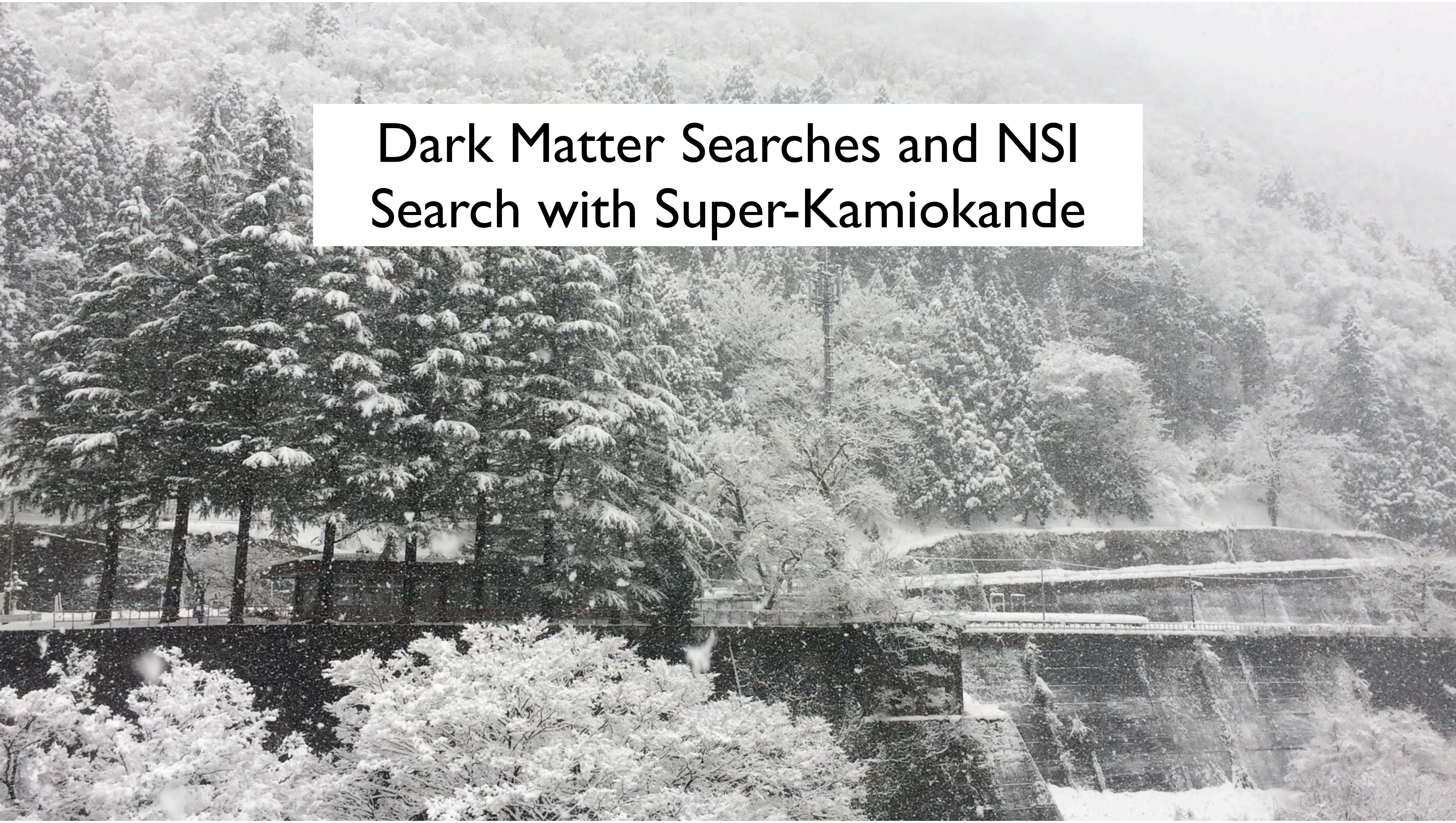
AstroDark-2021 (Dec 7-10, 2021)
IPMU, Japan (online)

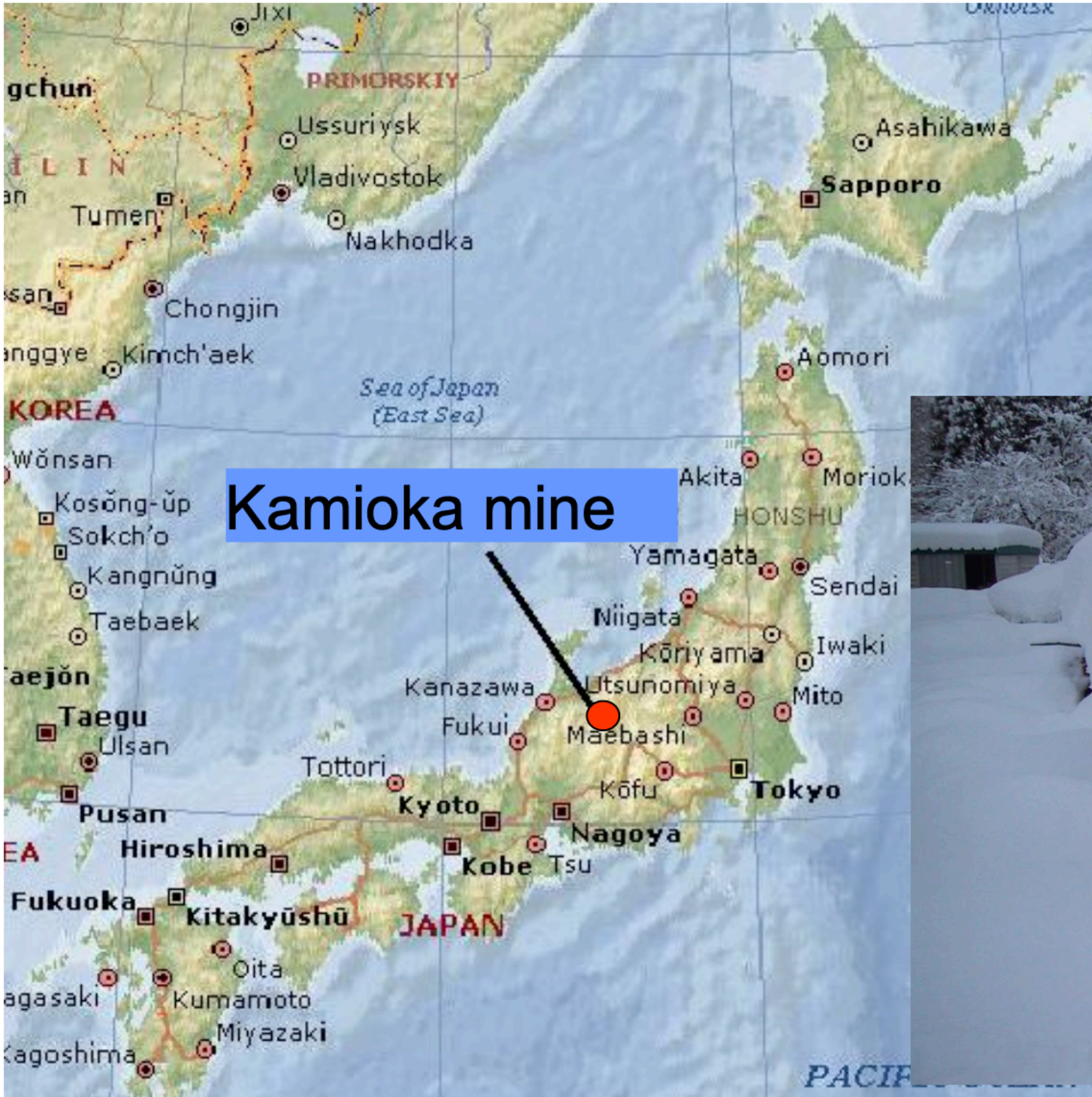
Dark Matter Searches and NSI Search with Super-Kamiokande

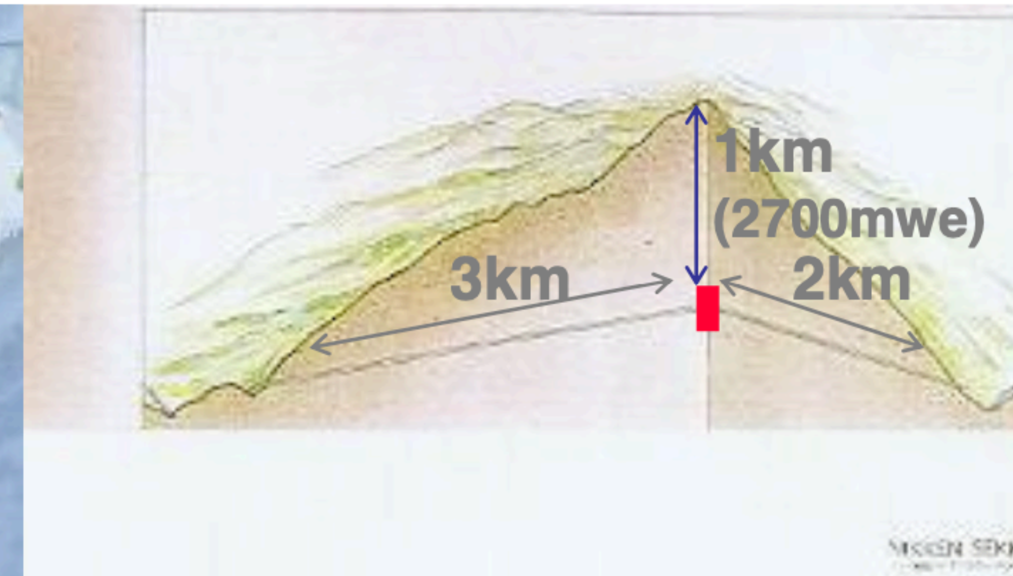


21/12/07 Koun Choi, IBS-CUP
for the Super-Kamiokande Collaboration

기초과학연구원
Institute for Basic Science

Kamioka underground observatory

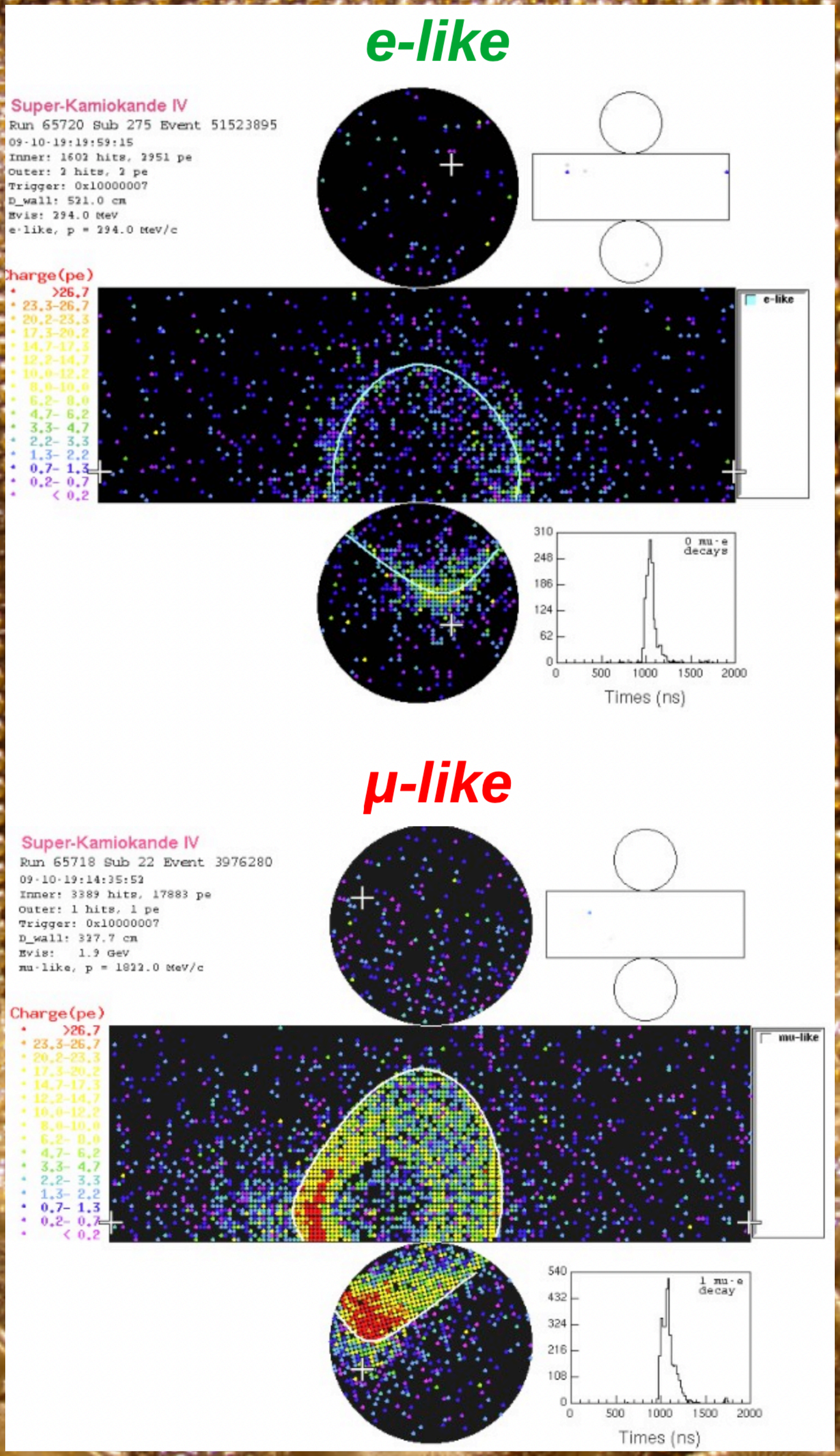




The Super-Kamiokande (SK)

20-inch PMT (Hamamatsu R3600)
• Q.E. : 21% at 360~400nm

- Water Cherenkov ring-imaging detector
- 50 ktons water (22.5 ktons fiducial volume)
- 11,000 20” Photo-Multiplier Tubes
- Being operated since 1996
- SK-Gd (0.01% Gadolinium in SK) started in July. 2020



Outline

- Indirect Searches for dark matter

  - Galactic Center & Halo (2020)
  - Earth (2018)
  - Sun (2015)

