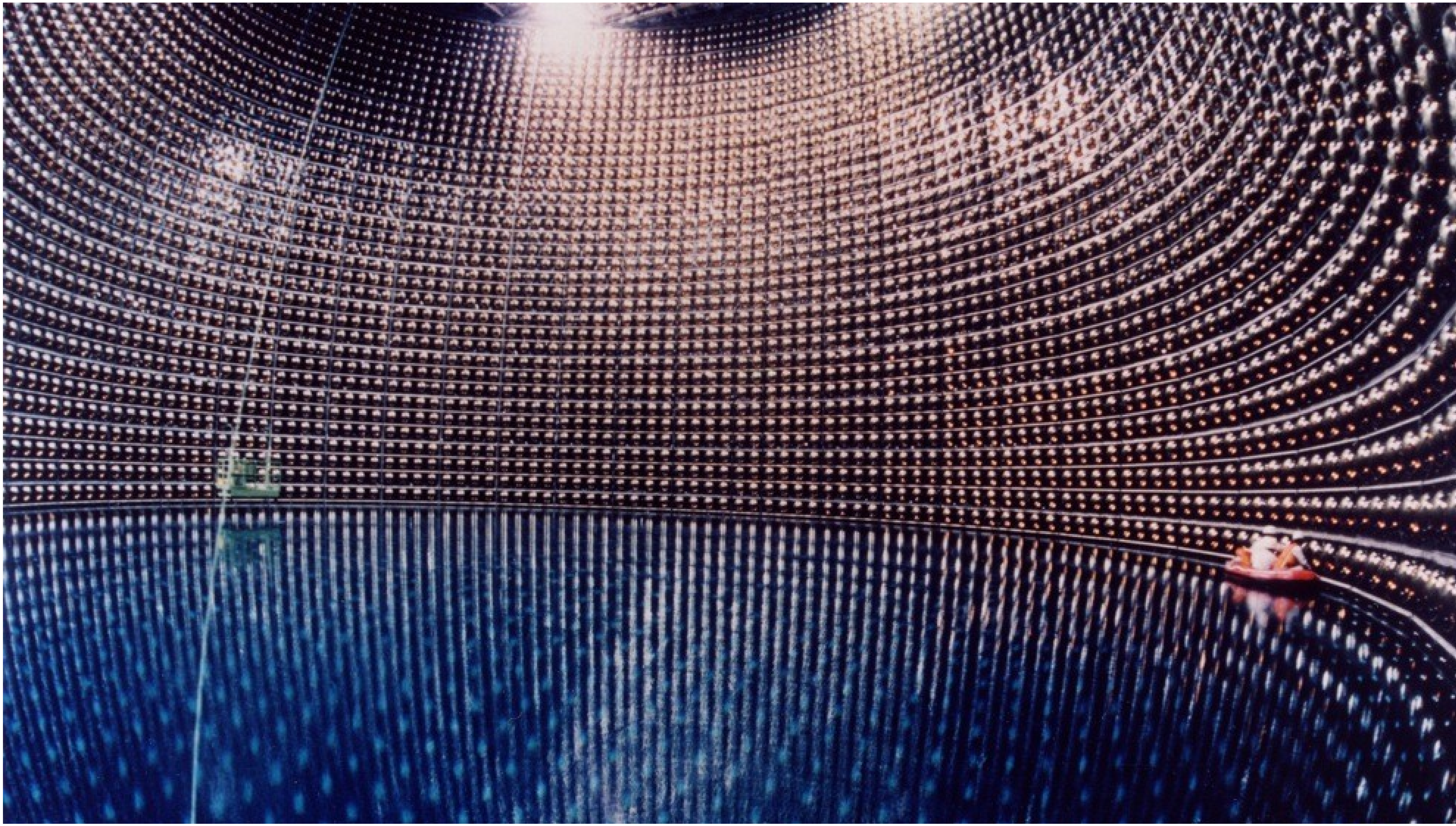
Searches for dark matter with the Super-Kamiokande detector

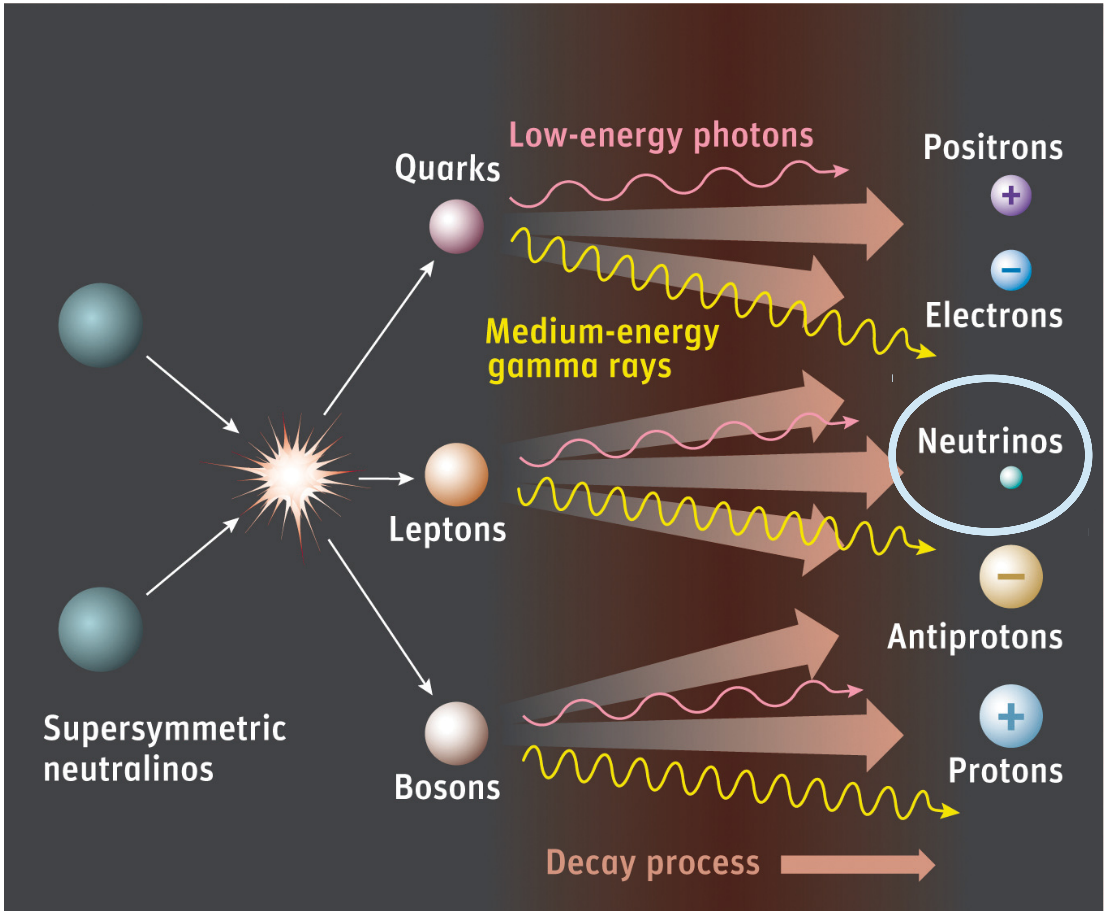


Katarzyna Frankiewicz

DPF meeting, 2017/08/01

Indirect dark matter detection

- Search for the products of WIMP annihilation or decay

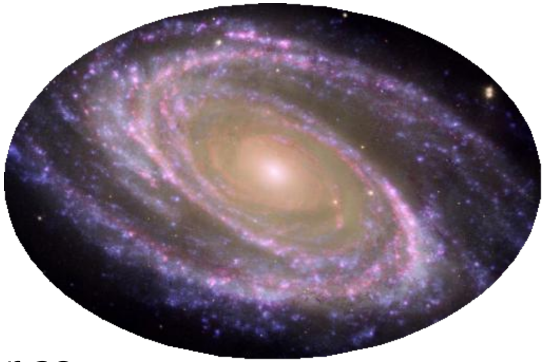


Produced ν's provide very good information about:

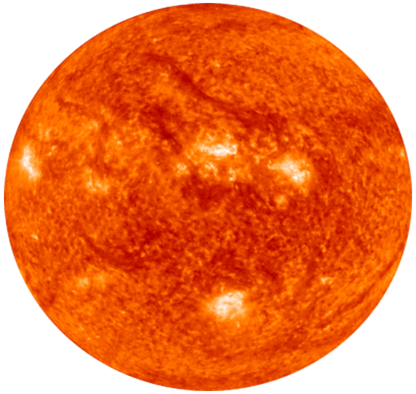
- source position
- generated energy spectra
- flavor composition

Where we are searching:

Diffuse signal from entire Galaxy, peaked from Galactic Center



Sun, consider as point source

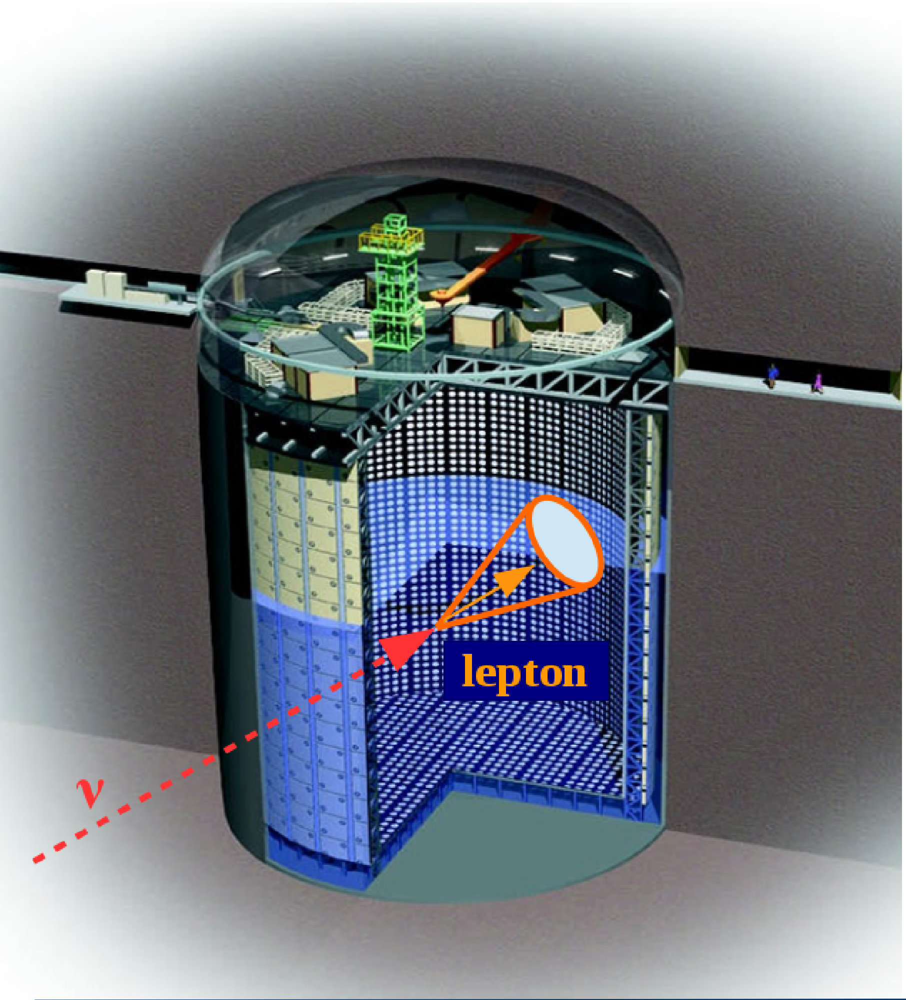


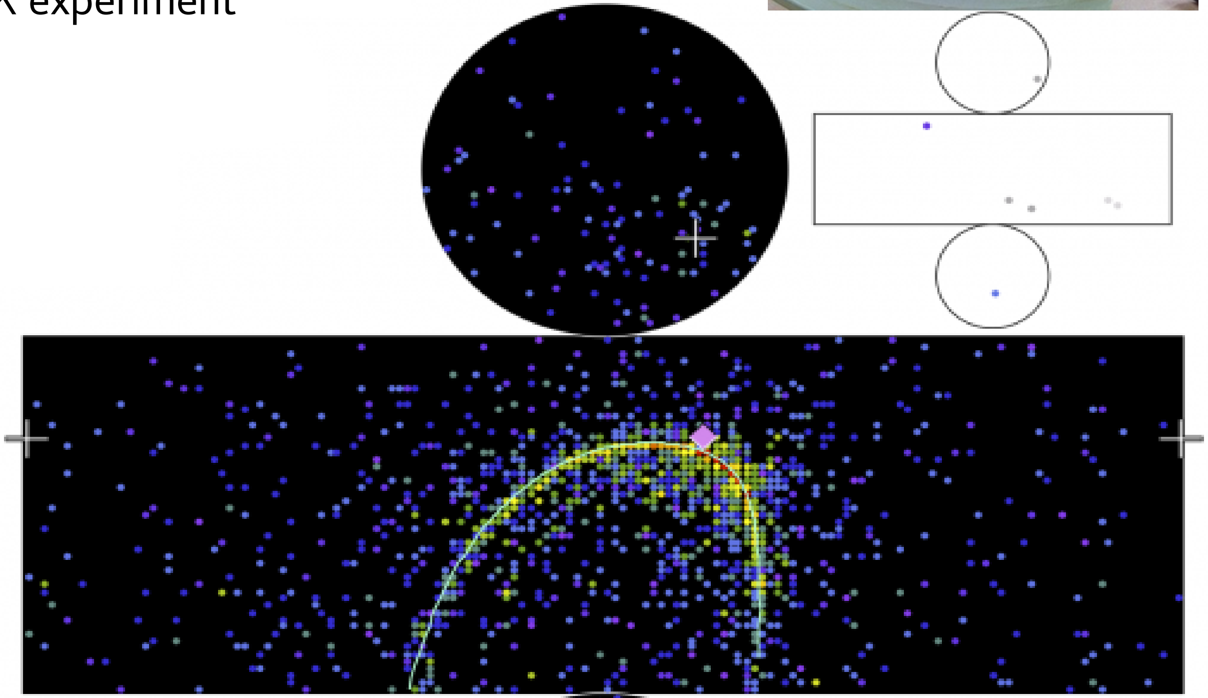
Earth core

Super-Kamiokande

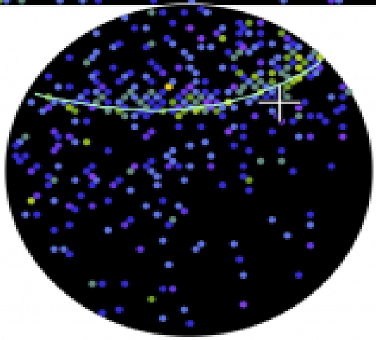
Detector measures solar, atmospheric, cosmic, and accelerator neutrinos

- 50 000 tons of water (22.5 kton FV)
- located in Mozumi mine, 1 km underground
- ID ~11 000 PMTs, OD ~1 800 PMTs
- far detector for T2K experiment

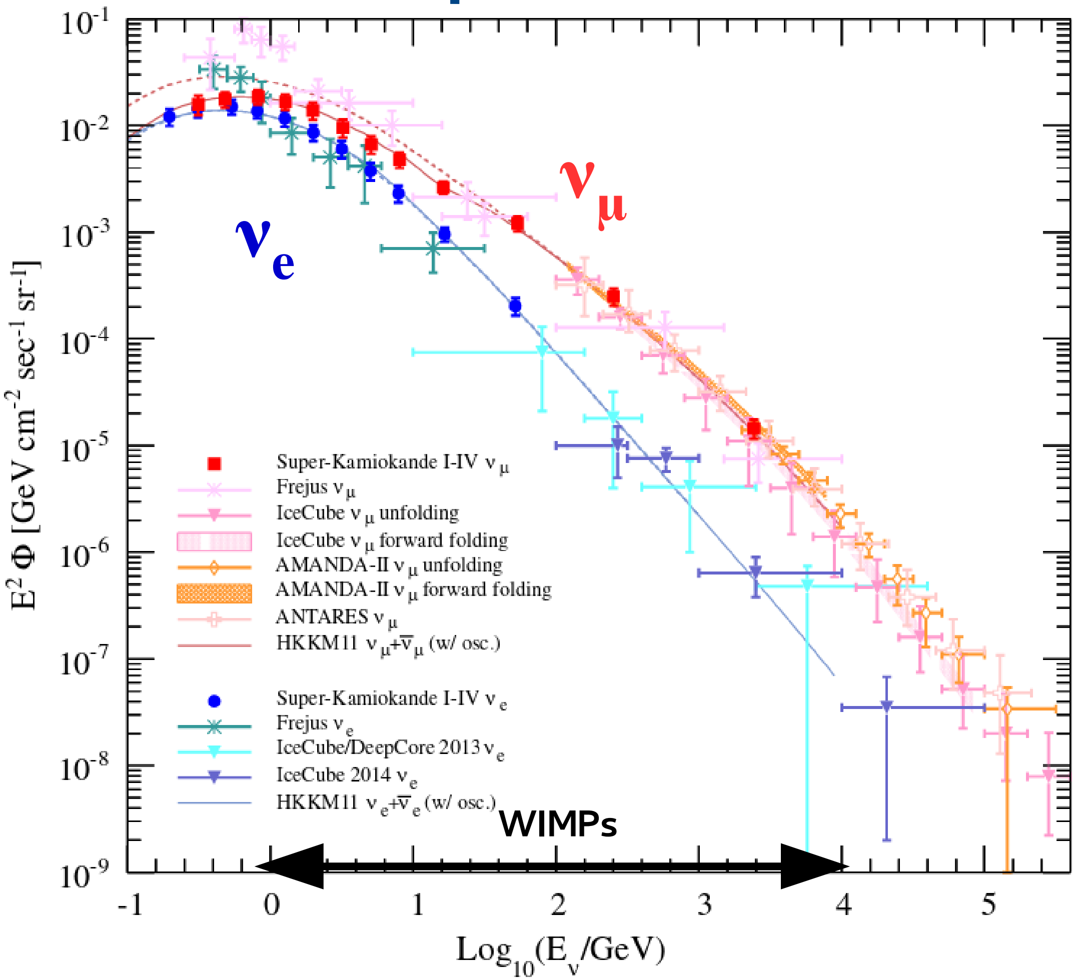




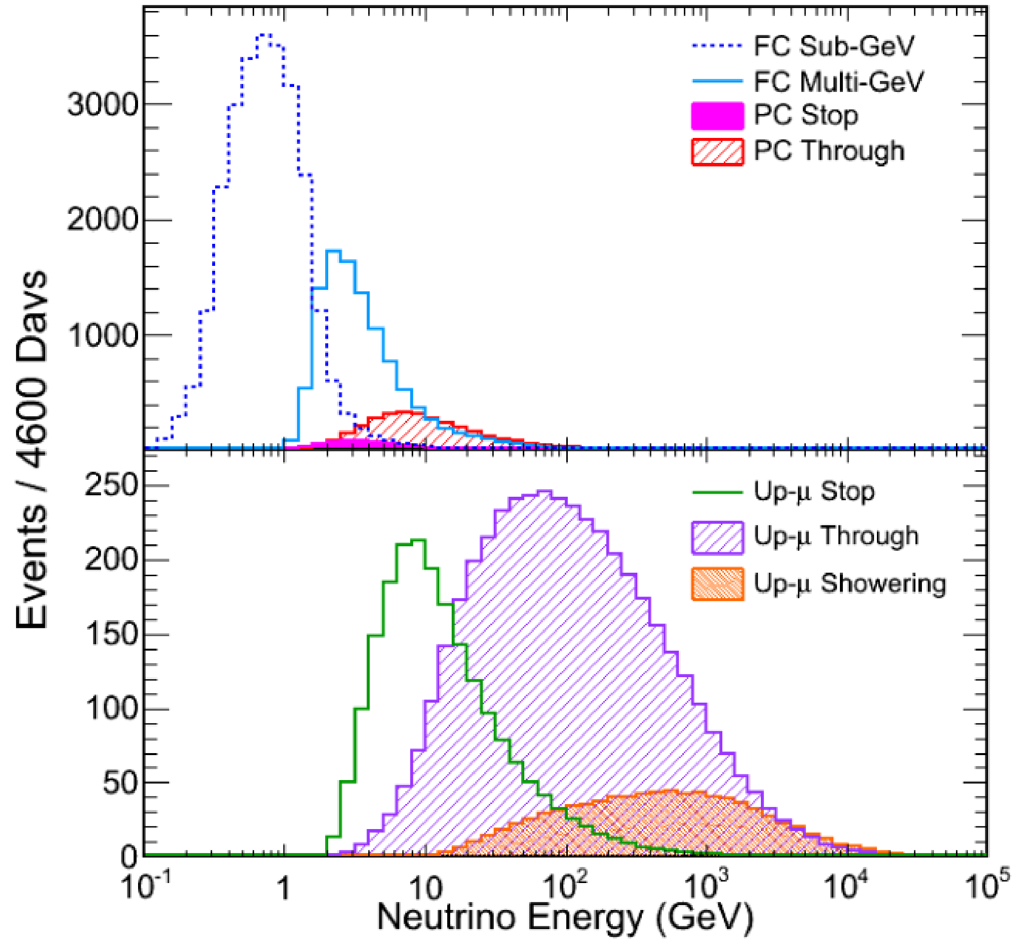
Detected Cherenkov light allows to reconstruct energy, direction, and flavor of produced lepton



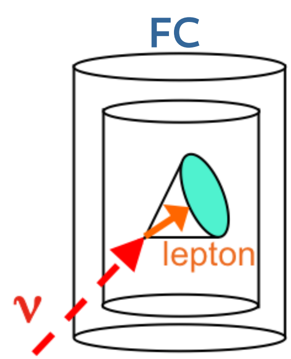
Atmospheric neutrinos

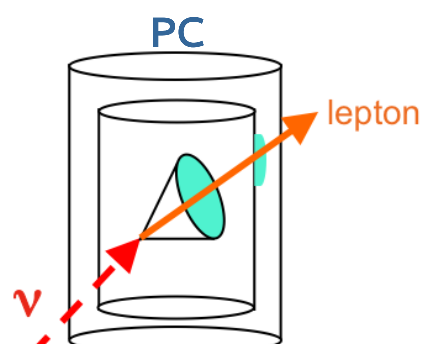


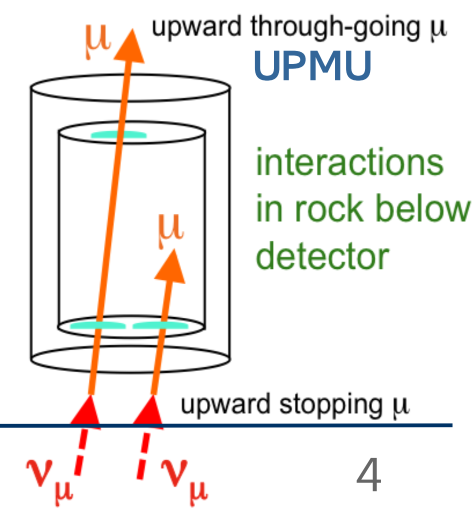
Data samples at SK



- main background for WIMP searches
- ~10 events/day
- data period 1996-2016
- ~50 000 events in total



