Search for energetic neutrinos from the Sun - Dark Matter or Solar Atmospheric Neutrinos ?

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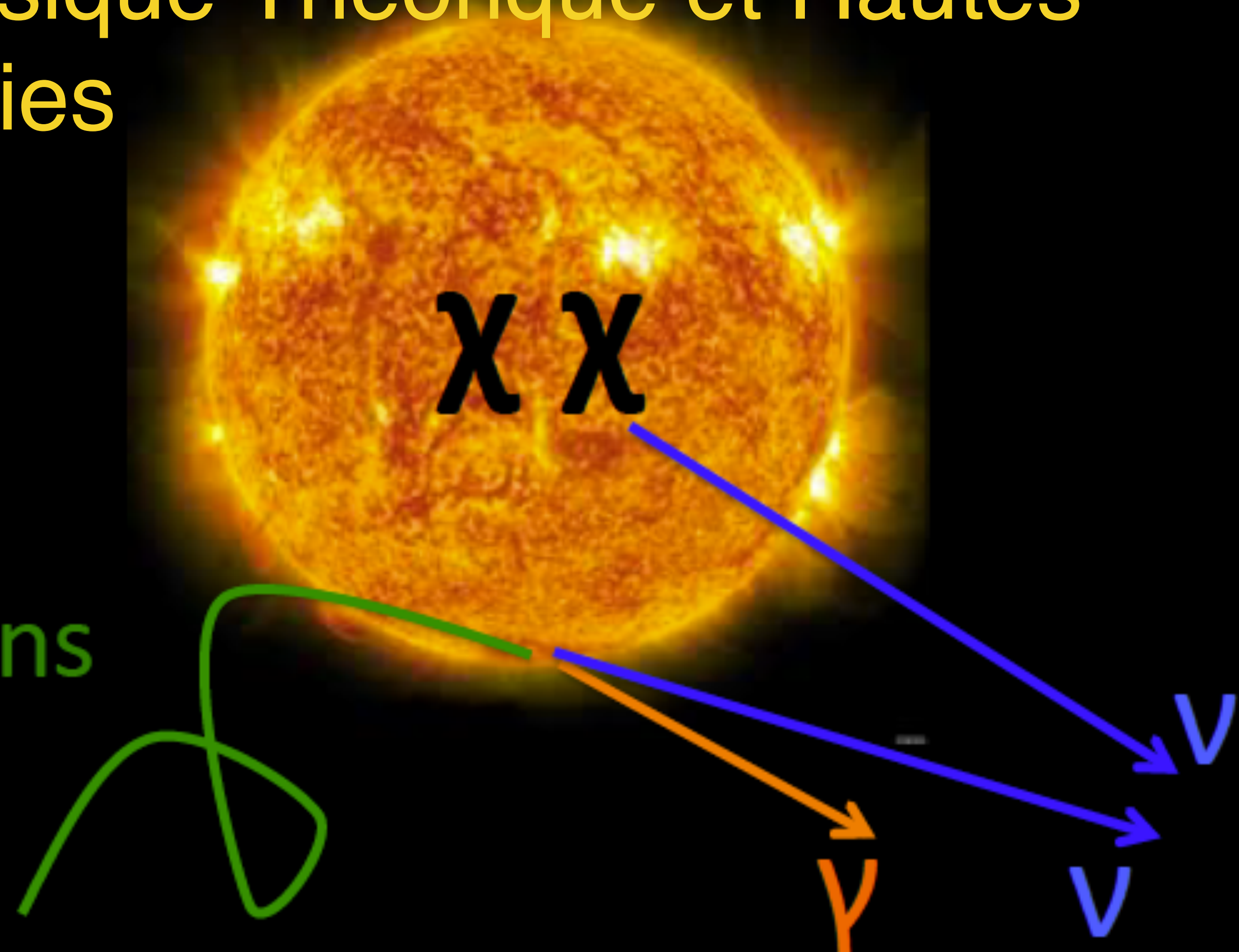
December 22nd 2017

Seminar - Laboratoire de Physique Théorique et Hautes Energies



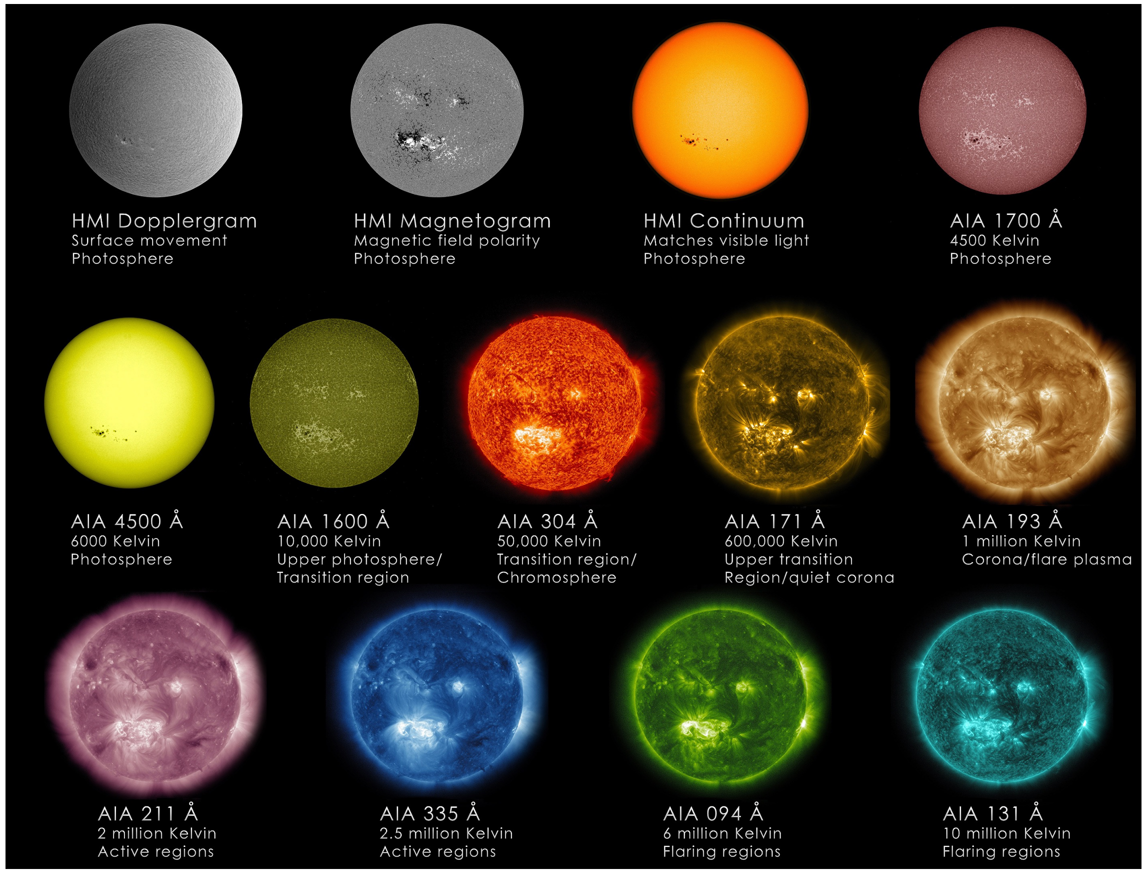
LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

Outline

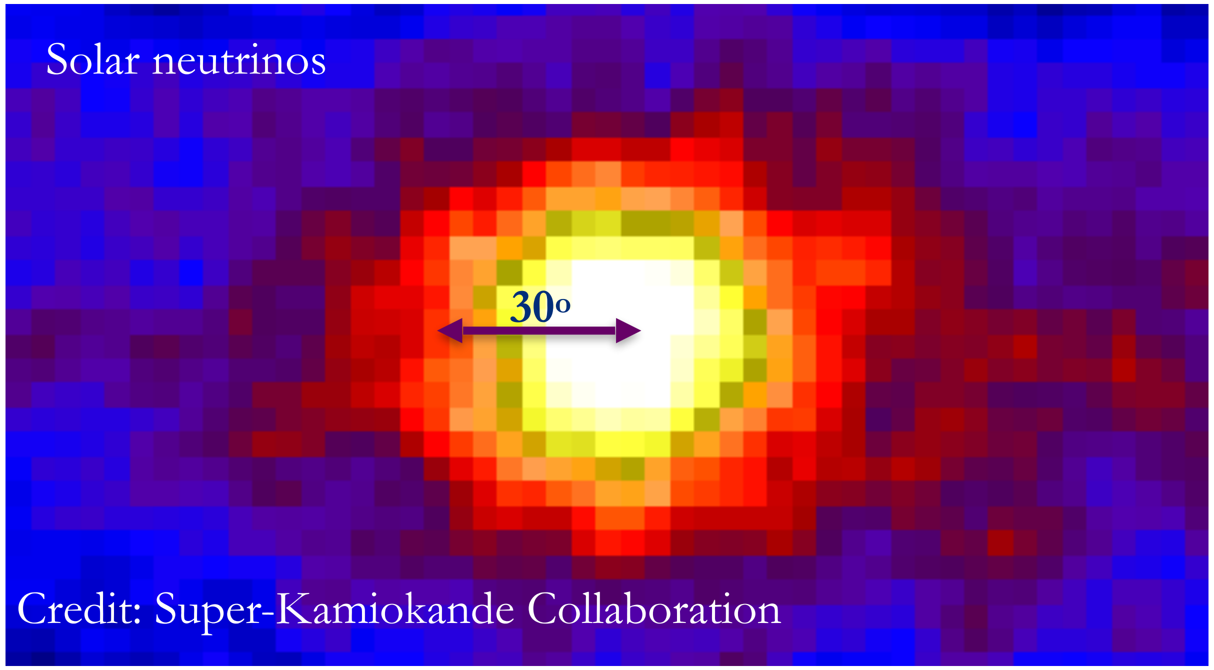
- Motivation
- Energetic Radiation from the Sun
  - Gamma-rays from the Sun
- Observing the Sun with IceCube
  - IceCube Neutrino Telescope
  - Sun Shadow
  - Solar Dark Matter
  - Solar Atmospheric Neutrinos and the Dark Matter Neutrino Floor
- Outlook and Conclusions

Motivation

Motivation



Credit: NASA/SDO/Goddard Space Flight Center

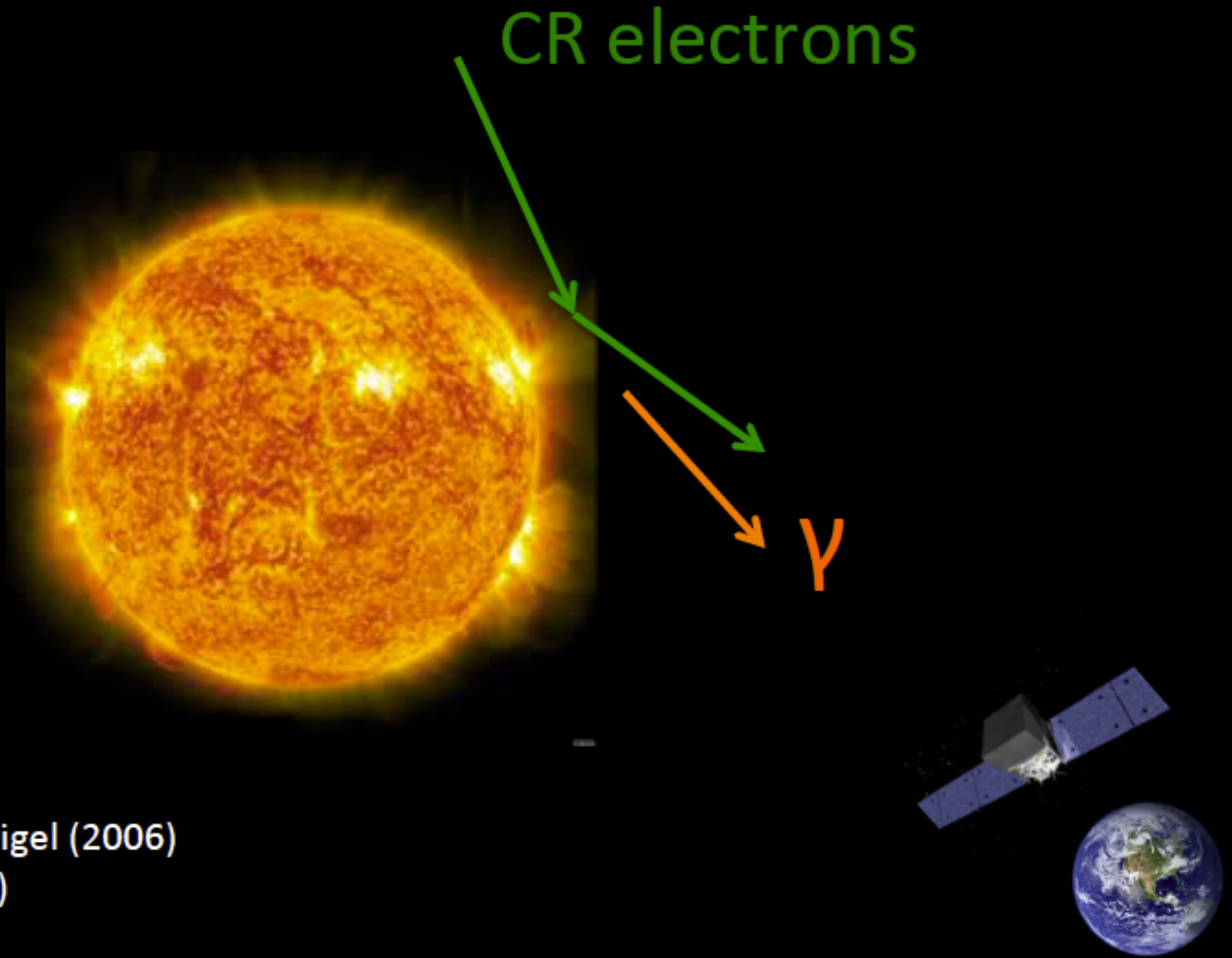


- GeV Radiation from the Sun
  - Inverse Compton (IC)
    - Cosmic ray electrons and positrons on solar photons
  - Solar Disk (Disk)
    - Cosmic rays with solar atmosphere
  - Exotics
    - Dark matter, …

Energetic Radiation from the Sun

Sun – Cosmic-Ray Beam Dump

- Leptonic

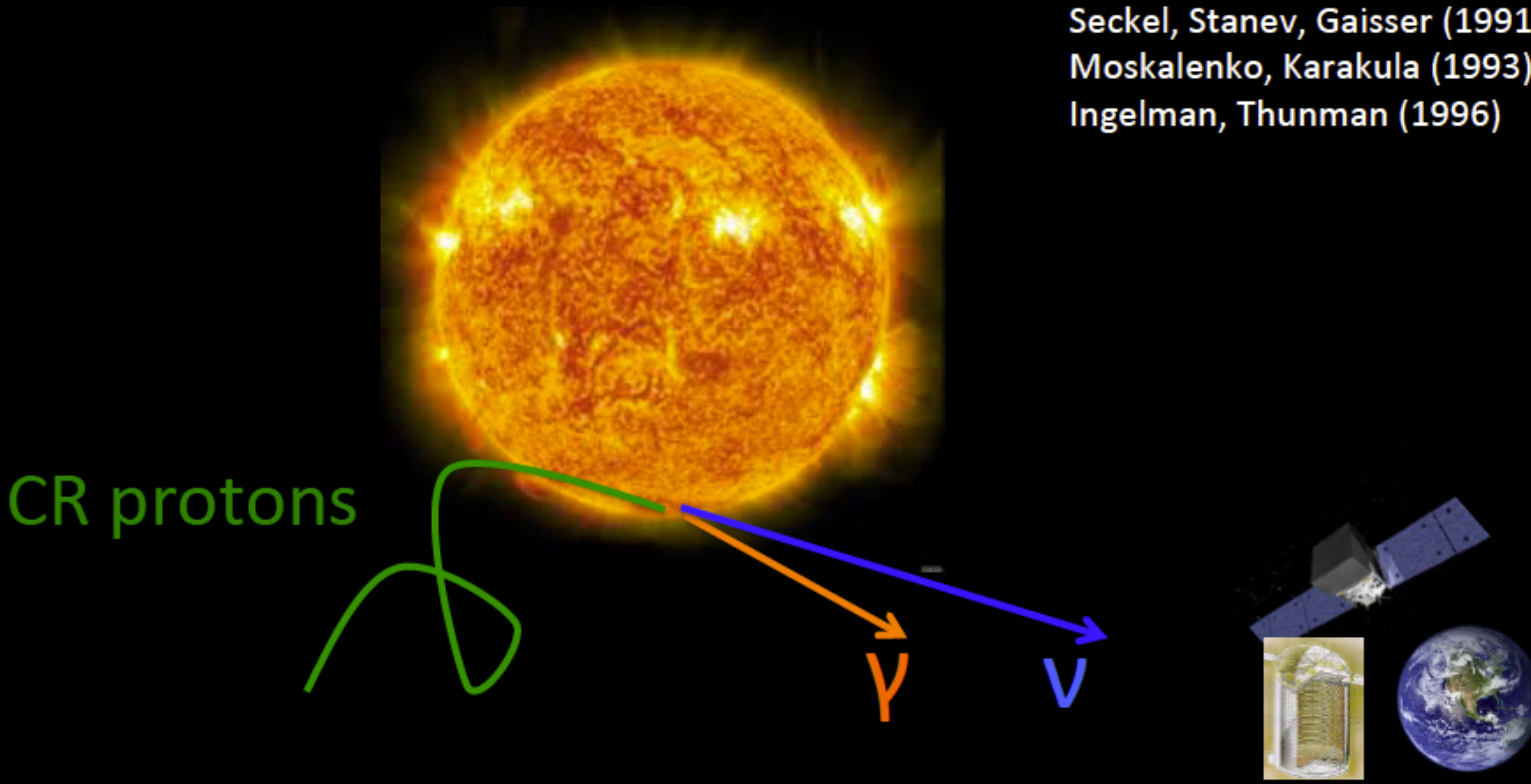


Moskalenko, Porter, Digel (2006)
Orlando, Strong (2007)

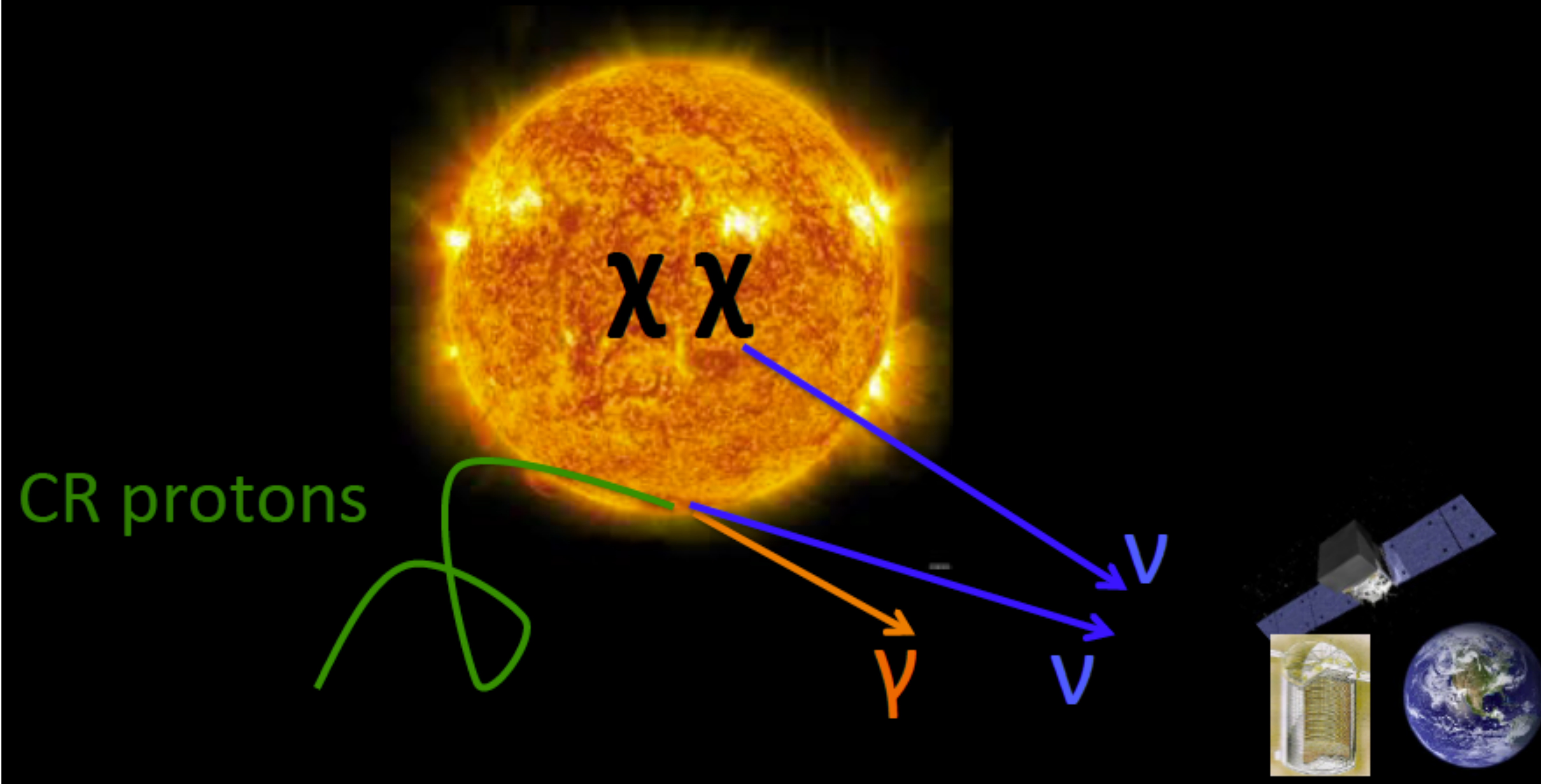
Sun – Cosmic-Ray Beam Dump

- Hadronic

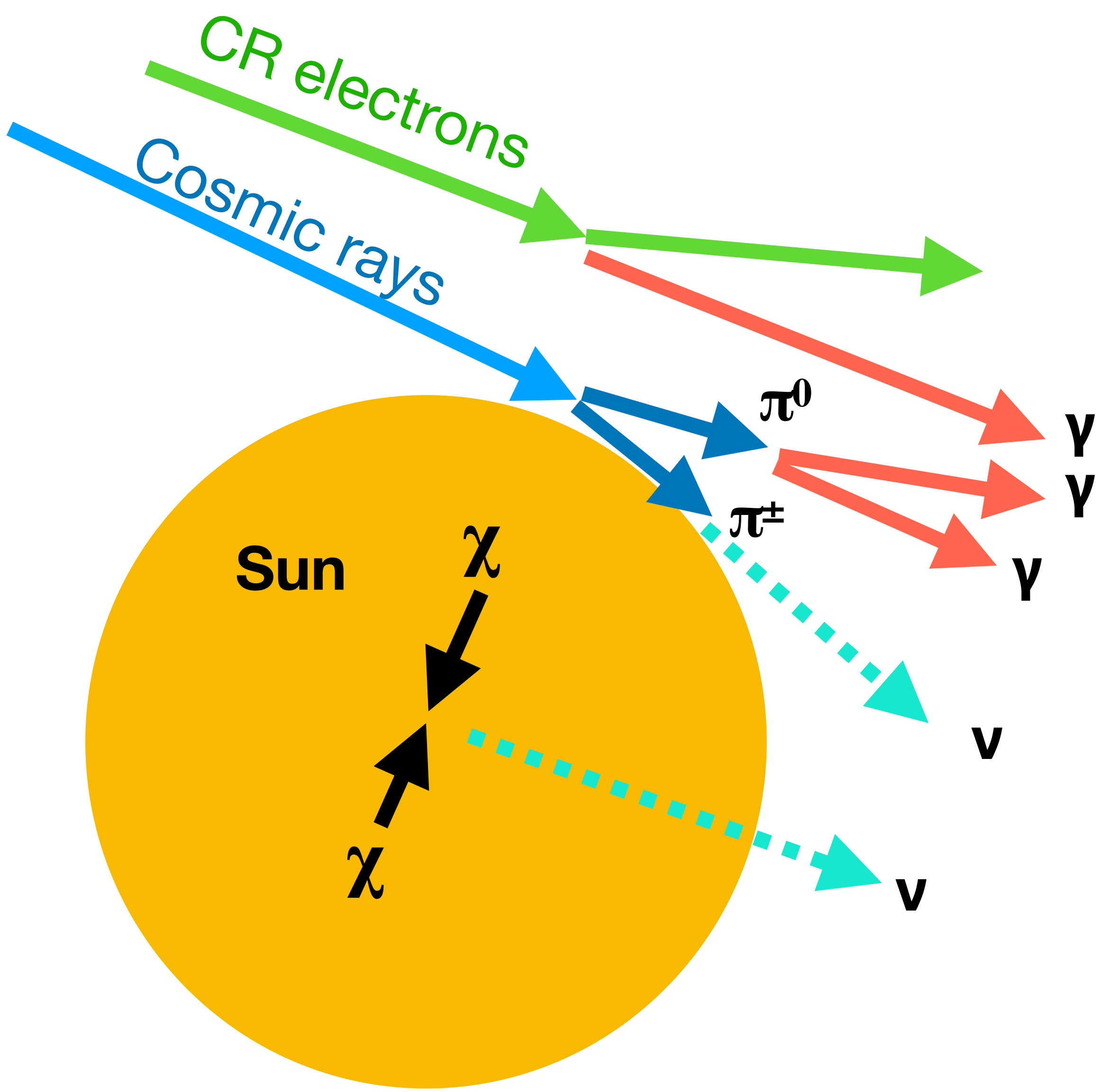
Seckel, Stanev, Gaisser (1991)
Moskalenko, Karakula (1993)
Ingelman, Thunman (1996)

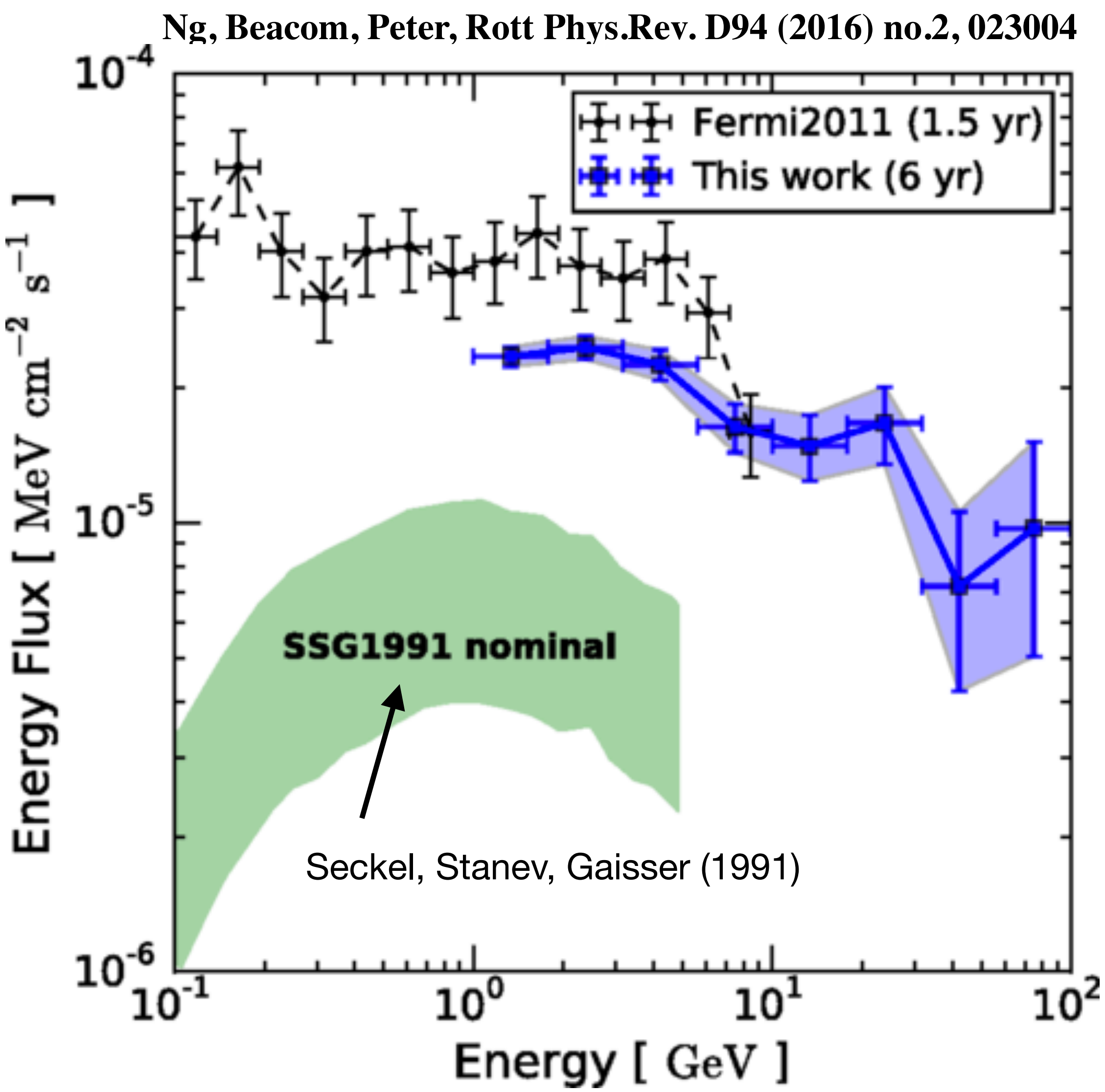


Cosmic Rays vs Dark Matter



Cosmic ray interactions with the Sun





- Cosmic-ray interactions with the solar atmosphere produce gamma-rays and neutrinos
  - Neutrino background to dark matter search from the Sun
  - First high-energy neutrino point source ?

Leptonic

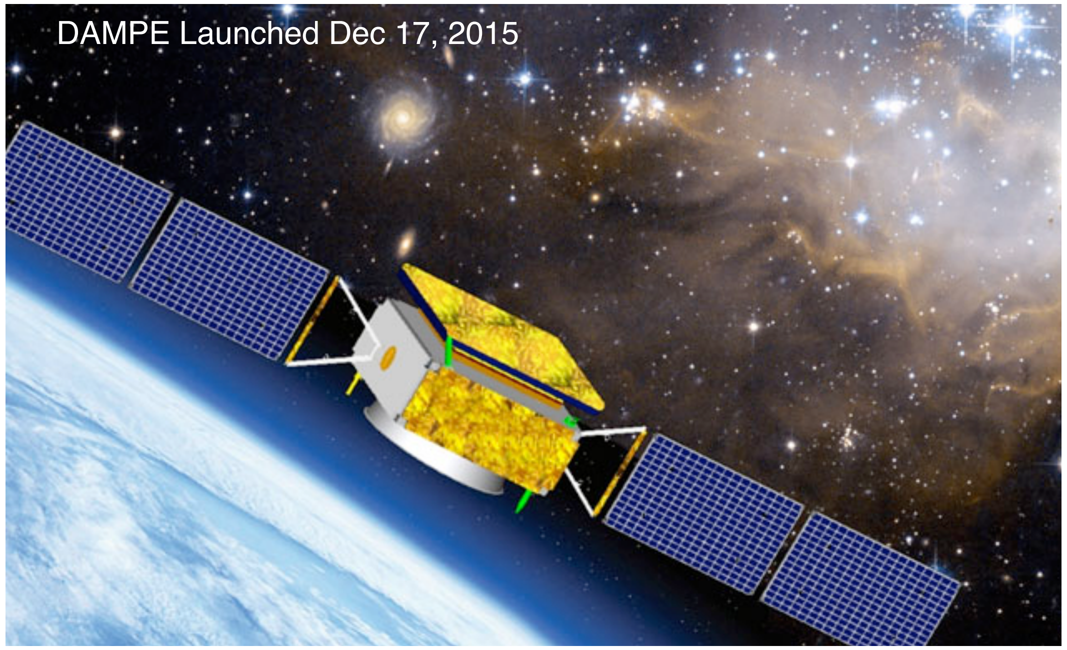
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadronic

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

Gamma-ray Observations of the Sun (GeV Range)

- The Sun is the best understood and measured star, yet poorly studied at energies beyond a GeV
  - Past
    - EGRET
  - Present
    - Fermi-LAT
    - (DAMPE)
  - Future
    - GAMMA-400
    - HERD
    - ….



