Beyond the Standard Model Physics Prospects at Deep Underground Neutrino Experiment

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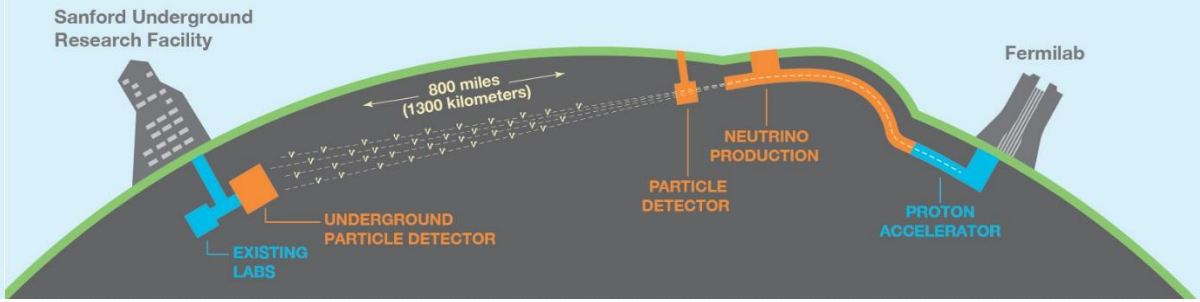
DUNE Experiment

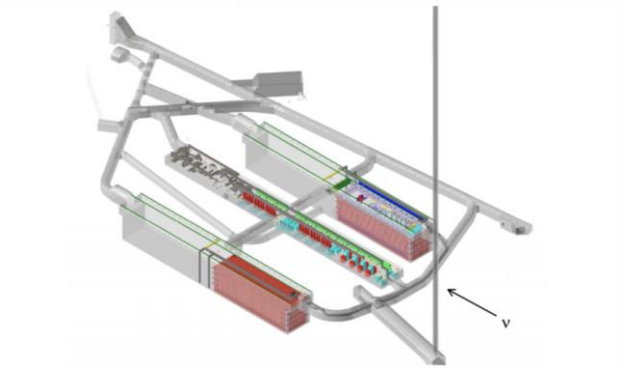
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- The DUNE science program includes:
  - Long-baseline neutrino oscillations: leptonic CP violation, neutrino mass ordering, and precision test of the 3-neutrino mixing framework
  - Neutrino astrophysics (detection of supernova neutrinos)
  - Nucleon decay and other searches for **physics beyond the Standard Model (BSM)**
- Highly intensified energetic (60-120 GeV) proton beam (~10^{21} protons on target per year, or 1.2 MW upgradable to 2.4 MW) can create high intensity neutrino fluxes and potentially **new physics signals**.
- Large-volume detectors (in particular, far detectors) can be sensitive to neutrino and **new physics signals from astrophysical sources**.



Detectors

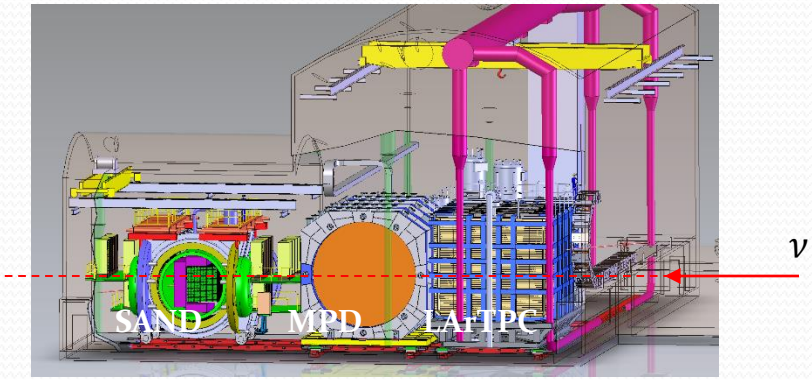
Far detectors (FD)



- **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber technology (LArTPC)
- Low energy threshold, high resolutions in energy/angle/position
- 10 kt fiducial mass (17 kt total mass) × 4 modules

Near detectors (ND)

(See Patrick Dunne's talk)



- Three sub-detectors:
  - LArTPC (ArgonCube)
  - **M**ulti-**P**urpose **D**etector (MPD) = **H**igh **P**ressure **g**aseous argon **TPC** (HPgTPC) + ECAL in a 0.5 T B field
  - **S**ystem for on-**A**xis **N**eutrino **D**etection (SAND)
- LArTPC and MPD are movable sideways up to 33 m. ⇒ DUNE-PRISM

BSM Physics and Prospects in DUNE

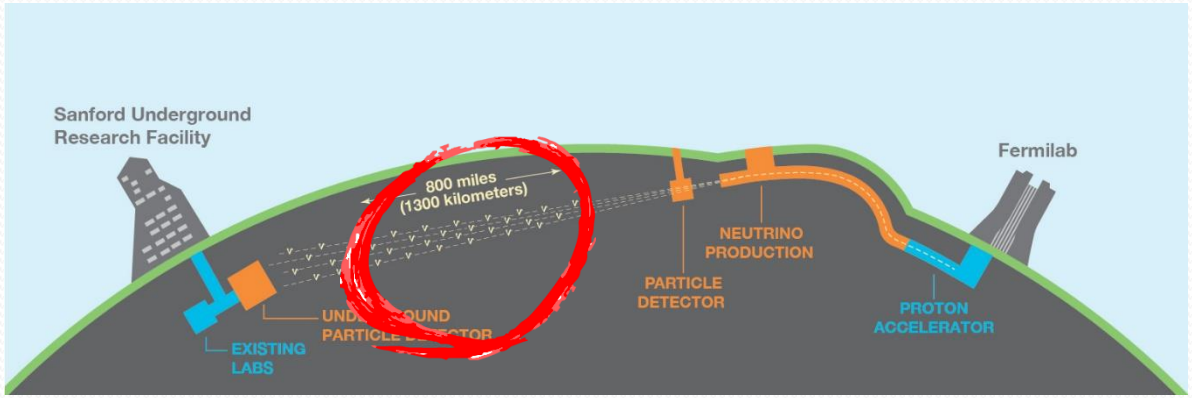
(*: Not discussed in this talk)

- Topics investigated include:
  - Non-standard short-baseline and long-baseline ν oscillation:
    - ✓ **Sterile neutrino mixing**,
    - ✓ Non-unitarity*,
    - ✓ **NSIs**,
    - ✓ **CPT violation**,
    - ✓ ν_τ appearance*,
    - ✓ Large-extra dimensions*.
  - Searches for beam-induced new phenomena/particles at ND
    - ✓ **Neutrino tridents**,
    - ✓ **Low-mass DM**,
    - ✓ Heavy neutral leptons*.
  - Searches for cosmic-origin new phenomena/particles at FD
    - ✓ **(Galactic) inelastic boosted dark matter**,
    - ✓ **Solar boosted dark matter**,
    - ✓ DM annihilation in the sun*.

