WIMPs searches for monoenergetic neutrinos from stopped meson decay in the Sun

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Seongjin In, SKKU

This presentation based on
C.Rott, S.In, J.Kumar,D.Yayali, JCAP 11(2015)039

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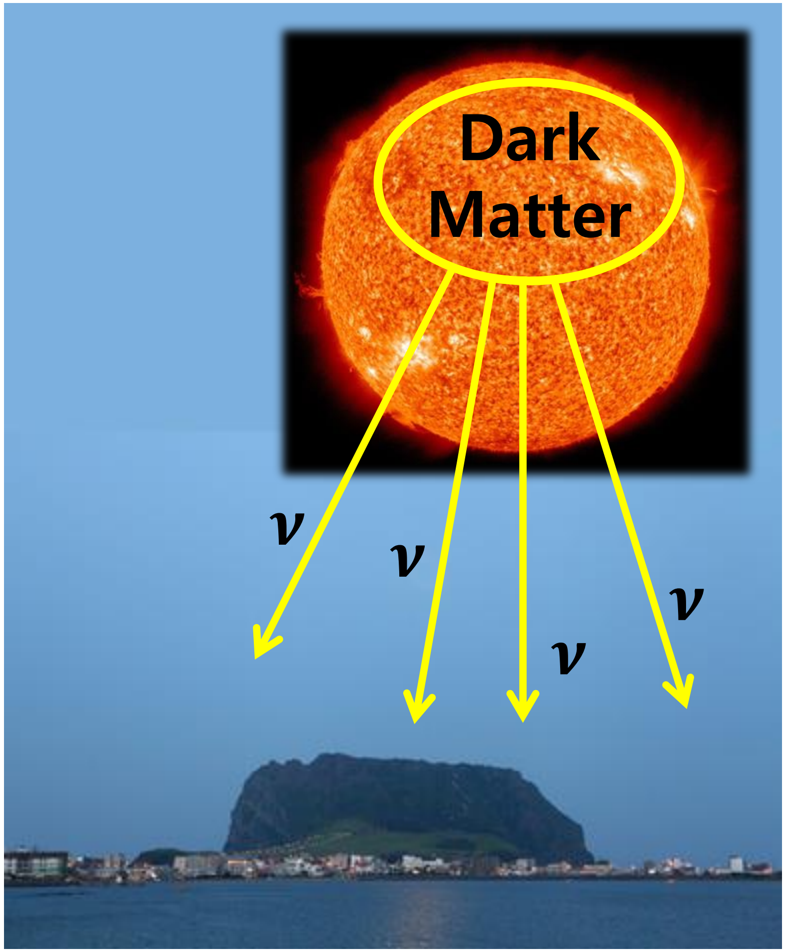
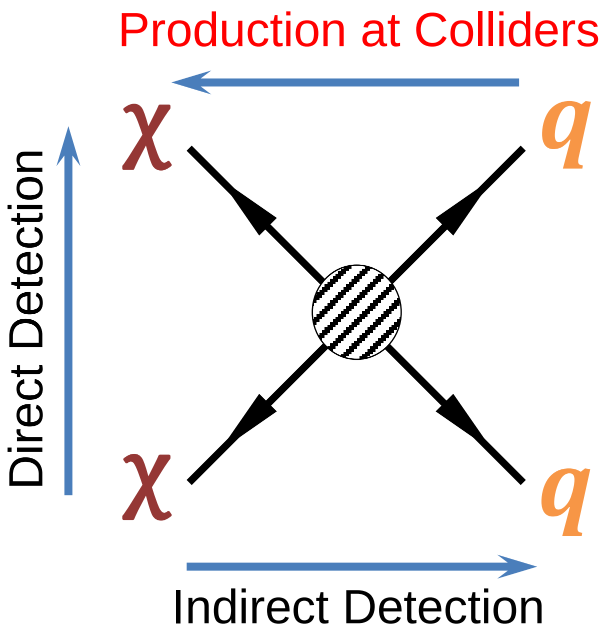


Neutrino Telescope

- Solar WIMPs
- Simulation
- Neutrino Telescope
- Results
- Conclusion

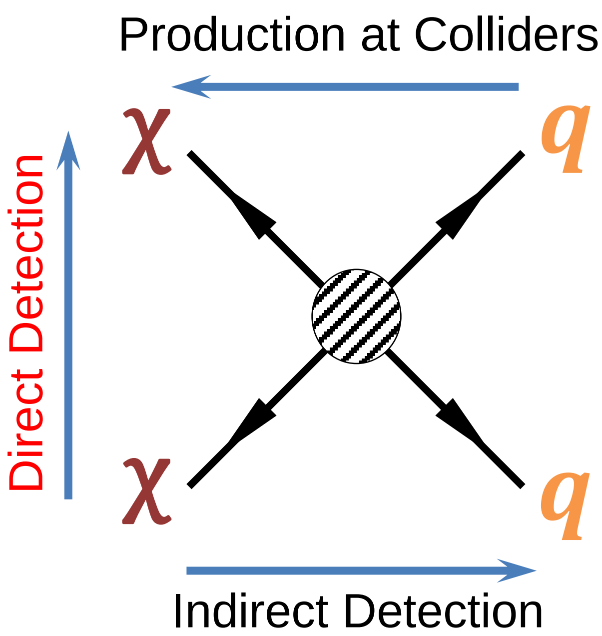
Dark Matter Searches



How to find Dark Matter(DM)?

- Just make it! - Production at Colliders
- Catch the signal of the interaction of DM with the target material
  – Direct detection (KIMS, XENON…)
- Catch the signal of the interaction of DM from the far sources like the Sun, the Earth or Galaxy etc.
  – Indirect detection (any astroparticle telescopes…)

Dark Matter Searches



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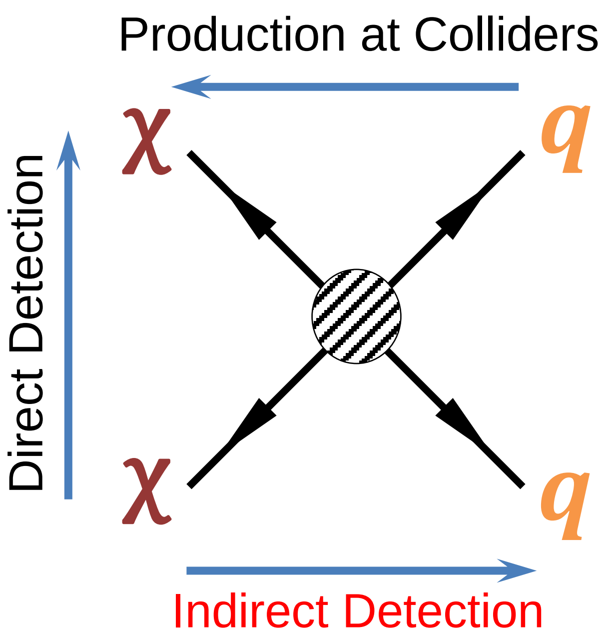

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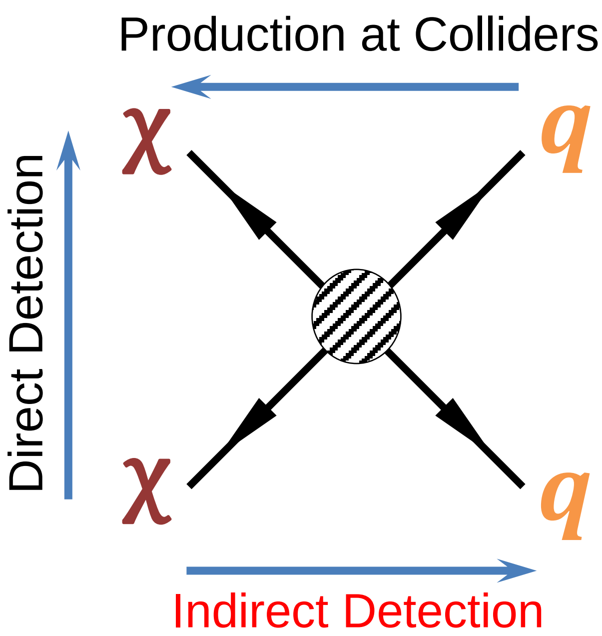

