Theory Meeting Experiment – European Workshop on Water Cherenkov Precision Detectors for Neutrino and Nucleon Decay Physics, 19 – 21 September 2018, Warsaw, PL

tmeν WCP2018

Dark Matter Searches at Super-Kamiokande

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Warsaw, Poland

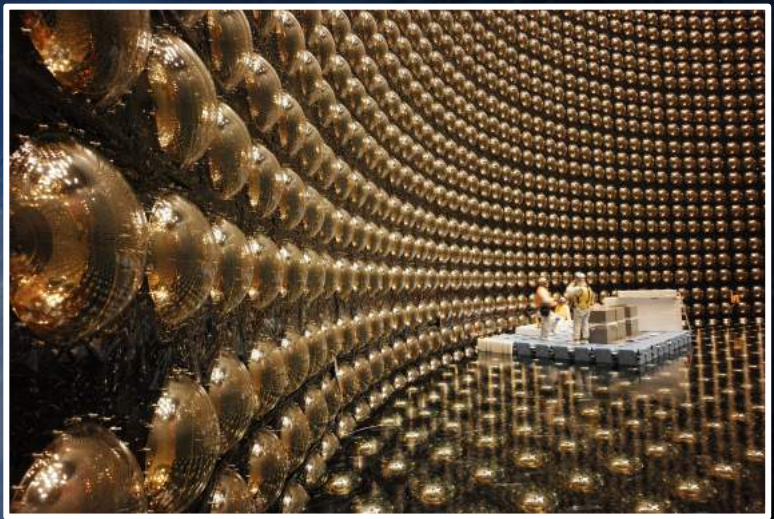
SUPER SK

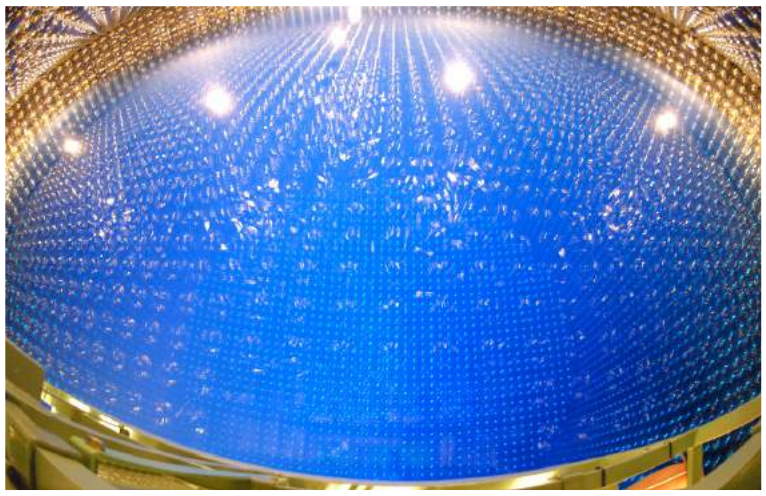
NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

OUTLINE

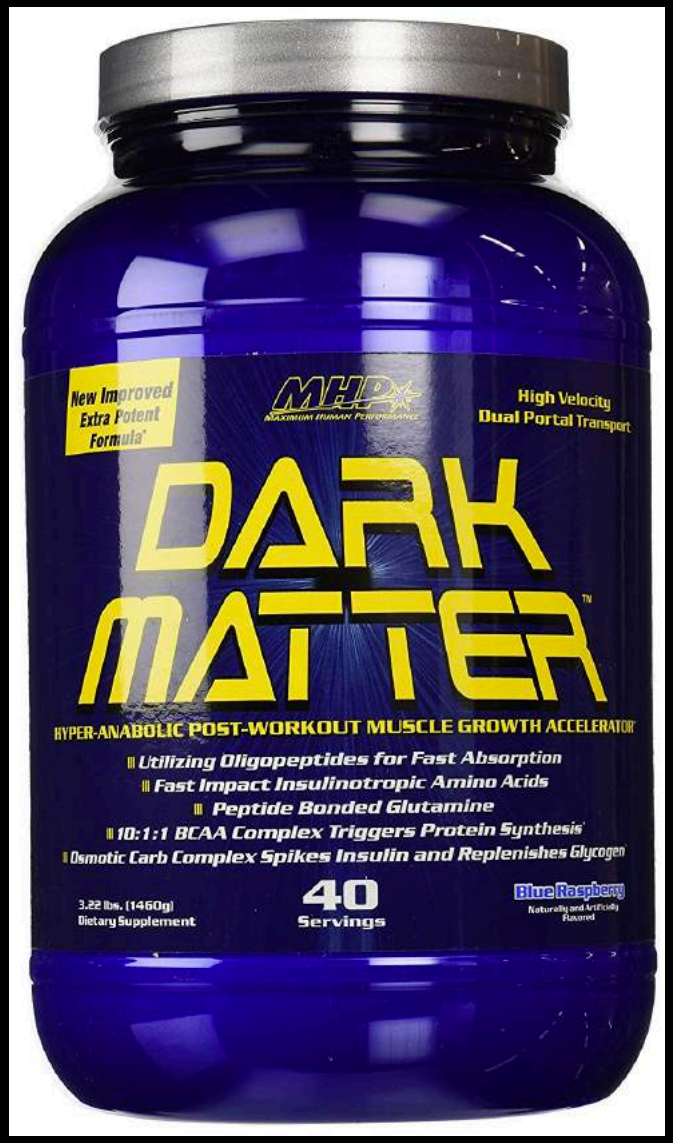
Indirect dark matter searches at Super-Kamiokande

- Galactic WIMP search
  ON/OFF-source analysis (2016)
- Galactic WIMP search
  Global Fit analysis (2017)
- Solar WIMP search
  Global Fit analysis (2015)
- Earth WIMP search
  Global Fit analysis (2017/18)





(non-scientific) WIMP searches

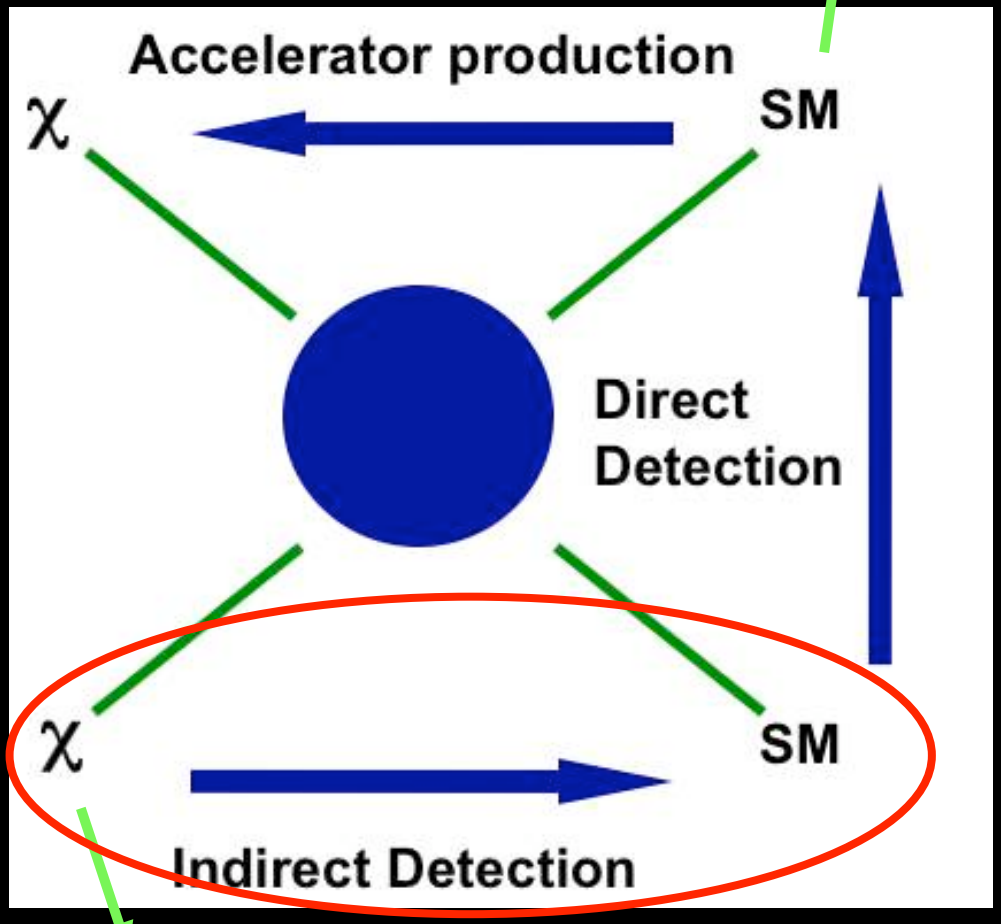


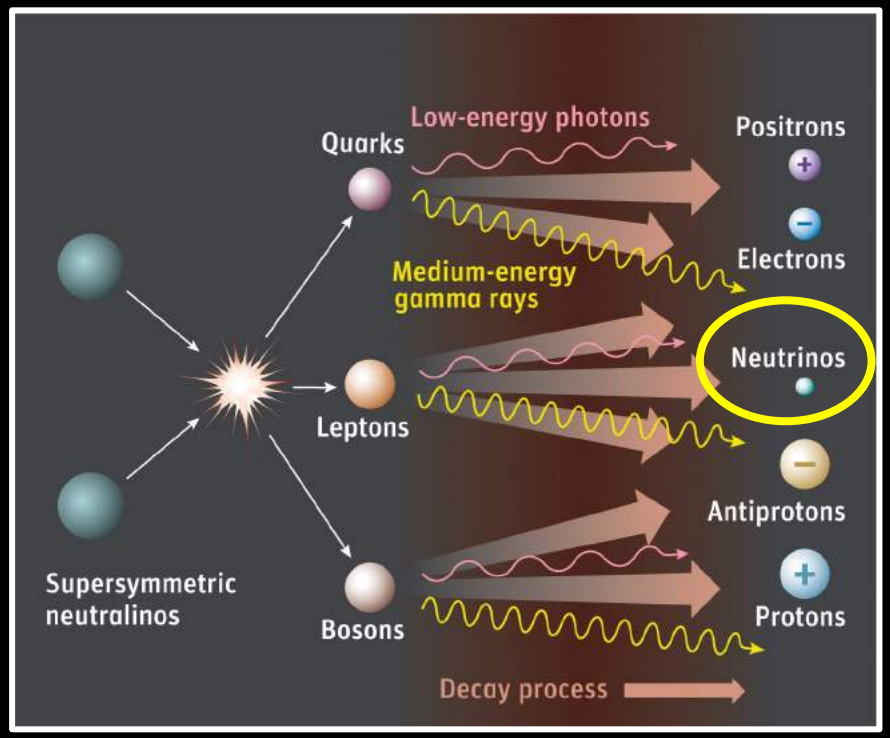
$127.98 per 40 servings on ebay

Available in 3 flavors: Blue Raspberry, Fruit Punch and Grape....

(scientific) WIMP searches

SM: Standard Model particle

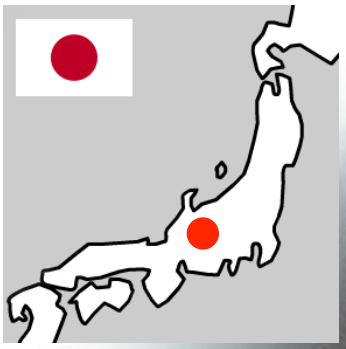


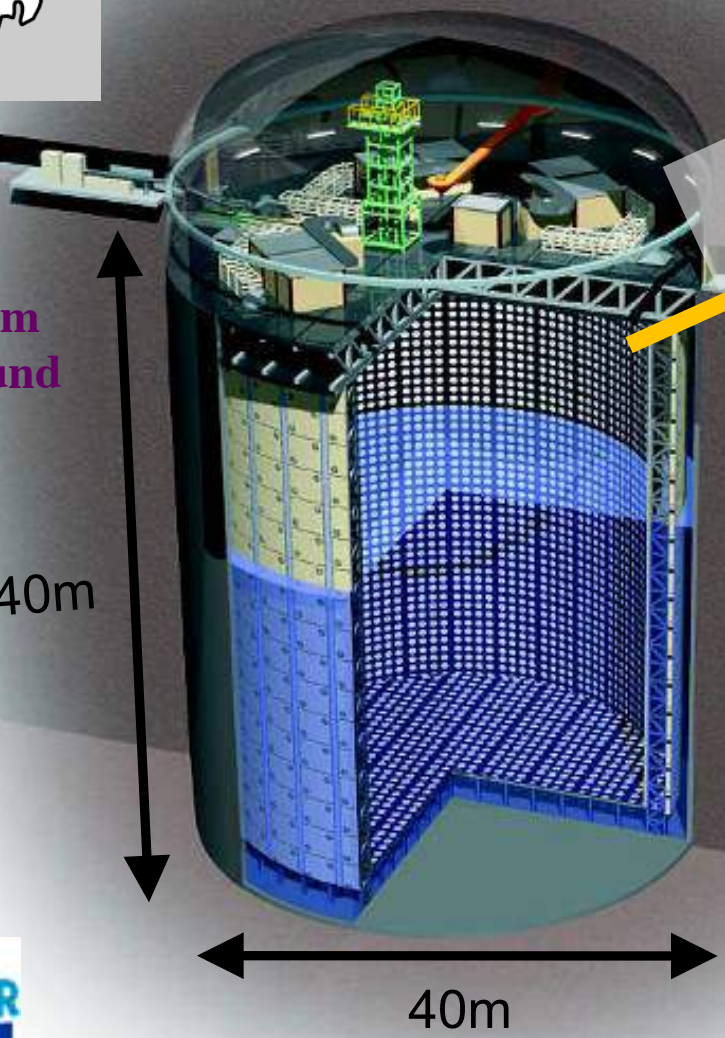


χ: Dark Matter particle

Super-Kamiokande

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

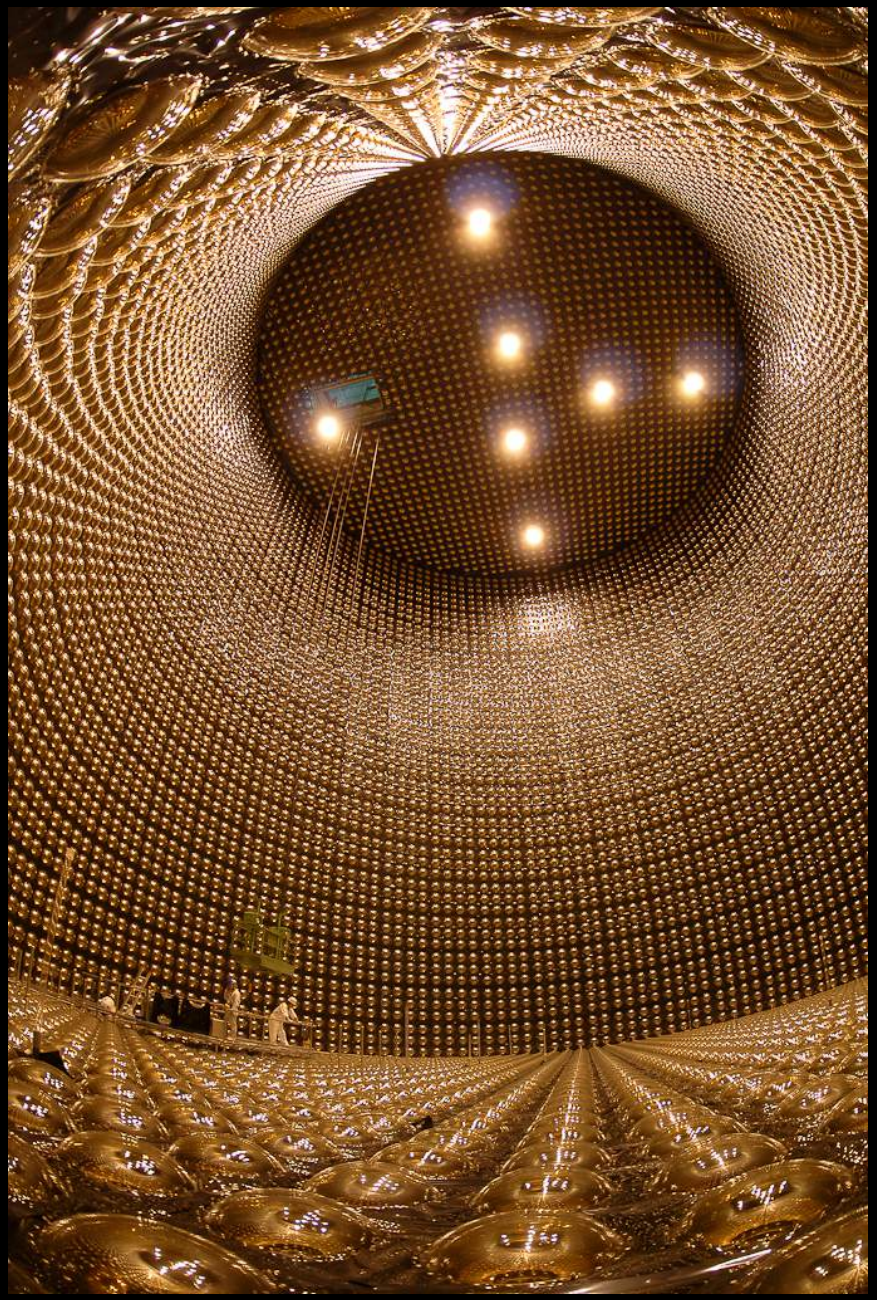




located 1km underground

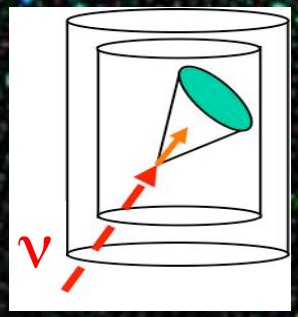
photomultipliers (PMTs) detect Cherenkov light

