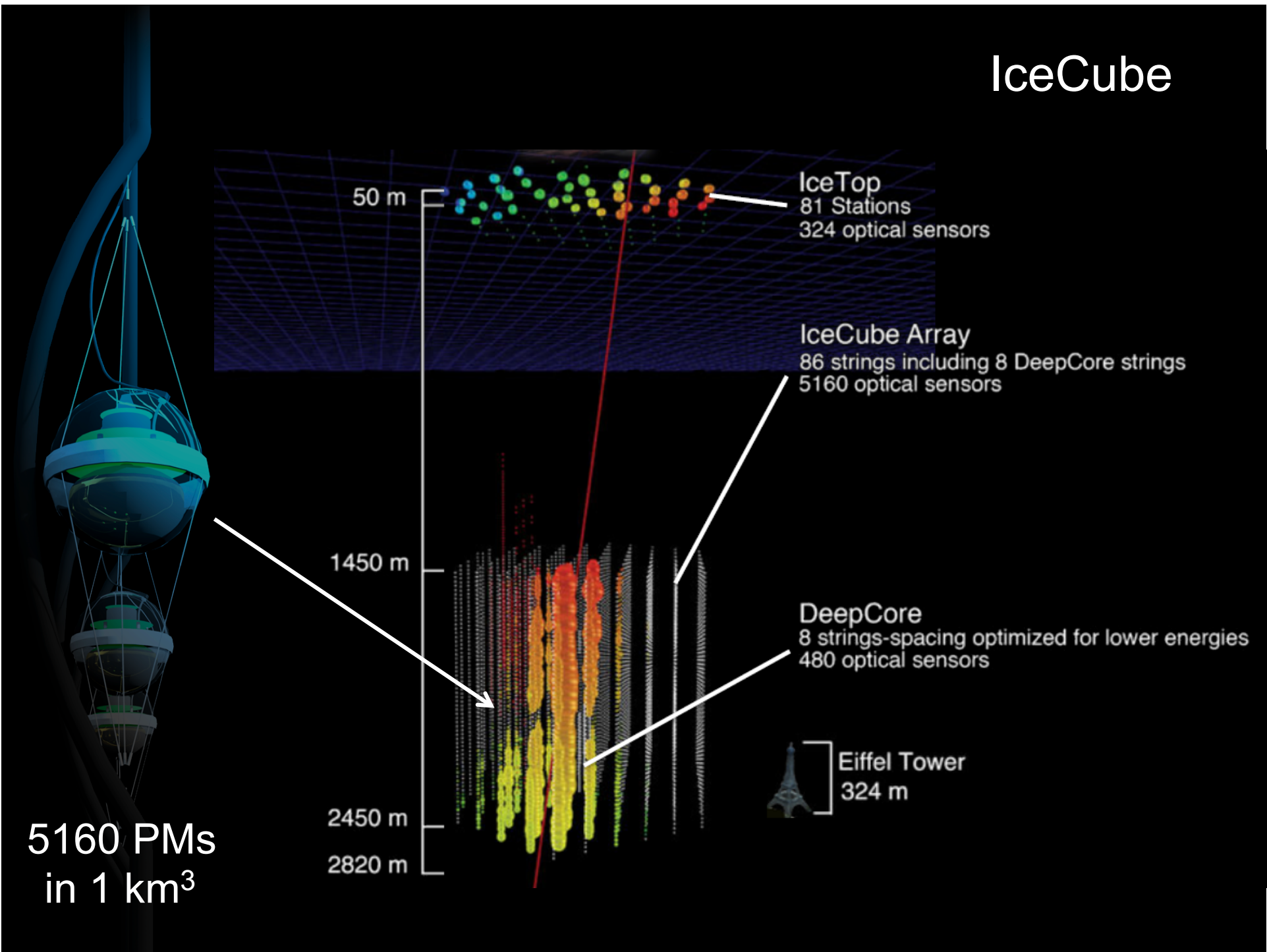


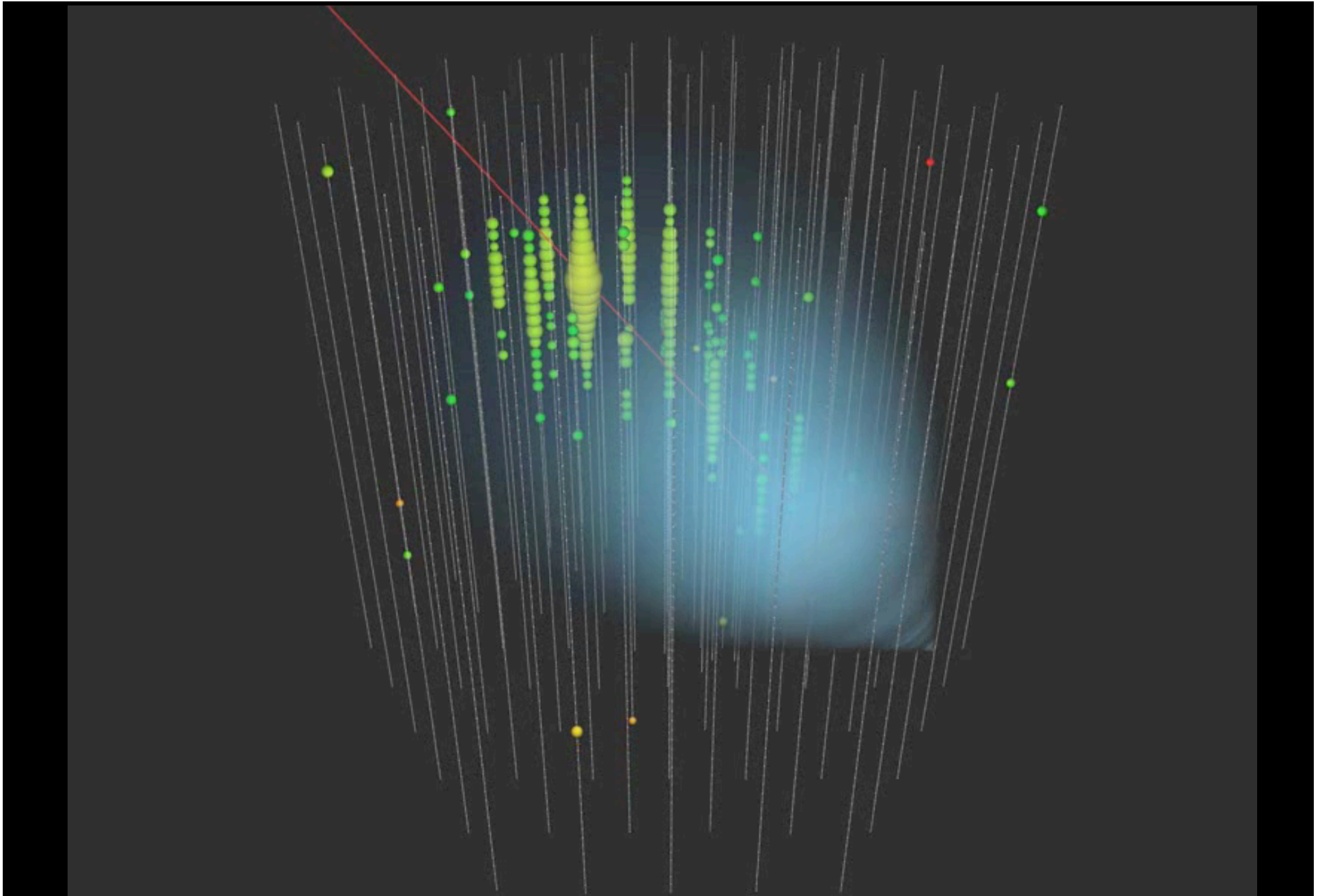
IceCube: beyond neutrino astronomy

Francis Halzen

- muon astronomy: search for the sources of the Galactic cosmic rays
- detecting a Galactic supernova explosion
- search for dark matter
- neutrino oscillations
- search for sterile neutrinos
- ...

IceCube





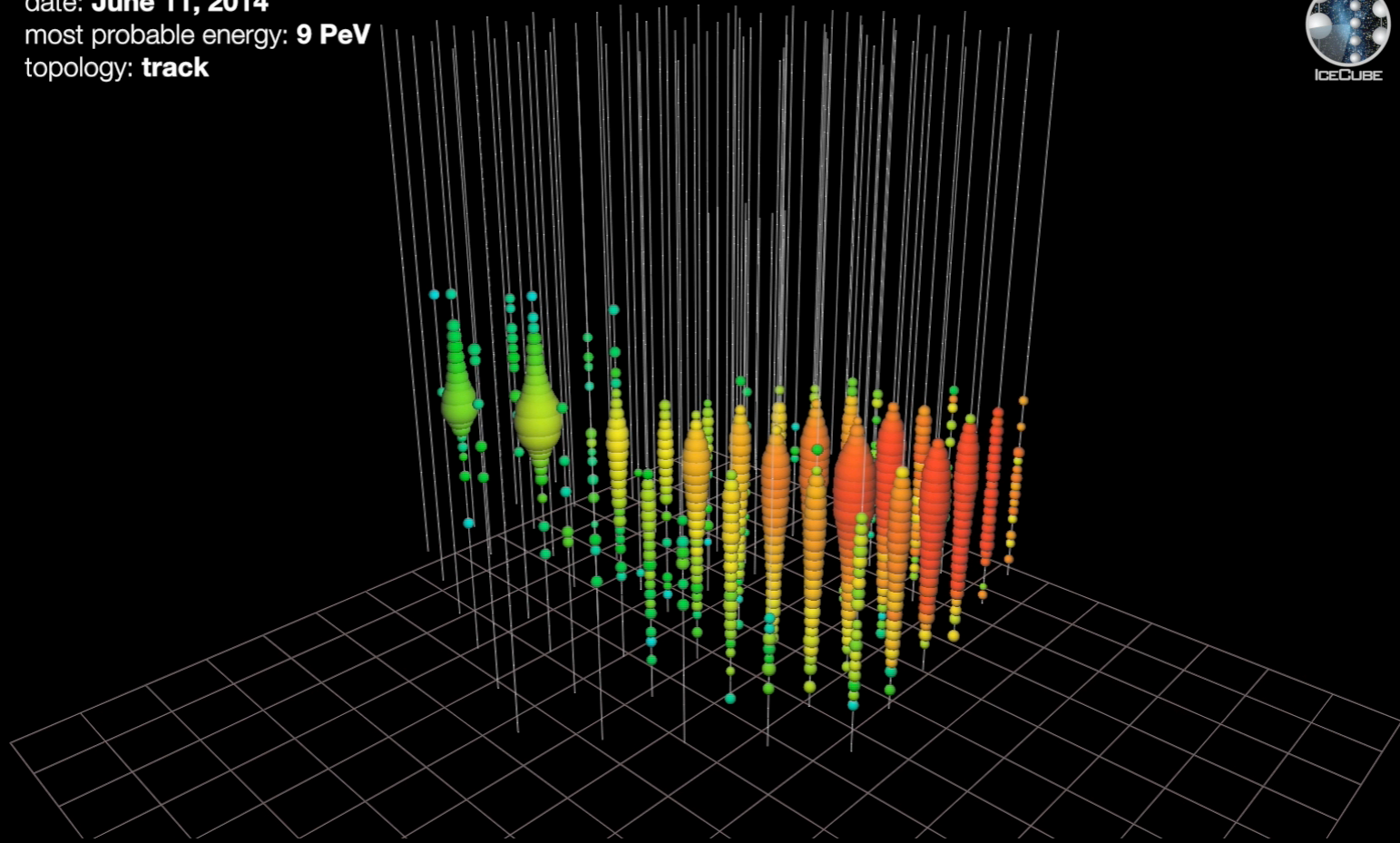
muon track: time is color; number of photons is energy

up-going muon track from muon neutrino (9 PeV)

date: **June 11, 2014**

most probable energy: **9 PeV**

topology: **track**



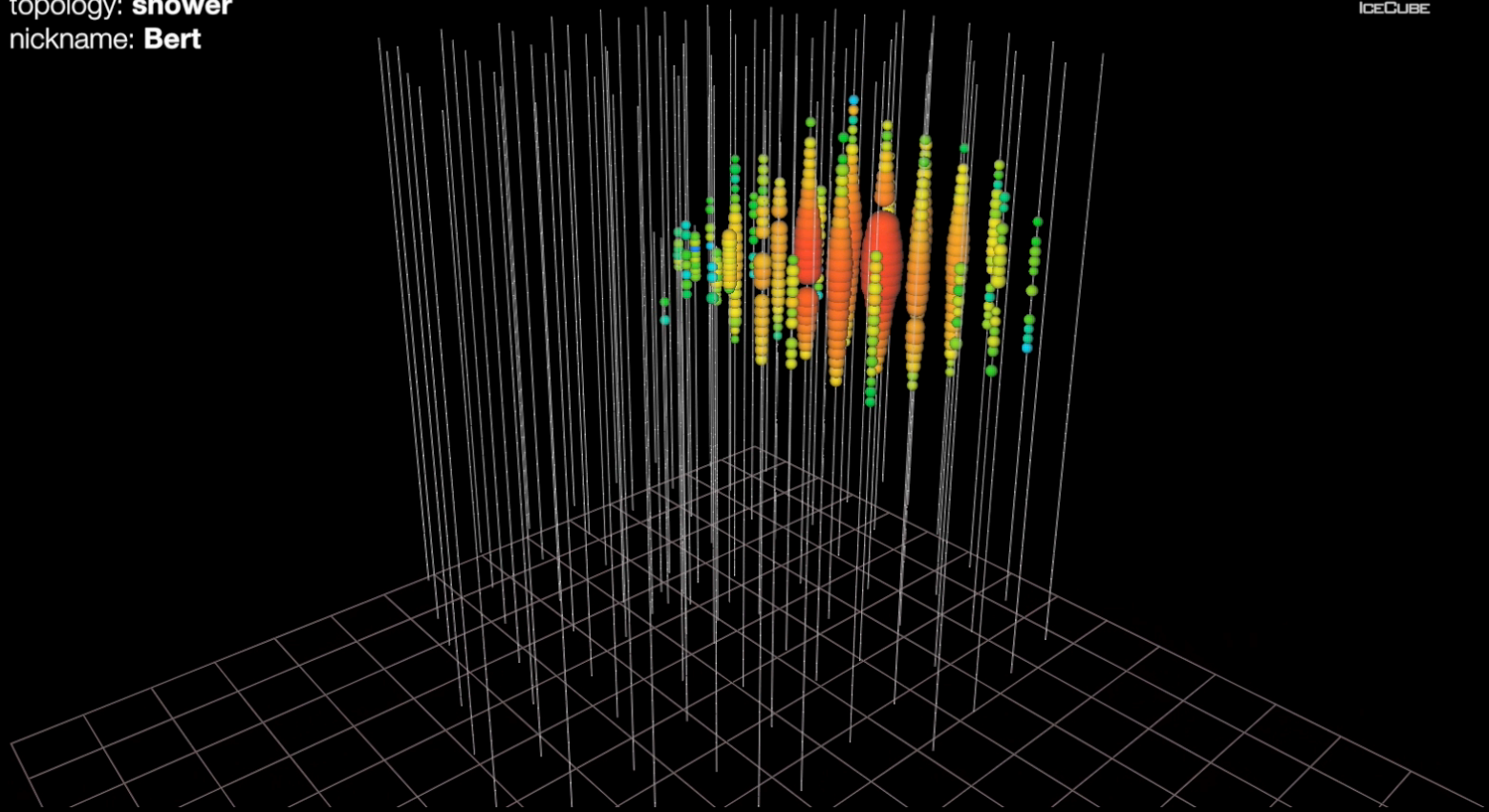
shower initiated inside the detector by electron neutrino (1 PeV)

date: **August 9, 2011**

energy: **1.04 PeV**

topology: **shower**

nickname: **Bert**



muons detected per year:

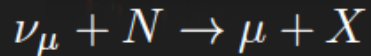
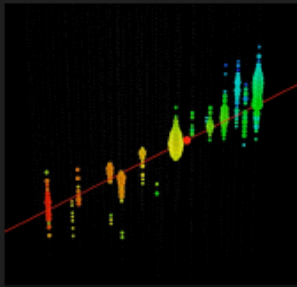
- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^5$
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second

** 1 every 6 minutes

neutrino flavors in IceCube

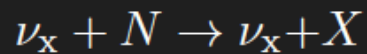
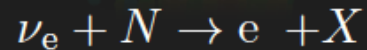
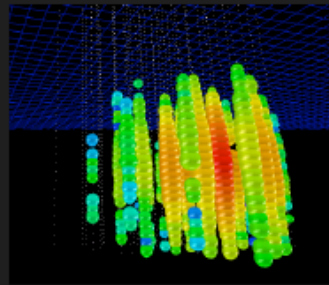
CC Muon Neutrino



track (data)

factor of ≈ 2 energy resolution
 $< 1^{\circ}$ angular resolution at high
 energies

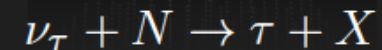
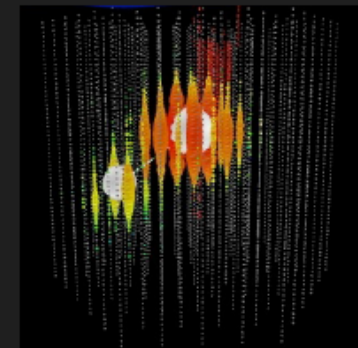
Neutral Current / Electron Neutrino



cascade (data)

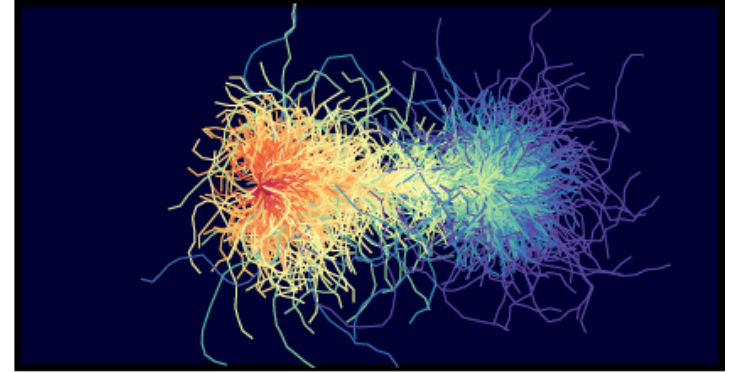
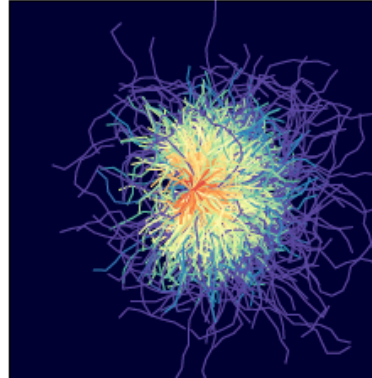
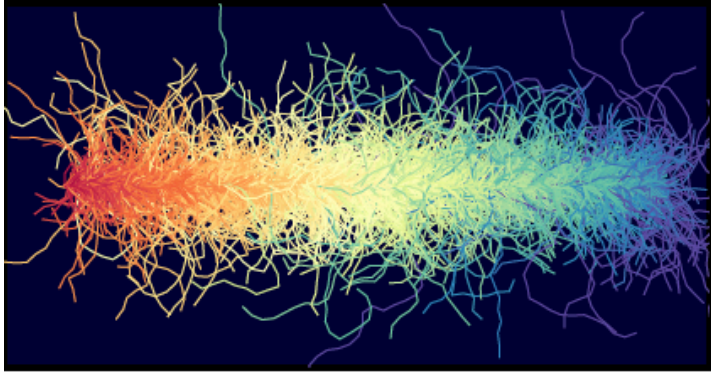
$\approx \pm 15\%$ deposited energy resolution
 $\approx 10^{\circ}$ angular resolution (in IceCube)
 (at energies ≈ 100 TeV)

CC Tau Neutrino



“double-bang” (≈ 10 PeV) and other
 signatures (simulation)
 (not observed yet: τ decay length is
 50 m/PeV)



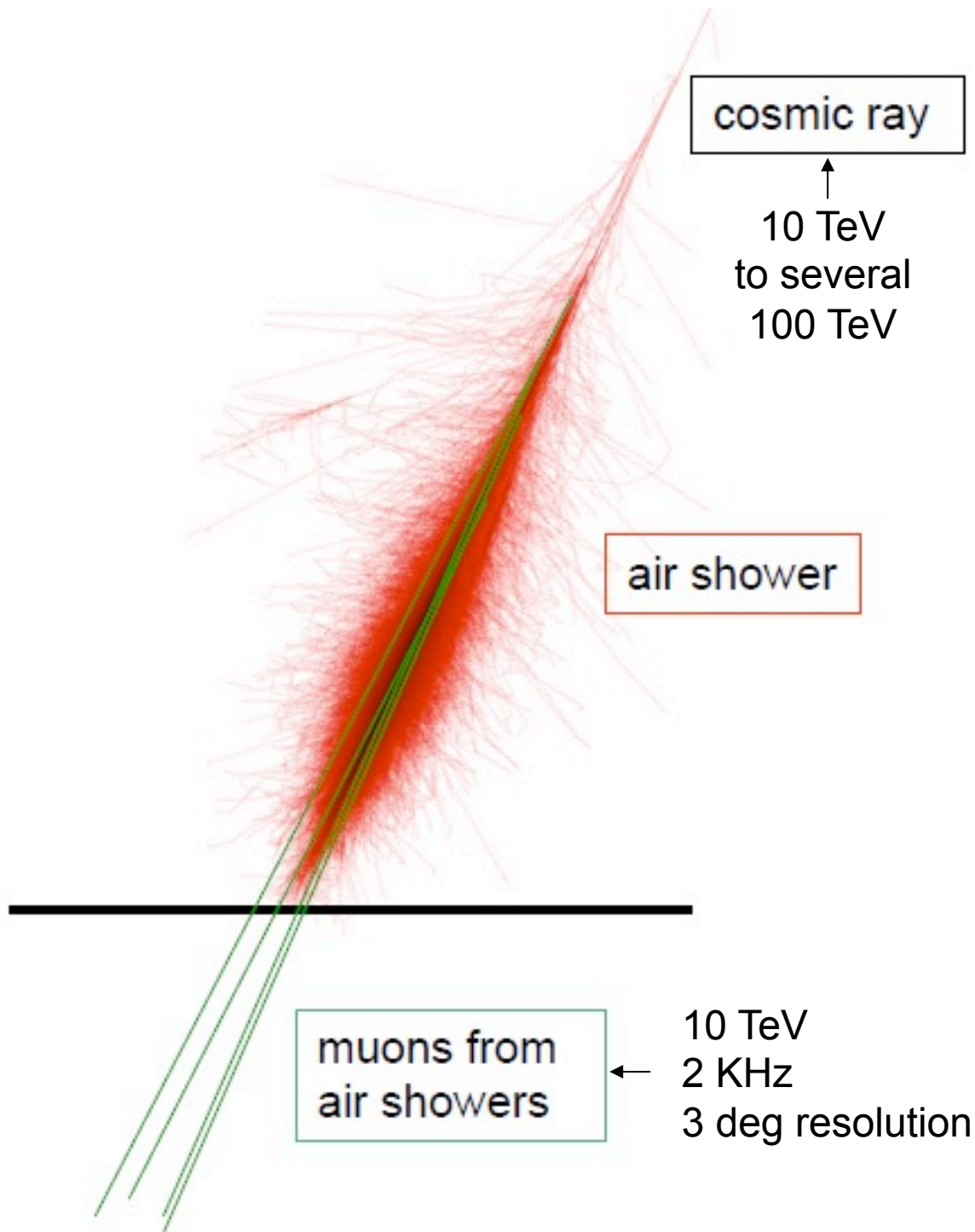




IceCube: beyond neutrino astronomy

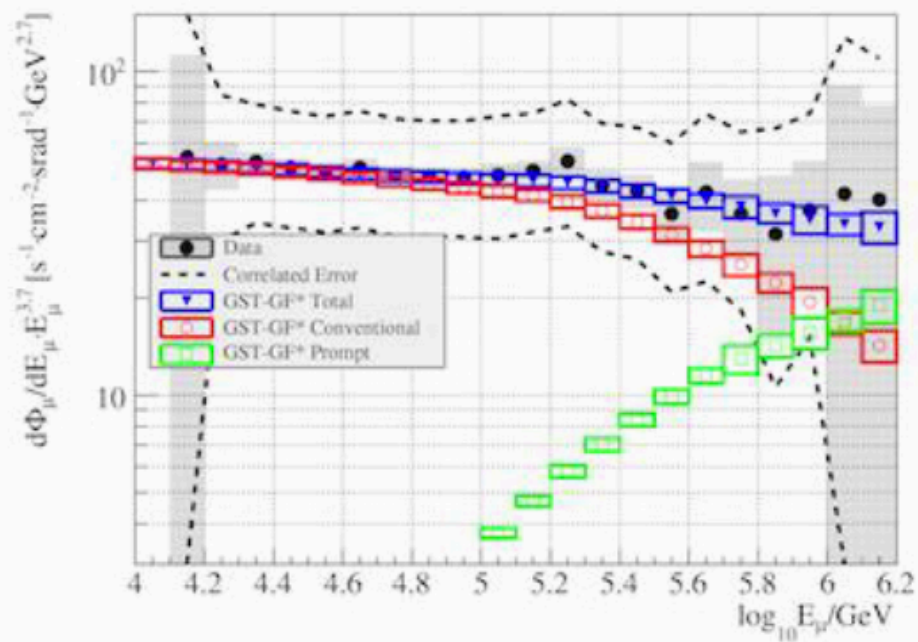
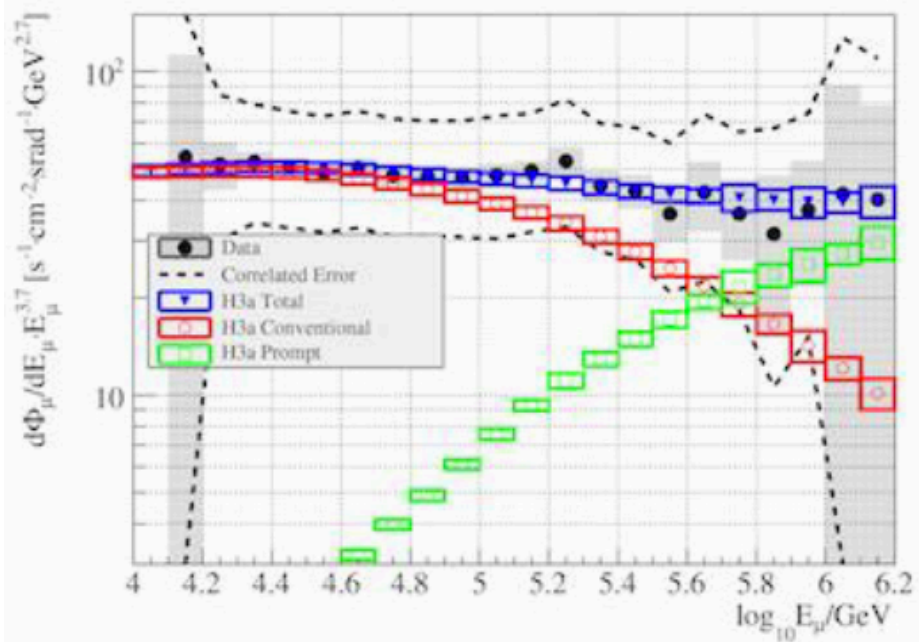
Francis Halzen

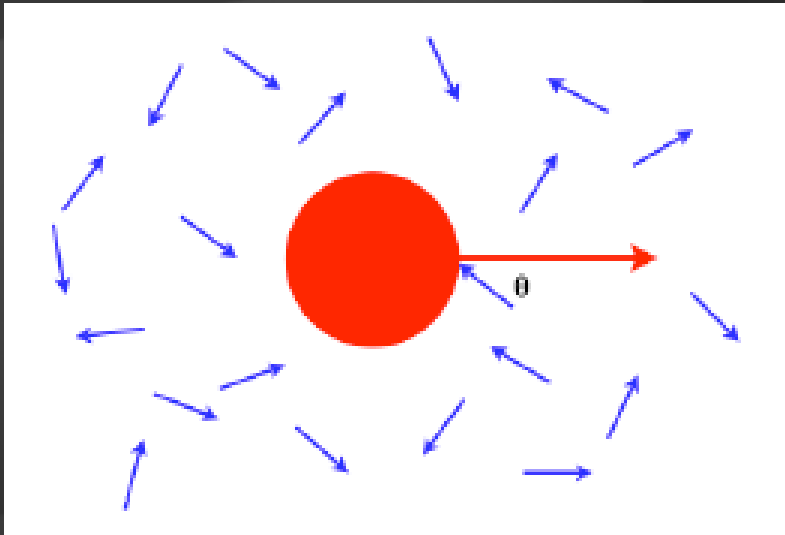
- muon astronomy: search for the sources of the Galactic cosmic rays
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- ...



cosmic rays in IceCube

- galactic
- not solar
- highest energies approach the “knee”
- gyroradius < 1 pc in microgauss field
- closest sources < 100 pc

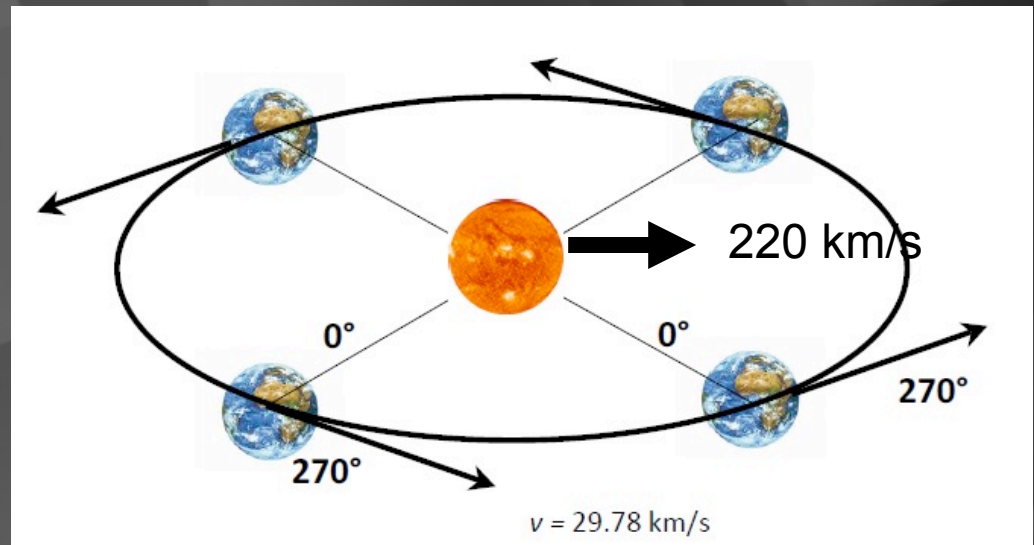




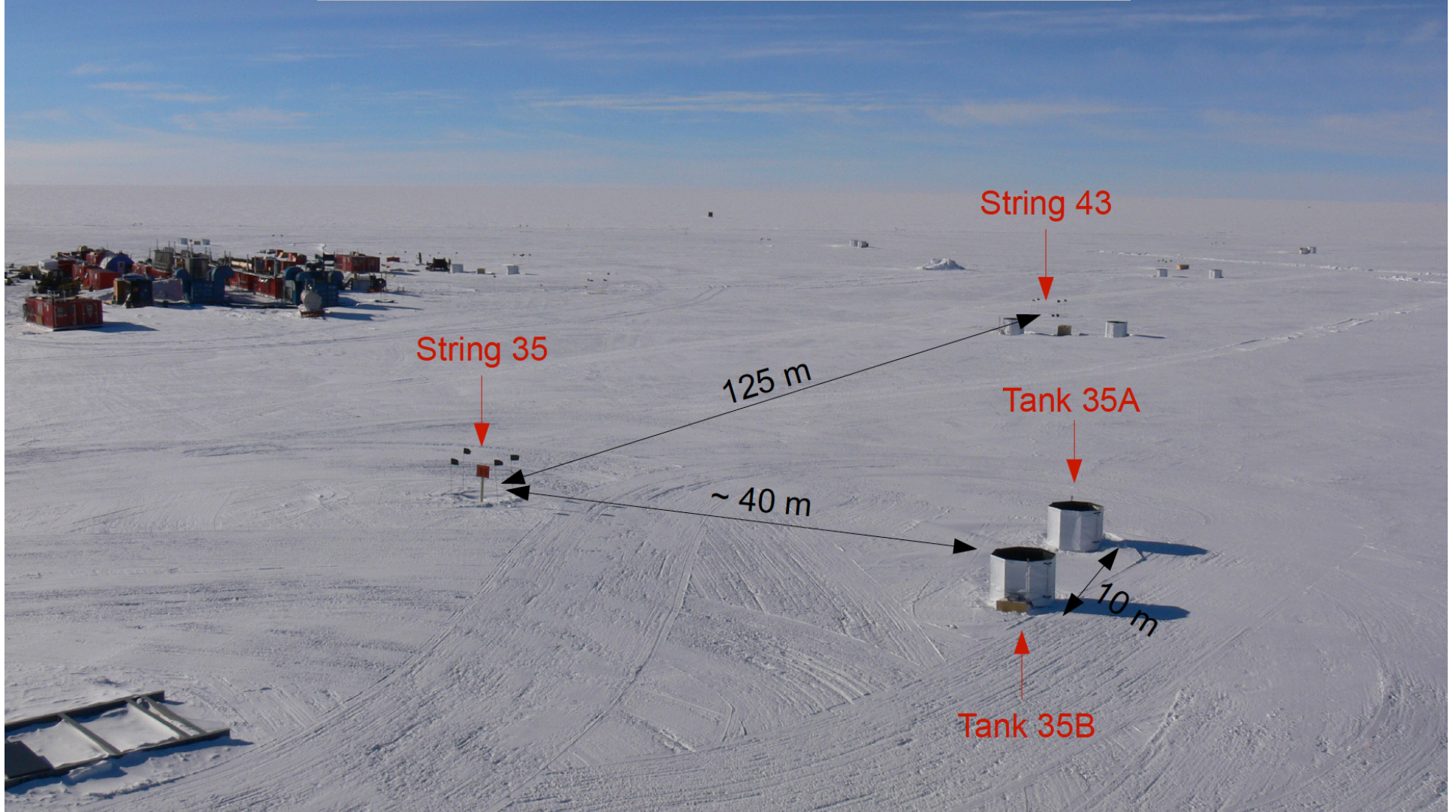
dipole anisotropies

motion of the Earth in the frame of the cosmic rays?

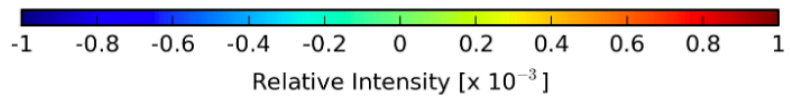
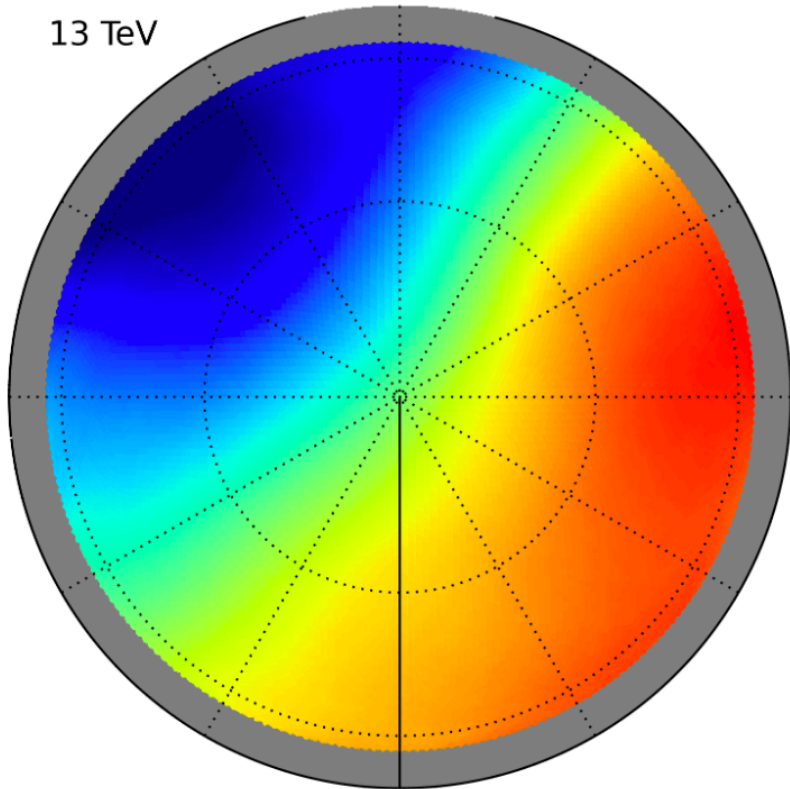
- solar dipole:
motion of the Earth around the sun
- motion of the Sun relative to the Galaxy
(Compton-Getting)



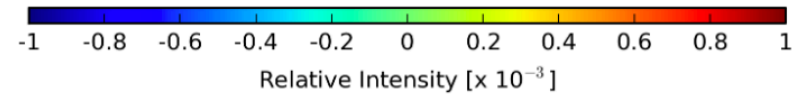
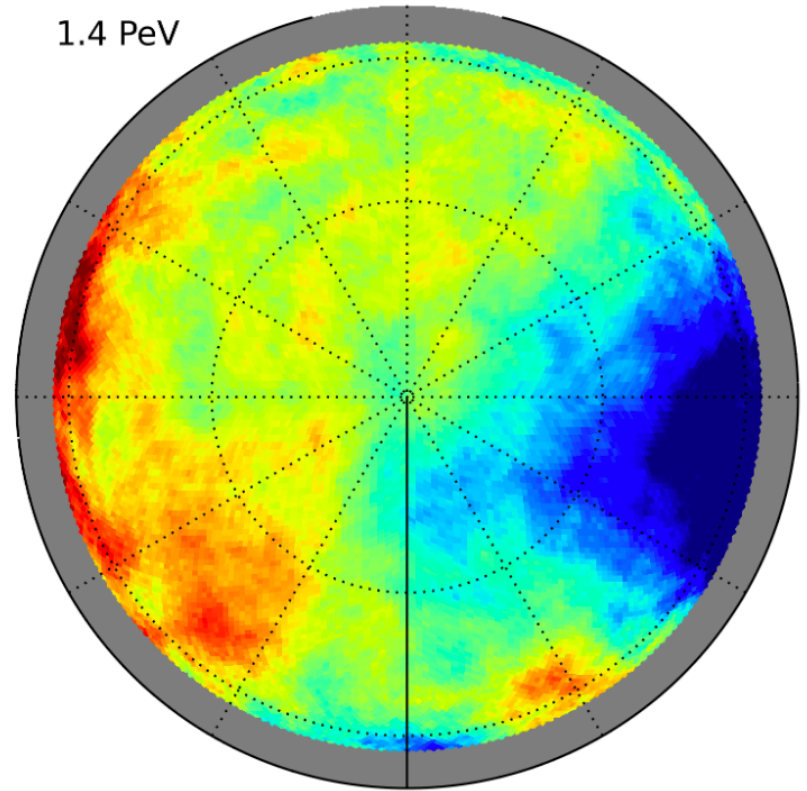
look at the cosmic rays directly



