Search for Solar Atmospheric Neutrinos with IceCube

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(for the IceCube Collaboration)

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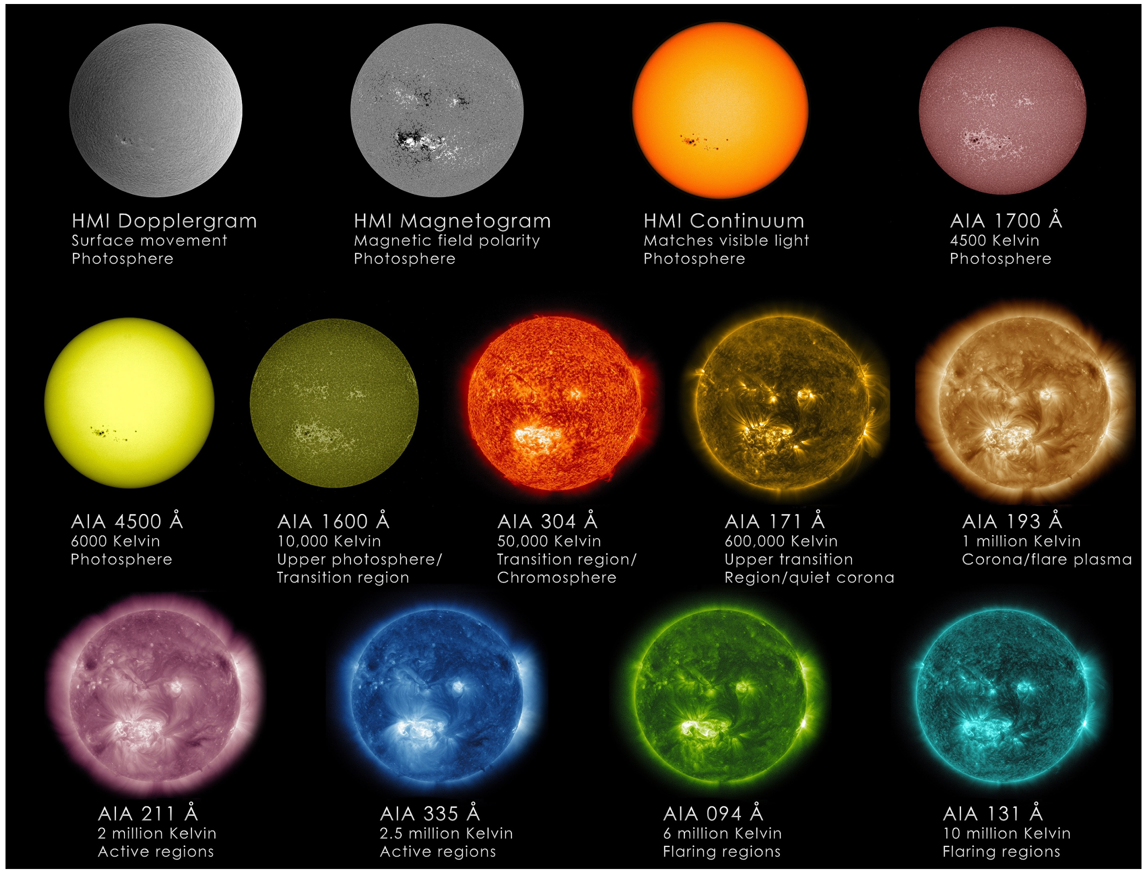
Outline

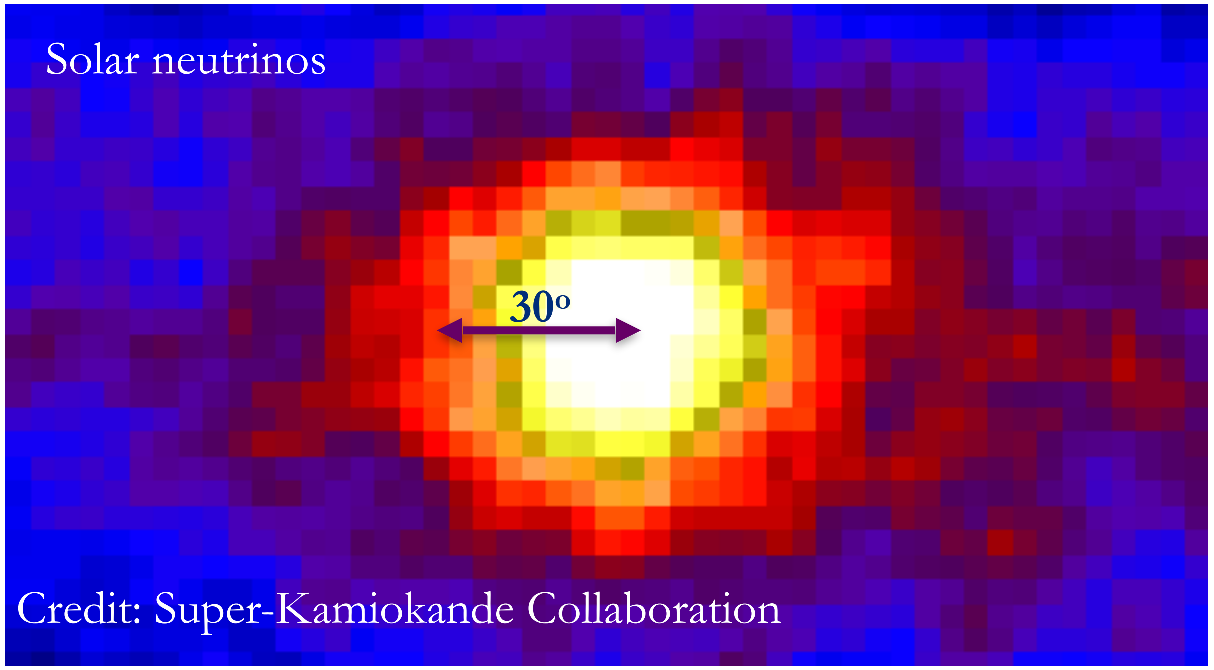
- Motivation
- Energetic radiation from the Sun
- IceCube Neutrino Telescope
- Observing the Sun with IceCube
  - Sun Shadow
  - Solar Dark Matter
  - Solar Atmospheric Neutrinos and the Dark Matter Neutrino Floor
- Outlook and Conclusions

Motivation

Motivation



Credit: NASA/SDO/Goddard Space Flight Center



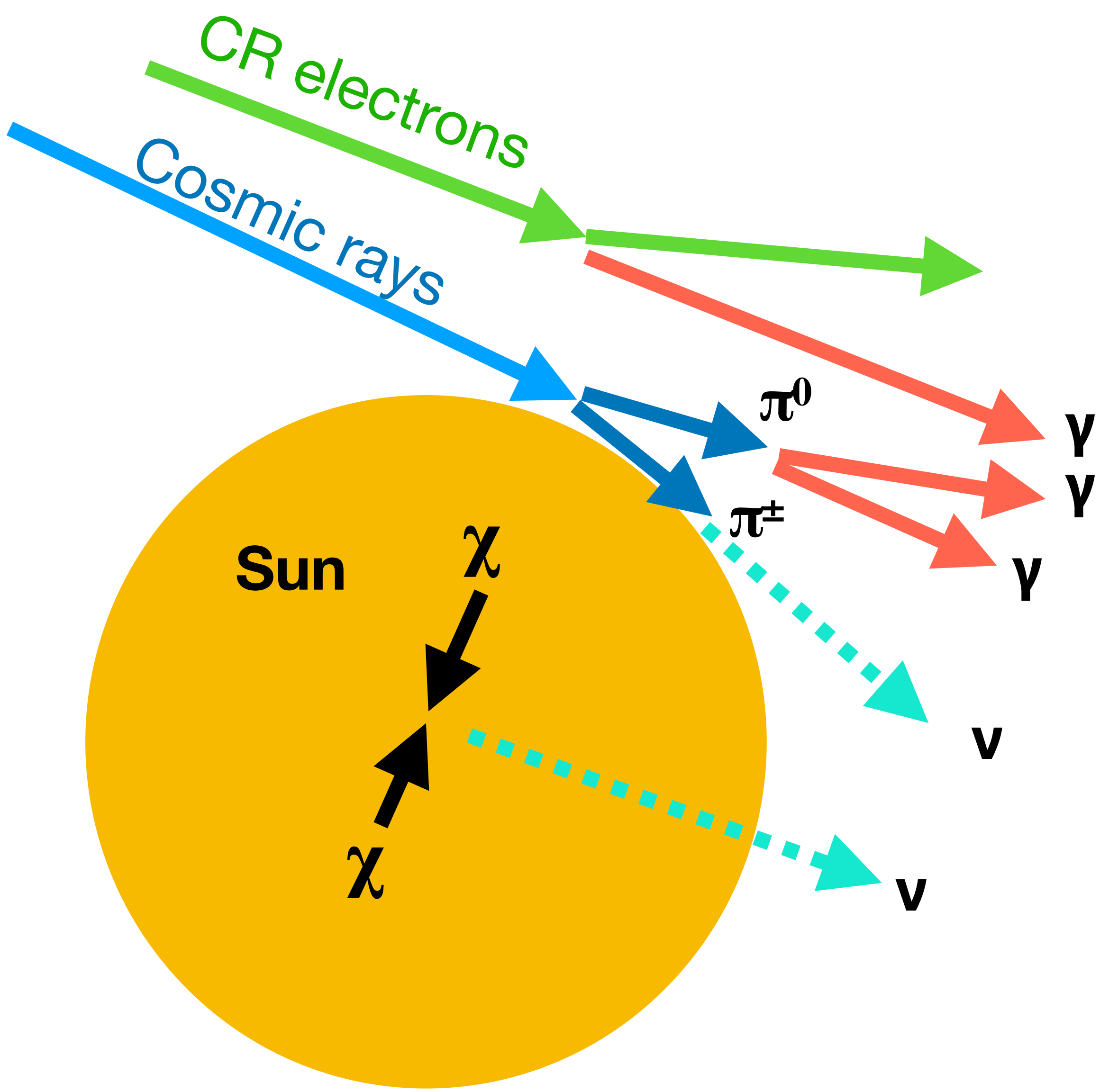
Credit: Super-Kamiokande Collaboration

- GeV Radiation from the Sun
  - Inverse Compton (IC)
    - Cosmic ray electrons and positrons on solar photons
  - Solar Disk (Disk)
    - Cosmic rays with solar atmosphere
  - Exotics
    - Dark matter, …

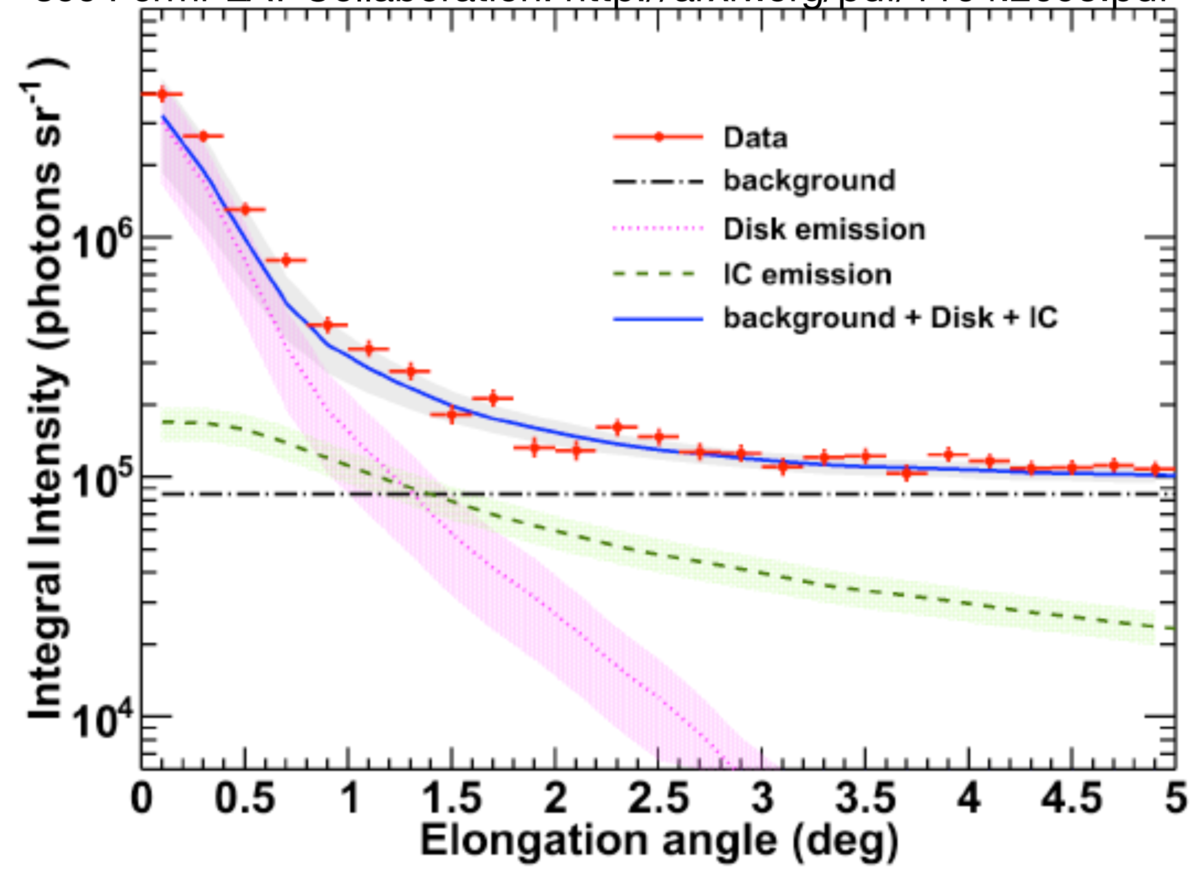
Energetic Radiation from the Sun

see talks by Kenny Ng/ Bei Zhou

Cosmic ray interactions with the Sun



see Fermi-LAT Collaboration: http://arxiv.org/pdf/1104.2093.pdf



- Cosmic-ray interactions with the solar atmosphere produce gamma-rays and neutrinos
- Background to dark matter search from the Sun, that soon will be relevant and a first high-energy neutrino point source ?

