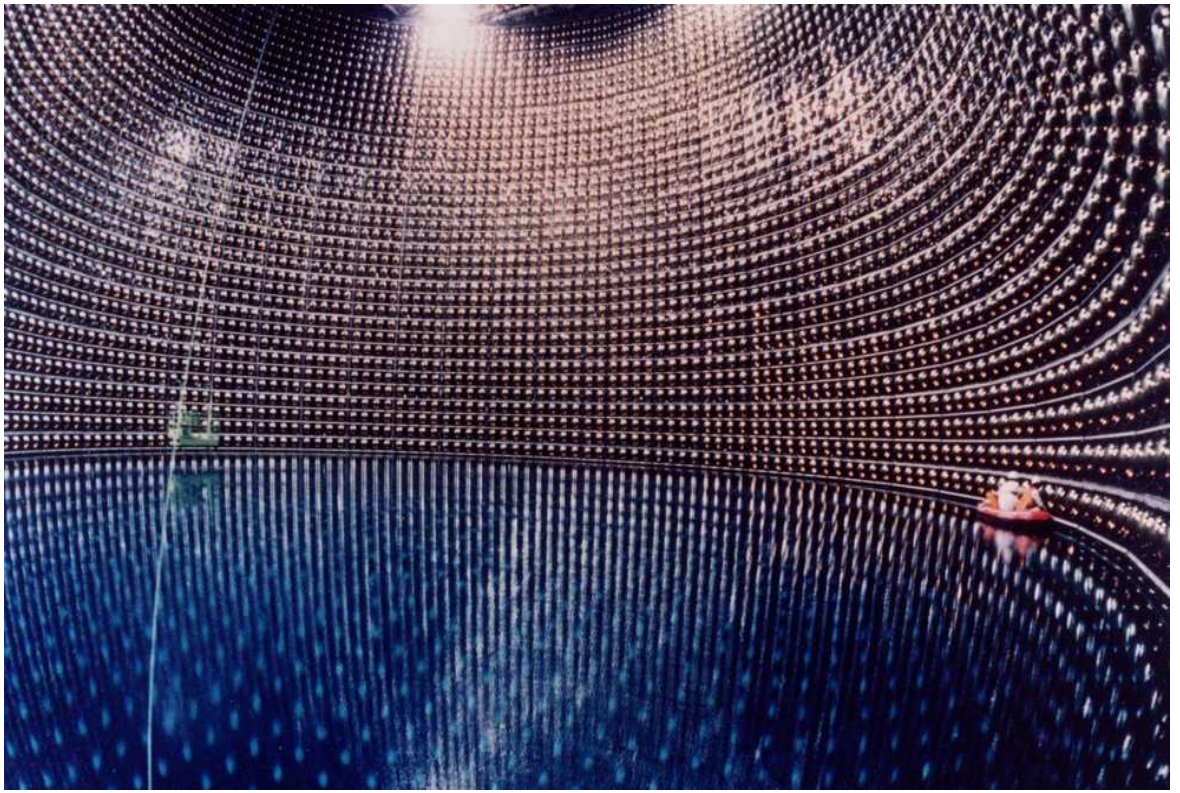
Indirect searches for dark matter particles with the Super-Kamiokande detector



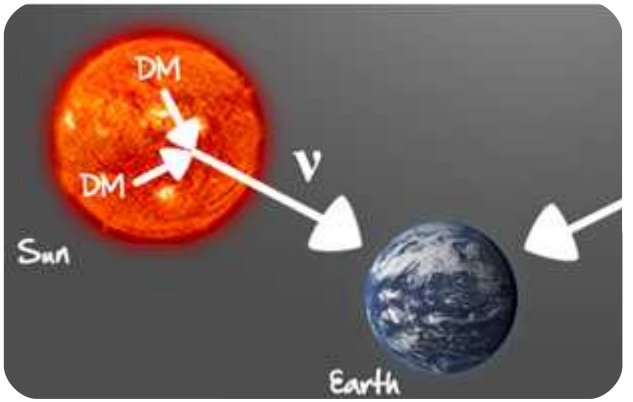
Katarzyna Frankiewicz
National Center For Nuclear Research

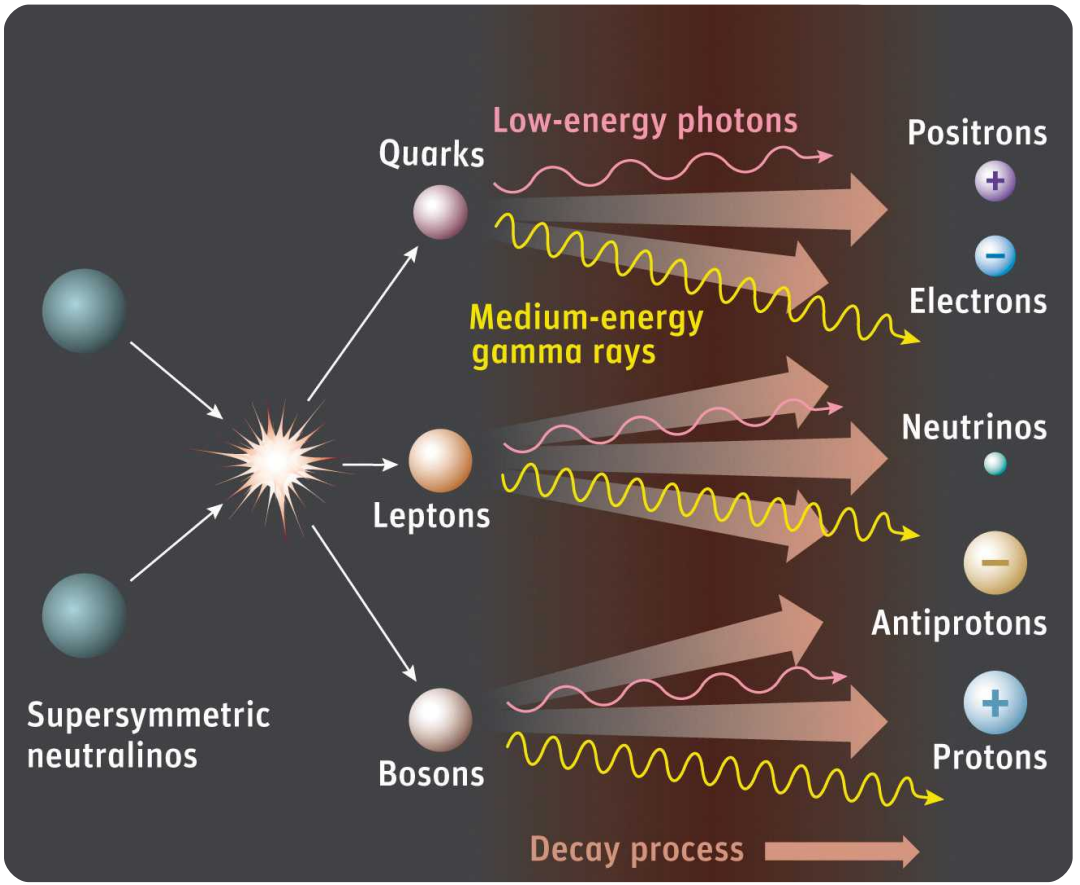
Meeting of the American Physical Society, Division of Particles and Fields, 4-8 VIII 2015

Indirect dark matter detection

– Search for the products of WIMP annihilation or decay

- Antimatter
- Photons
- Neutrinos





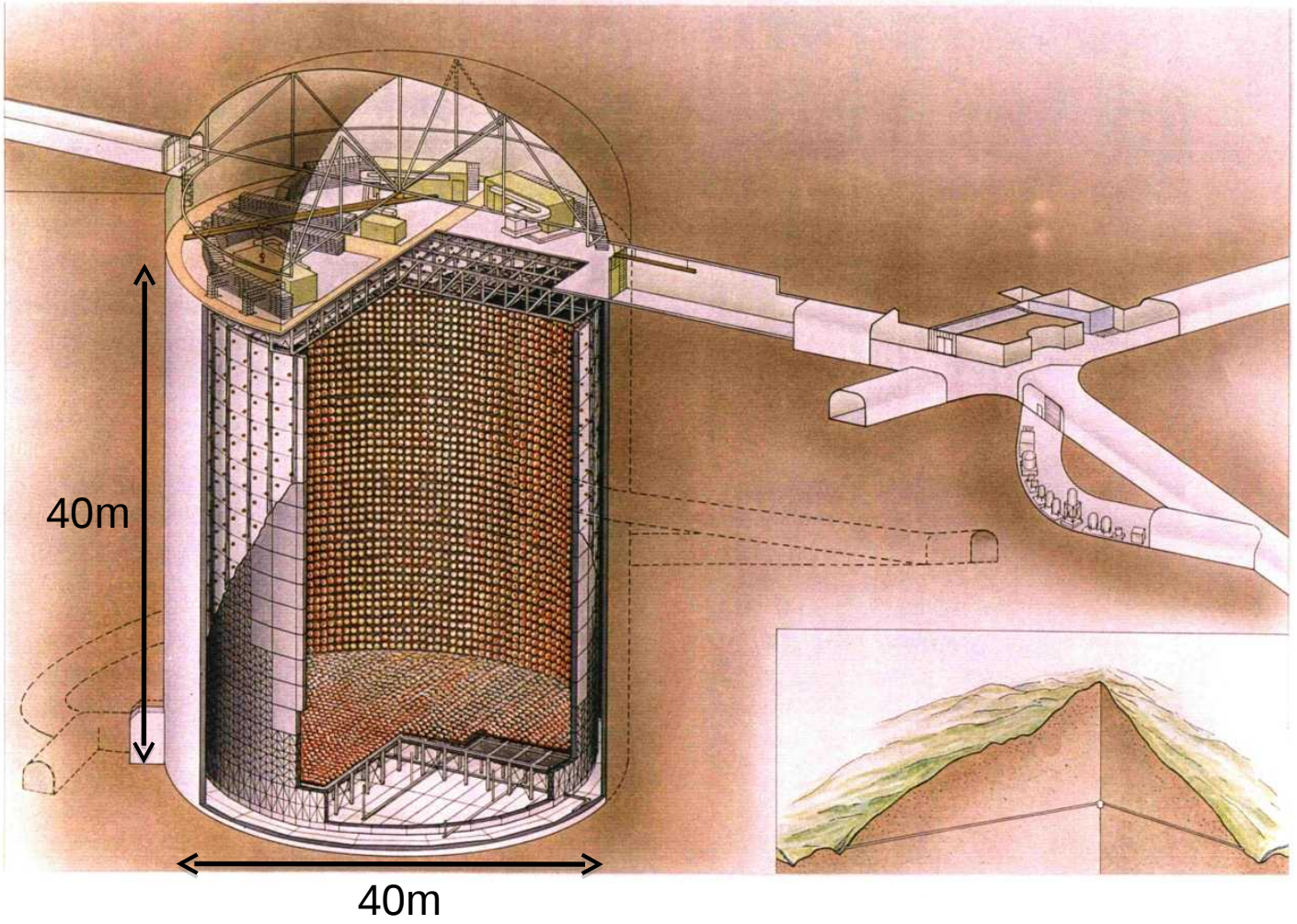
Produced ν's provide very good information about:

- source position
- generated energy spectra

Super-Kamiokande

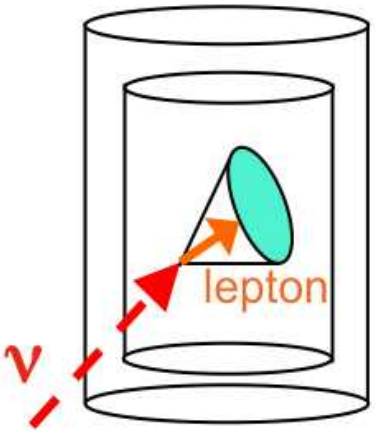
Water Cherenkov detector

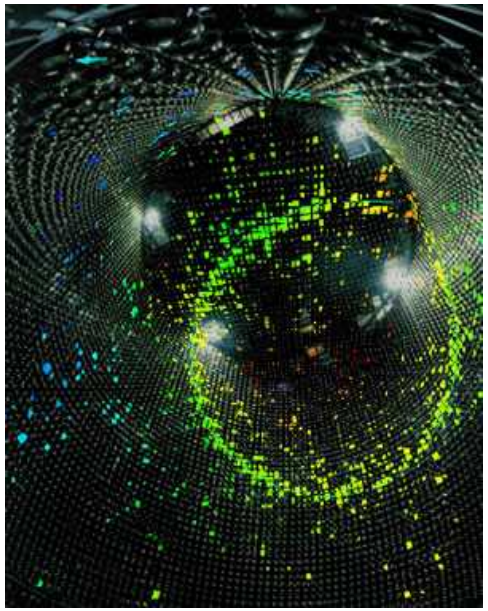
- 50 000 tons of water (22.5 000 ton FV)
- located in Mozumi mine, 1 km underground
- ID ~12 000 PMTs, OD ~2 000 PMTs
- far detector for T2K experiment



Detector measures **solar**, **atmospheric**, **cosmic** and **accelerator** neutrinos