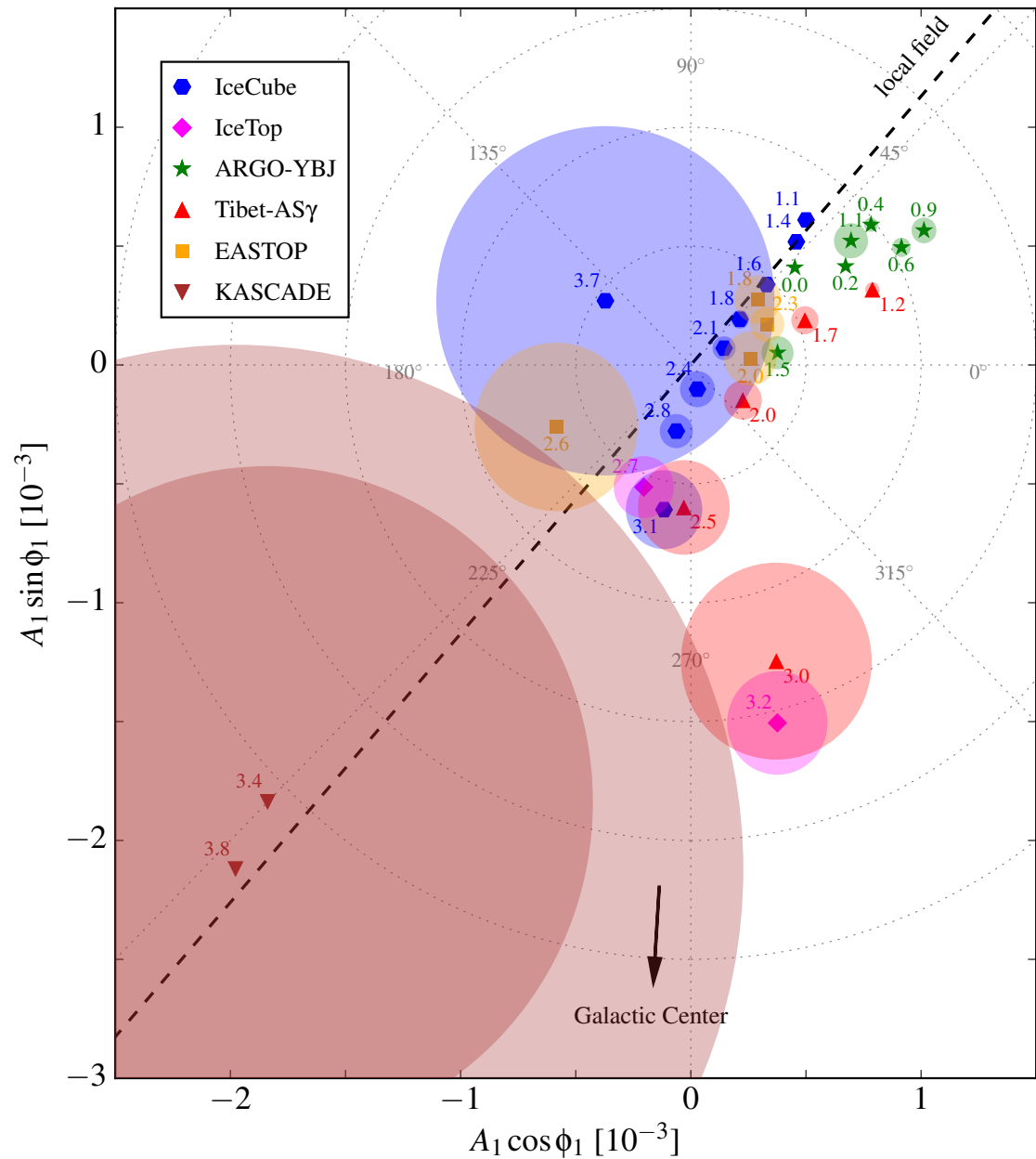
13 TeV

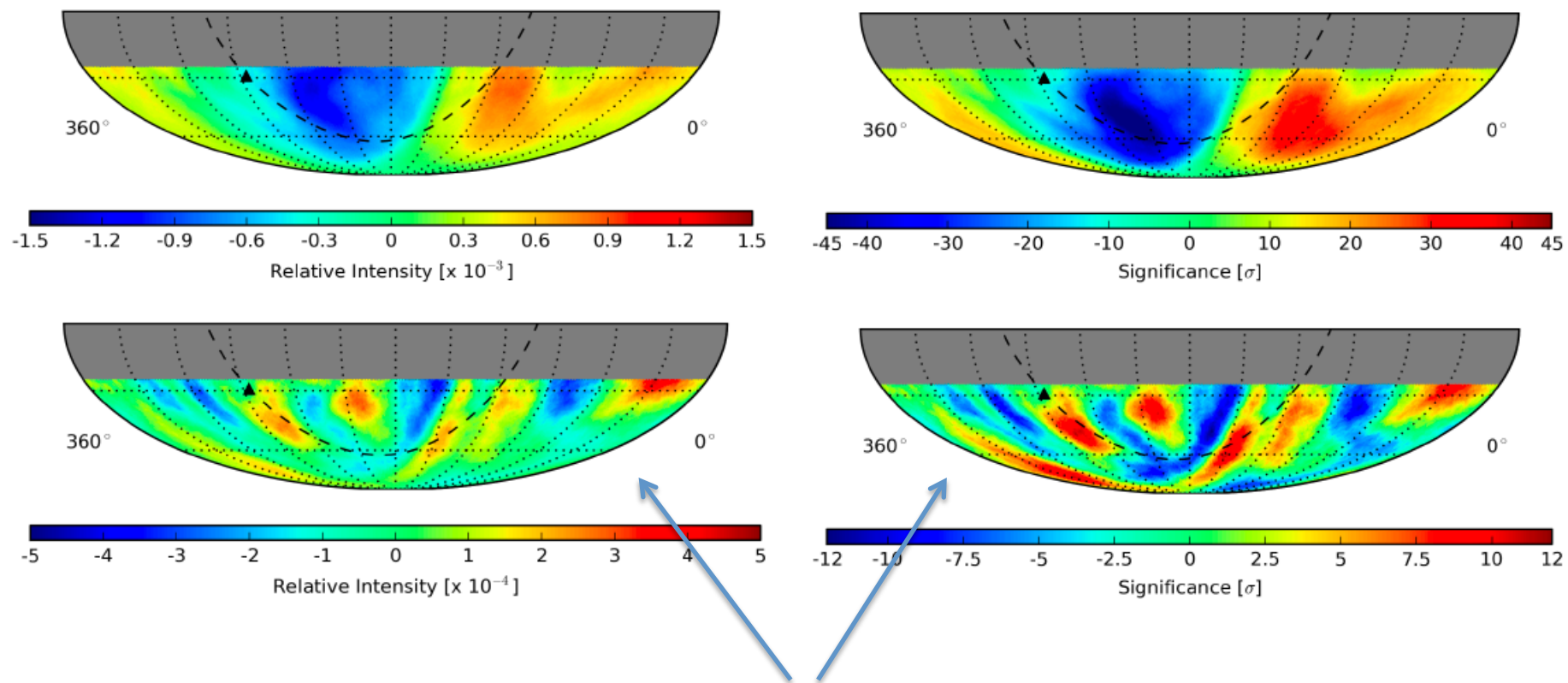


1.4 PeV



dipole rotates from the direction of the local magnetic field at TeV energy to the direction of the Galactic center at PeV energy possibly reflecting nearby sources (in the Orion region?)





after subtraction of dipole and quadrupole

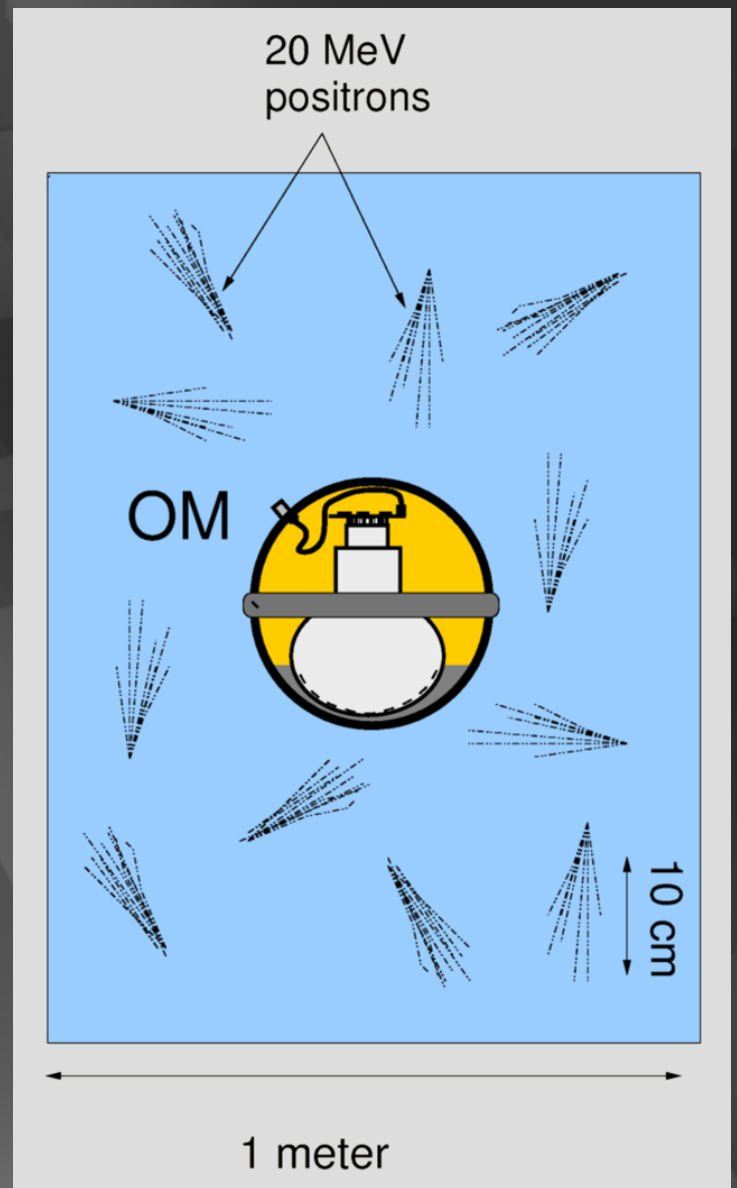
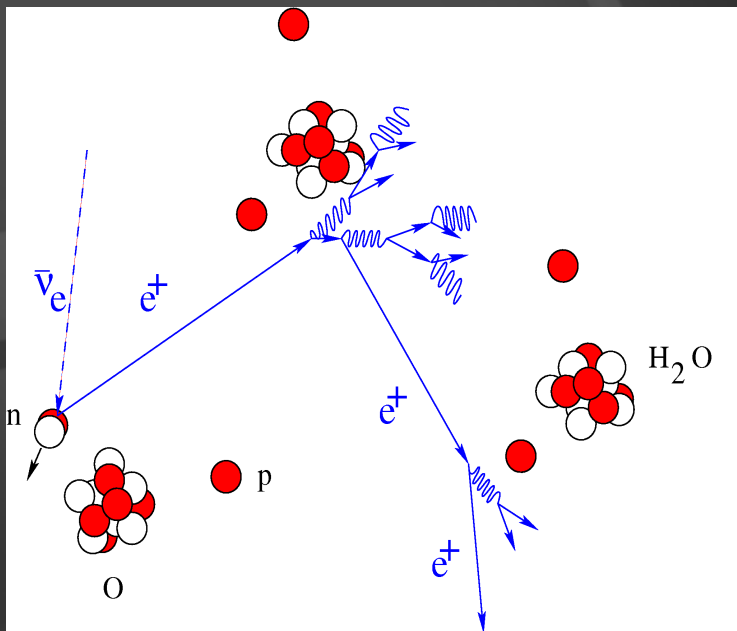


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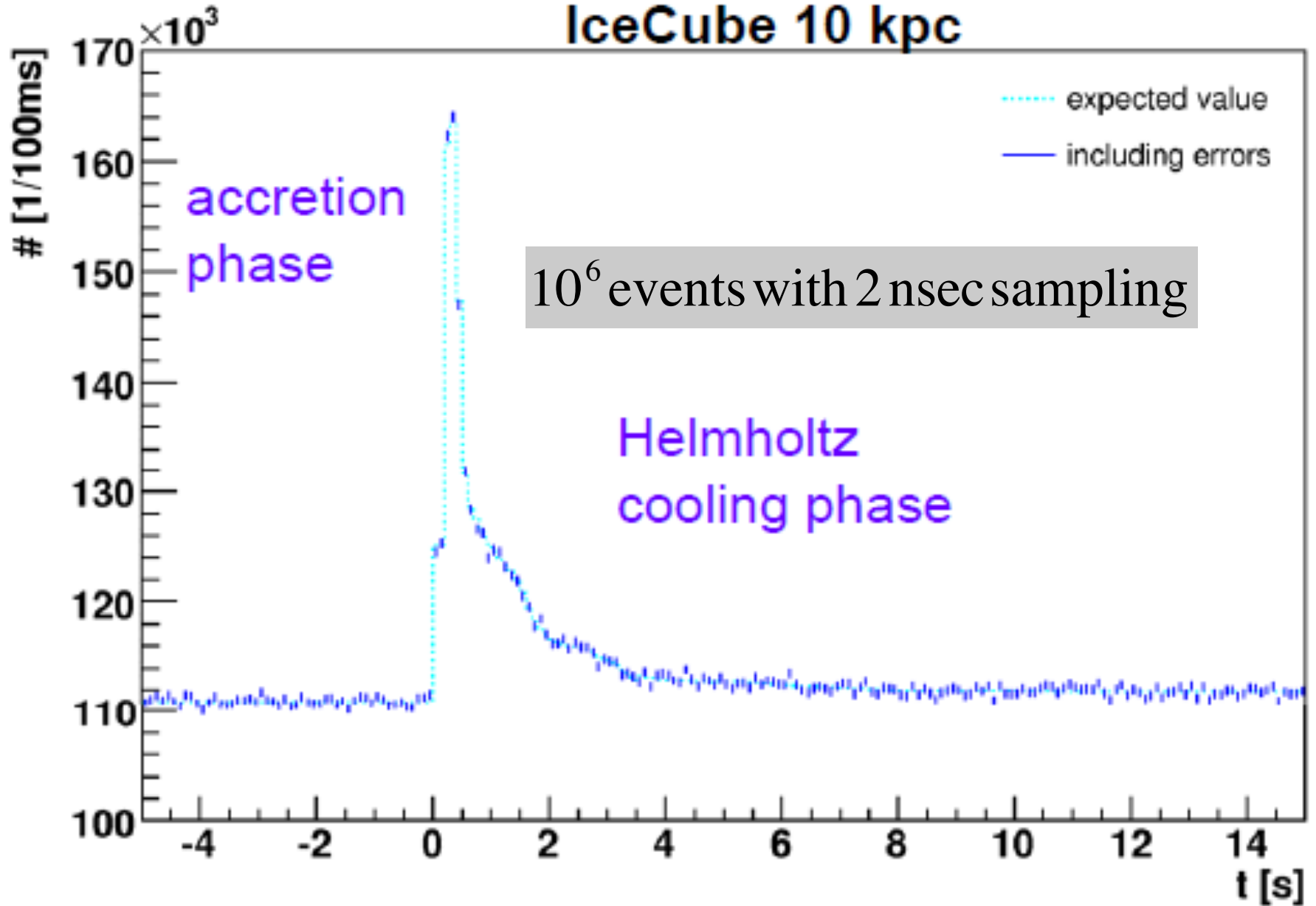
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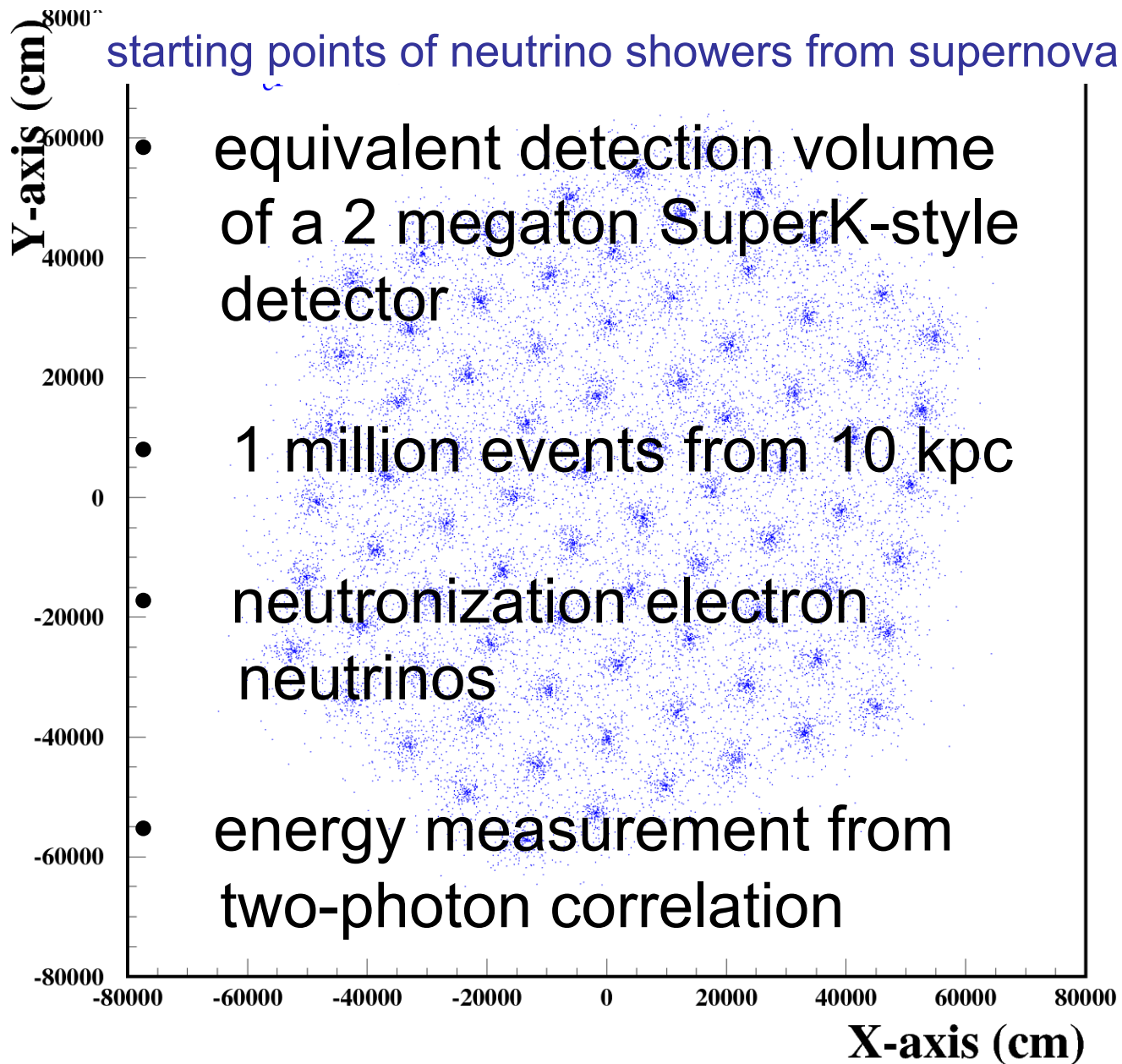
supernova burst: light from $\bar{\nu}_e + p \rightarrow n + e^+$

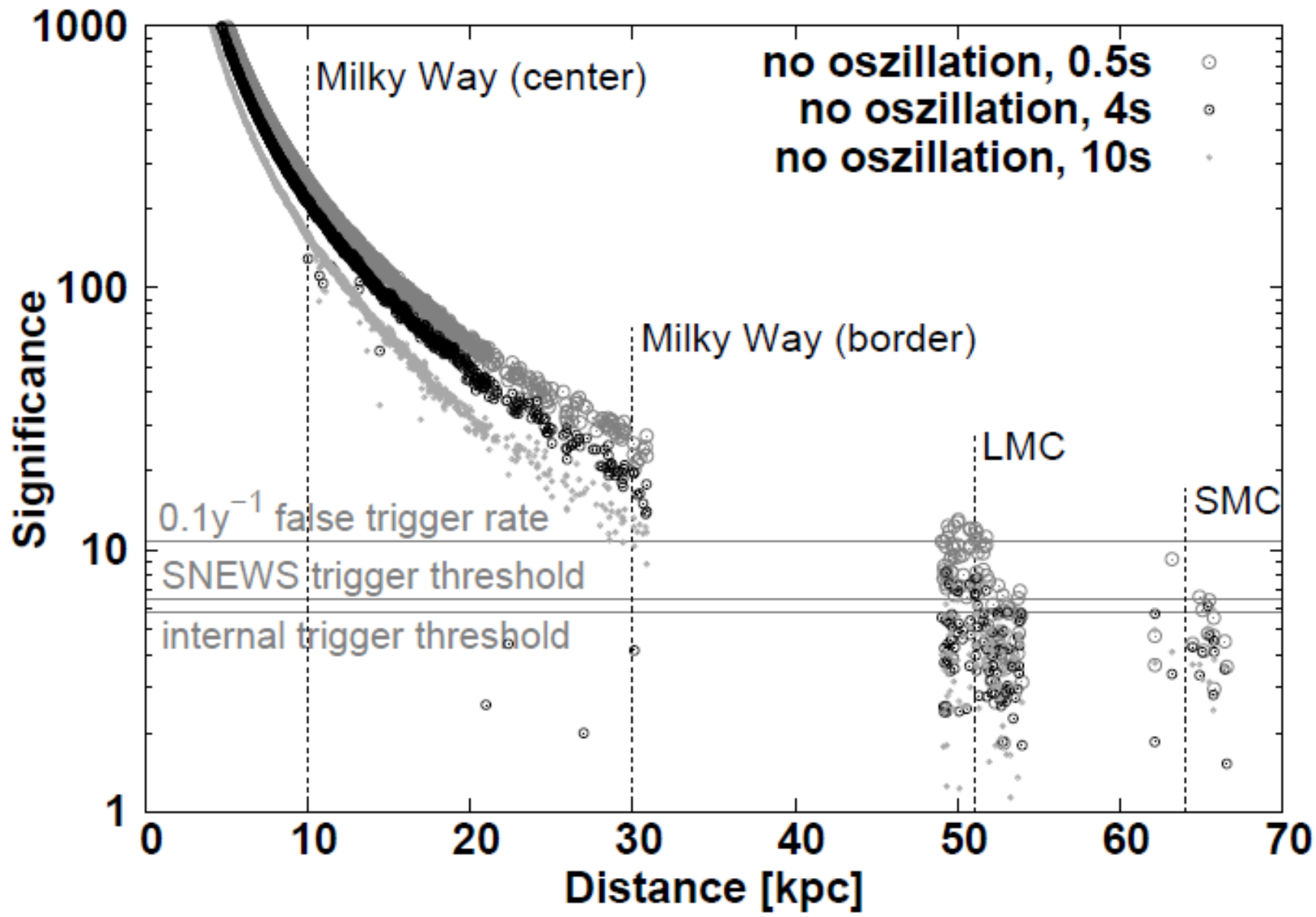


- ☞ PMT noise low (280 Hz)
- ☞ detect correlated rate increase on top of PMT noise when supernova neutrinos pass through the detector

IceCube 10 kpc

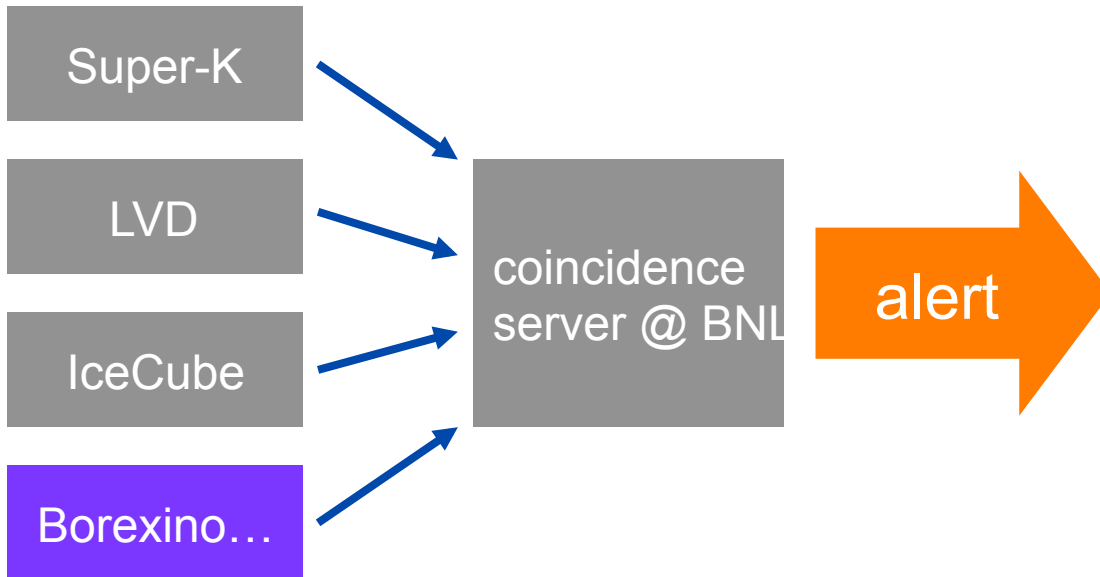






Participation in SNEWS

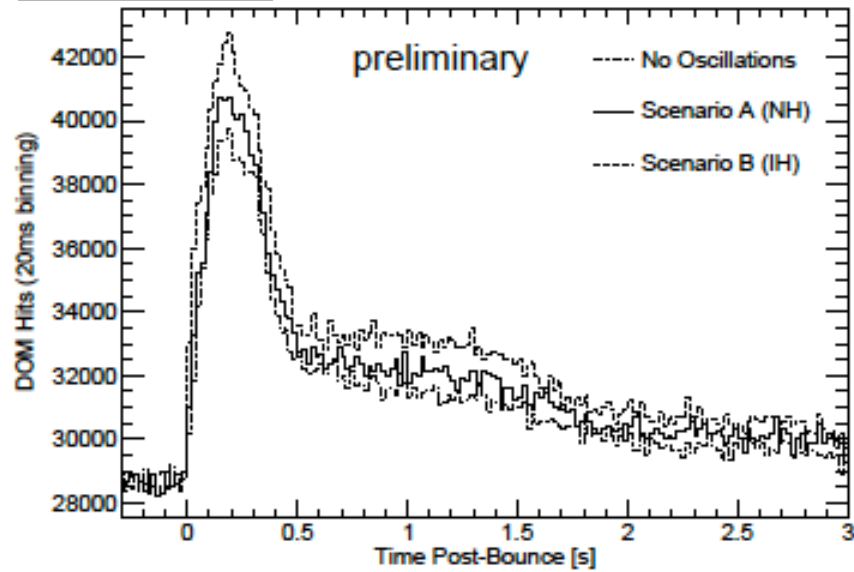
...several hours advanced notice to astronomers ...



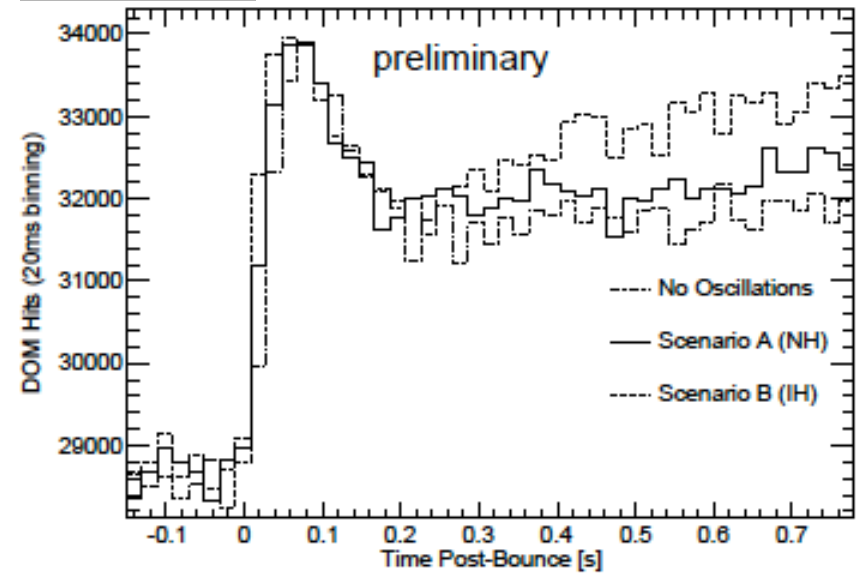
received iridium messages (last 4 weeks)			
message type	time (UTC)	time delay to reception (seconds)	needed modem dial attempts
missing test message(s)			
test	Mon Jul 10 08:19:38 2006	224	1
test	Sun Jul 9 11:15:12 2006	218	1
test	Sat Jul 8 11:15:12 2006	208	1
test	Fri Jul 7 11:15:12 2006	208	1
test	Thu Jul 6 11:15:11 2006	214	1
test	Thu Jul 6 11:09:05 2006	205	1
missing test message(s)			
test	Mon Jul 3 09:45:12 2006	195	1
sn	Sun Jul 2 11:17:12 2006	445	1
signal strength is [8.716532e+00 ± 1.325448e+00] Hz analysis timebase is [4] sec, active channels are [476], χ^2 is [5.421858e+02]			
test	Sun Jul 2 09:45:11 2006	196	1
test	Sat Jul 1 09:45:12 2006	195	1
test	Fri Jun 30 09:45:12 2006	185	1
test	Thu Jun 29 09:45:12 2006	181	1
sn	Wed Jun 28 11:20:29 2006	448	1
signal strength is [7.296678e+00 ± 8.447978e-01] Hz analysis timebase is [10] sec, active channels are [474], χ^2 is [5.770201e+02]			
test	Wed Jun 28 09:45:12 2006	185	1
test	Tue Jun 27 09:45:12 2006	175	1
test	Mon Jun 26 09:45:12 2006	175	1
test	Sun Jun 25 09:45:12 2006	176	1
sn	Sun Jun 25 02:15:47 2006	571	2
signal strength is [9.946102e+00 ± 1.333087e+00] Hz analysis timebase is [4] sec, active channels are [475], χ^2 is [5.061309e+02]			
test	Sat Jun 24 09:45:12 2006	165	1
test	Fri Jun 23 09:45:12 2006	165	1
test	Fri Jun 23 09:26:21 2006	170	1
test	Fri Jun 23 08:59:13 2006	732	10
test	Thu Jun 22 10:33:23 2006	162	1
test	Thu Jun 22 09:45:12 2006	160	1
test	Thu Jun 22 09:38:29 2006	163	1
test	Thu Jun 22 09:27:30 2006	167	1
test	Thu Jun 22 08:45:12 2006	173	1
missing test message(s)			
test	Tue Jun 20 09:30:12 2006	154	1

<http://snews.bnl.gov> astro-ph/0406214

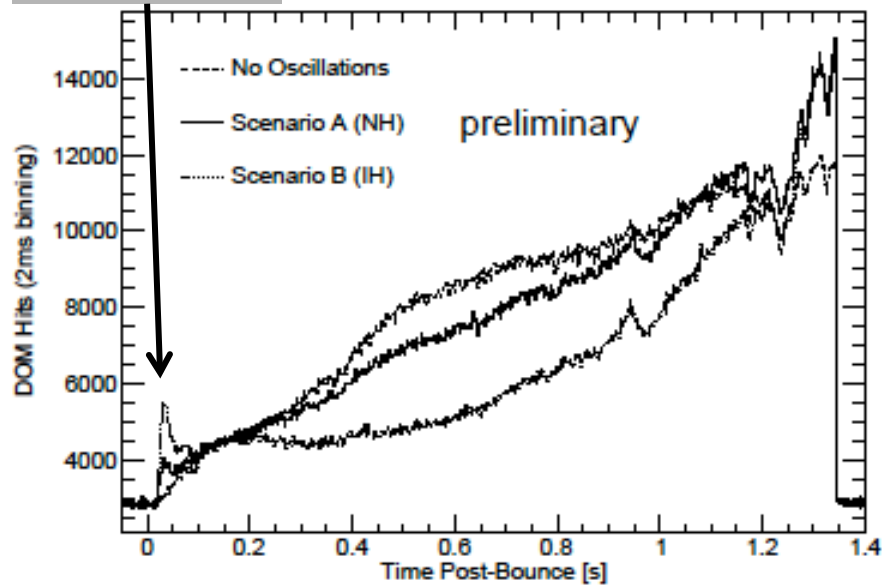
Livermore



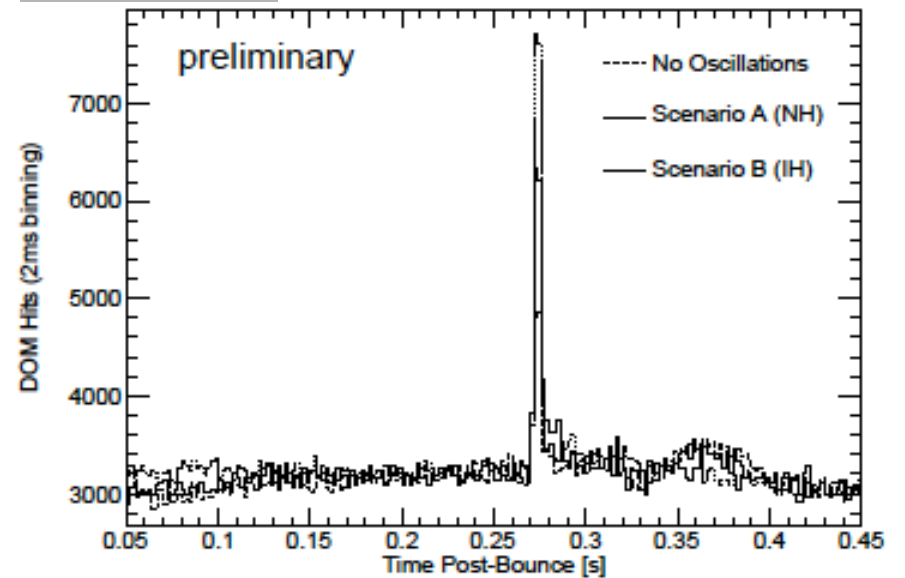
Garching



quark star



black hole





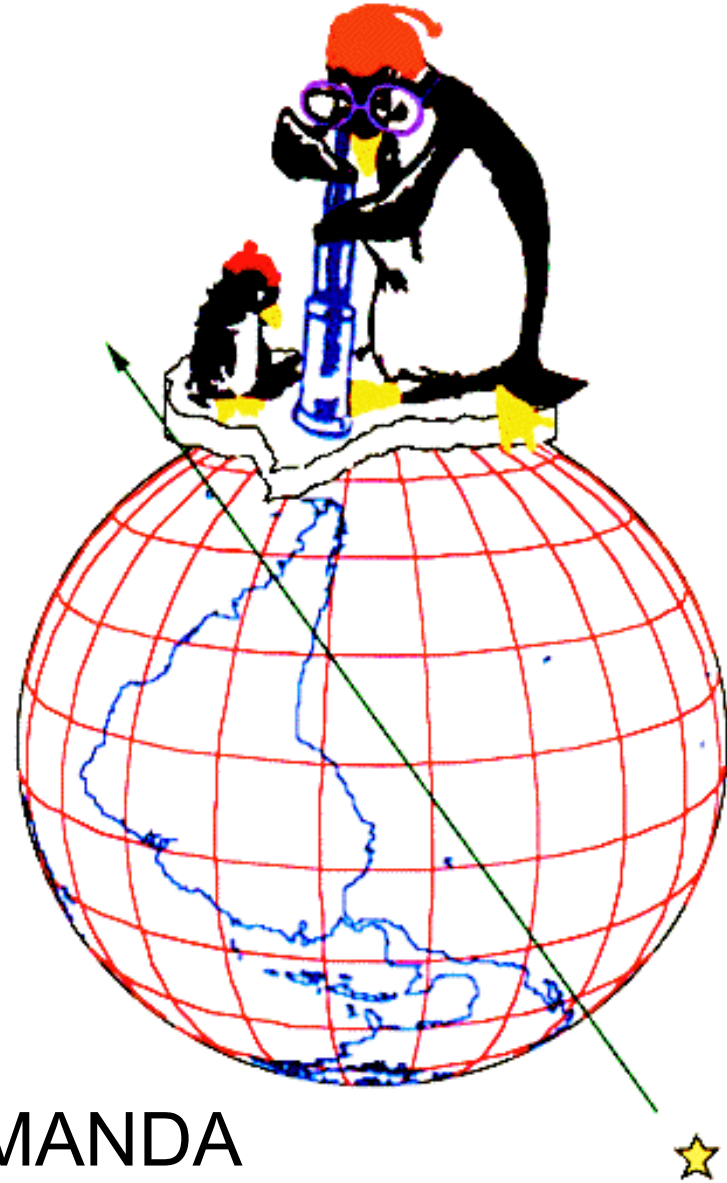
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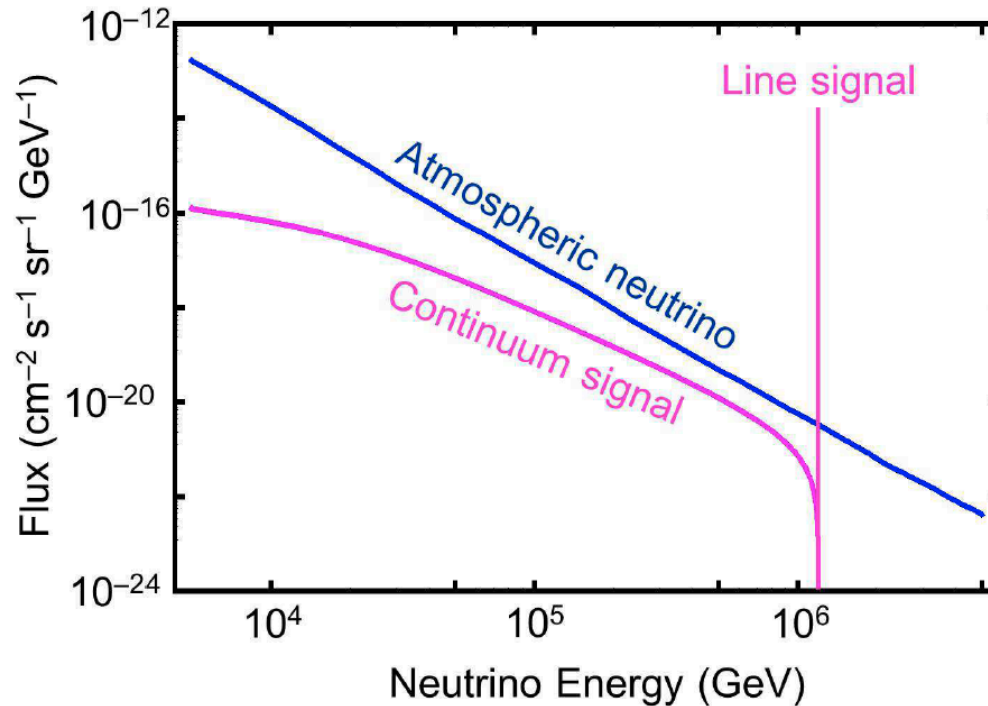
1992 Cline meeting at UCLA

The Economist FEBRUARY 29TH-MARCH 6TH 1992	FLAWED SUPERFUND	pages 18 and 80
	CALIFORNIA'S WOMEN	page 32
	MULTI-MEDIA MADNESS	pages 17 and 73
	ANTARCTIC SCIENCE	pages 91-93

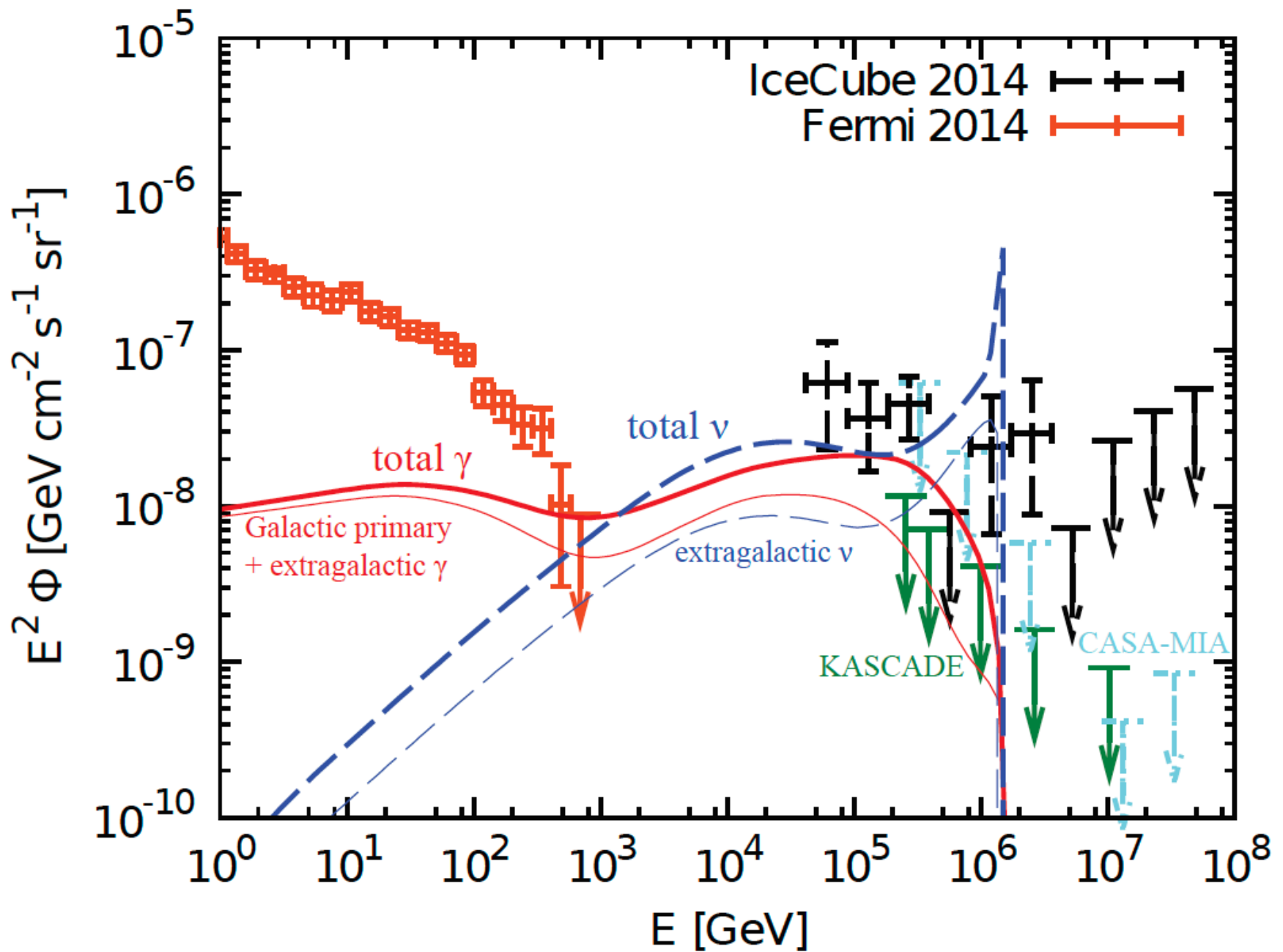


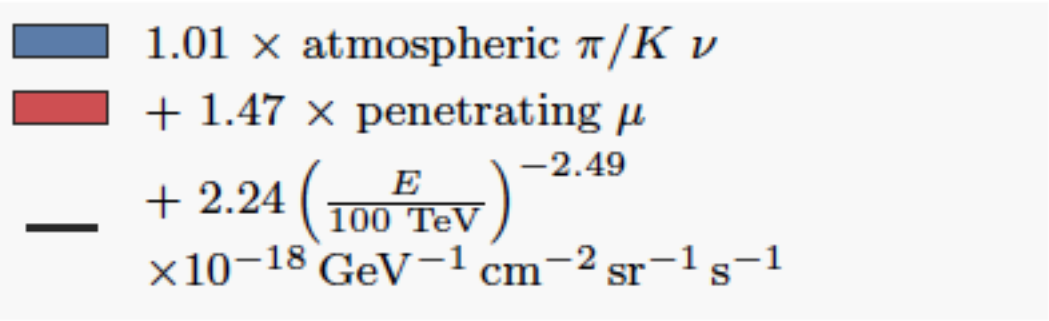
AMANDA

late decay of PeV-mass dark matter

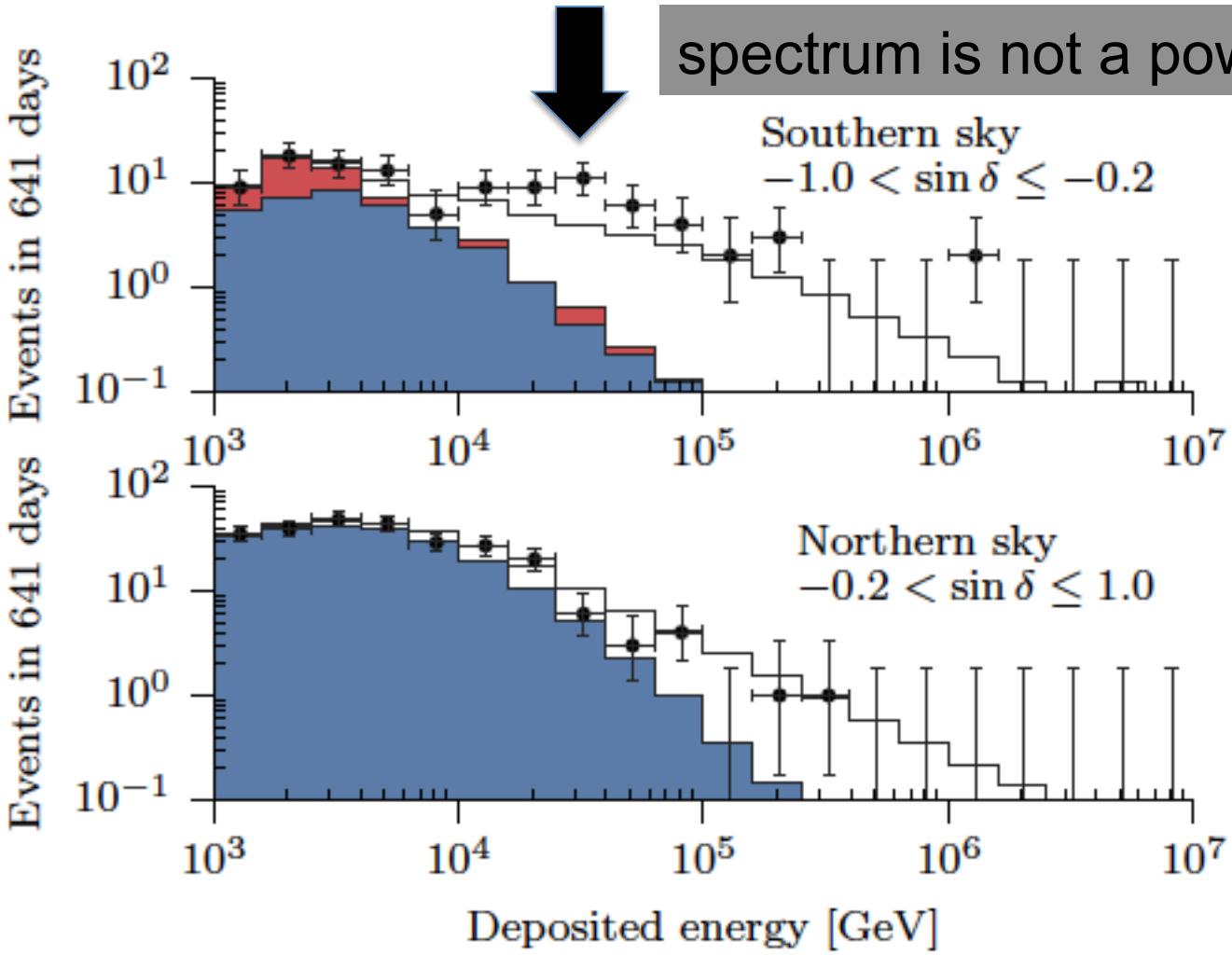


Brian Feldstein^(a), Alexander Kusenko^(a,b),
Shigeki Matsumoto^(a), and Tsutomu T. Yanagida^(a)





spectrum is not a power





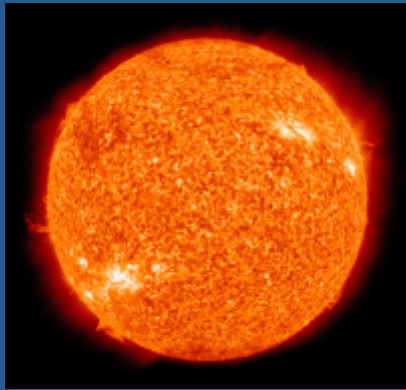
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- ...

