Hunting for Light Dark Matter

WITH THE

NOvA DETECTOR

Peter Filip
Institute of Physics, Prague, Czech Academy of Sciences
(for NOvA collaboration)

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Dark Matter (DM) Indications

- Anomalous Visible Matter Rotation: F. Zwicky 1933 (Coma Cluster) V.C. Rubin 1978 (Galaxies)
- Gravitational Lensing of Light: A. Einstein 1936, Zwicky 1937
- Galaxy Cluster Collisions: Bullet Cluster (8σ, 2006)
- Cosmology: Planck 2014: CMB spectrum: $\Omega_{DM} / \Omega_b \approx 5/1$

Direct detection of Dark Matter is Ultimate Goal of Experimental Physics
NOvA Experiment

• 810km Long-Baseline Neutrino Oscillation ($\nu_\mu \sim \nu_e$).
NOvA Experiment

• 810km Long-Baseline Neutrino Oscillation ($\bar{\nu}_\mu \sim \bar{\nu}_e$)

FAR detector: 60m Long, 16m high
14000 tons, Liquid scintillator (oil)
344064 pixels, 10752 APDs
APD sensors: cooled to -15°C

NEAR detector: 16m
identical functionality
20192 pixels, 631 APDs
300 tons
Avalanche PhotoDiodes

APDs cooled by Peltier Modules to $T = -15^\circ C$

Front-End-Boards GPS synchronized (Far + Near detector)

$\approx 20$ minutes of DATA stored in Memory (buffer PC Nodes) for Trigger decisions

45 sec of continuous data can be saved to permanent storage upon "SN" Trigger
NOvA Experiment

- 810km Long-Baseline Neutrino Oscillation
  \[ (\nu_\mu \sim \nu_e) \]
  \[ (\bar{\nu}_\mu \sim \bar{\nu}_e) \]

Fermilab
NEAR detector
FAR detector
Carbon
Target

700 kW
120 GeV

0.8° off axis

\[ \langle E_\nu \rangle \approx 2 \text{ GeV} \]

Decay Pipe

1 km from the Target

Focusing Horns

675m long

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DM at NOvA Experiment

• Dark Matter \([ V_{DM} \rightarrow \chi \chi ]\) production via Vector Portal

EXAMPLE

120 GeV P P P 700 kW

( ~200 kA Pulsed Horn Currents )

1km from the Target

675m long
PRODUCTION

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DARK Matter Search in NOvA-Near detector.

**DETECTION**

- $\chi \overset{\nu}{\rightarrow} \chi$
- $e, N \rightarrow e, N$

ELASTIC interaction: electrons (nucleons)

- Dark mediator: $M_{\text{DP}} \approx 60-1000 \text{ MeV}$
- Kinetic mixing: $\epsilon \approx 10^{-3} - 10^{-4}$
- DM coupling to $V_{\text{DM}}$: $\alpha_D \approx 0.5 - 0.05$
- DM particles mass: $M_\chi \approx 20-300 \text{ MeV}$

**Diagram:**
- 990m
- $L = \text{distance}$
- $E_p = 120 \text{ GeV}$
- $T = 2.97 \times 10^{20} \text{ POT}$
CC and NC elastic [\(\nu_\mu\)] interactions in Near Detector (NuMI \(\nu_\mu\) Beam)

Muon neutrino cross sections

\[
\sigma(\nu,N) \approx 10^{-38} \left(\frac{E_\nu}{\text{GeV}}\right) \text{cm}^{-2}
\]

CC

\[
\sigma(\nu,e) \approx 10^{-42} \left(\frac{E_\nu}{\text{GeV}}\right) \text{cm}^{-2}
\]

elastic

DM and Neutrino elastic interactions with Electrons in NOvA

Elastic Scattering cross sections:

