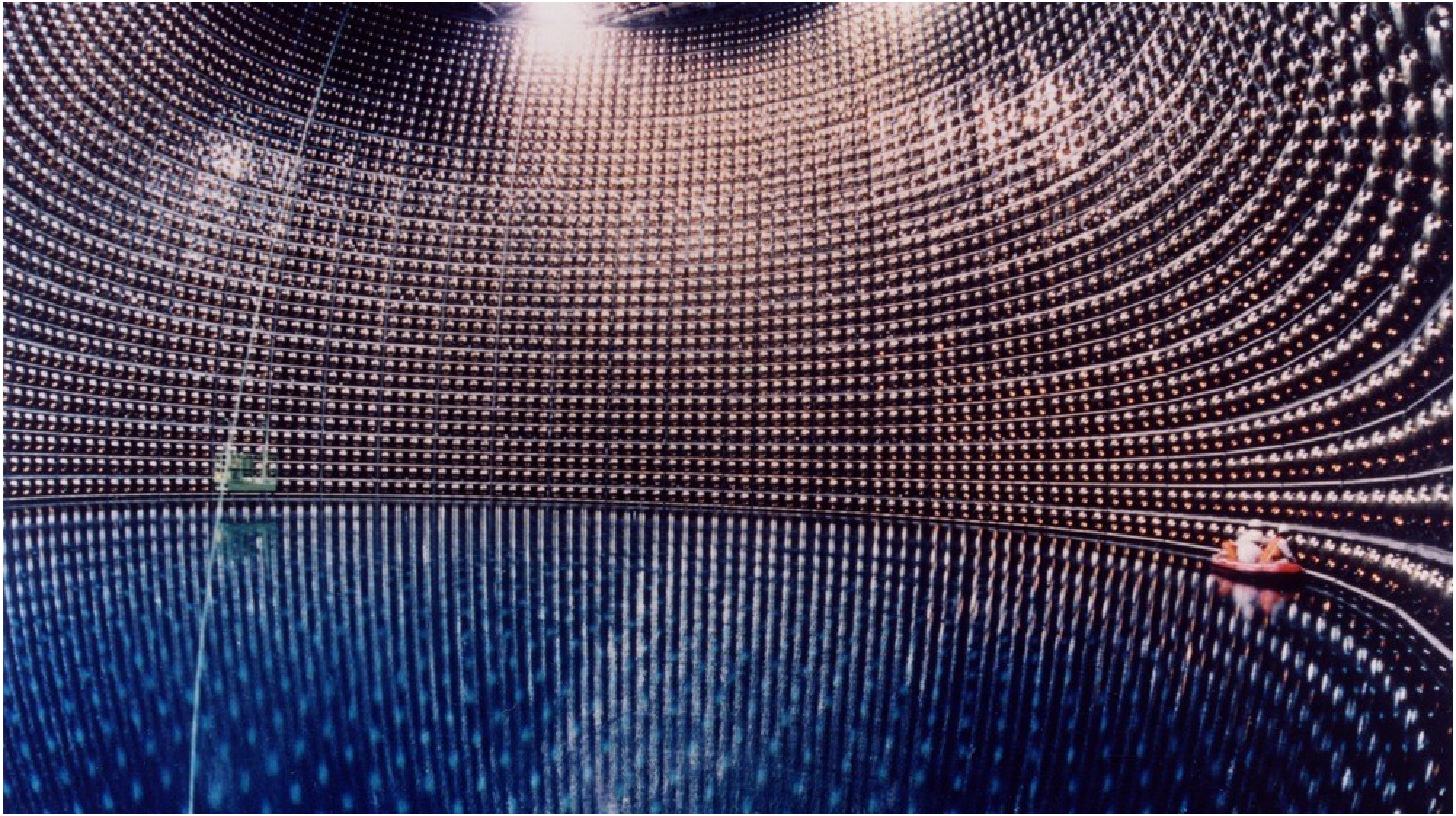
Search for dark matter induced neutrinos with the Super-Kamiokande detector



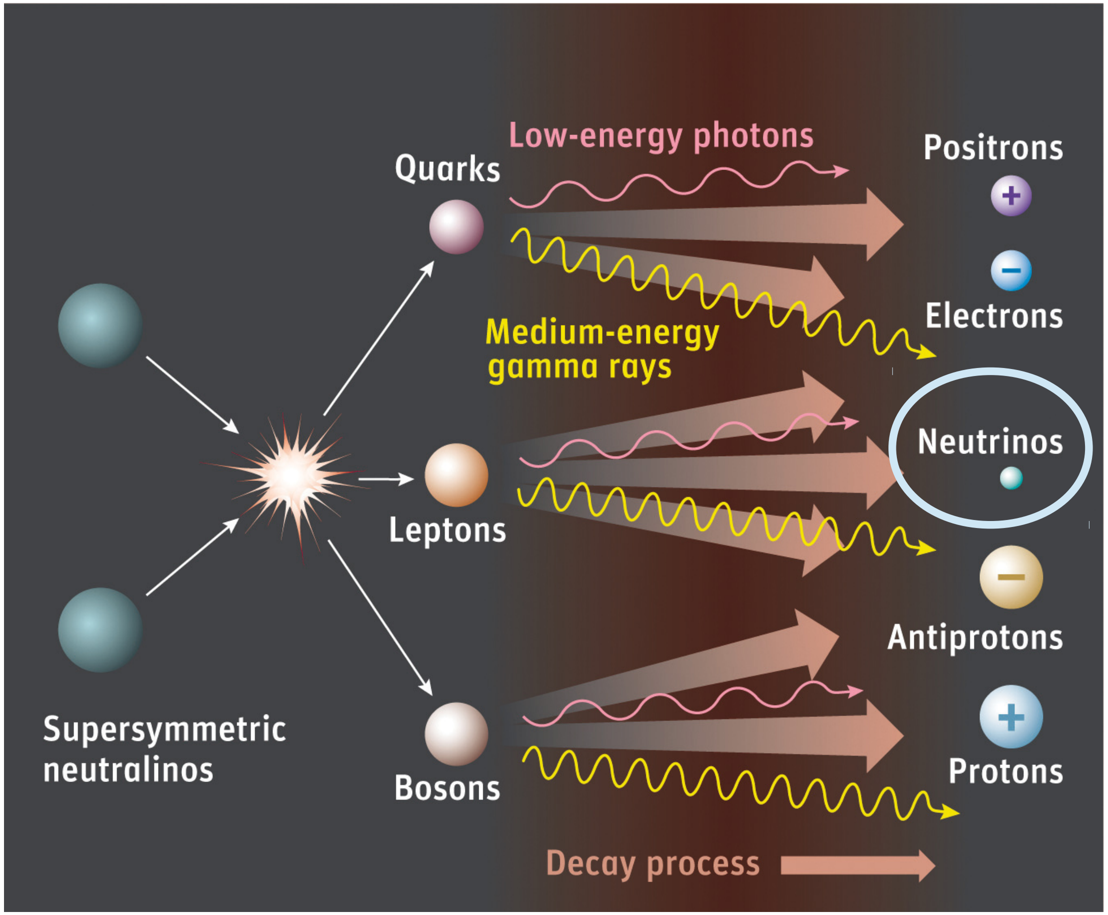
Katarzyna Frankiewicz

PATRAS, 2018/06/18

Indirect dark matter detection

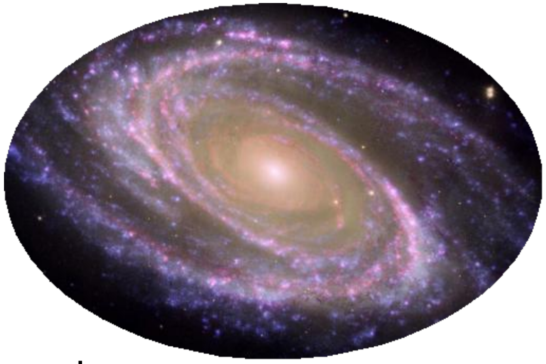
- Search for the products of WIMP annihilation or decay

→ most popular WIMP candidate: the lightest supersymmetric particle (LSP) **neutralino χ**

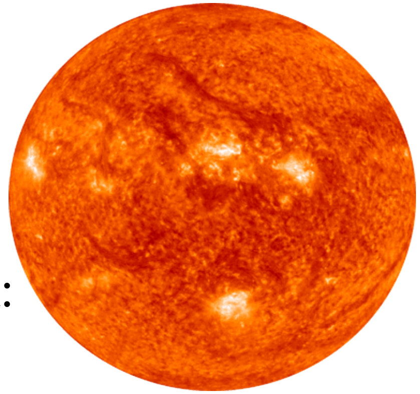


Where we are searching:

Diffuse signal from entire Galaxy, peaked from Galactic Center



Sun, considered as point source



Earth's core

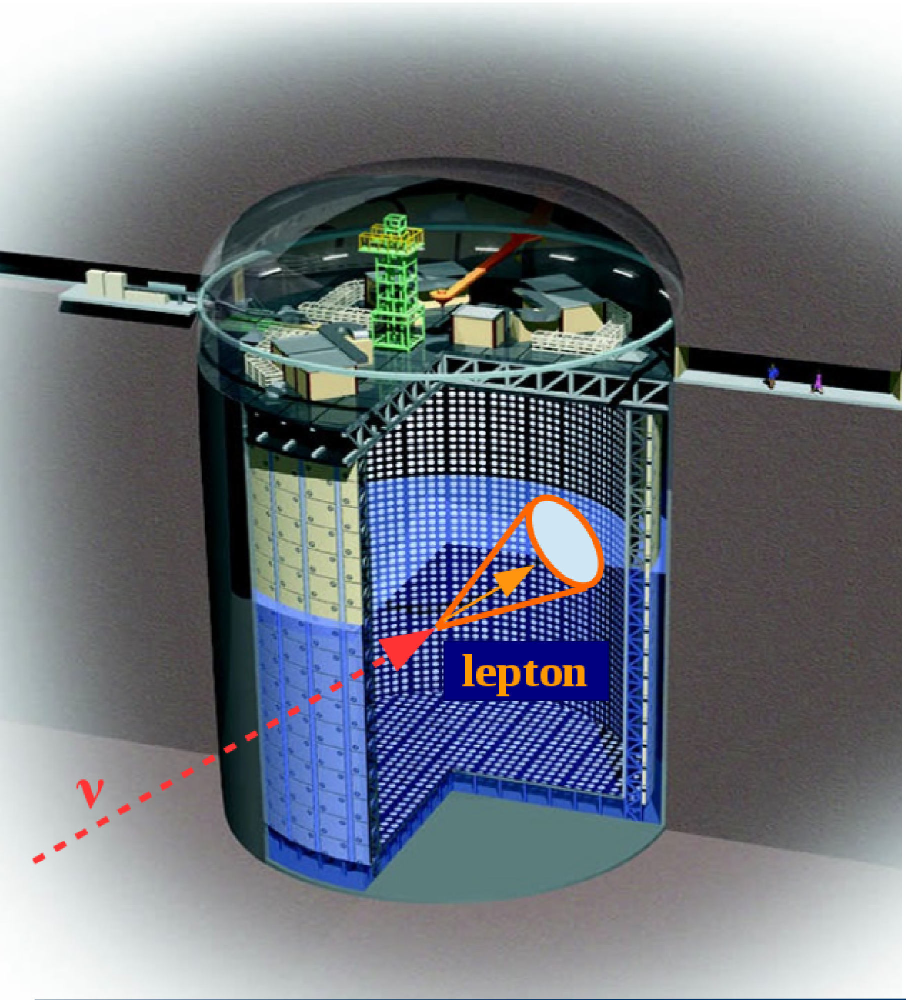
Produced neutrinos provide very good information about:

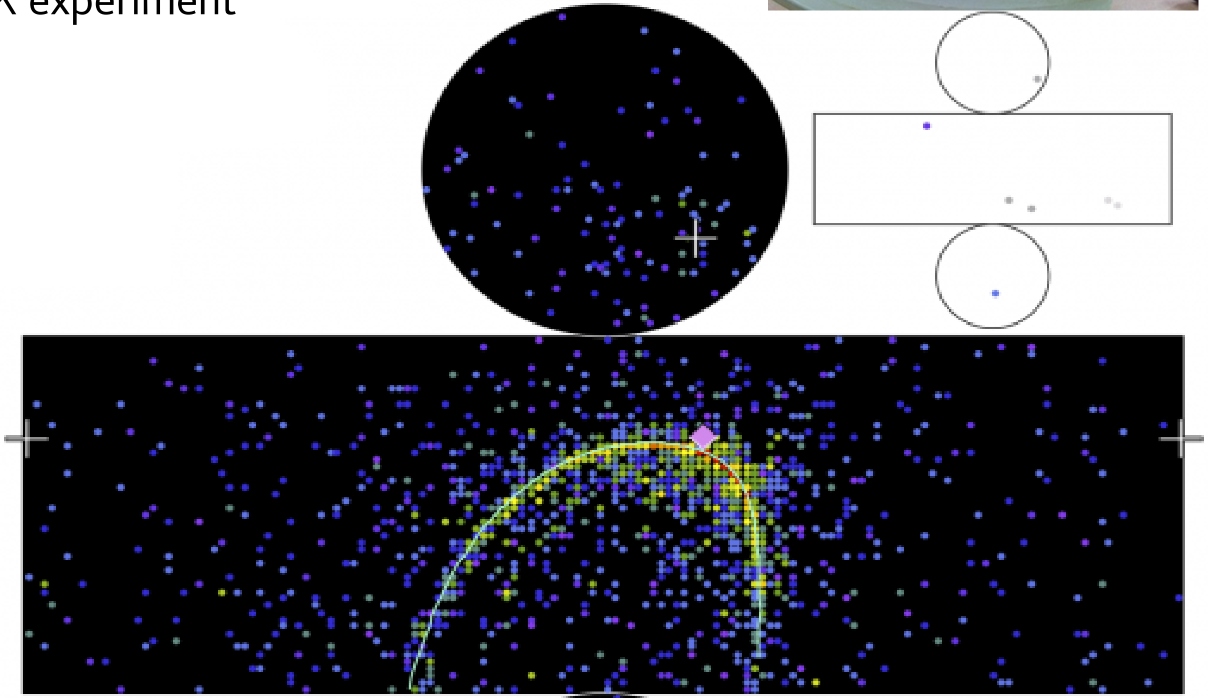
- source position
- generated energy spectra
- flavor composition

Super-Kamiokande

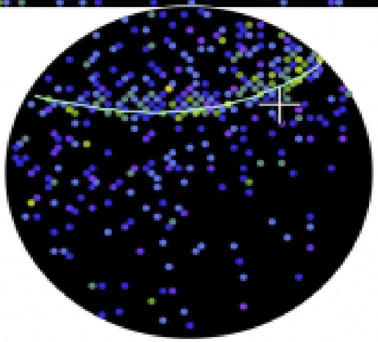
Detector measures solar, atmospheric, cosmic, and accelerator neutrinos

- 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

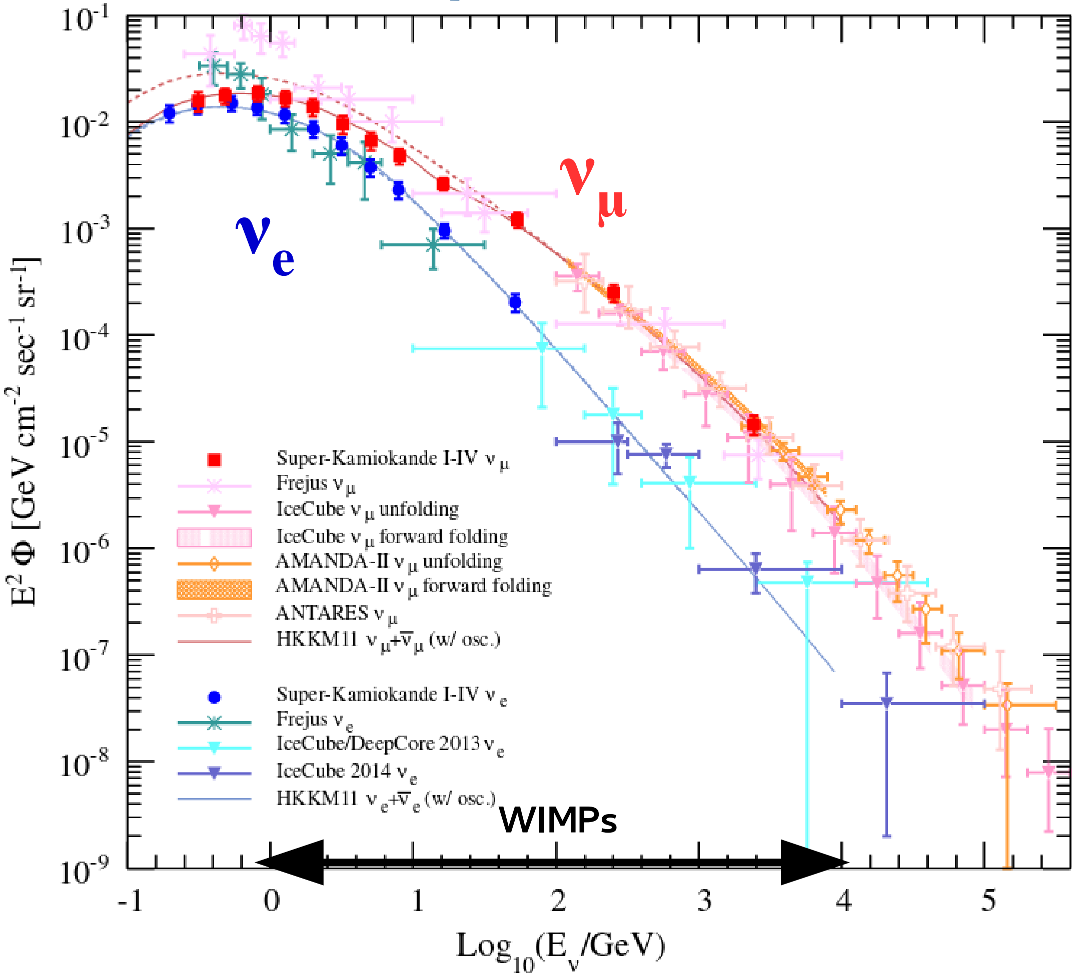




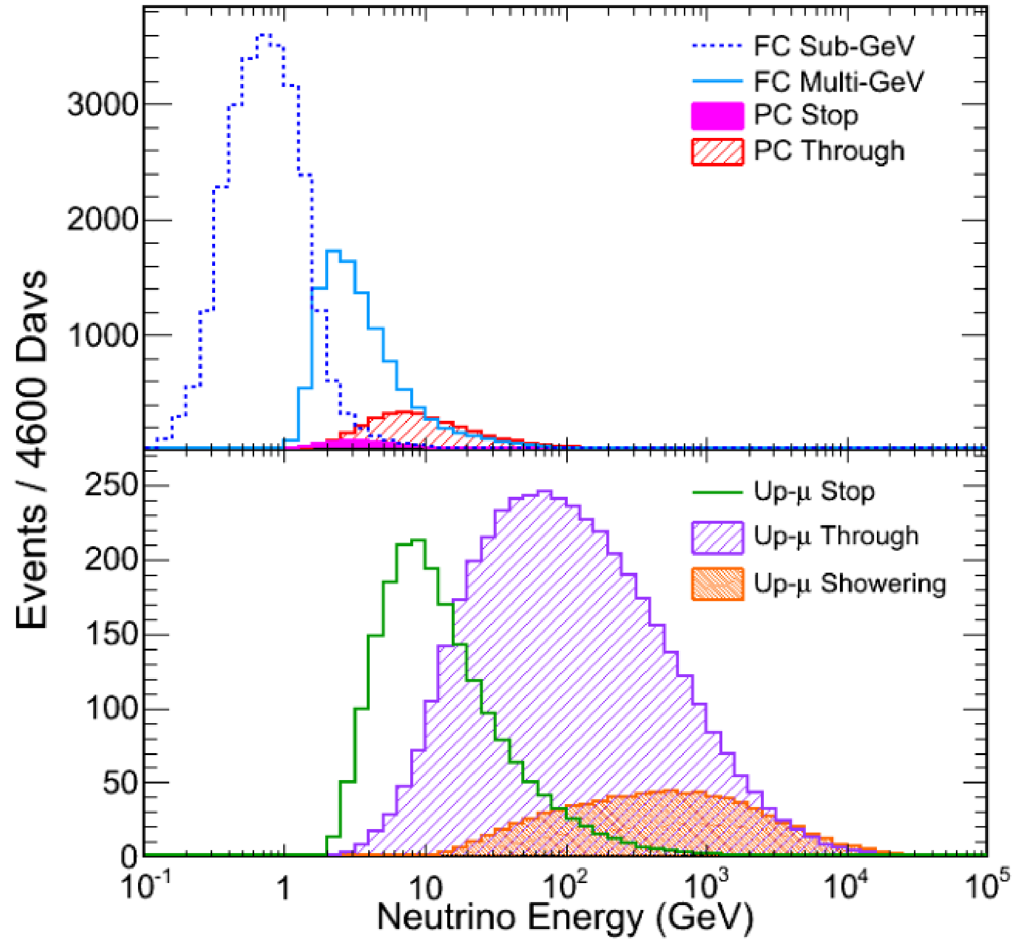
Detected Cherenkov light allows to reconstruct energy, direction, and flavor of produced lepton