IceCube targets for dark matter annihilation

Sun



Galactic Centre



Dwarf galaxies



Earth

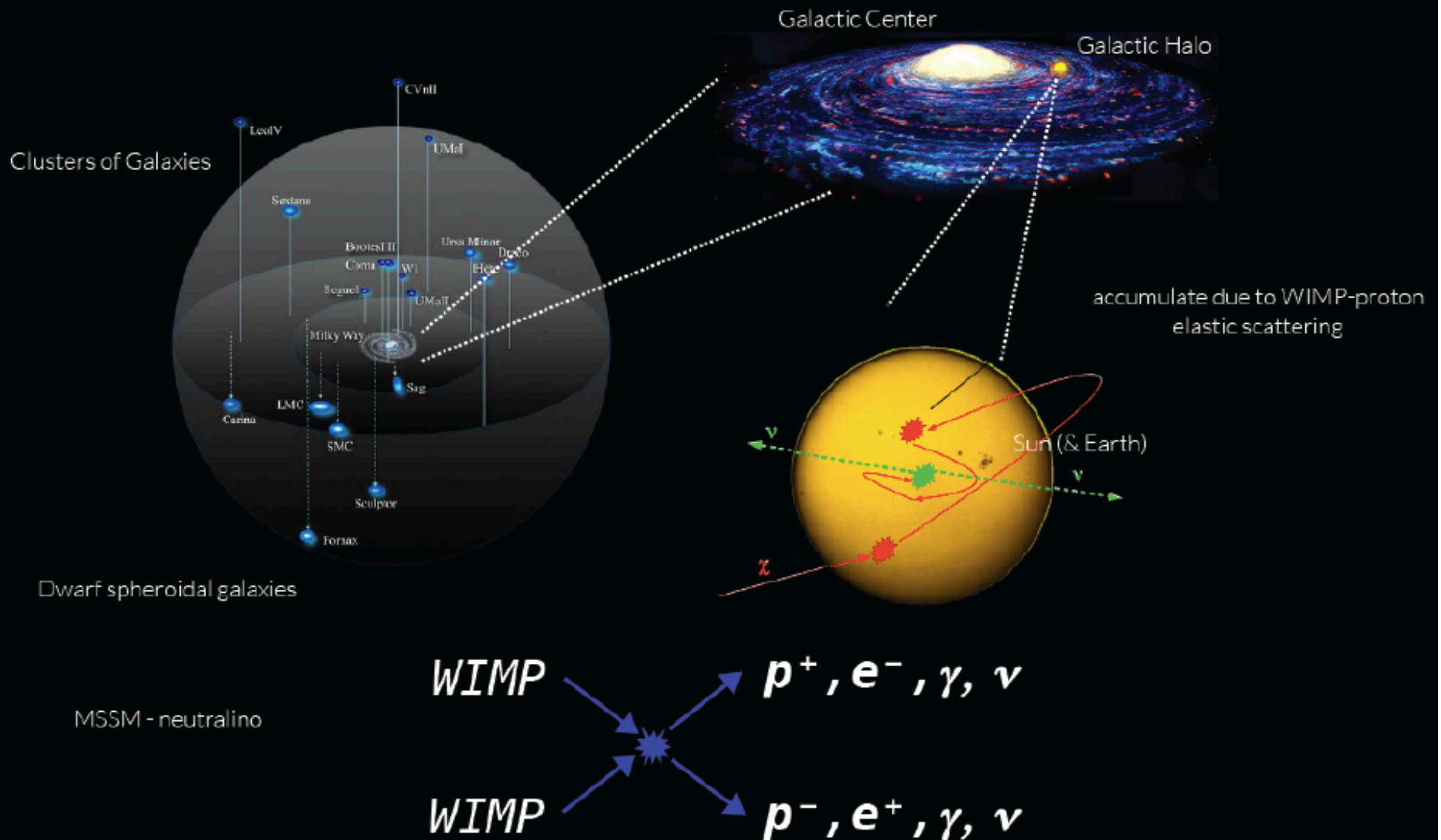


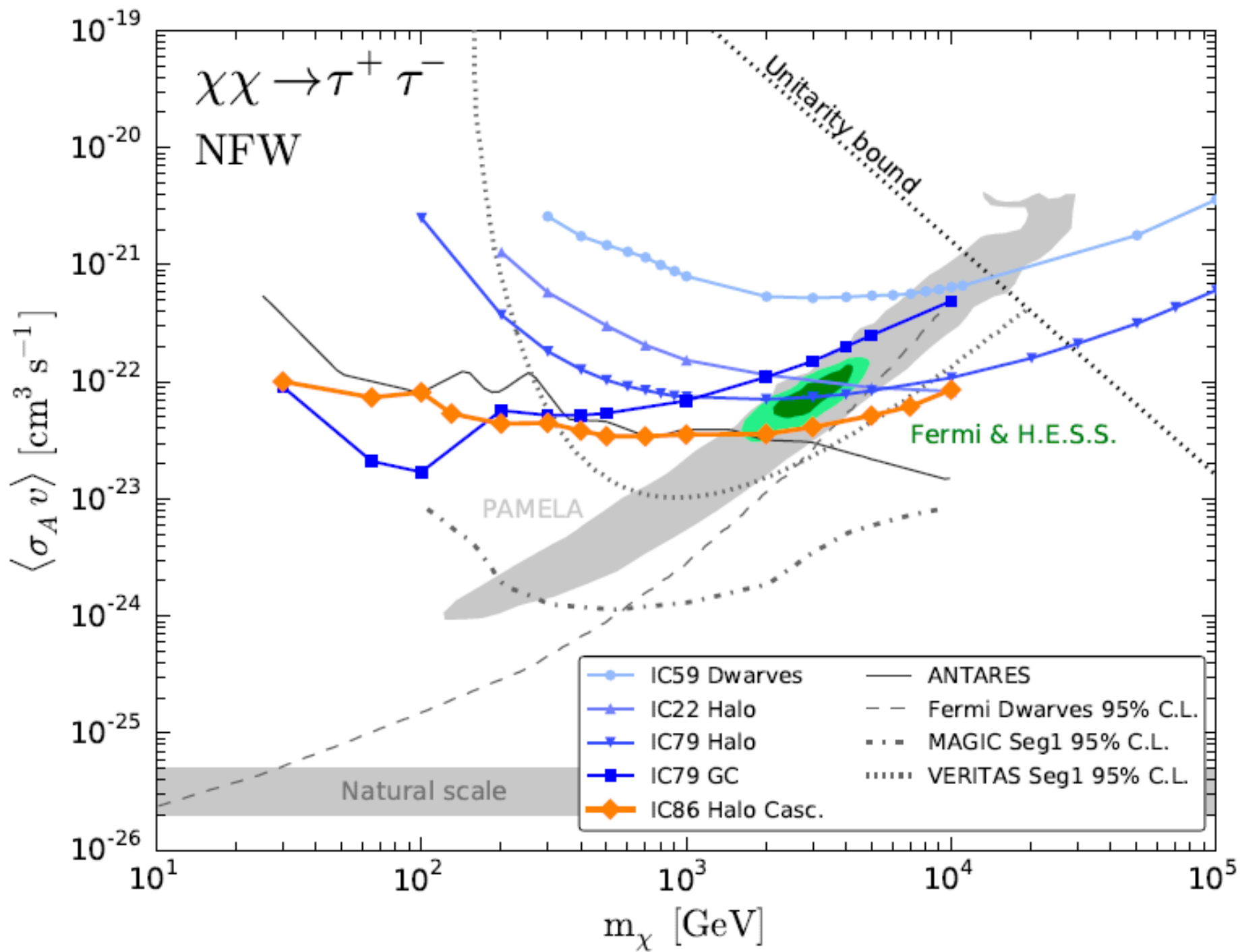
Galactic Halo



Galaxy clusters

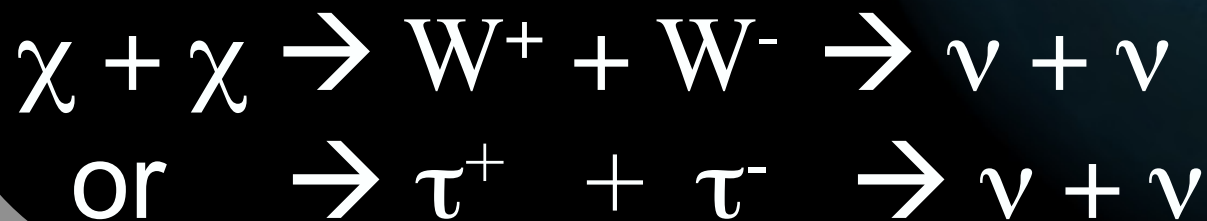
IceCube DM targets

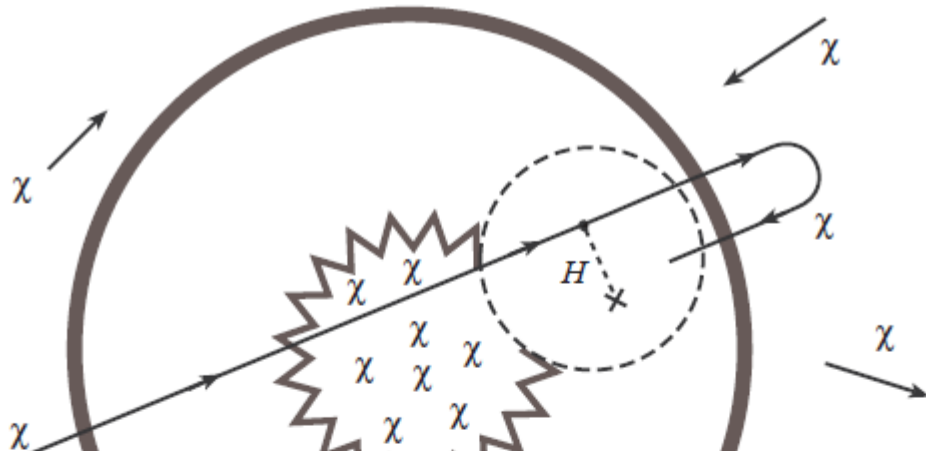




WIMP Capture and Annihilation

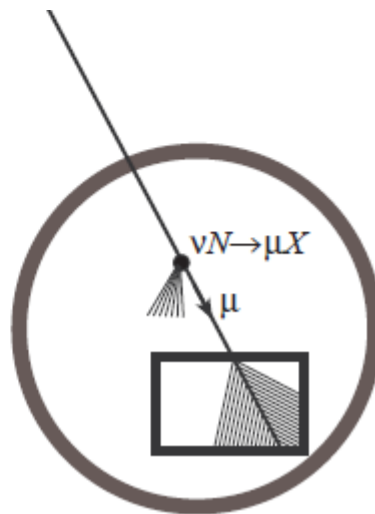
- 1 Halo WIMPs scatter on nuclei in the Sun
- 2 Some lose enough energy in the scatter to be gravitationally bound
- 3 Scatter some more, sink to the core
- 4 Annihilate with each other, producing neutrinos
- 5 Propagate+oscillate their way to the south pole, convert into muons in the ice





$$C^\odot \approx 3.35 \times 10^{20} \text{ sec}^{-1} \left(\frac{\rho_{\text{local}}}{0.3 \text{ GeV/cm}^3} \right) \left(\frac{270 \text{ km/s}}{\bar{v}_{\text{local}}} \right)^3 \left(\frac{100 \text{ GeV}}{m_\chi} \right)^2$$

$$\times \left(\frac{\sigma_{\chi\text{H,SD}} + \sigma_{\chi\text{H,SI}} + 0.07 \sigma_{\chi\text{He,SI}} + 0.0005 S(m_\chi/m_\text{O}) \sigma_{\chi\text{O,SI}}}{10^{-6} \text{ pb}} \right).$$



supersymmetry on
the back of an
envelope
arXiv 9404252

$$\frac{dN_{\chi}}{dt} = C_{sun} = \varphi_{\chi} \sigma_{sun}$$

- $\varphi_{\chi} = \left[\frac{\rho}{m_{\chi}} \right] v_{\chi}$

- $\sigma_{sun} = \frac{M_{sun}}{m_p} \sigma_{\chi p}$

- $C_{sun} = 2 C_{annihilation}$ (equilibrium)

given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via τ , b or W for instance) the model is seen or ruled out

$$\frac{dN_\chi}{dt} = C_{sun} = \varphi_\chi \sigma_{sun}$$

- $\varphi_\chi = \left[\frac{\rho}{m_\chi} \right] v_\chi$

- $\sigma_{sun} = \left(\frac{M_{sun}}{m_p} \right) \sigma_{\chi p}$

- $C_{sun} = 2 C_{annihilation}$ (equilibrium)

astrophysical assumptions !!!

number of protons in the sun

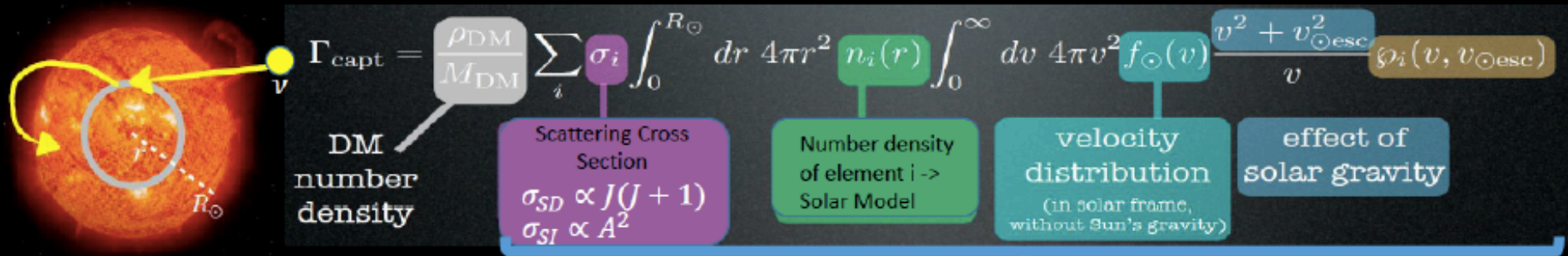
given a cross section on protons and a branching ratio of the annihilation products into neutrinos (via τ , b or W for instance) the model is seen or ruled out

detection is a smoking gun

- indirect rates are dictated by the interaction cross section of WIMPS with hydrogen.
→ no unknown astrophysics
- in the neutrino case there is a direct connection between theory and observation and the background is understood.

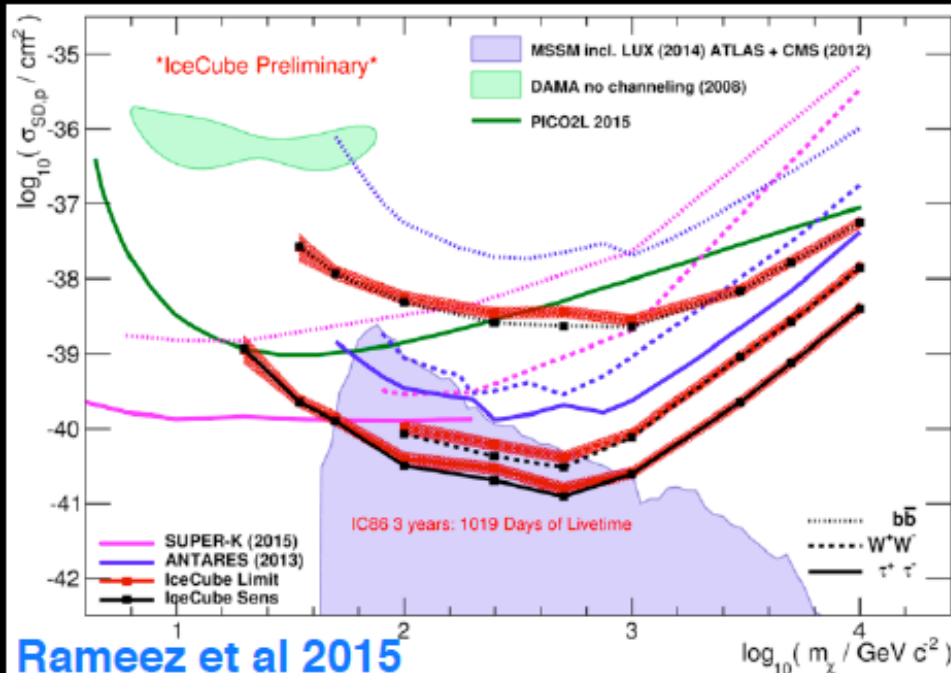
3yrs of WIMP search from the Sun

WIMP Capture and Annihilation in the Sun

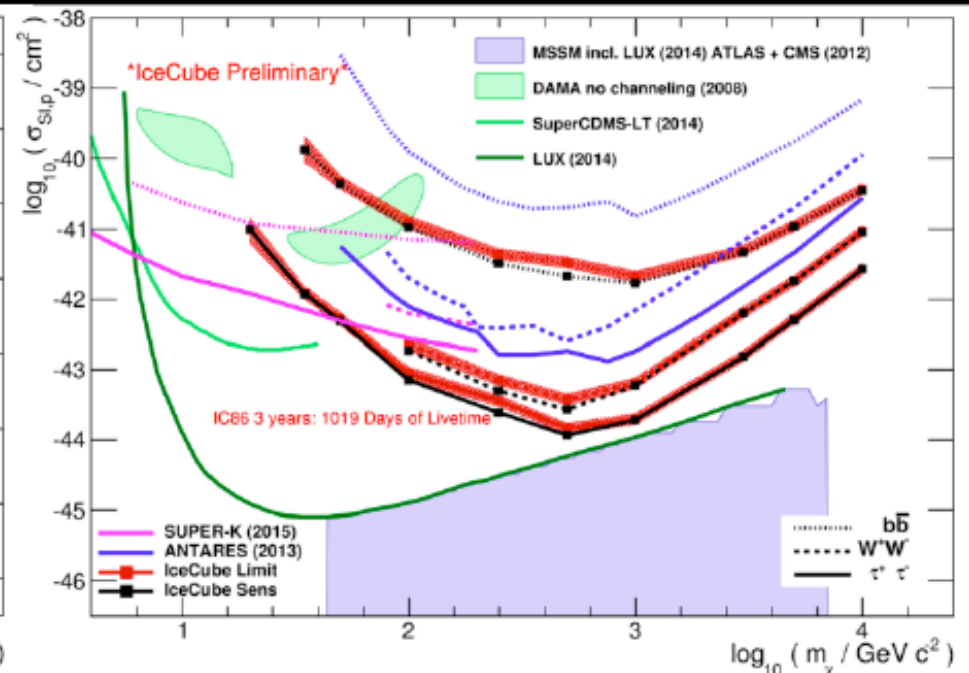


Spin dependent

Spin independent



Rameez et al 2015



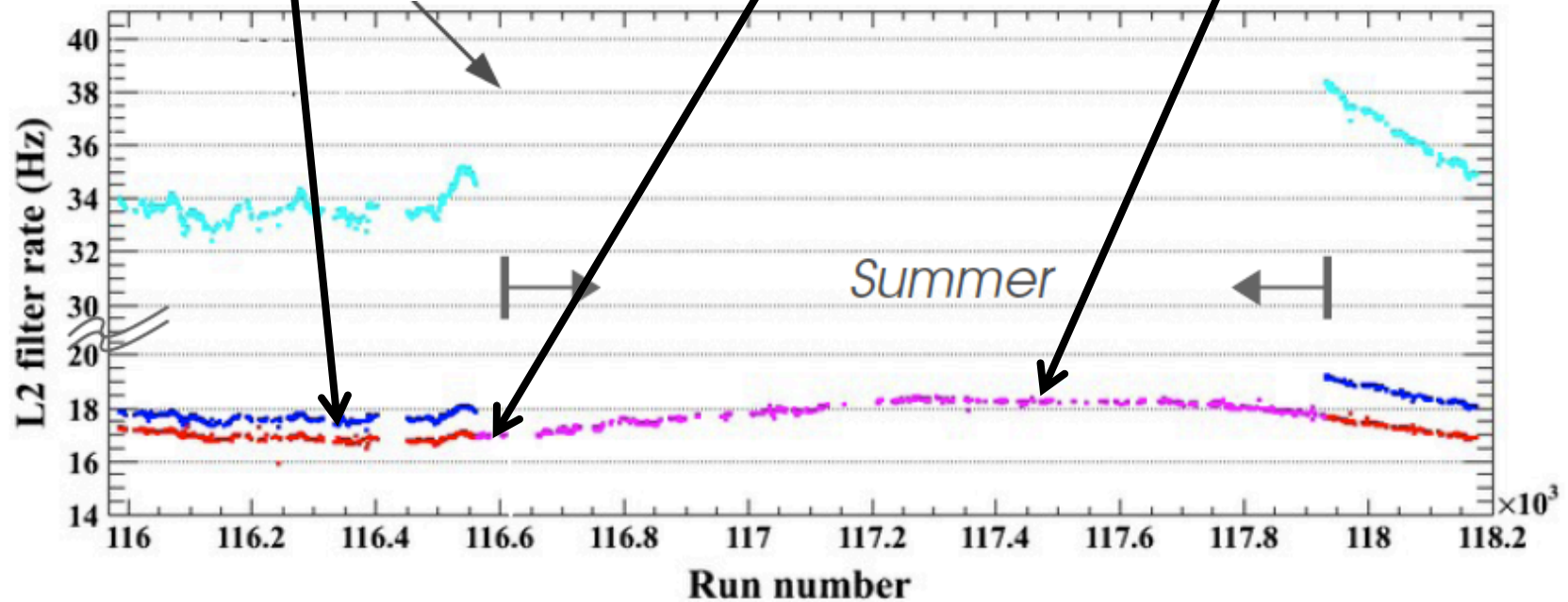
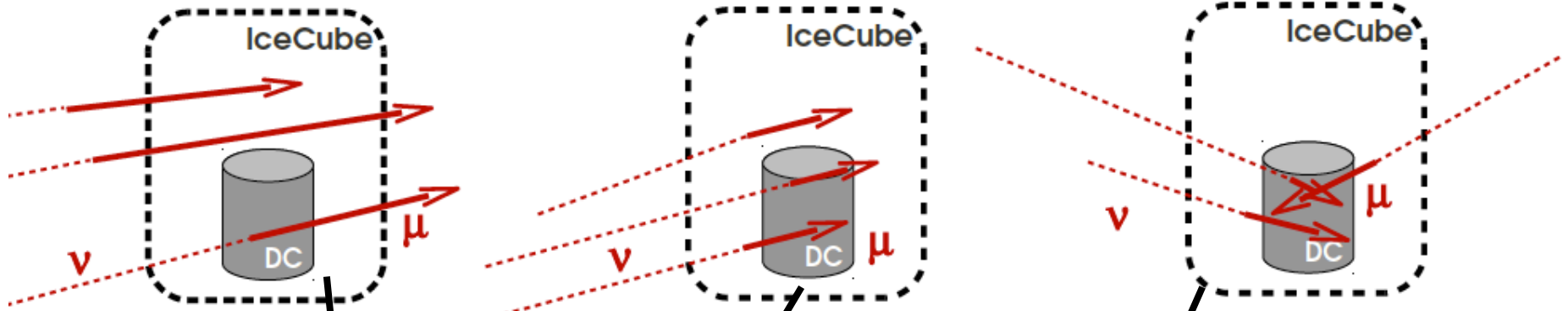
IceCube 79 data

starting events \rightarrow lower energy

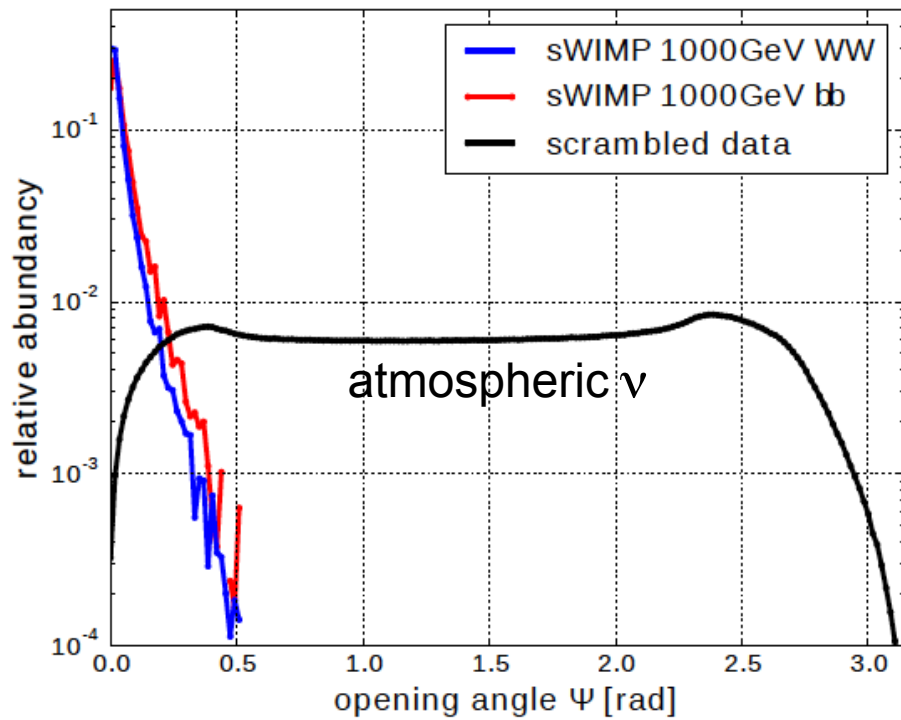
- Up-going ①
- No containment

- Up-going ②
- strong containment

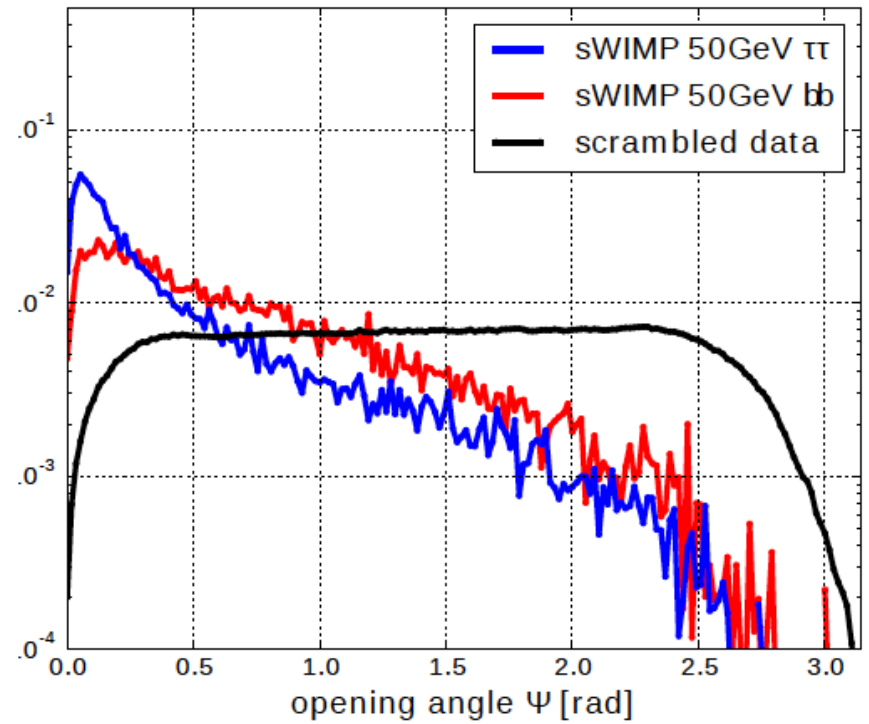
- Down-going ③
- strong containment



sun



$$m_{\chi} = 1 \text{ TeV}$$



$$m_{\chi} = 50 \text{ GeV}$$

Simple shape-Likelihood

Signal PDF from simulation

Background PDF obtained by scrambling Sun-azimuth in exp. data

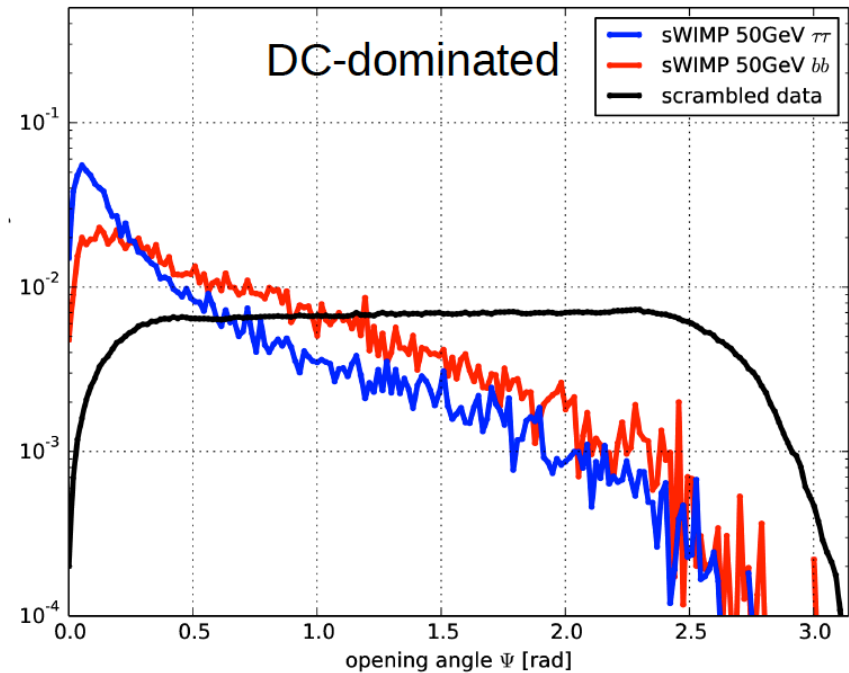
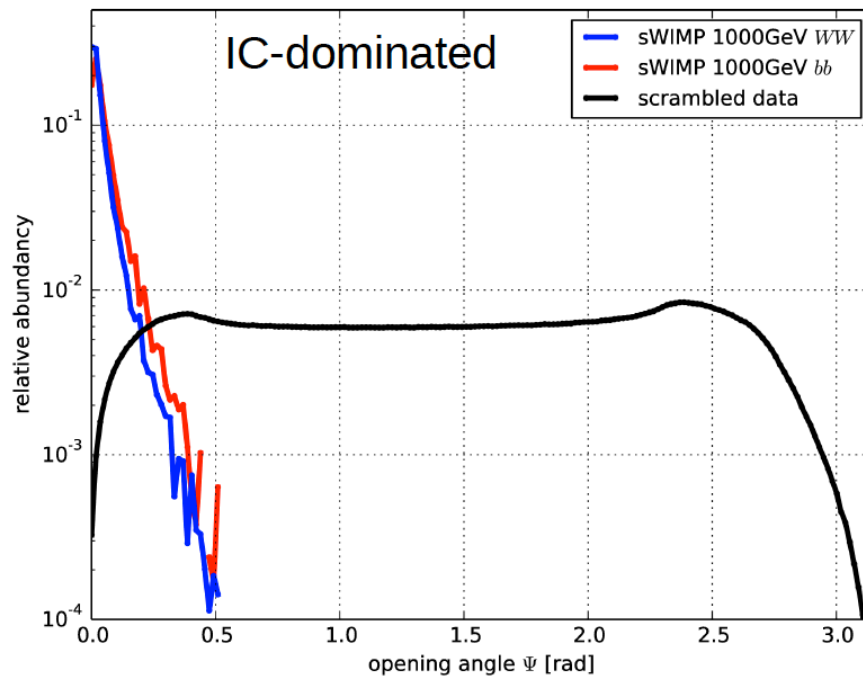
Feldman-Cousins Limits

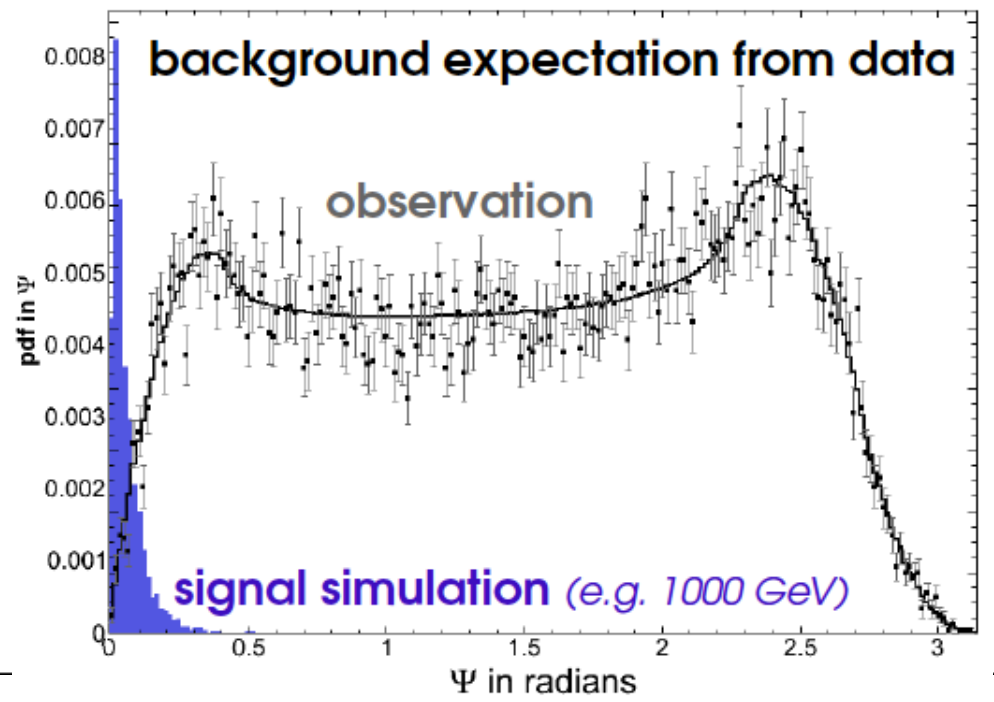
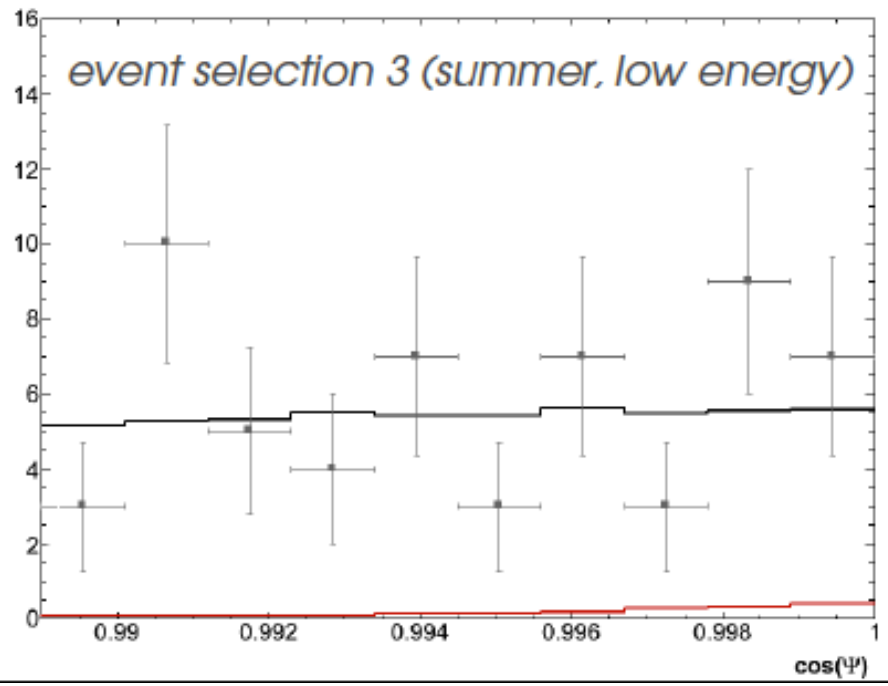
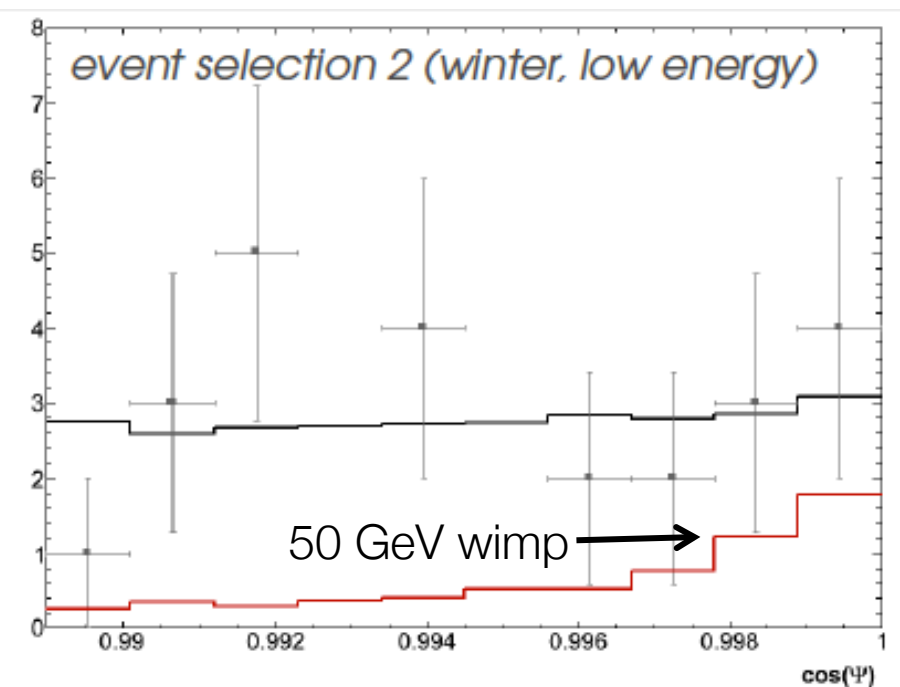
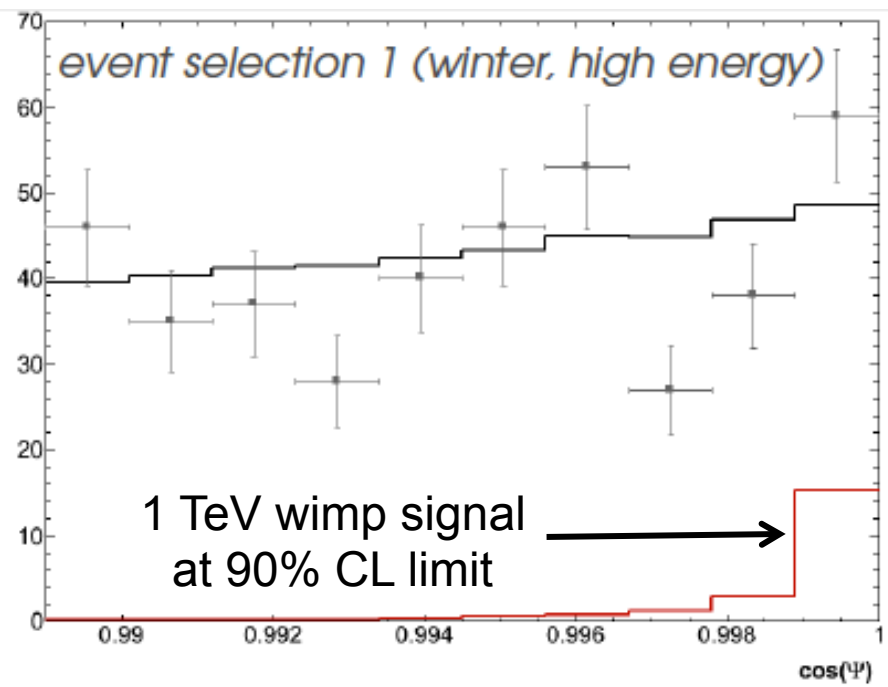
Opening angle towards the Sun

$$\Psi = \text{acos}(r_{\text{reco}}(\theta, \phi) \cdot r_{\text{Sun}}(\theta, \phi))$$