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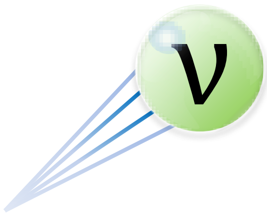
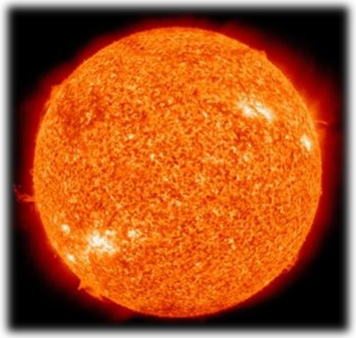
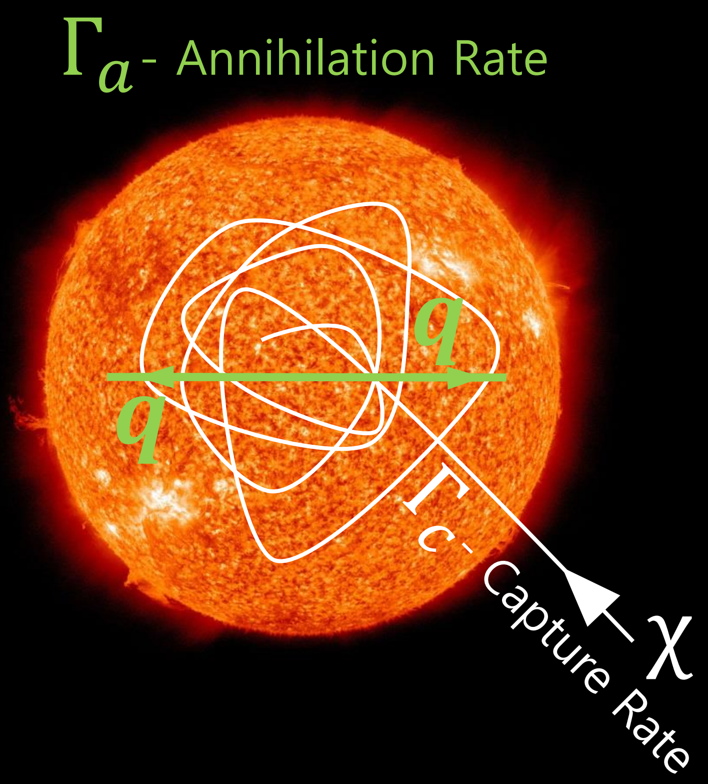
Indirect search with  from 

Solar WIMPs



The change of the number of WIMPs is

$$\frac{dN}{dt} = \Gamma_c - 2\Gamma_a$$

In equilibrium, we can write down

$$\frac{dN}{dt} = 0 \rightarrow \Gamma_a = \Gamma_c \,/\, 2$$

in terms of cross-section

$$\Gamma_c \propto C_0^{SD}(m_\chi) \cdot \sigma_{SD}^{p}$$

The number of WIMPs are equilibrium with the assumption of

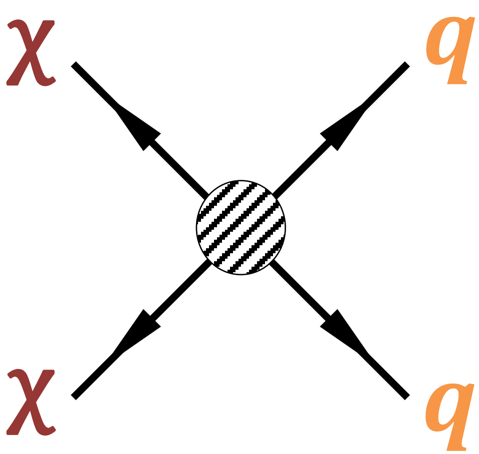
$$t_{Equilibrium} \ll t_{Solar}$$

For $m_\chi \leq 4GeV$, the captured WIMPs can be ejected from the Sun again; evaporation

; [K. Griest and D. Seckel, Nucl. Phys. B 283, 681 (1987) [Erratum-ibid. B 296, 1034 (1988)]; A. Gould, Astrophys. J. 321, 560 (1987)]

Solar WIMPs

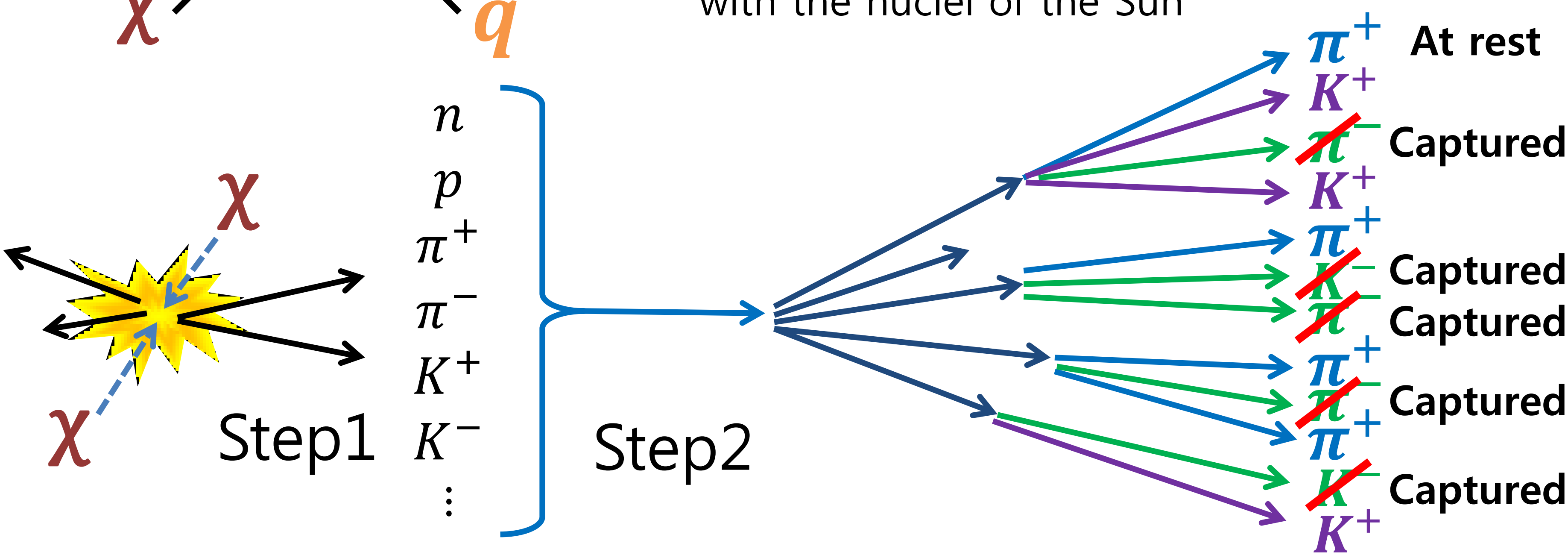
After annihilation…



= standard model particles are produced

WIMPs mass is heavy enough to produce multiple hadrons. They would scatter with the solar nuclei

1. Short-lived particles promptly decay
2. Longer-lived particles would be interacting with the nuclei of the Sun

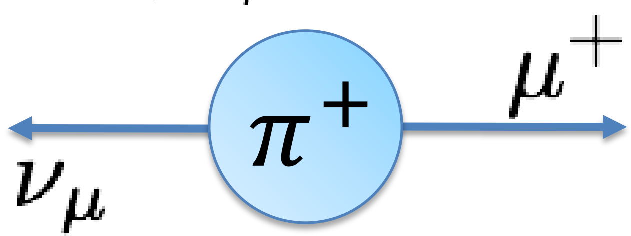


Solar WIMPs

Now, we obtained lots of stopped long lived mesons… And then?

π^-, K^- : captured, π^0 : promptly decay into two photons,
π^+, K^+ only give neutrinos through at rest decay.

