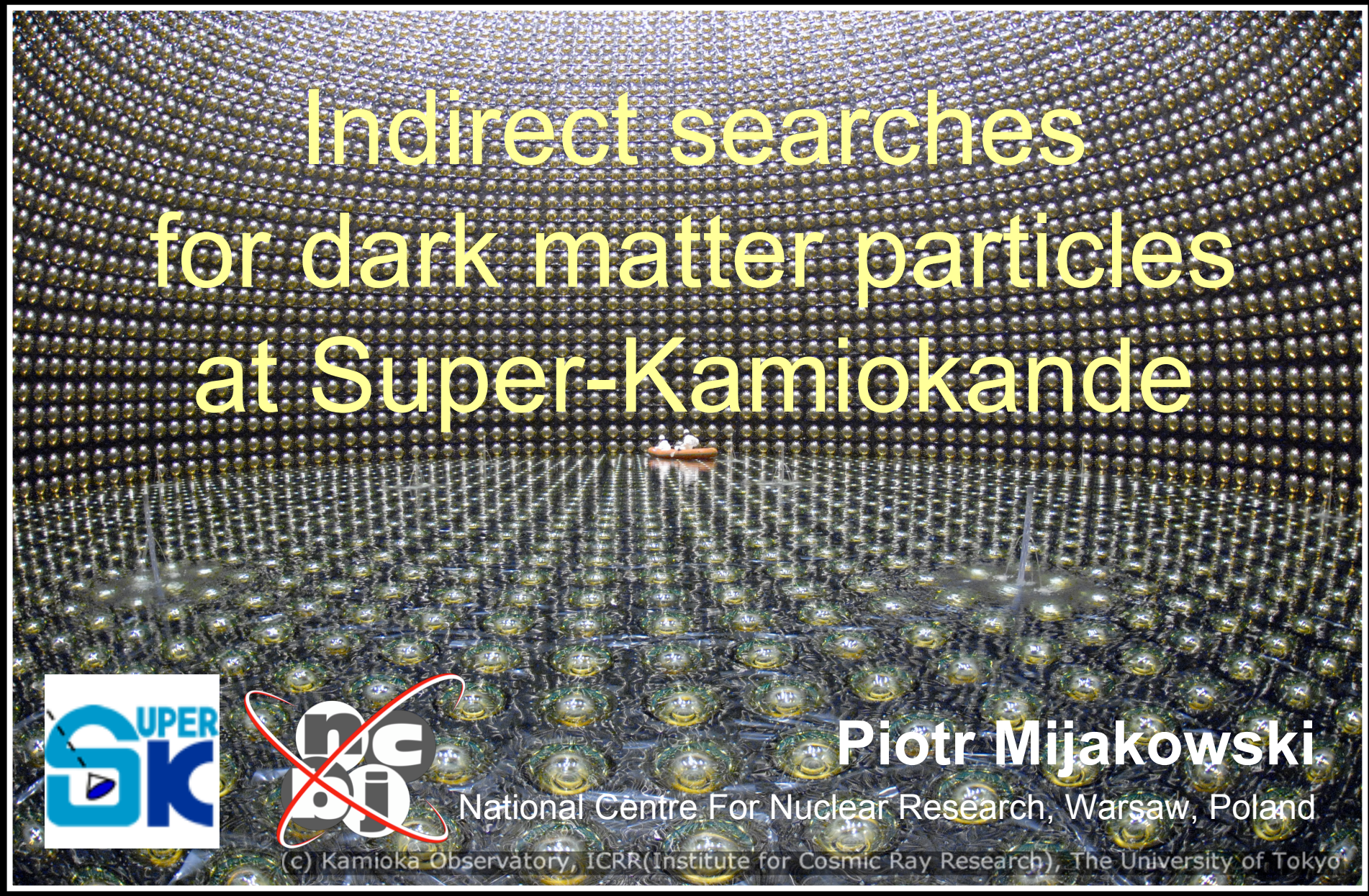
XIV International Conference on Topics in Astroparticle and Underground Physics
7-11 September 2015, Turin



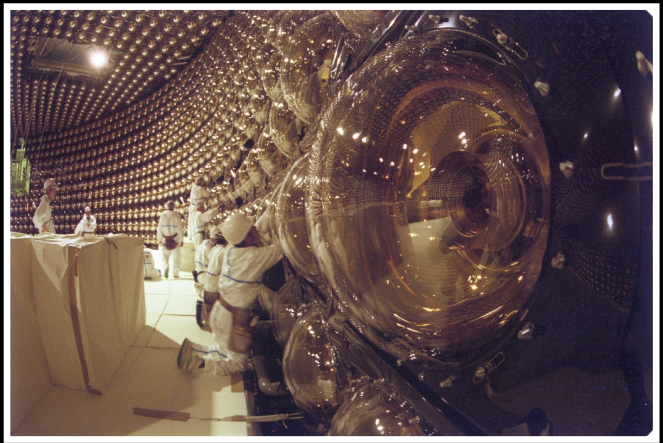
Indirect searches for dark matter particles at Super-Kamiokande

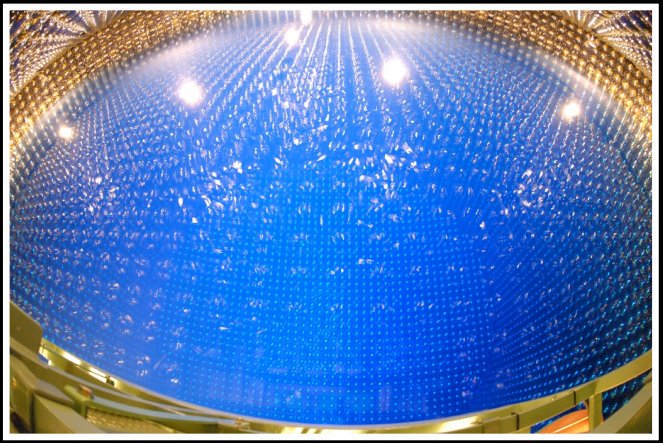
Piotr Mijakowski
National Centre For Nuclear Research, Warsaw, Poland

OUTLINE

- Super-Kamiokande
- Indirect Dark Matter searches for neutrinos from:

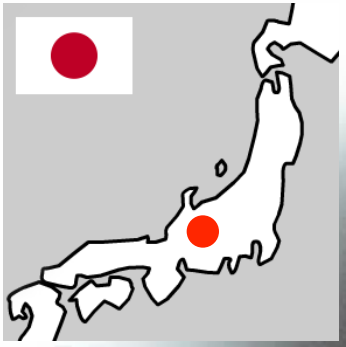
1. SUN
2. Milky Way: global fit
3. Milky Way: ON- & OFF-source

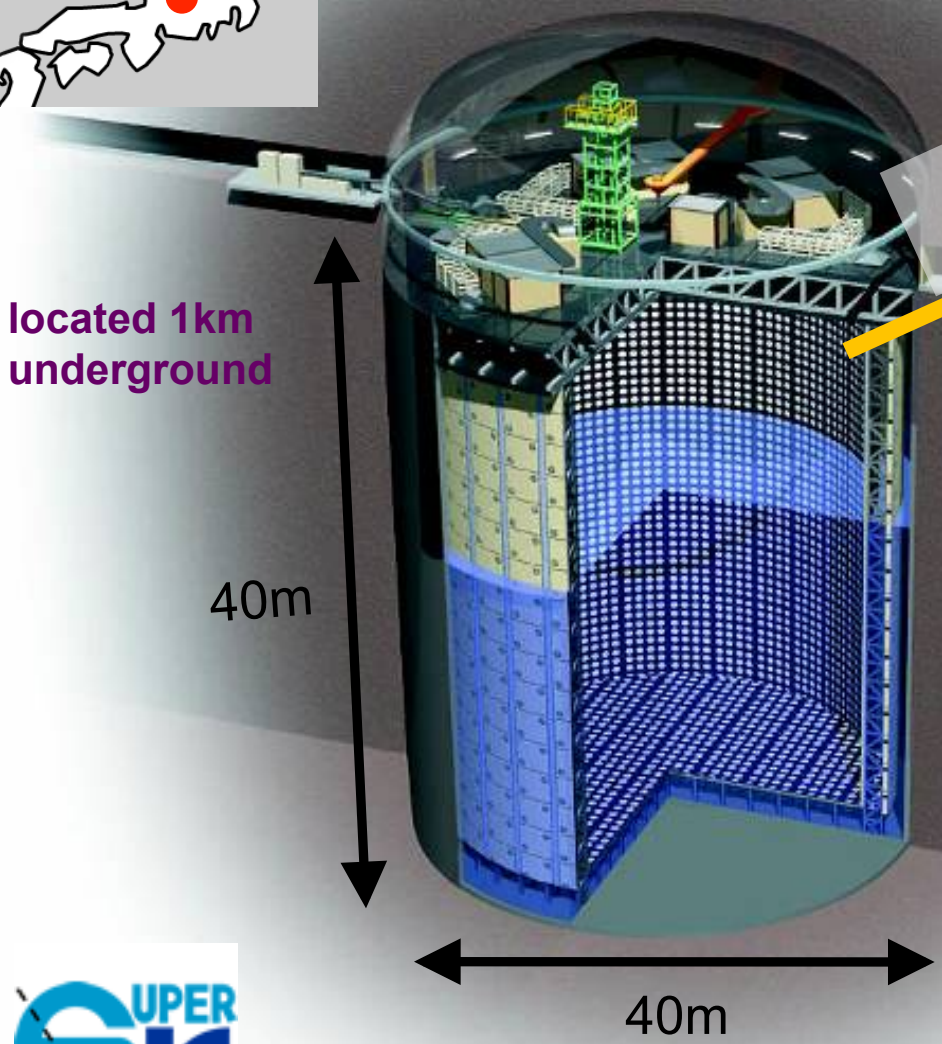




Super-Kamiokande

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

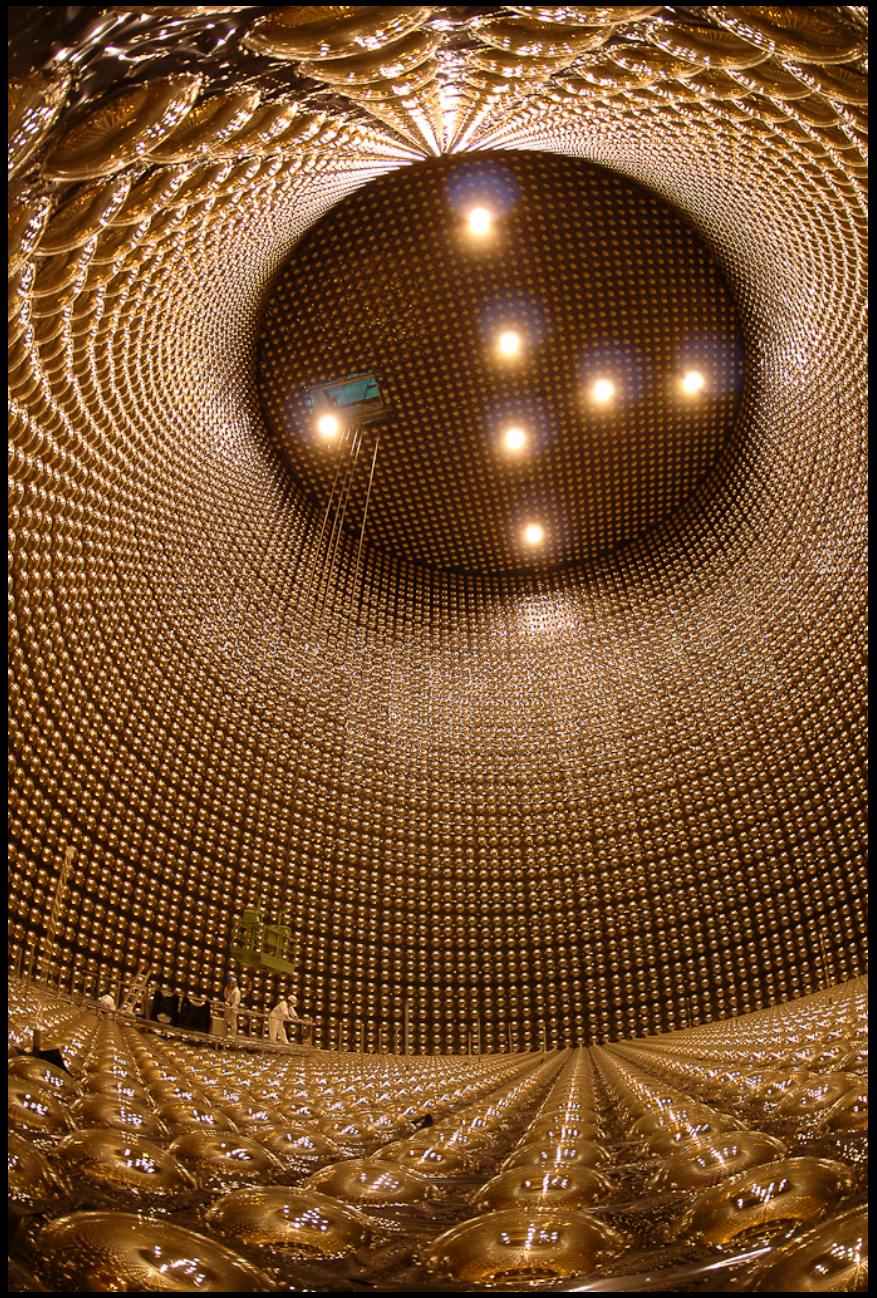




located 1km underground

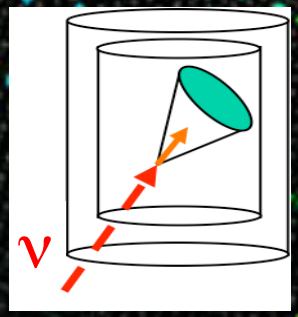
photomultipliers (PMTs) detect Cherenkov light

