Search for Solar Atmospheric Neutrinos and the Neutrino Floor

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DarkGhosts Nov 13-14, 2018

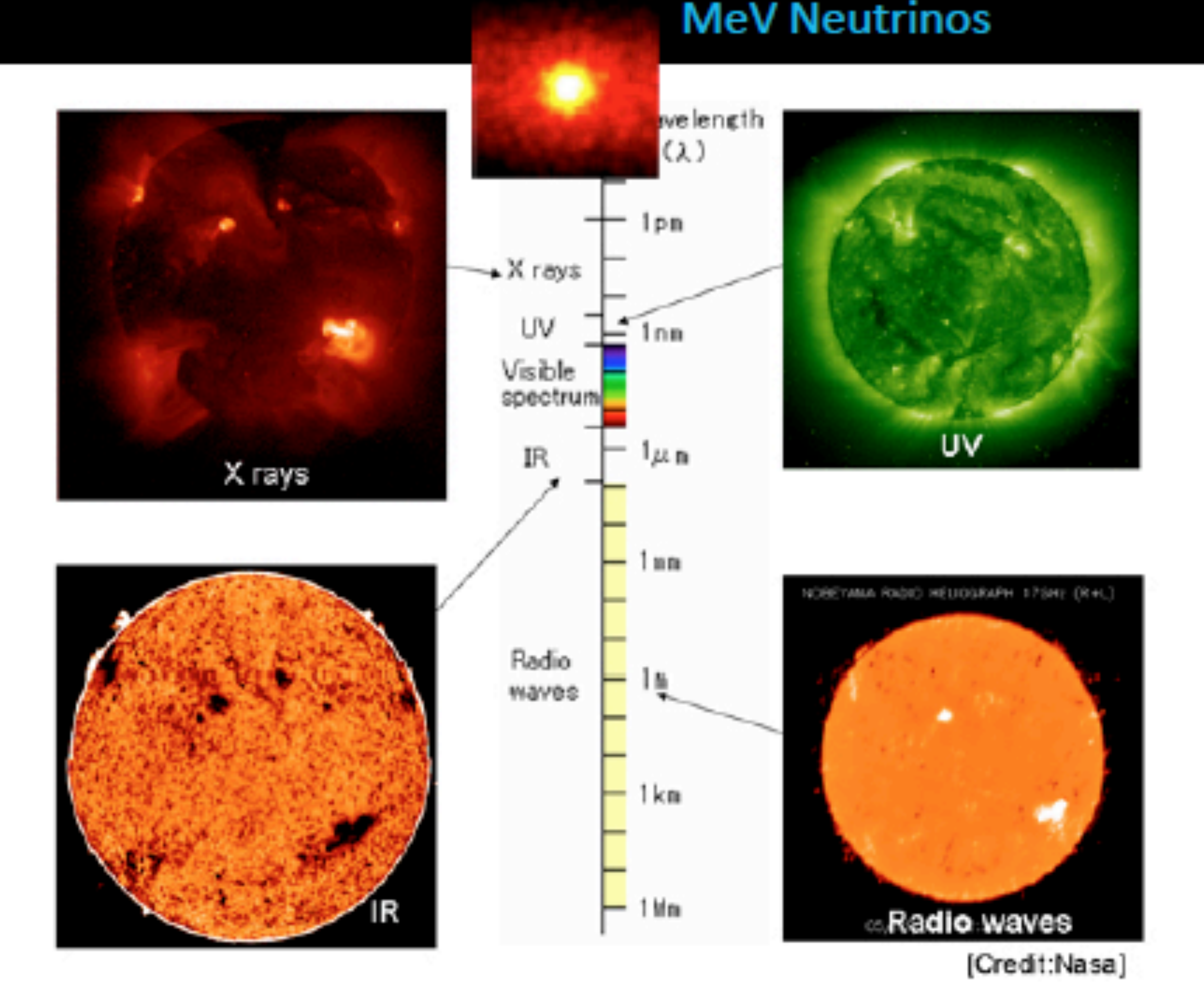
Motivation

Observations of the Sun

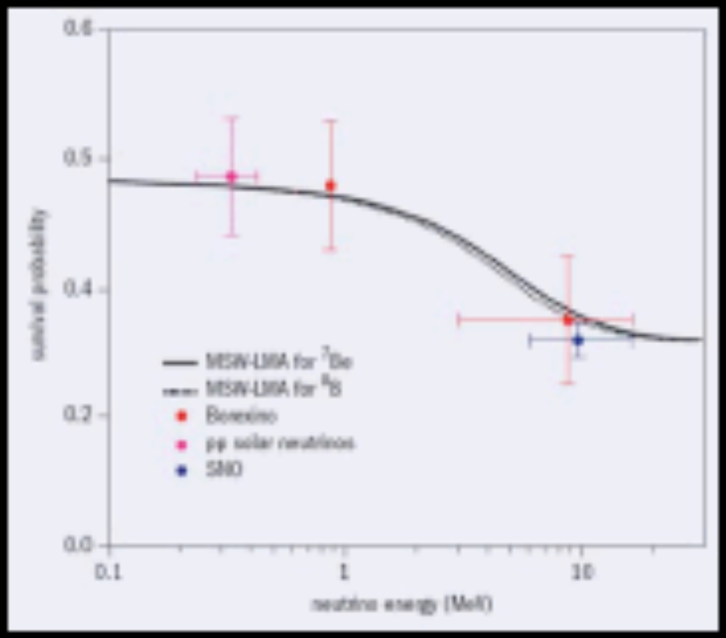
GeV ??? → The Sun is not hot enough!

Fundamental Physics from the Sun

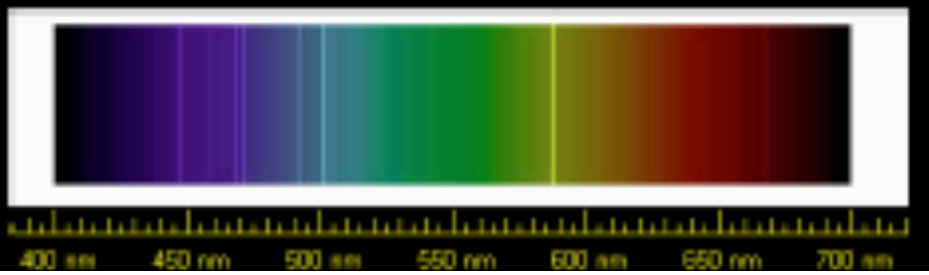
MeV Neutrinos



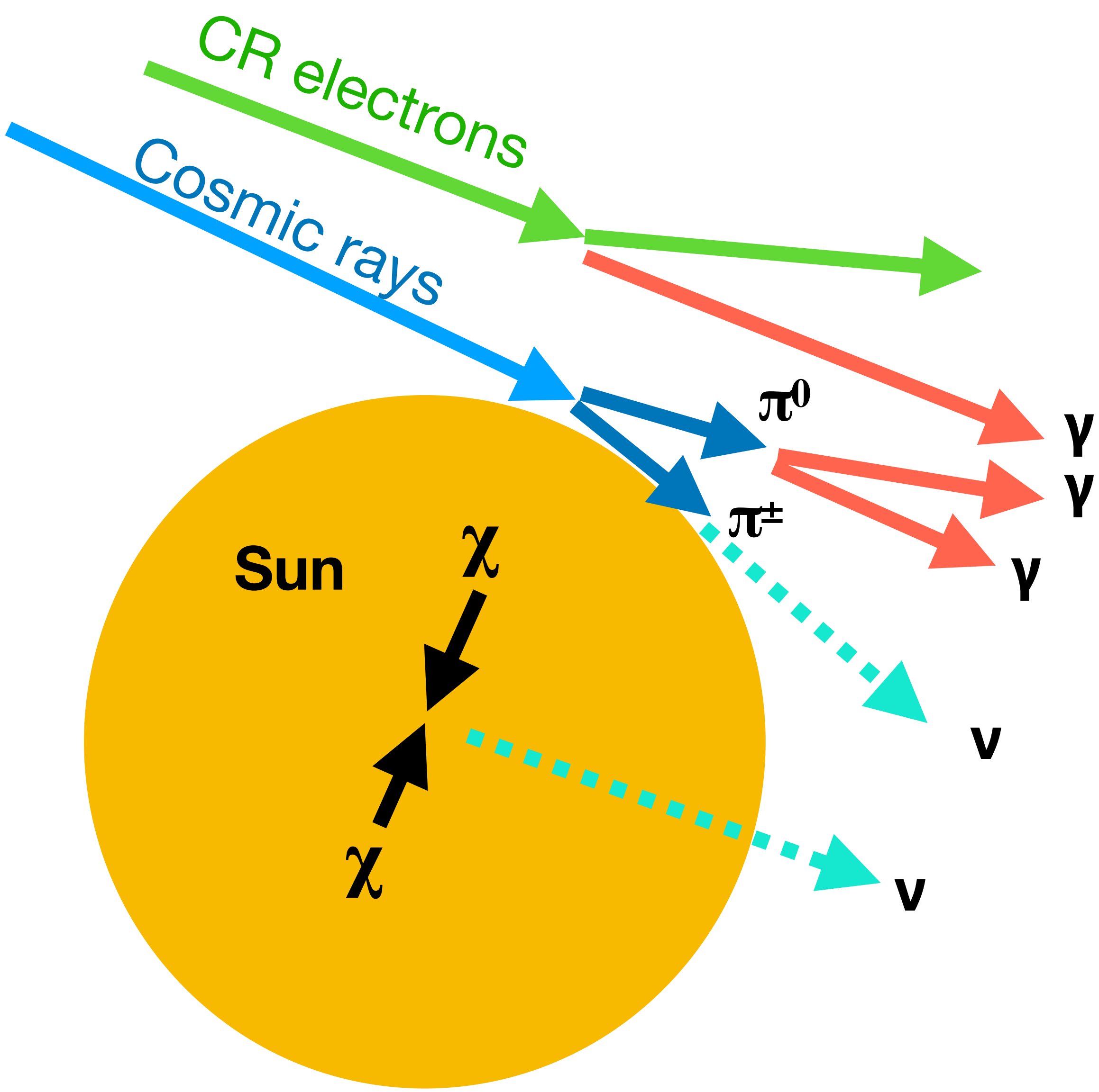
Neutrino Mass



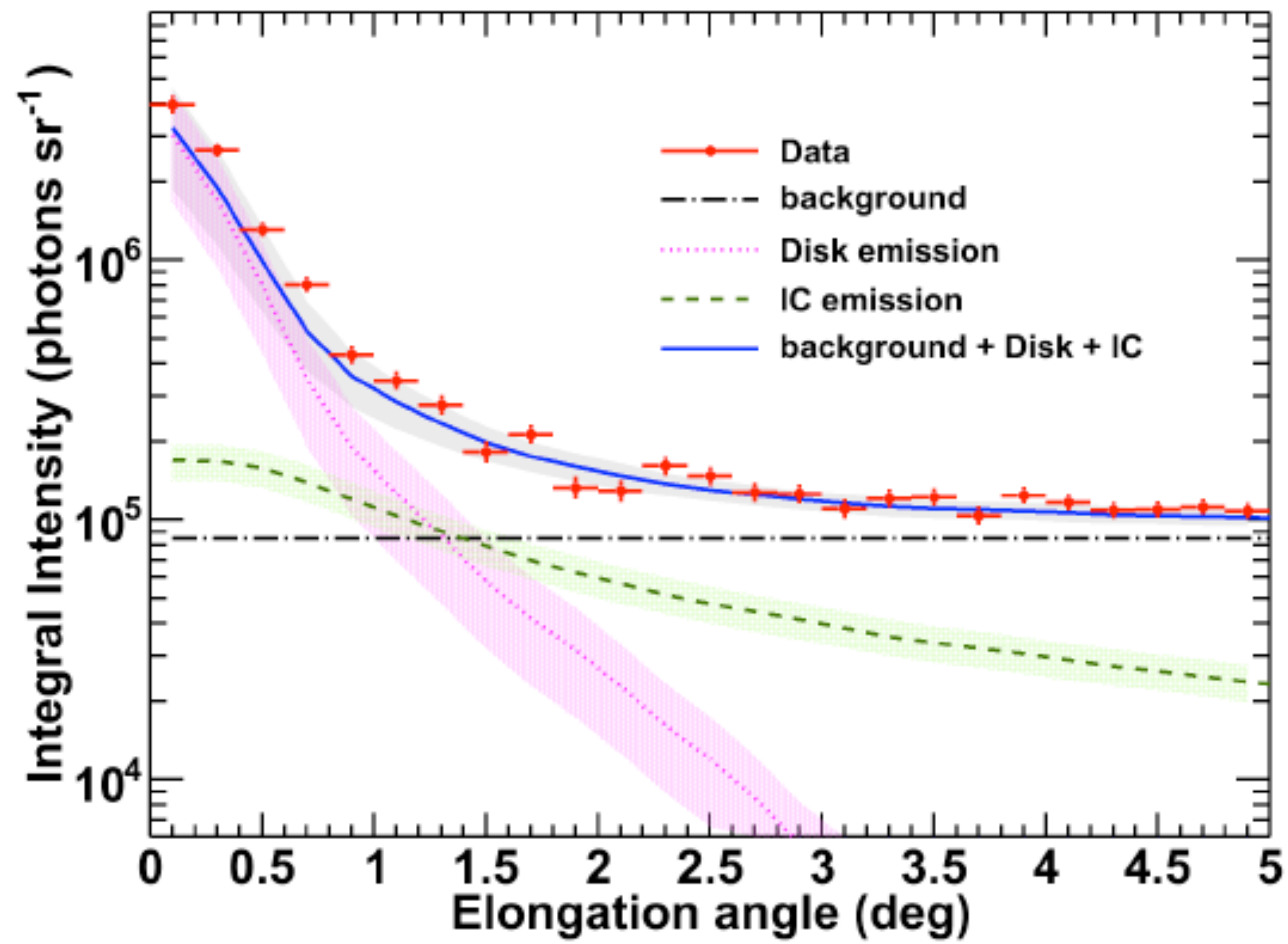
Helium Discovery



Cosmic ray interactions with the Sun



see Fermi-LAT Collaboration: The Astrophysical Journal 734 (2011) 116 (arxiv:1104.2093)