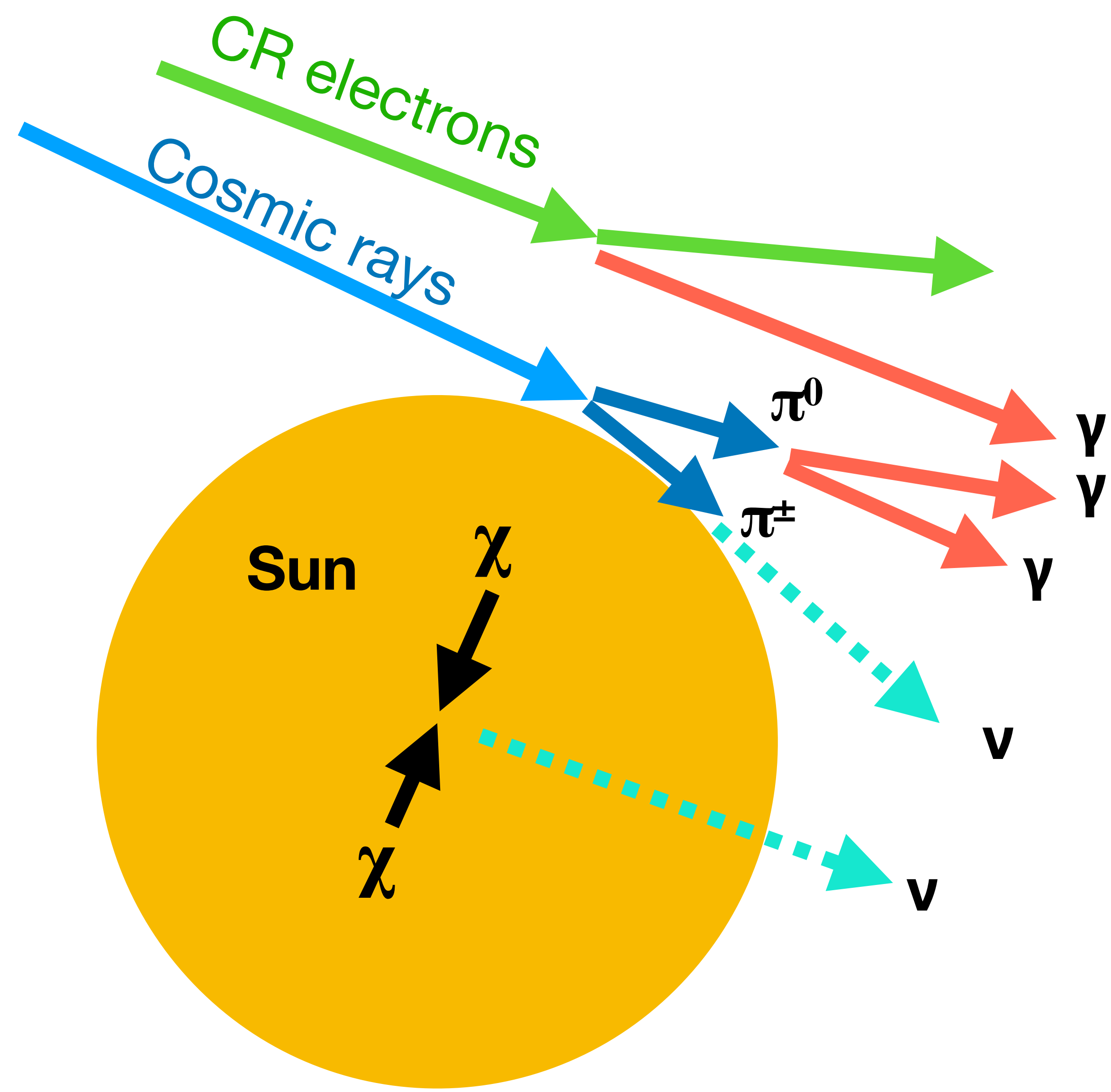
Leptonic

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

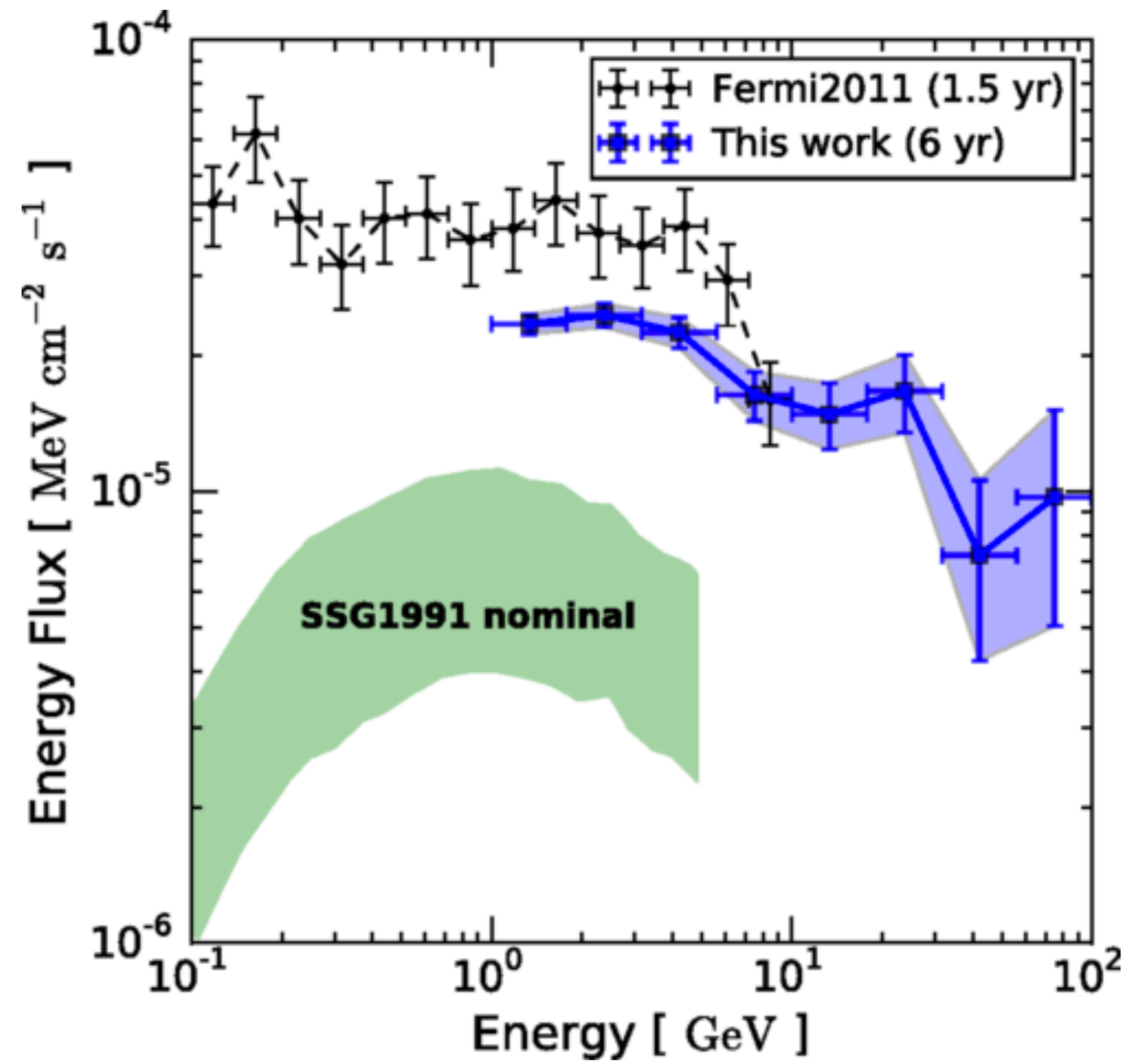
Hadronic

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

Cosmic ray interactions with the Sun



Ng, Beacom, Peter, Rott Phys.Rev. D94 (2016) no.2, 023004



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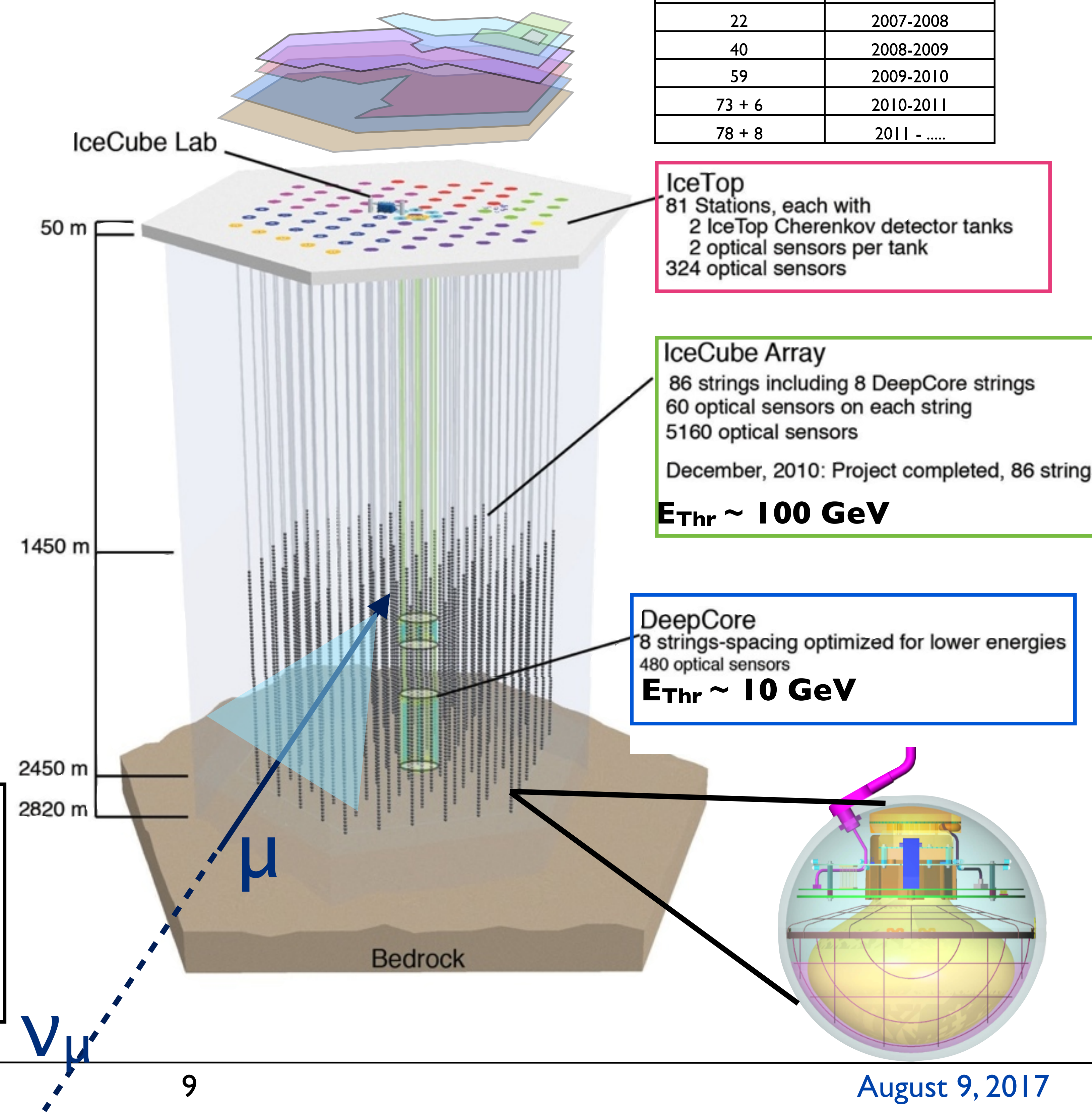
The IceCube Neutrino Observatory

The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, start of data taking with full detector May 2011
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

Strings	Dataset
1	2005-2006
9	2006-2007
22	2007-2008
40	2008-2009
59	2009-2010
73 + 6	2010-2011
78 + 8	2011 - .....