- All topics discussed in **TDR Vol. II** [arXiv:2002.03005]
- **BSM physic paper** available soon

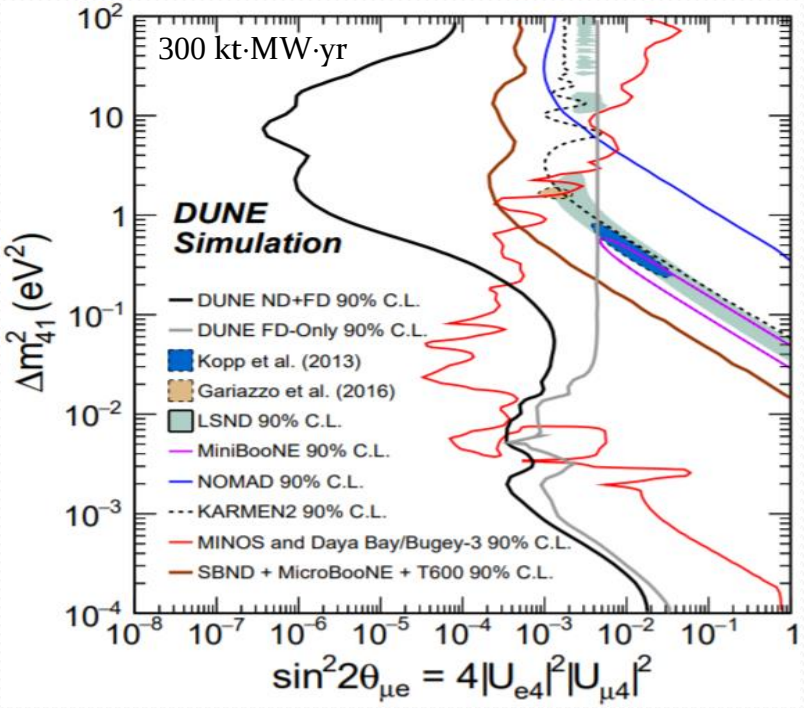
- Different searches/studies are done with different levels of detector response and background considerations and/or for different exposures.

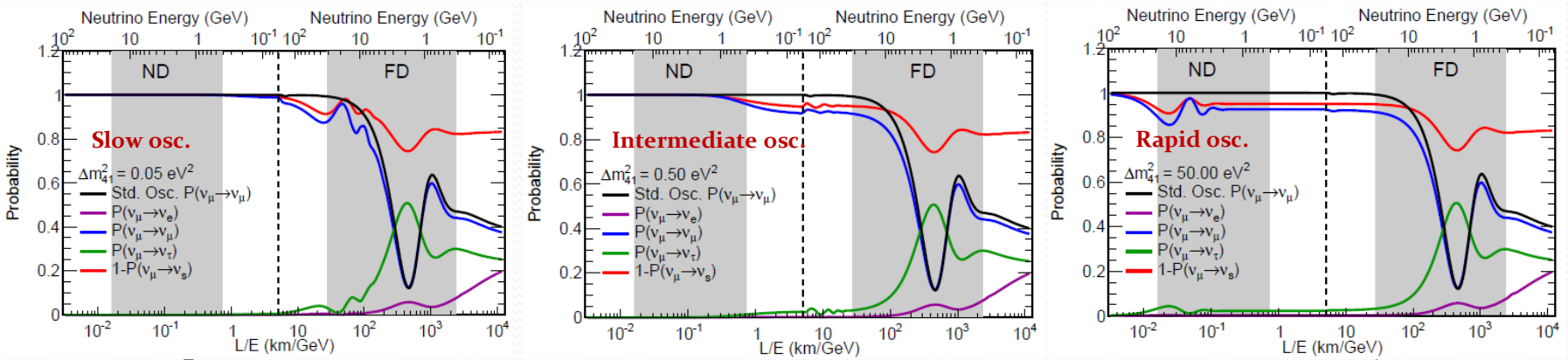
Non-Standard Neutrino Oscillations



Sterile Neutrino

- Sterile (right-handed) neutrinos are predicted in many BSM models to explain the origin of neutrino masses.
- Mixing between active and sterile neutrinos can distort the standard oscillation probabilities. DUNE will be sensitive to this phenomenon (if exists) through the ν_μ and ν_e spectra at both ND and FD.
- DUNE will probe parameter space of sterile neutrinos with **competitive sensitivities**.



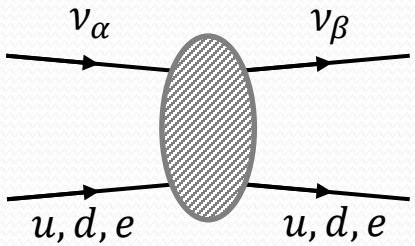


「Neutrino appearance and disappearance probability distortion by the existence of sterile neutrino.」

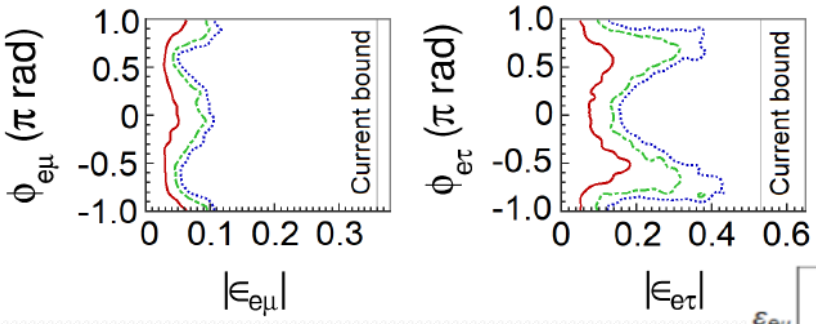
Non-Standard Neutrino Interactions

- Neutral-current non-standard interactions in propagation can be described as new contributions to the MSW effect:

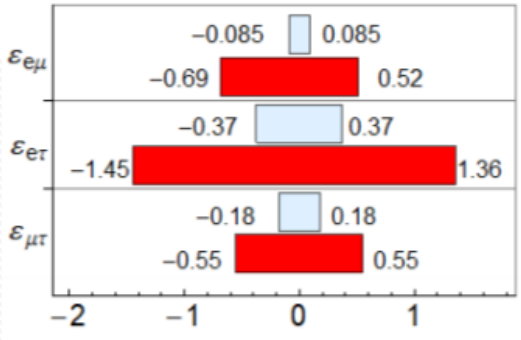
$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW}\,, \quad \tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$



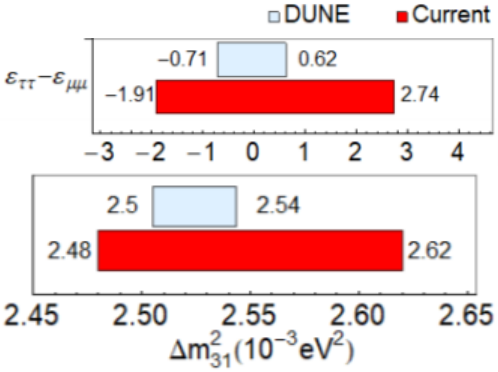
- DUNE may **improve current constraints on $|\epsilon^m_{e\tau}|$ and $|\epsilon^m_{e\mu}|$** by a factor of 2 – 5 [arXiv:1209.2710; 1505.06254;1710.09360].