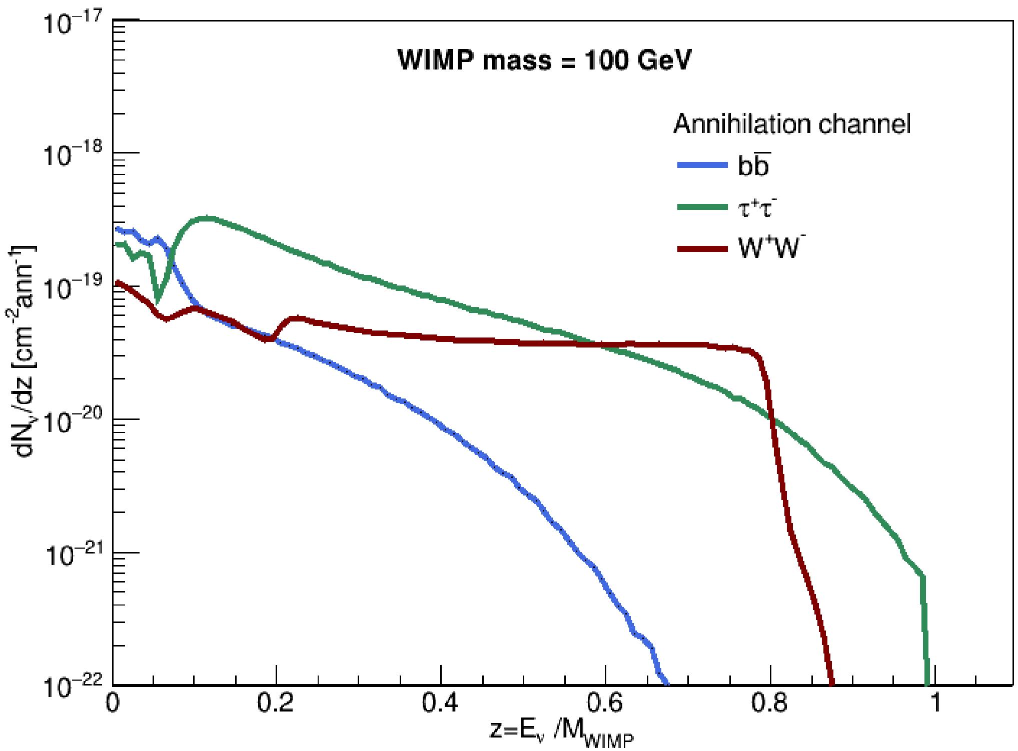


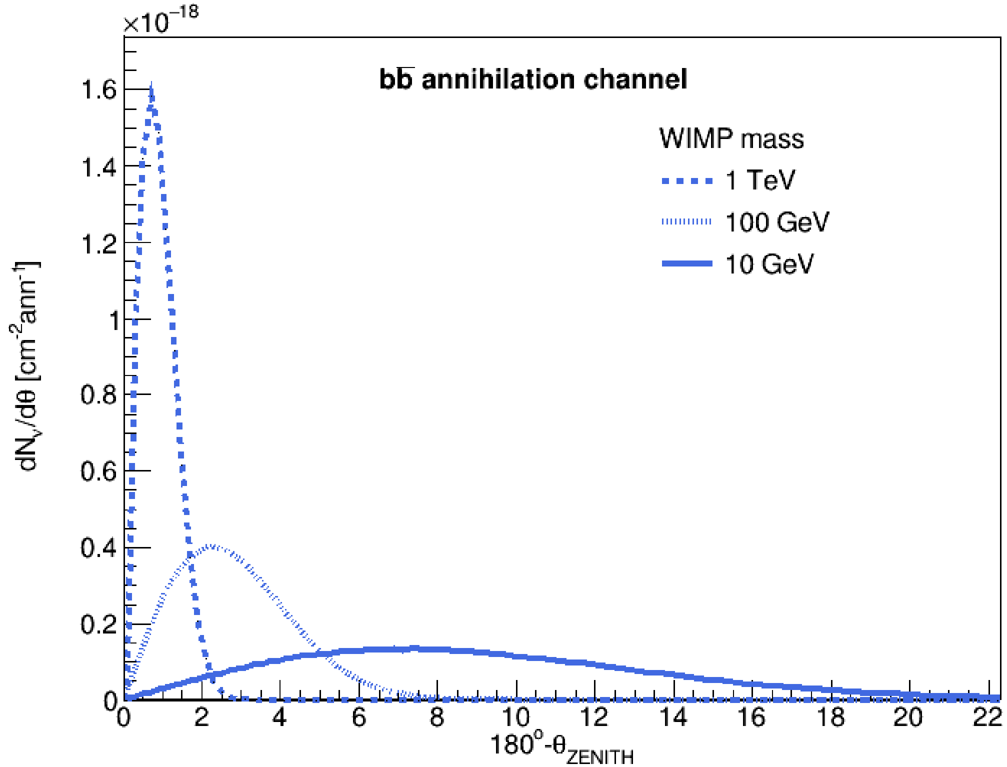


Signal simulation

DarkSUSY - package for supersymmetric dark matter calculations P. Gondolo et al., JCAP 07, 008 (2004)
WimpSim - code calculates the annihilation of WIMPs inside the Earth/Sun and propagates products to the detector M. Blennow et al., arXiv: 0709.3898 (2008)

- Example: muon neutino flux produced in WIMP annihilation in the Earth core





- Energy spectra and angular distribution for each neutrino flavor are calculated for given annihilation channel and assumed WIMP mass
- Neutrino interactions and oscillations in a fully consistent three-flavor way are included

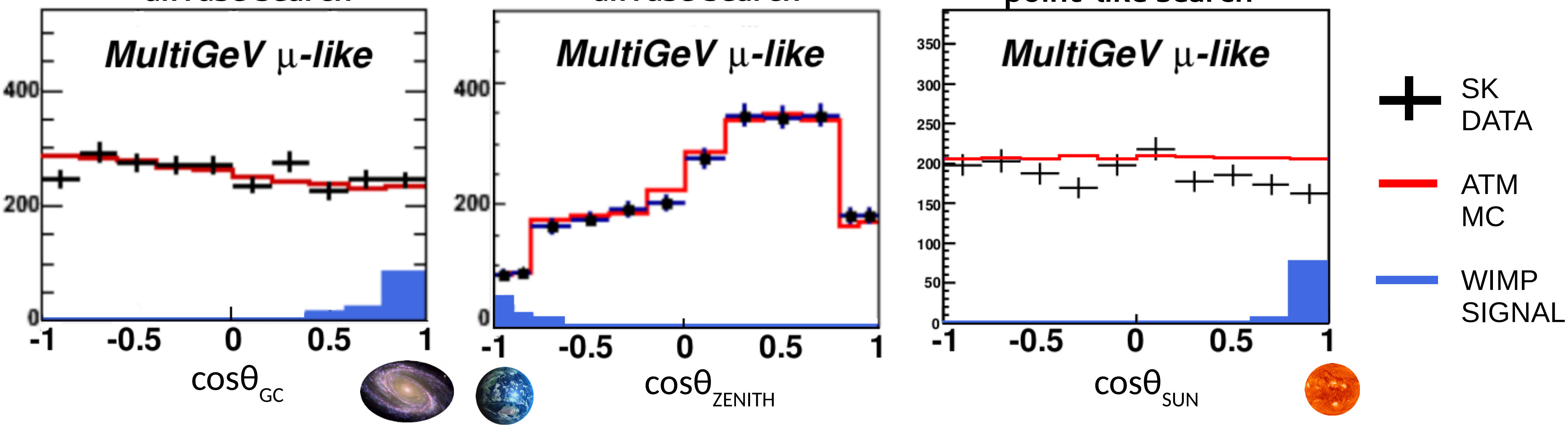
Analysis

Search for excess of neutrinos from the **Milky Way/Earth/Sun** as compared to atmospheric neutrino background

→ For each tested WIMP mass, find the best configuration of **ATM MC** + **WIMP SIGNAL** that would match **DATA** the best

- **Example:** signal for 6 GeV WIMPs annihilating into $b\bar{b}$ for one of data samples

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



- **Each analysis is performed in the coordinate system in which the expected signal is peaked and possible to distinguish from the atmospheric neutrino background**

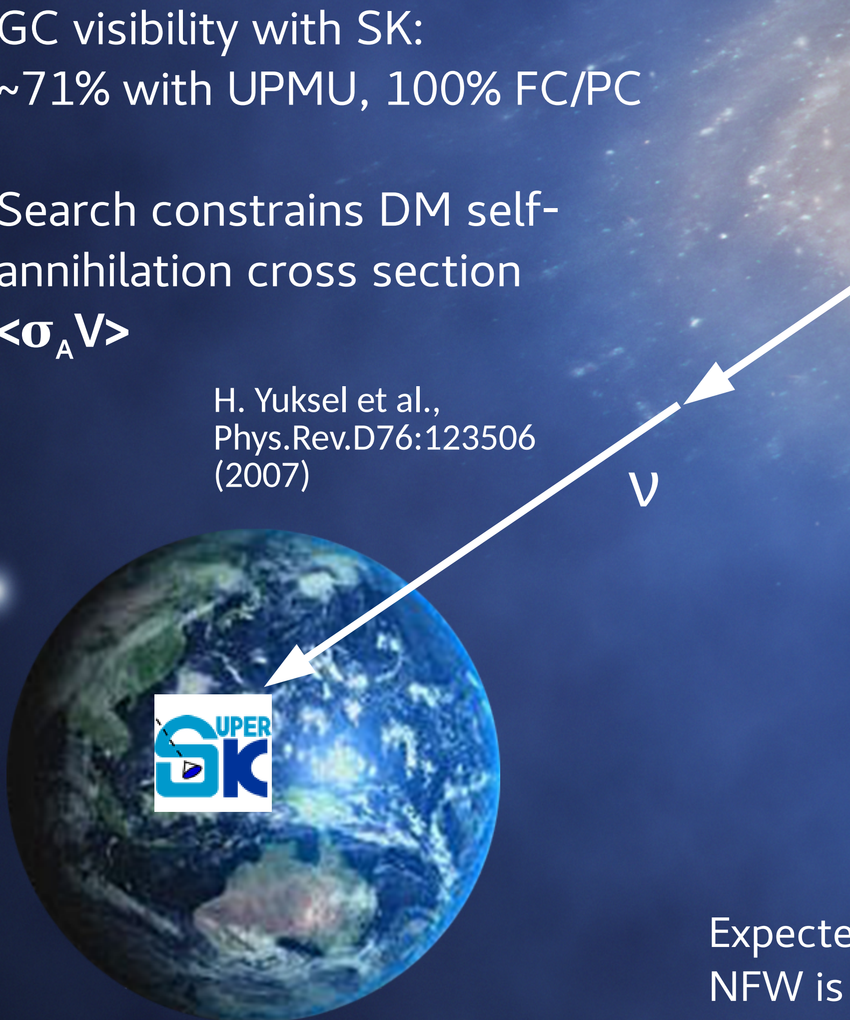
Galactic WIMP search

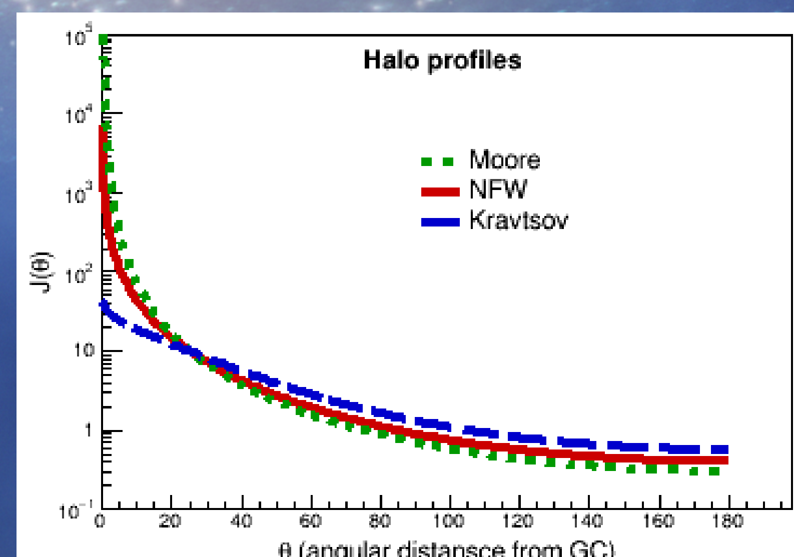
Diffuse signal from entire Galaxy, peaked from Galactic Center

GC visibility with SK:
~71% with UPMU, 100% FC/PC

Search constrains DM self-annihilation cross section
$\langle\sigma_A V\rangle$

H. Yuksel et al., Phys.Rev.D76:123506 (2007)



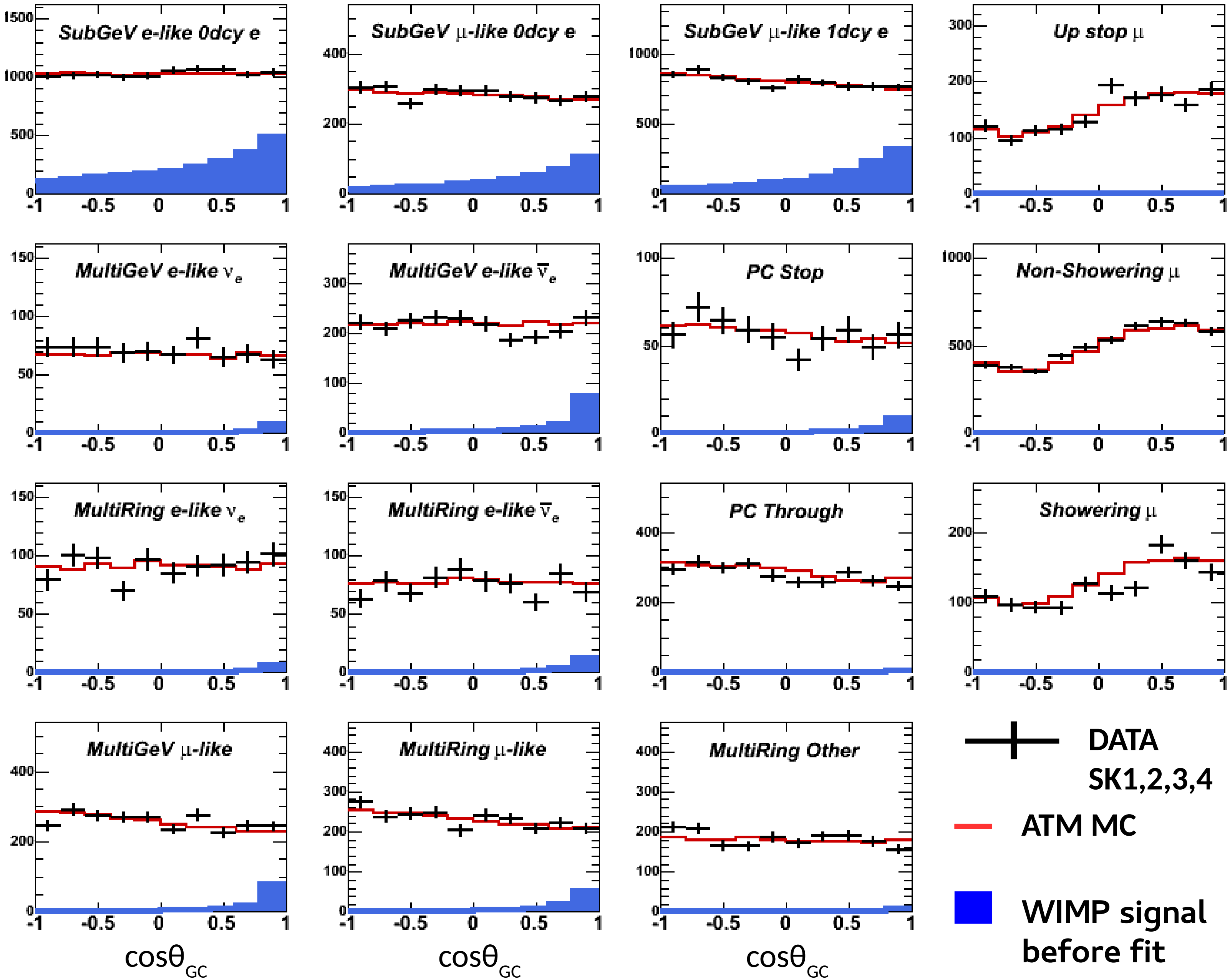


Expected signal intensity strongly depends on halo model
NFW is considered as a benchmark model in this analysis

Galactic WIMP search – data

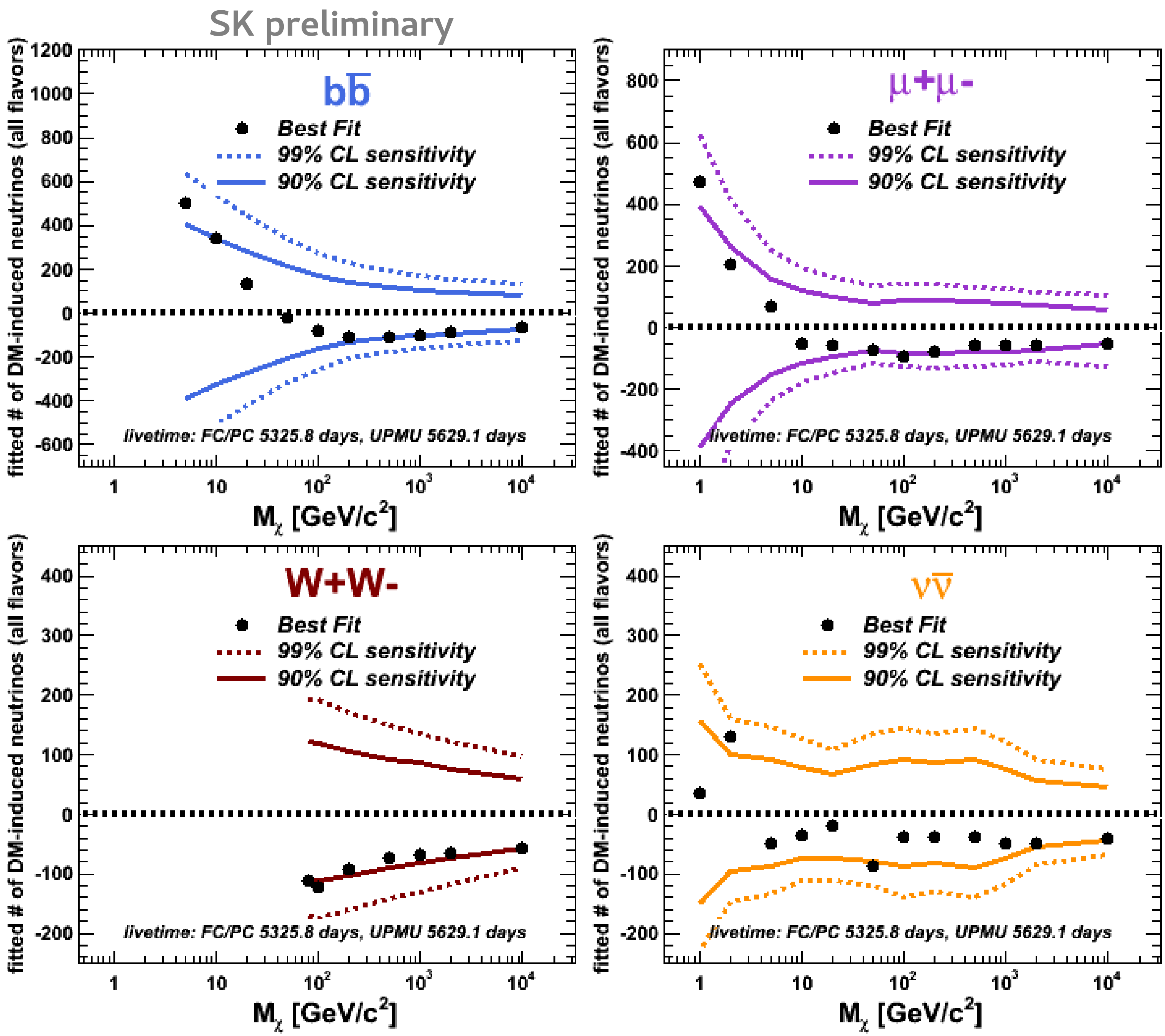
SK preliminary   Example for: 5 GeV WIMPs , $b\bar{b}$ ann. channel

- **FIT based on lepton mom. & $\cos\theta_{GC}$ distributions**
- **NFW halo model is assumed**
- Fit results are consistent with zero
- 90 % upper limits on DM self-annihilation cross section $<\sigma_A V>$