Solar Observations

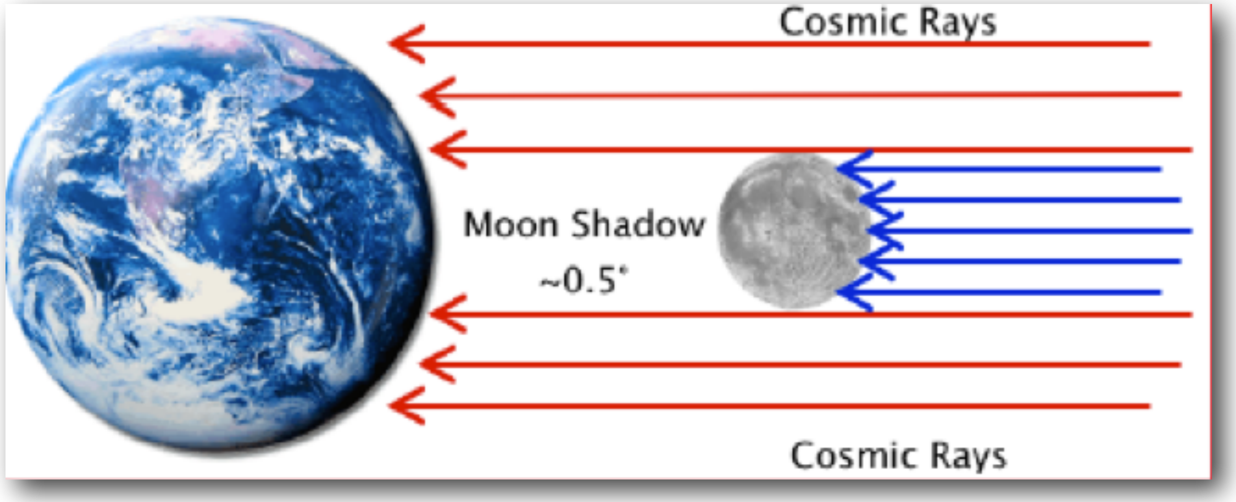
- **At the South Pole the Sun is between +/- 23°**

IceCube Performance and Moon/Sun Shadows

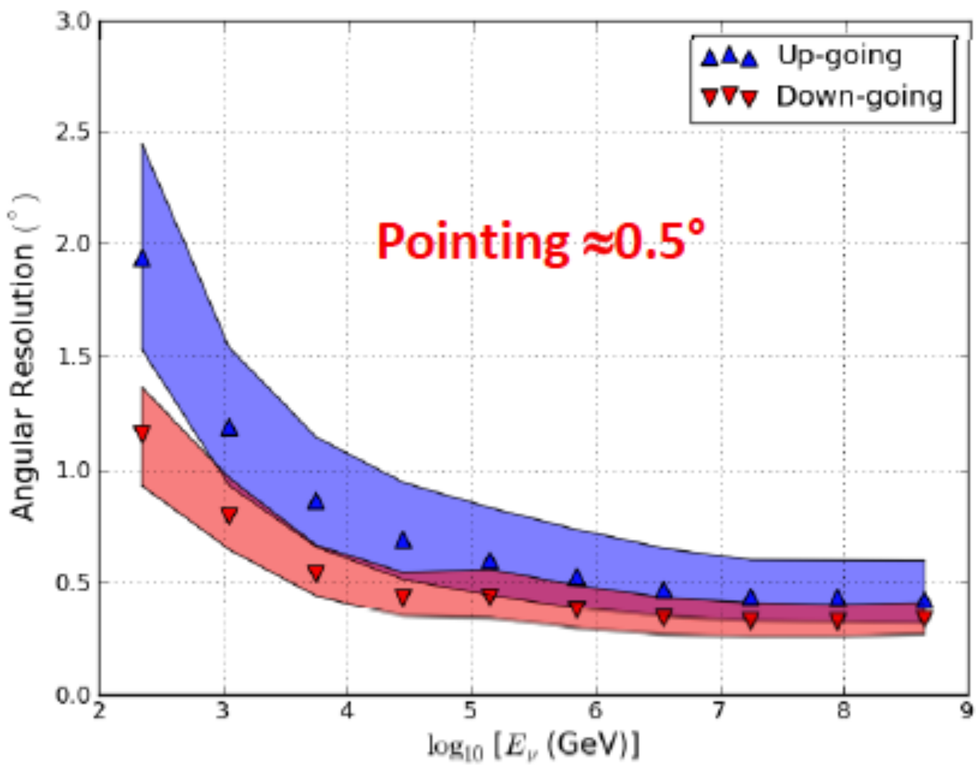
Calibration and Performance

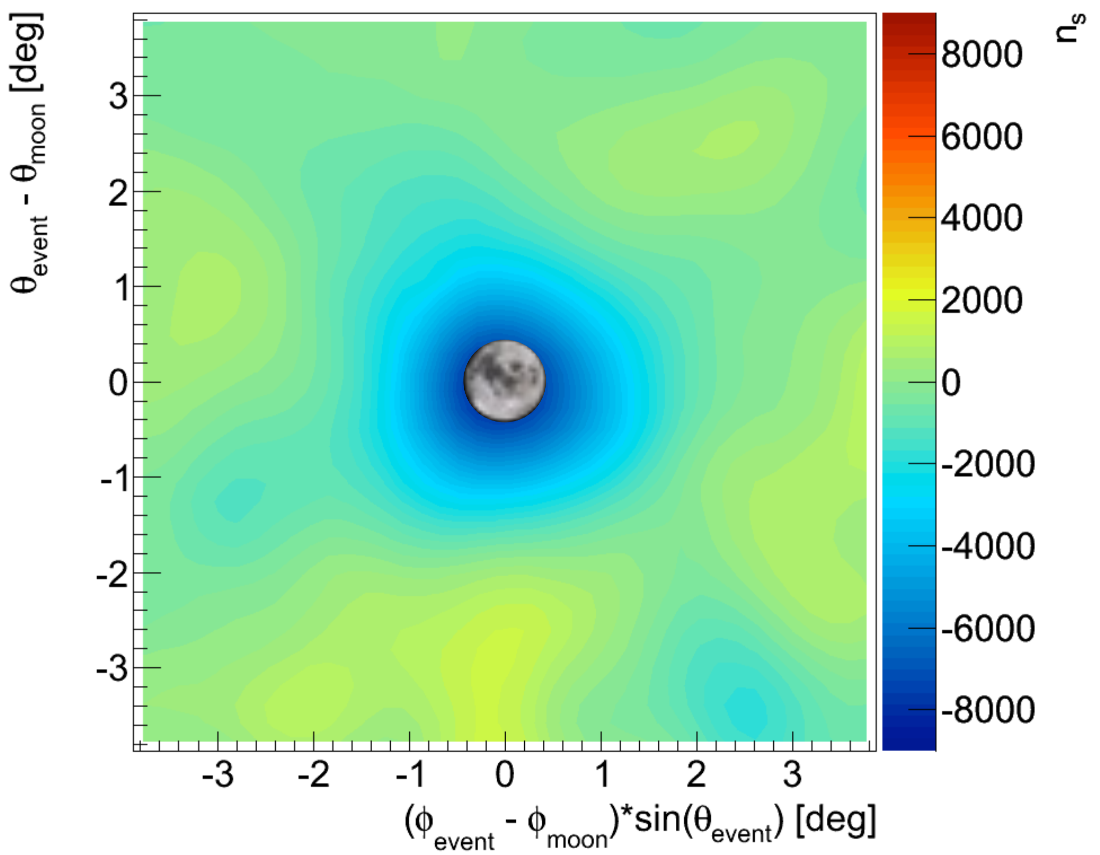
Physical Review D89 (2014) 102004

- Calibration Sources:
    - 12 LED flashers on each DOM
    - In-Ice Calibration Laser
    - Cosmic Rays
    - Moon Shadow
    - Atmospheric Neutrinos
    - Minimum-ionizing Muons

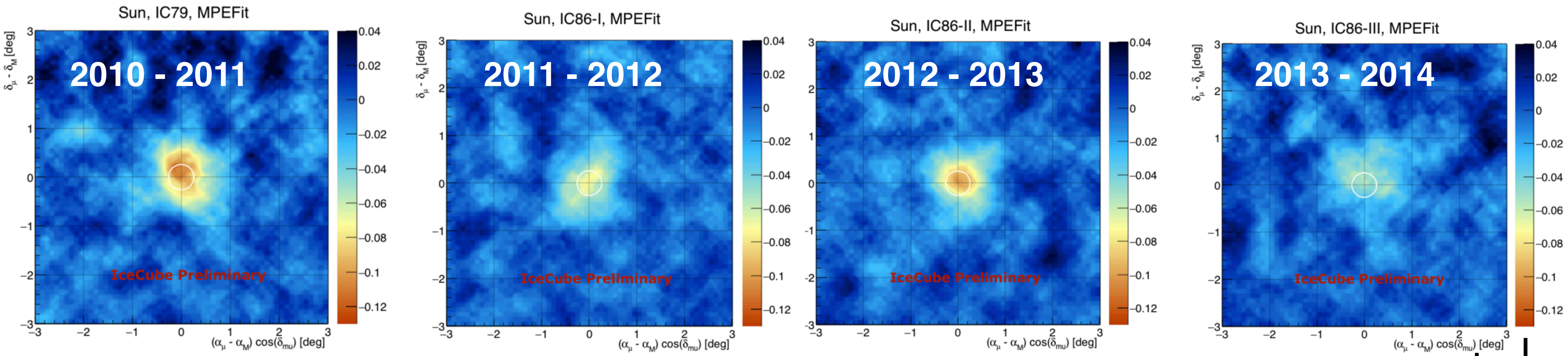


- Moon blocks cosmic rays - Observed muon deficit 14σ significance
    - systematic pointing error <0.1°