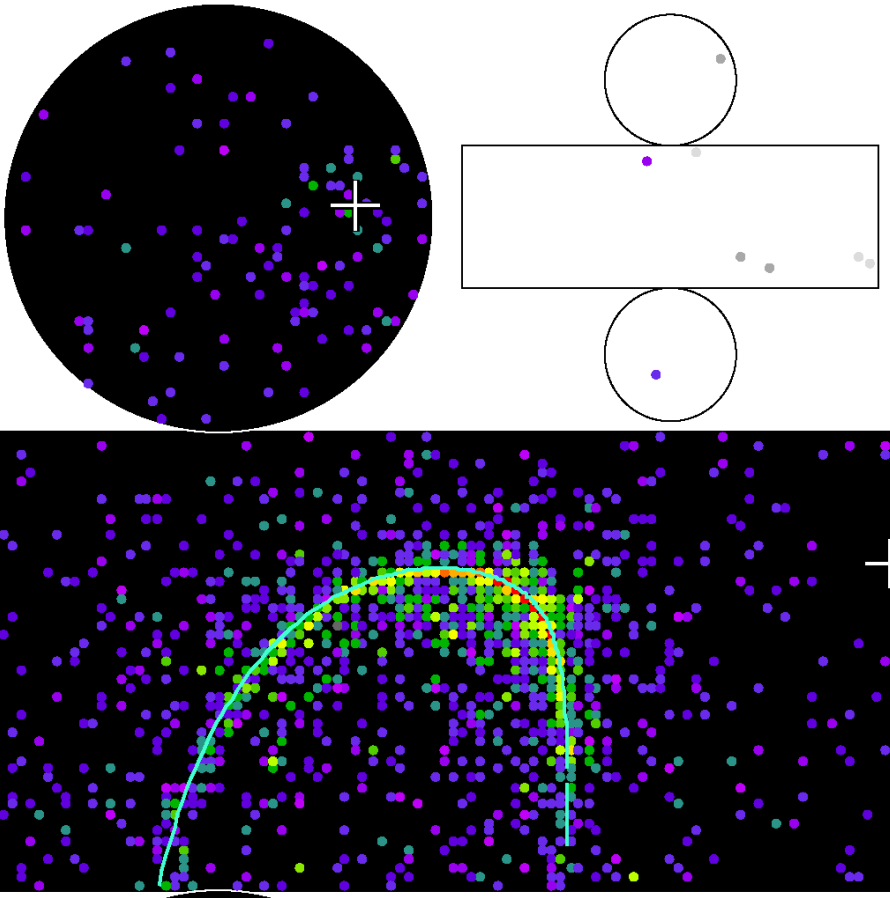
Neutrino detection at Super-Kamiokande



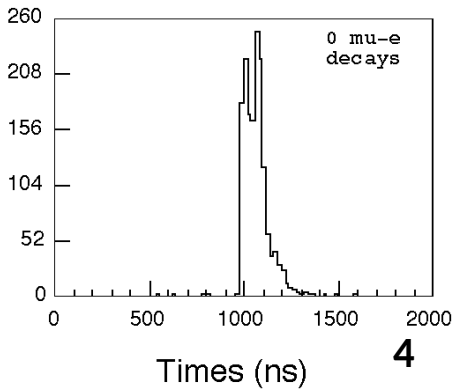


Super-Kamiokande IV

T2K Beam Run 33 Spill 822275
Run 66778 Sub 585 Event 134229437
10-05-12:21:03:22
T2K beam dt = 1902.2 ns
Inner: 1601 hits, 3681 pe
Outer: 2 hits, 2 pe
Trigger: 0x80000007
D_wall: 614.4 cm
e-like, p = 381.8 MeV/c

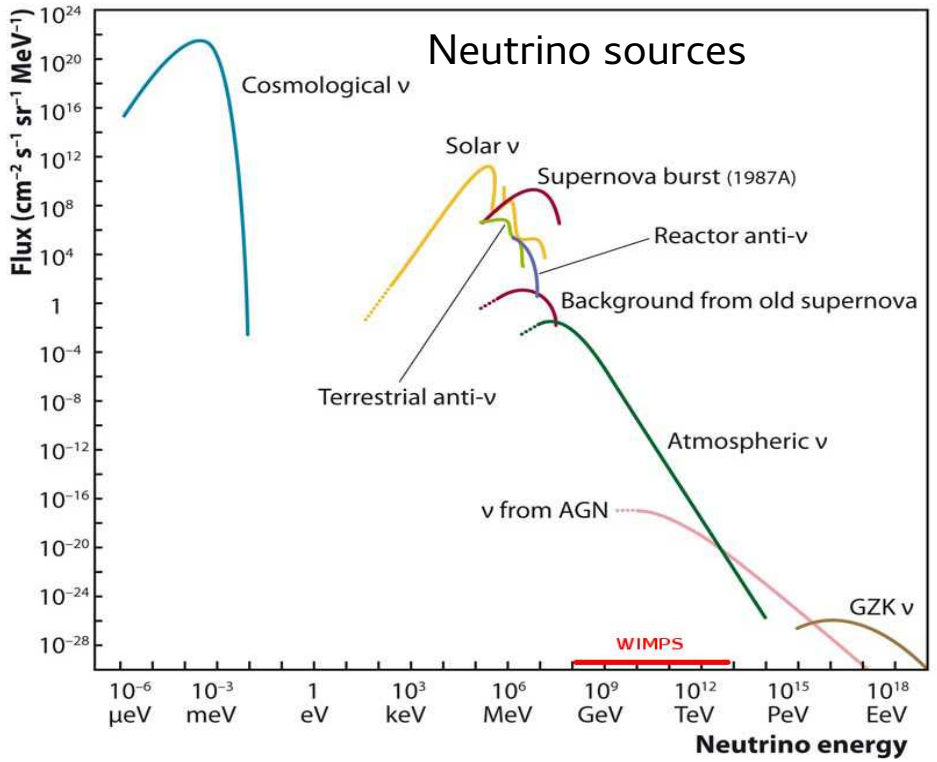


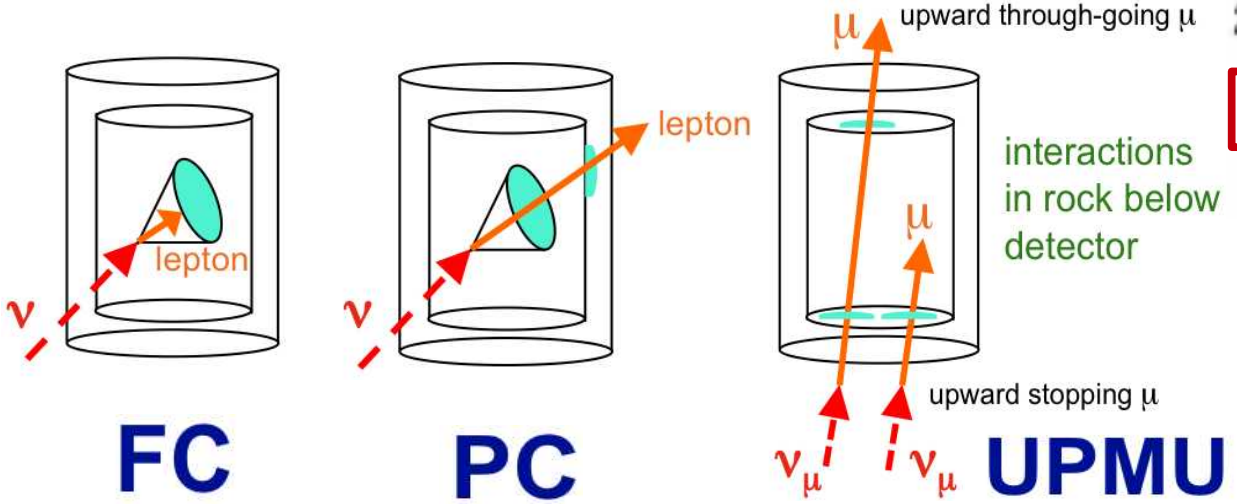
Detected Cherenkov light allow to reconstruct **energy**, **direction** and **flavor** of produced lepton



