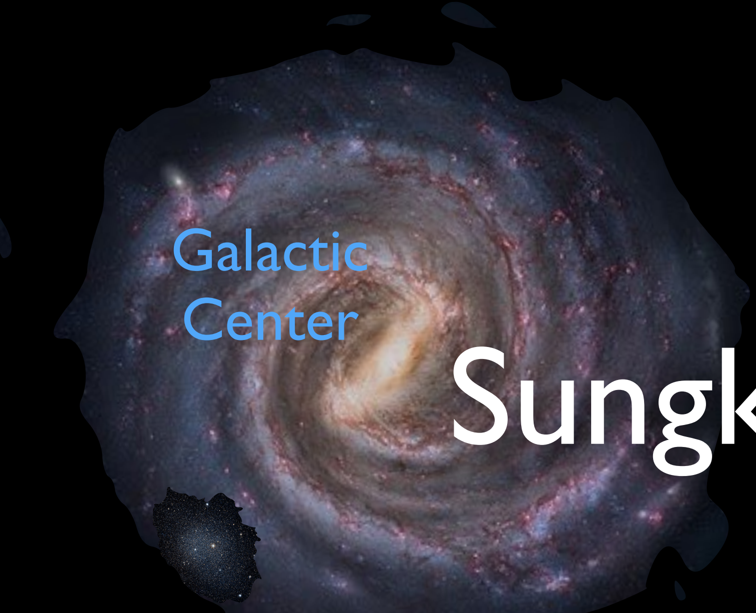
The Abdus Salam International Centre for Theoretical Physics



Carsten Rott

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June 1, 2018

Indirect Search for Dark Matter (and Solar Atmospheric Neutrinos)

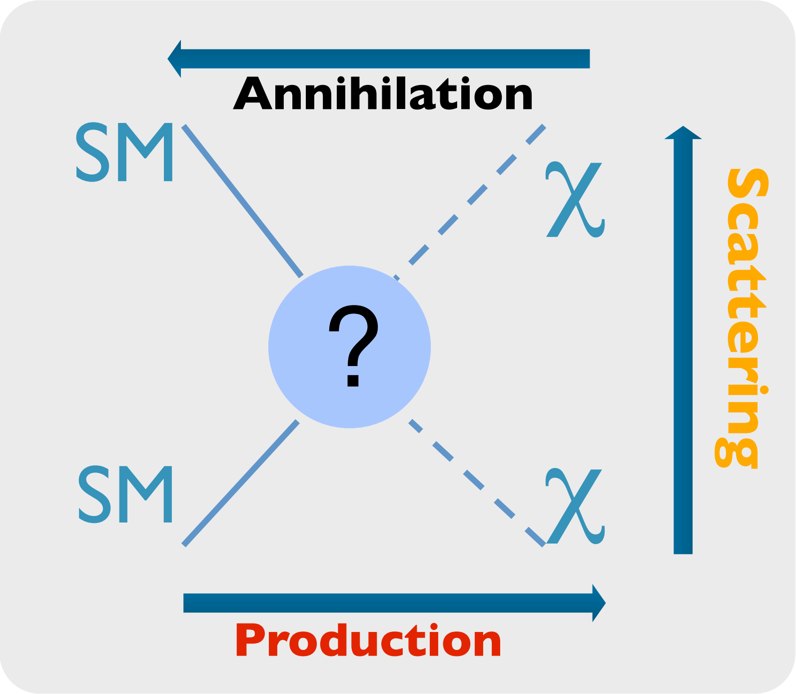
Advanced Workshop on Physics of Atmospheric Neutrinos - PANE 2018
Abdus Salam International Centre for Theoretical Physics (ICTP), in Trieste,
28 May to 1 June 2018

Image Credits:
ESA/Hubble Galaxy Cluster Abell 1689
ESO/Digitized Sky Survey 2 - Fornax dSph
M31 Andromeda

Outline

- Motivation
- Search for self-annihilating dark matter
- Search for decaying dark matter
- Dark Matter capture in the Earth and the Sun
- Solar Atmospheric Neutrino and associated Neutrino Floor
- Outlook & Conclusions

Role of Neutrinos



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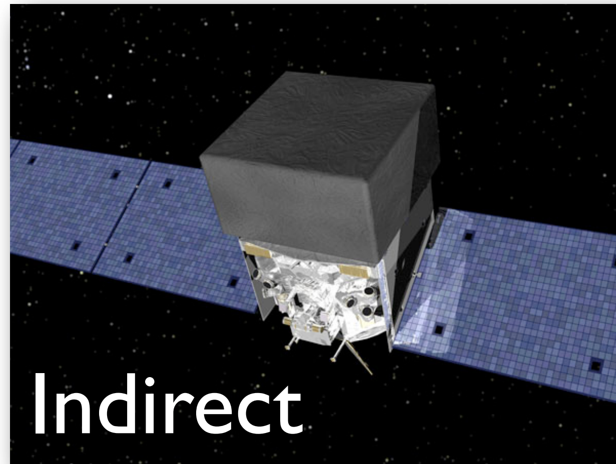

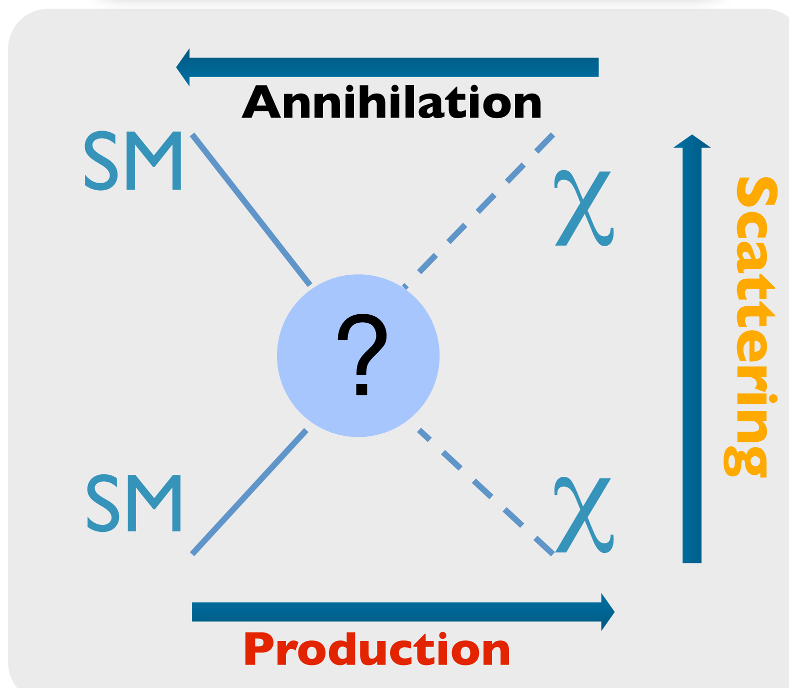

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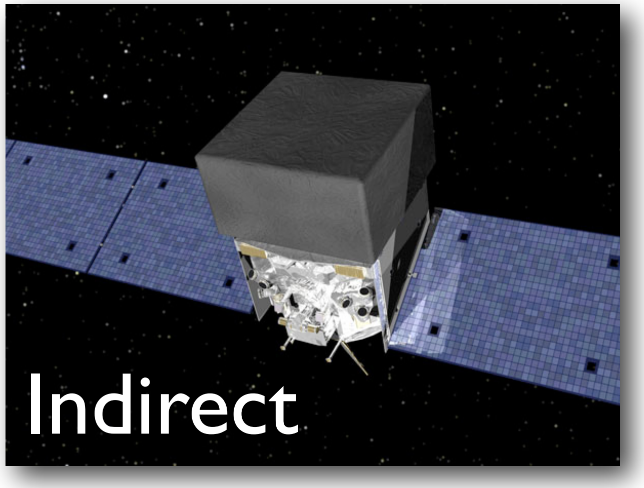

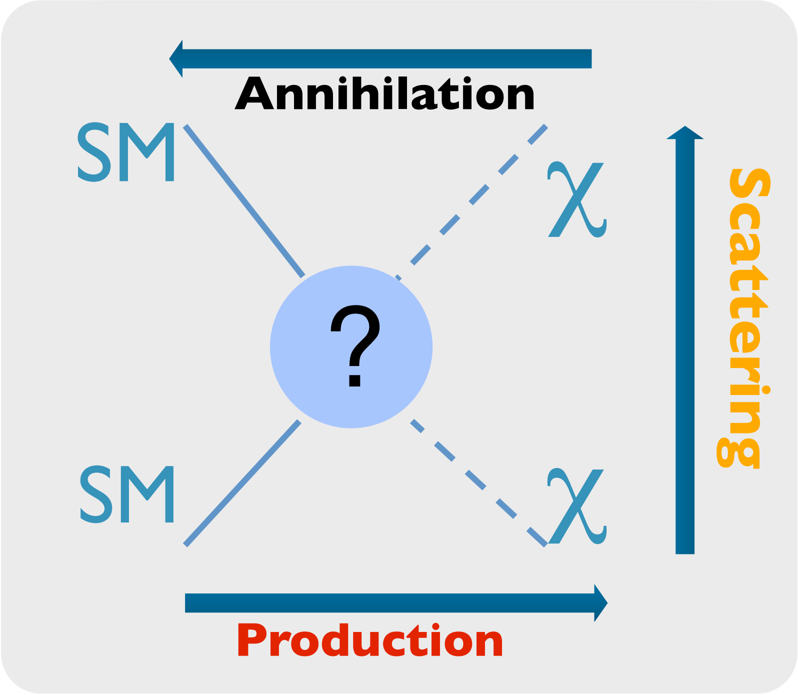

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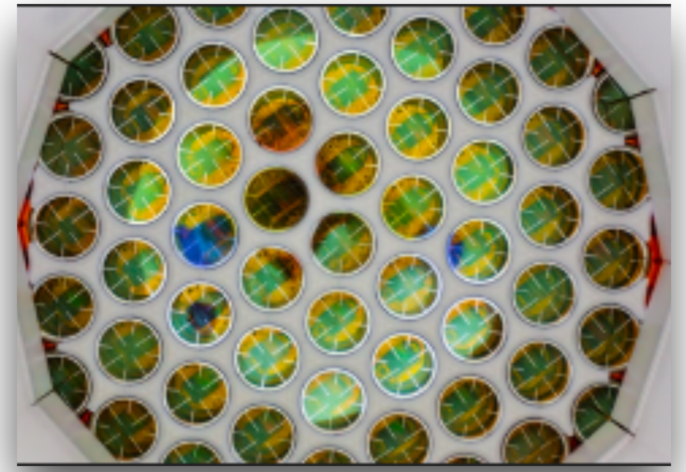

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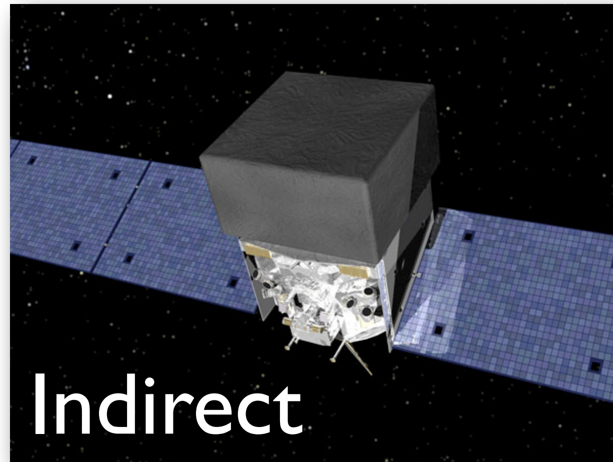

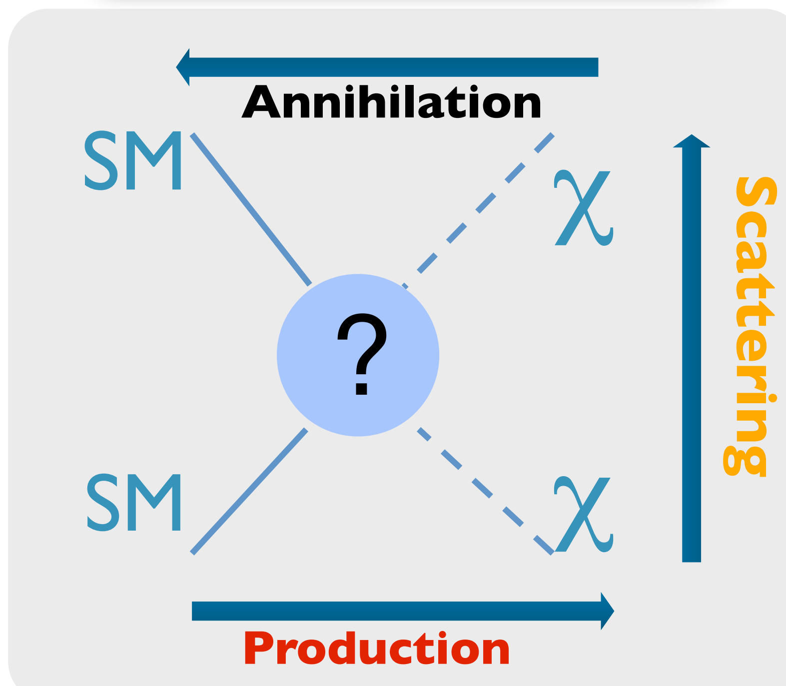

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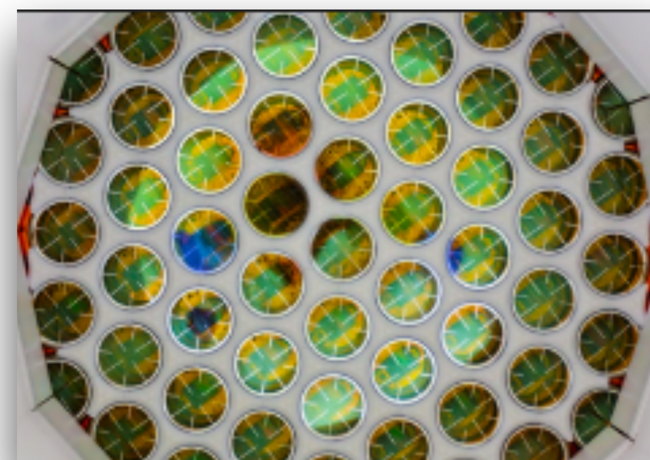
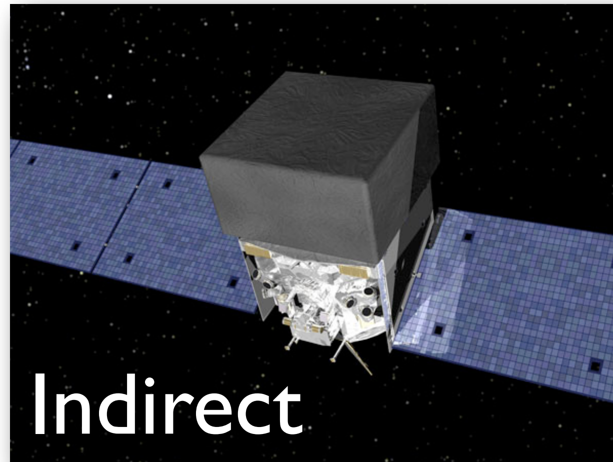
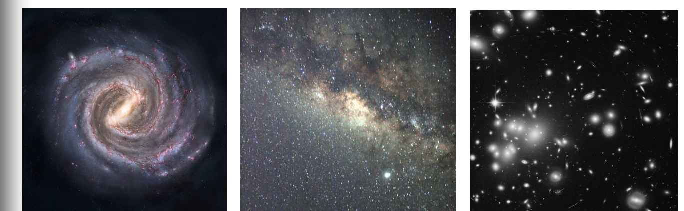


Role of Neutrinos



Neutrinos from



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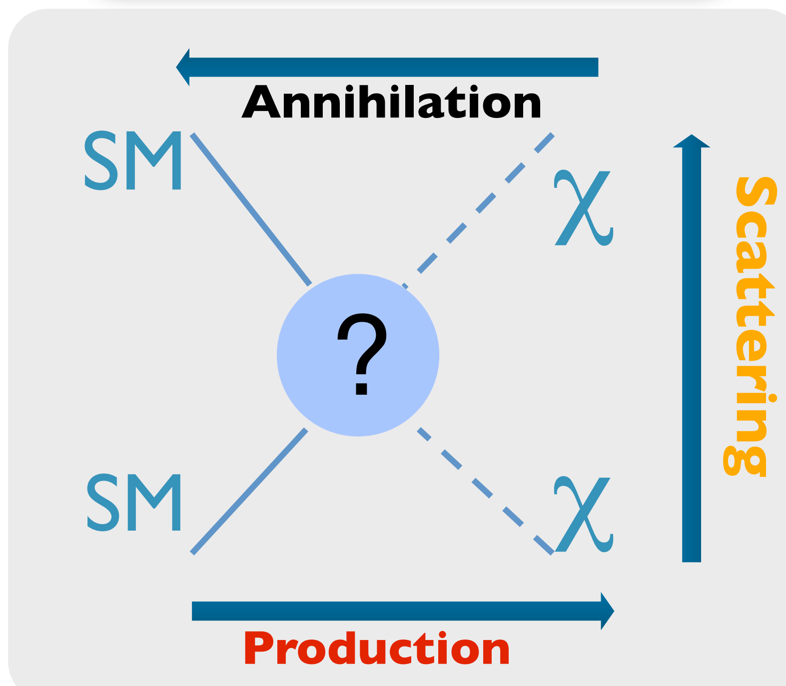

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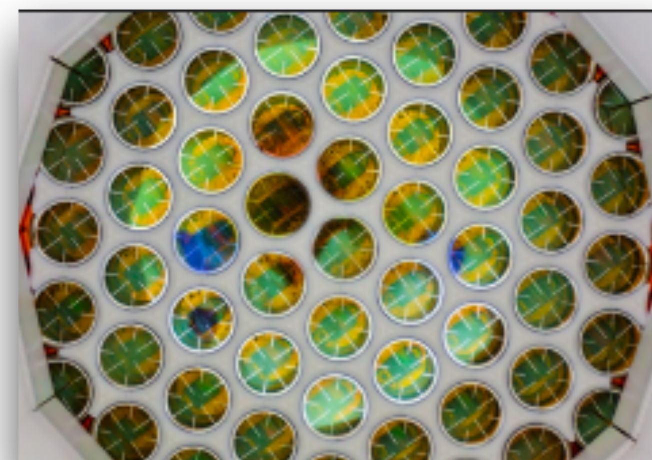

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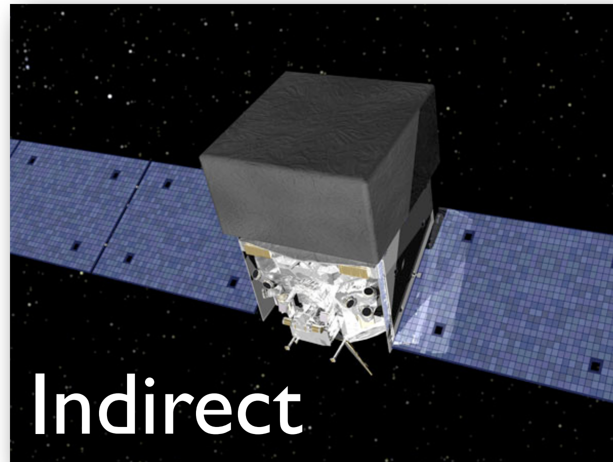

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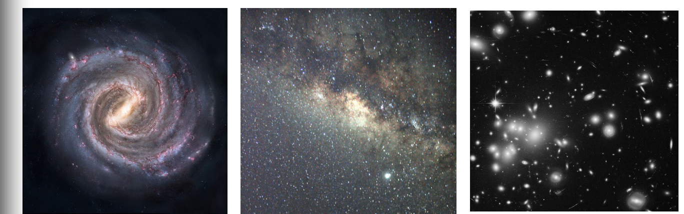

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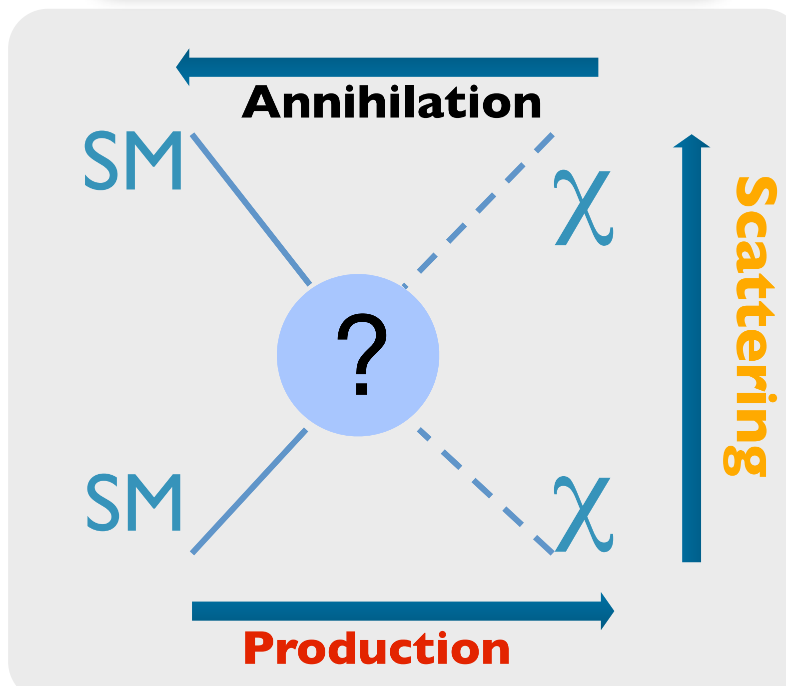

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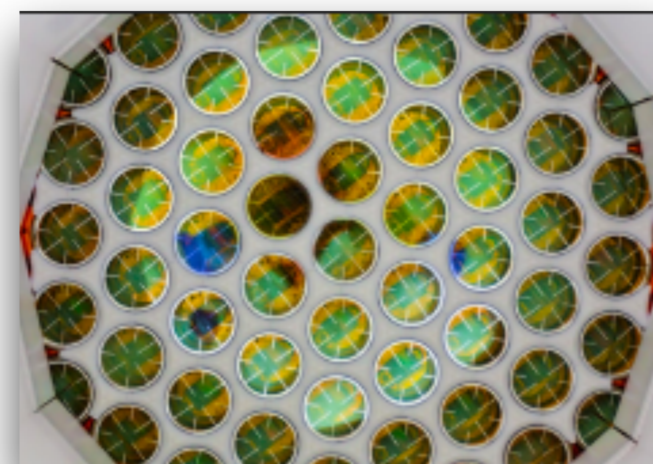

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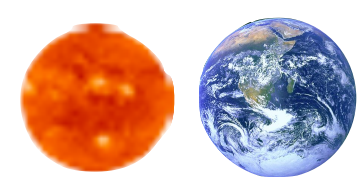

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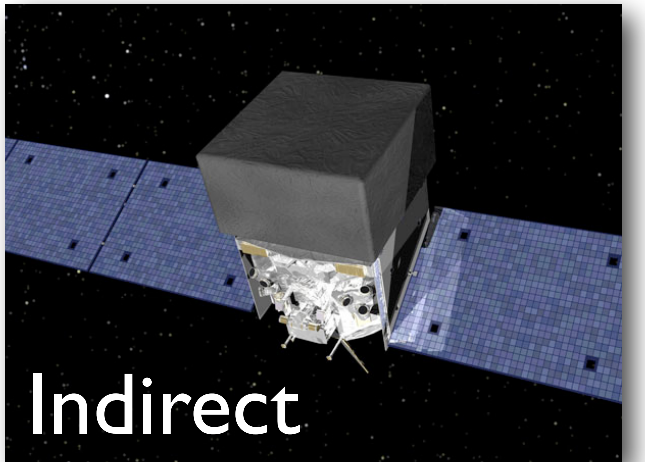

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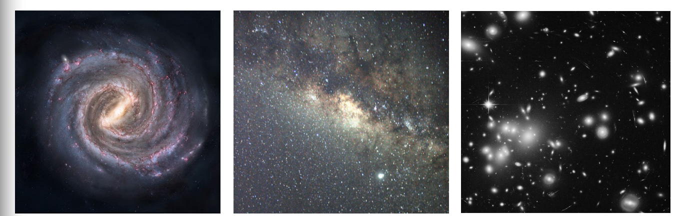

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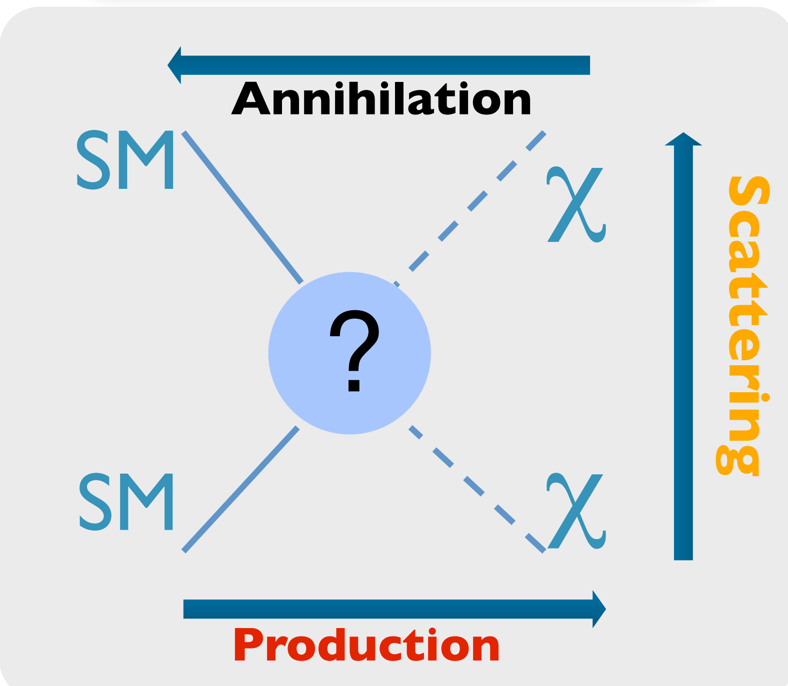

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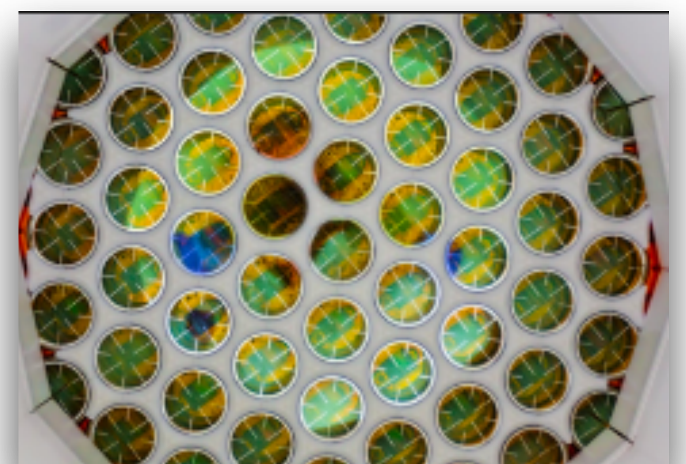

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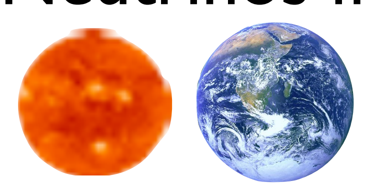
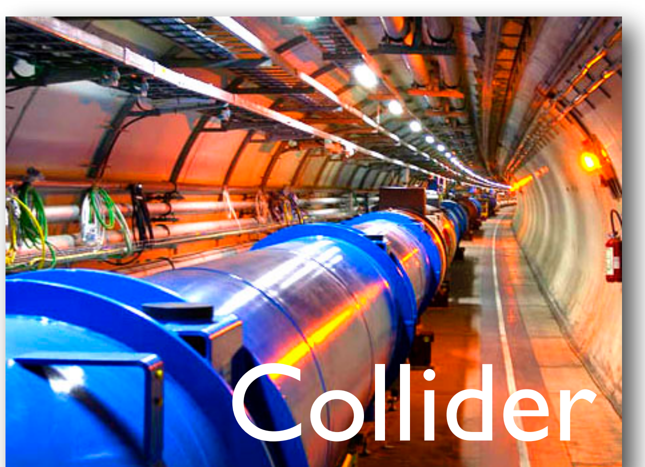
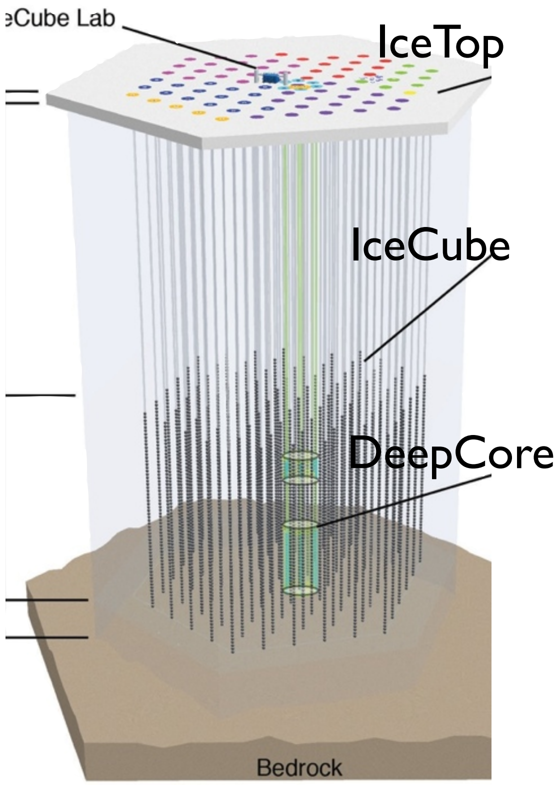


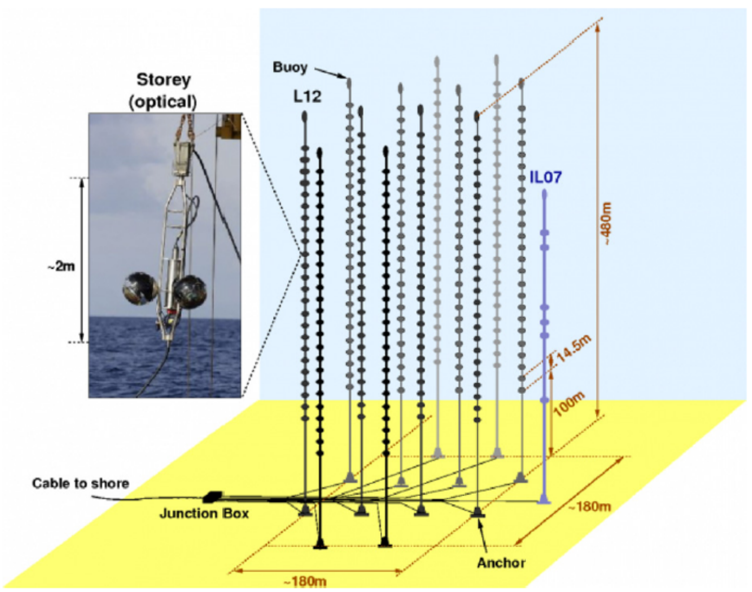


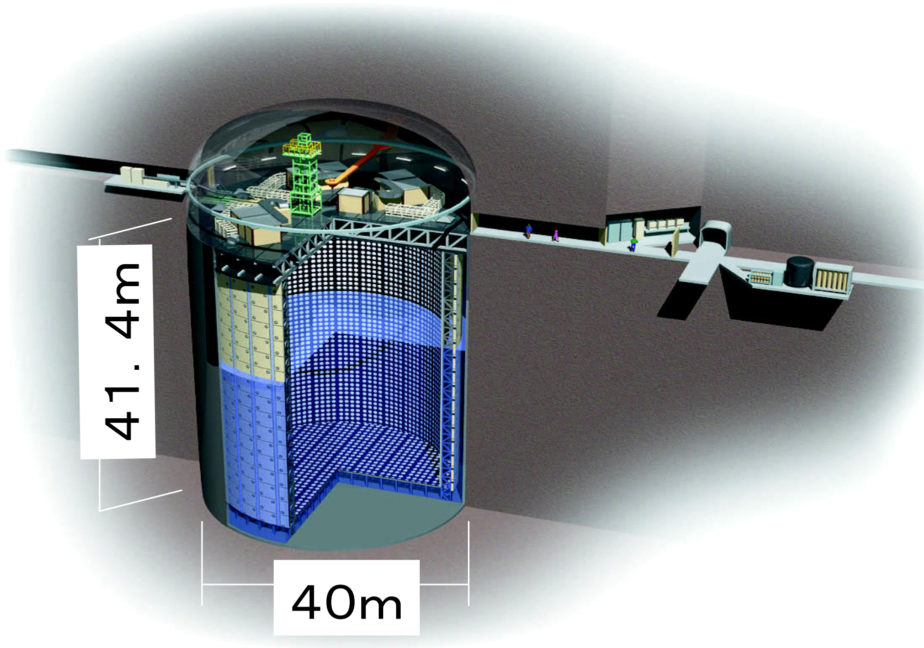
The case for Neutrinos

- Search for signals from the Galaxy, etc.
  - Probe DM self-annihilation cross section or lifetime (for decaying DM)
- Search for signals of dark matter captured in the Sun (and Earth)
  - Probe DM-Nucleon scattering
- Neutrino detectors naturally observe the entire sky (all-sky coverage)
- Neutrino detection efficiency rises with energy, and angular resolution improves

Atmospheric Neutrino Telescopes / Detectors Searching for Dark Matter …







- **IceCube** at the Geographic South Pole
- 5160 10"PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km³
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension

- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10"PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008 ; Phyiscs data taking since 2007

- **Super-Kamiokande** at Kamioka uses 11K 20" PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

Detect Cherenkov light from neutrino interaction products

Main backgrounds: Atmospheric neutrino, atmospheric muons (down-going)

Dark Matter Self-annihilations

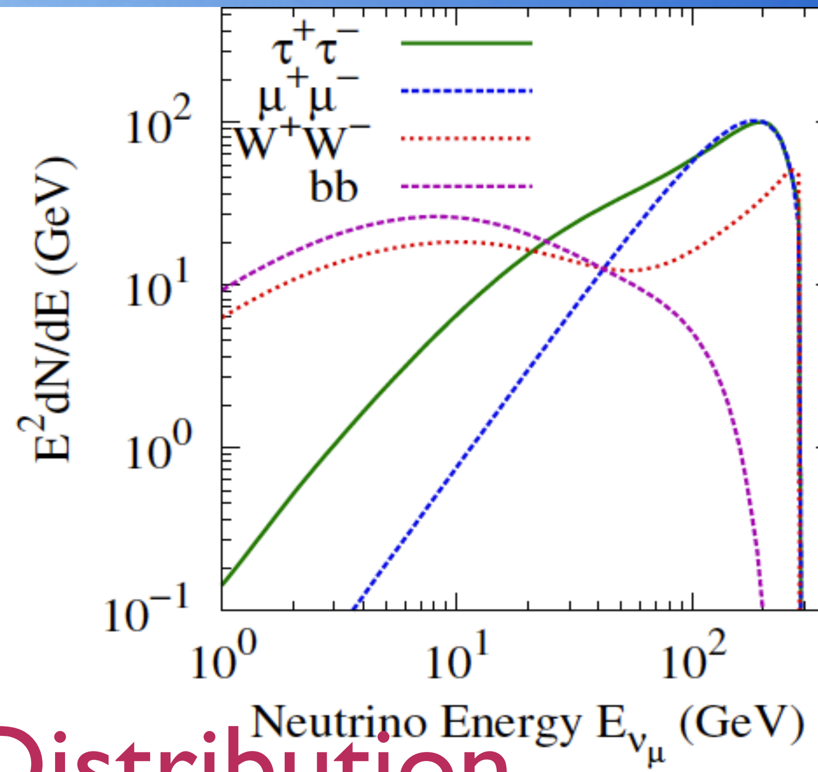
$<\sigma_A v>$

Dark Matter Annihilation

Measure Flux

Particle Physics

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f$$



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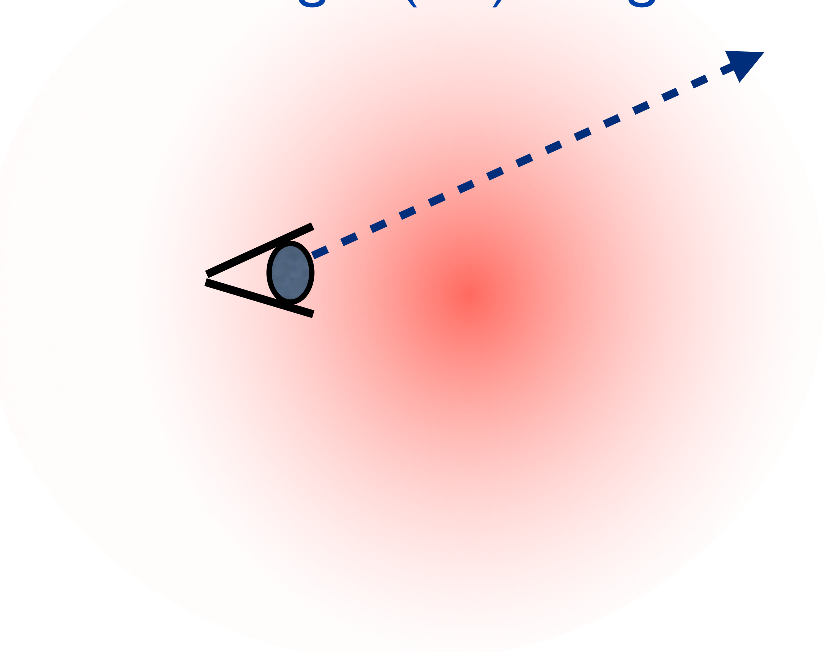
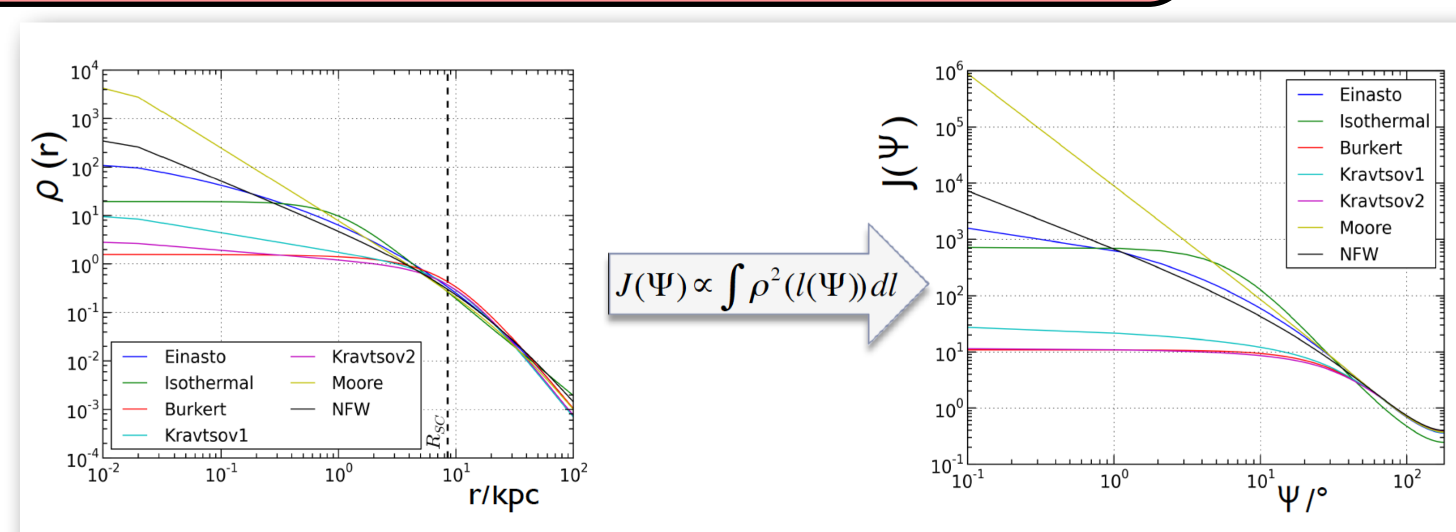
Dark Matter Distribution