Galactic WIMP search – fitted number of DM-induced neutrinos

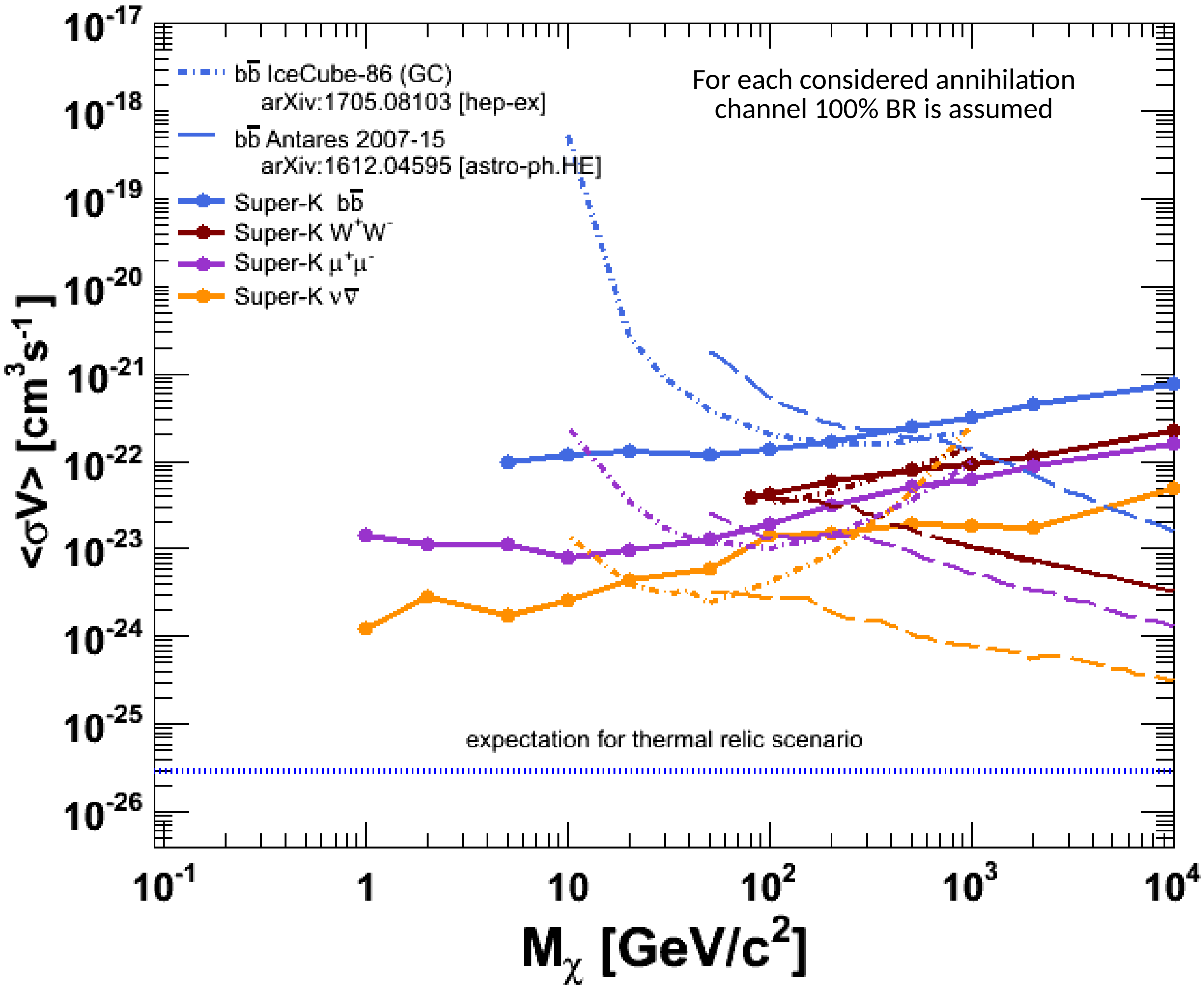
- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions
- NFW halo model is assumed
- **Fit results are consistent with zero**
- 90 % upper limits on DM self-annihilation cross section $<\sigma_A V>$



Galactic WIMP search – WIMP self-annihilation cross section

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions
- NFW halo model is assumed
- Fit results are consistent with zero
- **90% CL upper limits on DM self-annihilation cross section $<\sigma_A V>$**

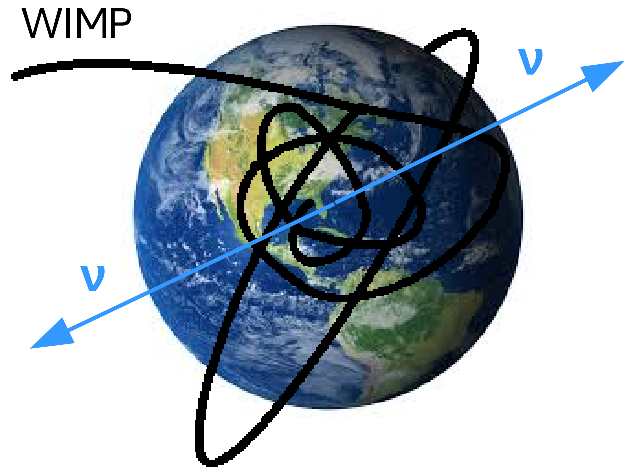
SK preliminary

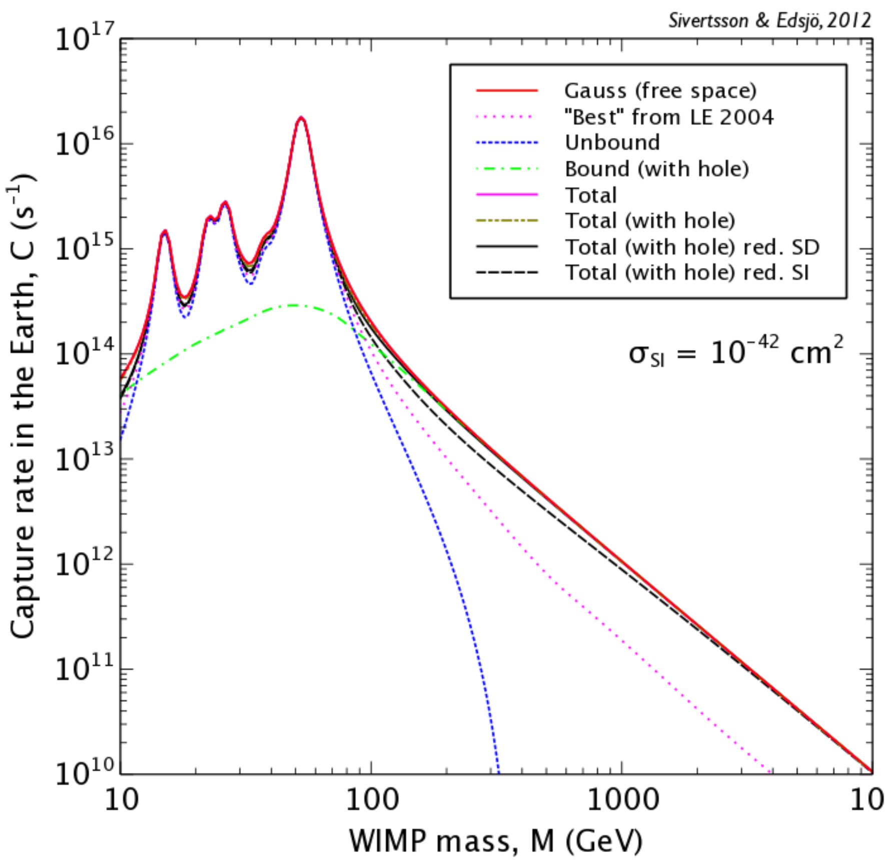


Earth WIMP search

For the Earth, the spin-independent interactions dominate in the capturing process.
→ scalar interaction in which WIMPs couple to the nucleus mass

If the mass of DM almost matches one of the heavy elements in the Earth, the capture rate will increase considerably.





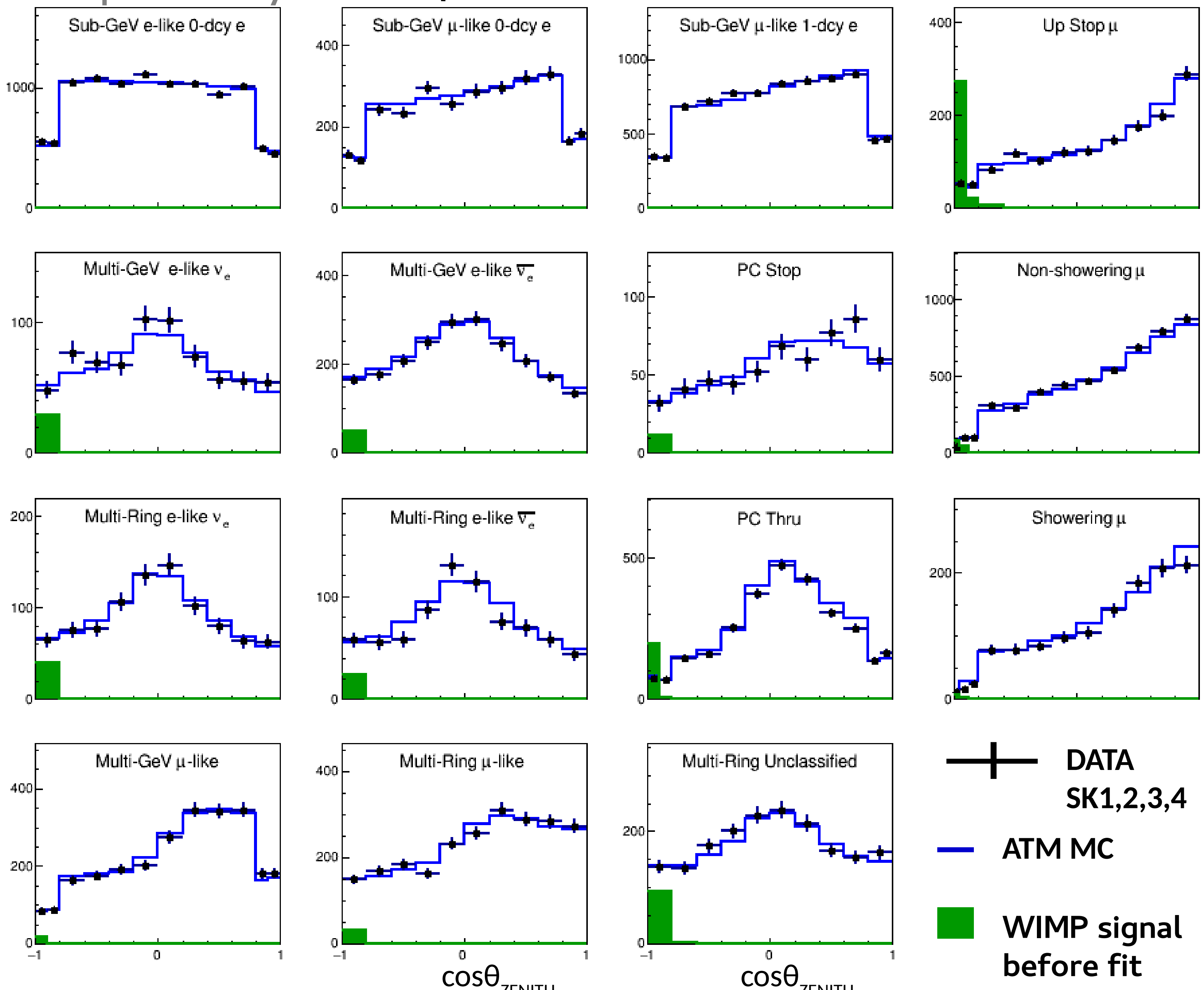
Capture rate for DM particles captured to the Earth core. The peaks correspond to **resonant capture** on the most abundant elements **^{16}O**, **^{24}Mg**, **^{28}Si** and **^{56}Fe** and their isotopes.

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

Earth WIMP search – data

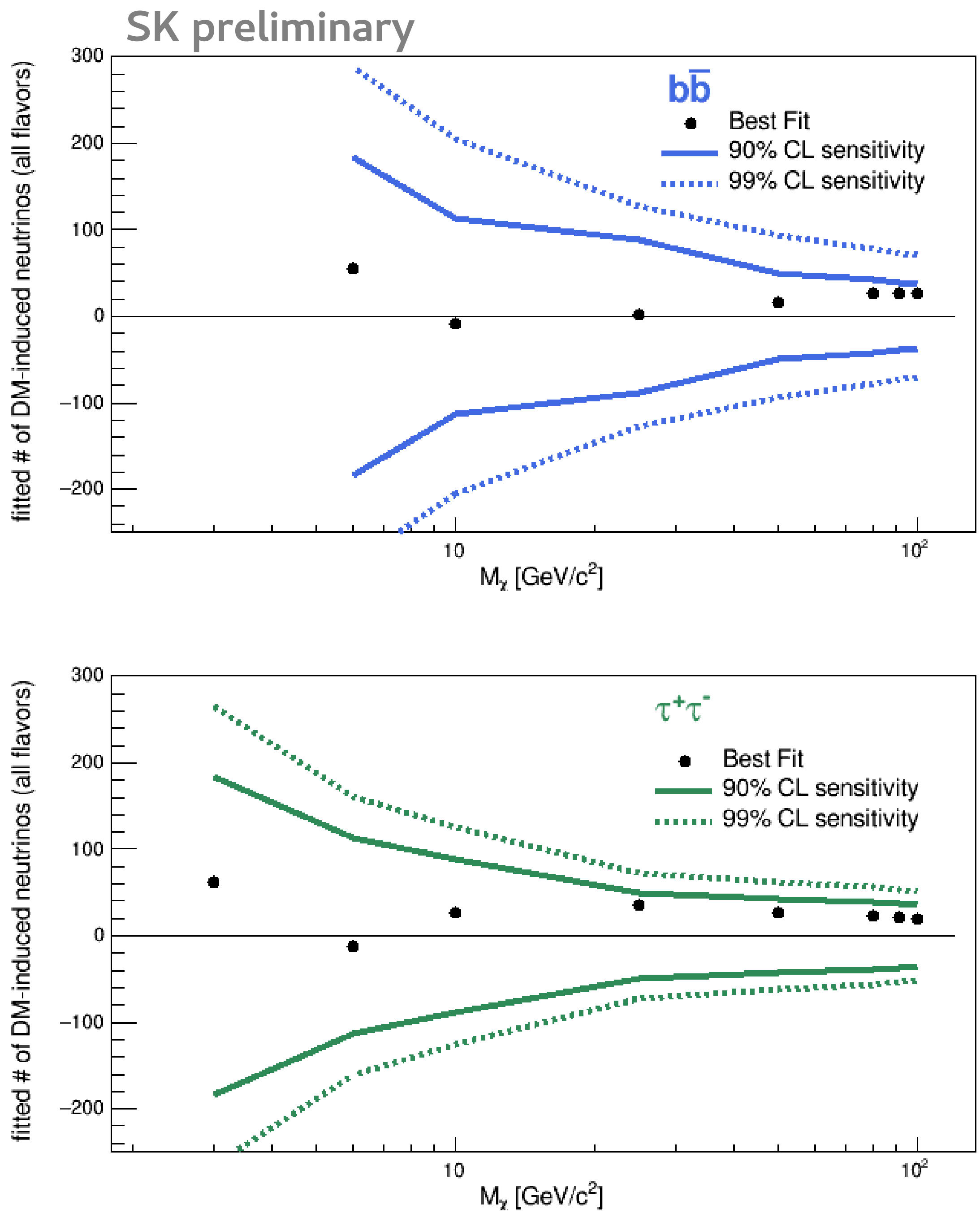
- **FIT based on lepton mom. & $\cos\theta_{ZENITH}$ distributions**
- Fit results are consistent with zero
- 90 % upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi}n$

SK preliminary   Example for: 25 GeV WIMPs , $\tau^{+}\tau^{-}$ ann. channel



Earth WIMP search – fitted number of DM-induced neutrinos

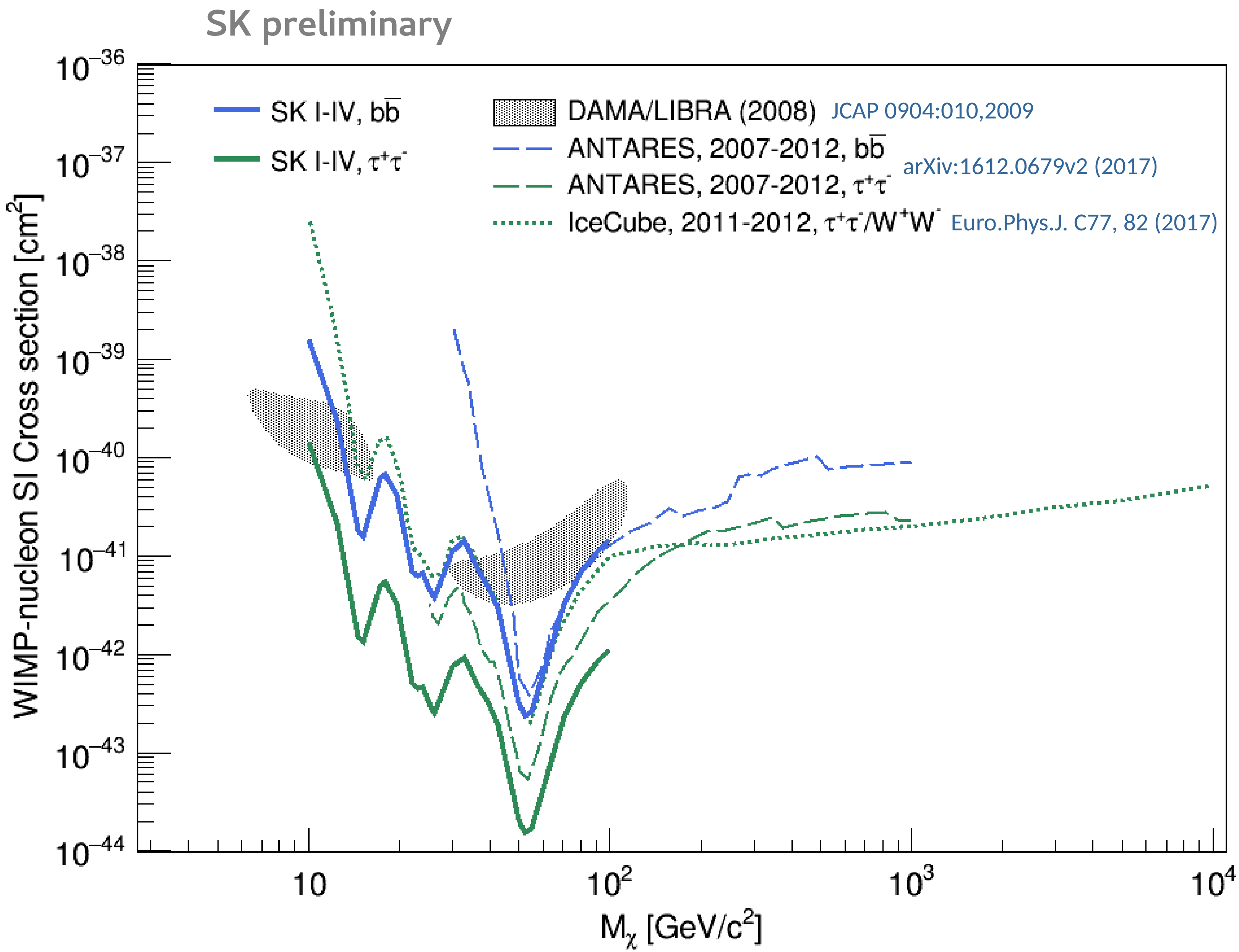
- FIT based on lepton mom. & $\cos\theta_{ZENITH}$ distributions
- **Fit results are consistent with zero**
- 90 % upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi}n$



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

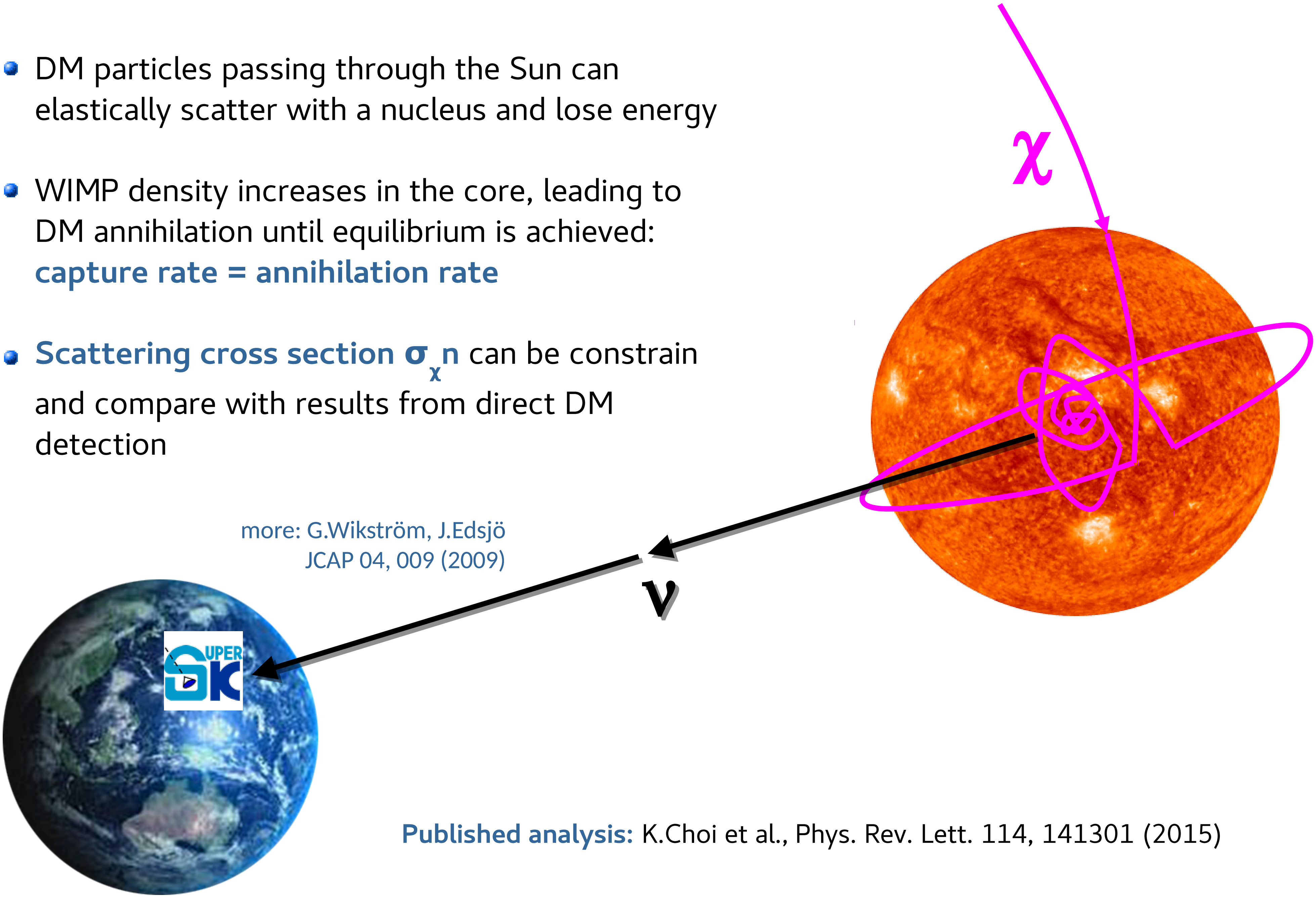
→ scalar interaction in which WIMPs couple to the nucleus mass

- FIT based on lepton mom. & $\cos\theta_{ZENITH}$ distributions
- Fit results are consistent with zero
- **90 % upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi}n$**



Solar WIMP search

- DM particles passing through the Sun can elastically scatter with a nucleus and lose energy
- WIMP density increases in the core, leading to DM annihilation until equilibrium is achieved: **capture rate = annihilation rate**
- **Scattering cross section $\sigma_{\chi}n$** can be constrain and compare with results from direct DM detection