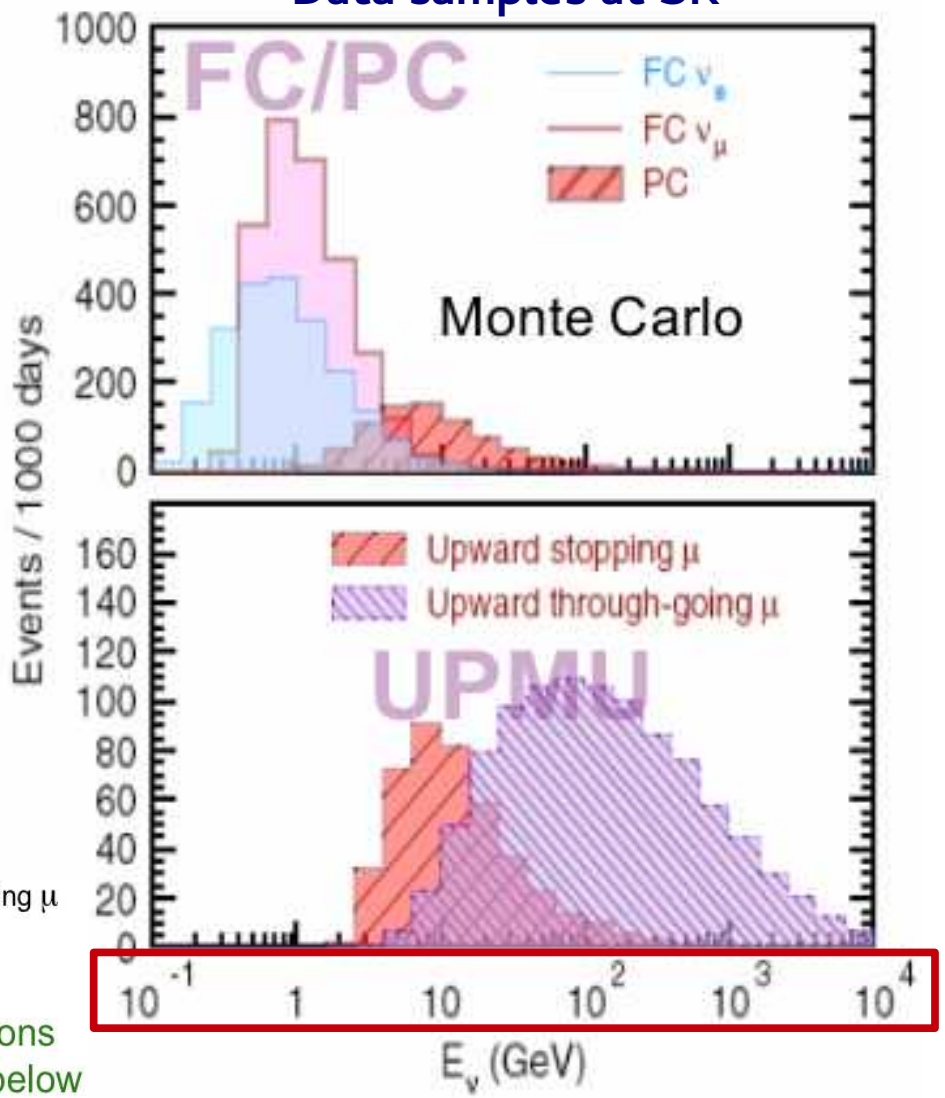
Atmospheric neutrinos

– main background for DM search





Data samples at SK



~10 events /day

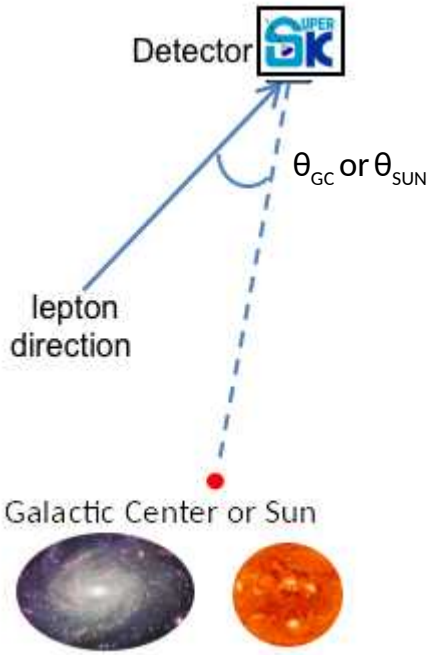
Data period 1996–2014

~40 000 events in total

Dark matter searches at SK

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

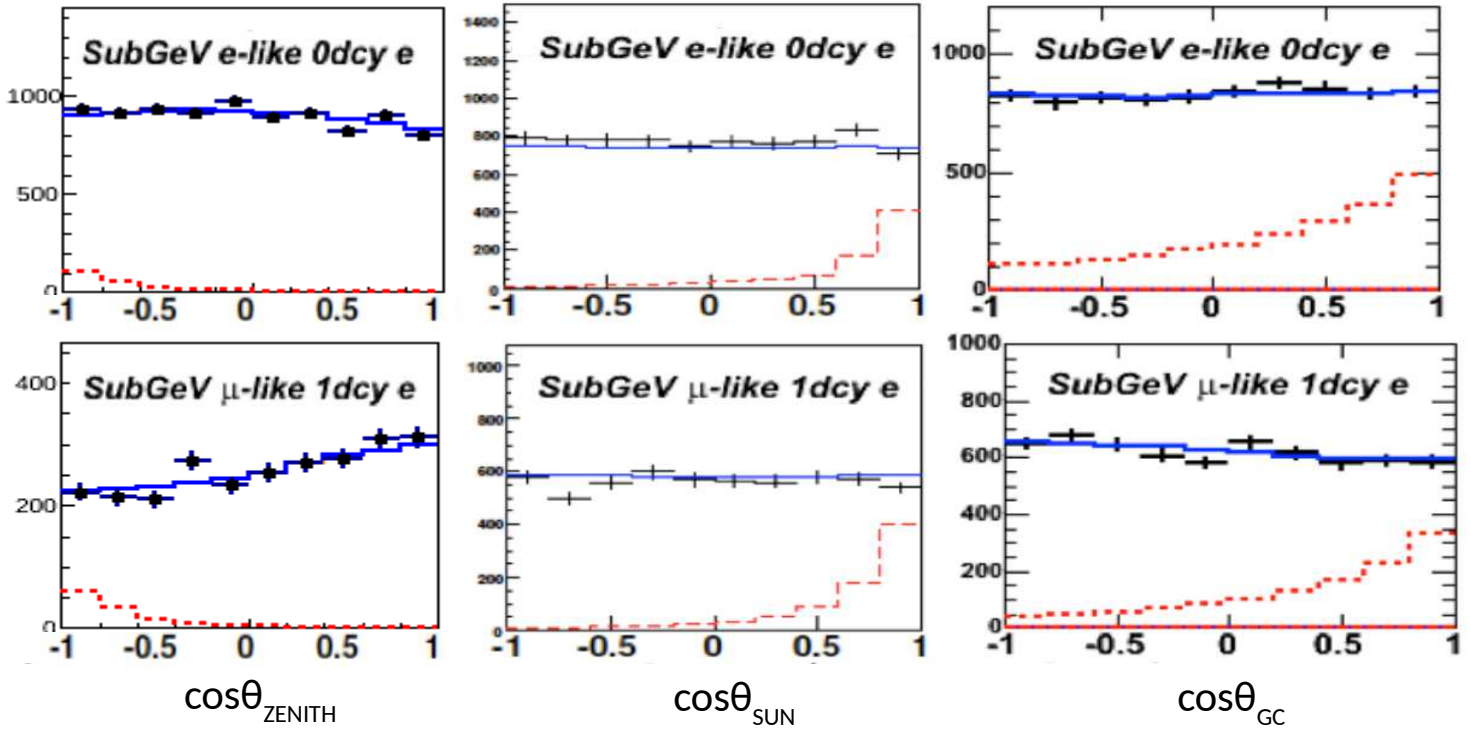
- **FIT:** for each tested WIMP mass, find the configuration of **ATM υ's + DM signal** that would match **DATA** the best



Earth WIMP search
– diffuse search

Solar WIMP search
– point–like search

Galactic WIMP search
– diffuse search



Example: bb signal before fit shown for 2 data samples

SK DATA

ATM MC (BKG) with oscillations

DM signal shape enhanced for illustration

- **Analysis is performed in the coordinate system in which expected signal is easy to distinguish from the atmospheric background**

Analysis steps

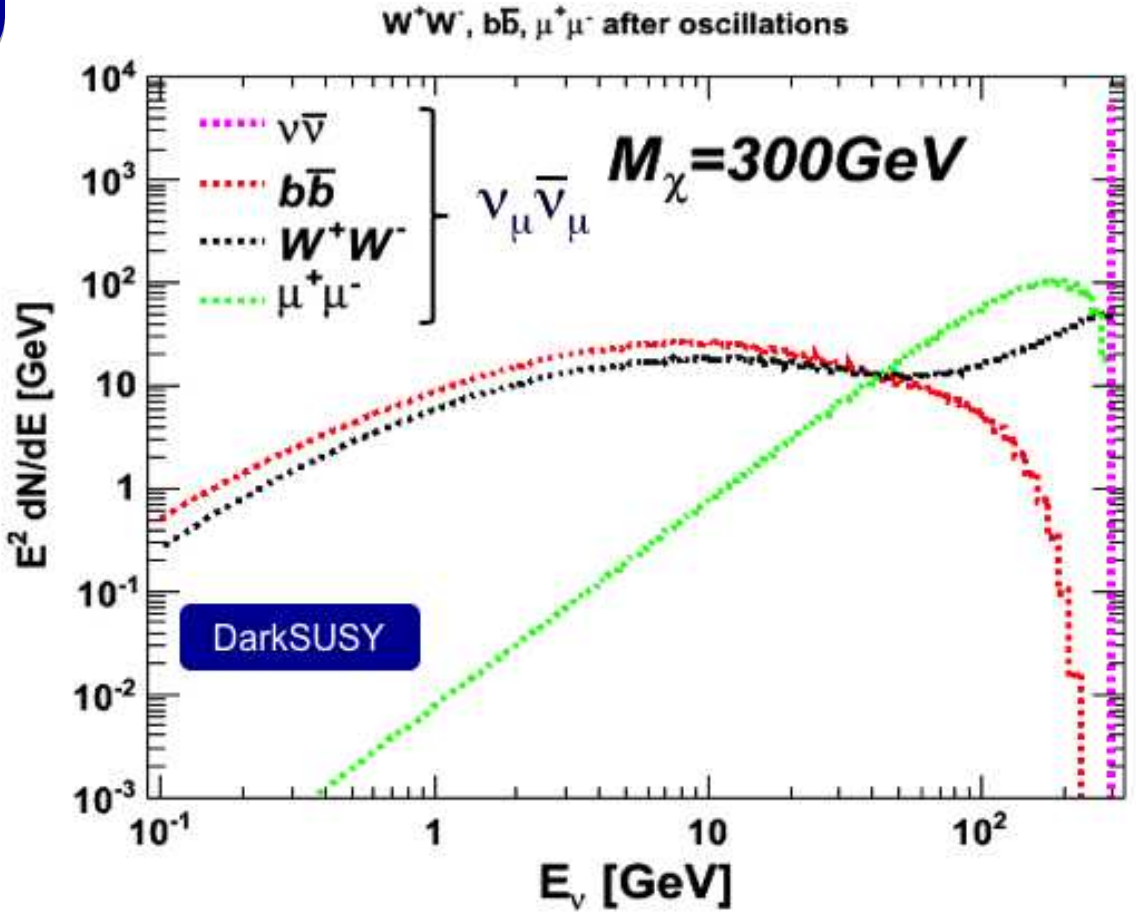
1 **Simulate DM signal before detection ➡ DarkSUSY & WimpSim**

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 constraints from systematic uncertainties

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



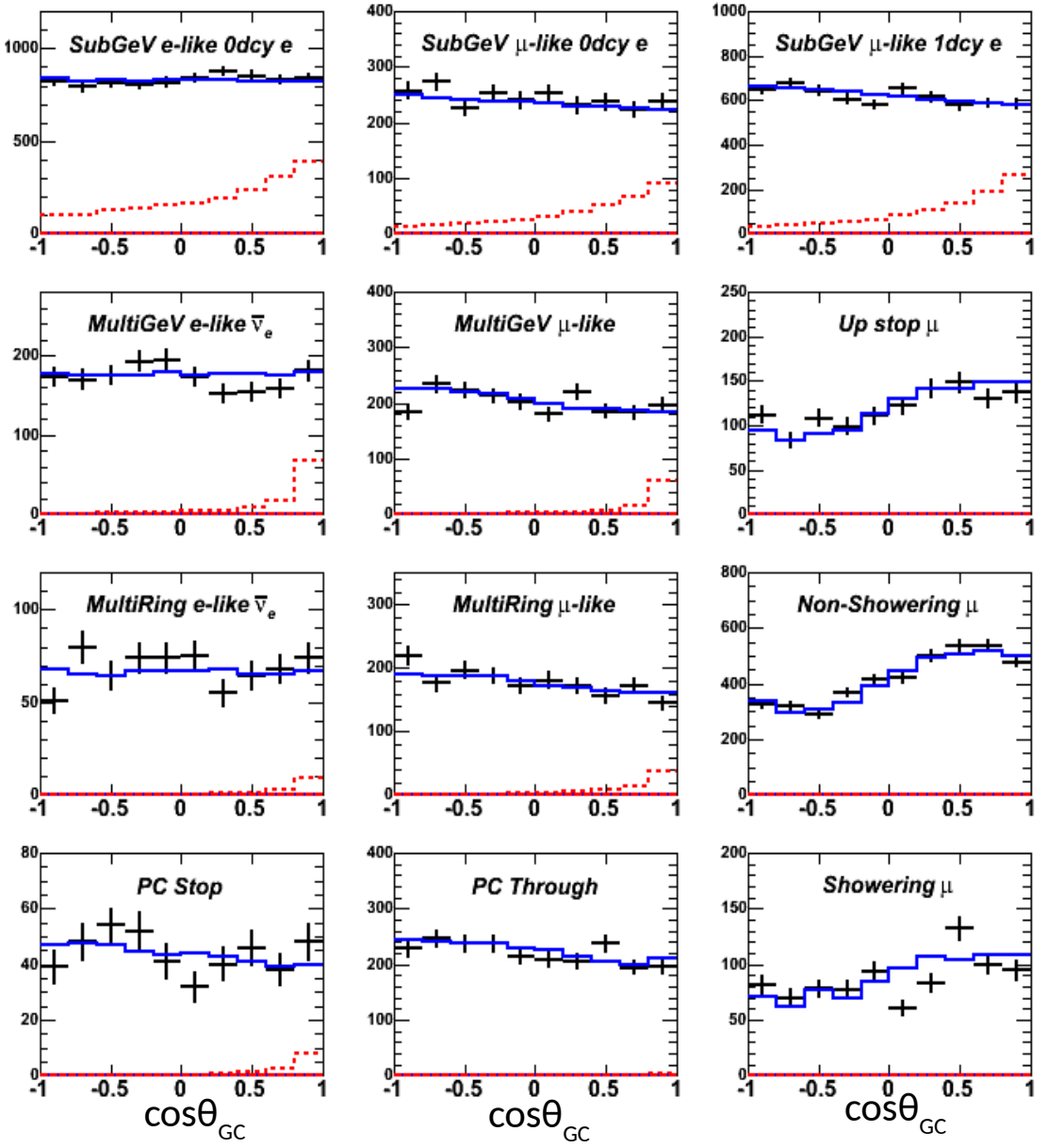
Analysis steps

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 constraints from systematic uncertainties

Example: 5 GeV WIMPs from GC, $b\bar{b}$ annihilation channel



→ proportions of the signal in various samples are reflected

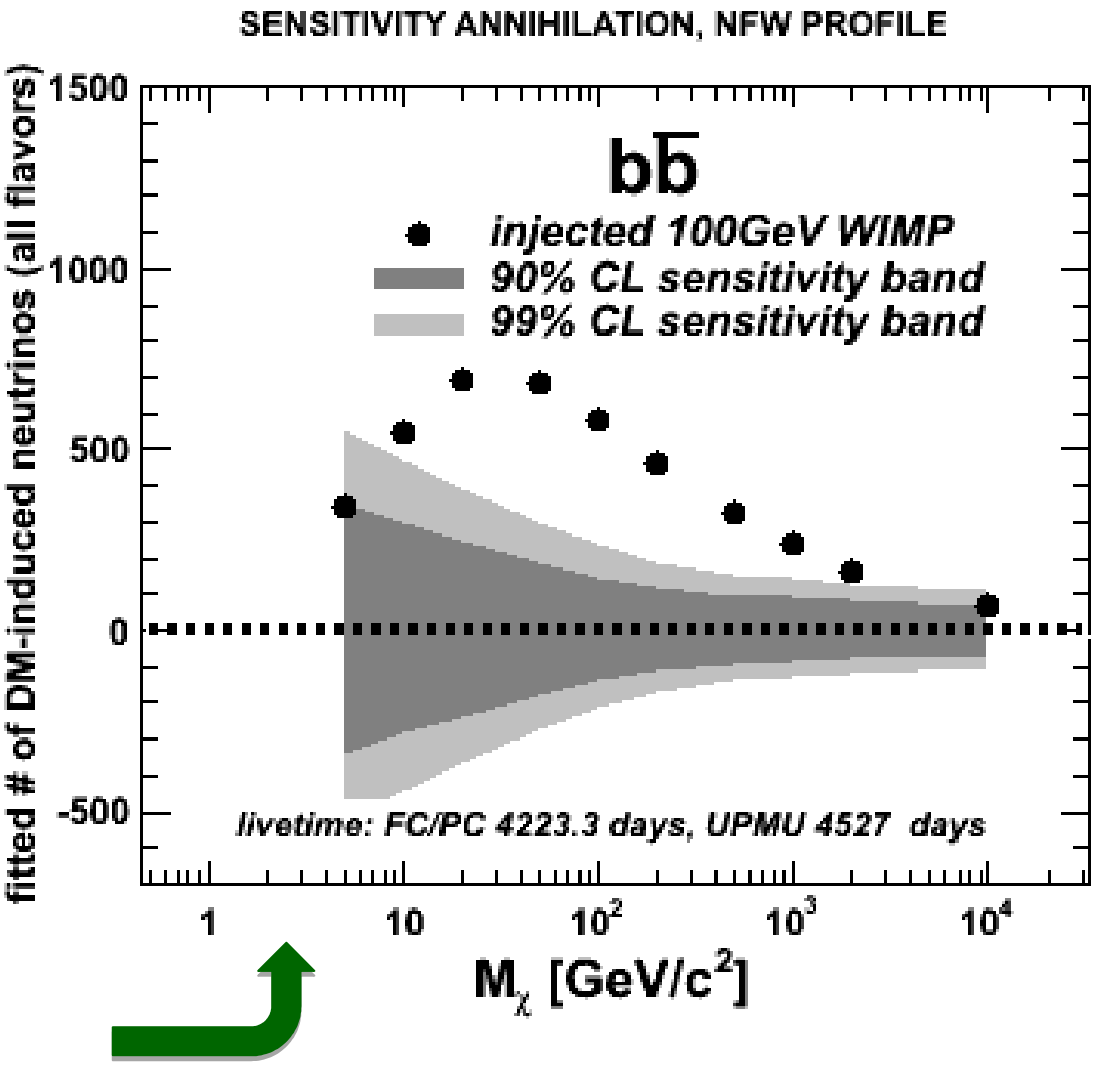
Analysis steps

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 constraints from systematic uncertainties**

