Milky Way

Galaxies

Galaxy clusters

Galactic Center

dwarf spheroidal galaxy (dSph)

Carsten Rott

Sungkyunkwan University, Korea

rott@skku.edu

Feb 21, 2018

Indirect Searches for Dark Matter with Neutrinos

Dark Matter 2018

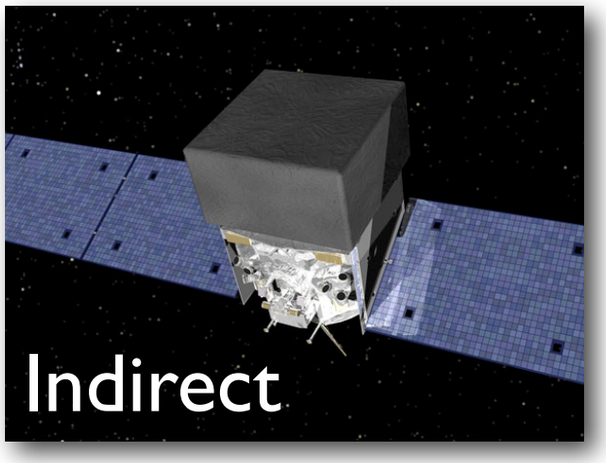
UCLA Dark Matter - February 21-23, 2018

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

Outline

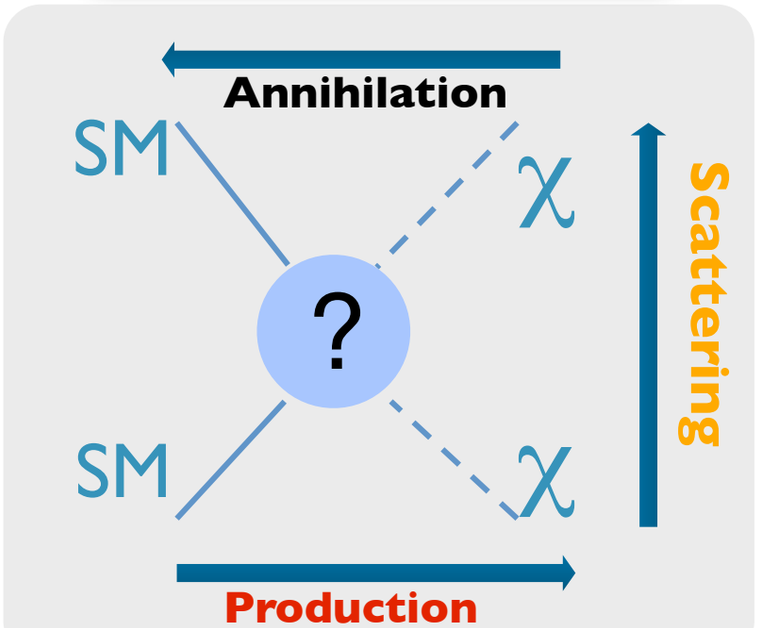
- Motivation
- The case for neutrinos
- Search for self-annihilating dark matter
- Astrophysical neutrinos and decaying dark matter
- Dark Matter capture in the Earth and the Sun
- Solar Atmospheric Neutrino Floor
- Outlook & Conclusions

Role of Neutrinos

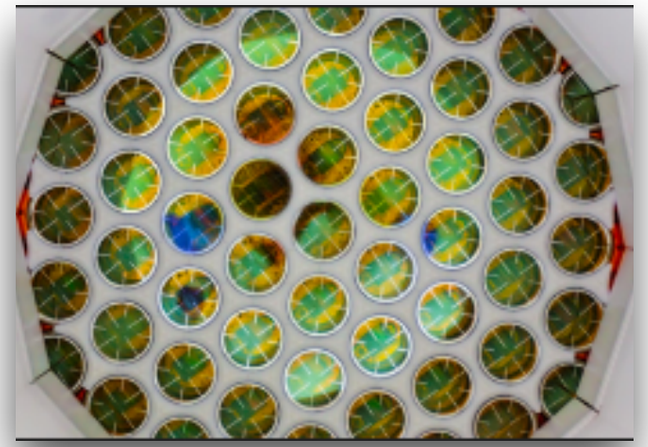


Neutrinos from

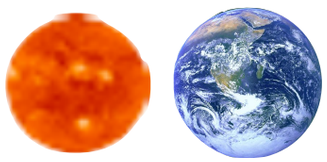
…



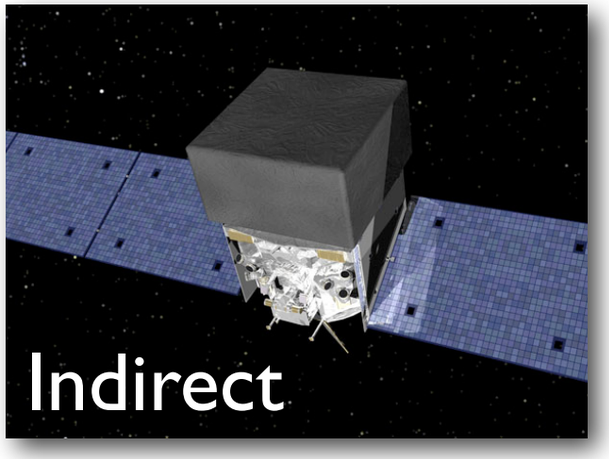
Direct



Neutrinos from

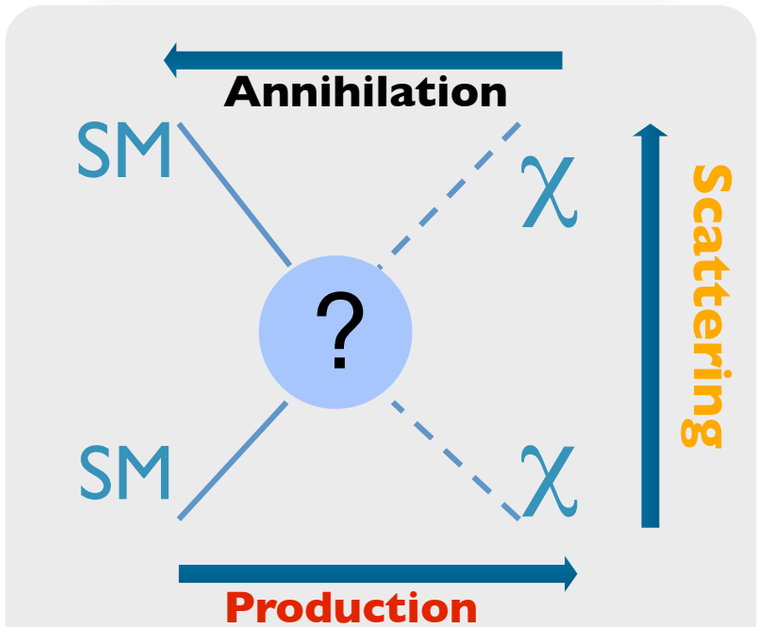


Role of Neutrinos



Neutrinos from

…



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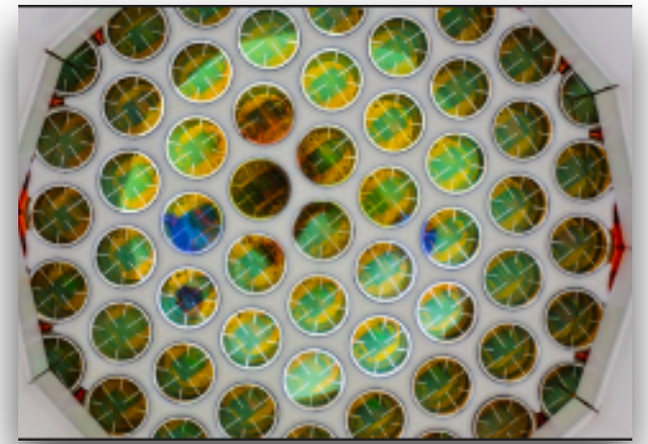
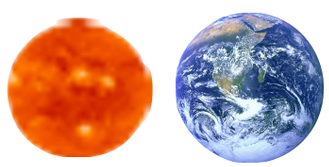


Neutrinos from

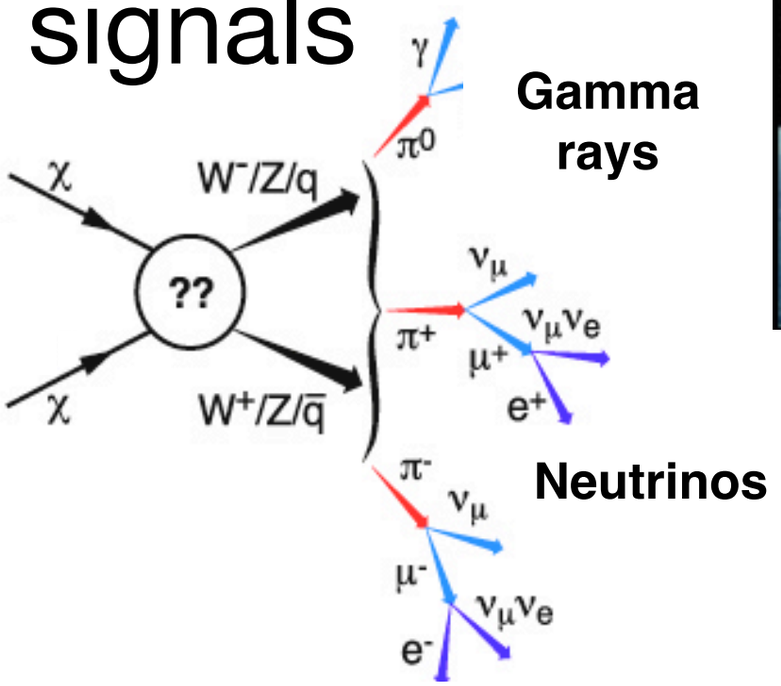


The case for Neutrinos

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

Indirect Detection of Dark Matter

Annihilation signals

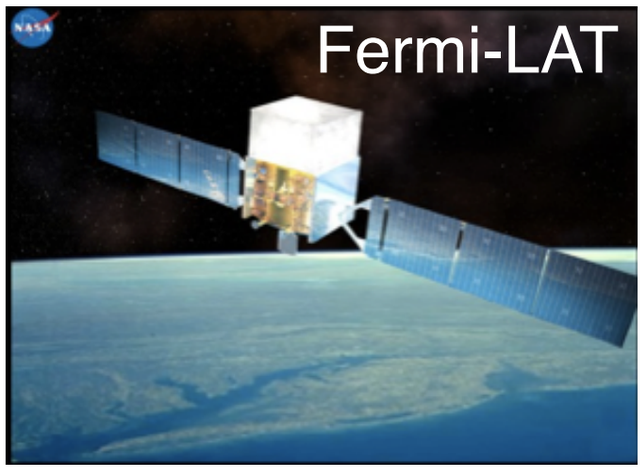


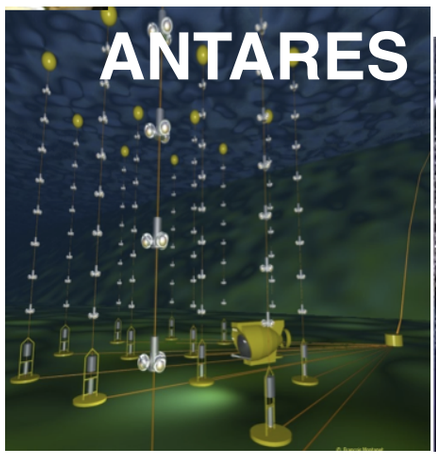
Gamma rays

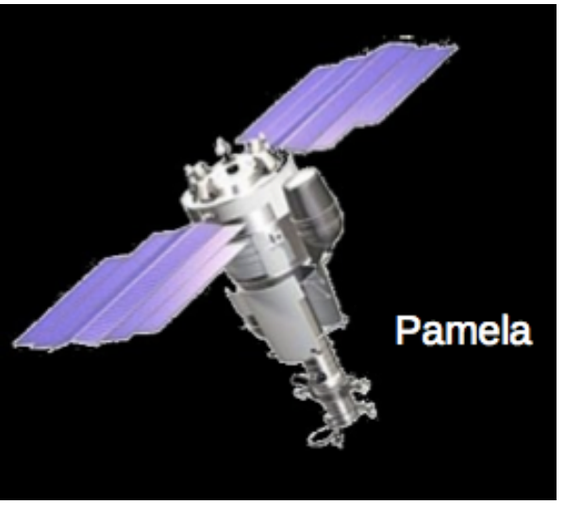
Neutrinos

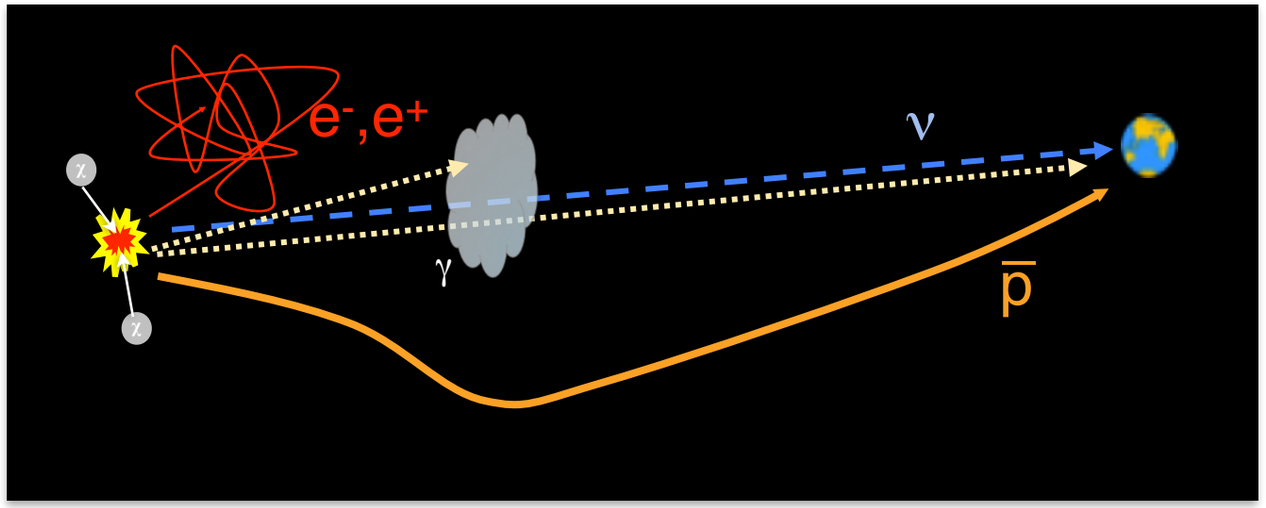
& p/p̄, d/d̄

e+/e- Anti-matter

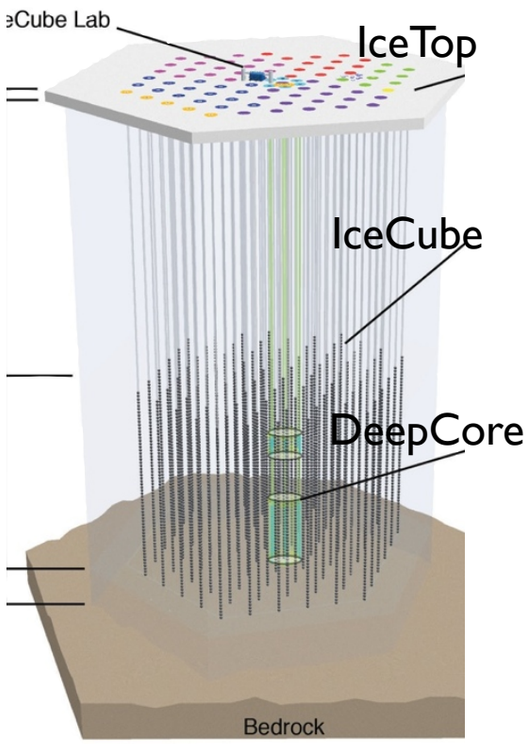


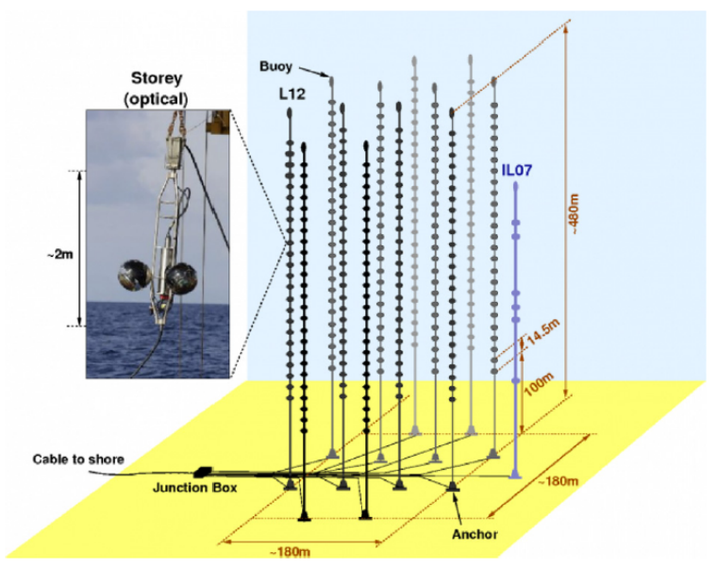


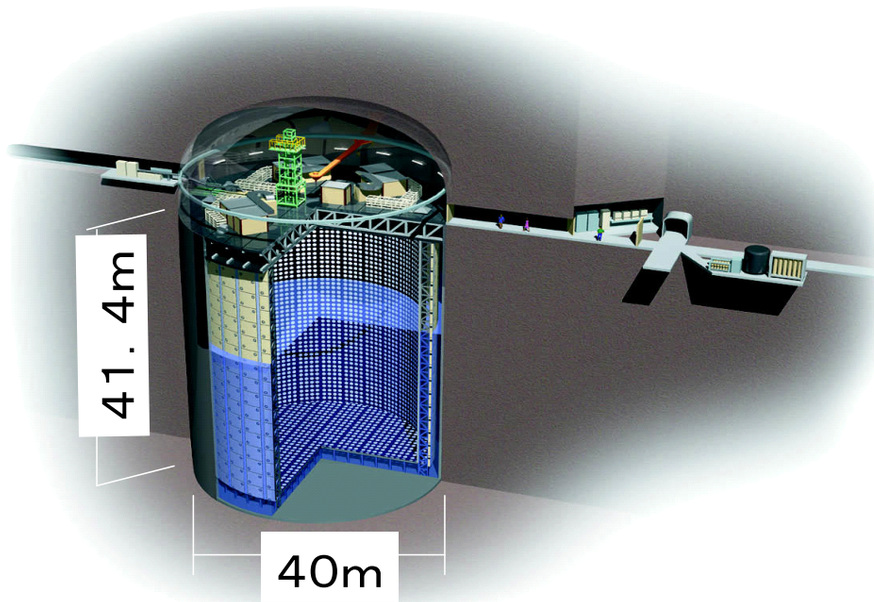




Neutrino Telescopes / Detectors







- **IceCube** at the Geographic South Pole
- 5160 10"PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km^3
- 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

- **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

$\langle \sigma_A v \rangle$

Dark Matter Annihilation

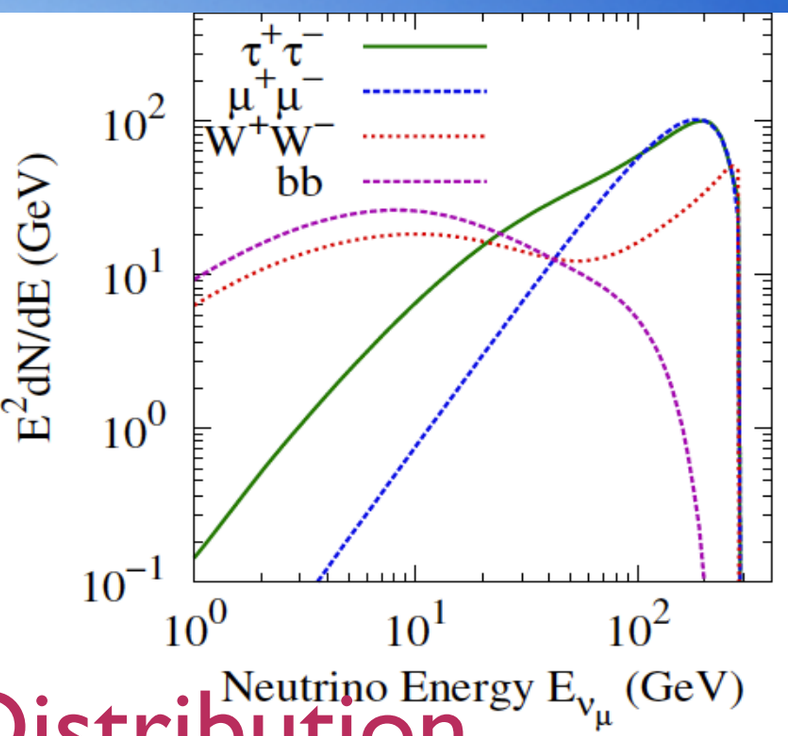
Measure Flux

$$\frac{d\Phi}{dE}(E,\phi,\theta)$$

=

Particle Physics

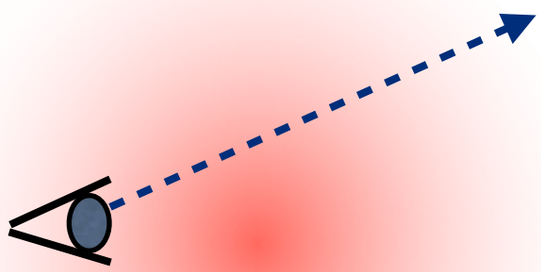
$$\frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f\frac{dN}{dE}B_f$$



