March 21, 2025

Vikram Discussion on Neutrino Astrophysics, PRL

Probing Dark Matter Annihilation in the Sun with DUNE

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based on *JCAP* 01 (2024) 030

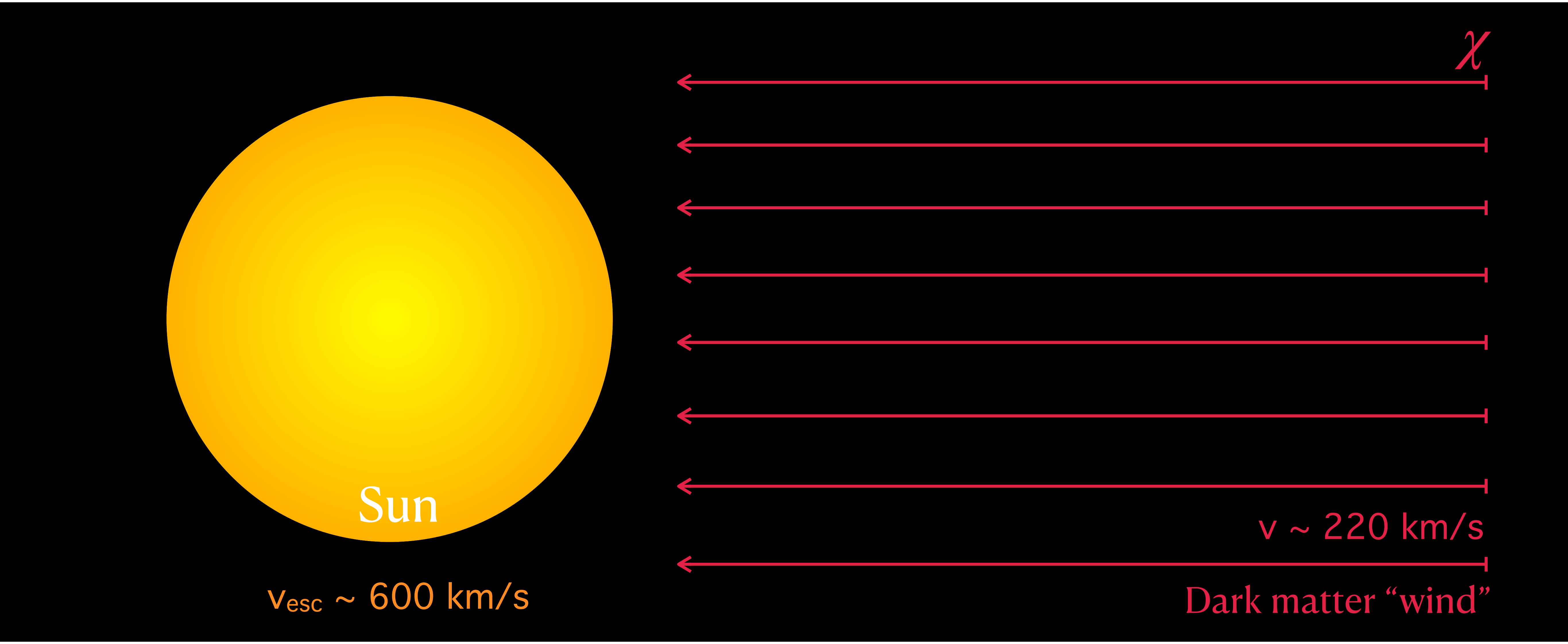
with Mary Hall Reno, Carsten Rott, and Ina Sarcevic

Trailer

- The source pointing resolution of DUNE at $\mathcal{O}$(GeV) neutrino energy $\mathcal{O}(SM)$
- Sensitivity of DUNE to Dark Matter annihilation in the Sun, and comparison with other experiments (neutrino and direct-detection) $\mathcal{O}(BSM)$
- Sensitivity of DUNE to Inelastic Dark Matter annihilation in the Sun $\mathcal{O}(B^2SM)$
- Future directions

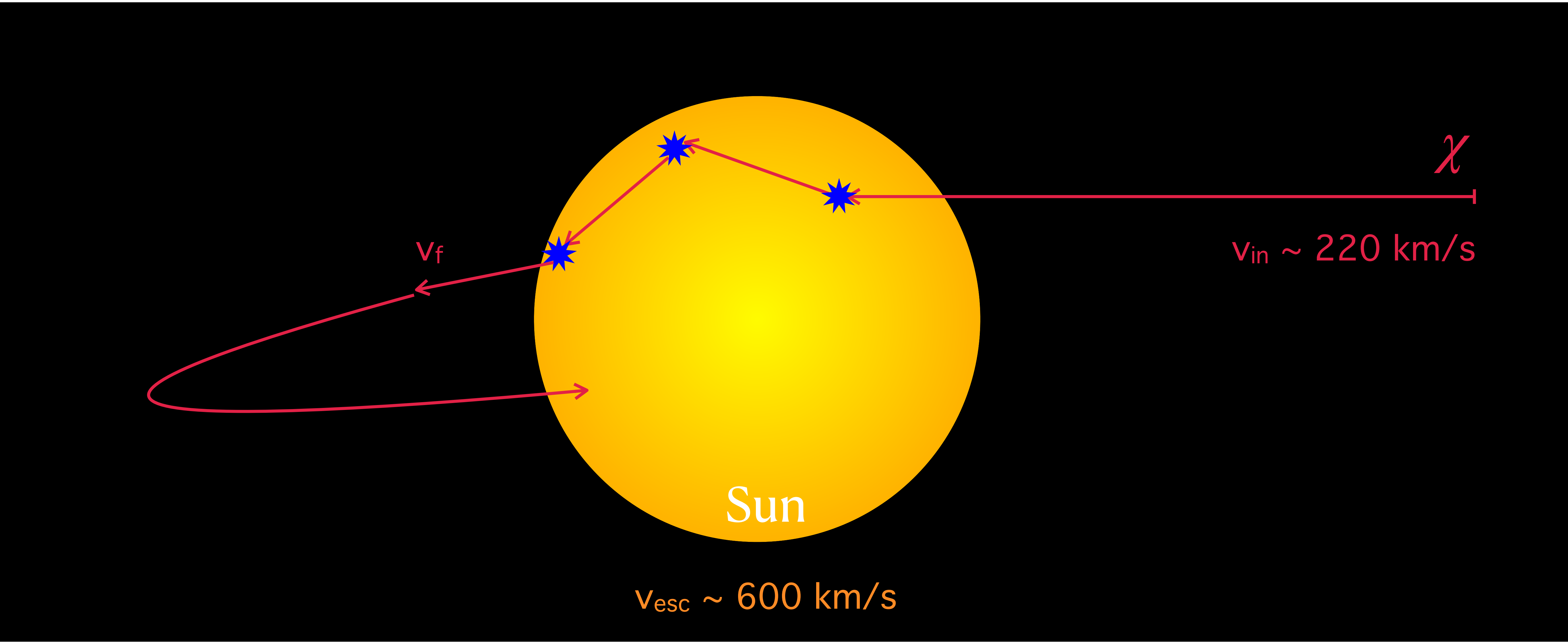
Gravitational Capture of Dark Matter

The Sun moves through a halo of dark matter which is gravitationally bound to our galaxy.



Gravitational Capture of Dark Matter

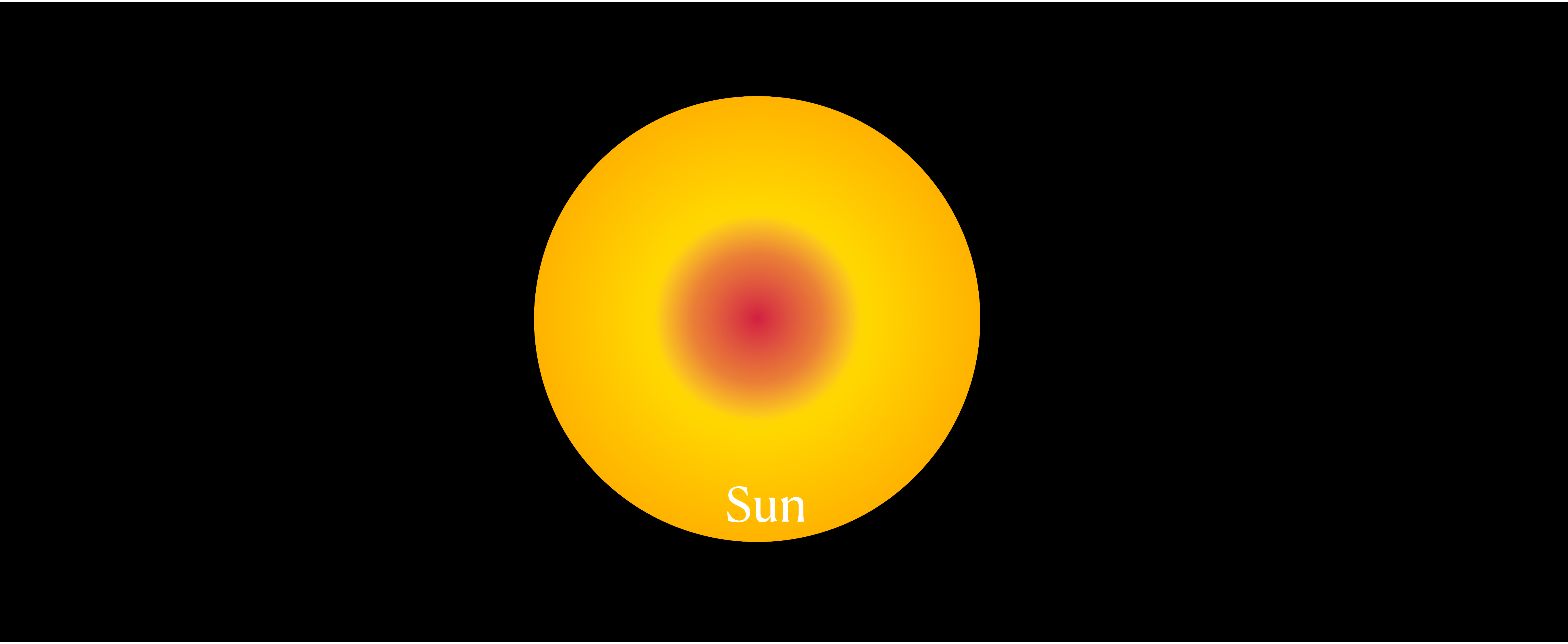
A fraction of these incident DM particles interact with solar media, lose kinetic energy, get gravitationally bound to the Sun, and eventually drift to the core.



Press and Spergel [1985]; A. Gould [1987]; Griest and Seckel [1987]; …

Gravitational Capture of Dark Matter

The number density of DM in the Sun keeps increasing till an equilibrium between capture, evaporation, and annihilation is achieved.

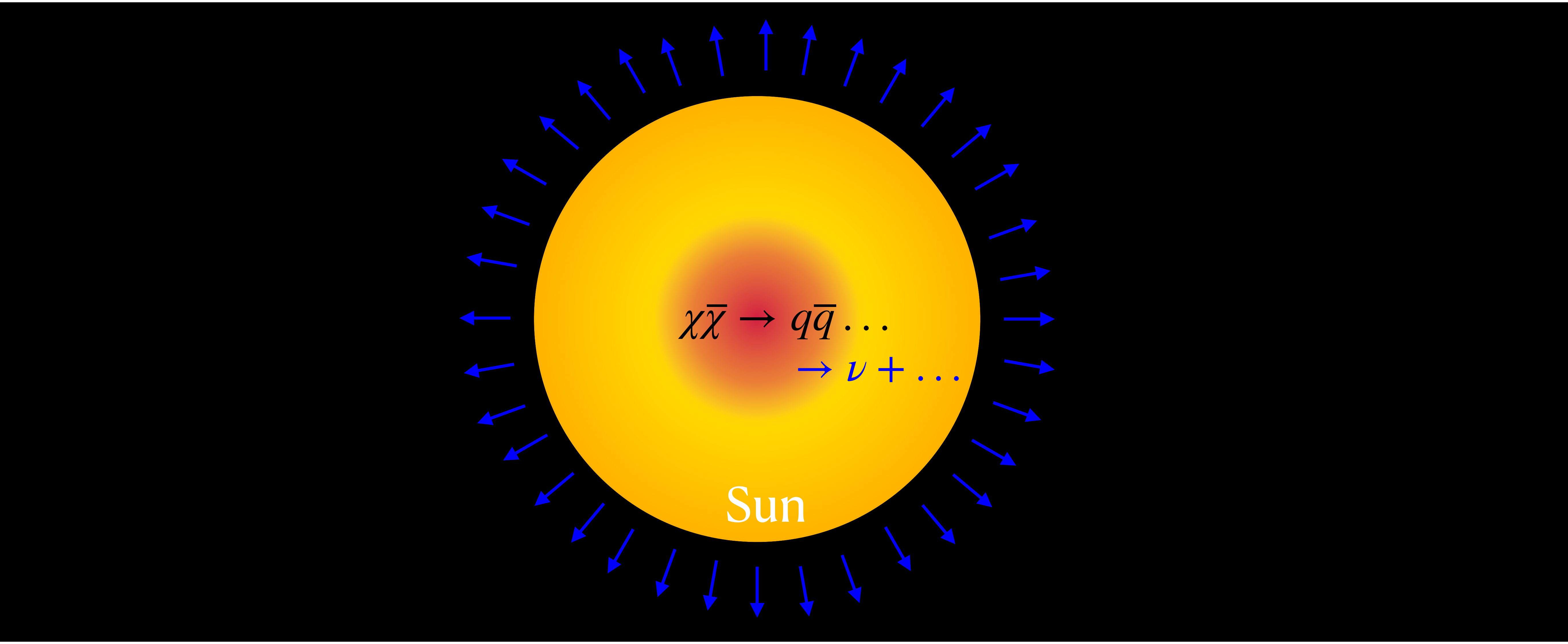


$$\dot{N}_\chi = \Gamma_C - \Gamma_E - \Gamma_A \equiv C - E N_\chi - A N_\chi^2$$

Gravitational Capture of Dark Matter

The neutrinos produced in DM annihilation escape the Sun,

and can be detected by large volume underground neutrino experiments.



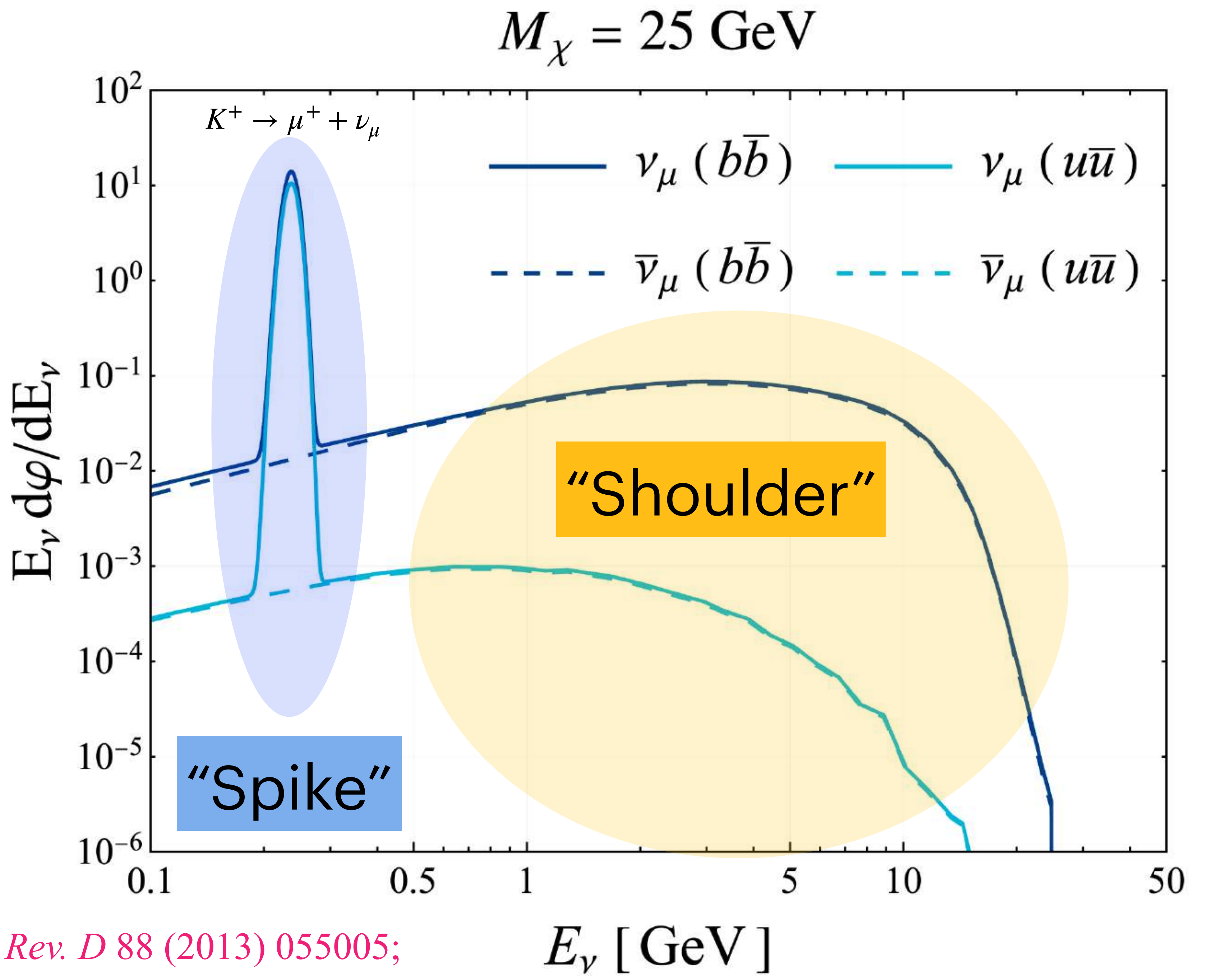
Neutrino flux from DM in the Sun

- If dark matter annihilates to quarks, they produce mesons that eventually decay inside Sun, producing neutrinos.
- We use *"Poor Particle Physicist's Cookbook for Neutrinos from Dark Matter annihilation in the Sun"* (PPPC 4 DMν) to get the spectrum of neutrinos