- Cosmic ray interactions in the Solar atmosphere produce gamma-rays and neutrinos
- Background to dark matter searches from the Sun, that soon will be relevant

Leptonic

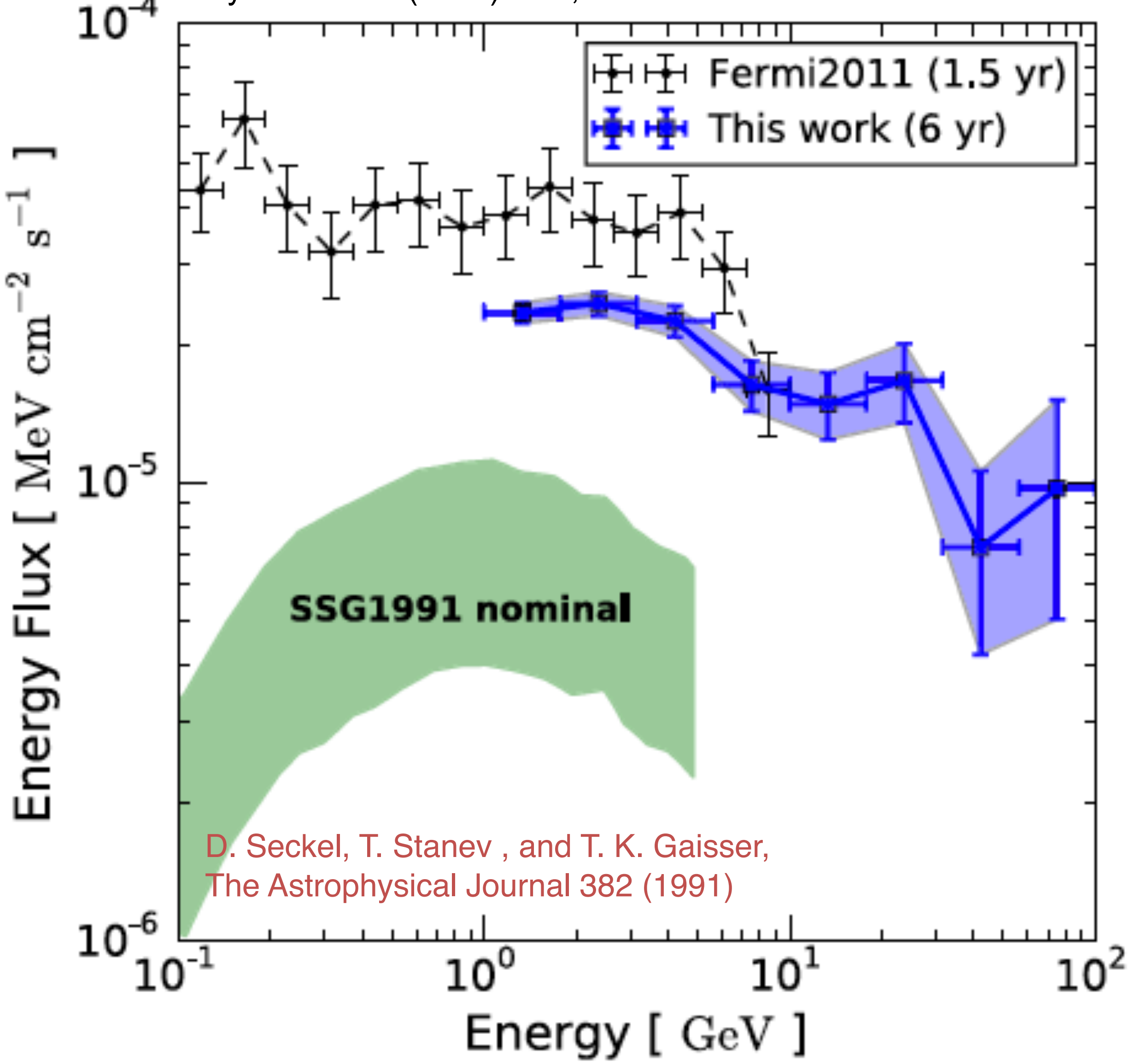
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadronic

- Seckel, Stanev, Gaisser (1991)
- Moskalenko, Karakula (1993)
- Ingelman & Thunman (1996)

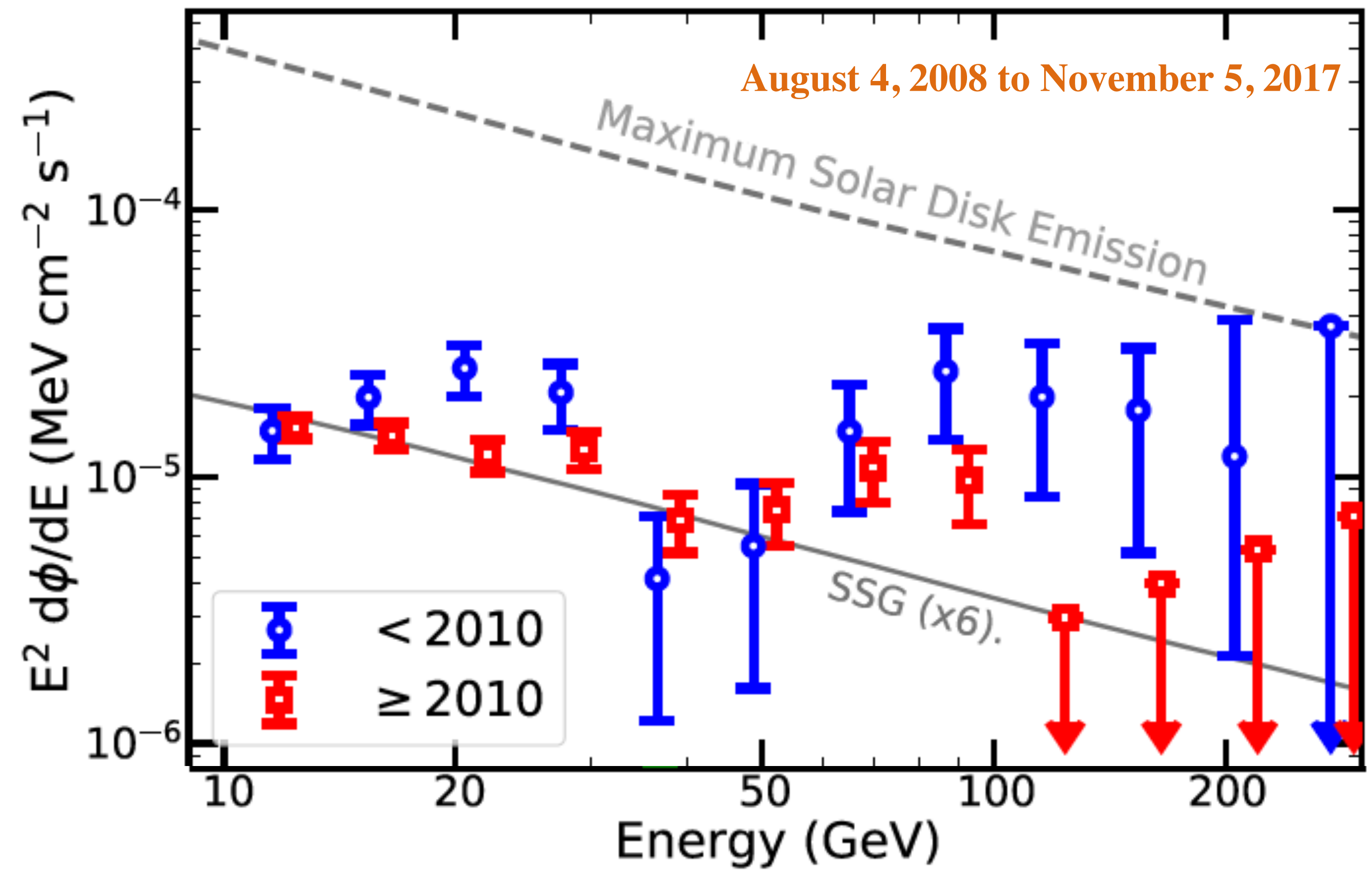
Cosmic ray interactions with the Sun

Kenny C.Y. Ng, John F. Beacom, Annika H.G. Peter, Carsten Rott
Phys.Rev. D94 (2016) no.2, 023004



- Gamma-ray flux extends to 100GeV and beyond
- Gamma-rays below 10GeV anti-correlations with solar activity
- Observed flux factor 5 larger compared to central prediction of SSG1991
- Spectrum could be fit by single power law (γ~2.3)

Tim Linden, Bei Zhou, John F. Beacom, Annika H. G. Peter, Kenny C. Y. Ng, and Qing-Wen Tang arXiv:1803.05436



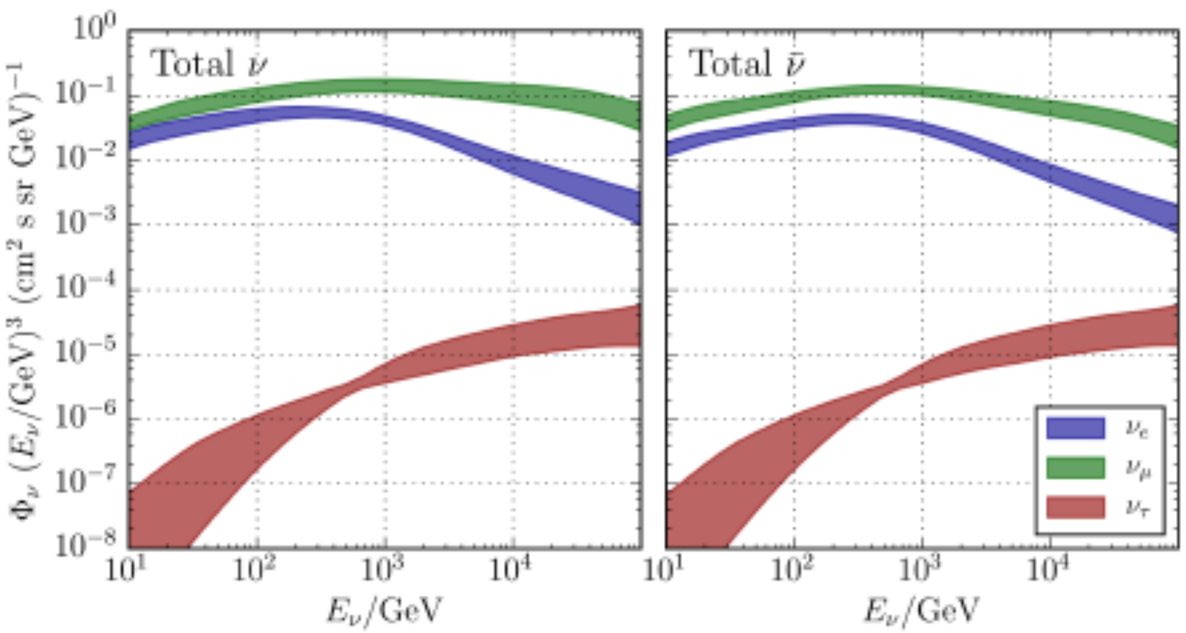
- Six gamma rays above 100 GeV are observed during the 1.4 years of solar minimum, none are observed during the next 7.8 year
- From morphology: Evidence that emission is produced by two separate mechanisms
- To understand the underlying physics, gamma-ray (HAWC, Fermi, ...) and neutrino (IceCube) observation of the imminent Cycle 25 solar minimum are crucial

Neutrino Flux from the Sun

- Solar atmosphere significantly more extended and less dense compared to terrestrial counterpart
  - High energy hadrons more likely to decay rather than reinteract
    - Reduced suppression of high-energy neutrino flux (compared to Earth)
  - High-energy muons decay
- High-energy neutrino absorption for neutrinos propagating through central region of the Sun

Solar Atmospheric Neutrino Flux

- The solar atmospheric neutrino spectrum is predicted to be harder compared to the Earth atmospheric background.



