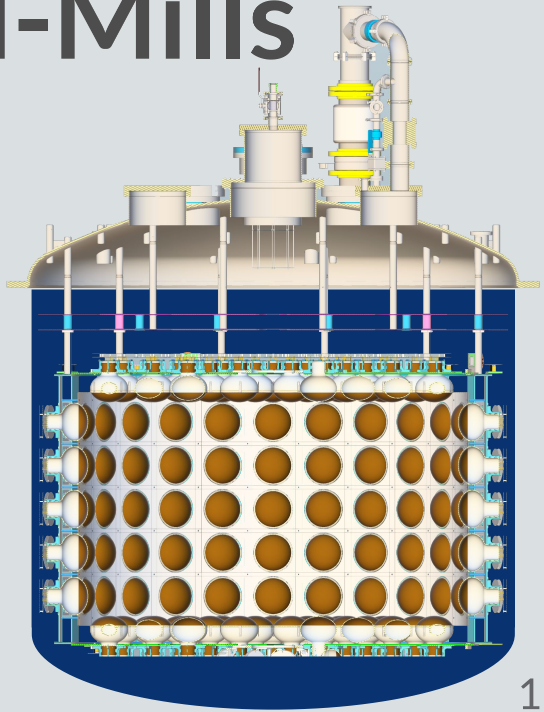
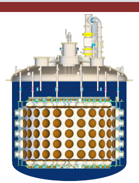
The Coherent CAPTAIN-Mills Experiment (CCM)

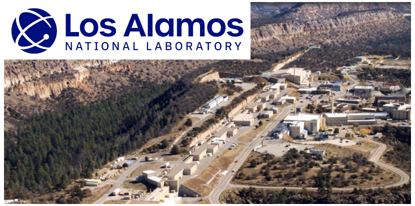


Short-Baseline Experiment-Theory Workshop
2024-04-03
Austin Schneider

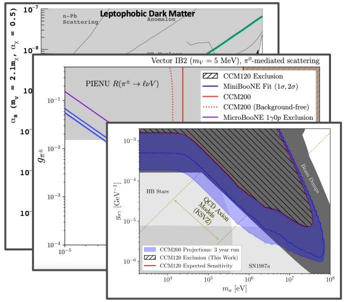
Outline

- Coherent CAPTAIN-Mills (CCM)

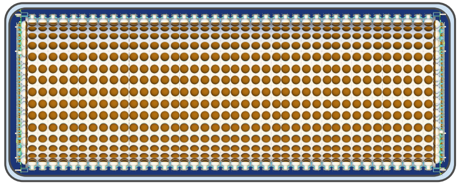


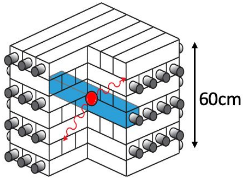


- CCM in the Lujan target hall as LANSCE
- Results from CCM120 engineering run / projections for CCM200



- Beyond CCM

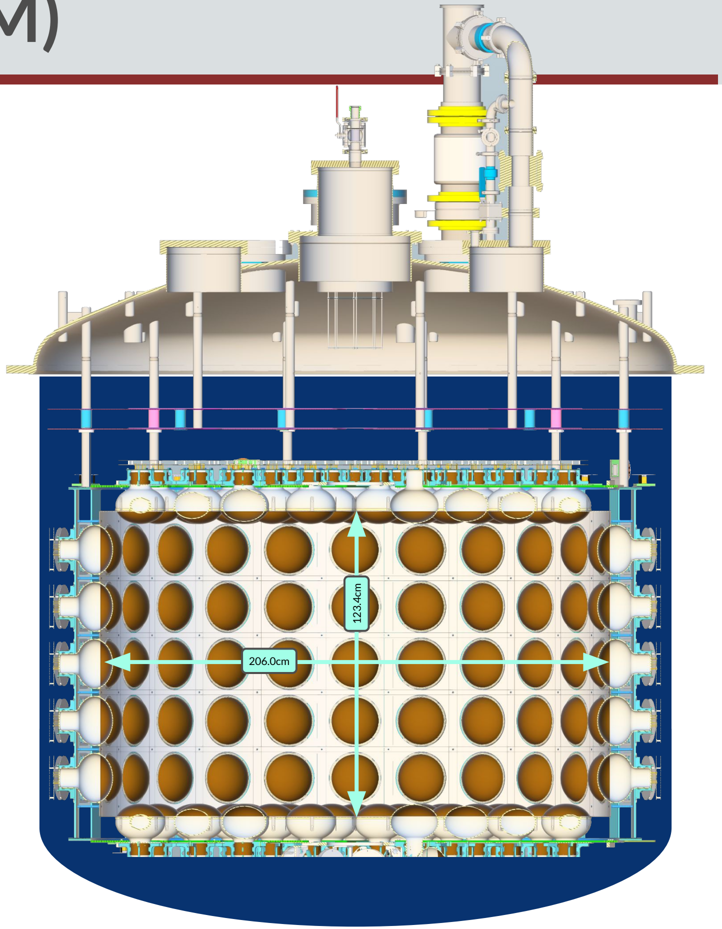




one-ton CCl (pure)

Coherent CAPTAIN-Mills (CCM)

- 10 ton liquid Argon (LAr) scintillation and Cherenkov detector
- Largest photo-cathode area of any light-based LAr detector
- 200 8” PMTs provide 50% photo-coverage of a 5 ton fiducial volume
- 3 ton active veto region
- Recently completed engineering run
- Mid-way through 3yr data taking period
  - 2.25×10^{22} POT

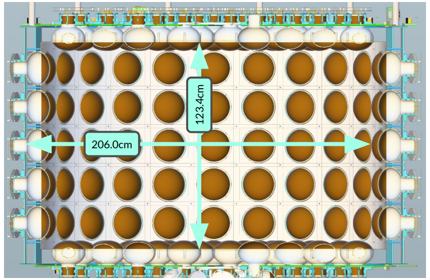


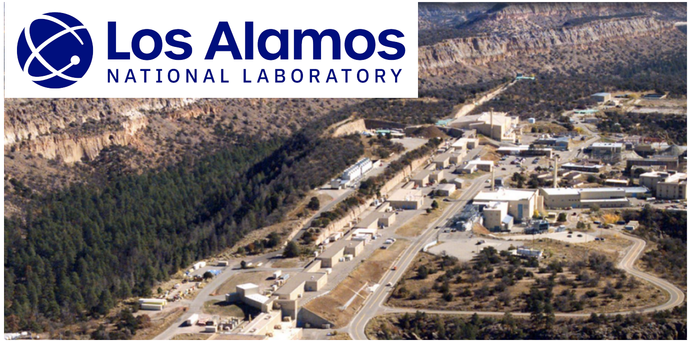
Coherent CAPTAIN-Mills (CCM)

Not affiliated with the COHERENT collaboration

CCM

- Located at Los Alamos National Lab
- Lujan Center
- 7 ton active interior volume
- Largest LAr detector by photo-cathode area
- Analysis dependent 10 - 100 keV threshold

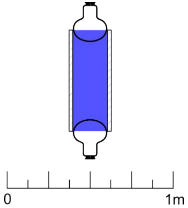


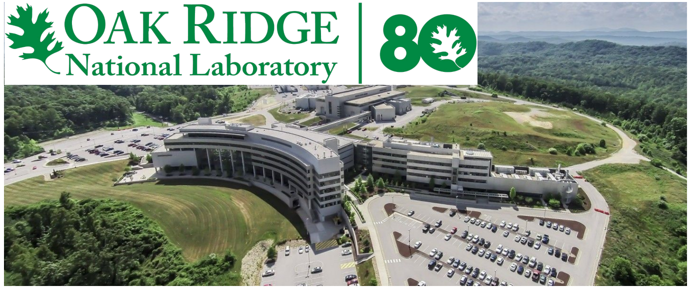


CENNS-10 (COHERENT collaboration)

- Located at Oak Ridge National Lab
- Spallation Neutron Source
- 24 kg active interior volume
- 20 keV threshold

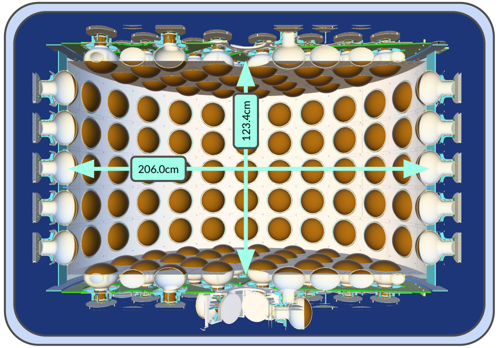
To scale

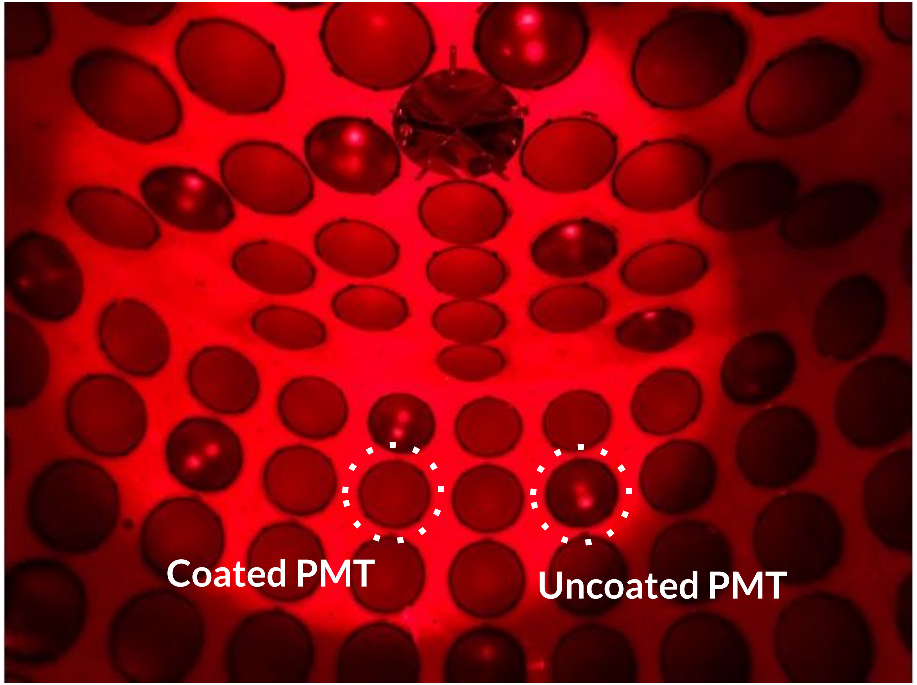




Coherent CAPTAIN-Mills (CCM)

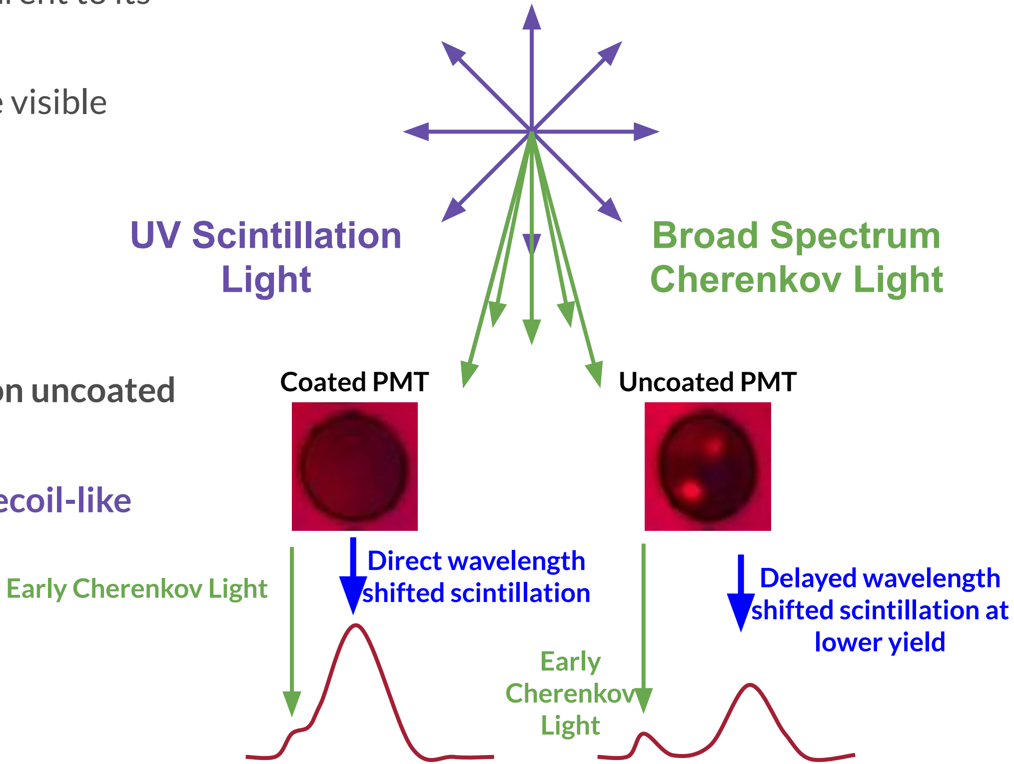
- Electronics have **2ns** sampling time
- Sensitive between ~10keV and ~200MeV
- 80% of PMTs coated in 1,1,4,4-Tetraphenyl-1,3-butadiene (TPB) to **wavelength shift LAr scintillation light**
- TPB foils cover detector walls

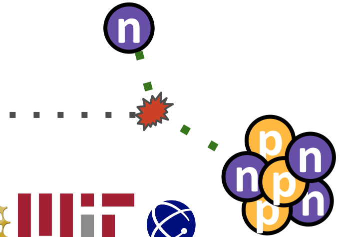


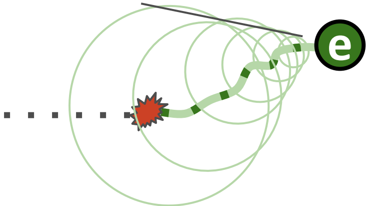


CCM light collection

- 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**

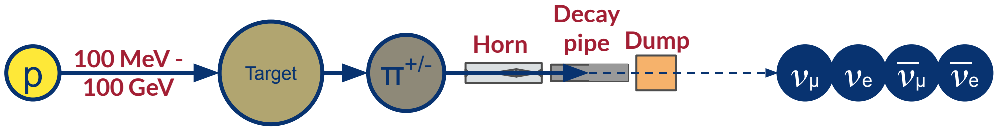


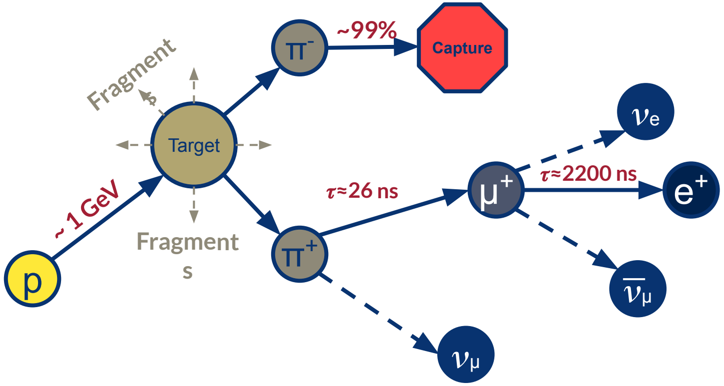


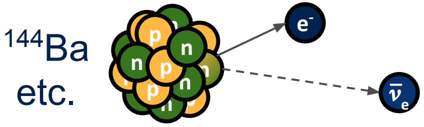


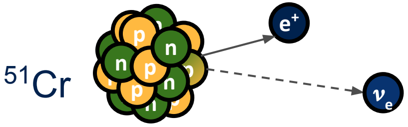
Neutrino sources: 100 keV to 100 MeV

- Decay in flight neutrino beams
  - O(1 MeV - 10 GeV)
  - BNB, NuMI, J-PARC
- Pion decay at rest
  - O(1 - 50 MeV) NuE and NuMuBar
  - Predominantly 29.9 MeV prompt NuMu
  - SNS, Lujan, …
- Kaon decay at rest
  - O(1 - 200 MeV) NuE, NuMu
  - Predominantly 236 MeV NuMu
  - J-PARC
- Reactor neutrinos
  - O(0.1 MeV - 10 MeV)
- Intense radionuclide neutrino sources
  - O(100 keV - 1 MeV)