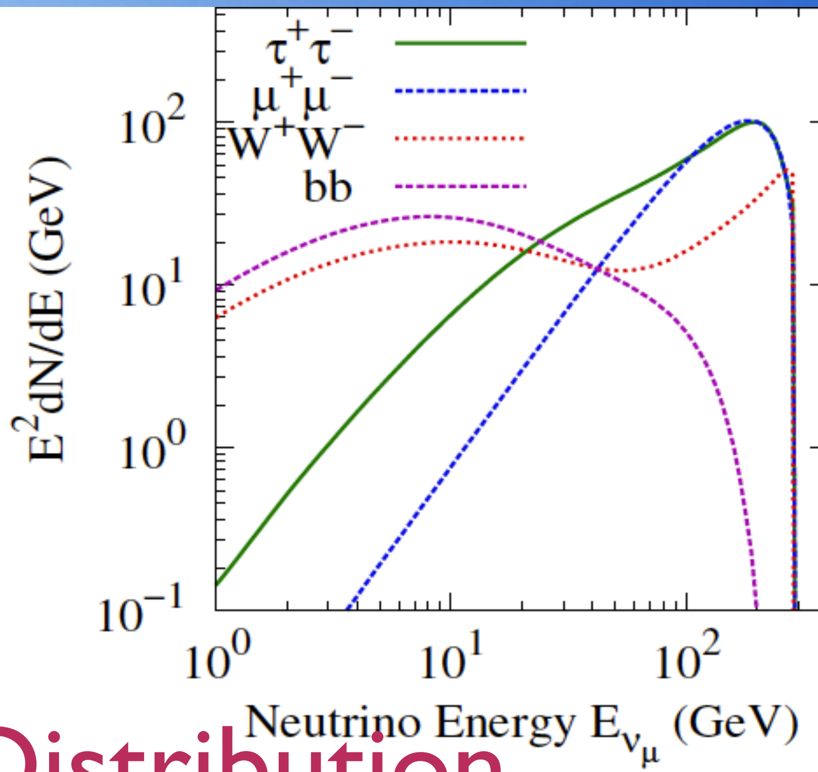
line of sight (los) integral



$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$



Dark Matter Annihilation



Measure Flux

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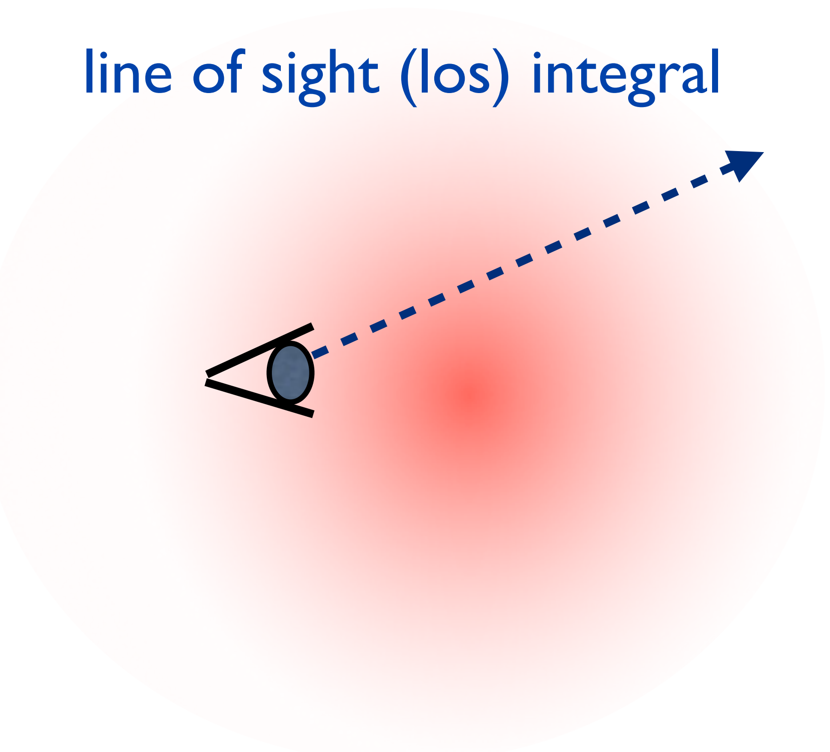

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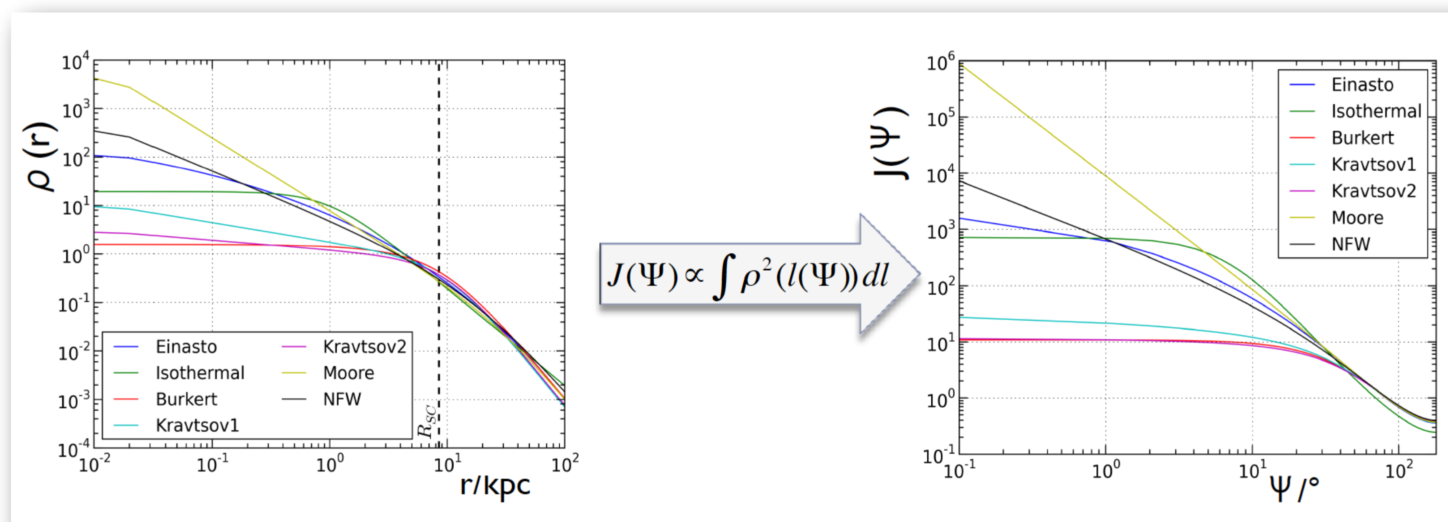
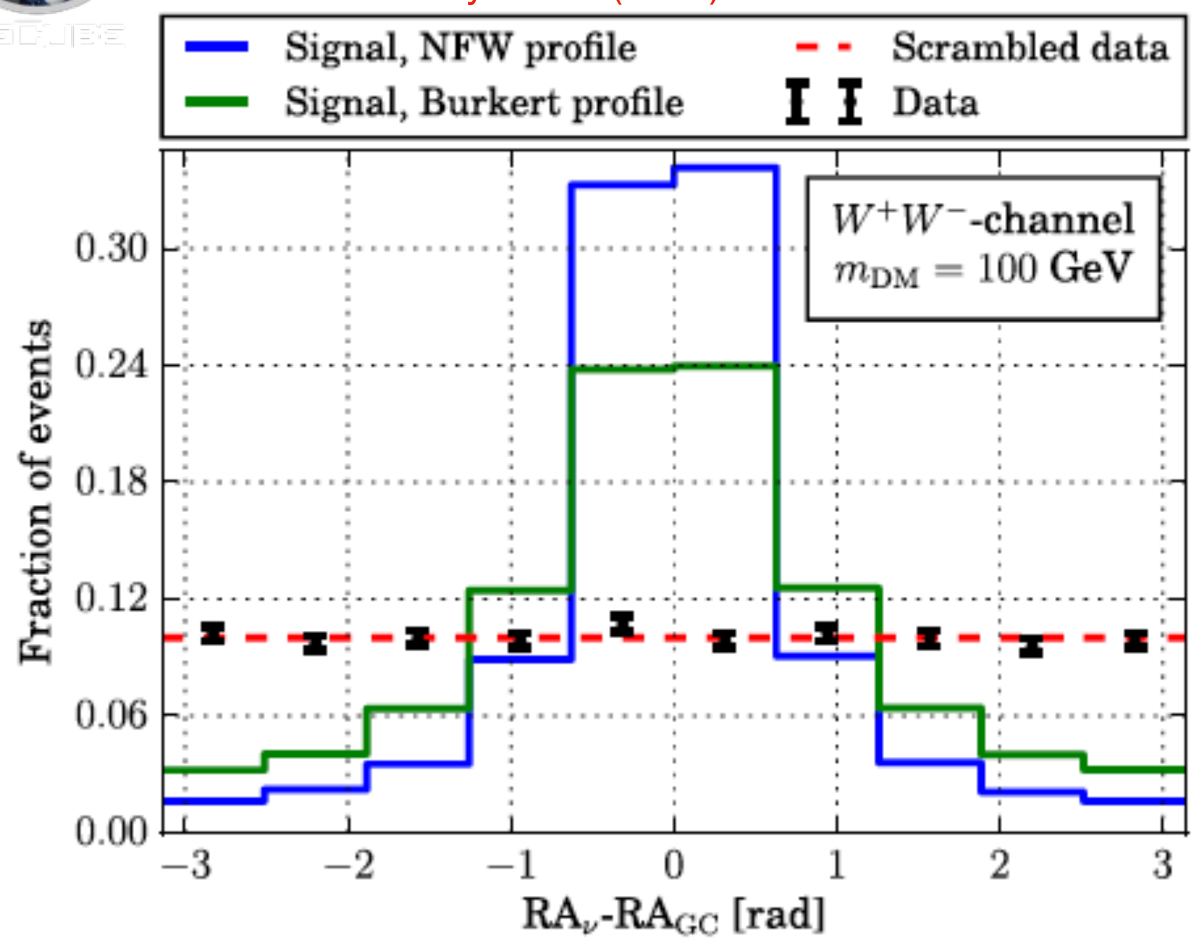
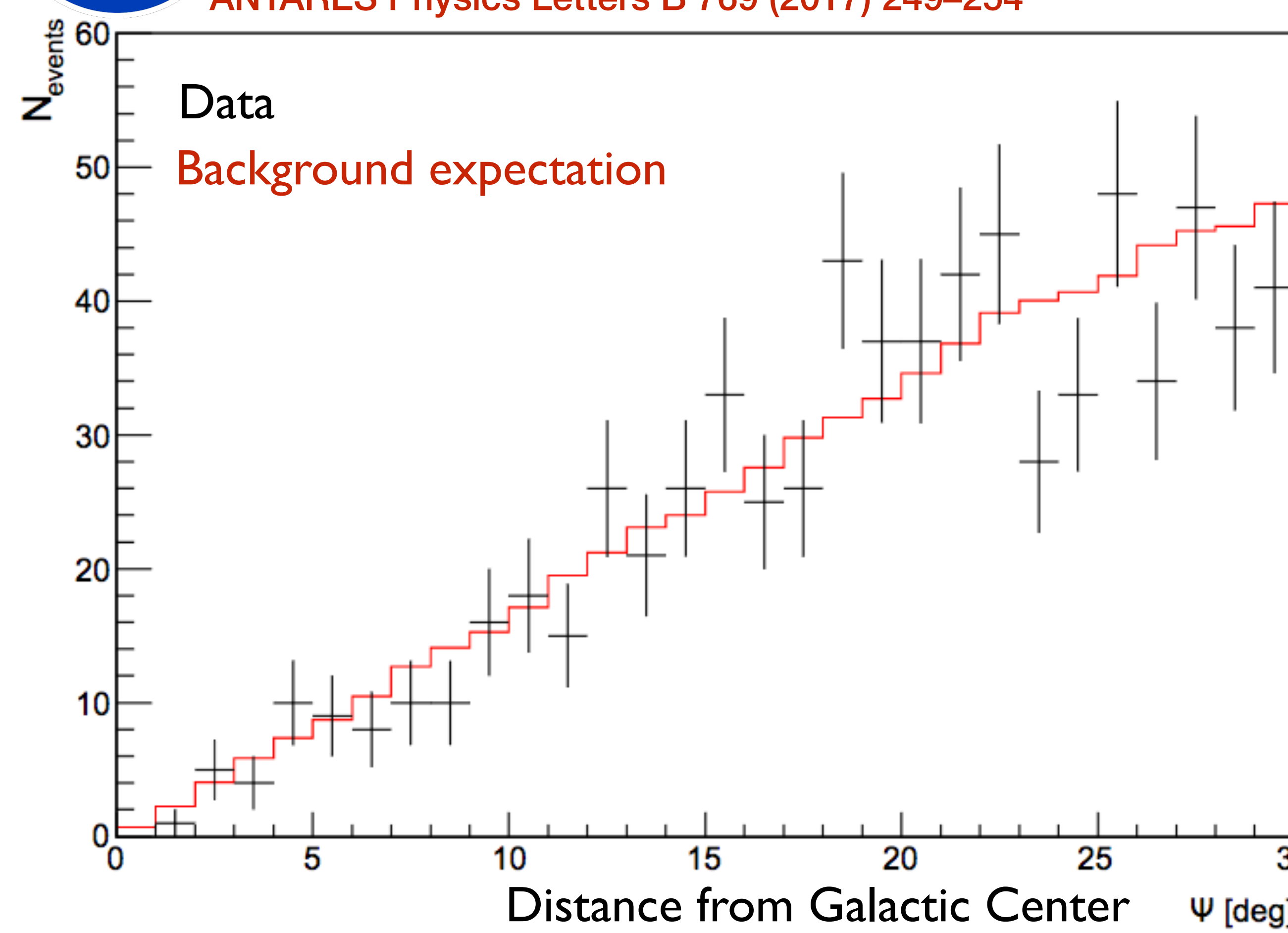


INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES

IceCube Eur. Phys. J. C (2017) 77: 627



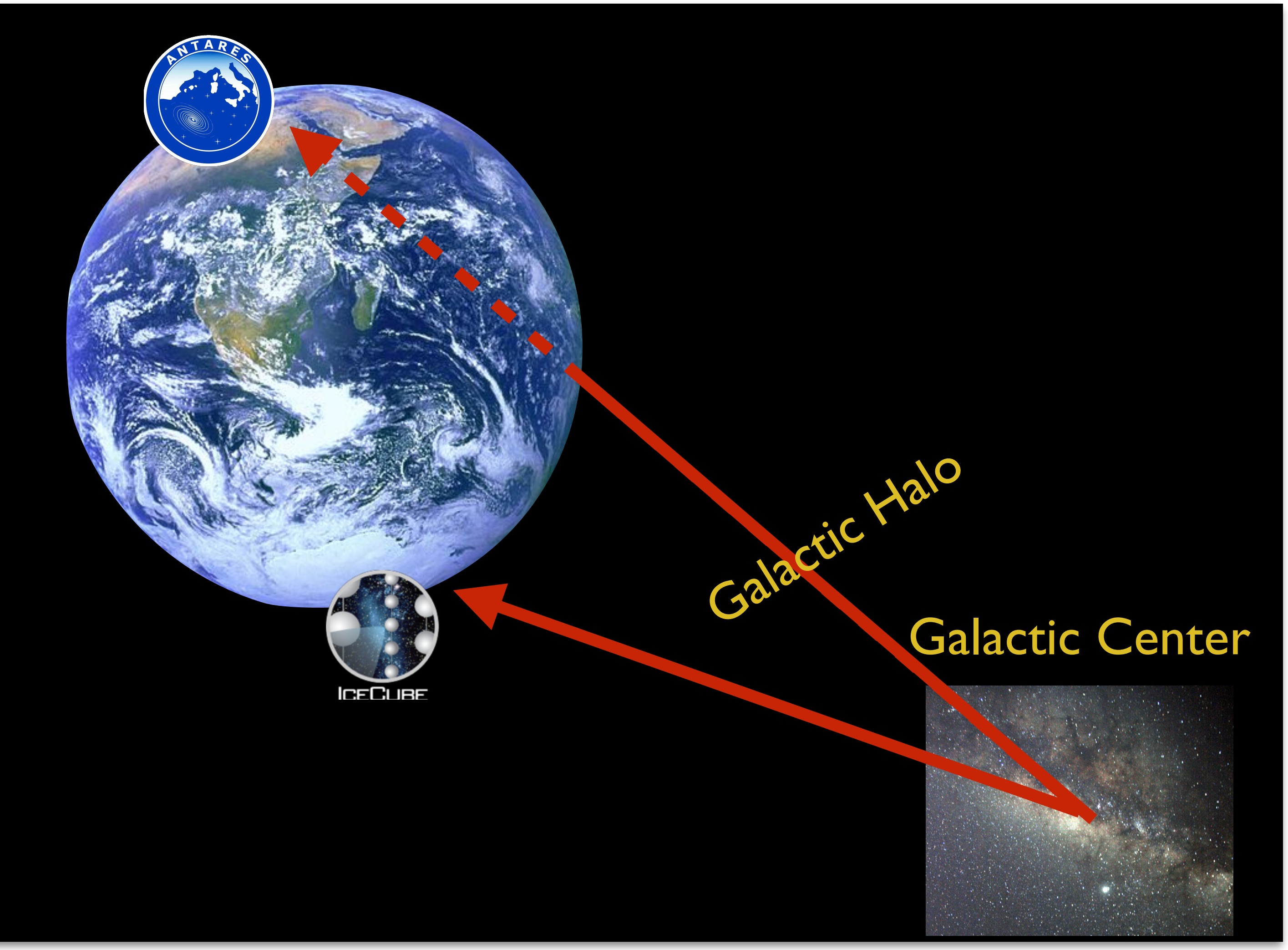
ANTARES Physics Letters B 769 (2017) 249–254



Search for DM annihilation in the Galactic Halo (IceCube) and Galactic Center (ANTARES)

Observations consistent with background expectations

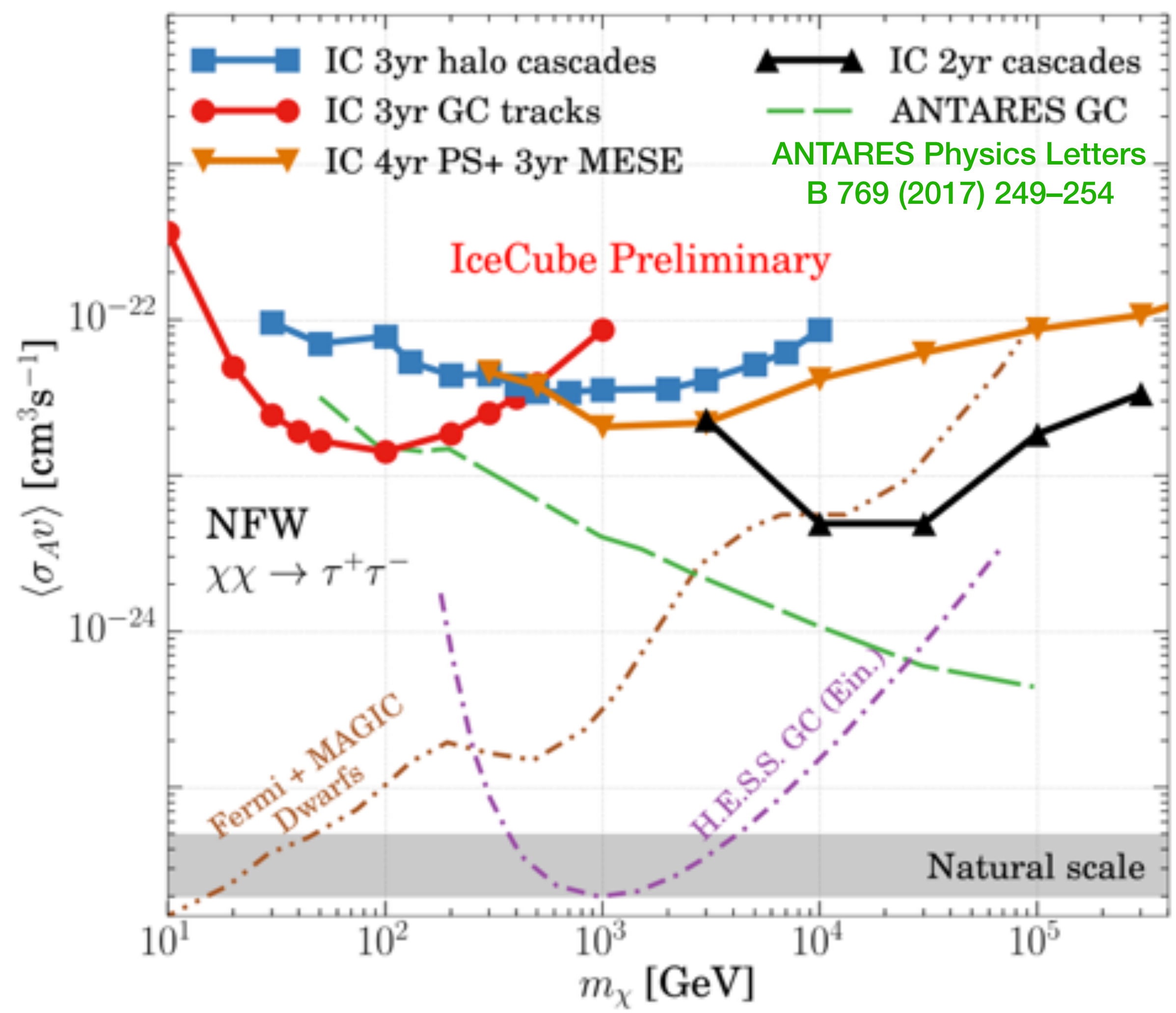
INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES



- ANTARES and IceCube complementary positioned on Northern and Southern Hemisphere
- Galactic Center only accessible in down-going events for IceCube
- Weak halo model dependence for observation of extended DM halo

Galactic Halo DM annihilation searches cover 10 GeV - 300 TeV Dark Matter masses with 4 analyses:

- ANTARES GC 2007 to 2015
- IceCube Galactic Halo Cascades 2yrs
- IceCube Galactic Center Tracks 4yrs (incl. 3yr MESE)
- IceCube Galactic Center Track 3yrs (low-energy)
  - IceCube [arXiv:1705.08103] Eur. Phys. J. C (2017) 77: 627



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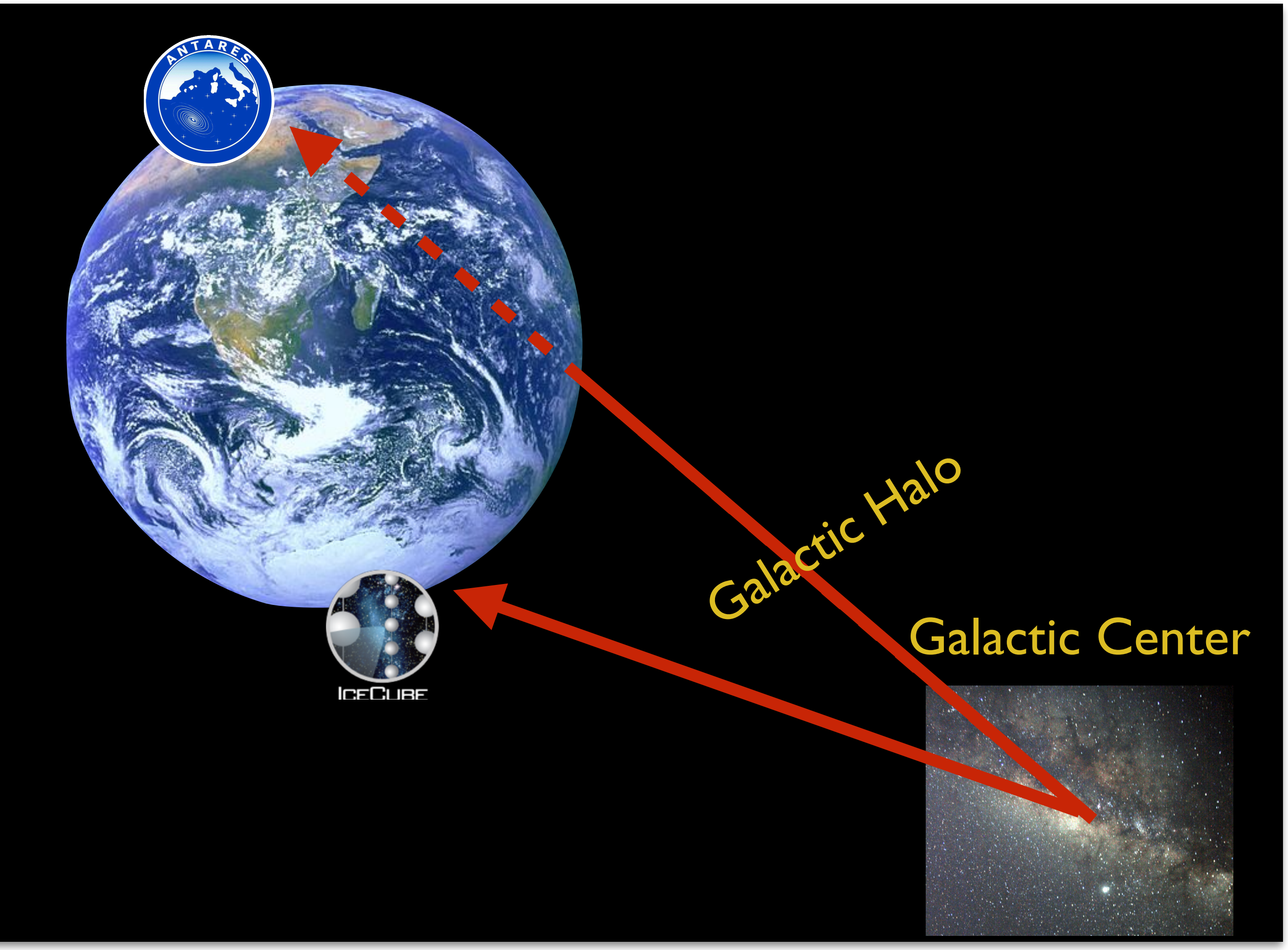

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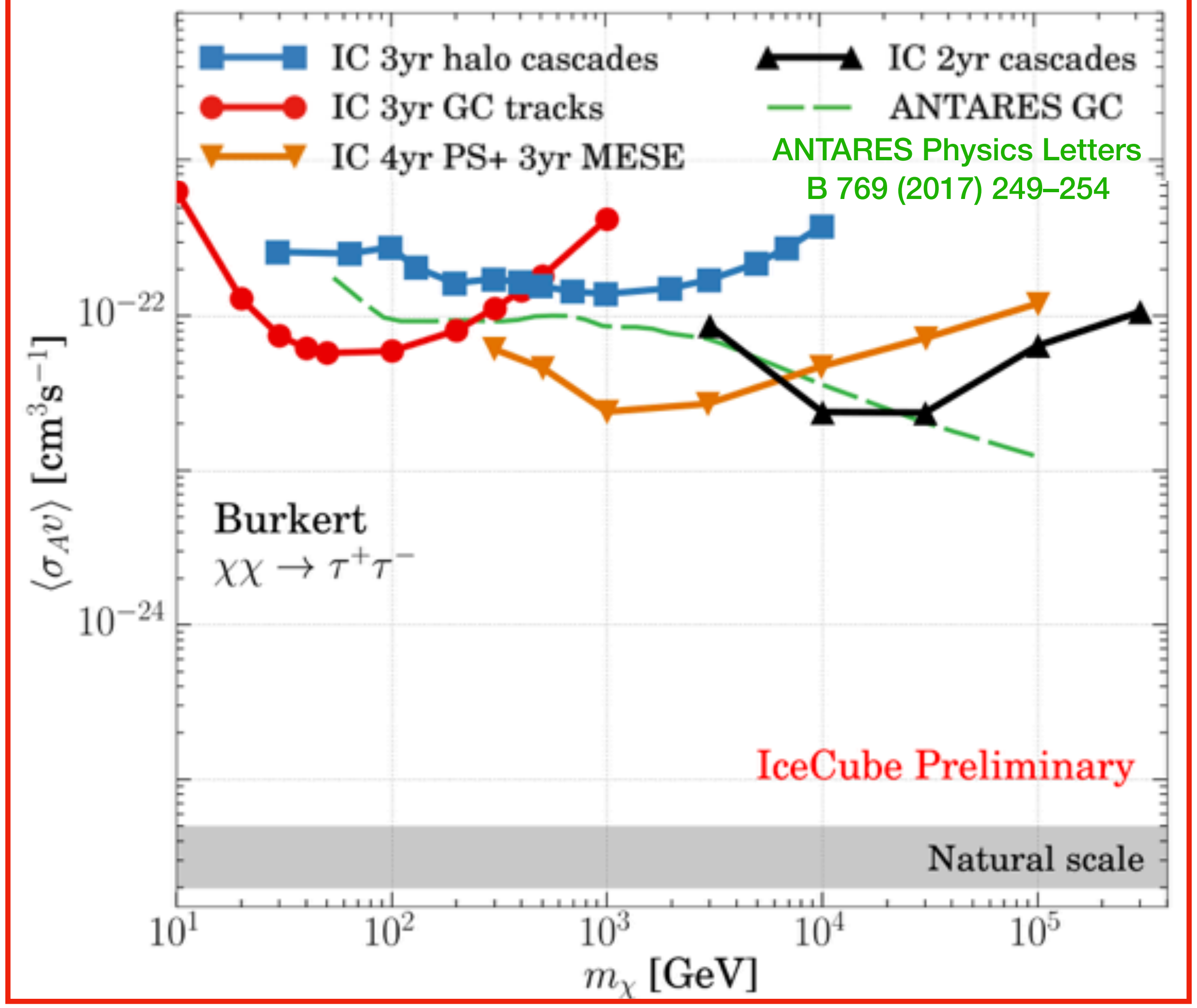
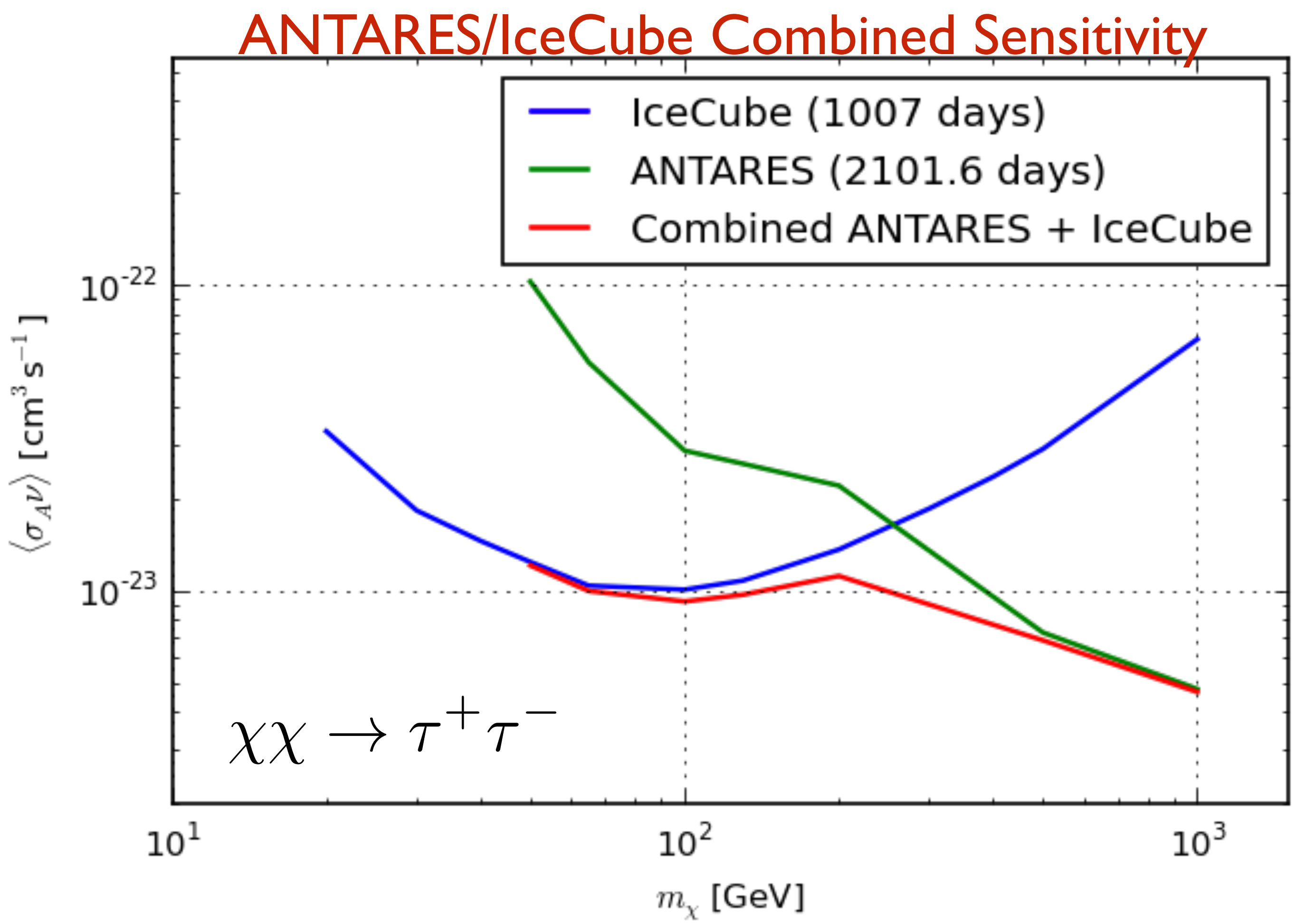
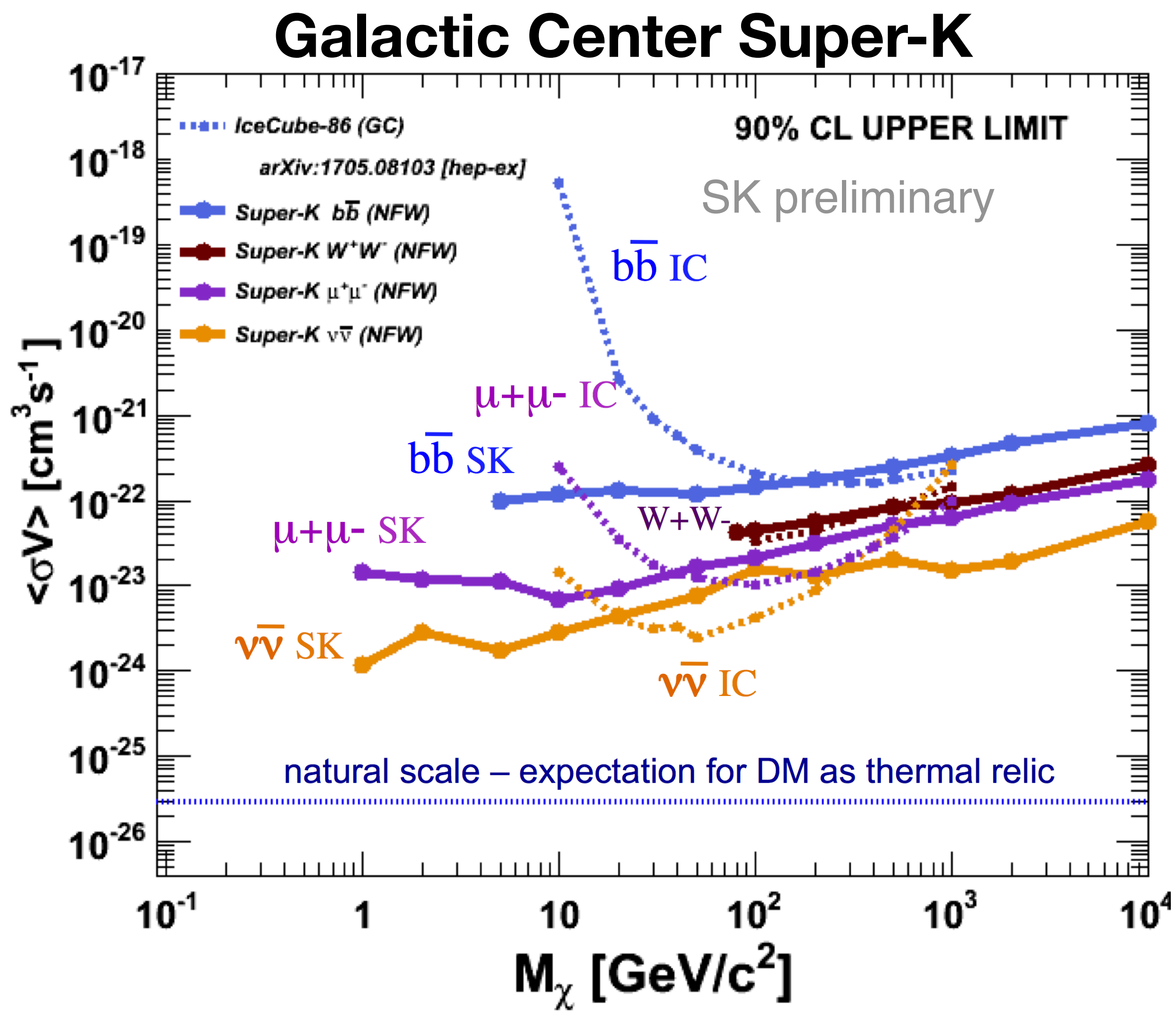


Galactic Center / Galactic Halo - IceCube/ ANTARES/Super-K

J.A. Aguilar Sánchez [ANTARES & IceCube] ICRC2017 (911)

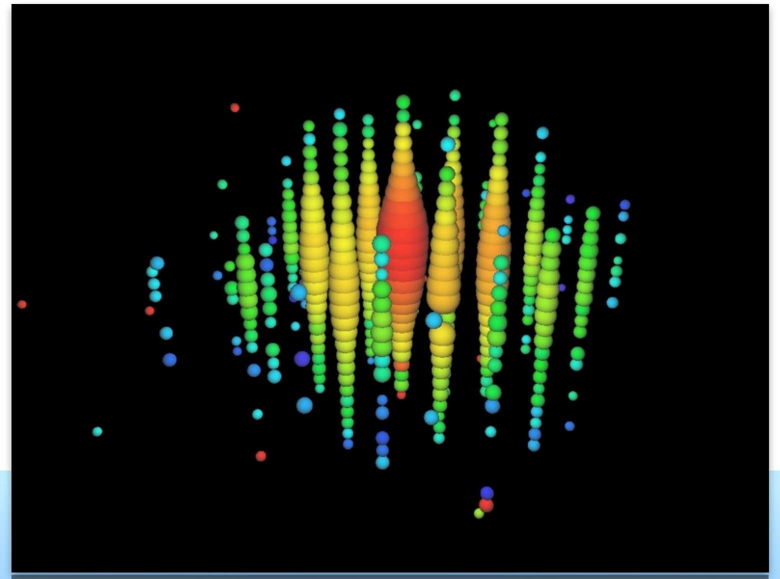


Combined Search for Neutrinos from Dark Matter Annihilation in the Galactic Center using IceCube and ANTARES

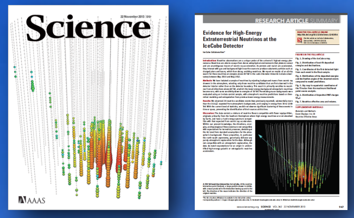


- Combined analysis enhances sensitivity in overlap region and helps to make analyses more comparable
- Very competitive result from Super-K for dark matter masses below a 100GeV