- 50 kton of pure water (22.5 kton FV)
- inner (ID) & outer/veto (OD) detection regions
- SK runs from 1996
- measures solar, atmospheric, cosmic & accelerator neutrinos
- T.Kajita → Nobel Prize 2015



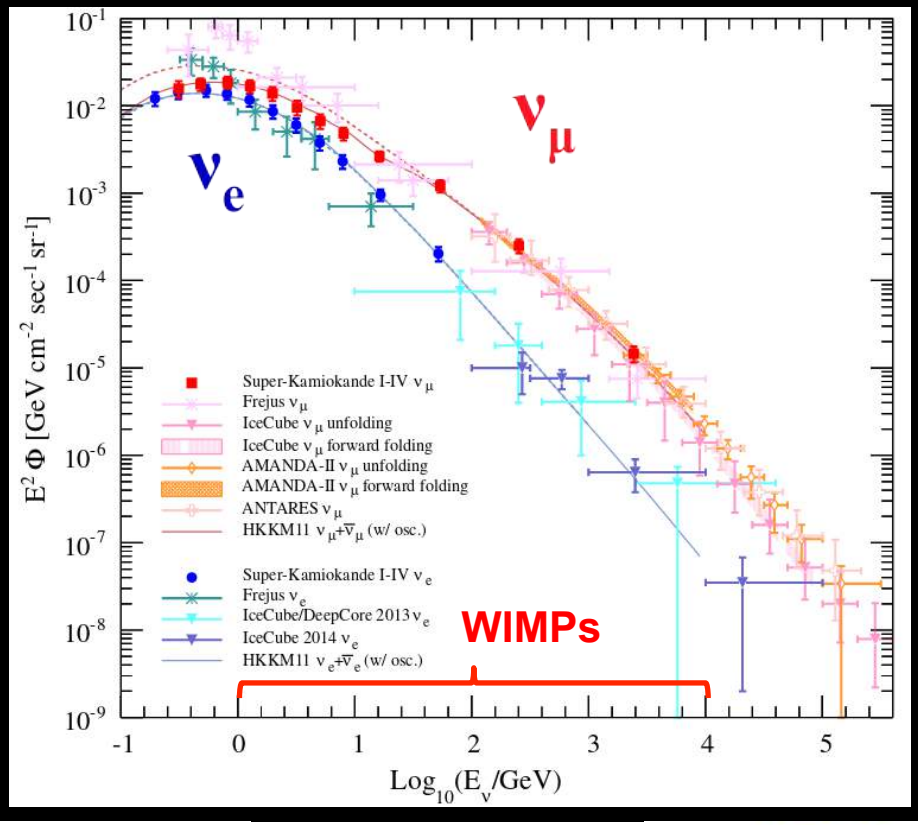
Detected Cherenkov light allows for reconstruction of:

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

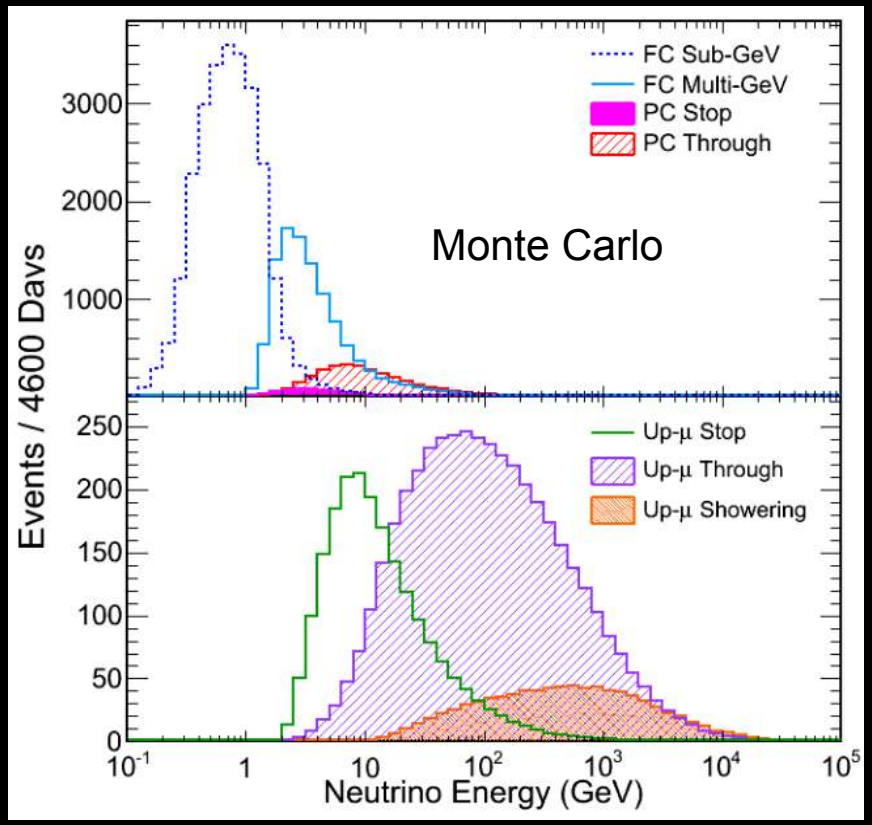


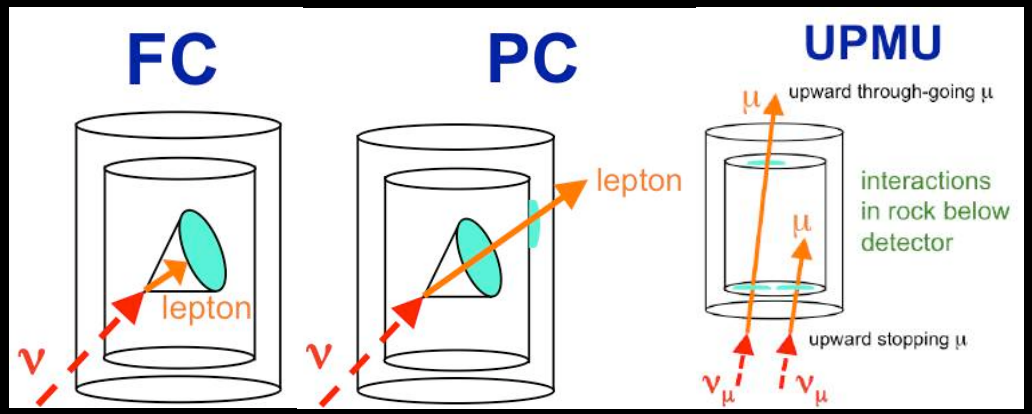
$$\nu_e + N \rightarrow e^- + N'$$

Atmospheric neutrinos: main background in DM-induced ν searches



atmospheric neutrinos at SK





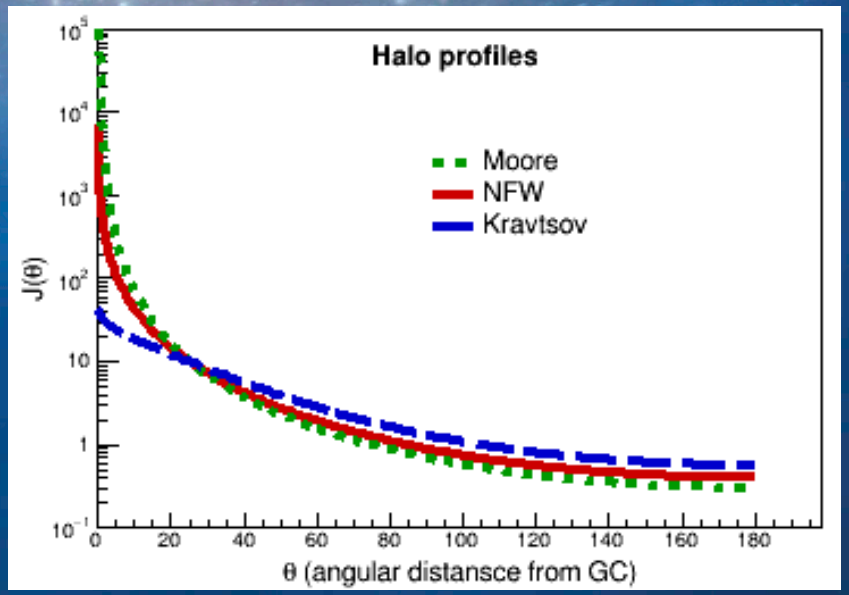
- ~10 events/day
- data period: 1996-2016
- ~50 000 events in total

Galactic WIMP search

ON-/OFF-source analysis (K.Frankiewicz)

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 <σV>



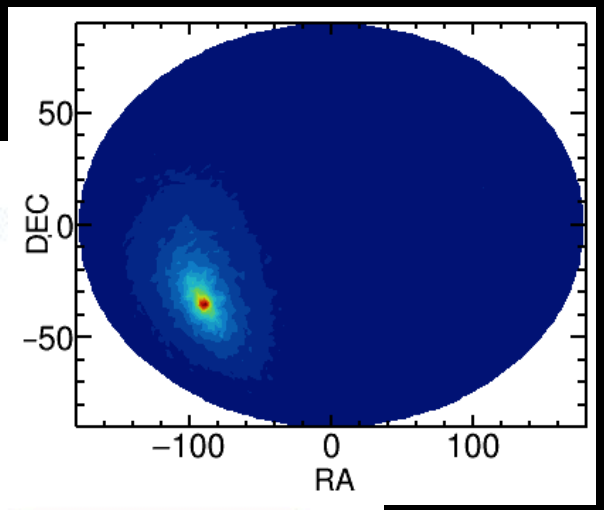
Expected signal intensity strongly depends on halo model
NFW is considered as a benchmark model

Galactic WIMP search: ON-/OFF-source

Analysis by K. Frankiewicz

Search for large-scale anisotropy due to DM-induced ν's from Milky Way

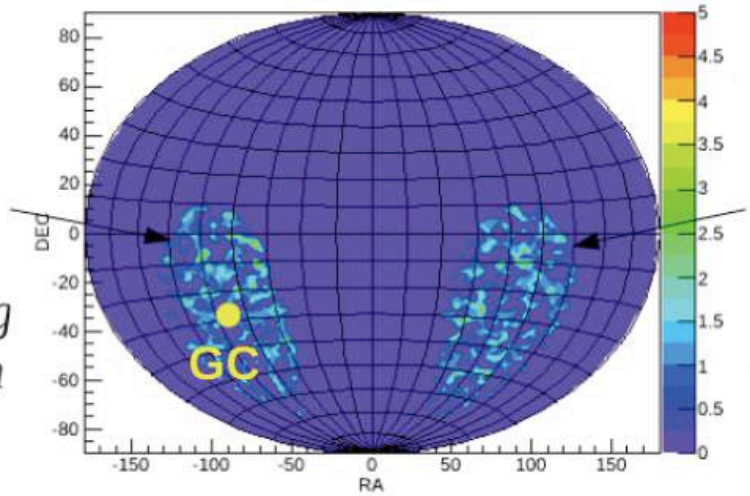
expectation for DM-induced neutrinos



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

on-source

$$N_{on}^{bkg} + N_{on}^{sig}$$

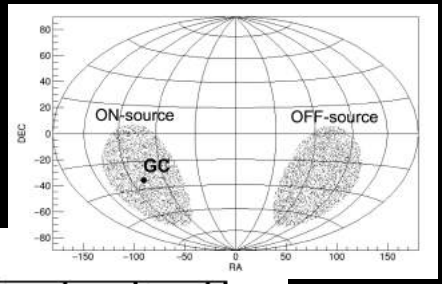


off-source

$$N_{off}^{bkg} + N_{off}^{sig}$$

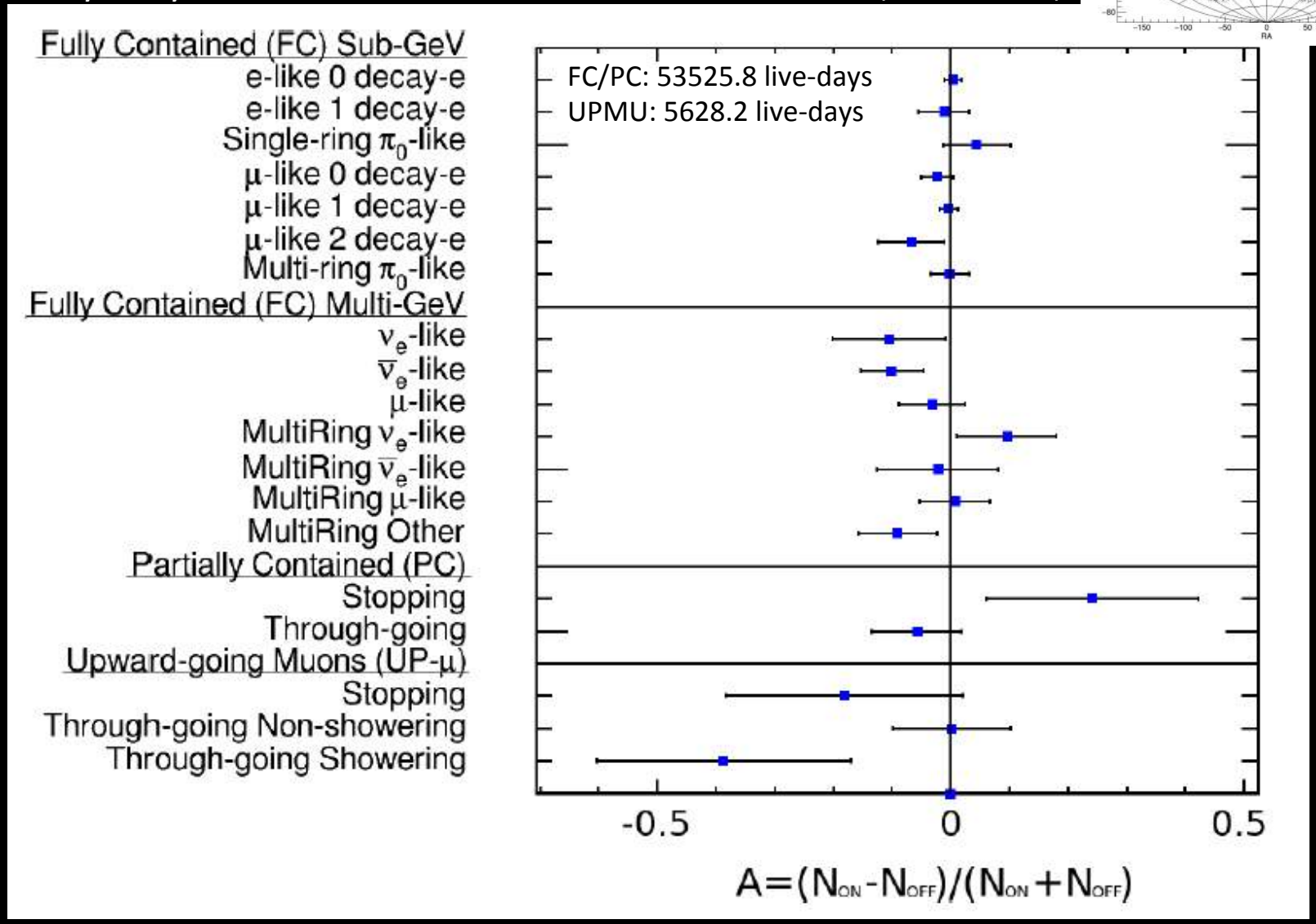
- Analysis uses ON-/OFF-source concept to estimate background directly from data
- Independent on MC simulations and related systematic uncertainties

ON-/OFF-source results



Analysis by K. Frankiewicz

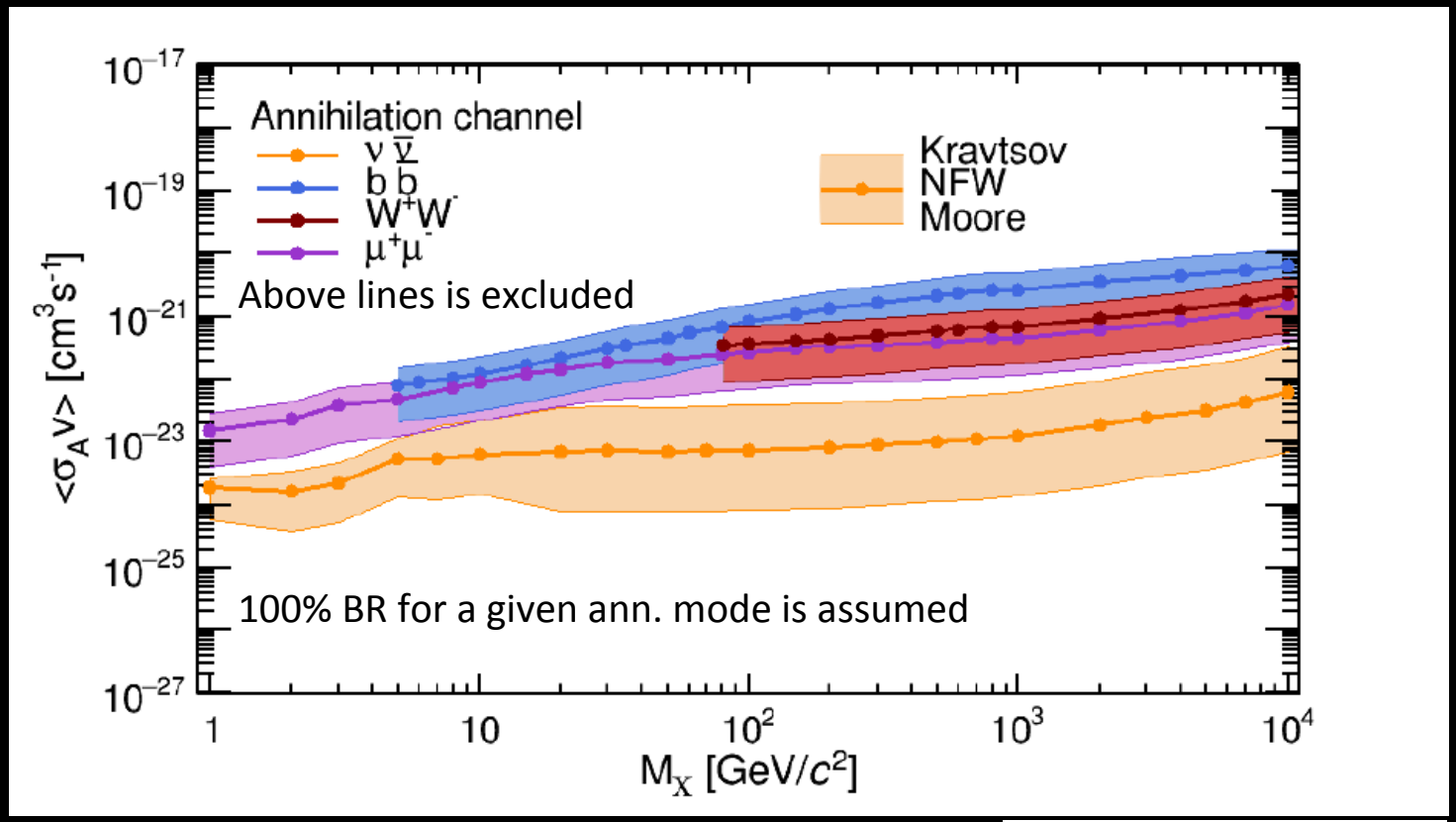
Based on SK-I-IV data (1996-2016)