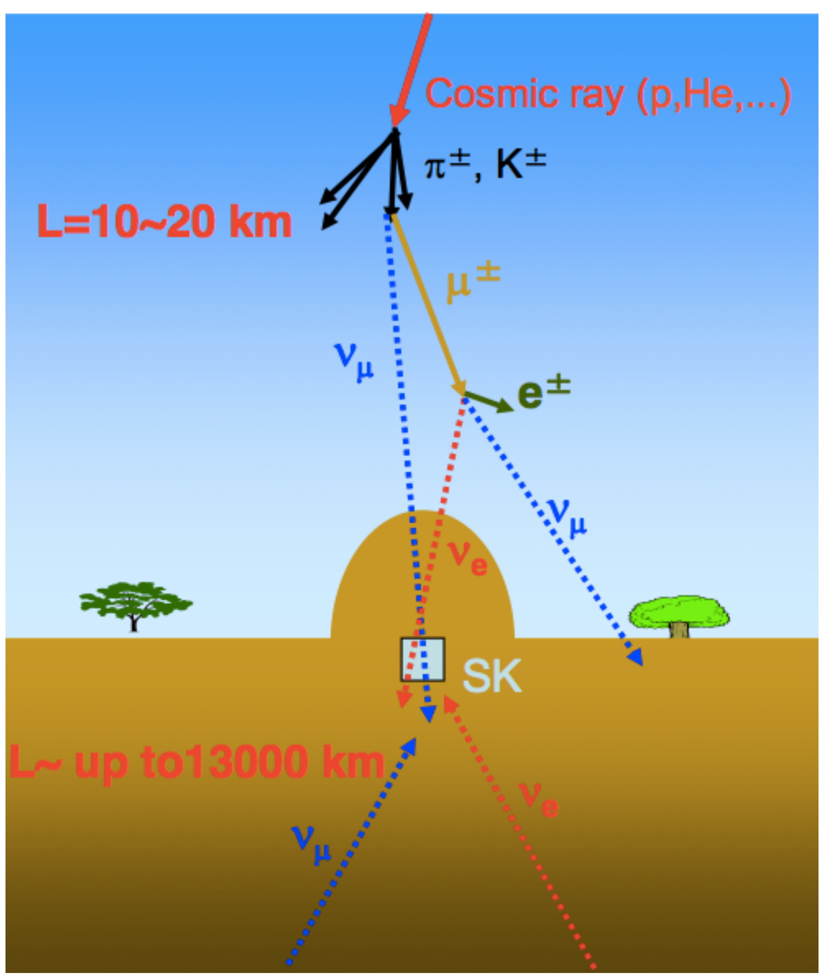
- Direct search for boosted dark matter

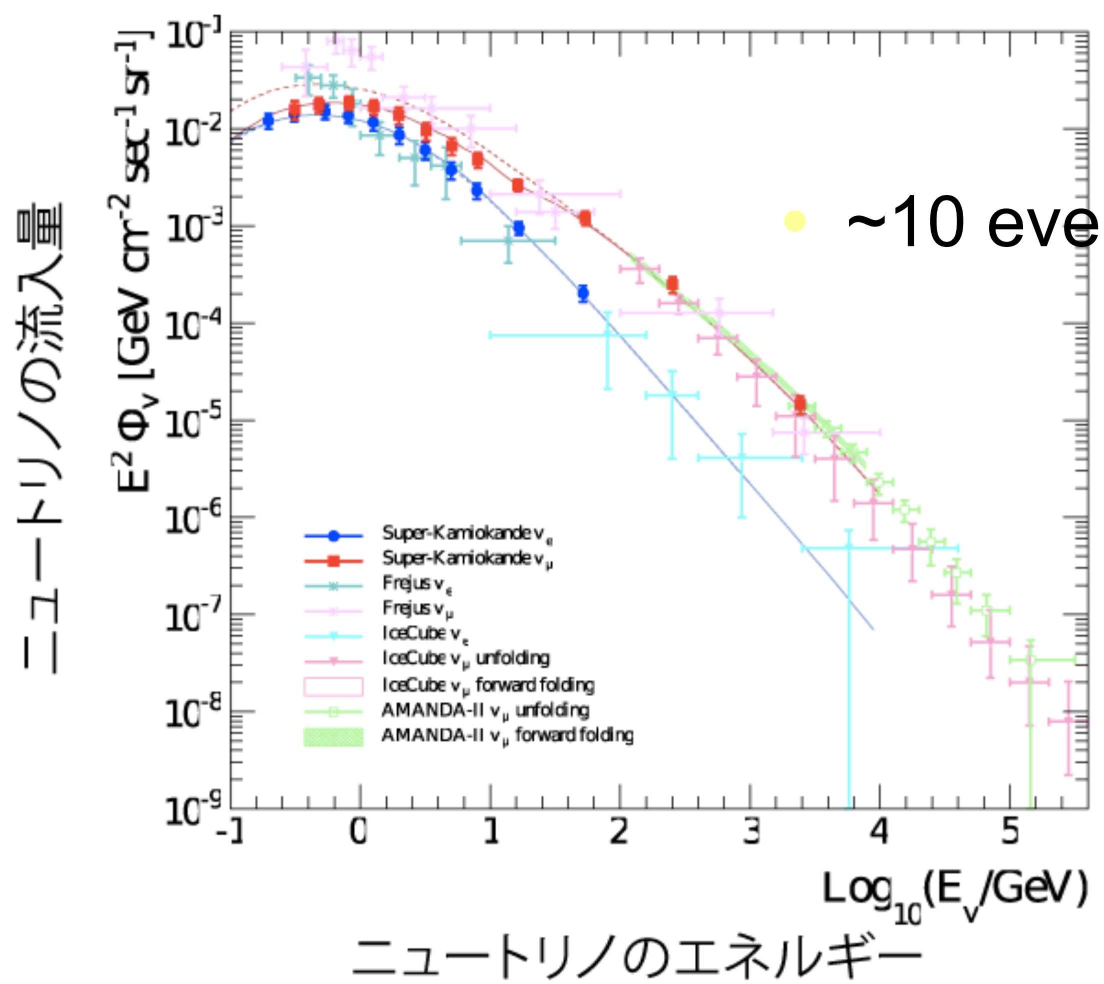
  - motivation
  - electron elastic scattering search (2017)

- Non Standard Interaction Search (2020)

High energy neutrinos in SK = atmospheric (atm) neutrinos (background for proton decay, DM signal, …)

- Neutrinos produced by interaction of cosmic rays (p, α, …) with the atmosphere
- coming from all direction (half of them through the Earth)
- wide range of energies: $O(10^{-1})$ GeV to $O(10^{2})$ GeV
- wide range of baselines: $O(10)$ km to $O(10^{4})$ km



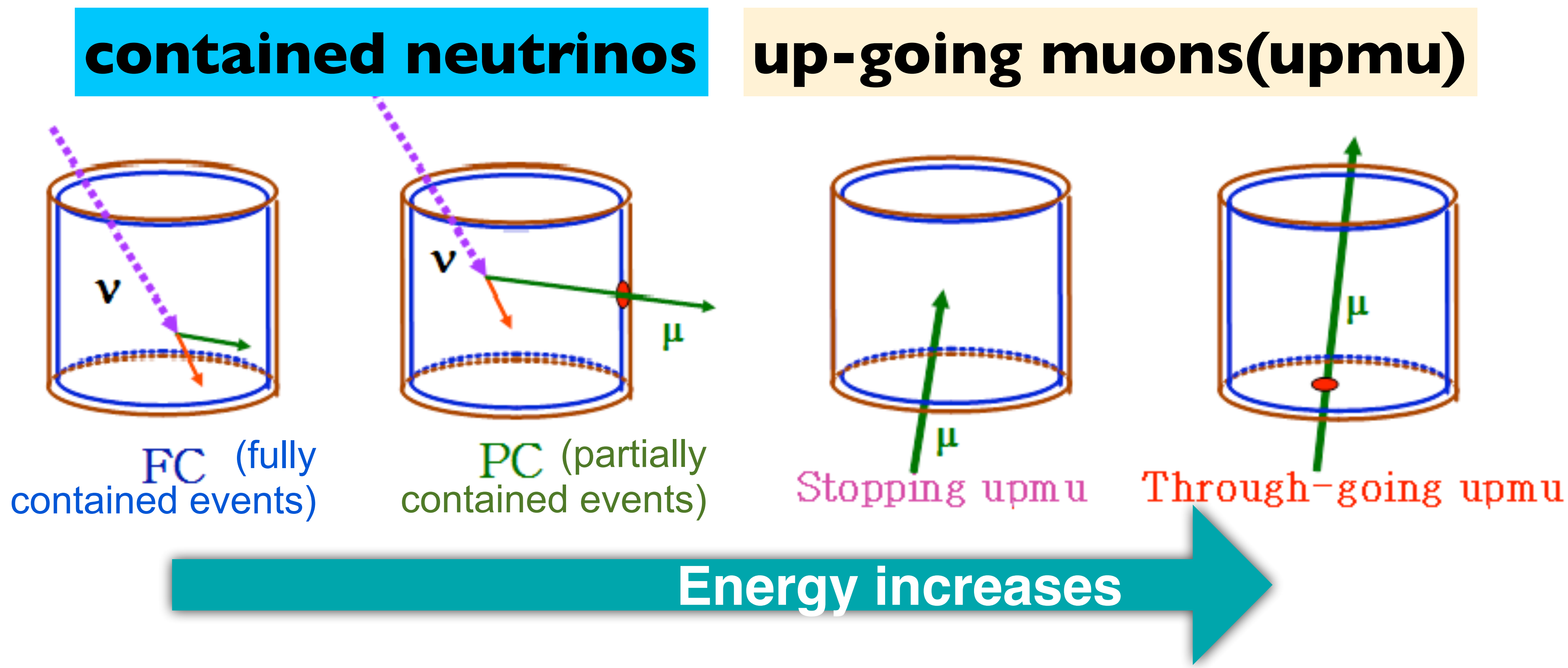


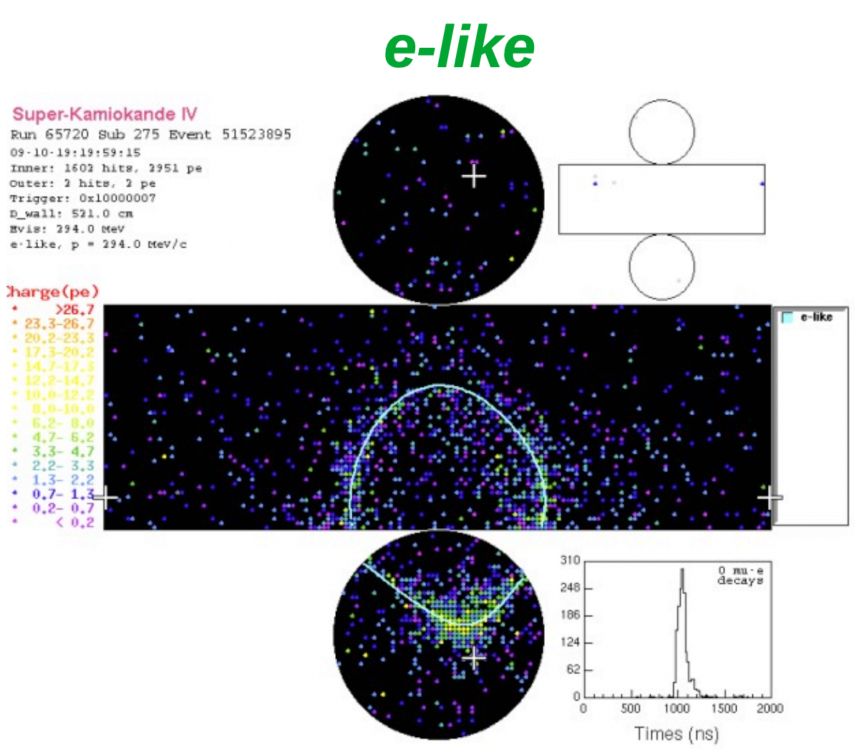
- ~10 events/day

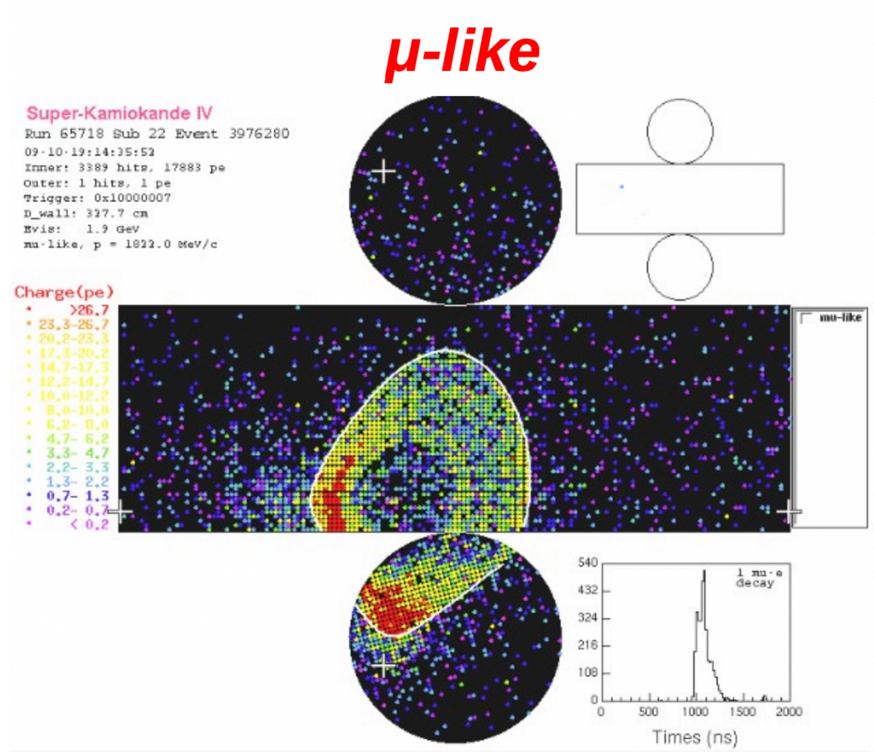
http://www-sk.icrr.u-tokyo.ac.jp/sk/sk/atmos-e.html

Atmospheric neutrinos

Atm ν classification:
FC sub-GeV (<1.3GeV),
FC multi-GeV,
PC,
Upmu



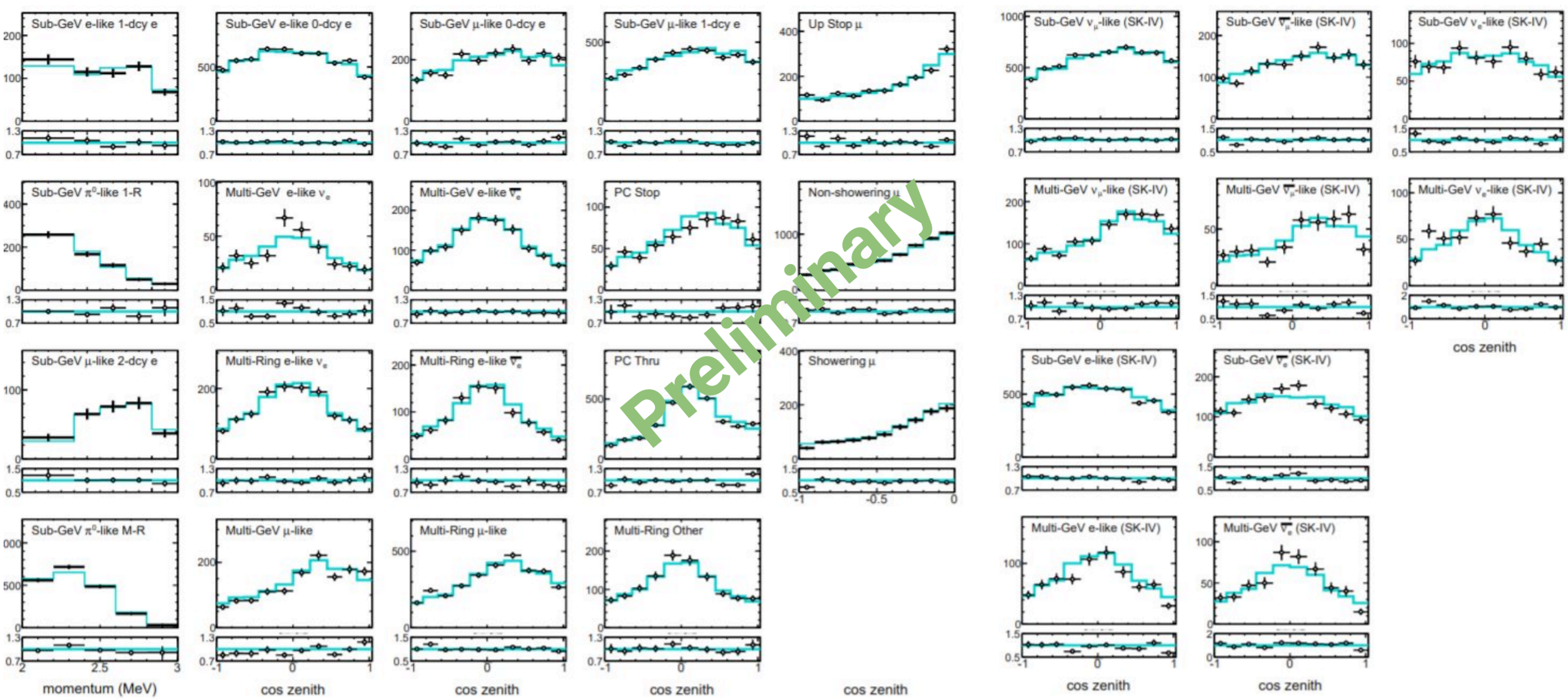




rings are identified as e-like or μ-like, based on the features of the Cherenkov rings

Atmospheric neutrino oscillation analysis frame

- Energy and direction are critical information - distribute events in 2d zenith angle & energy bins
- Events are classified into many sub samples (14 samples for FC) according to kinematics, number of rings and other features
- Oscillation parameters are fit by maximum likelihood method together with 'pulls' of the systematics (~150 of them)



Indirect DM searches

- It's a directional search for excess of neutrino flux. We've done 'cut & count analysis' in past. But for a wide-spread signal buried under BG, not so efficient

- Basically we follow oscillation analysis framework; Instead of fitting oscillation parameters, fit parameters of DM model, i.e. DM flux strength.