EGRET

- *Energetic Gamma Ray Experiment Telescope* (EGRET) --- one of four instruments on the NASA's Compton Gamma Ray Observatory satellite
  - 30 MeV to 30 GeV sensitivity
  - Consisted of spark chamber (pair production), calorimeter (NaI(Ti)), plastic scintillator anti-coincidence dome

1. **Type:** spark chambers, NaI(Tl) crystals, and plastic scintillators.
2. **Energy Range:** 20 MeV to about 30 GeV.
3. **Energy Resolution:** approximately twenty percent over the central part of the energy range.
4. **Total Detector Area:** approximately 6400 cm^2
5. **Effective Area:** approximately 1500 cm^2 between 200 MeV and 1000 MeV, falling at higher and lower energies.
6. **Point Source Sensitivity:** varies with the spectrum and location of the source and the observing time. Under optimum conditions, well off the galactic plane, it should be approximately 6×10^{-8} $cm^{-2}s^{-1}$ for E > 100 MeV for a full two week exposure.
7. **Source Position Location:** Varies with the nature of the source intensity, location, and energy spectrum from 5 - 30 arcmin.
8. **Field of View:** approximately a gaussian shape with a half width at half maximum of about 20. Note that the full field of view will not generally be used.
9. **Timing Accuracy:** 0.1 ms absolute
10. **Weight:** about 1830 kg (4035 lbs)
11. **Size:** 2.25 m x 1.65 m diameter
12. **Power:** 190 W (including heater power)

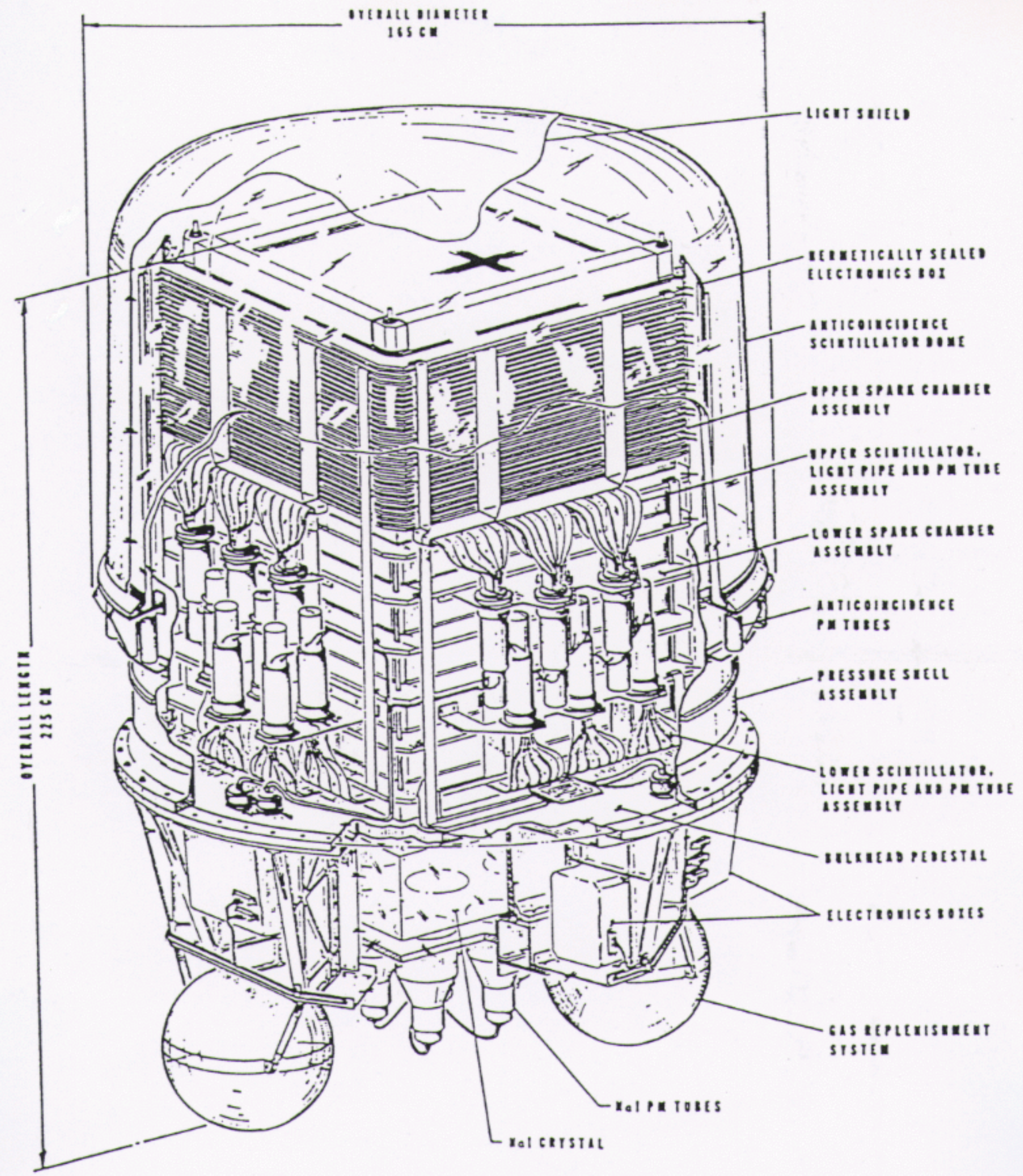
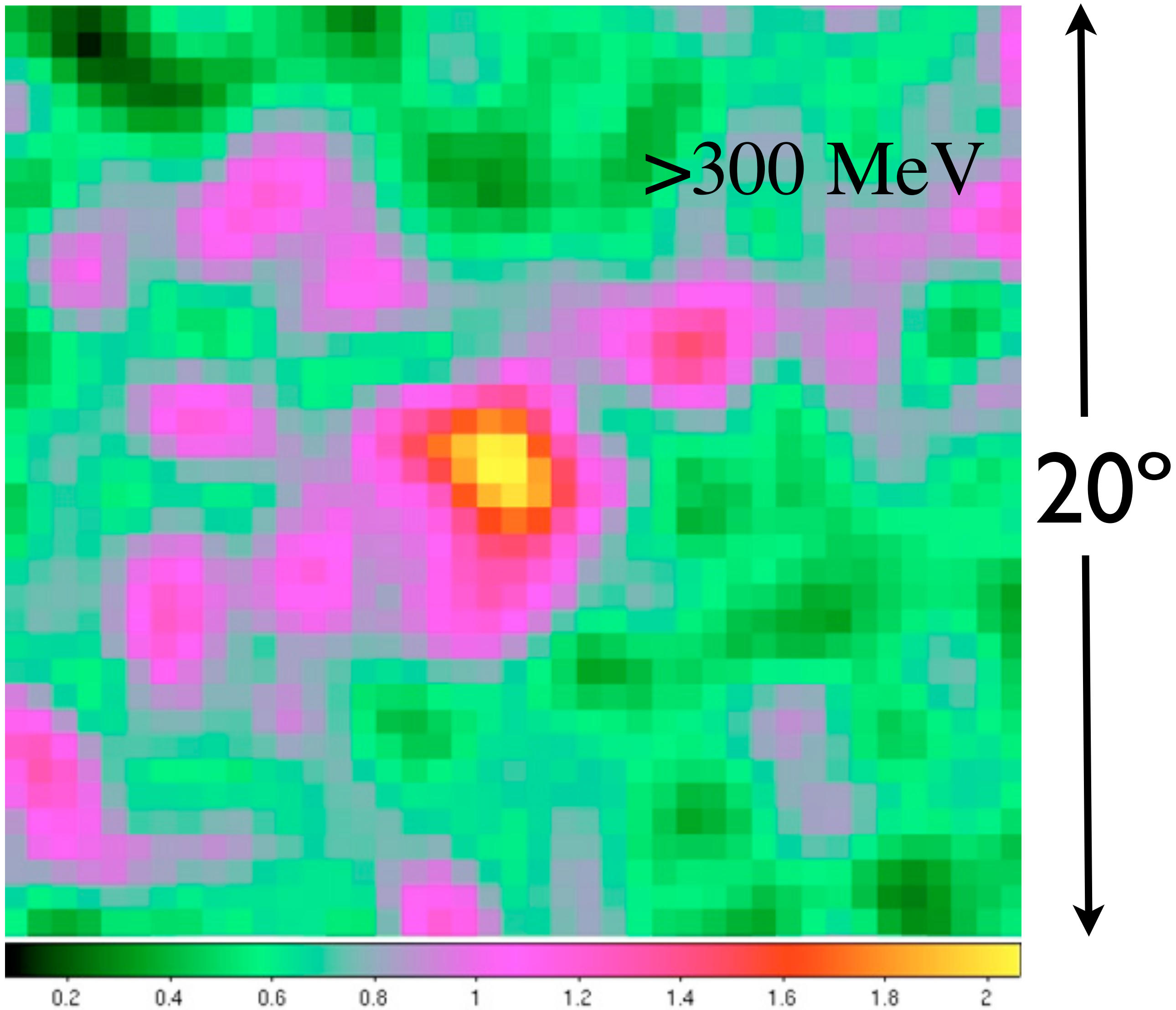


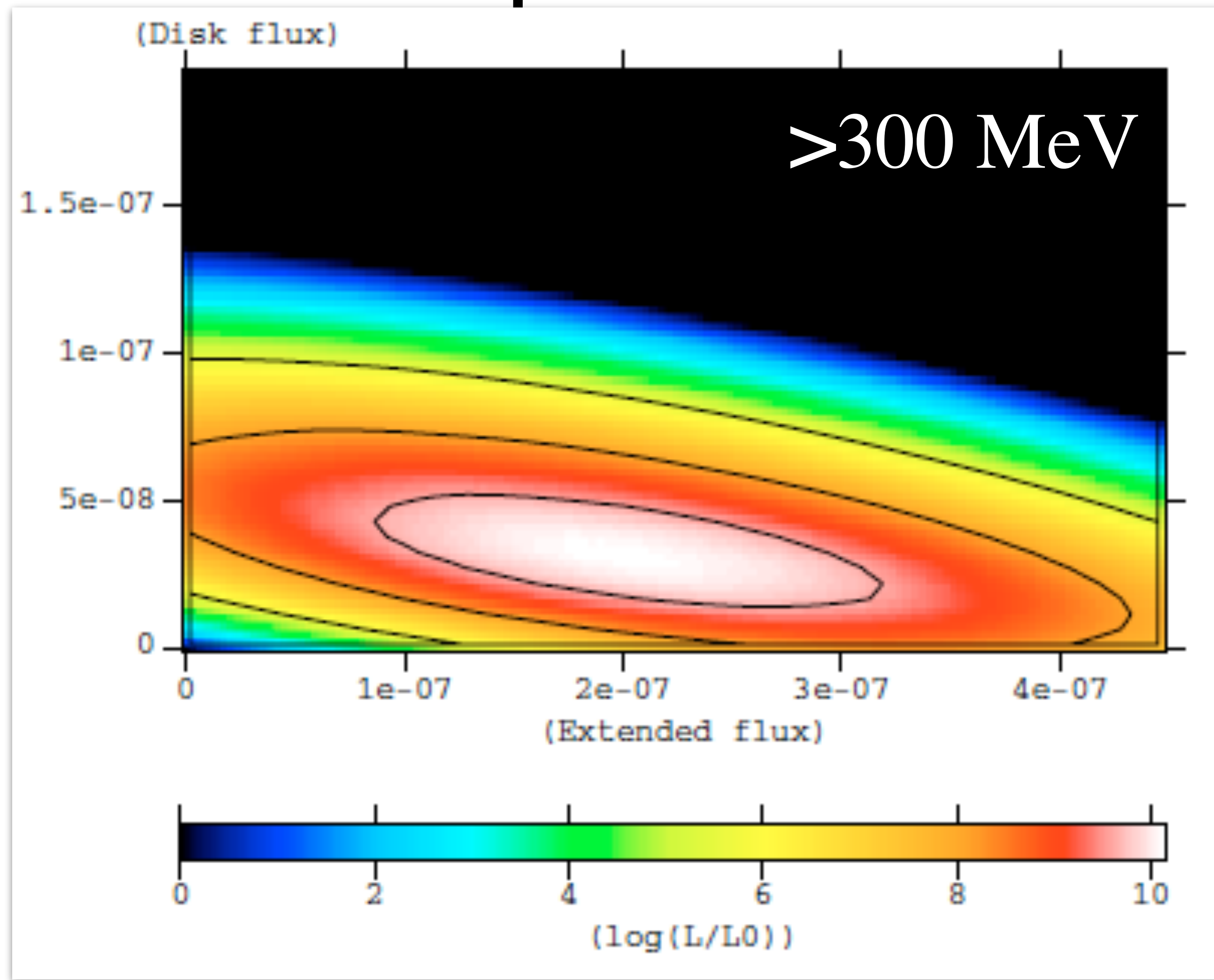
Figure IV-1. The EGRET Instrument

EGRET Solar Analysis

Orlando & Strong 2008

EGRET Sun-centred counts maps





- ***Evidence for the gamma-ray emission from the sun***

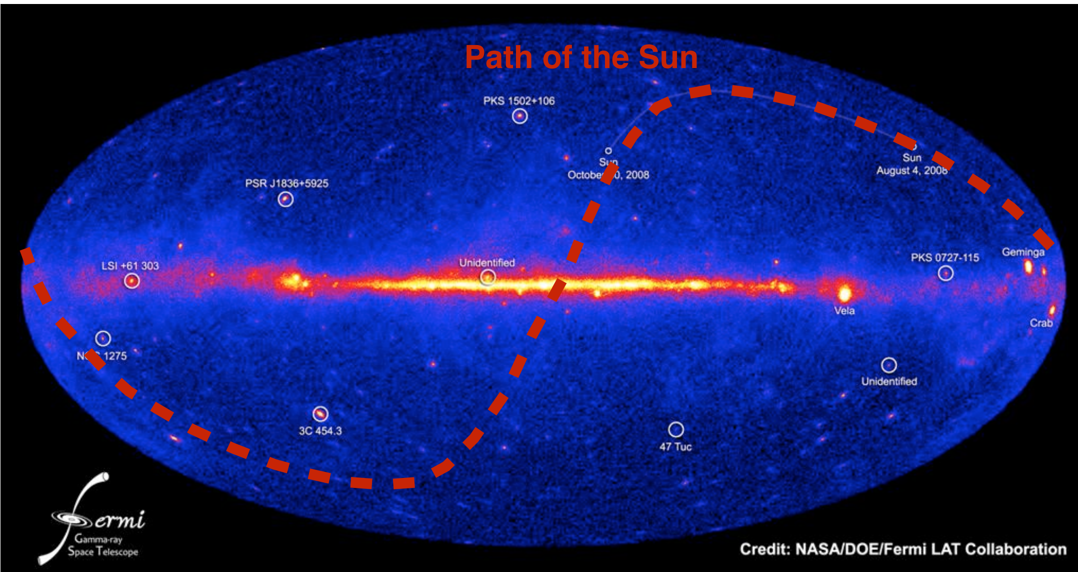
Table 5. Fluxes used to produce the plotted solar spectra. Fluxes are in 10^{-7} cm^{-2} s^{-1}.

Source	100–300 MeV	>300 MeV
Extended	2.1 ± 1.3	1.7 ± 0.9
Model extended	1.3	0.9
Disk	1.4 ± 0.9	0.4 ± 0.2
Seckel's disk model	0–1.1	0.1–0.5

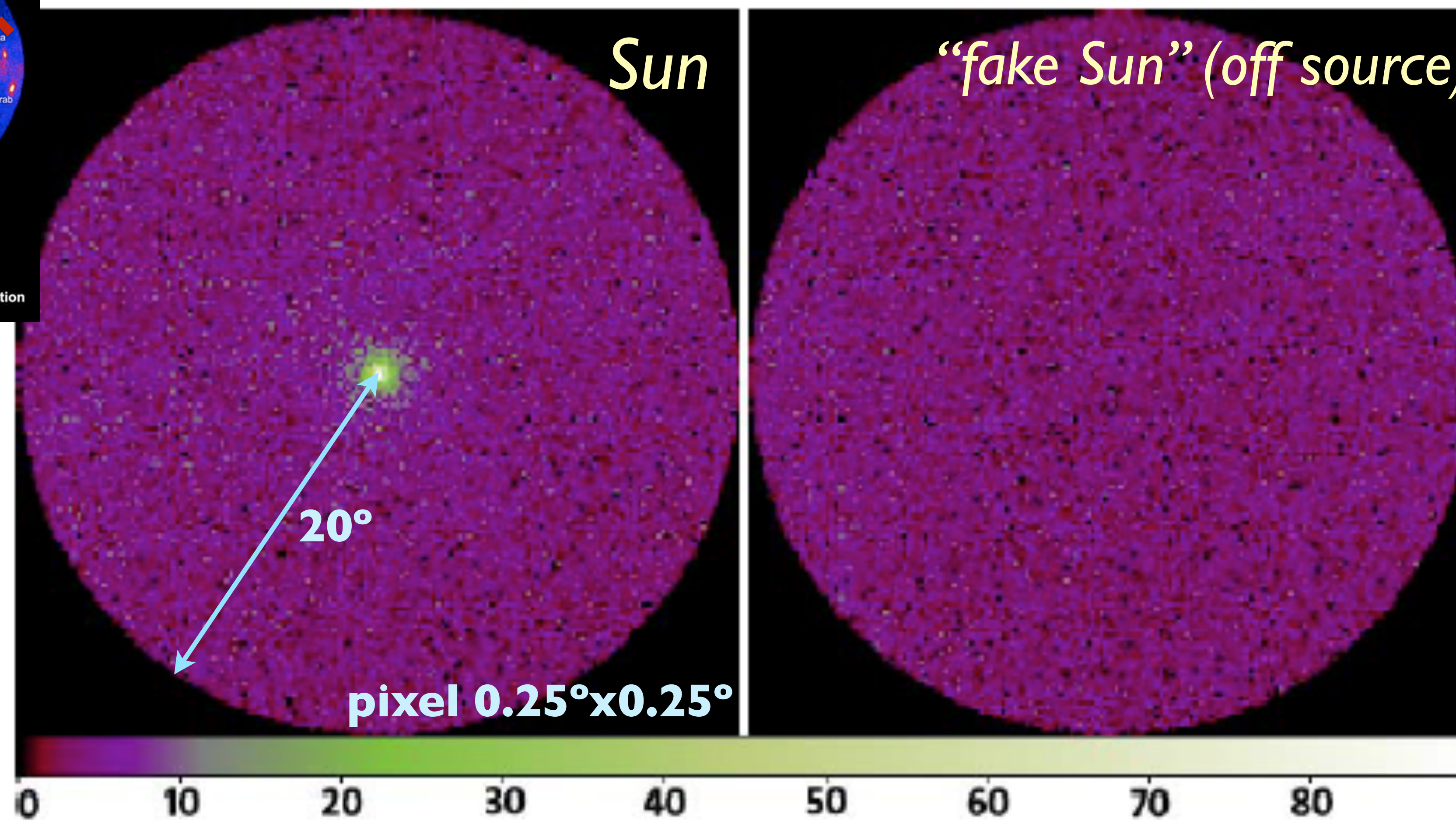
Fermi-LAT Sun observations

(1) Fermi-LAT Collaboration: The Astrophysical Journal 734 (2011) 116 (http://arxiv.org/pdf/1104.2093.pdf)
(2) Kenny Ng, John Beacom, Annika Peter, Carsten Rott "First Observation of Time Variation in the Solar-Disk Gamma-Ray Flux with Fermi" Phys.Rev. D94 (2016) no.2, 023004

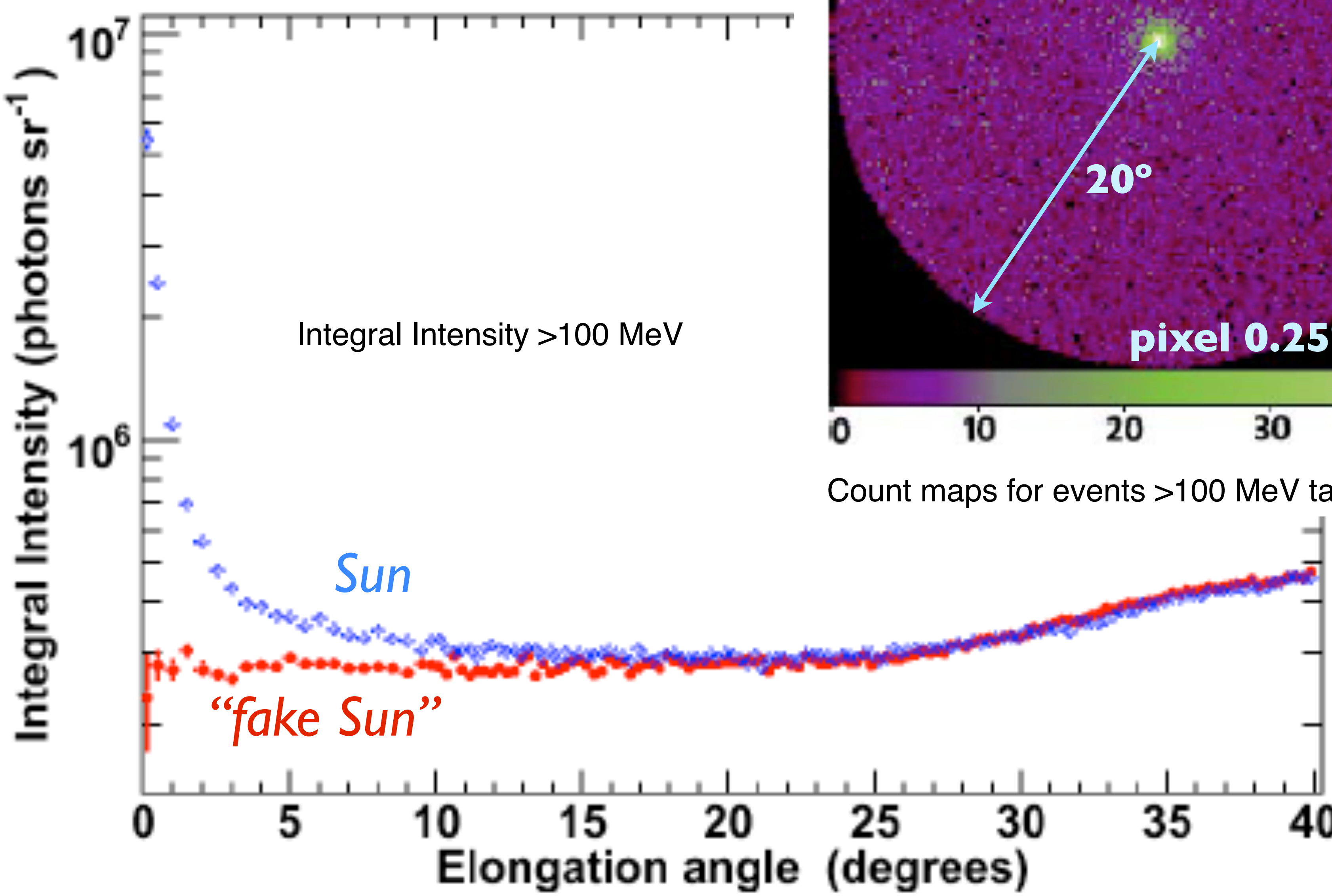
Fermi-LAT Analysis



Galactic coordinates → Sun centered coordinates



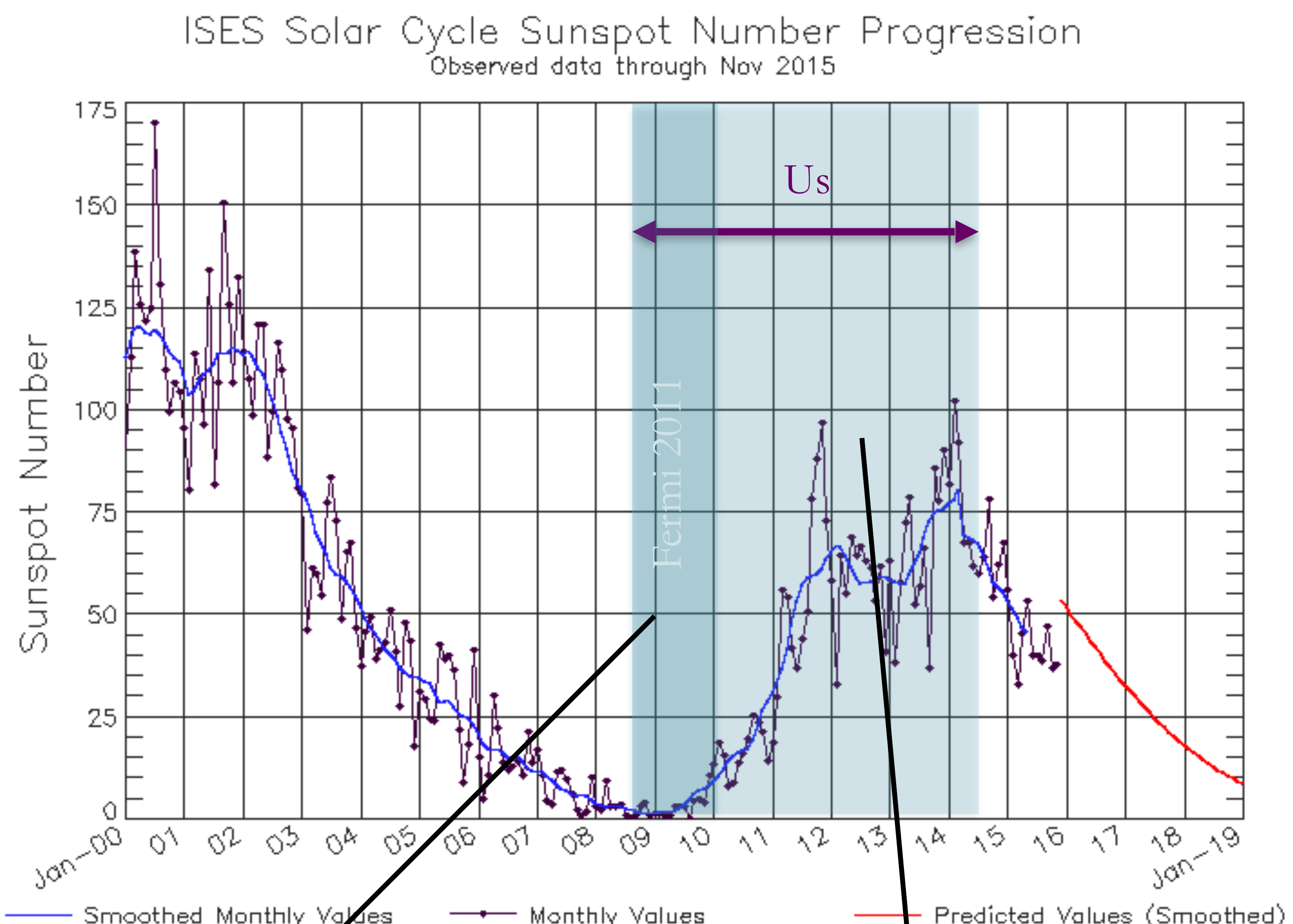
Count maps for events >100 MeV taken between August 2008 and February 2010



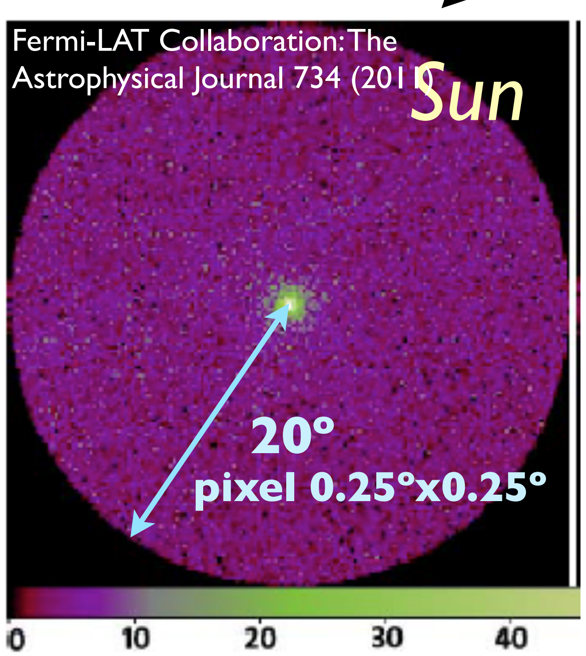
- 1.5 yrs of data during solar minimum
  - Aug 2008 - Feb 2010
- Standard Fermi analysis selection criteria

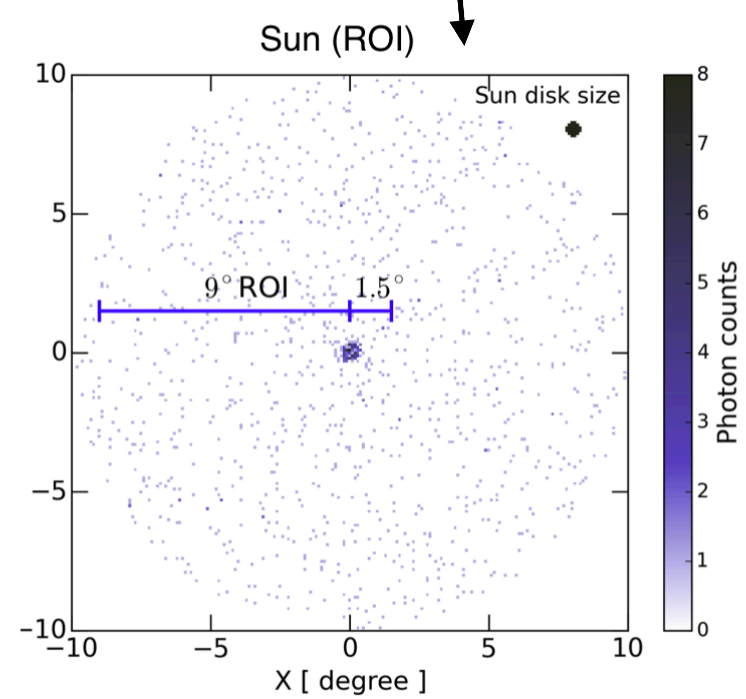
6 years of Fermi data

- More data (and better understood)
- Time variability
  - Flares: Flux should increase with solar activity
  - Cosmic Rays: Flux should decrease with solar activity

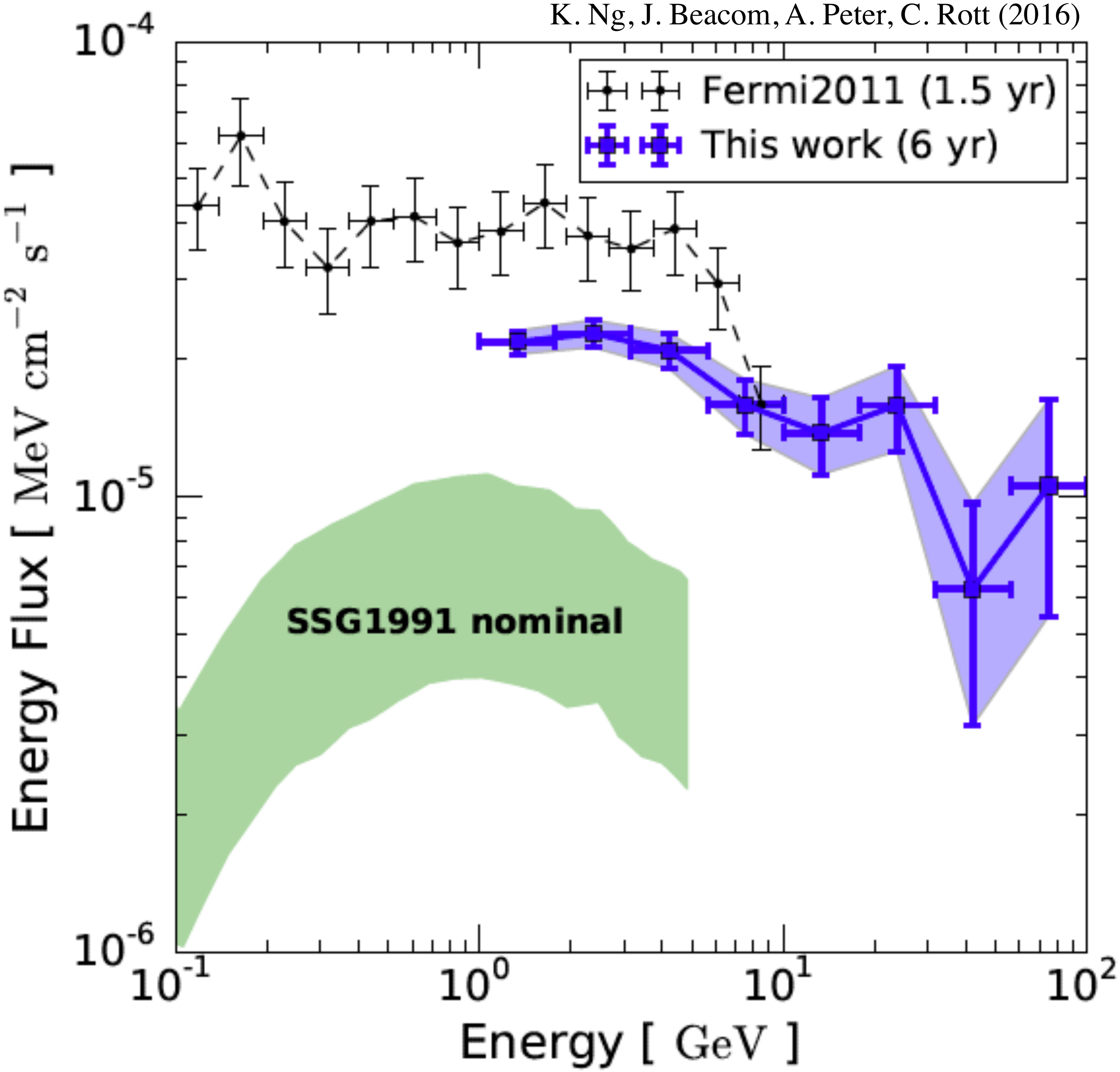


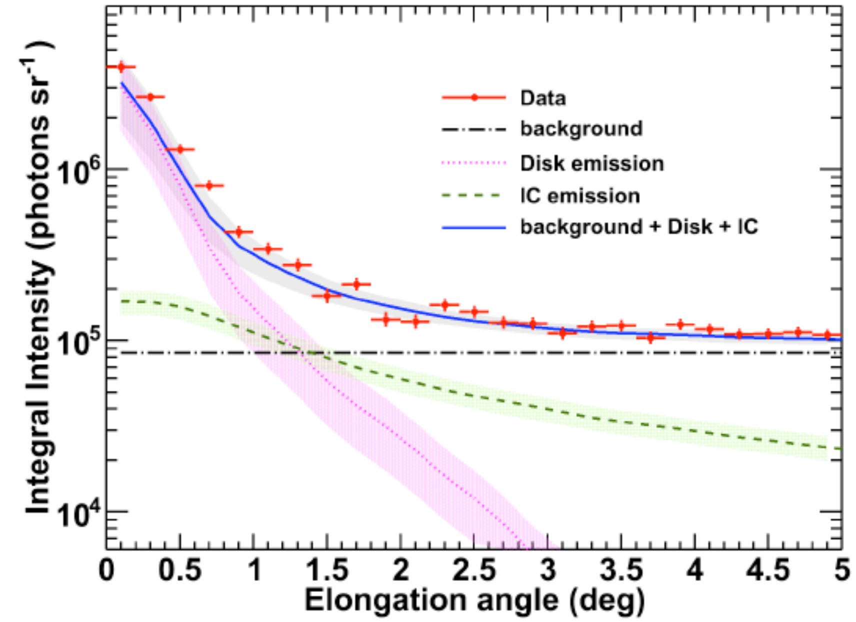
Fermi-LAT Collaboration (2011)
- 18month
Ng, Beacom, Peter, Rott (2017)
- 6 years





Gamma-ray flux

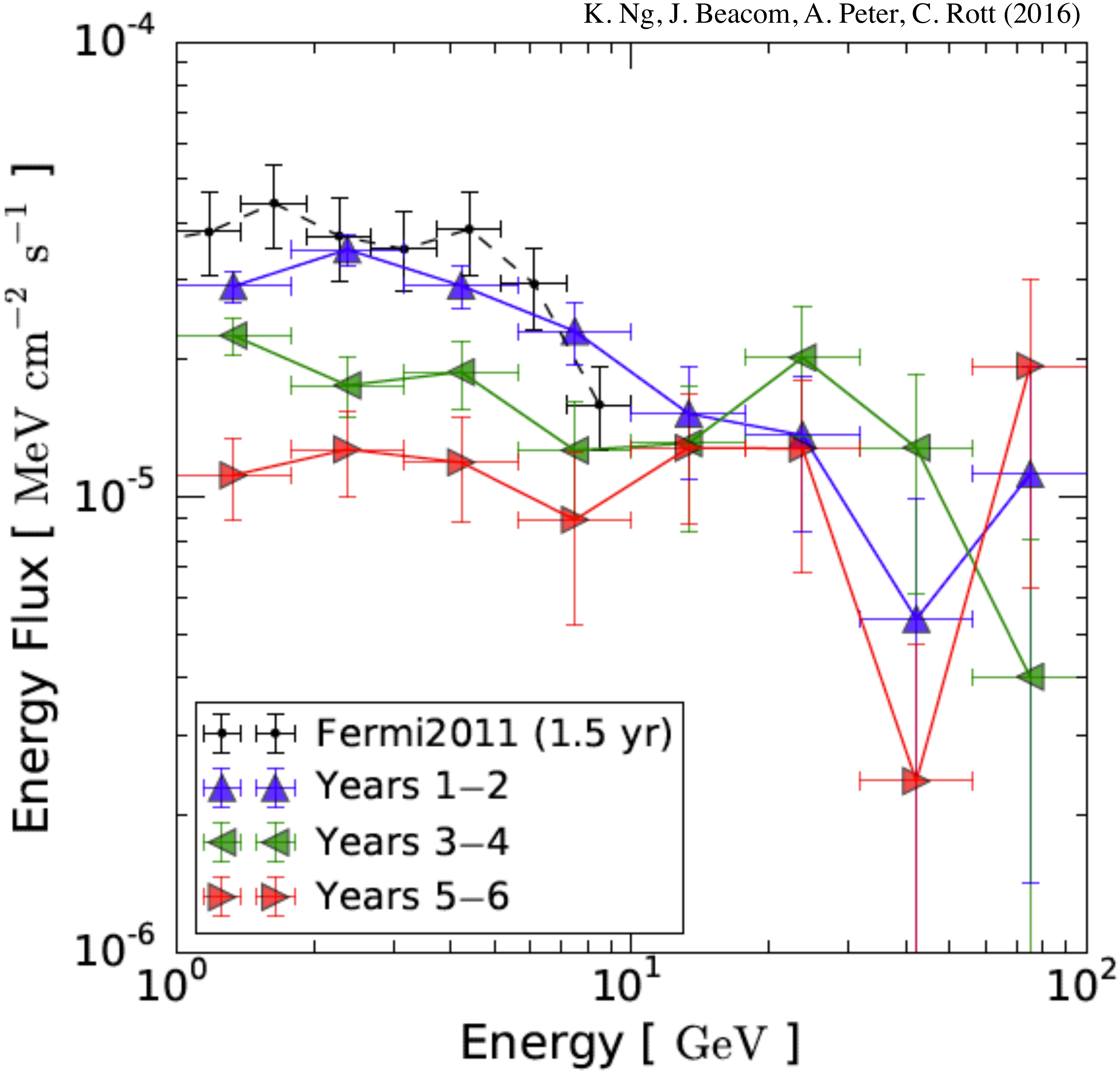




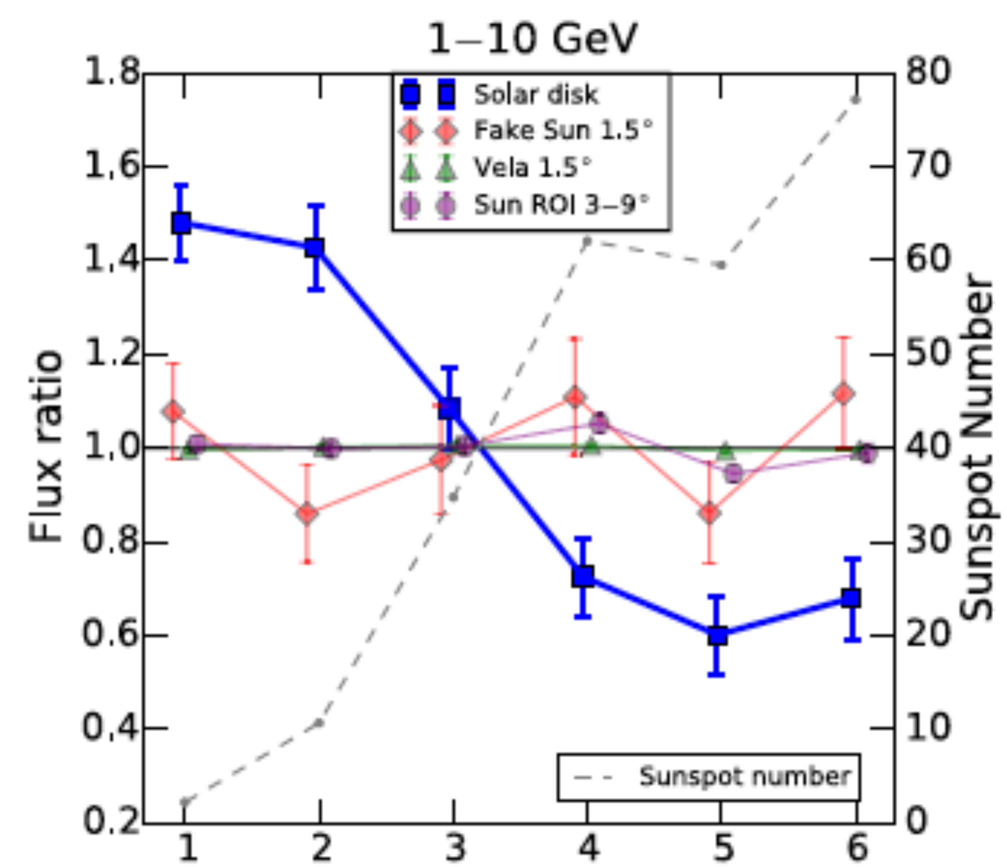
- Gamma-ray flux extends to 100GeV and beyond
- 6yr data is lower compared to Fermi2011 (1.5yrs)
- Observed flux factor 5 larger compared to central prediction of SSG1991
- Spectrum could be fit by single power law (γ~2.3)