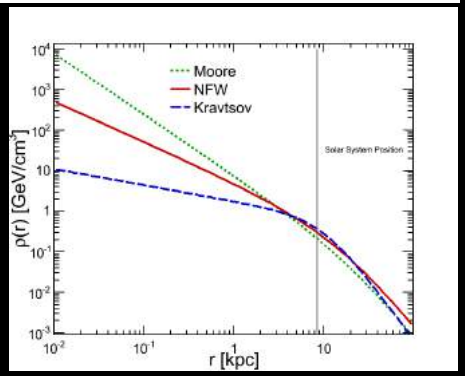
DATA is consistent with background, no asymmetry in neutrino flux observed

ON-/OFF-source results

90% CL upper limits on dark matter self-annihilation cross-section + halo model choice impact



- Intensity factors for halo profiles differs orders of magnitude →
- Comparison of these limit with other experimental results on the next slides



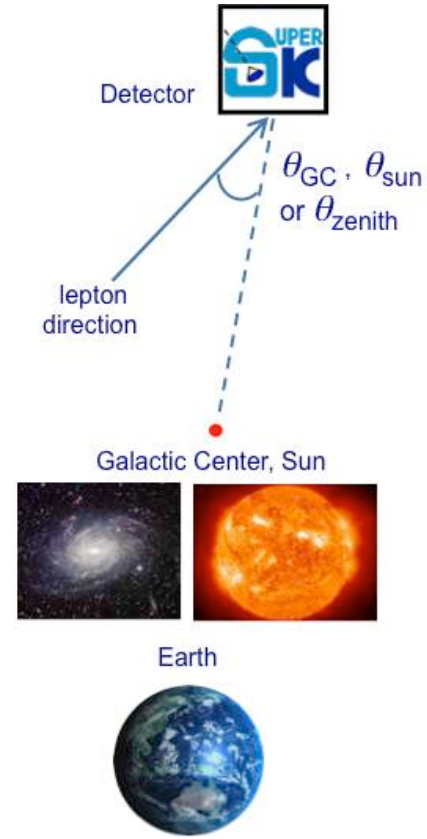
Galactic WIMP search

Global Fit analysis (P.Mijakowski)

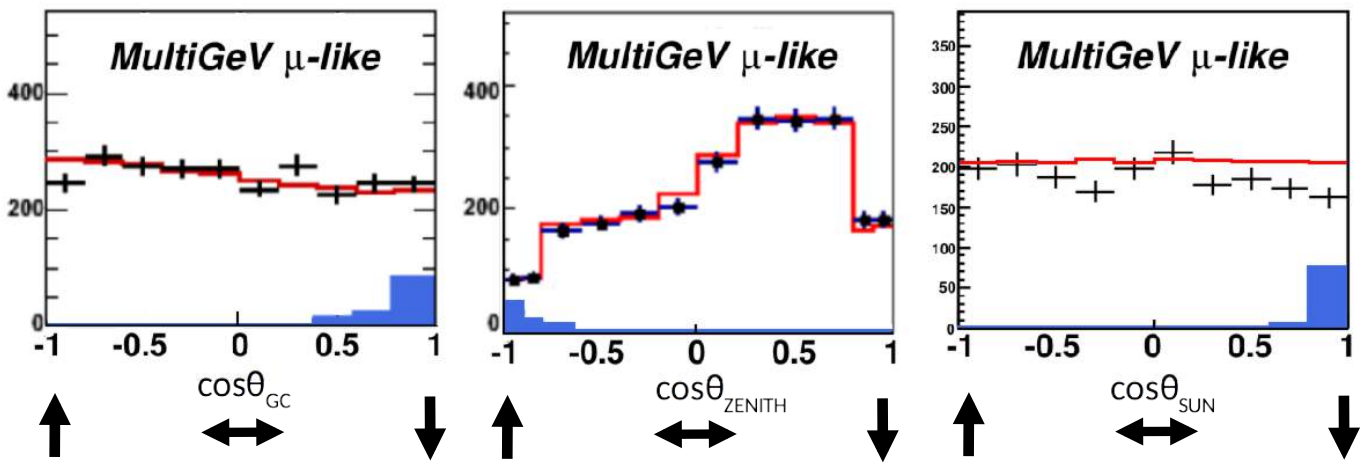
Global Fit method: DM searches at Super-K

- Search for excess of neutrinos form **Earth/Sun/Milky Way**
- **FIT:** for each tested WIMP mass & ann. mode, find configuration of ATM ν + DM signal that would match DATA the best using reconstructed angular & momentum distributions

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



Galactic WIMP search | **Earth WIMP search** | **Solar WIMP search**
point-like source



SK DATA

ATM MC (BKG) with oscillations

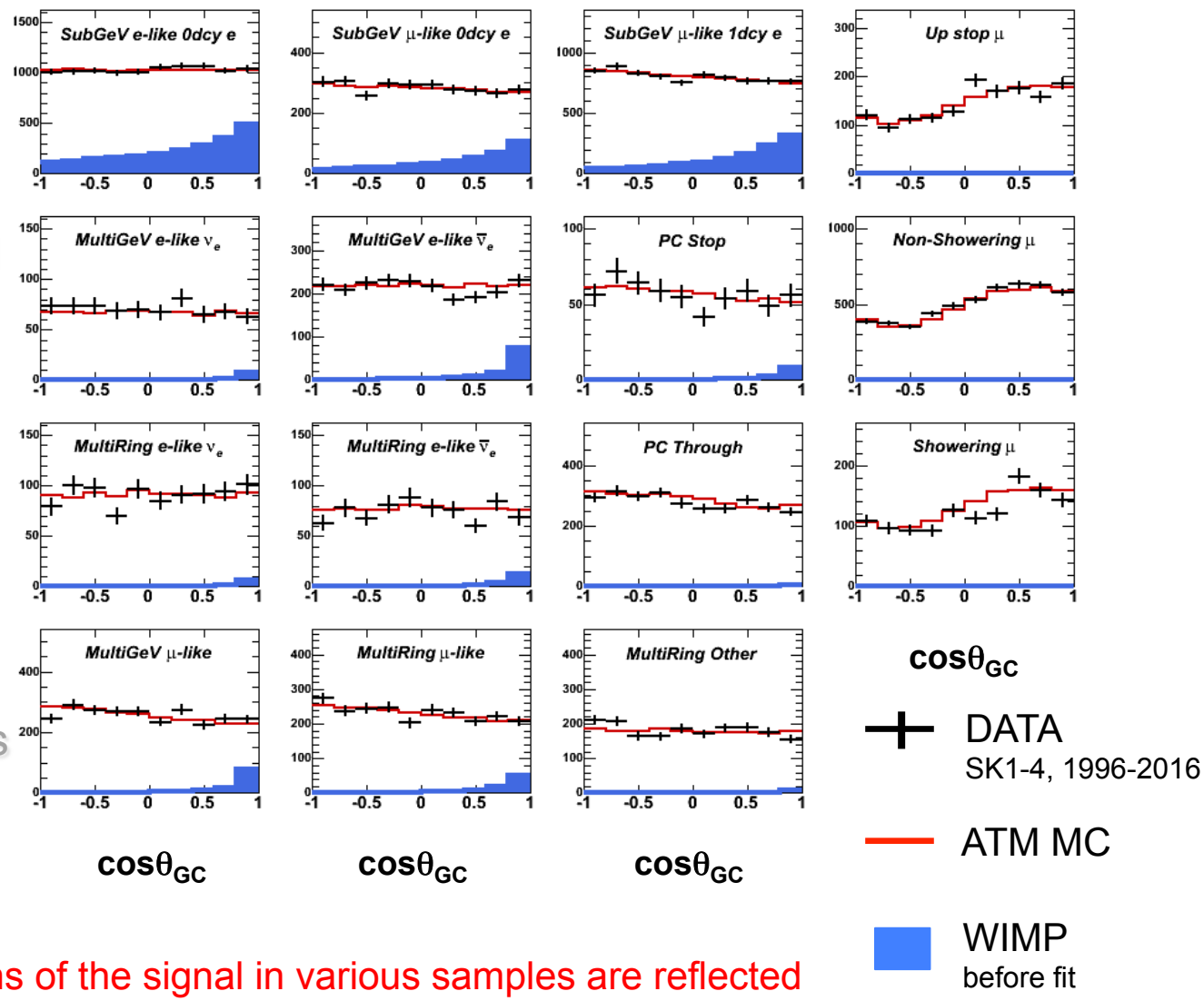
WIMP signal enhanced for illustration

- In these coordinate systems signal is easy to distinguish from atmospheric neutrino background

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 $<\sigma_A V>$

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



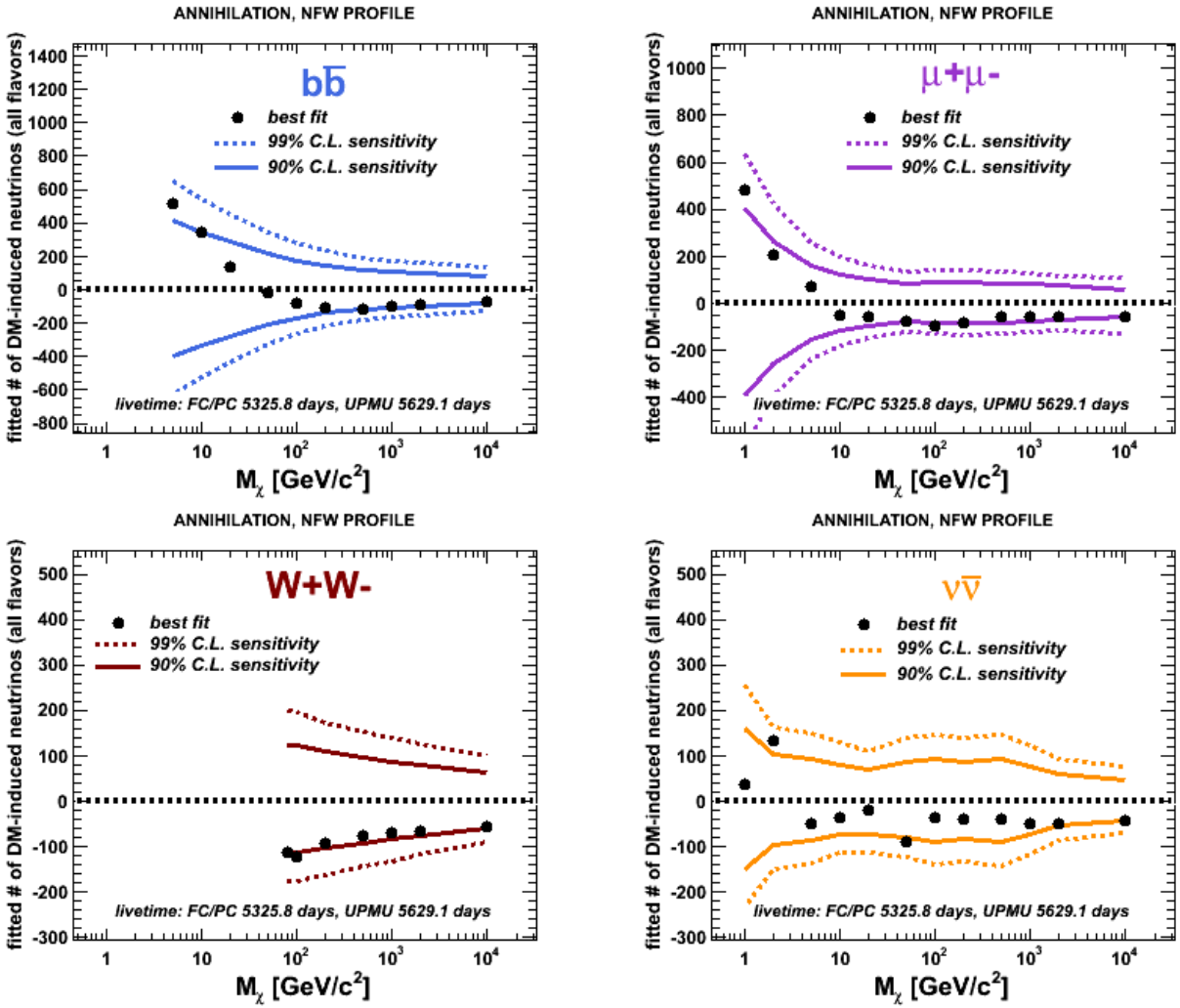
proportions of the signal in various samples are reflected

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

- 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 $\langle\sigma_A V\rangle$

SK preliminary

points on the plots are not independent



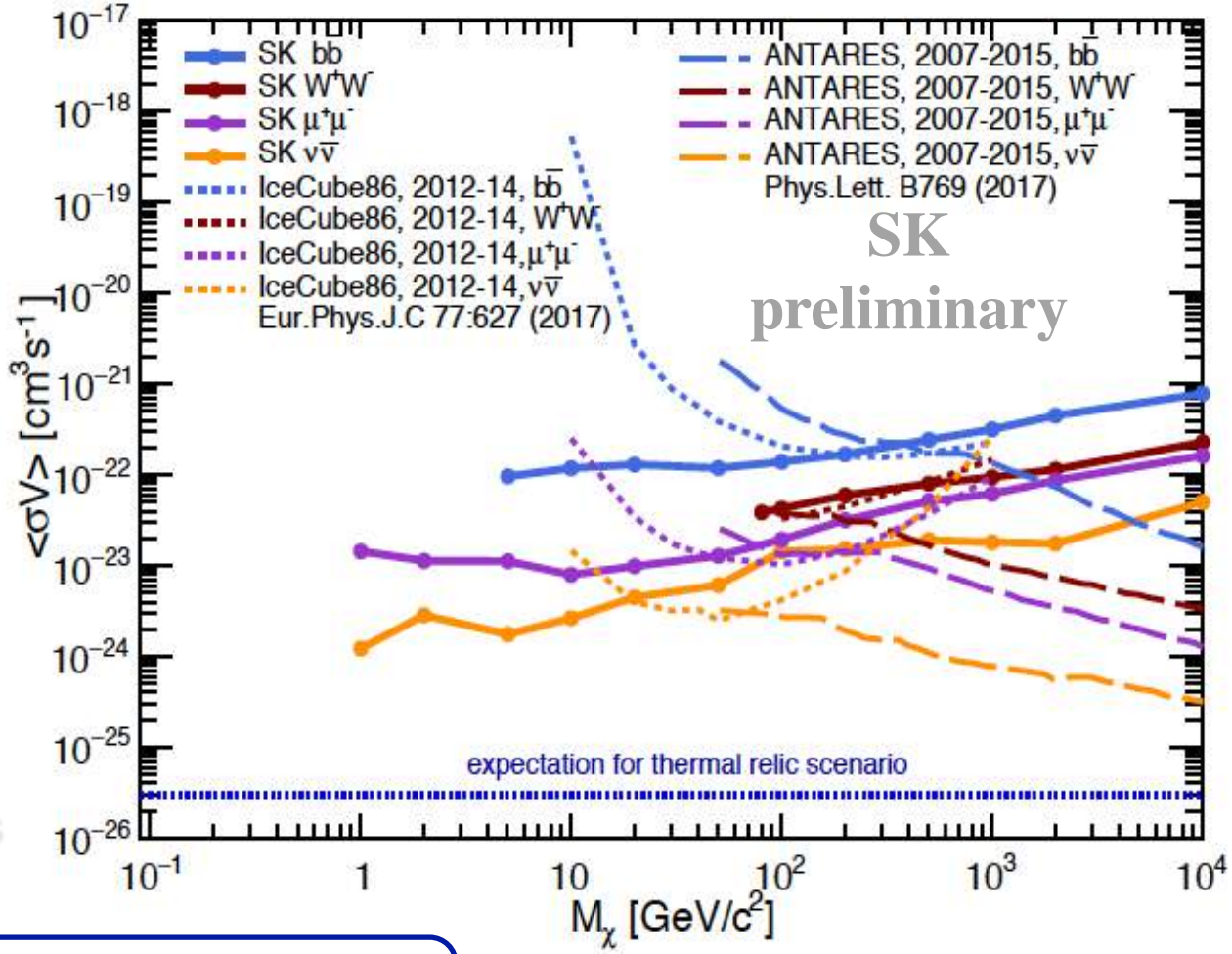
~150 systematic uncertainty terms included in the fit

p-values in backup

Galactic WIMP search: DM self-annihilation cross section

- 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 $\langle\sigma_A V\rangle$

90% CL upper limit



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

Galactic WIMP searches comparison

- Global Fit analysis yields ~1 order of magnitude stronger constraints than ON-/OFF-source

- If positron excess seen by *AMS-02* and *others* is due to leptohilic DM annihilation into $\mu^+\mu^-$ then we can probe the favored phase-space regions