Neutrino Telescopes can probe models motivated by the cosmic-ray positron excess (PAMELA, AMS-02, …)



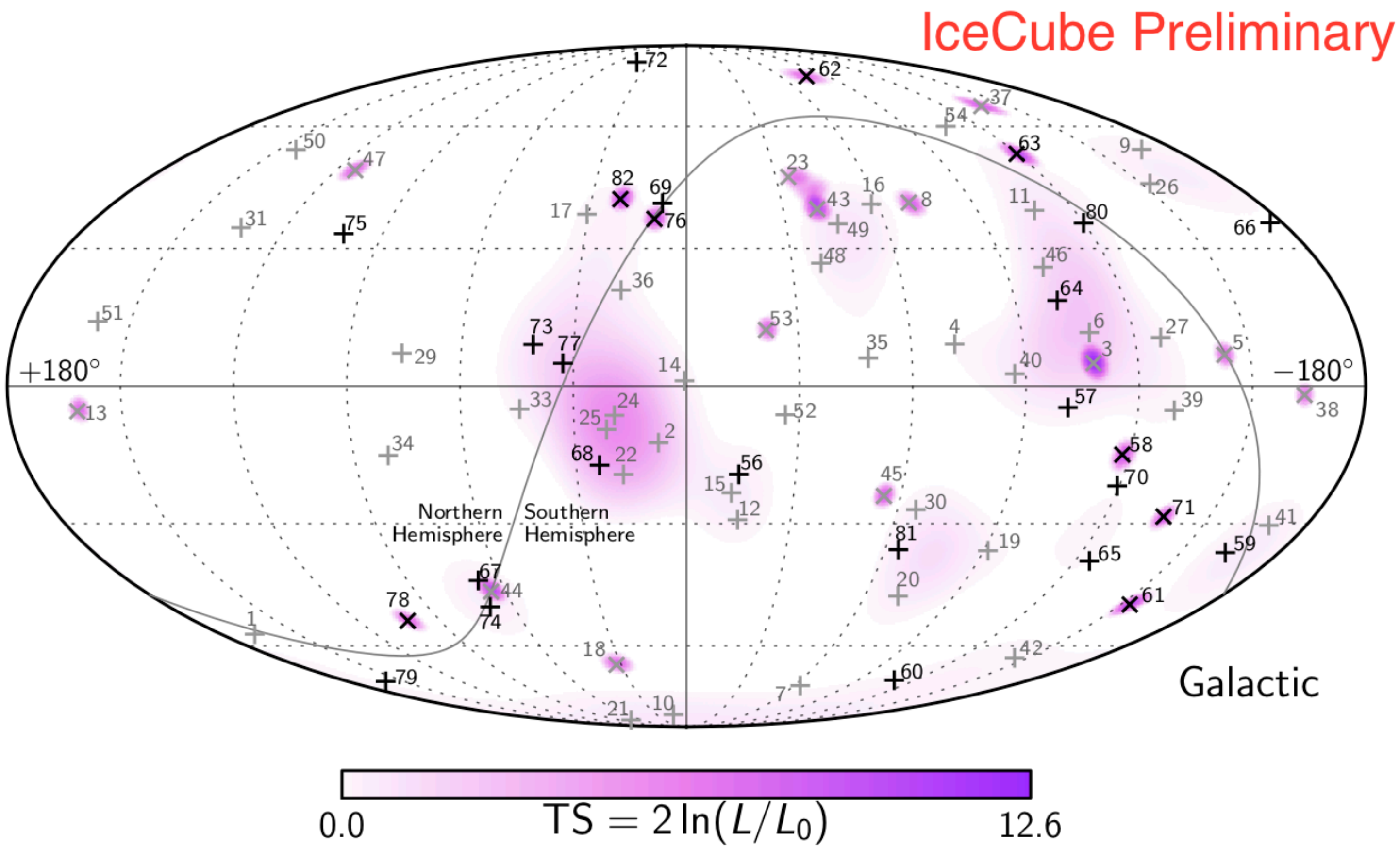
Dark Matter Decay / Astro-physical Neutrinos

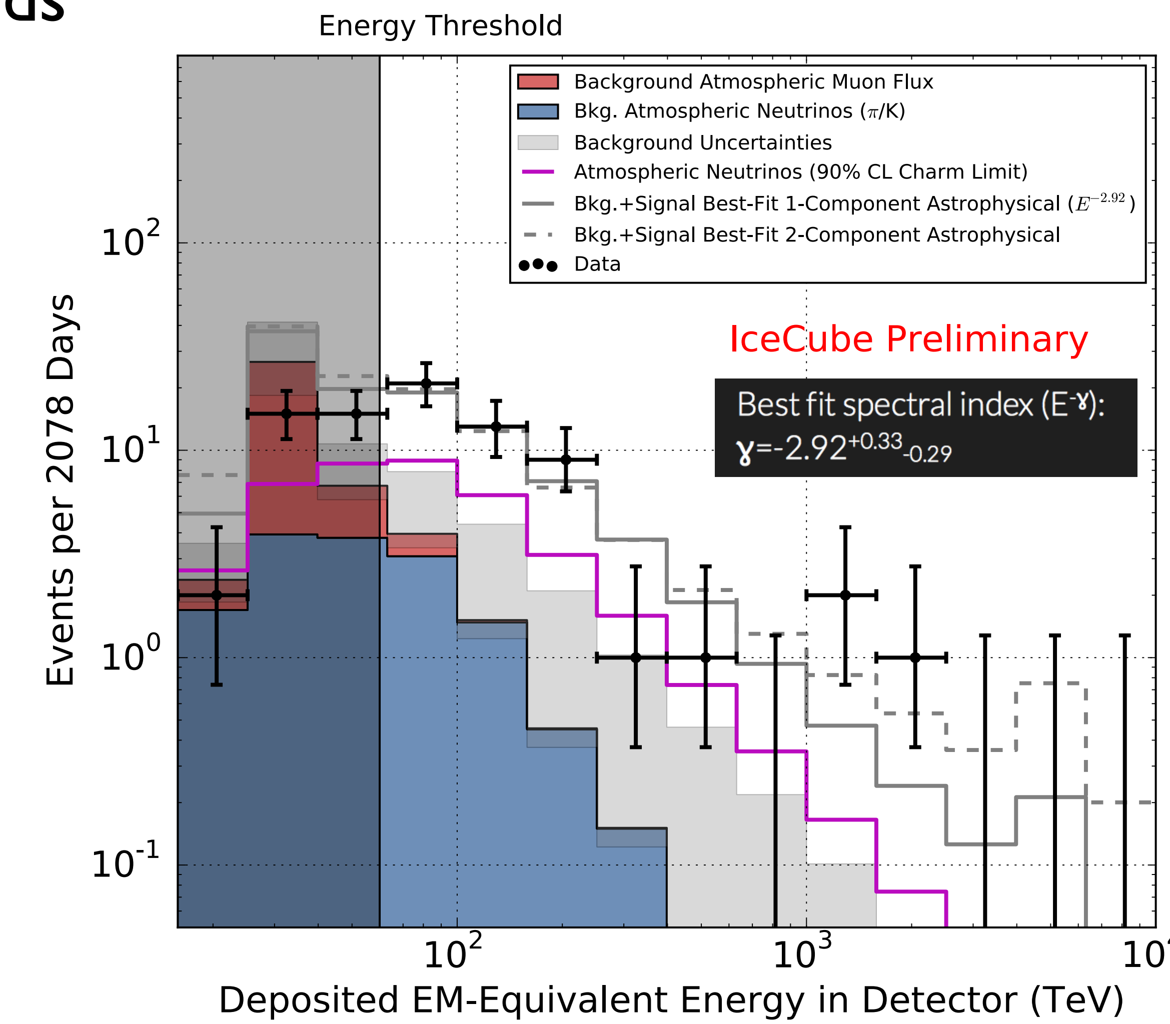


IceCube - High-energy neutrino search 6years

“HESE” - High Energy Starting Events
80 events observed (track-like & showers)
41 events expected from atmospheric backgrounds

IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*





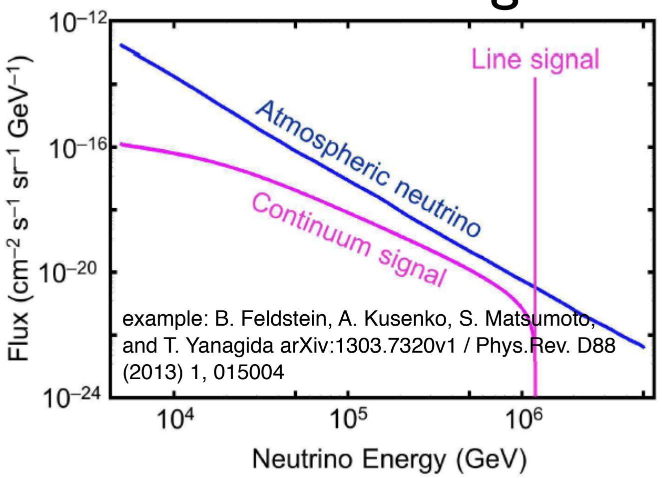
No significant clustering observed
- consistent with isotropic

Best fit spectral index $E^{-2.92}$

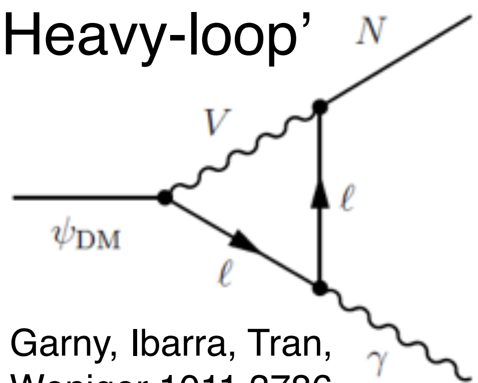
Observation not well described by simplest astrophysical neutrino source scenarios

Heavy Dark Matter Decay

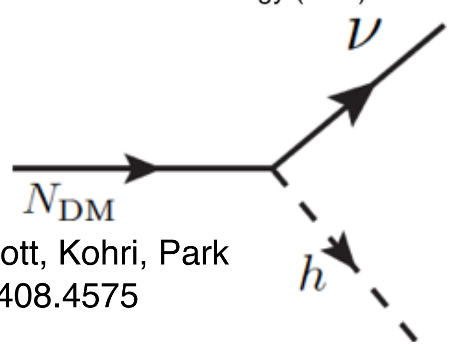
Decay process might produce mono-energetic neutrinos



'Heavy-loop'

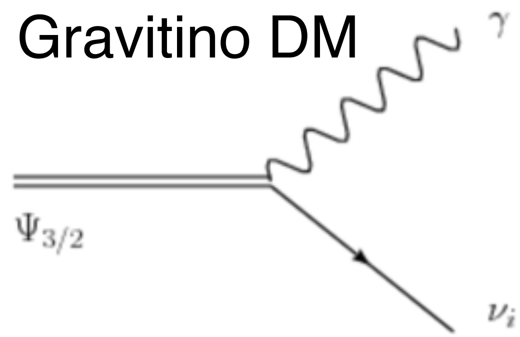


Garny, Ibarra, Tran, Weniger 1011.3786

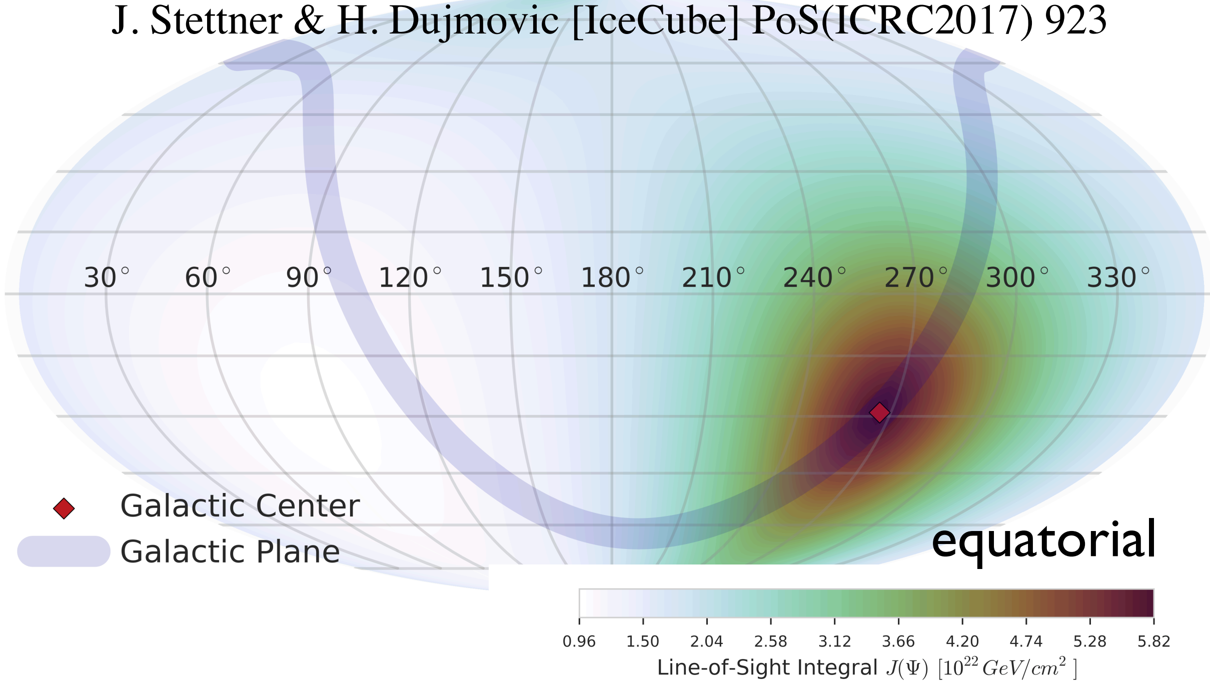


Rott, Kohri, Park 1408.4575

Gravitino DM



J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923



Two flux contributions:
Galactic and Extra galactic

$$\frac{d\Phi_{DM,\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{G,\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu}$$

- Characteristics of the signal components:
  - (1) Dark Matter decay in the Galactic Halo (Anisotropic flux + decay spectrum)

$$\frac{d\Phi^{G}}{dE_\nu} = \frac{1}{4\pi\, m_{DM}\, \tau_{DM}} \frac{dN_\nu}{dE_\nu} \int_0^\infty \rho(r(s,l,b))\, ds$$

  - Dark Matter decay at cosmological distances (Isotropic flux + red-shifted spectrum)

$$\frac{d\Phi^{EG}}{dE} = \frac{\Omega_{DM}\, \rho_c}{4\pi\, m_{DM}\, \tau_{DM}} \int_0^\infty \frac{1}{H(z)} \frac{dN_\nu}{dE_\nu} [(1+z)E_\nu]\, dz$$

Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034
Rott, Kohri, Park PRD92, 023529 (2015)
El Aisati, Gustafsson, Hambye 1506.02657

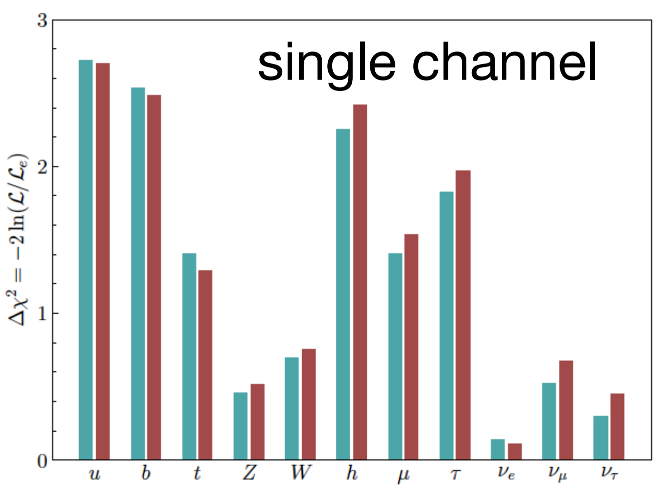
Heavy Decaying Dark Matter

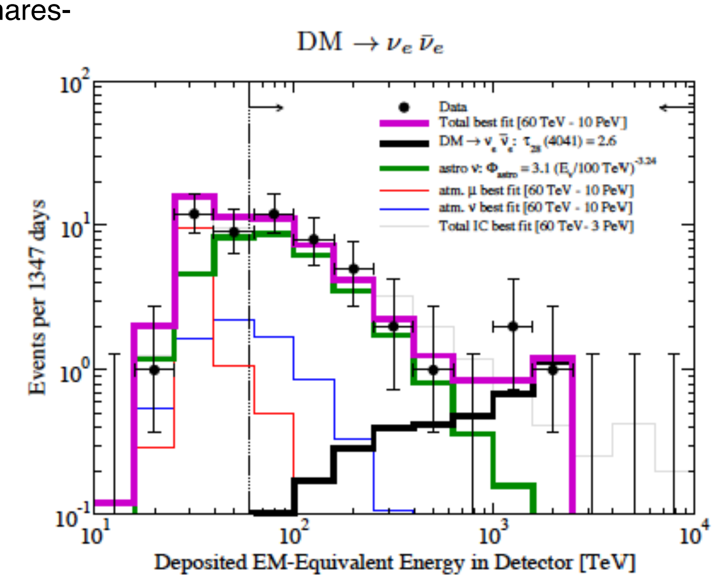
Could the observed neutrino flux be due to only dark matter decaying into multiple channels?

$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}$$

Take Galactic and Extra galactic contributions into account

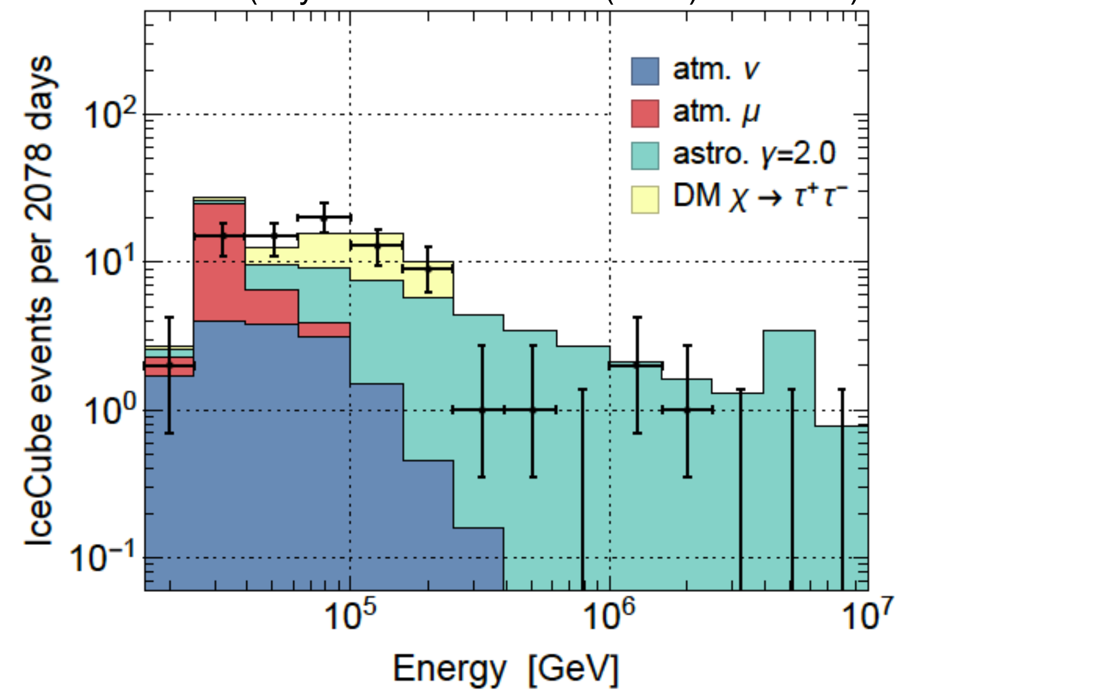
Atri Bhattacharya, Arman Esmaili, Sergio Palomares-Ruiz and Ina Sarcevic, arXiv:1706.05746

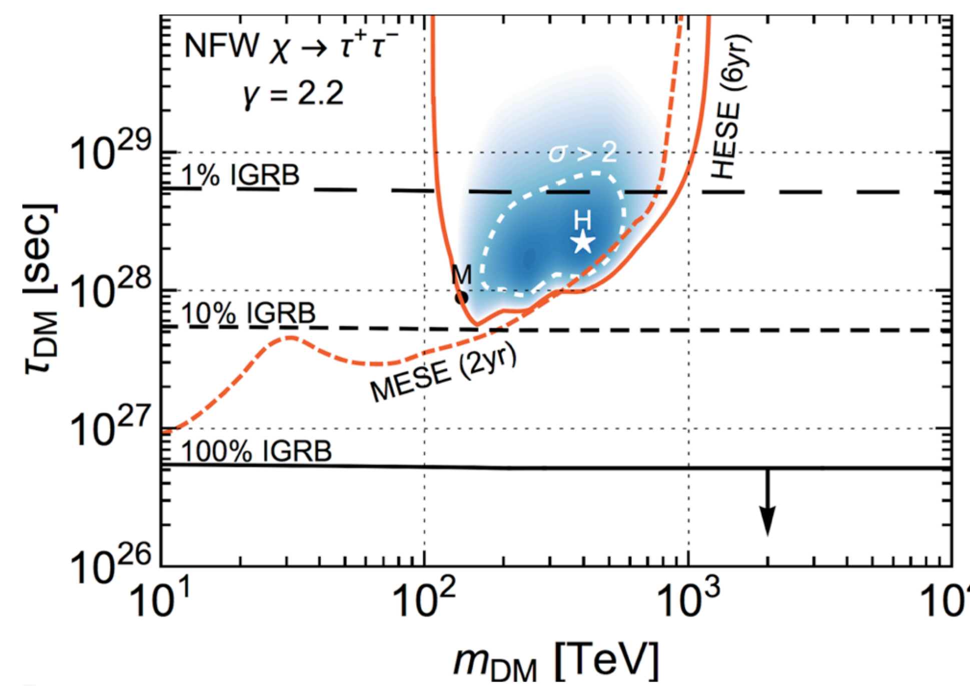




Find that HESE data can be best described with the combination of the astrophysical neutrino flux and the dark matter decay

Marco Chianese, Gennaro Miele, and Stefano Morisi [1707.05241]
(Physics Letters B 773 (2017) 591–595)





A general word of caution when interpreting HESE events:
- Earth absorption needs to be considered
- Outcome can strongly depends on background assumptions (astrophysical and atmospheric neutrino flux)

Dark Matter Decay with IceCube

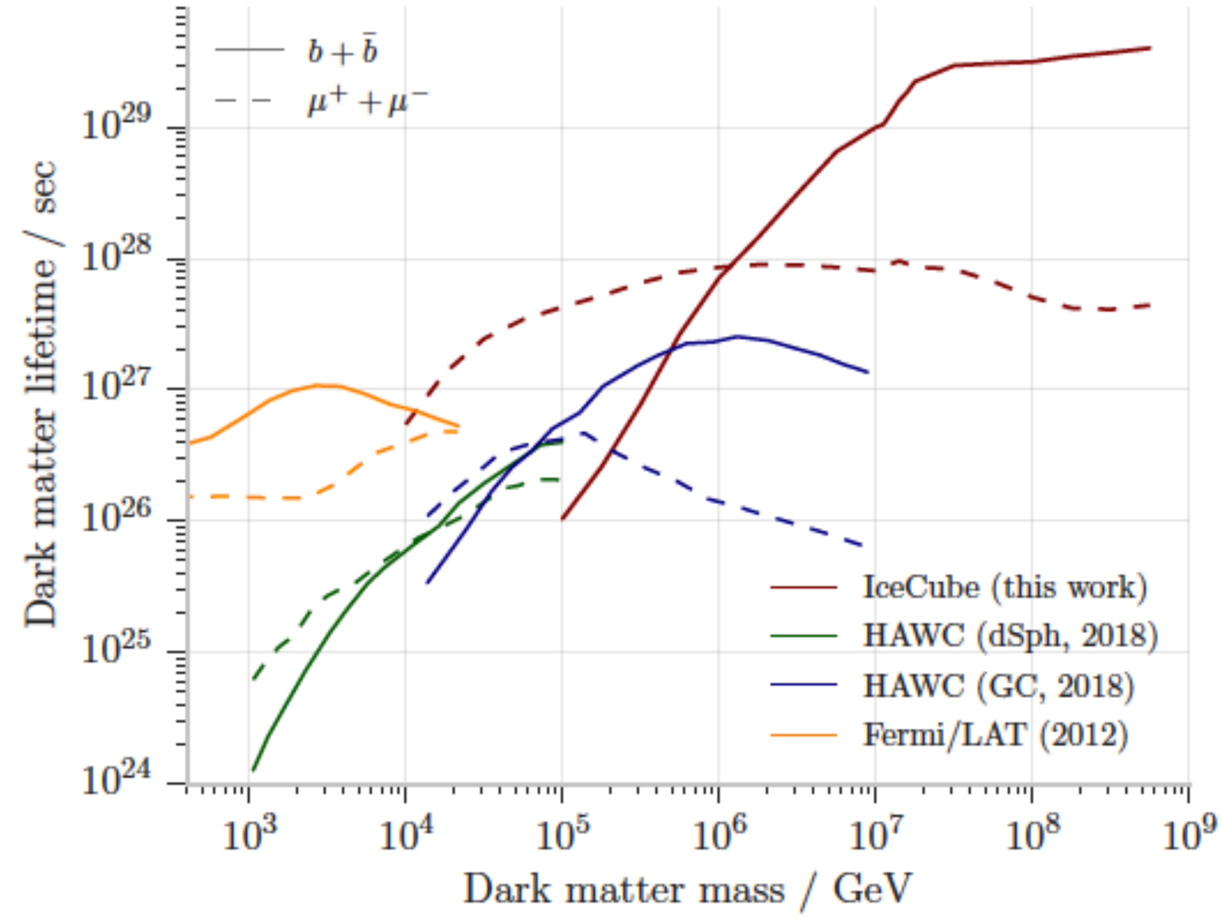
see also HAWC arXiv:1710.10288

J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923
IceCube Collaboration arXiv:1804.03848v1

- Two IceCube analyses have been performed on independent data samples
  - Track-like with six years of data
  - Cascade-like with two years of data

	Track-like	Cascade-like
Number of events	352,294	278
Livetime	2060 days	641 days
Sky coverage	North (zenith > 85°)	Full Sky
Atm. muon background	0.3%	10%
Median reconstr. error	$< 0.5°$ ($E_\nu > 100$ TeV)	$\sim 10°$
Energy uncertainty	$\sim 100\%$	$\sim 10\%$

Test-Statistic: $TS = 2 \times \log \dfrac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM} = \infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$



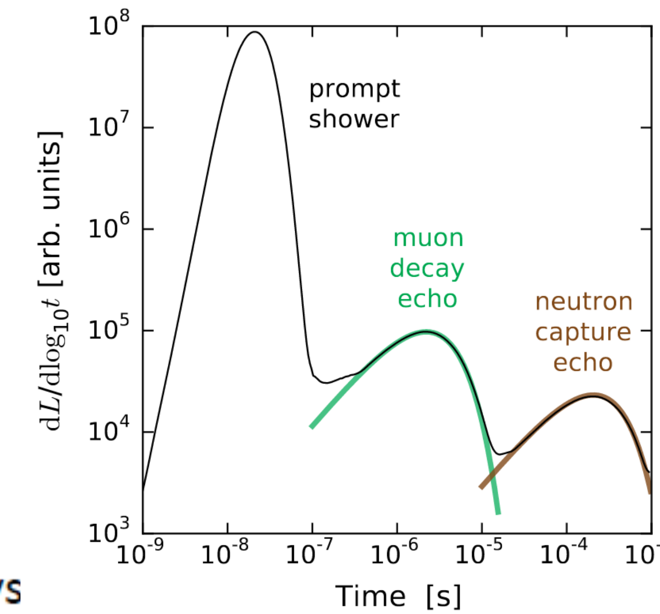
Bound on DM lifetime at ~10^{27}s obtained with IceCube data for m_{DM}>10TeV

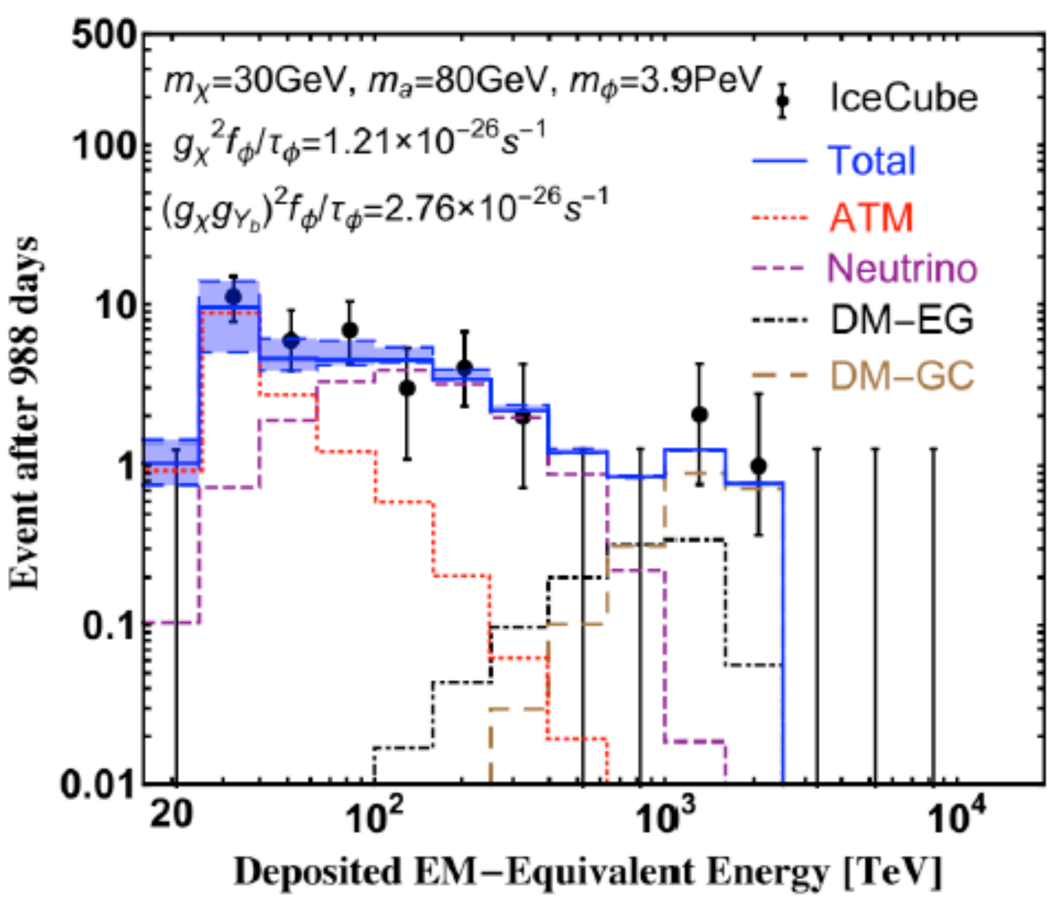
- Dark matter alone cannot explain the observed astrophysical neutrino flux in IceCube
- Scenarios with a PeV neutrino line became less attractive with IceCube's observation of neutrino events well above this energy

IceCube Boosted Dark Matter

Following search proposed by Kopp, Liu, Wan (2015)

using "Echo Technique" Li, Bustamante, Beacom (2016)





Very heavy dark matter particle ϕ decays to lighter stable dark matter χ →boost!

Recoil (only hadronic cascades)

$\phi \rightarrow \chi\,\overline{\chi}\,a,\ a \rightarrow b\,\overline{b}$

$\rightarrow \nu$'s

Neutrons capture on hydrogen and product 2.2MeV gamma. In seawater, 33% of neutrons capture on Cl; the emitted gamma rays have 8.6 MeV, making the neutron echoes more visible

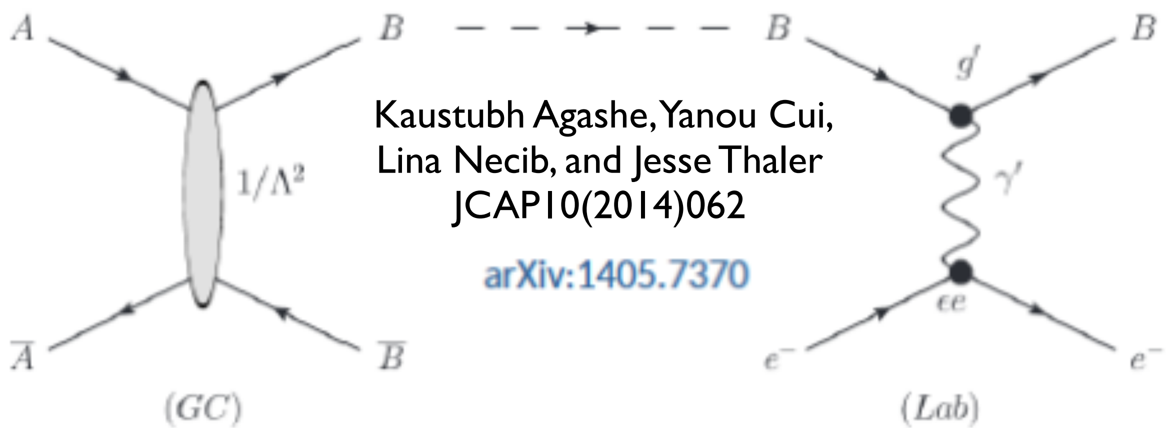
"Echo Technique" holds prospects to individually tag high-energy NC and CC interactions !

May sound crazy, but is just an example for exotic interactions in IceCube detectable via recoil

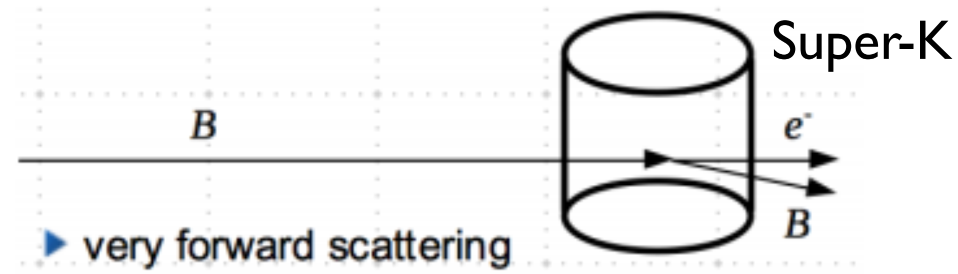
see also A. Steuer, L. Koepke [IceCube] PoS(ICRC2017)1008

C. Kachulis et al [Super-K] arXiv:1711.05278

Super-K Boosted Dark Matter

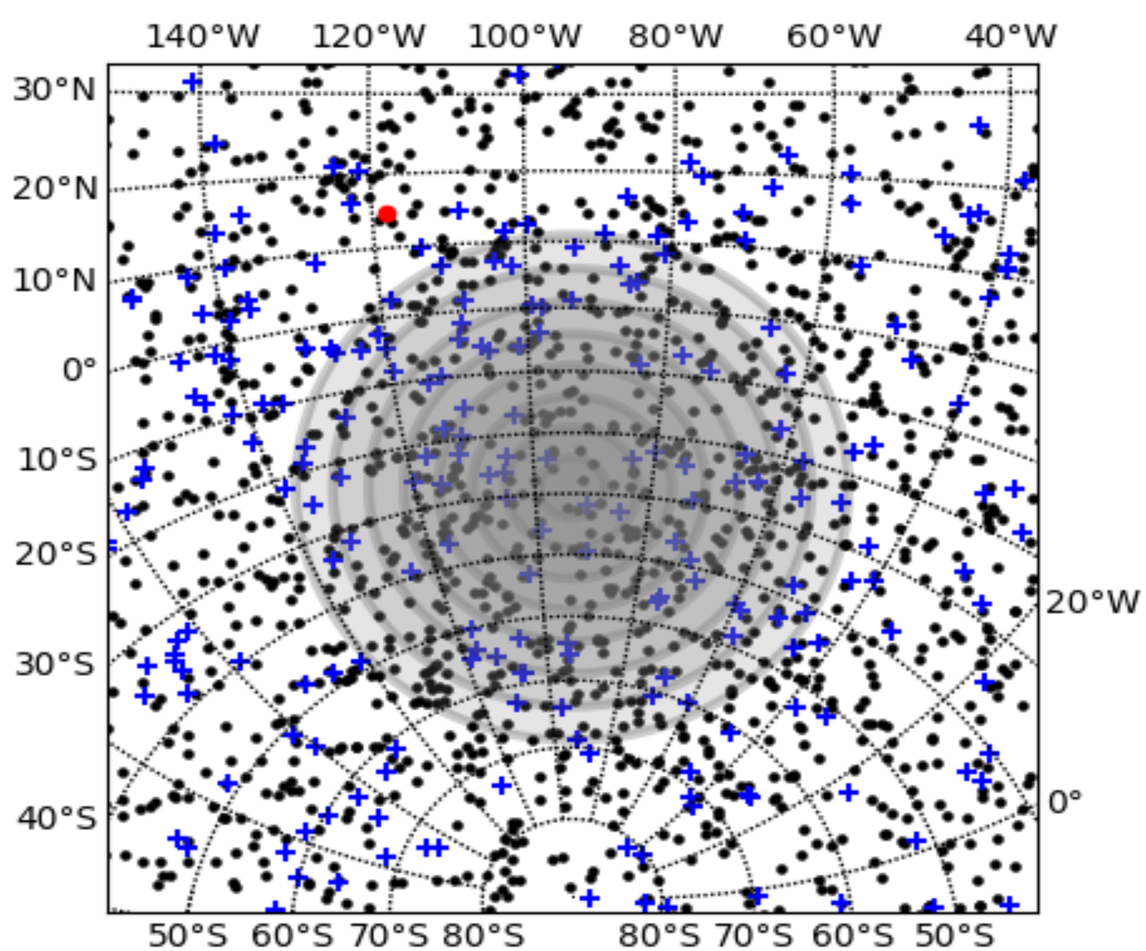


Kaustubh Agashe, Yanou Cui, Lina Necib, and Jesse Thaler
JCAP10(2014)062
arXiv:1405.7370