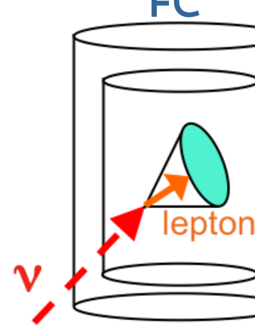
Atmospheric neutrinos

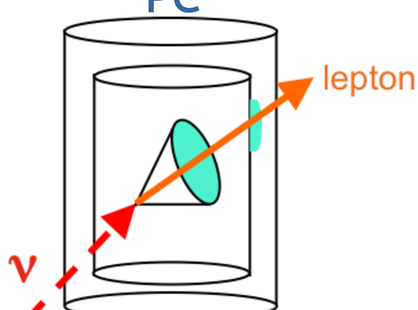


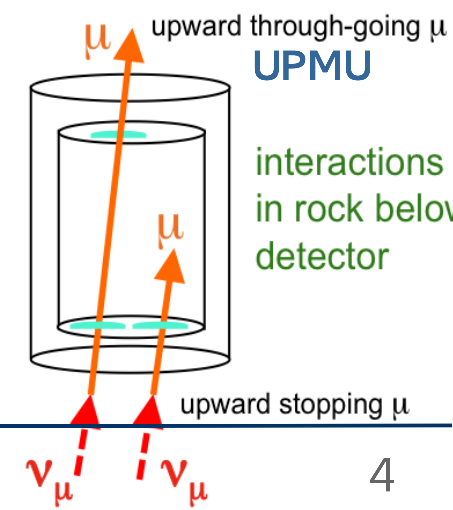
Data samples at SK



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



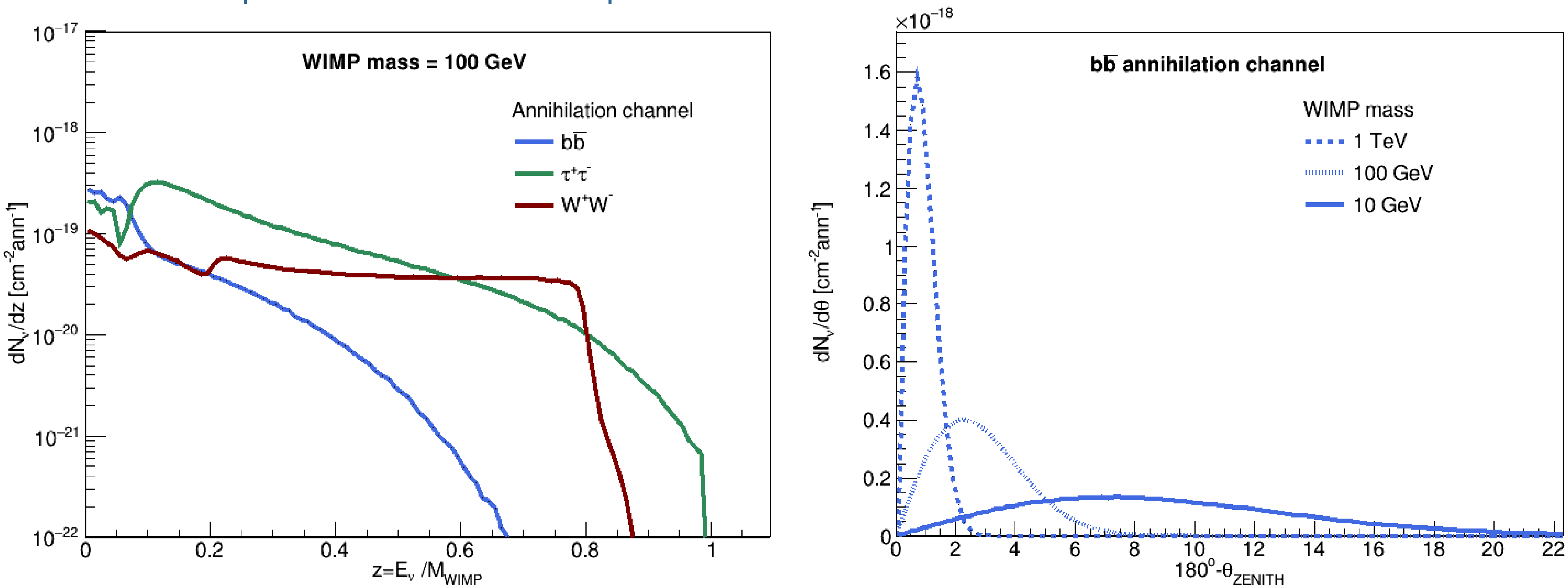




Signal simulation

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

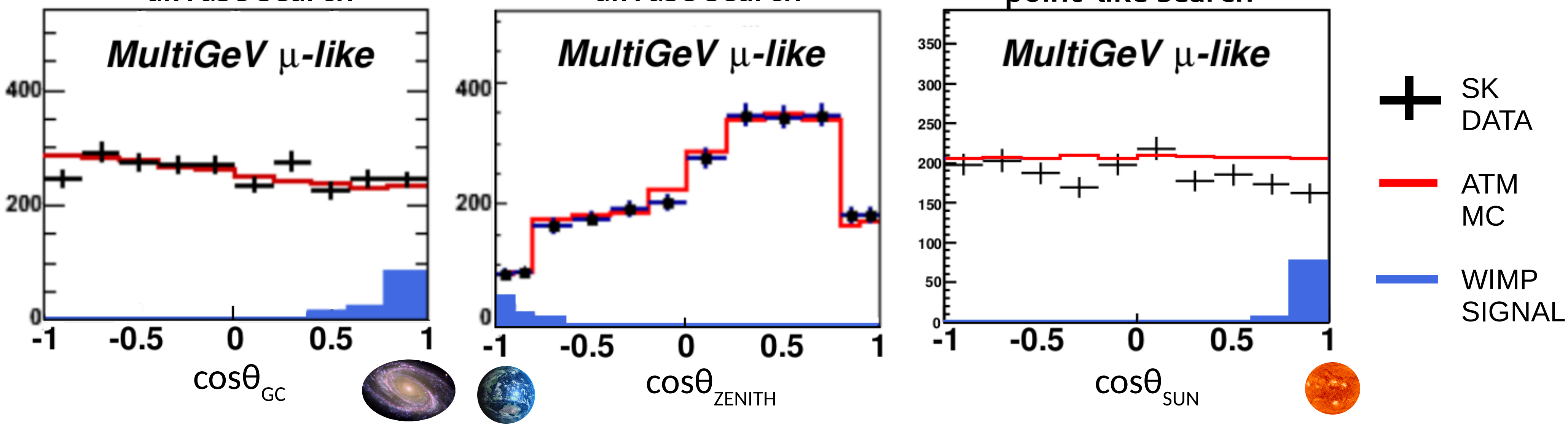
Analysis

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 the **DATA**

- **Example:** signal for 6 GeV WIMPs annihilating into $b\bar{b}$ quarks, 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**

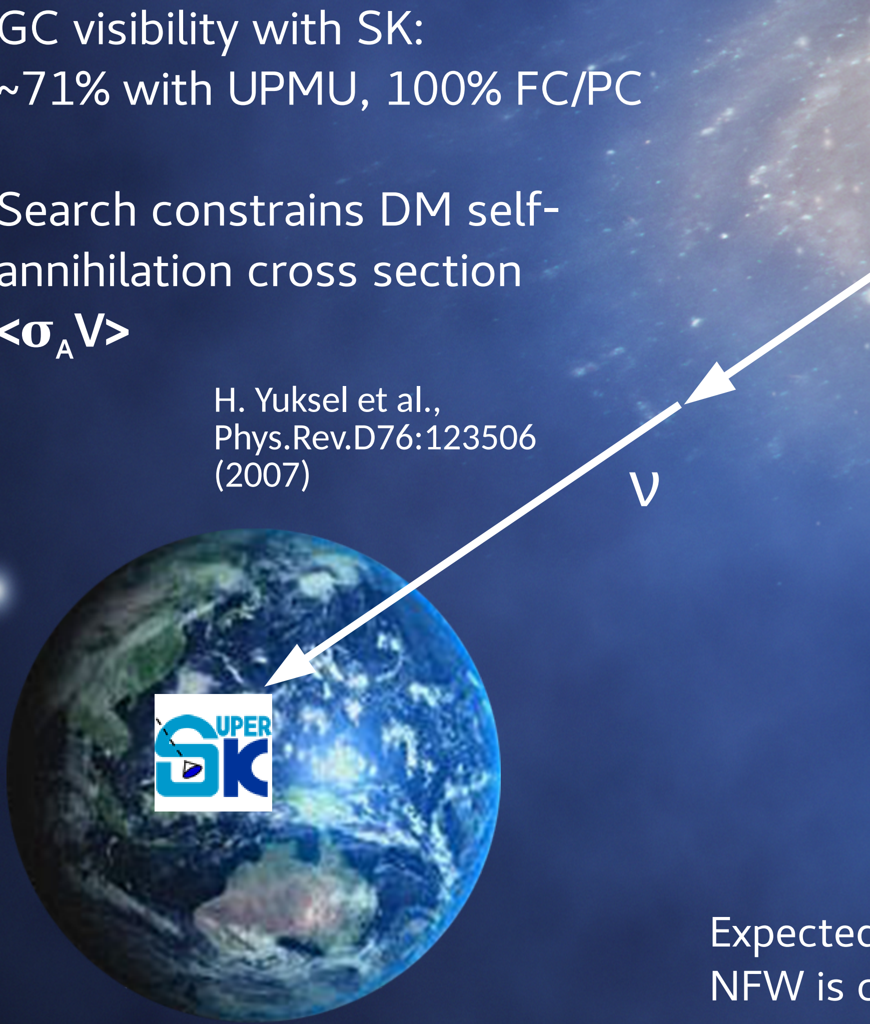
Galactic WIMP search

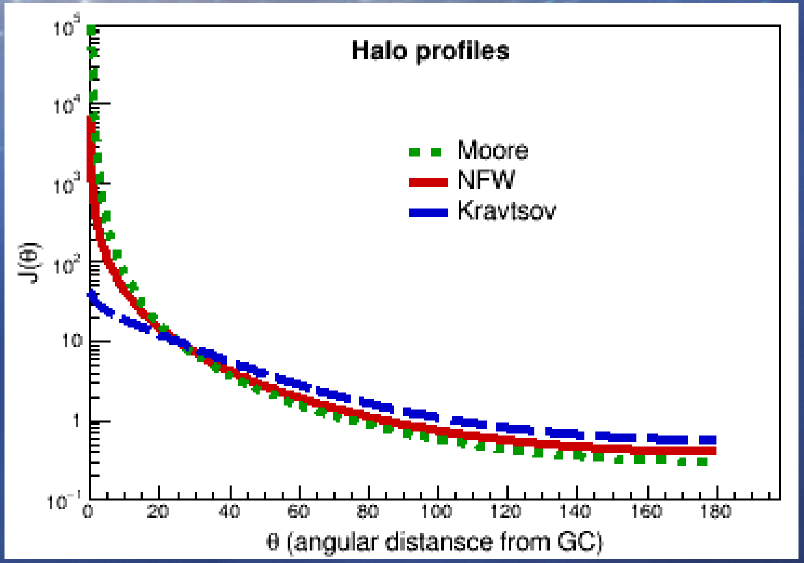
Diffuse signal from entire Galaxy, peaked from Galactic Center

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)



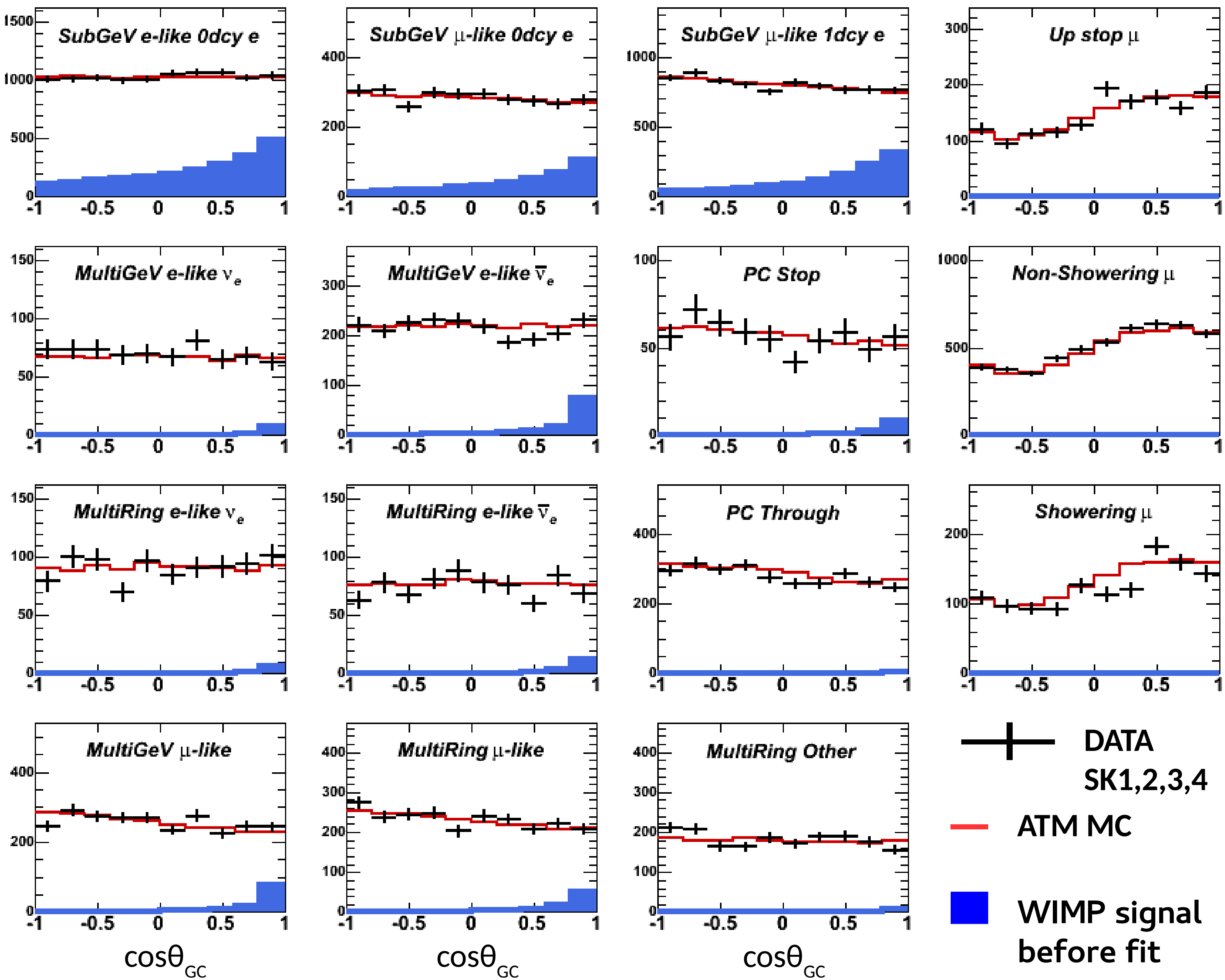


Expected signal intensity strongly depends on halo model
NFW is considered as a benchmark model in this analysis