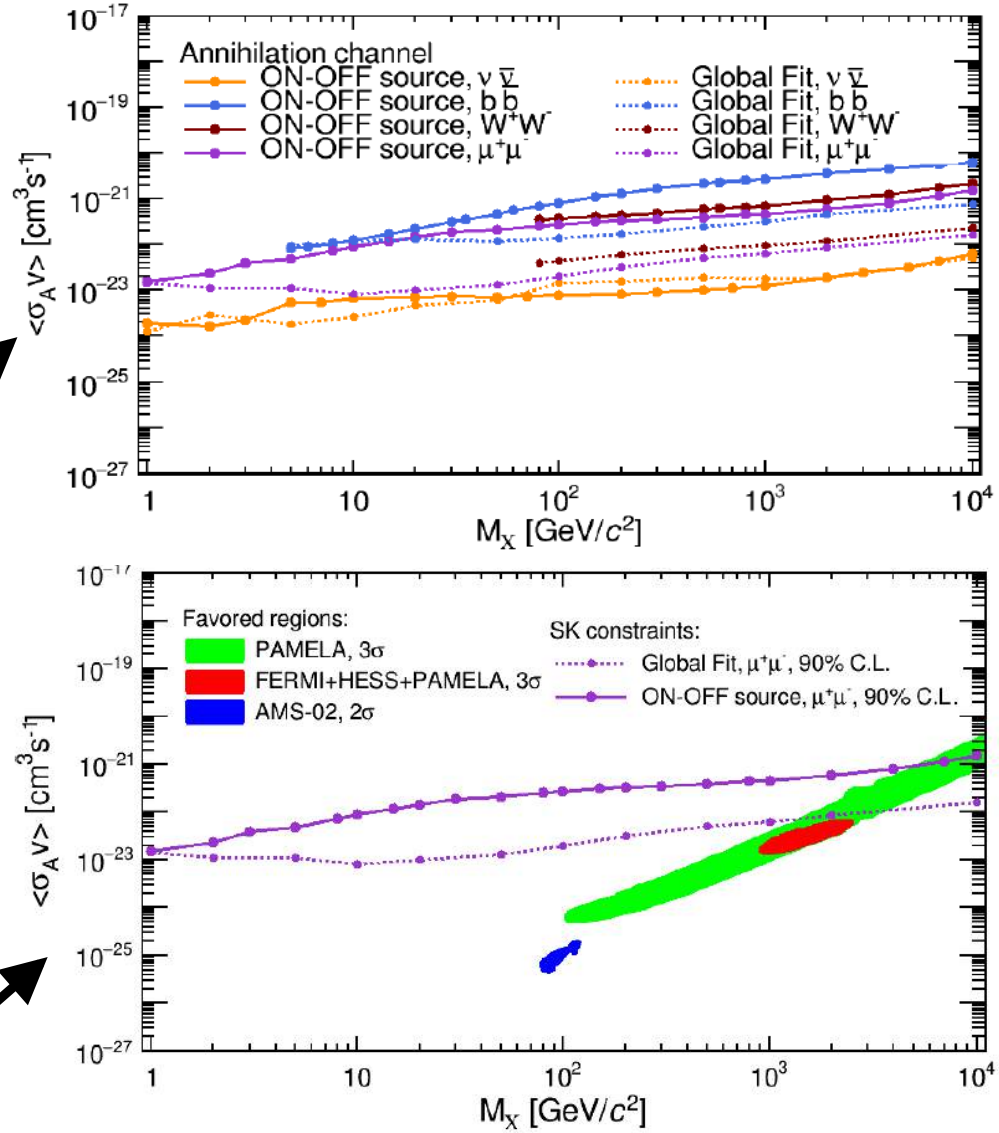


FIGURE 12.1: Favored regions obtained by interpreting the observed positron and electron excesses as due to dark matter annihilation in $\mu^+\mu^-$. Green region is favored by PAMELA (at 3σ), red region is favored by the global fit of FERMI, HESS and PAMELA data (at 3σ) (Meade et al., 2010), and blue region is favored by AMS-02 data (at 2σ) (Di Mauro et al., 2016). The 90% C.L. limits from SK data are plotted with solid purple line for "ON-OFF souce" analysis (this thesis), and with solid line for "Global fit" approach (Mijakowski, 2018). NFW halo model is assumed in all cases.

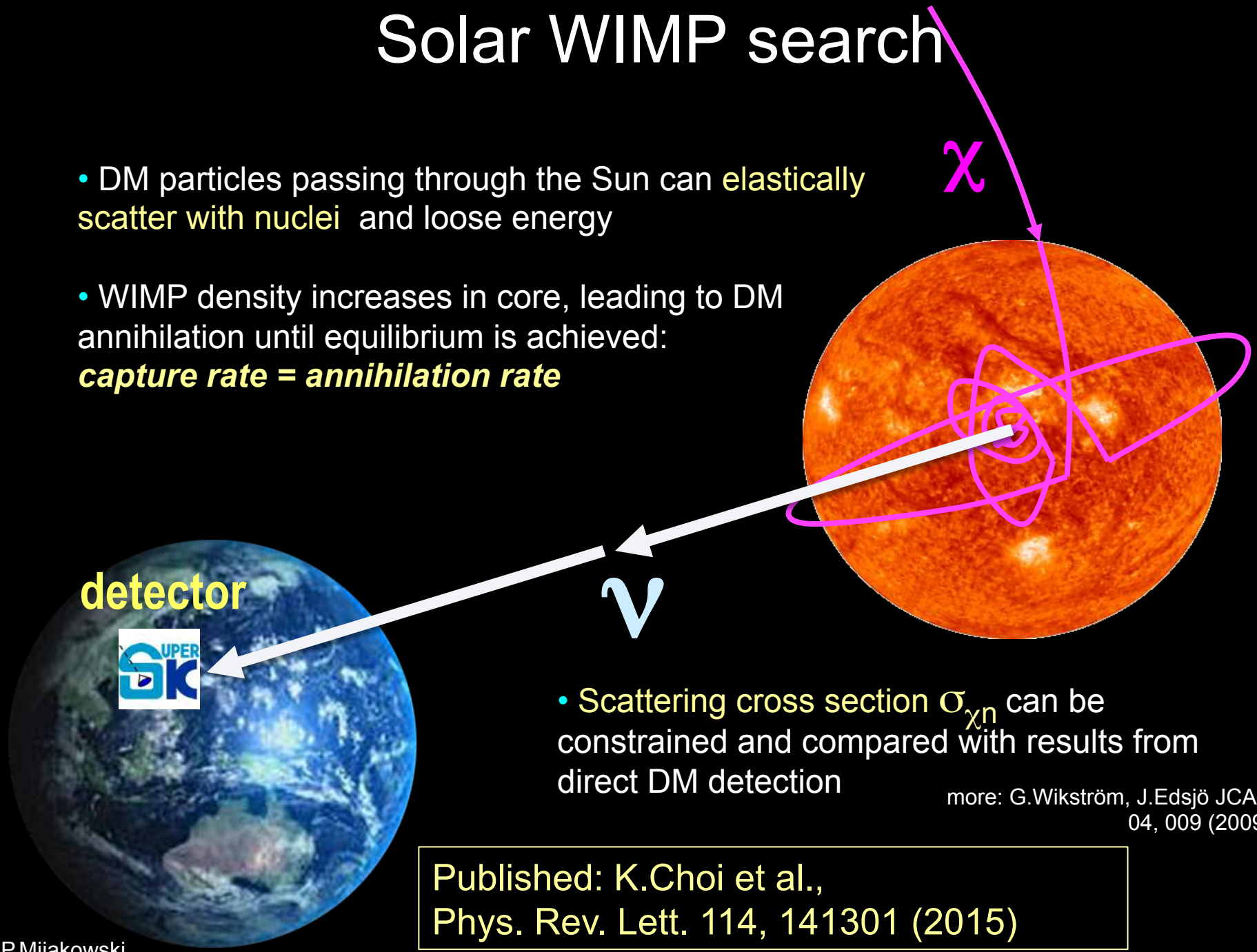
Solar WIMP search

Global Fit analysis (K. Choi)

Solar WIMP search

- DM particles passing through the Sun can elastically scatter with nuclei and loose energy

- WIMP density increases in core, leading to DM annihilation until equilibrium is achieved:
capture rate = annihilation rate



- Scattering cross section $\sigma_{\chi n}$ can be constrained and compared with results from direct DM detection

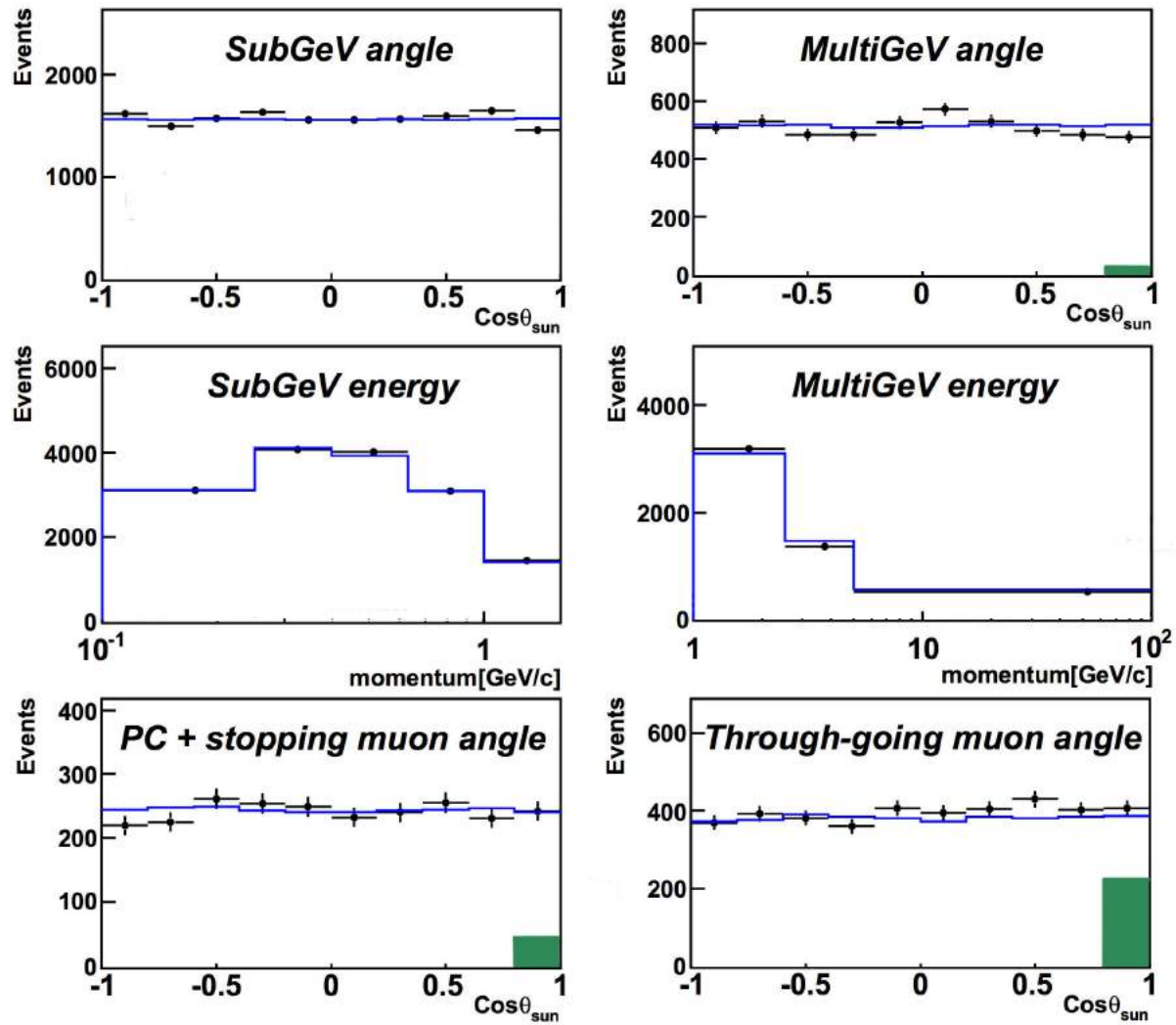
more: G.Wikström, J.Edsjö JCAP 04, 009 (2009)

Published: K.Choi et al., Phys. Rev. Lett. 114, 141301 (2015)

Solar WIMP search

- FIT based on lepton mom. & $\cos\theta_{SUN}$ distributions, 3903 days of SK data (1996-2012)
- No excess of ν's from the SUN as compared to atm bkg
- 90% CL upper limit on WIMP-nucleon scattering cross section σ_{Xn} for $\tau^+\tau^-$, $b\bar{b}$ and W^+W^- channels

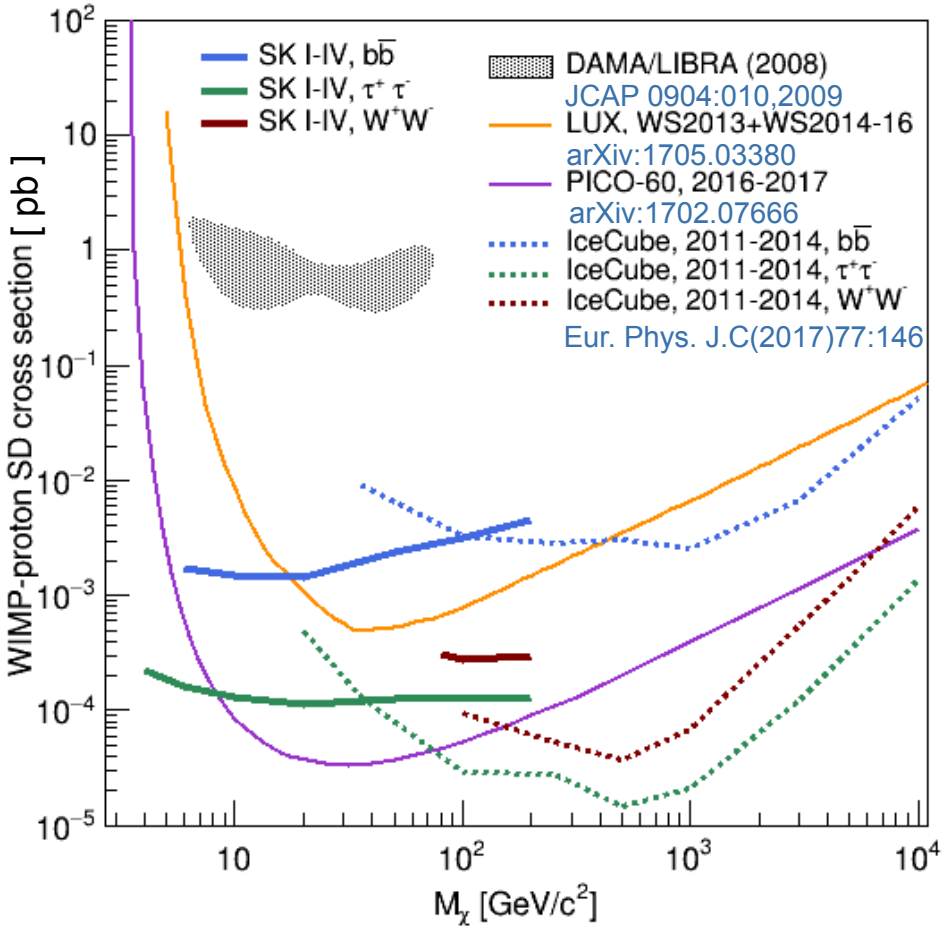
example for: 200 GeV WIMPs, $\tau^+\tau^-$ ann. channel



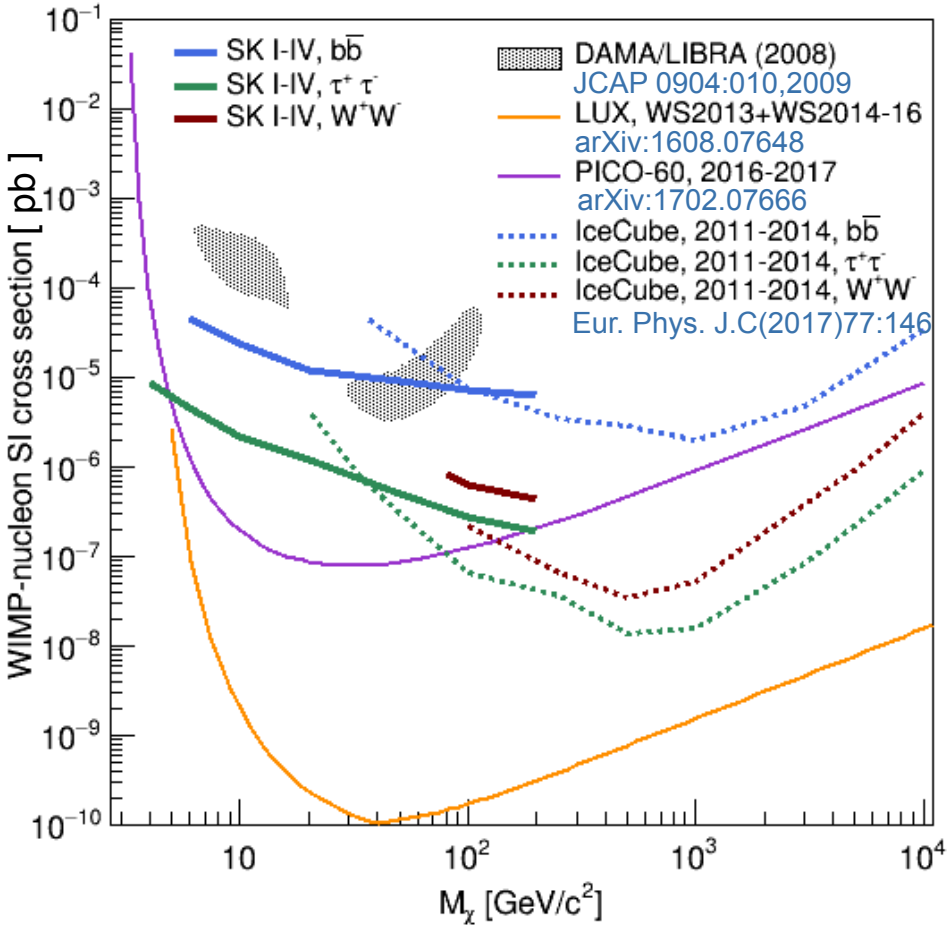
Solar WIMP search: WIMP-nucleon SI & SD cross section limit