Example: Injected 100 GeV WIMP as 1.5% of BKG



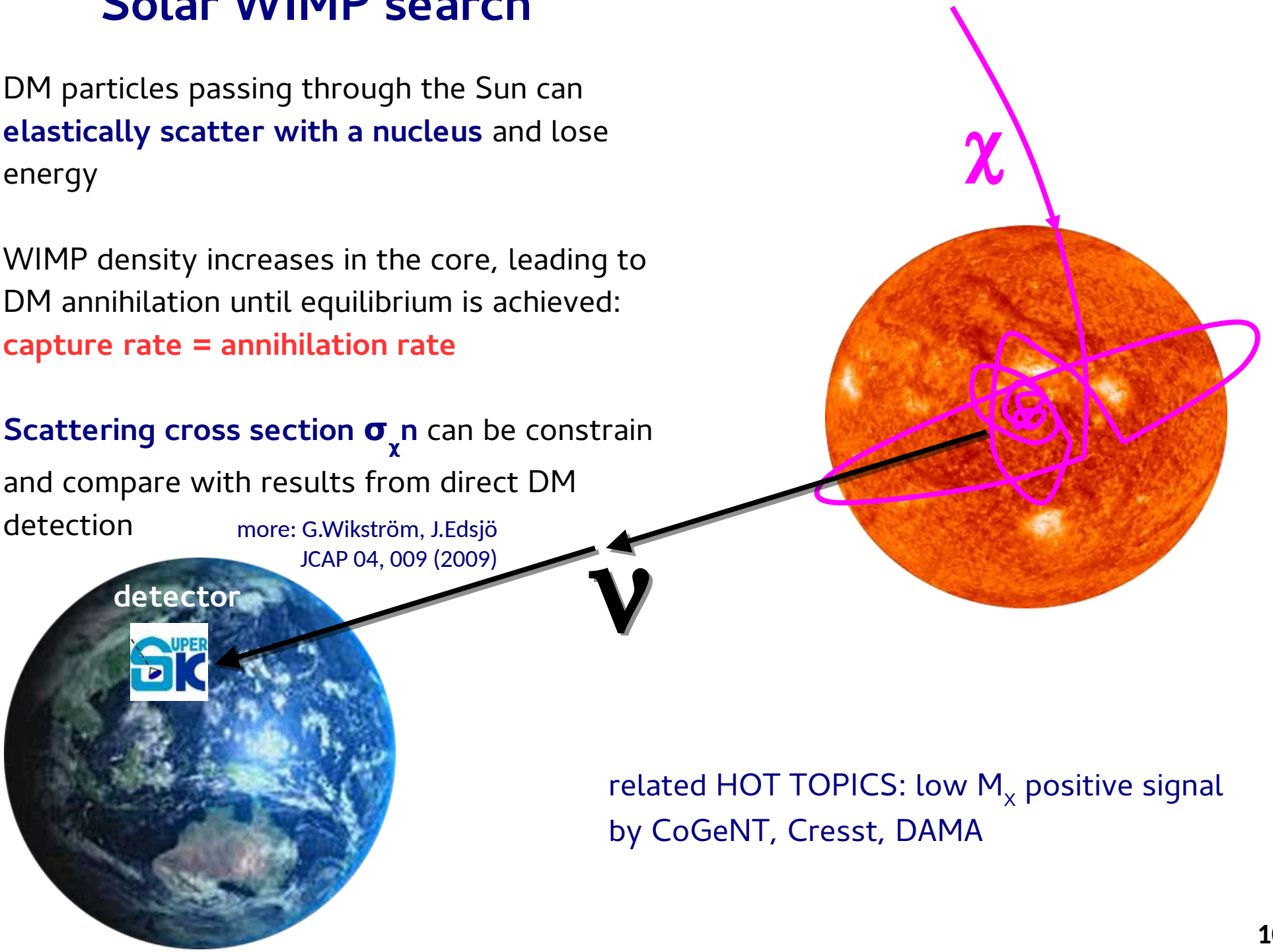
Solar WIMP search

- 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

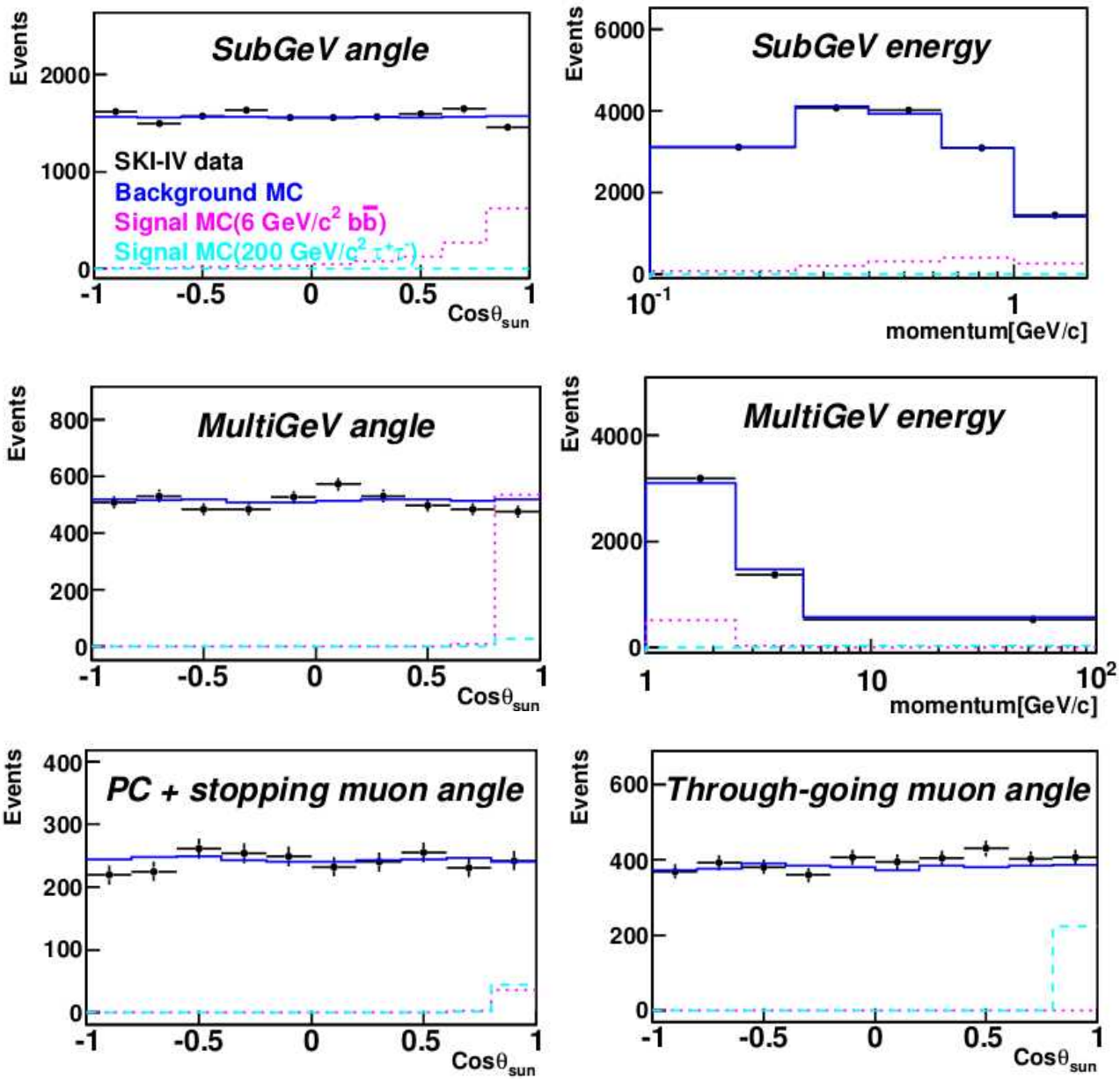
more: G.Wikström, J.Edsjö JCAP 04, 009 (2009)



