Search for light WIMPs captured in the Sun using contained events in Super-Kamiokande

12/09/2013

TAUP2013 in Asilomar

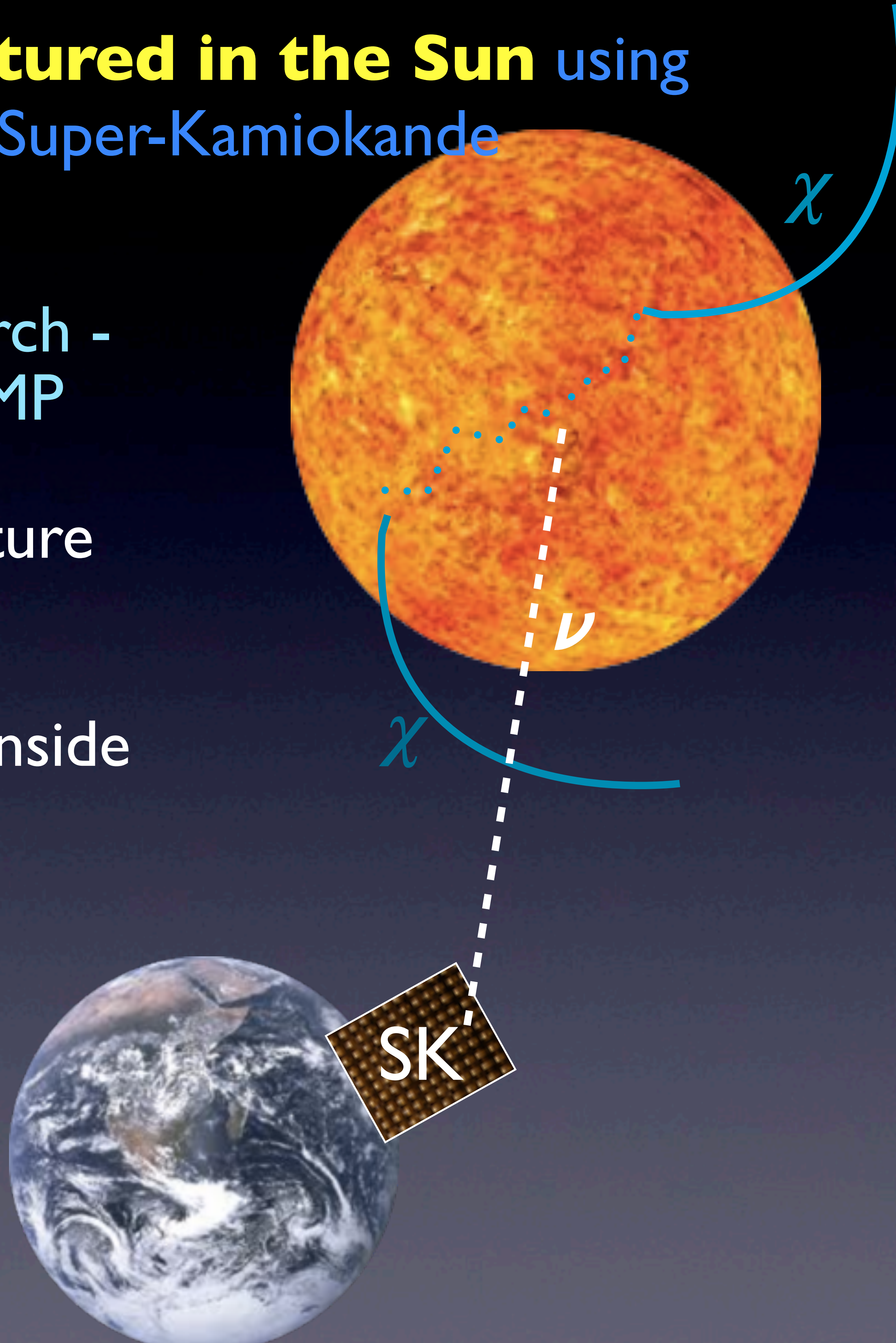
Nagoya univ. Koun Choi
for Super-Kamiokande collaboration

Search for the WIMPs **captured in the Sun** using contained events in Super-Kamiokande

indirect solar WIMP neutrino search -
"The Sun is a large Hydrogen WIMP detector for free"

- Huge gravity allows enough capture to achieve equilibrium between capture & annihilation
- The capture process of WIMPs inside the Sun is the same with direct detection

"Strong sensitivity to SD cross-section, competitive to direct detections"



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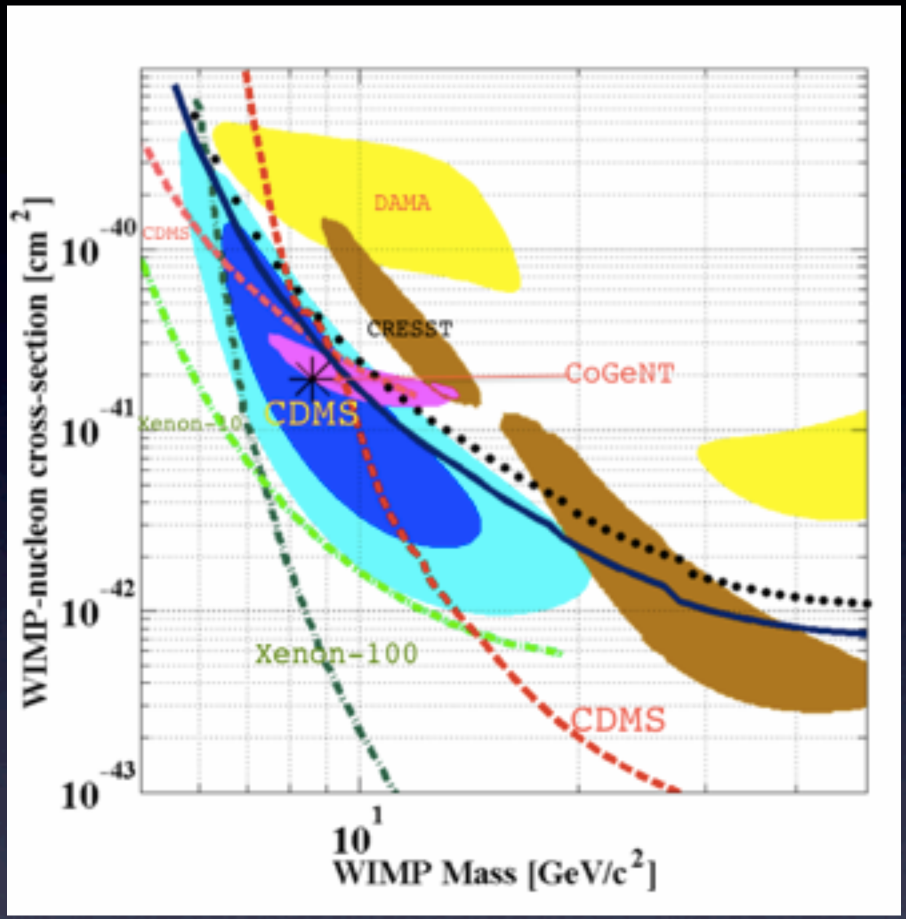
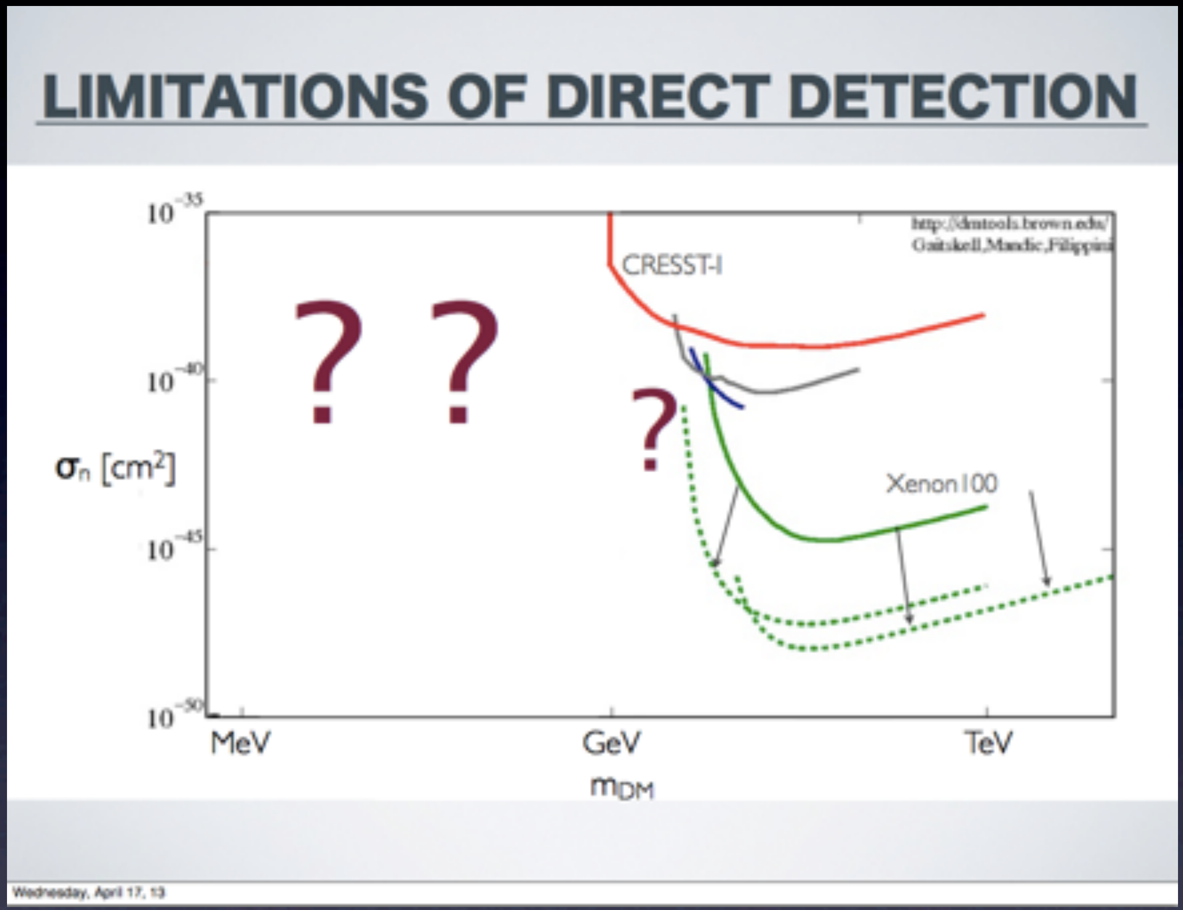


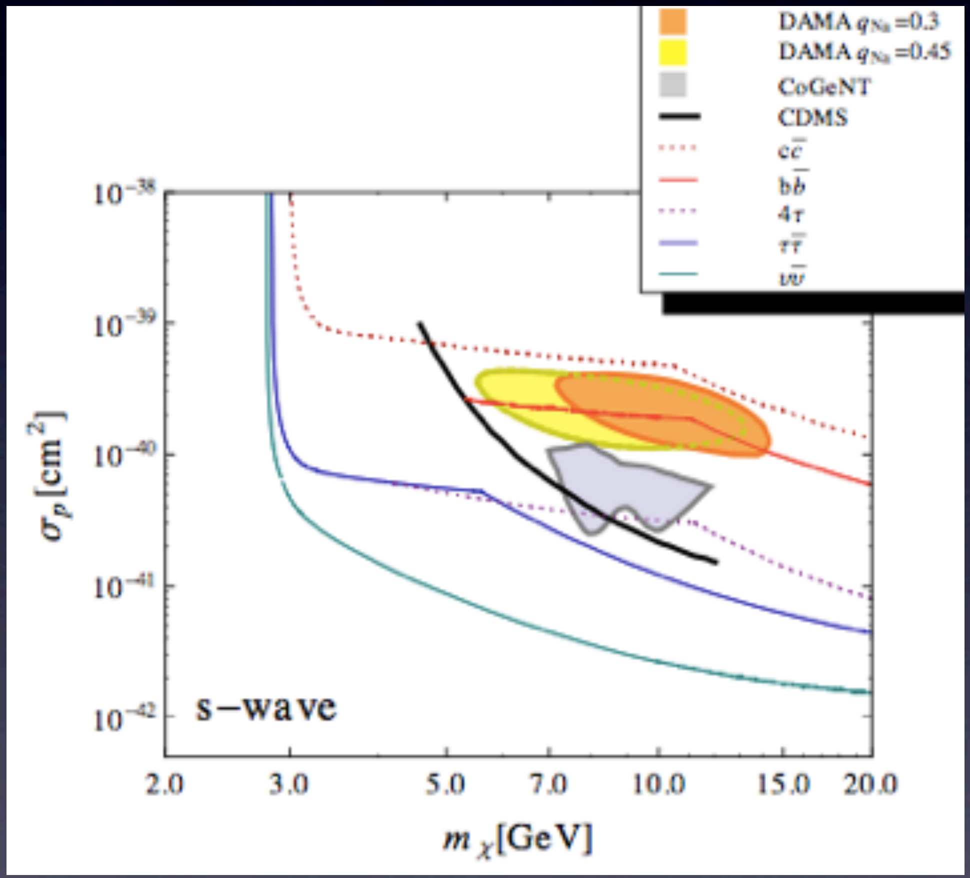
CDMS collaboration 1304.4279

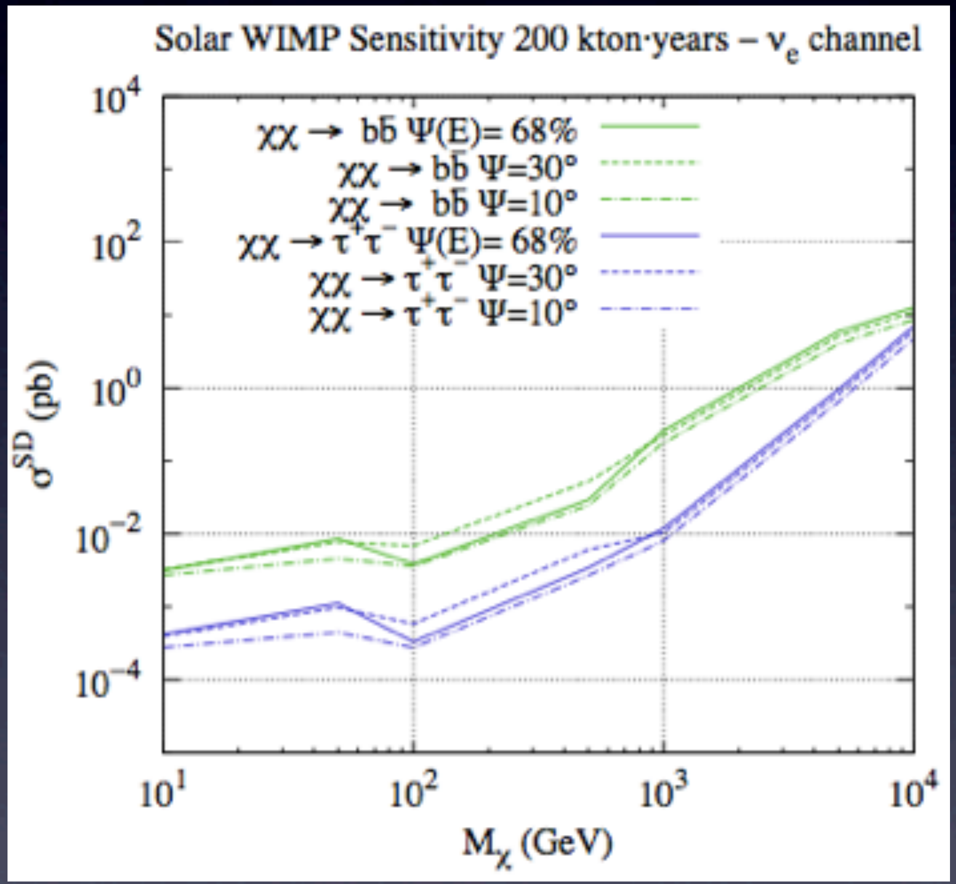


Mardon, Light-WIMP Lovefest, 2013

Search for **light WIMPs** captured in the Sun using contained events in Super-Kamiokande