- Flux predictions vary by <30%, based on
  - primary models
  - hadronic and composition models
  - extremal solar density and composition models

C. Argüelles, G. de Wasseige, A. Fedynitch, B. Jones **JCAP 1707 (2017) no.07, 024** [arXiv:1703.07798]

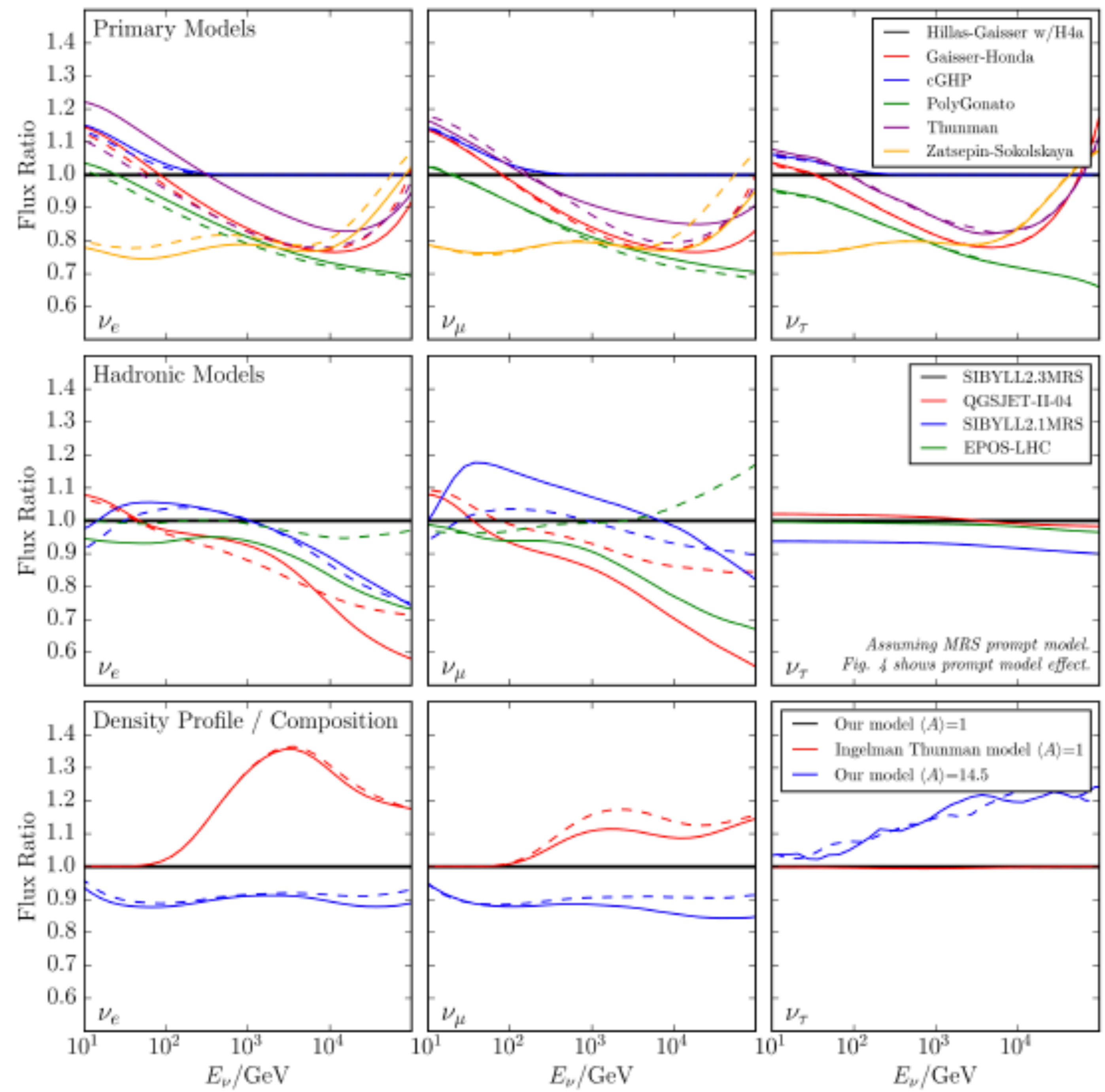
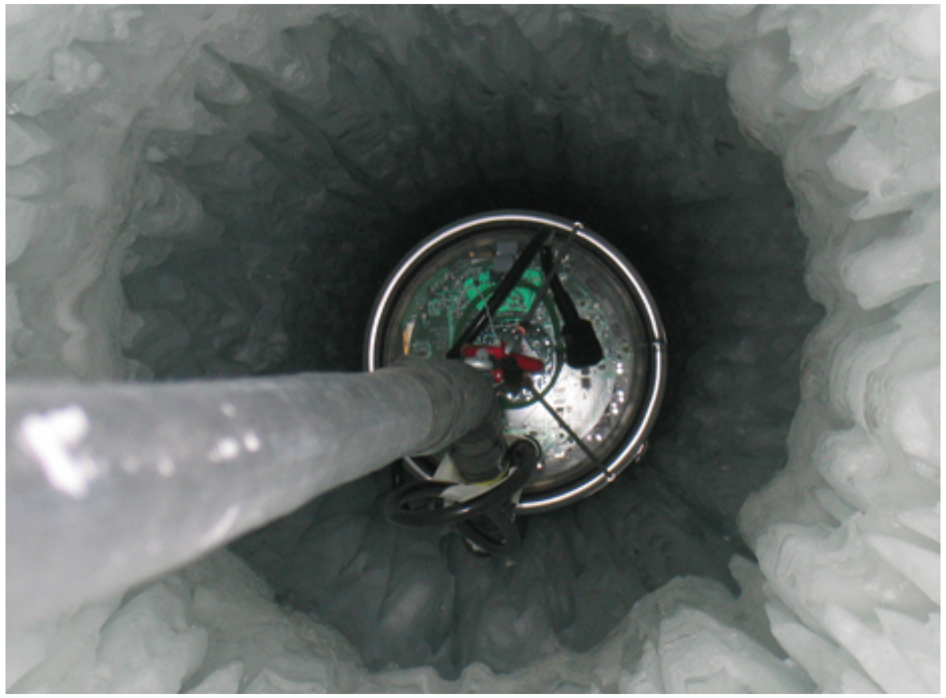


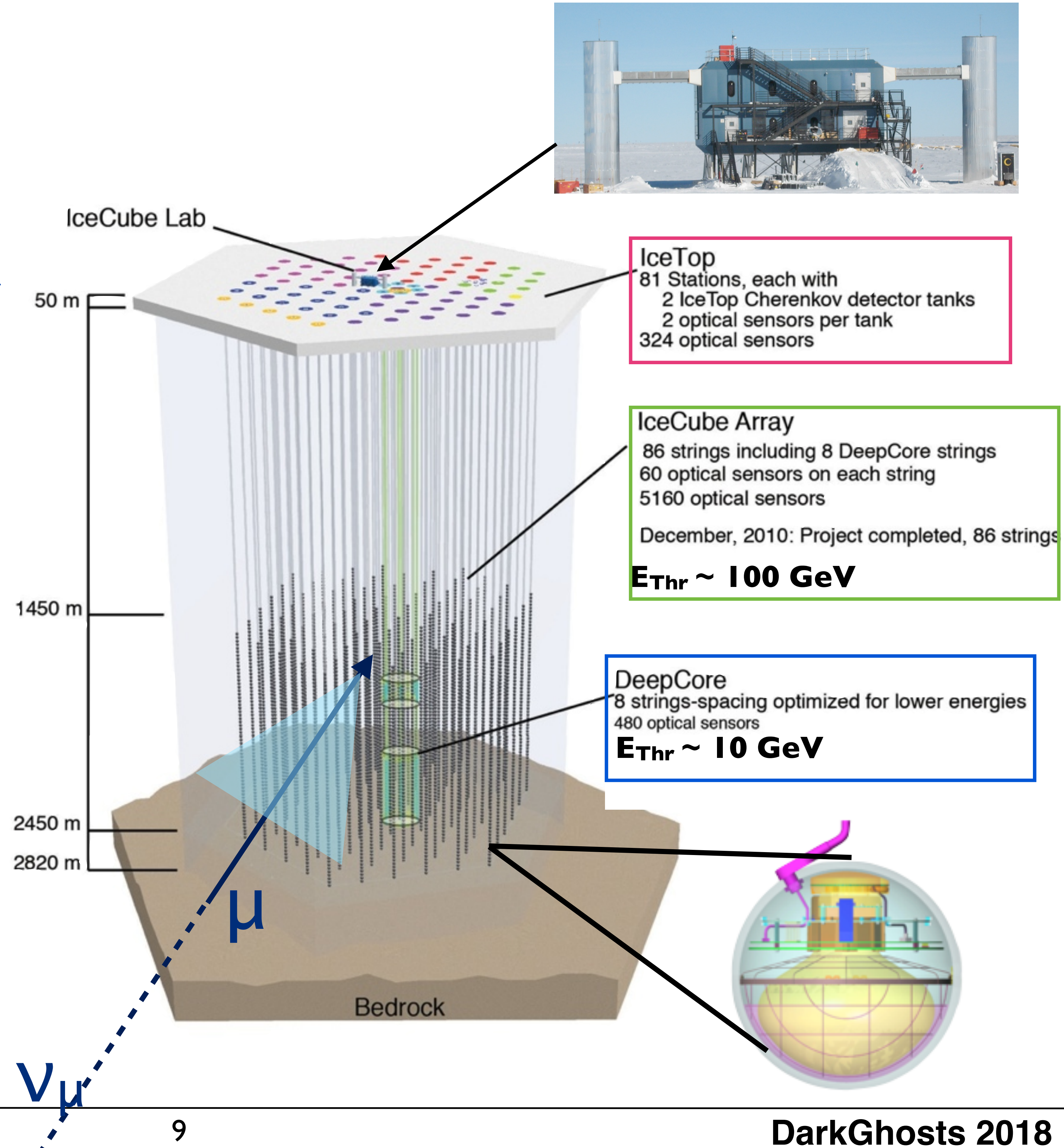
Figure 3. Effects of different models on our flux prediction, for impact parameter b=0. The top row shows various primary models; the second row, hadronic and composition models; the third row, extremal solar density and composition models. See text for more information and references.

IceCube

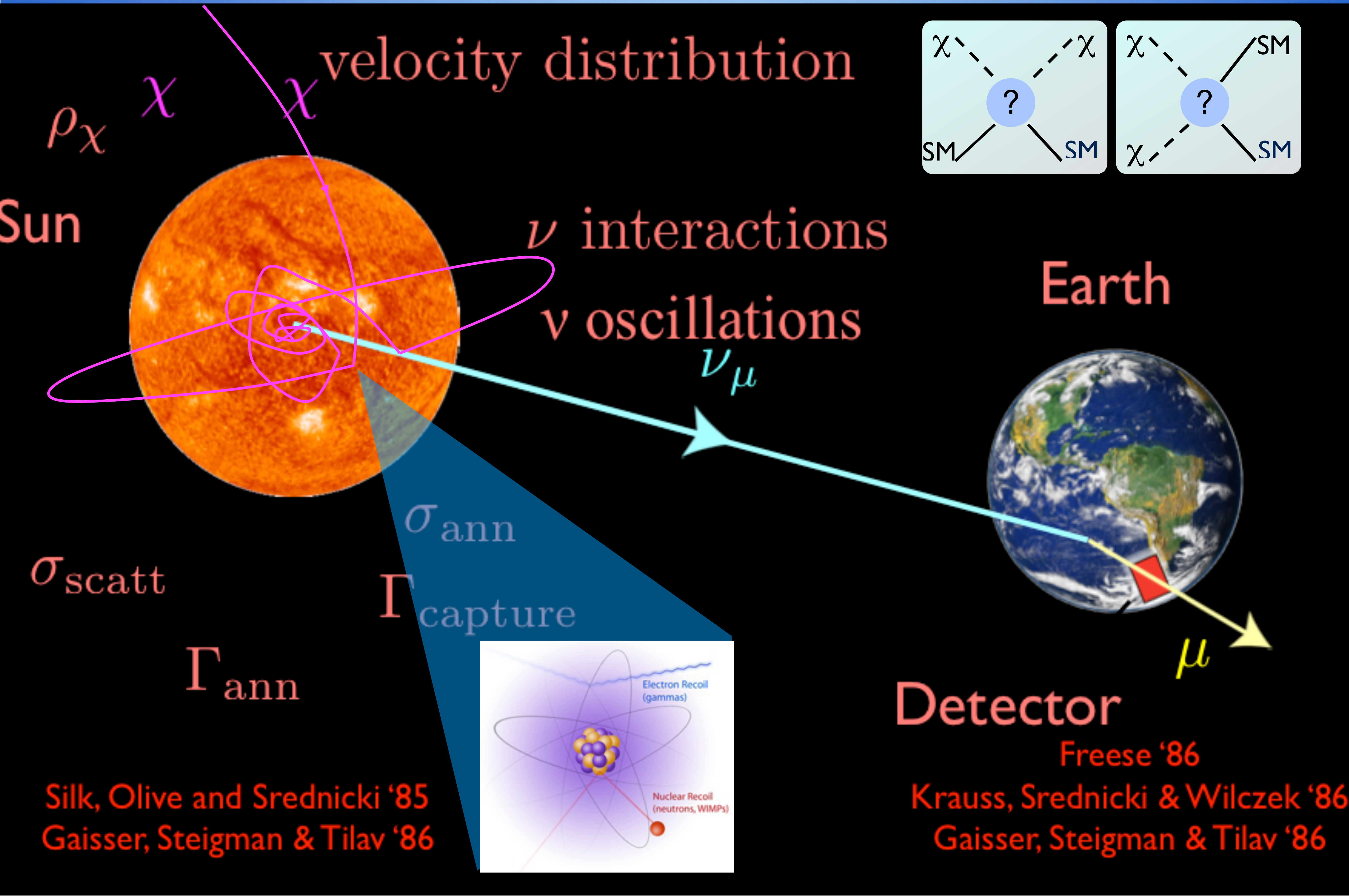
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Detector completed in December 2010 after 7 years construction
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