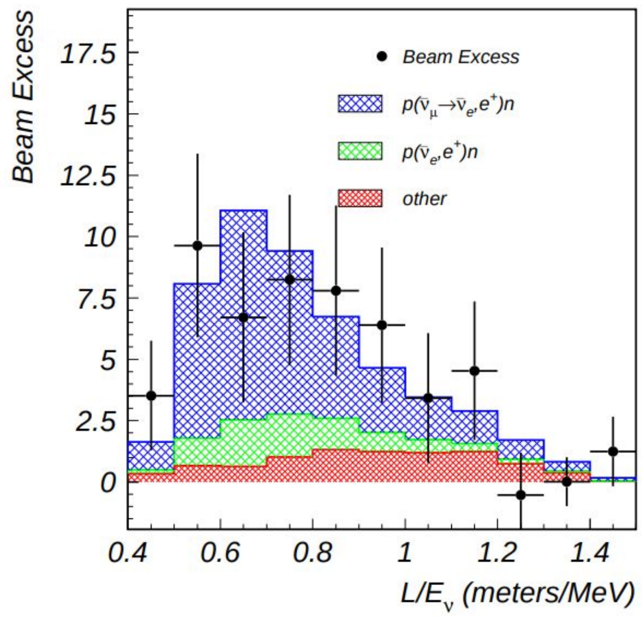


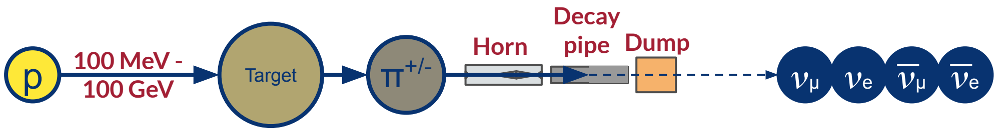


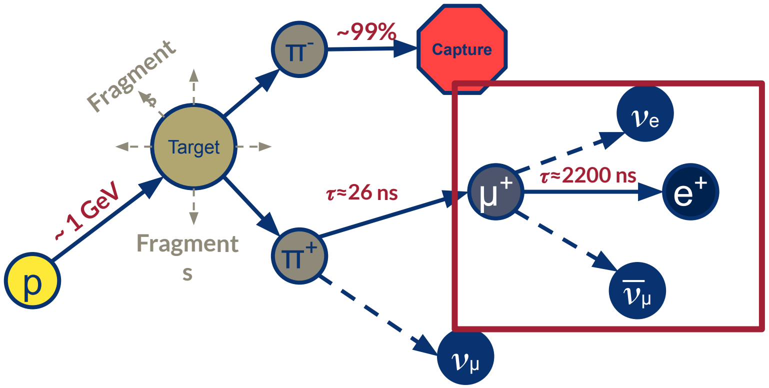


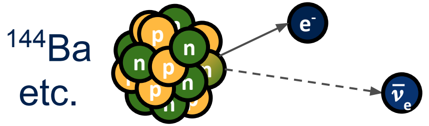


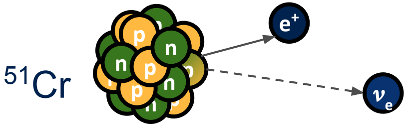
Neutrino sources: 100 keV to 100 MeV



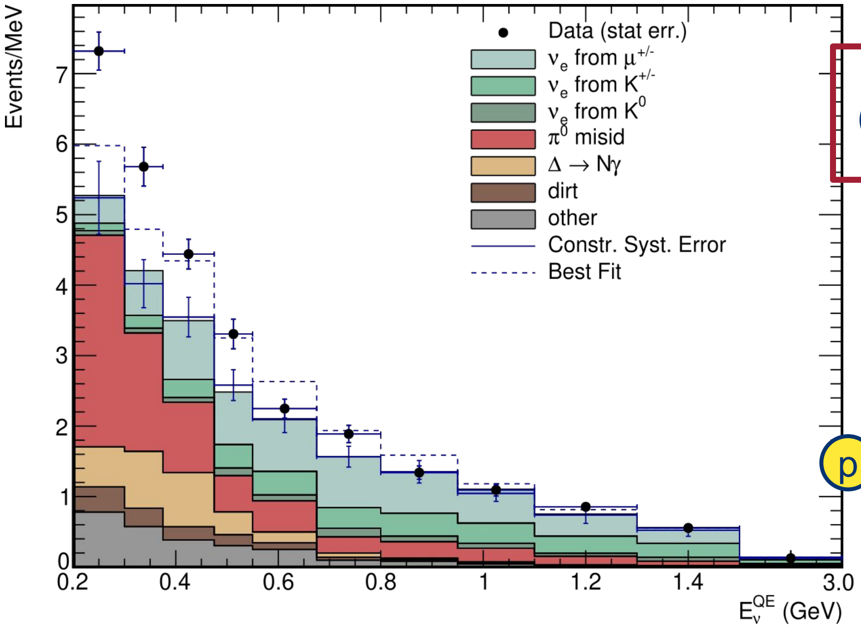


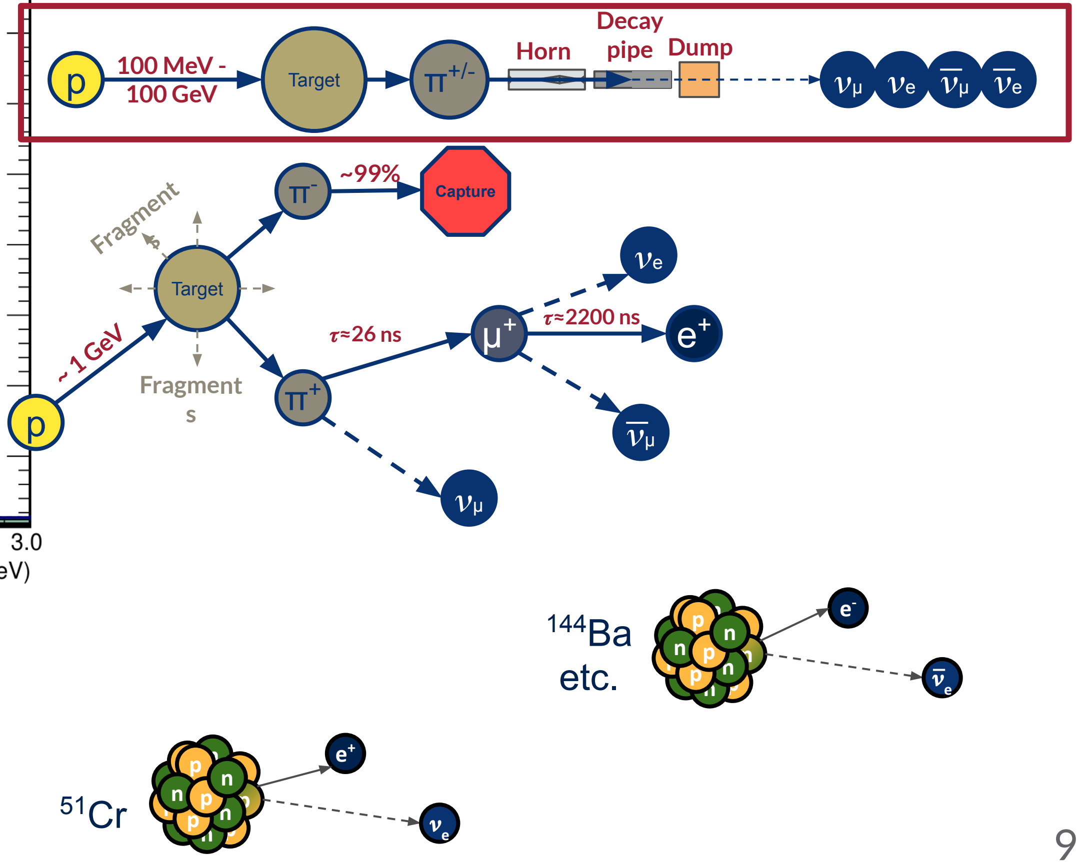




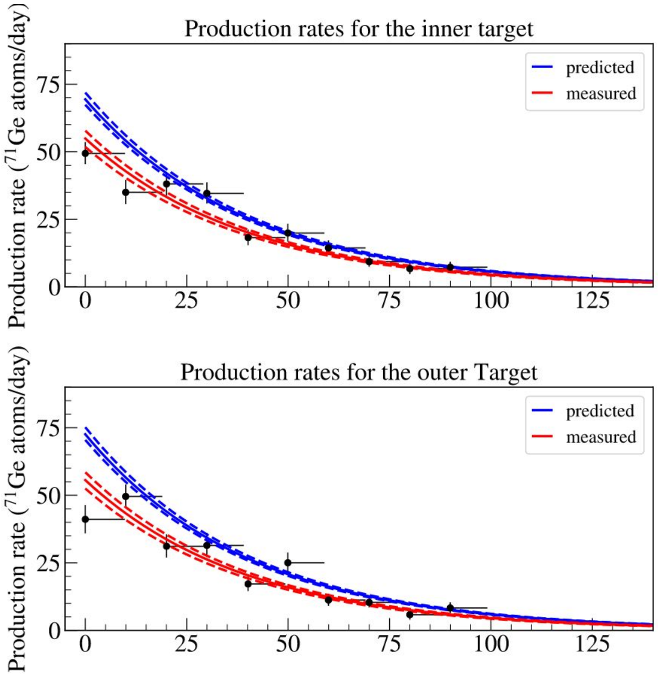


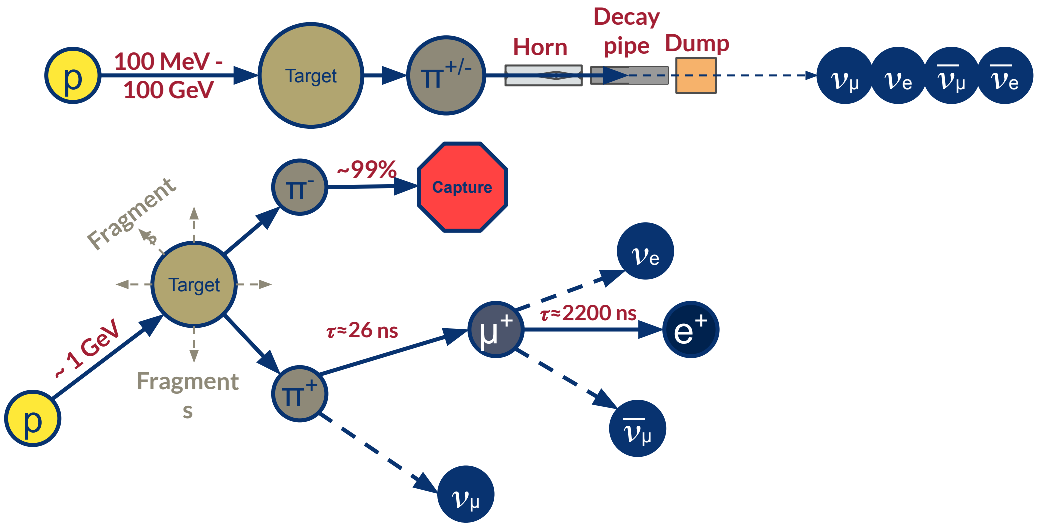
Neutrino sources: 100 keV to 100 MeV

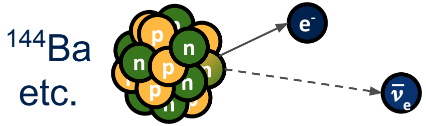


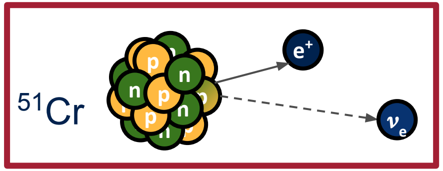


Neutrino sources: 100 keV to 100 MeV









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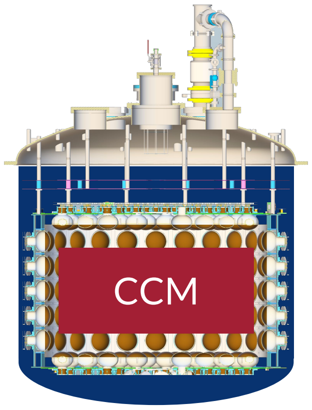
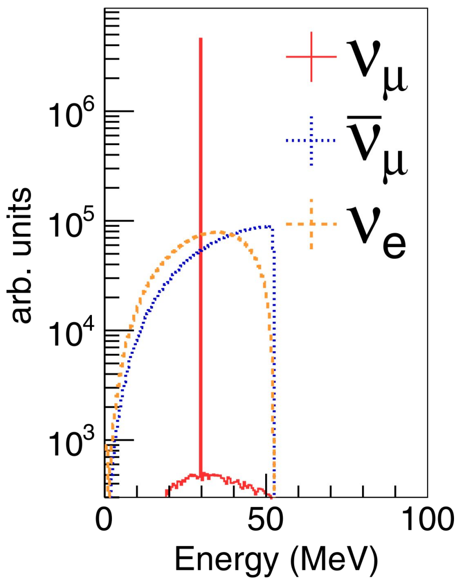
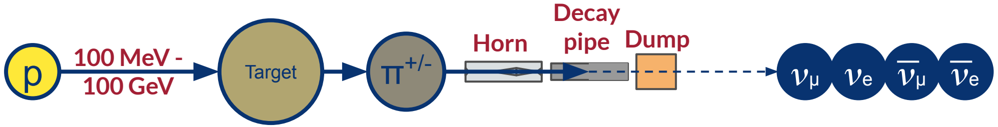
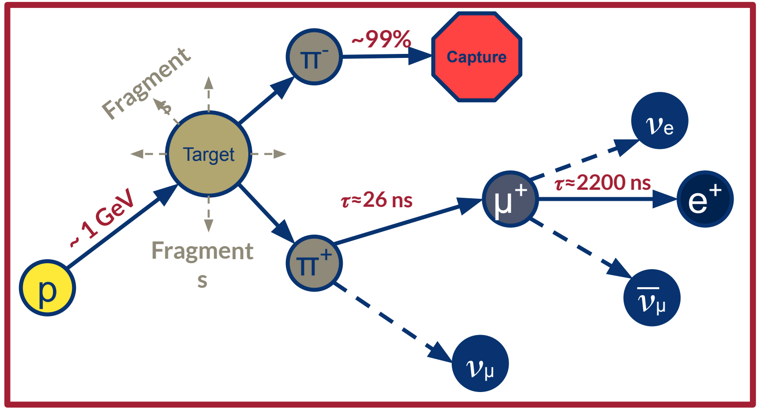
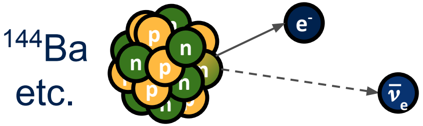
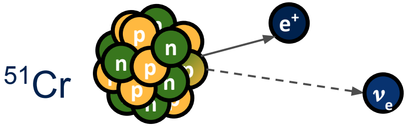




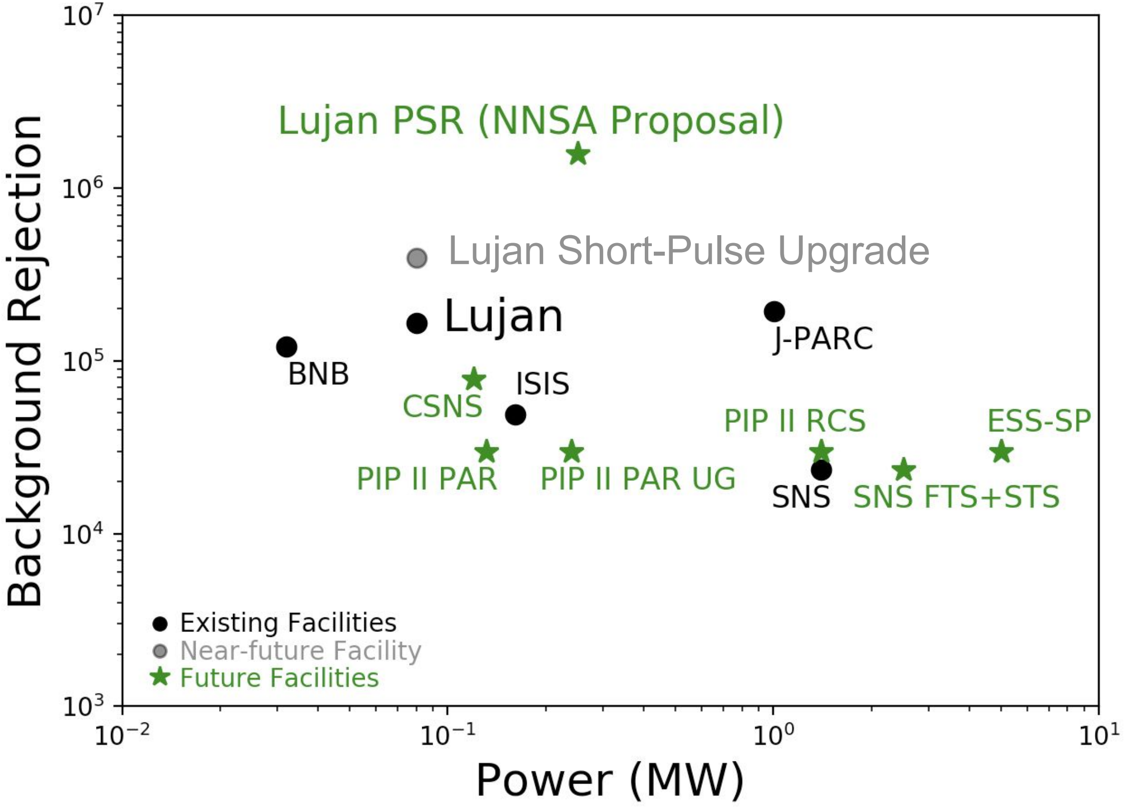








The Beam Dump Landscape...



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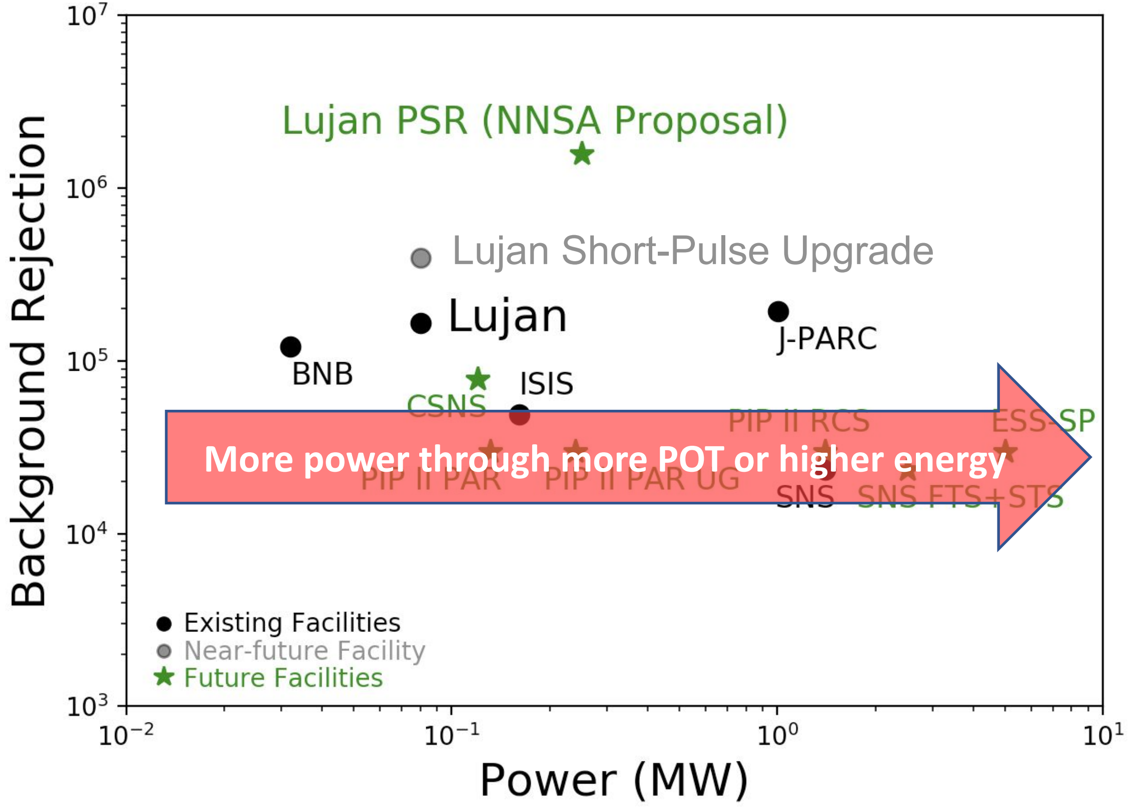
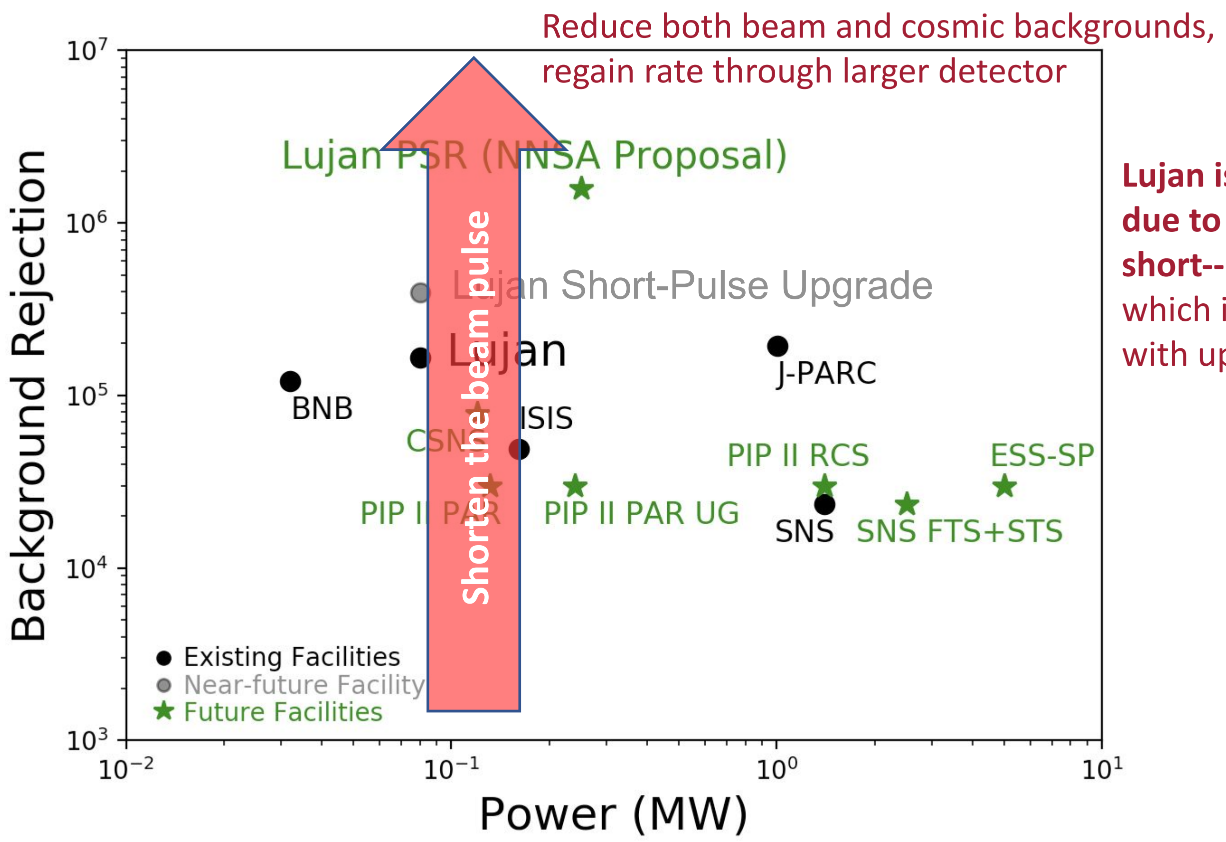