Galactic WIMP search – data samples

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

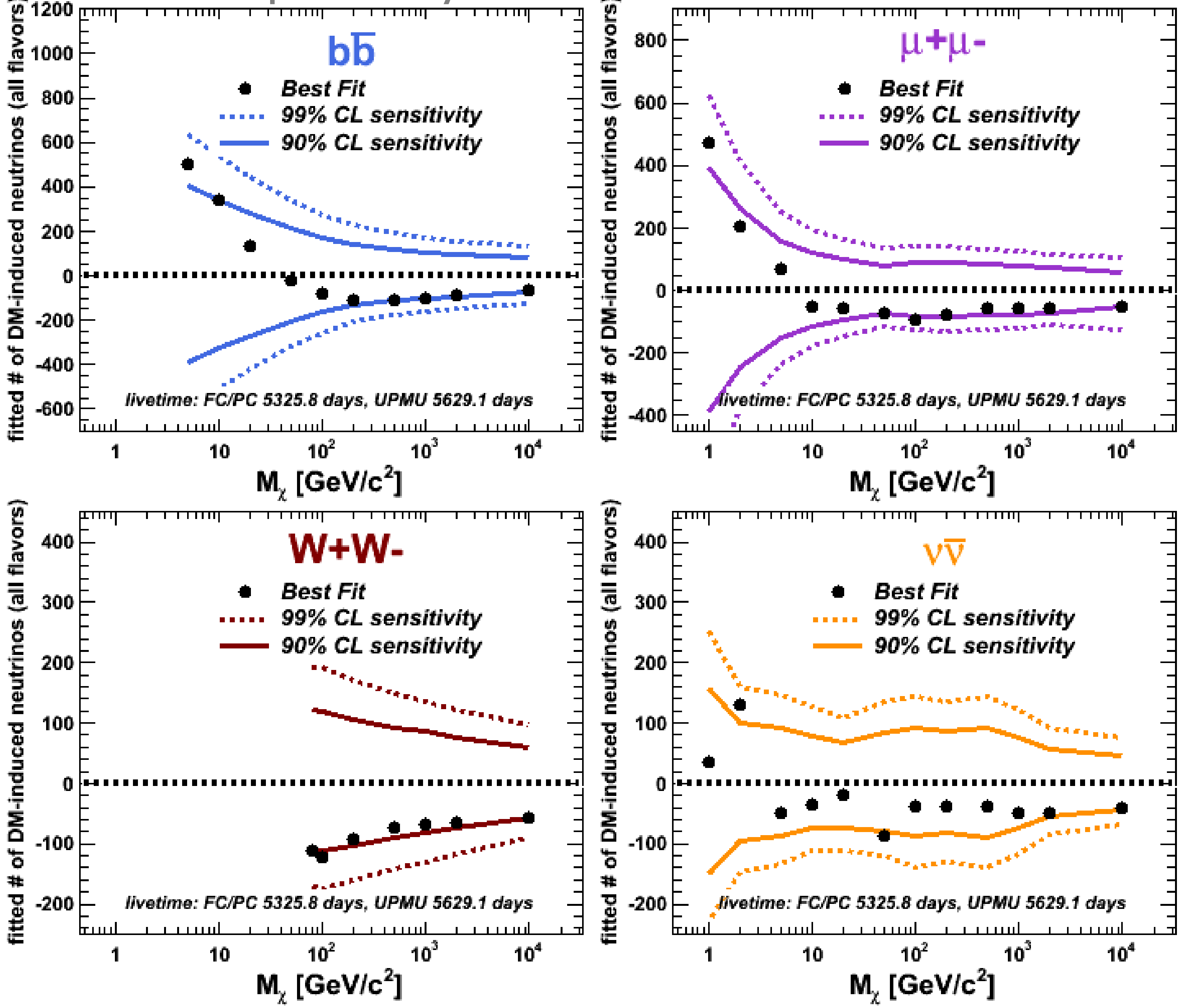
SK preliminary **Example for:** 5 GeV WIMPs , $b\bar{b}$ ann. channel



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 $\langle\sigma_A V\rangle$

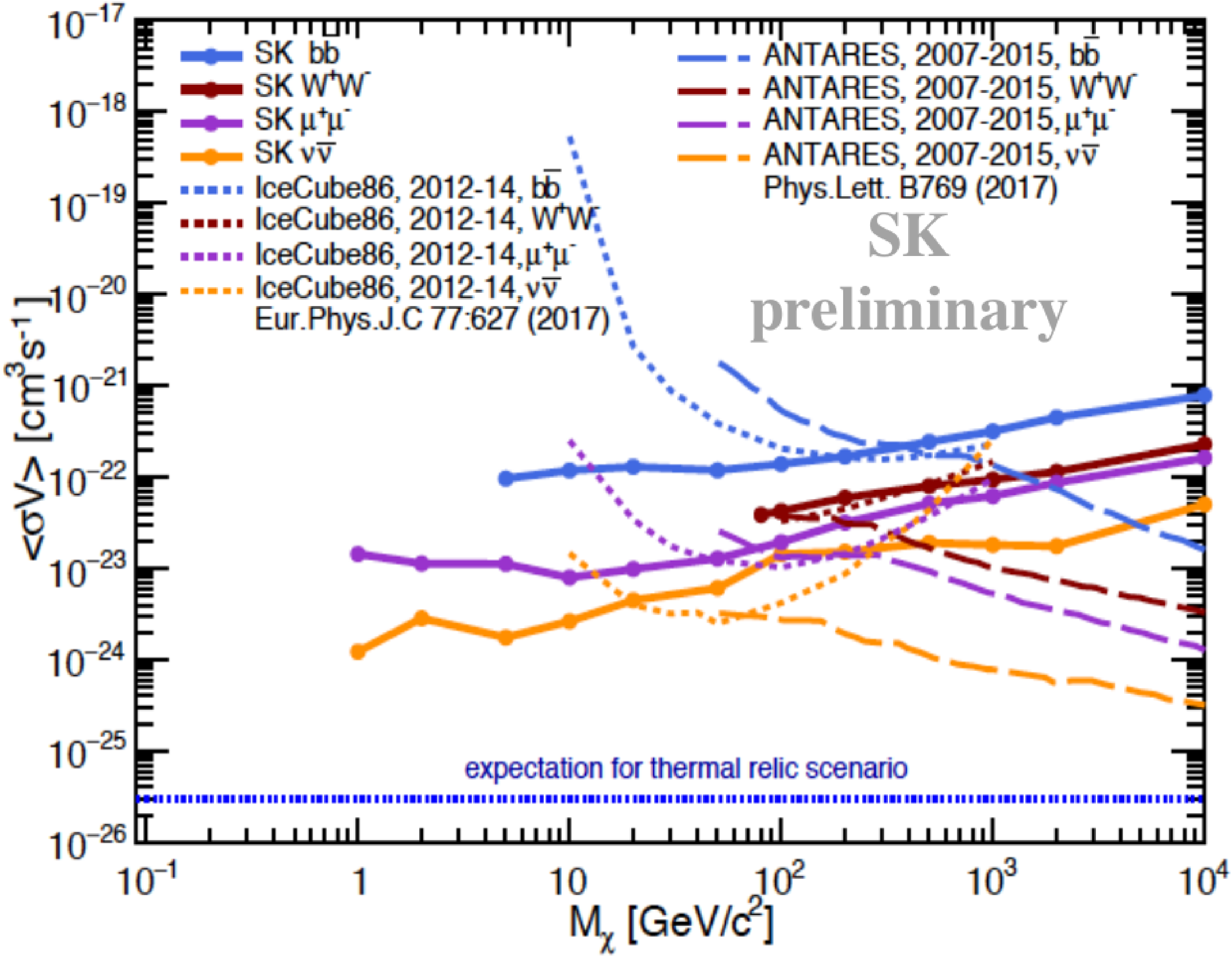
SK preliminary



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 $<\sigma_A V>$**

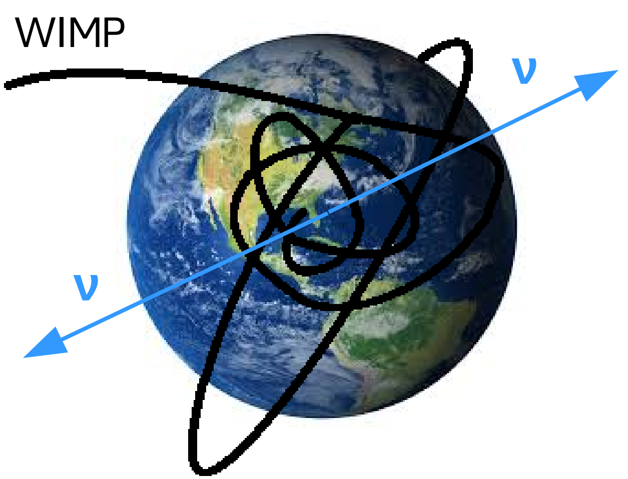
For each considered annihilation channel 100% BR is assumed

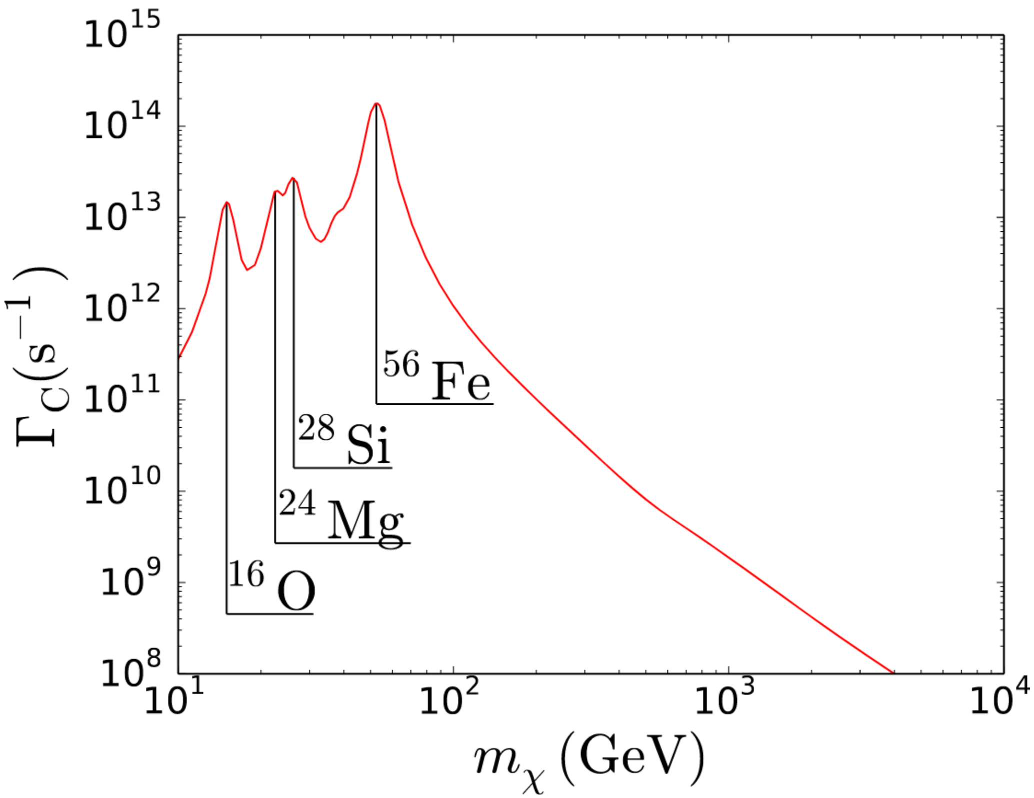


Earth WIMP search

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 mass of one of the heavy element in the Earth, the capture rate will increase considerably.





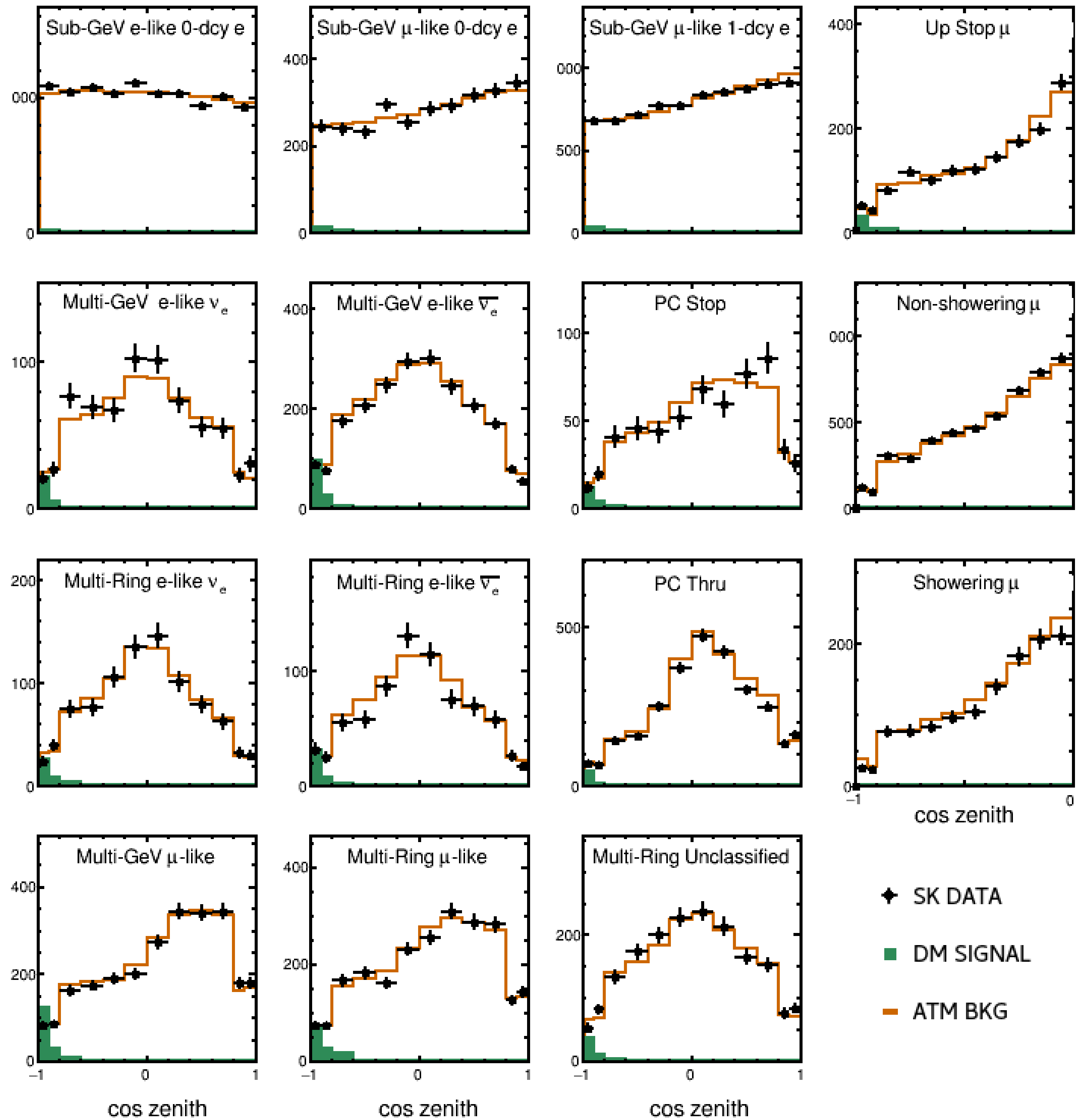
The peaks correspond to **resonant capture** on the most abundant elements **^{16}O**, **^{24}Mg**, **^{28}Si** and **^{56}Fe** and their isotopes.

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

Earth WIMP search – data

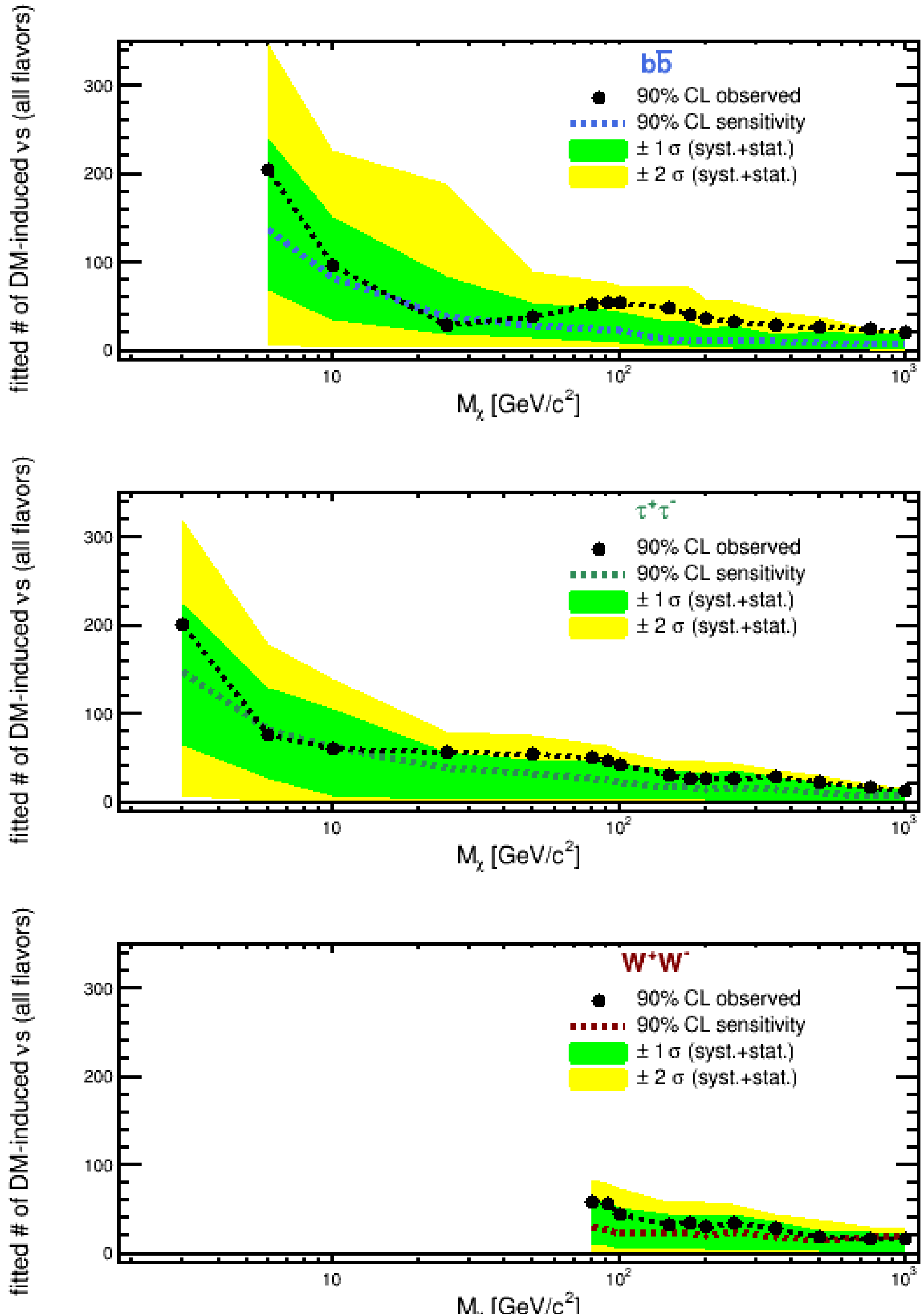
- FIT based on lepton mom. & $\cos\theta_{ZENITH}$ distributions
- Fit results are consistent with zero
- 90 % upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi n}$

Example for:
100 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 $\sigma_{\chi}n$