related HOT TOPICS: low M_χ positive signal by CoGeNT, Cresst, DAMA

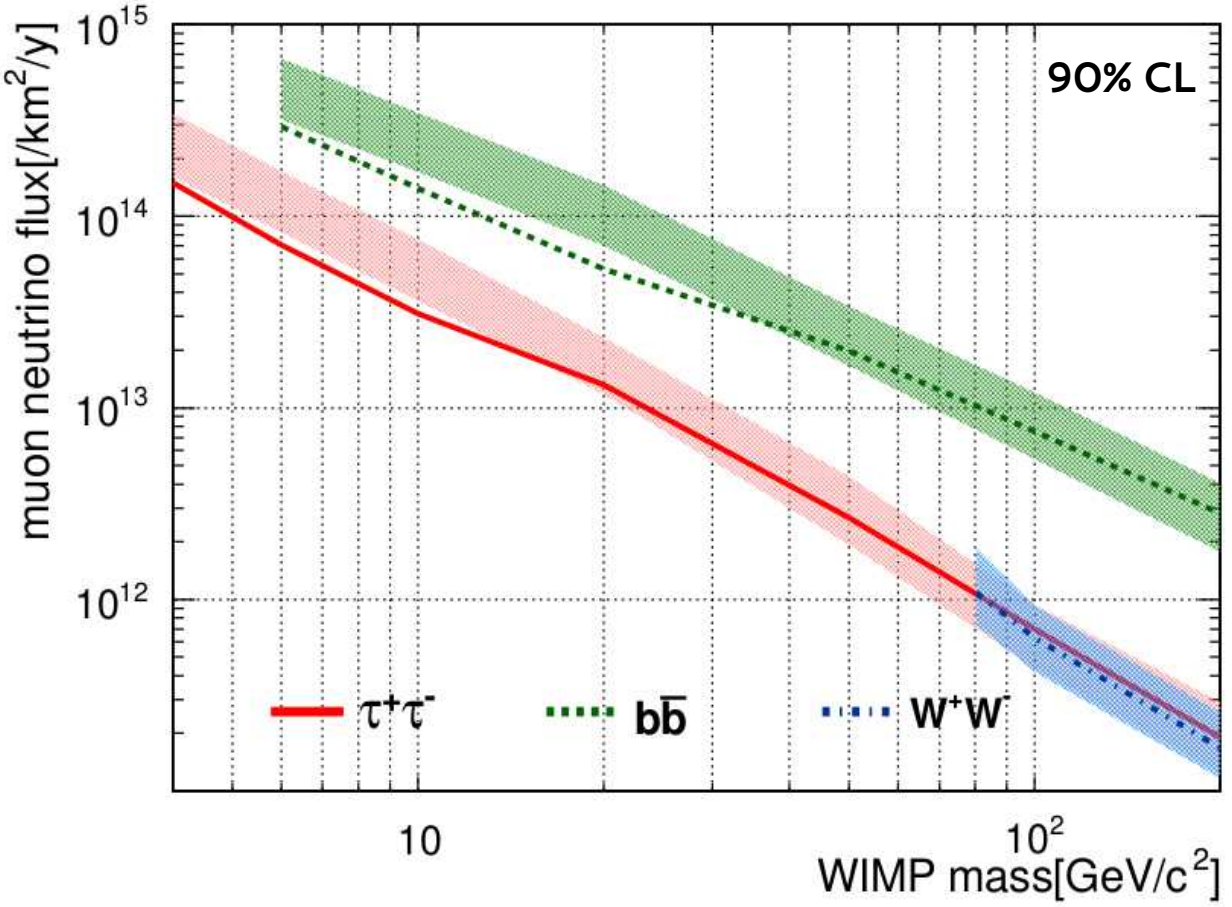
Solar WIMP search – fit results

- 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 $\sigma_{\chi n}$



Solar WIMP search – muon neutrino flux

- 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

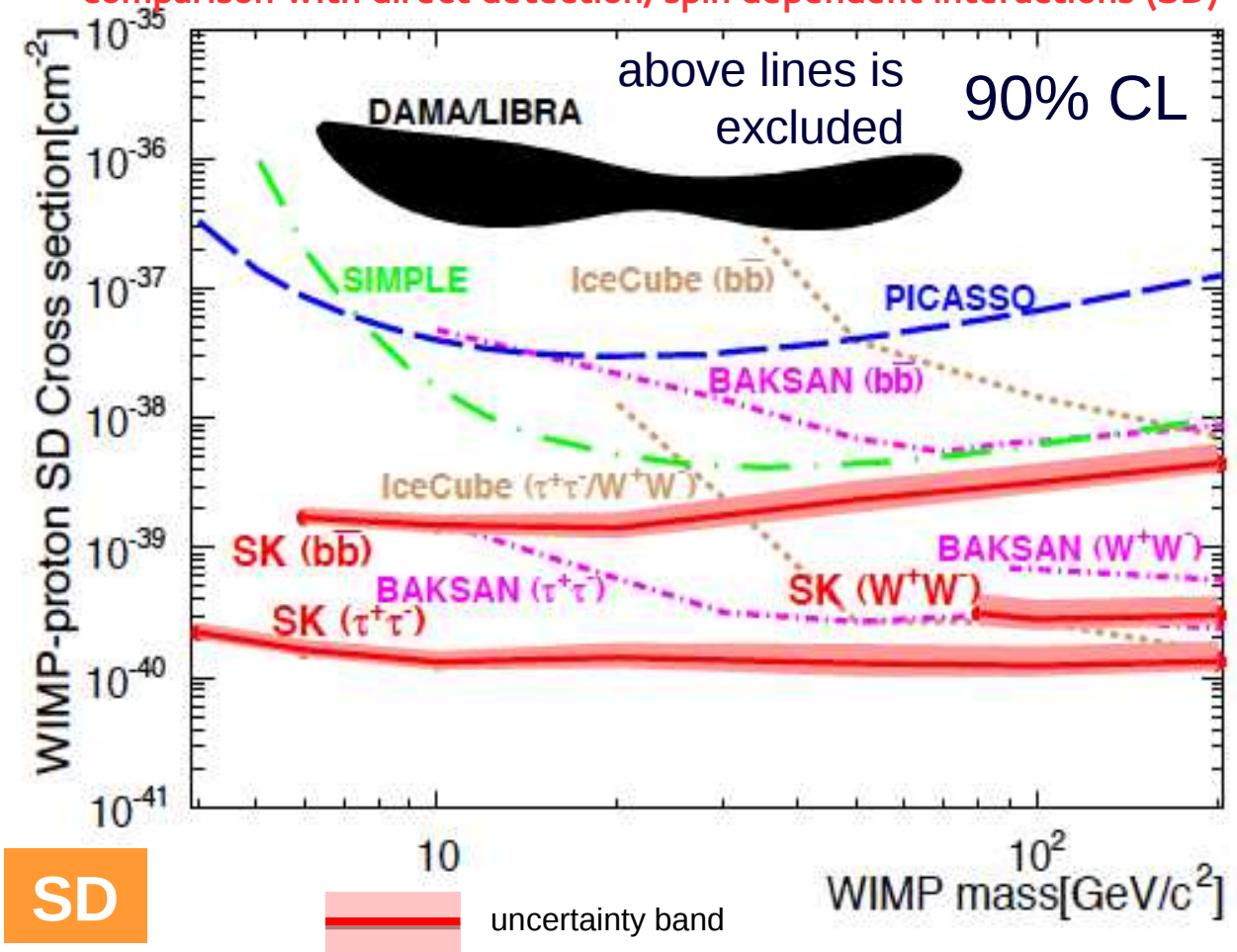
Solar WIMP search – WIMP–proton SD cross section

→ axial vector interaction in which WIMPs couple to the nuclear spin

- 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 $\sigma_{x}n$**

→ DAMA region excluded

comparison with direct detection, spin dependent interactions (SD)



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

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

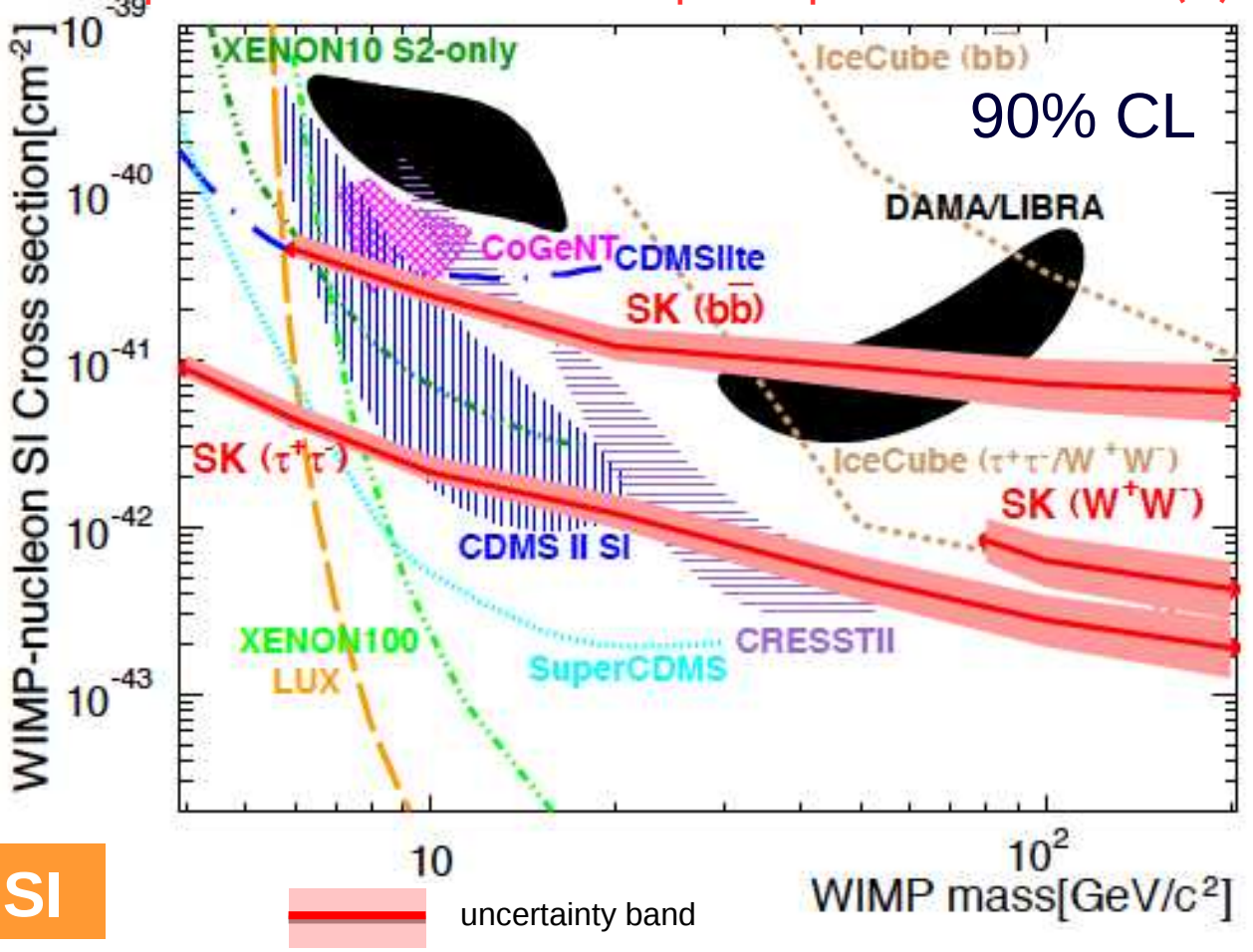
Solar WIMP search – WIMP–nucleon SI cross section

→ scalar interaction in which WIMPs couple to the nucleus mass

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

→ exclusions in the "confusion zone" of positive results

comparison with direct detection, spin independent interactions (SI)



SI

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

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

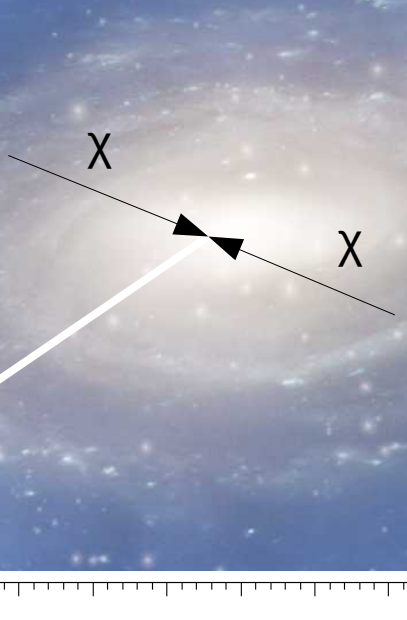
Galactic WIMP search

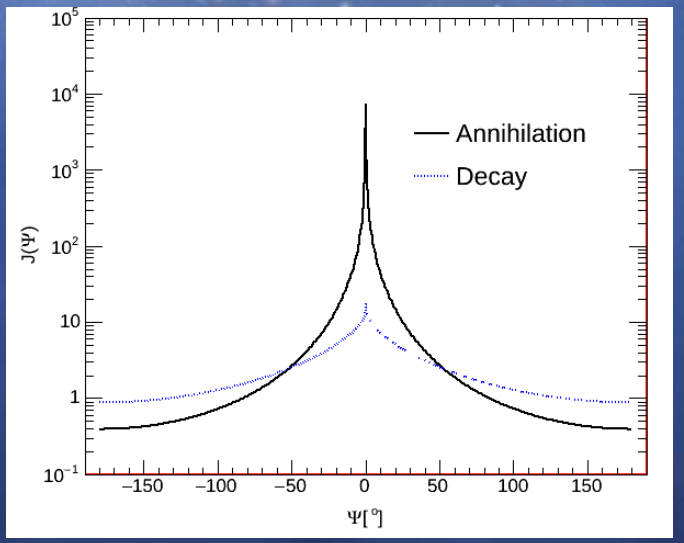
diffuse signal from entire Galaxy, peaked from Galactic Center

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)

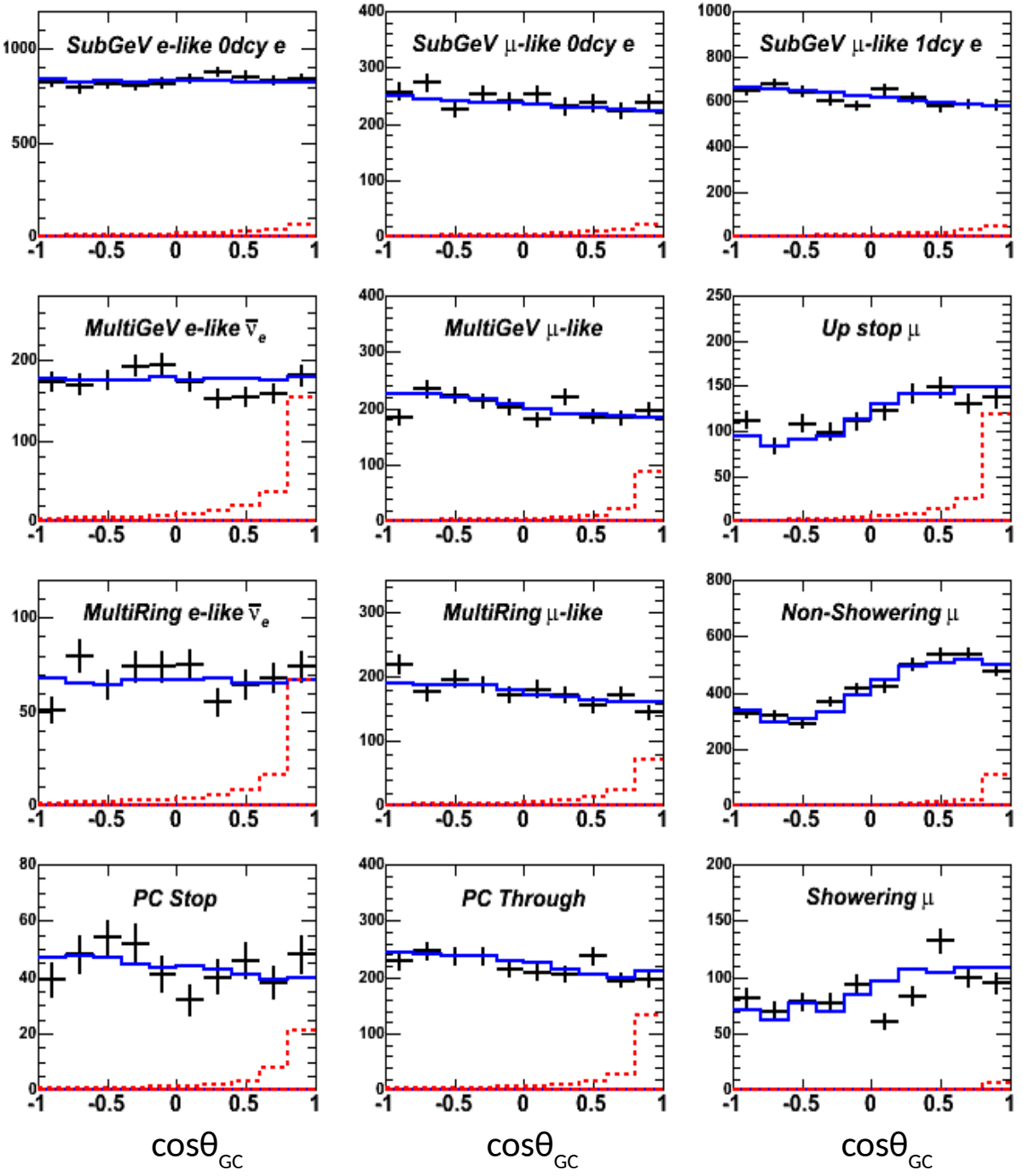




Expected signal intensity

Galactic WIMP search – fit results

- 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 $\langle\sigma_A V\rangle$