Event rates go up,
but so do
beam backgrounds

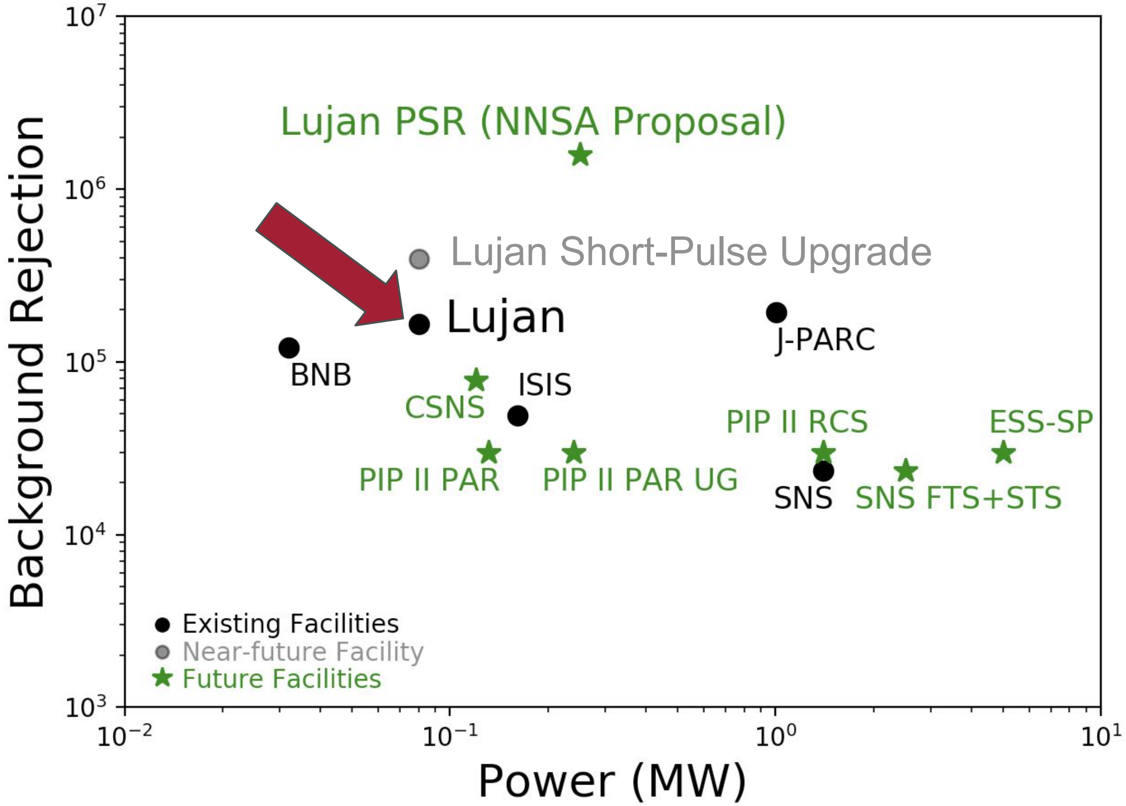
The Beam Dump Landscape...



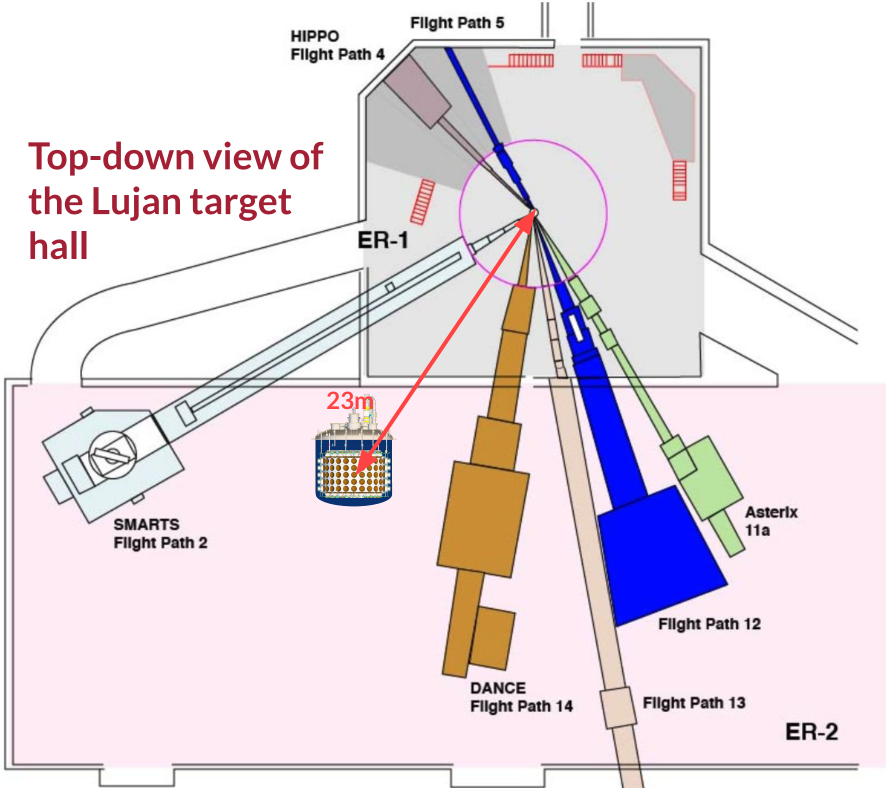
Lujan is special due to the short--pulse source, which is likely to improve with upgrades.

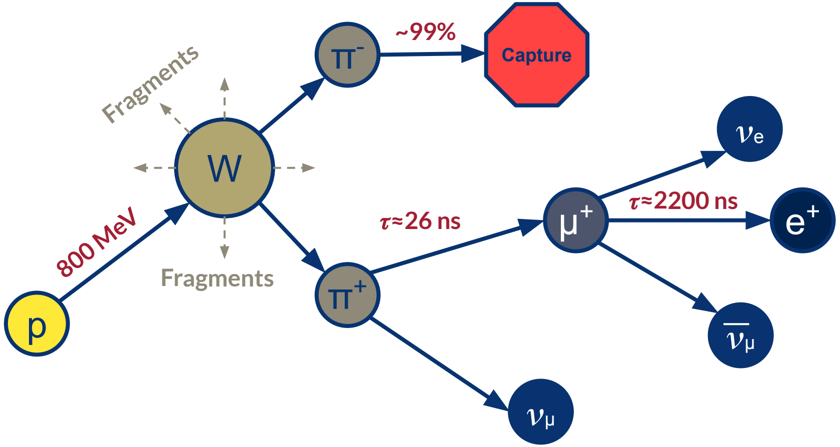
The Beam Dump Landscape...

- Lujan is unique in its background rejection capabilities
- piDAR provides a very clean flux of neutrinos
- The short 290 ns proton pulse allows us to remove neutrons through arrival time
- Future upgrades will improve performance



CCM at Lujan





- CCM is 90° off axis from the beam
- Prompt numu neutrinos at 30 MeV
- Delayed nue and numubar
- Target environment has an intense flux of: <u>charged pions</u>, <u>neutral pions</u>, <u>gamma-rays</u>, <u>muons</u>, <u>neutrinos</u>, and <u>neutrons</u>
- Ripe for dark-sector production

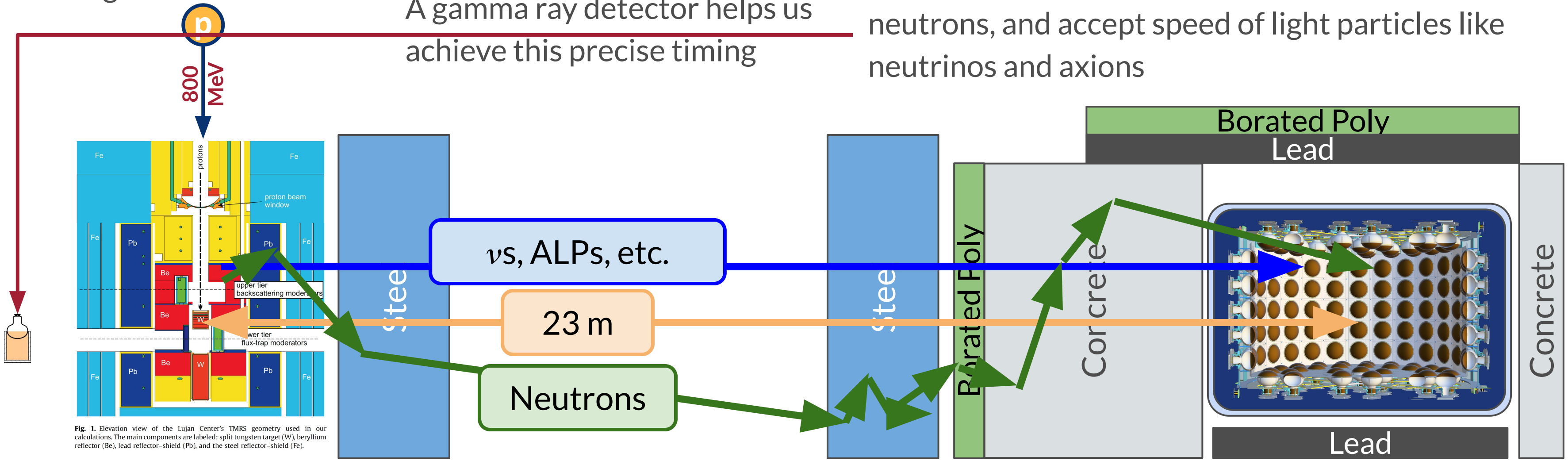
CCM shielding at Lujan

- 90° off-axis from the beam
- No decay in-flight backgrounds
- Signals produced isotropically
- Dominant background is neutrons from the target

3 ways we eliminate neutron backgrounds

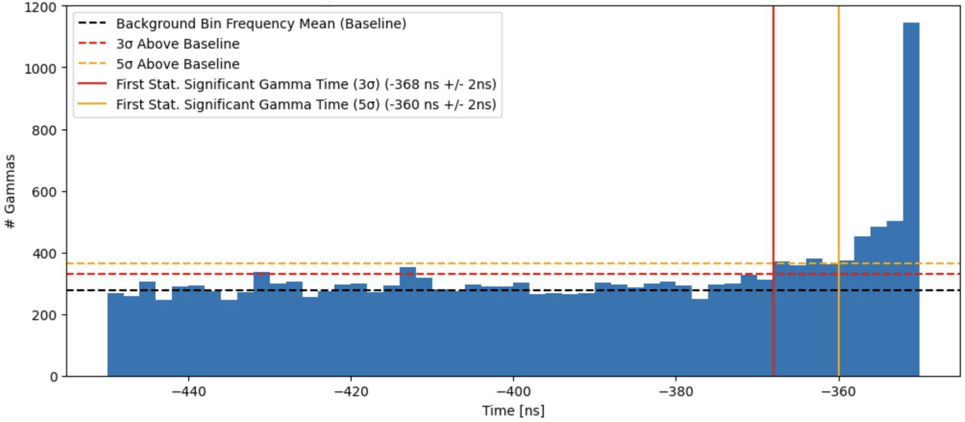
- Shielding attenuates and slows neutrons
- An active veto region tags incoming neutrons
- Precise timing allows us to reject these slowed neutrons, and accept speed of light particles like neutrinos and axions

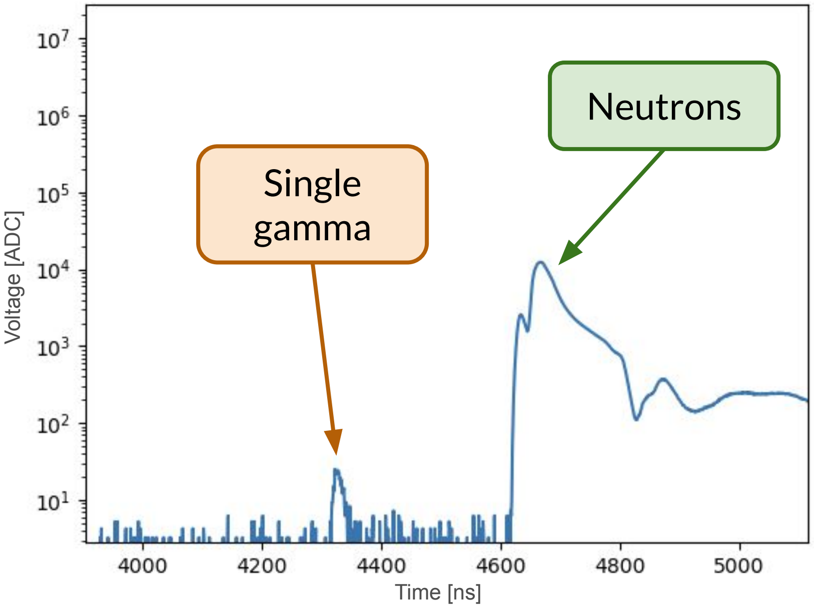
A gamma ray detector helps us achieve this precise timing



Precise arrival timing with gamma rays

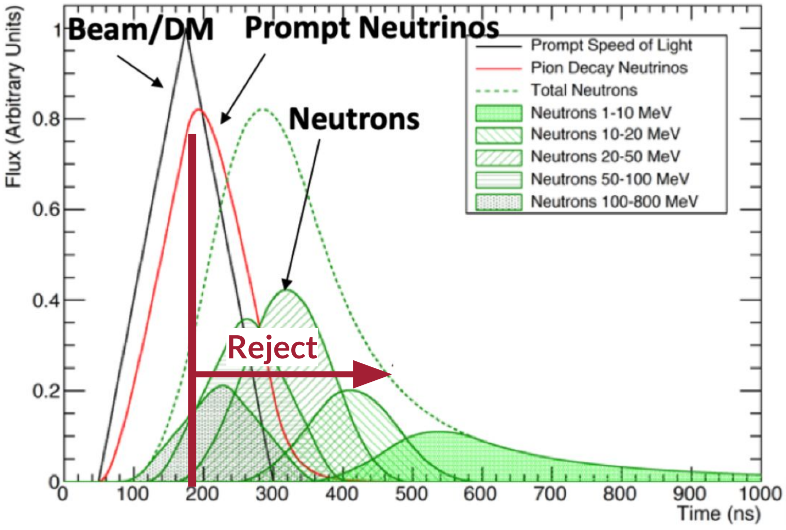
- Gamma detector placed close to target
- Pinhole in shielding allows single gamma-rays through
- Prompt, speed of light, gammas give us a reference time for when speed of light particles will arrive at CCM

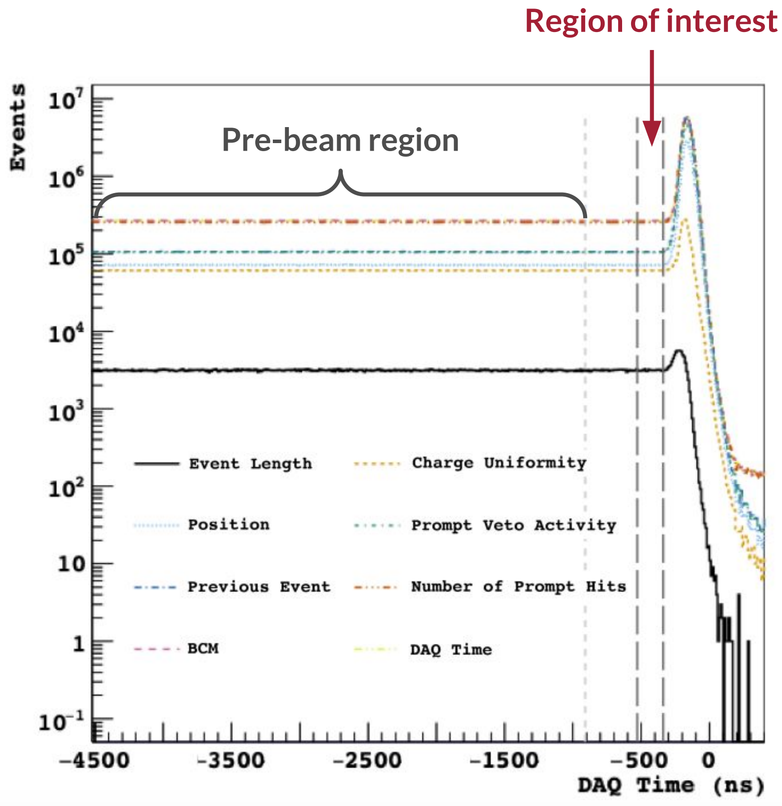




CCM timing and backgrounds

- Signals (neutrinos/ALPs/DM and others) arrive promptly
- Dominant background is neutrons from the target
  - Shielding attenuates and slows neutrons
  - Neutron background can be rejected almost entirely through timing cuts
- Steady state backgrounds are directly measured with pre-beam data