Energy spectrum solar-disk

K. Ng, J. Beacom, A. Peter, C. Rott (2016)

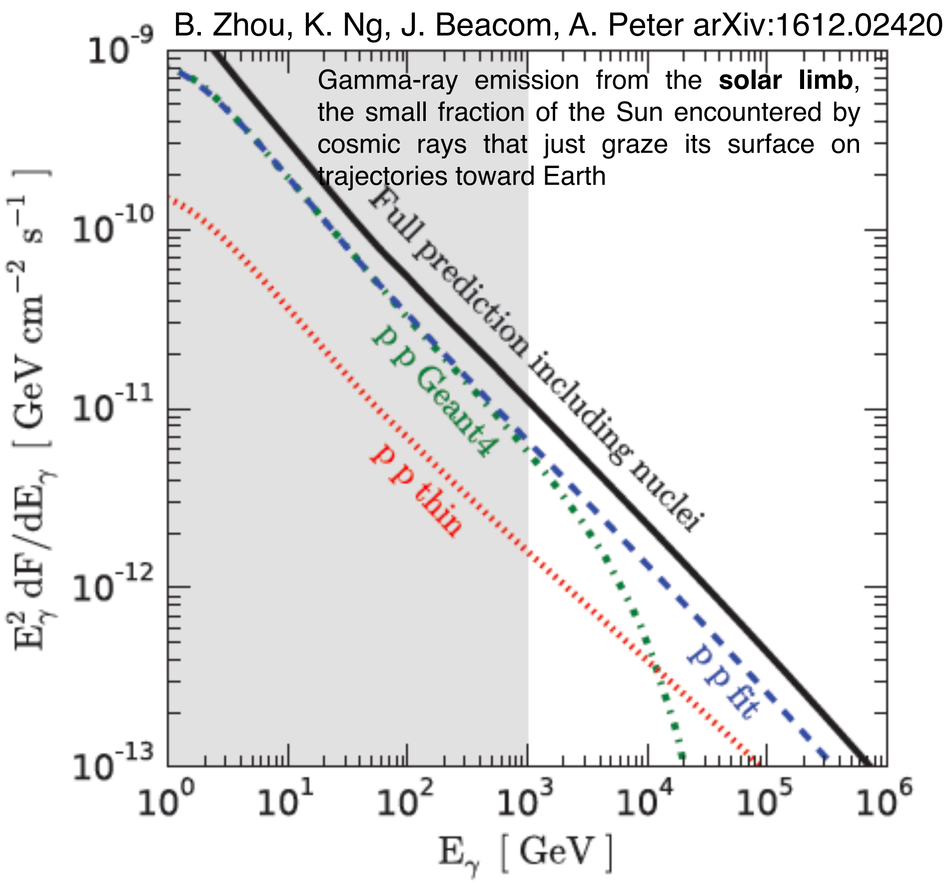


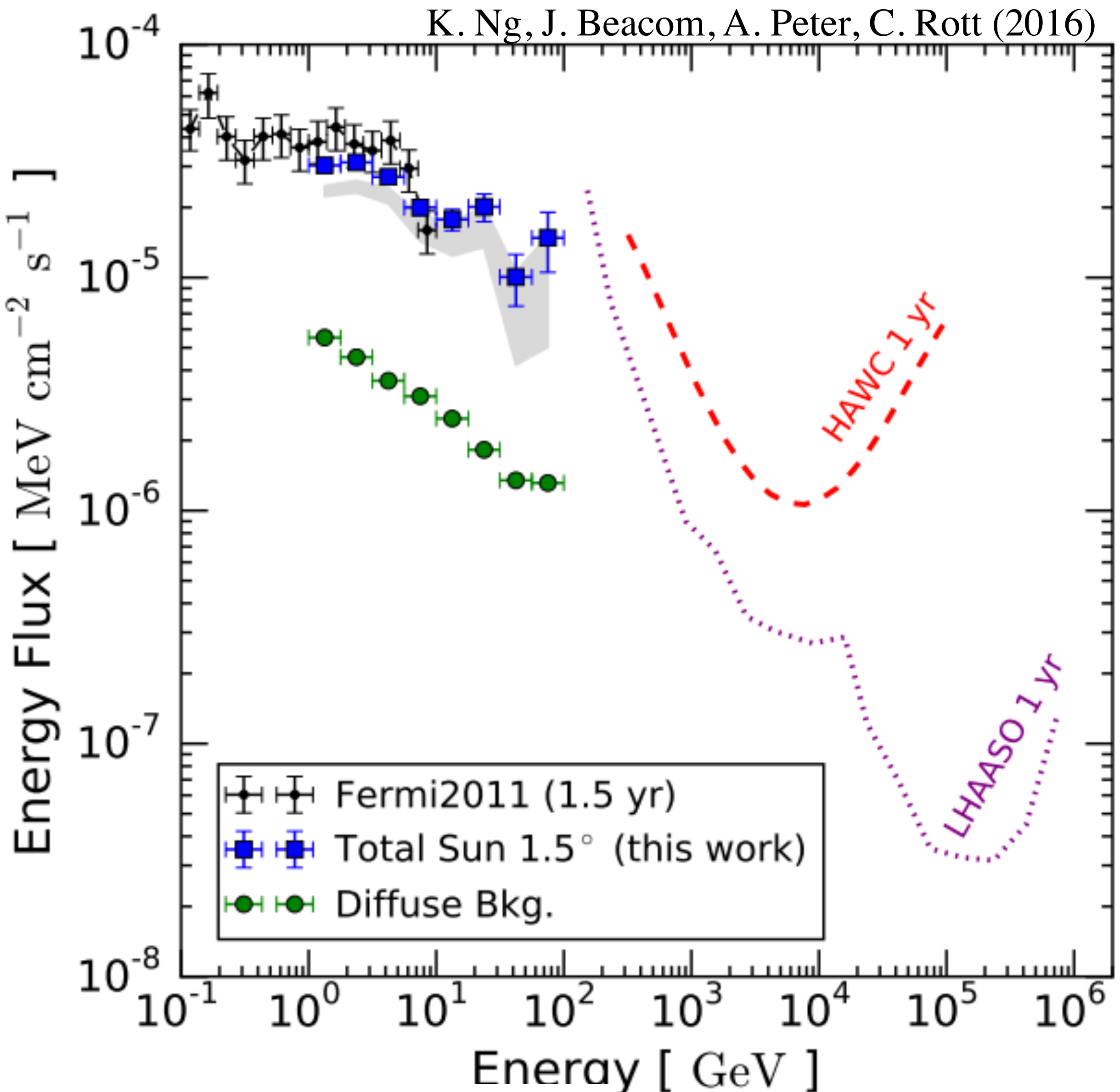
- Significant reduction in later periods for (1-10GeV)
- Anti-correlation with solar activity

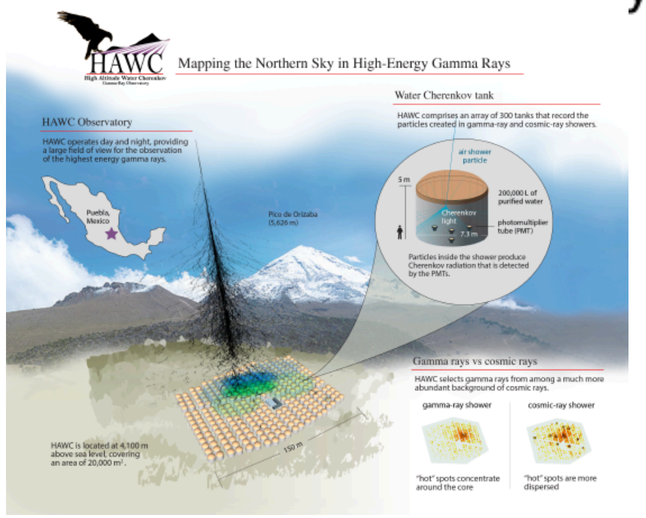


High Energy Gamma-rays from the Sun

- How far does the gamma-ray spectrum extend ?
    - cut-off ?
    - shape ?
- Water Cherenkov
    - HAWC (now performing this analysis)
    - LHASSO (proposed, ~2020)

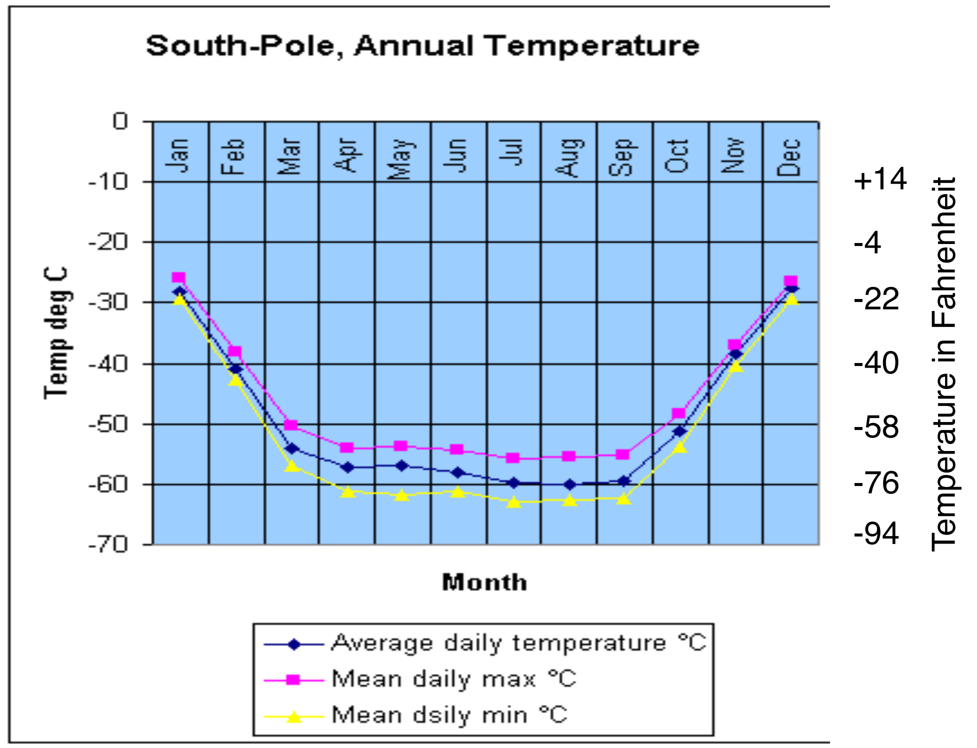


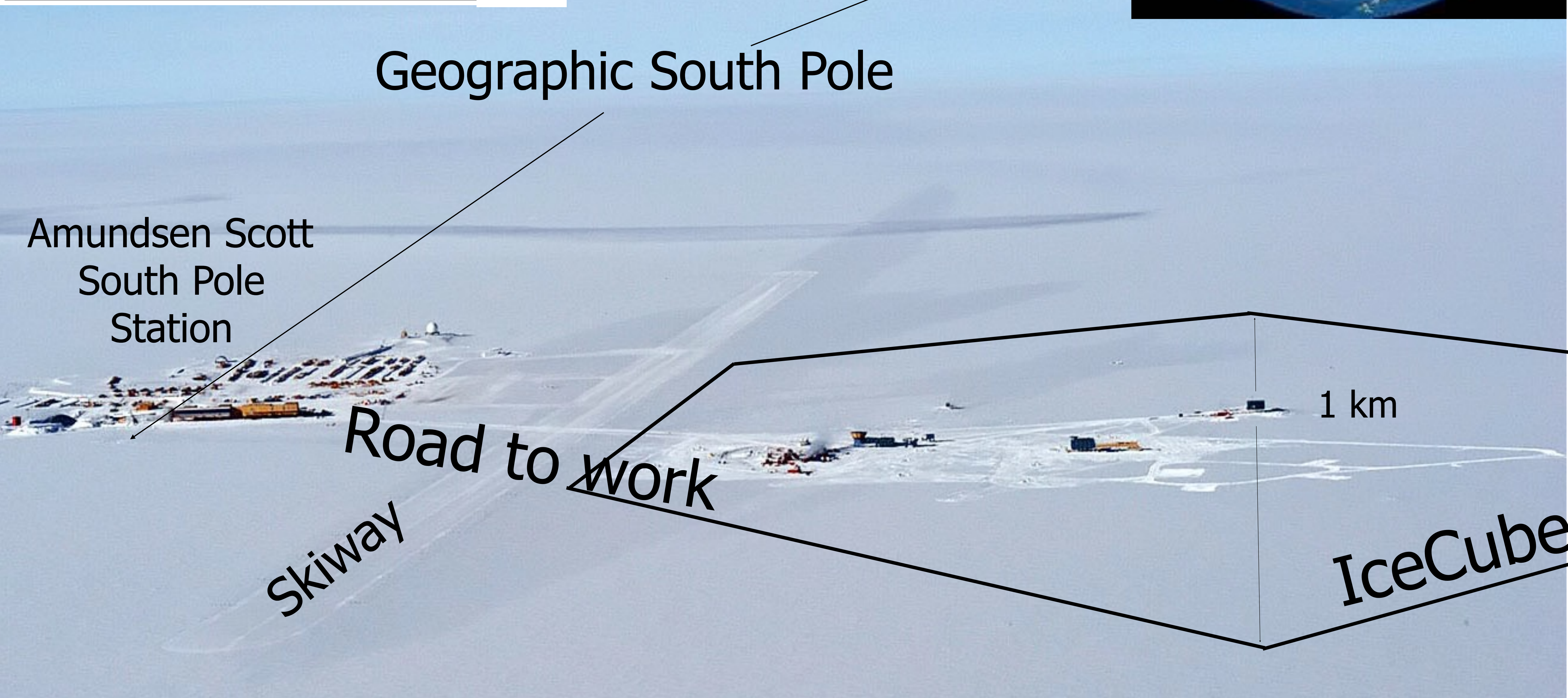




The IceCube Neutrino Observatory

Laboratory at the South Pole





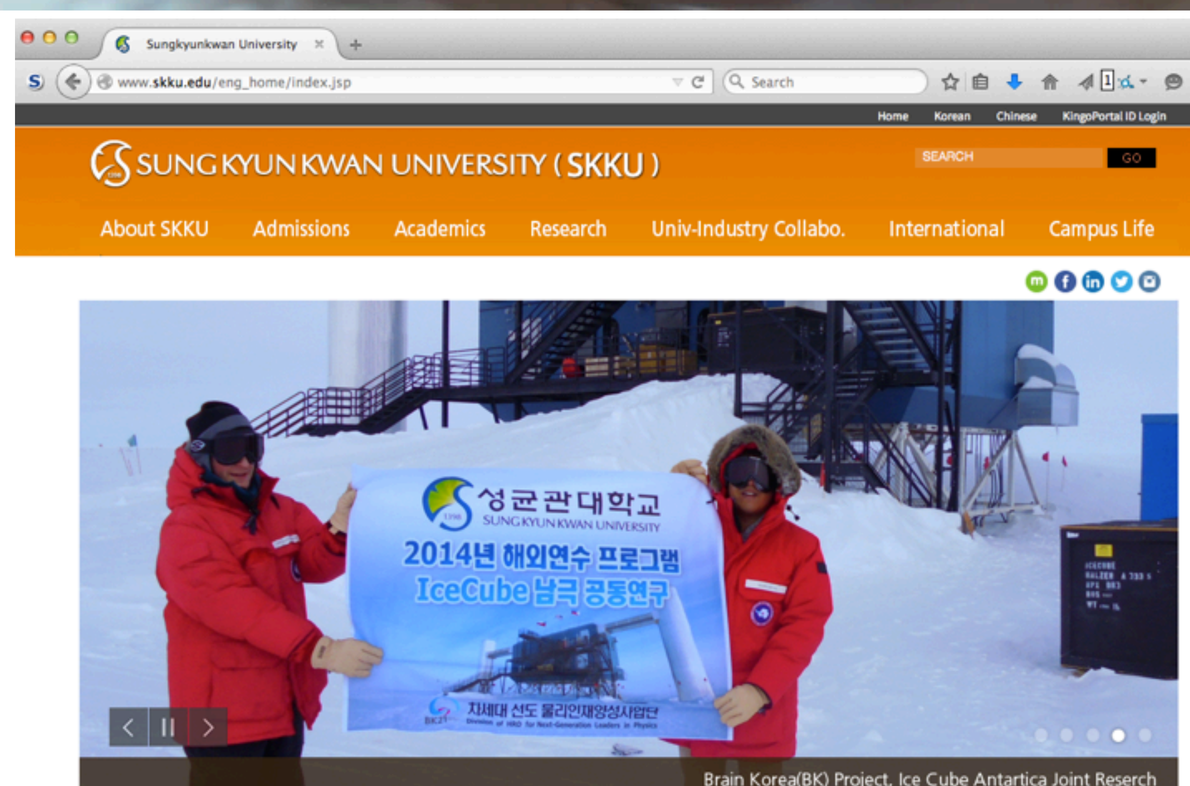
Christmas at the South Pole


Race Around the Word on Christmas Day


Christmas greetings from other Antarctic bases

Christmas at the South Pole

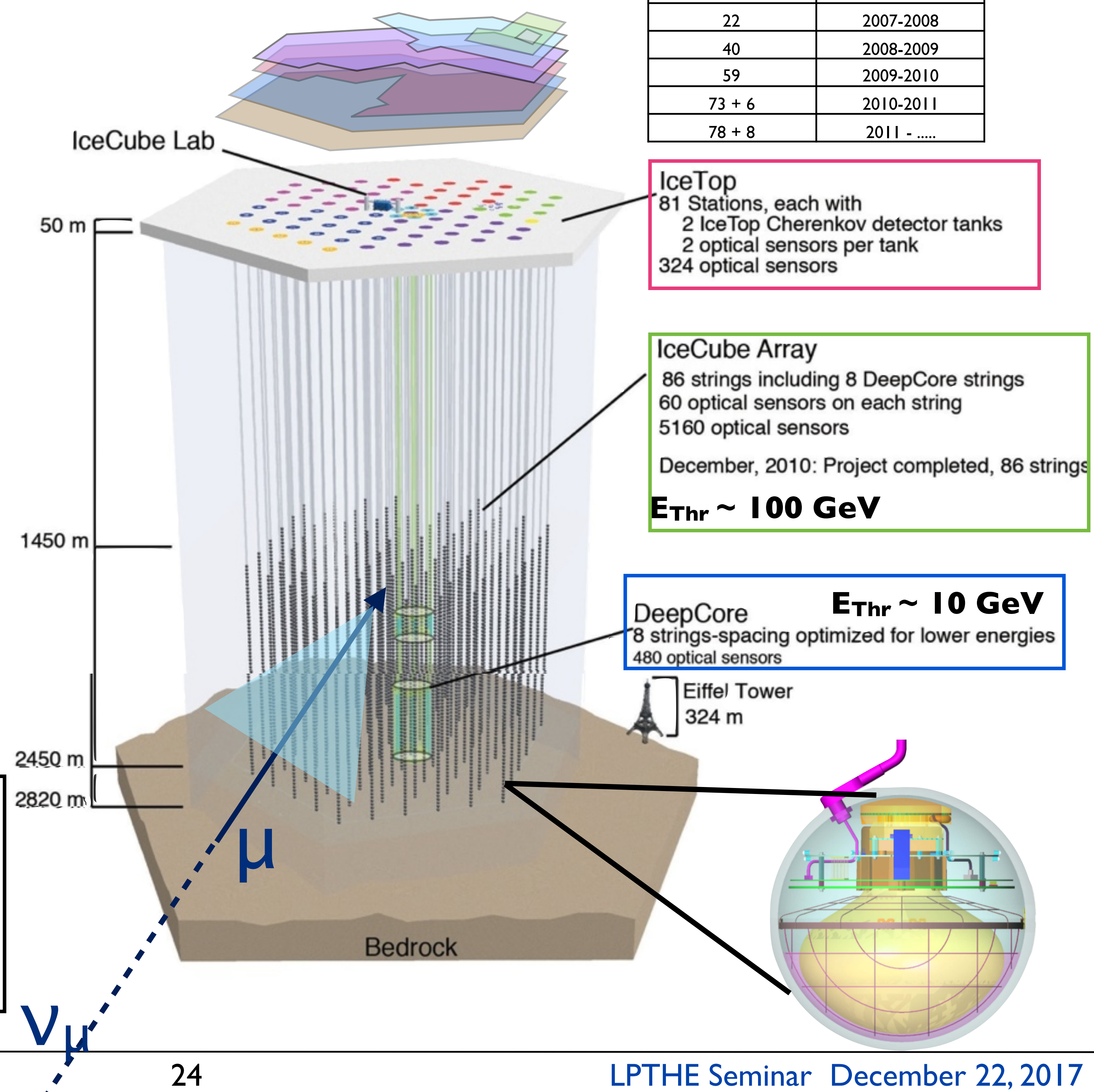
Seongjin In at the Pole. Image: Seongjin In, IceCube.



The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, data taking with full detector since 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°**

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen
Technische Universität Dortmund
Technische Universität München
Universität Münster
Universität Mainz
Universität Wuppertal

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms Universitet
Uppsala Universitet

SWITZERLAND
Université de Genève

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

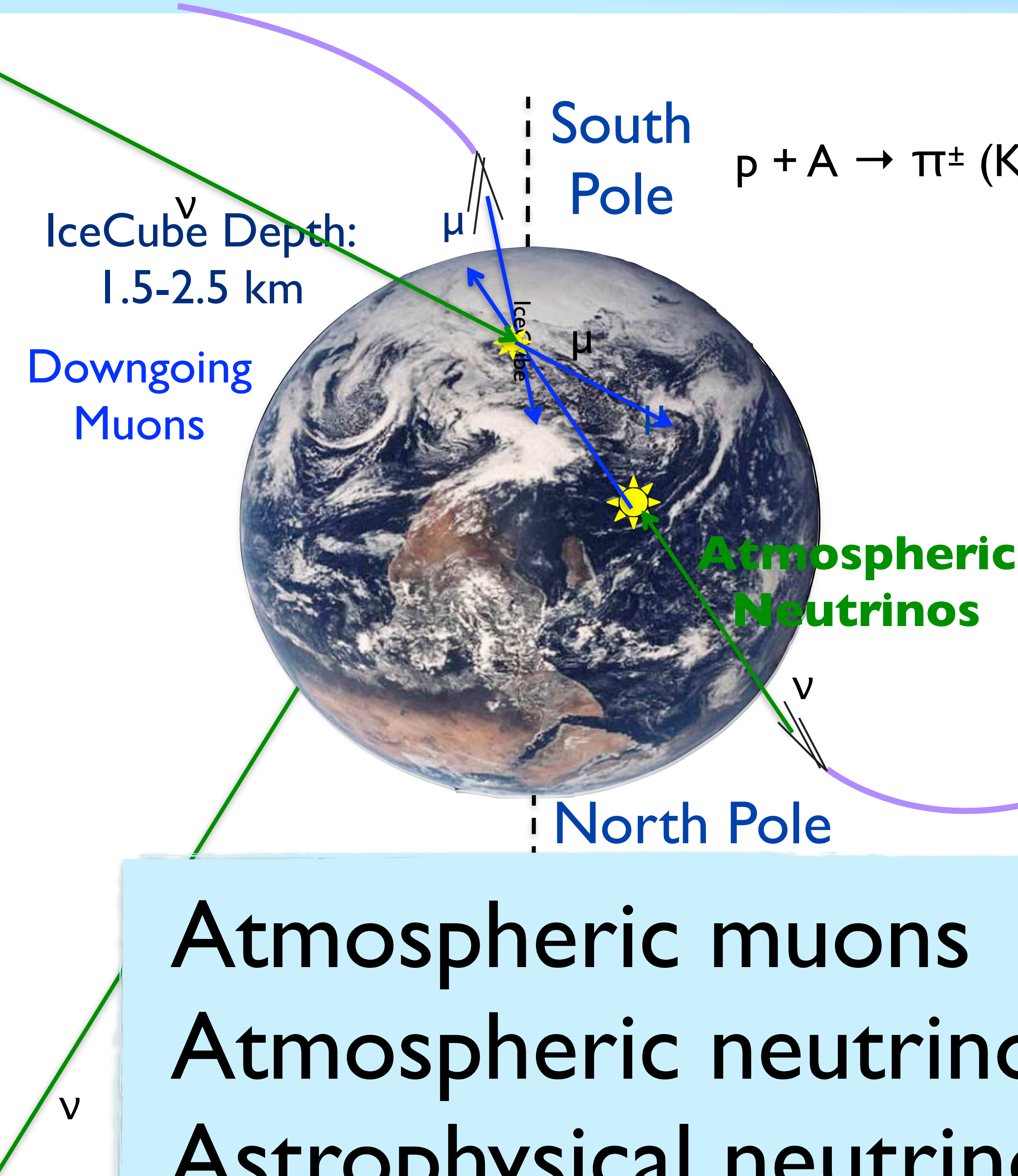
FUNDING AGENCIES

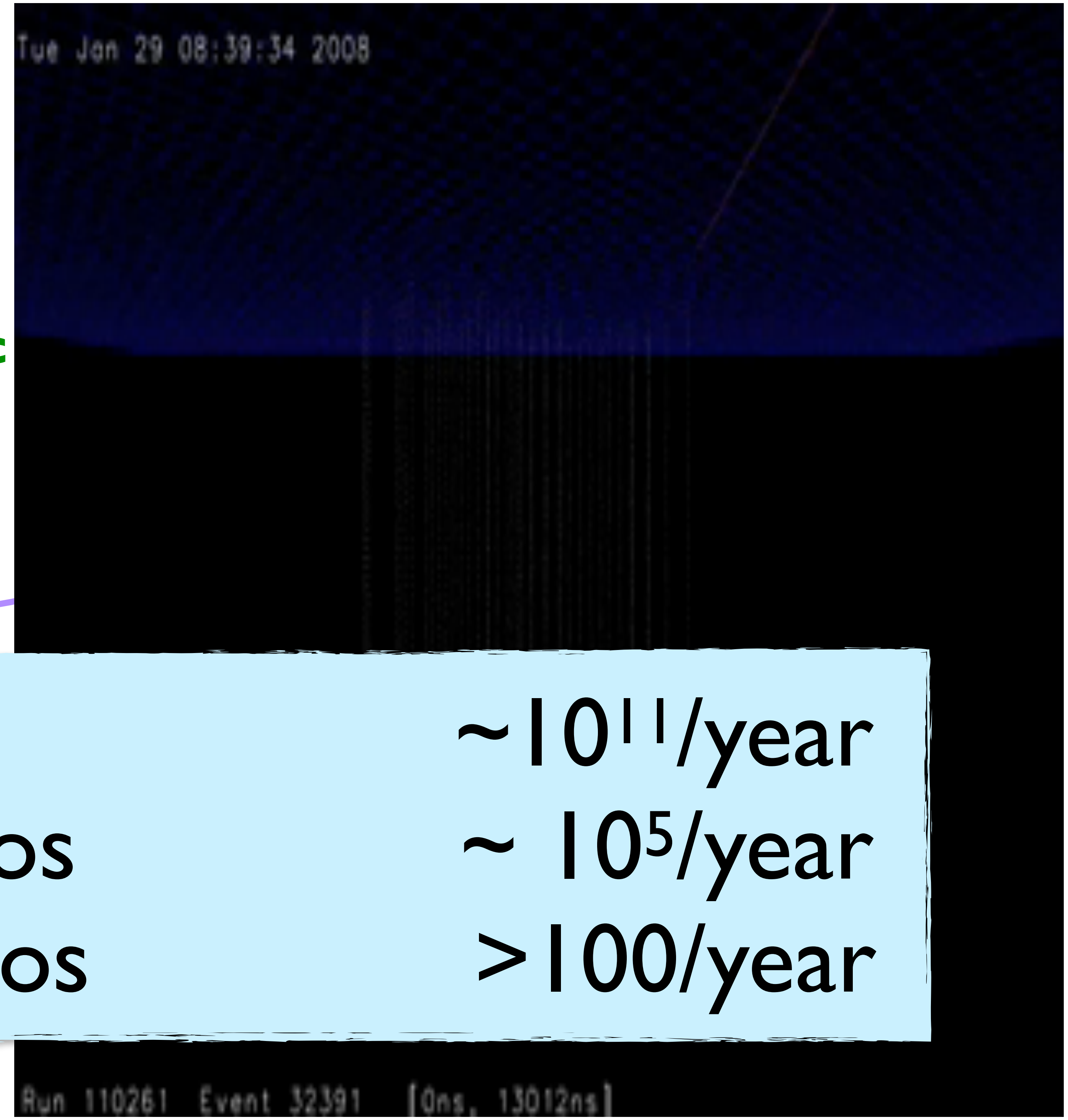
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Signals in IceCube

$p + A \rightarrow \pi^{\pm} (K^{\pm})$ + other hadrons ... $\pi^{+} \rightarrow \mu^{+}\nu_{\mu} \rightarrow e^{+}\nu_{e}\nu_{\mu}\nu_{\mu}$





Atmospheric muons	~10^{11}/year
Atmospheric neutrinos	~ 10^{5}/year
Astrophysical neutrinos	>100/year

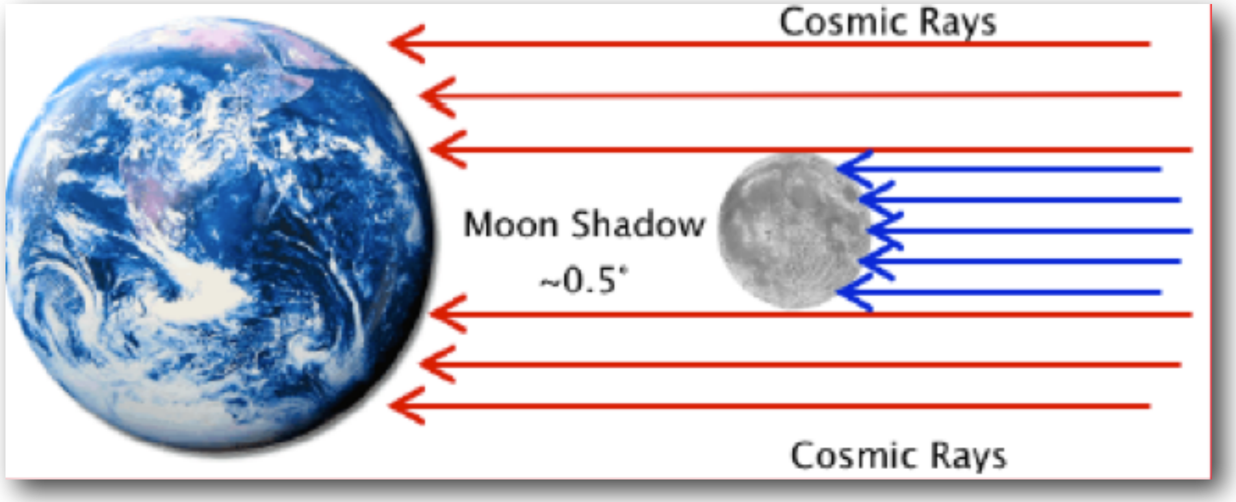
extra terrestrial neutrino fluxes

IceCube "Observations" of the Sun

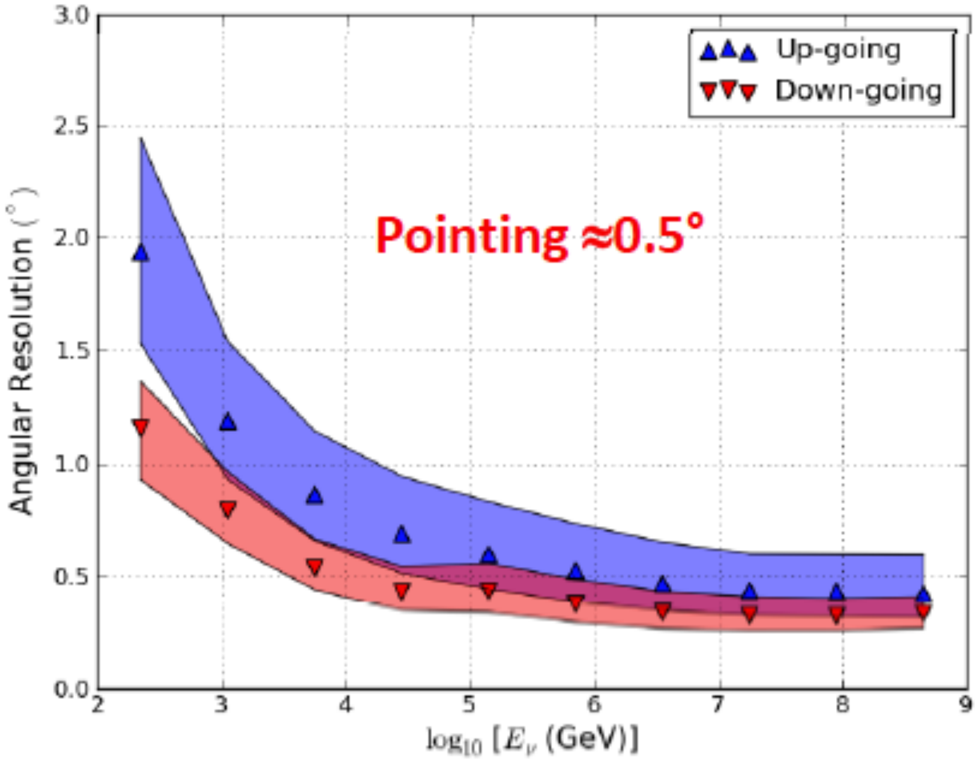
Calibration and Performance

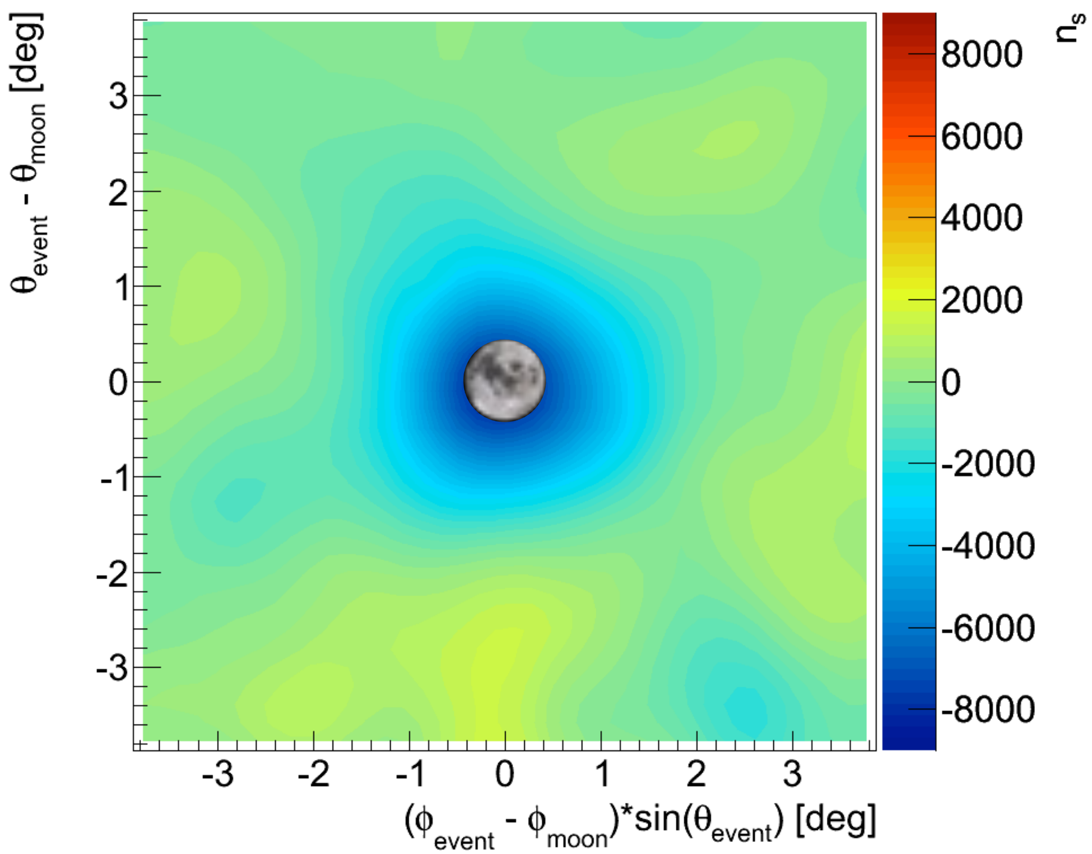
Physical Review D89 (2014) 102004

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

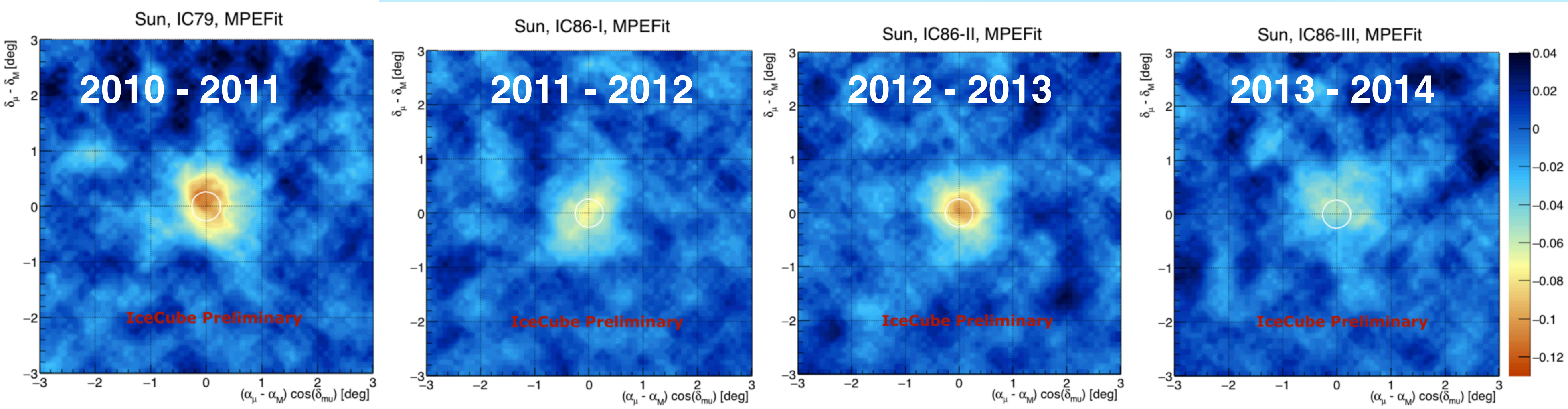


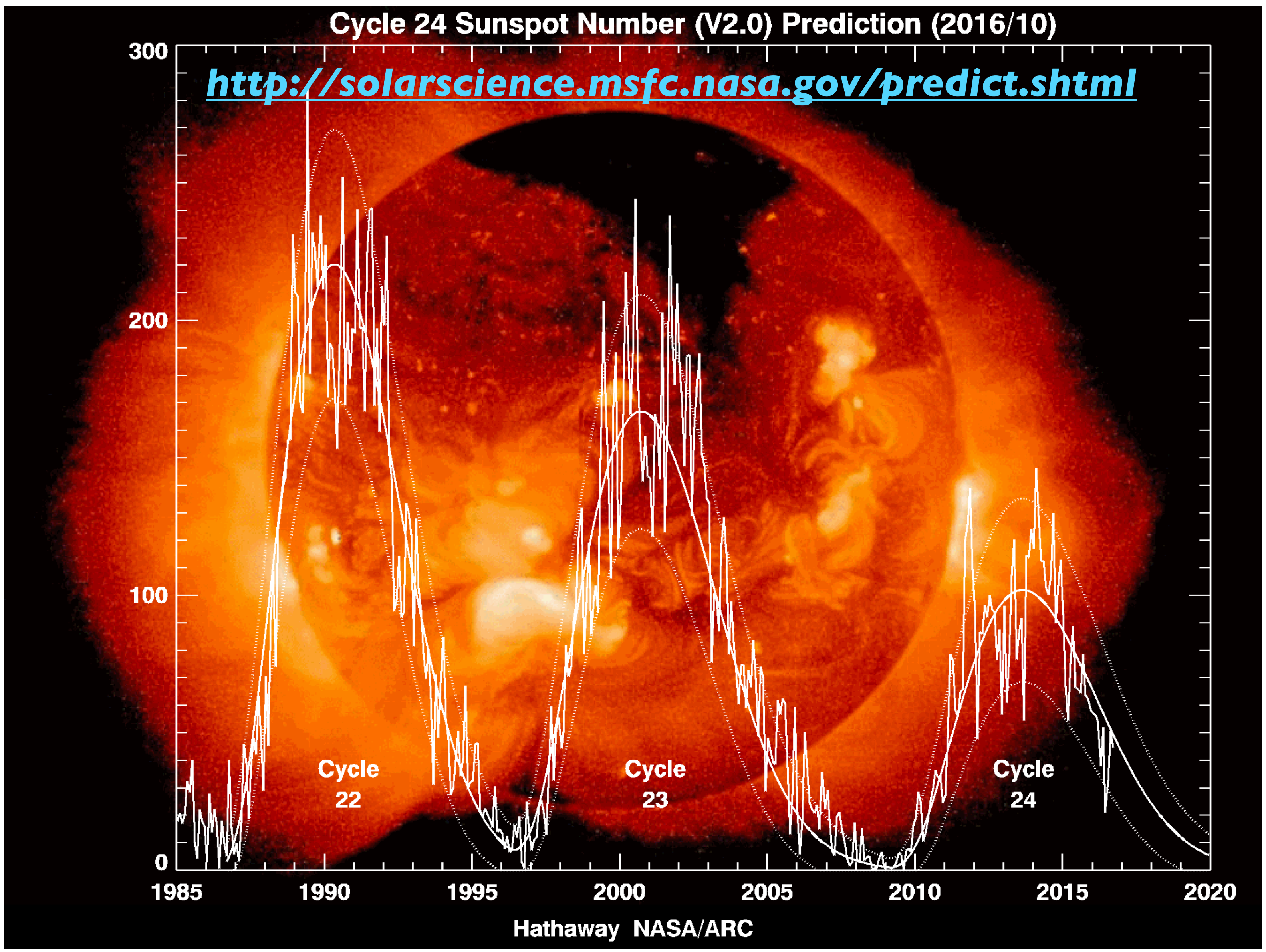
- Moon blocks cosmic rays - Observed muon deficit 14σ significance
  - systematic pointing error <0.1°

