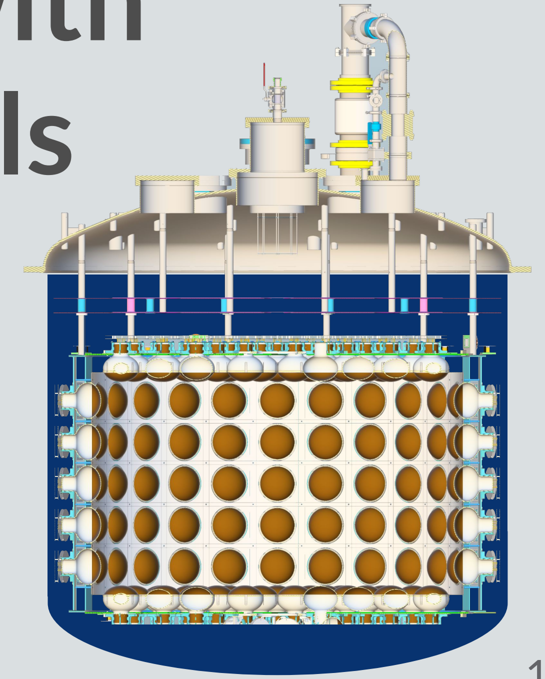
Dark Sector Searches with Coherent CAPTAIN Mills



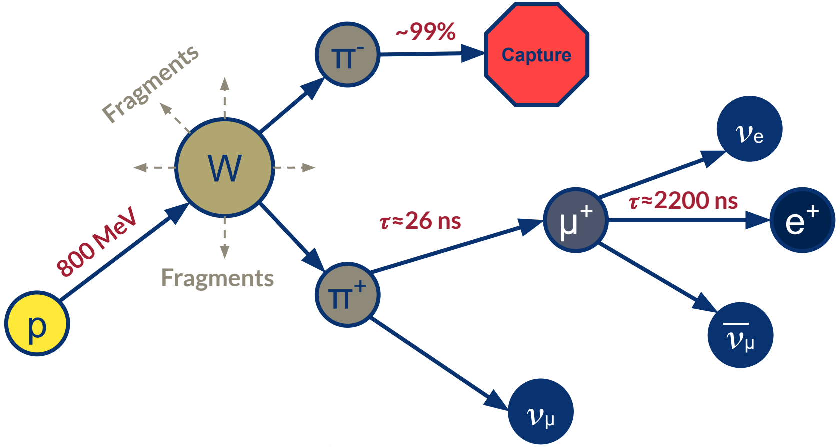
Austin Schneider
Magnificent CEvNS 2024
2024-06-14

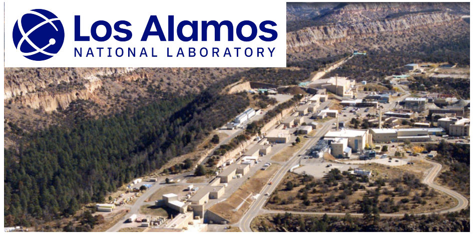
Lujan target neutrino production

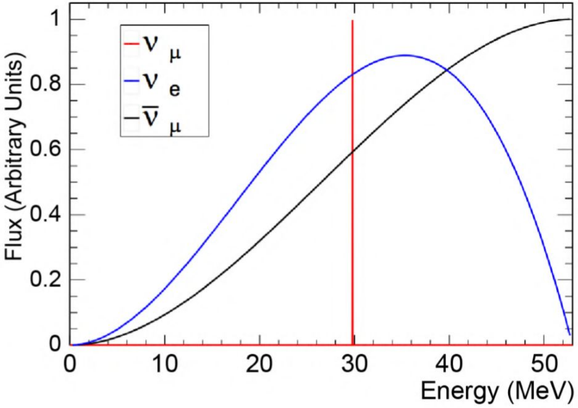
- 800 MeV pulsed proton beam
- 20 Hz | 100 micro-amps | 290 nsec spill

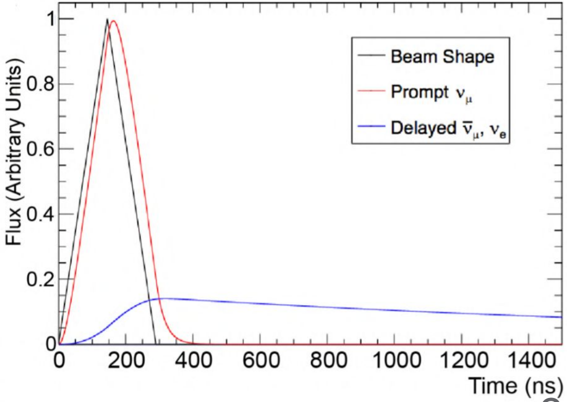
- π+ decay at rest is a prolific source of neutrinos
- Prompt NuMu neutrinos at 30 MeV
- Delayed NuE and NuMuBar

- Target environment has an intense flux of: charged pions, neutral pions, gamma-rays, muons, neutrinos, and neutrons





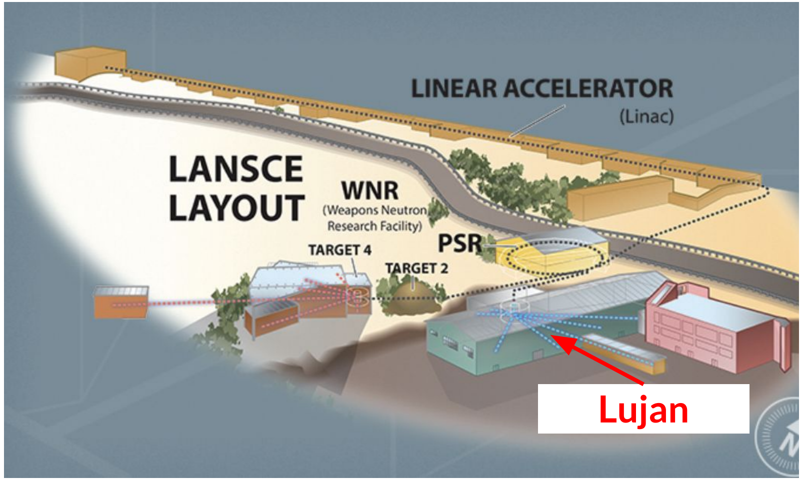


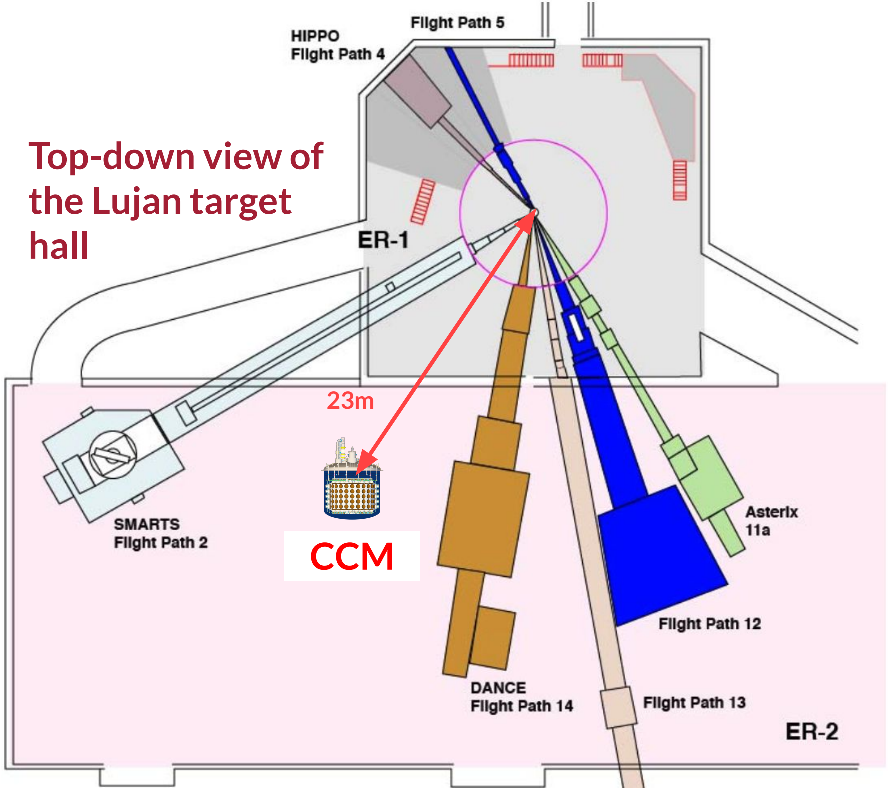


CCM at Lujan

- CCM is 90° off axis from the beam
- Avoids decay-in-flight backgrounds
- 23m from target

Top-down view of the Lujan target hall





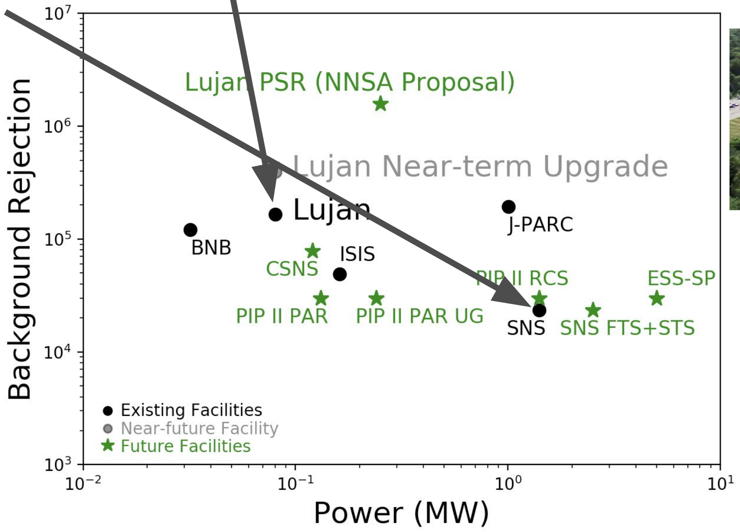
Comparing Lujan to SNS

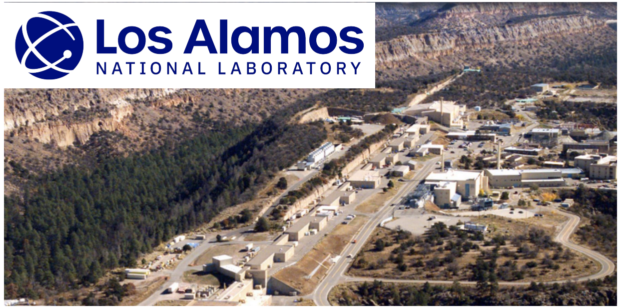
Lujan target at LANSCE

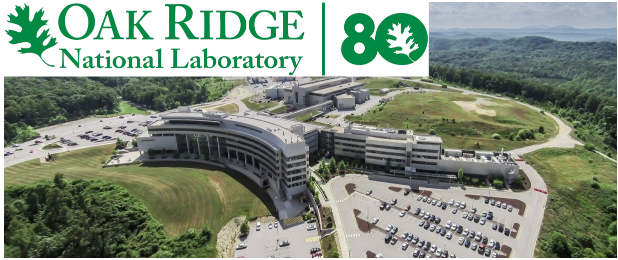
- Located at Los Alamos National Laboratory
- 800 MeV protons
- 20 Hz | 100 μA | 290 ns spill

Spallation Neutron Source (SNS)

- Located at Oak Ridge National Laboratory
- 1 GeV protons
- 60 Hz | 1 mA | 700 ns spill

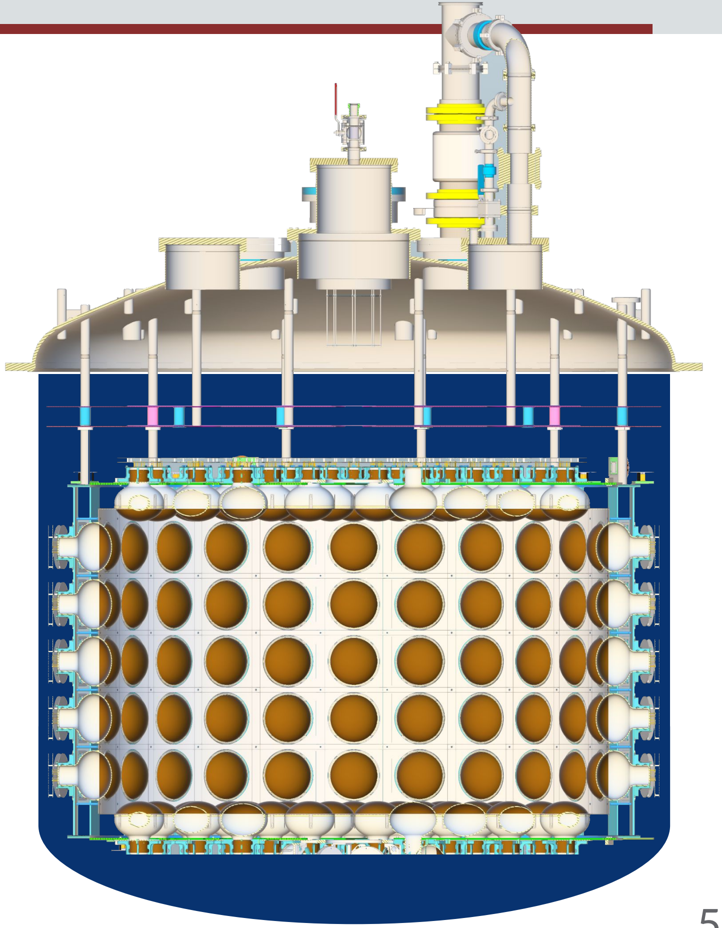


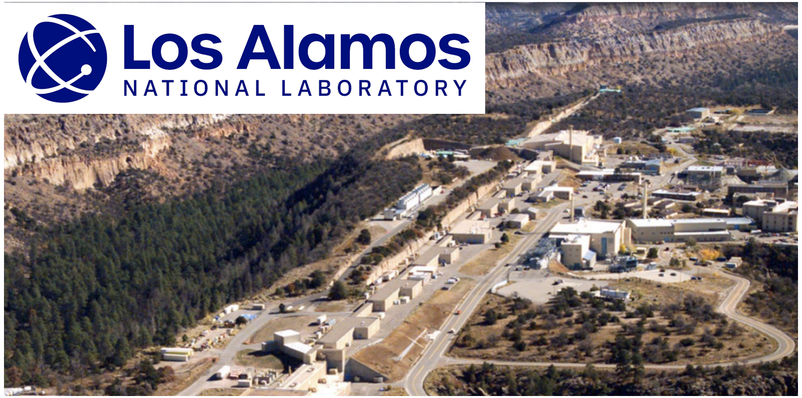




Coherent CAPTAIN-Mills (CCM)