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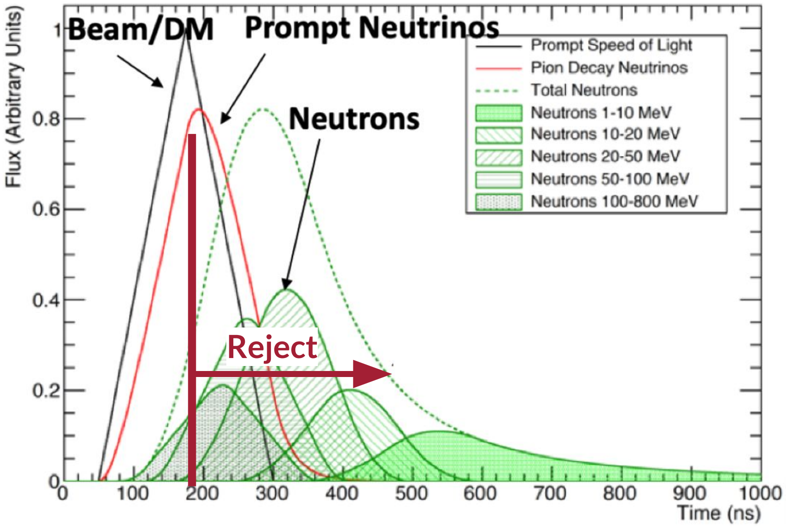
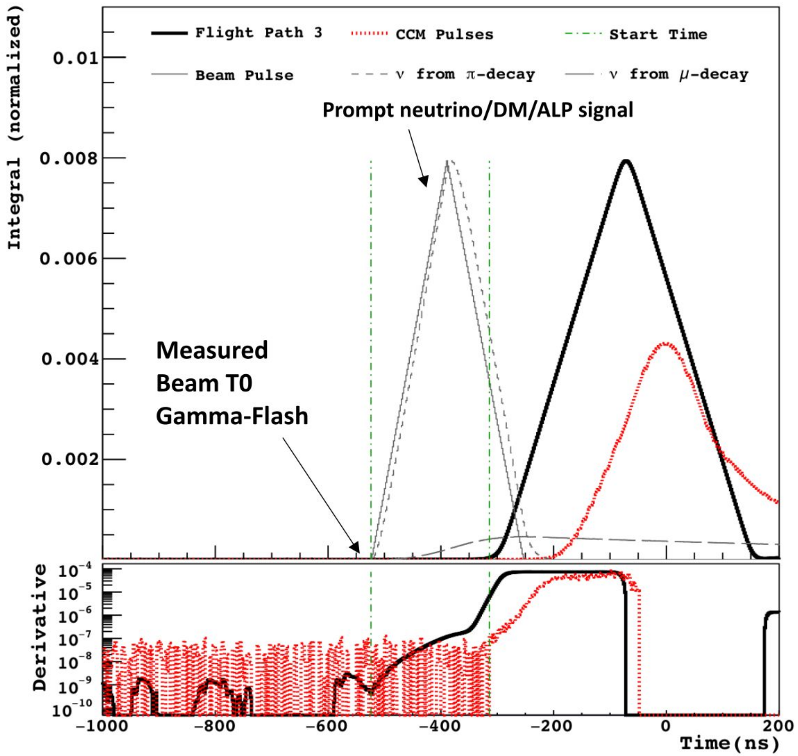
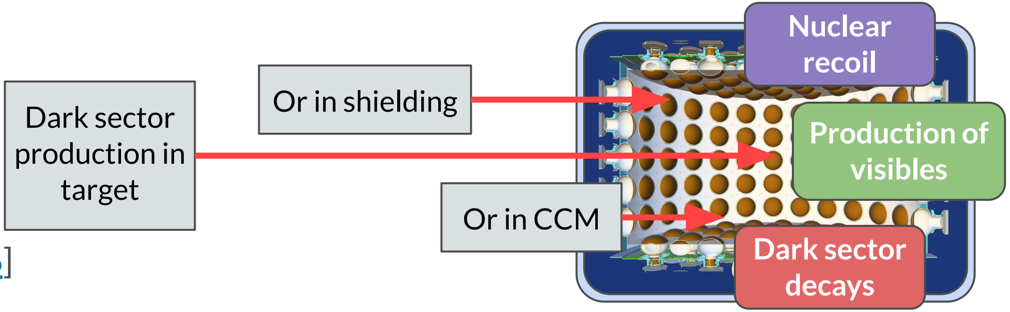




CCM physics program

Broad program of dark sector searches

- Search for Axion-Like-Particles and MeV-scale QCD axion [https://doi.org/10.1103/PhysRevD.107.095036]
- Search for leptophobic MeV-scale dark matter [https://doi.org/10.1103/PhysRevLett.129.021801]
- Search for light-dark-matter [https://doi.org/10.1103/PhysRevD.106.012001]
- Testing Meson Portal Dark Sector Solutions to the MiniBooNE Anomaly [https://arxiv.org/abs/2309.02599]
- Search for the X17 ATOMKI particle
- Search for Heavy Neutral Leptons
- Search for dark photons

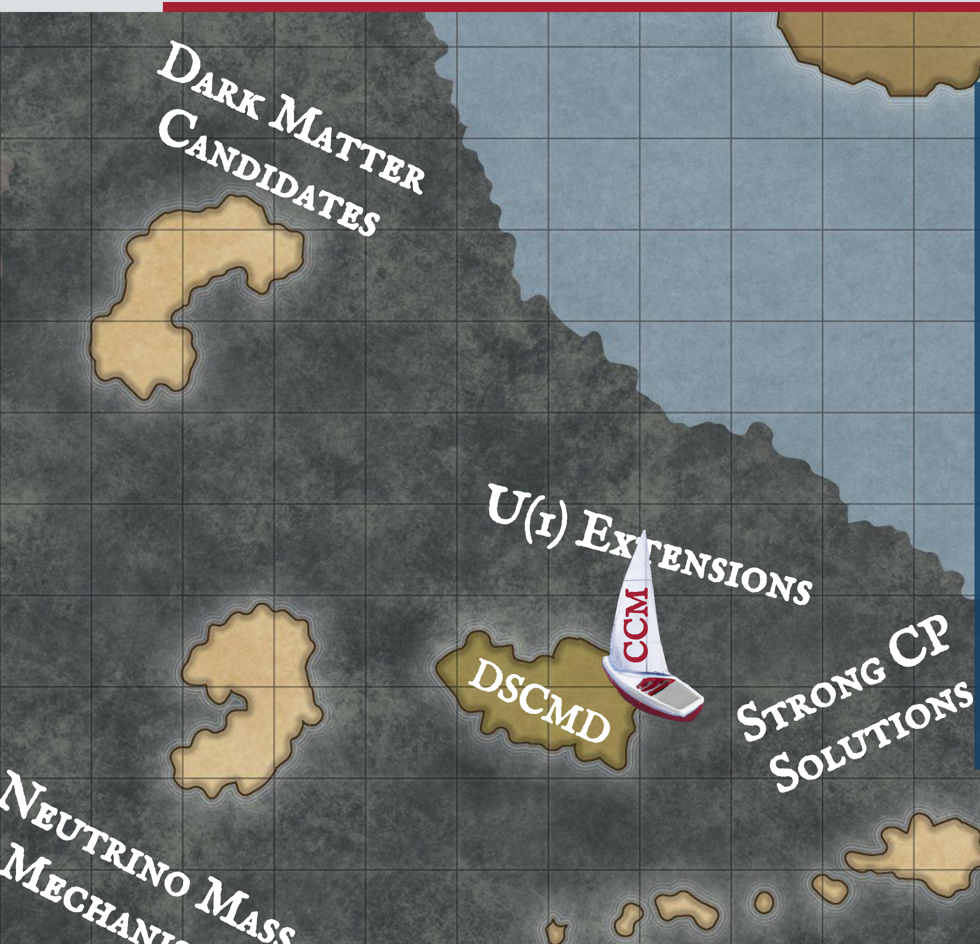


Critical Standard Model measurements

- Coherent Elastic Neutrino Nucleus Scattering (CEvNS) cross section measurement at the 10 keV to 100 keV scale
- CC and NC cross section measurements on Argon at the MeV to 10’s of MeV scale

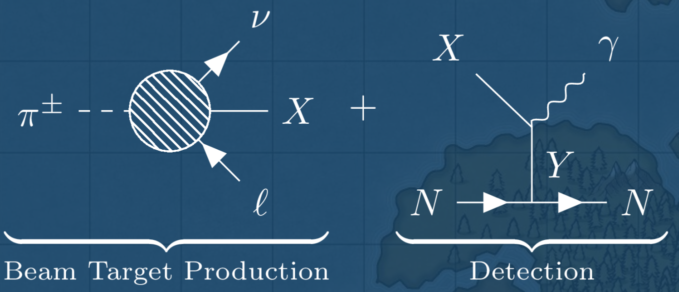
Results from CCM120 and projections for CCM200

Dark Sector Coupling to Meson Decay (DSCMD)

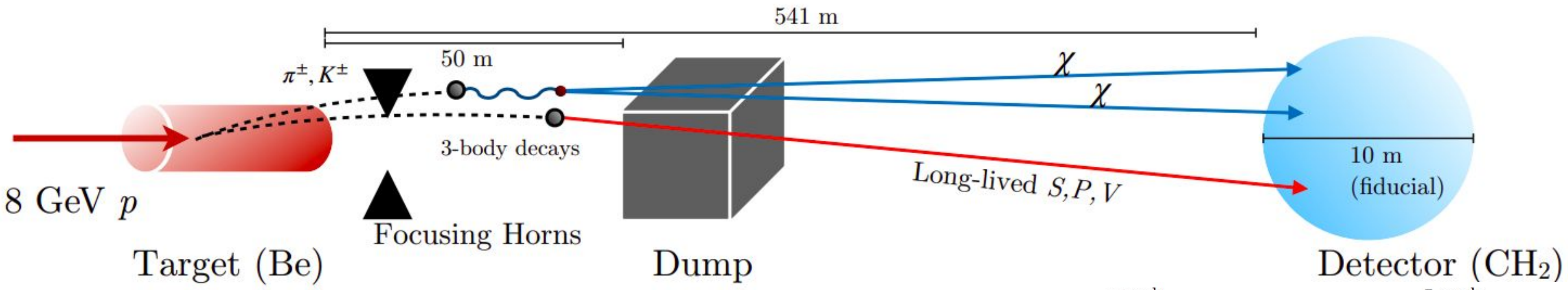


Schematically we introduce

- 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



Dark Sector Explanations of the MiniBooNE LEE



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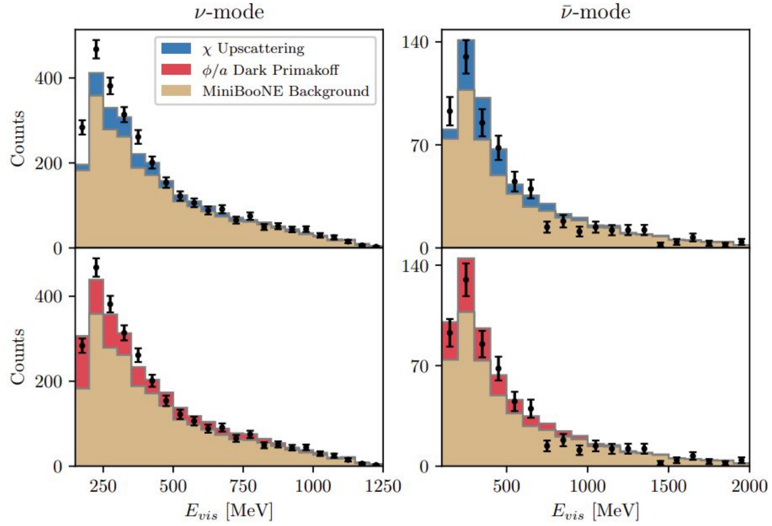
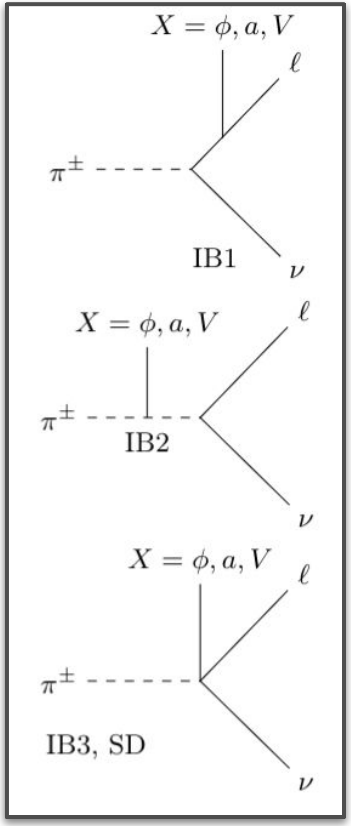


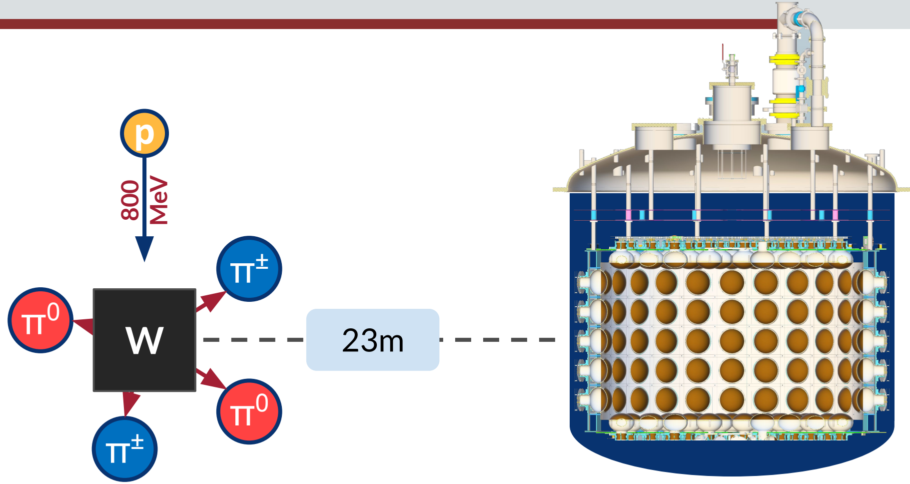
- 4.8σ excess at MiniBooNE **target mode** runs
- No excess in **dump mode** run
- If excess is due to new long-lived particles (**LLPs**) or light dark matter (**LDM**), it may be correlated to the charged meson decays
- We can test this possibility in a complementary way at CCM

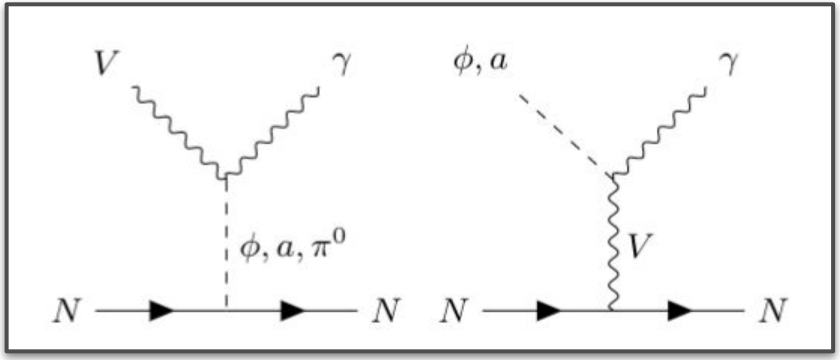
Dark Sector Coupling to Meson Decay (DSCMD)

Big picture: lots of possible operators to explain the MiniBooNE excess

We can test these systematically with both **charged** and **neutral** pion decays at CCM







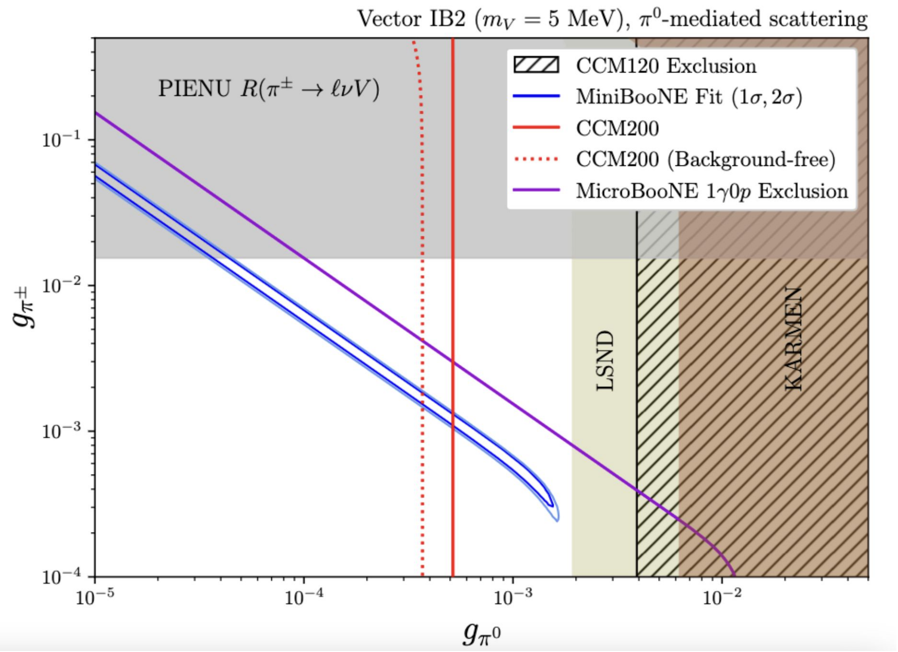
DSCMD in CCM

- Proposed explanation of MB Low Energy Excess
- 3 body meson decay producing scalar (or pseudo-scalar)
- Visibly interact in the detector

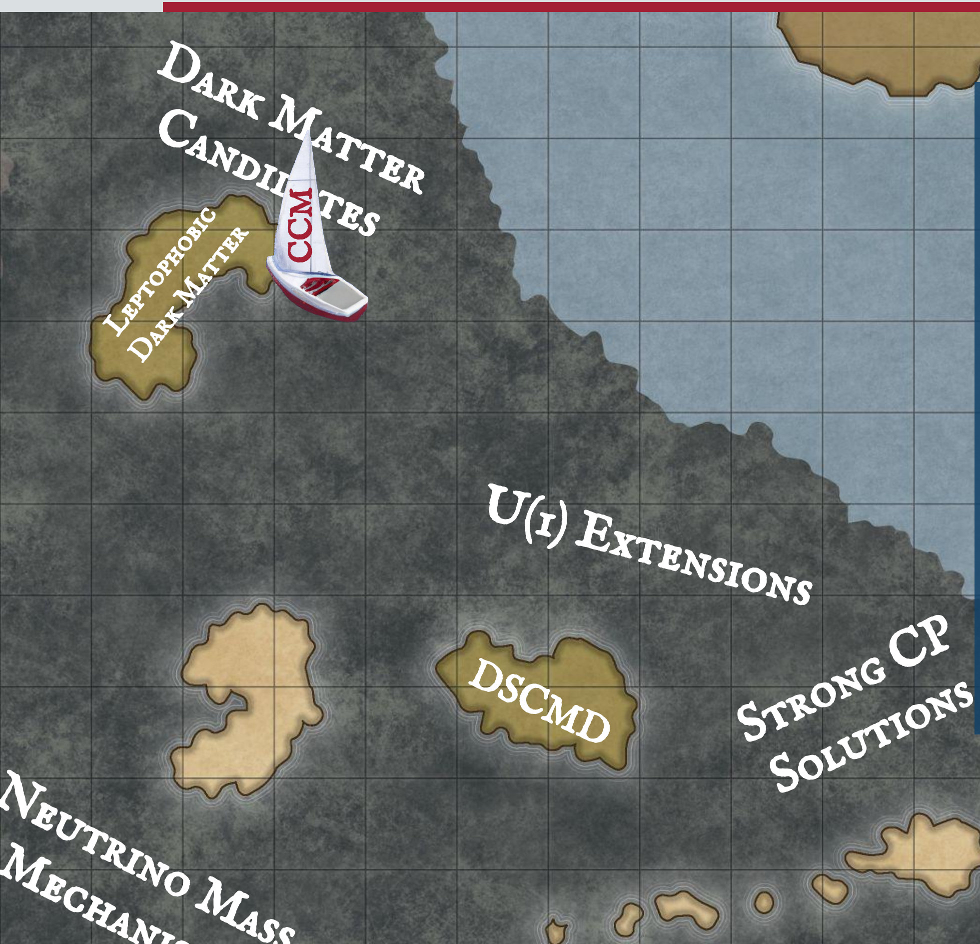
- CCM can cut into MB scalar model parameter space with current background projections
- Measurement can break potential model degeneracies with SBN

arXiv:2309.02599

Arian Thompson's Tuesday Talk

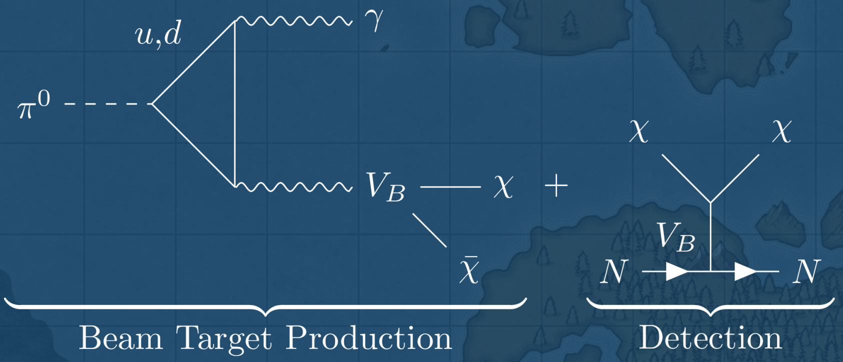


Leptophobic dark matter



Vector portal coupled to SM quarks

- Production through rare π^0 decay in the target
- Detection through coherent scattering off Argon nuclei → nuclear recoil