Baratella et al. *JCAP* 03 (2014) 053

Neutrino flux from DM in the Sun

Flux at source obtained using PPPC 4 DMν

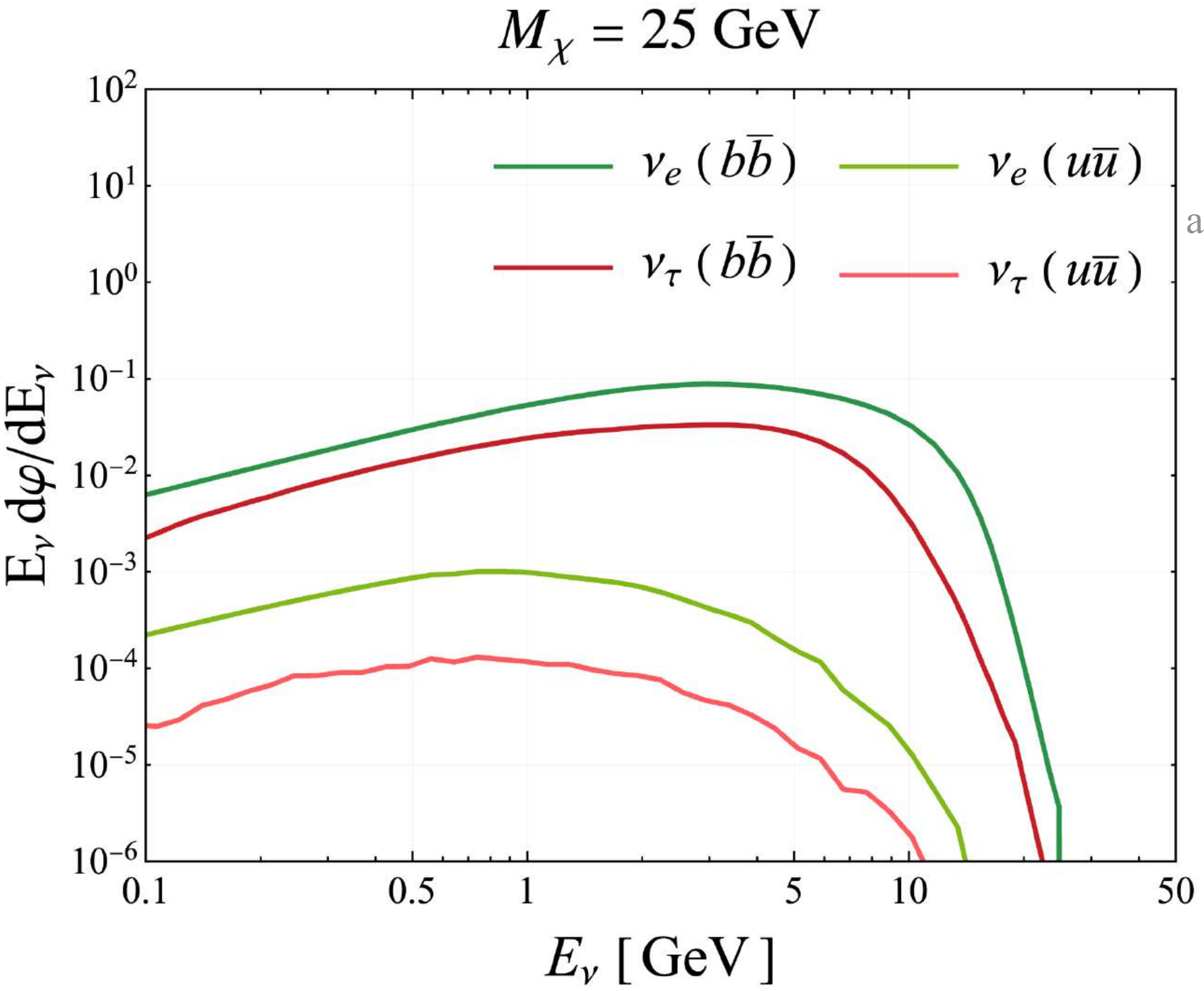


Rott et al., *Phys. Rev. D* 88 (2013) 055005;

Bernal et al., *JCAP* 08 (2013) 011

Neutrino flux from DM in the Sun

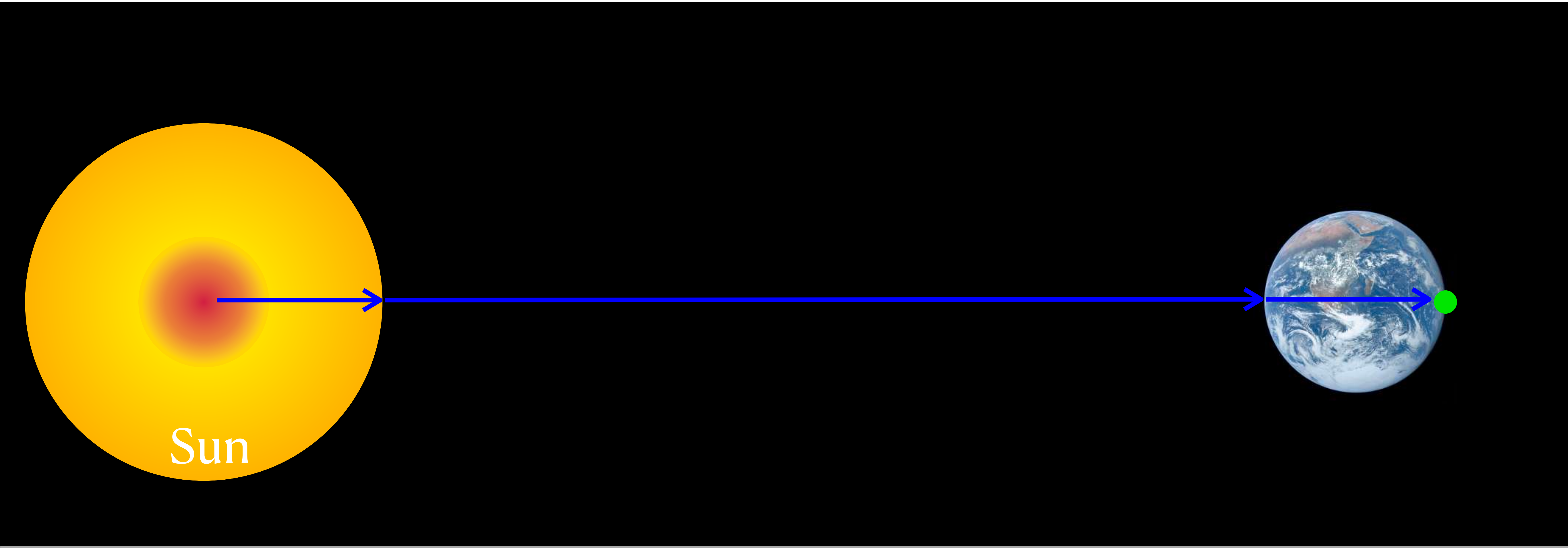
Flux at source obtained using PPPC 4 DMν



and anti-neutrinos

Neutrino Flux from DM in the Sun

The neutrinos undergo flavor conversion inside the Sun, in vacuum to Earth, and inside Earth during night.

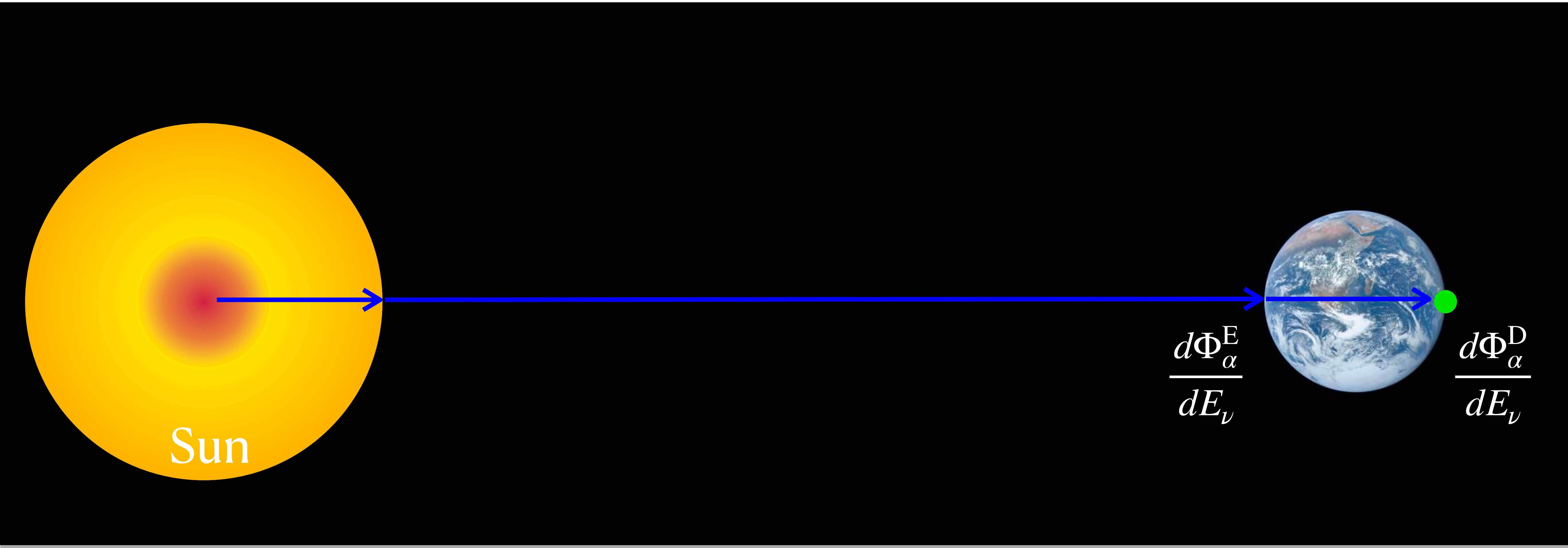


Neutrino Flux from DM in the Sun

Obtained using PPPC 4 DMν

$$\frac{d\Phi^{\mathrm{D}}_{\alpha}}{dE_{\nu}} = \frac{d\Phi^{\mathrm{E}}_{e}}{dE_{\nu}} \times \langle P^{ED}_{e\alpha} \rangle + \frac{d\Phi^{\mathrm{E}}_{\mu}}{dE_{\nu}} \times \langle P^{ED}_{\mu\alpha} \rangle + \frac{d\Phi^{\mathrm{E}}_{\tau}}{dE_{\nu}} \times \langle P^{ED}_{\tau\alpha} \rangle$$

Obtained using NuCraft and AstroPy

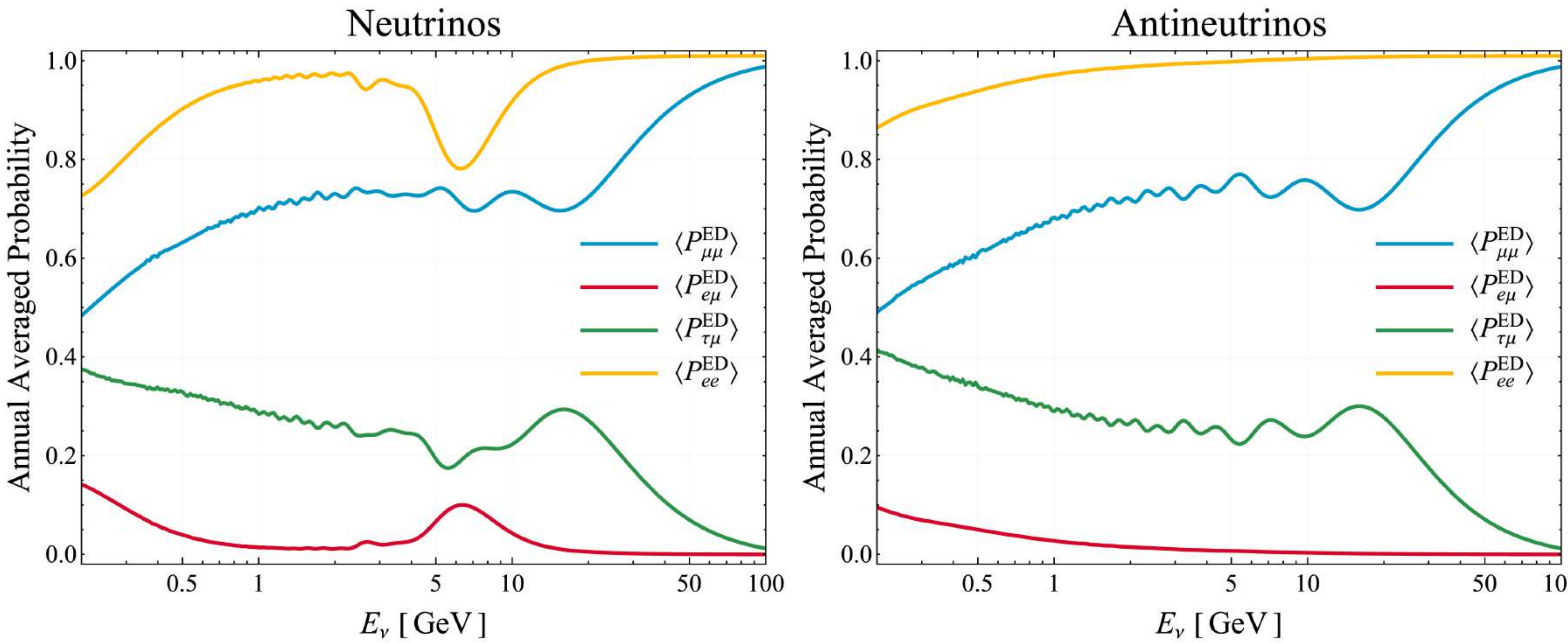


Neutrino Flux from DM in the Sun

Obtained using PPPC 4 DMν

$$\frac{d\Phi_\alpha^{\mathrm{D}}}{dE_\nu} = \frac{d\Phi_e^{\mathrm{E}}}{dE_\nu} \times \langle P_{e\alpha}^{ED} \rangle + \frac{d\Phi_\mu^{\mathrm{E}}}{dE_\nu} \times \langle P_{\mu\alpha}^{ED} \rangle + \frac{d\Phi_\tau^{\mathrm{E}}}{dE_\nu} \times \langle P_{\tau\alpha}^{ED} \rangle$$

Obtained using NuCraft and AstroPy



Neutrino flux from DM in the Sun

In summary, the flux of ν_α at the detector is —

$$\frac{d\Phi_\alpha^{\mathrm{D}}}{dE_\nu} = \frac{d\Phi_e^{\mathrm{E}}}{dE_\nu} \times \langle P_{e\alpha}^{ED} \rangle + \frac{d\Phi_\mu^{\mathrm{E}}}{dE_\nu} \times \langle P_{\mu\alpha}^{ED} \rangle + \frac{d\Phi_\tau^{\mathrm{E}}}{dE_\nu} \times \langle P_{\tau\alpha}^{ED} \rangle$$

where,

$$\frac{d\Phi_\alpha^E}{dE_\nu} = \frac{\Gamma_{\mathrm{A}}}{4\pi d^2} \sum_\beta P_{\alpha\beta}^{SE} \frac{d\varphi_\beta}{dE_\nu}$$

Different for elastic and inelastic dark matter

How do we detect neutrinos?

Scintillation Detectors	Water/Ice Cherenkov	Time Projection Chamber
Good Energy Resolution	Poor Energy Resolution	Good Energy Resolution
Poor Direction Reconstruction	Good Direction Reconstruction	Good Direction Reconstruction
Borexino, KamLAND, SNO+, …	Super-Kamiokande, IceCube, SNO …	MircoBooNE, DUNE

Current Status

Can reconstruct neutrino energy

Can reconstruct neutrino direction

		ν_e			ν_μ		
		E_ν	θ_ν	Ref.	E_ν	θ_ν	Ref.
Spike (QEL)	SuperK	✓	✗	[23, 24]	✓	✗	–
	IceCube	✗	✗	–	✗	✗	–
	DUNE	✓	✓	[23, 24]	✓	✓	[24],[26]*
Shoulder (DIS)	SuperK	✓	✓	[8]* #	✓	✓	[6–8]*
	IceCube	✓	✗	–	✓	✓	[11, 12]*
	DUNE	✓	✓	[27]	✓	✓	This Work