- 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
- Far detector of **T2K**



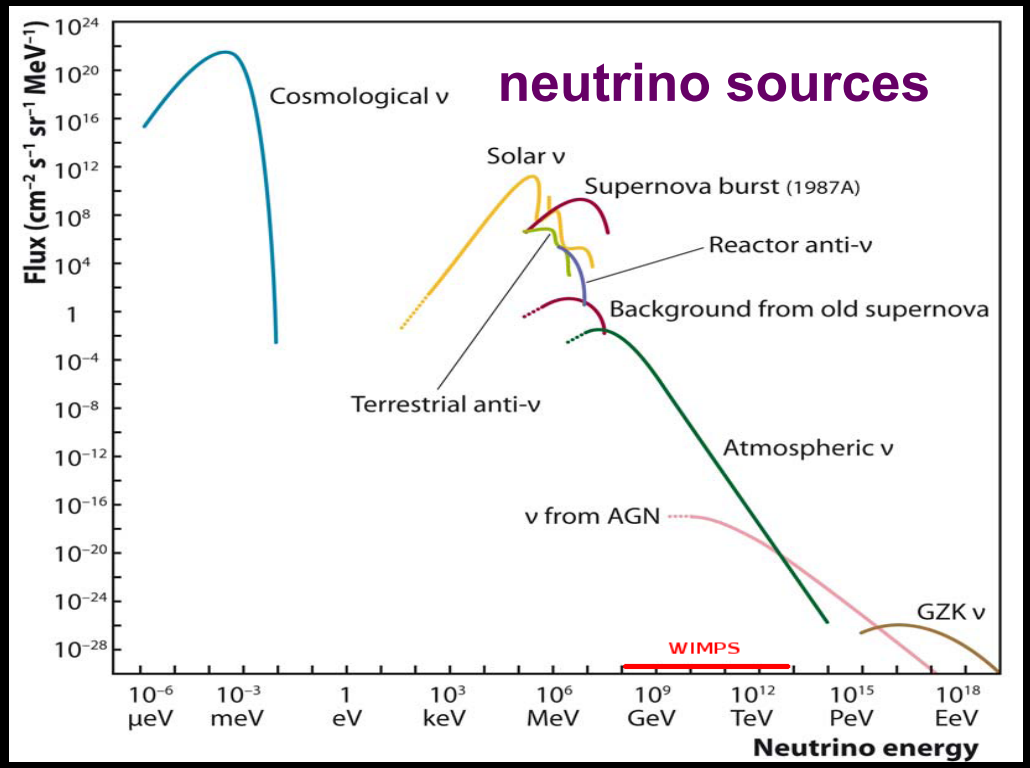
Detected Cherenkov light allows for reconstruction of:

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

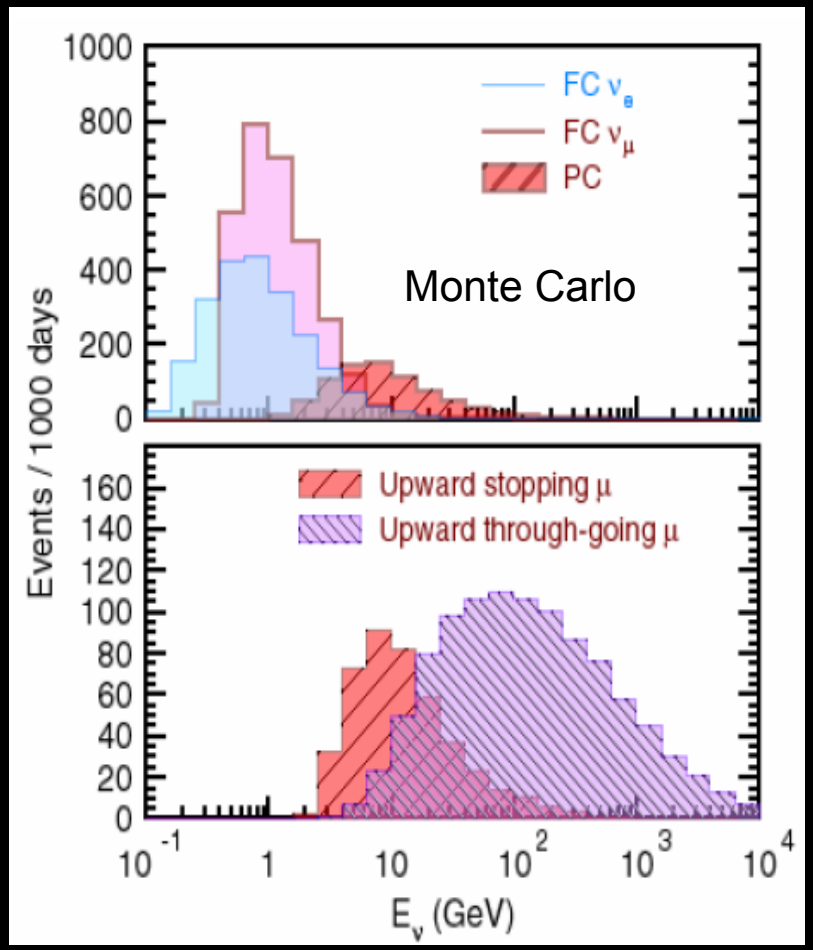


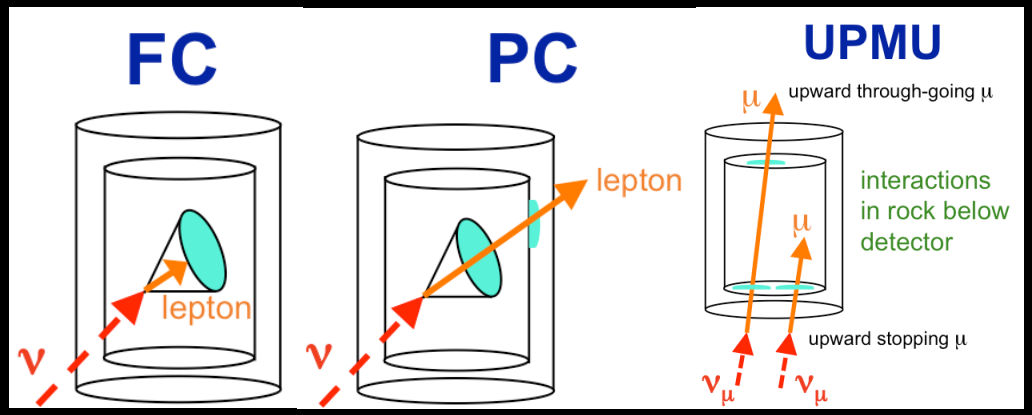
$$\nu_e + N \rightarrow e^- + N'$$

Atmospheric neutrinos: main background in DM-induced ν searches



atmospheric neutrinos at SK



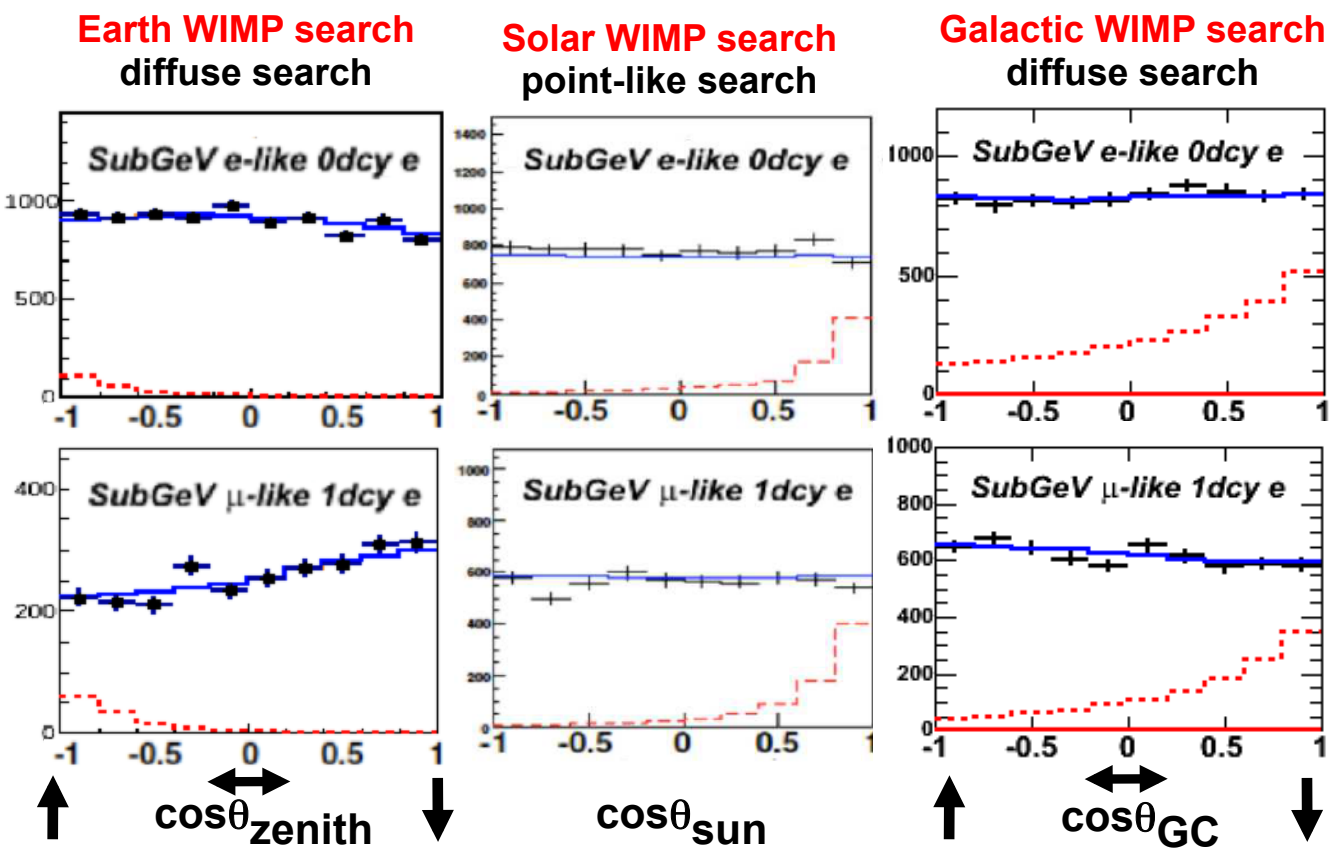


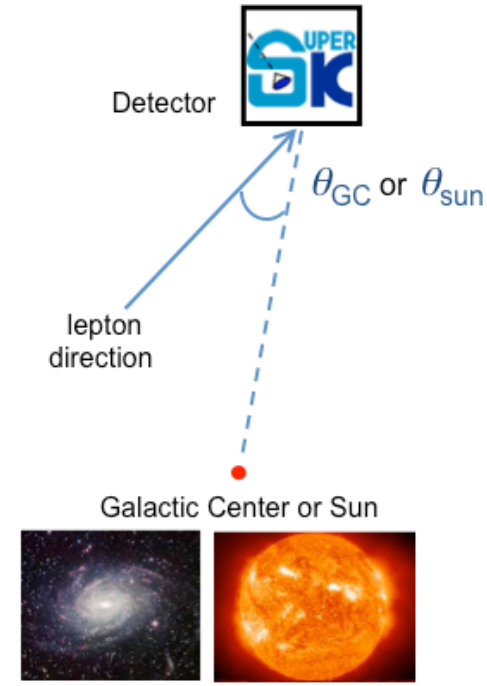
~10 events/day

~40k evts collected 1996-2014

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





Example: $b\bar{b}$ signal before fit shown in 2 data samples

SK DATA

ATM MC (BKG) with oscillations

DM signal shape enhanced for illustration

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

Analysis steps

1 **Simulate DM signal before detection → DarkSUSY & WimpSim**

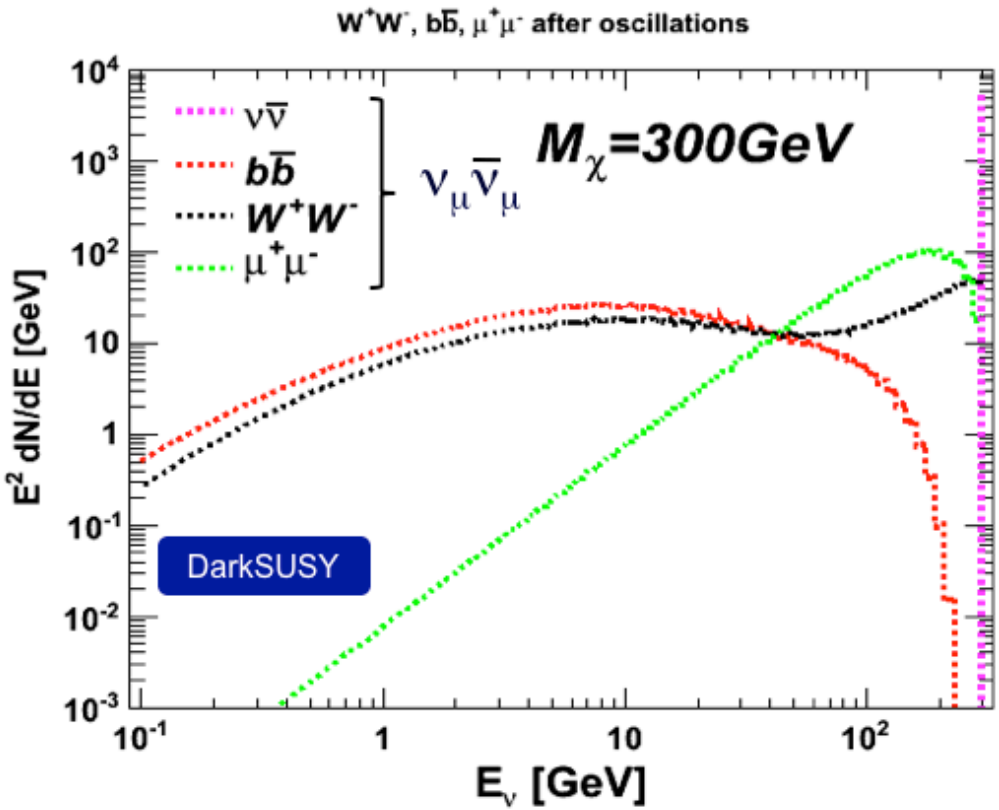
P. Gondolo et al., JCAP 07, 008 (2004)
M. Blennow et al., arXiv: 0709.3898 (2008)