Super-K, the most sensitive detector for few GeV neutrino, has power to investigate this region





Right : Kappl, Winkler, 1104.0679

Rott, Tanaka, Itow, 1107.3182

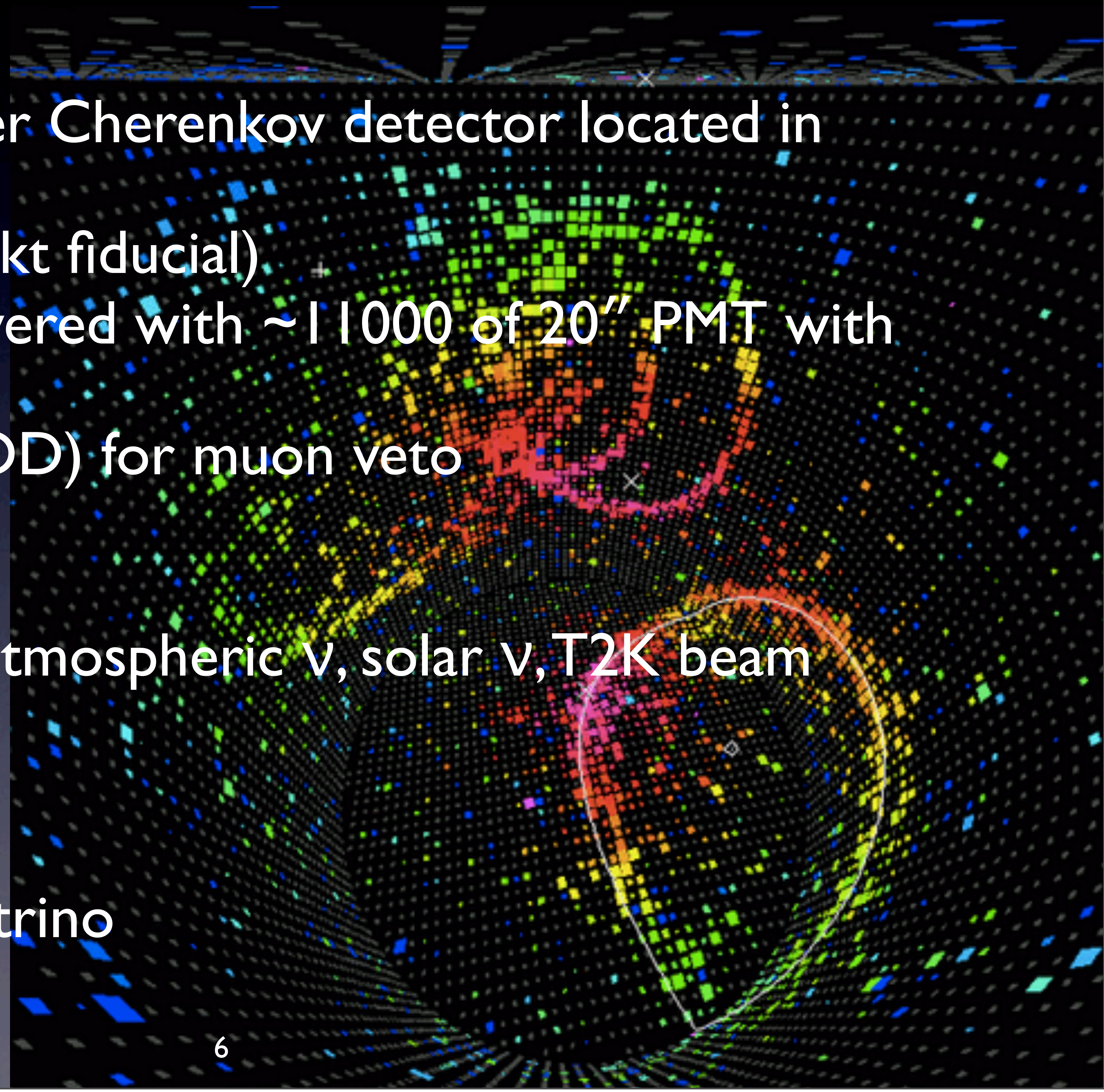
Search for **light WIMPs** captured in the Sun using contained events in Super-Kamiokande

Our analysis is model-independent

putting assumptions as :

- Local WIMP phase space(ρ=0.3GeV/cm^3, Vsun=220km/s, Vd=270km/s)
- elastic scattering off nuclei, axial vector(SD) only coupling
- pair annihilation to fermion mono channel(bb-bar, $\tau\tau$)
- Equilibrium between Capture & Annihilation

Search for light WIMPs captured in the Sun using contained events **in Super-Kamiokande**

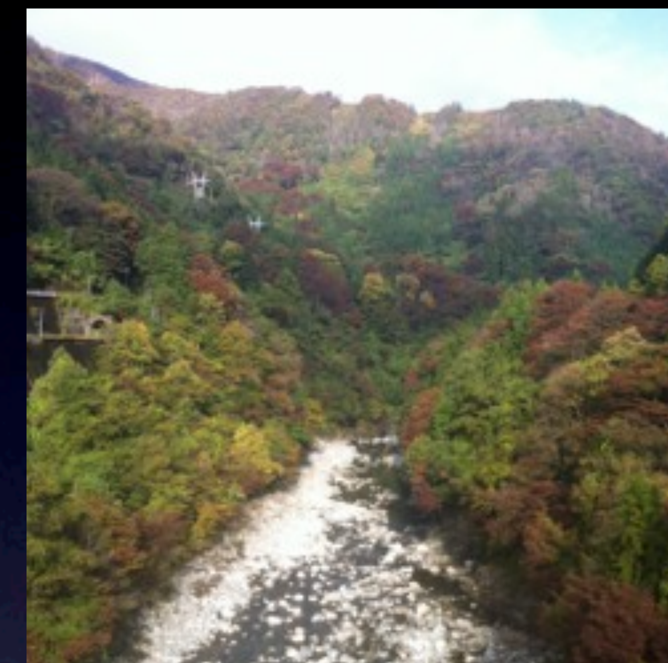


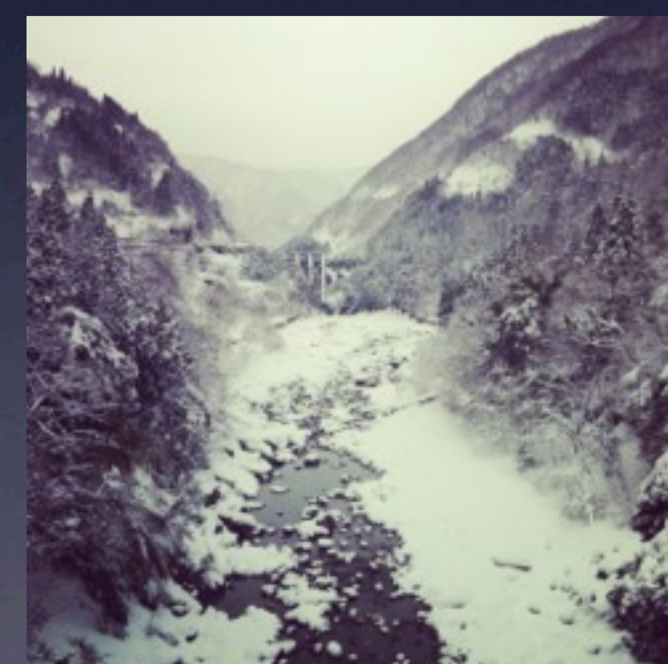
- The world largest water Cherenkov detector located in Kamioka mine
- 50kt pure water (22.5 kt fiducial)
- Inner detector(ID) covered with ~11000 of 20″ PMT with acrylic cover
- 2m outside detector(OD) for muon veto

Analysis :

- Neutrino oscillation : atmospheric ν, solar ν, T2K beam
- Nucleon decay
- Astrophysics
  - Dark matter search
  - Supernova Relic Neutrino
  - monopole search

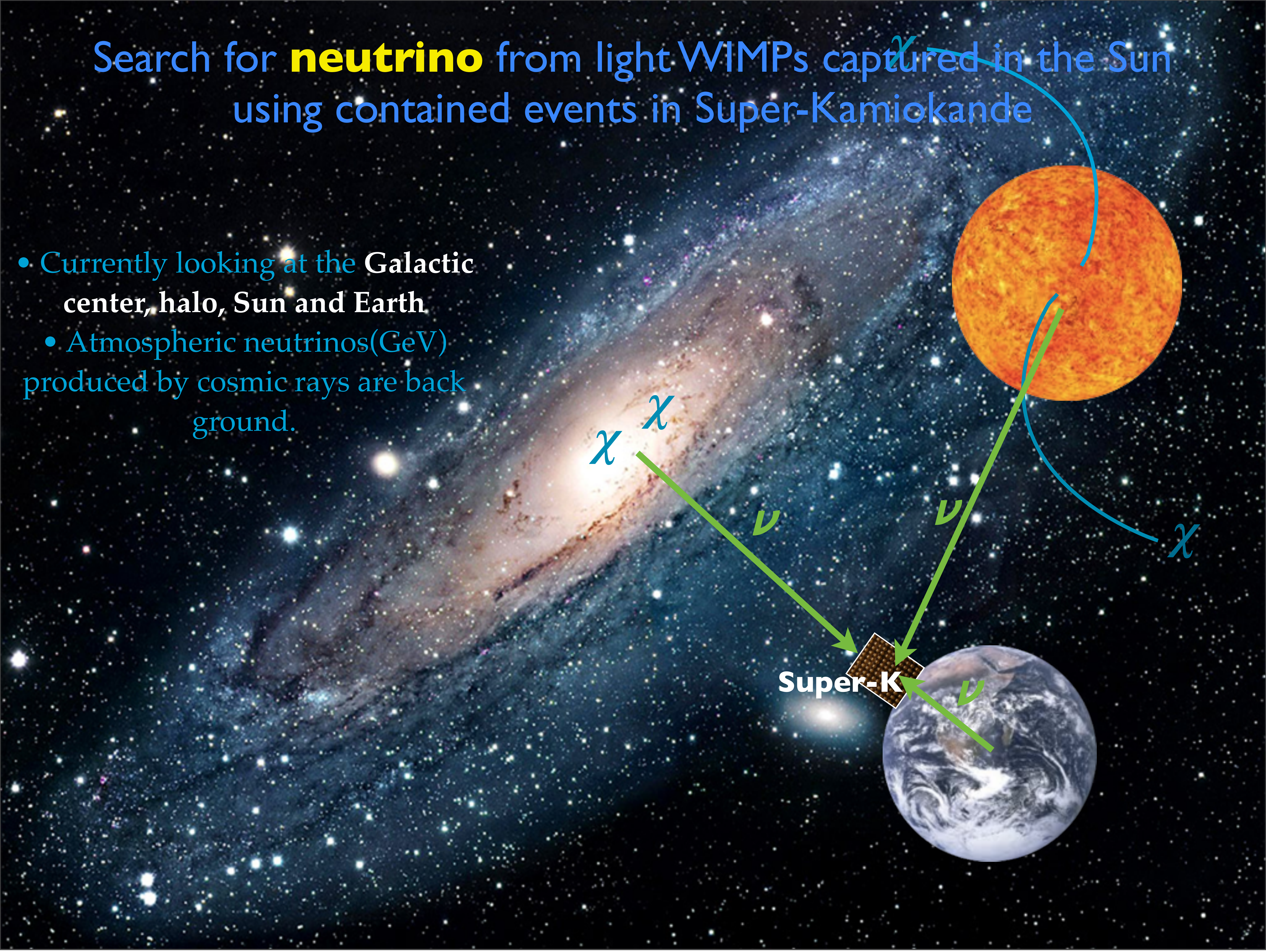
Search for light WIMPs captured in the Sun using contained events **in Super-Kamiokande**