「Allowed regions (l.h.s. of the lines) for an exposure of 300 kt·MW·yr. Current bounds are taken from [arXiv:1307.3092].」

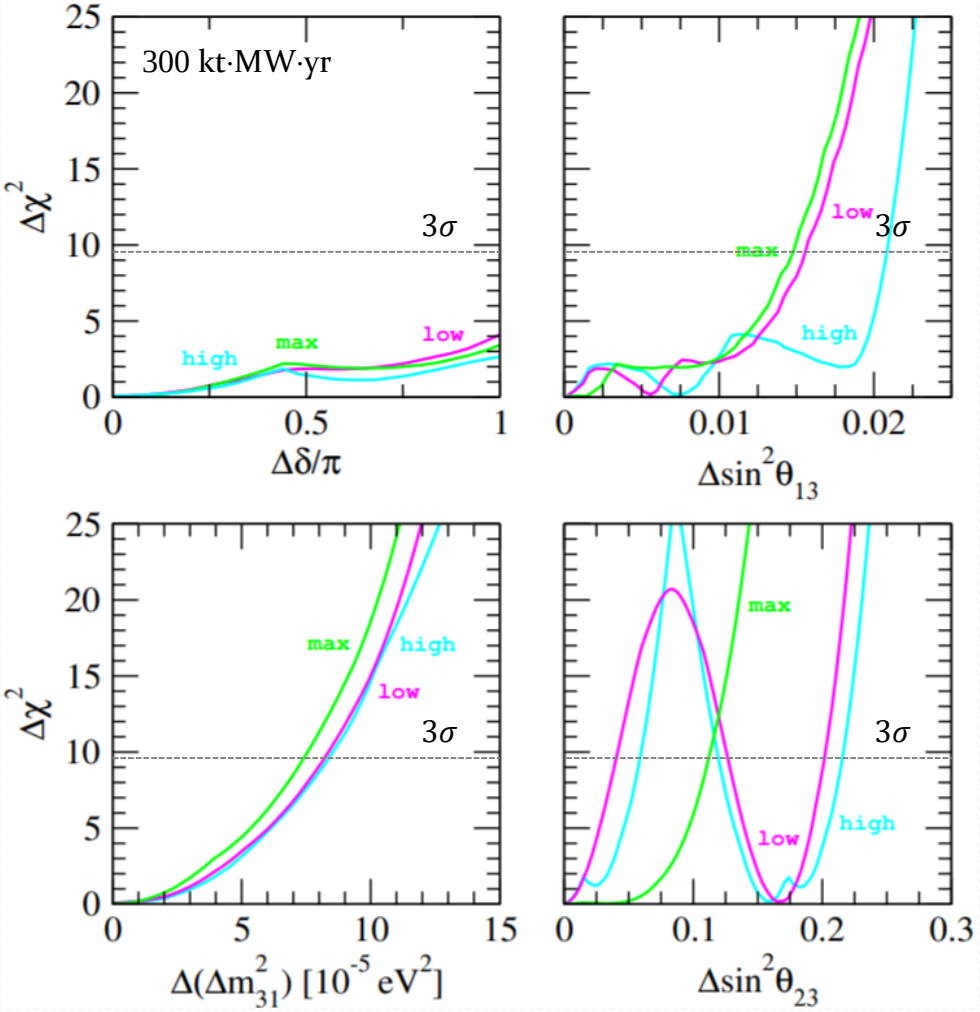


「90% C.L. one-dimensional DUNE constraints compared with current constrains in [arXiv:1710.09360].」



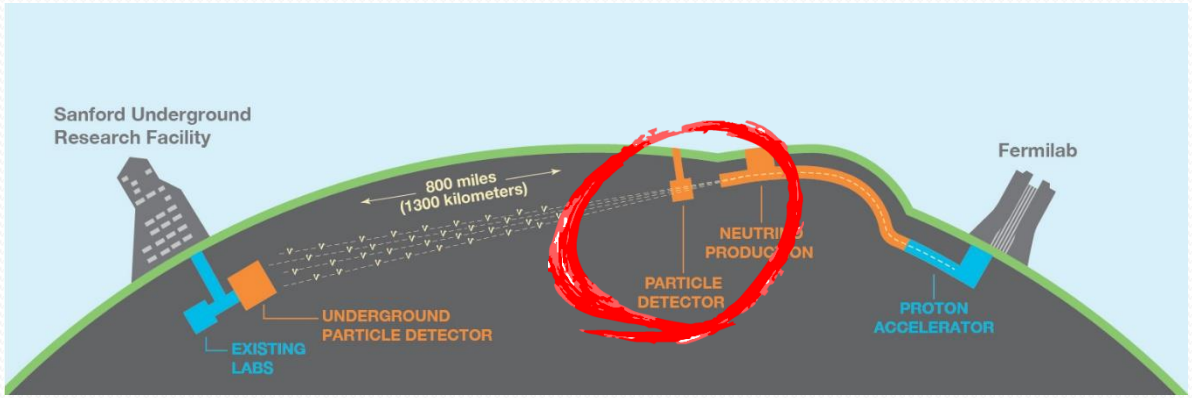
CPT Symmetry Violation

- CPT violation in the ν sector is measured by analyzing ν and $\bar{\nu}$ oscillation parameters, separately.
- Projected sensitivity of DUNE to CPT violation for three different values of the θ_{23} mixing angle: maximal mixing (green), lower octant (magenta), and upper octant (blue).
- DUNE will put **stronger bounds on $\Delta(\Delta m^2_{31})$**, improving the current bound by an order of magnitude: $\Delta(\Delta m^2_{31}) < 8.1 \times 10^{-5}$ eV^2



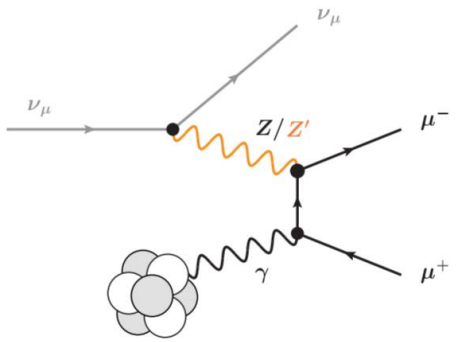
[arXiv: 1712.01714]