- Neutrinos
  \[ \sigma(\nu,e) \approx 10^{-42} \left( \frac{E_\nu}{\text{GeV}} \right) \text{cm}^{-2} \]
- DM
  \[ \sigma(\chi,e) \approx 10^{-27} \alpha_D \epsilon^2 \left( \frac{100\text{MeV}}{M_{\text{DP}}} \right)^2 \text{cm}^{-2} \]


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DARK Matter Flux in NOvA-ND Detector

**Near Detector**

Nearly All DM = \(\chi\) Flux originates in the Target except: small fraction

\[K^\pm \rightarrow \pi^\pm(\pi^0 \rightarrow \rightarrow \chi\chi)\]

No Focusing for \(\chi\chi^\dagger, \pi^0, \eta\)

Energy distribution for DM = \(\chi\)

ICHEP-2018 poster: F.J. Assuming \(M_{DP} = 1\) GeV

\[m_\chi = 300\text{ MeV}\]

Reconstructed Shower Energy \(T\) (GeV)

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Expected LDM Upper Limits from NOvA-ND detector

- **Theoretical paper MC simulation**
  - $M_\chi$ region: 6 MeV – 70 MeV
  - $M_{DP}$ region: 18 MeV – 210 MeV
  - DM-Mediator coupling: $\alpha_D = 0.5$
  - Kinetic $\gamma^* - V_{DM}$ mixing: $\epsilon = 10^{-3}$
Excess of the elastic-like forward electron showers could mean: LDM signal in NOvA-ND.

NuMI beam for elastic $\nu$–e scatt.

Signal region: $E\theta^2 < 0.005$

Sideband for $\nu$–e scattering good for LDM signal search

arXiv:1710.03428 $\nu$–e Signal Region

DATA Not shown

140 ev.
Excess of the elastic-like forward electron showers could mean: LDM signal in NOvA-ND

Signal region $E\theta^2 < 0.005$

Sideband Region for $\nu-e$
good for LDM signal search

$8.28 \times 10^{20}$ POT MC simulation

NuMI beam

NOvA Preliminary

DATA points Not officially available

$\nu-e$ Sideband region

DM – electron

High Recoil

$m_\chi = 300$ MeV

NEUTRINO 2016 conference

NOvA Simulation

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Sideband Elastic electron showers may come from LDM

whenever ANGLE $\theta$ is too Large for $\nu$–$e$ Elastic scattering

ANGLE $\theta$ in $\nu$-$e$ Elastic scattering is very small
NOvA Statistics Accumulation: $\Sigma$ POT $\rightarrow$ $6 \times 10^{21}$

Gradually Increasing the NuMI beam intensity (power) $\rightarrow$ 700 kW
Summary: 1) DM search in NOvA Far Detector
Annihilation of DM in Sun $\rightarrow$ Upward going Muons

SUN: $L = 1 \text{ Au} = 1.5 \text{M km}$
$T_{\text{Sun}} = 10 \text{ Mega Kelvin}$

E$_{\nu} > 0.5 \text{ GeV}$

( Sun is at $\pm 10^\circ$ off the horizon)

DATA taking + Analysis in Progress

Hunting For LDM with NOvA
before Summary:
2) DM search in Far+Near Detector
Interstellar or DM Stream \(\Rightarrow\) mini-SNova-like events

( low-energy neutrinos )

**THIS EFFORT ASSUMES:**

* 'slow' DM stream in Milky Way
* oriented FROM/TO Galactic Center
* DM Gravitational Focusing by Sun

Sun – Earth – Sagit. A* alignment

* during Summer/Winter solstices
SUMMARY

• NOvA-ND can put competitive Limits on LDM
  
  \[ \text{for } p + ^{12}C \rightarrow (M_{DP}: 20 - 200 \text{ MeV}) \rightarrow \chi \chi^\dagger \]

• DATA taking plan: until 2025 (POT → 6 \times 10^{21})
  
  improving several aspects (CNN & Syst. err.) not shown here

+ Far Det. NOvA Dark Matter Project Active
  
  search for WIMP annihilation in Sun + DM stream focusing

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Thank You and NDM-2020 organizers

for the Attention and Hospitality.