

Dark matter searches at Super-Kamiokande and its extensions



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Piotr Mijakowski

National Centre For Nuclear Research

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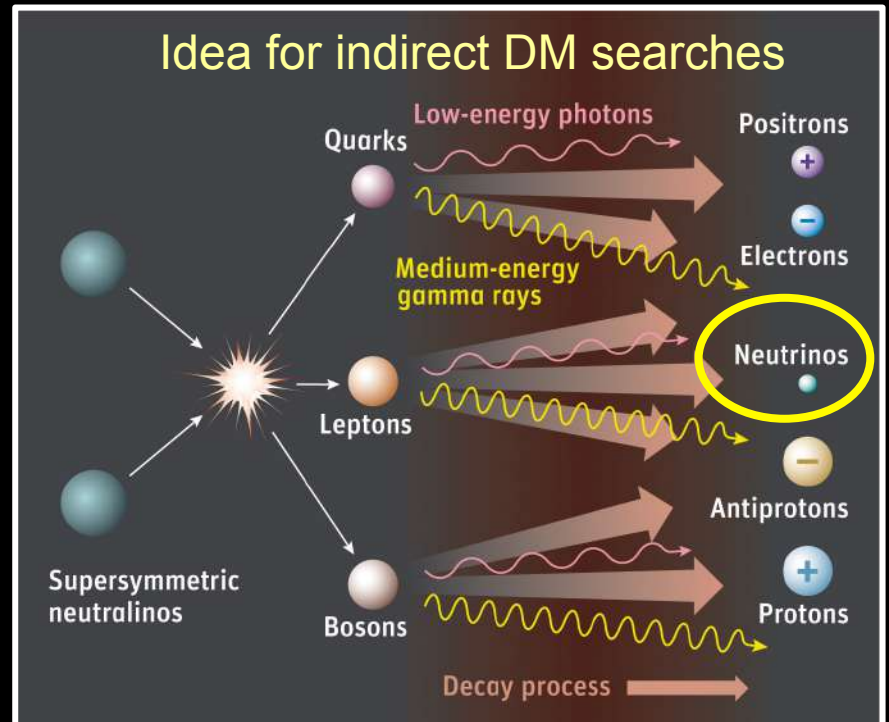
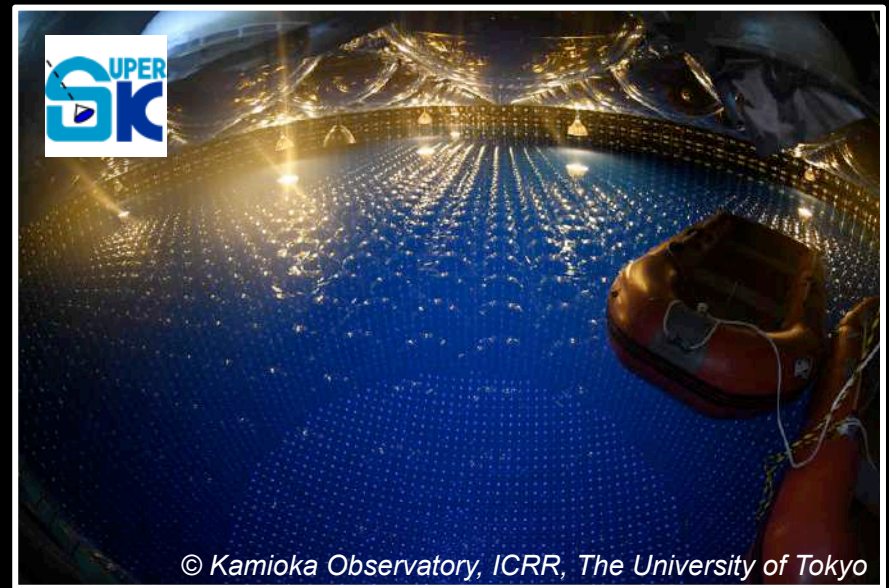
Piotr Mijakowski

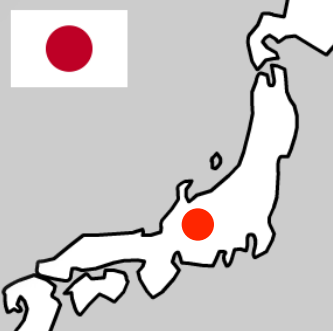
National Centre For Nuclear Research

OUTLINE

- Next phase of Super-Kamiokande: SK-V(**Gd**)
- Indirect searches for dark matter induced neutrinos at Super-Kamiokande:

- Earth WIMP search 
- Galactic Center & Halo 
- Prospects





Super-Kamiokande

@ Kamioka Observatory (ICRR, University of Tokyo), Japan

located 1km
underground

40m

40m



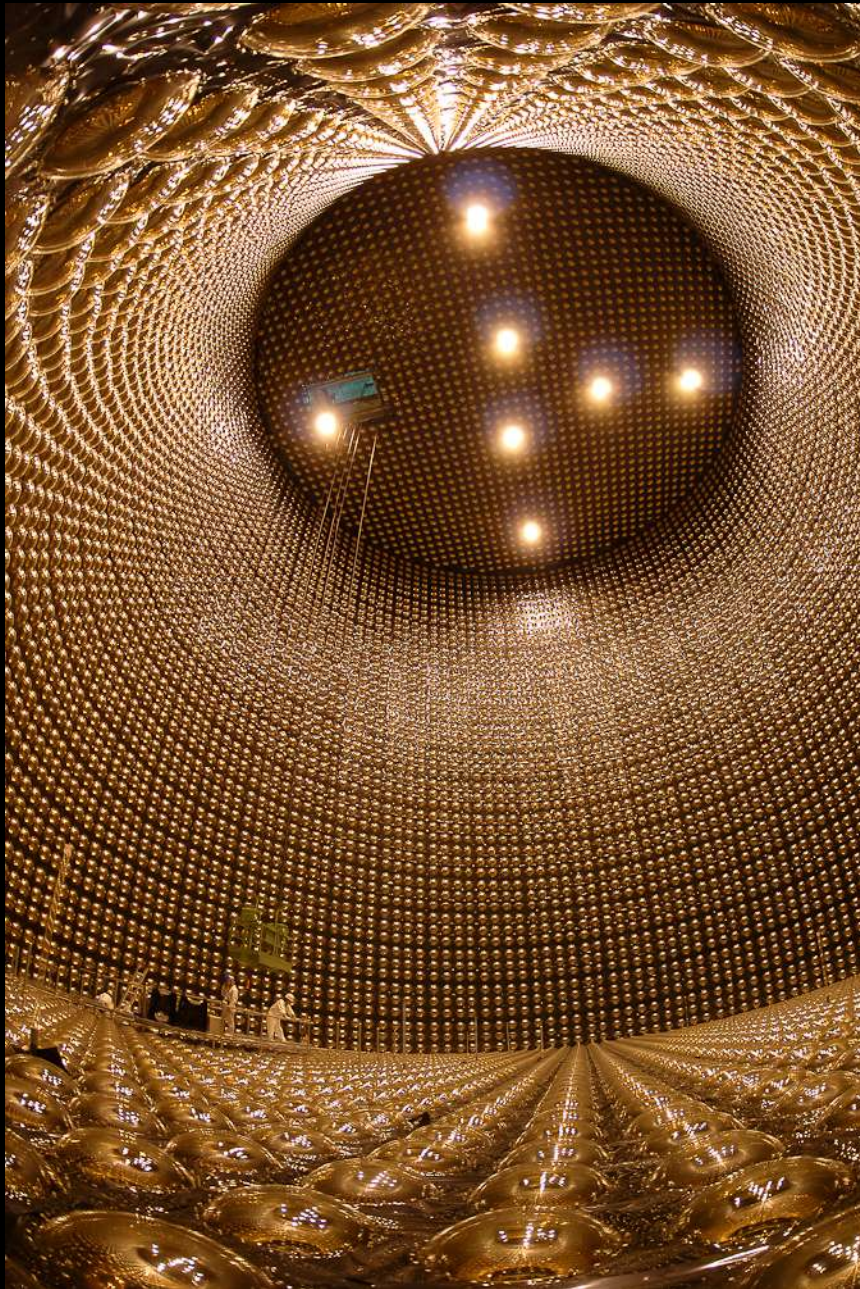
photomultipliers (PMTs)
detect Cherenkov light

PMT

~11k ID
~1.8k OD
PMTs

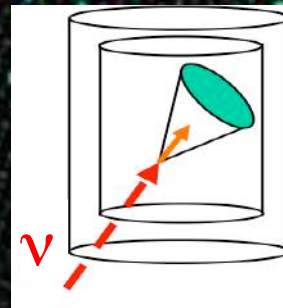
- 50 kton of pure water (22.5 kton fiducial mass)
- inner (ID) & outer/veto (OD) detection regions
- SK runs from 1996
- measures solar, atmospheric, cosmic & accelerator neutrinos
- Far detector of T2K experiment