Likelihood

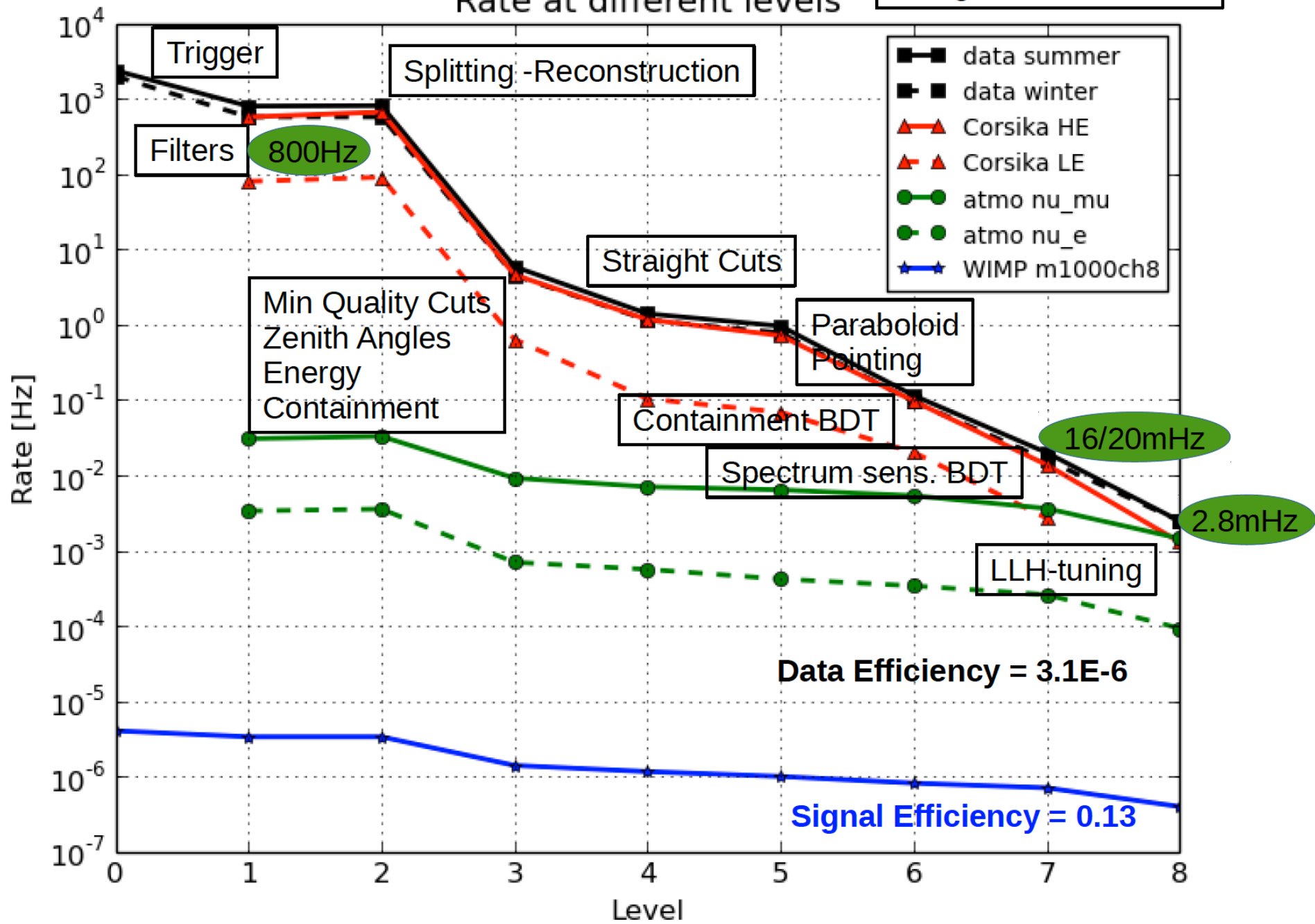
$$f(\Psi|\mu) = \frac{\mu}{n_{\text{obs}}} f_s(\Psi) + \left(1 - \frac{\mu}{n_{\text{obs}}}\right) f_{bg}(\Psi)$$
$$\mathcal{L}(\mu) = \prod_i^N f(e_i|\mu)$$

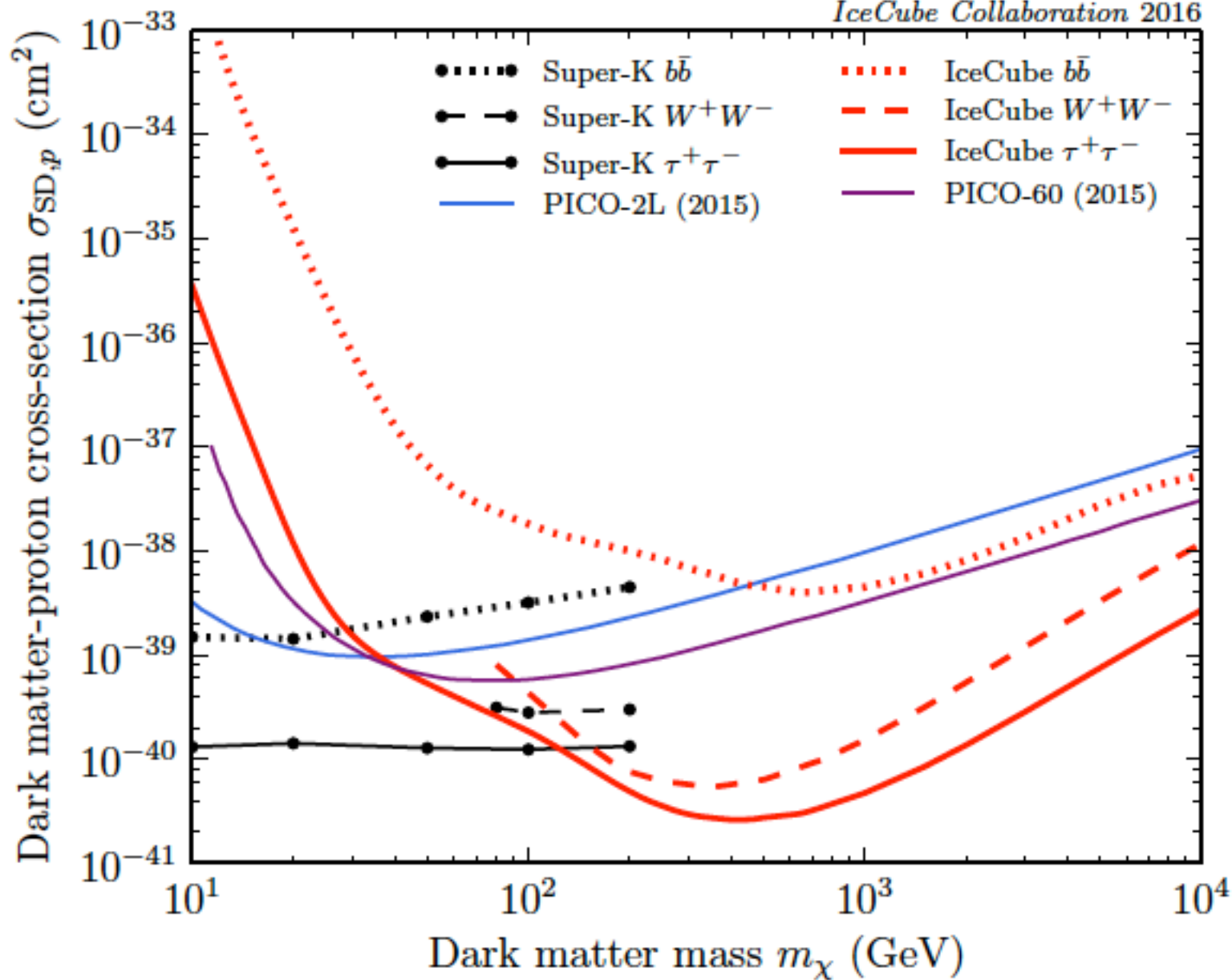




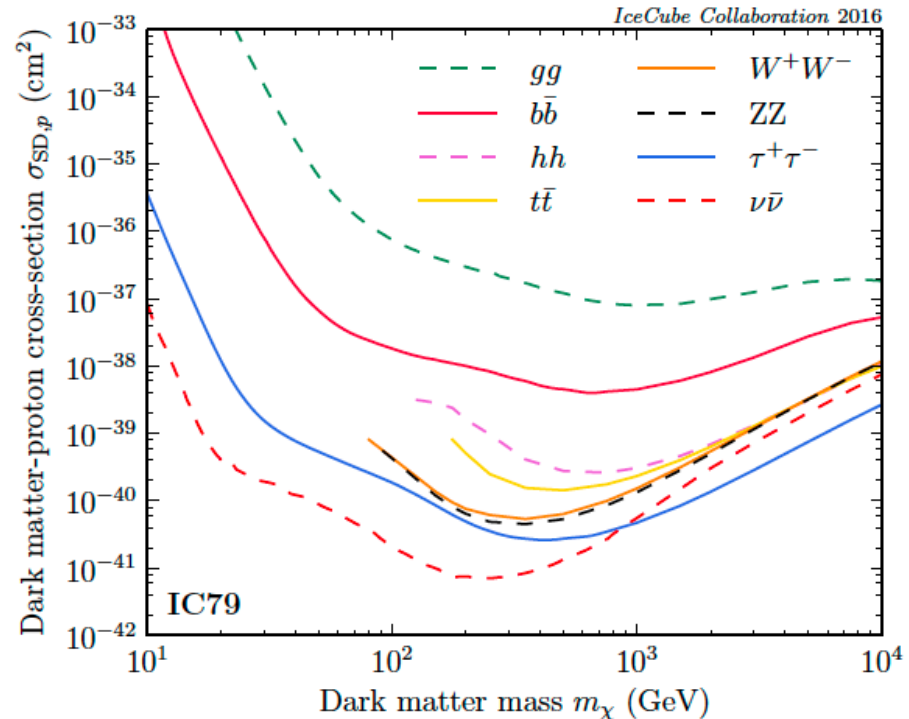
Using **ALL** Selections !

Rate at different levels



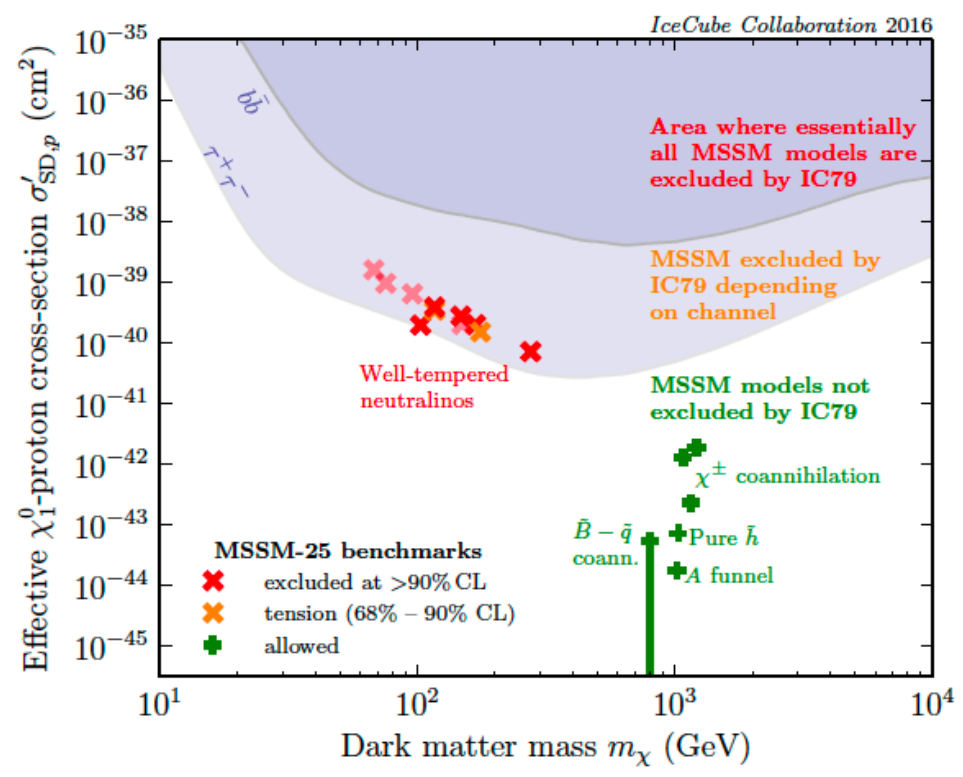


perform your own
IceCube dark matter search

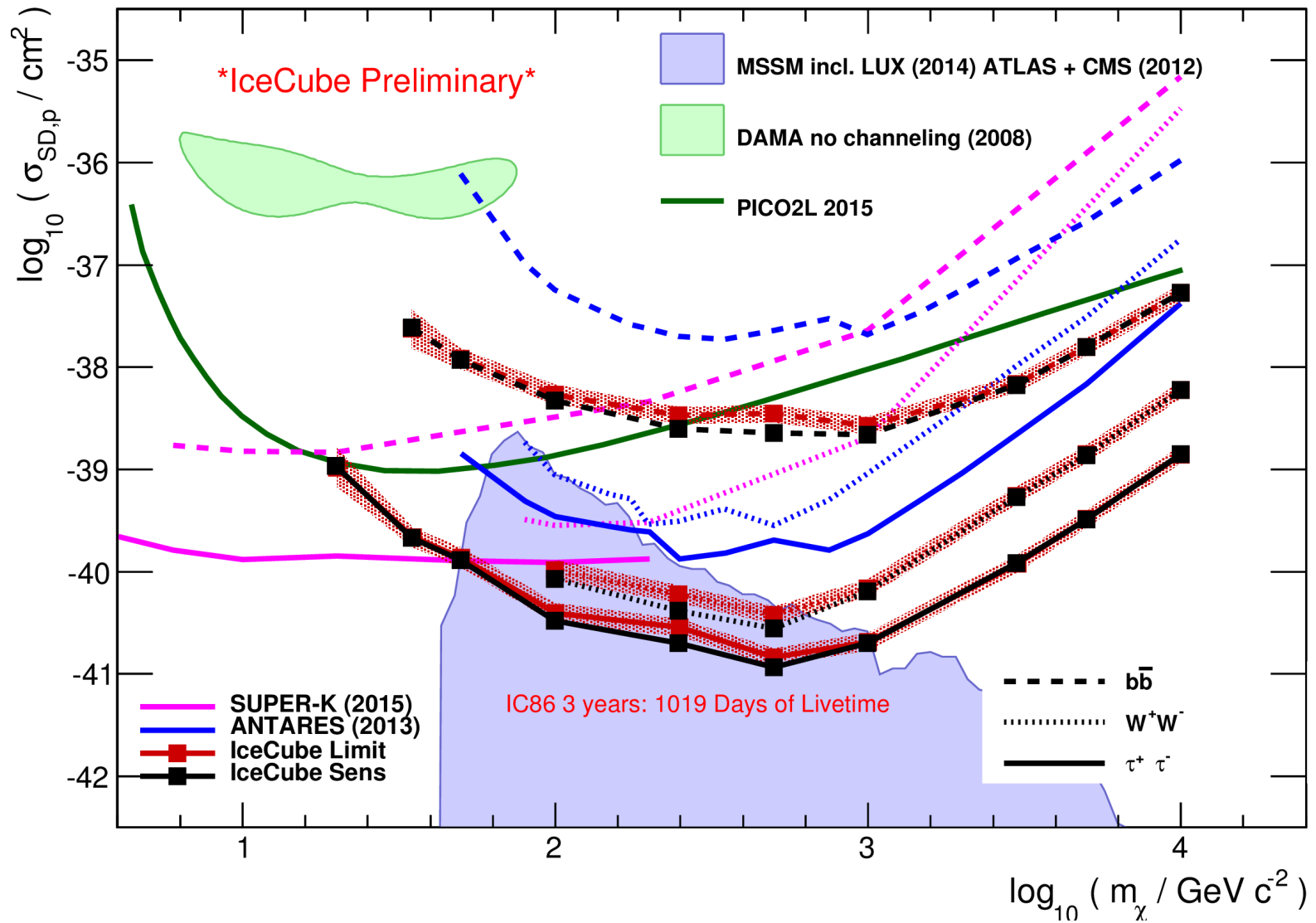


<http://arxiv.org/abs/1601.00653>

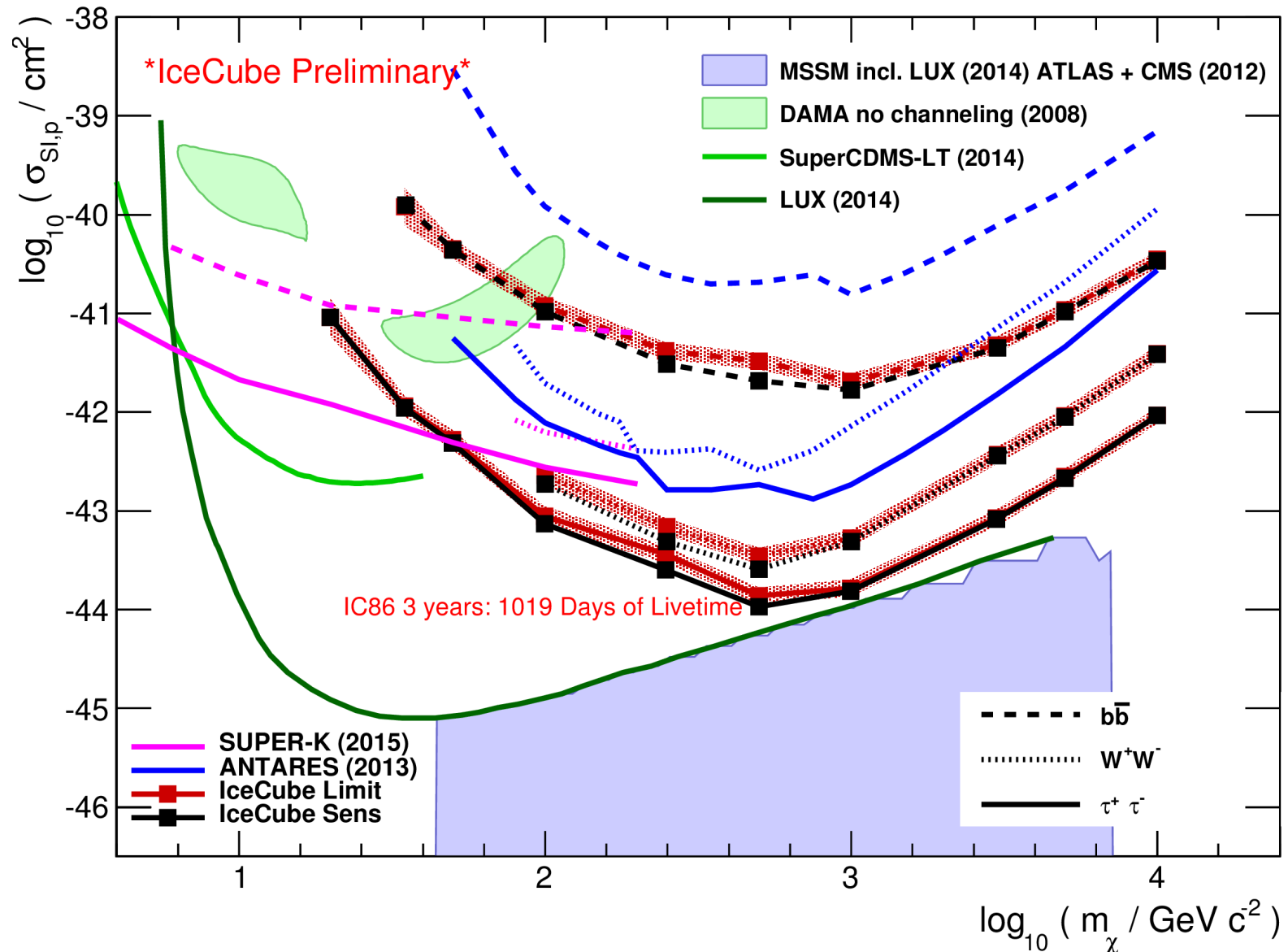
- software to test your own model (cross section/branching ratios)
- IceCube data available

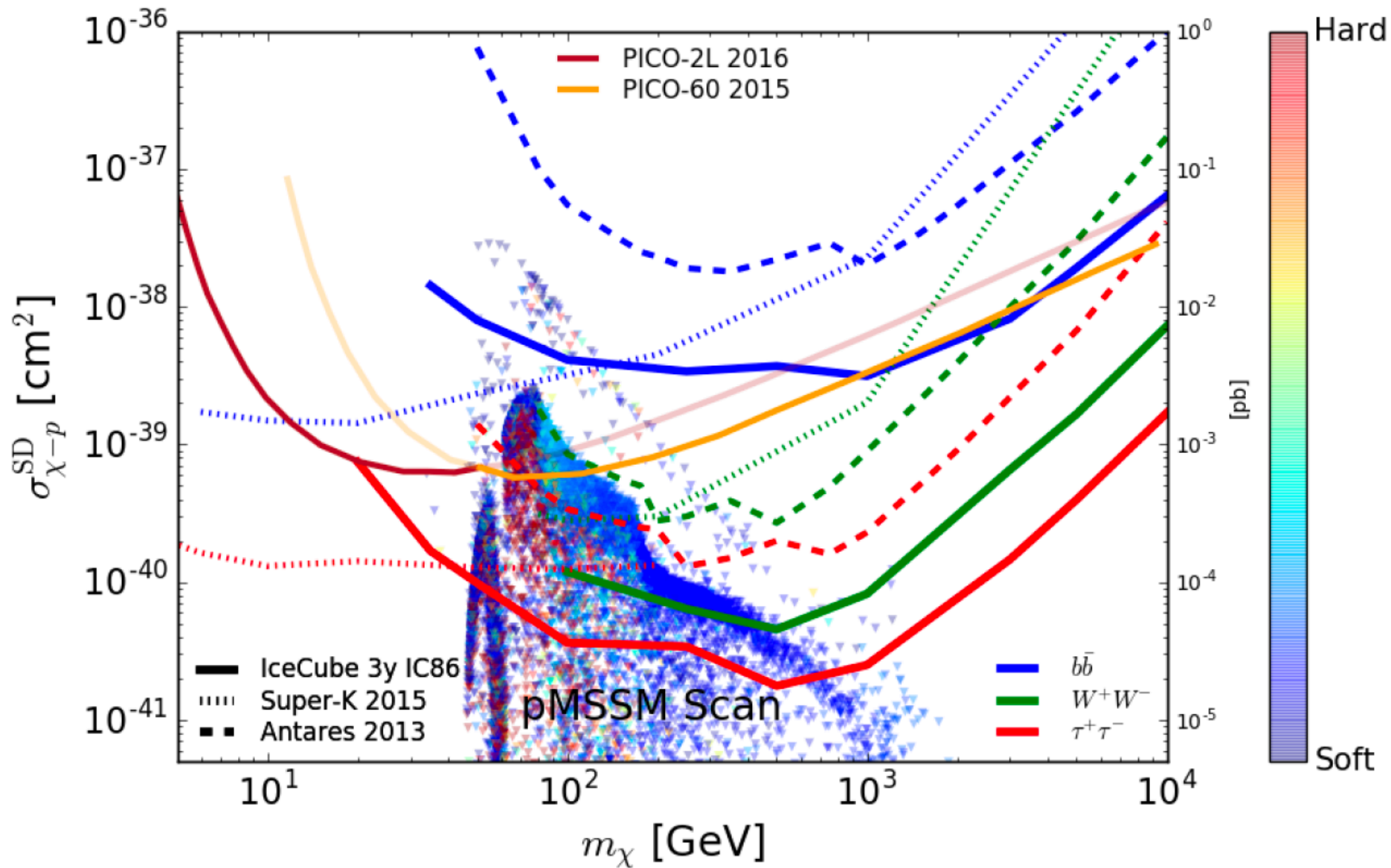


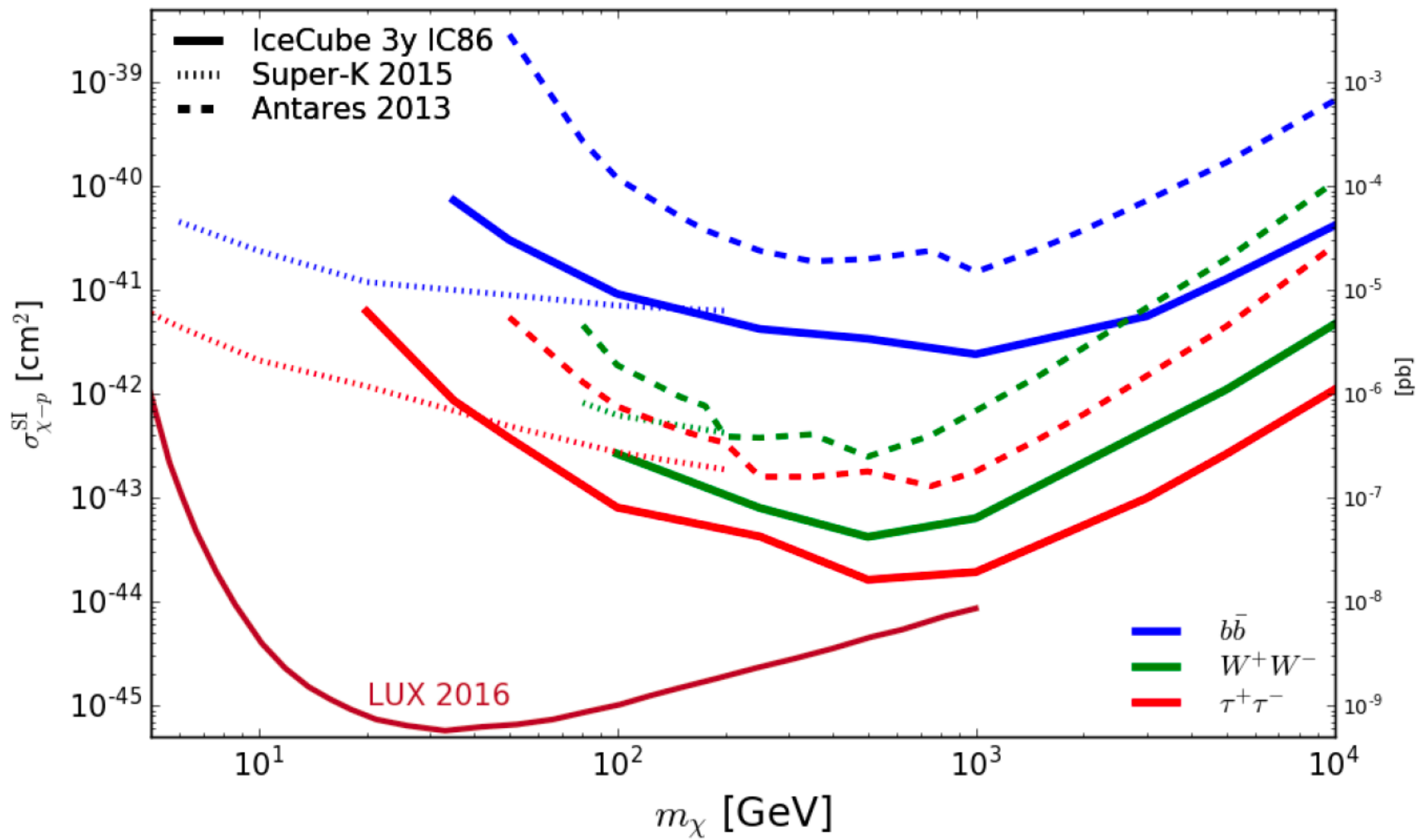
Limits after 3 years (6 soon)
spin dependent ($A^2=1$)



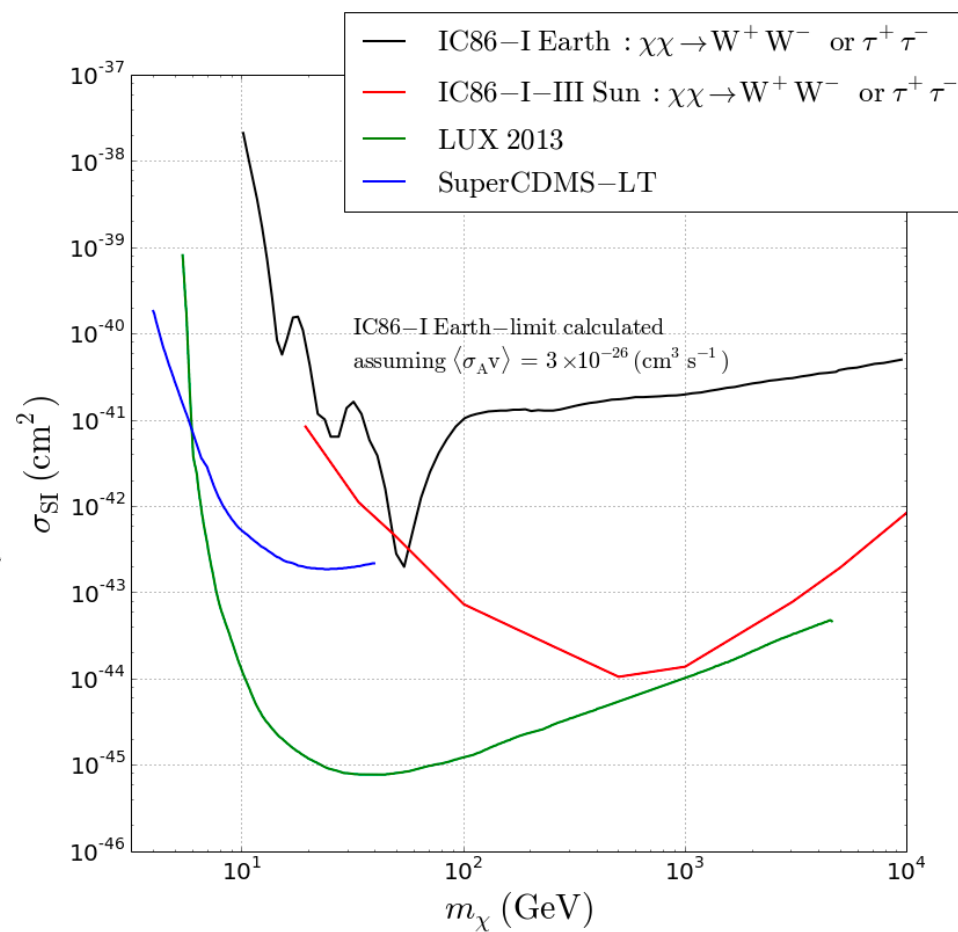
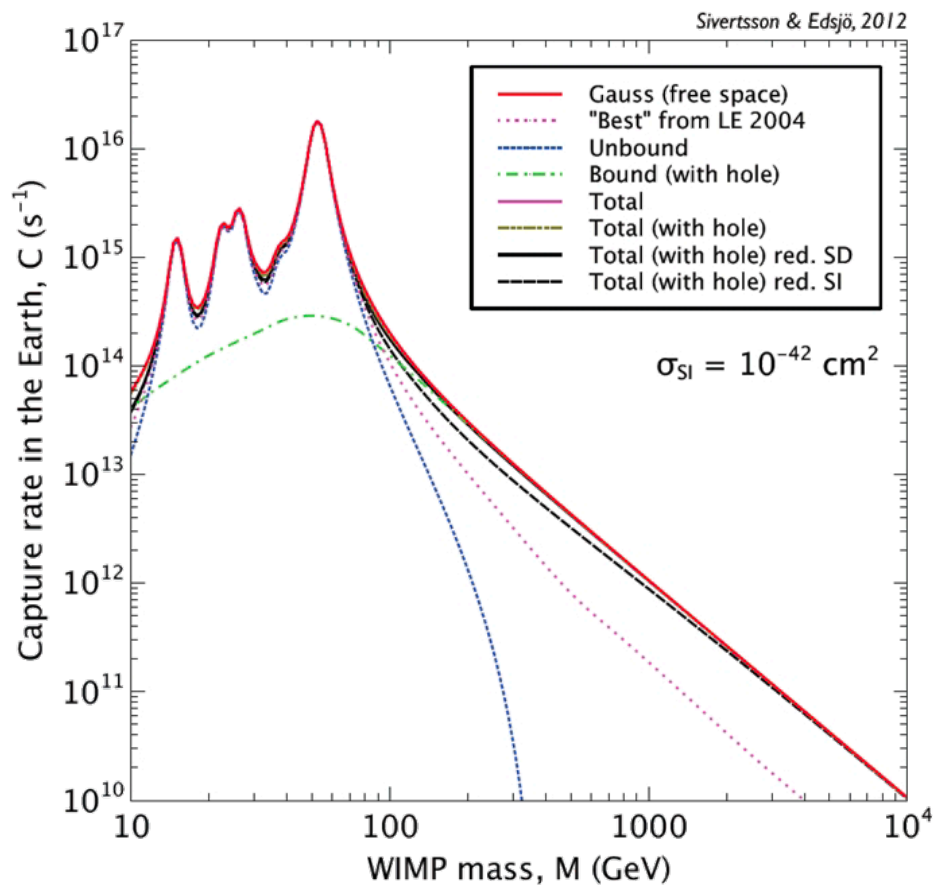
Limits after 3 years (6 soon) spin independent (A^2 handicap)







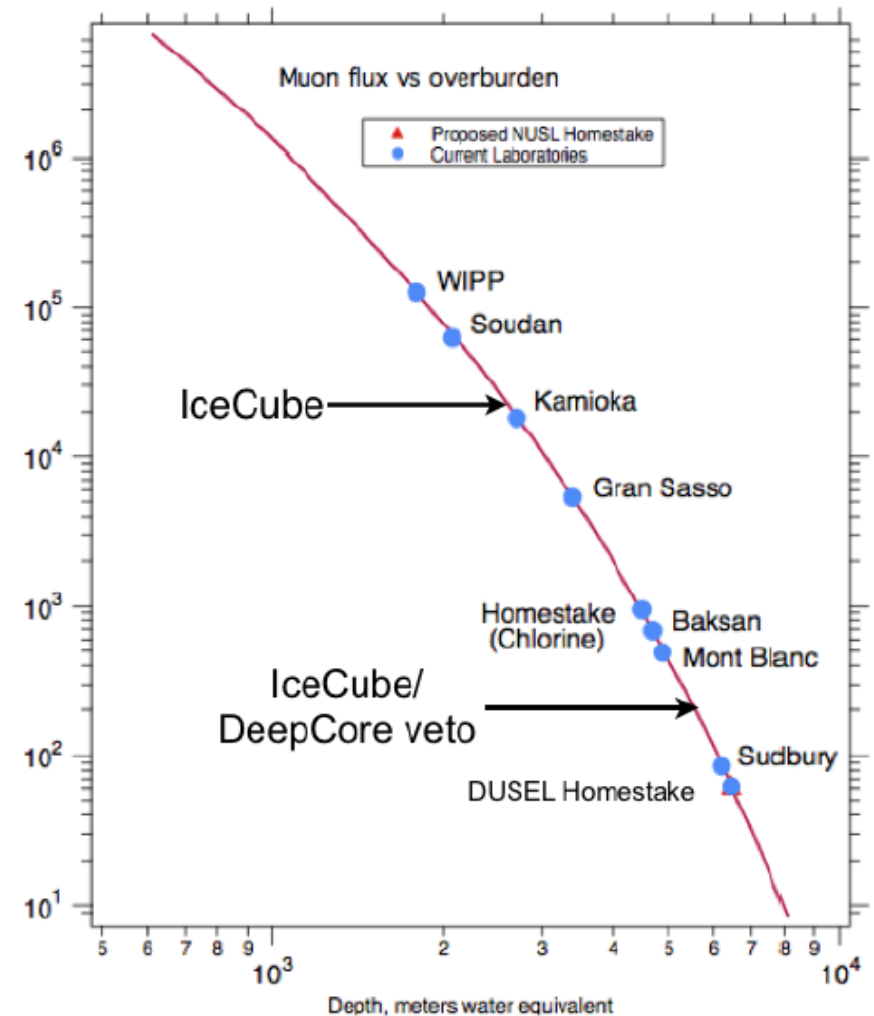
wimp annihilation in the center of the Earth



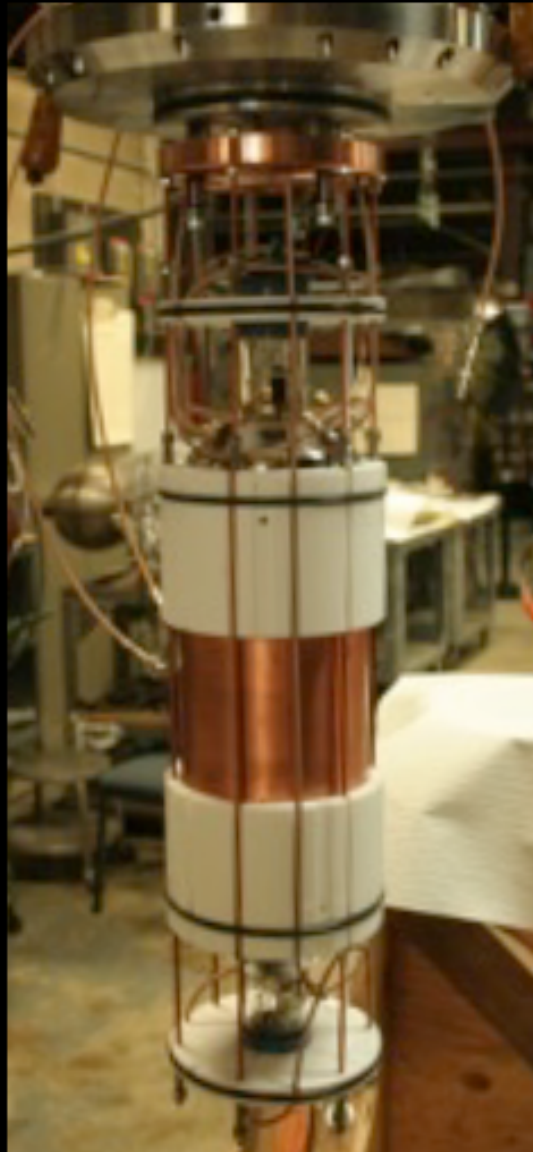
IceCube drilling to best low background site on Earth:

- radio-pure ice
- no seasonal variations (temperature, humidity,...)
- shielded from cosmic rays by IceCube veto