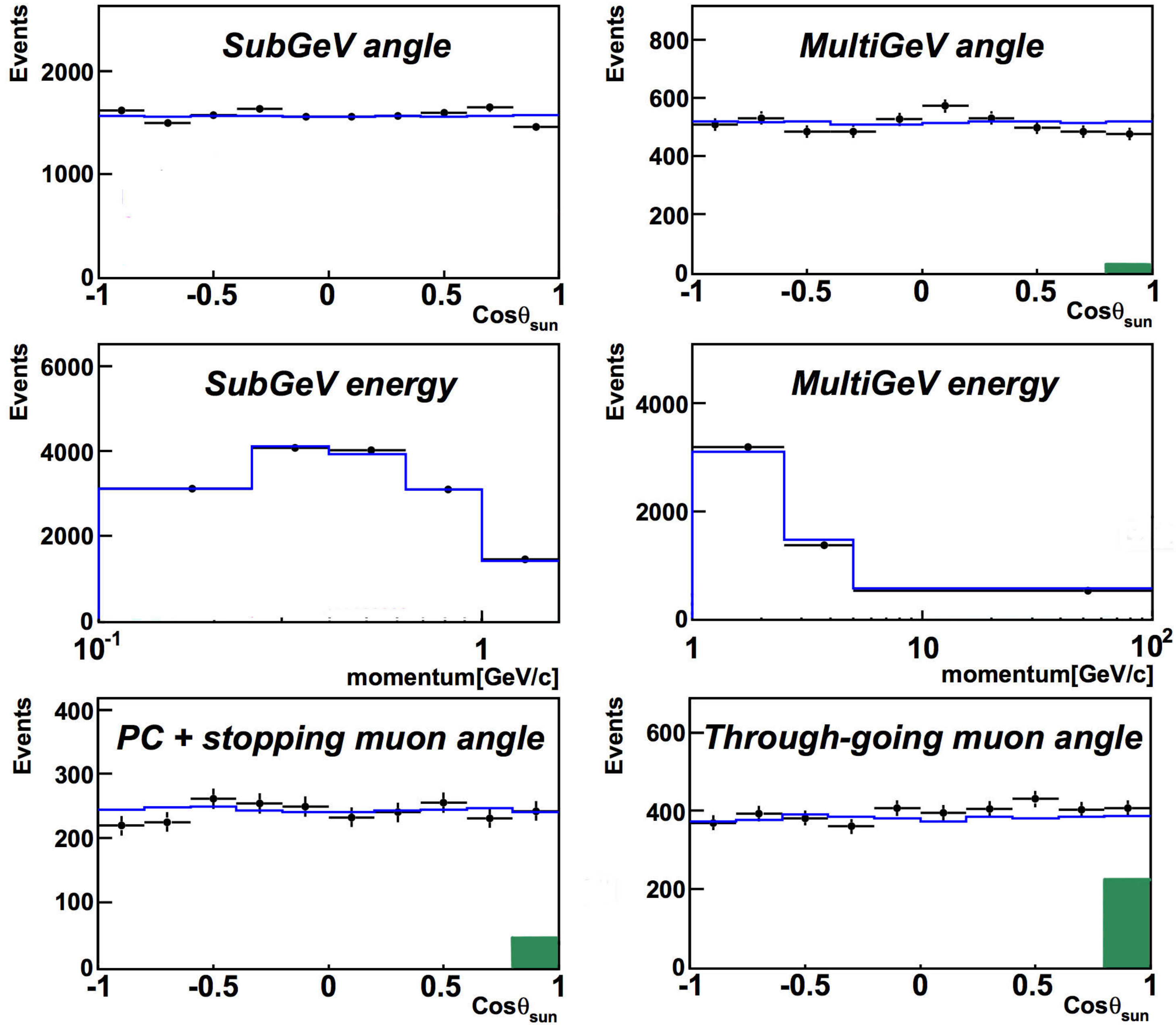
more: G.Wikström, J.Edsjö
JCAP 04, 009 (2009)

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

Solar WIMP search – data

- FIT based on lepton mom. & $\cos\theta_{SUN}$ distributions
- Fit results are consistent with zero
- 90 % upper limits on SD and SI WIMP-nucleon scattering cross section $\sigma_{\chi}n$

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



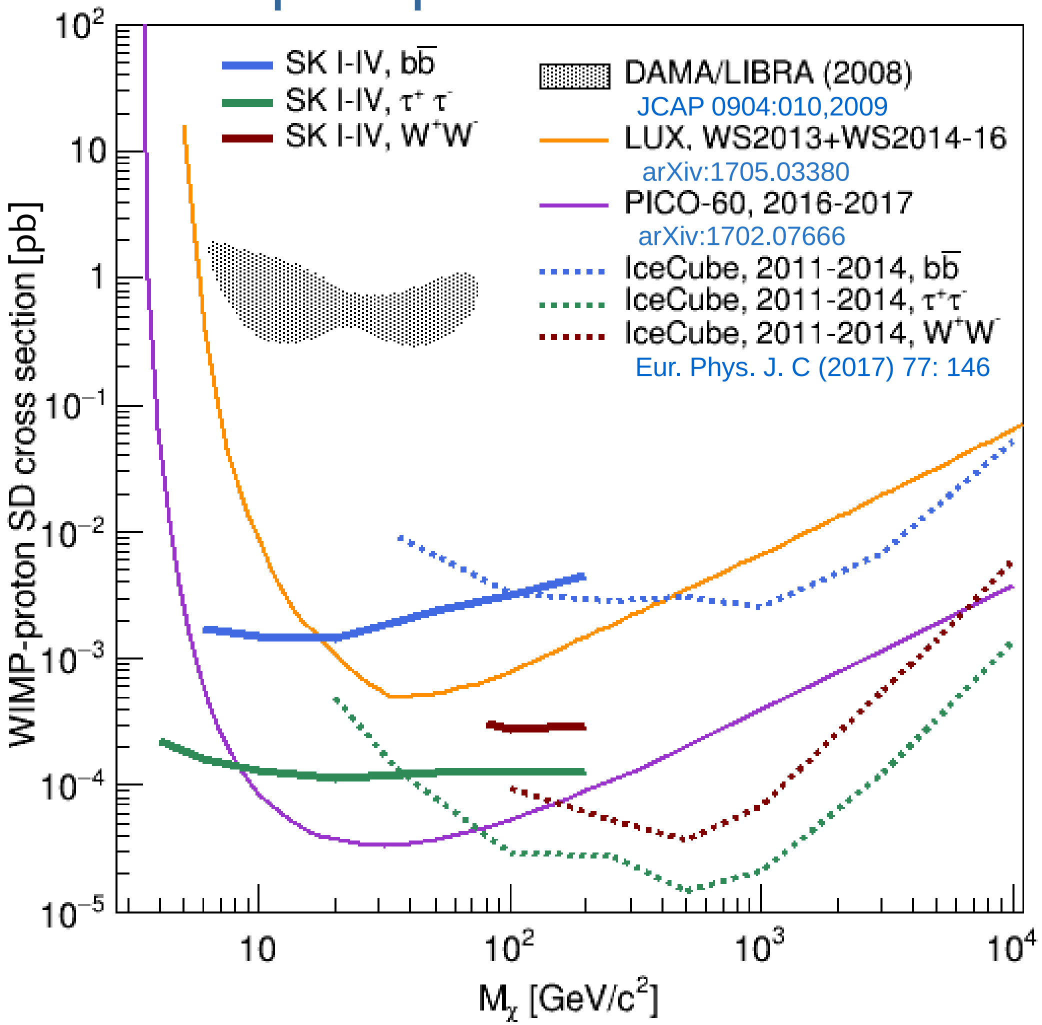
DATA SK1,2,3,4

ATM MC

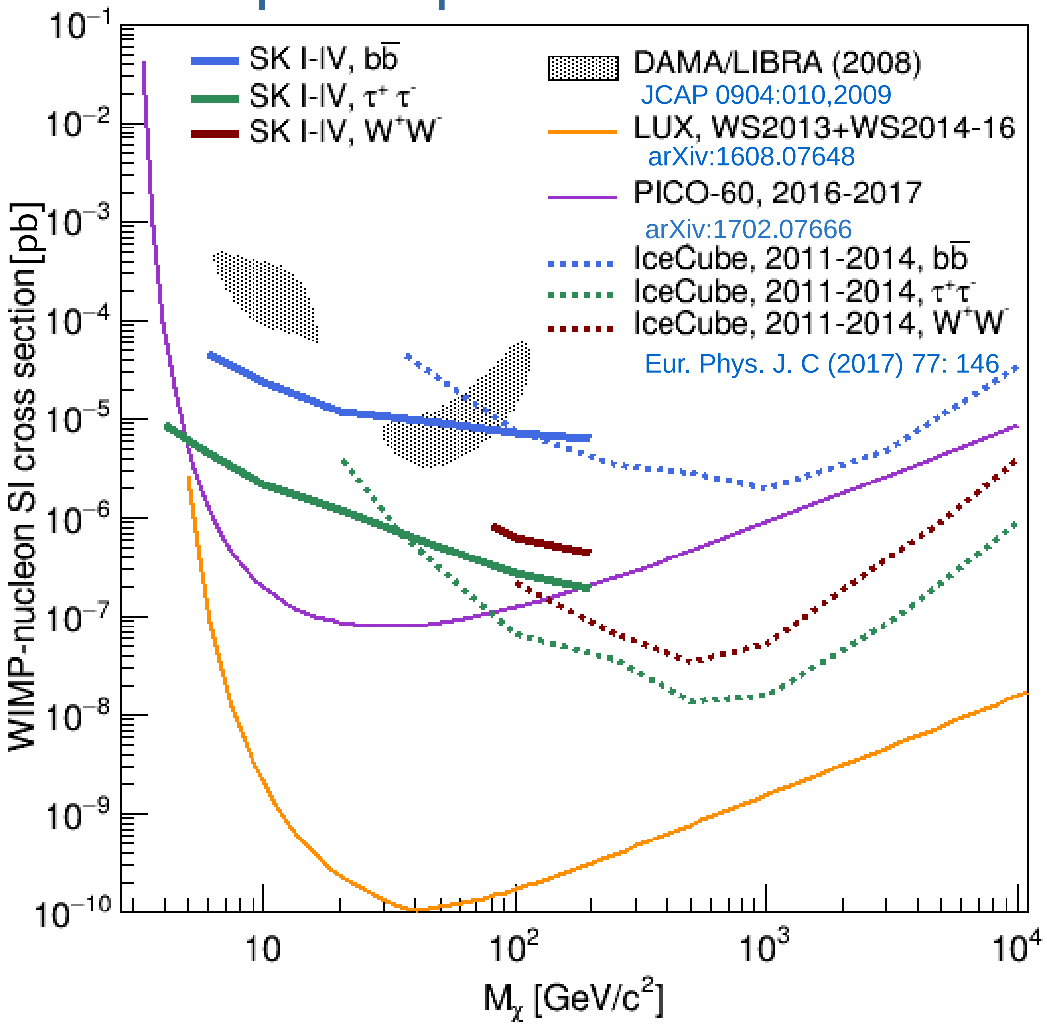
WIMP signal before fit

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

Spin-dependent interactions

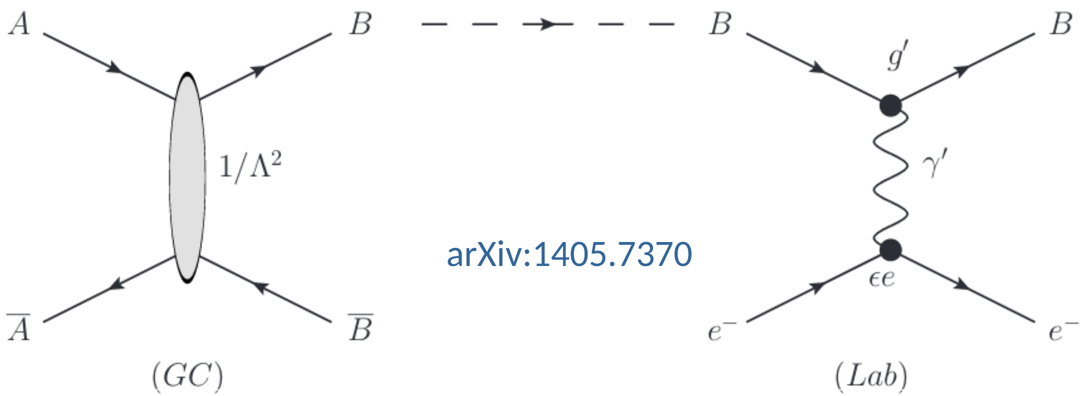


Spin-independent interactions

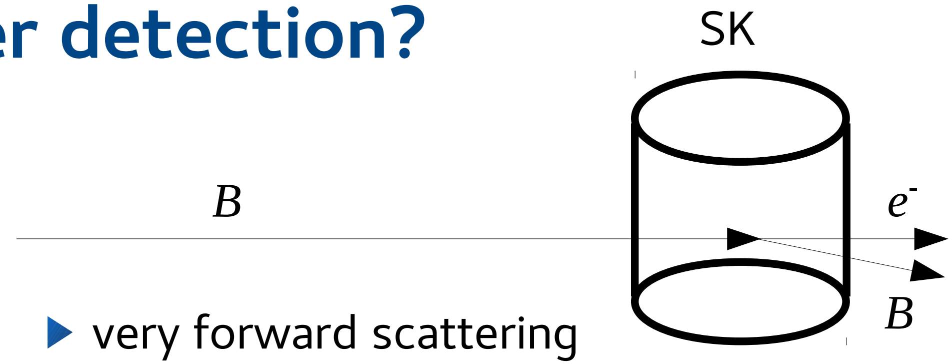


Published analysis: K.Choi et al., Phys. Rev. Lett. 114, 141301 (2015)

(In)direct dark matter detection?



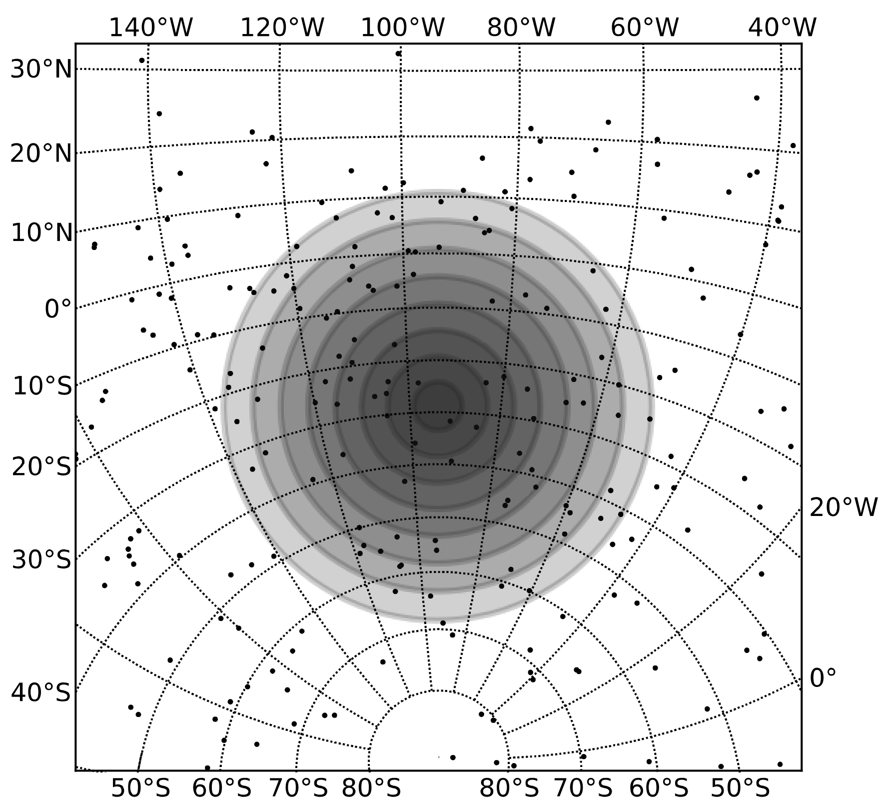
arXiv:1405.7370



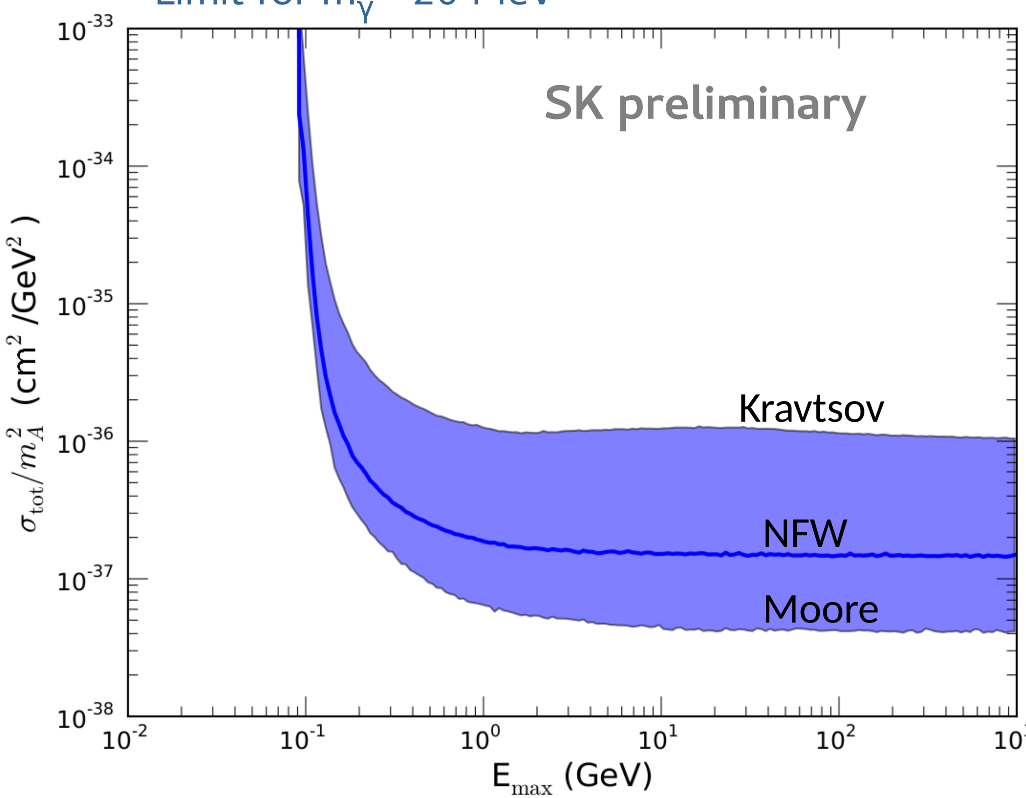
- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

Cone search: 8 cones from 5° to 40° around GC

→ **No clusters visible**



Limit for m_{γ}'=20 MeV



Summary

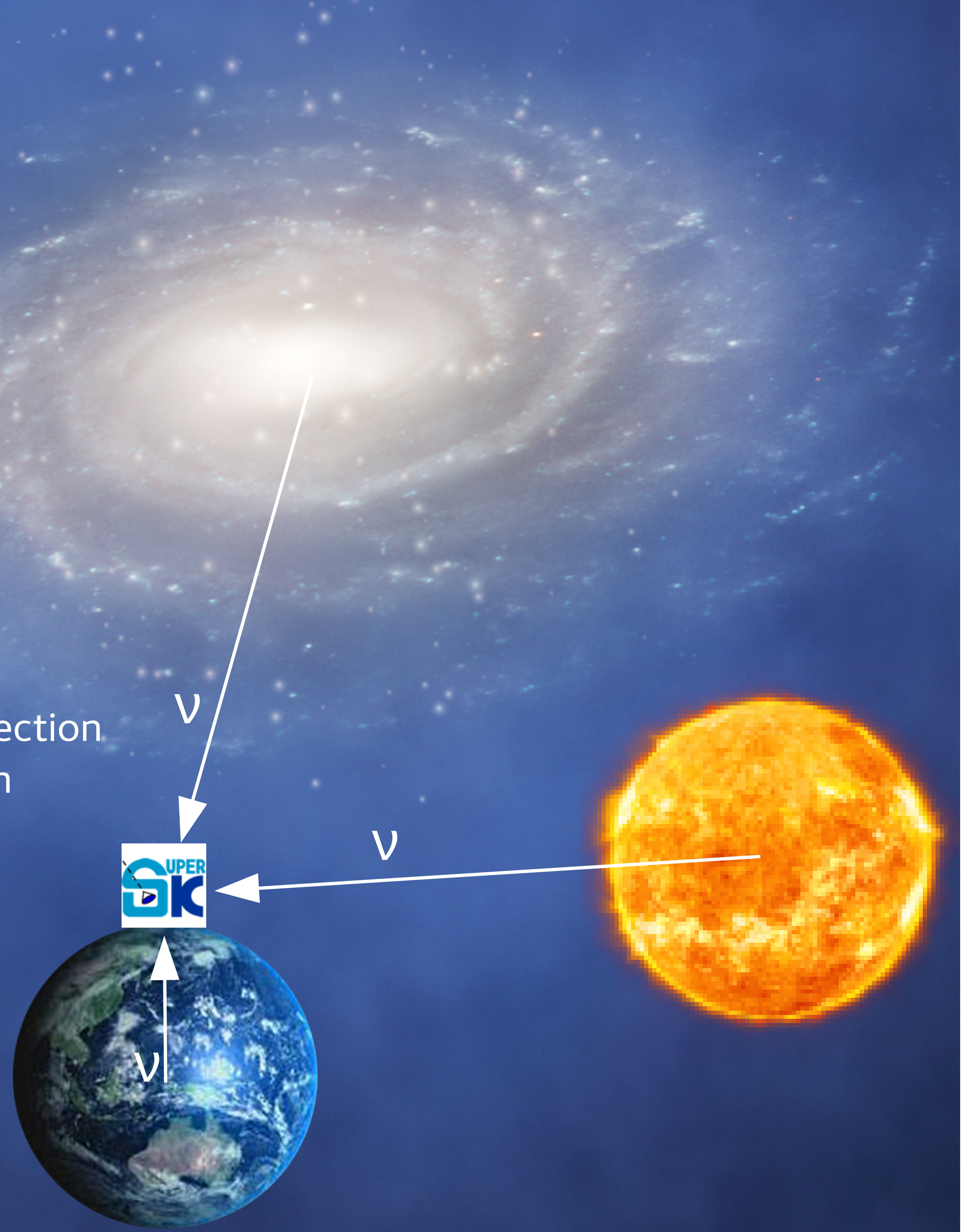
- **No excess of DM induced υ's has been observed at SK so far**

- **Galactic WIMP search**
  - upper limits on <σ_AV> for wide range of WIMPs masses (1 GeV to 10 TeV)

