Dark Matter Searches at Super-Kamiokande

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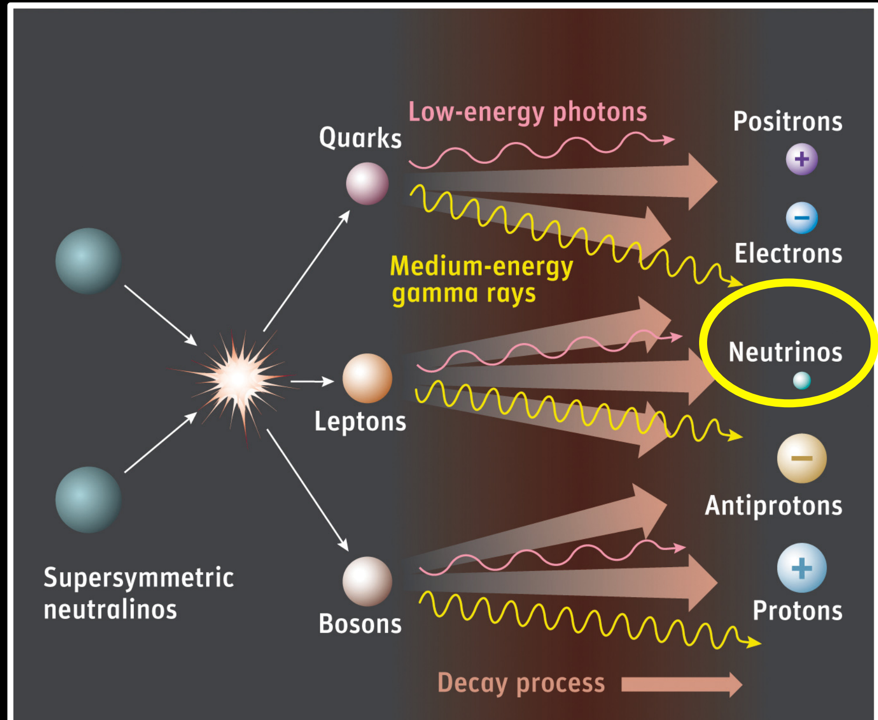
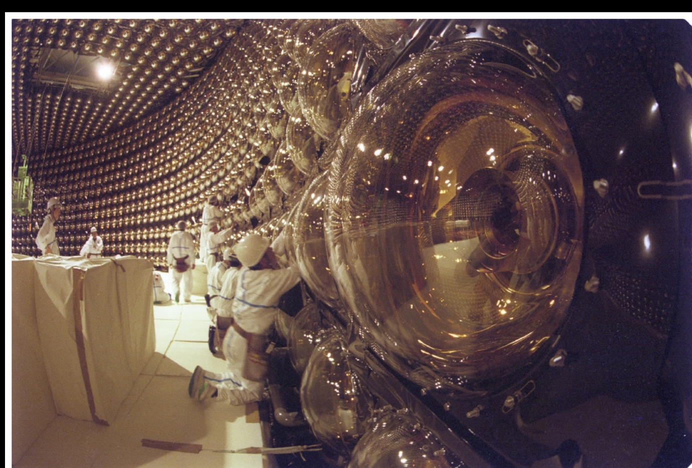
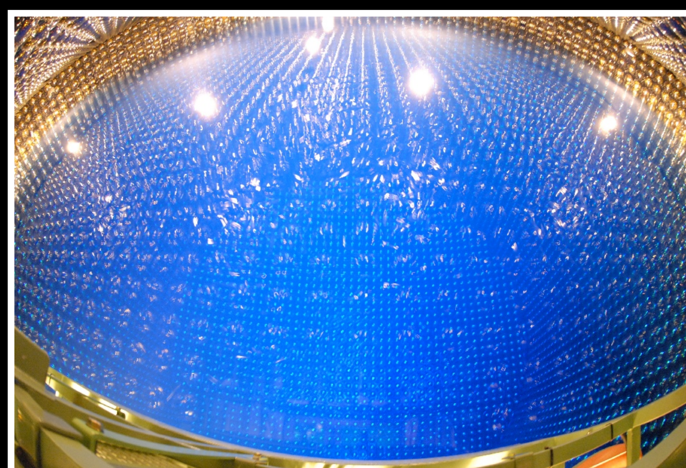
OUTLINE

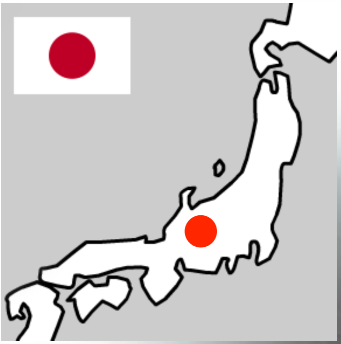
Indirect searches for dark matter induced neutrinos at Super Kamiokande:

1. Galactic Center & Halo 2017
2. Earth 2017
3. Sun 2015



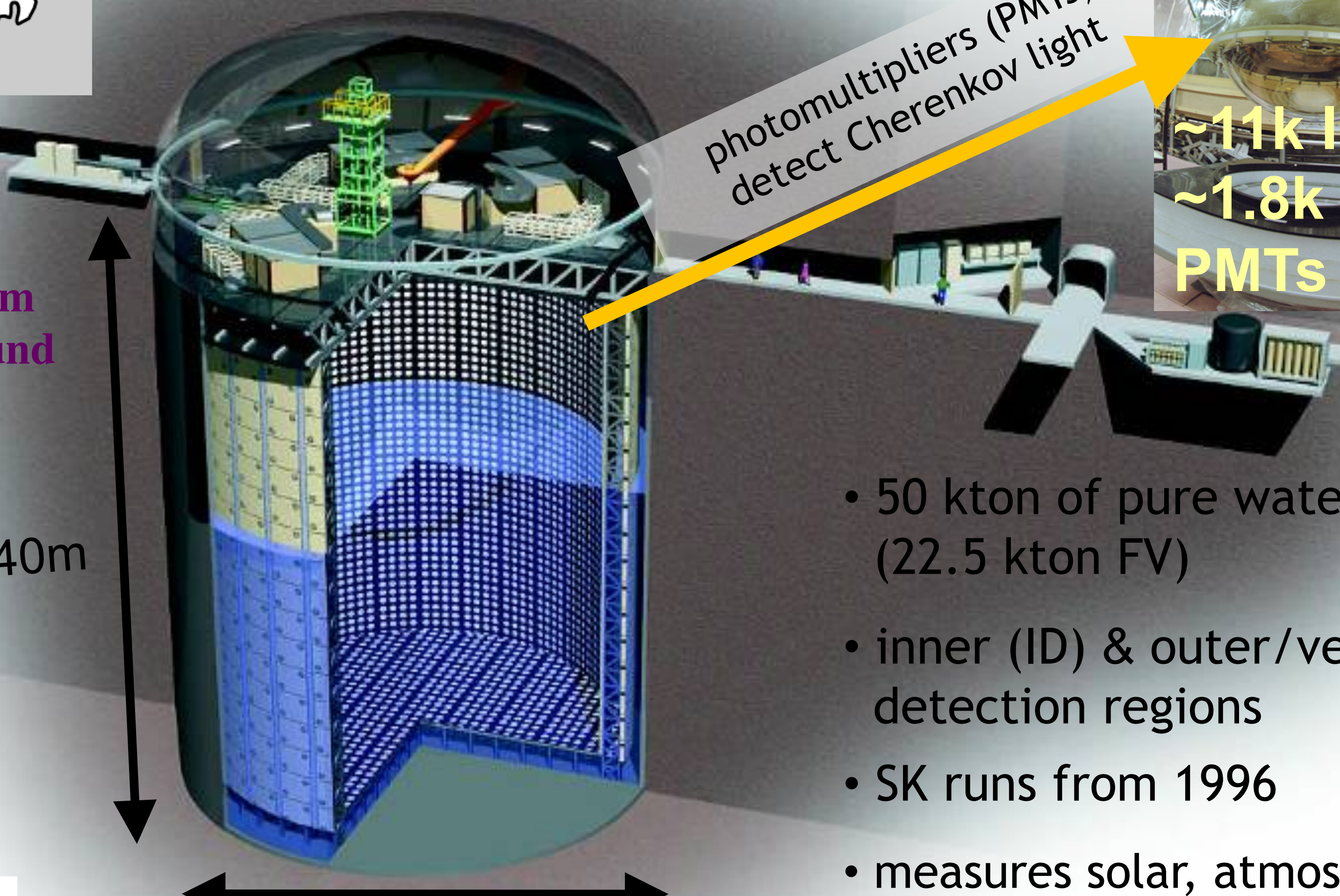






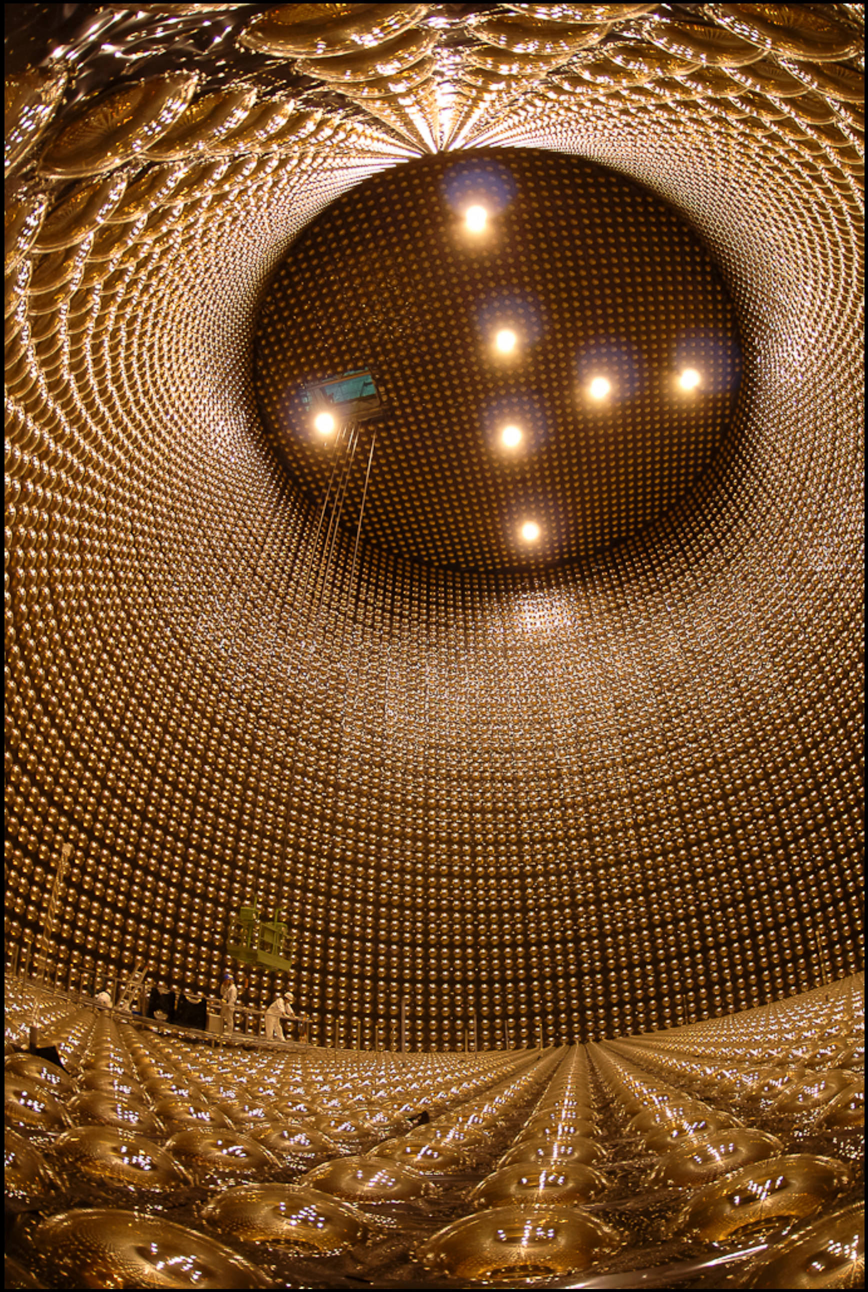
Super-Kamiokande

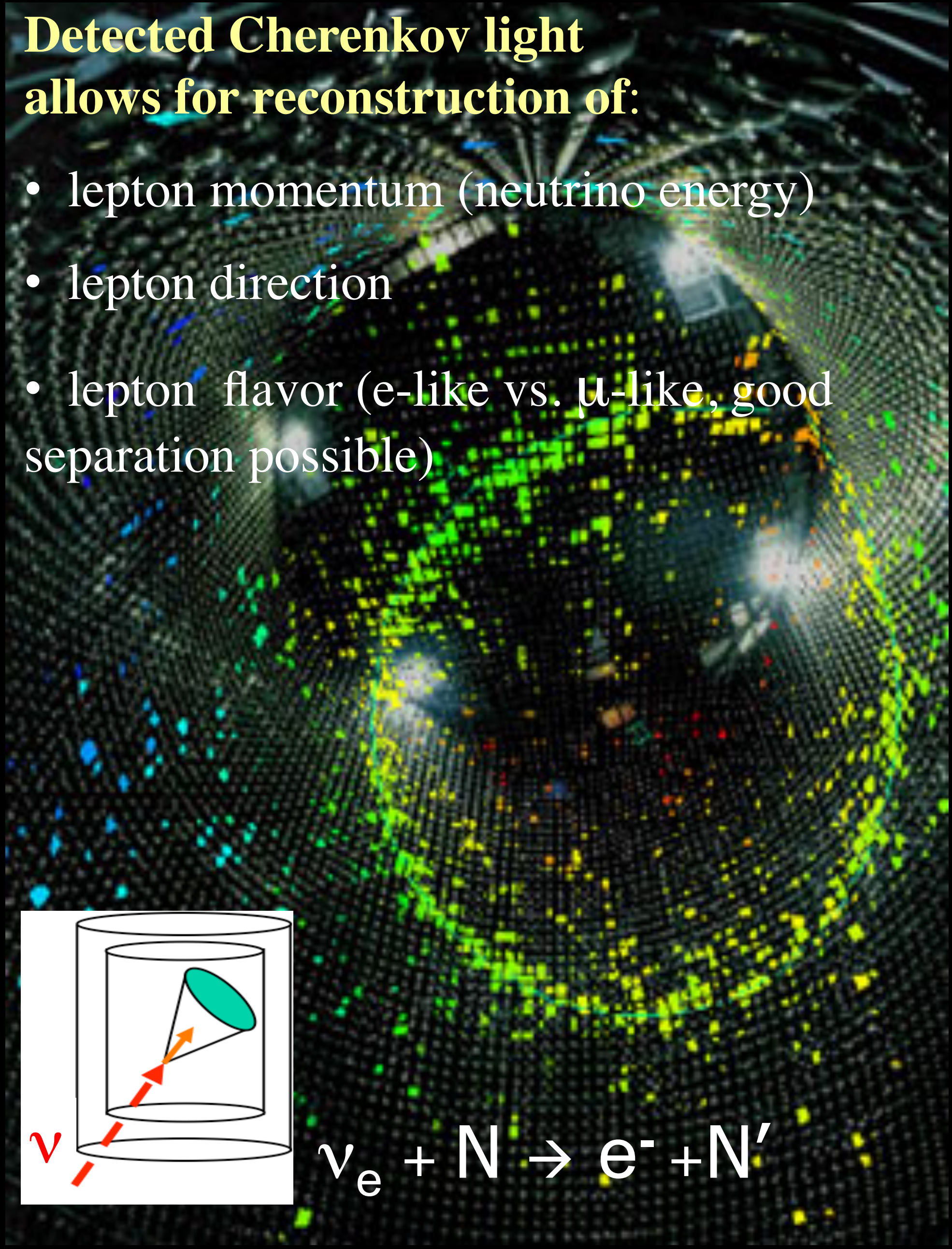
@ Kamioka Observatory (ICRR, University of Tokyo), Japan



located 1km underground

- 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
- Far detector of **T2K**