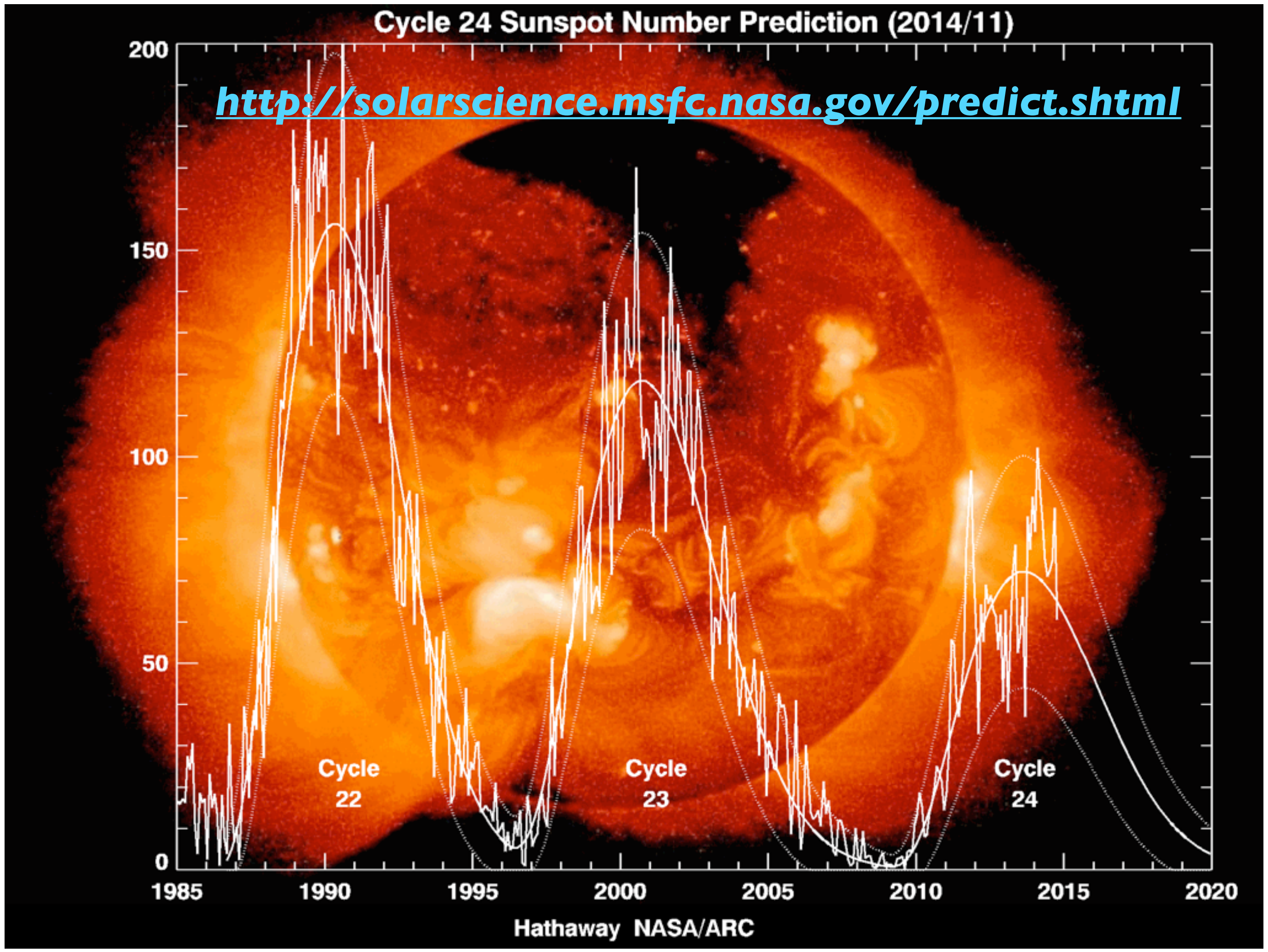




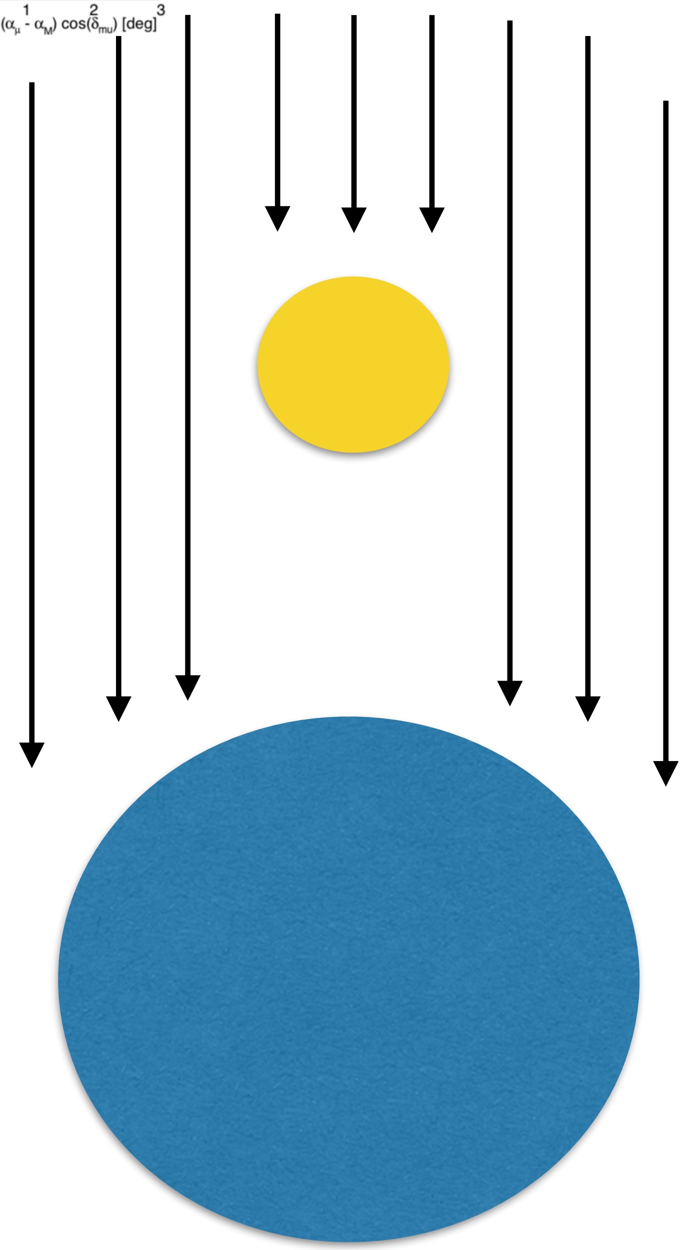
Sun Shadow



Sun, IC79, MPEFit
2010 - 2011
IceCube Preliminary
Sun, IC86-I, MPEFit
2011 - 2012
IceCube Preliminary
Sun, IC86-II, MPEFit
2012 - 2013
IceCube Preliminary
Sun, IC86-III, MPEFit
2013 - 2014
IceCube Preliminary

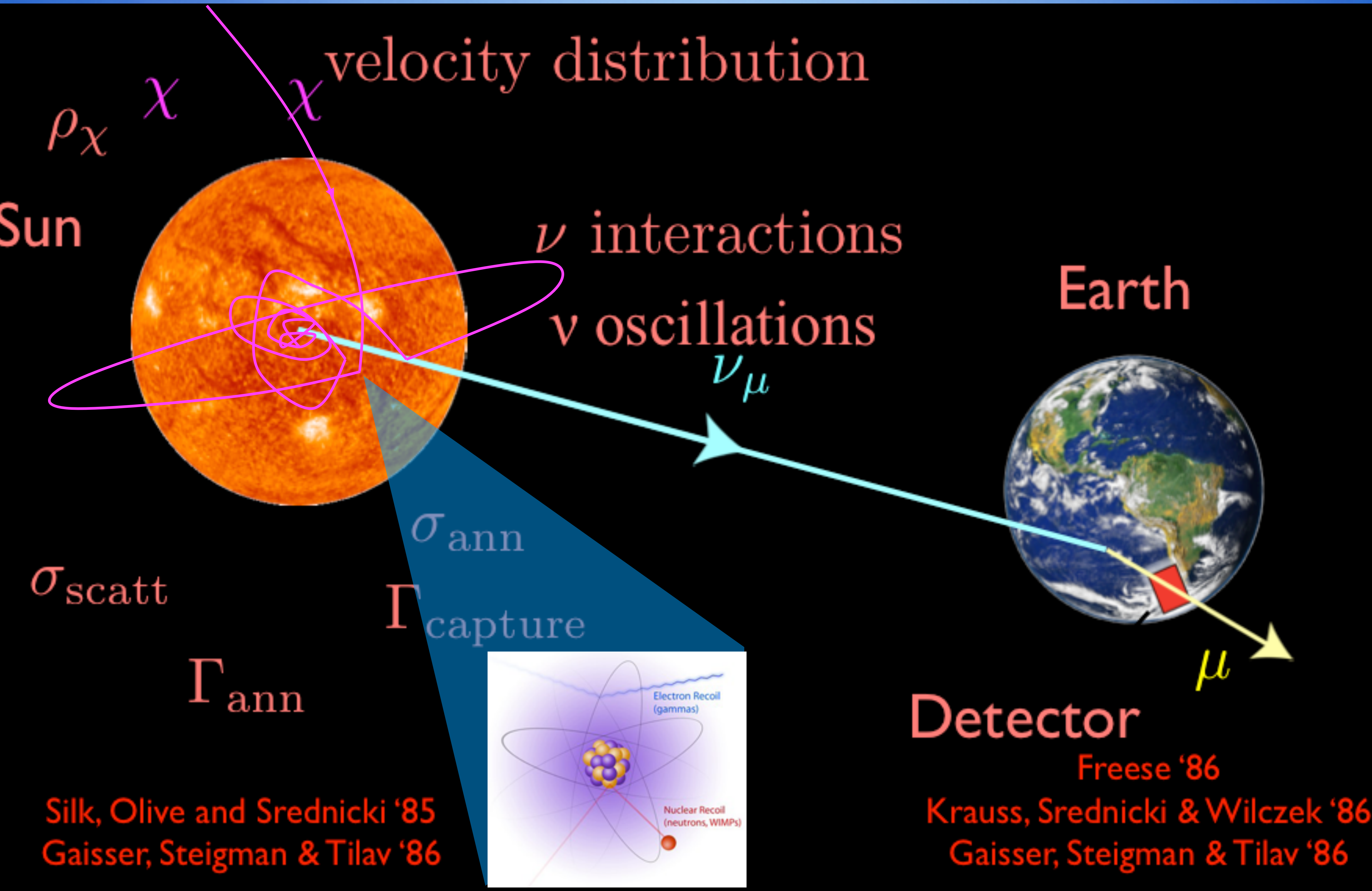


Cycle 24 Sunspot Number Prediction (2014/11)
http://solarscience.msfc.nasa.gov/predict.shtml
200
150
100
50
0
Cycle 22
Cycle 23
Cycle 24
1985
1990
1995
2000
2005
2010
2015
2020
Hathaway NASA/ARC