- 10 ton LAr optical detector
- 200 8” PMTs → 50% photo-coverage
- 5 ton fiducial volume
- 3 ton active veto region
- Mid-way through 3yr data taking period
    - 2.25×10^{22} POT
- Located at the Los Alamos Neutron Science Center



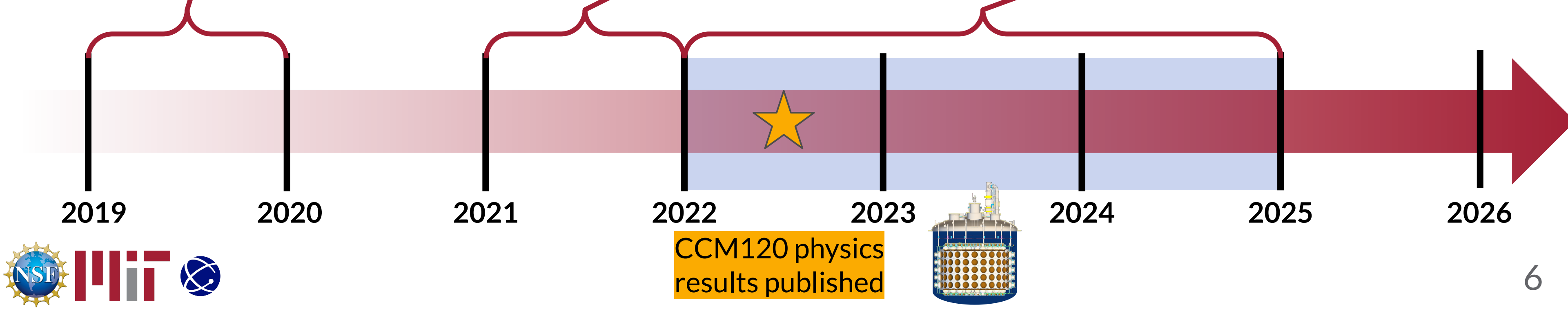


Timeline

CCM120 Engineering run
- Prototype run
- Testing 120 PMTs for SBND
- First physics results

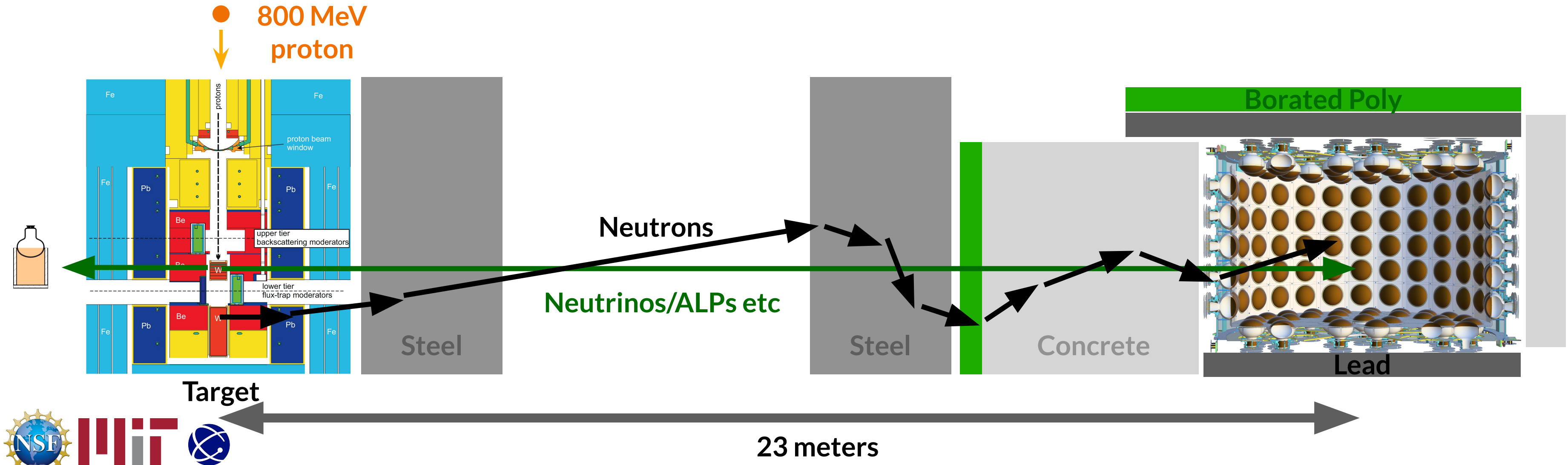
CCM200 Engineering run
- Upgraded detector to 200 8” PMTs
- Doubled veto PMT coverage
- Increased forward shielding

CCM200 Physics run 2022 - 2025
- Improved DAQ to handle increased data rate
- Installed additional top shielding
- Higher energy calibration sources
- Improved analysis techniques



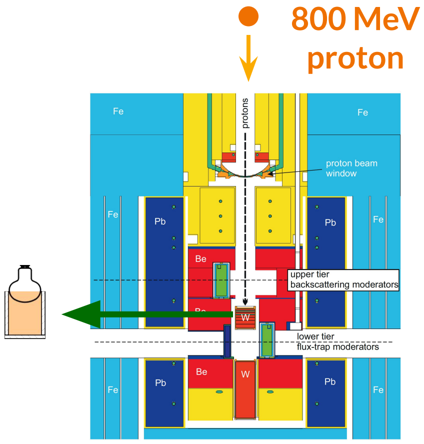
Backgrounds

- 90 degrees off axis → no decay-in-flight contamination
- Lots of neutrons produced by spallation source
- Shielding attenuates neutrons, active veto allows us to tag neutrons entering our detector

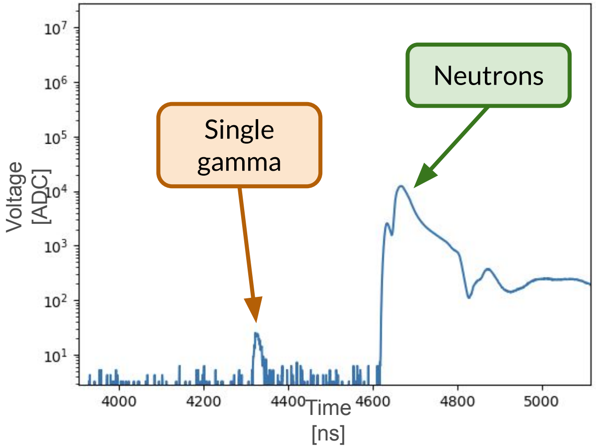


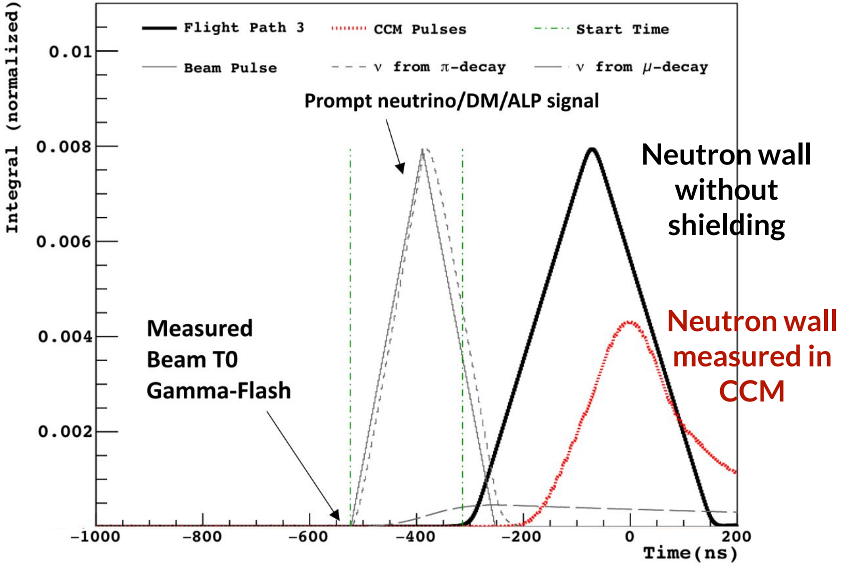
Backgrounds

- Precise timing using measured gamma flash allows us to isolate speed of light particles
- Remaining backgrounds are **steady-state** and **measured in-situ**



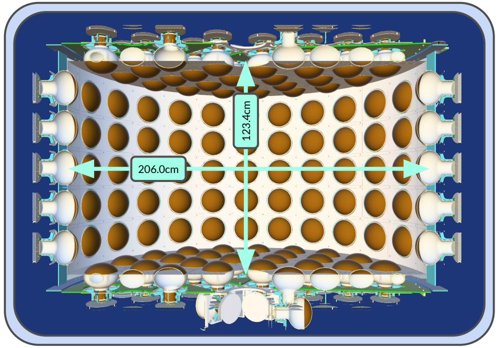
Target

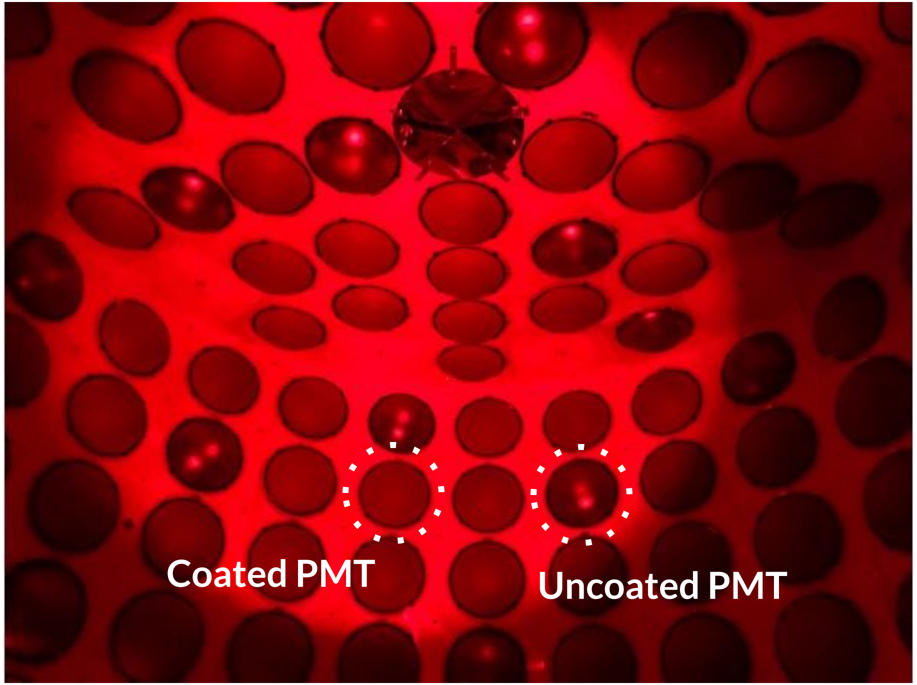




Coherent CAPTAIN-Mills (CCM)

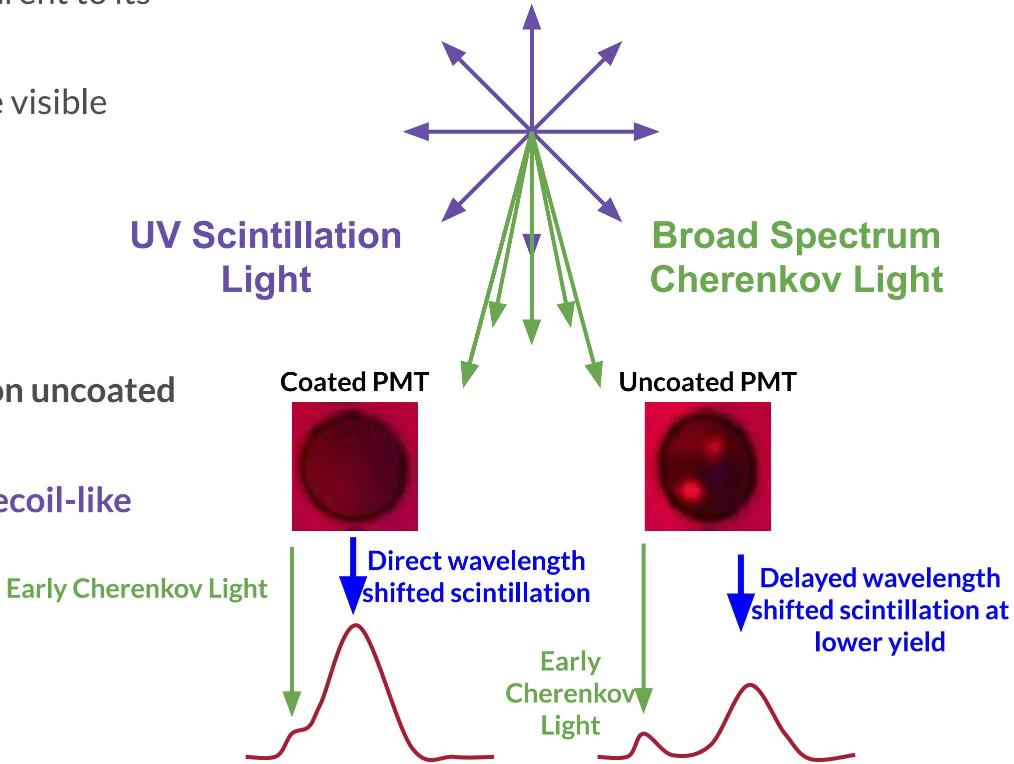
- Electronics have **2ns** sampling time
- Sensitive between ~10keV and ~200MeV
- 80% of PMTs coated in 1,1,4,4-Tetraphenyl-1,3-butadiene (TPB) to **wavelength shift LAr scintillation light**
- TPB foils cover detector walls