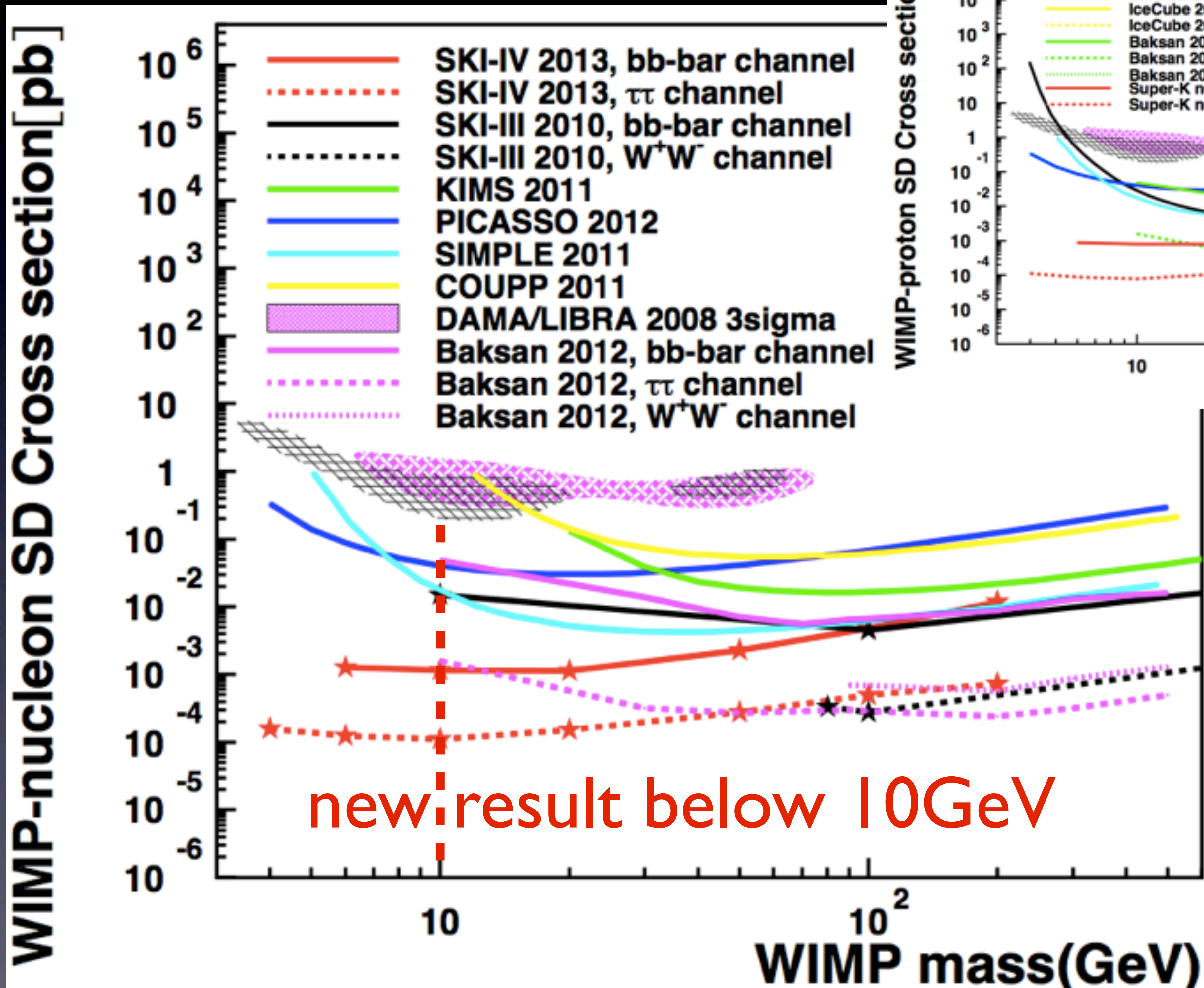


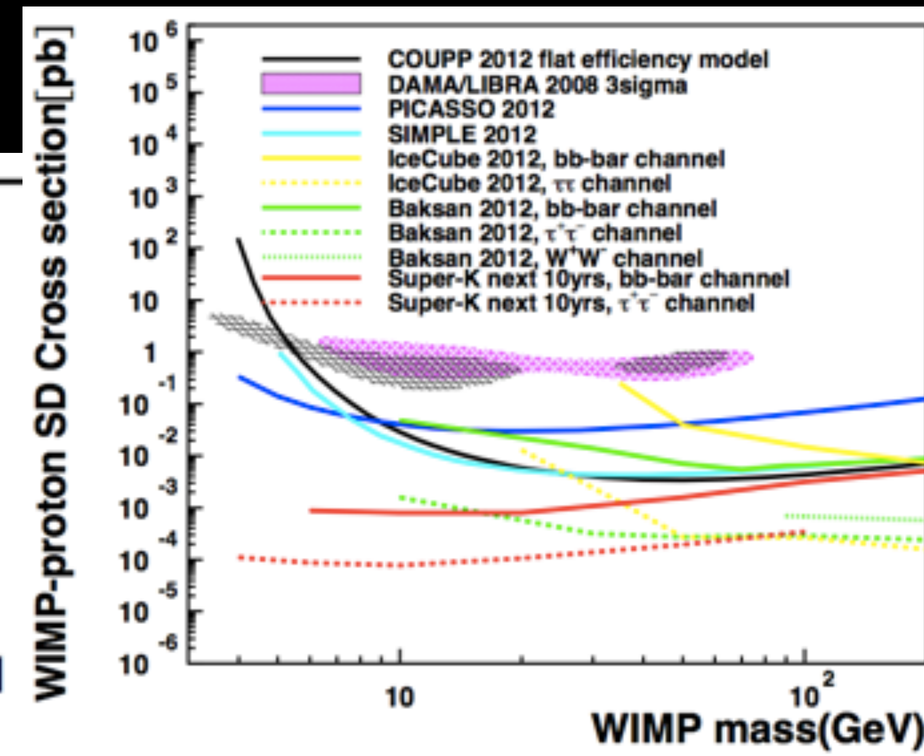
Search for **neutrino** from light WIMPs captured in the Sun using contained events in Super-Kamiokande

- Currently looking at the **Galactic center, halo, Sun and Earth**
- Atmospheric neutrinos(GeV) produced by cosmic rays are back ground.



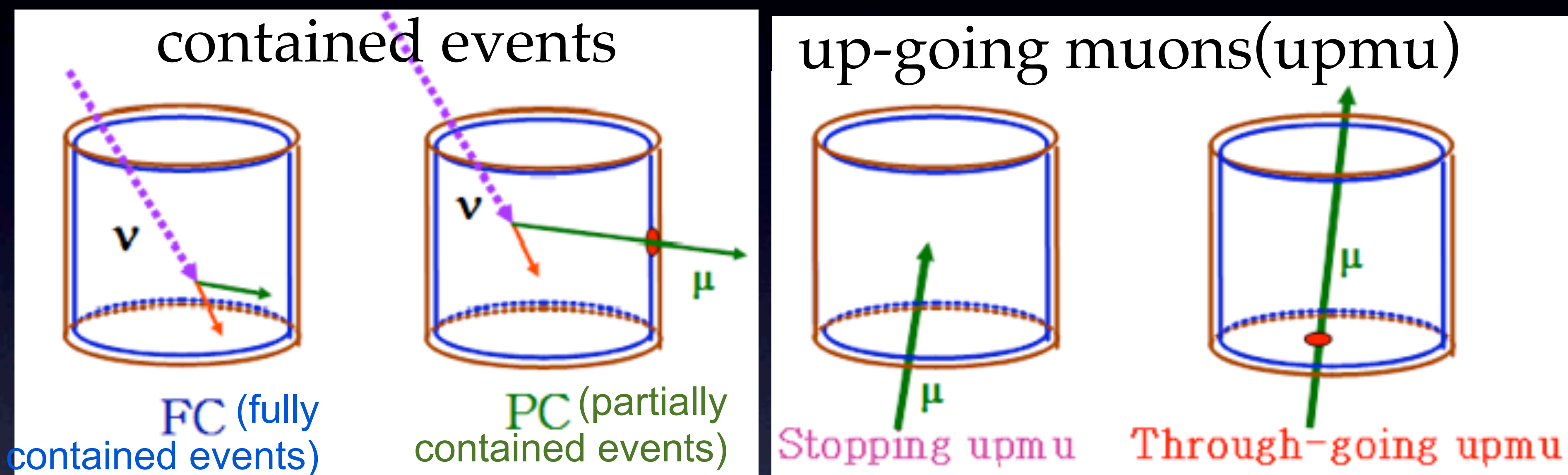
Upper limit on WIMP-proton SD scattering cross-section

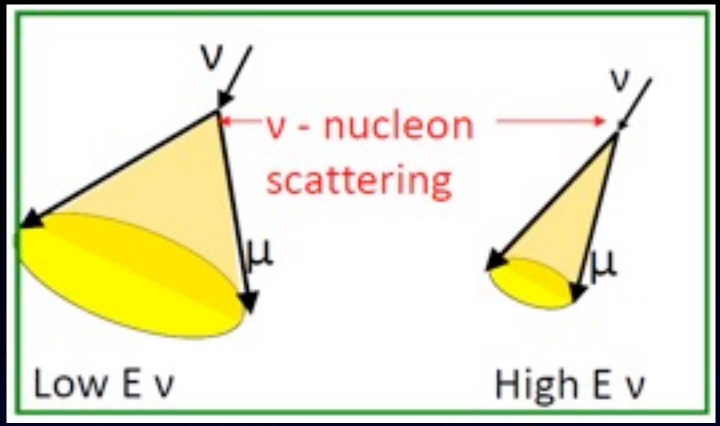


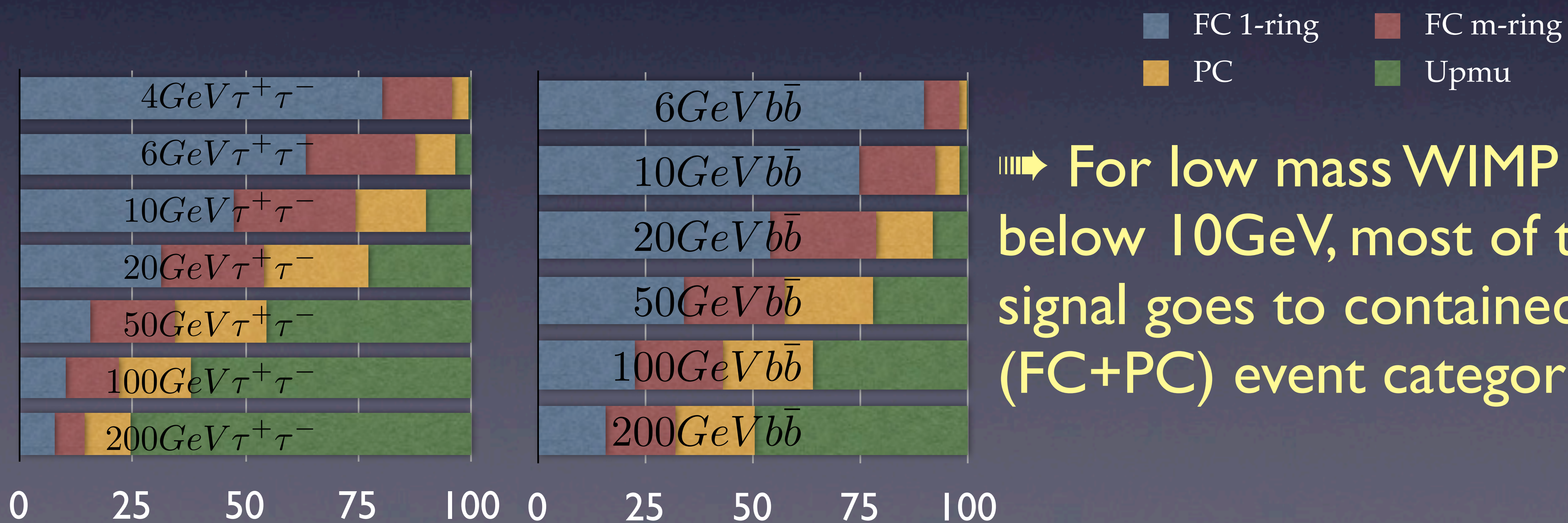


Search for light WIMPs captured in the Sun **using contained events** in Super-Kamiokande

Event categories in Super-K







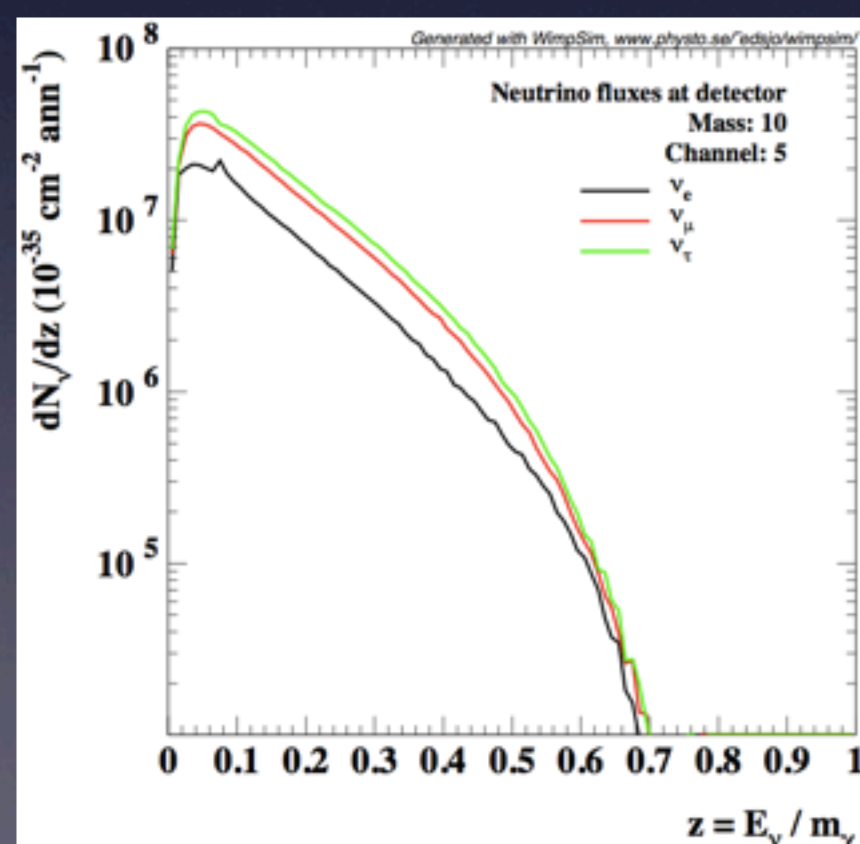
➠ For low mass WIMP below 10GeV, most of the signal goes to contained (FC+PC) event categories.