- This is possible thanks to the precise atmospheric neutrino MC and systematic error table, which also allows us to have a signal MC by re-weighting treatment (public DM-induced neutrino flux generator, "DarkSUSY" is used to calculate re-weighting factor)

Test signal contribution by pulled χ^2 method

Maximum log likelihood (based on Poissonian statistics) fit for "SK data" against "atmospheric neutrino MC + WIMP-induced neutrino MC" to find <u>best fit value of WIMP contribution</u>

$$\chi^2 = \min_{\{\epsilon_j\}} \left[2 \sum_{i=1}^{N} \{ N_i^{exp} - N_i^{data} + N_i^{data} ln(N_i^{data}/N_i^{exp}) \} + \sum_{j=1}^{J} (\frac{\epsilon_j}{\sigma_j})^2 \right], \text{ where}$$

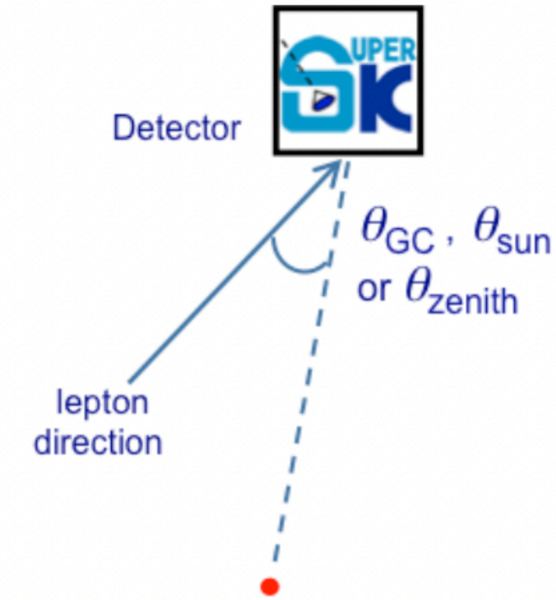
$$N_i^{exp} = N_i^{BG}(1 + \sum_{j=1}^{J} f_j^i \epsilon_j) + \beta N_i^{\chi}(1 + \sum_{j=1}^{J} g_j^i \epsilon_j).$$

i: bin index;
j: systematic error index;
σj: systematic error;
εj: "pull";
fji (gji): predicted fractional change of i-th bin due to σj

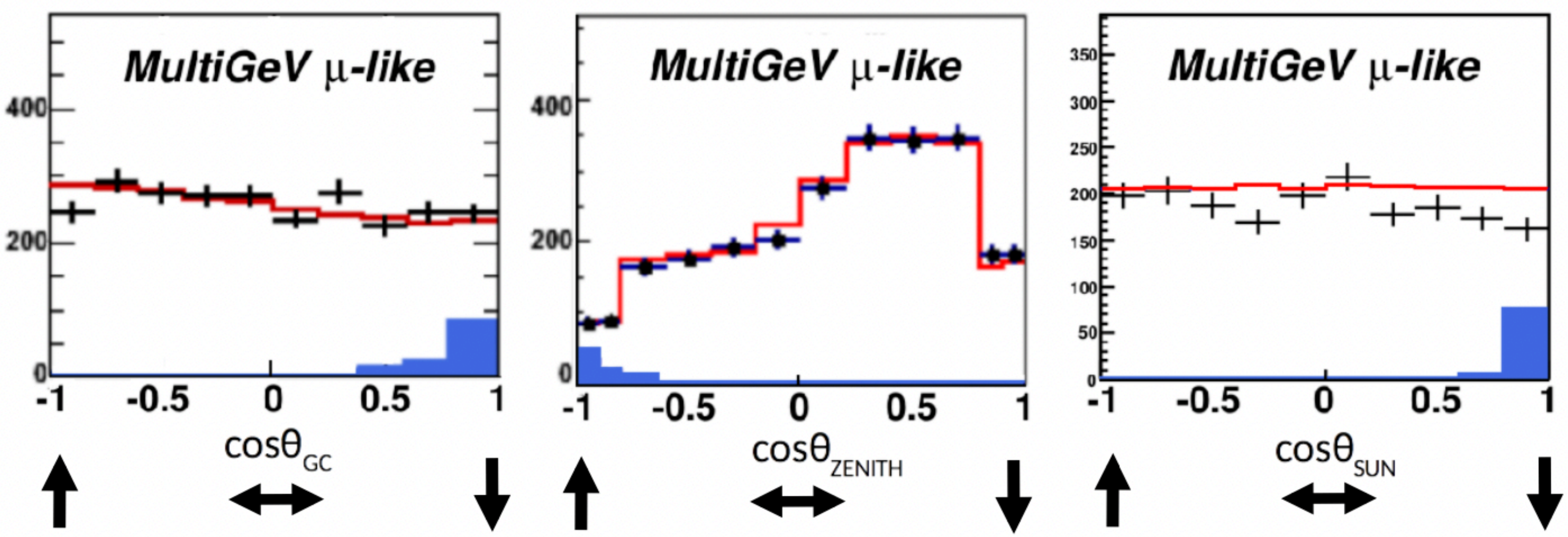
β is the global normalization parameter stands for the allowed fraction of the signal MC input

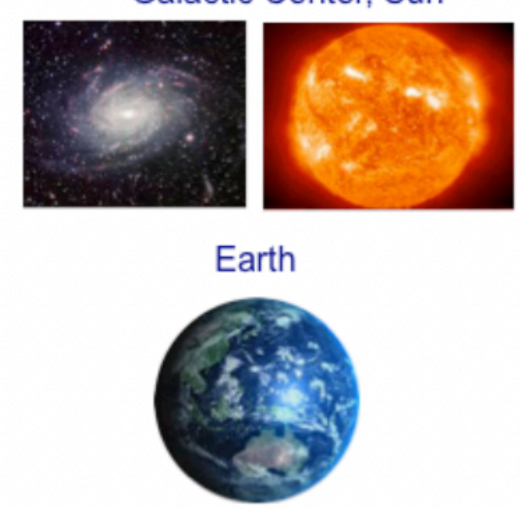
Dark matter searches at Super-Kamiokande

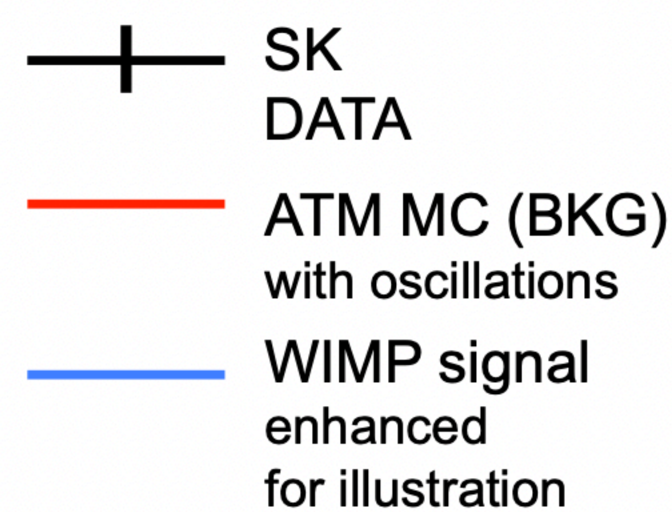
- Search for excess of neutrinos form **Earth/Sun/Milky Way**
- **FIT:** for each tested WIMP mass, find configuration of ATM ν + DM signal that would match DATA the best



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

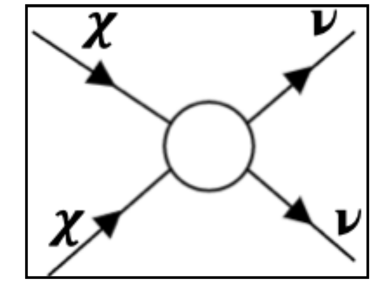






- In these coordinate systems signal is easy to distinguish from atmospheric neutrino background

Indirect Galactic Dark Matter Search



in case of annihilation

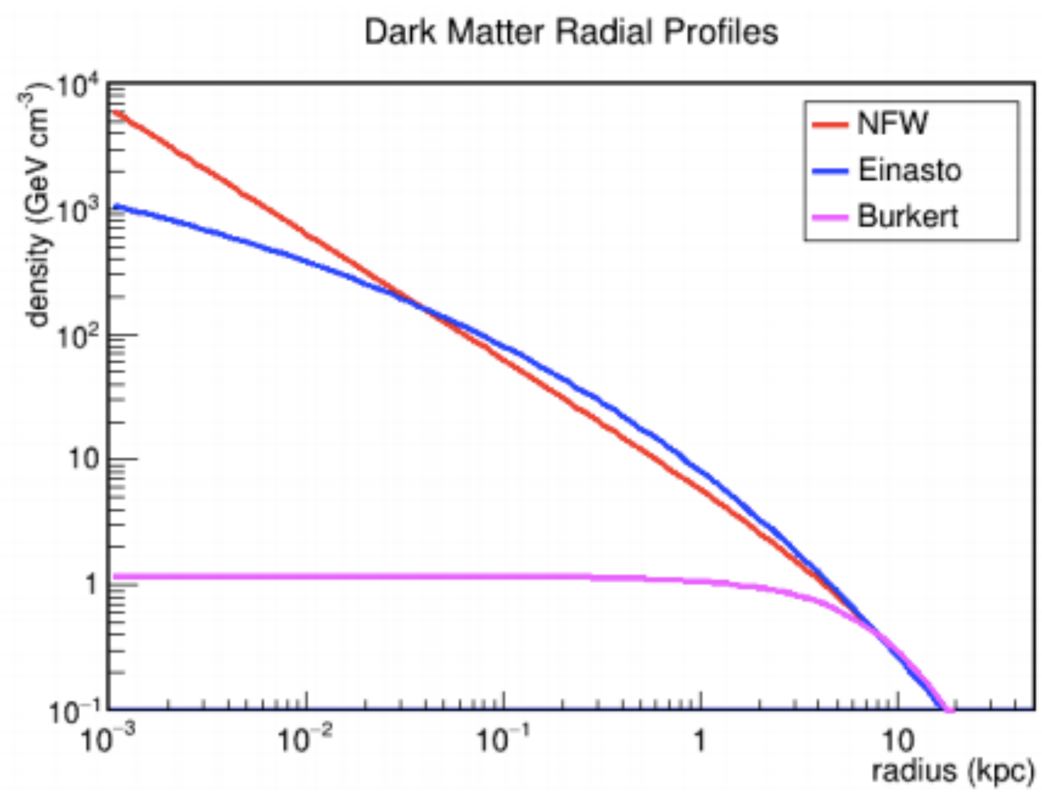
constraint!

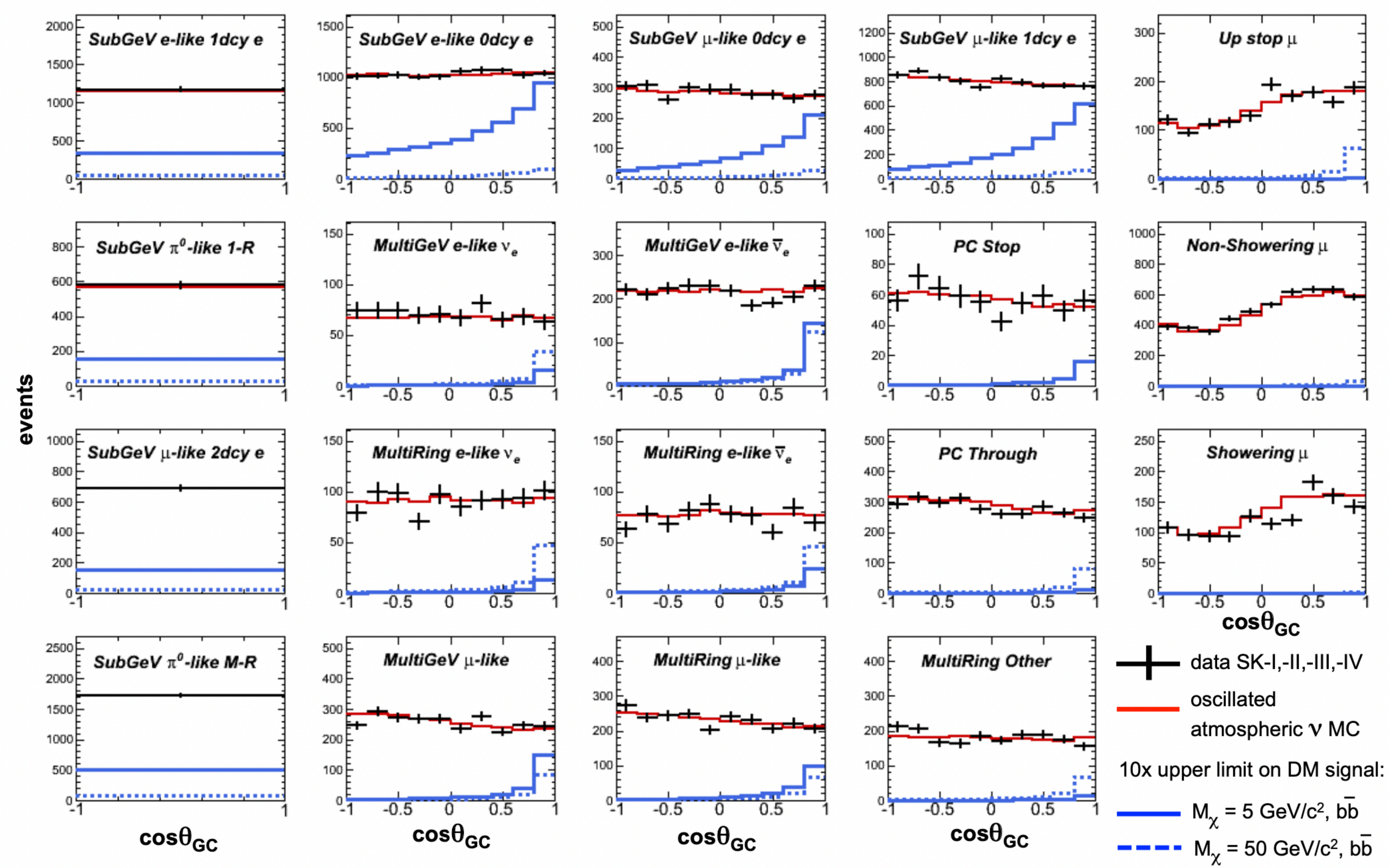
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\frac{dN_\nu}{dE_\nu}\int_0^{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi^2(r(s,\Psi,\theta))ds$$