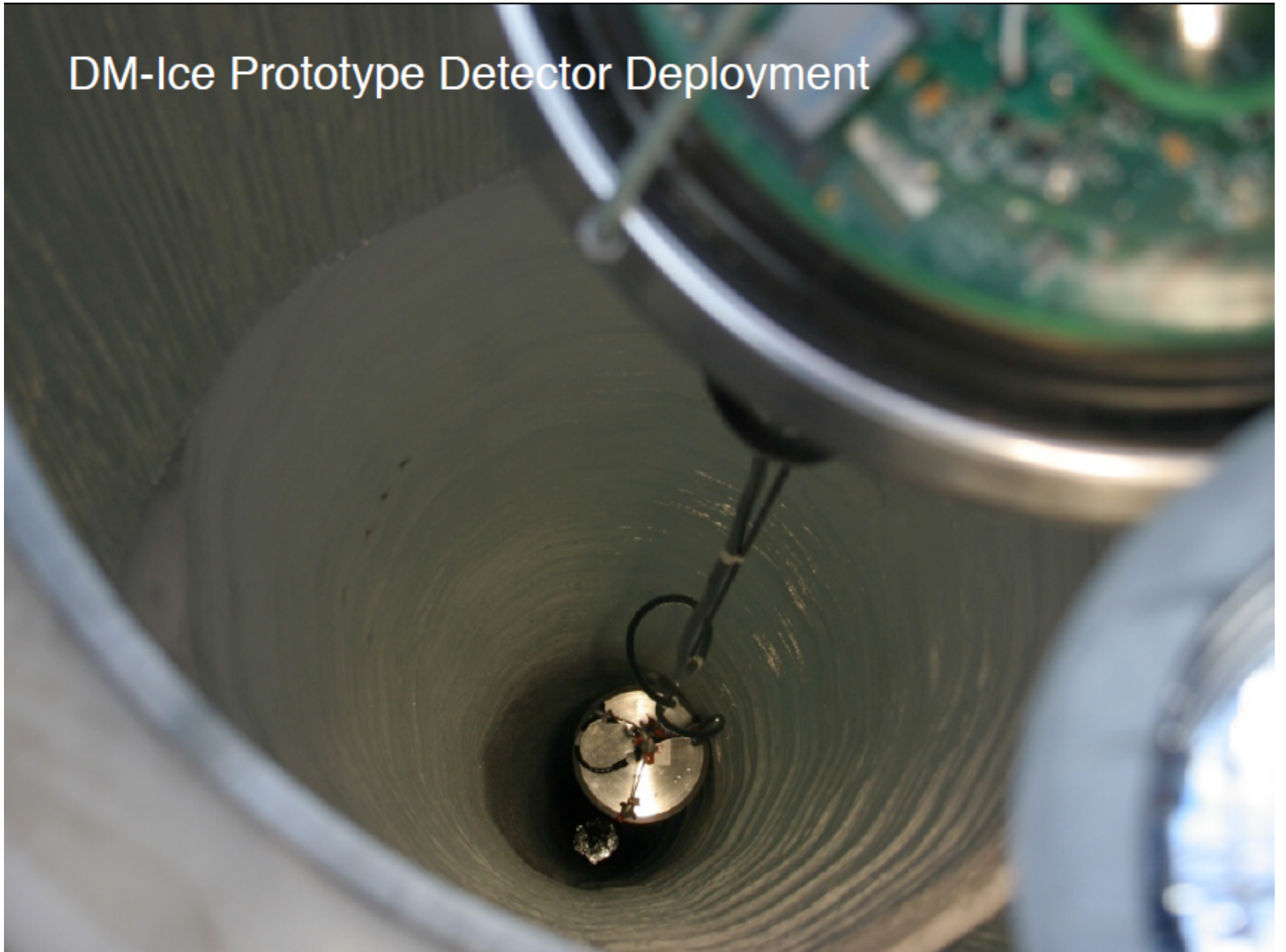
- DM-ice, DeepCore upgrades
- \$1.25M per string of 60 ten inch PMTs (data to your pc, includes logistics)



DM-Ice Prototype Detector



DM-Ice Prototype Detector Deployment



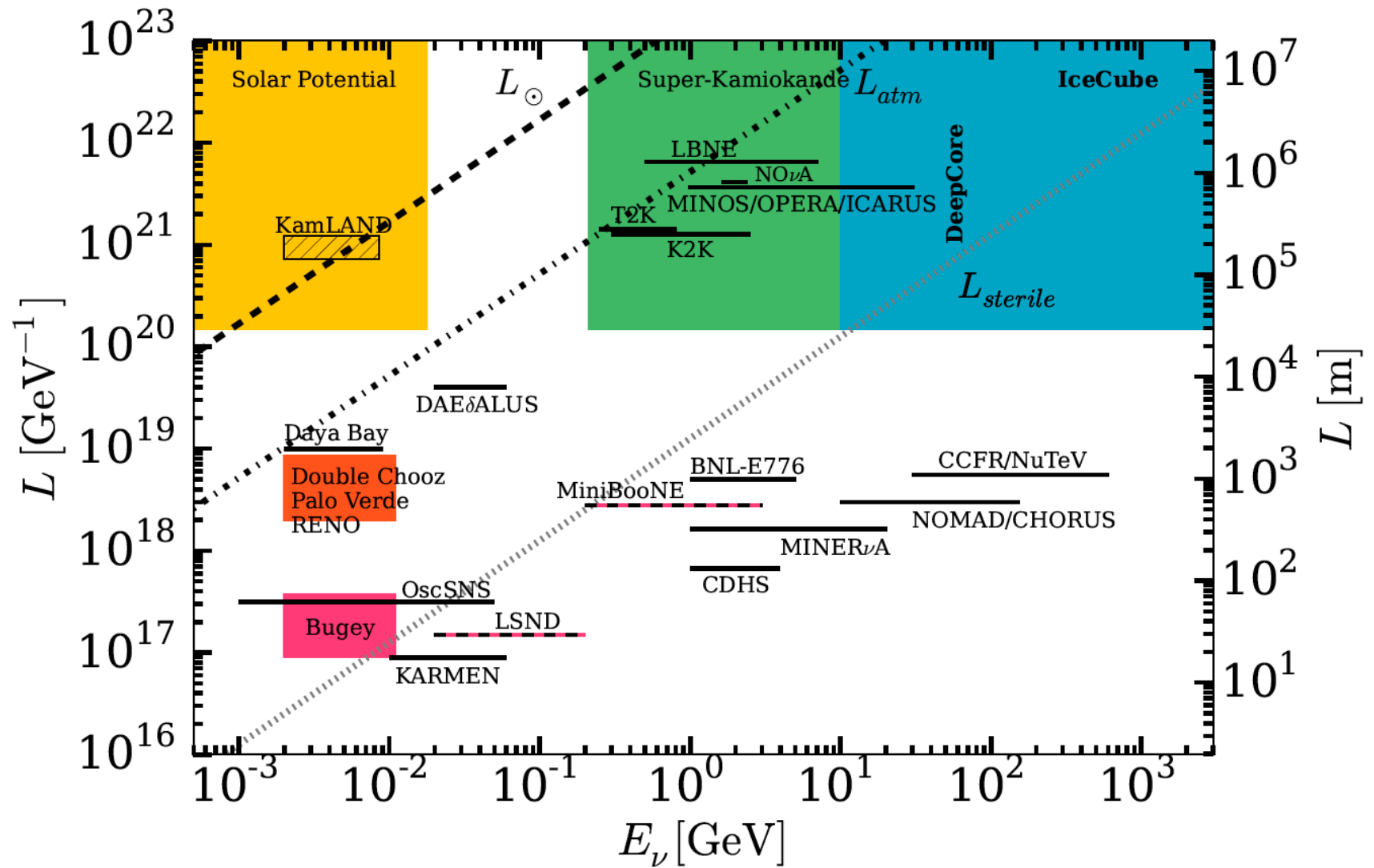


IceCube: beyond neutrino astronomy

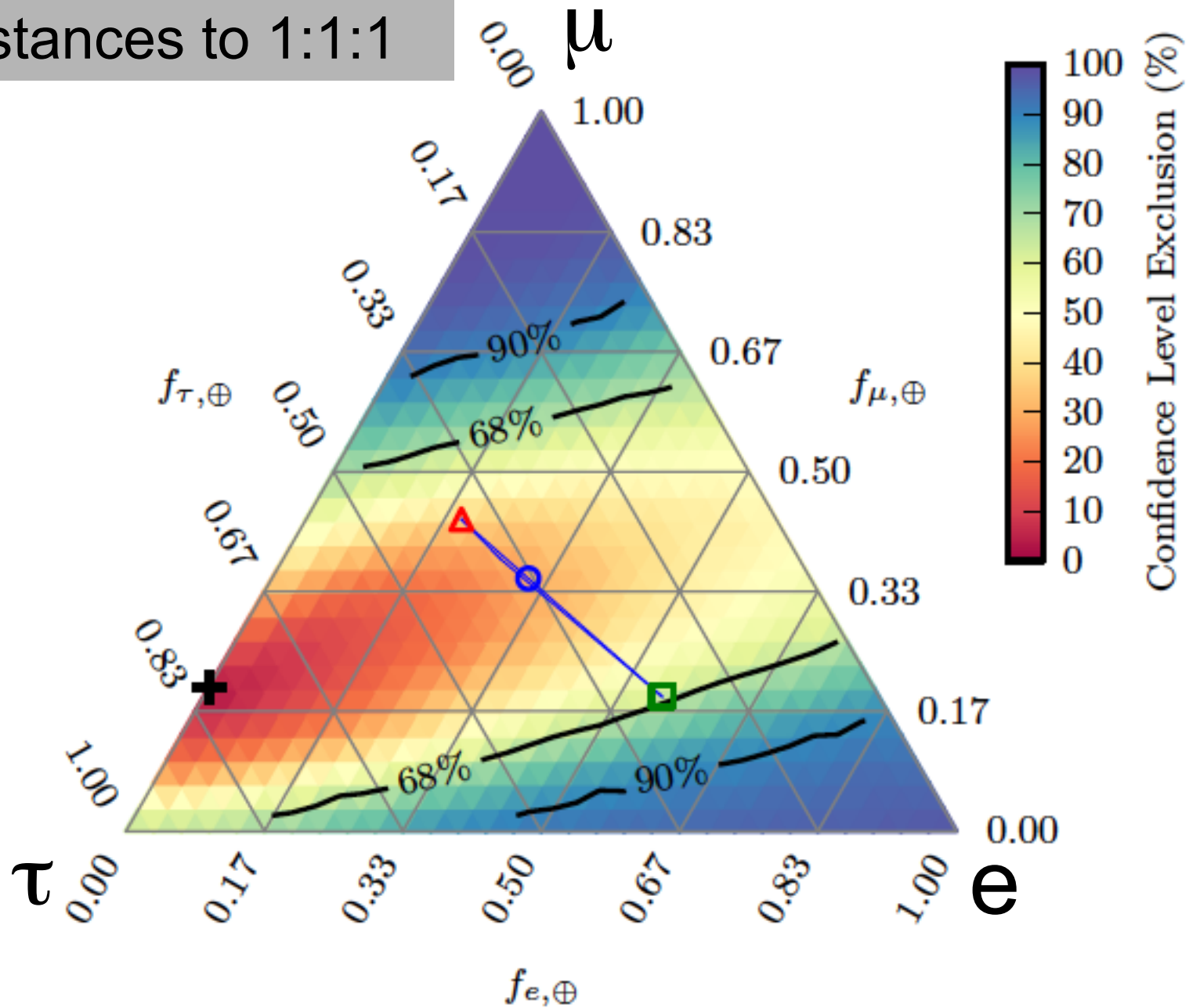
Francis Halzen

- muon astronomy: search for the sources of the Galactic cosmic rays
- detecting a Galactic supernova explosion
- search for dark matter
- neutrino oscillations
- search for sterile neutrinos
- ...

Experiments: $L_{\text{osc}} = 2\pi \frac{E}{\Delta m^2} \mid \Delta m_{\text{LSND}}^2 = 1 \text{eV}^2$

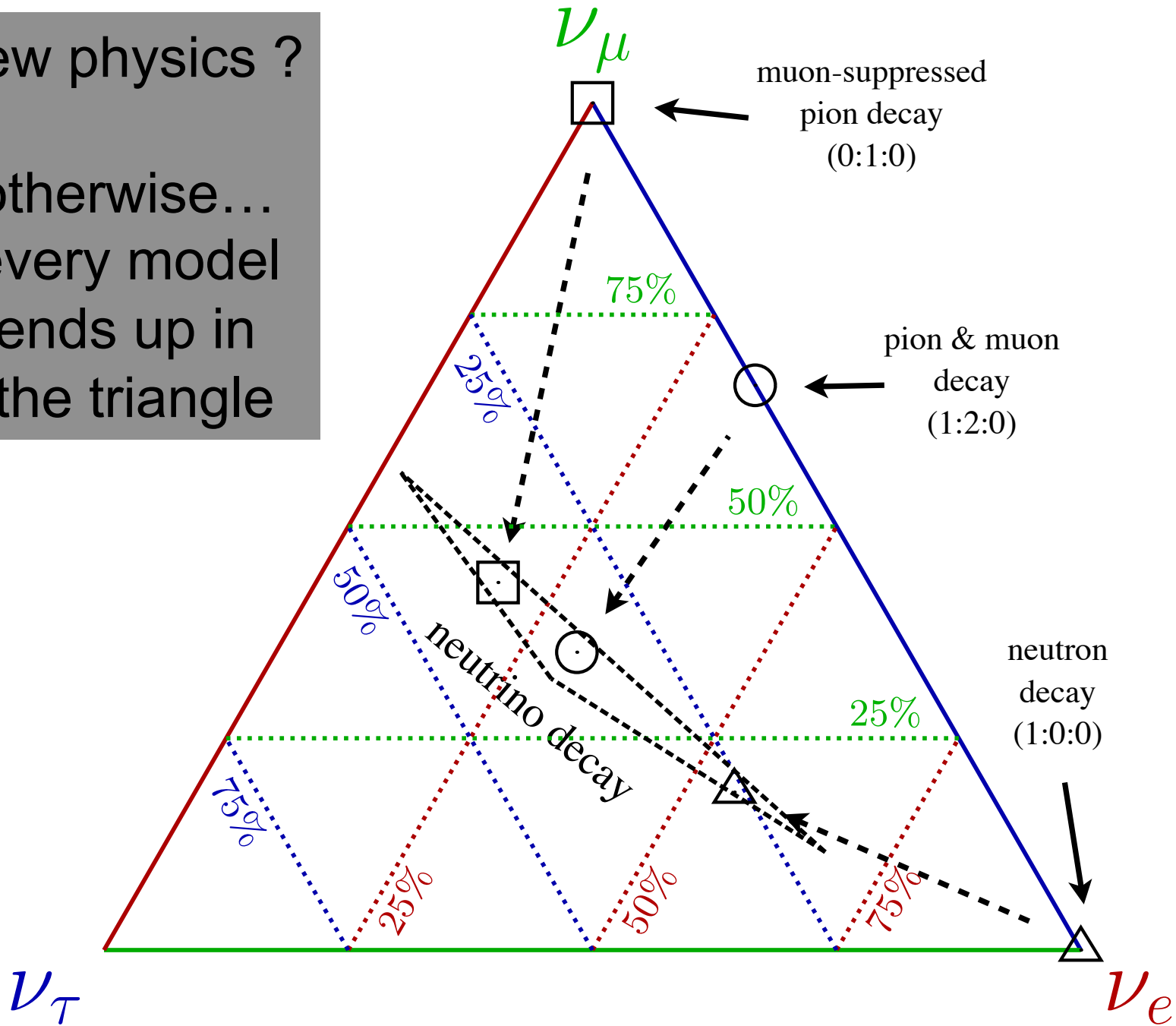


oscillate over cosmic distances to 1:1:1

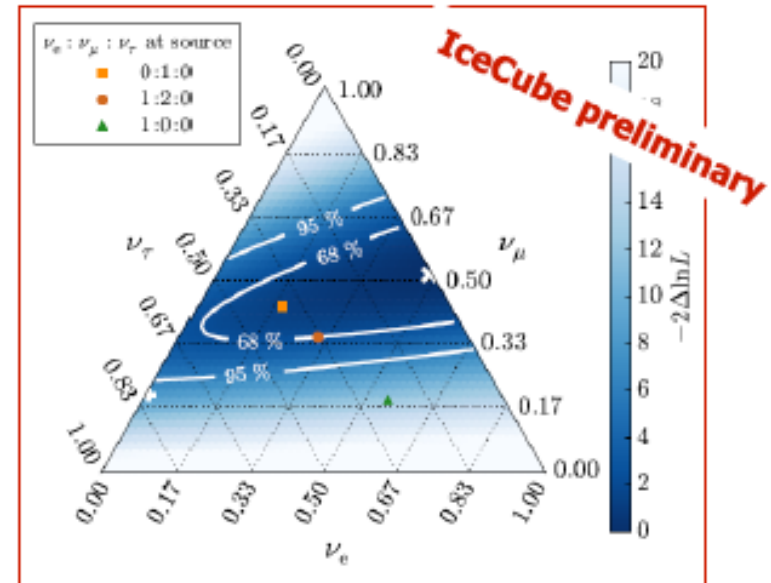
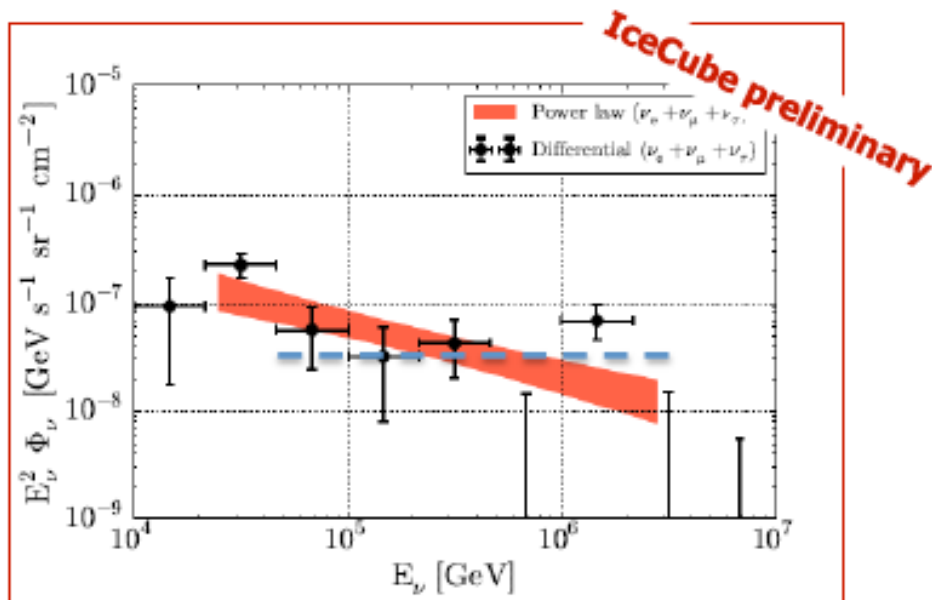


new physics ?

otherwise...
every model
ends up in
the triangle



- 6 different data samples based on data from 2008 – 2012
- different strategies to suppress the atm. μ background
- large samples of track-like and cascade-like events

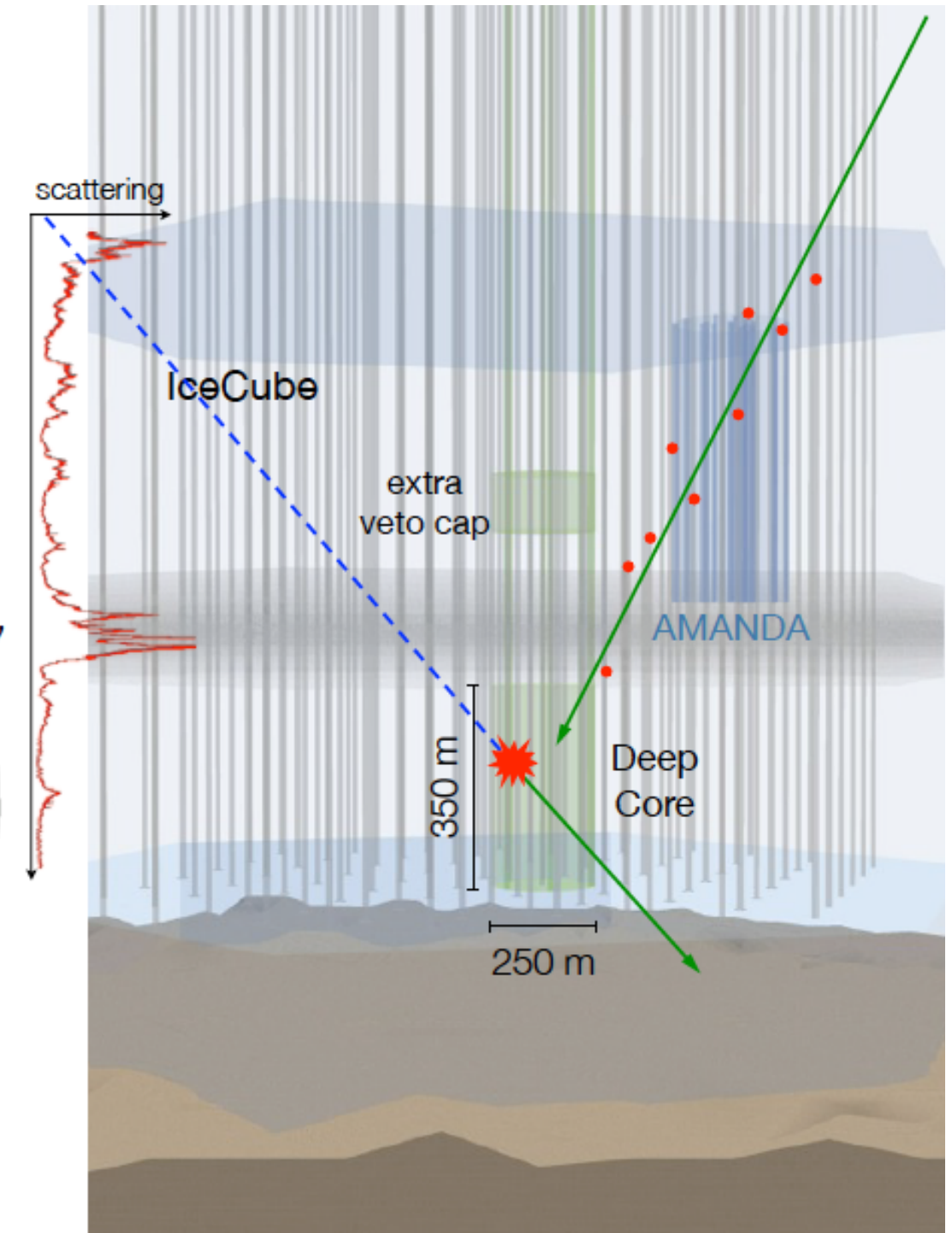
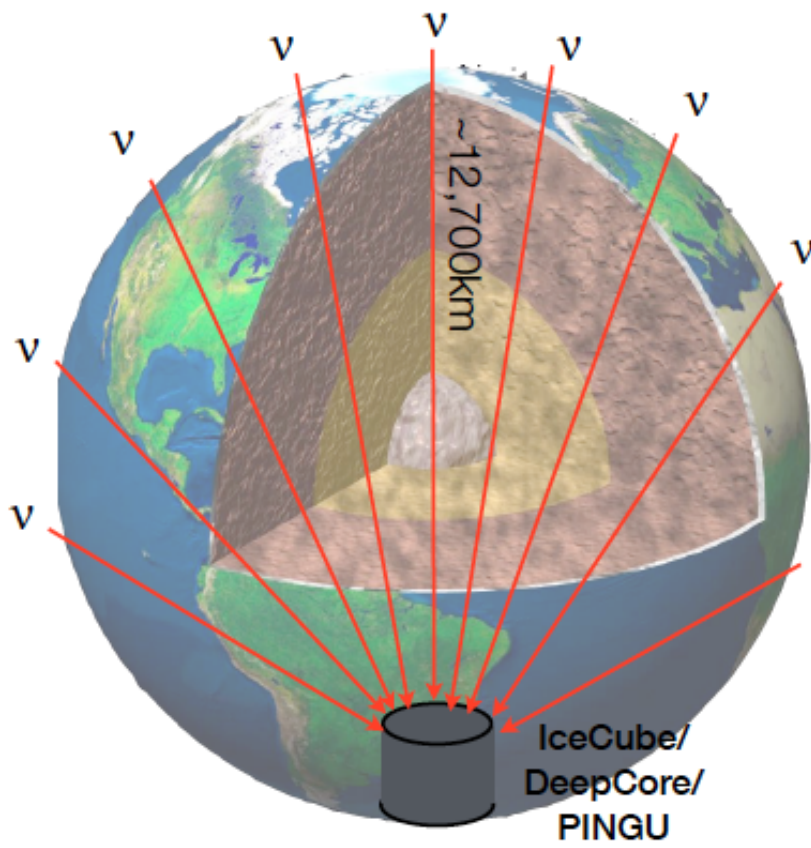


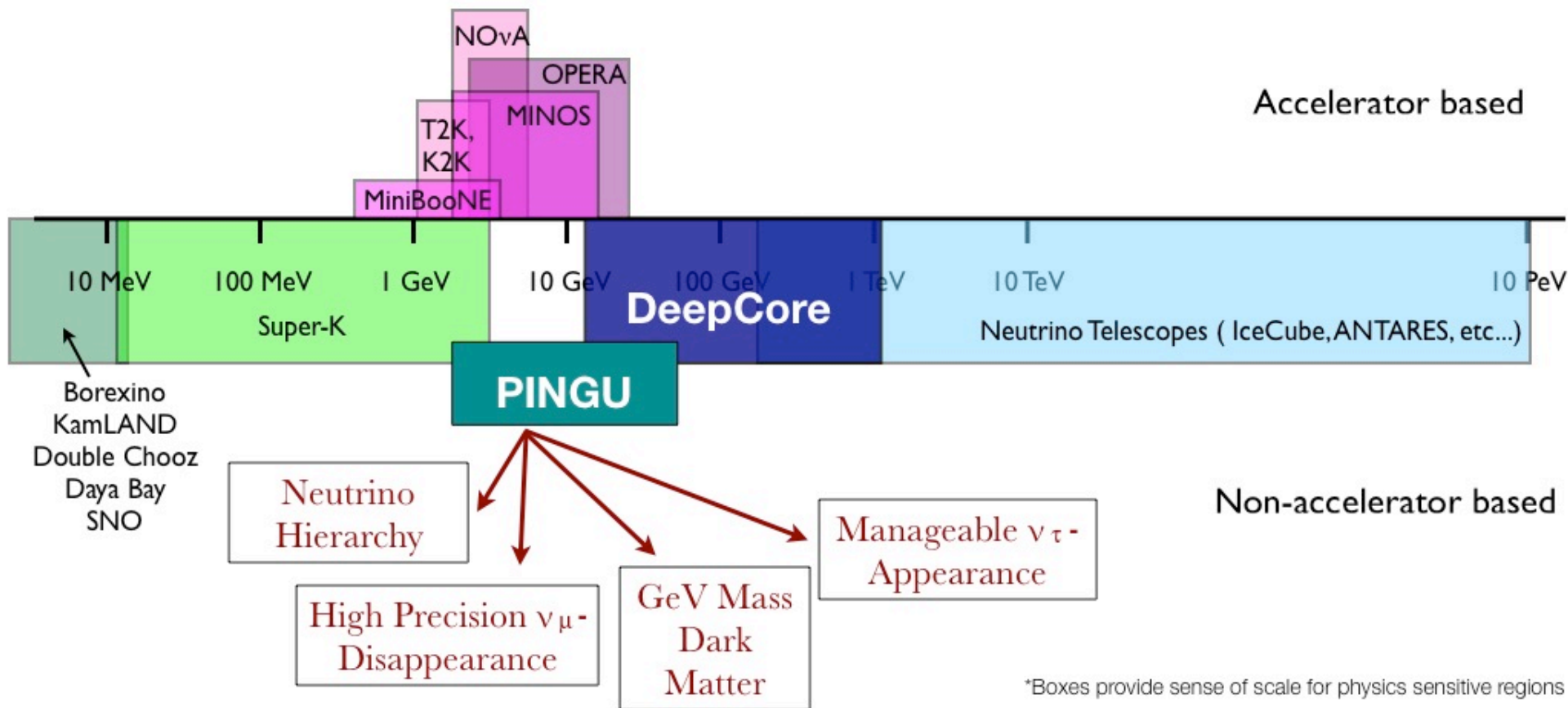
assuming isotropic astrophysical flux and $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ at Earth \rightarrow

unbroken power-law between 25 TeV and 2.8 PeV
 spectral index -2.5 ± 0.09 (-2 disfavored at 3.8σ)
 flux at 100 TeV $(6.7 \pm 1.2) \times 10^{-18} (\text{GeV} \cdot \text{cm}^2 \cdot \text{s} \cdot \text{sr})^{-1}$

the best fit flavor composition **disfavors 1:0:0** at source at 3.6σ

one half million
atmospheric
neutrinos...

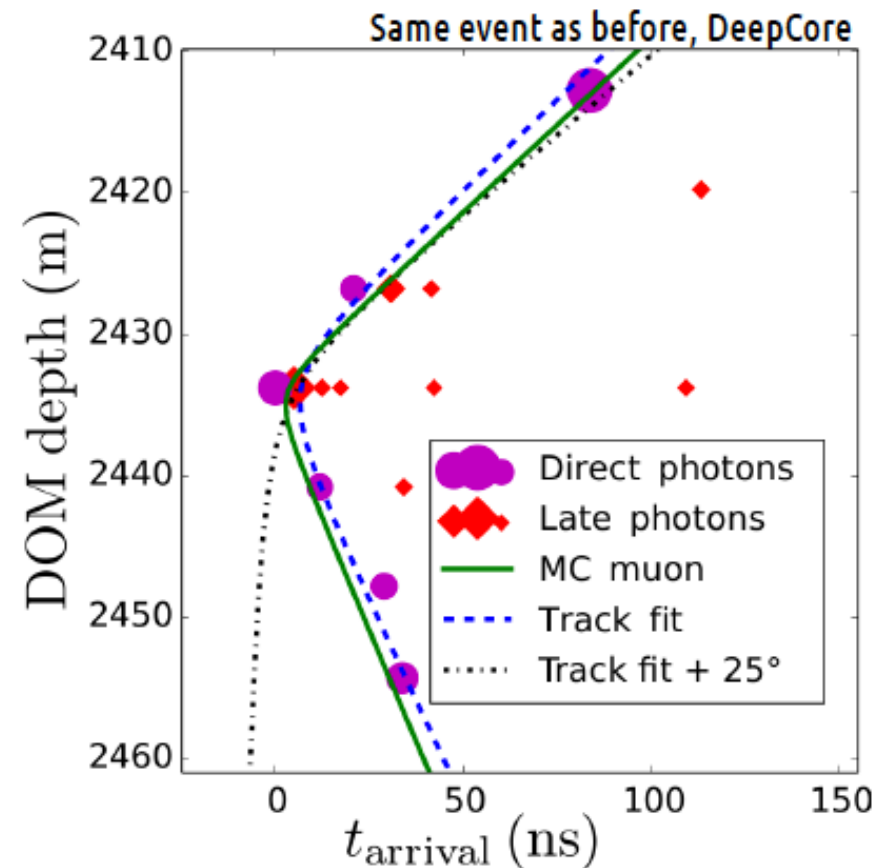




neutrino reconstruction

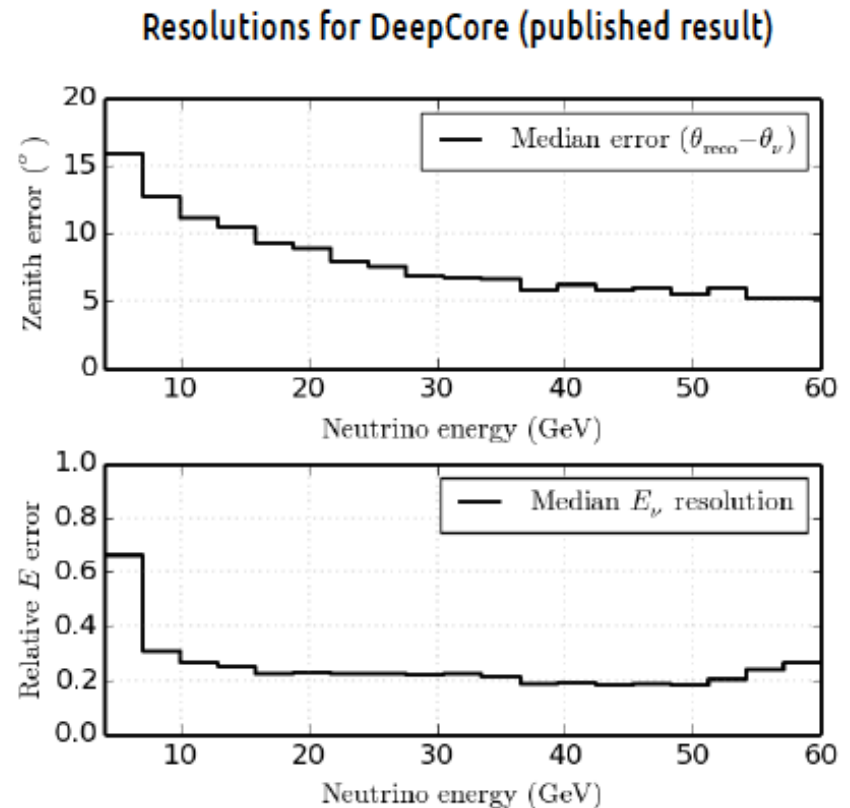
Latest published DeepCore results

- » Zenith: Require a core of *direct* (unscattered) photons
 - » **Minimize impact of ice properties**
 - » 30% efficiency
 - » **Fit zenith angle with direct photons (assume no scattering)**
- » Energy: track+cascade hypothesis
 - » Fit track length and vertex position/E
 - » Keep direction fixed
 - » Assume track and cascade are collinear



Latest published DeepCore results

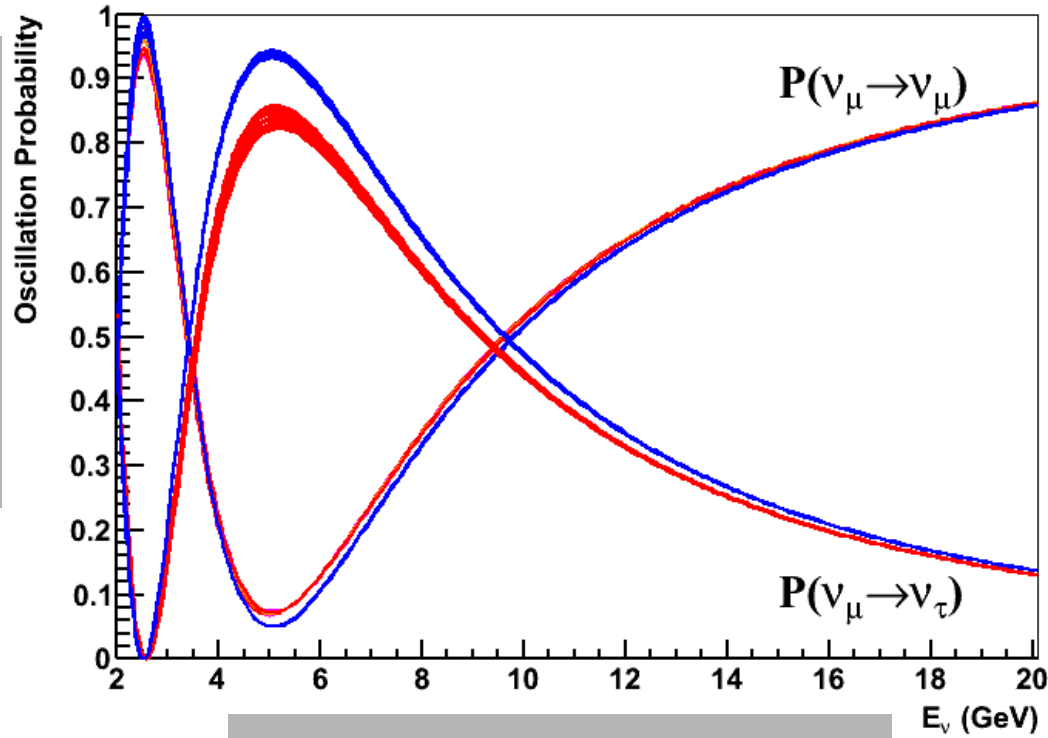
- » Zenith: Require a core of *direct* (unscattered) photons
 - » Minimize impact of ice properties
 - » 30% efficiency
 - » Fit zenith angle with direct photons (assume no scattering)
- » Energy: track+cascade hypothesis
 - » Fit track length and vertex position/E
 - » Keep direction fixed
 - » Assume track and cascade are collinear



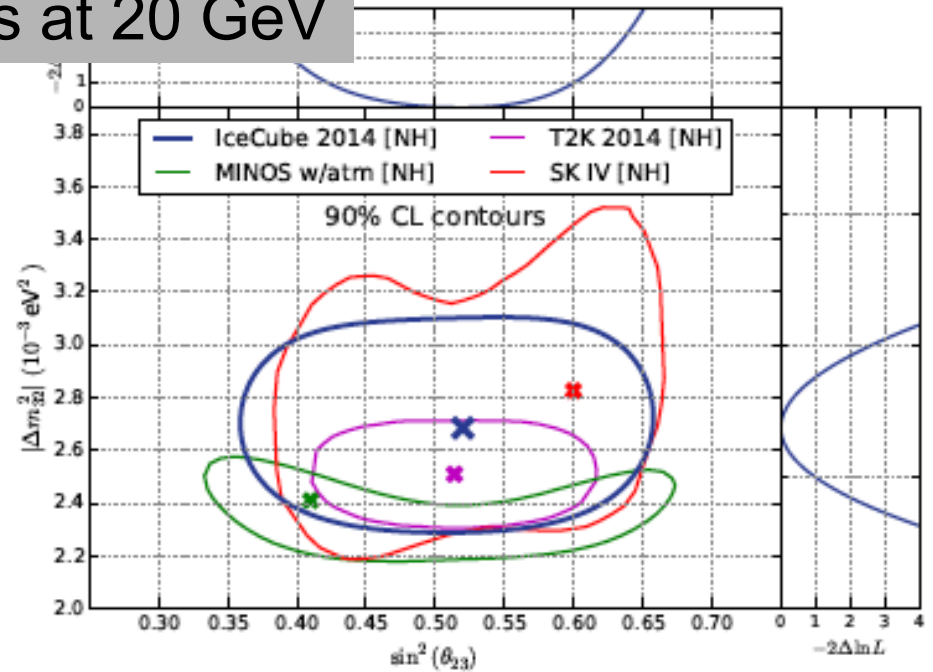
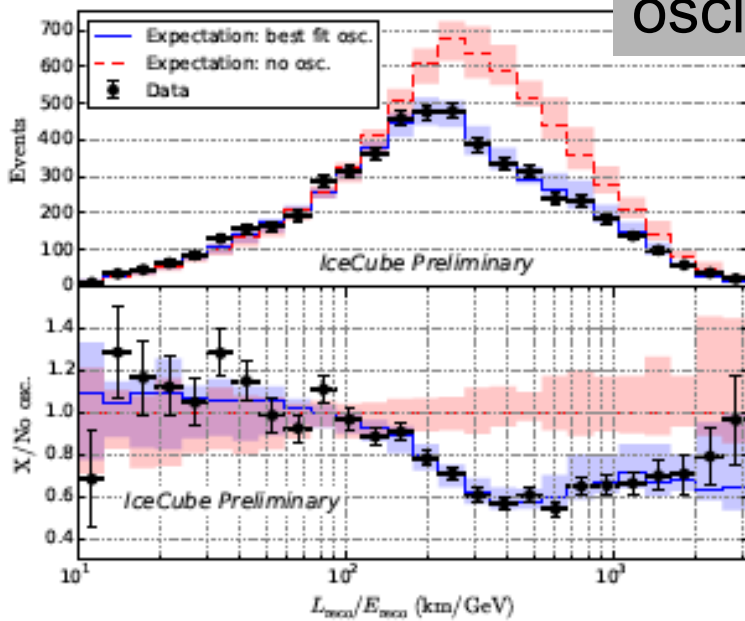
IceCube