WIMP induced neutrino flux at Super-K

Simulation package DarkSUSY(WIMPsim) calculates

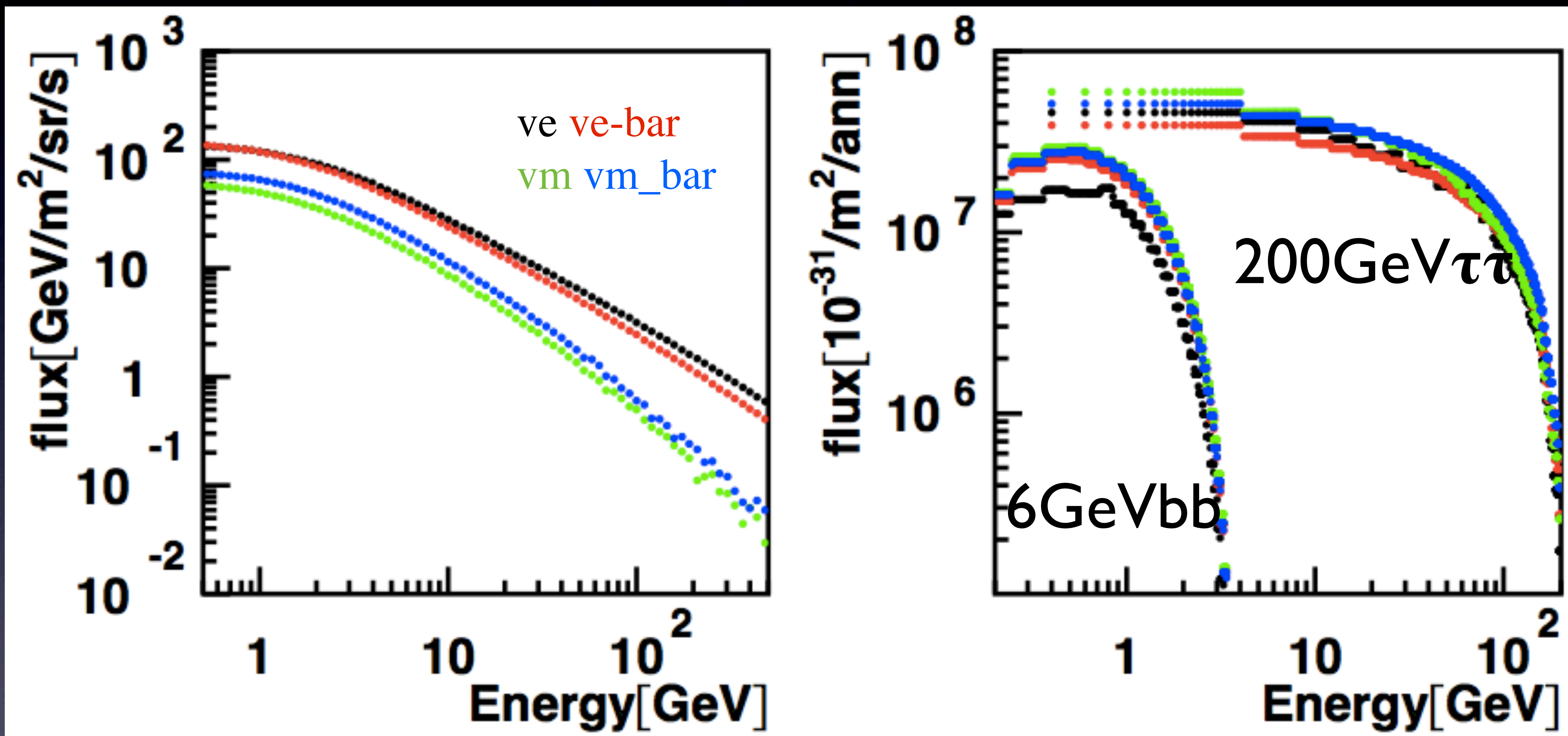
- Capture/annihilation of WIMPs
- Propagation inside the Sun/vacuum/the Earth considering oscillation & interaction

WIMPsim(J. Edsjö, http://www.fysik.su.se/~edsjo/wimpsim/) & DarkSUSY(P. Gondolo et al., JCAP 07 (2004) 008)



☚ at SK site considering 3 flavor oscillation

mimic WIMP flux using atm flux



True energy spectrum of
atmospheric / mimiced WIMP neutrino flux

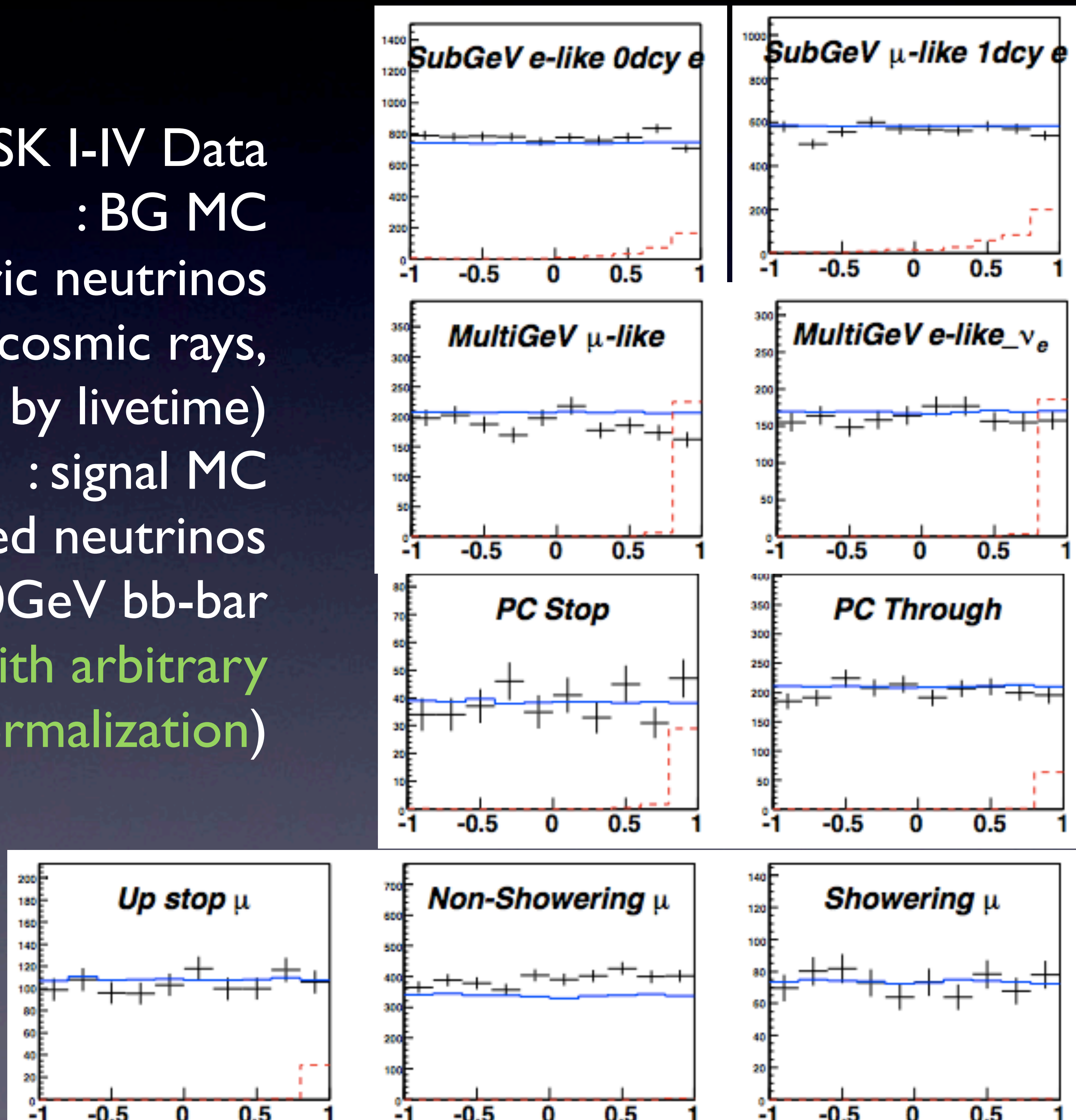
WIMP induced neutrino events at Super-K

Reconstructed angle(to the Sun) distribution

: SK I-IV Data

: BG MC
(Atmospheric neutrinos produced by cosmic rays, normalized by livetime)

: signal MC
(WIMP induced neutrinos for 10GeV bb-bar sample, with arbitrary normalization)



CosΘsun=1:
from the Sun

WIMP induced neutrino events at Super-K

Reconstructed energy distribution

: SK I-IV Data

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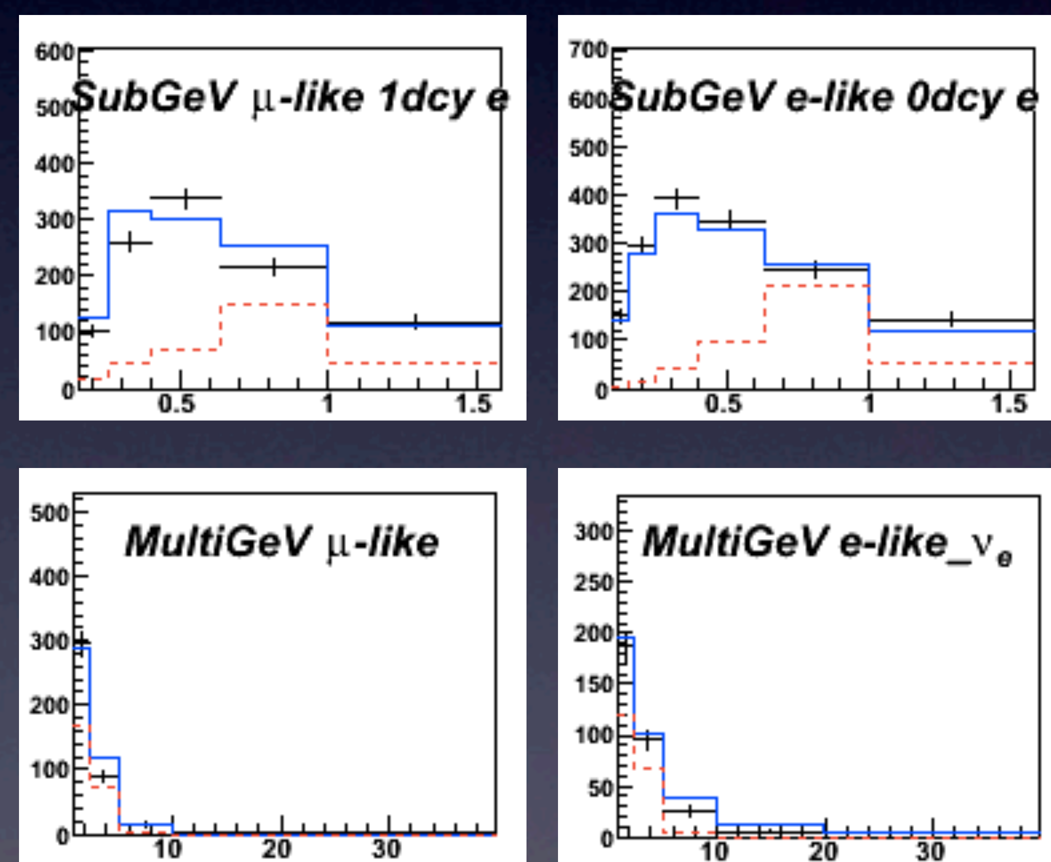


SK tau MC (1206.0328) used to tag tau-neutrino signal/BG

Test signal contribution by pulled χ^2 method

$$\chi^2 = 2\Sigma_{n=1}^{\#of bins}[N_n^{BG}(1+\Sigma_j f_j^n \varepsilon_j) + \beta N_n^{\chi}(1+\Sigma_k f_k^n \varepsilon_k) - N_n^{data} + N_n^{data} ln(\frac{N_n^{data}}{N_n^{BG}(1+\Sigma_j f_j^n \varepsilon_j)+\beta N_n^{\chi}(1+\Sigma_k f_k^n \varepsilon_k)})] + \Sigma_j(\frac{\varepsilon_j}{\sigma_j}) + \Sigma_k(\frac{\varepsilon_k}{\sigma_k})$$

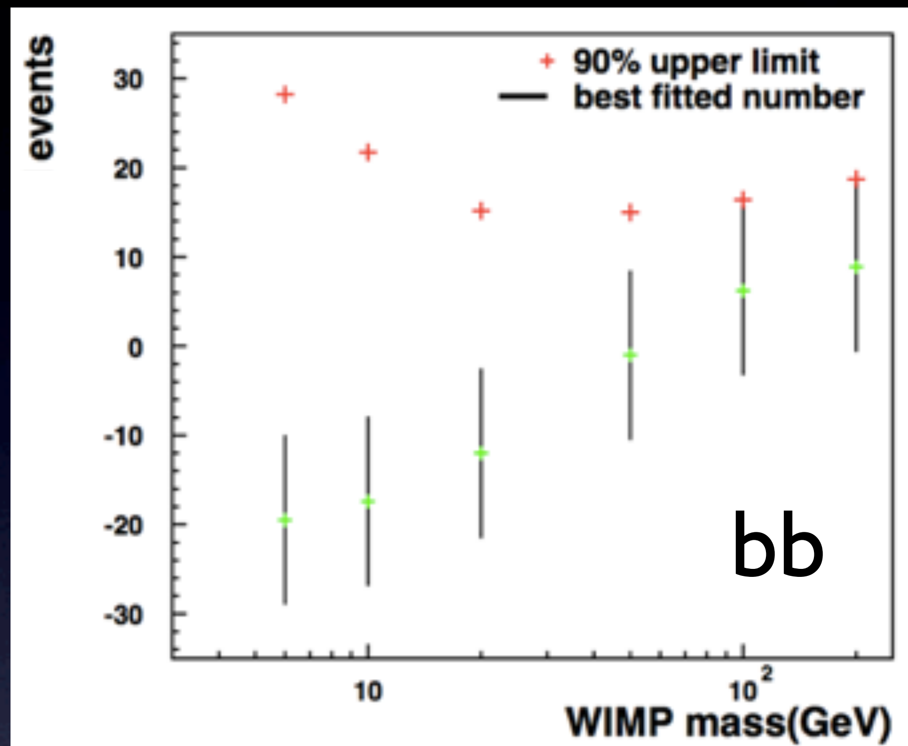
normalization parameter for WIMP contribution