Solar Dark Matter Searches

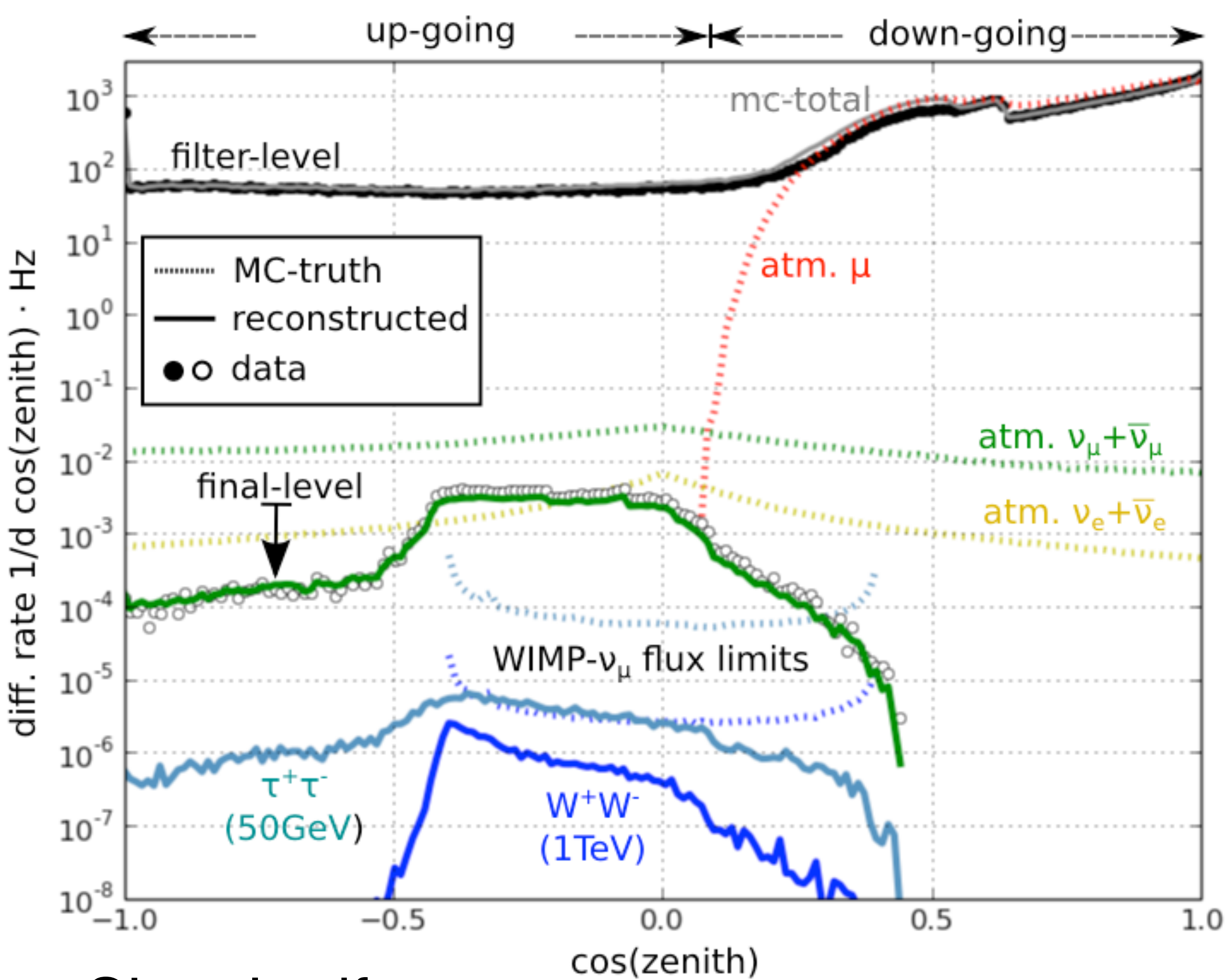
Solar Dark Matter



Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

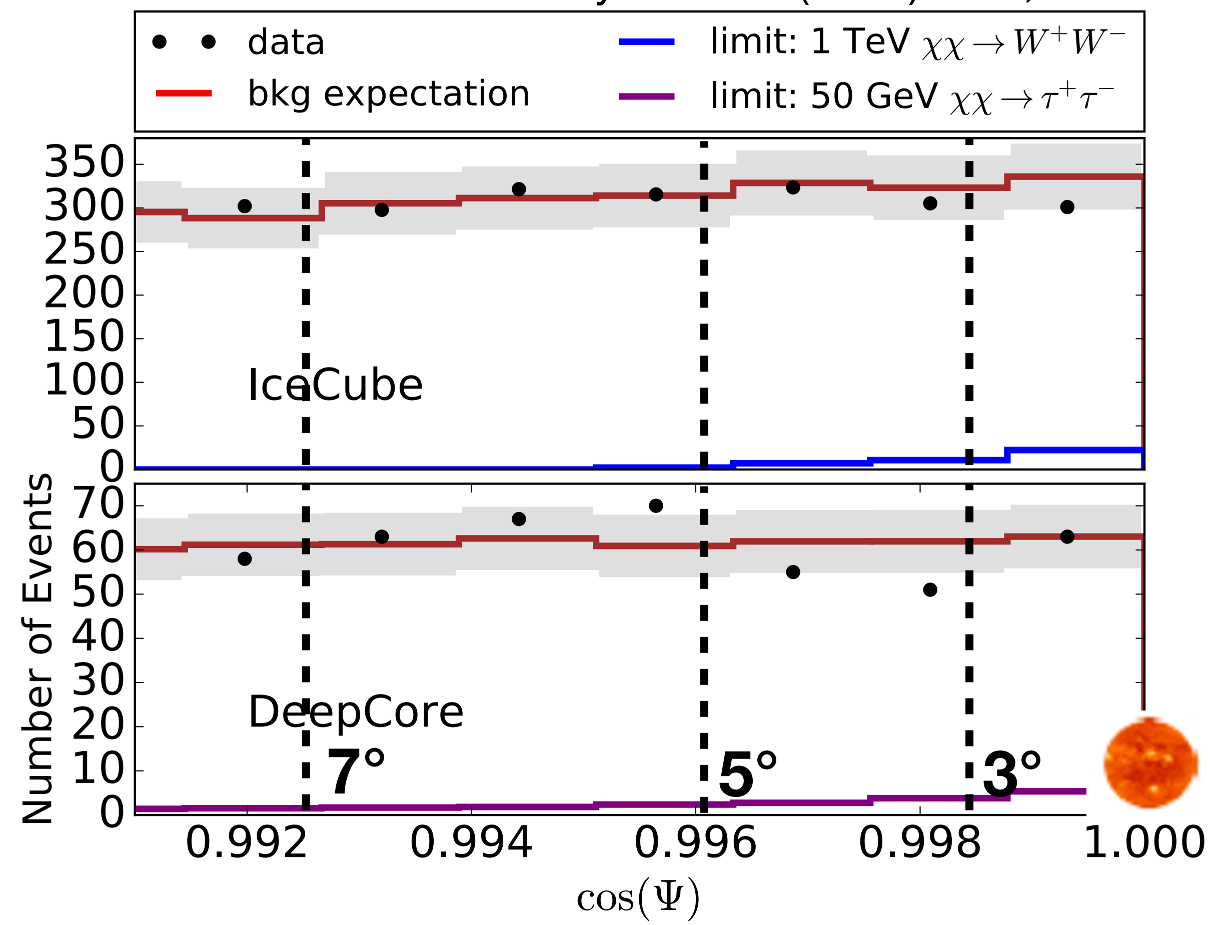
Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

3yrs IceCube Solar Dark Matter Analysis



Observed events

IceCube Eur.Phys.J. C77 (2017) no.3, 146



Signal pdf:

Spectral part

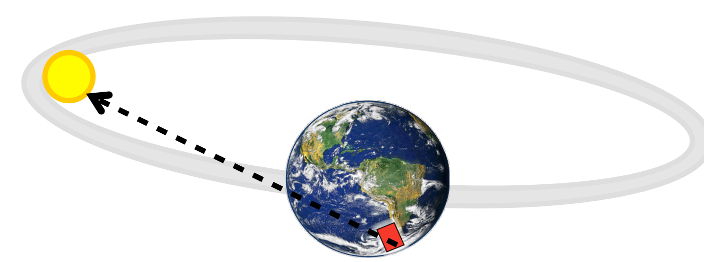
$$S_i(|\vec{x}_i-\vec{x}_{\rm sun}(t_i)|,E_i,m_\chi,c_{\rm ann})$$
$$=\mathscr{K}(|\vec{x}_i-\vec{x}_{\rm sun}(t_i)|,\kappa_i)\times\mathscr{E}_{m_\chi,c_{\rm ann}}(E_i)$$

Monovariate Fisher Bingham distribution from directional statistics

Background pdf: $\mathscr{B}_i(tx_i,E_i)=B(\delta_i)\times P(E_i|\phi_{\rm atm})$

Likelihood: $\mathscr{L}(n_s)=\prod_N\left(\frac{n_s}{N}S_i+(1-\frac{n_s}{N})\mathscr{B}_i\right)$

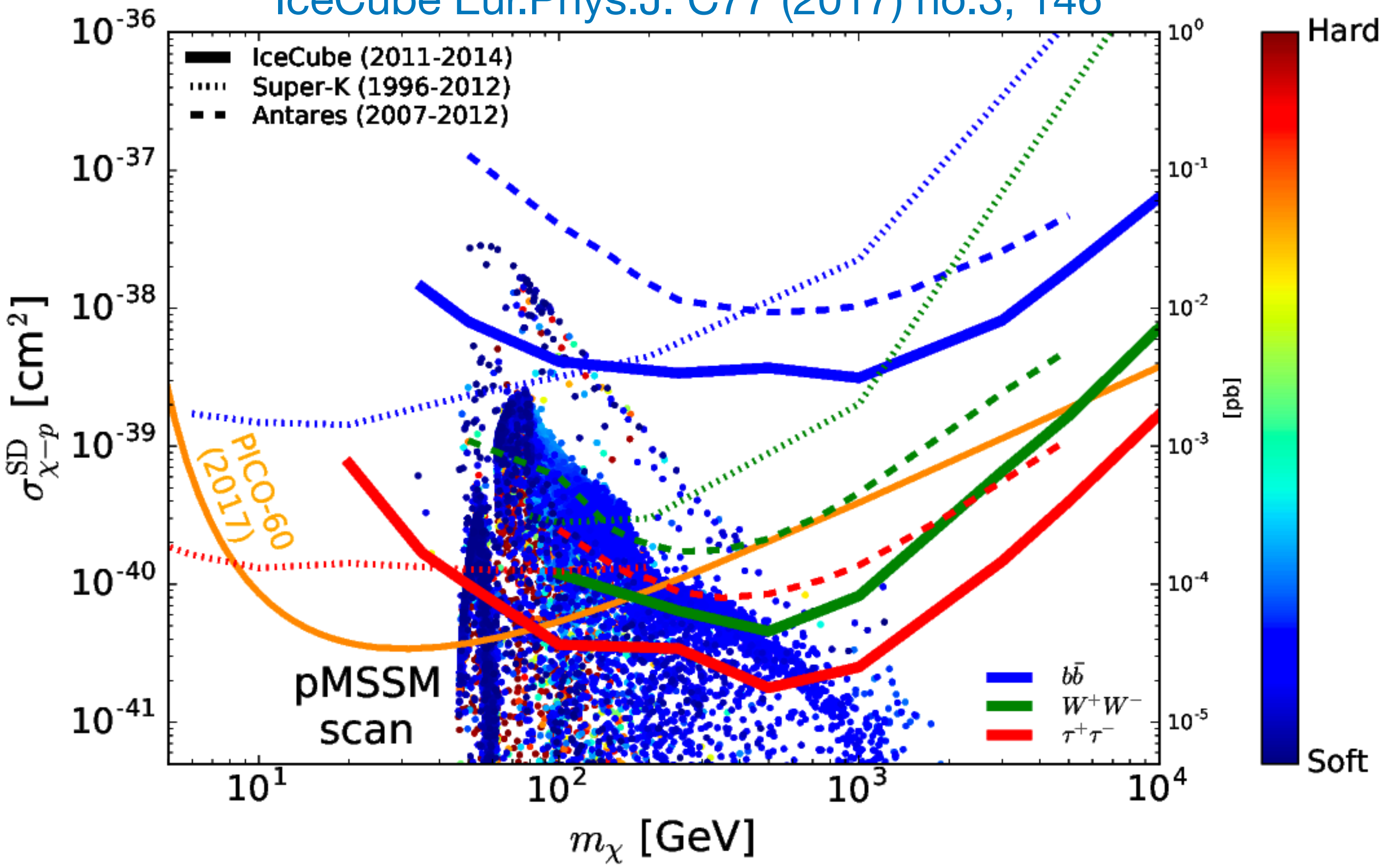
- Use track events for better pointing
- Search for an excess of events from the direction of the Sun
- Observed events consistent with background only expectations



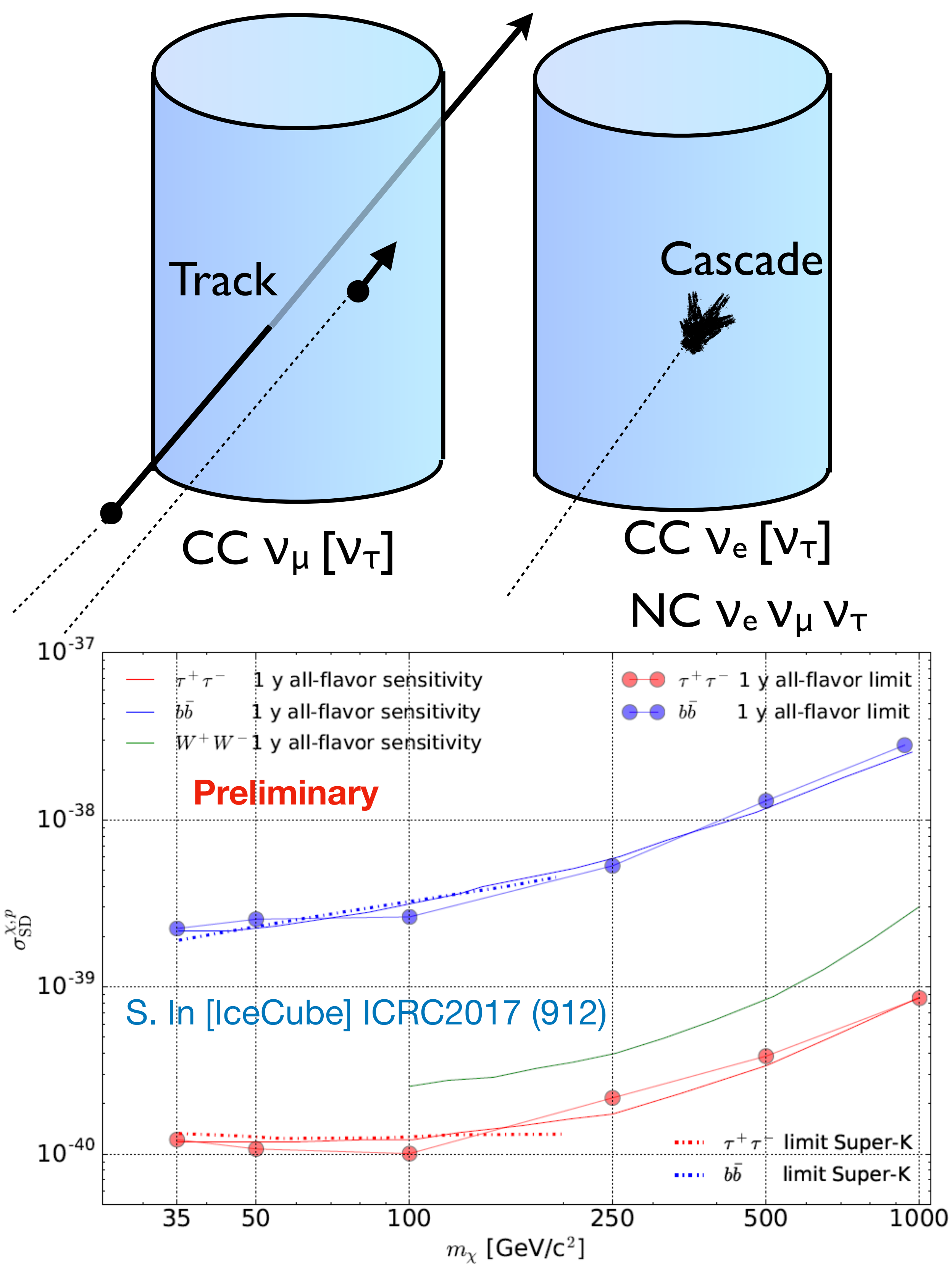
Solar Dark Matter - IceCube/ANTARES

- Convert neutrino flux limit into limit on WIMP-nucleon scattering cross section