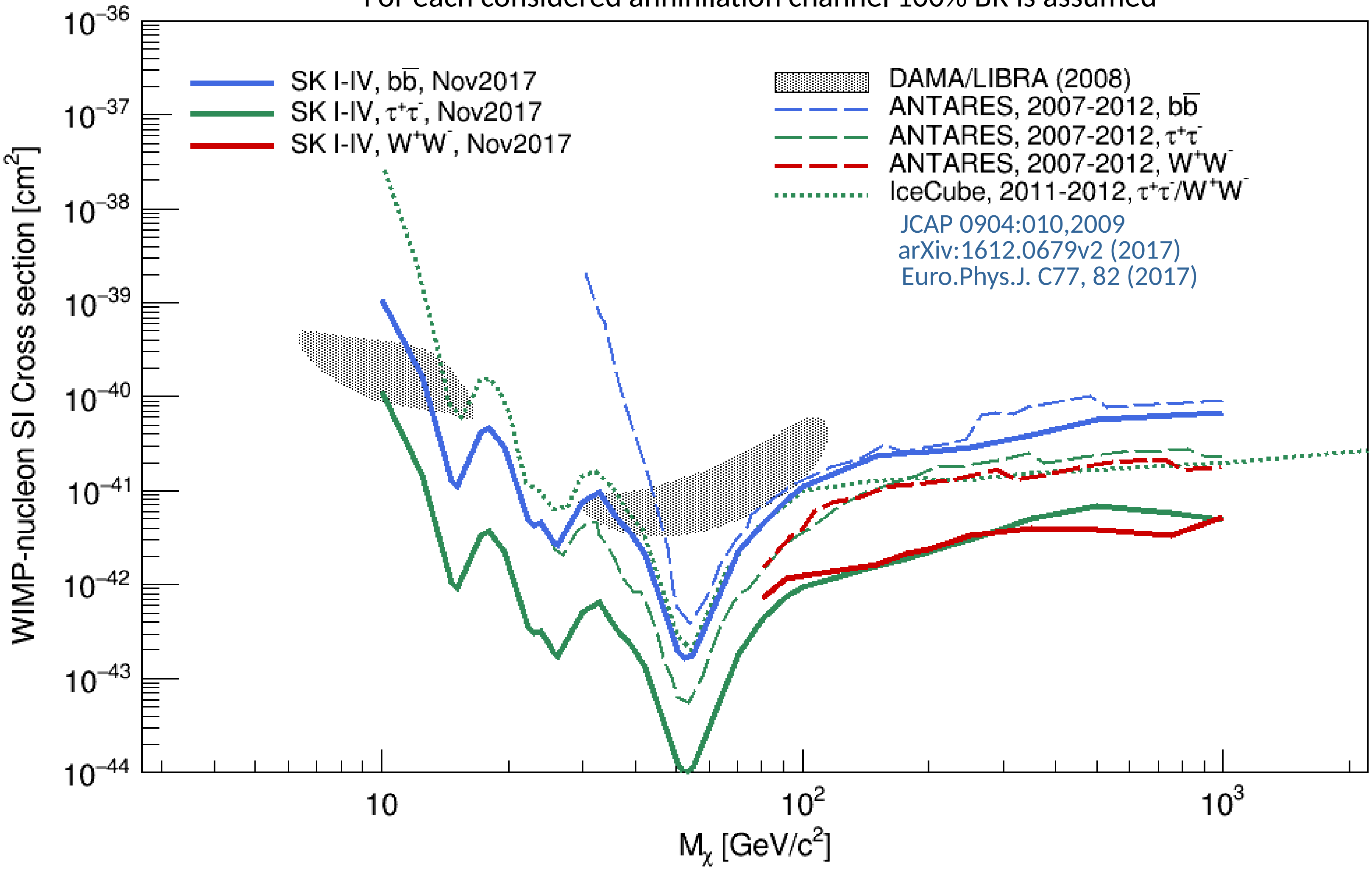


Earth WIMP search

– WIMP-nucleon SI scattering cross-section limit

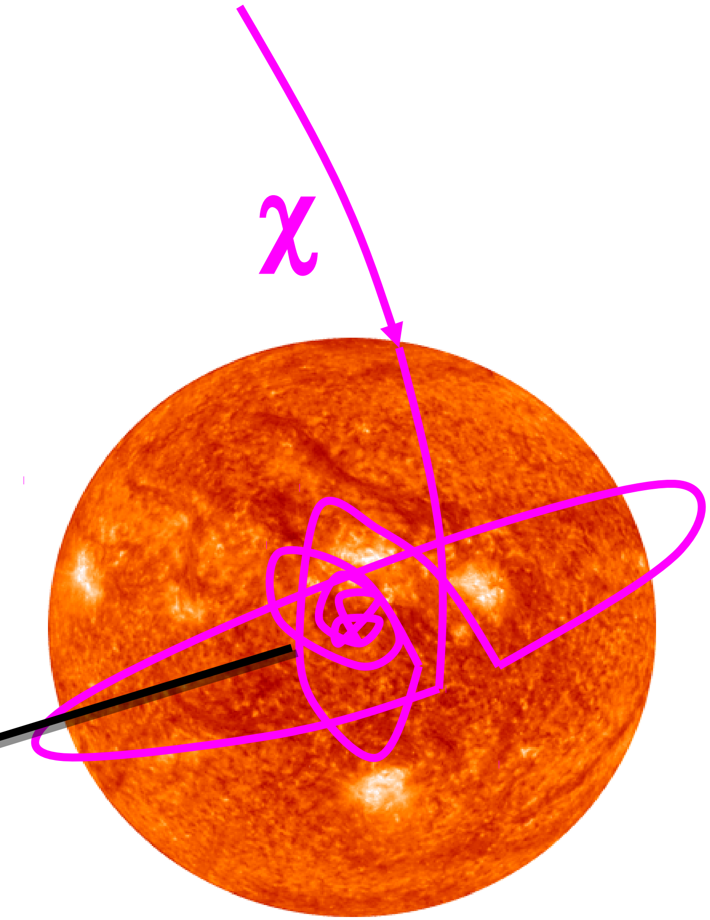
- FIT based on lepton mom. & $\cos\theta_{ZENITH}$ distributions
- Fit results are consistent with zero
- **90 % upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi}n$**

For each considered annihilation channel 100% BR is assumed



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 σ_{χ}n** can be constrain and compare with results from direct DM detection



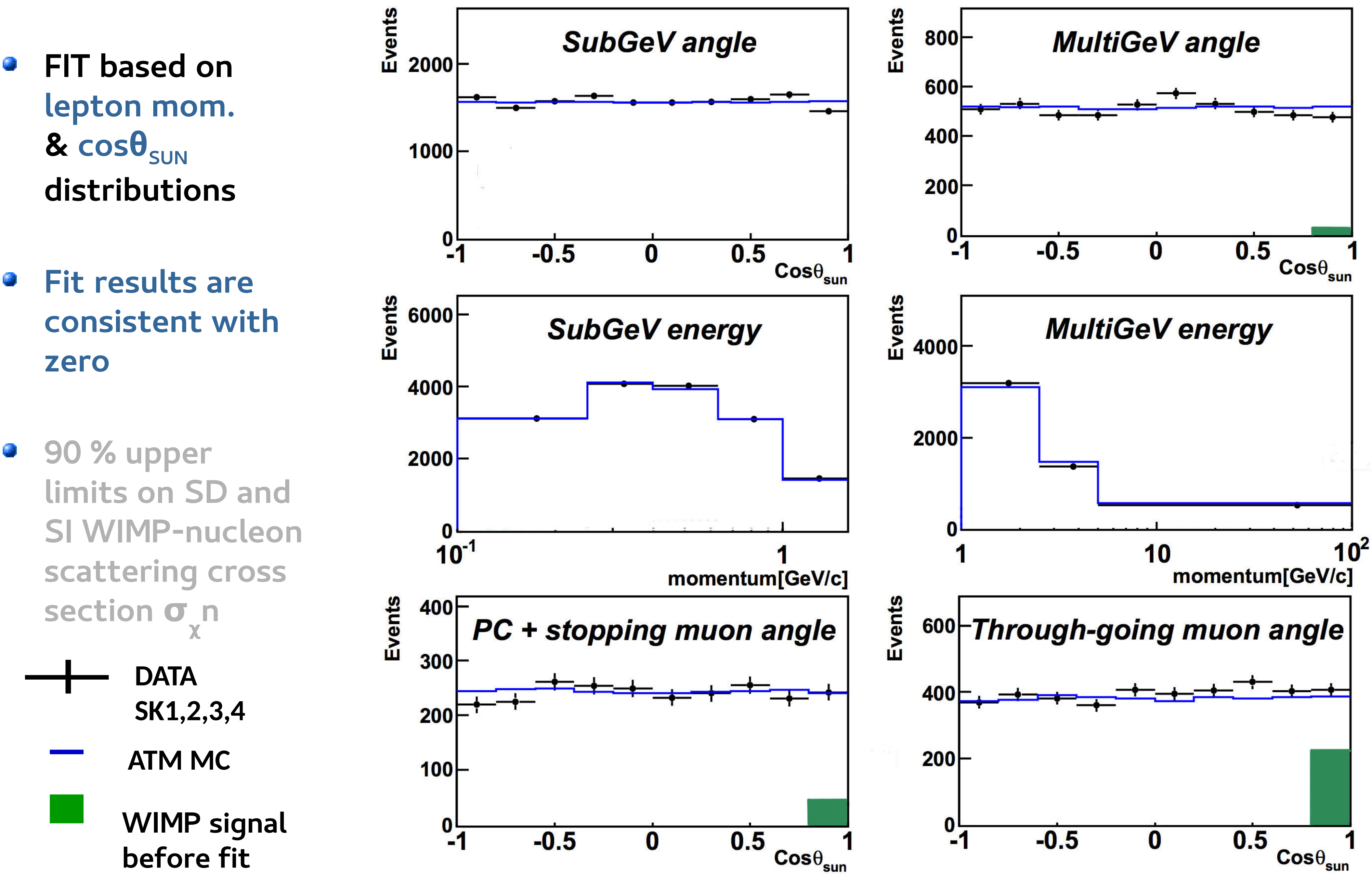
more: G.Wikström, J.Edsjö
JCAP 04, 009 (2009)

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

Solar WIMP search – data samples

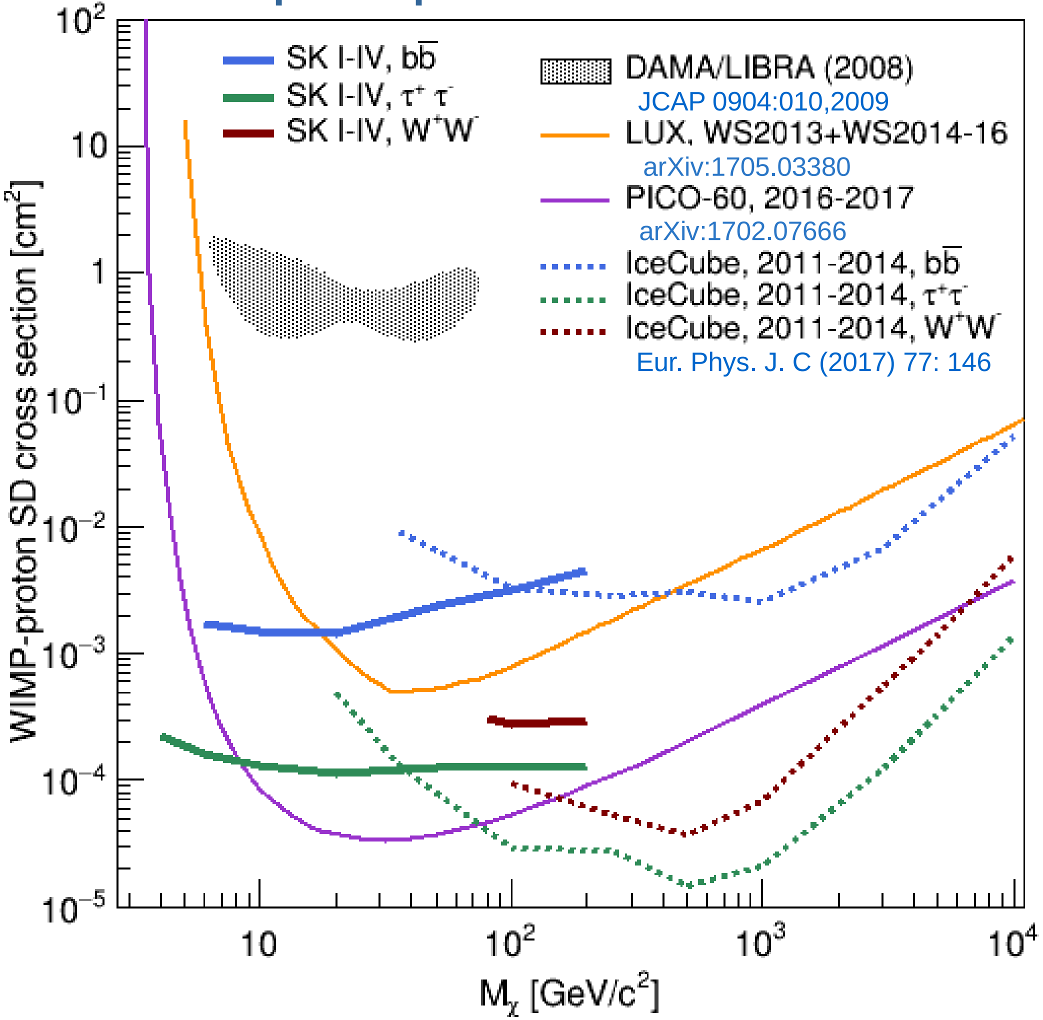
- FIT based on lepton mom. & $\cos\theta_{SUN}$ distributions
- Fit results are consistent with zero
- 90 % upper limits on SD and SI WIMP-nucleon scattering cross section $\sigma_{\chi}n$

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

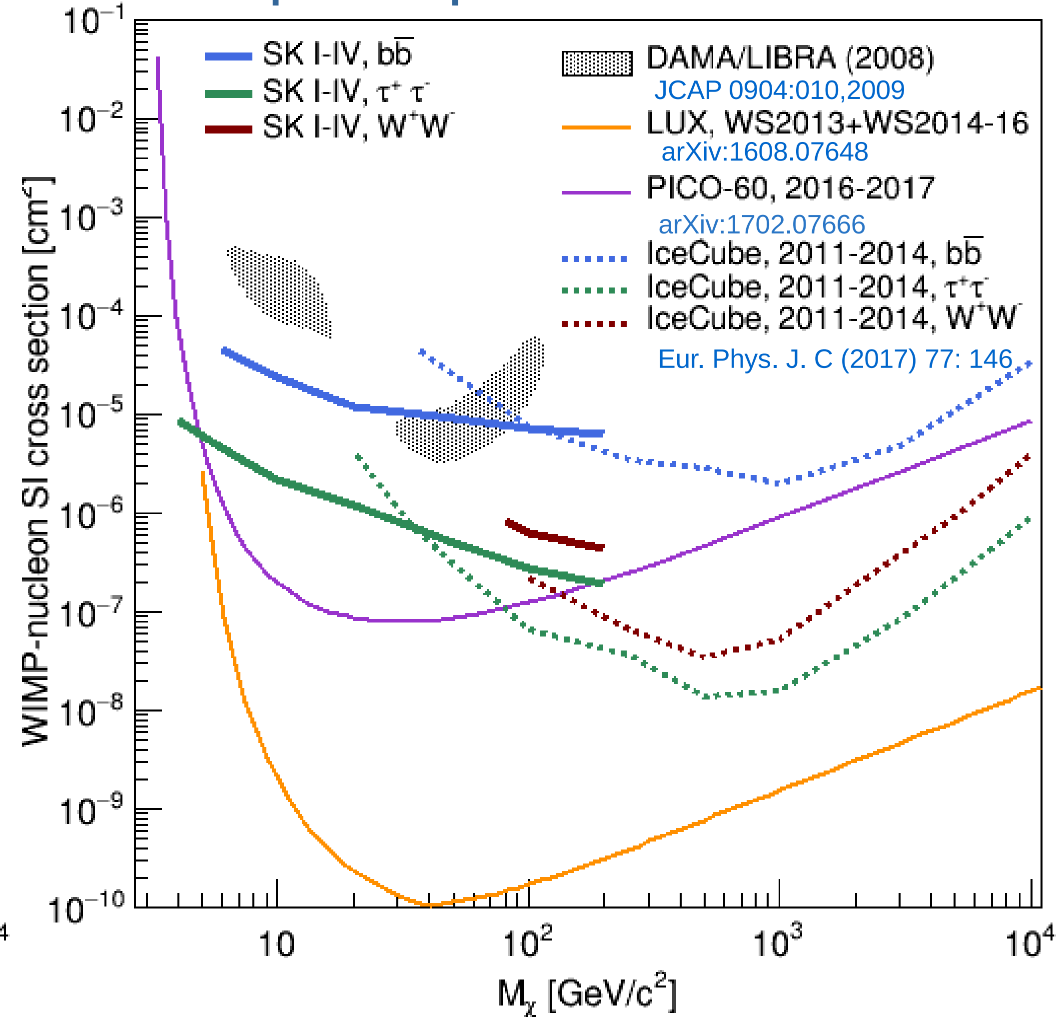


Solar WIMP search – WIMP-nucleon SD & SI cross-section limit

Spin-dependent interactions

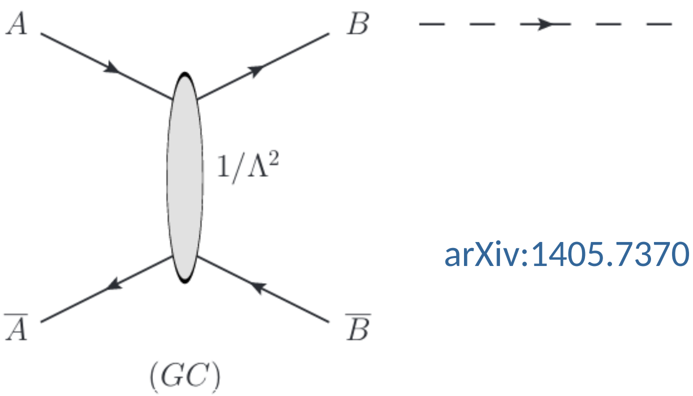


Spin-independent interactions

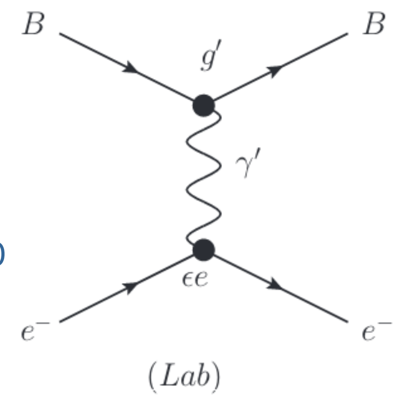


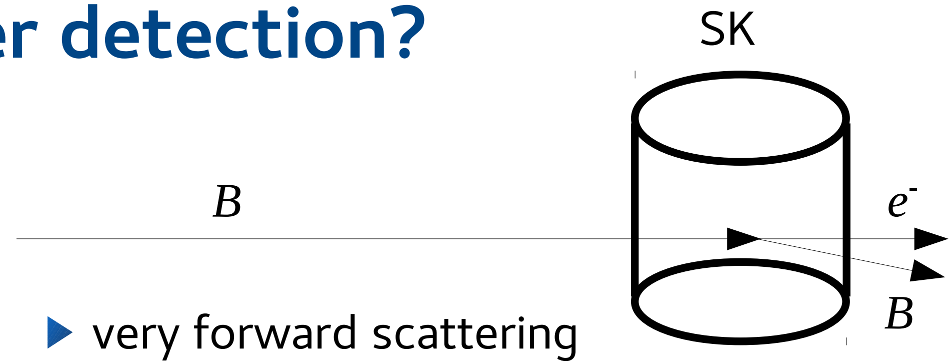
Published analysis: K.Choi et al., Phys. Rev. Lett. 114, 141301 (2015)

(In)direct dark matter detection?