particle physics

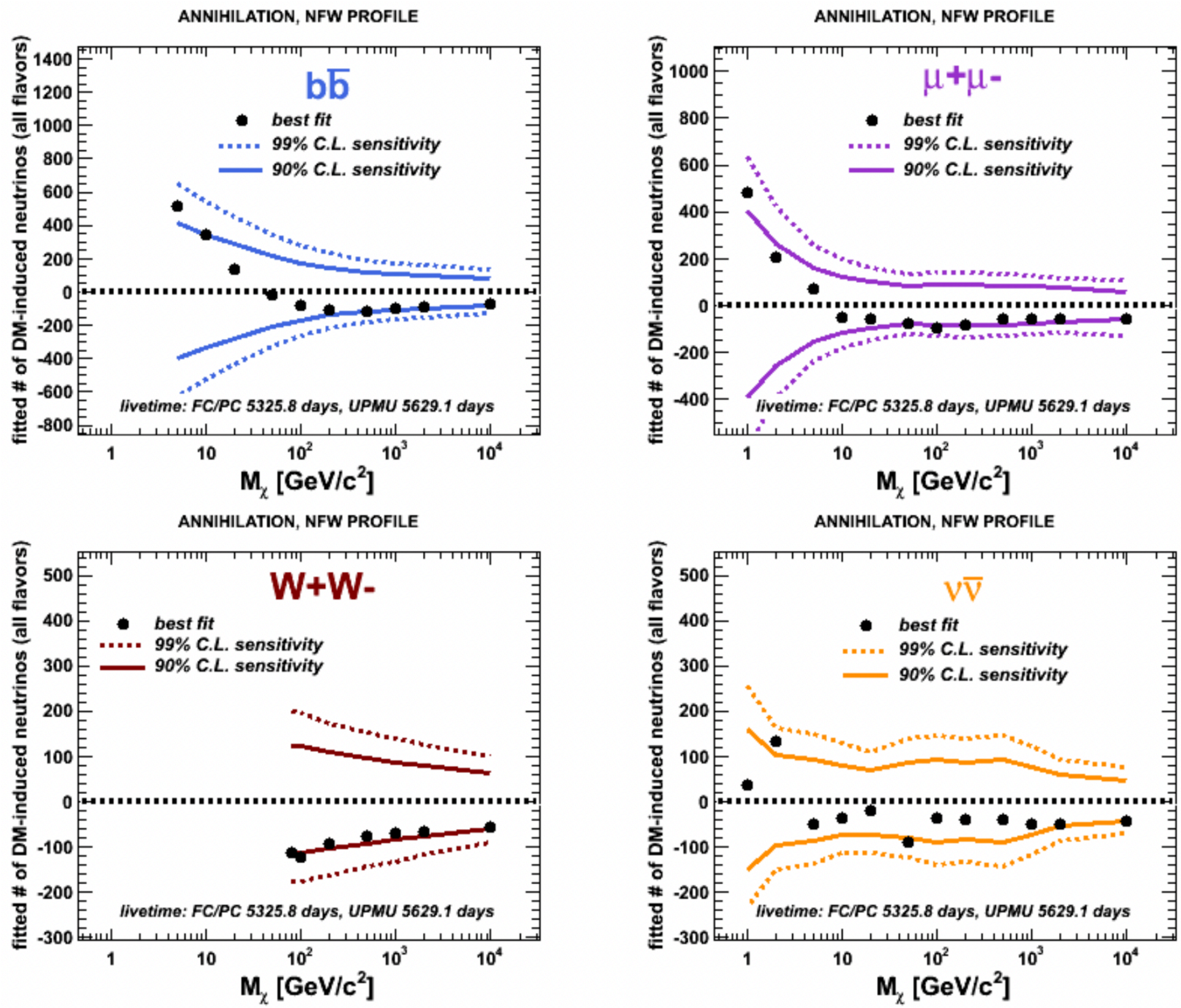
astrophysics

- WIMPs annihilate to known particles, which produce neutrinos
- GC visibility with SK:
  ~71% with UPMU, 100% FC/PC
- diffuse signal from entire Galaxy, peaked from Galactic Center
- Expected signal intensity strongly depends on halo model:
  NFW is considered as a benchmark model
- In case of neutrino annihilation channel, line signal in energy:
  best sensitivity among the annihilation channels



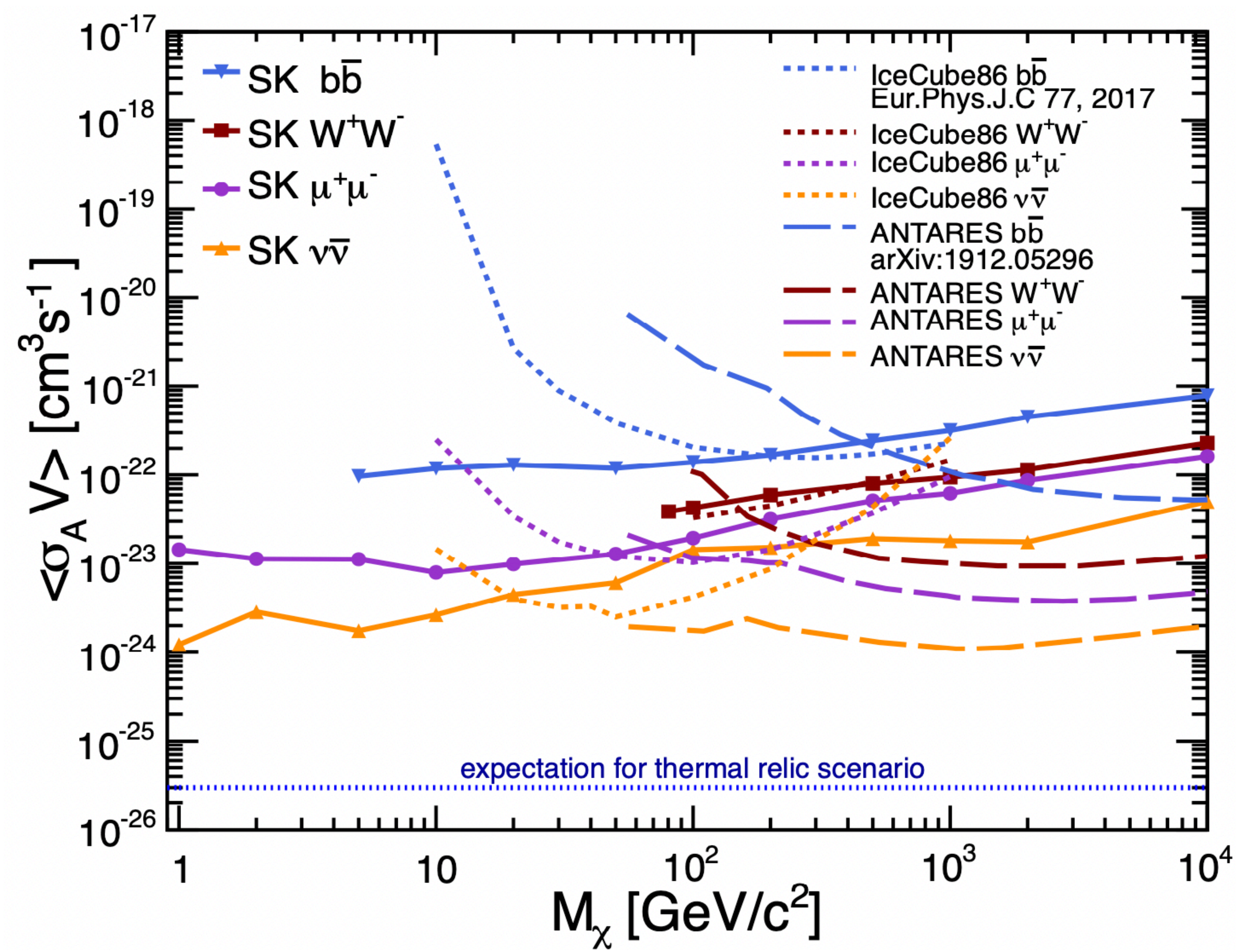


SubGeV e-like 1dcy e
SubGeV e-like 0dcy e
SubGeV μ-like 0dcy e
SubGeV μ-like 1dcy e
Up stop μ
SubGeV π⁰-like 1-R
MultiGeV e-like ν_e
MultiGeV e-like ν̄_e
PC Stop
Non-Showering μ
SubGeV μ-like 2dcy e
MultiRing e-like ν_e
MultiRing e-like ν̄_e
PC Through
Showering μ
SubGeV π⁰-like M-R
MultiGeV μ-like
MultiRing μ-like
MultiRing Other
events
cosθ_GC
data SK-I,-II,-III,-IV
oscillated atmospheric ν MC
10x upper limit on DM signal:
M_χ = 5 GeV/c², bb̄
M_χ = 50 GeV/c², bb̄



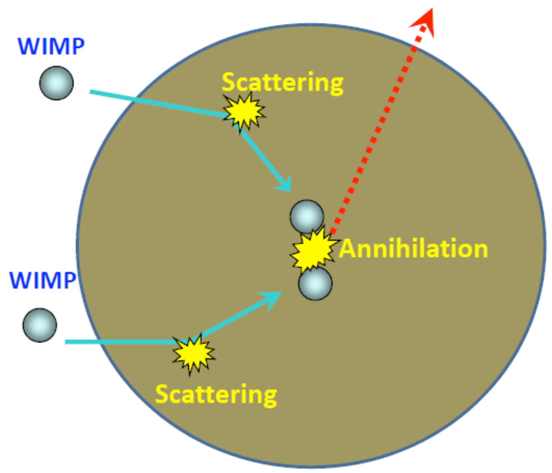
- ~150 systematic uncertainty terms included in the fit
- Fit results are consistent with null WIMP contribution
- 90% C.L. upper limit on DM self-annihilation cross section $<\sigma_A V>$

SK-I - IV data taken from 1996 to 2016
(5325.8 live-days)



Super-Kamiokande,
Phys.Rev.D 102 (2020) no.7, 072002

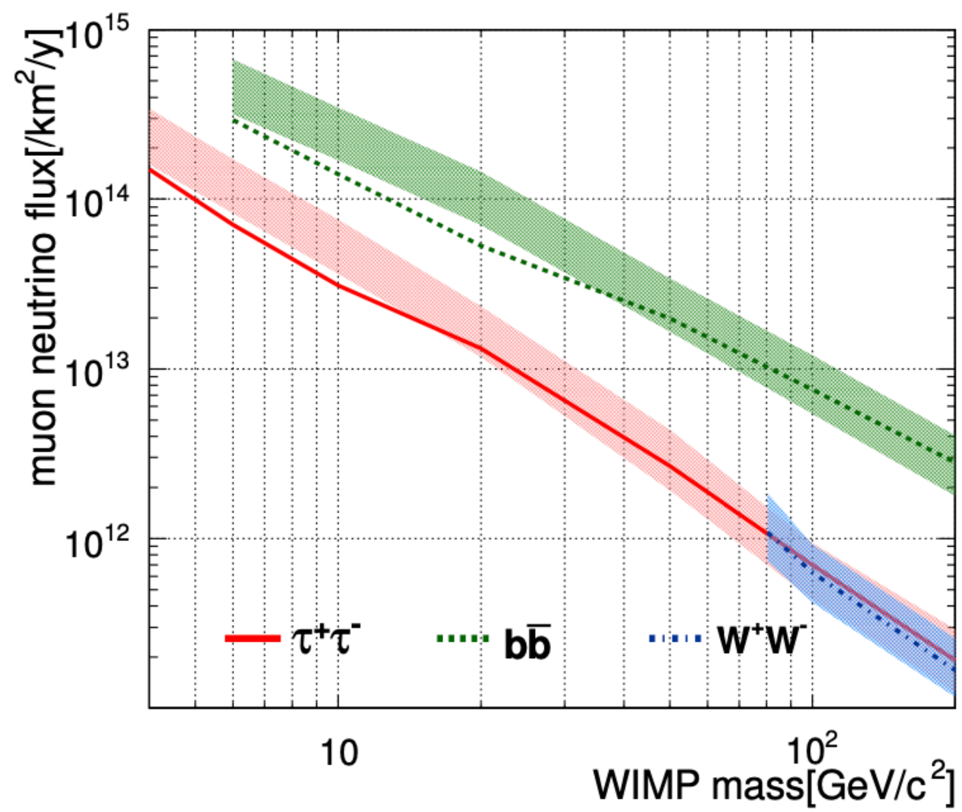
Indirect Solar Dark Matter Search



- WIMP at rest in the Galactic halo can get captured and settle in solar core by its interaction with nucleon
- Neutrinos escape the Sun, detected
- Equilibrium between capture rate and annihilation rate inside the Sun is assumed