* denotes analysis by the respective collaboration

See the paper for references

Atmospheric Neutrino Background

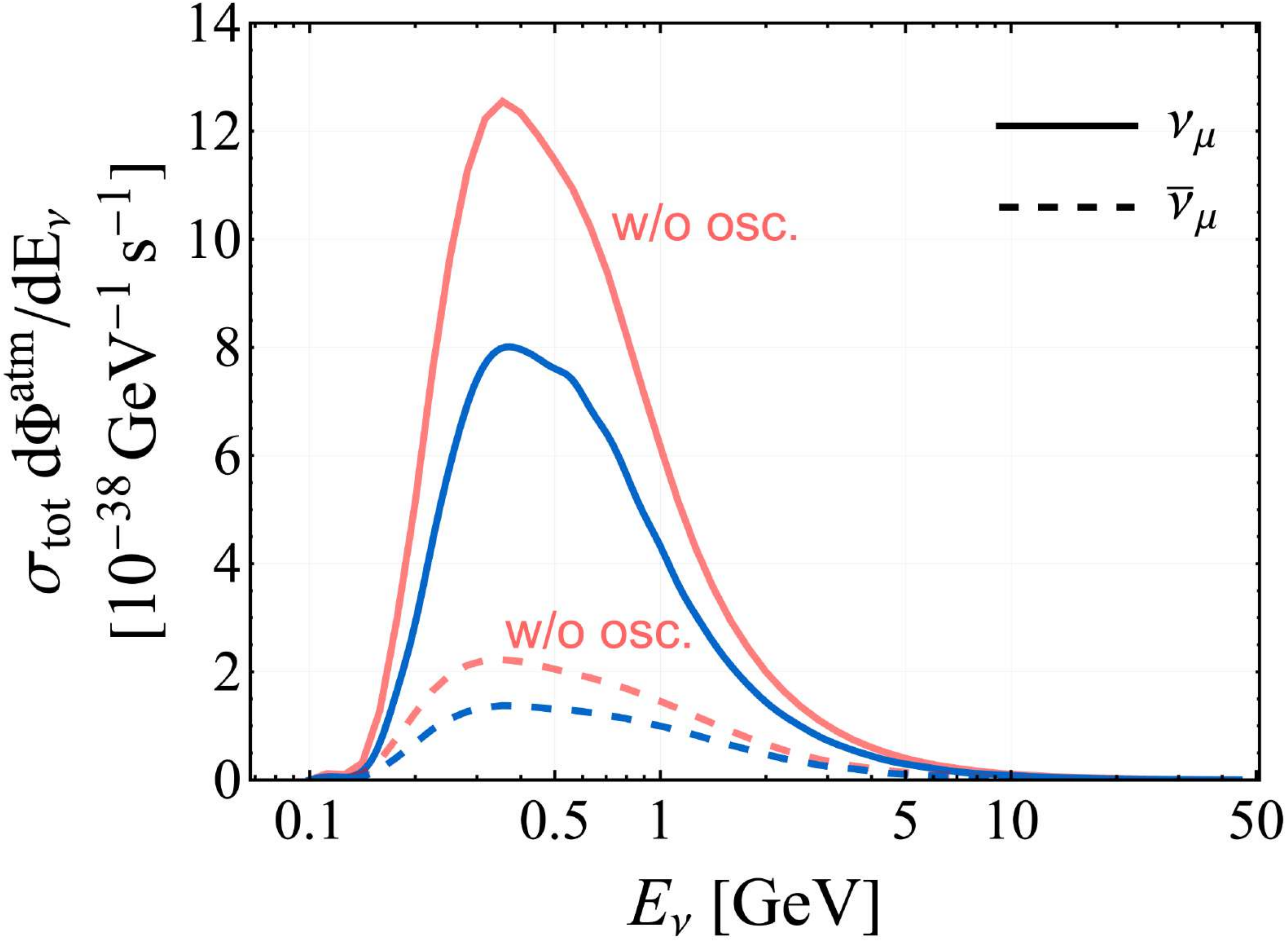
- We are interested in detecting neutrinos with energy in the range 100 MeV — 100 GeV
- At these scales, earth atmospheric neutrinos are the dominant background

Phys. Rev. D 92 (2015) 2, 023004

- We use the flux predictions at Super-Kamiokande by Honda et al. and account for flavor conversion inside Earth using **NuCraft**
- Interaction cross sections & differential distributions are obtained using the Monte Carlo generator **NuWro**

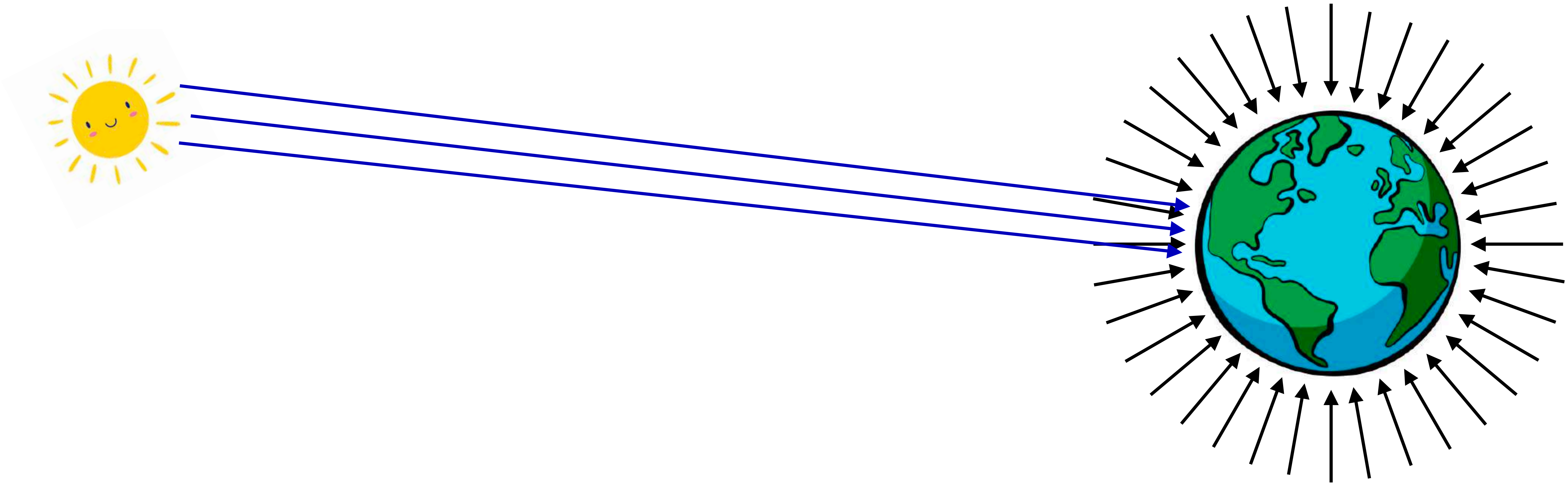
Phys. Rev. C 86 (2012) 015505

Atmospheric Neutrino Background



Atmospheric Neutrino Background

- For a 34 kton Liquid Argon Time Projection Chamber (LArTPC) detector (DUNE), we estimate **2300** charged-current events every year from atmospheric muon neutrinos above 100 MeV.
- However, not all of these events constitute the background.



Atmospheric Neutrino Background

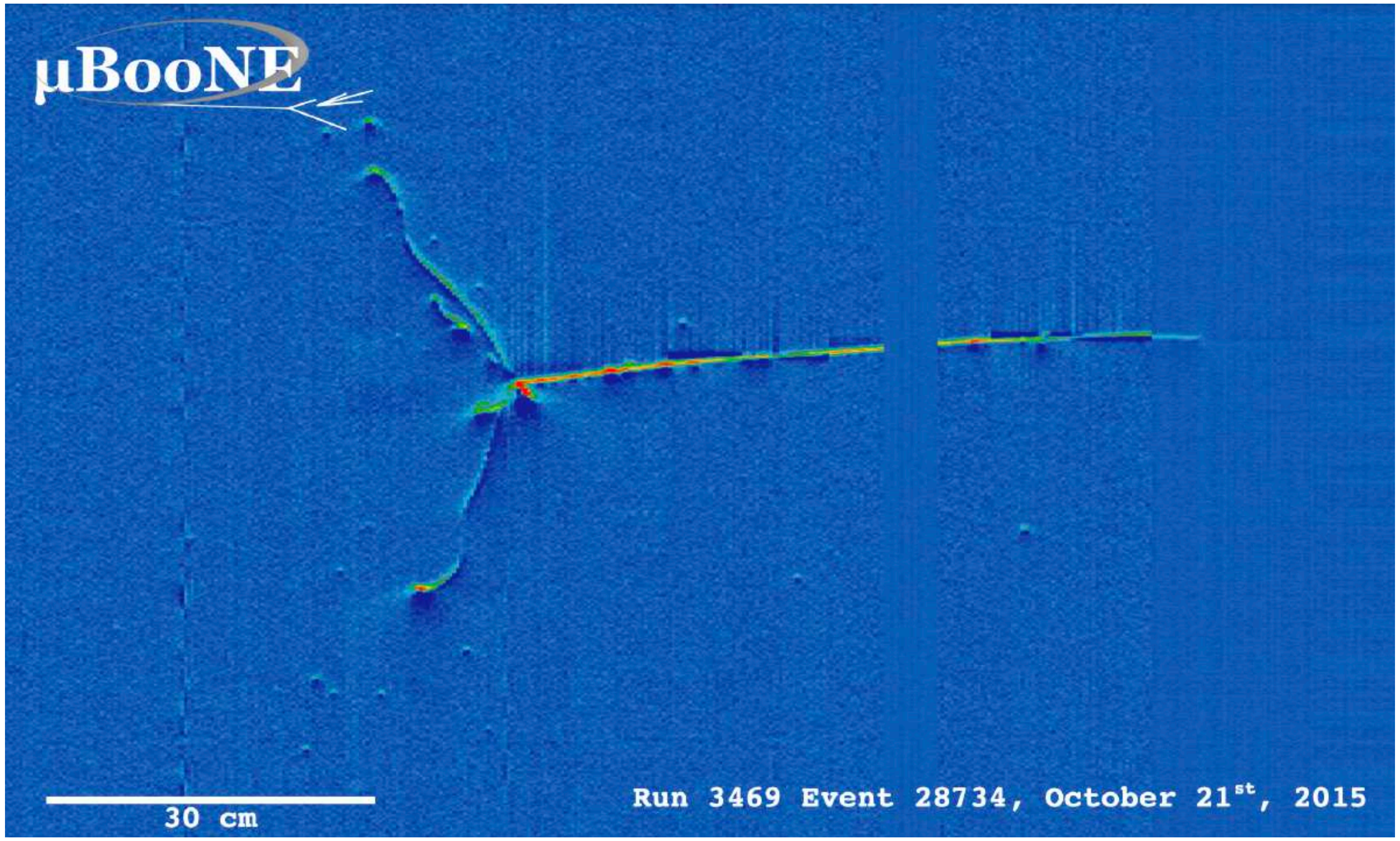
Allegory of the ~~Cave~~ Neutrino Detector

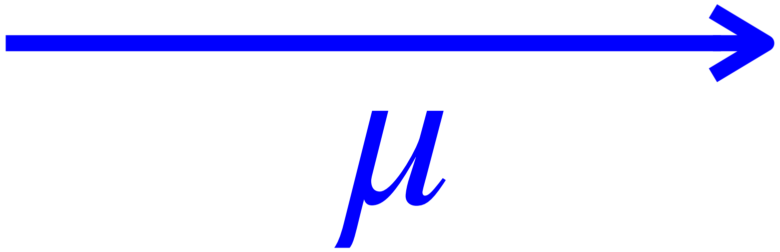
- As any neutrino detector can only see the charged particles produced in the interactions, the direction of the incident neutrino can only be inferred.
- We look at 'starting tracks' in DUNE which are most likely due to charged-current interactions of ν_μ ***and*** $\bar{\nu}_\mu$
- There may be auxiliary particles (protons and pions) that may help in reconstruction, but we do not consider them.
- We also assume perfect energy and angular resolution for the tracks

Atmospheric Neutrino Background

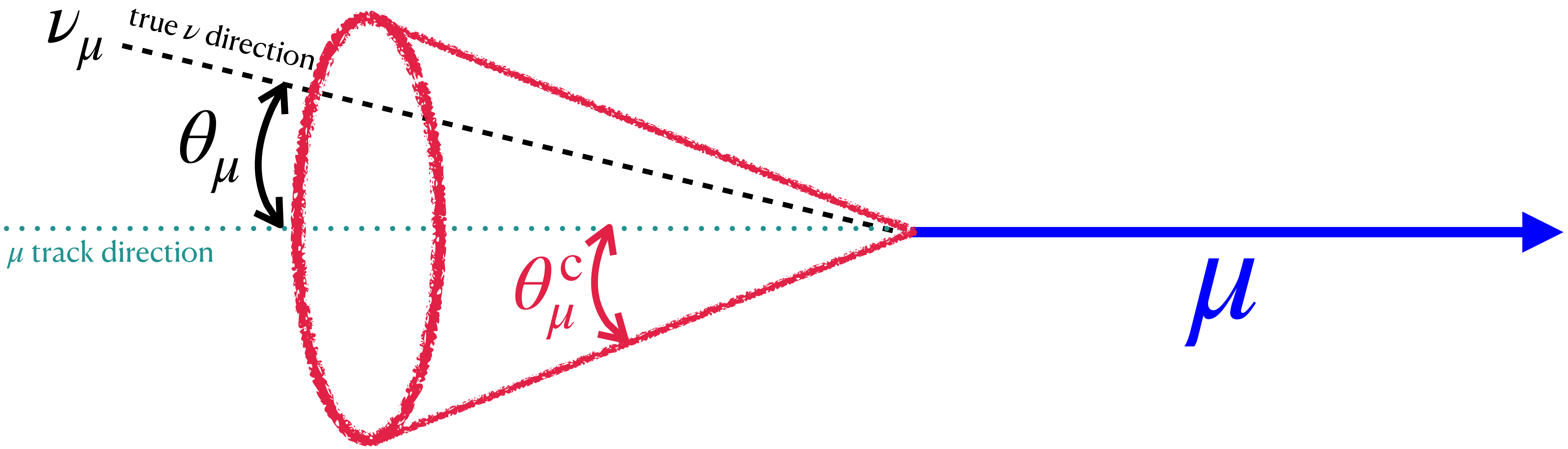
The question is —

Given a muon-like track, can we say whether the initial neutrino originated in the Sun?





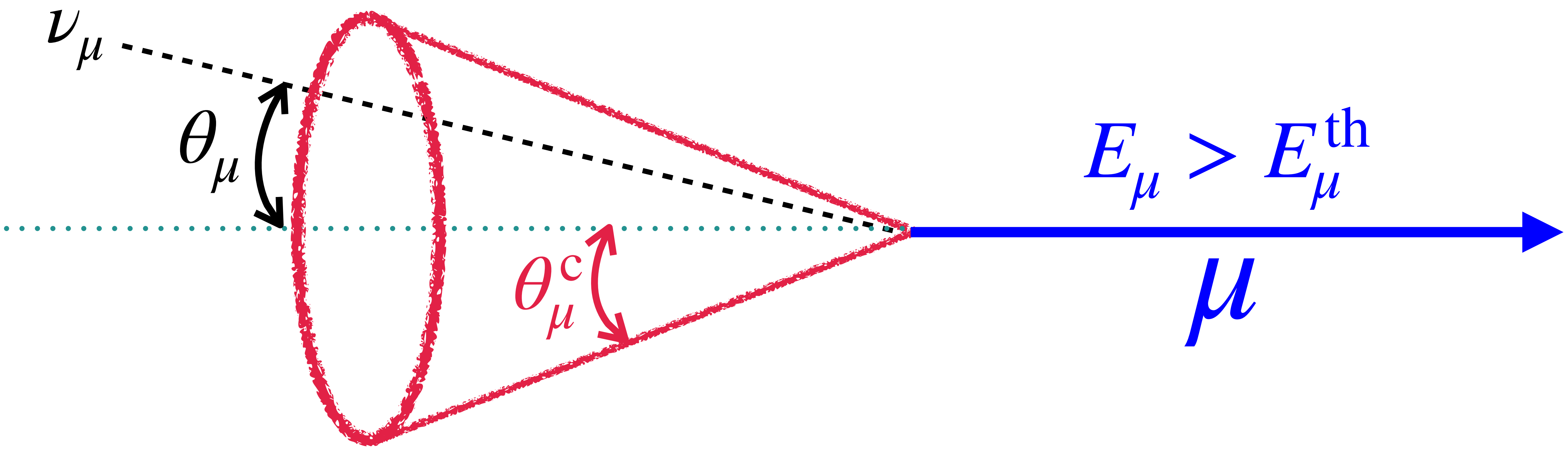
Atmospheric Neutrino Background



We want to determine θ_μ^{c} such that there is a reasonable (say, 90%) chance that the incident neutrino is within the cone

The first step is to look at high-energy tracks as they are more collinear

Atmospheric Neutrino Background

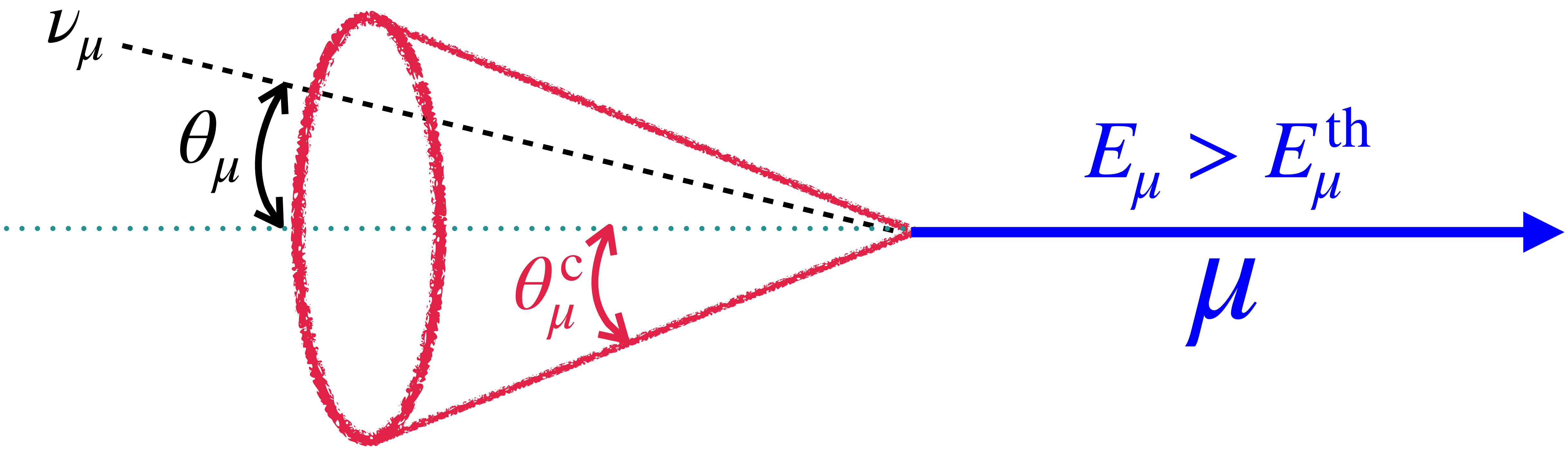


We consider three benchmark choices*

for E_μ^{th}: 500 MeV, 1 GeV, and 5 GeV

*We do not optimise this choice but it represents a low-, moderate-, and high-energy cutoff

