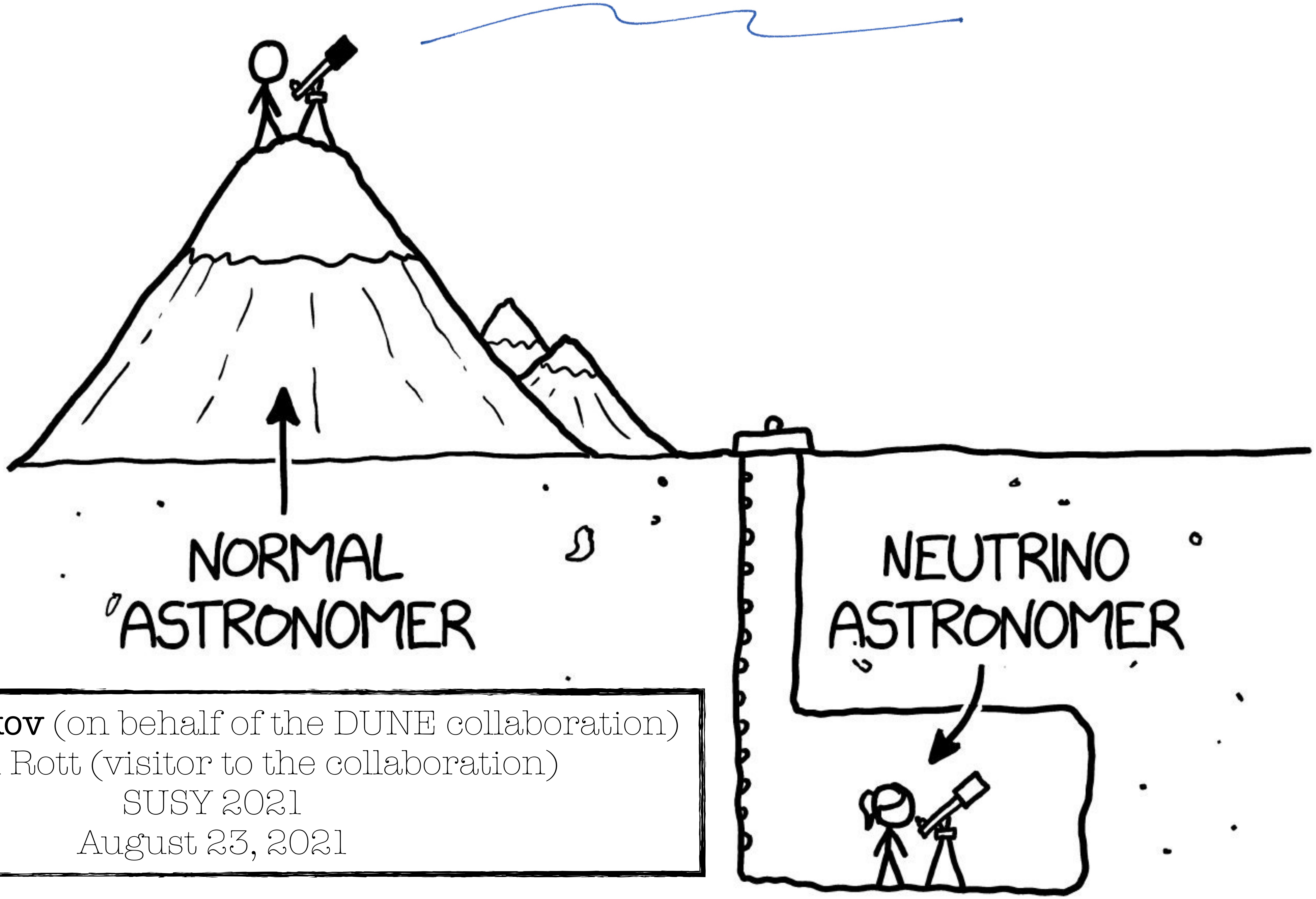
DEEP UNDERGROUND NEUTRINO EXPERIMENT

# Searching for Solar Kaon-decay-at-rest (KDAR)

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Carsten Rott (visitor to the collaboration)
SUSY 2021
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arXiv: 2107.09109
Submitted to JCAP

Image Credit:
The New York Times, Randall Munroe (July 7, 2020)

# Outline

- What is DUNE?
- Solar Kaon-decay-at-rest (KDAR) Explanation
- DUNE Simulation & Reconstruction
- Signal Kinematics & Search Strategy
- Atmospheric Background
- Solar KDAR Flux
- Application: Search for Inelastically Scattered Dark Matter
- Summary

# DUNE

(Deep Underground Neutrino Experiment)

An observatory of accelerator and cosmic neutrinos.

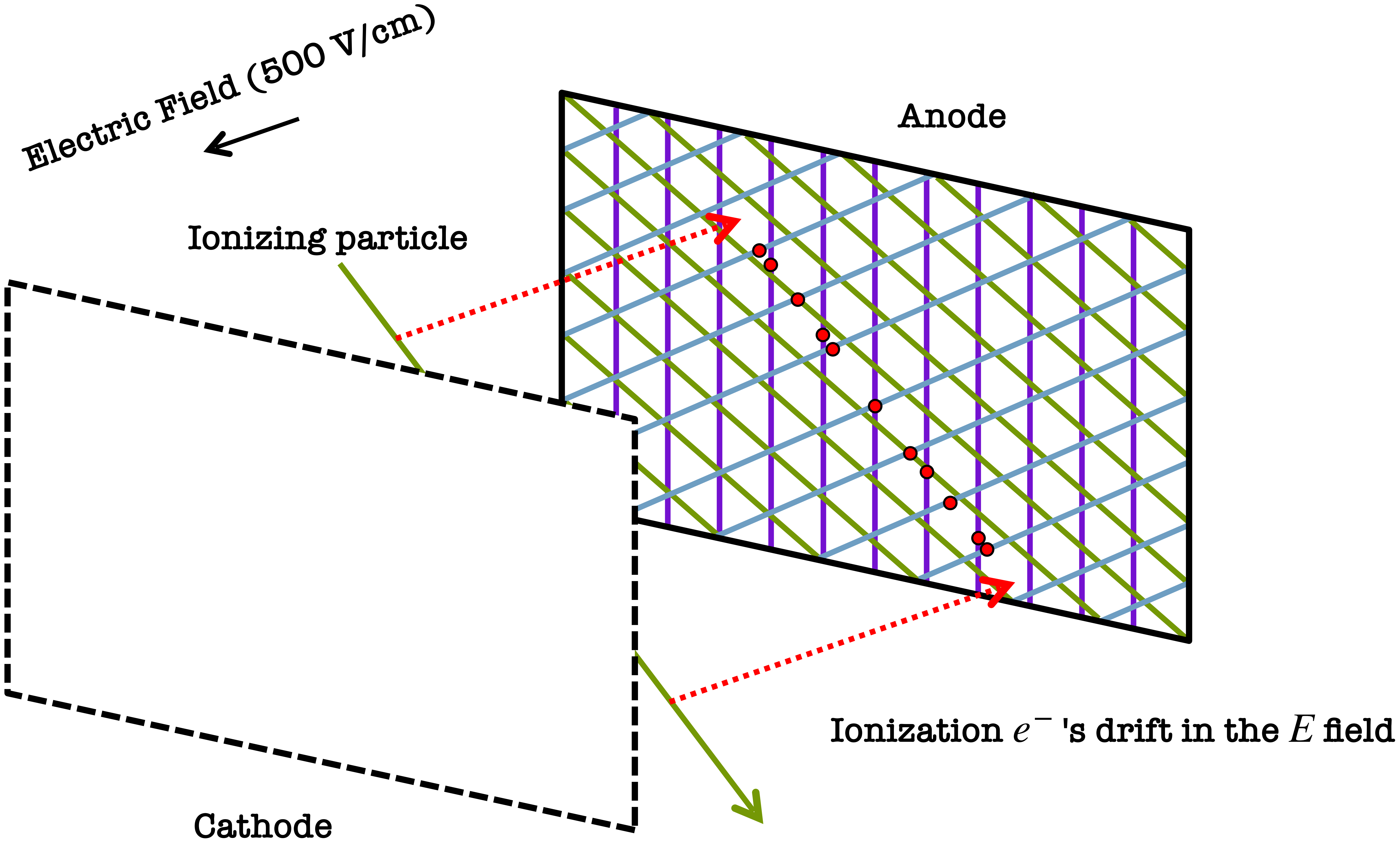
4 far detector modules deployed in stages
17 kton each (total LAr mass)
1.5 km underground

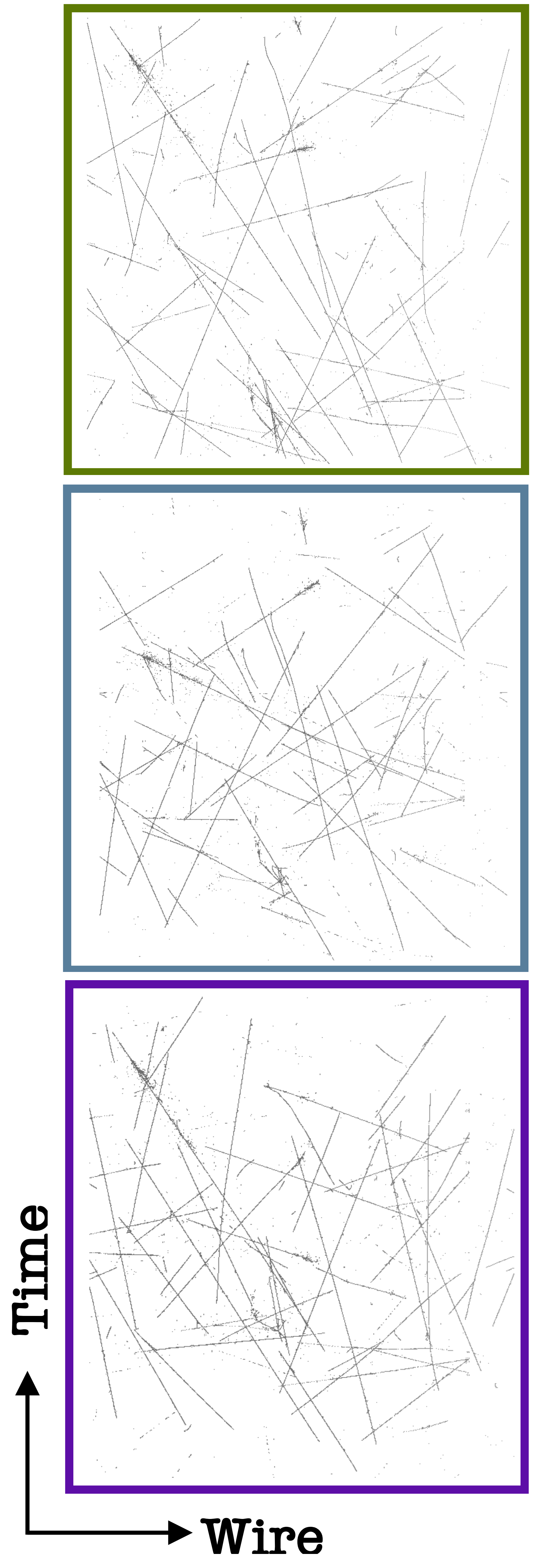
DUNE will study $\nu$ oscillations , the $\nu$ mass hierarchy and search for $\delta_{CP}$.
$\nu$'s will travel 1,300km between Fermilab and South Dakota.

