

The background of the slide is a deep space image featuring a dense field of galaxies and distant stars. A prominent, bright star with a four-pointed diffraction pattern is located in the lower right quadrant. The overall color palette is dominated by deep blues and purples, with golden-yellow highlights from the celestial objects.

Opportunity to study physics beyond standard neutrino oscillations at the upcoming accelerator-based neutrino experiments

Animesh Chatterjee

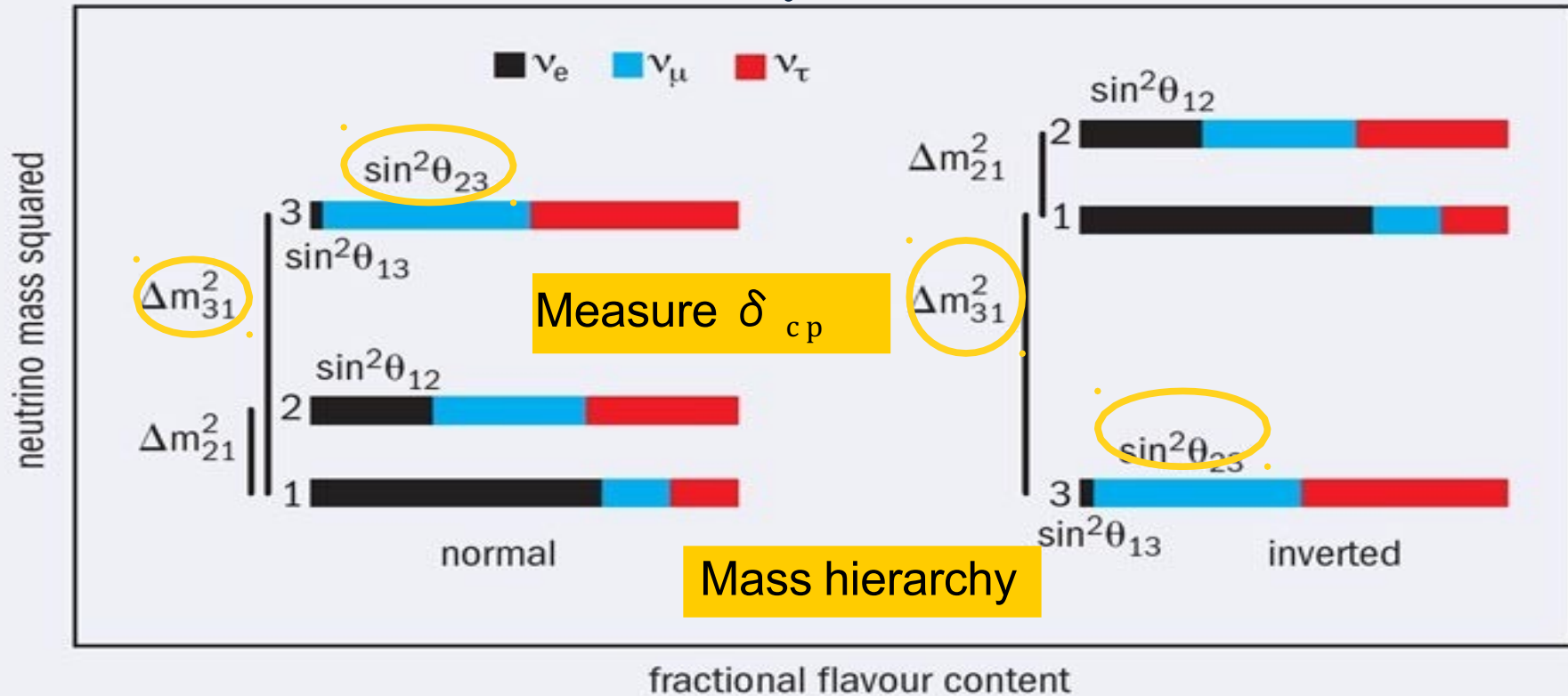
SNOWMASS JOINT WORKSHOP

University of Pittsburgh

February 11, 2022

Neutrino Oscillations

Primary Questions



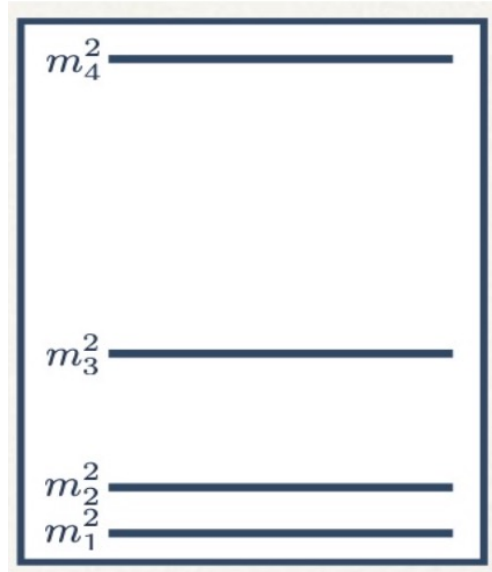
Neutrino mixing matrix :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

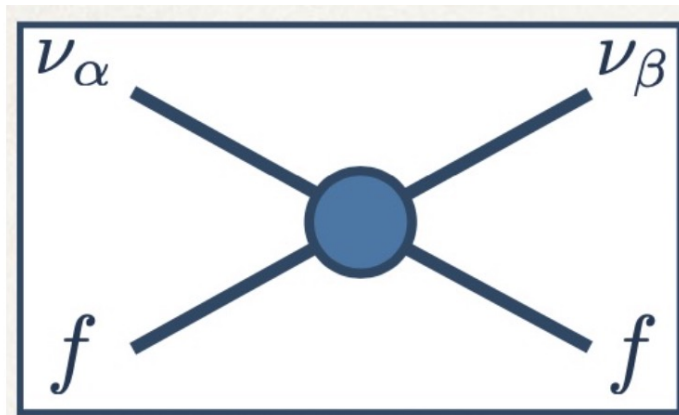
$|U_{e3}|$
(recent
discovery)

Neutrinos have BSM interactions that can modify oscillations ?

- ❖ Are there additional light neutrinos ? eV-scale or otherwise ?



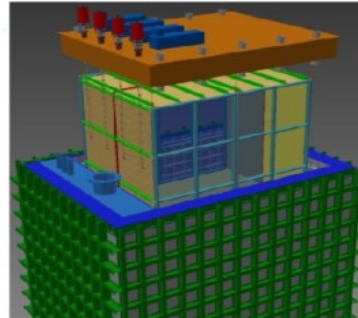
- ❖ Do neutrinos have any additional interactions?



and much, much more

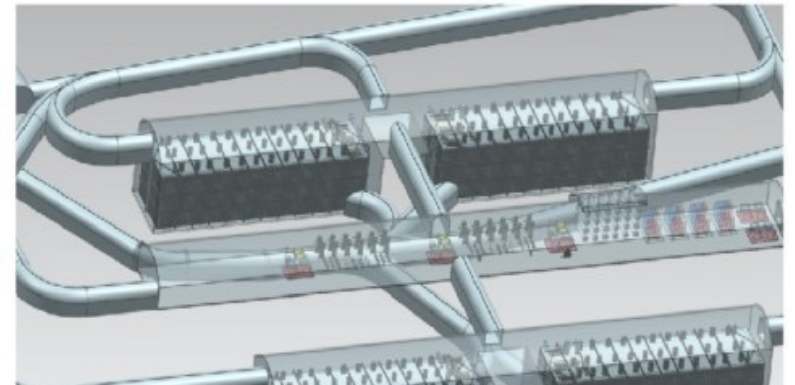
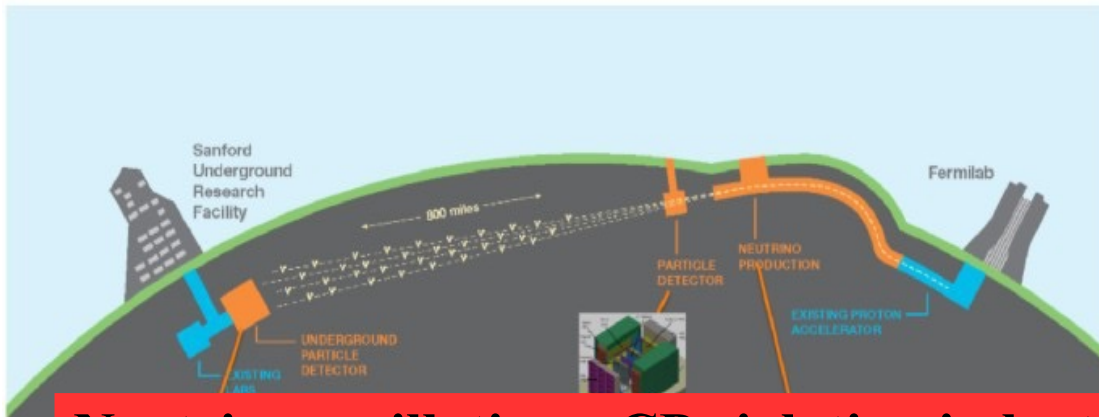
LArTPC for neutrino physics : planned