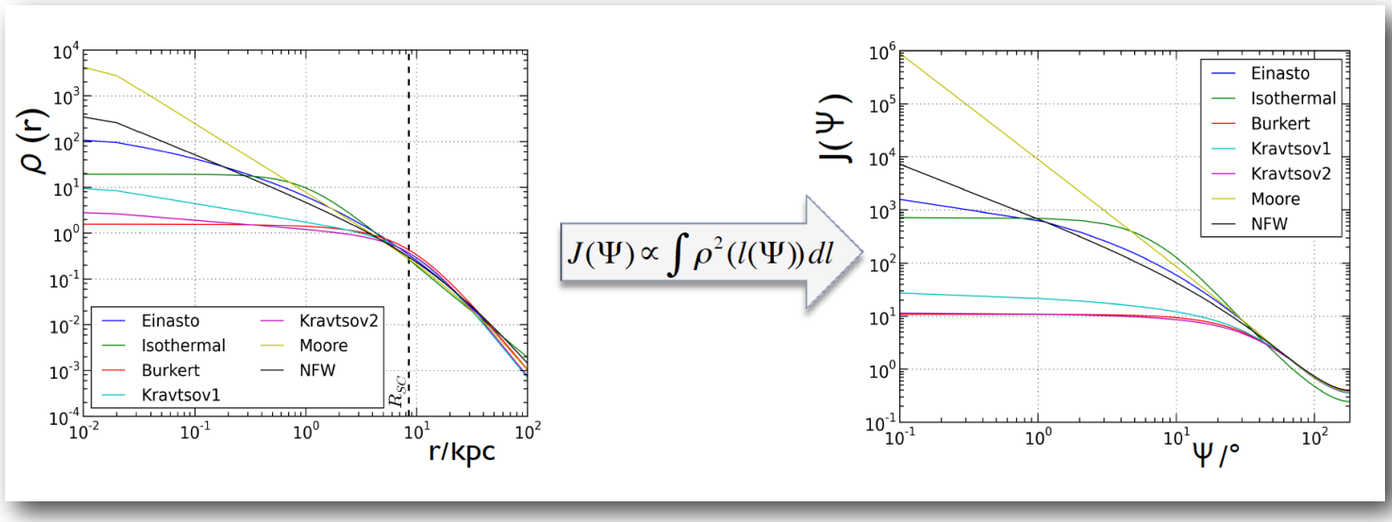
x

Dark Matter Distribution

line of sight (los) integral

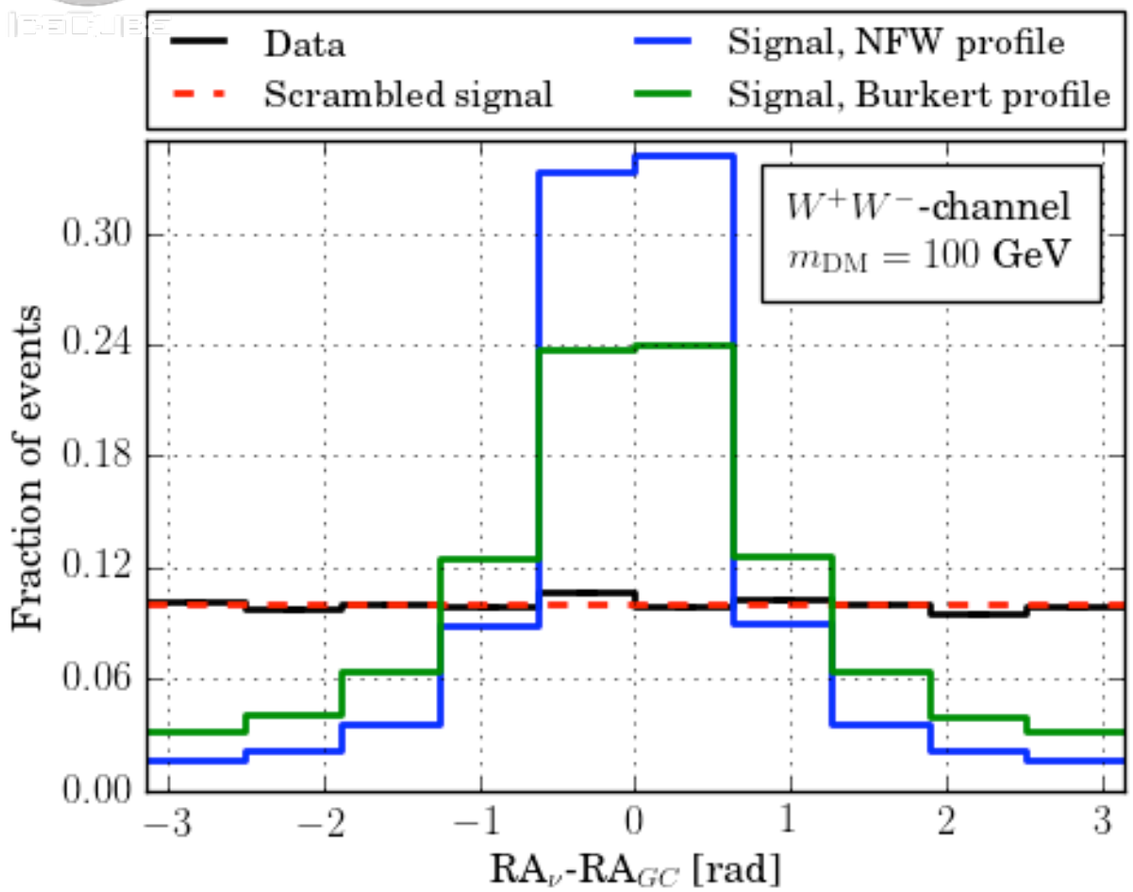


$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$

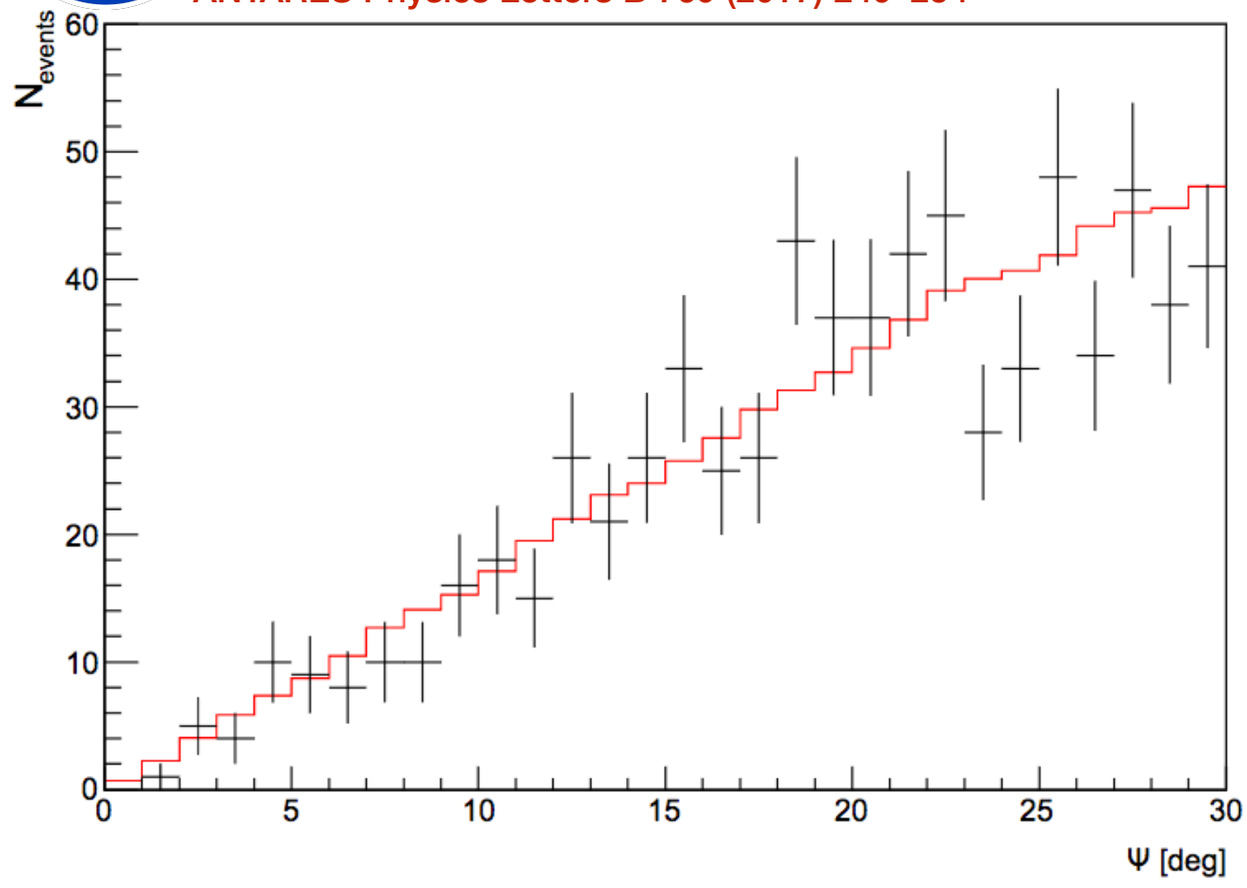


INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES

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



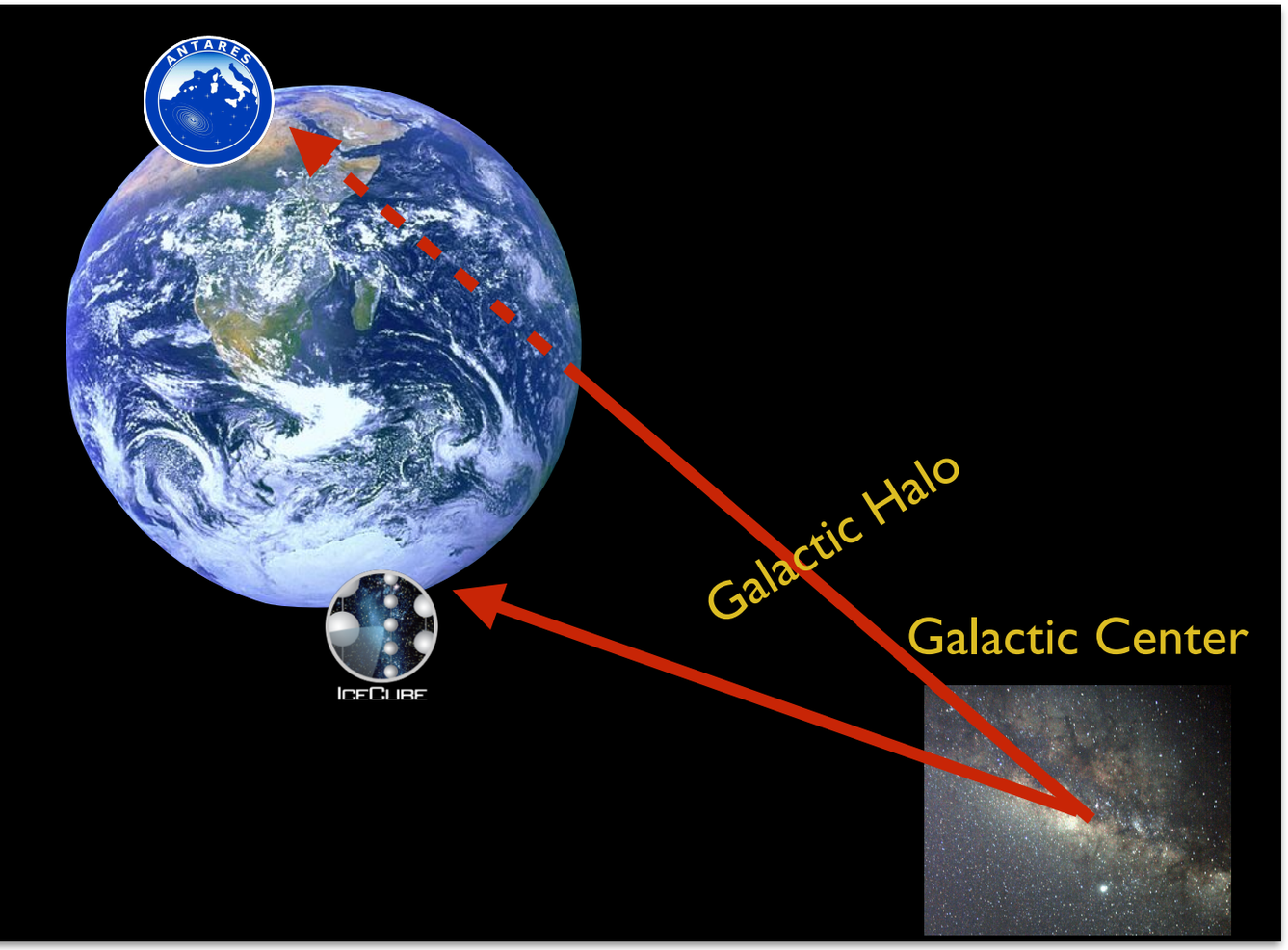
ANTARES Physics Letters B 769 (2017) 249–254



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

Observations consistent with background expectations

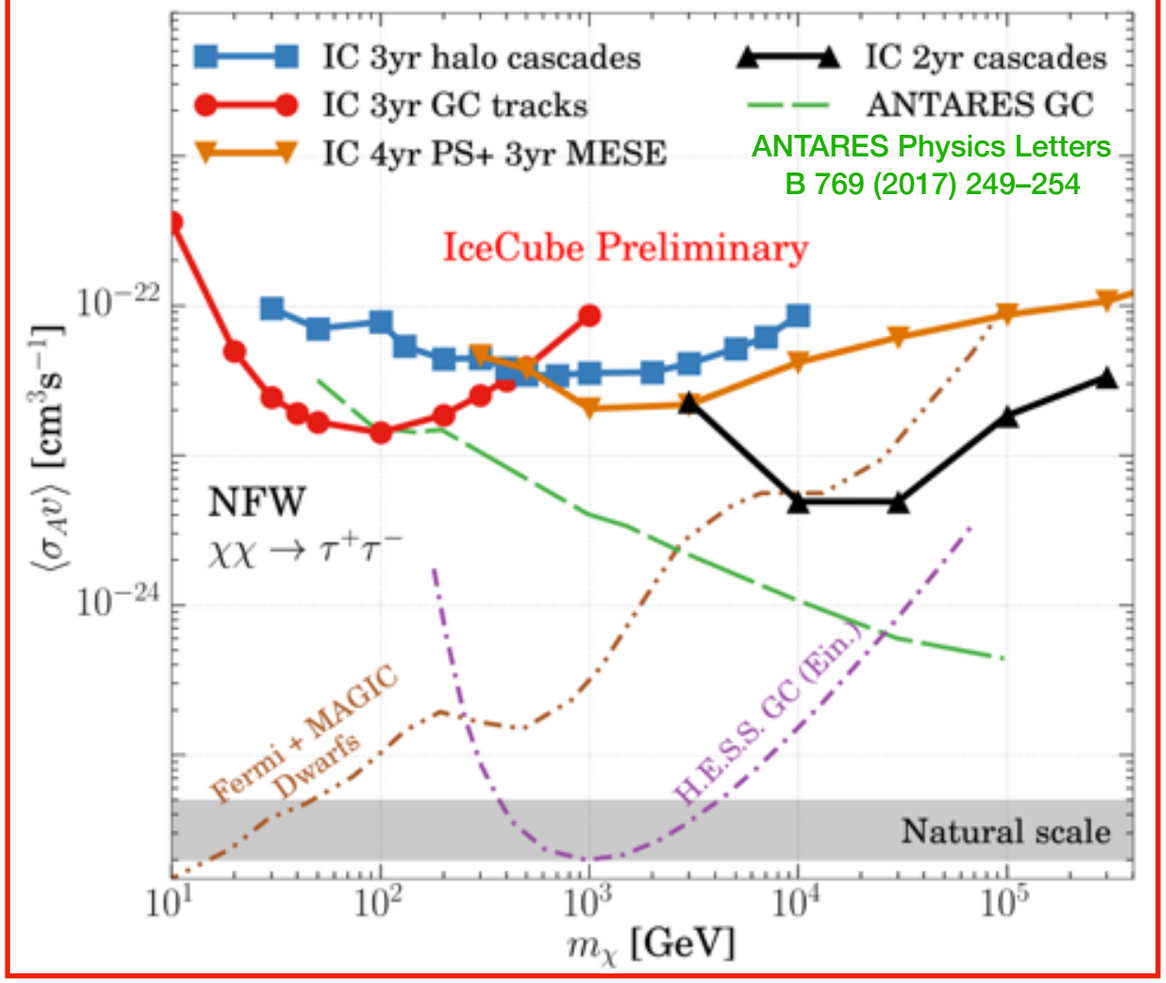
INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES



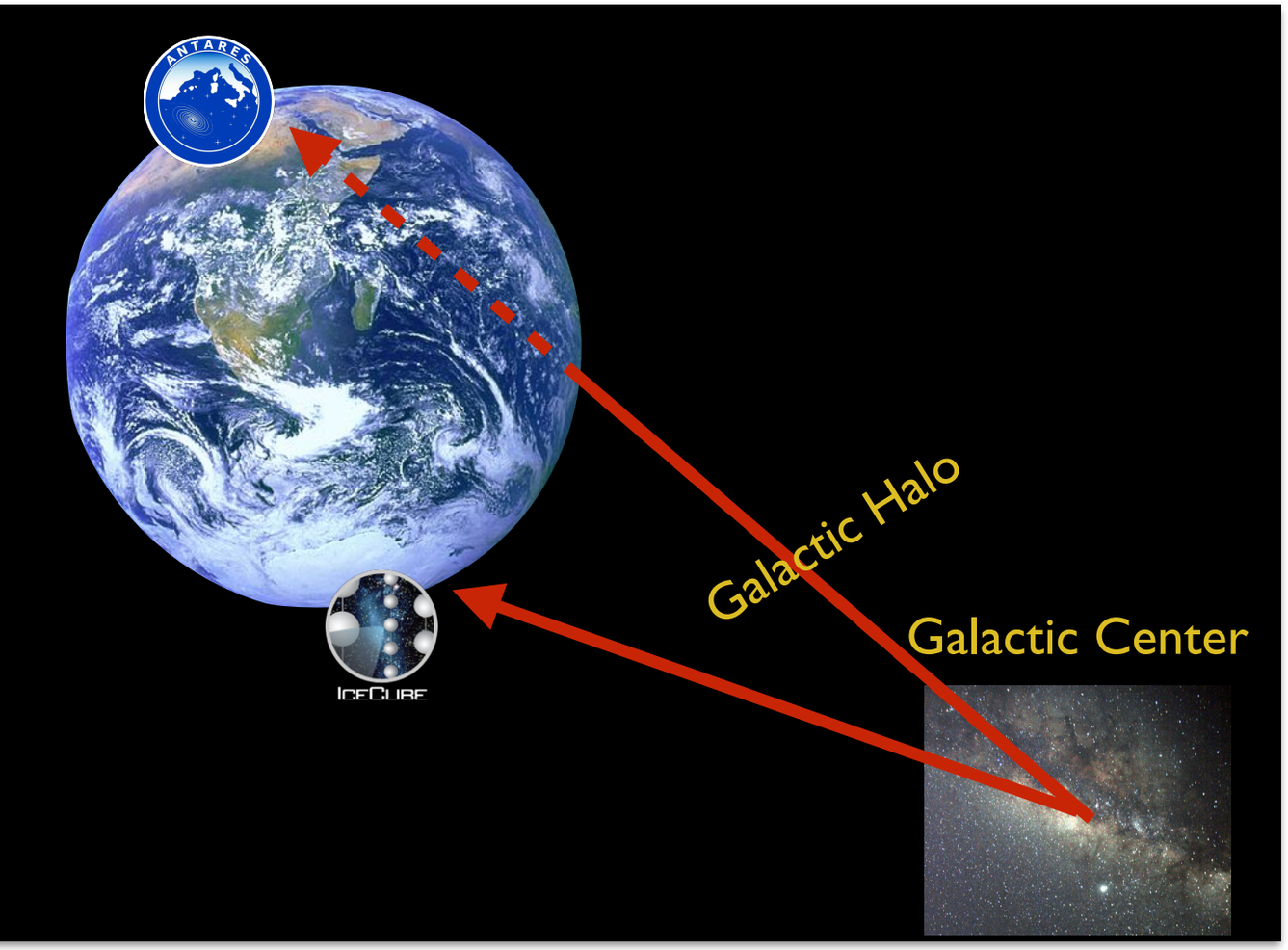
- ANTARES and IceCube complementary positioned on Northern and Southern Hemisphere
- Galactic Center only accessible in down-going events for IceCube
- Weak halo model dependence for observation of extended DM halo

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



INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES



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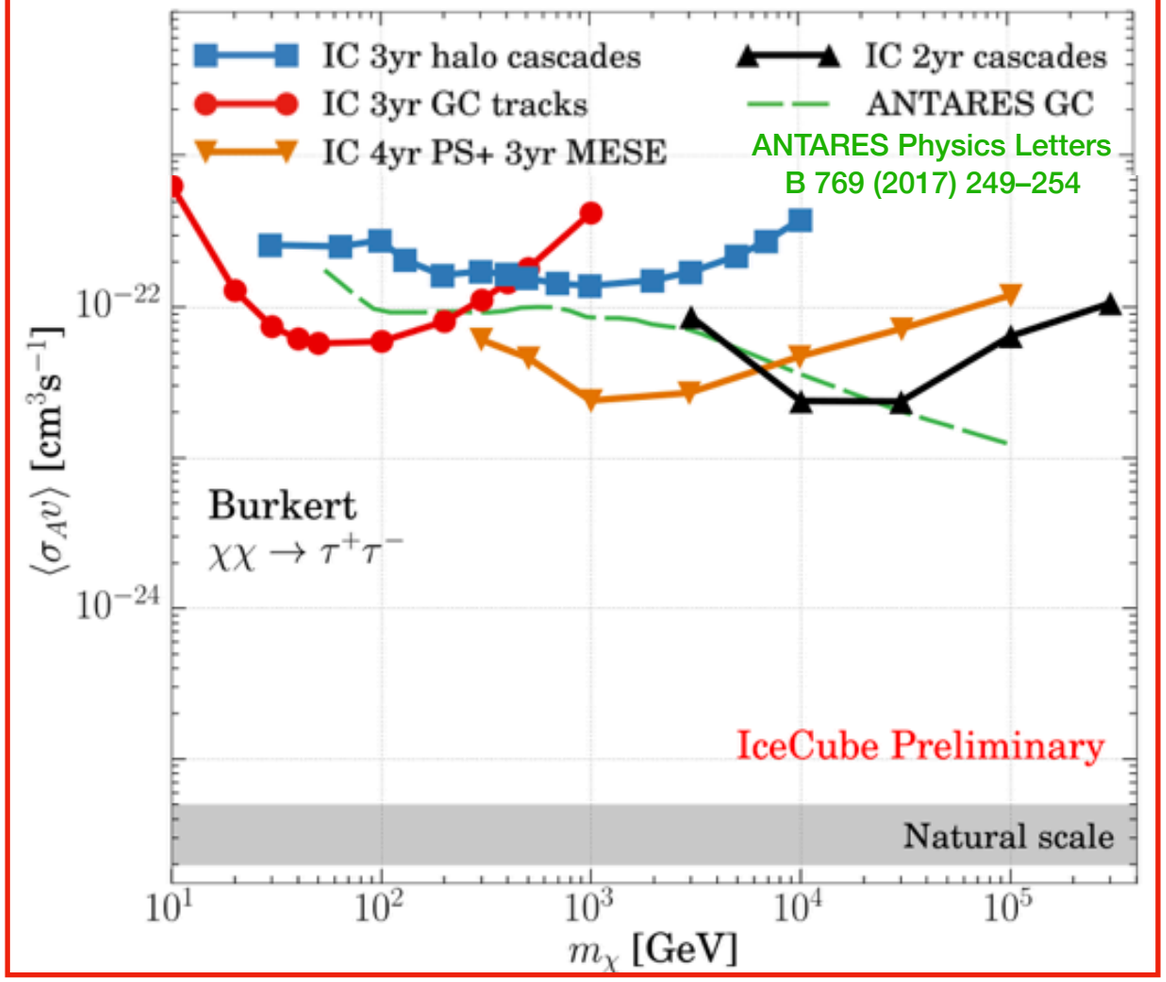
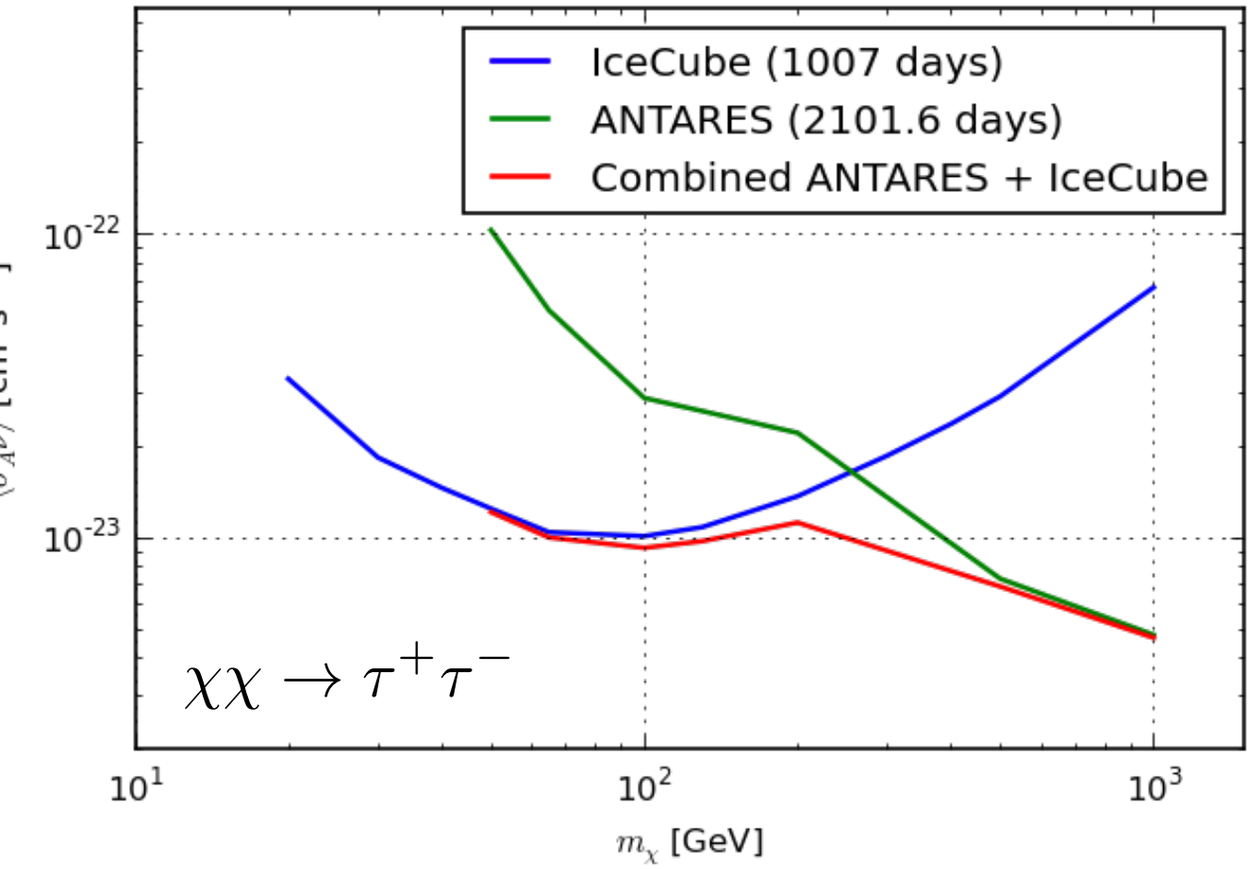
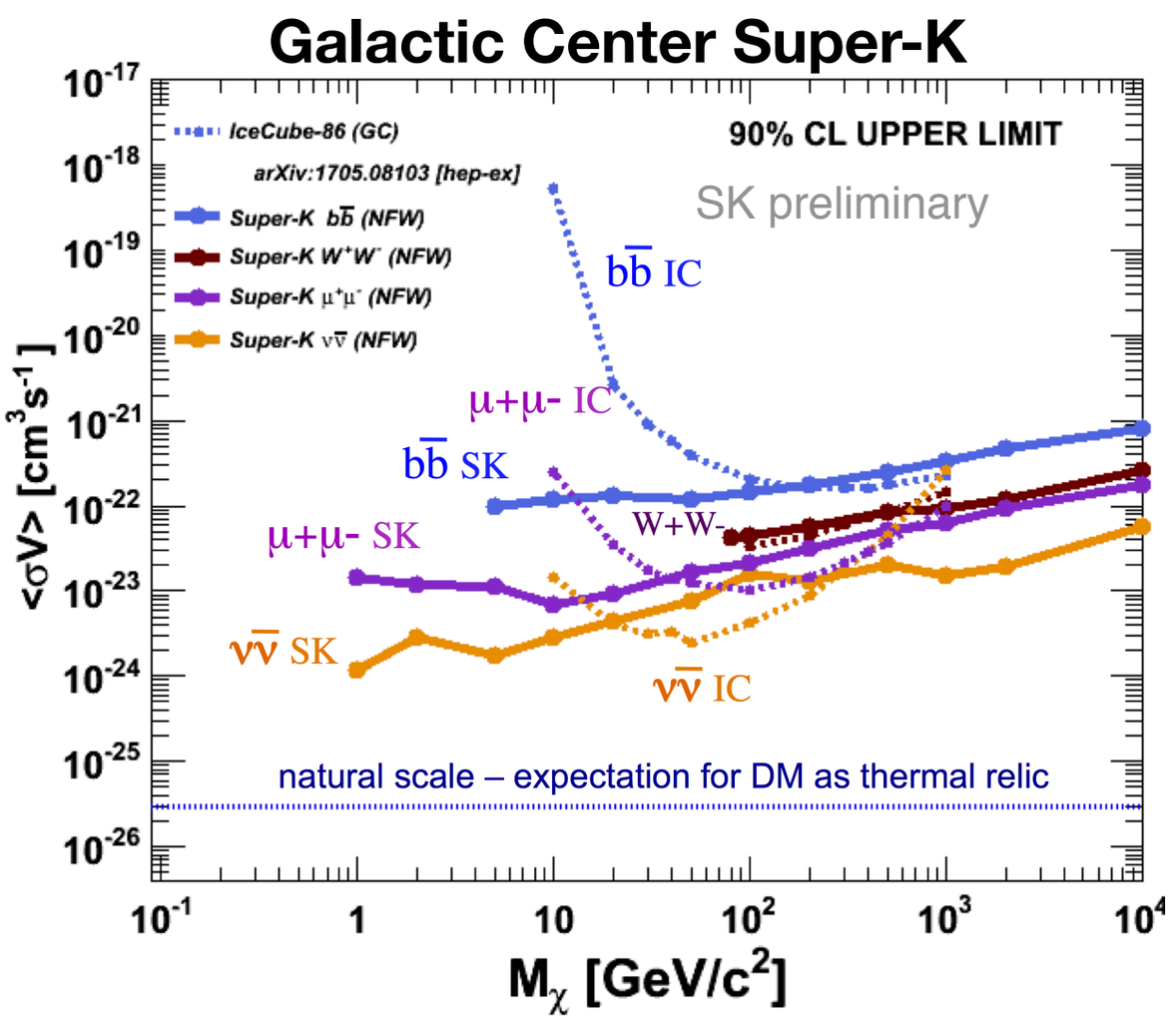


Galactic Center / Galactic Halo - IceCube/ ANTARES/Super-K

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

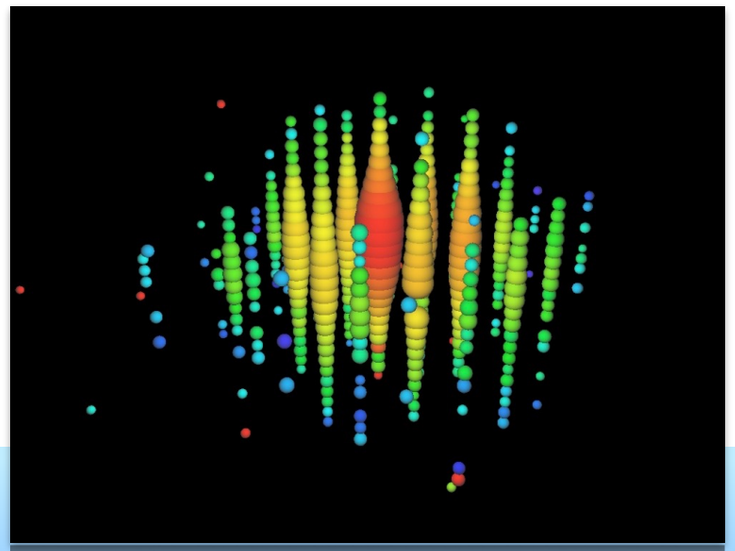


Combined Search for Neutrinos from Dark Matter Annihilation in the Galactic Center using IceCube and ANTARES

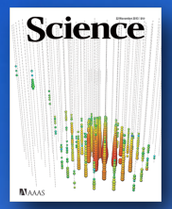
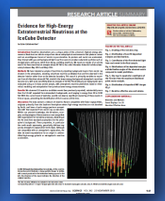


- Combined analysis enhances sensitivity in overlap region and helps to make analyses more comparable
- Very competitive result from Super-K for dark matter masses below a 100GeV