DUNE  will also look for solar and supernova $\nu$'s and test BSM physics.
(Sterile $\nu$'s, DM, Baryon Number Violation, etc.)

Sandbox Studio, Pedro Rivas (2019)

# What is a Liquid Argon Time Projection Chamber (LArTPC)?



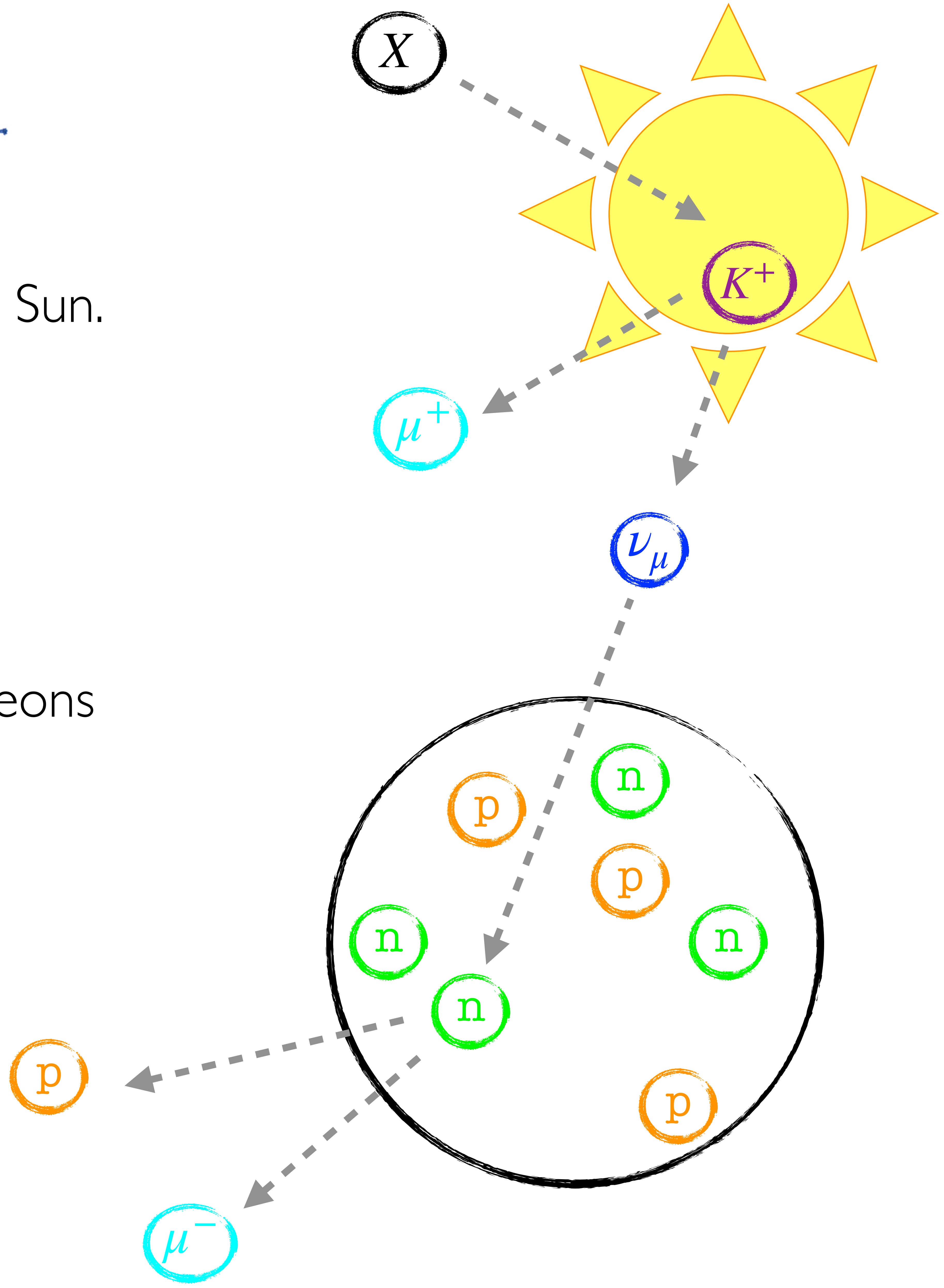




- Additionally, photon detectors are used for triggering and calorimetry (to supplement the charge gathered on the wires).

"Neutrino Event Reconstruction in DUNE using Pandora"
Leigh Whitehead, ICHEP Conference 2020

# KDAR: Very Briefly

1. Dark matter scatters off solar nuclei and collects in the core of the Sun.
2. Annihilates to Standard Model quarks which then hadronize.
3. Resulting $K^{+}$'s decay at rest to mono-energetic $\nu_{\mu}$'s (236 MeV).
4. $\nu_{\mu}$'s get out, reach the Earth, and interact quasi-elastically with nucleons in DUNE.
5. Sometimes a $\mu^{-}$ and a $p$ pop out.



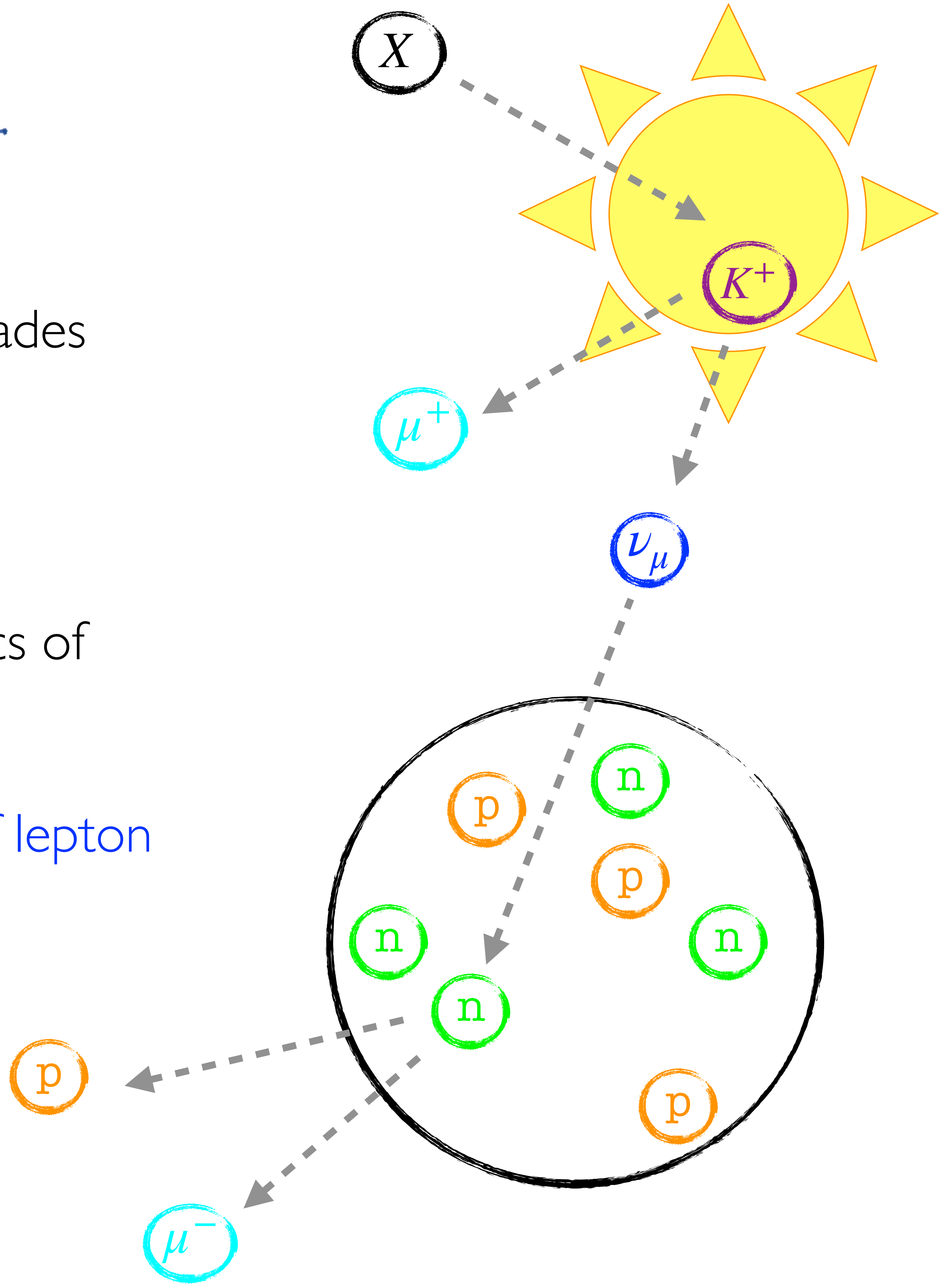


Refs:
R. Lehnert and T. Weiler, Phys. Rev. D77, 125004 (2008)
C. Rott et al JCAP11 (2015) 039
C.Rott et al JCAP01 (2017) 016
MiniBooNE Collaboration, Phys. Rev. Lett. 120, 141802 (2018)