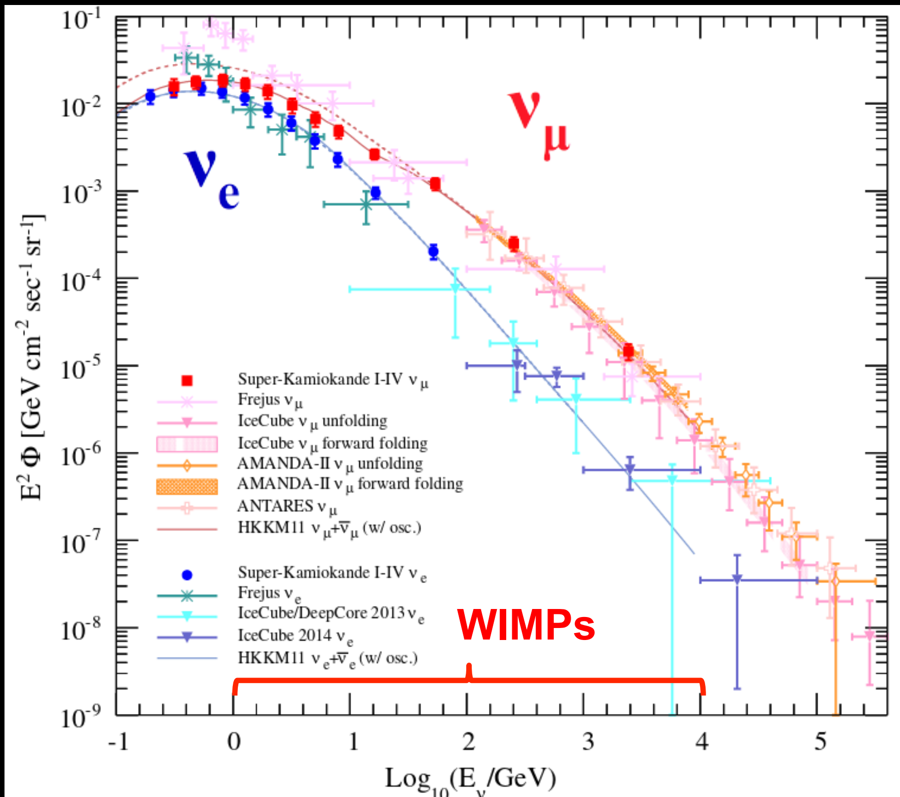


Detected Cherenkov light allows for reconstruction of:

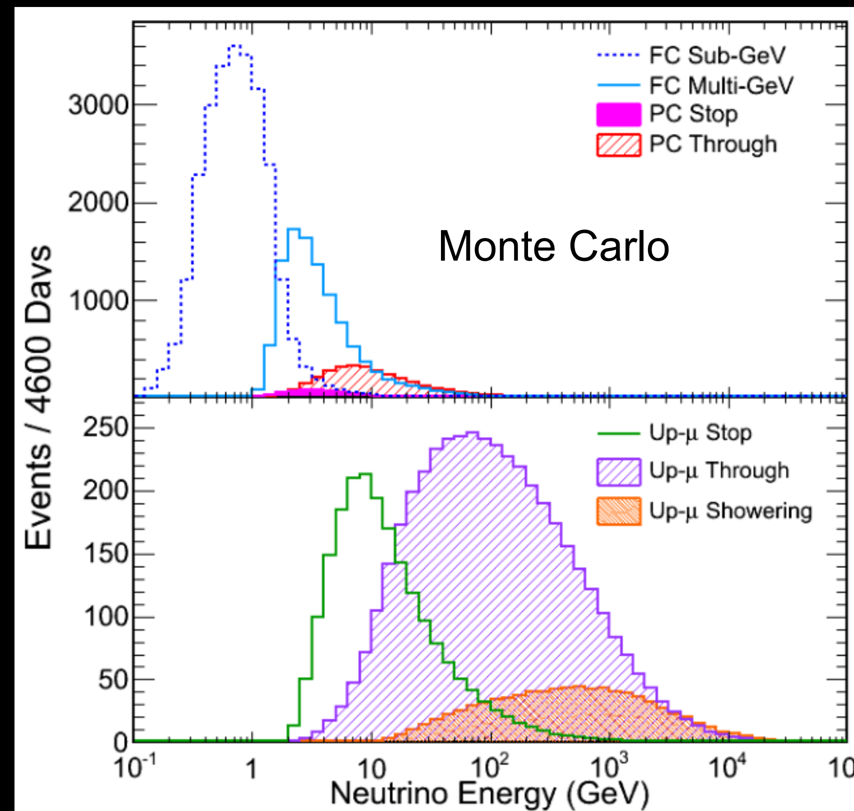
- lepton momentum (neutrino energy)
- lepton direction
- lepton flavor (e-like vs. μ-like, good separation possible)

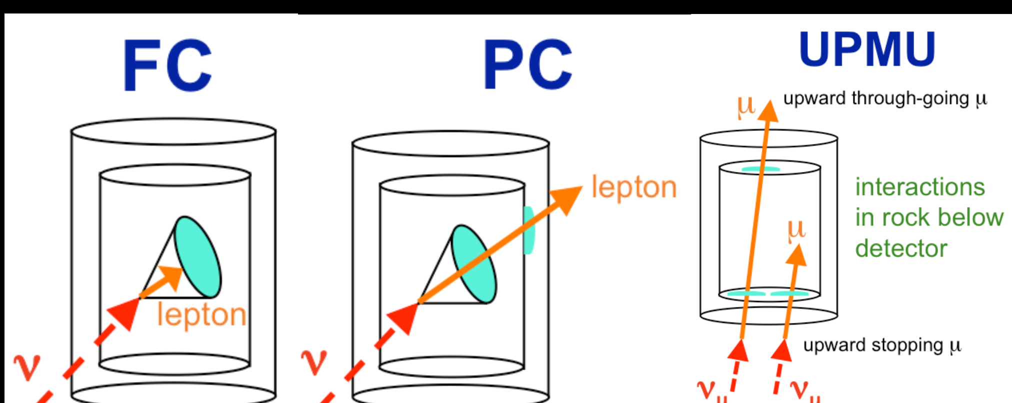
$\nu_e + N \rightarrow e^- + N'$

Atmospheric neutrinos: main background in DM-induced ν searches



atmospheric neutrinos at SK

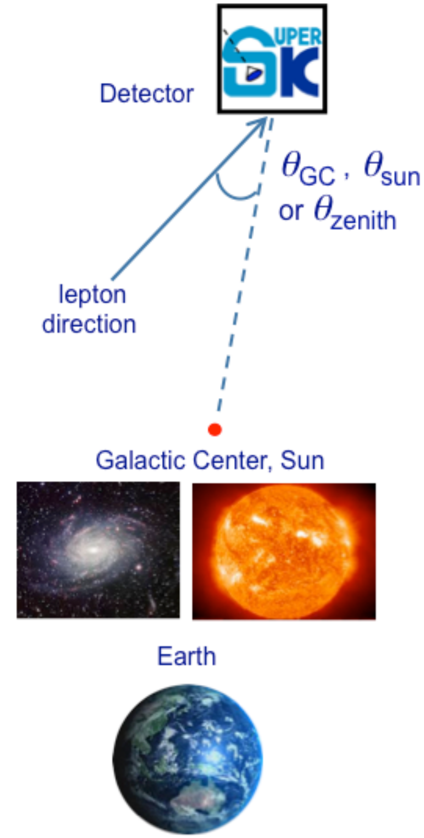




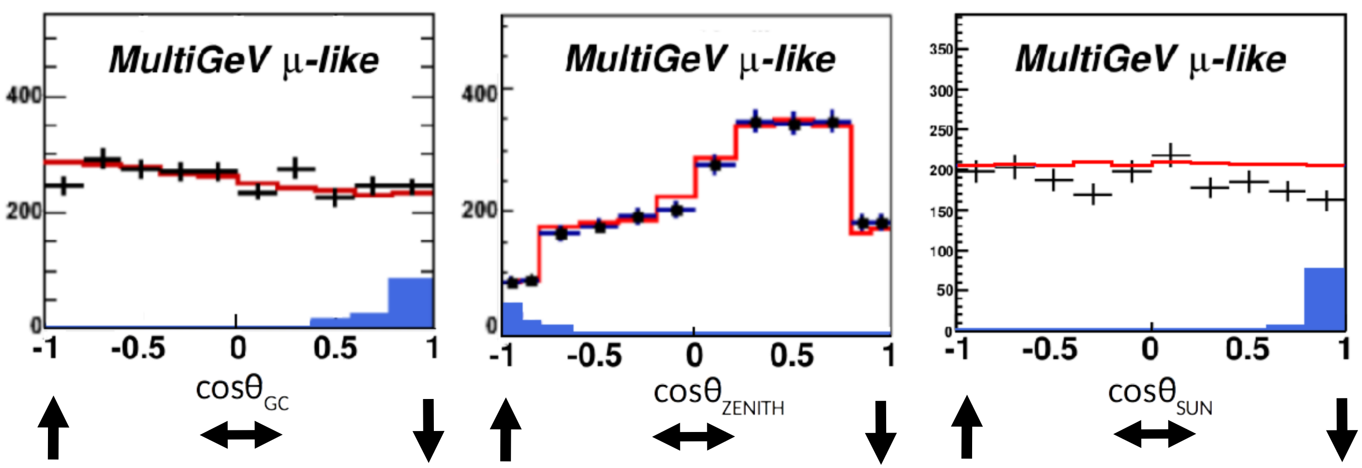
- ~10 events/day
- data period: 1996-2016
- ~50 000 events in total

Dark matter searches at Super-Kamiokande

- Search for excess of neutrinos form **Earth/Sun/Milky Way**
- **FIT:** for each tested WIMP mass, find configuration of ATM ν + DM signal that would match DATA the best



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

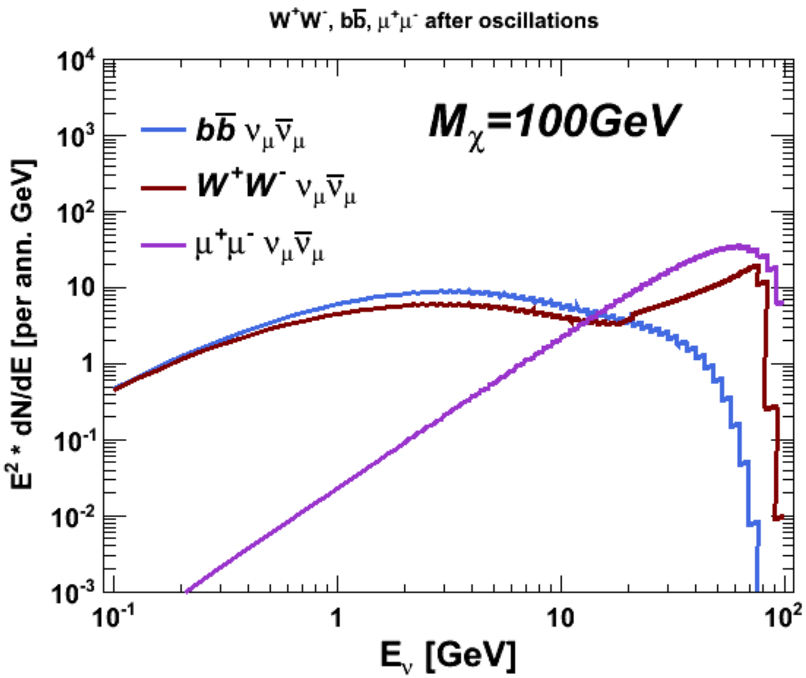
Signal simulation

Simulate DM signal before detection → DarkSUSY & WimpSim

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

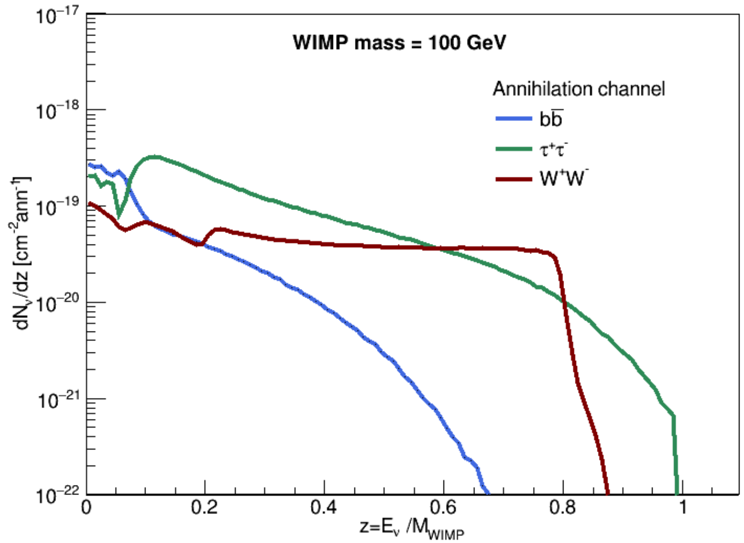
EXAMPLE: Galactic WIMP search

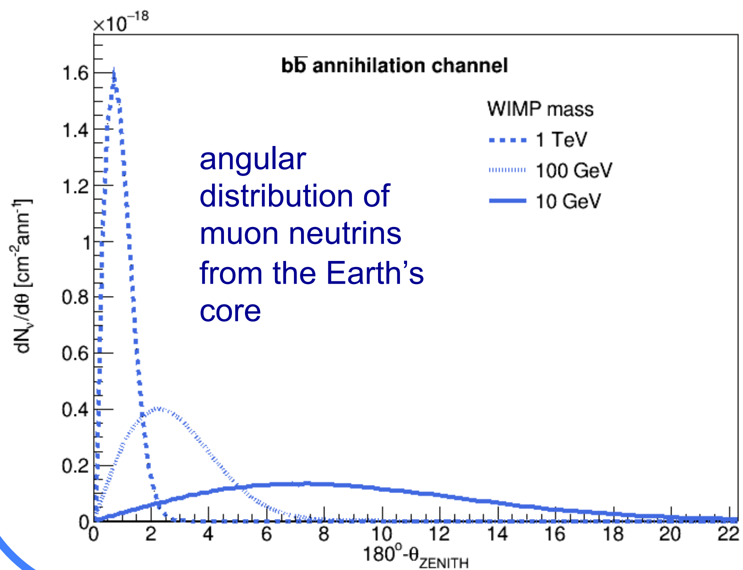
differential $\nu_\mu \bar{\nu}_\mu$ energy spectra per DM annihilation for M_χ=100 GeV (oscillated throughout Galaxy)



EXAMPLE: Earth WIMP search

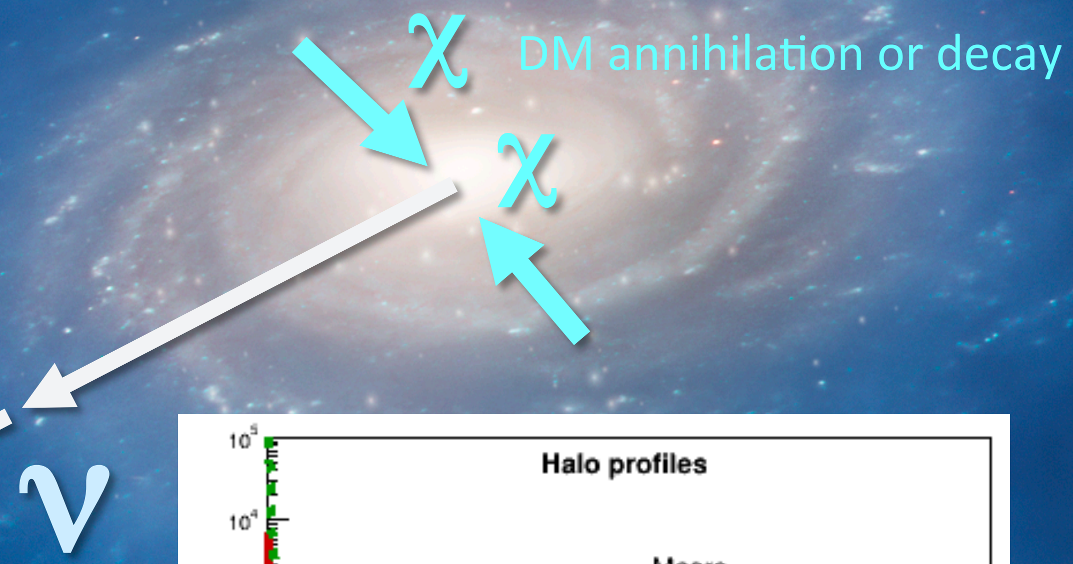
muon neutrino flux produced in WIMP annihilation in the Earth's core