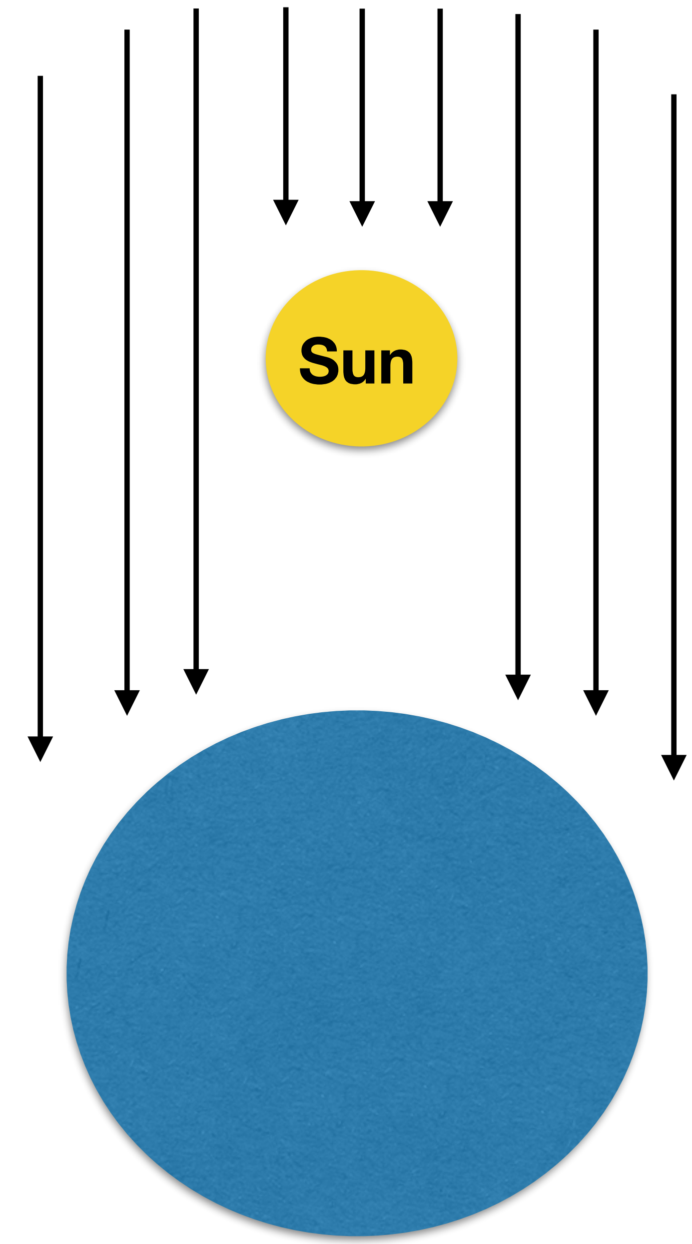




Sun Shadow



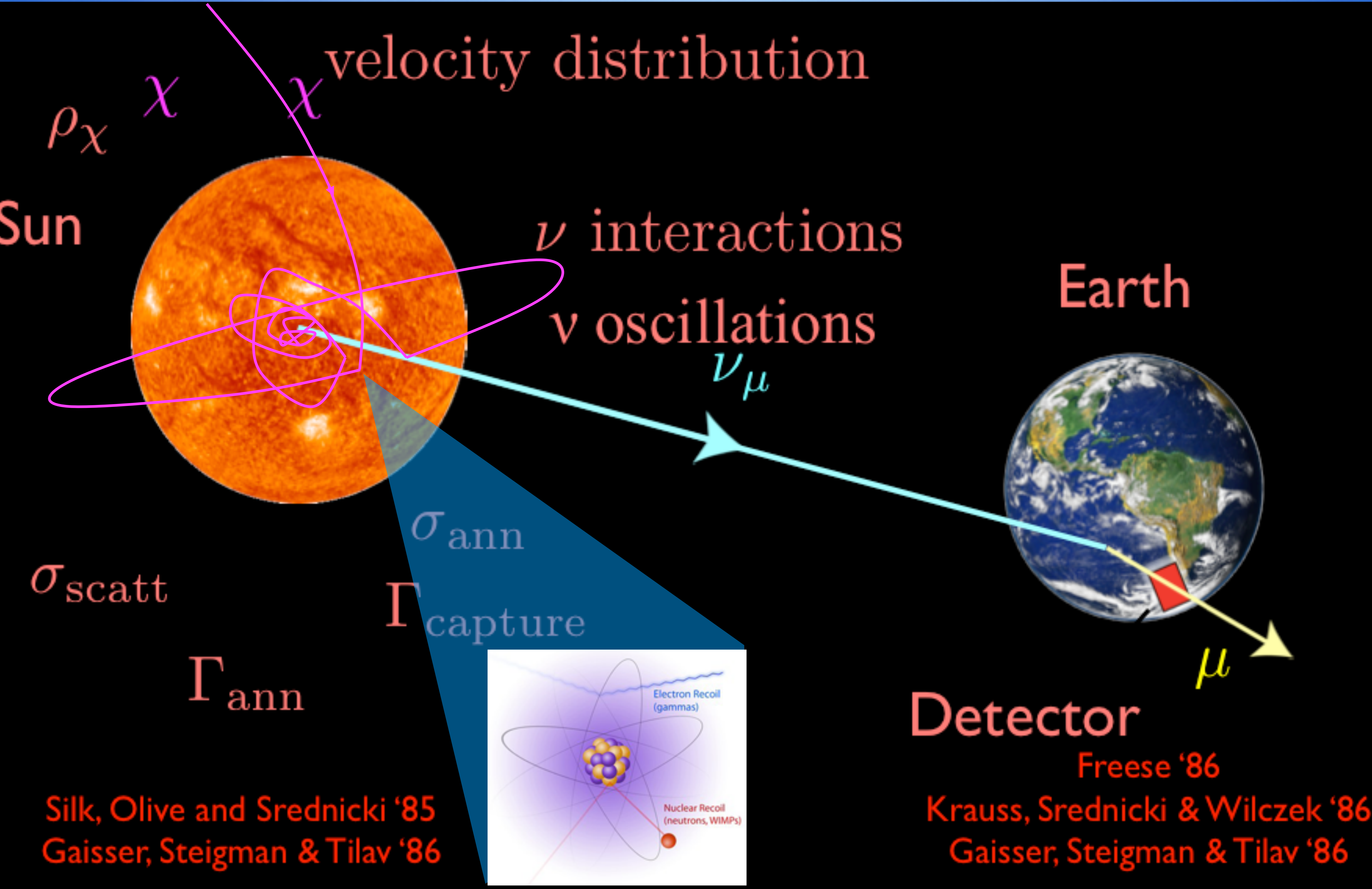




- Sun shadow observed during austral summer
- Variations are clearly visible

Solar Dark Matter Searches

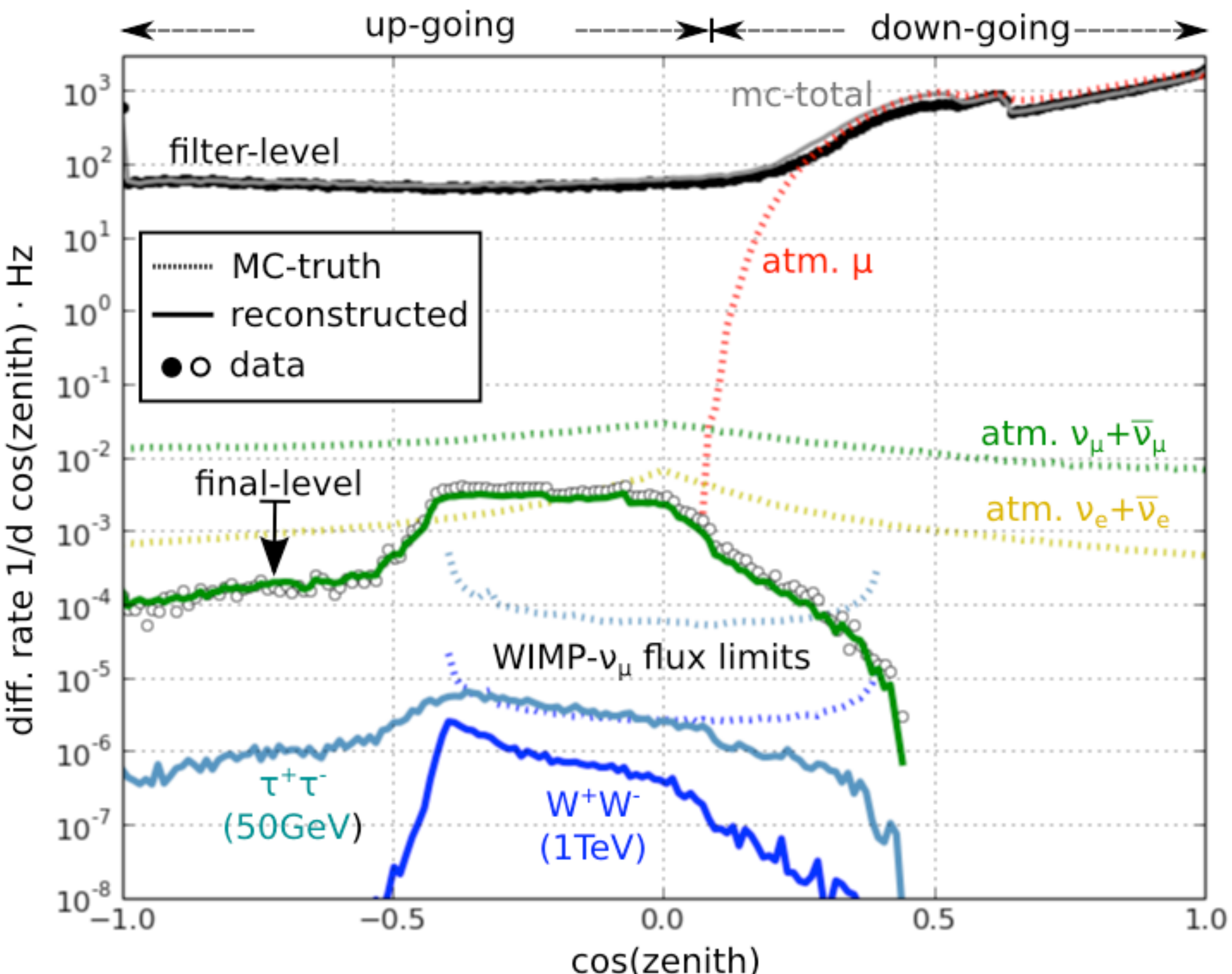
Solar Dark Matter



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

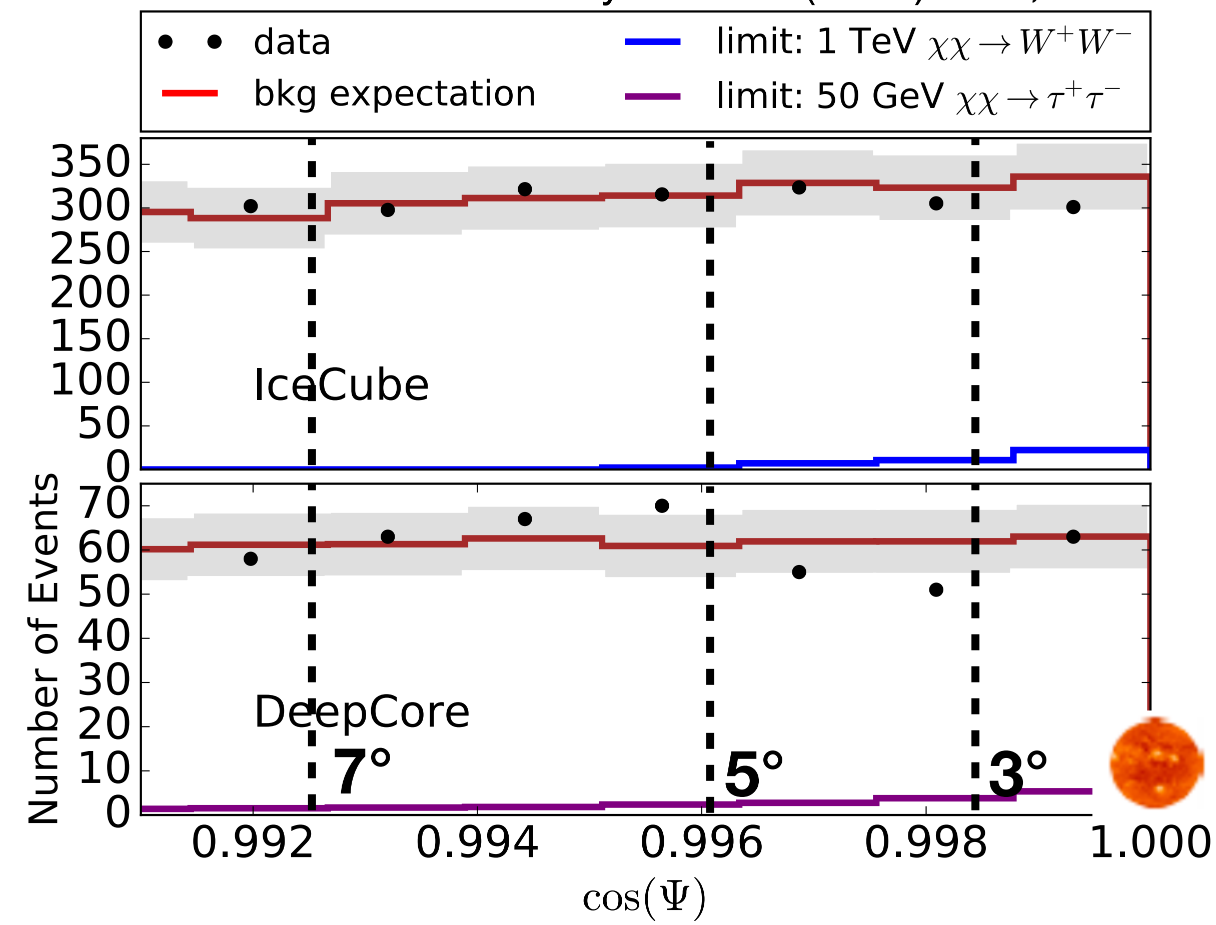
Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

3yrs IceCube Solar Dark Matter Analysis



Observed events

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



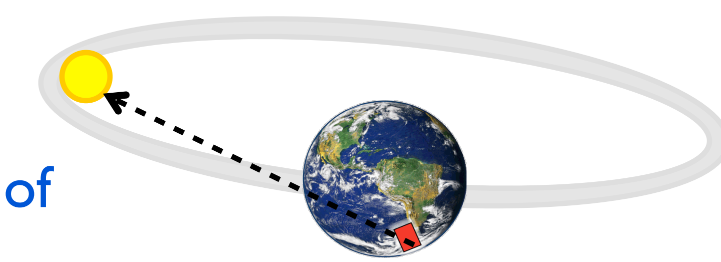
Signal pdf:

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

Spectral part

Monovariate Fisher Bingham distribution from directional statistics

- 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

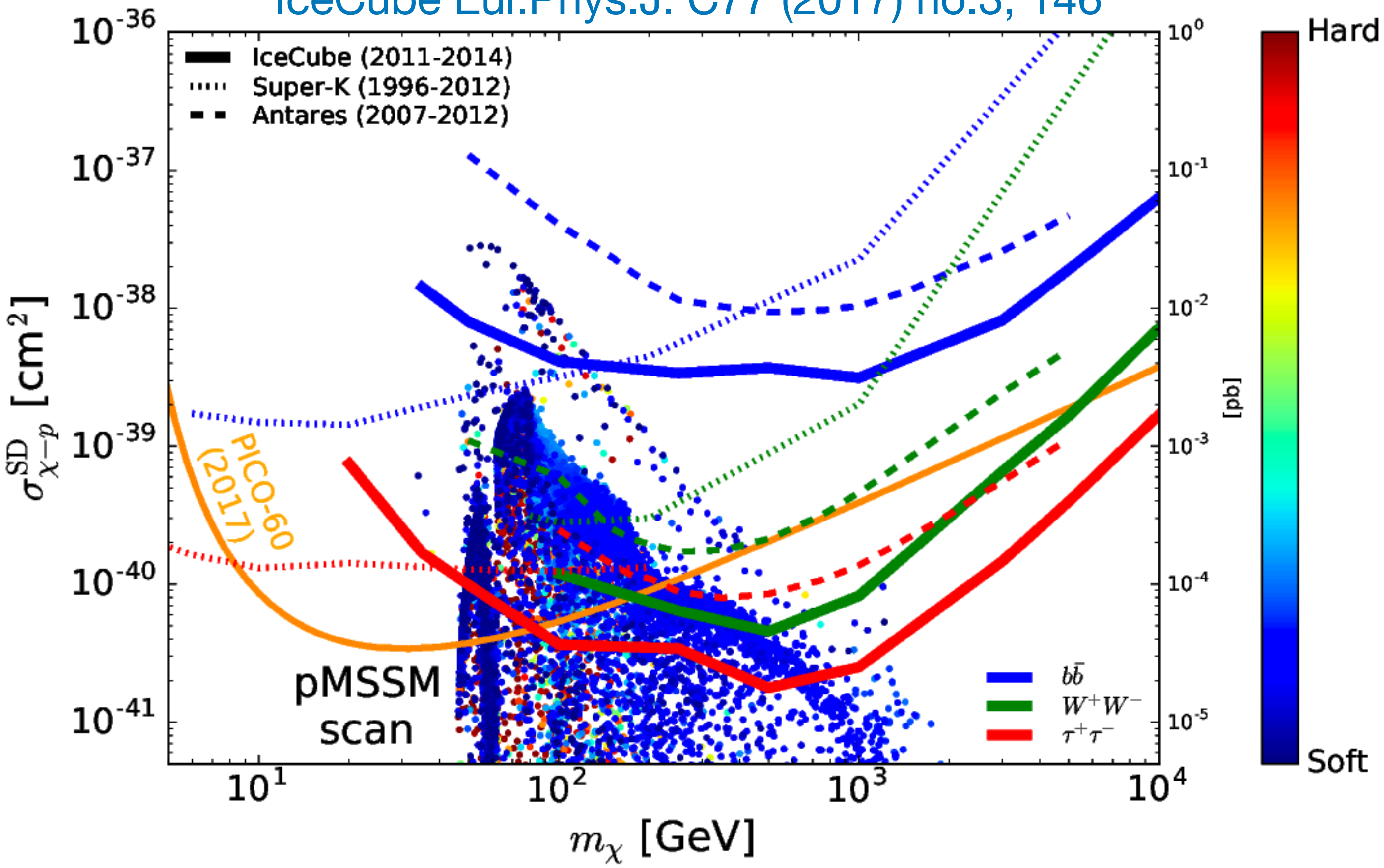
Background pdf: $\mathscr{B}_i(tx_i, E_i) = B(\delta_i) \times P(E_i|\phi_{\text{atm}})$

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

Solar Dark Matter IceCube

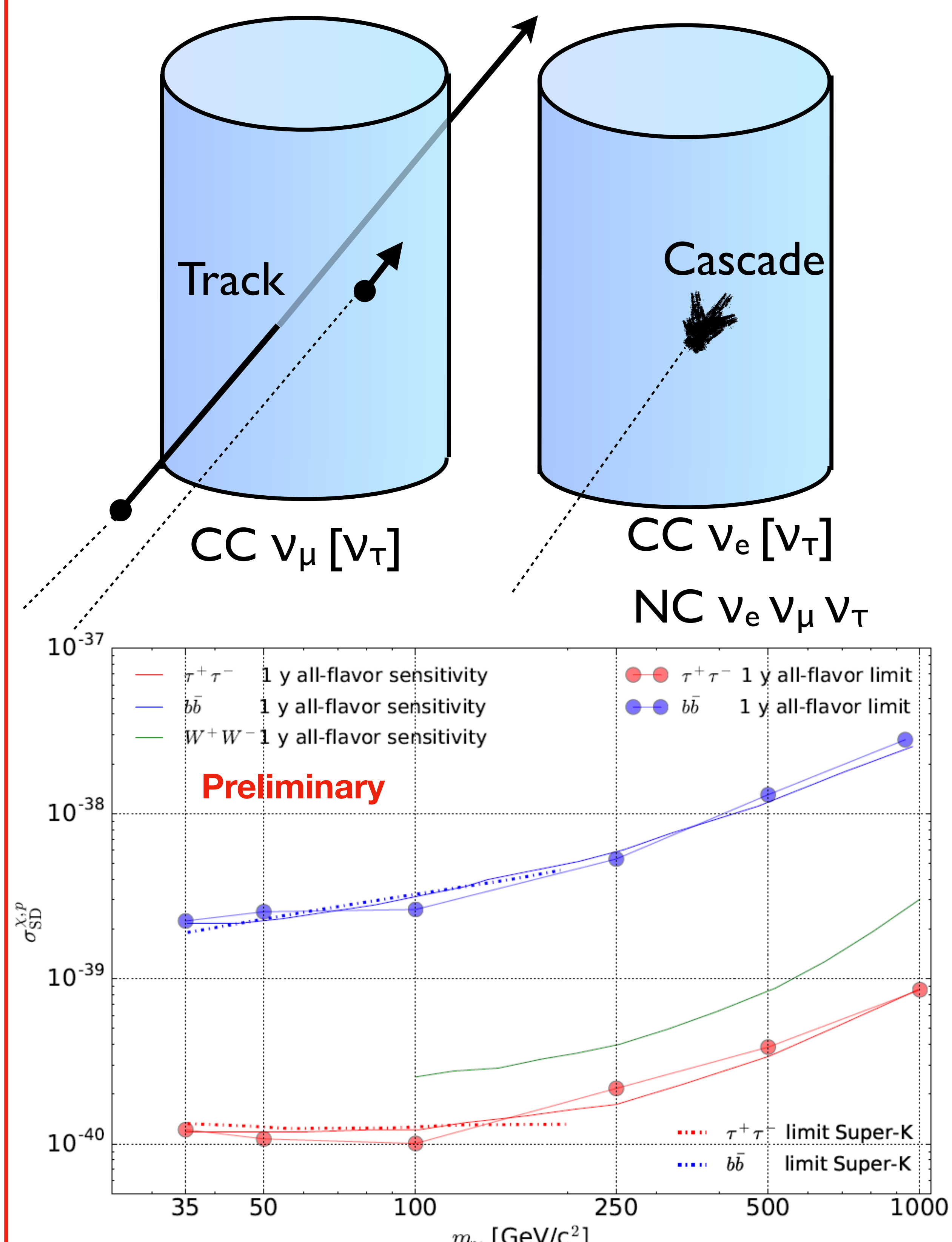
- Convert neutrino flux limit into limit on WIMP-nucleon scattering cross section

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



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

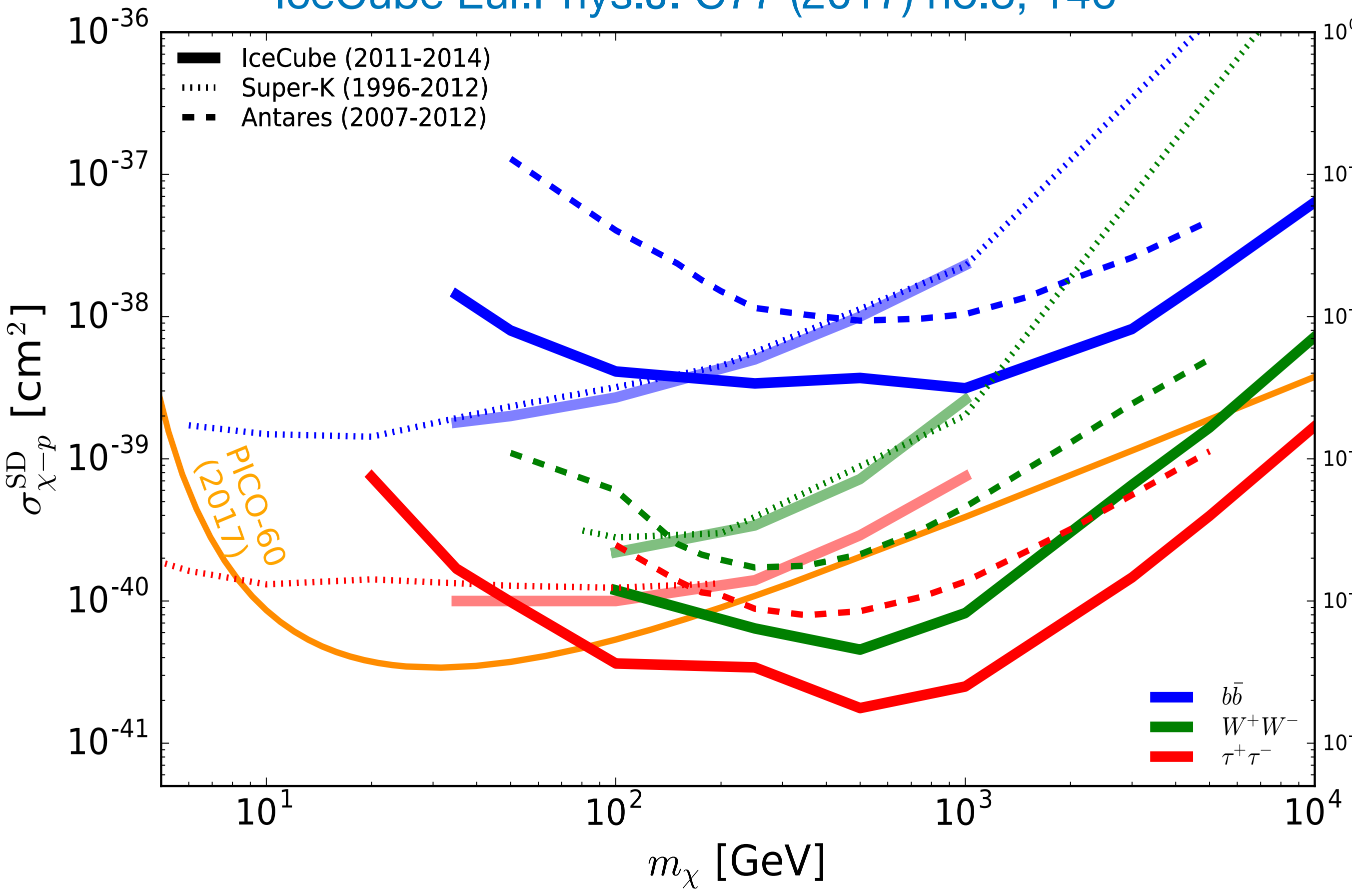
All flavor Solar WIMP - IceCube



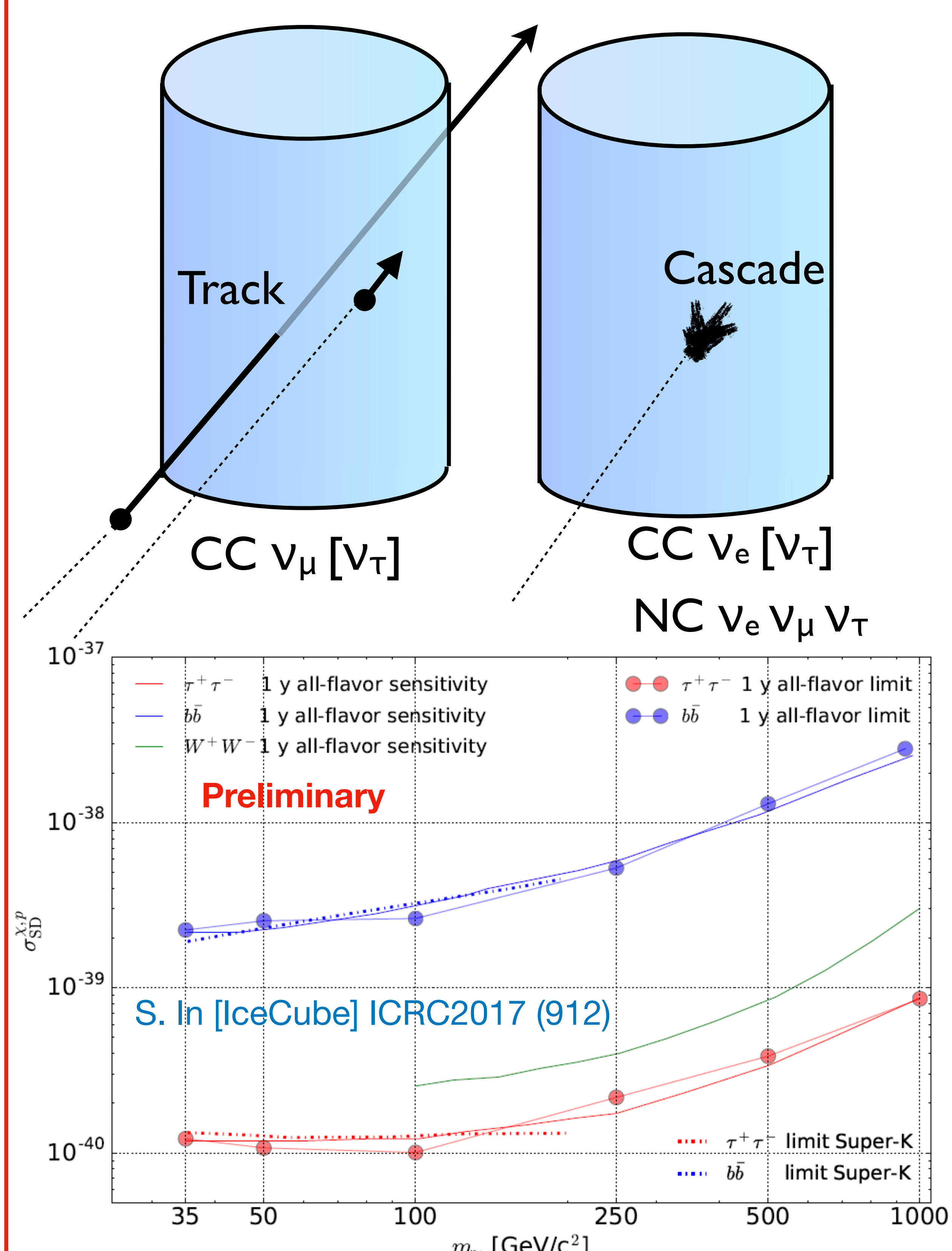
Solar Dark Matter - IceCube/ANTARES

- 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
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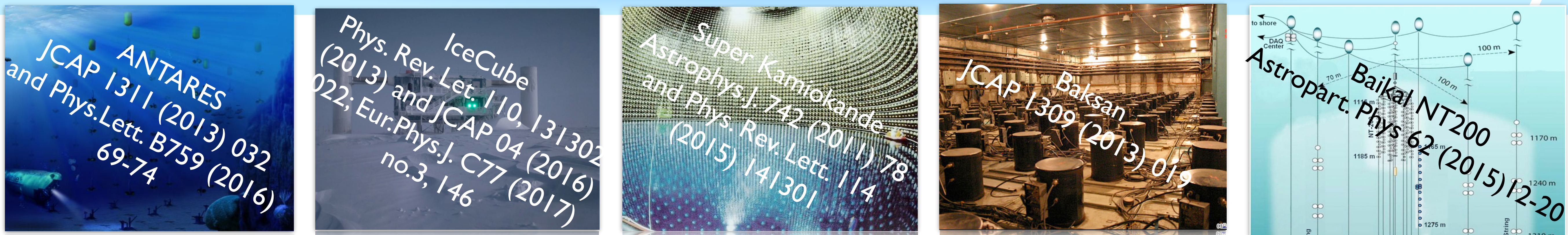
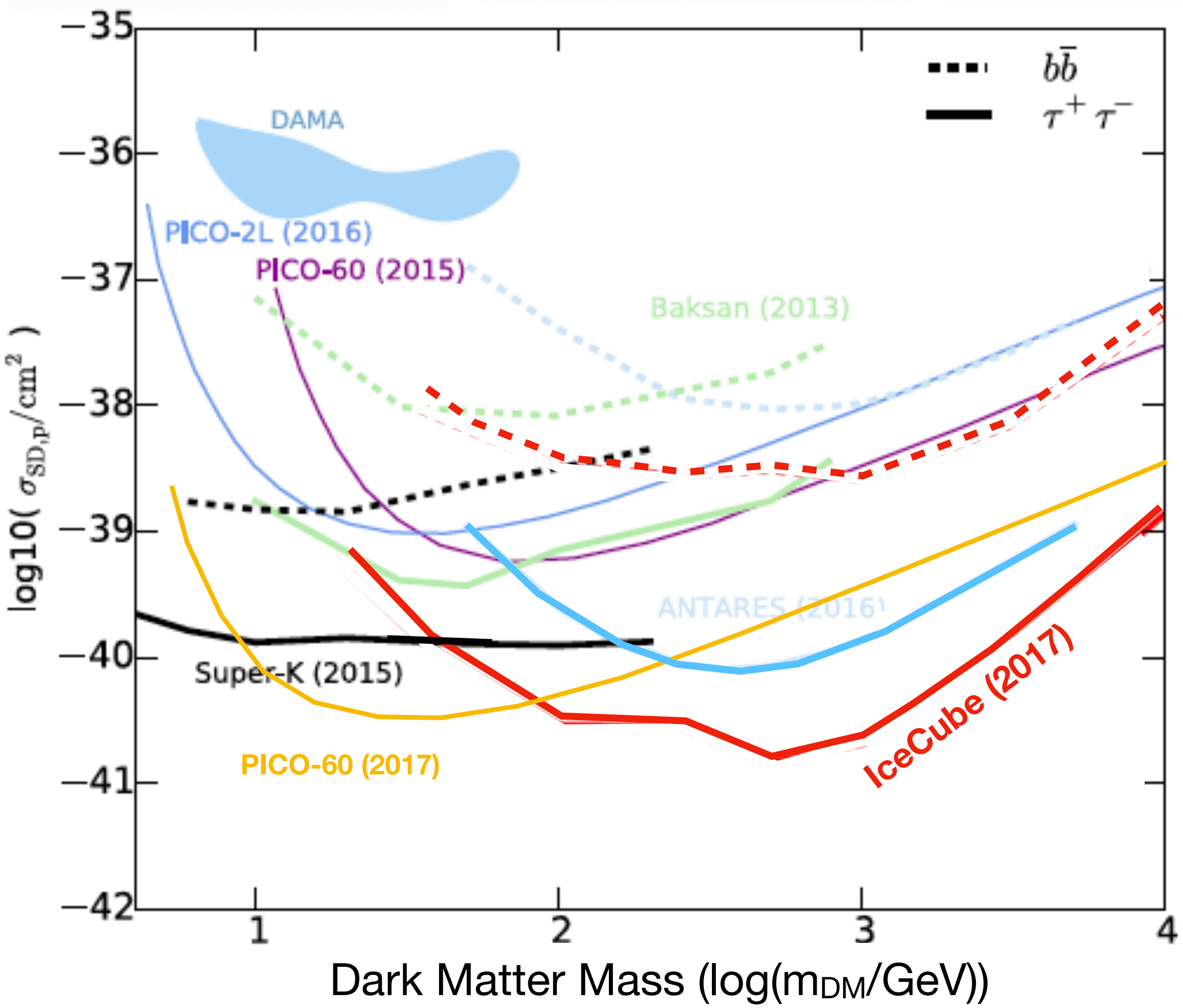
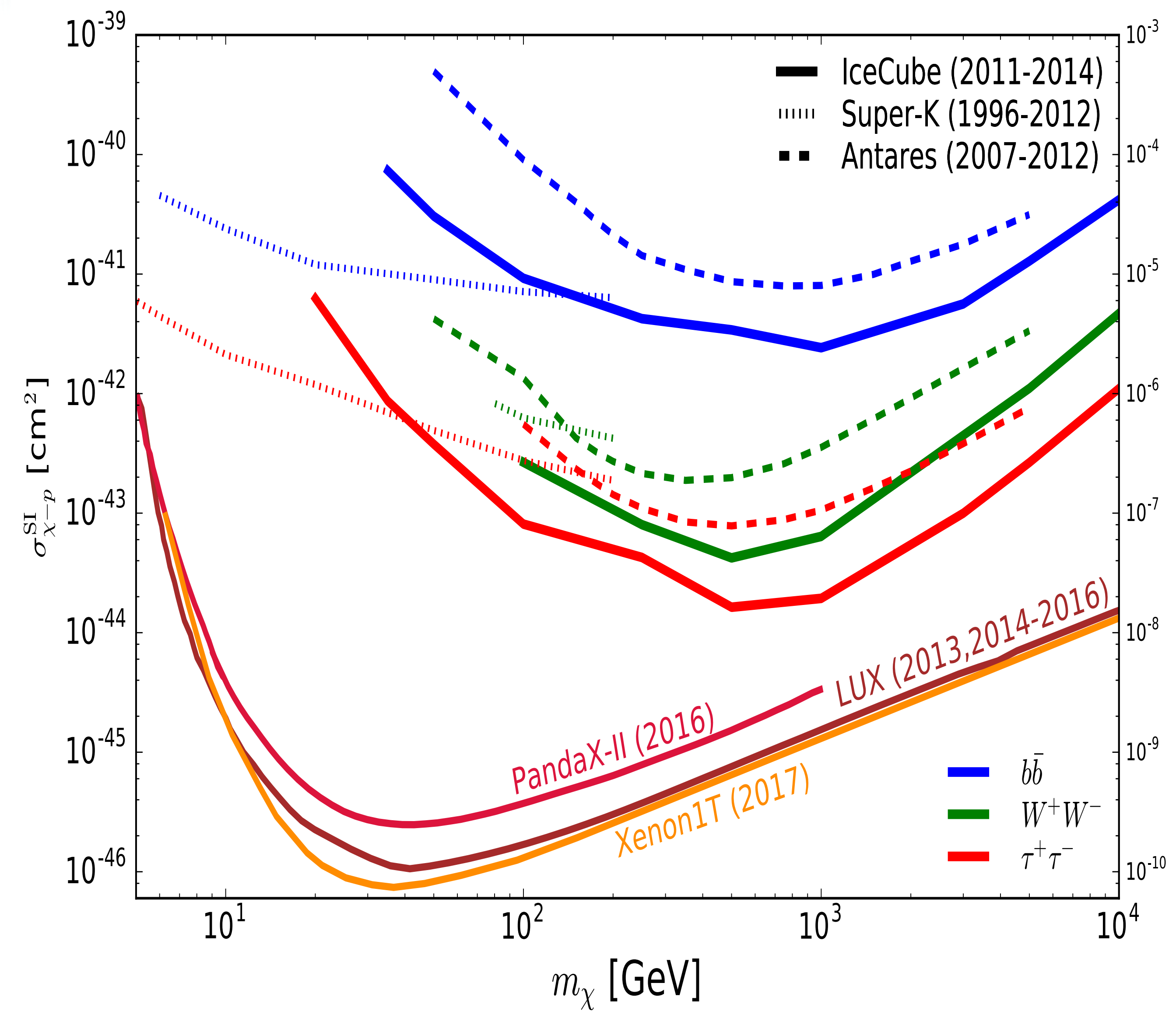
Solar Dark Matter Summary