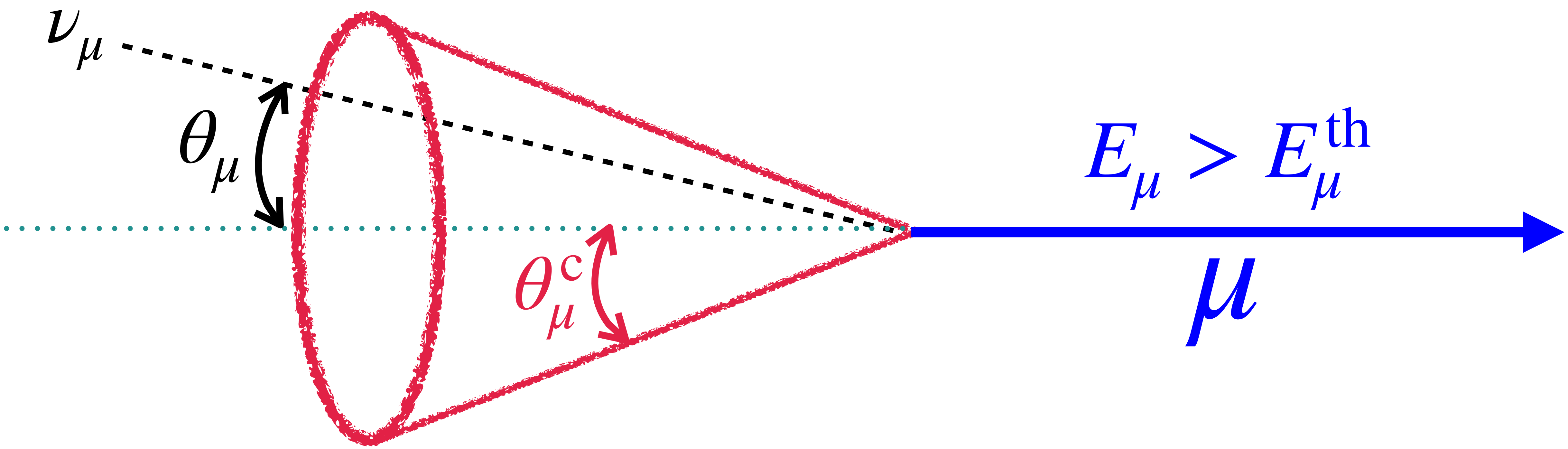
Atmospheric Neutrino Background



Component	$E_\mu^{\rm th}$=500 MeV	$E_\mu^{\rm th}$=1 GeV	$E_\mu^{\rm th}$=5 GeV
ν_μ	884	552	120
$\overline{\nu}_\mu$	325	232	58
Total	1209	784	178

Note: 2300 events/(34 kton-yr) above 100 MeV

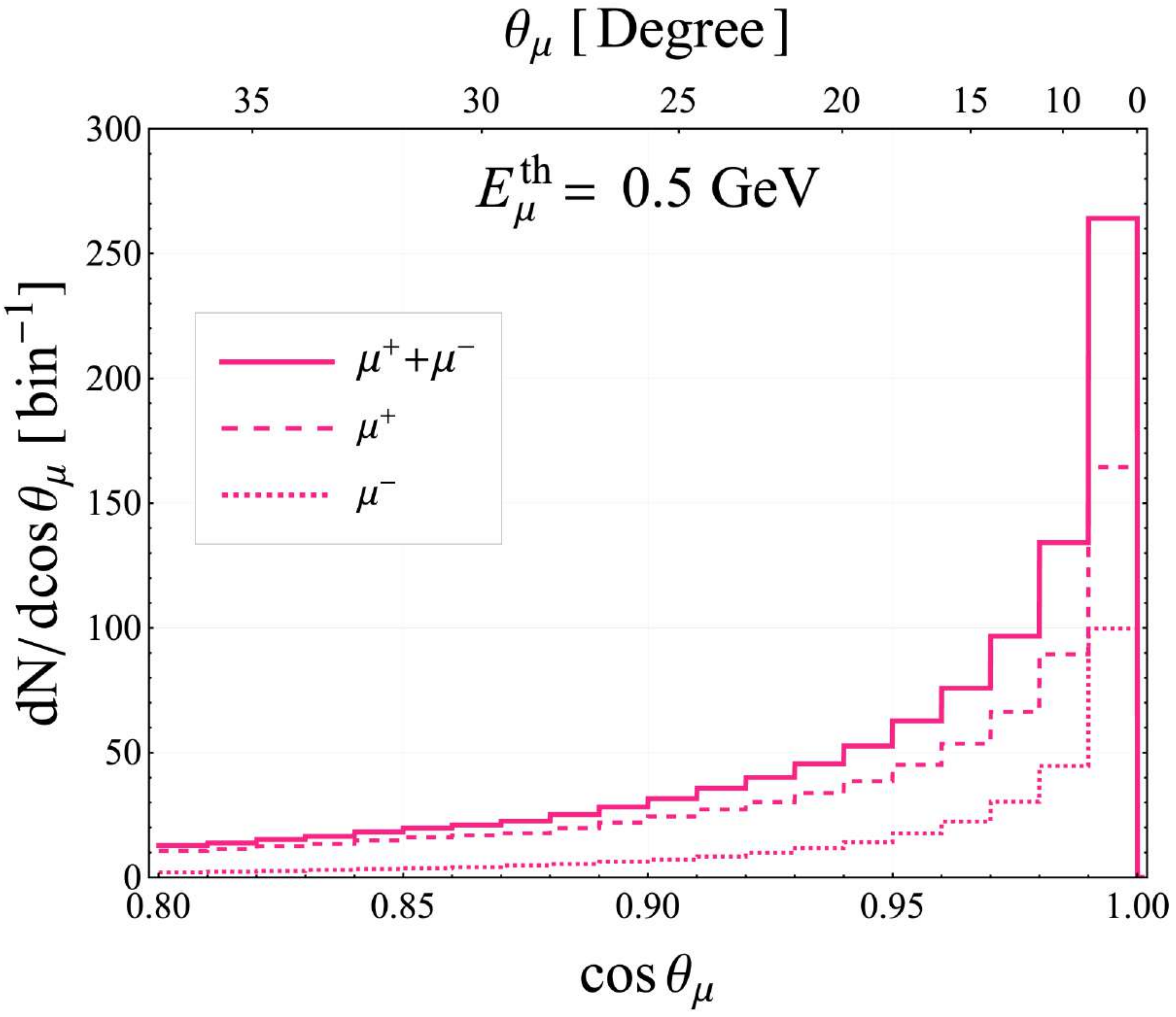
Atmospheric Neutrino Background



To determine the cone half-angle such that 90% neutrinos are inside the cone (θ_μ^{90}) we evaluate the distribution of θ_μ folded with the *oscillated* atmospheric neutrino flux using NuWro