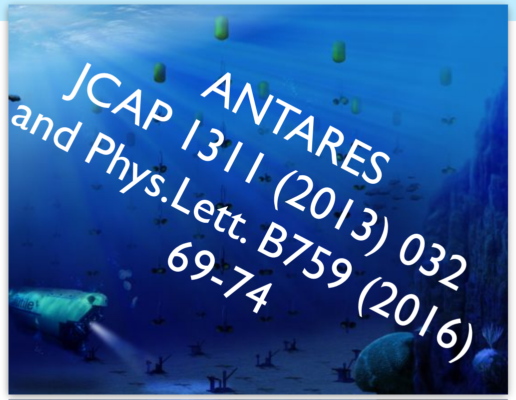


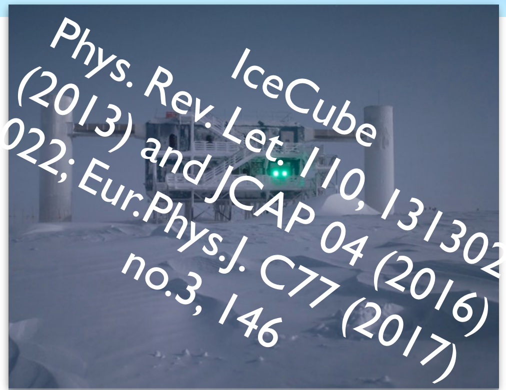


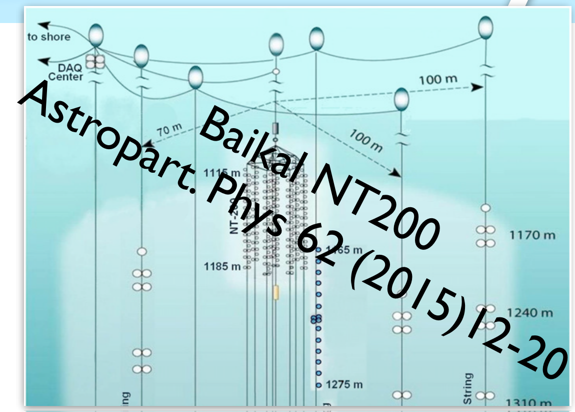
Solar Dark Matter



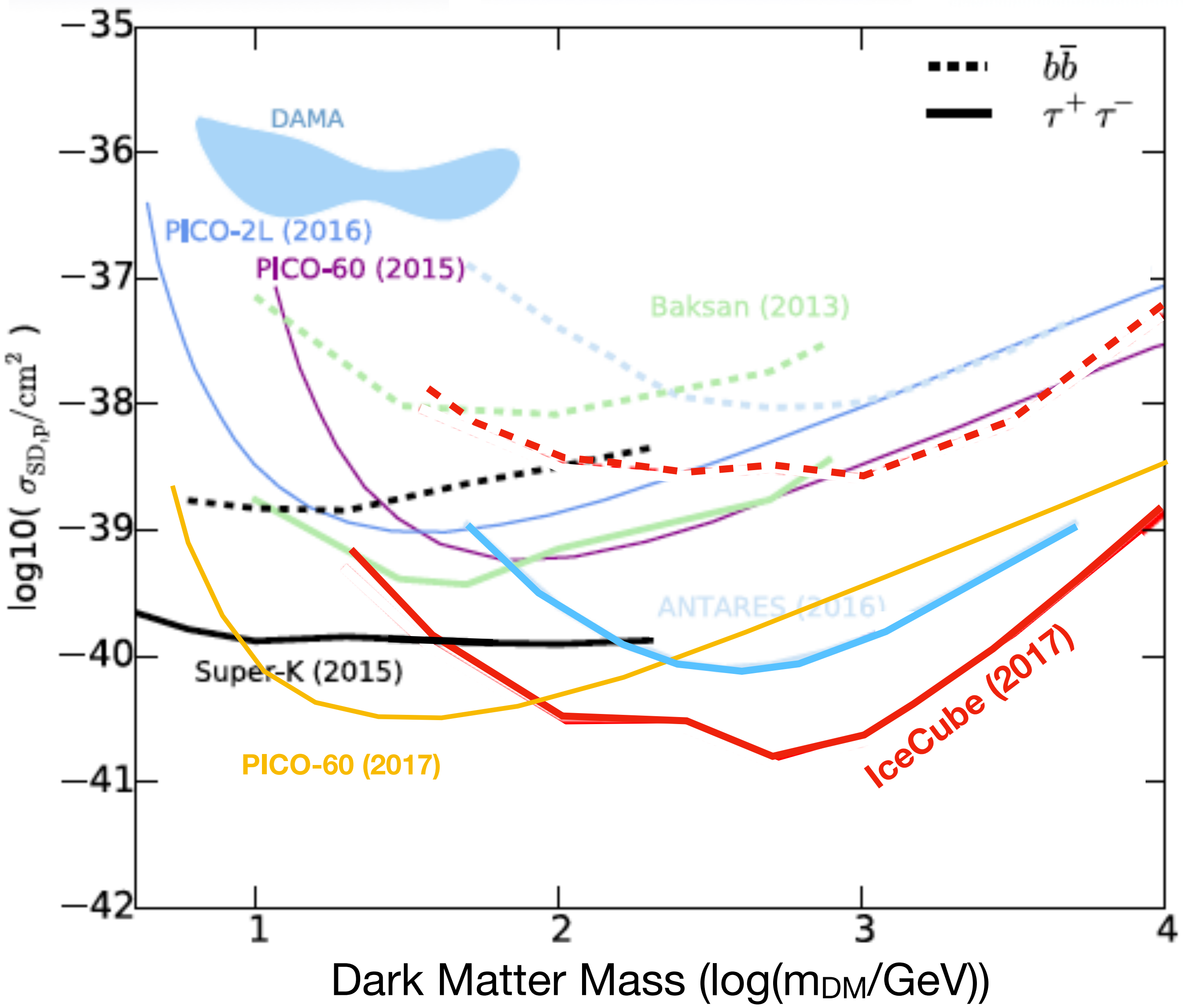
Solar Dark Matter Summary



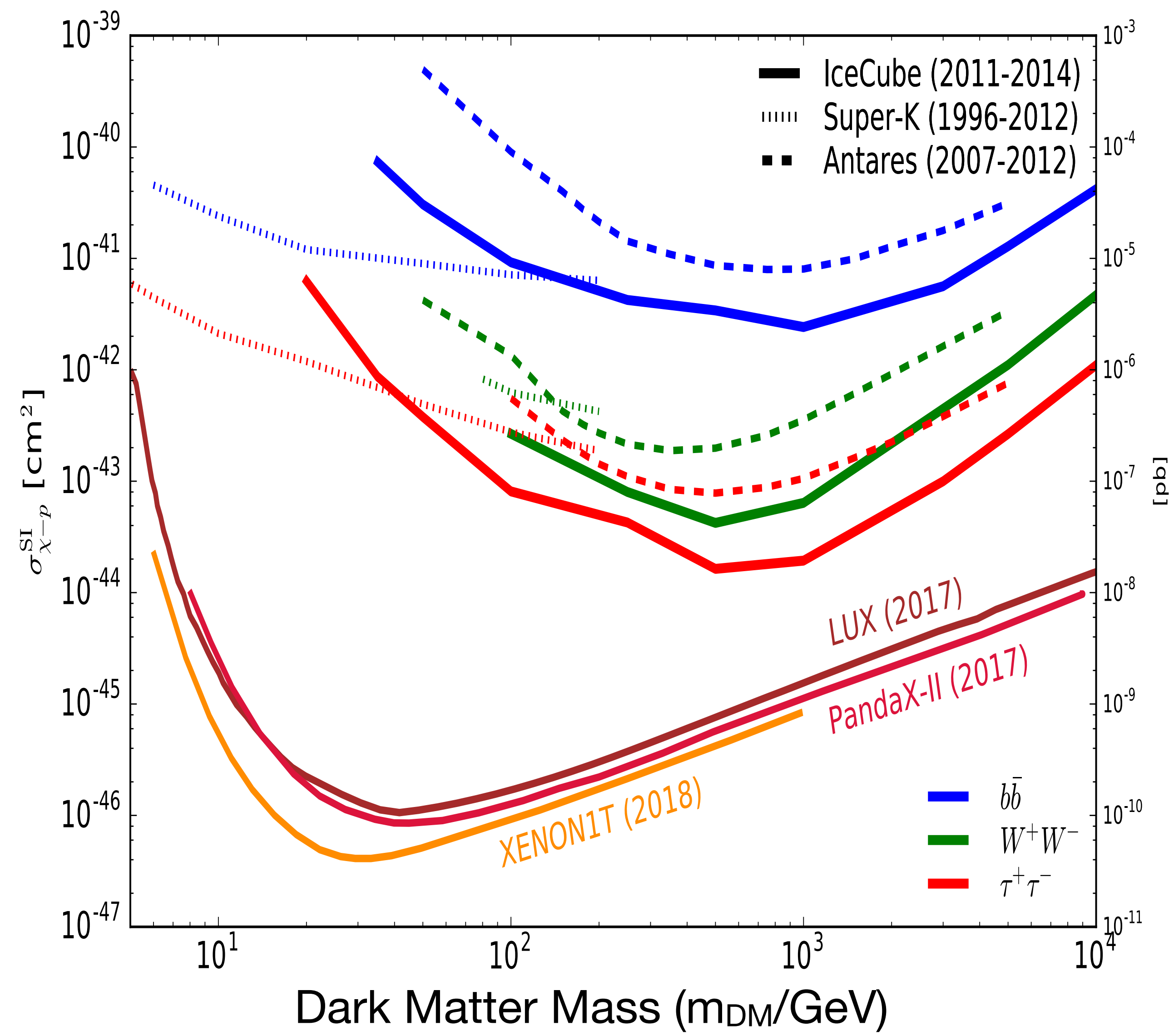




Spin-dependent scattering

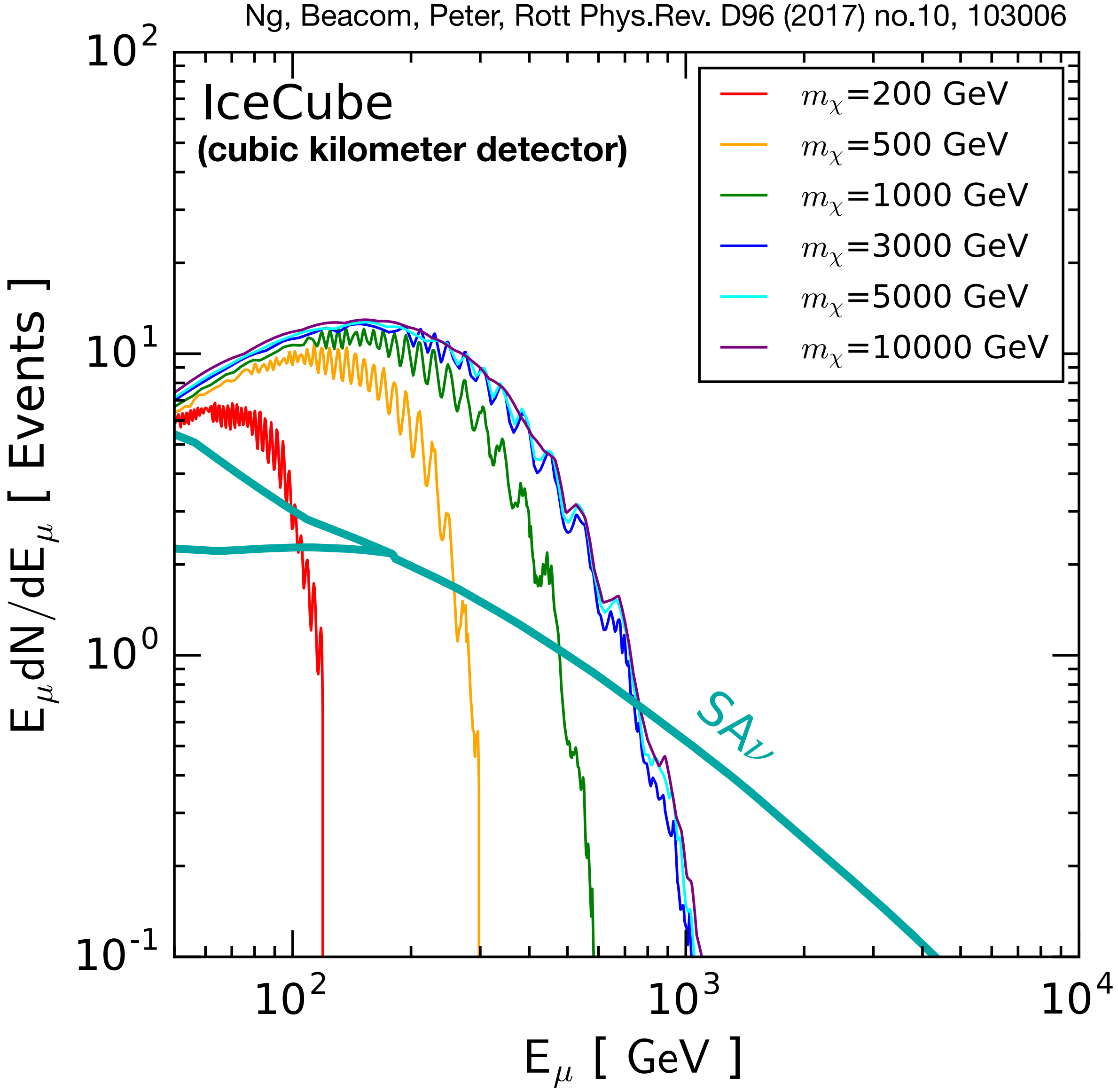


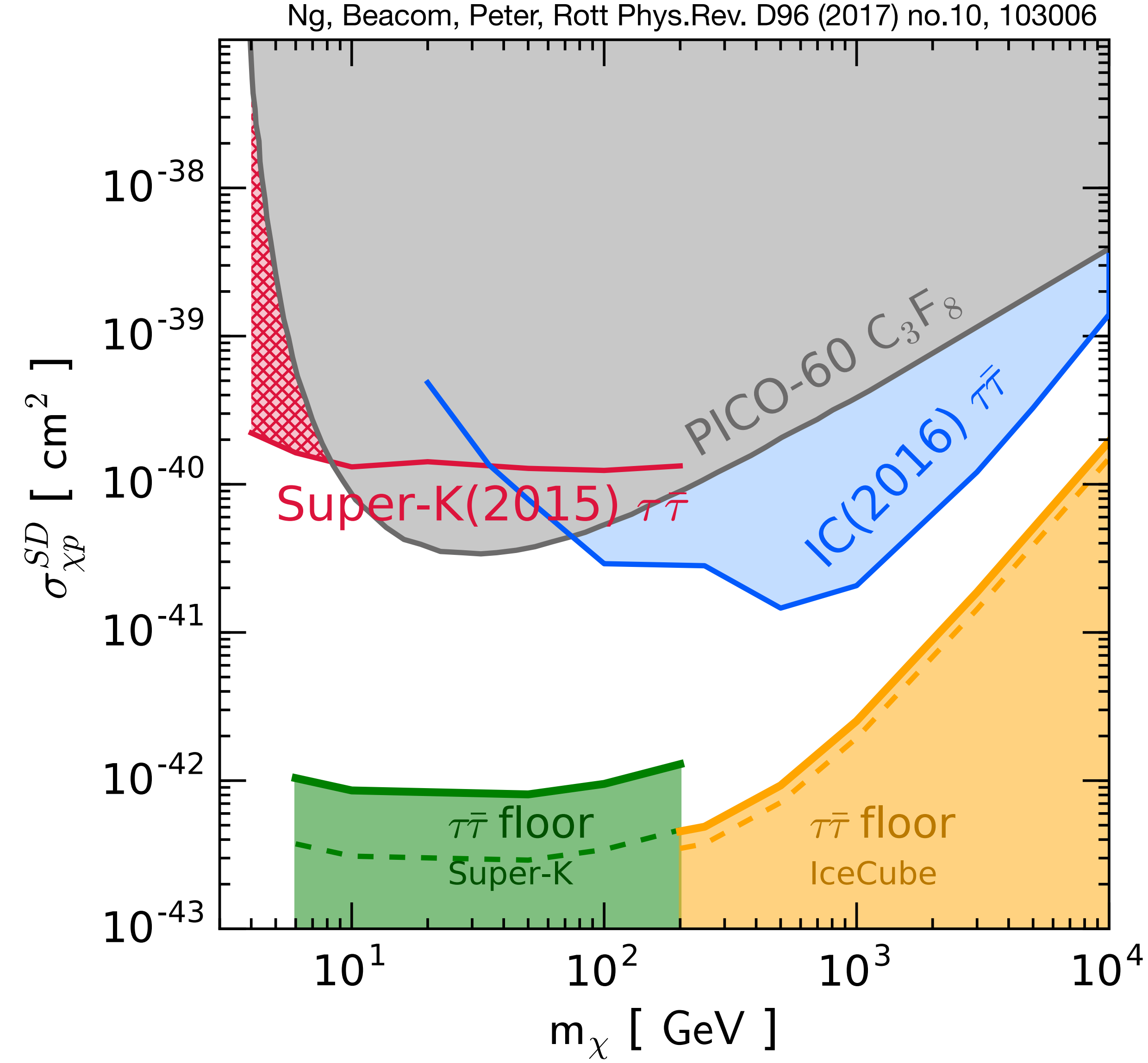
Spin-independent scattering



Solar Atmospheric Neutrino Floor

Cosmic background from the Sun





- Solar Atmospheric neutrinos give a new background to solar dark matter searches
  - However, energy spectrum expected to be different
  - In DM annihilation neutrinos significantly attenuated above a few 100GeV

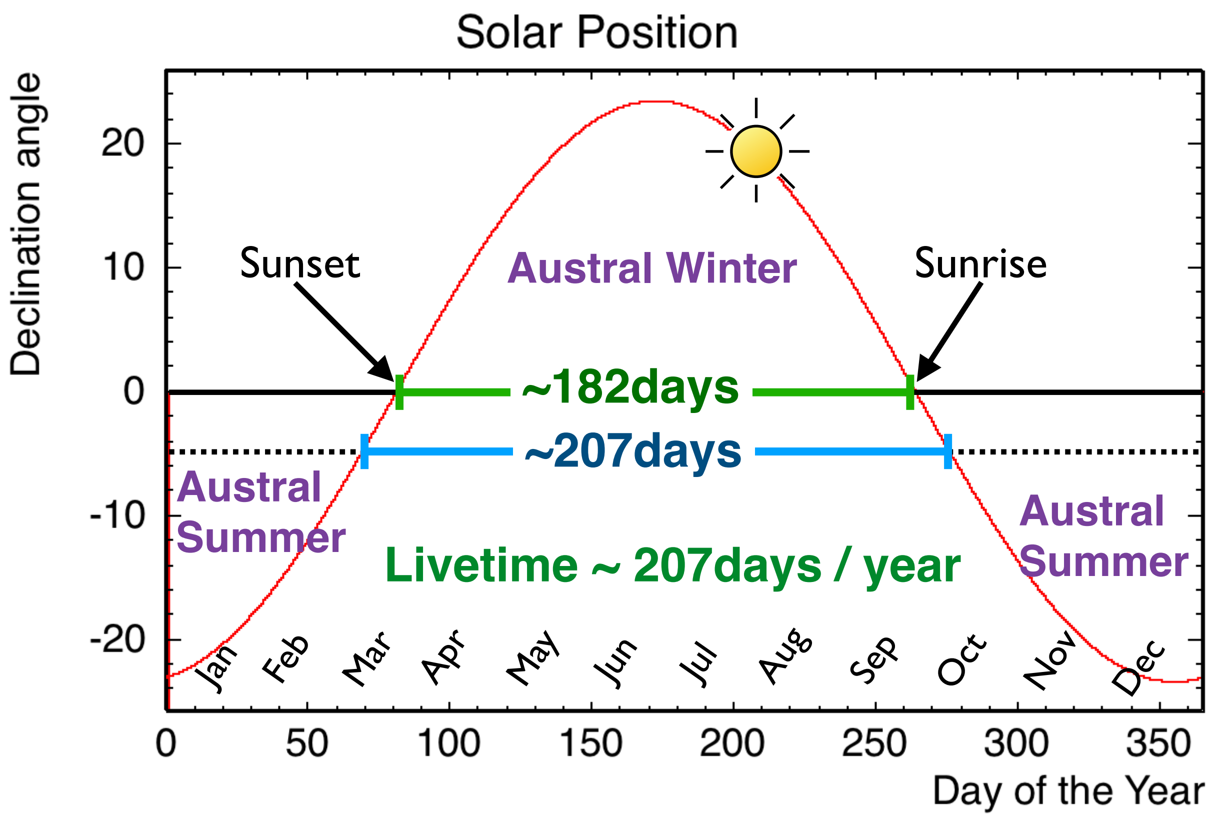
Recent works on the Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor

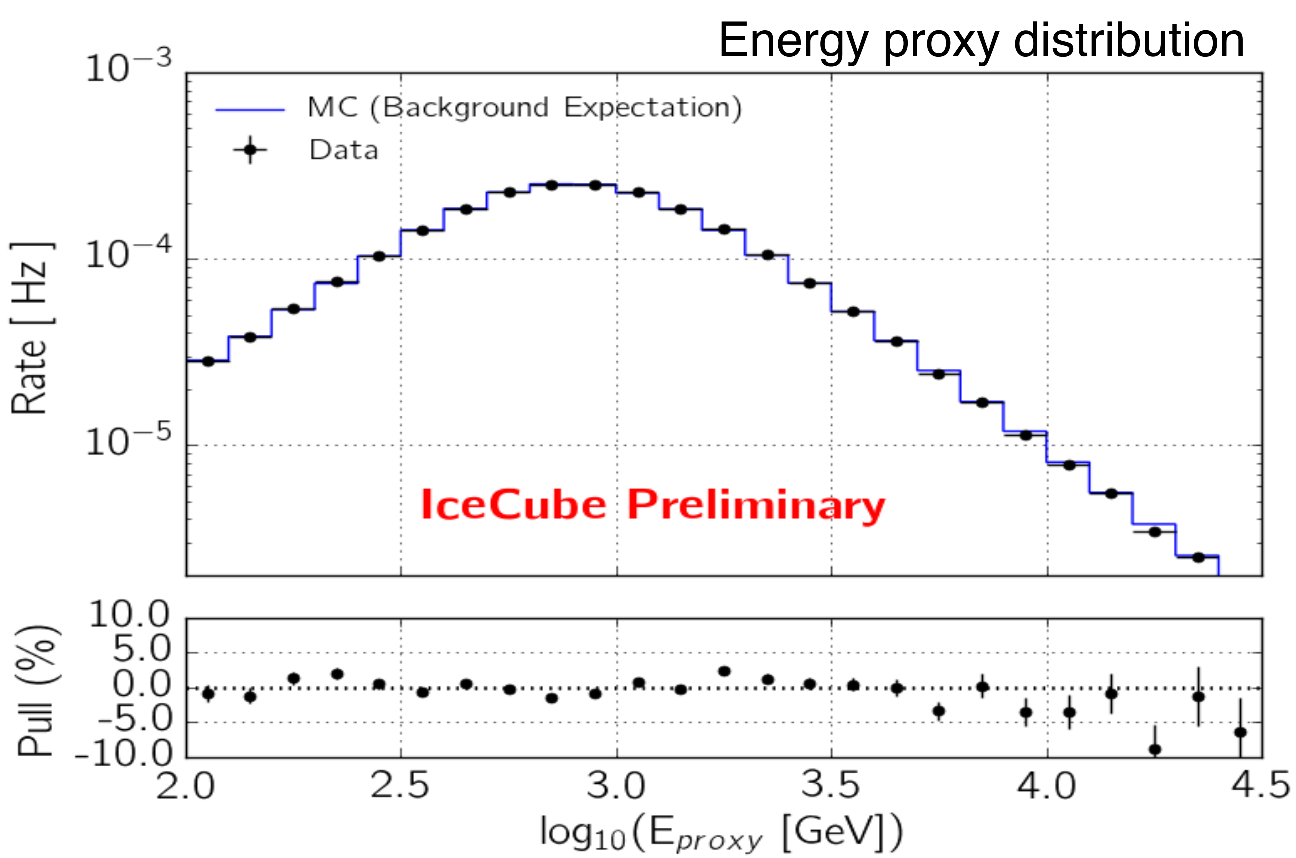