90% CL upper limit

spin dependent interactions



spin independent interactions



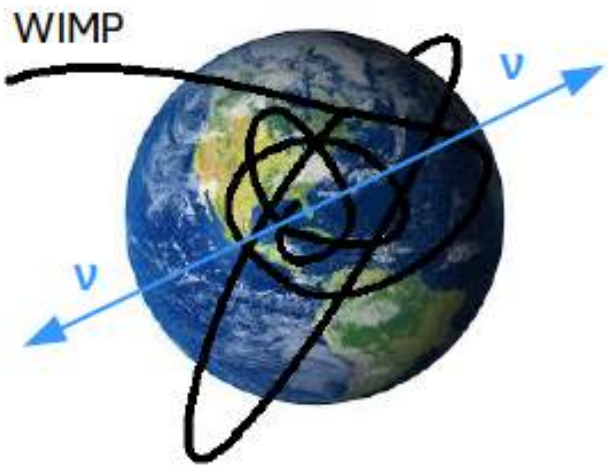
published: K.Choi et al., Phys. Rev. Lett. 114, 141301 (2015)

Earth WIMP search

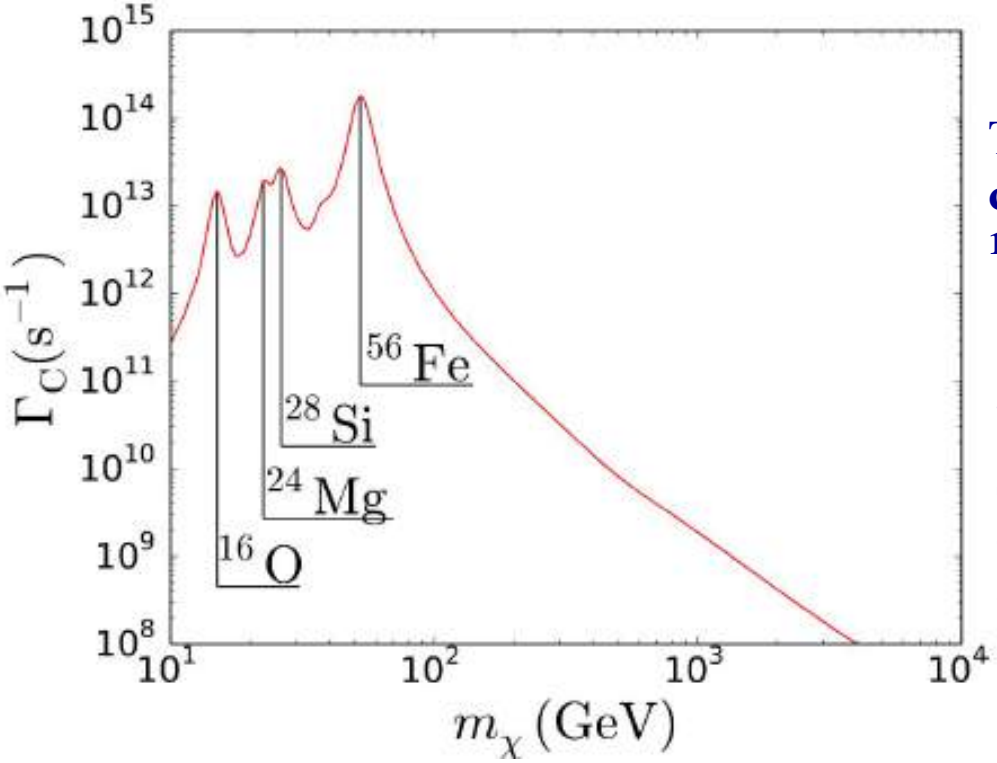
Global Fit analysis (K.Frankiewicz)

Earth WIMP search

- Spin-independent interactions dominate in the capturing process → scalar interaction in which WIMPs couple to the nucleus mass
- If the mass of DM matches given heavy element, the capture rate increases considerably



WIMP caputure rate in the Earth



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

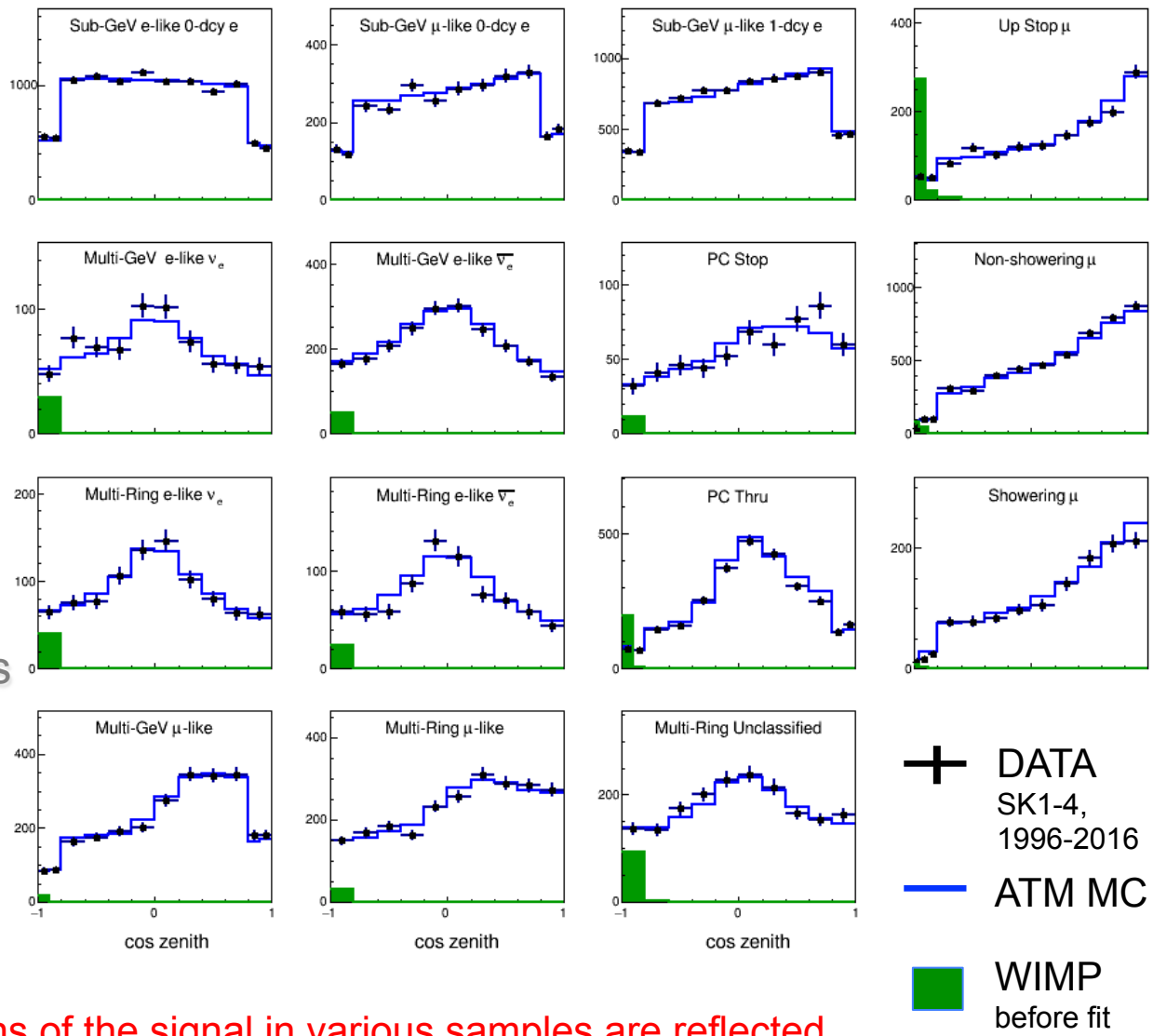
WIMP-nucleon SI scattering cross section $\sigma_{\chi\text{-}N}$ can be constrained and compared with results from direct DM detection.

Earth WIMP search: data fit

SK preliminary

- FIT based on lepton mom. & $\cos\theta_{zenith}$ 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 $\sigma_{\chi\text{-}n}$

example: 25GeV WIMPs $\tau^+\tau^-$ ann. channel

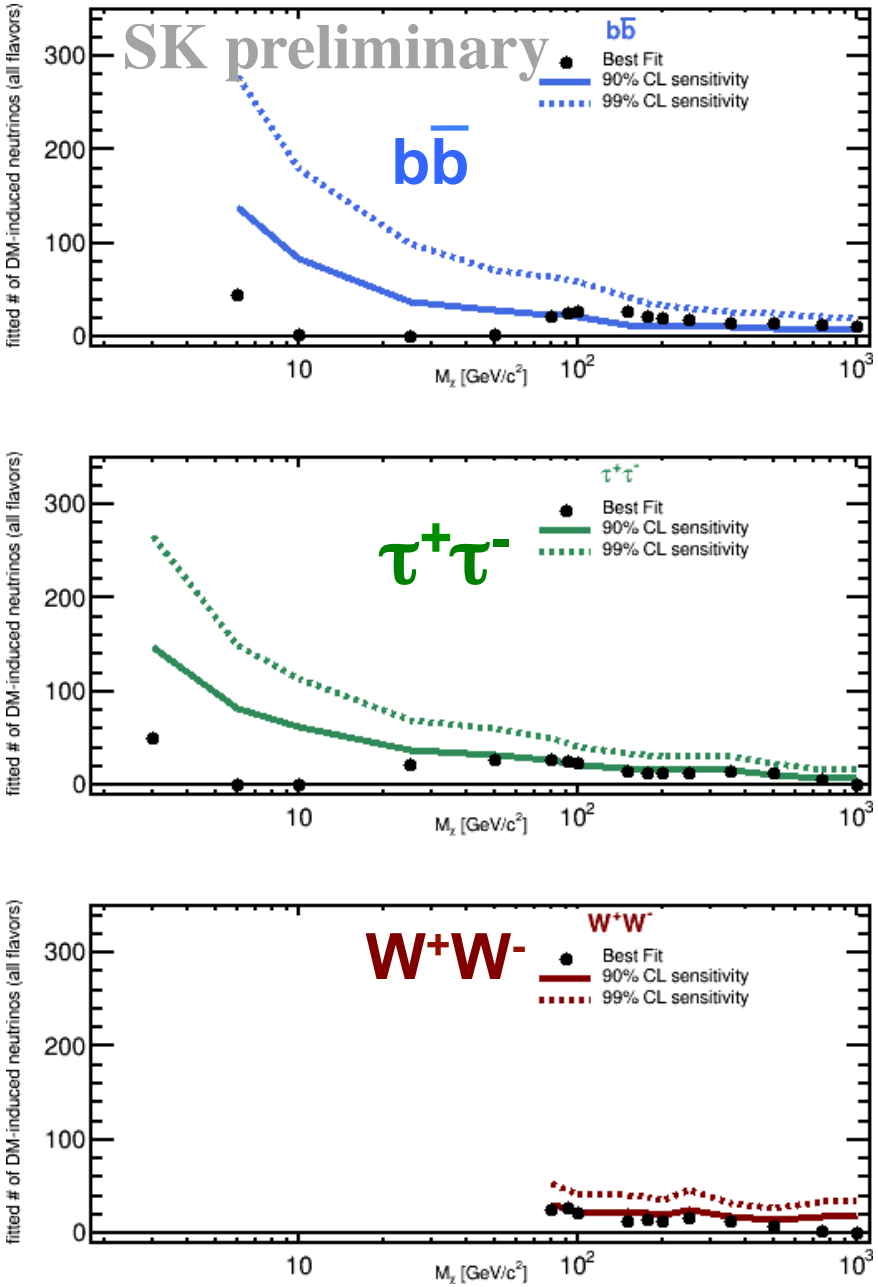


proportions of the signal in various samples are reflected

Earth WIMP search: fitted number of DM-induced ν̀s

Analysis by K. Frankiewicz

- FIT based on lepton mom. & $\cos\theta_{zenith}$ 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 $\sigma_{\chi\text{-}n}$



Earth WIMP search: fitted number of DM-induced ν̀s

Analysis by K. Frankiewicz

- FIT based on lepton mom. & $\cos\theta_{zenith}$ distributions, 5326-5629 live-days,1996-2016
- Fit results are consistent with null WIMP contribution
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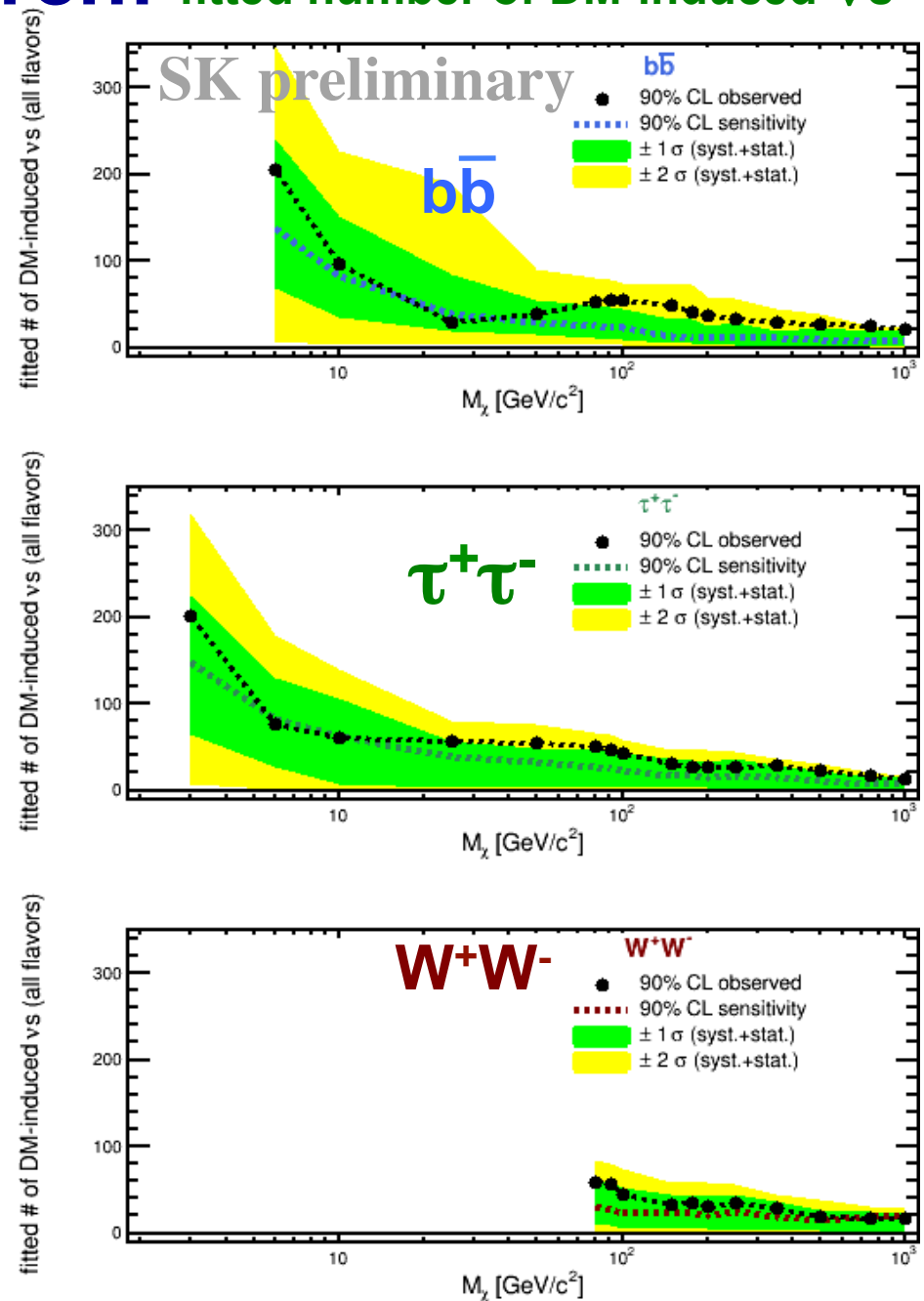
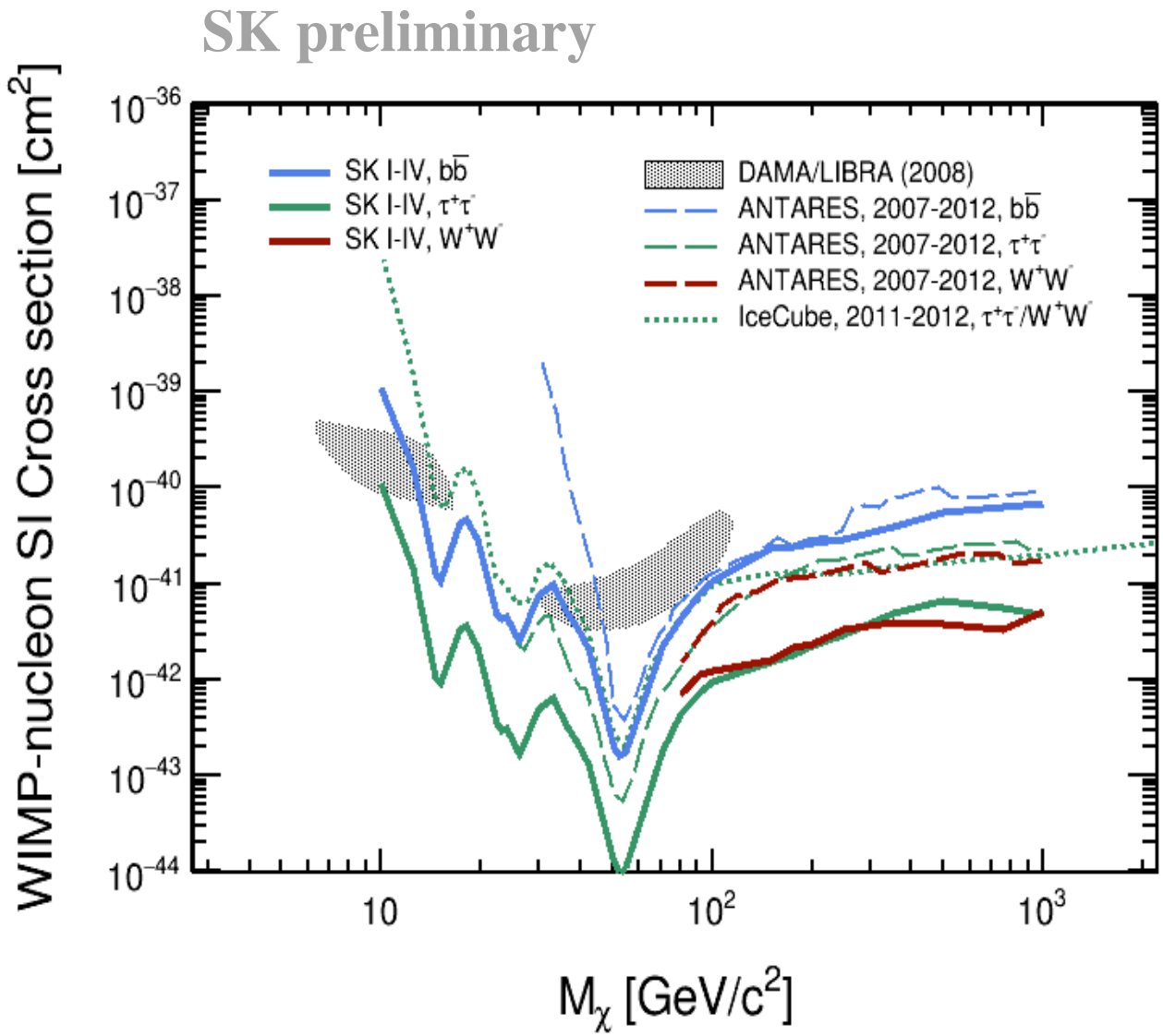


Earth WIMP search: WIMP-nucleon SI cross-section limit

Analysis by K. Frankiewicz

- FIT based on lepton mom. & $\cos\theta_{zenith}$ 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 $\sigma_{\chi\text{-}n}$



best limit among neutrino telescopes!