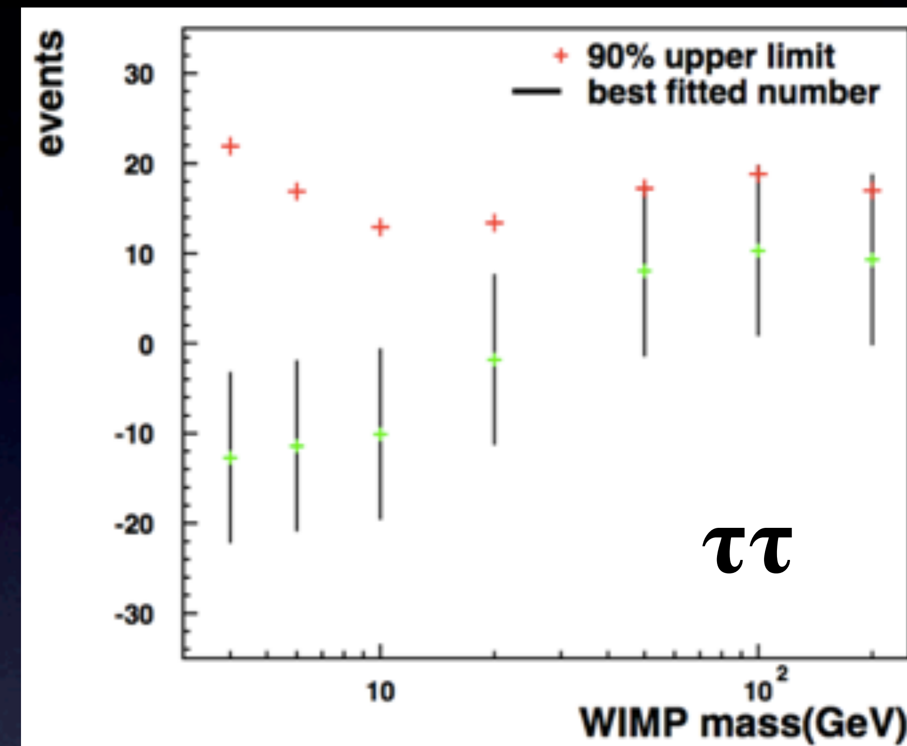
Fit data to atmospheric neutrino
adding extra contribution from WIMP induced neutrino
to find best fit value of β

$$\partial\chi^2/\partial\epsilon_k = 0$$

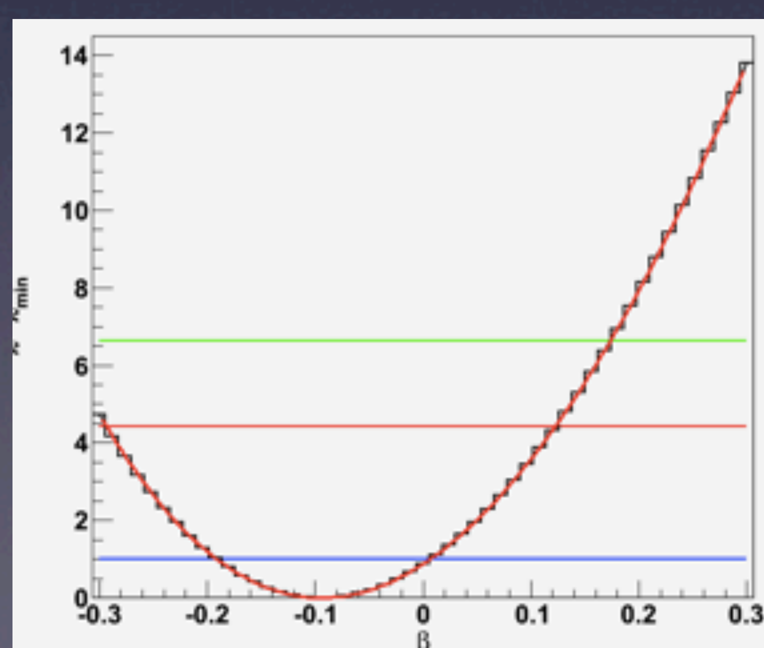
used SK I-IV data (3903days)
used energy / angle / flavor information (distributed in 684 bins)

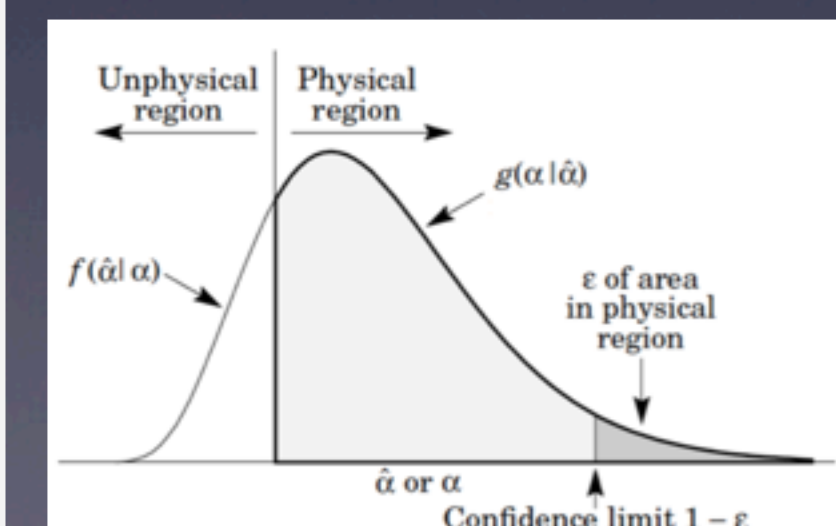
Derive 90% upper limit by Poisson probability distribution



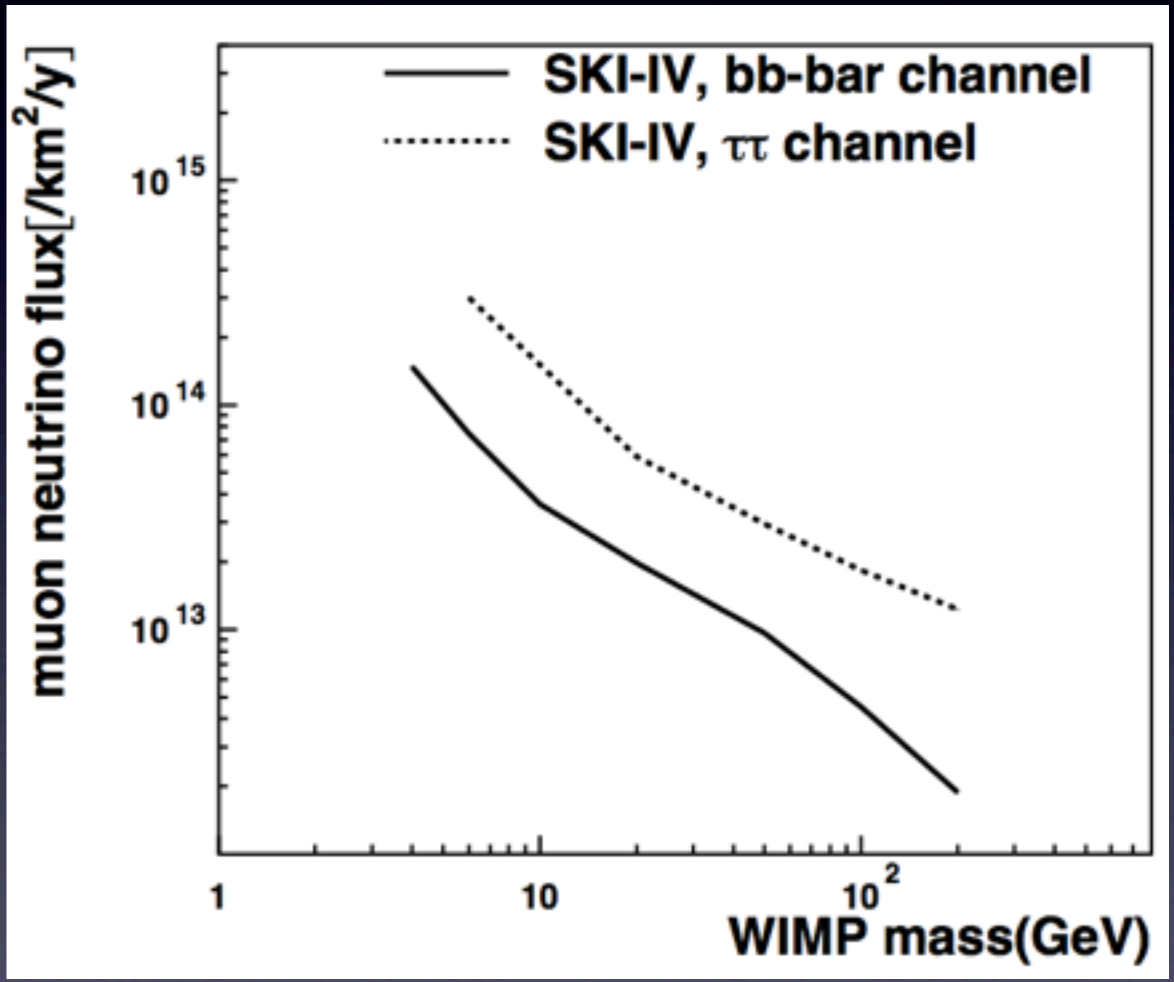


90% Bayesian upper limit on WIMP induced muon-neutrino events





➠ Conversion from event to flux considering detection efficiency, target # & cross section, livetime ➠



Upper limit on WIMP induced muon-neutrino flux from the Sun

Impact of structure formation on probes of dark matter

		LSS		Halos				Substructure						Local		
		voids, walls, filaments	halo mass functions	concentration-mass relation	halo shapes	density profiles	pseudo-phase-space density	mass (or V_{max}) functions	density profiles	central density	spatial distribution	streams	folds & caustics	local density	tidal streams	dark disk
Astrophysical	Dwarf galaxy abundance				■	■		■	■	■	■				■	■
	Dwarf galaxy kinematics							■	■	■						
	Stellar streams				■	■		■			■	■				
	Gravitational lensing	■	■	■	■	■		■	■		■					
Indirect Detection	Extra-galactic DGRB	■	■	■		■		■	■							
	Galactic DGRB				■	■		■	■		■					
	Clusters			■	■	■		■	■							
	Galactic Center					■										
	Milky Way Dwarfs			■		■			■	■						
	Dark Subhalos			■		■		■	■	■	■					
	Local anti-matter													■		
	Neutrinos from Earth & Sun													■	■	■
	Substructure boost							■	■		■		■			
	Sommerfeld boost						■					■	■		■	■
Direct	"Vanilla" ~ 100 GeV DM													■		
	light / inelastic DM													■	■	■
	axions												■	■	■	■
	directionally sensitive experiments													■	■	■

Kuhlen, Vogelsberger & Angulo 2012

Wechsler, taup2013

Systematic errors in neutrino flux & detector

BG flux : atmospheric flux normalization, 5 oscillation parameters, matter effect in the Earth are treated

Detector related (common for signal & BG) :
neutrino interaction / reconstruction / reduction etc
are originally well-studied for SK atmospheric oscillation analysis

Systematic Error			SK-I fit	SK-I σ	SK-II fit	SK-II σ	SK-III fit	SK-III σ
FC reduction			0.005	0.2	0.008	0.2	0.061	0.8
PC reduction			-0.99	2.4	-2.12	4.8	0.034	0.5
FC/PC separation			-0.058	0.6	0.068	0.5	-0.28	0.9
PC-stop/PC-through separation (top)			7.84	14	-17.47	21	-20.03	31
PC-stop/PC-through separation (barrel)			-2.27	7.5	-31.51	17	3.44	23
PC-stop/PC-through separation (bottom)			-2.32	11.	-7.32	12	1.59	11
Non-ν BG (e-like)	Sub-GeV		0.077	0.5	0.004	0.2	0.003	0.1
	Multi-GeV		0.047	0.3	0.005	0.3	0.011	0.4
Non-ν BG (μ-like)	Sub-GeV		-0.01	0.1	0.02	0.1	0.052	0.1
	Multi-GeV		-0.01	0.1	0.02	0.1	0.11	0.2
	Sub-GeV 1-ring	μ-like 0-decay	-0.04	0.4	0.02	0.1	0.052	0.1
	PC		-0.02	0.2	0.14	0.7	0.95	1.8
Fiducial volume			-0.23	2	0.43	2	0.93	2
Ring separation	< 400 MeV	e-like	1.23	2.3	-1.67	1.3	0.12	2.3
		μ-like	0.37	0.7	-2.96	2.3	0.037	0.7
	> 400 MeV	e-like	0.21	0.4	-2.19	1.7	0.021	0.4
		μ-like	0.37	0.7	-0.90	0.7	0.036	0.7
	Multi-GeV	e-like	1.97	3.7	-3.35	2.6	0.19	3.7
		μ-like	0.91	1.7	-2.19	1.7	0.089	1.7
	Multi-ring sub-GeV	μ-like	-2.40	-4.5	10.56	-8.2	-0.24	-4.5
	Multi-ring multi-GeV	e-like	0.05	0.1	-2.45	1.9	0.16	3.1
		μ-like	-2.19	-4.1	1.03	-0.8	-0.21	-4.1
Particle identification	Sub-GeV	e-like	-0.007	0.1	0.13	0.5	0.004	0.1
		μ-like	0.007	-0.1	-0.13	-0.5	-0.004	-0.1
	Multi-GeV	e-like	-0.014	0.2	0.023	0.1	0.008	0.2
		μ-like	0.014	-0.2	-0.023	-0.1	-0.008	-0.2
Particle identification (multi-ring)	Sub-GeV	μ-like	-0.18	-3.9	-0.55	-2.2	-0.15	-3.9
	Multi-GeV	e-like	0.078	1.7	0.45	1.8	0.063	1.7
		μ-like	-0.13	-2.9	-0.86	-3.4	-0.11	-2.9
Energy calibration			-0.002	1.1	-0.56	1.7	-0.35	2.7
Up/Down asymmetry energy calibration			-0.4	0.6	-0.15	0.6	-0.03	1.3
Upward-going muon reduction	Stopping		-0.057	0.7	-0.14	0.7	0.14	0.7
	Through-going		-0.041	0.5	-0.10	0.5	0.10	0.5
Upward stopping/through-going μ separation			-0.04	0.4	0.006	0.4	0.04	0.6
Energy cut for upward stopping μ			-0.13	0.8	-0.26	1.4	0.78	2.1
Path length cut for upward through-going μ			0.39	1.8	-1.0	2.1	0.4	1.6
Upward through-going μ showering separation			9.42	9.0	2.28	13.0	6.1	6.0
BG subtraction of upward μ [a]	Stopping		4.16	16	-7.47	21	0.004	20
	Non-showering		-1.24	11	8.08	15	6.34	19
	Showering		2.27	18	-18.16	14	24.7	24
Multi-GeV Single-Ring Electron BG			5.95	16.3	-4.67	23.4	1.06	41.4
Multi-GeV Multi-Ring Electron BG			-4.38	35.6	-1.4	22.3	-16.8	38.0
Multi-GeV Multi-Ring e-like likelihood			-1.12	6.4	0.5	11.1	-0.3	5.3
Sub-GeV 1-ring π^0 selection	$100 < P_e < 250$	MeV/c	-3.94	11.2	-4.08	7.5	-5.34	7.7
	$250 < P_e < 400$		-4.05	11.5	-4.85	8.9	-18.37	26.4
	$400 < P_e < 630$		-8.23	23.4	-9.52	17.5	-8.70	12.5
	$630 < P_e < 1000$		-6.72	19.1	-5.81	10.7	-18.58	26.7
	$1000 < P_e < 1330$		-4.57	13.0	-6.03	11.1	-18.58	26.7
Sub-GeV 2-ring π^0			-0.31	2	0.024	2	0.009	1
Decay-e tagging			0.16	1.5	0.41	1.5	1.06	1.5
Solar Activity			0.6	20	27.9	50	3.78	20