$\pi^+ \to \mu^+ \nu_\mu$ ~ 100%

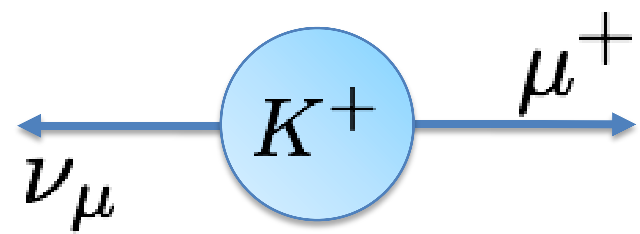


For the π^+

$$m_\mu{}^2 + p_\mu^2 = m_\pi^2 + p_{\nu_\mu}^2 - 2m_\pi \cdot p_{\nu_\mu}$$

$$p_{\nu_\mu} = \frac{m_\pi{}^2 - m_\mu{}^2}{2m_\pi} = \underline{29.8MeV}$$

$K^+ \to \mu^+ \nu_\mu$ ~ 64%



For the K^+

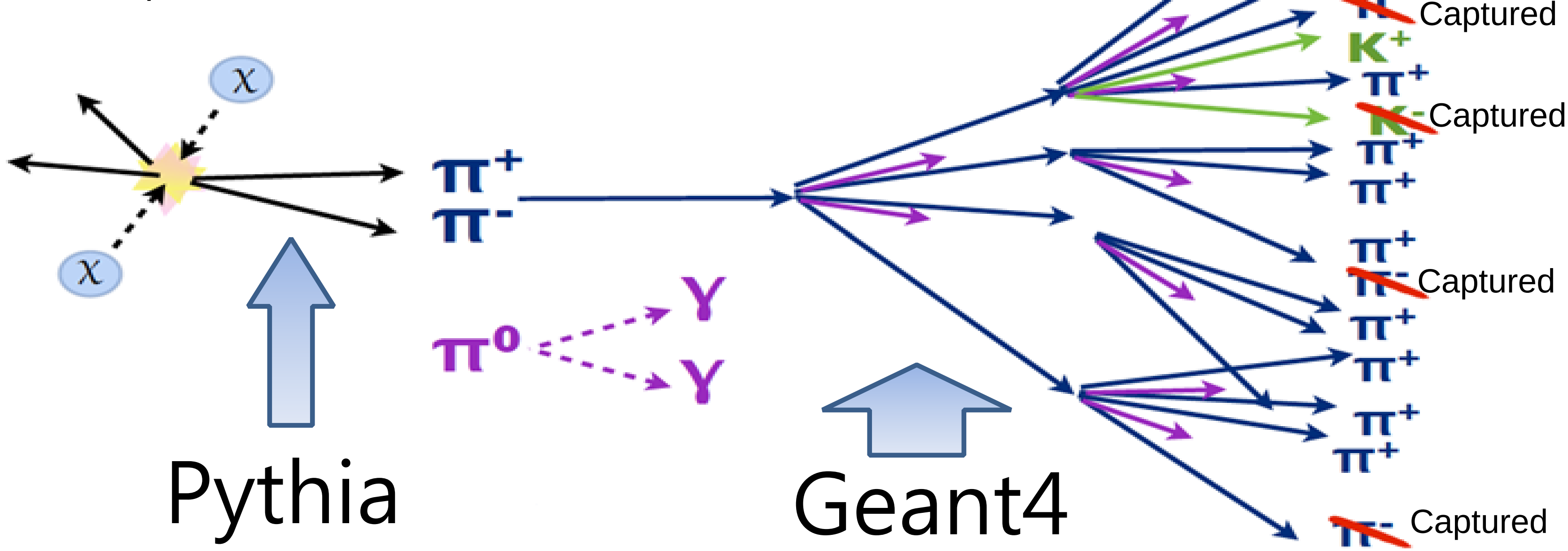
$$m_\mu{}^2 + p_\mu^2 = m_K^2 + p_{\nu_\mu}^2 - 2m_K \cdot p_{\nu_\mu}$$

$$p_{\nu_\mu} = \frac{m_K{}^2 - m_\mu{}^2}{2m_K} = \underline{235.5MeV}$$

The two-body decay at rest results in a monoenergetic neutrino signal

Simulation

Whole processes are in the Sun



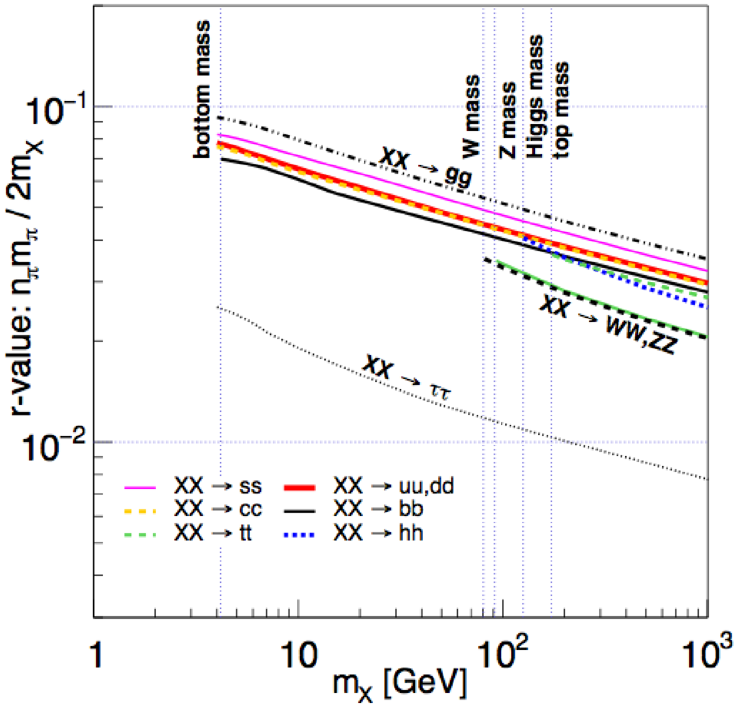
- Calculate the decay of the short lived part icles (also, high energy neutrinos would b e calculated)
- Generate the energy density table of hadr ons & neutrinos from decay
- Calculate the scattering process in the Core of the Sun
- Stopped meson can give mono-en ergetic neutrinos; low energy neut rinos

r-value - for the amount of mesons

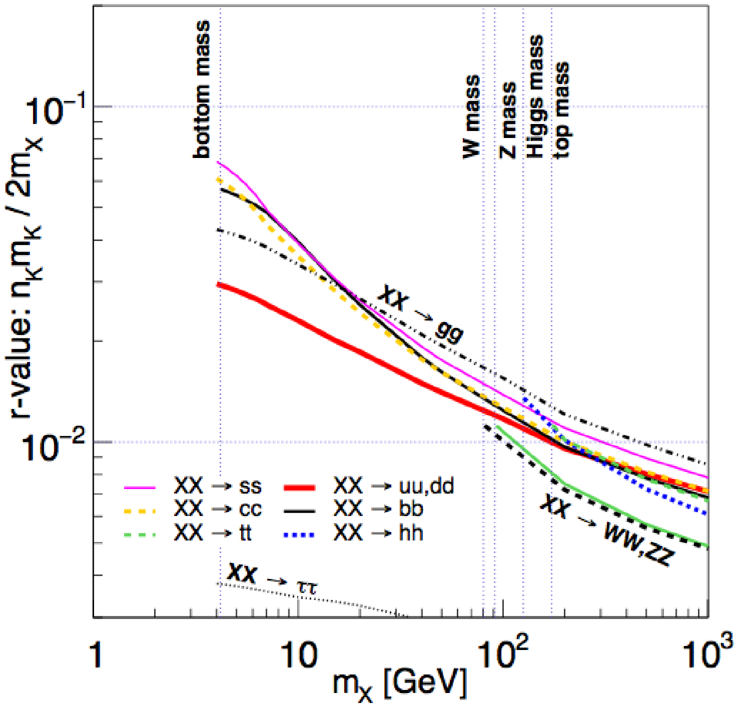
We defined "r-value", which is the mass fraction of WIMP mass converted into the stopped π^+ and K^+

For example, for $XX \rightarrow b\bar{b}$ with 5GeV WIMP mass, r-value for π^+ is 0.07
It means 7% of WIMP mass becomes the stopped π^+

r-value for π^+



r-value for K^+

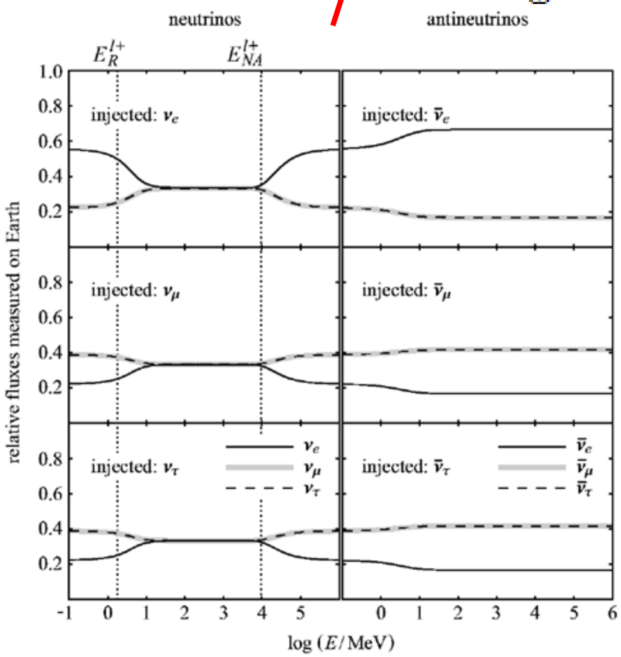


C.Rott, S.In, J.Kumar,D.Yayali, JCAP 11(2015)039[arXiv:1510.00170 [hep-ph]]