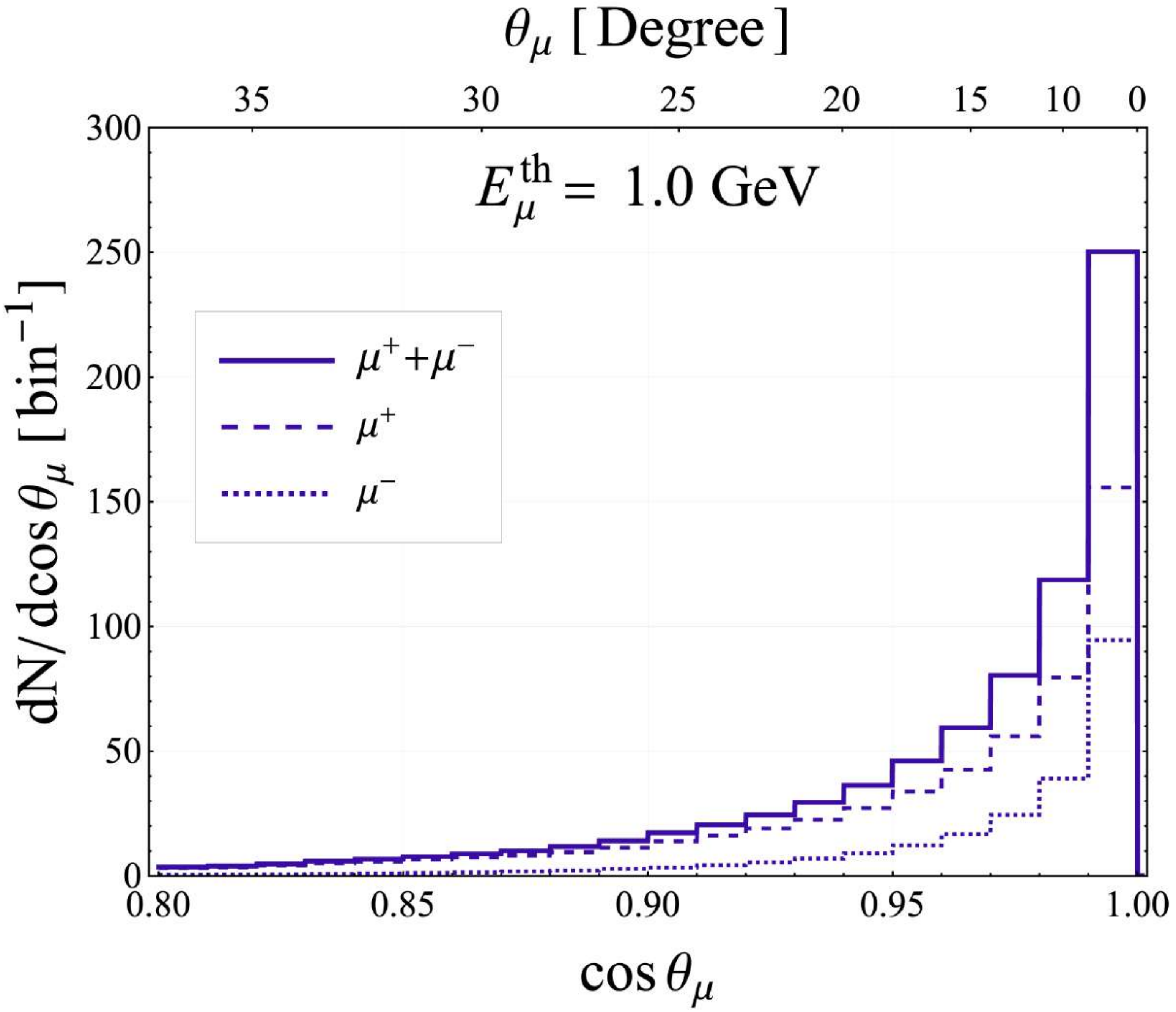
Atmospheric Neutrino Background

Simulated with **NuWro** using oscillated atmospheric neutrino flux



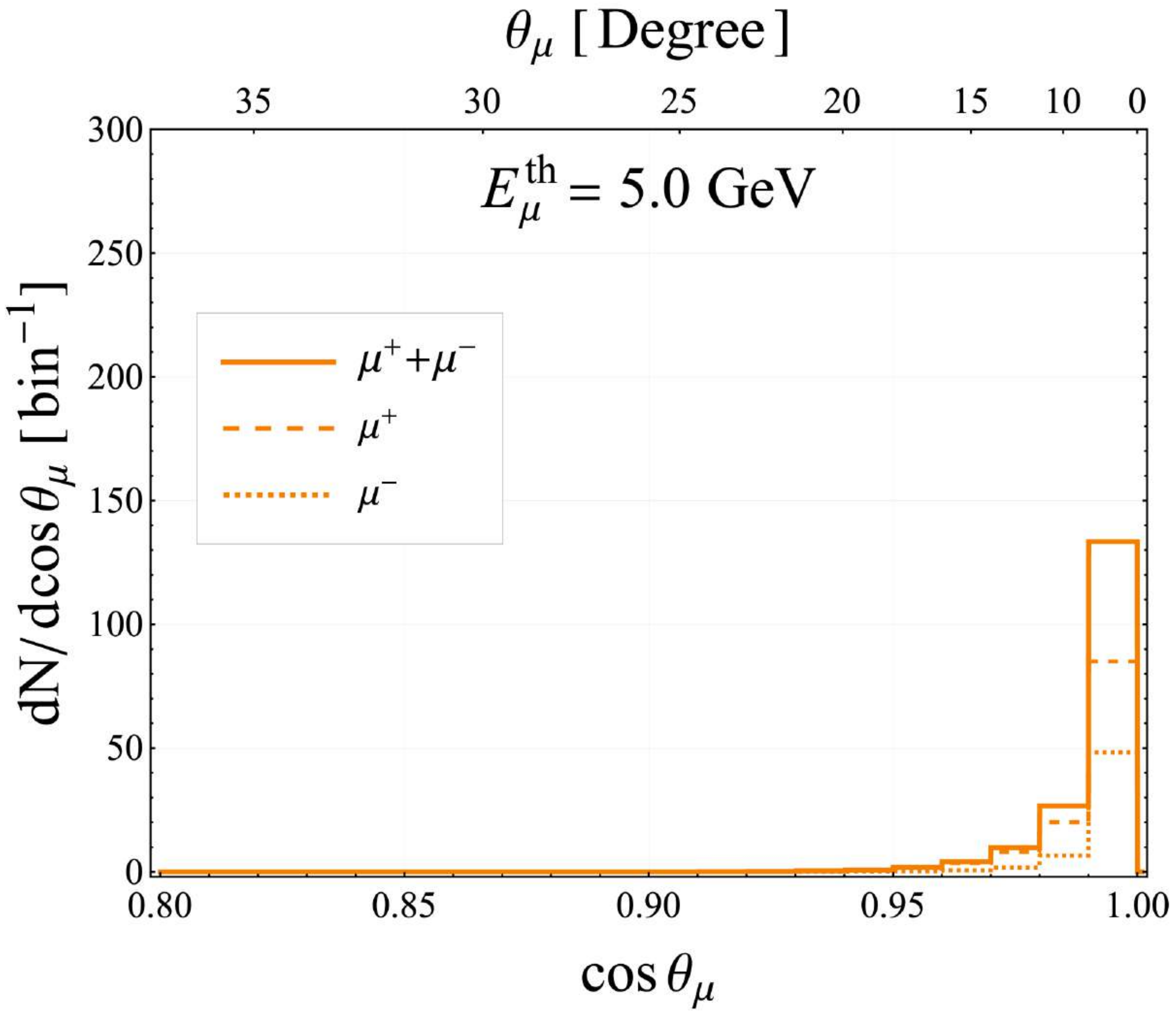
Atmospheric Neutrino Background

Simulated with **NuWro** using oscillated atmospheric neutrino flux



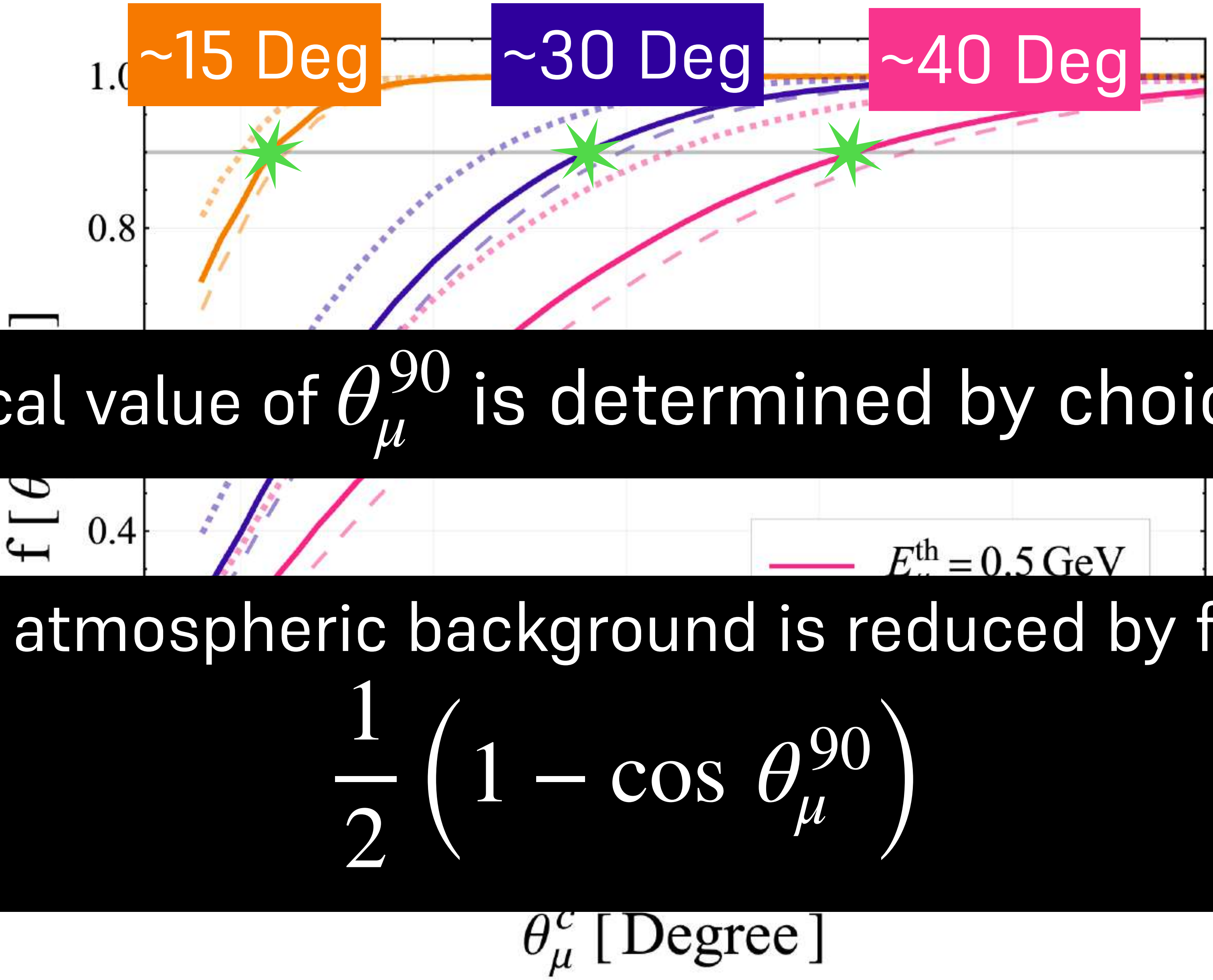
Atmospheric Neutrino Background

Simulated with NuWro using oscillated atmospheric neutrino flux



Atmospheric Neutrino Background

Determine θ_μ^{90} for which f $[\theta_\mu < \theta_\mu^{c}] = 0.9$



~15 Deg

~30 Deg

~40 Deg

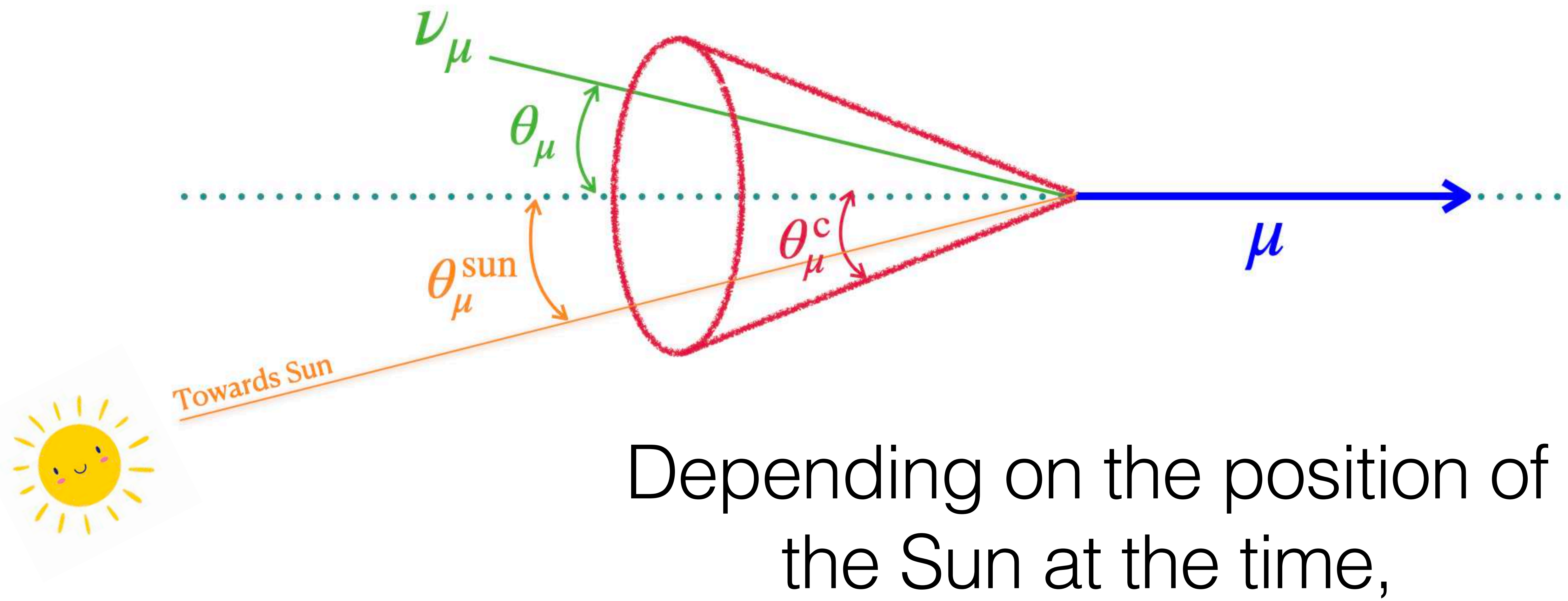
Numerical value of θ_μ^{90} is determined by choice of $E_\mu^{\rm th}$

The atmospheric background is reduced by factor

$$\frac{1}{2}\left(1 - \cos\,\theta_\mu^{90}\right)$$

Atmospheric Neutrino Background

In practice, if you observe a muon with energy > 1 GeV, there is 90% chance that the incident neutrino is within a cone of half-angle 30 Degree



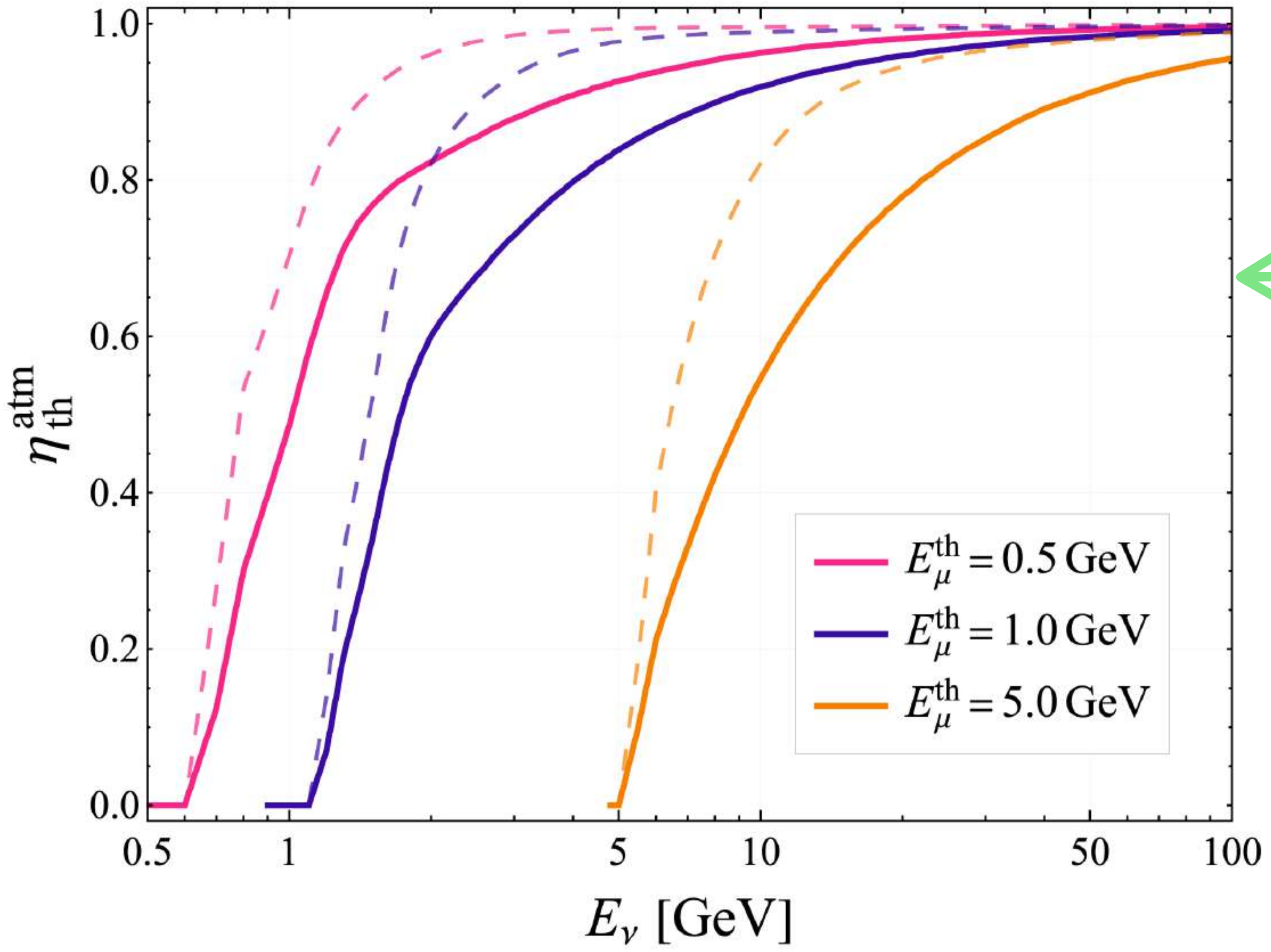
Depending on the position of the Sun at the time, the event is accepted/rejected

Atmospheric Neutrino Background

For numerical estimate of the irreducible background rate —

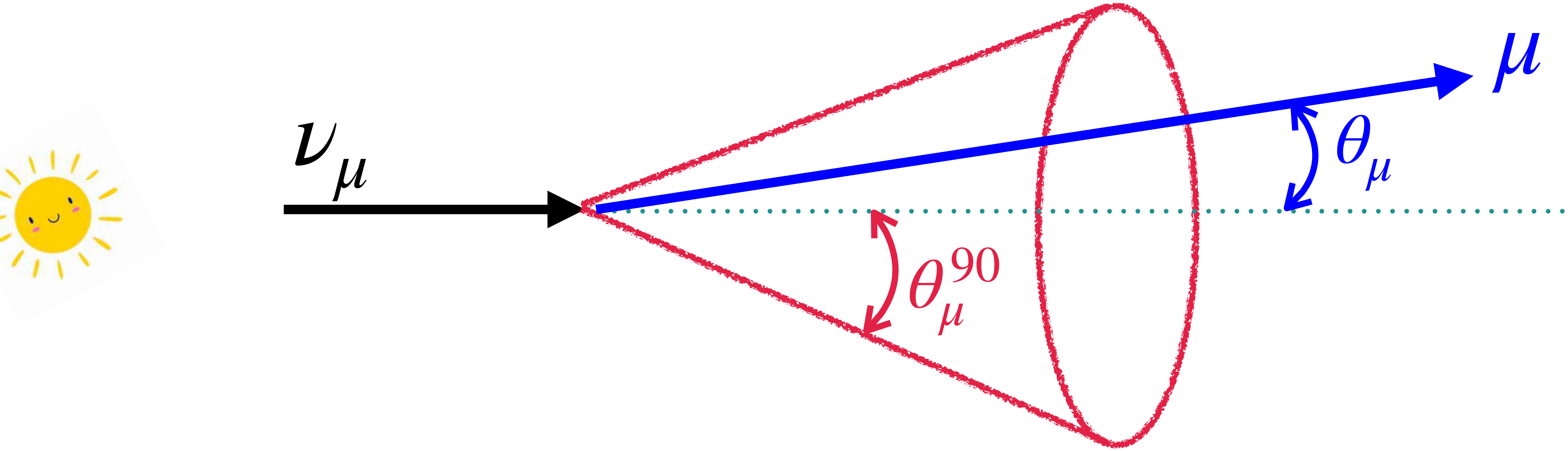
$$N_{\text{sel}}^{\text{atm}} = N_{\text{Ar}} \cdot t \times \frac{1}{2}(1 - \cos\theta_\mu^{90}) \sum_{\mu^\pm} \int dE_\nu \frac{d\Phi^{\text{atm}}}{dE_\nu} \times \sigma_{\text{tot}} \times \eta_{\text{th}}^{\text{atm}}(E_\nu, E_\mu^{\text{th}})$$

atmospheric background events that pass the selection criterion



Reduced Signal

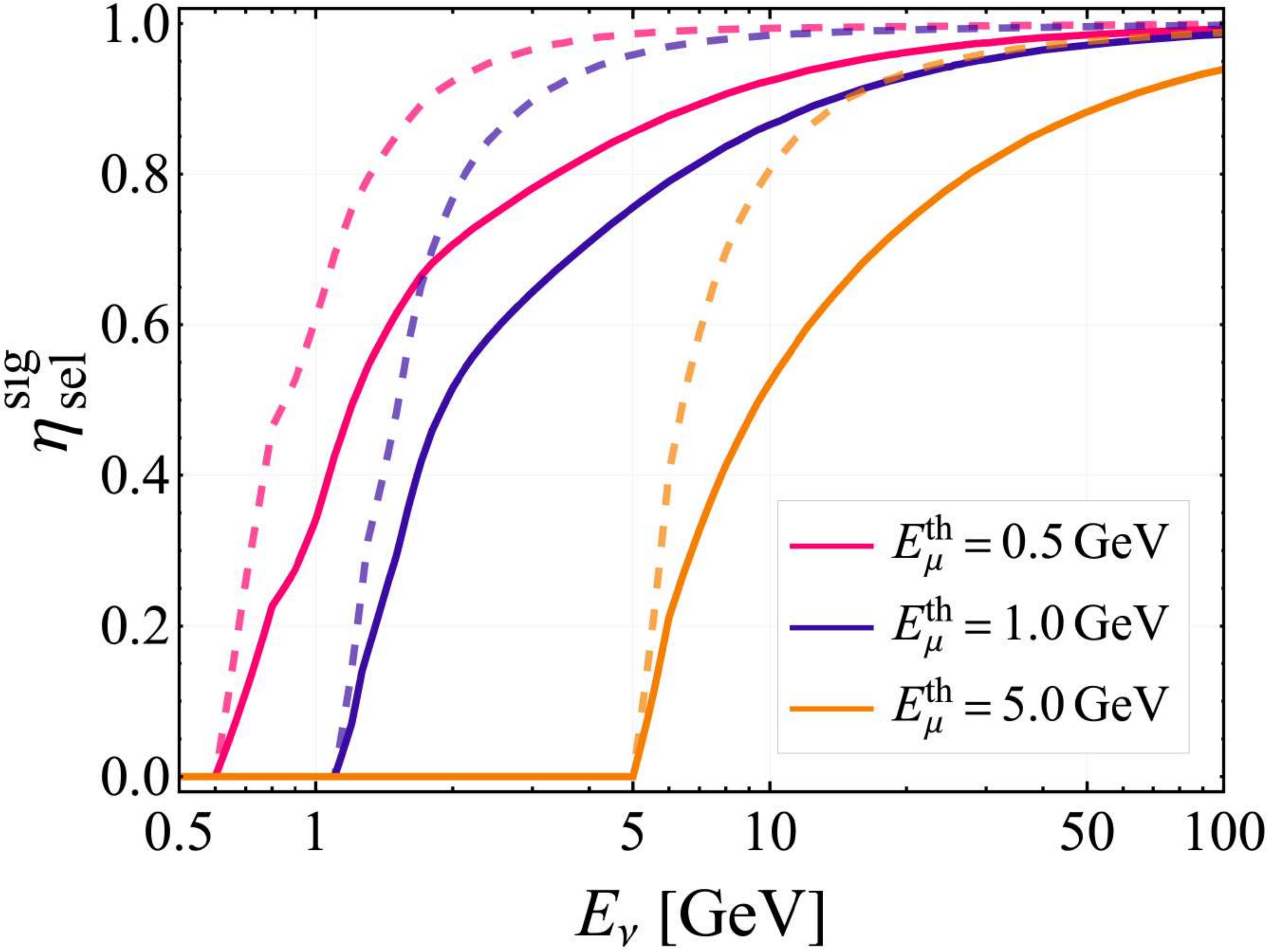
Same filters must be applied to ‘signal’ from the Sun



For neutrino of energy E_ν, we determine the probability of creating a muon with $E_\mu > E_\mu^{\mathrm{th}}$ and $\theta_\mu < \theta_\mu^{90}$

Reduced Signal

$\eta_{\rm sel}^{\rm sig}$ = Probability of creating a muon with $E_\mu > E_\mu^{\rm th}$ and $\theta_\mu < \theta_\mu^{90}$



Reduced Signal

- The signal event rate —

$$N_{\text{sel}}^{\text{sig}} = N_{\text{Ar}} \cdot t \times \sum_{\mu^{\pm}} \int dE_{\nu} \frac{d\Phi^{\text{D}}}{dE_{\nu}} \times \sigma_{\text{tot}} \times \eta_{\text{sel+dir}}(E_{\nu}, E_{\mu}^{\text{th}})$$

- 90% C.L. Sensitivity obtained by assuming Poisson statistics and ‘rejecting signal+background’

E_{μ}^{th}	θ_{μ}^{90}	$N_{\text{sel}}^{\text{atm}}$	N_{90}^{excl}
0.5 GeV	40°	1664	57.5
1.0 GeV	30°	618	34.4
5.0 GeV	15°	36	9.4

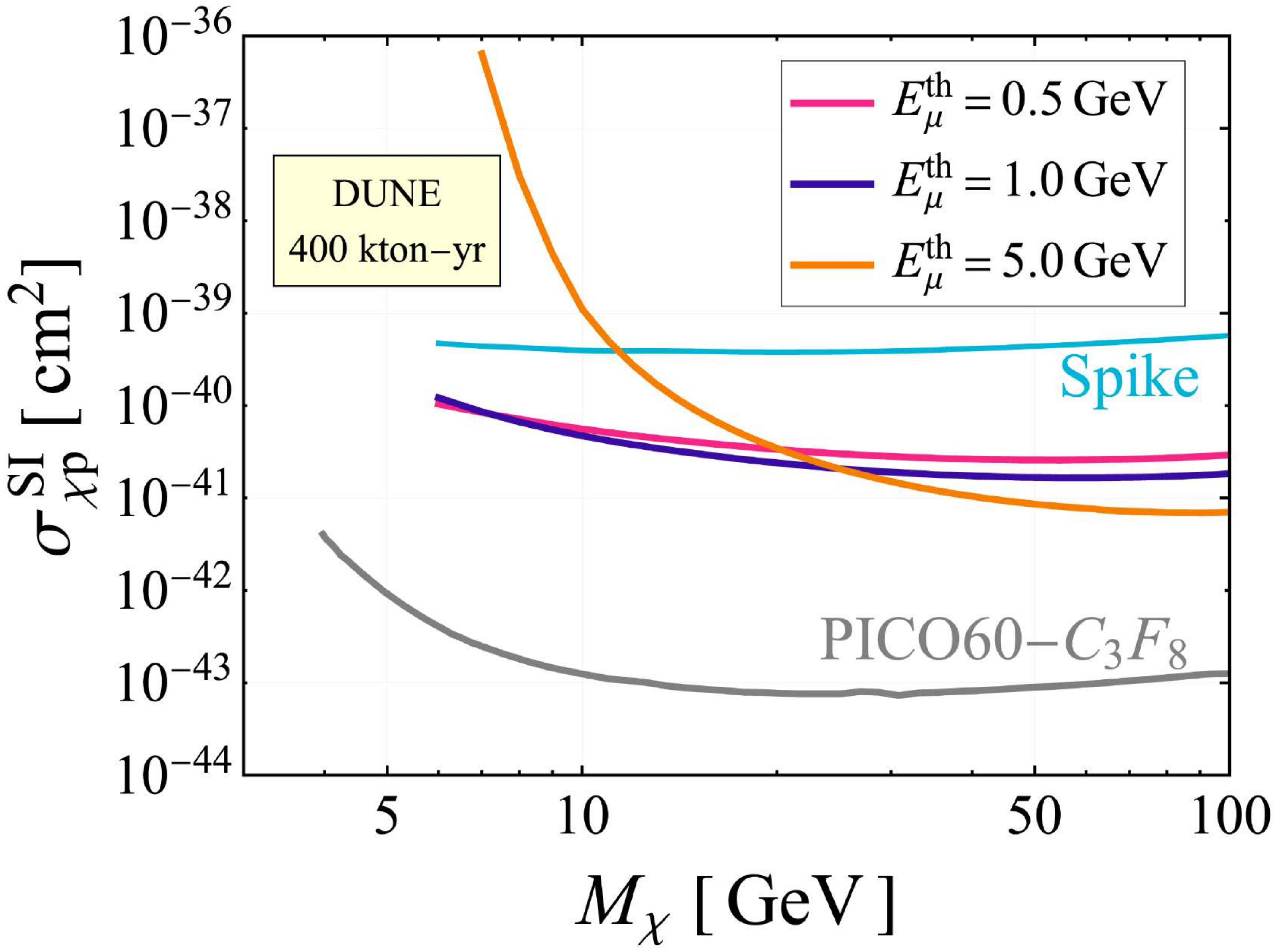
Excluded if

$$N_{\text{sel}}^{\text{sig}} \sim N_{90}^{\text{excl}}$$

Dark Matter Parameters

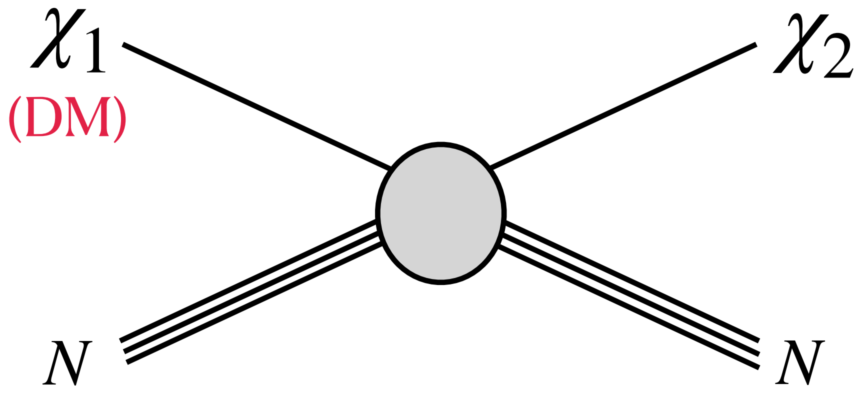
Detector physics and Backgrounds

DUNE Sensitivity — Spin Independent Elastic DM



The case for
Inelastic Dark Matter

Inelastic Dark Matter



$$\delta = M_2 - M_1 > 0$$

- The dark sector has **two** particles separated in mass by a small splitting δ Tucker-Smith and Weiner *Phys. Rev. D* 64 (2001) 043502
- Lighter state is the cosmological Dark Matter
- Only off-diagonal interactions are allowed