arXiv:1405.7370

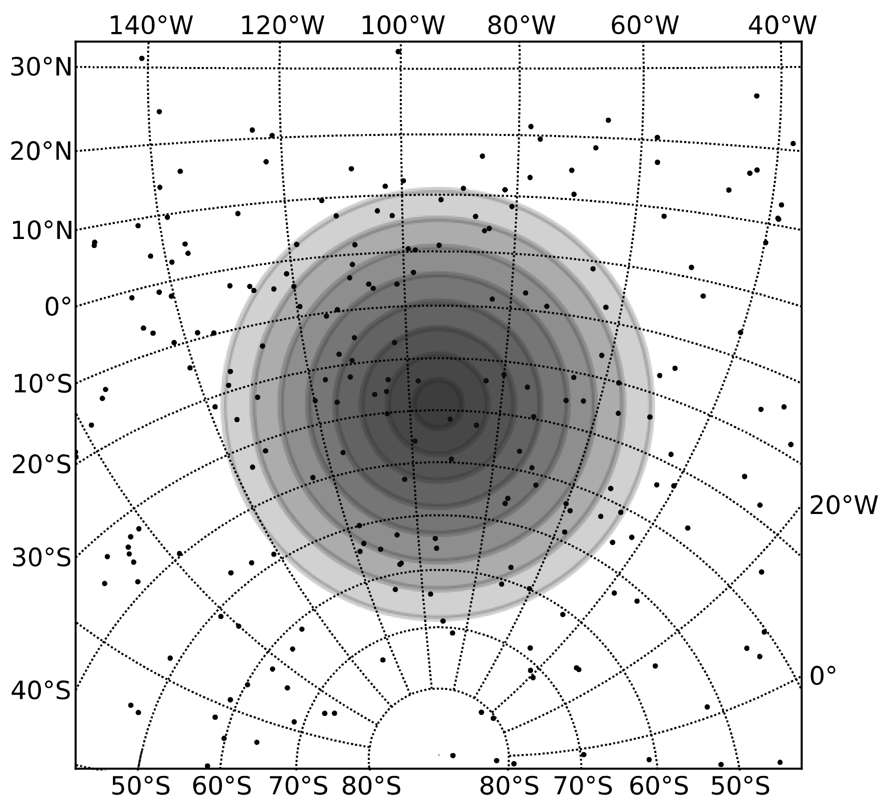




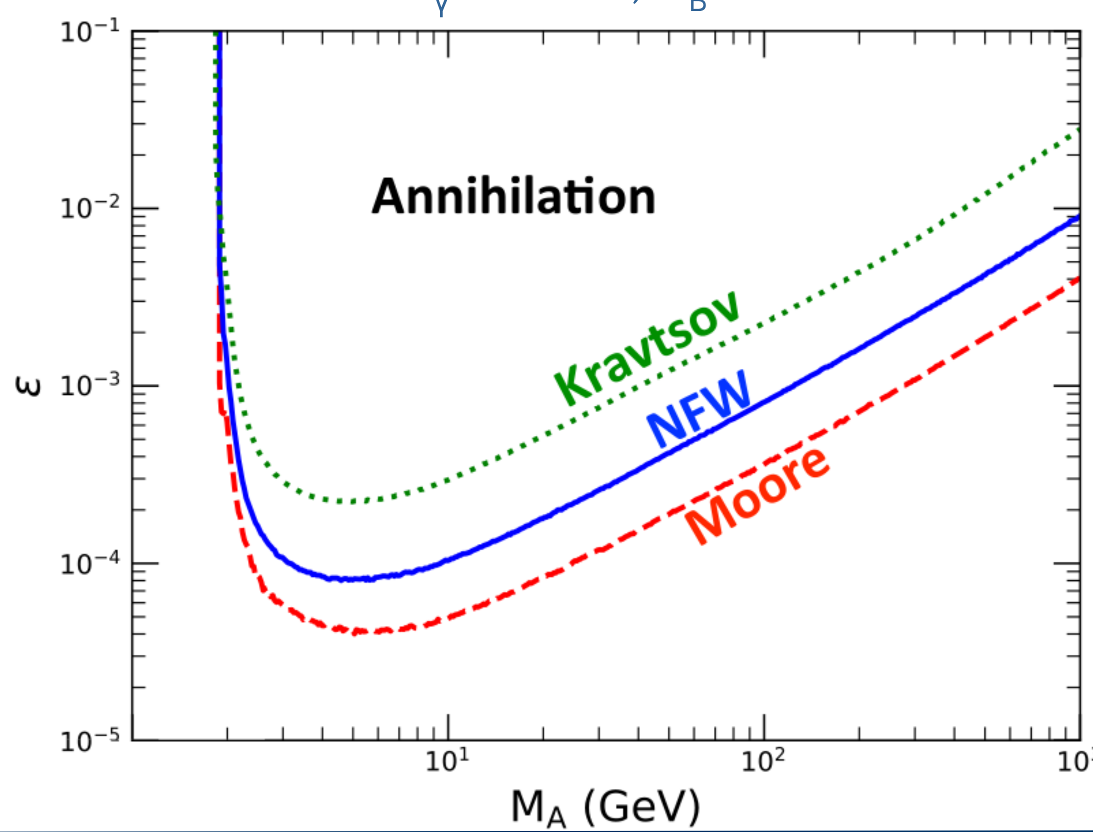
- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

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

→ **No clusters visible**



Limit for m_{γ}'=20 MeV, m_B=200MeV



Published results: Phys.Rev.Lett. 120 (2018) no.22, 221301

Summary

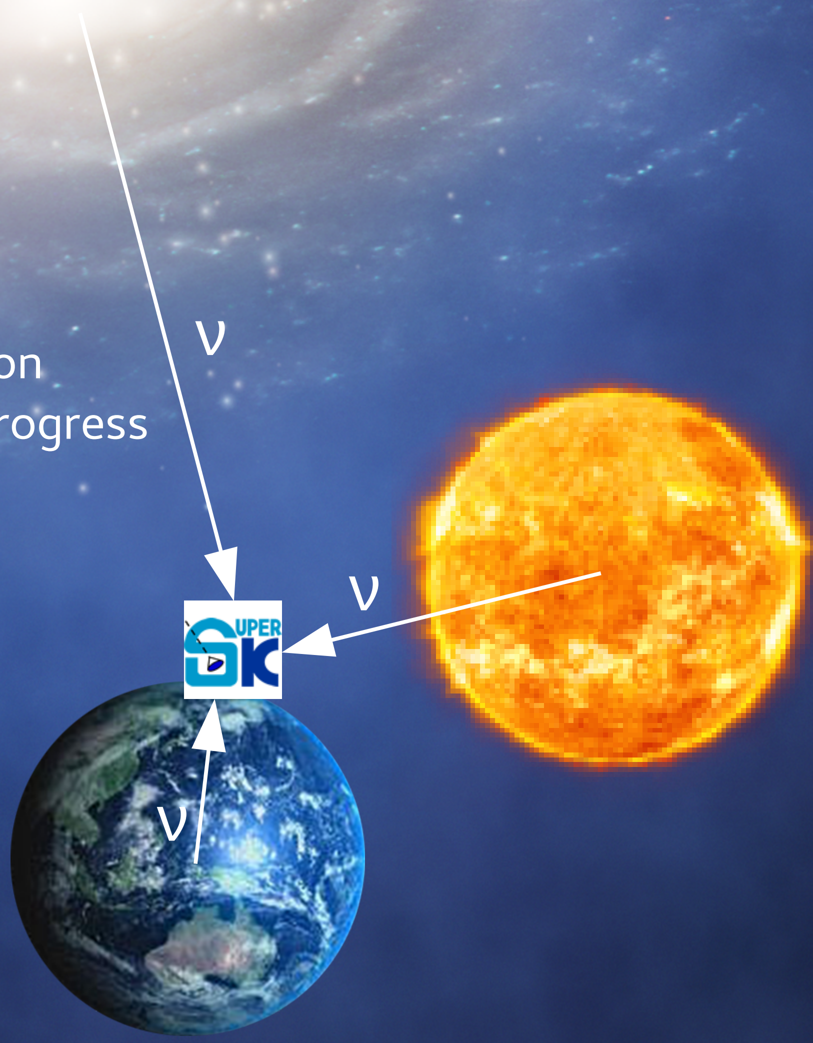
- **No excess of DM induced neutrinos has been observed at SK so far**

- **Galactic WIMP search**
  - upper limits on $<\sigma_A V>$ for wide range of WIMPs masses (1 GeV to 10 TeV) → paper in progress

- **Earth WIMP search**
  - upper limits on SI WIMP-nucleon scatteringcross-section
  - high sensitivity to resonant capture region → paper in progress

- **Solar WIMP search**
  - strong constrains for low WIMP masses
  - results published in 2015 (Phys. Rev. Lett. 114, 141301 (2015))

- **Boosted dark matter search**
  - alternative DM models can also be tested with the SK detector **(Phys.Rev.Lett. 120 (2018) no.22, 221301)**

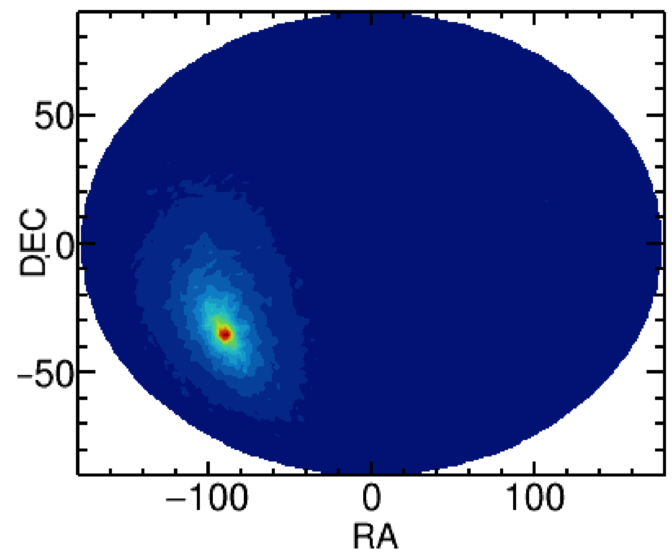


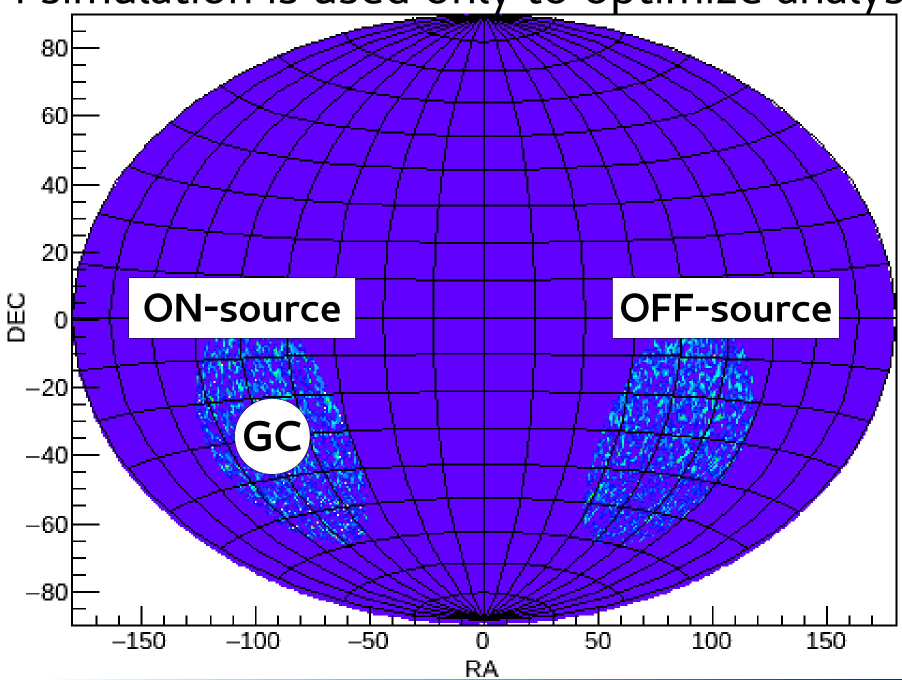
Analysis idea: ON-OFF source method

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

- analysis is performed in the equatorial coordinate system (RA, DEC) in which the expected signal is peaked and possible to distinguish from the atmospheric neutrino background
- Analysis uses on-source/off-source method to estimate the background directly from the data
  - method independent of MC simulations and related systematic uncertainties
- DM simulation is used only to optimize analysis

Expected flux of DM-induced ν's

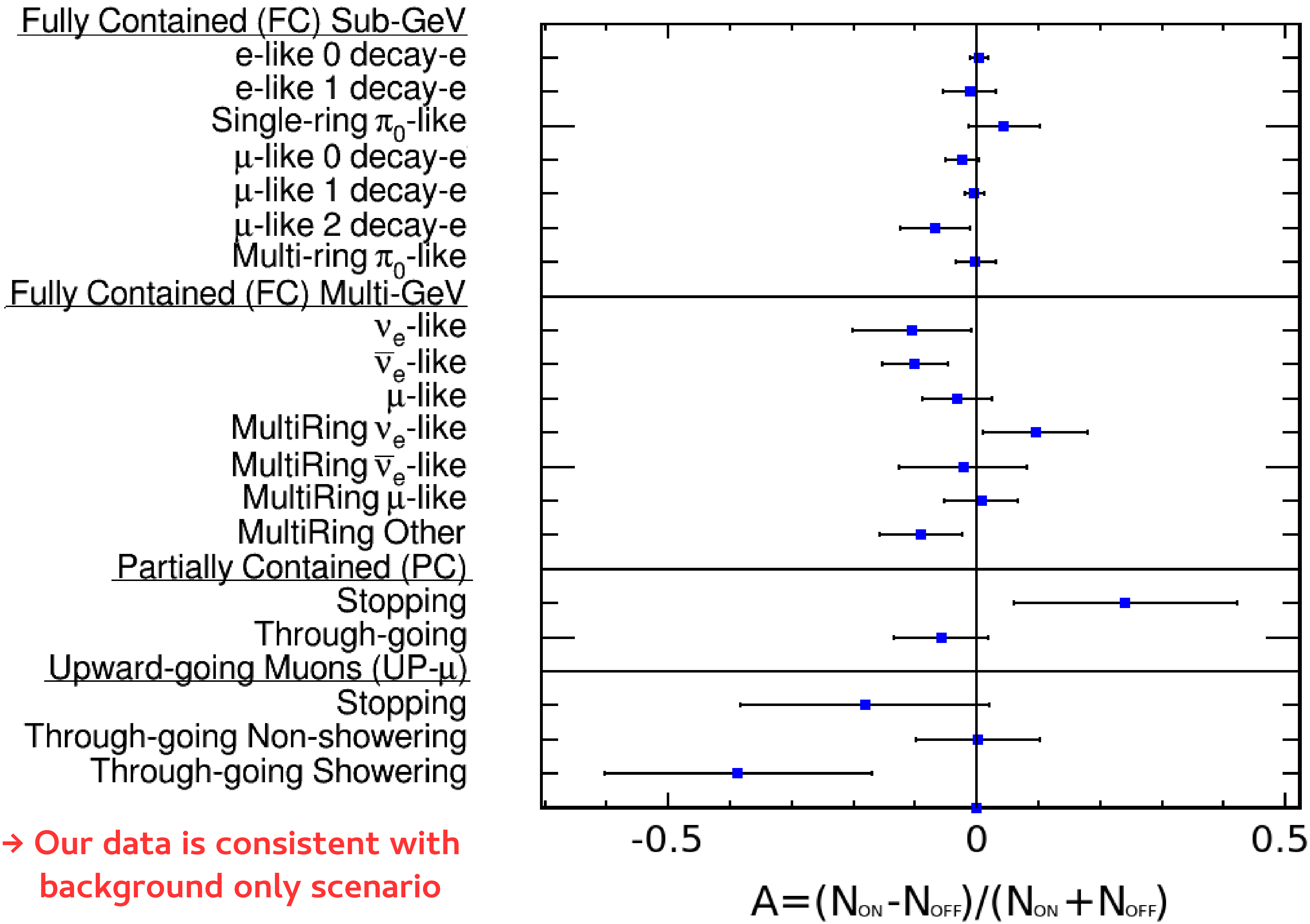




$$\Delta N = N_{ON} - N_{OFF}$$

$$\Delta N \propto \langle \sigma_A v \rangle$$

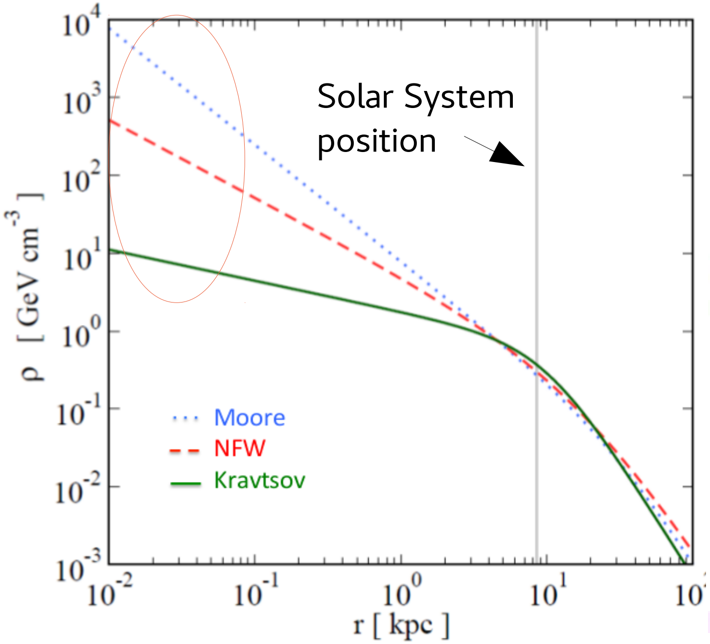
Asymmetry in observed number of events



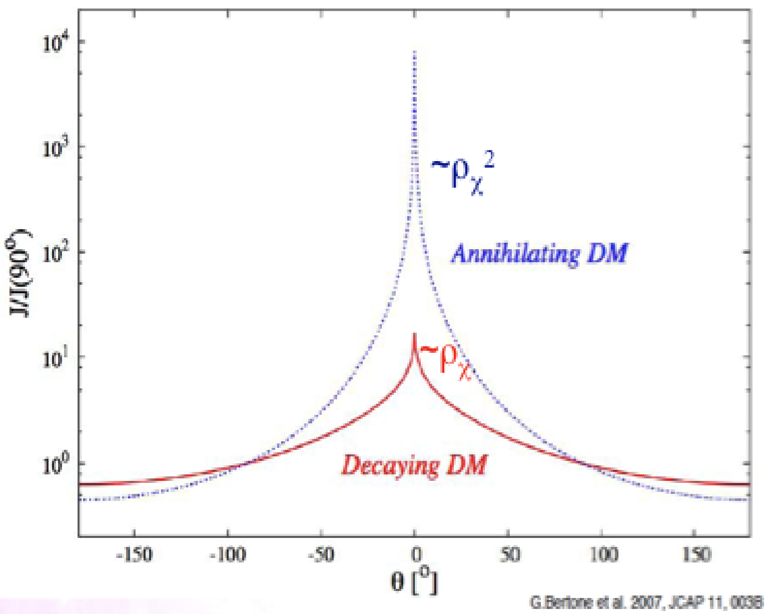
→ **Our data is consistent with background only scenario**

