Recent Progress in Solar Atmospheric Neutrino Searches with IceCube

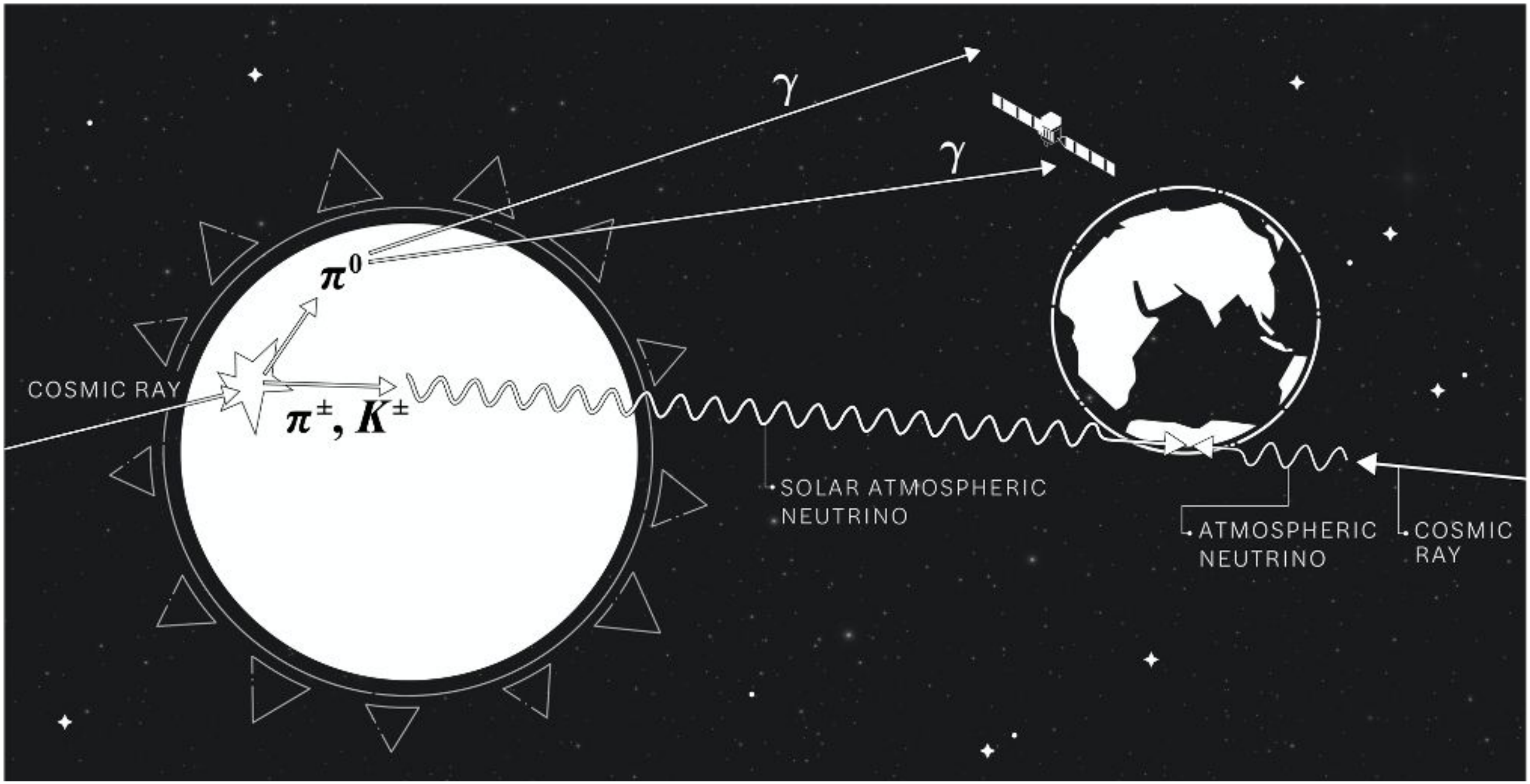
Josh Villarreal, Gerrit Roellinghoff, Jeff Lazar