Planned @FNAL short baseline MicroBooNE + SBND + ICARUS



Search for the existence (or not) of sterile neutrino

Planned DUNE : FNAL to SURF



Neutrino oscillations, CP violation in lepton sector, nucleon decay, observation of unpredicted rare events

DUNE Overview

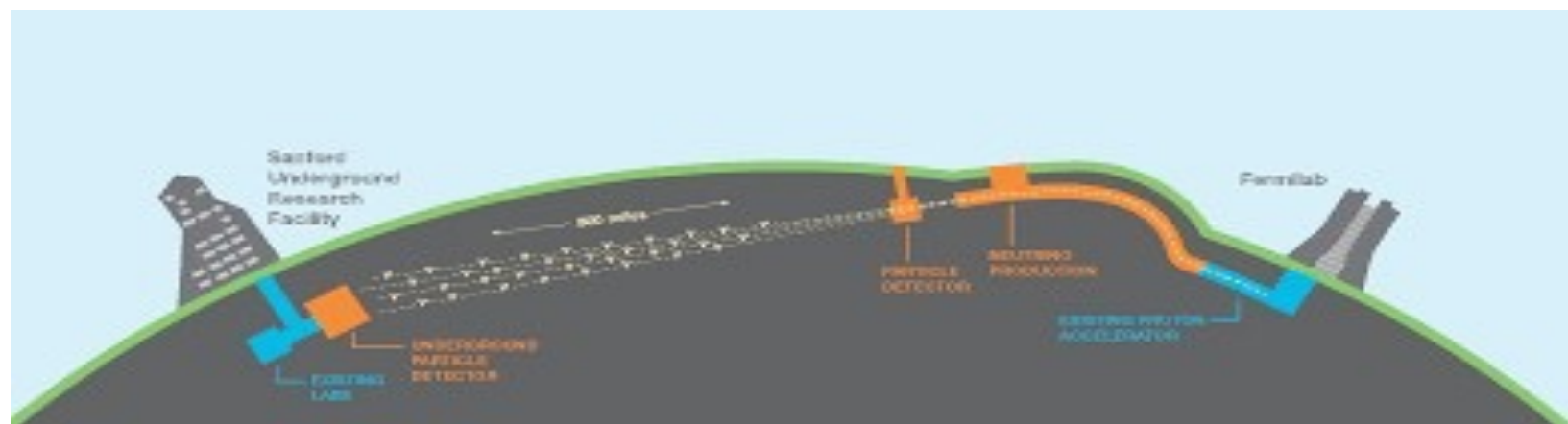
The Deep Underground Neutrino Experiment (DUNE) is a leading edge, international experiment for neutrino science and proton decay

Features of DUNE:

- 1300 km baseline : "LBL"
- Most intense neutrino beam : "LBNF"
- Large (40kt) LArTPC far detector and near detector
- Far detector 1.5 km underground

Primary Physics goals :

- ν oscillations
 $MH, \delta_{cp}, \theta_{23}$
- Physics beyond standard model
- Nucleon decay
- Supernova burst neutrinos



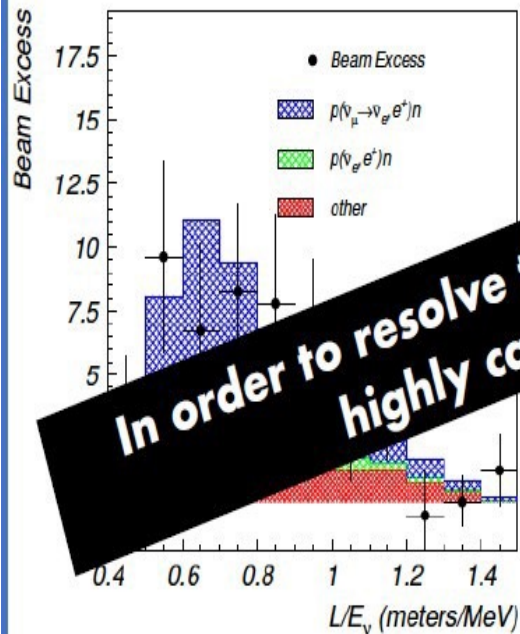
DUNE prototype LArTPC detectors developed at CERN

*** protoDUNE Single Phase LArTPC**

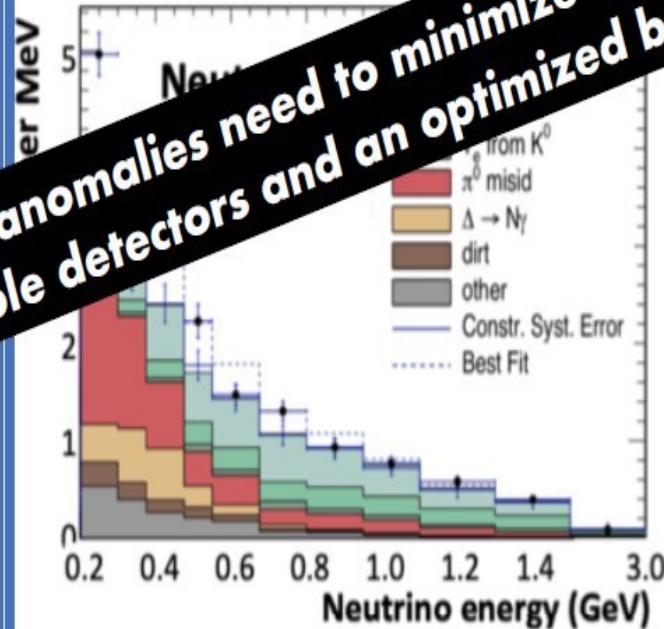
*** protoDUNE Dual Phase LArTPC**

Short Baseline Neutrino (SBN) program: Motivation

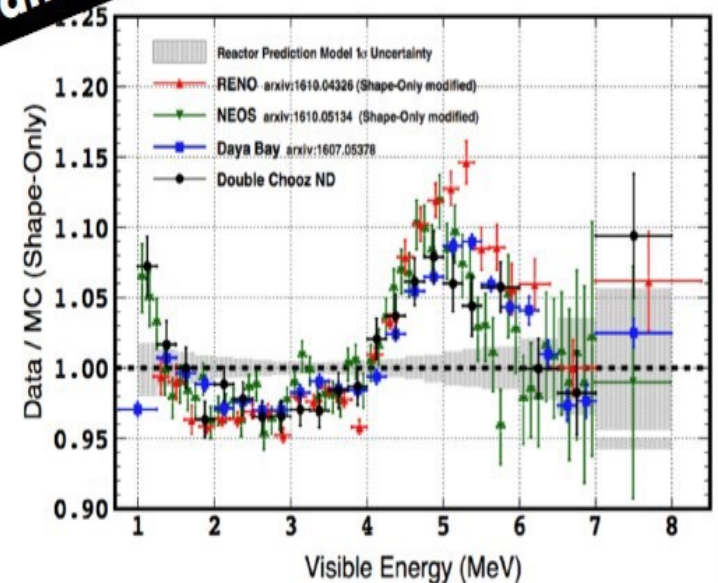
- **LSND** anomaly (1998): π decay at rest with $\langle E_\nu \rangle = 30 \text{ MeV}$, $L/E \sim 1 \text{ m/MeV}$, **3.8σ** excess