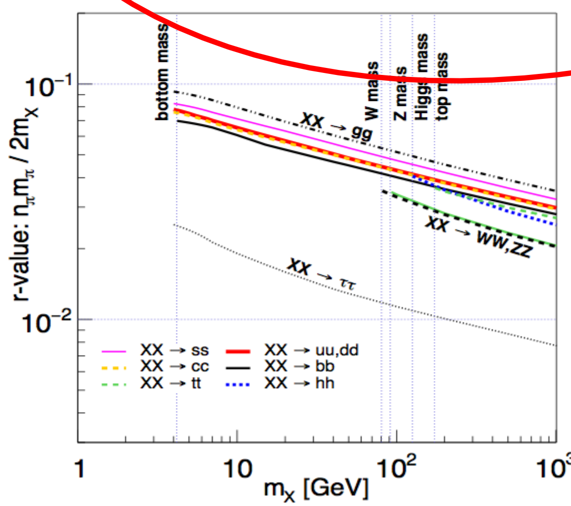
Signals & Backgrounds

The flux of monoenergetic electron neutrino at the Earth

$$\frac{d^2\Phi_{\pi,K}}{dE\,d\Omega} = \frac{(F_{\nu_e})(1/2)\Gamma_C}{4\pi r_\oplus^2}\left(\frac{2m_X r_{\pi,K}}{m_{\pi,K}}\right)\delta(E-E_0)\delta(\Omega)$$



R. Lehnert and T. J.Weiler, Phys. Rev. D 77, 125004 (2008) [arXiv:0708.1035 [hep-ph]].



C.Rott, S.In, J.Kumar,D.Yayali, JCAP 11(2015) 039[arXiv:1510.00170 [hep-ph]]

Factor which is from muon to electron neutrino

m_X (GeV)	C_0^{SD}
10	0.094
20	0.038
30	0.021
40	0.013
50	8.7×10^{-3}
60	6.3×10^{-3}
70	4.8×10^{-3}
80	3.8×10^{-3}
90	3.0×10^{-3}
100	2.5×10^{-3}
200	6.6×10^{-4}
300	3.0×10^{-4}
400	1.7×10^{-4}
500	1.1×10^{-4}
600	7.6×10^{-5}
700	5.6×10^{-5}
800	4.3×10^{-5}
900	3.4×10^{-5}
1000	2.7×10^{-5}
2000	6.9×10^{-6}
3000	3.1×10^{-6}
4000	1.7×10^{-6}
5000	1.1×10^{-6}

TABLE VI. Capture coefficient $C_0^{SD}(m_X)$ in units of $10^{29}\,\mathrm{s}^{-1}\mathrm{pb}^{-1}$.

Y. Gao, J. Kumar and D. Marfatia, Phys. Lett. B 704, 534 (2011) [arXiv:1108.0518] [hep-ph].

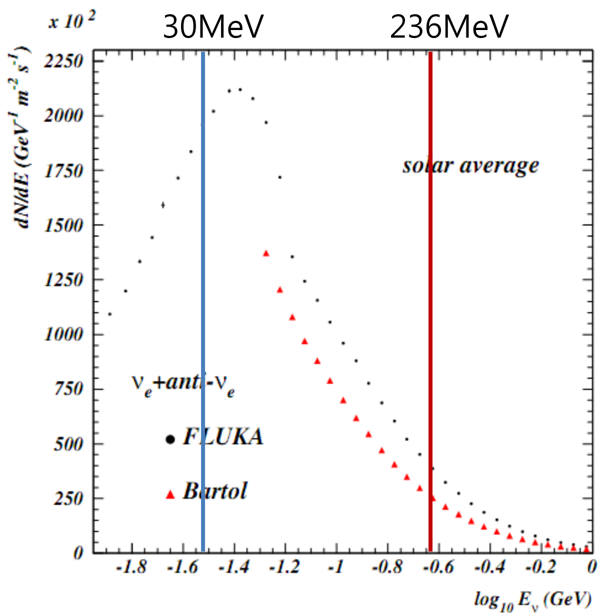
Signals & Backgrounds

Main background is atmospheric electron neutrinos and their flux are

$$\frac{d^2\Phi}{dEd\Omega}(E = 30MeV) \sim 10\, m^{-2}s^{-1}sr^{-1}MeV^{-1}$$

$$\frac{d^2\Phi}{dEd\Omega}(E = 236MeV) \sim 1\, m^{-2}s^{-1}sr^{-1}MeV^{-1}$$

Otherwise, the stopped pions/kaons from cosmic ray at the Earth, the Sun and the Moon could be backgrounds.



G.Battistoni, A.Ferrari, T.Montaruli and P.R.Sala, Astropart. Phys. 23, 526 (2005)

However,
In the Earth, few cosmic rays convert into pions/kaons, but just a few stopped pions/kaons arrive the surface. (it's an order of magnitude smaller)

In the Moon/Sun, because of huge distance, they are insignificant

Signals & Backgrounds

Now, we can estimate the number of signal and background

$$N_{\mathrm{S,B}} = \left[f_{\mathrm{S,B}} \int_{(1-\epsilon/2)E_0}^{(1+\epsilon/2)E_0} dE \int d\Omega \frac{d^2\Phi_{\mathrm{S,B}}}{dE\,d\Omega} \right] \times A_{\mathrm{eff}} \times T$$

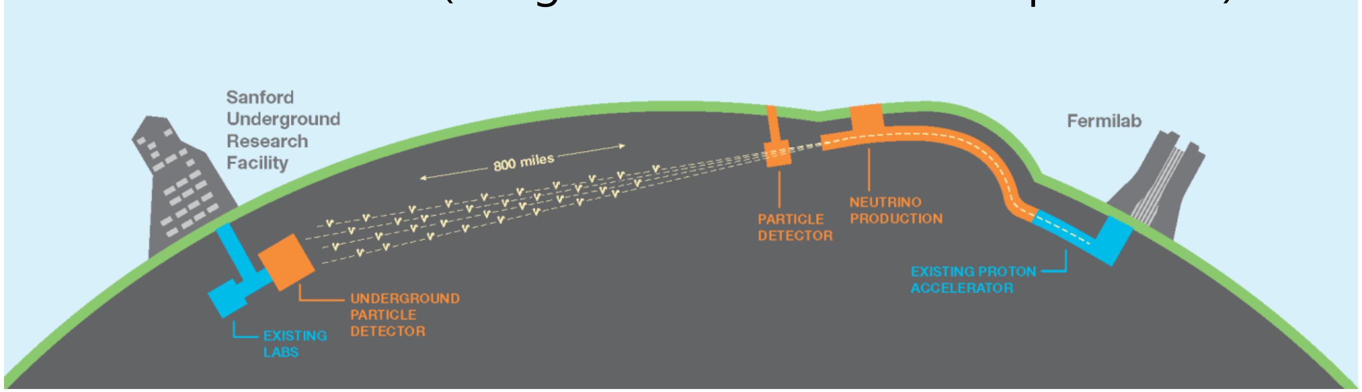
- $f_{\mathrm{S,B}}$: The fraction of events falling within the energy bin centered at 29.8MeV, 235.6MeV
- $\int_{(1-\epsilon/2)E_0}^{(1+\epsilon/2)E_0} dE$: Energy Window
- $\int d\Omega \frac{d^2\Phi_{\mathrm{S,B}}}{dE\,d\Omega}$: Signal/Background flux
- $A_{\mathrm{eff}} \times T$: Exposure of detectors

Now, let's determine the sensitivity of detectors

Neutrino Telescope Survey

Liquid Scintillator	**Argon**	**Water**	**Water**
KamLAND	DUNE	Super-K	Hyper-Kamiokande

Previous LBNE(Long Baseline Neutrino Experiment)