# KDAR: More Details

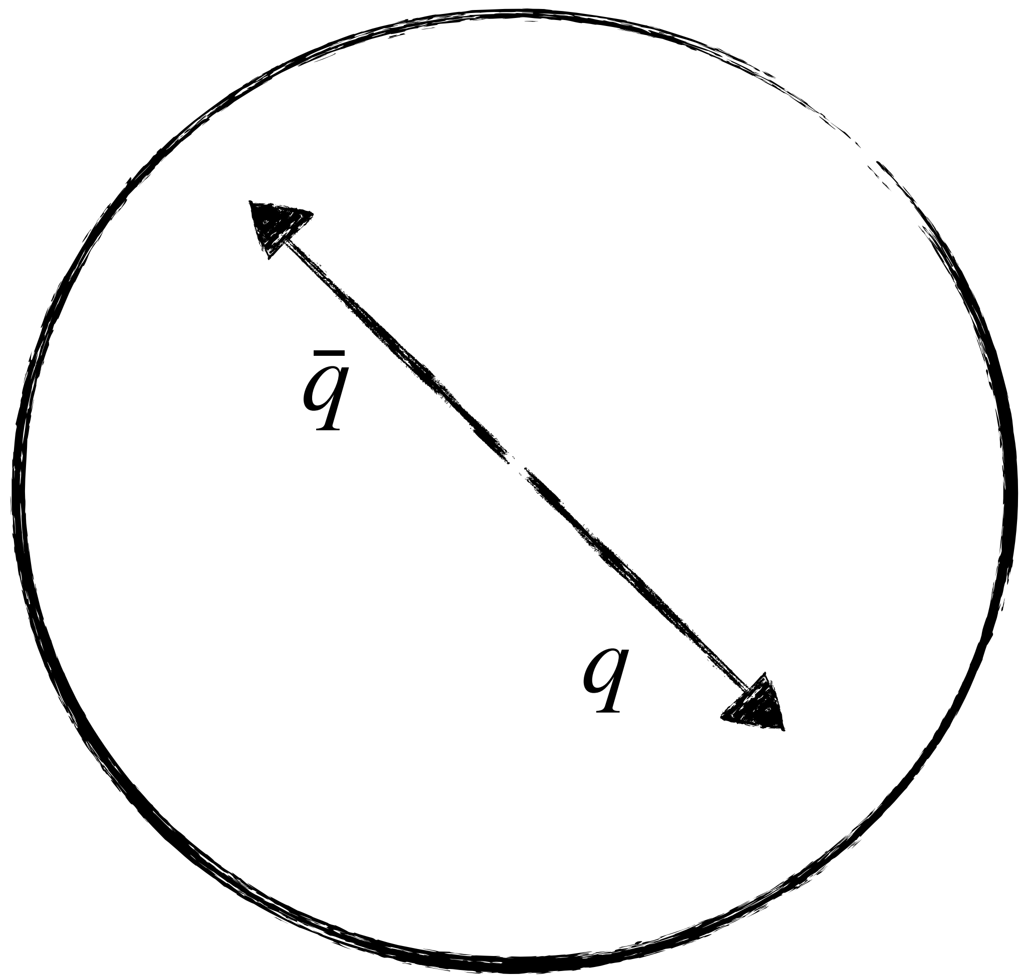
- u, d, s final state quarks produce plenty of $K^+$ through hadronic cascades
- light hadrons stop in the Sun before decaying
- kaon-decay-at-rest (KDAR) produces 236 MeV mono-energetic $\nu$'s

- DUNE carries a promising potential for reconstructing the kinematics of charged-current (CC) interactions
- sensitive to a line signal
- can get the direction of the $\nu$ from the nucleon recoil, correlation of lepton with nucleon
  - novel directionality search
  - reduces systematic uncertainty

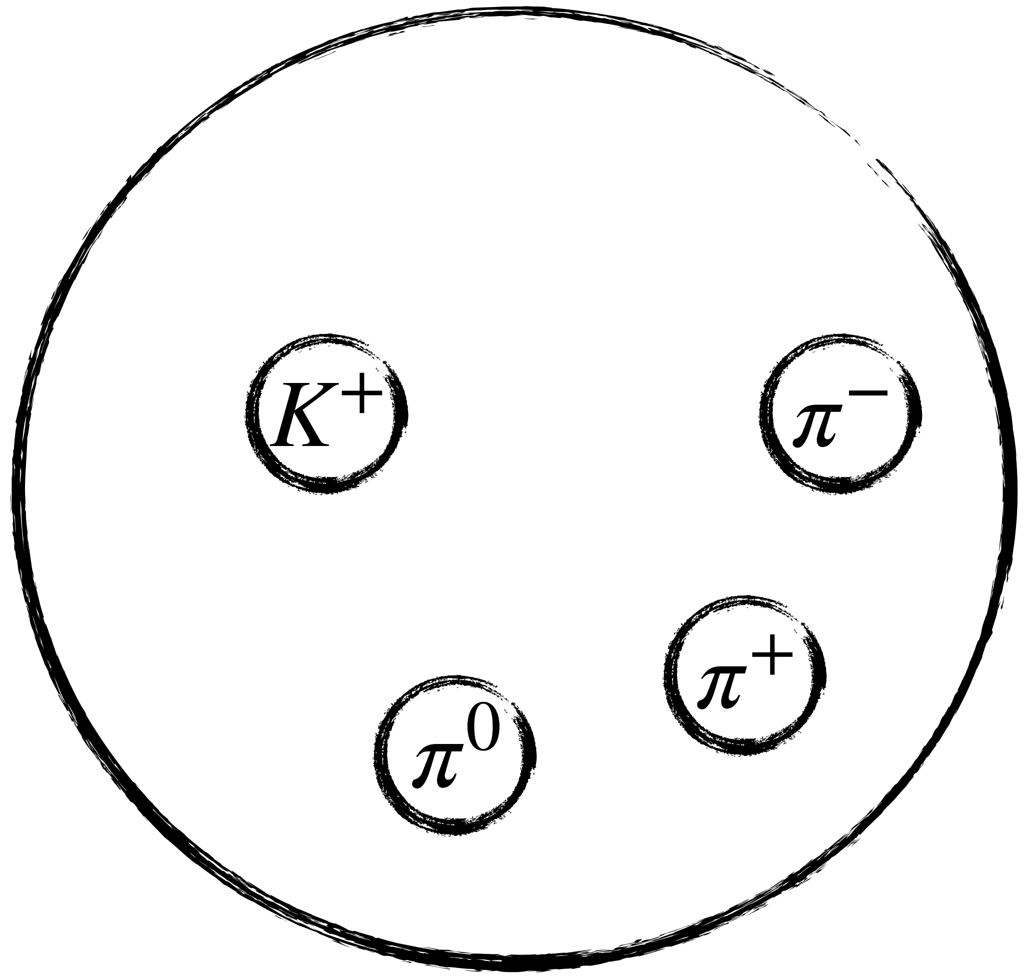


# 236 MeV $\nu$'s from the Sun

- u, d, s final states are light hadrons and have a hard spectrum
  - stop in the Sun before decaying
  - resulting $\nu$ spectrum is very soft
  - measurement subject to a large background, small detector effective area




- BUT, the stopping process produces numerous $\pi$'s, $K$'s
  - trade a hard spectrum for a softer one, with a larger flux

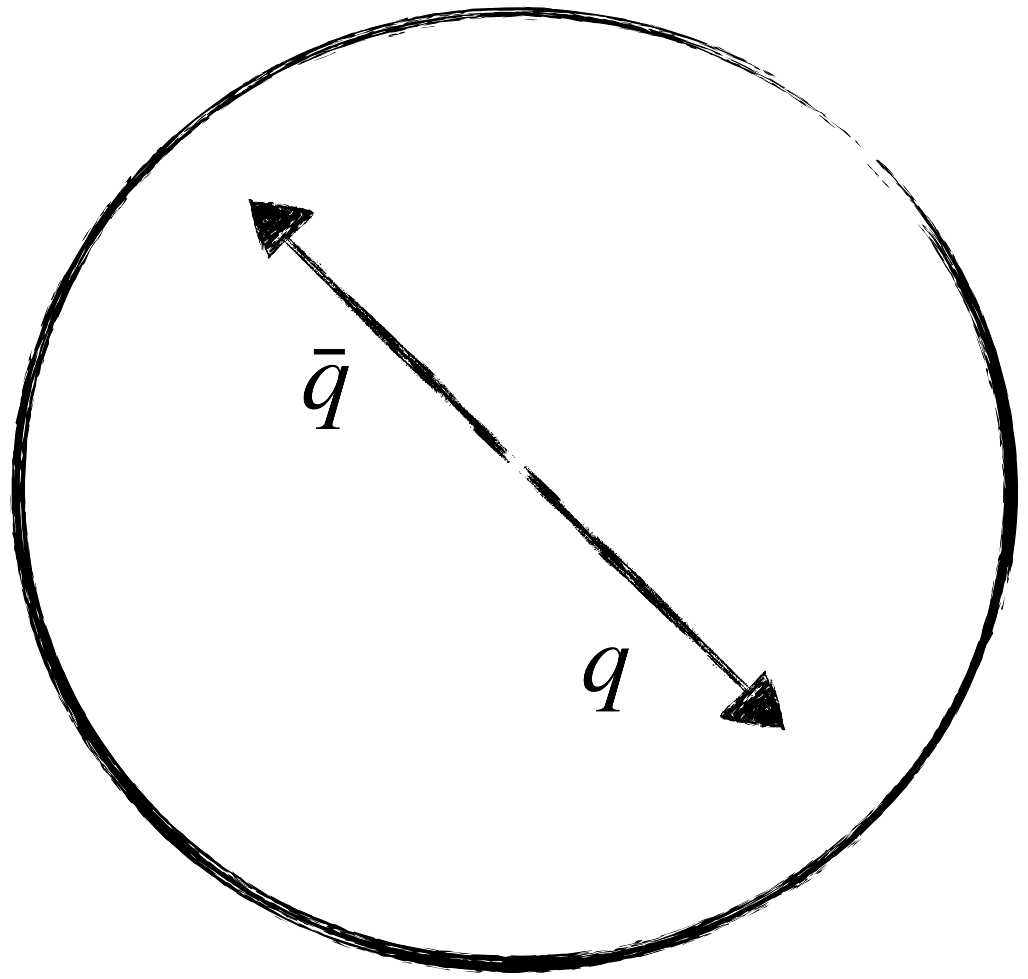




Refs:
Rott, Siegal-Gaskins, Beacom, Phys.Rev. D 88, 055005 (2013)
N. Bernal et al JCAP08 (2013) 011

## Mono-energetic $\nu$'s

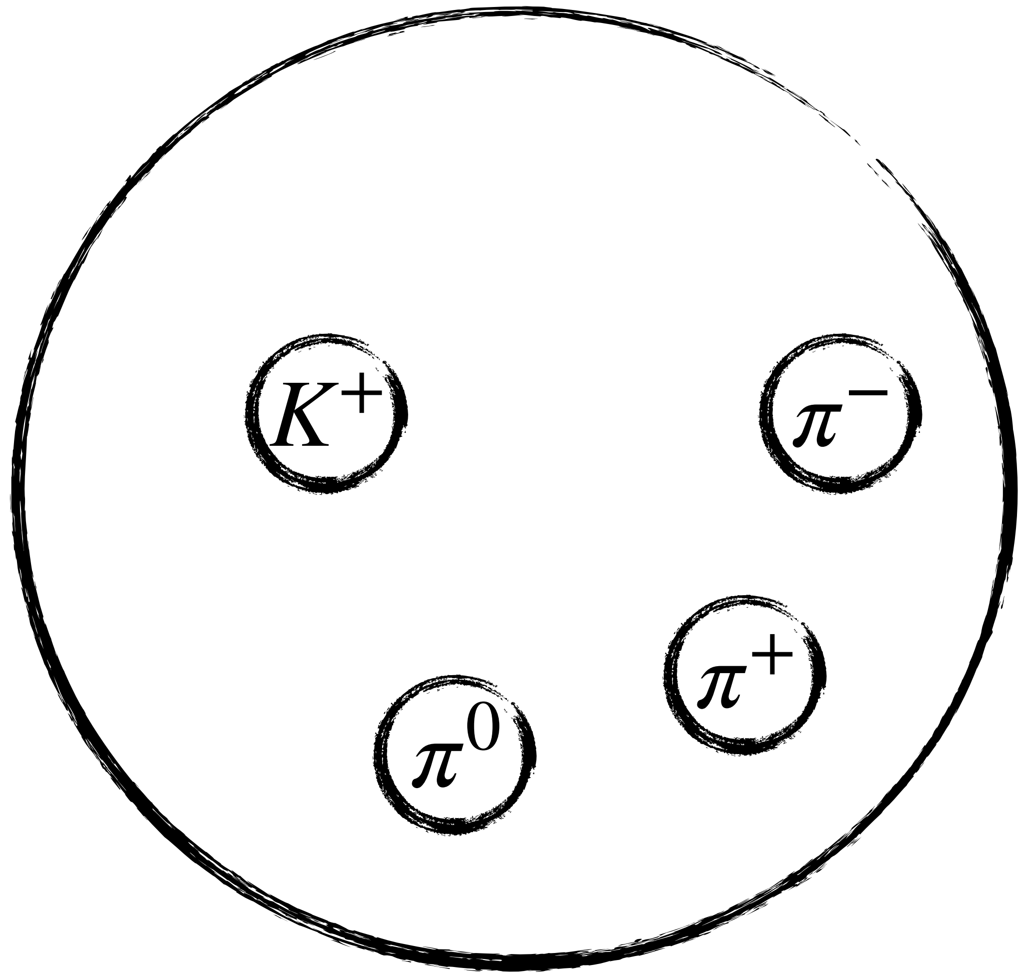
- Care about $\pi^+$ and $K^+$
- $\pi^0 \to \gamma\gamma$
- $\pi^-, K^-$ Coulomb-captured by nuclei (not a lot of $\nu$'s)