Leptophobic dark matter

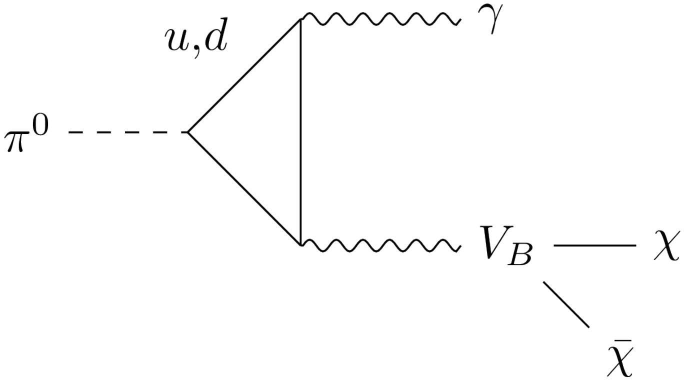
- Direct thermal relic detection is limited by abundance and mediator mass
- Can only probe mediators masses above ~1 GeV

CCM is exploring accelerator produced dark matter

- Relativist DM production means we can probe mediator masses in the less explored ~10 MeV regime

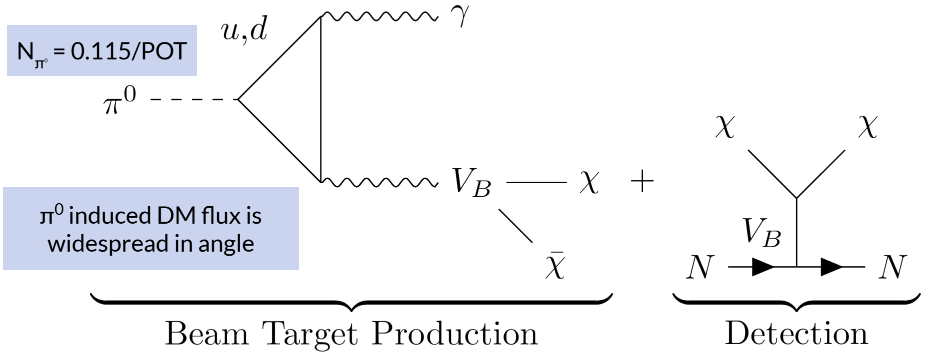
Leptophobic scenario

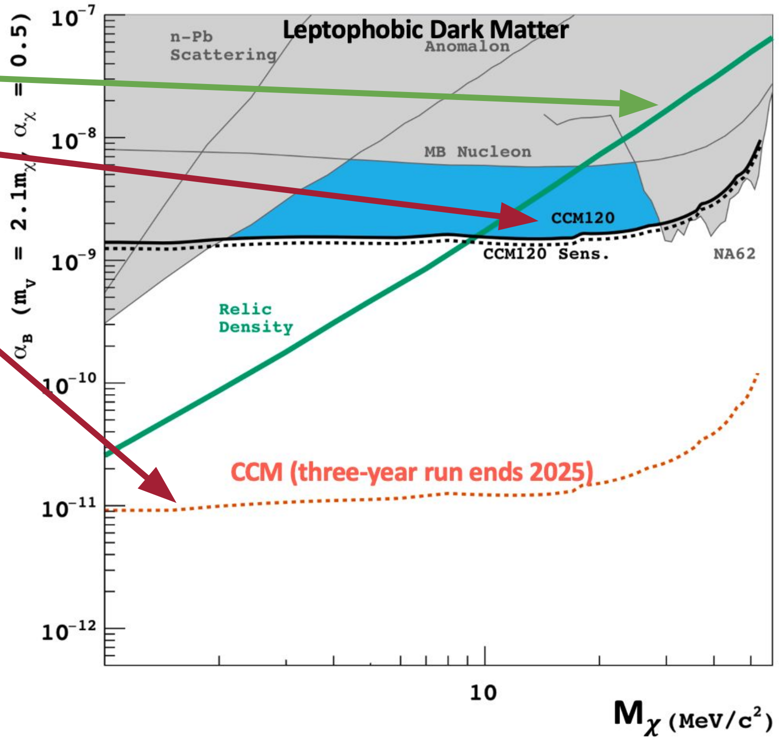
- Scalar DM candidate χ
- Vector portal communicating with the SM quarks via gauged baryon number
- Production happens through a rare π^0 decay in the target
- Detection is through a coherent interaction that results in a low-energy nuclear recoil



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





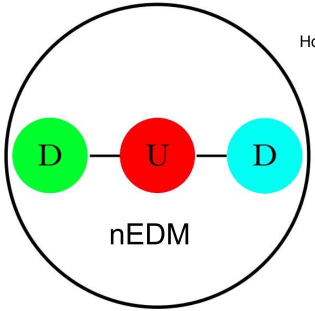
First Leptophobic Dark Matter Search from the Coherent–CAPTAIN-Mills Liquid Argon Detector
PhysRevLett.129.021801

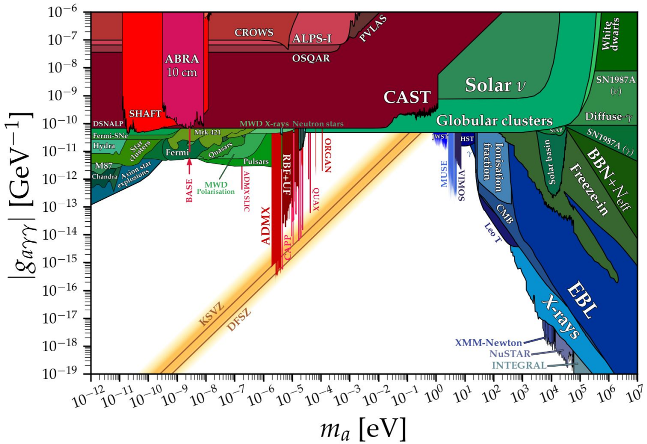
Axion-Like Particles (ALPs) and the QCD Axion

Axion-Like Particles (ALPs) and the QCD Axion

- Axion-Like-Particles (ALPs) show up in many well-motivated BSM theories, like dark matter explanations, dark mediators, and BSM neutrino physics
  - Generically interesting to search across the parameter space
- (QCD) Axions are a proposed solution to the Strong-CP problem in QCD
  - Why is the neutron dipole moment so small? $d_n < 10^{-26}$ e cm
  - Related to CP violating term in QCD: $\mathcal{L} \supset \theta G\tilde{G}$
  - Axions provide a mechanism to dynamically conserve CP
  - Minimal QCD axions live in a small band in the mass-coupling parameter space

Hook [1812.02669]

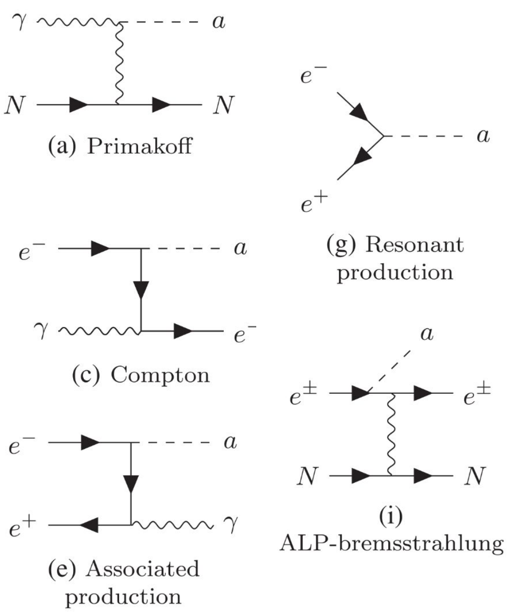




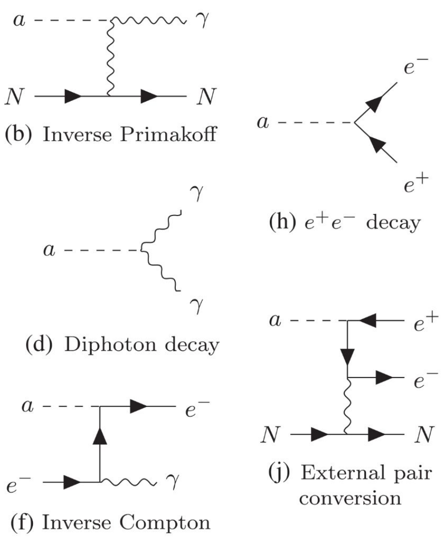
CCM is sensitive to ALPs with masses up to ~100 MeV (not shown in this plot)

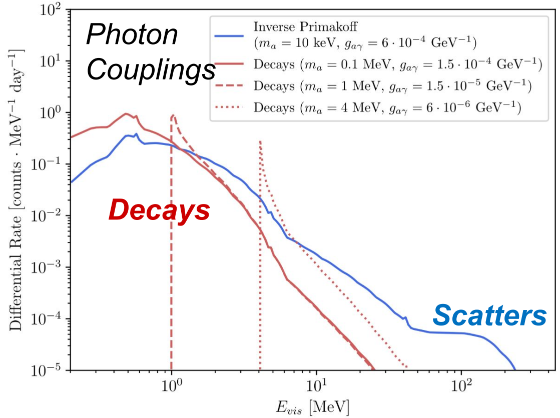
Phenomenology: ALP Detection in CCM

Production Channels in W Target

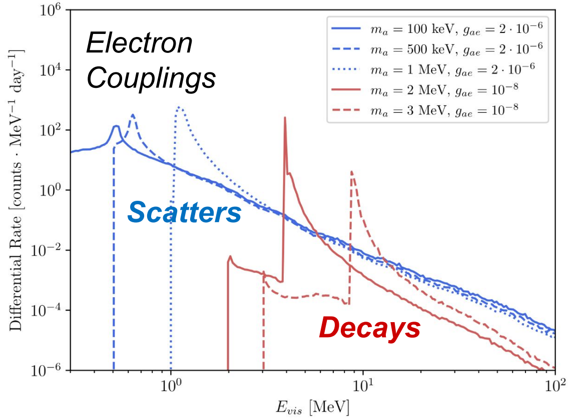


Detection Channels



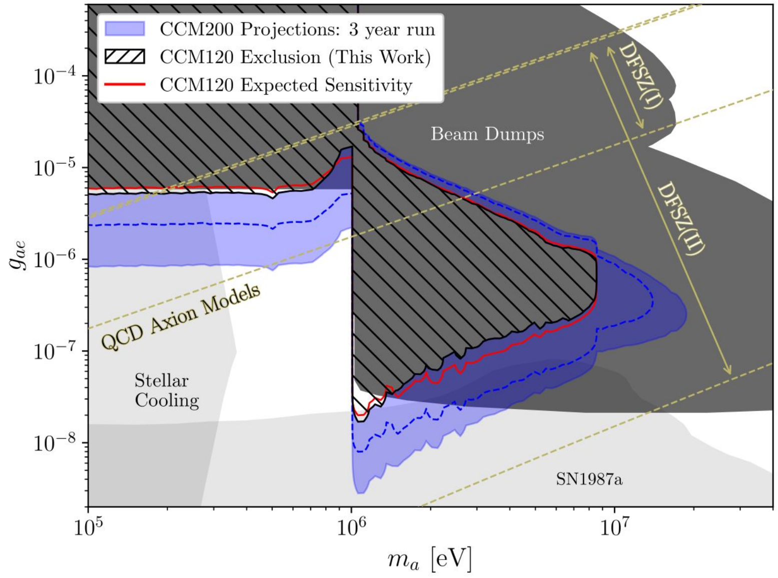


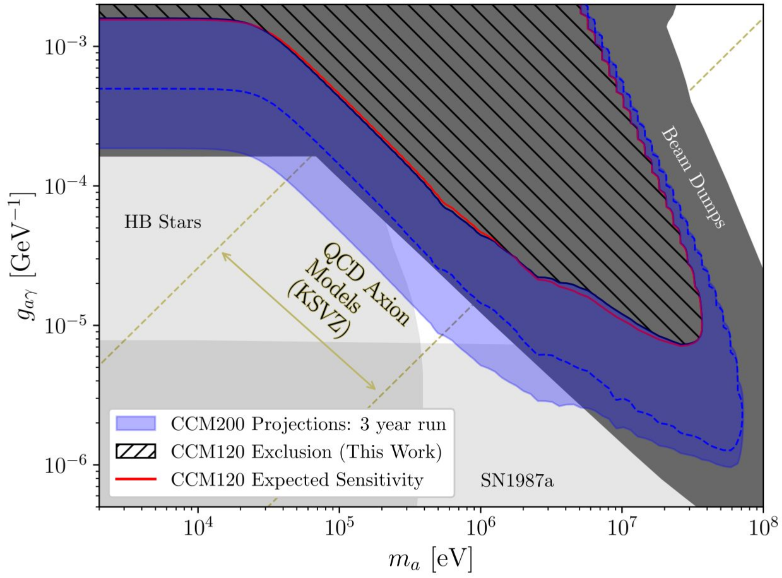
Phys. Rev. D 107 (2023) 9, 9 [2112.09979]



CCM: Axion-Like Particles

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





Beyond CCM

Coherent Cesium Iodide (CCI)

CCI: A small-scale counterpart to CCM

- Compact size make the detector easy to shield and easy to move
- 1 ton segmented CsI scintillation detector, instrumented with PMTs
- Critical design characteristics
  - 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
- Provides sensitivity to CEvNS
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  - Large event rate
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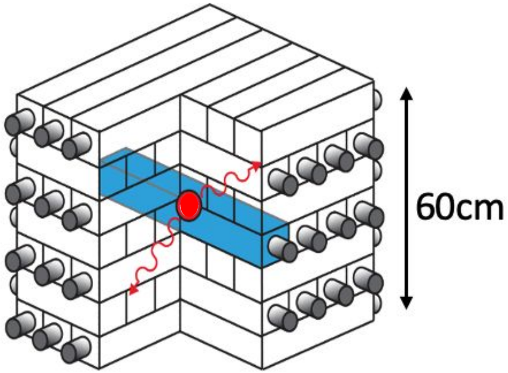
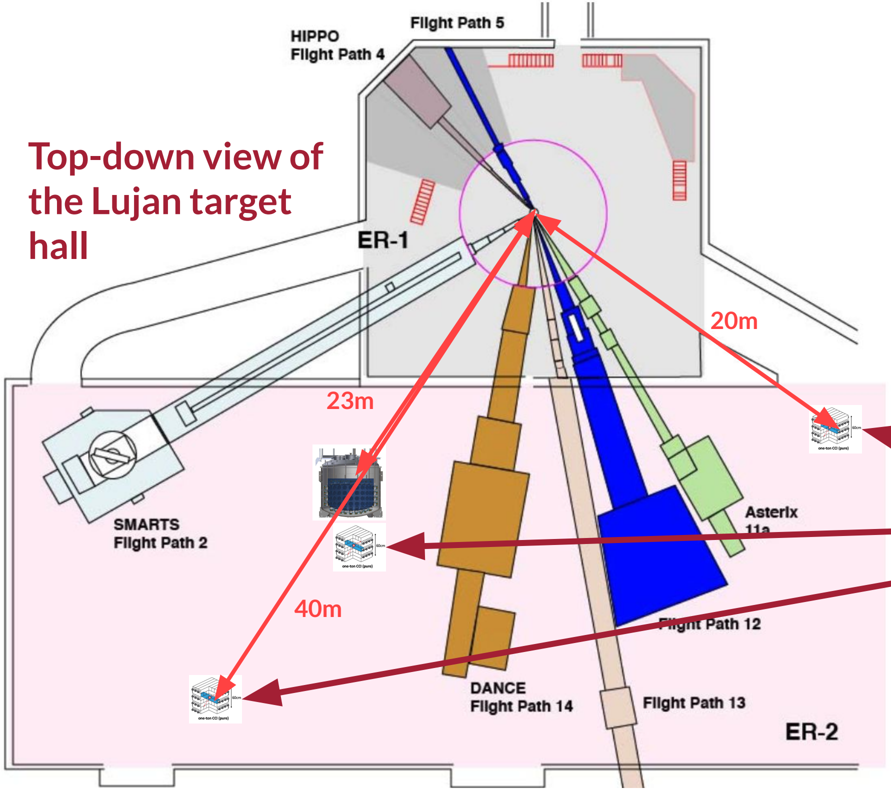


one-ton CCI (pure)

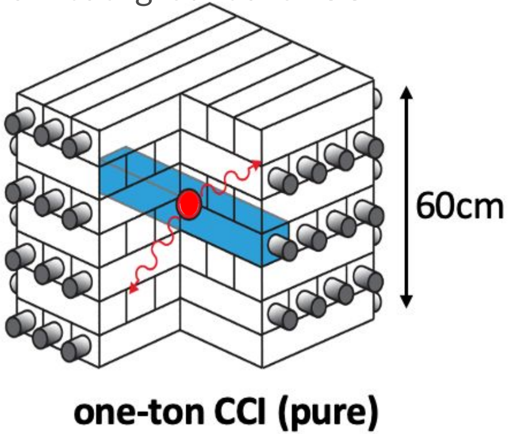
Assembled from spare CsI crystals available at LANL