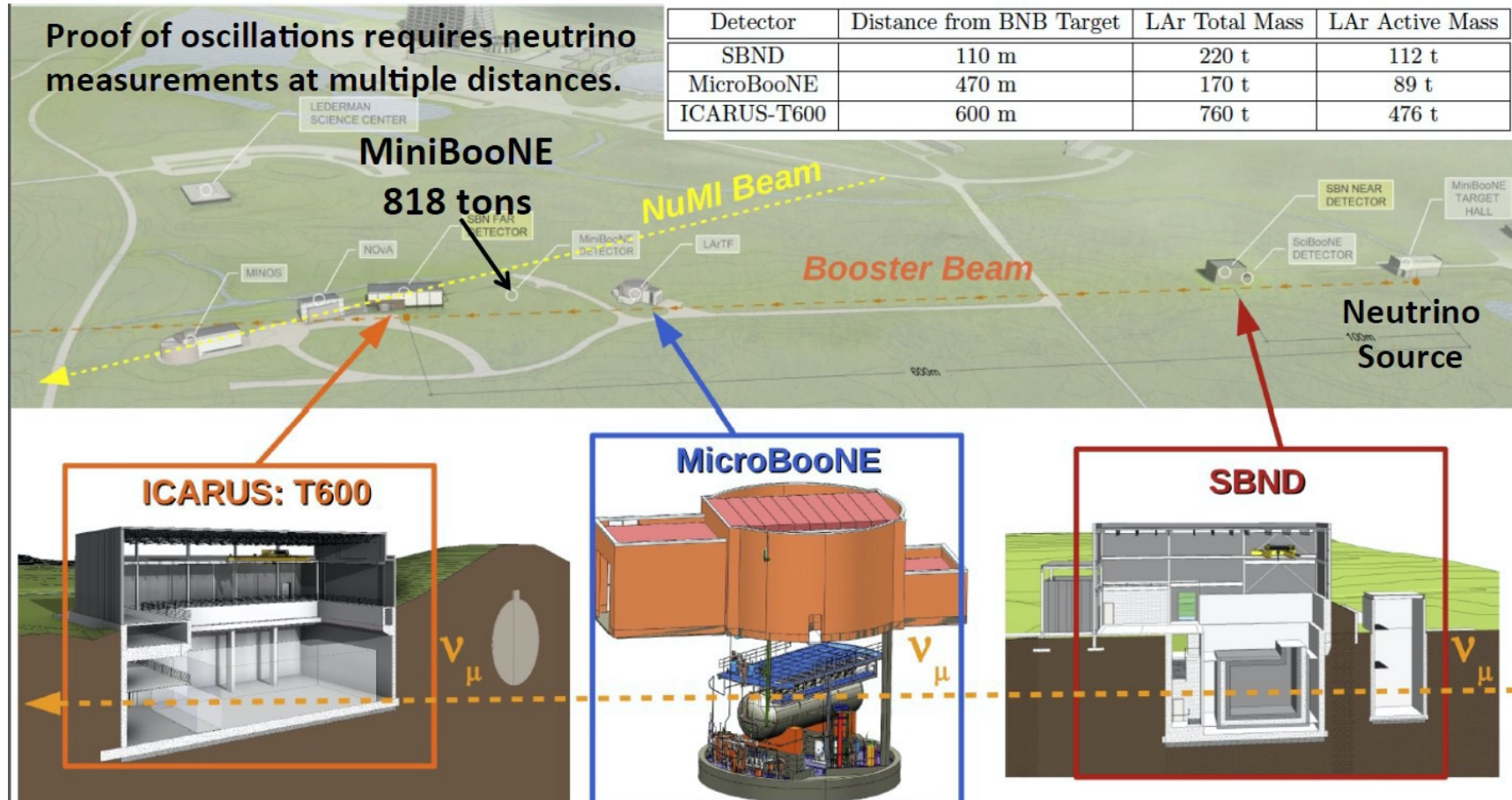
- **MiniBooNE** anomaly (2007): (Anti-) ν_μ beam with $200 < E_\nu [\text{MeV}] < 1250$, same L/E , **4.7σ** excess



- **Reactor** anomaly (2011): A recent reevaluation of flux measurements from reactor experiments now show a $\sim 6\%$ deficit



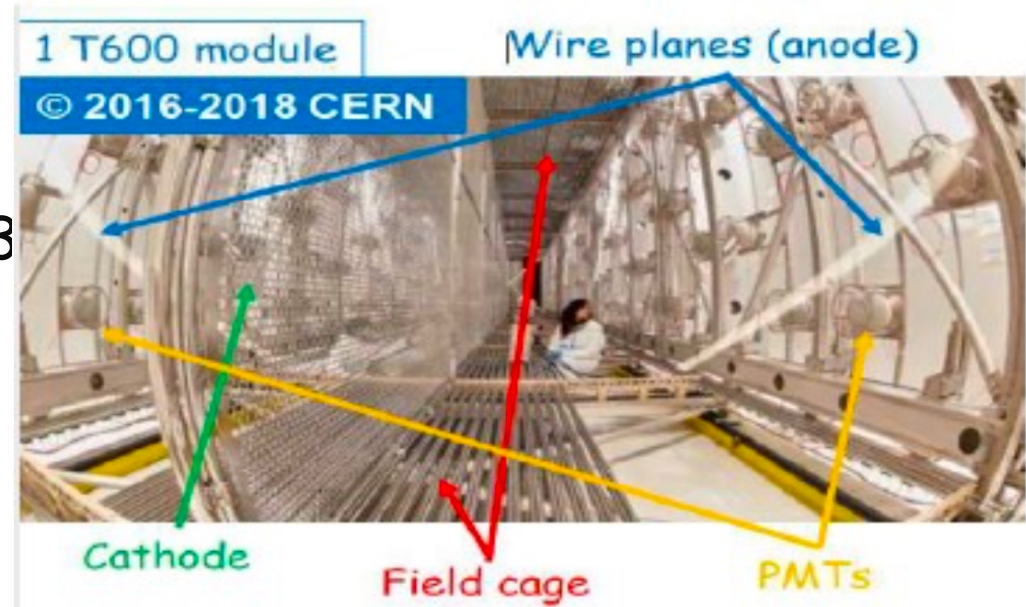
Search for Sterile Neutrino: Short-baseline neutrino experiment



- ❖ Short-baseline neutrino experiment (SBN) designed to solve anomaly by looking with the existence (or not) sterile neutrino
- ❖ Same experimental setup can be used for looking other BSM using fixed target data

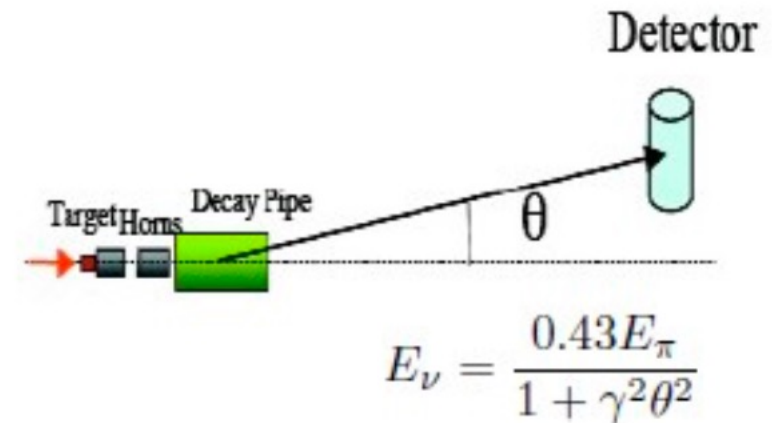
ICARUS-T600 at SBN Program

- ❖ First large-scale LAr-TPC in a neutrino beam
- ❖ Two identical modules: each module size : 19.6 (L) x 3.6(W) x 3.9(H) m³ ; total LAr mass ~760 tons, active LAr mass 476 tons.
- ❖ Drift distance 1.5m, drift field 500V/cm → drift time ~ 1ms.
- ❖ Detector commissioning ongoing, will start “physics data” taking with neutrino beam soon!