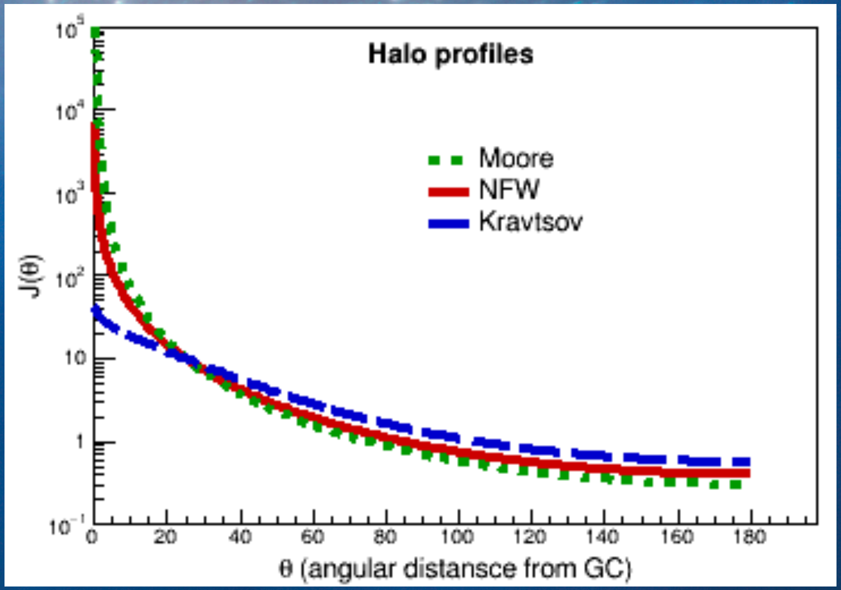




Galactic WIMP search

- 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>



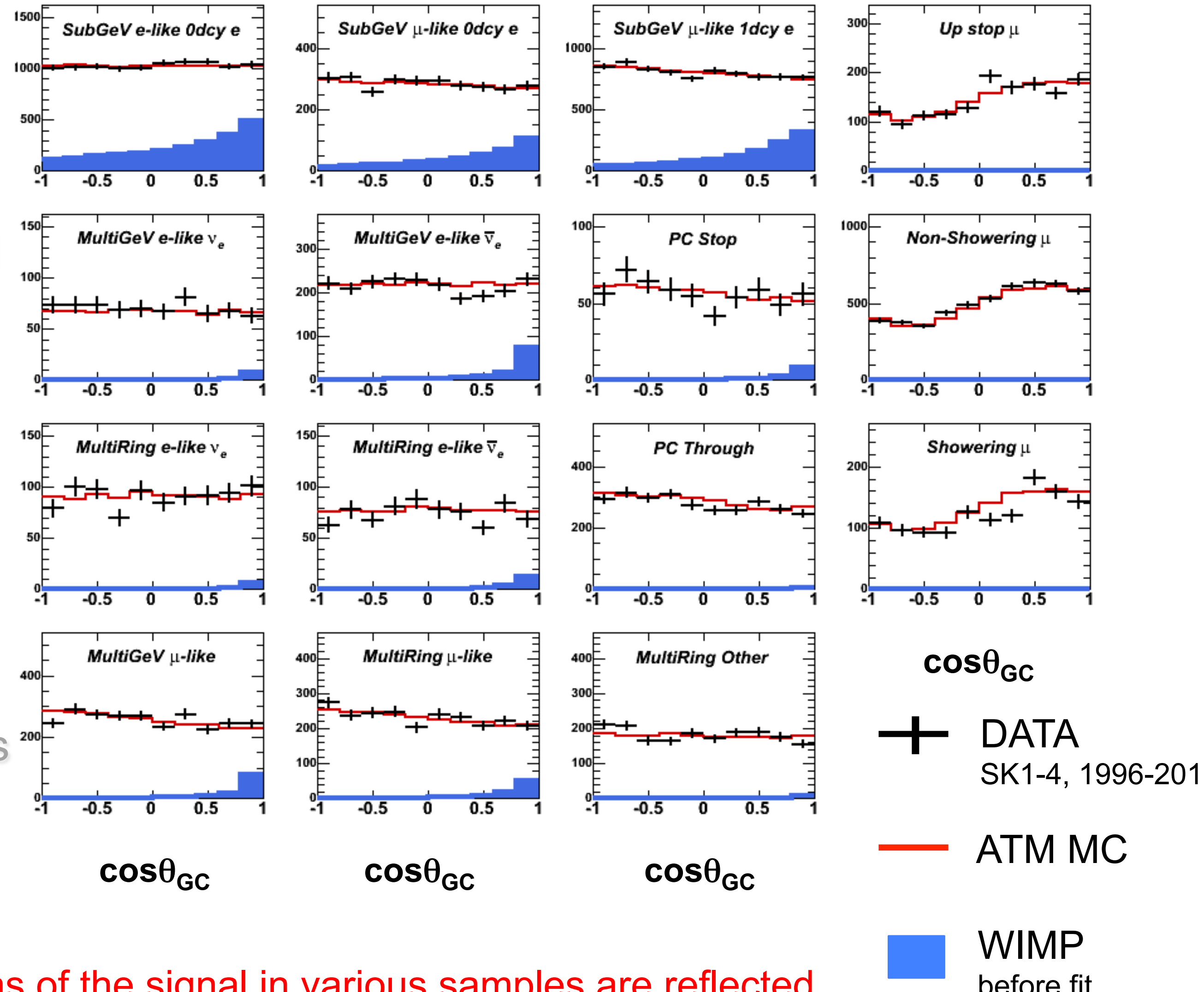


Expected signal intensity strongly depends on halo model
NFW is considered as a benchmark model in this analysis

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
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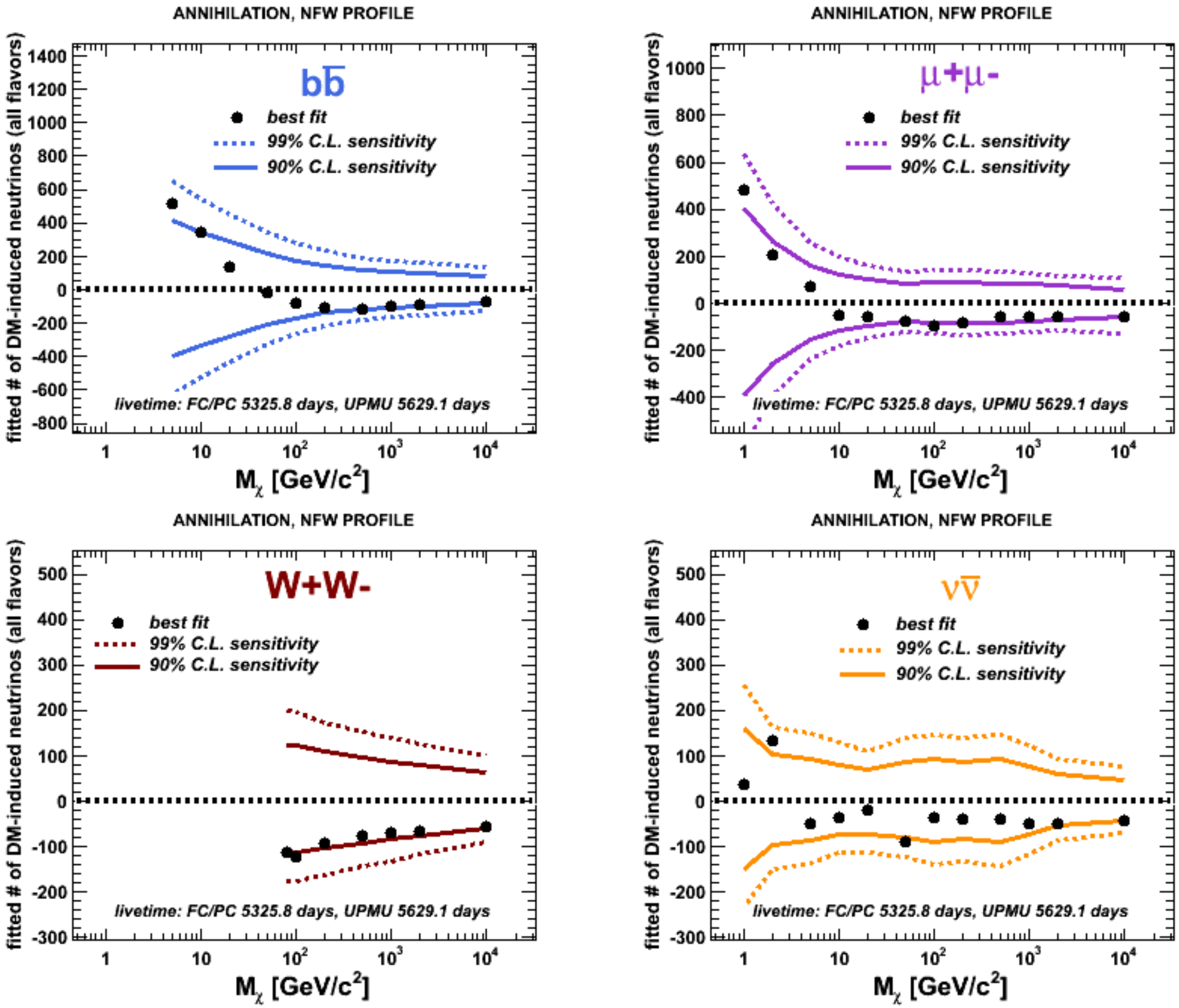
- 90% CL upper limit on DM self-annihilation cross section $\langle\sigma_A V\rangle$

SK preliminary



~150 systematic uncertainty terms included in the fit

p-values in backup

Galactic WIMP search: DM self-annihilation cross section

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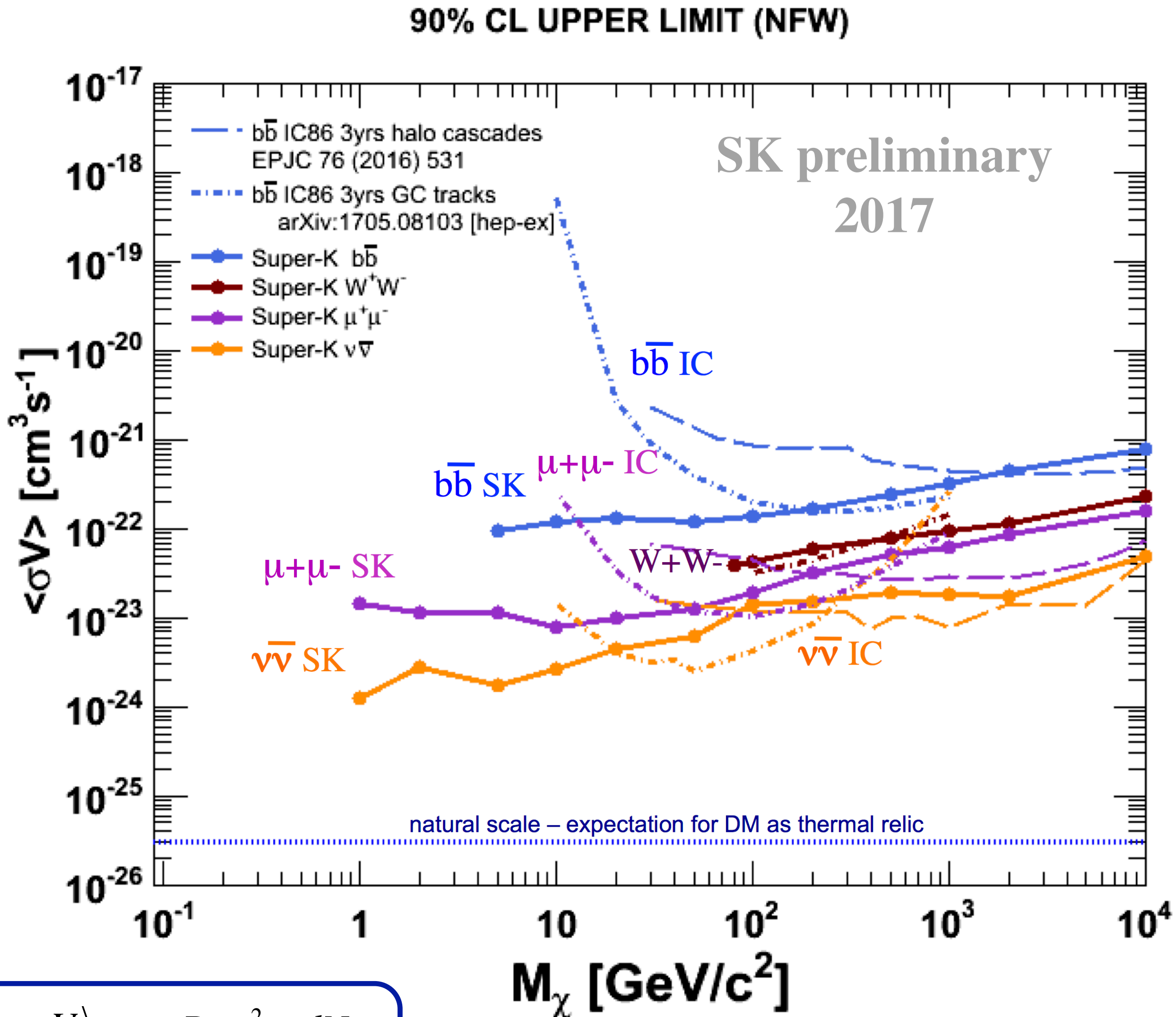

$$\frac{d\phi_{\Delta\Omega}}{dE} = \frac{\langle \sigma_A \cdot V \rangle}{2} J_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi \cdot M_\chi^2} \frac{dN}{dE}$$

Galactic WIMP search: DM self-annihilation cross section

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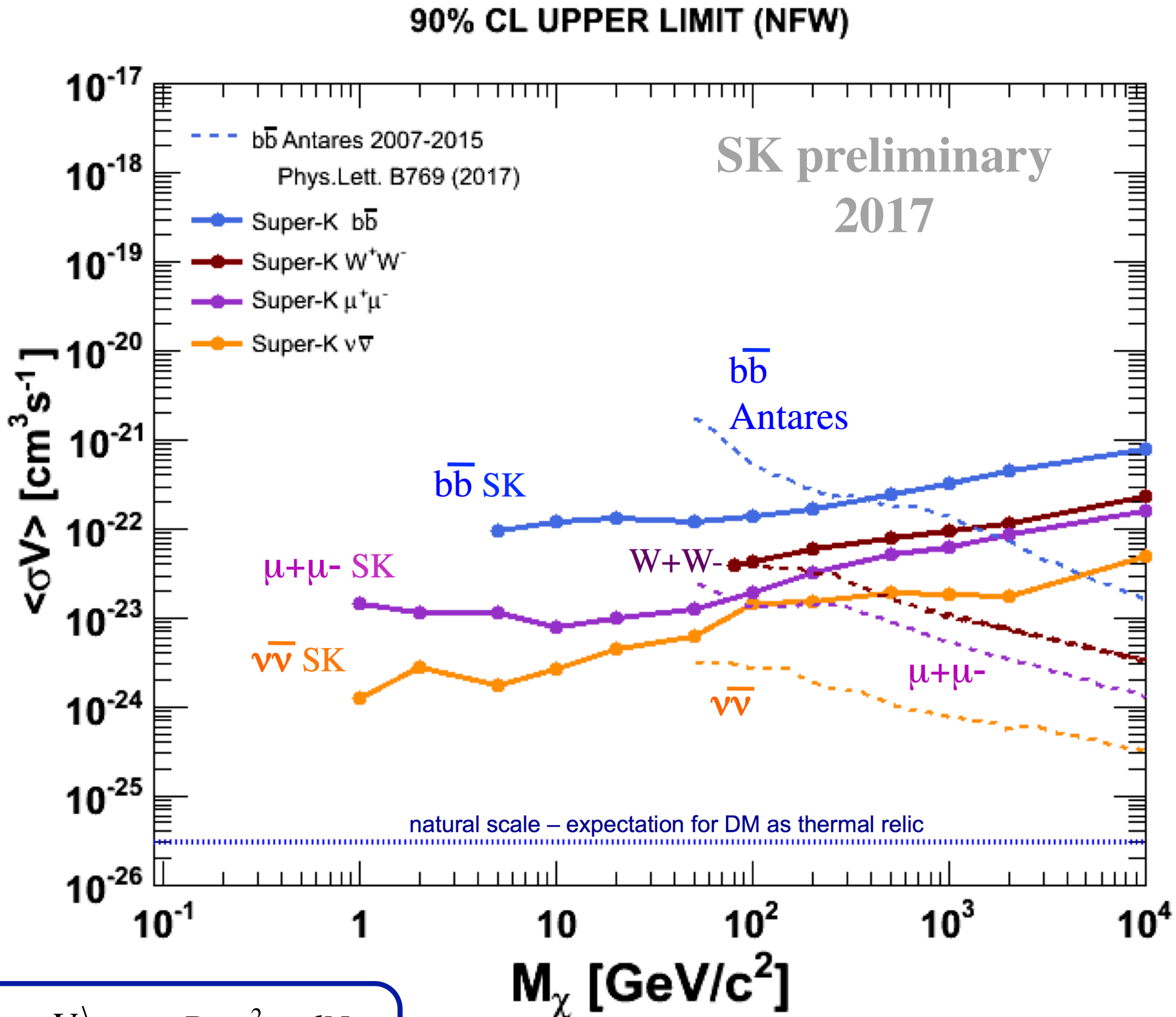