CCI at Lujan

Top-down view of the Lujan target hall



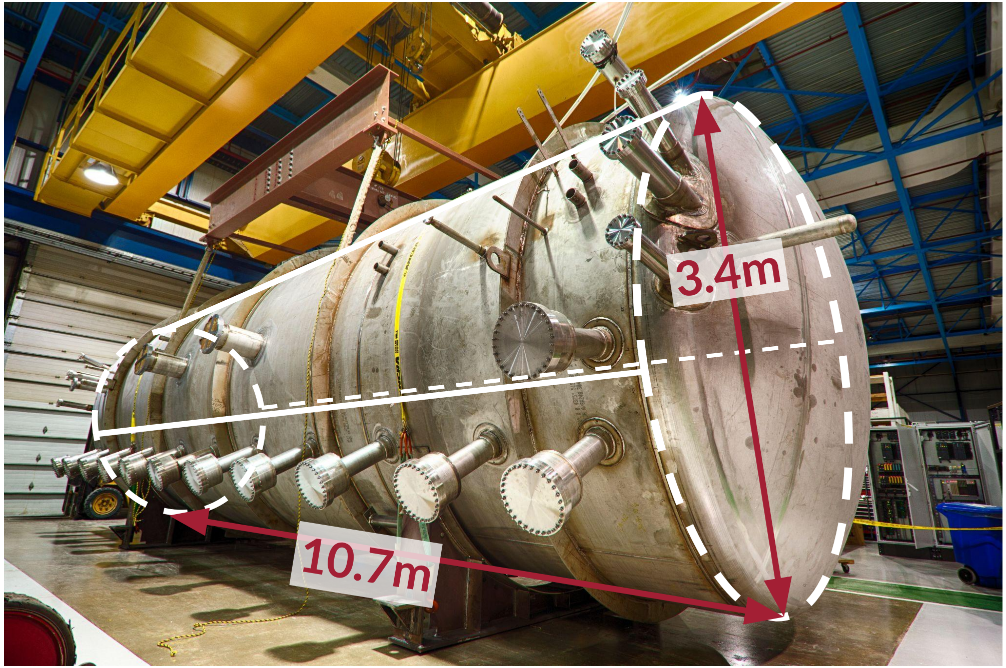
- Initially to be placed behind CCM to take advantage of existing shielding
- Can be moved to perform measurements at different distances
- Provides us flexibility to hunt down different signals or constrain backgrounds for CCM



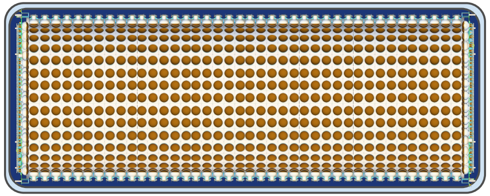
Lujan Liquid Argon Measurement Apparatus (LLAMA)

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

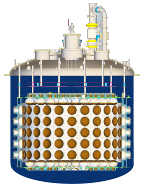
- Instrument it like CCM: 1.5k 8in PMTs
- Orient it towards the beam
- Detector can be constructed for under $30M



LLAMA



CCM



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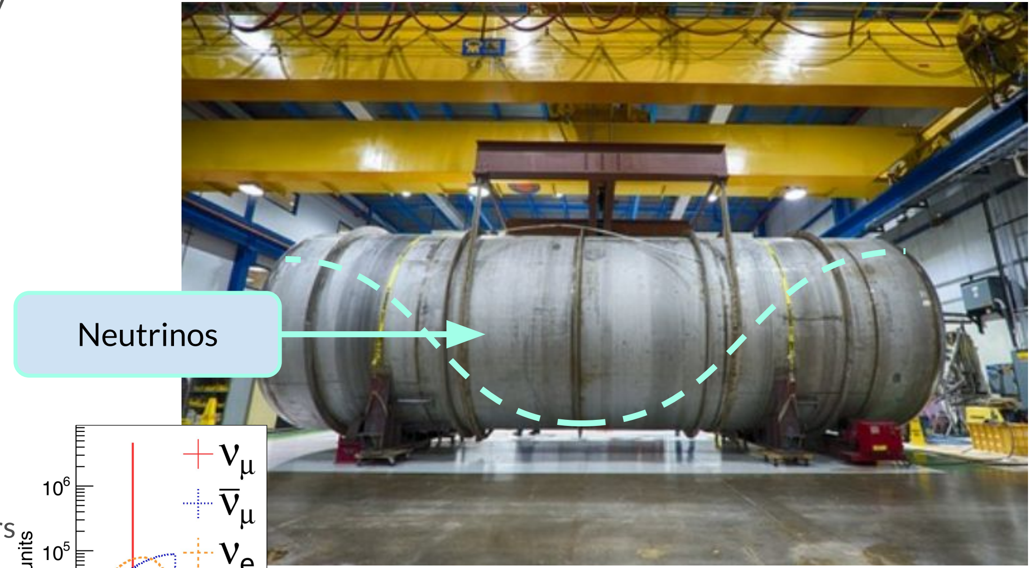
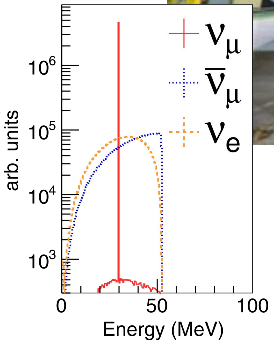
  - Allows us to test the BEST oscillation scenario
  - Precision cross section measurement
- Sterile neutrino oscillations can be probed over the length of the detector
  - CEvNS gives a very large sample of neutrino interactions
  - Timing can be used to distinguish between flavors
  - Can be supplemented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

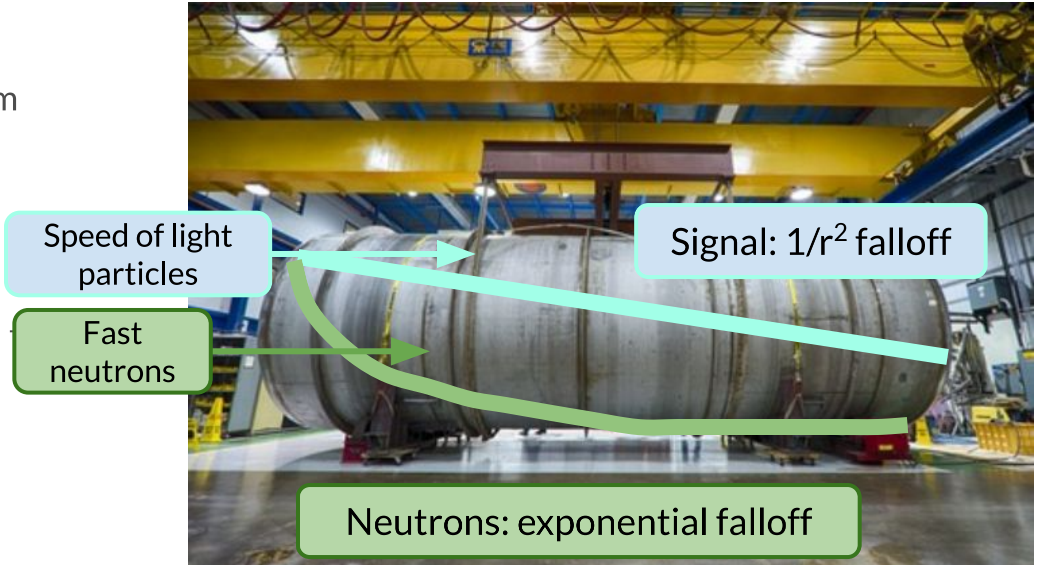




LLAMA

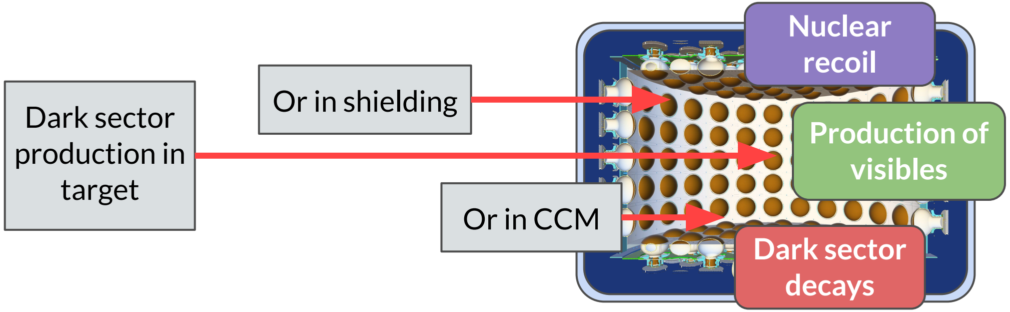
Key improvements over CCM

- 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



Summary

- Access to an intense source of pions allows CCM to probe possible explanations to the MB excess
- Lower energy + off-axis PiDAR source + fast timing ⇒ very low backgrounds



Standard Model measurements

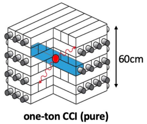
- Coherent Elastic Neutrino Nucleus Scattering (CEvNS) cross section measurement at the 10 keV to 100 keV scale
- Neutral current and charged current neutrino cross section measurements at the MeV to 10's of MeV scale

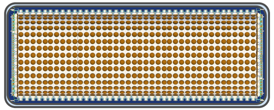
Broad program of dark sector searches

- 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
- ...

CCM: In the process of analyzing our 2022 and 2023 data samples

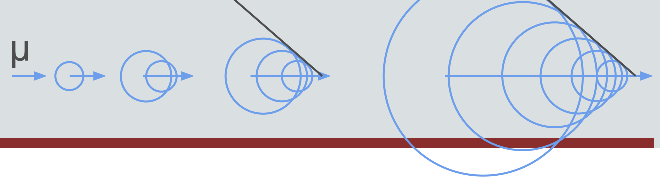
Plans beyond CCM at Lujan:



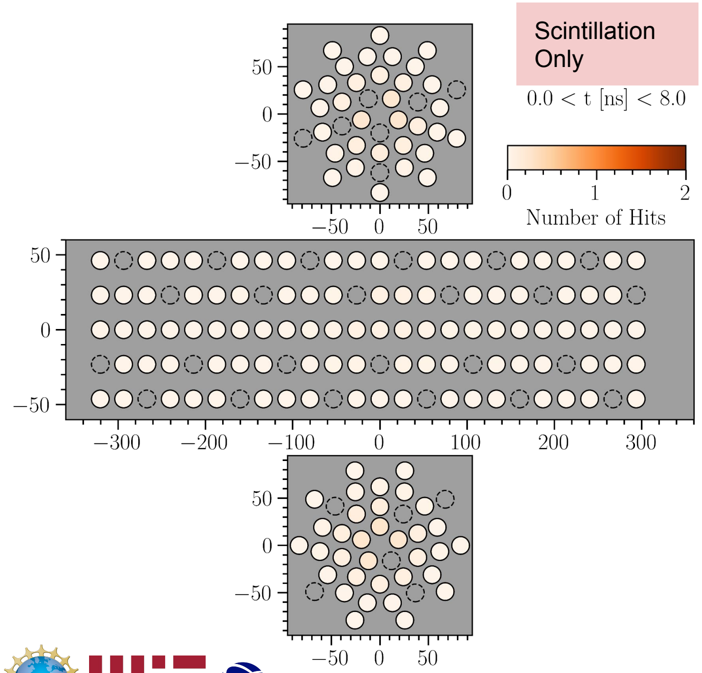


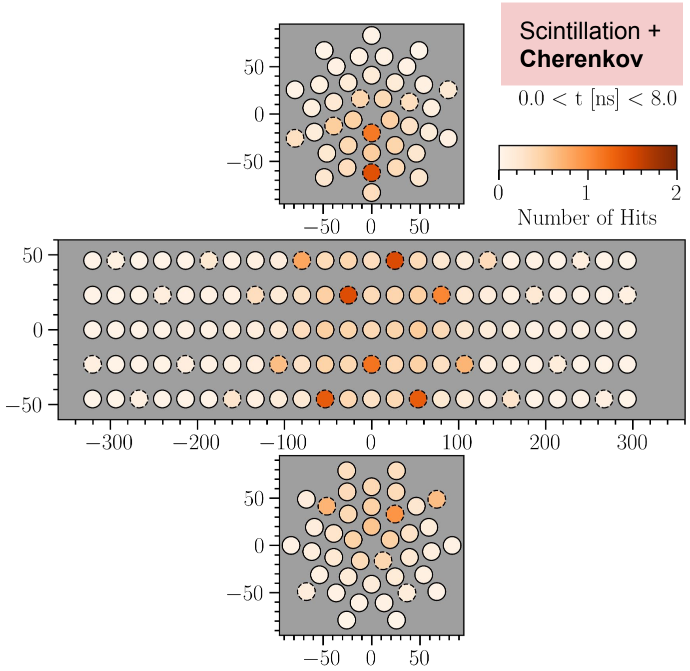
Bonus Slides

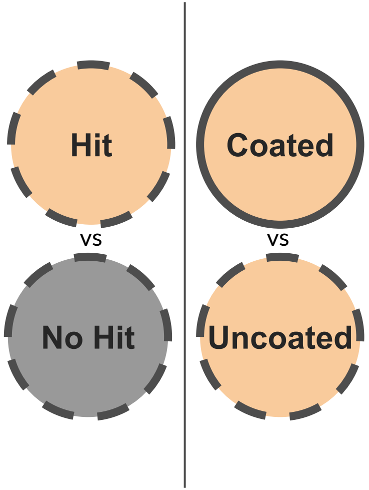
CCM Cherenkov light



- Cherenkov light is **direct**, **directional**, **broad spectrum**
- Scintillation light is **delayed**, **isotropic**, and in the **UV**
- Average photo-electrons over 1000 simulated events

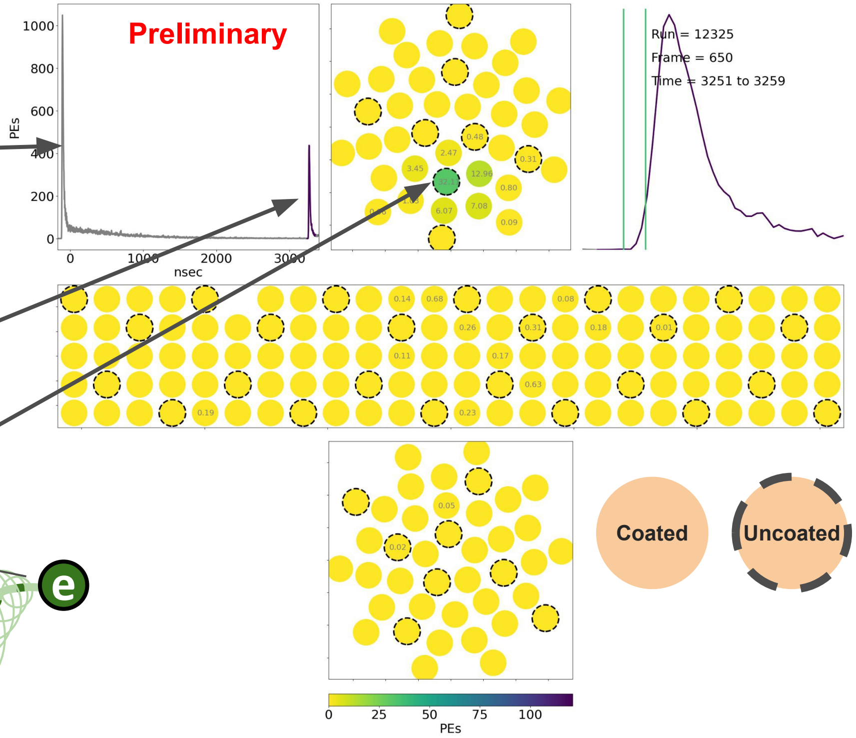


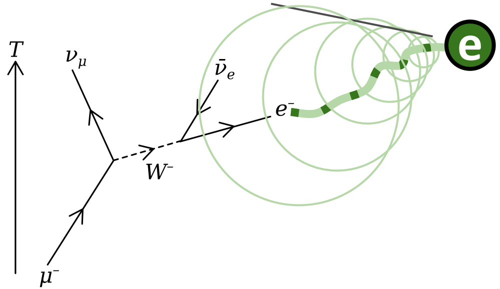




Cherenkov light with Michel electrons

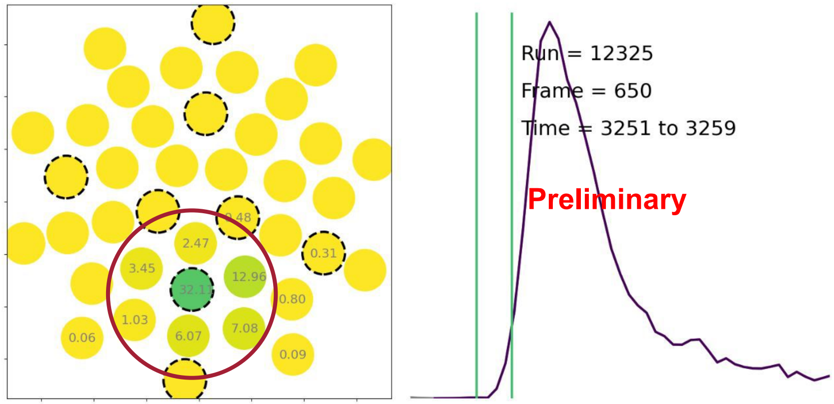
- Cosmic ray muon is tagged by external plastic scintillator detector
- Muon enters the detector causing bright scintillation, and coming to a stop (1/10 muons)
- Stopped muon subsequently decays, creating a Michel electron with energy up to 53 MeV
- Michel electron produces Cherenkov and scintillation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