Neutrino Telescopes can probe models motivated by the observed lepton anomalies



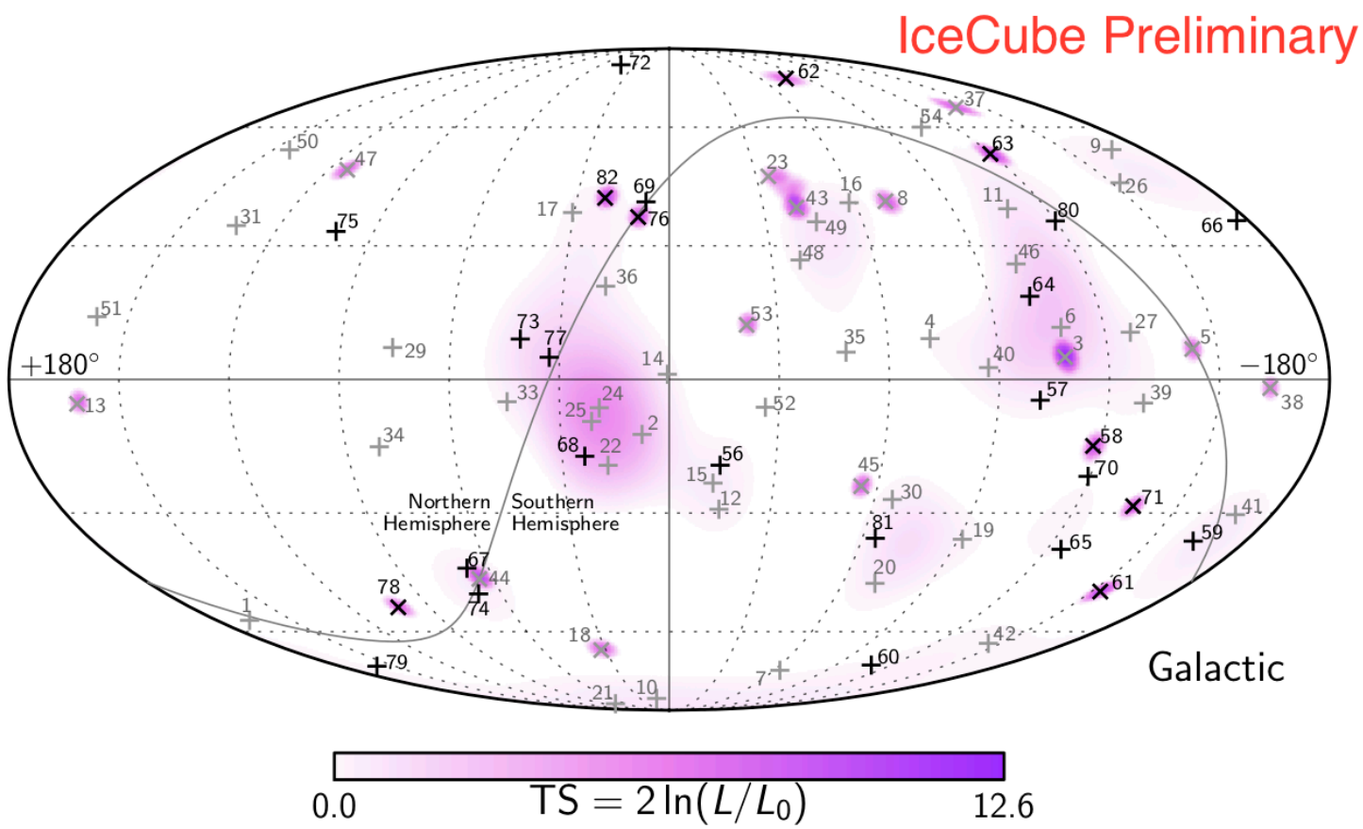
Dark Matter Decay / Astro-physical Neutrinos

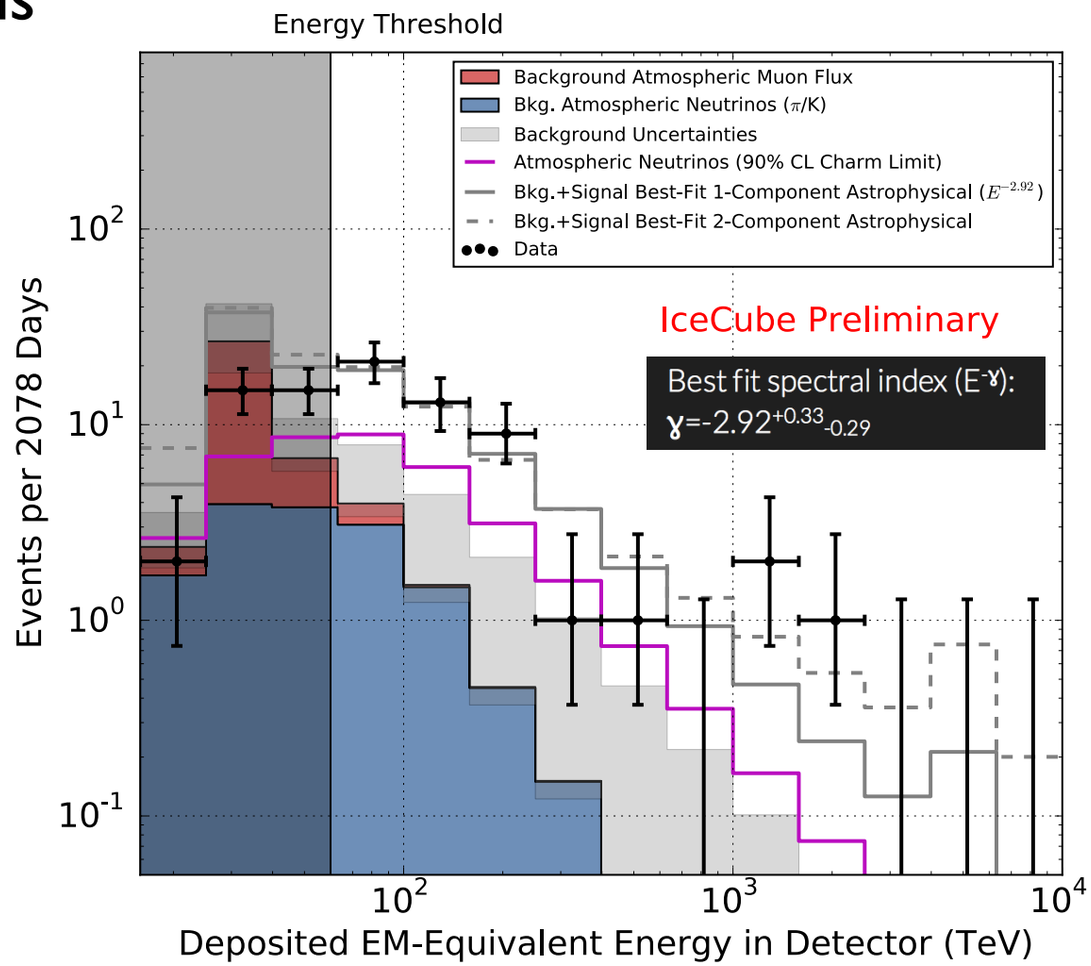



IceCube - High-energy neutrino search 6years

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

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





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

Two flux contributions:
Galactic and Extra galactic

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

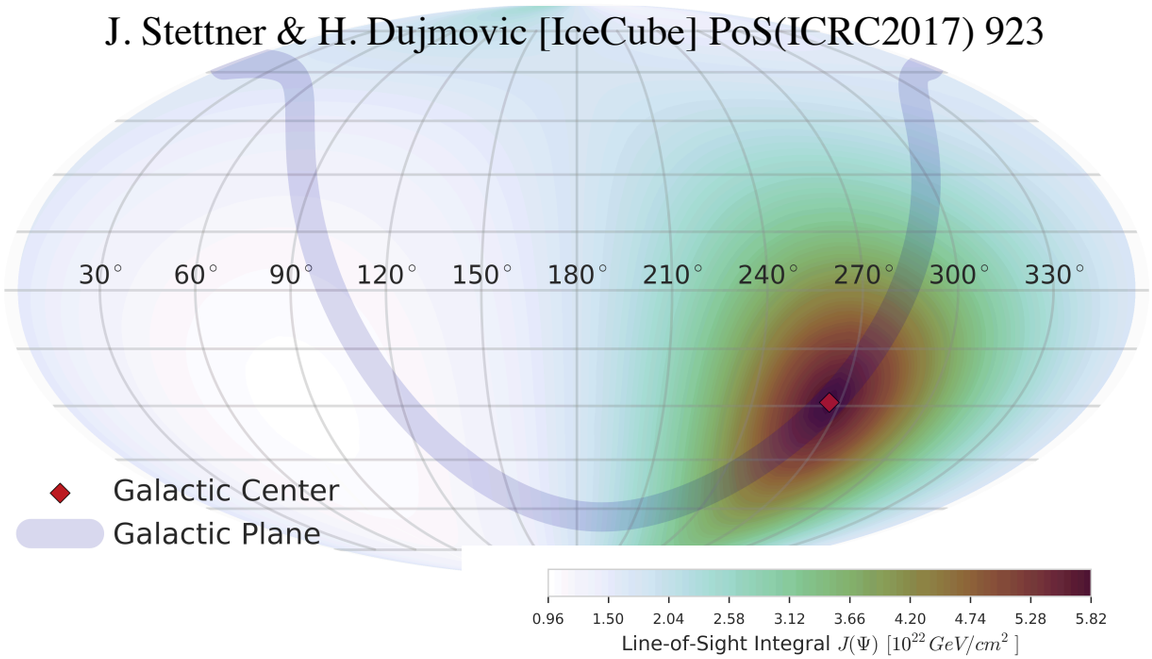
Characteristics of the signal components:

- (1) Dark Matter decay in the Galactic Halo (Anisotropic flux + decay spectrum)

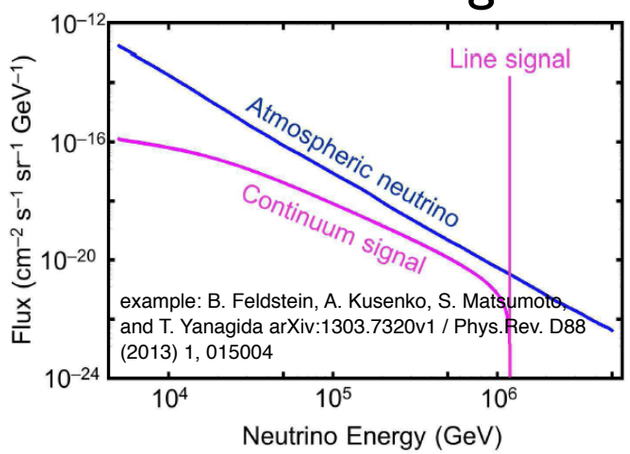
$$\frac{\mathrm{d}\Phi^{\mathrm{G}}}{\mathrm{d}E_\nu} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \rho(r(s,l,b))\, \mathrm{d}s$$

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

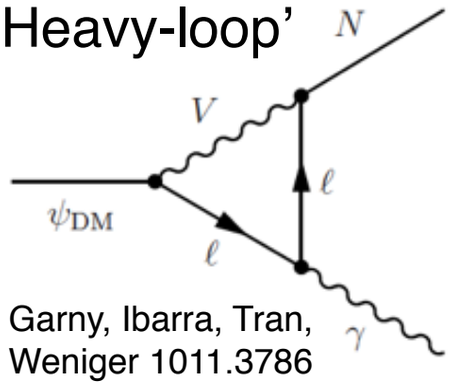
$$\frac{\mathrm{d}\Phi^{\mathrm{EG}}}{\mathrm{d}E} = \frac{\Omega_{\mathrm{DM}}\, \rho_{\mathrm{c}}}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} [(1+z)E_\nu]\, \mathrm{d}z$$



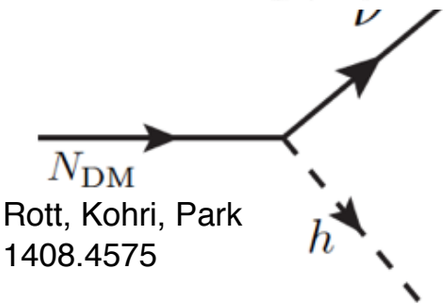
Decay process might produce mono-energetic neutrinos



‘Heavy-loop’

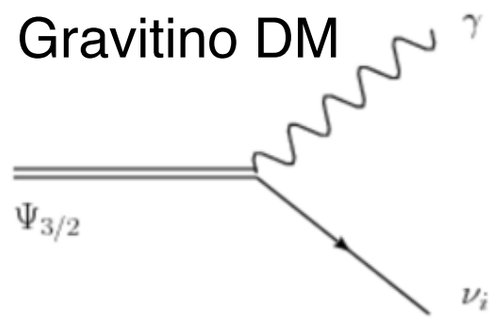


Garny, Ibarra, Tran, Weniger 1011.3786



Rott, Kohri, Park 1408.4575

Gravitino DM



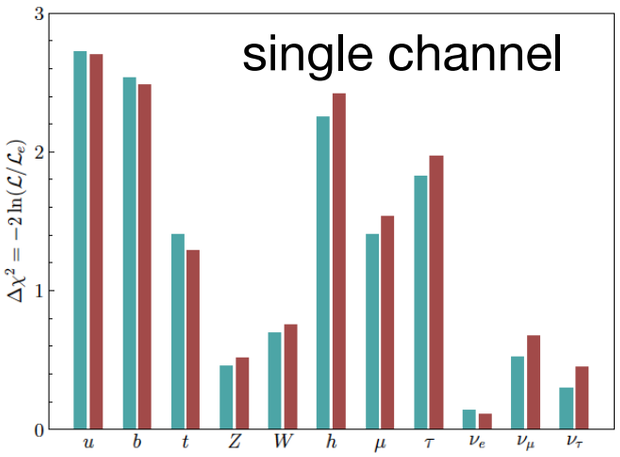
Heavy Decaying Dark Matter

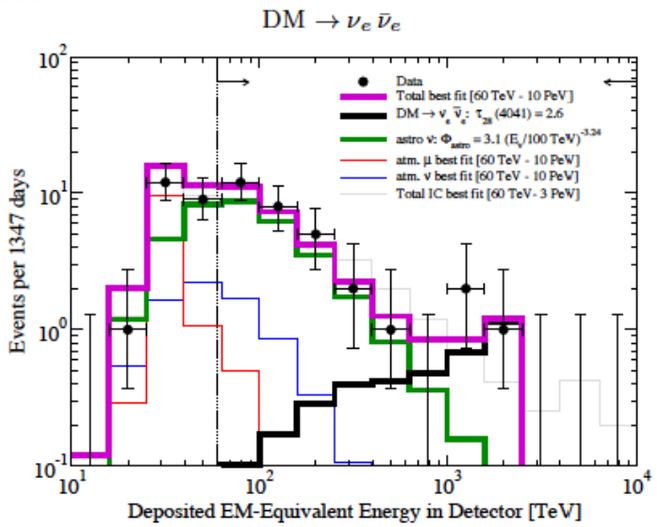
Could the observed neutrino flux be due to only dark matter decaying into multiple channels?

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

Take Galactic and Extra galactic contributions into account

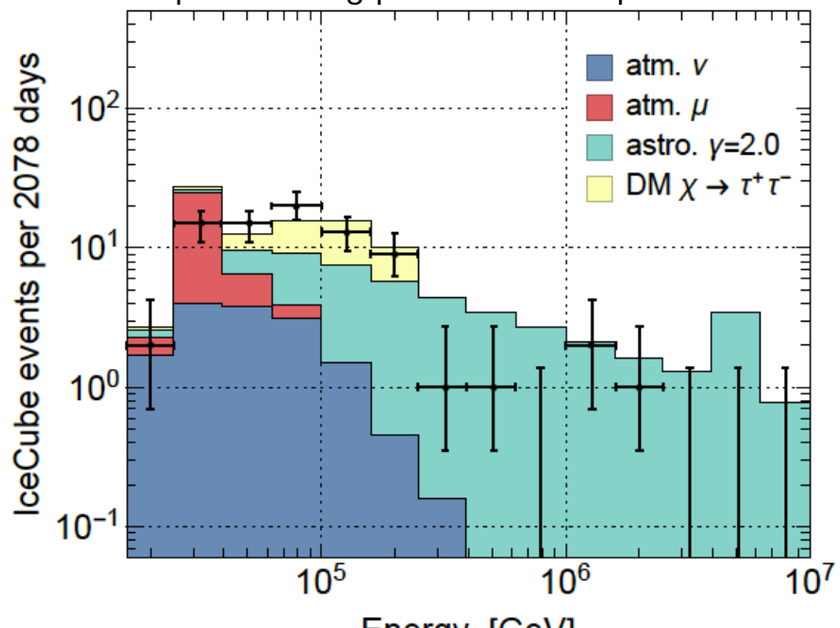
Atri Bhattacharya, Arman Esmaili, Sergio Palomares-Ruiz and Ina Sarcevic, arXiv:1706.05746

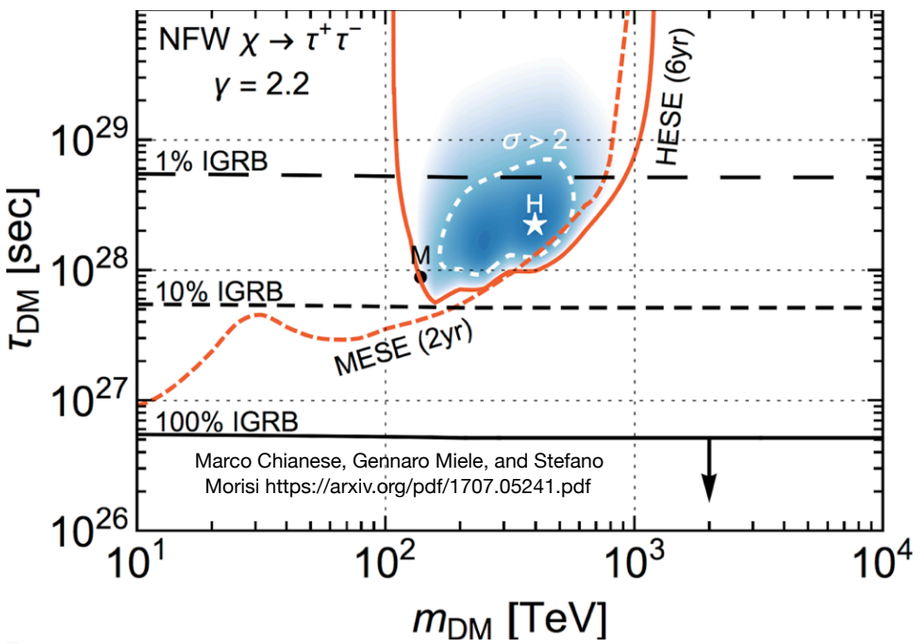




Find that HESE data can be best described with the combination of the astrophysical neutrino flux and the dark matter decay

Marco Chianese, Gennaro Miele, and Stefano Morisi
https://arxiv.org/pdf/1707.05241.pdf





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

A general word of caution when interpreting HESE events:
- Earth absorption needs to be considered
- Outcome strongly depends on background assumption

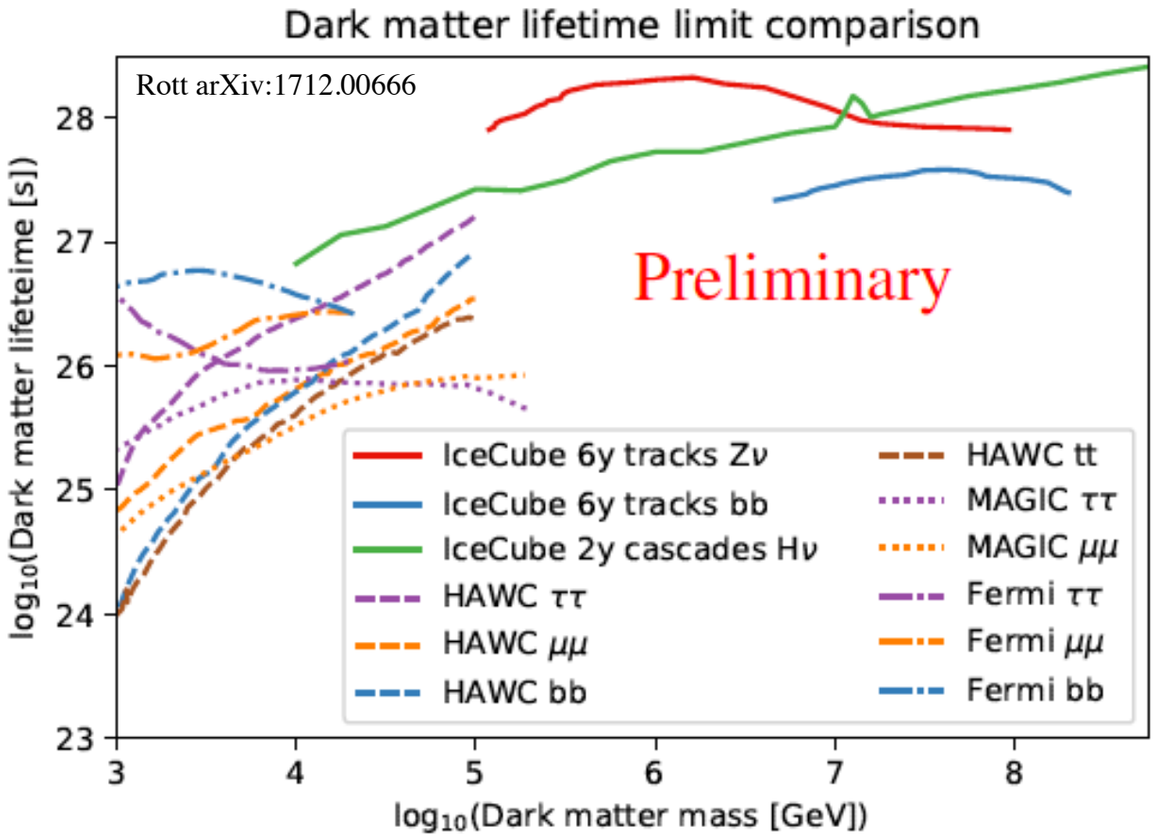
Dark Matter Decay with IceCube

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

- Two independent IceCube analyses have been performed:
  - Muon tracks with six years of data
  - Cascades with two years of data

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

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



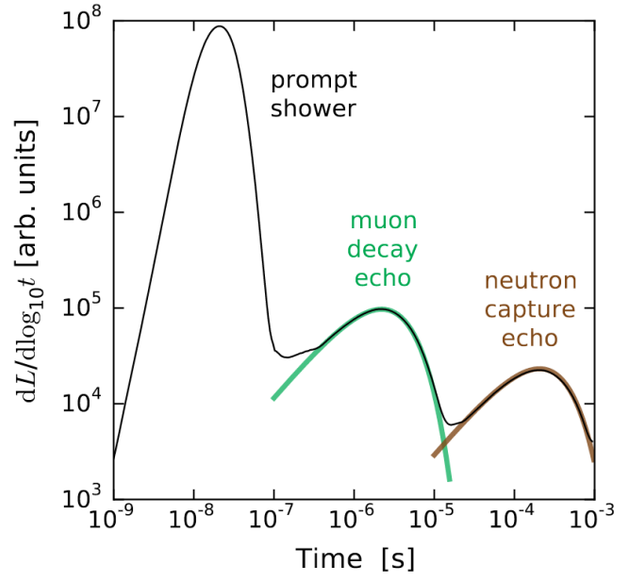
(Gamma-ray results see talks by Simona Murgia and James Buckley)
see also HAWC arXiv:1710.10288

- 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

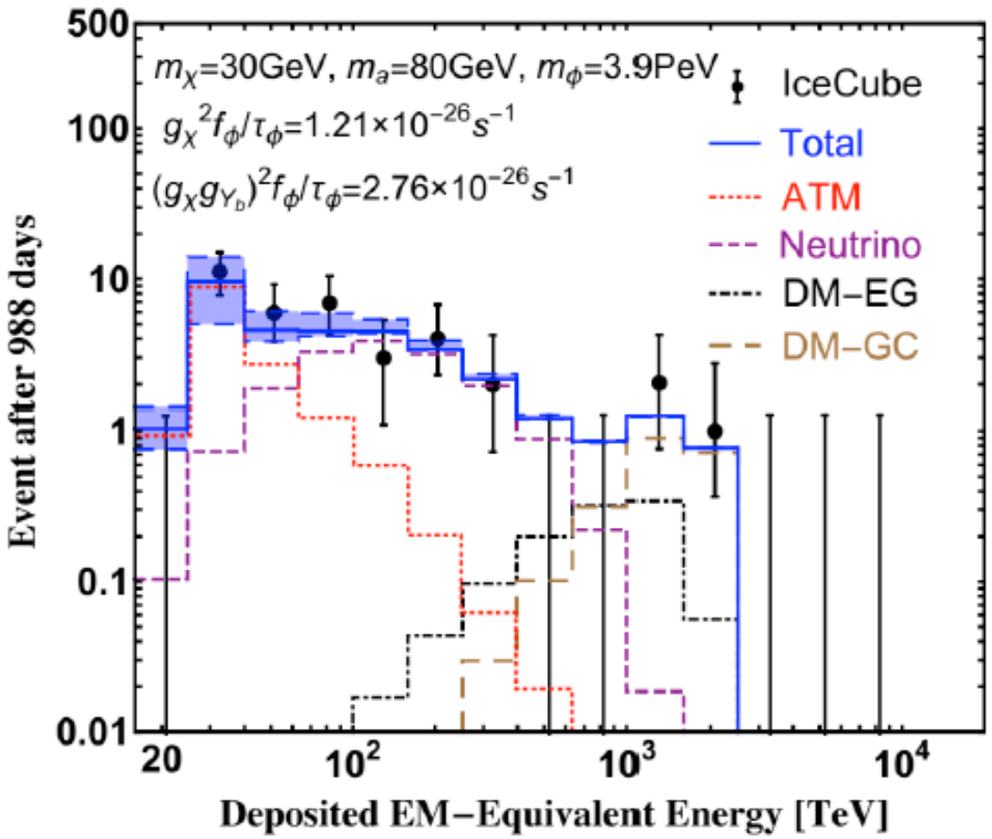
IceCube Boosted Dark Matter

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

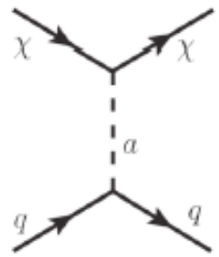
using "Echo Technique" Li, Bustamante, Beacom (2016)

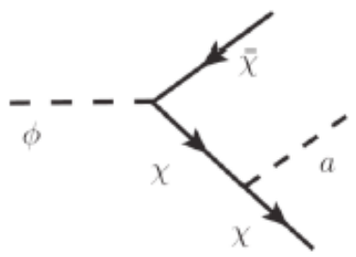


Neutrons capture on hydrogen and product 2.2MeV gamma. In seawater, 33% of neutrons capture on Cl; the emitted gamma rays have 8.6 MeV, making the neutron echoes more visible



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





Recoil (only hadronic cascades)

$\phi \to \chi\,\bar{\chi}\,a$, $a \to b\,\bar{b}$ →ν's

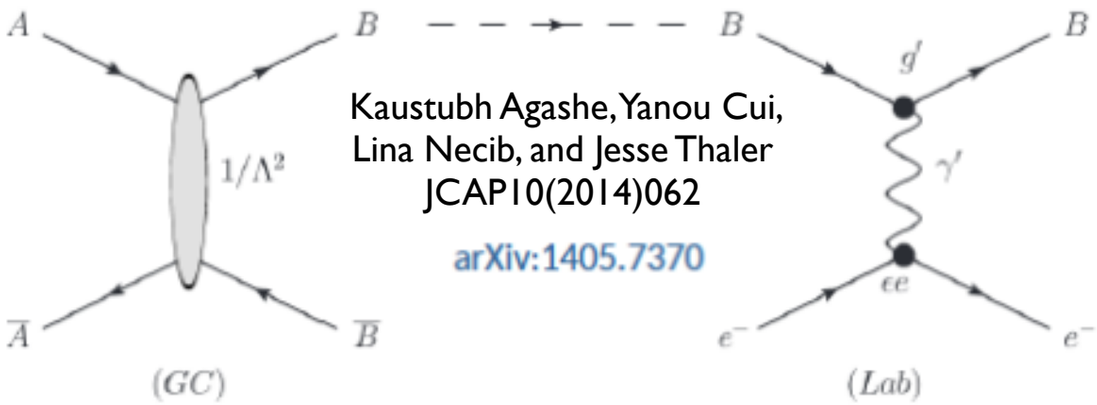
"Echo Technique" holds prospects to individually tag high-energy NC and CC interactions !