- Promising decays are $\pi^+, K^+ \to \nu_\mu \mu^+$
- mono-energetic $\nu$ of $E = 29.8$ MeV ($\pi^+$ − 100 %) or 235.5 MeV ($K^+$ − 64 %)
- line signal (including oscillations)

- Focus on $K^+ \to \nu_\mu \mu^+$
- much larger cross section (offsets the smaller number of $K$'s per annihilation)

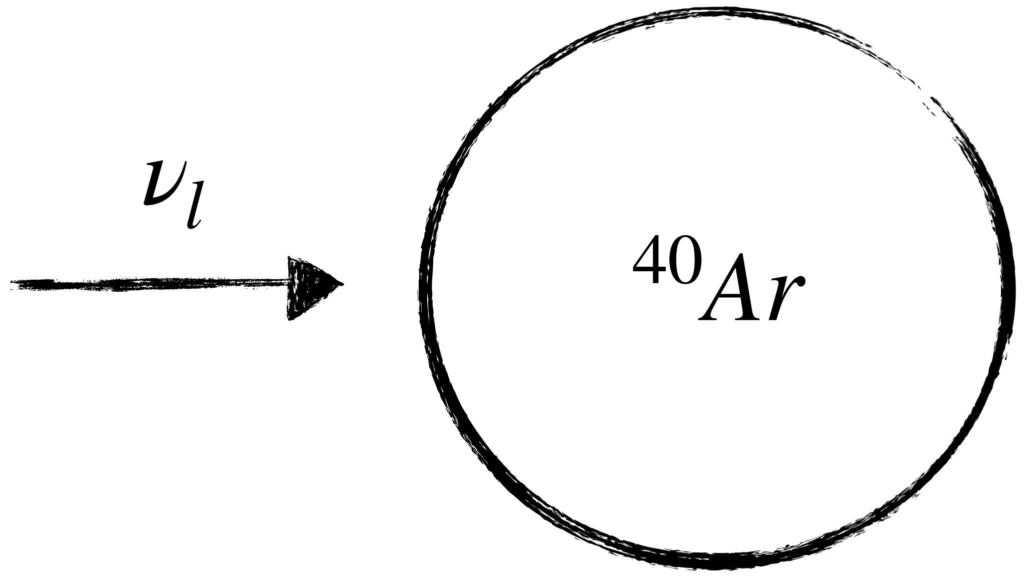
- Fraction of DM energy going into the stopped $K^+$'s found in a previous paper.
- used Pythia to simulate showering and hadronization and output the spectra of long-lived hadrons
- used GEANT for interactions in the dense solar medium





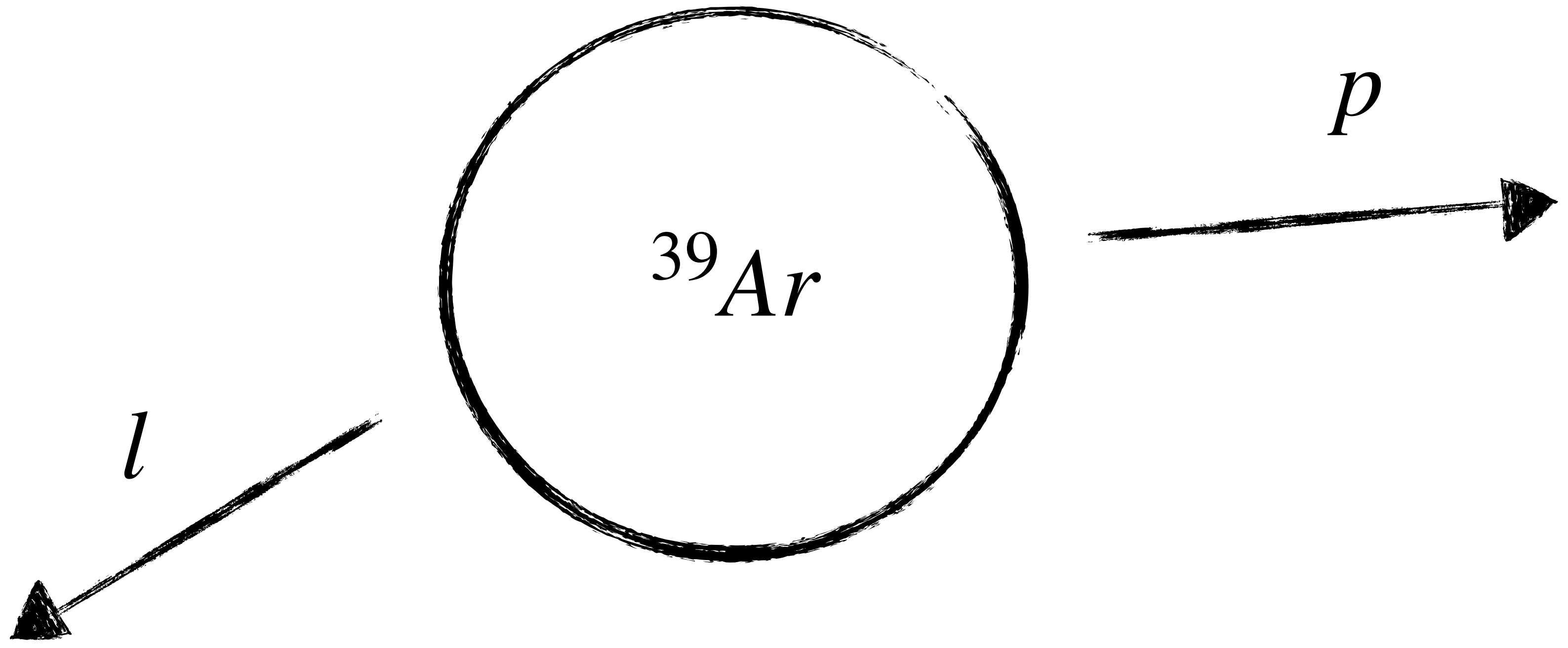
Refs:
C. Rott et al JCAP11 (2015) 039

# Sub-GeV $\nu$ Directionality




- Atmospheric $\nu$'s are a significant background for DUNE
  - select only the $\nu$'s arriving from the Sun
  - compare on-axis and off-axis rates to reduce systematic uncertainties and improve statistical significance

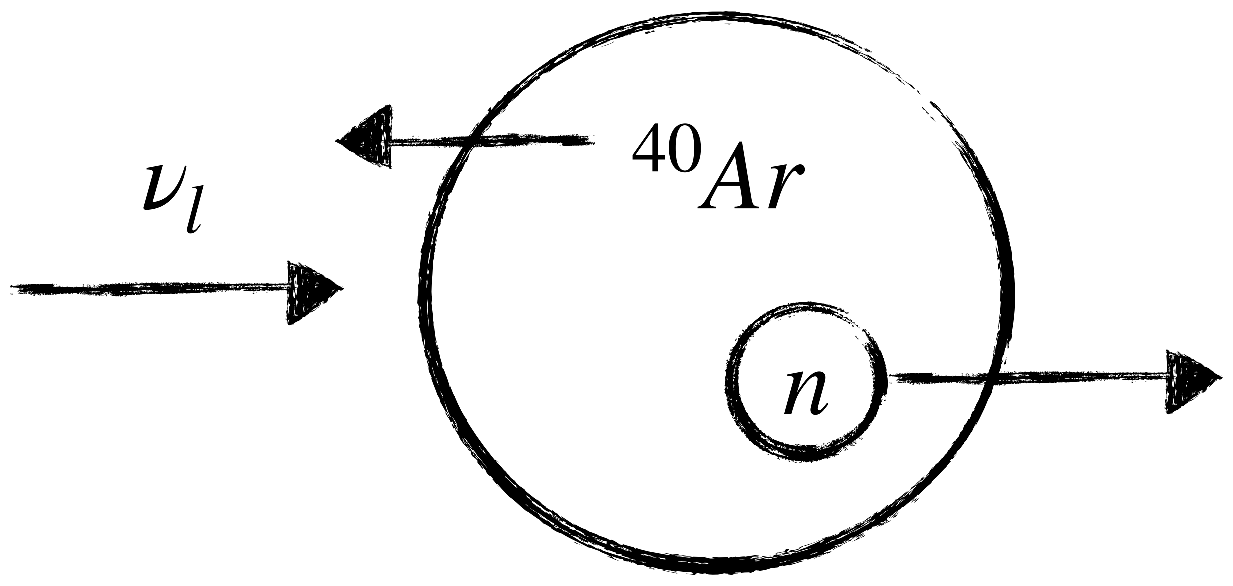
- Search proposals for $\nu$'s arising from DM annihilation often invoke directionality.
  - BUT, in a different energy range where a very energetic $\nu$ CC interaction ejects a forward-peaked charged lepton
  - for sub-GeV $\nu$'s, the charged lepton is mostly isotropic
  - BUT, the hadronic recoil is not!