IceCube Eur.Phys.J. C77 (2017) no.3, 146



All flavor Solar WIMP - IceCube



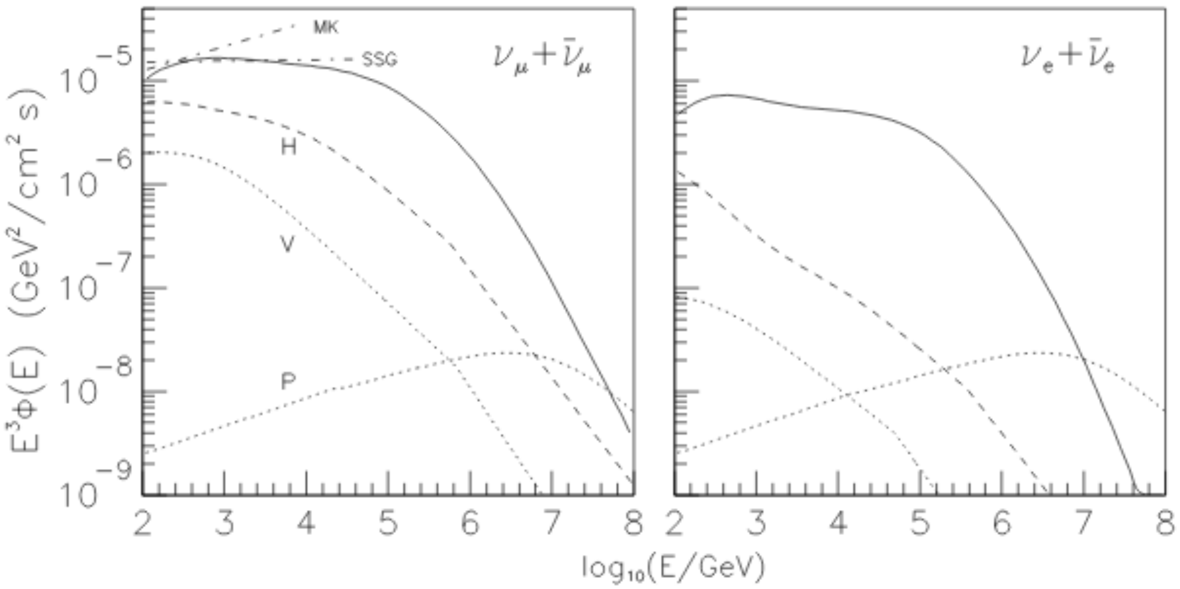
Solar WIMPs

- IceCube Eur.Phys.J. C77 (2017) no.3, 146
- S. In and K. Wiebe [IceCube] ICRC2017 (912)

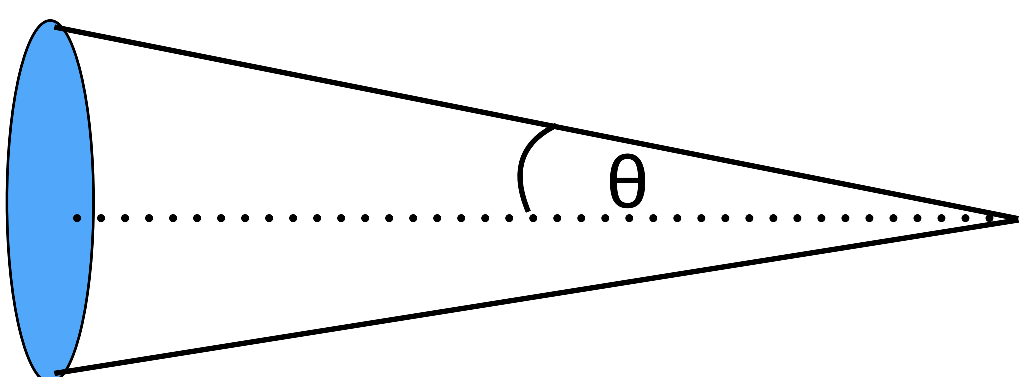
Solar Atmospheric Neutrino Search

Solar Atmospheric Neutrino Analysis

- Ingelman & Thunman flux as reference signal
- Honda atmospheric neutrino flux as background



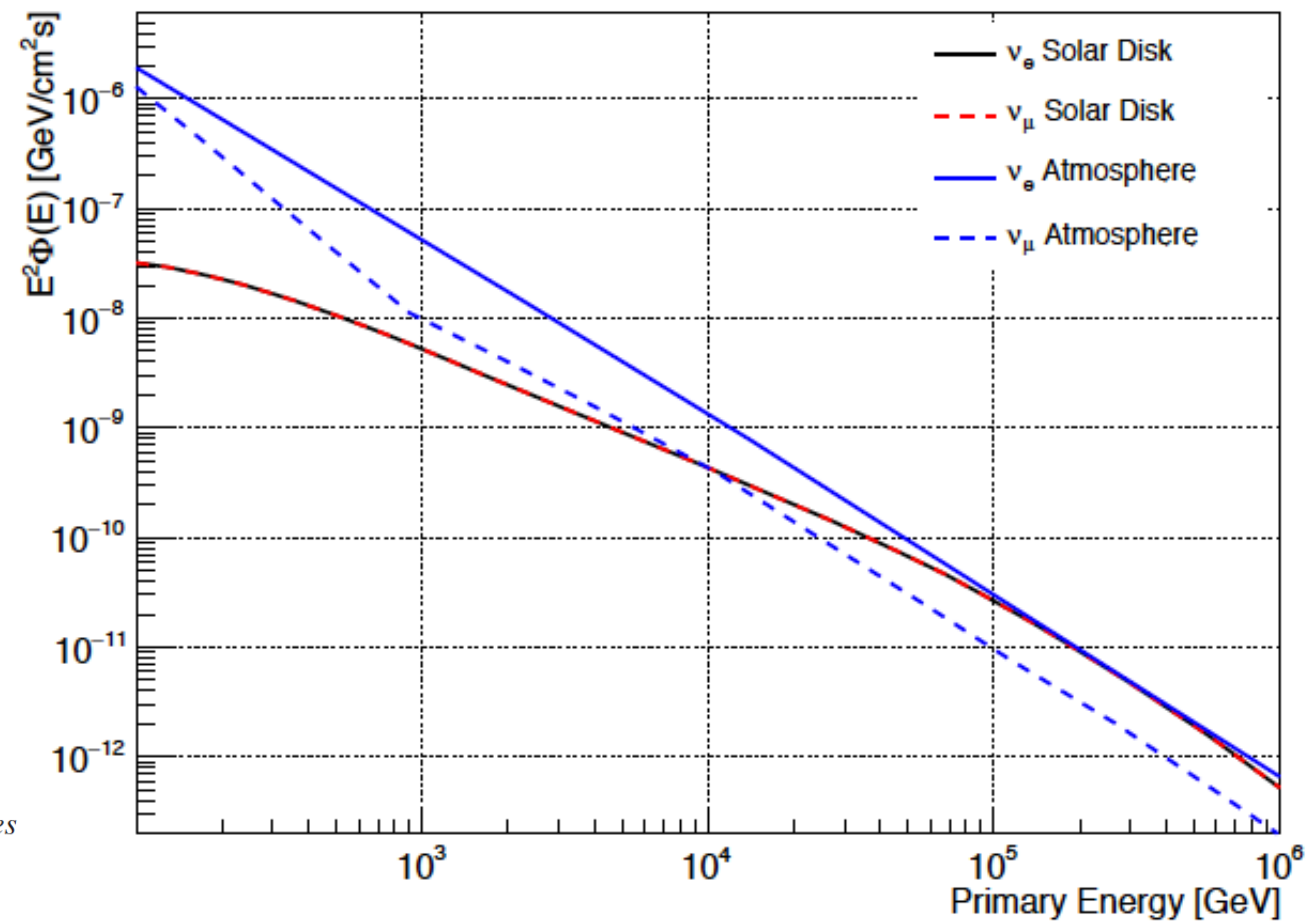
G. Ingelman and M. Thunman, Phys. Rev. D54 (1996) 4385-4392.



$$A(E,\nu_i) = \begin{cases} \sqrt{100+900/E[GeV]}^\circ & \nu_e,\ for\ all\ energies \\ 30^\circ/\sqrt{E/GeV} & \nu_\mu,\ E < 900GeV \\ 1^\circ & \nu_\mu,\ E > 900GeV \end{cases}$$

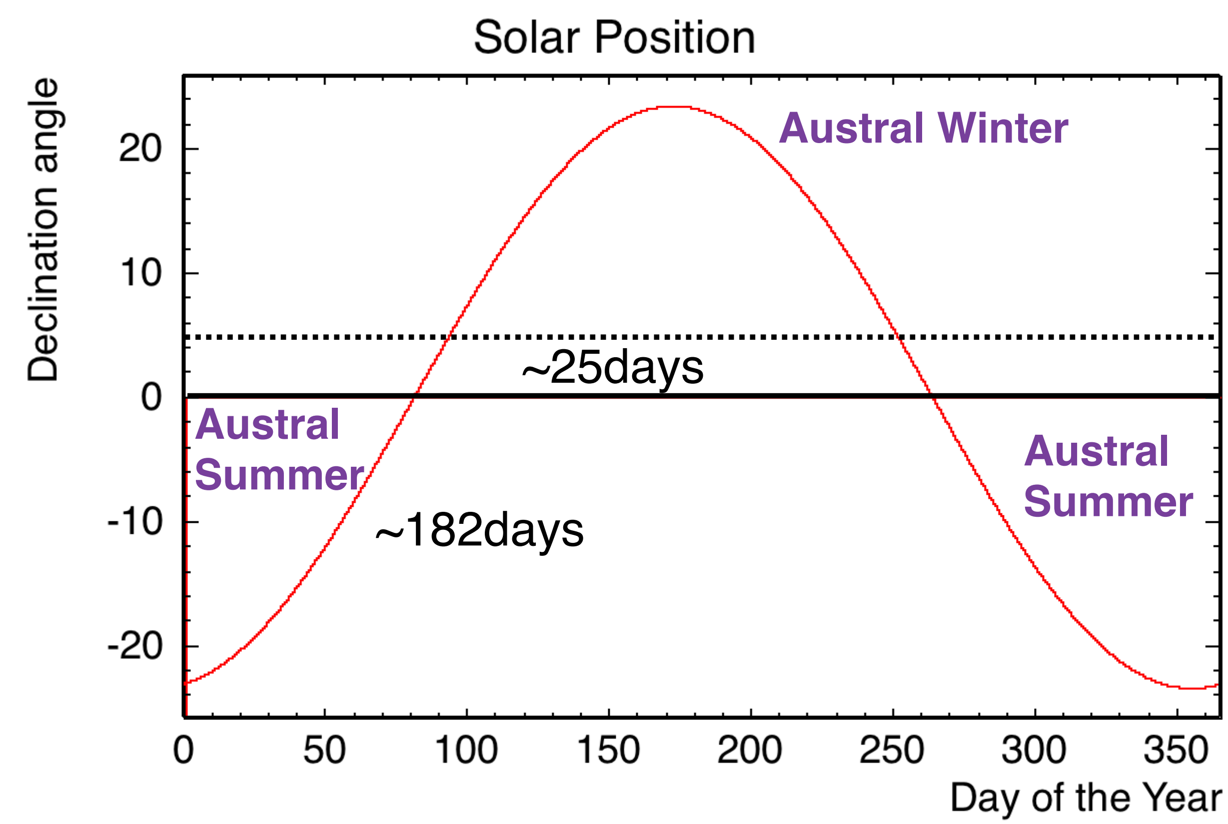
Calculate flux within cone opening angle matching kinematic angle at given neutrino energy

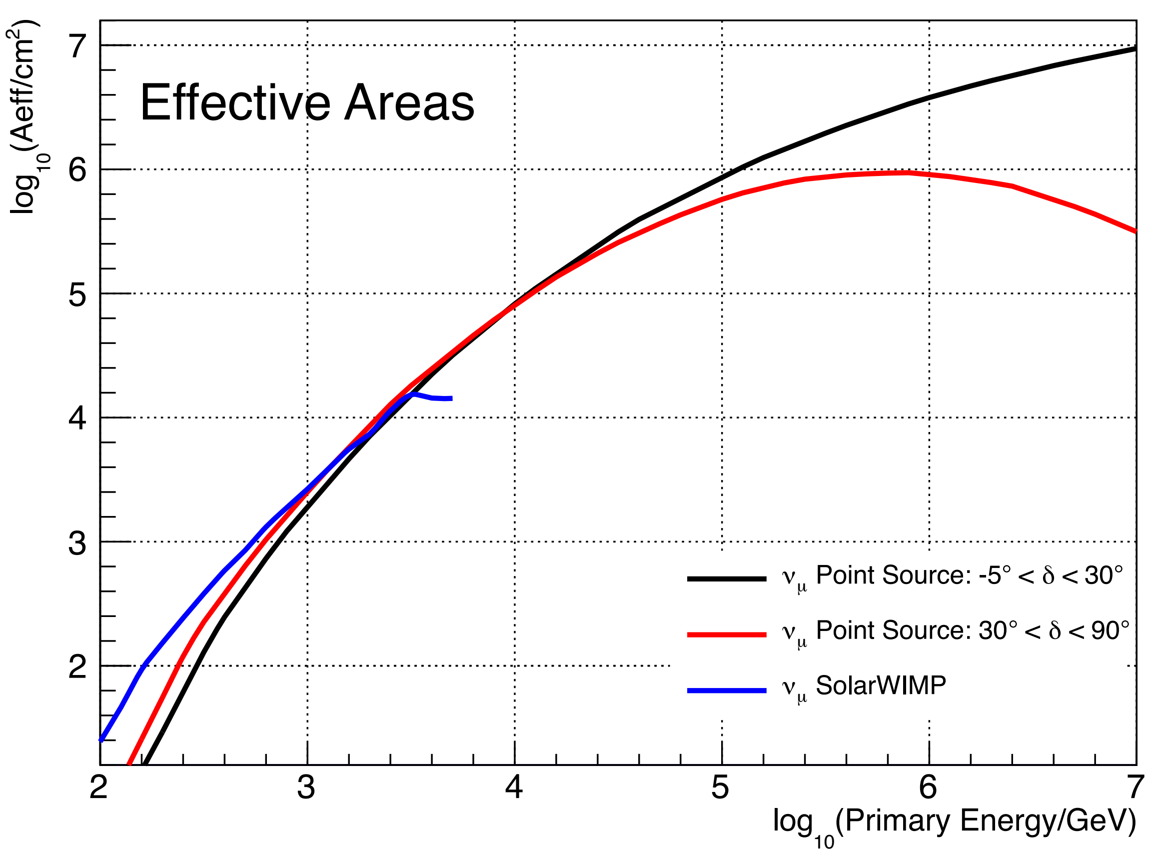
- 68% of solar disk neutrino flux falls within the cone (assume Sun is a point source)
- Background isotrope (angle averaged flux)