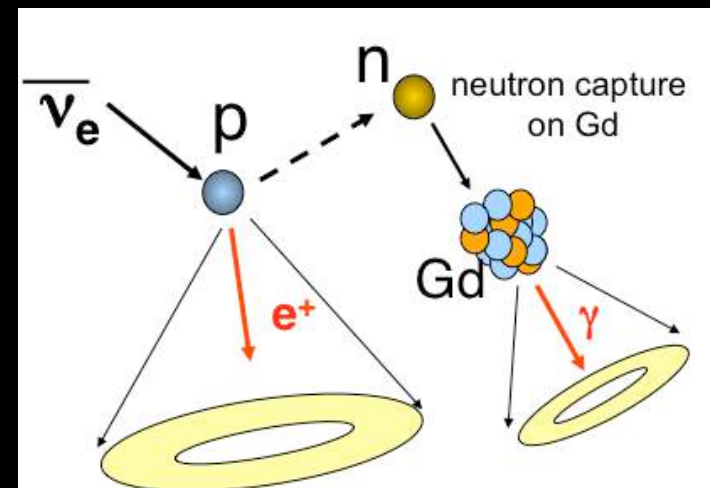
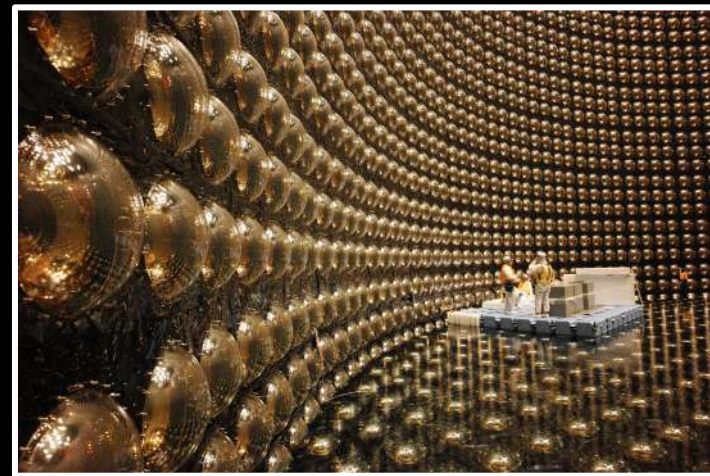
Detected Cherenkov light allows for reconstruction of:

- lepton momentum (neutrino energy)
- lepton direction
- lepton flavor (e-like vs. μ -like, good separation possible)



Super-Kamiokande upgrade

- Tank upgrade work → Summer 2018
- 5 people from NCBJ participated in upgrade: K.Frankiewicz, P.Kalaczyński, K.Kowalik, P.Mijakowski, G.Żarnecki
- PMT checks & calibration, rust removal, tyvek installation, surface cleaning → detector will have to be water sealed, before we loose ~1.5 ton of water/day
- **GOAL:** SK-Gd phase, ~8 tons of gadolinium sulfate dissolved in water (0.2% concentration) increase sensitivity to **SN anti- ν** which is limited currently by backgrounds
- Possibility to discover diffuse **SN background** neutrinos by coincidence reaction with n capture (up to ~5 **events/year** at Super-K & ~800 evts at Hyper-K)
- work is done, detector again in operation since Jan/2019, water leak is at least less than **7.5kg/day**



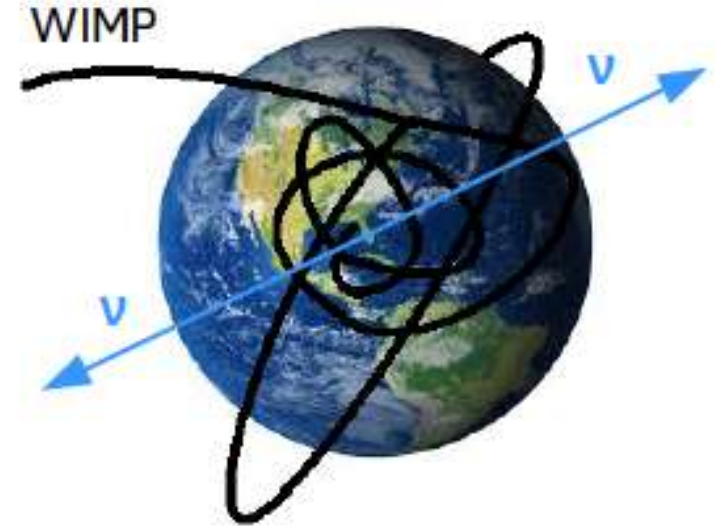
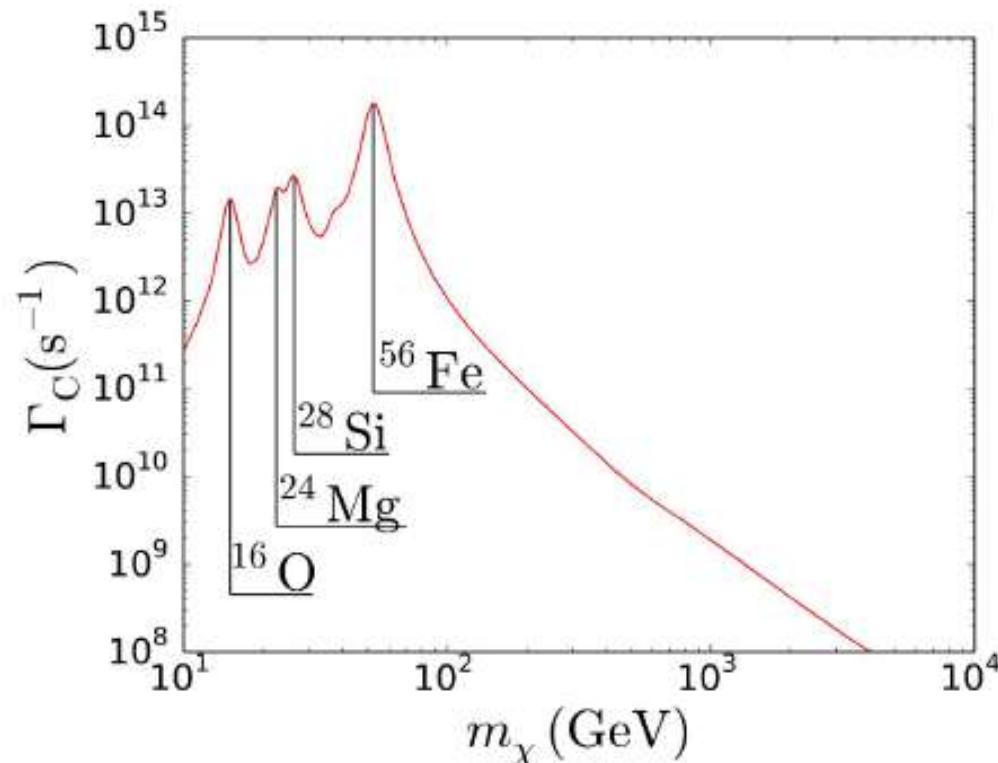
TANK WORK 2018



Earth WIMP search

- WIMPs get captured in core of Earth
- If the mass of DM matches given heavy element, the capture rate increases considerably

WIMP capture rate in the Earth

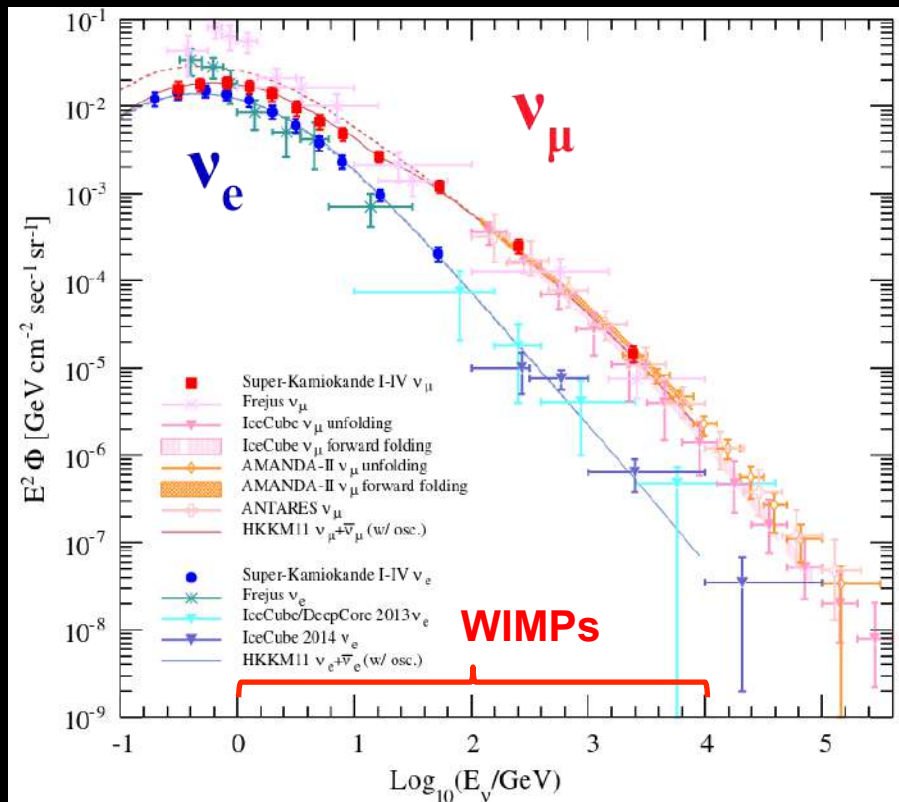


The peaks correspond to **resonant capture** of WIMPs on most abundant elements ^{16}O , ^{24}Mg , ^{28}Si and ^{56}Fe and their isotopes

WIMP-nucleon spin independent scattering cross section $\sigma_{\chi-N}$ can be constrained and compared with results from direct DM detection experiments