Physics Motivation :

- ❖ Primary physics motivation of ICARUS experiment is search for the existence (or not) sterile neutrino.
- ❖ ICARUS is located 103 mrad off axis from NuMI beam.
- ❖ ICARUS Detector with NuMI Off axis beam will play a key role in BSM search



Are there any new interactions ?

- ❖ Neutrino interactions via the SM W- and Z-bosons have been observed, but what if there are additional interactions ?
- ❖ Neutral current non-standard neutrino interactions in neutrino propagation can be described as new contributions to the MSW effect.

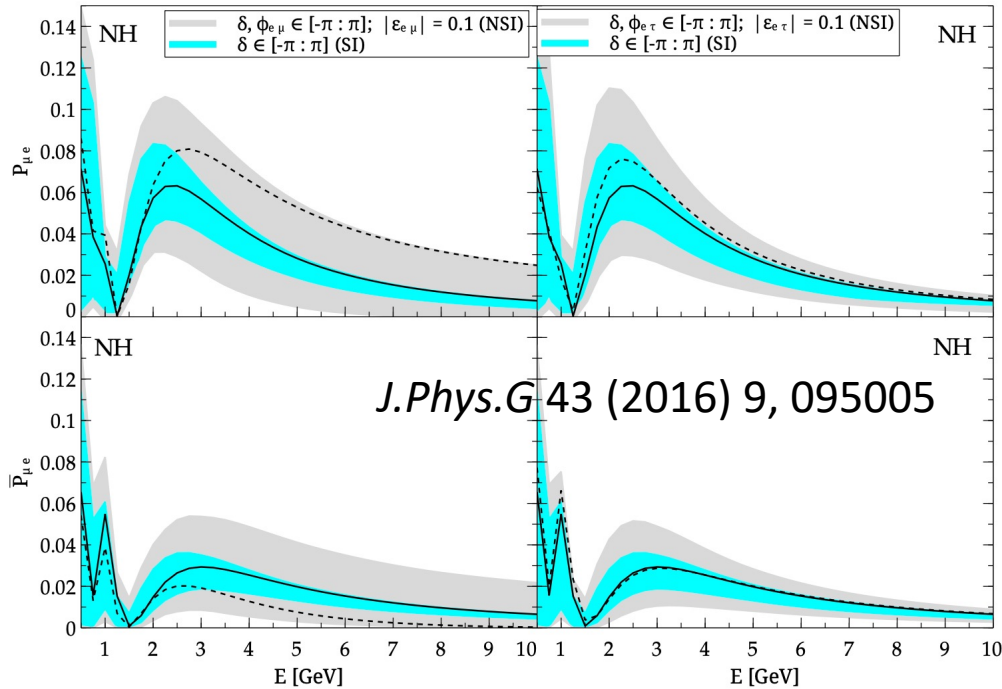


$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{2E} \left[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + a \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

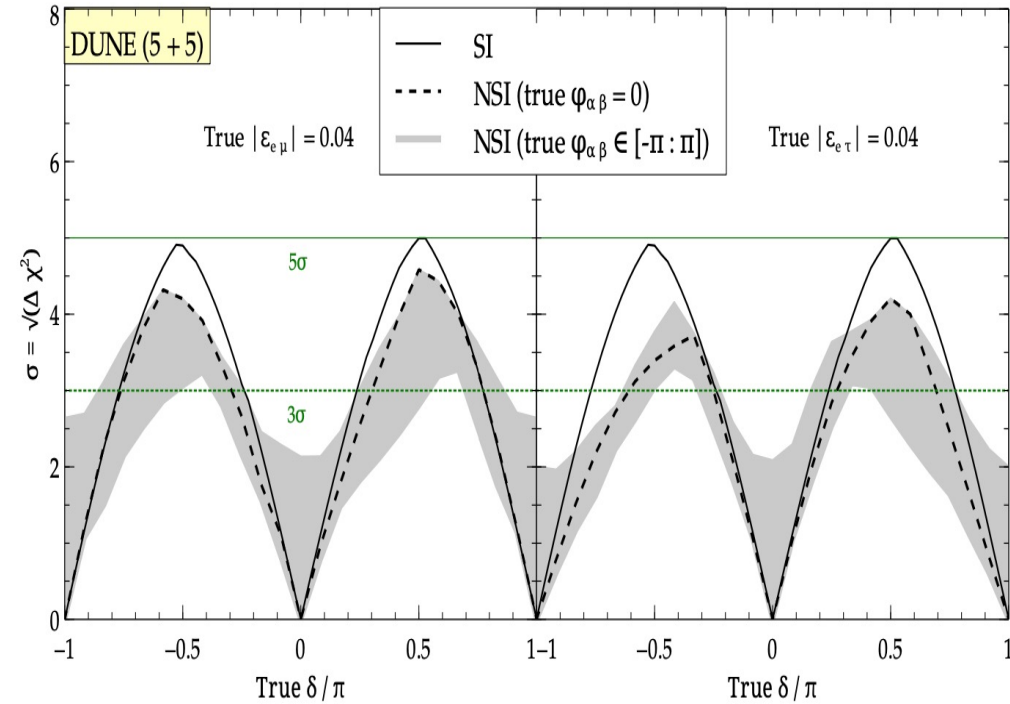
- ❖ Recent studies show the impact of the NSI parameters on the measurement of neutrino oscillation parameters at DUNE.

Effect of NSI on the δ_{cp} measurement

SI-NSI degeneracy on appearance probability



Effect of NSI on the CP Violation sensitivity at DUNE



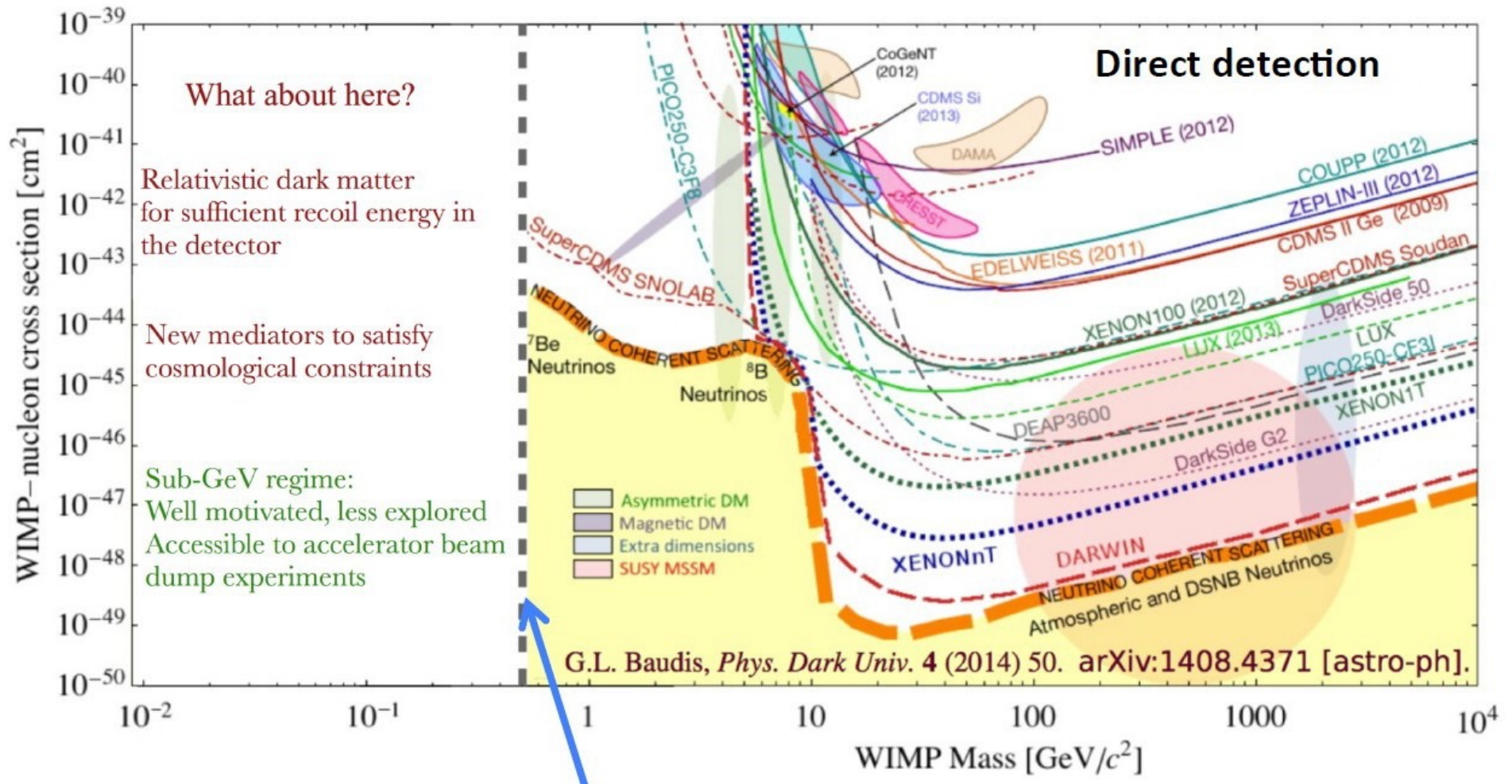
- ❖ The effect of nsi parameters (amplitude and phase) on the appearance probability is significant
- ❖ The impact of $\epsilon_{e\mu}$ ($\epsilon_{e\tau}$) is shown in the left (right) plot. The black solid (dashed) line depicts the case of SI (NSI with true values of all the NSI phases set to zero).
- ❖ Need to resolve the degeneracy in order to conclude about the discovery of the cp violation.