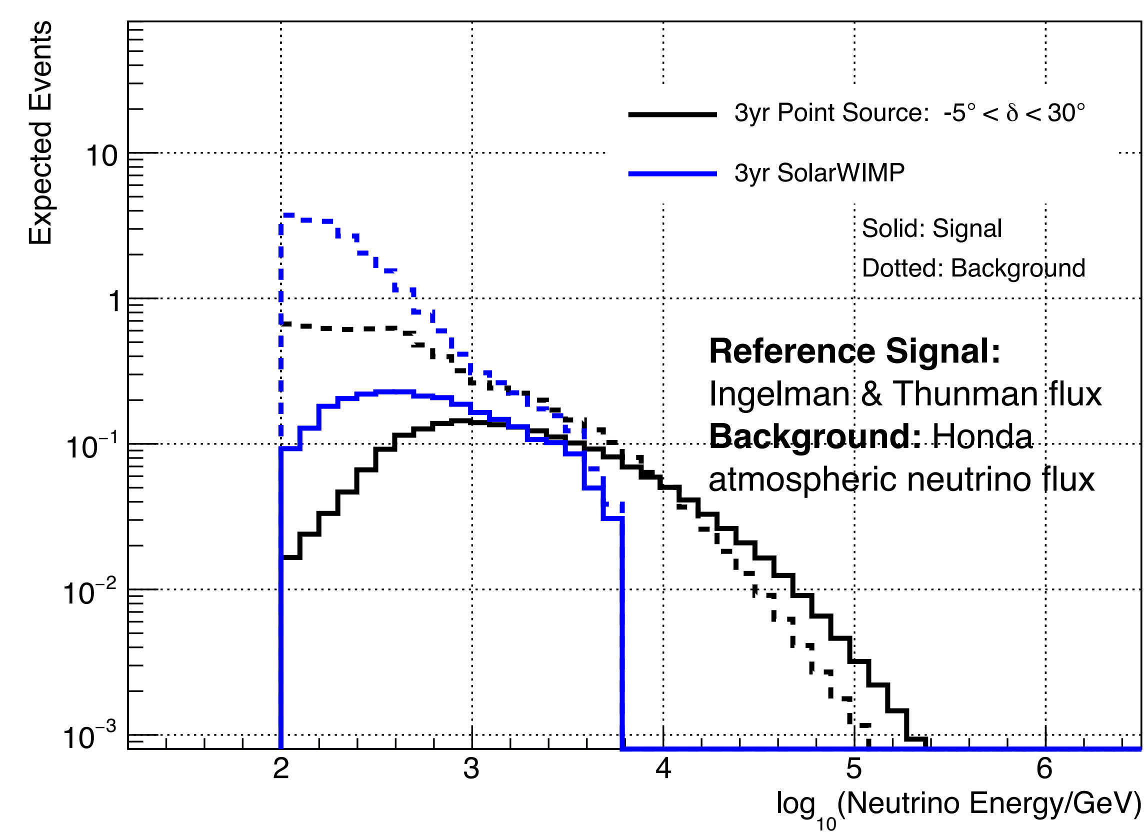


Solar Atmospheric Neutrino Analysis

- Strategy:
  - Muon neutrinos for good pointing
  - Up-going neutrino events (reject large atmospheric muon background) → consider declination angles of δ = 5° to -30°
  - Base analysis on well tested existing data samples
    - Check suitable samples for their sensitivity and optimize cuts where needed



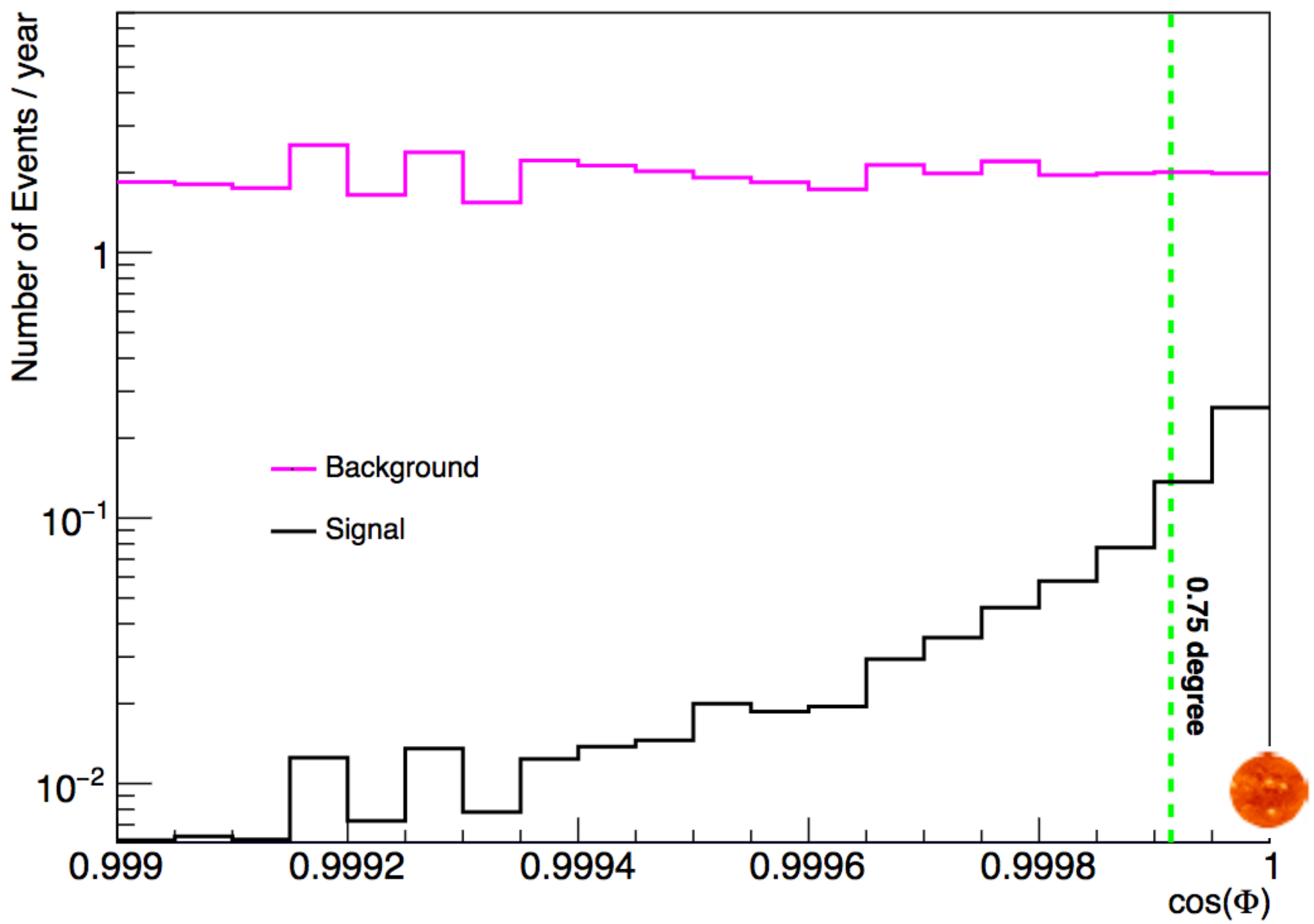




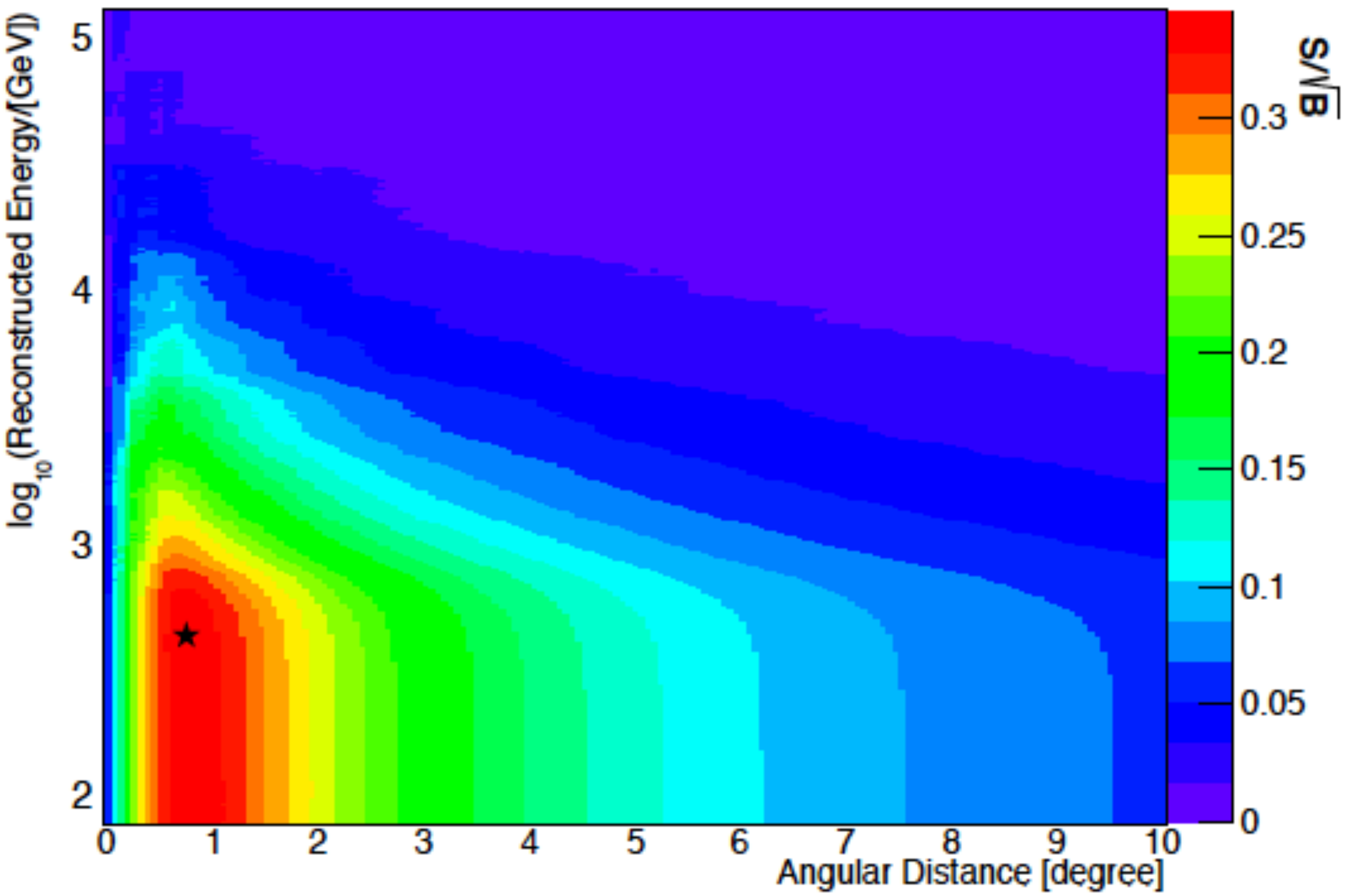
Point Source Sample suites the solar atmospheric neutrino analysis well