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

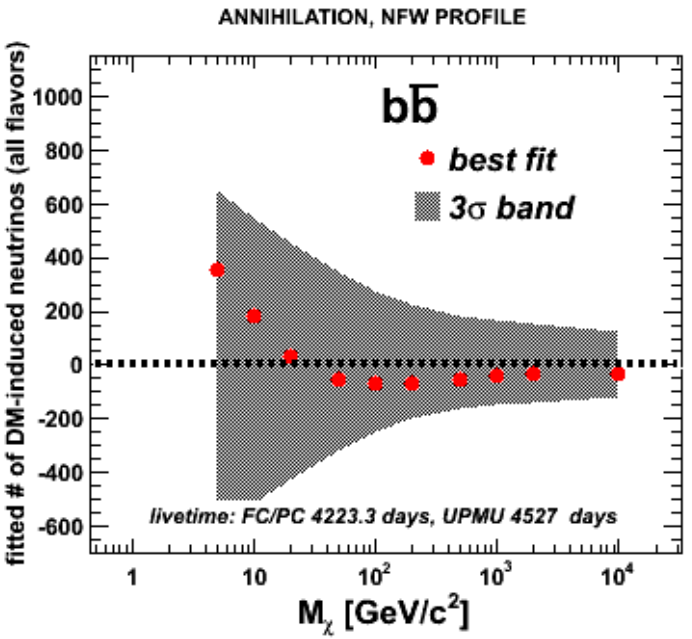
DATA
SK1,2,3,4

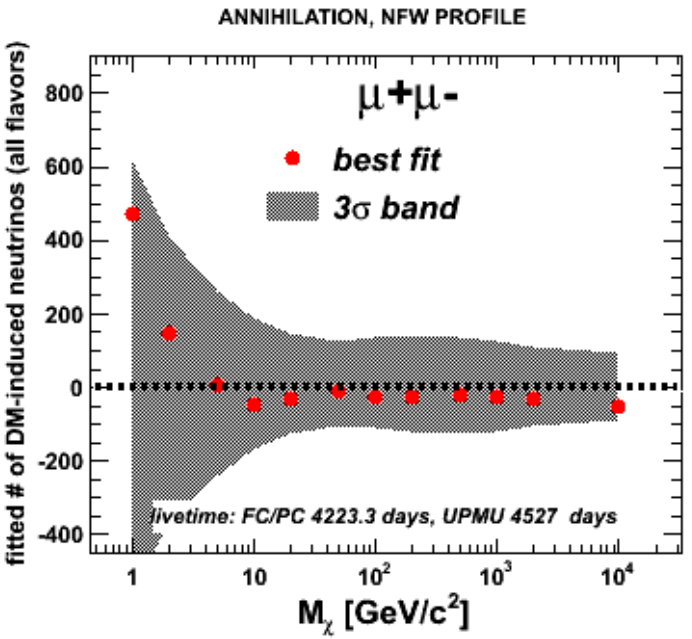
ATM MC+WIMP
at best fit point

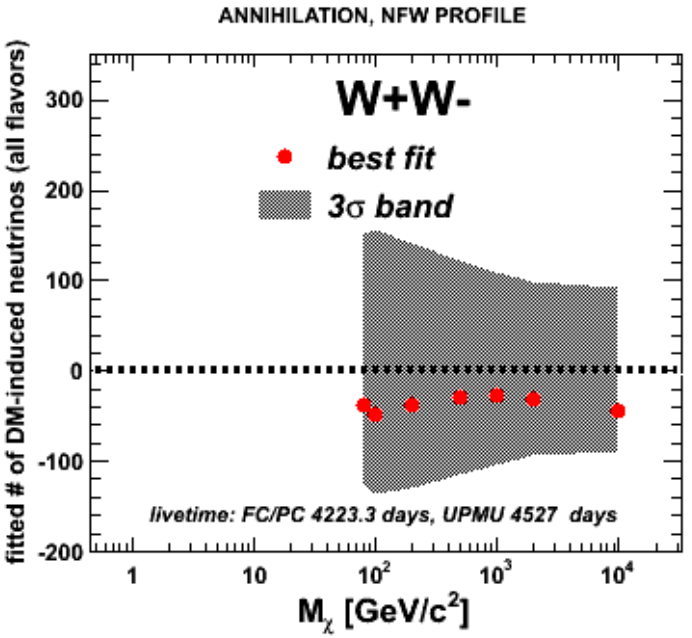
DM ann. signal
illustration
before fit

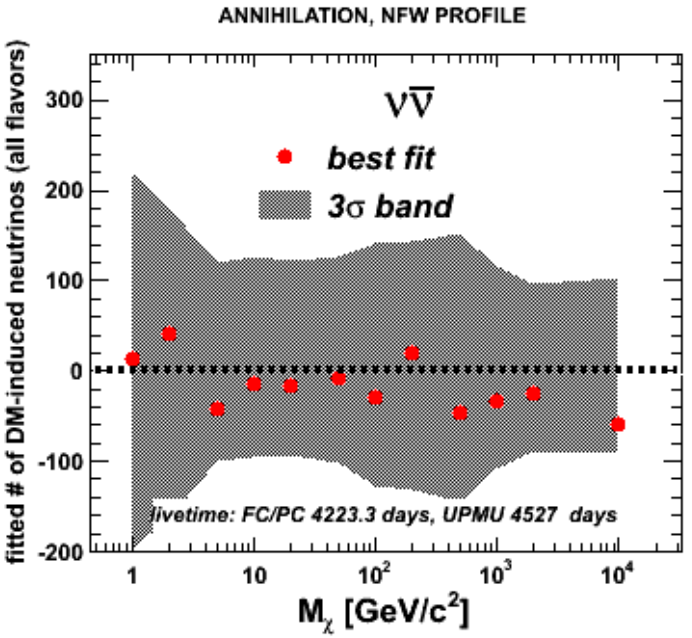
Galactic WIMP search – fitted number of DM-induced neutrinos

- 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 $\langle\sigma_A V\rangle$



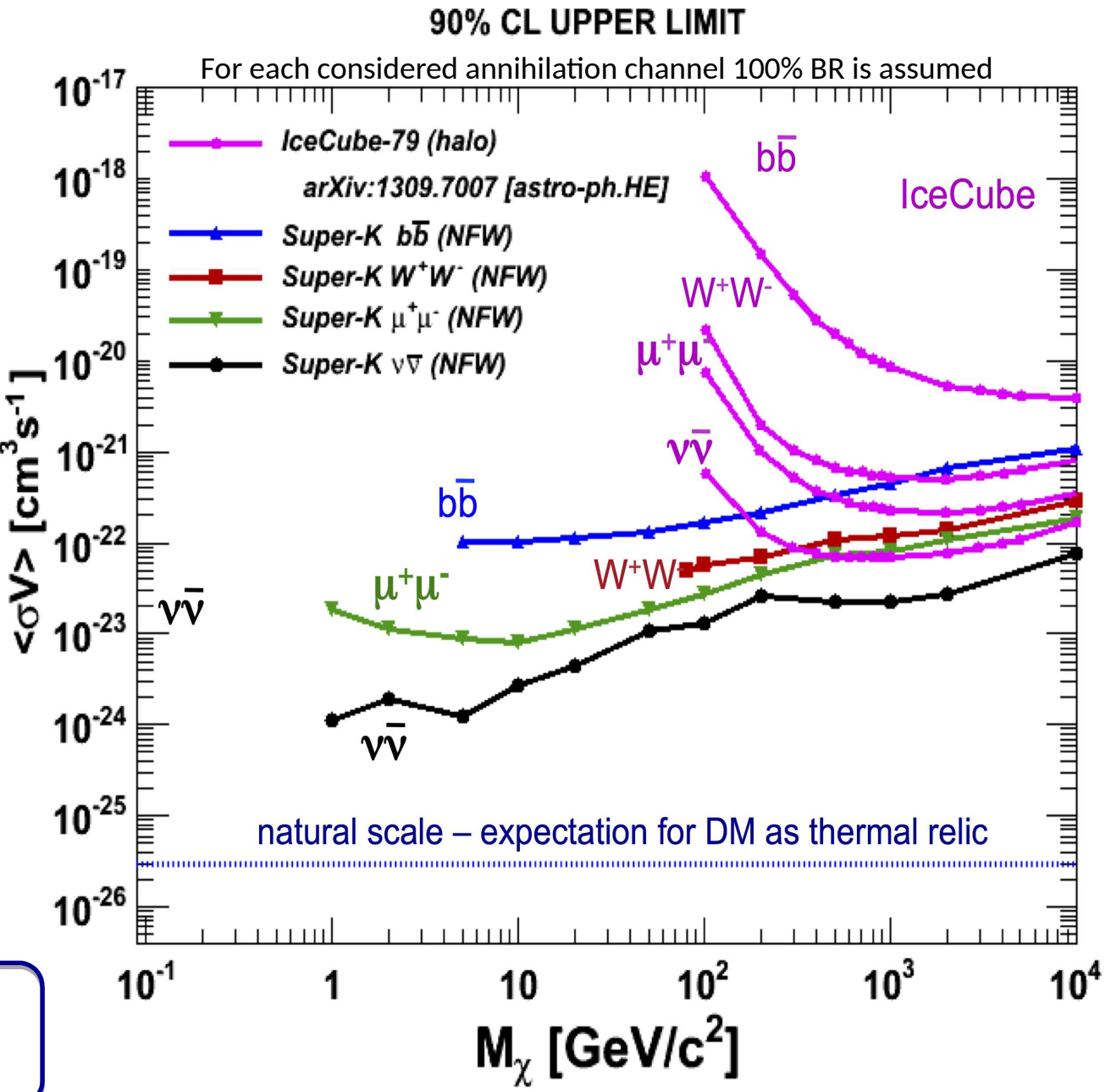






Galactic WIMP search – DM annihilation cross section

- 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 $\langle\sigma_A V\rangle$



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

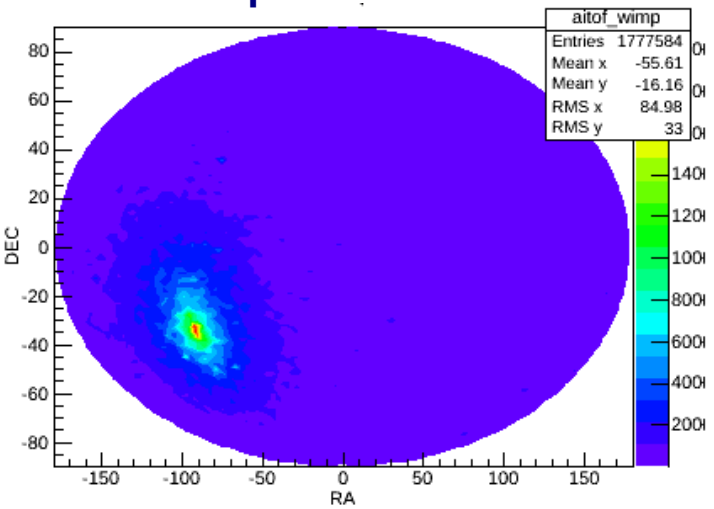
$J_{\Delta\Omega}$ is integrated intensity over all sky, depends on DM halo profile