2 Simulate detector response in outgoing lepton momentum and $\cos\theta_{GC}$ or $\cos\theta_{SUN}$

3 FIT signal + bkg to DATA with constrains from systematic uncertainties

EXAMPLE: Galactic search

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



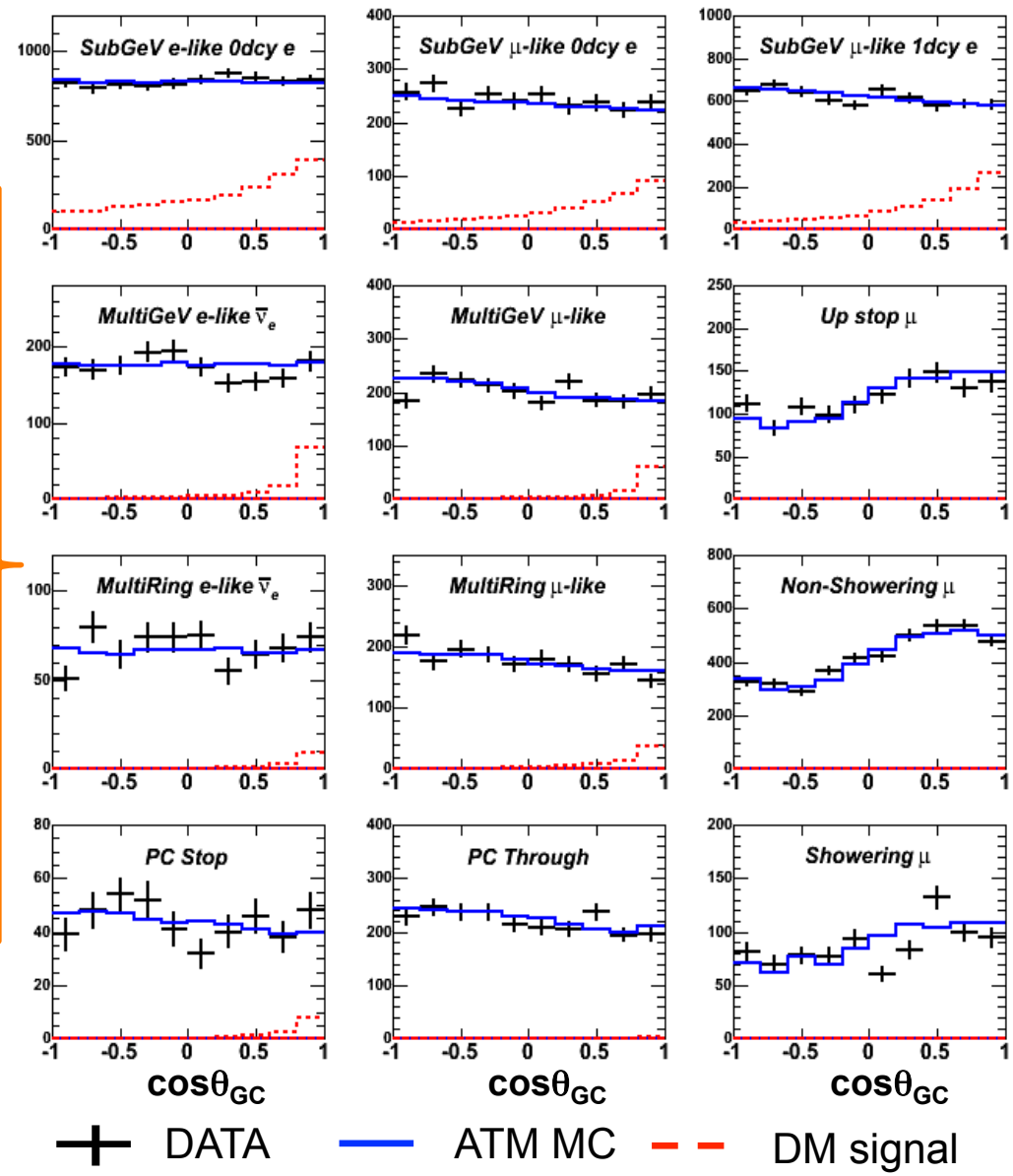
Analysis steps

EXAMPLE: Galactic search
5GeV WIMPs from GC, $b\bar{b}$ ann. channel

1 Simulate DM signal before detection → DarkSUSY & WimpSim

2 **Simulate detector response in outgoing lepton momentum and $\cos\theta_{GC}$ or $\cos\theta_{SUN}$**