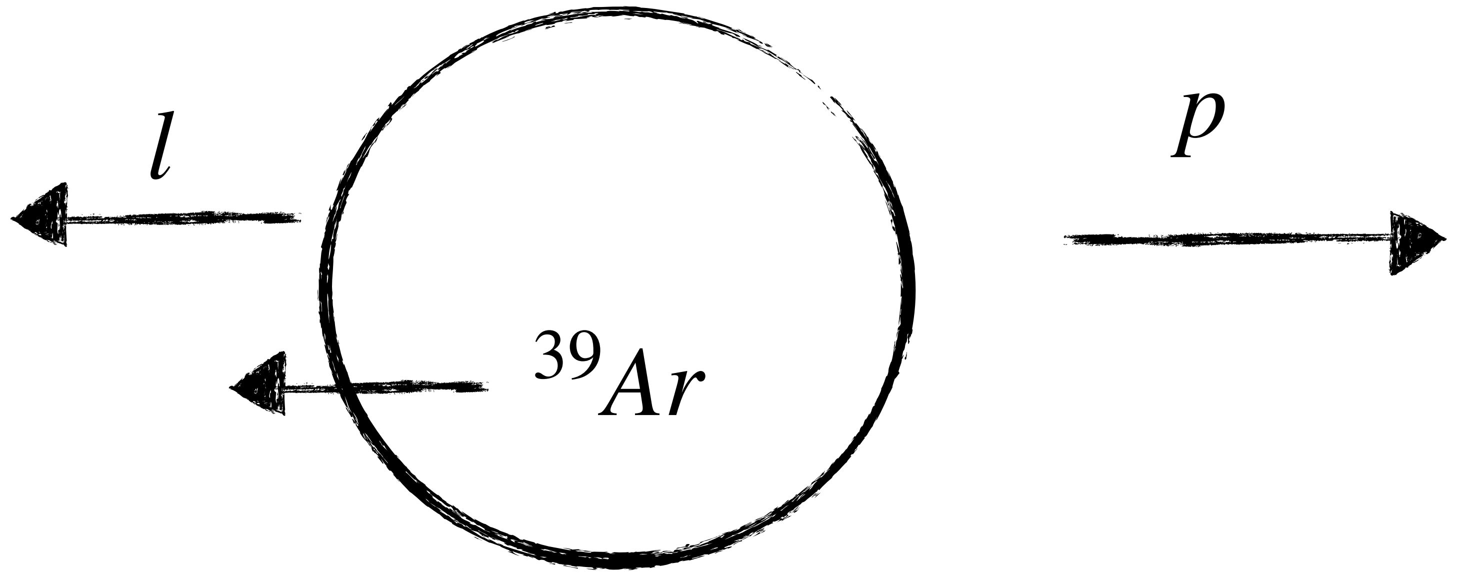



- At 236 MeV $\nu$ often ejects a proton
  - $\nu_l + {}^{40}Ar \rightarrow l + p + {}^{39}Ar$
  - the proton is forward directed (useful cut)

# Nuclear Backscatter

- when an ejected p is very forward, the struck nucleon is preferentially moving away from the Sun and the rest of the nucleus is moving towards the Sun
  - analytical approximations to the cross sections and angular distributions are uncertain and lacking < GeV.
  - rely on numerical techniques (**NuWro** Generator)
  - **NuWro** uses a spectral function for the nucleus, rather than the Fermi Gas model. Final state interactions are modeled with an intra-nuclear cascade (INC).



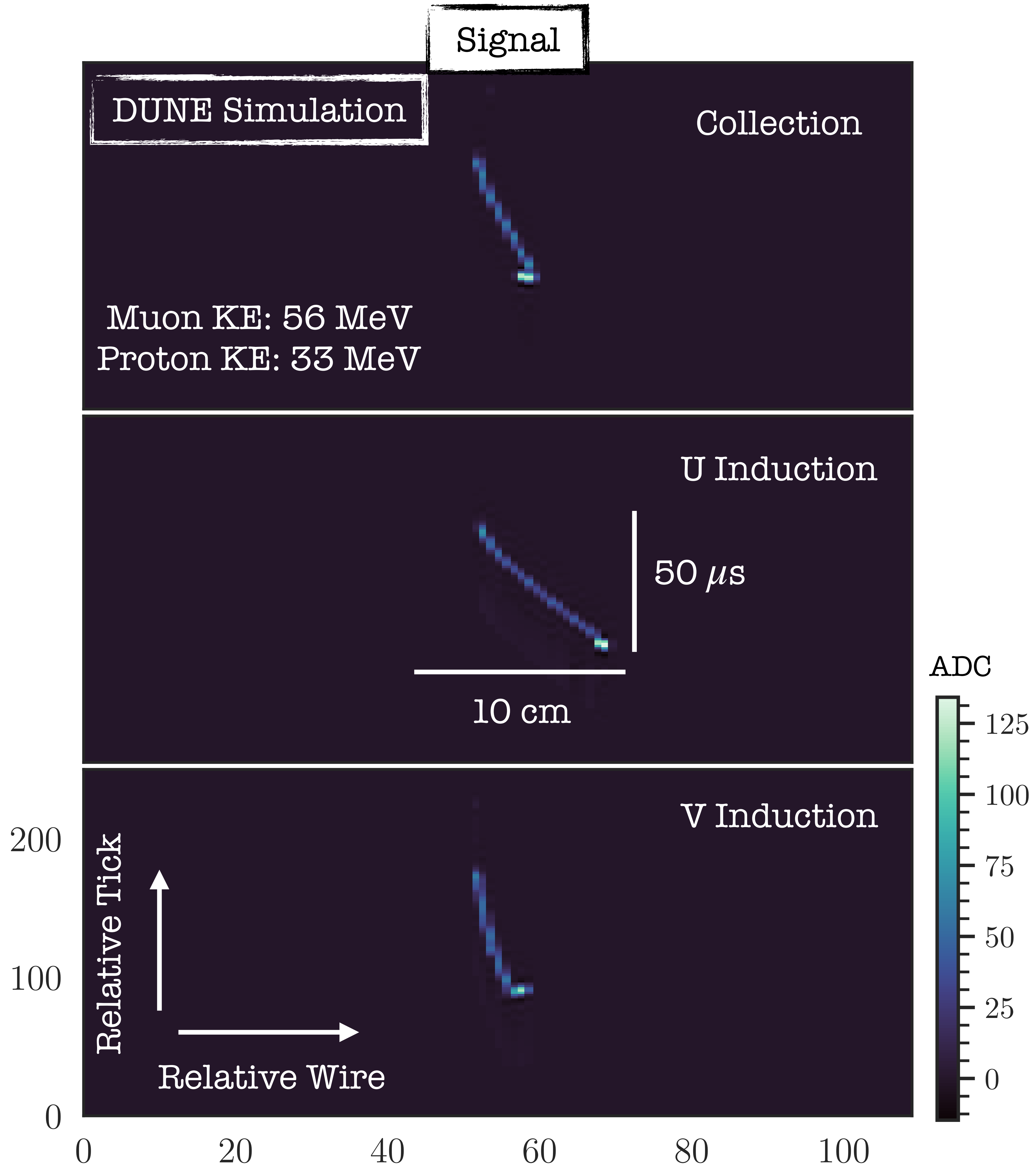

- cannot measure the remnant nucleus but can define an observable $\theta_N$
- sensitive to the nuclear scattering model and DUNE's energy and angular resolutions
- if the incoming $\nu_\mu$ came from the Sun with an energy of 236 $\mathbf{MeV}$ then $\theta_N$ would be the angle between the reconstructed remnant nucleus momentum and the direction of the Sun

$$\vec{p}_{^{39}Ar} \equiv (236\,\mathrm{MeV})\hat{p}_\odot - \vec{p}_\mu - \vec{p}_p$$

$$\cos\theta_N \equiv \hat{p}_\odot \cdot \left(\vec{p}_{^{39}Ar} / |\vec{p}_{^{39}Ar}|\right)$$

# Simulation & Reconstruction

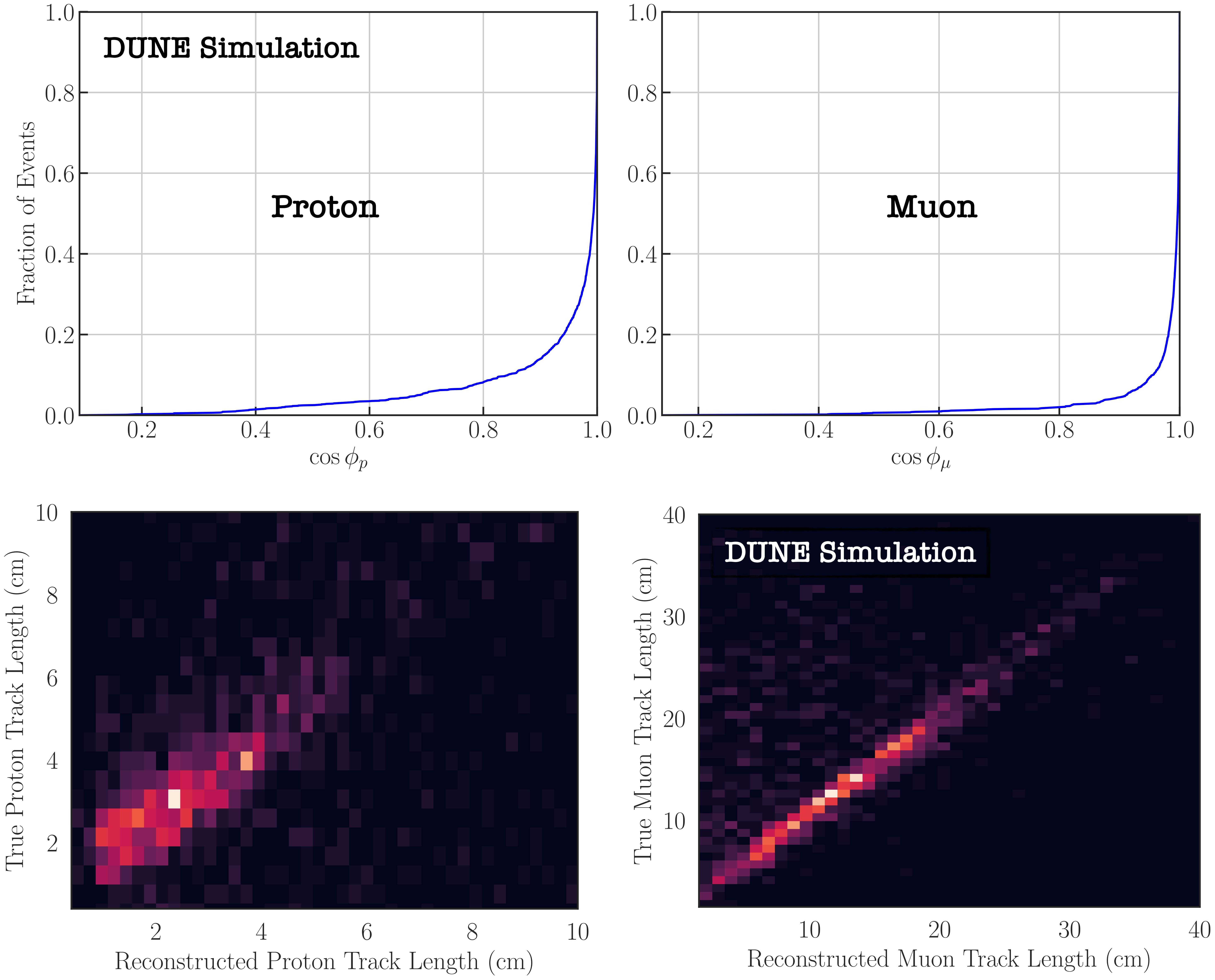
- We simulate signal (arriving from the Sun) and background (atmospheric) events with the *NuWro* generator.
- Ejected particles are propagated in the detector with *GEANT4*.
- The detector response is simulated with the *LArSoft (Liquid Argon Software)* package and the signals are reconstructed with the *Pandora* pattern recognition software.