Event Expectation Solar Atmospheric Neutrinos

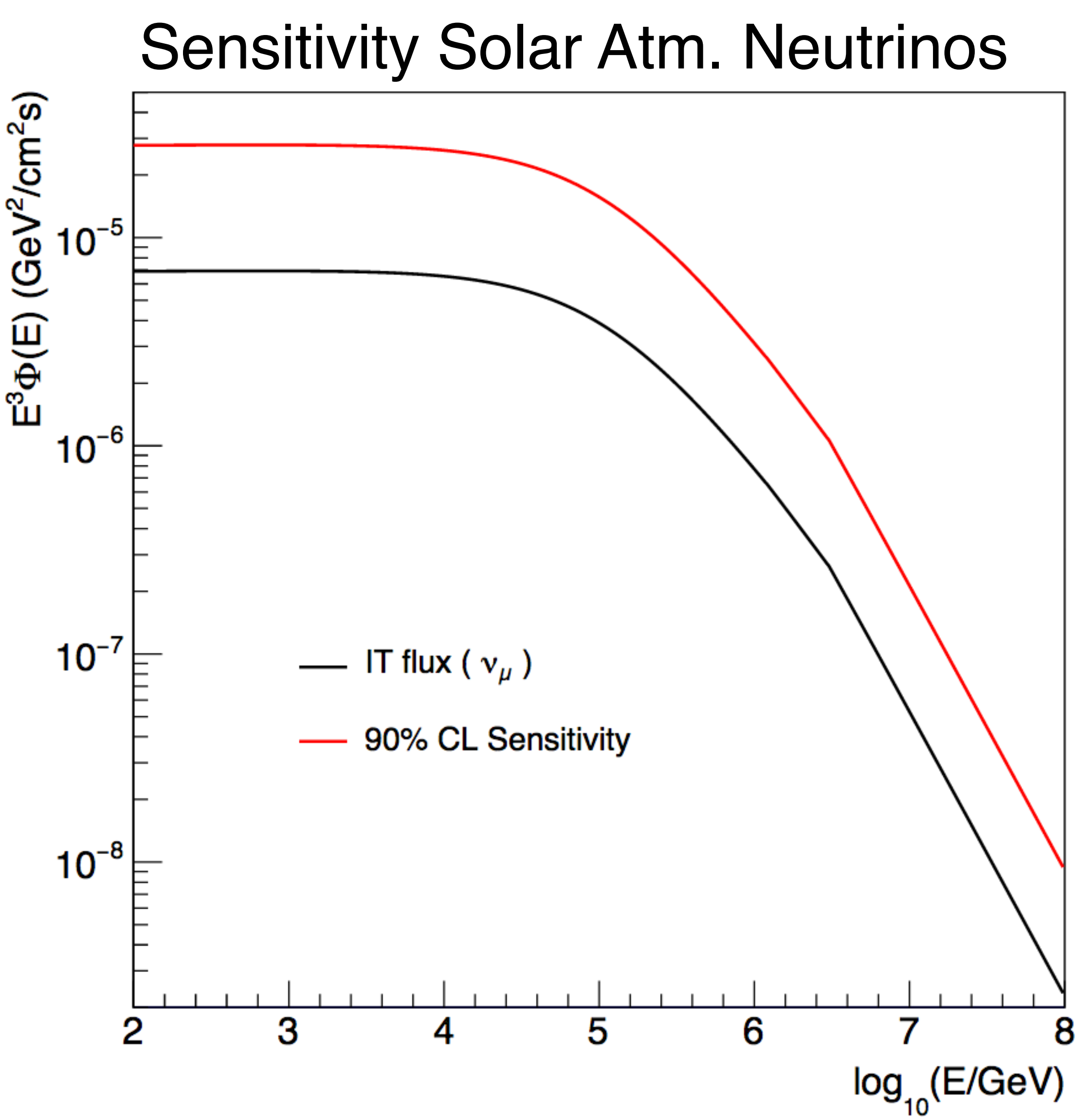
- Using point source analysis sample we determine the expected event rates as function of the distance from the Sun
- Assume emission of solar atmospheric neutrinos homogeneously over the surface of the Sun
- Optimize signal to sqrt(background) ratio based on energy and angle selection cut



Event Expectation Solar Atmospheric Neutrinos



- Preliminary optimization yields the following selection cuts:
  - E > 430GeV
  - ψ < 0.75°
- Next likelihood method …

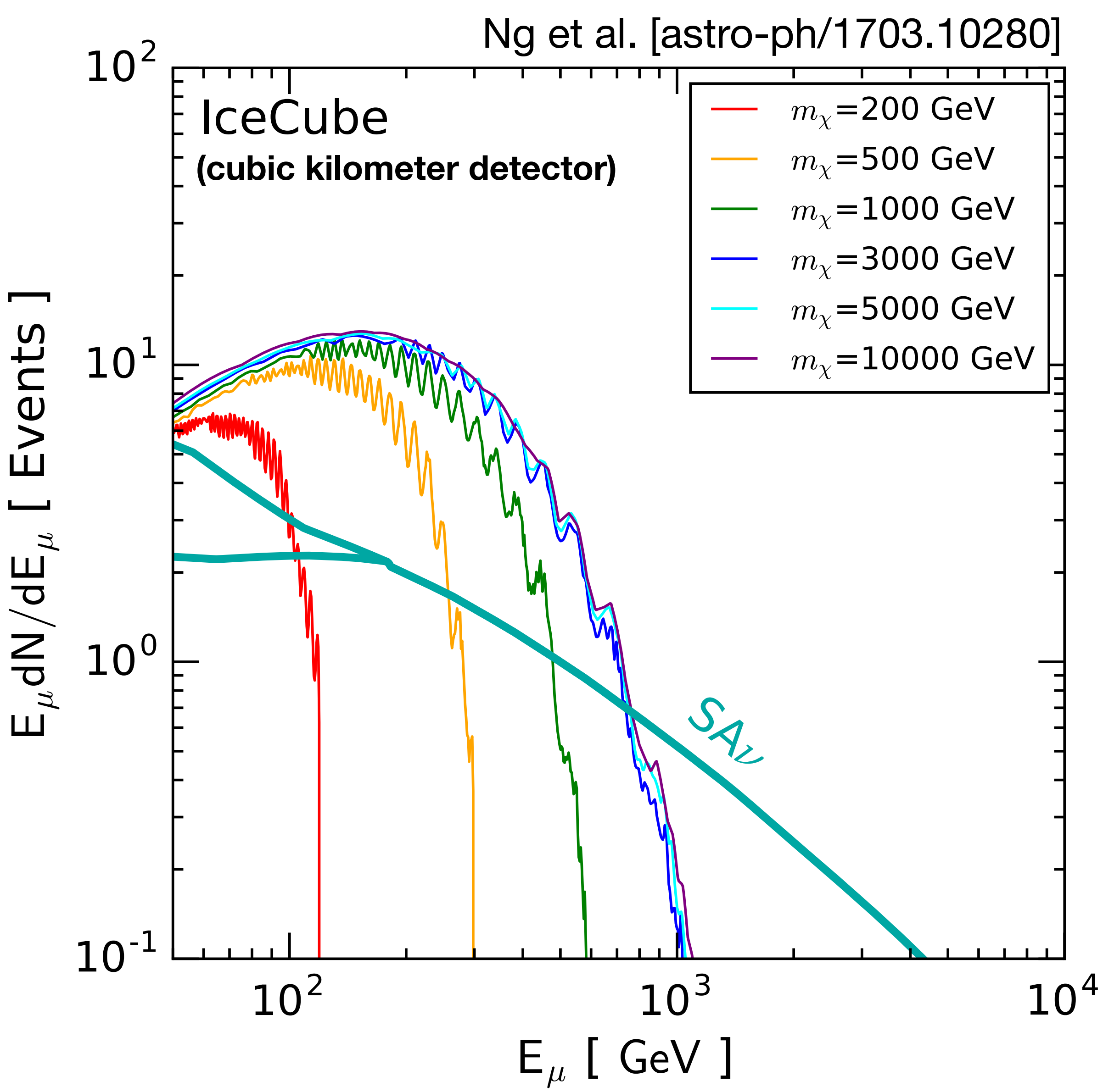


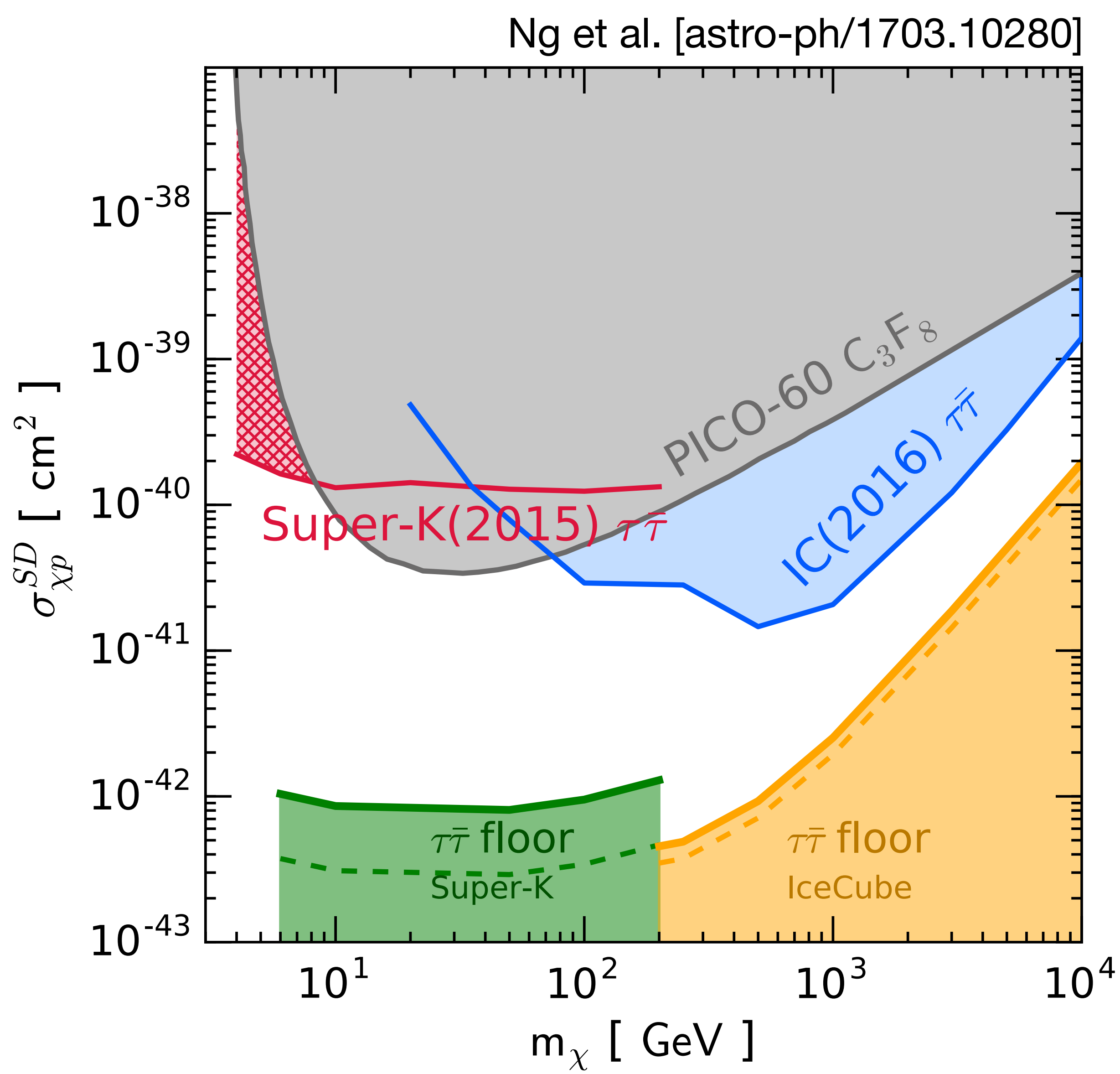
- Sensitivity computed assuming 3 yrs of data computed after optimization
  - Event expectations:
    - Background: 10.5 ± 0.2 events
    - Signal (assuming IT1996) 1.1 ± 0.2 events

Solar Atmospheric Neutrino Floor

see talks by Kenny Ng / Carlos Argüelles

Cosmic background from the Sun





- Natural background to Solar Dark Matter Searches !
- However, energy spectrum expected to be different
- DM annihilation neutrinos significantly attenuated above a few 100GeV

Expect ~2events per year at cubic kilometer detector

Recent works on the Solar Atmospheric Neutrino Floor

- Argüelles et al. [astro-ph/1703.07798]
- Ng et al. [astro-ph/1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, JCAP 2017 .06 (2017), p. 033, [astro-ph/1704.02892]
- M. Masip (2017), [hep-ph/1706.01290]

Conclusions

Conclusions

- The Sun is an exciting target for neutrino telescopes
  - IceCube set the worlds best bound on spin-dependent dark matter nucleon scattering for masses above 100GeV
  - Cosmic ray shadow provides clues about propagation in the inner solar system
  - Solar atmospheric neutrinos might be observable in the near future
    - First sensitivity evaluated further optimization on going
- Observing solar atmospheric neutrinos is important for:
  - Understanding solar magnetic fields
  - Cosmic ray propagation in the inner solar system
  - Improving models of CR interactions in the solar atmosphere
  - Identifying a first high-energy neutrino point source