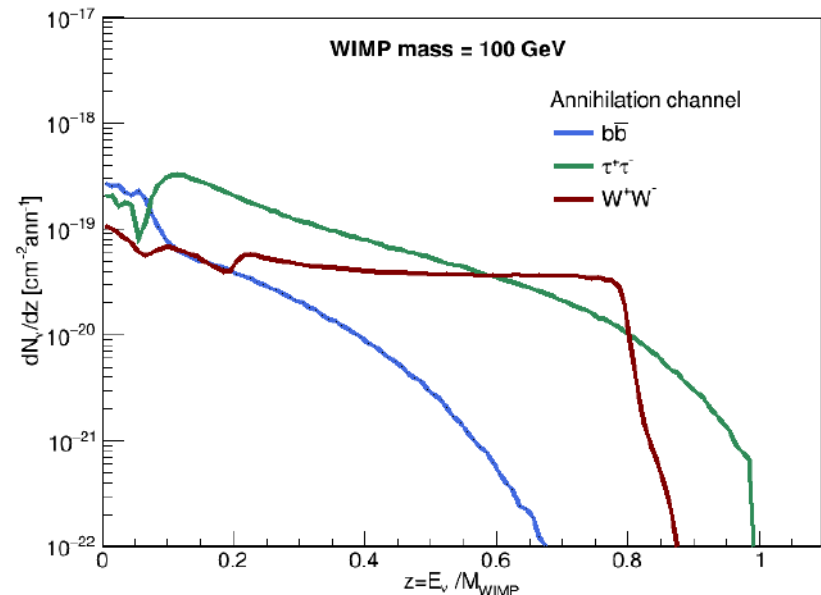
Earth WIMP search: background & signal

Background:
atmospheric neutrinos



Simulated signal
(before detection)

muon neutrino flux produced in 100 GeV
WIMP annihilation in the Earth's core



- ~10 events/day @ SuperK
- SK data period: 1996-2016
- ~50 000 events in total

**DarkSUSY & WimpSim used to
simulated DM-induced neutrino flux**

P. Gondolo et al., JCAP 07, 008 (2004)
M. Blennow et al., arXiv: 0709.3898 (2008)

Earth WIMP search: results

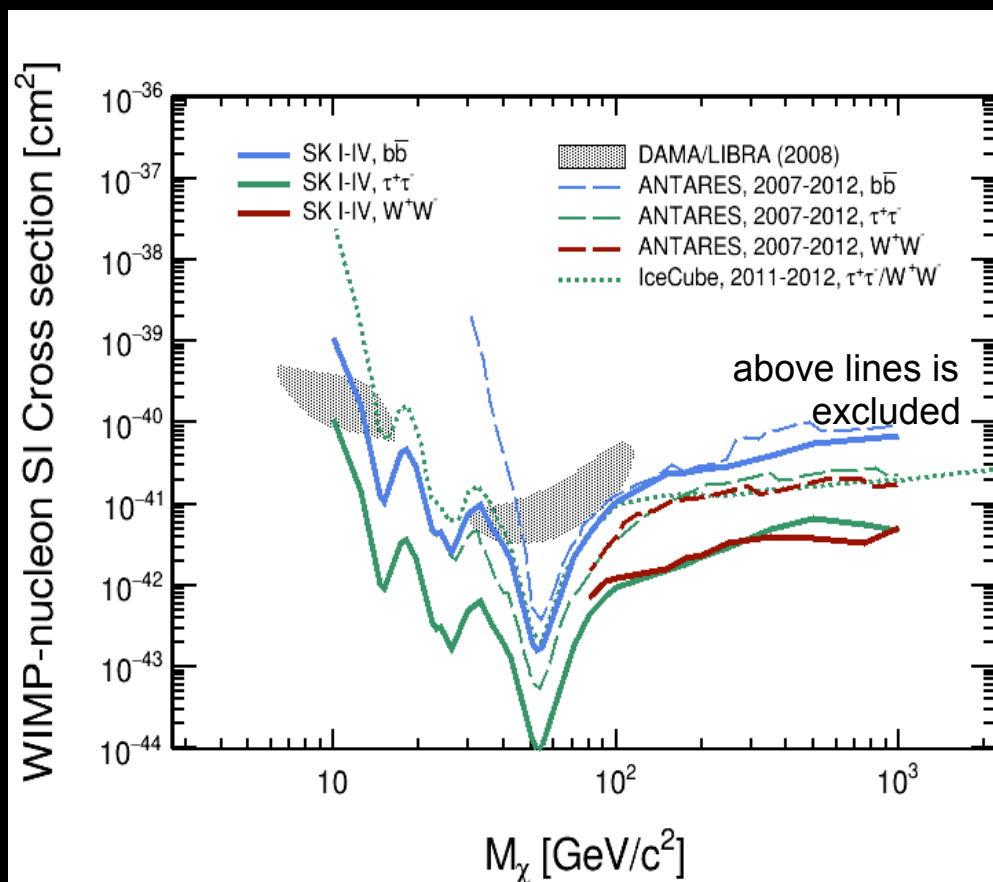
- Search for DM-induced neutrinos using a fit method

$$\chi\chi \rightarrow \nu\bar{\nu}, W^+W^-, b\bar{b}, \mu^+\mu^- \rightarrow \dots \nu_{e/\mu/\tau}$$

$$\text{DATA} = \underbrace{\text{DM} + \text{V ATM}}_{\text{Monte Carlo}} \quad ?$$

- FIT based on lepton momentum & $\cos\theta_{\text{zenith}}$ distributions, 5326-5629 live-days, 1996-2016
- Fit results are consistent with null WIMP contribution
- 90 % upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi-n}$
- KF PhD thesis, now paper in preparation

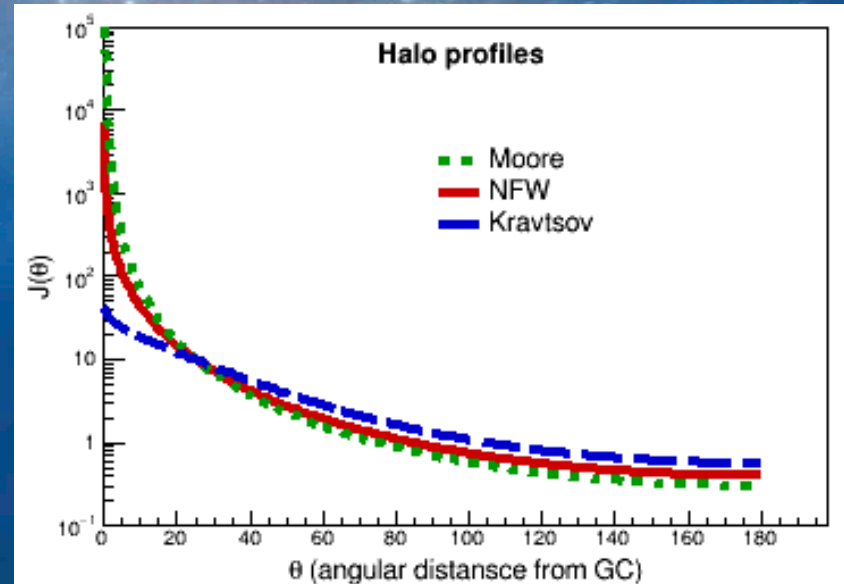
EARTH WIMP search, SK limits 2018
(Katarzyna Frankiewicz, PhD thesis)



The strongest limits among
all neutrino experiments!

Galactic WIMP search

- diffuse signal from entire Galaxy, peaked from Galactic Center
- GC visibility with SK:
~71% with UPMU, 100% FC/PC
- search constrains DM self-annihilation cross section $\langle\sigma v\rangle$



Expected signal intensity strongly depends on halo model
NFW is considered as a benchmark model in this analysis

Galactic WIMP search: results

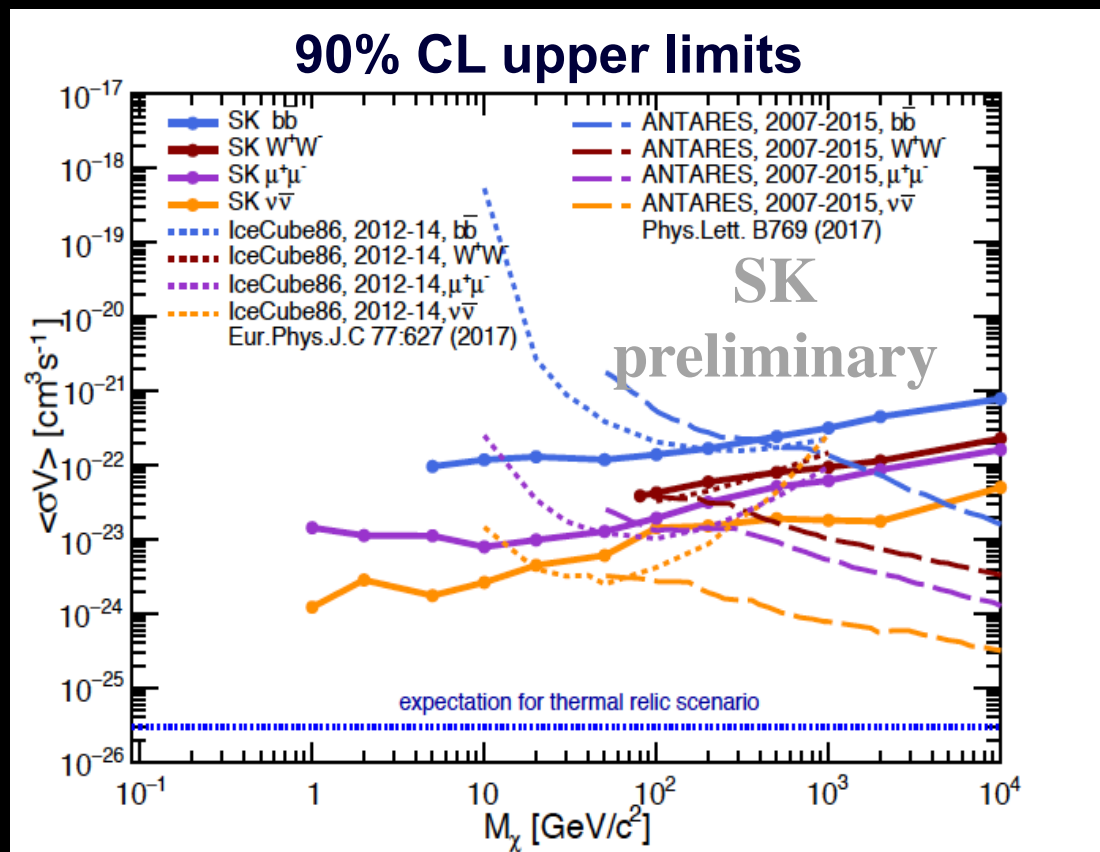
- Search for DM-induced neutrinos using a fit method

$$\chi\chi \rightarrow \nu\bar{\nu}, W^+W^-, b\bar{b}, \mu^+\mu^- \rightarrow \dots \nu_{e/\mu/\tau}$$

$$\text{DATA} \stackrel{?}{=} \underbrace{\text{DM} + \text{V ATM}}_{\text{Monte Carlo}}$$