Time (ticks) vs. wire (number) view of a incoming $\nu_\mu$ of 236 MeV knocking out a $\mu^-$ and a $p$ at DUNE. The $\mu^-$ leaves a longer ionization trail. Each panel corresponds to an individual wire plane.

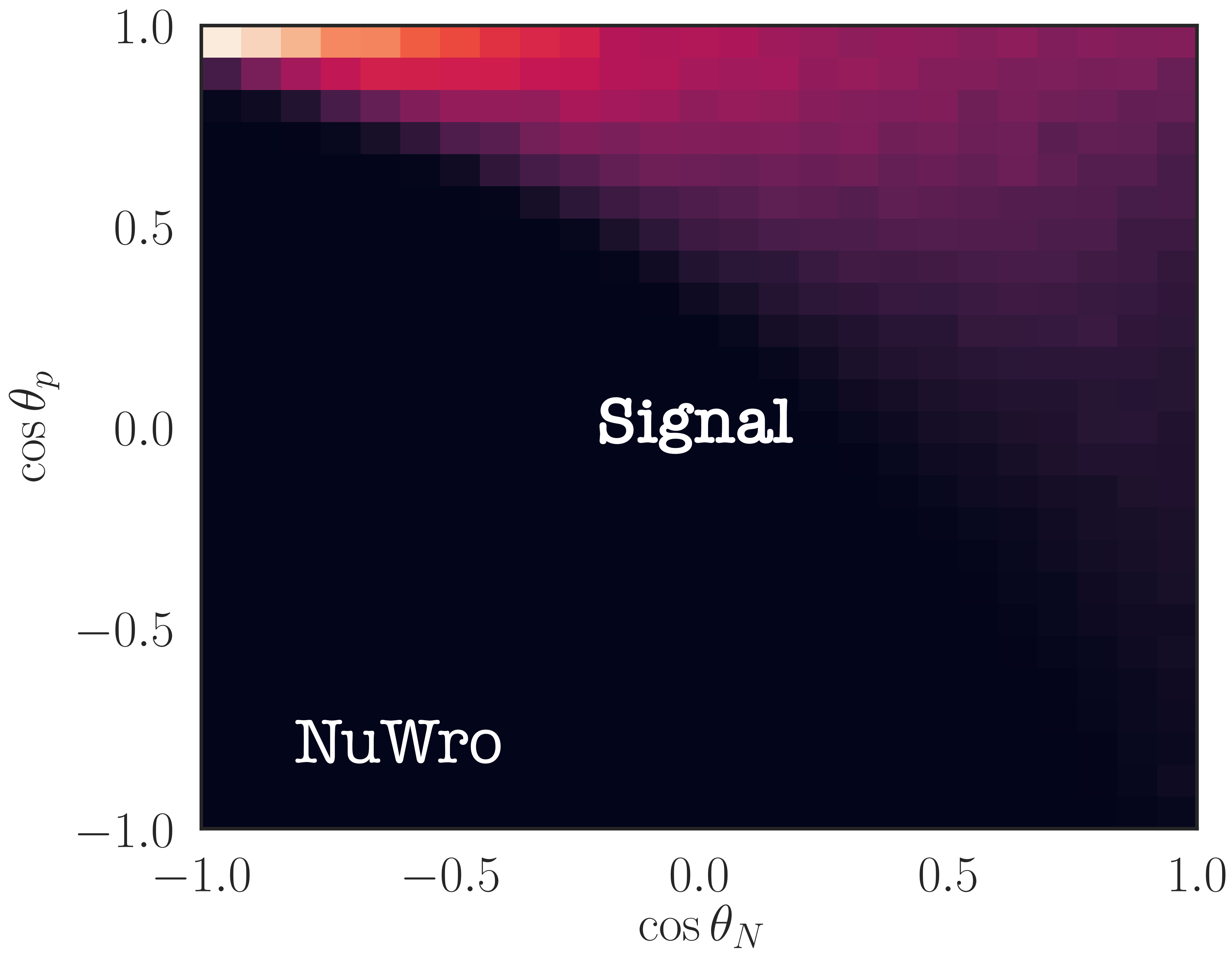

Refs:
T. Golan et al, Phys. Rev. C 86, 015505 (2012)
A.M. Ankowski and J.T. Sobczyk, AIP Conf. Proc. 967, 106 (2007)
http://www.icrr.u-tokyo.ac.jp/~mhonda/

# Reconstruction Resolution




- Cumulative distributions of the angular difference between the true and the reconstructed track directions.
- Comparison of the true (GEANT4) and the reconstructed track lengths for the muon and the proton.

# Signal Kinematics



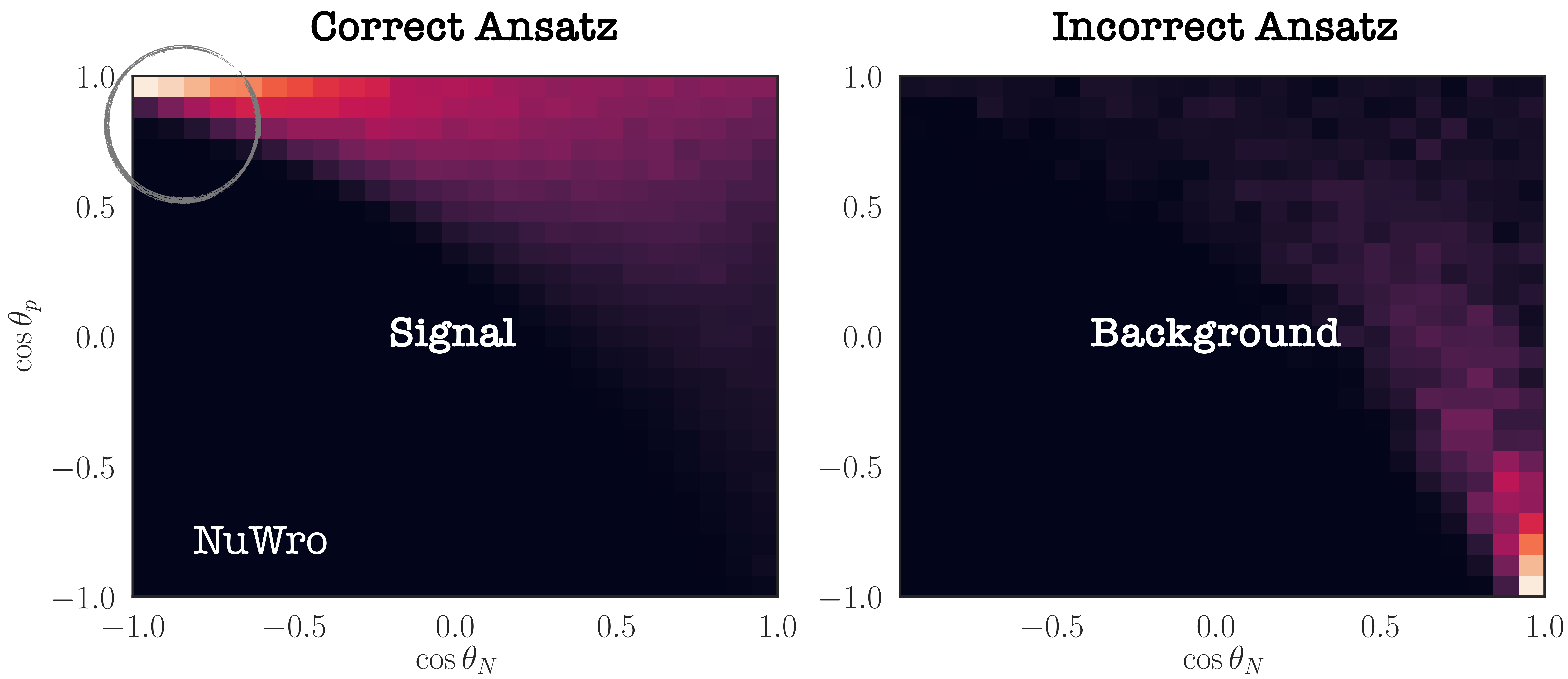

Phase space of the proton and remnant nucleus angles respect to the incoming $\nu_\mu$.

$$\vec{p}_{^{39}Ar} \equiv (236\,\mathrm{MeV})\hat{p}_{\odot} - \vec{p}_{\mu} - \vec{p}_{p}$$

$$\cos\theta_N \equiv \hat{p}_{\odot} \cdot \left(\vec{p}_{^{39}Ar} / |\vec{p}_{^{39}Ar}|\right)$$

If the incoming $\nu_\mu$ came from the Sun with an energy of 236 $\mathbf{MeV}$ then $\theta_N$ would be the angle between the reconstructed remnant nucleus momentum and the direction of the Sun.

# Search Strategy




*Generator* level phase space of the proton and remnant nucleus angles respect to the incoming $\nu_\mu$.

We discriminate signal and background by selecting events in the grey circle.

# Atmospheric Background

# of background events

$$N_B^{\mu} = \eta_B^{\mu} \int_{E_{min}^{bgd}}^{E_{max}^{bgd}} dE_{\nu}\, d\Omega \frac{d^2\Phi_B^{\mu}}{dE_{\nu} d\Omega} \times \left(\bar{A}_{\rm eff}^{(\mu)} T\right)$$