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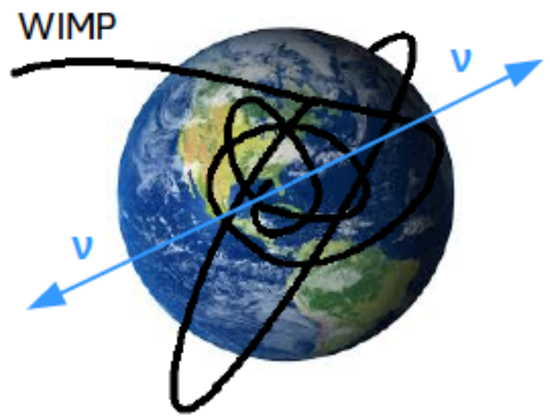
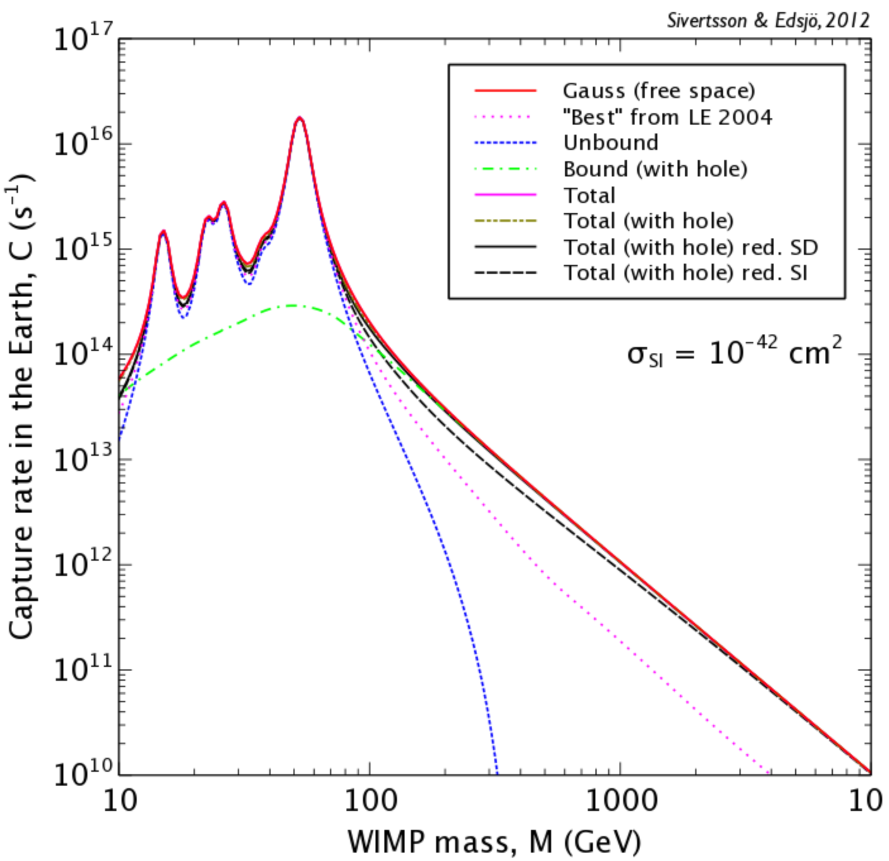
Earth WIMP search

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





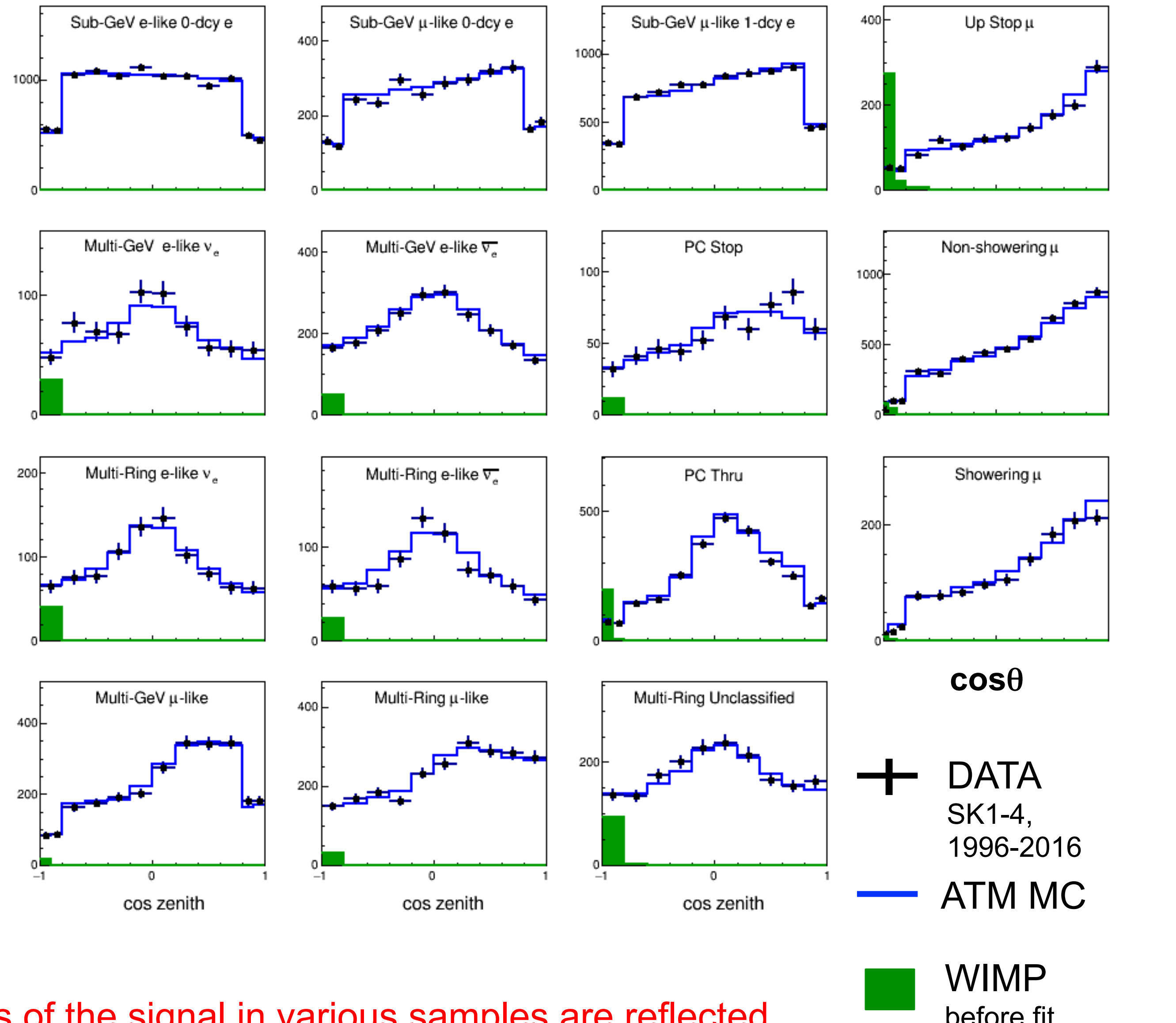
The peaks correspond to **resonant capture** on the most abundant elements **^{16}O**, **^{24}Mg**, **^{28}Si** and **^{56}Fe** and their isotopes