Galactic WIMP search

different approach

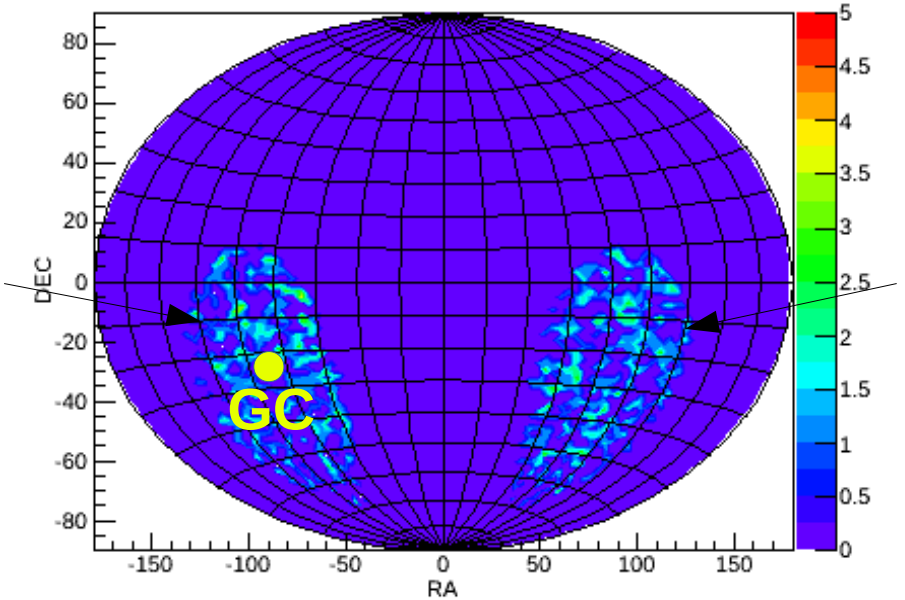
- Analysis uses **on–source/off–source method** to estimate the background directly from the data
  - method independent of MC simulations and related systematic uncertainties
- DM simulation is used only to optimize analysis

Expectations:



on-source

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



off-source

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

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

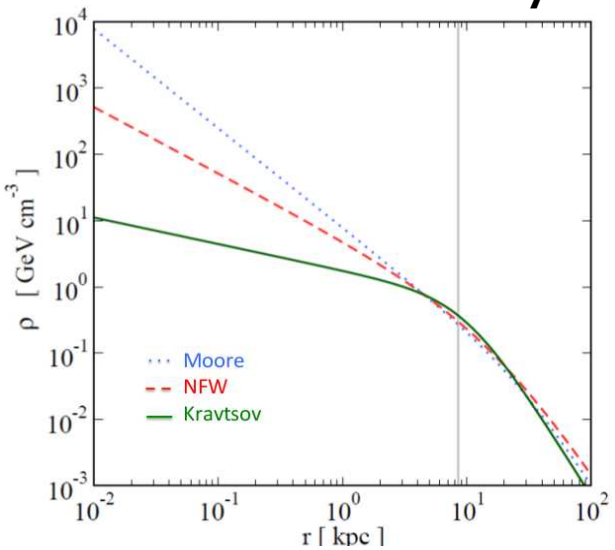
Galactic WIMP search

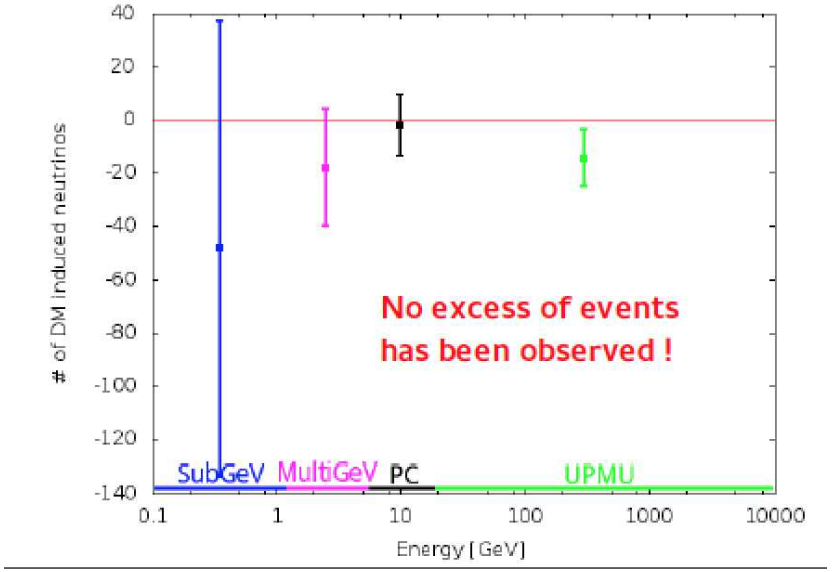
ON– & OFF–source methods results

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

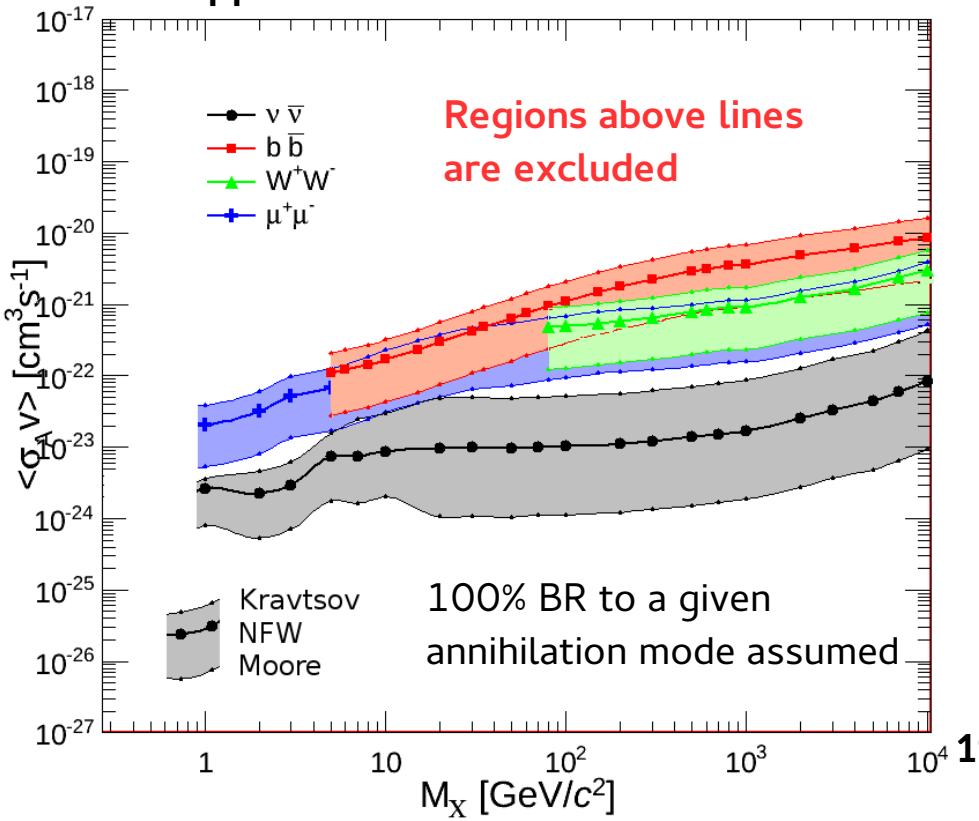
Sample	Size	On–source	Off–source	ΔN sig	90% CL ΔN sig
FC Sub GeV	80	3628	3676	-48 ± 85.5	114.4
FC Multi GeV	30	233	251	-18±22	26.9
PC	20	65	67	-2 ± 11.5	17.7
UPMU	10	49.2	63.5	-14.3 ± 10.6	10.8
ALL	35	2010.4	2161.1	-150.7±64.6	49.3

Dark Matter density





90% CL upper limits + halo model choice influence



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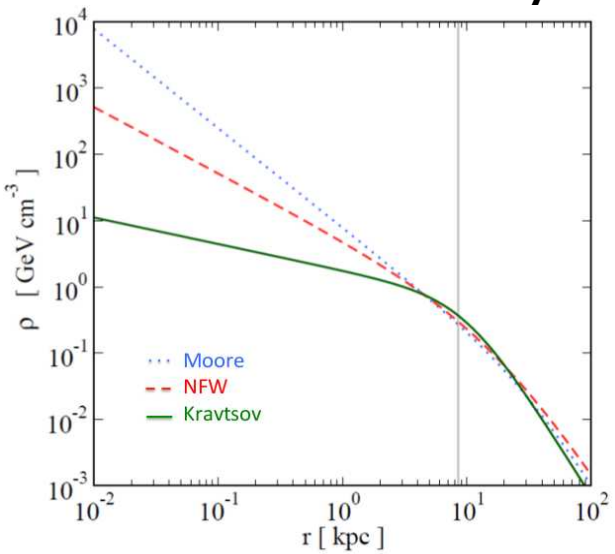
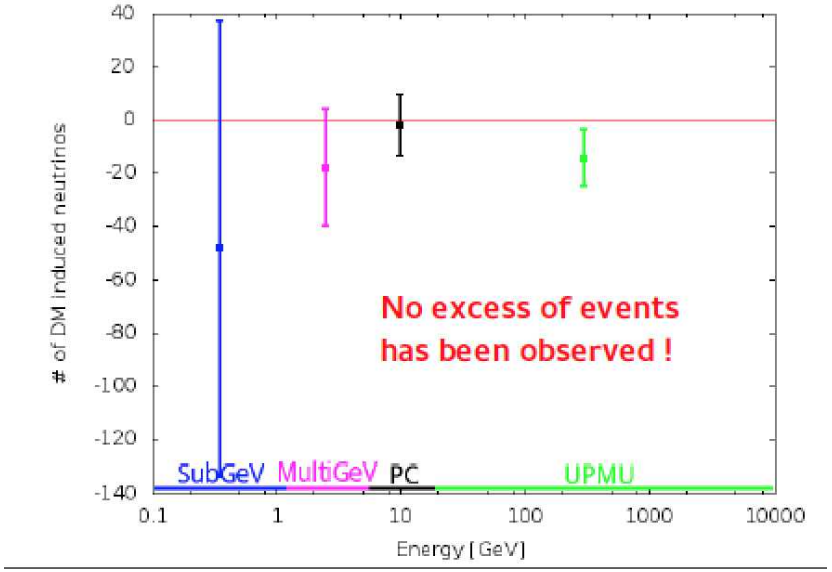
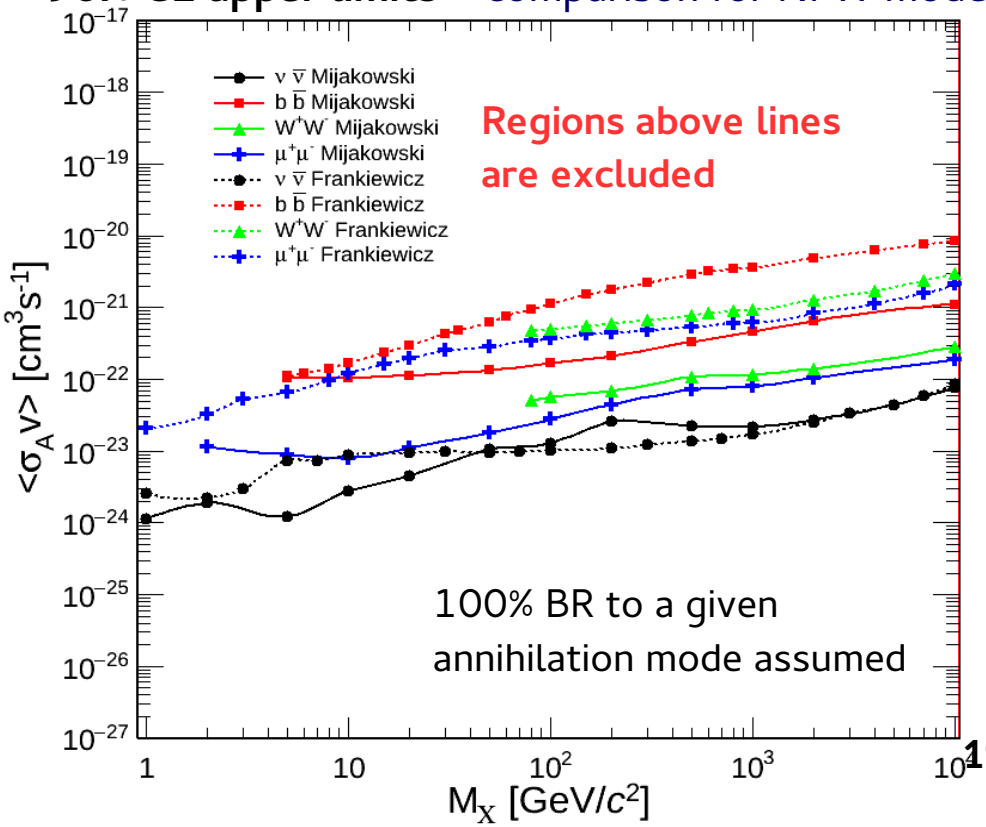
Dark Matter density





90% CL upper limits – comparison for NFW model



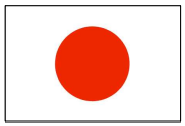
Summary

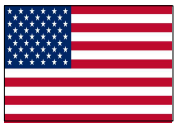
- No excess of DM induced υ's has been observed at SK

- Solar WIMP search – results recently published
  - current best limits on the SD WIMP–proton cross section for WIMP masses below 200 GeV/c^2

- Galactic WIMP search
  - upper limits on DM self–annihilation cross section $<\sigma_A V>$ in wide energy range from 1 GeV to 10 TeV
  - estimated DM halo model influence

Super-Kamiokande collaboration


~60%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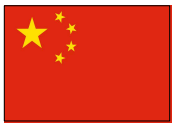
~6%