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

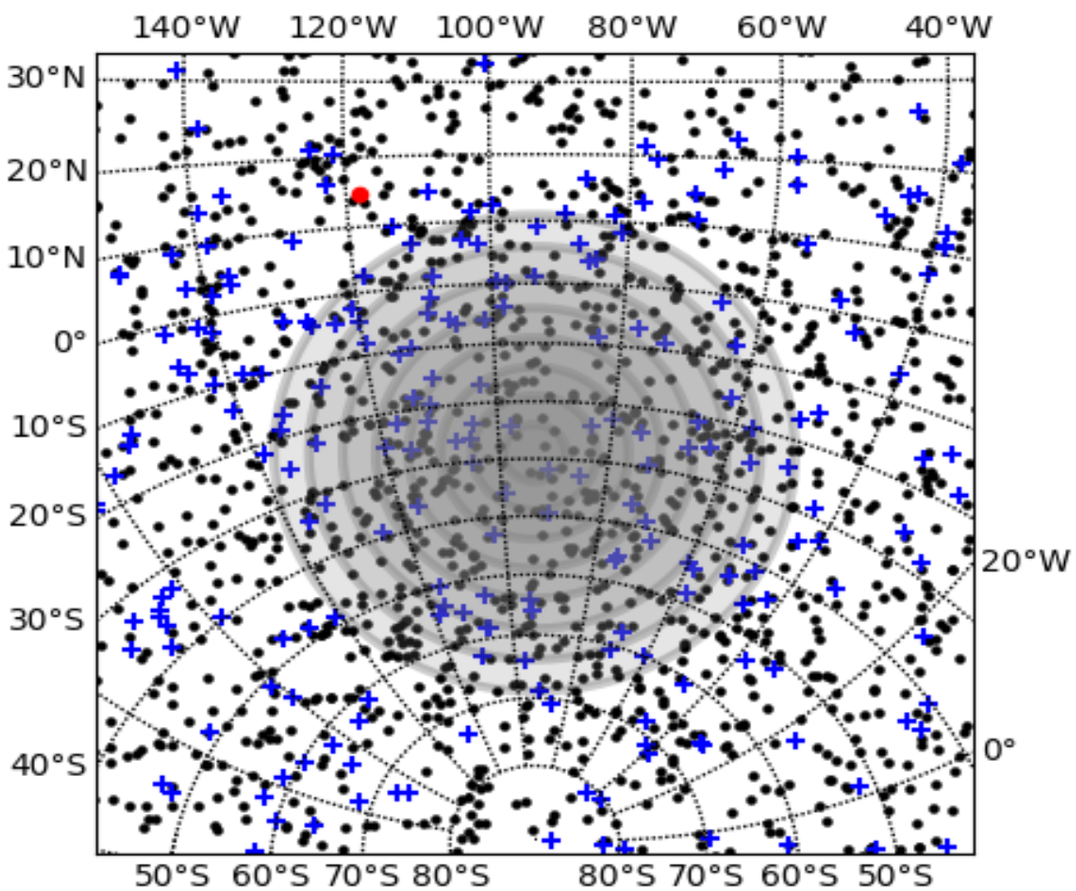
Super-K Boosted Dark Matter



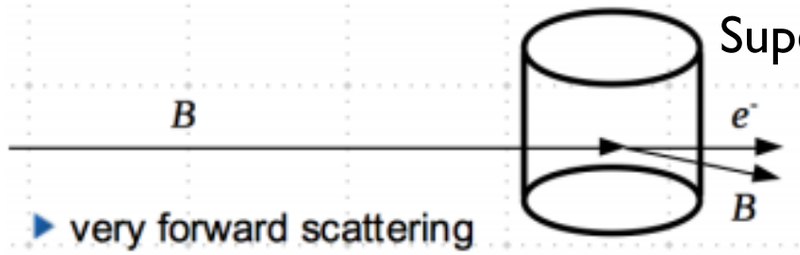
Kaustubh Agashe, Yanou Cui, Lina Necib, and Jesse Thaler
JCAP10(2014)062

arXiv:1405.7370

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

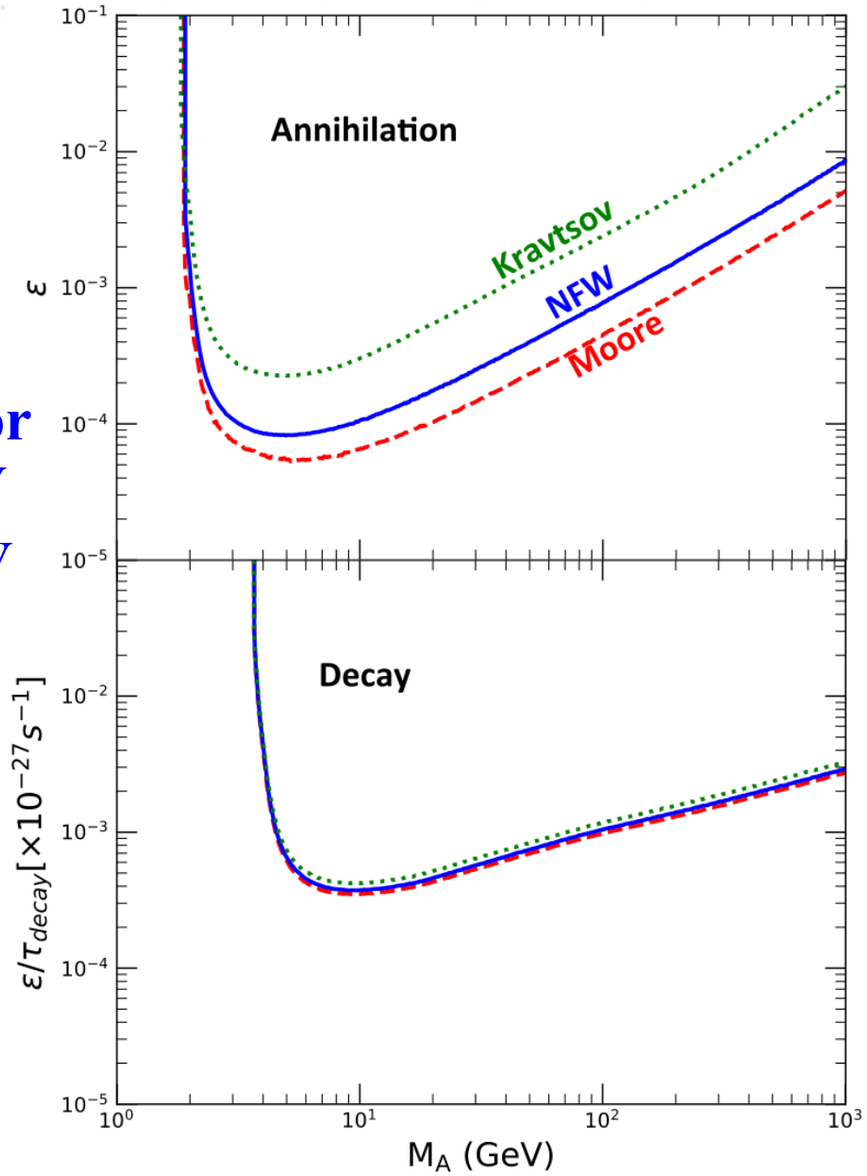


• < 1.33 GeV + 1.33 GeV-20 GeV • >20 GeV



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

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



Dark Matter Capture in the Sun

Solar Dark Matter

velocity distribution

ρ_χ χ χ

Sun

ν interactions

ν oscillations

ν_μ

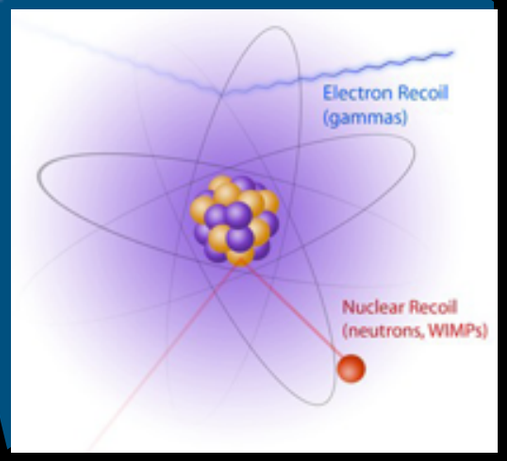
Earth

$\sigma_{\rm ann}$

$\sigma_{\rm scatt}$

$\Gamma_{\rm capture}$

$\Gamma_{\rm ann}$



μ

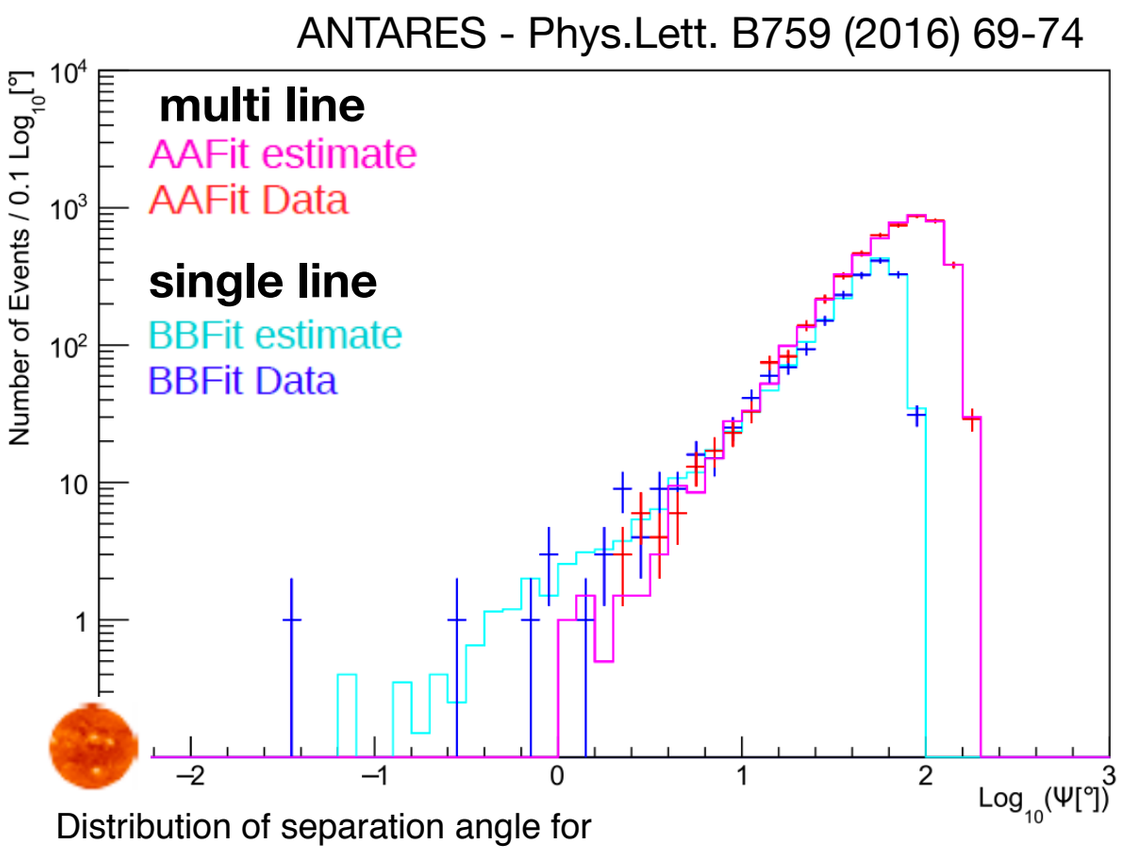
Detector

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

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

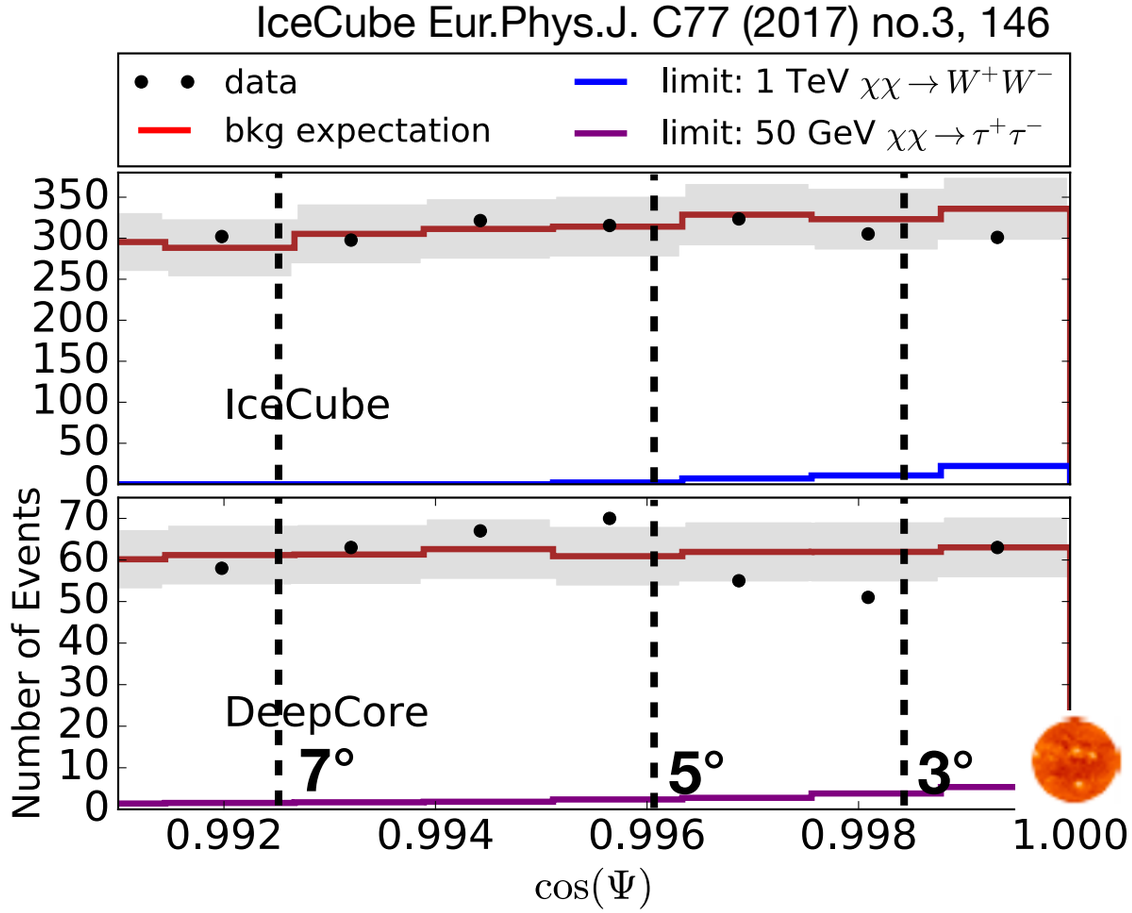
Solar Dark Matter - IceCube/ANTARES

ANTARES



Distribution of separation angle for 2007-2012 ANTARES data

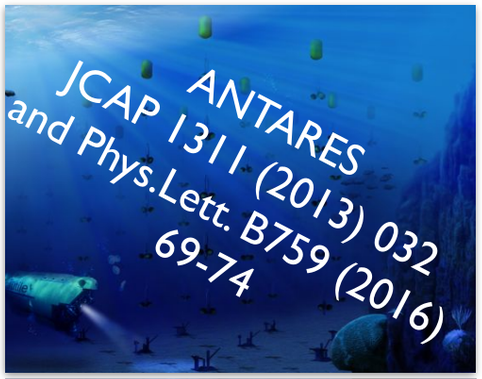
IceCube

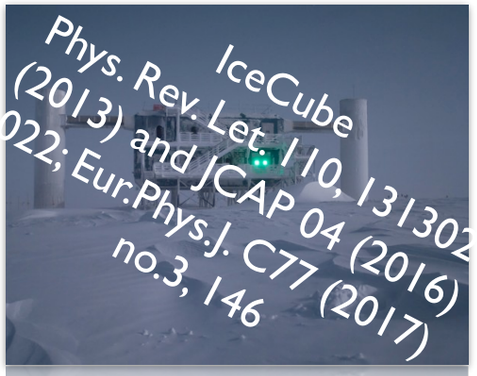


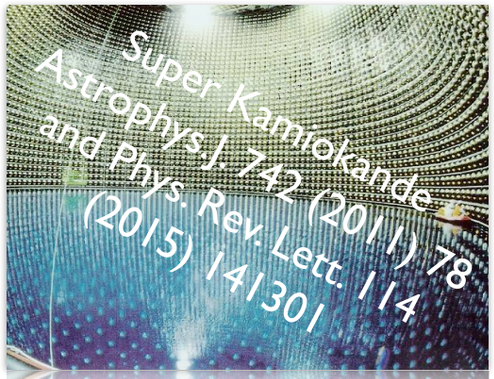
- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data
- Energy and angular information taken into account

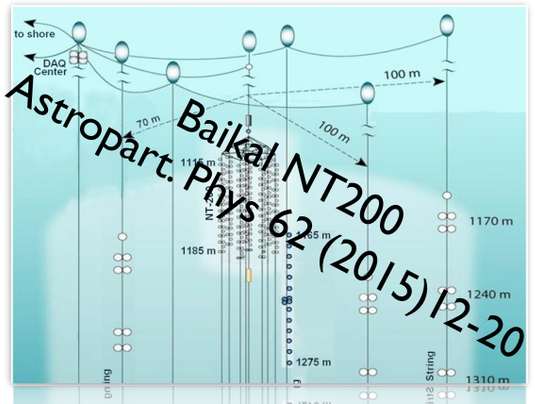
No excess observed - set limit …

Solar Dark Matter Summary

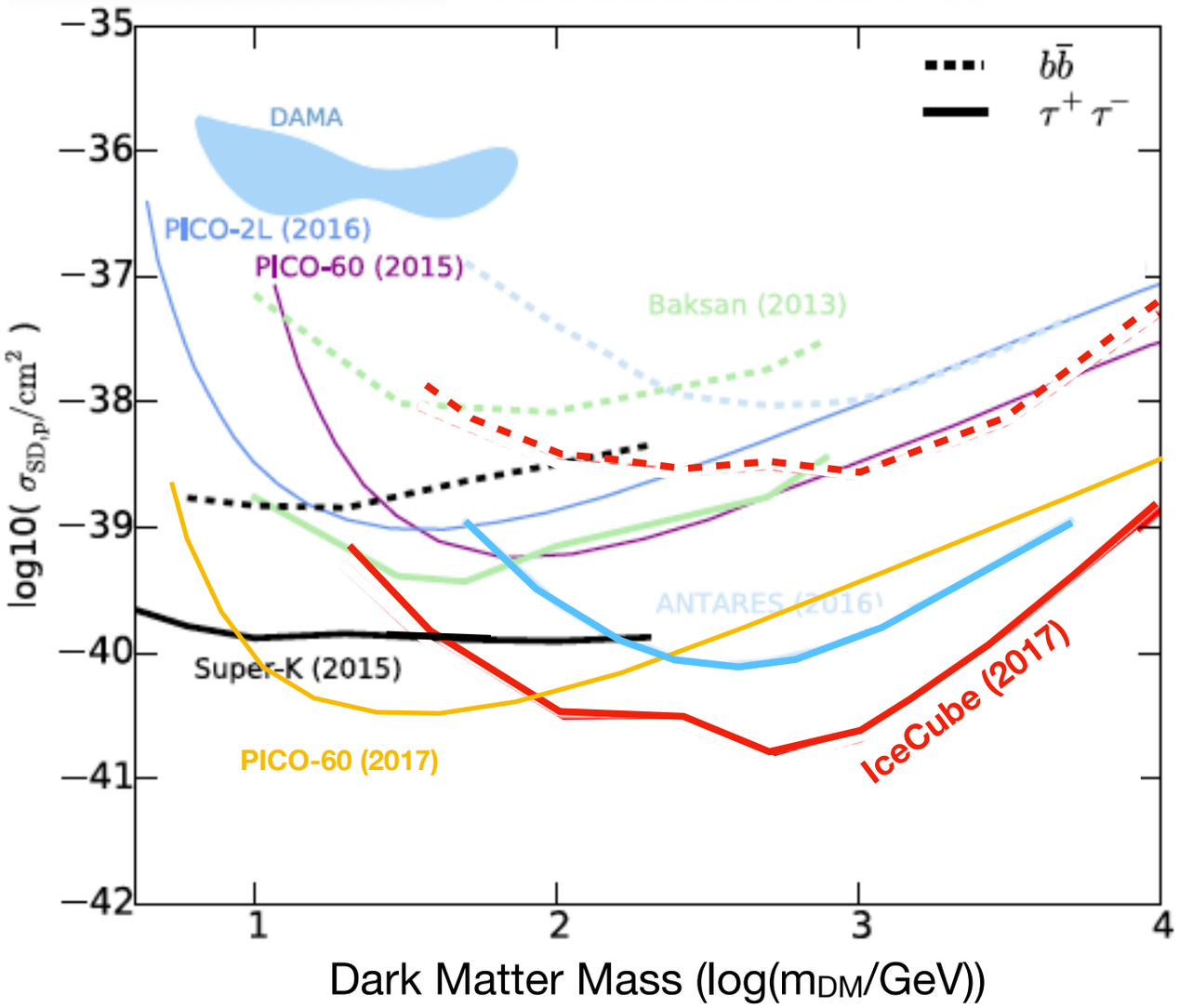




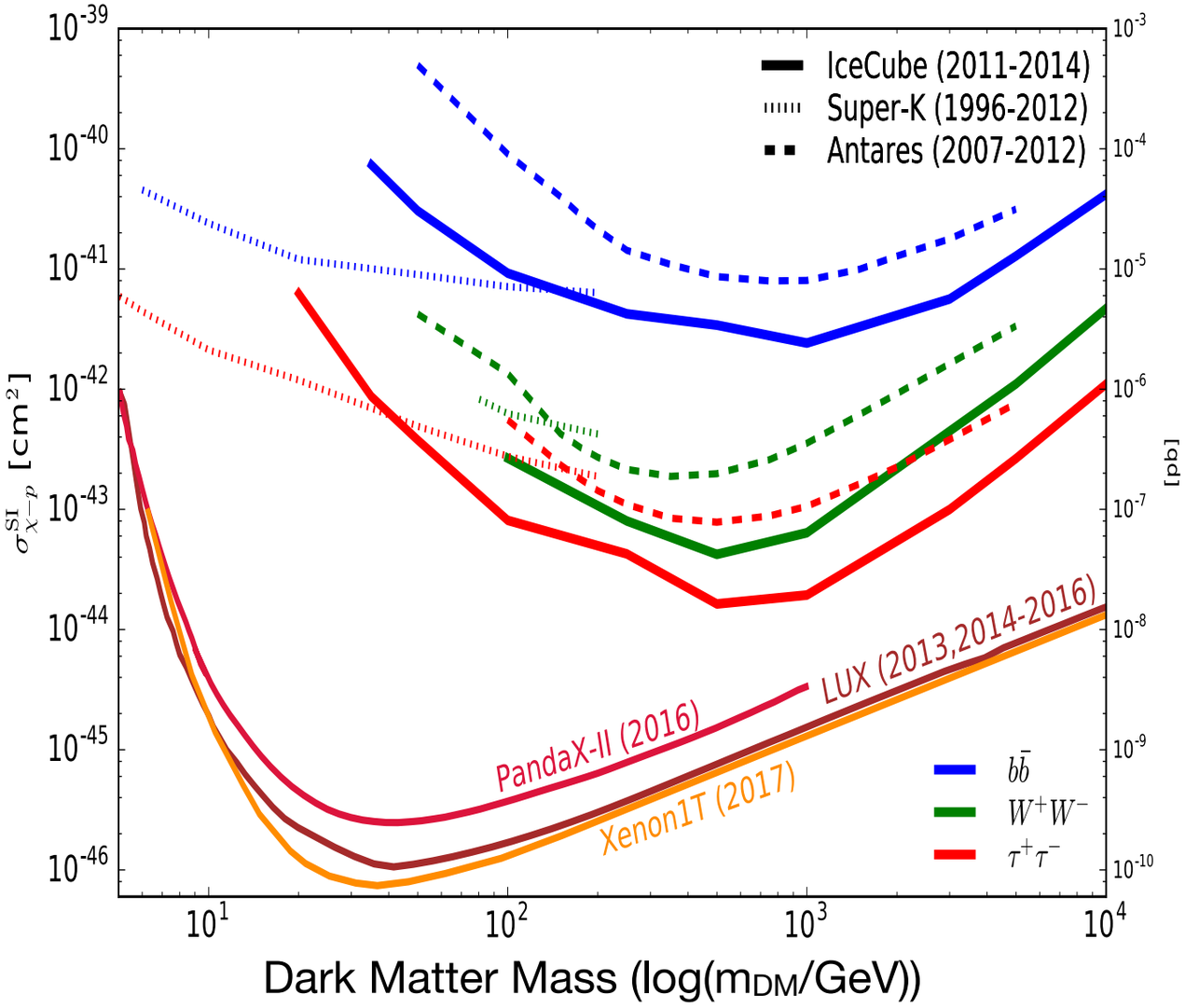




Spin-dependent scattering

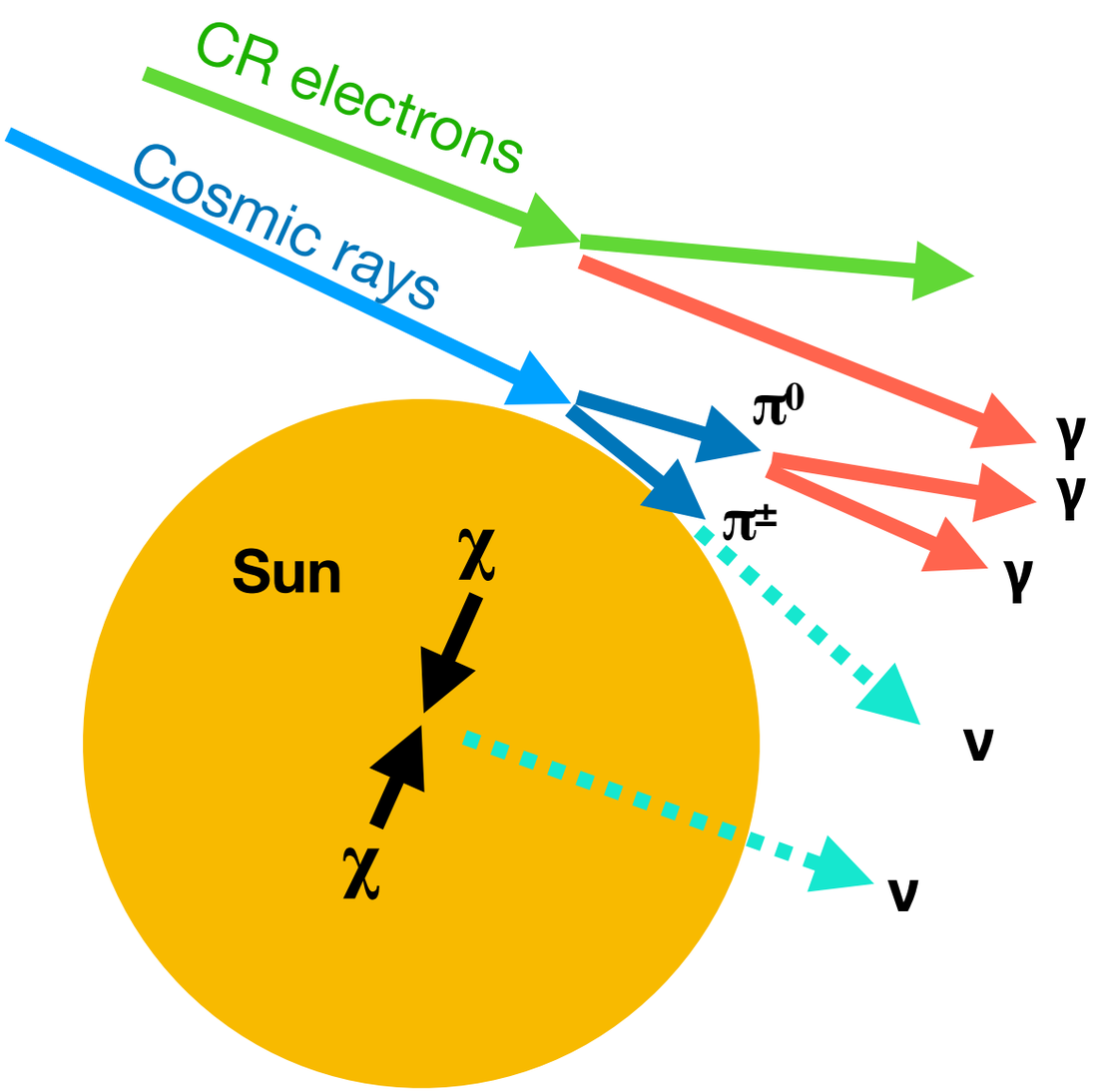


Spin-independent scattering

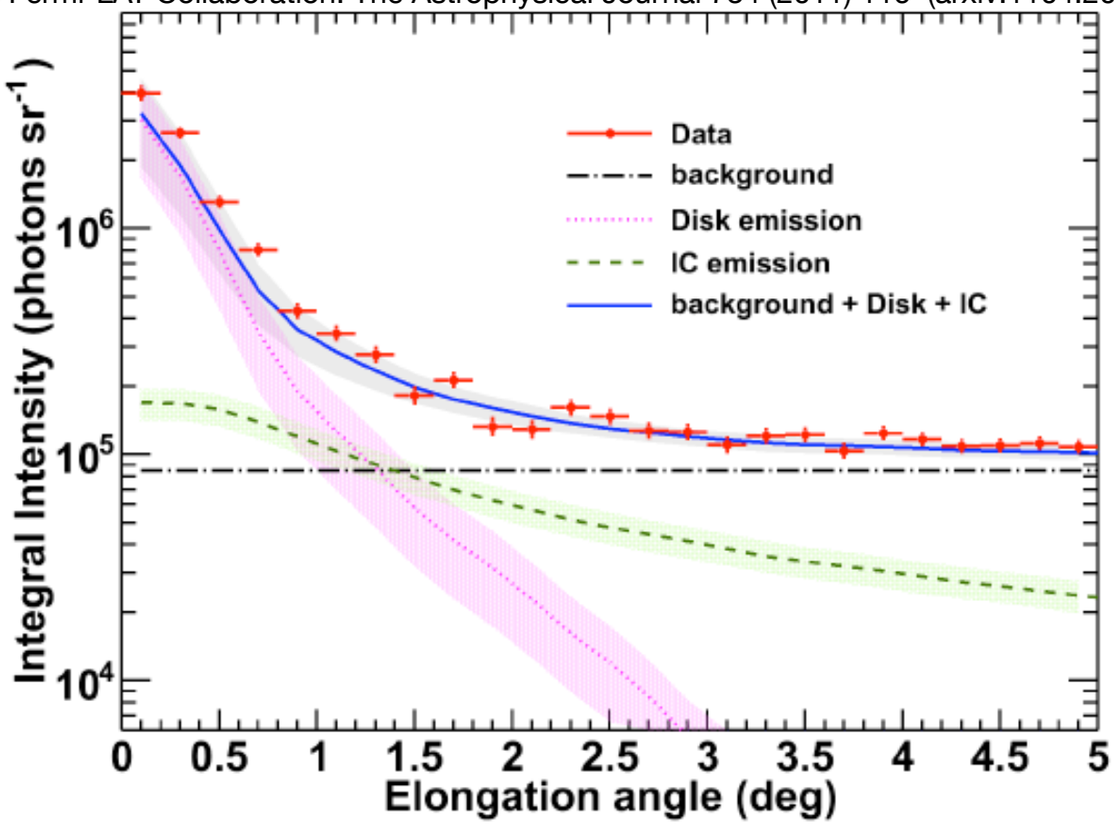


Solar Atmospheric Neutrino Floor

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)