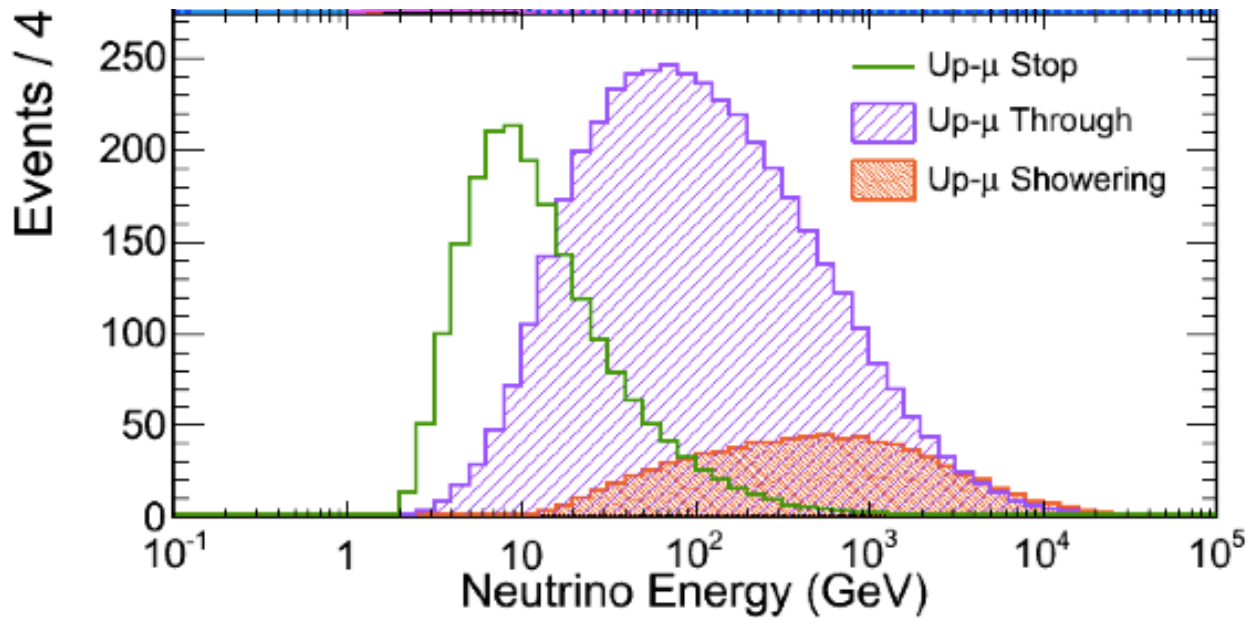
DeepCore

PINGU



oscillations at 20 GeV



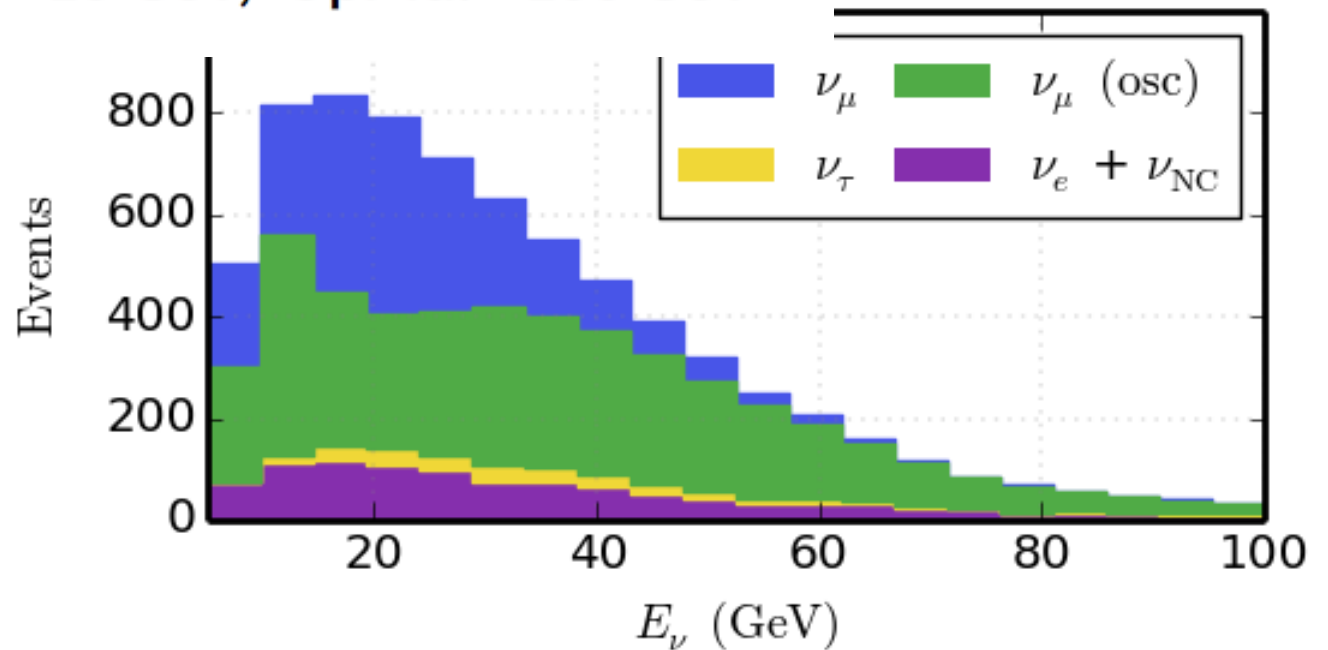


SuperK

■ Average energies

- FC: ~ 1 GeV , PC: ~ 10 GeV, UpMu: ~ 100 GeV

IceCube



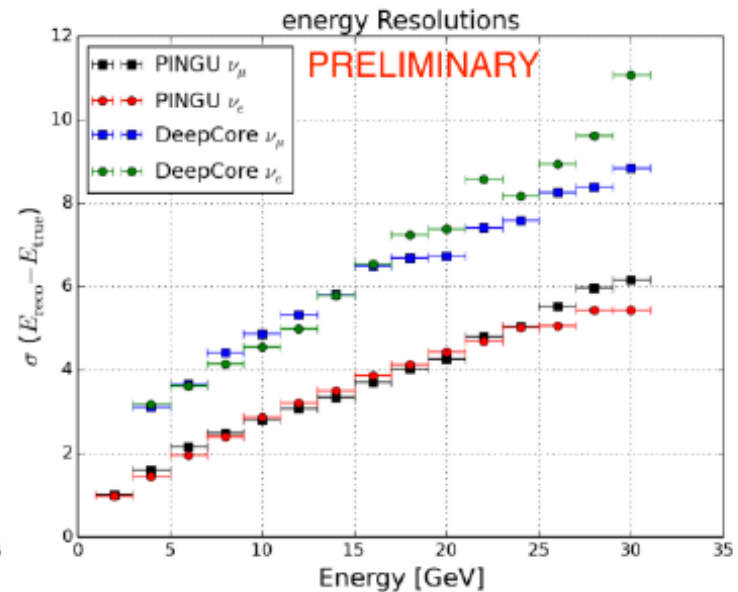
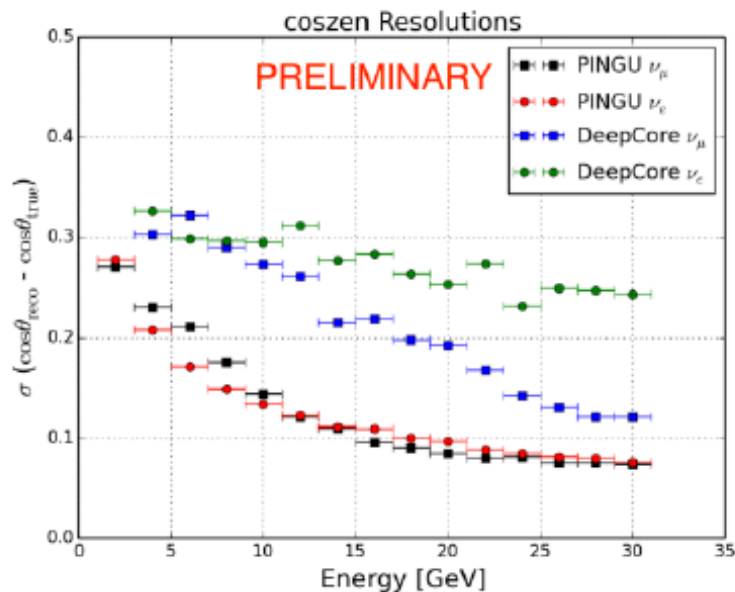
coming soon

More sophisticated reconstruction

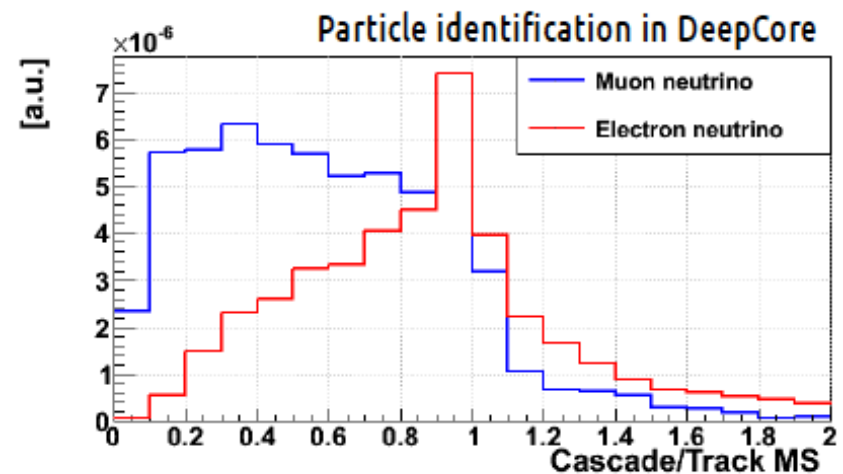
- » Use arrival time of individual photons
- » Fit energy + direction simultaneously
- » No need for direct photons, use all events
- » Similar resolutions in DeepCore
- » Higher efficiency
- » Working in DeepCore, testing vs data

» Include in reconstruction (from model)

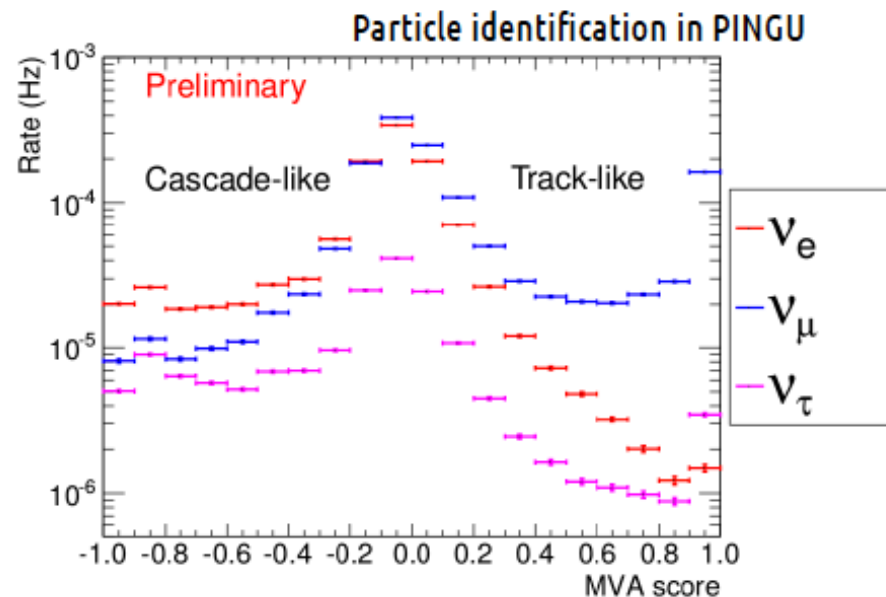
» Used in PINGU analysis



- » In **DeepCore** → ratio of 2 fits
- » Assume track+cascade vs only cascade
- » Current results: χ^2 in directional fit
- » Δ LLH in sophisticated reconstruction



- » In **PINGU** → multivariate method
- » Exploit topological variables
- » Combine discrimination power
- » Can be optimized for sensitivity



projected sensitivity

Projected MC sensitivity from re-analysis of 3 years of DeepCore data*

» Classify interactions:

» Between track- and cascade-like

» Inclusive selection:

» Direct hits required (5 → 3)

» Sophisticated reconstruction

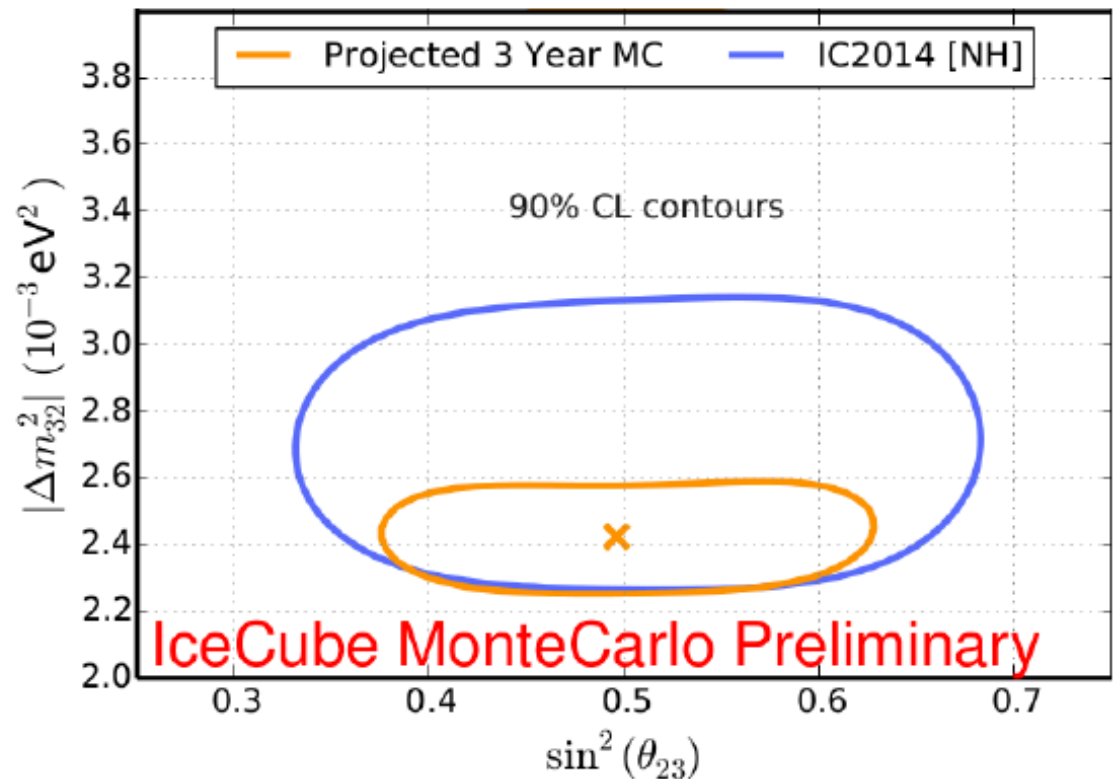
» Global fit of all parameters

» Including events from all directions

» Also down-going (atm. Muons)

» Renewed calibration efforts

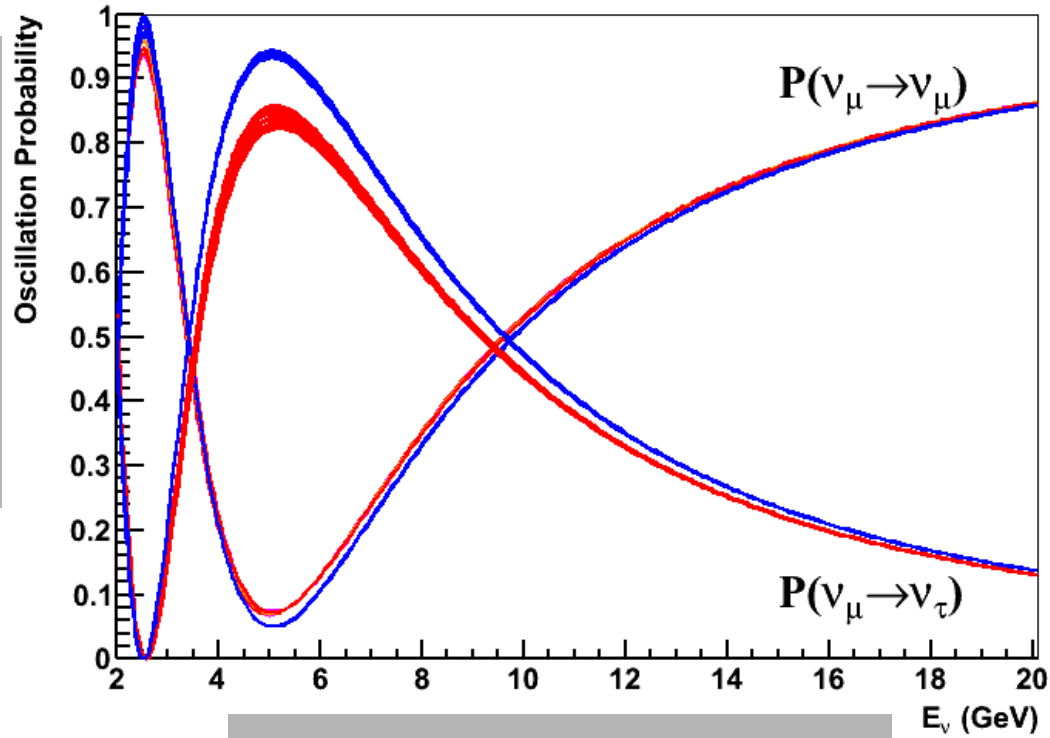
» Noise modeling, angular acceptance, individual DOM behavior



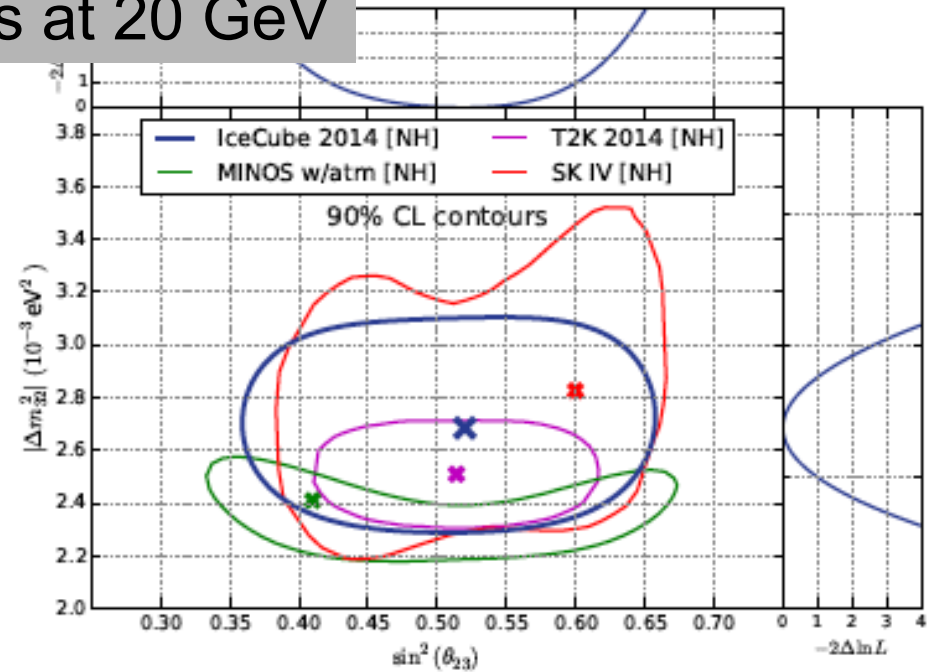
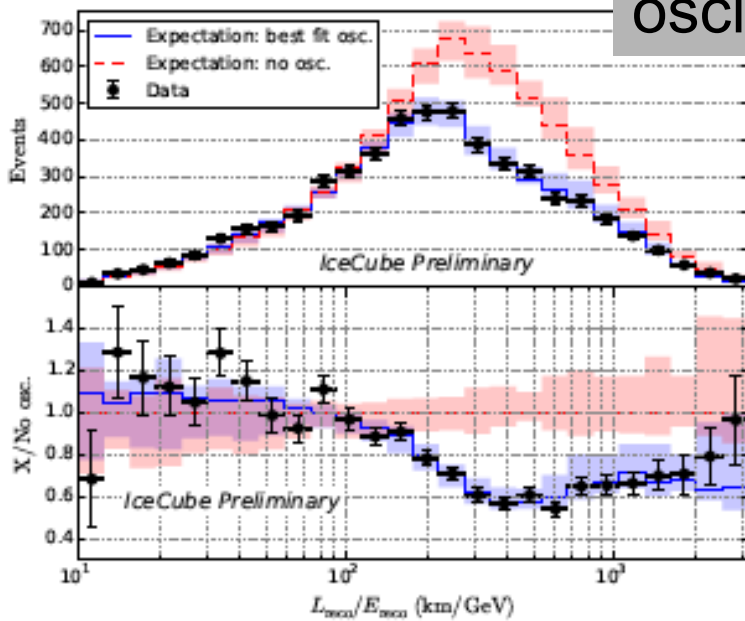
IceCube

DeepCore

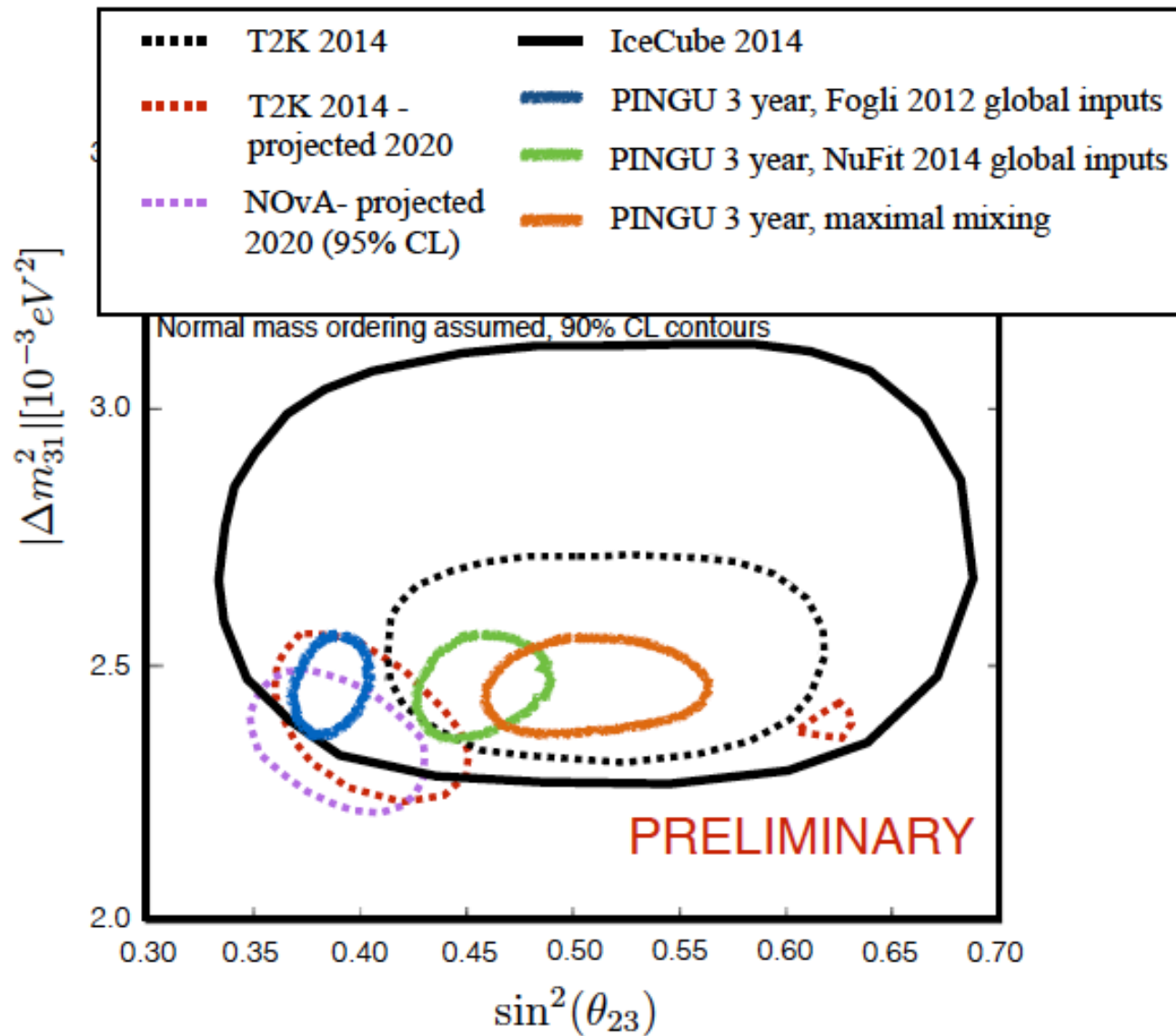
PINGU



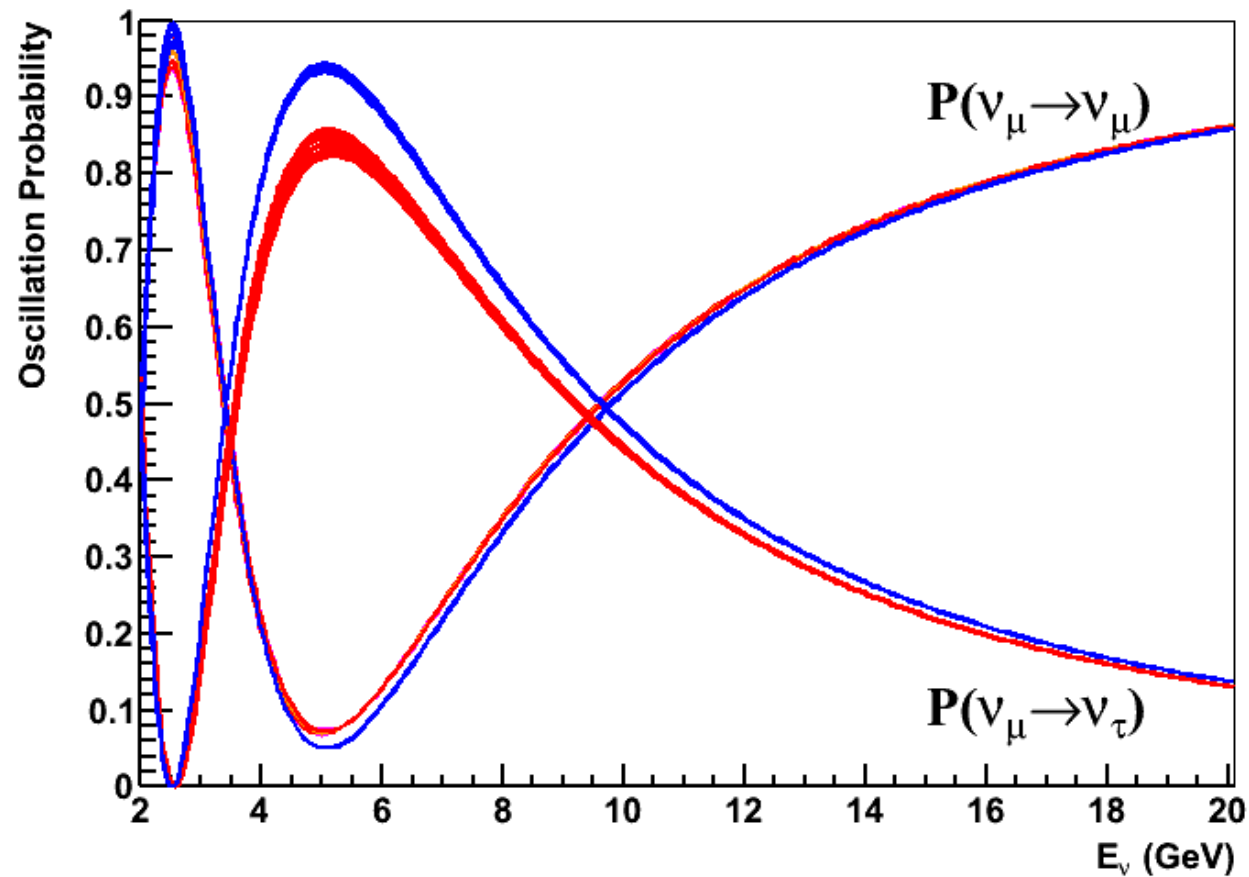
oscillations at 20 GeV



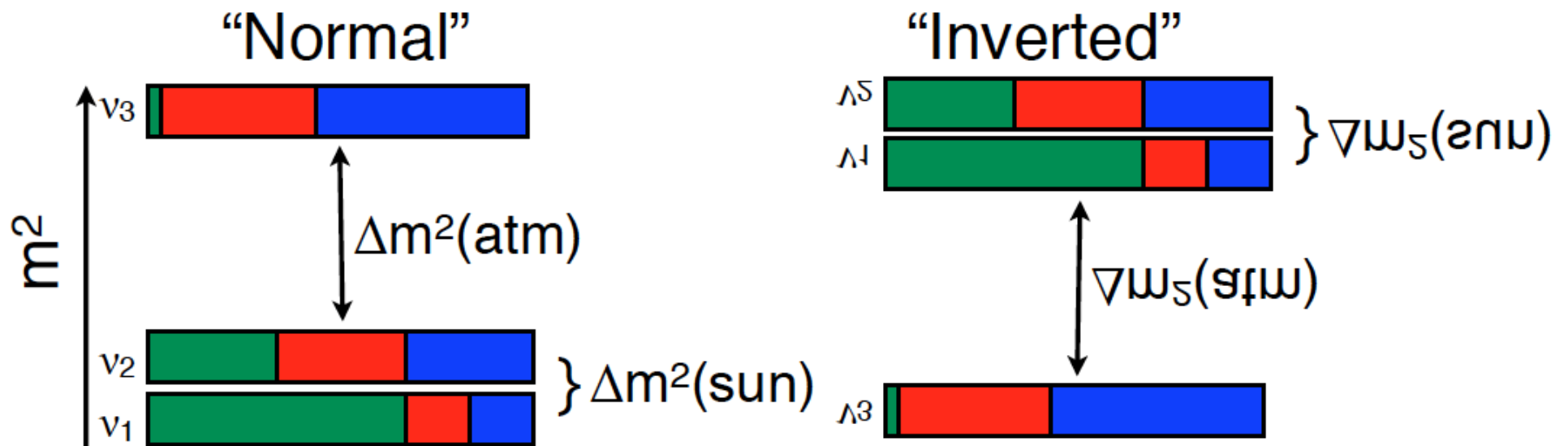
and with PINGU



- oscillations at 10 GeV energy and above
- same oscillation parameters measured in a new energy range.

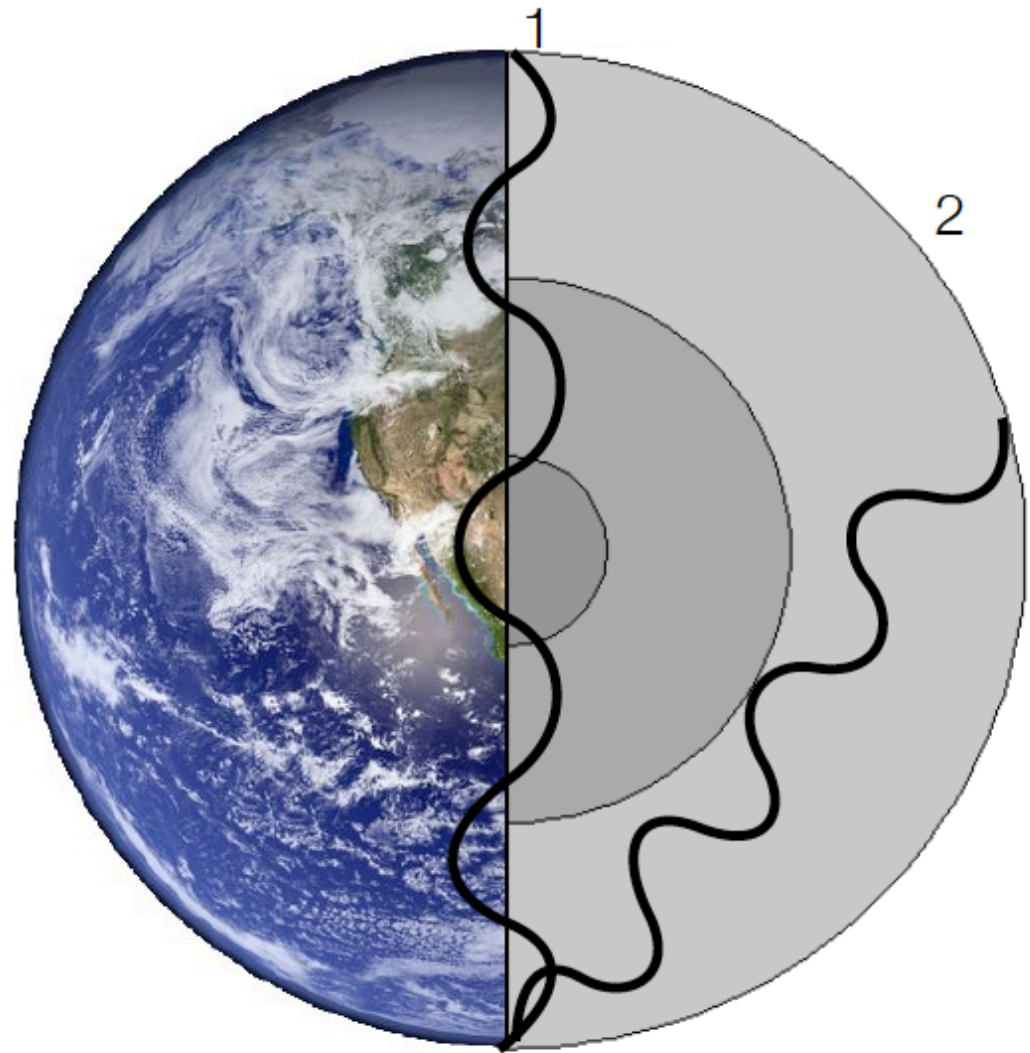
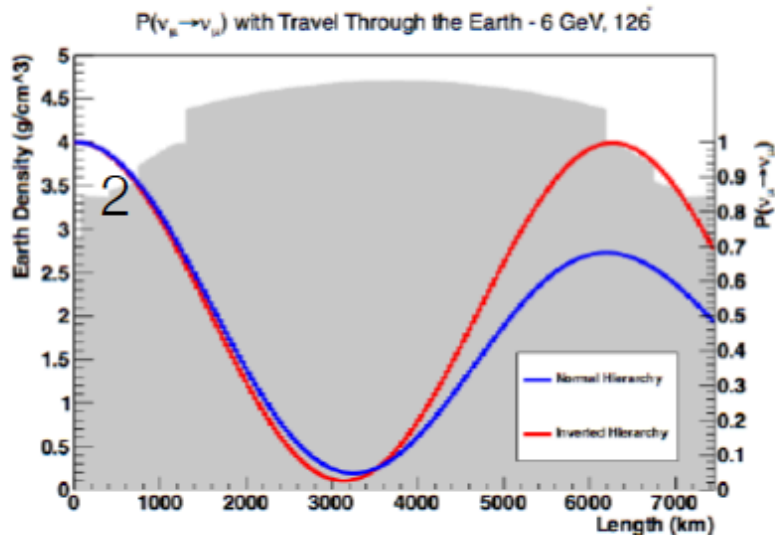
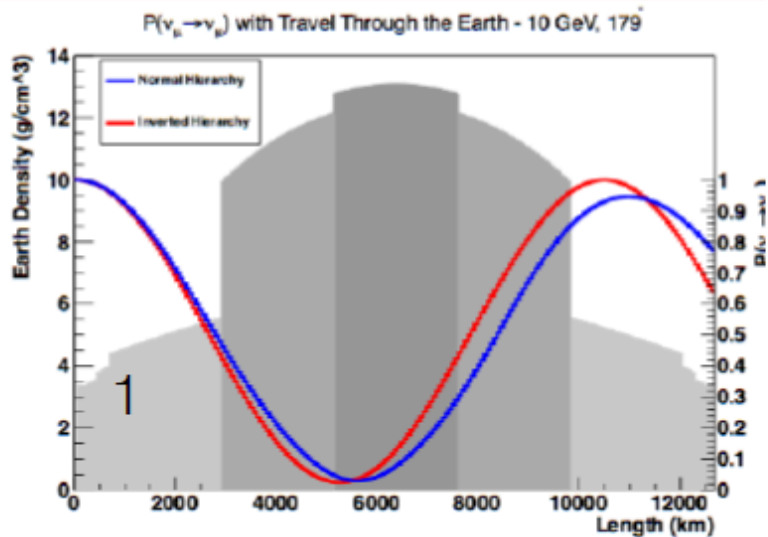


neutrino mass hierarchy ?



Using atmospheric neutrinos to measure the NMH

Up to 20% differences in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy



~ 10 GeV : hierarchy revealed by
“large” matter effects in the Earth

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left[\cos 2\theta_{13} \pm \frac{\sqrt{2G_F n_e}}{\Delta_{13}} \right]}$$

(mostly) neutrino + antineutrino -

sign Δ_{13} : hierarchy !



IceCube: beyond neutrino astronomy

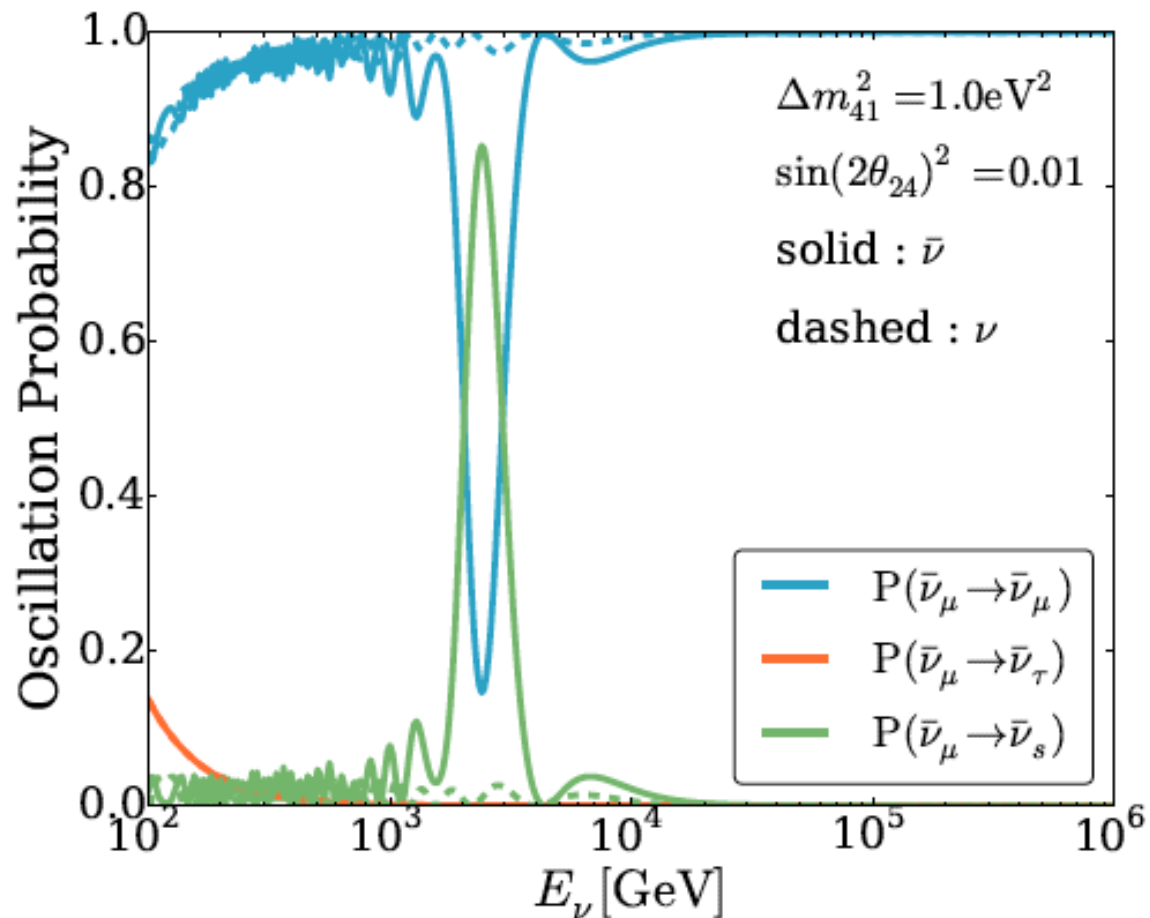
Francis Halzen

- muon astronomy: search for the sources of the Galactic cosmic rays
- detecting a Galactic supernova explosion
- search for dark matter
- neutrino oscillations
- search for sterile neutrinos
- ...