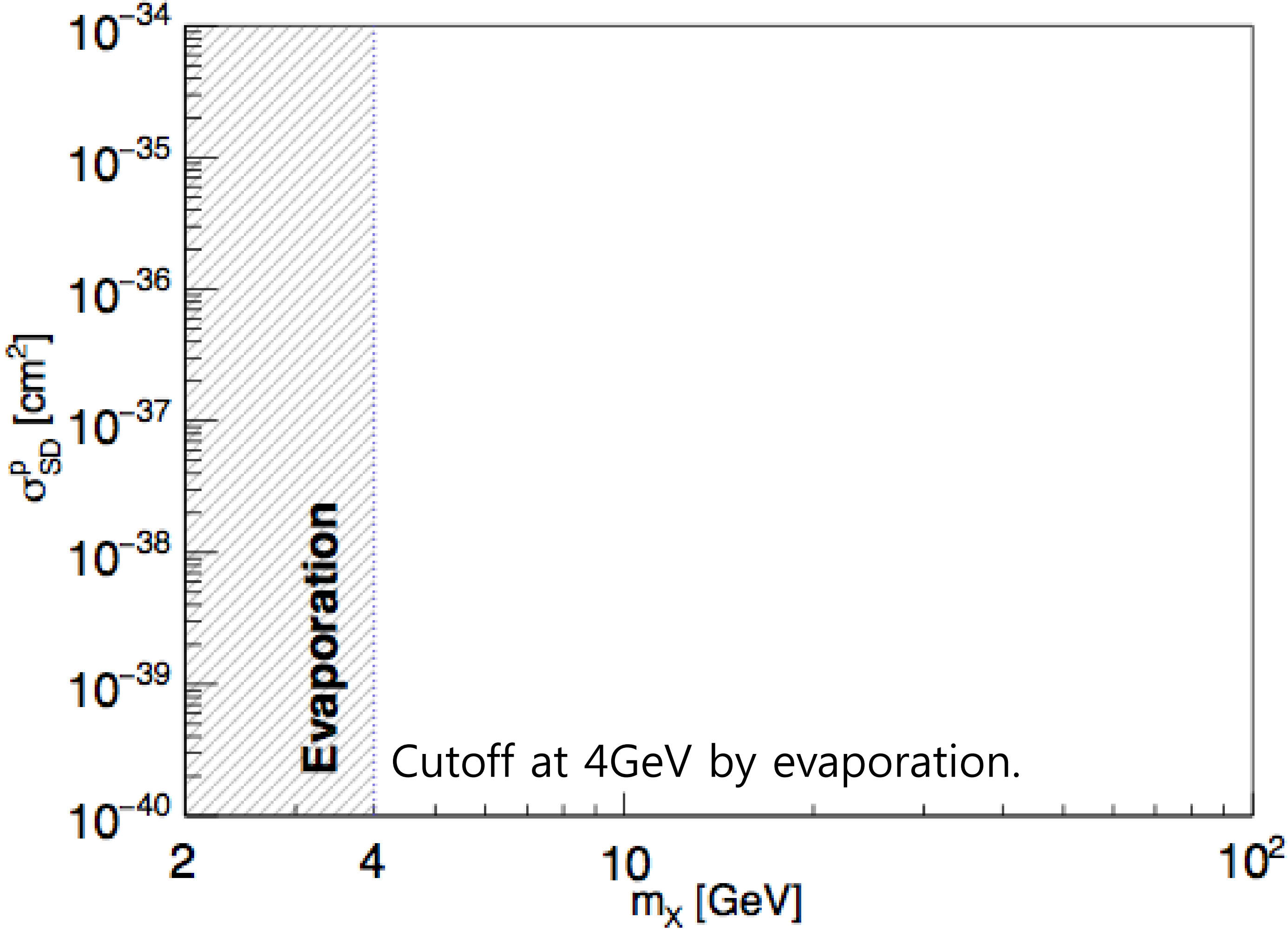


http://lbnf.fnal.gov

experiment	status	exposure	N_B^π	N_{obs}^π	f_S^π	N_S^π	N_B^K	N_{obs}^K	f_S^K	N_S^K
KamLAND	current	4 kT yr	—	—	—	—	5.1	6	0.68	5.5
DUNE	future	34 kT yr	0.2	0	1	2.3	50	50	0.68	10.3
Super-K	current	240 kT yr	—	—	—	—	305	305	0.68	28.7
Hyper-K	future	600 kT yr	—	—	—	—	762.5	763	0.68	45.4

C.Rott, S.In, J.Kumar,D.Yayali, JCAP 11(2015)039[arXiv:1510.00170 [hep-ph]]