- C. Argüelles, G. de Wasseige, A. Fedynitch, B. Jones **JCAP 1707 (2017) no.07, 024** [arXiv:1703.07798]
- K. Ng, J. Beacom, A. Peter, C. Rott **Phys.Rev. D96 (2017) no. 10, 103006** [arXiv:1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, **JCAP 2017 . 06 (2017), p. 033**, arXiv: 1704.02892 [astro-ph.HE]
- M. Masip **Astropart.Phys. 97 (2018) 63-68** [arXiv: 1706.01290]

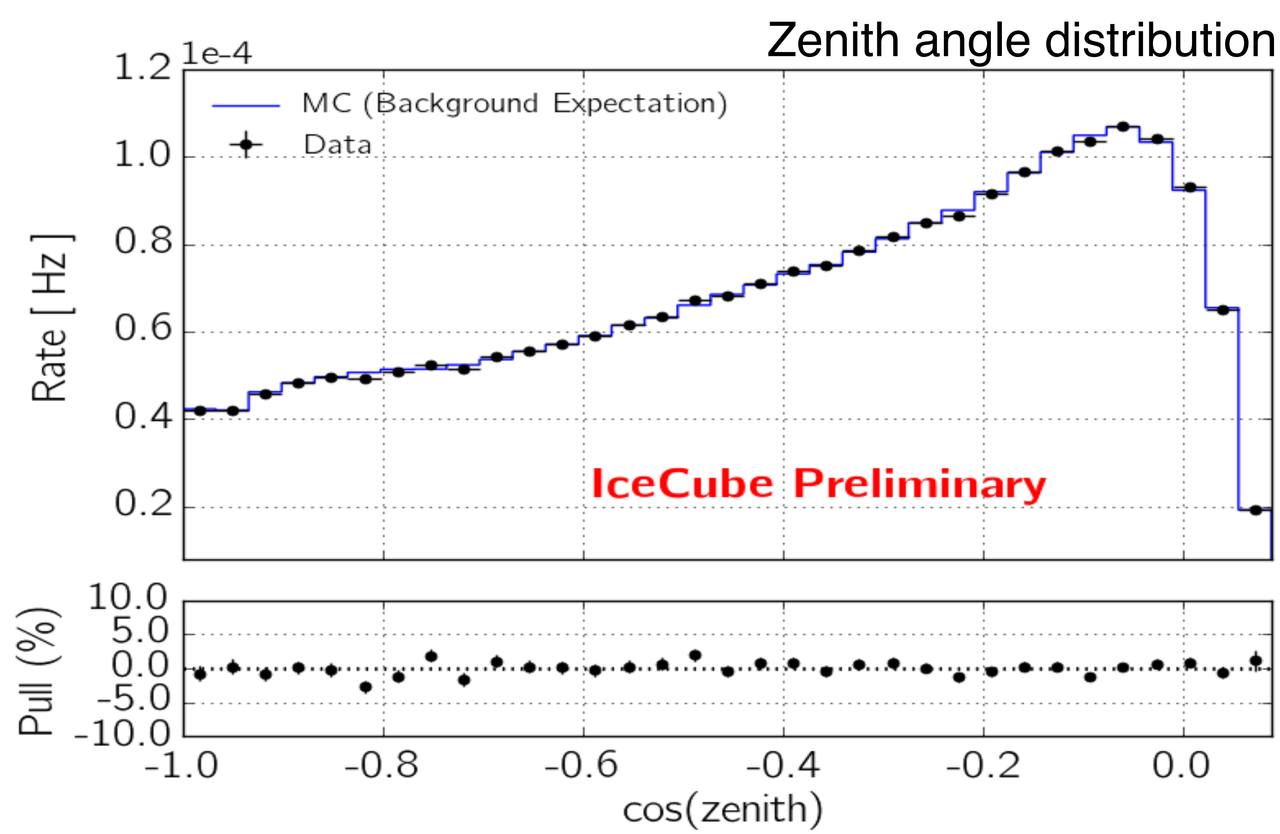
Solar Atmospheric Neutrino Search

Data sample

- The analysis utilizes data collected over a 7 year period (May 31, 2010 - May 18, 2017)
  - Up-going muon neutrino candidate events are selected using the well established IceCube point source analysis selection procedure
  - We only consider events from the winter season when the Sun is below the horizon (δ=[-5°,23°]). This results in a total analysis livetime of 1420.73 days.