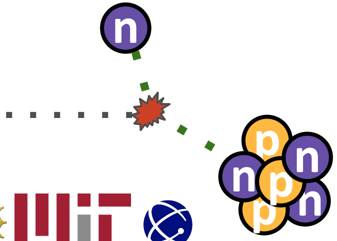


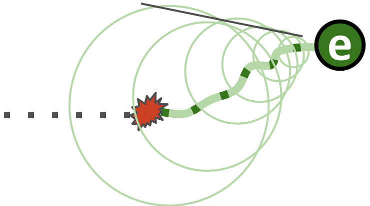


CCM light collection

- Liquid argon is a prolific UV scintillator, transparent to its own scintillation light
- TPB shifts 128nm scintillation photons into the visible spectrum (increasing light yield)
- Walls of detector are TPB coated
- Mix of coated and uncoated PMTs aid particle identification
- **Can isolate broad-spectrum Cherenkov light on uncoated PMTs**
- Provides a handle for differentiating **nuclear-recoil-like** and **electron-like events**







Physics searches with CCM

Contaminants (O_2 / N_2) absorb LAr scintillation light

⇒ Threshold raised to ~100 keV ⇒ ~~CEvNS~~

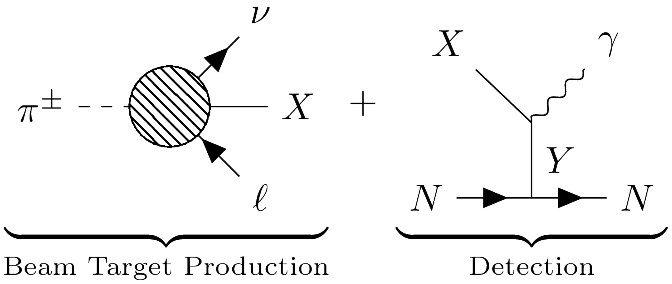
Sensitive to MeV-scale BSM signatures

Dark Sector Coupling to Meson Decay

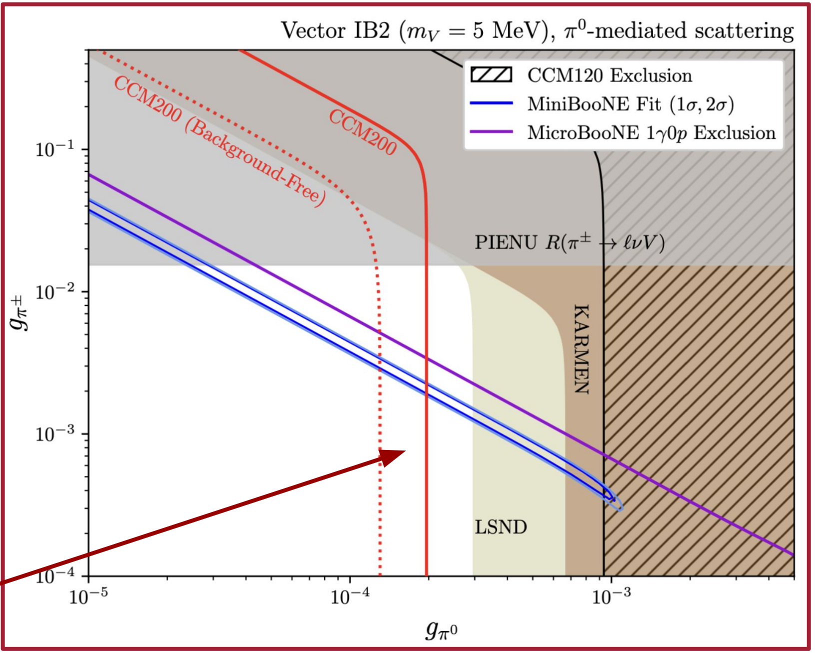
PhysRevD.109.095017

Introduce:

- A rare 2-body neutral pion decay to a photon and a bosonic long-lived particle (LLP),
- the production of this LLP from the three-body decay of the charged mesons,
- and subsequent photoconversion of the LLP



- CCM 200 provides complementary sensitivity

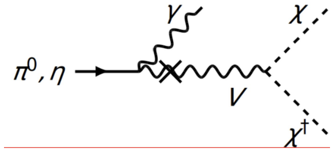


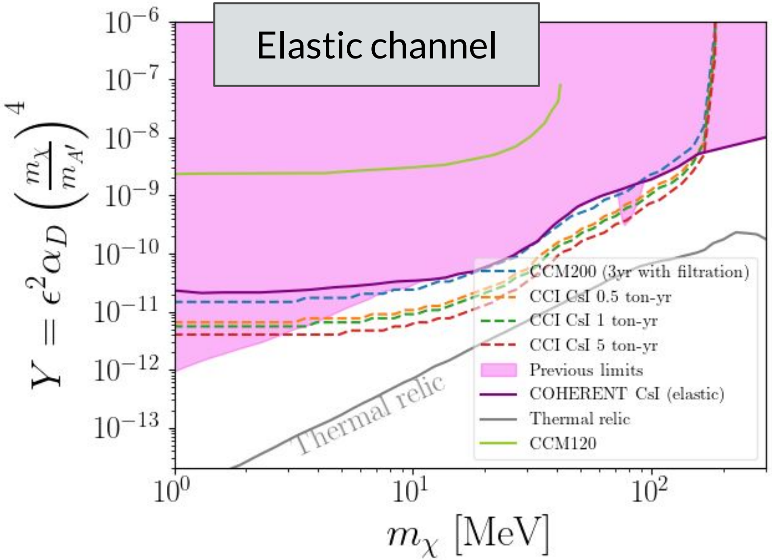
Possible explanation for MiniBooNE's low-energy-excess

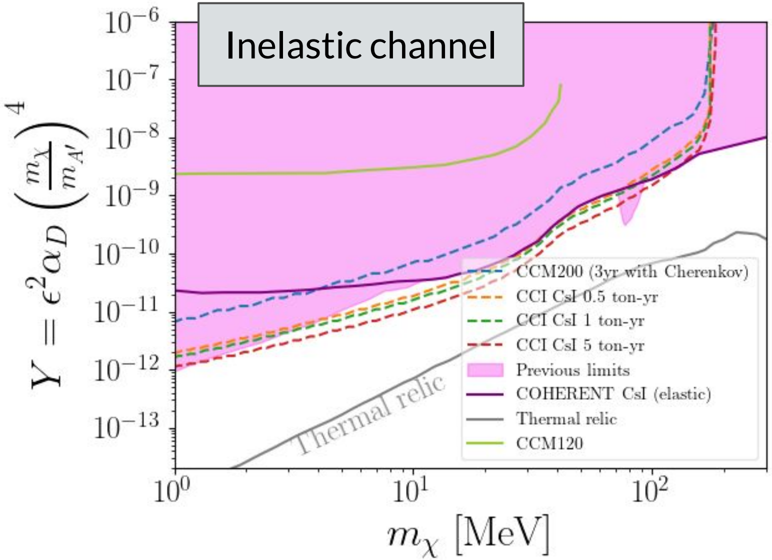
Vector portal DM

- Scalar mediator
- Kinetic mixing with SM photon
- Production through rare π^0 decay in the target
- Elastic or inelastic scattering off of Argon nuclei

See talk by Prof. Bhaskar Dutta





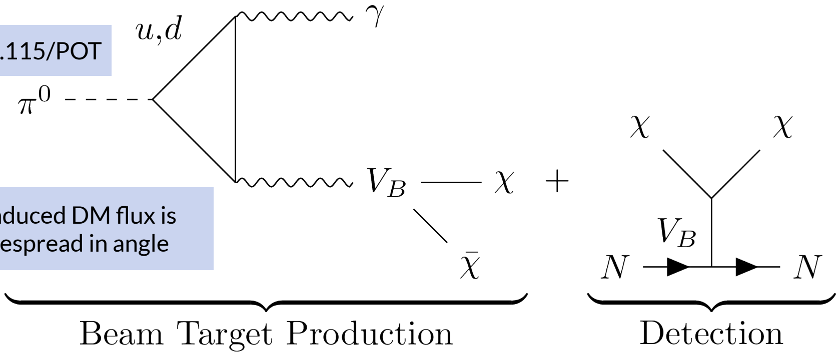


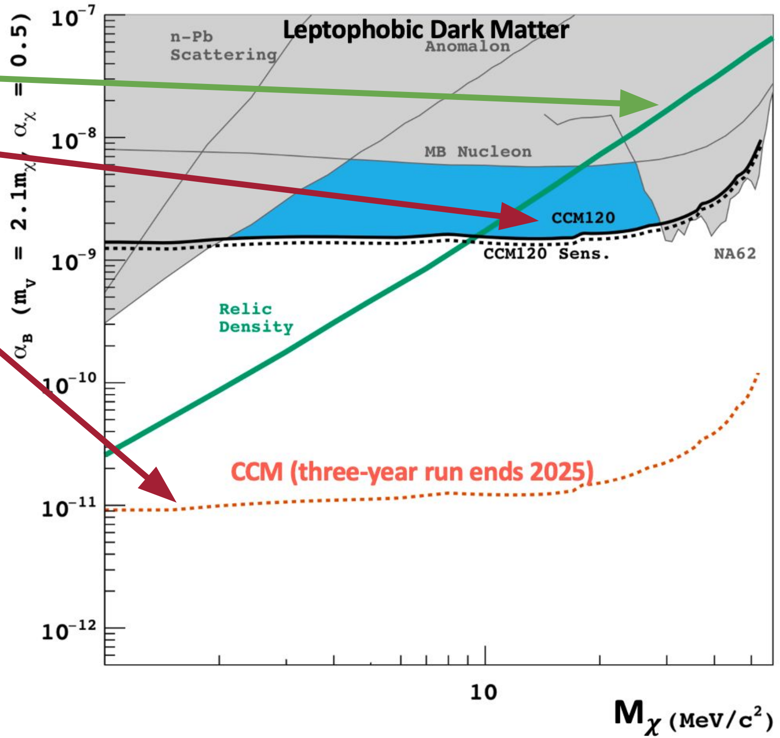
Leptophobic dark matter search with CCM120

- Dark matter abundance expected from cosmology
- CCM engineering run already probing new parameter space in this region of interest
- CCM 3 yr run will place strong constraints in the region of interest for this model

N_{π^0} = 0.115/POT

π^0 induced DM flux is widespread in angle



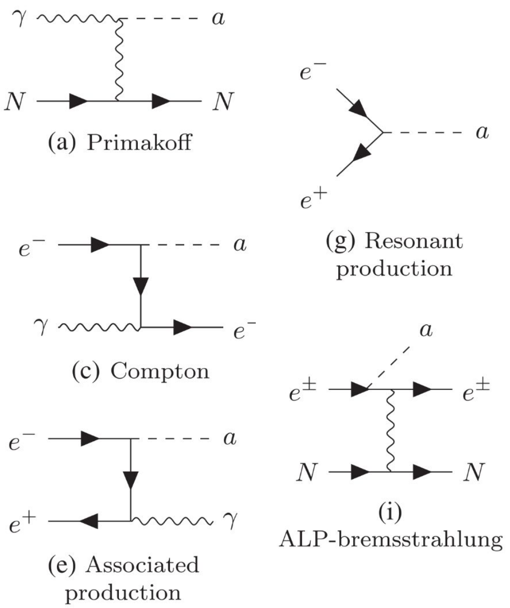


First Leptophobic Dark Matter Search from the Coherent–CAPTAIN-Mills Liquid Argon Detector PhysRevLett.129.021801

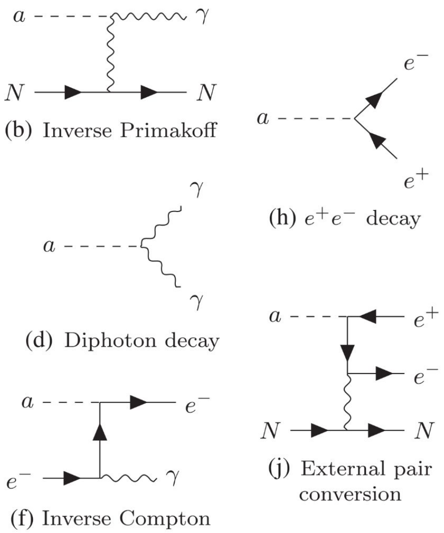
First Dark Matter Search Results from Coherent–CAPTAIN-Mills PhysRevD.106.012001