For the IceCube Collaboration

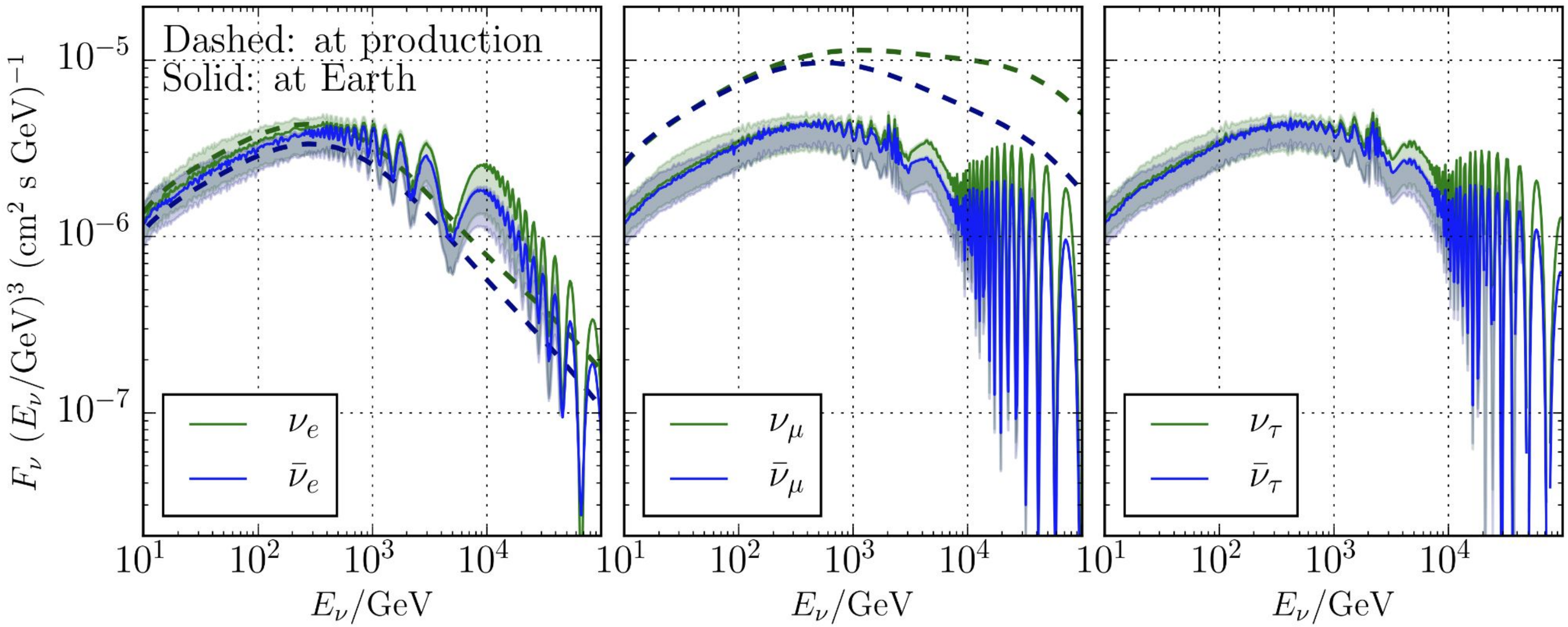
ICRC 2021

Motivation and project relevance

- Solar atmospheric neutrinos are produced by cosmic rays interacting with matter in the sun's atmosphere, sharing a production mechanism with solar gamma rays
- Relevant to solar dark matter searches as an irreducible background
- Remain one of the few naturally occurring high-energy neutrinos yet to be detected



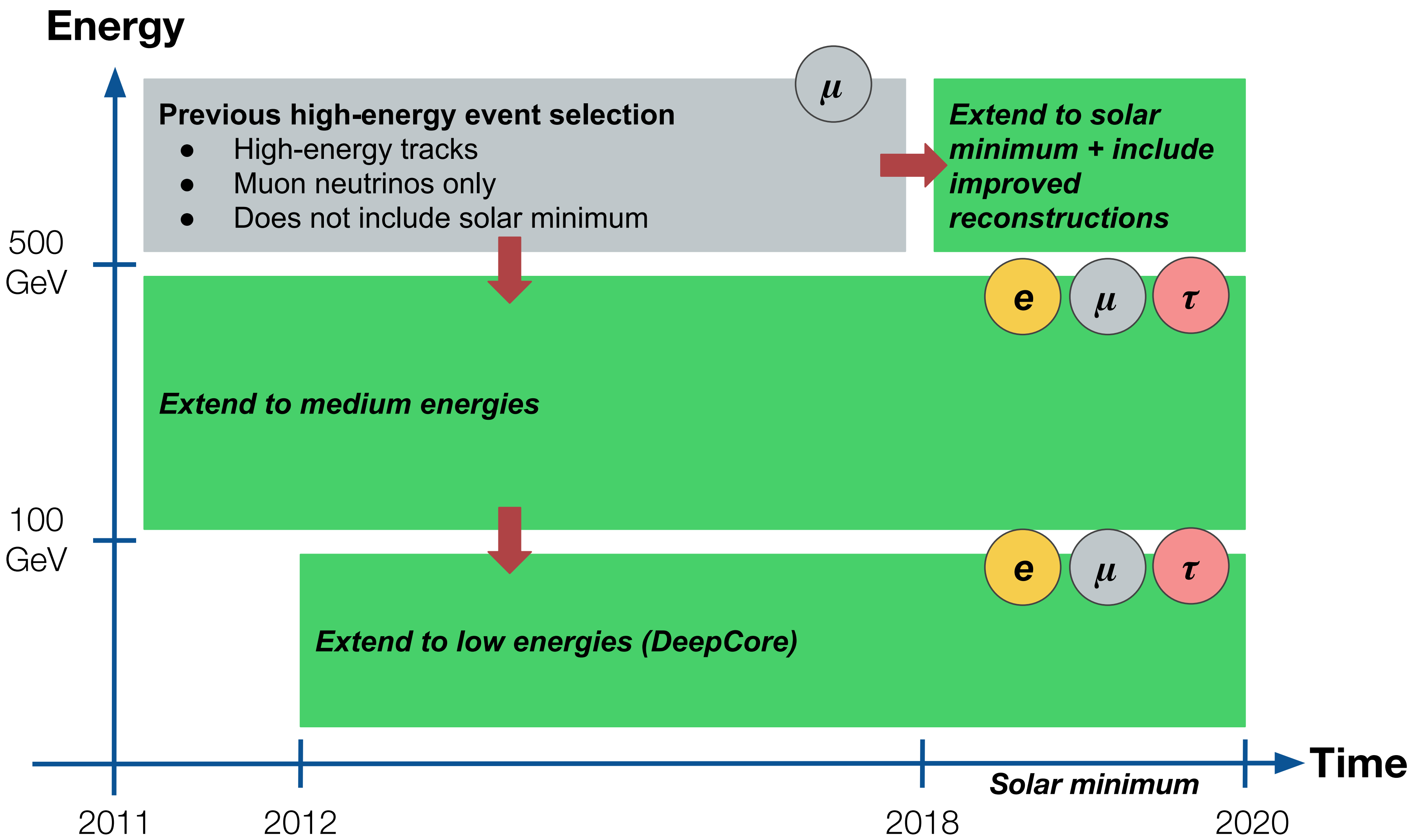
Solar atmospheric neutrino flux predictions