Inelastic Dark Matter - Direct Detection

The rate of nuclear recoils in a direct-detection experiment is -

0.3 — 0.4 GeV/cm^3

Particle physics models
and Form Factors

$$\mathcal{R}_{\mathrm{DD}} = \int_{E_R^{\mathrm{min}}}^{E_R^{\mathrm{max}}} dE_R \, \frac{\rho_\chi}{M_N M_\chi} \int_{v_{\mathrm{min}}} d^3v \, v \, f(\vec{v}) \, \frac{d\sigma_{\chi N}}{dE_R}$$

Detector
thresholds

Thermal distribution
with a cut-off

“The minimum dark matter velocity
required for detectable recoils”

Inelastic Dark Matter - Direct Detection

- As a part of the energy budget goes into producing the heavier state, only DM particles with sufficient kinetic energy (i.e., from the high-velocity tail) take part in the interactions

$$v_{\min}(E_R) = \frac{1}{\sqrt{2M_N E_R}}\left(\frac{M_N}{\mu_{\chi N}}E_R + \delta\right)$$

$\delta = M_2 - M_1 > 0$

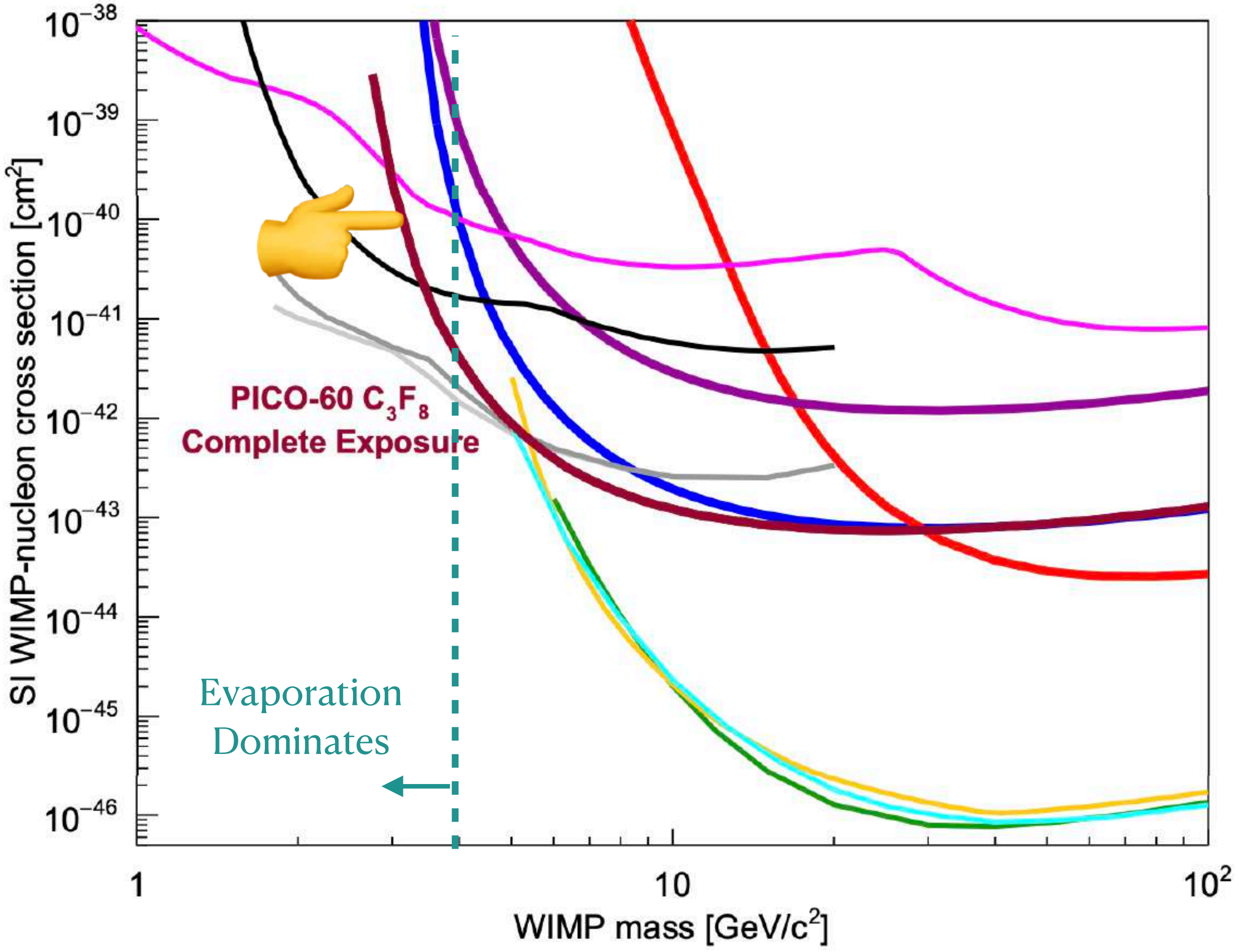
- Event rates are suppressed w.r.t. elastic DM

- We use WimPyDD to calculate the event rates $\mathscr{R}$

Jeong et al. Comput. Phys. Commun. 276 (2022) 108342

Inelastic Dark Matter - Direct Detection

We focus on two of the most* sensitive direct detection experiments - PICO and LZ



PICO Collaboration Phys. Rev. D 100, 022001 (2019)

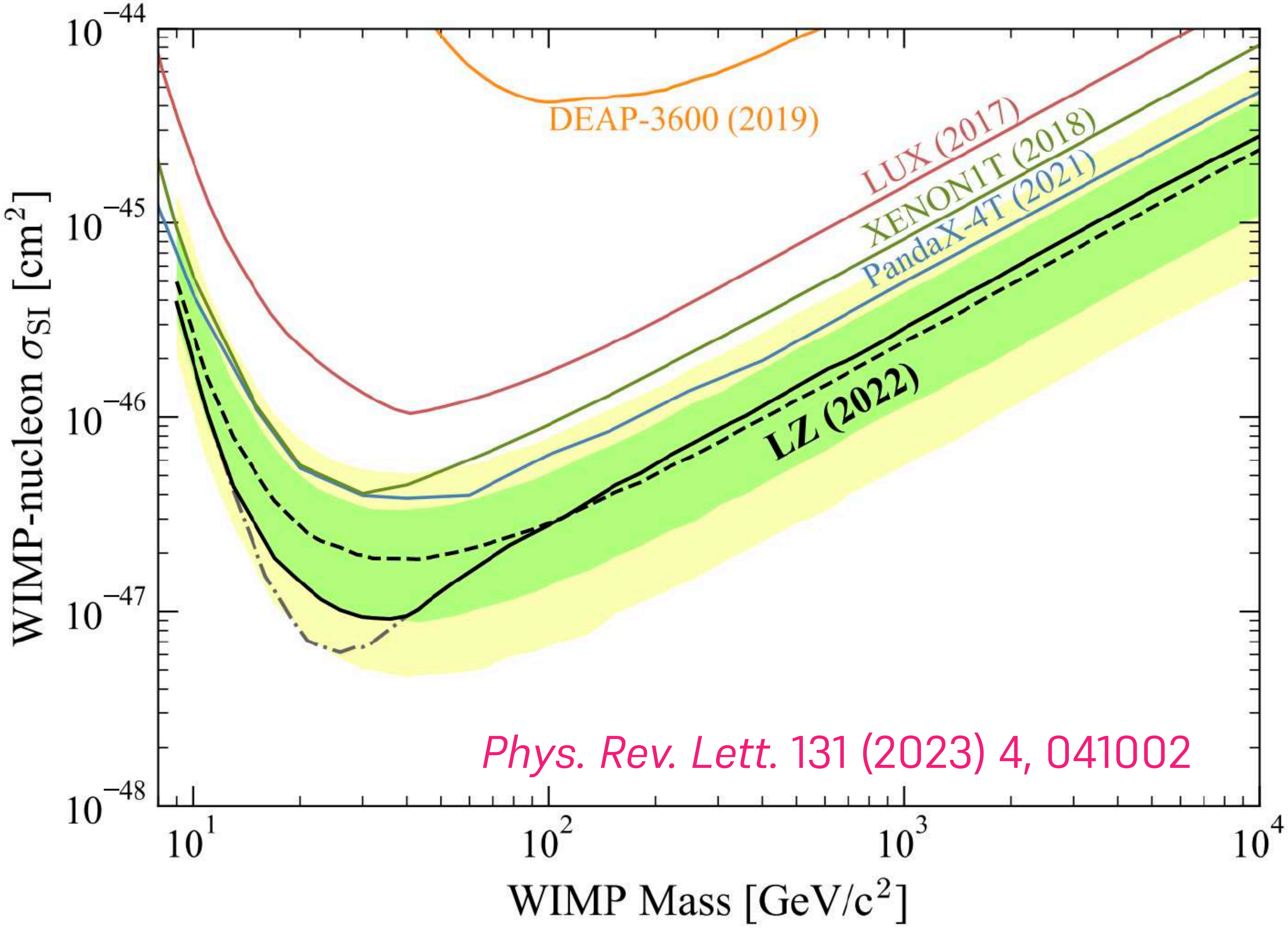
The bubble chamber detector PICO-60 with C_3F_8 target.

Sensitive to low-mass dark matter

Inelastic Dark Matter - Direct Detection

The xenon based scintillation detector : LUX-ZEPLIN (LZ)

World-leading sensitivity for dark matter heavier than 9 GeV



Phys. Rev. Lett. 131 (2023) 4, 041002

Inelastic Dark Matter - Direct Detection

To "map" the limits for elastic dark matter to the parameters of inelastic dark matter, we use the relative event rate -

$$k_{\mathrm{DD}}(M_\chi, \delta) = \frac{\mathscr{R}_{\mathrm{DD}}(M_\chi, \delta)}{\mathscr{R}_{\mathrm{DD}}(M_\chi, 0)}$$

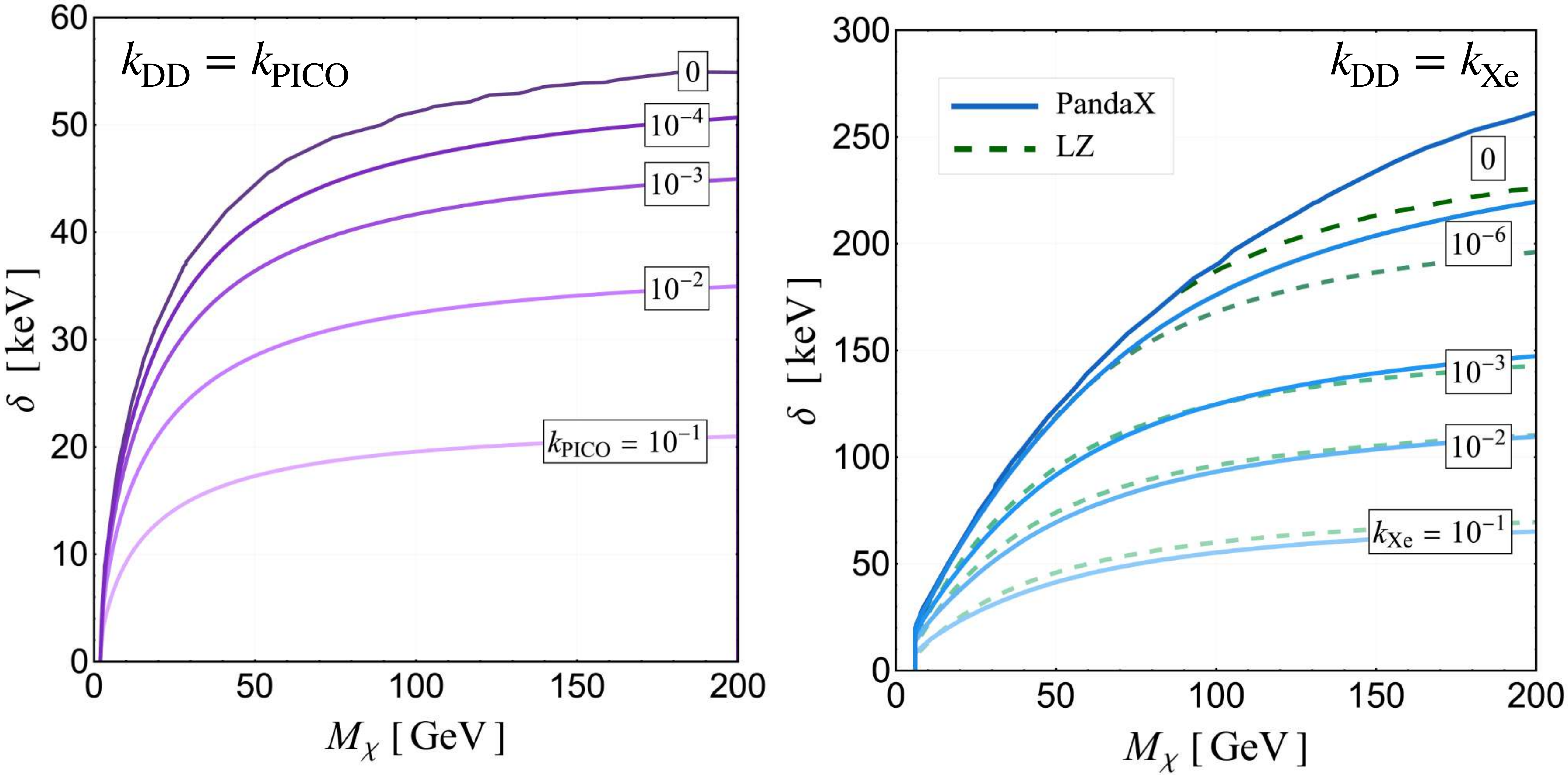
Both elastic and inelastic event rates obtained using WimPyDD

$$\sigma_{\mathrm{DD}}^{\mathrm{lim}}(M_\chi, \delta) = \sigma_{\mathrm{DD}}^{\mathrm{lim}}(M_\chi, 0) \times k_{\mathrm{DD}}(M_\chi, \delta)$$

Limit for Elastic DM

Inelastic Dark Matter - Direct Detection

$$k_{\mathrm{DD}}(M_\chi, \delta) = \mathscr{R}_{\mathrm{DD}}(M_\chi, \delta) / \mathscr{R}_{\mathrm{DD}}(M_\chi, 0)$$