- FIT based on lepton momentum & $\cos\theta_{\text{GC}}$ distributions, 5326-5629 live-days, 1996-2016
- NFW halo model assumed
- Fit results are consistent with null WIMP contribution
- 90 % upper limits on DM self-annihilation cross section $\langle\sigma_A V\rangle$

Galactic WIMP search, SK limits 2018-17



$$\frac{d\phi_{\Delta\Omega}}{dE} = \frac{\langle\sigma_A \cdot V\rangle}{2} J_{\Delta\Omega} \frac{R_{sc} \rho_{sc}^2}{4\pi \cdot M_\chi^2} \frac{dN}{dE}$$

Galactic WIMP search prospects

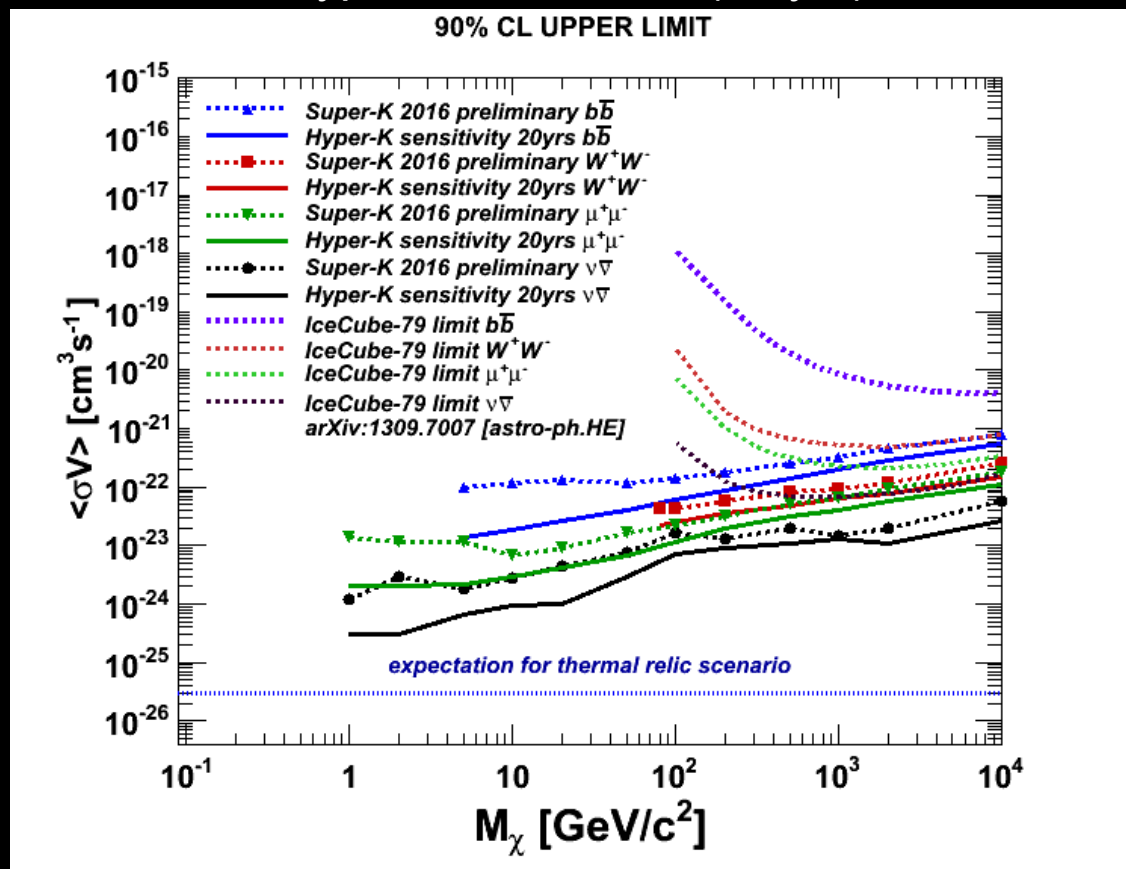
- Prosepects at future neutrino telescopes: Hyper-Kamiokande, KM3NeT

Galactic WIMP search sensitivity for Hyper-Kamiokande (20 yrs)

Super-K: 0.45 Mton•yrs
(current limit)

Hyper-K: 3-10x improvement
in 20 yrs

Sun & Earth WIMP searches:
similar level of improvement is
expected at Hyper-
Kamiokande



More on KM3NeT ARCA & ORCA → next talk by Rafał Wojaczyński

More on Hyper-Kamiokande → talk today by Joanna Zalipska

Galactic WIMP search prospects

- Prosepects at future neutrino telescopes: Hyper-Kamiokande, KM3NeT

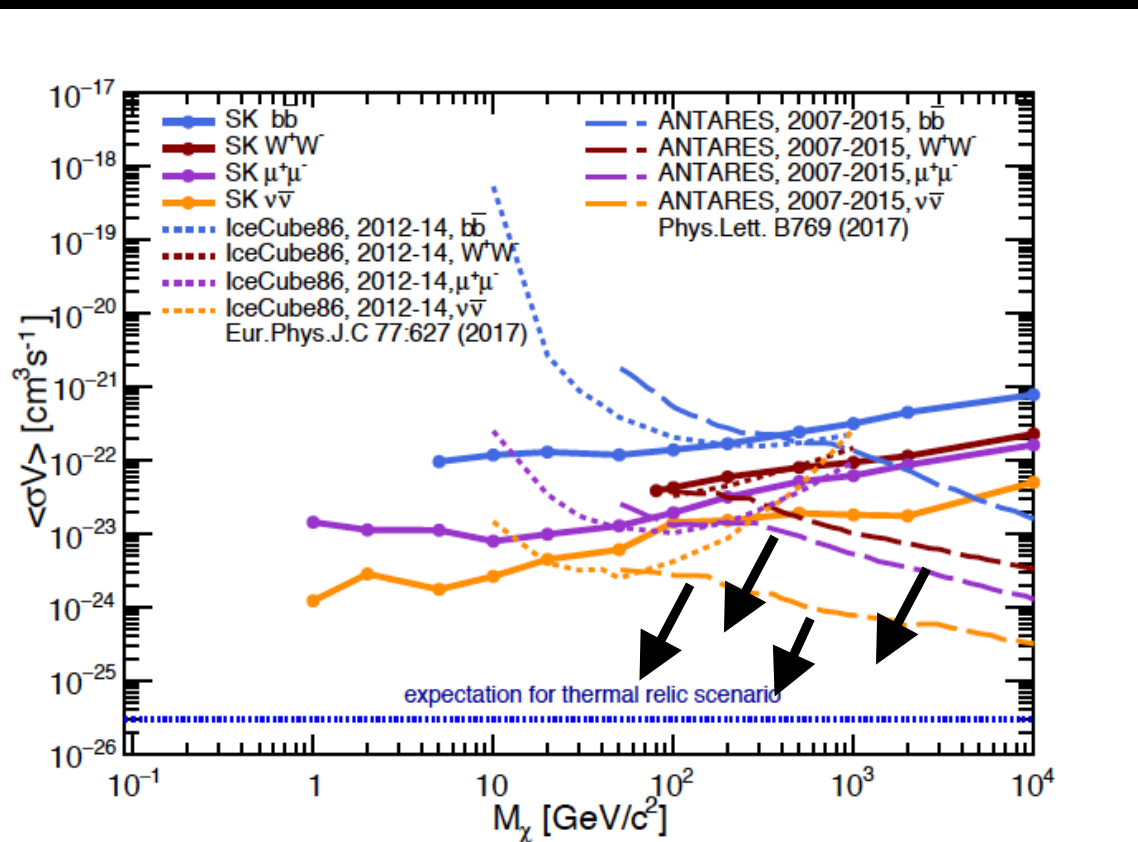
What KM3NeT sensitivity will be?
It will move down ANTARES limits

Super-K: 0.45 Mton•yrs
(current limit)

Hyper-K: 3-10x improvement
in 20 yrs

ORCA: 3-10x imprv. in ~ 1 yr
(wrt. SK)

ARCA (2 blocks): 30- 10^2 x
imprv. in ~ 1 yr



More on KM3NeT ARCA & ORCA → next talk by Rafał Wojaczyński

More on Hyper-Kamiokande → talk today by Joanna Zalipska

SUMMARY

- Super-Kamiokande has undergone an upgrade → dissolve Gd
- DM induced neutrinos has not been observed at Super-Kamiokande so far
- Polish group is responsible for the analyses:

Earth WIMP search (2018)

- upper limits on spin-independent WIMP-nucleon cross-section
- high sensitivity to resonant capture region → currently the strongest limits from ν experiments
- PRL targeted paper in revision

Galactic WIMP search (2017-18)

- upper limits on $\langle \sigma_A V \rangle$ for wide range of WIMPs masses (1 GeV to 10 TeV)
- strongest limits < 20-100 GeV among ν experiments
- PRD paper in revision



Horizon 2020
European Union funding
for Research & Innovation



NATIONAL SCIENCE CENTRE
POLAND

H2020-MSCA-RISE-2014-GA641540, SKPLUS (SK+)

SONATA-BIS 2015/18/E/ST2/00758

SUPPLEMENTARY SLIDES

Future: Hyper-Kamiokande

- start 2026 (after 7 years construction)
- main goal: neutrino mass hierarchy and δCP
- some astro potential: SN, DSNB (~ 2 evts per day), WIMPs, cosmic neutrinos