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

Earth WIMP search: data

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

- 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 $\sigma_{\chi\text{-}n}$

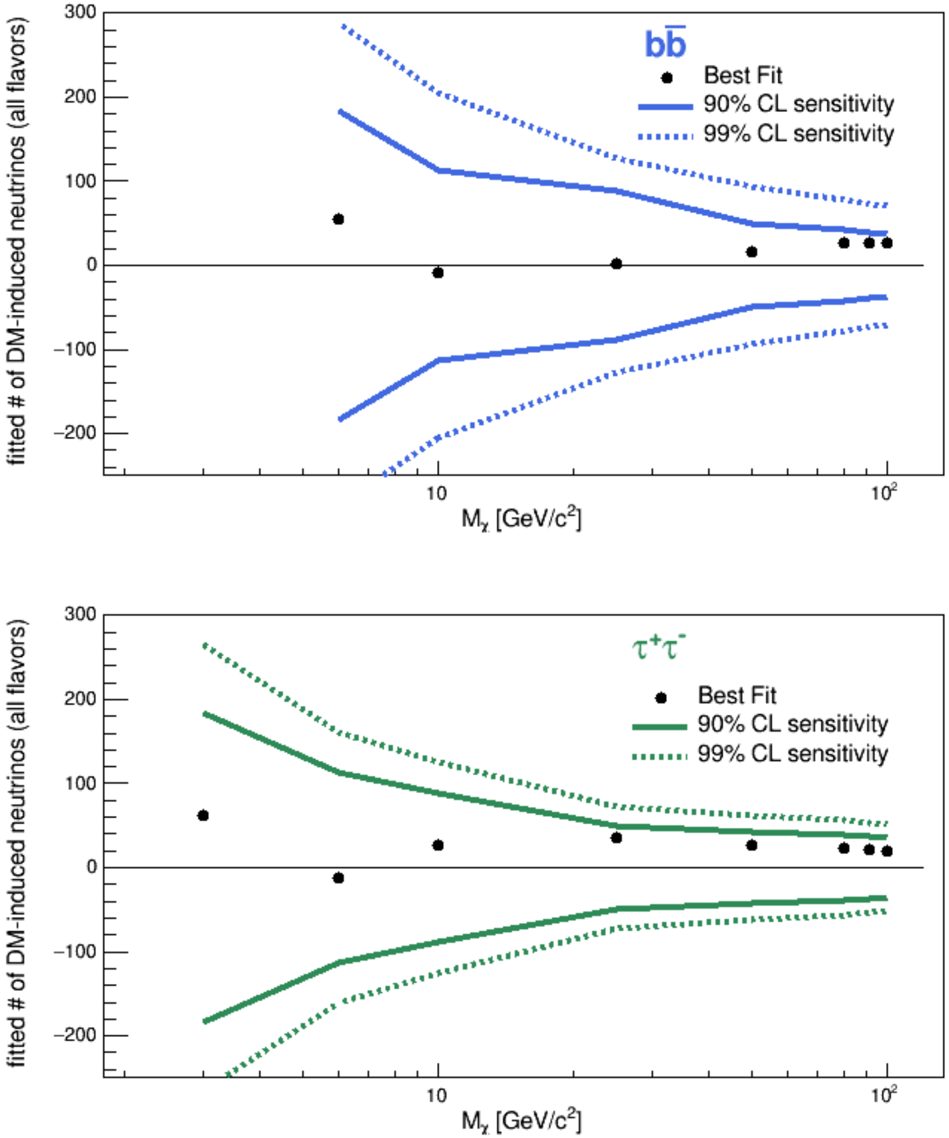


proportions of the signal in various samples are reflected

Earth WIMP search: fitted number of DM-induced νs

- 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 $\sigma_{\chi\text{-}n}$

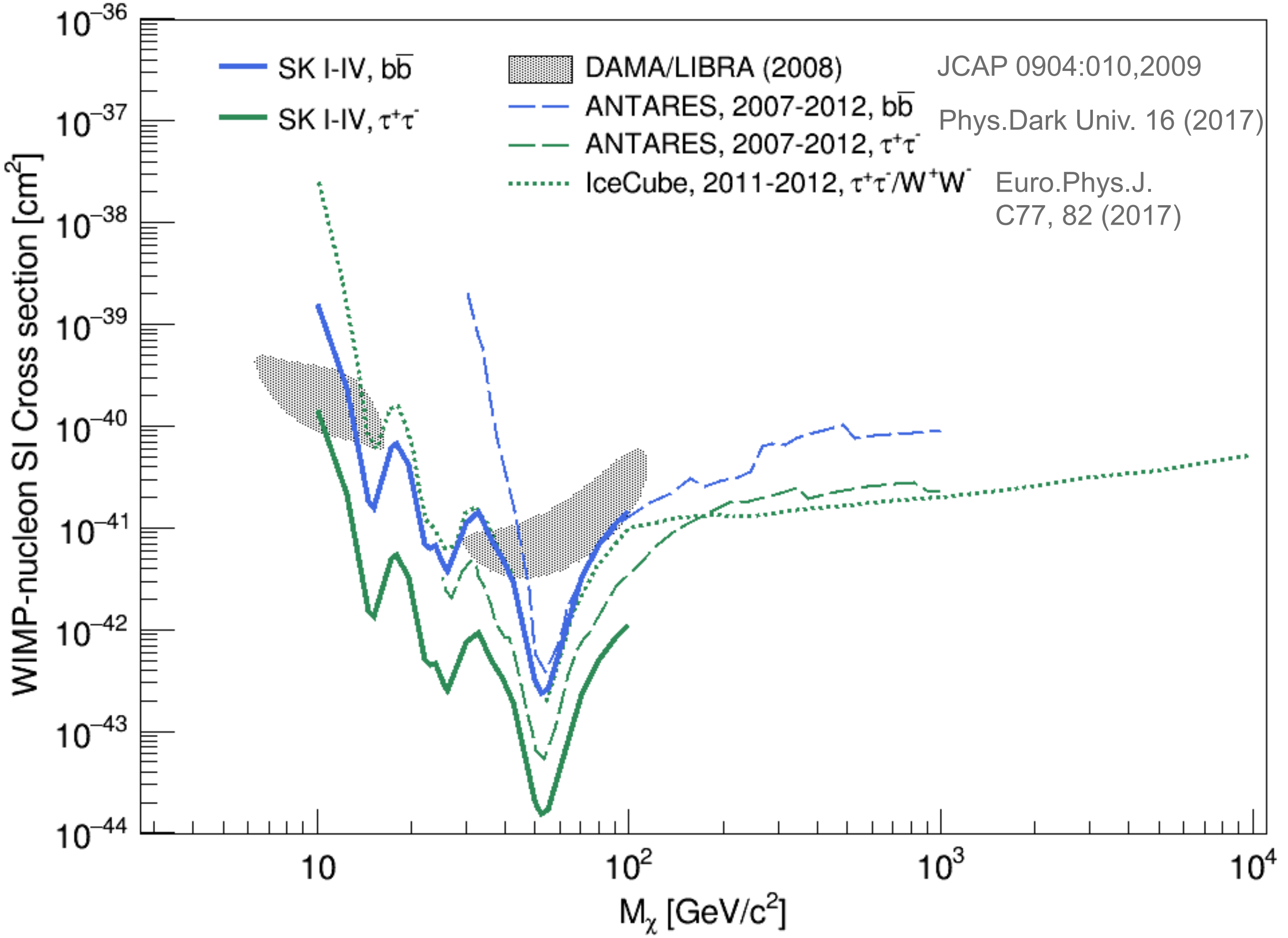
SK preliminary



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

- 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 $\sigma_{\chi\text{-}n}$

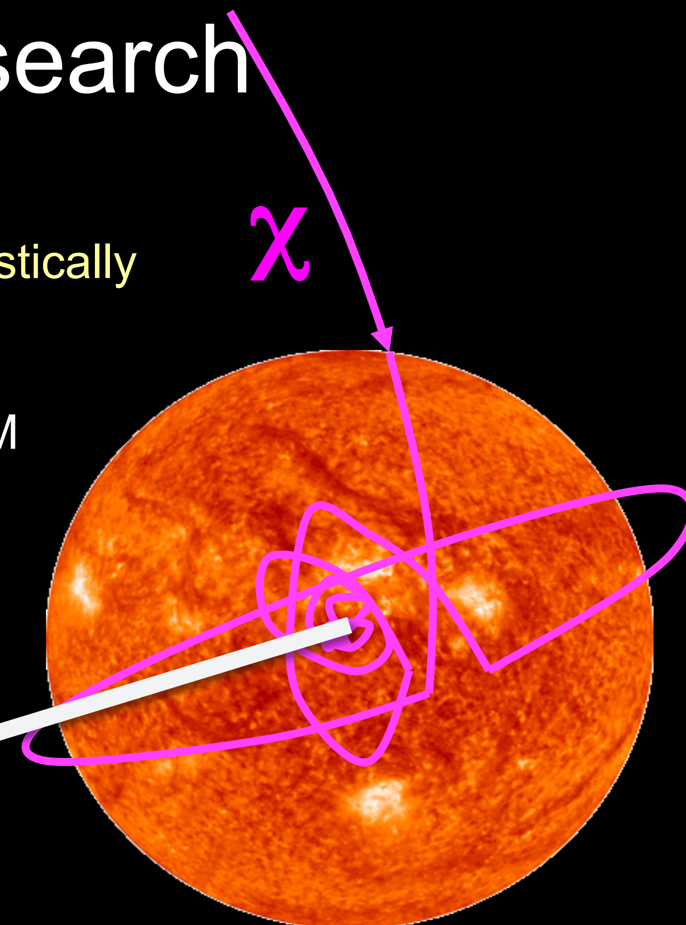
SK preliminary



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

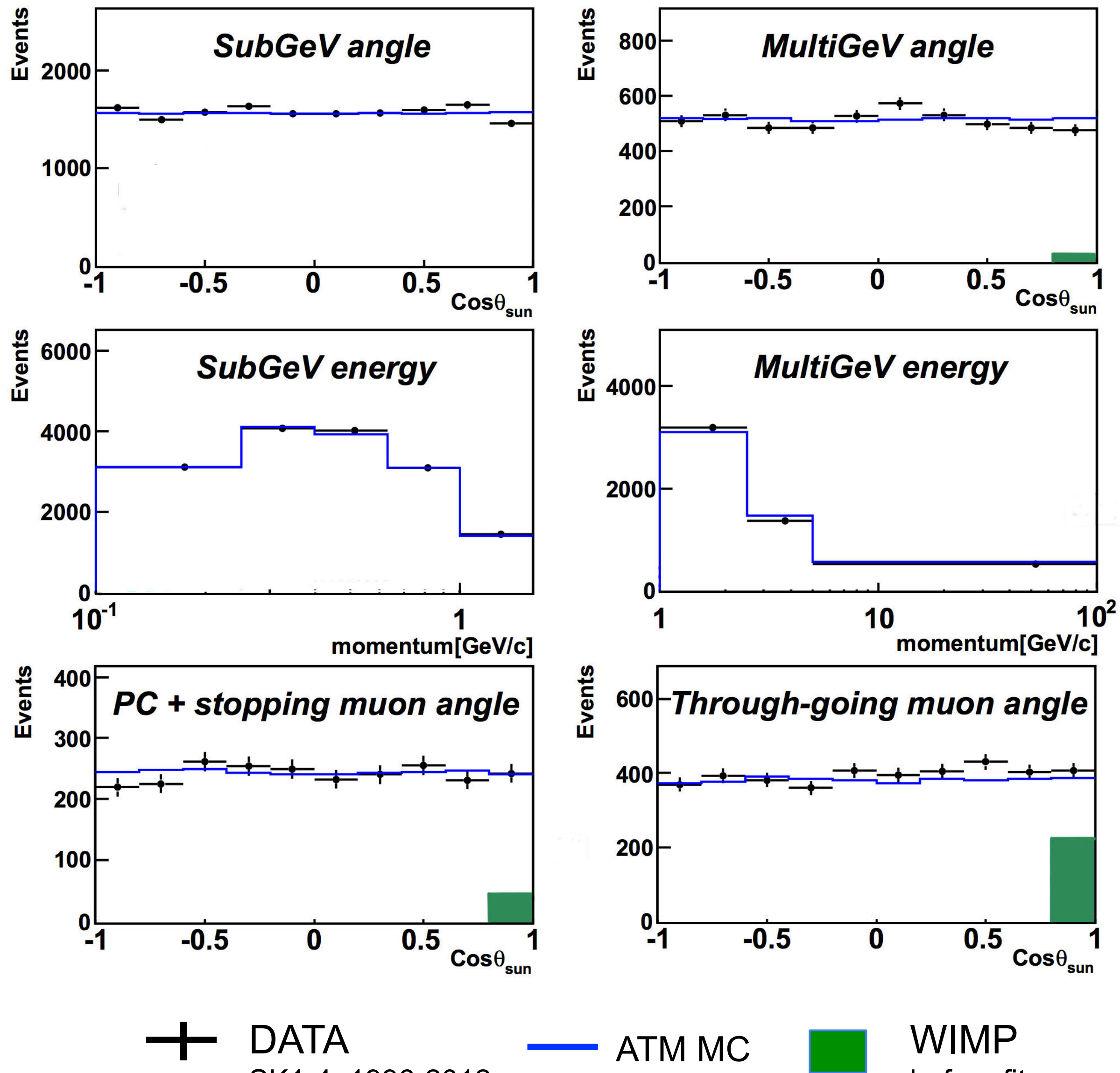
more: G.Wikström, J.Edsjö JCAP 04, 009 (2009)

Published analysis: 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 σXn for $\tau^+\tau^-$, $b\bar{b}$ and W^+W^- channels

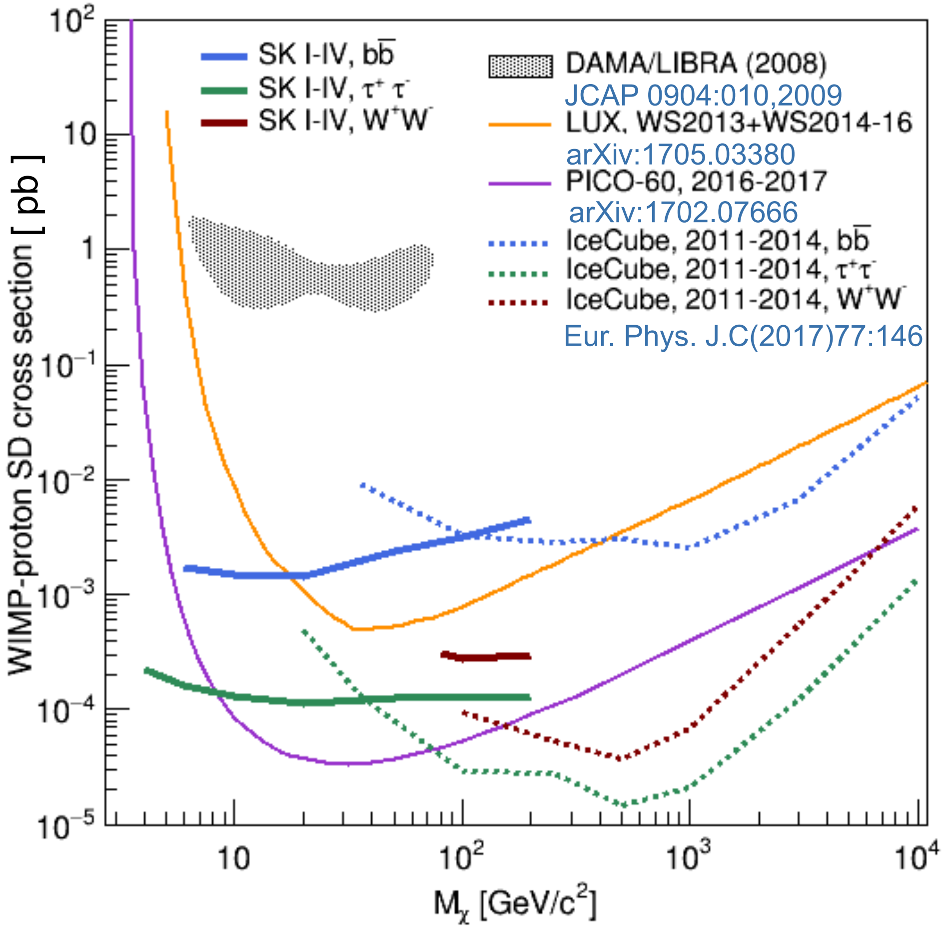
example for: 200 GeV WIMPs, $\tau^+\tau^-$ ann. channel



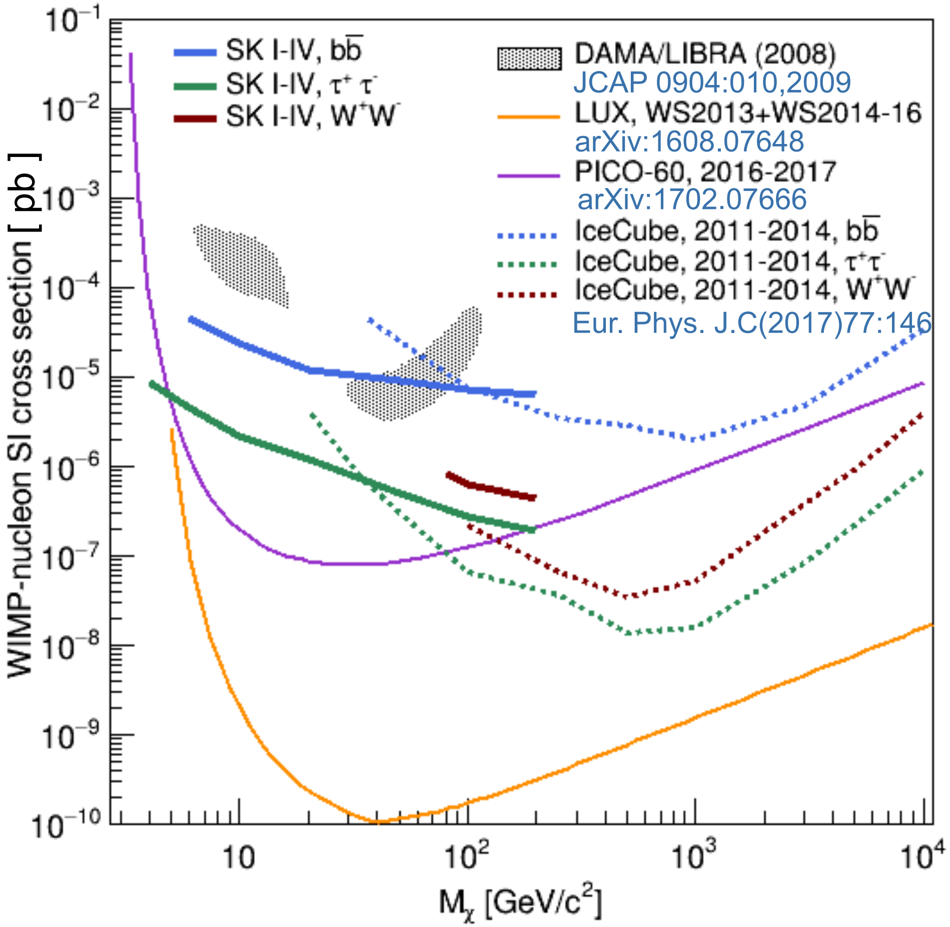
Solar WIMP search: WIMP-nucleon SI & SD cross section limit

90% CL upper limit

spin dependent interactions



spin independent interactions



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

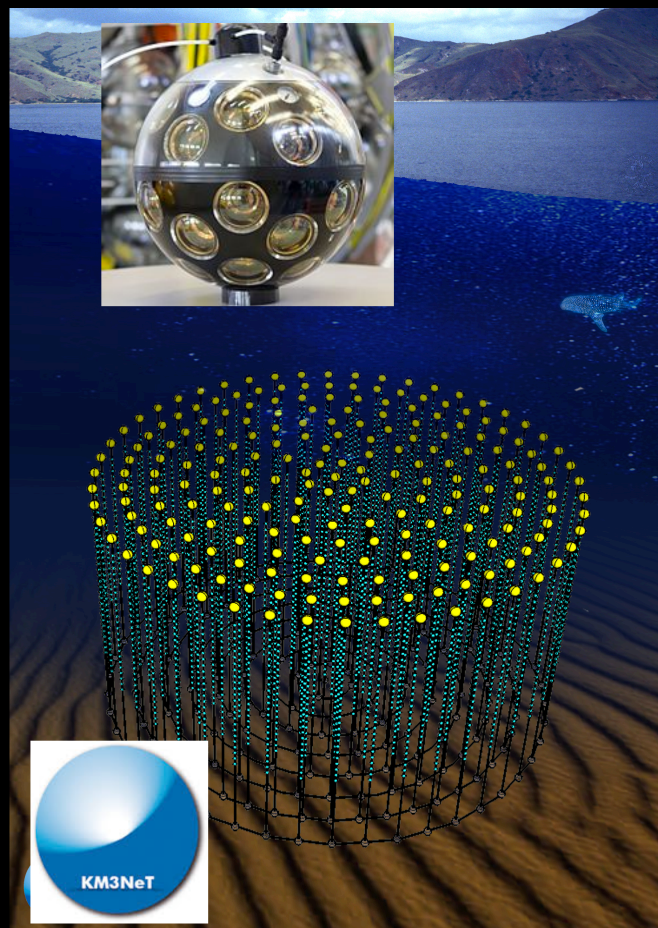
Future: KM3NeT / Hyper-Kamiokande

- Open positions in our group to work on indirect DM detection with present and future water Cherenkov detectors

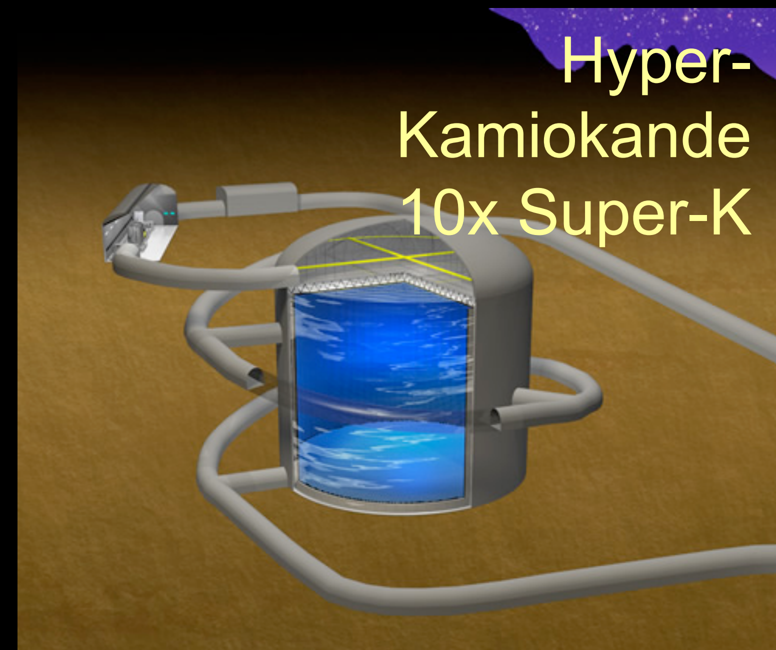
PhD & Post-Doc positions available (call closes October/1st)

KM3NeT

- Modular neutrino research infrastructure the Mediterranean Sea (aim for several km^3)
- 2 parts: ARCA (Italy) & ORCA (France)



Hyper-Kamiokande
10x Super-K



Summary

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

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

- Earth WIMP search (2017)
  Katarzyna Frankiewicz
  - upper limits on spin-independent WIMP-nucleon cross-section
  - high sensitivity to resonant capture region → currently the strongest limits from ν experiments <100 GeV