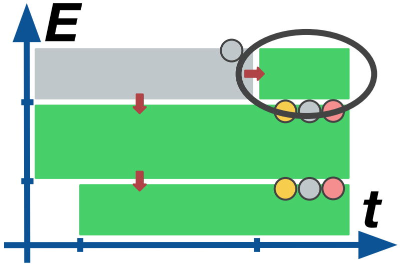
Source: Argüelles, Wasseige, Fedynitch, Jones.
https://iopscience.iop.org/article/10.1088/1475-7516/2017/07/024.

- Soft energy spectrum, falls off like E^{-3}
- Gamma ray flux measured to be higher during periods of decreased solar activity, hinting at a higher neutrino flux during periods of solar minima
- Background for solar atmospheric neutrino signal searches include conventional atmospheric neutrinos and cosmic-ray muons

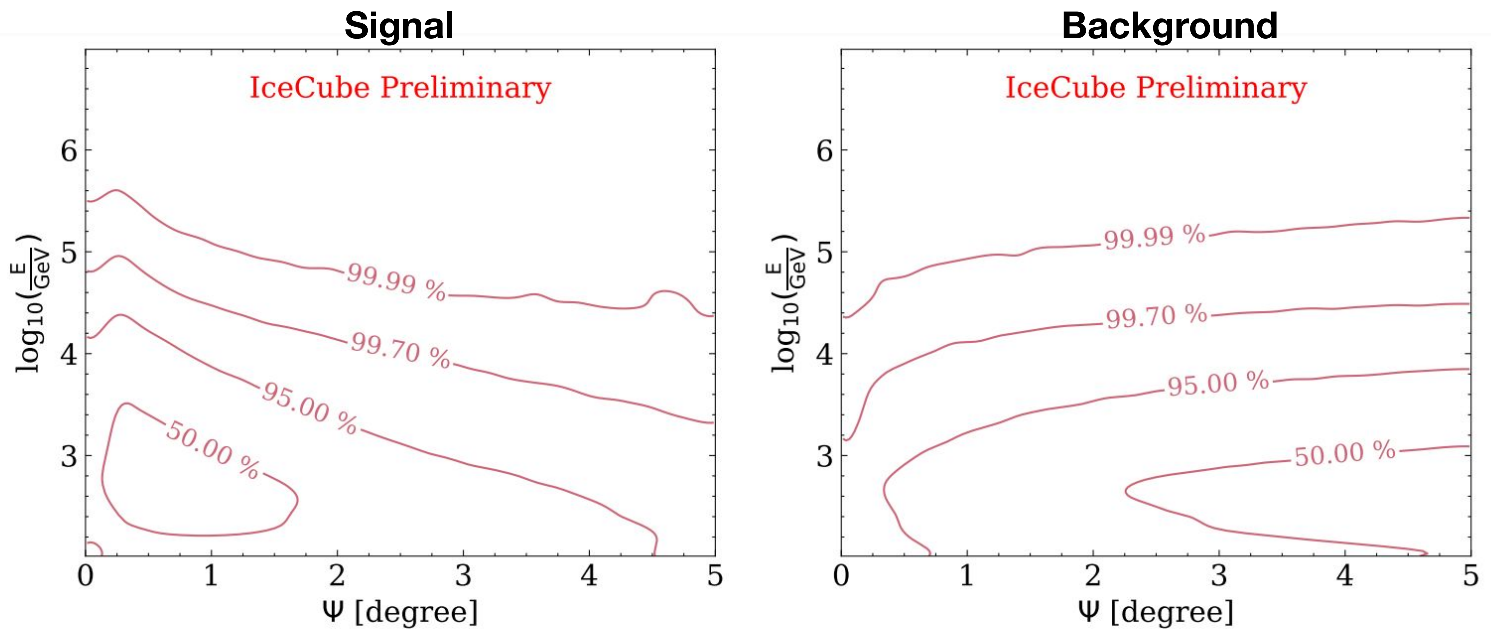
Event selection and its extensions



Analysis method for HE selection

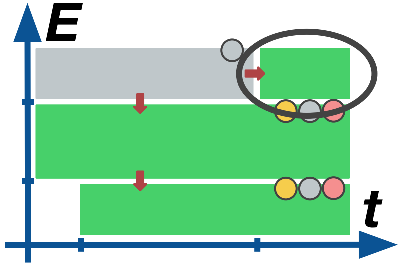


- For our preliminary sensitivities, we calculate our probability density functions by weighting MC simulation events with the expected flux, looking at the bivariate distribution in $\theta = [\Psi, E]$.



Probability density contours of expected signal (left) and background (right) events in the high-energy event selection depending on angular distance from the Sun Ψ and reconstructed energy E in a circular region of interest of 5° around the sun.