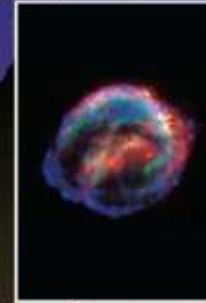
Accelerator Neutrino beam from J-PARC



Atmosphere



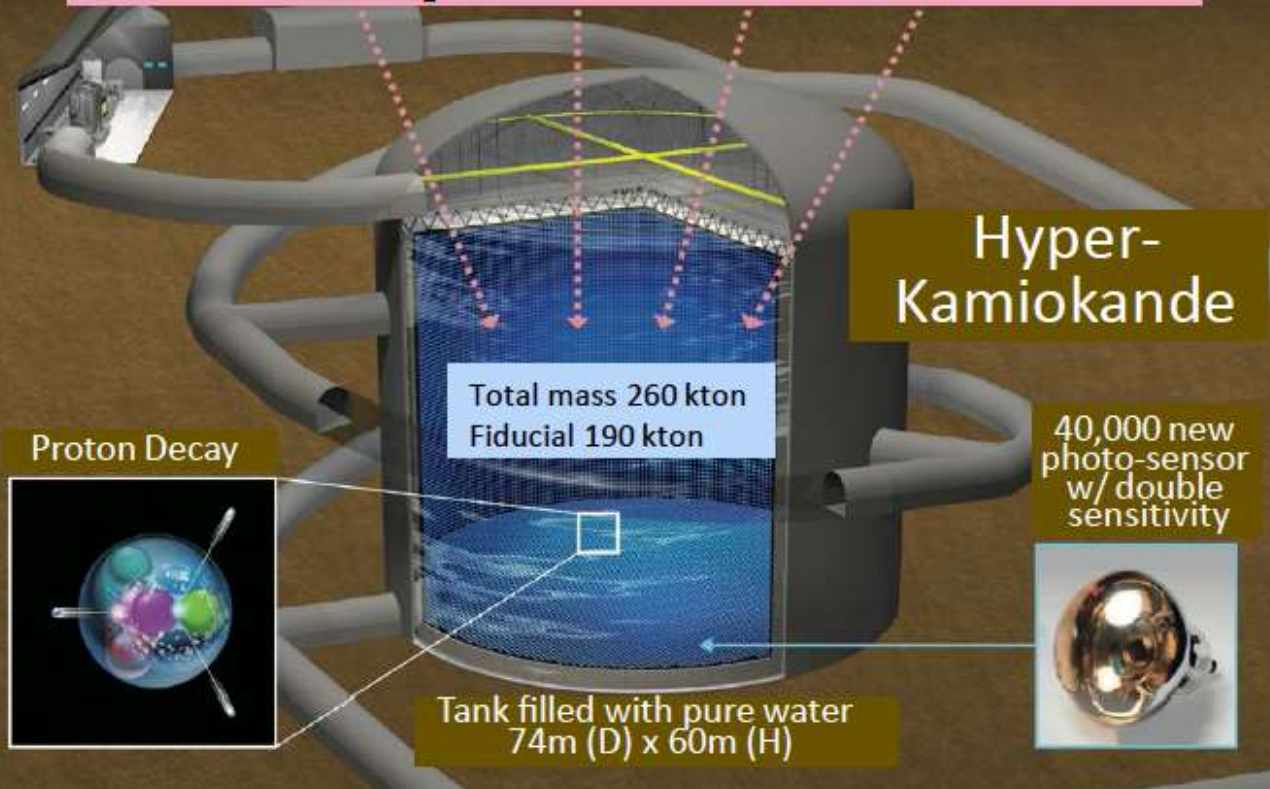
Supernova



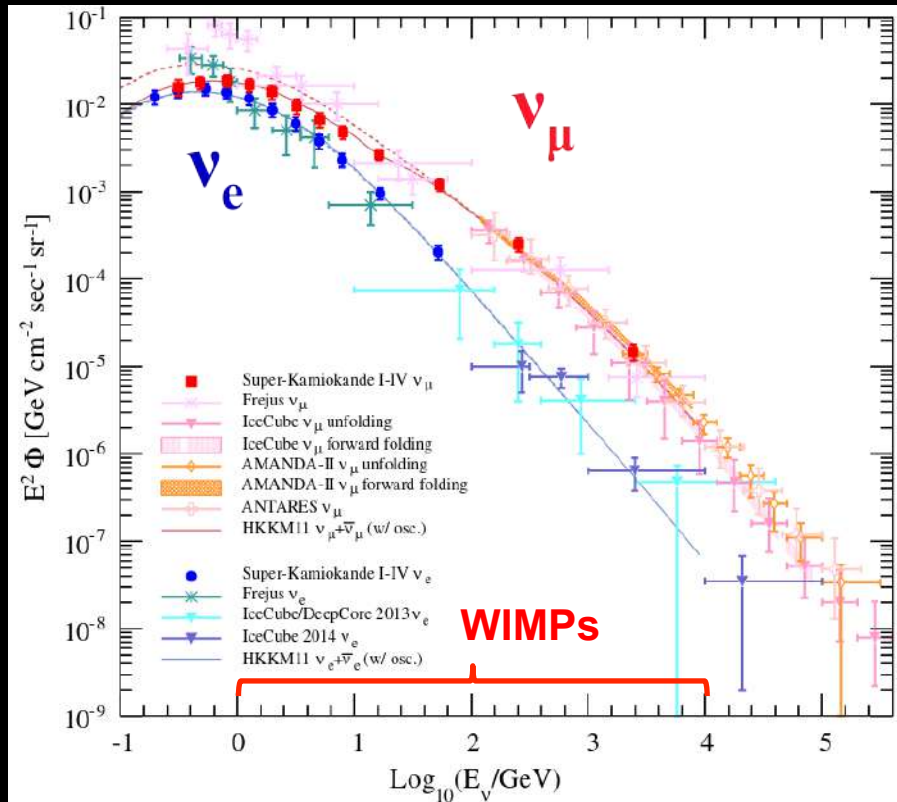
Sun



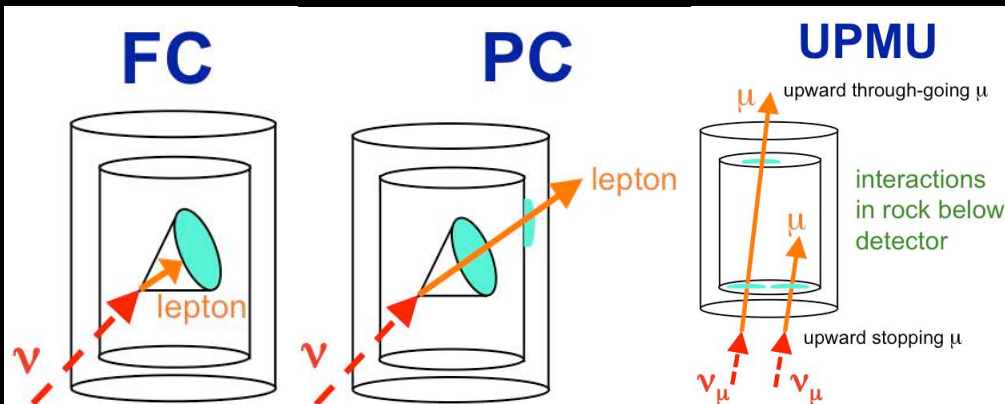
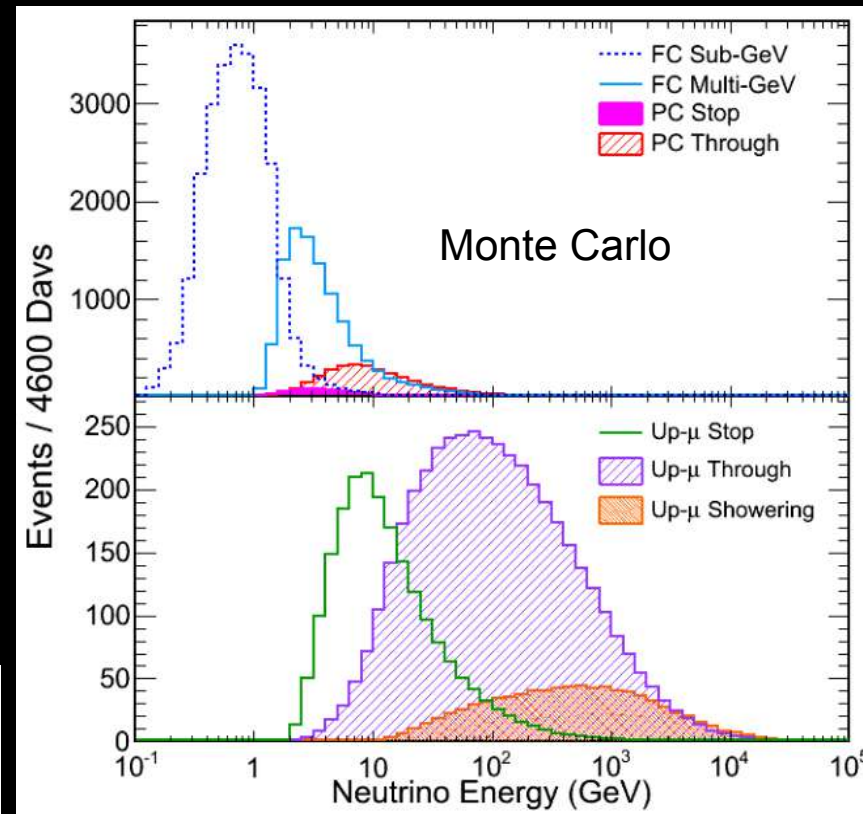
$\sim 10 \times$ Super-K fiducial mass