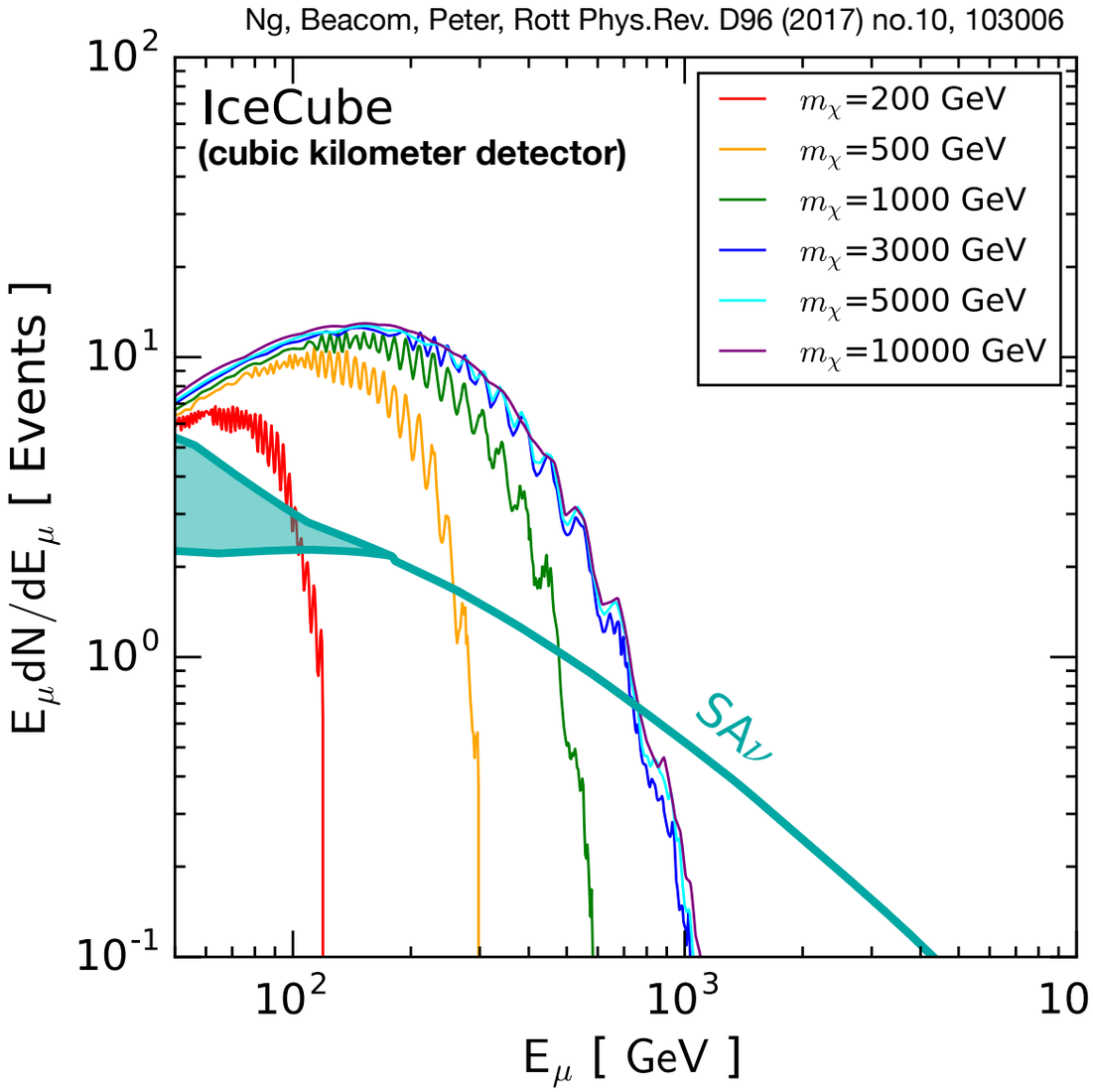
Leptonic

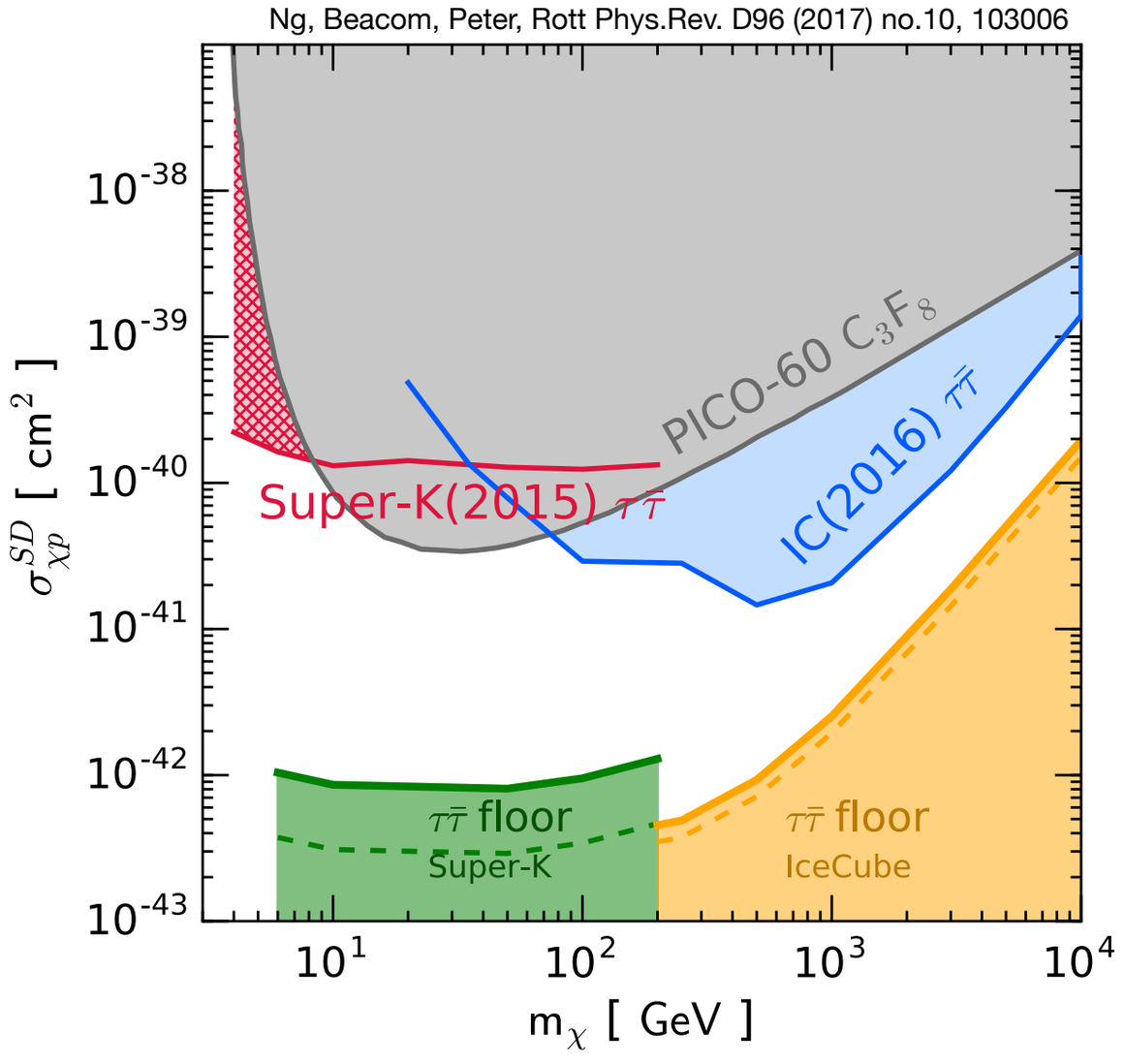
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadronic

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

Cosmic background from the Sun





- Solar Atmospheric give a new background to solar dark matter search
- 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

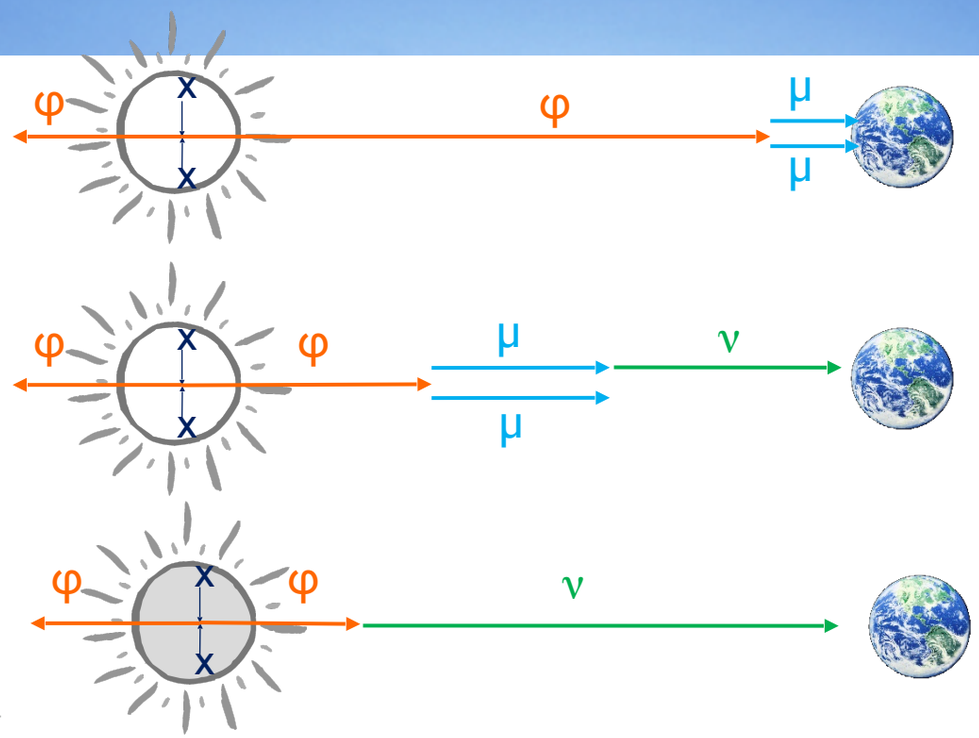
- C. Argüelles, G. de Wasseige, A. Fedynitch, B. Jones **JCAP 1707 (2017) no.07, 024** [arXiv:1703.07798]
- K. Ng, J. Beacom, A. Peter, C. Rott **Phys.Rev. D96 (2017) no. 10, 103006** [arXiv:1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, **JCAP 2017 . 06 (2017), p. 033**, arXiv: 1704.02892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

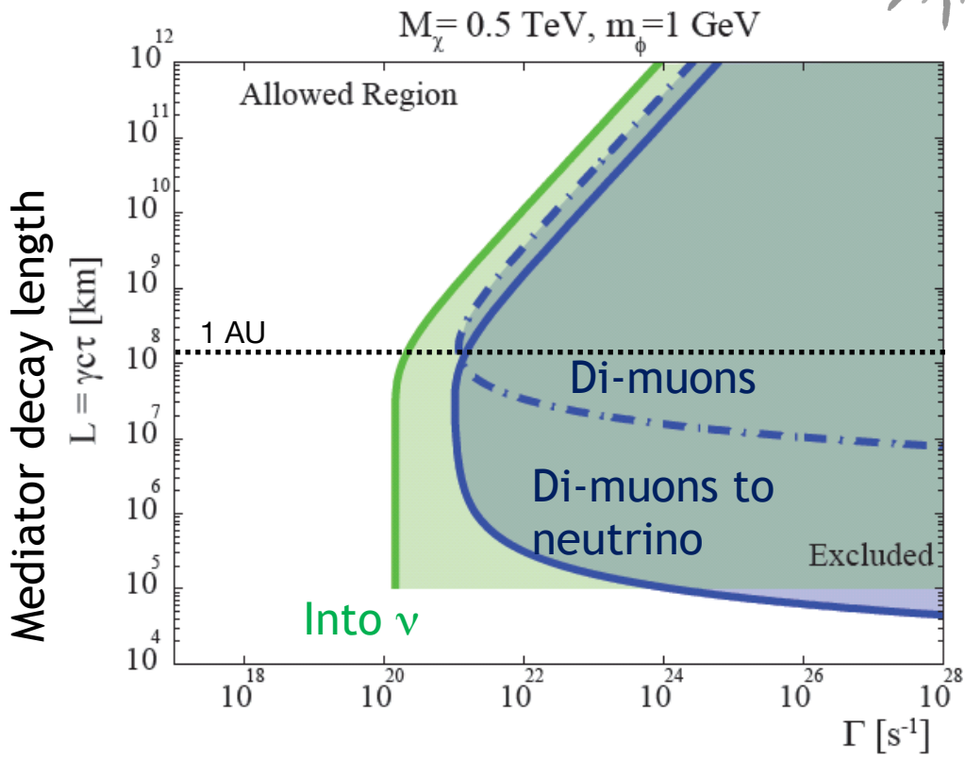
Secluded Dark Matter

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

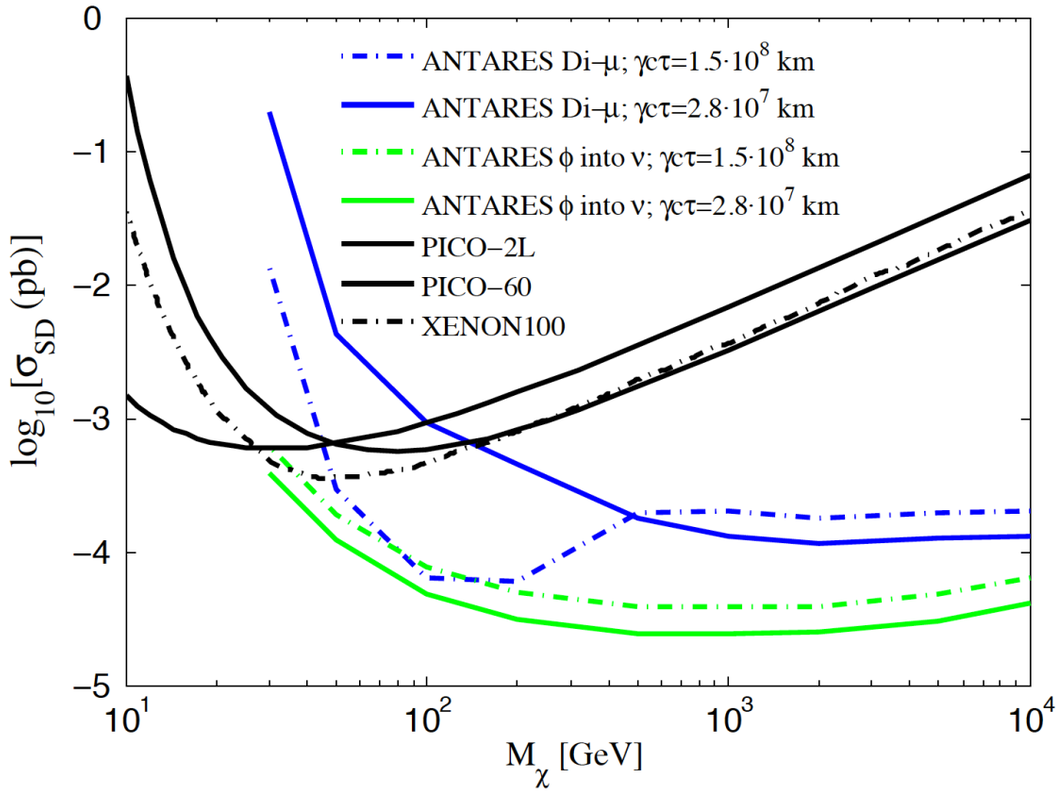
ANTARES Secluded Dark Matter

- 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

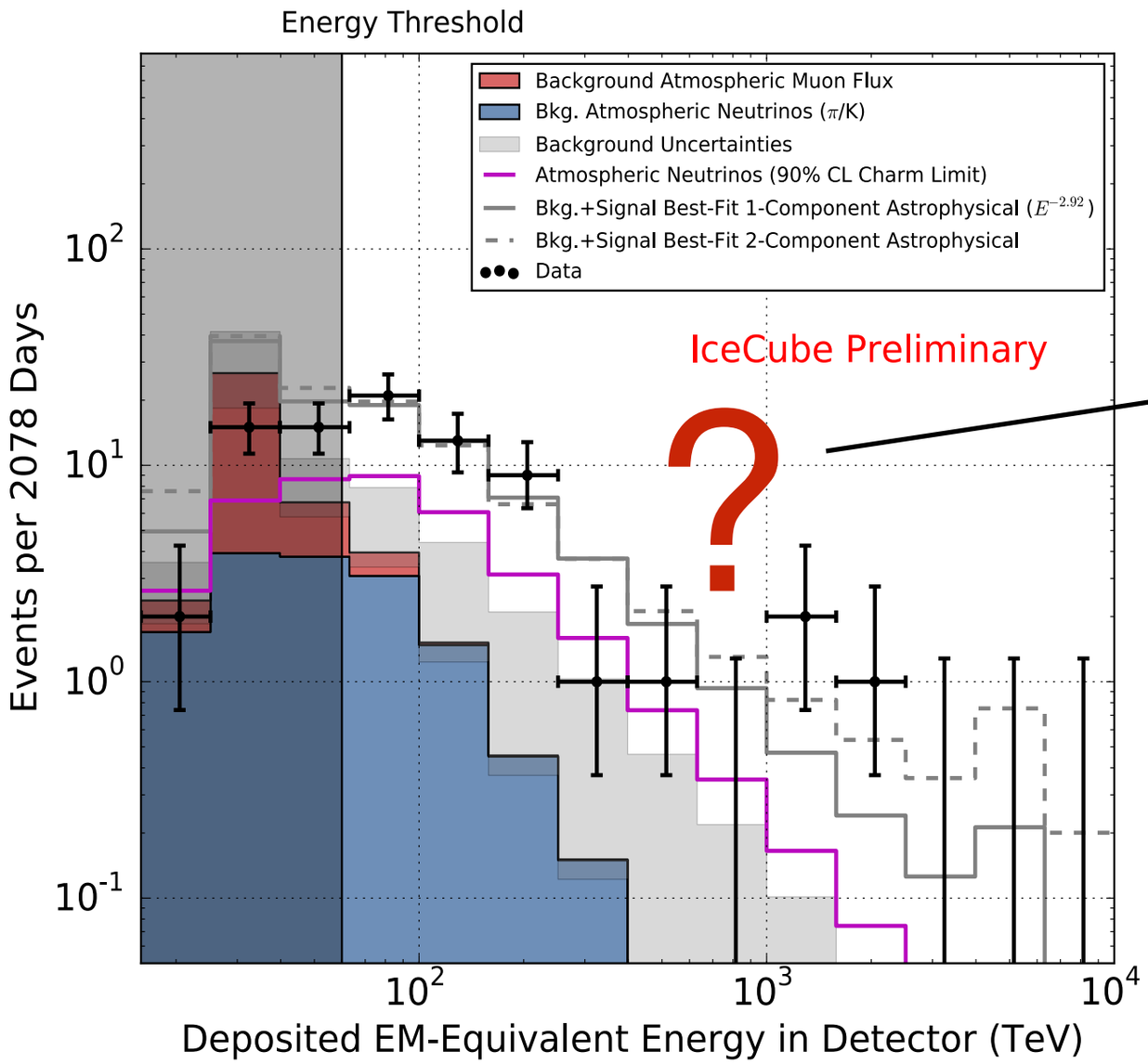


- Contrarily to standard solar WIMP scenarios, secluded dark matter can produce neutrinos > 1TeV
- For most channels, EM signals are expected, cross checks with HAWC, etc. possible

Outlook

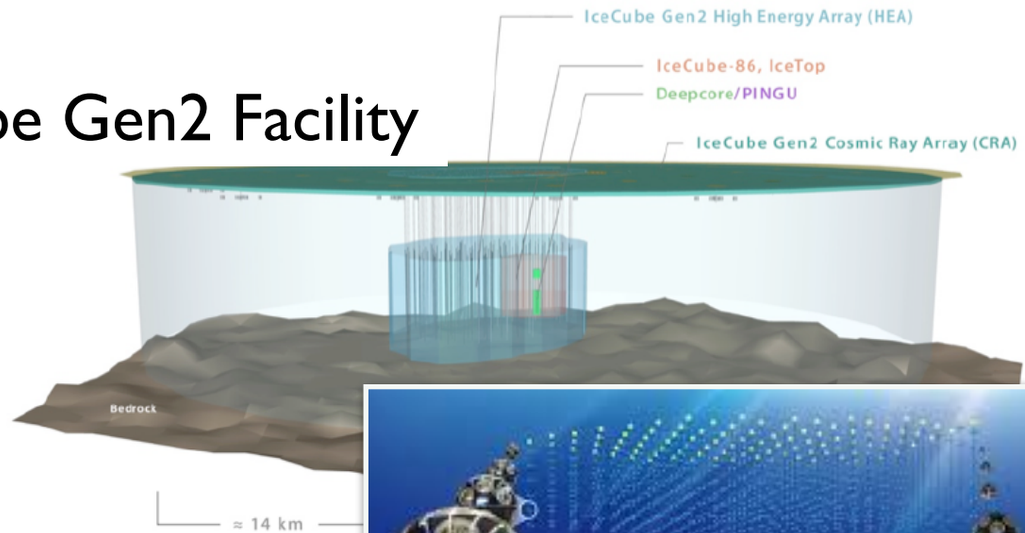
IceCube Coll. Gen2 LOI arXiv:1412.5106
KM3NeT LOI J.Phys. G43 (2016) no.8, 084001

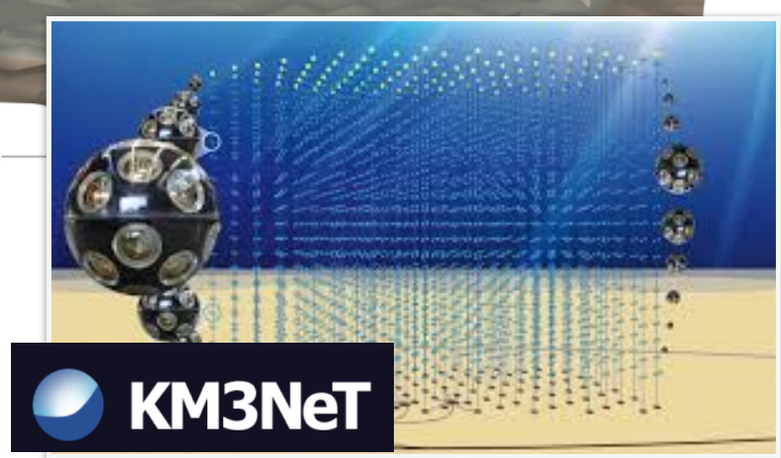
Beyond Standard Model Physics at the PeV scale



- PeV Scale Right Handed Neutrino Dark Matter
- Super Heavy Dark Matter
- Neutrino Portal Dark Matter
- Right-handed neutrino mixing via Higgs portal
- Heavy Right Handed Neutrino Dark Matter
- Leptophilic Dark Matter
- PeV Scale Supersymmetric Neutrino Sector Dark Matter
- Dark matter with two- and many-body decays
- Shadow Dark Matter
- Boosted Dark Matter
- …

IceCube Gen2 Facility





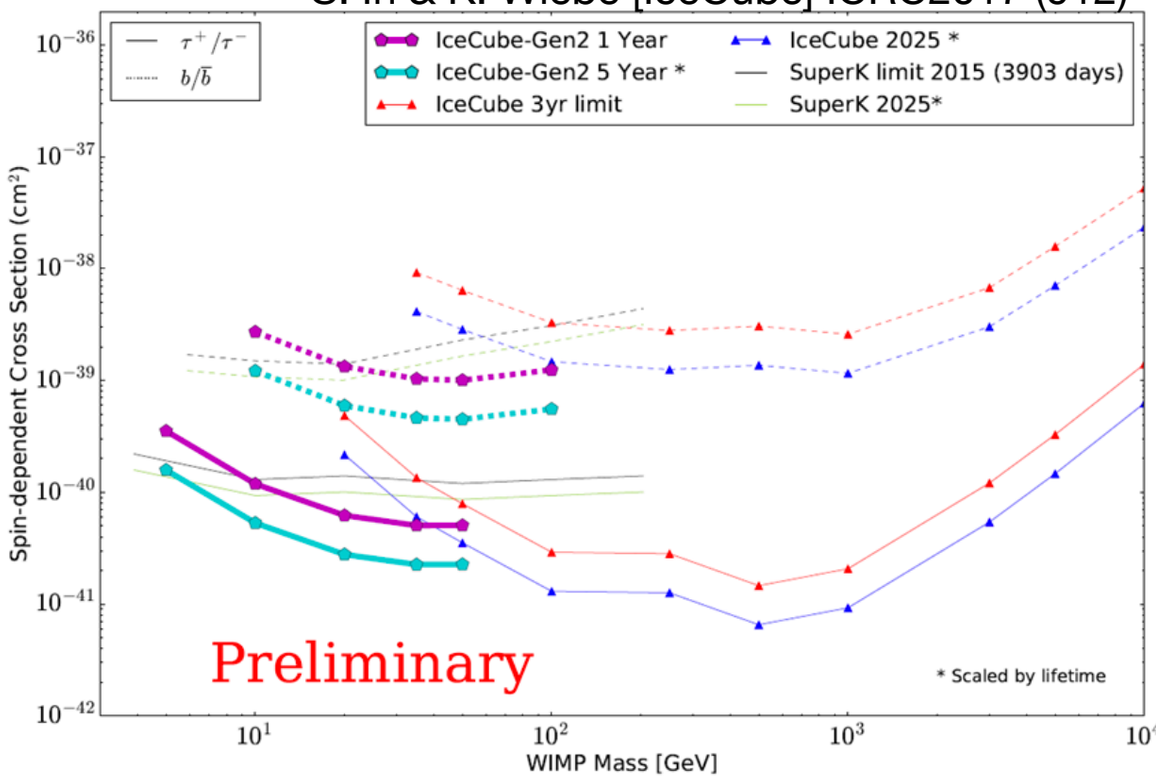
- Intense interest in high-energy neutrino region
  - Observations defy any simple explanation from a single generic source class
    - Multiple sources classes ?
    - Hints of new physics ?