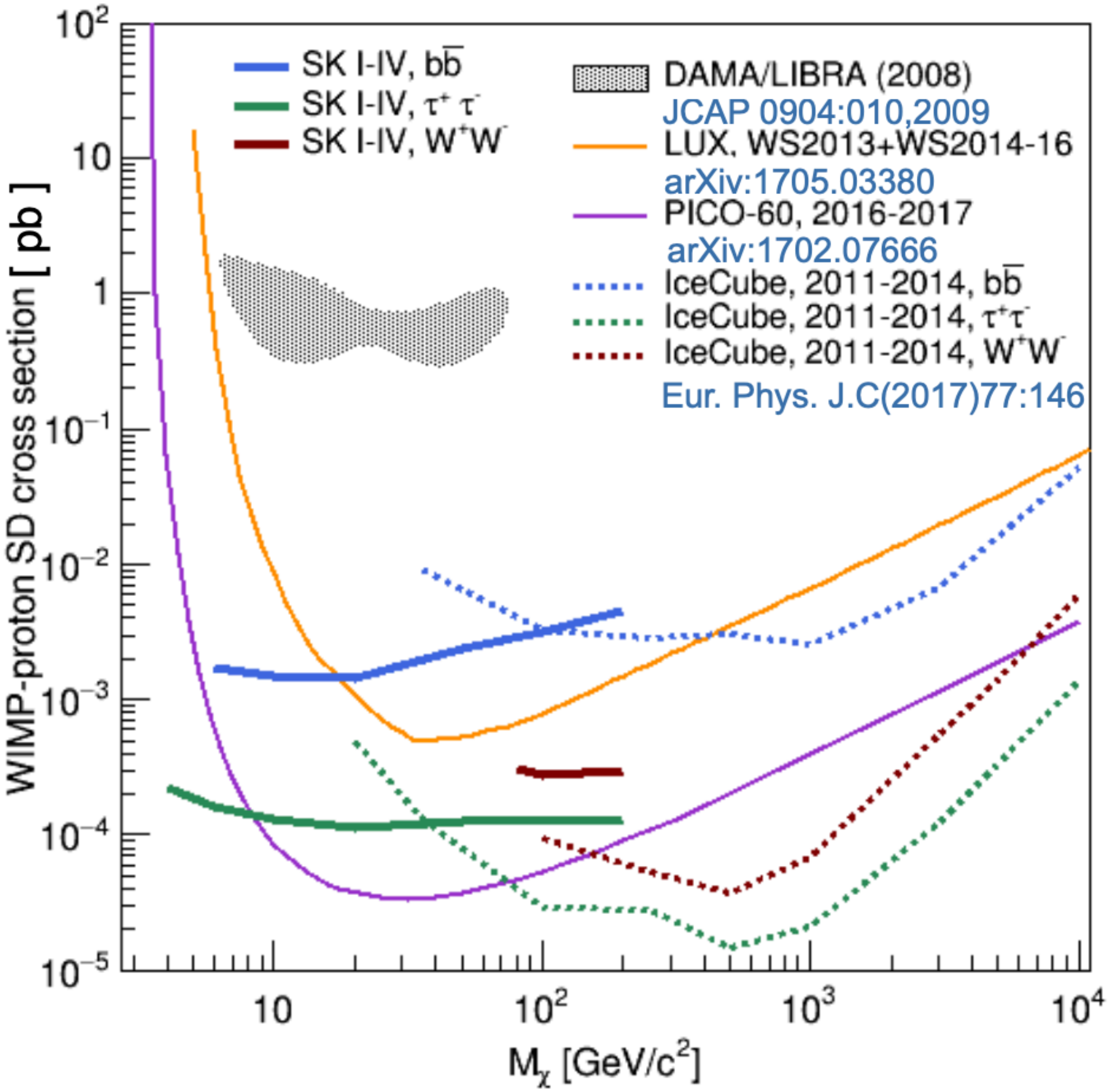
$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N \quad \Rightarrow \quad \Gamma_A^{\mathrm{equi}} = \frac{1}{2} C_C$$

- Fit results are consistent with null WIMP contribution
- 90% C.L. upper limit on DM-nucleon scattering cross section $\boldsymbol{\sigma_{\chi n}}$

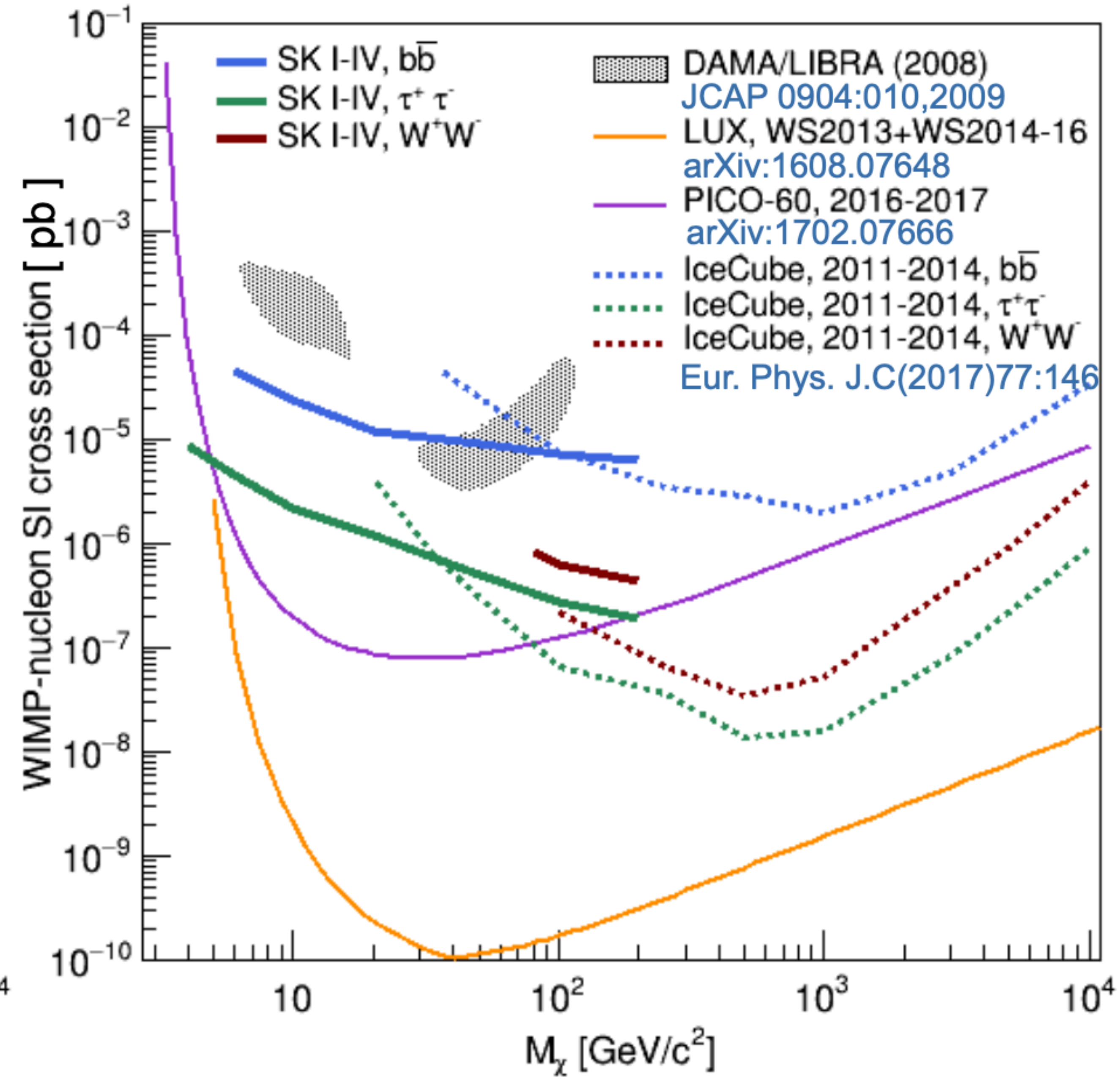


SK-I - IV data taken from 1996 to 2012
(3903 live-days)

spin dependent interactions

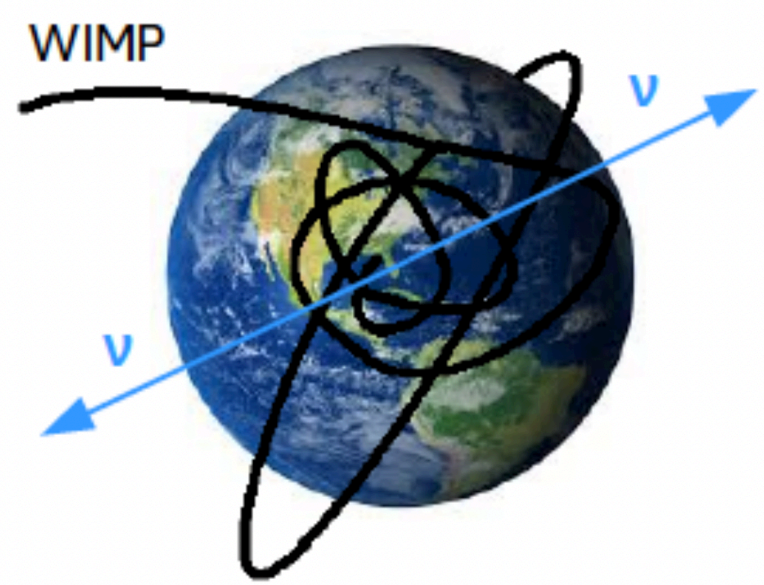


spin independent interactions

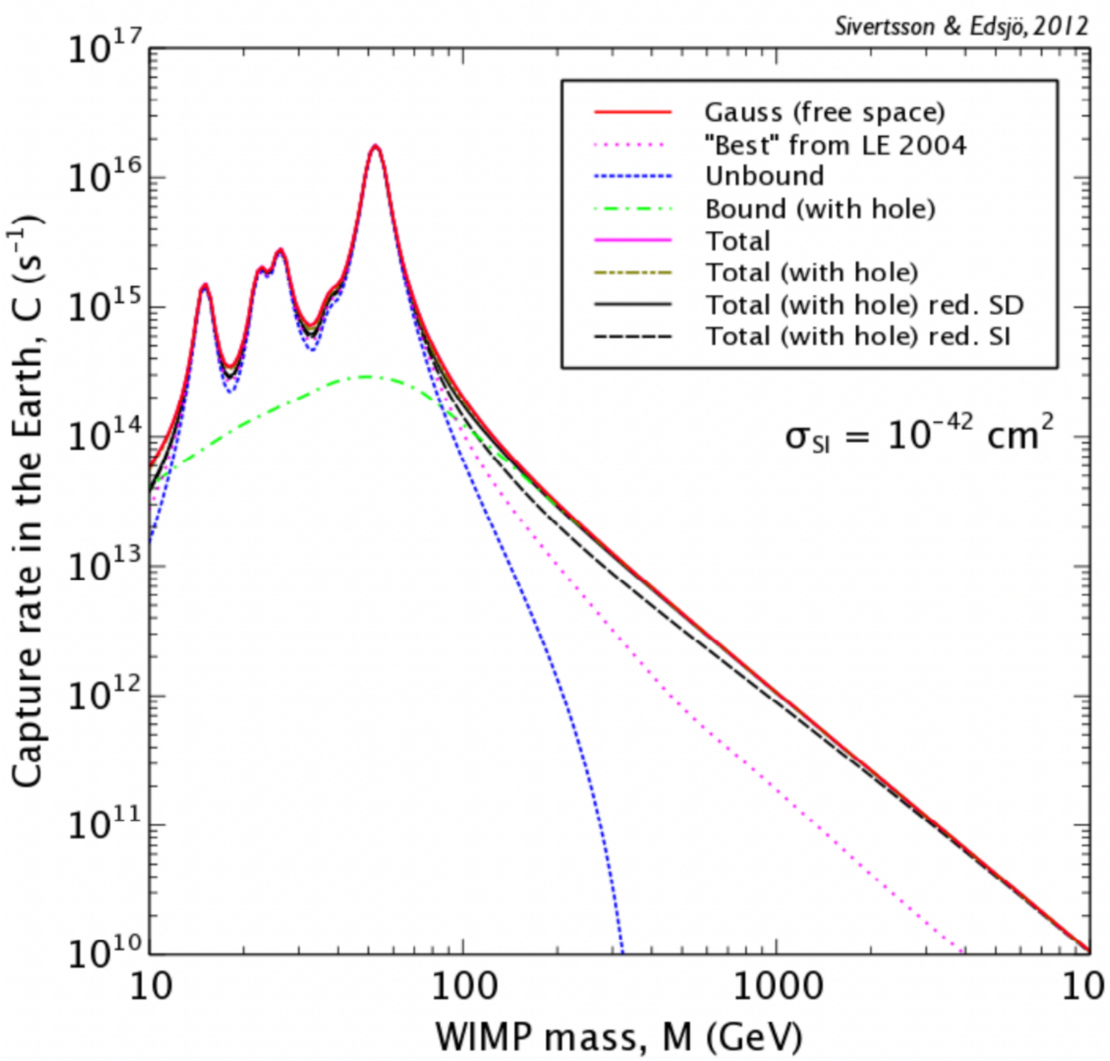


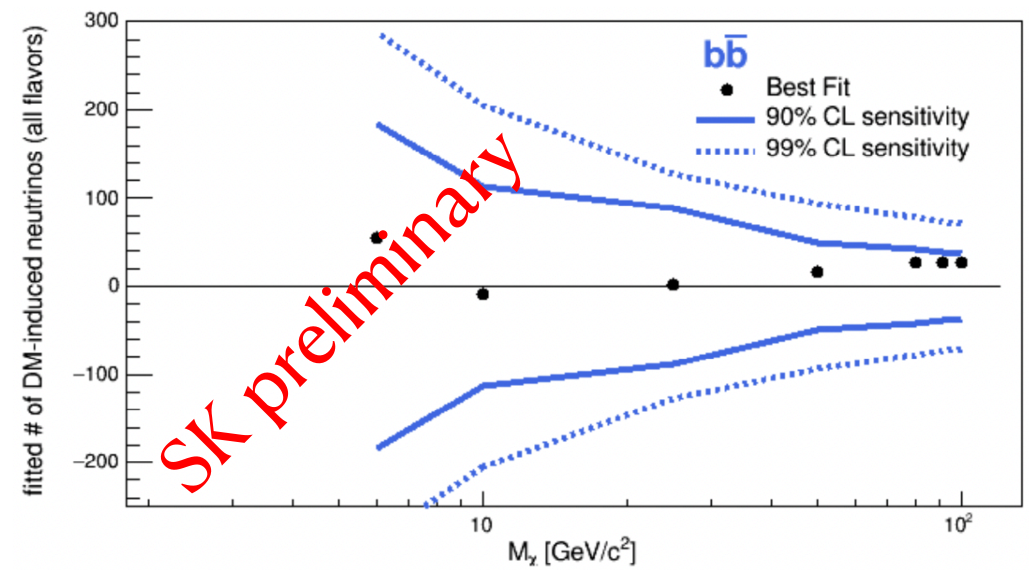
K.Choi for the Super-Kamiokande,
Phys.Rev.Lett. 114 (2015) no.14, 141301