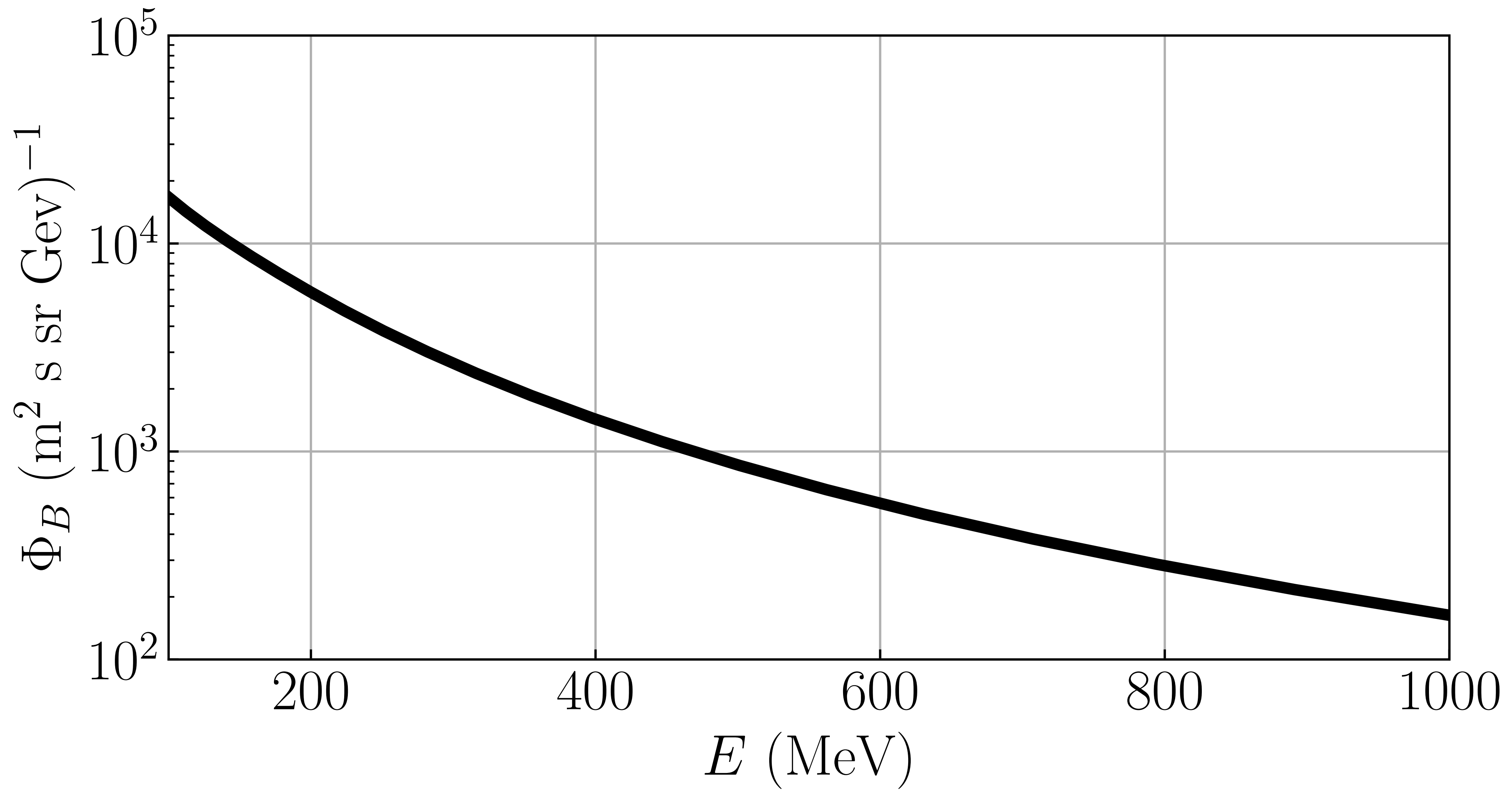
Background acceptance fraction
(post kinematic cuts)

Atmospheric $\nu_{\mu}$ flux
(at detector)

$$\bar{A}_{\rm eff}^{(\mu)} = (6.0 \times 10^{-10} m^2) \left(\frac{\sigma_{\nu-Ar}^{(\mu)bgd.}}{10^{-38} cm^2}\right) \left(\frac{M_{\rm target}}{40kT}\right)$$

Detector mass

Time and direction averaged atmospheric $\nu_{\mu}$ flux at the Homestake mine





Refs:
C.Rott et al JCAP01 (2017) 016
http://www.icrr.u-tokyo.ac.jp/~mhonda/

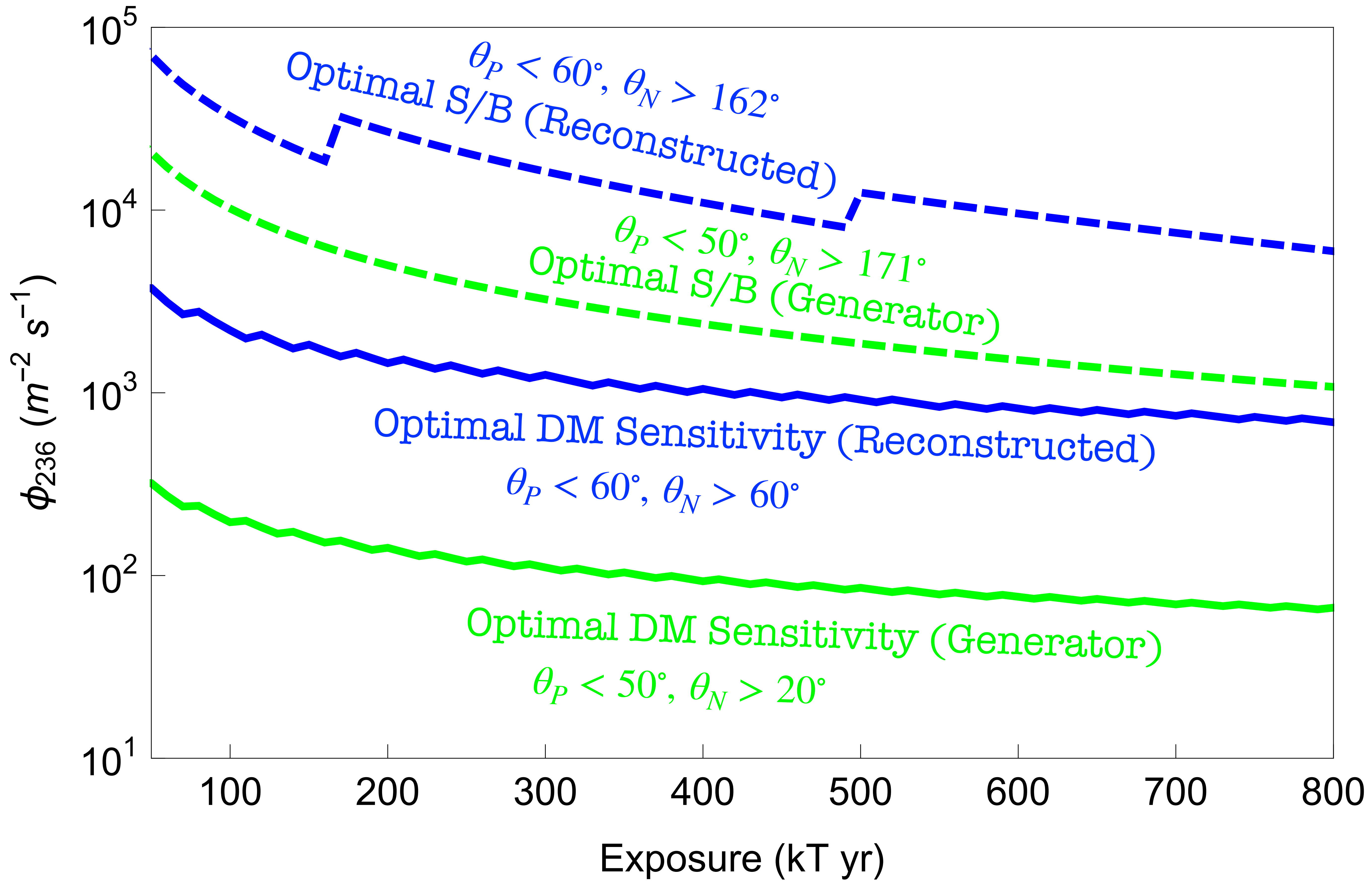
# 236 MeV $\nu_\mu$ Flux from the Sun

- Calculate the expected # of signal events $N_S^\mu$ stemming from new physics in order for that model to be ruled out at 90% C.L. (assuming that we observe only the # of events expected from the background $N_B^\mu$ ).

- Using $\eta_S^\mu$ (a signal acceptance fraction) and the detector exposure translate this into $\Phi_{236}$ (the maximum flux of 236 MeV $\nu_\mu$'s emanating from the core of the Sun which would be allowed at 90% C.L.).

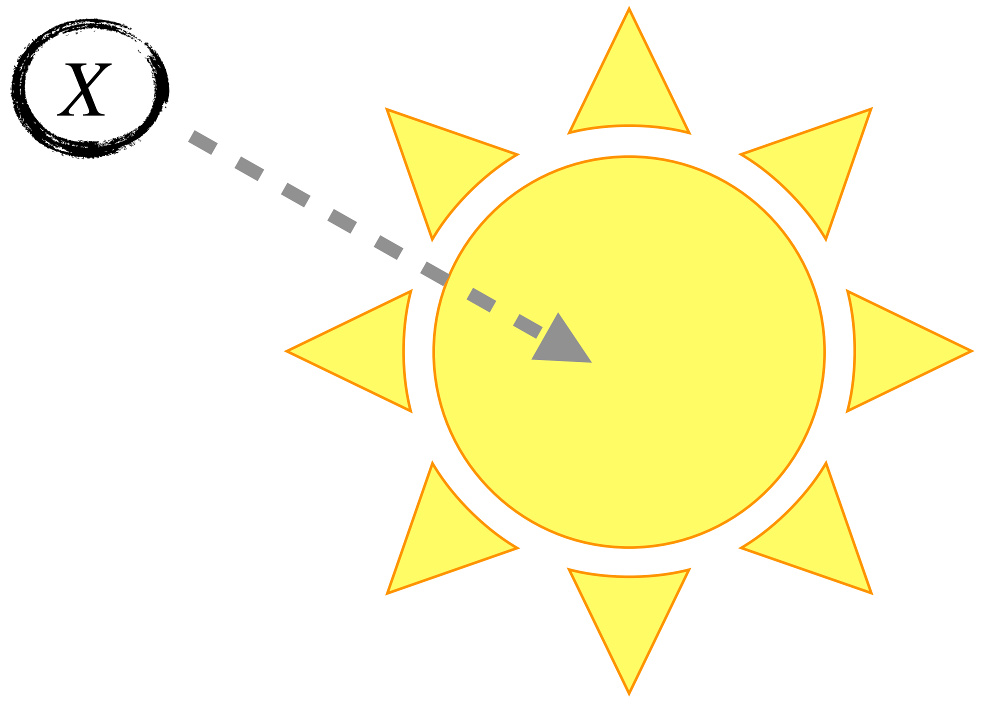
$$\Phi_{236} = \frac{N_S^\mu}{\eta_S^\mu A_{\text{eff}}^{(\mu)}(E_\nu) T}$$

$\Phi_{236}$ is independent of the $\nu$ production model




See the appendix for more on the kinematic cuts.

# Application: Search for Inelastically Scattered Dark Matter



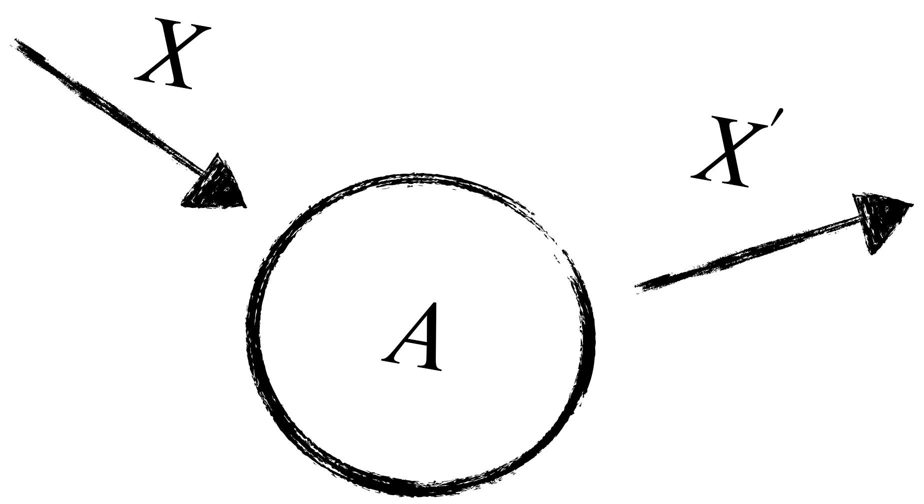

## Model Assumptions

- Annihilates to first generation quarks

- Capture and annihilation rates in the Sun are in equilibrium ( $\Gamma_C = 2\Gamma_A$ )

- So, the $\nu$ event rate probes the DM capture rate ( $\sim \sigma$ )

- Scattering with nuclei is spin-independent and velocity-independent, with an equal coupling to proton and neutrons. The emerging dark particle $X'$ is $\delta$ = 50 keV heavier than the incoming dark particle $X$.