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

Next generation neutrino detectors

IceCube-Gen2 (PINGU fill in)

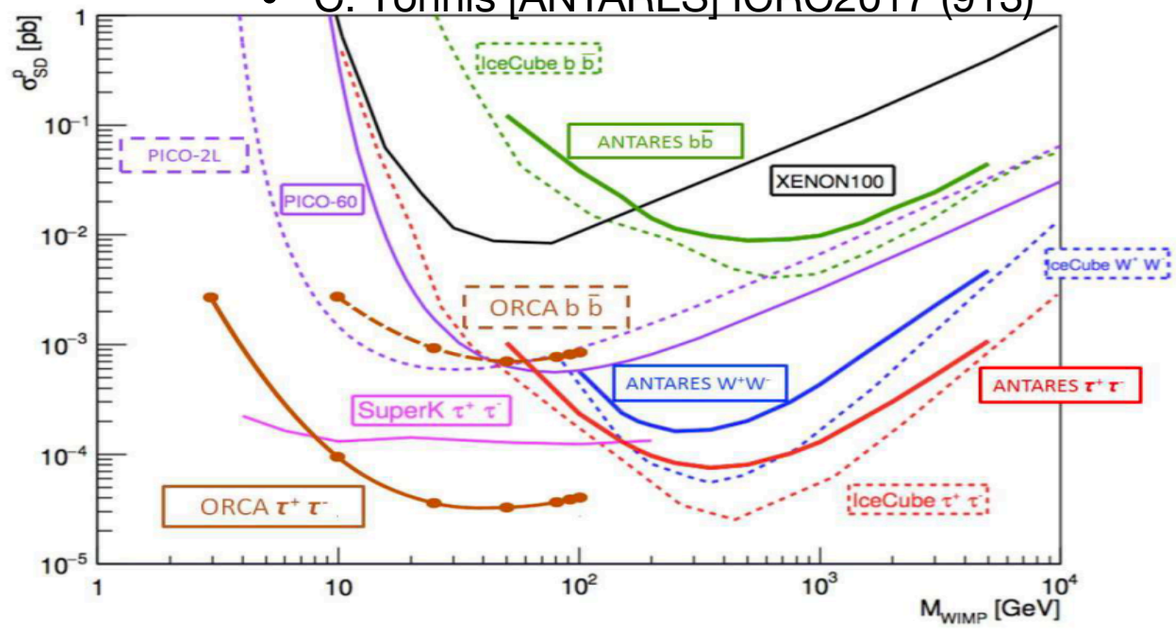
S. In & K. Wiebe [IceCube] ICRC2017 (912)

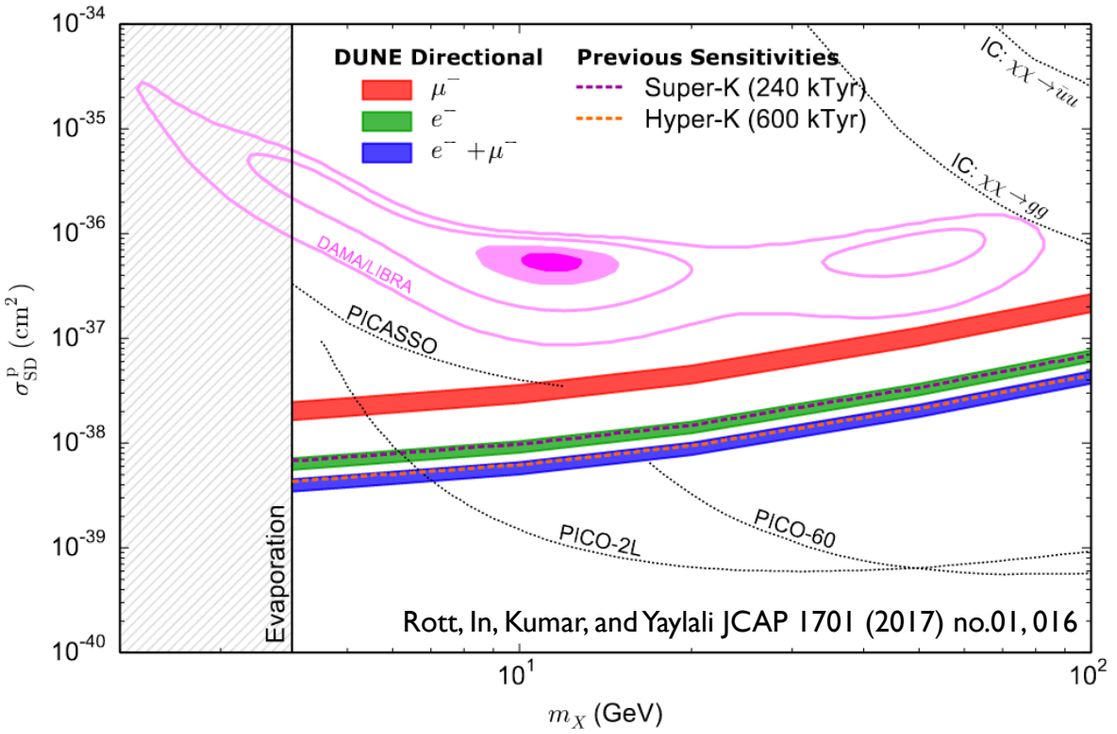


- ORCA and IceCube-Gen2 (PINGU infill) have unique capability to explore DM between 4-50GeV in indirect solar DM searches
  - This will also be an interesting region for Hyper-K / DUNE
- KM3NeT and IceCube-Gen2 extremely competitive for high-mass DM decay

ORCA

- C. Tönnis [ANTARES] ICRC2017 (913)





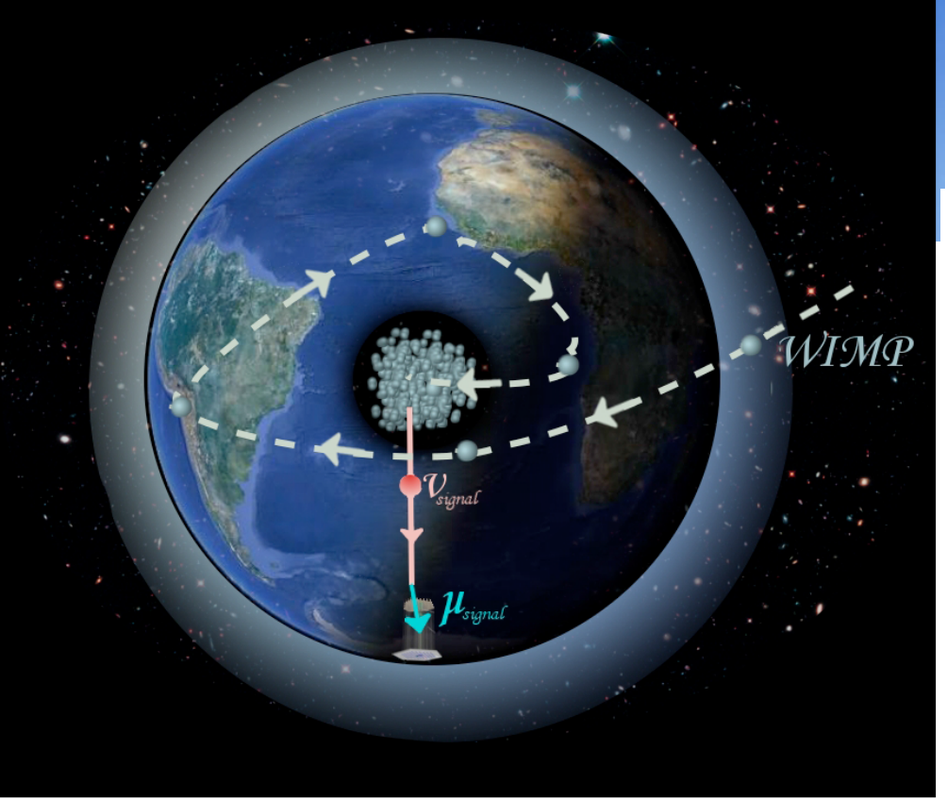
(see also talk on boosted DM sensitivities by Joshua Berger - Friday Feb 23)

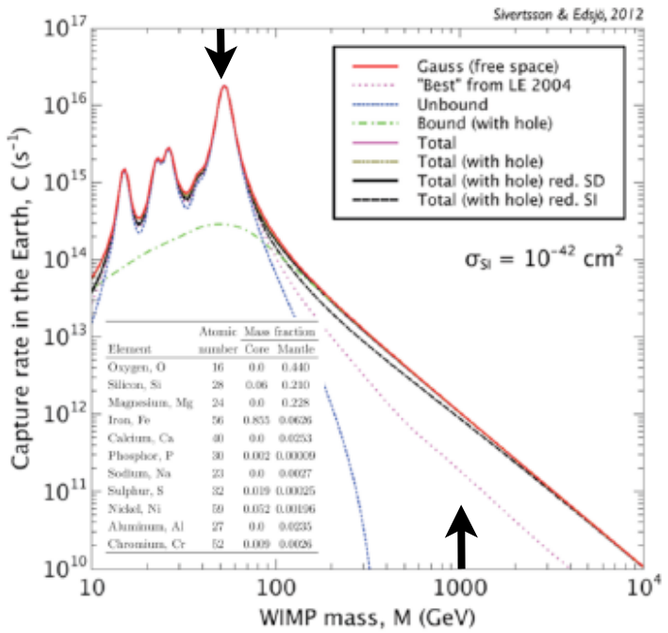
Conclusions

- Striking DM 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 provide world best limits on SD 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

Thanks !

Earth WIMPs

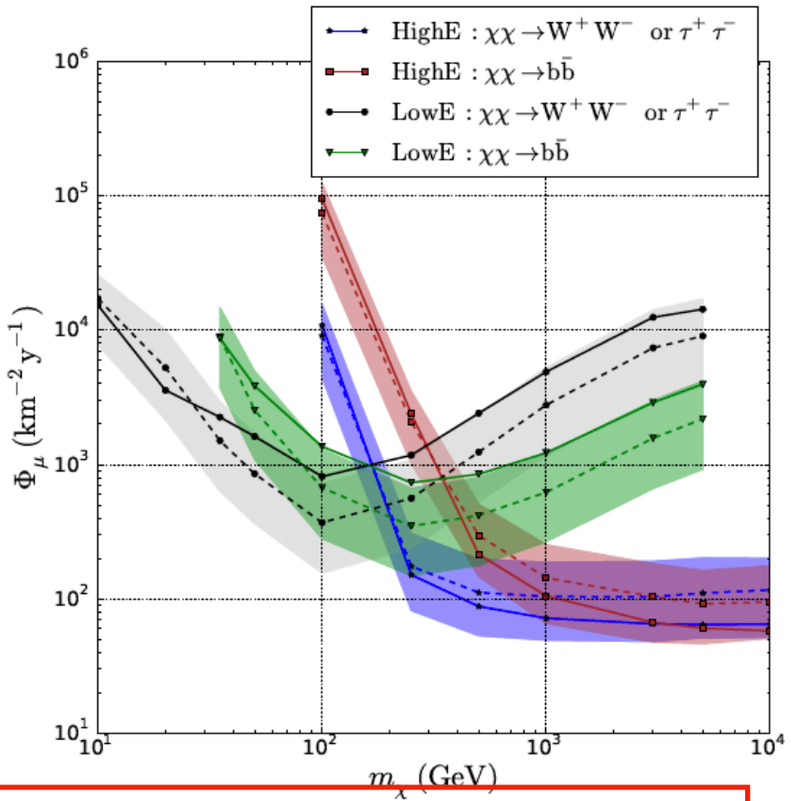




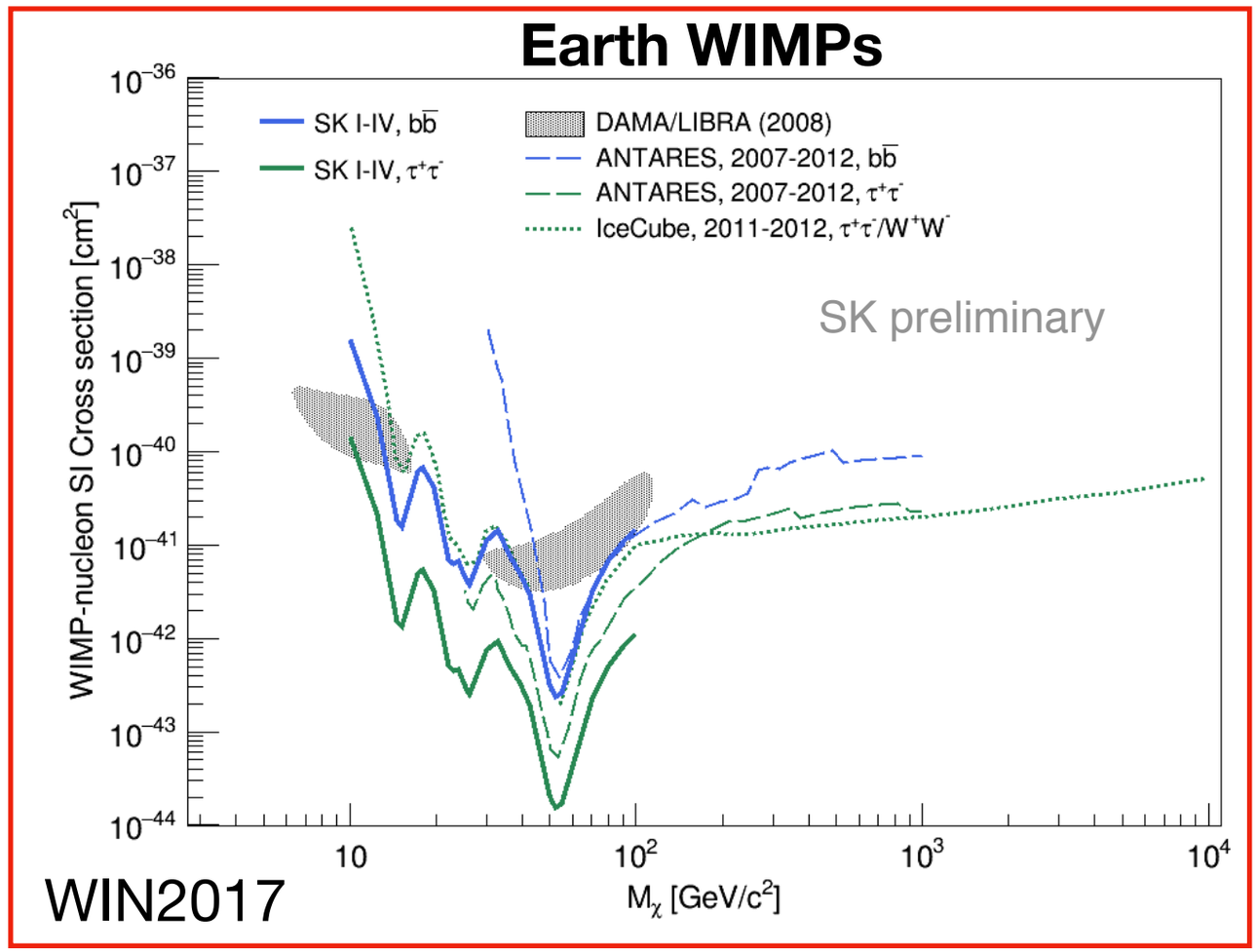
Element	Atomic number	Mass fraction Core	Mass fraction Mantle
Oxygen, O	16	0.0	0.440
Silicon, Si	28	0.06	0.210
Magnesium, Mg	24	0.0	0.228
Iron, Fe	56	0.855	0.0626
Calcium, Ca	40	0.0	0.0253
Phosphor, P	30	0.002	0.00009
Sodium, Na	23	0.0	0.0027
Sulphur, S	32	0.019	0.00025
Nickel, Ni	59	0.052	0.00196
Aluminum, Al	27	0.0	0.0235
Chromium, Cr	52	0.009	0.0026

Dark Matter could be captured in the Earth and produce a vertically up-going excess neutrino flux

Jan Luenemann PoS(ICRC2017)896

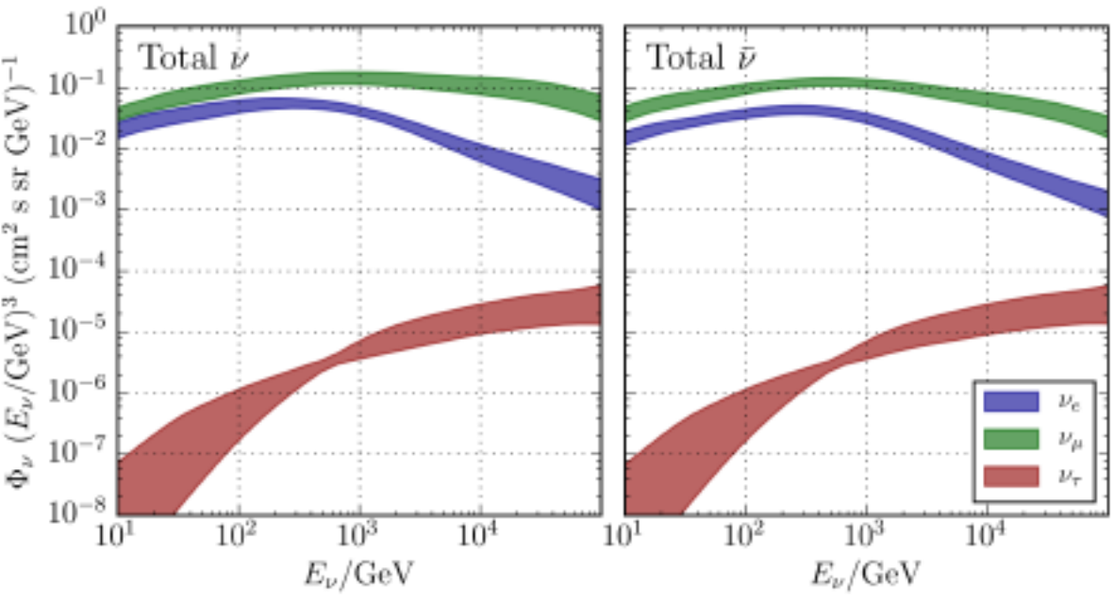


Earth WIMPs
- J. Luenemann ICRC2017 (896)
- C. Tönnis [ANTARES] ICRC2017 (913)



Solar Atmospheric Neutrino Flux

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



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

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

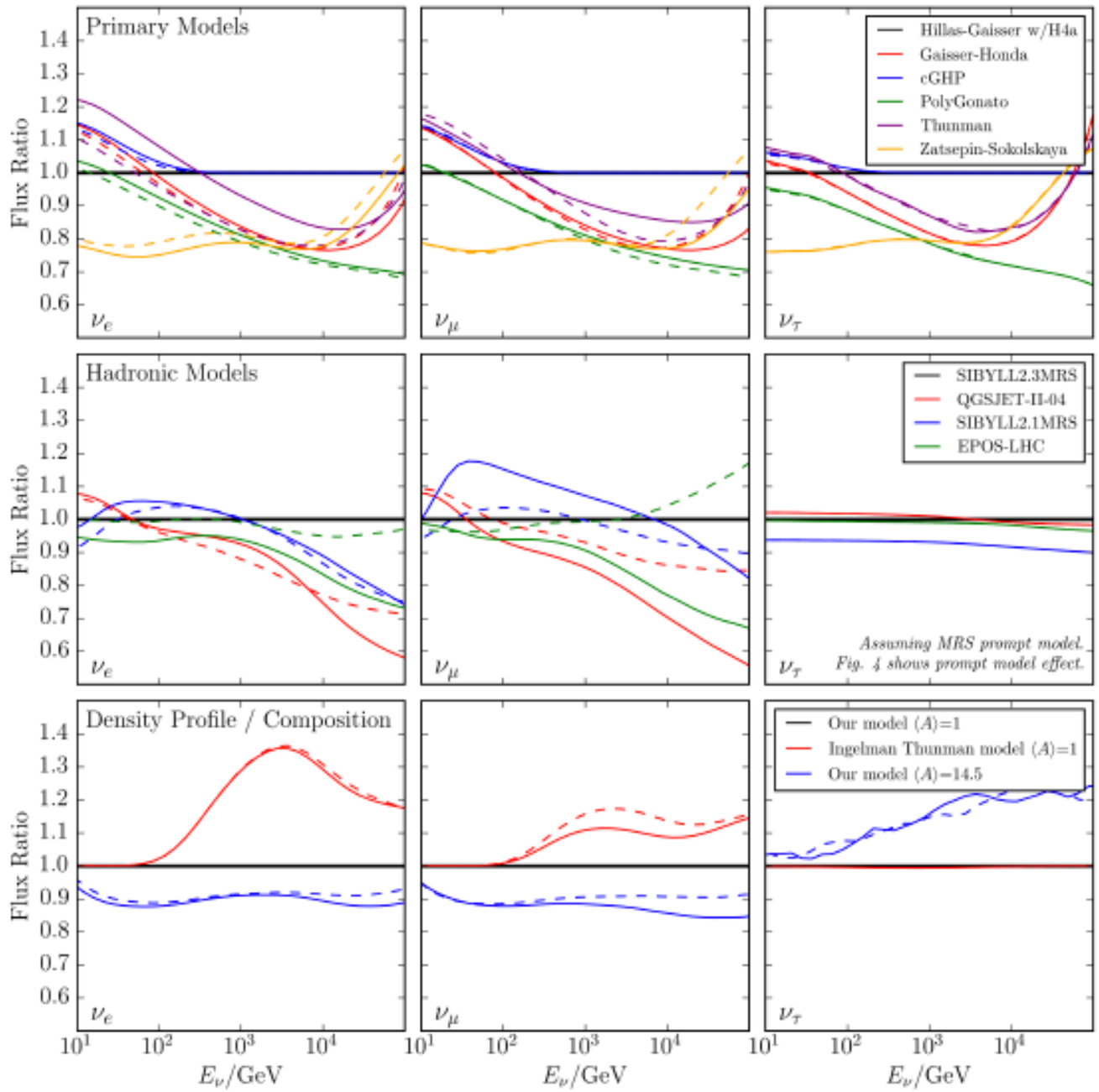


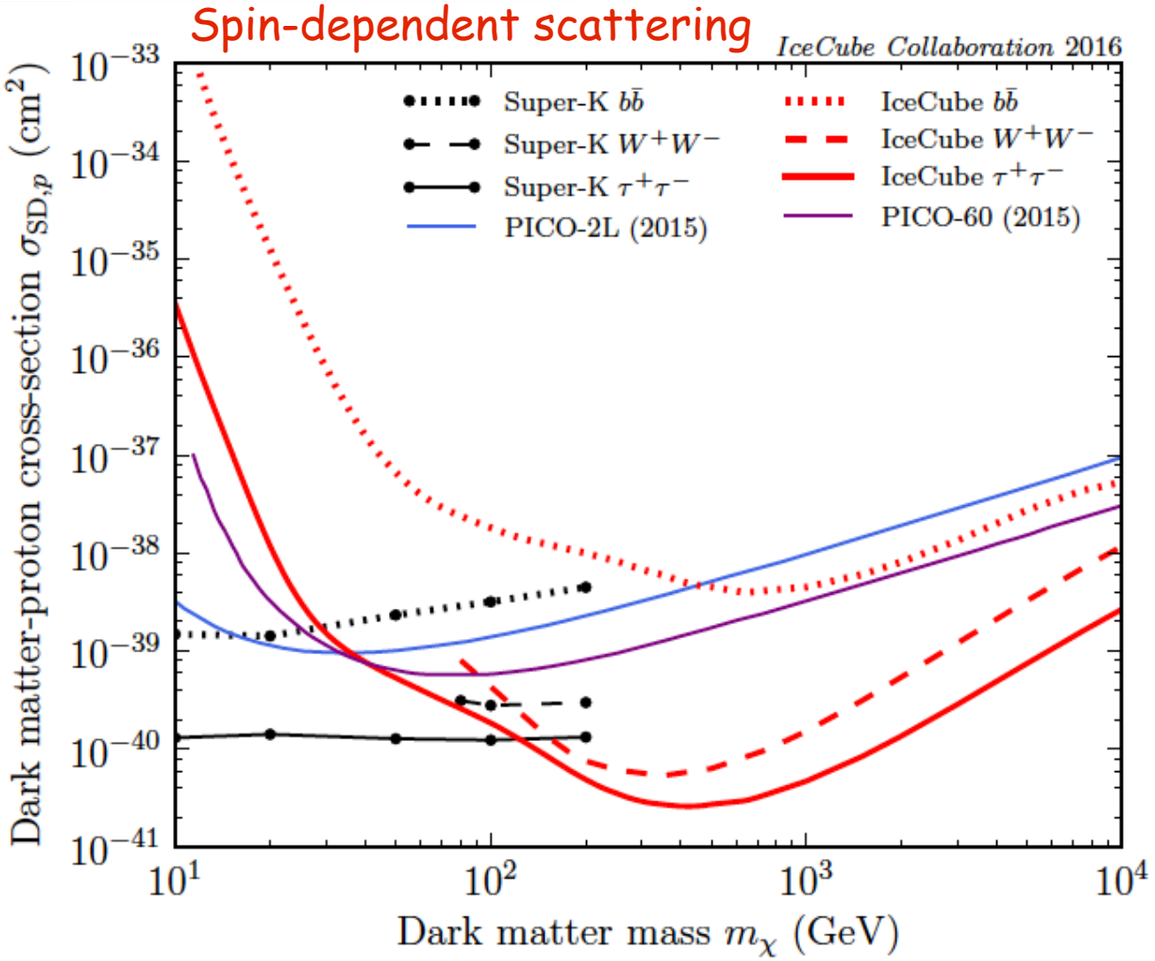
Figure 3. Effects of different models on our flux prediction, for impact parameter b=0. The top row shows various primary models; the second row, hadronic and composition models; the third row, extremal solar density and composition models. See text for more information and references.