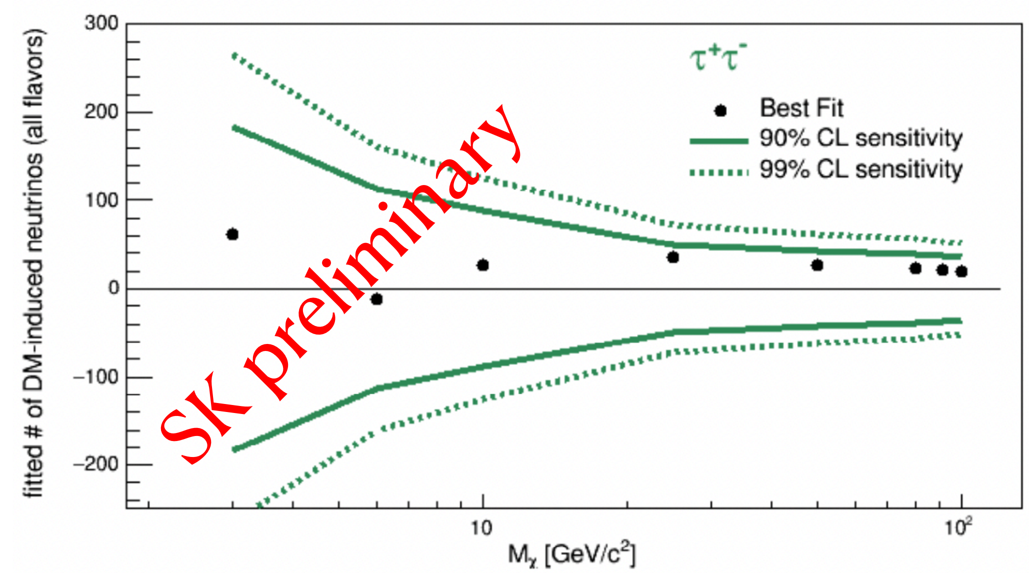
Indirect Earth Dark Matter Search



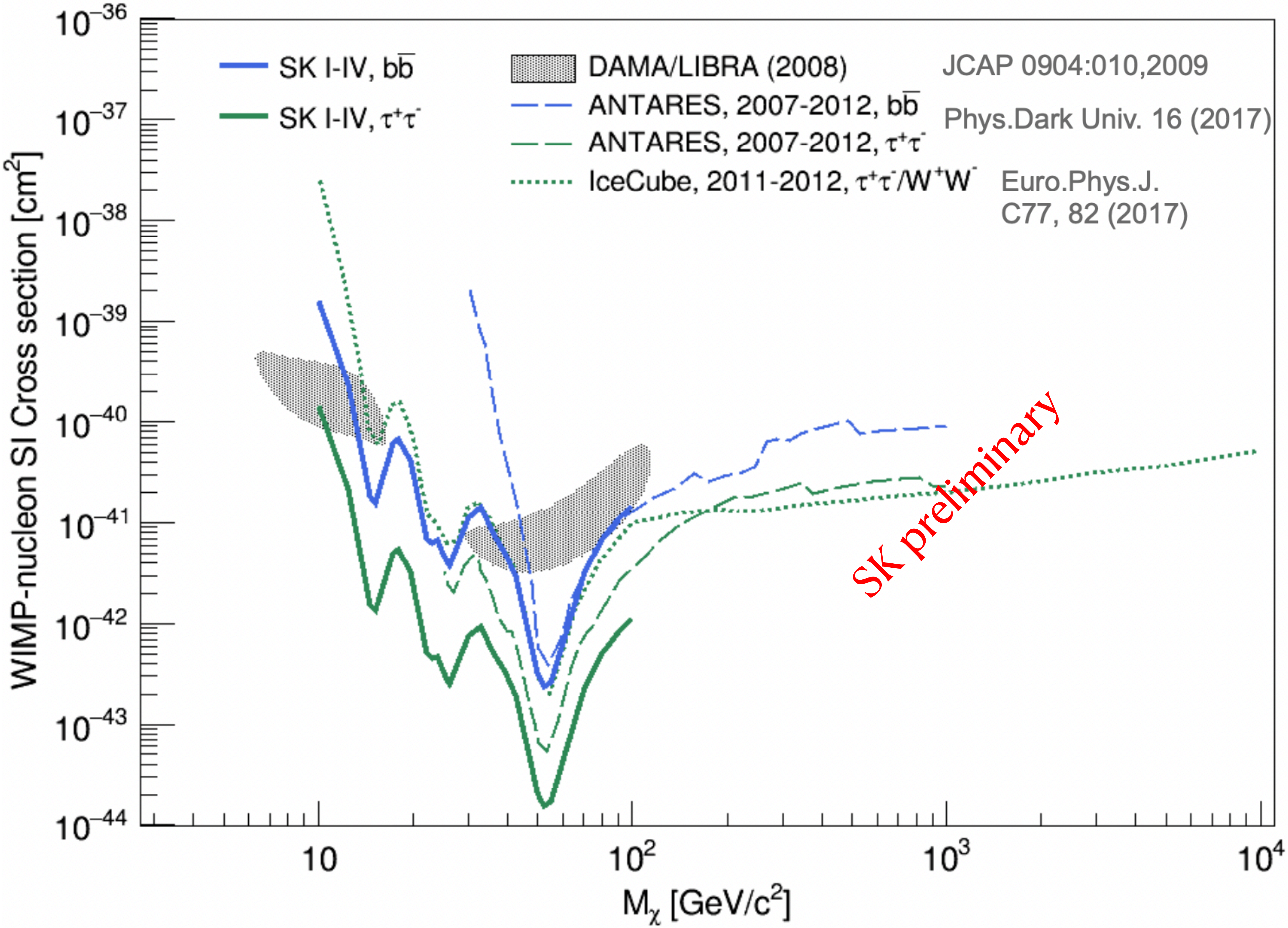
- Spin-independent interactions dominate the capturing process
- If the mass of DM matches given heavy element, the capture rate increases considerably - resonant capture on the most abundant elements ^{16}O, ^{24}Mg, ^{28}Si and ^{56}Fe and their isotopes







SK-I - IV data taken from 1996 to 2016



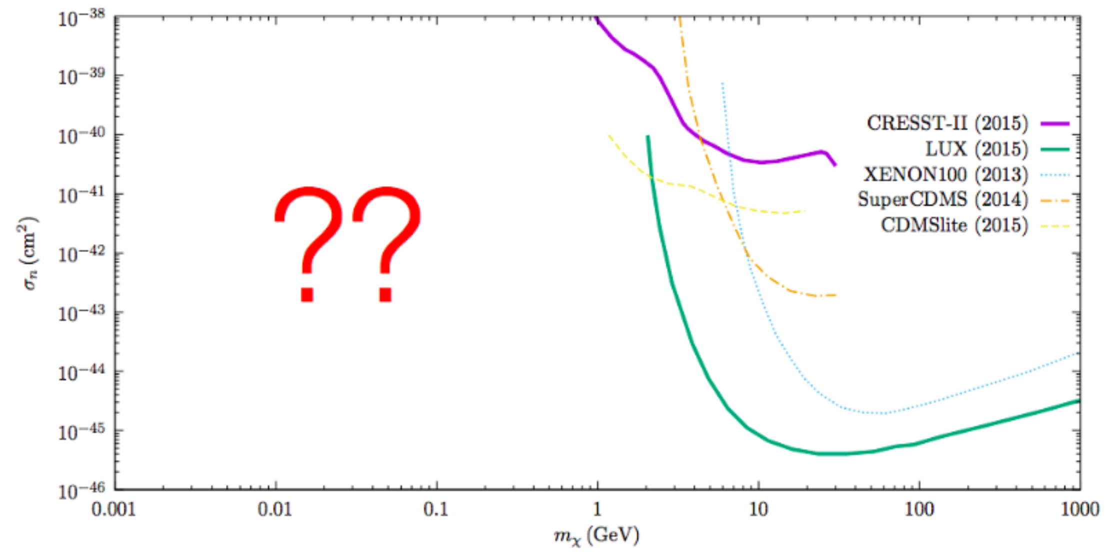
K.Frankiewicz thesis (paper is under preparation)

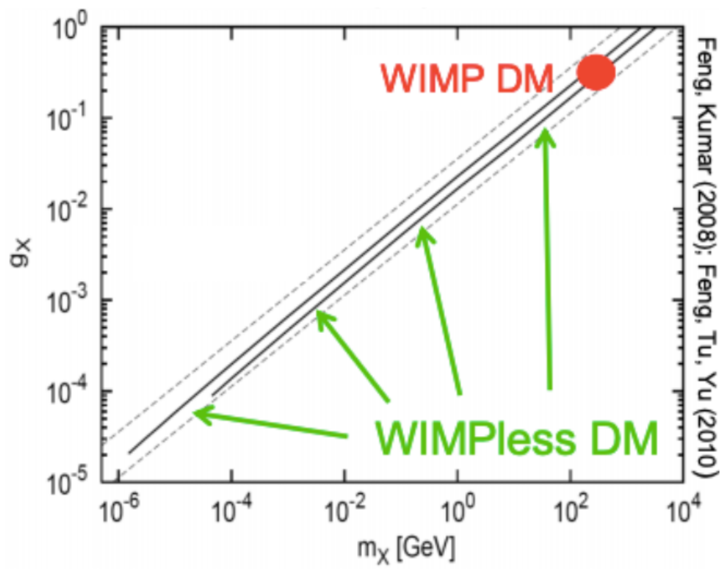
dark matter not found so far…

- A few anomalies but no consistent signal
- Dark matter may not be WIMP? Then what to do?
  - persistently look in (WIMP parameter space not yet closed)
  - look in every corner (experiment-driven strategy)

Go to Sub-GeV

- Sub-GeV DM is less searched because
  - "WIMP miracle" >2 GeV
  - direct detection experiments lose sensitivity

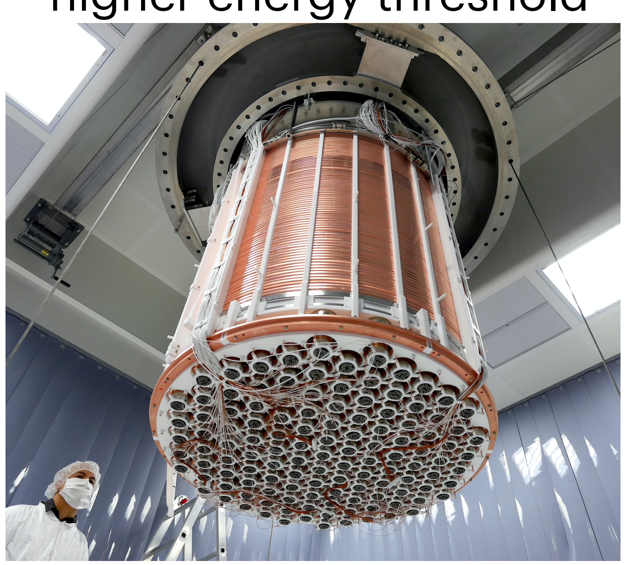


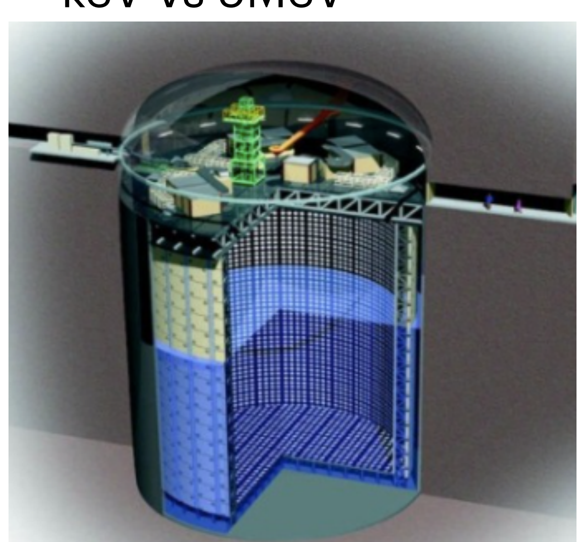


- However,
  Sub-GeV DM can also be a minimal thermal relic candidate &
  comes from wider modelings

- Current efforts in direct detection to detect sub-GeV signal (CRESST, DAMIC, SENSEI, CDMS, …)

SK compared to direct detection experiments:
larger volume - ~1T vs 50kT
higher energy threshold - ~keV vs 5MeV





- How can SK contribute?
  - Indirect detection of sub-GeV DM - no problem
  - Direct detection of sub-GeV DM?

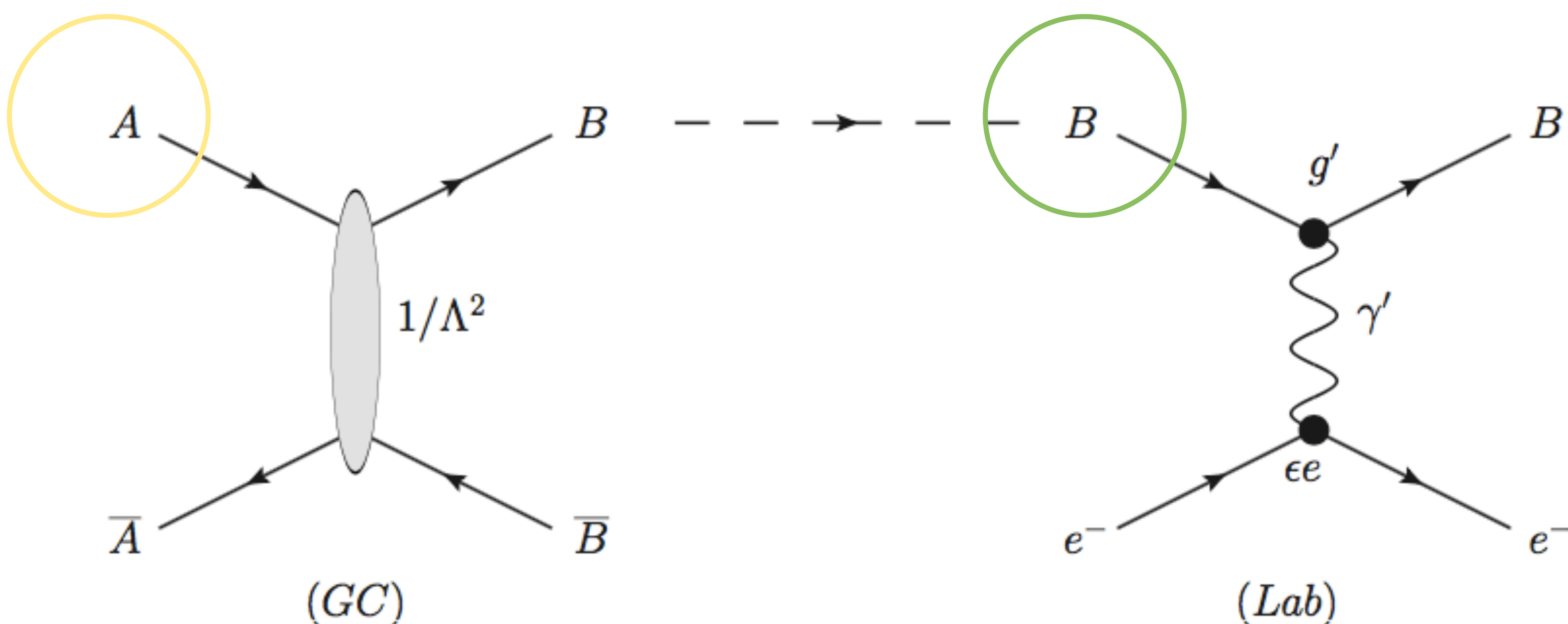
Typical velocity of dark matter ~ $O(10^{-3})$ c
-> typical signal <100 keV

Boosted DM Search in SK

- insight: sometimes it's easier to find "friend" of dark matter than dark matter itself (Agashe et al., arxiv:1405.7370)

thermal relic (secluded)

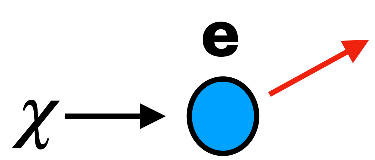
friend (detectable)