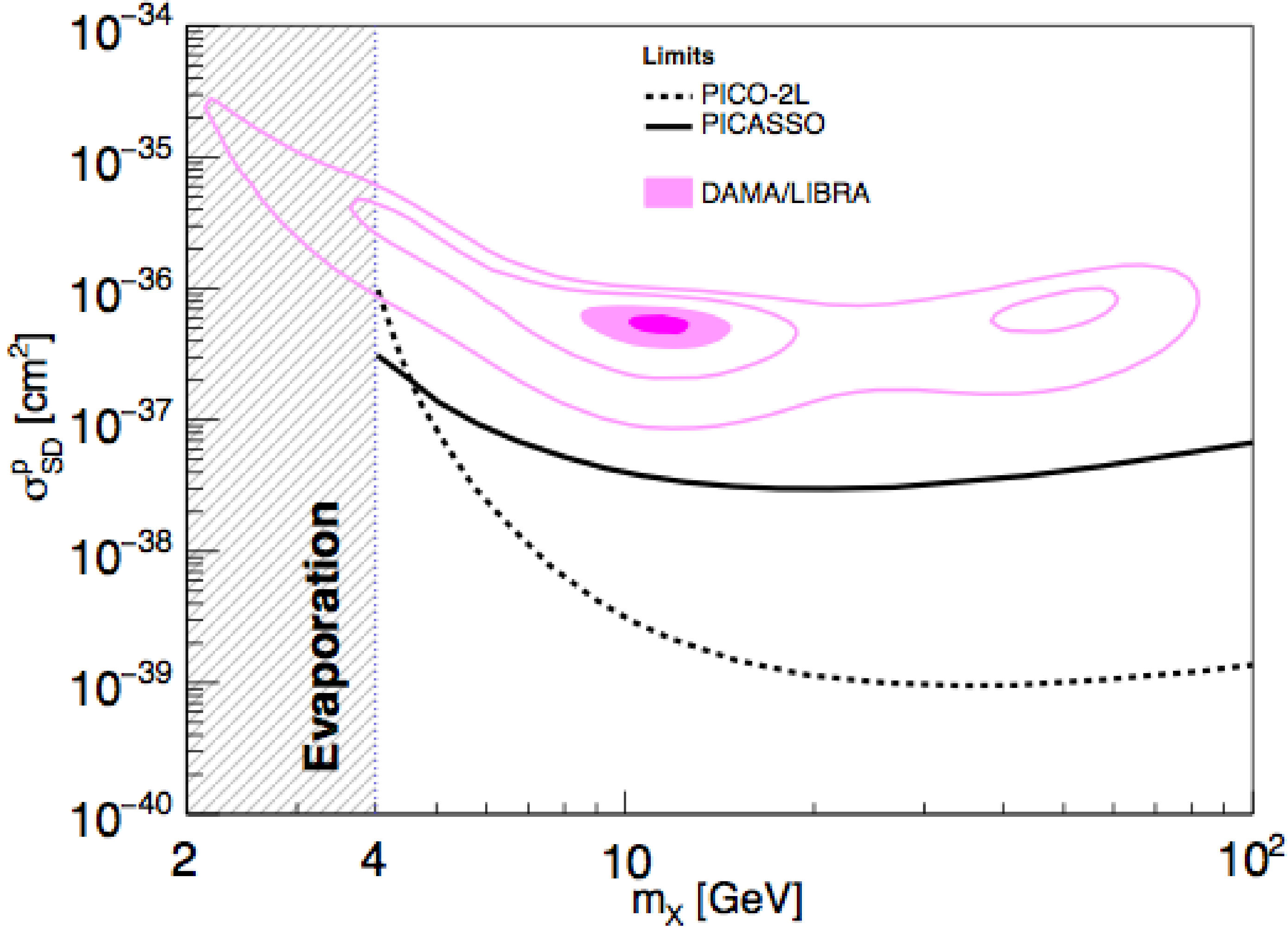
Results



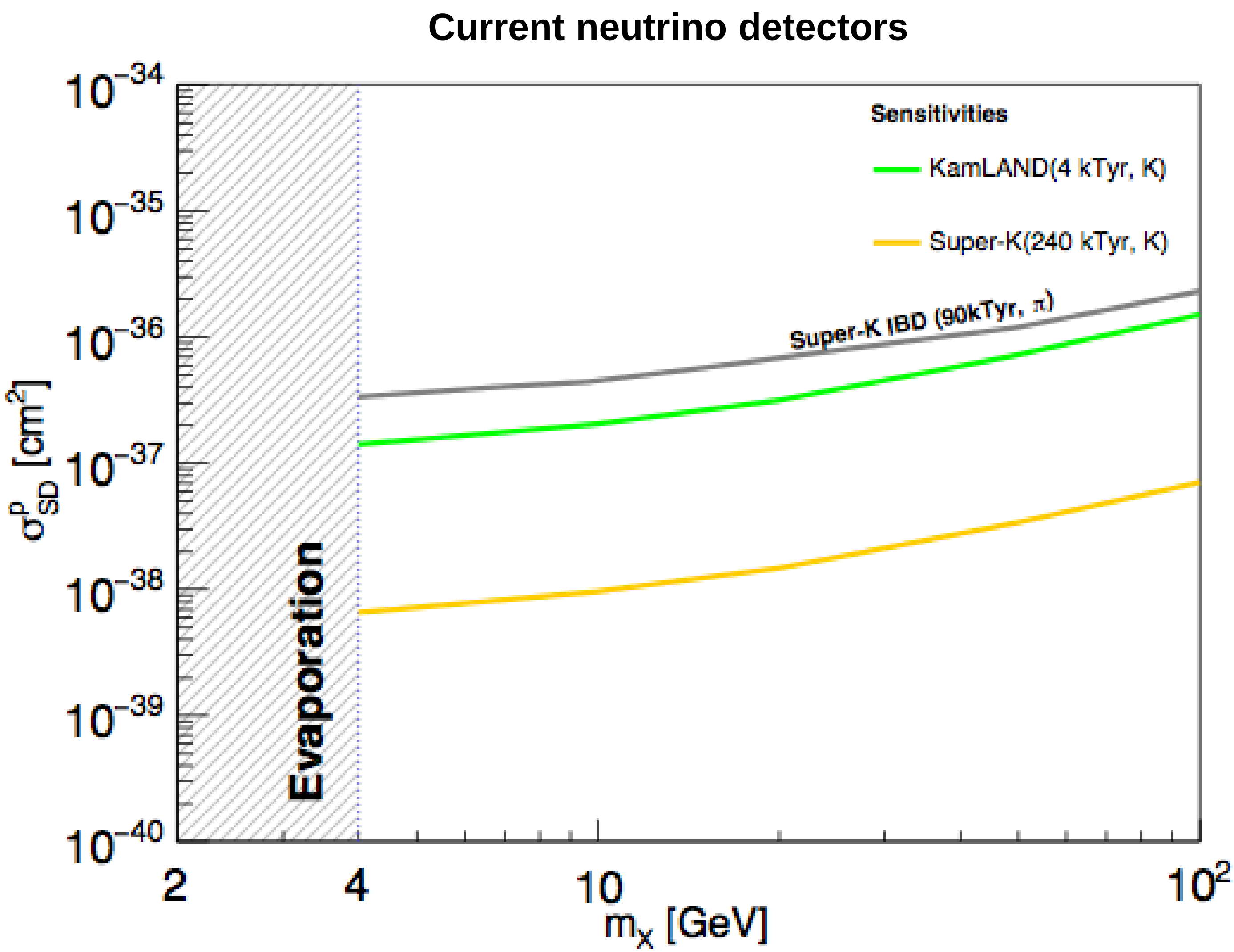
Cutoff at 4GeV by evaporation.