Summary

- DM induced neutrinos has not been observed at Super-Kamiokande so far

- Galactic WIMP search (2017)
  - upper limits on $<\sigma_A V>$ for wide range of WIMPs masses (1 GeV to 10 TeV)
  - strongest limits < 20-100GeV among ν experiments

- Solar WIMP search (2015)
  - strongest limits < 20-100GeV among ν experiments, published PRL.114, 141301 (2015)

- Earth WIMP search (2017)
  - upper limits on spin-independent WIMP-nucleon cross-section
  - high sensitivity to resonant capture region → currently the strongest limits from ν experiments
  - PhD of K.Frankiewicz, paper in preparation, target PRL

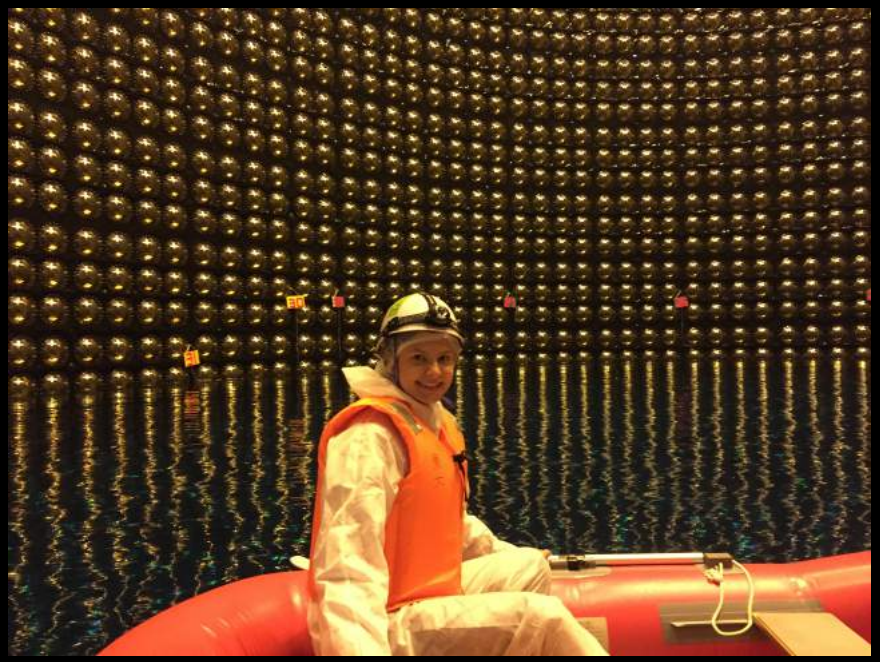
European Commission | Horizon 2020 European Union funding for Research & Innovation

NATIONAL SCIENCE CENTRE POLAND

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

SONATA-BIS 2015/18/E/ST2/00758
PRELUDIUM 2015/17/N/ST2/04064

Thank you!

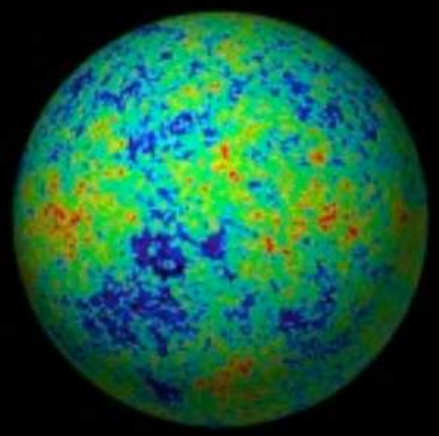


… we keep looking

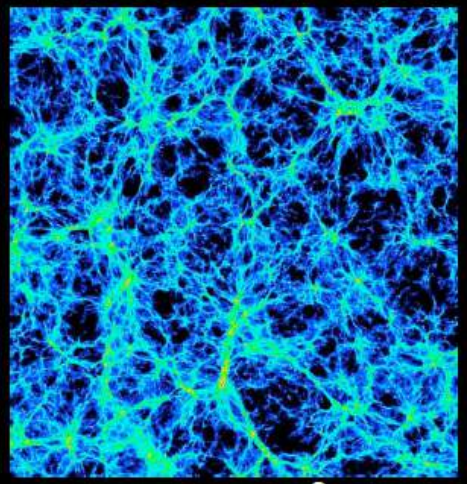
supplementary slides

Dark Matter

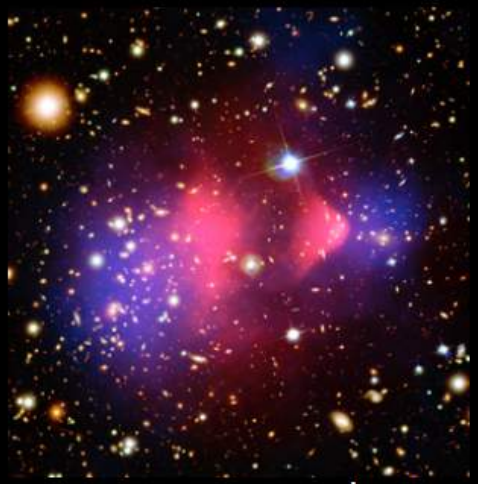
CMB



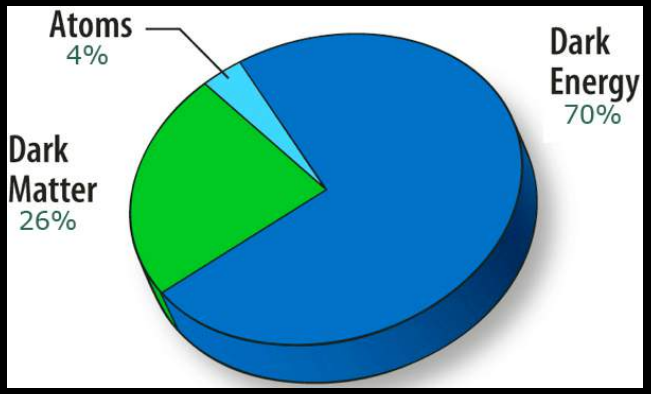
Supernova

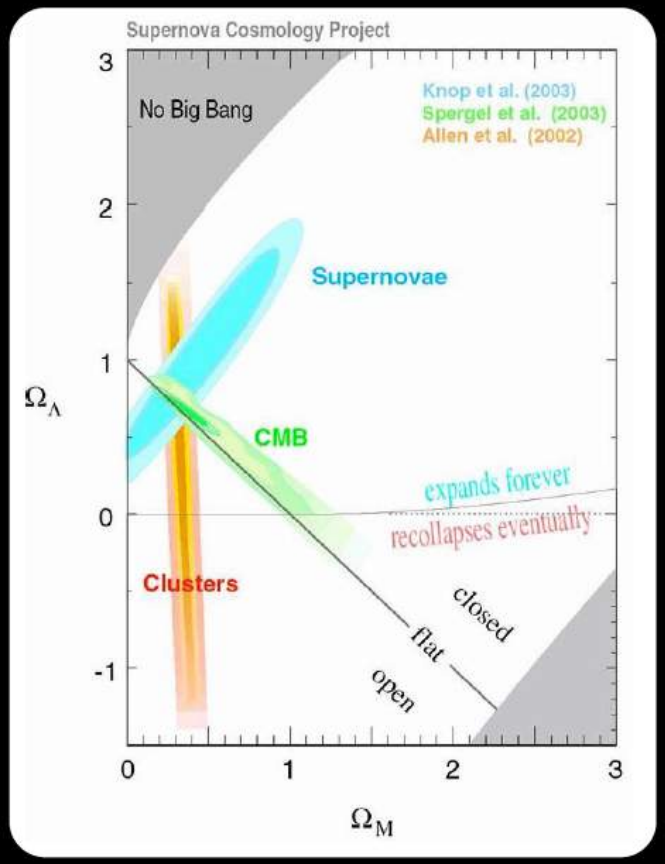


Structure



Lensing



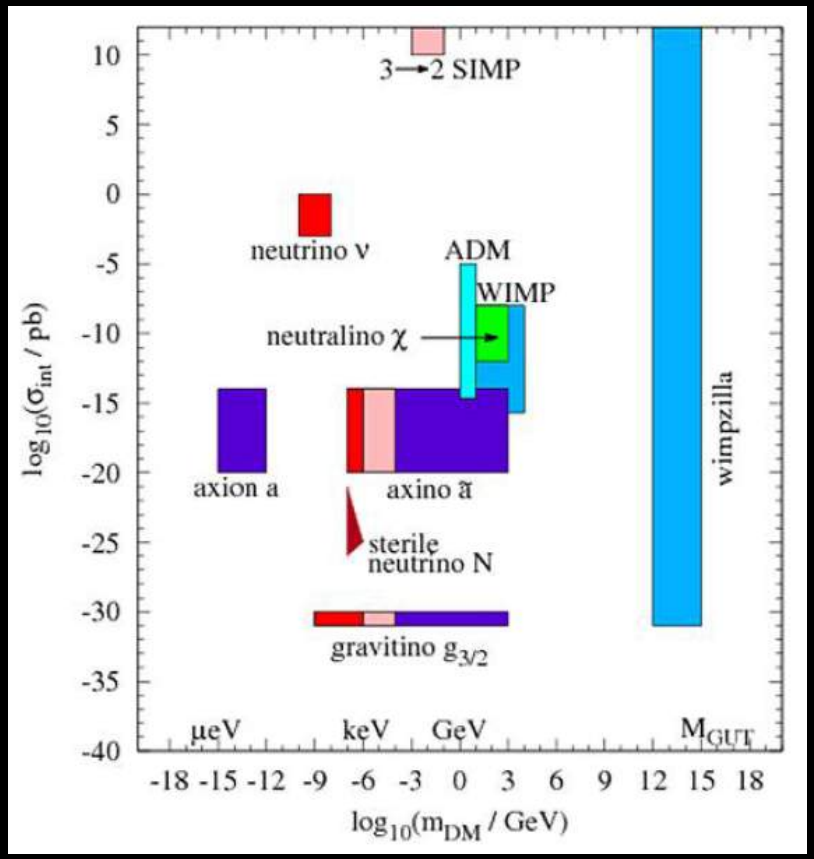


Dark Matter Candidates

Well motivated:

- ~~neutrino~~ – 'hot' DM
- WIMP
- neutralino χ
- gravitino $\tilde{G}$
- axion a
- axino $\tilde{a}$

still main candidate



WIMP (Weakly Interacting Massive Particle)

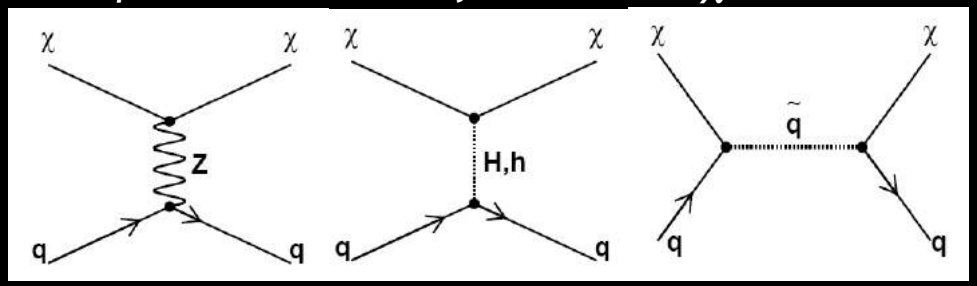
- neutral
- long livetime
- massive (GeV - TeV)
- weekly interacting with matter

Good WIMP candidate from SUSY → LSP

neutralino χ

$$\tilde{\chi} = a_1\tilde{\gamma} + a_2\tilde{Z} + a_3\tilde{H}_1 + a_4\tilde{H}_2$$

Example interactions of neutralino χ



Jungman, Kamionkowski, Griest, Phys. Rep., 267, 195 (1996)

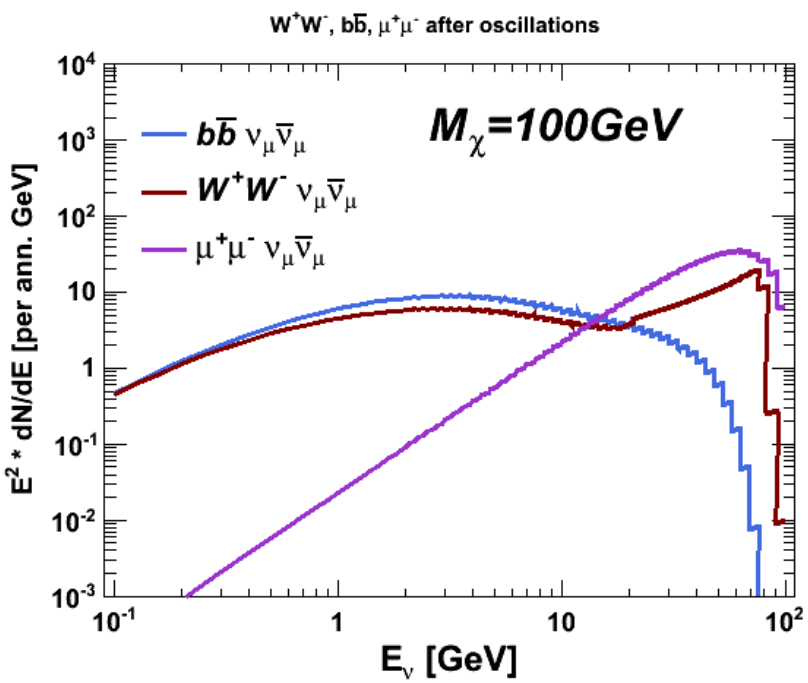
Signal simulation

Simulate DM signal before detection → DarkSUSY & WimpSim

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

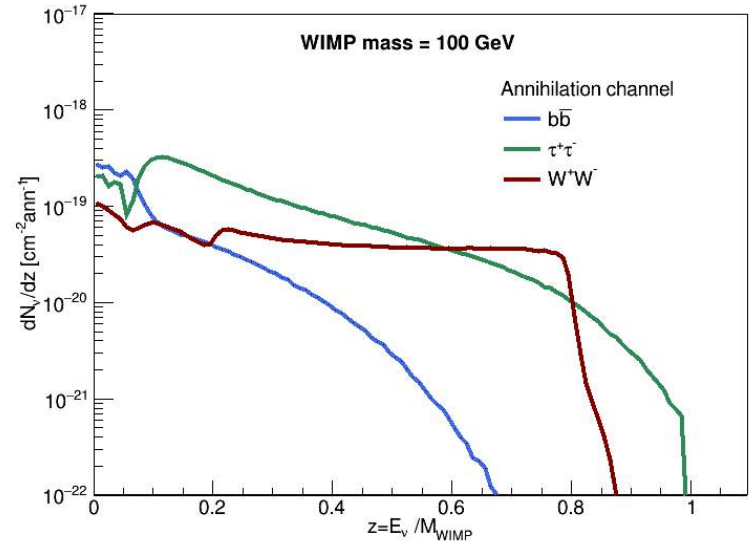
EXAMPLE: Galactic WIMP search

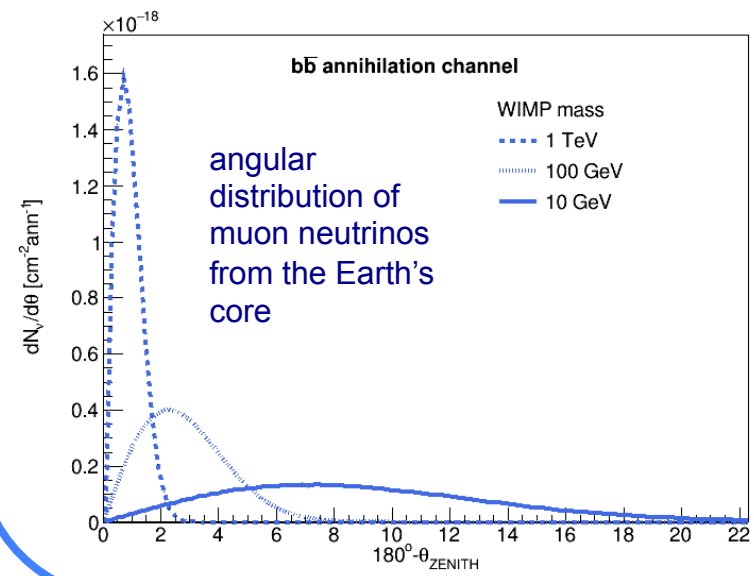
differential $\nu_\mu \bar{\nu}_\mu$ energy spectra per DM annihilation for **M_χ=100** GeV (oscillated throughout Galaxy)