Atmospheric neutrinos: main background in DM-induced ν searches



atmospheric neutrinos at SK

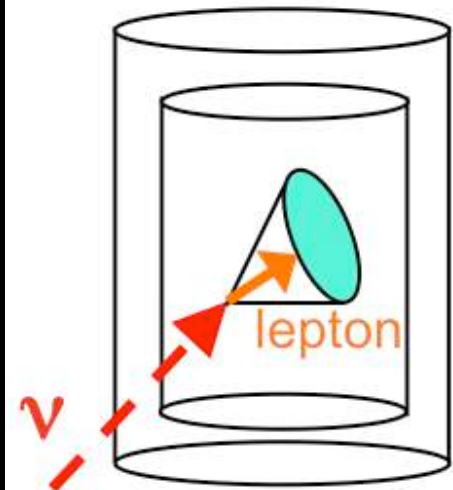


- ~10 events/day
- data period: 1996-2016
- ~50 000 events in total

Super-K data samples

Fully-contained

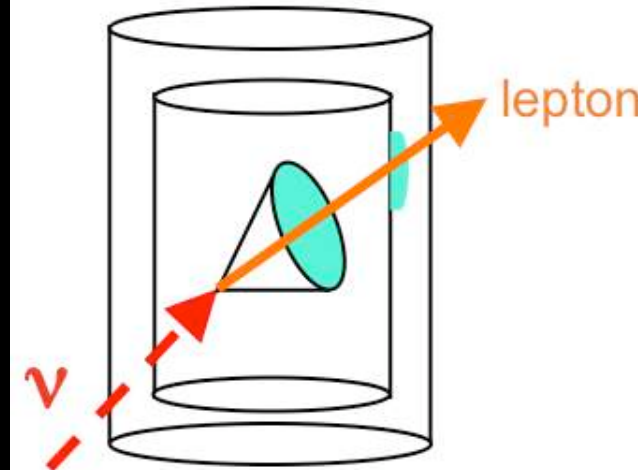
FC



- » ν energy reconstruction
- » ν direction info
- » e/μ identification possible

Partially-contained

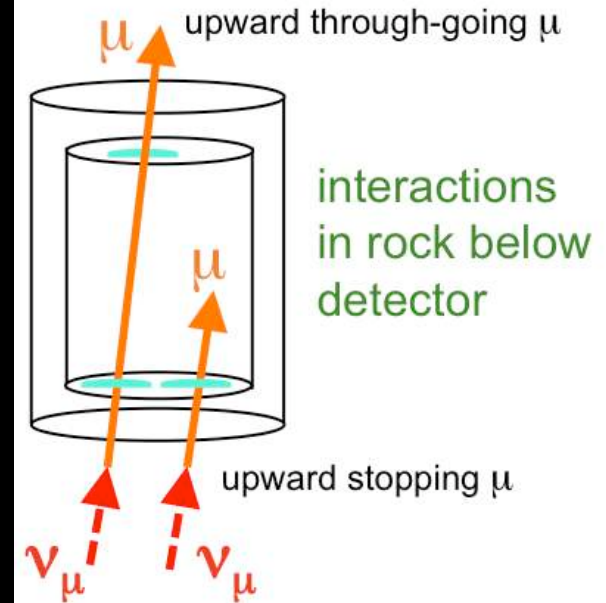
PC



- » partial E_ν info (lepton leaves detector)
- » ν direction info

Upward-going muons

UPMU

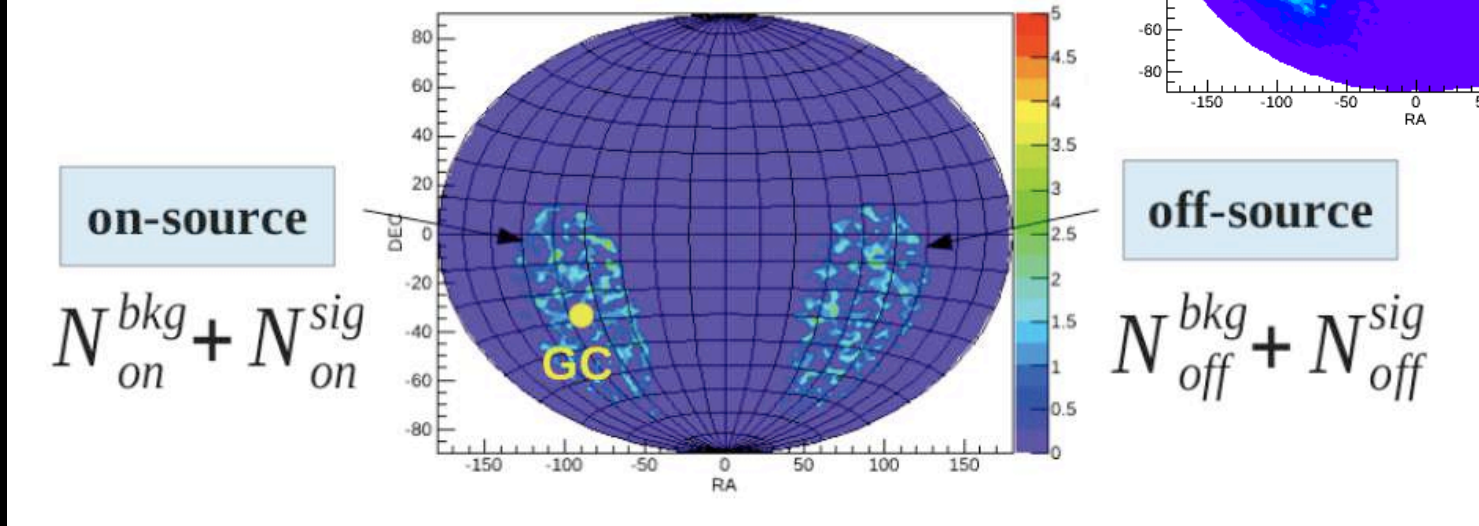


- » no E_ν info
- » excellent ν direction info
- » downward-going muons are neglected (mainly cosmic ray μ)

Galactic WIMP search: **ON-/OFF-source**

Different approach: search for large-scale anisotropy due to DM-induced ν 's from Milky Way

$$\Delta N \approx N_{on}^{sig} - N_{off}^{sig} = \Delta N^{sig} \propto \langle \sigma_A v \rangle$$



expectation for DM-induced neutrinos

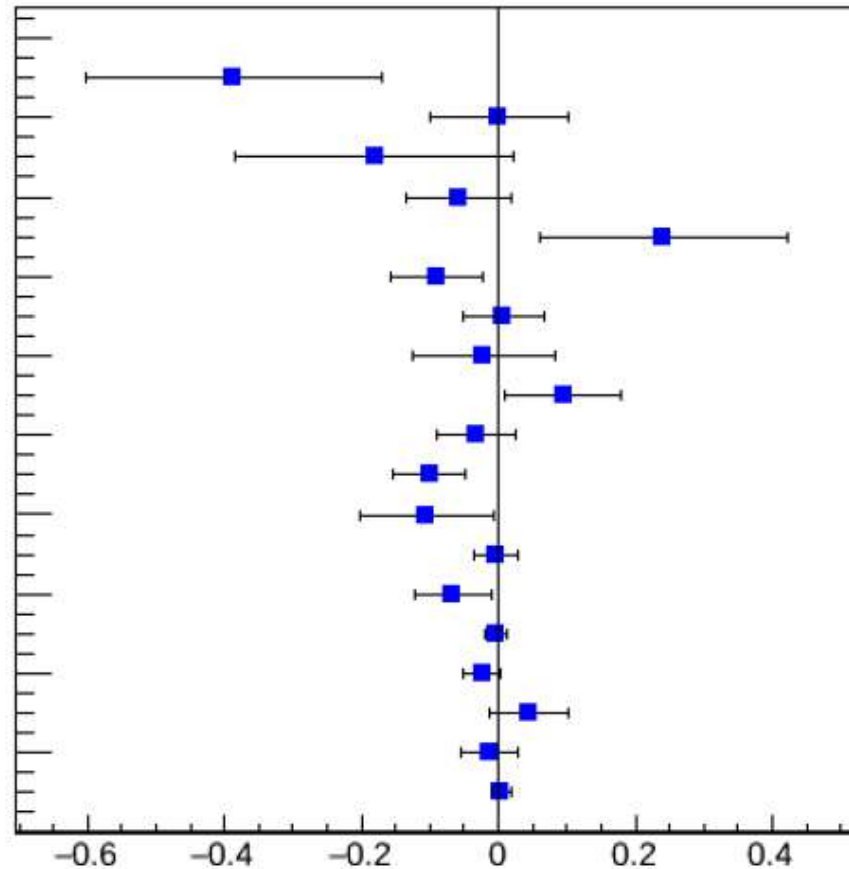
- Analysis uses ON-/OFF-source concept to estimate background directly from data
- Independent on MC simulations and related systematic uncertainties