Similar degeneracy have been studied for other oscillation parameters; one needs to develop a mechanism to resolve the degeneracy

DARK MATTER

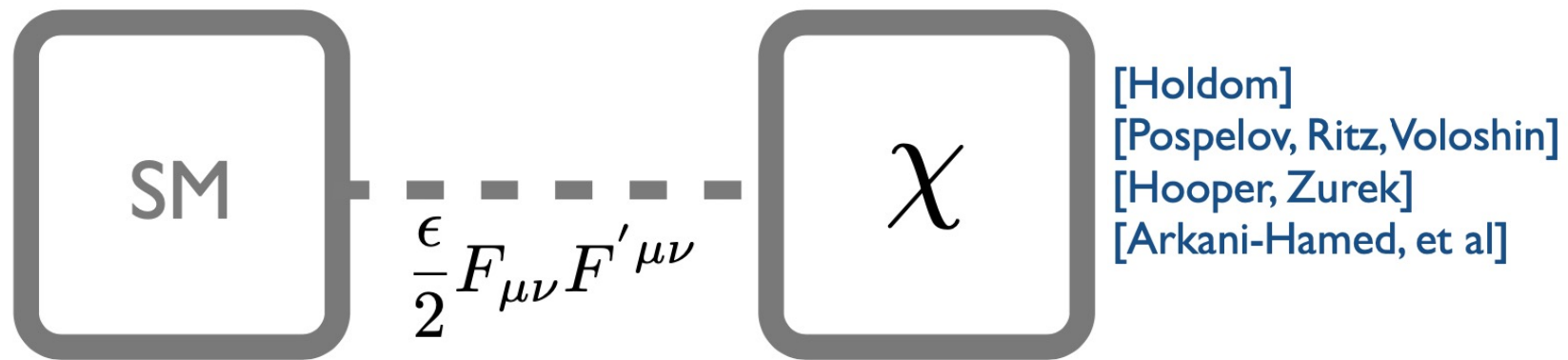


Experimental motivation for searching sub-GeV DM using Neutrino detectors



- ❖ Direct detection $\sim \text{GeV}$ threshold limit
- ❖ Accelerator based fixed target experiment has experienced much recent theoretical and experimental activity below GeV range

Benchmark model : vector portal dark matter

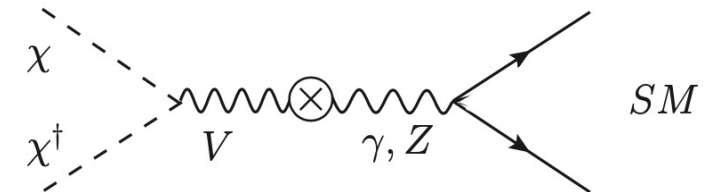


$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} (F'_{\mu\nu})^2 + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \dots$$

❖ *Dark photon mediates interaction between DM and SM*

❖ *4 new parameters; $m_\chi, m_{A'}, \alpha_D, \epsilon$*

❖ *Can obtain correct relic abundance*

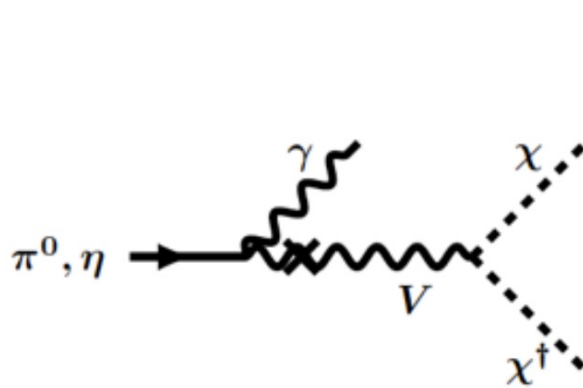


❖ *Variations in cosmology and phenomenology obtained by changing mediator, or dark matter properties - important to explore all options*