BSM at the Near Detectors



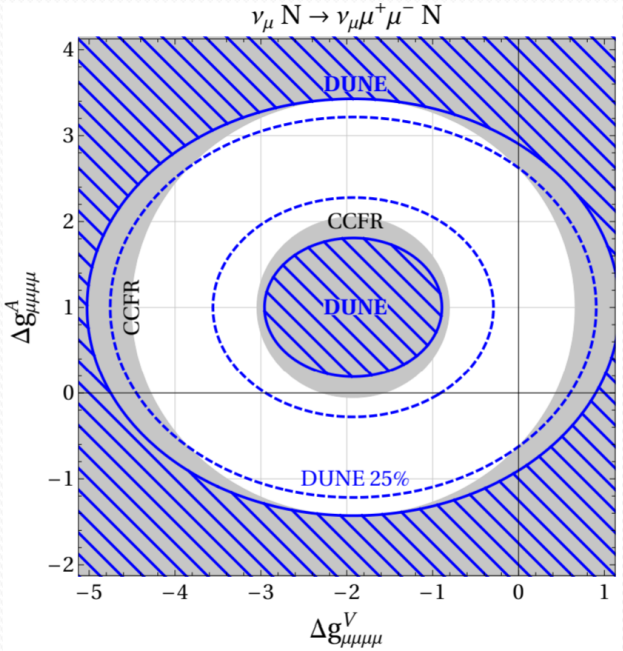
Neutrino Tridents

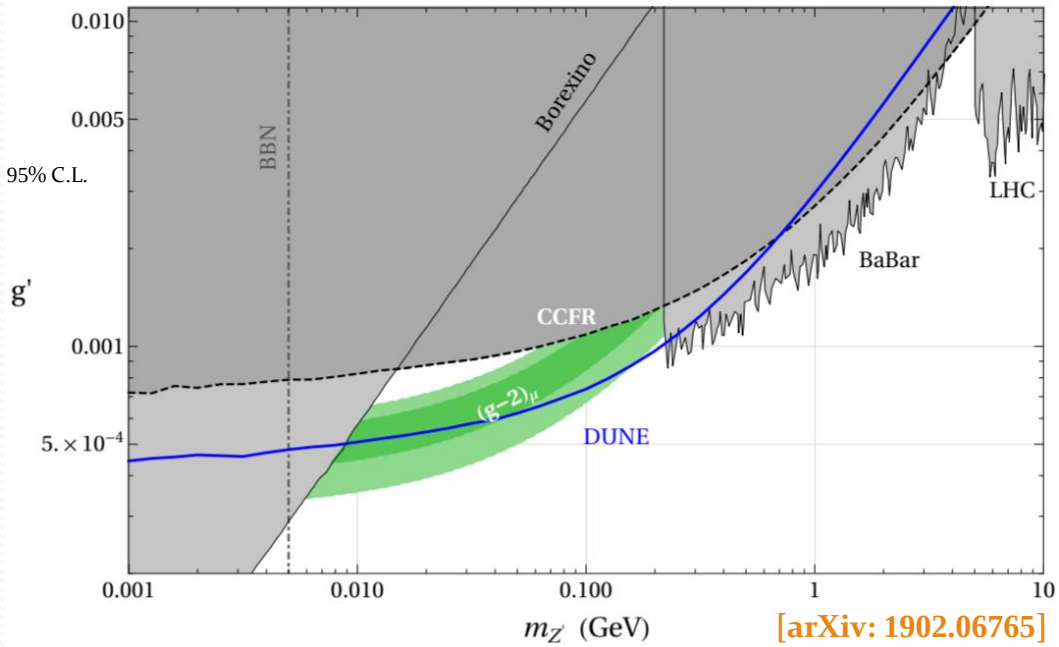
- Rare process in SM: Previous experiments (e.g., CCFR) observed a few tens of events.
- A departure from the SM prediction can be evidence for new physics: DUNE will be sensitive to the existence of light vector mediators, e.g., $L_\mu - L_\tau$ Z', which could explain $g_\mu - 2$ anomaly.



「E.g. Contribution of $L_\mu - L_\tau$ Z' to a trident diagram.」

- **ML-based event selection** can improve the existing limits.

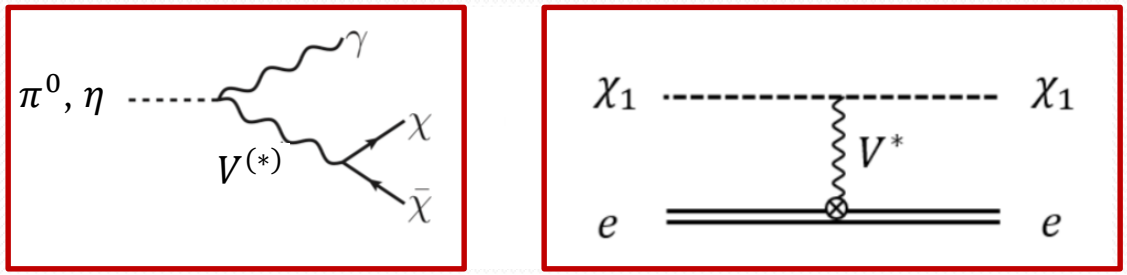




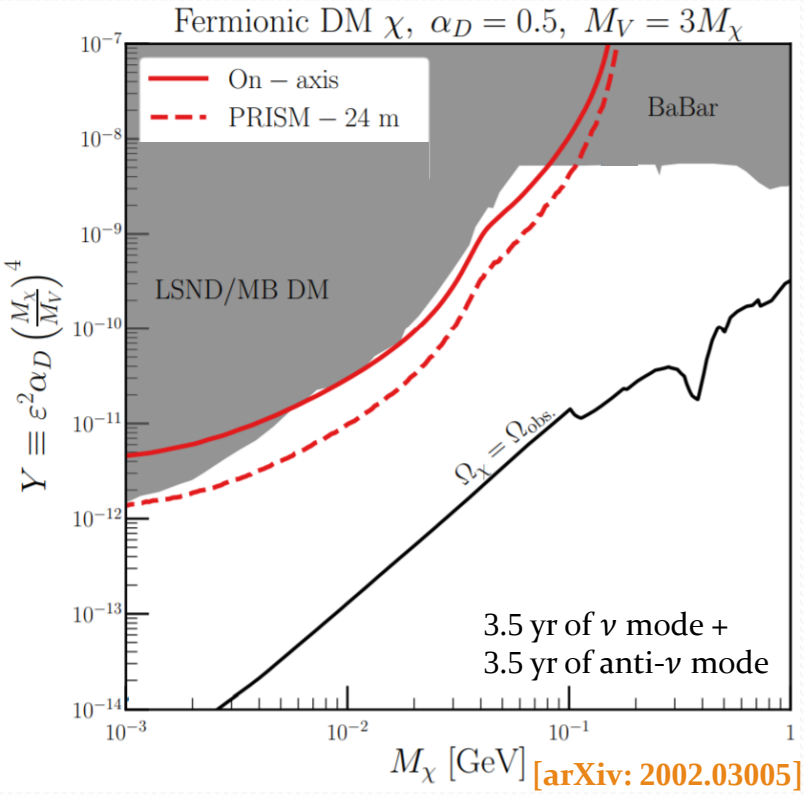
[arXiv: 1902.06765]

Low-Mass Dark Matter

「Production of low-mass DM at the target」 「Detection of low-mass DM at the ND」

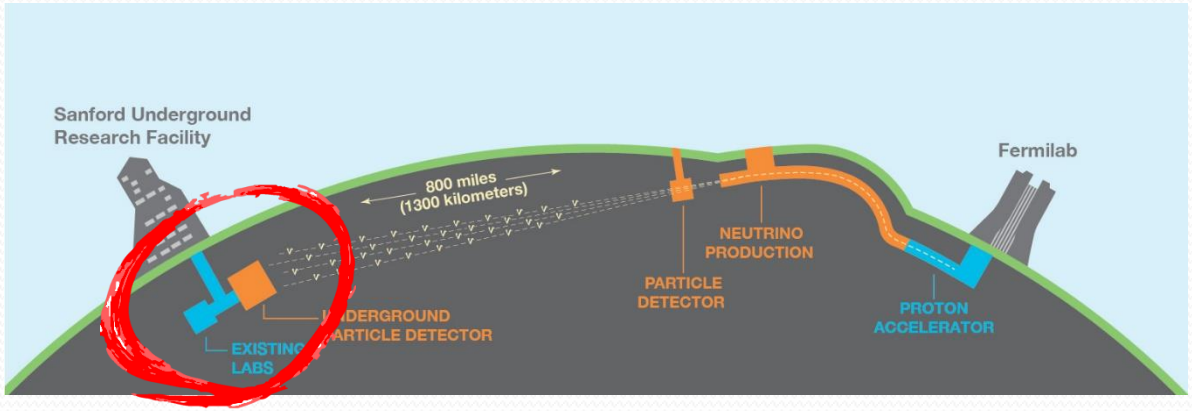


- The highly intensified proton beam in DUNE can produce (low-mass) DM via hypothetical meson (π^0, η) decays into dark photon V.
- DM (elastically) interacting with electrons at ND is considered.
- The main background (neutrino-electron scattering) can be **suppressed by taking data off-axis** (DUNE-PRISM)