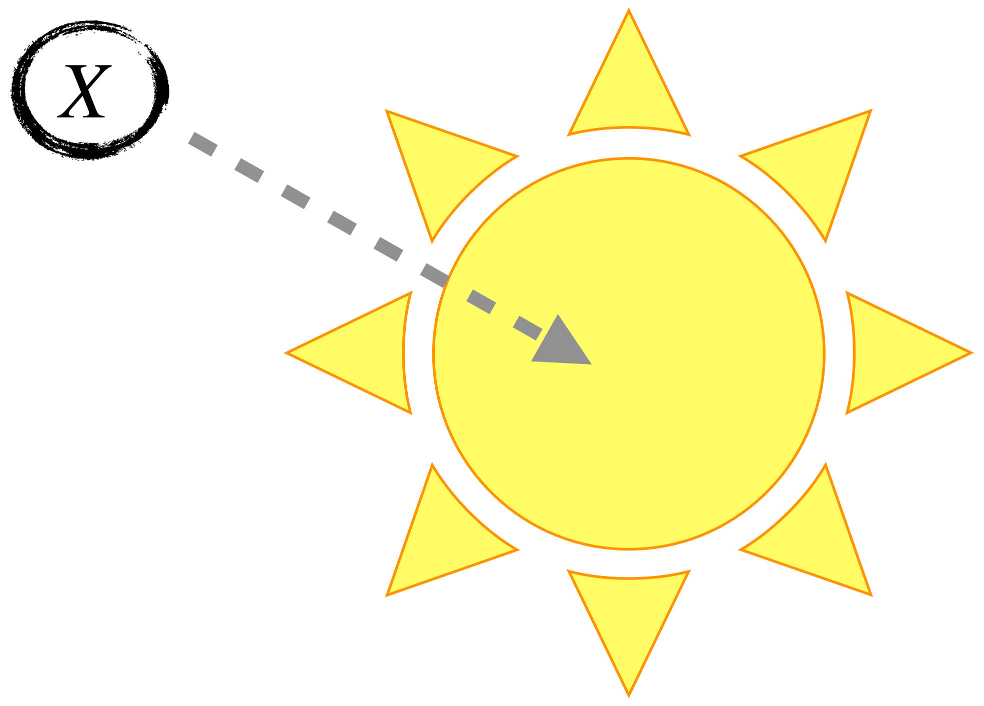



- Constant solar system density $\rho$ = 0.3 GeV/cm^3

- Nominal Maxwell-Boltzmann velocity distribution over the age of the solar system

# Why use DUNE to search fo inelastically scattered dark matter?

- Direct detection searches are hard
- given the DM mass (~ 5 - 10 GeV) and mass splitting ( ~ 50 keV), scattering on earth is not kinematically allowed (not enough energy to upscatter and be seen at PICO)
- BUT gravitational infall gives enough energy to upscatter in the Sun and thereafter annihilate to light quarks




- DUNE can constrain this DM model

# Relating $\Phi_{236}$ to a contour in the $\{m_x, \sigma_0\}$ plane

Fraction of $\nu_\mu$ produced by stopped $K^+$ decay which arrive at the detector as $\nu_\mu$ (assuming a normal hierarchy)

The total $\sigma$ for DM - nucleon scattering, extrapolated to $\delta = 0$ ($\delta$ is the mass difference between $X$ and $X'$). $\sigma_0$ can be related to the differential cross section for scattering against any nucleus at $\delta = 50$ keV.

$$\Phi_{236} = \frac{(C_\delta(m_X) \times \sigma_0/2)\, F^\mu}{4\pi r_\oplus^2}\left(0.64 \times \frac{2m_X}{m_K} r_K(m_X)\right)$$

DM capture rate in the Sun

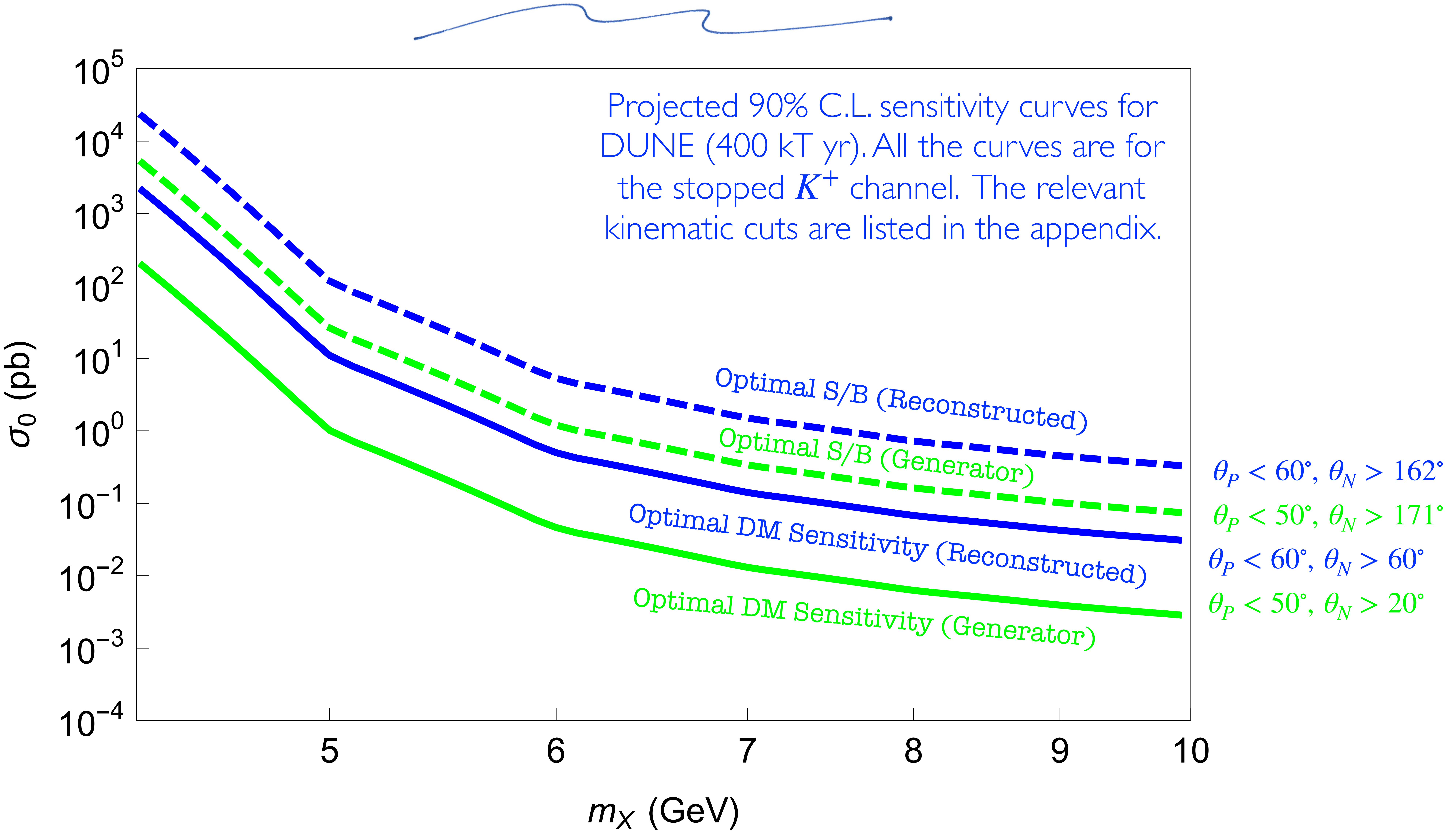
Earth-Sun distance

Branching fraction for $K^+ \to \mu^+\nu_\mu$

Fraction of the C-o-M energy in the annihilation which goes into stopped $K^+$'s as a result of hadronization and subsequent nuclear processes in the Sun

Refs:
R. Lehnert and T. Weiler, Phys. Rev. D77, 125004 (2008)
C.Rott et al JCAP01 (2017) 016

# DUNE Sensitivity to Inelastically Scattered Dark Matter



## DUNE can…

- search for solar KDAR with its unique sub-GeV $\nu$ directionality capability
- indirectly probe non-standard DM models

- solar KDAR can be linked to inelastically scattered DM

# Appendix: Kinematic Cuts

| $\theta_P^{reco} <$ | $\theta_N^{reco} >$ | $\eta_S^{reco}$ | $\eta_B^{reco}$ | $N_S^{reco,90}$ | $N_B^{reco}$ | $S/B^{reco}$ | $\Phi^{reco}_{236\text{ MeV}}[\text{ m}^{-2}\text{ s}^{-1}]$ |
|---|---|---|---|---|---|---|---|
| 60° | 162° | $5.0 \times 10^{-4}$ | $1.9 \times 10^{-4}$ | 2.7 | 1.2 | 2.2 | $1.1 \times 10^4$ |
| 60° | 60° | $2.7 \times 10^{-2}$ | $1.4 \times 10^{-2}$ | 13.9 | 92.7 | 0.2 | $1.1 \times 10^3$ |
| $\theta_P <$ | $\theta_N >$ | $\eta_S$ | $\eta_B$ | $N_S^{90}$ | $N_B$ | $S/B$ | $\Phi_{236\text{ MeV}}[\text{ m}^{-2}\text{ s}^{-1}]$ |
| 50° | 171° | $1.8 \times 10^{-3}$ | $3.3 \times 10^{-5}$ | 2.1 | 0.2 | 10.5 | $2.4 \times 10^3$ |
| 50° | 20° | $3.9 \times 10^{-1}$ | $2.6 \times 10^{-2}$ | 17.8 | 173.3 | 0.1 | 93.1 |

**Table 1**. The angular cuts (including the energy cut of $236 \pm 30$ MeV) and the resulting signal and background efficiencies, the expected number of signal and background events, the expected signal to background ratio at DUNE, and the maximum flux of 236 MeV neutrinos emanating from the Sun which would be allowed (at 90% CL). The first two rows are cuts on reconstructed events and the last two rows are cuts on generator level events (no detector simulation/reconstruction). We include the generator level information to illustrate the optimistic case of perfect reconstruction.