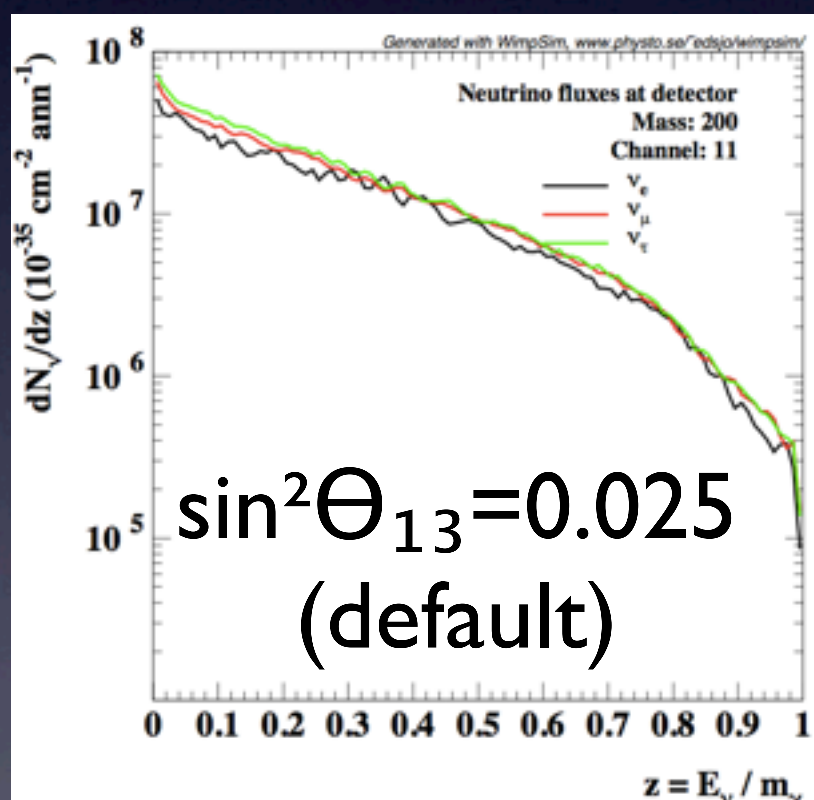
Systematic Error			fit value	σ
Flux normalization	$E_\nu < 1$ GeV		34.7	25[a]
	$E_\nu > 1$ GeV		8.8	7[b]
ν_μ/ν_e				
	$E_\nu < 1$ GeV		-1.9	2
	$1 < E_\nu < 10$ GeV		-2.5	3
	$E_\nu > 10$ GeV		-3.7	5[c]
$\bar{\nu}_e/\nu_e$				
	$E_\nu < 1$ GeV		5.54	5
	$1 < E_\nu < 10$ GeV		1.13	5
	$E_\nu > 10$ GeV		-0.10	8[d]
$\bar{\nu}_\mu/\nu_\mu$				
	$E_\nu < 1$ GeV		-0.48	2
	$1 < E_\nu < 10$ GeV		-1.35	6
	$E_\nu > 10$ GeV		-1.75	6[e]
Up/down ratio	< 400 MeV	e-like	-0.07	0.1
		μ-like	-0.23	0.3
		0-decay μ-like	-0.84	1.1
	> 400 MeV	e-like	-0.61	0.8
		μ-like	-0.38	0.5
		0-decay μ-like	-1.29	1.7
	Multi-GeV	e-like	-0.53	0.7
		μ-like	-0.15	0.2
	Multi-ring Sub-GeV	μ-like	-0.15	0.2
	Multi-ring Multi-GeV	e-like	-0.23	0.3
		μ-like	-0.15	0.2
	PC		-0.15	0.2
Horizontal/Vertical ratio	< 400 MeV	e-like	-0.01	0.1
		μ-like	-0.01	0.1
		0-decay μ-like	-0.03	0.3
	> 400 MeV	e-like	-0.14	1.4
		μ-like	-0.19	1.9
		0-decay μ-like	-0.14	1.4
	Multi-GeV	e-like	-0.33	3.2
		μ-like	-0.23	2.3
	Multi-ring Sub-GeV	μ-like	-0.13	1.3
	Multi-ring Multi-GeV	e-like	-0.29	2.8
		μ-like	-0.15	1.5
	PC		-0.17	1.7
K/π ratio in flux calculation			-12.9	10[f]
Neutrino path length			-8.8	10
Sample-by-sample	FC Multi-GeV		-4.5	5
	PC + Up-stop μ		-7.1	5

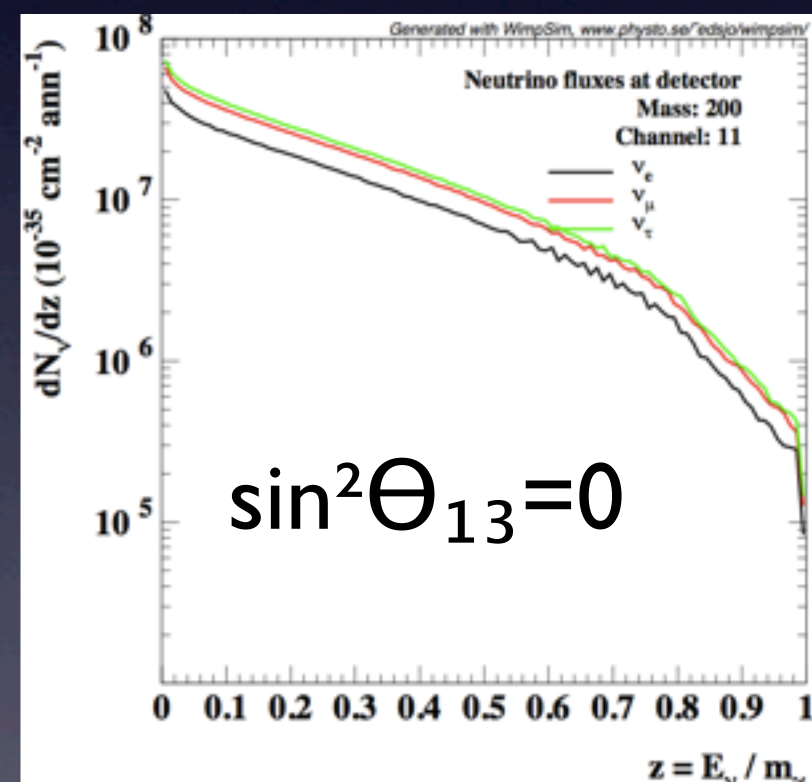
Systematic Error		fit value	σ
MA in QE and single π		-2.4	10
CCQE cross section		0.66	1.0[a]
Single meson production cross section		7.8	20
DIS cross section ($E_{nu} < 10$ GeV)		-0.16	1.0[b]
DIS cross section		2.27	5
Coherent π production		1.53	100
NC/(CC)		1.51	20
Nuclear effect in ^{16}O nucleus		-13.8	30
Nuclear effect in pion spectrum		0.8	1.0[c]
ν_τ contamination		1.0	30
NC in FC μ-like (hadron simulation)		-4.6	10
CCQE $\bar{\nu}_i/\nu_i$ (i=e,μ) ratio		0.84	1.0[a]
CCQE μ/e ratio		1.12	1.0[a]
Single π production, $\pi^0/\pi^\pm$ ratio		-29.0	40
Single π production, $\bar{\nu}_i/\nu_i$ (i=e,μ) ratio		-0.04	1.0[d]
π^+ decay uncertainty Sub-GeV 1-ring	e-like 0-decay	-0.48	0.5
	μ-like 1-decay	0.77	-0.8
	e-like 1-decay	3.9	-4.1
	μ-like 0-decay	-0.77	0.8
	μ-like 2-decay	5.46	-5.7

Wendell & Super-Kamiokande collaboration, 1002.3471

Dark SUSY

Signal flux : errors from 3 flavor oscillation parameters, matter effects, interaction





"Treatment of uncertainties in fitting doesn't affect the result significantly"

Uncertainties in capture process

Hydrogen detector is form factor error free!

Mainly Hydrogen ⇨ not much affects

no impact above 4GeV

negligible for low mass WIMP

recently went back to 'free space'(Sivertsson&Joakim, 1201.1895)

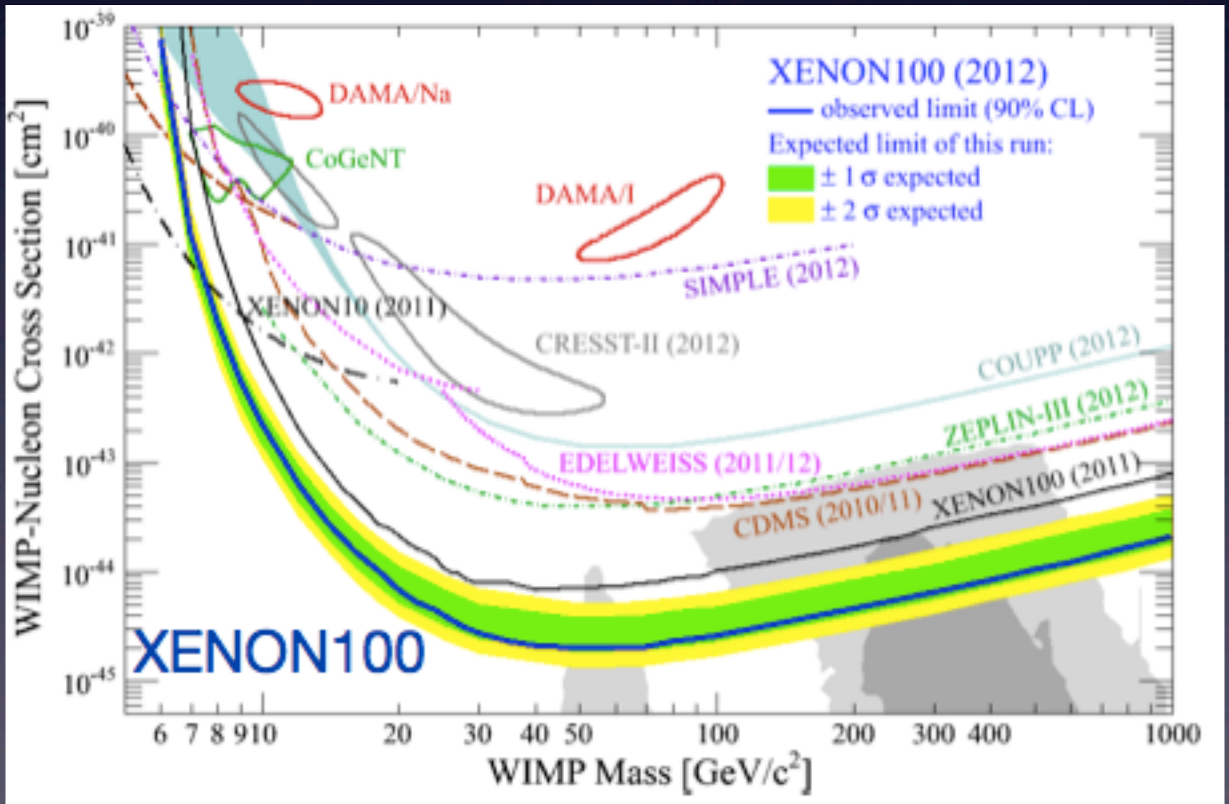
	form factor	DarkSUSY solar model	solar evaporation	solar diffusion
4~20GeV	1%	3%	<1%	<1%
50~100GeV	1%	4%	<1%	<1%
200GeV	1%	6%	<1%	<1%