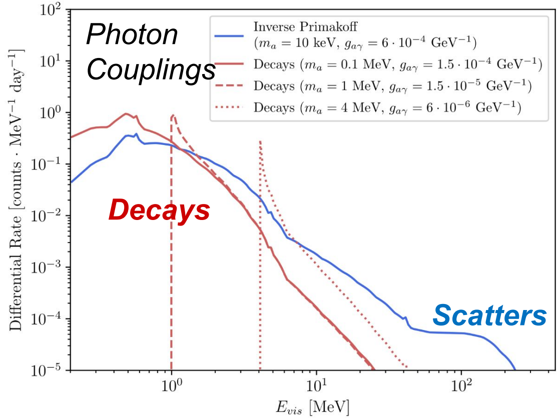
Phenomenology: ALP Detection in CCM

Production Channels in W Target

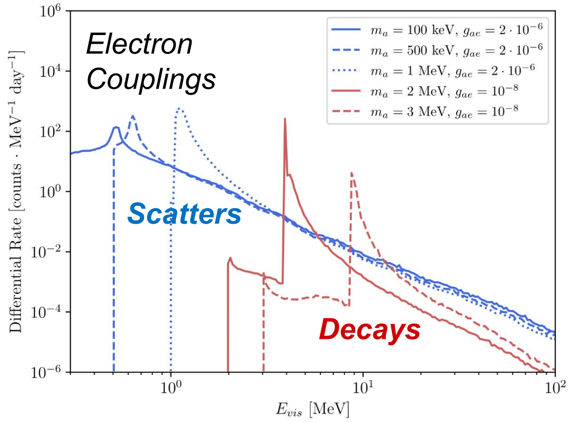


Detection Channels



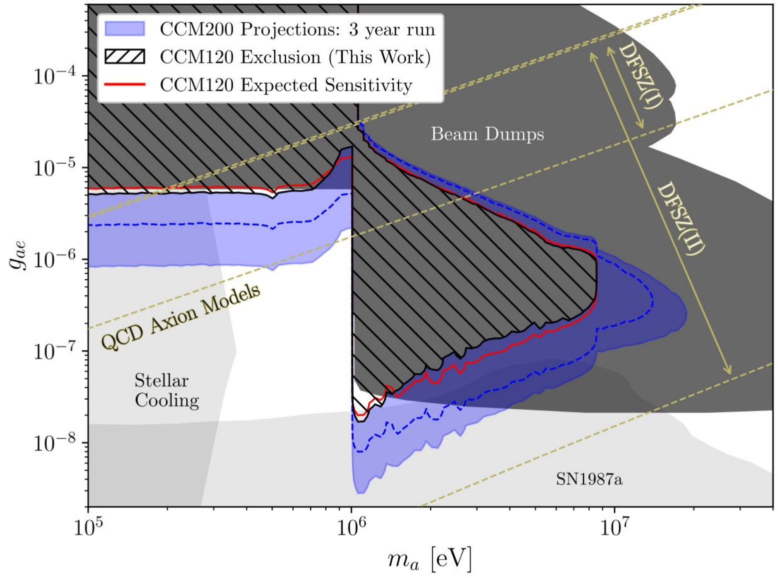


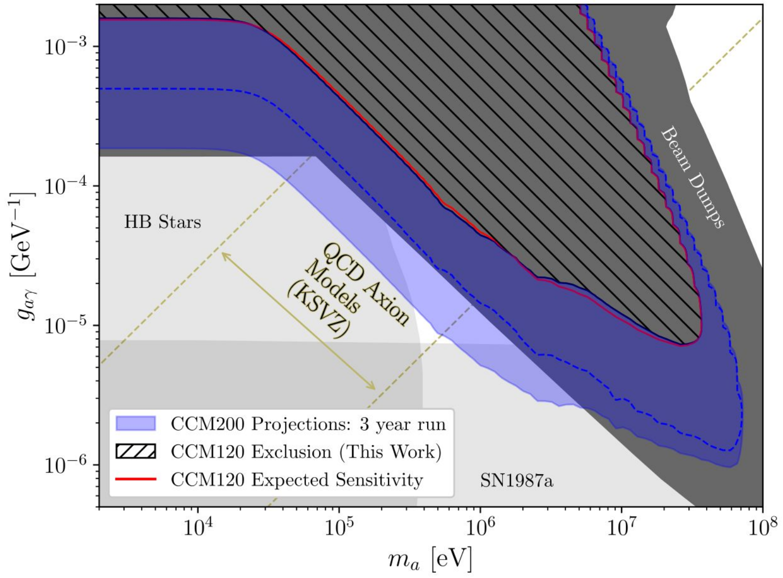
Phys. Rev. D 107 (2023) 9, 9 [2112.09979]



CCM: Axion-Like Particles

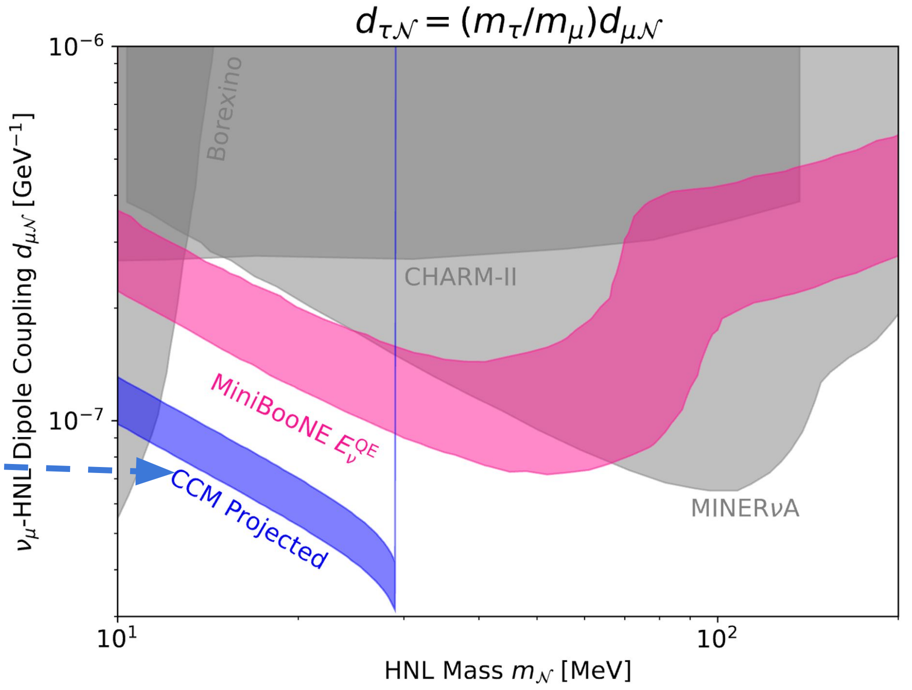
- High energy EM signals (1-10 MeV)
- Sensitivity at 90% CL
- Can probe "cosmological triangle" with terrestrial measurement

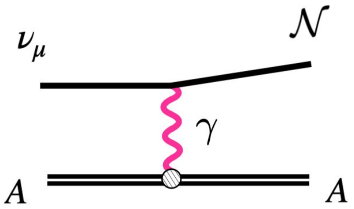


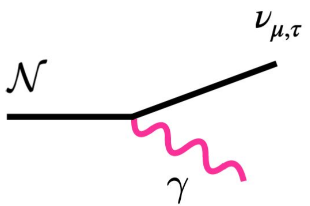


Heavy Neutral Leptons

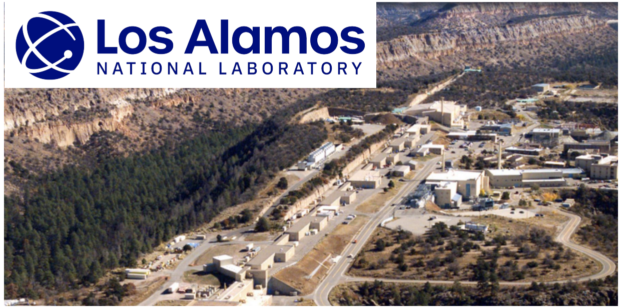
- This is just one particular model → neutrino magnetic-dipole moment
- Current projections only consider production from Primakov-process neutrino-upscattering
  - Limits are bounded in HNL mass by the **pi-DAR neutrino energy**
- Other HNL models exist, and other production processes are possible in this model
- Take a significant chunk out of the parameter-space with these limited considerations

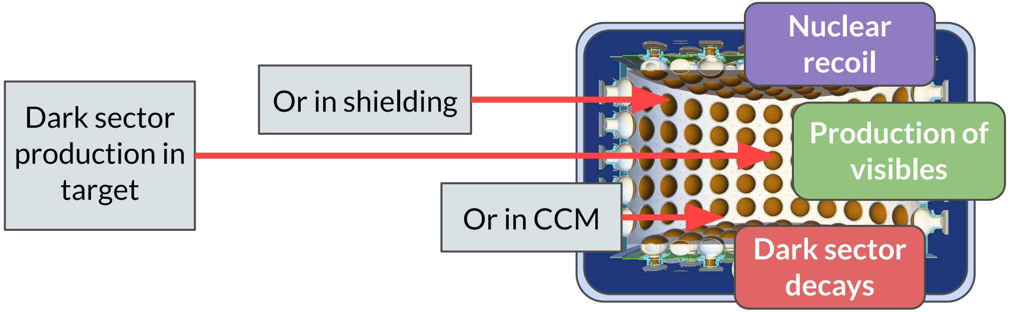






Summary





- Access to an intense source of pions allows CCM to probe MeV-scale dark-sector physics
- Lower energy + off-axis PiDAR source + fast timing
  ⇒ very low backgrounds

Standard Model measurements

- NuE CC measurements at 10 MeV scale
- Neutron cross section measurements

Broad program of dark sector searches at the MeV-scale

- Search for Axion-Like-Particles and MeV-scale QCD axion
- Search for leptophobic MeV-scale dark matter
- Search for light-dark-matter
- Testing meson portal explanations for the MiniBooNE anomaly
- Search for the X17 ATOMKI particle
- Search for Heavy Neutral Leptons
- Search for dark photons
- …

Bonus Slides

Simulating BSM processes

Simulation and Injection of Rare EveNts (**SIREN**)

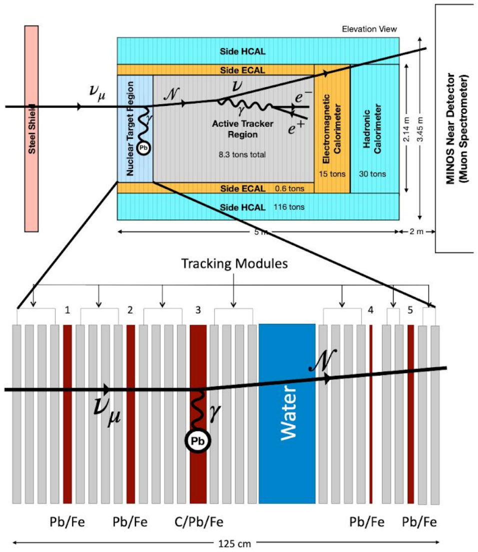
- A new software tool for BSM event injection
- Rich injection and reweighting capabilities
- Near arbitrary extensibility for models and detectors
- Detailed geometric modeling
- Fast and lightweight

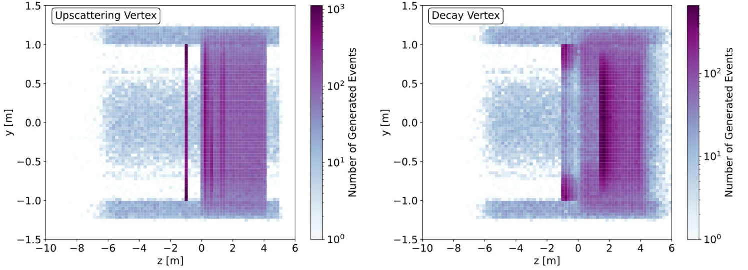
[arXiv:2406.01745](https://arxiv.org/abs/2406.01745)