- Solar WIMP search (2015)
  - strongest limits < 20-100GeV among ν experiments

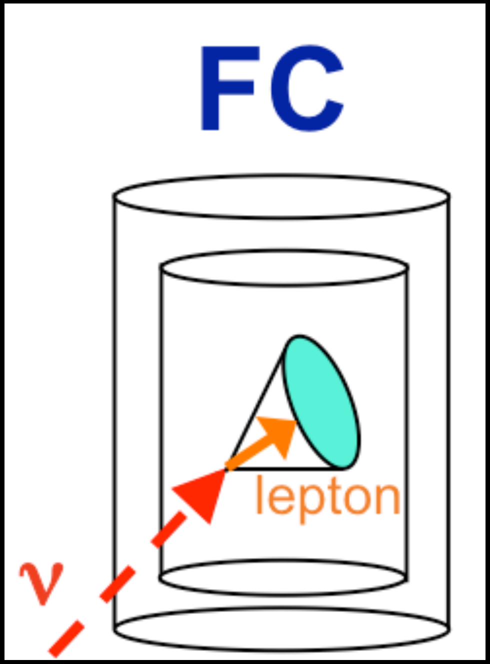

Thank you!
… we keep looking

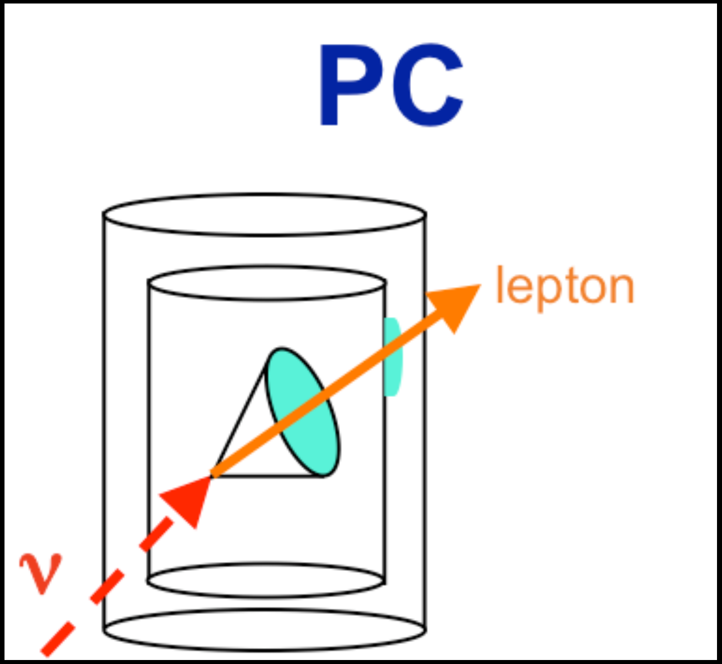
supplementary slides

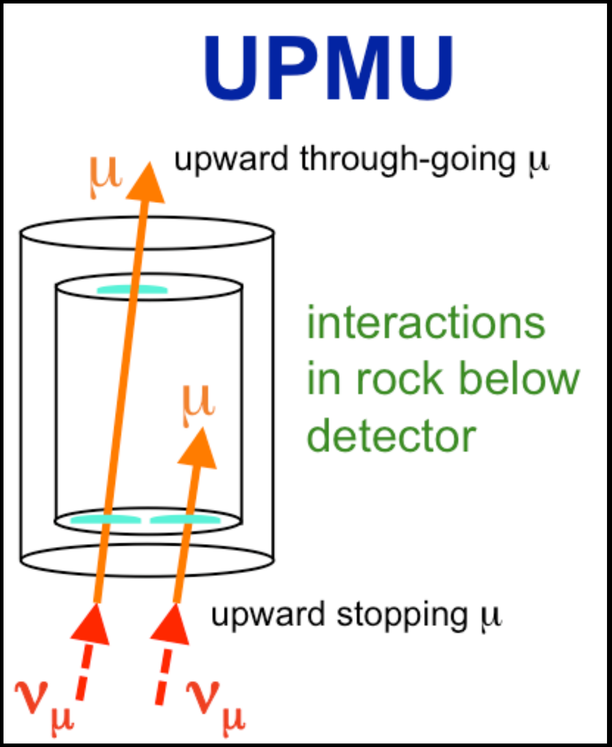
Super-Kamiokande Collaboration

Super-K data samples

Fully-contained	Partially-contained	Upward-going muons







Fully-contained
- ν energy reconstruction
- ν direction info
- e/μ identification possible

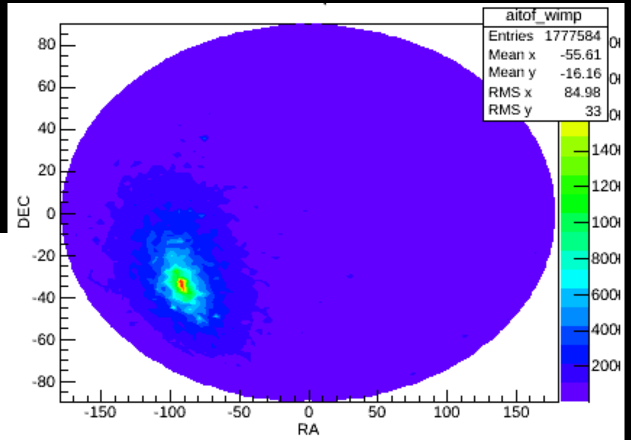
Partially-contained
- partial E_ν info (lepton leaves detector)
- ν direction info