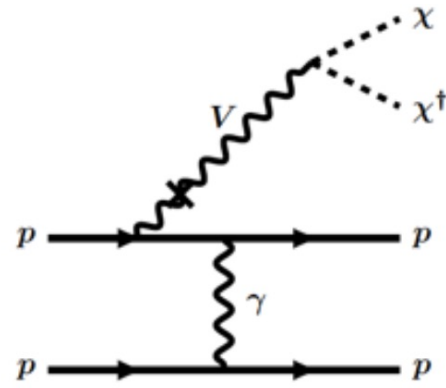
Sub-GeV DM Production and detection

❖ *MeV-GeV gauge boson kinetically mixed*

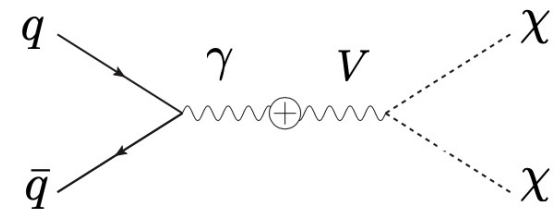
❖ *Production of DM beam:*



Neutral mesons decays

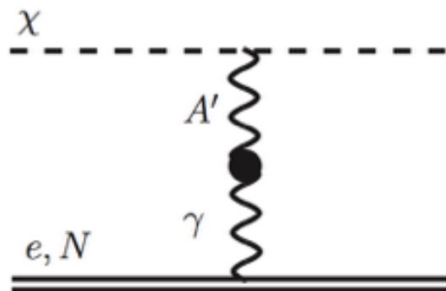


Bremsstrahlung + vector
meson mixing

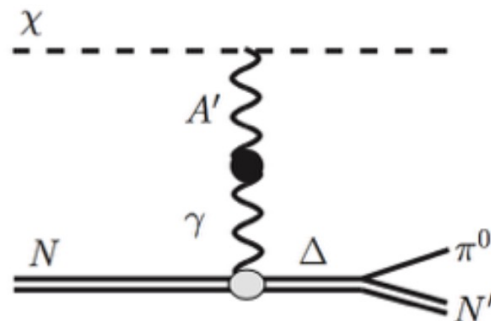


Direct production

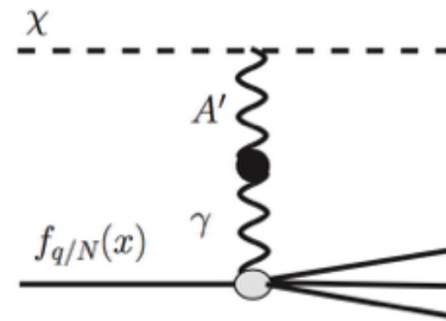
❖ *Detection of DM via scattering :*



Elastic NC nucleon or
electron scattering

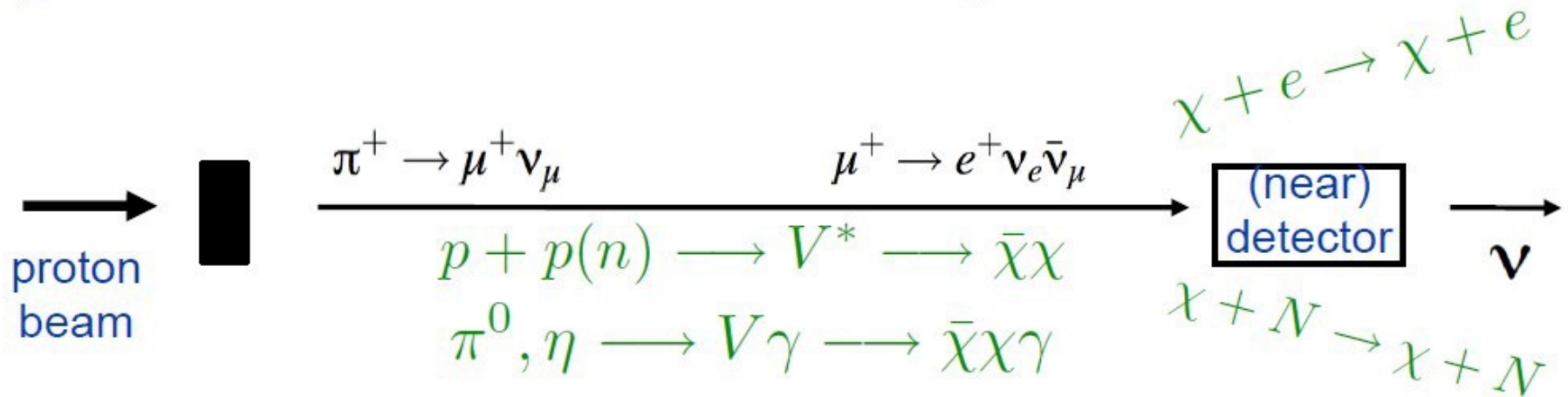


Inelastic NC neutral pion -
like scattering



Deep Inelastic scattering

DM Search with fixed target: Neutrino detectors



We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now with accelerator based proton beam

MiniBooNE

8GeV BNB Beam
540m to the mineral oil detector

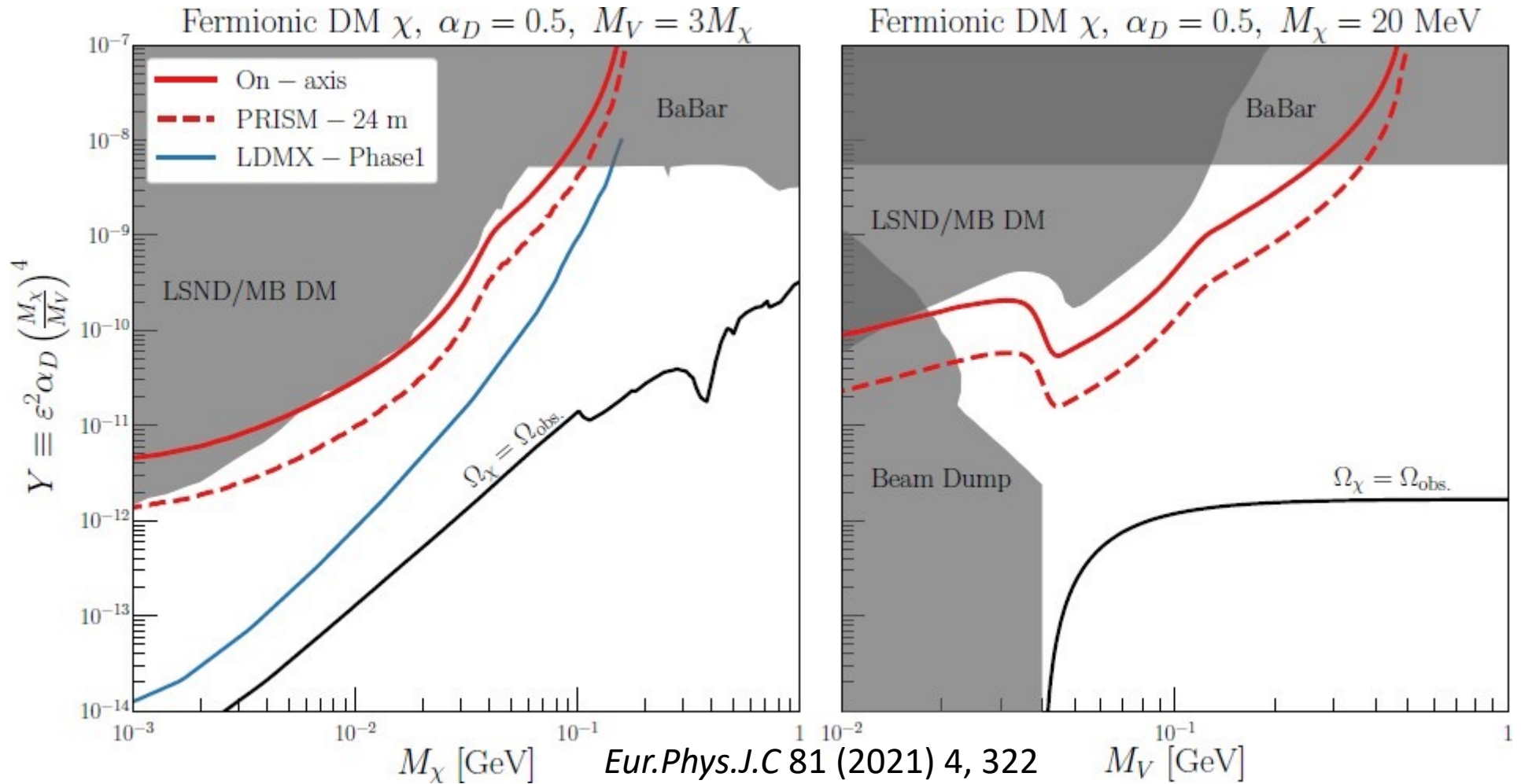
SBN

8.9 GeV BNB and 120 GeV NuMI Beam, 3 LArTPC detector

DUNE Near detector

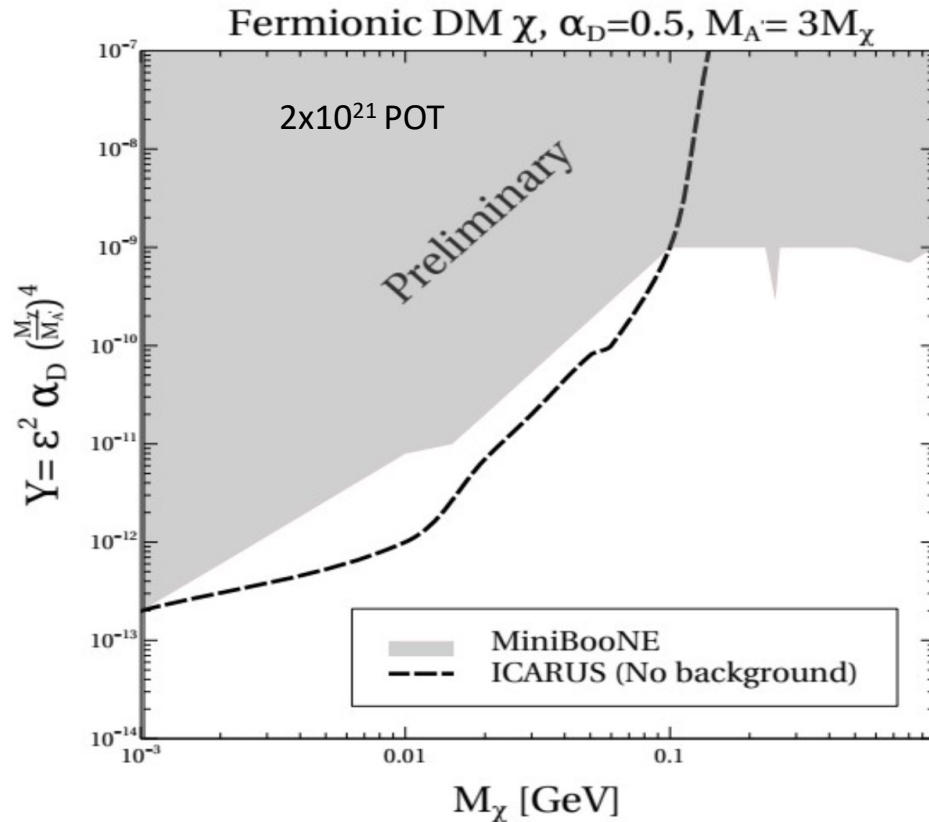
120 GeV LBNF Beam
Multipurpose near detector