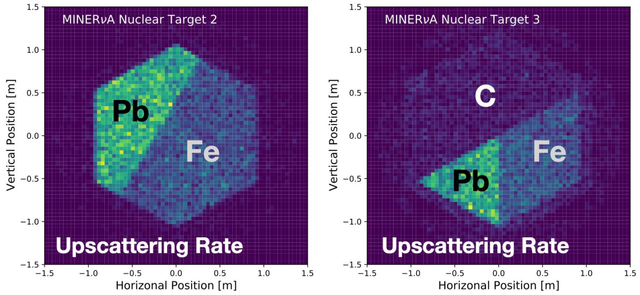
github.com/Harvard-Neutrino/SIREN

pypi.org/project/siren

```
> pip install siren
```

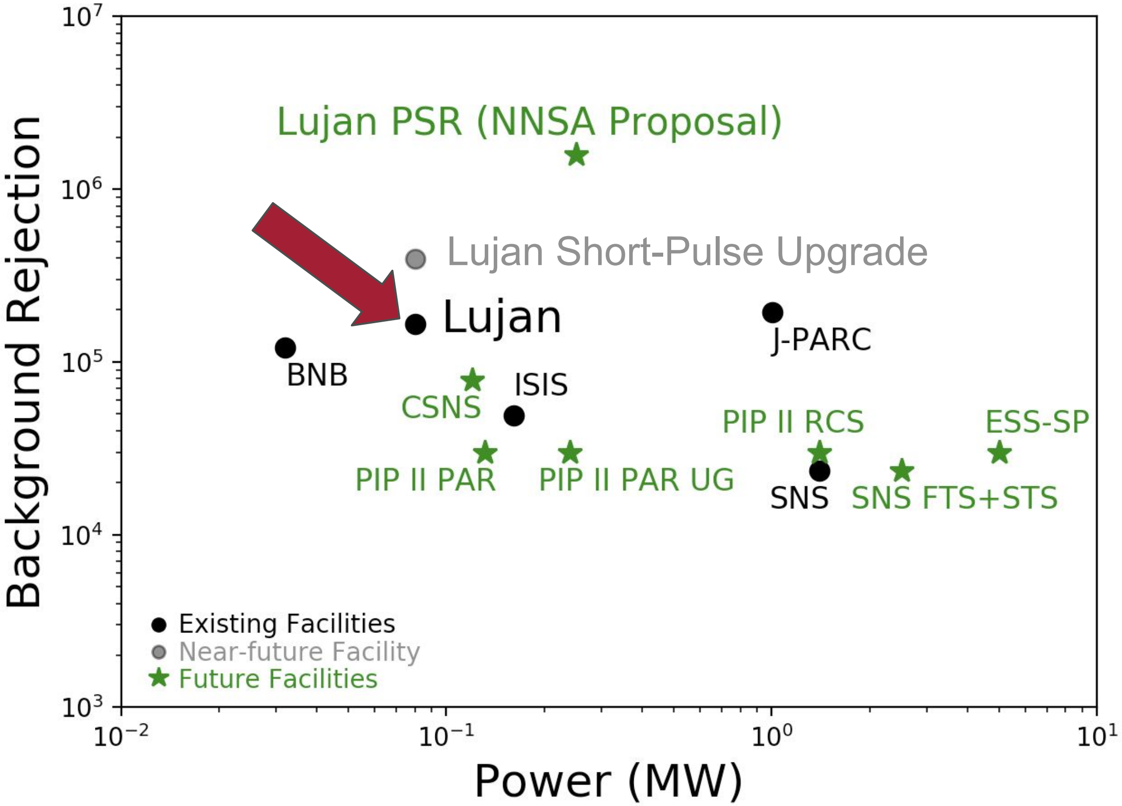






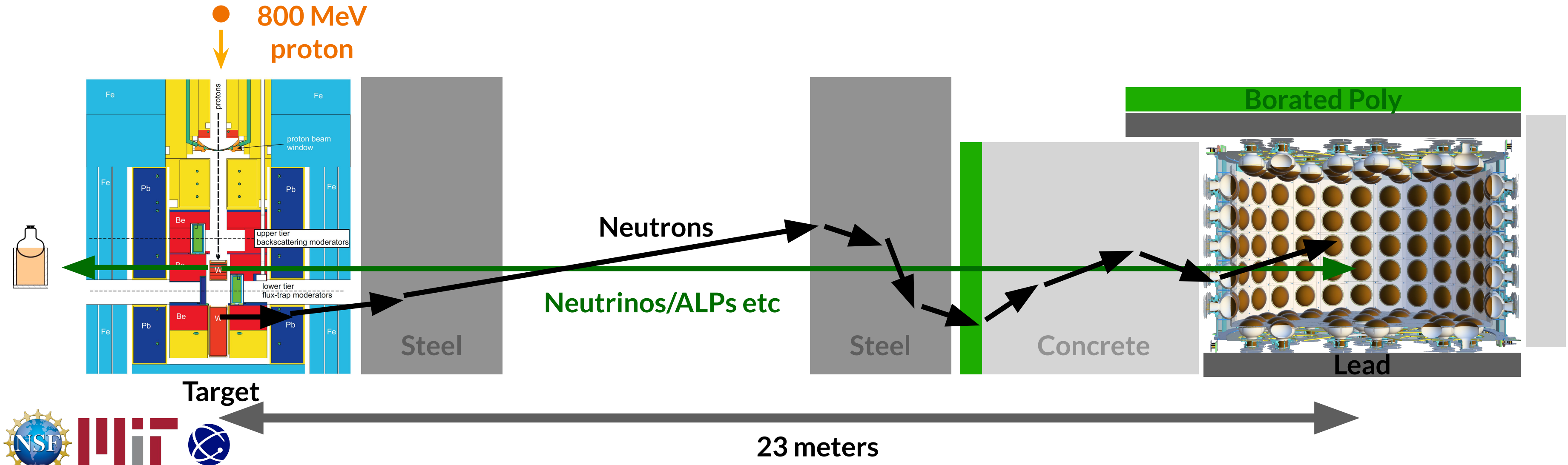
The Lujan sources

- piDAR provides a very clean flux of neutrinos
- Off-axis detection removes most backgrounds
- Primary background is neutrons
- The short 290 ns proton pulse allows us to remove neutrons through arrival time
- Future upgrades will improve performance



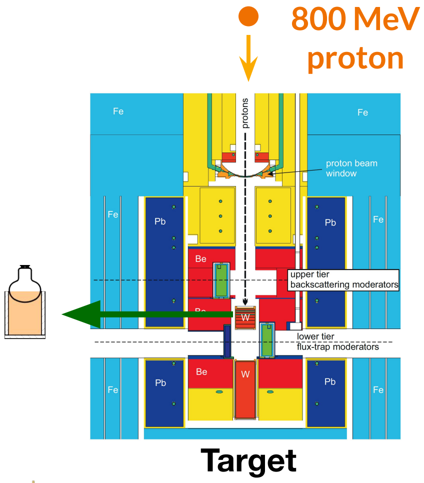
Backgrounds

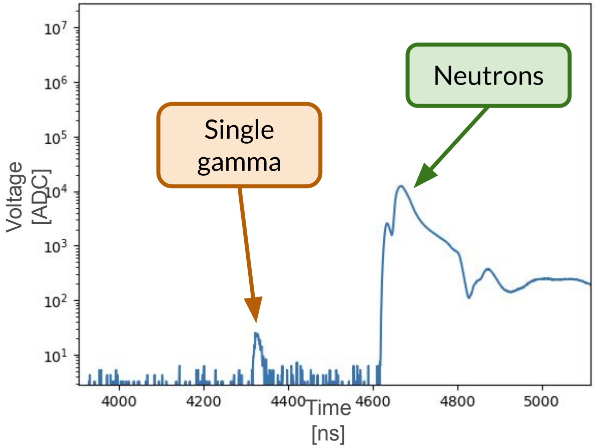
- 90 degrees off axis → no decay-in-flight contamination
- Primary backgrounds are fast neutrons
- Shielding attenuates neutrons, active veto allows us to tag neutrons entering our detector

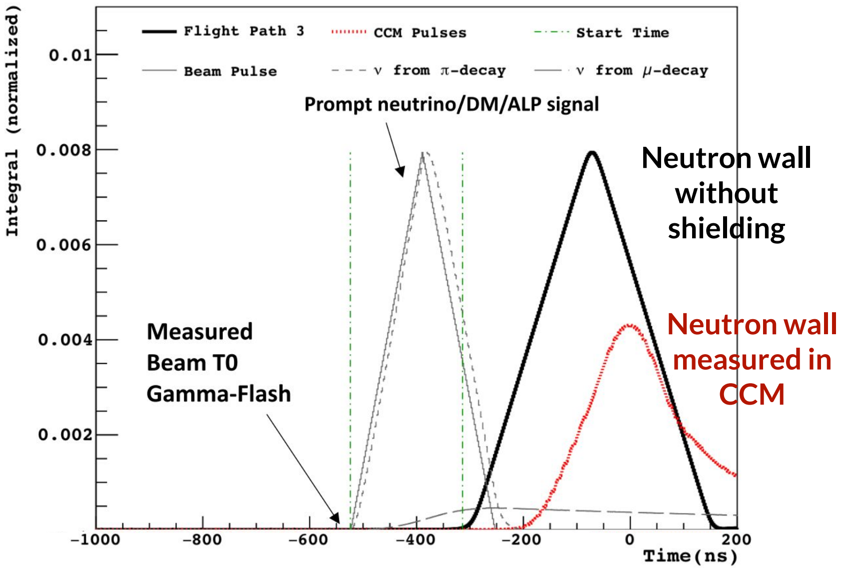


Backgrounds

- Precise timing using measured gamma flash allows us to isolate speed of light particles
- Can measure steady state backgrounds using pre-beam region of data collection

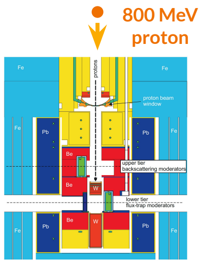


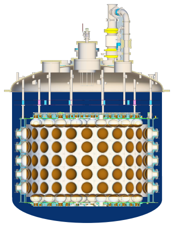


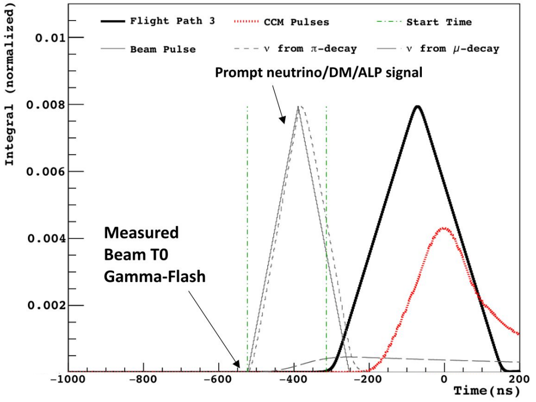


piDAR sources: The general approach

1. Very intense proton beam on a fixed target (100 μA)
    a. Allows you to perform rare process searches
    b. But, produces a bunch of neutrons
2. Go off axis to avoid “Decay In Flight” backgrounds
3. Shield your detector to attenuate and delay neutrons
4. Use a narrow (290 ns) pulsed beam to concentrate your signal in time
5. Use timing cuts to remove neutron backgrounds
6. Measure steady state backgrounds in-situ

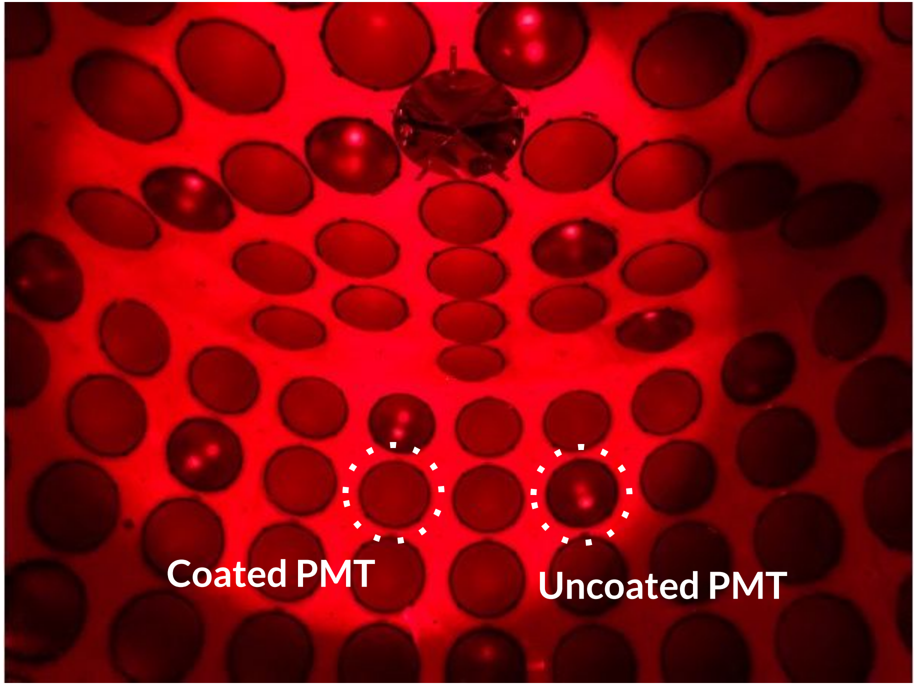


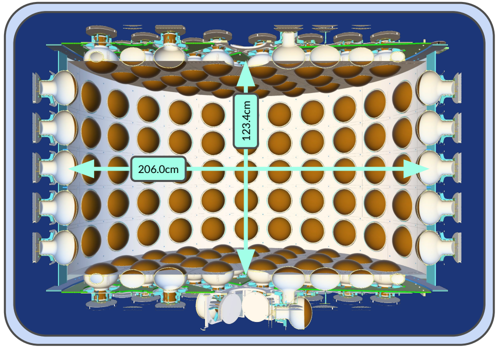




Coherent CAPTAIN-Mills (CCM)

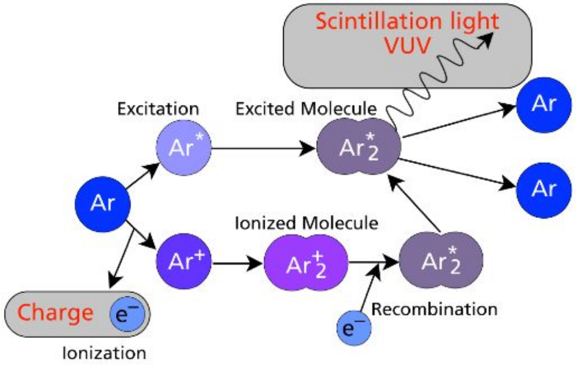
- Electronics have **2ns** sampling time
- Sensitive between ~100 keV and ~2 GeV
- 80% of PMTs coated in 1,1,4,4-Tetraphenyl-1,3-butadiene (TPB) to **wavelength shift LAr scintillation light**
- TPB foils cover detector walls