EXAMPLE: Earth WIMP search

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





angular distribution of muon neutrinos from the Earth's core

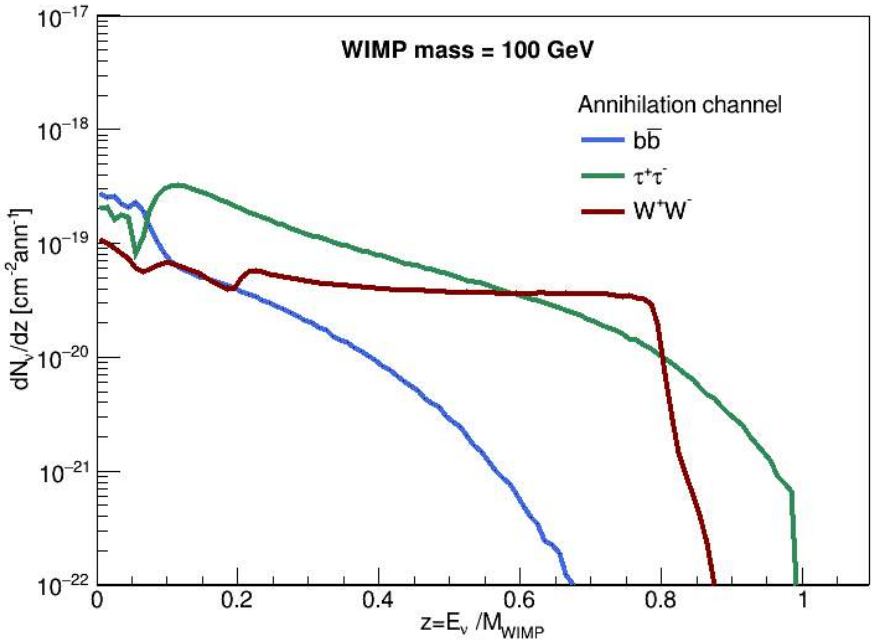
Earth WIMP search: signal simulation

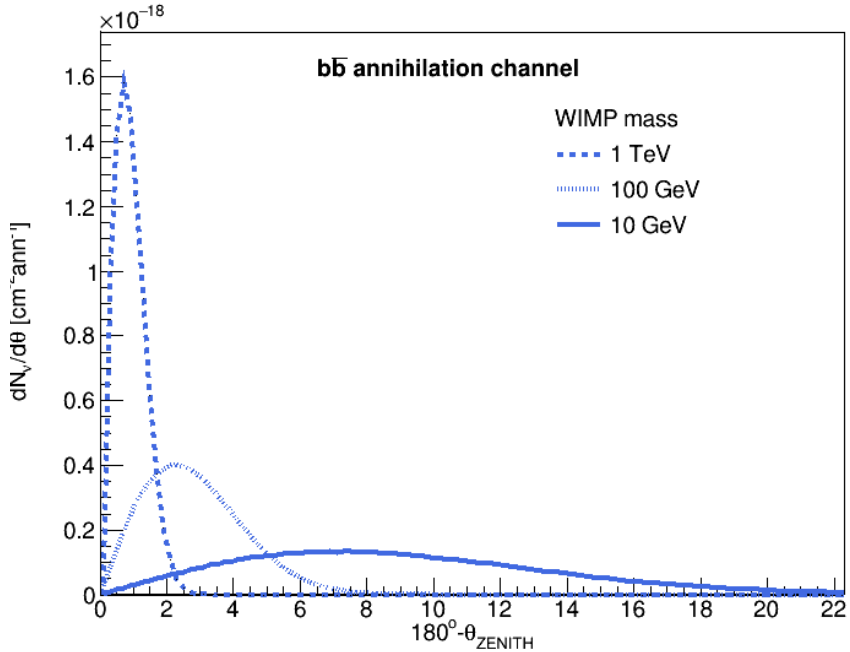
Simulate DM signal before detection → DarkSUSY & WimpSim

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

EXAMPLES

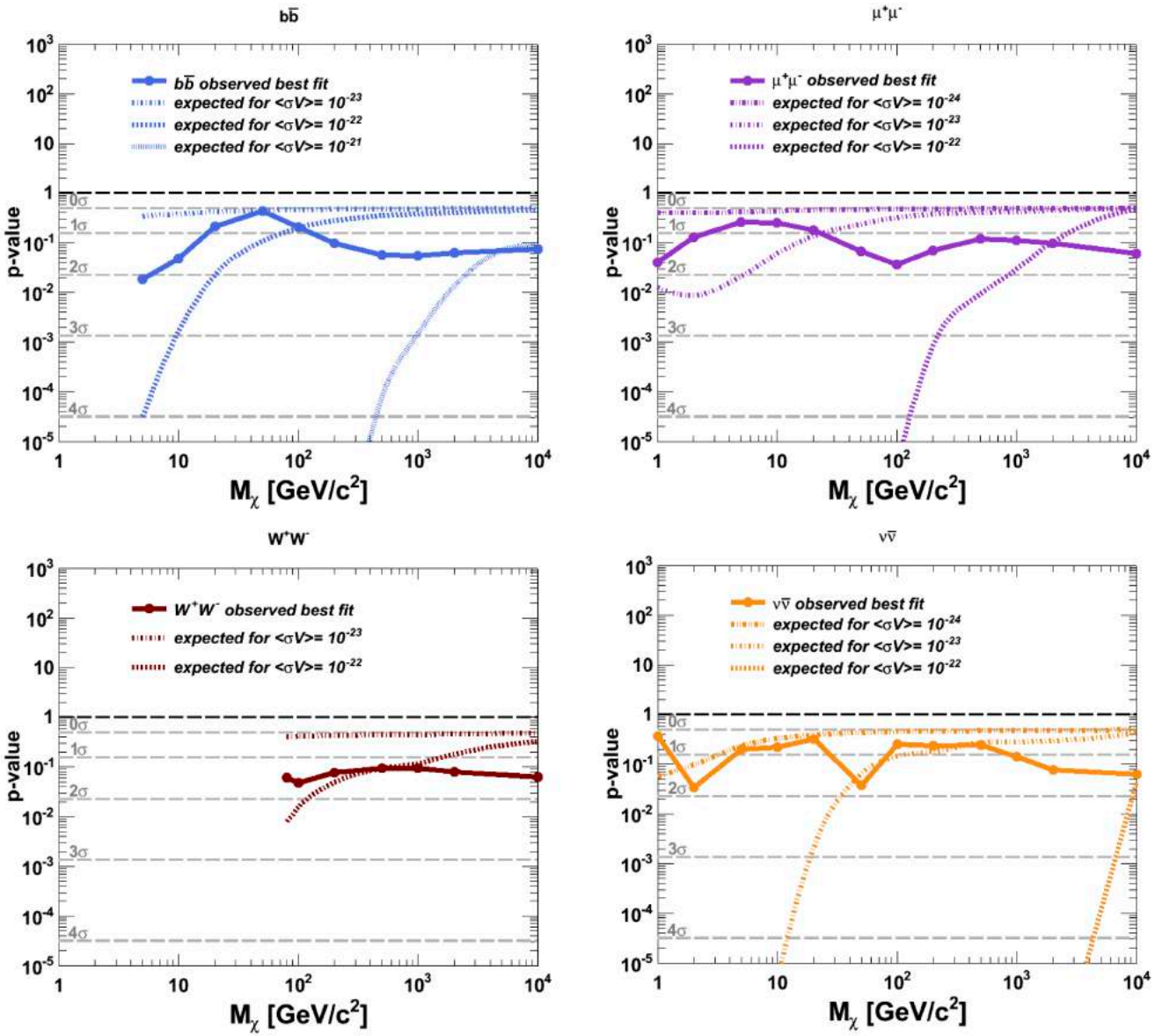
muon neutrino flux produced in WIMP annihilation in the Earth's core



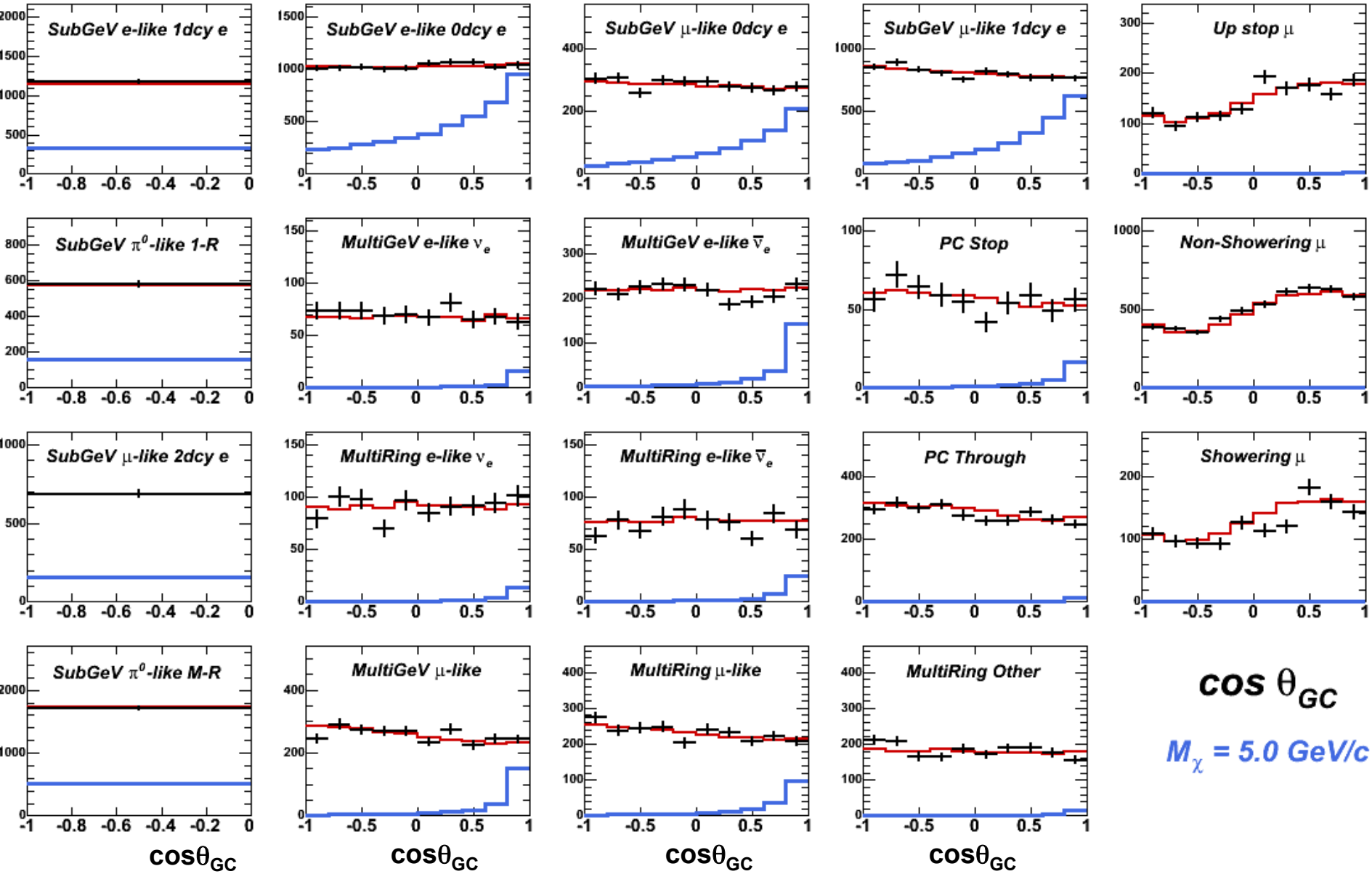


- Energy spectra and angular distribution for each neutrino flavor are calculated for given annihilation channel and assumed WIMP mass
- 3-flavor ν oscillations and interactions included