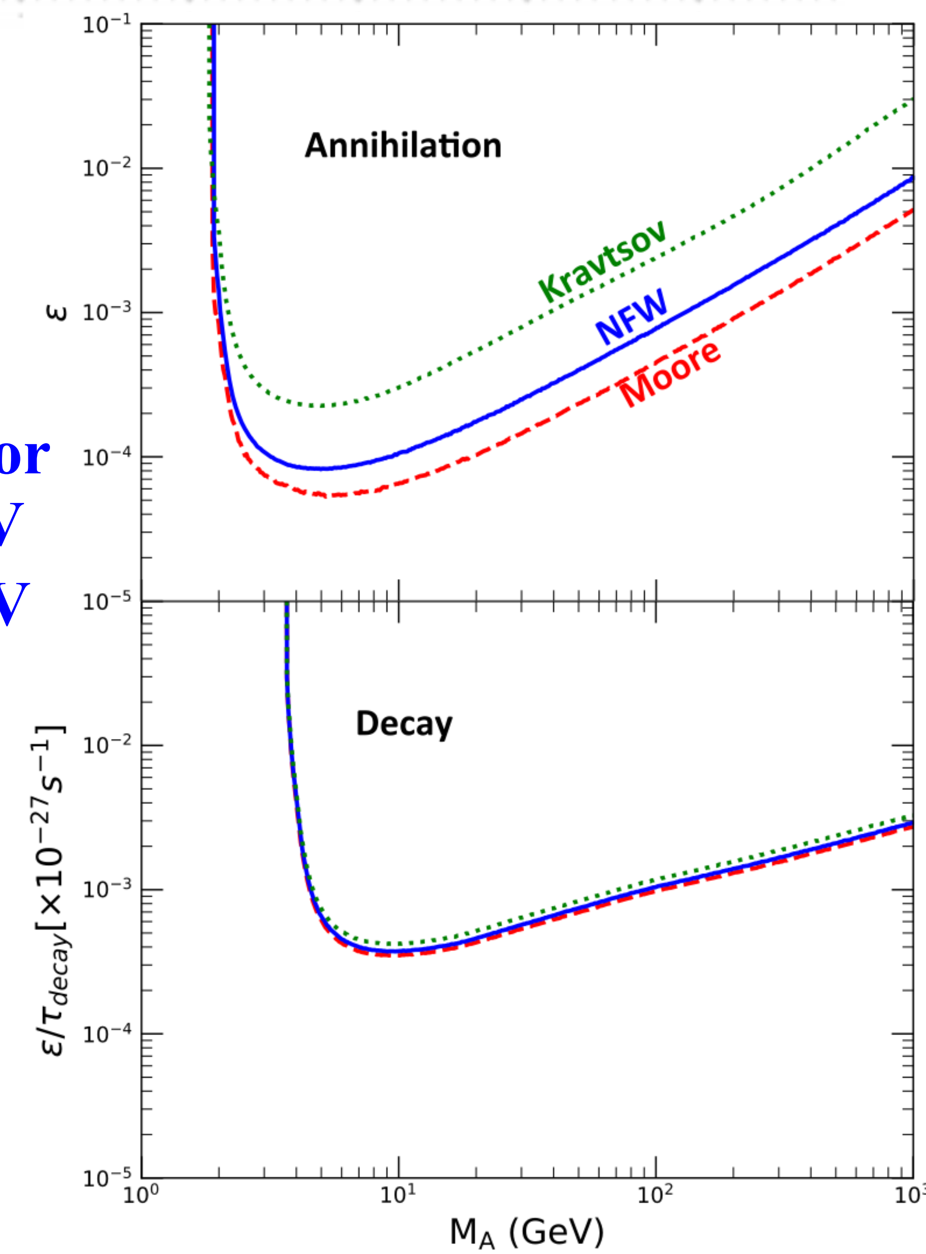
- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

Cone search: 8 cones from 5° to 40° around GC
➔ no cluster found around Galactic Center



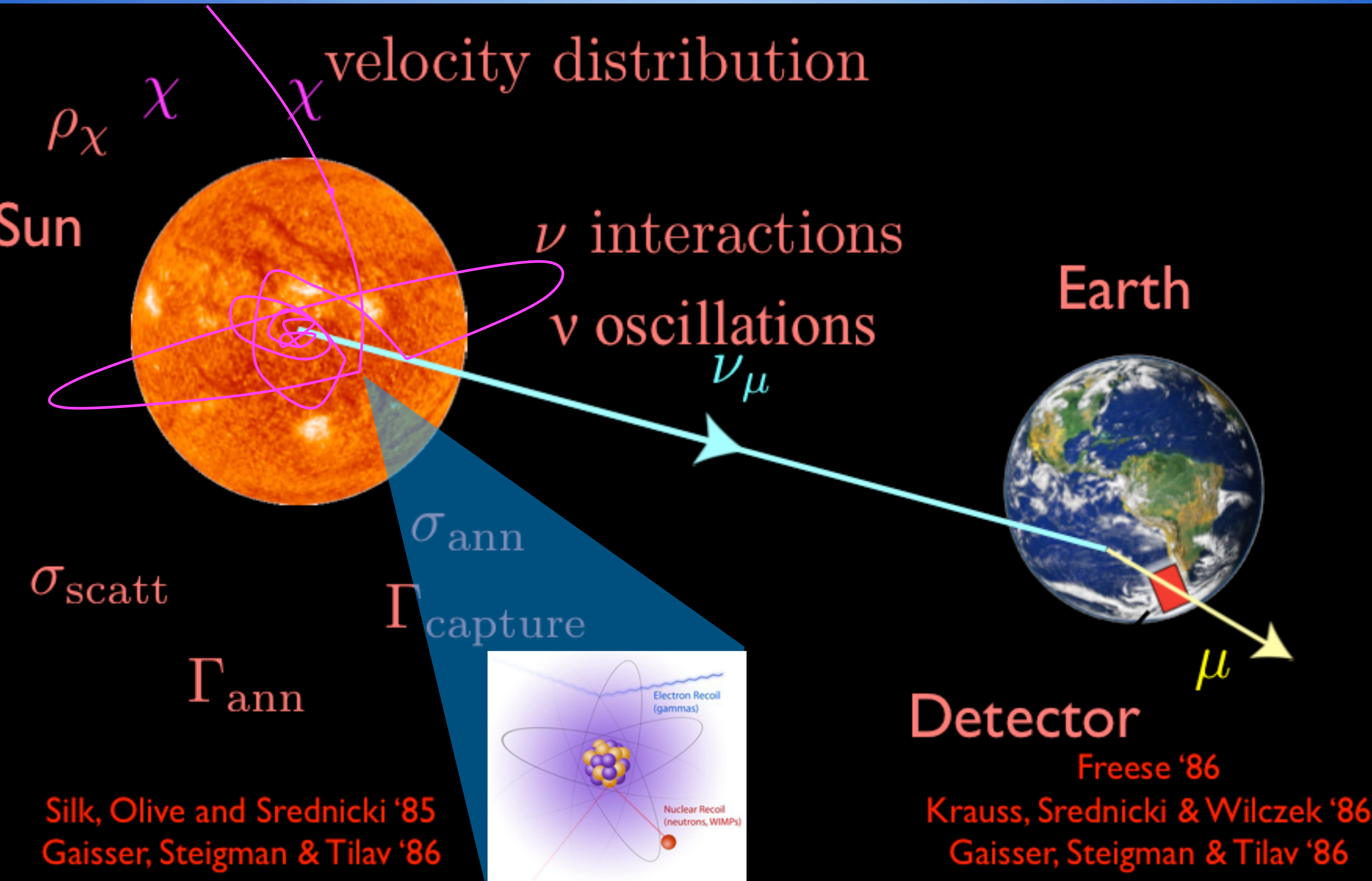
• < 1.33 GeV + 1.33 GeV-20 GeV • >20 GeV

90% limits for $m_{\gamma'}$=20 MeV m_{B}=200 MeV g'=0.5



Dark Matter Capture in the Sun

Solar Dark Matter



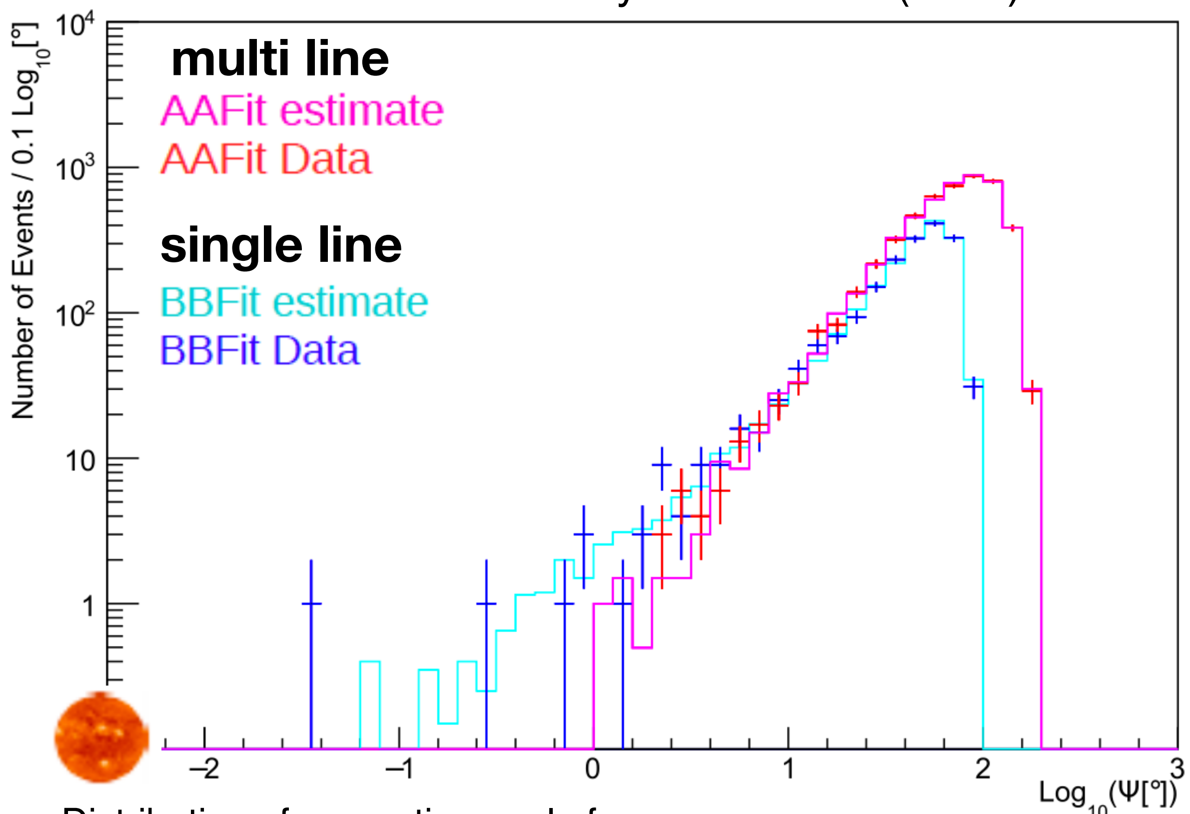
Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

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

Solar Dark Matter - IceCube/ANTARES

ANTARES

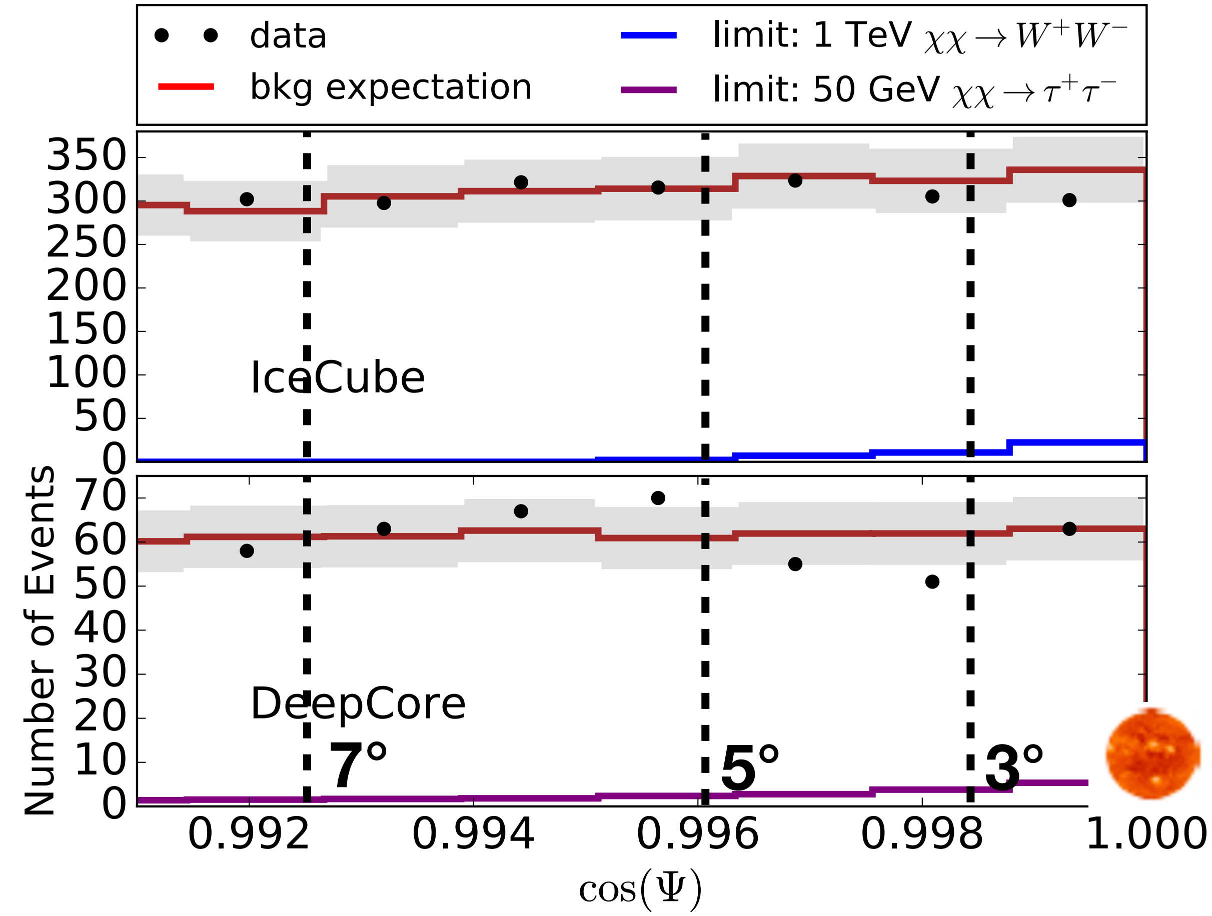
ANTARES - Phys.Lett. B759 (2016) 69-74



Distribution of separation angle for 2007-2012 ANTARES data

IceCube

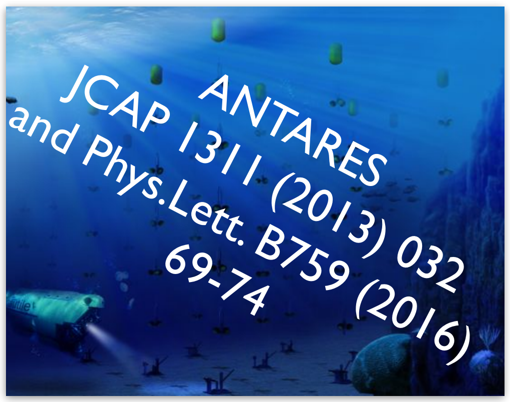
IceCube Eur.Phys.J. C77 (2017) no.3, 146

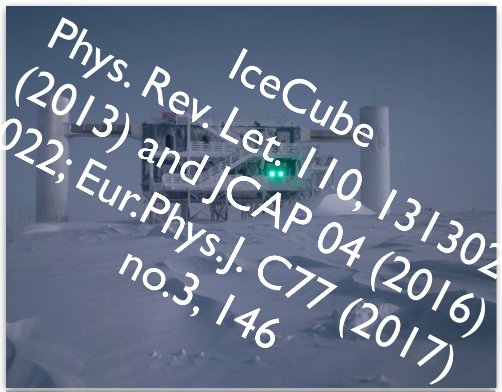


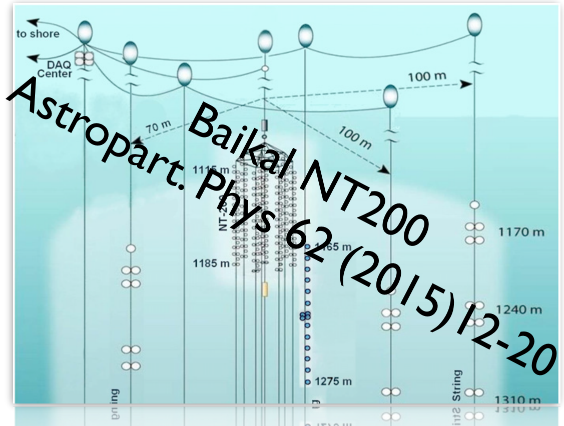
- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data
- Energy and angular information taken into account

No excess observed - set limit …

Solar Dark Matter Summary

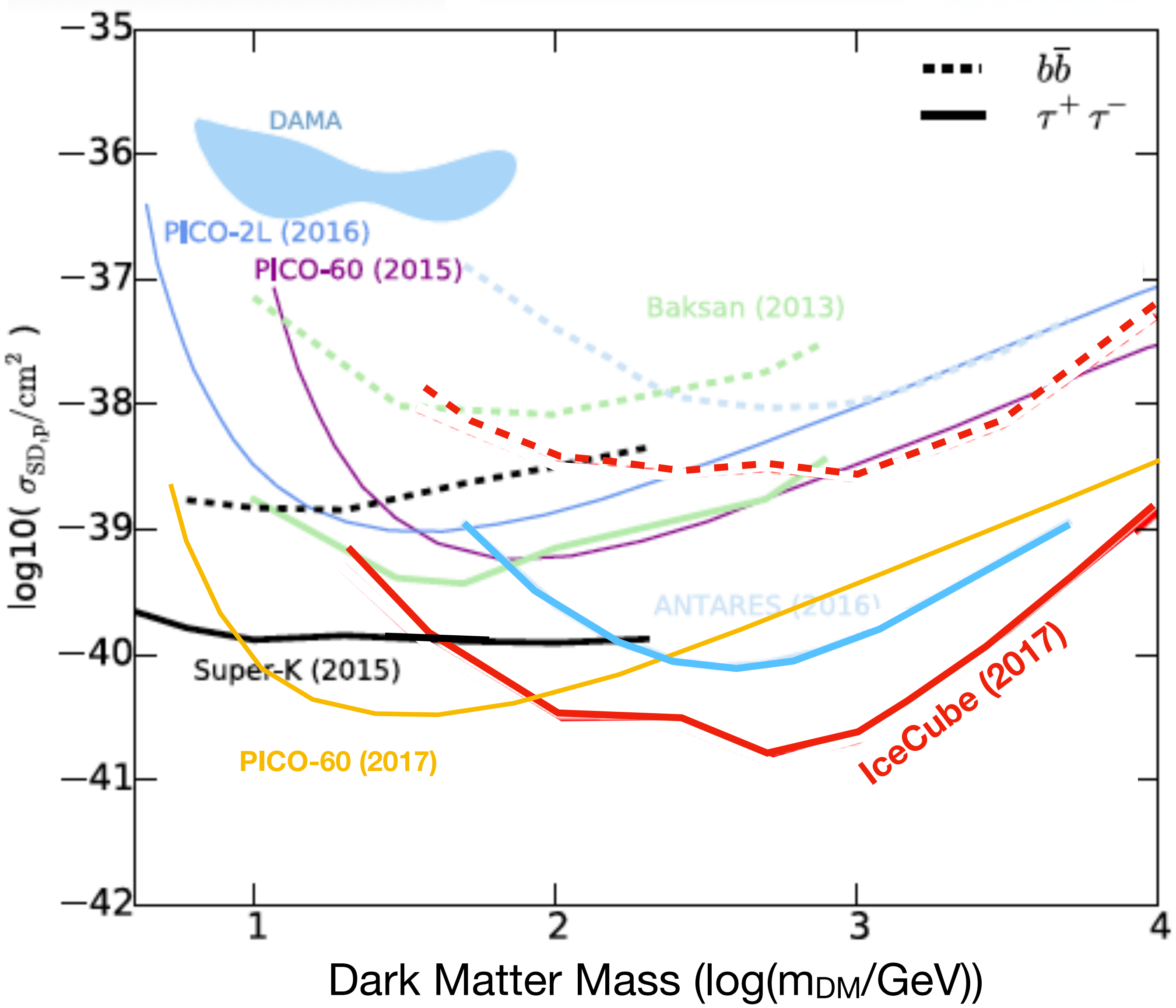


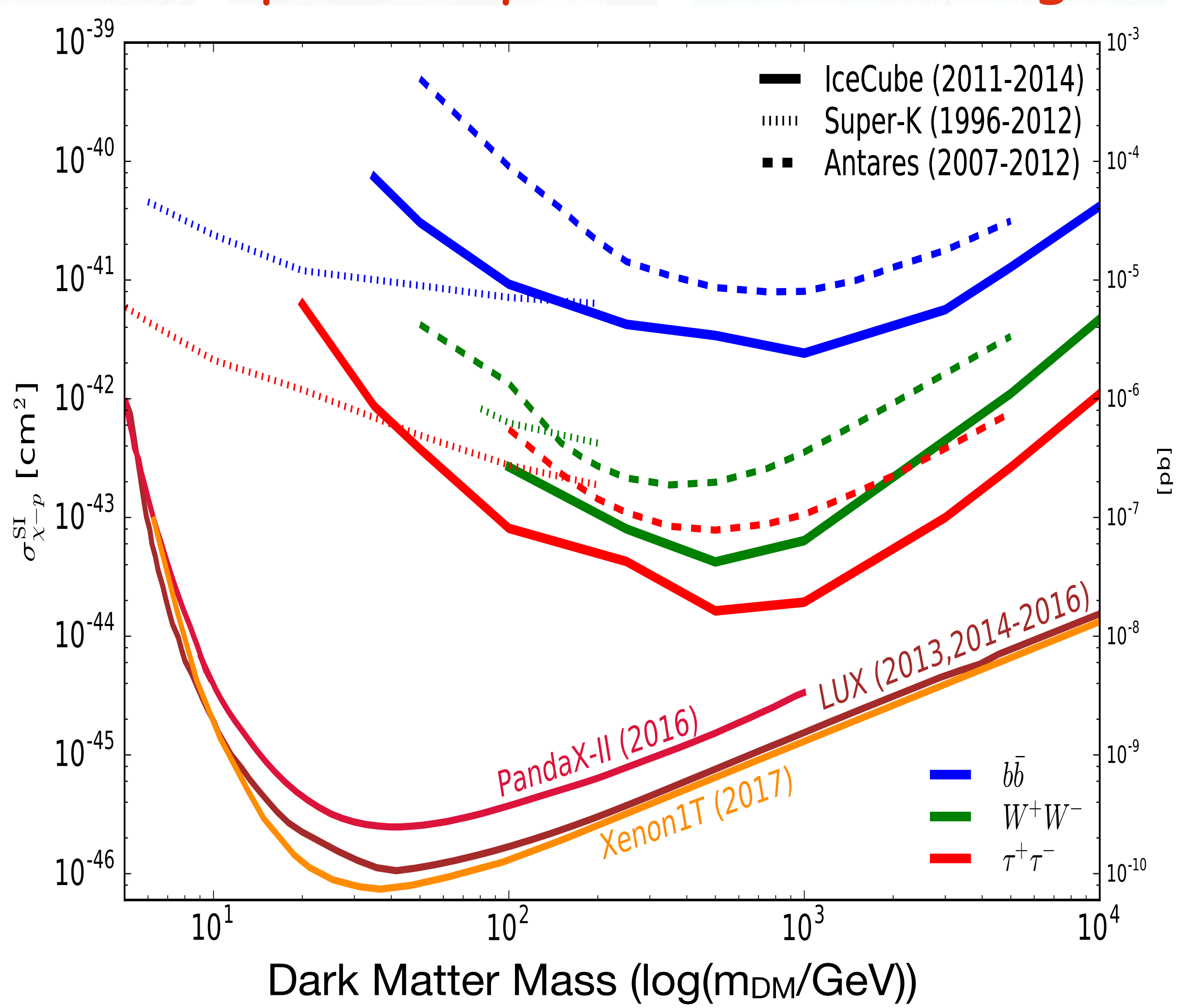




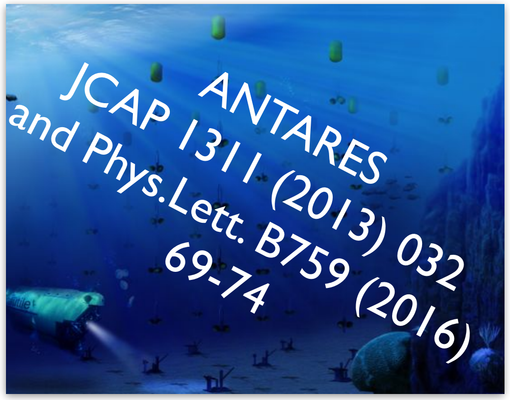
Spin-dependent scattering

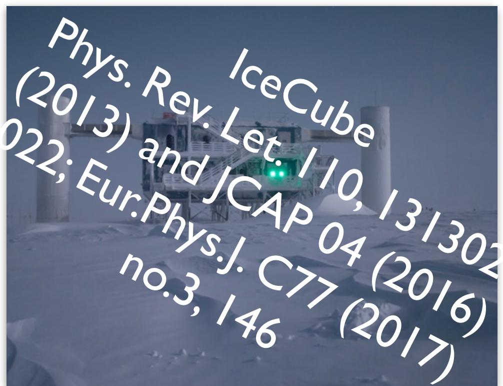
Spin-independent scattering

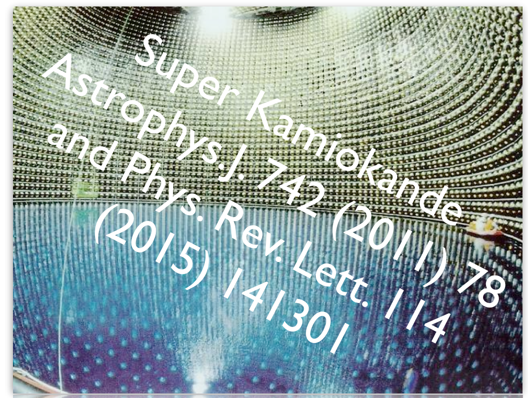


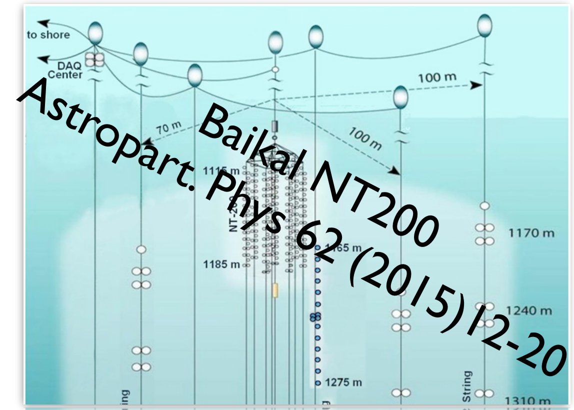


Solar Dark Matter Summary



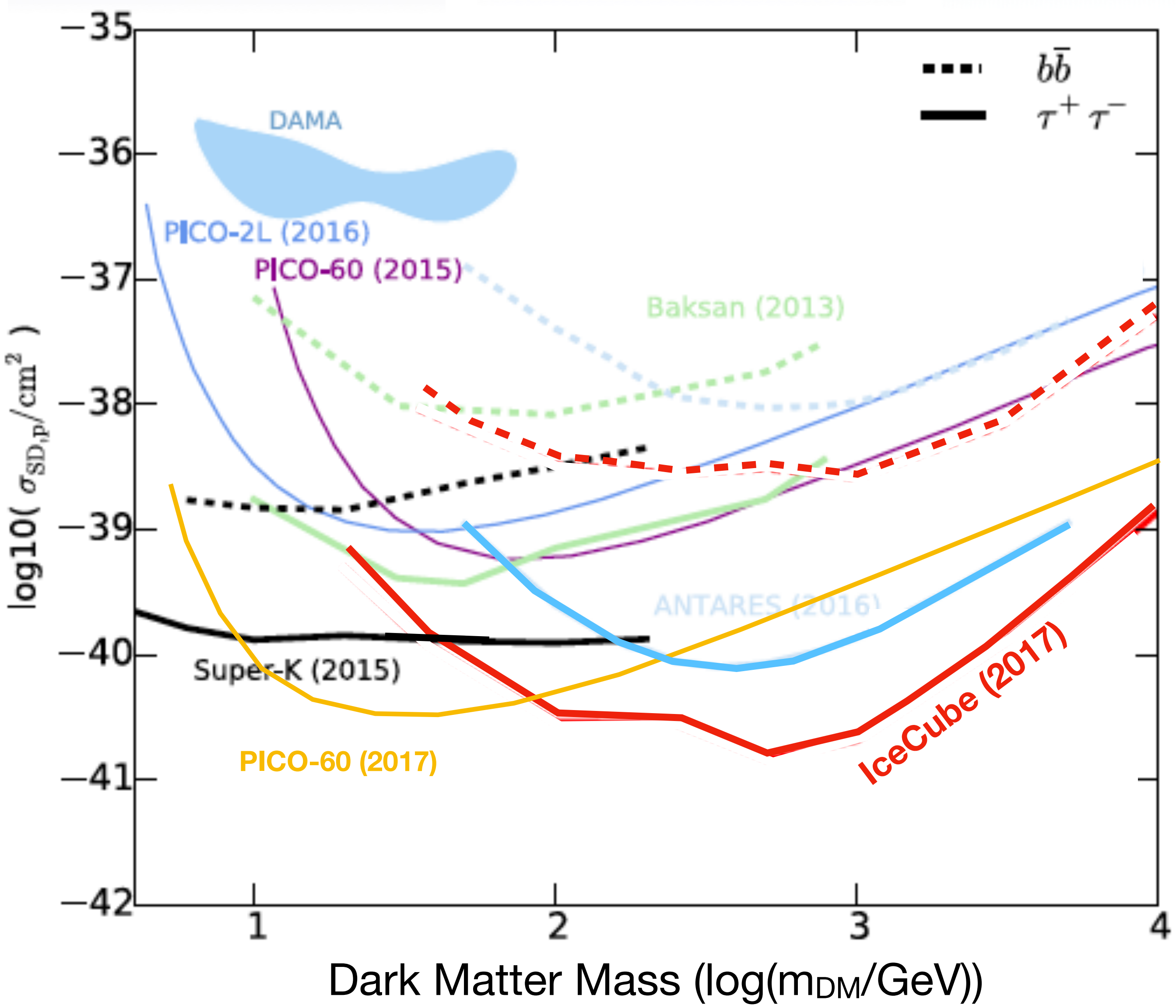


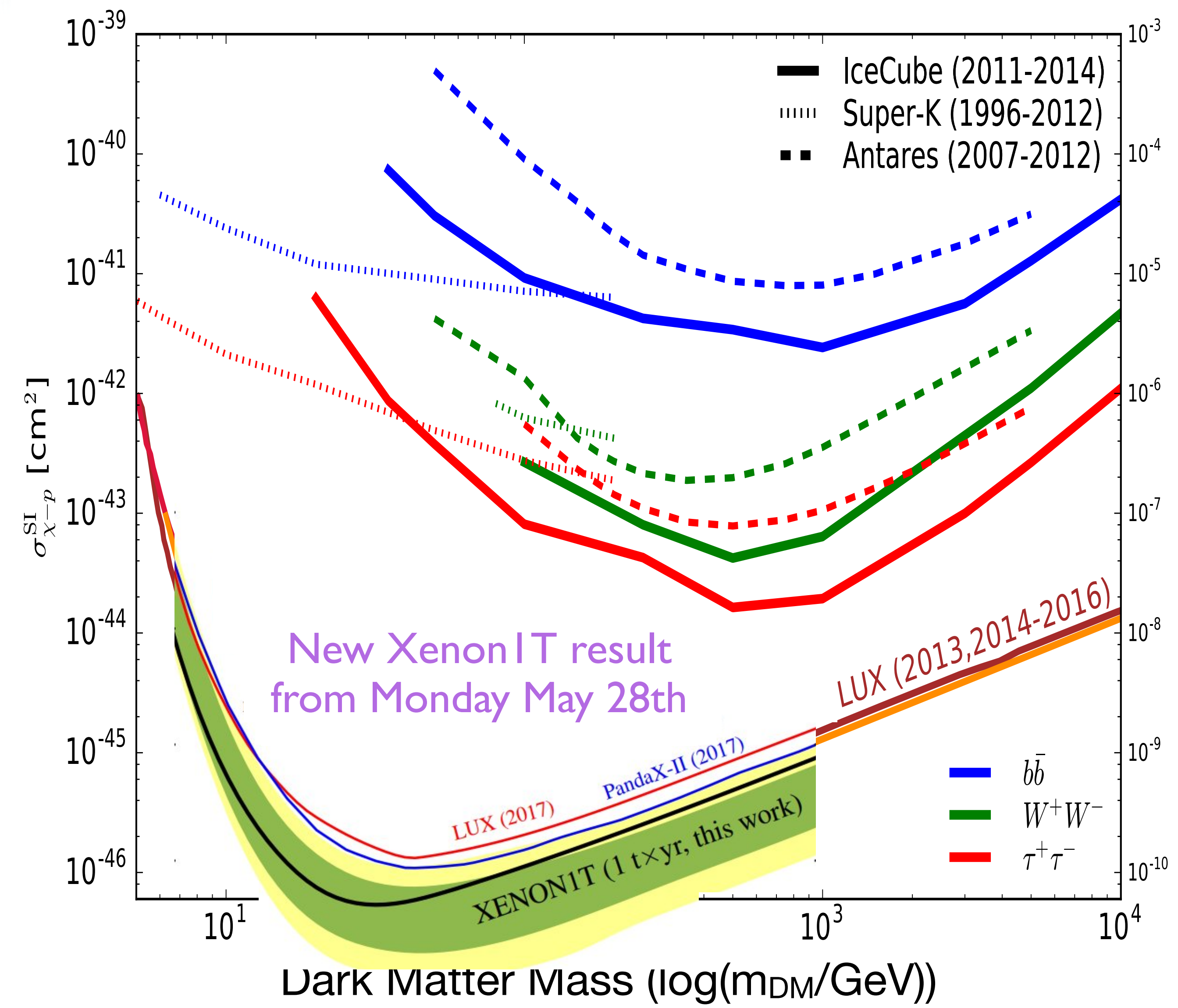




Spin-dependent scattering

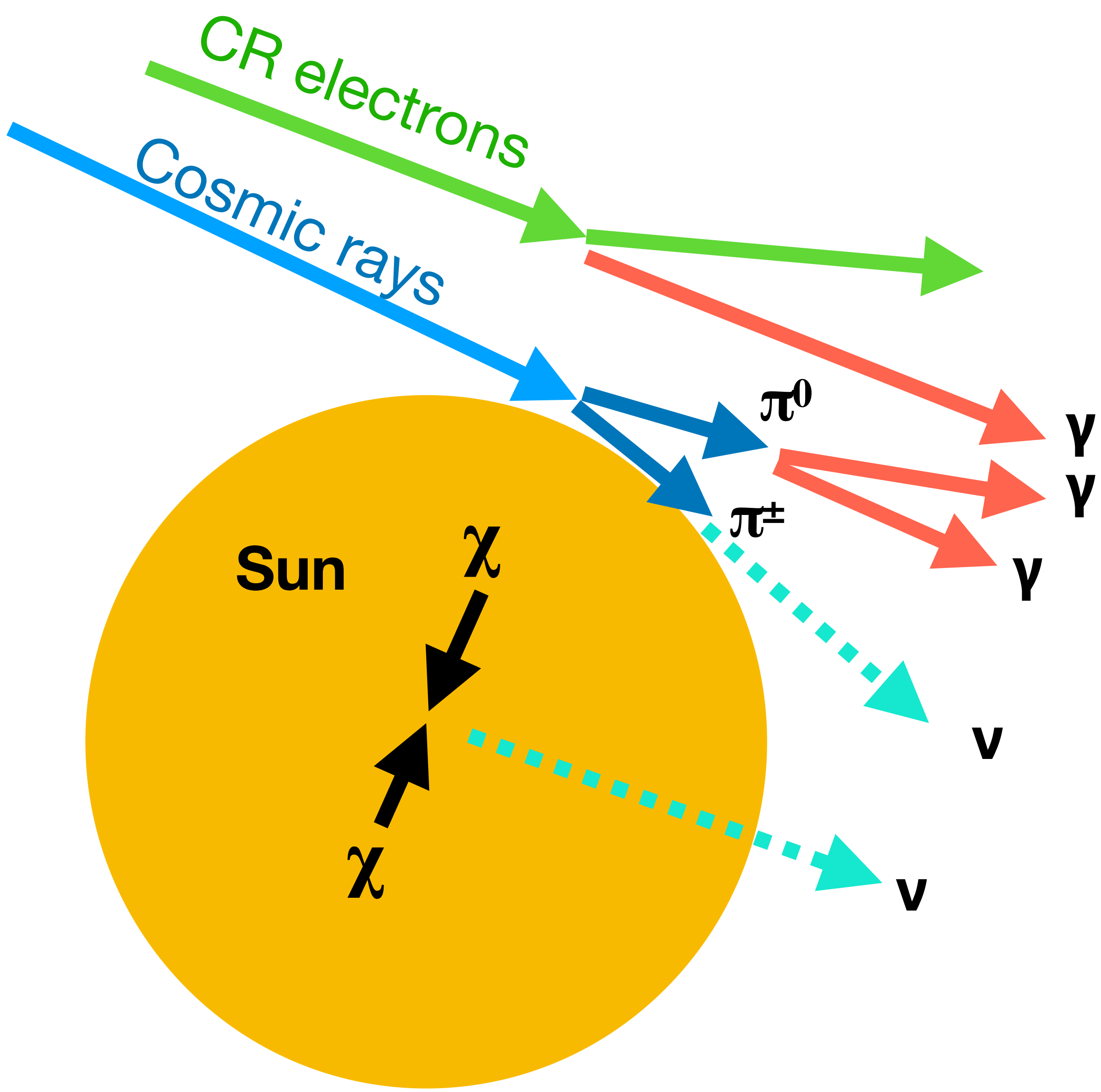
Spin-independent scattering



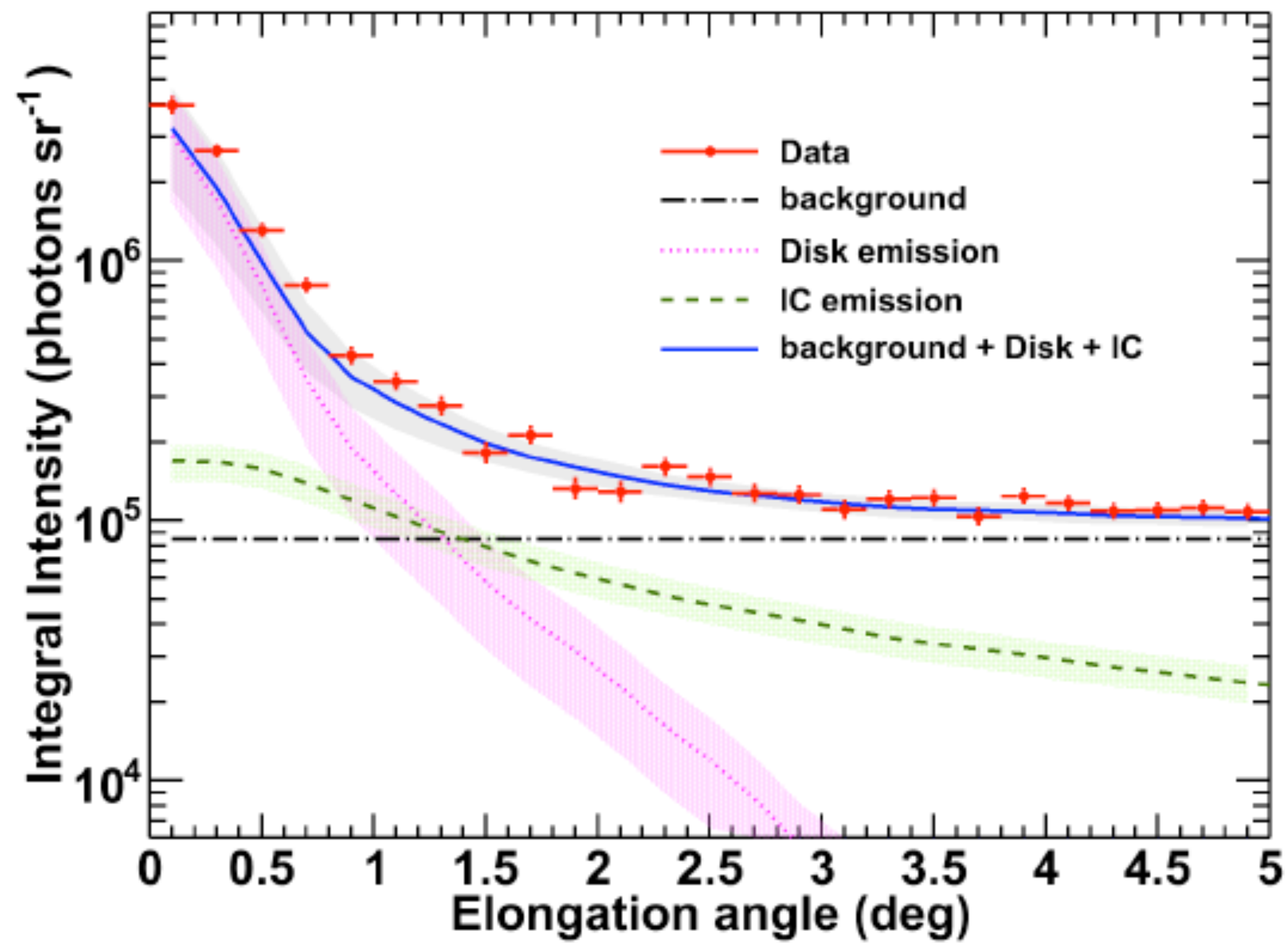


Solar Atmospheric Neutrinos / Solar Atmospheric Neutrino Floor

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 (and could result in the first high-energy neutrino point source)