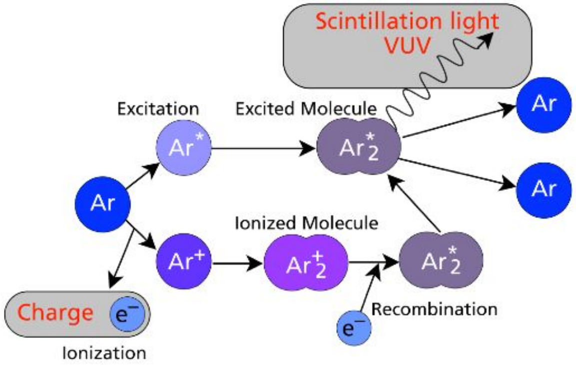
Light production in Liquid Argon

Quality	Scintillation Light
Intensity	~ 40k photons/MeV
Direction	Isotropic
Timing	Fast component (ns) and slow component (μs) EPJC-s10052-020-7789-x
Wavelength	Spectrum peaks at 128nm

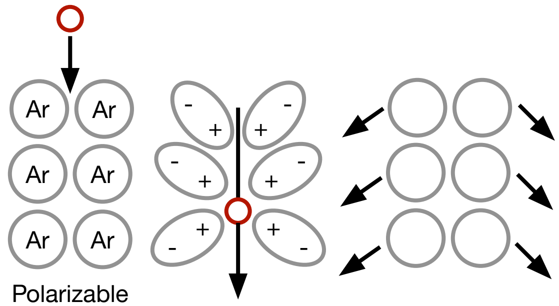


Light production in Liquid Argon

Quality	Scintillation Light	Cherenkov Light
Intensity	~ 40k photons/MeV	~700 photons/MeV (above 100 nm)
Direction	Isotropic	Directional
Timing	Fast component (ns) and slow component (μs) EPJC-s10052-020-7789-x	Prompt (ps)
Wavelength	Spectrum peaks at 128nm	Broad spectrum

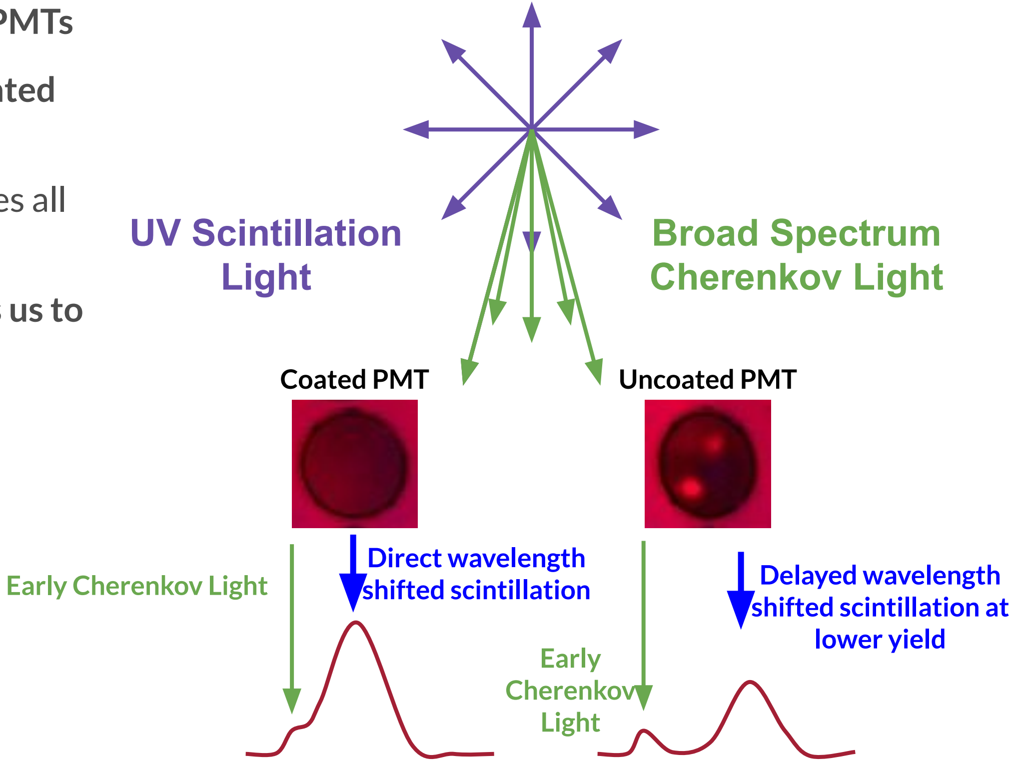


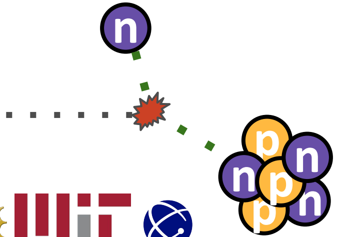
Charged particle

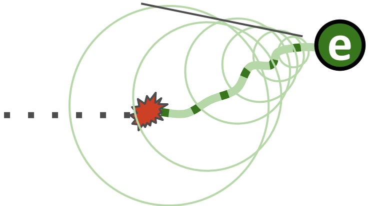


CCM light collection

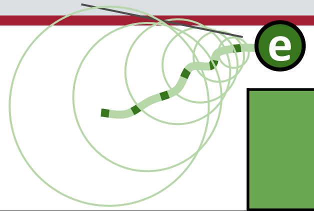
- UV scintillation light is “direct” to **only coated PMTs**
- Cherenkov light is “direct” to **coated and uncoated PMTs**
- Wavelength shifted light is isotropic and reaches all PMTs after some additional delays
- **Fast timing and coated/uncoated tubes allows us to identify Cherenkov light**
- Provides a handle for differentiating nuclear-recoil-like and electron-like events

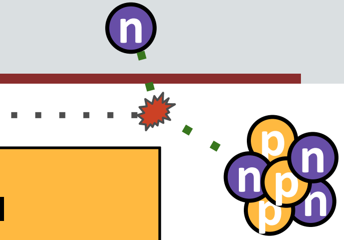






Basic signatures in CCM

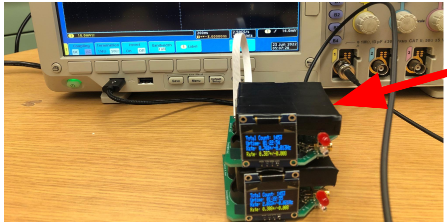


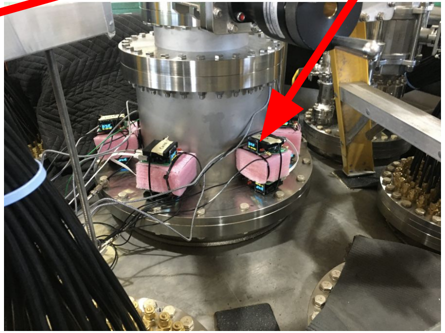


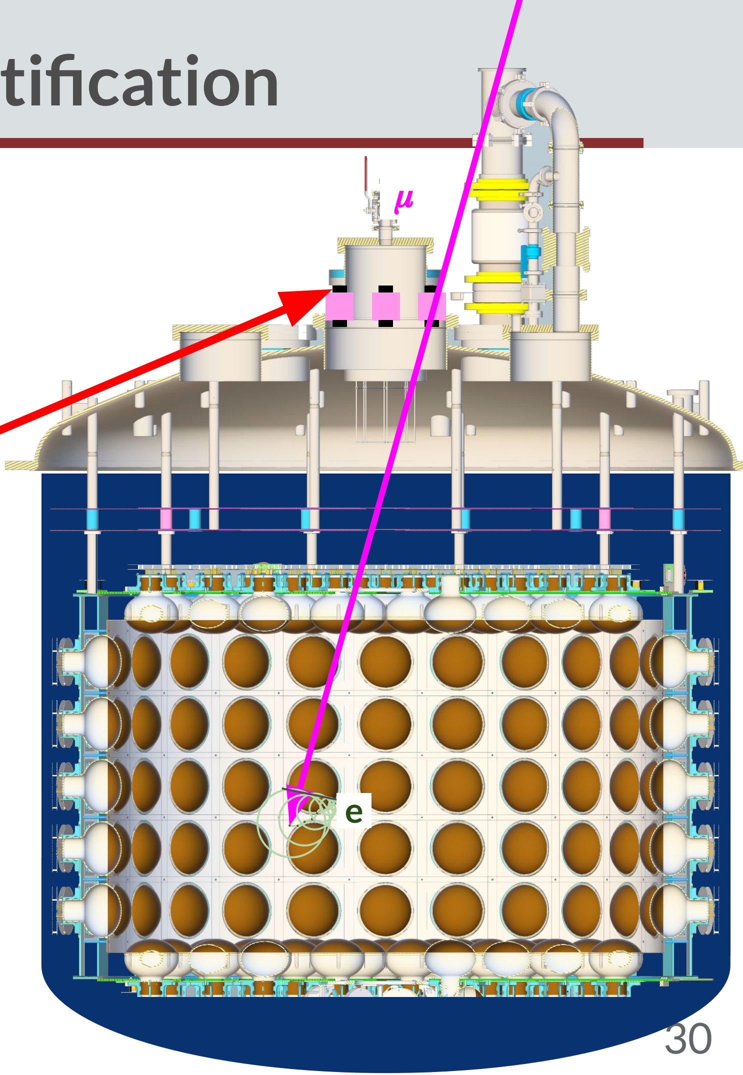
	Electron/Photon	Nuclear Recoil
Energy Range	~1 - 15 MeV	~100 keV
Scintillation Light	**Yes**	**Yes**
Cherenkov Light	**Yes**	**No**
Primary background	Neutron scatters	Low energy beta decays (^{39}Ar)
Background signal	Scintillation light only	Scintillation and cherenkov light

Developing Cherenkov light identification

- Need a well known, bright source of Cherenkov light for refining the procedure
- Michel electrons from stopped cosmic ray muons have a well known spectrum and are up to 53 MeV
- Tag muons entering the detector with "[Cosmic Watch]" detectors

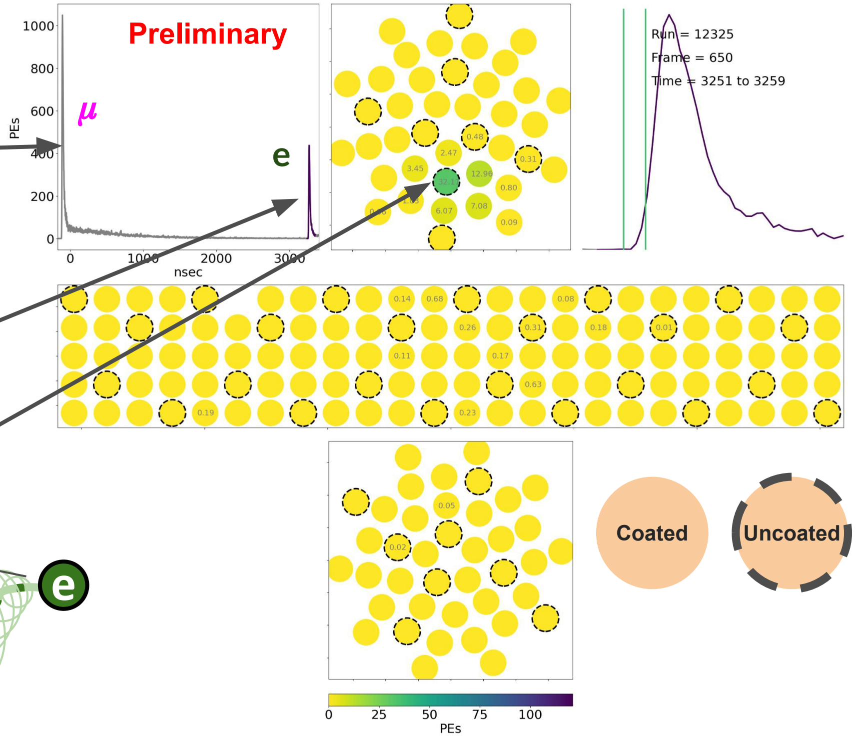


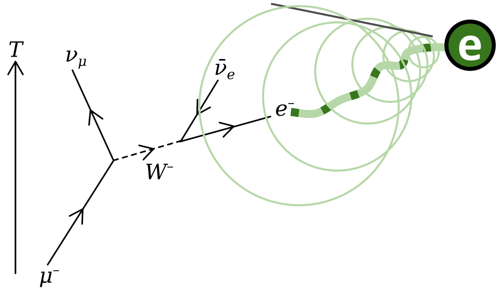




Cherenkov light with Michel electrons

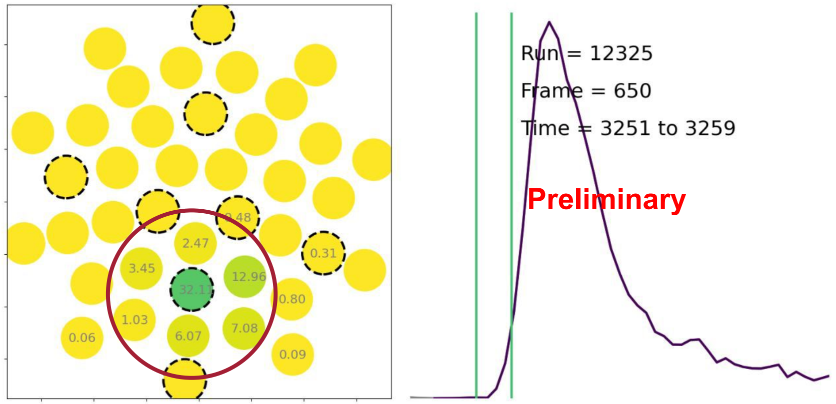
- Cosmic ray muon is tagged by external plastic scintillator detector
- Muon enters the detector causing bright scintillation, and coming to a stop (1/10 muons)
- Stopped muon subsequently decays, creating a Michel electron with energy up to 53 MeV
- Michel electron produces Cherenkov and scintillation light
- Uncoated tubes are efficient at picking up the early Cherenkov light