Spin-dependent scattering



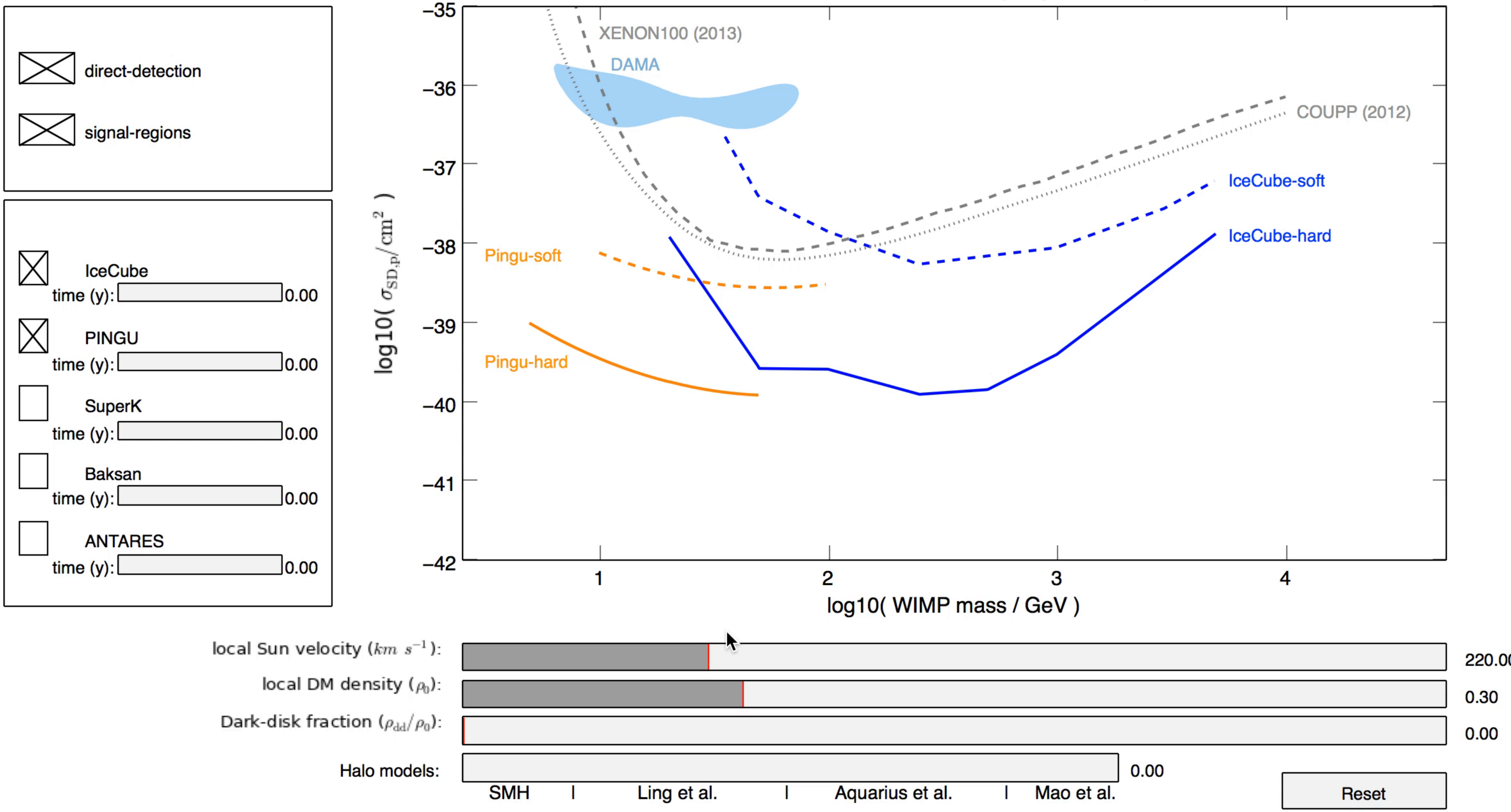
Spin-independent scattering



Impact of astrophysical uncertainties

M. Danninger & C. Rott "Solar WIMPs Unraveled" – Physics of the Dark Universe (Nov 2014)

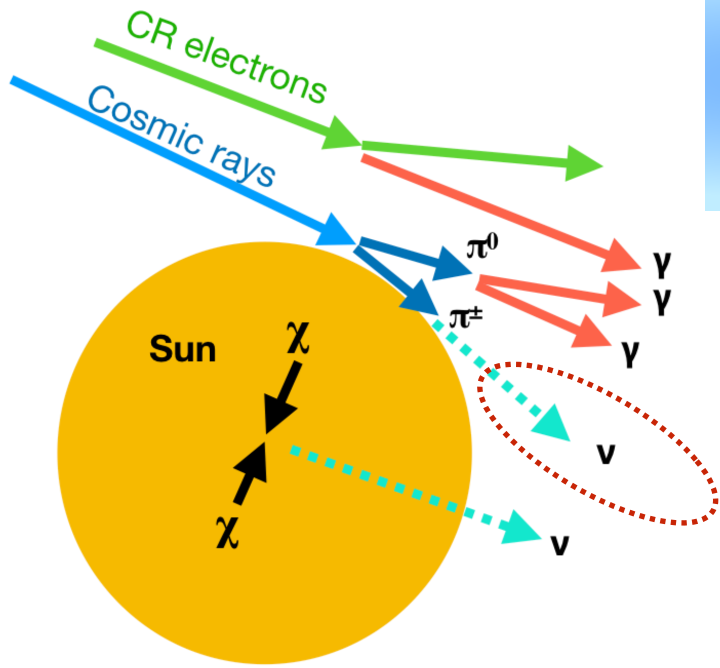
Interactive tool to study impact of astrophysical parameters

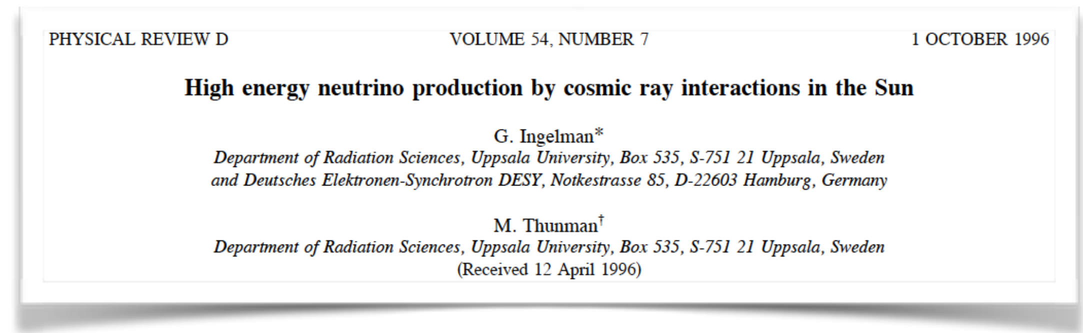


https://mdanning.web.cern.ch/mdanning/public/Interactive_figures/

Solar Atmospheric Neutrino Search

Neutrinos from the Sun





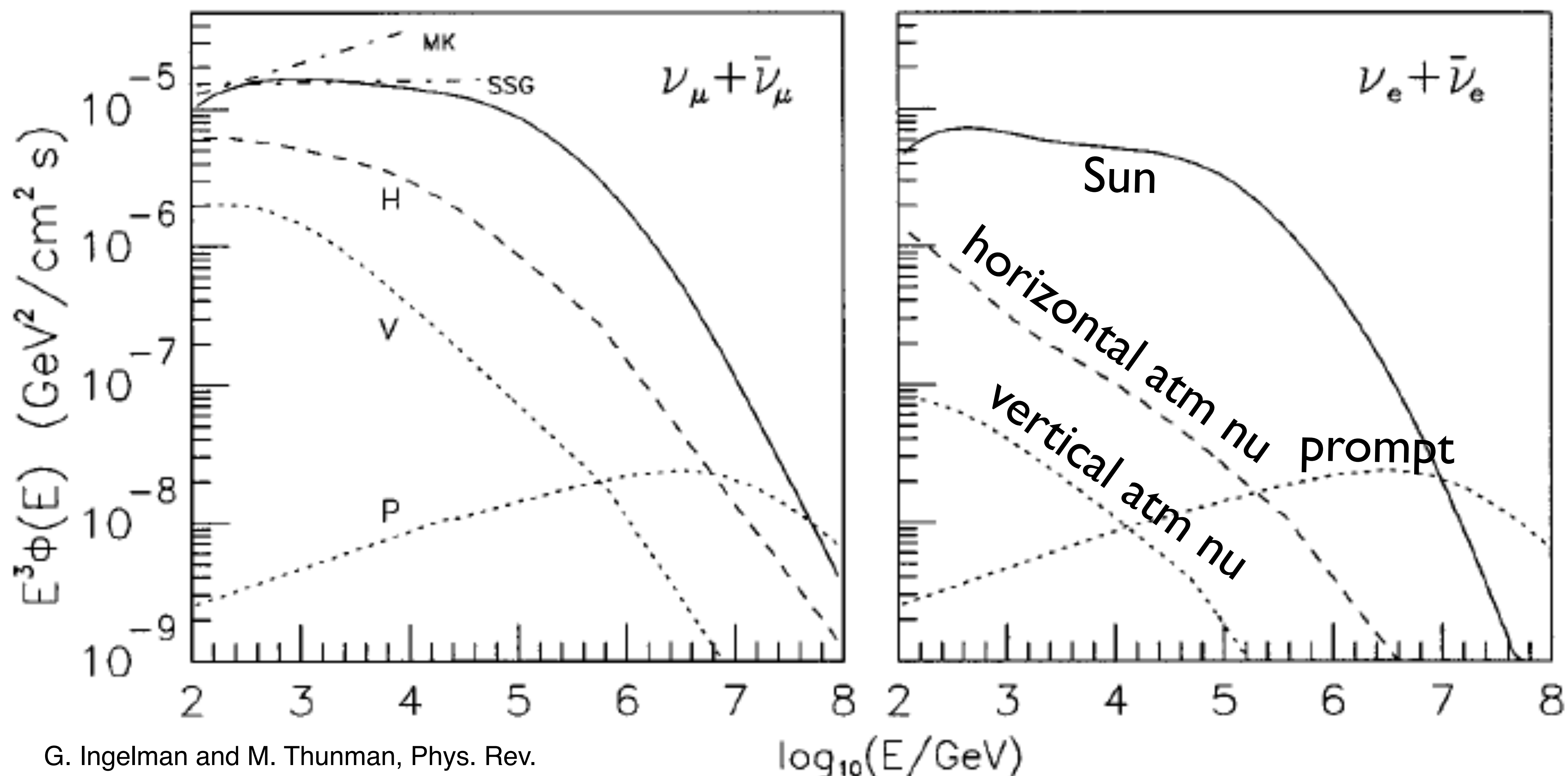
PHYSICAL REVIEW D VOLUME 54, NUMBER 7 1 OCTOBER 1996

High energy neutrino production by cosmic ray interactions in the Sun

G. Ingelman*
Department of Radiation Sciences, Uppsala University, Box 535, S-751 21 Uppsala, Sweden
and Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, D-22603 Hamburg, Germany

M. Thunman†
Department of Radiation Sciences, Uppsala University, Box 535, S-751 21 Uppsala, Sweden

(Received 12 April 1996)



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

Theoretical predictions

- Argüelles et al. [astro-ph/1703.07798]

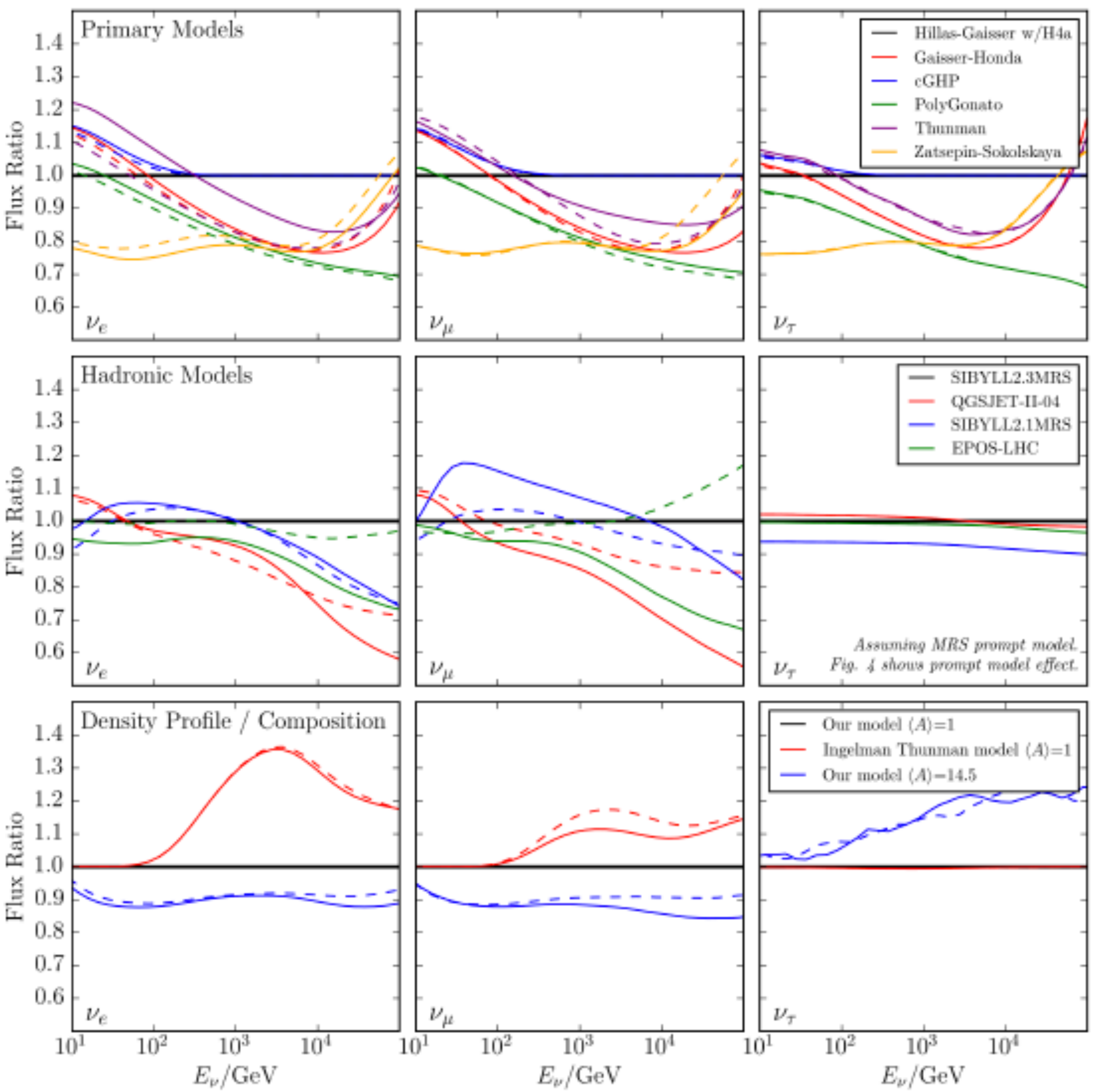
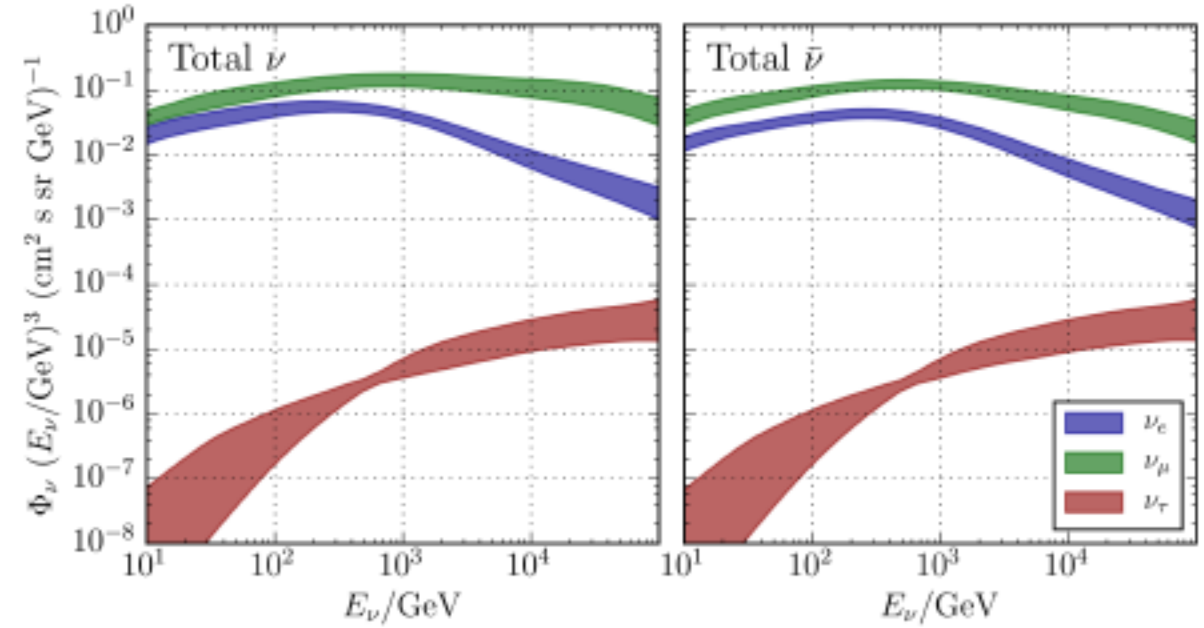


Figure 3. Effects of different models on our flux prediction, for impact parameter b=0. The top row shows various primary models; the second row, hadronic and composition models; the third row, extremal solar density and composition models. See text for more information and references.



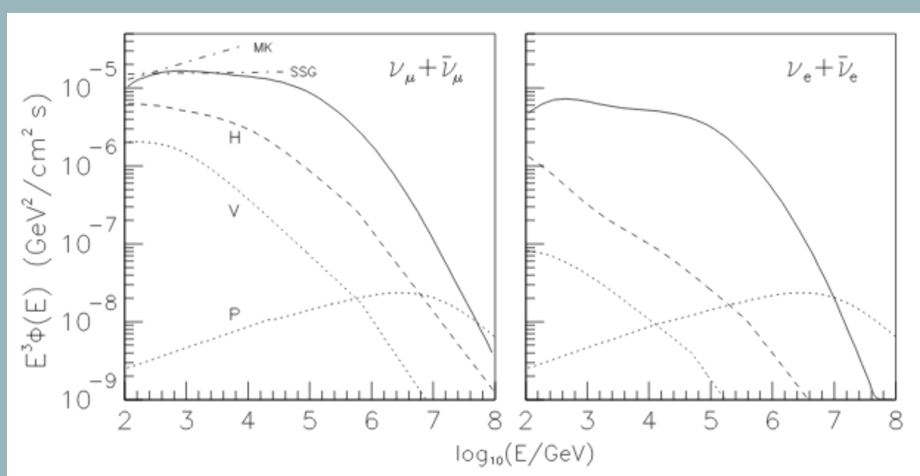
- Flux predictions vary by <30%, based on
  - primary models
  - hadronic and composition models
  - extremal solar density and composition models

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 Analysis

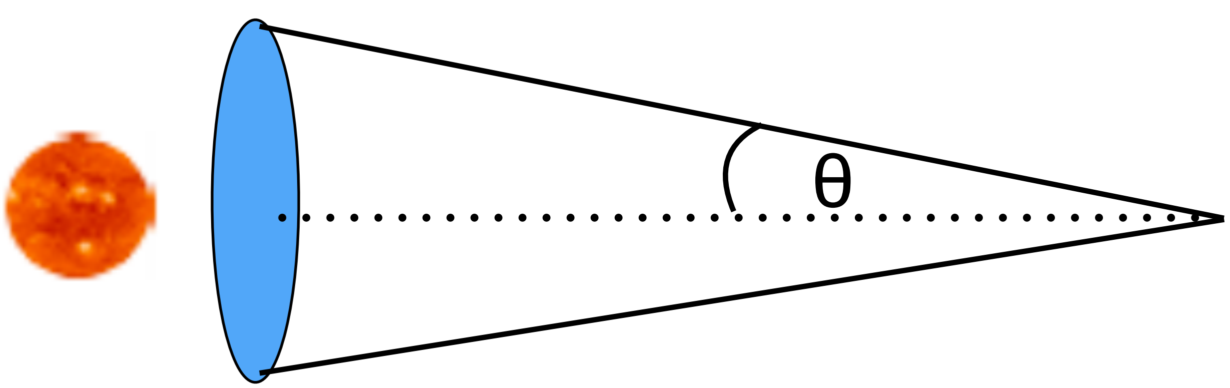
- Ingelman & Thunman flux as **reference signal**
- Honda atmospheric neutrino flux as background

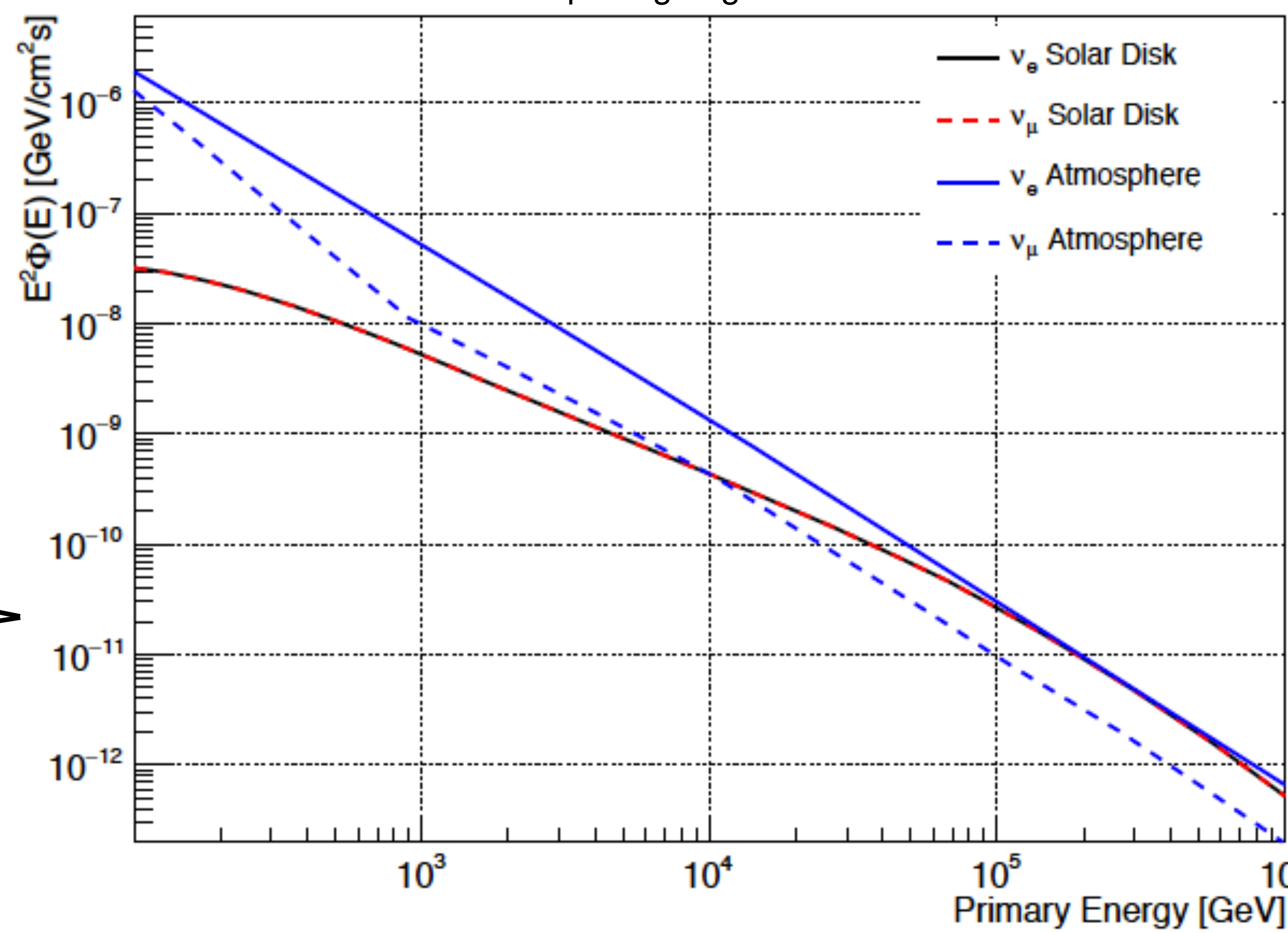


G. Ingelman and M. Thunman, Phys. Rev. D54 (1996) 4385-4392.

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 isotropic (angle averaged flux)



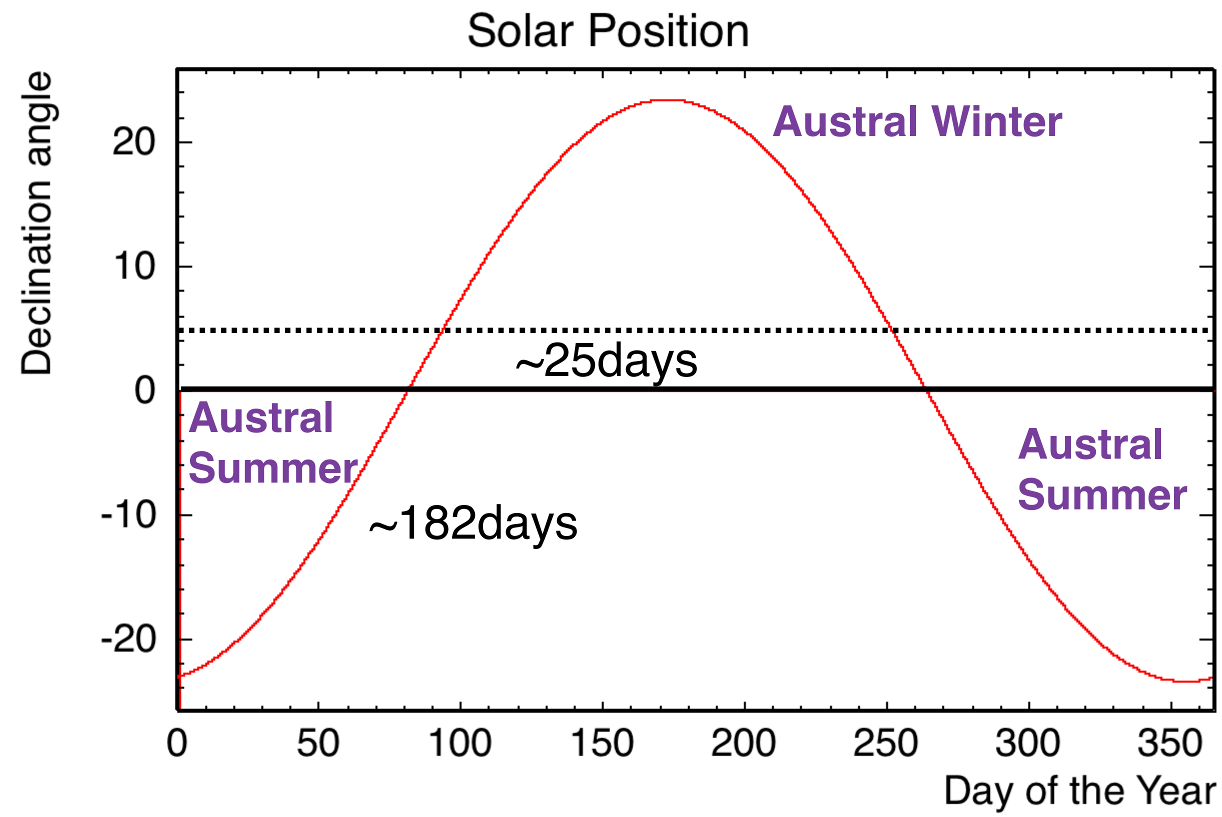


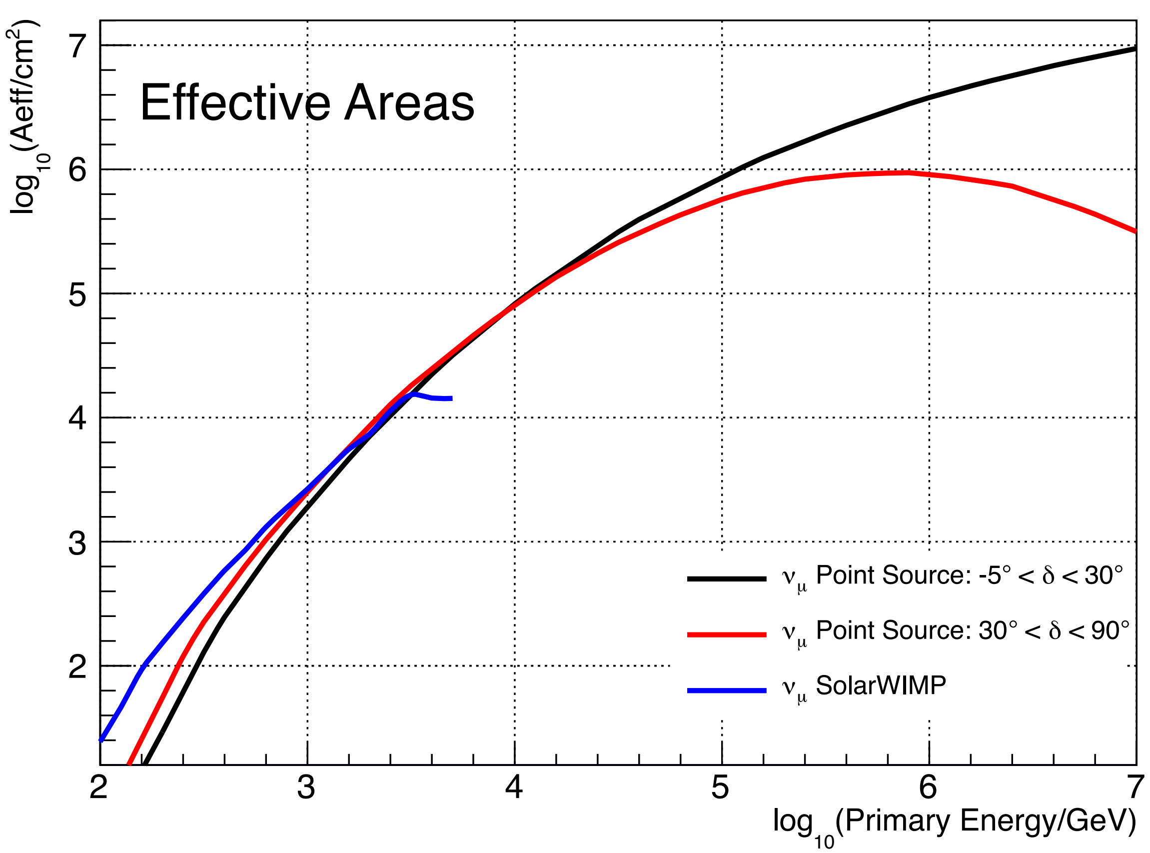
Opening angle used

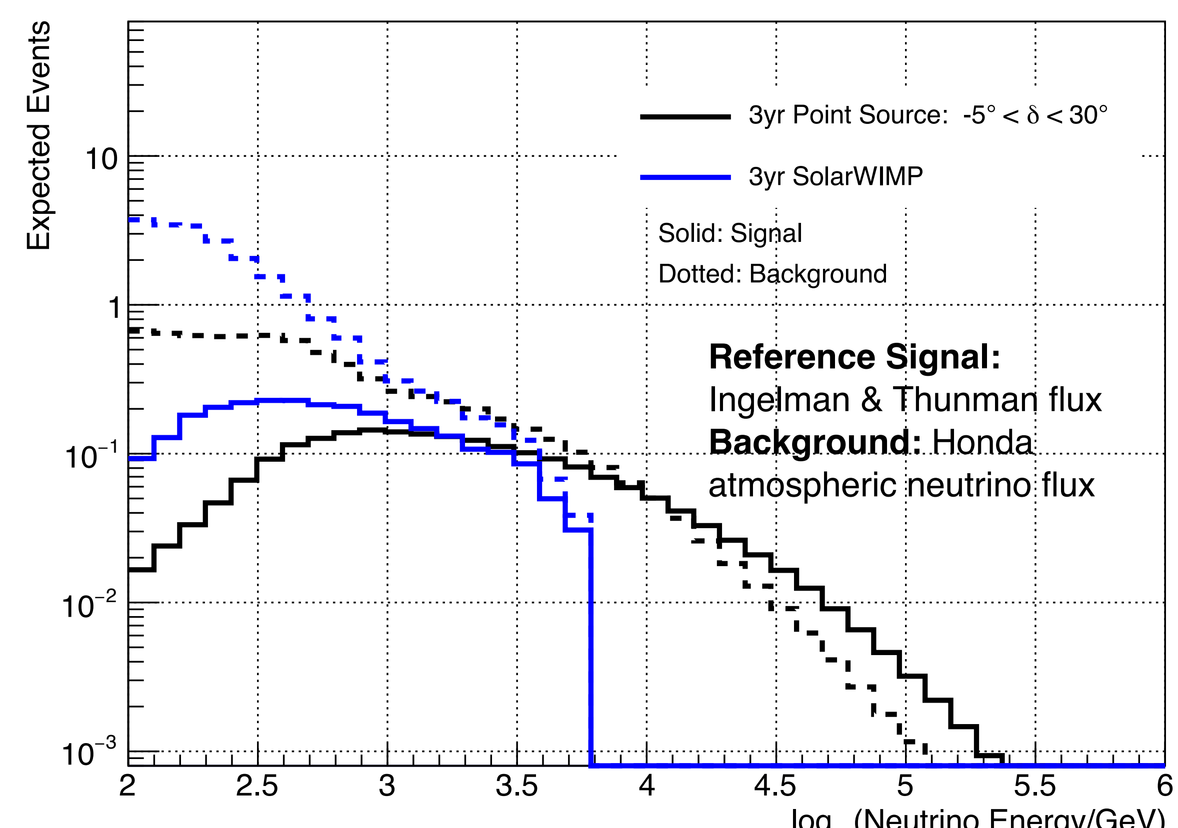
$$\Theta(E,\nu_i) = \begin{cases} \sqrt{100+900/E[GeV]}^{\circ} & \nu_e,\ for\ all\ energi \\ 30^{\circ}/\sqrt{E/GeV} & \nu_\mu,\ E<900GeV \\ 1^{\circ} & \nu_\mu,\ E>900GeV \end{cases}$$