3 FIT signal + bkg to DATA with constrains from systematic uncertainties



→ **proportions of signal in various samples are reflected**

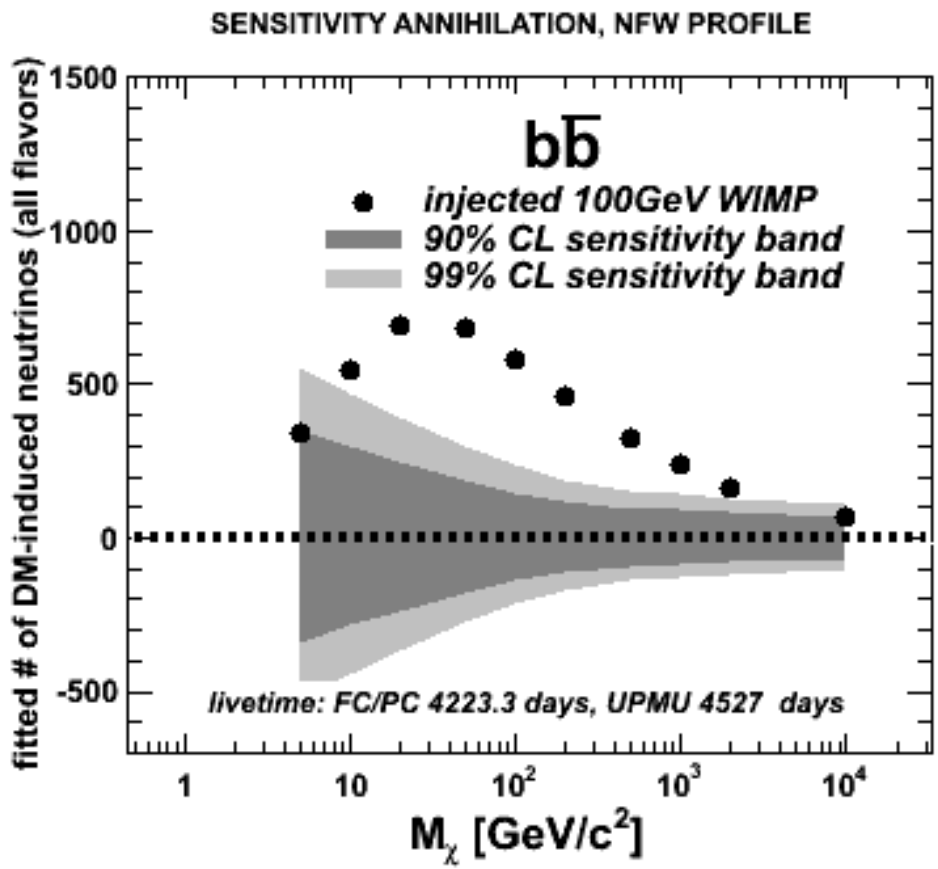
Analysis steps

EXAMPLE: Galactic search

1 Simulate DM signal before detection → DarkSUSY & WimpSim

2 Simulate detector response in outgoing lepton momentum and $\cos\theta_{GC}$ or $\cos\theta_{SUN}$

3 **FIT signal + bkg to DATA with constrains from systematic uncertainties**

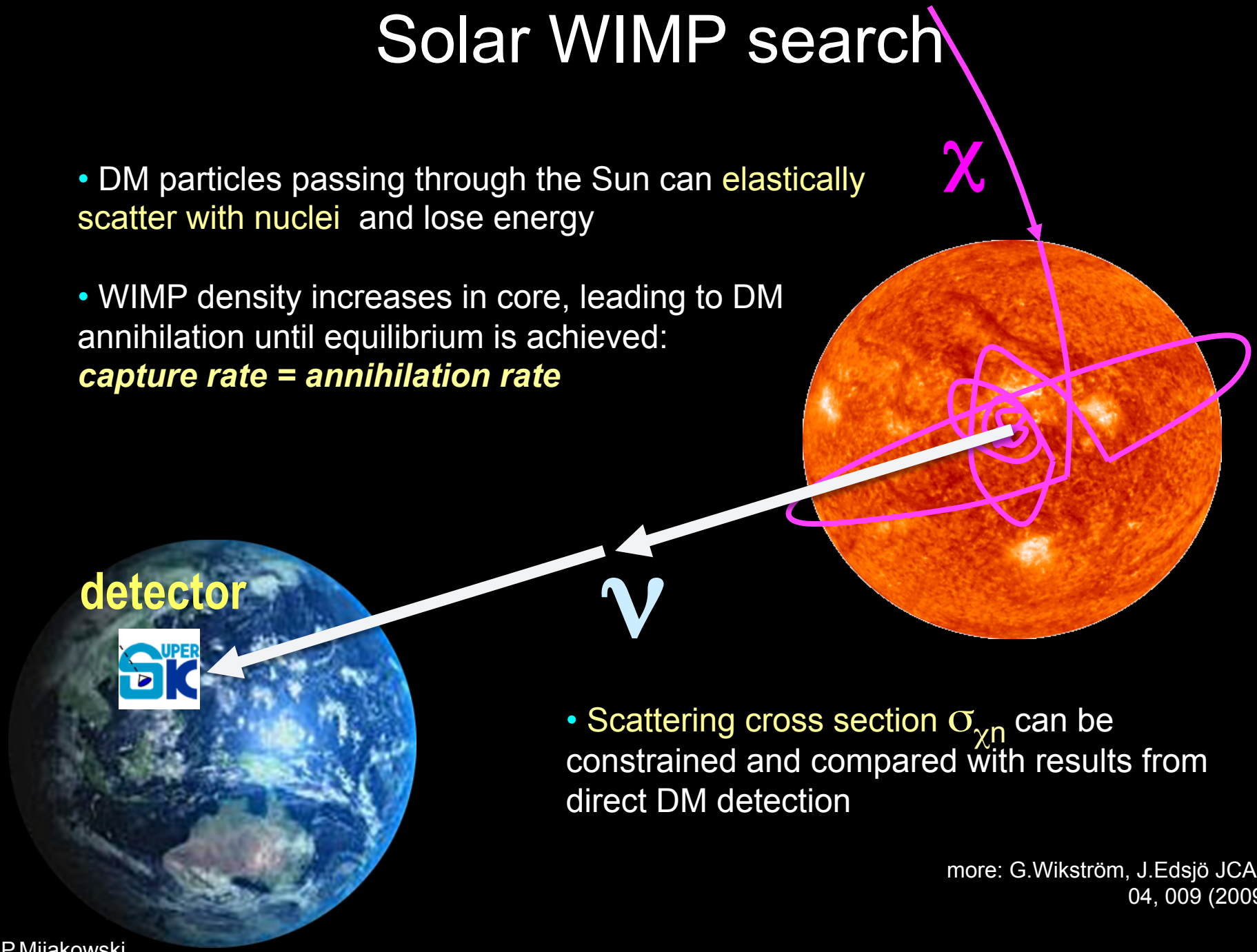


SENSITIVITY study: injected 100 GeV WIMP as 1.5% of BKG

Solar WIMP search

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

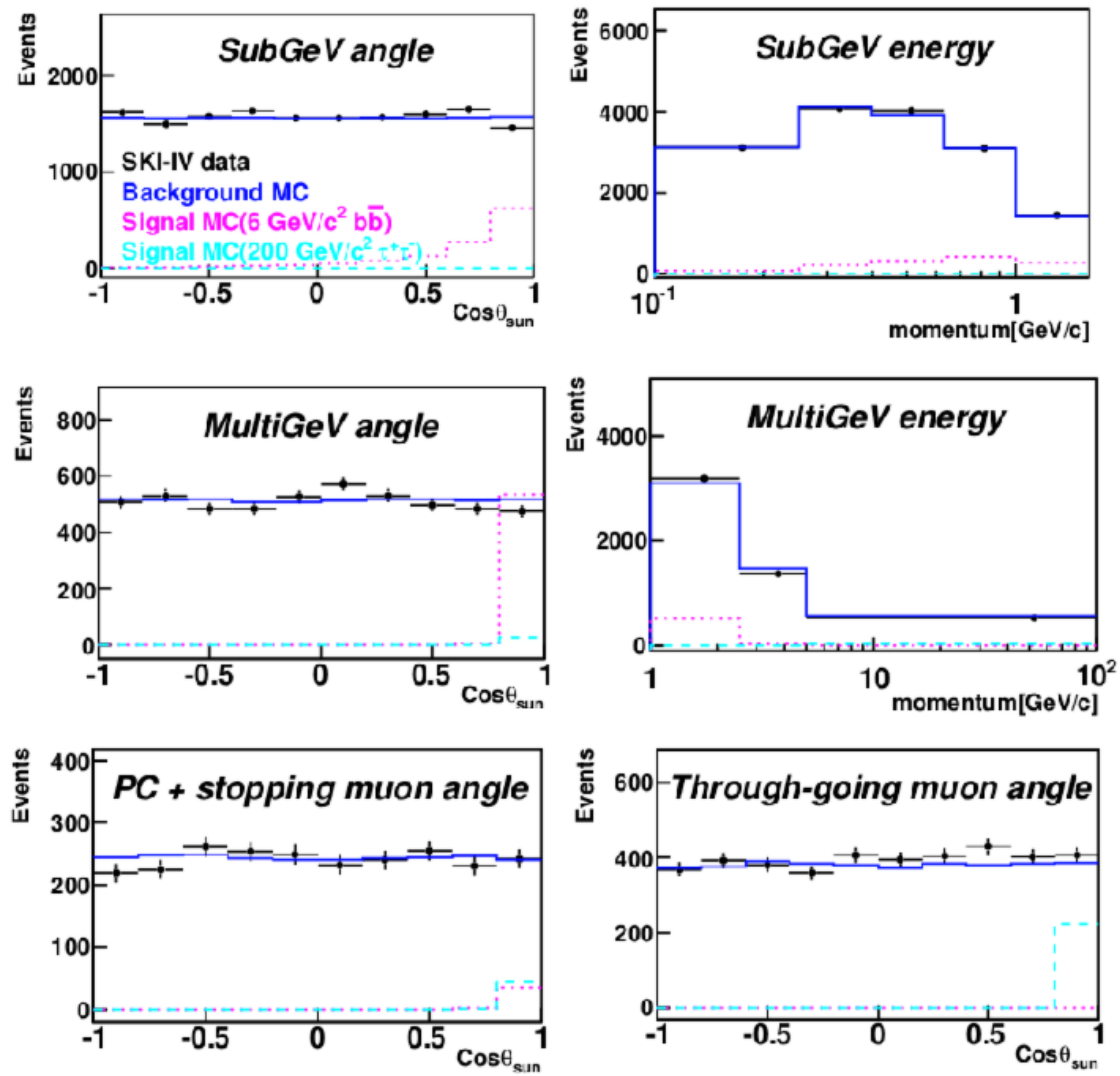
more: G.Wikström, J.Edsjö JCAP 04, 009 (2009)

Solar WIMP search: fit results

6 GeV $b\bar{b}$

200 GeV $b\bar{b}$

- 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 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 $\sigma_X n$



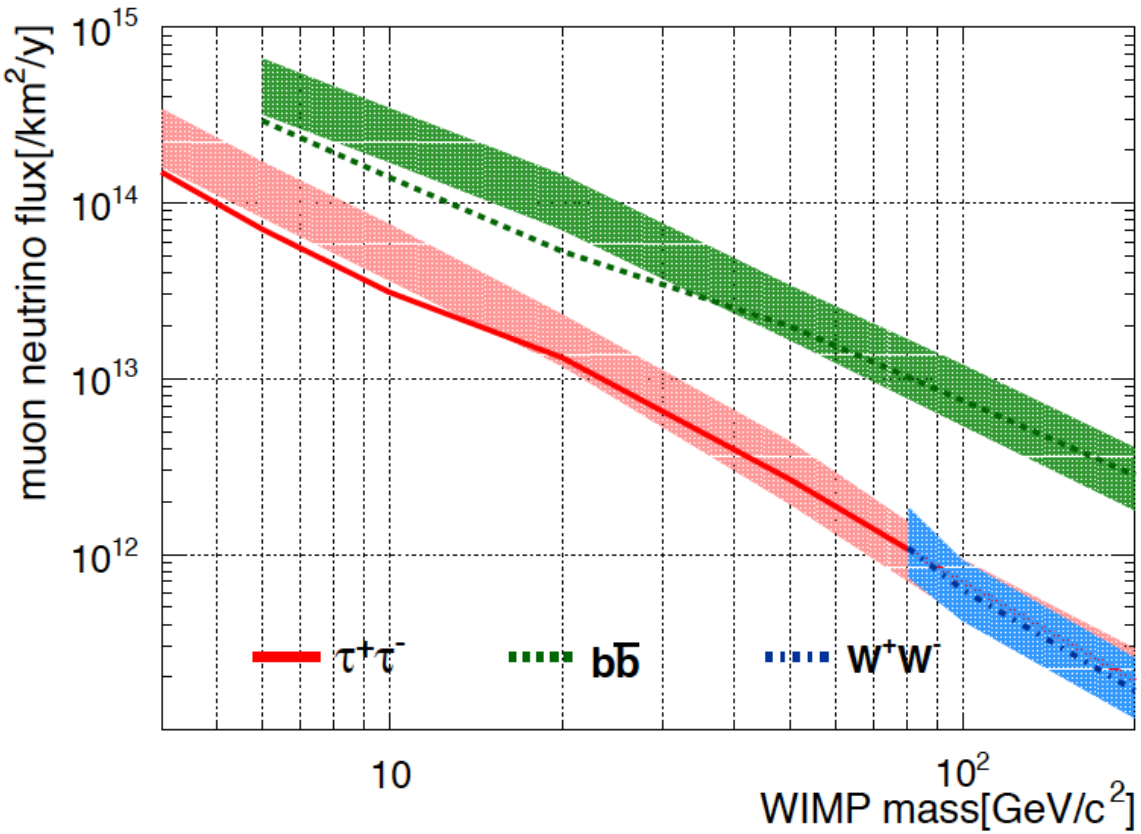
different event subsamples grouped here in 3 categories

Solar WIMP search: muon neutrino flux

- FIT based on lepton mom. & $\cos\theta_{SUN}$ distributions, 3903 days of SK data used (1996-2013)
- 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 $\sigma_X n$

90% CL upper limit

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



- *Shadowed regions show 1σ band of the sensitivity study results*
- ~150 systematic uncertainty terms included in the fit

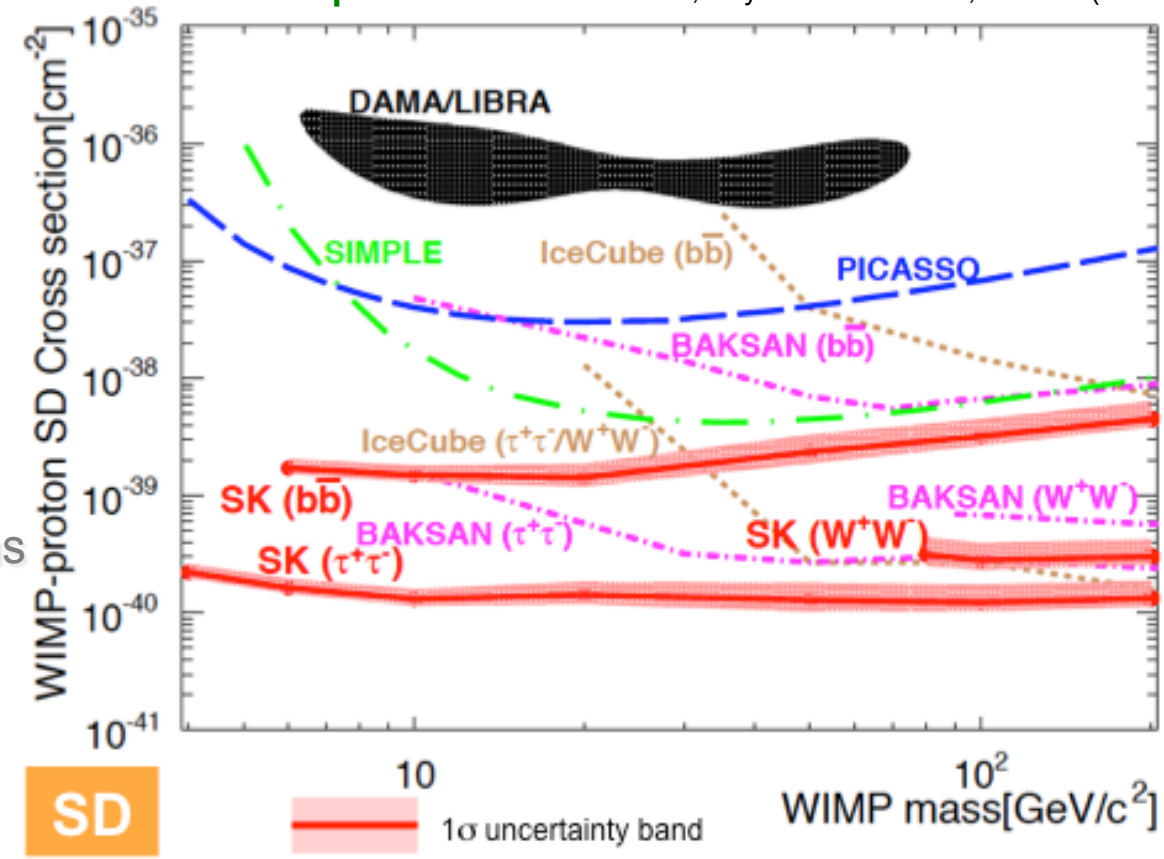
Solar WIMP search: WIMP-proton SD cross section

- FIT based on lepton mom. & $\cos\theta_{SUN}$ distributions, 3903 days of SK data used (1996-2013)
- 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 $\sigma_{\chi n}$

→ DAMA region excluded

90% CL upper limit

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



uncertainty bands take into account uncertainties in capture rate for the $b\bar{b}$, W^+W^- and $\tau^+\tau^-$ channels

for the first time limits from SK <10GeV

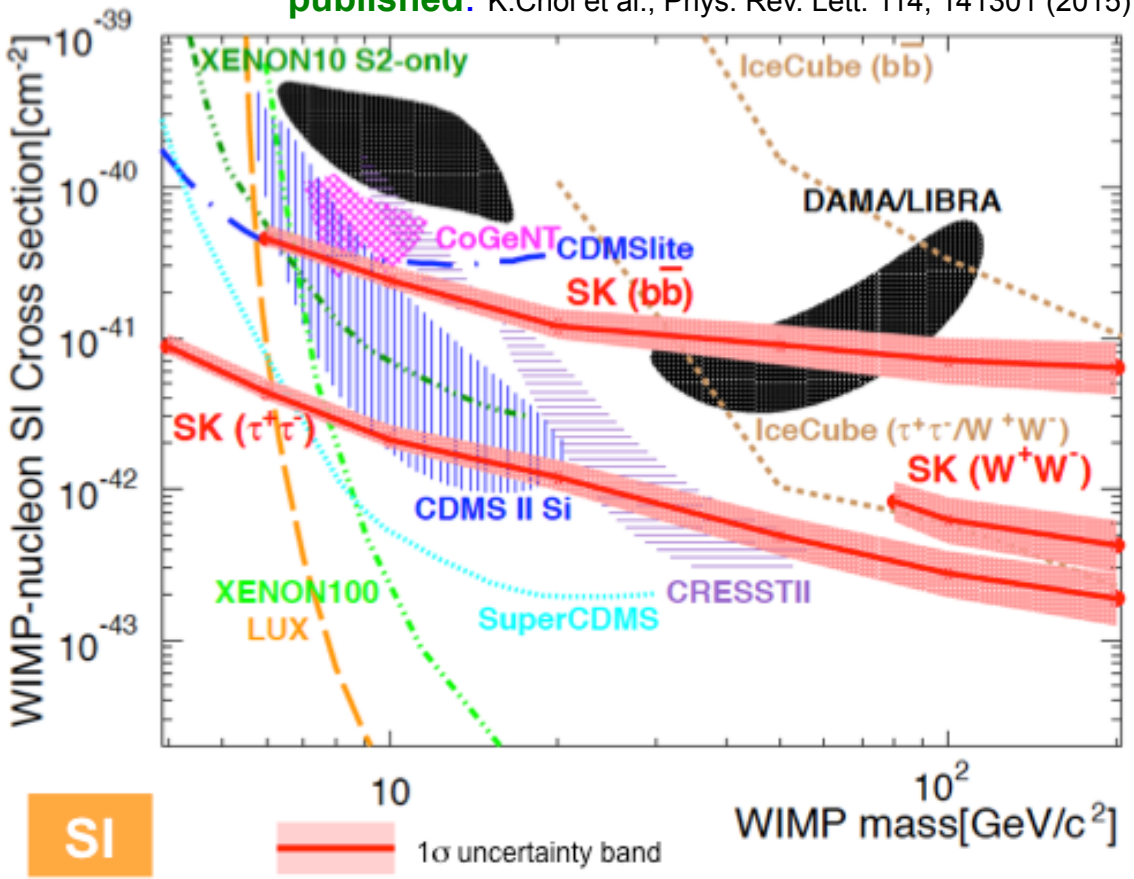
Solar WIMP search: WIMP-proton SI cross section