ON- & OFF-source results

$$A = \frac{N_{\text{ON}} - N_{\text{OFF}}}{N_{\text{ON}} + N_{\text{OFF}}}$$

SK 1-4, 1996-2016

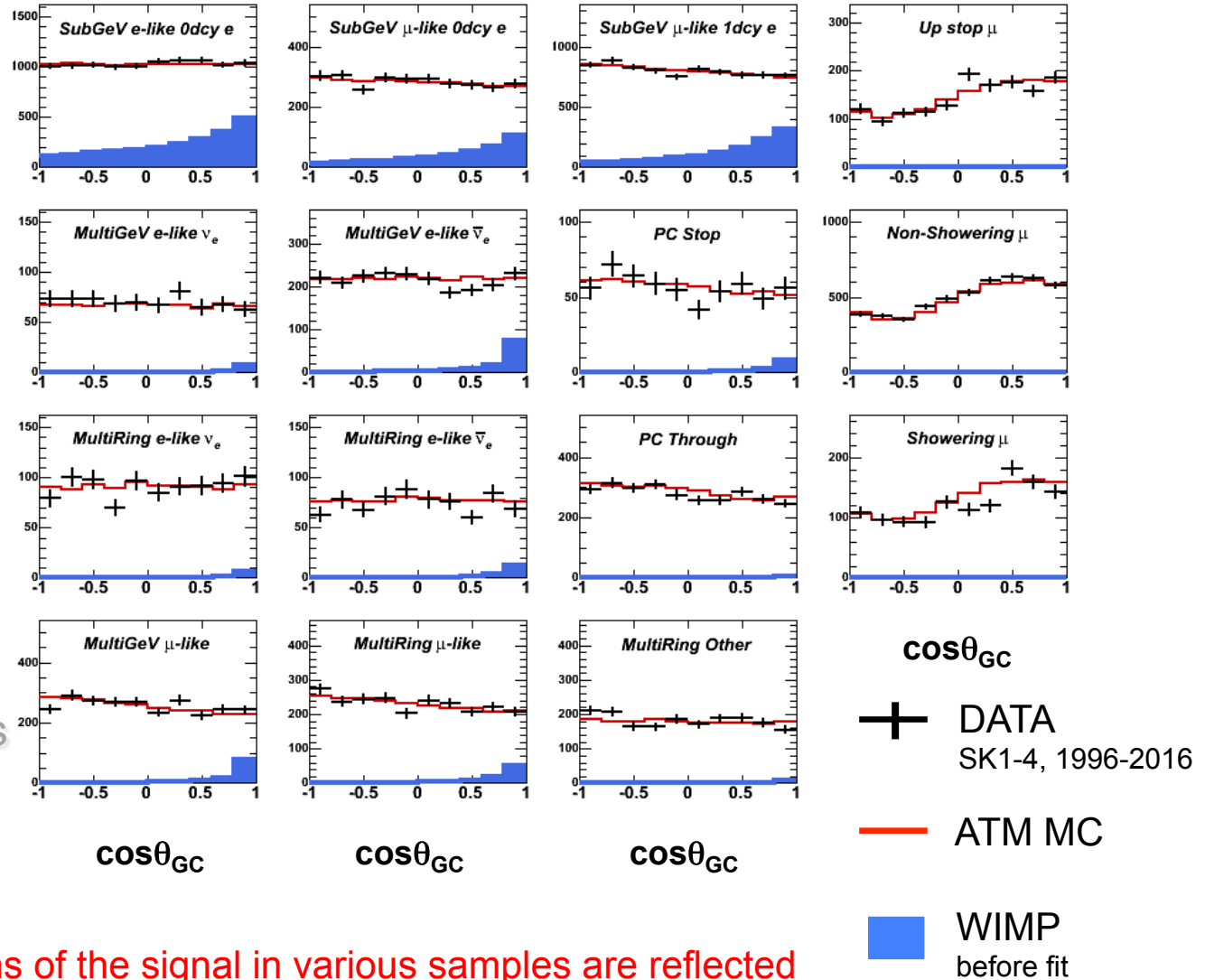
UpThruShower_mu
UpThruNonShower_mu
UpStop_mu
PCThru
PCStop
MultiRingOther
MultiRing_mulike
MultiRing_eline_nuebar
MultiRing_eline_nue
MultiGeV_mulike
MultiGeV_eline_nuebar
MultiGeV_eline_nue
SubGeV_pi0like
SubGeV_mulike_2dcy
SubGeV_mulike_1dcy
SubGeV_mulike_0dcy
SubGeV_SingleRing_pi0like
SubGeV_eline_1dcy
SubGeV_eline_0dcy



Galactic WIMP search: data

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 5326-5629 live-days, 1996-2016
- NFW halo model assumed
- Fit results are consistent with null WIMP contribution
- 90% CL upper limit on DM self-annihilation cross section $\langle\sigma_A V\rangle$

example: 5GeV WIMPs $b\bar{b}$ ann. channel



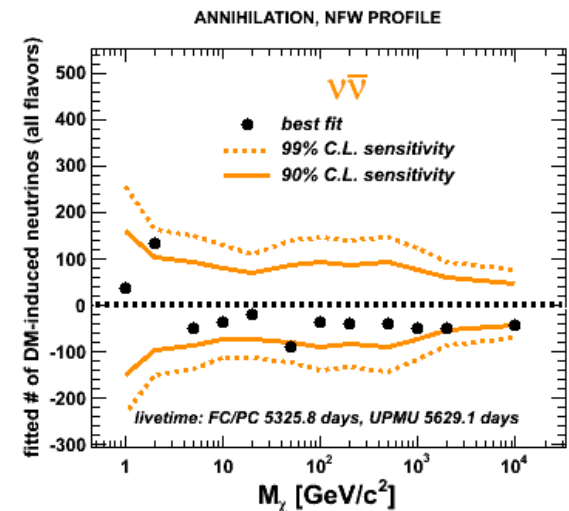
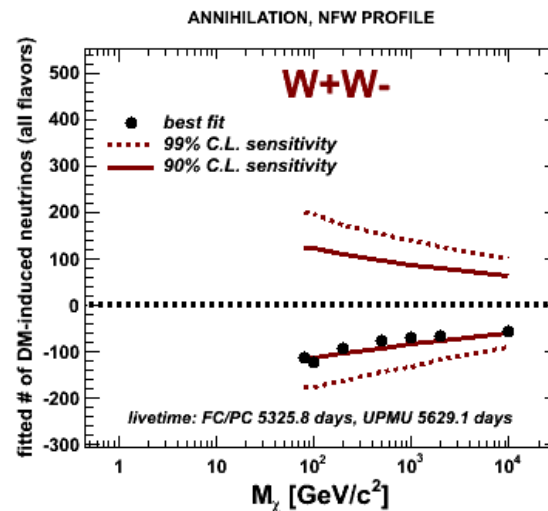
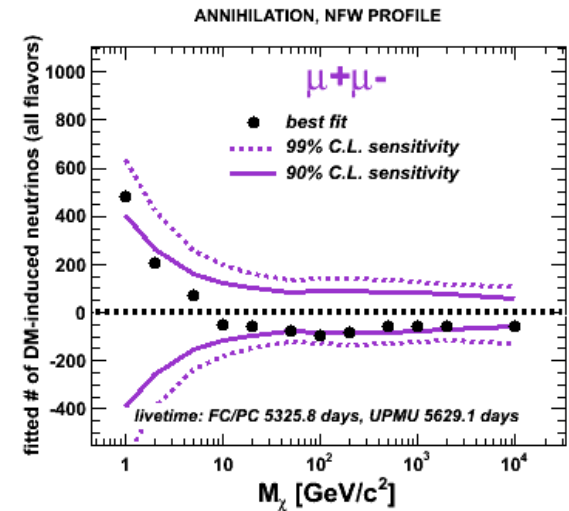
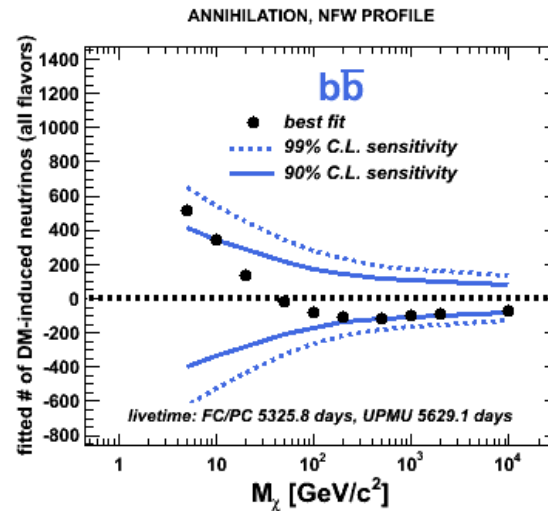
proportions of the signal in various samples are reflected

Galactic WIMP search: fitted number of DM-induced V 's

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- Fit results are consistent with null WIMP contribution
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SK preliminary

points on the plots are not independent



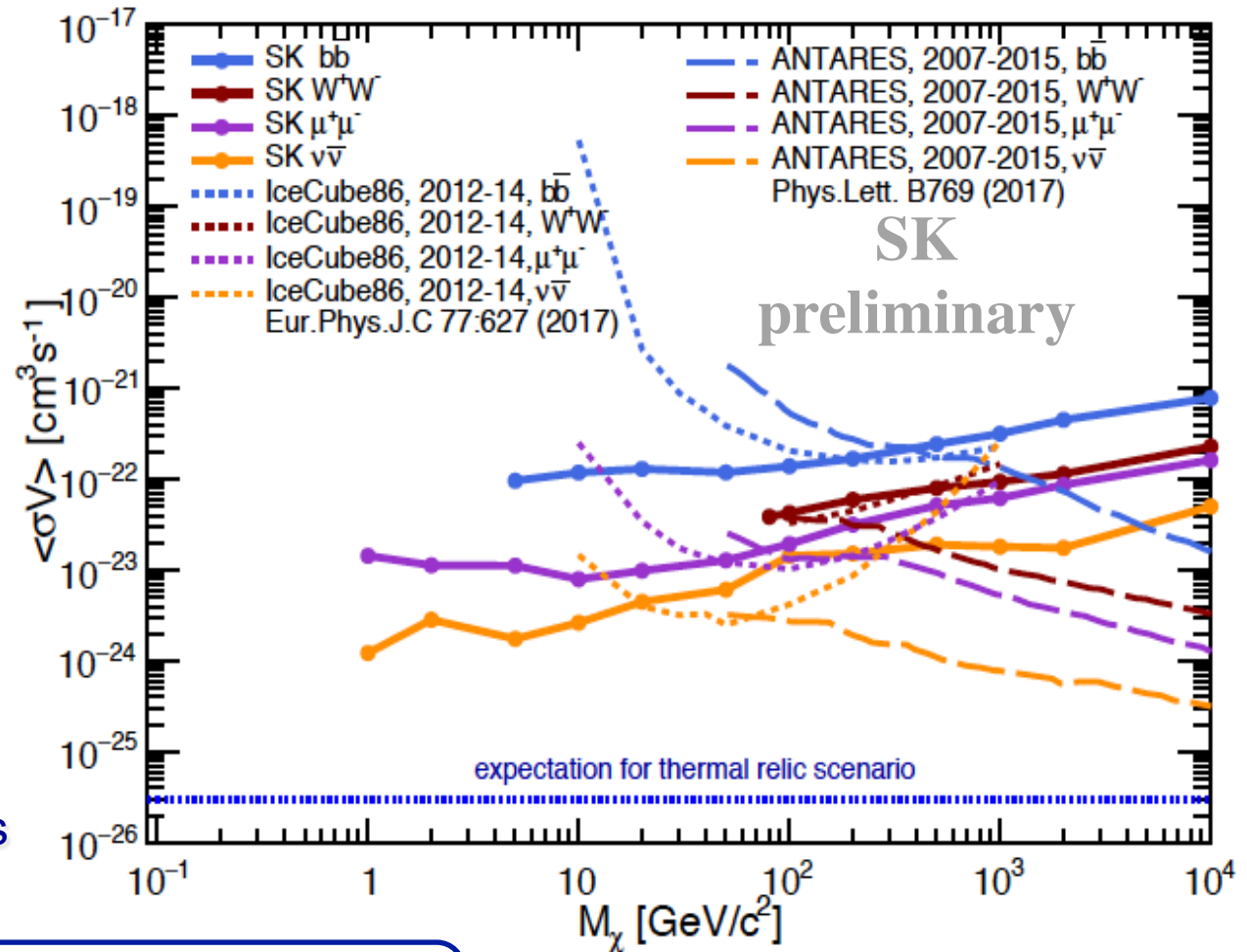
~150 systematic uncertainty terms included in the fit