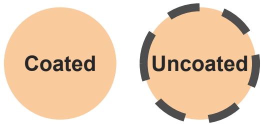


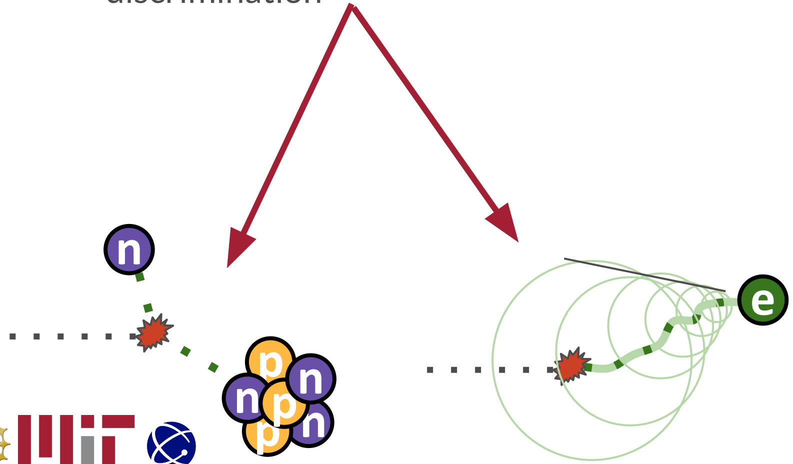


Cherenkov light with Michel electrons

- First demonstration of event-by-event identification of Cherenkov light in liquid Argon
- Working now to incorporate Michel electrons into the calibration
- Will provide an important reference point for developing Cherenkov light based particle discrimination



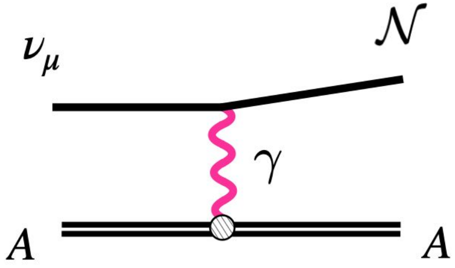




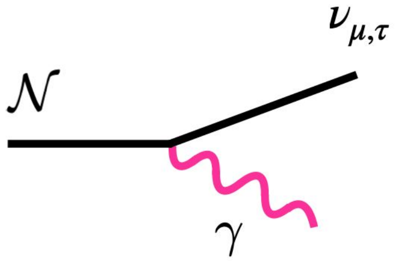
1 Neutrissimos (HNLs) - Oscillation and decay

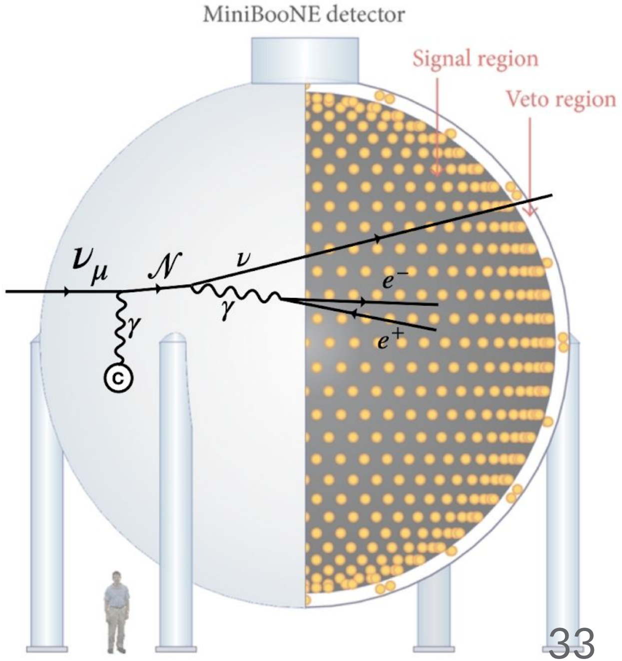
Introduce an MeV-scale heavy neutral lepton with a transition magnetic moment, or neutrissimo

Upscattering from SM neutrinos to neutrissimos occurs in transit from beam



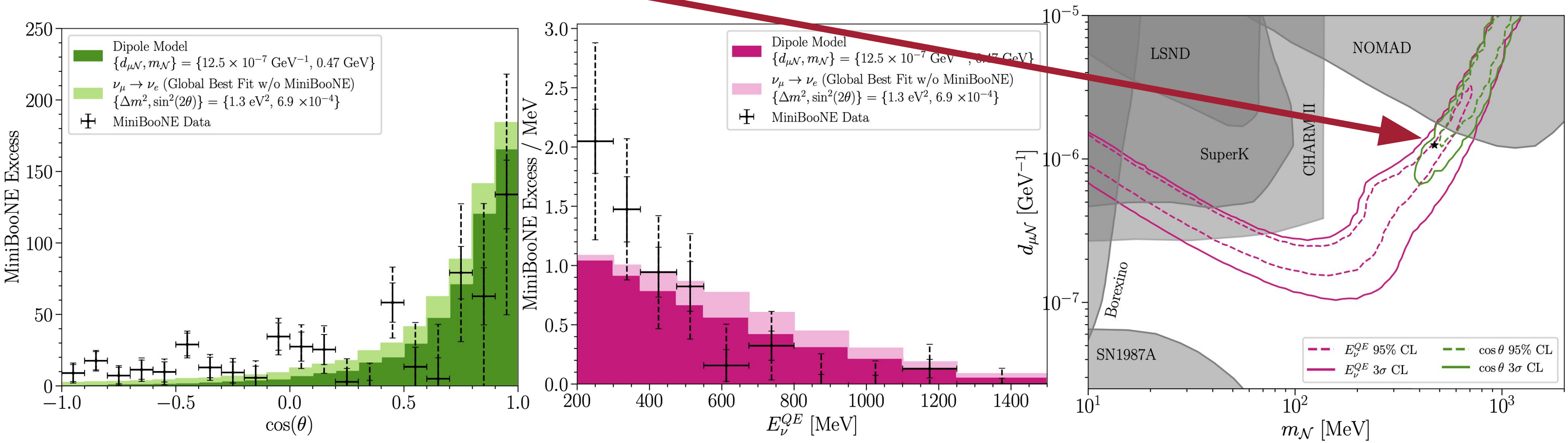
Subsequent decay of neutrissimo to a photon can produce the MiniBooNE signature





1 Fitting to MiniBooNE data

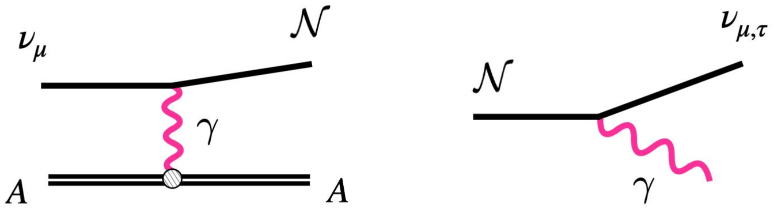
- Parameters: 3+1 oscillation | dipole coupling | HNL mass
  - Scanning over combined parameter space is prohibitive
- Fits Assume best-fit sterile neutrino from global neutrino data *without* MiniBooNE
- Reasonable agreement with both **energy** and **angular** distributions!
- **Allowed regions overlap**

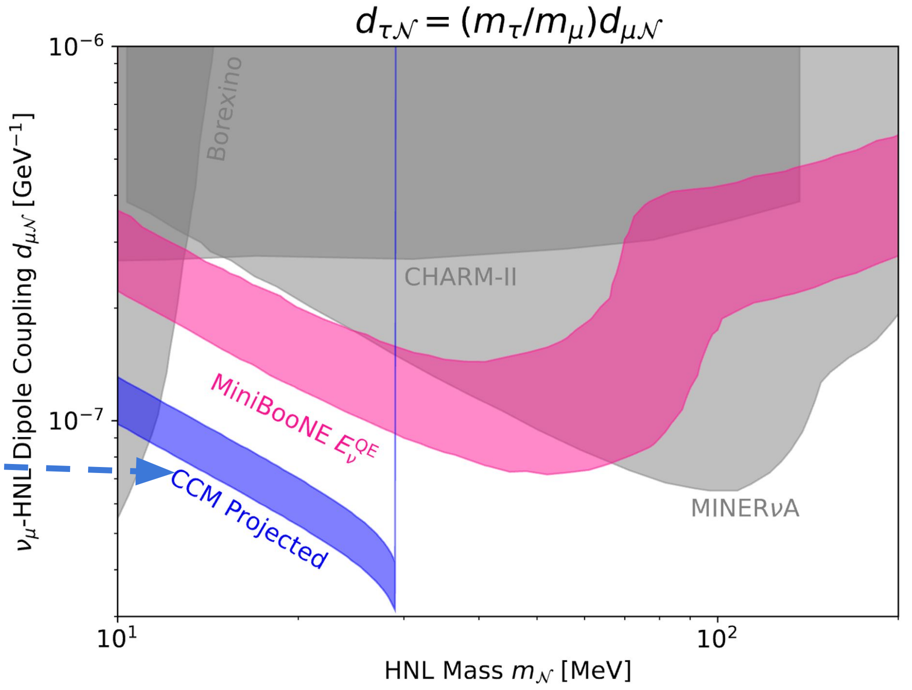


https://doi.org/10.48550/arXiv.2206.07100

1 HNLs in CCM

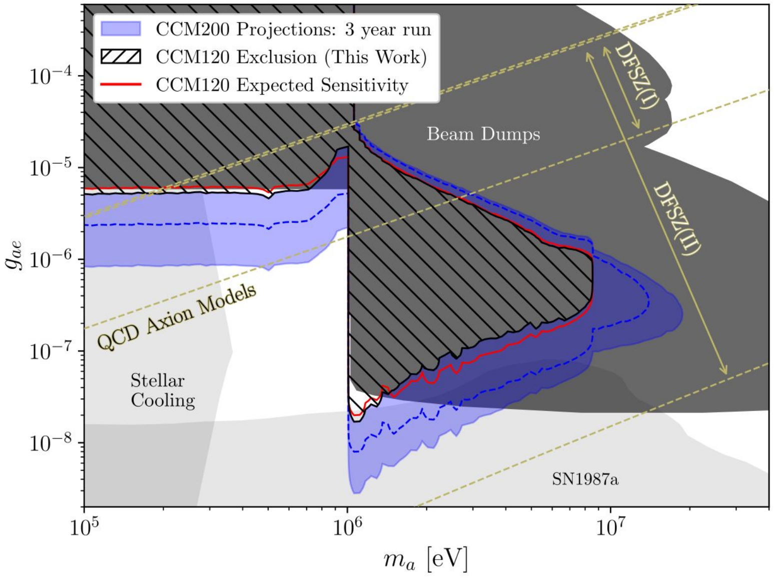
- This is just one particular model → neutrino magnetic-dipole moment
- Current projections only consider production from Primakov-process neutrino-upscattering
  - Limits are bounded in HNL mass by the **pi-DAR neutrino energy**
- Other HNL models exist, and other production processes are possible in this model
- Take a significant chunk out of the parameter-space with these limited considerations

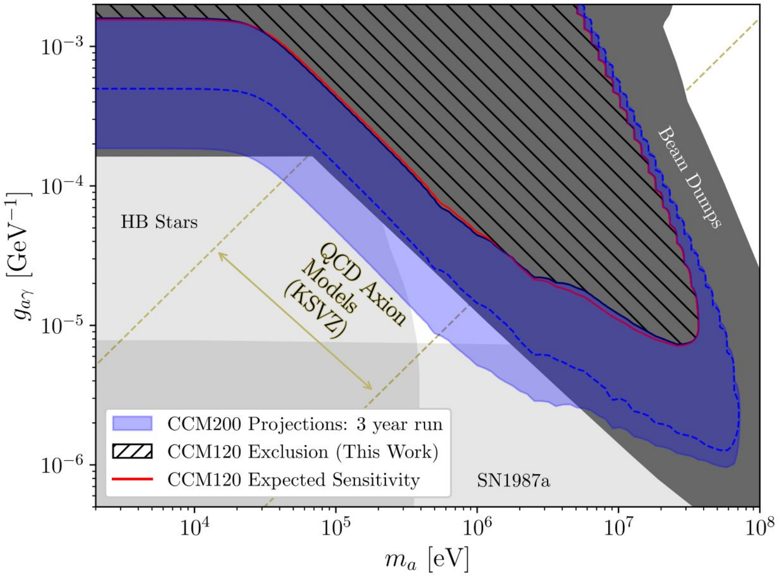




2 CCM: Axion-Like Particles

- High energy EM signals (1-10 MeV)
- Sensitivity at 90% CL
- Can probe “cosmological triangle” with terrestrial measurement