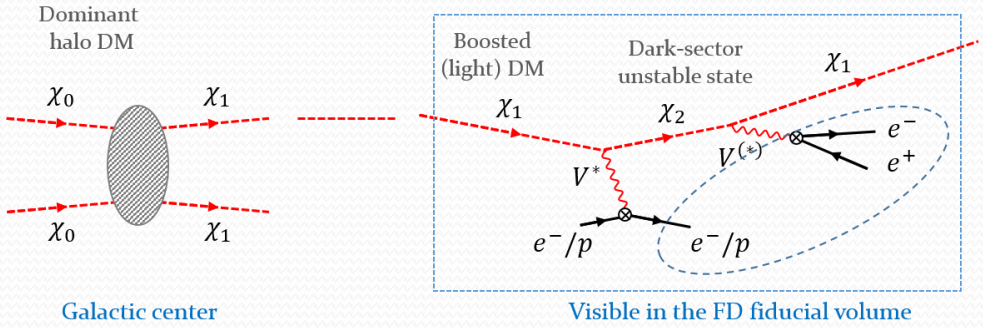
[arXiv: 2002.03005]

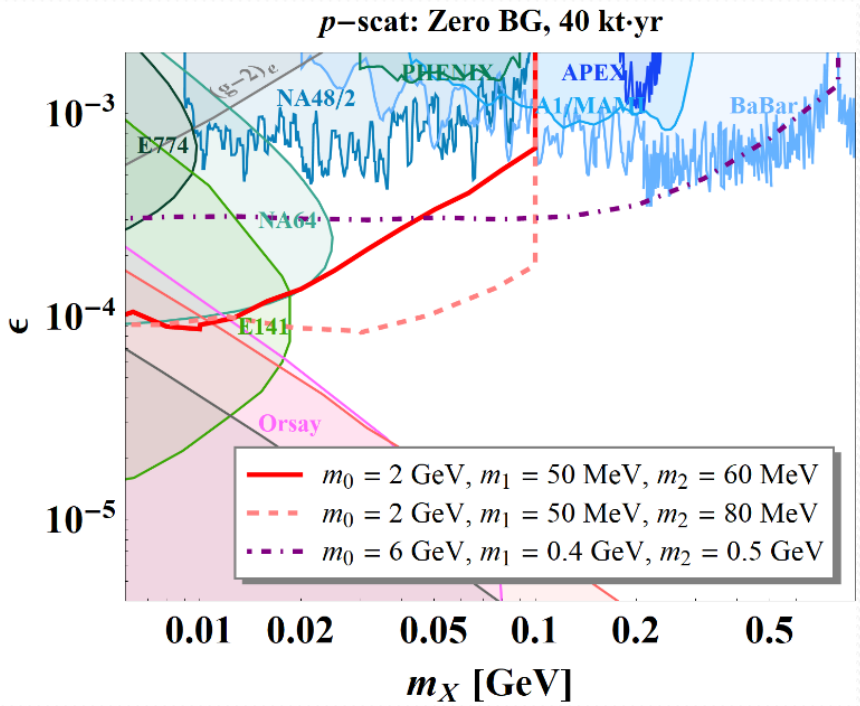
BSM at the Far Detectors

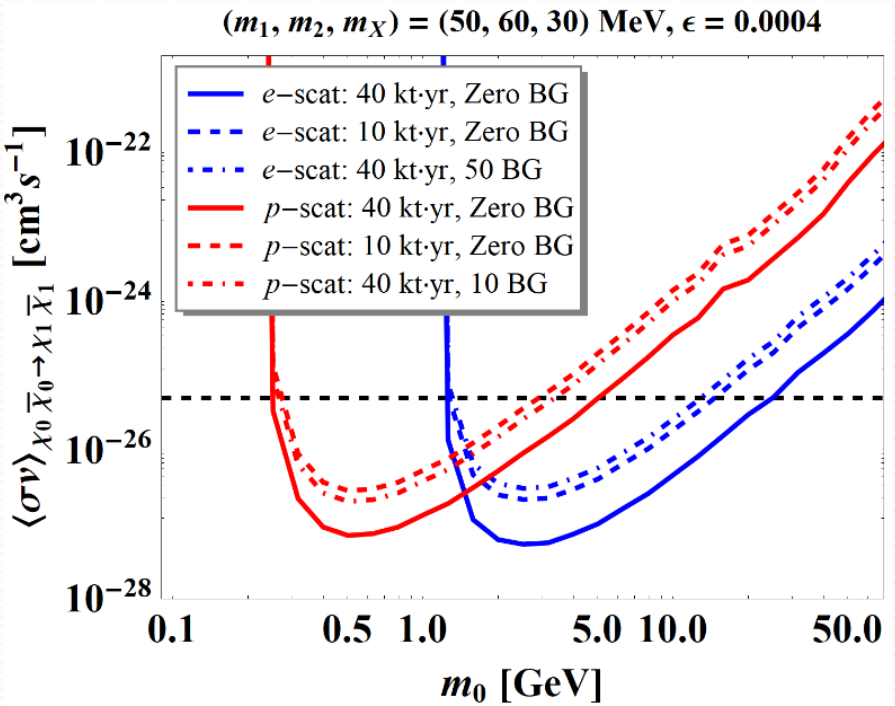


Inelastic Boosted Dark Matter

- The DUNE far detectors can be sensitive to the boosted (light) dark matter signals with **multiple particle tracks**, e.g., inelastic boosted dark matter from the galaxy [arXiv: 1612.06867].