Likelihood for HE event selection

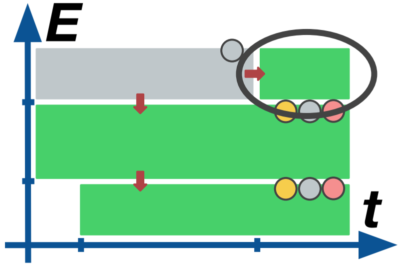


- To compute the sensitivity for high-energy data, we use an unbinned likelihood method given by:

$$\mathcal{L}(n_s) = \prod_{i=1}^{N} \left[\frac{n_S}{N} p_{sig}(\vec{\theta}_i; \phi_{sig}) + (1 - \frac{n_S}{N}) p_{bkg}(\vec{\theta}_i; \phi_{atm} + \phi_{astro}) \right]$$

  - p_{sig}/p_{bkg} PDFs of expected signal/background events,
  - N the total number of events in the events selection,
  - n_S the number of signal events,
  - ϕ_{sig} the assumed signal flux model, and
  - $\phi_{atm} + \phi_{astro}$ the combined background flux of conventional atmospheric and diffuse astrophysical neutrinos

Sensitivity for 9 years of HE selection

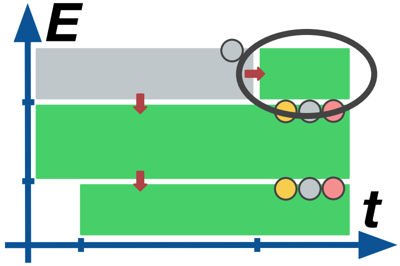


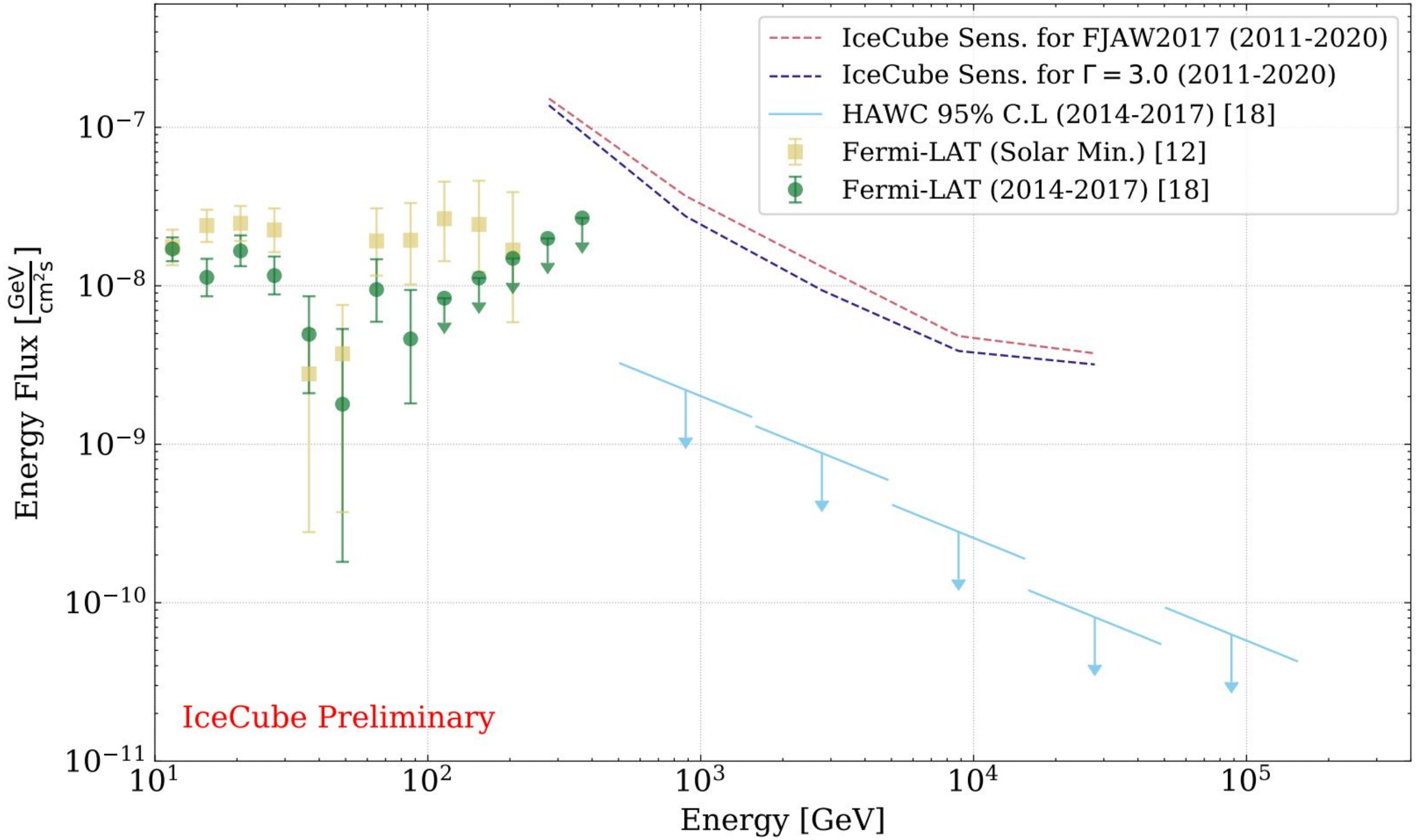
	Sens. in units of model flux	Sens. at 1 TeV [GeV^{-1} cm^{-2} s^{-1}]
Edsjo2017 *	2.61	$1.72 \cdot 10^{-14}$
FJAW2017 **	3.51	$1.95 \cdot 10^{-14}$

- We calculate our sensitivity for all 9 years of data for a reference flux from Edsjo2017 and FJAW2017 each using the Neyman method.
- Depending on flux model, resulting sensitivities are a factor of 2-4 larger than model predictions
- Further improvements in event selection, likelihood method and incorporation of the solar shadow are expected to result in further improvements.