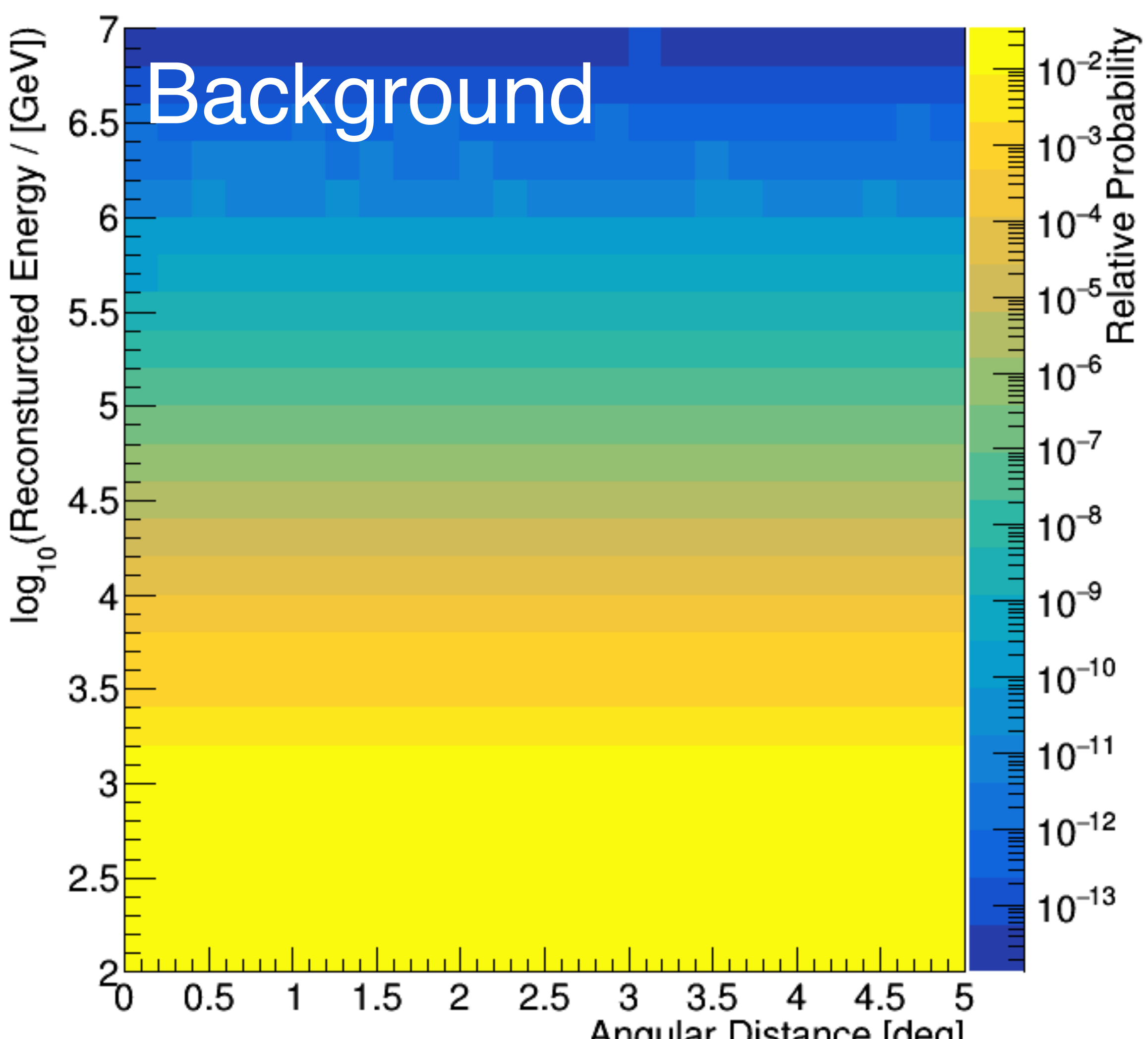
Likelihood

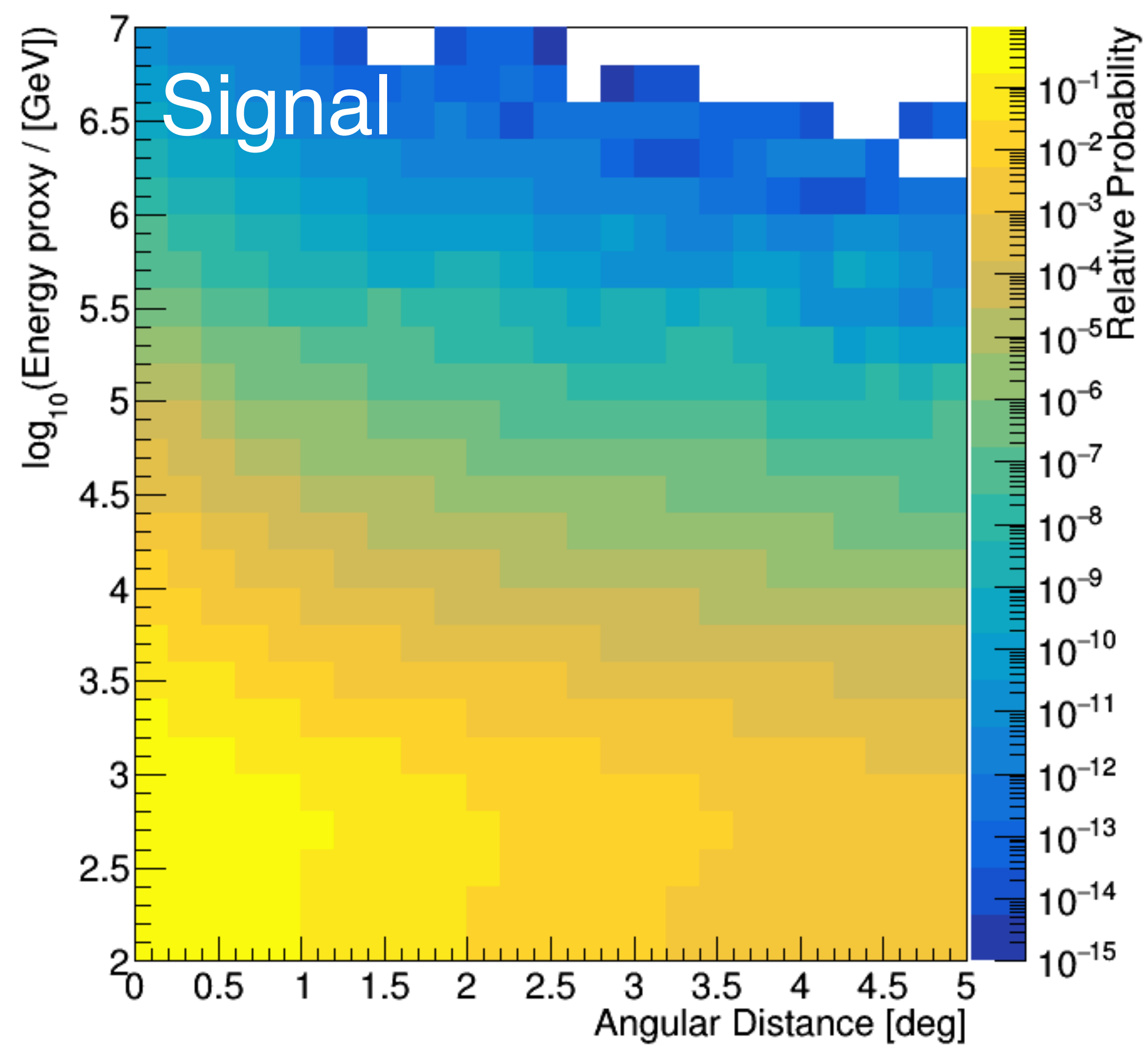
- Maximum log likelihood method is used to calculate significant with a test statistic (TS) distribution
  - The likelihood function is defined by

$$L(E,\Theta) = \Pi\left(\frac{\mu}{N} \times \mathrm{p}_{\mathrm{sig}}(E,\Psi\,|\,\mu) + (1-\frac{\mu}{N}) \times \mathrm{p}_{\mathrm{bkg}}(E,\Psi)\right)$$

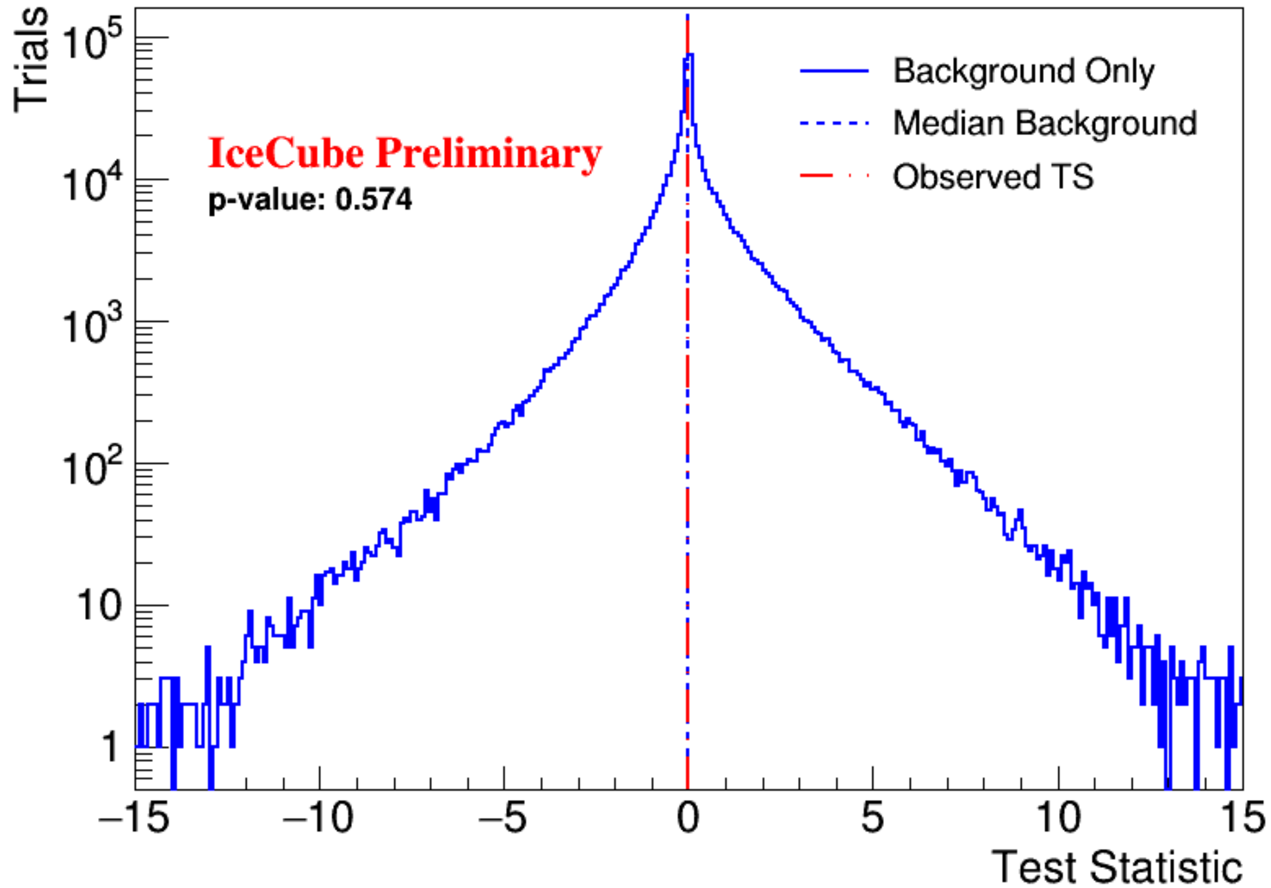
N = total number of events,
μ = number of signal events
E = neutrino energy proxy
Ψ= angular distance to the Sun's center