~3%


~5%


~1%


~1%

A recent author list for the **Super-Kamiokande Collaboration**

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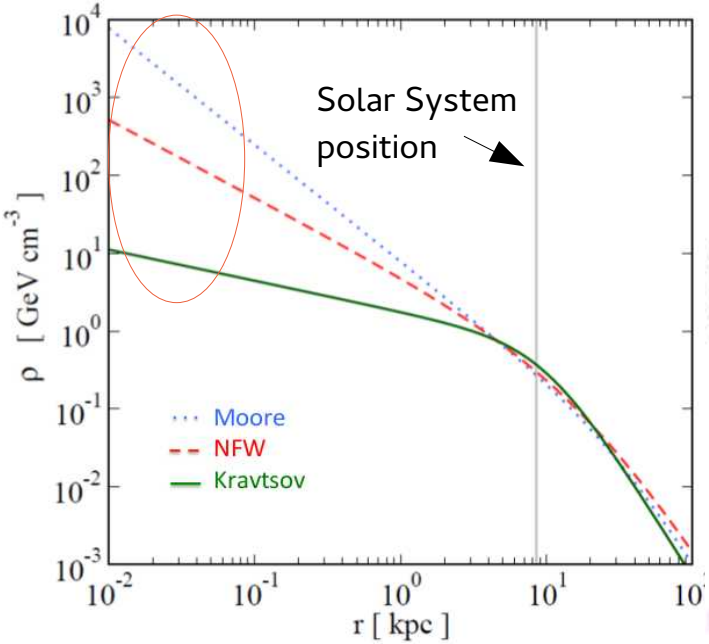
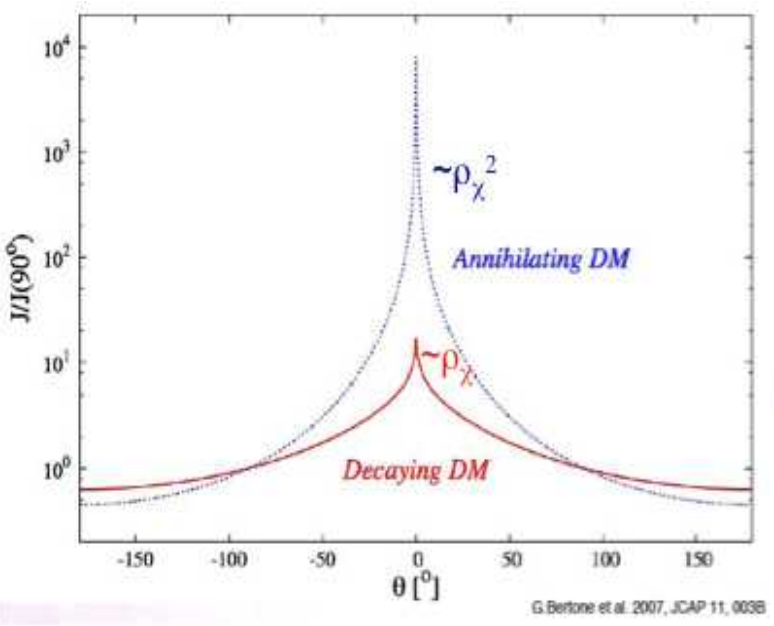
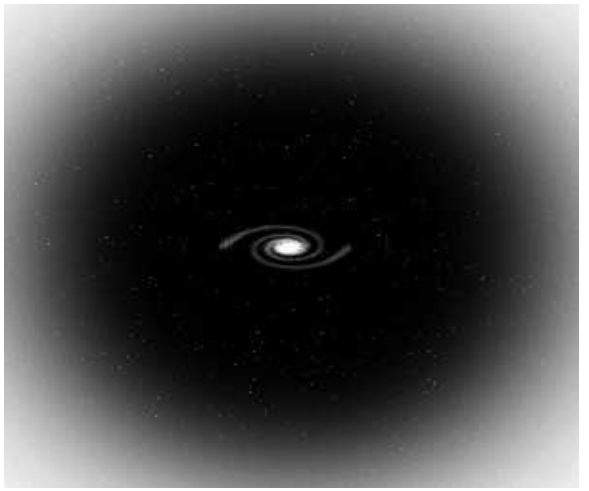
Dark Matter halo models

Dark Matter density



Expected DM intensity





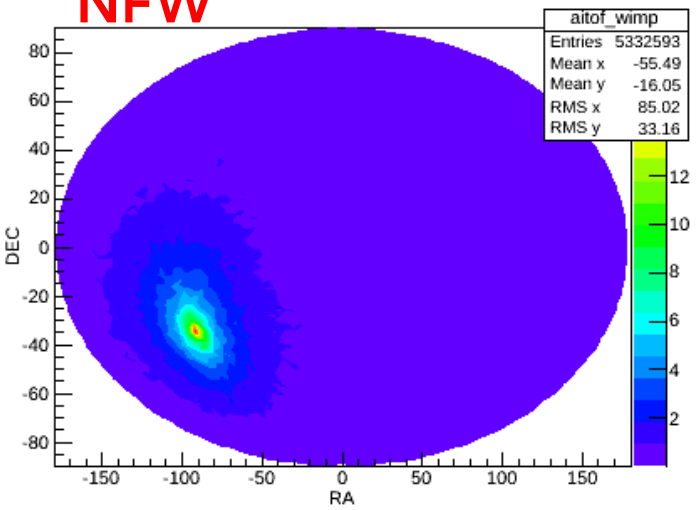
Local DM density

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

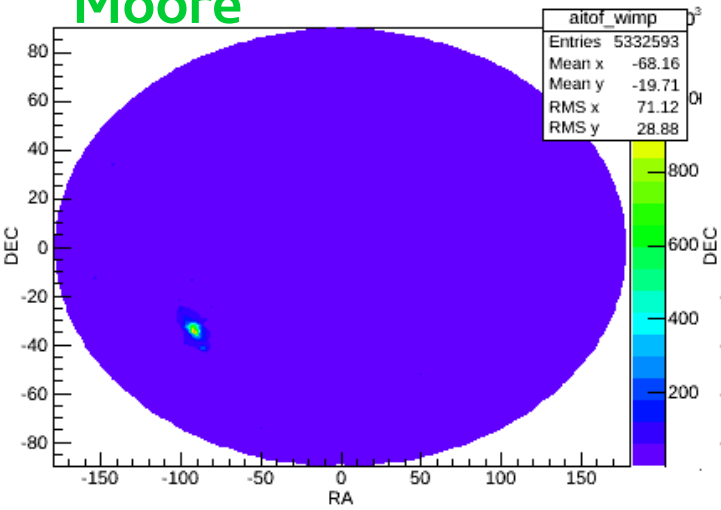
Expected local DM flux

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

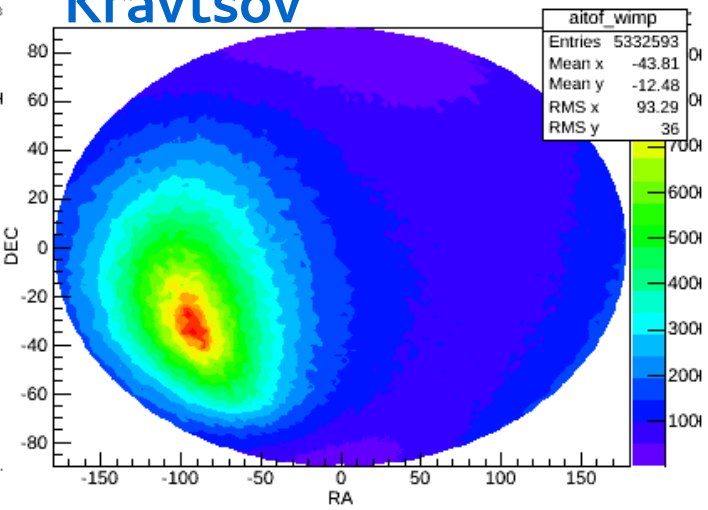
NFW



Moore



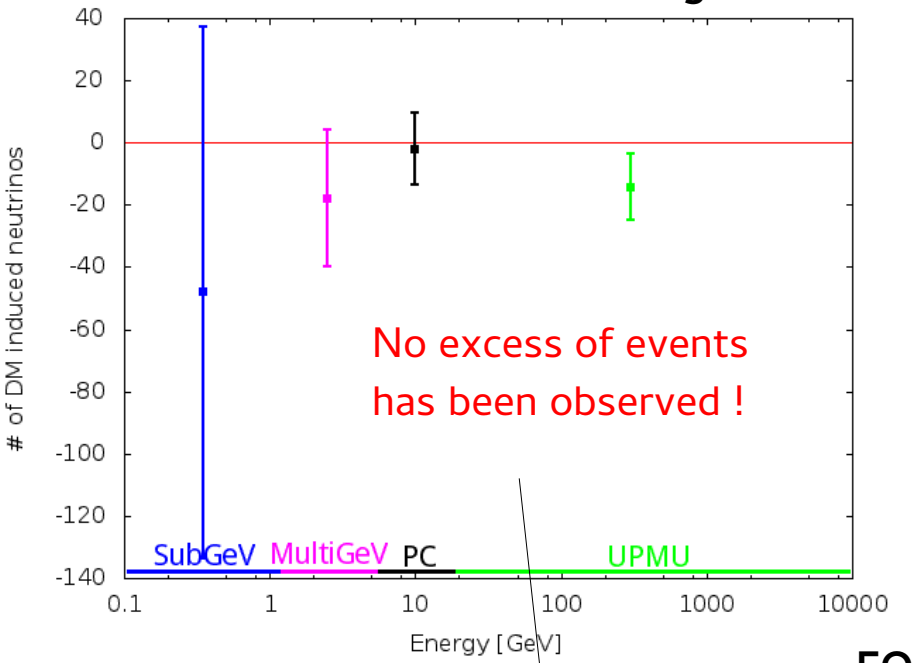
Kravtsov



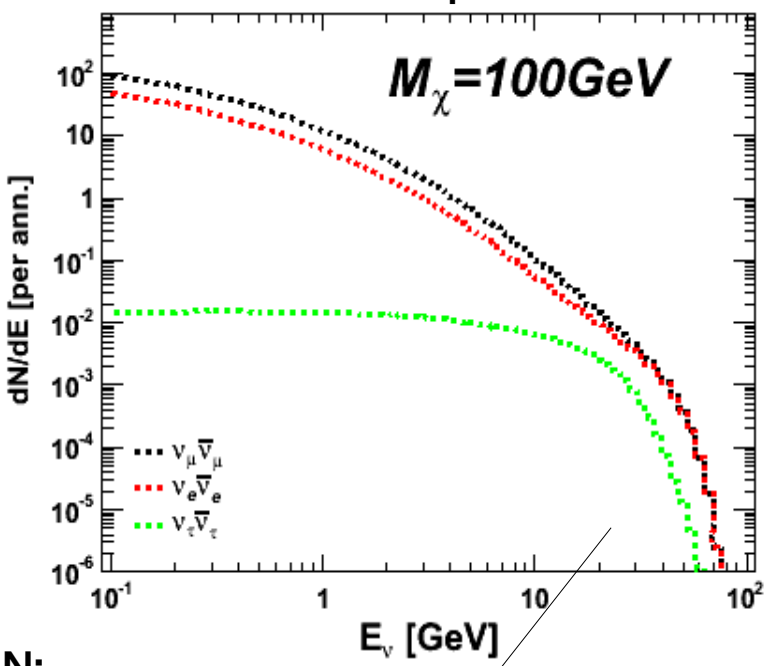
NFW – benchmark model

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 $b\bar{b}$:

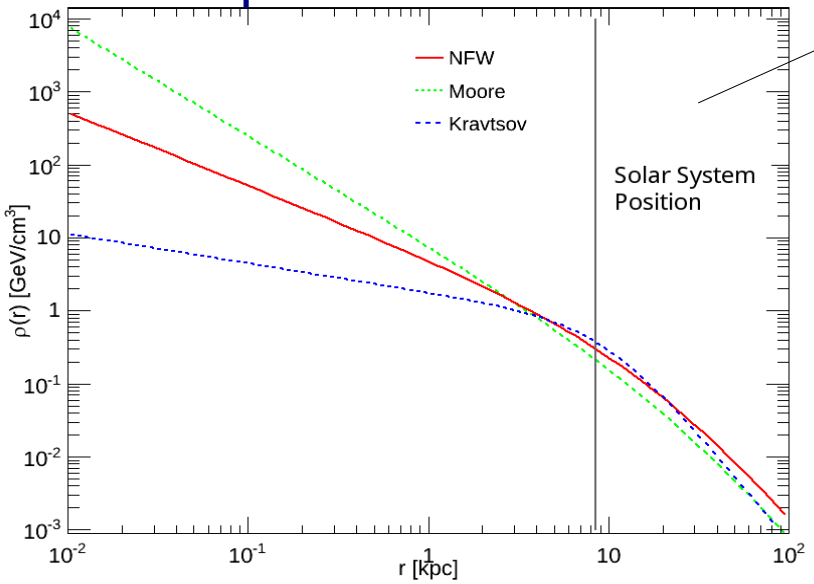


FOR ANNIHILATION:

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

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

DM halo profiles



Futher interpretation:

For assumed m_χ
we can calculate $\langle\sigma_A v\rangle$

The same procedure
for DM decay analysis