Constraints on DM coupling with SM: DUNE



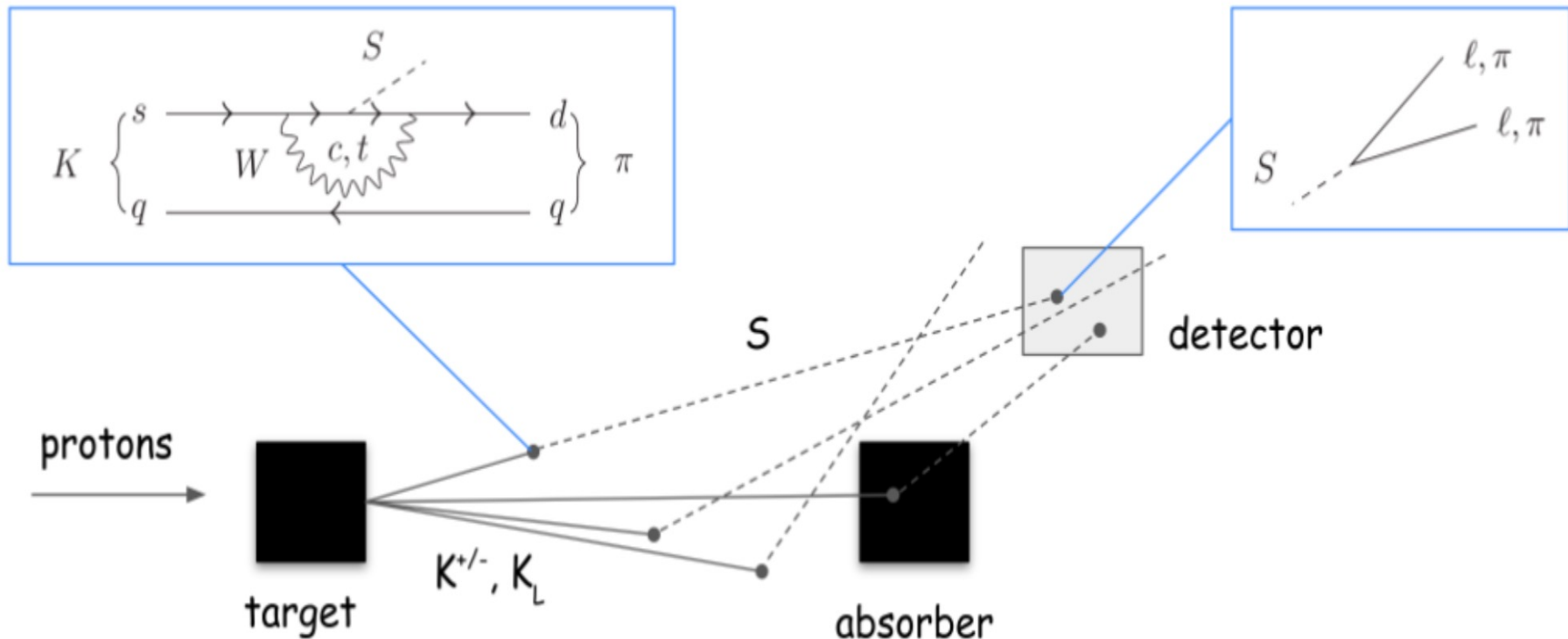
DUNE-PRISM located at 24 m off-axis from the beam will be very useful, currently under consideration within the collaboration

Sub-GeV DM study: ICARUS@SBN



- ❖ The ICARUS detector is located 103 mrad off axis from NuMI (120GeV) beam.
- ❖ Off axis location and larger fiducial volume of the detector will give better sensitivity compared to MiniBooNE experiment
- ❖ ICARUS will start data taking from next month.

Higgs Portal @ICARUS using NuMI beam

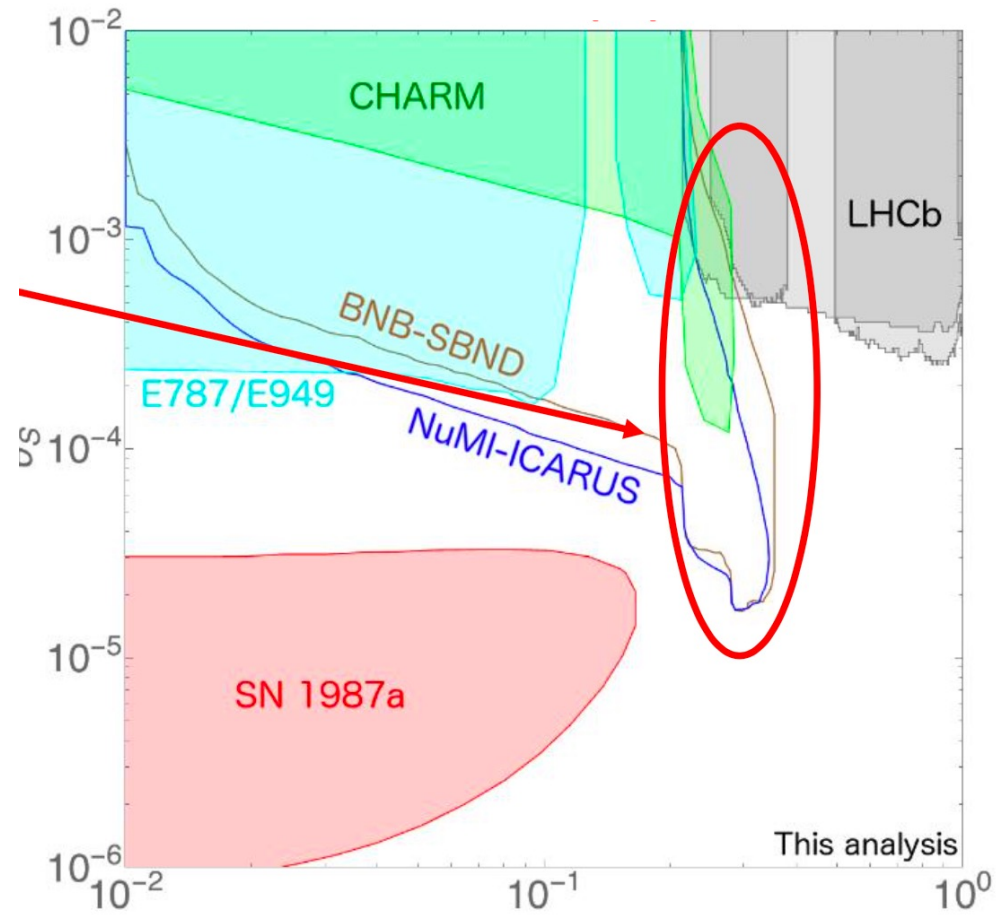
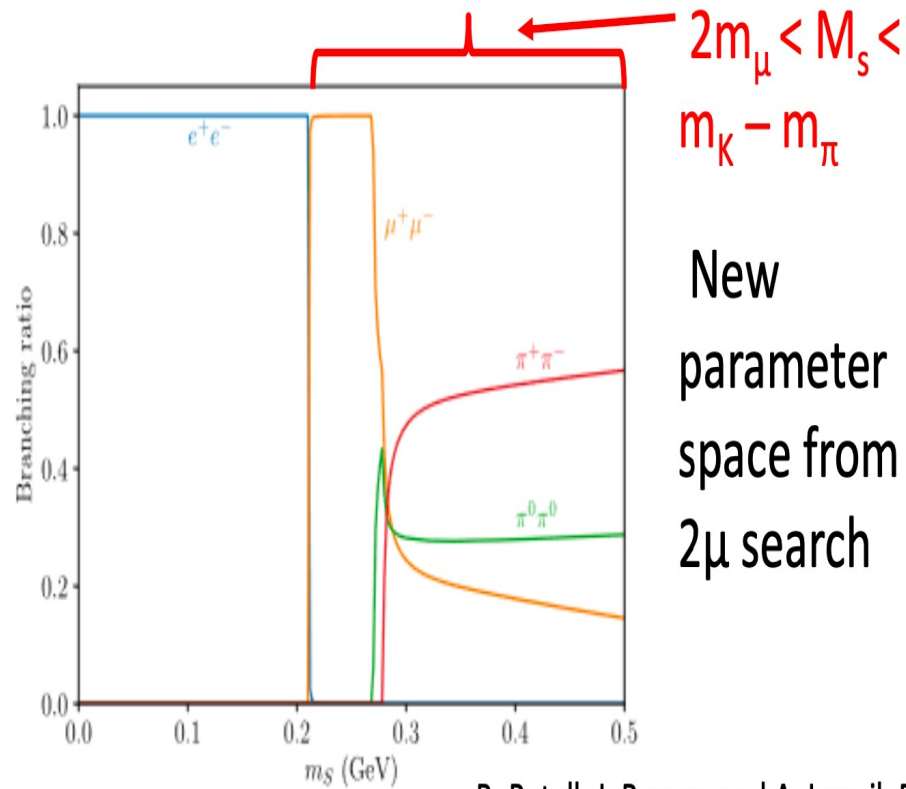