http://nulike.hepforge.org./

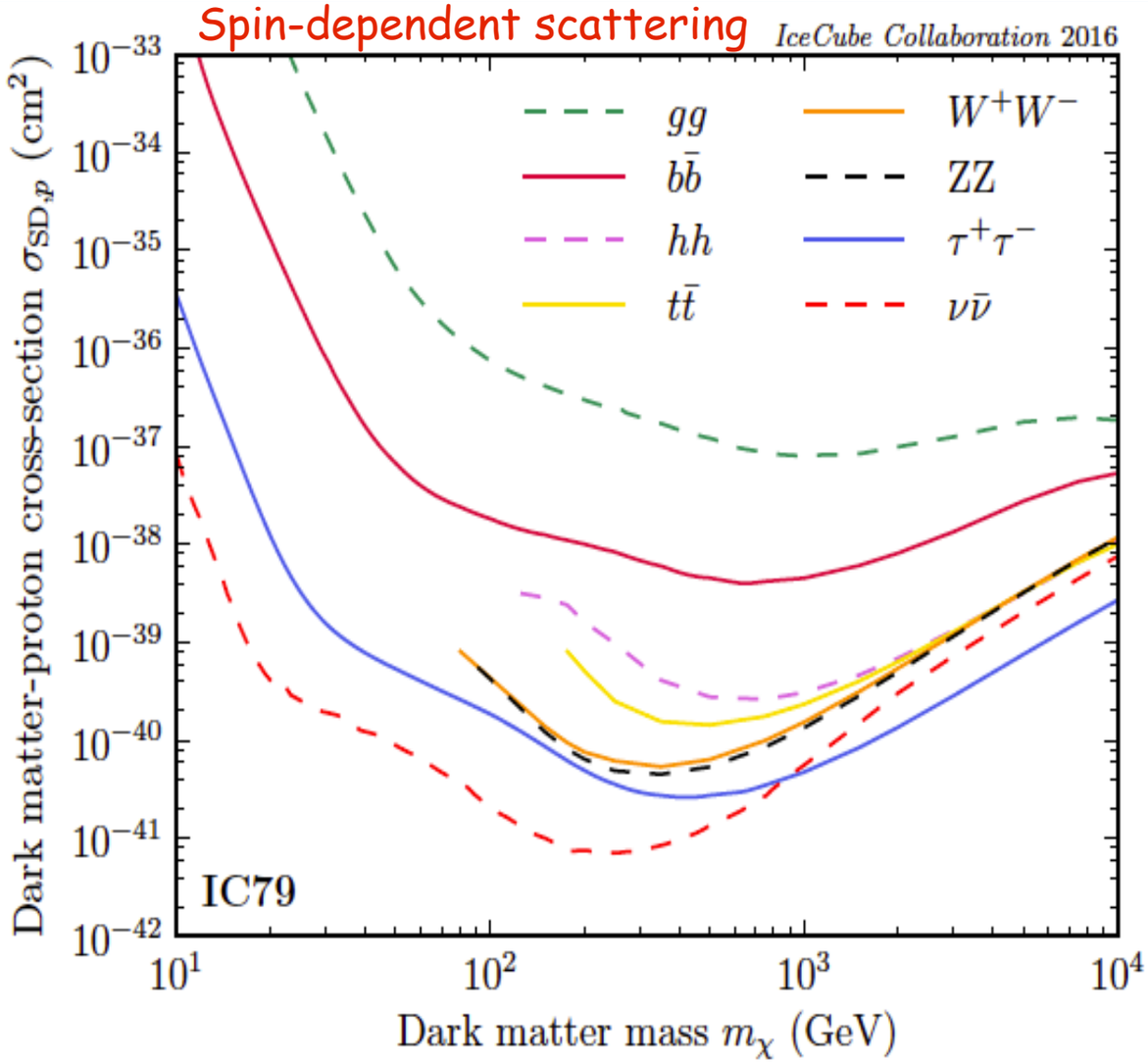
Availability of IceCube data

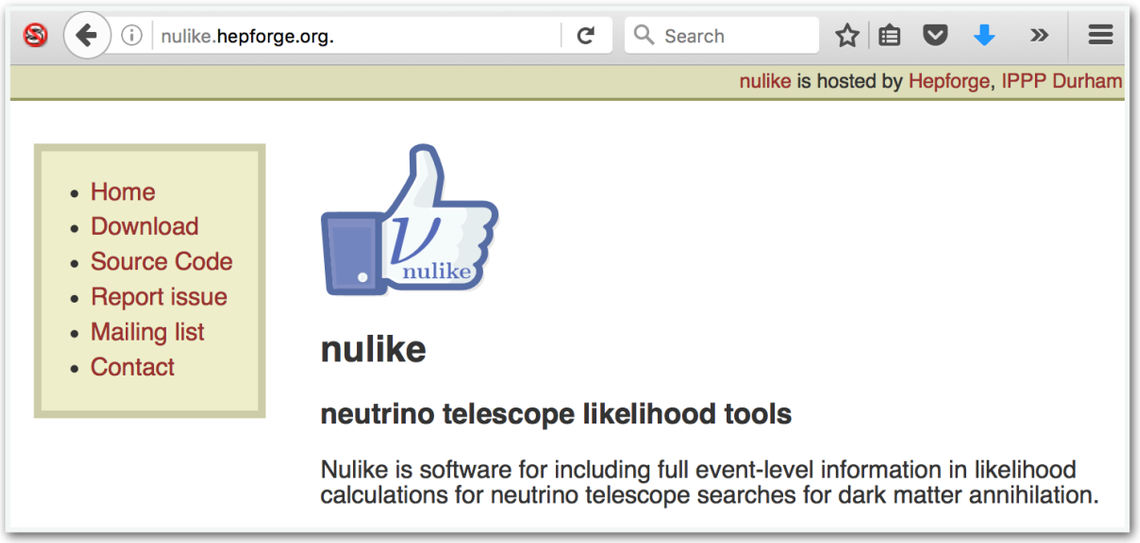
JCAP 04 (2016) 022 / http://arxiv.org/pdf/1601.00653.pdf

Spin-dependent scattering



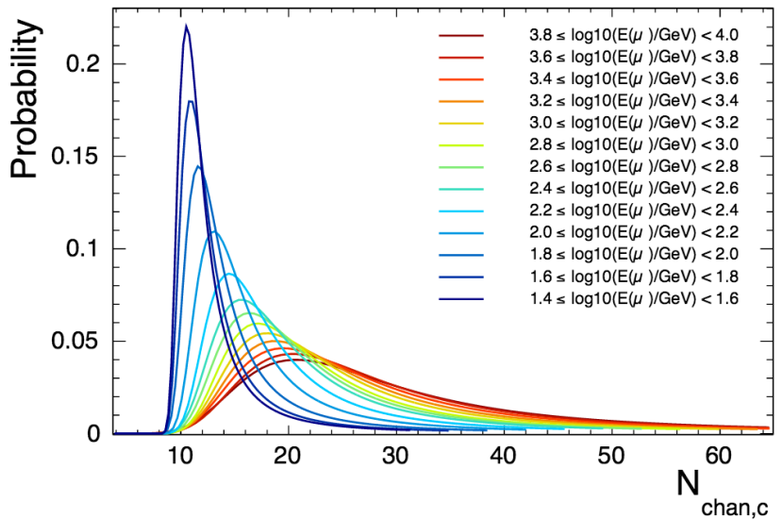
Spin-dependent scattering





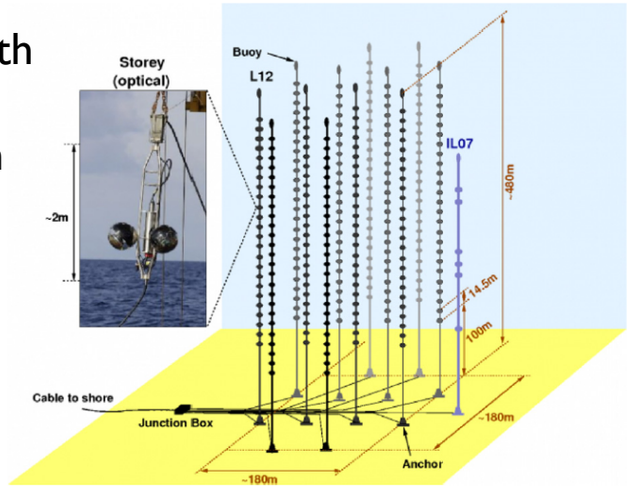
software to test your own model (cross section/ branching ratios)
• IceCube data released

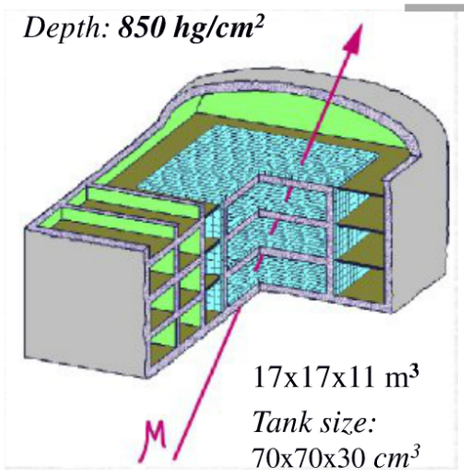
- Likelihood includes:
  - energy and directional information



Neutrino Telescopes / Detectors

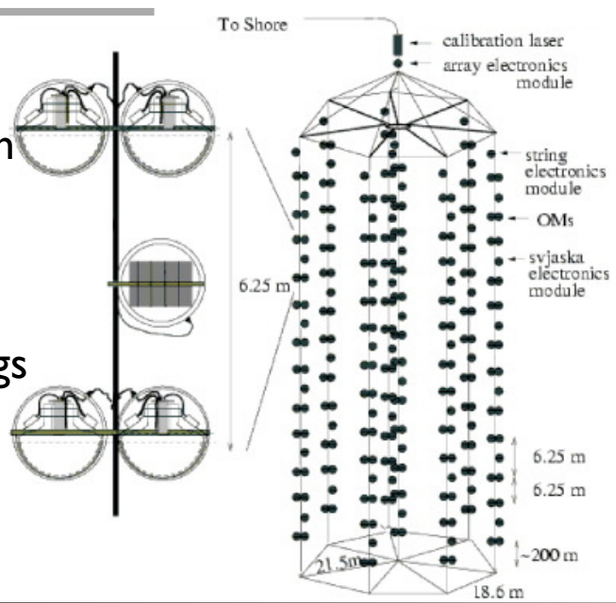
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10"PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008



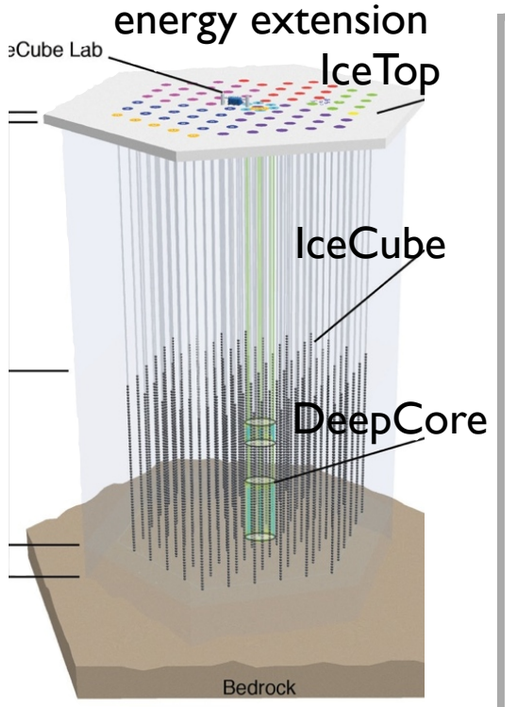


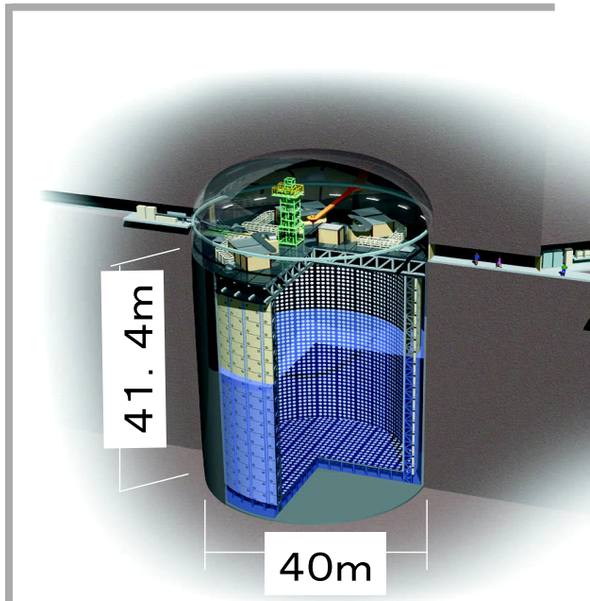
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using 3,150 liquid scintillation counters
- Operating since Dec 1978 ; More than 34 years of continuous operation

- Lake **Baikal**, Siberia, at a depth 1.1 km NT36 in 1993
- NT200 (since Apr 1998) consists of one central and seven peripheral strings of 70m length



- **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



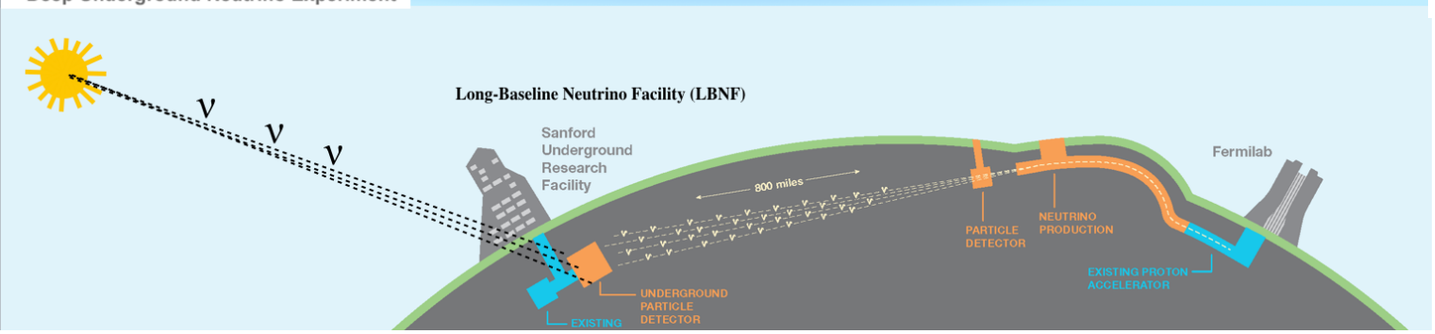


- **Super-Kamiokande** at Kamioka uses 11K 20" PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

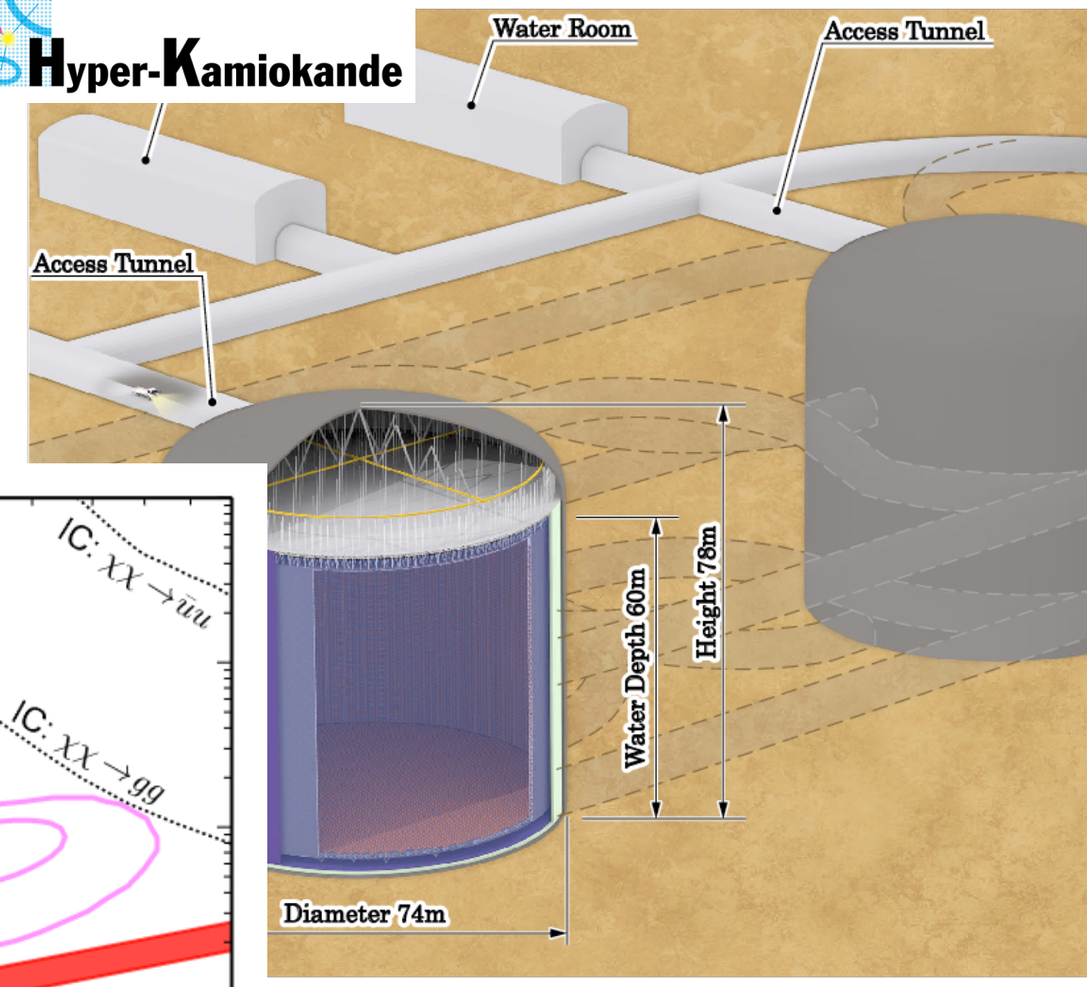
Sensitivity

DUNE
Deep Underground Neutrino Experiment

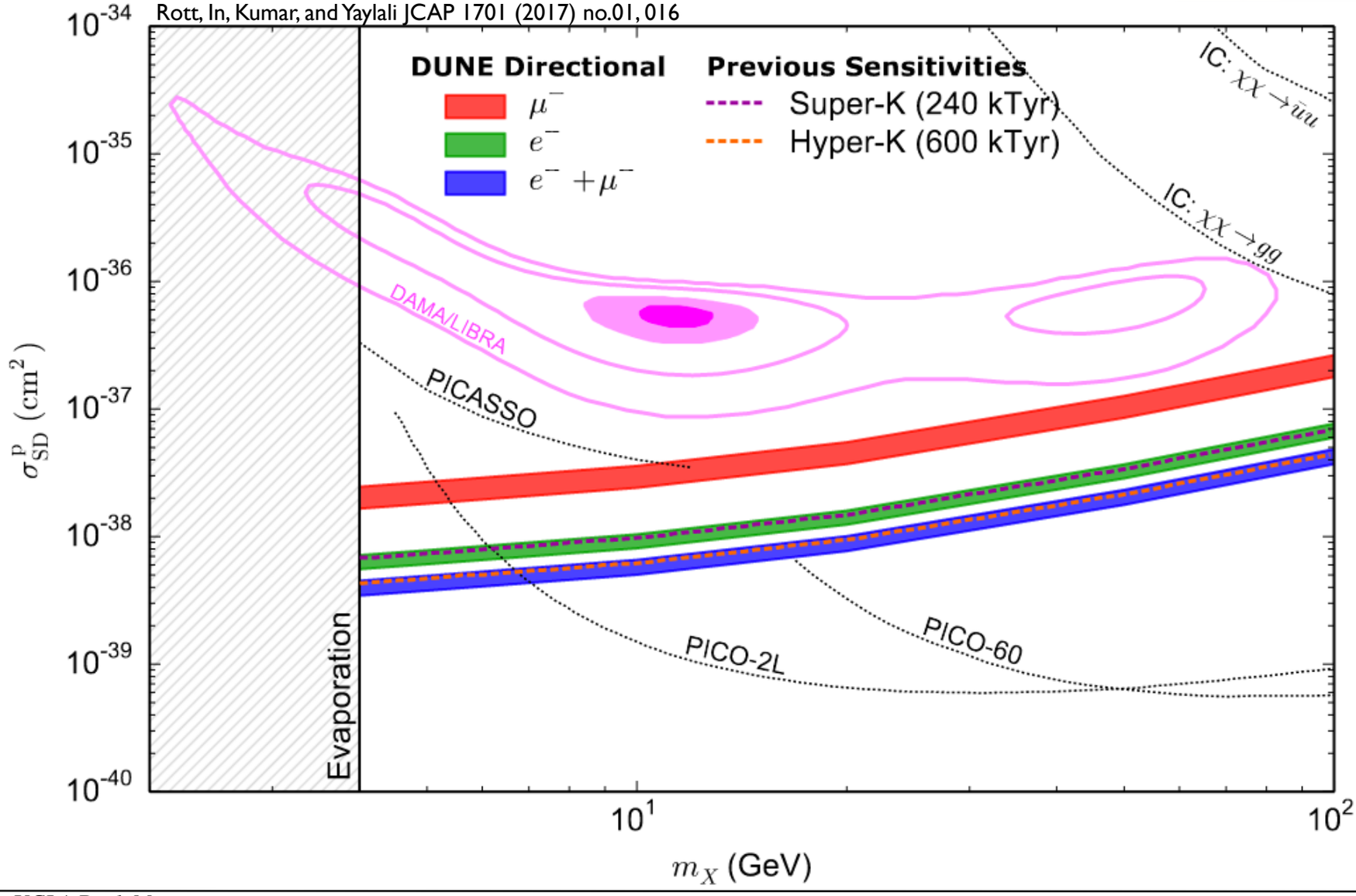
http://www.dunescience.org/

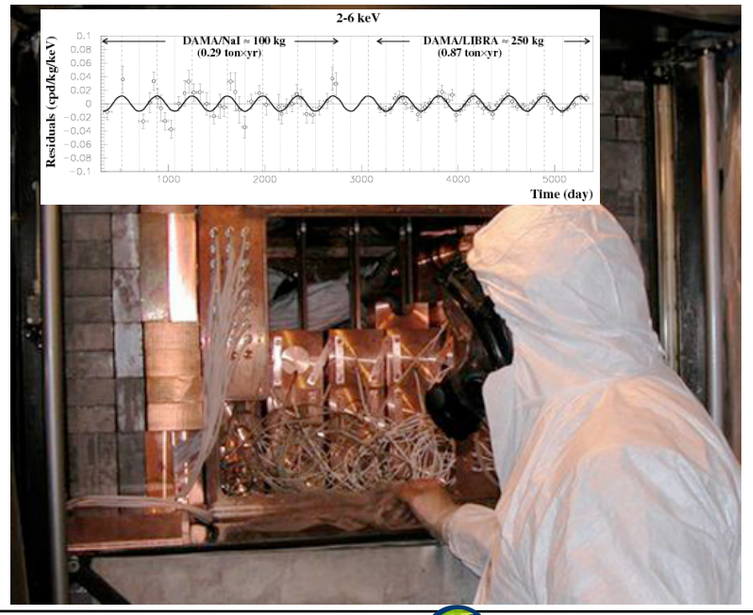


Hyper-Kamiokande



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





Low-Energy Neutrinos from the Sun

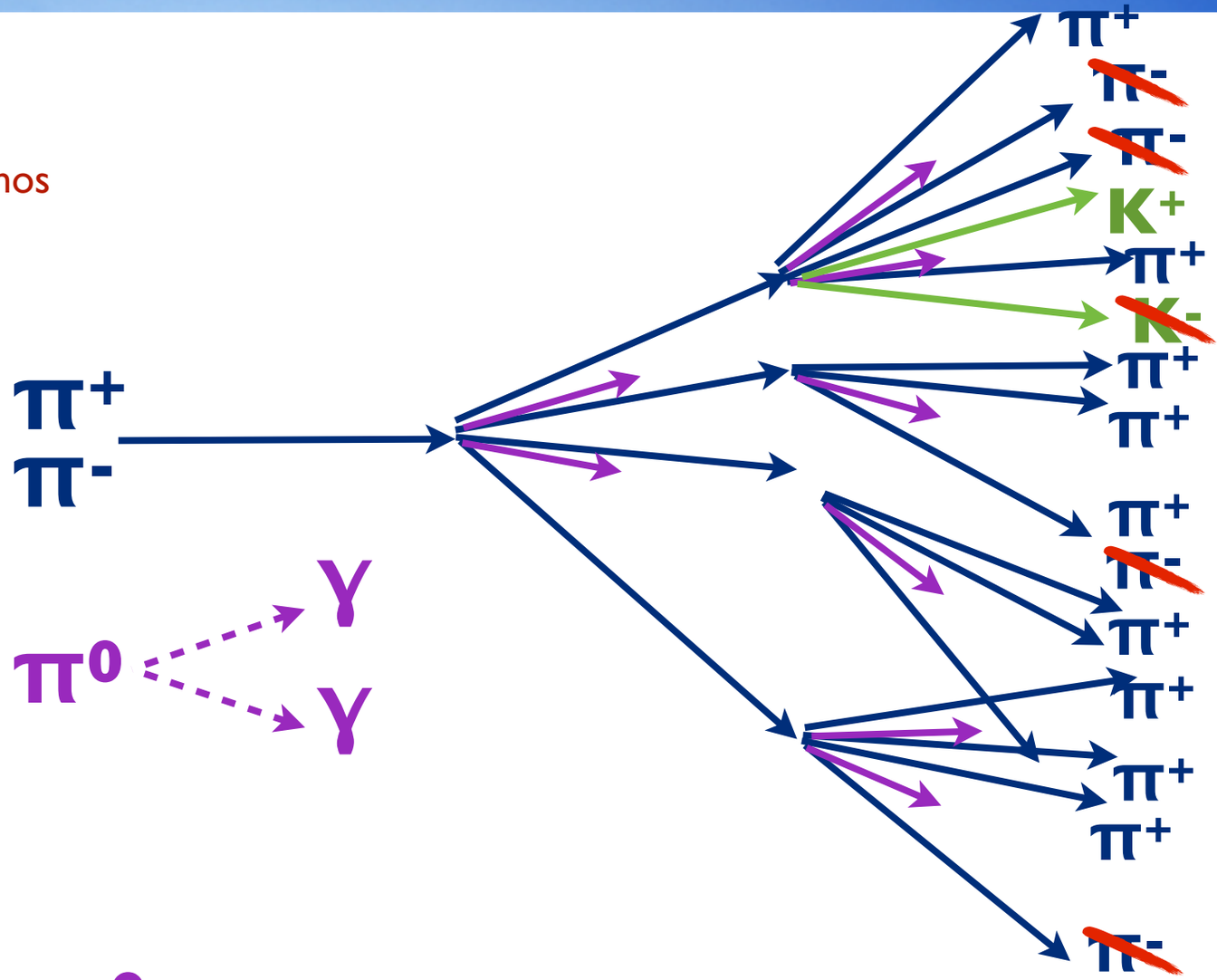
Possible annihilation channels:

qq,gg,cc,ss,bb,tt,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

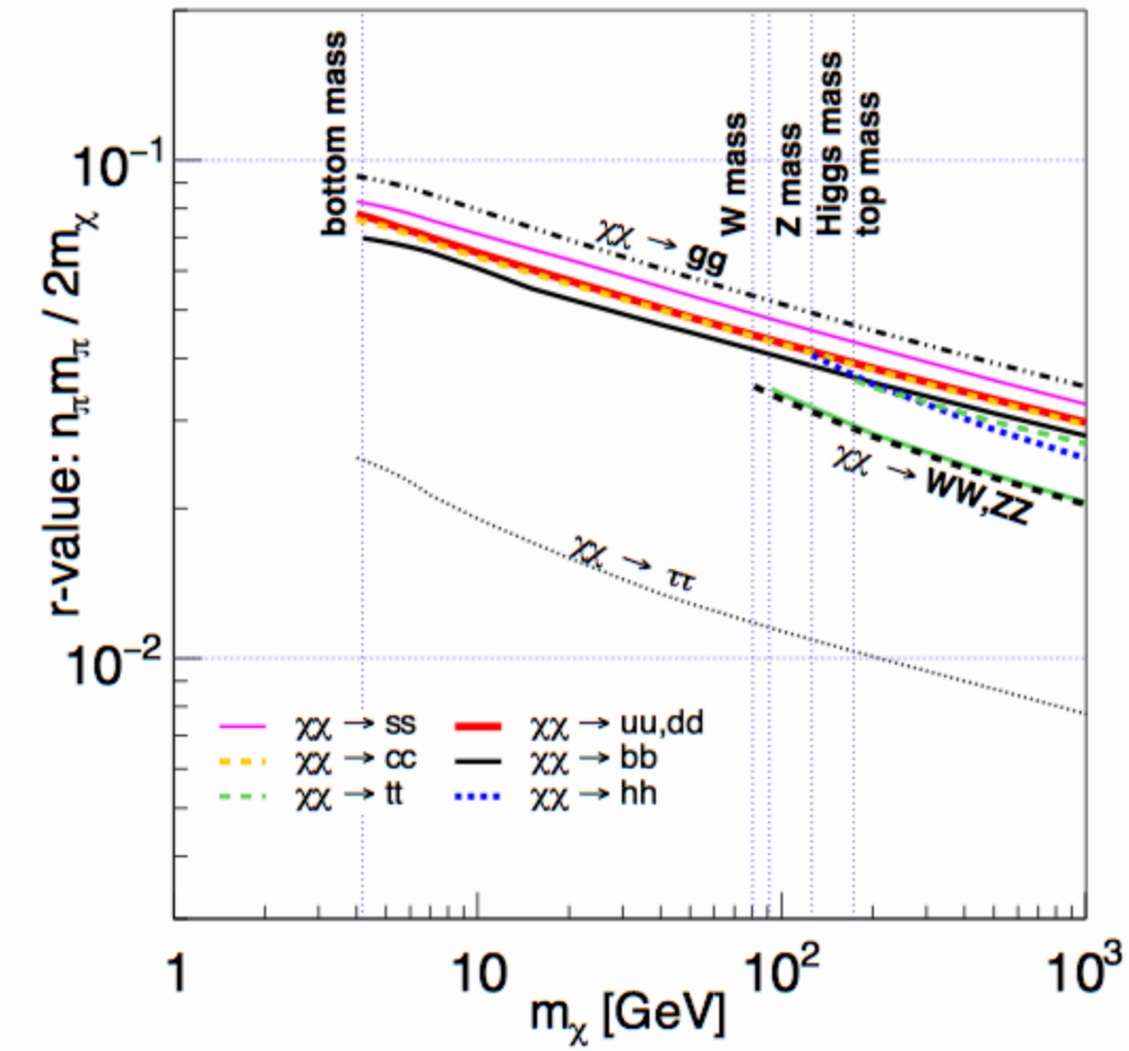
π^-

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

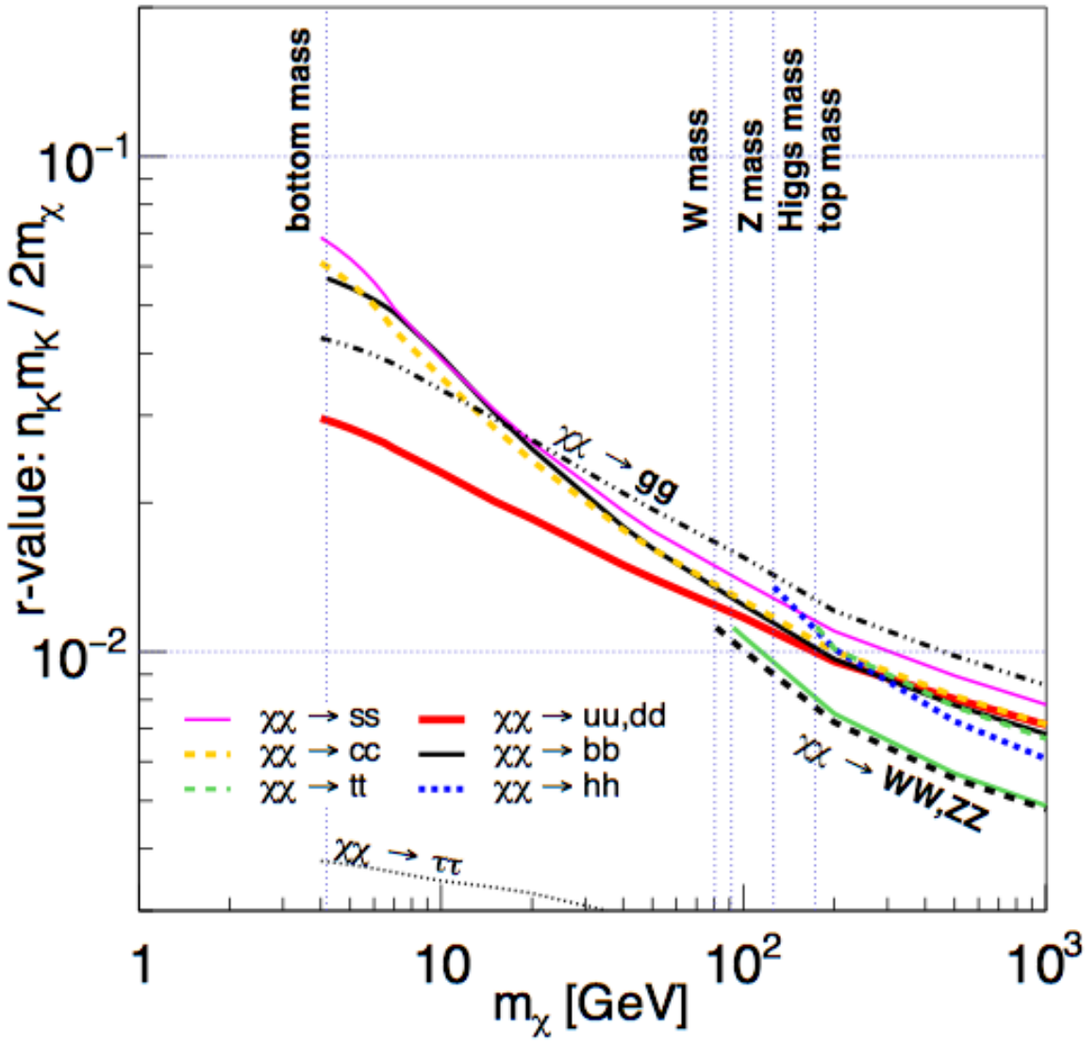
C.Rott, S.In, J.Kumar, D.Yaylali JCAP11(2015)039

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^+

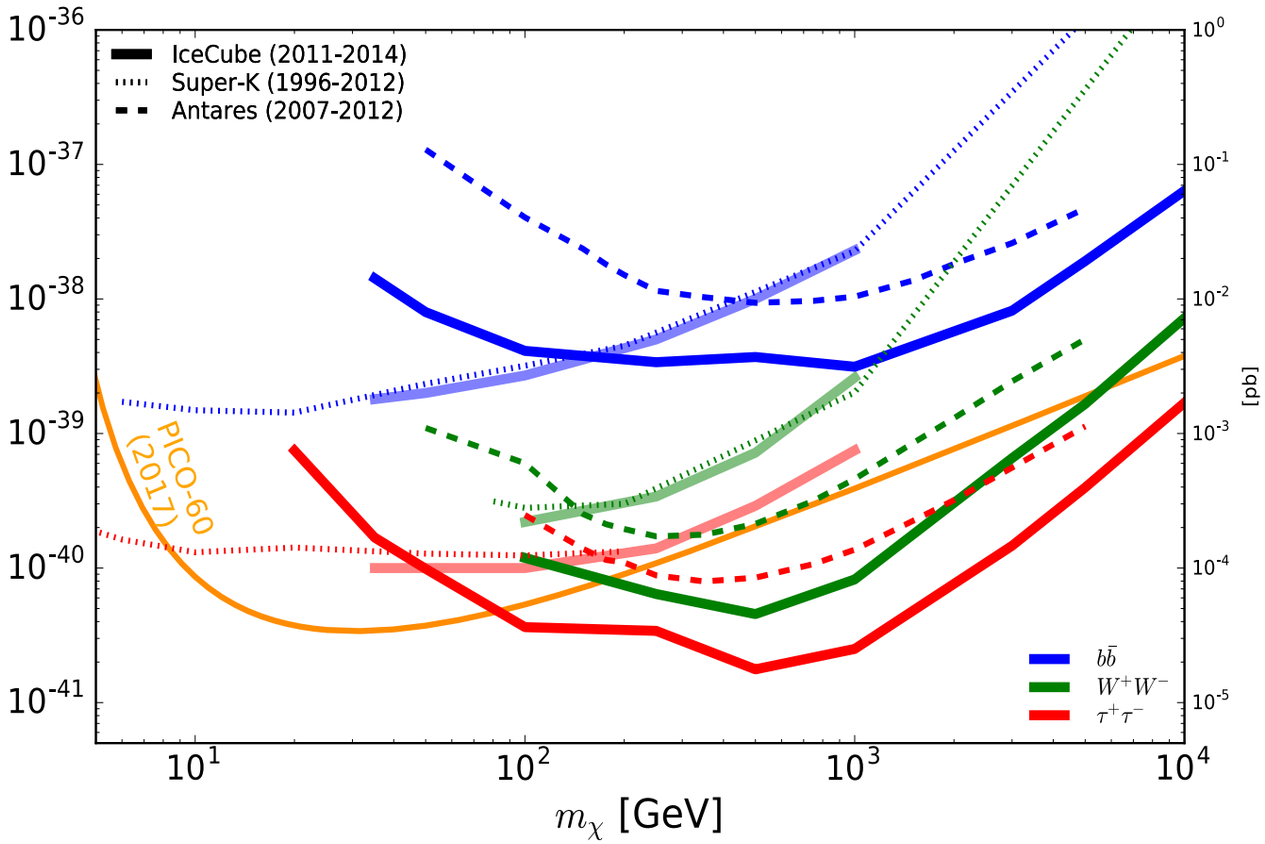


For low dark matter masses difference between flux from stopped pion and kaon decay at rest can be used to disentangle annihilation final states

Solar Dark Matter - IceCube/ANTARES

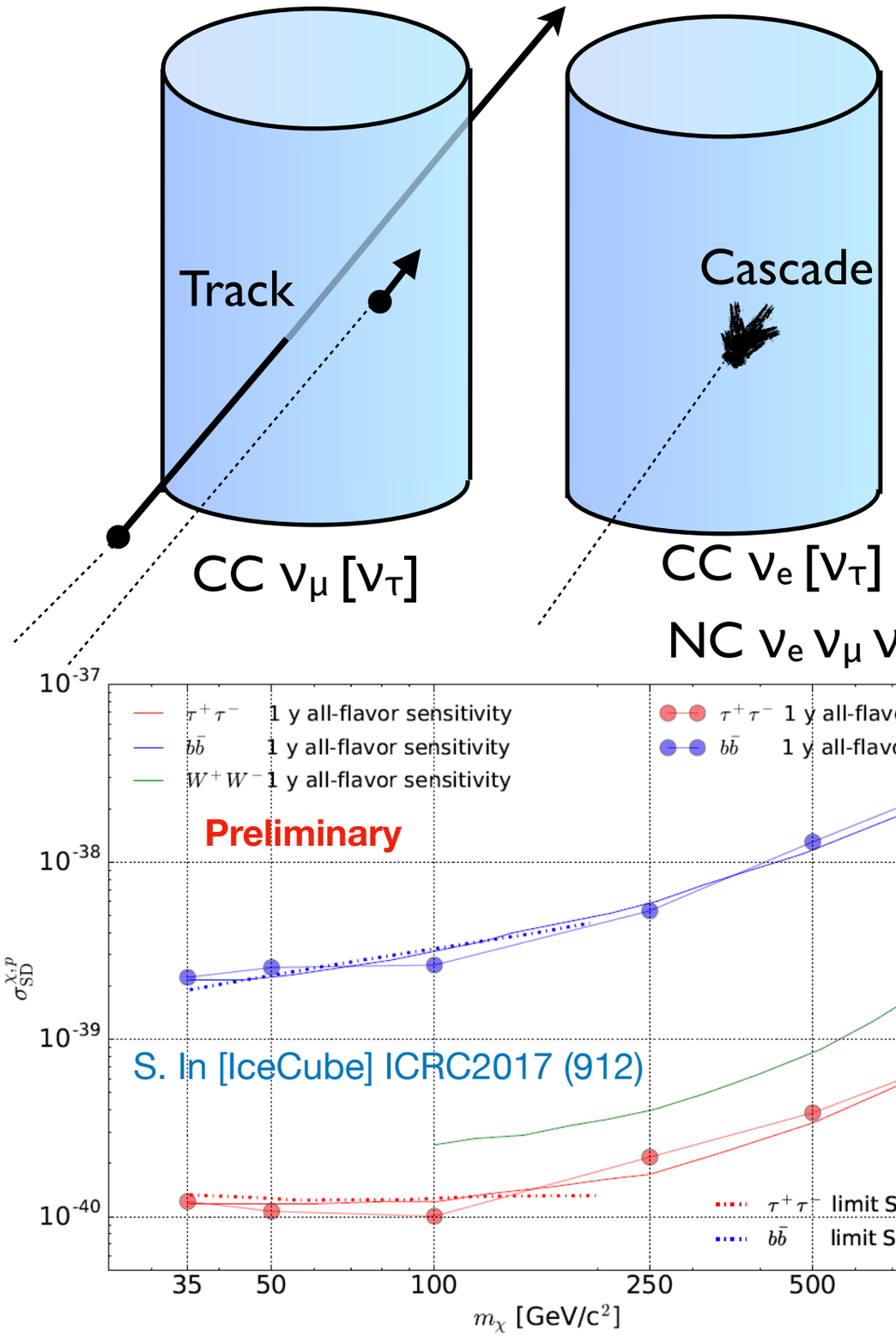
- Convert neutrino flux limit into limit on WIMP-nucleon scattering cross section

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



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)

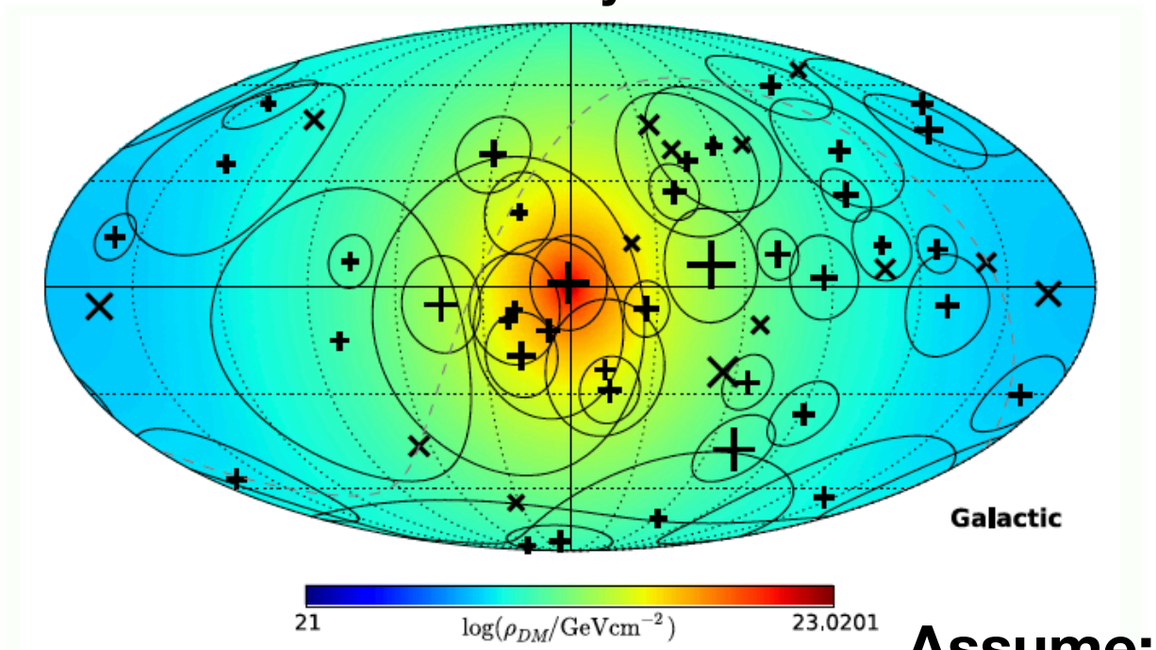
All flavor Solar WIMP - IceCube



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)]

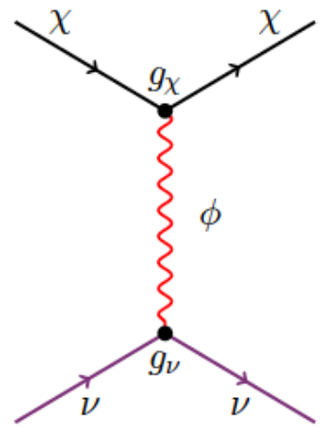
Dark Matter Column Density* as seen from Earth



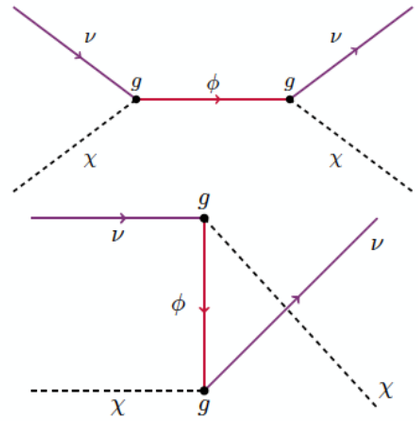
*Einasto Profile

Dark Matter - Neutrino Interaction

(1) Fermion DM, vector mediator

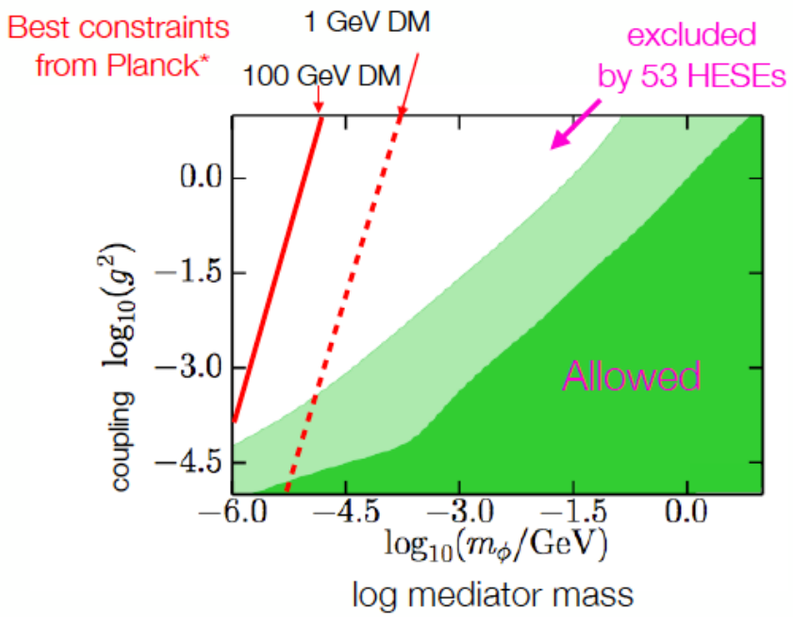


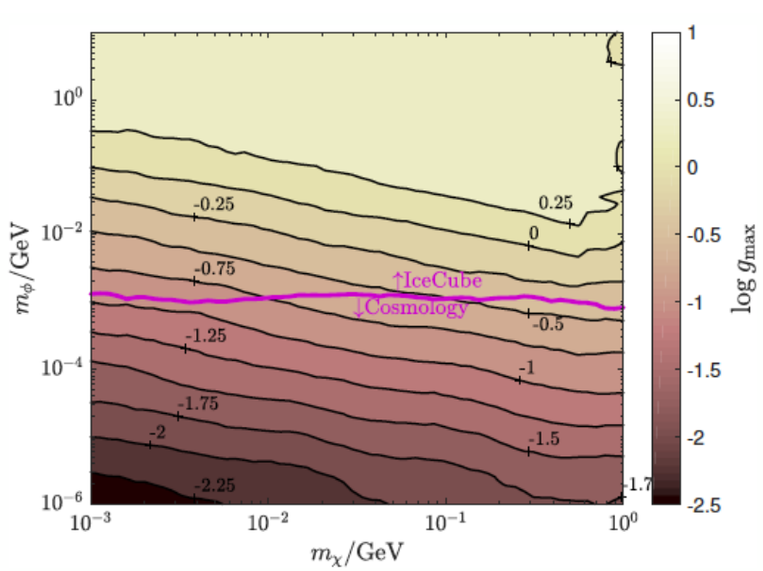
(2) Scale DM, ferminonic mediator

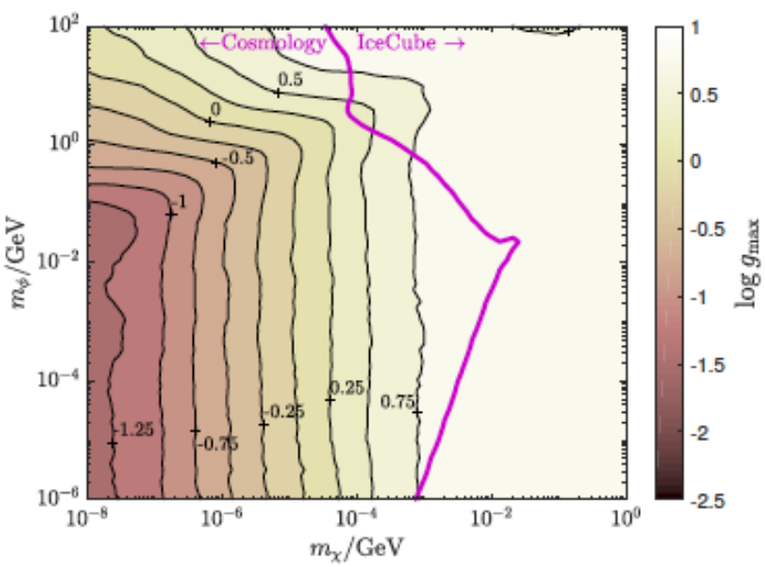


Assume:

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

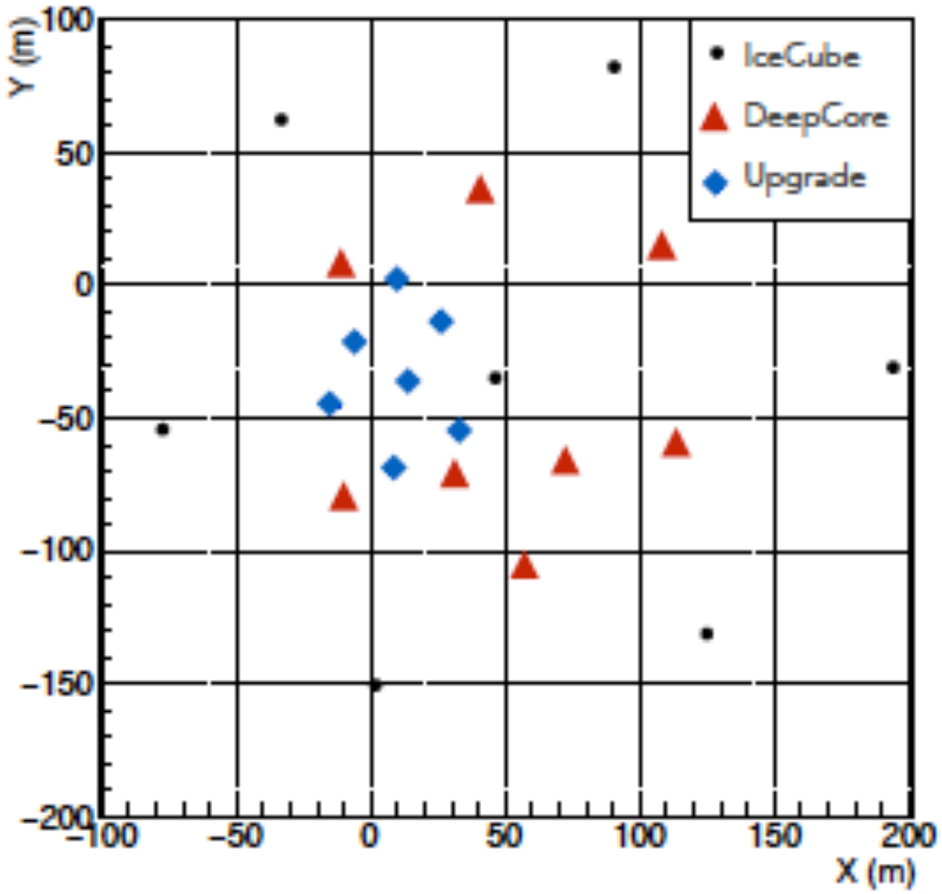


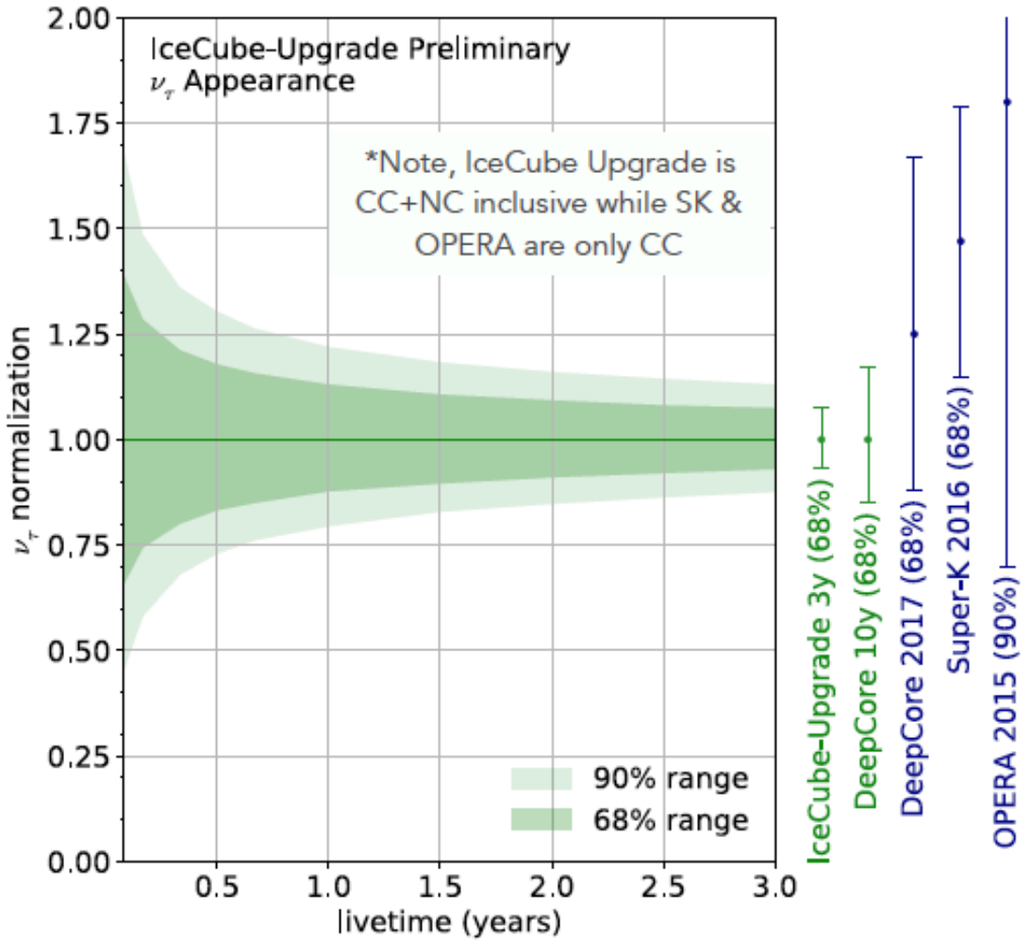




The IceCube Upgrade

"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