*Edsjo2017 is shorthand for the 2017 paper by J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus.
**FJAW2017 is shorthand for the 2017 paper by C. Argüelles, G. de Wasseige, A. Fedynitch, and B. Jones.

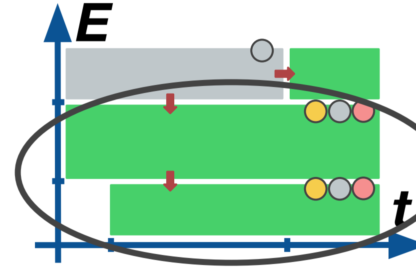
HE selection differential sensitivity

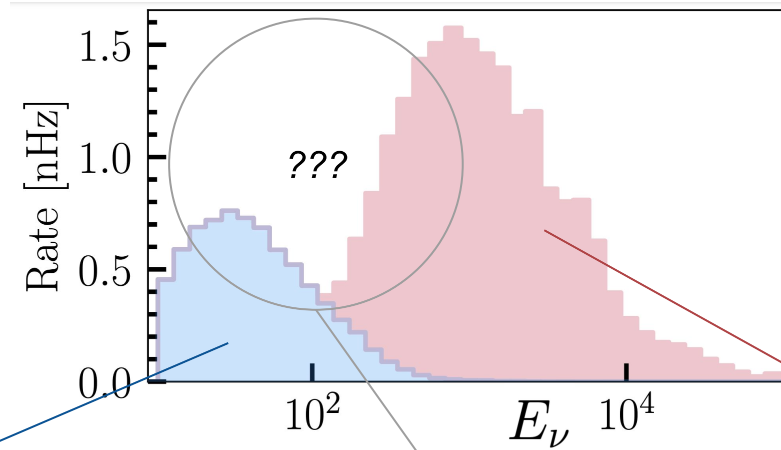




Differential Sensitivity in half-decade energy bins for 9 years of data for a reference flux from FJAW2017 and for a power law with Γ=3.0. Also shown are gamma-ray observations/limits from HAWC and Fermi-LAT. We omit showing the sensitivity for our other reference flux from Edsjo2017 due to the high shape similarities between the two.

To an all-energy event selection

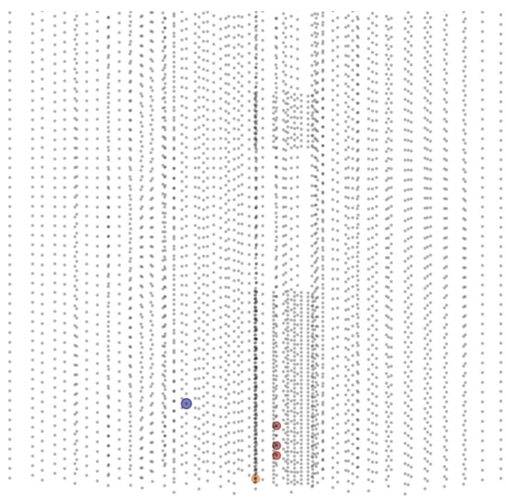


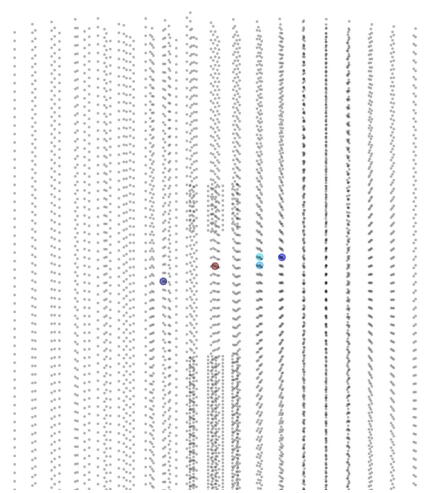


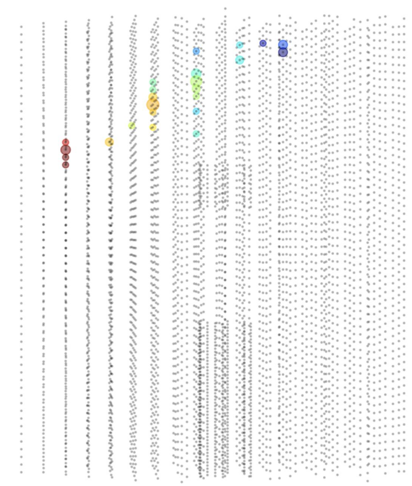
Low energy (<300 GeV)

Medium energy (100-500 GeV)