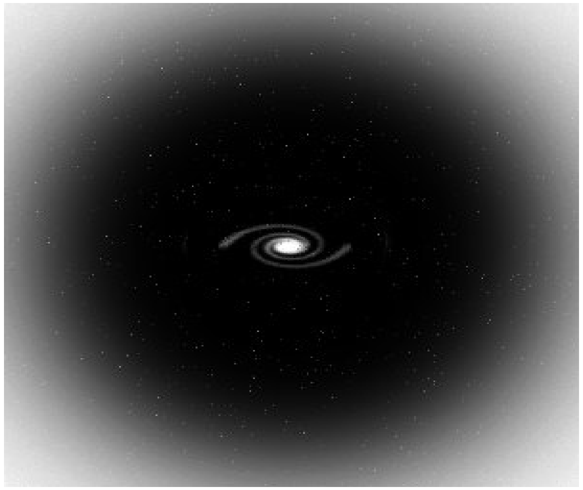
Dark Matter halo models

Dark Matter density



Expected DM intensity





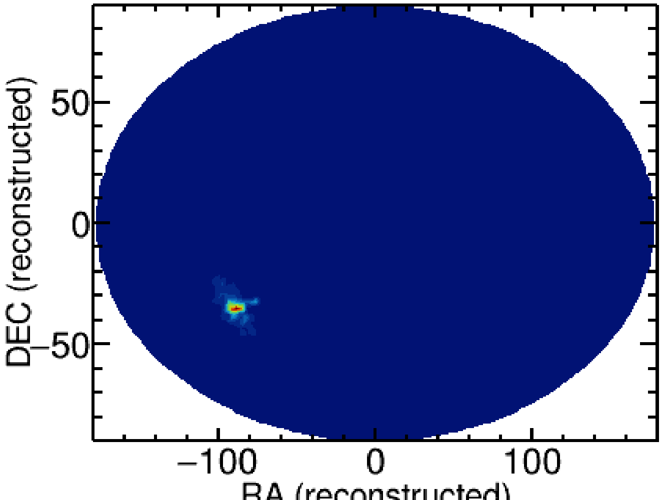
Local DM density

$$\rho_\chi \approx 0.389 \pm 0.025\,\mathrm{GeV\,cm^{-3}}$$

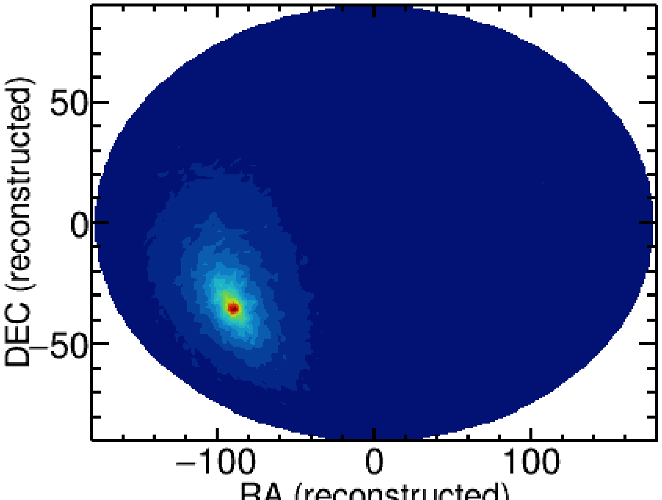
Expected local DM flux

$$\phi_\chi \sim 10^5\,\mathrm{cm^{-2}s^{-1}}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)$$

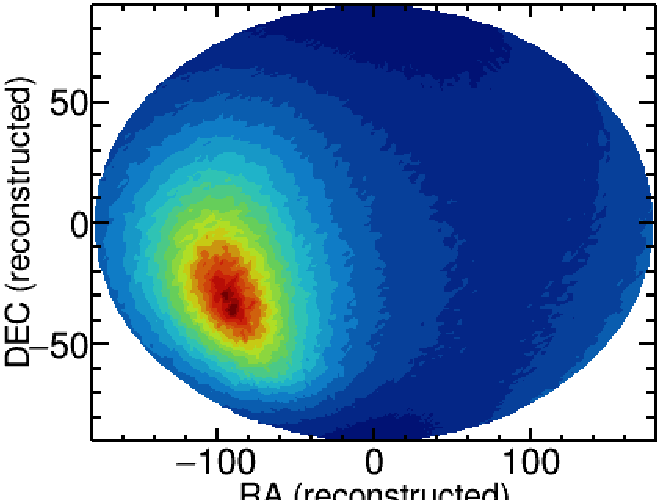
NFW



Moore



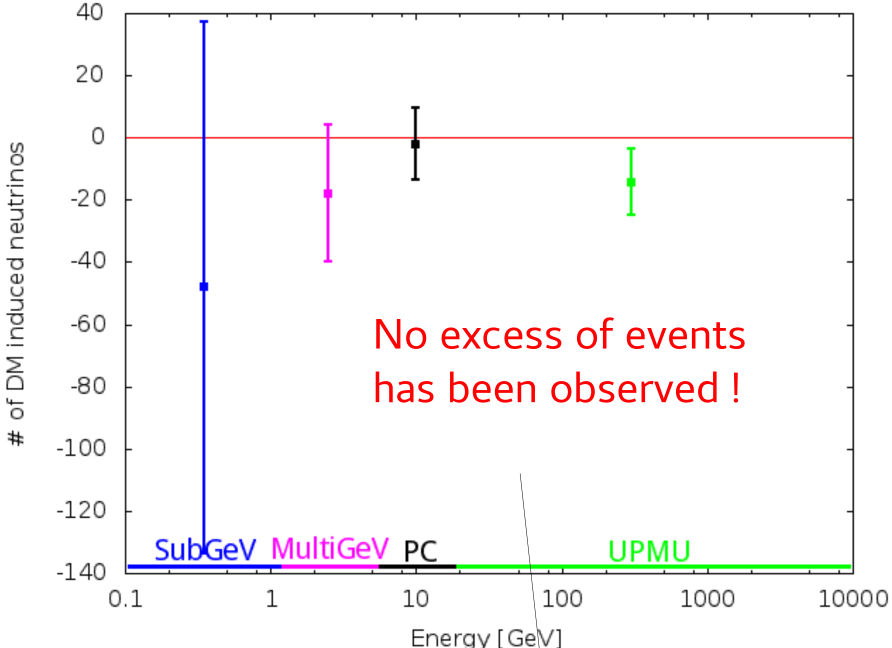
Kravtsov



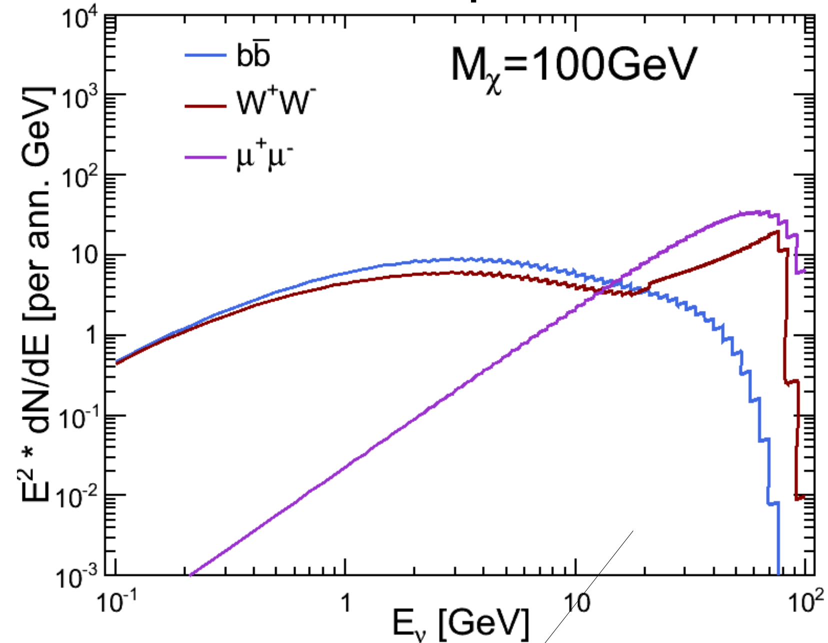
NFW – benchmark model

Moore & Kravtsov – extreme cases (to estimate the impact of halo model choice on the results)

Based on SK 1-4 data: ΔNsig → Φ



DarkSUSY: Example for 100 GeV

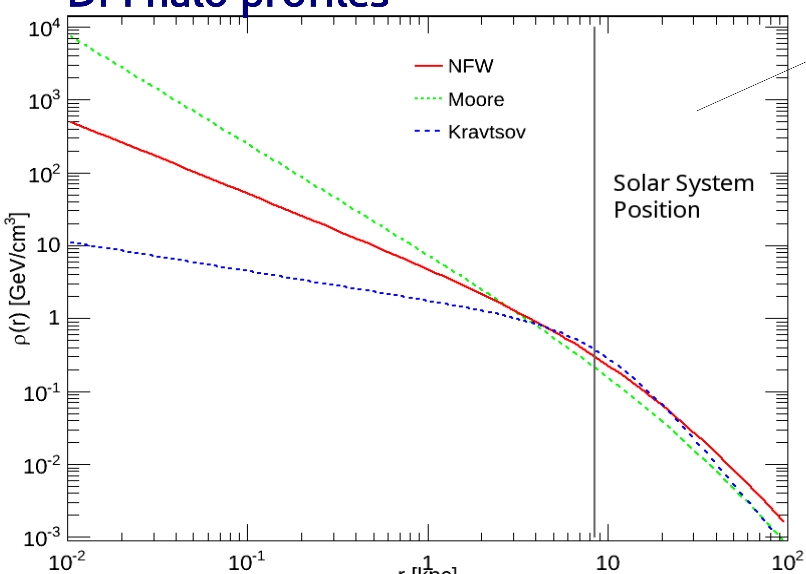


FOR WIMP ANNIHILATION:

$$\frac{d\Phi_{\Delta\Omega on}}{dE} - \frac{d\Phi_{\Delta\Omega off}}{dE} = \frac{\langle \sigma_A v \rangle}{2} \left(J_{\Delta\Omega on} - J_{\Delta\Omega off} \right) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

$\nu\bar{\nu}$, $b\bar{b}$, W^+W^-, $\mu^+\mu^-$ channels considered

DM halo profiles



Results interpretation:

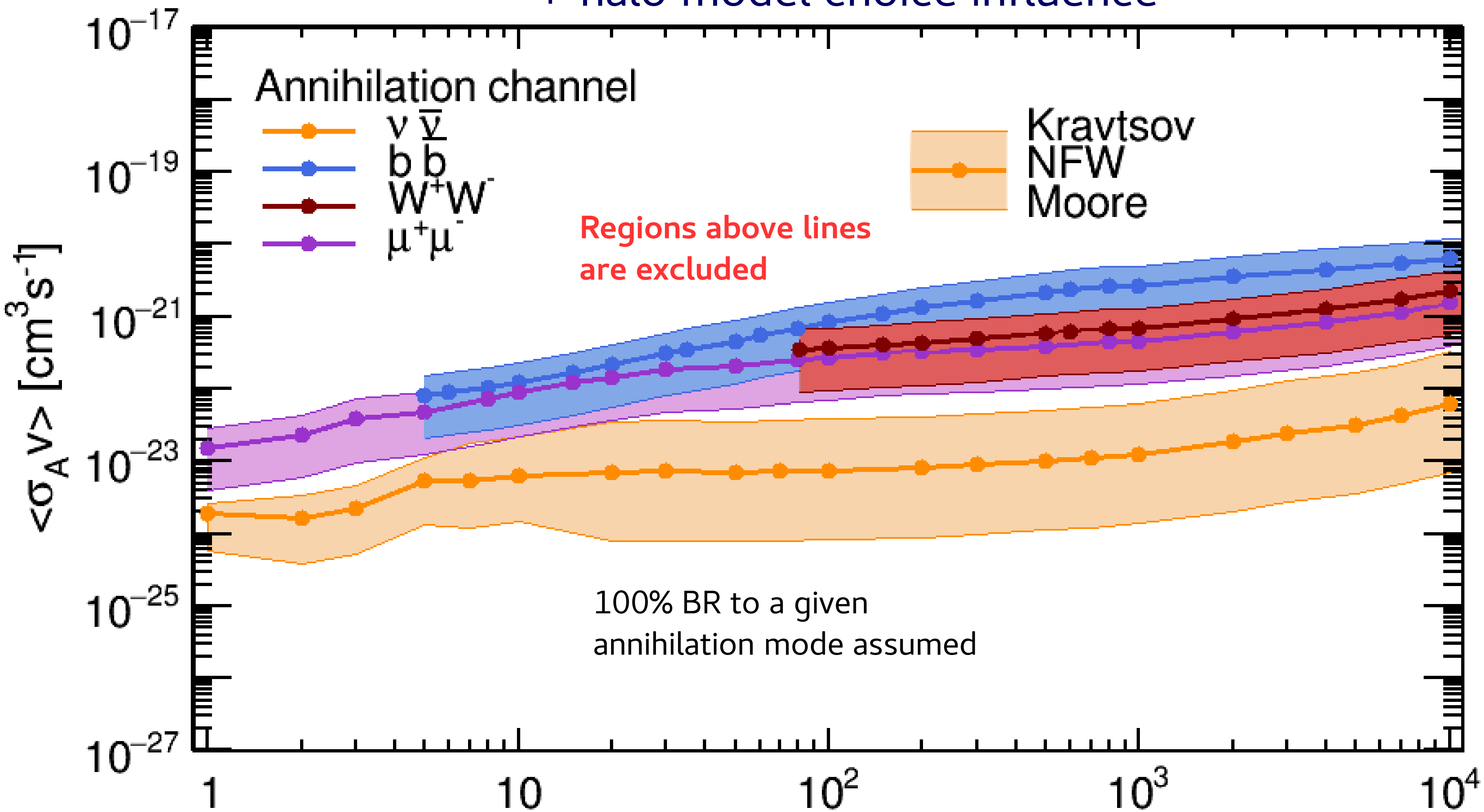
Based on constrains on neutrino flux for assumed

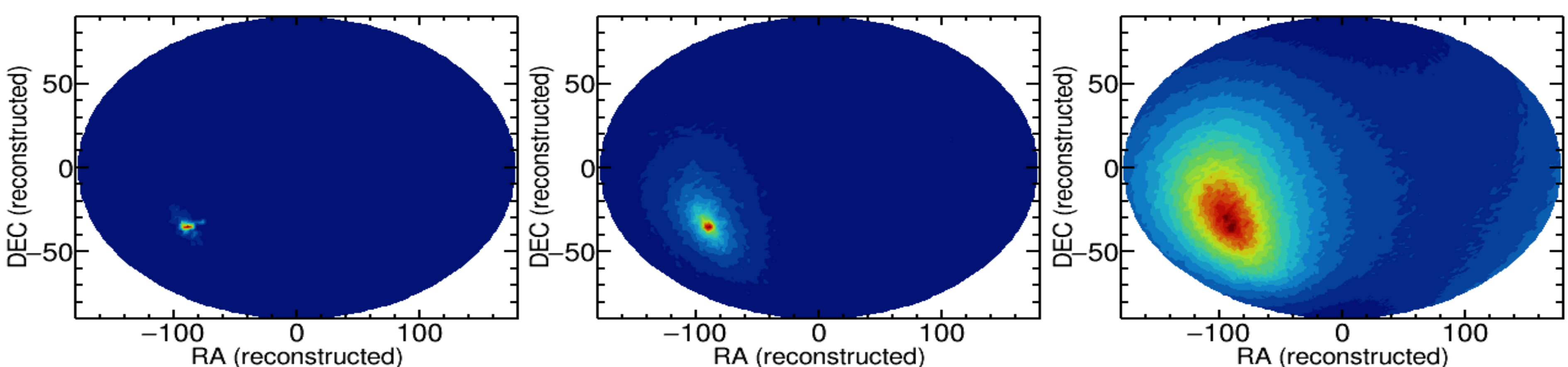
- WIMP mass
- annhilation channel
- halo model

we can calculate cross section for dark matter self-annihilation

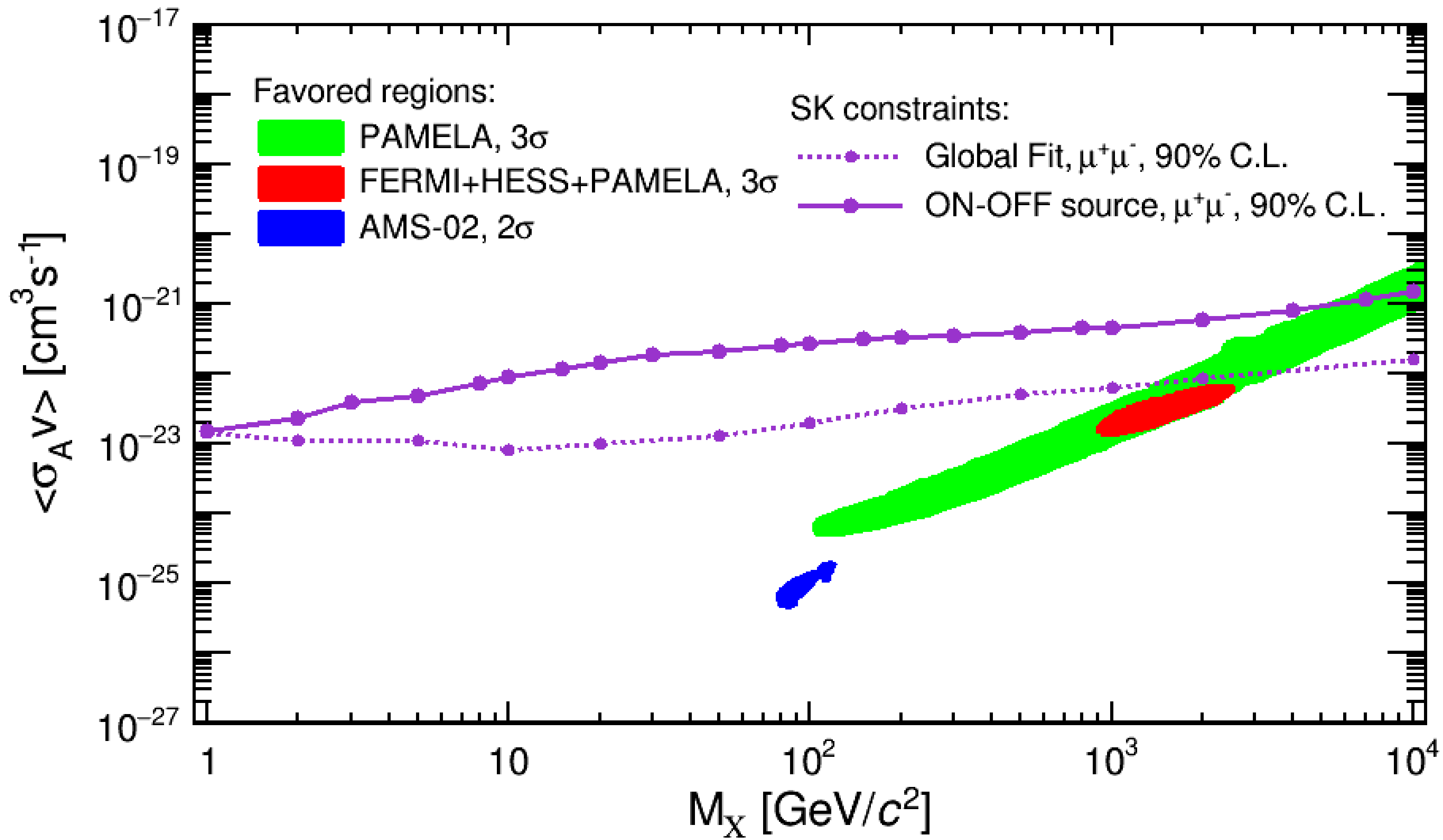
Results: 90% CL upper limits on dark matter self-annihilation cross-section