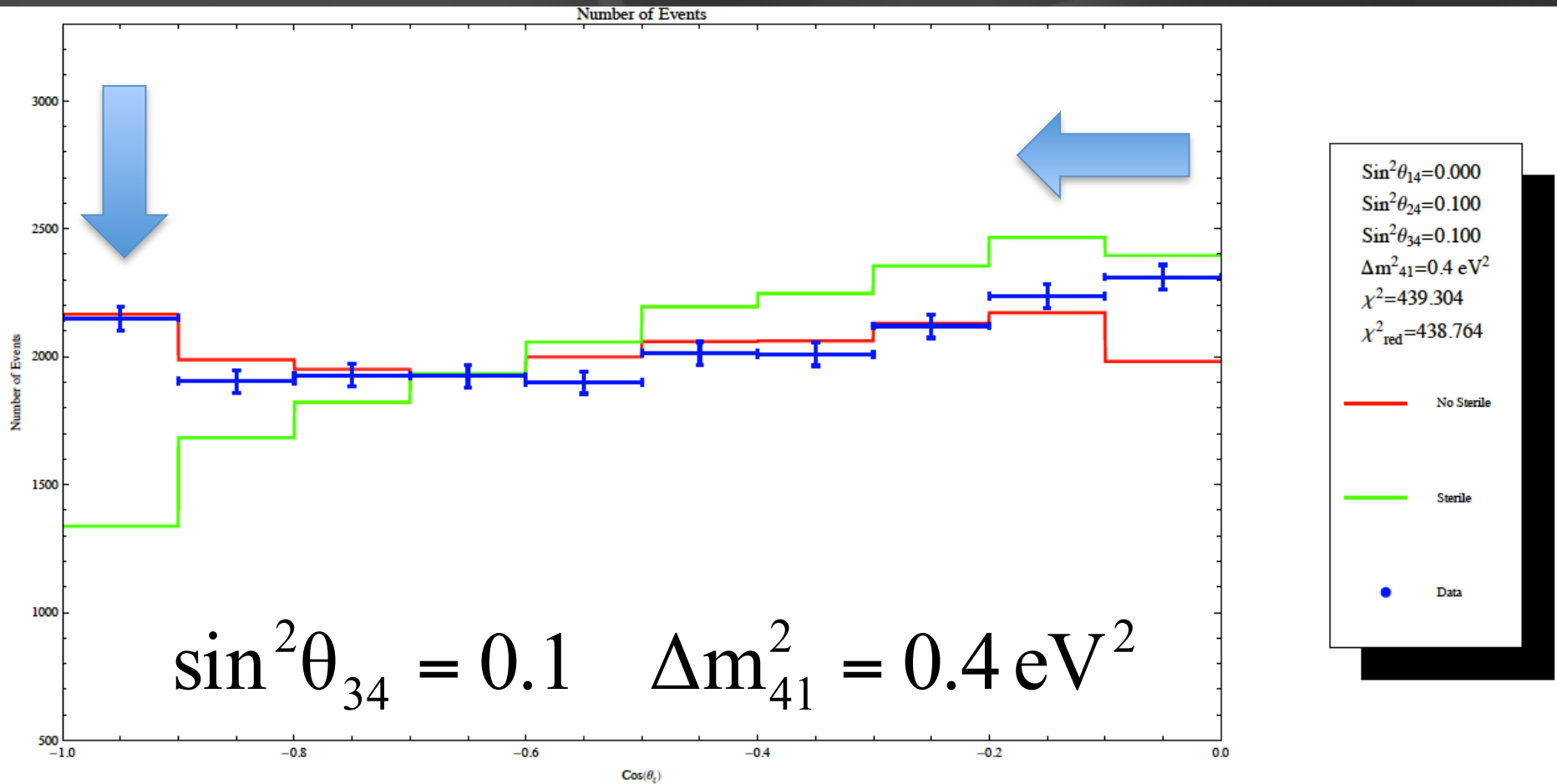
eV sterile neutrino \rightarrow Earth MSW resonance for TeV neutrinos

In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N} \sim O(\text{TeV})$$

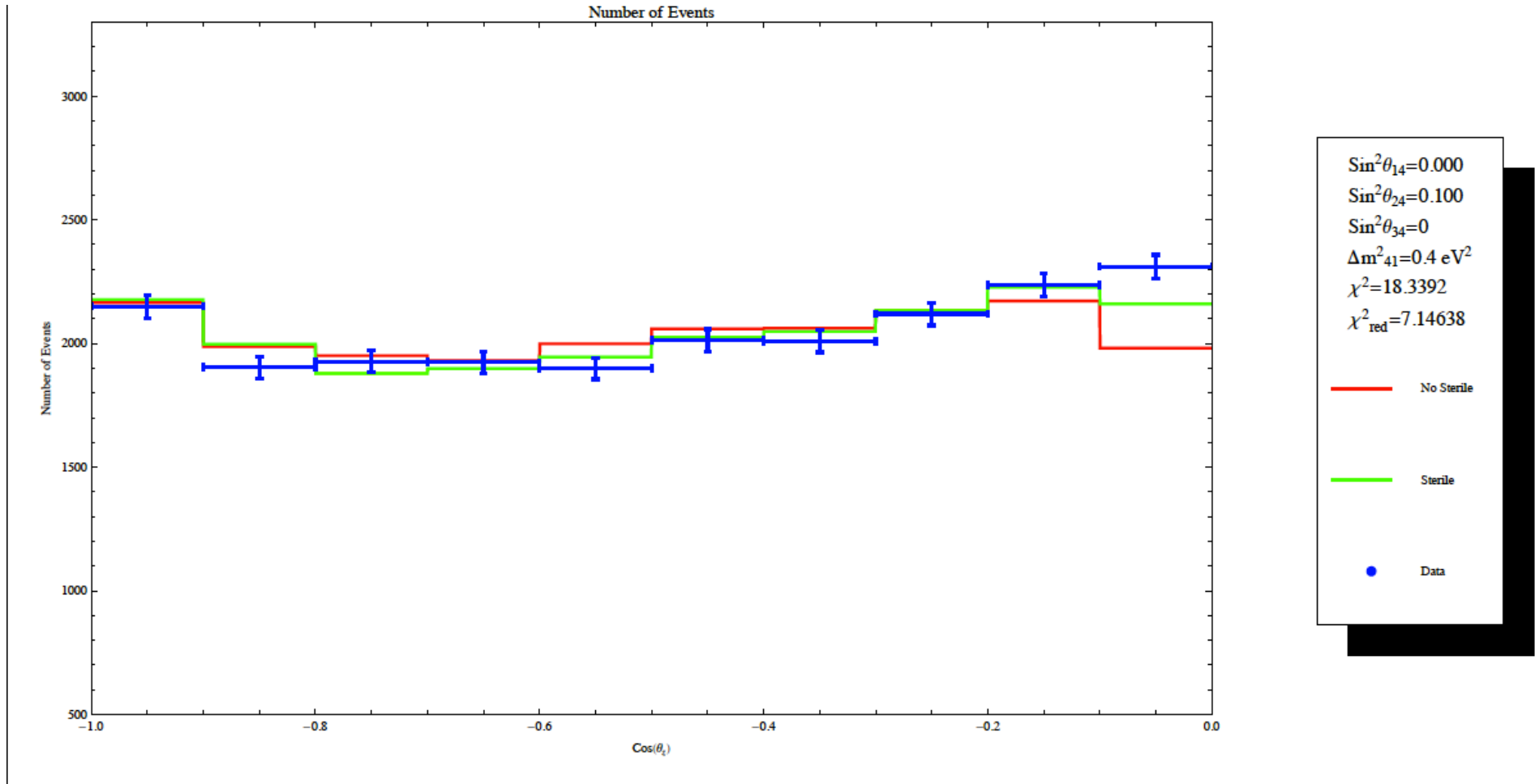


number of ν_μ observed versus zenith angle



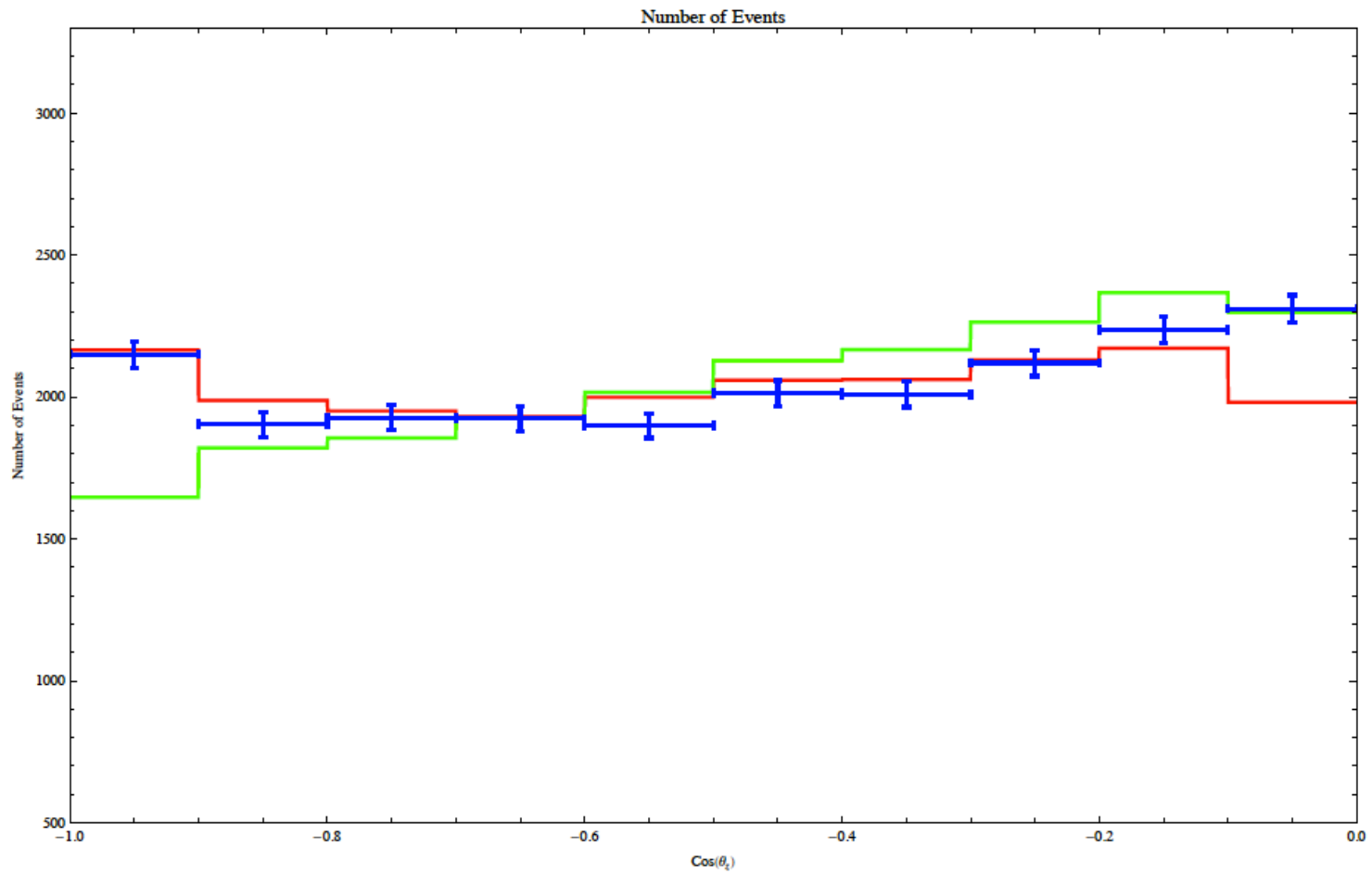
~ 2000 events per bin

number of nu-mu events versus $\cos\theta$ in IceCube 40



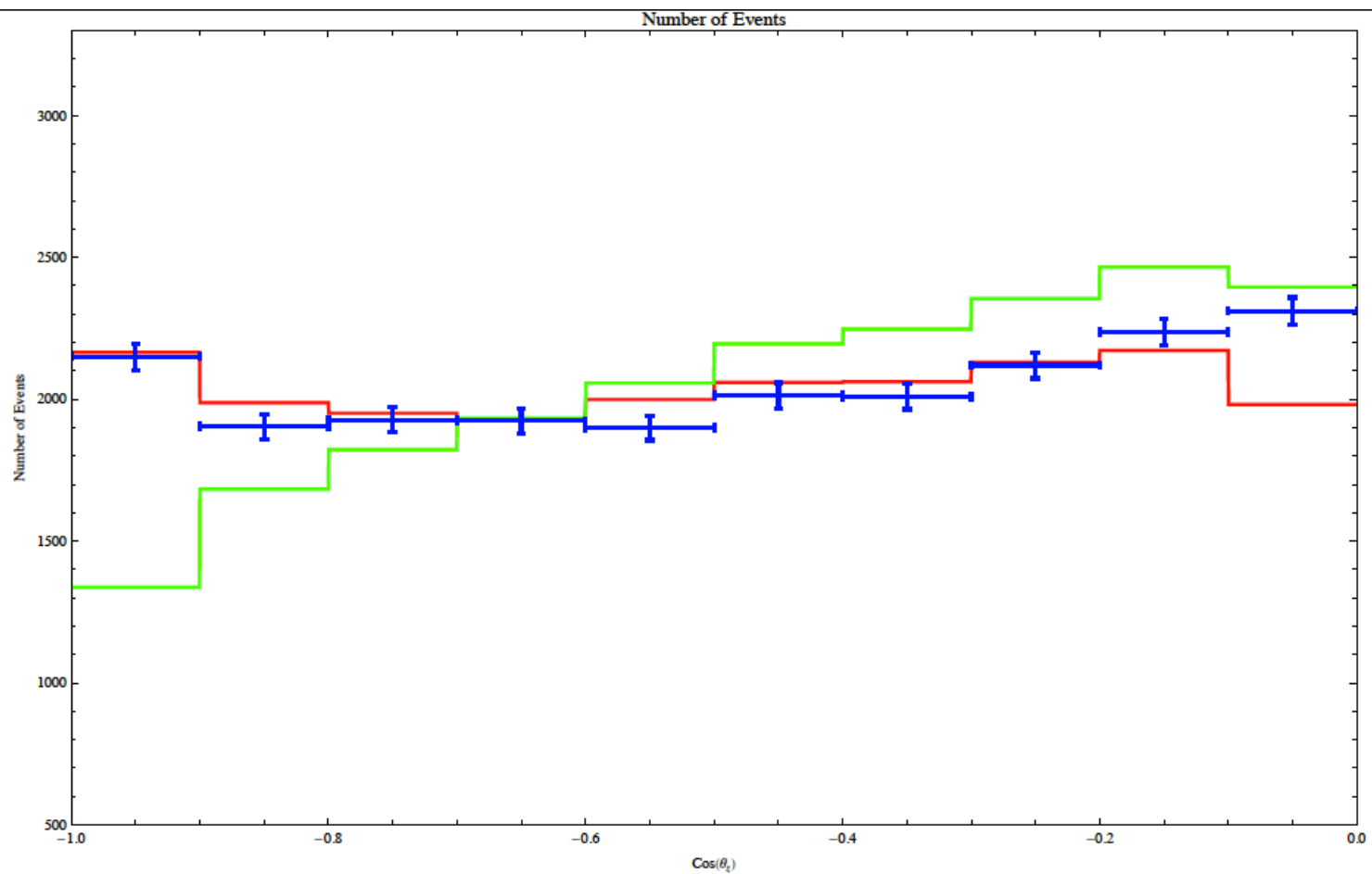
$$\Delta m^2 = 0.4 \text{ eV}^2 \text{ and } \sin^2\theta_{34} = 0 \rightarrow 0.5$$

Arman Esmaili



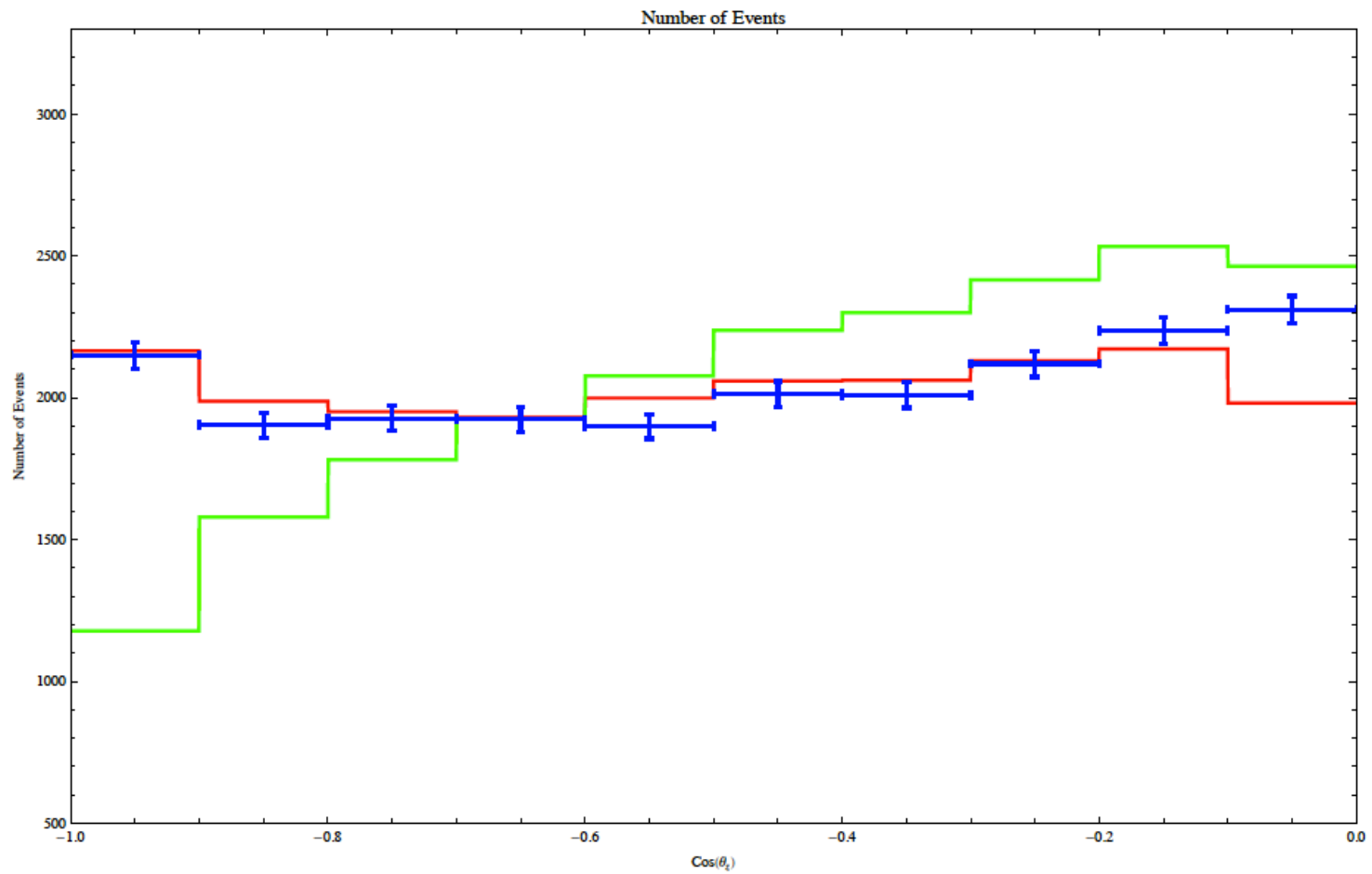
$\text{Sin}^2\theta_{14}=0.000$
 $\text{Sin}^2\theta_{24}=0.100$
 $\text{Sin}^2\theta_{34}=0.0500$
 $\Delta m^2_{41}=0.4 \text{ eV}^2$
 $\chi^2=166.471$
 $\chi^2_{\text{red}}=165.997$

— No Sterile
— Sterile
• Data



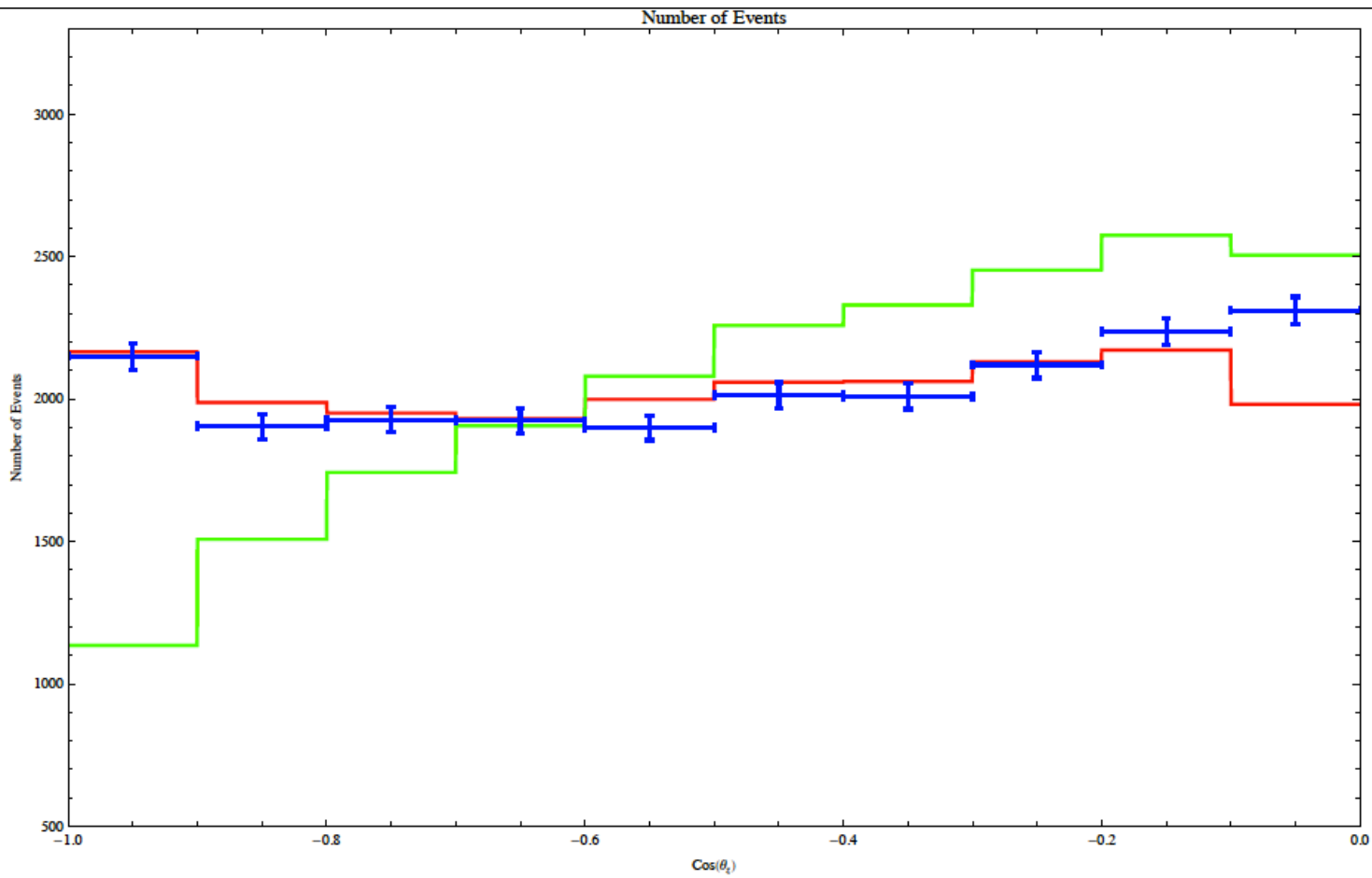
$\text{Sin}^2\theta_{14}=0.000$
 $\text{Sin}^2\theta_{24}=0.100$
 $\text{Sin}^2\theta_{34}=0.100$
 $\Delta m^2_{41}=0.4 \text{ eV}^2$
 $\chi^2=439.304$
 $\chi^2_{\text{red}}=438.764$

— No Sterile
— Sterile
• Data



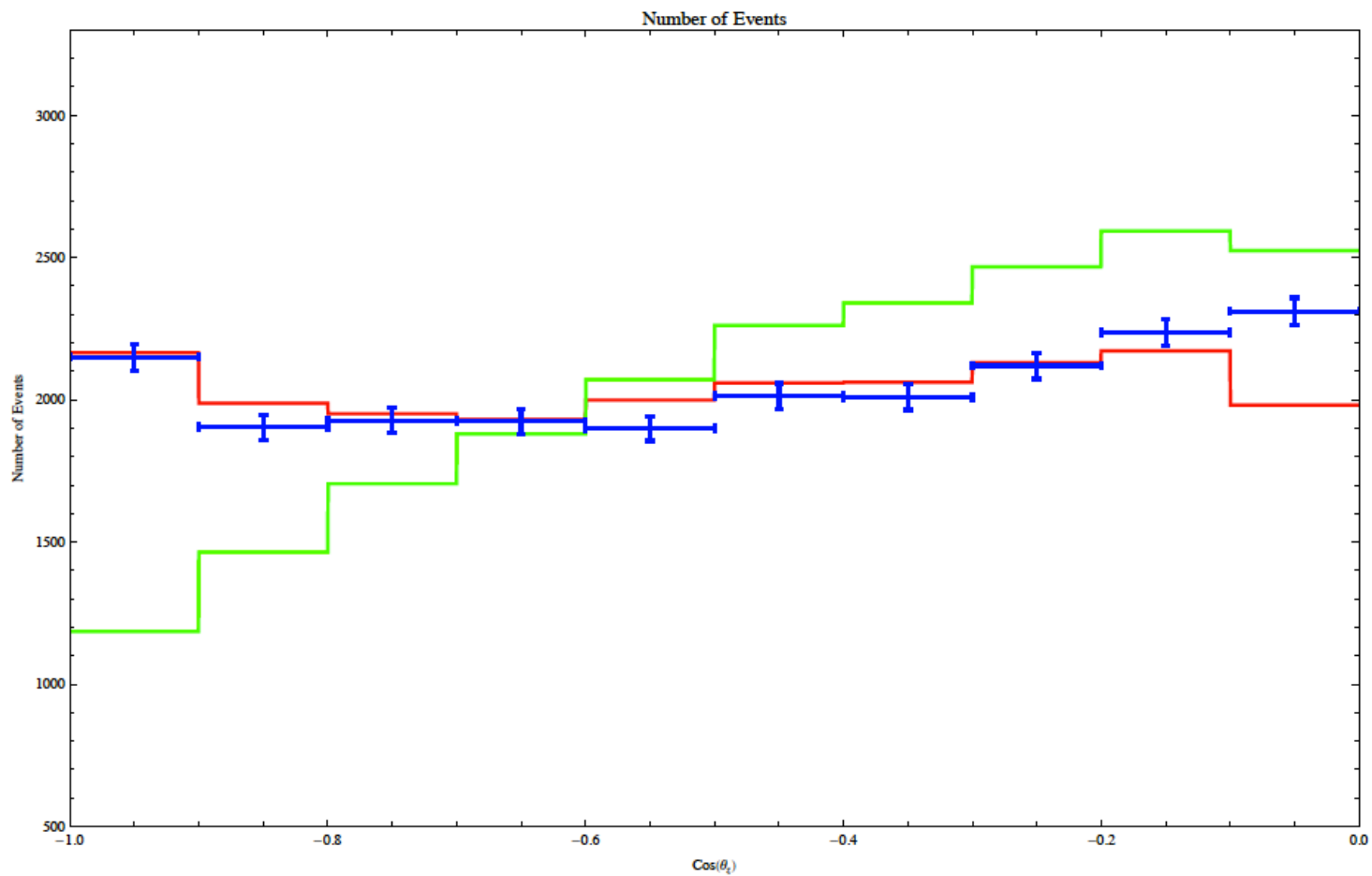
$\text{Sin}^2\theta_{14}=0.000$
 $\text{Sin}^2\theta_{24}=0.100$
 $\text{Sin}^2\theta_{34}=0.150$
 $\Delta m^2_{41}=0.4 \text{ eV}^2$
 $\chi^2=658.593$
 $\chi^2_{\text{red}}=655.973$

— No Sterile
— Sterile
• Data



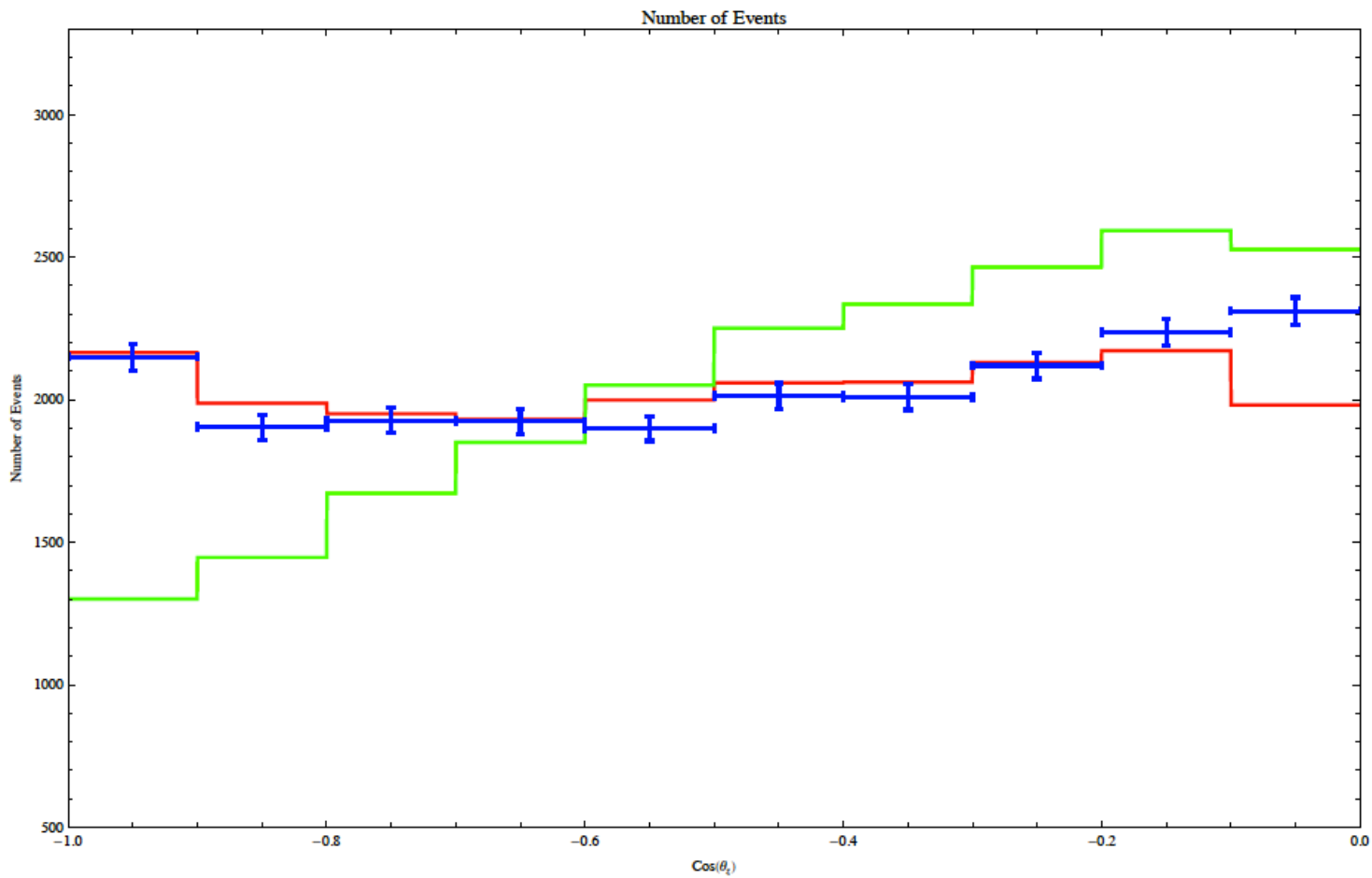
$\text{Sin}^2\theta_{14}=0.000$
 $\text{Sin}^2\theta_{24}=0.100$
 $\text{Sin}^2\theta_{34}=0.200$
 $\Delta m^2_{41}=0.4 \text{ eV}^2$
 $\chi^2=767.372$
 $\chi^2_{\text{red}}=762.402$

— No Sterile
— Sterile
• Data



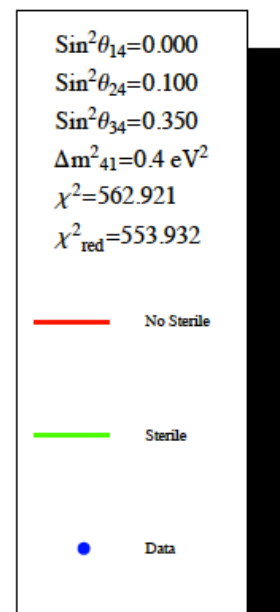
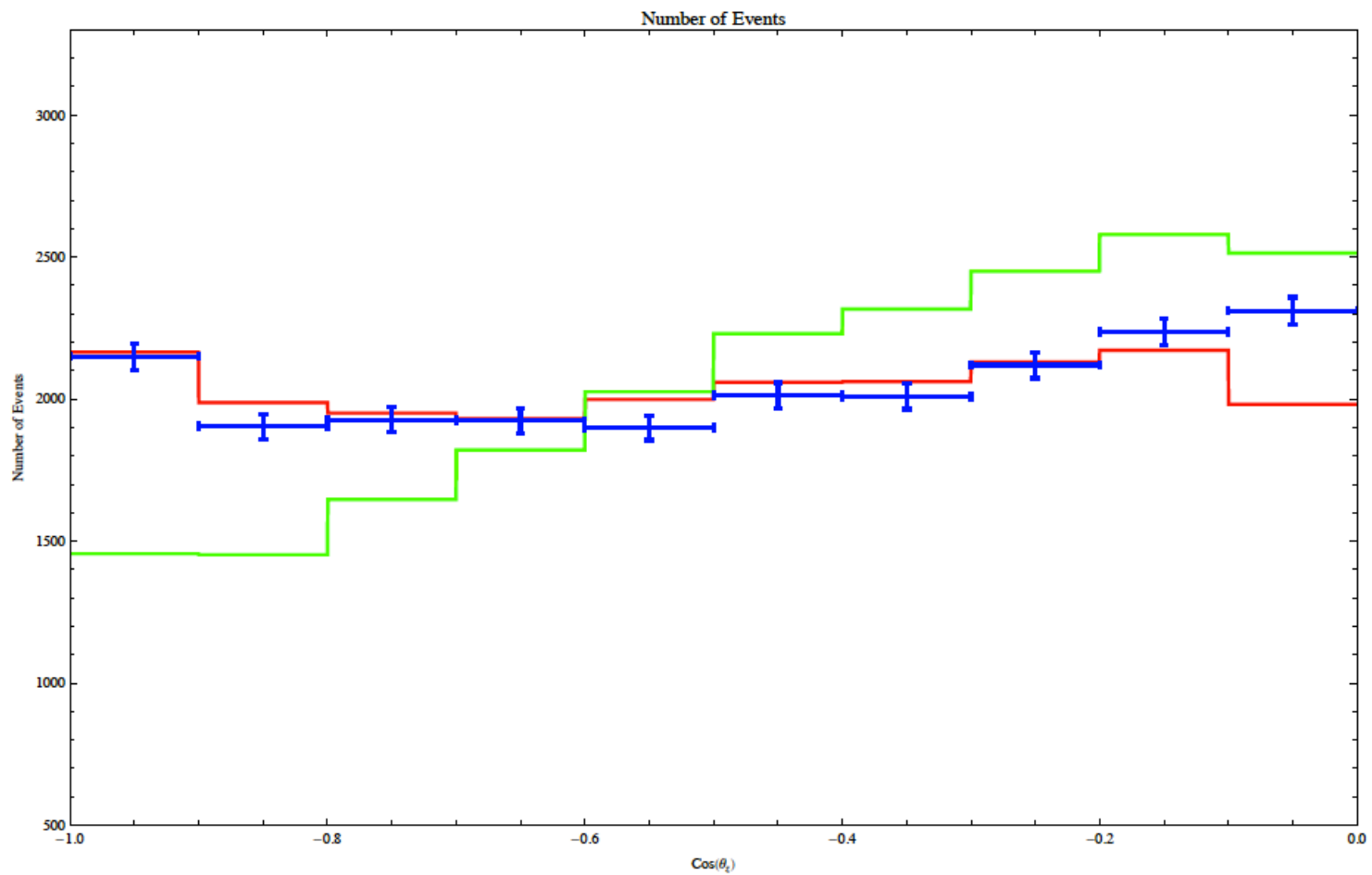
$\sin^2\theta_{14}=0.000$
 $\sin^2\theta_{24}=0.100$
 $\sin^2\theta_{34}=0.250$
 $\Delta m^2_{41}=0.4 \text{ eV}^2$
 $\chi^2=765.849$
 $\chi^2_{\text{red}}=758.76$

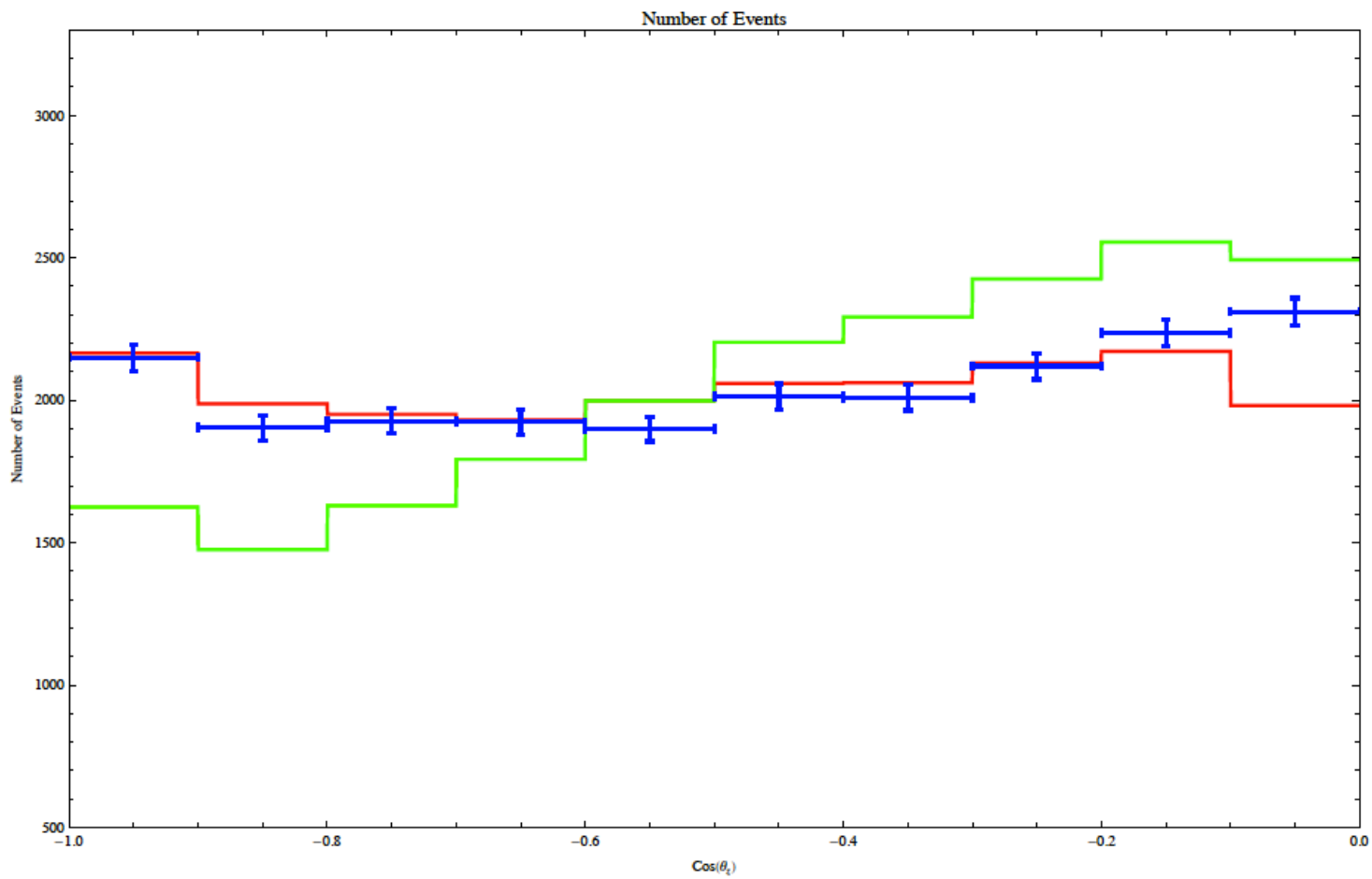
- No Sterile
- Sterile
- Data



$\text{Sin}^2\theta_{14}=0.000$
 $\text{Sin}^2\theta_{24}=0.100$
 $\text{Sin}^2\theta_{34}=0.300$
 $\Delta m^2_{41}=0.4 \text{ eV}^2$
 $\chi^2=684.279$
 $\chi^2_{\text{red}}=675.718$

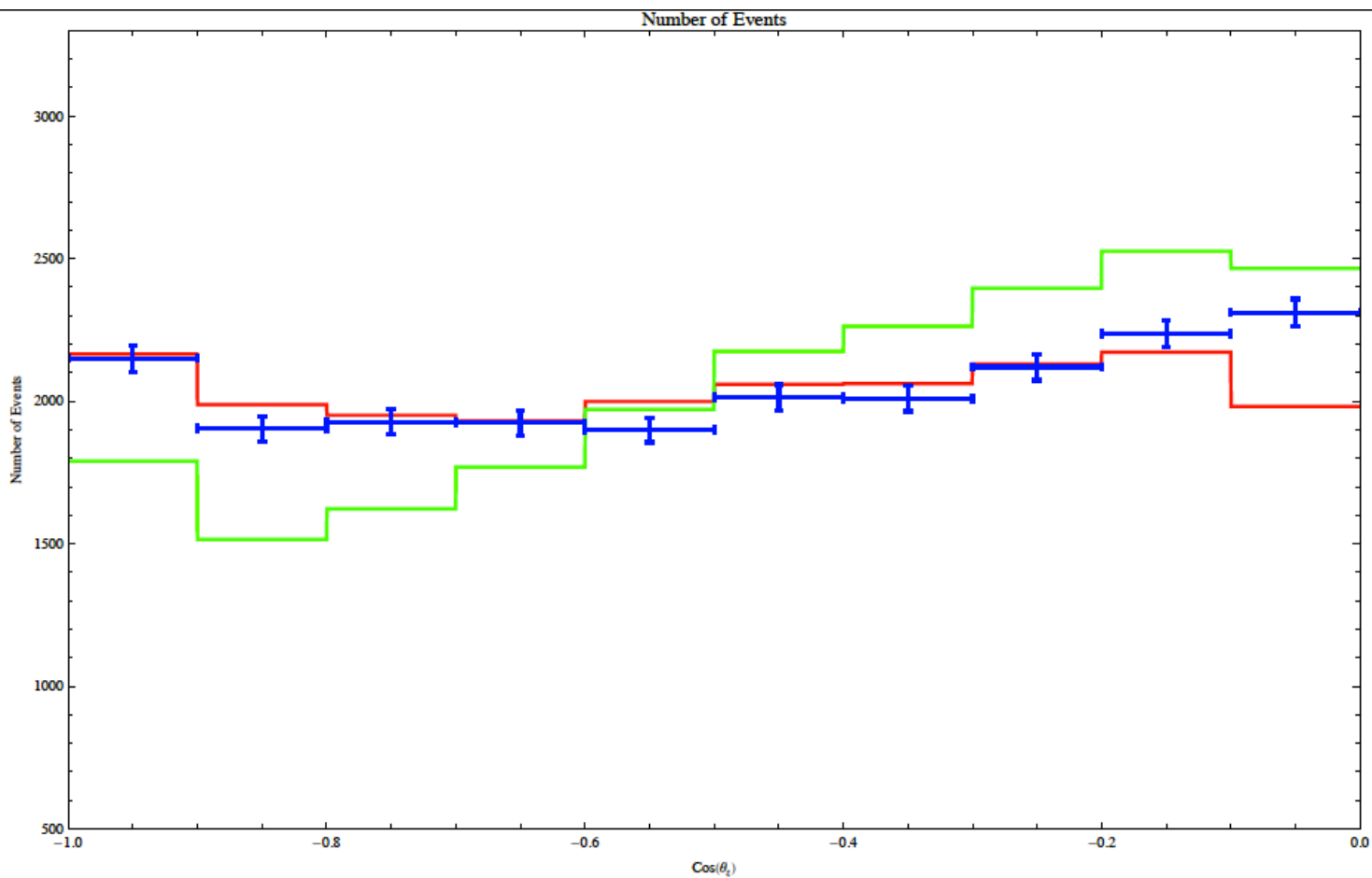
— No Sterile
— Sterile
• Data





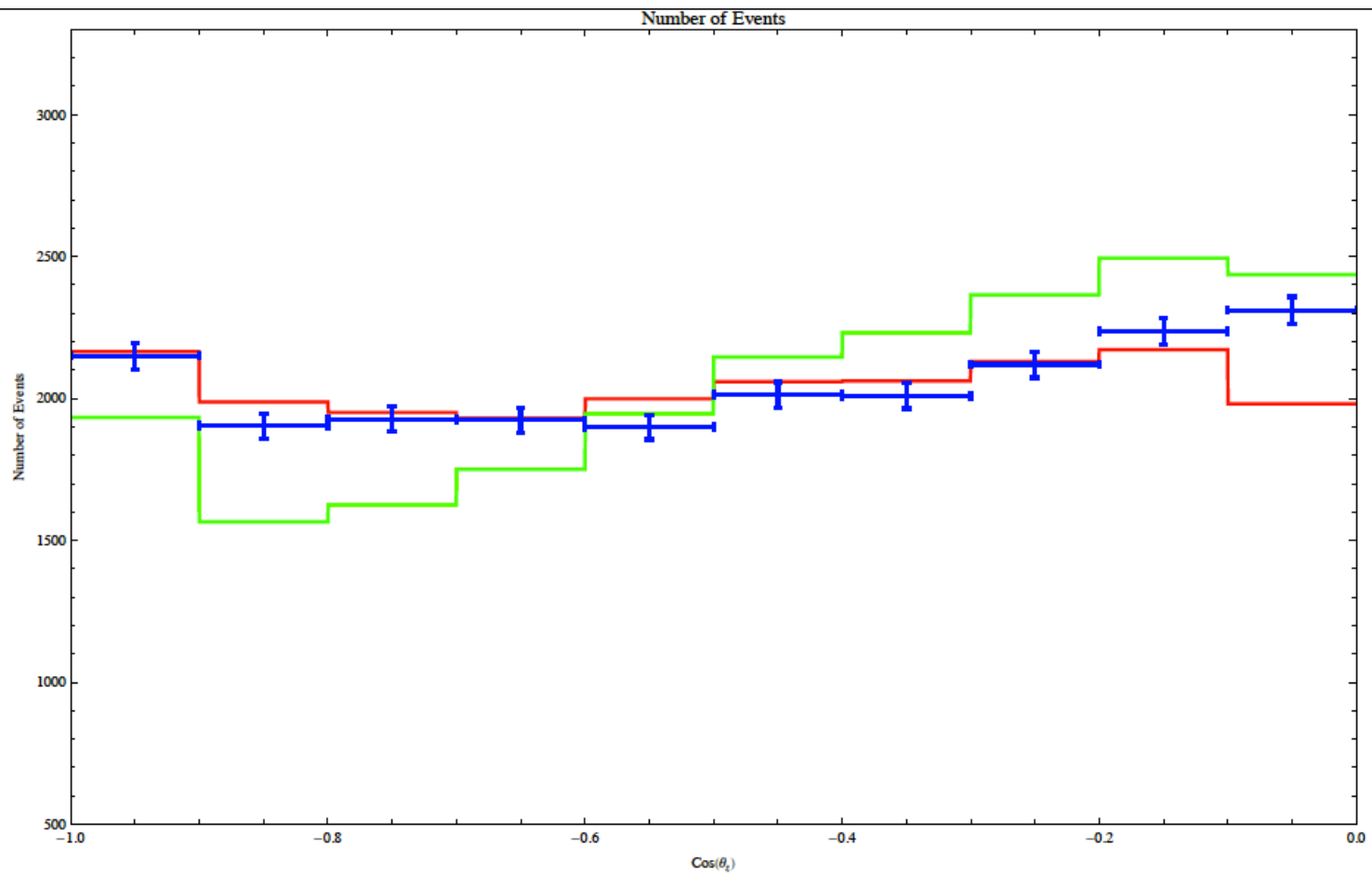
$\text{Sin}^2\theta_{14}=0.000$
 $\text{Sin}^2\theta_{24}=0.100$
 $\text{Sin}^2\theta_{34}=0.400$
 $\Delta m^2_{41}=0.4 \text{ eV}^2$
 $\chi^2=436.643$
 $\chi^2_{\text{red}}=428.396$