- FIT based on lepton mom. & $\cos\theta_{SUN}$ distributions, 3903 days of SK data used (1996-2013)
- 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 $\sigma_{\chi n}$

→ Exclusions in the "confusion zone" of positive results

90% CL upper limit

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

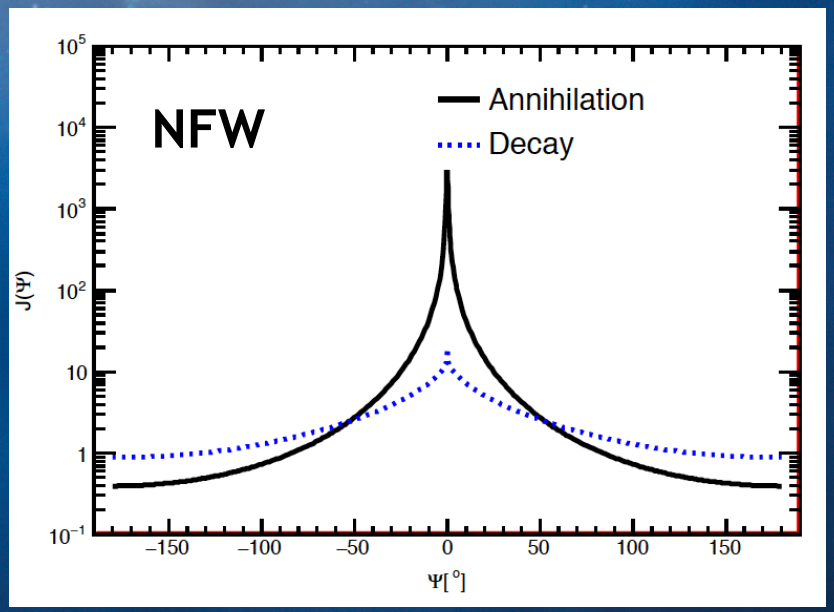


uncertainty bands take into account uncertainties in capture rate for the $b\bar{b}$, W^+W^- and $\tau^+\tau^-$ channels

for the first time limits from SK <10GeV

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>

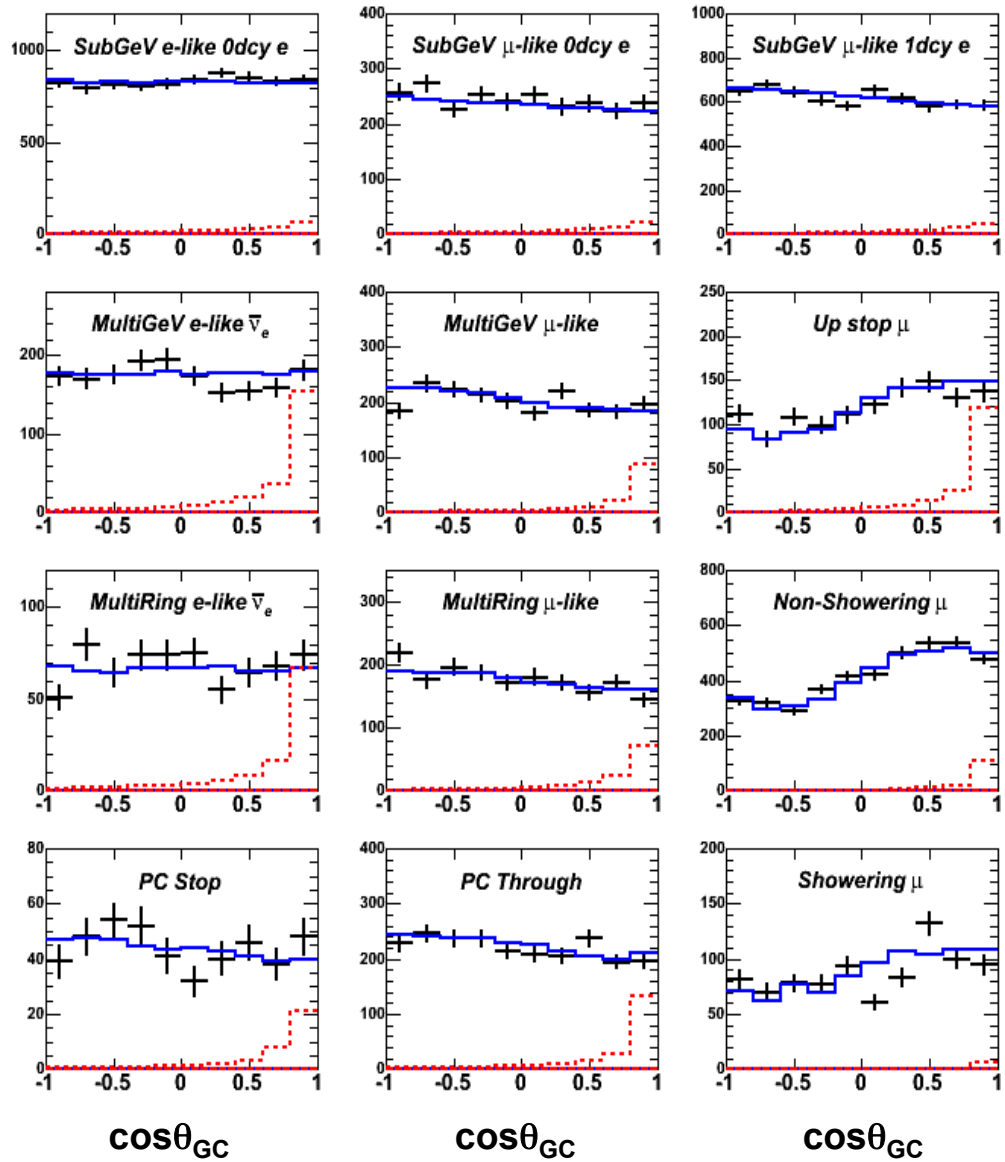


Expected signal intensity

Galactic WIMP search: fit illustration

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 4223 days of SK data used (1996-2014)
- NFW halo model is assumed
- Fit results are consistent with zero
- 90% CL upper limit on DM self-annihilation cross section $\langle\sigma_A V\rangle$

100GeV WIMPs $b\bar{b}$ ann. channel



DATA SK1,2,3,4 1996-2013

ATM MC +WIMP at best fit point

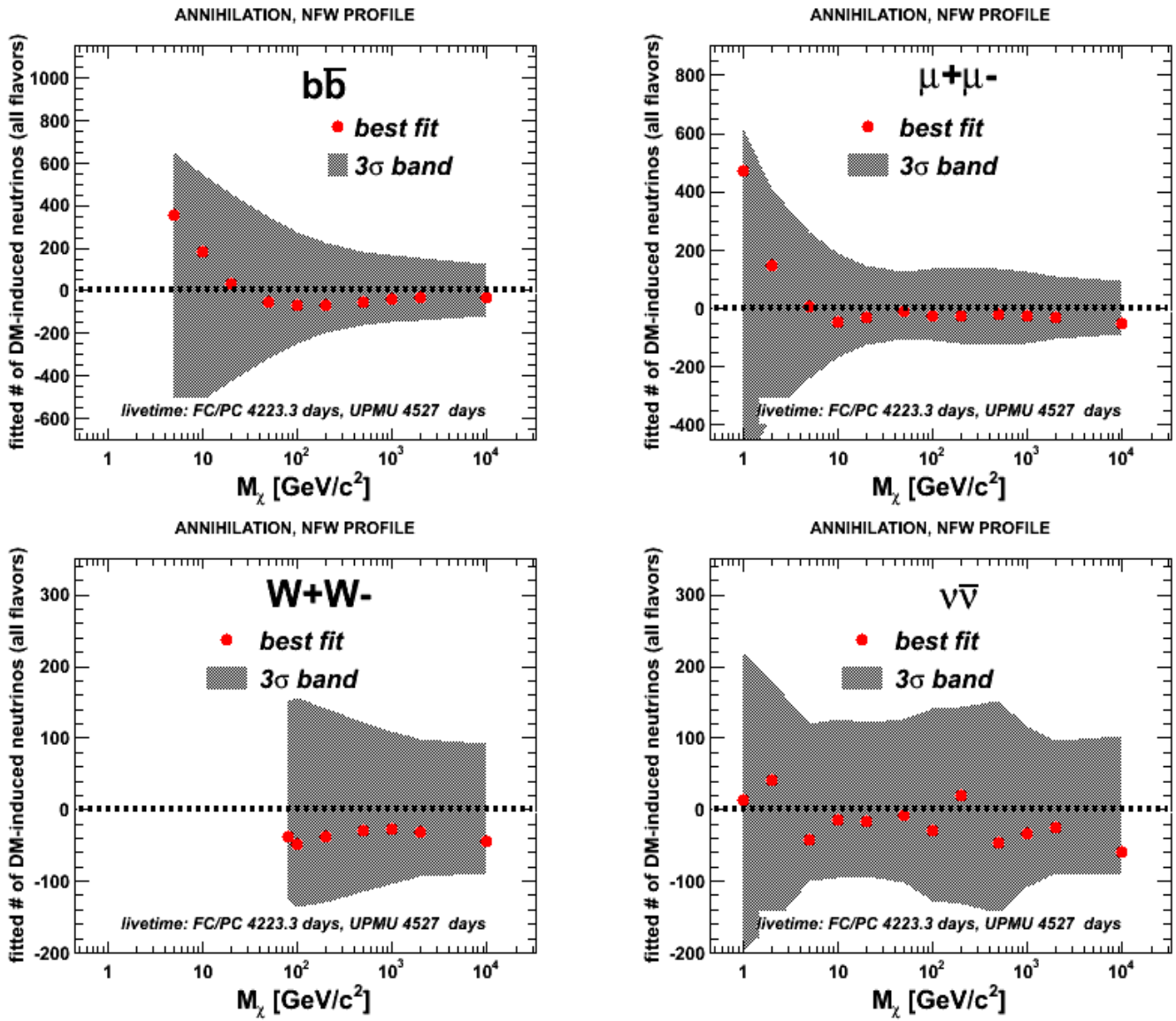
DM ann. signal shape before fit

proportions of the signal in various samples are reflected

Galactic WIMP search: fitted number of DM-induced ν̀s

100% branching ratio to given annihlation channel is assumed

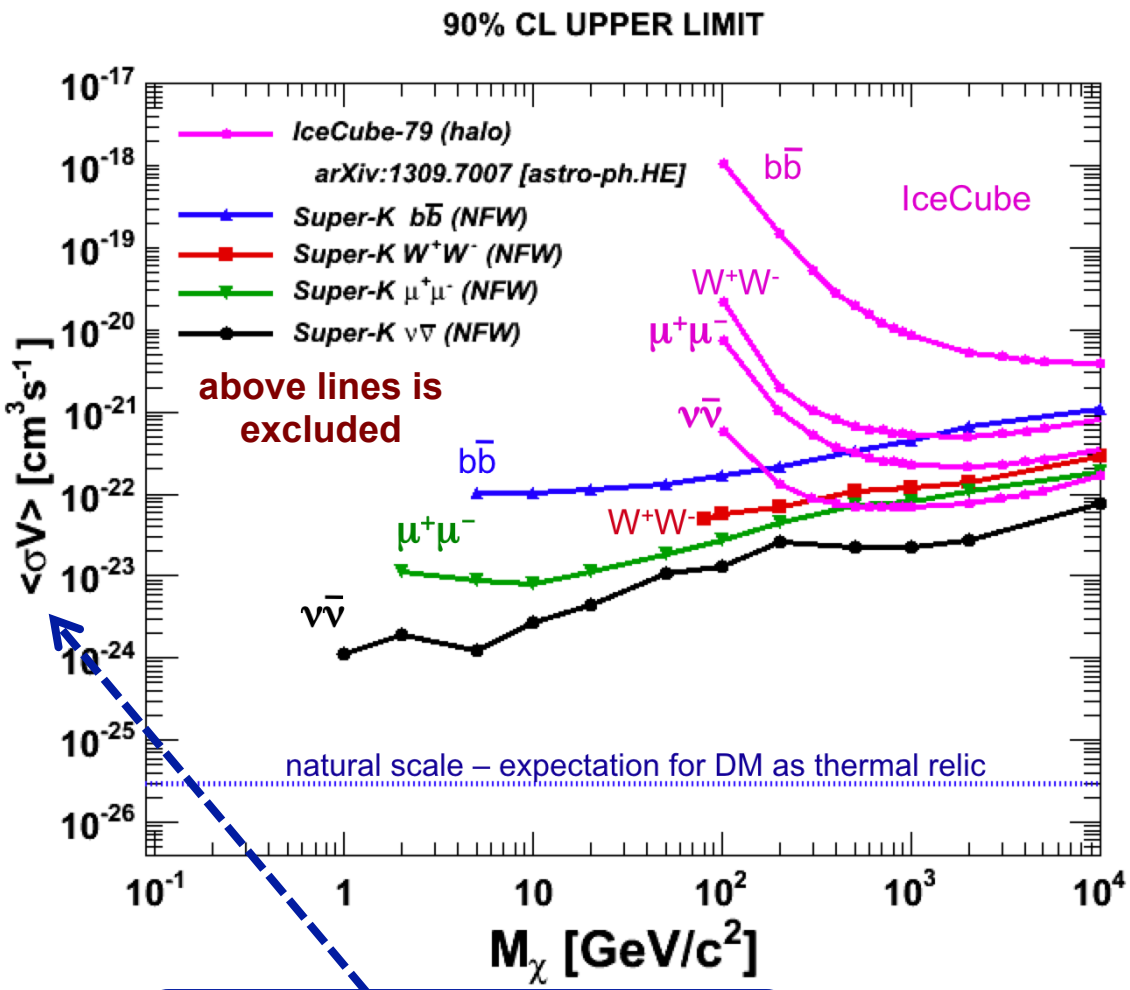
- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 4223 days of SK data used (1996-2014)
- NFW halo model is assumed
- Fit results are consistent with zero
- 90% CL upper limit on DM self-annihilation cross section $\langle\sigma_A V\rangle$