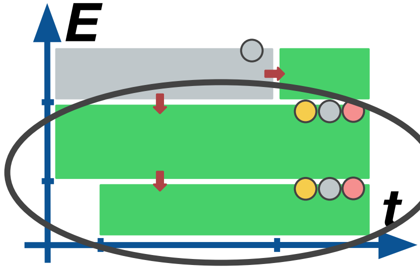
High energy (>500 GeV)

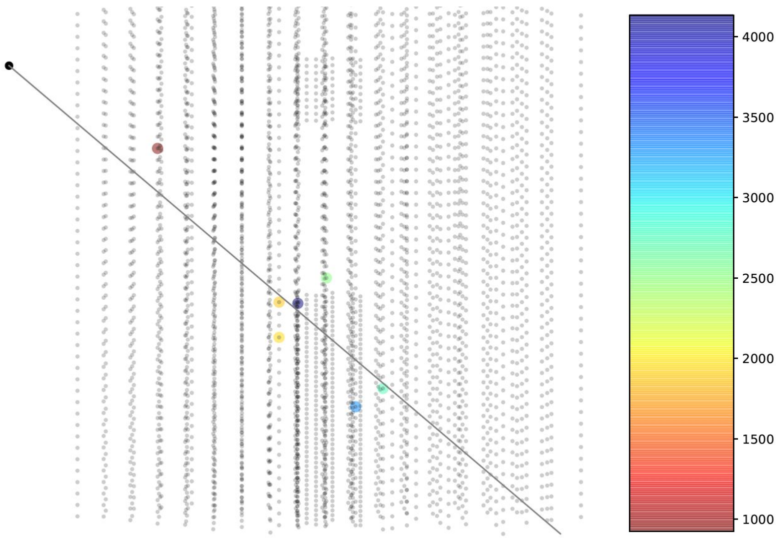




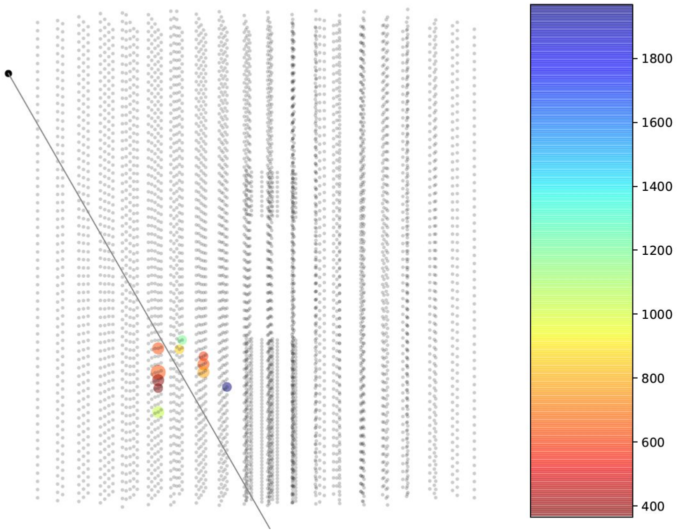


To an all-flavor event selection





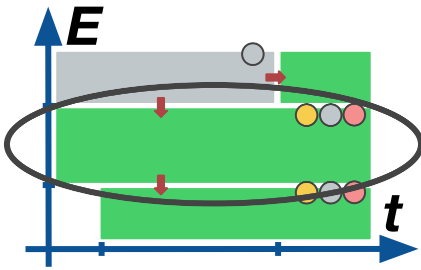
Example of a ~200 GeV
muon track



Example of a ~200 GeV
electron cascade

- Previous event selection used only high-energy tracks from muon neutrinos
- Extending to ~100 GeV regime includes events with poorer angular resolutions
  - Natural extension for event selection to handle neutrinos of all flavors
  - Neutrinos from the sun have time to oscillate, so we expect a flat flavor distribution at Earth
  - Cascade signal:background ~10x higher than tracks