Results

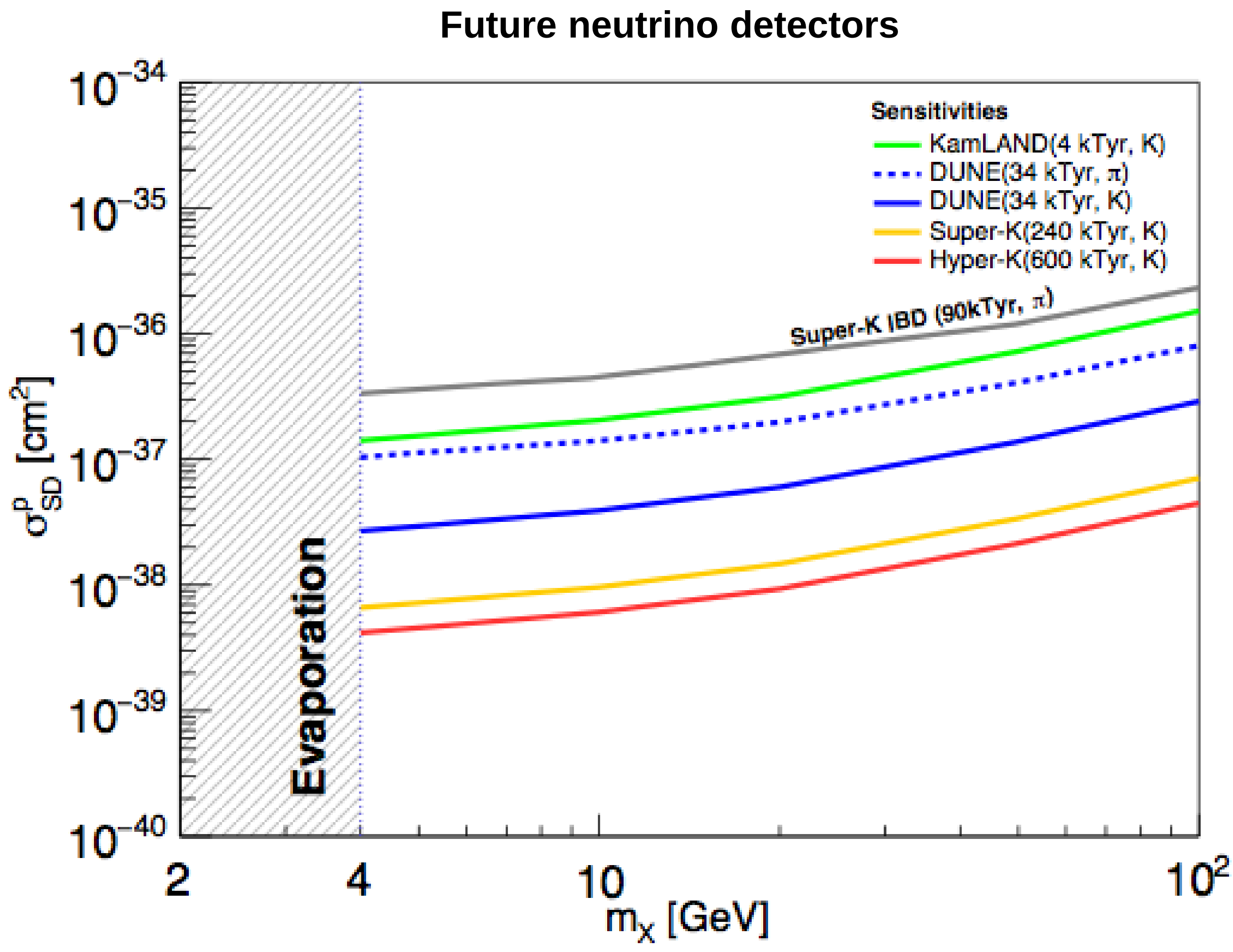
The sensitivity of direct detection



Results

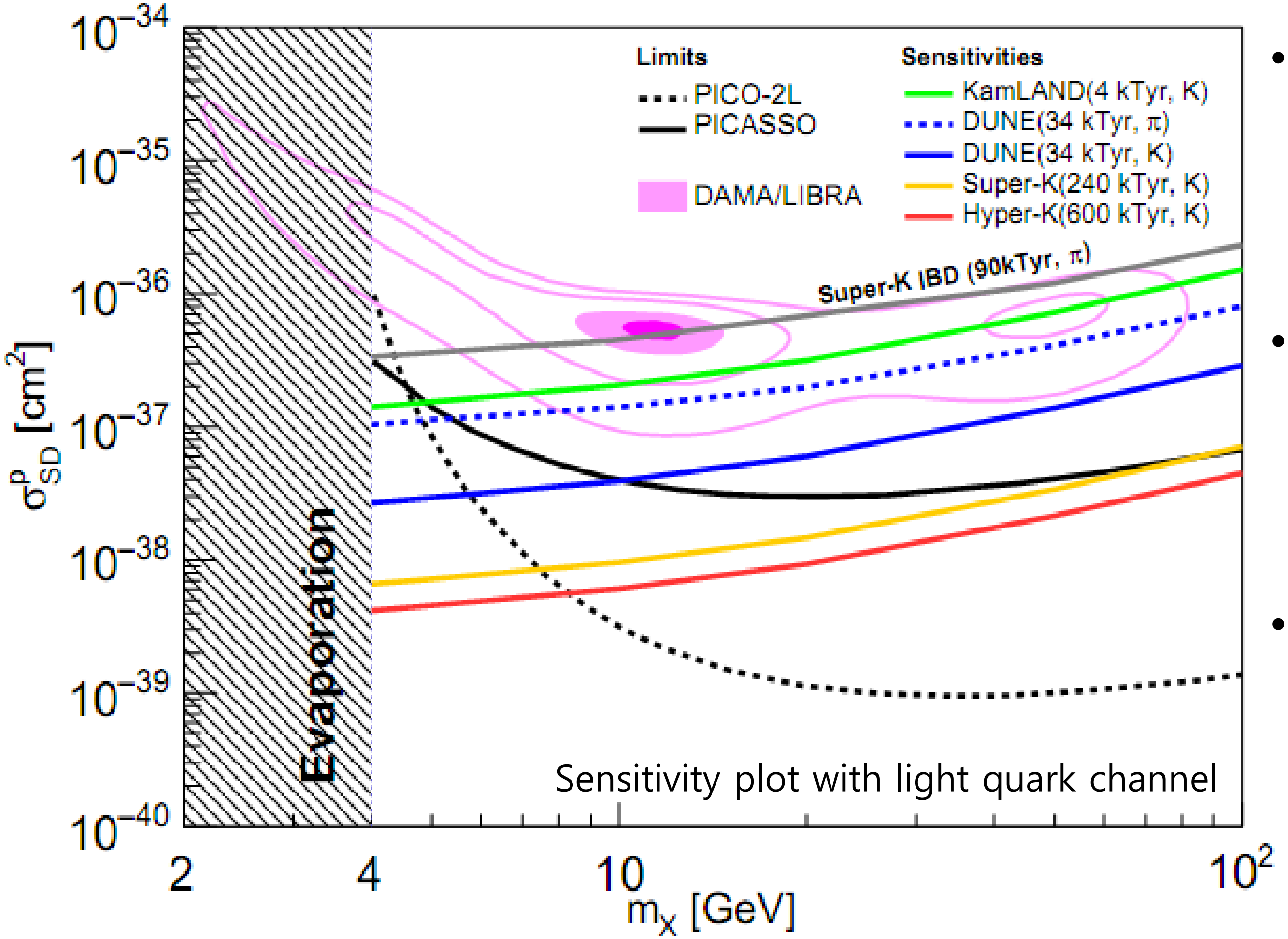

Current neutrino detectors
Sensitivities
KamLAND(4 kTyr, K)
Super-K(240 kTyr, K)
Super-K IBD (90kTyr, π)
Evaporation
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
σ^{p}_{SD} [cm^2]
2
4
10
10^2
m_X [GeV]

Results



Future neutrino detectors
Sensitivities
KamLAND(4 kTyr, K)
DUNE(34 kTyr, π)
DUNE(34 kTyr, K)
Super-K(240 kTyr, K)
Hyper-K(600 kTyr, K)
Super-K IBD (90kTyr, π)
Evaporation
σ^{p}_{SD} [cm^2]
m_X [GeV]
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
2
4
10
10^2

Results



C.Rott, S.In, J.Kumar,D.Yayali, JCAP 11(2015)039[arXiv:1510.00170 [hep-ph]]

- Some of indirect detecti on can give competitive sensitivity for low WIMP s mass
- Because of more proba ble interaction for kaon's neutrino, kaon line gives better sensitivity
- Because of large amoun t of yields of stopped pio ns/kaons, light quark ch annel is attractive

Conclusion

- We considered solar WIMPs annihilation process carefully and included the scatte ring between solar nuclei and hadrons
- Using Pythia & Geant4, we estimated the number of stopped pions/kaons
- The amount of the stopped meson is large enough to be detectable signal, com pared with backgrounds. That is, it can be additional WIMPs detection channel
- Monoenergetic signals can give competitive sensitivity. Specially, neutrinos from s topped kaon decay can give better upper limit for WIMP-nucleon spin-dependen t cross section for low WIMP mass

Thank you

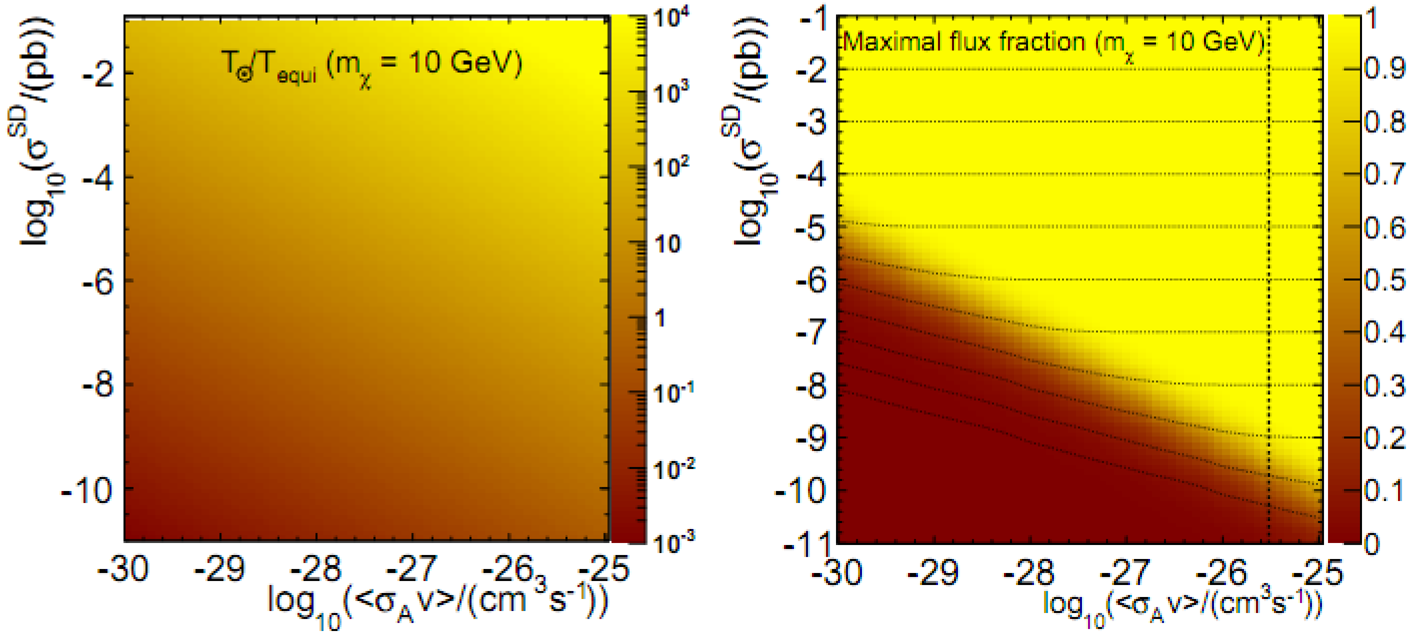


Figure 6. Left: Average factor by which the age of the Sun exceeds the equilibration time scale, as function of the self-annihilation cross section and the WIMP-nucleon spin-dependent scattering for a WIMP of mass 10 GeV. Right: The corresponding fraction of the neutrino flux compared to the maximal flux reached at equilibrium. The dotted line indicates the thermal relic cross section, while the dashed lines indicate the affect on a constrained on the WIMP Nucleon cross section if the dark matter self-annihilation cross section is reduced so that the Sun is not in equilibrium anymore.

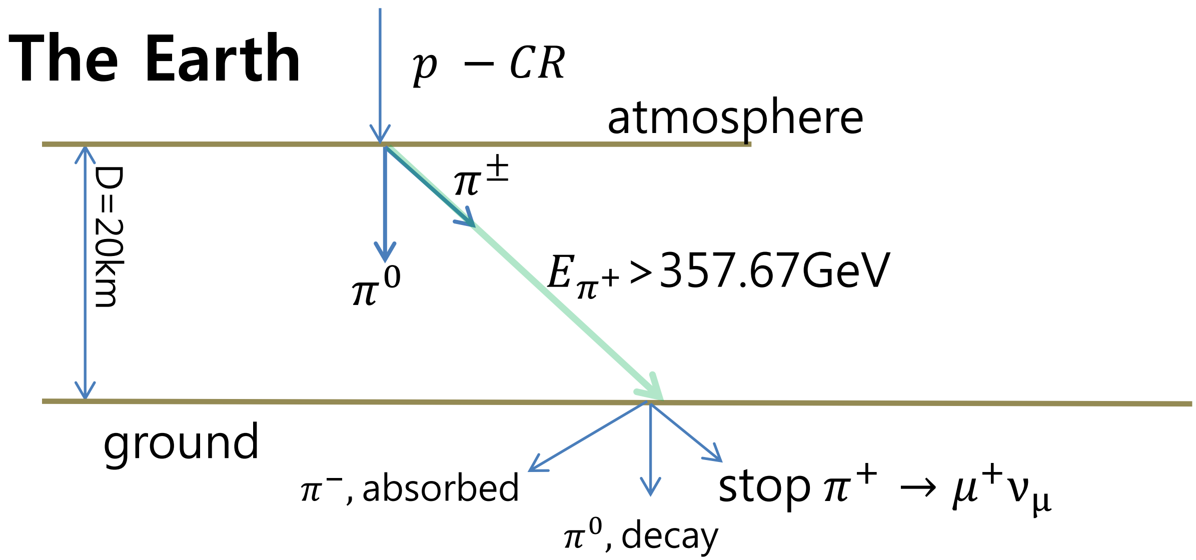
Carsten Rott, Takayuki Tanaka, Yoshitaka Itow, JCAP09(2011)029 [arXiv:1107.3192 [astro-ph.HE]]