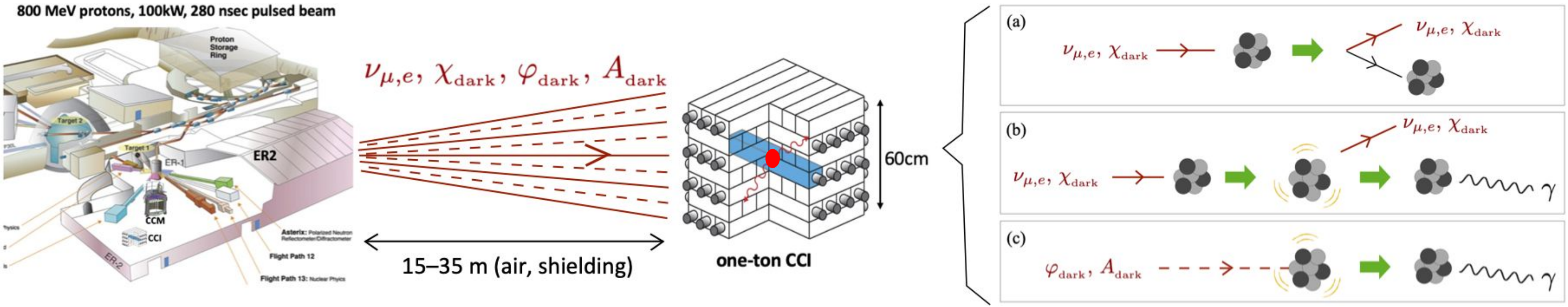




Coherent Cesium Iodide (CCI)

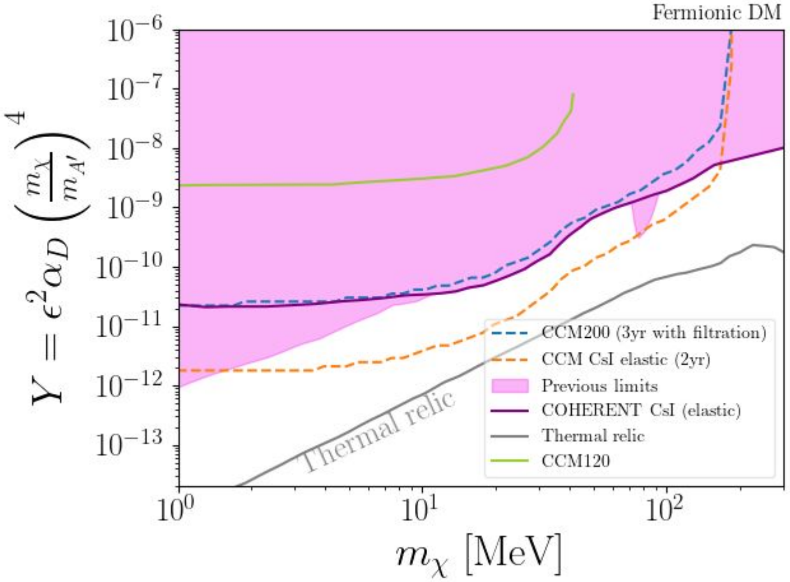
- 1 ton compact segmented CsI detector
- Fast CsI(pure) scintillation light time of ~30 nsec
- High coherent cross section of Cs: 3.5 times larger than Ar
- Low intrinsic radioactive background from CsI
- Large light output of 3000 photons/MeV
- Very low background

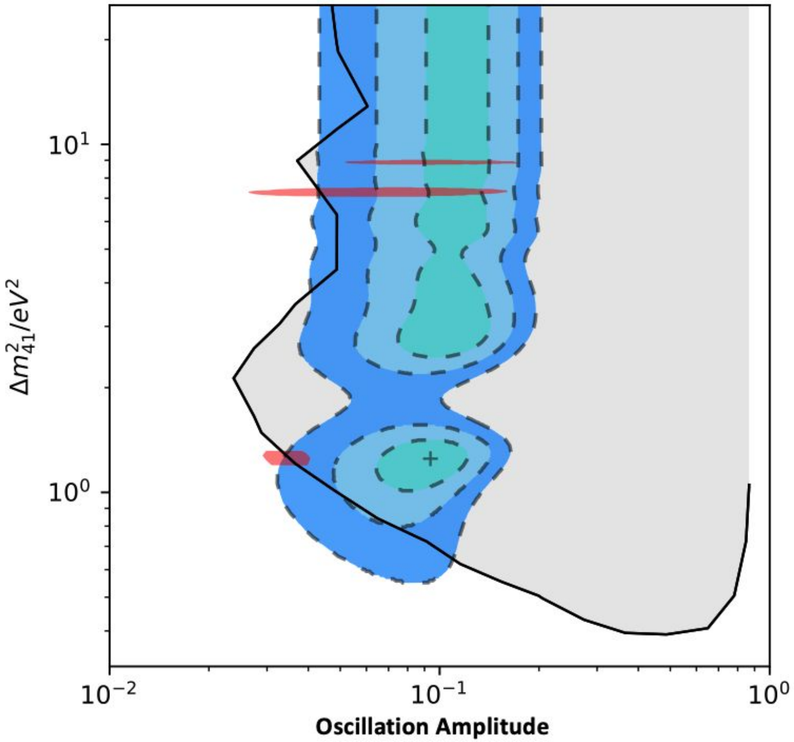
Recently made it to the second stage of LDRD ER proposal review



CCI projections

- Improved sensitivity to vector-portal dark matter scenario
- Coverage of BEST parameter space at 90% CL



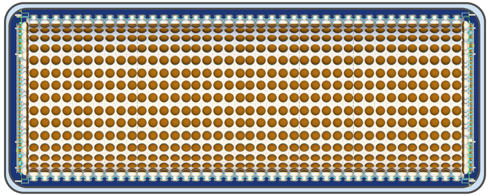


Lujan Liquid Argon Measurement Apparatus (LLAMA)

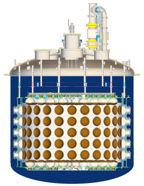
- Reuse MicroBooNE cryostat and cryogenics
- 10m long and 3m diameter
- 100 ton fiducial volume
- Remove Time Projection Chamber (TPC)

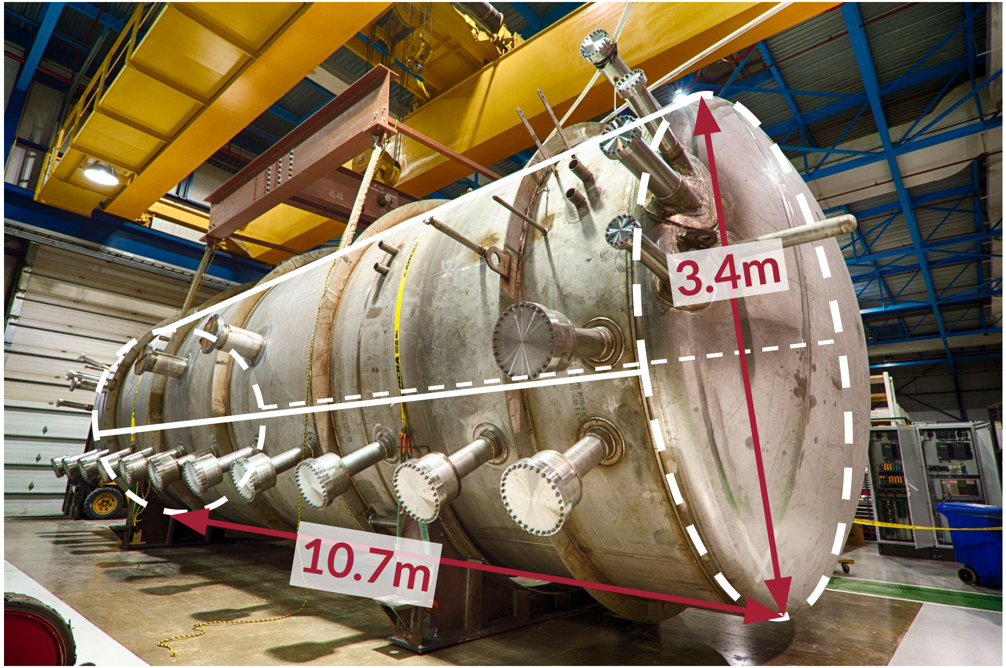
- Instrument it like CCM: 1.5k 8in PMTs
- Orient it towards the beam
- Detector can be constructed for under $30M

LLAMA



CCM





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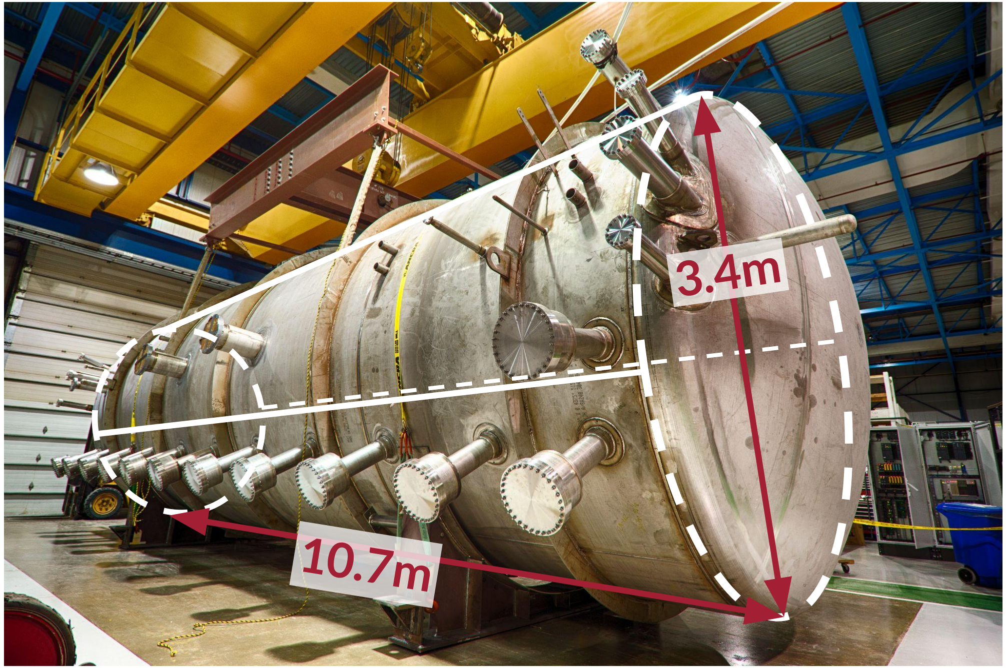
- Orient it towards the beam
- Detector can be constructed for under $30M

- Partially instrumenting with **SiPMs** could greatly improve performance
- Sub-ns timing would allow us to perform precise vertex reconstruction even for low-energy nuclear recoils (like CEvNS)



LLAMA

Key improvements over CCM

- 14x active mass gives us 14x more events in any physics search
- Filtration of the Argon can lower the energy threshold to 5 keV
  - Gives us access to CEvNS
  - Many BSM models have a coherent channel
  - Allows us to test the BEST oscillation scenario
  - Precision cross section measurement

LLAMA

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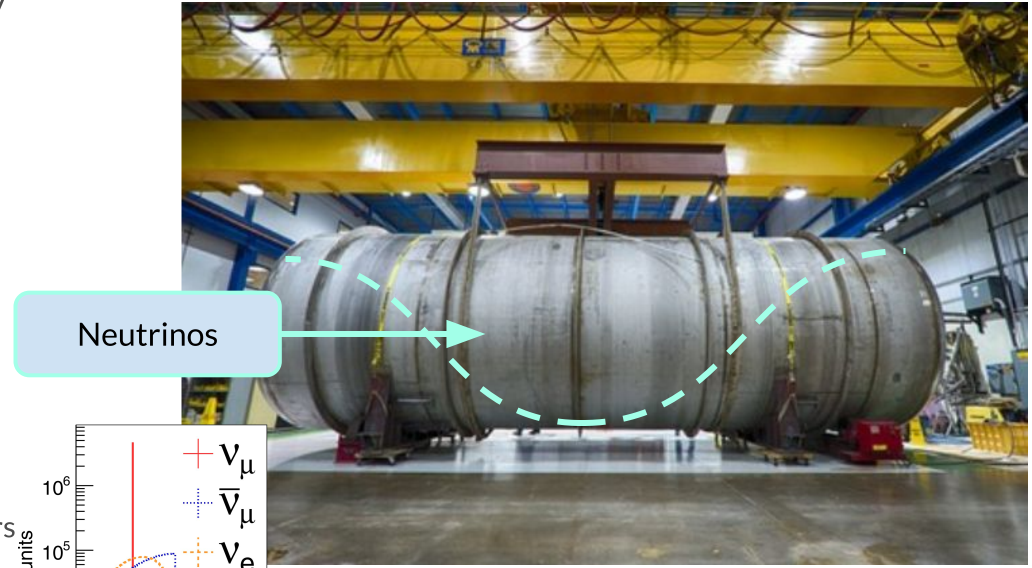
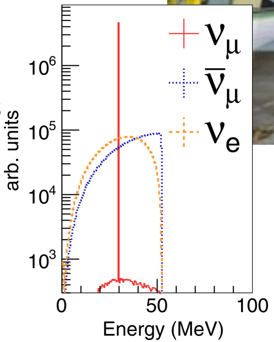
  - Many BSM models have a coherent channel
  - Allows us to test the BEST oscillation scenario
  - Precision cross section measurement
- Sterile neutrino oscillations can be probed over the length of the detector
  - CEvNS gives a very large sample of neutrino interactions
  - Timing can be used to distinguish between flavors
  - Can be supplemented with CC measurements
  - Has sensitivity to the BEST allowed regions L/E ≅ 1





LLAMA

Key improvements over CCM

- Shielding the detector is much easier. Most shielding can be concentrated at the front
- Fast neutrons are attenuated by 1/10 across 2m of LAr
  - Neutron background very low at the back of the detector
  - Neutron background has a distinct exponential fall-off that is not present for signal events