~150 systematic uncertainty terms included in the fit

Galactic WIMP search: DM annihilation cross section

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 4223 days of SK data used (1996-2014)
- NFW halo model is assumed
- Fit results are consistent with zero
- 90% CL upper limit on DM self-annihilation cross section $\langle\sigma_A V\rangle$

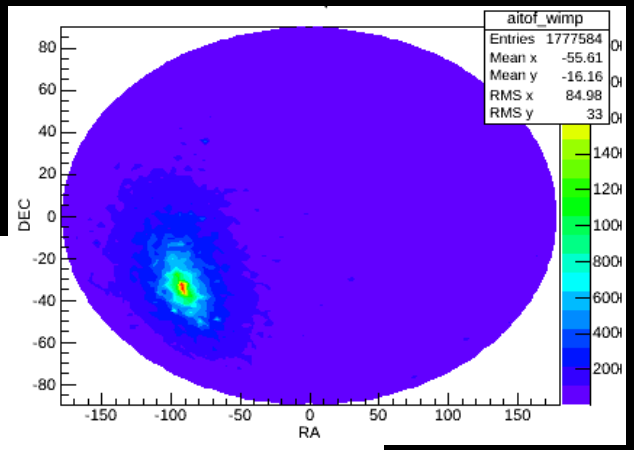


$$\frac{d\phi_{\Delta\Omega}}{dE} = \frac{\langle\sigma_A \cdot V\rangle}{2} J_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi \cdot M_\chi^2} \frac{dN}{dE}$$

$J_{\Delta\Omega}$ is integrated intensity over all sky, depends on DM halo profile

Galactic WIMP search: ON-/OFF-source

expectation for DM-induced neutrinos

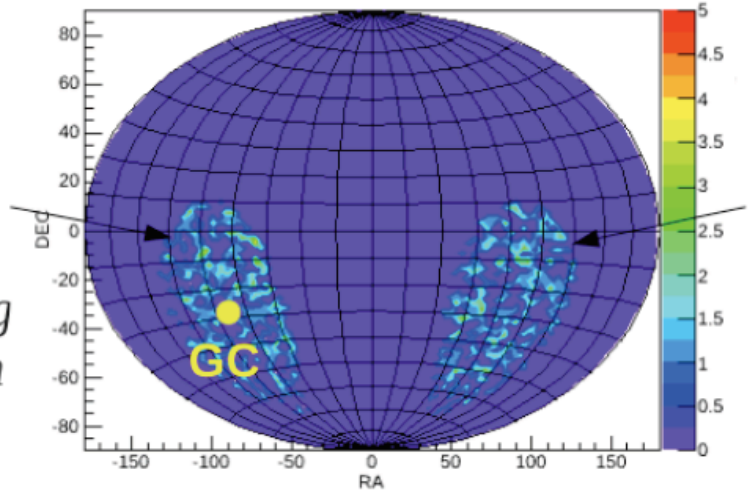


Different approach: search for large-scale anisotropy due to DM-induced ν's from Milky Way

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

on-source

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



off-source

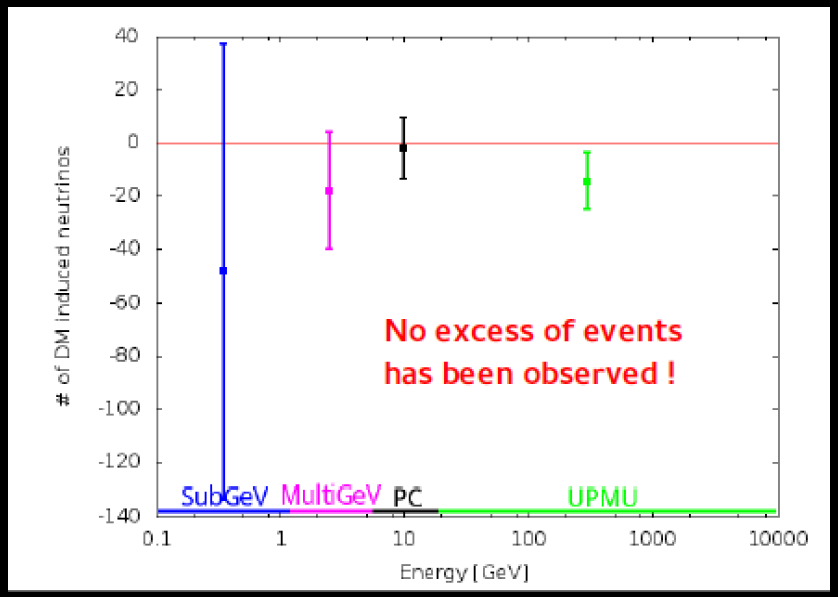
$$N_{off}^{bkg} + N_{off}^{sig}$$

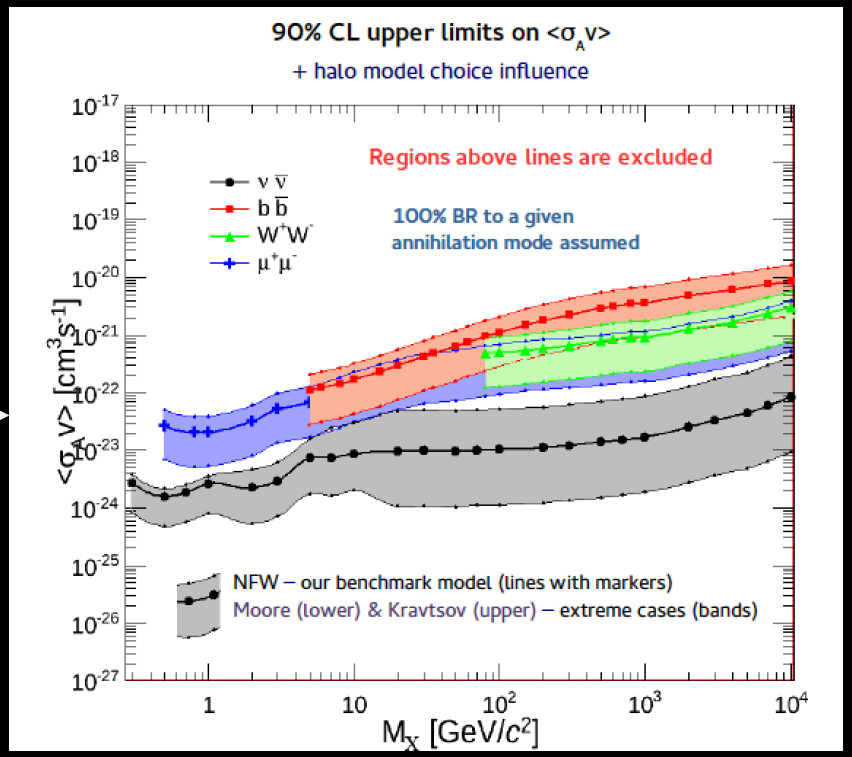
- Analysis uses ON-/OFF-source concept to estimate background directly from data
- Independent on MC simulations and related systematic uncertainties

ON- & OFF-source method results

Based on SK 1-4 data (1996-2014)

	Sample	Size	On-source	Off-source	ΔN sig	90% CL ΔN sig
$\nu\bar{\nu}$	FC Sub GeV	80	3628	3676	-48 ± 85.5	114.4
$\nu\bar{\nu}$	FC Multi GeV	30	233	251	-18±22	26.9
$\nu\bar{\nu}$	PC	20	65	67	-2 ± 11.5	17.7
$b\bar{b}$, W^+W^-, $\mu^+\mu^-$	UPMU	10	49.2	63.5	-14.3 ± 10.6	10.8
$b\bar{b}$, W^+W^-, $\mu^+\mu^-$	ALL	35	2010.4	2161.1	-150.7±64.6	49.3





RESULTS: ON-/OFF-source analysis

Based on SK 1-4 data (1996-2014)

	Sample	Size	On-source	Off-source	ΔN sig	90% CL ΔN sig
$\nu\bar{\nu}$	FC Sub GeV	80	3628	3676	-48 ± 85.5	114.4
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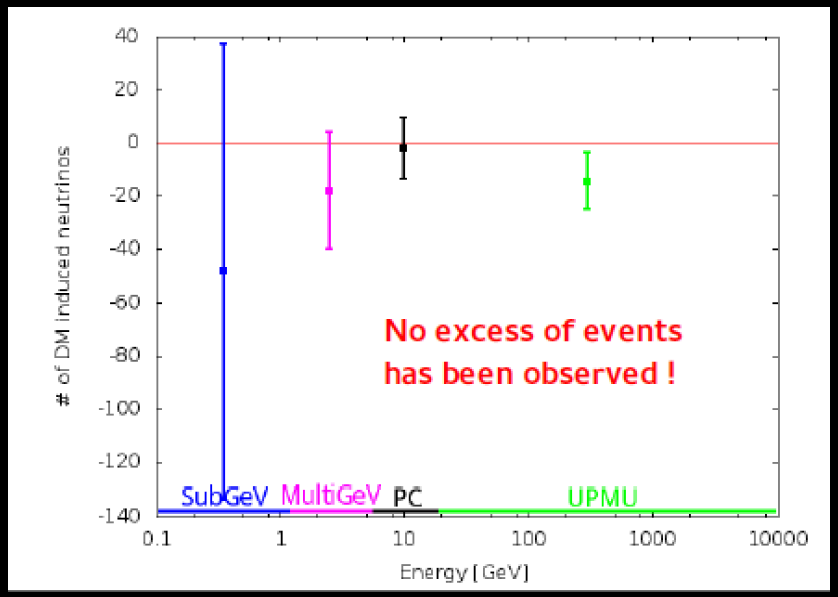
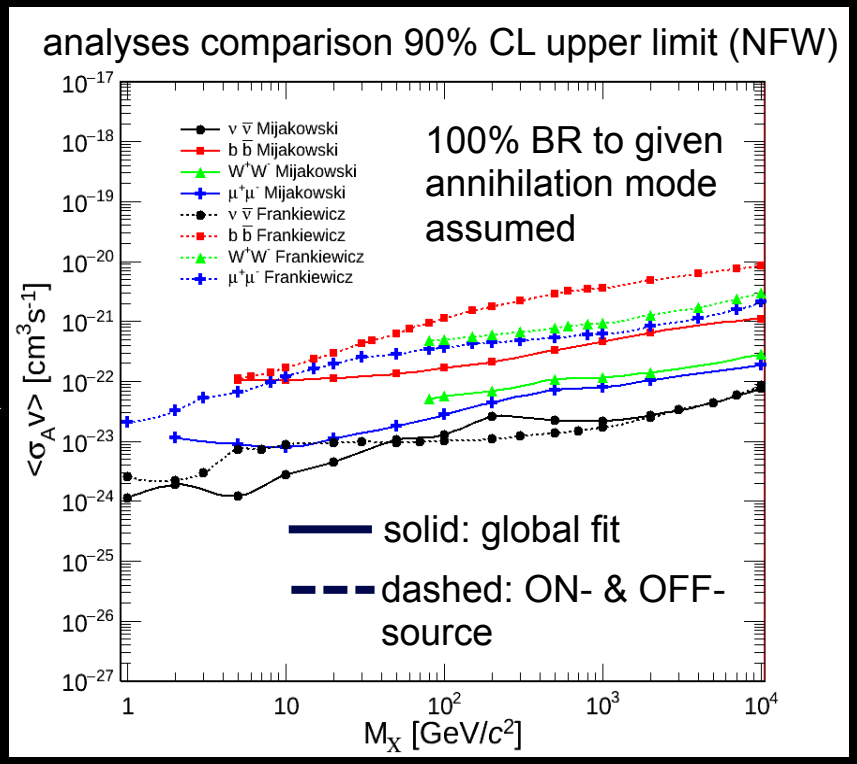