Signal and background pdfs





Test Statistics

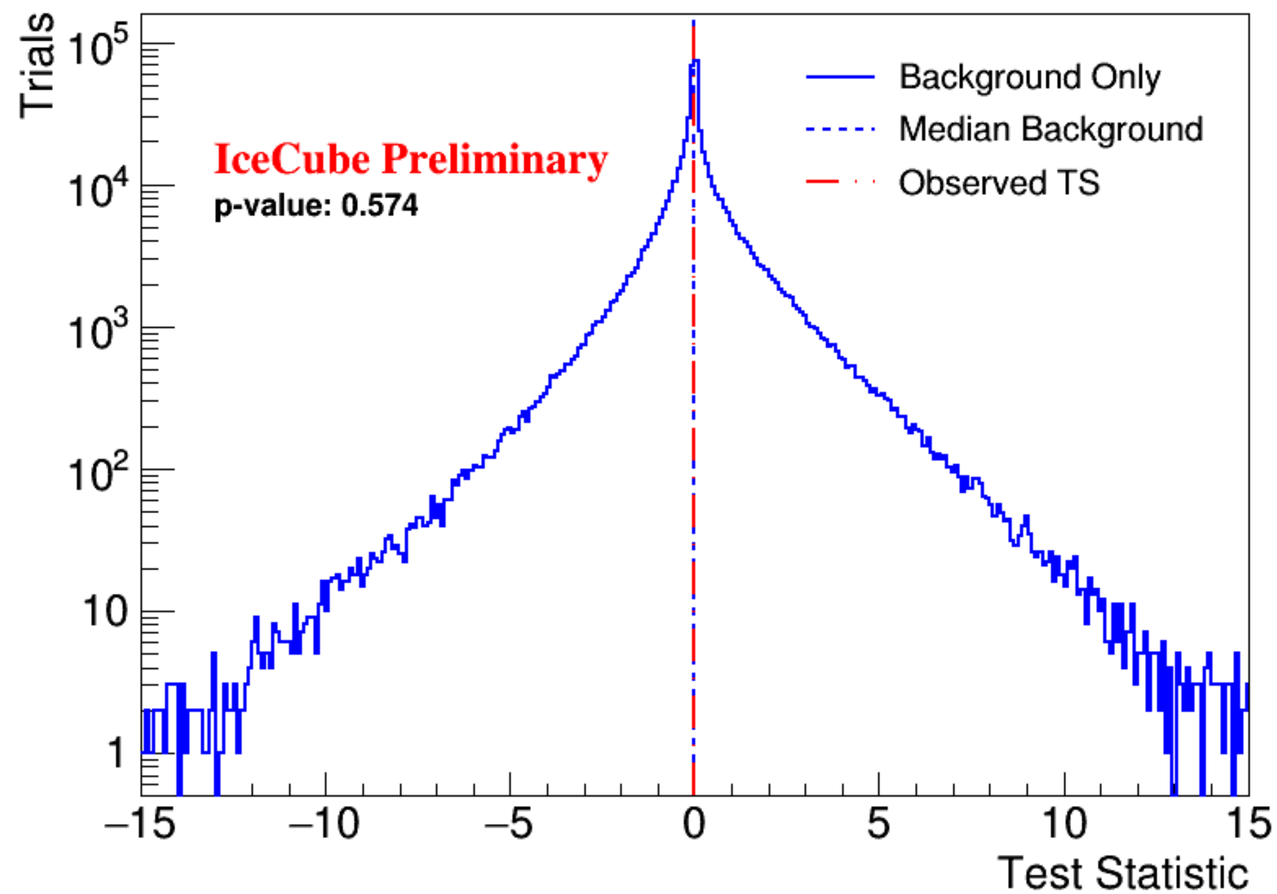


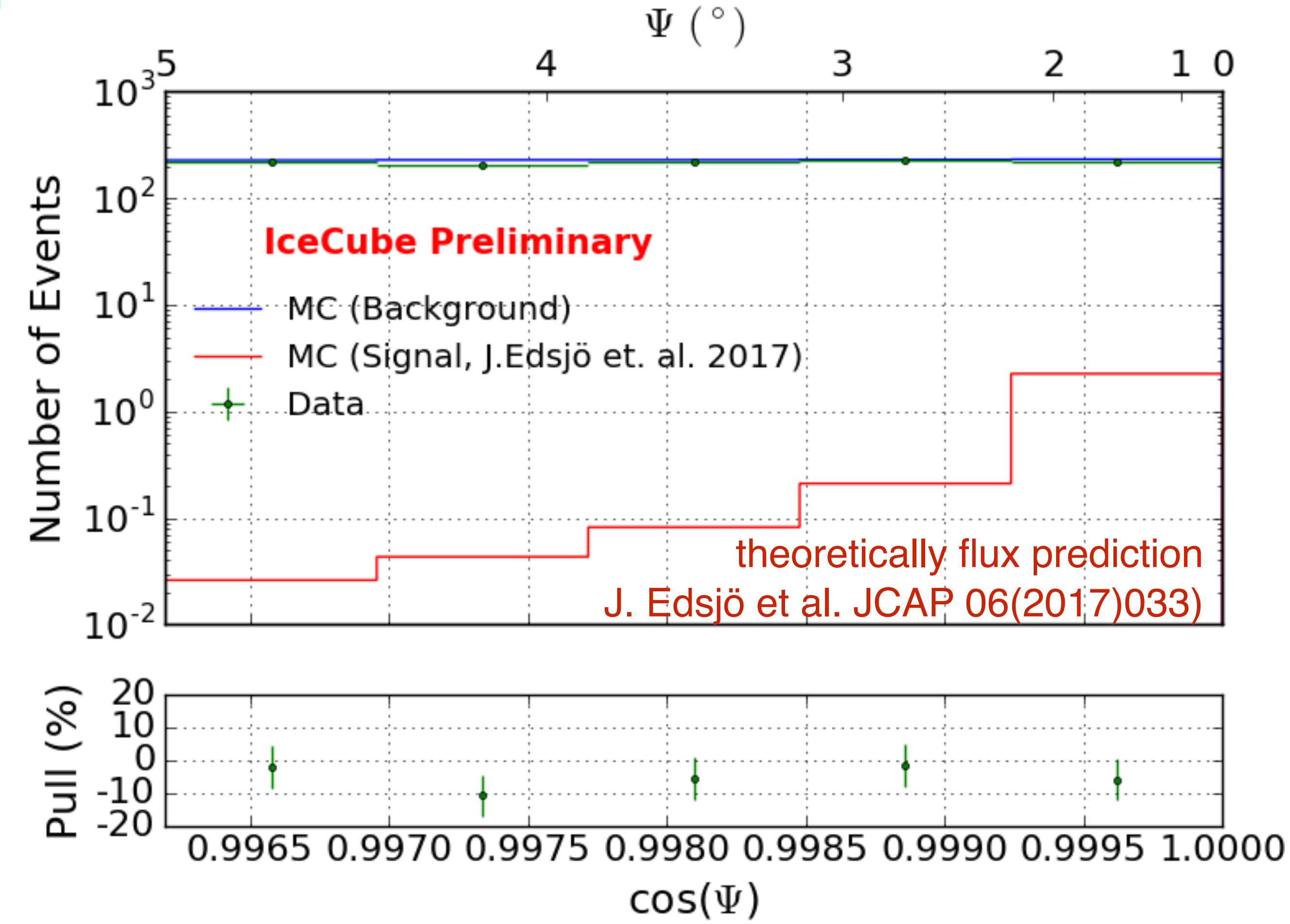
- Test statistics (TS) is defined as a ratio of likelihood function

$$TS = -2\ln(L(0)/L(\hat{\mu})) \qquad \hat{\mu} > 0$$

$$= -\left(\frac{d}{d\mu}L(\mu)|_0\right)^2 / \left(2\frac{d^2}{d\mu^2}L(\mu)\right) \qquad \hat{\mu} = 0$$

- The p-value calculate based on a background only assumption is 0.57. Hence, no excess of solar atmospheric neutrinos is seen.





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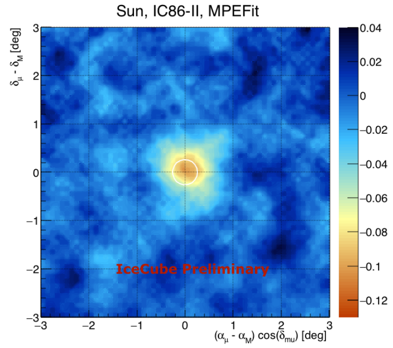
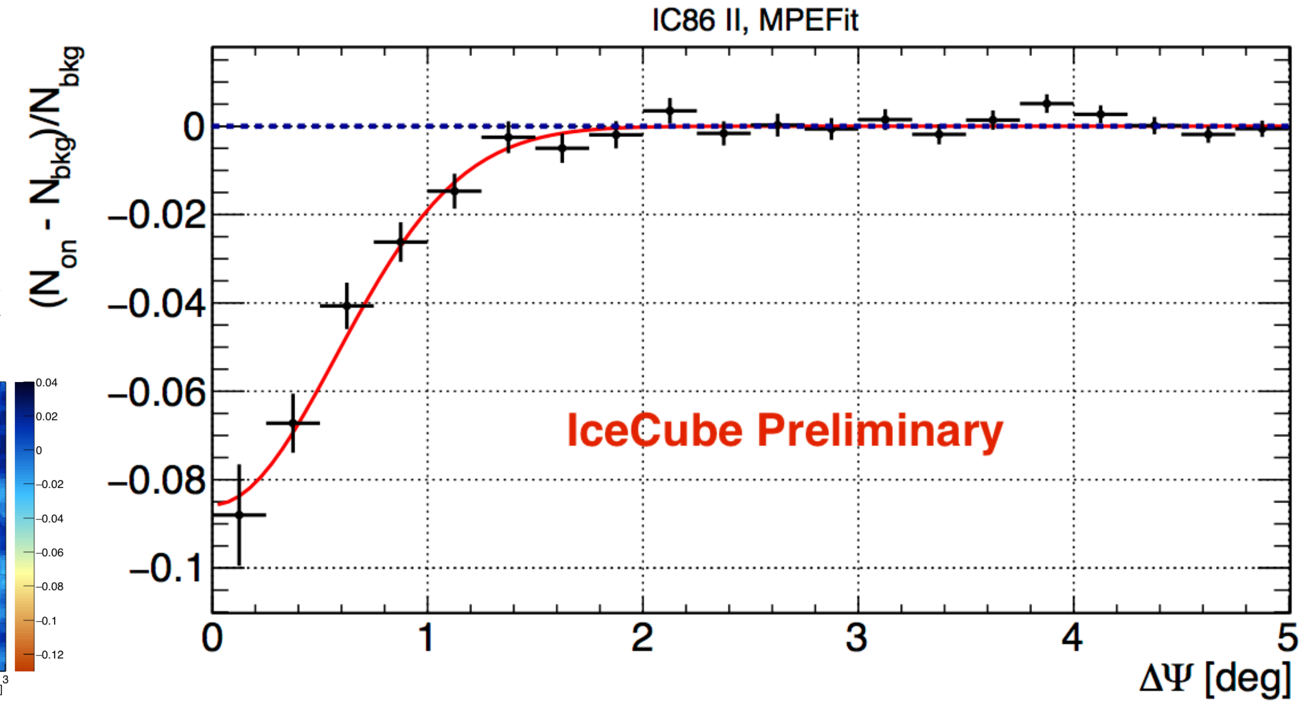
Systematic uncertainties

Cosmic ray Sun shadow
Cosmic rays are absorbed by the Sun, resulting in a deficit in muon and neutrino flux. Two extreme cases were compared:

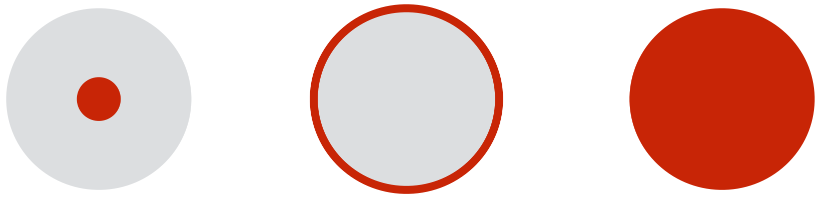
- no absorption
- neutrino flux deficit as measured for muon flux

Systematic effect~ 2%





Source distribution
Three extreme cases are considered to derive a sys. uncertainty