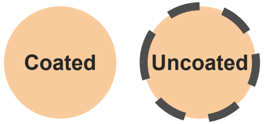


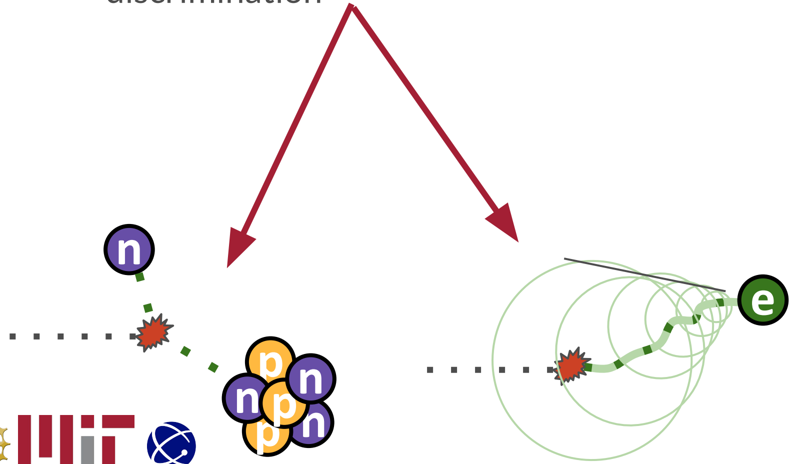


Cherenkov light with Michel electrons

- 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

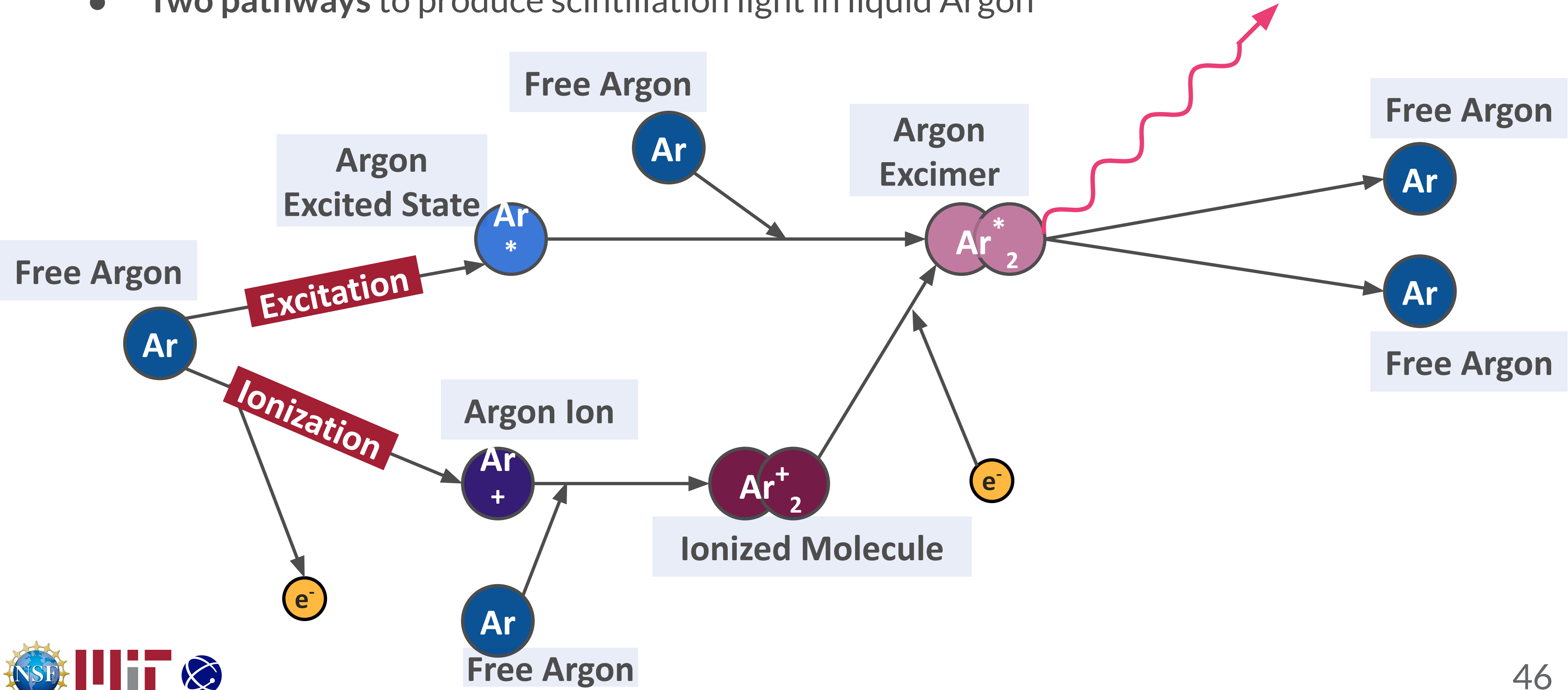






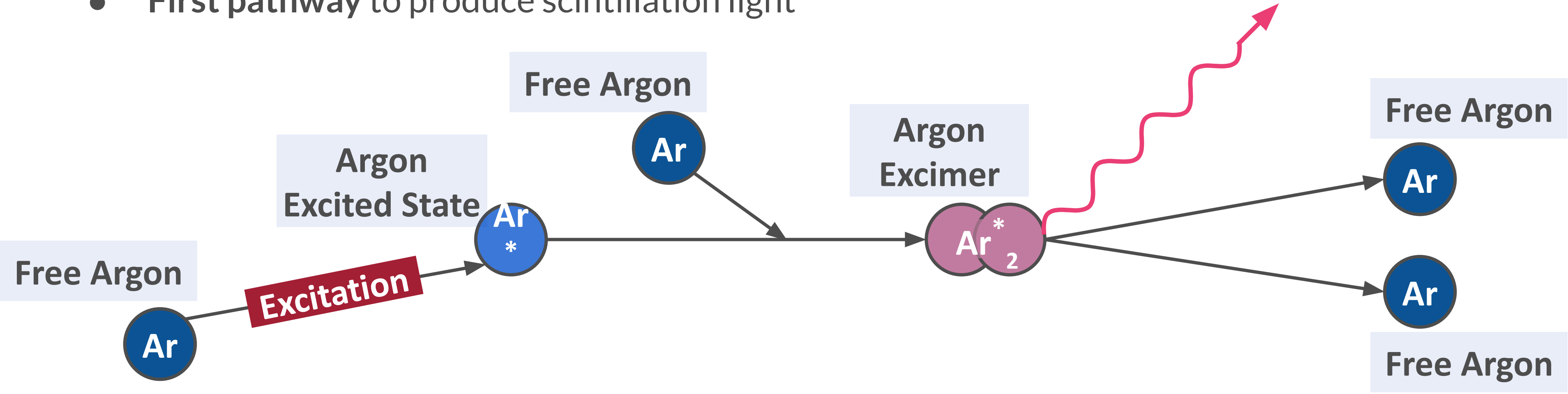
Scintillation light in liquid argon

- **Two pathways** to produce scintillation light in liquid Argon



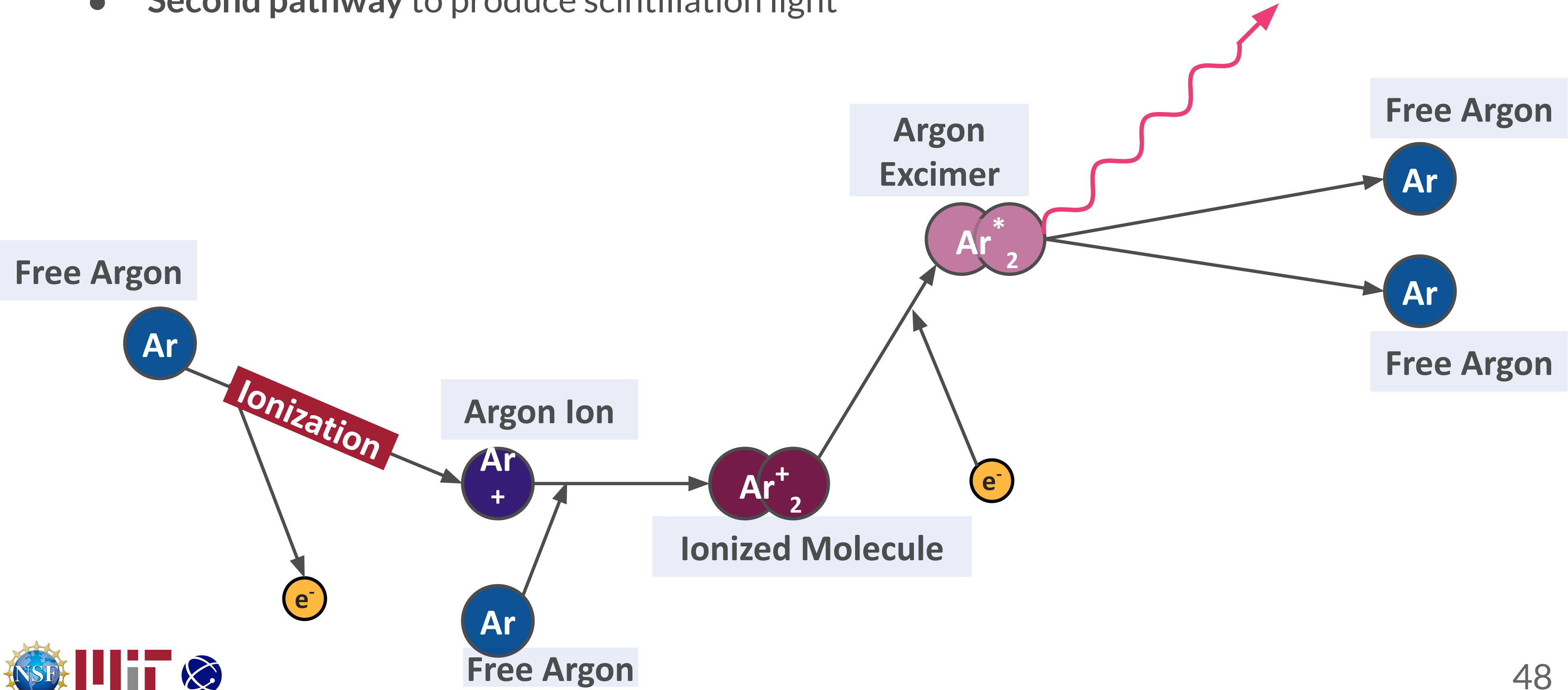
Scintillation light in liquid argon

- **First pathway** to produce scintillation light



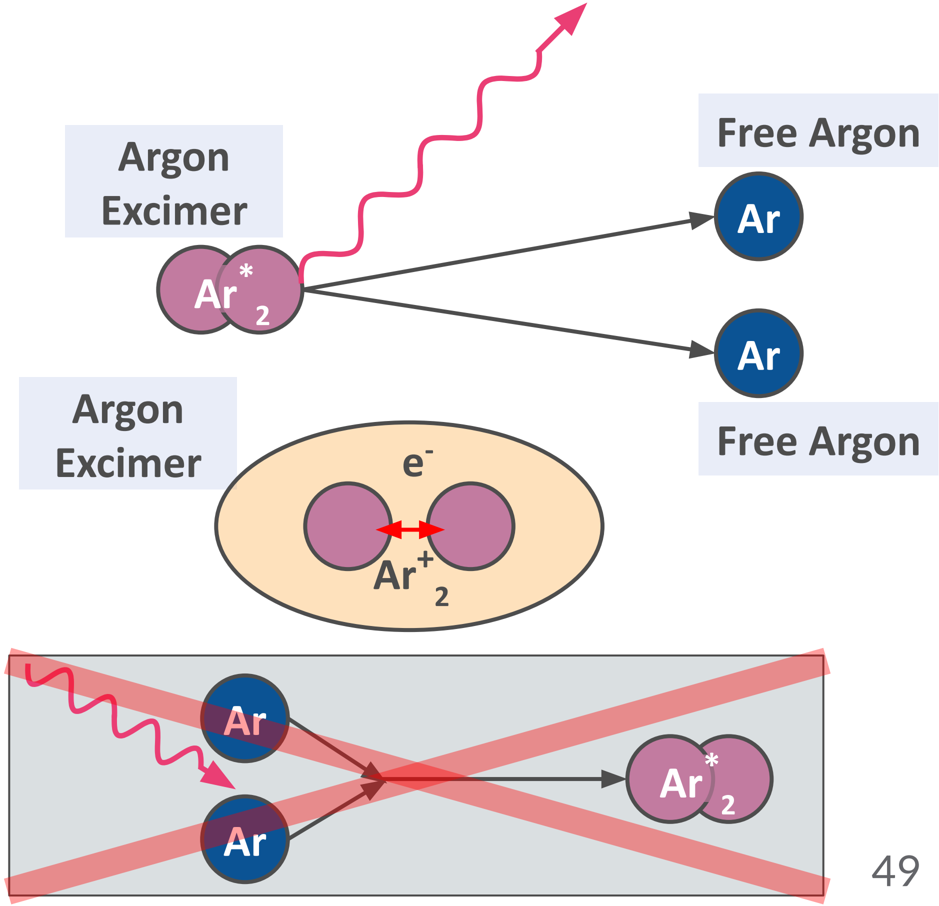
Scintillation light in liquid argon

- **Second pathway** to produce scintillation light



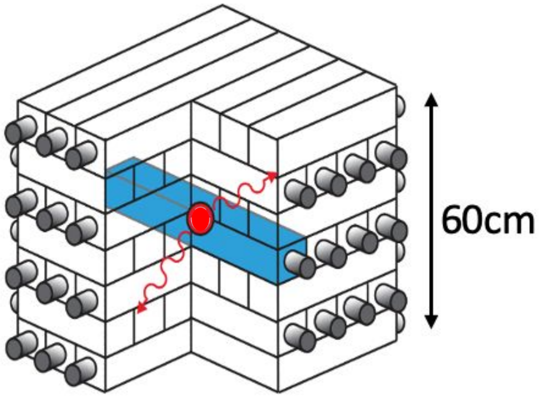
Scintillation light in liquid argon

- All liquid argon scintillation light comes from an Argon excimer
- The Argon excimer is an Ar_2^+ dimer core with a bound single bound electron
  - This Rydberg state has a nuclear separation of ~2Å
  - Decay of the excimer emits 128nm UV light
- Two excimer states of nearly identical energy exist: the **singlet state**, and the **triplet state**
- The two states have decay times of **6 ns** and **1500 ns** respectively
- Free atoms in liquid Argon are approximately 4 Å apart, making liquid Argon transparent to its own scintillation light

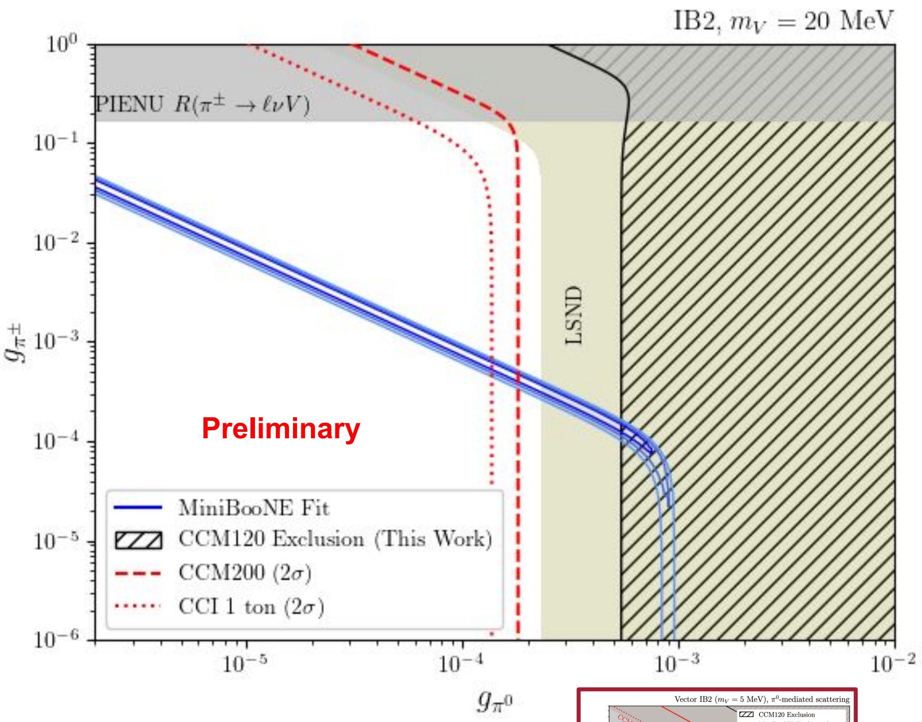


DSCMD in CCI

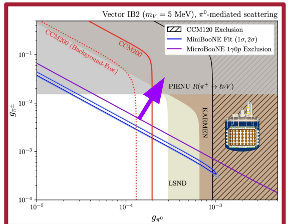
- CCI provides a modest improvement over CCM in sensitivity
- Low radioactive backgrounds and higher cross section compensates for lower mass



one-ton CCI (pure)



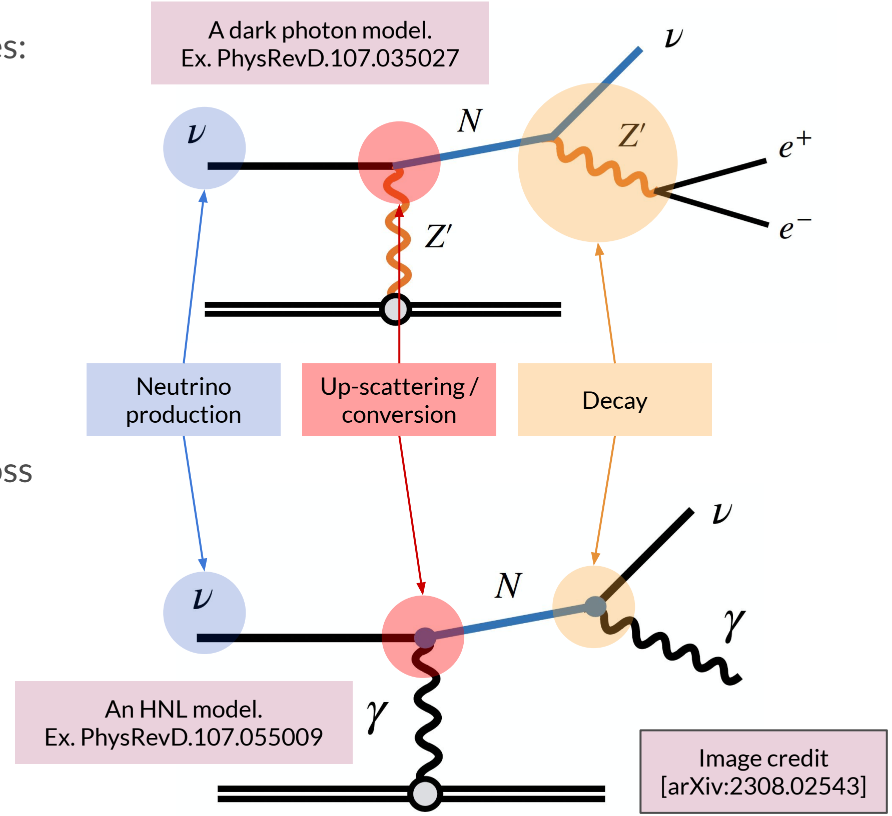
Different mediator mass than prev. slide

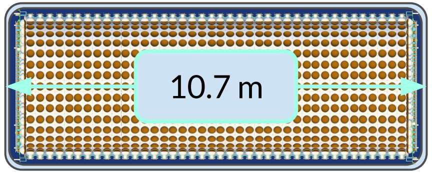


Dark photons and other “3 vertex” models

“3 vertex” models

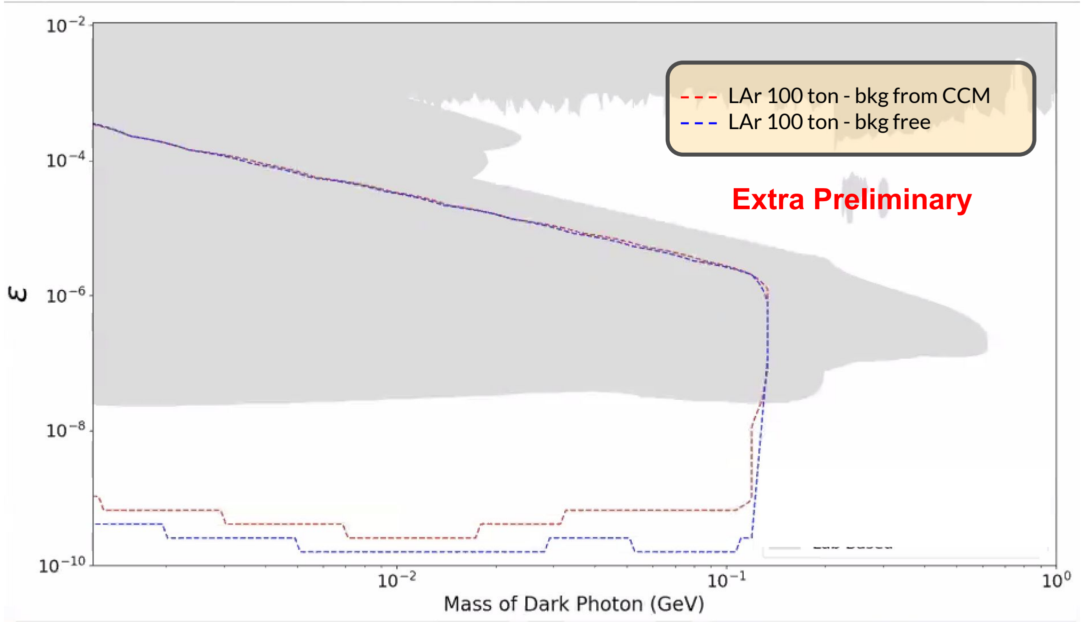
- Two related trends in interpreting neutrino anomalies:
    - Looking at more complex models: in their theory, and number of parameters
    - Looking at more complex models: in their spatial geometry
- Many of these have “3 vertices” that we care about
    - Neutrino production
    - Upscattering / conversion
    - Decay
- A consequence of this is that longer detector geometries become advantageous for detection across a wide range of the decay model parameter space
- LLAMA benefits greatly from this