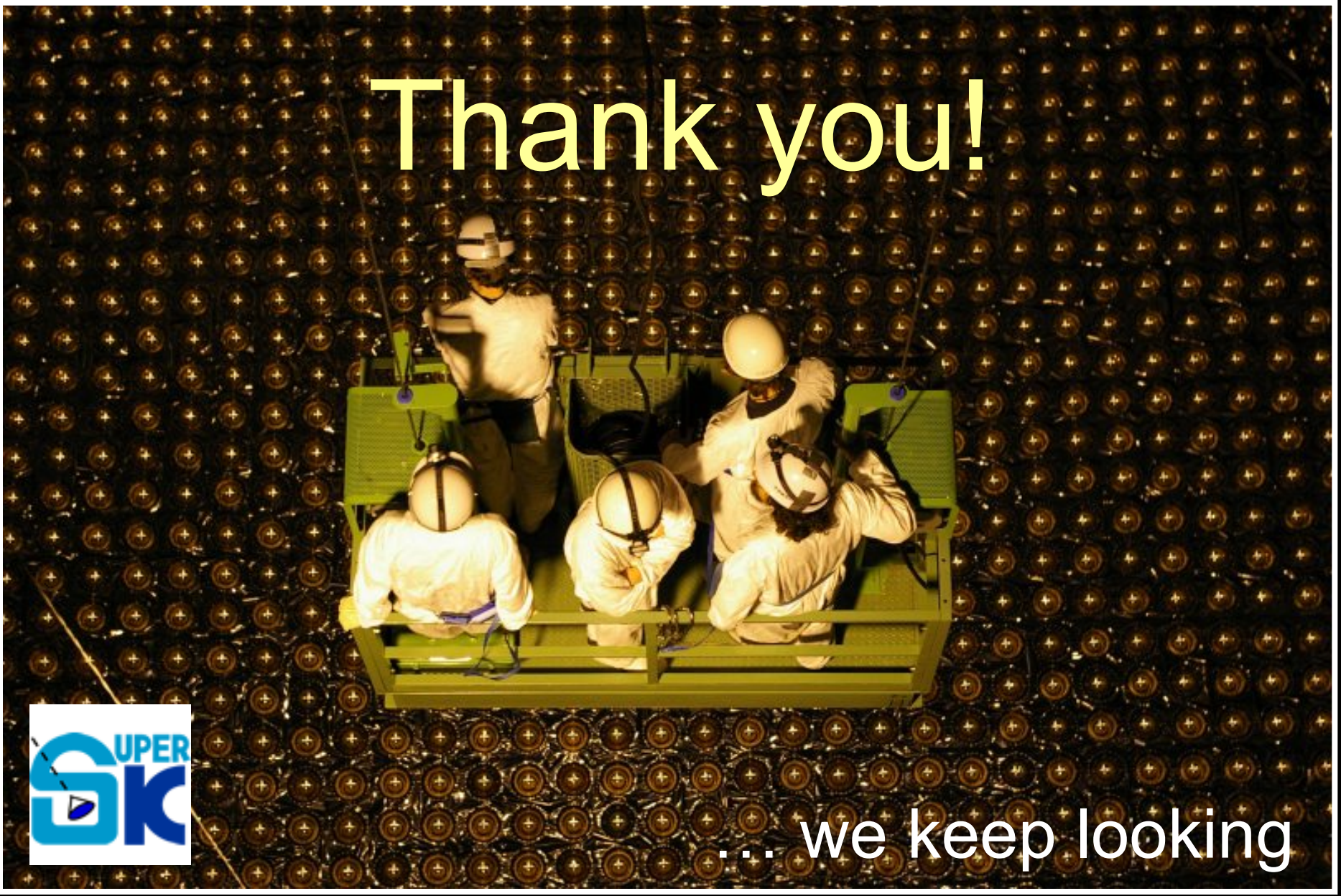


Summary

- No excess of DM induced neutrinos has been observed at Super-Kamiokande

- Solar WIMP search – results published this year
  - First limits <10 GeV from SK, current best limits on SD WIMP-proton cross section in indirect detection of WIMP masses <200 GeV/c^2

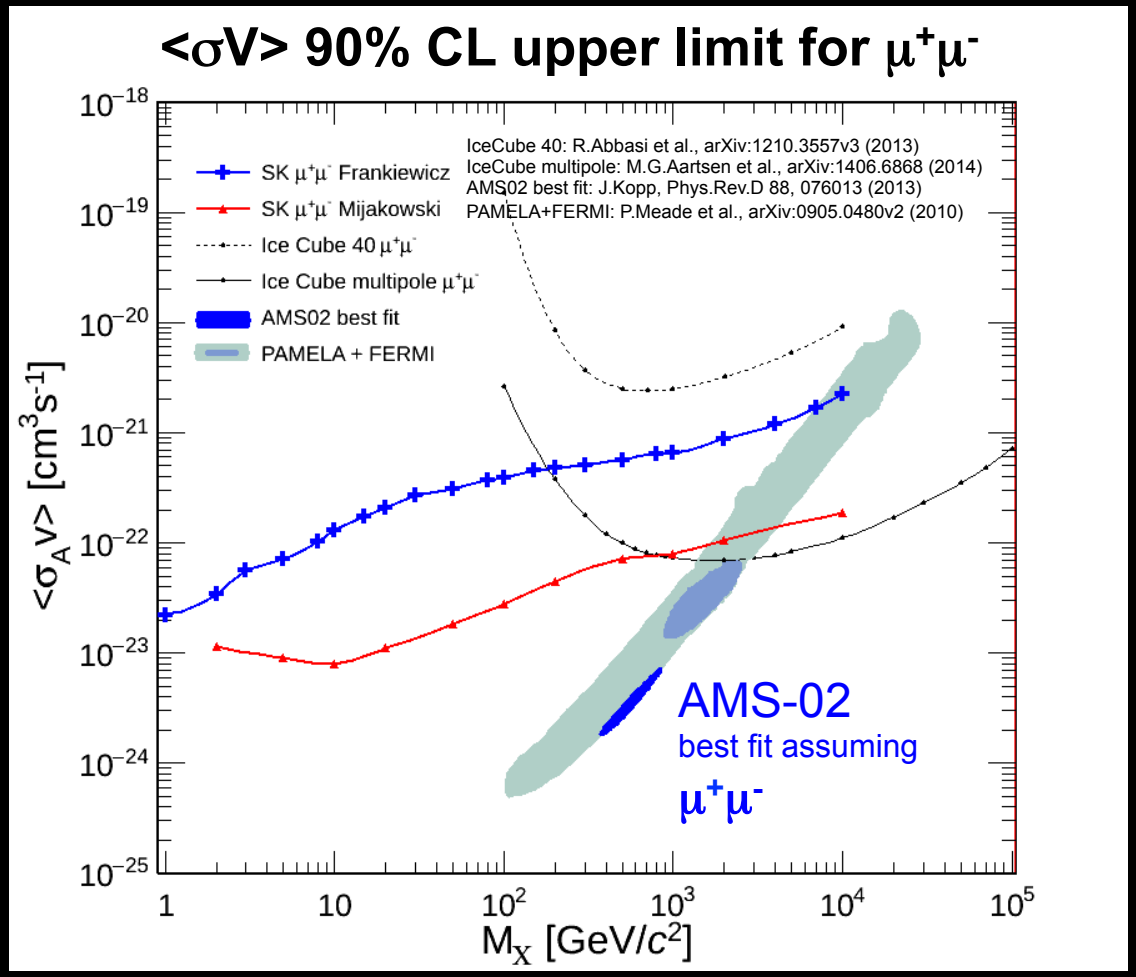
- Galactic WIMP search
  - 2 analyses, upper limits on DM self-annihilation cross section $\langle\sigma_A V\rangle$ in wide energy range from 1 GeV to 10 TeV


Thank you!
… we keep looking

Supplementary slides

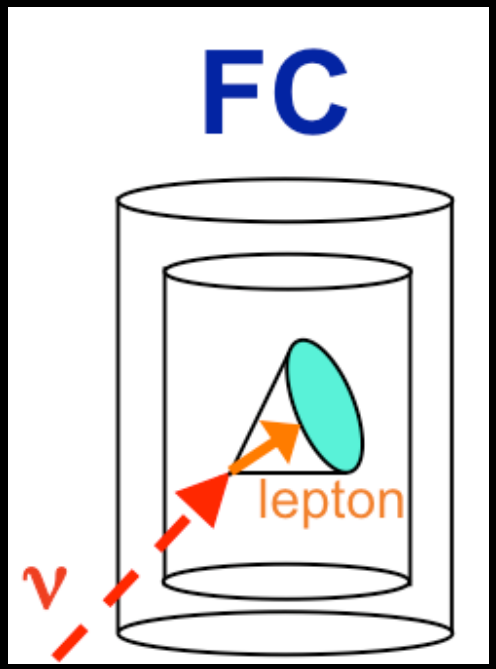
Comparison with AMS-02

- DM annihilation into $\mu^+\mu^-$ may explain positron excess seen by PAMELA/ FERMI/AMS-02
- SK limits for DM ann. in the Milky Way come along



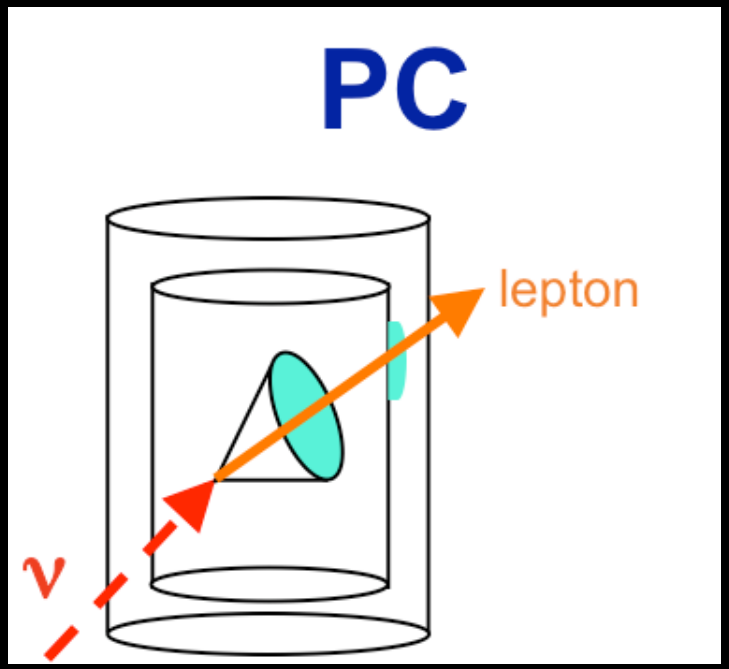
Super-K data samples

Fully-contained



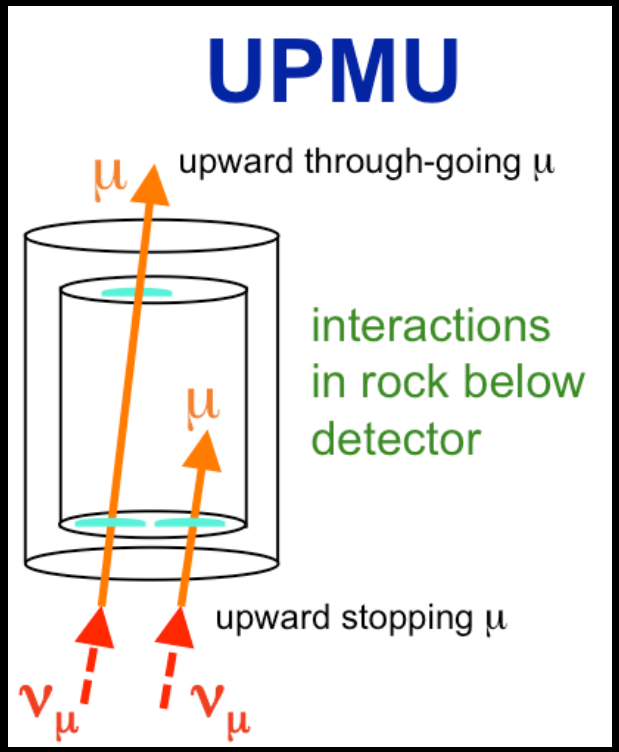
- » ν energy reconstruction
- » ν direction info
- » e/μ identification possible