B. Batell, J. Berger, and A. Ismail. Phys. Rev. D 100, 115039

- ❖ For the SBN experiments the most important production channel will be through kaon decays
- ❖ With the higher energy of the NuMI beam and the angular spread in the produced scalars, the ICARUS detector @SBN can have significant sensitivity to scalars produced with the beam.

Higgs Portal at ICARUS NuMI

- ❖ The NuMI beam at ICARUS can probe new parameter space of the Higgs Portal

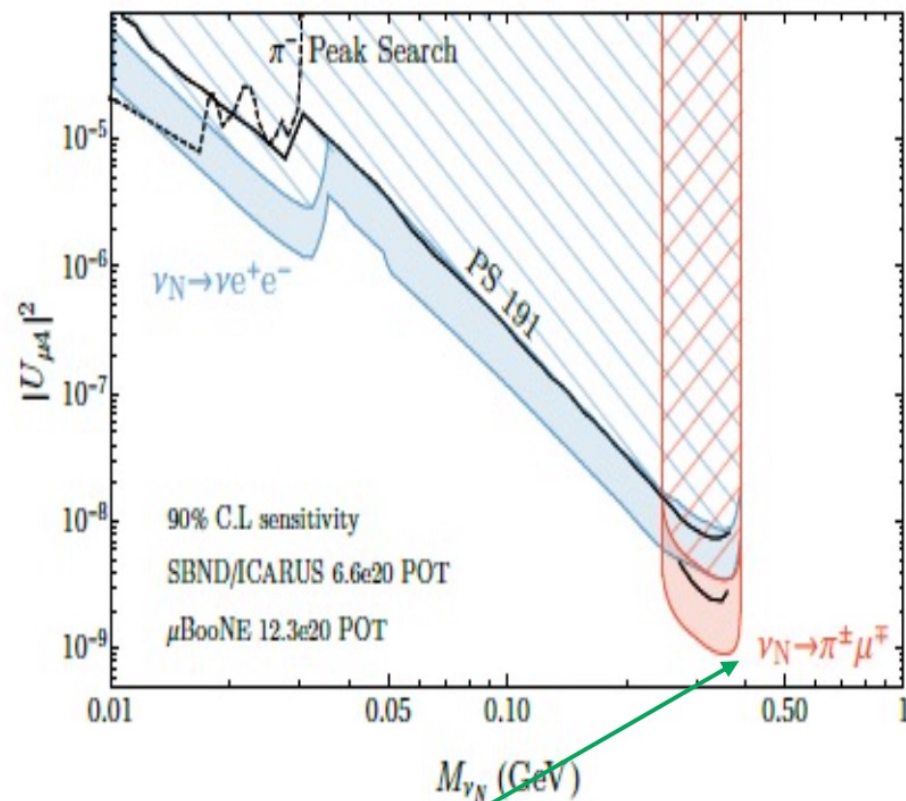


B. Batell, J. Berger, and A. Ismail. Phys. Rev. D 100, 115039

- ❖ There are on-going effort at ICARUS to look both for $2u$ and e^+e^- channel

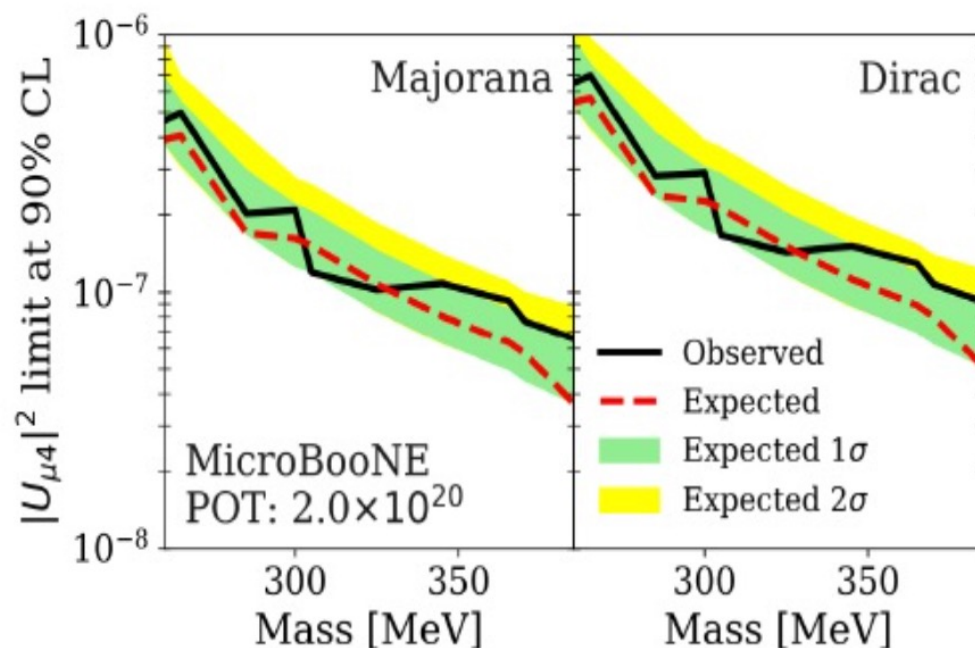
Search for Heavy Neutral Lepton

Searches for HNL's have been studied for BNB@SBN



Projected BNB limit for $\mu \pi$ final state (arxiv:1610.08512)

uBooNE experiment published the result with the data (PhysRevD.101.052001)



In addition to the Higgs Portal, Heavy Neutral Leptons look like promising candidate to search @ICARUS

Outlook

- ❖ Over the last twenty years, extraordinary discoveries in neutrino physics have led to the development of new, intense neutrino sources and new, very sensitive and very large neutrino detectors.
- ❖ Understanding the degeneracy between the standard neutrino oscillations and non-standard effects is very crucial for the discovery of unknown neutrino oscillations parameters.
- ❖ Multiple detectors at the DUNE-ND will be ideal to probe different neutrino BSM as well as DM searches.
- ❖ SBN program with three LArTPC detector designed for the sterile neutrino search, will play key role for the BSM searches.
- ❖ ICARUS detector with NuMI off-axis beam will be suitable set-up for BSM searches.
- ❖ ICARUS will start “physics data” taking soon! Stay tuned

A wide-angle photograph of a large industrial facility, likely a cleanroom or a high-tech manufacturing plant. The floor is made of large, polished metal plates that reflect the overhead lights. On either side of the central aisle, there are concrete walls topped with orange safety railings. The ceiling is high and features a complex network of steel beams, pipes, and numerous bright industrial lights. In the background, a yellow overhead crane is visible. The overall atmosphere is clean, modern, and industrial.

Thank you