Inelastic Dark Matter - Capture in Sun

The phase-space for gravitational capture is much smaller for inelastic DM

Nussinov et al. *JCAP* 08 (2009) 037
Menon et al. *Phys.Rev.D* 82 (2010) 015011

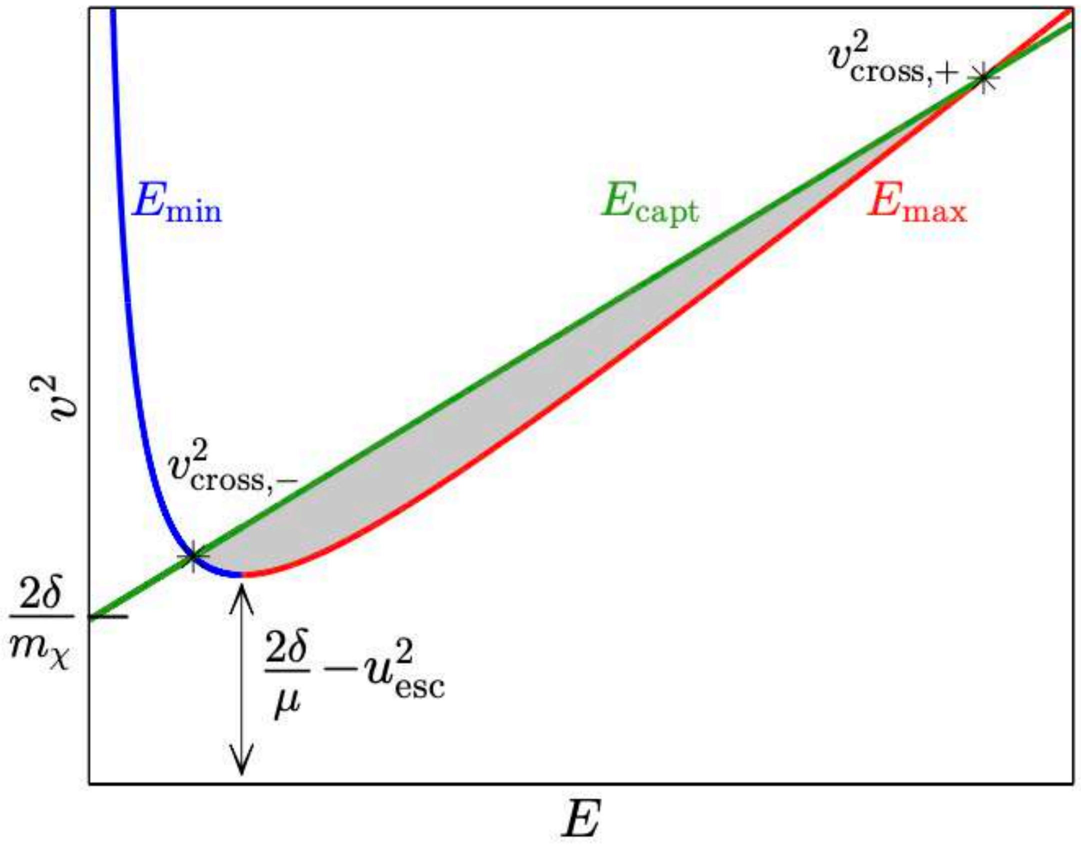


Figure from Blennow et al. *JCAP* 04 (2016) 004

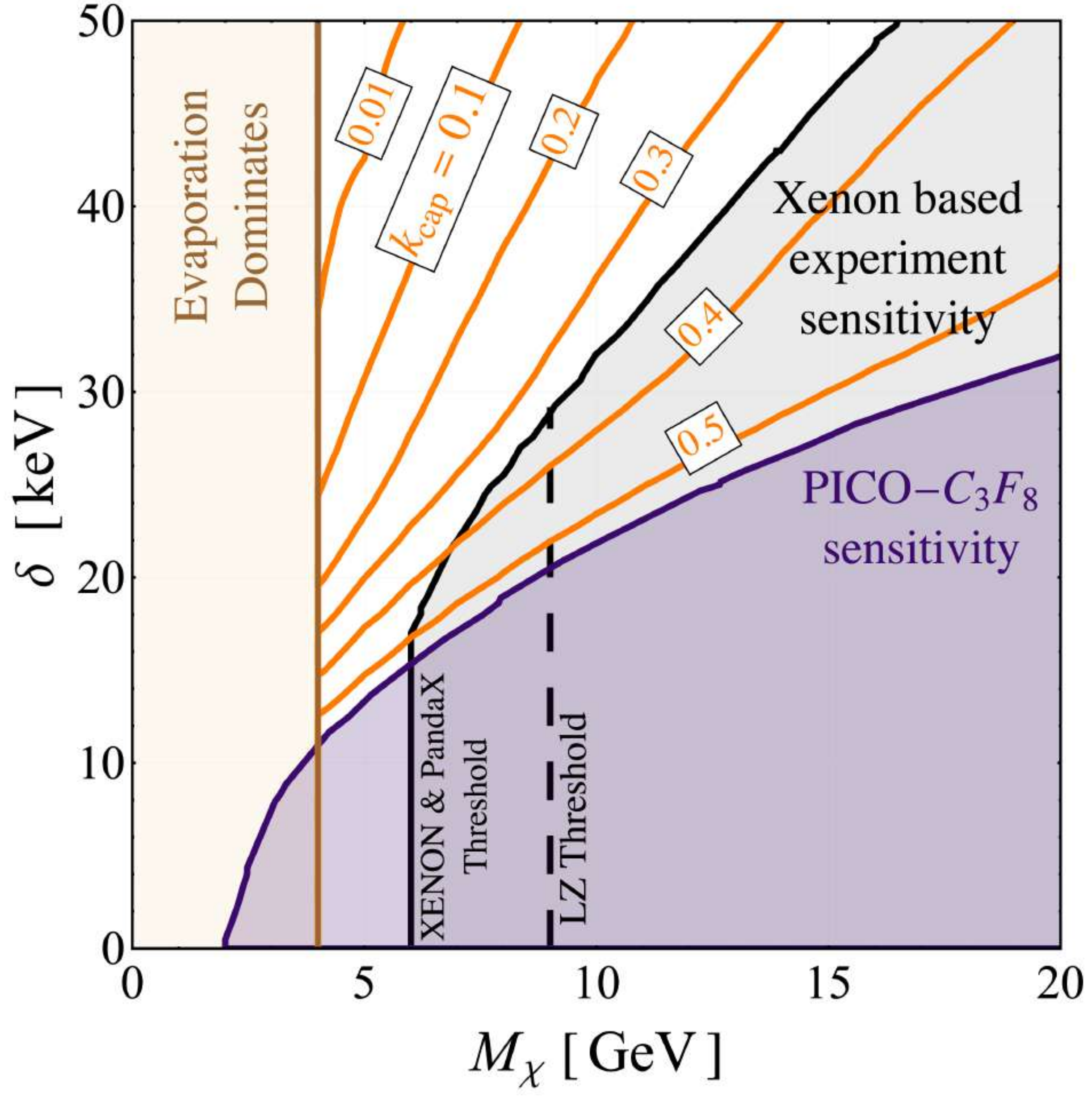
Inelastic Dark Matter - Capture in Sun

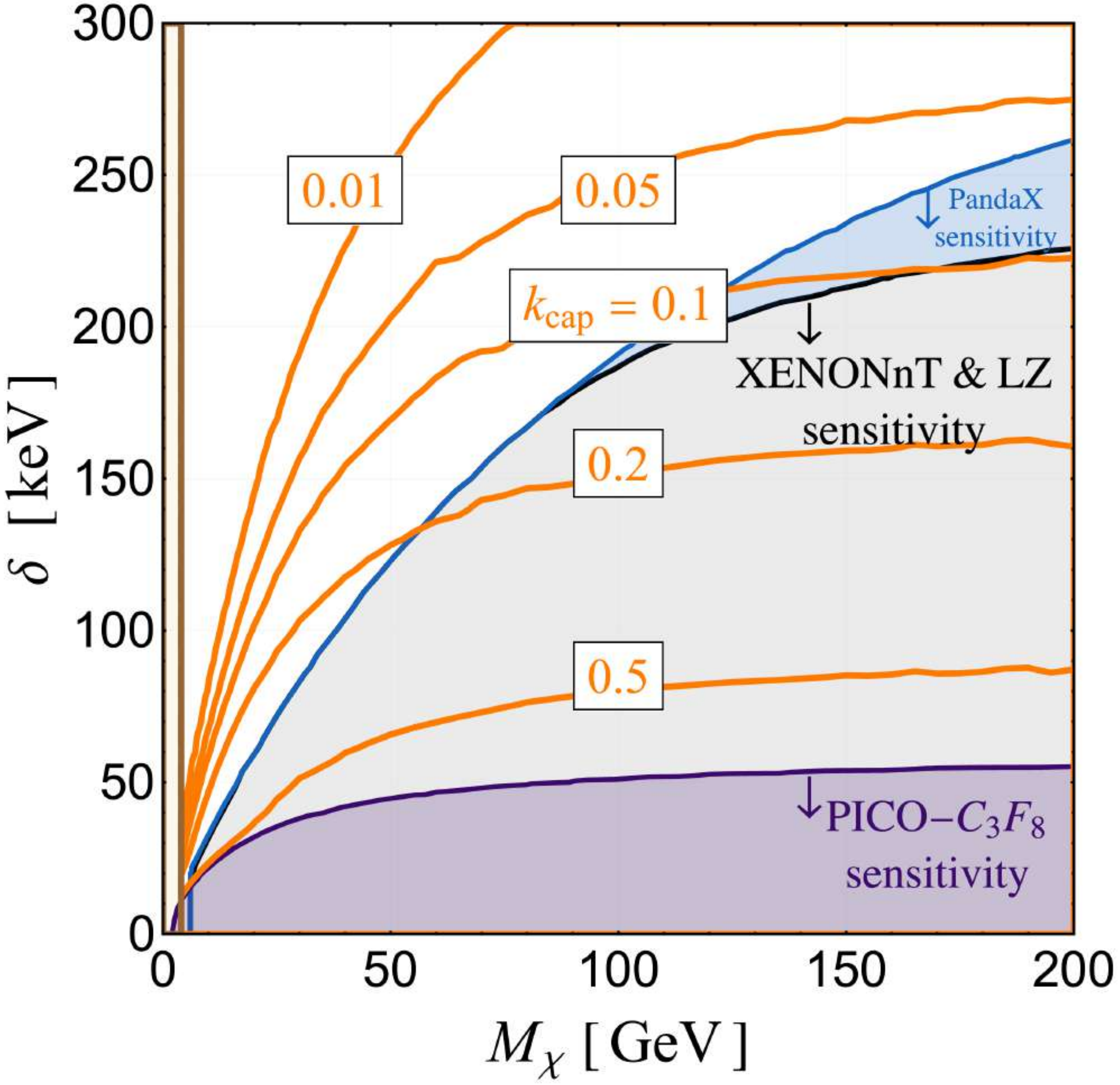
The phase-space for gravitational capture is much smaller for inelastic DM

We evaluate the relative capture rate using method outlined in Blennow et al. *JCAP* 04 (2016) 004

$$k_{\rm cap}(M_\chi, \delta) = \frac{\Gamma_{\rm cap}(M_\chi, \delta)}{\Gamma_{\rm cap}(M_\chi, 0)}$$

Inelastic Dark Matter - Capture in Sun





There exists parameter space where capture isn't drastically suppressed but direct-detection experiments are *insensitive*

Inelastic Dark Matter - Capture in Sun

- The inelasticity parameter δ does not change the neutrino spectrum and only affects the capture rate in the Sun.
- The existing limits on elastic DM from Super-Kamiokande and IceCube can be translated using k_{cap}

$$\sigma^{\text{SI}}_{\text{lim}}(\text{M}_\chi, \delta) = \sigma^{\text{SI}}_{\text{lim}}(\text{M}_\chi) \times \text{k}_{\text{cap}}(\text{M}_\chi, \delta)$$

Limit for Elastic DM

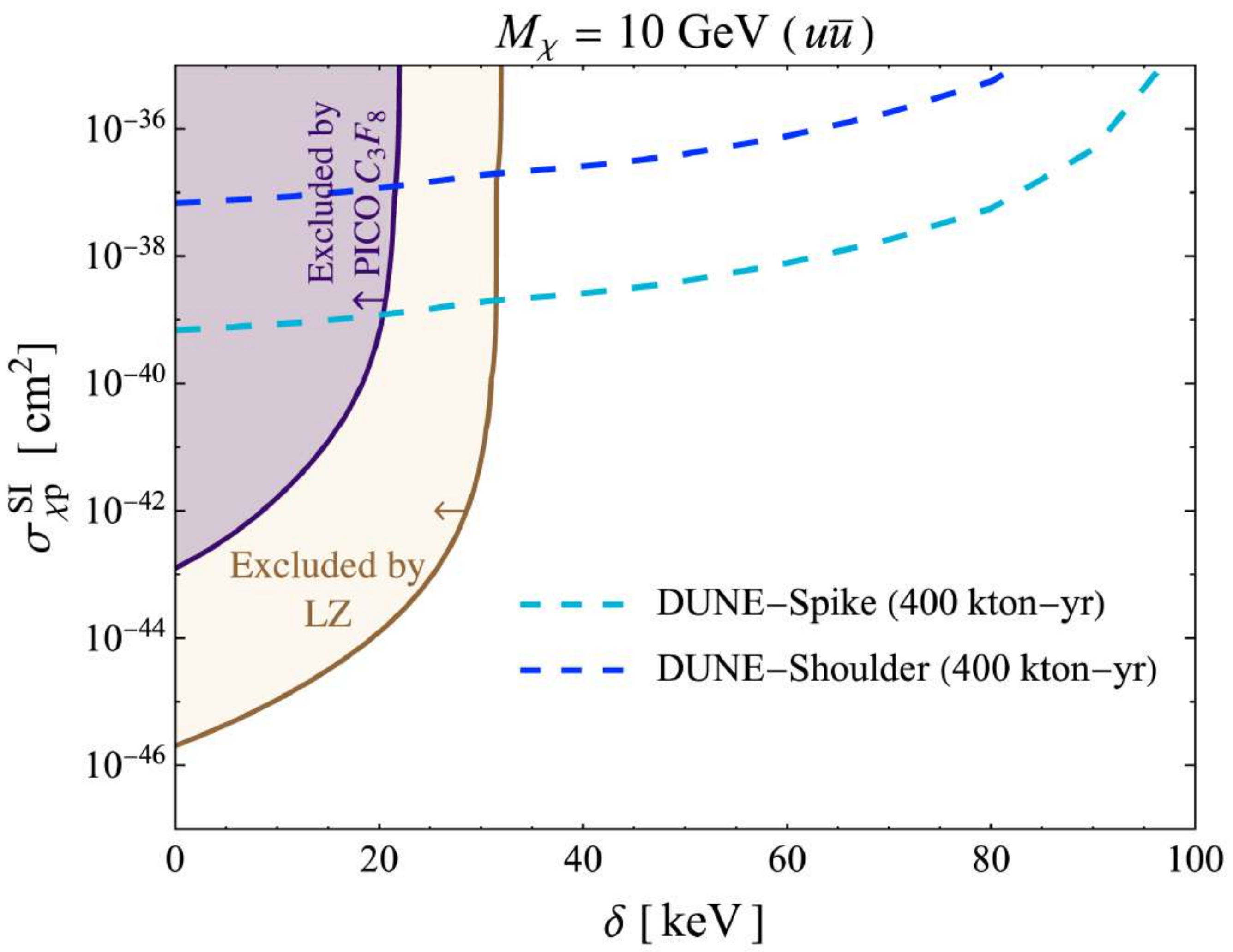
$$\sigma^{\text{SI}}_{\text{lim}}(\text{M}_\chi, \delta) = \sigma^{\text{SD}}_{\text{lim}}(\text{M}_\chi)\,\frac{\Gamma^{\text{SI}}_{\text{cap}}(\text{M}_\chi, \sigma_0)}{\Gamma^{\text{SD}}_{\text{cap}}(\text{M}_\chi, \sigma_0)} \times \text{k}_{\text{cap}}(\text{M}_\chi, \delta)$$

Results

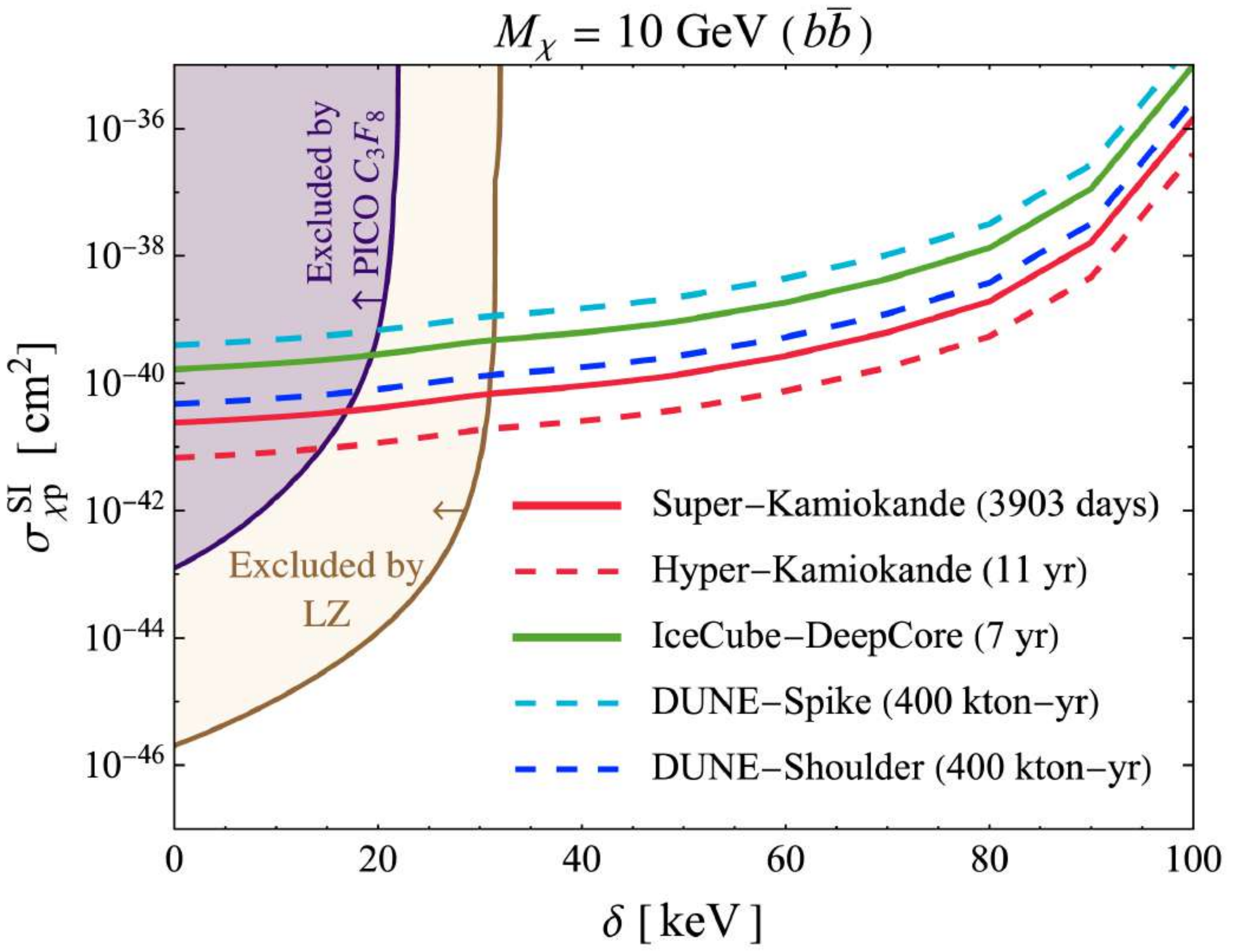
- Three parameters of inelastic dark matter —
    - Mass of dark matter (M_χ),
    - mass-splitting ($\delta = M_2 - M_1$), and
    - spin-independent interaction cross section ($\sigma_{\chi p}^{\mathrm{SI}}$)
- In the following plots, we will show —
    - Mapped existing limits from direct-detection experiments
    - Mapped existing limits from Super-Kamiokande and IceCube
    - Mapped Projected Sensitivity of Hyper-Kamiokande
    - Projected Sensitivity of DUNE:
        — Mapped for Spike
        — Evaluated for Shoulder