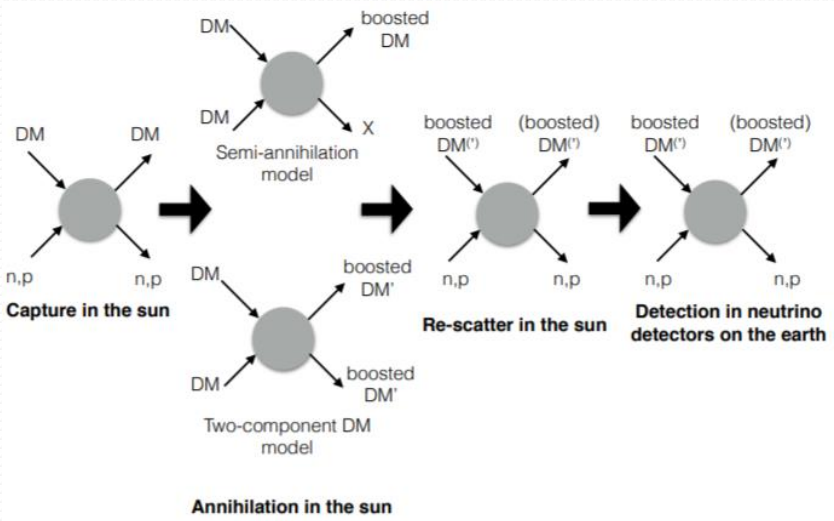


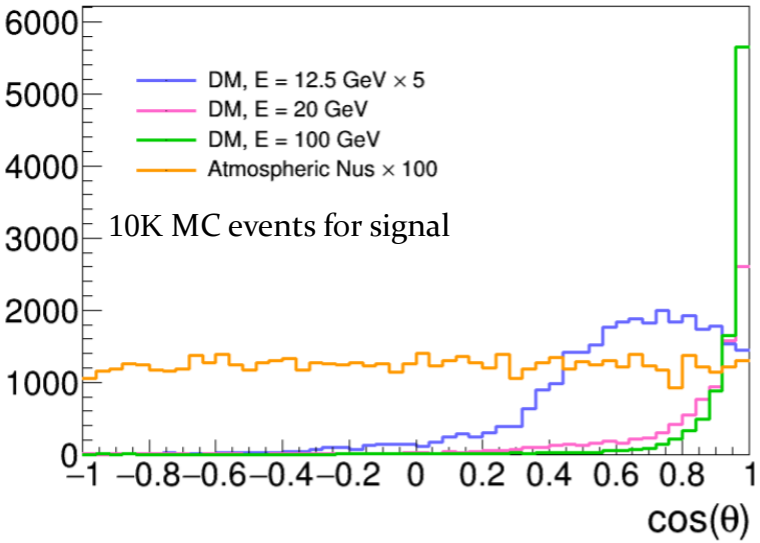


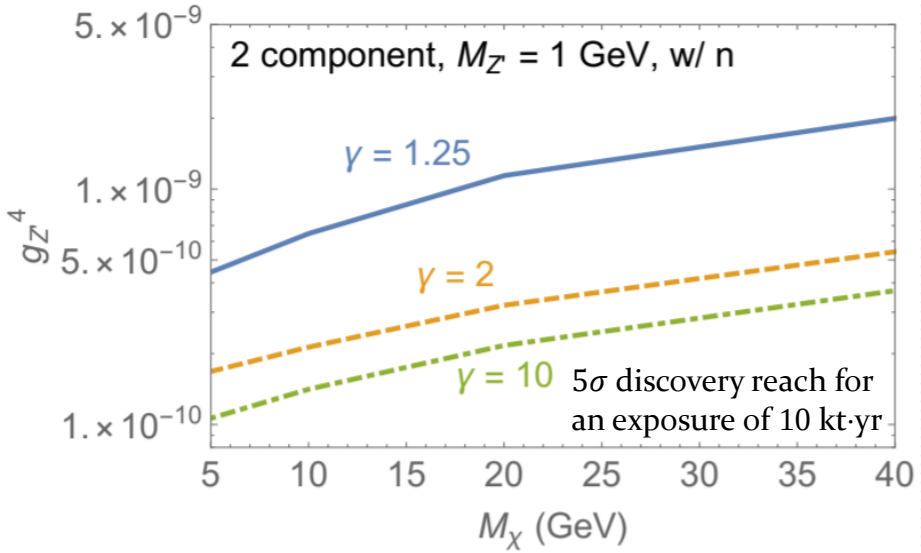
[arXiv: 2005.08979]

Solar Boosted Dark Matter

- The DUNE far detectors can be sensitive to the boosted dark matter signals from **close and localized sources**, e.g., solar boosted dark matter [arXiv: 1410.2264; 1411.6632], dwarf galaxies [arXiv: 1610.03486]







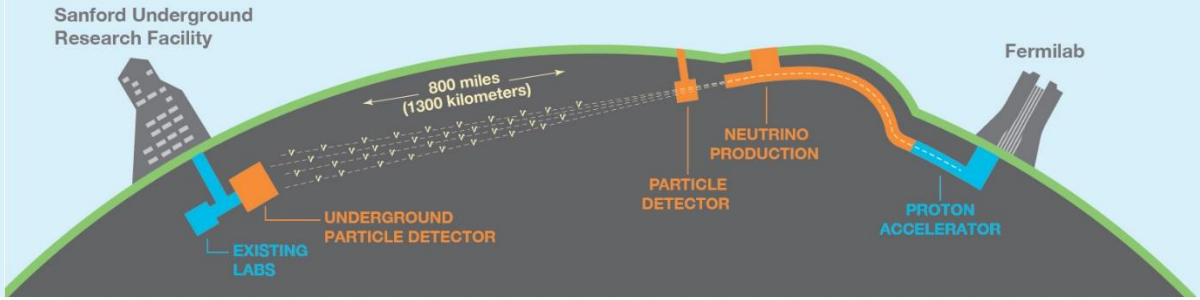
θ: angle of recoiling target w.r.t the source direction (i.e., sun)

[arXiv: 2002.03005]

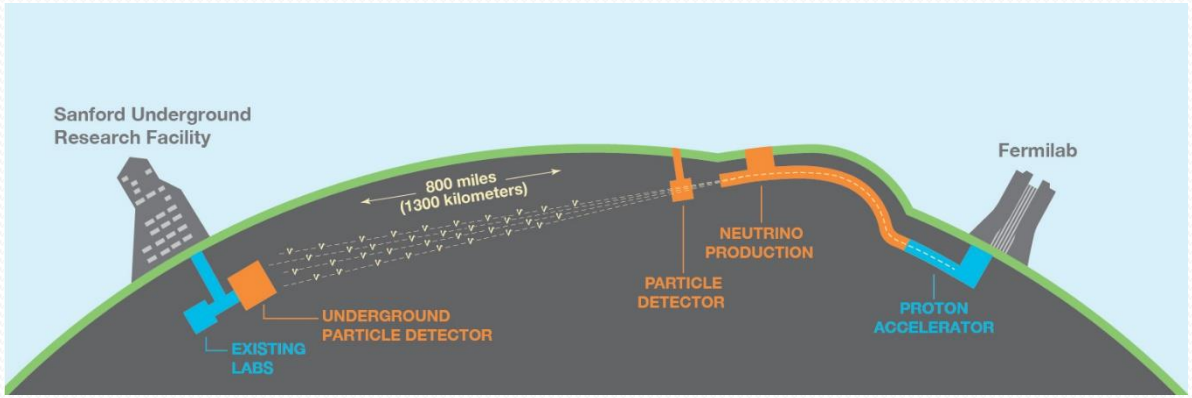
Summary

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- BSM physics at neutrino facilities has been receiving growing attention, and the DUNE experiment can provide great opportunities to test and study various BSM phenomenology.
- The high-capability near and far detectors and the powerful LBNF beam can allow for a rich experimental program of neutrino and non-neutrino BSM physics studies, including
  - new physics related to short-baseline and long-baseline **neutrino oscillation**,
  - searches for **beam-induced** new phenomena and/or particles at ND (with various complementary designs),
  - searches for **cosmic-origin** new phenomena and/or particles at FD benefiting from their large mass and high resolution.
- There are increasing active collaborations between experimentalists and theorists/ phenomenologists. **New ideas and proposals are welcome!**



Backup


Sanford Underground
Research Facility
800 miles
(1300 kilometers)
Fermilab
NEUTRINO
PRODUCTION
PARTICLE
DETECTOR
PROTON
ACCELERATOR
UNDERGROUND
PARTICLE DETECTOR
EXISTING
LABS