Partially-contained



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

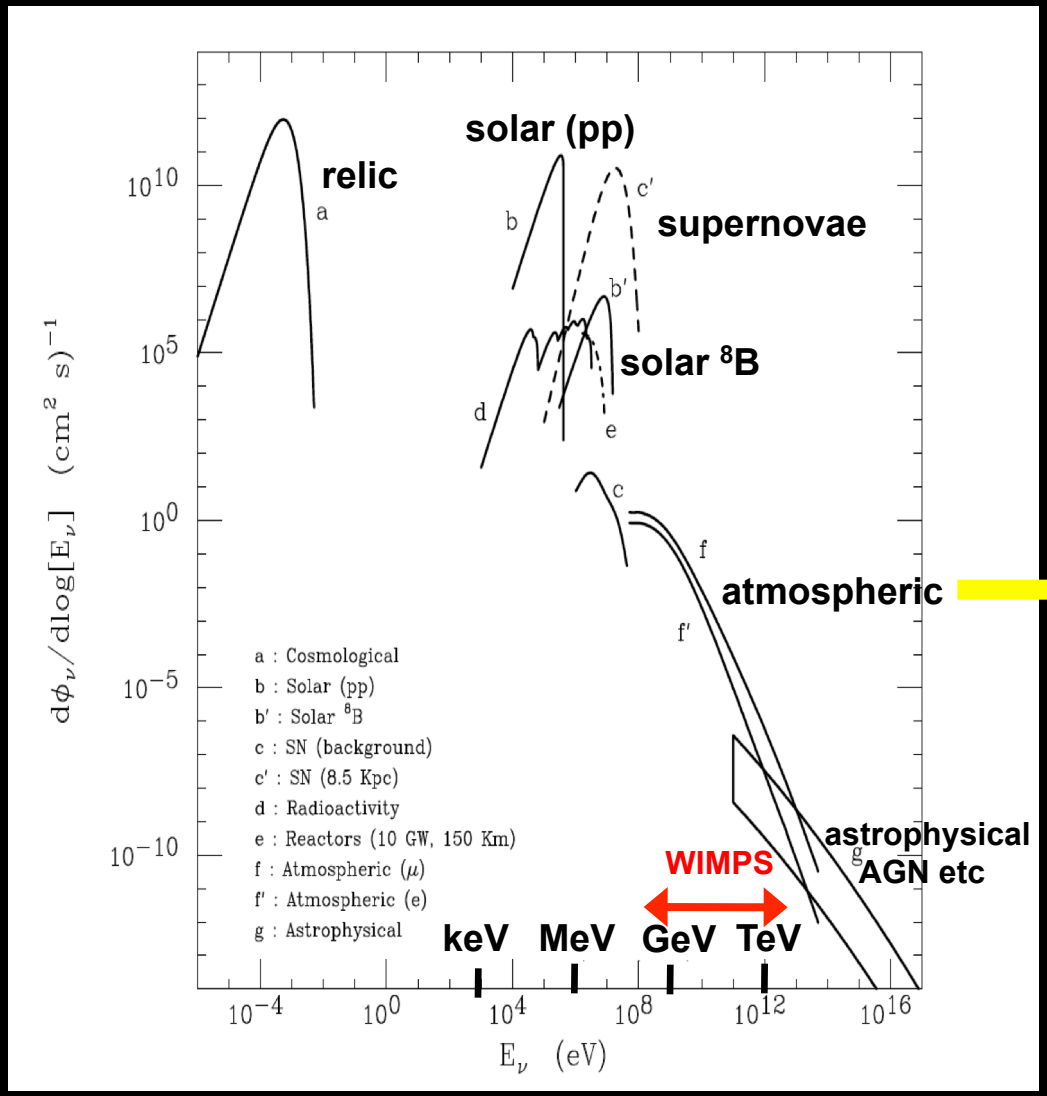
Upward-going muons



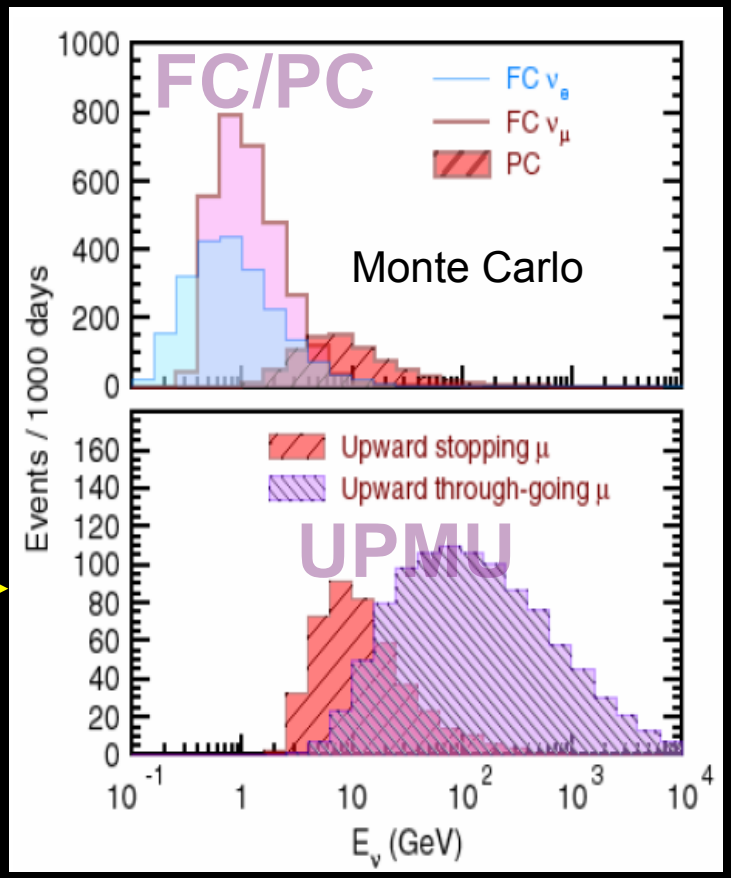
- » no E_ν info
- » excellent ν direction info
- » downward-going muons are neglected (mainly cosmic ray μ)

Neutrino sources

Neutrino sources



Expected # evts in each category for atmospheric neutrinos @ Super-K

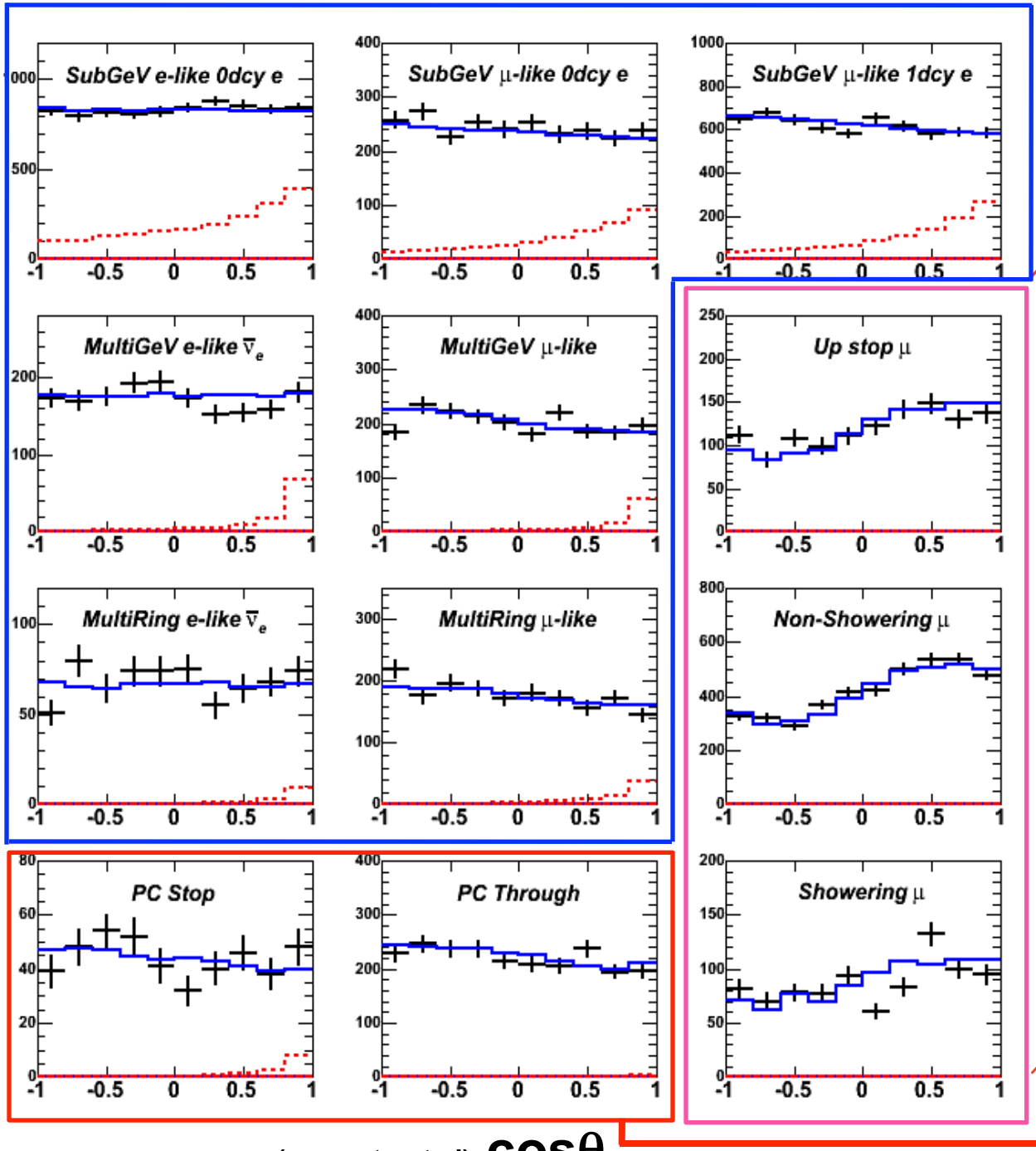


FC = ~8.3 evts/day

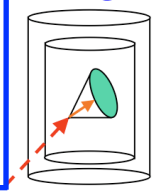
PC = ~0.7 evts/day

UPMU = ~1.5 evts/day

DM signal illustration



FC

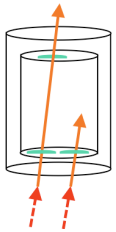


$b\bar{b}$

annihilation mode

M_χ = 5GeV

UPMU



DATA

SK1,2,3,4

ATM MC+WIMP

at best fit point

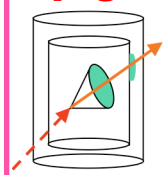
DM ann. signal

x15

at best fit point

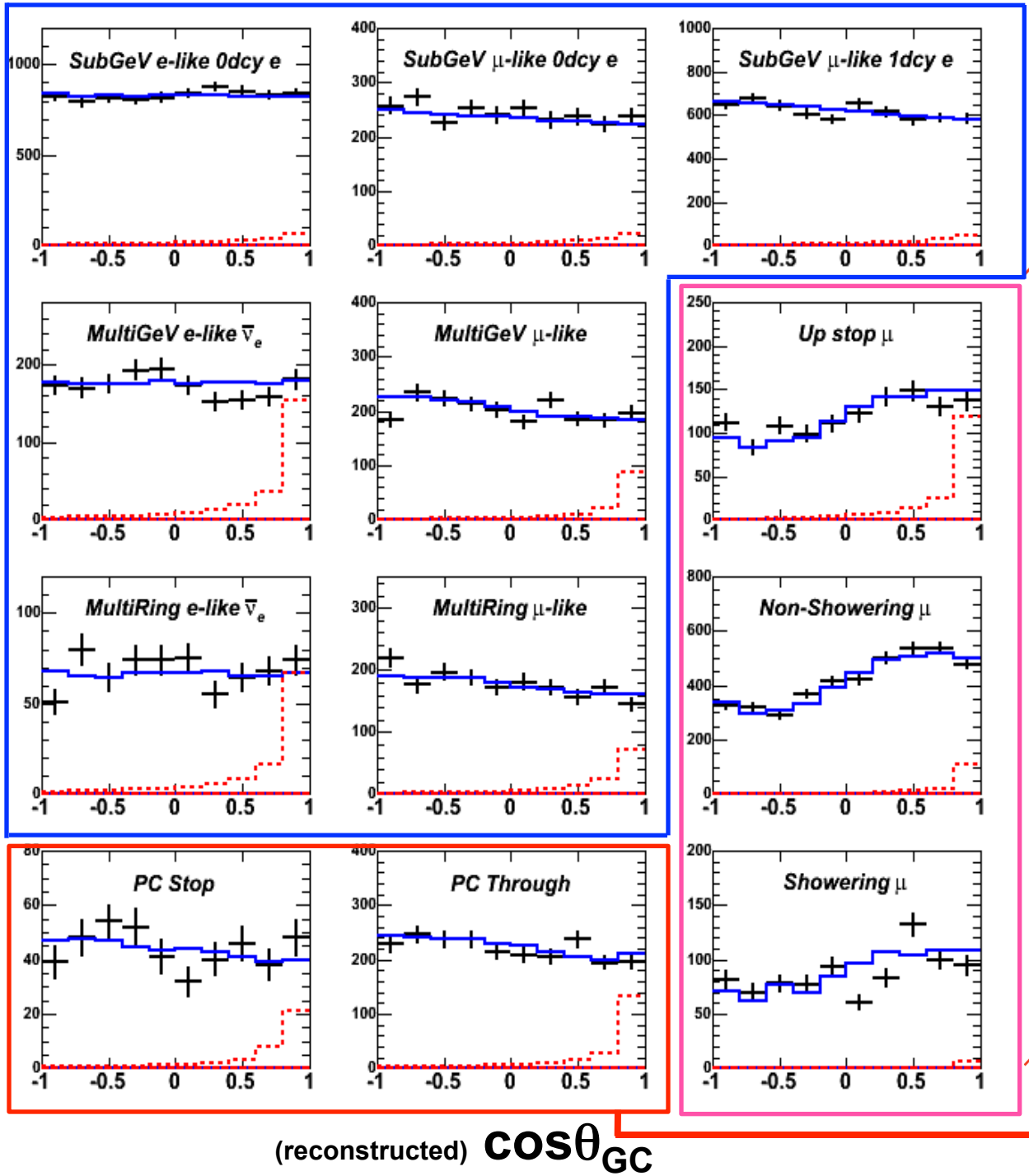
proportions of the signal in various samples are reflected

PC

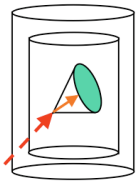


$\phi(\nu_e)=\phi(\nu_\mu)=\phi(\nu_\tau)$ for WIMP signal

DM signal illustration



FC

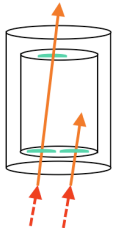


$b\bar{b}$

annihilation mode

M_χ = 100GeV

UPMU



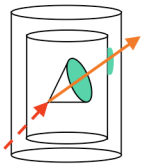
DATA
SK1,2,3,4

ATM MC+WIMP
at best fit point

DM ann. signal
illustration
before fit

proportions of the signal in various samples are reflected

PC



$\phi(\nu_e)=\phi(\nu_\mu)=\phi(\nu_\tau)$
for WIMP signal