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



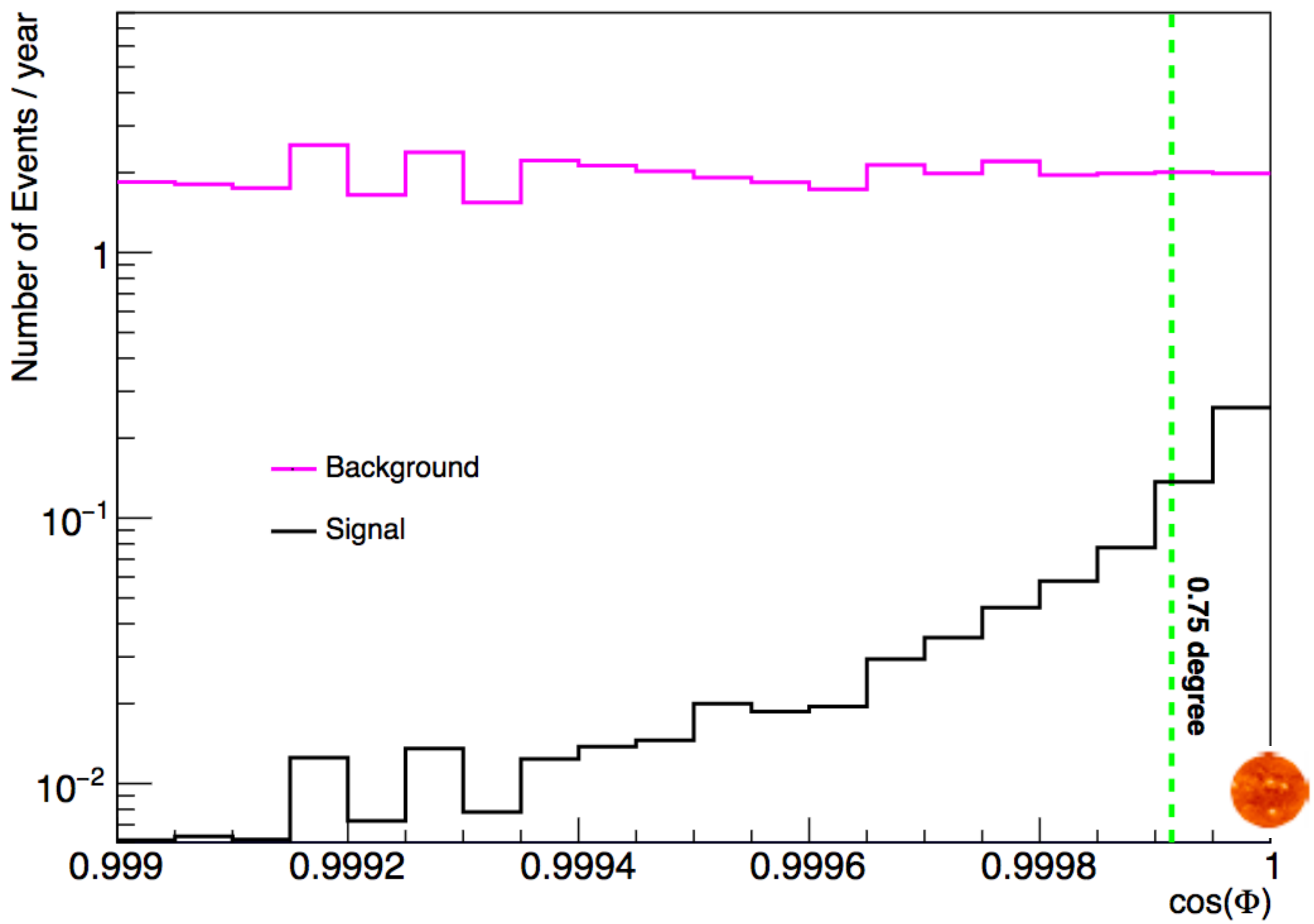




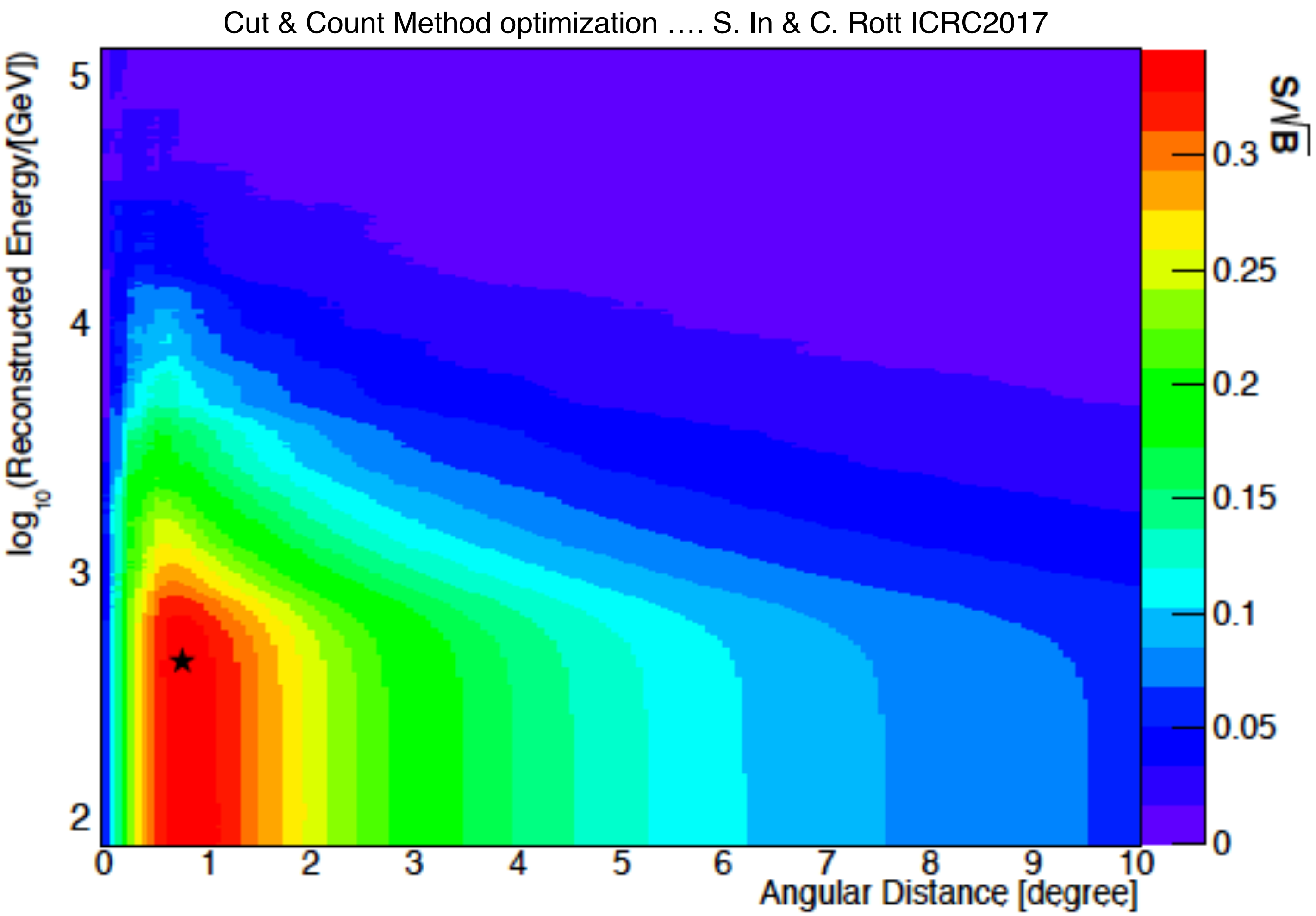
Point Source Sample suites the solar atmospheric neutrino analysis well

Event Expectation Solar Atmospheric Neutrinos

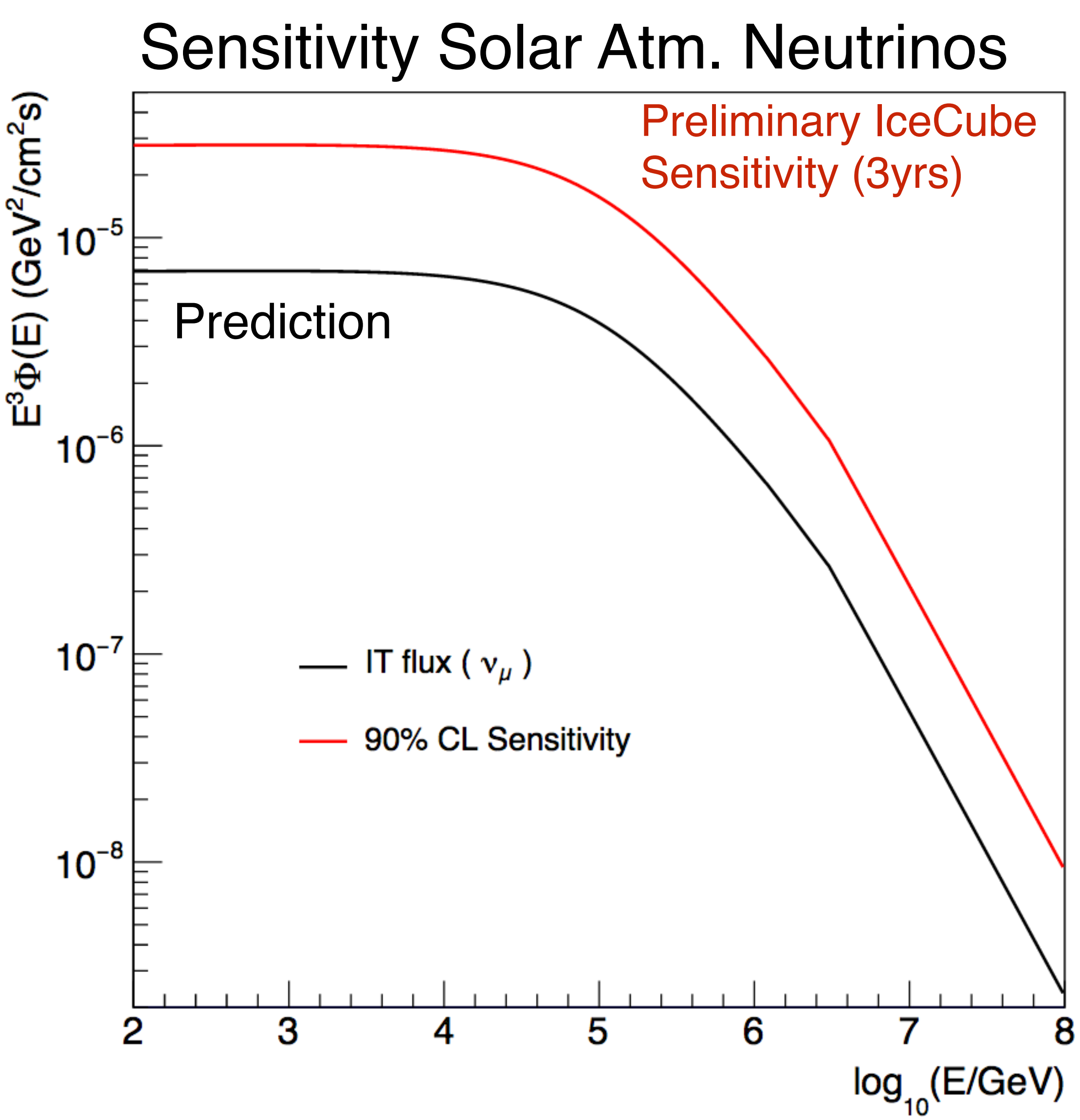
- Using point source analysis sample we determine the expected event rates as function of the distance from the Sun
- Assume emission of solar atmospheric neutrinos homogeneously over the surface of the Sun
- Optimize signal to sqrt(background) ratio based on energy and angle selection cut



Event Expectation Solar Atmospheric Neutrinos



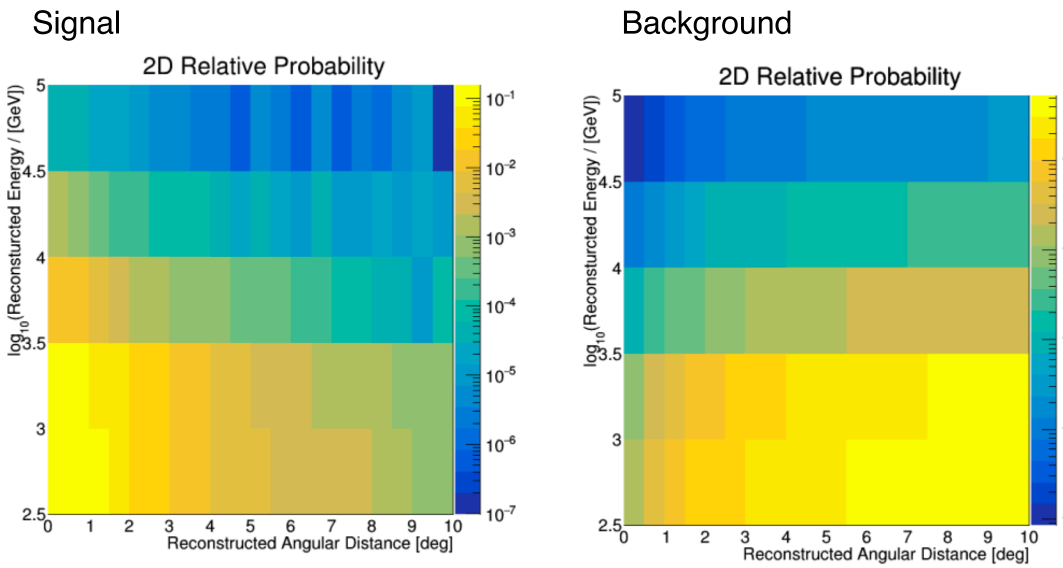
- Preliminary optimization yields the following selection cuts:
  - E > 430GeV
  - ψ < 0.75°
- Next: likelihood method …



- 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

Next steps

- Cut & Count sensitivity
  - Sensitivity falls short by factor of ~3 compared to expected signal flux (assuming 3 years of data)
    - Promising ! With careful optimization we might be able to find an excess ?
- Improvements
  - Lifetime
    - 7years of full IceCube detector data are available
  - Detection channels
    - All flavors (not just muon neutrinos)
  - Likelihood analysis
    - Likelihood based on energy (E) and angle to the Sun (ψ)



$$L(E,\theta) = \prod(f_{sig}(\mu) * p_{sig}(E,\theta|\mu) + f_{bkg}(\mu) * p_{bkg}(E,\theta\,|\mu))$$

Signal Expectation and Systematics

- Signal expectations
  - Consider extreme cases:
  - (1) Point source at the center of the Sun
  - (2) Rim of the Sun
  - (3) Homogenous over the surface of the Sun
  - Different Signal Models / Distributions
- Systematics
  - Signal acceptance
    - Detector systematics (ice, DOM efficiency, …)
  - Background
    - Use off-source region (background prediction from data itself)

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]
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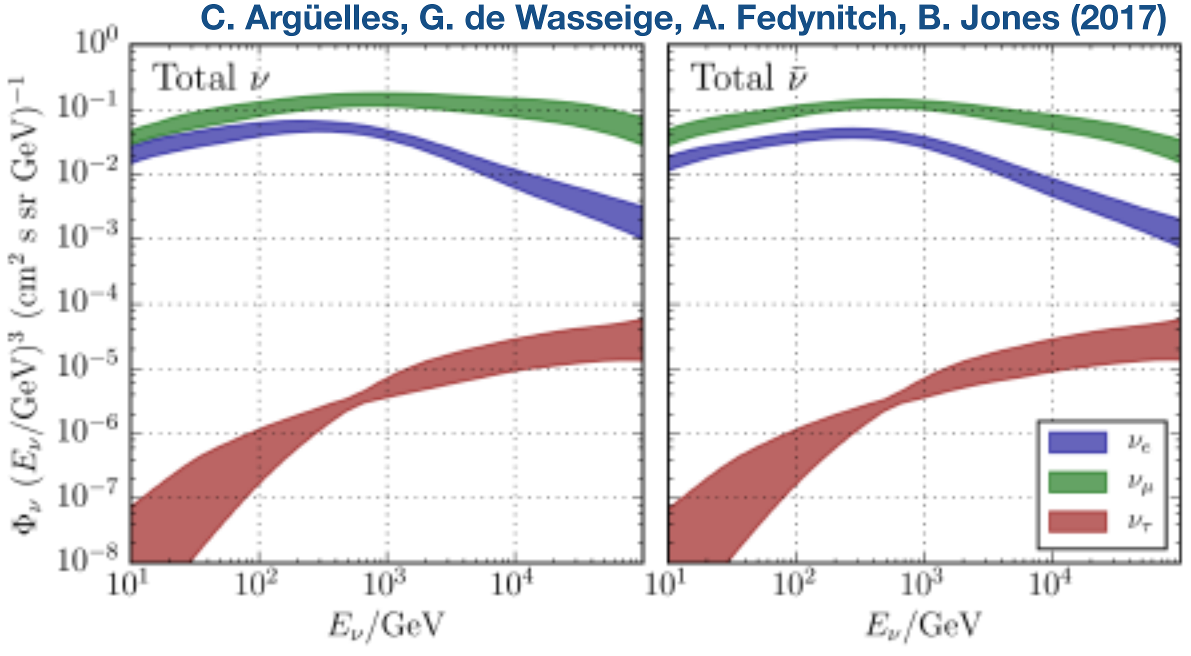
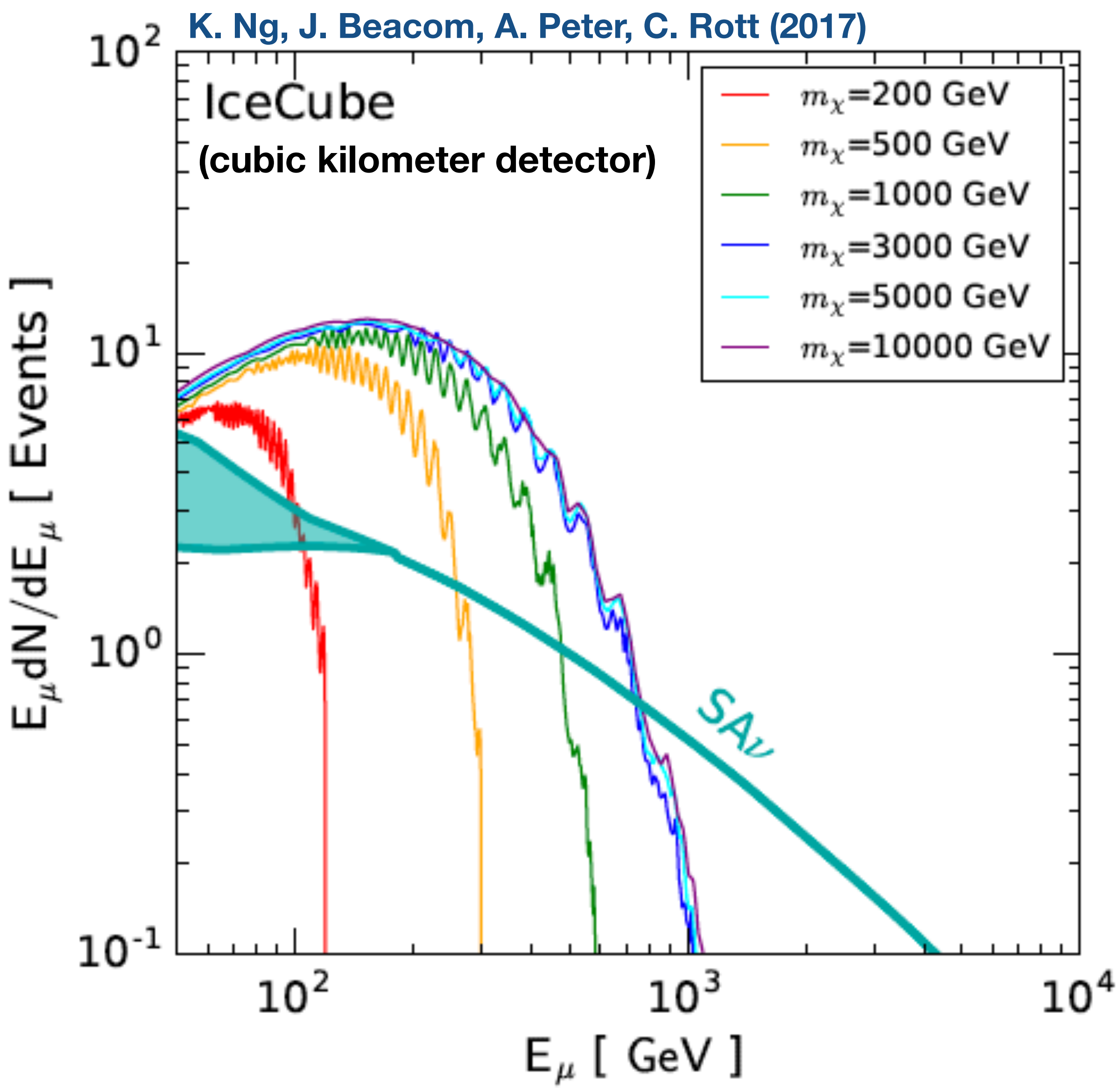
C. Argüelles, G. de Wasseige, A. Fedynitch, B. Jones (2017)

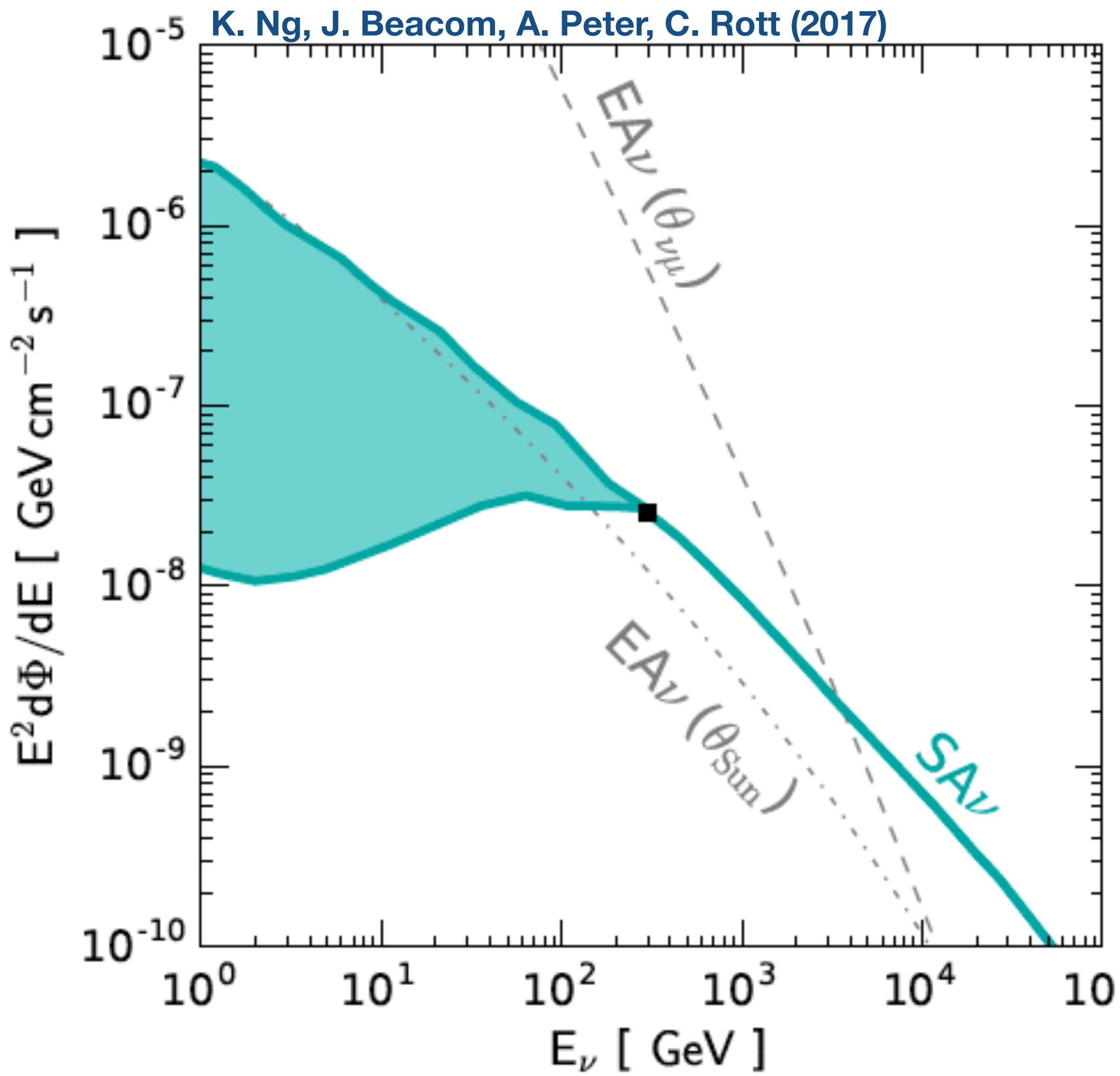


Solar Atmospheric Neutrino Floor

Kenny C. Y. Ng, John F. Beacom, Annika H. G. Peter, **Carsten Rott**
Phys.Rev. D96 (2017) no.10, 103006 [astro-ph/1703.10280]

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

Recent works on the Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor

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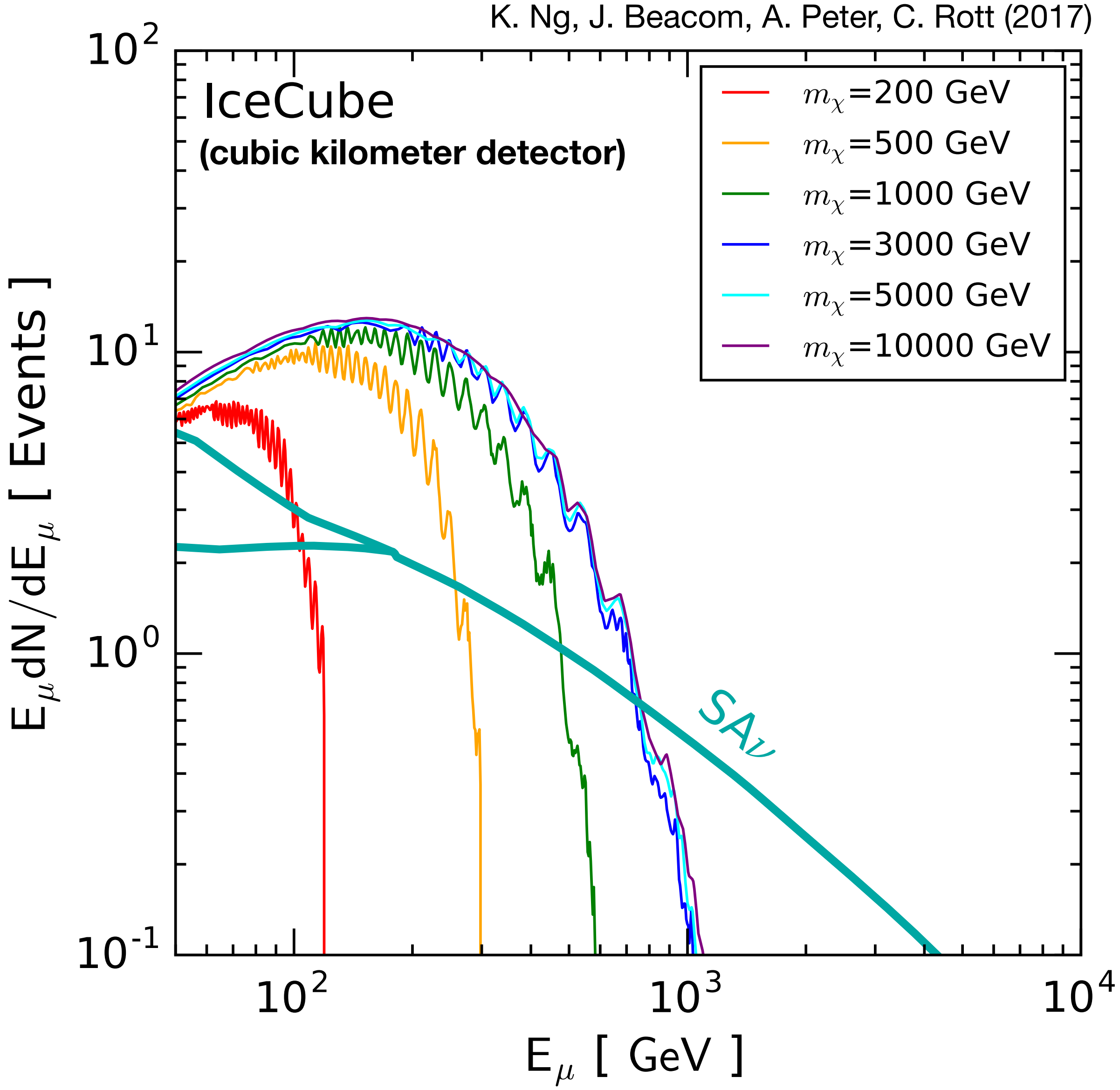

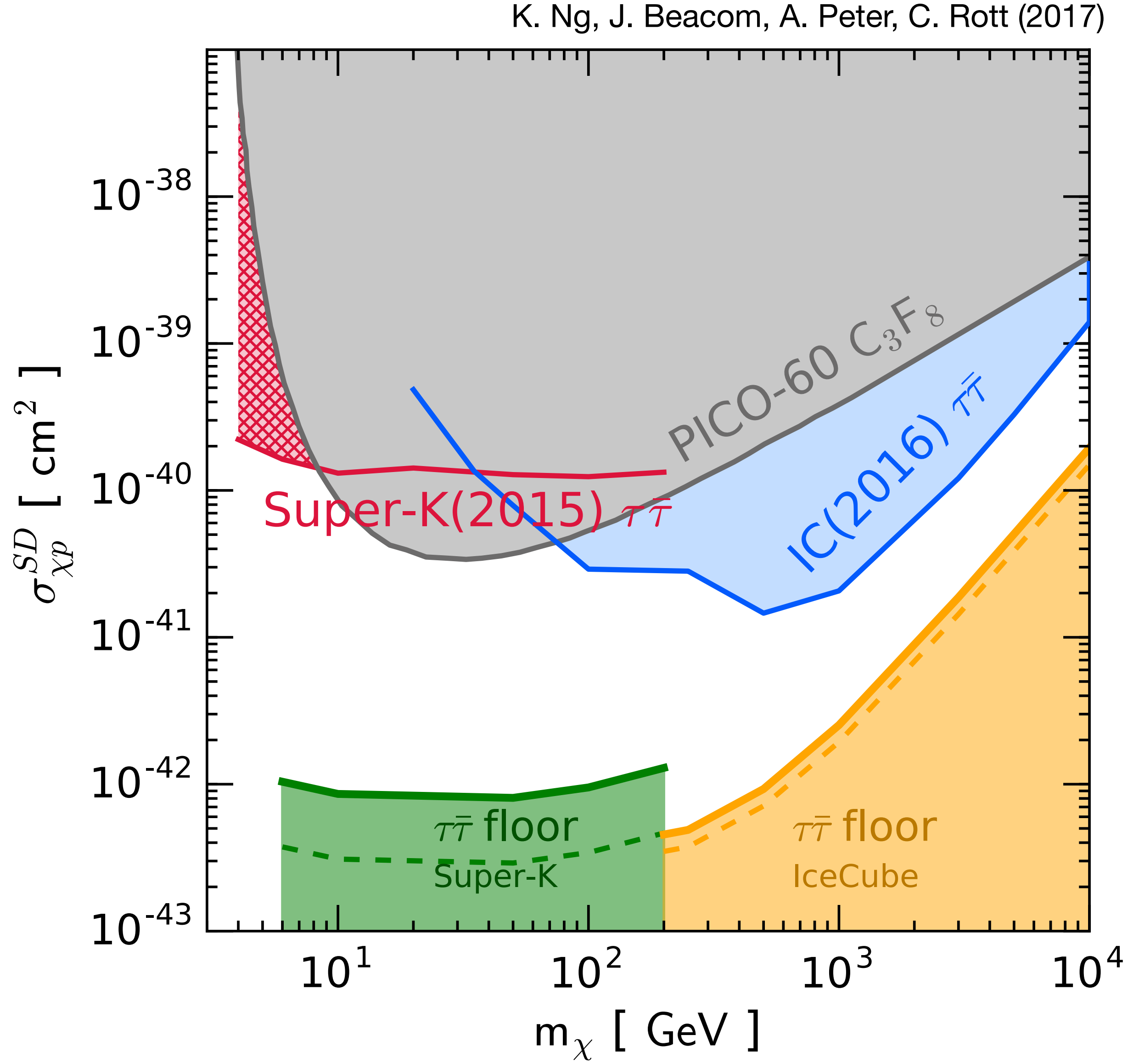

- Natural background to Solar Dark Matter Searches !
- However, energy spectrum expected to be different
- DM annihilation neutrinos significantly attenuated above a few 100GeV

Expect ~2events per year at cubic kilometer detector

Recent works on the Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor

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- M. Masip **Astropart.Phys. 97 (2018) 63-68** [arXiv: 1706.01290]

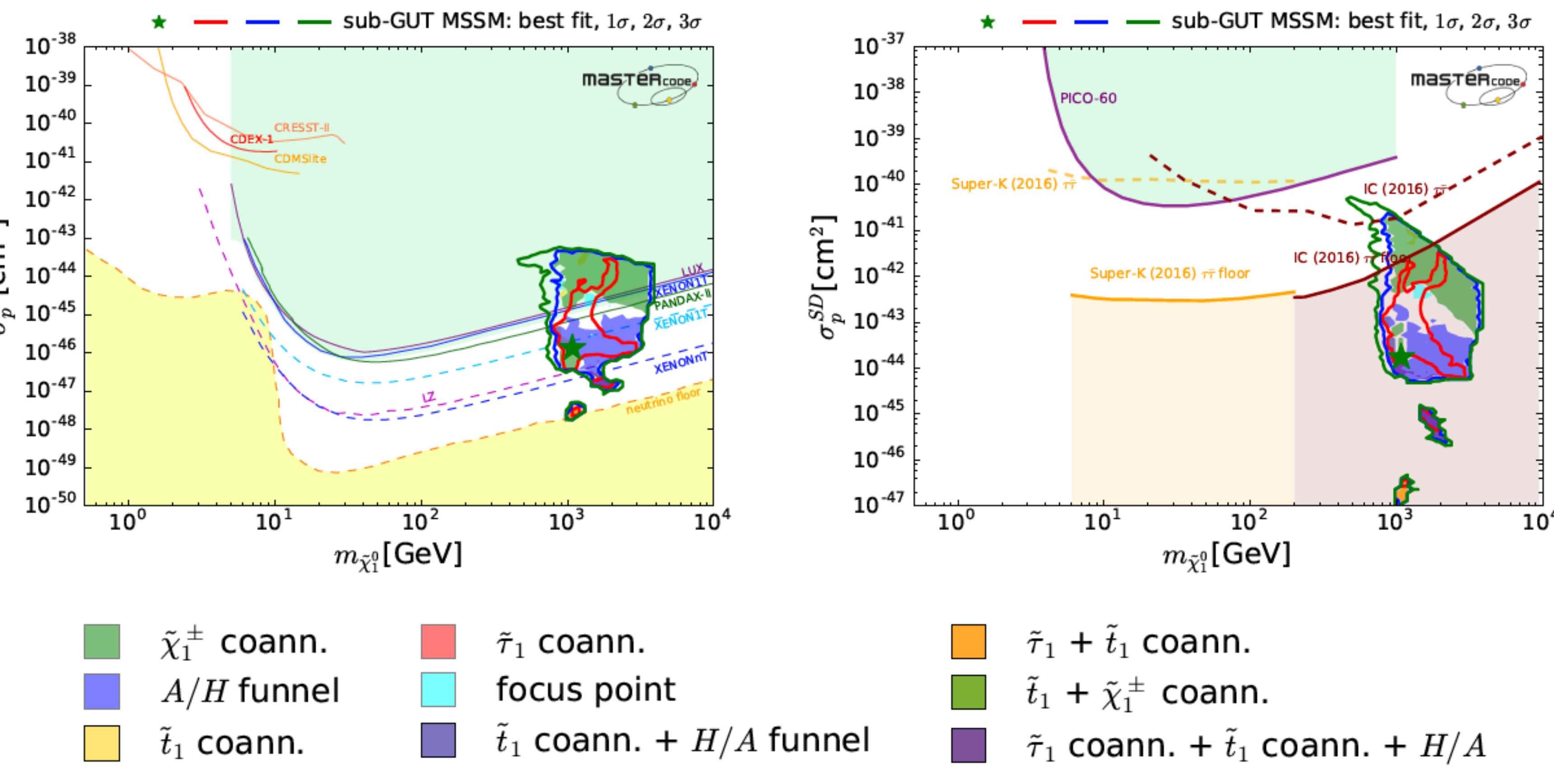
Supersymmetry and Neutrino Floor

- SUSY parameter space scans reveal that many models fall below the neutrino floor
  - Energy spectral information needs to be included to distinguish solar atm. neutrinos from a DM signal
  - Solar atm. neutrinos are identifiable through their high energy (TeV) component