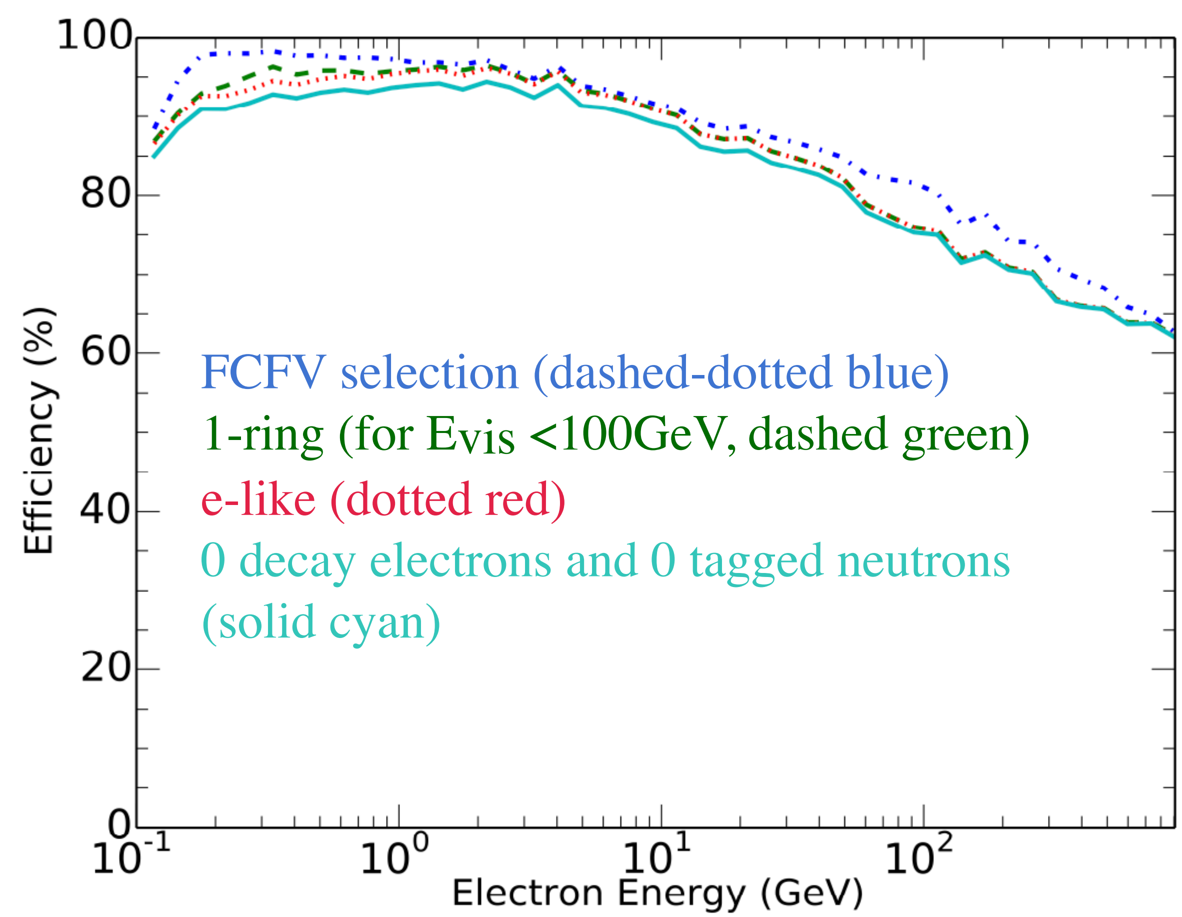
one example interaction - via dark photon

If scattering signal of B is expected above SK E threshold
→ direct detection of "boosted dark matter"

Search for X-e scattering in the SK



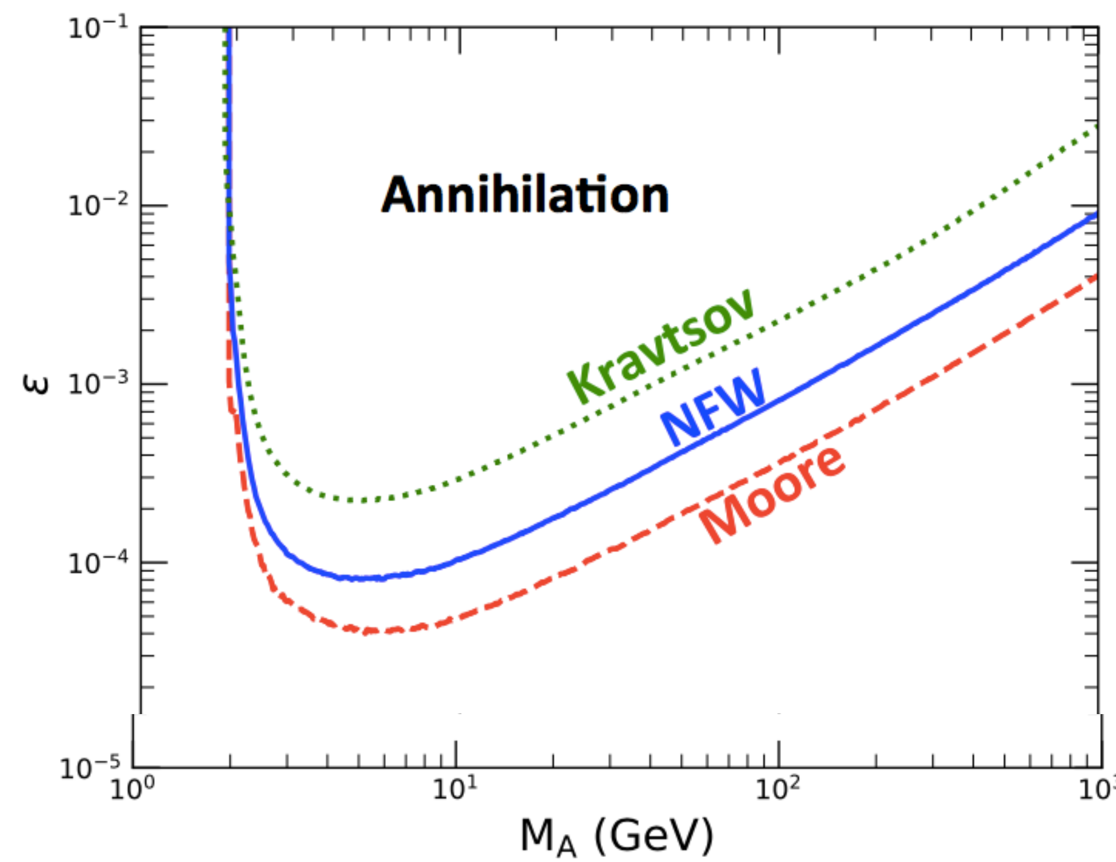
- Very forward elastic scattering - good angular pointing even at low energy
- e-like single ring, no hadrons -> no decay e, no neutrons
- background = atm ν elastic scattering, (also CCQE contamination, …)
- cut & count analysis for various cone-half angle to cover wide range of potential signal, background modeled by off-source data (except high-energy)
- Only SK-IV data used (previous data has no neutron trigger)



Search Cone	100 MeV $< E_{vis} <$ 1.33 GeV Expected Bckg	Data	Sig Rate Limit $(\text{kT-y})^{-1}$	1.33 GeV $< E_{vis} <$ 20 GeV Expected Bckg	Data	Sig Rate Limit $(\text{kT-y})^{-1}$	$E_{vis} >$ 20 GeV Expected Bckg	Data	Sig Rate Limit $(\text{kT-y})^{-1}$
GC 5°	8.4 ± 0.7	5	0.017	1.6 ± 0.3	1	0.018	0.016 ± 0.005	0	0.015
GC 10°	32.0 ± 1.9	24	0.023	6.3 ± 0.84	5	0.026	0.060 ± 0.018	0	0.015
GC 15°	72.5 ± 3.5	69	0.078	13.6 ± 1.6	11	0.032	0.14 ± 0.04	0	0.014
GC 20°	126.5 ± 5.4	125	0.123	23.3 ± 2.3	18	0.028	0.25 ± 0.07	0	0.014
GC 25°	196.8 ± 7.6	202	0.201	35.4 ± 3.3	31	0.049	0.37 ± 0.11	0	0.013
GC 30°	283.7 ± 10.1	285	0.214	49.3 ± 4.3	48	0.081	0.53 ± 0.16	0	0.012
GC 35°	384.8 ± 12.8	375	0.187	68.1 ± 5.4	67	0.101	0.70 ± 0.21	0	0.011
GC 40°	499.6 ± 15.9	494	0.249	90.2 ± 6.9	90	0.124	0.90 ± 0.27	0	0.011
Sun 5°	7.59 ± 0.18	5	0.017	1.25 ± 0.07	1	0.020	0.015 ± 0.004	0	0.015

- The analysis was done in a model-independent way for any electron-scattering signal coming from the GC & the Sun
- One example constraint for dark photon interaction given for boosted dark matter B produced by annihilation in the GC (for m_B=200 MeV, $m_{\gamma'}$=20 MeV, and g′=0.5)

2628.1 days of SK-IV data



C. Kachulis for the Super-Kamiokande, Phys.Rev.Lett. 120 (2018) no.22, 221301

Non-Standard Interactions in Neutrino Oscillations

- A way of treating flavor-changing or non-universal (different amplitude for different flavor) interactions of neutrinos, with an effective four fermion Lagrangian
- Possible in many theory models of neutrino mass generation, GUT models…
- Atmospheric neutrinos interact with with u,d,e fermions during the propagating through the Earth

Vacuum oscillations

Matter oscillations

$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} (U^\dagger)_{k\beta} + V_{\mathrm{MSW}} + \sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} \varepsilon_{ee} & \varepsilon^*_{e\mu} & \varepsilon^*_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon^*_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Standard oscillations

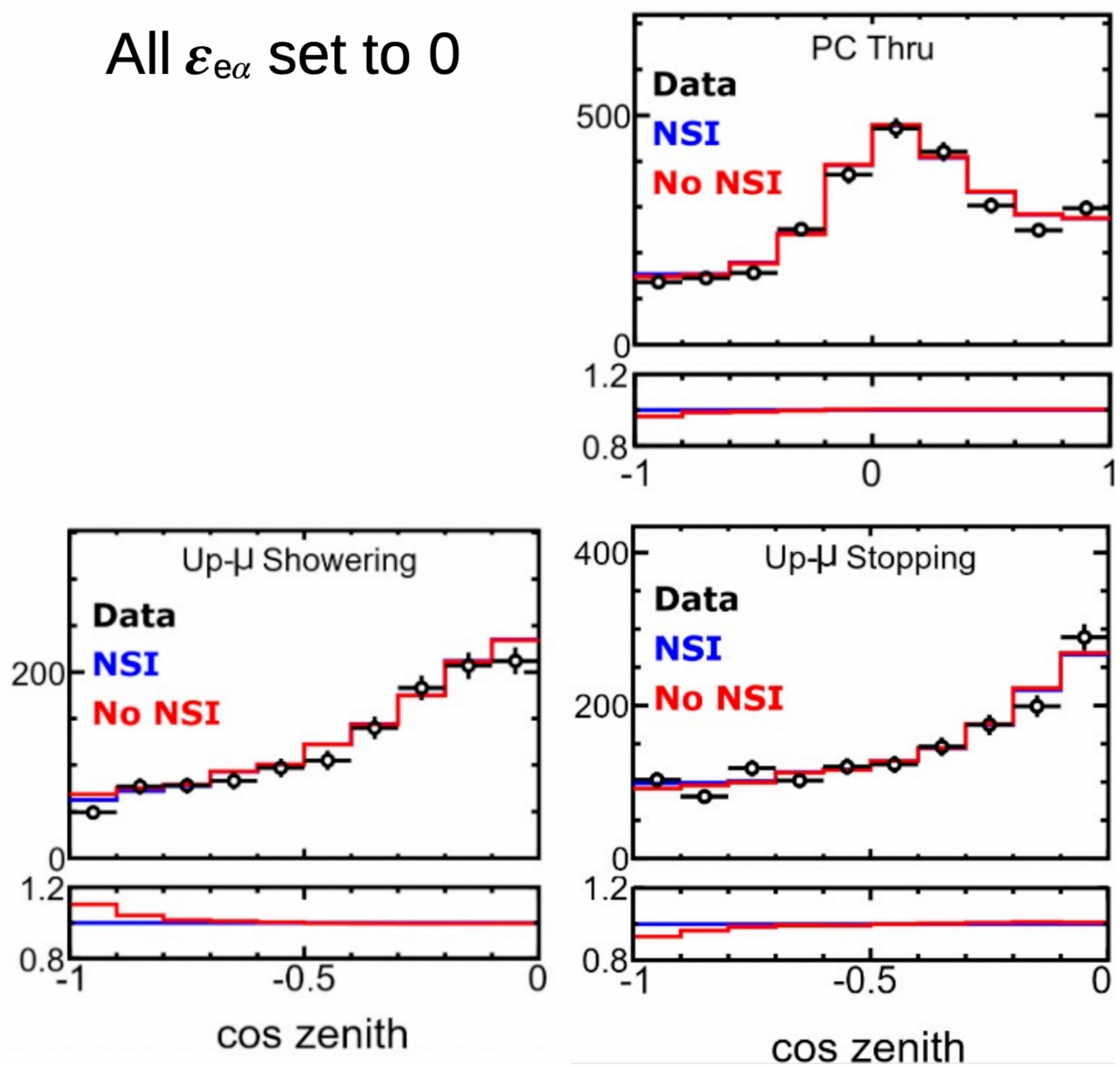
NSI

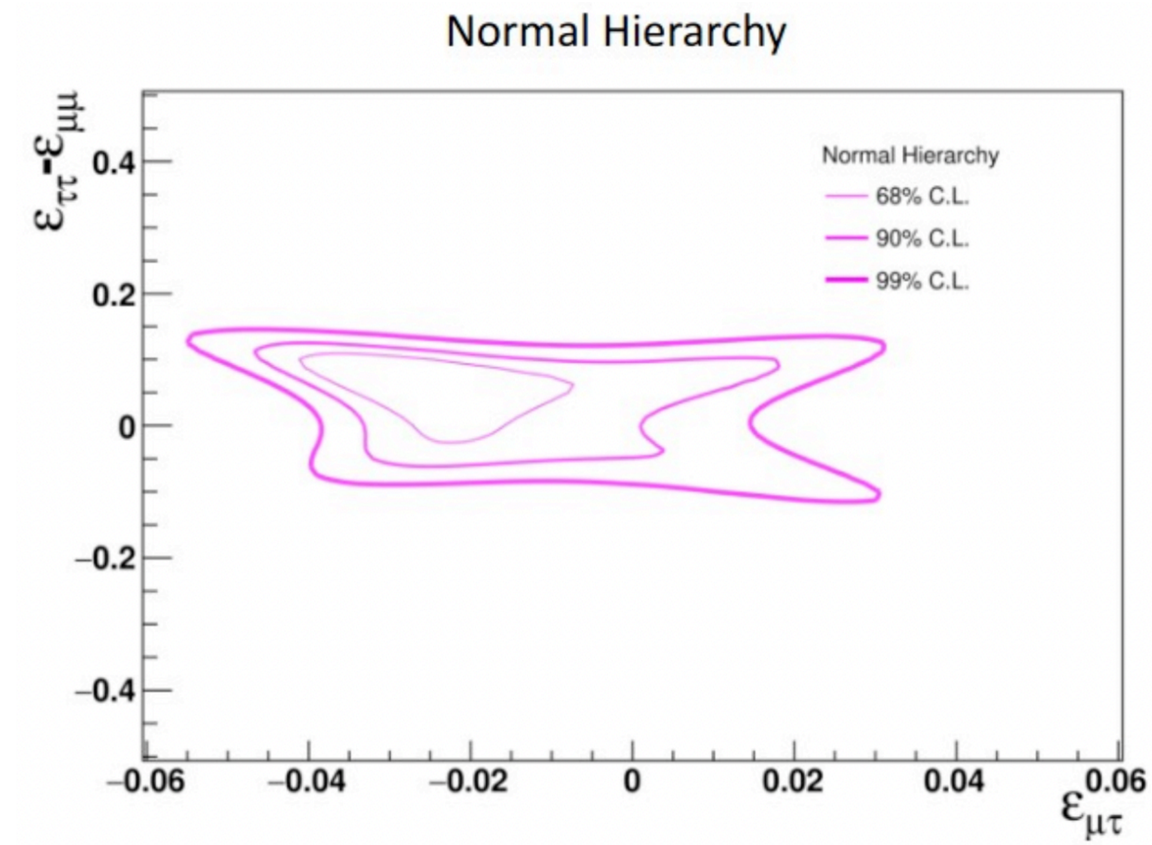
Fit to the μ-τ sector

SK-I - IV data taken from 1996 to 2016
(5326 days live-days)