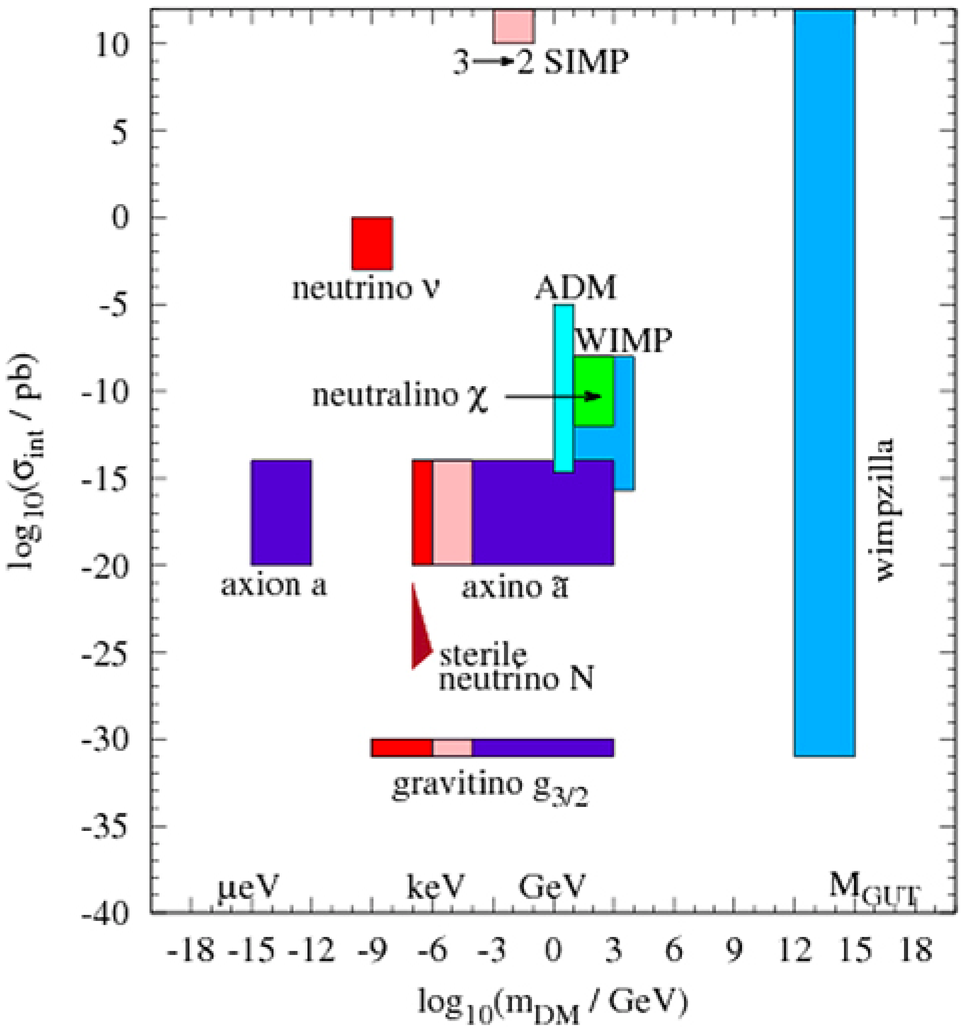
- **Earth WIMP search**
  - upper limits on SI WIMP-nucleon cross-section
  - high sensitivity to resonant capture region

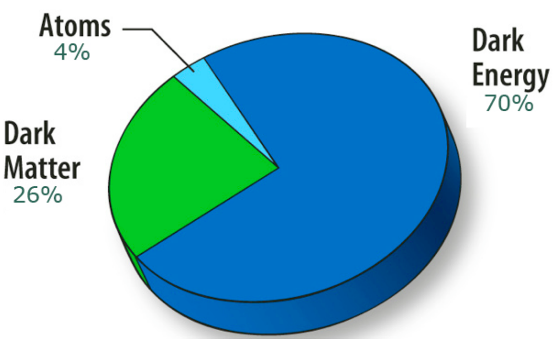
- **Solar WIMP search**
  - strong constrains for low WIMP masses
  - results published in 2015

- **Boosted dark matter search**
  - alternative DM models can also be tested with SK detector



Dark matter candidates





- Dynamics of galaxy clusters
- Galaxy rotation curves
- Gravitational lensing
- Cosmic Microwave Background
- Structure formation

Weekly Interacting Massive Particle (WIMP):

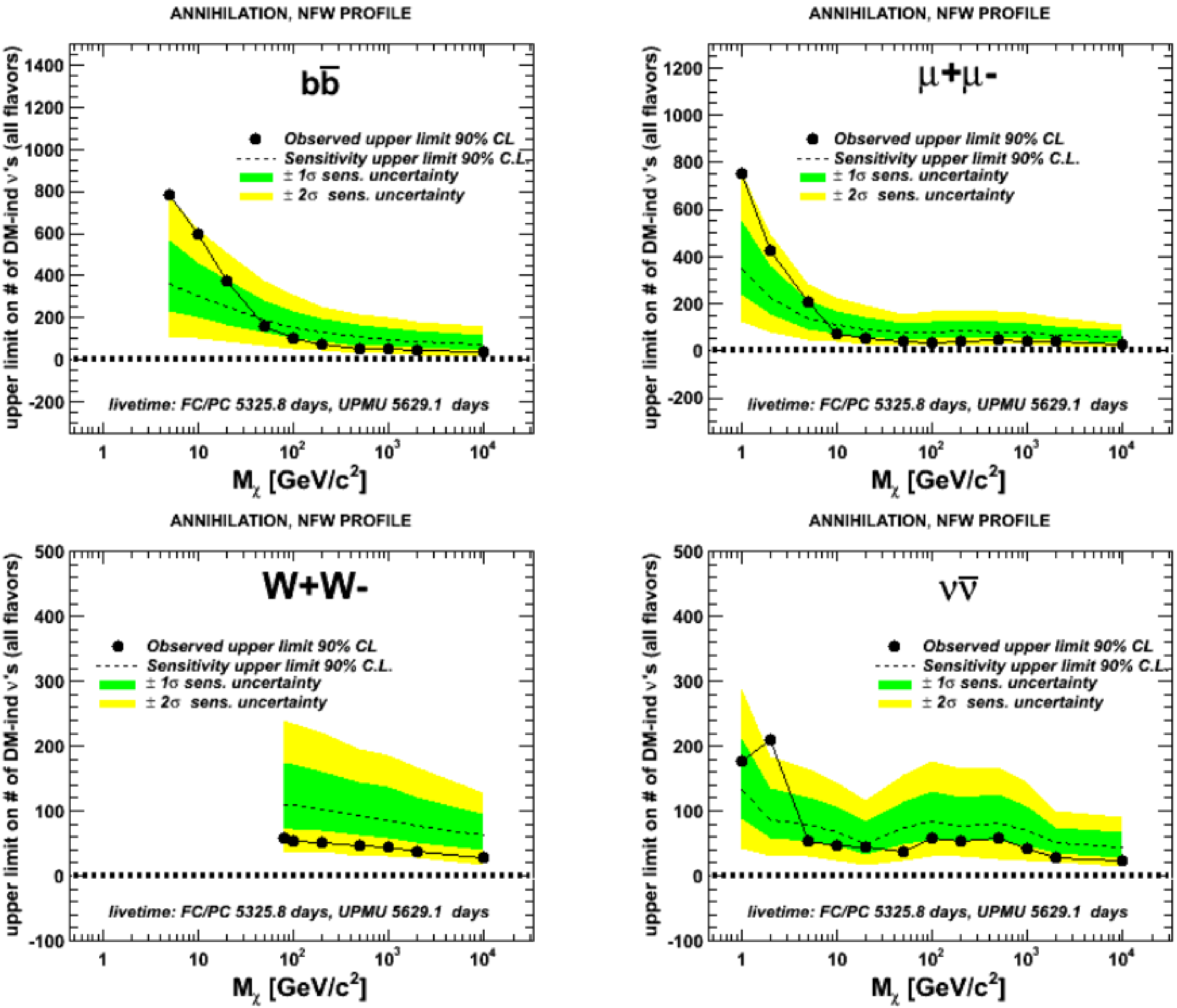
- neutral
- long livetime
- massive (10 GeV - 10 TeV)
- weekly interacting with matter

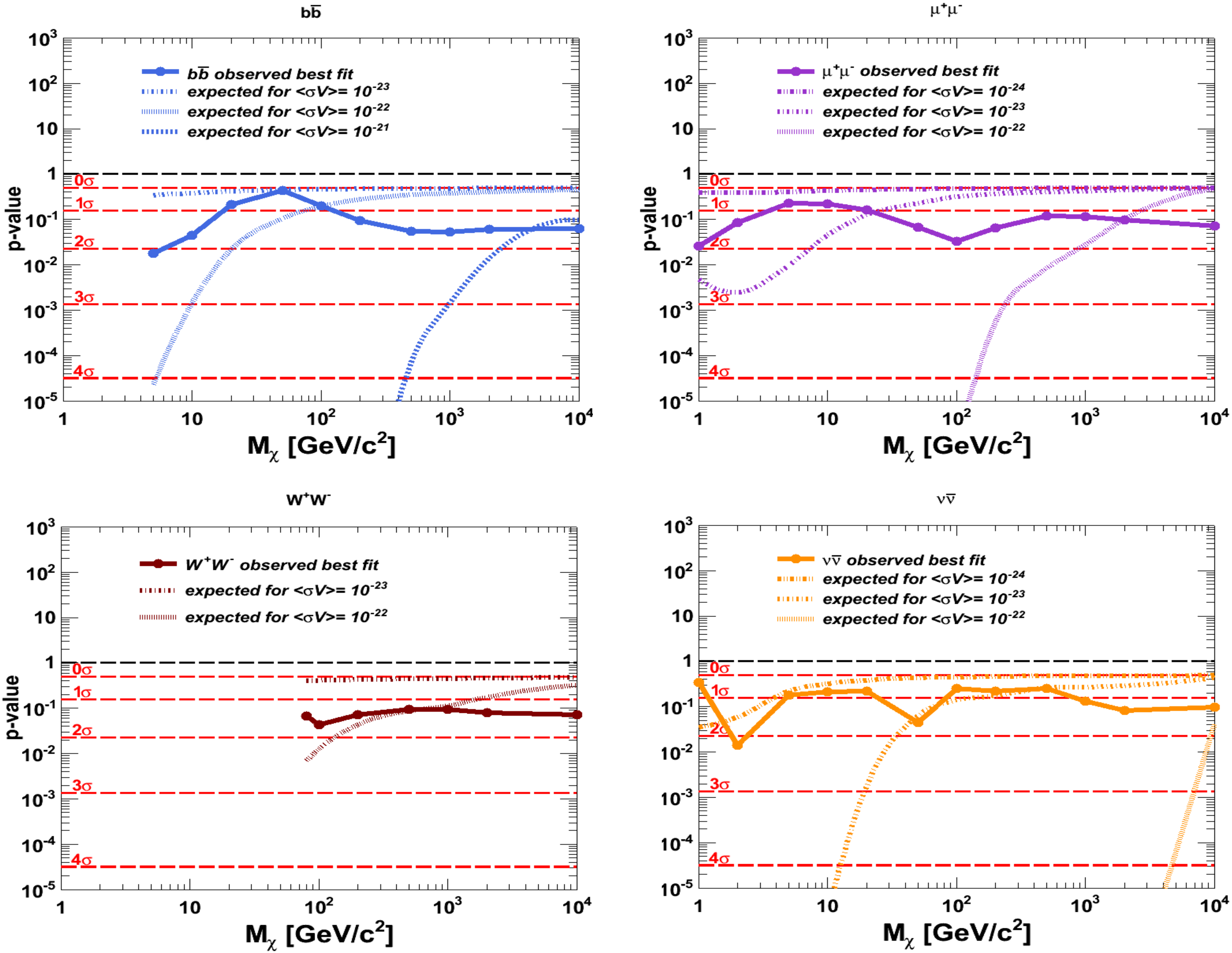
Many possibilities, various detection techniques, many experiments..

most popular WIMP candidate:
the lightest supersymmetric particle (LSP)
neutralino χ - Majorana fermion

FIT result – brazil plot

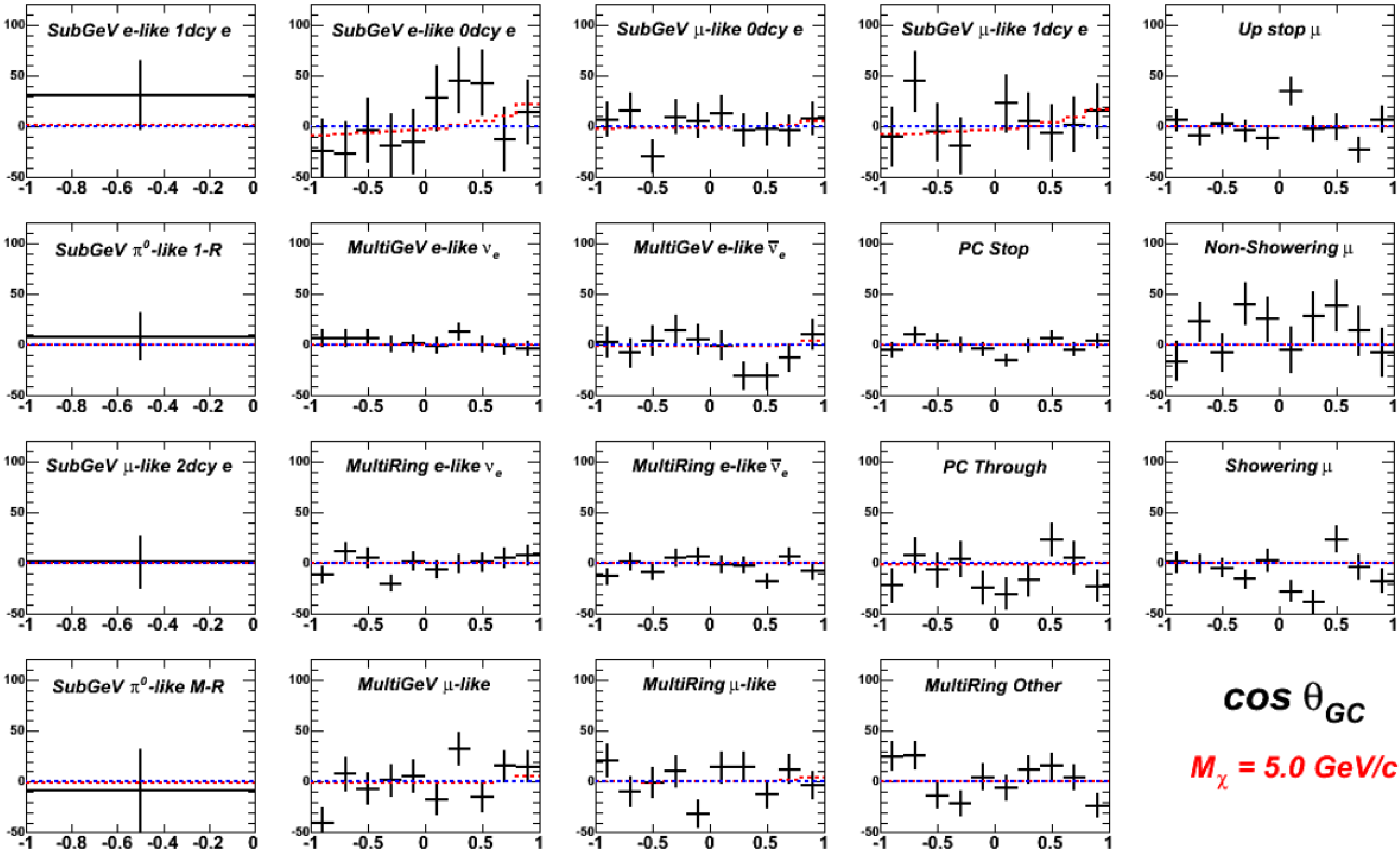
1200 TOY MCs





$b\bar{b}$
$b\bar{b}$ observed best fit
expected for <σV>= 10^{-23}
expected for <σV>= 10^{-22}
expected for <σV>= 10^{-21}
$\mu^+\mu^-$
$\mu^+\mu^-$ observed best fit
expected for <σV>= 10^{-24}
expected for <σV>= 10^{-23}
expected for <σV>= 10^{-22}
W^+W^-
W^+W^- observed best fit
expected for <σV>= 10^{-23}
expected for <σV>= 10^{-22}
$\nu\bar{\nu}$
$\nu\bar{\nu}$ observed best fit
expected for <σV>= 10^{-24}
expected for <σV>= 10^{-23}
expected for <σV>= 10^{-22}
p-value
M_χ [GeV/c^2]
0σ
1σ
2σ
3σ
4σ

RESIDUAL 5GeV BB-BAR

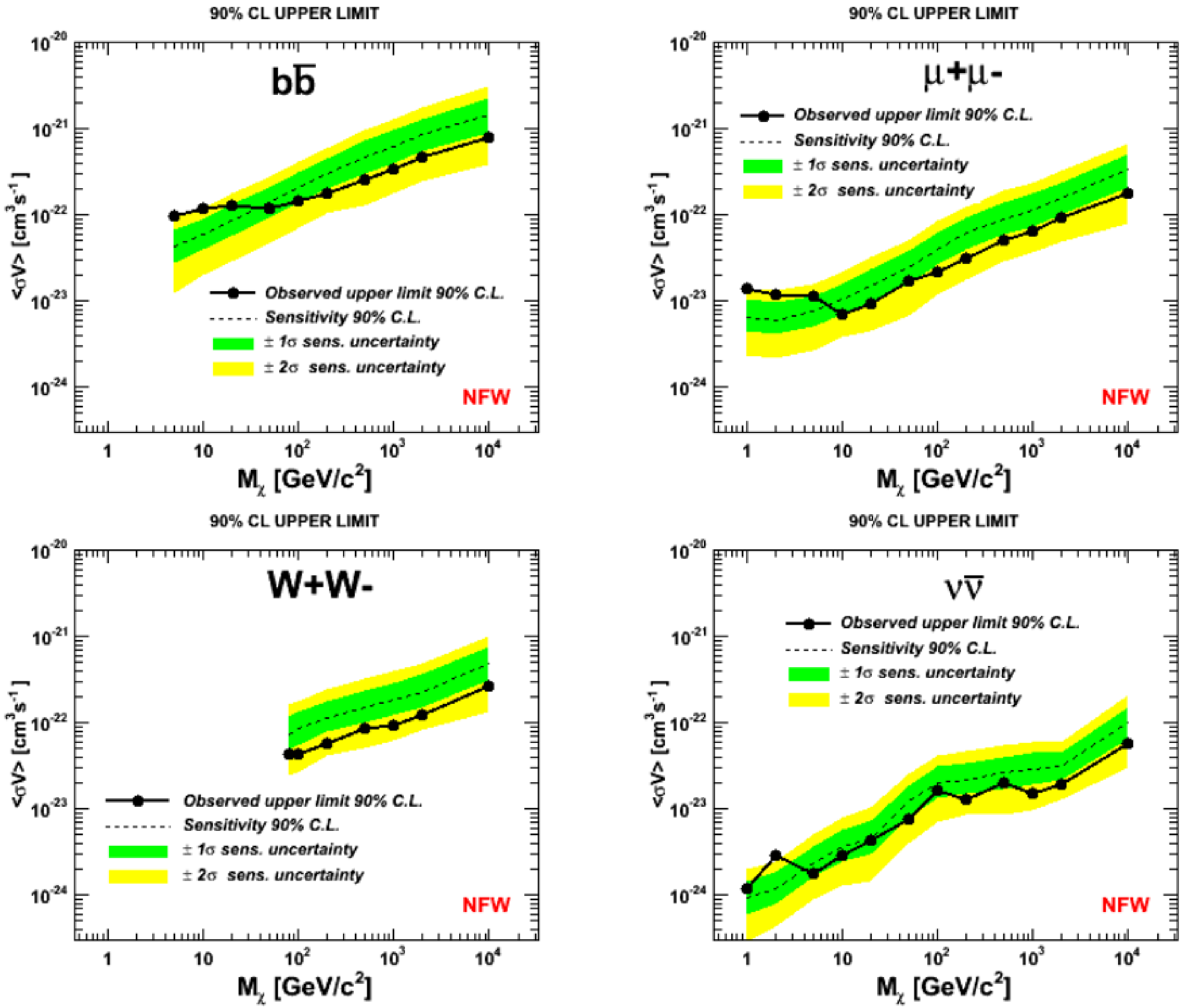


points: TOY MC data set blue line: ATM MC (with pulls) red dashed line: best fitted signal with ATM MC (all with pulls)

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

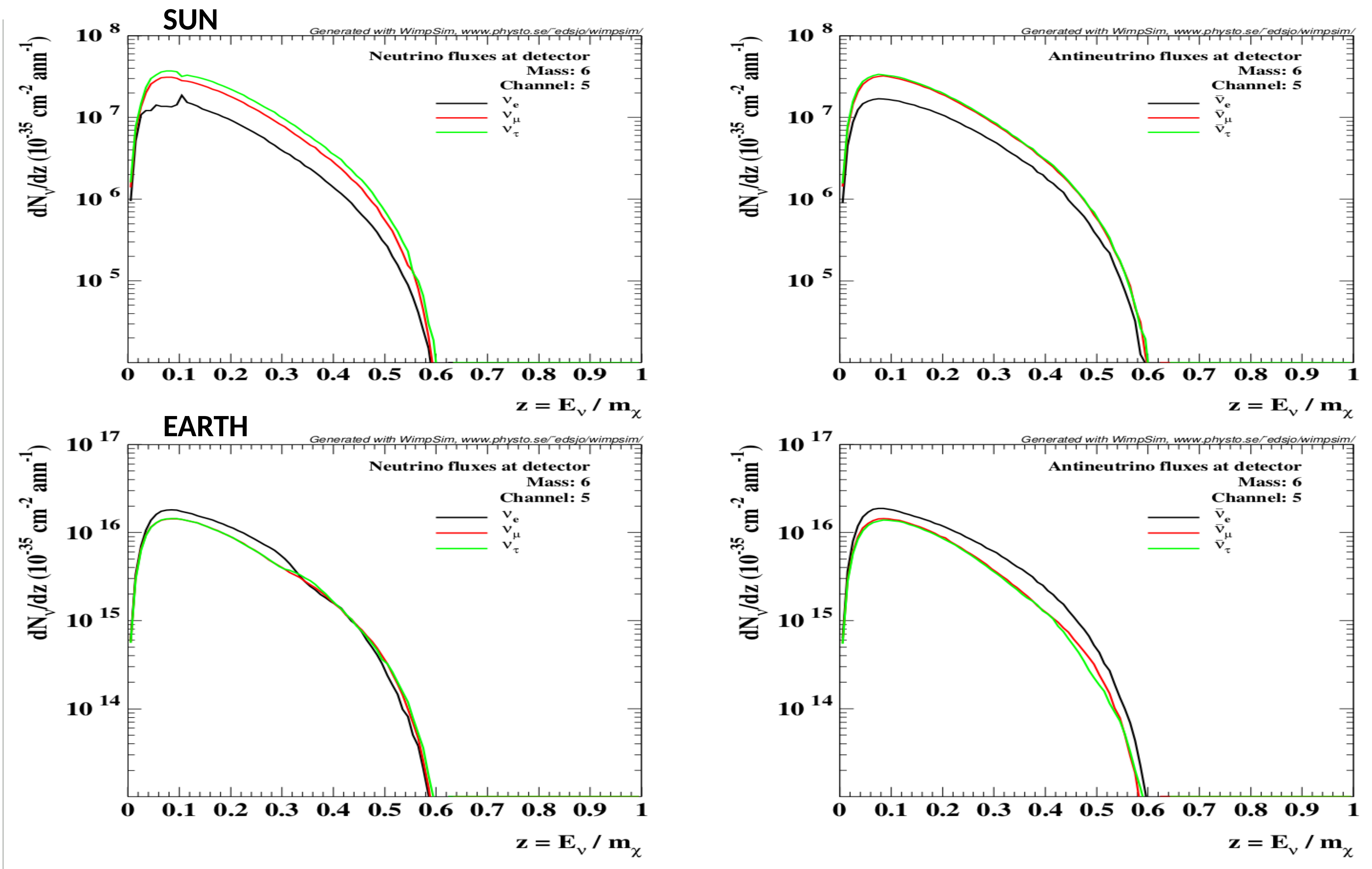
<σV> limit – brazil plot

1200 TOY MCs



- **Example:** 6 GeV WIMPs, $b\bar{b}$ ann. channel - spectra at detector position