Leptonic

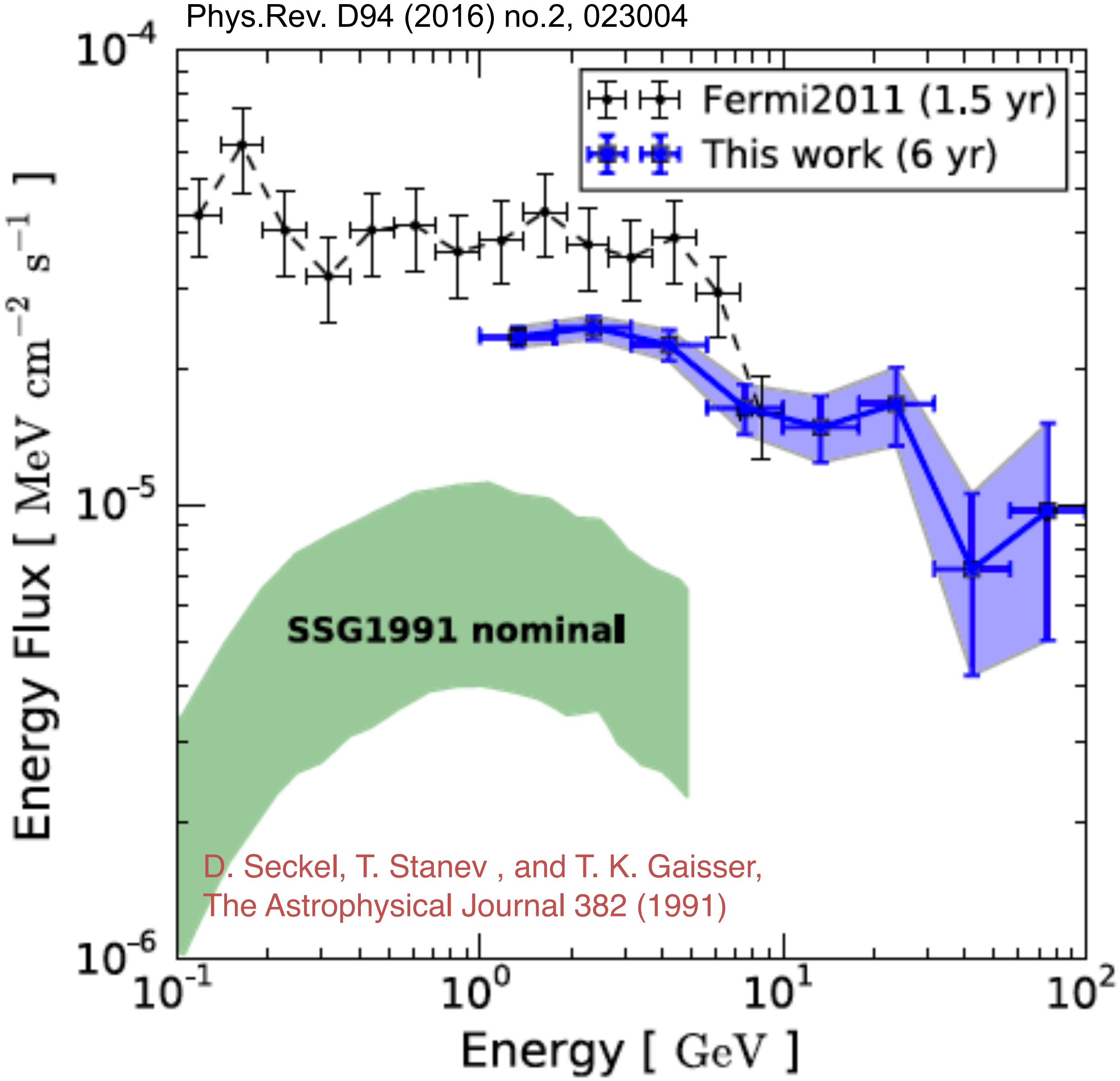
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadronic

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

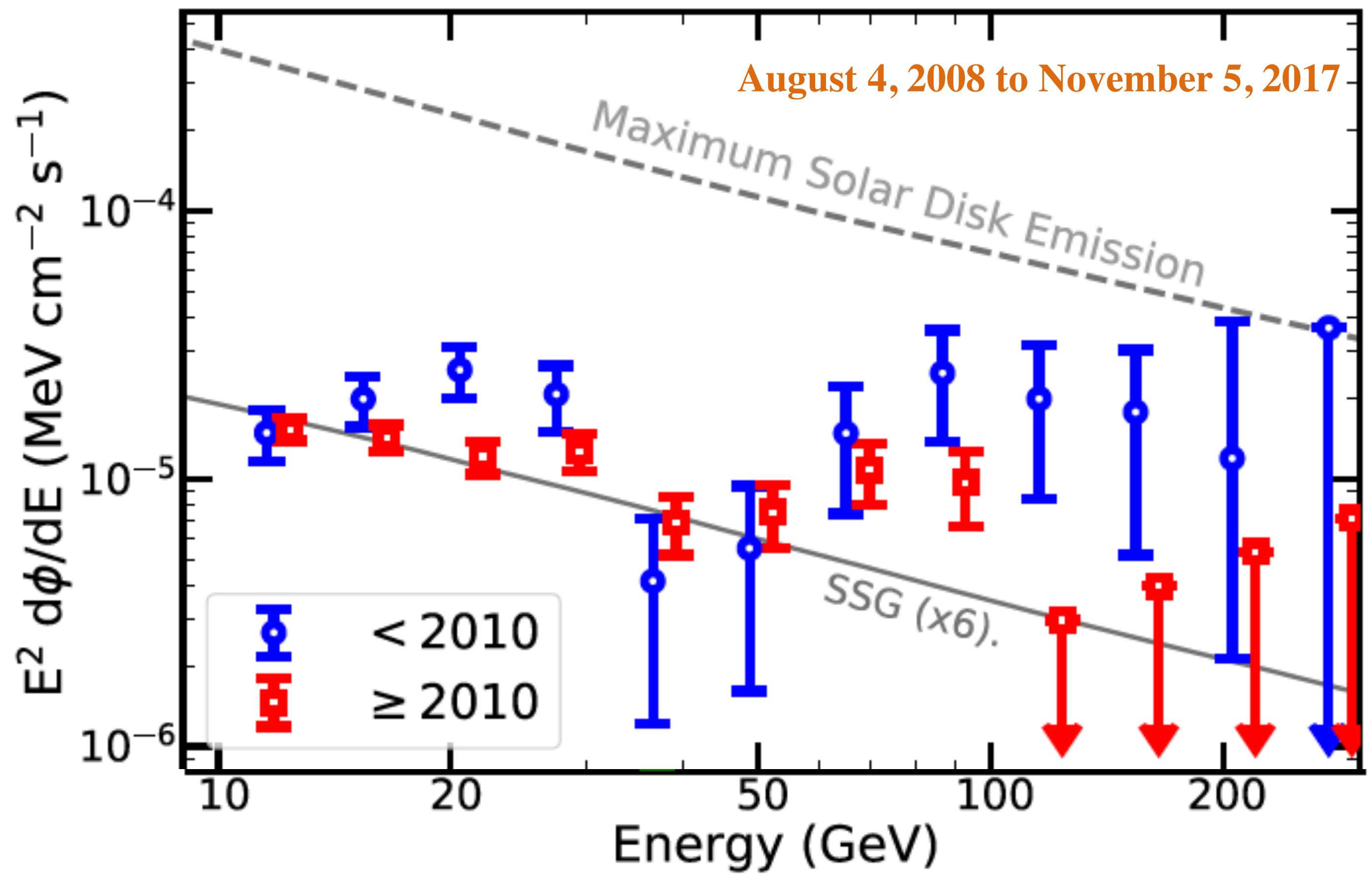
Cosmic ray interactions with the Sun

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

Neutrino flux predictions

FJAWs (C. Argüelles et al. [astro-ph/1703.07798])

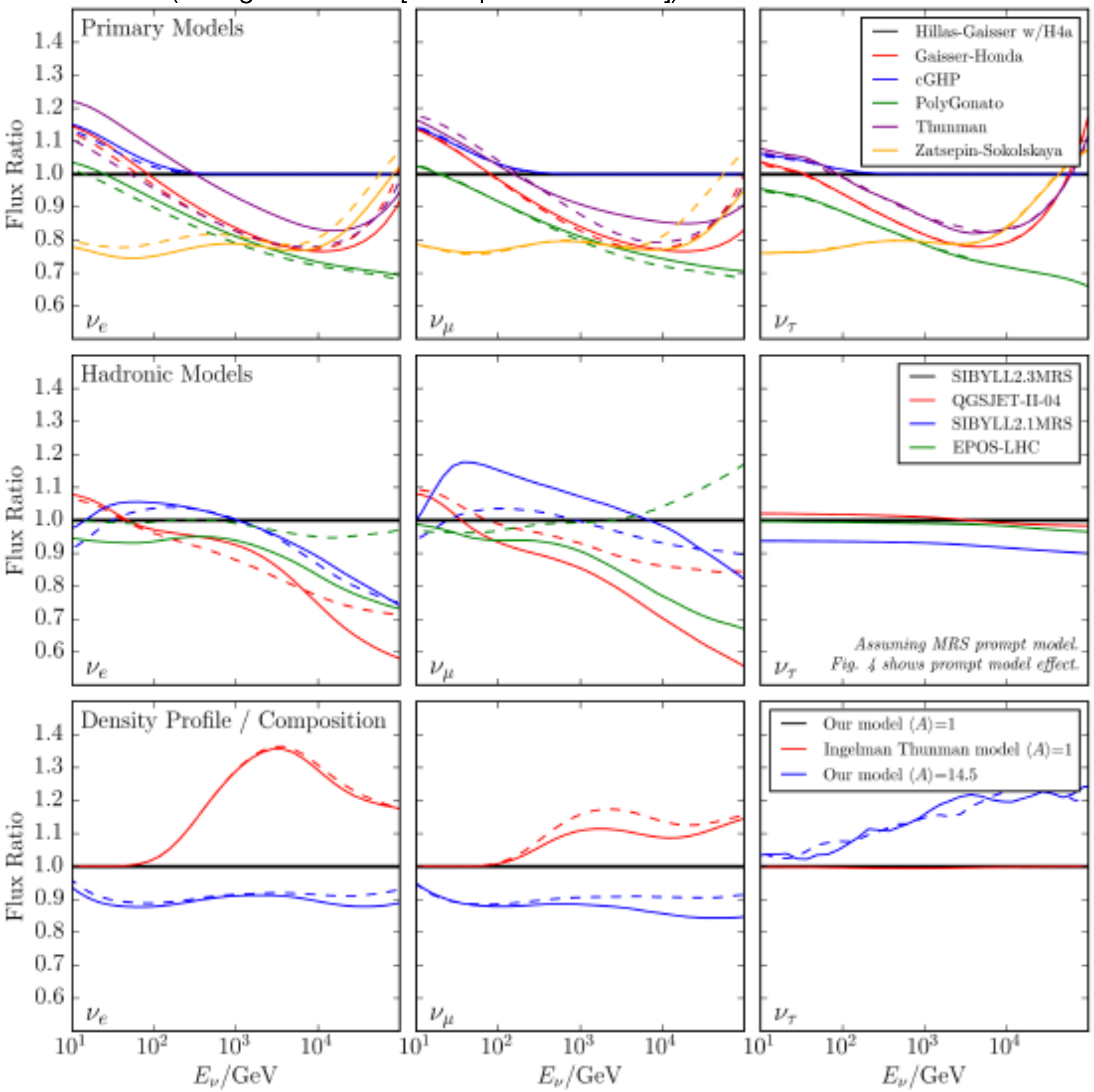
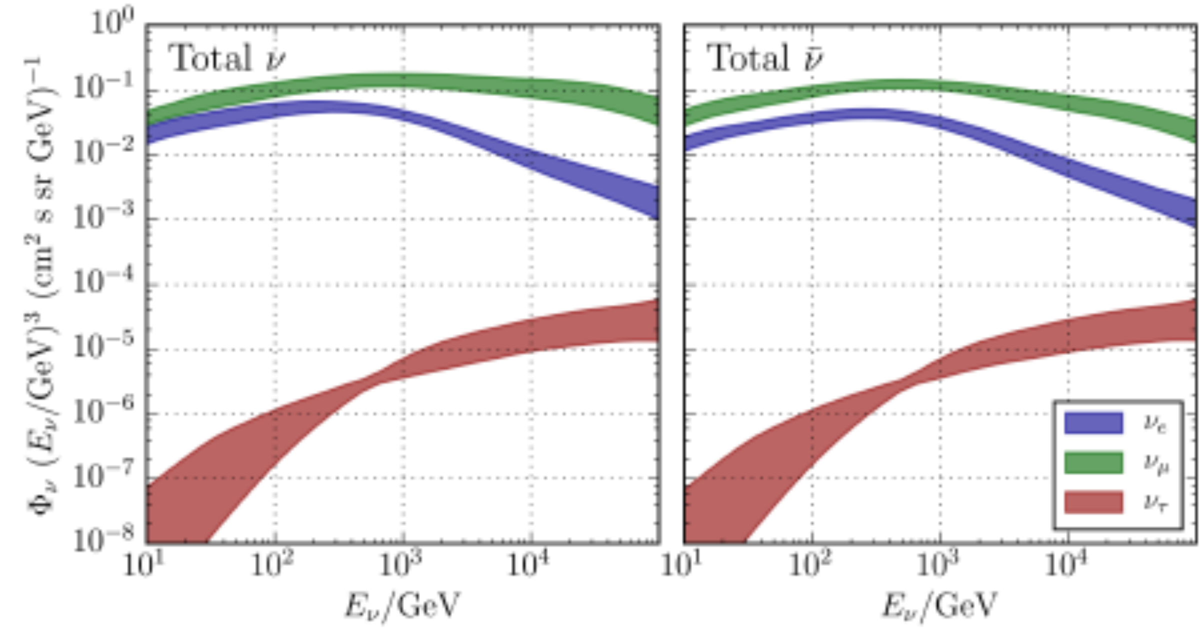


Figure 3. Effects of different models on our flux prediction, for impact parameter b=0. The top row shows various primary models; the second row, hadronic and composition models; the third row, extremal solar density and composition models. See text for more information and references.

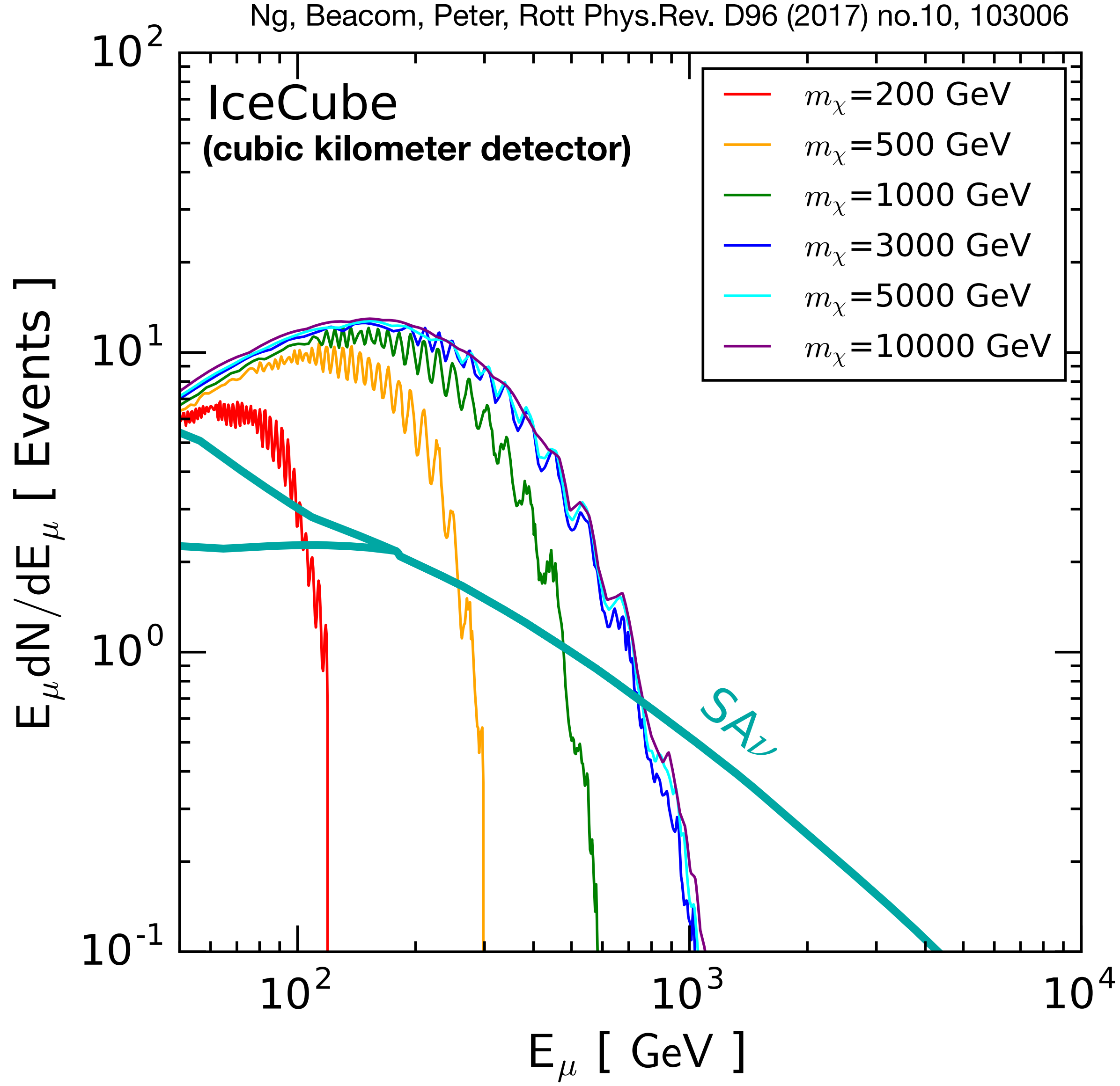


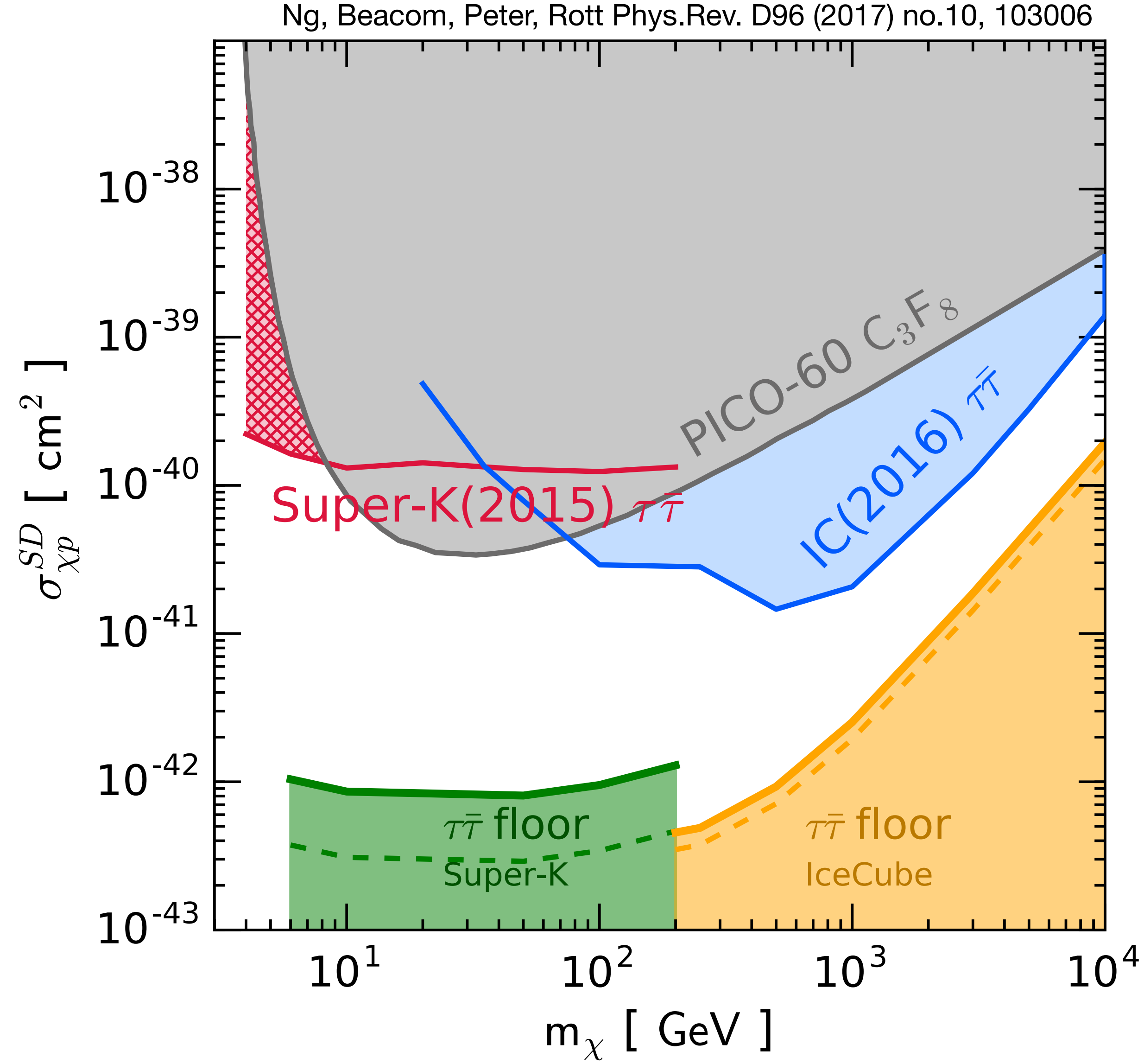
- Flux predictions vary by <30%, based on
  - primary models
  - hadronic models
  - extremal solar density and composition models

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]

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

Expect ~2events per year at cubic kilometer detector

Recent works on the Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor

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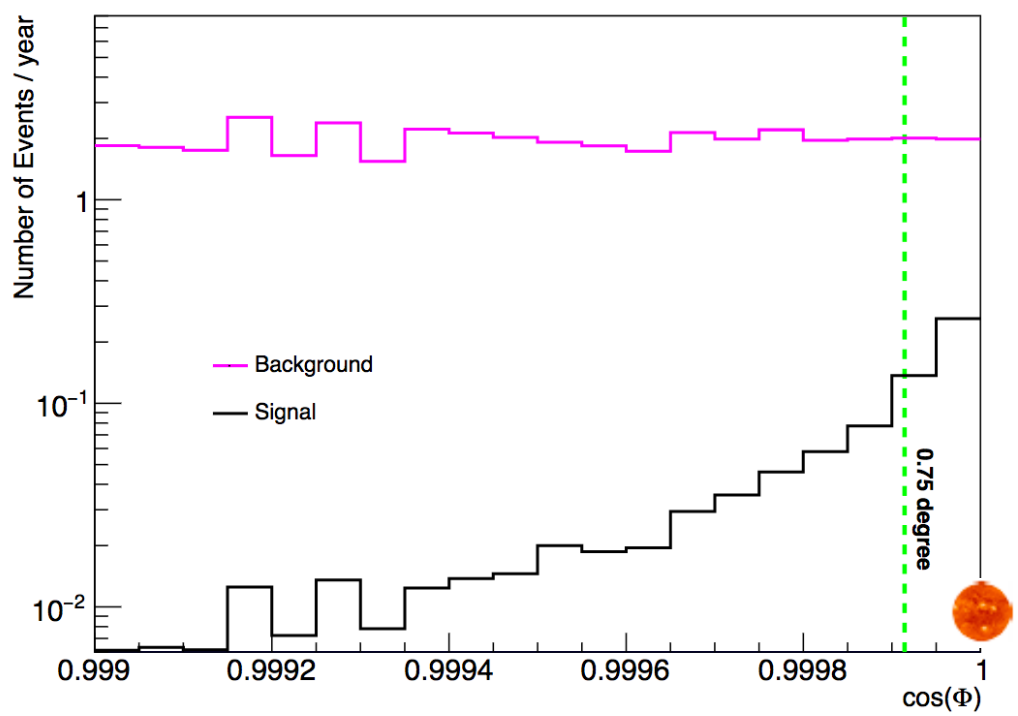
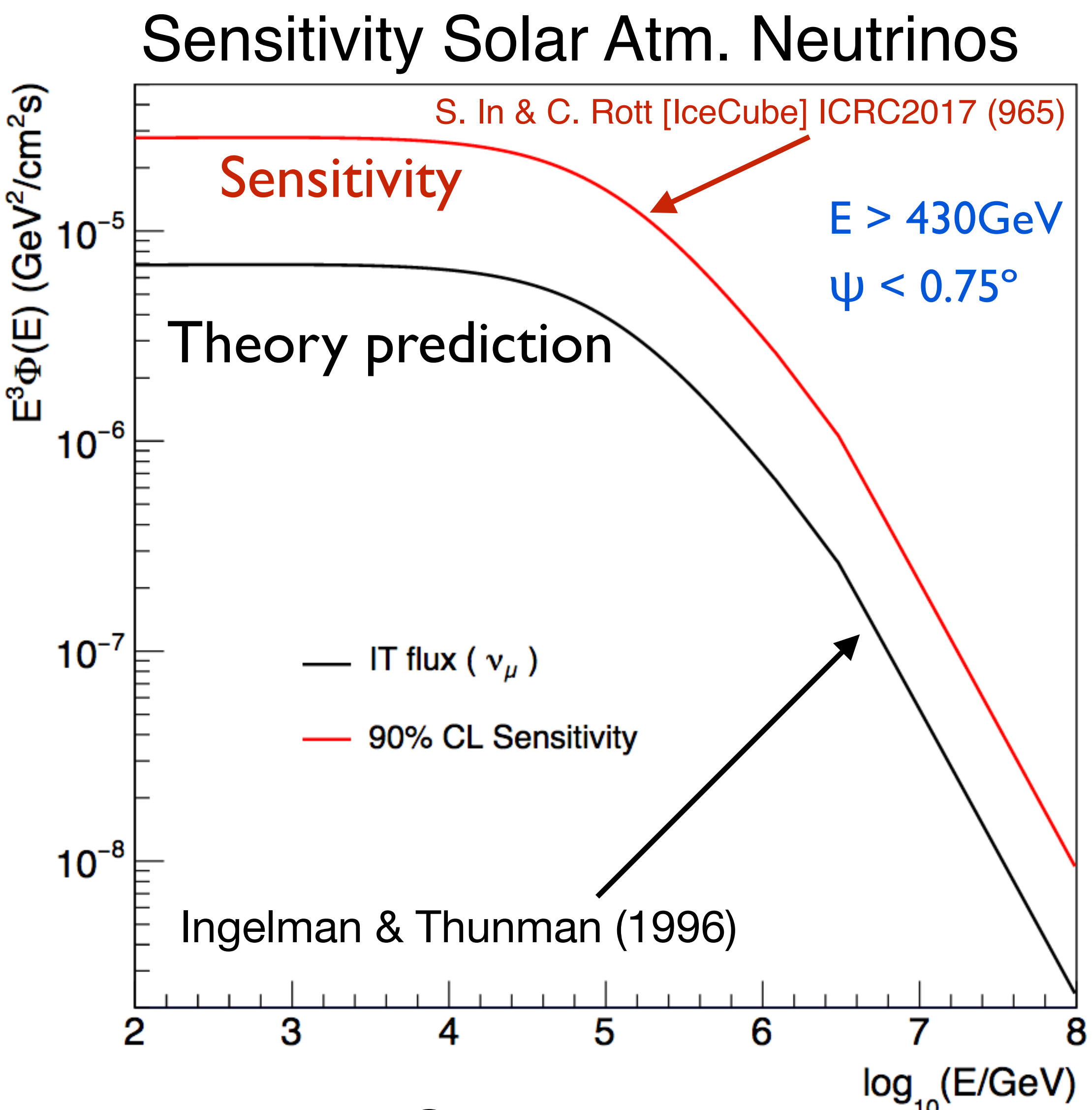
- M. Masip **Astropart.Phys. 97 (2018) 63-68** [arXiv: 1706.01290]

Solar Atmospheric Neutrino Search

- Experimental searches have started at
  - IceCube and ANTARES
  - Off-source data for background prediction
  - Cosmic-ray Sun shadow needs to be included as systematic uncertainty





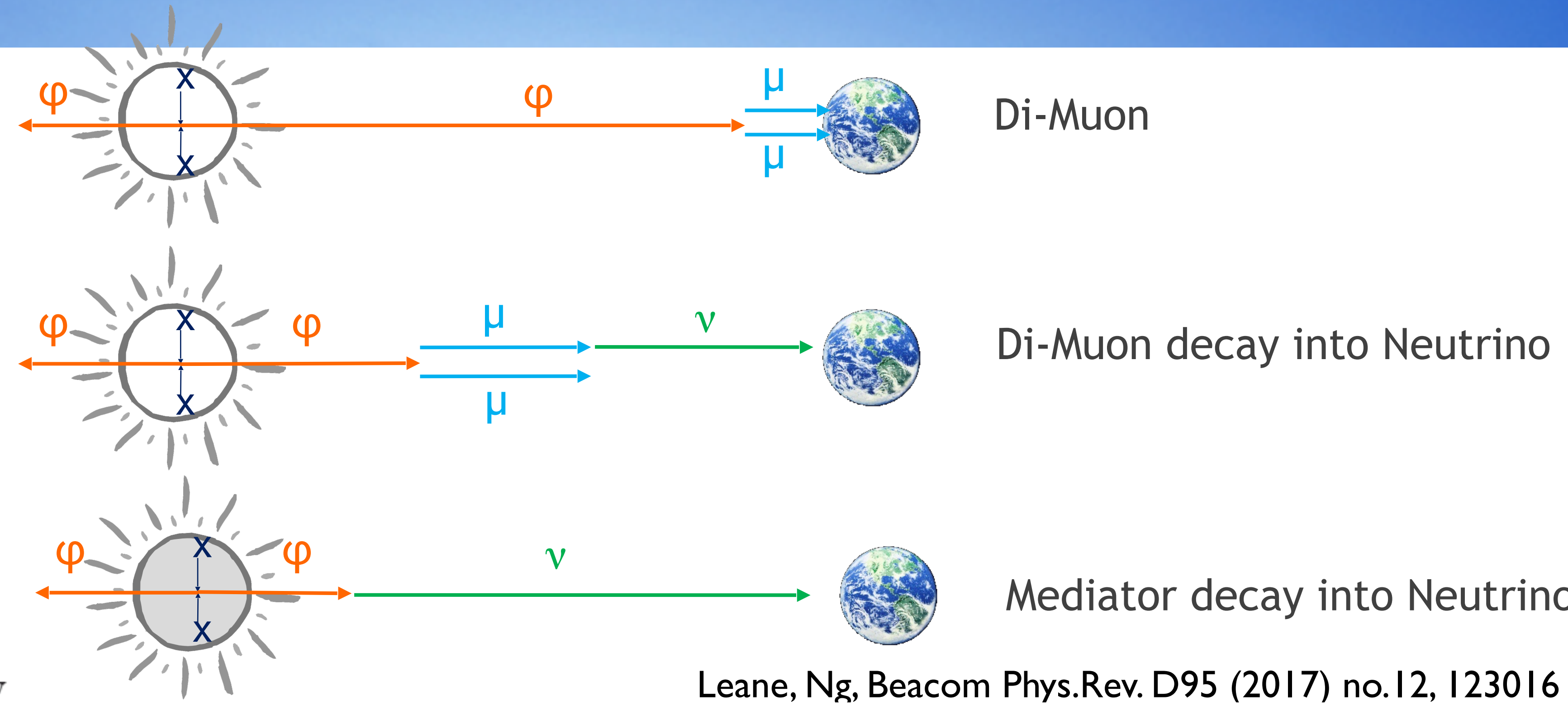
- Solar Atmospheric neutrinos might be observable with IceCube
- Observing solar atmospheric neutrinos is important for:
  - Understanding solar magnetic fields;
  - Cosmic ray propagation in the inner solar system;
  - Improving models of cosmic ray interactions in the solar atmosphere;
  - Finding a high-energy neutrino point source
  - Better understand the background for dark matter searches

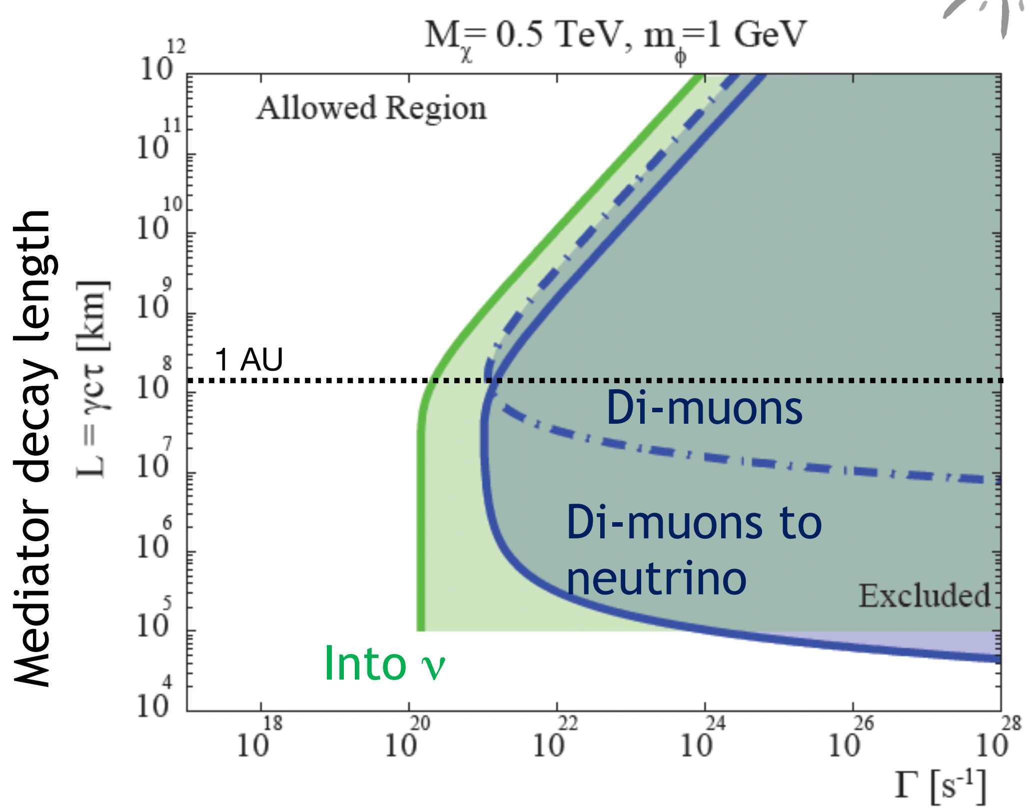
Secluded Dark Matter

ANTARES Coll. JCAP 1605 (2016) no.05, 016

ANTARES Secluded Dark Matter

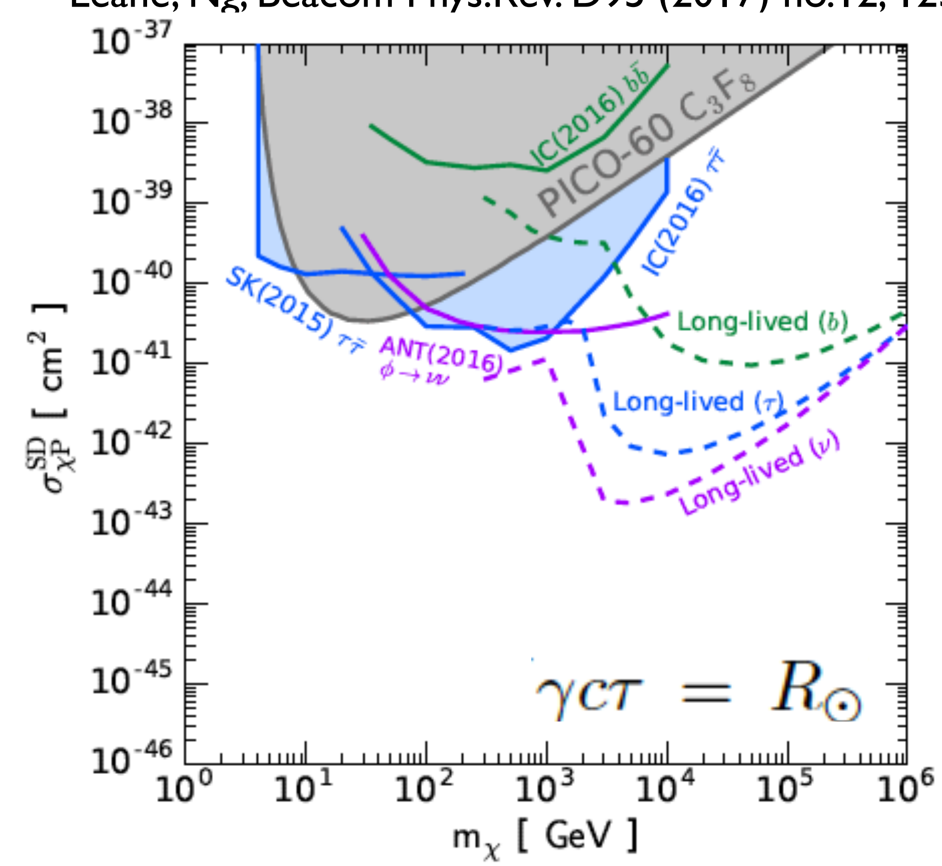
- Dark matter annihilates into meta-stable particle
  - χχ annihilates into mediator ϕ
    - ϕ → νν or μμ
- Livetime of 1321 days (Jan 2007 to Oct 2012)





Annihilation of DM in the Sun x Branching ratio

Leane, Ng, Beacom Phys.Rev. D95 (2017) no.12, 123016



- Contrarily to standard solar WIMP scenarios, secluded dark matter can produce neutrinos > 1TeV
- For most channels, EM signals are expected, cross checks with HAWC, etc. possible