- Standard oscillation : 2-flavor approximation (standard osc. parameters fixed to SK best fit)

All $\varepsilon_{e\alpha}$ set to 0





$$-4.5\times10^{-2} < \varepsilon_{\mu\tau} < 1.9\times10^{-2}$$

$$-5.1\times10^{-2} < \varepsilon_{\tau\tau}-\varepsilon_{\mu\mu} < 1.4\times10^{-1}.$$

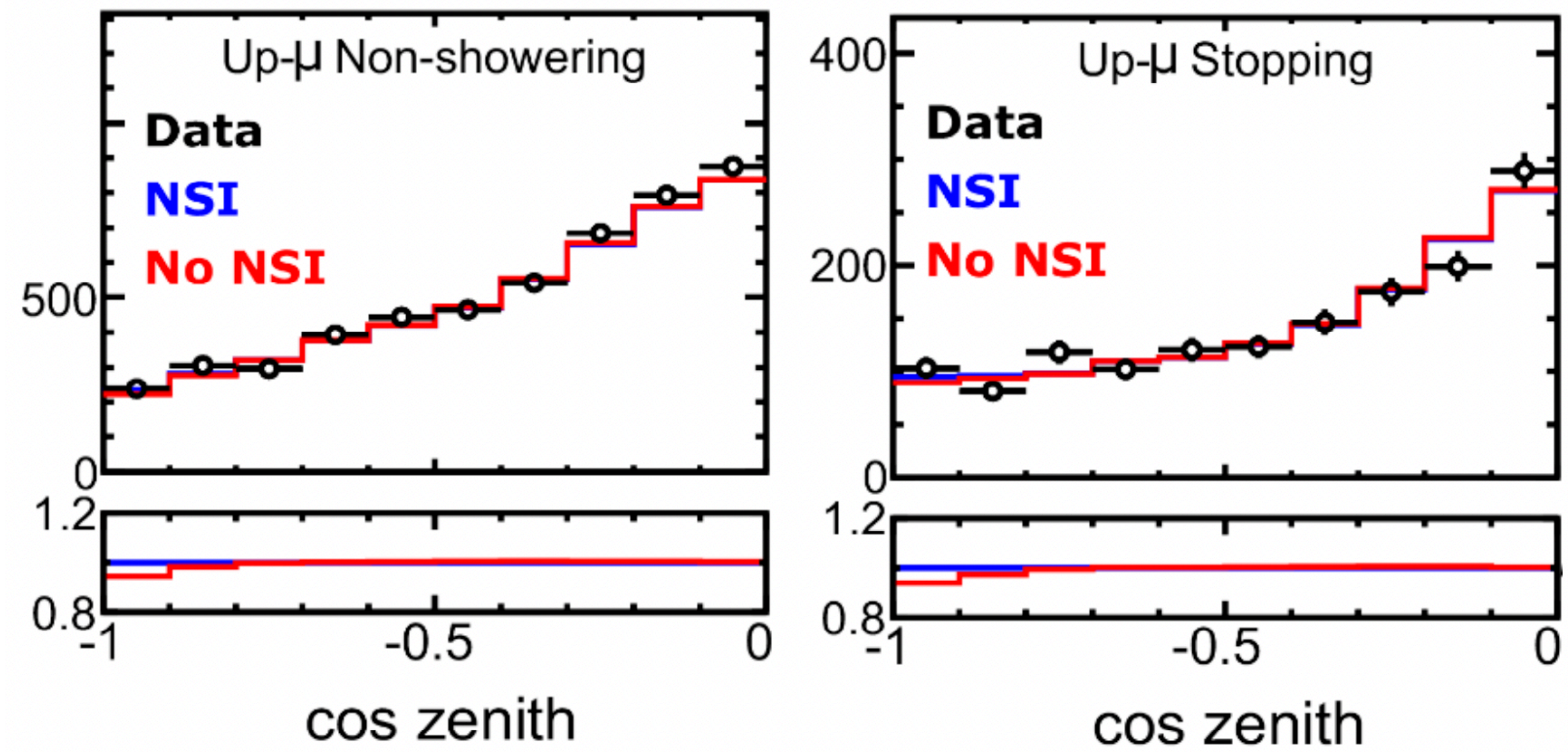
Consistent with the latest published results from IceCube DeepCore *(Phys. Rev. D 97, 072009)*:

$$-6.7\times10^{-3} < \varepsilon_{\mu\tau} < 8.1\times10^{-3}$$

M.Taani thesis

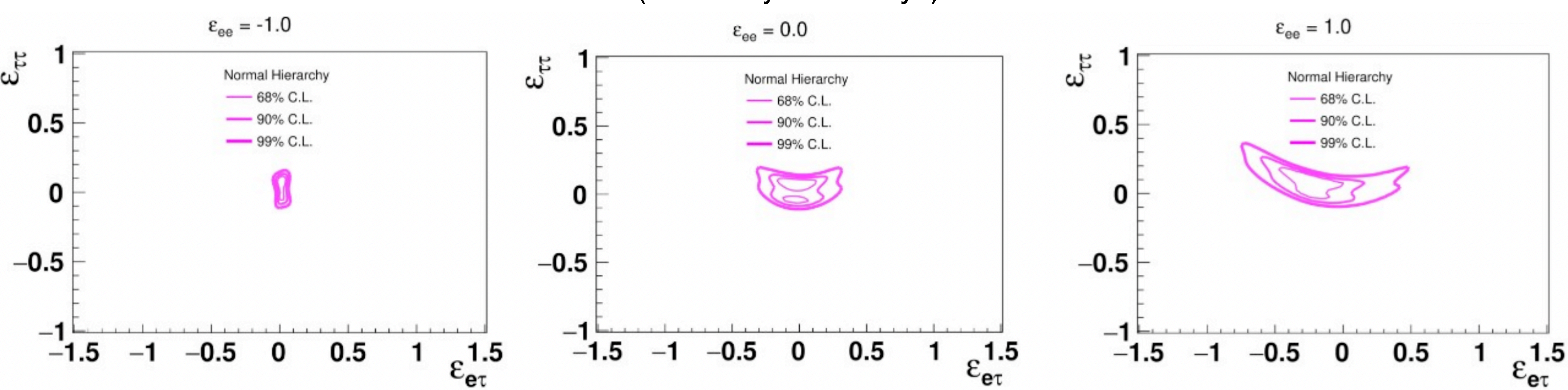
Fit to the e-τ sector

- 3-flavor oscillation with 3 fit parameters (standard osc. parameters fixed to SK best fit)
- result shown in $\varepsilon_{e\tau}$ - $\varepsilon_{\tau\tau}$ plane or various ε_{ee} values ranging [-4,4]



all $\varepsilon_{\mu\alpha}$ set to 0

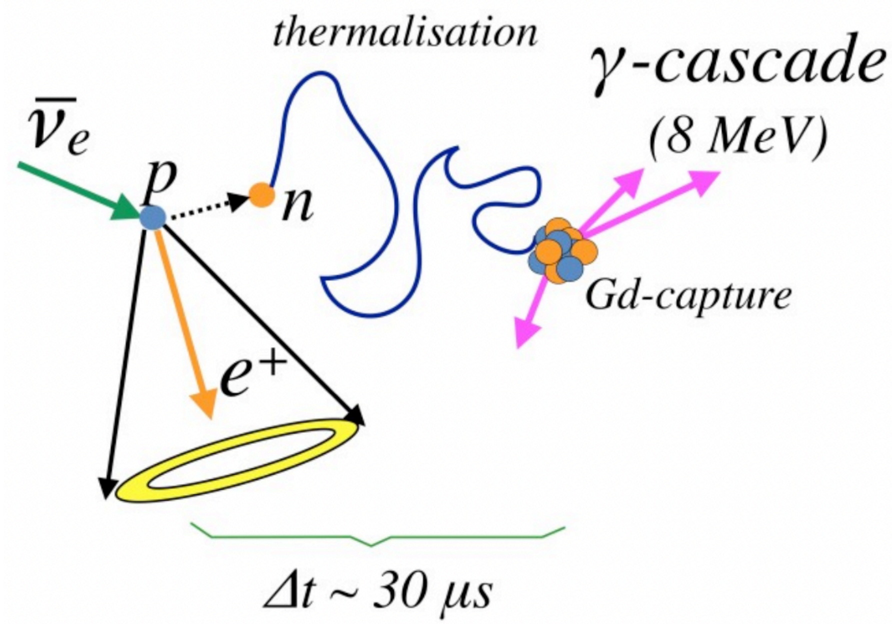
SK-I - IV data taken from 1996 to 2016
(5326 days live-days)



M.Taani thesis

Neutron tagging in Gd loaded water

- In July 2020, dissolved 0.02% gadolinium-sulfate ($Gd_2(SO_4)_3$) into the SK water
  -> 50% neutron tagging efficiency (double the Hydrogen-tagging efficiency)
- Plan to dissolve more in 2022



Thermal neutron capture cross section (barns)

Gd = 49700

S = 0.53

H = 0.33

O = 0.0002

With greater neutron tagging efficiency,
- Better classification of neutrinos and antineutrinos
- Improve the neutrino energy reconstruction
- Additional power in discriminating CC events from NC events

Primary physics goal: first observation of DSNB,
Also will improve
sensitivity to NSI & boosted DM searches

Conclusion

- Leading limits on DM annihilation cross-section to neutrinos, SD/SI scattering cross section with nucleon, especially at low energy
- First search for boosted dark matter from the Galactic Center or the Sun interacting in a terrestrial detector
  - first analysis of "electron elastic scatter-like" events in the SK high energy data
- Results for neutrino oscillations with NSI is consistent with no NSI in both μ-τ and e-τ sectors
- After 25 years since the beginning, SK has renovated once again to stay at the forefront of ν physics: SK-Gd
  - results from SK-Gd data coming soon!

Back Up

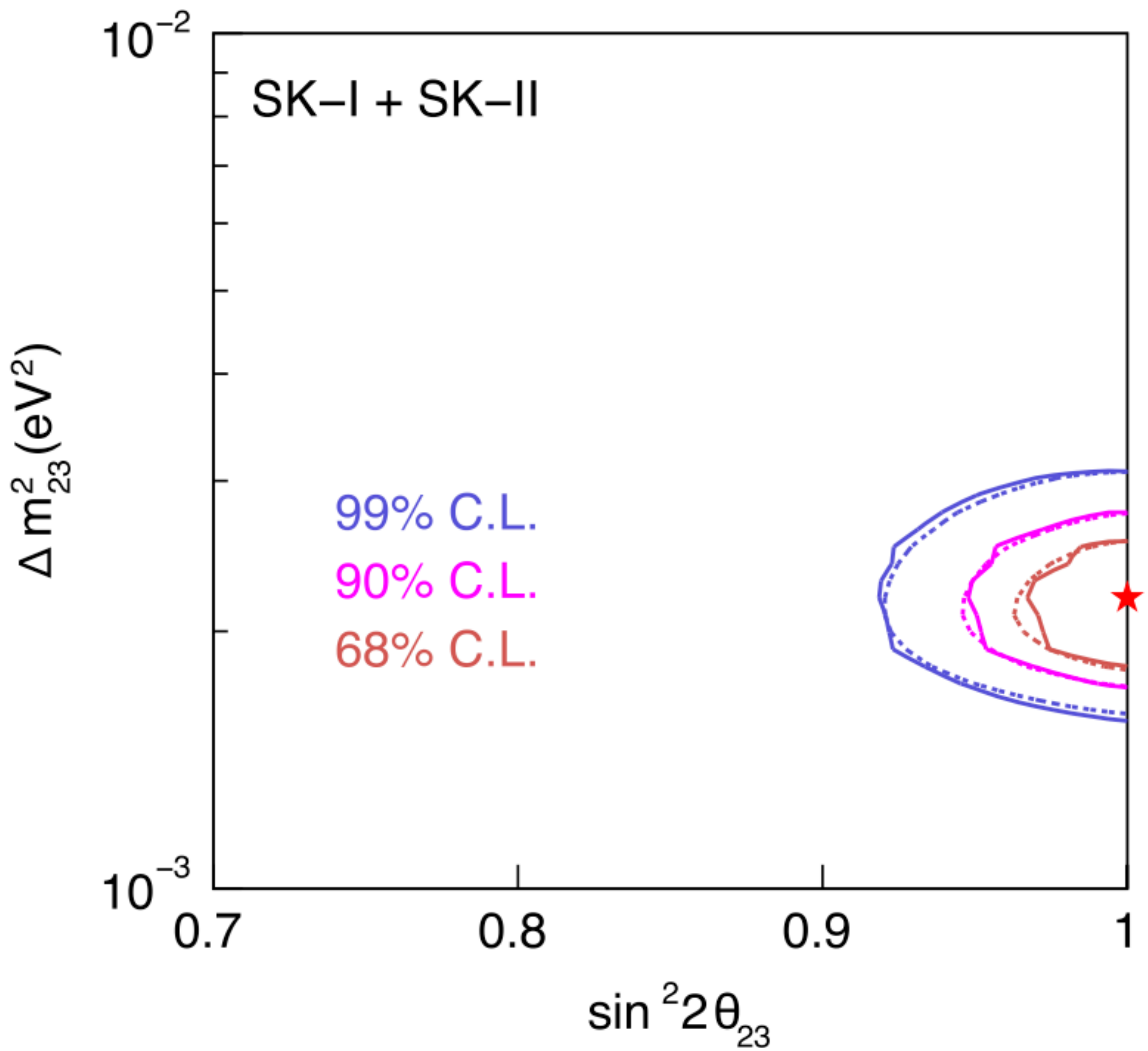


Figure 8.3 *The allowed standard oscillation parameter regions. Solid lines show allowed regions when including NSI and the dotted lines show the regions without NSI. Taken from [133].*

ε_{ee}	SK NSI 2011	New Result
1.5	-0.09 $< \varepsilon_{\tau\tau} <$ 0.15	-0.05 $< \varepsilon_{\tau\tau} <$ 0.35
0.0	-0.09 $< \varepsilon_{\tau\tau} <$ 0.21	-0.075 $< \varepsilon_{\tau\tau} <$ 0.15
-1.5	-0.15 $< \varepsilon_{\tau\tau} <$ 0.09	-0.075 $< \varepsilon_{\tau\tau} <$ 0.125

ε_{ee}	SK NSI 2011	New Result
1.5	$\lvert\varepsilon_{e\tau}\rvert <$ 0.54	-0.75 $< \varepsilon_{e\tau} <$ 0.325
0.0	$\lvert\varepsilon_{e\tau}\rvert <$ 0.39	-0.225 $< \varepsilon_{e\tau} <$ 0.225
-1.5	$\lvert\varepsilon_{e\tau}\rvert <$ 0.24	-0.1 $< \varepsilon_{e\tau} <$ 0.125