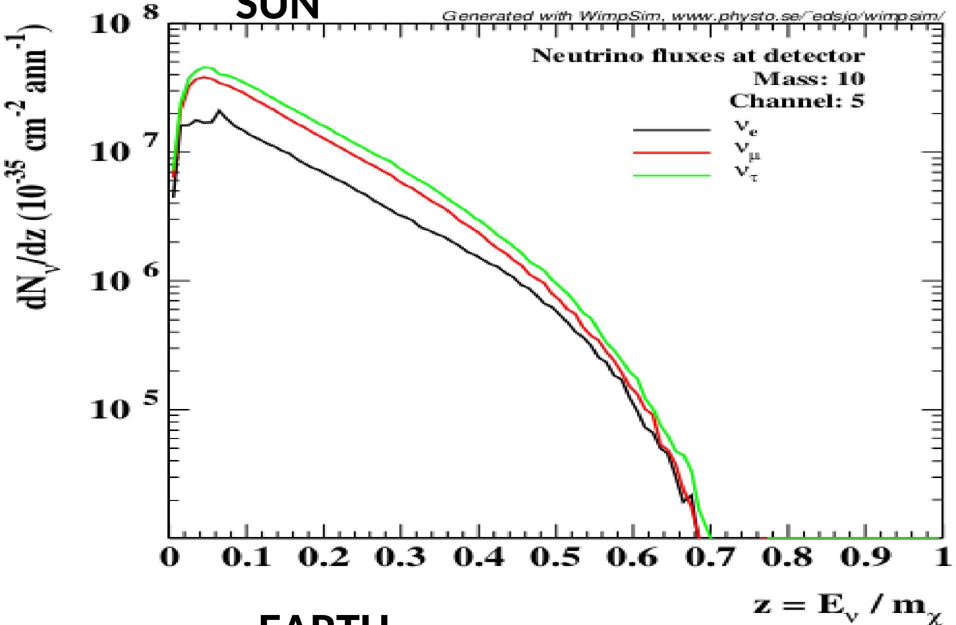
  - very similar shape of energy spectra from Sun and Earth



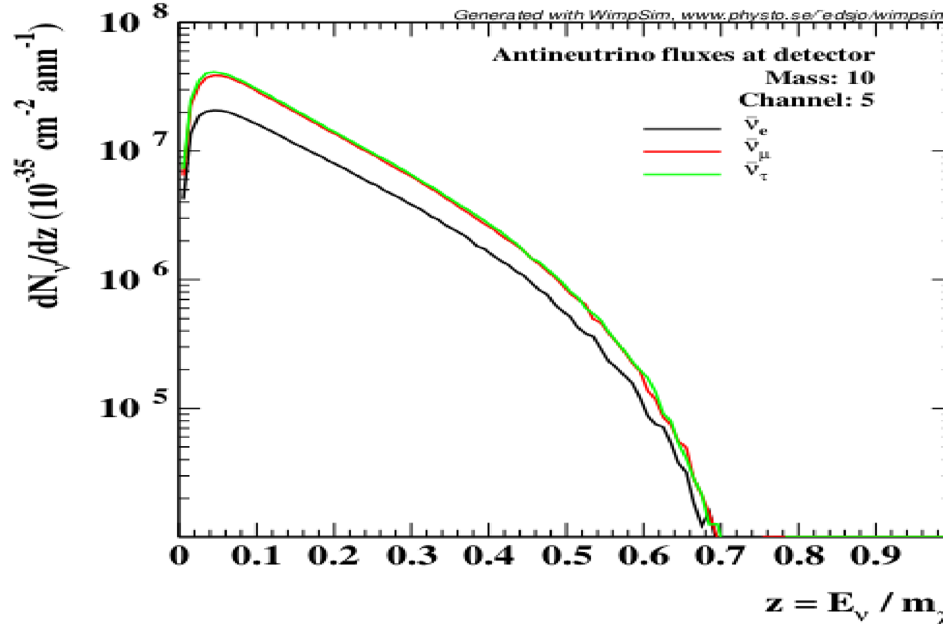
- **Example:** 10 GeV WIMPs, $b\bar{b}$ ann. channel - spectra at detector position

  - very similar shape of energy spectra from Sun and Earth

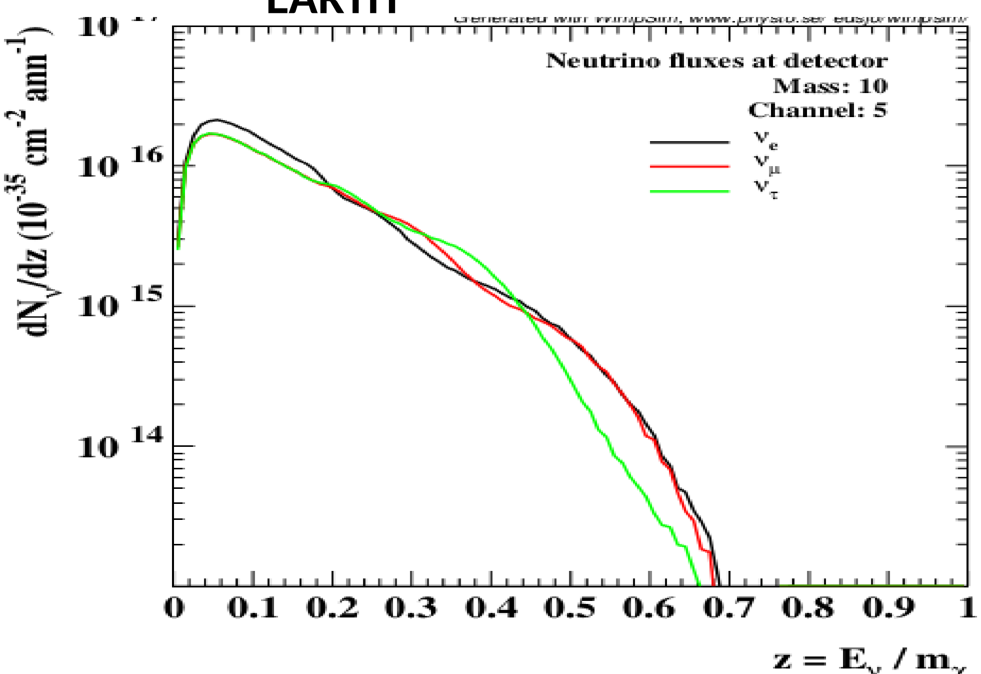
SUN

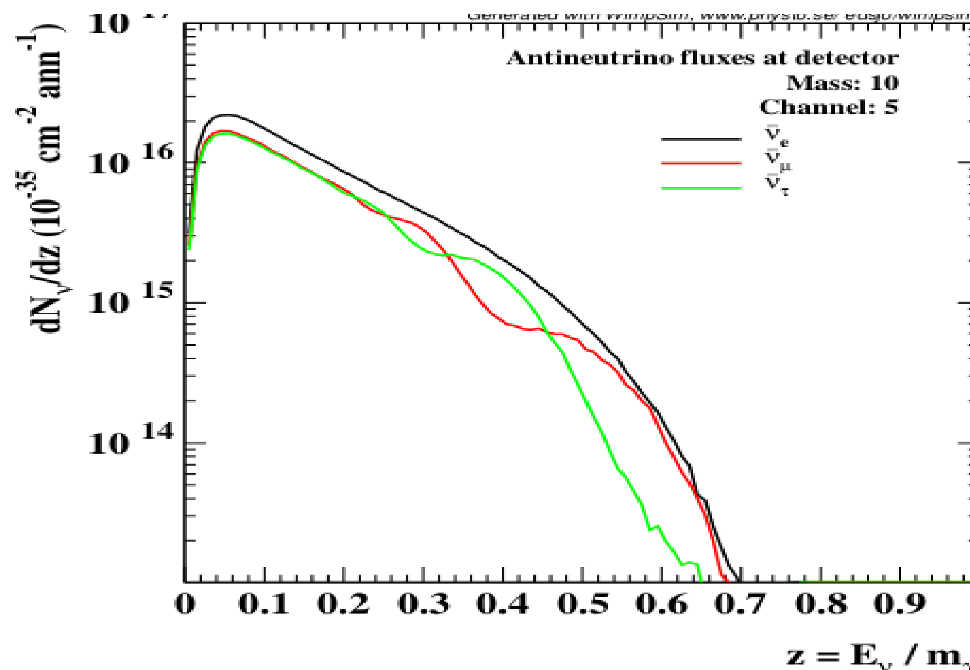


f

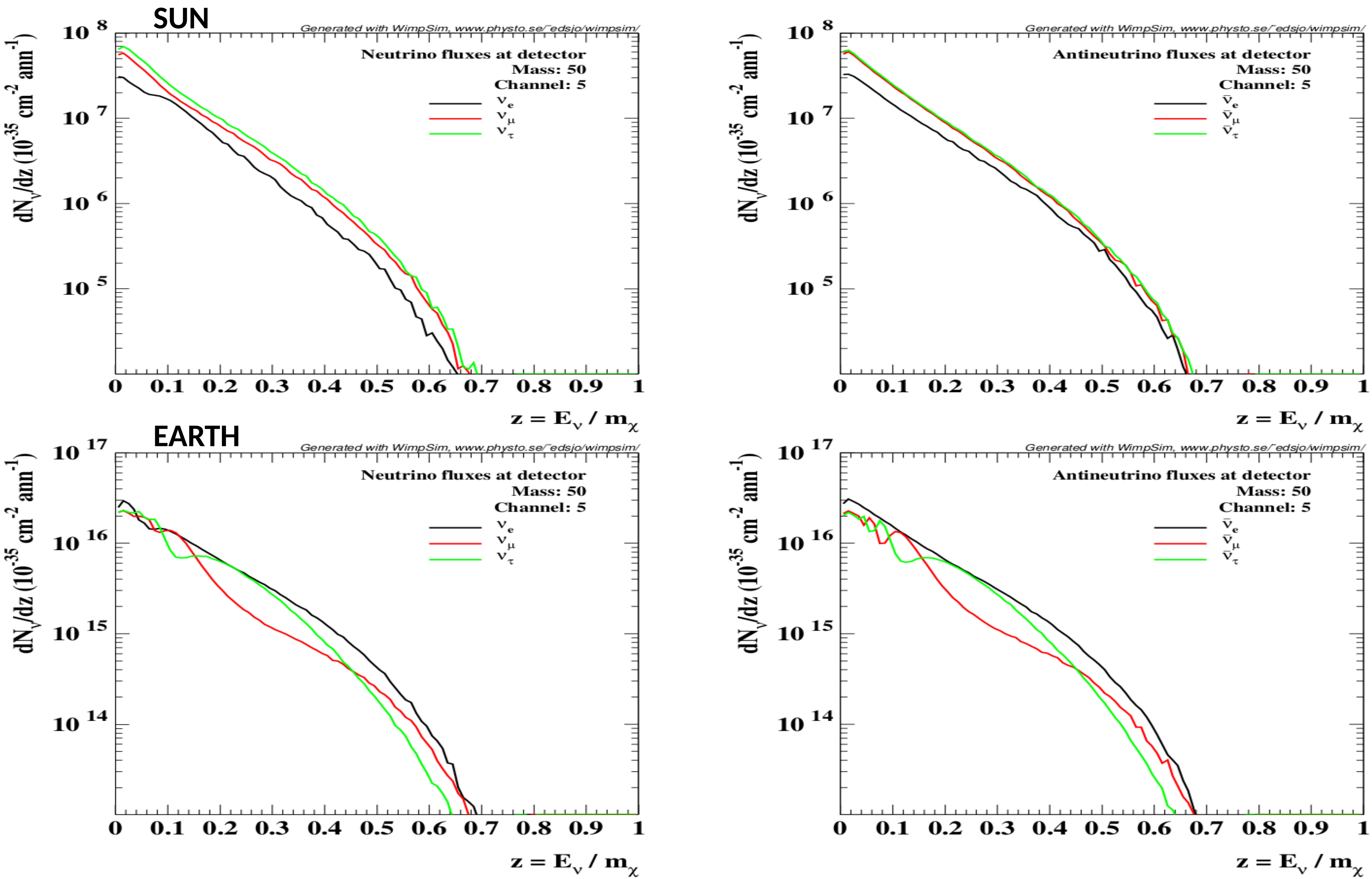


EARTH

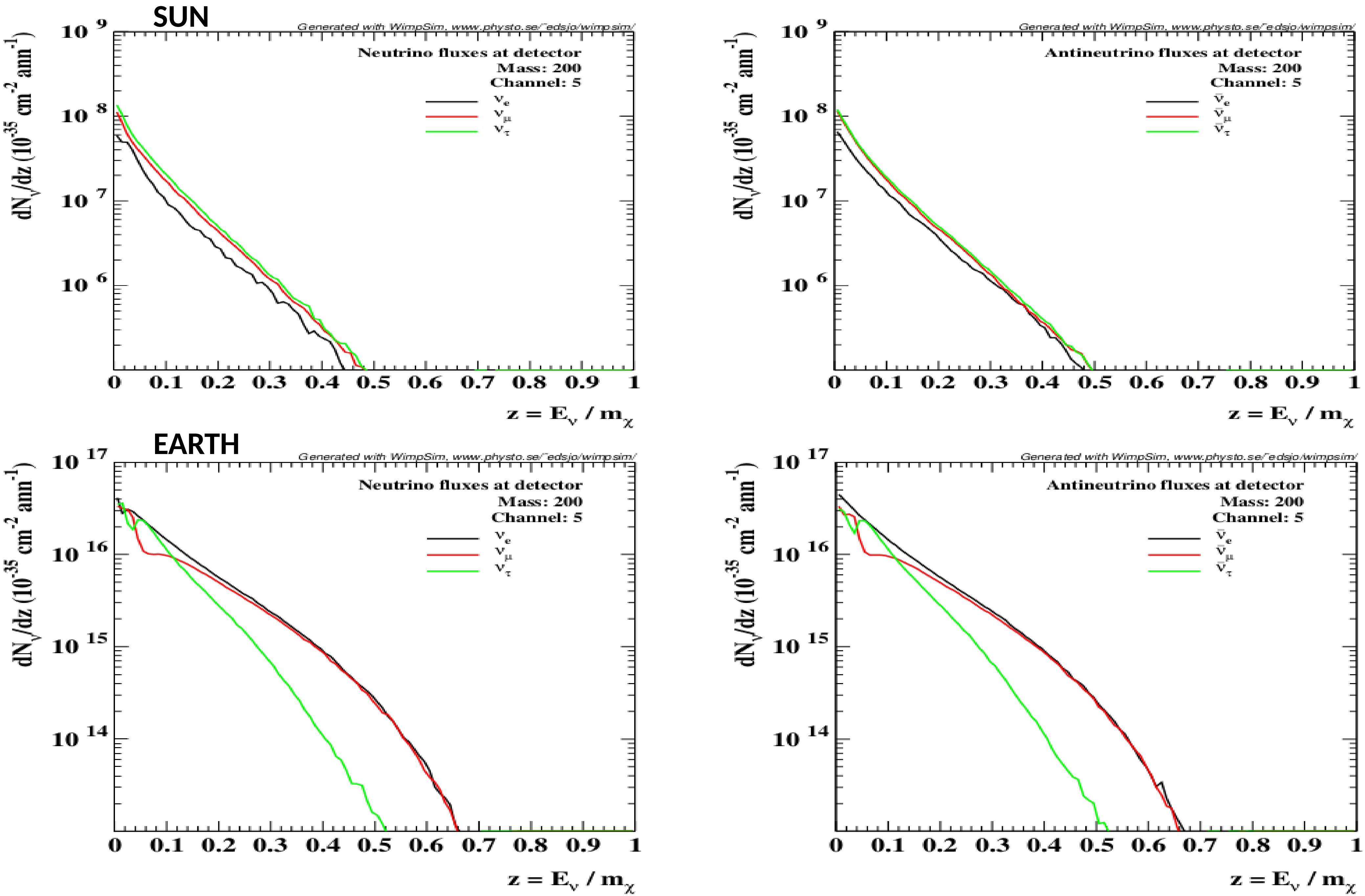




- **Example:** 50 GeV WIMPs, $b\bar{b}$ ann. channel - spectra at detector position
    - similar shape of energy spectra from Sun and Earth

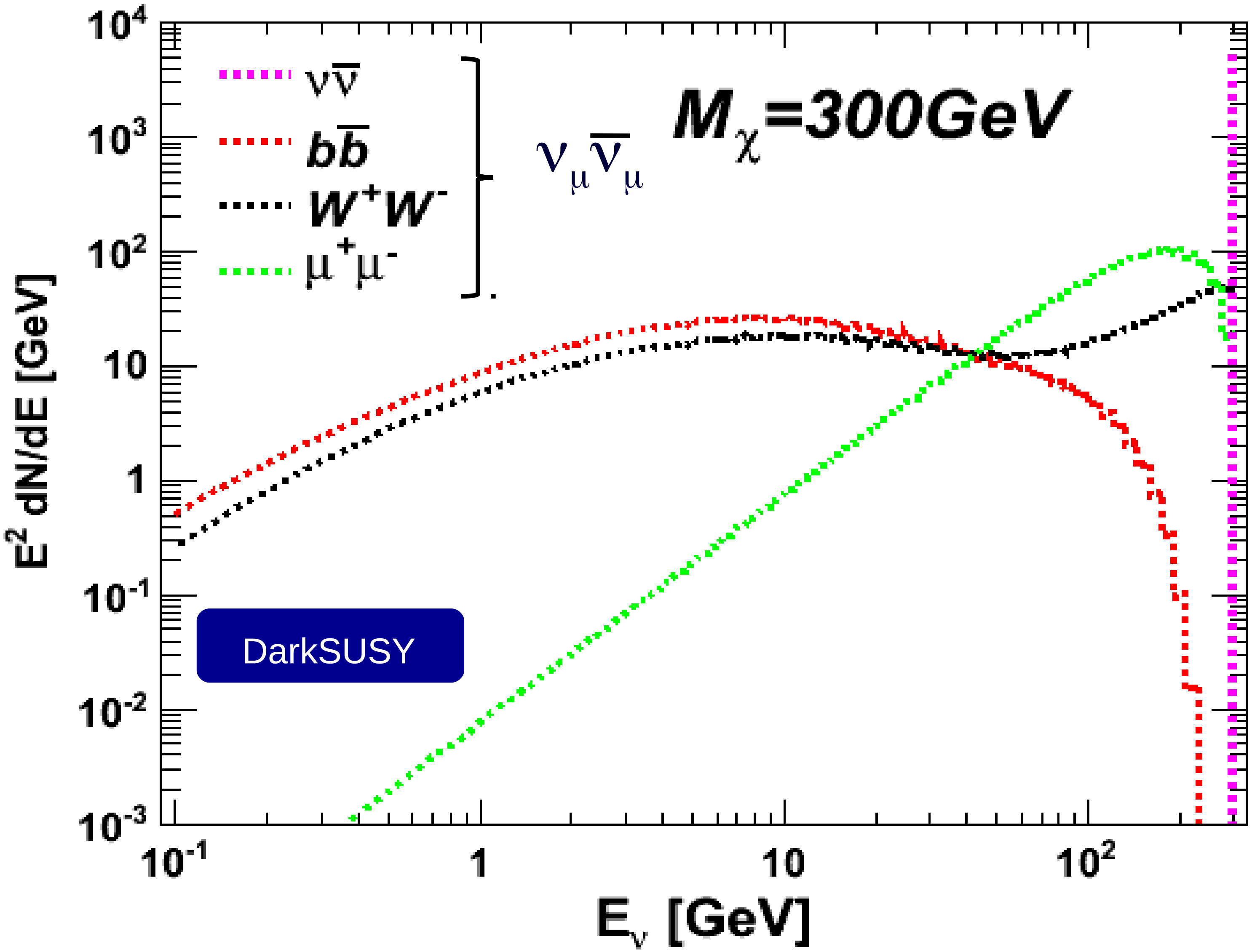


- **Example:** 200 GeV WIMPs, $b\bar{b}$ ann. channel - spectra at detector position