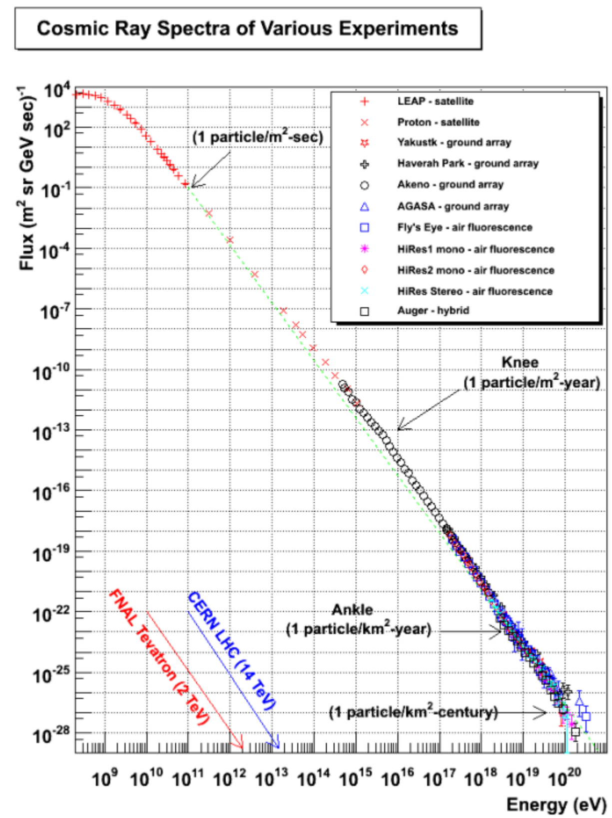
$$I_N(E) \approx 1.8 \times 10^4 \left(\frac{E}{GeV}\right)^{-\alpha} \frac{nucleons}{m^2\ s\ sr\ GeV}$$

Suppose cosmic ray only consisting of proton.

$$\alpha = 2.7\ [3m_\pi, 10^6]GeV$$

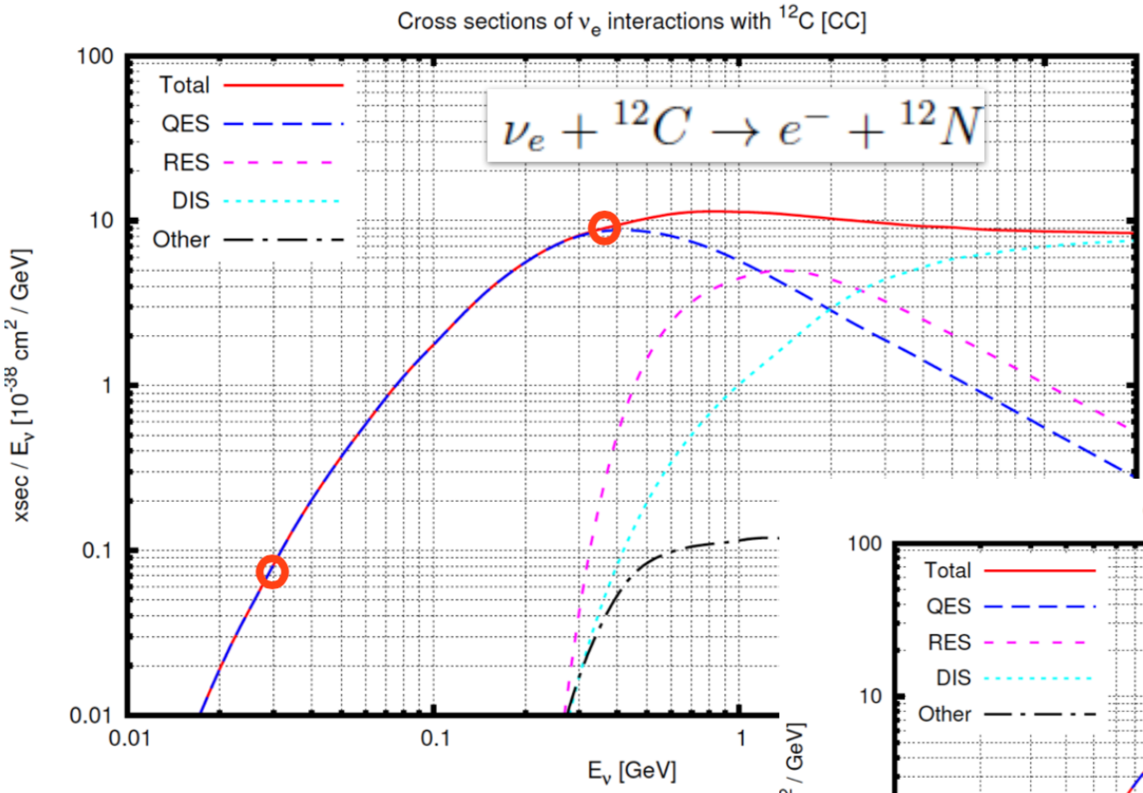
$$\alpha = 3.0\ [10^6, 10^8]GeV$$



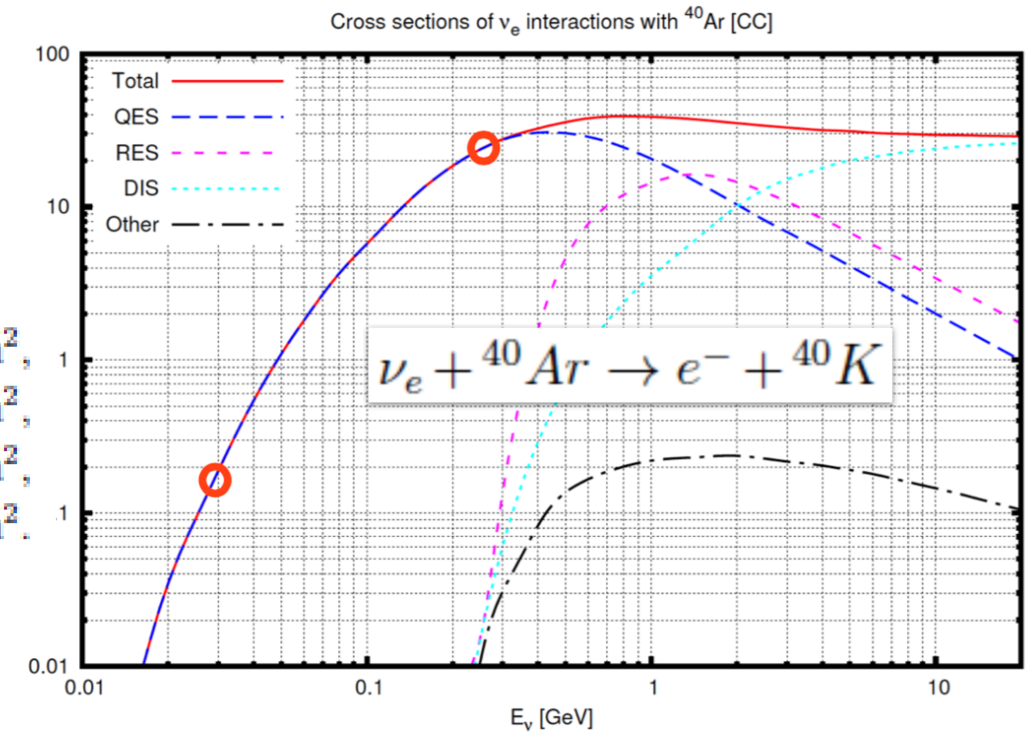


$$E_{CR_E}(surface) \rightarrow N_{\pi^+} m_{\pi^+} * b\%$$

$$I_{CR\_E} = \frac{a}{100} \cdot \frac{b}{100} \cdot 4.62 \cdot 10^2\ [neutrinos][m^2\ s\ sr]^{-1}$$



- 29.8MeV
  - charged current quasi-elastic
- 235.5MeV
  - charged current quasi-elastic,
  - just at the edge of pion production, deep inelastic scattering, resonance, coherent



$$\sigma_{\nu_e+{}^{40}\mathrm{Ar}\to e^-+A'+X}(30\ \mathrm{MeV}) \sim 1.8\times 10^{-40}\ \mathrm{cm}^2,$$
$$\sigma_{\nu_e+{}^{12}\mathrm{C}\to e^-+A'+X}(236\ \mathrm{MeV}) \sim 1.6\times 10^{-38}\ \mathrm{cm}^2,$$
$$\sigma_{\nu_e+{}^{40}\mathrm{Ar}\to e^-+A'+X}(236\ \mathrm{MeV}) \sim 5.2\times 10^{-38}\ \mathrm{cm}^2,$$
$$\sigma_{\nu_e+{}^{16}\mathrm{O}\to e^-+A'+X}(236\ \mathrm{MeV}) \sim 2.0\times 10^{-38}\ \mathrm{cm}^2.$$

thanks to Shao-Feng Ge for Genie cross sections