+ halo model choice influence



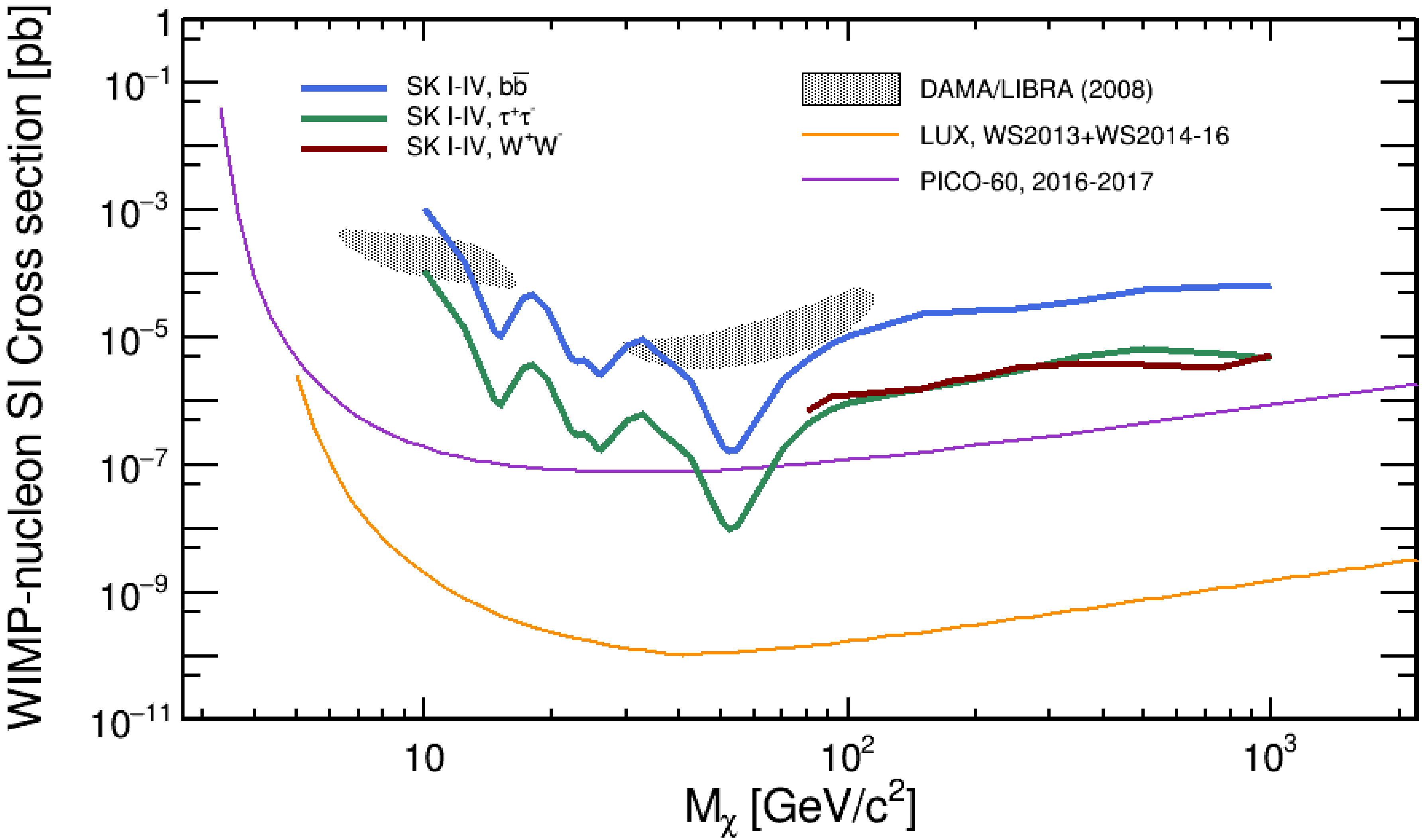


Galactic WIMP search – WIMP self-annihilation cross section



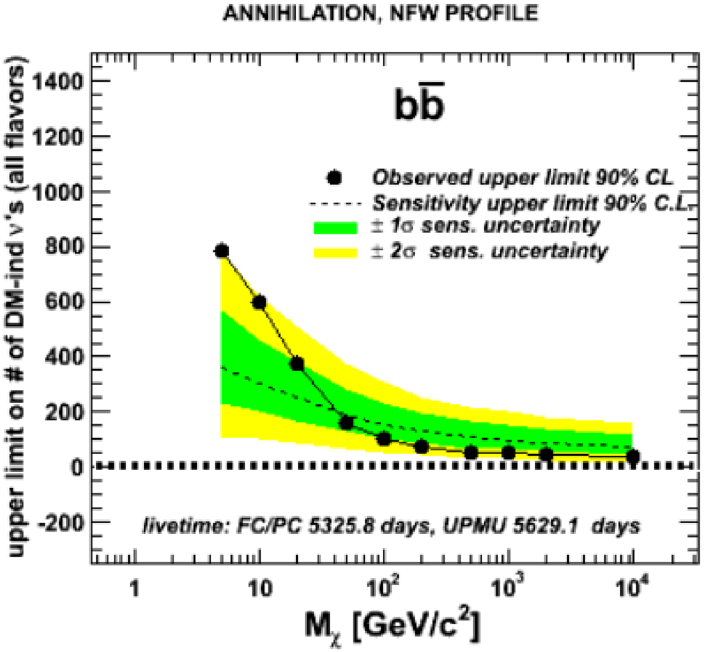
Earth WIMP search

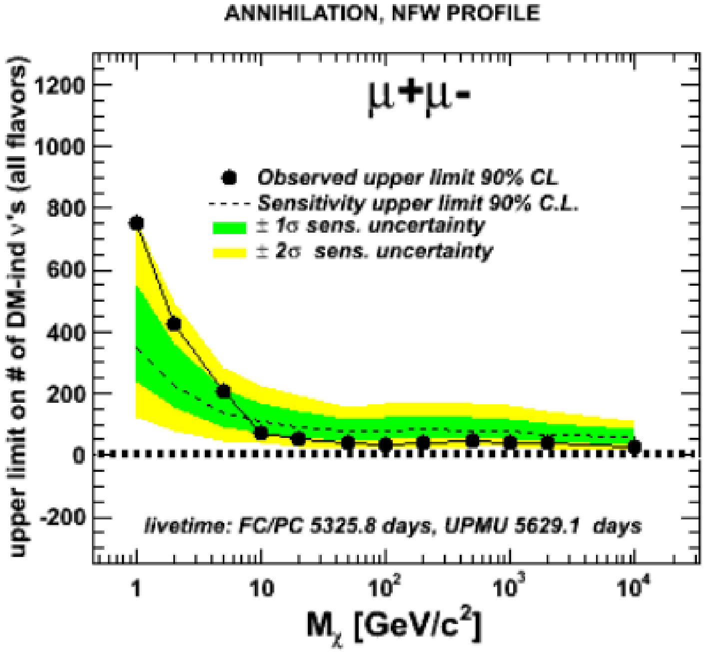
– WIMP-nucleon SI scattering cross-section limit

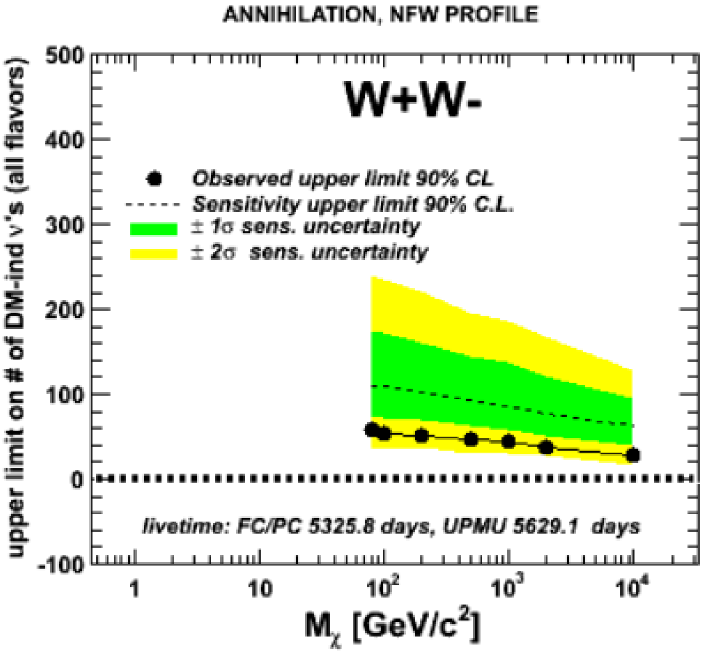


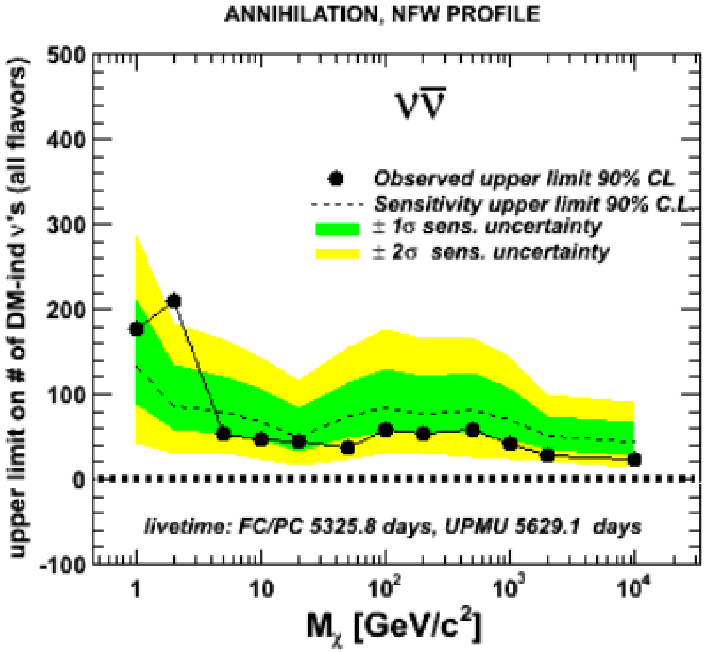
FIT result – brazil plot

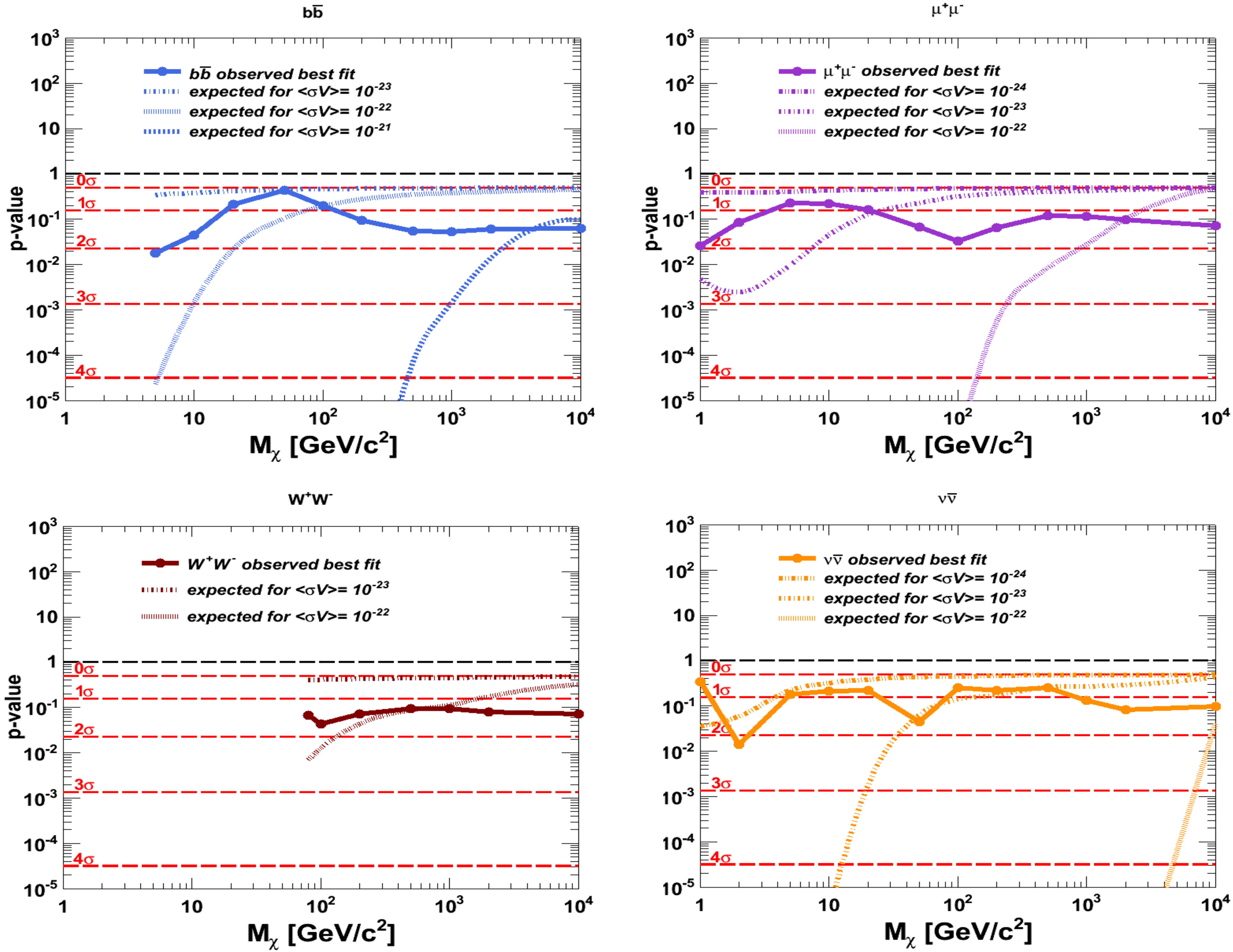
1200 TOY MCs





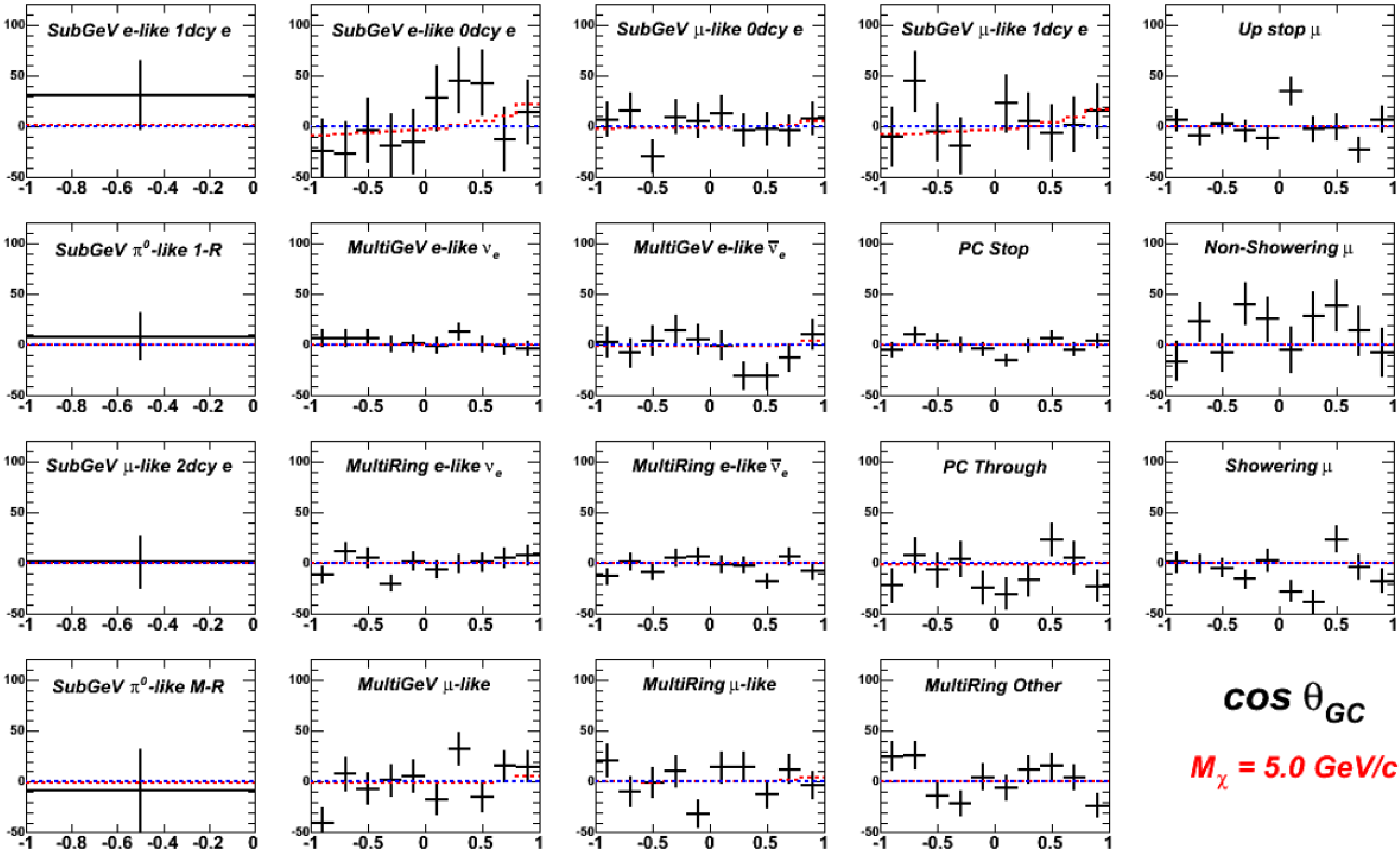






$b\bar{b}$
$b\bar{b}$ observed best fit
expected for <σV>= 10^{-23}
expected for <σV>= 10^{-22}
expected for <σV>= 10^{-21}
$\mu^+\mu^-$
$\mu^+\mu^-$ observed best fit
expected for <σV>= 10^{-24}
expected for <σV>= 10^{-23}
expected for <σV>= 10^{-22}
W^+W^-
W^+W^- observed best fit
expected for <σV>= 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