p-values in backup

Galactic WIMP search: DM self-annihilation cross section

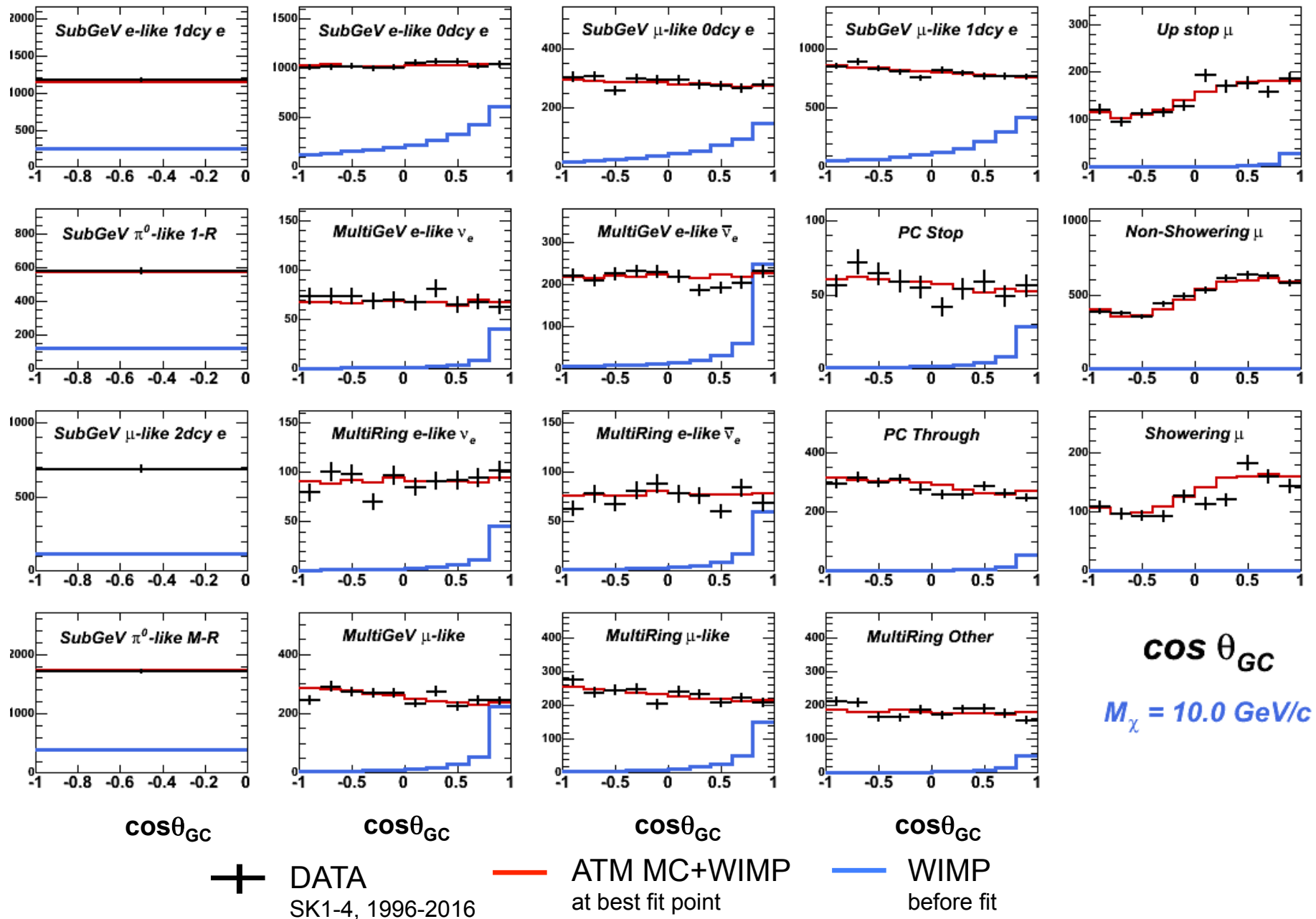
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90% CL upper limit

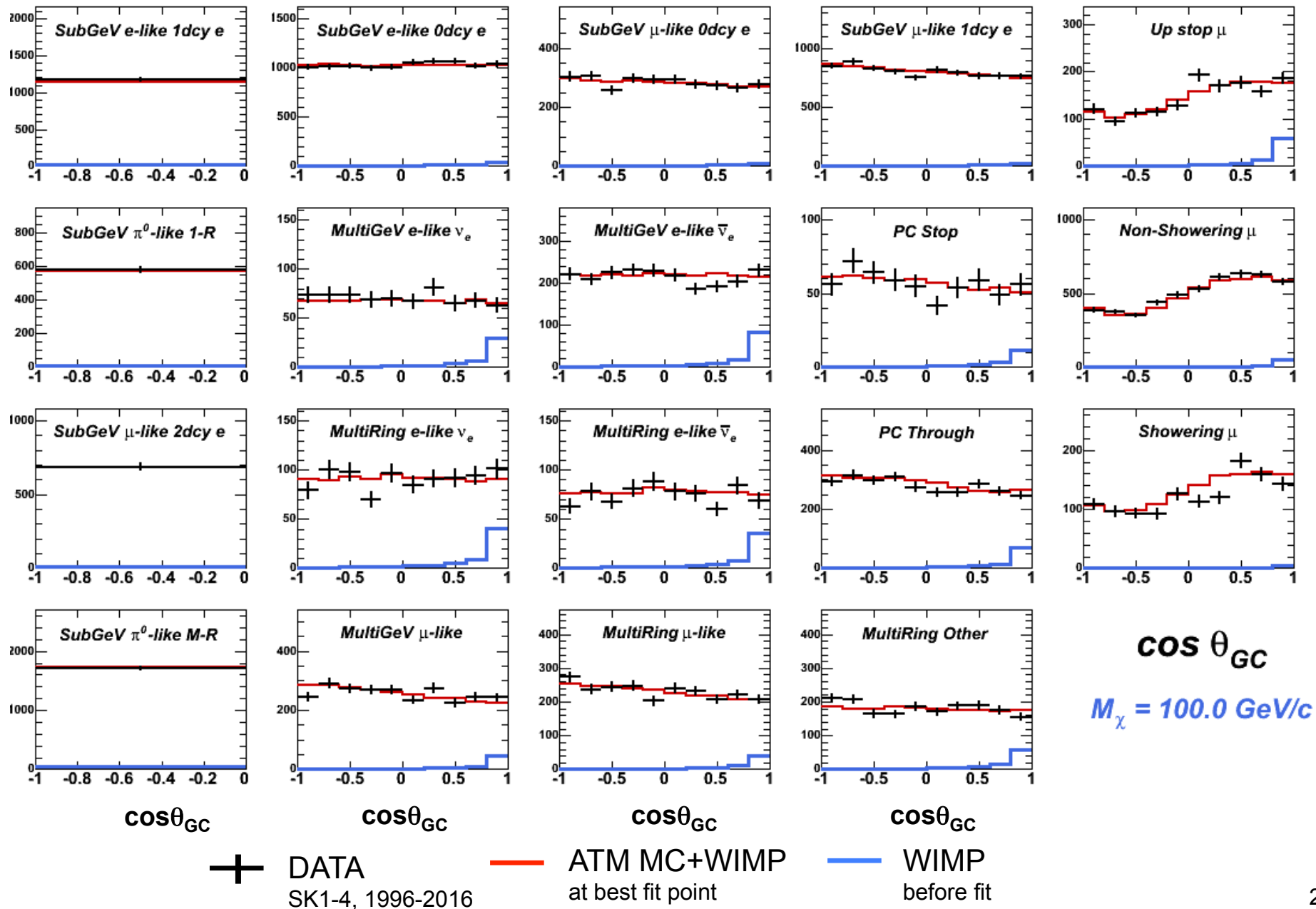


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Galactic WIMP search: signal illustration 10GeV bb-bar



Galactic WIMP search: signal illustration 100GeV bb-bar



Galactic WIMP search: signal illustration 1000GeV bb-bar