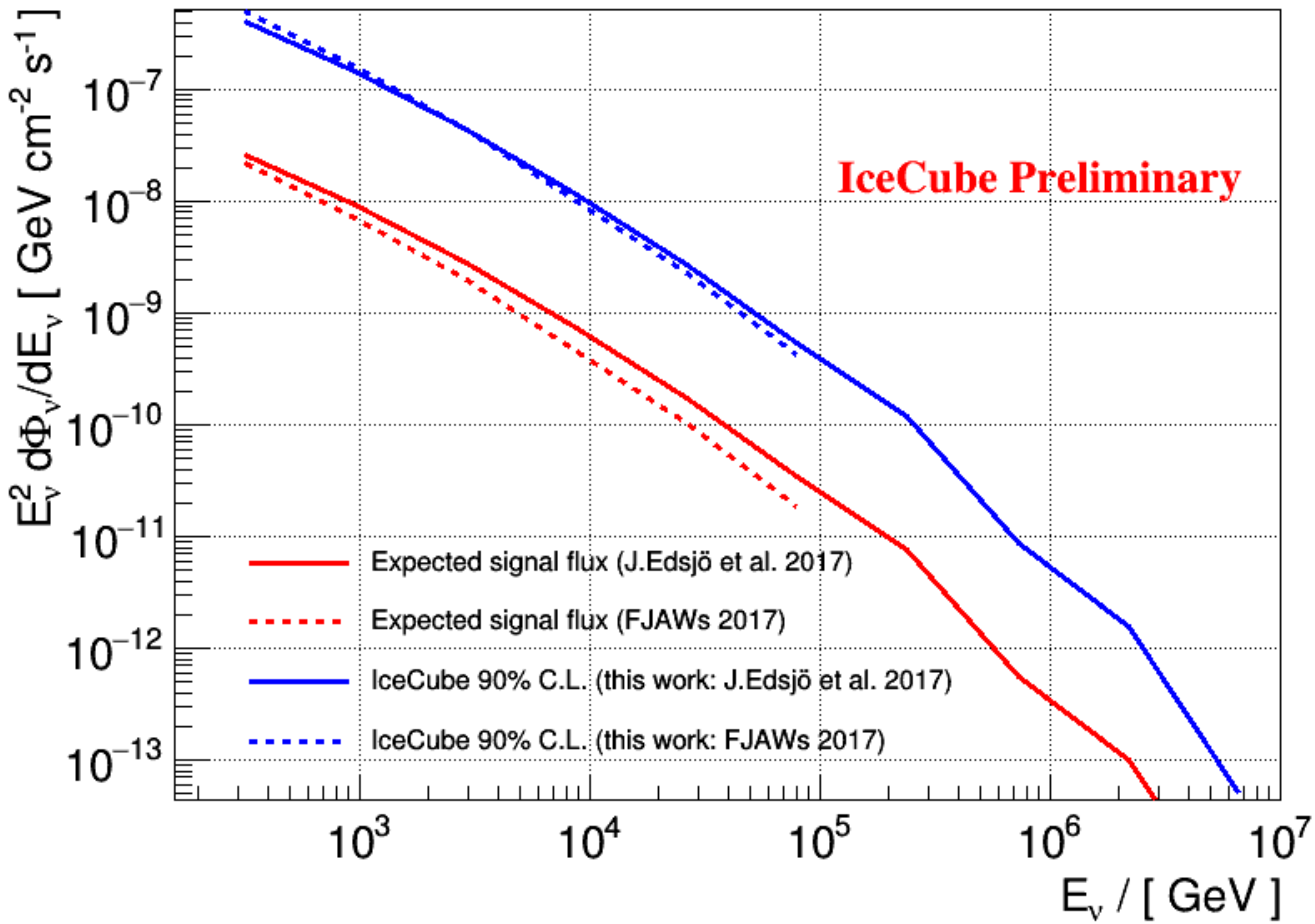


Systematic effect~ 4%

Systematic	Size
DOM efficiency	12%
Ice properties	4%
Source distribution	4%
Cosmic ray shadow	2%
Total	**13%**

Preliminary systematic study completed
Full study on-going

Upper limit

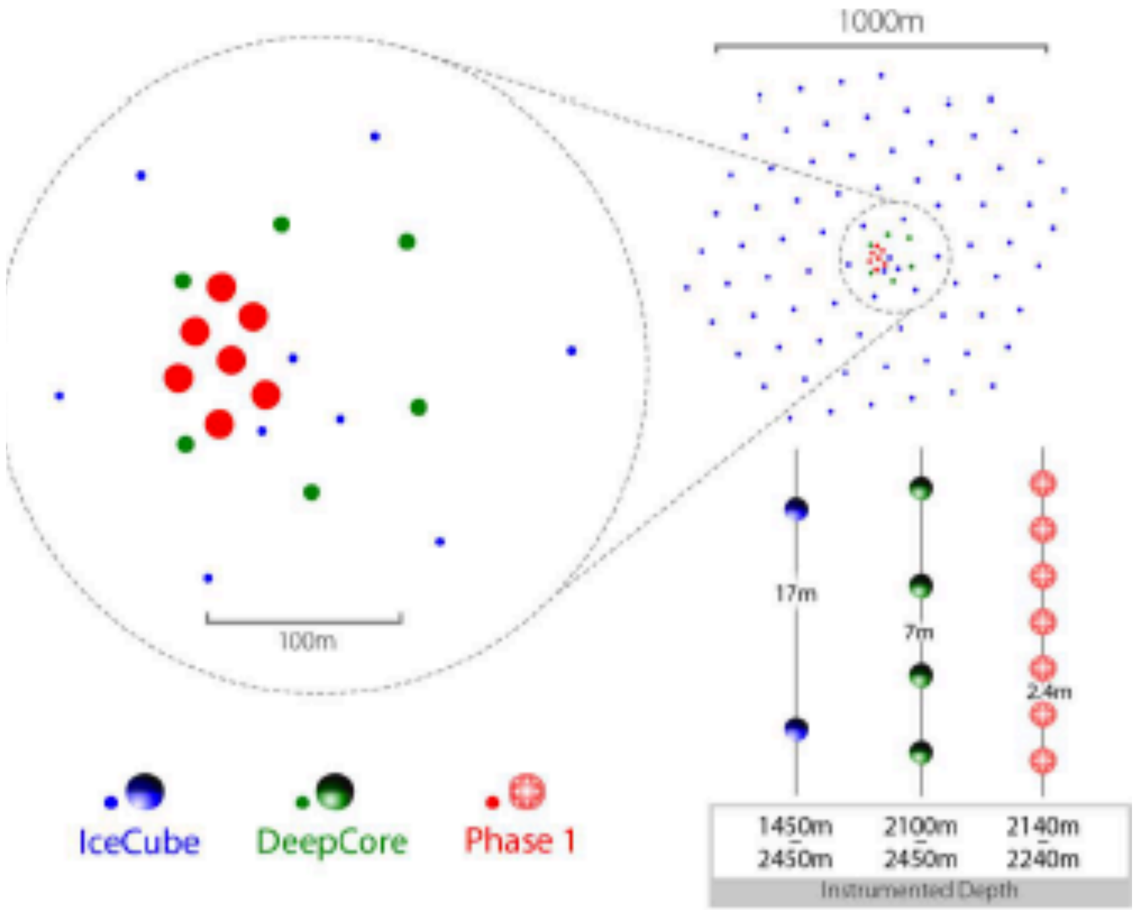


Feldman-Cousins Upper limit at 90% C.L.
- preliminary systematic uncertainties are included by worsening the limit by 13%

Future Plans

see also:
- PINGU LOI arXiv:1412.5106

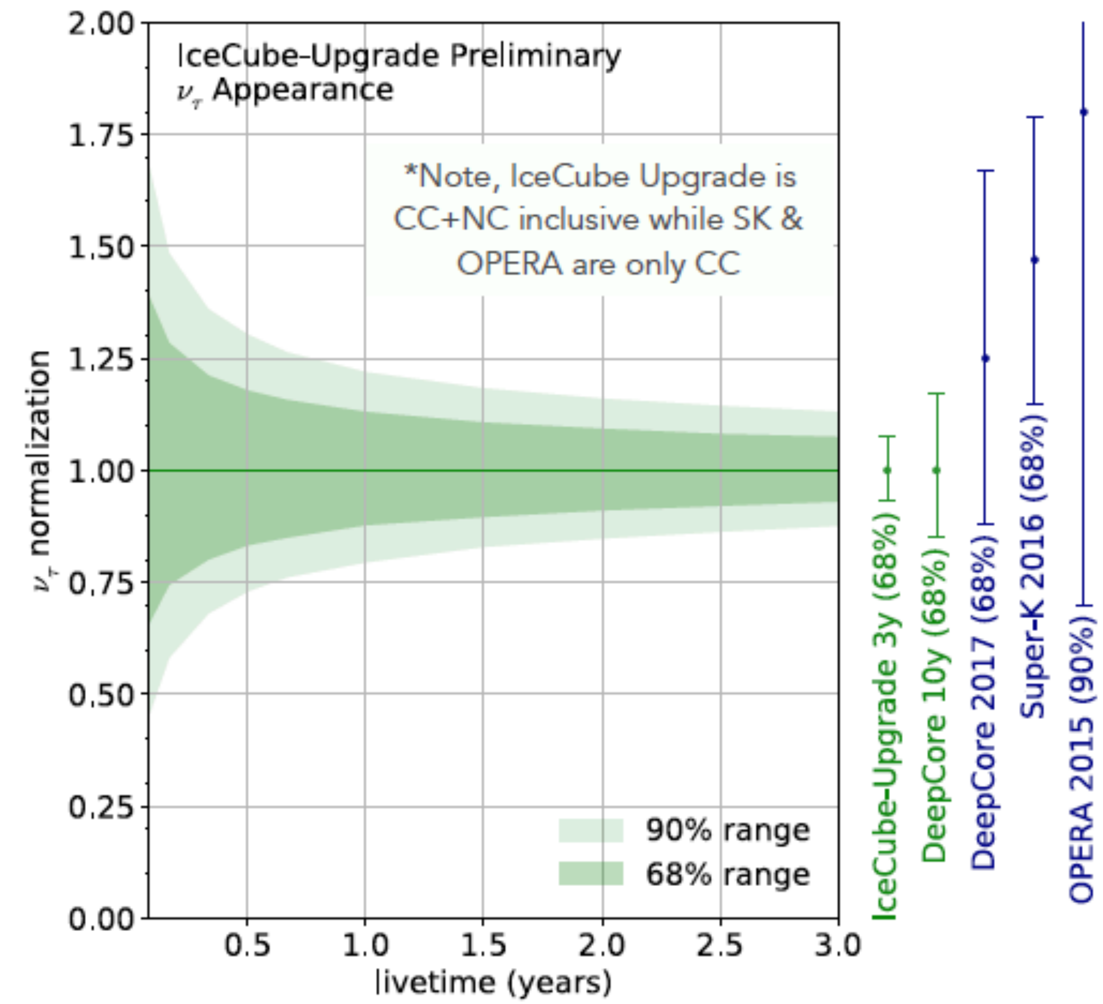
The IceCube Upgrade

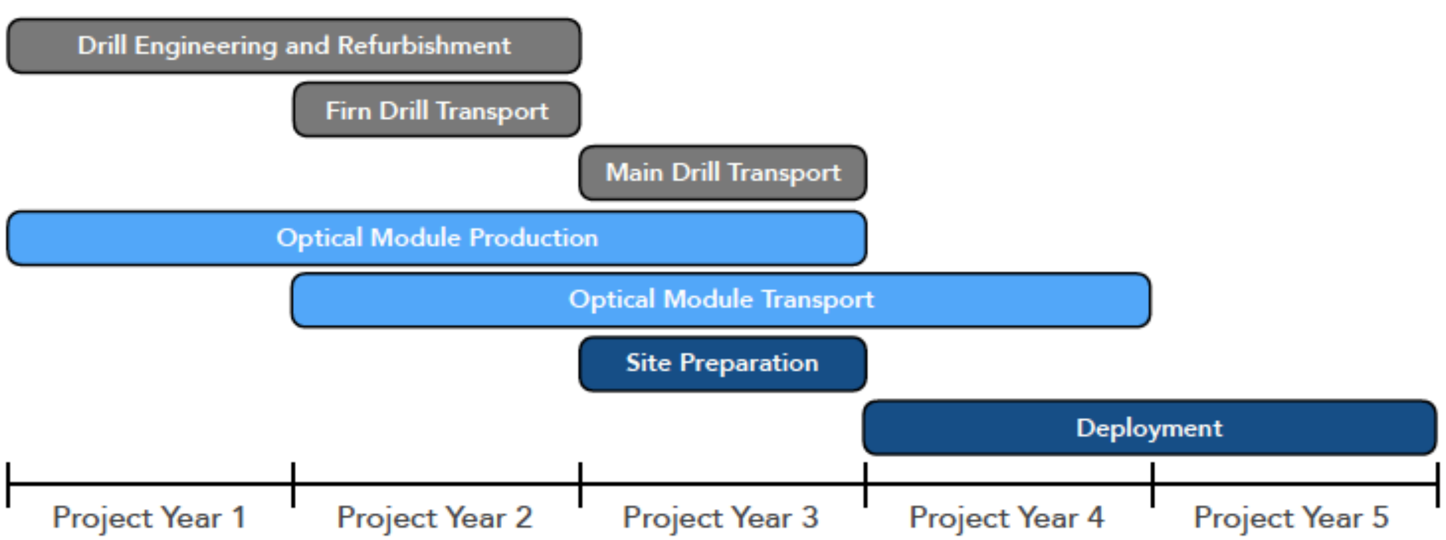


Array	String Spacing	Module Spacing	Modules / String
IceCube	125 m	17 m	60
DeepCore	75 m	7 m	60
Upgrade	20 m	2 m	125

First step to restart South Pole activities

- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Calibration devices
- Platform to test new technologies





- Cosmic-rays interacting in the solar atmosphere generate particle showers
    - Recently Fermi-LAT observed this solar disk emission. The observed flux is significantly above theoretical predictions
- First search for solar atmospheric neutrinos was able to place a stringent limit on the neutrino flux from the Sun
    - The analysis did not cover the solar minimum. Recent studies claim that the high-energy gamma-ray emission only occurred during the solar minimum. Opportunity for the next solar minimum ?

Image:Stephan Richter, IceCube/NSF