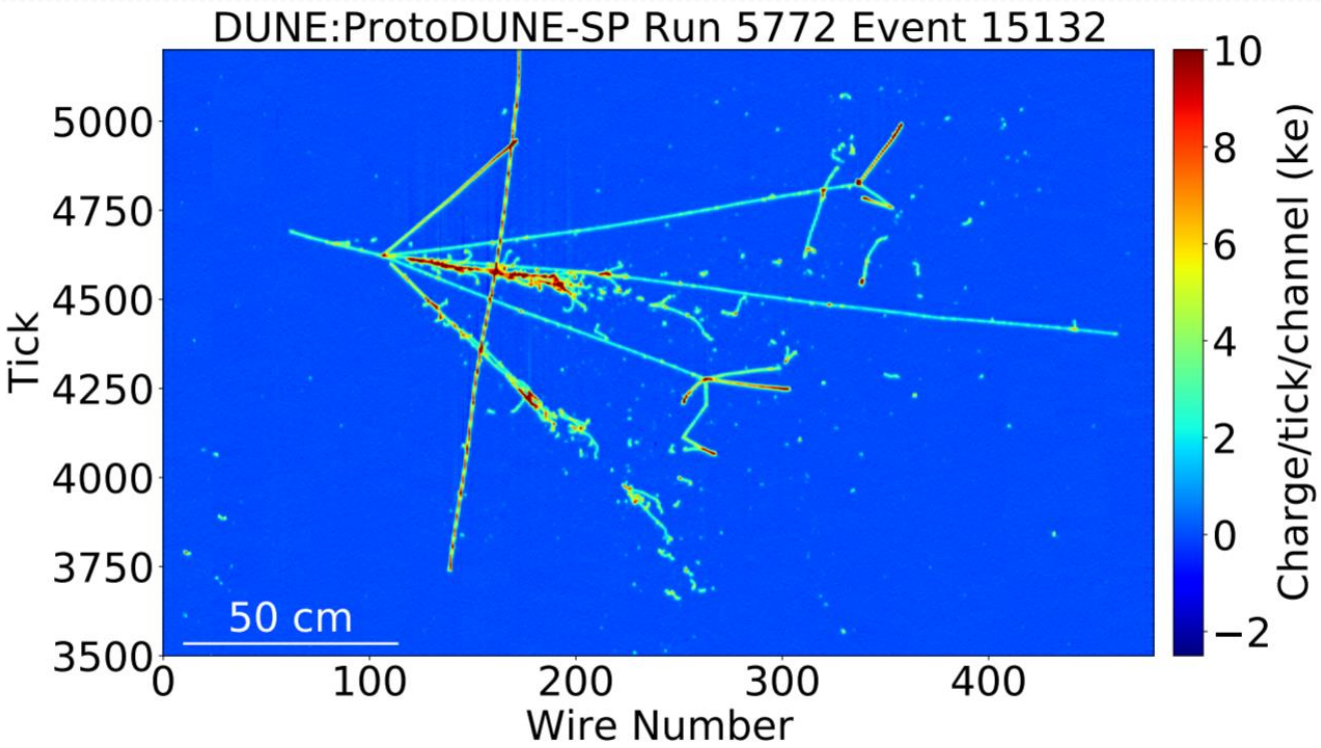
DUNE FD Staging Scenario

DUNE FD staging scenario

- Assumes equal ν and $\bar{\nu}$ running time
- The starting year (Year 1) is assumed to be 2026

Year	Number of FD modules	Total FD target mass (kt)	LBNF beam power (MW)	Exposure at year end (kt MW yr)
1	2	20	1.2	21
2	3	30	1.2	54
4	4	40	1.2	128
7	4	40	1.2	300
10	4	40	2.4	556

LArTPC



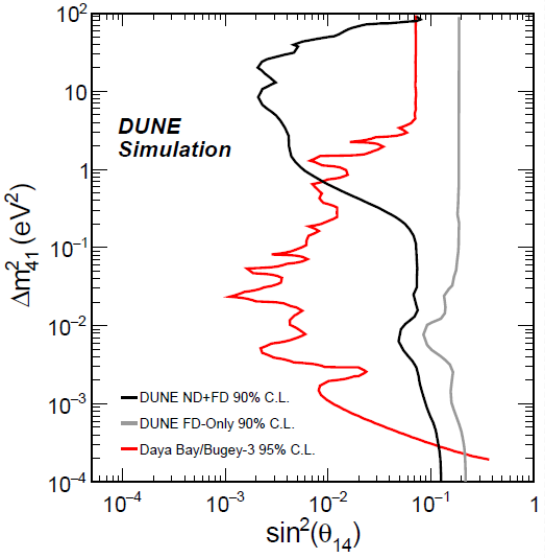
(d) A 6 GeV/*c* pion candidate.

[arXiv: 2007.06722]

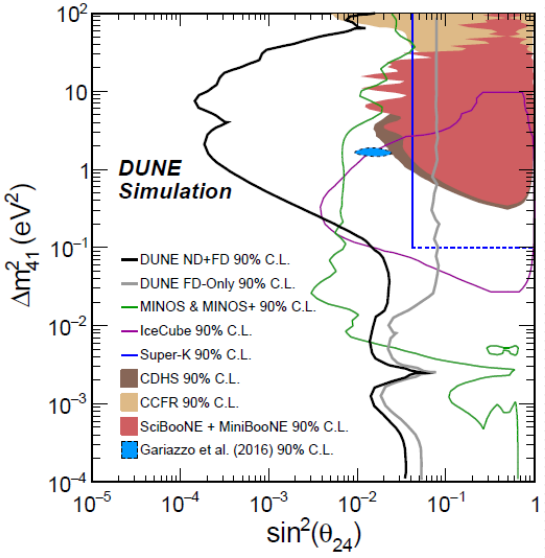
More Results in the Sterile Neutrino Search

- DUNE sensitivities to a 3 + 1 mixing model for an exposure of 300 kt·MW·yr.

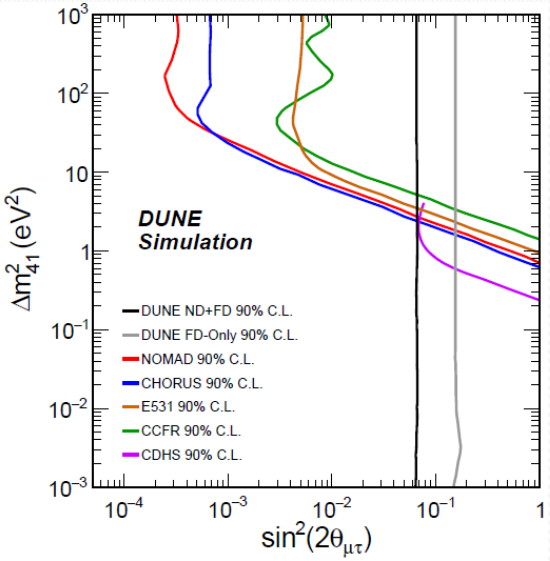
	θ_{24}	θ_{34}	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
DUNE Best-Case	1.8°	15.0°	0.001	0.067
DUNE Worst-Case	15.1°	25.5°	0.068	0.186
NOvA	20.8°	31.2°	0.126	0.268
MINOS/MINOS+	4.4°	23.6°	0.006	0.16
Super–Kamiokande	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15