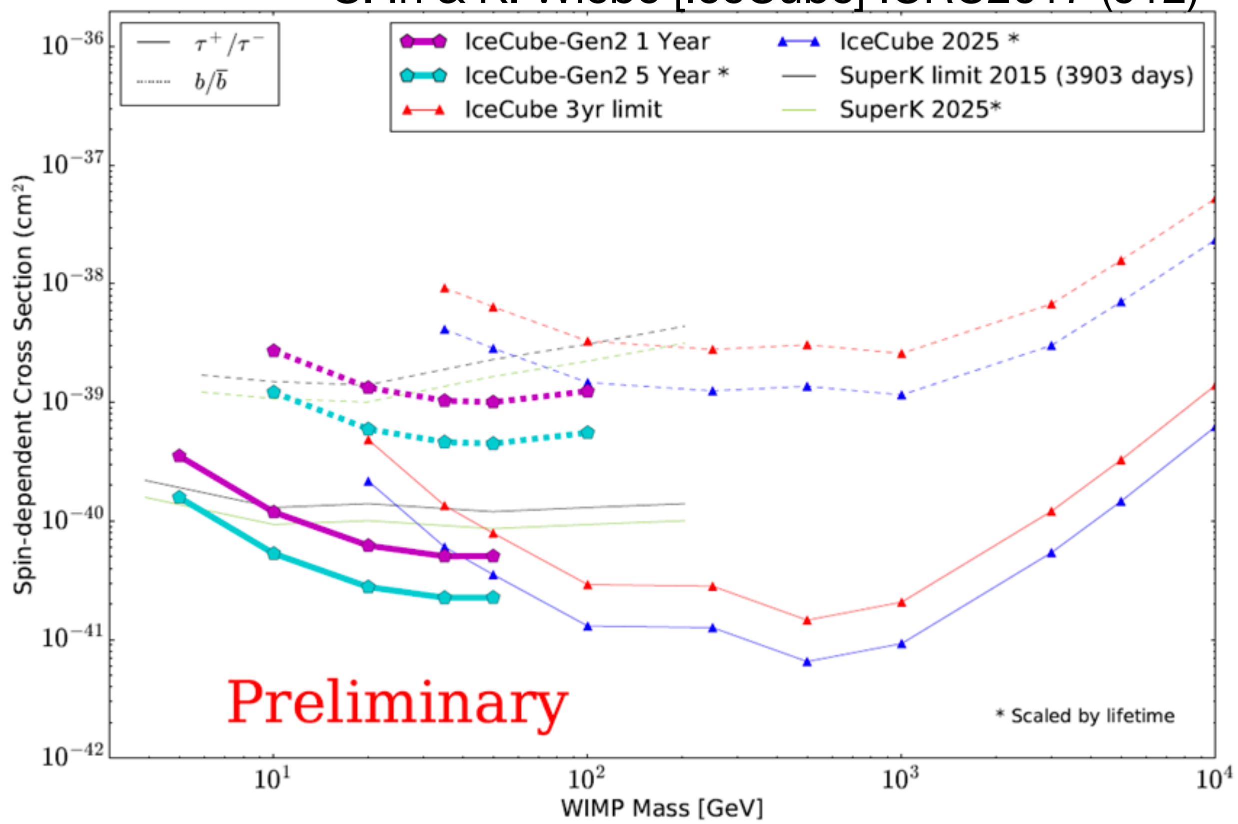
Outlook

IceCube PINGU Collaboration arXiv:1401.2046
Short version https://arxiv.org/pdf/1607.02671.pdf

Next generation neutrino detectors

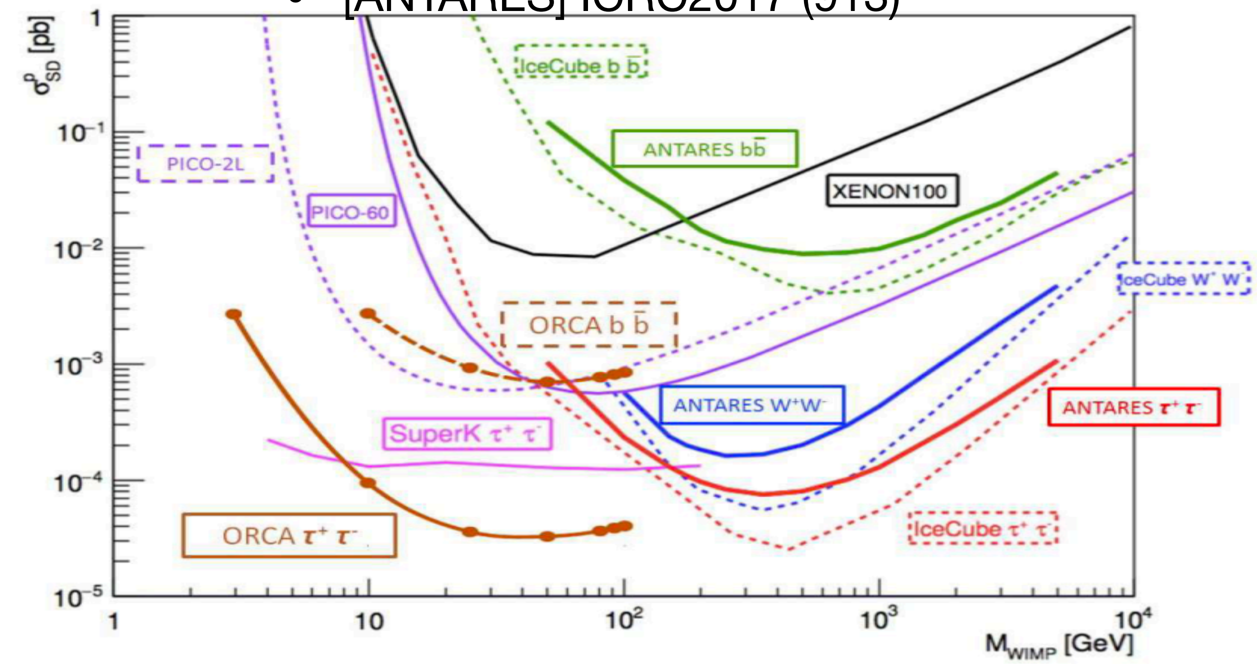
IceCube-Gen2 (PINGU fill in)

S. In & K. Wiebe [IceCube] ICRC2017 (912)

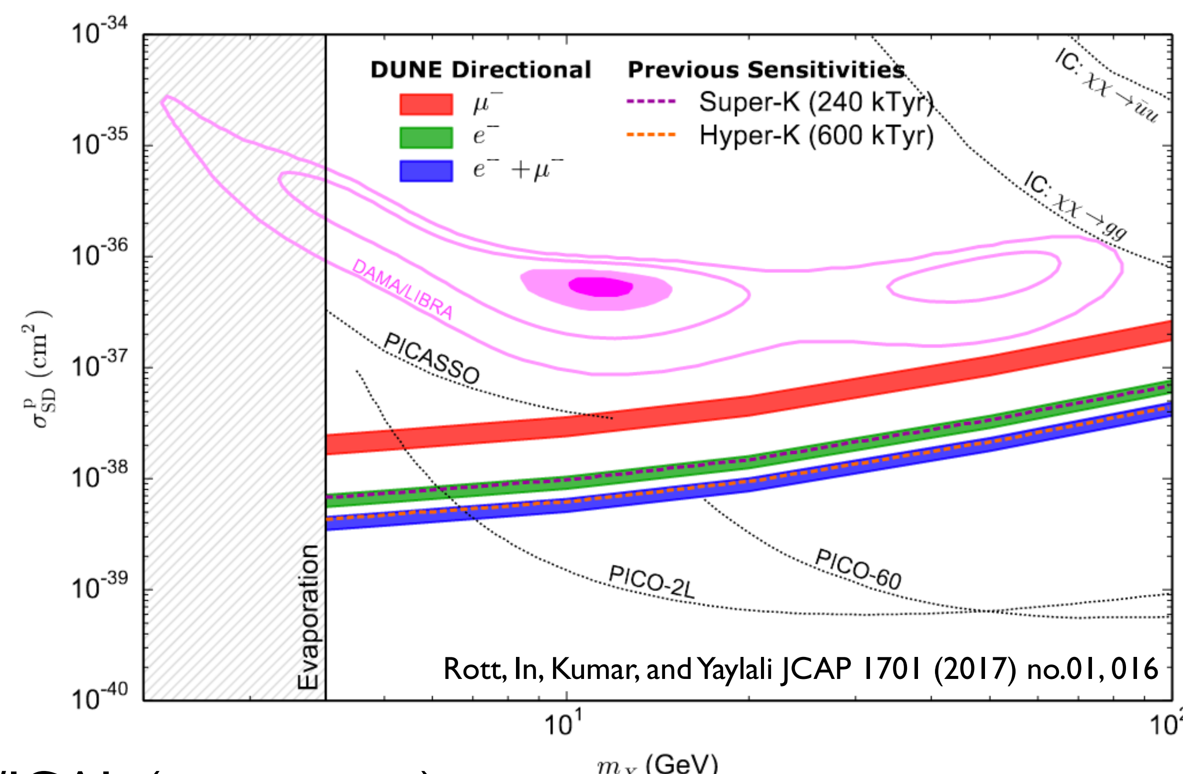


ORCA

- [ANTARES] ICRC2017 (913)



- ORCA and IceCube-Gen2 (PINGU infill) have unique capability to explore DM between 4-50GeV in indirect solar DM searches
  - This will also be an interesting region for Hyper-K / DUNE
- KM3NeT and IceCube-Gen2 extremely competitive for **high-mass DM decay**
  - BSM physics in the high-energy neutrino flux ?



Also interesting prospects for INO/ICAL (see posters)

Conclusions

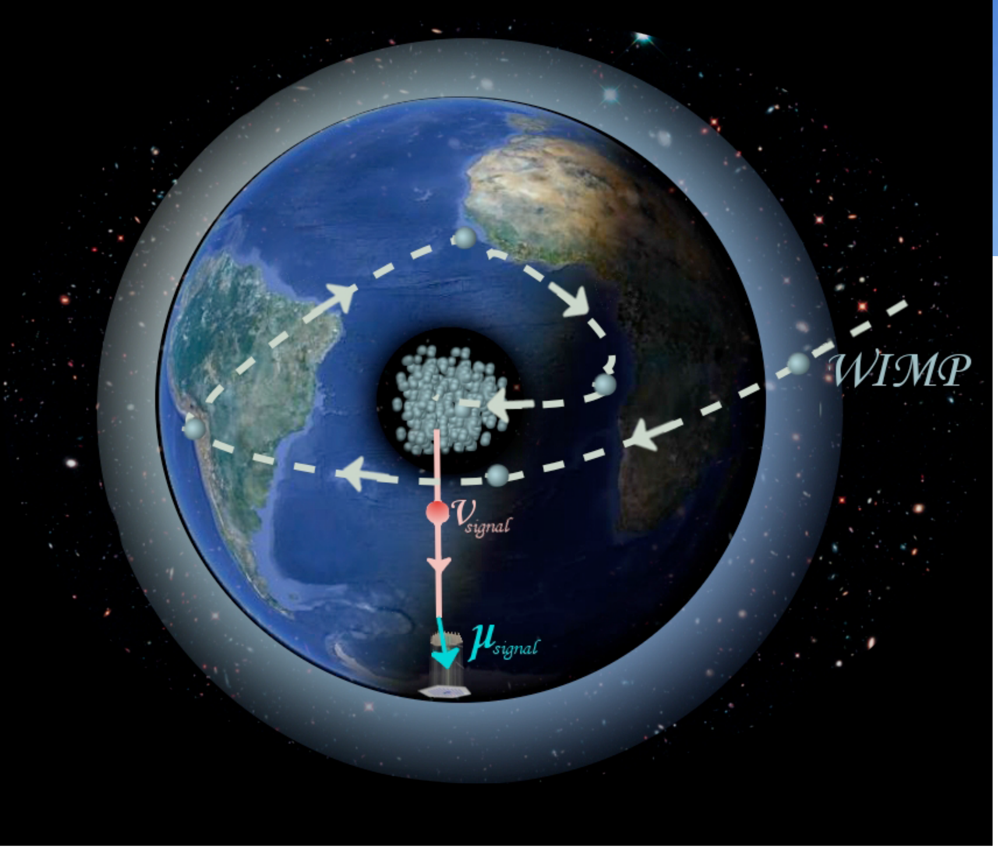
- Striking dark matter signatures might provide high discovery potential for indirect searches
- Models motivated by positron excess and gamma-ray observations can and have been tested with neutrino telescopes
- Lifetimes of heavy decaying dark matter can be constrained to 10^{28}s using neutrino signals
- Neutrino Telescopes/Detectors provide world best limits on the Spin-Dependent Dark Matter-Proton scattering cross section
- A new neutrino floor for solar dark matter searches has been calculated
- Efforts underway to expand searches beyond WIMP hypothesis

Discussion

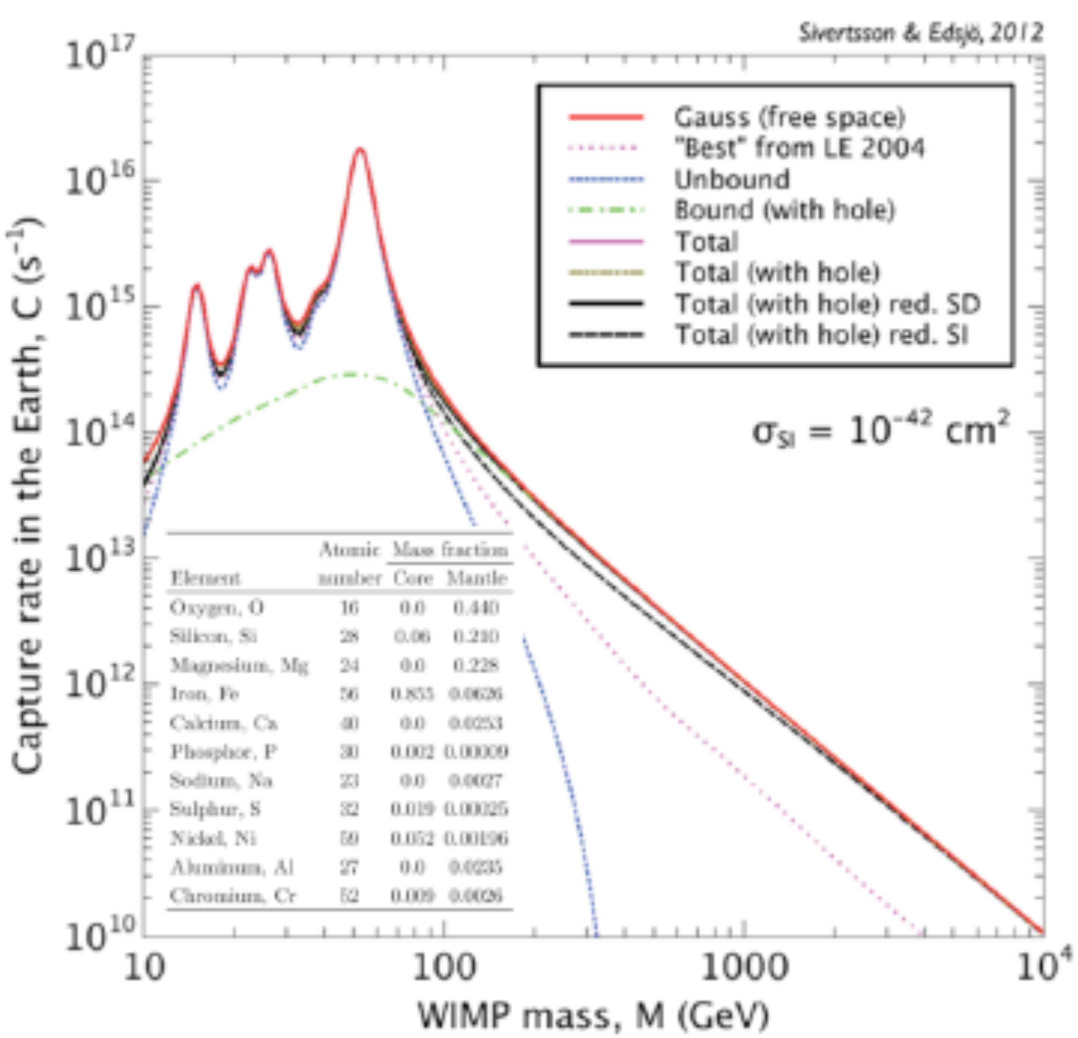
- Most indirect dark matter searches can utilize off-source regions to determine atmospheric background from the data itself
  - Exceptions are searches for dark matter captured in the Earth
- Solar dark matter searches have significantly improved in sensitivity so that second order effects in atmospheric backgrounds become more important
  - Cosmic ray sun shadow
- Search for energy features - example Dark Matter decay - strongly depend on astrophysical and atmospheric neutrino flux assumptions

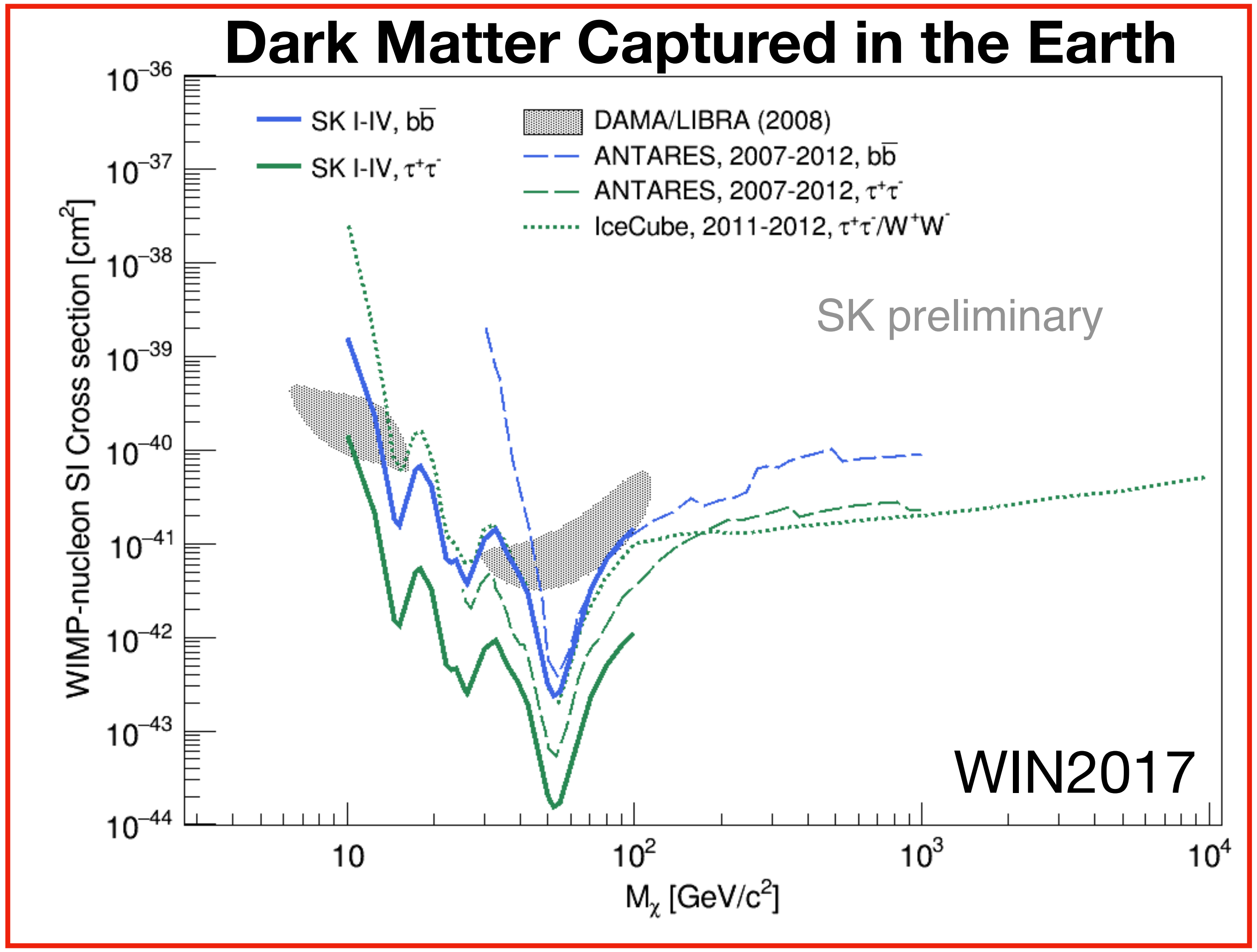
Thanks !

Earth WIMPs



- Dark Matter could be captured in the Earth and produce a vertically up-going excess neutrino flux
- No off-source region

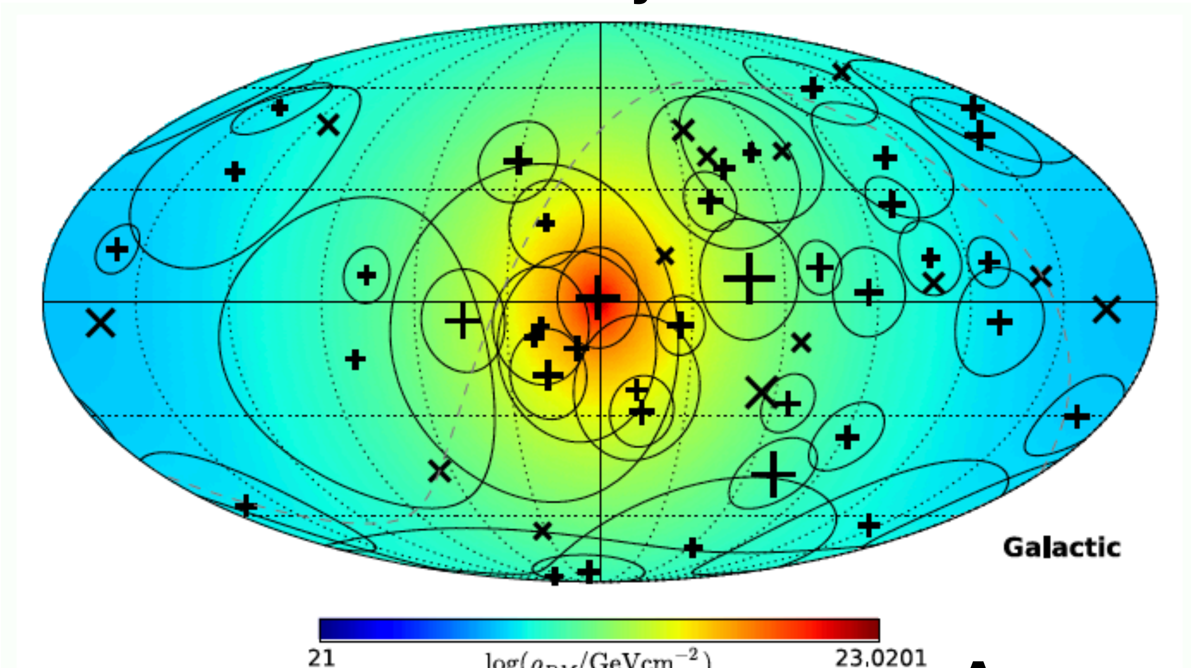




Imaging Galactic Dark Matter with IceCube's High-Energy Cosmic Neutrinos

[C. A. Argüelles, A. Kheirandish A. C. Vincent Phys.Rev.Lett. 119 (2017) no.20, 201801 (arXiv: 1703.00451)]

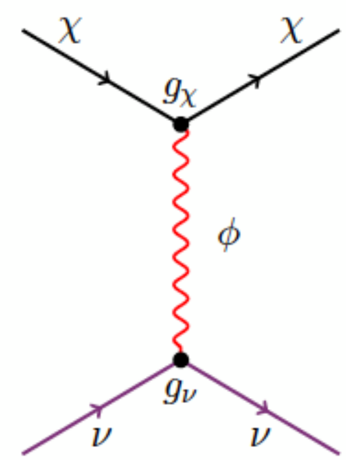
Dark Matter Column Density* as seen from Earth



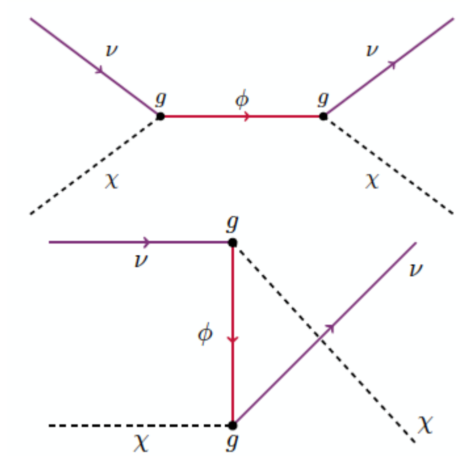
*Einasto Profile

Dark Matter - Neutrino Interaction

(1) Fermion DM, vector mediator

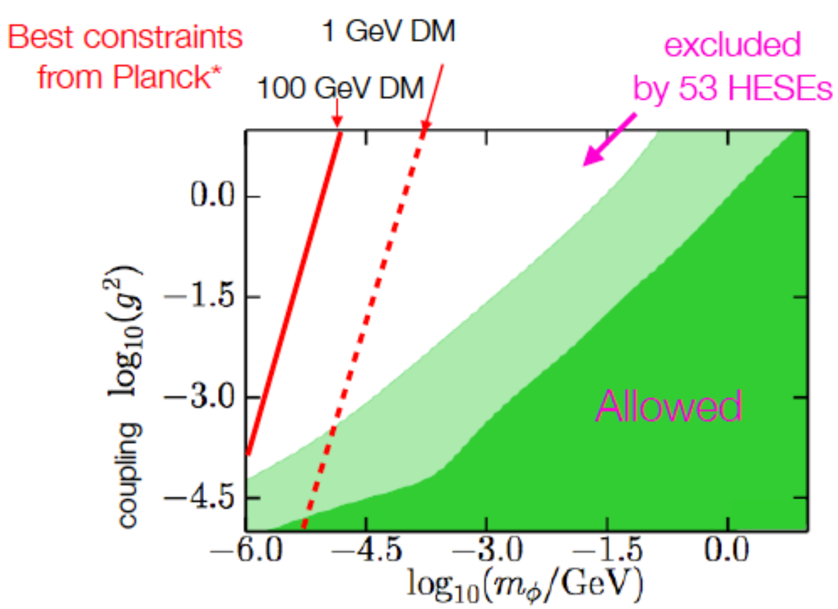


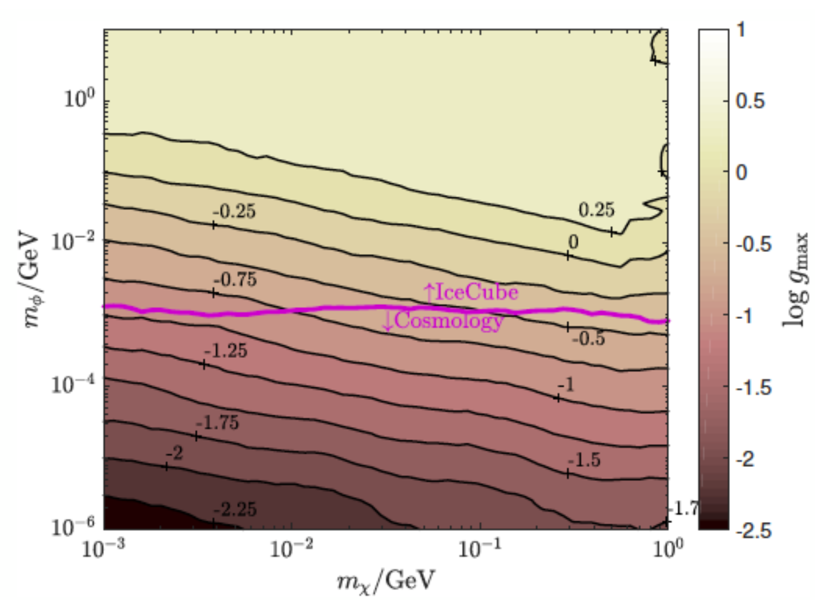
(2) Scale DM, ferminonic mediator

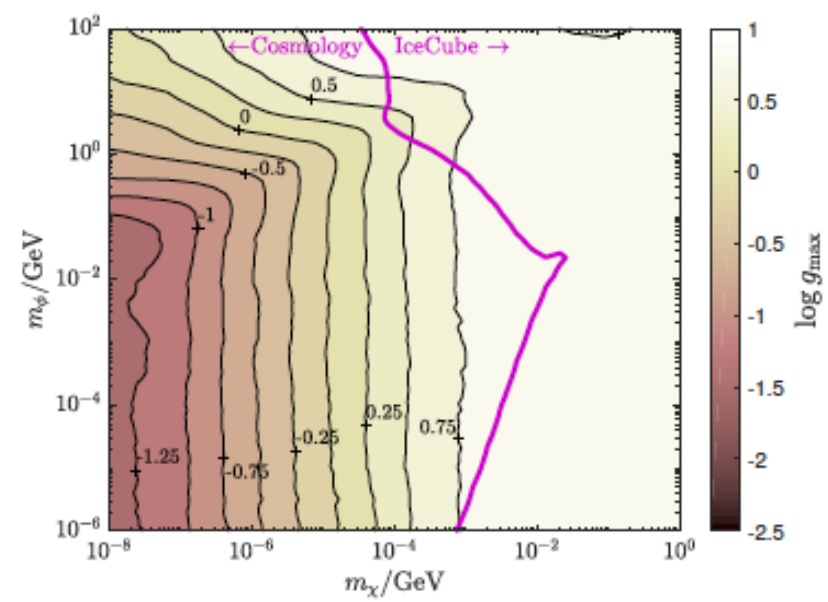


Assume:

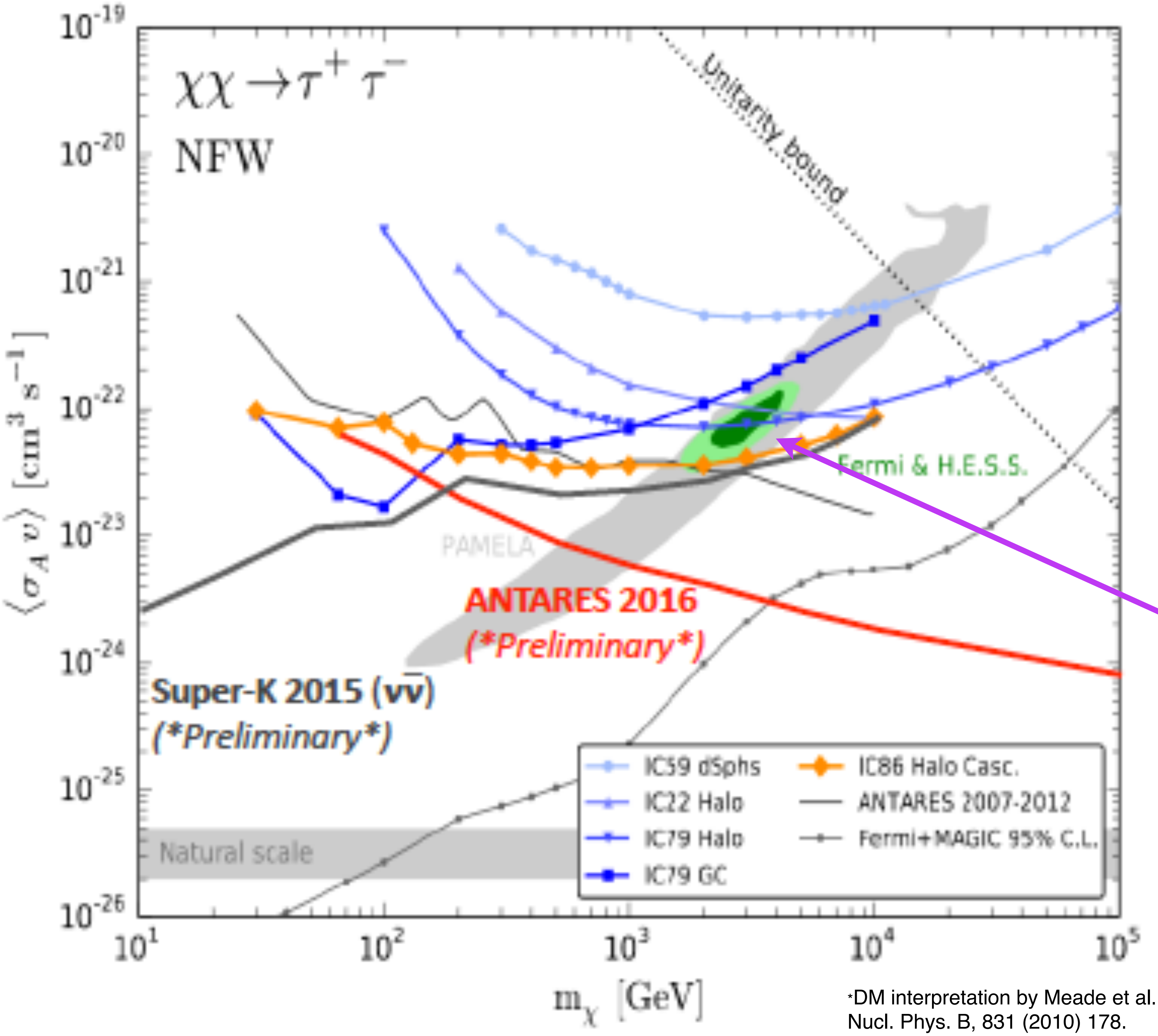
$$\sigma_{DM-\nu} \propto E_\nu^2$$







Neutrinos test lepton anomalies



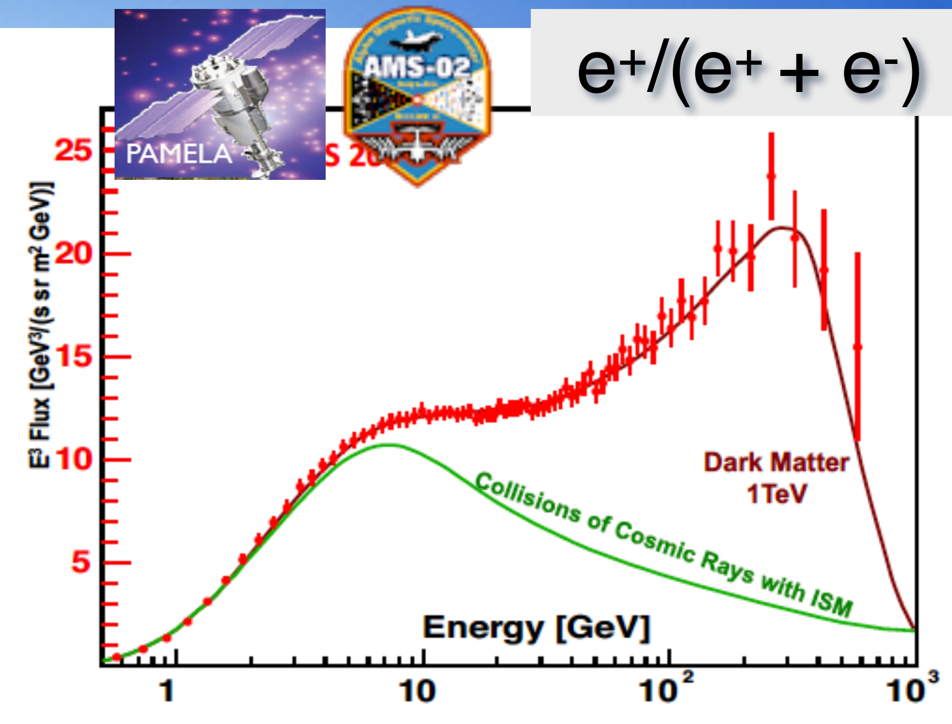
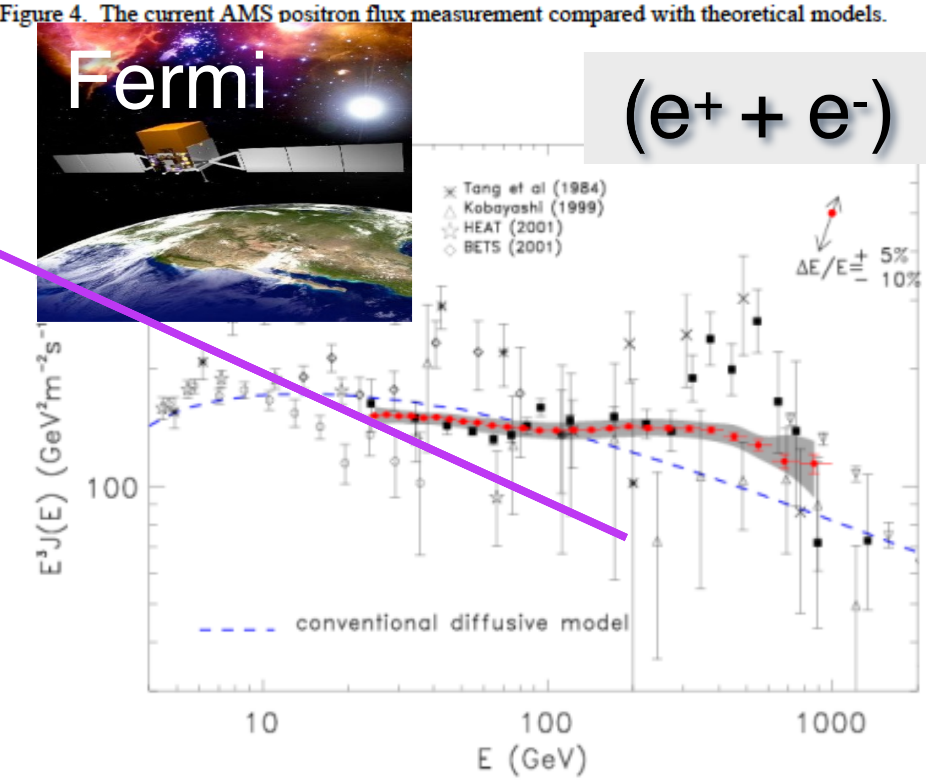


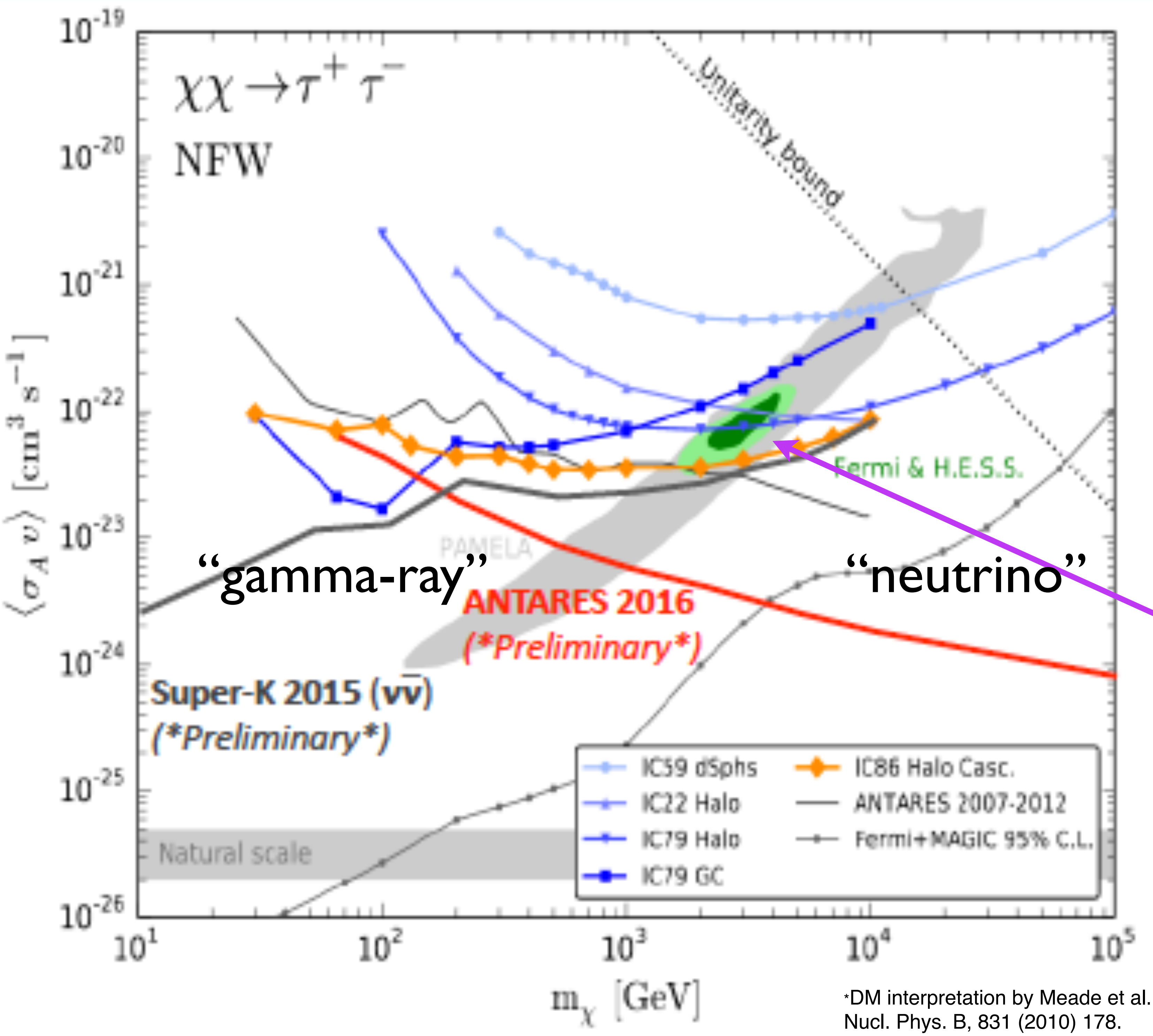
Figure 4. The current AMS positron flux measurement compared with theoretical models.