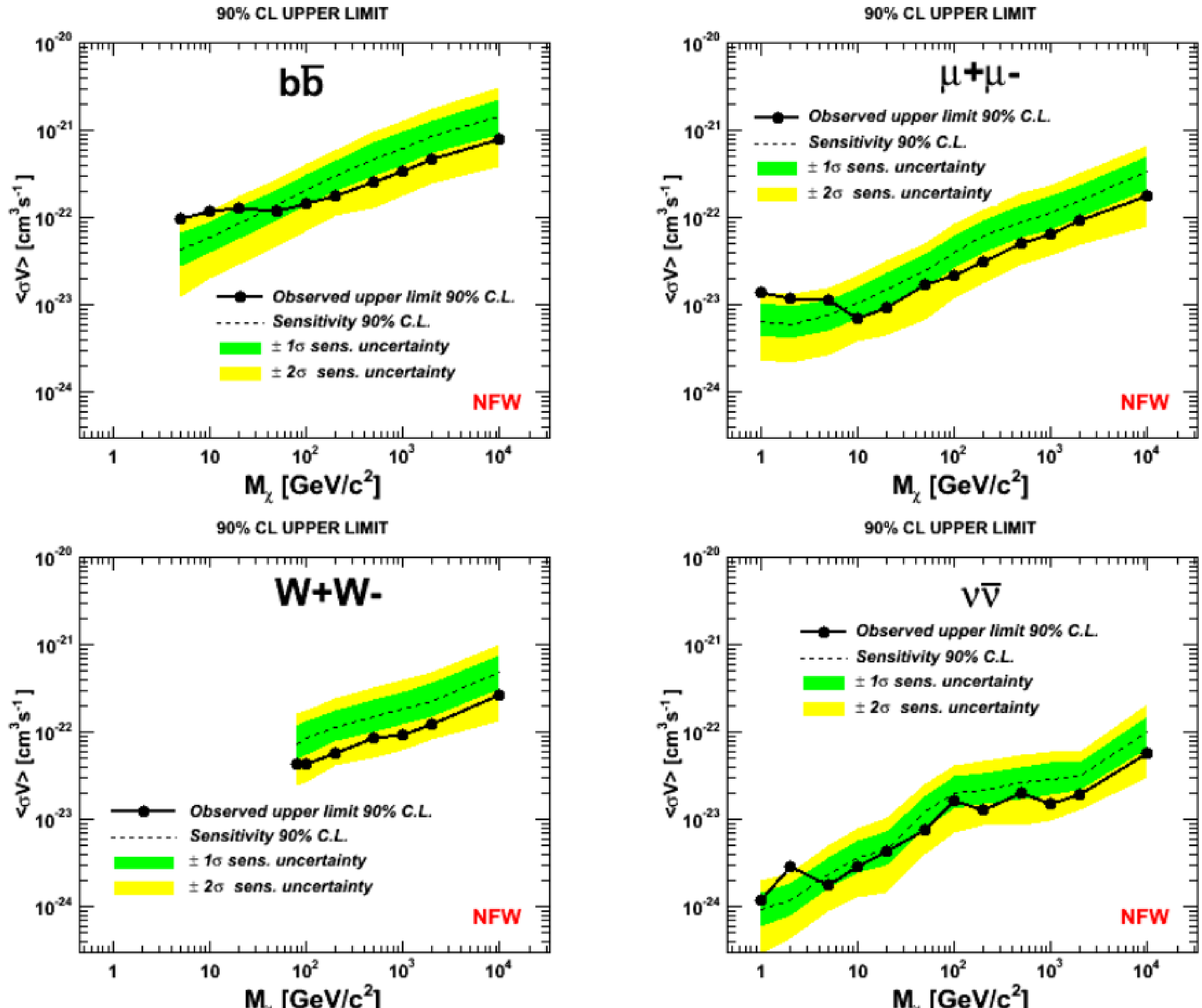


points: TOY MC data set blue line: ATM MC (with pulls) red dashed line: best fitted signal with ATM MC (all with pulls)

$\chi2_{total} = \chi2_{data} + \chi2_{syst}$ 604.0 = 566.9+37.0 601.6= 564.9+36.7 $\Delta\chi2$ = 2.4 = 2.0 + 0.4

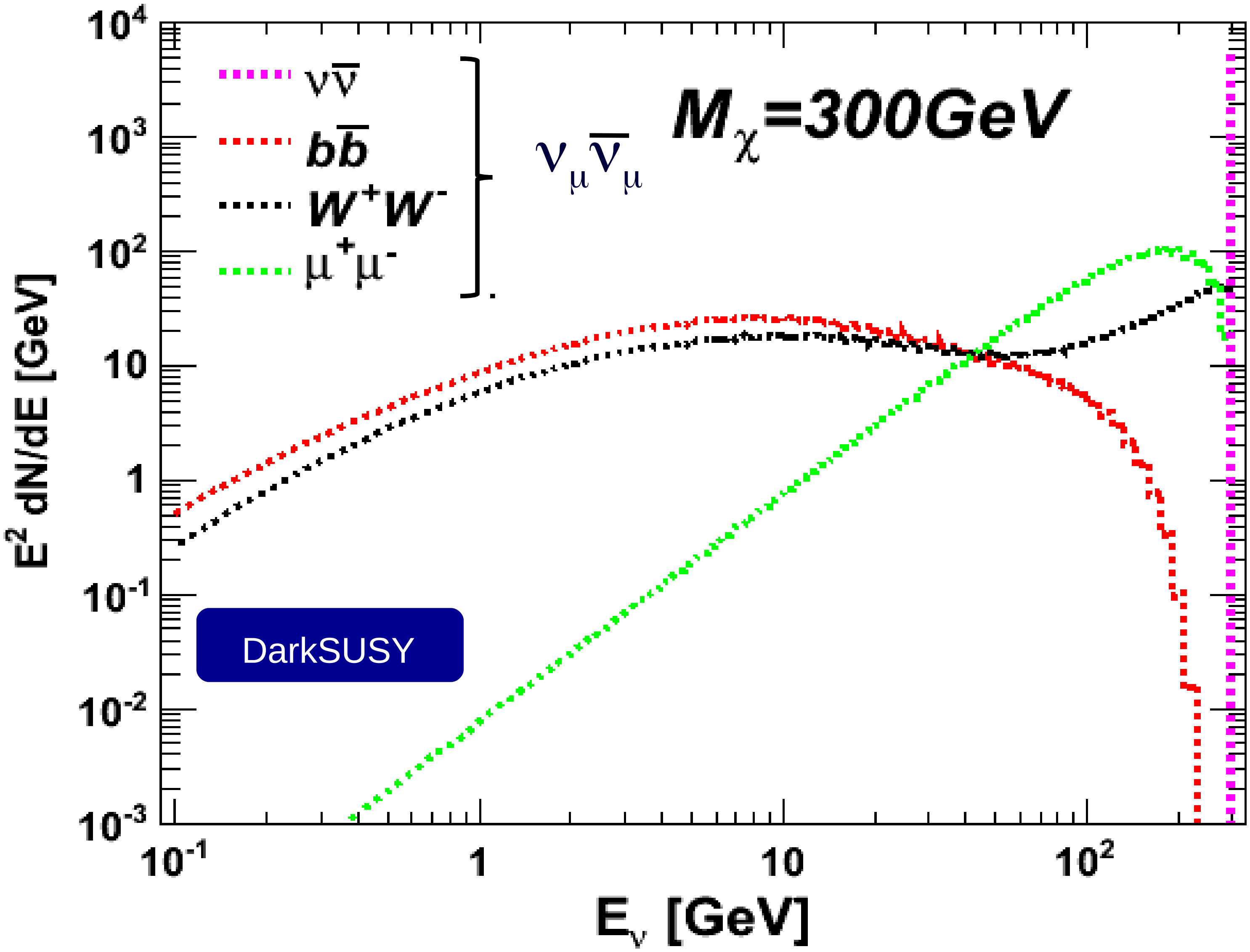
<σV> limit – brazil plot

1200 TOY MCs

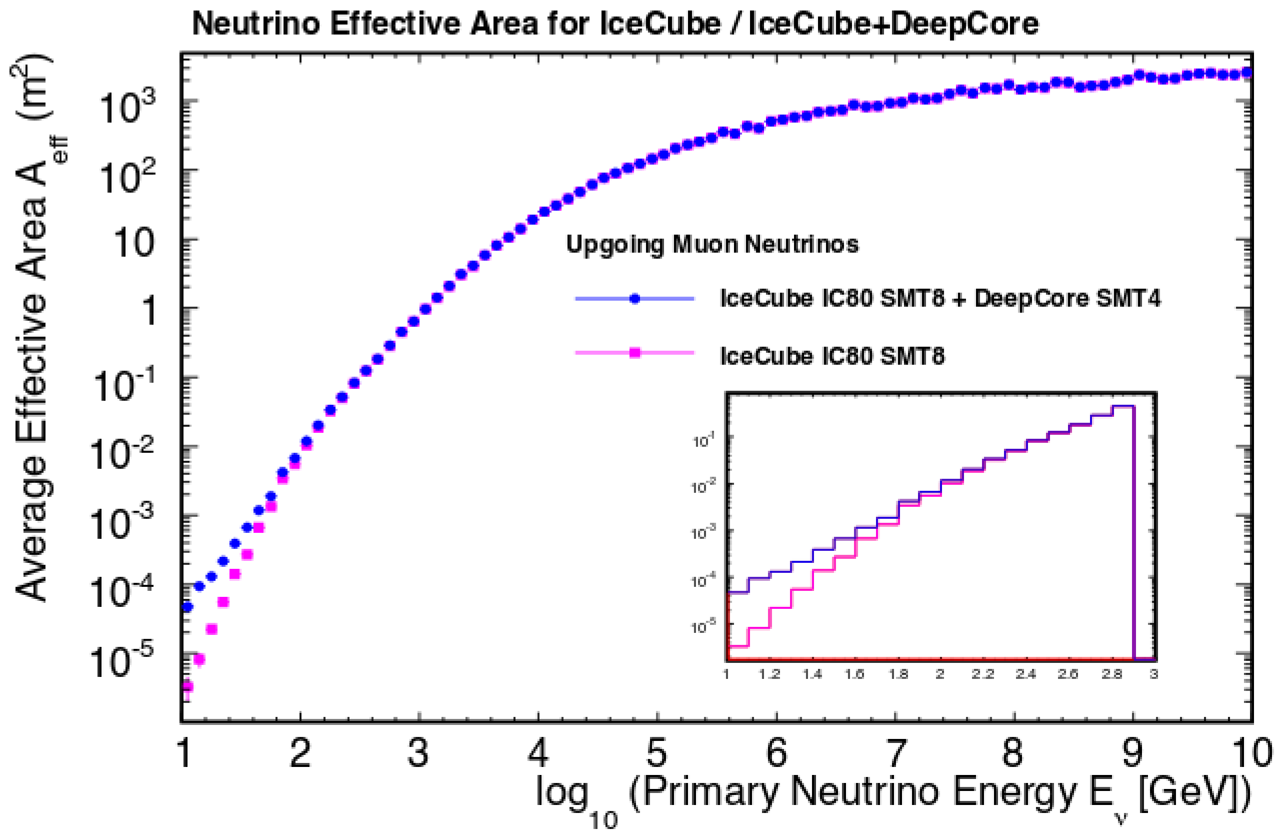


DM-induced neutrino signal

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



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:

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

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

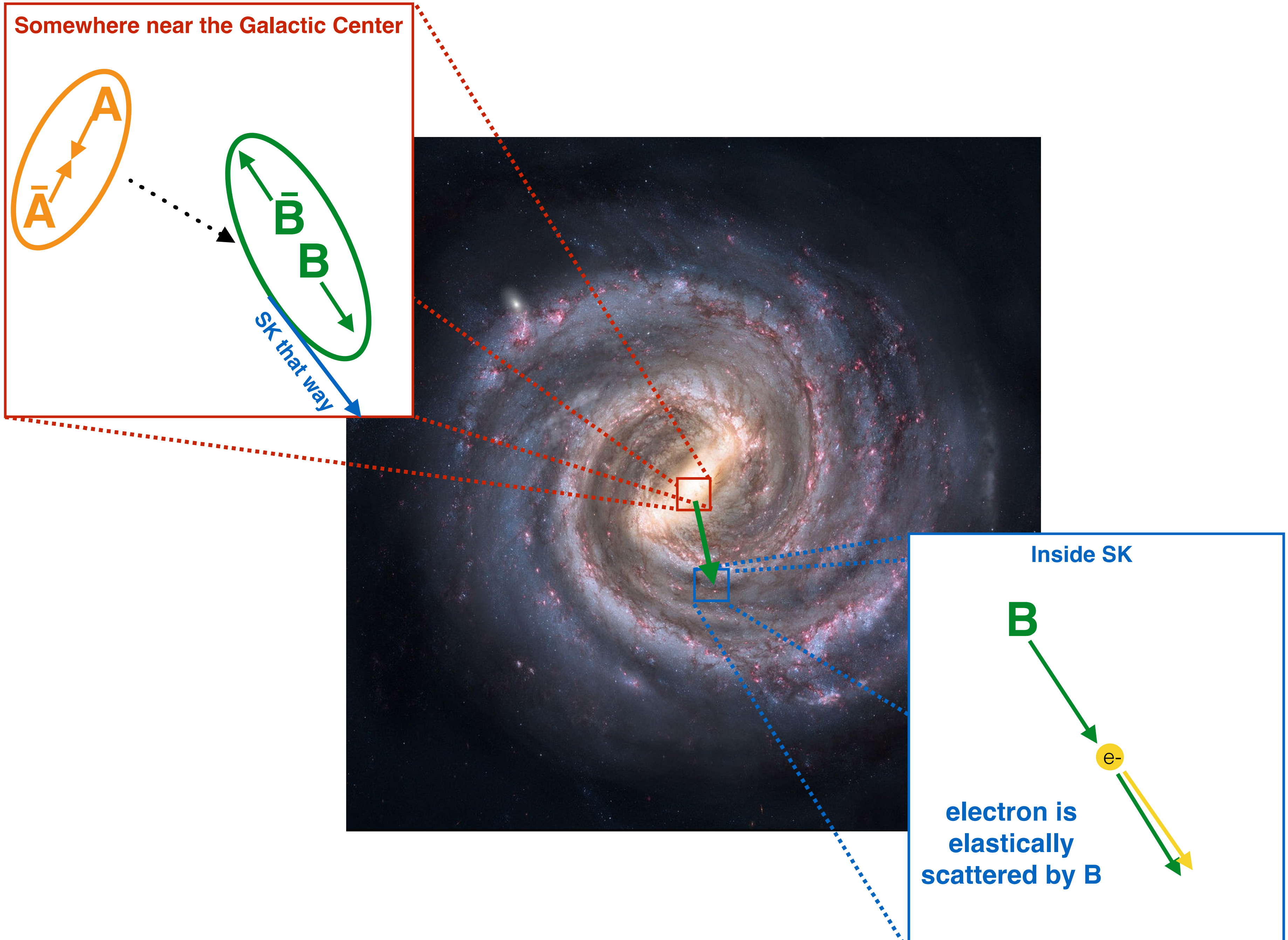
Livetime:
IceCube 327 days
SK FC/PC 5325.8, UPMU 5629.2

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

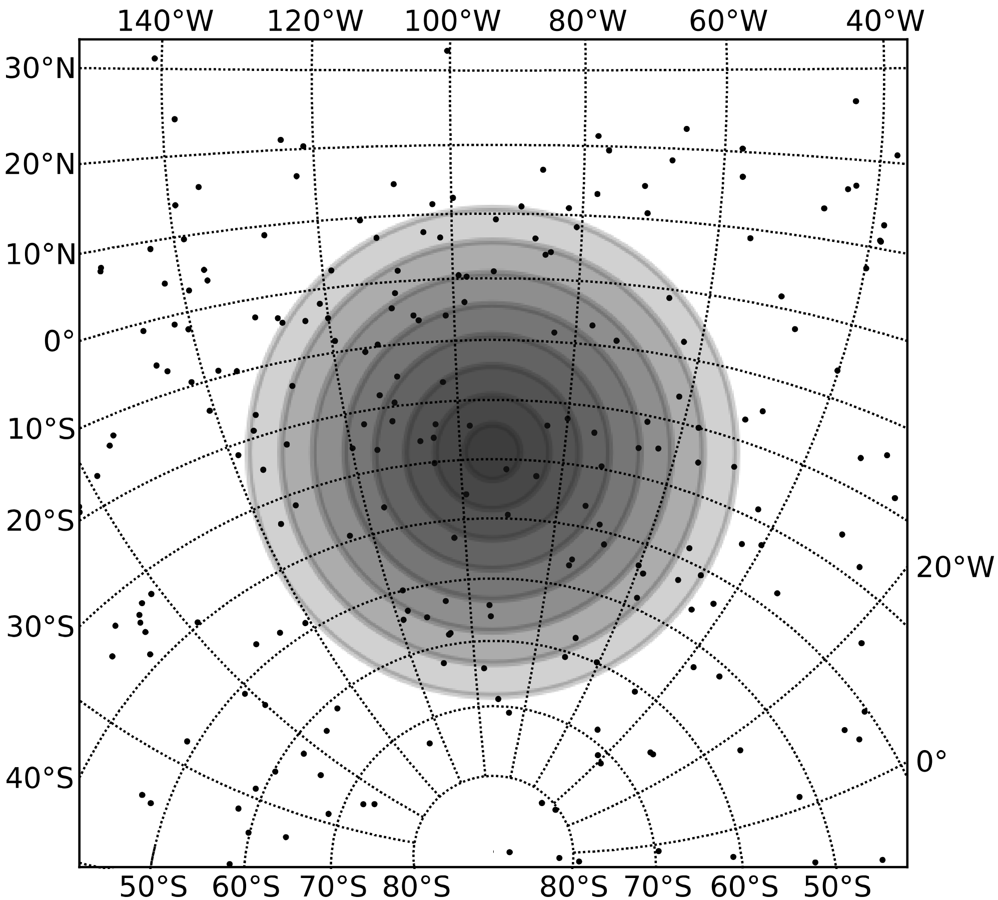
*evis>30 MeV
amome>100 MeV

4 Simple Cuts

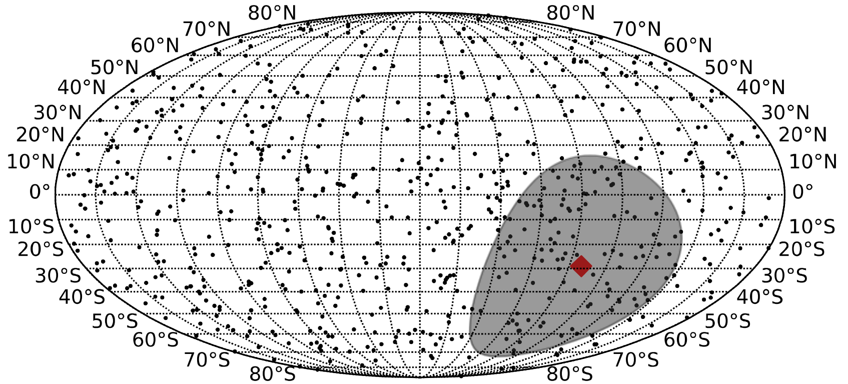
Total Data Events (Sep 16)

	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