LLAMA

- Examining a dark photon model with LLAMA
- Just one example of a model that has the “3 vertex” structure
- LLAMA provides excellent coverage of new parameter space
- We expect this to be true for many models with similar structure



Coherent Cesium Iodide (CCI)

CCI: A small-scale counterpart to CCM

- Compact size make the detector easy to shield and easy to move
- 1 ton segmented CsI scintillation detector, instrumented with PMTs
- Critical design characteristics
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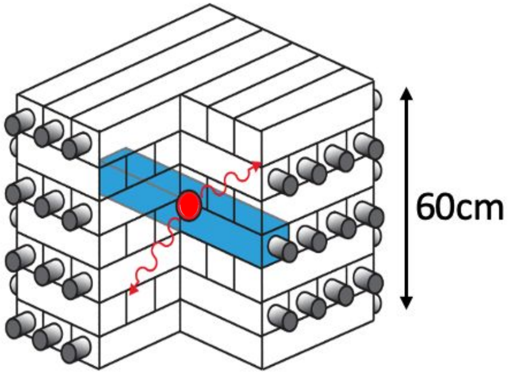

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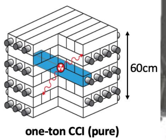
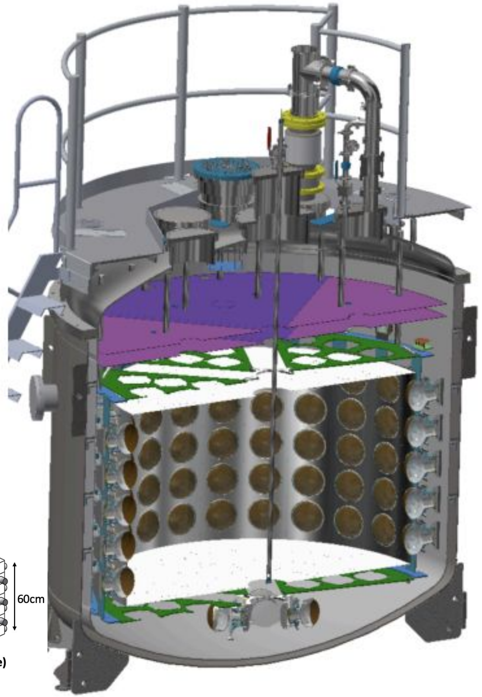
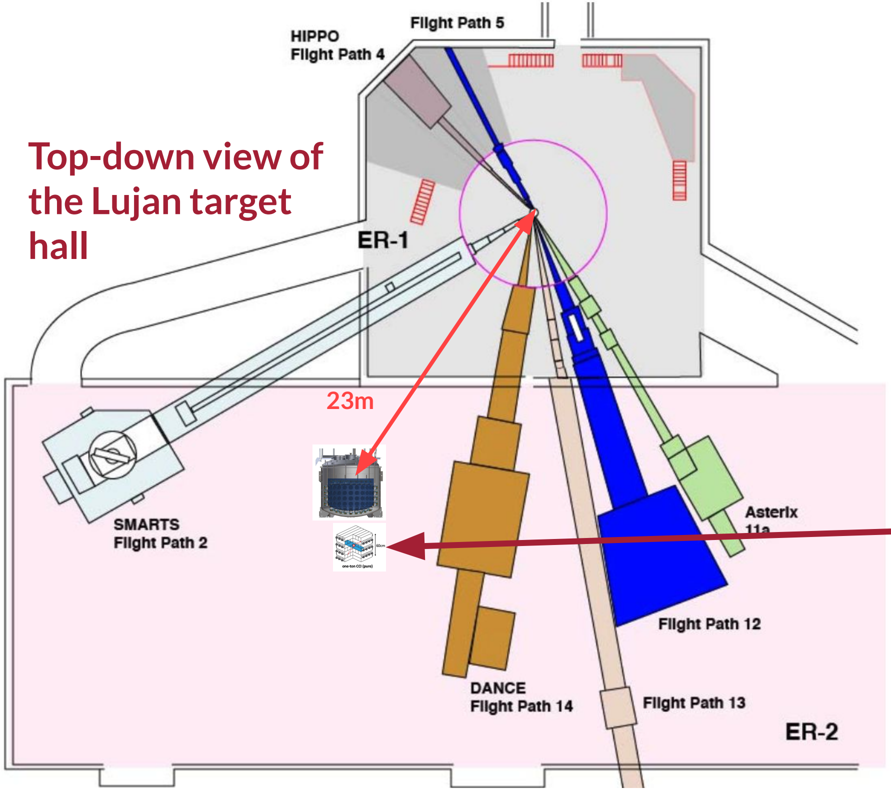




CCI at Lujan



- Initially to be placed behind CCM to take advantage of existing shielding
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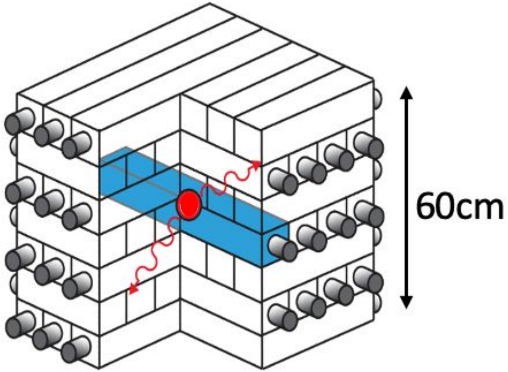
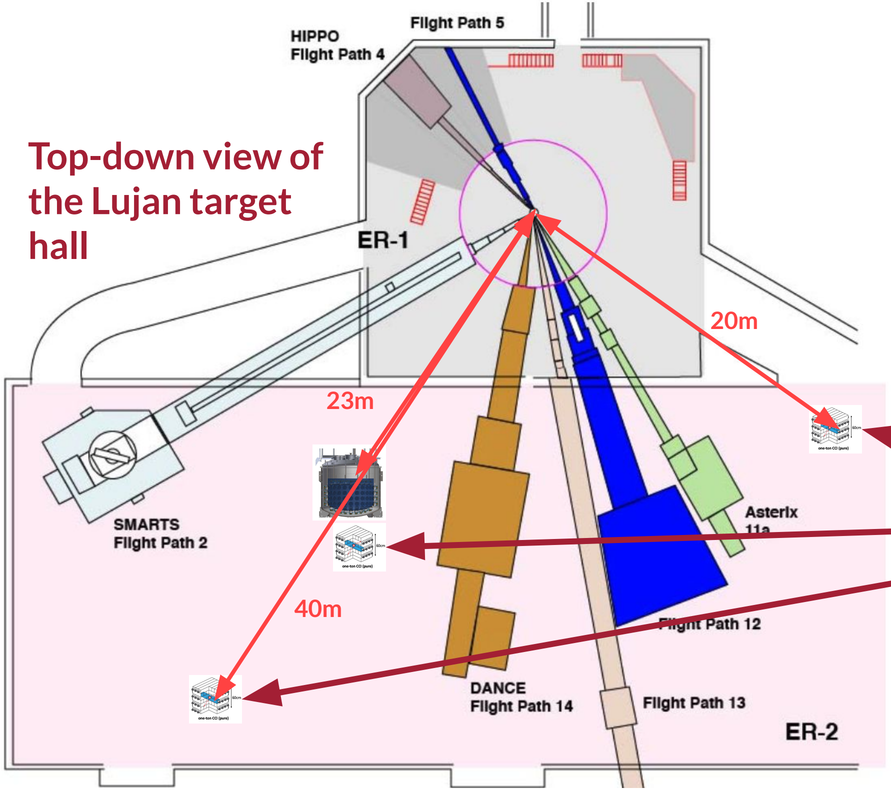


CCI at Lujan

Top-down view of the Lujan target hall



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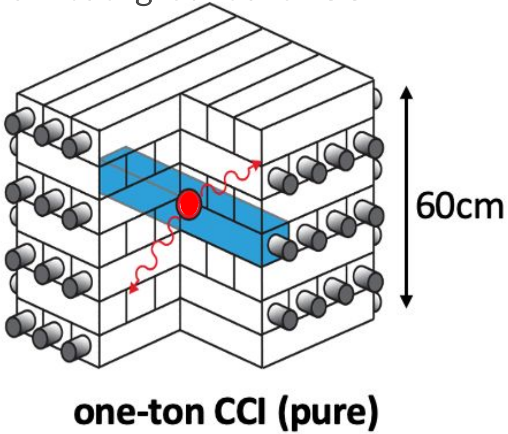

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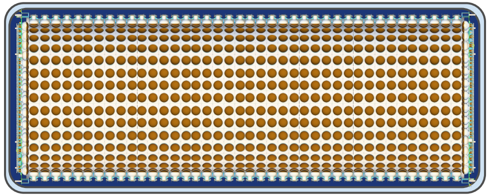
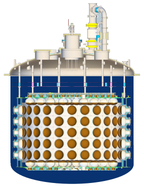
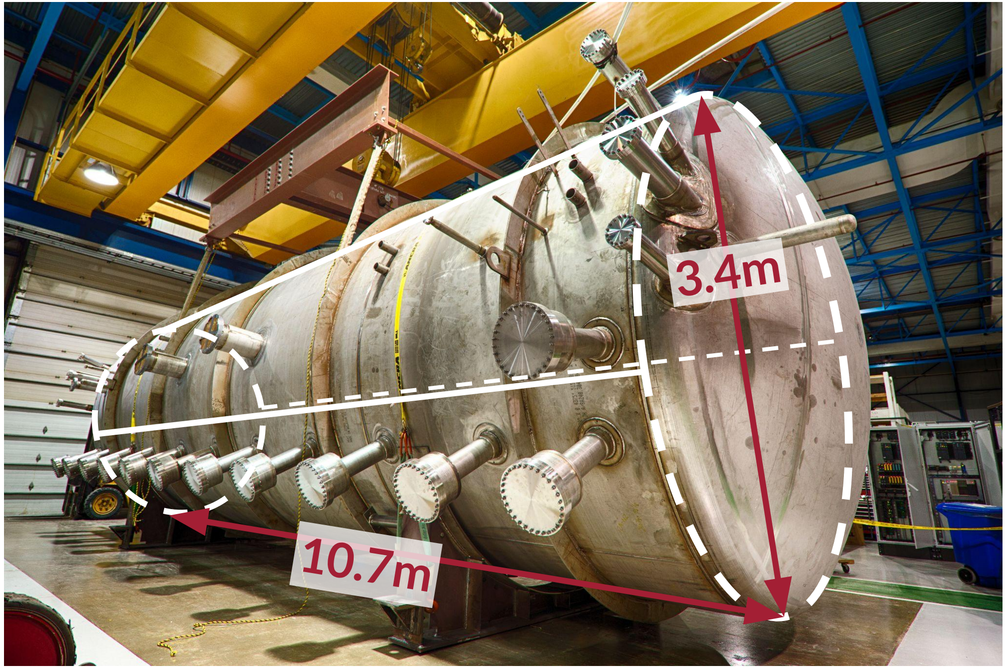
- Detector can be constructed for under $30M

LLAMA	CCM







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

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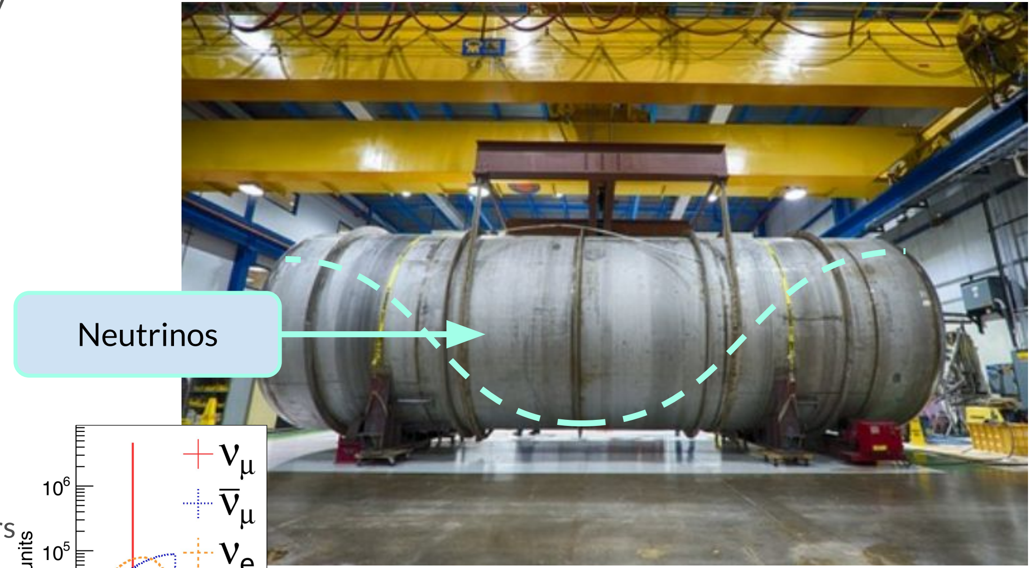
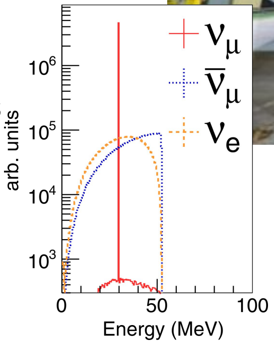
  - Precision cross section measurement
- Sterile neutrino oscillations can be probed over the length of the detector
  - CEvNS gives a very large sample of neutrino interactions
  - Timing can be used to distinguish between flavors
  - Can be supplemented with CC measurements
  - Has sensitivity to the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

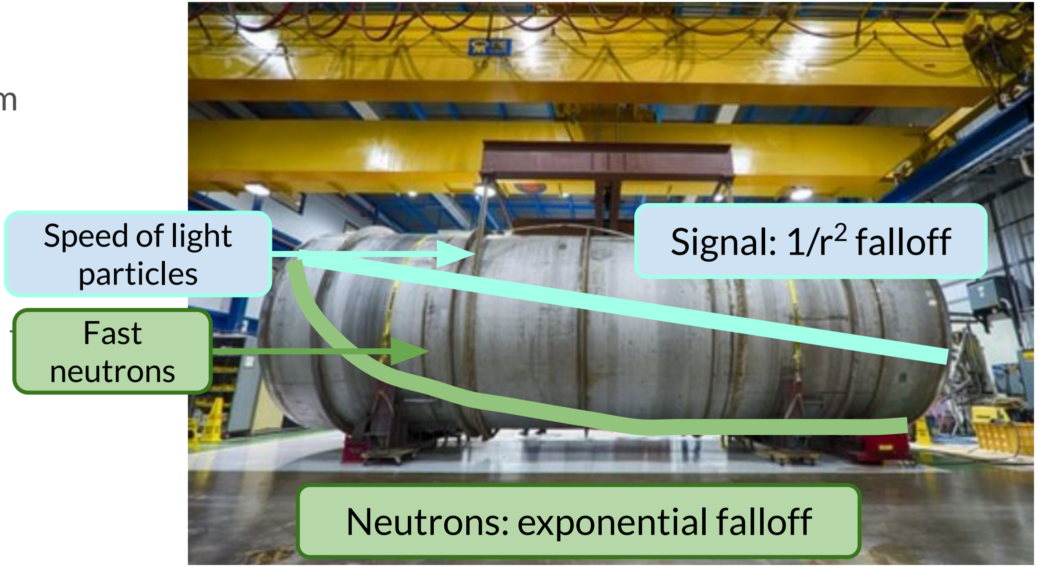




LLAMA

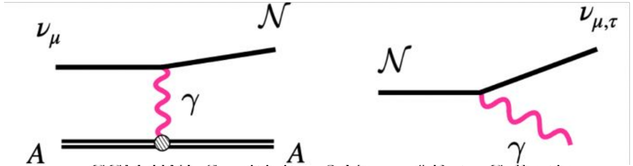
Key improvements over CCM

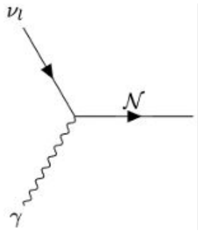
- Shielding the detector is much easier. Most shielding can be concentrated at the front
- Fast neutrons are attenuated by 1/10 across 2m of LAr
    - Neutron background very low at the back of the detector
    - Neutron background has a distinct exponential fall-off that is not present for signal events

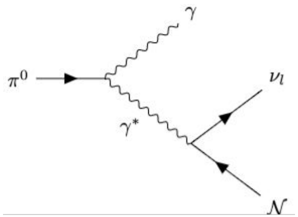


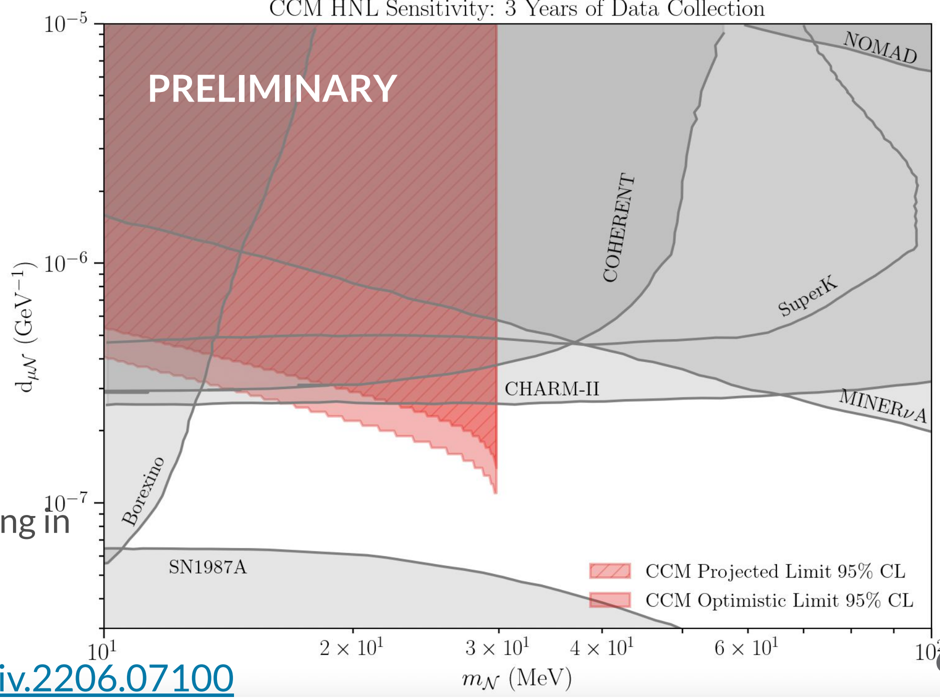
Heavy neutral leptons

- Considering HNL production from neutrino upscattering in shielding and detector materials only
- Potential to increase shielding if detector moved to 40m
- Projected limit: 100 bkg/year
- Optimistic limit: 10 bkg/year
- Other production channels to be considered:
  - Neutrino-photon resonant HNL production
  - Dalitz-like decay









- Can also search for nuclear recoil from upscattering in detector

Recent constraints on this model arXiv.2206.07100