Upward-going muons
- 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

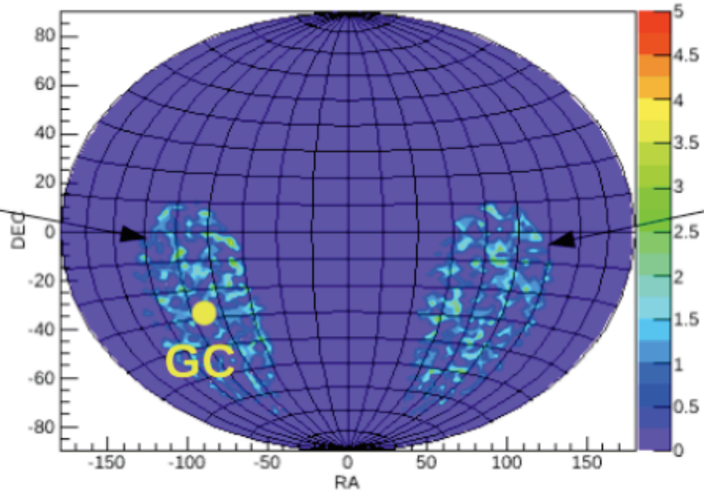
expectation for DM-induced neutrinos



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

on-source

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

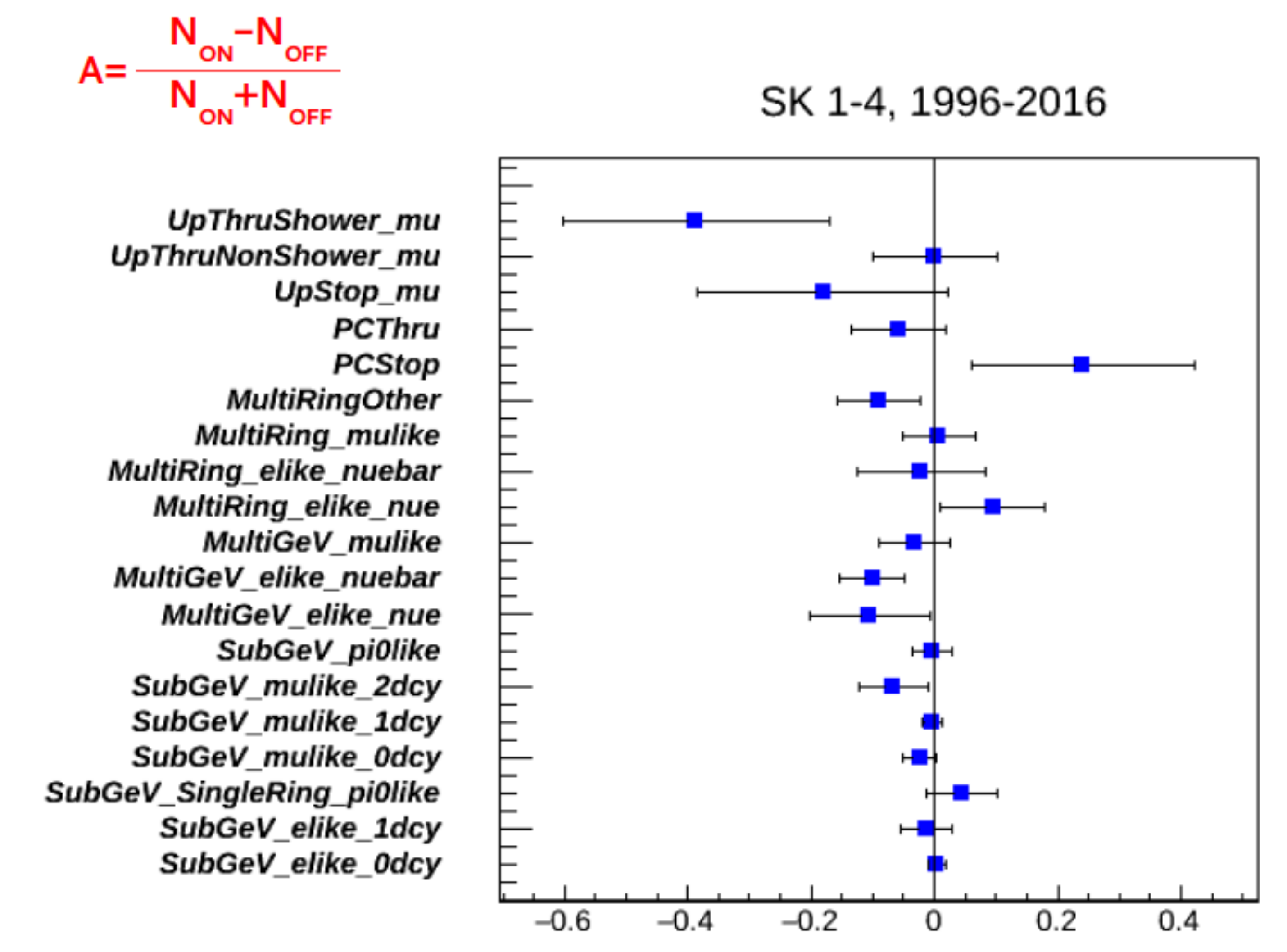


off-source

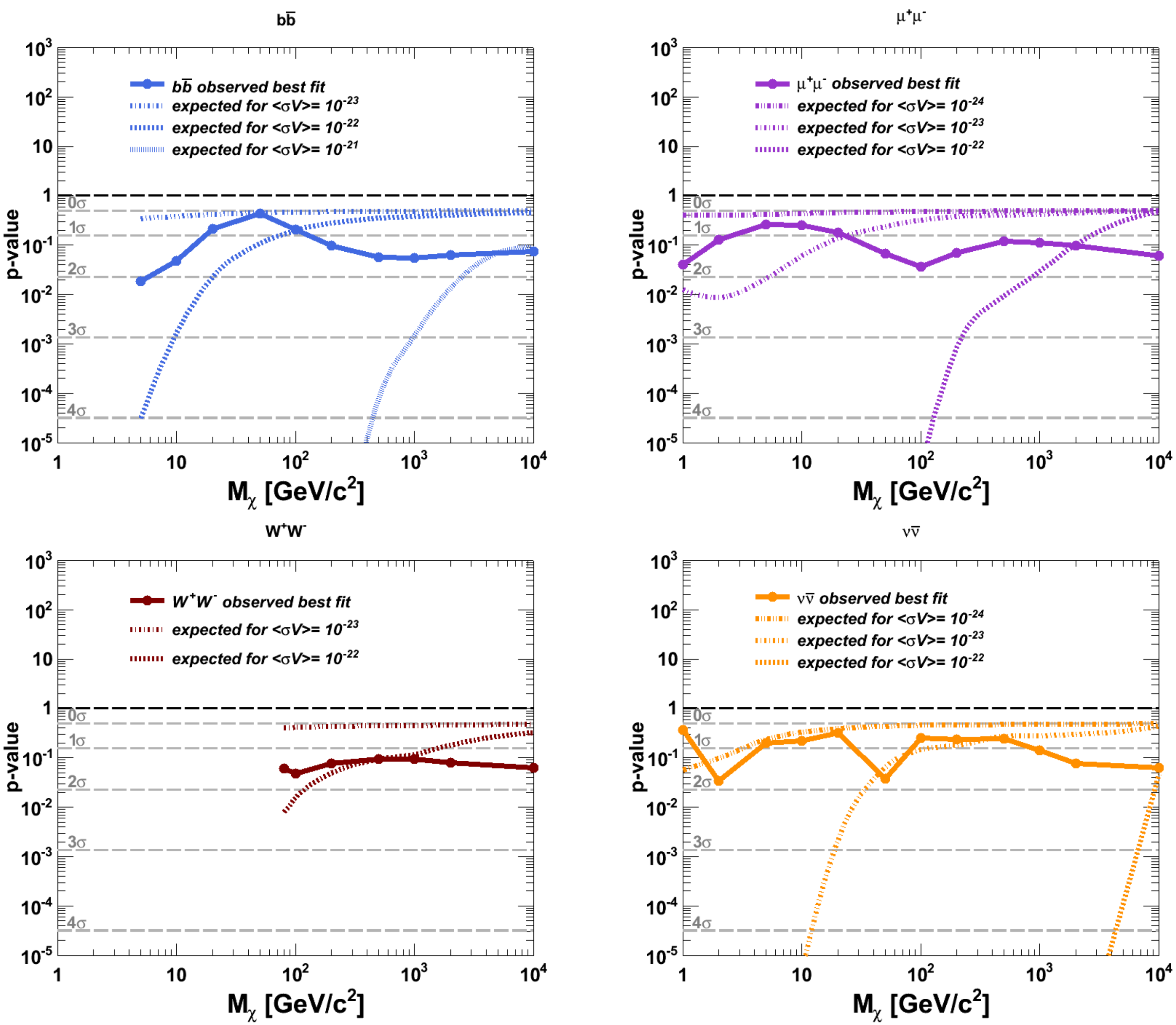
$$N_{off}^{bkg} + N_{off}^{sig}$$

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

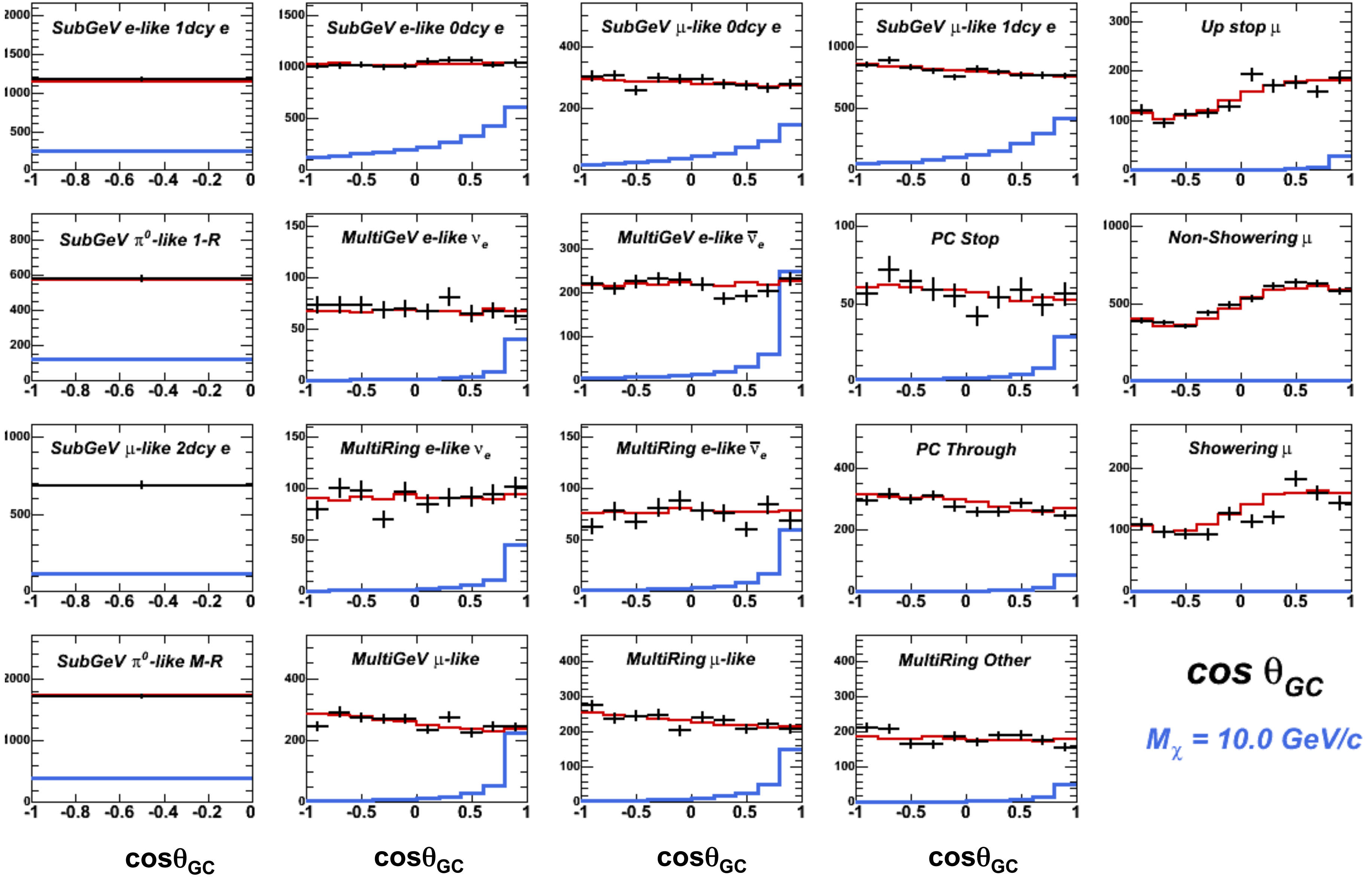
ON- & OFF-source results



Galactic WIMP search: p-value’s



Galactic WIMP search: signal Illustration 10GeV bb-bar

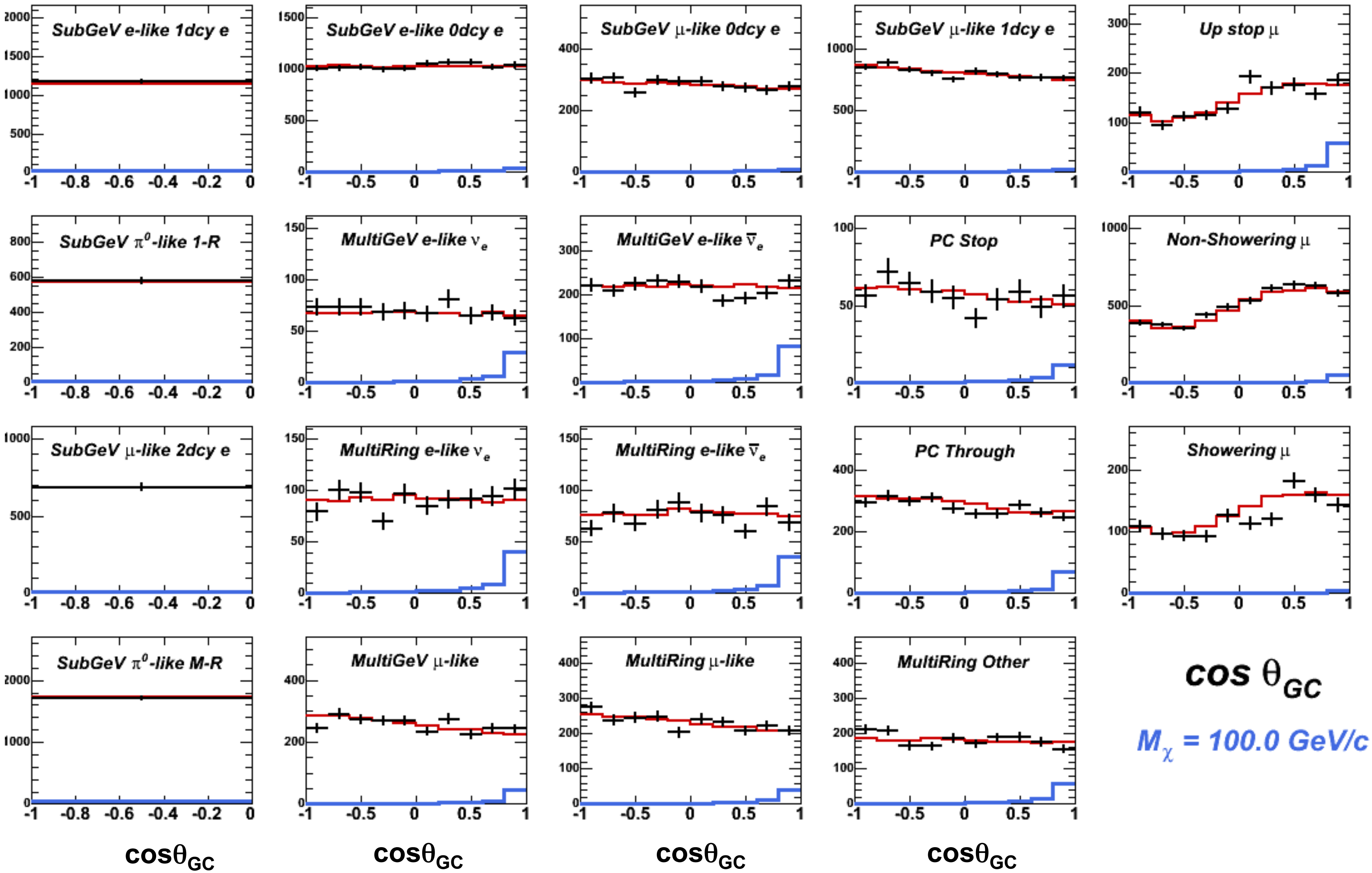


DATA
SK1-4, 1996-2016

ATM MC+WIMP
at best fit point

WIMP
before fit

Galactic WIMP search: signal Illustration 100GeV bb-bar

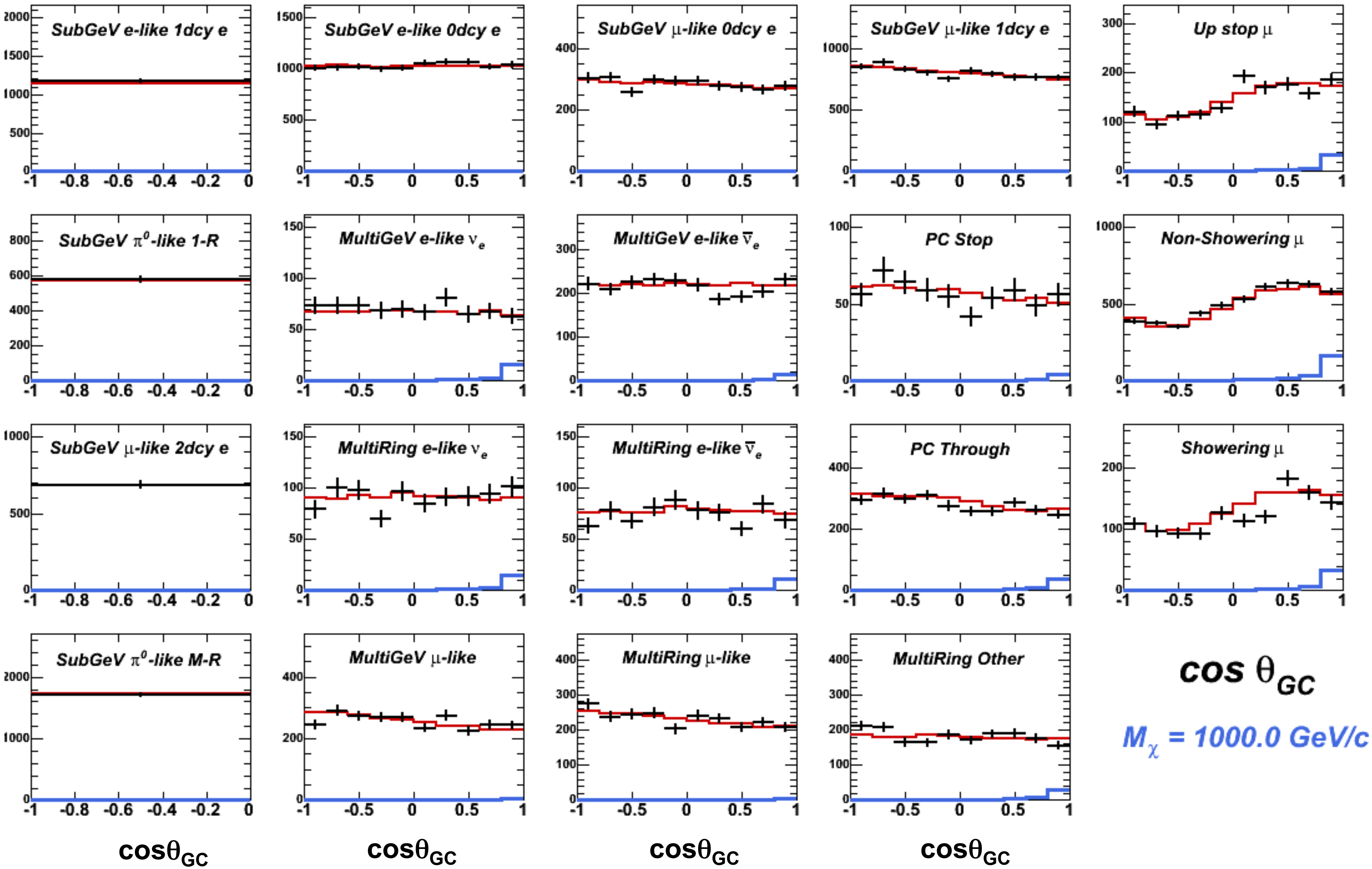


DATA
SK1-4, 1996-2016

ATM MC+WIMP
at best fit point

WIMP
before fit

Galactic WIMP search: signal Illustration 1000GeV bb-bar

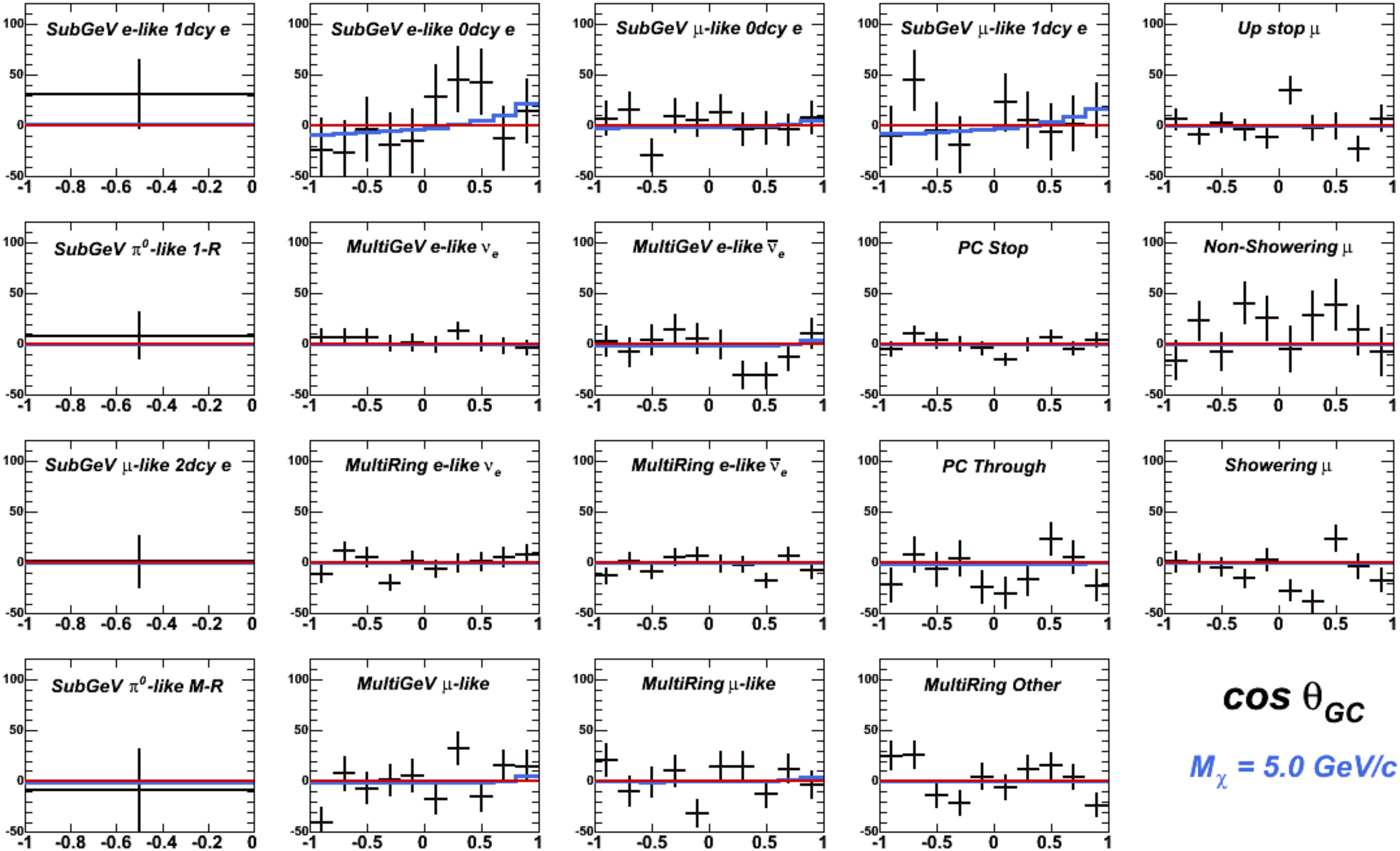


DATA
SK1-4, 1996-2016

ATM MC+WIMP
at best fit point

WIMP
before fit

Galactic WIMP search: residuals for 5GeV bb-bar best fit

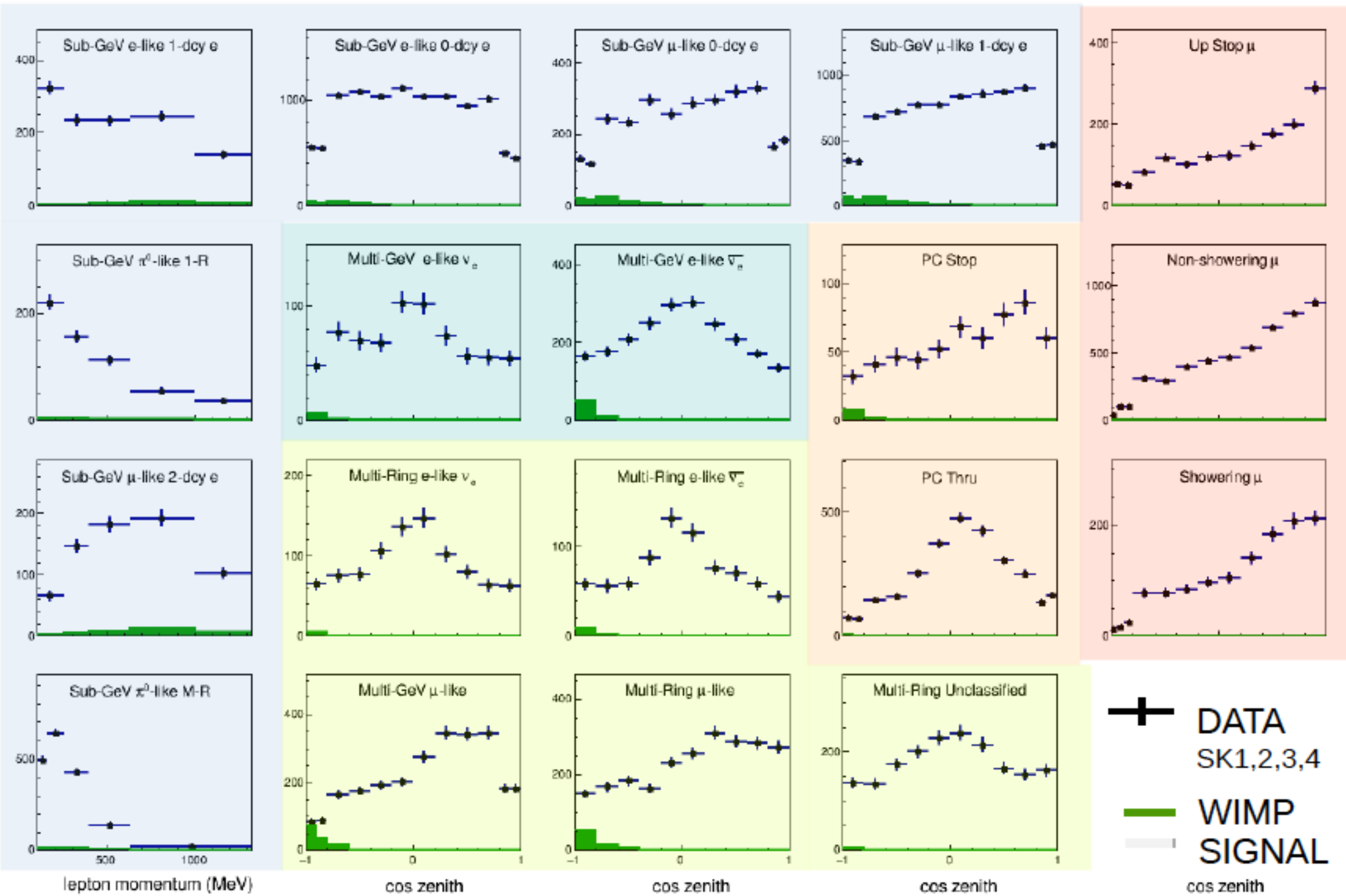


points: data set red line: only ATM MC (with pulls) color line: best fitted WIMP + ATM MC (all with pulls)