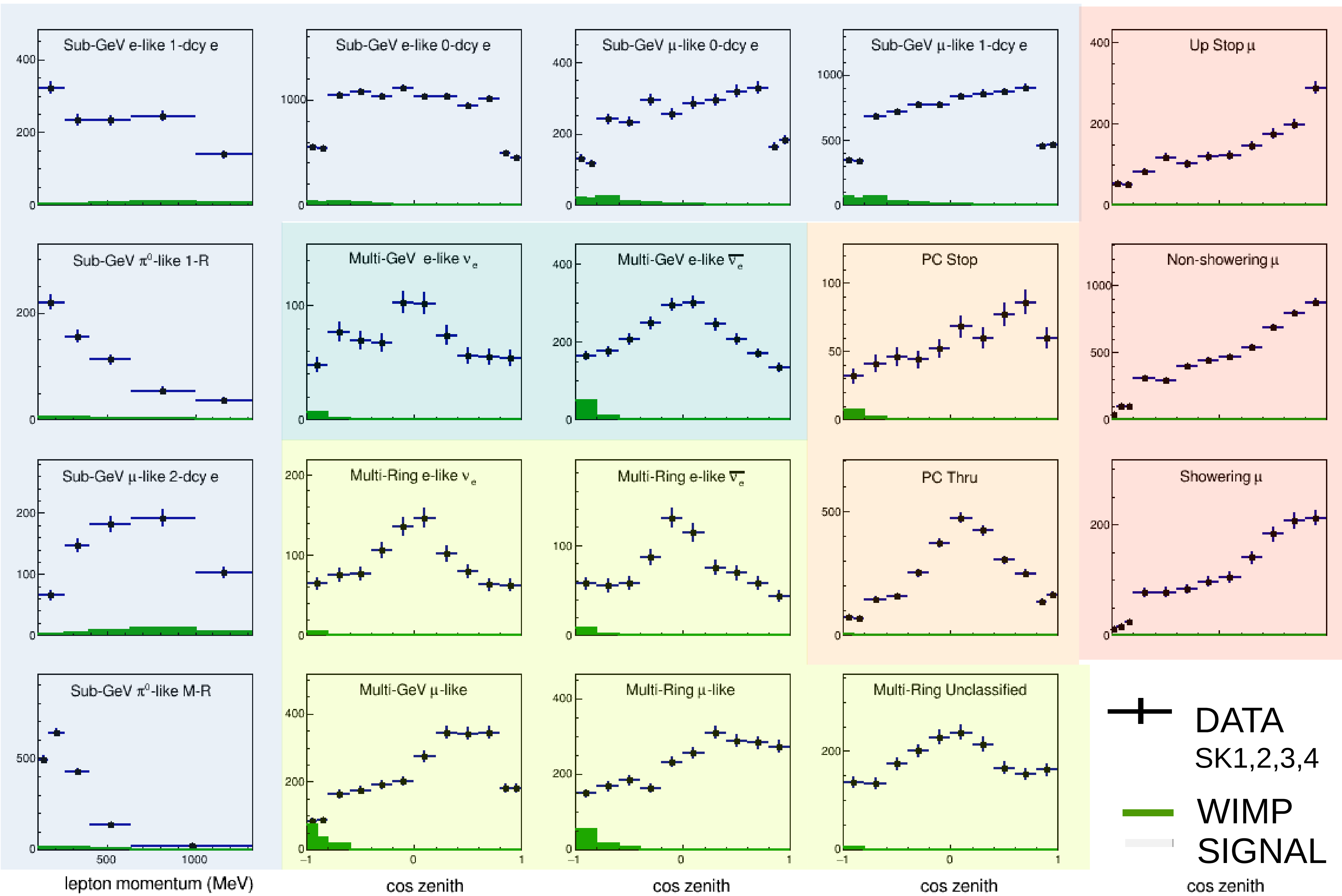
DM-induced neutrino signal

differential $\bar{\nu}_\mu \nu_\mu$ energy spectra per DM annihilation for Mχ=300 GeV
(oscillated throughout Galaxy)



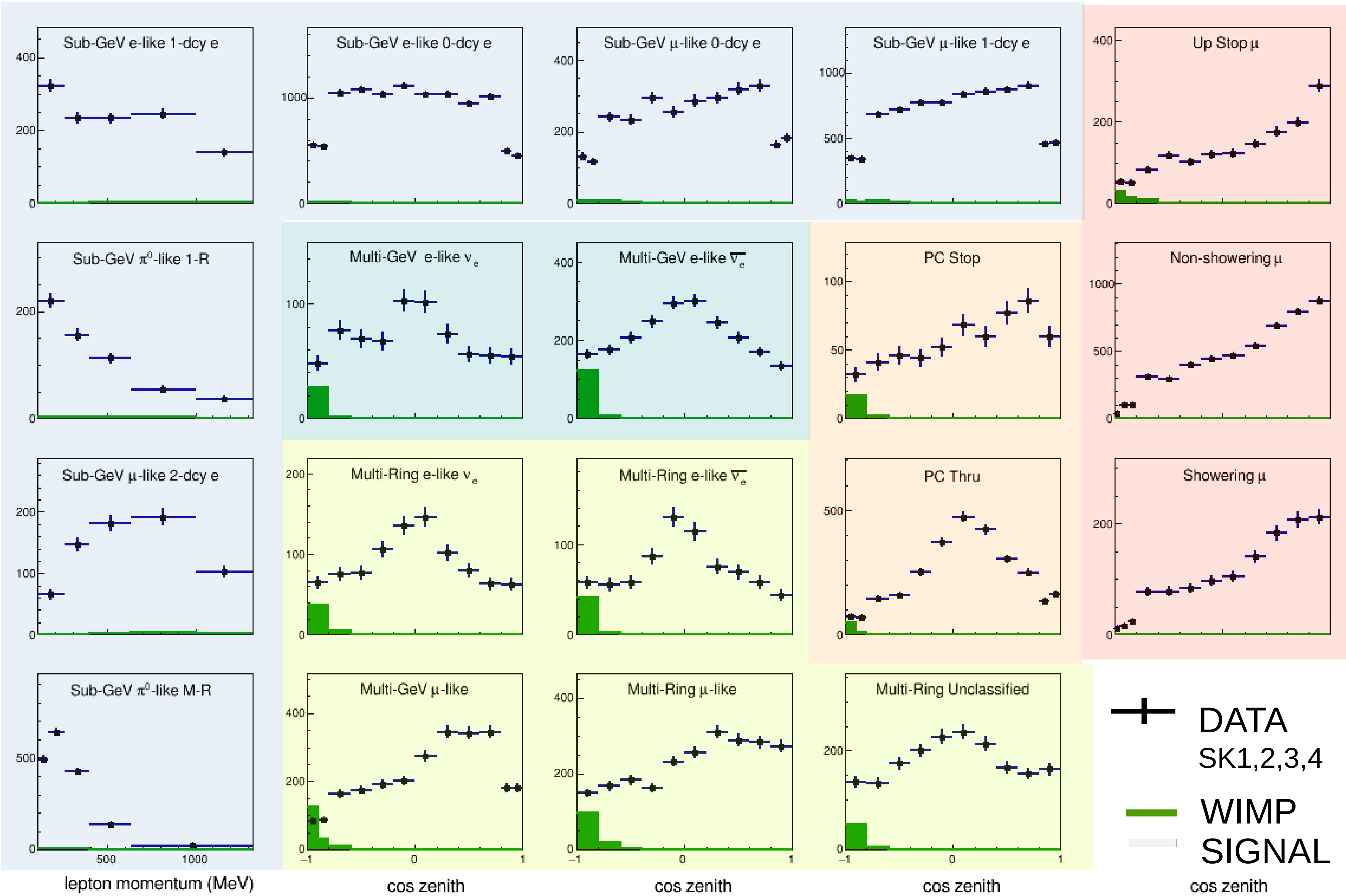
Signal illustration for Earth WIMP search

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



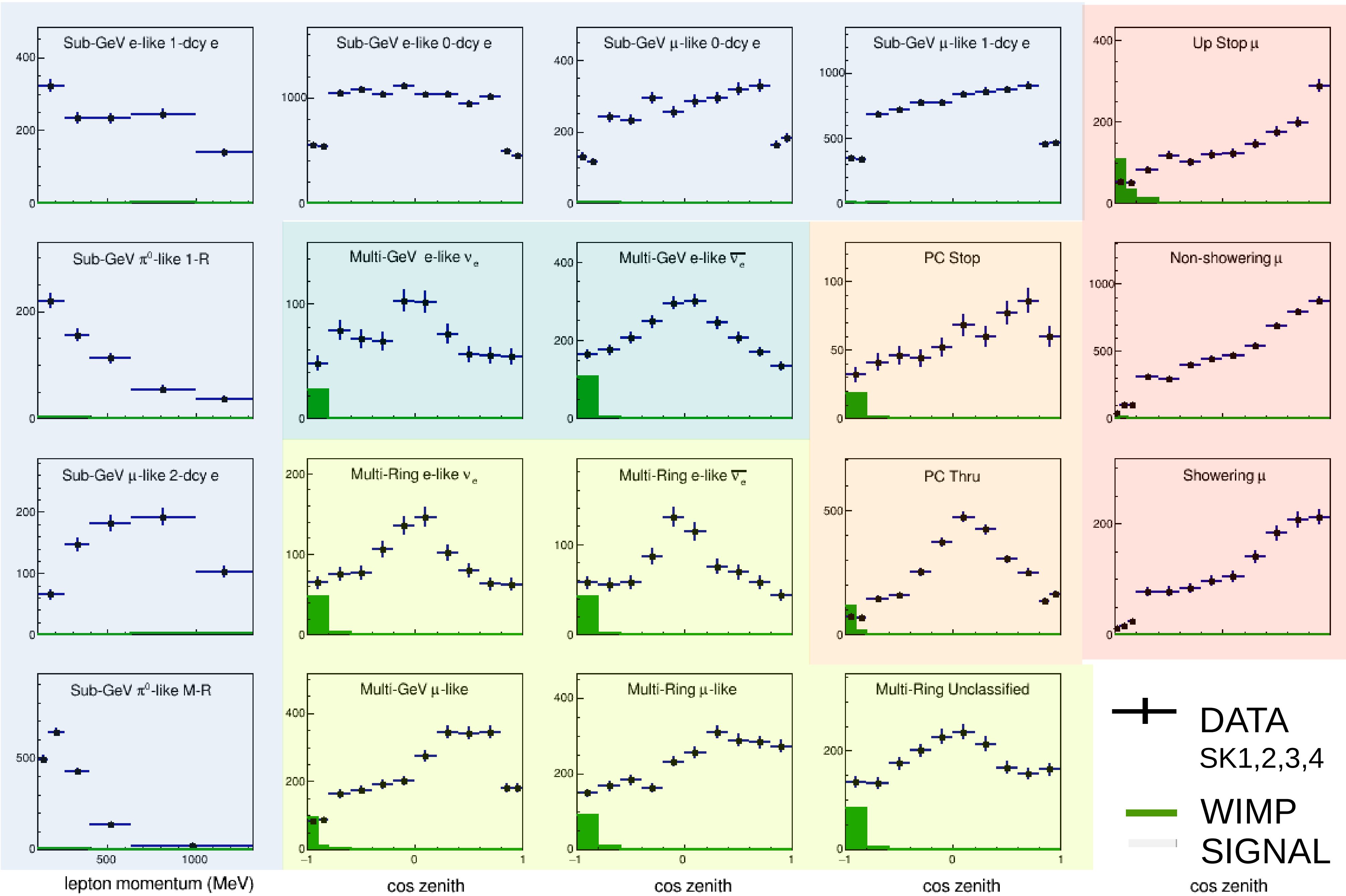
Signal illustration for Earth WIMP search

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



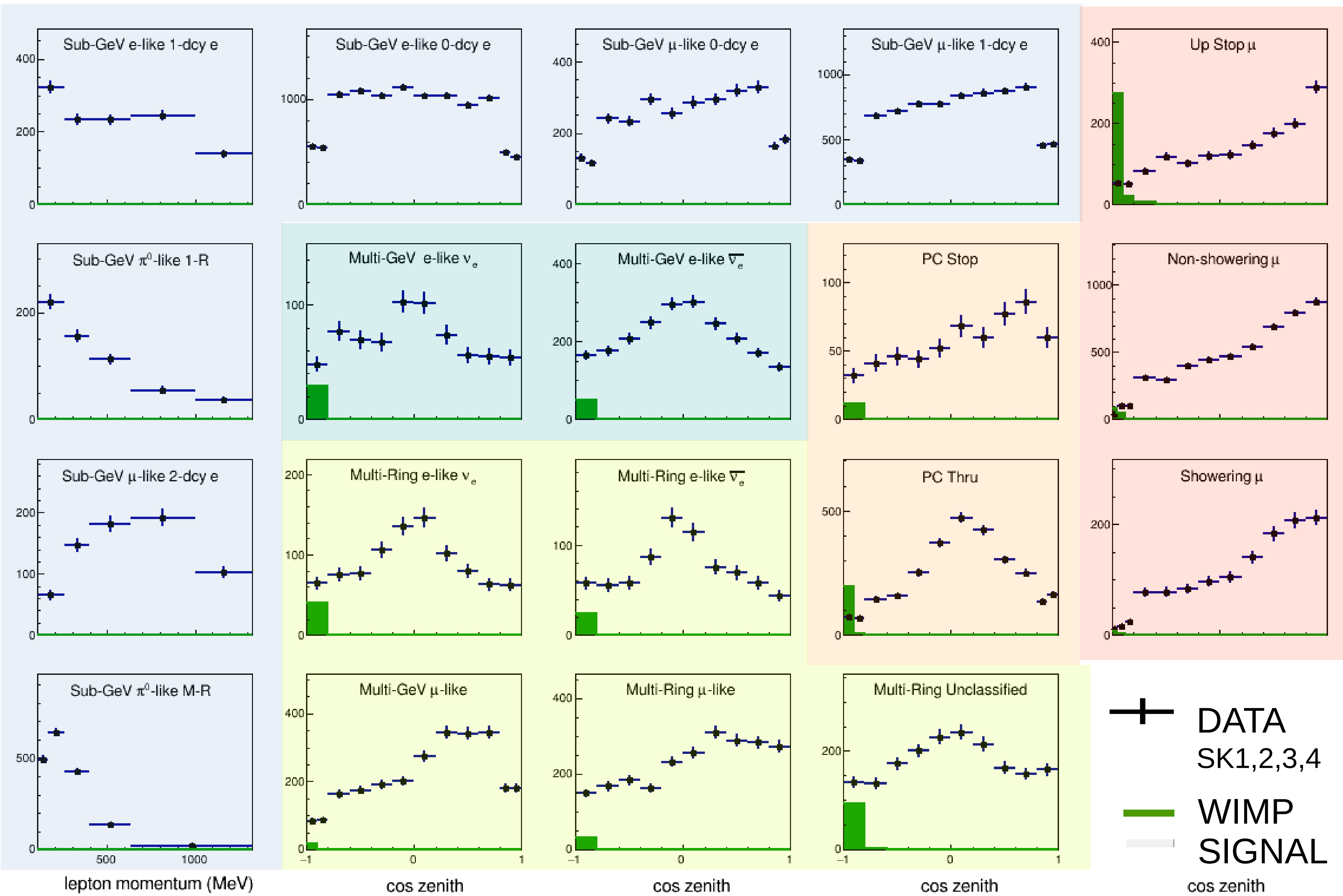
Signal illustration for Earth WIMP search

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



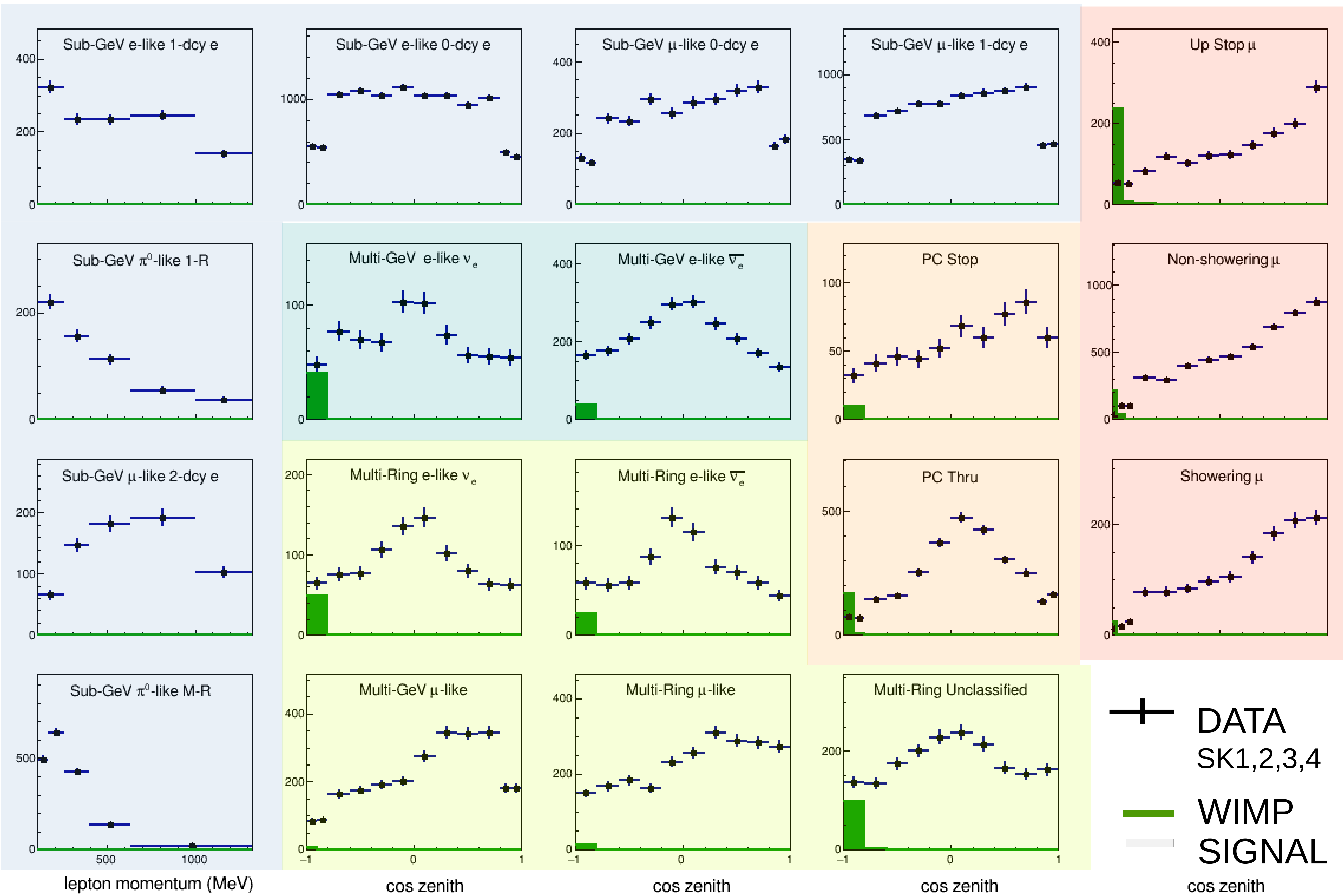
Signal illustration for Earth WIMP search

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



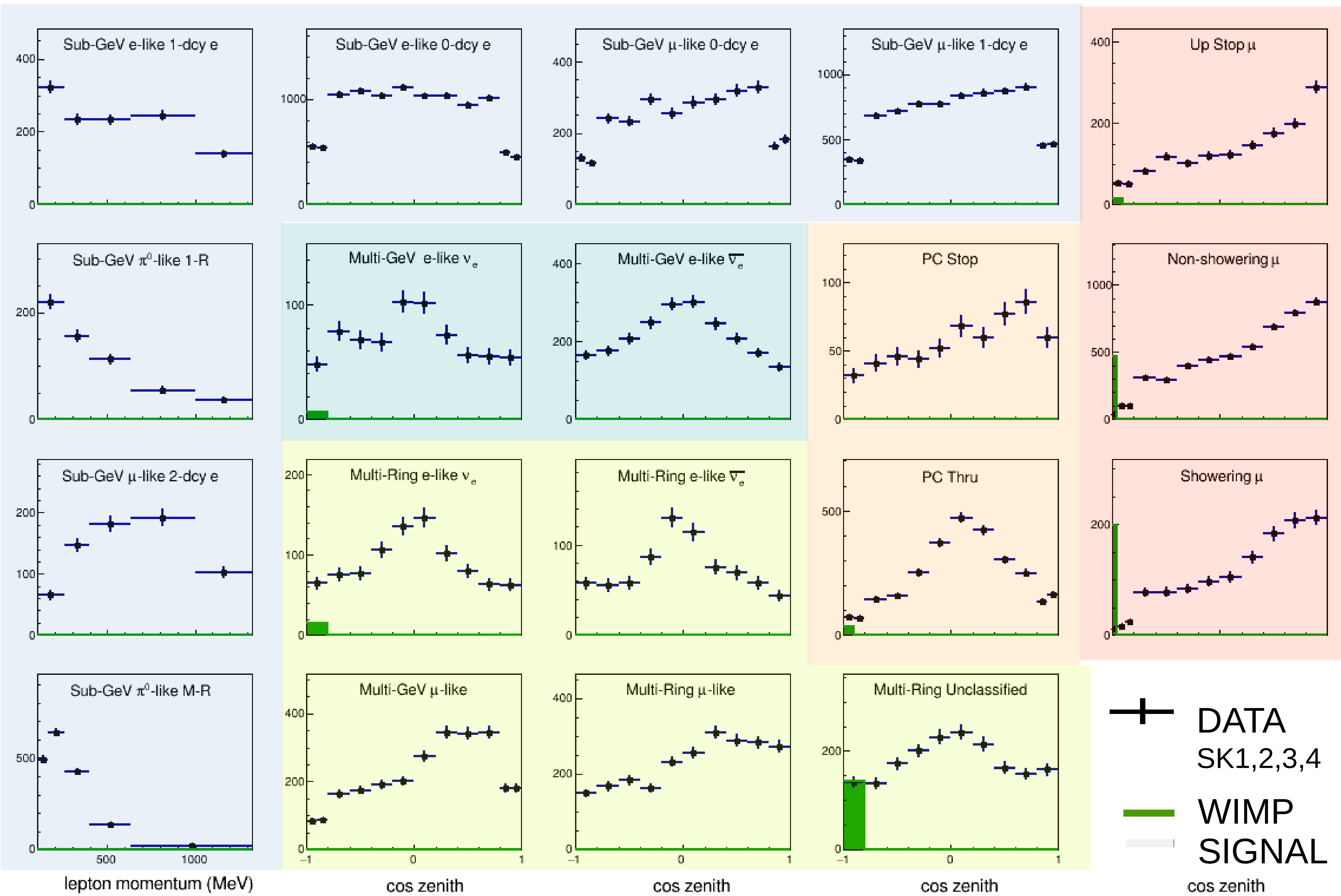
Signal illustration for Earth WIMP search