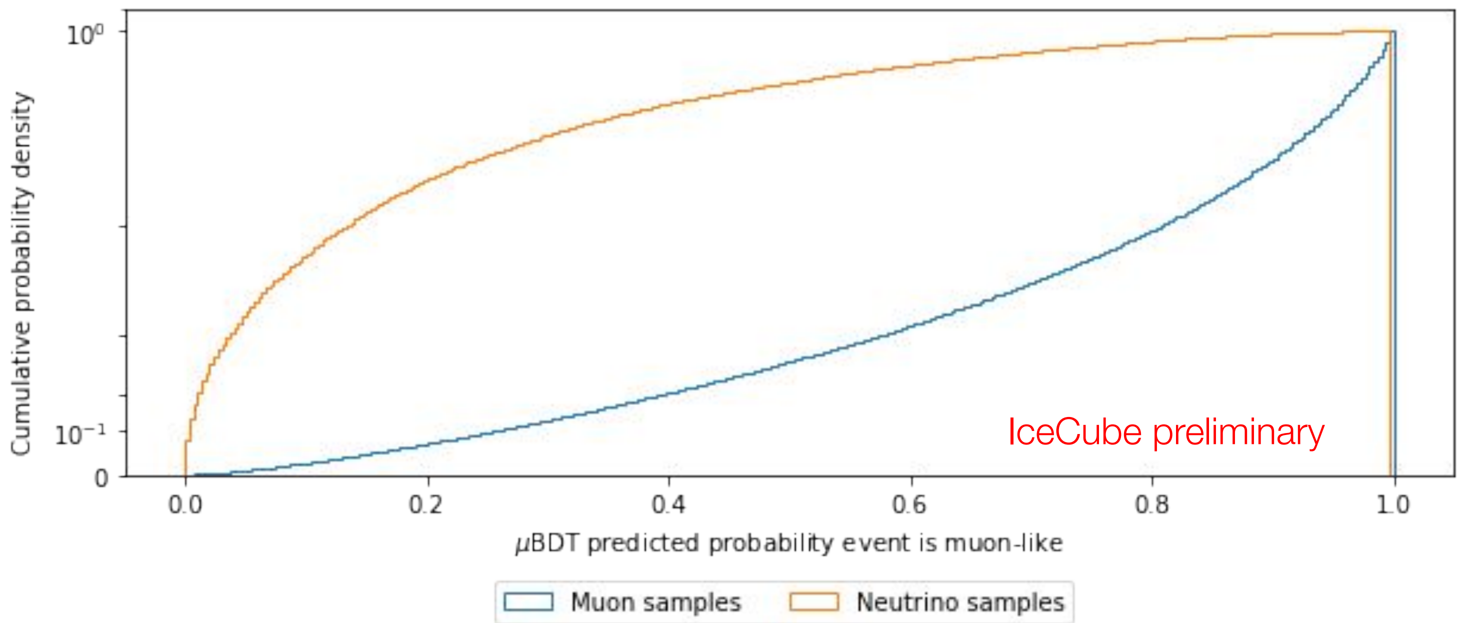
Current setup of ME selection



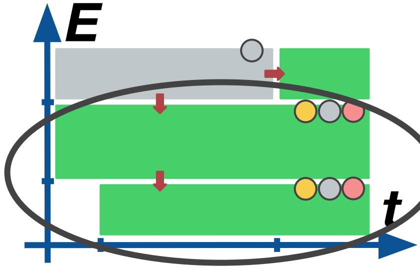
0. Pick events that medium-energy filter gives us

1. Cut on reconstructed zenith angle and reduced-log-likelihood of the track fits (effective at filtering out atmospheric muon background)

2. Pass output from **1.** to a Boosted Decision Tree trained to identify muon-like events ("muBDT"). Current score separation shown in test-set distribution below



Current sensitivities and next steps



Comparing sensitivities to FJAW model for various event selections

HE event selection	3.75
DeepCore LE selection	5.41
LE + HE	2.91

2.1. Optimize performance of μBDT

- DeepCore selection able to reduce background (muon) rate by factor 10^{-5}
- Hyperparameter tuning (learning rate, regularization, decision tree specifications)

3. νBDT trained to identify solar atmospheric neutrino events.

- **2.** reduces data to a higher concentration of neutrino-like events (including conventional atmospheric & solar atmospheric)
- Introduce additional features that may prove useful in discriminating between solar and conventional atmospheric neutrinos (e.g. morphology classifier helpful in differentiating neutrino flavor)