This Work

Results : 10 GeV Dark Matter



$M_\chi = 10$ GeV ($u\bar{u}$)



$M_\chi = 10$ GeV ($b\bar{b}$)

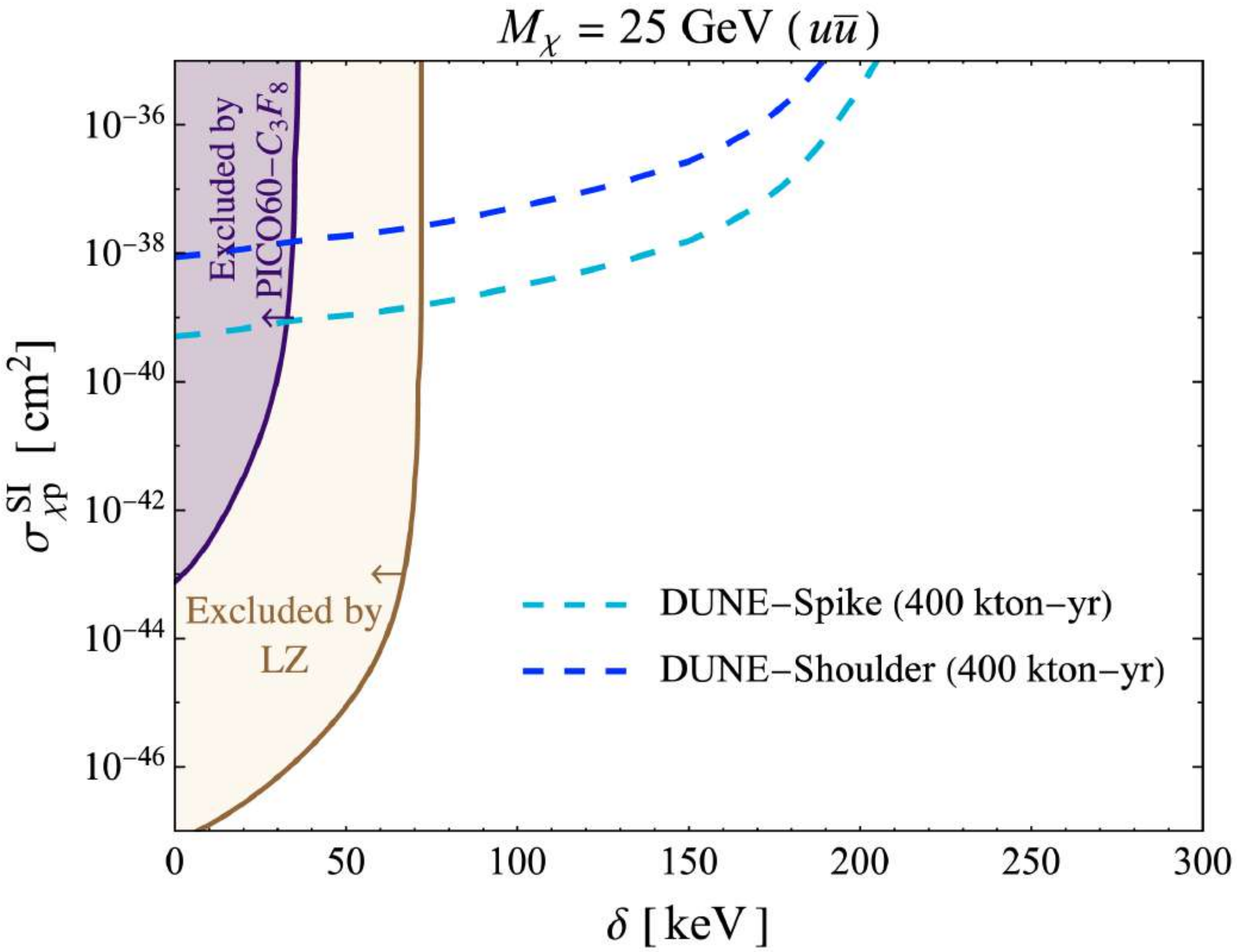
Light Quark Channel

Heavy Quark Channel

Only DUNE will be sensitive

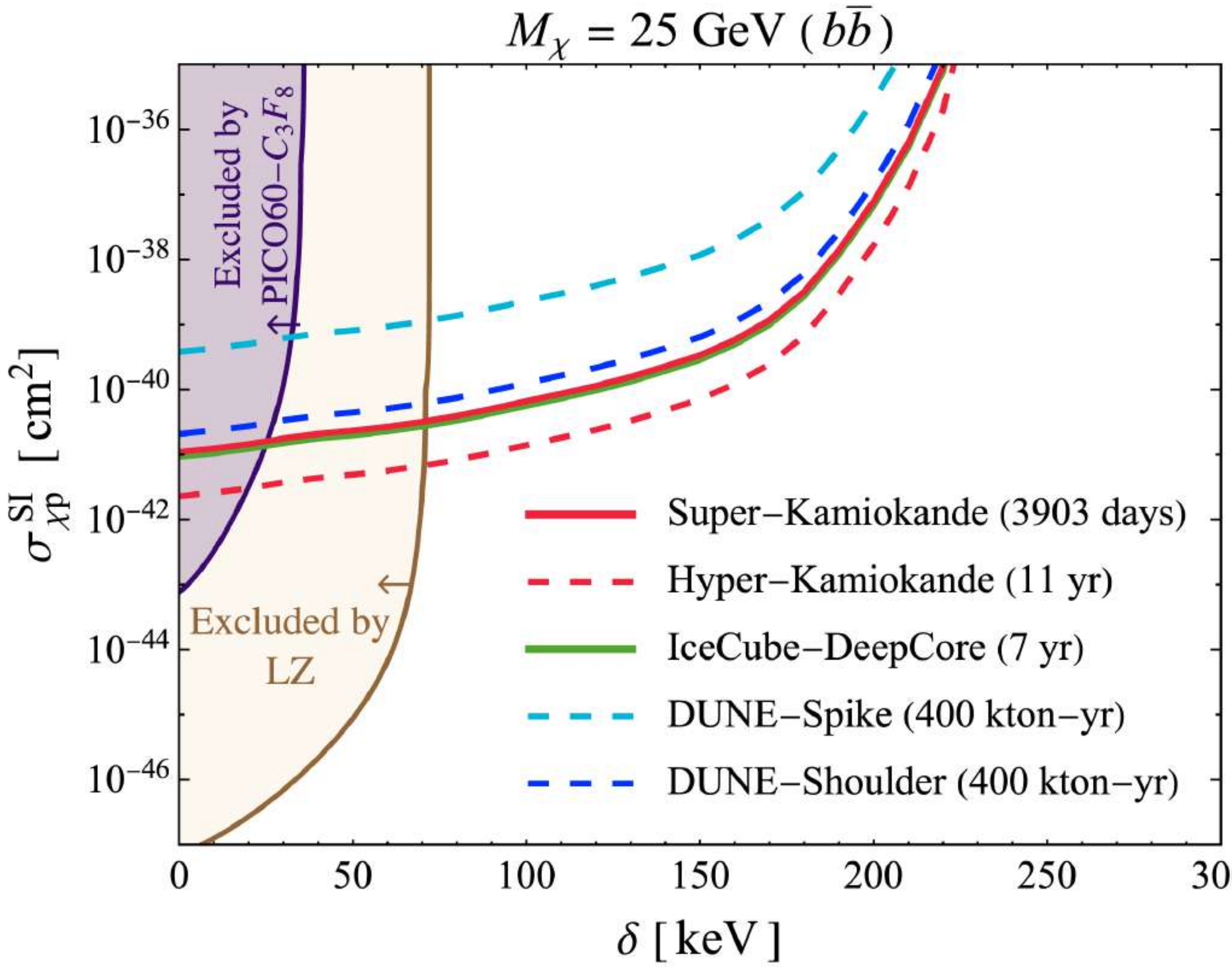
DUNE will not be able to compete with water Cherenkov detectors

Results : 25 GeV Dark Matter



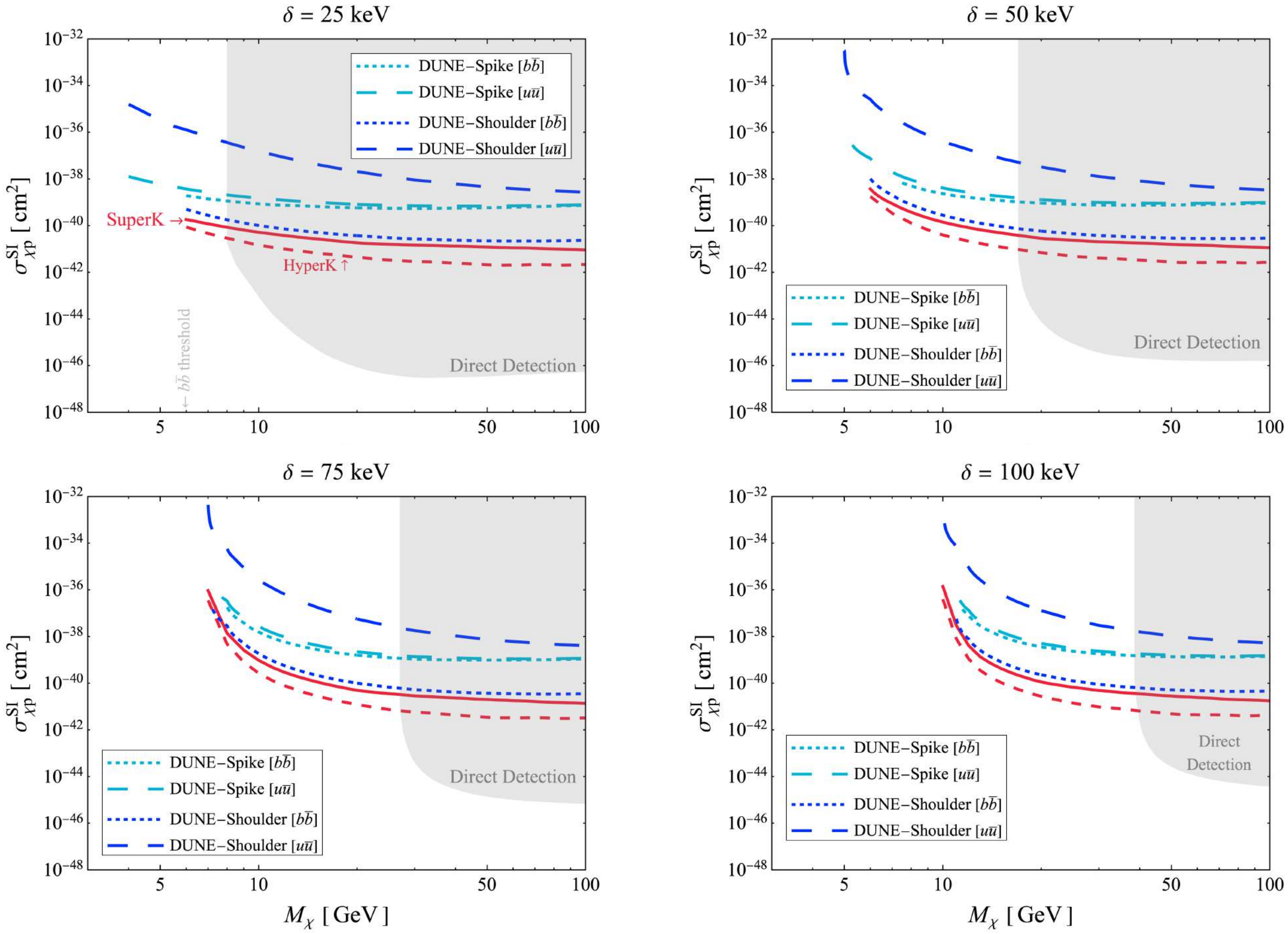
Light Quark Channel

Only DUNE will be sensitive



Heavy Quark Channel

DUNE will not be able to compete with water Cherenkov detectors



$\delta = 25$ keV
$\delta = 50$ keV
$\delta = 75$ keV
$\delta = 100$ keV
DUNE−Spike [$b\bar{b}$]
DUNE−Spike [$u\bar{u}$]
DUNE−Shoulder [$b\bar{b}$]
DUNE−Shoulder [$u\bar{u}$]
SuperK →
HyperK ↑
← $b\bar{b}$ threshold
Direct Detection
Direct Detection
Direct Detection
Direct Detection
$\sigma^{\rm SI}_{\chi p}$ [cm^2]
10^{-32}
10^{-34}
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
5
10
50
100
M_χ [GeV]

Future Directions

Improvements :

- Include the auxiliary particles in the direction reconstruction
- Event-by-event analysis

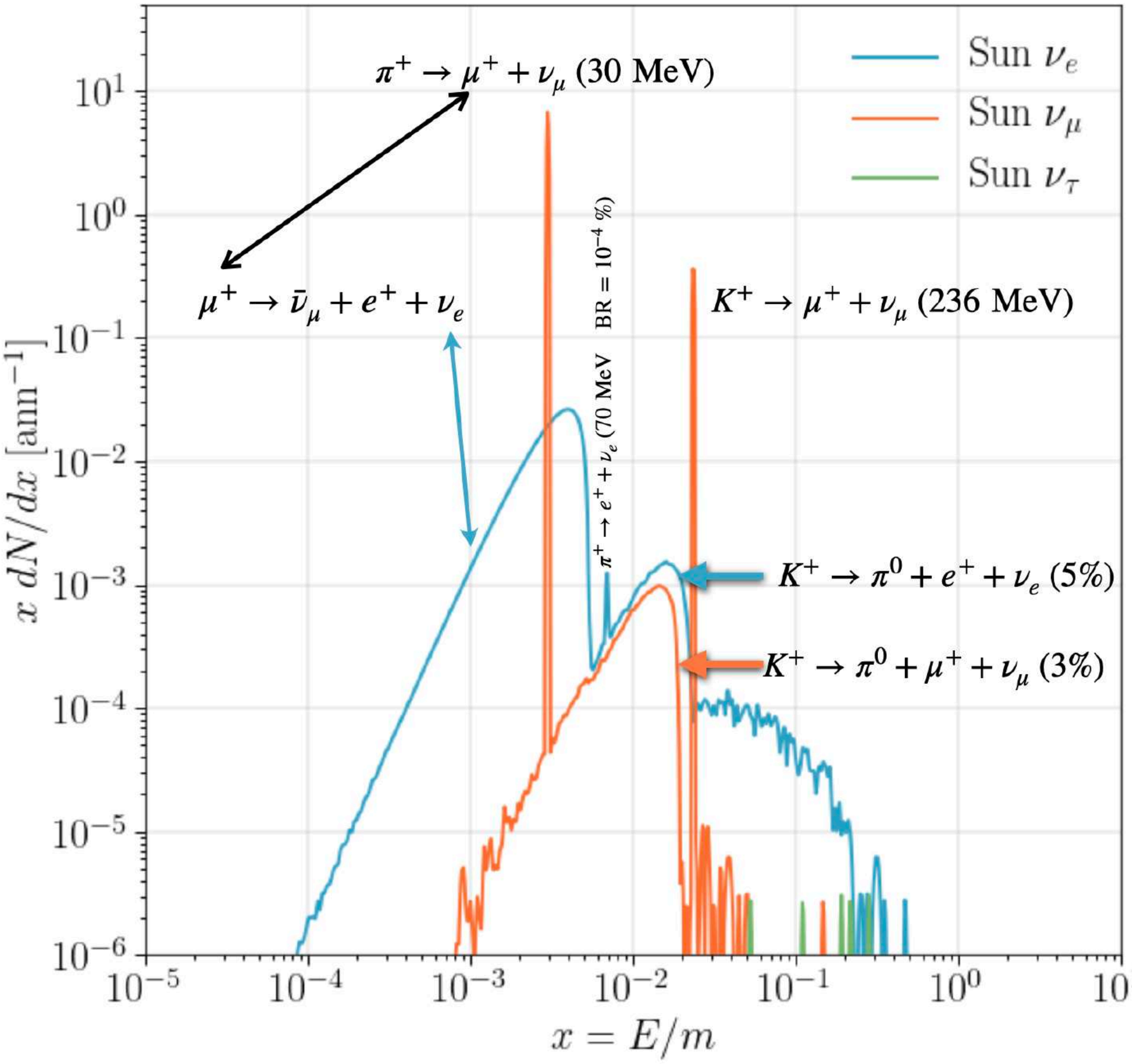
Sources :

- Inelastic Dark Matter in the Halo
- Non-galactic component

Summary and Outlook

- Large volume underground neutrino detectors (such as IceCube, Super/Hyper-Kamiokande, DUNE, …) can search for high energy neutrinos from the direction of the Sun.
- We find that the neutrino constraints on inelastic dark matter captured in the Sun are stronger than direct-detection experiments for low-mass dark matter.
- The water/ice Cherenkov detectors have better sensitivity to shoulder neutrinos, so they are important for heavy-quark channel.
- Only DUNE will be sensitive to dark matter annihilation to light-quarks through spike-neutrinos
- Current limits do **NOT** rule out the possibility of low-mass inelastic dark matter that couples only to light-quarks, and DUNE can test this scenario.

Backup


Sun ν_e
Sun ν_μ
Sun ν_τ
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ (30 MeV)
$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$
$\pi^+ \rightarrow e^+ + \nu_e$ (70 MeV BR = 10^{-4} %)
$K^+ \rightarrow \mu^+ + \nu_\mu$ (236 MeV)
$K^+ \rightarrow \pi^0 + e^+ + \nu_e$ (5%)
$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$ (3%)
$x\, dN/dx$ [ann^{-1}]
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
$x = E/m$