*DM interpretation by Meade et al., Nucl. Phys. B, 831 (2010) 178.

Neutrino Telescopes can probe models motivated by the observed lepton anomalies

Neutrinos test lepton anomalies



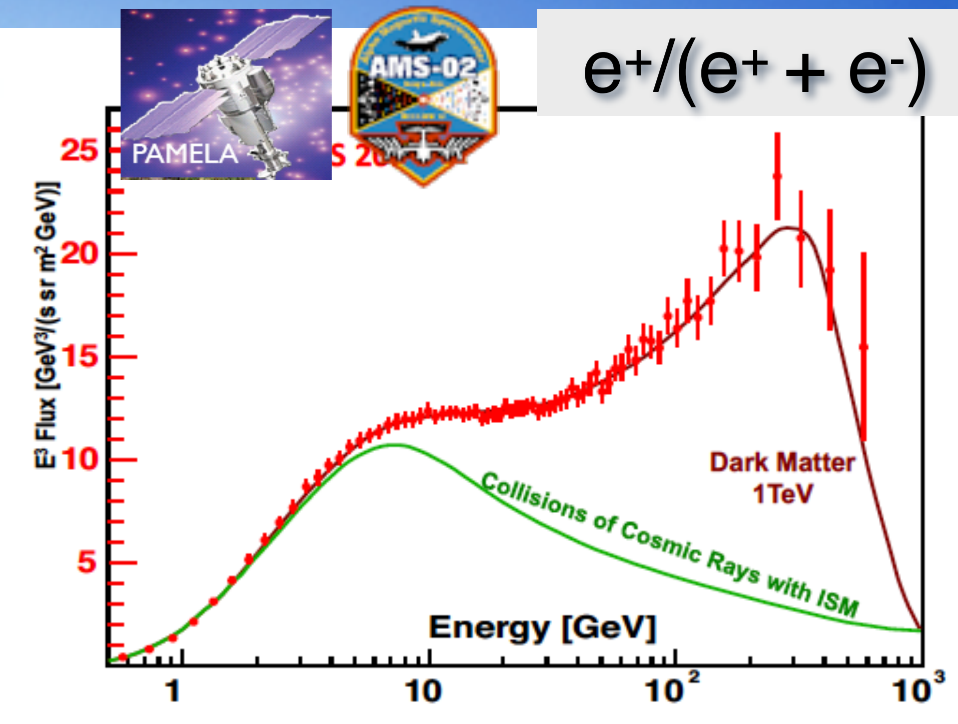
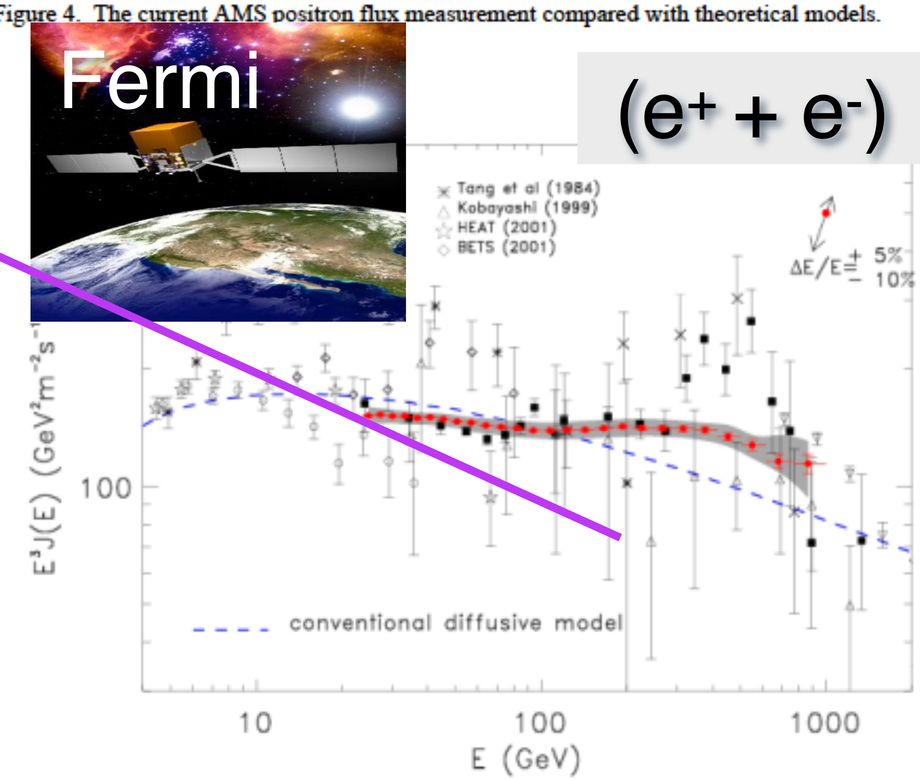


Figure 4. The current AMS positron flux measurement compared with theoretical models.



*DM interpretation by Meade et al., Nucl. Phys. B, 831 (2010) 178.

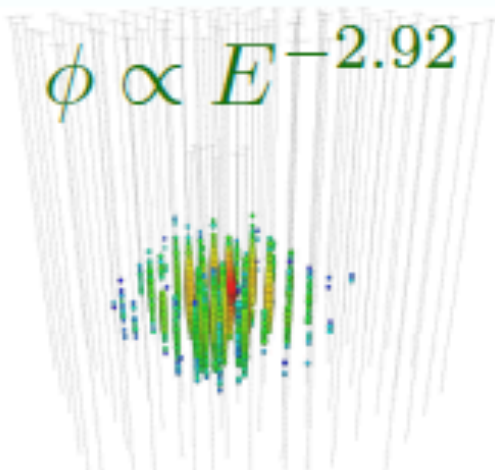
Neutrino Telescopes can probe models motivated by the observed lepton anomalies

High-energy astrophysical neutrinos

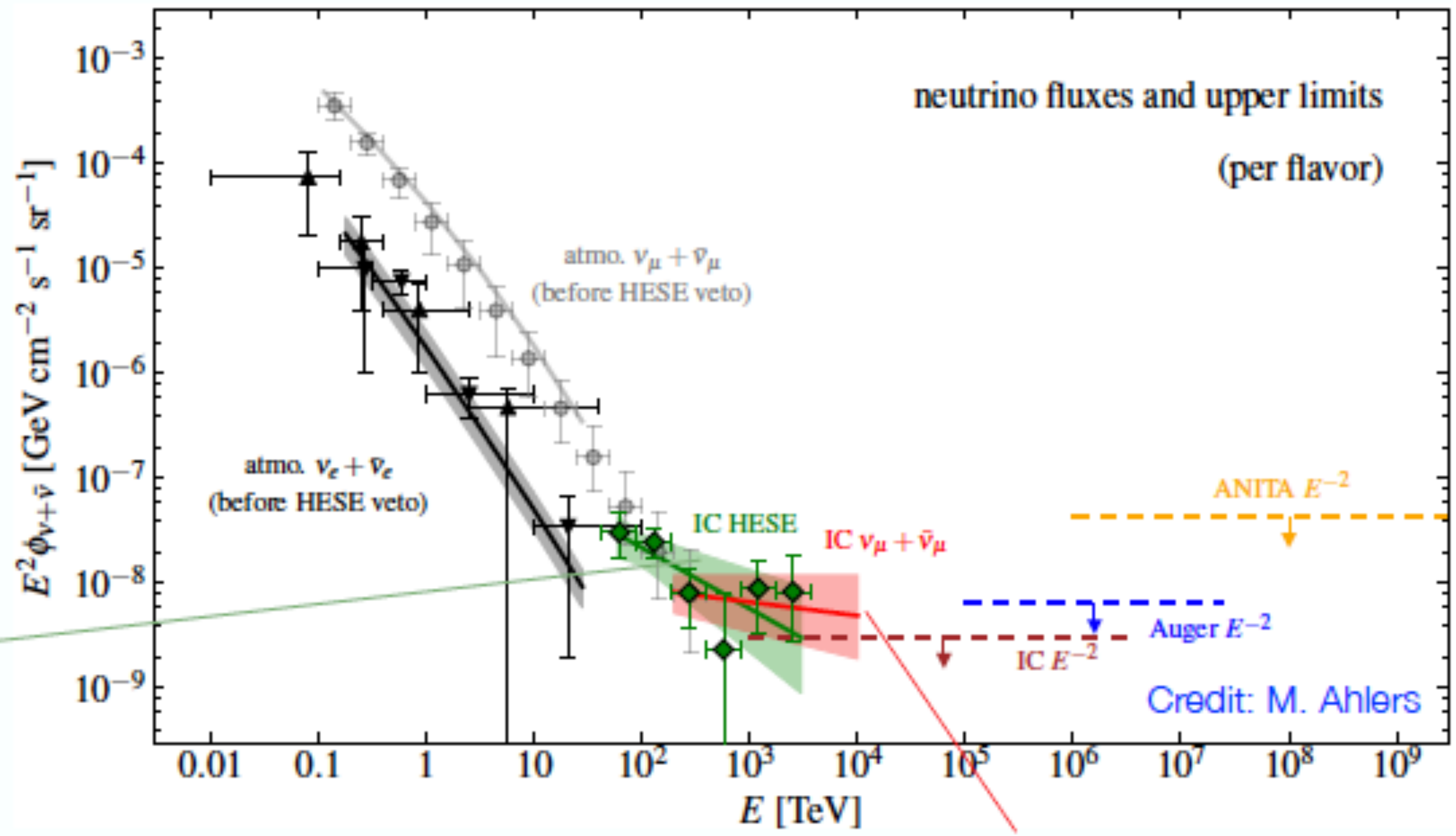
High-Energy Starting Events

6 years Observation ➙ 8σ

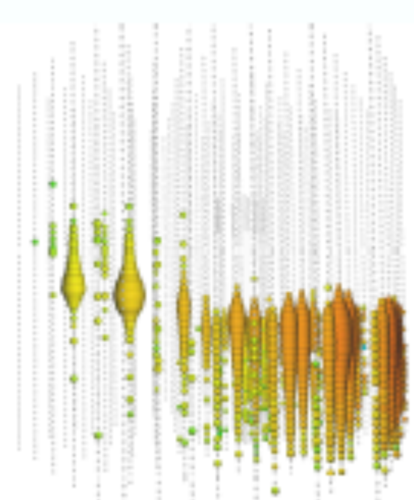
80 events (all flavor)



$\phi \propto E^{-2.92}$



- Observation confirmed in independent channels.
- Hardening of the spectrum at high energies.
- Low-energy excess hinting at spectral features.
- fluxes are compatible in the common energy range



Up-going Muon Tracks

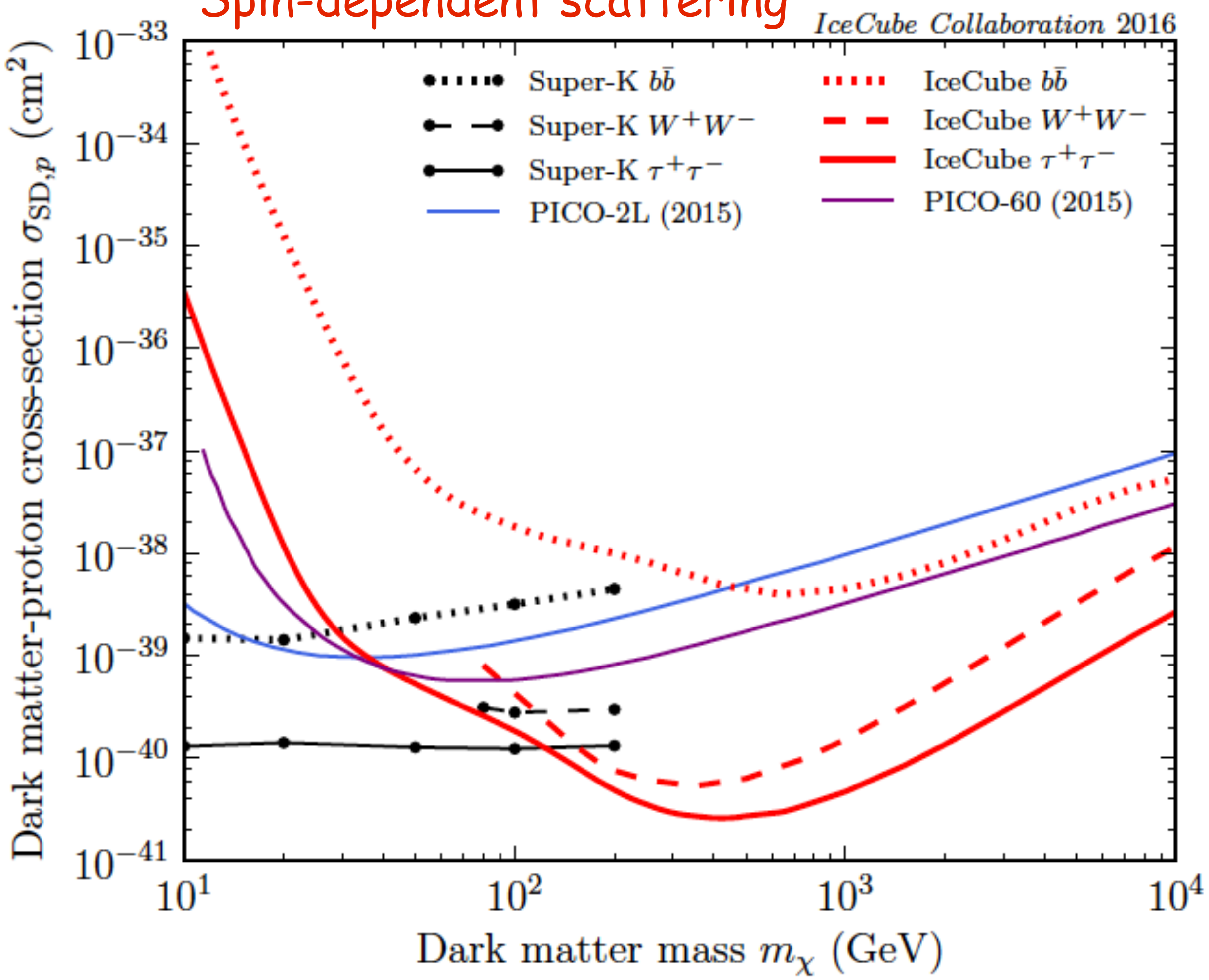
8 years Observation ➙ 6.7σ

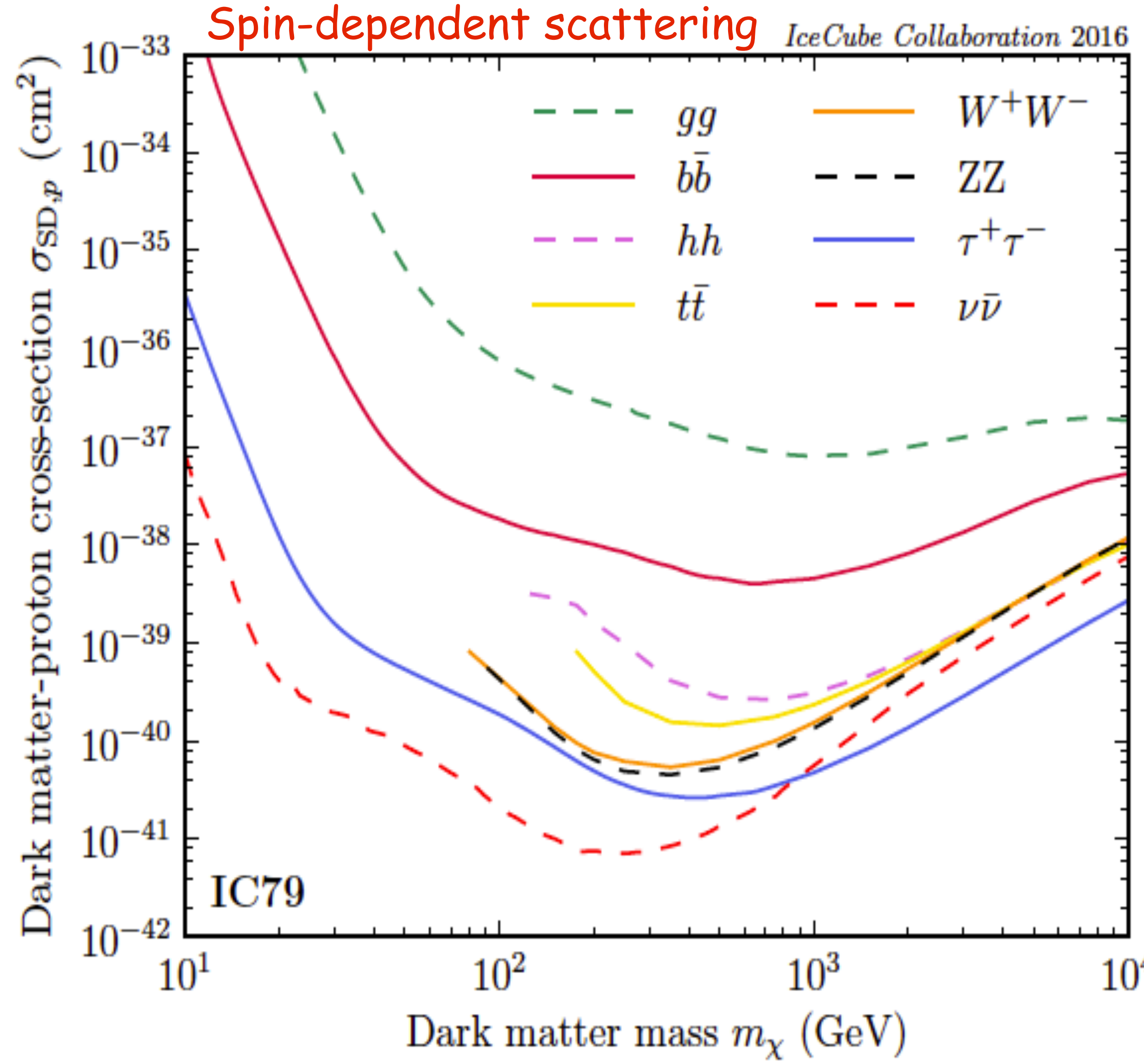
~ 500 astrophysical neutrinos

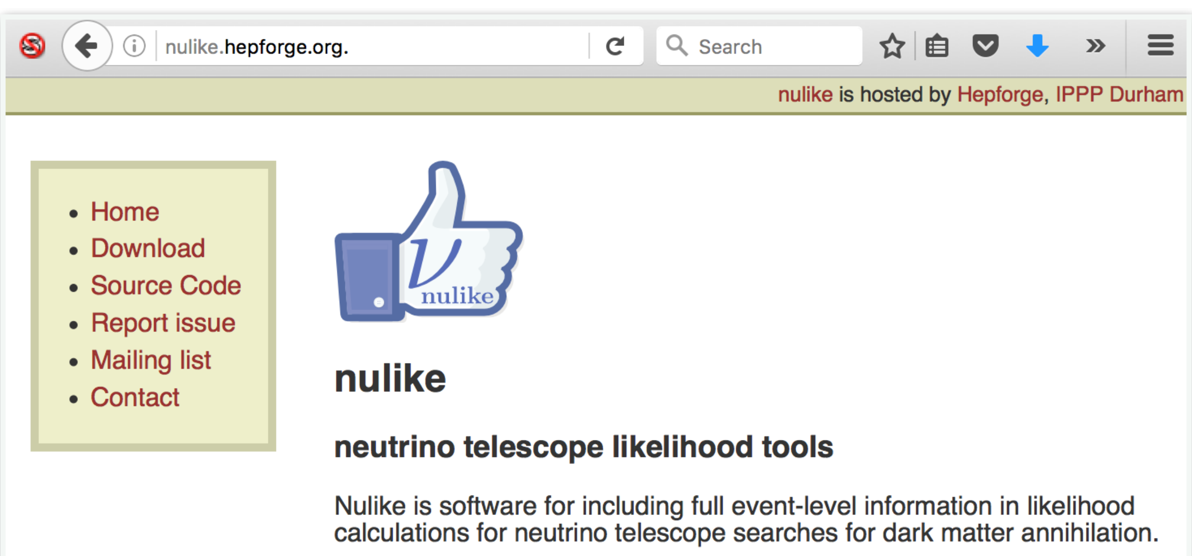
$\phi \propto E^{-2.19}$

Availability of IceCube data

JCAP 04 (2016) 022 / http://arxiv.org/pdf/1601.00653.pdf

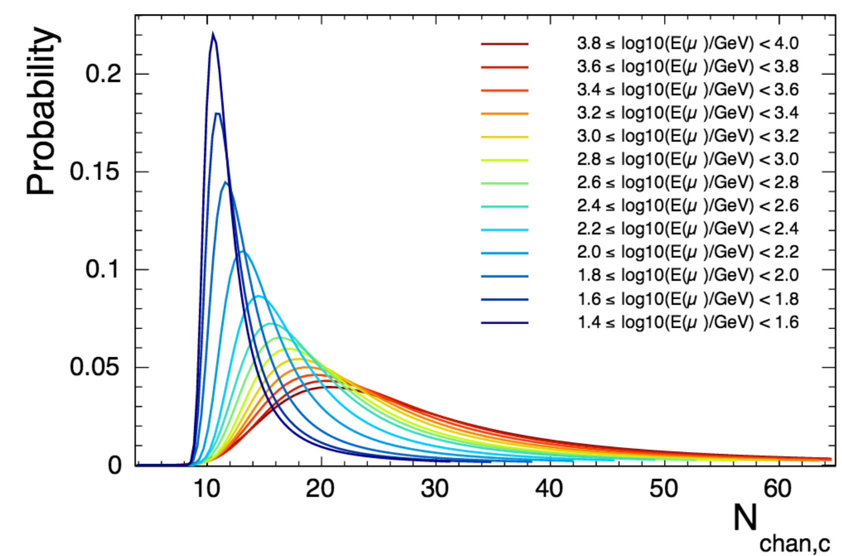




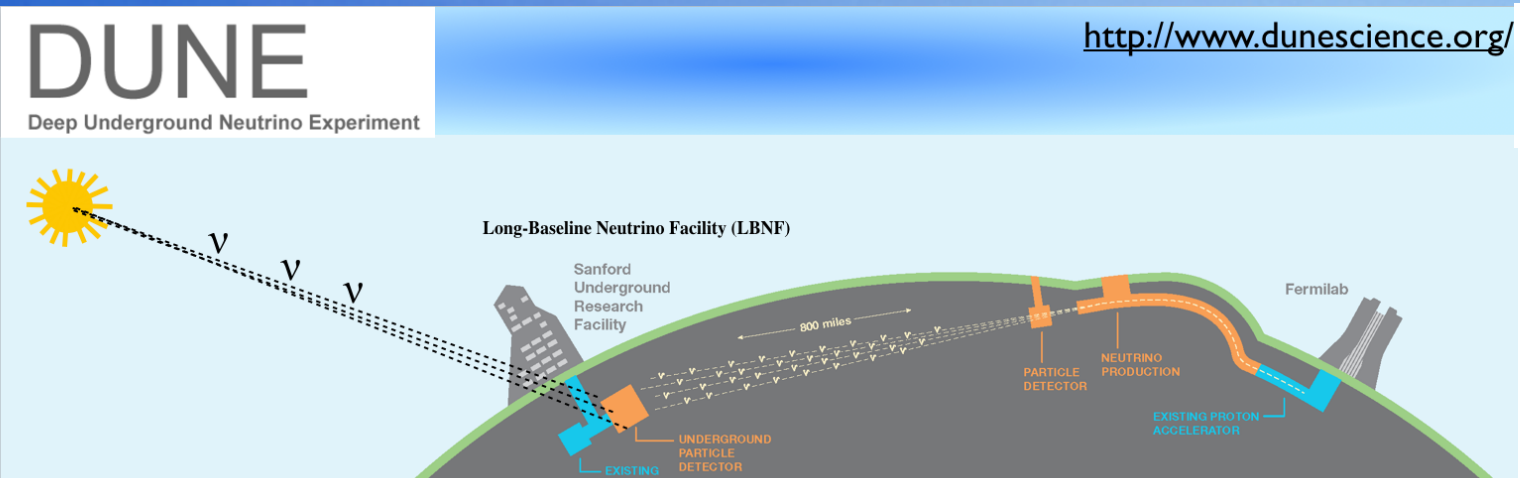


software to test your own model (cross section/ branching ratios)

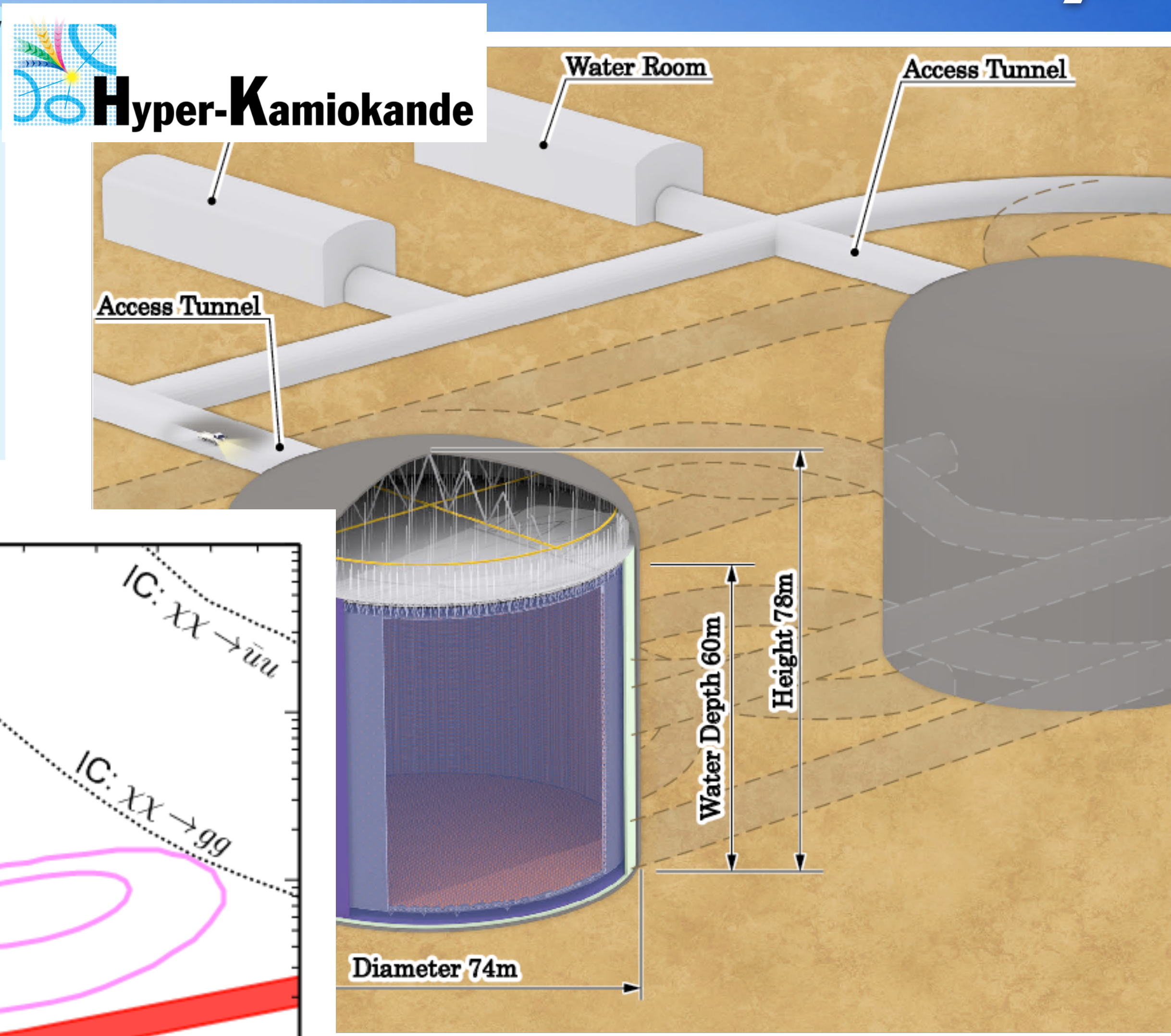
- IceCube data released
- Likelihood includes:
  - energy and directional information



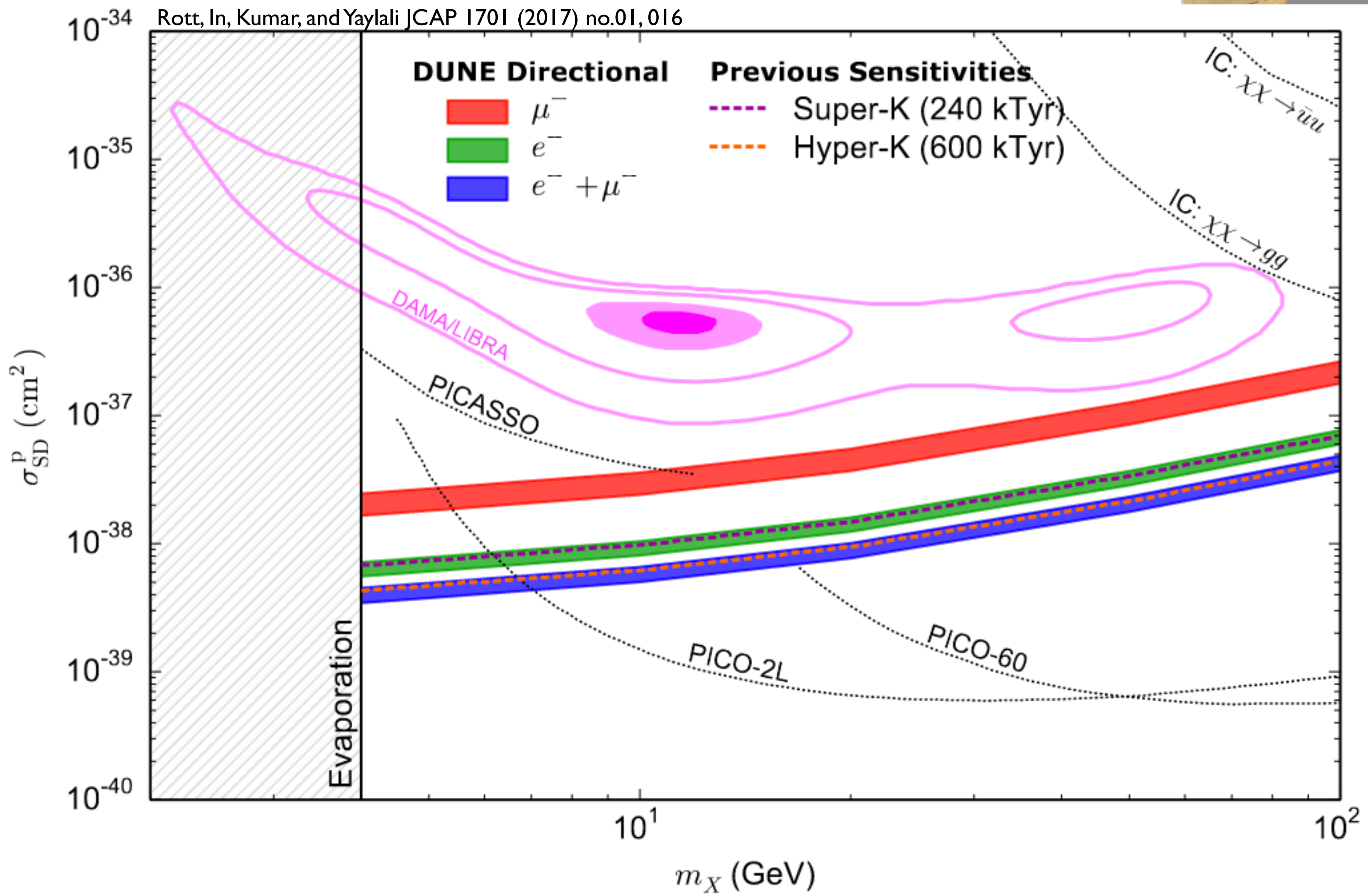
Sensitivity

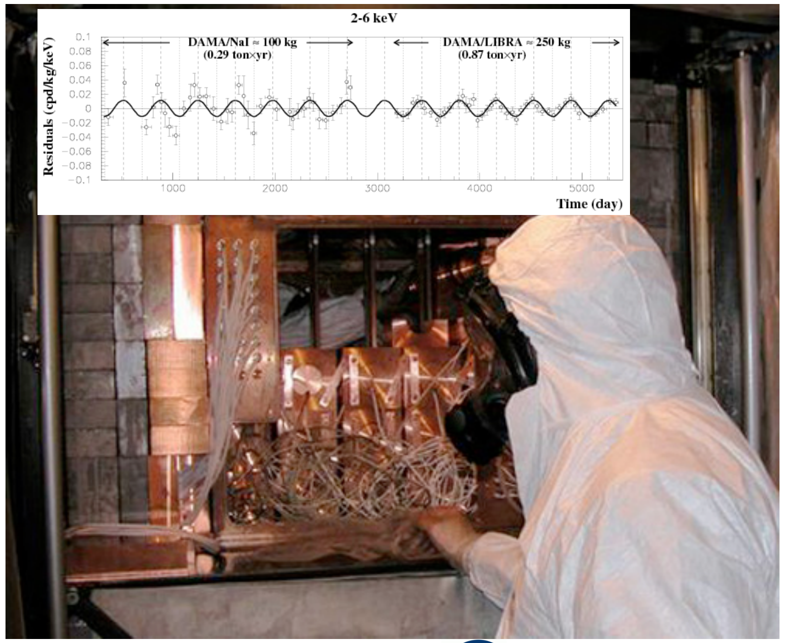


http://www.dunescience.org/



Rott, In, Kumar, and Yaylali JCAP 1701 (2017) no.01, 016





Low-Energy Neutrinos from the Sun

Possible annihilation channels:

$q\bar{q}, g\bar{g}, c\bar{c}, s\bar{s}, b\bar{b}, t\bar{t}, W^+W^-, ZZ, \tau^+\tau^-, \mu^+\mu^-, \nu\bar{\nu}, e^+e^-, \gamma\gamma$

few neutrinos

Low-Energy Neutrinos from the Sun

Possible annihilation channels:

qq,gg,cc,ss,bb,tt,W^+W^-, ZZ, $\tau^+\tau^-$,$\mu^+\mu^-$, νν, e^+e^-,γγ

few neutrinos

some “high energy” neutrinos in decays

⇒ basis of present day searches

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dominant decay into hadrons

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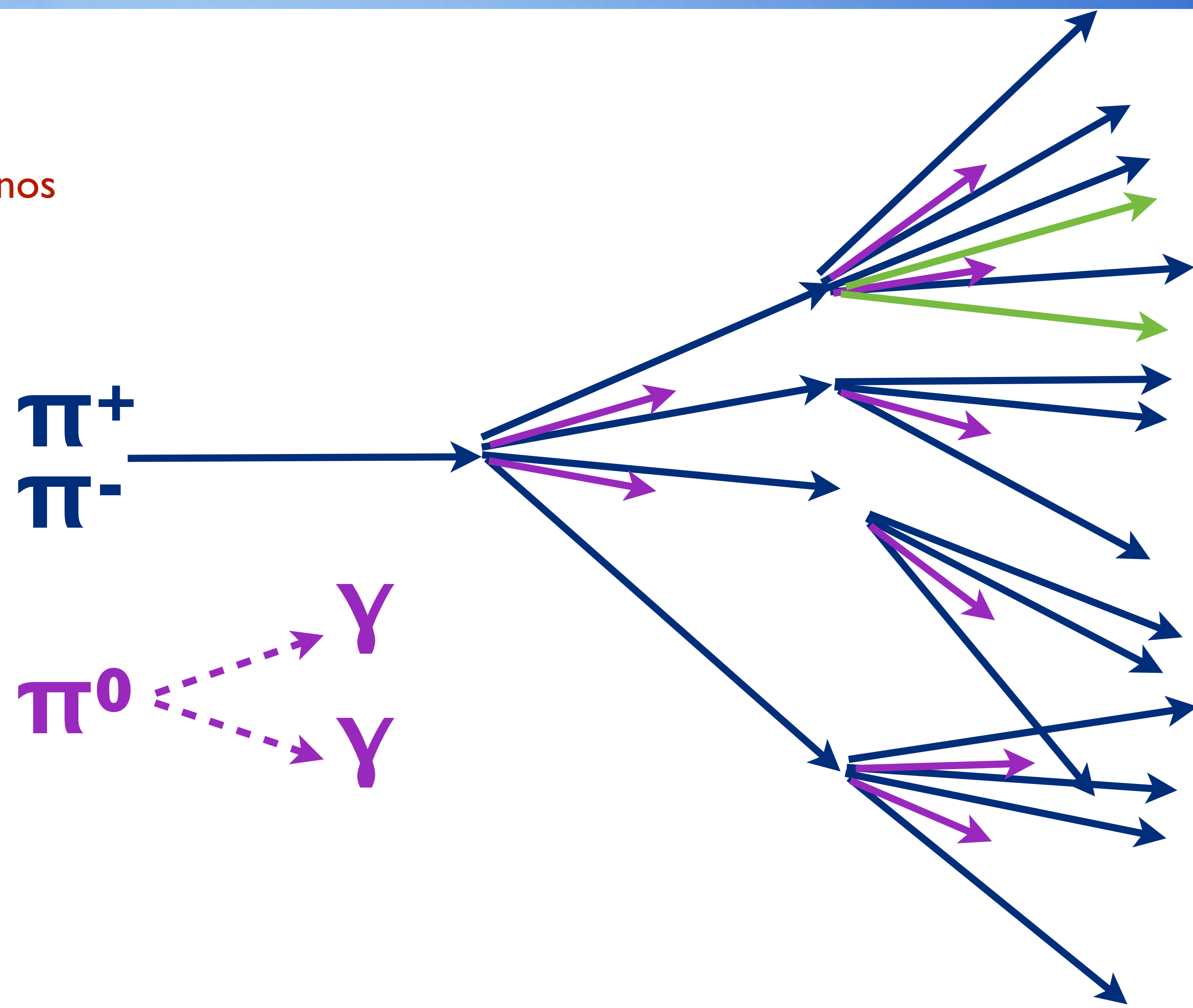