— No Sterile
— Sterile
• Data



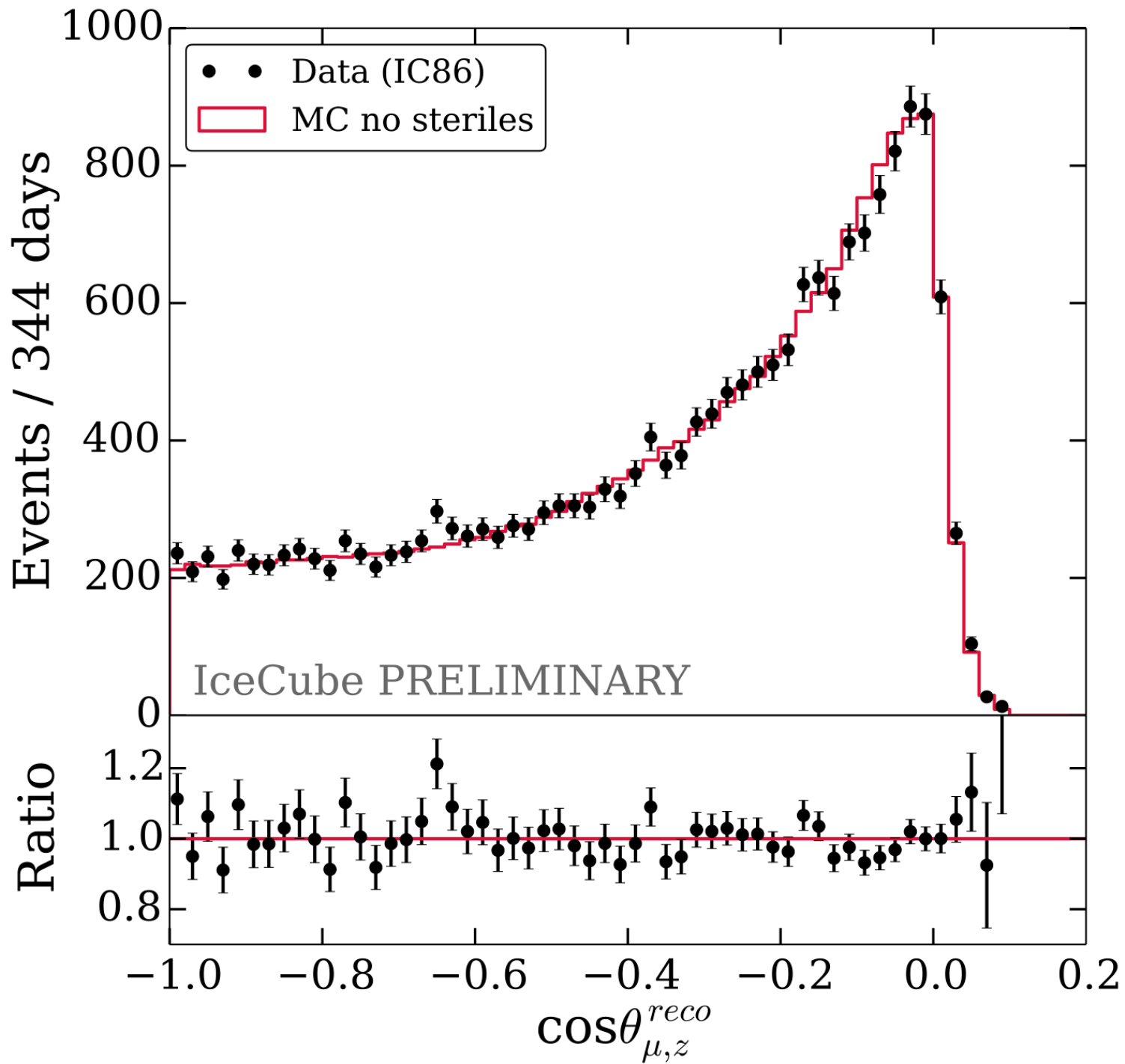
$\text{Sin}^2\theta_{14}=0.000$
 $\text{Sin}^2\theta_{24}=0.100$
 $\text{Sin}^2\theta_{34}=0.450$
 $\Delta m^2_{41}=0.4 \text{ eV}^2$
 $\chi^2=326.895$
 $\chi^2_{\text{red}}=320.294$

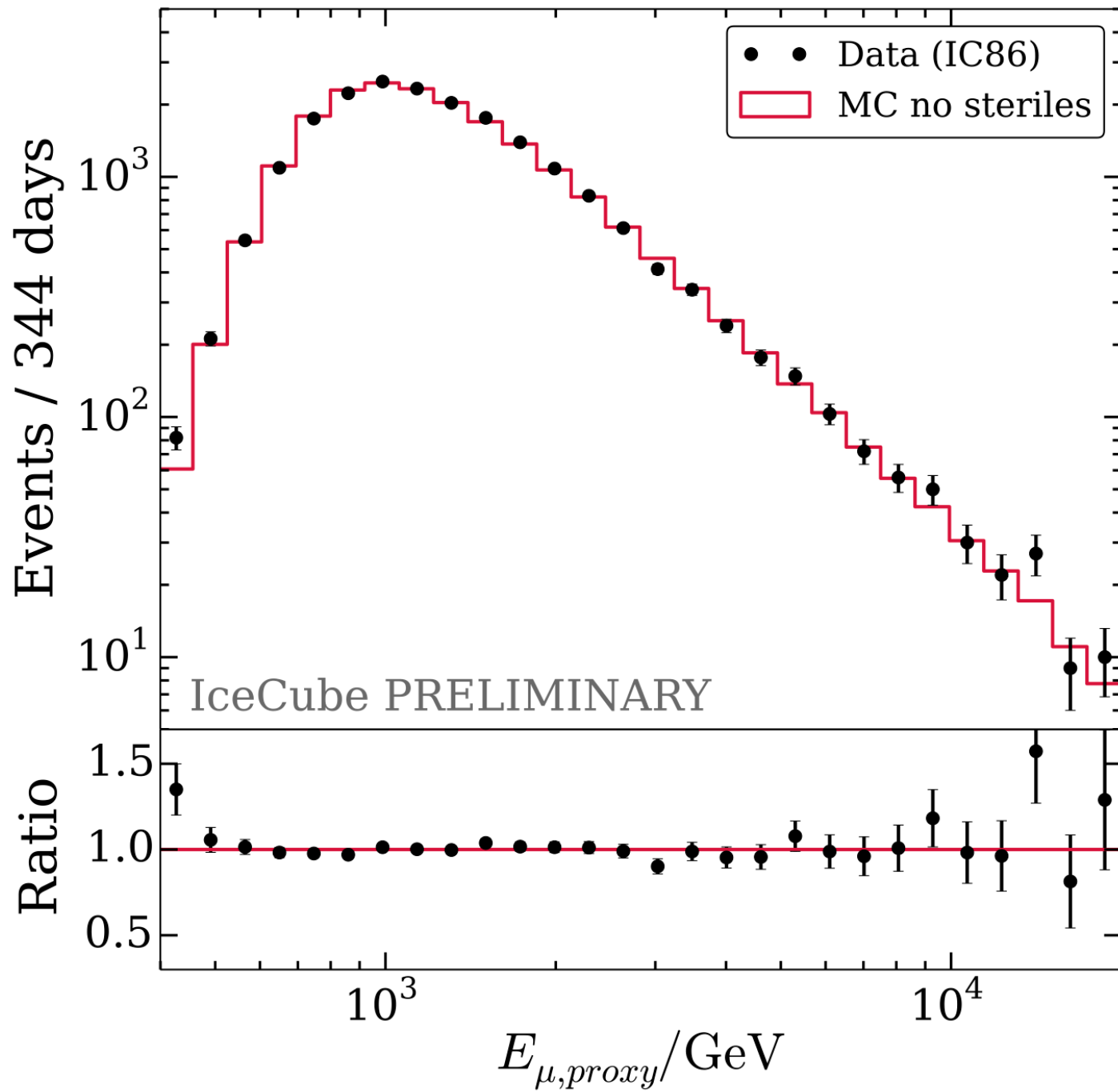
— No Sterile
— Sterile
• Data



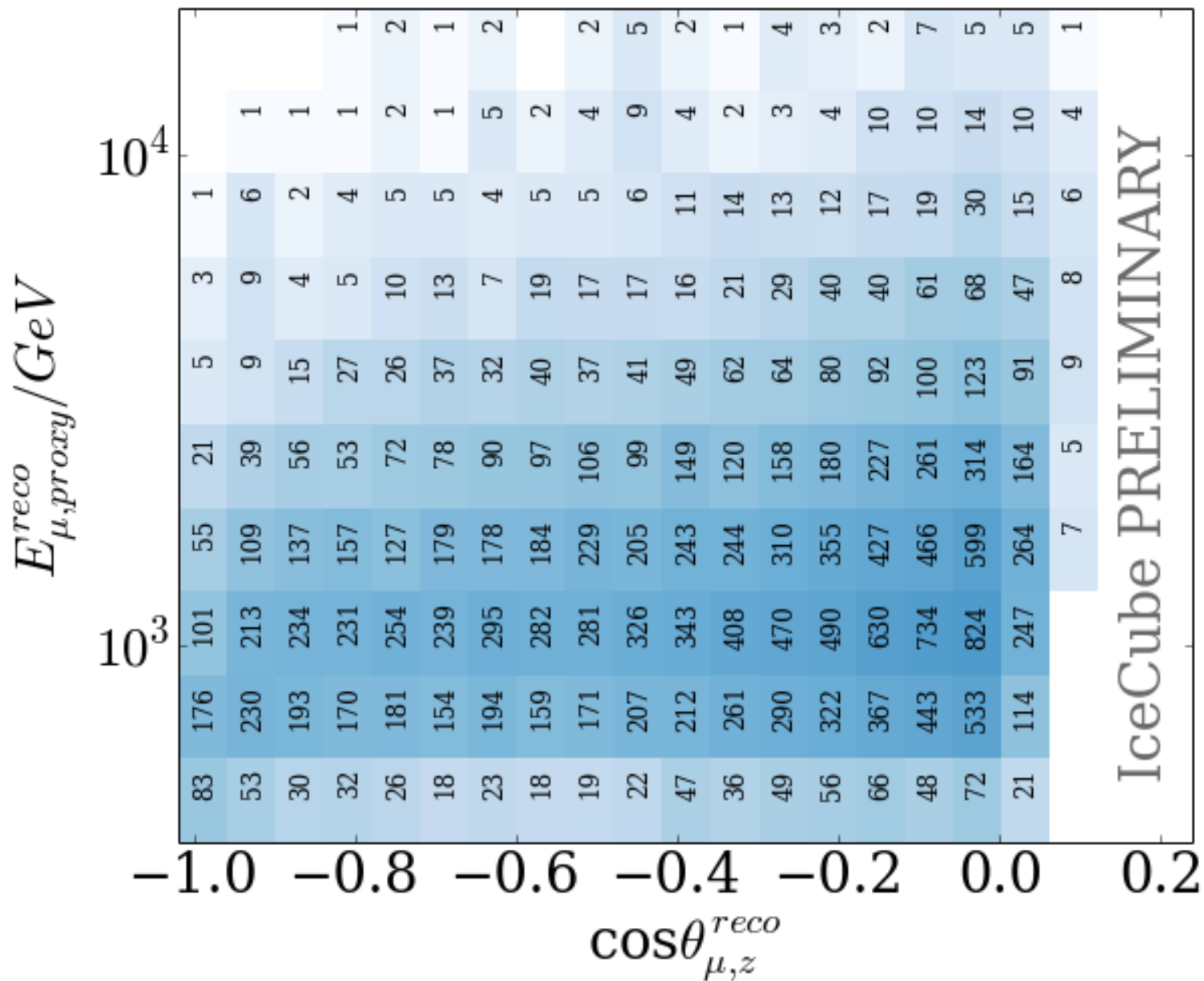
$\text{Sin}^2\theta_{14}=0.000$
 $\text{Sin}^2\theta_{24}=0.100$
 $\text{Sin}^2\theta_{34}=0.500$
 $\Delta m^2_{41}=0.4 \text{ eV}^2$
 $\chi^2=241.386$
 $\chi^2_{\text{red}}=236.818$

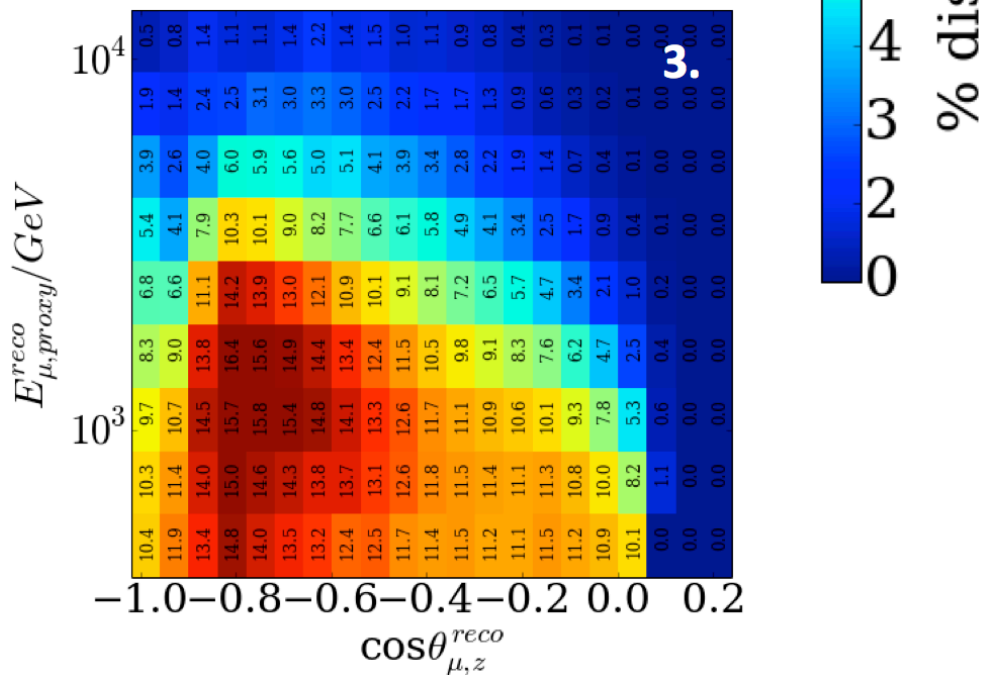
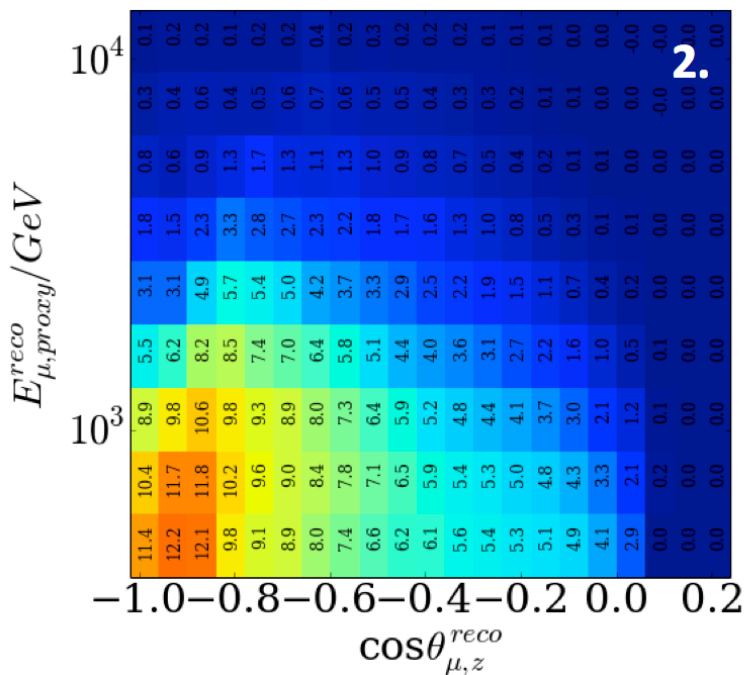
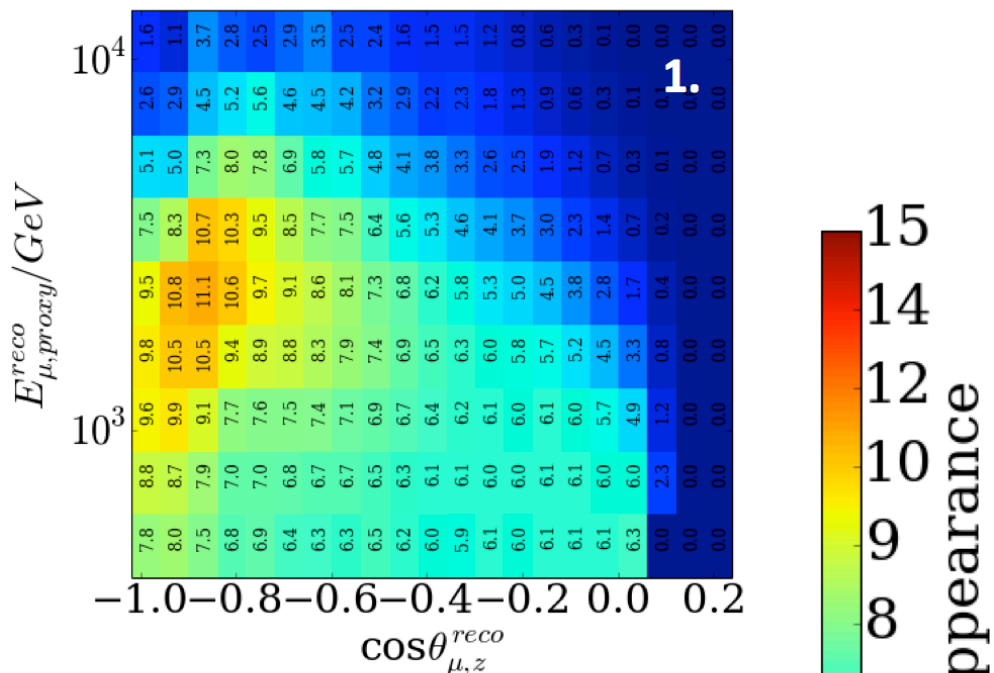
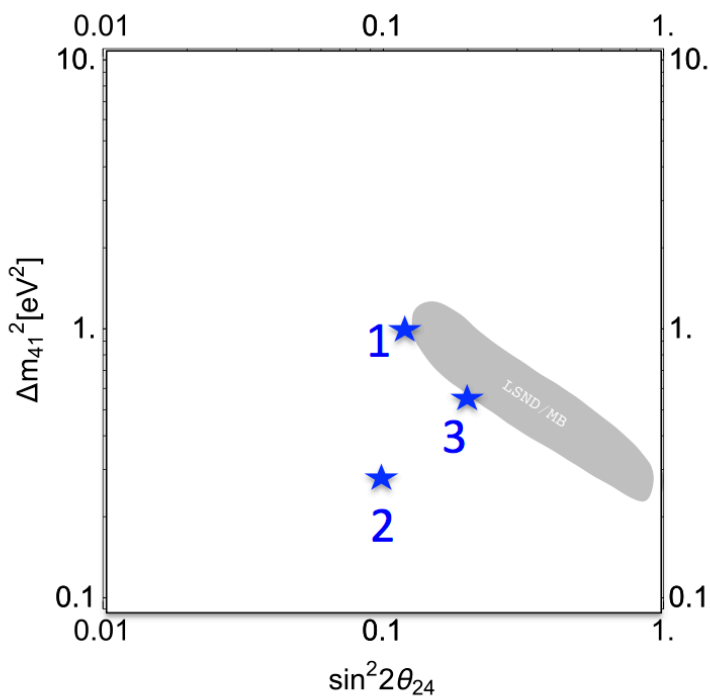
— No Sterile
— Sterile
• Data



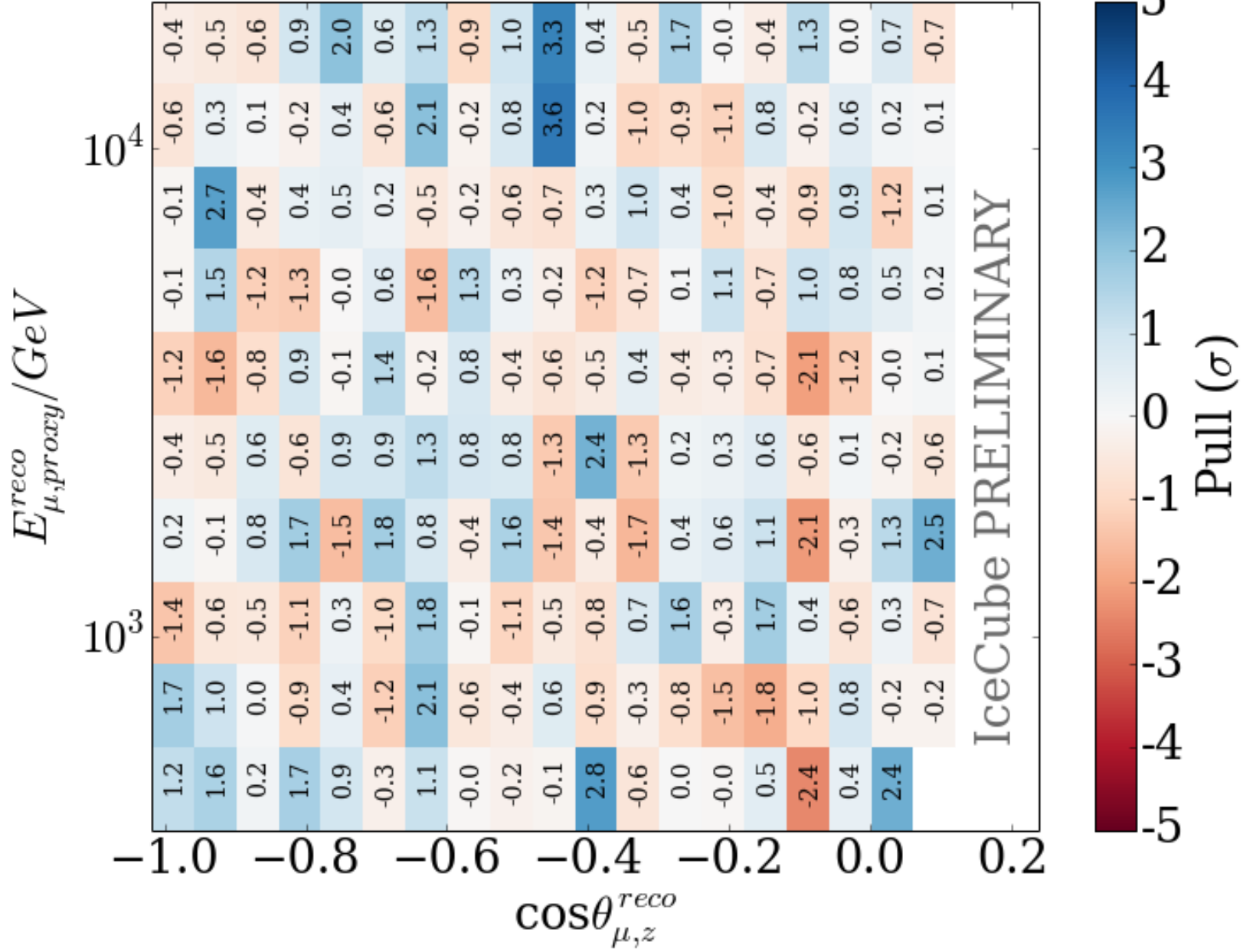


Data (events per bin)





Pulls per bin, no steriles



Systematics!

Systematics are **super** important; *some more than others*. These are the systematics we considered:

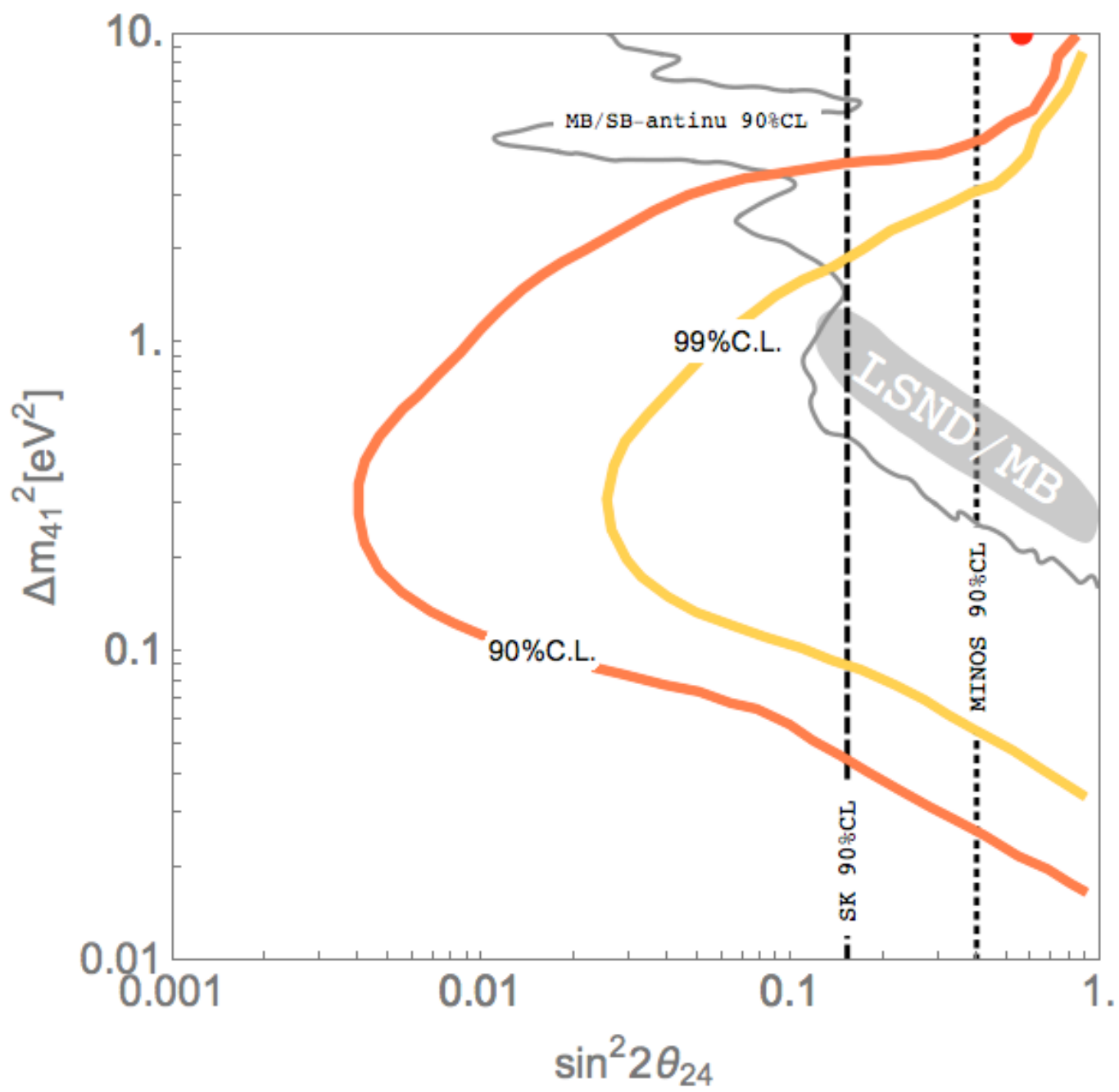
- ▶ DOM efficiency
- ▶ Flux continuous parameters
 - ▶ spectral index
 - ▶ π/K ratio
 - ▶ $\nu/\bar{\nu}$ ratio
- ▶ Air shower hadronic models
- ▶ Primary cosmic ray fluxes
- ▶ Hole Ice
- ▶ Neutrino cross sections
- ▶ Bulk ice scattering/absorption
- ▶ Earth model

continuous systematics
discrete systematic



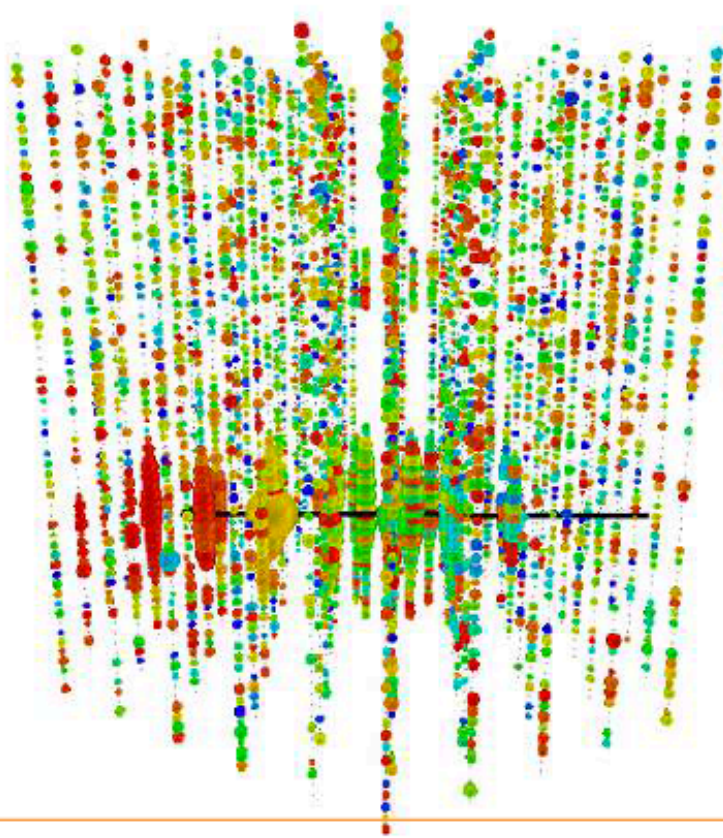
Important

Not important

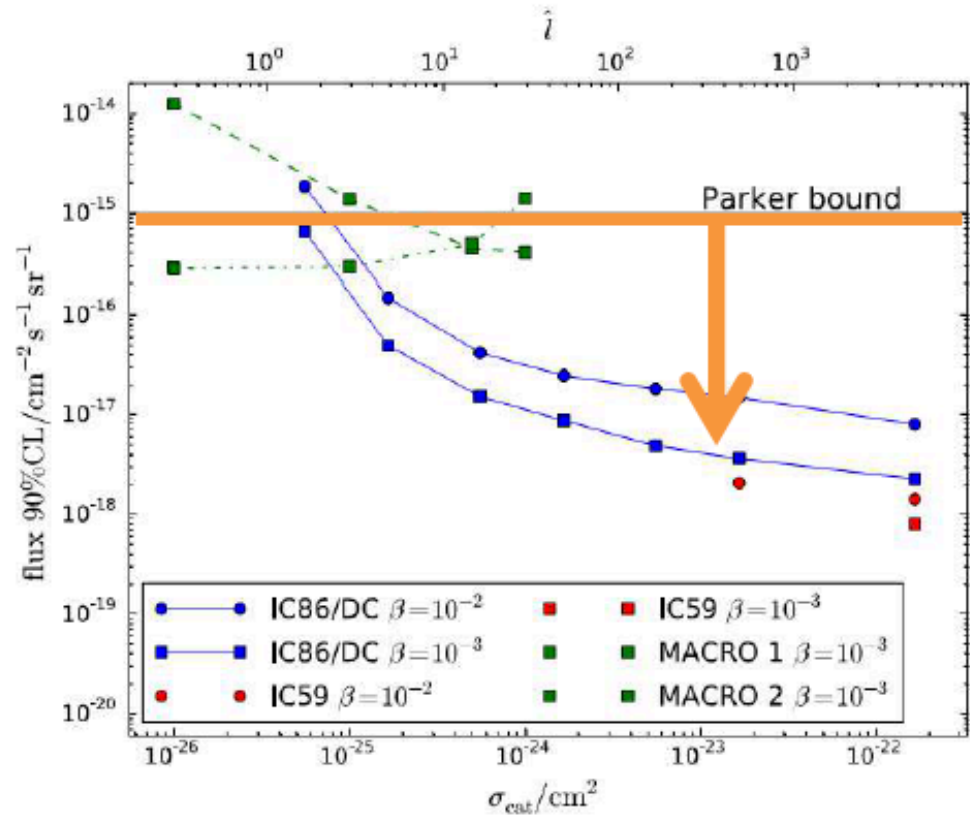


GUT monopoles

Example: slowly moving magnetic monopole catalyzing proton decay:



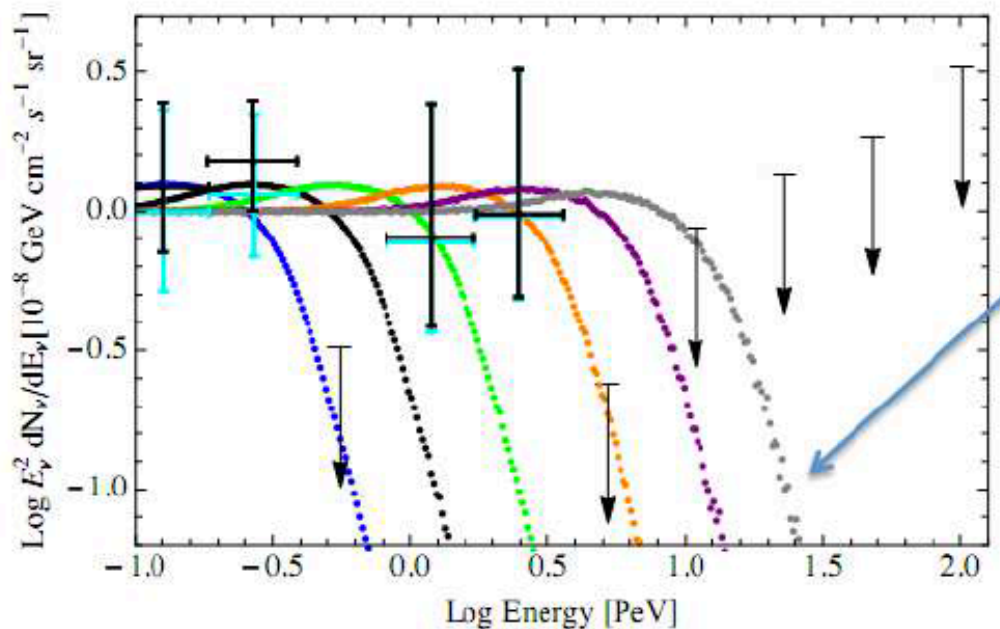
$v \sim c/1000$, 10 ms data, special trigger
Strong signal above integrated noise



EPJC 74, 7 (cover print)

superluminal motion

Existence of high energy neutrinos limits on superluminal velocity:



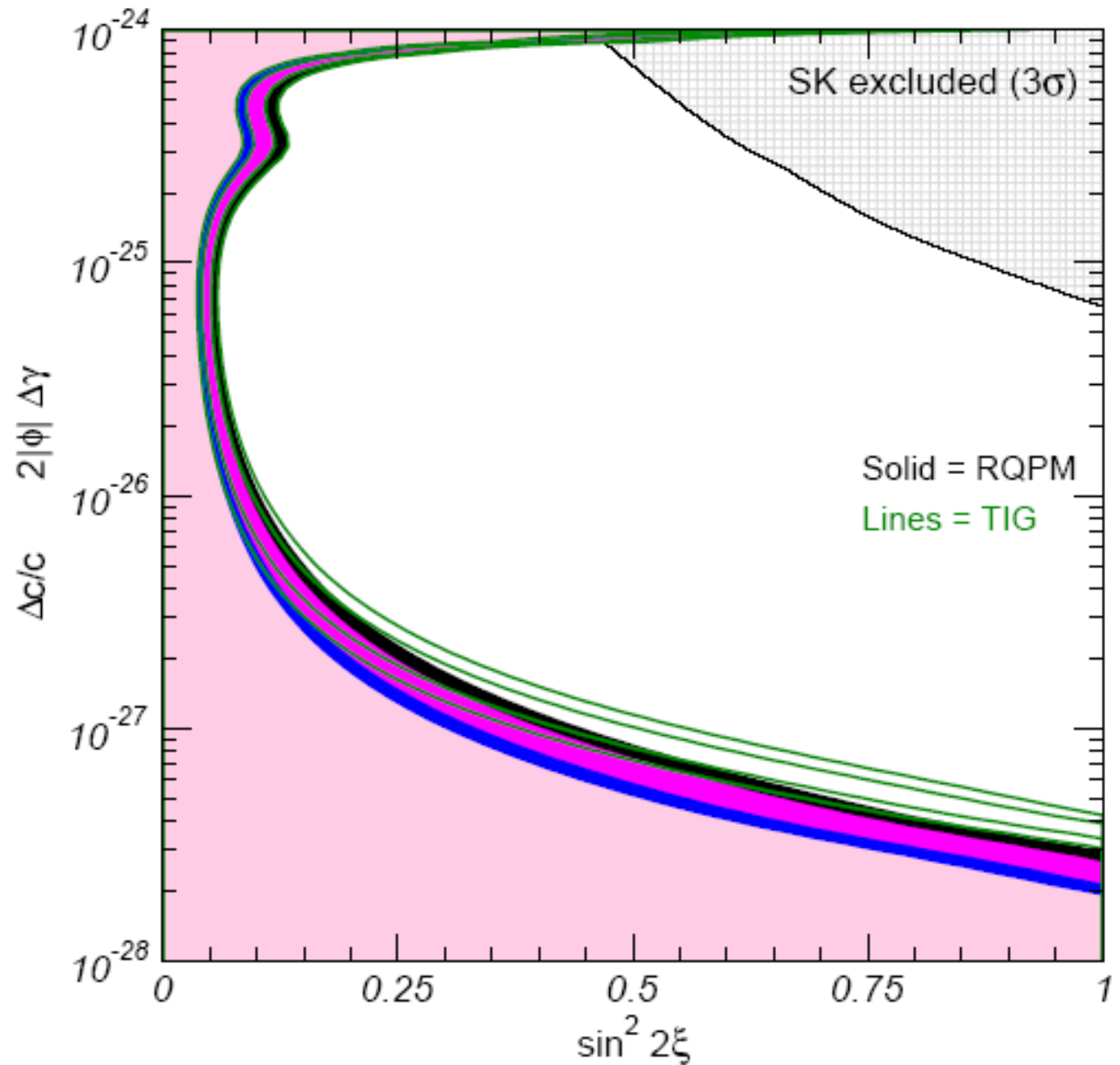
$$\delta_\nu - \delta_e < 5.2 \times 10^{-21}$$

Pair-production threshold of 10 PeV
required for consistency with IceCube

Reason for cut-off could be vacuum pair emission (astrophysics more likely ...)

- tests
- equivalence principle and
 - Lorentz invariance

...general relativity will not last 200 years...
M. Turner





IceCube: beyond neutrino astronomy

Francis Halzen

- muon astronomy: search for the sources of the Galactic cosmic rays
- detecting a Galactic supernova explosion
- search for dark matter
- neutrino oscillations
- search for sterile neutrinos
- ...