Likelihood Analysis of the Sub-GUT MSSM in Light of LHC 13-TeV Data

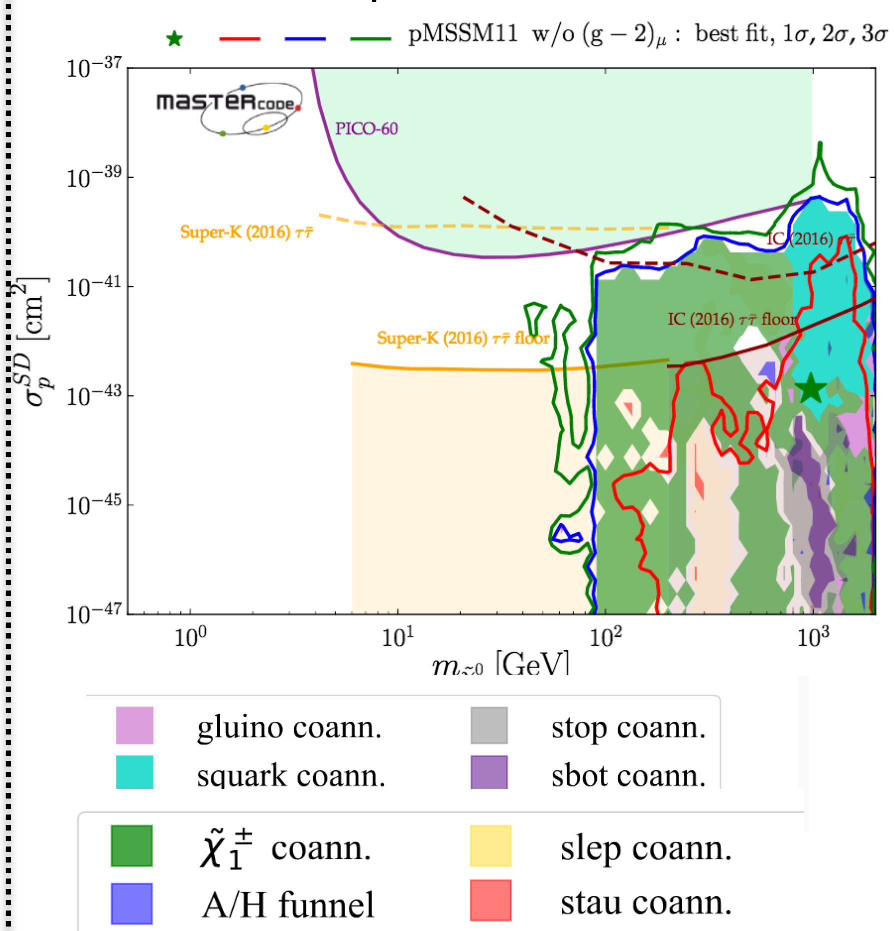
J.C. Costa[a], E. Bagnaschi[b], K. Sakurai[c], M. Borsato[d], O. Buchmueller[a] M. Citron[a], A. De Roeck[e], M.J. Dolan[f], J.R. Ellis[g], H. Flächer[h], S. Heinemeyer[i], M. Lucio[d], D. Martínez Santos[d], K.A. Olive[j], A. Richards[a], G. Weiglein[b]

sub-GUT MSSM



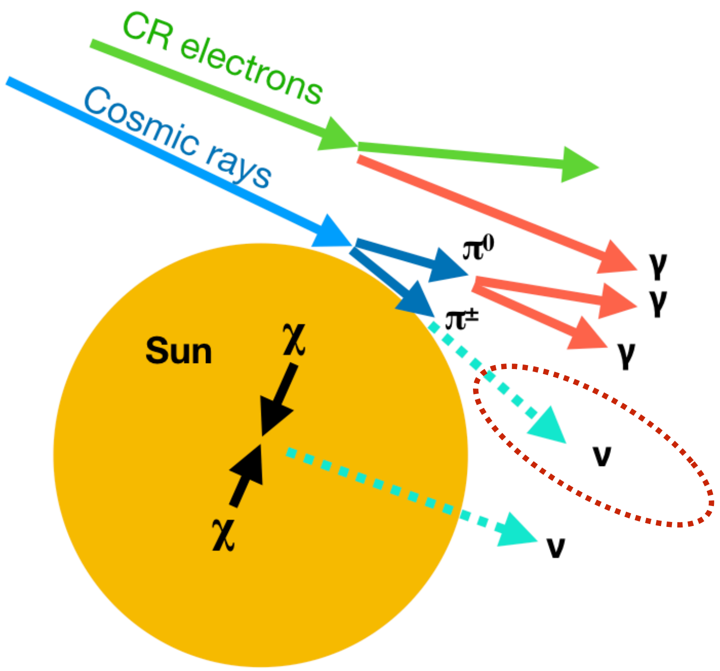
https://arxiv.org/pdf/1711.00458.pdf

pMSSM11



https://arxiv.org/pdf/1710.11091.pdf

Future



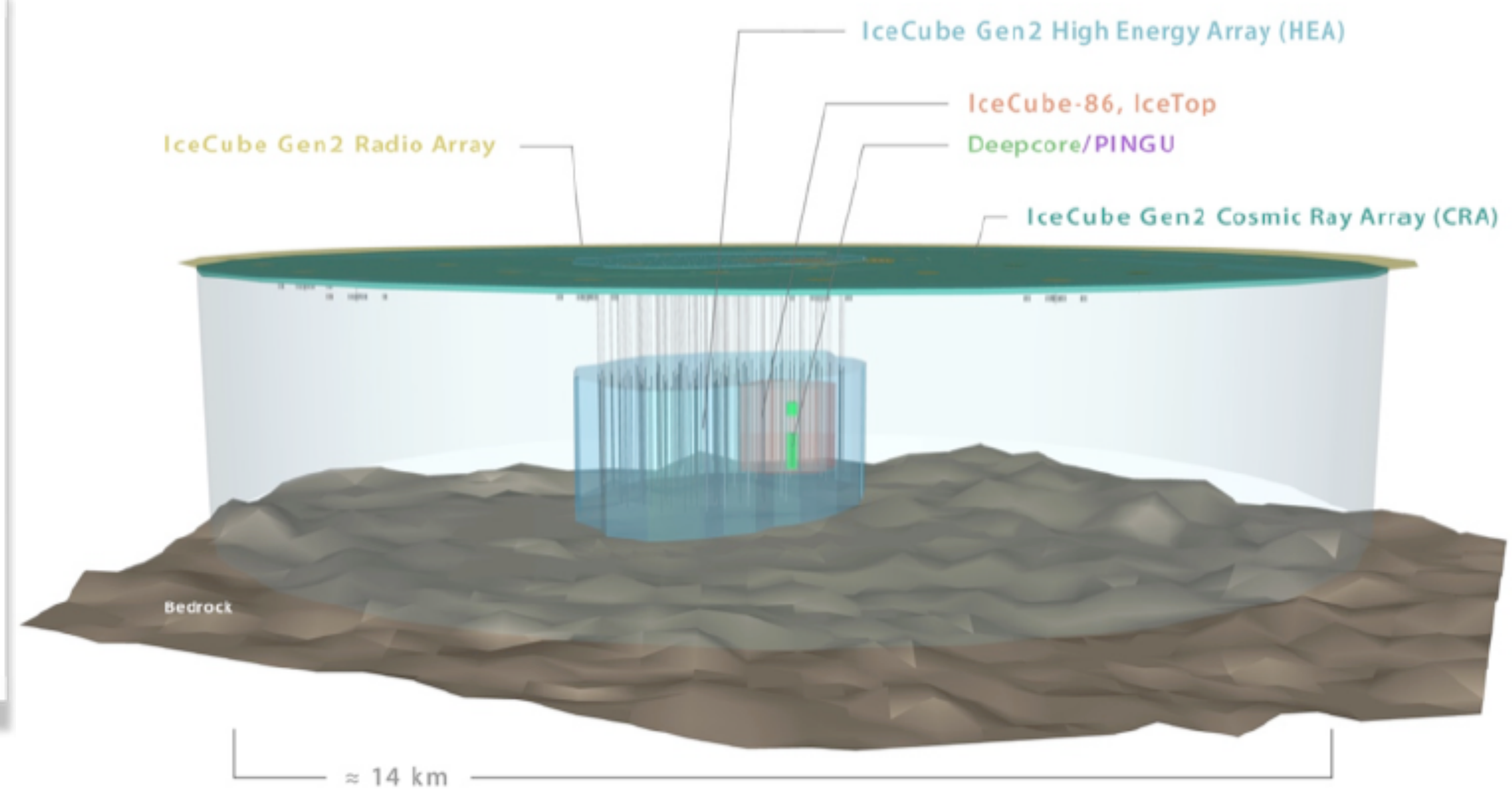
- Solar Atmospheric Neutrinos seem to be in reach of IceCube
    - First high energy neutrino point source ?
    - Expect results early next year

10 Big Ideas for Future NSF Investments

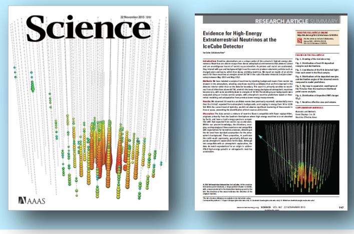
Windows on the Universe: The Era of Multi-messenger Astrophysics

We have arrived at a special moment in our quest to understand the universe. For years, we have been making observations across the known electromagnetic spectrum -- from radio waves to gamma rays -- and many great discoveries have been made as a result. Now, for the first time, we are able to observe the world around us in fundamentally different ways than we previously thought possible. Using a powerful and synthetic collection of approaches, we have expanded the known spectrum of understanding and observing reality. Just as electromagnetic radiation gives one view of the universe, particles such as neutrinos and cosmic rays provide a different view. Gravitational waves give yet another.

IceCube Gen2 Facility

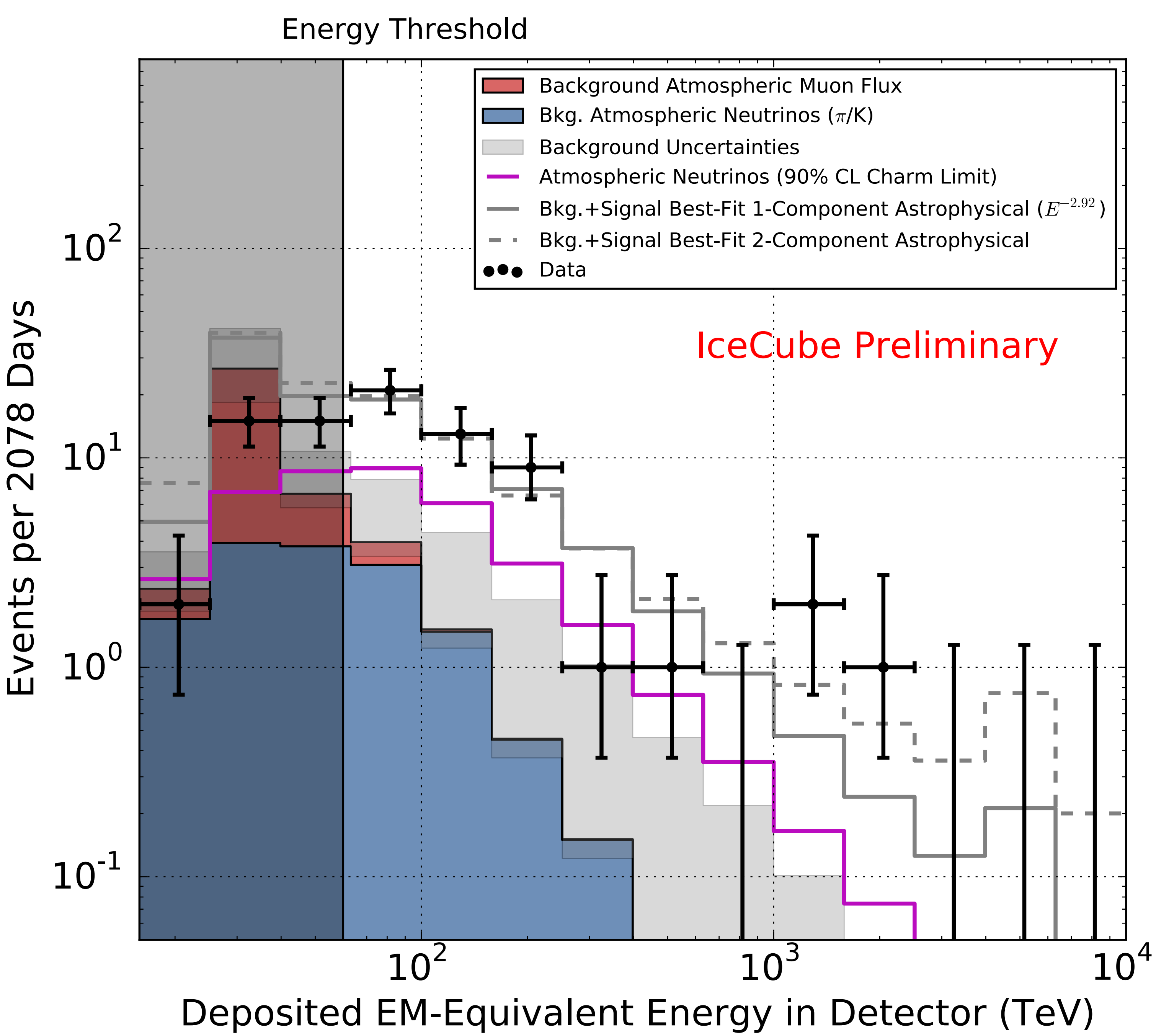


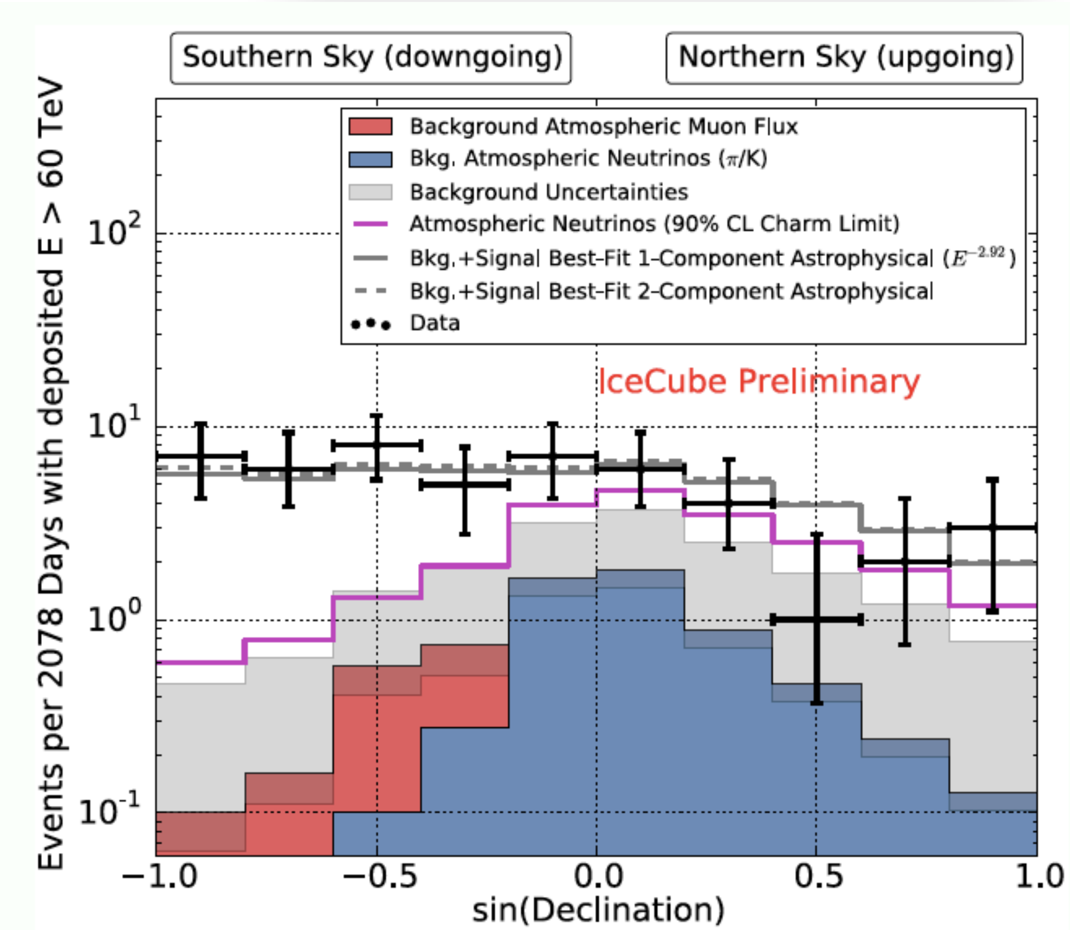
High-energy neutrino search 6years



HESE 6yrs 80 events (track-like & showers) observed

Expected from the Earth atmosphere ~41events

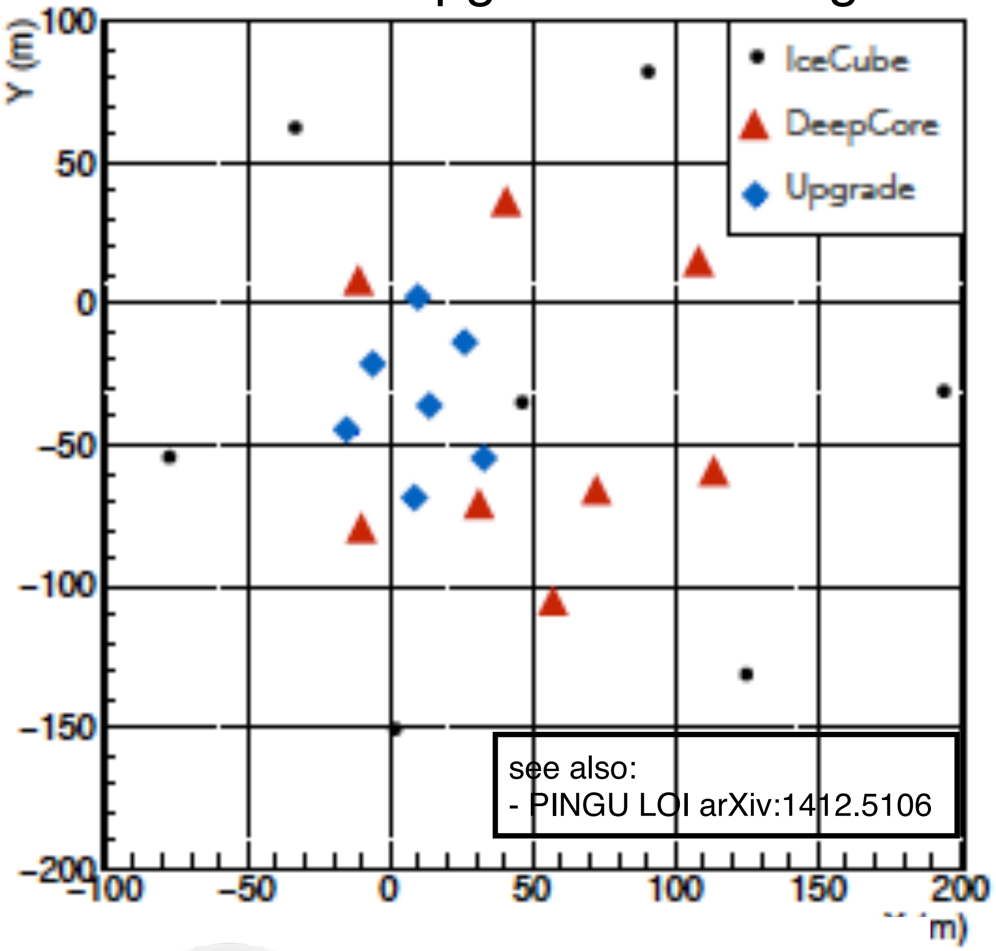


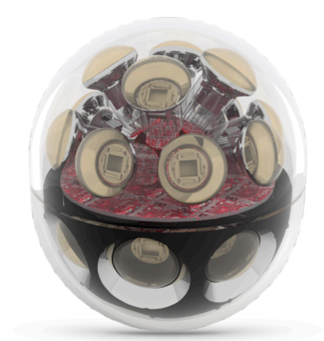


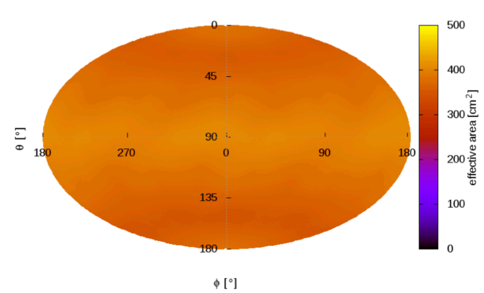
Best fit spectral index ($E^{-\gamma}$): $\gamma=-2.92^{+0.33}_{-0.29}$

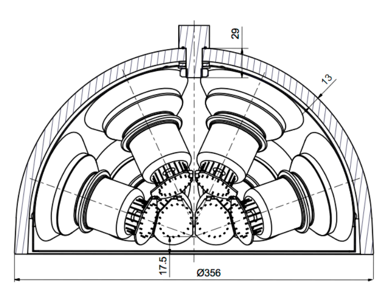
The IceCube Upgrade

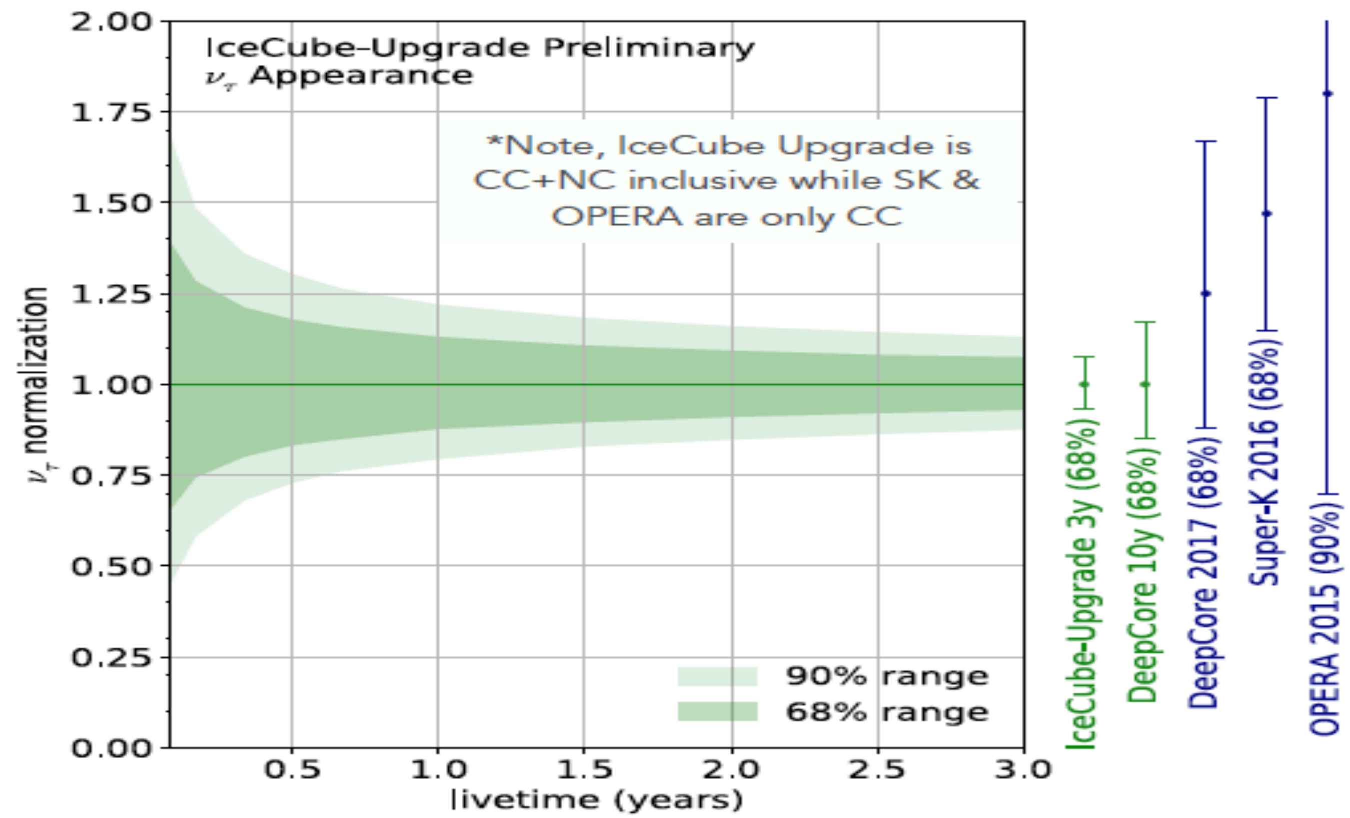
“The IceCube Upgrade” ~7strings





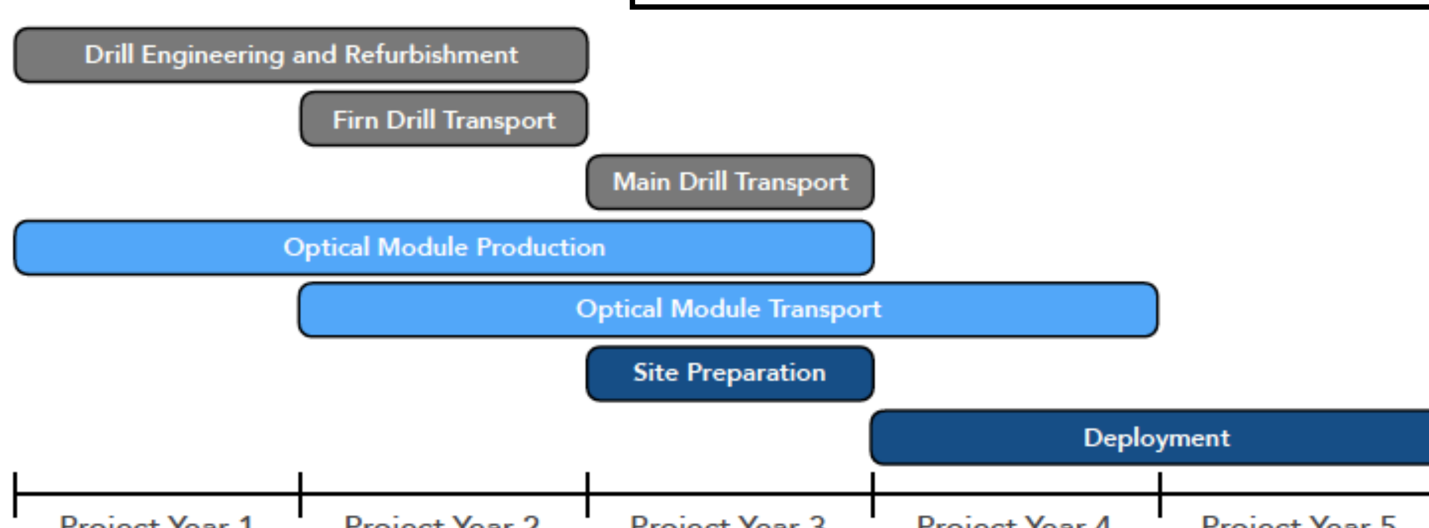




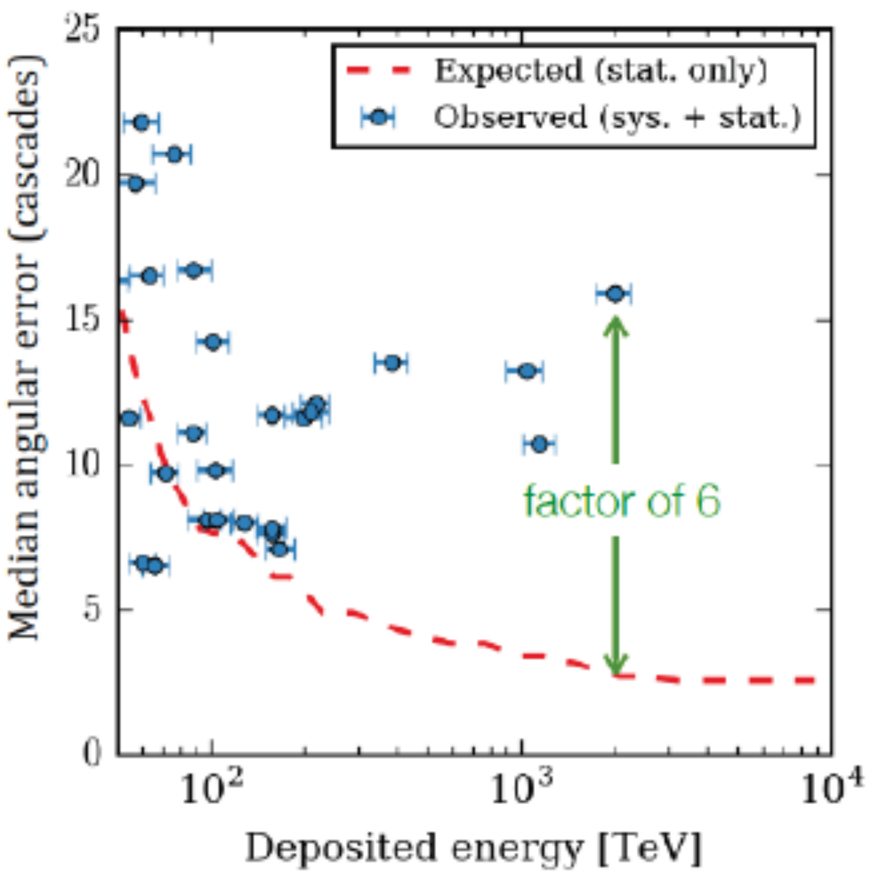


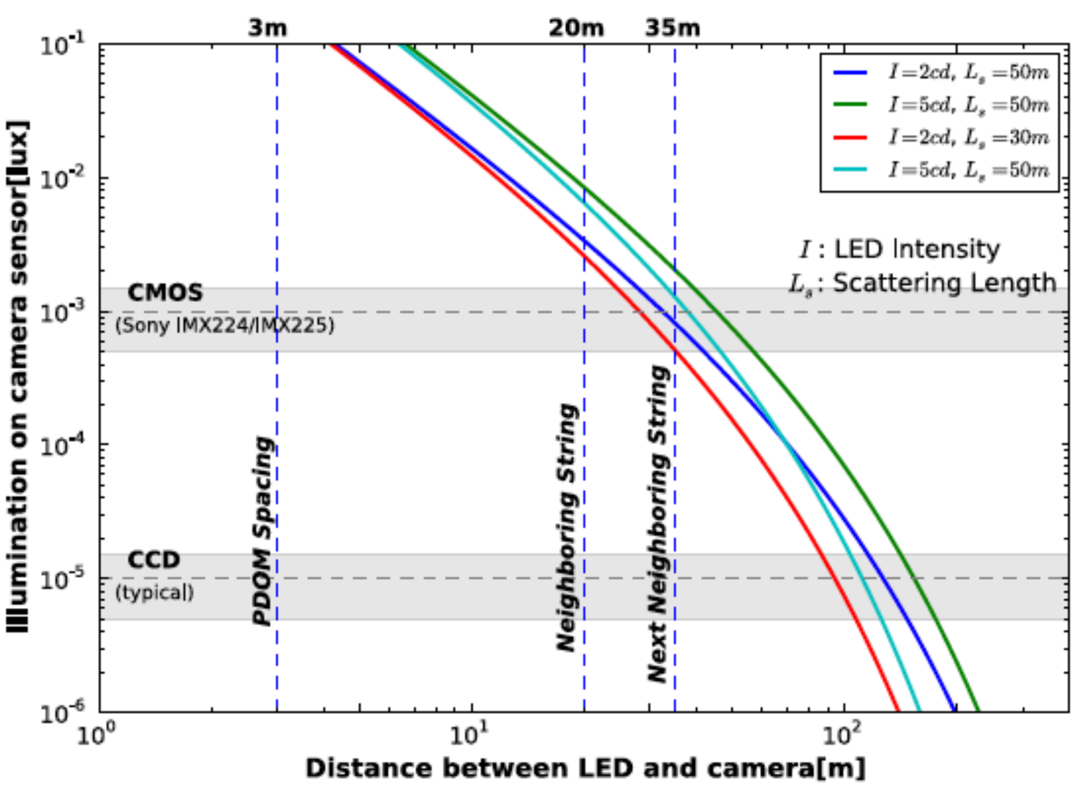
First step to restart South Pole activities

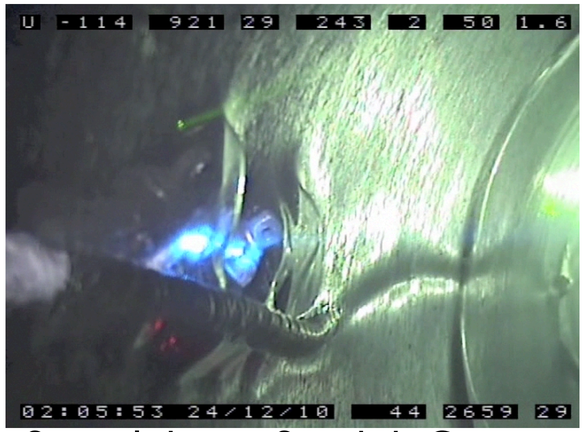
- Tau neutrino appearance
- Calibration devices
- Platform to test new technologies



Sungkyunkwan Gen2 Ice Camera System





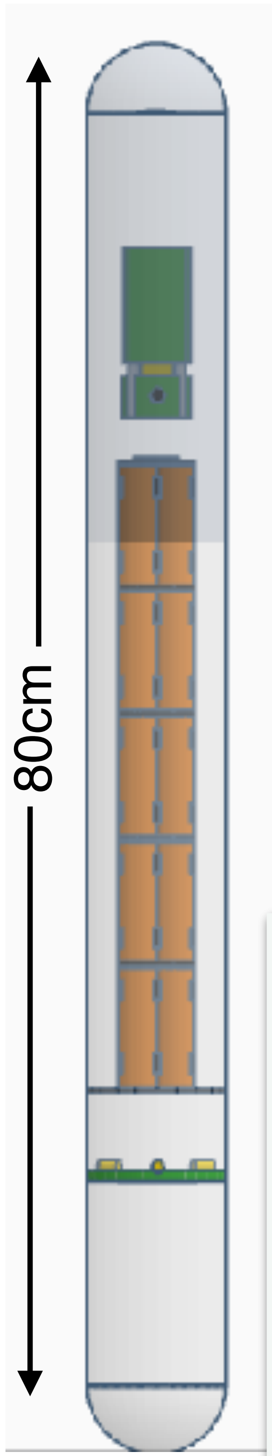


Special device Swedish Camera

- Ice properties dominant source of sys. uncertainties for most analyses
- Solution: <u>Low cost camera system</u>
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability

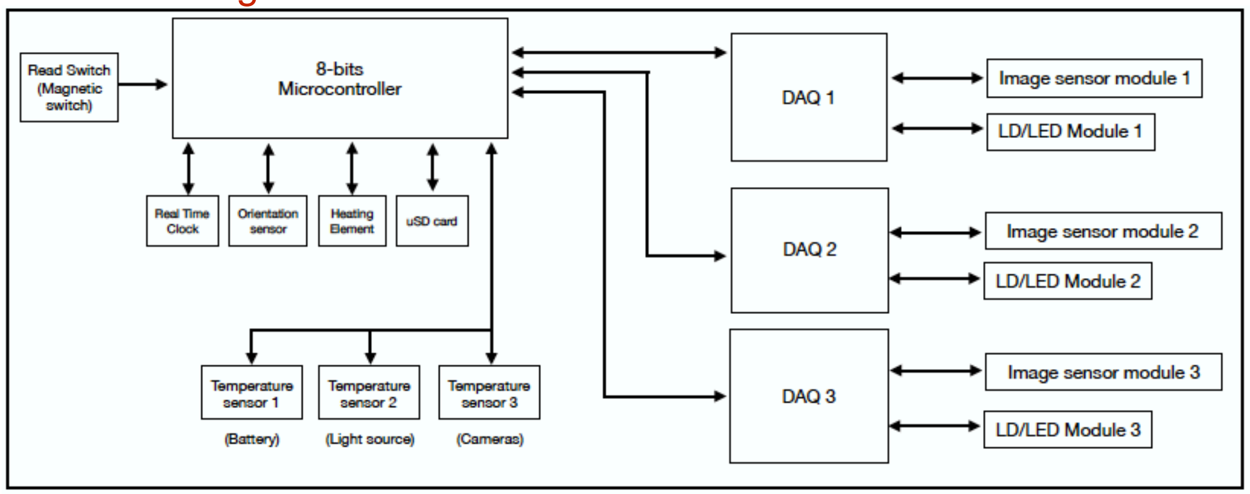
SKKU Spice Core Camera

SKKU SPICE Hole camera

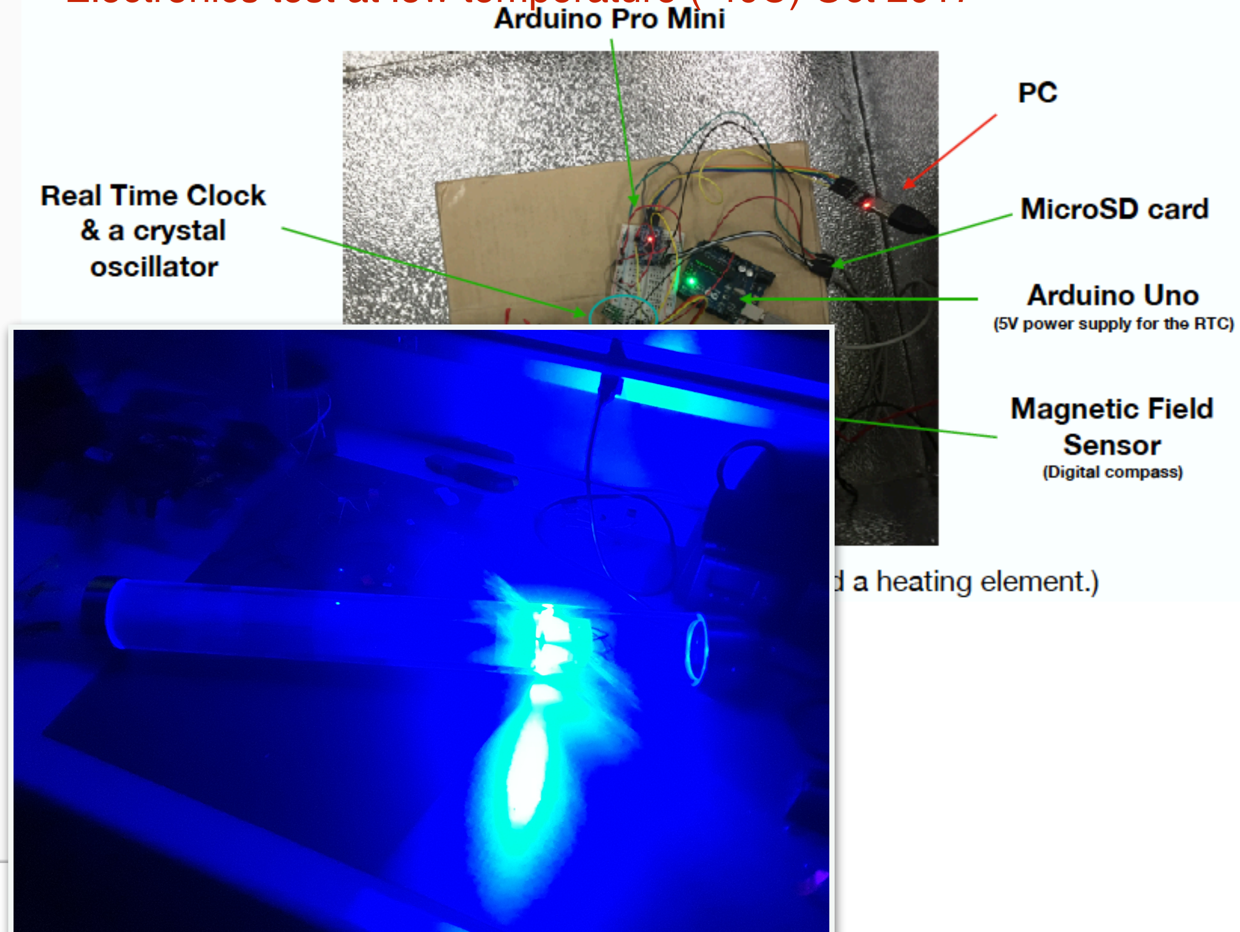


9.2cm

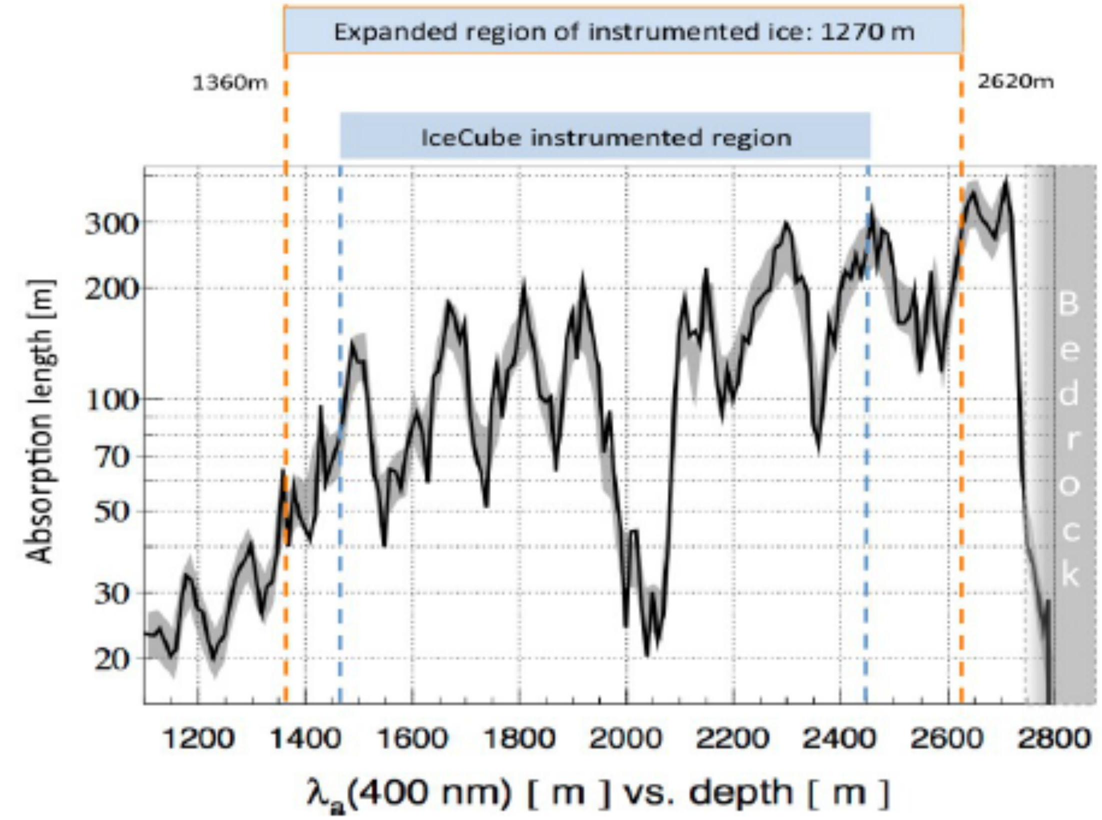
Function Diagram



Electronics test at low temperature (-40C) Oct 2017



Scheduled for deployment at the South Pole in 2018
SPICE Core hole (0-1750m) 1km from IceCube side



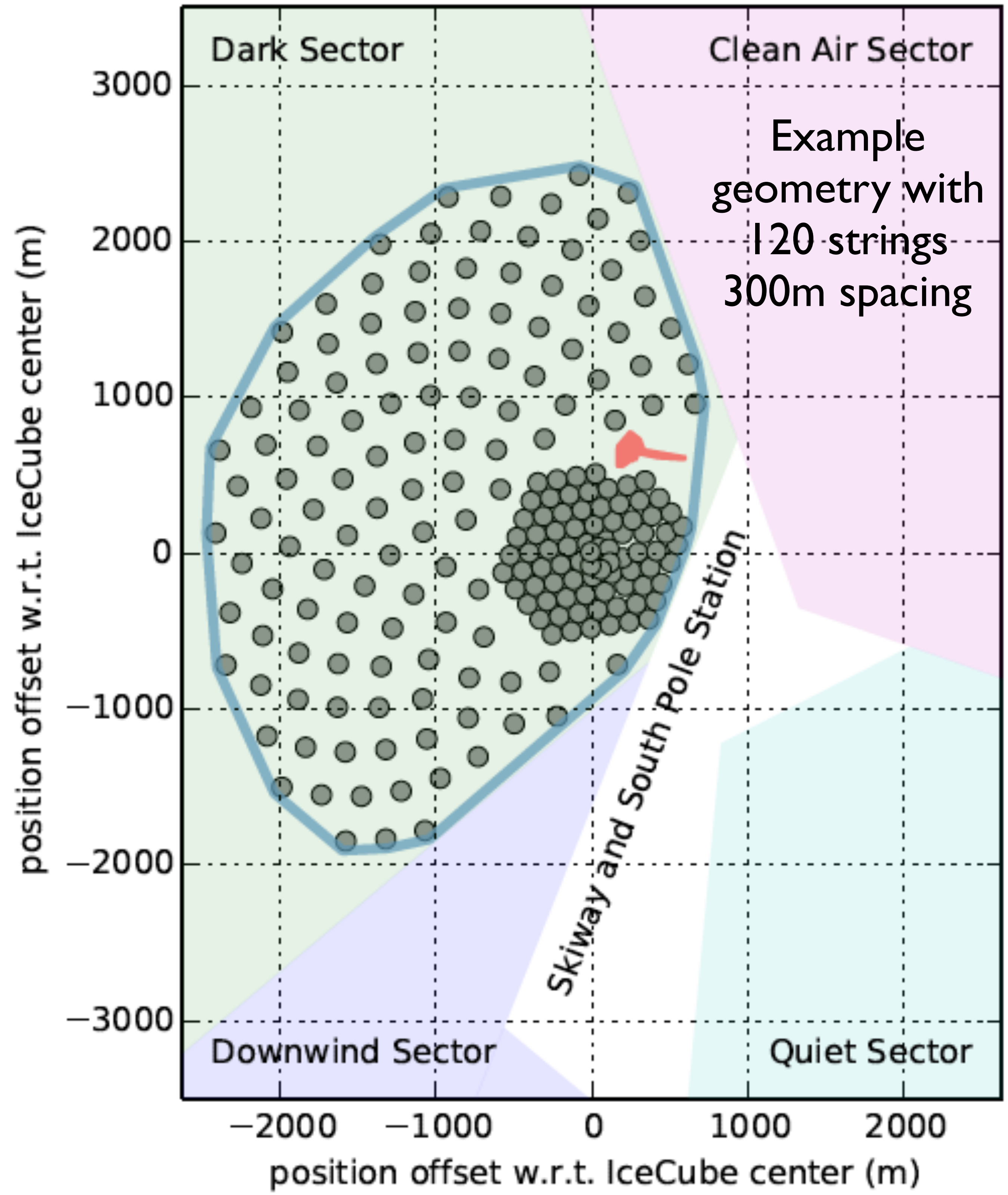
- Goals of the SPICE Hole camera
  - Measure anisotropy in the ice
  - Demonstrate that cameras can be used to perform quantitate ice property measurements

Interdisciplinary science

IceCube Gen2

- IceCube has provided an amazing san
  of events, but is still statistics limited
- Observed astrophysical flux is consis
  with a isotropic flux of equal amount
  all neutrino flavors
  - So far non of the analyses has sho
    any evidence for point sources
- Where are the point sources?
- What is the flavor composition?
- What is the spectrum? Cutoff?
- Transients ?
- Multi-messenger physics?
- GZK neutrinos?
- New physics or something unexpecte
- …

IceCube Coll. Gen2 LOI arXiv:1412.5106



Conclusions

Conclusions

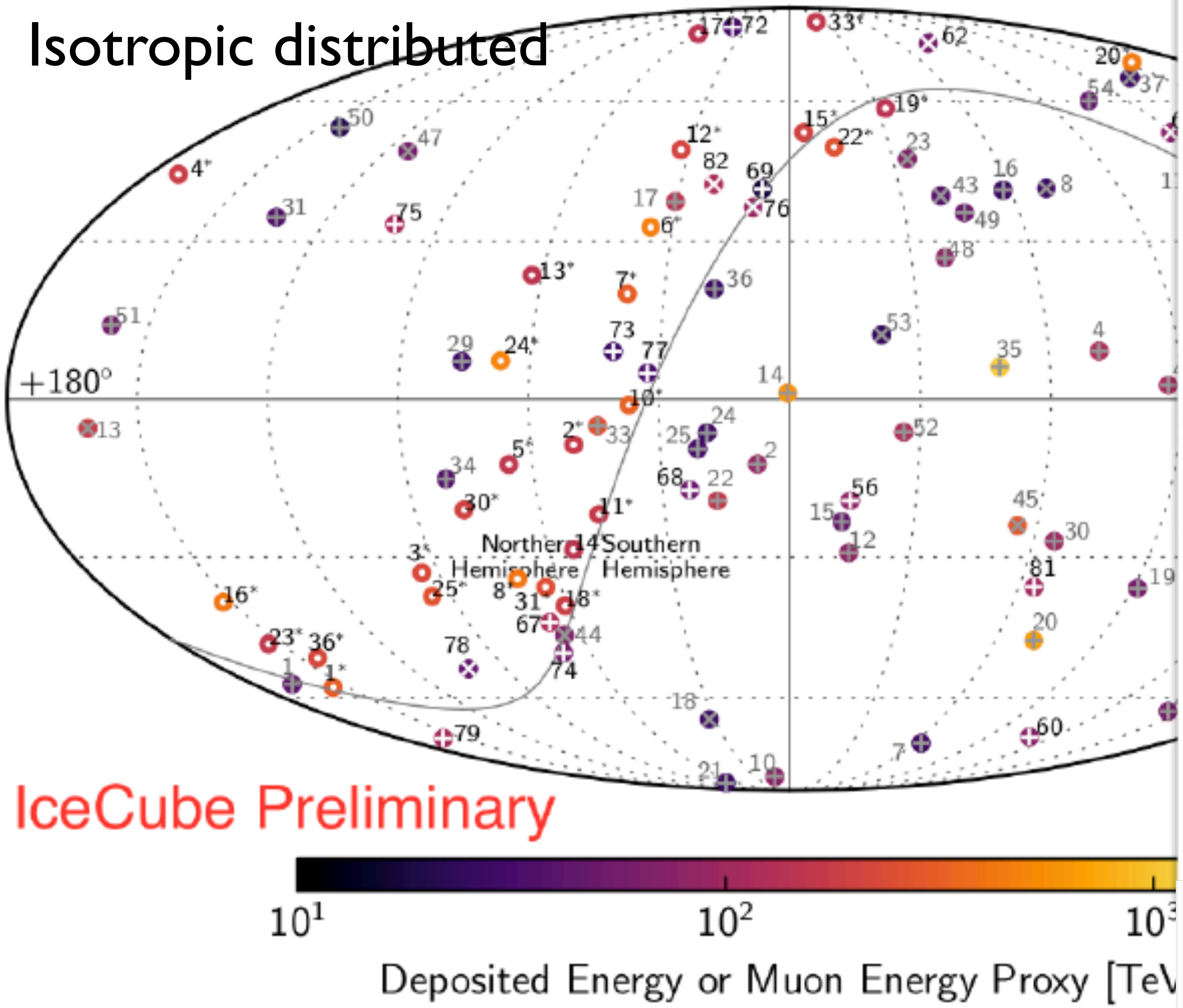
- The Sun is an exciting target for neutrino telescopes
    - IceCube set the worlds best bound on spin-dependent dark matter nucleon scattering for masses above 100GeV
    - Cosmic ray shadow provides clues about propagation in the inner solar system
    - Solar atmospheric neutrinos might be observable 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

Image:Stephan Richter, IceCube/NSF

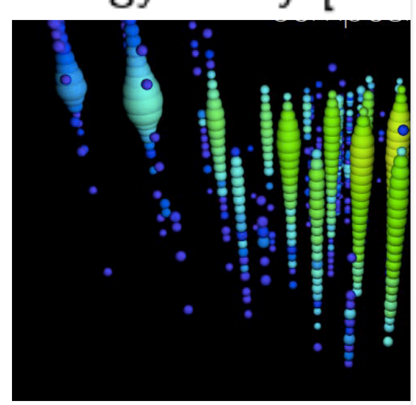
Arrival directions (highest energy events)

IceCube Collaboration, *Science* 342, 1242856 (2013)

Isotropic distributed



- N New Starting Tracks
- N New Starting Cascades
- N Earlier Starting Tracks
- N Earlier Starting Cascades
- N^* Throughgoing Tracks



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Neutrino-Experiment

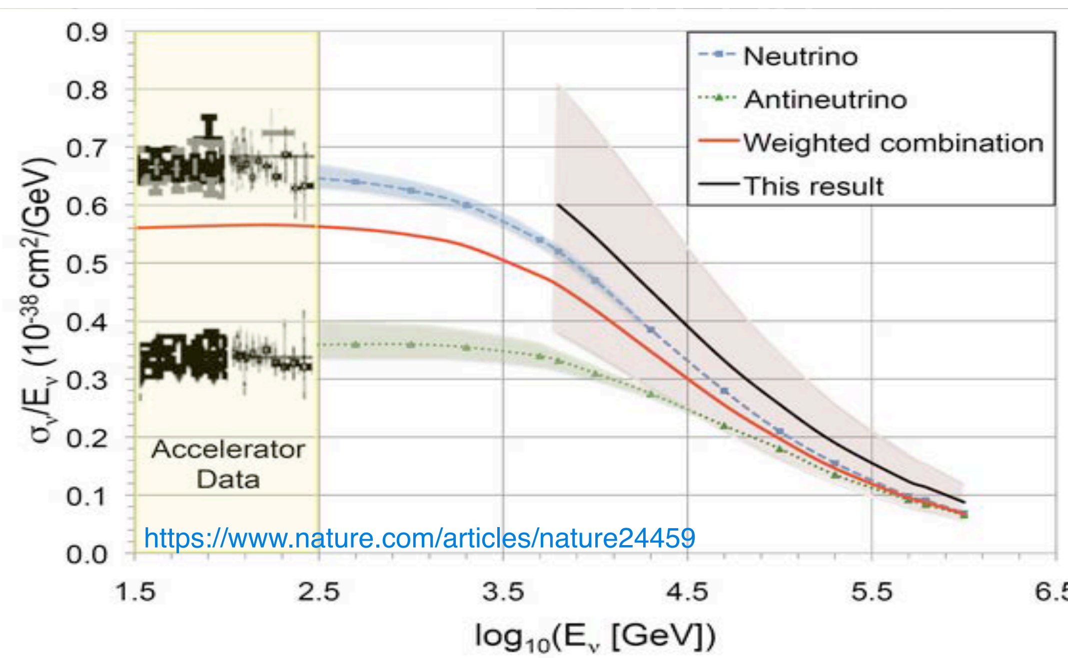
Erde verschluckt geheimnisvolle Geisterteilchen

Neutrinos rasen weitgehend ungestört durchs All, weil sie fast nicht mit normaler Materie interagieren. Aber nur fast. Ausgerechnet unsere Erde ist ein effizienter Neutrino-Killer, wie ein Experiment beweist.

Von Christoph Seidler

Fotos

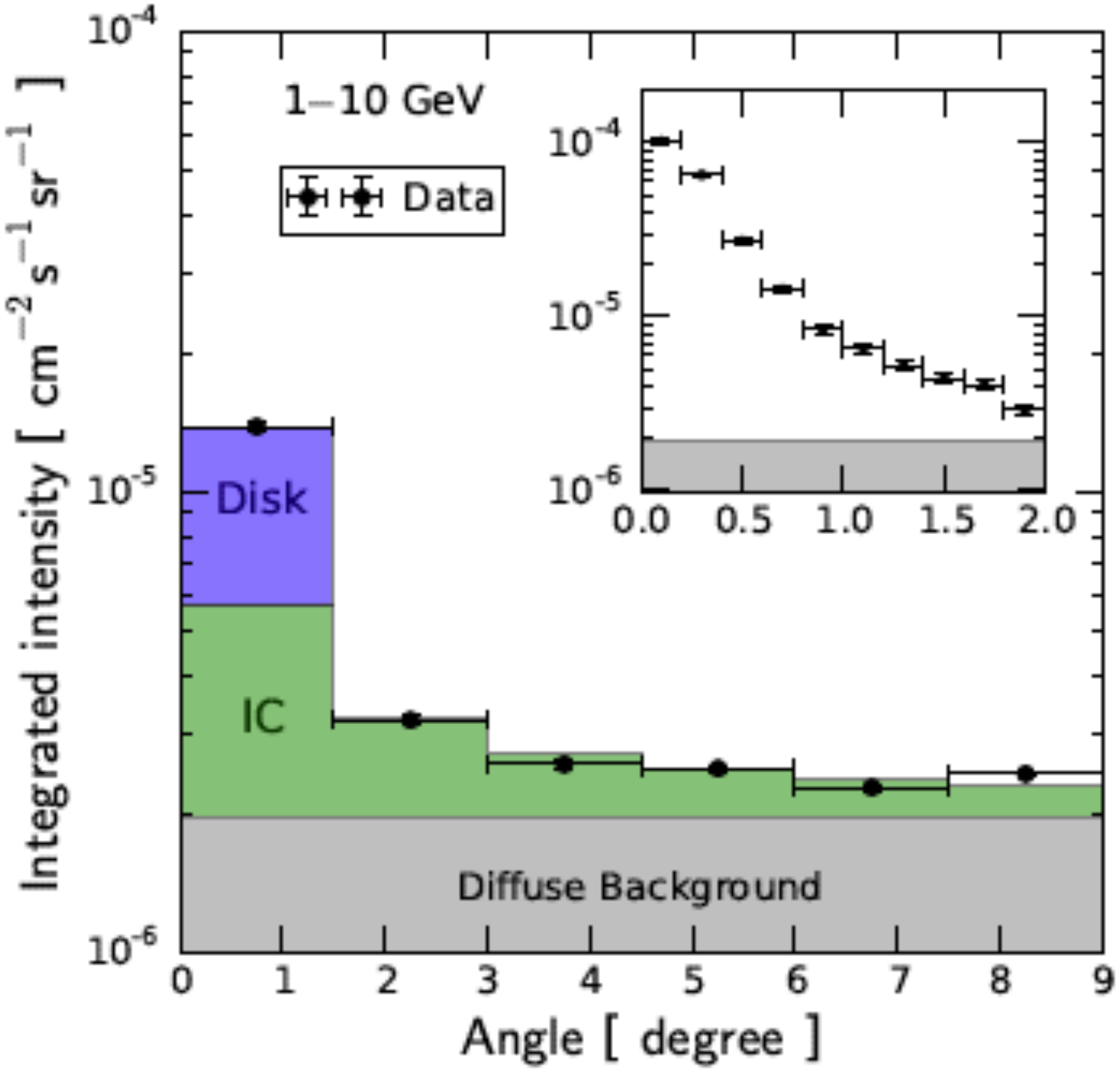
DRV/ Felipe Pedreros/ IceCube/ NSF



Gamma-ray flux within 9° of the Sun

- Photon count maps are divided by exposure maps to obtain flux
- We expect three components:
  - Disk
    - Point source
  - Inverse Compton
    - Extended
  - Diffuse background
    - Isotropic

1-10GeV



$$s_i = s_1\,\delta_{i1}$$

$$b_i^{\mathrm{IC}} = f^{\mathrm{IC}} \sum_j \mathcal{E}_{i,j}\,\alpha_{i,j}^{-1}$$

$$b_i^{\mathrm{BKG}} = f^{\mathrm{BKG}} \sum_j \mathcal{E}_{i,j}$$

Profile likelihood analysis

$$\mathcal{L}(s_1; f^{\mathrm{IC}}, f^{\mathrm{BKG}}) = G(f^{\mathrm{BKG}}) \prod_i P(s_i + b_i^{\mathrm{IC}} + b_i^{\mathrm{BKG}} | d_i)$$

Gaussian term to constrain diffuse background to the value obtained by the fakeSun method

Poisson Probability

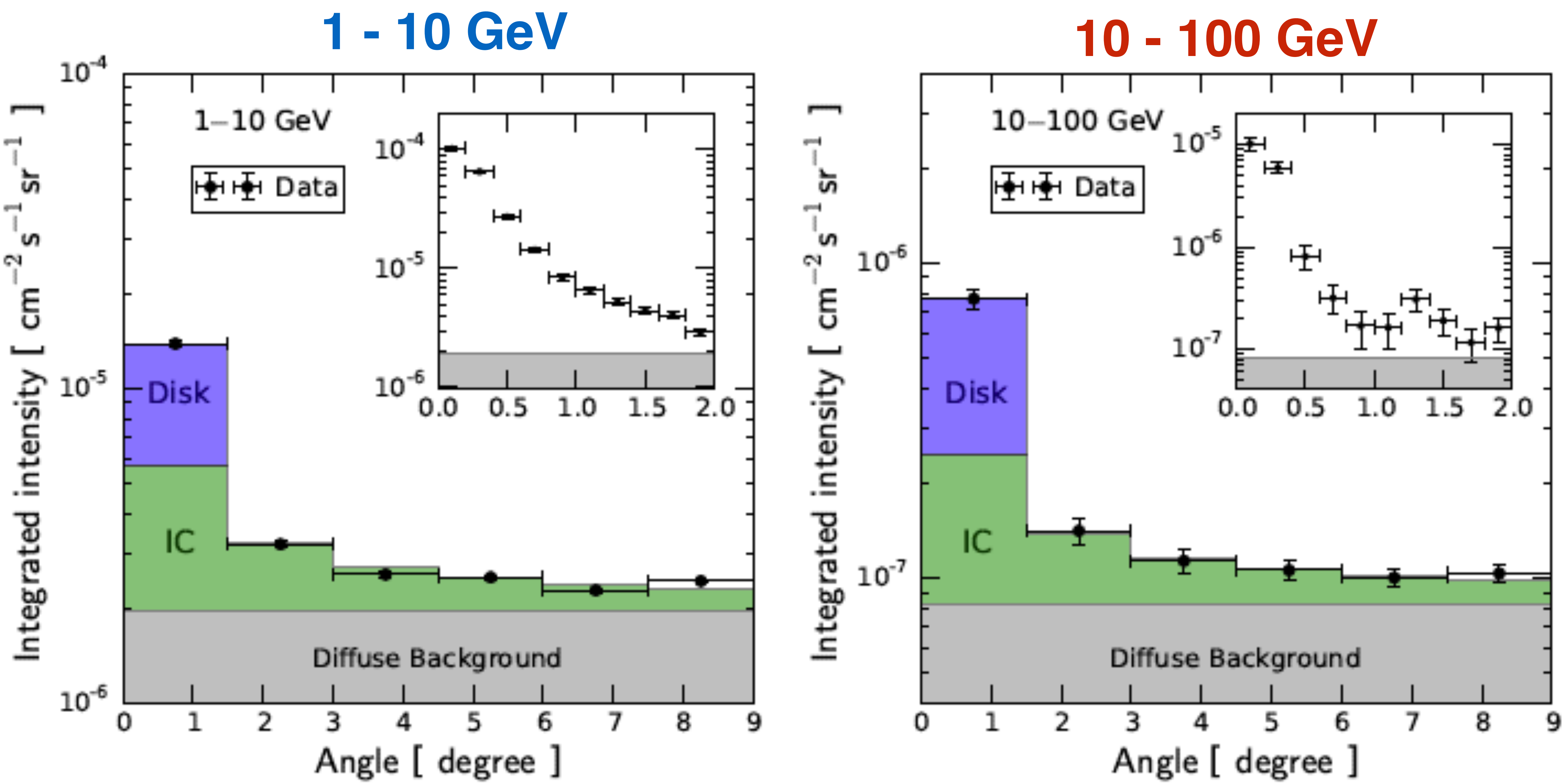
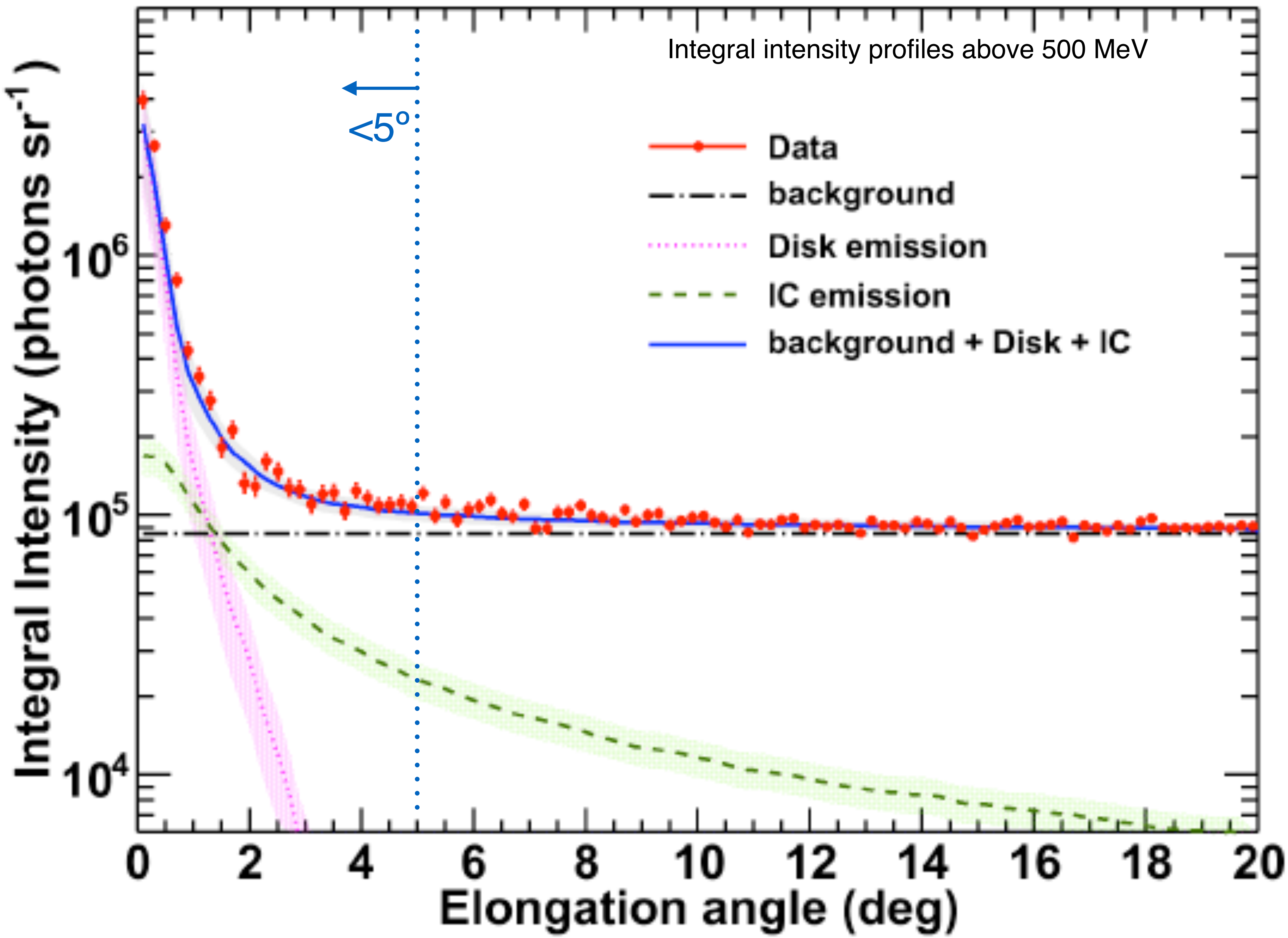
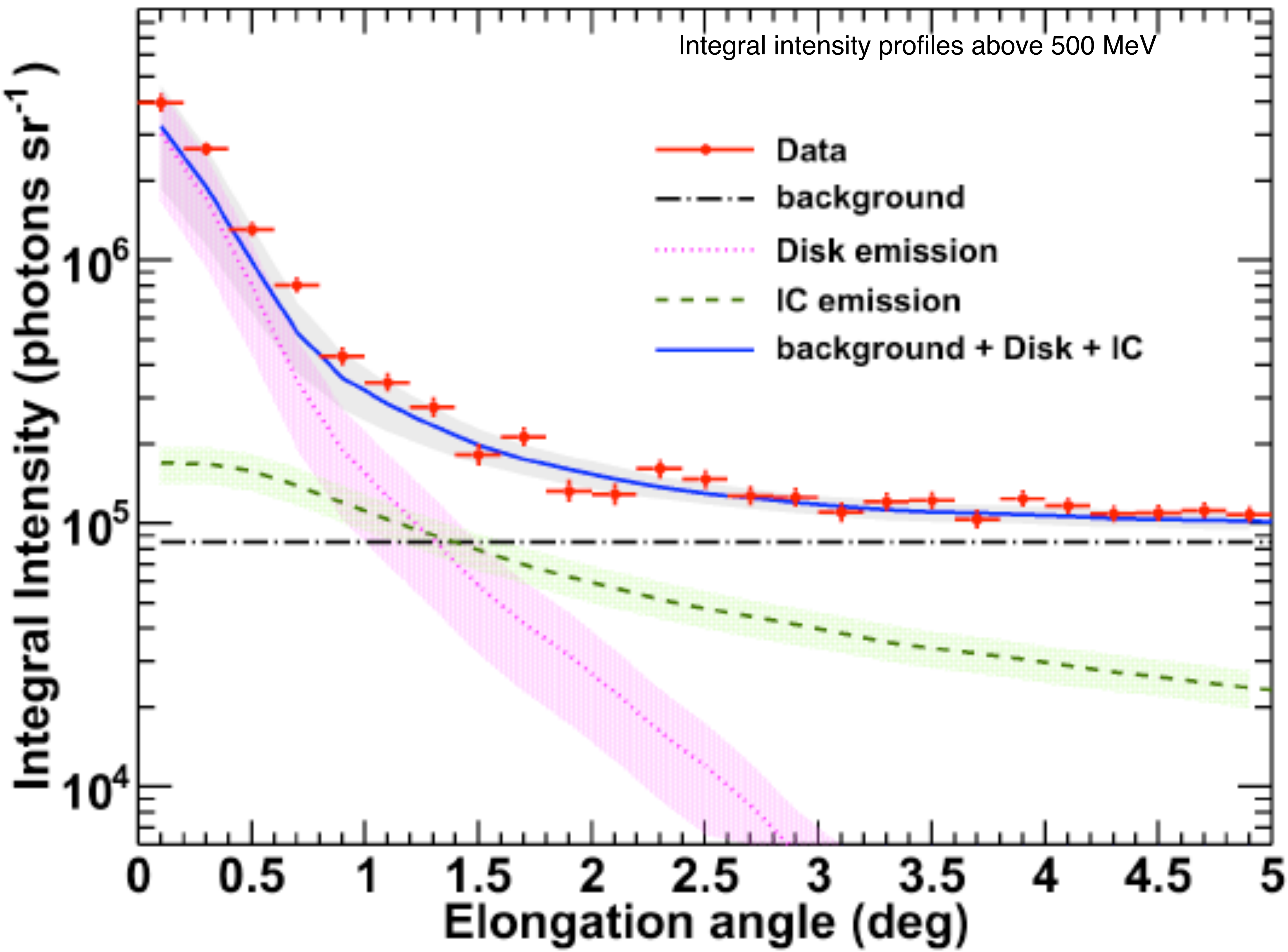


FIG. 2. **Left:** Angular distribution of the 1–10 GeV intensity in the Sun ROI. Black points show the observed data with statistical uncertainties only. Colored histograms show the fitted results for the signal and two backgrounds (the estimate of the diffuse background incorporates independent data from the fake Suns). The inset shows the same with smaller angular bins, but without the two solar components (note the different vertical scale). **Right:** Same, but for 10–100 GeV (note the lower flux).

Fermi 18month Analysis



Fermi 18month Analysis



Data Analysis

- Fermi science tools version **v9r33p0**
- Weekly **P7REP** data set from week 010 - 321
  - 2008-08-07 to 2014-07-31
- Weeks are divided into 40 equal time segments
  - The data of the time segments are stacked with the Sun in the centre position
    - Binning with pixel size of 0.1°x0.1°
    - Movement of the Sun is small compared to its diameter

Solar Positional drift ~0.2°
Sun diameter ~0.5°
LAT PSF ~1° (@1GeV) / 0.1° (>10GeV)

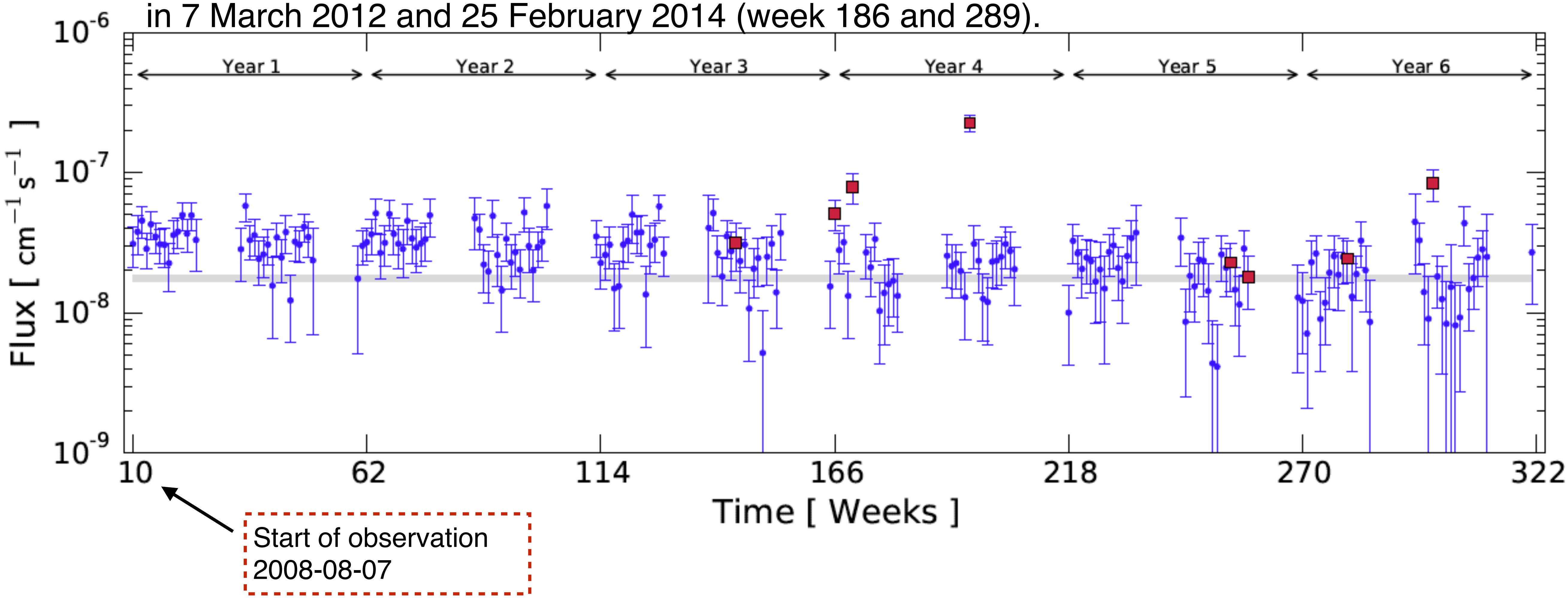
- Event Selections
  - **DATA_QUAL == 1**
  - **LAT_CONFUG==1**
  - **ABS(ROCK_ANGLE<52)**

Remove data periods when the Sun is near the Galactic plane |b|<30°

Exposure time reduced by 40%
Total photon count reduced by 76%

Data Selection

Some anomalously bright periods are correlated with solar ares, most notably the ones in 7 March 2012 and 25 February 2014 (week 186 and 289).



- Total gamma-ray flux (1-1.8 GeV) within 1.5° from the Sun
- Periods with significant flaring have been remove