$\chi^2_{total} = \chi^2_{data} + \chi^2_{syst}$ 604.0 = 566.9+37.0 601.6= 564.9+36.7 $\Delta\chi^2$ = 2.4 = 2.0 + 0.4

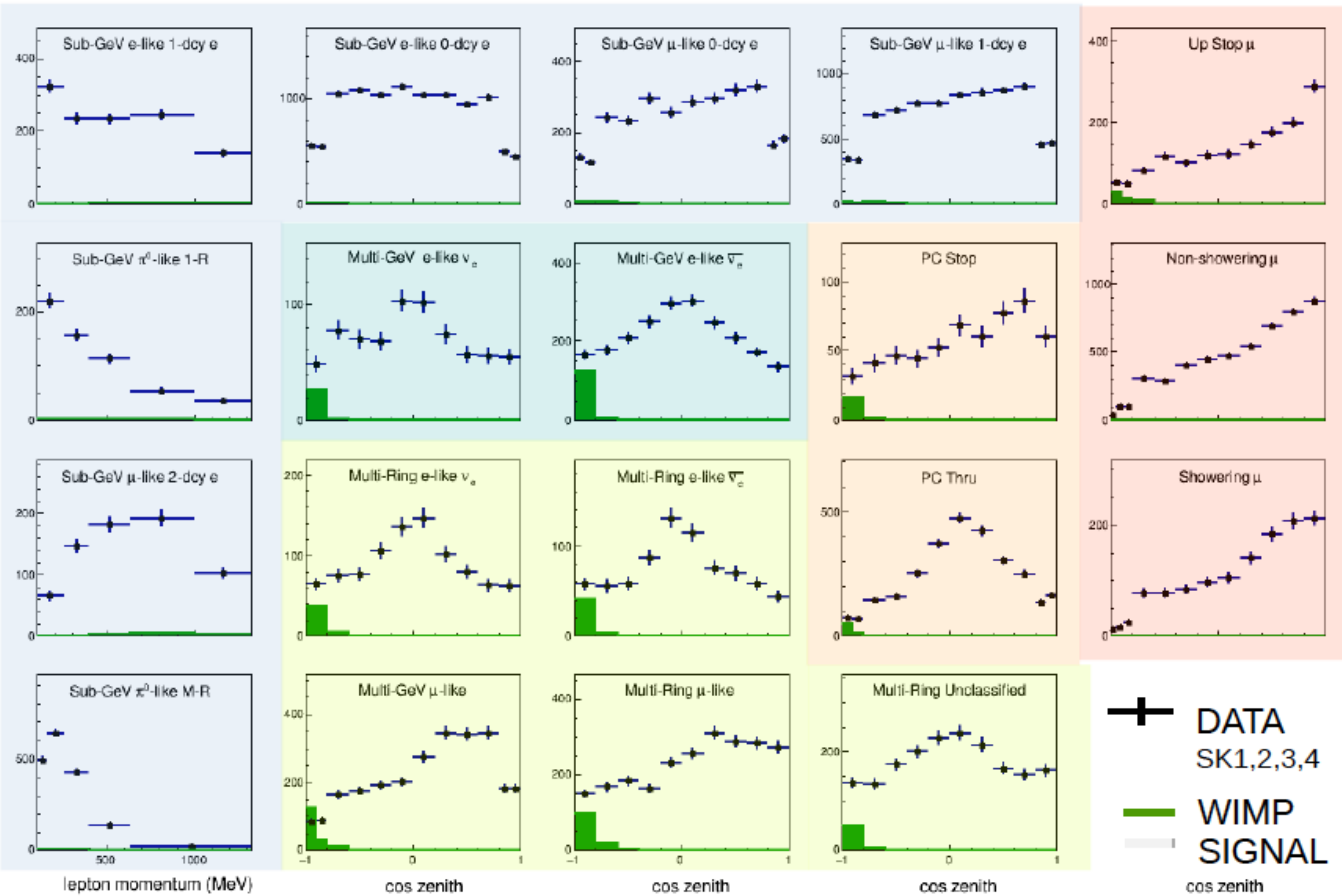
Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 3 GeV



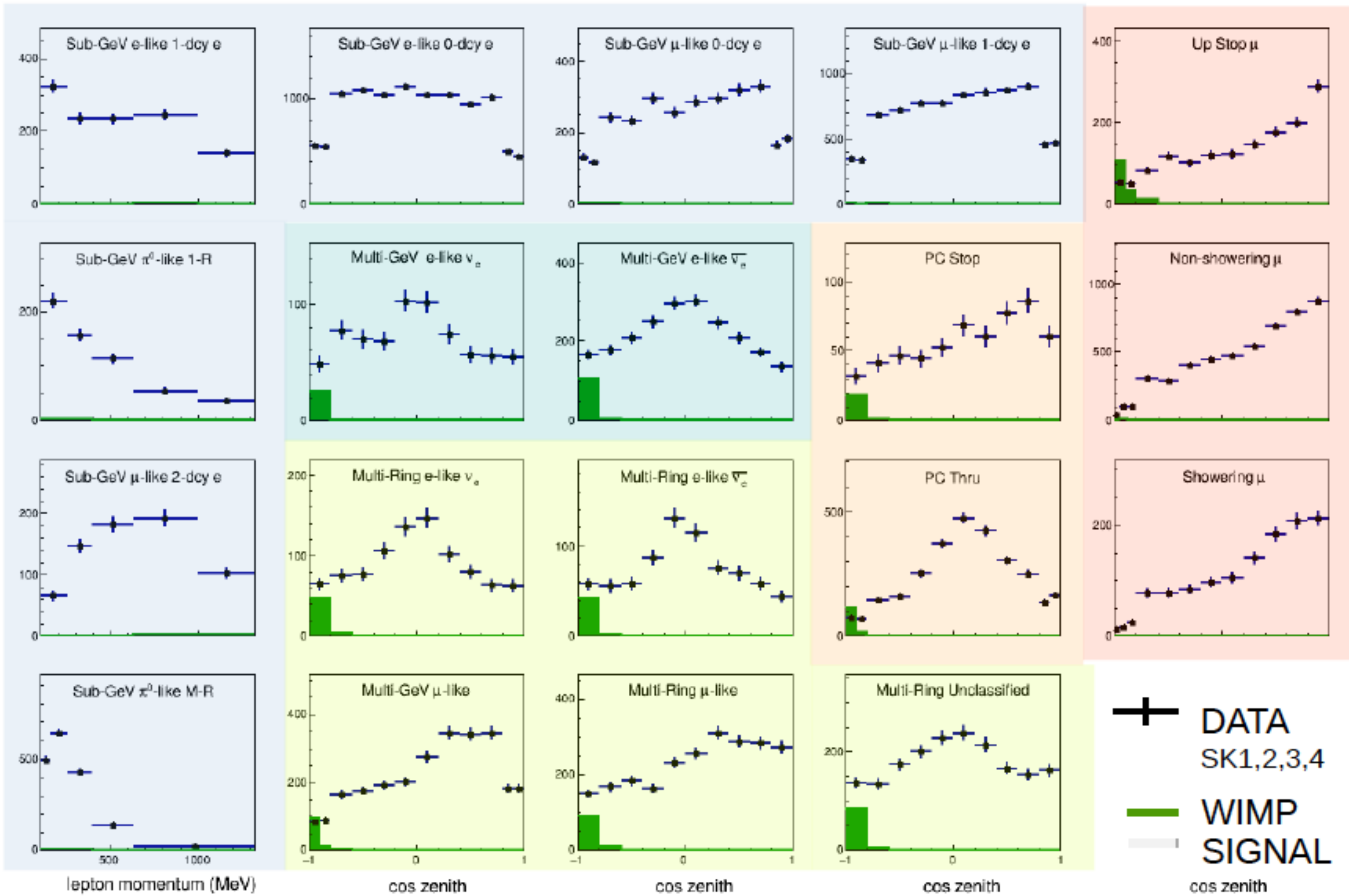
Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 6 GeV



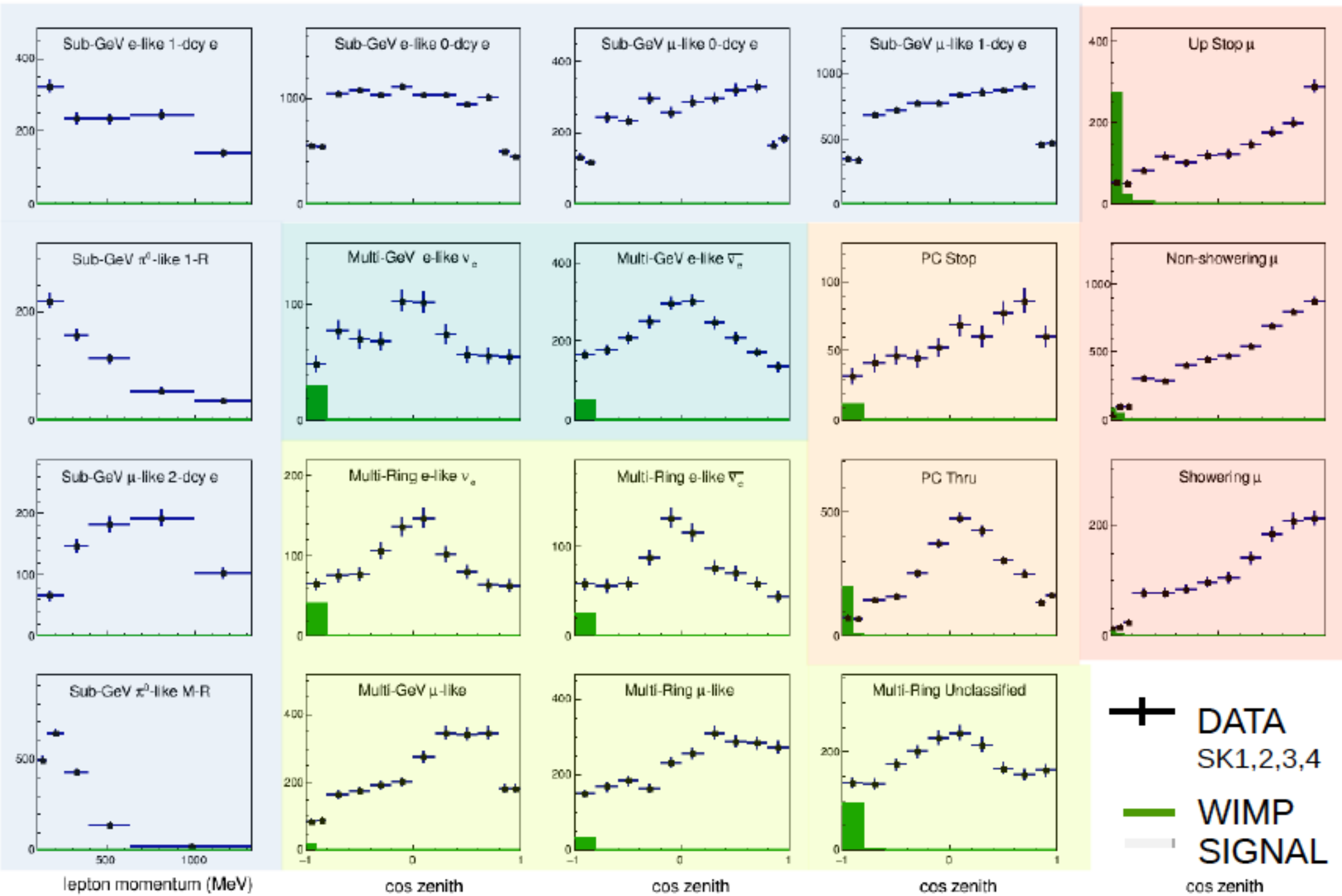
Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 10 GeV



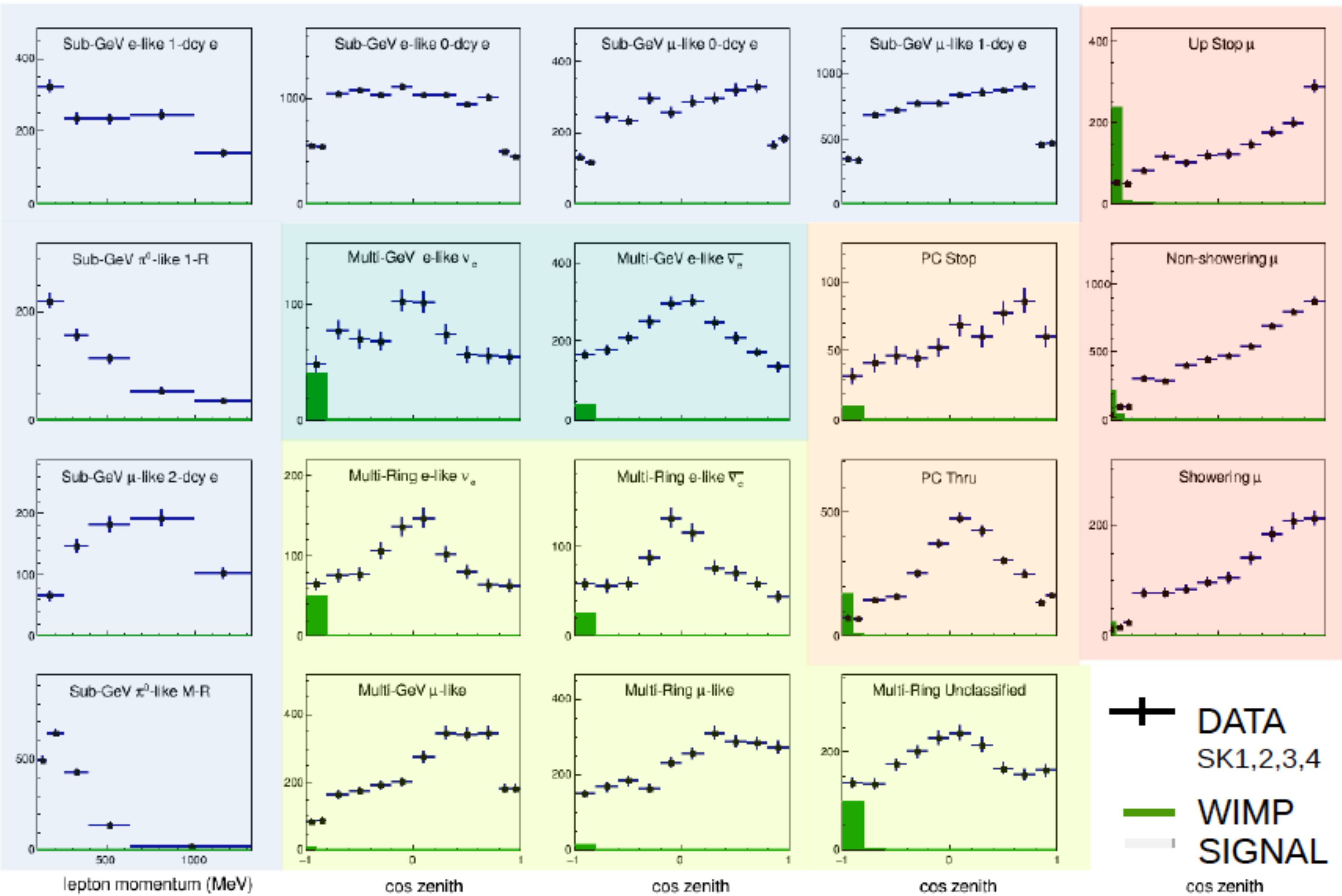
Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 25 GeV



Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 50 GeV



Signal illustration for Earth WIMP search

$\tau^+\tau^-$ ann. channel
WIMP mass = 1 TeV