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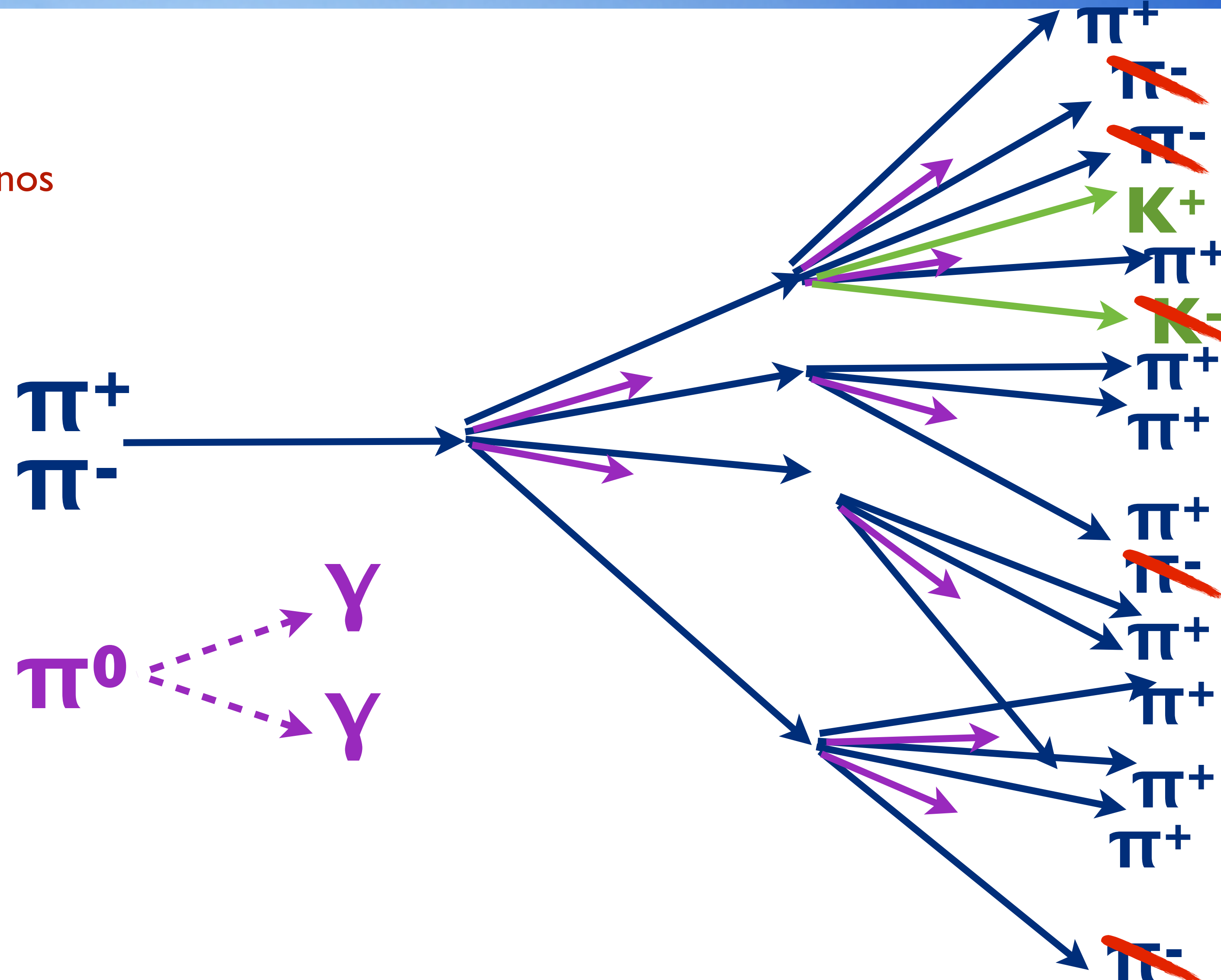


π^0

- Lifetime too short to interact

π^-

- Interaction length short compared to losses
- Produces secondary particles in collision with protons
- Dominant energy loss term is π^0 production

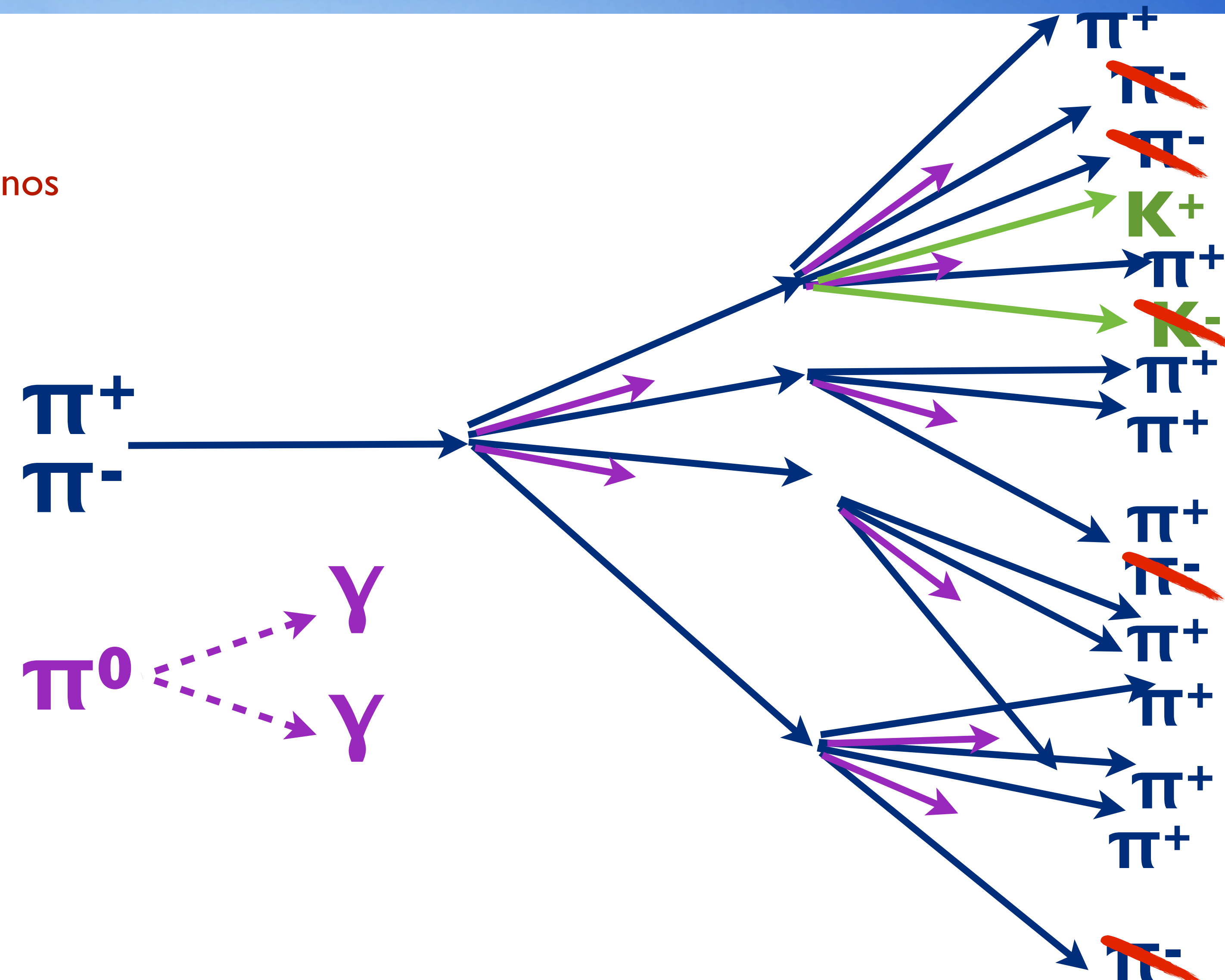
Low-Energy Neutrinos from the Sun

Possible annihilation channels:

$q\bar{q}, gg, c\bar{c}, s\bar{s}, b\bar{b}, t\bar{t}, W^+W^-, ZZ, \tau^+\tau^-, \mu^+\mu^-, \nu\nu$, $e^+e^-, \gamma\gamma$ few neutrinos

some "high energy" neutrinos in decays
⇒ basis of present day searches

dominant decay into hadrons



Charged pions and kaons decay at rest producing mono-energetic neutrinos

$\pi^+ \rightarrow \mu^+ \nu_\mu$ E_ν= 29.8MeV

$K^+ \rightarrow \nu_\mu \mu^+$ E_ν=235.5MeV

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

C. Rott, J. Siegal-Gaskins, J.F.Beacom Physical Review D 88, 055005 (2013) (arXiv1208.0827)
Bernal, Martín-Albo, Palomares-Ruiz JCAP 1308 (2013) 011
C.Rott, S.In, J.Kumar, D.Yaylali JCAP11 (2015) 039

π^0

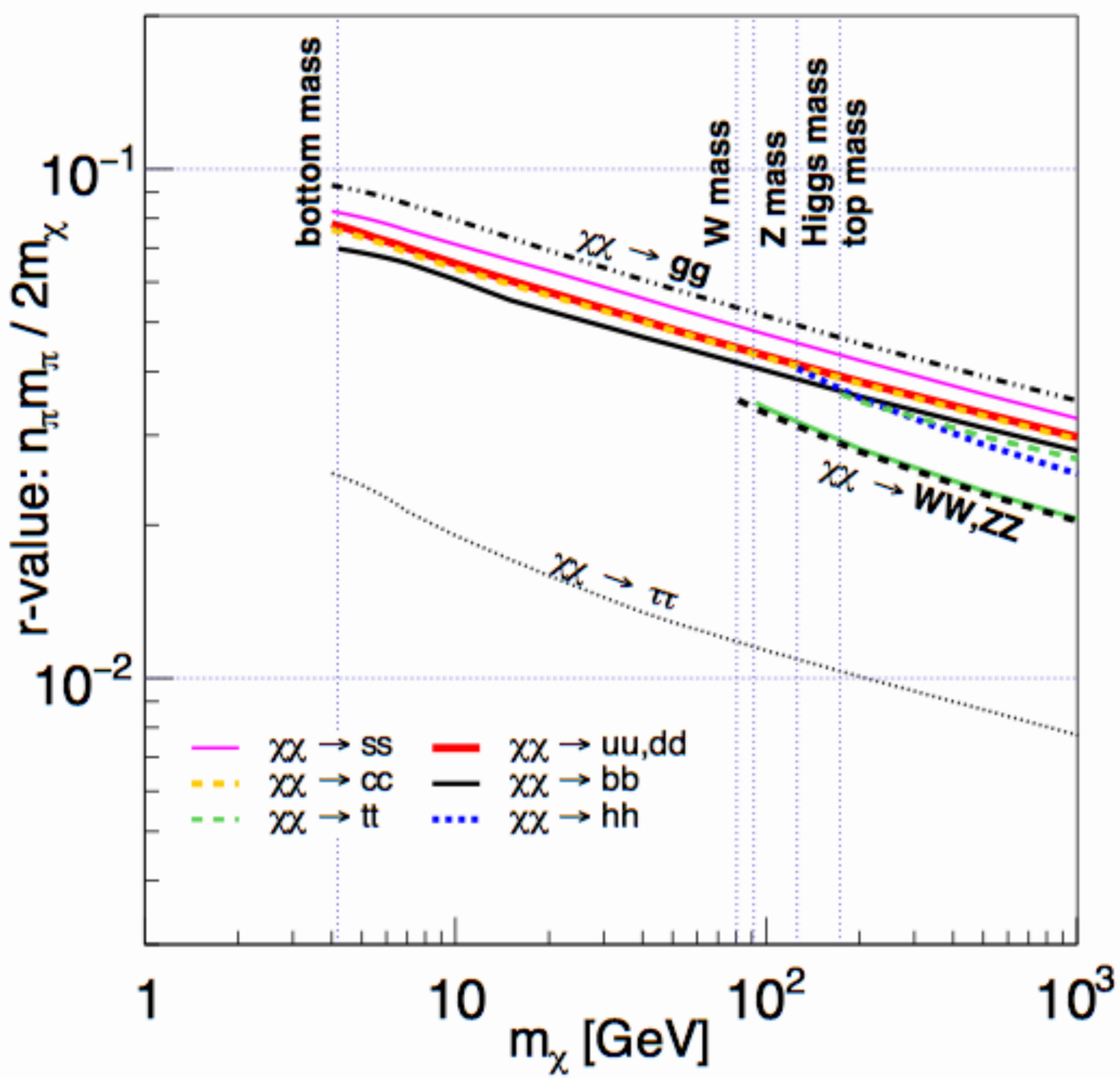
- Lifetime too short to interact

π^-

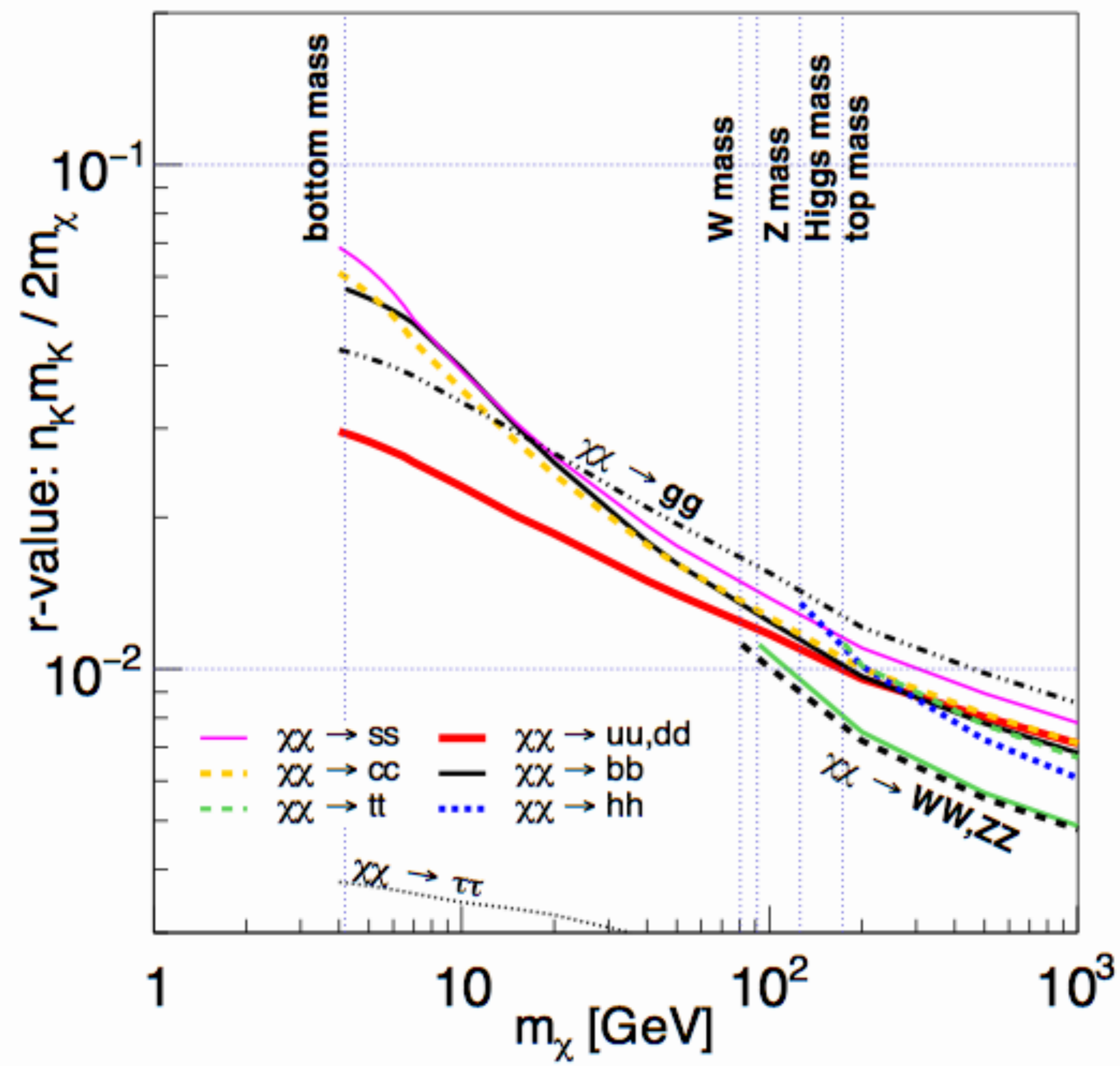
- Interaction length short compared to losses
- Produces secondary particles in collision with protons
- Dominant energy loss term is π^0 production

Pion and Kaon yields

π^+ r-value - fraction of center-of-mass energy which goes into π^+



K^+ r-value - fraction of center-of-mass energy which goes into K^+



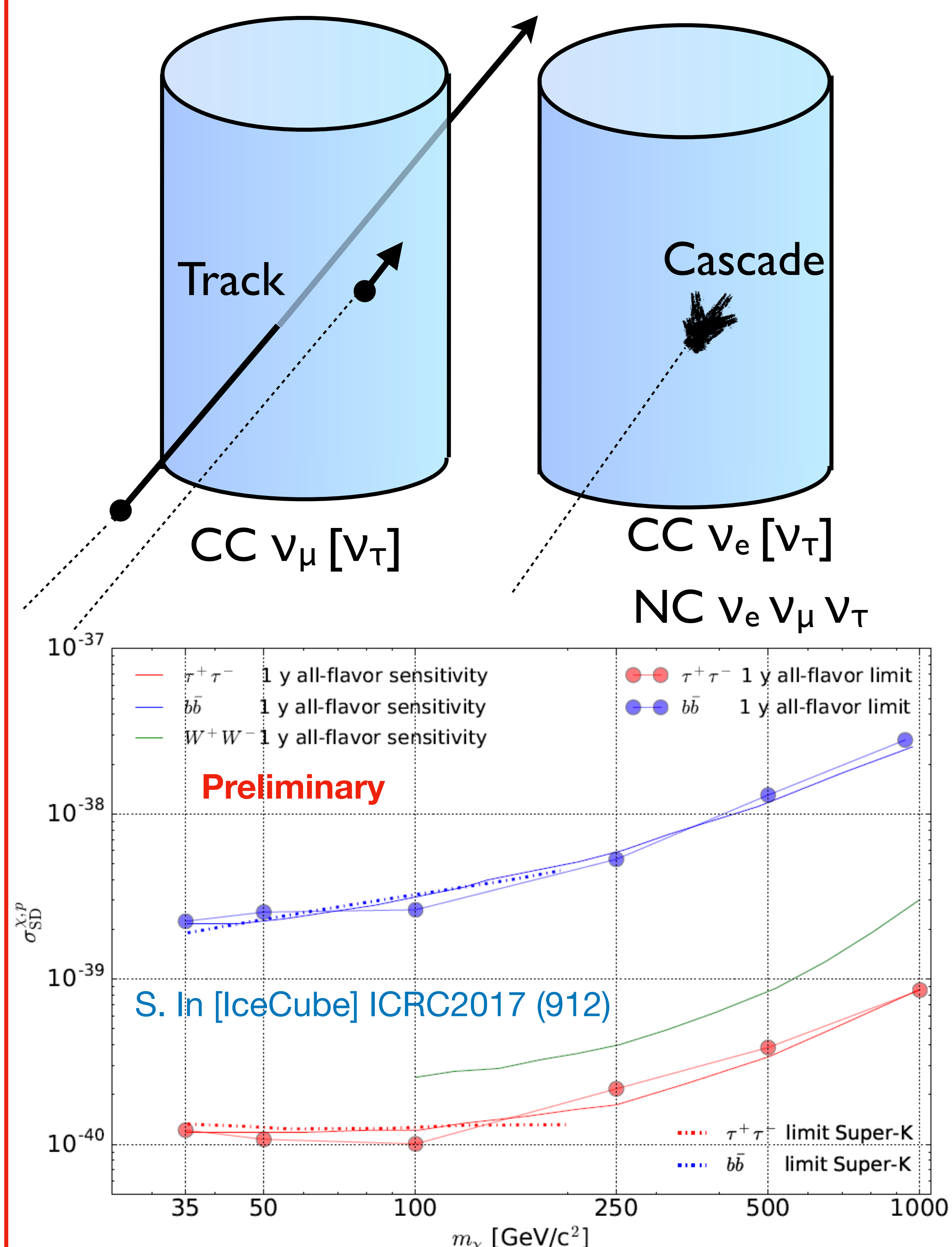
For low dark matter masses difference between flux from stopped pion and kaon decay at rest can be used to disentangle annihilation final states

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
- ANTARES - Phys.Lett. B759 (2016) 69-74
- IceCube Eur.Phys.J. C77 (2017) no.3, 146
- S. In and K. Wiebe [IceCube] ICRC2017 (912)

Solar Dark Matter - IceCube/ANTARES

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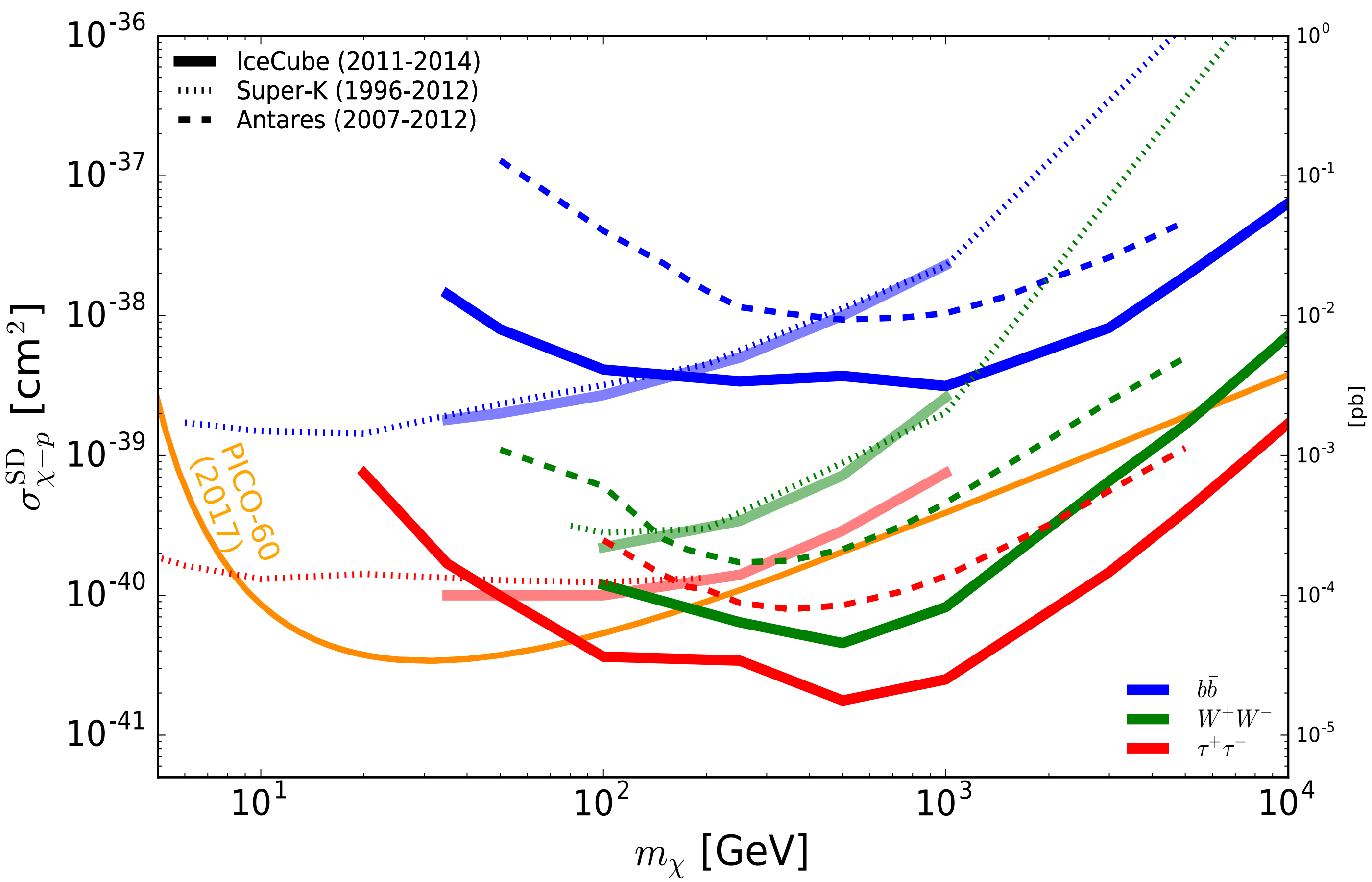
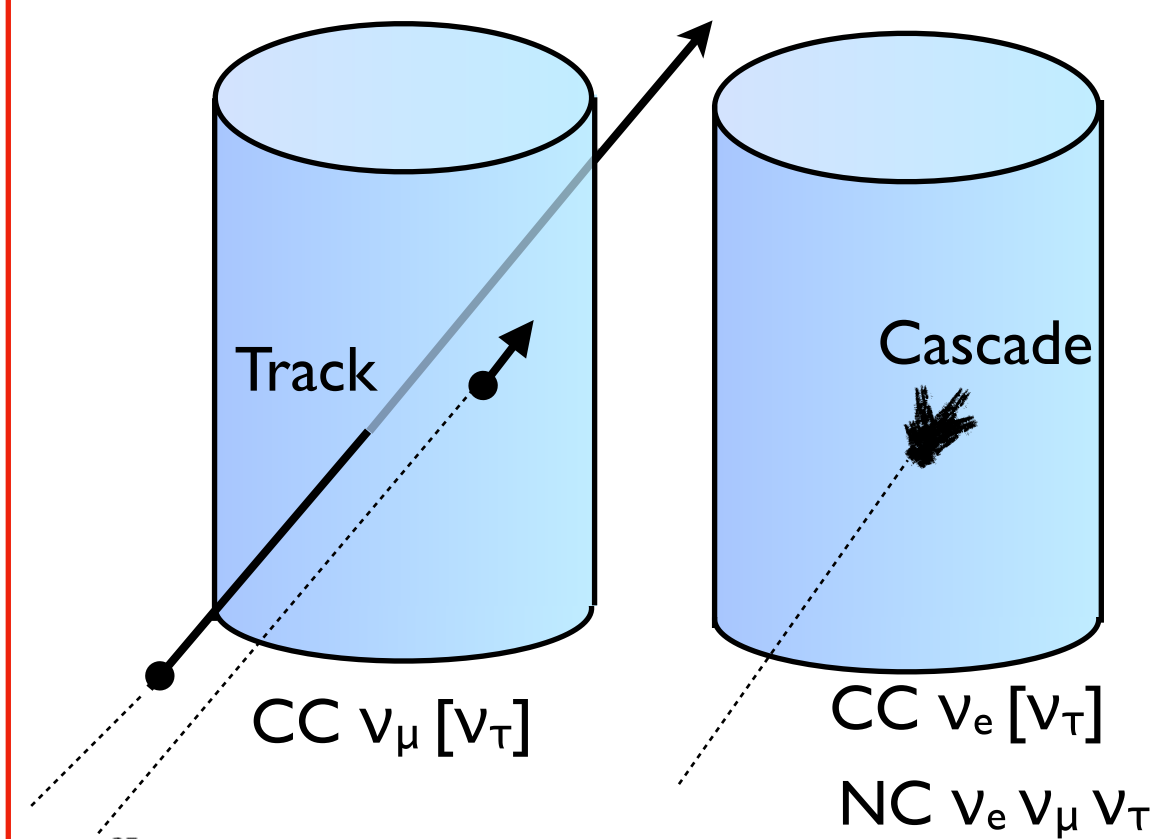
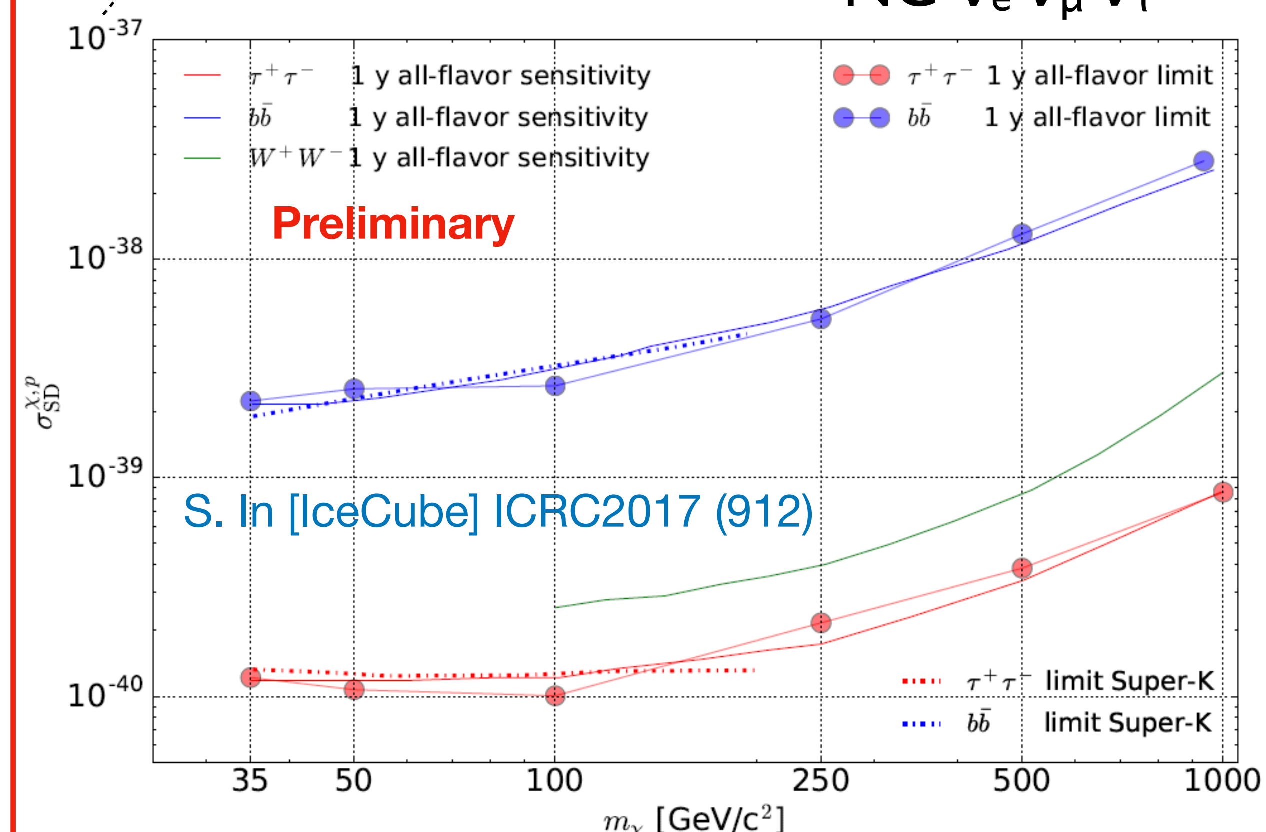


All flavor Solar WIMP - IceCube





S. In [IceCube] ICRC2017 (912)

Solar WIMPs

- ANTARES - Phys.Lett. B759 (2016) 69-74
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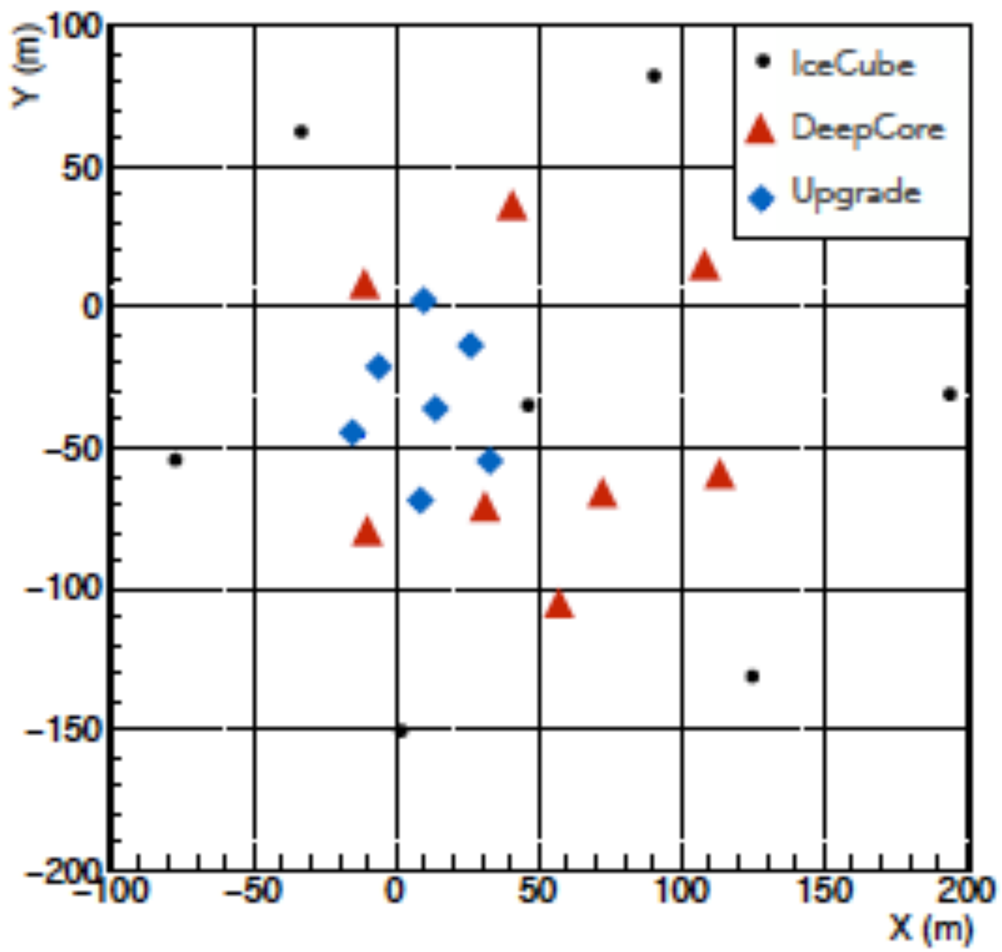
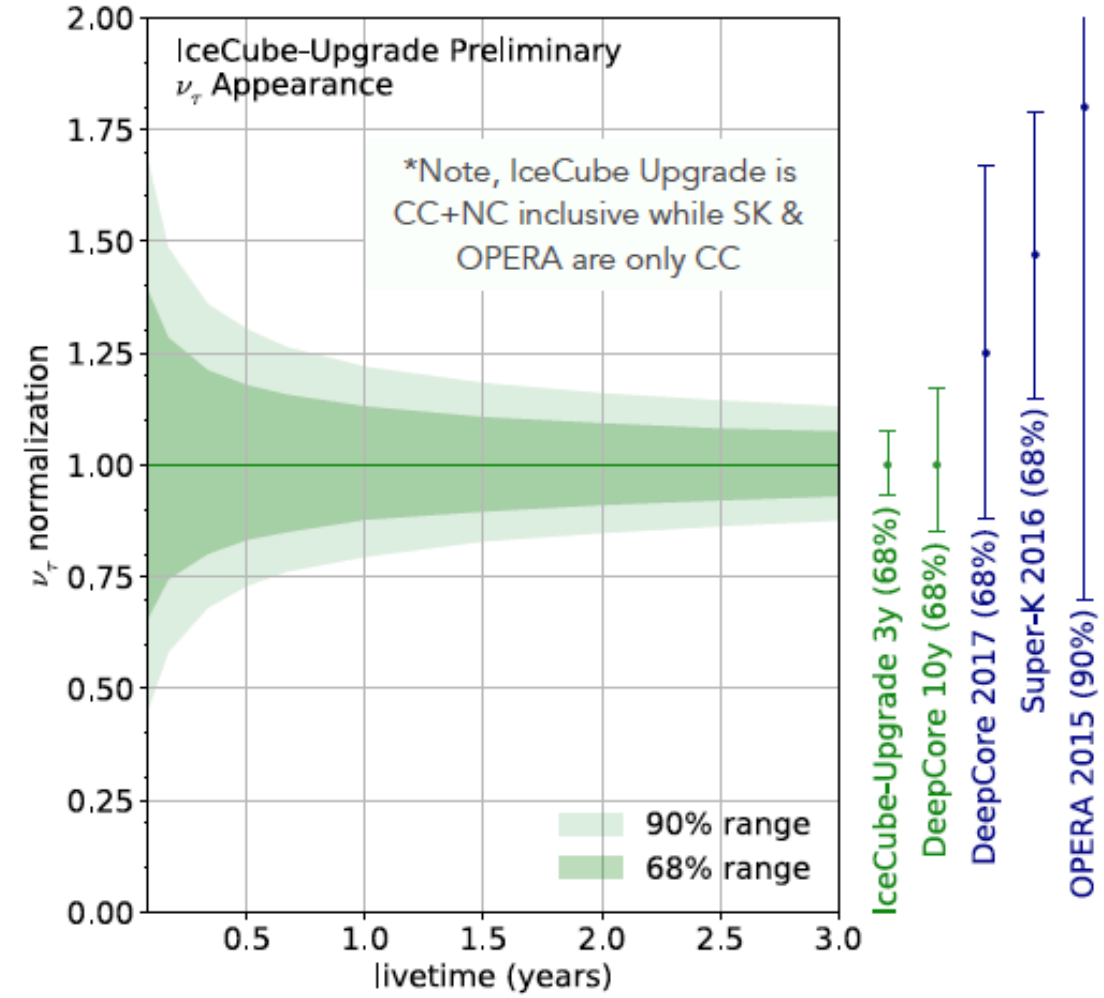
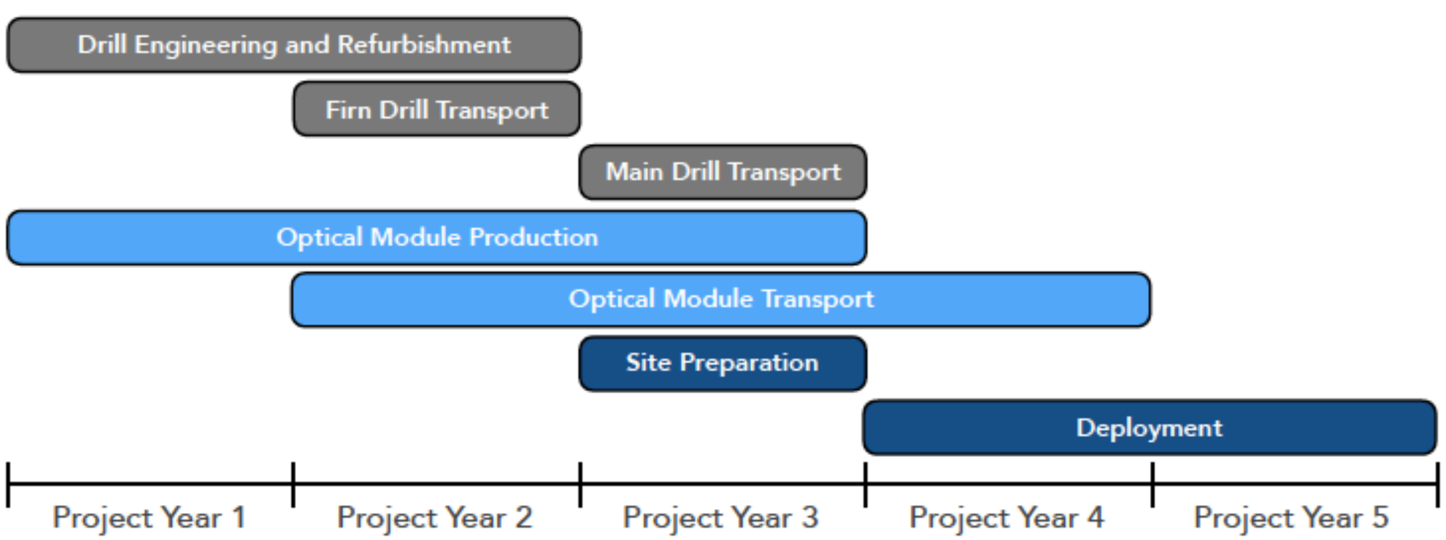
The IceCube Upgrade

"The IceCube Upgrade" ~7strings





First step to restart South Pole activities
- Tau neutrino appearance
- Calibration devices
- Platform to test new technologies



see also:
- PINGU LOI arXiv:1412.5106