Galactic WIMP search: p-value's



Galactic WIMP search: signal llustration 5GeV bb-bar

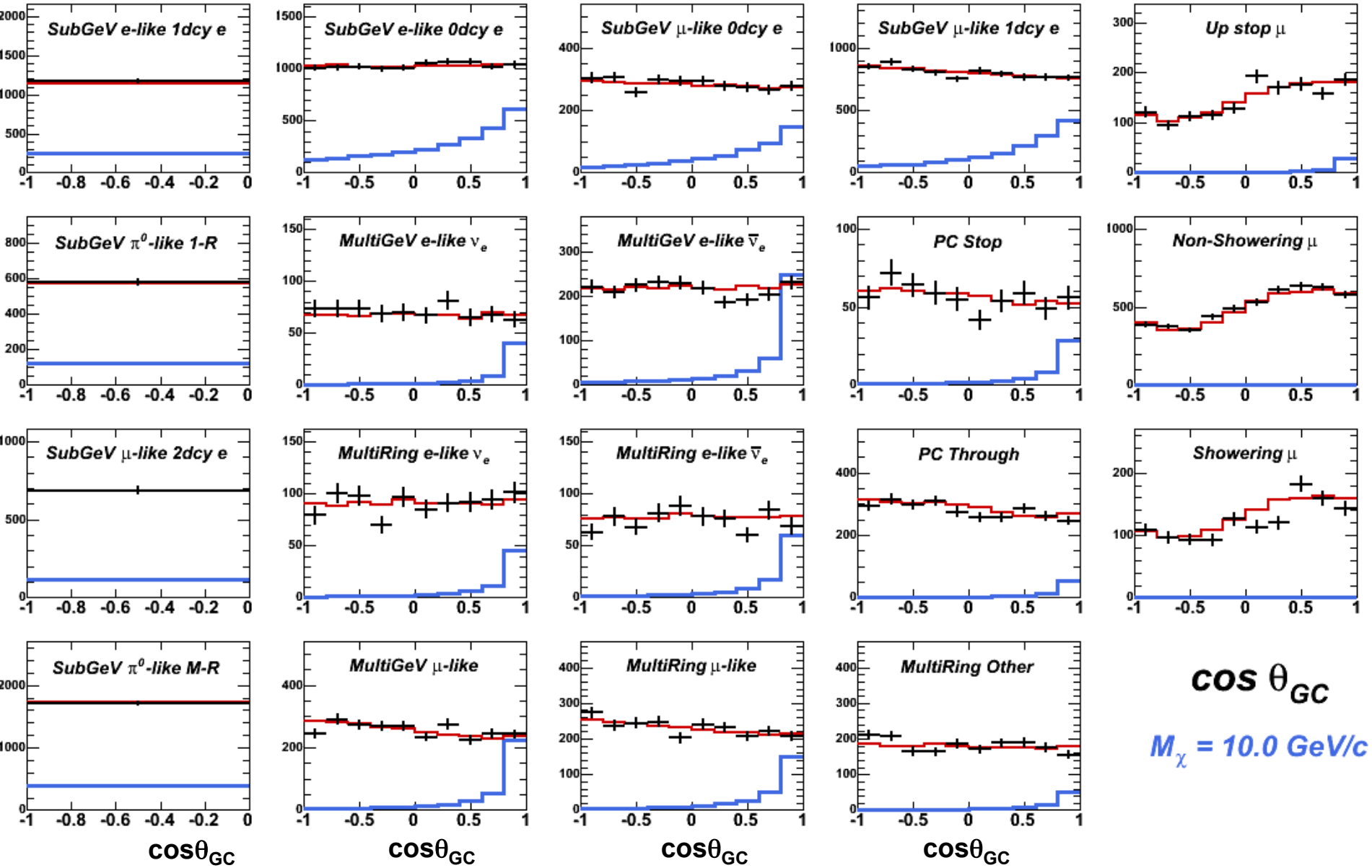


DATA
SK1-4, 1996-2016

ATM MC+WIMP
at best fit point

WIMP
before fit

Galactic WIMP search: signal llustration 10GeV bb-bar

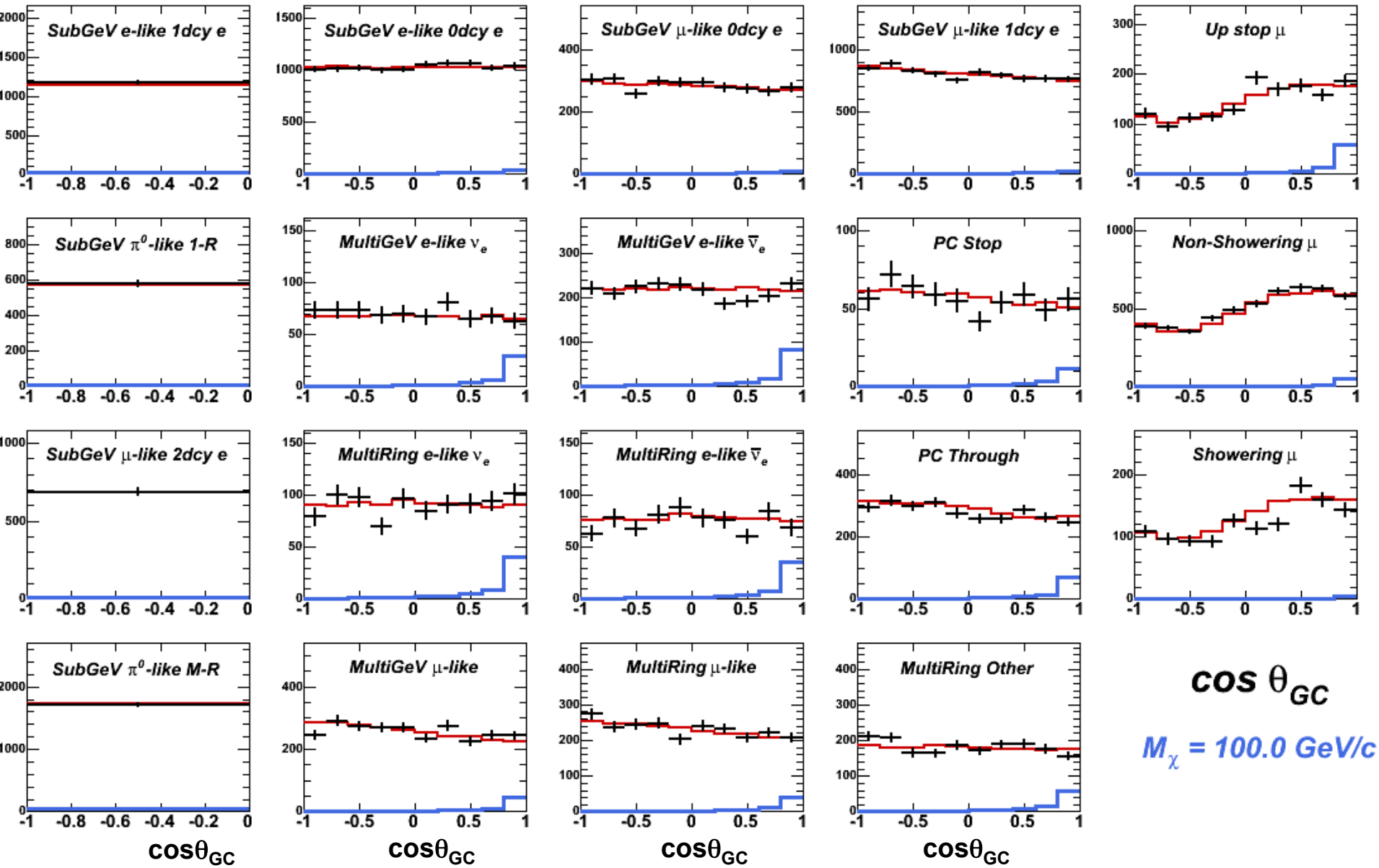


DATA
SK1-4, 1996-2016

ATM MC+WIMP
at best fit point

WIMP
before fit

Galactic WIMP search: signal llustration 100GeV bb-bar



DATA
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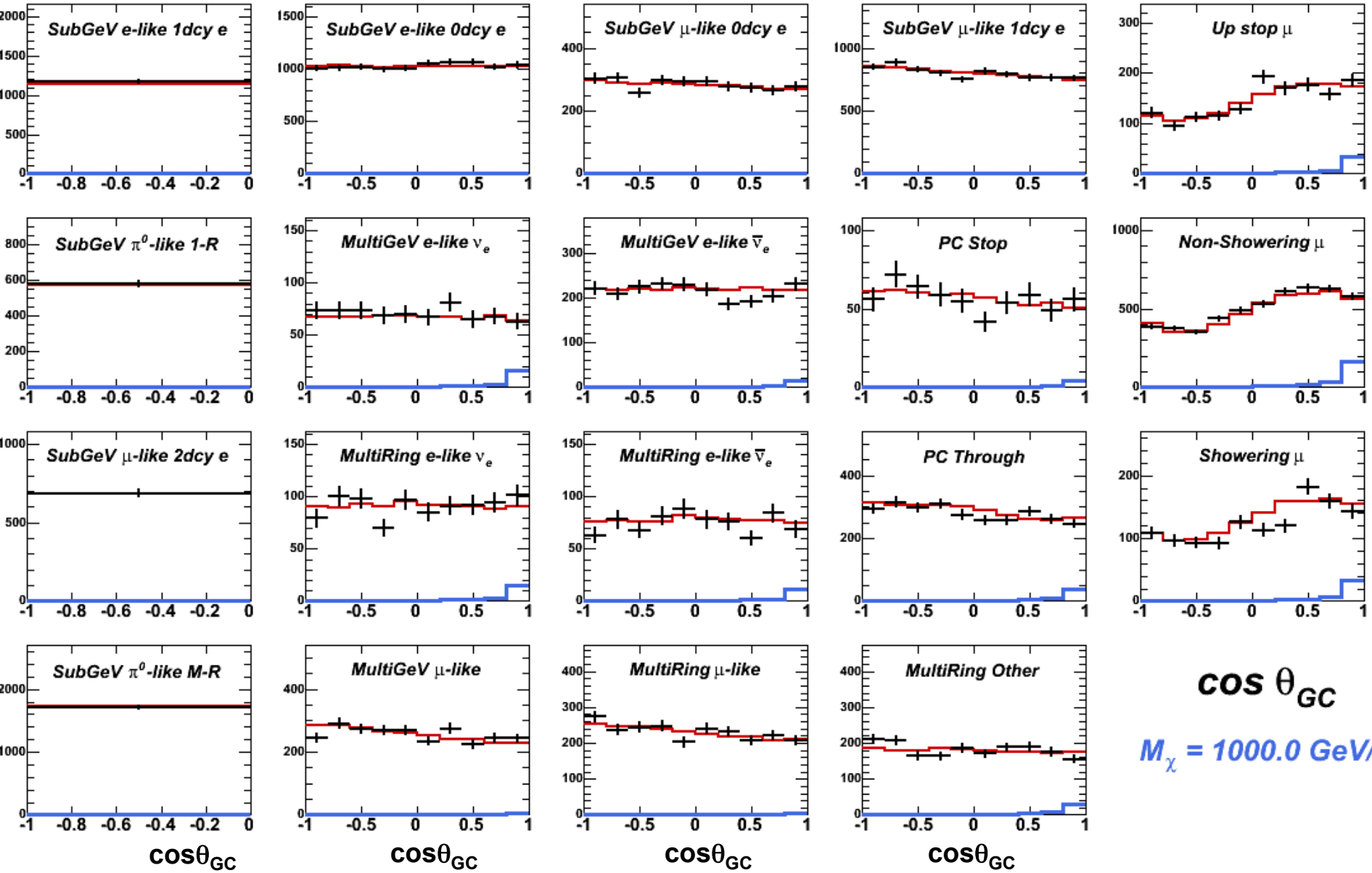
ATM MC+WIMP
at best fit point

WIMP
before fit

Galactic WIMP search: signal llustration 1000GeV bb-bar



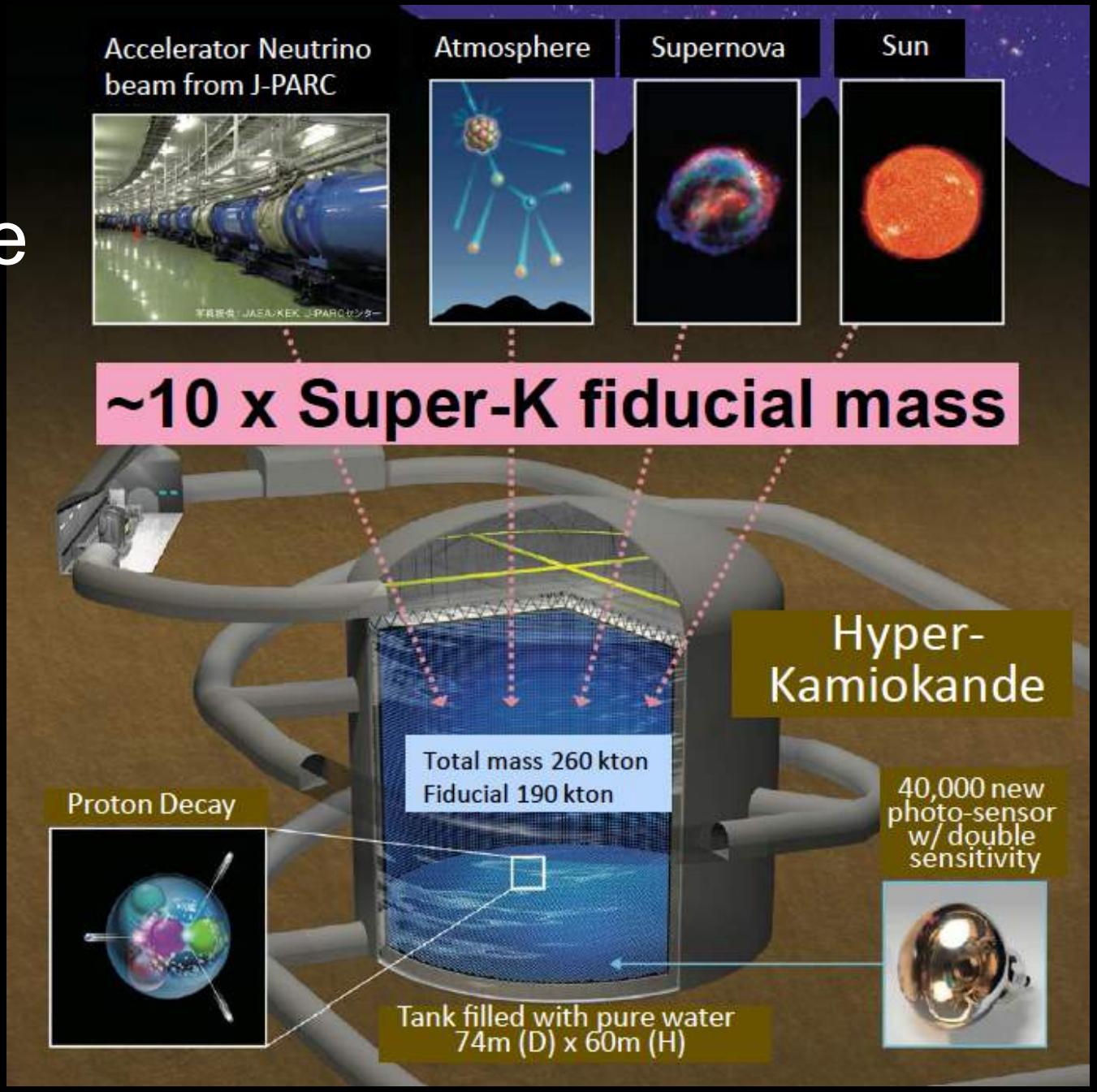
DATA
SK1-4, 1996-2016

ATM MC+WIMP
at best fit point

WIMP
before fit

Future: Hyper-Kamiokande

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



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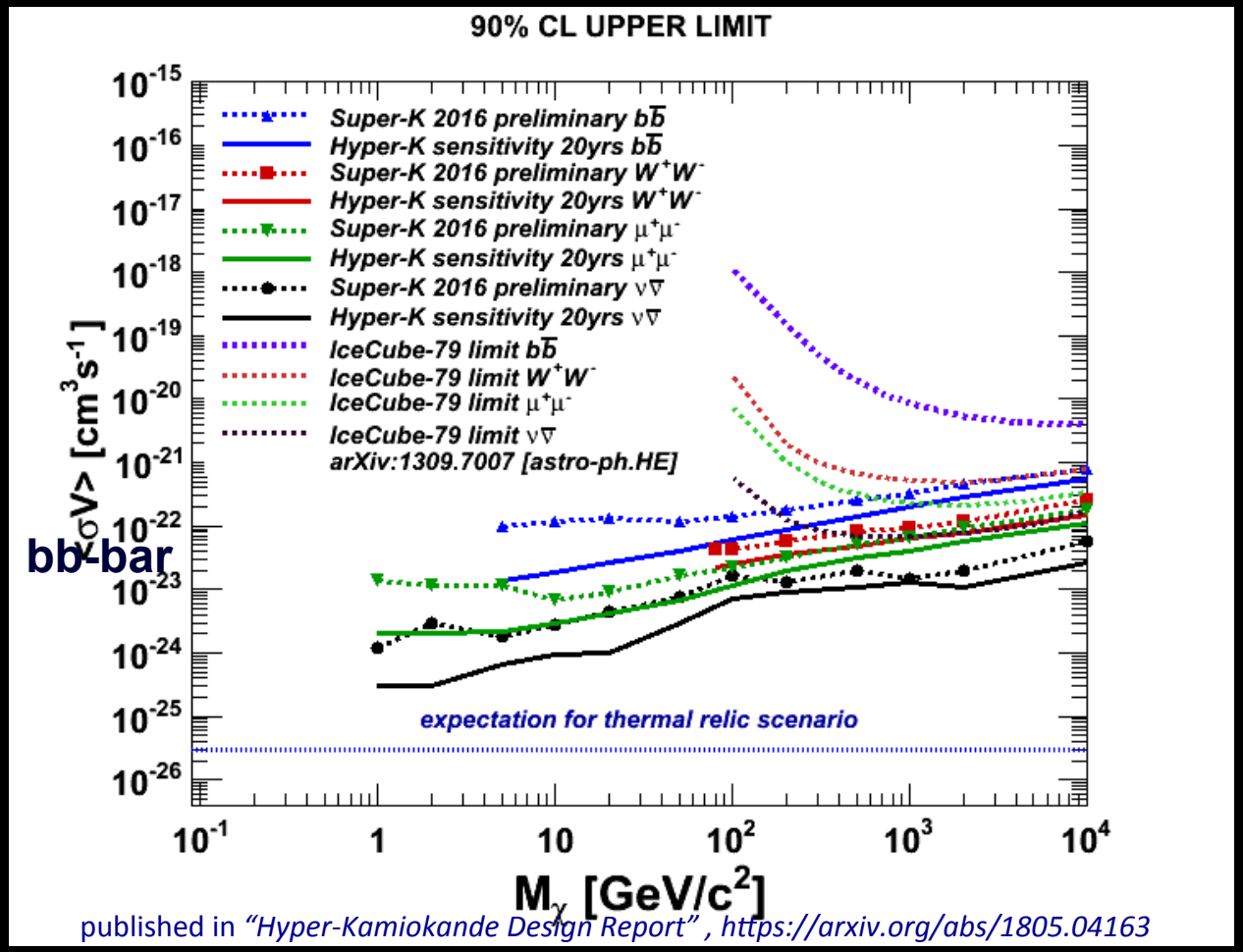
Galactic WIMP search sensitivity
~3-10x improvement after 20 yrs of Hyper-Kamiokande running

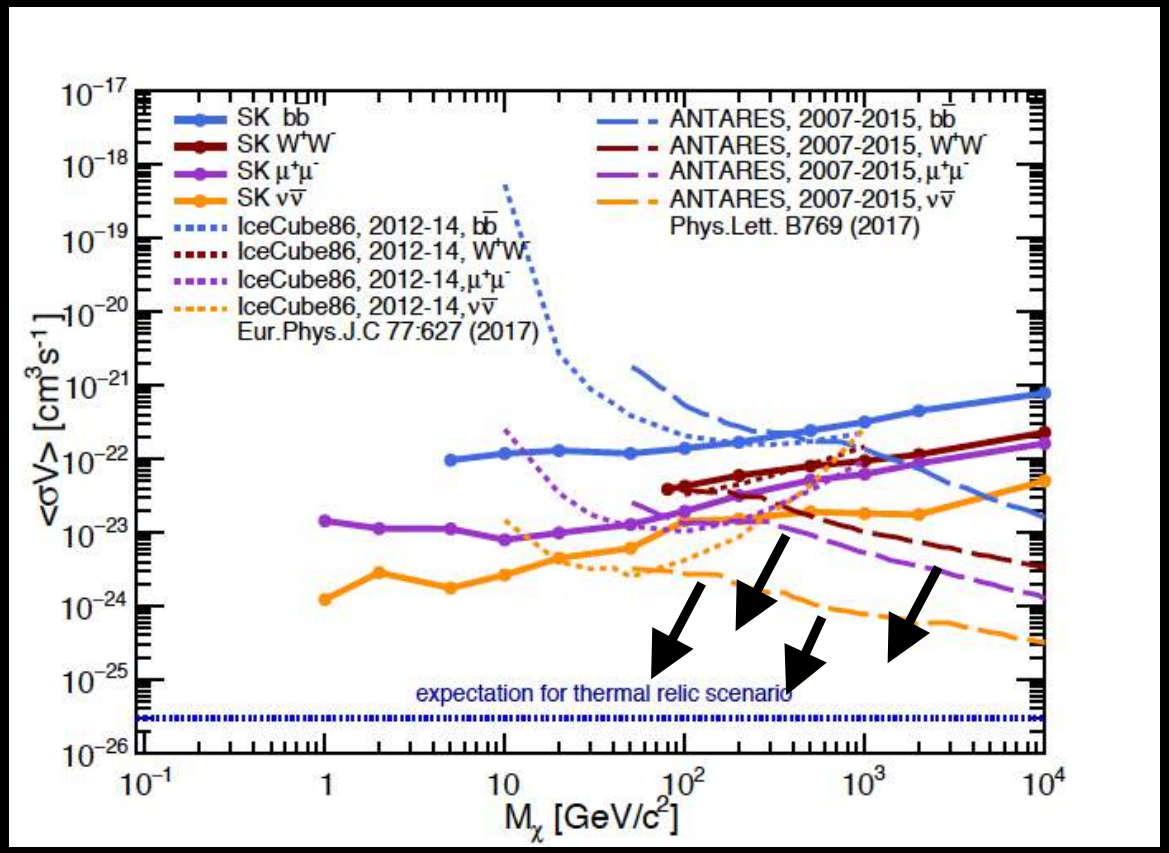


published in *"Hyper-Kamiokande Design Report"*, *https://arxiv.org/abs/1805.04163*

Sun & Earth WIMP searches: similar level of improvement is expected

Prospects at KM3NeT

Strong limits from Antares (0.01km^3, 12 strings) → great potential of KM3NeT (0.1 → ~1km^3, 230 strings)



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 ~ 1yr