ν_e disappearance in the ν_e CC sample



ν_μ disappearance in the ν_μ CC sample + disappearance in the NC sample

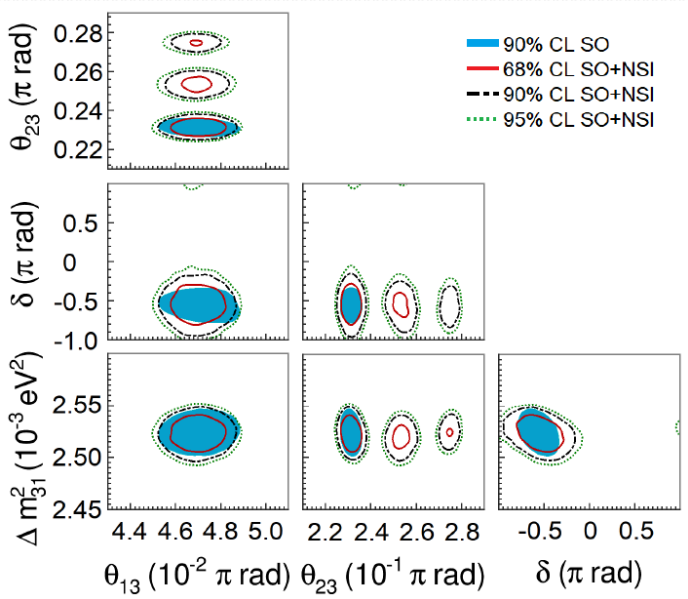


Disappearance in the NC sample

NSI Searches in DUNE

Parameter	Nominal	1σ Range ($\pm$)
θ_{12}	0.19π rad	2.29%
$\sin^2(2\theta_{13})$	0.08470	0.00292
$\sin^2(2\theta_{23})$	0.9860	0.0123
Δm^2_{21}	$7.5 \times 10^{-5}\text{eV}^2$	2.53%
Δm^2_{31}	$2.524 \times 10^{-3}\text{eV}^2$	free
δ_{CP}	1.45π rad	free

「Oscillation parameters and priors implemented in MCMC for the sensitivity results.」



「Projections of the standard oscillation parameters with non-zero NSIs.」

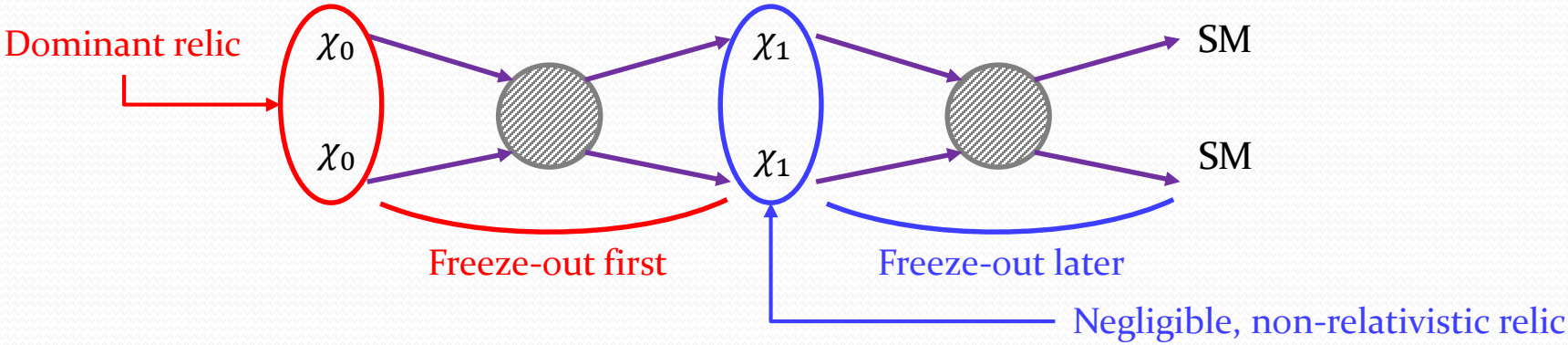
CPT Simulation Parameters

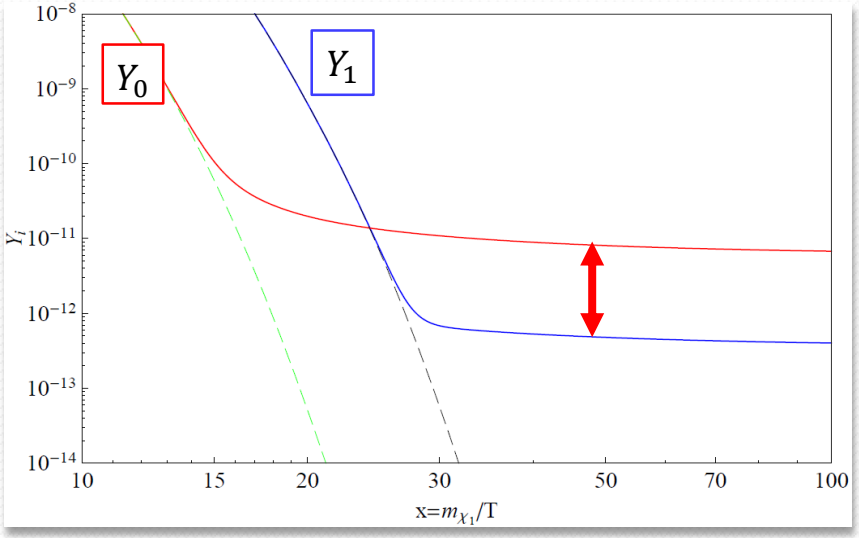
Parameter	Value
Δm^2_{21}	$7.56 \times 10^{-5}\text{eV}^2$
Δm^2_{31}	$2.55 \times 10^{-3}\text{eV}^2$
$\sin^2\theta_{12}$	0.321
$\sin^2\theta_{23}$	0.43, 0.50, 0.60
$\sin^2\theta_{13}$	0.02155
δ	1.50π

「Oscillation parameters for simulation.」

Two-Component Boosted DM Scenario

- A possible relativistic source: BDM scenario (cosmic frontier), stability of the two DM species ensured by separate symmetries, e.g., $Z_2 \otimes Z_2'$, $U(1) \otimes U(1)'$, etc.

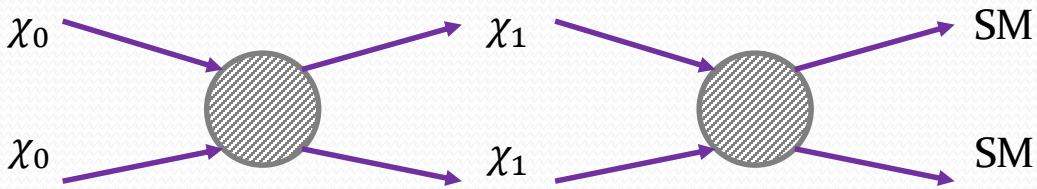




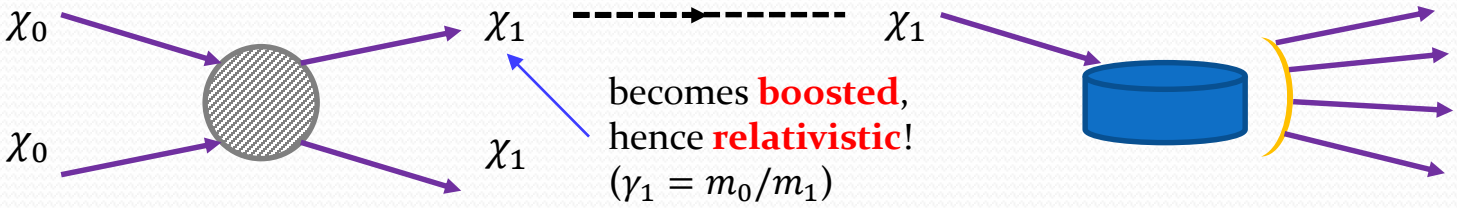
"Assisted" freeze-out mechanism

[arXiv: 1112.4491]

"Relativistic" Dark Matter Search



- ✓ Heavier relic χ_0: hard to detect it due to tiny/negligible coupling to SM
- ✓ Lighter relic χ_1: hard to detect it due to small amount



(Galactic Center at **CURRENT** universe)

(DUNE FD)

[arXiv: 1405.7370]