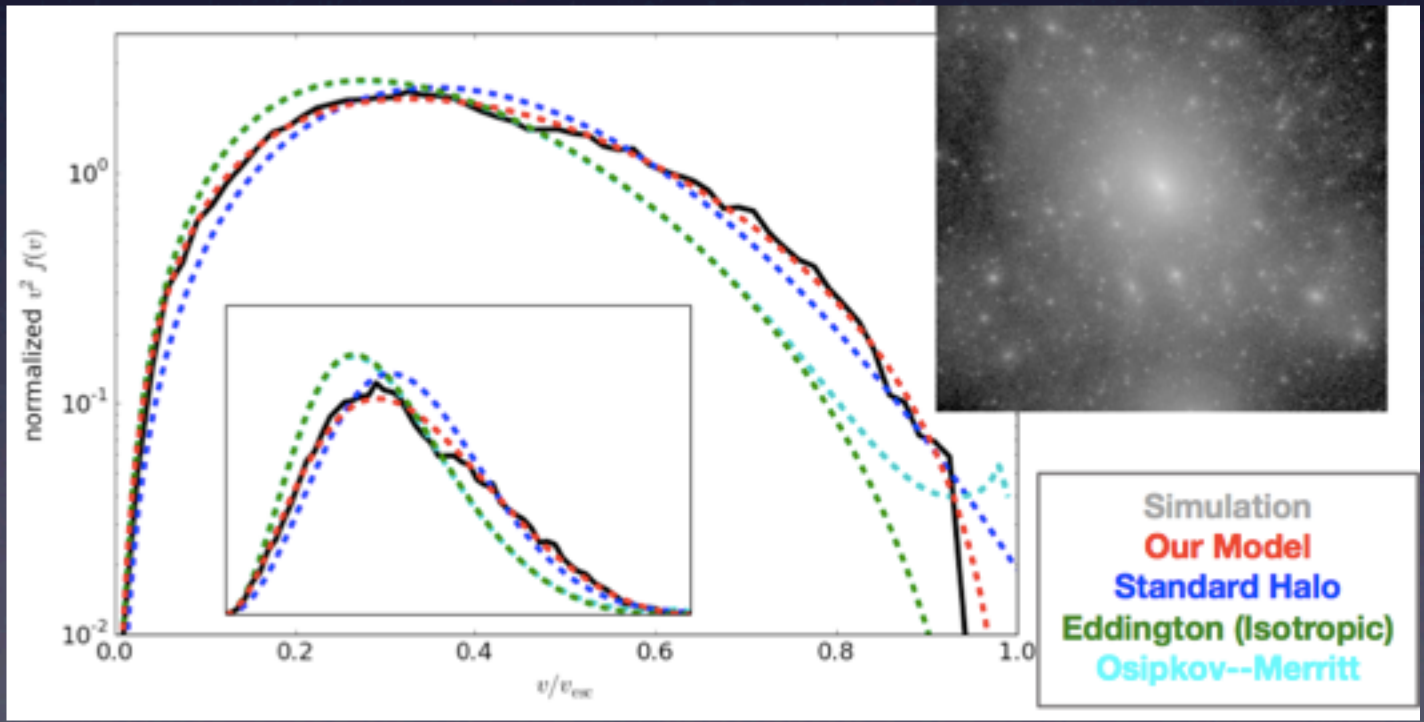
combined all errors affect the solar analysis result < 7% for SD

taken account in conversion to WIMP-proton scattering cross-section limit

good to have very different detector

- at low mass where DD signals suddenly disappear -
- with/without high velocity tail cut of SMH
  < 1% for ID.



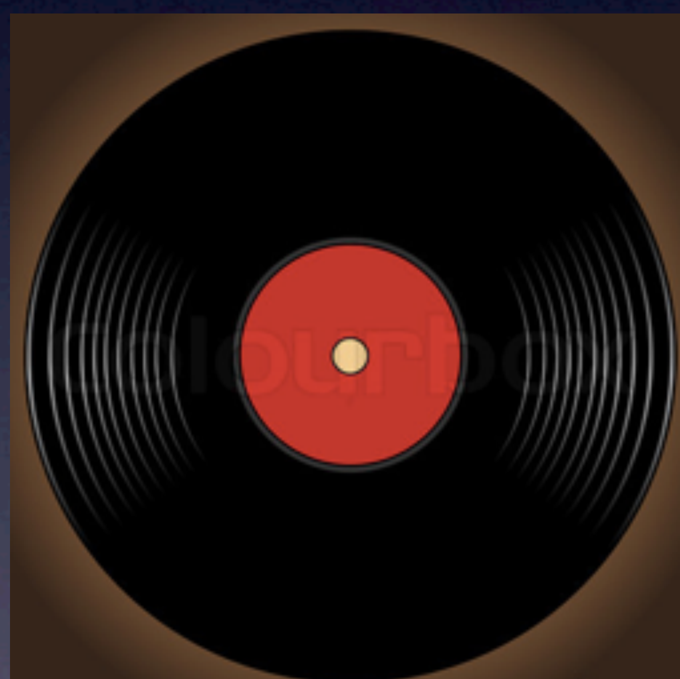


Baudis, taup2013

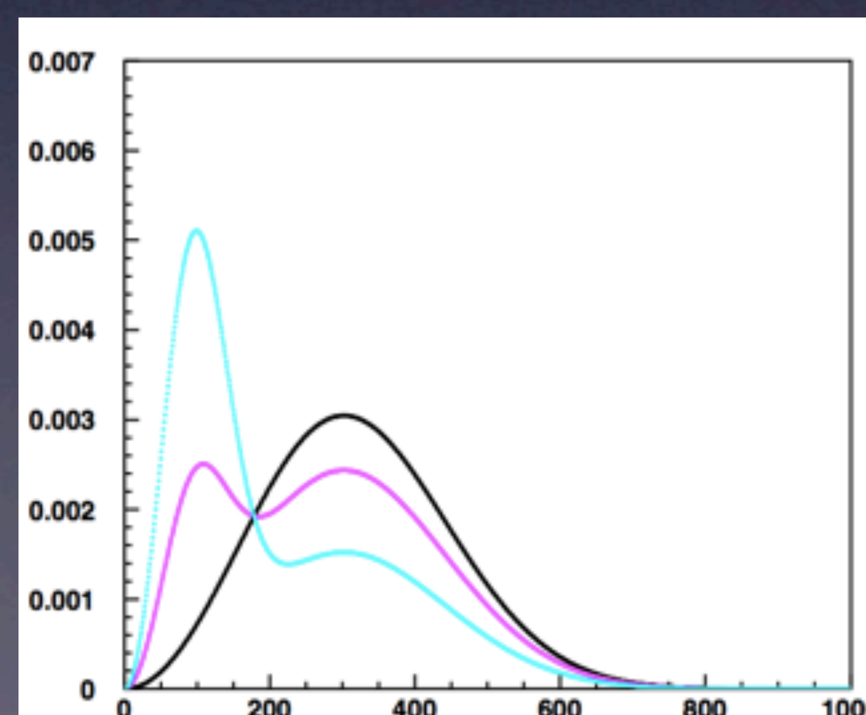
Wechsler, taup2013

good to have very different detector

- what happens for possible modification of low velocity region?
  i.e. dark disc?



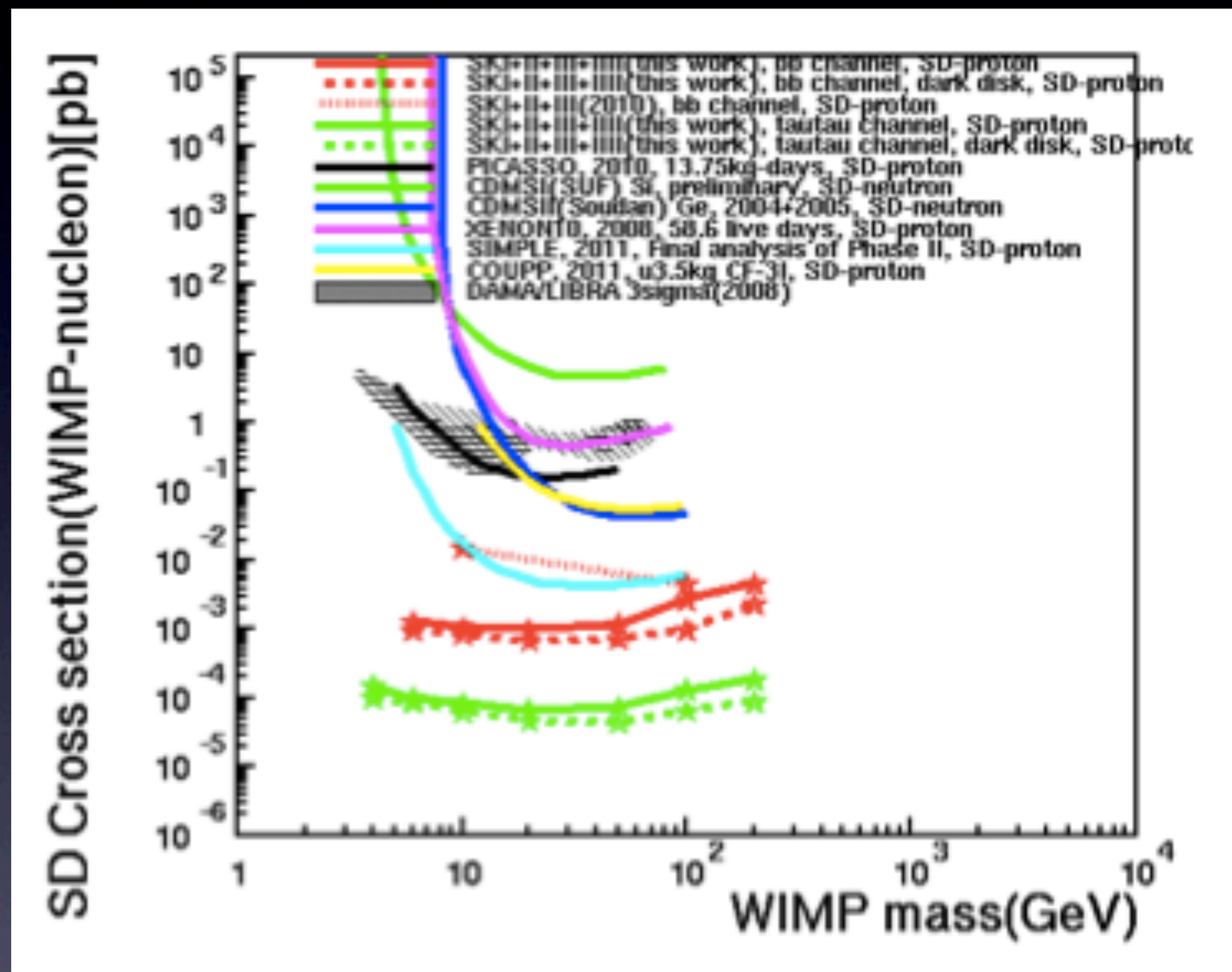
Existence of co-rotating invisible structure, dark disc in the solar neighbor, claimed to be robust by cosmological simulations



VDF of strong dark disc(blue, 50% of halo density), 25% (pink)

Abundance in low velocity region can boost neutrino detection

(Bruch et al, 0902.4001, Ling, 0911.2321)



Conclusion

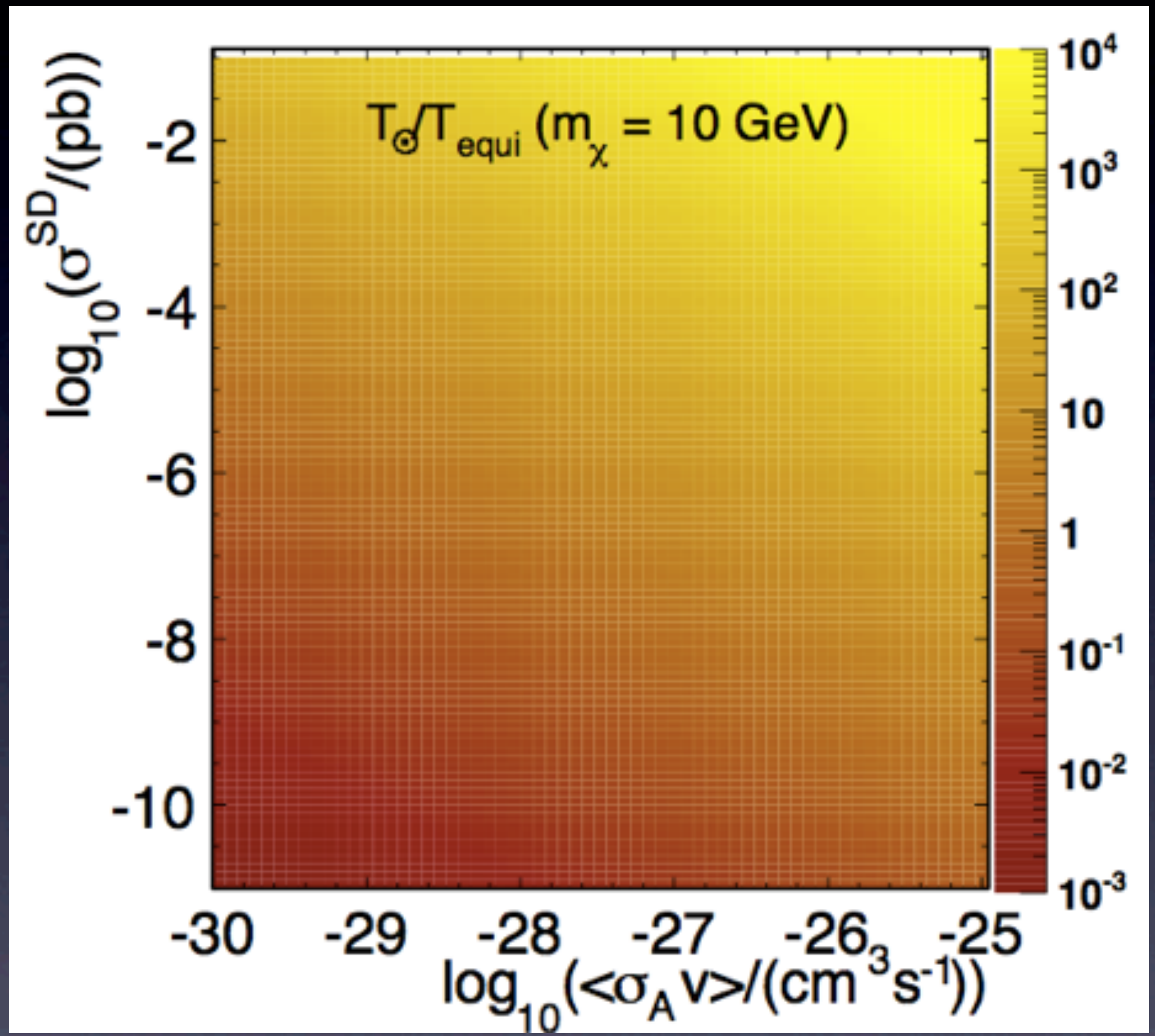
Increased signal acceptance using low energy & electron neutrino,
fitting with angle + energy + flavor informations
➠ SK result is current world's best of finding no WIMP competition in SD cross-section below 100GeV