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



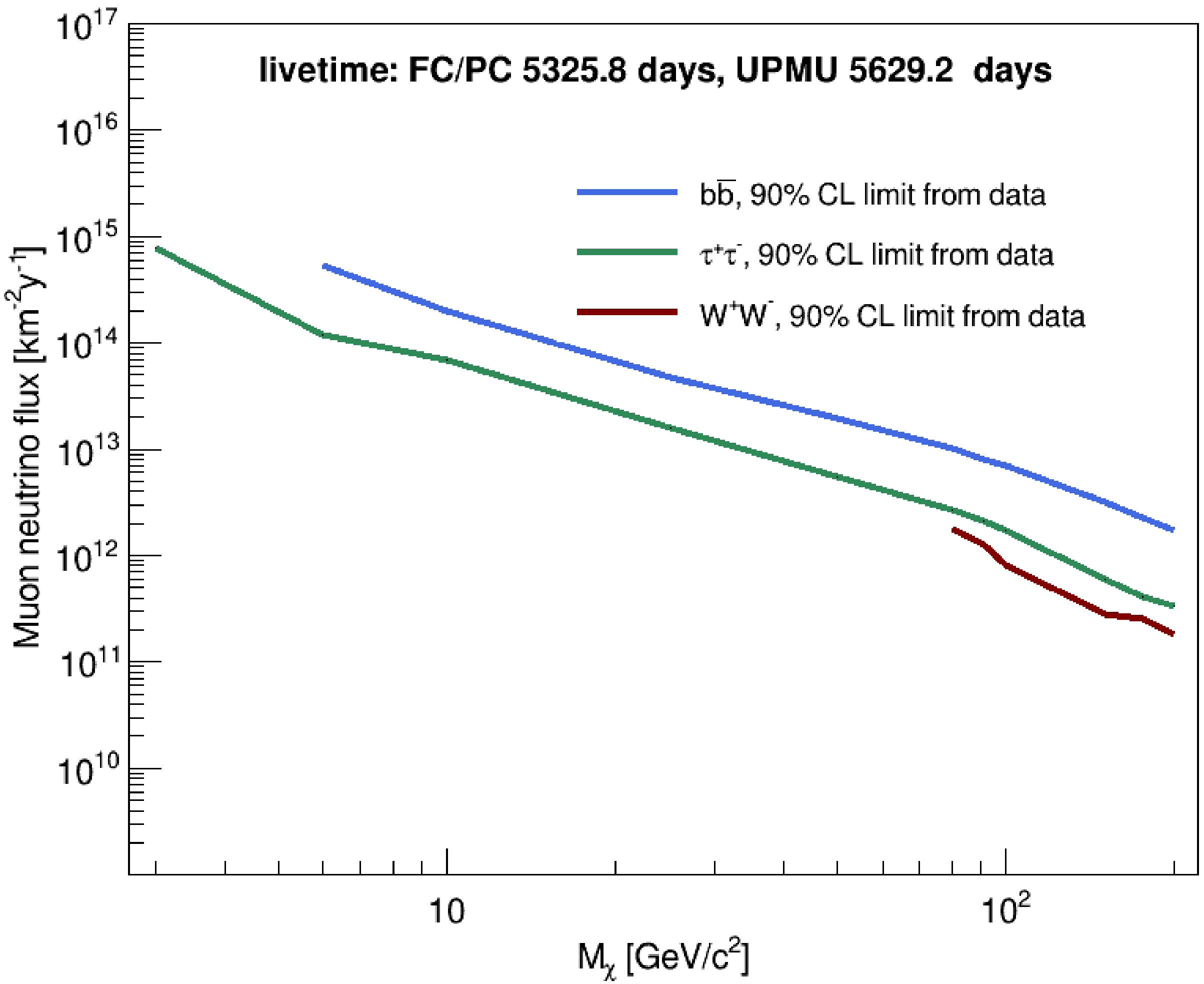
Signal illustration for Earth WIMP search

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



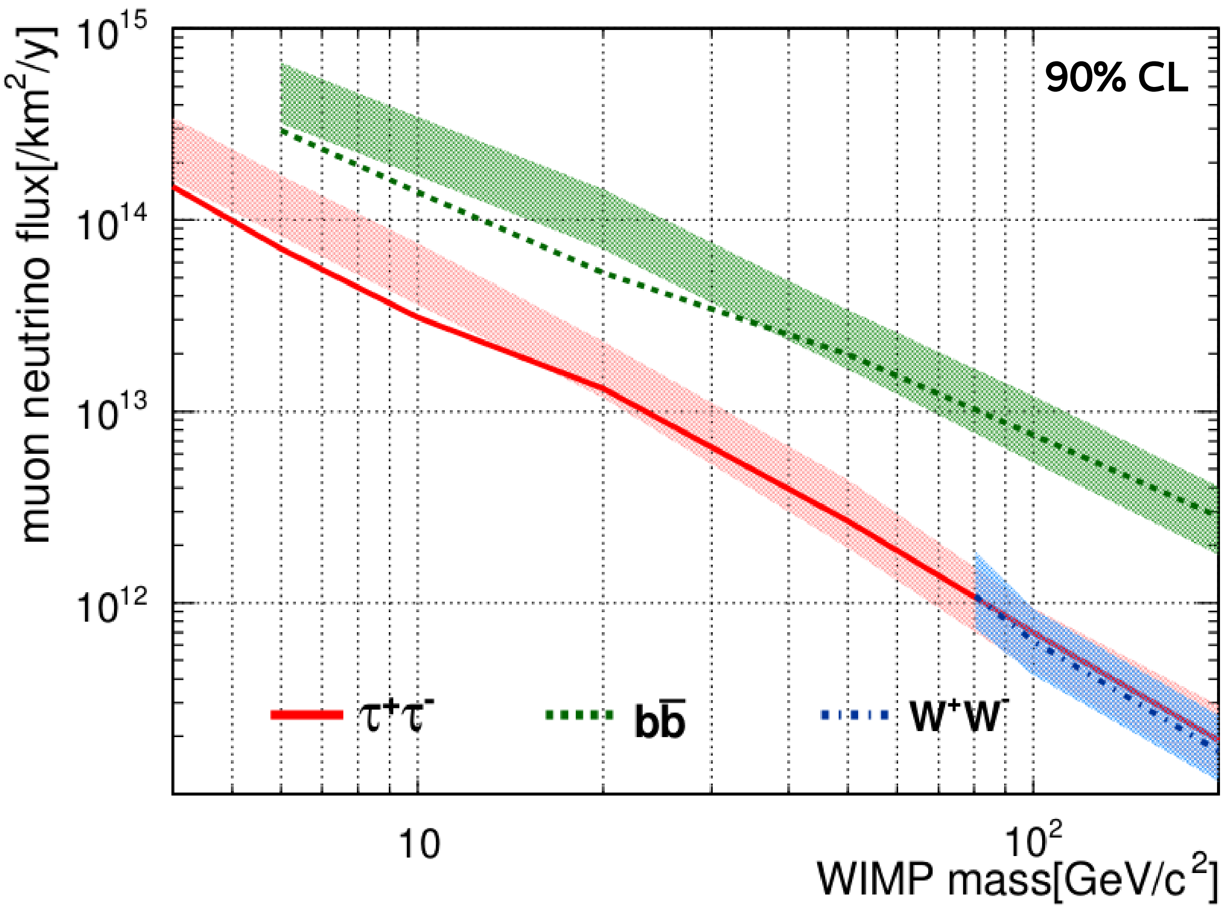
Earth WIMP search – muon neutrino flux limit

- FIT based on lepton mom. & $\cos\theta_{ZENITH}$ distributions,
- No excess of **ν** 's from the EARTH as compared to atm bkg is observed
- **90% CL upper limit on total integrated muon-neutrino flux from WIMP annihilations in the Earth core for $\tau^+\tau^-$, $b\bar{b}$ and W^+W^- channels**
- 90% CL upper limit on SI WIMP-nucleon scattering cross section $\sigma_{\chi}n$



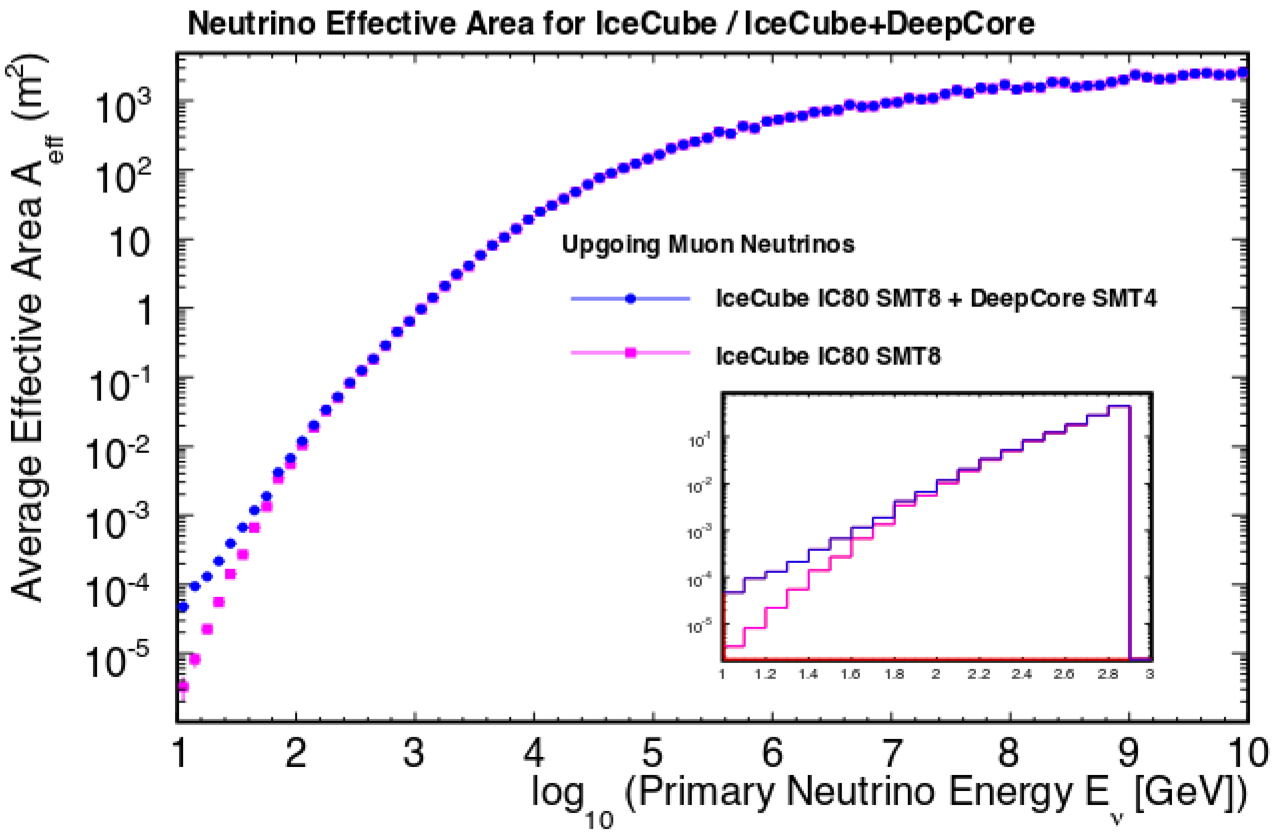
Solar WIMP search – muon neutrino flux limit

- FIT based on lepton mom. & $\cos\theta_{SUN}$ distributions, 3903 days of SK data used
- **No excess of ν 's from the SUN as compared to atm bkg is observed**
- **90% CL upper limit on total integrated muon-neutrino flux from WIMP annihilations in the Sun for $\tau^+\tau^-$, $b\bar{b}$ and W^+W^- channels**
- **90% CL upper limit on WIMP-nucleon scattering cross section $\sigma_{\chi}n$**



The shadowed regions show 1σ bands of the sensitivity study results

Ice Cube + Deep core effective area:



- **Effective area:** The effective area A_{eff} relates a measured event rate $\mathcal{R}_{exp}(\theta)$ to the total incident flux Φ:

$$\mathrm{d}\,\mathcal{R}_{exp}(\theta) = A_{eff}(\theta, E) \cdot \frac{\mathrm{d}\,\Phi}{\mathrm{d}\,E}\,\mathrm{d}\,E \qquad (5.1)$$

Here θ is the event zenith angle. The energy dependence of A_{eff} is introduced through the energy dependence of the detector efficiency. In IceCube A_{eff} is typically given related to a neutrino or a muon flux. The concept of an effective area is based on the assumption of infinite tracks (where only the projection of the detector volume into the plane perpendicular to the event direction is of importance). This is well justified for muons with a few 100 GeV as these can cross the whole detector, but at the lowest energetic events effective volumes pose a clearer definition.

Comparison with SK:

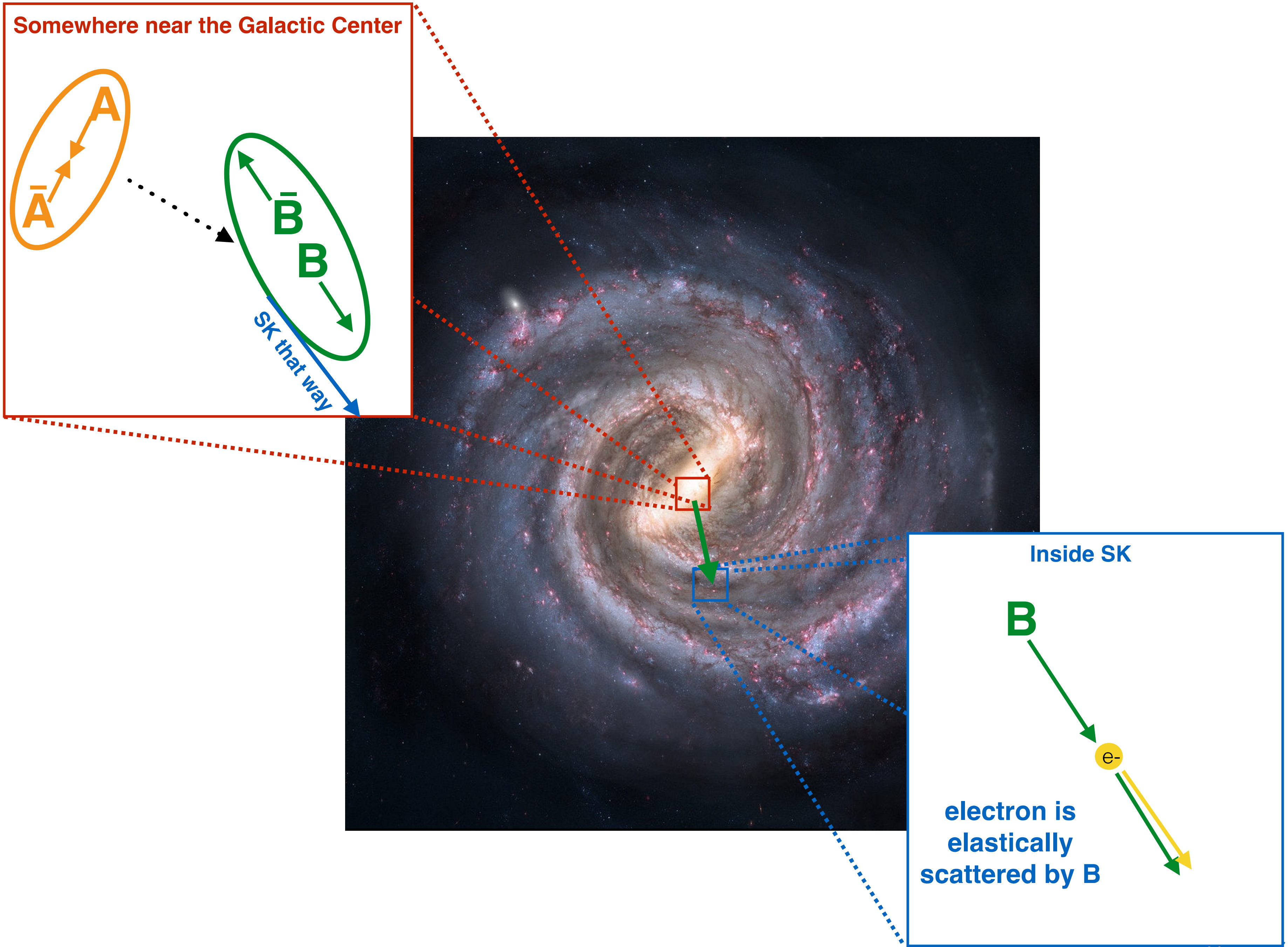
Super-Kamiokande effective area for 10 GeV WIMPs
~ 10^{-1} m^2
IceCube + Deep Core effective area for 10 GeV WIMPs
~ 10^{-4} m^2

Livetime:
IceCube 327 days
SK FC/PC 5325.8, UPMU 5629.2

Comparison for 10 GeV WIMPs, $\tau^+\tau^-$ ann. channel:
10^{-1} * 5500 / 10^{-4} * 327 ~ 16000 → 100x better limit

Super-K limit: $1.4 * 10^{-40}$
IceCube limit: $2.5 * 10^{-38}$

Boosted dark matter search



Analysis Technique

- Divide into three energy ranges, by evis
  - Sub GeV: 100 MeV*-1.33 GeV
  - Mid Energy: 1.33 GeV-20 GeV
  - High Energy: >20 GeV
- For 8 cones from 5 to 40 degrees around Galactic Center, count number of events and compare to estimated background

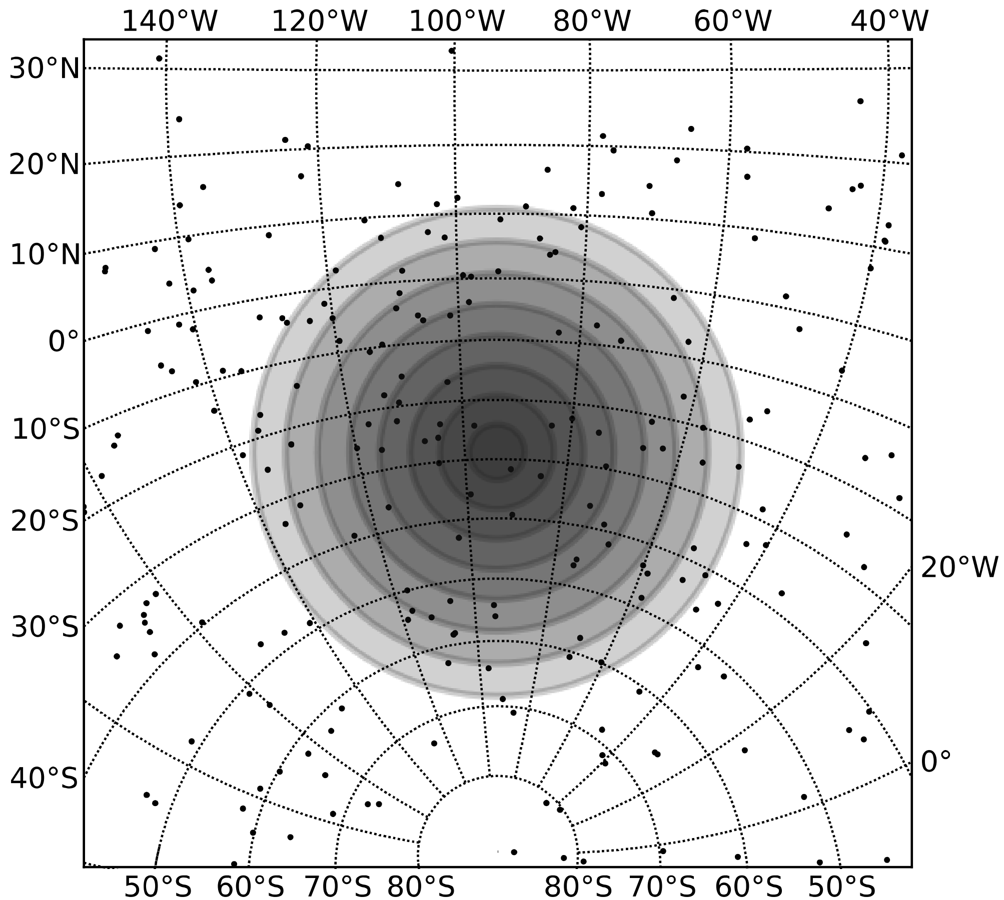
*evis>30 MeV
amome>100 MeV

4 Simple Cuts

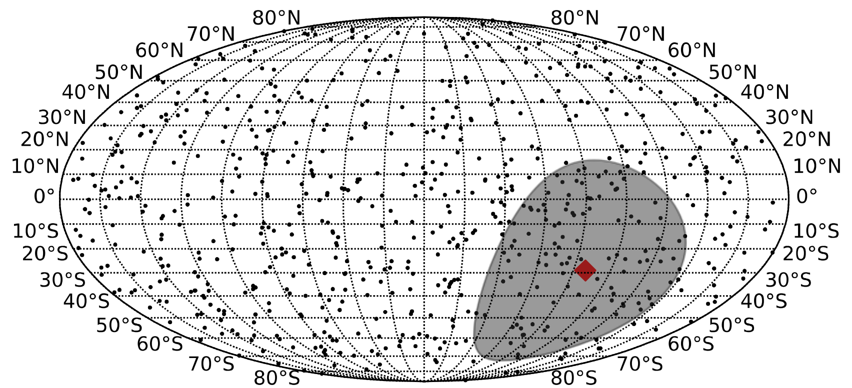
Total Data Events (Sep 16)

	Evis<1.33 GeV	1.33 GeV<Evis<20 GeV	20 GeV< Evis
FCFV	15206	4908	97
and single ring	11367	2868	53
and e-like	5655	1514	53
and 0 decay-e	5176	1134	17
and 0 tagged neutrons	4132	683	4

Mid Energy



Grey are 8 cones from 5° to 40° around GC



=Galactic Center

Grey is 40° cone around GC

No clusters visible

Results

162 kton yrs

Evis<1.33GeV

	Expected Bckg	Data	Signal 90% C.I.
GC 5° cone	8.6 ± 0.7	7	0-4.5
GC 10° cone	32.9 ± 1.9	24	0-3.7
GC 15° cone	74.4 ± 3.6	70	0-11.9
GC 20° cone	129.5 ± 5.5	127	0-19.5
GC 25° cone	201.4 ± 7.7	211	0-37.5
GC 30° cone	290.3 ± 10.2	292	0-35.6
GC 35° cone	394.1 ± 13.0	387	0-33.1
GC 40° cone	511.2 ± 16.0	502	0-37.6

1.33GeV<Evis<20GeV

	Expected Bckg	Data	Signal 90% C.I.
GC 5° cone	1.6 ± 0.3	1	0-2.9
GC 10° cone	6.3 ± 0.84	4	0-3.0
GC 15° cone	13.9 ± 1.6	12	0-5.7
GC 20° cone	23.9 ± 2.4	19	0-5.2
GC 25° cone	36.4 ± 3.3	31	0-7.2
GC 30° cone	50.6 ± 4.3	50	0-14.3
GC 35° cone	69.7 ± 5.5	70	0-17.7
GC 40° cone	92.1 ± 6.9	94	0-22.4

Evis>20GeV

	Expected Bckg	Data	Signal 90% C.I.
GC 5° cone	0.011 ± 0.003	0	0-2.5
GC 10° cone	0.041 ± 0.012	0	0-2.4
GC 15° cone	0.096 ± 0.029	0	0-2.4
GC 20° cone	0.17 ± 0.05	0	0-2.3
GC 25° cone	0.26 ± 0.08	0	0-2.2
GC 30° cone	0.37 ± 0.11	0	0-2.1
GC 35° cone	0.49 ± 0.15	0	0-2.0
GC 40° cone	0.63 ± 0.19	0	0-1.9

No evidence of excess in any energy region or cone