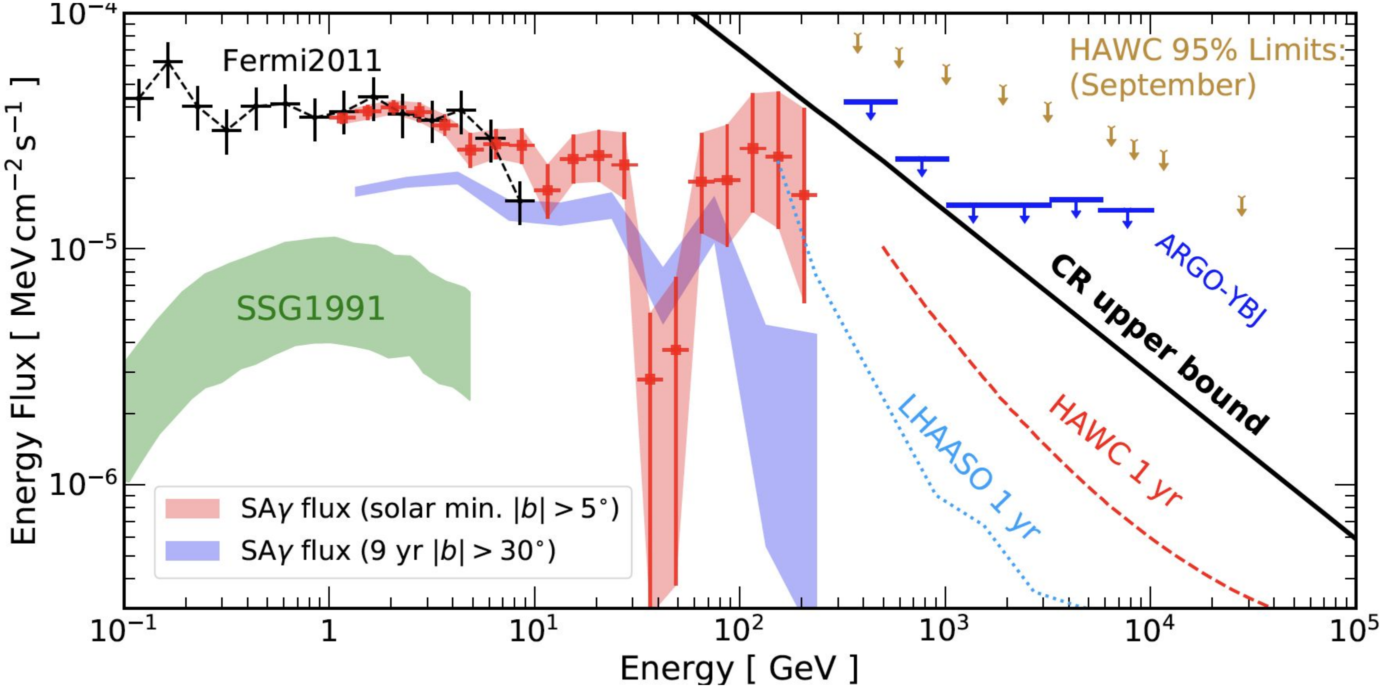
Conclusion and outlook

- Improving existing solar atmospheric neutrino searches by extending on both time and energy
- Custom event selection designed to fill gap between low- and high-energy event selections
- Combined HE and LE sensitivity a 4x improvement on previous limit, only going to improve with inclusion of ME event selection

Thank you!

Backup

Solar gamma-rays

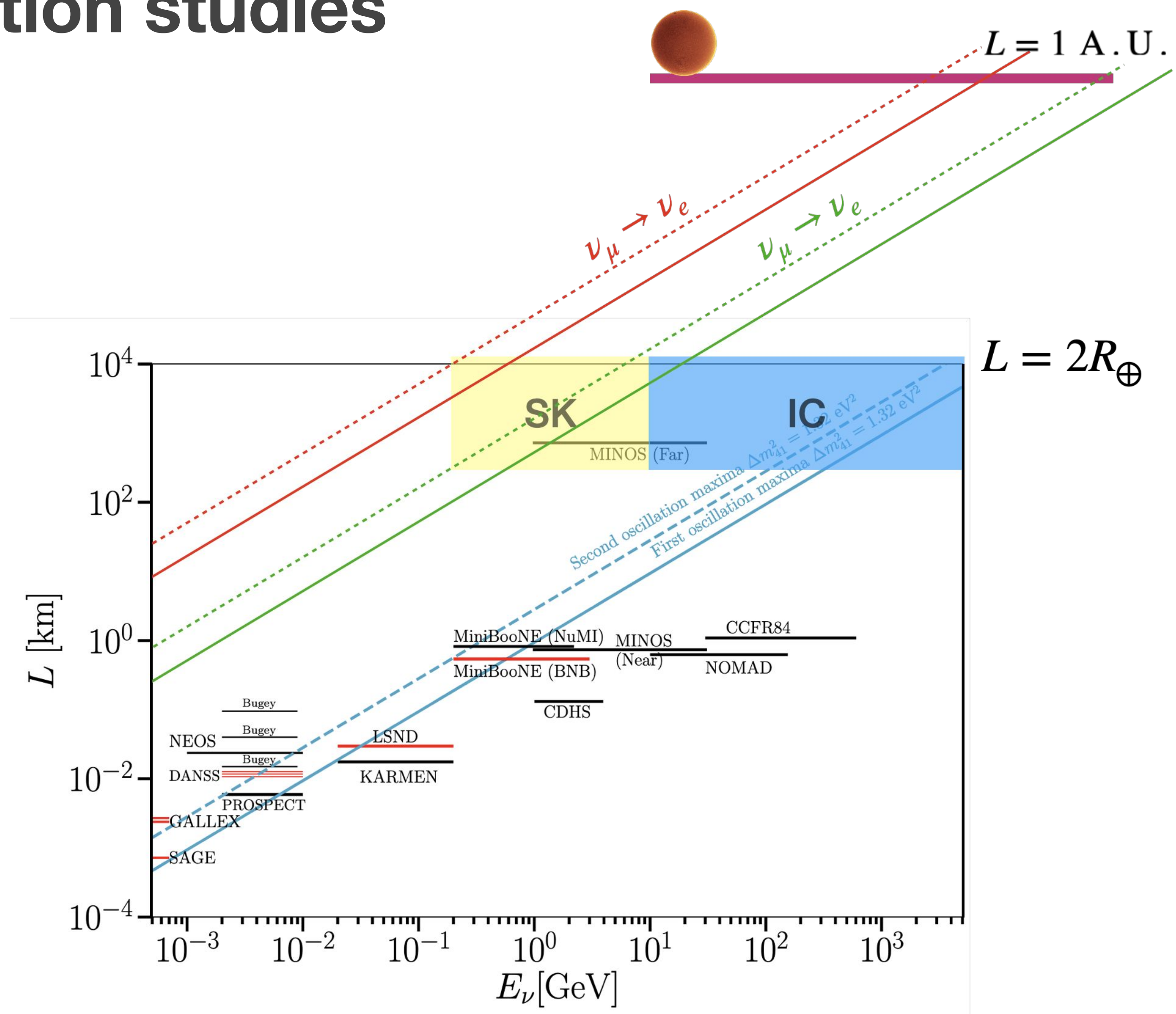


Source: Q-W. Tang, K.C.Y. Ng, T. Linden, B. Zhou, J.F. Beacom, A.H.G. Peter.
10.1103/PhysRevD.98.063019

- Harder spectrum of solar atmospheric gamma-rays evident during period of solar minimum
- Unexplained dip in flux between 30-50 GeV

Future oscillation studies

- Solar atmospheric neutrino searches may allow for 1 A.U. oscillation study baselines



Source: from A. Diaz, C.A. Argüelles, G.H. Collin, J.M. Conrad, M.H. Shaevitz. doi:10.1016/j.physrep.2020.08.005