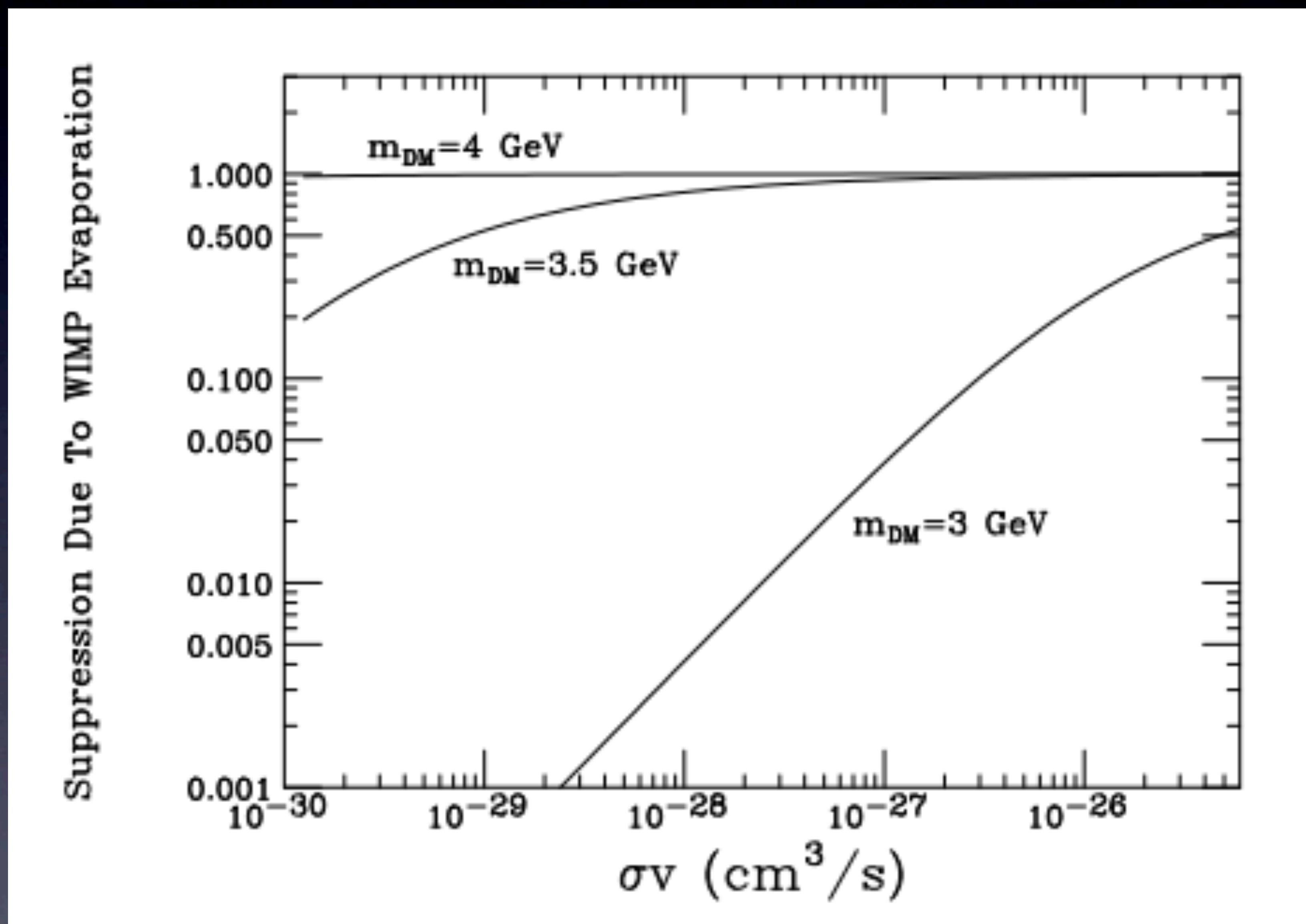
With careful care of uncertainties,
➠ Ready to be seriously (not indirectly) taken in parameter space

SI result will be published soon!

Thank you for listening!

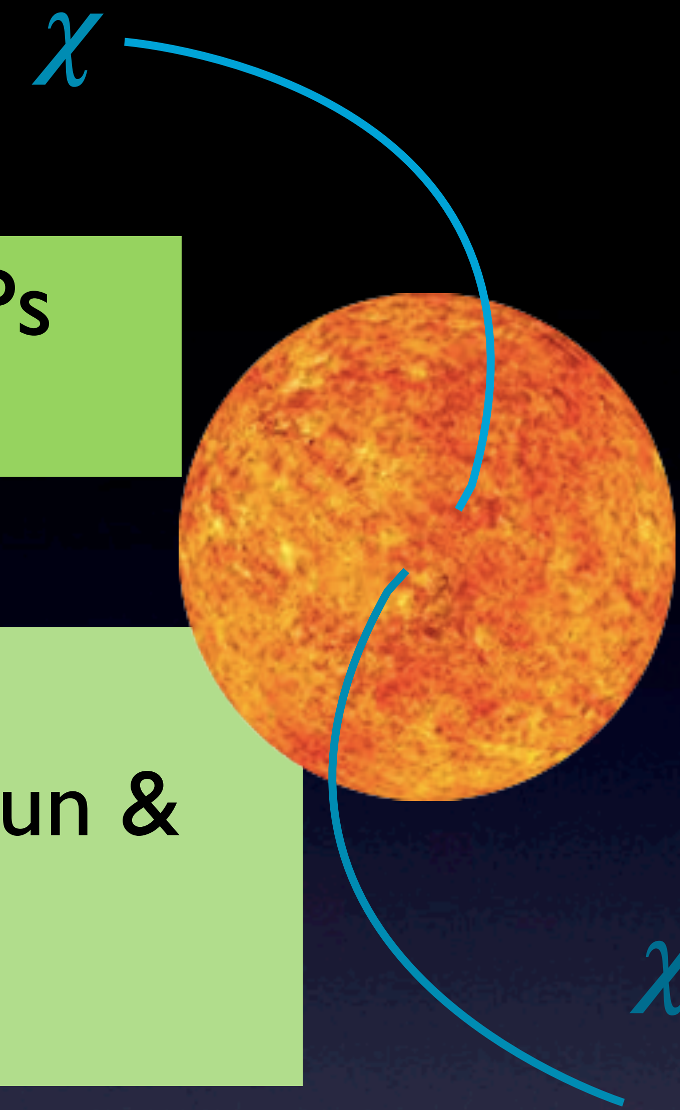
백업


$T_\odot/T_{equi}$ (m_χ = 10 GeV)
$\log_{10}(\sigma^{SD}/(pb))$
-2
-4
-6
-8
-10
-30
-29
-28
-27
-26
-25
$\log_{10}(\langle\sigma_A v\rangle/(cm^3 s^{-1}))$
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}


Suppression Due To WIMP Evaporation
1.000
0.500
0.100
0.050
0.010
0.005
0.001
m_{DM}=4 GeV
m_{DM}=3.5 GeV
m_{DM}=3 GeV
10^{-30}
10^{-29}
10^{-28}
10^{-27}
10^{-26}
σv (cm^3/s)

l.

WIMP capture inside the Sun

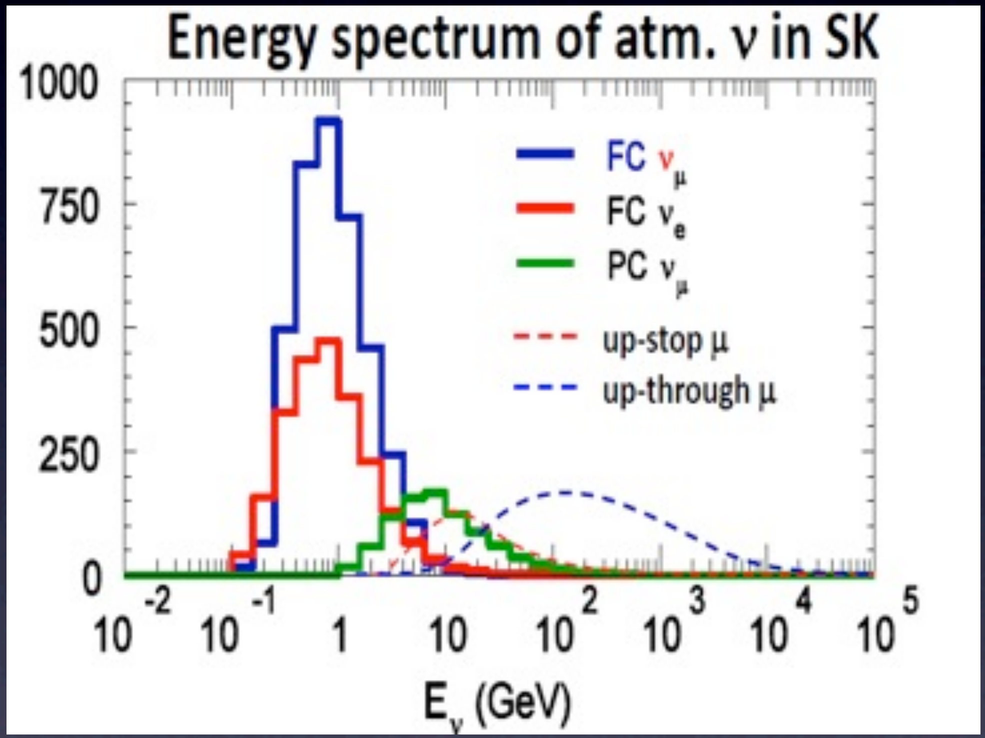


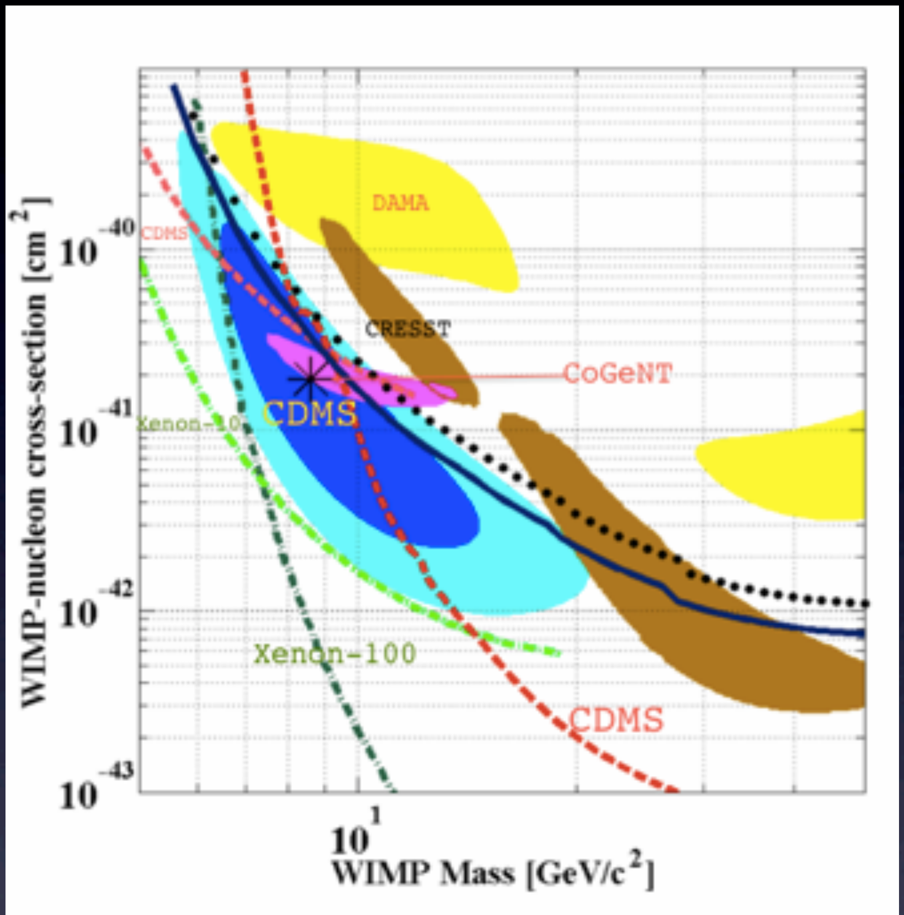
As the Sun passes through Galactic plane, WIMPs can scatter off a nucleus inside the Sun.

After transferring recoil energy to nucleus, WIMP becomes gravitationally bound to the Sun & undergoes additional scatters from elements and settles to the core.

WIMPs pair annihilates to the various channels of which b, tau channels can produce energetic neutrino before stop.

neutrinos can pass through the Sun and be detected in Super-Kamiokande & Icecube.


Energy spectrum of atm. ν in SK
1000
750
500
250
0
FC ν_μ
FC ν_e
PC ν_μ
up-stop μ
up-through μ
10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5
E_ν (GeV)



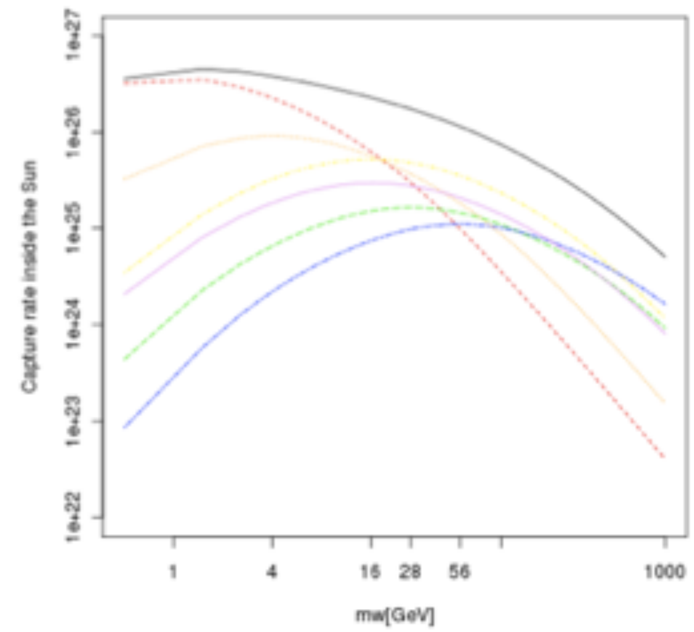


Figure 3.11: The capture rate of the Scalar-coupled WIMP in the Sun : *Black solid : Total, Red dashed : H, Orange dotted : He, Yellow dotdashed : O, Green longdashed : Si, Blue twodashed : Fe, Violet solid : the rest.*